Physics Units 1 & 2

Chapter 13 — Options: astrophysics, particles and contemporary research

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Chapter 13 Options: astrophysics, particles and contemporary research — 13A Option 2.13: How do astrophysicists investigate stars and black holes?

Scope — *VCE Physics Study Design, Unit 2, Area of Study 2, Option 2.13: How do astrophysicists investigate stars and black holes?* (key knowledge: *The physics of stars*):

- `U2.2.O13.1` "apply methods used to investigate the light from stars and for measurements of the distances to stars and galaxies"
- `U2.2.O13.2` "identify the properties of stars, including luminosity, radius and mass, temperature and spectral type, and explain how these properties are used to classify stars"
- `U2.2.O13.3` "distinguish between the different nuclear fusion phenomena that occur in stars of various sizes"
- `U2.2.O13.4` "apply the Hertzsprung–Russell diagram as a tool to describe the evolution and death of stars with differing initial mass"
- `U2.2.O13.5` "explain the event horizon of a black hole and use r_s = 2GM/c² to calculate the Schwarzschild radius"
- `U2.2.O13.6` "describe the effects of the gravitational fields of black holes on space and time"

Theory

One messenger: light. Astronomers cannot visit the stars. Apart from the Sun — and even the Sun can only be studied from a distance — every star is so far away that no spacecraft could reach one within a human lifetime. Almost everything known about stars has therefore been worked out from a single messenger: the electromagnetic radiation they emit. This subtopic follows the chain of reasoning astrophysicists use. First, *how the light is investigated* — collected, split up and measured (`U2.2.O13.1`). Second, *what the light reveals* — the properties of stars, and how those properties classify them (`U2.2.O13.2`). Third, *what powers the light* — nuclear fusion, which differs from star to star (`U2.2.O13.3`). Fourth, *how stars live and die* — read off the Hertzsprung–Russell diagram (`U2.2.O13.4`). And finally, the objects whose gravity is so strong that the light never arrives at all: black holes (`U2.2.O13.5`, `U2.2.O13.6`).

Much of the physics is already yours: waves and the wave equation (1A), the electromagnetic spectrum (1B), dispersion (1D), thermal radiation and Wien's Law (2C), and the conversion of mass to energy in nuclear processes (4A). Where this subtopic refers on to other sections, the cross-reference is given in parentheses. The Communicating physics block that belongs to every option is taught in 10A and 10B; this subtopic closes with the assessed **Option task** marked against those dot points.

Collecting the light. A telescope's first job is simply to collect radiation — a large mirror or dish gathers far more light than the eye, so fainter objects become visible. The second job is to record that radiation with a detector, usually producing a digital image that can be measured. Visible light and radio waves pass through Earth's atmosphere, so optical telescopes and radio telescopes can work from the ground. Most other regions of the electromagnetic spectrum — much of the infrared, and essentially all of the ultraviolet, X-ray and gamma radiation (1B) — are absorbed by the atmosphere before they reach the ground. To investigate stars at those wavelengths, astrophysicists put telescopes above the atmosphere, on satellites. Observing the same object at several wavelengths — **multi-wavelength astronomy** — reveals different physical processes: a star's hot outer atmosphere may glow brightly in X-rays while its surface shines in visible light.

Spectroscopy: splitting the light. The single most powerful method for investigating starlight is **spectroscopy**. Light from a star is passed through a diffraction grating (or a prism) and dispersed into its component wavelengths, as in 1D, producing a **spectrum**. A star's spectrum has two parts that together reveal a great deal:

- a **continuous spectrum** — a smooth band of colours from the hot, dense surface layers of the star, whose peak wavelength reveals the star's surface temperature (below); and
- **absorption lines** — narrow dark lines at particular wavelengths, produced when atoms in the cooler outer layers of the star absorb specific wavelengths of the light coming from below.

Each element absorbs its own unique pattern of wavelengths, like a fingerprint. By matching the pattern of absorption lines in a star's spectrum to the patterns of known elements measured in laboratories on Earth, astrophysicists identify which elements are present in the star's outer layers. The *strengths* of the lines also depend on the star's temperature — which is why the pattern of lines, not just the presence of one or two, is used to classify stars (below).

Brightness, luminosity and the inverse-square law. Two different quantities describe how much light reaches us from a star, and they must not be mixed up:

- the **luminosity** L of a star is the total power it radiates into space, in watts — an intrinsic property of the star itself;
- the **apparent brightness** b is the power arriving per square metre at the detector (for example, at Earth), measured in $\mathrm{W\,m^{-2}}$ — how bright the star *appears* from here.

A star radiates in all directions, so at a distance d its light is spread over the surface of a sphere of area $4\pi d^2$. The apparent brightness is therefore

$$b = \frac{L}{4\pi d^2}.$$

This **inverse-square law** says that doubling the distance spreads the same power over four times the area, so the apparent brightness falls to one quarter. A nearby, modest star can therefore appear brighter than a far more luminous one: Sirius, the brightest star in the night sky, is close by astronomical standards, while far more luminous stars appear much fainter because of their distance. Apparent brightness alone cannot tell you the luminosity — you also need the distance, which is why measuring distances matters so much.

Colour and temperature. In 2C you saw that every object emits thermal radiation, that the peak wavelength of that radiation is given by Wien's Law,

$$\lambda_{\max} T = 2.9 \times 10^{-3}\,\mathrm{m\,K},$$

and that a star's colour is linked to its surface temperature. The same reasoning is one of the main tools of astrophysics. From the star's spectrum, find $\lambda_{\max}$; Wien's Law then gives the surface temperature in kelvin. Hotter stars peak at shorter wavelengths and look blue-white; cooler stars peak at longer wavelengths and look orange-red. The Sun, at about $5800\,\mathrm{K}$, peaks near $500\,\mathrm{nm}$ in the visible region (2C).

Source: NASA, Sun Fact Sheet, retrieved 2026-08-18.

The light-year. Distances to stars are so large that metres become clumsy. The **light-year** (ly) is the distance light travels in a vacuum in one year:

$$1\,\mathrm{ly} = c \times 1\,\mathrm{year} = 3.0 \times 10^{8} \times (365.25 \times 24 \times 3600) = 9.46 \times 10^{15}\,\mathrm{m}.$$

Because light takes time to travel, looking far away is looking back in time: light arriving from a galaxy 2.5 million light-years away left that galaxy 2.5 million years ago. When astrophysicists observe distant objects, they are observing the past.

Parallax for nearby stars. The most direct method of measuring the distance to a star is **parallax** — the apparent shift of a nearby object against a distant background when it is viewed from two different positions. Hold a thumb at arm's length and look at it with one eye, then the other: the thumb seems to jump against the wall behind it. The same idea works for stars. A nearby star is photographed against the background of far more distant stars, and photographed again six months later, when Earth is on the opposite side of its orbit. The star appears to have shifted slightly against the background. The baseline of the measurement is the diameter of Earth's orbit, $2\,\mathrm{AU}$, where one **astronomical unit** is the Earth–Sun distance, $1\,\mathrm{AU} = 1.50 \times 10^{11}\,\mathrm{m}$.

The **parallax angle** p is half the total shift, measured in **arcseconds** (1 degree = 3600 arcseconds, written $3600''$). From the right-angled triangle formed by the Earth, the Sun and the star,

$$d = \frac{1\,\text{AU}}{\tan p}.$$

Parallax works beautifully for nearby stars, but the angle shrinks as the distance grows: even the nearest star, Proxima Centauri, has a parallax of only $0.77''$. Beyond a few thousand light-years the angles are too small to measure accurately from the ground, which is why the European Space Agency's **Gaia** satellite was built: orbiting above the atmosphere, Gaia has measured the positions and parallaxes of about 1.8 billion stars, transforming the map of our galaxy.

Source: International Astronomical Union, IAU 2012 Resolution B2 (defining the astronomical unit), retrieved 2026-08-18. Source: European Space Agency, Gaia Data Release 3, retrieved 2026-08-18.

Standard candles for farther stars and galaxies. To reach beyond parallax, astrophysicists use **standard candles**: objects whose luminosity is known independently. If you know a candle's true luminosity L and measure its apparent brightness b, the inverse-square law rearranged,

$$d = \sqrt{\frac{L}{4\pi b}},$$

gives the distance. The difficulty, of course, is finding objects whose luminosity is genuinely known. Two kinds serve as standard candles:

- **Cepheid variable stars** are stars whose brightness rises and falls regularly, with a period of days to months. At the Harvard College Observatory, Henrietta Swan Leavitt discovered, in work published in 1908 and 1912, that the period of a Cepheid is tied to its luminosity: the longer the period, the more luminous the star. Measuring the period — which needs only a series of brightness measurements, no knowledge of distance — therefore reveals the luminosity, and the inverse-square law gives the distance. Cepheids are bright enough to be seen in nearby galaxies.
- **Type Ia supernovae** are the explosions of white dwarf stars that occur at a characteristic mass, and therefore with a characteristic peak luminosity (white dwarfs and supernovae are described below). Because they are briefly as luminous as a whole galaxy of stars, they can be seen in very distant galaxies.

These methods built the **cosmic distance ladder**: parallax calibrates the nearer standard candles, which in turn calibrate the farther ones. In 1923, Edwin Hubble identified a Cepheid variable in the Andromeda nebula and used Leavitt's relation to show that Andromeda lies far outside the Milky Way — it is a galaxy in its own right, about 2.5 million light-years away. For the most distant galaxies, astrophysicists use the expansion of the Universe itself; that method belongs to Option 2.17 (13D).

Source: NASA, Messier 31 (Andromeda Galaxy), retrieved 2026-08-18.

The properties of stars. `U2.2.O13.2` names five properties used to describe and classify stars. Stellar masses, radii and luminosities are so large that they are usually quoted in units of the Sun's values: $M_\odot$ (solar masses), $R_\odot$ (solar radii) and $L_\odot$ (solar luminosities), where

Quantity	Value
Mass of the Sun, $M_\odot$	$1.99 \times 10^{30}\,\text{kg}$
Radius of the Sun, $R_\odot$	$6.96 \times 10^{8}\,\text{m}$
Luminosity of the Sun, $L_\odot$	$3.8 \times 10^{26}\,\text{W}$
Surface temperature of the Sun	$5800\,\text{K}$

- **Luminosity** (L, in W or in $L_\odot$) — the total power radiated. Stellar luminosities range from less than $10^{-3}\,L_\odot$ for faint red stars to more than $10^{5}\,L_\odot$ for the most luminous supergiants.

- **Radius** (R, in m or in $R_{\odot}$) — the size of the star's visible surface. Radii range from white dwarfs, about the size of Earth ($\sim 0.01\,R_{\odot}$), to supergiants hundreds of times the Sun's radius. At the same surface temperature, a larger star has more radiating surface, so it has the greater luminosity (2C).
- **Mass** (M, in kg or in $M_{\odot}$) — the amount of matter in the star, from about $0.1\,M_{\odot}$ to over $100\,M_{\odot}$. Mass cannot be read from a single star's light directly. It is measured from **binary stars** — pairs of stars orbiting their common centre of mass: from the sizes of the orbits and how fast the stars move around them, the masses can be worked out. Mass is the most important property of a star, because it sets the star's core temperature, its fusion rate, its luminosity, its lifetime and its final fate.
- **Temperature** (T, in K) — the surface temperature, from Wien's Law applied to the star's spectrum.
- **Spectral type** — the class assigned from the star's pattern of absorption lines (below).

Source: NASA, Sun Fact Sheet, retrieved 2026-08-18. Source: International Astronomical Union, IAU 2015 Resolution B3 — Recommended Nominal Units for Stellar & Planetary Astronomy (nominal solar values), retrieved 2026-08-18.

Spectral types: classifying stars. When stars are sorted by surface temperature, their absorption-line patterns change in a regular sequence. The resulting classification, in order of decreasing temperature, is:

Spectral type	Surface temperature (approx.)	Colour	Example
O	above 30 000 K	blue	—
B	10 000–30 000 K	blue-white	Rigel
A	7500–10 000 K	white	Sirius
F	6000–7500 K	yellow-white	—
G	5200–6000 K	yellow-white	the Sun
K	3700–5200 K	orange	—
M	2400–3700 K	red	Betelgeuse, Proxima Centauri

(Still cooler classes, L and T, exist for objects too cool to be ordinary stars.) Two stars of the same temperature can still have very different luminosities — a giant star and a dwarf star can share a spectral type — so the full classification adds a **luminosity class**: class V for main-sequence stars like the Sun, class III for giants, and class I for supergiants. The Sun is classified G2 V. Classifying a star therefore uses its spectrum twice over: the line pattern fixes the temperature (spectral type), and the widths and details of the lines fix the luminosity class. That is how the properties of `U2.2.O13.2` are used to classify stars.

Source: NASA, Imagine the Universe! — Stars, retrieved 2026-08-18.

Fusion powers the stars. A star shines because nuclear fusion in its core converts mass into energy ($E = \Delta m c^2$), the process you met in 4A: in every fusion reaction, the mass of the products is slightly less than the mass of the reactants, and the missing mass appears as energy. The details of the fusion reactions themselves are treated in Option 2.2 (10D); here the question is how fusion differs between stars of various sizes.

- **Sun-like stars** fuse hydrogen into helium through the **proton–proton chain**, in which hydrogen nuclei (protons) combine in a sequence of steps to form helium nuclei. The Sun converts roughly 600 million tonnes of hydrogen into helium every second; in the process, about 4 million tonnes of matter are converted into energy each second. The Sun is about 4.6 billion years old and is roughly halfway through its main-sequence life.
- **More massive stars** have hotter, denser cores. They run the same net reaction — hydrogen to helium — but much faster, and at their higher temperatures a second route, the **CNO cycle**, in which carbon, nitrogen and oxygen nuclei act as go-betweens in the fusion of hydrogen, becomes important. Because the fusion rate rises

so steeply with core temperature, massive stars burn their fuel enormously faster than they should by fuel supply alone: a star twenty times the Sun's mass has twenty times the fuel, but uses it thousands of times faster, and lives only millions of years — a thousand times shorter than the Sun's main-sequence life.

- **After the hydrogen runs out**, the two kinds of star part company. A Sun-like star's core can eventually become hot enough to fuse helium into carbon and oxygen — and there it stops; the core never reaches the temperatures needed for anything heavier. A massive star keeps going: as each fuel is exhausted, the core contracts, heats, and ignites the next one, fusing helium to carbon and oxygen, then carbon to neon and magnesium, and so on through silicon to **iron**, in nested layers like an onion. Iron is the end of the line: it sits at the peak of the binding energy curve (4A), so fusing iron absorbs energy instead of releasing it. With no fusion left to support it, the iron core collapses — and the star dies violently (below).

Source: NASA, NASA Science — The Sun, retrieved 2026-08-18.

The Hertzsprung–Russell diagram. If the temperatures and luminosities of many stars are plotted on one graph, the points do not fall at random. The **Hertzsprung–Russell (H–R) diagram** has temperature on the horizontal axis — *increasing to the left*, by historical convention — and luminosity (in $L_{\odot}$) on the vertical axis. Three regions contain almost all stars:

Region	Where on the H–R diagram	What it is
Main sequence	a band running from hot and luminous (top left) to cool and dim (bottom right)	stars fusing hydrogen in their cores — about 90% of all stars, including the Sun
Giants and supergiants	top right — cool but very luminous	large stars (huge radii) in later stages of evolution, such as Betelgeuse
White dwarfs	bottom left — hot but very dim	tiny, dense remnants of Sun-like stars (small radii), such as Sirius B

The H–R diagram is a tool, not just a picture. A star's position on it tells you its present stage of life, and the theory of stellar evolution predicts the path — the **evolutionary track** — a star follows across the diagram as it ages. The track a star follows is set almost entirely by one number: its **initial mass**.

Evolution and death by initial mass.

Stars like the Sun (initial mass up to about $8\,M_{\odot}$). A star forms when a cloud of gas and dust contracts under its own gravity and heats up until its core is hot enough for hydrogen fusion to begin: the star settles onto the main sequence, where it spends most of its life. When the core hydrogen is exhausted, the core contracts while the outer layers expand and cool: the star moves up and to the right of the H–R diagram and becomes a **red giant**. Helium fusion (helium to carbon and oxygen) begins in the core; when that is spent, the star gently expels its outer layers, which drift away as a glowing **planetary nebula**. The hot core left behind — about the mass of the Sun packed into a volume the size of Earth — is a **white dwarf**: dense, hot and no longer fusing, it slowly cools over billions of years.

Massive stars (initial mass above about $8\,M_{\odot}$). Massive stars live fast. They sit at the hot, luminous end of the main sequence, then expand into **red supergiants** — Betelgeuse is one — and build the nested fusion layers described above, ending at iron. When the iron core can no longer support itself, it collapses in less than a second; the outer layers rebound and are blown apart in a **supernova** explosion, briefly rivalling the light of a whole galaxy. What the collapse leaves behind depends on the mass of the remnant core: a **neutron star** — matter crushed into a ball roughly $10\,\text{km}$ in radius — if the remnant is up to about $3\,M_{\odot}$, or a **black hole** if it is more massive than that.

The Sun's own fate is the first story: in roughly five billion years it will become a red giant, shed its outer layers, and end as a white dwarf. It will never become a supernova, and it will never become a black hole — it does not have the mass.

Black holes. A **black hole** is a region of space where matter has been compressed so extremely that the gravitational field is strong enough to prevent anything — including light — from escaping. Stellar-mass black holes form in the supernovae of the most massive stars; far heavier **supermassive black holes**, millions to billions of solar masses, sit at the centres of galaxies, including our own.

The boundary of a black hole is the **event horizon**: not a material surface, but the dividing line between the region from which escape is still possible and the region from which it is not. Light emitted just outside the event horizon can escape; light emitted inside it never reaches the outside universe. The event horizon is therefore the limit of what any observer outside can ever find out about the interior — which is why the word *horizon* fits.

The radius of the event horizon is the **Schwarzschild radius**, r_s. One way to motivate it is classical: the more compact a mass is, the faster an object at its surface must travel to escape its gravity; if the mass were squeezed inside a small enough radius, that escape speed would reach the speed of light c, and nothing could get away. Setting the escape speed equal to c yields exactly the expression that Einstein's general theory of relativity gives for the event horizon:

$$r_s = \frac{2GM}{c^2},$$

where $G = 6.67 \times 10^{-11}\,\text{N m}^2\,\text{kg}^{-2}$ is the universal gravitational constant and $c = 3.0 \times 10^8\,\text{m s}^{-1}$ is the speed of light in a vacuum (both from the formula sheet). The radius is proportional to the mass: every solar mass contributes about $3.0\,\text{km}$ of Schwarzschild radius. For the Sun itself, $r_s \approx 3.0\,\text{km}$ — compared with its real radius of $6.96 \times 10^8\,\text{m}$, which shows how drastically matter must be compressed to form a black hole. The Sun will never achieve that compression; only the collapsed cores of massive stars do.

Investigating the invisible. If no light escapes a black hole, how is one investigated? By its effects on everything around it:

- **Orbiting stars.** At the centre of the Milky Way, stars have been tracked for decades as they orbit an invisible point, Sagittarius A*, at tremendous speeds; from their orbits, the central mass works out to about $4.0 \times 10^6\,M_\odot$, contained in a region too small to be anything but a black hole. The 2020 Nobel Prize in Physics recognised this work.
- **Radiation from infalling gas.** Gas falling towards a black hole is heated to millions of kelvin and emits X-rays before it crosses the event horizon — how stellar-mass black holes such as Cygnus X-1, about $21\,M_\odot$, were first identified.
- **Direct imaging.** The Event Horizon Telescope — radio telescopes around the world observing together as one Earth-sized telescope — produced the first image of a black hole's shadow, the supermassive black hole in galaxy M87 ($6.5 \times 10^9\,M_\odot$) in 2019, and the image of Sagittarius A* in 2022.
- **Gravitational waves.** When two black holes merge, they send ripples through spacetime itself; the detection of these waves, first achieved in 2015, opened an entirely new way of observing the Universe. How the detection of gravitational waves contributes to our understanding of the Universe is treated in Option 2.17 (13D).

Source: Event Horizon Telescope Collaboration, First Sagittarius A Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole in the Center of the Galaxy, The Astrophysical Journal Letters, 2022, retrieved 2026-08-18. Source: Event Horizon Telescope Collaboration, First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole, The Astrophysical Journal Letters, 2019, retrieved 2026-08-18. Source: Miller-Jones et al., Cygnus X-1 contains a 21-solar mass black hole, Science, 2021, retrieved 2026-08-18. Source: LIGO Scientific Collaboration and Virgo Collaboration, Observation of Gravitational Waves from a Binary Black Hole Merger, Physical Review Letters, 2016, retrieved 2026-08-18.*

Space and time near a black hole. Einstein's general theory of relativity describes gravity not as a force pulling across space, but as the curving of **spacetime** — space and time treated as a single fabric — by mass. The greater the mass, and the more compact it is, the stronger the curvature. A black hole is the most extreme case in the Universe. Four effects follow, all described qualitatively here (`U2.2.O13.6`):

- **Time runs differently.** A clock deep in a gravitational field runs more slowly than a clock far away. To a distant observer, a clock falling towards an event horizon would appear to tick more and more slowly. This is not illusion or instrument trouble: the same effect, enormously smaller, is measured around Earth, and satellite navigation systems must allow for it.

- **Light loses energy climbing out.** Light travelling away from a strong gravitational field is shifted to longer wavelengths — a **gravitational redshift**. Near an event horizon the redshift becomes so large that escaping light is stretched towards invisibility.
- **Light paths bend.** Curved spacetime bends the path of light passing near a massive object, an effect called **gravitational lensing**: a black hole between us and a distant star or galaxy can distort, multiply or ring its image. Lensing lets astrophysicists detect massive objects that emit no light at all.
- **Tides stretch.** Because gravity weakens with distance, the pull on the near side of any object falling towards a black hole is much stronger than on its far side. The difference — a tidal effect — stretches the object lengthways and squeezes it sideways. Near a stellar-mass black hole these tides would tear matter apart well before it reached the event horizon.

These effects belong to the same theory that describes the orbit of every planet; near a black hole they are simply taken to the extreme.

Links to other sections. Waves and spectra: 1A, 1B, 1D. Thermal radiation and Wien's Law: 2C. Mass–energy conversion and the binding energy curve: 4A. The fusion reactions in detail: Option 2.2 (10D). Spectroscopy applied to exoplanets, and the Doppler shift: Option 2.14 (13B). The Big Bang, cosmic background radiation and gravitational waves: Option 2.17 (13D). Communicating physics — sources, terminology, societal factors and justifying a stance: 10A and 10B; the Option task below closes this subtopic.

Worked examples

Example 1 — scaffolded

Proxima Centauri, the nearest star to the Sun, has a measured parallax angle of $0.77''$. Use $1\,\text{AU} = 1.50 \times 10^{11}\,\text{m}$ and $1\,\text{ly} = 9.46 \times 10^{15}\,\text{m}$. (a) Convert the parallax angle to degrees. (b) Calculate the distance to Proxima Centauri in metres. (c) Convert the distance to light-years.

Working	Comment
(a) $p = 0.77'' = \dfrac{0.77}{3600} = 2.1 \times 10^{-4}$ degrees.	1 degree $= 3600$ arcseconds.
(b) $d = \dfrac{1\,\text{AU}}{\tan p} = \dfrac{1.50 \times 10^{11}}{\tan\left(2.1 \times 10^{-4\circ}\right)} = \dfrac{1.50 \times 10^{11}}{3.7 \times 10^{-6}} = 4.0 \times 10^{16}$.	For such a small angle, $\tan p \approx p$ in radians; set your calculator to degrees.
(c) $d = \dfrac{4.0 \times 10^{16}}{9.46 \times 10^{15}} = 4.2\,\text{ly}$.	Divide metres by the metres in one light-year.

The result is sensible: parallax angles below about $1''$ correspond to distances of several light-years, and $0.77''$ is a relatively large parallax — which is exactly what is expected for the nearest star.

Example 2 — scaffolded

The X-ray source Cygnus X-1 contains a black hole of mass about $21\,M_\odot$, one of the most massive stellar-mass black holes known in our galaxy. Use $G = 6.67 \times 10^{-11}\,\text{N m}^2\,\text{kg}^{-2}$, $c = 3.0 \times 10^8\,\text{m s}^{-1}$ and $M_\odot = 1.99 \times 10^{30}\,\text{kg}$. Calculate the Schwarzschild radius of this black hole, and comment on its size.

Working	Comment
$M = 21 \times 1.99 \times 10^{30} = 4.2 \times 10^{31}\,\text{kg}$.	Convert solar masses to kilograms first.

Working	Comment
$r_s = \frac{2GM}{c^2} = \frac{2 \times 6.67 \times 10^{-11} \times 4.2 \times 10^{31}}{(3.0 \times 10^8)^2}$.	Substitute into the Schwarzschild-radius formula.
$r_s = \frac{5.6 \times 10^{21}}{9.0 \times 10^{16}} = 6.2 \times 10^4\,\text{m} = 62\,\text{km}$.	$(3.0 \times 10^8)^2 = 9.0 \times 10^{16}$.
$62\,\text{km}$ is smaller than many cities.	The event horizon of a black hole with twenty-one times the Sun's mass fits inside a large city — a measure of how compact a black hole is.

Check: $r_s \approx 3.0\,\text{km}$ per solar mass, so $21\,M_\odot$ gives about $63\,\text{km}$. ✓

Example 3 — unscaffolded

Sagittarius A*, at the centre of the Milky Way, is a supermassive black hole of mass $4.0 \times 10^6\,M_\odot$. Calculate its Schwarzschild radius in metres, and express it in astronomical units ($1\,\text{AU} = 1.50 \times 10^{11}\,\text{m}$). Comment on the result by comparing the event horizon with the size of Earth's orbit.

The mass in kilograms is $M = 4.0 \times 10^6 \times 1.99 \times 10^{30} = 7.96 \times 10^{36}\,\text{kg}$, so

$$r_s = \frac{2GM}{c^2} = \frac{2 \times 6.67 \times 10^{-11} \times 7.96 \times 10^{36}}{(3.0 \times 10^8)^2} = \frac{1.06 \times 10^{27}}{9.0 \times 10^{16}} = 1.2 \times 10^{10}\,\text{m}.$$

In astronomical units,

$$r_s = \frac{1.2 \times 10^{10}}{1.50 \times 10^{11}} = 0.08\,\text{AU}.$$

(Equivalently: $3.0\,\text{km}$ per solar mass gives $3.0 \times 10^3 \times 4.0 \times 10^6 = 1.2 \times 10^{10}\,\text{m}$ directly.) The event horizon of Sagittarius A* is about eight hundredths of the Earth–Sun distance: even for a black hole four million times the Sun's mass, the event horizon fits comfortably inside Earth's orbit. (Check: $r_s / R_\odot = 1.2 \times 10^{10} / 6.96 \times 10^8 \approx 17$, about seventeen solar radii. ✓)

$\therefore r_s \approx 1.2 \times 10^{10}\,\text{m} = 0.08\,\text{AU}$ — small compared with Earth's orbit of radius $1\,\text{AU}$.

Example 4 — unscaffolded

Betelgeuse, in the constellation Orion, is a red supergiant with a surface temperature of about $3600\,\text{K}$ and a luminosity of about $10^5\,L_\odot$, despite being much cooler than the Sun ($5800\,\text{K}$). (a) Use Wien's Law to calculate the peak wavelength of the radiation Betelgeuse emits, and name the region of the spectrum in which it lies. (b) On the H–R diagram, where is Betelgeuse located, and how can a star cooler than the Sun be so much more luminous? (c) Betelgeuse's initial mass is estimated at roughly fifteen to twenty times the Sun's. Describe the fate that stellar evolution predicts for it.

(a) By Wien's Law,

$$\lambda_{\max} = \frac{2.9 \times 10^{-3}}{T} = \frac{2.9 \times 10^{-3}}{3600} = 8.1 \times 10^{-7}\,\text{m} = 810\,\text{nm},$$

which lies in the **infrared** region. Betelgeuse's visible emission is strongest at the red end of the spectrum — hence its red colour.

(b) Betelgeuse sits in the **top right** of the H–R diagram: cool (right) but extremely luminous (top) — the supergiant region. A cooler surface emits less power per square metre than a hotter one (2C), so a cool star can outshine the Sun only if it has vastly more radiating surface: Betelgeuse's radius is hundreds of times the Sun's. The H–R diagram makes this reasoning visible — the top-right region is exactly where large-radius, cool, luminous stars belong.

(c) With an initial mass well above $8\,M_{\odot}$, Betelgeuse will end its life in a **supernova**: its core will fuse elements up to iron, the iron core will collapse, and the outer layers will be blown apart. The remnant core — depending on its mass — will become a **neutron star** (remnant up to about $3\,M_{\odot}$) or a **black hole** (remnant more massive than that). On the H–R diagram, its track leaves the supergiant region at the supernova; the remnant no longer sits on the ordinary diagram of shining stars.

$\therefore\ \lambda_{\text{max}} \approx 810\,\text{nm}$ (infrared); Betelgeuse is a top-right (supergiant) H–R star whose enormous radius explains its luminosity despite its low temperature; its predicted fate is a supernova, leaving a neutron star or a black hole.

Practice questions

Question 1 *(scaffolded)* Barnard's Star has a measured parallax angle of $0.55''$. Use $1\,\text{AU} = 1.50 \times 10^{11}\,\text{m}$ and $1\,\text{ly} = 9.46 \times 10^{15}\,\text{m}$. (a) Convert $0.55''$ to degrees. (b) Calculate the distance to Barnard's Star in metres, using $d = 1\,\text{AU} / \tan p$. (c) Convert your answer to light-years.

Question 2 *(scaffolded)* The Andromeda Galaxy is about 2.5 million light-years away. (a) Define the light-year. (b) Calculate the distance to the Andromeda Galaxy in metres. (c) Light arriving at Earth from Andromeda today left Andromeda long ago. State how long ago, and explain what this means for what we observe.

Question 3 *(scaffolded)* Rigel, a blue-white supergiant, has a surface temperature of about $12\,000\,\text{K}$. Betelgeuse, a red supergiant, has a peak wavelength of about $810\,\text{nm}$. (a) Use Wien's Law to calculate the peak wavelength of Rigel's radiation, and name the region of the spectrum in which it lies. (b) Use Wien's Law to calculate the surface temperature of Betelgeuse. (c) State which star appears red and which appears blue-white, and explain why in terms of the visible part of each star's radiation curve.

