OCR A Level Physics

Your notes

Cosmology

Contents

Units for Astronomical Distances

Your notes

Units for Astronomical Distances

- Astronomical distances are very large and as a result, are usually measured using:
  - Astronomical Units (AU)
  - Light-years (ly)
  - Parsecs (pc)

Astronomical Unit (AU)

- The astronomical unit (AU) is defined as

  The mean distance from the centre of the Earth to the centre of the Sun

- As the Earth's orbit around the Sun is **elliptical** it will be slightly closer to the Sun in January (1.471×10^{11} m) than it is in July (1.521×10^{11} m)
- Calculating the mean of these two values gives:

$$\frac{(1.471 \times 10^{11}) + (1.521 \times 10^{11})}{2} = 1.496 \times 10^{11} \text{ m}$$

- Therefore, 1 astronomical unit = 1.496×10^{11} m $\approx 1.5 \times 10^{11}$ m
- The astronomical unit is useful for studying distances on the scale of the **solar system**

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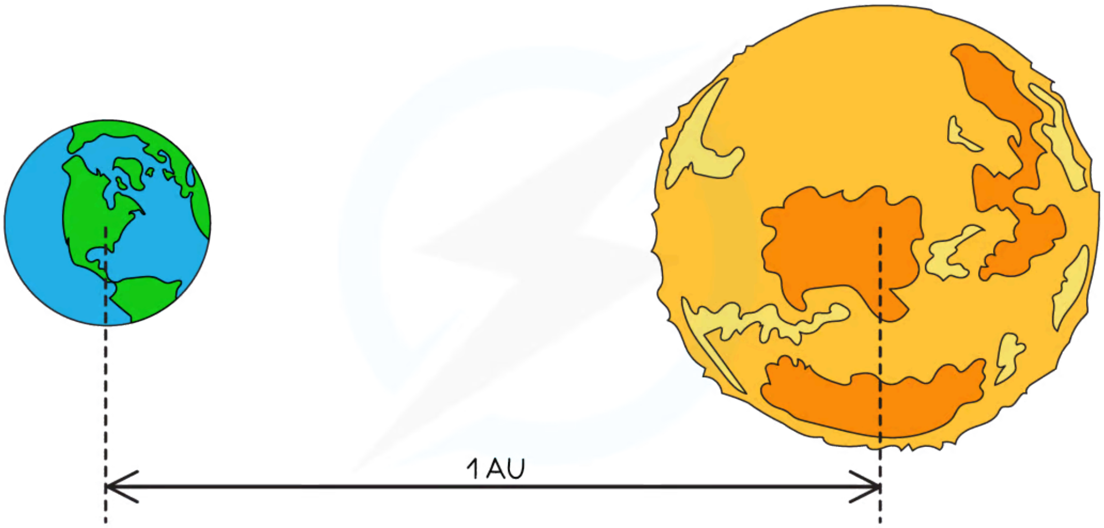


Light-year (ly)

- A light-year is defined as:

  The distance travelled by light in one year

- This can be calculated using:

Distance = speed × time

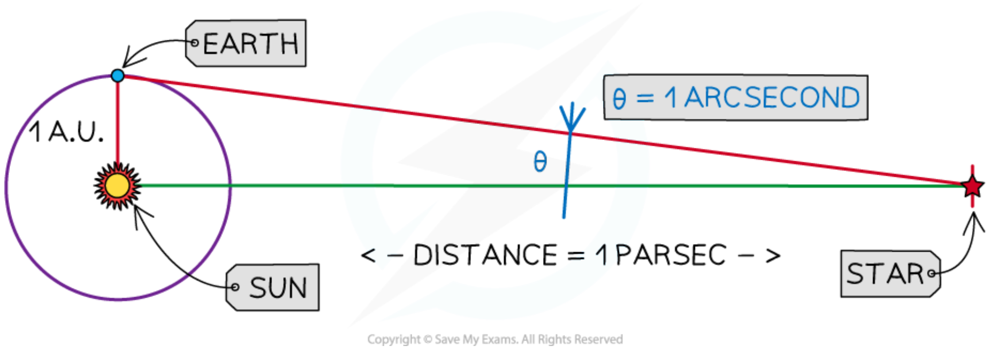
- Where:
  - The speed of light is 3×10^8 m s^{-1}
  - 1 year = 60 × 60 × 24 × 365 = 3.15×10^7 s
- Hence, the distance travelled by light in one year = $(3 \times 10^8) \times (3.15 \times 10^7) = 9.46 \times 10^{15}$ m
  - Therefore, 1 light-year ≈ 9.5×10^{15} m

Parsec (pc)

- Angles smaller than 1 degree can be measured in arcminutes or arcseconds
  - 1 degree = 60 arcminutes
  - 1 arcminute = 60 arcseconds
  - Therefore, 1 degree = 60 x 60 = 3600 arcseconds

- 1 arcsecond = 1/3600 degree
- The parsec is defined as

A unit of distance that gives a parallax angle of 1 second of an arc (of a degree), using the radius of the Earth's orbit (1 AU) as the baseline of a right-angled triangle



- Given that 1 AU = 1.496×10^{11} m, trigonometry can be used to express 1 parsec in metres:

$$\tan\theta = \frac{opp}{adj} = \frac{1\ AU}{1\ pc}$$

$$\tan\left(\frac{1}{3600}\right) = \frac{1\ AU}{1\ pc}$$

$$1\text{ pc} = \frac{1\ AU}{\tan\left(\frac{1}{3600}\right)} = \frac{1.496 \times 10^{11}}{\tan\left(\frac{1}{3600}\right)} = 3.09 \times 10^{16}\text{ m}$$

- Therefore, 1 parsec ≈ 3.1×10^{16} m
- The parsec (1 pc = 3.1×10^{16} m) and the light-year (1 ly = 9.5×10^{15} m) are much **greater** in size than the astronomical unit (1 AU = 1.496×10^{11} m)
- This makes them useful when studying **interstellar distances**
  - For example, on the scale of distances between the Earth and stars, or neighbouring galaxies

Worked Example

The closest star to Earth is a