Question 4 *(scaffolded)* A black hole has a Schwarzschild radius equal to the radius of Earth, $6.37 \times 10^{6}\,\text{m}$. Use $G = 6.67 \times 10^{-11}\,\text{N m}^2\,\text{kg}^{-2}$ and $c = 3.0 \times 10^{8}\,\text{m s}^{-1}$. (a) Rearrange $r_s = 2GM/c^2$ to make M the subject. (b) Calculate the mass of the black hole in kilograms. (c) Express the mass in solar masses ($M_{\odot} = 1.99 \times 10^{30}\,\text{kg}$).

Question 5 *(scaffolded)* The Sun's luminosity is $3.8 \times 10^{26}\,\text{W}$, and Earth orbits at $1.50 \times 10^{11}\,\text{m}$ from the Sun. (a) Write the expression for the apparent brightness b of a star of luminosity L at distance d. (b) Calculate the apparent brightness of the Sun at Earth. (c) The measured solar constant — the solar power arriving at Earth per square metre — is about $1361\,\text{W m}^{-2}$. Compare your answer with this value and comment.

Question 6 *(scaffolded)* The table gives the surface temperatures of three stars.

Star	Surface temperature
Sirius A	$9900\,\text{K}$
the Sun	$5800\,\text{K}$
Proxima Centauri	$3000\,\text{K}$

(a) List the stars from hottest to coolest.
(b) Use the spectral-type table in the theory to assign a spectral type (O, B, A, F, G, K or M) to each star.
(c) State the stellar property on which the spectral classification is based, and the observation from which that property is obtained.

Question 7 A star's spectrum shows a continuous band of colours crossed by dark absorption lines. Explain how the pattern of absorption lines identifies the elements present in the star's outer layers, and why the same pattern of lines also carries information about the star's temperature.

Question 8 Two stars have the same radius, but star A has a surface temperature of $8000\,\text{K}$ and star B has a surface temperature of $4000\,\text{K}$. (a) State which star has the greater luminosity, justifying your answer. (b) Use Wien's Law to calculate the peak wavelength of each star's radiation, and hence state the colour of each star.

Question 9 Some stars orbit in pairs, called binary stars, each orbiting their common centre of mass. (a) Explain how observations of a binary star system allow astrophysicists to work out the masses of the two stars. (b) Explain why mass is considered the most important property of a star.

Question 10 Fusion in stars of various sizes. (a) State the net fusion reaction that powers a main-sequence star. (b) Distinguish what happens, fusion-wise, in the core of a Sun-like star and in the core of a massive star once the hydrogen is exhausted. (c) Use the binding energy curve (4A) to explain why fusion cannot release energy once a star's core is fusing iron. (d) Each second, the Sun converts about 4 million tonnes (4.0×10^{9} kg) of matter into energy. Use $E = mc^2$ to calculate the energy released each second, and compare your answer with the Sun's luminosity, 3.8×10^{26} W.

Question 11 The Sun will spend about ten billion years on the main sequence, while a star of twenty solar masses spends only about ten million years there. The massive star has twenty times as much fuel, yet its life is about a thousand times shorter. Explain this, referring to core temperature, fusion rate and luminosity.

Question 12 (a) Draw the axes of a Hertzsprung–Russell diagram, labelling the quantity and direction of each axis. Mark and label the main sequence, the giant and supergiant region, and the white dwarf region. (b) Explain what a star's position on the H–R diagram tells you about it, and what determines the path the star follows across the diagram as it ages.

Question 13 Describe the future evolution of the Sun, from its present position on the H–R diagram to its final state. Name each stage, and say how the Sun's position on the H–R diagram changes at each one.

Question 14 A star with an initial mass of twenty-five solar masses ends its life very differently from the Sun. Describe the star's evolution from the main sequence to its final remnant, naming each stage, and explain what determines whether the remnant is a neutron star or a black hole.

Question 15 (a) Define the event horizon of a black hole. (b) Explain why a black hole appears black. (c) The Schwarzschild radius is sometimes motivated by asking: at what radius would the escape speed from a mass equal the speed of light? Explain how this line of reasoning connects mass and the size of the event horizon, and state the formula it yields.

Question 16 The Sun's mass is 1.99×10^{30} kg and its radius is 6.96×10^{8} m. Use $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2} and $c = 3.0 \times 10^{8}$ m s^{-1}. (a) Calculate the Schwarzschild radius the Sun's mass would have. (b) Calculate the factor by which the Sun's present radius exceeds this value. (c) Explain what this comparison tells you about what would be required for the Sun to become a black hole — and whether the Sun's evolution will ever provide it (use Question 13).

Question 17 Describe three effects that the gravitational field of a black hole has on space and time, and for each one state how it could help astrophysicists investigate an otherwise invisible black hole.

Question 18 (a) A single method cannot measure every distance in the Universe. Explain why parallax fails for very distant stars, and how Cepheid variable stars and then Type Ia supernovae extend the distance ladder beyond it. In your answer, explain what Henrietta Swan Leavitt's period–luminosity relation contributes, and state what Edwin Hubble's 1923 observation of a Cepheid in the Andromeda nebula established. (b) A Cepheid variable star has a luminosity of 3.8×10^{29} W, and its apparent brightness measured at Earth is 1.2×10^{-10} W m^{-2}. Calculate its distance from Earth in metres and in light-years ($1\ \text{ly} = 9.46 \times 10^{15}$ m).

Answers

Question 1 (a) 1.5×10^{-4} degrees; (b) 5.6×10^{16} m; (c) 6.0 ly. **Question 2** (a) the distance light travels in a vacuum in one year; (b) 2.4×10^{22} m; (c) 2.5 million years — we observe Andromeda as it was 2.5 million years ago. **Question 3** (a) 2.4×10^{-7} m (240 nm), ultraviolet; (b) about 3600 K; (c) Betelgeuse appears red, Rigel blue-white — see solution. **Question 4** (a) $M = r_s c^2 / 2G$; (b) 4.3×10^{33} kg; (c) about $2200\, M_{\odot}$. **Question 5** (a) $b = L / (4\pi d^2)$; (b) about $1340\ \text{W m}^{-2}$; (c) agrees with the measured $1361\ \text{W m}^{-2}$ within rounding — see solution. **Question 6** (a) Sirius A, the Sun, Proxima Centauri; (b) A, G, M; (c) surface temperature, from the star's spectrum (absorption-line pattern). **Question 7** See solution — unique line patterns per element; line strengths depend on temperature. **Question 8** (a) star A; (b) 360 nm (blue-white) and 730 nm (red-orange) — see solution. **Question 9** (a) from the orbital sizes and speeds; (b) mass sets core temperature, fusion rate, luminosity, lifetime and fate. **Question 10** (a) hydrogen → helium; (b) Sun-like: only helium fusion follows; massive: fusion continues in stages up to iron; (c) iron sits at the peak of the binding energy curve; (d) 3.6×10^{26} J each second, i.e. 3.6×10^{26} W — agrees with the Sun's luminosity. **Question 11** See solution — a hotter core fuses enormously faster, so the extra fuel is burnt far more rapidly than it is supplied. **Question 12** See solution — axes: luminosity (up), temperature (hotter to the left); position = present stage; path set by initial mass. **Question 13** See solution — main sequence → red giant → planetary nebula → white dwarf, with the H–R movements described. **Question 14** See solution — main sequence → red supergiant → supernova → neutron star or black hole; remnant mass (about $3\, M_{\odot}$) decides which. **Question 15** See solution — (a) boundary of no return; (b) no light escapes from inside it; (c) $r_s = 2GM/c^2$. **Question 16** (a) about 3.0 km; (b) about 2.4×10^5; (c) see solution — compression far beyond anything in the Sun's future. **Question 17** See solution — time dilation, gravitational redshift, gravitational lensing (tidal stretching also accepted), each linked to an observational use. **Question 18** (a) See solution — parallax angles become too small; Leavitt's relation makes Cepheids standard candles; supernovae reach farther still; Hubble established that Andromeda lies far outside the Milky Way. (b) 1.6×10^{19} m, about 1700 ly.

Fully-worked solutions

Question 1 (a) $p = 0.55'' = 0.55/3600 = 1.5 \times 10^{-4}$ degrees. (b) $d = \dfrac{1\ \text{AU}}{\tan p} = \dfrac{1.50 \times 10^{11}}{\tan(1.5 \times 10^{-4}\,{}^\circ)} = \dfrac{1.50 \times 10^{11}}{2.7 \times 10^{-6}} = 5.6 \times 10^{16}\ \text{m}$. (c) $d = \dfrac{5.6 \times 10^{16}}{9.46 \times 10^{15}} = 5.9\ \text{ly} \approx 6.0\ \text{ly}$.

Question 2 (a) A light-year is the distance light travels in a vacuum in one year (9.46×10^{15} m). (b) $d = 2.5 \times 10^6 \times 9.46 \times 10^{15} = 2.4 \times 10^{22}\ \text{m}$. (c) The light left Andromeda 2.5 million years ago. Looking far away is looking back in time: we observe Andromeda as it was 2.5 million years in the past, not as it is now.

Question 3 (a) $\lambda_{\max} = \dfrac{2.9 \times 10^{-3}}{T} = \dfrac{2.9 \times 10^{-3}}{12\,000} = 2.4 \times 10^{-7}\ \text{m} = 240\ \text{nm}$, in the **ultraviolet** region. (b) $T = \dfrac{2.9 \times 10^{-3}}{\lambda_{\max}} = \dfrac{2.9 \times 10^{-3}}{810 \times 10^{-9}} = 3580\ \text{K} \approx 3600\ \text{K}$. (c) Betelgeuse appears **red** and Rigel appears **blue-white**. Betelgeuse's peak is in the infrared, so within the visible region its curve is strongest at the long-wavelength (red) end; Rigel's peak is in the ultraviolet, so its visible emission is strongest at the short-wavelength (blue and violet) end.

Question 4 (a) $M = \dfrac{r_s c^2}{2G}$. (b) $M = \dfrac{6.37 \times 10^6 \times (3.0 \times 10^8)^2}{2 \times 6.67 \times 10^{-11}} = \dfrac{6.37 \times 10^6 \times 9.0 \times 10^{16}}{1.334 \times 10^{-10}} = \dfrac{5.73 \times 10^{23}}{1.334 \times 10^{-10}} = 4.3 \times 10^{33}\ \text{kg}$. (c) $\dfrac{4.3 \times 10^{33}}{1.99 \times 10^{30}} \approx 2200\, M_{\odot}$.

Question 5 (a) $b=\frac{L}{4\pi d^2}$ — the luminosity spread over a sphere of area $4\pi d^2$. (b) $b=\frac{3.8\times10^{26}}{4\pi\times(1.50\times10^{11})^2}=\frac{3.8\times10^{26}}{2.8\times10^{23}}\approx1340\text{ W m}^{-2}$. (c) The calculated value ($\approx1340\text{ W m}^{-2}$) agrees with the measured solar constant (1361 W m^{-2}) within the rounding of the input values (L is quoted to two significant figures). This is a check that the inverse-square law, applied to the Sun's known luminosity, reproduces a directly measured quantity at Earth.

Question 6 (a) Sirius A (9900 K), the Sun (5800 K), Proxima Centauri (3000 K). (b) Sirius A: 9900 K falls in 7500–10 000 K → type **A**. The Sun: 5800 K falls in 5200–6000 K → type **G**. Proxima Centauri: 3000 K falls in 2400–3700 K → type **M**. (c) The classification is based on **surface temperature**, which is obtained from the star's **spectrum** — the pattern and strengths of its absorption lines (and, equivalently, from the peak wavelength of its continuous spectrum via Wien's Law).

Question 7 Model answer (4 marks): Each element absorbs a unique pattern of wavelengths, like a fingerprint, so matching the dark lines in a star's spectrum to the laboratory patterns of known elements identifies which elements are present in the star's cooler outer layers (2 marks: the mechanism — absorption by cooler gas — and the uniqueness of each element's pattern). The strength of the lines also depends on temperature: at different temperatures, different lines stand out, so the overall line pattern is also a thermometer for the star's surface (2 marks: line strengths vary with temperature; this is why spectra classify stars, not just identify elements).

Question 8 (a) Star A has the greater luminosity. At the same radius the two stars have the same radiating surface area, and a hotter surface emits more power per square metre — its radiation curve lies above the cooler one at every wavelength (2C) — so star A radiates more total power. (b) $\lambda_{\text{max,A}}=\frac{2.9\times10^{-3}}{8000}=3.6\times10^{-7}\text{ m}=360\text{ nm}$; $\lambda_{\text{max,B}}=\frac{2.9\times10^{-3}}{4000}=7.3\times10^{-7}\text{ m}=730\text{ nm}$. Star A peaks at the shorter wavelength and its visible emission is strongest at the blue end, so it appears blue-white; star B peaks near the red end of the visible region and appears red-orange.

Question 9 (a) The two stars orbit their common centre of mass; by measuring the size of each star's orbit and the time taken to go around it (the orbital period), astrophysicists know how fast the stars move. From the orbital motion, the masses of the two stars can be worked out using Newton's laws of motion — binary stars are the most direct way of measuring stellar masses. (b) Mass sets everything that follows: the pressure and temperature of the core, and therefore which fusion reactions can run and how fast; the star's luminosity; its lifetime; and its final fate (white dwarf, neutron star or black hole). Every other property is, in part, a consequence of mass.

Question 10 (a) Hydrogen nuclei fuse to form helium nuclei (with energy released). (b) A Sun-like star's core can become hot enough to fuse helium into carbon and oxygen, but it never reaches the temperatures needed to fuse heavier nuclei — fusion stops there. A massive star's core keeps contracting and heating after each fuel is exhausted, fusing helium, then carbon, and so on through silicon all the way to iron, in nested layers. (c) Iron sits at the peak of the binding energy curve (4A): it is the most tightly bound nucleus. Fusing nuclei lighter than iron releases energy because the products are more tightly bound than the reactants; fusing iron would produce less tightly bound products, so it absorbs energy instead of releasing it. The star's core therefore loses its energy source, and collapse follows. (d) $E=mc^2=4.0\times10^9\times(3.0\times10^8)^2=4.0\times10^9\times9.0\times10^{16}=3.6\times10^{26}\text{ J}$. Released each second, this is a power of $3.6\times10^{26}\text{ W}$, which agrees with the Sun's luminosity ($3.8\times10^{26}\text{ W}$) within rounding. The mass converted in fusion is the source of the Sun's power.

Question 11 Model answer (4 marks): A more massive star has a greater gravitational force compressing its core, so the core is hotter and denser (1 mark). Fusion rates rise very steeply with core temperature, so the massive star fuses its hydrogen enormously faster per second than the Sun does — which is also why it is far more luminous (1 mark). It has twenty times the fuel, but it is burning that fuel thousands of times faster, so the fuel runs out sooner, not later (1 mark). Lifetime on the main sequence is fuel supply divided by the rate of burning: a larger supply divided by a vastly larger rate gives a much shorter life (1 mark).

Question 12 (a) The H–R diagram has luminosity (in $L_\odot$) on the vertical axis, increasing upwards, and surface temperature on the horizontal axis, increasing to the *left* (the historical convention). The main sequence runs as a band from top left (hot, luminous) to bottom right (cool, dim). The giant and supergiant region occupies the top right (cool but luminous), and the white dwarf region sits bottom left (hot but dim). (Any correctly labelled sketch earns the marks.) (b) A star's position on the diagram tells you its present stage of life — whether it is fusing hydrogen on the main sequence, swollen into a giant or supergiant, or fading as a white dwarf. The path a star follows across the diagram as it ages — its evolutionary track — is determined almost entirely by its initial mass.

Question 13 Model answer (5 marks): The Sun is now on the main sequence, fusing hydrogen in its core (1 mark). In roughly five billion years the core hydrogen will be exhausted; the core will contract while the outer layers expand and cool, and the Sun will move up and to the right of the H–R diagram to become a red giant (1 mark). Helium fusion will then begin in the core (helium to carbon and oxygen) (1 mark). When that fuel is spent, the Sun will expel its outer layers as a planetary nebula, leaving its hot core exposed as a white dwarf — on the H–R diagram this remnant sits bottom left: hot but very dim, because it is so small (1 mark). The white dwarf fuses nothing and slowly cools, fading over billions of years (1 mark).

Question 14 Model answer (5 marks): The star spends a short life on the main sequence, hot and luminous, fusing hydrogen in its core (1 mark). It then expands into a red supergiant, moving to the top right of the H–R diagram, and fuses heavier and heavier elements in nested layers up to iron (1 mark). Because fusing iron absorbs energy, the iron core can no longer support itself and collapses; the outer layers rebound and are blown apart in a supernova (1 mark). The remnant core survives as either a neutron star or a black hole (1 mark). Which one depends on the mass of the remnant core: up to about $3\,M_\odot$ a neutron star (matter crushed into a ball about $10\,\text{km}$ in radius); above about $3\,M_\odot$ nothing can stop the collapse and a black hole forms (1 mark).

Question 15 (a) The event horizon is the boundary around a black hole separating the region from which nothing can escape from the region from which escape is still possible. It is not a material surface. (b) A black hole appears black because nothing that crosses the event horizon — matter or light — can escape to an outside observer, so the region inside the horizon sends no light at all. (c) Classically, the more compact a mass is, the faster an object must travel to escape its gravity. If the mass were compressed inside a small enough radius, the escape speed would reach the speed of light — and since nothing travels faster than light, nothing could escape. Setting the escape speed equal to c connects the mass M to that critical radius, and yields $r_s = 2GM/c^2$, which is exactly the event-horizon radius that general relativity gives. A larger mass has a proportionally larger Schwarzschild radius.

Question 16 (a) $r_s = \dfrac{2GM}{c^2} = \dfrac{2 \times 6.67 \times 10^{-11} \times 1.99 \times 10^{30}}{(3.0 \times 10^8)^2} = \dfrac{2.65 \times 10^{20}}{9.0 \times 10^{16}} \approx 2950\,\text{m} \approx 3.0\,\text{km}$. (b) $\dfrac{6.96 \times 10^8}{2950} \approx 2.4 \times 10^5$ — about 240 000 times. (c) For the Sun to be a black hole, its mass would have to be compressed to roughly three kilometres in radius — more than two hundred thousand times smaller than it actually is. Nothing in the Sun's evolution will do this: as Question 13 shows, the Sun will end its life shedding mass and fading as a white dwarf, not collapsing. Only the collapsed cores of far more massive stars reach such compression.

Question 17 Model answer (6 marks; any three effects, each described and linked to an observational use). For example: - **Time dilation:** a clock deep in a gravitational field runs more slowly than one far away (1 mark). Matter orbiting close to a black hole shows this through the behaviour of its emitted radiation, which helps confirm the strength of the field (1 mark). - **Gravitational redshift:** light climbing out of the field loses energy and is shifted to longer wavelengths (1 mark); measuring the redshift of light emitted near the event horizon reveals how strong the field is (1 mark). - **Gravitational lensing:** the black hole's curved spacetime bends light from stars or galaxies behind it, distorting or multiplying their images (1 mark); lensing reveals massive objects that emit no light of their own, so an otherwise invisible black hole can be detected and its mass measured (1 mark). (Tidal stretching of infalling matter, and its observable consequences, is also accepted.)

Question 18 (a) Model answer (6 marks): Parallax relies on measuring a tiny angle; for very distant stars the angle becomes too small to measure accurately, even from space, so parallax reaches only so far (1 mark). Cepheid variable stars extend the ladder because of Henrietta Swan Leavitt's period–luminosity relation: the period of a Cepheid's brightness variation reveals its luminosity without any knowledge of distance (1 mark). With the luminosity known and the apparent brightness measured, the inverse-square law gives the distance — Cepheids are standard candles, bright enough to be seen in nearby galaxies (1 mark). Type Ia supernovae extend the ladder farther still: because they explode at a characteristic mass, they have a characteristic peak luminosity, and being briefly as bright as a whole galaxy, they are visible in very distant galaxies — again giving distance from luminosity and apparent brightness (1 mark). Each rung is calibrated by the one below it, which is why this is called the cosmic distance ladder (1 mark). In 1923 Edwin Hubble identified a Cepheid in the Andromeda nebula and, using Leavitt's relation, showed that Andromeda lies far outside the Milky Way — it is a galaxy in its own right (1 mark). (b) $d=\sqrt{\frac{L}{4\pi b}}=\sqrt{\frac{3.8\times10^{29}}{4\pi\times1.2\times10^{-10}}}=\sqrt{\frac{3.8\times10^{29}}{1.5\times10^{-9}}}=\sqrt{2.5\times10^{38}}=1.6\times10^{19}\,\text{m}$. In light-years: $\frac{1.6\times10^{19}}{9.46\times10^{15}}\approx1700\,\text{ly}$.

Option task

Option 2.13 — house Option task (30 marks). This task closes the subtopic, as every option subtopic does (§7.3). All assessment at Units 1 and 2 is school-based, and the 30-mark total is **house convention** — the study design fixes no marks for Units 1 and 2 (§2.2), and nothing in this task contributes to a study score. The task type is one of the study design's own Unit 2 Outcome 2 formats: *"a report of a selected physics phenomenon"* (*VCE Physics Study Design, Unit 2, Outcome 2, suitable tasks for assessment*).

Task. Choose **one** of the following phenomena and write a physics-referenced report (800–1200 words) explaining how astrophysicists investigate it and what they have found:

1. **Betelgeuse** — the life and approaching death of a red supergiant.
2. **Sagittarius A*** — the supermassive black hole at the centre of the Milky Way.
3. **The distance ladder** — how distances are measured from Proxima Centauri to the Andromeda Galaxy.
4. **The Event Horizon Telescope** — imaging the black holes M87* and Sagittarius A*.

Your report must include each of the following (the letters correspond to the rubric criteria):

- **(CP.1) Sources.** Use at least three sources, and evaluate the validity of each using the validity checklist of 10A (expertise, independence, quality of evidence, currency, corroboration, transparency). Every real datum you quote must carry a source line naming the organisation, the document and the retrieval date (14G).
- **(CP.2) Physics concepts and terminology.** Define the key terms your report uses (for example: luminosity, parallax, standard candle, spectral type, event horizon — whichever your phenomenon needs). Use the study design's terminology and conventions correctly: SI units, significant figures, correct symbols.
- **(CP.3) Representations, models and limitations.** Include at least two calculations drawn from this subtopic's methods — parallax distances, Wien's Law, apparent brightness and luminosity, or the Schwarzschild radius — shown with full working. Include at least one data representation (a table, a scale comparison, or a sketched H–R diagram showing your star's position or track), and state at least one limitation of a model or explanation you use.
- **(CP.4) Societal factors.** Discuss factors in at least **two** of the four categories of `U2.2.CP.4` (sociocultural, economic, legal, political), tracing each factor's influence rather than listing it (10B). Angles that suit this option include: the cost and international cooperation behind large projects such as Gaia and the Event Horizon Telescope (economic and political); the public attention captured by the first images of black holes (sociocultural); and the radio quiet zones that protect radio telescopes from interference (legal).
- **(CP.5) A justified stance.** Take a stance on a claim connected to your phenomenon — for example, *"Large international astronomy projects are worth their cost"* or *"Space-based telescopes should be funded ahead of ground-based ones"* — and use your physics understanding to justify it, presenting the strongest case on the other side and acknowledging the limits of your evidence. (Under Option 2.13 the study design prints this dot point as *"use physics understanding to justify a stance…"*; the expectation is the same as the *"apply…"* wording printed under the other options — 10B.)

Marks are awarded for the quality of the reasoning, not the conclusion reached (10B).

Marking rubric — keyed to the Communicating physics dot points (`U2.2.CP.1–.5`, taught in 10A and 10B).

Criterion	5–6 marks	3–4 marks	1–2 marks
CP.1 — validity of sources	Three or more sources evaluated with the validity checklist; each evaluation names strengths and weaknesses; all real data carry dated source lines	Two sources evaluated, or three sources named with thin evaluation; most data sourced	Sources named but not evaluated, or unsourced claims repeated
CP.2 — concepts, terms, conventions	Key terms defined at first use; physics correct throughout; units, symbols and significant figures correct	Most terms defined; physics mostly correct with minor slips in conventions	Key terms undefined or physics errors that weaken the report
CP.3 — representations, models, limitations	Two or more calculations shown with full working and correct answers; an accurate, labelled representation included; at least one limitation of a model or explanation stated and discussed	Calculations present but with slips or gaps; a representation included; a limitation named but not discussed	One calculation or representation only; no limitations acknowledged
CP.4 — societal factors	Factors from two or more categories, each traced from existence to influence and consequence (a discussion, not a list — 10B)	Factors from two categories named with some tracing of influence	Factors listed without influence traced, or only one category covered
CP.5 — justified stance	Stance clearly stated; physics understanding used to support it; the strongest opposing case presented fairly; limits of the evidence acknowledged	Stance stated with physics support; the other side or the limits are thin	Stance asserted without physics support, or the other side is dismissed rather than engaged

Total: **30 marks** (house convention).

Chapter 13 Options: astrophysics, particles and contemporary research — 13B Option 2.14: How can we detect possible life beyond Earth's Solar System?

Theory

This section is **Option 2.14 — The physics of life beyond the Solar System**, one of the eighteen options of Unit 2, Area of Study 2. A student studies exactly one option; this section is self-contained for a student who has chosen Option 2.14. It applies the wave and spectrum ideas of Chapter 1 — the electromagnetic spectrum, dispersion and $v = f\lambda$ — to the oldest question in science: are we alone? Everything we know about places beyond the Solar System arrives as electromagnetic radiation, so this section is about what starlight can and cannot tell us. The section closes with the assessed Option task.

The key knowledge for this option, verbatim from the study design:

ID	Key knowledge (verbatim)
`U2.2.O14.1`	"identify spectroscopy as a tool to investigate the light from stars, and interpret and analyse spectroscopic data with reference to information from beyond our Solar System"
`U2.2.O14.2`	"compare methods of exoplanet detection including astrometric, radial velocity, transit method and microlensing, referring to databases that differentiate for size, eccentricity and radius, and by observing the gravitational effect of a planetary system on a star"
`U2.2.O14.3`	"explain and apply Doppler shift including spectral shift and 'wobble' of planetary systems using: $\Delta\lambda / \lambda_0 = v / c$" (formula as printed in the study design)
`U2.2.O14.4`	"explain the use of the Fermi paradox and the Drake equation to question the possibility of life outside Earth's Solar System and of predicting the likelihood of life existing in the Universe"
`U2.2.O14.5`	"distinguish between targeted and untargeted searches for extra-terrestrial intelligence (ETI), and describe optimising strategies including where to look and how to 'listen' with reference to choice of frequency and bandwidth"
`U2.2.O14.6`	"explain the nature of information that humans transmit beyond Earth to signal that intelligent life exists on Earth"

Two different questions are asked under one heading, and they must not be confused. The first is whether **life of any kind** exists beyond the Solar System — microbes count. The second is whether **intelligent life** exists — beings able to build transmitters and technology. The first is searched for with telescopes studying starlight and planets; the second with searches for deliberate signals (SETI, the search for extra-terrestrial intelligence). The study design does not define *life*. In this subtopic, **life** is treated as a system that takes in energy and materials from its surroundings, maintains itself, grows and reproduces — and every question here is answerable on that definition alone. **Intelligent life** is treated operationally as life able to produce a signal or artefact we could detect from Earth.

An exoplanet is a home, possibly. An **exoplanet** (or extrasolar planet) is a planet that orbits a star other than the Sun. Life as defined above needs liquid water as a solvent in which its chemistry can happen, so a planet is judged **habitable** — capable of supporting life — chiefly by whether liquid water could exist on its surface. That depends mostly on the planet's distance from its star: too close and water boils away, too far and it freezes. The range of distances in which a planet could hold liquid water on its surface is called the **habitable zone** of the star. These terms describe possibility, not proof: a planet in the habitable zone is a candidate, nothing more.

Spectroscopy: reading starlight. When white light passes through a prism or a diffraction grating it spreads into its component wavelengths — a **spectrum** (Section 1D). The spectrum of a star is not a smooth rainbow. It is crossed by many narrow dark lines, called **absorption lines**, at particular wavelengths. They form because the cooler gas in a star's outer layers absorbs exactly those wavelengths that its atoms and molecules can absorb; each element and molecule absorbs its own characteristic set of wavelengths, a fingerprint as individual as a barcode. **Spectroscopy** is the technique of spreading light into a spectrum and reading these lines to find out what the light passed through.

The same fingerprints are known from laboratory light sources on Earth. If the spectrum of a star shows the full fingerprint pattern of hydrogen, then hydrogen is present in that star's outer layers — this is how helium was first identified in 1868, in the Sun's spectrum, before it had been found on Earth. Spectroscopy therefore lets us read the composition of objects trillions of kilometres away from nothing but their light.

Spectroscopic data from beyond the Solar System. When an exoplanet passes in front of its star, some of the starlight travels through the planet's atmosphere on its way to us, and the atmosphere's gases add their own absorption lines to the spectrum. Comparing the spectrum during a transit with the spectrum of the star alone shows what the planet's atmosphere absorbed. This is **transmission spectroscopy**, and it has produced real detections from beyond the Solar System: water vapour in the atmosphere of the planet K2-18b, a planet about 120 light-years away in the habitable zone of its star (Source: NASA, *Hubble Finds Water Vapor on Potentially Habitable Exoplanet*, retrieved 2026-08-18), and carbon dioxide in the atmosphere of the hot planet WASP-39b (Source: NASA, *NASA's Webb Detects Carbon Dioxide in Exoplanet Atmosphere*, retrieved 2026-08-18). Gases that could be produced by living systems — water vapour, oxygen, ozone, methane — are called **biosignature gases**. A biosignature gas is evidence to be weighed, not proof of life: each of these gases can also be made by non-living geology, which is why spectroscopic data is analysed for a *combination* of gases, and why every detection is reported with its uncertainties.

The star feels its planets: the gravitational wobble. A planet does not simply orbit its star; the star and the planet orbit their common centre of mass. Because the star is far more massive, that centre lies close to (usually inside) the star, and the star's motion is a small orbit of its own — a **wobble**. The wobble is the gravitational effect of a planetary system on its star, and two of the four detection methods below (radial velocity and astrometric) watch it directly. The more massive the planet and the closer it sits to the star, the larger the wobble.

Radial velocity. As the wobbling star moves towards us, its spectral lines shift to shorter wavelengths; as it moves away, they shift to longer wavelengths; and the shift repeats with the planet's orbital period. Measuring this periodic **Doppler shift** of the star's absorption lines is the **radial velocity method**. It finds the planet's orbital period from the repetition of the shift, and the size of the shift gives the star's speed along our line of sight. Motion across the line of sight produces no Doppler shift, so the method sees only part of the wobble unless the orbit happens to be edge-on; the planet's mass deduced is therefore a *minimum* mass. The method is best at massive planets close to their stars — exactly the planets that produce the largest wobble. It made the first discovery of an exoplanet orbiting a Sun-like star, 51 Pegasi b in 1995, a planet whose star wobbles at of order $50\,\mathrm{m\,s^{-1}}$ with a period of only 4.2 days.

Astrometric. The **astrometric method** watches the wobble from the other direction: it measures the tiny side-to-side change in the star's *position* on the sky as it orbits the common centre of mass. The angles are extremely small — a star a few light-years away swaying by the width of a coin seen from across an ocean — so the method needs the most precise position measurements in astronomy, now supplied by space observatories such as the European Space Agency's Gaia mission. Where radial velocity sees only the line-of-sight part of the wobble, astrometry sees the wobble in the plane of the sky, and combining the two gives the true shape of the orbit and the true mass of the planet. The astrometric method is most sensitive to massive planets in wide, slow orbits — the opposite bias to radial velocity.

Transit method. If the orbit happens to be aligned edge-on to us, the planet crosses the face of its star once per orbit and blocks a small fraction of the starlight. The **transit method** detects planets as periodic dips in a star's measured brightness. The fraction of light blocked is the area of the planet's disc divided by the area of the star's disc, and since the area of a disc is proportional to the radius squared,

$$\text{fraction of light blocked} = \left(\frac{R_p}{R_\star}\right)^2,$$

where R_p is the planet's radius and $R_\star$ the star's radius. The depth of the dip therefore gives the planet's **radius** (relative to the star's), and the time between dips gives the orbital period. A Jupiter-sized planet crossing a Sun-sized star dims it by about 1%; an Earth-sized planet by less than 0.01% — one part in ten thousand, which is why transit surveys need stable measurements from space, above the blurring of Earth's atmosphere. The Kepler space telescope stared at about 150 000 stars in one patch of sky and found thousands of planets this way (Source: NASA, *Kepler Mission*, retrieved 2026-08-18); its successor TESS surveys the whole sky. The transit method's bias is alignment: a planet that does not cross the star's face as seen from Earth is invisible to it.

Microlensing. Einstein showed that mass bends the path of light. If a star passes almost directly in front of a more distant star, its gravity acts as a lens, focusing the background star's light and making it briefly brighter. If the lensing star has a planet, the planet adds a short extra spike to the brightening. This is gravitational **microlensing**. It can find planets too small and too far from their star for the other methods, at great distances, but each alignment happens once and never repeats, so a microlensing planet cannot be studied again. The first such discovery, OGLE-2005-BLG-390Lb in 2006, is a cold planet of about five Earth masses.

Comparing the four methods.

Method	What the planet does	What it yields	What it needs	Best at finding
radial velocity	wobbles the star along our line of sight	orbital period; minimum mass	precise spectroscopy over many orbits	massive planets close to the star
astrometric	wobbles the star across the sky	orbit shape; true mass	extremely precise positions	massive planets in wide orbits
transit	crosses the star's face	orbital period; planet radius	edge-on alignment; stable photometry	small planets; many planets at once
microlensing	lenses a background star with its host	planet mass (approximate)	a chance alignment, once only	distant, small, wide-orbit planets

No single method sees every planet; each has a **detection bias** — a kind of planet it finds easily and a kind it misses. That is why the methods are compared and combined, and why the catalogues they feed are used with care.

Exoplanet databases. The discoveries are collected in public databases such as the NASA Exoplanet Archive and the Extrasolar Planets Encyclopaedia. Each confirmed planet carries entries for its mass or size, its radius where measured, its orbital period and its **eccentricity** — a number describing the shape of the orbit, from 0 for a perfect circle towards 1 for a very stretched ellipse. A few real entries, values approximate:

Planet	Method	Mass	Radius	Period	Eccentricity
51 Peg b	radial velocity	at least $0.5\,M_\mathrm{J}$	—	4.2 days	≈ 0
HD 209458 b	radial velocity + transit	$0.7\,M_\mathrm{J}$	$1.4\,R_\mathrm{J}$	3.5 days	≈ 0
HD 80606 b	radial velocity	$\approx 4\,M_\mathrm{J}$	$\approx 1.0\,R_\mathrm{J}$	111 days	≈ 0.93
Proxima Centauri b	radial velocity	at least $1.3\,M_\oplus$	—	11.2 days	≈ 0
TRAPPIST-1e	transit	$\approx 0.7\,M_\oplus$	$\approx 0.92\,R_\oplus$	6.1 days	≈ 0

Source: NASA Exoplanet Archive, Confirmed Planets table, exoplanetarchive.ipac.caltech.edu, retrieved 2026-08-18. M_J, R_J are Jupiter's mass and radius; $M_\oplus$, $R_\oplus$ Earth's.

Read the table the way an astronomer does. 51 Peg b and Proxima Centauri b have no radius entry because radial velocity alone cannot measure a radius; HD 209458 b has one because it also transits. "At least" marks the minimum mass of a radial-velocity planet whose orbit is not edge-on. HD 80606 b's eccentricity of about 0.93 is a wildly stretched orbit, against the near-circular orbits of the others. Proxima Centauri b — at least 1.3 Earth masses, orbiting the star nearest to the Sun every 11.2 days, in its habitable zone — is exactly the kind of entry that makes the questions of this option feel close.

Doppler shift. When a source of waves moves towards an observer, each wave crest is emitted from a slightly closer position than the one before, so the crests arrive squeezed together: the wavelength measured by the observer is shorter. When the source moves away, the crests arrive stretched apart and the measured wavelength is longer. For light, a shift to longer wavelength is a **redshift** and to shorter wavelength a **blueshift**. The same effect changes the pitch of a siren as it passes you; for light it changes the colour, by a tiny amount.

For speeds small compared with the speed of light, the study design's relationship is:

$$\frac{\Delta\lambda}{\lambda_0}=\frac{v}{c},$$

where λ_0 is the **rest wavelength** — the wavelength measured in a laboratory when the source is not moving relative to the observer — $\Delta\lambda=\lambda_{\text{obs}}-\lambda_0$ is the change in wavelength measured by the observer, v is the speed of the source towards or away from the observer (its radial velocity), and $c=3.0\times10^8\ \text{m s}^{-1}$ is the speed of light. By convention $\Delta\lambda$ is positive when the source recedes (redshift) and negative when it approaches (blueshift). Because absorption lines sit at known rest wavelengths, any shift of the whole pattern is measurable, and the equation turns that shift into a speed.

The wobble in numbers. The radial velocity method is the Doppler shift applied to a wobbling star. As the star swings towards us and away, every line in its spectrum swings blueward and redward together, repeating with the orbital period of the planet. The period of the shift is the planet's year; the size of the shift is the star's line-of-sight speed; and a star that wobbles at all is a star that has a planet pulling on it. The shifts are astonishingly small. A star wobbling at $1.4\ \text{m s}^{-1}$ — walking pace — shifts a line at $656.28\ \text{nm}$ by only

$$\Delta\lambda=\lambda_0\frac{v}{c}=656.28\times\frac{1.4}{3.0\times10^8}\approx3.1\times10^{-6}\ \text{nm},$$

about three millionths of a nanometre, one part in about two hundred million of the wavelength. Detecting a Proxima-Centauri-b-like planet therefore demands spectrographs of extreme stability, and it is only in recent decades that instruments have reached that precision. That one number — a wavelength change smaller than the width of an atomic nucleus, measured across four light-years — is the wobble of a planetary system, read from starlight.

The Fermi paradox. The Galaxy contains hundreds of billions of stars, many older than the Sun, and the observable Universe contains hundreds of billions of galaxies. If even a tiny fraction of those stars host life that becomes intelligent and builds transmitters, then over the billions of years available, the Galaxy should have filled with detectable signs of them. Yet every search so far has found no such sign — no signal, no artefact, nothing. The clash between the apparent likelihood of extra-terrestrial life and the complete absence of evidence for it is the **Fermi paradox**, named for the physicist Enrico Fermi, who raised it in conversation around 1950 with his question "where is everybody?" (Source: Wikipedia, *Fermi paradox*, retrieved 2026-08-18).

The paradox is used to *question* the possibility of life beyond the Solar System by forcing every optimistic assumption to face the empty sky. Proposed resolutions include: distances and times are so vast that civilisations miss each other (a signal crossing the Galaxy takes tens of thousands of years); technological civilisations may be brief, destroying themselves or switching to undetectable technology before they are noticed; or life, or intelligent life, may genuinely be rare. Each resolution changes one of the assumptions on which the "Galaxy should be full" argument rests. The paradox does not prove we are alone; it proves that at least one apparently reasonable assumption in the chain is wrong, and that we do not yet know which.

The Drake equation. The **Drake equation**, written by Frank Drake in 1961, organises the same problem as a product of factors, so that the question "are we alone?" becomes "what does each step contribute?" (Source: Wikipedia, *Drake equation*, retrieved 2026-08-18):

$$N = R_* f_p n_e f_l f_i f_c L$$

where N is the number of civilisations in our Galaxy whose signals we could currently detect, and the factors are:

- R_* — the average rate of star formation in the Galaxy, per year;
- f_p — the fraction of stars that have planets;
- n_e — the average number of planets per star that could support life;
- f_l — the fraction of those planets on which life actually appears;
- f_i — the fraction of those on which intelligent life evolves;
- f_c — the fraction of those that develop technology releasing detectable signals;
- L — the average length of time, in years, that such signals are released.

The equation's use is to *predict the likelihood* of life in the Universe in the only honest way available: by showing how the answer depends on each step. The first three factors are becoming measurable — exoplanet databases now show that most stars have planets and that small, possibly habitable planets are common, so f_p and n_e are no longer guesses. The biological and sociological factors f_l, f_i and f_c remain almost completely unknown, and L most of all. Reasonable optimists multiply to N of hundreds or more; reasonable pessimists to N far below 1, meaning we may be the only signal in the Galaxy at this moment. The Drake equation is therefore not a calculator with one correct answer; it is a framework that locates our ignorance, shows which parts of the chain astronomy is currently measuring, and makes clear why the searches described next are worth running at all.

Searching for intelligence: targeted and untargeted. A search for extra-terrestrial intelligence (ETI) looks for deliberate or accidental signals, and there are two shapes such a search can take. A **targeted search** points a telescope at chosen candidates — typically nearby Sun-like stars, or stars known to host habitable-zone planets — and listens to each for a long time. Its strength is depth: all of the instrument's collecting power is spent on the most promising targets. Its weakness is coverage: only the chosen stars are checked. An **untargeted search** sweeps the sky without choosing stars in advance, scanning wide areas so that any strong transmitter anywhere in the surveyed sky could be caught, including ones nobody thought to target. Its strength is coverage and the chance of surprise; its weakness is that each direction is sampled briefly and shallowly. Modern programmes mix both shapes: Breakthrough Listen, the largest ETI programme to date, surveys targeted lists of nearby stars and also scans the Galactic centre and the wider sky, using among other instruments the Parkes (Murriyang) radio telescope in New South Wales (Source: Wikipedia, *Breakthrough Listen*, retrieved 2026-08-18).

Where to look. Optimising a search begins with distance and likelihood: nearby stars first, because signals weaken with distance; stars with known planets in the habitable zone, because that is where life as defined here could arise; and for untargeted sweeps, the plane of the Galaxy, where most stars are.

How to listen, and the choice of frequency. Radio waves are the preferred carrier for a search: they pass through interstellar dust and a planet's atmosphere, they can be produced with modest energy, and natural radio noise from stars and gas is relatively low at some frequencies. The most discussed window is the **water hole**, the quiet band between the emission line of hydrogen at $1.42\,\text{GHz}$ (the 21 cm line of Section 1B's radio region) and the lines of the hydroxyl radical near $1.66\,\text{GHz}$. Hydrogen and hydroxyl together make water, so any civilisation that knows radio astronomy would know this band; it is also genuinely quiet, between the noise of the Galaxy at lower frequency and the noise of the atmosphere at higher. Using $v = f\lambda$ (Section 1A), the hydrogen line's wavelength is

$\lambda = c/f = \dfrac{3.0\times10^8}{1.42\times10^9} \approx 0.21\,\text{m}$ — 21 cm.

The choice of bandwidth. Natural sources emit over broad ranges of frequency; a deliberate beacon would concentrate its power into a very narrow band, a single thin channel of the spectrum. A search therefore splits its frequency range into millions of narrow channels and looks for power appearing in one channel only — narrowness itself is the signature of technology. The cost of narrow channels is the number that must be checked: the water hole spans $1.66 - 1.42 = 0.24\,\text{GHz} = 2.4 \times 10^8\,\text{Hz}$, which at 1 Hz channel width is 2.4×10^8 separate channels, before any star has even been chosen. Choice of bandwidth is thus the central trade-off of listening: narrow enough to reject nature, wide enough that the search can be finished.

Quiet places to listen. A receiver sensitive enough to hear a whisper from another star must be protected from transmitters at home. Radio telescopes are built in remote country, and some are protected by law. The Murchison region of Western Australia, site of the future Square Kilometre Array's low-frequency telescope, sits inside a legally protected radio quiet zone (Source: Australian Communications and Media Authority, *Australian Radio Quiet Zone Western Australia*, retrieved 2026-08-18) — an example of the legal and political factors that shape real searches.

Messages from Earth. Humans have already done what we hope others do: sent deliberate information beyond Earth. In 1974 the Arecibo radio telescope in Puerto Rico transmitted a binary message towards the globular cluster M13, about 25 000 light-years away (Source: Wikipedia, *Arecibo message*, retrieved 2026-08-18). The message was 1679 bits — chosen as the product of the primes 23 and 73, a hint that the bits should be arranged as a 23 × 73 grid — and the grid, read in order, is a pictorial summary: the numbers one to ten, the elements of DNA, a human figure, the Solar System with Earth marked, and the telescope itself. The Pioneer plaques (1972–73) and the Voyager Golden Records (1977) travelled as physical artefacts on spacecraft leaving the Solar System: the plaques carry human figures and a map of the Sun's position relative to nearby pulsars, rapidly spinning stars that send out regular pulses of radio waves (Source: Wikipedia, *Pioneer plaque*, retrieved 2026-08-18); the Golden Records carry sounds of Earth, images encoded as audio, music, and greetings in many languages (Source: NASA, *The Golden Record*, voyager.jpl.nasa.gov, retrieved 2026-08-18).

The **nature** of this information is what matters for this option. With no shared language, history or biology, every message begins from what any technological civilisation would share: mathematics (numbers, primes, geometry), physics (the hydrogen line, pulsar periods) and chemistry (the elements of DNA) — universal reference points used to anchor the rest. The Arecibo message and the plaques are therefore structured as *pictures built from mathematics*; the Golden Records as a *sample of a biosphere and a culture*, for any finder patient enough to decode it. Alongside these deliberate messages, our accidental leakage — decades of radio and television broadcasts — spreads outward at the speed of light, a thin bubble of technological noise marking the Solar System as occupied. Deliberate or accidental, each carries the same claim: intelligent life exists on Earth. Whether anyone is listening is the question this section studies. And the distances say patience: the Arecibo message, travelling since 1974, has covered about fifty light-years of its 25 000 light-year journey — a two-way conversation with M13 would take about 50 000 years.

A data investigation connects directly to this section: open the NASA Exoplanet Archive (or a table your teacher provides), filter confirmed planets by discovery method, and compare the radii, masses, periods and eccentricities of the planets each method finds. The patterns you see are the detection biases of this section, read from real data. The study design requires a minimum of ten hours of practical work across Areas of Study 1 and 2 of Unit 2; your teacher will organise how those hours are spent.

The equations of this section are summarised below.

Quantity	Equation	Notes
Doppler shift	$\Delta\lambda / \lambda_0 = v / c$	λ_0 rest wavelength; $\Delta\lambda$ positive for recession; v radial speed; $c = 3.0 \times 10^8\,\text{m s}^{-1}$
transit depth	fraction of light blocked $= (R_p / R_\star)^2$	gives planet radius relative to the star
wave equation (Section 1A)	$v = f\lambda$, so $\lambda = c / f$ for light	used for the water hole
Drake equation	$N = R_* f_p n_e f_l f_i f_c L$	a framework for the likelihood of detectable life
light-year	$1\,\text{ly} = 9.46 \times 10^{15}\,\text{m}$	the distance light travels in one year

Worked examples

Example 1 — scaffolded

A star's spectrum shows the hydrogen absorption line whose rest wavelength is $\lambda_0 = 656.28\,\text{nm}$. On one night the line is observed at $656.35\,\text{nm}$. Use $c = 3.0 \times 10^8\,\text{m s}^{-1}$.

(a) Calculate the change in wavelength, $\Delta\lambda$.
(b) Use the Doppler shift relationship to calculate the star's radial velocity v.
(c) State whether the star is approaching or receding, justifying your answer.
(d) Over the following months, superimposed on that steady recession, the line is seen to wobble back and forth by a tiny additional amount — about $\pm 0.00011\,\text{nm}$, which corresponds to speeds of about $\pm 50\,\text{m s}^{-1}$ — repeating with a period of 4.2 days. Suggest what this shows.

Working	Comment
(a) $\Delta\lambda = \lambda_{obs} - \lambda_0 = 656.35 - 656.28 = 0.07\,\text{nm}$	Observed minus rest.
(b) $\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}$, so $v = c\frac{\Delta\lambda}{\lambda_0} = 3.0 \times 10^8 \times \frac{0.07}{656.28}$	Rearrange the study-design formula.
$v = 3.0 \times 10^8 \times 1.07 \times 10^{-4} \approx 3.2 \times 10^4\,\text{m s}^{-1}$	About $32\,\text{km s}^{-1}$, to 2 significant figures.
(c) $\Delta\lambda$ is positive — the line moved to a longer wavelength (a redshift) — so the star is **receding**.	Recession stretches the waves.
(d) The tiny shift repeats, swinging from redshift to blueshift with a fixed period: the star is wobbling as it orbits a common centre of mass with an unseen companion. A 4.2-day period means the companion orbits every 4.2 days, and a wobble of only $50\,\text{m s}^{-1}$ means the companion is a planet rather than another star — the signature of a close-in planet (the radial velocity method).	Periodic Doppler shift = wobble = planet.

Example 2 — scaffolded

The Sun's radius is $696\,000\,\text{km}$, Jupiter's is $69\,911\,\text{km}$ and Earth's is $6\,371\,\text{km}$ (Source: NASA, *Planetary Fact Sheet* and *Sun Fact Sheet*, retrieved 2026-08-18). Imagine each planet crossing the face of the Sun as seen from a distant observer.

(a) Calculate the fraction of the Sun's light blocked by a transiting Jupiter.
(b) Express the answer as a percentage.
(c) Calculate the same fraction for a transiting Earth.
(d) Hence explain why finding an Earth-sized planet by the transit method needs instruments in space.

Working	Comment
(a) $\left(\frac{R_p}{R_\star}\right)^2 = \left(\frac{69\,911}{696\,000}\right)^2 = (0.1004)^2 = 1.0 \times 10^{-2}$	Disc-area ratio; radius ratio first.
(b) $1.0 \times 10^{-2} = 1.0\,\%$	A 1% dip — measurable from the ground with care.
(c) $\left(\frac{6\,371}{696\,000}\right)^2 = (9.15 \times 10^{-3})^2 = 8.4 \times 10^{-5}$, i.e. $0.0084\,\%$	About 120 times shallower than Jupiter's dip.
(d) An Earth-sized transit dims the star by less than one part in ten thousand. Turbulence and brightness changes in Earth's own atmosphere add noise larger than the signal, so the steady, precise measurements needed are only obtainable above the atmosphere — from space	The dip is smaller than the ground-based noise.

telescopes such as Kepler and TESS.

Example 3 — unscaffolded

(a) Using the Drake equation, estimate N with the following optimistic values: $R_* = 10\,\text{yr}^{-1}$, $f_p = 0.5$, $n_e = 2$, $f_l = 1$, $f_i = 0.01$, $f_c = 0.01$, $L = 10\,000\,\text{yr}$.

(b) Estimate N with the following pessimistic values: $R_* = 1\,\text{yr}^{-1}$, $f_p = 0.2$, $n_e = 0.5$, $f_l = 0.1$, $f_i = 0.01$, $f_c = 0.01$, $L = 100\,\text{yr}$.

(c) The two estimates differ by a factor of about one hundred thousand. Explain what this tells you about the Drake equation and how it should be used.

(d) $N = 10 \times 0.5 \times 2 \times 1 \times 0.01 \times 0.01 \times 10\,000$. Step by step: $10 \times 0.5 = 5$; $\times 2 = 10$; $\times 1 = 10$; $\times 0.01 = 0.1$; $\times 0.01 = 0.001$; $\times 10\,000 = 10$. So $N \approx 10$: about ten detectable civilisations in the Galaxy at this moment.

(e) $N = 1 \times 0.2 \times 0.5 \times 0.1 \times 0.01 \times 0.01 \times 100$. Step by step: $1 \times 0.2 = 0.2$; $\times 0.5 = 0.1$; $\times 0.1 = 0.01$; $\times 0.01 = 1 \times 10^{-4}$; $\times 0.01 = 1 \times 10^{-6}$; $\times 100 = 1 \times 10^{-4}$. So $N \approx 0.0001$: far below 1, meaning that on these values a detectable civilisation (us aside) would essentially never be present in the Galaxy at any one time.

(f) Both calculations are arithmetic on guesses. The factors f_l, f_i, f_c and L are not measured by any instrument; changing them by factors of ten changes N by factors of ten. The huge spread between the estimates therefore shows that the Drake equation does not *predict* a number so much as *organise* the question: it lists every step that must happen for a detectable civilisation to exist, shows which steps astronomy has now measured (f_p and n_e, from exoplanet surveys) and which remain pure uncertainty, and converts “are we alone?” into a set of separate, testable questions. Used that way it is a serious scientific framework; used as a calculator it gives whatever answer its user already believed.

Example 4 — unscaffolded

The table below repeats five entries from the NASA Exoplanet Archive (values approximate; Source: NASA Exoplanet Archive, retrieved 2026-08-18).

Planet	Method	Mass	Radius	Period	Eccentricity
51 Peg b	radial velocity	at least $0.5\,M_J$	—	4.2 days	≈ 0
HD 209458 b	radial velocity + transit	$0.7\,M_J$	$1.4\,R_J$	3.5 days	≈ 0
HD 80606 b	radial velocity	$\approx 4\,M_J$	$\approx 1.0\,R_J$	111 days	≈ 0.93
Proxima Centauri b	radial velocity	at least $1.3\,M_\oplus$	—	11.2 days	≈ 0
TRAPPIST-1e	transit	$\approx 0.7\,M_\oplus$	$\approx 0.92\,R_\oplus$	6.1 days	≈ 0

(a) Identify which column of the table can only be filled for planets that transit, and explain why the radial velocity method cannot fill it.

(b) Identify the planet with the most non-circular orbit and state how the table shows this.

(c) Explain why the masses of 51 Peg b and Proxima Centauri b are printed as “at least”.

(d) A transit survey wants the deepest possible dip for an Earth-sized planet. Which star type should it target — a large Sun-like star or a small cool star like TRAPPIST-1 — and why?

(e) The **radius** column. A radius comes from the depth of a transit dip, $(R_p / R_\star)^2$; a planet that never crosses its star’s face produces no dip. The radial velocity method measures the star’s wobble speed, which depends on the planet’s *mass* and orbit, not on the planet’s size — a small dense planet and a large fluffy planet of the same mass wobble the star identically. Hence the “—” radius entries for the radial-velocity planets without transits.

(f) **HD 80606 b**, eccentricity ≈ 0.93. Eccentricity runs from 0 (a circle) towards 1 (a very stretched ellipse); 0.93 is close to the stretched extreme, while the other four planets sit at ≈ 0, near-circular orbits.

(g) Radial velocity sees only the part of the wobble along our line of sight. Unless the orbit is edge-on, the true wobble is larger than the part measured, so the planet's true mass is larger than the mass deduced; the method yields a minimum mass, printed as "at least". (An astrometric measurement of the same system would remove this limitation.)

(h) The small star. The depth of a dip is $(R_p / R_\star)^2$, so the smaller $R_\star$, the deeper the dip for the same planet. An Earth-sized planet crossing TRAPPIST-1 ($R_\star \approx 83\,000\,\text{km}$) gives $(6\,371 / 83\,000)^2 \approx 5.9 \times 10^{-3}$, a 0.59% dip — about seventy times deeper than the 0.0084% dip the same planet gives crossing a Sun-sized star, and far easier to detect. Small stars are therefore the favoured targets in the search for habitable Earth-sized worlds.

Practice questions

Question 1 *(scaffolded)* A star's spectrum shows absorption lines at 656.3 nm, 486.1 nm and 434.0 nm — the same three wavelengths at which hydrogen gas in the laboratory absorbs. (a) State what the matching pattern shows about the star. (b) Explain why the lines appear dark against the star's continuous spectrum. (c) If the whole pattern were found shifted to longer wavelengths by the same small amount, state what that would show, and name the effect.

Question 2 *(scaffolded)* An absorption line with rest wavelength $\lambda_0 = 500.00\,\text{nm}$ is observed in a star's spectrum at $500.05\,\text{nm}$. Use $c = 3.0 \times 10^8\,\text{m s}^{-1}$. (a) Calculate $\Delta\lambda$. (b) Calculate the star's radial velocity using $\Delta\lambda / \lambda_0 = v / c$. (c) State whether the star is approaching or receding, giving a reason.

Question 3 *(scaffolded)* The star Proxima Centauri wobbles at about $1.4\,\text{m s}^{-1}$ because of its planet Proxima Centauri b. Consider its hydrogen line at $\lambda_0 = 656.28\,\text{nm}$. (a) Calculate the size of the wavelength shift $\Delta\lambda$ the wobble produces. (b) Express your answer in metres. (c) Comment on what this size of shift demands of the measuring instrument.

Question 4 *(scaffolded)* An Earth-sized planet ($R_p = 6\,371\,\text{km}$) transits a Sun-sized star ($R_\star = 696\,000\,\text{km}$). (a) Calculate the ratio $R_p / R_\star$. (b) Calculate the fraction of the star's light blocked, as a percentage to 2 significant figures. (c) State why a dip of this size was first measured reliably from space rather than from the ground.

Question 5 *(scaffolded)* The hydrogen line used in ETI searches has a frequency of $1.42\,\text{GHz}$. (a) Write this frequency in hertz. (b) Calculate its wavelength using $\lambda = c / f$. (c) Express the wavelength in centimetres.

Question 6 *(scaffolded)* A class estimates the Drake equation factors as follows: $R_* = 5\,\text{yr}^{-1}$, $f_p = 0.5$, $n_e = 1$, $f_l = 0.5$, $f_i = 0.1$, $f_c = 0.1$, $L = 2\,000\,\text{yr}$. (a) Calculate N. (b) State, in one sentence, what N represents in this equation.

Question 7 During a transit of the planet K2-18b, the star's spectrum shows absorption by water vapour that is absent when the planet is not in front of the star. (a) Explain where the absorbing water vapour is, and how the comparison of spectra locates it. (b) Explain why this detection is evidence to weigh rather than proof of life on K2-18b.

Question 8 A star's brightness is monitored and shows a repeating dip of depth 1.0%. (a) Calculate the ratio $R_p / R_\star$ for the transiting planet. (b) If the star is Sun-sized ($R_\star = 696\,000\,\text{km}$), calculate the planet's radius and compare it with Jupiter's radius ($69\,911\,\text{km}$). (c) State two things the transit method cannot tell you about this planet that the radial velocity method could.

Question 9 The star 51 Pegasi wobbles at of order $50\,\text{m s}^{-1}$ with a period of 4.2 days, the signature that revealed its planet in 1995. Consider a spectral line at $\lambda_0 = 550.00\,\text{nm}$. (a) Calculate the size of the Doppler shift $\Delta\lambda$ as the star moves towards Earth at $50\,\text{m s}^{-1}$. (b) State whether this motion is a redshift or a blueshift. (c) Explain what the 4.2-day period of the shift reveals about the planet.

Question 10 TRAPPIST-1 is a small cool star of radius about $83\,000\,\text{km}$. (a) Calculate the depth of the dip produced by an Earth-sized planet ($6\,371\,\text{km}$) transiting TRAPPIST-1, as a percentage. (b) Compare your answer with the

0.0084% dip an Earth-sized planet gives crossing a Sun-sized star, and hence explain why surveys of small stars have found many Earth-sized worlds.

Question 11 Proxima Centauri is 4.2 light-years from Earth. Use $1\,\mathrm{ly} = 9.46 \times 10^{15}\,\mathrm{m}$. (a) Calculate the distance to Proxima Centauri in metres. (b) A radio signal travels at $c = 3.0 \times 10^{8}\,\mathrm{m\ s^{-1}}$. Calculate how long a signal from Earth takes to reach Proxima Centauri. (c) The astrometric and microlensing methods both rely on gravity. Distinguish between them: what does each measure, and what is the practical limitation of microlensing?

Question 12 State the Fermi paradox in one or two sentences, and describe two proposed resolutions of it.

Question 13 Estimate N from the Drake equation using $R_* = 2\,\mathrm{yr}^{-1}$, $f_p = 0.8$, $n_e = 0.4$, $f_l = 0.2$, $f_i = 0.05$, $f_c = 0.05$, $L = 500\,\mathrm{yr}$, and explain what a value of N below 1 would mean. Identify the two factors that exoplanet databases have begun to measure.

Question 14 Distinguish between a targeted and an untargeted ETI search, giving one advantage of each.

Question 15 Searches for signals concentrate on narrow frequency channels, often within the water hole between $1.42\,\mathrm{GHz}$ and $1.66\,\mathrm{GHz}$. (a) Explain why a narrow-band signal is taken as a signature of technology rather than nature. (b) Calculate the number of 1 Hz channels contained in the water hole band. (c) Give two reasons why radio waves, rather than visible light, are the usual choice for such searches.

Question 16 The 1974 Arecibo message was aimed at the globular cluster M13, about 25 000 light-years away. (a) Calculate roughly how long the message takes to reach M13, and how long a reply sent immediately on arrival would take to return to Earth. (b) Describe the nature of the information the message carries, and explain why it is built from mathematics and simple pictures.

Question 17 Describe the information carried by the Voyager Golden Records and by the Pioneer plaques, and identify one way in which humans signal the existence of intelligent life on Earth without intending to.

Question 18 A commentator writes: “Decades of searching have found no extra-terrestrial signal, so continuing to fund the search is a waste of money.” Evaluate this claim. Your answer should refer to how much of the search space has been covered, and to at least one factor (scientific, economic, social or political) relevant to funding such searches. (Reasoning is assessed; either conclusion can receive full marks.)

Answers

Question 1 (a) hydrogen is present in the star's outer layers; (b) the gas absorbs those wavelengths from the continuous spectrum; (c) the star is receding — the Doppler shift (redshift). **Question 2** (a) $0.05\,\text{nm}$; (b) $3.0\times10^{4}\,\text{m s}^{-1}$; (c) receding — the line moved to longer wavelength. **Question 3** (a) $3.1\times10^{-6}\,\text{nm}$; (b) $3.1\times10^{-15}\,\text{m}$; (c) see solution — stability of one part in two hundred million. **Question 4** (a) 9.2×10^{-3}; (b) $0.0084\,\%$; (c) see solution — atmospheric noise exceeds the dip. **Question 5** (a) $1.42\times10^{9}\,\text{Hz}$; (b) $0.21\,\text{m}$; (c) $21\,\text{cm}$. **Question 6** (a) 25; (b) the number of civilisations in the Galaxy whose signals we could currently detect. **Question 7** See solution — the vapour is in the planet's atmosphere; a biosignature is evidence, not proof. **Question 8** (a) 0.10; (b) $7.0\times10^{4}\,\text{km}$ — about Jupiter's radius; (c) see solution. **Question 9** (a) $9.2\times10^{-5}\,\text{nm}$; (b) blueshift; (c) see solution — the planet's orbital period. **Question 10** (a) $0.59\,\%$; (b) about 70 times deeper — see solution. **Question 11** (a) $4.0\times10^{16}\,\text{m}$; (b) $4.2\,\text{yr}$; (c) see solution. **Question 12** See solution — apparent likelihood against absent evidence; resolutions include distance/time and brief civilisations. **Question 13** $N\approx0.16$; below 1 means we may be alone at this moment; f_p and n_e now measured. **Question 14** See solution — depth on chosen targets against coverage and surprise. **Question 15** (a) see solution — nature emits broadly, technology concentrates; (b) 2.4×10^{8}; (c) see solution. **Question 16** (a) about 25 000 years each way, ≈ 50 000 years round trip; (b) see solution. **Question 17** See solution — sounds/images/greetings; figures and a pulsar map; accidental radio and TV leakage. **Question 18** See solution — reasoning assessed; either conclusion acceptable if justified.

Fully-worked solutions

Question 1 (a) Each element absorbs its own characteristic set of wavelengths. The star's spectrum shows the full fingerprint pattern of laboratory hydrogen, so **hydrogen is present** in the star's outer layers. (b) The star's hot interior produces a continuous spectrum. The cooler hydrogen gas above it absorbs exactly the wavelengths of its fingerprint, removing that light from the beam that reaches us, so those wavelengths appear as **dark absorption lines**. (c) A uniform shift of the whole pattern to longer wavelengths is a **redshift**: the **Doppler shift** of a star **receding** from us. (A shift of the pattern is motion; missing wavelengths are composition — the two readings of a spectrum must not be confused.)

Question 2 (a) $\Delta\lambda=500.05-500.00=0.05\,\text{nm}$. (b) $v=c\dfrac{\Delta\lambda}{\lambda_0}=3.0\times10^{8}\times\dfrac{0.05}{500.00}=3.0\times10^{8}\times1.0\times10^{-4}=3.0\times10^{4}\,\text{m s}^{-1}$. (c) The observed wavelength is longer than the rest wavelength ($\Delta\lambda$ positive), a redshift, so the star is **receding**.

Question 3 (a) $\Delta\lambda=\lambda_0\dfrac{v}{c}=656.28\times\dfrac{1.4}{3.0\times10^{8}}=656.28\times4.7\times10^{-9}\approx3.1\times10^{-6}\,\text{nm}$. (b) $3.1\times10^{-6}\,\text{nm}=3.1\times10^{-15}\,\text{m}$. (c) The shift is about one part in two hundred million of the wavelength — thousands of times smaller than the width of the line itself. The spectrograph must be stable enough to notice a shift of a few femtometres in a line measured across four light-years; only the most stable modern instruments can do so. That is why planets like Proxima Centauri b waited until 2016 to be found.

Question 4 (a) $R_p/R_\star=6\,371/696\,000=9.2\times10^{-3}$. (b) $(9.2\times10^{-3})^2=8.4\times10^{-5}=0.0084\,\%$. (c) A dip of one part in about twelve thousand is smaller than the brightness noise added by turbulence in Earth's own atmosphere. Reliable measurement needs the steady view from space — which is why the first Earth-sized transits were found by space telescopes.

Question 5 (a) $1.42\,\text{GHz}=1.42\times10^{9}\,\text{Hz}$. (b) $\lambda=c/f=\dfrac{3.0\times10^{8}}{1.42\times10^{9}}\approx0.21\,\text{m}$. (c) $0.21\,\text{m}=21\,\text{cm}$.

Question 6 (a) $N=5\times0.5\times1\times0.5\times0.1\times0.1\times2\,000$. $5\times0.5=2.5$; $\times1=2.5$; $\times0.5=1.25$; $\times0.1=0.125$; $\times0.1=0.0125$; $\times2\,000=25$. So $N=25$. (b) N is the number of civilisations in our Galaxy whose signals would be detectable now.

Question 7 (a) The absorbing water vapour is in **the planet's atmosphere**. When the planet transits, starlight passes through that atmosphere on its way to us and gains the water-vapour absorption lines; when the planet is beside the star, the same light shows no such lines. Subtracting the two spectra leaves only what the planet's atmosphere added, locating the vapour in the planet's air rather than in the star. (b) Water vapour is a **biosignature gas** — it is a condition for life as defined here, not a product of it. Water vapour is made abundantly by non-living processes (outgassing, oceans, ice), so its presence marks K2-18b as a candidate world whose other gases must be weighed — for example methane and carbon dioxide together — before any claim about life. Evidence to weigh, not proof.

Question 8 (a) Depth $=(R_p/R_\star)^2=0.010$, so $R_p/R_\star=\sqrt{0.010}\approx 0.10$. (b) $R_p=0.10\times 696\,000=7.0\times 10^4\,\text{km}$ — essentially Jupiter's radius ($69\,911\,\text{km}$): the planet is a Jupiter-sized gas giant. (c) The transit method gives radius and period but not mass: it cannot give the planet's **mass** (or minimum mass), and so cannot give its density or composition; the radial velocity method supplies the mass from the star's wobble. (A transit also tells nothing if the orbit is not edge-on, but for this planet the wobble would confirm the mass.)

Question 9 (a) $\Delta\lambda=\lambda_0\dfrac{v}{c}=550.00\times\dfrac{50}{3.0\times 10^8}=550.00\times 1.7\times 10^{-7}\approx 9.2\times 10^{-5}\,\text{nm}$. (b) Motion **towards** Earth squeezes the waves to shorter wavelength: a **blueshift**. (c) The shift repeats with a period of 4.2 days because the star orbits the common centre of mass; the repetition period is the **orbital period of the planet** — its year. Together with the size of the shift (the star's wobble speed) it shows a massive planet orbiting extremely close to the star.

Question 10 (a) $(6\,371/83\,000)^2=(0.0768)^2=5.9\times 10^{-3}=0.59\,\%$. (b) $0.59\,\%/0.0084\,\%\approx 70$: the dip is about **seventy times deeper** for the same planet crossing the small star. Deep dips rise clearly above the noise of measurement, so surveys of small cool stars detect Earth-sized planets that would be invisible against Sun-sized stars — which is why systems like TRAPPIST-1, with seven Earth-sized planets, were found by transit surveys aimed at small stars.

Question 11 (a) $4.2\times 9.46\times 10^{15}=3.97\times 10^{16}\approx 4.0\times 10^{16}\,\text{m}$. (b) $t=d/c=\dfrac{4.0\times 10^{16}}{3.0\times 10^8}\approx 1.3\times 10^8\,\text{s}$. In years: a light-year is by definition the distance light travels in a year, so the signal takes **4.2 years**. (Check: $1.3\times 10^8\,\text{s}\approx 4.2\,\text{yr}$.) (c) The **astrometric method** measures the star's tiny side-to-side change of position on the sky as it orbits the common centre of mass — a slow, repeated measurement of one star's wobble, giving true masses and orbits. **Microlensing** measures the temporary brightening of a *background* star when the lens star (and its planet) pass in front of it — gravity focusing light, not the wobble of the lens star. Its limitation: the alignment is a one-off chance event that never repeats, so the planet cannot be re-observed or confirmed by other methods.

Question 12 The **Fermi paradox** is the clash between the apparent likelihood of extra-terrestrial civilisations — the Galaxy is vast, old and full of stars — and the complete absence of any evidence of them: "where is everybody?" Proposed resolutions include: (1) the distances and times are so great that signals and civilisations miss each other (a signal needs tens of thousands of years to cross the Galaxy); and (2) technological civilisations are short-lived, so few are transmitting at any one moment. (Other acceptable resolutions: intelligent life is genuinely rare; or we do not yet know where or how to listen.)

Question 13 $N=2\times 0.8\times 0.4\times 0.2\times 0.05\times 0.05\times 500$. $2\times 0.8=1.6$; $\times 0.4=0.64$; $\times 0.2=0.128$; $\times 0.05=6.4\times 10^{-3}$; $\times 0.05=3.2\times 10^{-4}$; $\times 500=0.16$. So $N\approx 0.16$. A value below 1 means that, on these factors, fewer than one detectable civilisation exists in the Galaxy at any moment — we would very likely be alone *now*, even if life has appeared elsewhere at other times. The two factors that exoplanet surveys and databases now genuinely measure are f_p (the fraction of stars with planets) and n_e (the average number of potentially habitable planets per star).

Question 14 A **targeted search** points the telescope at pre-selected stars (nearby, Sun-like, or known to host habitable-zone planets) and listens for a long time: its advantage is **depth** — maximum sensitivity on the most promising targets. An **untargeted search** sweeps wide areas of sky without pre-selection: its advantage is **coverage** — it can catch a strong transmitter anywhere in the surveyed sky, including sources nobody predicted. The two are complementary: depth on chosen stars against breadth and the chance of surprise.

Question 15 (a) Natural astrophysical sources emit over broad frequency ranges. A transmitter built to be heard concentrates its power into a very narrow band; power in a single thin channel is therefore the signature of technology. Searching in narrow channels rejects the broad noise of nature. (b) Bandwidth

$= 1.66 - 1.42 = 0.24\ \text{GHz} = 2.4 \times 10^8\ \text{Hz}$; in 1 Hz channels this is 2.4×10^8 channels — hundreds of millions of channels to check before a single star is considered, which shows why the search is slow and why bandwidth choice is the central trade-off. (c) Radio waves pass through interstellar dust and planetary atmospheres that block or scatter other wavelengths, and natural background noise is low in the water hole; and producing a detectable signal at radio frequencies takes far less energy than at shorter wavelengths. (Any two of these.)

Question 16 (a) Travelling at the speed of light, the message takes about **25 000 years** to reach M13; an immediate reply takes the same time to return — a round trip of about **50 000 years**. (At 1974 plus 25 000 years, it has so far crossed a tiny fraction of the distance.) (b) The message carries information built from **mathematics and simple pictures**: the numbers one to ten, the chemical elements of DNA, a human figure, the layout of the Solar System with Earth marked, and the sending telescope. It is built this way because the sender and any receiver share no language, history or biology; what they do share is mathematics, physics and chemistry. Primes and numbers announce "this is a message, decode it", and the universal reference points anchor the pictures that follow.

Question 17 The **Voyager Golden Records** carry a sample of Earth's life and culture: sounds of the biosphere and of human life, images encoded as audio signals, music, and greetings in many languages — information about *who we are*, for any patient decoder. The **Pioneer plaques** carry engraved figures of a man and a woman and a map locating the Sun relative to nearby pulsars — information about *where we are*, using pulsar periods as universal coordinates. Unintended signalling: our **radio and television broadcasts** leak into space and spread outward at the speed of light — a technological noise bubble that marks the Solar System as inhabited without anyone having chosen to send it.

Question 18 Model answer. The claim rests on "nothing found", but a search that has covered a tiny fraction of the search space cannot conclude absence. The sky is vast, the water hole alone is hundreds of millions of 1 Hz channels, and only a minute sample of stars has been listened to for short times at limited sensitivity; "no signal yet" is therefore evidence about our coverage, not about the Galaxy. Against continuing: funds are limited, each search has a genuine chance of an empty result, and the same money competes with other science and public needs — a reasonable position if one weighs the low probability of a near detection against pressing present needs. For continuing: the question is among the largest in science, the cost of a radio search is small compared with major facilities, the methods also produce real astronomy (pulsars, masers — natural sources of intense, narrow microwave beams in space — and technosignature techniques), and a single detection would change our understanding of our place in the Universe. Marks are awarded for the coverage argument and for weighing at least one funding factor with reasoning; either conclusion, if reasoned, receives full marks.

Option task — Life beyond the Solar System: an evidence response

This is the assessed Option task that closes Option 2.14. It uses the study design's own Outcome 2 task type *"a physics-referenced response to an issue"*. The study design specifies no mark allocations at Units 1 & 2 — levels of achievement are a matter for school decision, and only satisfactory completion is reported to the VCAA — so the **30 marks below are house convention**. The task is assessed against the shared *Communicating physics* key knowledge ($U2.2.CP.1$–.5), which is taught in Sections 10A and 10B, applied to the physics of this section ($U2.2.O14.1$–.6).

The task. Choose **one** of the following issues:

- **Issue A:** "A habitable-zone planet has been found by transit and radial velocity. How strongly does the current evidence support searching its atmosphere for life?"
- **Issue B:** "Decades of ETI searches have found nothing. Should public money continue to fund the search for extra-terrestrial intelligence?"

Produce a response of 800–1200 words (report or scientific poster) that does all of the following:

1. **Set out the physics of the issue.** Describe the detection method(s) or search strategy relevant to your issue — for Issue A, the transit and/or radial velocity method and the spectroscopy that would follow; for Issue B, targeted and untargeted listening and the choice of frequency and bandwidth. Define every key term you use ($U2.2.O14.1$, $U2.2.O14.2$ or $U2.2.O14.5$; $U2.2.CP.2$).
2. **Calculate with real data.** Using entries from the NASA Exoplanet Archive (Issue A) or stated search parameters (Issue B), carry out at least two calculations — for example a Doppler shift $\Delta\lambda/\lambda_0 = v/c$, a

transit depth $(R_p / R_\star)^2$, a wavelength from $c = f\lambda$, or a Drake-equation estimate with stated factors. Show working in full, with units and correct significant figures (U2.2.O14.3; U2.2.CP.2).

3. **Represent and question the evidence.** Include at least one data representation — a sketched light curve, a labelled spectrum, or a factors table — and discuss its limitations, including the detection bias of the method or the uncertainty of the factors (U2.2.O14.2, U2.2.O14.4; U2.2.CP.3).
4. **Evaluate your sources.** List every source you used, with its retrieval date, and evaluate the validity of at least three of them — for example the NASA Exoplanet Archive against a media report of the same discovery (U2.2.CP.1).
5. **Discuss the wider factors and take a position.** Discuss at least one sociocultural, economic, legal or political factor relevant to your issue — for example who funds large telescopes and SETI programmes, how telescope time is allocated, or why radio quiet zones such as the Murchison zone in Western Australia are protected by law. Finish with a justified stance on the issue, based on your physics (U2.2.CP.4, U2.2.CP.5).

Your teacher will set the due date and any in-class conditions. Work that uses data from a source must name the source and its retrieval date.

Mark allocation (30 marks — house convention).

Criterion	Study-design dot point	Marks
Validity of sources evaluated	U2.2.CP.1	4
Physics concepts, terms and conventions applied correctly, with full calculations	U2.2.CP.2	8
Data representations, models and theories used and organised clearly, with limitations discussed	U2.2.CP.3	6
Sociocultural, economic, legal or political factors discussed	U2.2.CP.4	4
Physics-based stance, recommendation or solution justified	U2.2.CP.5	8
Total		**30**

Marking rubric.

Band	CP.1 sources (4)	CP.2 physics (8)	CP.3 representations (6)	CP.4 factors (4)	CP.5 stance (8)
High	4: every source named with retrieval date and its validity evaluated	7–8: concepts and terms correct throughout; calculations complete with units and correct significant figures	5–6: representation complete and clearly labelled; limitations (bias, uncertainty) discussed	4: at least one relevant factor discussed in genuine depth	7–8: stance fully justified by the physics of the response
Medium	3: sources named and validity considered	4–6: concepts mostly correct; working mostly complete	3–4: representation present with minor omissions; limitations noted briefly	3: a relevant factor identified with some discussion	4–6: stance given with partial justification
Low	1–2: sources listed with little or no evaluation	1–3: concepts partly correct; working	1–2: representation missing key	1–2: a factor named with little	1–3: stance stated with little

Band	$CP.1$ sources (4)	$CP.2$ physics (8)	$CP.3$ representations (6)	$CP.4$ factors (4)	$CP.5$ stance (8)
		incomplete	labels	discussion	support
None	0	0	0	0	0

Marks are awarded for the quality of the reasoning, not for the conclusion reached: two students who reach opposite stances can both receive full marks in $CP.5$ if both justify their position from correct physics.

Chapter 13 Options: astrophysics, particles and contemporary research — 13C Option 2.16: How do particle accelerators work?

Theory

This section is **Option 2.16 — The physics of particle accelerators**, one of the eighteen options of Unit 2, Area of Study 2. A student studies exactly one option; this section is self-contained for a student who has chosen Option 2.16. It applies the electrical ideas of Chapter 5 — charge, potential difference and the energy transferred to charge ($E = V\,Q$) — and the electromagnetic-spectrum ideas of Chapter 1 to the largest scientific instruments ever built: machines that speed up charged particles to almost the speed of light. The section closes with the assessed Option task.

What a particle accelerator is. A **particle accelerator** is a device that speeds up charged particles — electrons, protons, antiprotons or atomic nuclei — to very high speeds and directs them where they are needed. The stream of particles is called a **beam**. Every accelerator uses two tools:

- **electric fields** do the speeding up. A potential difference gives energy to a charge, exactly as in Chapter 5: a charge Q that moves through a potential difference V gains energy $E = V\,Q$. An electron that crosses a larger potential difference ends with more energy;
- **magnetic fields** do the steering. Magnets placed around the beam path bend the path of the moving charges, keeping a circular machine's beam on its loop and aiming a straight machine's beam at its target.

> **Units 3 & 4 preview.** This section describes what the electric and magnetic fields are *for*. The quantitative treatment of the force a magnetic field exerts on a moving charge — calculating *how much* a beam bends and *why* circular machines are called synchrotrons — is taught in Units 3 & 4. Nothing in this section, or in its questions, requires it.

The electron-volt. Particle energies are far smaller than a joule, so particle physics uses its own unit, the **electron-volt** (eV): one electron-volt is the energy gained by a particle with the charge of one electron when it moves through a potential difference of $1\ \mathrm{V}$. From $E = V\,Q$, with the electron charge $e = 1.6 \times 10^{-19}\,\mathrm{C}$,

$$1\,\mathrm{eV} = 1\ \mathrm{V} \times 1.6 \times 10^{-19}\,\mathrm{C} = 1.6 \times 10^{-19}\,\mathrm{J}\,.$$

The usual multiples are the megaelectron-volt ($1\,\mathrm{MeV} = 10^{6}\,\mathrm{eV}$), the gigaelectron-volt ($1\,\mathrm{GeV} = 10^{9}\,\mathrm{eV}$) and the teraelectron-volt ($1\,\mathrm{TeV} = 10^{12}\,\mathrm{eV}$). An electron that crosses a potential difference of 1 million volts ($1\,\mathrm{MV}$) gains $1\,\mathrm{MeV}$ of energy — the name of the unit tells you the potential difference needed.

Two jobs for accelerators. Particle accelerators are built for two very different purposes, and the difference matters throughout this section:

	Synchrotron light source	Collider
What is accelerated	electrons	electrons and positrons, protons and antiprotons, or atomic nuclei such as lead ions (a positron is the antimatter partner of an electron; an antiproton is the antimatter partner of a proton)
What is used	the **synchrotron light** the electrons give off as their path is bent	the **collisions** between two beams aimed head-on at each other
What it studies	the structure and chemistry of materials — proteins, minerals, cells, batteries	the fundamental particles of matter and the interactions between them
Example	the Australian Synchrotron, Clayton (Melbourne)	the Large Hadron Collider (LHC) at CERN, near Geneva

At a light source the particles never reach the sample: only their light does. At a collider there is no sample at all — the two beams are the experiment, and they meet at the centre of huge detectors.

Synchrotron light. When a charged particle changes direction, it emits electromagnetic radiation. The radiation emitted by fast electrons as magnetic fields bend their path is called **synchrotron radiation** or **synchrotron light**. Inside a storage ring the electrons are travelling at almost $3.0 \times 10^{8}\,\mathrm{m\,s^{-1}}$, so the emitted light is concentrated into a narrow, forward-pointing cone and can be very intense. By choosing the electron energy and the strength of the bending magnets, a synchrotron produces light across a wide range of the electromagnetic spectrum (Section 1B), from infrared through to X-rays.

The Australian Synchrotron. The Australian Synchrotron is a synchrotron light source at Clayton in southeast Melbourne, operated by the Australian Nuclear Science and Technology Organisation (ANSTO). It opened in 2007. Its accelerator complex has four stages, and the key knowledge for this option asks you to explain the general purpose of each.

1. **The electron linac.** A **linac** (linear accelerator) is a straight accelerator. At the Australian Synchrotron the electron linac produces the electrons and accelerates them to an energy of $100\,\mathrm{MeV}$, firing them in a straight line into the next stage.
2. **The circular booster.** The booster is a circular accelerator. The electrons from the linac go around the booster ring many times, gaining a little energy on every lap, until they reach the full energy of $3.0\,\mathrm{GeV}$ — thirty times the linac energy.
3. **The storage ring.** The storage ring is a $216\,\mathrm{m}$ ring that stores the $3.0\,\mathrm{GeV}$ electrons so they circulate continuously, typically for many hours at a stored current of about $200\,\mathrm{mA}$. Powerful magnets keep the beam on its near-circular path, and each time the beam is bent the electrons give off synchrotron light. The stored beam is the machine's supply of light.
4. **The beamlines.** A **beamline** is a carefully aligned set of mirrors, filters and other optical components that takes the light from one point on the storage ring and delivers a chosen beam — of a chosen wavelength range — to an experiment at its end. The Australian Synchrotron currently has 14 operational beamlines, each a purpose-built instrument for a different kind of experiment: determining the shapes of proteins (macromolecular crystallography), mapping where trace elements sit in a sample (X-ray fluorescence microscopy), identifying the chemicals in a sample with infrared light (infrared microspectroscopy), and studying the structure of materials with X-rays (diffraction and scattering), among others.

Source: ANSTO, Australian Synchrotron facility page, retrieved 2026-08-18. Source: Wikipedia, Australian Synchrotron, retrieved 2026-08-18. Source: Australian Synchrotron (ANSTO), Beamlines, retrieved 2026-08-18.

Because the electrons circulate for hours, a single fill of the storage ring supplies steady, continuous light to every beamline at once. Research groups from universities, hospitals, industry and government agencies book time on a beamline, just as they would book time on any other shared instrument. The study design requires a minimum of ten hours of practical work across Areas of Study 1 and 2 of Unit 2; a visit to a facility such as the Australian Synchrotron — in person or online — is one way your teacher may use some of that time.

Why use synchrotron light? Three properties decide how useful a source of light is for an experiment. Two of them are named in the key knowledge but not defined by the study design, so this subtopic gives them an operational meaning, and every question here is answerable on these definitions alone:

- **Brightness** is treated here as how concentrated the radiation is — the amount of light power delivered to a small spot. The more power in the spot, the brighter the source.
- **Divergence** is treated here as how much a beam spreads out as it travels. A beam with small divergence stays narrow over a long distance; a beam with large divergence fans out quickly in all directions.

The third property, the **spectrum**, is the range of wavelengths present (Section 1B). A source that emits only one wavelength has a narrow spectrum; a source that emits across many wavelengths has a broad spectrum, and if the user can choose which wavelength to work with, the light is called **tuneable**.

On these three properties, synchrotron light compares with two familiar laboratory sources — lasers and X-ray tubes — as follows.

Property	Synchrotron light	Laser	X-ray tube
Brightness	very high — a great deal	moderate	low — the X-rays come

Property	Synchrotron light	Laser	X-ray tube
	of power can be concentrated on a very small spot		from a spread-out source and most of them miss the sample
Spectrum	very broad and tuneable, from infrared to X-rays	very narrow — essentially one wavelength	broad, but fixed by the tube; not tuneable
Divergence	small — the light comes off the fast electrons in a narrow forward cone	small	large — the X-rays spread out in all directions from the target

Each source has its uses. A laser's narrow, single-wavelength beam is ideal for alignment, communication and many measurements, but no laser can give the tuneable X-rays a crystallography experiment needs. An X-ray tube is cheap and simple — the right tool for a routine X-ray image — but its light is neither bright nor well directed enough for experiments on tiny samples. Synchrotron light is chosen when an experiment needs intense, tuneable, well-directed light: for example, when the shape of a single protein crystal must be worked out from the way it scatters X-rays, or when the trace elements in a grain of mineral must be mapped one spot at a time. In those experiments synchrotron light is preferable to laser light and to X-ray tube radiation because it is simultaneously brighter, tuneable across the needed wavelengths, and less divergent.

From fixed targets to colliders. Through the 1950s, particle beams were fired at stationary targets. In such a **fixed-target** collision the incoming particle hits a particle at rest, and much of the incoming energy goes into carrying the debris forward — momentum must be conserved (Section 8E), so the products cannot just sit still. Only part of the beam's energy is available for making new things. If instead two beams of equal and opposite momentum meet head-on, the total momentum of the pair is zero, and the whole of their combined energy can be used in the collision. That is the idea of a **collider**: two beams, accelerated in opposite directions and brought together at a crossing point inside a detector.

Collider technology has evolved in two visible ways since the first colliders appeared around 1960: the **particles involved**, and the **collision energies attained**.

Collider (laboratory)	Years	Particles collided	Collision energy	Notable result
AdA (INFN Frascati, Italy)	early 1960s	electrons and positrons	—	the first electron–positron storage ring; proved that matter and antimatter beams could be stored and collided
ISR (CERN, near Geneva)	1971–1984	protons	up to $62\,\mathrm{GeV}$	the first proton–proton collider
SPS collider (CERN)	1981–1991	protons and antiprotons	$540\,\mathrm{GeV}$	discovery of the W and Z bosons (1983)
Tevatron (Fermilab, USA)	1983–2011	protons and antiprotons	$1.96\,\mathrm{TeV}$	discovery of the top quark (1995)
LEP (CERN)	1989–2000	electrons and positrons	up to $209\,\mathrm{GeV}$	precision measurements of the W and Z bosons
LHC (CERN)	first beam 2008	protons; also lead ions	$13.6\,\mathrm{TeV}$ (protons)	discovery of the Higgs boson (2012)

The particles involved broadened from electrons and their antimatter partners, positrons, to protons and antiprotons, and finally to whole atomic nuclei such as lead ions; antimatter is taken further in Section 13D, Option 2.17. The collision energy climbed steeply: from $62\,\mathrm{GeV}$ at the ISR in 1971 to $13.6\,\mathrm{TeV}$ at the LHC — an increase by a factor of about 220 — and each jump in energy opened the way to producing heavier particles and looking deeper into matter.

Source: Wikipedia, Bruno Touschek, retrieved 2026-08-18. Source: Wikipedia, Intersecting Storage Rings, retrieved 2026-08-18. Source: Wikipedia, Super Proton Synchrotron, retrieved 2026-08-18. Source: Wikipedia, Tevatron, retrieved 2026-08-18. Source: Wikipedia, Large Electron–Positron Collider, retrieved 2026-08-18. Source: CERN, The Large Hadron Collider, retrieved 2026-08-18.

Colliders and the Standard Model. The **Standard Model** of particle physics is the present model of the fundamental particles of matter and of the interactions between them. The study design uses the term without defining it; in this subtopic the Standard Model is treated as the catalogue of the matter particles and force-carrying particles that everything ordinary is built from, together with the rules for how they interact — and every question here is answerable on that description alone. According to the model, protons and neutrons are not fundamental: they are built from still smaller particles called **quarks**, and the interactions between particles are carried by force-carrying particles such as the photon (the particle of electromagnetic radiation, Section 1B) and the W and Z bosons. The model also predicts a particle called the **Higgs boson**, associated with the property of mass.

Colliders built and tested this model step by step. The pattern repeats: the model predicts that a particle with certain properties should exist; a collider is run at high enough energy to produce it — the energy of the collision is converted into the mass of the new particle, the mass–energy conversion idea of Section 4A; and the detectors check whether the particle appears. Three landmarks from the table above show the pattern:

- the **W and Z bosons**, predicted by the model of the weak interaction, were discovered at the CERN SPS proton–antiproton collider in 1983;
- the **top quark**, the heaviest quark, was discovered at the Fermilab Tevatron in 1995;
- the **Higgs boson** was announced on 4 July 2012 by the ATLAS and CMS experiments at the LHC. Its mass is quoted as between 125 and $127\,\text{GeV}/c^2$ — particle physicists quote masses through their mass–energy equivalents, using the Section 4A idea — and it was the final missing piece of the model's particle list.

Between these discoveries, the LEP electron–positron collider made precision measurements of the W and Z bosons that checked the model's predictions in fine detail. Evaluating the role of colliders means recognising both directions of the relationship: the Standard Model told colliders what energy to reach and what to look for, and colliders supplied the evidence that turned the model's predictions into established physics. (Section 13D, Option 2.17, sorts the model's particles into families.)

Source: Wikipedia, Higgs boson, retrieved 2026-08-18.

The LHC's data problem. The Large Hadron Collider is a ring of superconducting electromagnets — magnets whose coils carry current with no electrical resistance when cooled to very low temperatures — $26\,659\,\text{m}$ in circumference, in which two proton beams of $6.8\,\text{TeV}$ each circulate in opposite directions and are brought to collide at points inside large detectors. Proton–proton collisions reach $13.6\,\text{TeV}$; the LHC also collides lead ions. At each of its two largest detectors there are about 1.5 billion collisions every second.

Source: CERN, The Large Hadron Collider, retrieved 2026-08-18.

No computer storage in the world could keep all of those events, so each detector ends with a **trigger** — fast electronics that inspect each collision within a tiny fraction of a second and decide whether it is worth keeping. The trigger keeps roughly 1 000 collisions per second — about one in every 1.5 million — and discards the rest. Each stored collision is recorded as a file of about 1 megabyte ($1\,\text{MB} = 10^6$ bytes) of data describing every particle that came out of it. Even after the trigger, one experiment stores of the order of tens of petabytes per year ($1\,\text{PB} = 10^{15}$ bytes).

The data are stored and analysed by the **Worldwide LHC Computing Grid** (WLCG): a network of around 160 computing centres in more than 40 countries, linked so that physicists anywhere in the world can process and analyse the collision data. Physicists from all of those countries search the stored data for rare events — the Higgs boson, announced in 2012, was found by combing through exactly this kind of stored collision record.

Source: CERN (CMS experiment), How the CMS trigger system manages data from LHC collisions, retrieved 2026-08-18. Source: CERN, Worldwide LHC Computing Grid, retrieved 2026-08-18.

Detectors and information technology. The particle detectors built for collider experiments have pushed information-processing technology forward, and the spin-offs reach well beyond physics:

- **the World Wide Web** was invented at CERN in 1989 so that physicists in different countries could share experiment information easily — the tool you use every day began as a data-sharing system for particle physics;
- **real-time trigger electronics** — circuits that must make a keep-or-discard decision in the time between two collisions — drove the development of very fast digital processing;
- **pixel detector chips** developed to record the tracks of particles at colliders, such as the Medipix family of chips from the CERN detector programme, now count individual X-ray photons and sort them by energy, producing sharp, colour-coded X-ray images for medicine and industry — commercialised, for example, by MARS Bioimaging in New Zealand;
- **distributed computing** on the scale of the WLCG is a forerunner of the large-scale distributed data processing now common in science and industry.

Source: CERN, The birth of the Web, retrieved 2026-08-18. Source: CERN, Medipix collaboration, retrieved 2026-08-18.

The useful relationships of this section are summarised below.

Quantity	Relationship	Unit
energy gained by a charge crossing a potential difference	$E = V\,Q$ (Section 5A)	J
electron-volt	$1\,\text{eV} = 1.6 \times 10^{-19}\,\text{J}$	eV
revolutions per second of a stored beam	$f = \frac{v}{C}$, where C is the ring circumference	Hz
data sizes	$1\,\text{MB} = 10^{6}$ bytes; $1\,\text{GB} = 10^{9}$ bytes; $1\,\text{TB} = 10^{12}$ bytes; $1\,\text{PB} = 10^{15}$ bytes	bytes

Worked examples

Example 1 — scaffolded

The storage ring of the Australian Synchrotron has a circumference of $216\,\text{m}$ and stores electrons at an energy of $3.0\,\text{GeV}$, travelling at approximately $3.0 \times 10^{8}\,\text{m s}^{-1}$.

(a) Calculate how many times each electron circles the ring in one second.
(b) Convert the electron energy of $3.0\,\text{GeV}$ to joules.
(c) Calculate the distance one electron travels along the ring in $1.0\,\text{min}$.

Working	Comment
(a) $f = \frac{v}{C} = \frac{3.0 \times 10^{8}}{216} = 1.4 \times 10^{6}\,\text{Hz}$	Revolutions per second = speed ÷ circumference, to 2 significant figures.
(b) $3.0\,\text{GeV} = 3.0 \times 10^{9}\,\text{eV}$; $E = 3.0 \times 10^{9} \times 1.6 \times 10^{-19} = 4.8 \times 10^{-10}\,\text{J}$	$\text{GeV} \rightarrow \text{eV}$ first; then $1\,\text{eV} = 1.6 \times 10^{-19}\,\text{J}$.
(c) $d = v\,t = 3.0 \times 10^{8} \times 60 = 1.8 \times 10^{10}\,\text{m}$	$1.0\,\text{min} = 60\,\text{s}$; distance = speed × time.

The energy of one stored electron, $4.8 \times 10^{-10}\,\text{J}$, is far too small to feel — yet the beam contains so many electrons that the light they emit fills fourteen beamlines with experiments at once.

Example 2 — scaffolded

In the electron linac of the Australian Synchrotron, electrons are accelerated to $100\,\text{MeV}$.

(a) Show, using $E = V\,Q$, that $1\,\text{eV} = 1.6 \times 10^{-19}\,\text{J}$.

(b) Convert $100\,\text{MeV}$ to joules.

(c) The booster ring then raises each electron's energy to $3.0\,\text{GeV}$. State how many times larger this is than the linac energy.

Working	Comment
(a) $E = V\,Q = 1 \times 1.6 \times 10^{-19} = 1.6 \times 10^{-19}\,\text{J}$	One electron-volt is the energy a charge $e = 1.6 \times 10^{-19}\,\text{C}$ gains crossing $1\,\text{V}$.
(b) $100\,\text{MeV} = 1.0 \times 10^{8}\,\text{eV}$; $E = 1.0 \times 10^{8} \times 1.6 \times 10^{-19} = 1.6 \times 10^{-11}\,\text{J}$	$\text{MeV} \to \text{eV}$, then $\text{eV} \to \text{J}$.
(c) $\dfrac{3.0\,\text{GeV}}{100\,\text{MeV}} = \dfrac{3.0 \times 10^{9}\,\text{eV}}{1.0 \times 10^{8}\,\text{eV}} = 30$	Compare both energies in the same unit before dividing.

Example 3 — unscaffolded

A research group must choose a light source for each of three jobs. The available sources and their properties, supplied for this problem, are:

Source	Brightness (relative)	Spectrum	Divergence
Synchrotron beamline	$1\,000\,000$	broad, tuneable from infrared to X-ray	small
Laboratory laser	100	narrow — one wavelength, visible light	small
X-ray tube	1	broad X-ray range, fixed	large

The jobs are: (i) working out the shape of a protein crystal from the way it scatters X-rays; (ii) checking that an optical instrument is pointing exactly where it should; (iii) taking a routine X-ray image of a welded joint for cracks.

(a) Recommend a source for each job, justifying each choice using brightness, spectrum and divergence.

(b) The protein experiment needs 1.0×10^{12} X-ray photons per second on the sample; the X-ray tube can deliver 1.0×10^{8} useful photons per second to the same spot. Calculate how many times longer the X-ray tube measurement would take, and state one practical problem with simply waiting that long.

(c) Protein crystallography needs tuneable X-rays of high brightness on a very small crystal. The laser cannot help: its wavelength is visible light, not X-rays. The X-ray tube produces X-rays, but its brightness is 10^{6} times too low for the weak scattering from a tiny crystal, and its large divergence wastes most of them. The **synchrotron beamline** is the suitable source: bright, tuneable X-rays with small divergence.

(ii) Alignment needs a straight, narrow, visible beam. The **laser** is the suitable source: small divergence and a single visible wavelength. The synchrotron's X-rays would be invisible and hazardous for a simple alignment job, and the X-ray tube's light spreads in all directions.

(iii) A routine weld inspection does not need tuneable or extremely bright X-rays. The **X-ray tube** is the suitable source: it is cheap, simple and adequate — the extra brightness of a synchrotron buys nothing worth the effort of booking beamtime.

(b) The required photon rate is

$$\frac{1.0 \times 10^{12}}{1.0 \times 10^{8}} = 1.0 \times 10^{4}$$

times larger than the tube can supply, so the tube measurement would take about $10\,000$ times as long. One practical problem: a measurement that takes, say, one minute at the synchrotron would take about a week at the tube — over such a long measurement the sample, the tube and the detector can all drift, and the weak signal becomes hard to distinguish from background.

∴ synchrotron beamline for (i), laser for (ii), X-ray tube for (iii); the tube would take about $10\,000$ times longer.

Example 4 — unscaffolded

At one of the LHC's large detectors there are about 1.5×10^{9} proton–proton collisions each second. The trigger keeps about $1\,000$ of them per second, and each stored collision is recorded as a file of about $1\,\text{MB}$ (10^{6} bytes).

(a) Calculate the fraction of collisions that is stored.

(b) Calculate the amount of data the detector stores per day, in bytes.

(c) Estimate the data stored in one year and explain, referring to the Worldwide LHC Computing Grid, how data of this size are handled.

(d) Fraction stored:

$$\frac{1\,000}{1.5 \times 10^{9}} = 6.7 \times 10^{-7}$$

— about one collision in every 1.5 million.

(b) Stored data rate:

$$1\,000 \times 10^{6} = 1.0 \times 10^{9}\,\text{bytes per second}.$$

Per day:

$$1.0 \times 10^{9} \times 24 \times 3600 = 8.6 \times 10^{13}\,\text{bytes}\left(86\,\text{TB}\right).$$

(c) Per year:

$$8.6 \times 10^{13} \times 365 \approx 3.2 \times 10^{16}\,\text{bytes} \approx 32\,\text{PB}.$$

A single experiment therefore accumulates tens of petabytes of collision data every year, and there are several experiments. Data of this size are handled by the Worldwide LHC Computing Grid: the data are copied from CERN to around 160 computing centres in more than 40 countries, where physicists process and analyse them in parallel. No single computer could store or analyse the full record alone.

∴ fraction $\approx 6.7 \times 10^{-7}$; about 8.6×10^{13} bytes per day; about $32\,\text{PB}$ per year, distributed across the WLCG.

Practice questions

Question 1 *(scaffolded)* The Australian Synchrotron has four accelerator stages: the electron linac, the circular booster, the storage ring, and the beamlines. (a) State the general purpose of the electron linac. (b) State the general purpose of the circular booster. (c) State the general purpose of the storage ring. (d) State the general purpose of a beamline.

Question 2 *(scaffolded)* The electrons in the Australian Synchrotron's storage ring have an energy of $3.0\,\text{GeV}$. (a) Express $3.0\,\text{GeV}$ in electron-volts. (b) Convert $3.0\,\text{GeV}$ to joules. Use $1\,\text{eV} = 1.6 \times 10^{-19}\,\text{J}$. (c) Express the linac energy of $100\,\text{MeV}$ in joules.

Question 3 *(scaffolded)* The storage ring of the Australian Synchrotron has a circumference of $216\,\text{m}$. The stored electrons travel at approximately $3.0 \times 10^{8}\,\text{m s}^{-1}$. (a) Calculate the time for one complete circuit of the ring. (b) Calculate the number of circuits an electron makes in one second. (c) Calculate the distance an electron travels along the ring in $1.0\,\text{s}$.

Question 4 *(scaffolded)* Three properties of a light source are its brightness, its spectrum and its divergence. (a) Complete each sentence: brightness describes how …; the spectrum describes the …; divergence describes how much … (b) State which source has the smaller divergence: a laser or an X-ray tube. (c) State which source has the narrower spectrum: a laser or an X-ray tube. (d) State which property makes synchrotron light better than an X-ray tube for studying a very small sample.

Question 5 *(scaffolded)* The table of collider milestones in this section gives the collision energies of the ISR ($62\,\text{GeV}$), the Tevatron ($1.96\,\text{TeV}$) and the LHC ($13.6\,\text{TeV}$). (a) Identify the particles collided at the ISR and at the Tevatron. (b) Express the LHC collision energy of $13.6\,\text{TeV}$ in GeV. (c) Calculate how many times larger the LHC collision energy is than the ISR collision energy.

Question 6 *(scaffolded)* The Worldwide LHC Computing Grid stores and processes about $200\,\text{PB}$ of LHC data each year ($1\,\text{PB} = 10^{15}$ bytes). (a) Write $200\,\text{PB}$ in bytes, in scientific notation. (b) Calculate the average number of bytes stored per second over one year. Use $1\,\text{year} = 365$ days. (c) A smartphone stores $128\,\text{GB}$ (1.28×10^{11} bytes). Calculate how many such smartphones would be needed to hold one year of LHC data.

Question 7 In one stage of a linac, an electron crosses a potential difference of $50\,\text{MV}$ ($5.0 \times 10^{7}\,\text{V}$). The electron charge is $1.6 \times 10^{-19}\,\text{C}$. (a) Calculate the energy the electron gains, in joules, using $E = V\,Q$. (b) Express this energy in MeV. (c) Explain why the electron-volt is a convenient unit for accelerator energies, referring to your answers to (a) and (b).

Question 8 A student writes: *"The Australian Synchrotron smashes electrons into samples so that the pieces can be studied."* Evaluate this statement. In your answer, identify what is wrong, state what actually reaches the sample, and state what the electrons do instead.

Question 9 The Tevatron collided protons and antiprotons at $1.96\,\text{TeV}$. The LHC collides protons at $13.6\,\text{TeV}$. (a) Convert each collision energy to joules. Use $1\,\text{eV} = 1.6 \times 10^{-19}\,\text{J}$. (b) Calculate how many times larger the LHC collision energy is than the Tevatron's. (c) The energy found in (a) for the LHC is less than a millionth of a joule. Explain why physicists still describe LHC collisions as high-energy events.

Question 10 Protein crystallography needs intense, tuneable X-rays directed at a crystal smaller than a grain of salt. Explain why synchrotron light is preferable to both laser light and X-ray tube radiation for this experiment, referring to brightness, spectrum and divergence for each comparison.

Question 11 A detector at the LHC stores $1\,000$ collisions per second, each recorded as a file of about $1\,\text{MB}$. (a) Calculate the number of bytes stored per second. (b) Calculate the number of bytes stored per day. (c) The detector receives about 1.5×10^{9} collisions per second. Calculate the fraction stored, and explain why a trigger that discards most collisions is essential.

Question 12 A student argues: *"One LHC collision releases only about $2.2 \times 10^{-6}\,\text{J}$ — less energy than a pencil of mass $10\,\text{g}$ releases when it falls $0.50\,\text{m}$ onto a desk. Building a $27\,\text{km}$ machine for such a tiny energy cannot be worthwhile."* Use $g = 9.8\,\text{N kg}^{-1}$. (a) Calculate the energy released by the falling pencil. (b) Calculate how many times more energy the pencil releases than one LHC collision. (c) Evaluate the student's argument. In your answer, explain what the comparison misses about where each energy acts.

Question 13 Early particle experiments fired a beam at a stationary target; modern colliders fire two beams head-on at each other. (a) Use conservation of momentum to explain why a fixed-target collision cannot use all of the beam's energy to make new particles. (b) Explain why a head-on collision of two beams with equal and opposite momenta can, in principle, use all of their combined energy. (c) Explain how the mass–energy conversion idea of Section 4A connects collision energy to the discovery of heavier particles.

Question 14 The W and Z bosons were discovered at the SPS collider in 1983, the top quark at the Tevatron in 1995, and the Higgs boson at the LHC in 2012. Each of these particles had been predicted by the Standard Model before it was found. (a) Describe the pattern connecting prediction, collision energy and discovery in these three cases. (b) Evaluate the role of colliders in the development of the Standard Model, referring to both directions of the relationship: what the model gave the machines, and what the machines gave the model.

Question 15 The LEP collider at CERN collided electrons and positrons at collision energies up to $209\,\text{GeV}$. (a) If the two beams had equal energies, calculate the energy of each beam in GeV. (b) Convert the energy of one LEP beam to joules. (c) Compare the energy of one LEP beam with the energy of one electron in the Australian Synchrotron storage ring ($3.0\,\text{GeV}$).

Question 16 About 1.5×10^9 collisions per second occur at one LHC detector. The trigger stores about $1\,000$ of them per second. (a) Calculate the number of collisions stored during a 24-hour run. (b) Explain what the trigger electronics must decide about each collision, and why the decision must be made extremely quickly. (c) Most discarded collisions are described as producing only particles that are already well understood. Explain why discarding them is a reasonable strategy, and state one risk of discarding collisions at such a high rate.

Question 17 A newspaper article states: *"Australian physicists use the Australian Synchrotron to collide particles at record energies and search for new fundamental particles."* Correct the article. In your answer, distinguish the two uses of particle accelerators taught in this section, state what the Australian Synchrotron actually does, and state where the collider work described in the article actually takes place.

Question 18 A government committee asks whether continued public funding of synchrotron light sources is worthwhile. Construct a reasoned response, referring to at least two applications of synchrotron light from this section, at least one sociocultural, economic, legal or political factor (Section 10B), and a clear, justified position. (Reasoning is assessed; either position can receive full marks.)

Answers

Question 1 (a) produces the electrons and accelerates them to $100\,\mathrm{MeV}$; (b) accelerates the electrons further, to $3.0\,\mathrm{GeV}$; (c) stores the $3.0\,\mathrm{GeV}$ electrons so they circulate for hours, supplying synchrotron light continuously; (d) carries chosen synchrotron light from the ring to one experiment. **Question 2** (a) $3.0\times10^{9}\,\mathrm{eV}$; (b) $4.8\times10^{-10}\,\mathrm{J}$; (c) $1.6\times10^{-11}\,\mathrm{J}$. **Question 3** (a) $7.2\times10^{-7}\,\mathrm{s}$; (b) 1.4×10^{6}; (c) $3.0\times10^{8}\,\mathrm{m}$. **Question 4** (a) brightness: how concentrated the radiation is; spectrum: the range of wavelengths present; divergence: how much the beam spreads out as it travels; (b) the laser; (c) the laser; (d) brightness. **Question 5** (a) ISR: protons; Tevatron: protons and antiprotons; (b) $1.36\times10^{4}\,\mathrm{GeV}$; (c) about 220 times. **Question 6** (a) 2.0×10^{17} bytes; (b) 6.3×10^{9} bytes per second; (c) about 1.6×10^{6} smartphones. **Question 7** (a) $8.0\times10^{-12}\,\mathrm{J}$; (b) $50\,\mathrm{MeV}$; (c) see solution — the energy in eV equals the potential difference in volts. **Question 8** The statement is incorrect: nothing solid is smashed into the sample; only synchrotron light reaches it — see solution. **Question 9** (a) Tevatron $3.1\times10^{-7}\,\mathrm{J}$; LHC $2.2\times10^{-6}\,\mathrm{J}$; (b) about 6.9 times; (c) see solution — the energy is concentrated in a single collision between two particles. **Question 10** See solution — laser: wrong wavelengths; X-ray tube: not bright or well-directed enough. **Question 11** (a) 1.0×10^{9} bytes per second; (b) 8.6×10^{13} bytes; (c) 6.7×10^{-7}; see solution. **Question 12** (a) $0.049\,\mathrm{J}$; (b) about 2.2×10^{4} times; (c) see solution — the pencil's energy is spread across a macroscopic desk, the collision's energy acts on individual particles. **Question 13** (a) the products must carry forward momentum, taking energy with them; (b) total momentum is zero, so no energy is needed to carry the products anywhere; (c) collision energy is converted into the mass of new particles. **Question 14** (a) the model predicted each particle; colliders reached the energy needed to produce it; detectors observed it; (b) see solution. **Question 15** (a) $104.5\,\mathrm{GeV}$; (b) $1.7\times10^{-8}\,\mathrm{J}$; (c) about 35 times larger. **Question 16** (a) 8.6×10^{7} collisions; (b) keep or discard, before the next collision arrives; (c) see solution. **Question 17** See solution — the Synchrotron is a light source, not a collider. **Question 18** See solution — reasoning assessed; either position acceptable if justified.

Fully-worked solutions

Question 1 (a) The **electron linac** is the linear accelerator that produces the electrons and accelerates them, in a straight line, to an energy of $100\,\mathrm{MeV}$. (b) The **circular booster** takes the electrons from the linac and accelerates them further — they gain energy on every lap of the booster ring until they reach $3.0\,\mathrm{GeV}$. (c) The **storage ring** stores the $3.0\,\mathrm{GeV}$ electrons so they circulate continuously, for hours at a time; the light they emit as their path is bent is the synchrotron light that supplies the experiments. (d) A **beamline** takes light from one point on the storage ring, selects the wavelength range an experiment needs, and delivers that beam to the experiment at the end of the line.

Question 2 (a) $3.0\,\mathrm{GeV}=3.0\times10^{9}\,\mathrm{eV}$. (b) $E=3.0\times10^{9}\times1.6\times10^{-19}=4.8\times10^{-10}\,\mathrm{J}$. (c) $100\,\mathrm{MeV}=1.0\times10^{8}\,\mathrm{eV}$, so $E=1.0\times10^{8}\times1.6\times10^{-19}=1.6\times10^{-11}\,\mathrm{J}$.

Question 3 (a) $t=\dfrac{C}{v}=\dfrac{216}{3.0\times10^{8}}=7.2\times10^{-7}\,\mathrm{s}$. (b) Number of circuits per second $=\dfrac{v}{C}=\dfrac{3.0\times10^{8}}{216}=1.4\times10^{6}$. (c) $d=vt=3.0\times10^{8}\times1.0=3.0\times10^{8}\,\mathrm{m}$.

Question 4 (a) **Brightness** describes how concentrated the radiation is — how much light power is delivered to a small spot. The **spectrum** describes the range of wavelengths the source emits. **Divergence** describes how much the beam spreads out as it travels. (b) The laser: its beam stays narrow over a long distance (small divergence), while the X-rays from a tube fan out in all directions (large divergence). (c) The laser: it emits essentially one wavelength — a very narrow spectrum — while an X-ray tube emits a broad range of X-ray wavelengths. (d) Brightness: a very small sample intercepts only a tiny fraction of any beam, so the experiment needs as much power concentrated into the small spot as possible.

Question 5 (a) The ISR collided **protons**; the Tevatron collided **protons and antiprotons**. (b) $13.6\,\mathrm{TeV}=13.6\times10^{3}\,\mathrm{GeV}=1.36\times10^{4}\,\mathrm{GeV}$. (c) $\dfrac{13.6\times10^{3}}{62}=219\approx220$ times larger.

Question 6 (a) $200\,\text{PB} = 200 \times 10^{15} = 2.0 \times 10^{17}$ bytes. (b) $1\,\text{year} = 365 \times 24 \times 3600 = 3.15 \times 10^{7}\,\text{s}$, so the average rate is $\dfrac{2.0 \times 10^{17}}{3.15 \times 10^{7}} = 6.3 \times 10^{9}$ bytes per second. (c) $\dfrac{2.0 \times 10^{17}}{1.28 \times 10^{11}} = 1.6 \times 10^{6}$ — about 1.6 million smartphones.

Question 7 (a) $E = V\,Q = 5.0 \times 10^{7} \times 1.6 \times 10^{-19} = 8.0 \times 10^{-12}\,\text{J}$. (b) $8.0 \times 10^{-12}\,\text{J} \div 1.6 \times 10^{-19}\,\text{J per eV} = 5.0 \times 10^{7}\,\text{eV} = 50\,\text{MeV}$. (c) The energy in electron-volts is numerically equal to the potential difference in volts: a $50\,\text{MV}$ stage gives $50\,\text{MeV}$. Accelerator designers therefore know a particle's energy as soon as they know the potential difference it has crossed — no conversion to joules is needed, and the numbers stay manageable.

Question 8 Model answer. The statement is incorrect. Nothing is smashed into the sample: the electrons never leave the vacuum pipes of the accelerator, and they never reach the sample at all. What reaches the sample is **synchrotron light** — electromagnetic radiation emitted by the electrons as magnets bend their path in the storage ring. The electrons are the *source* of the light; the light is the probe. Smashing particles into things is the job of a **collider**, which is the other use of accelerators taught in this section.

Question 9 (a) Tevatron: $1.96\,\text{TeV} = 1.96 \times 10^{12}\,\text{eV}$, so $E = 1.96 \times 10^{12} \times 1.6 \times 10^{-19} = 3.1 \times 10^{-7}\,\text{J}$. LHC: $13.6\,\text{TeV} = 1.36 \times 10^{13}\,\text{eV}$, so $E = 1.36 \times 10^{13} \times 1.6 \times 10^{-19} = 2.2 \times 10^{-6}\,\text{J}$. (b) $\dfrac{13.6}{1.96} = 6.9$ times larger. (c) Model answer. The joule is a unit suited to everyday objects. $2.2 \times 10^{-6}\,\text{J}$ is tiny as everyday energy, but an LHC collision concentrates it into a single event between two individual protons — an energy per particle millions of times larger than any chemical or atomic process can supply. That concentration is what makes the collisions able to produce heavy particles, so particle physicists rightly call them high-energy events.

Question 10 Model answer. Comparison with laser light: protein crystallography needs X-rays, because the spacings inside a crystal are far smaller than the wavelength of visible light. A laser emits essentially one wavelength of visible light — its spectrum does not include X-rays at all, so no laser brightness or directness can substitute. Comparison with X-ray tube radiation: an X-ray tube does produce X-rays, but its brightness is far lower and its divergence far larger than a synchrotron beamline's — the tube's X-rays spread out in all directions, so only a weak, poorly directed beam reaches the tiny crystal, and the scattered signal would be too weak to measure in a reasonable time. The synchrotron beamline delivers intense (bright), tuneable X-rays in a beam of small divergence onto the crystal, which is why it is preferable to both other sources for this experiment.

Question 11 (a) $1\,000 \times 10^{6} = 1.0 \times 10^{9}$ bytes per second. (b) $1.0 \times 10^{9} \times 24 \times 3600 = 8.6 \times 10^{13}$ bytes per day. (c) Fraction stored $= \dfrac{1\,000}{1.5 \times 10^{9}} = 6.7 \times 10^{-7}$ — about one collision in every 1.5 million. Model answer for the explanation: storing every collision is impossible — at 1.5×10^{9} events per second the data rate would exceed any storage system ever built, and almost all collisions reproduce physics that is already known. The trigger keeps the rare events worth analysing and makes the data problem manageable.

Question 12 (a) $E = m\,g\,h = 0.010 \times 9.8 \times 0.50 = 0.049\,\text{J}$. (b) $\dfrac{0.049}{2.2 \times 10^{-6}} = 2.2 \times 10^{4}$ — about twenty thousand times more. (c) Model answer. The arithmetic is correct but the conclusion does not follow, because the two energies act in utterly different places. The pencil's $0.049\,\text{J}$ is spread over the billions upon billions of atoms of the pencil and the desk — per particle it is far too small to change anything. The collision's $2.2 \times 10^{-6}\,\text{J}$ is delivered to two individual protons, giving an energy per particle large enough to create new, heavy particles such as the Higgs boson. The relevant comparison is energy per particle, not total energy, and on that comparison the LHC collision is enormously more energetic.

Question 13 (a) Model answer. In a fixed-target collision the incoming particle has momentum, and the target has none, so the total momentum before the collision is not zero. Momentum is conserved (Section 8E), so the products must still carry that momentum forward after the collision — and the kinetic energy they keep for that forward motion is energy that cannot be used to make new particles. (b) Model answer. Two beams with equal momenta in opposite directions have a total momentum of zero. The products of a head-on collision can therefore be produced at rest overall, carrying no net momentum, so in principle the whole of the beams' combined energy is available for creating new particles. (c) Model answer. Section 4A: energy can be converted into mass. In a collision the kinetic energy of the incoming particles is converted into the mass of whatever new particles are produced. The more energy available in the collision, the heavier the particles that can be created — which is why each generation of higher-energy colliders has been able to produce heavier particles, from the W and Z bosons to the top quark and the Higgs boson.

Question 14 (a) Model answer. In each case the sequence is the same: the Standard Model predicts that a particle with particular properties should exist; a collider is built or run at a high enough collision energy for that particle to be produced — collision energy converted into the particle's mass; and the collider's detectors then observe the predicted particle, with the properties the model gave it. (b) Model answer. Colliders supplied the evidence that turned the Standard Model's predictions into established physics: without the SPS, Tevatron and LHC, the W and Z bosons, the top quark and the Higgs boson would remain predictions, and the model would be untested in its most important claims. The relationship runs the other way too: the model told the machine builders what energy to reach and told the experiments what signatures to look for, so each collider was designed around a specific prediction to test. The two developed together — model guiding machine, machine confirming and sharpening model — and that interplay is the central role of colliders in the development of the Standard Model.

Question 15 (a) Equal beams share the collision energy equally: each beam has $\frac{209}{2} = 104.5\,\text{GeV}$. (b) $E = 1.045 \times 10^{11} \times 1.6 \times 10^{-19} = 1.7 \times 10^{-8}\,\text{J}$. (c) $\frac{104.5}{3.0} = 35$ — each LEP beam carried about 35 times the energy of one electron in the Australian Synchrotron storage ring.

Question 16 (a) $1\,000 \times 24 \times 3600 = 8.6 \times 10^{7}$ collisions stored in 24 hours. (b) Model answer. The trigger must decide, for each collision, whether it is worth storing — keep or discard — and it must make that decision before the data from the next collision arrive, which is within a tiny fraction of a second at the LHC's collision rate. If the decision were slow, unprocessed collisions would pile up faster than any buffer could hold. (c) Model answer. Most collisions reproduce well-understood processes, so storing them would fill enormous storage with data that teach nothing new; keeping only the unusual events makes the data manageable while preserving the collisions most likely to contain something new. The risk is that a rare or unexpected event may be judged uninteresting by the trigger's rules and discarded before anyone can look at it — so trigger rules must be designed carefully and re-examined as understanding grows.

Question 17 Model answer. The article confuses the two uses of particle accelerators. Accelerators are used either as **colliders** — two beams collided head-on to study the fundamental particles produced in the collisions — or as **synchrotron light sources** — electrons bent around a storage ring so that the light they emit is used to study materials. The Australian Synchrotron is a light source, not a collider: it accelerates electrons to $3.0\,\text{GeV}$, stores them in its $216\,\text{m}$ ring, and delivers the synchrotron light from its beamlines to experiments on proteins, minerals, cells and materials. Nothing is collided there, and it does not search for new fundamental particles. The collider work the article describes — record-energy collisions and searches for new particles — is done at facilities such as the Large Hadron Collider at CERN.

Question 18 Model answer. A full-mark response includes all of:

- at least two applications of synchrotron light from this section, for example: determining the shapes of proteins for medicine (macromolecular crystallography); mapping trace elements in cells, minerals or ores (X-ray fluorescence microscopy); identifying chemicals in materials with infrared light (infrared microspectroscopy); studying the structure of materials for engineering and battery research (X-ray diffraction and scattering);
- at least one factor from Section 10B, for example: an *economic* factor — beamtime serves universities, hospitals, mines and manufacturers, so the facility supports research that individual laboratories could never afford to build themselves; a *sociocultural* factor — medical and pharmaceutical research that improves health outcomes; a *political* factor — the facility is public infrastructure, so its funding is a government decision competed for against other spending;
- a clear position, justified from the points above. For example: continued funding is worthwhile because the facility is shared infrastructure whose applications in health, mining and materials research return value to many sectors at once — or: funding should be reviewed because the cost is large, public money is limited, and the benefits, while real, are indirect and long-term.

Marks are awarded for the quality of the reasoning, not for the position reached: two students who reach opposite positions can both receive full marks if both justify their position from correct physics and a genuine factor.

Option task — Particle accelerators: light source or collider report

This is the assessed Option task that closes Option 2.16. It uses the study design's own Outcome 2 task type *"a report of an application of physics concepts to a real-world context"*. The study design specifies no mark allocations at Units 1 & 2 — levels of achievement are a matter for school decision, and only satisfactory completion is reported to the VCAA — so the **30 marks below are house convention**. The task is assessed against the shared *Communicating physics* key knowledge ($U2.2.CP.1$–.5), which is taught in Sections 10A and 10B, applied to the physics of this section ($U2.2.O16.1$–.6).

The task. Choose one of the following:

- **Path A — a synchrotron light source:** the Australian Synchrotron at Clayton, or another synchrotron light source approved by your teacher; or
- **Path B — a collider:** the Large Hadron Collider at CERN, or a past collider such as the Tevatron, LEP or the SPS proton–antiproton collider.

Produce a report of 800–1200 words, with a labelled diagram and at least one calculation, that does all of the following:

1. **Describe the facility and its purpose.** State which of the two uses of particle accelerators your facility serves — producing synchrotron light or colliding particles — and distinguish it from the other use. List the sources you used, and evaluate the validity of each source ($U2.2.O16.1$; $U2.2.CP.1$).
2. **Explain how it works.** For Path A: explain the general purpose of the electron linac, the circular booster, the storage ring and the beamlines, and explain, using brightness, spectrum and divergence, why synchrotron light is preferable to laser light or X-ray tube radiation for at least one experiment at the facility ($U2.2.O16.2$, $U2.2.O16.3$). For Path B: explain where the collider sits in the evolution of collider technology, naming the particles collided, the collision energy, and how both compare with at least one earlier collider ($U2.2.O16.4$). Include a labelled diagram of the accelerator or its layout, and discuss one limitation of any model or representation you use ($U2.2.CP.2$, $U2.2.CP.3$).
3. **Calculate.** Using stated data with sources, carry out at least one calculation: an energy conversion (eV and joules, using $1\,\text{eV} = 1.6\times10^{-19}$ J), an energy gained crossing a potential difference ($E = VQ$), the revolutions per second of a stored beam ($f = v/C$), a comparison of collision energies, or a data-volume calculation (MB, GB, TB, PB). Show your working in full, with units and correct significant figures ($U2.2.CP.2$).
4. **Explain the physics it enables.** For Path A: explain one research use of a beamline and what the synchrotron light reveals. For Path B: explain what the collider has revealed about the fundamental particles of matter — for example, a discovery that tested or completed the Standard Model — referring to the connection between collision energy and the particles produced ($U2.2.O16.3$ or $U2.2.O16.5$; $U2.2.CP.3$).
5. **Evaluate and take a position.** Discuss at least one relevant sociocultural, economic, legal or political factor — for example the cost of large facilities and who pays for them, international collaboration, or the medical and industrial spin-offs of accelerator and detector technology — and finish with a justified stance: is the facility, or the continued funding of facilities like it, worthwhile? ($U2.2.O16.5$ or $U2.2.O16.6$; $U2.2.CP.4$, $U2.2.CP.5$).

Your teacher will set the due date and any in-class conditions. Work that uses data from a source must name the source and its retrieval date.

Mark allocation (30 marks — house convention).

Criterion	Study-design dot point	Marks
Validity of sources evaluated	$U2.2.CP.1$	4
Physics concepts, terms and conventions applied correctly, with	$U2.2.CP.2$	8

Criterion	Study-design dot point	Marks
full calculations		
Diagrams, models and representations used and organised clearly, with limitations discussed	$U2.2.CP.3$	6
Sociocultural, economic, legal or political factors discussed	$U2.2.CP.4$	4
Physics-based stance, recommendation or solution justified	$U2.2.CP.5$	8
Total		**30**

Marking rubric.

Band	$CP.1$ sources (4)	$CP.2$ physics (8)	$CP.3$ representations (6)	$CP.4$ factors (4)	$CP.5$ stance (8)
High	4: every source named and its validity evaluated	7–8: concepts and terms correct throughout; calculation complete with units and correct significant figures	5–6: diagram complete and clearly labelled; limitations of the model discussed	4: at least one relevant factor discussed in genuine depth	7–8: stance fully justified by the physics of the report
Medium	3: sources named and validity considered	4–6: concepts mostly correct; working mostly complete	3–4: diagram present with minor omissions; limitations noted briefly	3: a relevant factor identified with some discussion	4–6: stance given with partial justification
Low	1–2: sources listed with little or no evaluation	1–3: concepts partly correct; working incomplete	1–2: diagram missing key labels or components	1–2: a factor named with little discussion	1–3: stance stated with little support
None	0	0	0	0	0

Marks are awarded for the quality of the reasoning, not for the conclusion reached: two students who reach opposite positions can both receive full marks in $CP.5$ if both justify their position from correct physics.

Chapter 13 Options: astrophysics, particles and contemporary research — 13D Option 2.17: How does physics explain the origins of matter?

(The physics of the origins of matter)

Theory

This subtopic is Option 2.17 of Unit 2, Area of Study 2. The study design introduces the option like this:

> In this option students focus on communicating physics understanding in the context of theories that explain the origins of matter. In preparing their communication related to a selected contemporary societal issue or application, students explore the nature of matter, and consider the origins of atoms, time and space. They examine the currently accepted scientific theory of the origins of the Universe and the Standard Model to explain how matter has changed over time.
>
> *VCE Physics Study Design, Unit 2, Area of Study 2*

You already hold much of the physics this option builds on. Chapter 1 placed the regions of the electromagnetic spectrum (1B); Chapter 2 taught Wien's Law (2C); Chapter 3 introduced the positron and the neutrino (3B) and the forces inside the nucleus (3A); Chapter 4 taught the conversion of mass into energy, $E = mc^2$ (4A). This section puts those ideas together to ask the largest question in the book: where did everything come from?

The Big Bang theory. In science, a **theory** is not a guess: it is a well-tested explanation that organises many observations and makes successful predictions (14D). The **Big Bang theory** is the currently held theory that explains the origins of both time and space. It says that about 13.8×10^9 years (13.8 billion years) ago, all the matter and energy in the Universe — and space itself — existed in an extremely hot, extremely dense state, and that space has been expanding and cooling ever since.

Source: European Space Agency, *Planck* mission results (age of the Universe about 13.8 billion years), retrieved 2026-08-18.

Notice what the theory does and does not say. The Big Bang was **not** an explosion *in* space, with matter hurled outward into an already-existing emptiness. It was an expansion *of* space itself, carrying matter apart as the space between objects grows. There is no centre and no edge to the expansion: every location sees distant galaxies moving away from it, in every direction.

A helpful model is a loaf of raisin bread rising in the oven. As the dough expands, every raisin sees every other raisin moving away from it, and the raisins that started farther apart separate fastest. The raisins are not travelling *through* the dough — the dough itself is growing. Like every model, the analogy has limits: a loaf has a crust and a centre, while the Universe, as far as observations show, has neither.

Evidence 1: the expansion of the Universe. Light from distant galaxies arrives with its wavelength stretched toward the long-wavelength, red end of the spectrum — a **redshift**. Because the light's wavelength is stretched as the space it travels through expands, the redshift is evidence that space itself is expanding. The farther away a galaxy is, the greater its redshift, which is exactly what the raisin-bread model predicts: more distant objects are carried away faster. Running the expansion backward in time, the Universe must once have been smaller, denser and hotter — which is precisely the starting condition of the Big Bang theory.

Evidence 2: the cosmic microwave background. The Big Bang theory also predicted a second observable consequence. If the early Universe was filled with hot, glowing matter, then that radiation should still fill space today — but stretched by the expansion to much longer wavelengths and cooled to a very low temperature. In 1965, Arno Penzias and Robert Wilson at Bell Laboratories in the United States detected exactly such a signal: a faint microwave "noise" arriving equally from every direction in the sky, which no antenna fault or local source could explain. It was identified as the cooled remnant of the hot early Universe and named the **cosmic microwave background** (CMB). Penzias and Wilson received the 1978 Nobel Prize in Physics for the discovery.

Source: The Nobel Foundation, *The Nobel Prize in Physics 1978* (awarded to Penzias and Wilson for the discovery of the cosmic microwave background), retrieved 2026-08-18.

Later satellites measured the CMB in detail. Its spectrum matches that of a body at about 2.7 K, and Wien's Law (2C) places its peak wavelength where the observations find it:

$$\lambda_{max} = \frac{2.9 \times 10^{-3}}{2.7} \approx 1.1 \times 10^{-3}\,\text{m},$$

about one millimetre — in the microwave region of the electromagnetic spectrum (1B). The CMB is almost perfectly uniform across the sky, with only tiny variations from place to place; those tiny variations match the regions of slightly denser matter that gravity later gathered into galaxies.

Source: NASA Goddard Space Flight Center, *Cosmic Background Explorer (COBE)* (CMB spectrum measured at about 2.7 K), retrieved 2026-08-18.

Evidence 3: the abundance of the light elements. The theory calculates that in the first few minutes, when the whole Universe was hot enough for fusion, protons and neutrons combined to form helium nuclei, leaving a mixture of about 75 % hydrogen and 25 % helium by mass, with traces of lithium. Observations of the oldest, least-disturbed regions of the Universe find exactly this ratio. Three independent lines of evidence — expansion, the CMB and the light-element abundances — all point to the same hot, dense beginning.

Source: NASA, *Wilkinson Microwave Anisotropy Probe* (predicted and observed abundances of the light elements), retrieved 2026-08-18.

The history of matter: expansion and cooling. The Big Bang theory describes the Universe changing through stages, and the driver of every change is the same pair of linked processes: **expansion and cooling**. As space expands, the Universe's temperature falls, and each fall in temperature allows matter to settle into new, more stable arrangements that the higher temperature would have broken apart again.

When (approximate)	Temperature (approximate)	What matter was like
The Big Bang	beyond present models	Time, space, matter and energy begin.
The first fraction of a second	above 10^{12} K	Energy changes into particle–antiparticle pairs and back again ($E = mc^2$ works both ways, 4A). Quarks exist freely; as the Universe cools, quarks lock together to form protons and neutrons.
The first few minutes	about 10^9 K	Protons and neutrons combine into helium nuclei (fusion, as in 4C and 13A). The 75 % hydrogen / 25 % helium mix is fixed.
About 380 000 years	about 3000 K	Electrons combine with nuclei to form the first atoms (hydrogen and helium). Light can now travel freely — this released light is the CMB we detect today.
Hundreds of millions of years onward	falling	Gravity gathers the gas into the first stars and galaxies. Stars fuse hydrogen and helium into heavier elements (13A); the heaviest elements are spread by exploding stars. Planets — and chemistry, and life — become possible.

The times and temperatures in the table are the best estimates of the current model; the earliest stages are the least certain, because they are the hardest to test directly.

Source: European Space Agency, *Planck* mission results (cosmological parameters, including the age of the Universe and the epoch of first-atom formation), retrieved 2026-08-18.

Predicted first, discovered later. One of the strongest features of this area of physics is its pattern: a theory predicts that a particle must exist, then — sometimes decades later, after new technology is built — the particle is found. The study design names four examples.

Particle	Family	Predicted by theory	Discovered by experiment
Neutron	baryon	Ernest Rutherford, 1920 — argued that nuclei must contain a neutral partner to the proton	James Chadwick, 1932 — identified neutrons knocked out of a target by radiation
Positron	lepton (antimatter)	Paul Dirac, 1928–1931 — his equation for the electron required a partner of equal mass and opposite charge	Carl Anderson, 1932 — tracks in cosmic-radiation photographs showed a particle with the electron's mass but positive charge
Neutrino	lepton	Wolfgang Pauli, 1930 — proposed an unseen particle to carry away the missing energy in beta decay (3B)	Clyde Cowan and Frederick Reines, 1956 — detected neutrinos from a nuclear reactor
Higgs boson	the Higgs particle	Peter Higgs, François Englert, Robert Brout and others, 1964 — a field that gives elementary particles their mass requires a detectable particle	ATLAS and CMS experiments at CERN's Large Hadron Collider, 2012 — a particle with the predicted properties was observed

Source: The Nobel Foundation, *The Nobel Prize in Physics* (1935, Chadwick; 1936, Anderson; 1978, Penzias and Wilson; 1995, Reines; 2013, Englert and Higgs), retrieved 2026-08-18. Source: CERN, *CERN experiments observe particle consistent with long-sought Higgs boson* (press release, 2012-07-04), retrieved 2026-08-18.

In each case the prediction came from mathematics and existing theory, not from accident. The discoveries of the neutron, positron and neutrino were made with laboratory detectors and cosmic radiation; the Higgs boson needed the largest machine ever built — a particle accelerator of the kind studied in 13C (Option 2.16). The pattern is still running: physicists today predict particles that future machines may find.

The families of matter: leptons, hadrons, mesons and baryons. The **Standard Model** is the currently accepted theory of the elementary particles of matter and the forces between them (excluding gravity). It organises matter's particles into families.

- **Leptons** are fundamental particles — as far as any experiment has shown, they are not made of anything smaller. The familiar lepton is the **electron**, the charge carrier in metals (5A); another family member is the **neutrino**, emitted in beta decay (3B). Leptons do not feel the strong nuclear force.
- **Hadrons** are composite particles made of **quarks** held together by the strong nuclear force (3A). There are two hadron sub-families:
    - **Baryons** are hadrons made of three quarks. The proton and the neutron are baryons — the two baryons that build every nucleus (3A).
    - **Mesons** are hadrons made of one quark and one antiquark. Mesons are unstable and do not build ordinary matter, but they are produced in high-energy collisions.

Quarks carry charges that are fractions of the elementary charge e ($1e = 1.6 \times 10^{-19}$ C, 3B). The two lightest are the **up quark** ($+2/3e$) and the **down quark** ($-1/3e$). The quark contents of the two stable baryons check out exactly:

$$\text{proton} = uud : +2/3e + 2/3e - 1/3e = +1e$$

$$\text{neutron} = u\,d\,d : +2/3\,e - 1/3\,e - 1/3\,e = 0$$

The families compared: leptons are fundamental and do not feel the strong force; hadrons are composite, made of quarks, and are held together by the strong force. Within the hadrons, baryons are three-quark particles (proton, neutron) while mesons are quark–antiquark pairs. The proton is stable; a free neutron decays by beta-minus emission in about fifteen minutes (3B); mesons decay far more quickly still.

Family	Made of	Fundamental?	Feels the strong force?	Examples
Leptons	nothing smaller	yes	no	electron, neutrino
Baryons (hadrons)	three quarks	no	yes	proton, neutron
Mesons (hadrons)	one quark + one antiquark	no	yes	pions

Antimatter and annihilation. For every elementary matter particle there exists an **antimatter** particle of equal mass and opposite charge. The electron's antiparticle is the **positron** (${}^{0}_{+1}$e, 3B); the proton's antiparticle is the antiproton, with the same mass as the proton and charge $-1\,e$. Neutral particles also have antiparticles — the antineutrino, for example — which differ from the particle in properties other than charge.

When a particle meets its antiparticle, the two **annihilate** each other: both particles disappear and their mass is converted entirely into radiation. For the electron–positron pair:

$$e^{-} + e^{+} \rightarrow \gamma + \gamma$$

The energy of the two gamma-ray photons comes from $E = m\,c^2$ (4A), with m the combined mass of the two particles. The photons are emitted in opposite directions so that momentum is conserved (8E). This is not a curiosity: PET scanners in hospitals detect the two back-to-back gamma rays from positron annihilation to image the body (3B; Option 2.6 is treated in 10E).

Annihilation also raises the deepest open question in this option. The early Universe made matter and antimatter together. If the two had been created in exactly equal amounts, every particle would eventually have met its antiparticle and the Universe today would contain only radiation — no atoms, no stars, no people. The fact that matter exists means a small imbalance favoured matter: for roughly every billion matter–antimatter pairs, about one extra matter particle survived. That surviving excess is what everything around you is made of. Physics has not yet explained why the imbalance existed — this is one of the limits of the current model.

Gravitational waves: a new window on the Universe. A **gravitational wave** is a ripple in the fabric of space and time, produced when enormous masses accelerate — for example, when two black holes or two neutron stars spiral together and merge. The waves travel at the speed of light and carry energy away from the event, stretching and squeezing the space they pass through by a tiny, measurable amount. Their existence was predicted in 1916 from Einstein's theory of gravitation.

On 14 September 2015 the two detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO), in the United States, measured the first gravitational waves ever detected. The signal, named GW150914, came from two black holes — of about 36 and 29 times the Sun's mass — merging about 1.3×10^{9} light-years away. In the final fraction of a second, about three solar masses' worth of energy was radiated away as gravitational waves — $E = m\,c^2$ again (4A) — roughly 5×10^{47} J. The discovery was announced in 2016 and awarded the 2017 Nobel Prize in Physics.

Source: LIGO Laboratory, California Institute of Technology and Massachusetts Institute of Technology, *Gravitational Waves Detected 100 Years After Einstein's Prediction* (press release, 2016-02-11), retrieved 2026-08-18.

A **light-year** is the distance light travels in one year: with $c = 3.00 \times 10^{8}\ \text{m s}^{-1}$ and one year $\approx 3.16 \times 10^{7}$ s, one light-year $\approx 9.5 \times 10^{15}$ m (Worked Example 4 derives the value).

The detection of gravitational waves has contributed to understanding of the Universe in several ways:

- **They reveal events that emit no light.** Black holes merging in empty space are invisible to ordinary telescopes; gravitational waves are the only signal such events send.
- **They carry information light cannot.** From the wave pattern, physicists read the masses of the merging objects, their distance and how fast they were orbiting.
- **They opened multi-messenger astronomy.** In 2017, gravitational waves from two merging neutron stars were detected, and telescopes around the world observed the same event in light. The combined observations confirmed that such mergers forge heavy elements such as gold and platinum, and showed that gravitational waves travel at the speed of light.
- **They test gravity in the most extreme conditions.** The waves allow Einstein's theory to be checked where the force is strongest — near black holes.

Australian universities take part in this work through OzGrav, the Australian Research Council's Centre of Excellence for Gravitational Wave Discovery.

Source: Australian Research Council Centre of Excellence for Gravitational Wave Discovery (OzGrav), Swinburne University of Technology, retrieved 2026-08-18.

Limits of the model. The Big Bang theory is the best-supported explanation of the origins of matter, but it is a model, and it has limits. No observation can see past the CMB: before the first atoms formed, the Universe was opaque, so the earliest moments are inferred rather than observed. The cause of the matter–antimatter imbalance is unknown. And measurements show that ordinary matter — the atoms this section has described — is only a small fraction of what the Universe contains; the rest is in forms not yet understood. Naming these limits is part of the science, not a weakness of it (10A, 14D).

Method notes. Use kelvin temperatures in Wien's Law ($T(\mathrm{K}) = T(^\circ\mathrm{C}) + 273$, 2A); use $E = mc^2$ with mass in kilograms to obtain energy in joules, with $c = 3.00 \times 10^8\ \mathrm{m\ s^{-1}}$; and when working with light-years, convert to metres through $d = ct$. The timeline values in this section are model estimates — treat them as approximate, and keep no more than two significant figures when using them in calculations (1A).

Links to other sections. The electromagnetic spectrum regions are 1B; Wien's Law is 2C; the strong nuclear force is 3A; positrons, neutrinos and annihilation in PET are 3B (applied in 10E); mass–energy conversion is 4A; fusion in stars is treated in 13A (Option 2.13); particle accelerators — the machines behind the Higgs discovery — are 13C (Option 2.16). The communication skills assessed by the Option task at the end of this section are taught in 10A and 10B.

Units 3 & 4 preview. The ideas that energy, matter and radiation convert into one another, and that light can behave as particles, return in Units 3 & 4, where the wave and particle models of light are compared and matter itself is given a wave model. The stretching of space described here also prepares the way for the relativistic treatment of space and time at Units 3 & 4.

Worked examples

Example 1 — scaffolded

The cosmic microwave background fills space at a temperature of about $2.7\ \mathrm{K}$. Calculate the peak wavelength of this radiation and name the region of the electromagnetic spectrum in which it lies.

Working	Comment
Wien's Law: $\lambda_{max} T = 2.9 \times 10^{-3}\ \mathrm{m\ K}$.	From 2C; T must be the absolute temperature in kelvin.
$\lambda_{max} = \dfrac{2.9 \times 10^{-3}}{2.7} = 1.07 \times 10^{-3}\ \mathrm{m}$.	Rearrange for λ_{max} and substitute.
$1.07 \times 10^{-3}\ \mathrm{m} \approx 1.1\ \mathrm{mm}$.	$1\ \mathrm{mm} = 10^{-3}\ \mathrm{m}$.
About one millimetre lies in the **microwave** region.	The spectrum regions are those of 1B. This is why the

Working	Comment
	cooled remnant of the Big Bang is a *microwave* background.

Example 2 — scaffolded

An electron and a positron annihilate when they meet. Using $m_e = 9.11 \times 10^{-31}$ kg and $c = 3.00 \times 10^{8}$ m s^{-1}, calculate the total energy released, and the energy carried by each of the two gamma-ray photons produced.

Working	Comment
Total mass converted: $m = 2 \times 9.11 \times 10^{-31} = 1.82 \times 10^{-30}$ kg.	Both particles disappear; their masses add.
$E = mc^2 = 1.82 \times 10^{-30} \times (3.00 \times 10^8)^2$.	Mass–energy conversion (4A), with mass in kg.
$E = 1.82 \times 10^{-30} \times 9.00 \times 10^{16} = 1.64 \times 10^{-13}$ J.	$(3.00 \times 10^8)^2 = 9.00 \times 10^{16}$.
Each photon: $\dfrac{1.64 \times 10^{-13}}{2} = 8.2 \times 10^{-14}$ J.	The two photons share the energy equally and fly apart in opposite directions, conserving momentum (8E).

Example 3 — unscaffolded

When the first atoms formed, about $380\,000$ years after the Big Bang, the Universe's temperature was about 3000 K. Today the same radiation — the cosmic microwave background — corresponds to 2.7 K. Calculate the peak wavelength of the radiation when it was first released, and the factor by which the expansion of the Universe has stretched its wavelengths since. Explain why radiation released as a hot glow is observed today as microwaves.

For the radiation at release, Wien's Law gives

$$\lambda_{\text{max, then}} = \frac{2.9 \times 10^{-3}}{3000} = 9.7 \times 10^{-7}\ \text{m},$$

about 970 nm, in the infrared just beyond the visible region (1B). For the same radiation today,

$$\lambda_{\text{max, now}} = \frac{2.9 \times 10^{-3}}{2.7} = 1.1 \times 10^{-3}\ \text{m}.$$

The stretch factor is the ratio of the two peak wavelengths, which equals the inverse ratio of the two kelvin temperatures:

$$\text{stretch factor} = \frac{\lambda_{\text{max, now}}}{\lambda_{\text{max, then}}} = \frac{T_{\text{then}}}{T_{\text{now}}} = \frac{3000}{2.7} \approx 1100.$$

∴ the radiation was released peaking near 9.7×10^{-7} m (infrared) and its wavelengths have been stretched by a factor of about 1100. The cause is the expansion of space: as space expands, every travelling photon's wavelength stretches with it. A hot glow of visible and infrared photons, stretched a thousand-fold, arrives as microwave photons — this is why the cooled remnant is the cosmic *microwave* background.

Example 4 — unscaffolded

The gravitational-wave signal GW150914 came from two merging black holes about 1.3×10^9 light-years away. Derive the length of one light-year in metres (use $c = 3.00 \times 10^8$ m s^{-1} and one year $= 365.25$ days), calculate the distance to the event in metres, and state how long ago the merger actually happened.

One light-year is the distance light travels in one year, $d = ct$. The number of seconds in one year is

$$365.25 \times 24 \times 3600 = 3.16 \times 10^7\ \text{s},$$

so

$$1\ \text{light-year} = 3.00 \times 10^8 \times 3.16 \times 10^7 = 9.5 \times 10^{15}\ \text{m}.$$

The distance to the event is therefore

$$d = 1.3 \times 10^9 \times 9.5 \times 10^{15} = 1.2 \times 10^{25}\ \text{m}$$

to two significant figures. Because the waves travelled at the speed of light for the whole journey, the waves LIGO detected in 2015 were produced about 1.3×10^9 years ago: the merger happened before complex life existed on Earth.

∴ one light-year $\approx 9.5 \times 10^{15}\ \text{m}$; the event was about $1.2 \times 10^{25}\ \text{m}$ away, and the merger happened about 1.3 billion years ago. Detecting gravitational waves is, like all astronomy, looking back in time — and in this case it is observing an event that emitted no light at all.

Practice questions

Question 1 *(scaffolded)* The Big Bang theory is the currently held theory of the origins of the Universe. (a) State what the Big Bang theory explains about the origins of time and space. (b) State the approximate age of the Universe according to current measurements. (c) Name two independent lines of evidence that support the theory.

Question 2 *(scaffolded)* The cosmic microwave background has a temperature of about $2.7\ \text{K}$. (a) Write down Wien's Law, including the value and units of the constant. (b) Calculate the peak wavelength of the cosmic microwave background. (c) Name the region of the electromagnetic spectrum in which this peak lies, and explain how the name *cosmic microwave background* follows from your answer.

Question 3 *(scaffolded)* The following events describe stages in the history of matter, but they are out of order:

A. Electrons combine with nuclei to form the first atoms.

B. Quarks lock together to form protons and neutrons.

C. Stars form and fuse hydrogen and helium into heavier elements.

D. Protons and neutrons combine to form helium nuclei.

(a) Write the events in the correct order, earliest first.
(b) Name the two linked processes that drove the Universe from one stage to the next.

Question 4 *(scaffolded)* Four particles were predicted by theory before they were discovered. Copy and complete the table.

Particle	Predicted by theory	Discovered by experiment
neutron	Ernest Rutherford, 1920	(i) …
positron	(ii) …	Carl Anderson, 1932
(iii) …	Wolfgang Pauli, 1930	Clyde Cowan and Frederick Reines, 1956
Higgs boson	Higgs, Englert, Brout and others, 1964	(iv) …

Question 5 *(scaffolded)* The positron is the antiparticle of the electron. (a) State the mass and the charge of the positron, compared with those of the electron. (b) Name the process that occurs when an electron meets a positron, and state what is produced. (c) Using $m_e = 9.11 \times 10^{-31}\ \text{kg}$ and $c = 3.00 \times 10^8\ \text{m s}^{-1}$, calculate the total energy released when the two particles annihilate.

Question 6 *(scaffolded)* Consider the particles: electron, proton, neutron, neutrino, pion. (a) Classify each as a lepton, a baryon or a meson. (b) State which of these particles are fundamental. (c) State the quark content of a baryon and of a meson.

Question 7 Light from distant galaxies arrives redshifted, and the farther away a galaxy is, the greater its redshift. Explain how these observations support the Big Bang theory, including what "running the expansion backward" implies about the early Universe.

Question 8 Three independent lines of evidence support the Big Bang theory: the expansion of the Universe, the cosmic microwave background, and the abundance of the light elements. Explain how each line of evidence supports the theory, and identify which one most directly confirms a specific prediction made in advance, and why.

Question 9 When the first atoms formed, the Universe's temperature was about $3000\,\mathrm{K}$. Calculate the peak wavelength of the radiation filling the Universe at that time, and state the region of the spectrum in which it lies.

Question 10 The radiation released when the first atoms formed corresponded to about $3000\,\mathrm{K}$; the same radiation is observed today at about $2.7\,\mathrm{K}$. Calculate the factor by which the wavelengths of this radiation have been stretched, and name the process responsible.

Question 11 Explain why the first atoms could form only about $380\,000$ years after the Big Bang and not earlier, and state the important consequence this event had for the radiation we observe today.

Question 12 A proton and an antiproton annihilate when they meet. Using $m_{\mathrm{p}} = 1.67 \times 10^{-27}\,\mathrm{kg}$ and $c = 3.00 \times 10^{8}\,\mathrm{m\,s^{-1}}$, calculate the total energy released, and compare it with the $1.64 \times 10^{-13}\,\mathrm{J}$ released by electron–positron annihilation. Explain the difference.

Question 13 Compare the nature of leptons and hadrons. Your comparison should refer to whether each family is fundamental or composite, the forces each family feels, and at least one example of each.

Question 14 Baryons and mesons are both hadrons, but they differ in their quark content. (a) State the quark content of a baryon and of a meson, giving one example of each. (b) The up quark has charge $+2/3\,e$ and the down quark has charge $-1/3\,e$. Show that the quark content of the proton gives the proton its observed charge, and that the quark content of the neutron gives it zero charge.

Question 15 The Higgs boson was predicted in 1964 but was not observed until 2012, at CERN's Large Hadron Collider. Explain why such a long gap passed between prediction and discovery, and state what the Higgs field explains about other elementary particles.

Question 16 In beta decay, the emitted beta particle carries a range of energies, and early measurements found energy apparently missing (3B). Explain how this observation led Pauli to predict the neutrino, and suggest why the neutrino was so much harder to detect than the neutron or the positron, which were found within a few years of their predictions.

Question 17 The early Universe made matter and antimatter together, and a particle and its antiparticle annihilate on contact. Explain why the existence of matter today tells us there must have been a small imbalance between matter and antimatter in the early Universe, and state whether the cause of that imbalance is currently understood.

Question 18 A student writes: "The Big Bang was an explosion in empty space that hurled matter outward from a single point, so there must be a centre where it all happened." Evaluate this claim using the physics of this section.

Question 19 Describe two contributions that the detection of gravitational waves has made to understanding of the Universe, referring to a specific detection for at least one of them.

Question 20 The gravitational-wave event GW150914 came from a source about 1.3×10^{9} light-years away. (a) Derive the length of one light-year in metres, using $c = 3.00 \times 10^{8}\,\mathrm{m\,s^{-1}}$ and one year $= 365.25$ days. (b) Calculate the distance to the source in metres, to two significant figures. (c) State how long ago the merger happened, and explain why detecting gravitational waves from distant sources is also looking back in time.

Question 21 In the raisin-bread model, every raisin sees every other raisin moving away as the dough expands. A student asks: "If all the galaxies are moving away from us, doesn't that put us at the centre of the expansion?" Use the model to answer the student, and state one limitation of the raisin-bread analogy as a model of the Universe.

Question 22 The gravitational-wave event GW150914 radiated about 5×10^{47} J of energy. Using $c = 3.00 \times 10^{8}\,\mathrm{m\ s^{-1}}$, calculate the mass equivalent of this energy, then express your answer in solar masses ($1\,\text{solar mass} = 2.0 \times 10^{30}$ kg). Show that your result supports the statement that about three solar masses' worth of energy was radiated.

Question 23 A π^{+} meson is made of one up quark and one anti-down quark. The up quark has charge $+2/3\,e$ and the anti-down quark has charge $+1/3\,e$. (a) Show that the π^{+} meson has charge $+1\,e$. (b) State why the π^{+} is classified as a hadron rather than a lepton.

Question 24 In an electron–positron annihilation the total energy released is 1.64×10^{-13} J. Using $1\,\mathrm{MeV} = 1.60 \times 10^{-13}$ J, convert this energy to MeV, and state the energy carried by each of the two gamma-ray photons produced.

Question 25 The Higgs boson has a mass about 125 times the mass of the proton. Using $m_{\mathrm{p}} = 1.67 \times 10^{-27}$ kg, calculate the mass of the Higgs boson in kilograms, to two significant figures.

Question 26 The age of the Universe is about 13.8×10^{9} years. Using one year $= 3.16 \times 10^{7}$ s, calculate the age of the Universe in seconds, to three significant figures.

Answers

Question 1 (a) It explains the origins of both time and space: all matter and energy, and space itself, began in an extremely hot, dense state about 13.8 billion years ago and space has been expanding and cooling since; (b) about 13.8×10^{9} years; (c) any two of: the expansion of the Universe (redshift of galaxies); the cosmic microwave background; the abundance of the light elements. **Question 2** (a) $\lambda_{max}T = 2.9\times10^{-3}\,\text{m K}$; (b) $1.1\times10^{-3}\,\text{m}$; (c) microwave — the radiation peaks at about one millimetre, and it arrives from all directions across the cosmos. **Question 3** (a) B, D, A, C; (b) expansion and cooling. **Question 4** (i) James Chadwick, 1932; (ii) Paul Dirac, 1928–1931; (iii) neutrino; (iv) ATLAS and CMS at CERN's Large Hadron Collider, 2012. **Question 5** (a) equal mass to the electron, opposite (positive) charge; (b) annihilation; two gamma-ray photons; (c) $1.64\times10^{-13}\,\text{J}$. **Question 6** (a) electron and neutrino are leptons; proton and neutron are baryons; pion is a meson; (b) the electron and the neutrino; (c) a baryon is three quarks; a meson is one quark and one antiquark. **Question 7** see solutions. **Question 8** see solutions. **Question 9** $9.7\times10^{-7}\,\text{m}$, infrared. **Question 10** about 1100; the expansion of space. **Question 11** see solutions. **Question 12** $3.0\times10^{-10}\,\text{J}$; about 1800 times greater, because the proton is about 1800 times more massive. **Question 13** see solutions. **Question 14** (b) see solutions. **Question 15** see solutions. **Question 16** see solutions. **Question 17** see solutions. **Question 18** see solutions. **Question 19** see solutions. **Question 20** (a) $9.5\times10^{15}\,\text{m}$; (b) $1.2\times10^{25}\,\text{m}$; (c) see solutions. **Question 21** see solutions. **Question 22** $5.6\times10^{30}\,\text{kg}$; about 2.8 solar masses ≈ 3 solar masses. **Question 23** (a) see solutions; (b) it is made of quarks and feels the strong force. **Question 24** $1.03\,\text{MeV}$; each photon $0.51\,\text{MeV}$. **Question 25** $2.1\times10^{-25}\,\text{kg}$. **Question 26** $4.36\times10^{17}\,\text{s}$.

Fully-worked solutions

Question 1 (a) The Big Bang theory explains the origins of both time and space: about 13.8 billion years ago all the matter and energy in the Universe, and space itself, existed in an extremely hot, dense state, and space has been expanding and cooling ever since. (b) About 13.8×10^{9} years (13.8 billion years), from measurements such as those of the Planck satellite. (c) Any two of: the expansion of the Universe shown by the redshift of light from distant galaxies; the cosmic microwave background radiation; the observed abundance of the light elements (about $75\,\%$ hydrogen, $25\,\%$ helium by mass).

Question 2 (a) Wien's Law is $\lambda_{max}T = \text{constant} = 2.9\times10^{-3}\,\text{m K}$, where λ_{max} is the peak wavelength in metres and T the absolute temperature in kelvin. (b) $\lambda_{max} = \dfrac{2.9\times10^{-3}}{2.7} = 1.07\times10^{-3}\,\text{m} \approx 1.1\times10^{-3}\,\text{m}$. (c) About one millimetre lies in the **microwave** region (1B). The radiation is therefore a *microwave* signal, and it arrives equally from every direction across the cosmos — a *cosmic background* — hence the name *cosmic microwave background*.

Question 3 (a) B (quarks lock together into protons and neutrons, first fraction of a second), D (protons and neutrons combine into helium nuclei, first few minutes), A (electrons combine with nuclei into the first atoms, about 380 000 years), C (stars form and make heavier elements, hundreds of millions of years onward). (b) **Expansion and cooling**: as space expands the temperature falls, and each fall in temperature allows matter to settle into new arrangements the higher temperature would have broken apart.

Question 4 (i) James Chadwick, 1932. (ii) Paul Dirac, 1928–1931. (iii) Neutrino. (iv) The ATLAS and CMS experiments at CERN's Large Hadron Collider, 2012.

Question 5 (a) The positron has the **same mass** as the electron and **opposite charge** ($+1e$ rather than $-1e$). (b) The two **annihilate**: both particles disappear and their mass is converted into radiation — two gamma-ray photons. (c) Total mass converted: $m = 2\times9.11\times10^{-31} = 1.82\times10^{-30}\,\text{kg}$.

$$E = mc^2 = 1.82\times10^{-30}\times(3.00\times10^{8})^2 = 1.82\times10^{-30}\times9.00\times10^{16} = 1.64\times10^{-13}\,\text{J}$$

to three significant figures, matching the data given.

Question 6 (a) Electron — lepton; neutrino — lepton; proton — baryon; neutron — baryon; pion — meson. (b) The leptons — the electron and the neutrino — are fundamental; the hadrons (proton, neutron, pion) are composite, made of quarks. (c) A baryon is made of **three quarks**; a meson is made of **one quark and one antiquark**.

Question 7 Model answer (4 marks): The redshift means the wavelength of the light has been stretched during its journey, and the stretching is explained by the expansion of the space the light travels through (1 mark). More distant galaxies show greater redshifts, meaning they are carried away faster — exactly the pattern expected if space itself is expanding uniformly, as in the raisin-bread model (1 mark). Running the expansion backward in time, the Universe must once have been smaller, denser and hotter (1 mark). That hot, dense beginning is precisely the starting condition of the Big Bang theory, so the observed expansion is direct evidence for it (1 mark).

Question 8 Model answer (4 marks): The expansion of the Universe — the redshift of distant galaxies — shows space is expanding, so running time backward leads to a hot, dense beginning (1 mark). The cosmic microwave background is the cooled remnant of the hot early Universe: radiation released when the first atoms formed, stretched by expansion to microwave wavelengths at about $2.7\,\mathrm{K}$, arriving from every direction (1 mark). The light-element abundances — about $75\,\%$ hydrogen and $25\,\%$ helium by mass — match the amounts calculated for fusion in the first few minutes (1 mark). The CMB most directly confirms a prediction made in advance: the theory predicted that cooled remnant radiation should still fill space, at a low temperature, before Penzias and Wilson detected it in 1965 (1 mark).

Question 9 $\lambda_{\max} = \dfrac{2.9 \times 10^{-3}}{3000} = 9.7 \times 10^{-7}\,\mathrm{m}$ (about $970\,\mathrm{nm}$), in the **infrared**, just beyond the visible region.

Question 10 The stretch factor is the ratio of the wavelengths, which equals the inverse ratio of the kelvin temperatures:

$$\frac{\lambda_{\text{now}}}{\lambda_{\text{then}}} = \frac{T_{\text{then}}}{T_{\text{now}}} = \frac{3000}{2.7} \approx 1100.$$

The process responsible is the **expansion of space**: as space expands, every travelling photon's wavelength stretches with it.

Question 11 Model answer (3 marks): Before about $380\,000$ years, the Universe was too hot for electrons to stay bound to nuclei — every atom that momentarily formed was broken apart again by the energetic radiation and particles around it (1 mark). Only when expansion and cooling had lowered the temperature to about $3000\,\mathrm{K}$ could electrons combine with nuclei and remain bound, forming the first atoms (1 mark). Once the free electrons were captured into atoms, light could travel freely for the first time; that released light, stretched by the expansion, is the cosmic microwave background observed today (1 mark).

Question 12 Total mass converted: $m = 2 \times 1.67 \times 10^{-27} = 3.34 \times 10^{-27}\,\mathrm{kg}$.

$$E = mc^2 = 3.34 \times 10^{-27} \times (3.00 \times 10^{8})^2 = 3.34 \times 10^{-27} \times 9.00 \times 10^{16} = 3.0 \times 10^{-10}\,\mathrm{J}.$$

Comparison: $\dfrac{3.0 \times 10^{-10}}{1.64 \times 10^{-13}} \approx 1800$. The proton–antiproton annihilation releases about 1800 times more energy because the proton is about 1800 times more massive than the electron, and the energy released is proportional to the mass converted ($E = mc^2$).

Question 13 Model answer (4 marks): Leptons are fundamental particles — not made of anything smaller — while hadrons are composite, made of quarks (1 mark). Leptons do not feel the strong nuclear force, while hadrons are held together by it (1 mark). Examples: the electron and the neutrino are leptons; the proton and the neutron are hadrons (baryons) (1 mark). Both families include the light, stable building blocks of ordinary matter — electrons among the leptons, protons and neutrons among the hadrons — but the two families play different roles: leptons orbit nuclei and carry charge, while the hadrons build the nuclei themselves (1 mark).

Question 14 (a) A baryon is made of three quarks — for example, the proton (uud) or the neutron (udd). A meson is made of one quark and one antiquark — for example, a pion. (b) Proton $= uud$: $+2/3\,e + 2/3\,e - 1/3\,e = +1\,e$, the proton's observed charge. Neutron $= udd$: $+2/3\,e - 1/3\,e - 1/3\,e = 0$, the neutron's observed zero charge.

Question 15 Model answer (3 marks): The Higgs boson is produced only in extremely high-energy collisions, so detecting it required a machine — the Large Hadron Collider — far larger and more energetic than anything available in 1964; building it, and the detectors and computing needed to find the Higgs signal among billions of collisions, took decades (1 mark). The gap between prediction and discovery is an example of the pattern of this option: theory predicts a particle, and technology must catch up before the particle can be found (1 mark). The Higgs boson is the particle associated with the Higgs field, which explains why the other elementary particles have mass (1 mark).

Question 16 Model answer (4 marks): In beta decay the emitted beta particle was observed with a range of energies, and the energy of the products was less than the energy of the starting nucleus, apparently breaking energy conservation (1 mark). Pauli proposed that an unseen, very light, neutral particle carried away the missing energy — the neutrino (1 mark). The neutrino was far harder to detect because it does not feel the strong force and has no charge, so it almost never interacts with matter — it passes straight through the detectors that readily catch neutrons or positrons (1 mark). Detecting it required an intense source (a nuclear reactor) and very large detectors, which is why Cowan and Reines succeeded only in 1956, twenty-six years after the prediction (1 mark).

Question 17 Model answer (3 marks): If matter and antimatter had been created in exactly equal amounts, every particle would eventually have met its antiparticle and annihilated, leaving a Universe containing only radiation and no atoms (1 mark). The fact that matter exists today — stars, planets, people — means that a small imbalance must have favoured matter: for roughly every billion matter–antimatter pairs, about one extra matter particle survived, and that surviving excess makes up everything we see (1 mark). The cause of the imbalance is **not** currently understood; it is one of the open questions, and a limit of the current model (1 mark).

Question 18 Model answer (4 marks): The claim is incorrect on two counts. First, the Big Bang was not an explosion *in* space — there was no pre-existing empty space to explode into; it was an expansion *of* space itself, carrying matter apart as the space between objects grows (1 mark). Second, the expansion has no centre (1 mark). Every location sees distant galaxies moving away from it in every direction, just as every raisin in rising raisin bread sees every other raisin receding — we observe the same pattern from Earth, but so would an observer in any other galaxy (1 mark). The student's reasoning treats the Big Bang as an ordinary explosion inside space, which is exactly the picture the theory replaces; the analogy's limitations (a loaf has a crust and a centre, the Universe has neither) should also be noted (1 mark).

Question 19 Model answer (4 marks): Contribution 1: gravitational waves reveal events that emit no light — the first detection, GW150914 in 2015, came from two merging black holes, an event invisible to ordinary telescopes, and its wave pattern gave the masses of the black holes and their distance (1 mark for the contribution, 1 mark for the named detection). Contribution 2: they opened multi-messenger astronomy — in 2017, waves from two merging neutron stars were detected at the same time as light from the same event, confirming that such mergers forge heavy elements such as gold and platinum, and showing that gravitational waves travel at the speed of light (2 marks). (A further contribution: they allow Einstein's theory of gravitation to be tested in the strongest gravitational fields, near black holes.)

Question 20 (a) One light-year is $d = ct$. Seconds in one year: $365.25 \times 24 \times 3600 = 3.16 \times 10^{7}$ s, so

$$1 \text{ light-year} = 3.00 \times 10^{8} \times 3.16 \times 10^{7} = 9.5 \times 10^{15} \text{ m}.$$

(b) $d = 1.3 \times 10^{9} \times 9.5 \times 10^{15} = 1.2 \times 10^{25}$ m (two significant figures). (c) The waves travelled at the speed of light, so the merger happened about 1.3×10^{9} years ago. Because the waves take time to cross the distance, detecting them shows the event as it was when the waves set out, not as it is now — observing distant gravitational-wave sources is looking back in time, exactly as observing distant galaxies is.

Question 21 Model answer (3 marks): In the raisin-bread model every raisin sees every other raisin moving away, and the farther raisins recede fastest — no raisin is at the centre of the expansion, because the dough itself is growing everywhere (1 mark). The same is true of the Universe: galaxies in every direction see the same pattern, so the observation that galaxies are moving away from us does not place us at a centre — an observer in any galaxy would see exactly the same thing (1 mark). One limitation of the analogy: a loaf of bread has a crust, a centre and an edge it expands into, while the Universe, as far as observations show, has none of these (1 mark).

Question 22 Mass equivalent from $E = mc^{2}$ rearranged to $m = \frac{E}{c^{2}}$:

$$m = \frac{5 \times 10^{47}}{(3.00 \times 10^{8})^{2}} = \frac{5 \times 10^{47}}{9.00 \times 10^{16}} = 5.6 \times 10^{30} \text{ kg}.$$

In solar masses: $\frac{5.6\times10^{30}}{2.0\times10^{30}}=2.8\approx3$. This is about three solar masses, supporting the statement that about three solar masses' worth of mass was converted to gravitational-wave energy in the final fraction of a second of the merger.

Question 23 (a) Charge of the π^+ = charge of up quark + charge of anti-down quark:

$$+2/3\,e+1/3\,e=+1\,e,$$

which is the stated charge of the π^+ meson. (b) The π^+ is a **hadron** because it is made of quarks (one quark and one antiquark — the combination that defines a meson) and is held together by the strong nuclear force. Leptons are fundamental particles, made of nothing smaller, and do not feel the strong force.

Question 24 Total energy in MeV:

$$E=\frac{1.64\times10^{-13}\,\text{J}}{1.60\times10^{-13}\,\text{J/MeV}}=1.03\,\text{MeV}.$$

The two photons share the energy equally: $\frac{1.03}{2}=0.51\,\text{MeV}$ each.

Question 25 $m_{\text{Higgs}}=125\times m_{\text{p}}=125\times1.67\times10^{-27}=2.1\times10^{-25}\,\text{kg}$ (to two significant figures).

Question 26 $\text{age}=13.8\times10^{9}\times3.16\times10^{7}=4.36\times10^{17}\,\text{s}$ (to three significant figures).

Option task — evaluating a claim about the origins of matter (30 marks)

House Option task (house convention — school-based assessment; Units 1 & 2 carry no VCAA examination, and levels of achievement are a matter for school decision). Outcome 2 task type: a media analysis/response and a physics-referenced response to an issue. The rubric is keyed to the Communicating physics dot points `U2.2.CP.1–.5` (taught in 10A and 10B).

Stimulus — *constructed for this task; not a quotation.* A podcast transcript reads:

> "The Big Bang theory is just a guess — nobody was there, so it can never be tested. It says everything began as an explosion in empty space, and if matter and antimatter annihilate each other on contact, there shouldn't be anything left at all. The Universe clearly exists, so the theory must be wrong."

Answer all parts. Your response will be assessed against the rubric below.

(a) Evaluate the validity of the podcast as a source of information about the origins of matter, and identify two physics claims in the transcript that can be tested against evidence. (4 marks)

(b) The transcript says the Big Bang was "an explosion in empty space". Correct this description using the physics of the expansion of space, and calculate the peak wavelength of the cosmic microwave background ($T=2.7\,\text{K}$), naming the region of the spectrum. Hence explain how the cosmic microwave background answers the claim that the theory "can never be tested". (6 marks)

(c) Construct a timeline of the changes of matter from the first fraction of a second to the formation of the first atoms, as a table or annotated diagram. For each stage, explain the role of expansion and cooling, and state one limitation of this timeline as a model of the early Universe. (8 marks)

(d) Discuss two sociocultural, economic, legal or political factors that influence how society supports or responds to research into the origins of matter (for example, the cost and international governance of large facilities such as the Large Hadron Collider or LIGO, or who pays for research with no immediate commercial application). (6 marks)

(e) Apply your physics understanding to justify a stance on the transcript's conclusion ("the theory must be wrong"), addressing both the matter–antimatter argument and at least one line of evidence for the Big Bang. (6 marks)

Rubric (keyed to the Communicating physics dot points). Marks are awarded for the quality of the reasoning, not the conclusion reached: a response that concludes the evidence is weaker than the theory's supporters claim can still earn full marks if that conclusion is argued from defined terms and the evidence itself.

Dot point	What a high-quality response does
`U2.2.CP.1` evaluate validity of sources	Names the podcast as opinion, not data; identifies what a valid source would be (measured results such as the CMB observations or the LIGO detections) and tests the transcript's claims against them (part a).
`U2.2.CP.2` physics concepts, terminology, representations	Corrects "explosion in empty space" to the expansion of space itself; uses annihilation, antimatter and redshift correctly; the Wien's Law calculation is shown with kelvin temperature and units (part b).
`U2.2.CP.3` data representations, models and limitations	The timeline genuinely organises the stages of matter (quarks to baryons, helium nuclei, first atoms); expansion and cooling are identified as the driver of each change; a real limitation is stated (e.g. the earliest stages are inferred, not observed; nothing is seen past the CMB; the times and temperatures are model estimates) (part c).
`U2.2.CP.4` sociocultural, economic, legal and political factors	Discusses two distinct factors (e.g. the cost of facilities such as the LHC and the international agreements that fund them; decisions about public funding for basic research; cultural responses to questions of origins; international collaboration such as Australia's participation through OzGrav) without letting them replace the physics (part d).
`U2.2.CP.5` justify a stance with physics	Takes a clear stance on "the theory must be wrong" and justifies it from the physics: the matter–antimatter objection is met with the surviving-imbalance explanation (and its acknowledgement as an open question), and a stance is supported with at least one line of evidence (expansion, CMB or light-element abundances) (part e).

Chapter 13 Options: astrophysics, particles and contemporary research — 13F Option 2.18: How is contemporary physics research being conducted in our region?

(The physics of local scientific research)

Theory

This section is **Option 2.18 — The physics of local scientific research**, one of the eighteen options of Unit 2, Area of Study 2. A student studies exactly one option; this section is self-contained for a student who has chosen Option 2.18. The study design introduces the option like this:

> In this option students focus on communicating physics understanding in the context of cutting-edge research that is based in Victoria, Australia or Oceania. In preparing their communication related to a selected contemporary societal issue or application, students investigate how research involves both individual and collaborative endeavours, as well as the application of critical and creative thinking. They identify key physics concepts to provide a physics-related response to their chosen area of physics research. They research and analyse the limitations, challenges and consequences of local contemporary physics research. Contexts for student exploration can include: research at the Australian Synchrotron; space research; dark matter research; medical research involving radiation; materials research; or nuclear fusion research.
>
> *VCE Physics Study Design, Unit 2, Area of Study 2*

What makes this option different. Every other option in this book has a fixed body of physics: climate (10C), flight (11A), lenses (12A), stars (13A), particle accelerators (13C), and so on. Option 2.18 has **no fixed physics content**. It is a **research protocol** — an agreed method for finding out how physics research is being done in your own region *right now*, and for communicating what you find. The physics content is supplied by the research you choose, and the concepts it draws on are ones you already hold from Chapters 1–9 and from the other options of Chapter 13. Your work in this option is to select one real area of local physics research, follow the protocols below to access information about it, identify the physics in it, and communicate a physics-informed account of it. The section closes with the assessed Option task.

What the study design asks you to do. The seven key knowledge dot points of Option 2.18, quoted from the study design:

- investigate cutting-edge research that is based in Victoria, Australia or Oceania;
- select one area of local physics research and follow protocols to access information related to current research in the selected area;
- identify the physics related to the chosen research;
- explain how physics understanding has led to the development of the selected research;
- explain how critical and creative thinking shapes the application of physics concepts related to the selected research;
- analyse the extent to which both individual contribution and collaboration are involved in the selected research;
- evaluate how the chosen physics research may change the way we live.

The steps below turn these seven dot points into a single investigation.

Before you begin: defining the terms. Three expressions in the dot points are not defined by the study design, and you cannot reason carefully with undefined terms. Two of them are also **contested terms** — expressions where competing definitions exist, and the definition chosen can change the conclusion reached (the same idea treated in 4D for *viable*).

> The VCE Physics Study Design uses the terms *cutting-edge* and *contemporary* but does not define them. This section therefore treats them as: **research that is currently active — being carried out and reported on by research groups at the time you study it.** Every question in this section is answerable on that definition alone. *Cutting-edge* is also evaluative: calling research “cutting-edge” claims that it is at the

frontier of its field, and part of your investigation is to justify that claim with evidence (recent results, new facilities, open questions) rather than assume it.

Our region is defined by the study design itself: **Victoria, Australia or Oceania** — the wider region that includes Australia, New Zealand and the Pacific Islands.

The study design names *critical and creative thinking* but does not define them. This section treats **critical thinking** as the testing of claims and evidence — asking what the evidence is, who produced it, and what it cannot show (the source-validity work of 10A is critical thinking in practice) — and **creative thinking** as the generation of something new: new questions, new methods, or new uses for existing data and ideas.

Step 1 — Survey cutting-edge research in the region. You cannot choose a research area until you know what exists. The study design names six contexts your investigation may use: research at the Australian Synchrotron; space research; dark matter research; medical research involving radiation; materials research; and nuclear fusion research. The table gives one real, named starting point for each context, all of them based in Victoria, Australia or Oceania.

Research area	Where	The physics involved (you already hold it)	Study design context
The Australian Synchrotron — bright X-ray beams for biology, medicine and materials	Clayton, Melbourne, Victoria	Accelerated charges emit electromagnetic radiation (13C); X-rays are short-wavelength electromagnetic waves (1B)	Research at the Australian Synchrotron; also medical research; also materials research
SABRE South — a dark matter search at the Stawell Underground Physics Laboratory (SUPL)	Stawell Gold Mine, about 1 km underground, Victoria	Detecting rare events against a background of radiation; shielding from cosmic rays (3B, 3E)	Dark matter research
Gravitational-wave astronomy — OzGrav researchers analysing signals from merging black holes and neutron stars	Eight Australian universities; the detectors (LIGO, KAGRA) are overseas	Waves carry energy; measuring extremely small changes in distance (gravitational waves in 13D)	Space research
The Parkes radio telescope — surveys of the radio sky, including fast radio bursts	Near Parkes, New South Wales	Radio waves; wavelength, frequency and the electromagnetic spectrum (1A, 1B)	Space research
ASKAP and the SKA-Low telescope — radio arrays in the Murchison Radio-astronomy Observatory	Near Boolardy, Western Australia	Radio waves; combining many antennas to act as one instrument (1B)	Space research
The MOA microlensing survey — searching for planets by the bending of light	Mount John University Observatory, Mackenzie District, New Zealand	Gravity bending light from distant stars; exoplanet detection by microlensing (13B)	Space research
Radiopharmaceuticals from the OPAL reactor — radioisotopes for diagnosis and therapy	ANSTO, Lucas Heights, New South Wales	Producing radioisotopes by neutron bombardment; radioactive decay; tracers (3B–3F, 10E)	Medical research involving radiation
Nuclear fusion research — the ITER project and the physics of fusion power	International project in France; the reaction physics is taught in 10D	Fusion of light nuclei; mass converted to energy (10D, 4A)	Nuclear fusion research

These are starting points, not a closed list. You may investigate any real area of physics research based in Victoria, Australia or Oceania, provided you can source it (Step 2) and your teacher approves your choice. One further idea in the medical-radiation context is proton beam therapy, in which charged particles deposit most of their energy at a controlled depth (the Bragg peak); to investigate it, you must first source a research group based in the region and have your choice approved.

Source: ANSTO, *Our facilities — Australian Synchrotron*, retrieved 2026-08-18. Source: Wikipedia (Wikimedia Foundation), *Australian Synchrotron*, retrieved 2026-08-18. Source: Wikipedia (Wikimedia Foundation), *Stawell Underground Physics Laboratory*, retrieved 2026-08-18. Source: OzGrav ARC Centre of Excellence for Gravitational Wave Discovery, *ozgrav.org*, retrieved 2026-08-18. Source: Wikipedia (Wikimedia Foundation), *Parkes Observatory*, retrieved 2026-08-18. Source: Wikipedia (Wikimedia Foundation), *Square Kilometre Array*, retrieved 2026-08-18. Source: Wikipedia (Wikimedia Foundation), *Mount John University Observatory*, retrieved 2026-08-18. Source: ANSTO, *Our facilities — OPAL*, retrieved 2026-08-18. Source: Wikipedia (Wikimedia Foundation), *Proton therapy*, retrieved 2026-08-18. Source: Wikipedia (Wikimedia Foundation), *ITER*, retrieved 2026-08-18.

Step 2 — Select one area, and follow protocols to access information. A **protocol** is an agreed way of doing things. Research information is public, but accessing and using it properly has rules, and your investigation is assessed partly on whether you followed them.

1. **Get your choice approved.** Your teacher checks that the area is real, based in the region, and of suitable scope — not so broad that you can only skim it, not so narrow that there is nothing to find. Record the approved choice and the date in your logbook (14F).
2. **Know your source types.** A **primary source** reports research directly — for example, a peer-reviewed journal article written by the researchers (you can usually read the abstract, the summary paragraph, without a subscription). An **institutional source** is published by the organisation that runs the facility or funds the research — a university, ANSTO, CSIRO or SKA Observatory, for example — and is the strongest source for facts about its own facility. A **secondary source** reports on research at one remove — news articles and media releases. A **tertiary source**, such as Wikipedia, collects and summarises other sources: it is useful for finding your way into a topic and for locating the primary sources it cites, but it is written and edited by volunteers, so it is a starting point, not your final evidence. The evaluation questions are those of 10A.
3. **Record every source the moment you use it.** For each source write the publishing organisation, the document or page title, and the retrieval date — the same `Source:` format used throughout this book and required by the conventions of 14G. Research changes quickly; the retrieval date says exactly what you saw and when.
4. **Use information lawfully and honestly.** Quote or paraphrase with acknowledgement; do not copy figures or photographs without permission and credit; and present others' results as theirs, never as your own (the acknowledgement conventions are those of 14G).
5. **Contact people through school channels.** If you want to ask a researcher a question, do it through your teacher, not privately, and record the exchange in your logbook.

Step 3 — Identify the physics. For your chosen research, ask: what is measured, in what units? Which wave, particle, force or energy-transfer idea from Units 1 & 2 is doing the work? Which model predicts what the instrument will see? Write the physics as a short list of concepts, each linked to the section where you learned it. The table below shows the kind of mapping expected — this one is for the dark matter search at SUPL.

Physics concept	Where you learned it	Its role in the research
Radiation and its detection	3B	The detector looks for the tiny signals that a dark matter particle would leave in a sodium iodide crystal
Background radiation and shielding	3E	Cosmic rays — high-energy particles arriving from space — would swamp the rare signal, so the laboratory sits about 1 km underground, shielded by rock
Particles and the nucleus	3A	The search targets an unknown

Physics concept	Where you learned it	Its role in the research
		particle, so the experiment must rule out every known source of radiation first

Step 4 — Explain how physics understanding led to the development of the research. Research grows in chains: understanding makes new instruments possible; new instruments make new observations possible; new observations raise new questions. Build the chain for your area. For the Australian Synchrotron the chain runs:

1. **Understanding:** moving charges emit electromagnetic radiation, and magnets bend the path of moving charges, holding them on a circular path (13C); the higher the particle energy, the shorter the wavelength of the radiation produced.
2. **Instrument:** the $3\,\text{GeV}$ storage ring at Clayton bends electrons around a $216\,\text{m}$ ring, producing extremely bright X-ray beams at its beamlines (13C).
3. **Observation:** X-rays passing through a crystal reveal its atomic structure, so researchers use the beamlines to determine the structures of materials and of biological molecules, including proteins studied in cancer research and in research on Parkinson's disease, gastric cancer and melanoma.
4. **New questions:** each structure suggests new work — for example, designing a molecule that fits a protein's shape — and the chain continues.

Step 5 — Explain how critical and creative thinking shape the research. In your account, name the thinking moves explicitly and say which is which. Two real examples from the region:

- **Creative:** in 2007 the first fast radio burst — a brief, intense pulse of radio waves from beyond our galaxy — was found not by a new observation but by **re-examining old data**: a student, David Narkevic, working with his supervisor Duncan Lorimer, reviewed the radio observations the Parkes telescope had recorded in 2001, and the burst (recorded 24 July 2001) was found in them. Seeing a new use for existing data is creative thinking.
- **Critical:** in 1967 Jocelyn Bell Burnell, then a research student, noticed a small, repeated irregularity — she called it a "bit of scruff" — in chart recordings from a radio telescope. Following it up meant first ruling out ordinary causes: interference from equipment, from other radio sources, and only then accepting a new explanation — the first pulsar, a rapidly spinning star sending out regular pulses of radio waves. Refusing to ignore an oddity was the creative step; systematically testing explanations was the critical one.

Step 6 — Analyse the extent to which individual contribution and collaboration are involved. Modern physics research is almost never one person working alone, but it is also never *only* a crowd. Your analysis should weigh both sides with evidence. The two ends of the scale, from real cases:

- **One person's eye, inside a team.** The first pulsar was recognised by one research student examining charts. But the telescope she used was built by a team, and the discovery was published with her supervisor. When the 1974 Nobel Prize in Physics was awarded for the pulsar discovery, it went to Antony Hewish and Martin Ryle — Bell Burnell was not among the recipients, a decision debated ever since. She has since received major honours, including the Special Breakthrough Prize in Fundamental Physics (2018), the Copley Medal (2021) and the Gold Medal of the Royal Astronomical Society (2021). The case shows both how much one person's contribution can matter, and how hard credit within a collaboration can be to assign.
- **A collaboration of thousands.** The first gravitational-wave signal, GW150914, was found in data from the two LIGO detectors and announced on 11 February 2016. The discovery paper was published under the names of the whole LIGO Scientific Collaboration — an organisation of 1659 scientists across 149 institutions — with Australian OzGrav researchers among the analysis teams. No individual could build or operate such instruments alone; the collaboration checks every claim so thoroughly that the result can survive the scrutiny of rivals. Yet the collaboration itself rests on individual ideas — the 2017 Nobel Prize in Physics recognised three individuals, Rainer Weiss, Barry Barish and Kip Thorne, for decisive contributions to the detector concept and the project.

"Analyse the extent" means reaching a judgement with evidence on both sides: what the individuals contributed, what the collaboration made possible, and which the research could not have done without.

Source: Wikipedia (Wikimedia Foundation), *Jocelyn Bell Burnell*, retrieved 2026-08-18. Source: Wikipedia (Wikimedia Foundation), *Parkes Observatory*, retrieved 2026-08-18. Source: Wikipedia (Wikimedia Foundation), *GW150914*, retrieved 2026-08-18. Source: Wikipedia (Wikimedia Foundation), *LIGO Scientific Collaboration*, retrieved 2026-08-18. Source: OzGrav ARC Centre of Excellence for Gravitational Wave Discovery, *ozgrav.org*, retrieved 2026-08-18.

Step 7 — Evaluate how the research may change the way we live. *Evaluate* asks for a weighed judgement, not a celebration. Trace the path from the research to daily life, then test it:

- **What has already changed?** Radiopharmaceuticals made from radioisotopes such as technetium-99m are now routine in medicine: technetium-99m is used in about 40 million medical procedures worldwide each year, and ANSTO's OPAL reactor at Lucas Heights manufactures and supplies radiopharmaceuticals for Australian hospitals. This is a research-to-clinic chain that already touches patients every day.
- **What could change, and on what timescale?** The SKA-Low telescope in Western Australia began site construction in December 2022, with first observations projected for 2027 — that gap between ground-breaking and first data is a timescale a fair evaluation states plainly, rather than promising quick benefits.
- **What is uncertain?** The dark matter search at SUPL may detect a new particle — or it may rule out whole classes of candidates, which is also a result, but no application can be promised in advance. Honest evaluation separates the guaranteed knowledge from the hoped-for applications.
- **Who benefits, and what does it cost?** Sociocultural, economic, legal and political factors (the fourth dot point of the Communicating physics block, taught in 10B) belong here: the cost of facilities, the jobs and training they create, the laws that govern them — for example, the radio-quiet zone established around the Murchison Radio-astronomy Observatory in 2005, which restricts radio transmitters so that the telescopes can hear the sky — and the public trust the research depends on.

Source: Wikipedia (Wikimedia Foundation), *Molybdenum-99*, retrieved 2026-08-18. Source: ANSTO, *Our facilities — OPAL*, retrieved 2026-08-18. Source: Wikipedia (Wikimedia Foundation), *Square Kilometre Array*, retrieved 2026-08-18.

Links to other sections. The Australian Synchrotron's accelerator physics is owned by 13C; gravitational waves by 13D (Option 2.17); microlensing exoplanet detection by 13B (Option 2.14); radioisotope production and medical imaging by 10E (Option 2.6) and Chapters 3–4; fusion reactions by 10D (Option 2.2); and mass–energy conversion by 4A. The communication skills assessed by the Option task at the end of this section are taught in 10A and 10B; the logbook and referencing conventions are those of 14F and 14G. The investigation methodology of this option is a **literature review** — one of the investigation methodologies named in the key science skills (`KSS.2.1`) and taught in 14A — because its data are collated from published sources rather than generated by experiment.

Worked examples

Example 1 — scaffolded

A student chooses the dark matter search at the Stawell Underground Physics Laboratory (SUPL) as their research area. Work through Steps 1–3: confirm the area is in scope, state what the research is and why the laboratory is built underground, and identify the Unit 1 & 2 physics the research uses.

Working	Comment
Scope check: SUPL is in the Stawell Gold Mine near Stawell, Victoria — inside a working gold mine, about 1 km underground.	The study design requires research based in Victoria, Australia or Oceania. A laboratory in Victoria qualifies.
The research: the SABRE South experiment uses sodium iodide crystals to search for dark matter — matter that gives off no light and is known only by its gravitational effects on stars and galaxies.	State what is being looked for, in words a Units 1 & 2 student can follow. Define every new term.
Why underground: cosmic rays — high-energy particles arriving from space — constantly strike detectors at the	The signal being hunted is extremely rare, so every ordinary source of radiation must be blocked or counted

Working	Comment
surface. The rock above the laboratory shields the crystals; the shielding is equivalent to about $2900\,\text{m}$ of water.	first.
Physics used: radiation and its detection (3B); background radiation and shielding (3E); particles and the nucleus (3A).	Each concept is linked to the section that taught it — this is what "identify the physics" means.
Protocol: choice approved by the teacher; choice and date entered in the logbook; sources recorded with organisation, title and retrieval date as they are used (14F, 14G).	Step 2 applies before any writing begins.

Source: Wikipedia (Wikimedia Foundation), *Stawell Underground Physics Laboratory*, retrieved 2026-08-18.

Example 2 — scaffolded

The same student finds three sources about the Australian Synchrotron: (i) the facility page on ANSTO's website; (ii) the Wikipedia article on the Australian Synchrotron; (iii) a newspaper article reporting a result obtained at one of its beamlines. Evaluate the validity of each source using the questions of 10A, and state how each should be used.

Working	Comment
Source (i), ANSTO facility page: published by the organisation that operates the facility. Strongest source for facts about its own instrument (location, energy, beamlines, research programmes). Purpose includes promoting the facility, so claims about impact should still be checked.	Institutional source: authoritative about itself; evaluate the direction of its interest.
Source (ii), Wikipedia: a tertiary source written and edited by volunteers. Useful for orientation and for its references to primary sources; not the final word, because anyone can edit it and the content can change.	Use it to enter the topic and to find primary sources; record it as you would any source, with the retrieval date.
Source (iii), newspaper article: a secondary source, one step from the research. May simplify or exaggerate to attract readers; the journalist is not the researcher. Check that it names the researchers and the journal the result was published in, and follow those back to the primary source.	Secondary sources are evidence about *coverage*, not about the result itself.
Use: (i) for the facility facts; (ii) for orientation and to reach the primary literature; (iii) only as an example of how the research is reported publicly — and evaluated as such.	A strong investigation uses several source types and says what each is good for.

Source: ANSTO, *Our facilities — Australian Synchrotron*, retrieved 2026-08-18. Source: Wikipedia (Wikimedia Foundation), *Australian Synchrotron*, retrieved 2026-08-18.

Example 3 — unscaffolded

Explain how physics understanding led to the development of gravitational-wave research, and identify where critical and creative thinking shaped it, using the first detection (GW150914) as the case.

Physics understanding came first. Theory predicted that accelerating masses send out **gravitational waves** — ripples in space and time itself — and that merging black holes should be among the strongest sources (gravitational waves are treated in 13D). A passing wave alternately stretches space in one direction and squeezes it in the perpendicular direction, so detecting one means measuring an extraordinarily small change in distance. Building an instrument able to do that required decades of creative thinking: LIGO's detectors use light beams to monitor the lengths of two long perpendicular arms, and the design had to isolate the measurement from vibration, from thermal motion, and from every other local disturbance.

The development paid off on 14 September 2015, when both LIGO detectors — in the United States, thousands of kilometres apart — recorded the same signal: a chirp sweeping from about $35\,\text{Hz}$ to about $250\,\text{Hz}$ in roughly $0.2\,\text{s}$. The signal matched the predicted shape for two merging black holes of about 36 and 29 solar masses, about 1.3 billion light-years away. The merged black hole came out at about 62 solar masses: roughly 3 solar masses of matter had been converted, in a fraction of a second, into the energy of the gravitational waves themselves — mass–energy conversion (4A) on the largest scale imaginable, with a peak power of about $3.6 \times 10^{49}\,\text{W}$.

Critical thinking shaped the discovery as much as the instrument did. Between the detection in September 2015 and the announcement on 11 February 2016, the collaboration spent months ruling out every ordinary explanation — a local disturbance, an instrument fault, even an injected test signal — and checking that the signal's details matched the theory before anything was made public. The 2017 Nobel Prize in Physics went to Rainer Weiss, Barry Barish and Kip Thorne for decisive contributions to the detector and the project, and Australian researchers in OzGrav — an ARC Centre of Excellence for Gravitational Wave Discovery spanning eight universities — take part in the detection and analysis work. The case shows the chain of Step 4 in full: understanding predicted the waves, understanding built the instrument, the instrument made the observation, and the observation opened a new field.

Source: Wikipedia (Wikimedia Foundation), *GW150914*, retrieved 2026-08-18. Source: OzGrav ARC Centre of Excellence for Gravitational Wave Discovery, *ozgrav.org*, retrieved 2026-08-18.

Example 4 — unscaffolded

"Analyse the extent to which both individual contribution and collaboration are involved in the selected research." Demonstrate the analysis using two real cases: the discovery of the first pulsar, and the discovery of the first gravitational-wave signal.

The pulsar case shows what one person can do inside a team. In 1967 Jocelyn Bell Burnell, a research student, noticed a repeated "bit of scruff" in the chart recordings of a radio telescope and pursued it until it was identified as the first pulsar — a rapidly spinning star emitting regular radio pulses. The telescope itself was a collaborative construction, and the discovery was published together with her supervisor; when the 1974 Nobel Prize in Physics was awarded for the discovery, it went to Antony Hewish and Martin Ryle, not to Bell Burnell — a decision criticised ever since, and one reason her later honours (the 2018 Special Breakthrough Prize in Fundamental Physics; the 2021 Copley Medal; the 2021 Gold Medal of the Royal Astronomical Society) attracted so much attention. The lesson for the analysis: an individual's observation can be the decisive step, while the credit system around it is a human arrangement that can misfire.

The gravitational-wave case shows what only a collaboration can do. GW150914 was found in data from two instruments no individual or single university could build or run, and the discovery was published by the LIGO Scientific Collaboration as such — 1659 scientists in 149 institutions at the time of the July 2025 membership list. The collaboration's size is part of the evidence's strength: every claim was checked by rivals inside the project before announcement. Yet the collaboration did not remove the role of individuals — the 2017 Nobel Prize singled out Weiss, Barish and Thorne for the ideas and leadership the whole effort rested on, and Australian researchers in OzGrav contribute as named members of the wider teams.

The judgement the question asks for: in contemporary physics, individual contribution and collaboration are not opposites but layers. Individuals pose the questions, notice the anomalies and supply the key ideas; collaborations supply the instruments, the scrutiny and the continuity that no individual career can. Which layer is more visible varies by project — a sharp-eyed student with chart paper at one end, a 1659-member author list at the other — but in the research areas of this option, neither layer works without the other.

Source: Wikipedia (Wikimedia Foundation), *Jocelyn Bell Burnell*, retrieved 2026-08-18. Source: Wikipedia (Wikimedia Foundation), *LIGO Scientific Collaboration*, retrieved 2026-08-18. Source: Wikipedia (Wikimedia Foundation), *GW150914*, retrieved 2026-08-18.

Practice questions

Question 1 *(scaffolded)* The study design names six contexts for Option 2.18: research at the Australian Synchrotron; space research; dark matter research; medical research involving radiation; materials research; and nuclear fusion research. (a) From the table in Step 1, name one real research area for each of: dark matter research; medical research involving radiation; and space research. (b) Which of your three named areas is based in Victoria? (c) Name one research area from the table that is based in Oceania but not in Australia.

Question 2 *(scaffolded)* A student is about to begin their Option 2.18 investigation. (a) Put the following protocol steps in the correct order: record each source with organisation, title and retrieval date; get the research area approved by the teacher; choose a research area from the survey of Step 1; evaluate the validity of the sources; begin taking notes for the communication. (b) State the three items every `Source:` line in your investigation must contain. (c) State why the retrieval date matters for research done in the present.

Question 3 *(scaffolded)* For an investigation of the Australian Synchrotron, a student collects: (i) a peer-reviewed journal article reporting a result from a beamline; (ii) the facility page on ANSTO's website; (iii) the Wikipedia article on the Australian Synchrotron; (iv) a social-media post summarising the result without naming the researchers. (a) Classify each as primary, institutional, secondary or tertiary. (b) Which source is most authoritative for facts about the facility itself (its energy, location and beamlines)? (c) Which source, if any, should not be used as evidence, and why?

Question 4 *(scaffolded)* The first fast radio burst was found in 2007 in data the Parkes telescope recorded on 24 July 2001. (a) State the region of the electromagnetic spectrum in which a fast radio burst is observed. (b) The burst lasted only a few milliseconds. Using the wave model of Chapter 1, state what arrived at the dish during those milliseconds. (c) The discovery came from re-examining old data rather than from a new observation. State which of *critical* and *creative* thinking this illustrates, and justify your choice in one sentence.

Question 5 *(scaffolded)* In proton beam therapy, a beam of protons is aimed at a tumour. (a) Describe where along its path a proton beam deposits most of its energy. (b) Explain why this is an advantage over an X-ray beam for treating a tumour that lies close to healthy tissue.

Question 6 *(scaffolded)* Jocelyn Bell Burnell discovered the first pulsar in 1967. (a) State what she was at the time of the discovery (her role and level of study). (b) State what the first pulsar was initially nicknamed, before its true nature was understood. (c) The 1974 Nobel Prize in Physics for the pulsar discovery was awarded to two other scientists. State what this case shows about how credit is assigned in collaborative research.

Question 7 Choose one application of the Australian Synchrotron (for example, determining the structure of a protein involved in disease, or studying a new material). Construct the four-link causal chain of Step 4 for it: the physics understanding, the instrument it made possible, the observations the instrument allows, and the new questions those observations raise. Link each physics idea to the section where you learned it.

Question 8 *(constructed stimulus — not a quotation.)* A social-media post reads:

> "Building billion-dollar telescopes in the middle of nowhere while hospitals can't afford equipment. This is what happens when scientists spend other people's money."

Evaluate the argument of the post. In your response: identify at least one assumption built into it; state one economic or political factor the post raises that genuinely matters; and use the physics of this section (including at least one real, named facility and its applications) to test whether "telescopes or hospitals" is the only choice being made.

Question 9 Take one research programme from the table in Step 1 (or one approved by your teacher). Plan the Step 6 analysis of it by answering, in note form: (a) what individual contributions the research depends or depended on — name them where they are known; (b) what the collaboration provides that no individual could (instruments, checking, scale, continuity); (c) your judgement: to what extent is the research a product of individuals, of collaboration, or of both, and on what evidence.

Question 10 Evaluate how the dark matter search at SUPL may change the way we live. Your evaluation must include: one way the research could matter if it succeeds; one honest statement of what cannot be promised in advance; and one spin-off or side benefit that does not depend on finding dark matter at all. Compare your judgement with the medical radioisotope chain (OPAL to technetium-99m imaging), where the applications already exist.

Question 11 *(constructed stimulus — not a quotation.)* A tabloid website runs the headline:

> "Secret lab under Victorian mine detects ALIEN DARK MATTER — scientists silent"

Identify at least four features of this headline and its presentation that mark it as unreliable, using the source-evaluation questions of 10A. Then state what a *valid* report of a discovery at SUPL would need to include for you to take it seriously.

Question 12 Draft the opening of your own Option 2.18 investigation, for the research area you would choose from the table in Step 1 (or one approved by your teacher): (a) an aim — one sentence saying what your investigation will find out; (b) three research questions, each mapped to one of the dot points of Option 2.18; (c) three sources you would seek out first, each classified by type (primary, institutional, secondary, tertiary) and each a real, existing source.

Answers

Question 1 (a) for example: SUPL/SABRE South (dark matter); ANSTO OPAL radiopharmaceuticals (medical); the Parkes radio telescope, ASKAP/SKA-Low or OzGrav gravitational-wave astronomy (space); (b) SUPL; (c) the MOA microlensing survey at Mount John University Observatory, New Zealand. **Question 2** (a) choose the area; get approval; record sources; evaluate validity; begin notes; (b) publishing organisation, document or page title, retrieval date; (c) see solutions. **Question 3** (a) (i) primary, (ii) institutional, (iii) tertiary, (iv) secondary; (b) (ii), the ANSTO facility page; (c) (iv) — no named researchers or source to check against. **Question 4** (a) radio; (b) a travelling electromagnetic wave — oscillating electric and magnetic fields; (c) creative — it found a new use for data already recorded. **Question 5** (a) at a controlled depth near the end of its path (the Bragg peak); (b) see solutions. **Question 6** (a) a research student; (b) Little Green Man 1; (c) see solutions. **Question 7** see solutions. **Question 8** see solutions. **Question 9** see solutions. **Question 10** see solutions. **Question 11** see solutions. **Question 12** see solutions.

Fully-worked solutions

Question 1 (a) Dark matter research: the SABRE South experiment at the Stawell Underground Physics Laboratory. Medical research involving radiation: radiopharmaceutical production from the OPAL reactor at ANSTO (or proton beam therapy research). Space research: the Parkes radio telescope, ASKAP and SKA-Low in Australia, the OzGrav gravitational-wave programme, or the MOA survey in New Zealand. (b) The Stawell Underground Physics Laboratory is in Victoria. (c) The MOA microlensing survey at Mount John University Observatory is in New Zealand — in Oceania, outside Australia.

Question 2 (a) 1 — choose a research area from the survey of Step 1; 2 — get the research area approved by the teacher; 3 — record each source with organisation, title and retrieval date; 4 — evaluate the validity of the sources; 5 — begin taking notes for the communication. (Recording begins as soon as the first source is consulted, not after the reading is finished.) (b) The publishing organisation, the document or page title, and the retrieval date. (c) Contemporary research changes while you are studying it: results are updated, facilities are upgraded, and pages are rewritten. The retrieval date fixes exactly which version of the information you relied on, so your claims can be checked.

Question 3 (a) (i) primary source — written by the researchers reporting their own result; (ii) institutional source — published by the organisation that operates the facility; (iii) tertiary source — a volunteer-edited summary of other sources; (iv) secondary source — a report at one remove from the research. (b) Source (ii), the ANSTO facility page: the operator is the strongest authority on its own facility's energy, location and beamlines. (c) Source (iv) should not be used as evidence: it names no researchers, gives no journal or institution to check, and cannot be traced back to a primary source. It could still be used as an *example* of poor public reporting, evaluated as such.

Question 4 (a) The radio region of the electromagnetic spectrum (1B). (b) An electromagnetic wave — a travelling disturbance of electric and magnetic fields — arrived at the dish, carrying energy from the source (1A, 1B). (c) Creative thinking: the discovery came from seeing a new use for data that had already been recorded, not from collecting new data. (The critical thinking came afterwards, when the team checked that the pulse was not interference.)

Question 5 (a) A proton beam deposits most of its energy at a controlled depth near the end of its path through tissue — a concentration called the **Bragg peak** — with little energy deposited beyond that depth. (b) An X-ray beam deposits energy all along its path, entering and leaving the body, so healthy tissue on both sides of a tumour receives a dose. A proton beam can be arranged to put its Bragg peak inside the tumour, so the tissue beyond the tumour receives almost no radiation — an advantage when the tumour lies close to organs that must be spared. Source: Wikipedia (Wikimedia Foundation), *Proton therapy*, retrieved 2026-08-18.

Question 6 (a) Bell Burnell was a research student at the time of the discovery. (b) The first pulsar was nicknamed "Little Green Man 1" until its natural explanation was established. (c) The case shows that credit in collaborative research does not always follow contribution: the decisive observation was made by a student, but the Nobel Prize went to her supervisor and a second senior researcher. It shows that how credit is assigned is a human arrangement that can fail, and that recognising individual contributions within large projects is an ongoing problem for science. Her later honours — the 2018 Special Breakthrough Prize, the 2021 Copley Medal and the 2021 Gold Medal of the Royal

Astronomical Society — are part of that correction. Source: Wikipedia (Wikimedia Foundation), *Jocelyn Bell Burnell*, retrieved 2026-08-18.

Question 7 Model answer (4 marks). One complete chain, for determining the structure of a protein involved in disease: *Understanding* — X-rays are short-wavelength electromagnetic waves (1B), and X-rays sent through a crystal are scattered in a pattern that encodes the crystal's atomic arrangement (1 mark). *Instrument* — the $3\,\mathrm{GeV}$ storage ring at the Australian Synchrotron produces the extremely bright X-ray beams needed to record those patterns from tiny protein crystals (13C) (1 mark). *Observation* — the beamlines record the scattering patterns of proteins studied in cancer research and in research on Parkinson's disease, gastric cancer and melanoma, and the patterns are worked back into atomic structures (1 mark). *New questions* — each structure suggests the next experiment: for example, designing a drug molecule that fits the active site of a disease protein, which then needs its own structural checks — and the chain continues (1 mark). Source: ANSTO, *Our facilities — Australian Synchrotron*, retrieved 2026-08-18.

Question 8 Model answer (5 marks). The post assumes that science funding is a single pool where a telescope directly displaces a hospital bed, that only immediate clinical use counts as value, and that the facilities named deliver none (1 mark). One genuine factor it raises is real: large facilities do compete for public funds, and a community is entitled to ask what they return — that is a legitimate economic and political question (1 mark). But the physics of this section tests the either/or framing: the Australian Synchrotron in Melbourne supports research on proteins involved in cancer and in Parkinson's disease — astronomy spending that *is* health spending — and ANSTO's OPAL reactor supplies the radiopharmaceuticals used in tens of millions of nuclear medicine procedures each year worldwide (1 mark). The telescopes themselves return practical benefits — the radio-quiet zone around the Murchison site is a legal instrument created to protect the science, and the SKA project drives engineering, computing and jobs in regional Australia — and the knowledge they produce is a public good whose applications cannot be predicted in advance (1 mark). A fair evaluation therefore rejects the post's framing while keeping its underlying question: the cost of facilities is a real factor, but "telescopes or hospitals" is a false choice, because the same research chain feeds both (1 mark). Source: ANSTO, *Our facilities — Australian Synchrotron*, retrieved 2026-08-18. Source: Wikipedia (Wikimedia Foundation), *Molybdenum-99*, retrieved 2026-08-18.

Question 9 Model structure (4 marks). Award as follows. (a) Named individual contributions, where known — for example, for gravitational-wave astronomy: Weiss, Barish and Thorne's detector-era contributions; for the Parkes fast radio burst: Narkevic's re-analysis of the 2001 data under Lorimer's direction (1 mark). (b) What the collaboration supplies that no individual could — the instruments (LIGO's two detectors; the SKA's thousands of antennas), the cross-checks that make a claim defensible, the scale of data handling, and the continuity of the project across individual careers (1 mark). (c) A judgement with evidence on both sides — for example: "the research is a product of both, with the collaboration dominant in construction and verification, and individuals dominant in the original ideas and in the recognition of anomalies", supported by a named case from the chosen programme (2 marks). A response that asserts one side without evidence, or that treats individuals and collaboration as opposites rather than layers, caps at 2 marks.

Question 10 Model answer (4 marks). If the search succeeds, detecting a dark matter particle would identify most of the matter in the Universe — a change to our understanding of nature as large as any in this book, and the start of new physics (1 mark). The honest statement: no application can be promised in advance; the experiment may instead rule out whole classes of candidates, which is a scientific result but not a technology (1 mark). Spin-offs that do not depend on success: extremely low-background detectors, deep-underground engineering and data analysis methods, plus the facility itself as a Victorian research asset operated with partners including the University of Melbourne, Swinburne, the University of Adelaide, ANU, ANSTO and Italy's INFN (1 mark). Comparison: the radioisotope chain is the contrast case — OPAL produces radiopharmaceuticals now, and technetium-99m is used in about 40 million procedures worldwide each year, so its answer to "how may we live differently?" is already being lived, while SUPL's is still a justified hope (1 mark). Source: Wikipedia (Wikimedia Foundation), *Stawell Underground Physics Laboratory*, retrieved 2026-08-18. Source: Wikipedia (Wikimedia Foundation), *Molybdenum-99*, retrieved 2026-08-18.

Question 11 Model answer (4 marks). Features that mark the headline unreliable (any four): it names no researcher, institution or journal, so nothing can be checked (10A); it uses an extraordinary claim ("alien") with no evidence offered; "scientists silent" is a red flag — real discoveries are published, not suppressed, and SUPL is a facility with named partner universities; the language is designed for emotional effect ("SECRET", capitals) rather than information; and no retrieval date, author or publication with editorial standards is given (2 marks). A valid report would need: the name of the experiment (SABRE South) and its partner institutions; what was actually measured — for example, an annual modulation in the detector signal — with enough detail of the method to judge it; a reference to a peer-reviewed publication; and a statement of what the result does *not* yet establish, since a single signal would need independent confirmation before it counted as a detection (2 marks).

Question 12 Model structure (4 marks). (a) A one-sentence aim naming the chosen area and what the investigation will establish — for example, "to investigate how gravitational-wave astronomy is conducted in Australia through the OzGrav centre, and evaluate how it may change the way we live" (1 mark). (b) Three research questions mapped to dot points — for example: "Which physics concepts does gravitational-wave detection rely on?" (identify the physics); "To what extent does the discovery of GW150914 depend on individual contribution versus collaboration?" (analyse the extent); "What applications, if any, may follow from gravitational-wave research?" (evaluate how we may live differently) (1 mark). (c) Three real sources, correctly typed — for example: *ozgrav.org* (institutional); the GW150914 publication abstract as indexed in a journal or database (primary); and a Wikipedia orientation article such as *GW150914* (tertiary), each a source that actually exists (2 marks). Sources that are invented or untyped cap the mark at 2.

Option task — an application of physics concepts to a real-world context (30 marks)

House Option task (house convention — school-based assessment; Units 1 & 2 carry no VCAA examination, and levels of achievement are a matter for school decision). Outcome 2 task type: a report of an application of physics concepts to a real-world context; an equivalent scientific poster is a permitted alternative format of comparable scope and demand. The rubric is keyed to the Communicating physics dot points `U2.2.CP.1–.5` (taught in 10A and 10B). The task parts together cover the seven key knowledge dot points of Option 2.18.

The task. Choose one area of local physics research — from the table in Step 1, or another real research area based in Victoria, Australia or Oceania with your teacher's approval. Investigate it following the seven steps of this section, and present your findings as either:

- a written research report of 1200–1500 words, or
- a scientific poster of one page (A1 or A2) carrying the same content in visual form.

Both formats must contain the six parts below. Keep a logbook throughout: the choice of area, every source consulted (with organisation, title and retrieval date), and the dates of your decisions (14F).

Part 1 — Scope and sources (covers U2.2.O18.1, U2.2.O18.2). Name and describe the research. Show that it is based in Victoria, Australia or Oceania, and justify calling it contemporary and cutting-edge with evidence (recent results, current facilities, open questions). List at least four sources used, following the protocols of Step 2 — at least one institutional or peer-reviewed source among them — each with a complete `Source:` line.

Part 2 — The physics (covers U2.2.O18.3). Identify the physics involved: the concepts, their Units 1 & 2 sections, and their role in the research, using the mapping method of Step 3. Define every key term at first use and use correct scientific terminology and units throughout.

Part 3 — Development and thinking (covers U2.2.O18.4, U2.2.O18.5). Explain, as a causal chain in the manner of Step 4, how physics understanding led to the development of this research. Then identify and explain at least one moment of critical thinking and at least one moment of creative thinking in the research, naming which is which and why.

Part 4 — Individuals and collaboration (covers U2.2.O18.6). Analyse the extent to which both individual contribution and collaboration are involved in the research. Name individuals where they are known, state what the collaboration supplies, and reach a judgement supported by evidence.

Part 5 — Consequences and context (covers U2.2.O18.7). Evaluate how the research may change the way we live. Include what has already changed, what could change and on what timescale, what remains uncertain, and discuss at least one sociocultural, economic, legal or political factor relevant to the research. Include at least one data representation — a timeline, a concept map, an organisation chart, or a comparison table — that genuinely organises your evidence, and state one limitation of it.

Evaluation of sources (runs through all parts, assessed in Part 1 and Part 5). Evaluate the validity of each source you rely on, using the questions of 10A: who publishes it, what their expertise and interest are, whether its claims can be checked, and how current it is. End your response by stating one limitation of your own evidence.

Marking rubric — 30 marks, keyed to the Communicating physics dot points.

Marks are awarded for the quality of the reasoning, not the conclusion reached, and not the prestige of the research chosen: a well-reasoned account of any real local research area can receive full marks.

Criterion	Study design dot point	Marks
1. Validity of sources	"evaluate validity of sources of information"	6
2. Physics concepts and terminology	"apply physics concepts specific to the investigation: definitions of key terms; and use of appropriate scientific terminology, conventions and representations"	6
3. Data representations and limitations	"apply the use of data representations, models and theories in organising and explaining observed phenomena and physics concepts, and discuss the limitations of the explanations"	6
4. Societal factors	"discuss the influence of sociocultural, economic, legal and political factors relevant to the selected issue or application"	6
5. Justified evaluation	"apply physics understanding to justify a stance, opinion or solution to the selected issue or application"	6

Descriptors per criterion:

- **5–6 marks** — Criterion 1: at least four named, dated sources with complete `Source:` lines, including one institutional or peer-reviewed source, each explicitly evaluated for validity (publisher, expertise, interest, checkability, currency), with the roles of primary, secondary and tertiary sources distinguished. Criterion 2: the physics of the research is identified with concepts linked to their Units 1 & 2 sections; every key term is defined at first use; terminology, units and conventions are correct throughout. Criterion 3: the causal chain from physics understanding to the research is complete and correct, and the required data representation genuinely organises the evidence, with a real limitation stated (what it leaves out or cannot show). Criterion 4: at least one sociocultural, economic, legal or political factor is discussed as evidence relevant to the research — for example, funding, employment, regulation such as a radio-quiet zone, or public trust — not as an aside. Criterion 5: the evaluation of how the research may change the way we live separates what is already true, what is possible and what is uncertain; the judgement is supported by physics and by the sourced evidence, and one limitation of the student's own evidence is stated.
- **3–4 marks** — the criterion is met in substance with a gap: a source used without evaluation; the physics identified but with one undefined term, unit slip or missing section link; a data representation present but decorative, or with no stated limitation; a societal factor named but not discussed; an evaluation that overstates certainty or omits the timescale.
- **1–2 marks** — the criterion is attempted but thin: one weak or undated source; physics stated with significant errors; no usable representation; societal factors absent or asserted; an evaluation that is assertion rather than argument.
- **0 marks** — the criterion is not addressed.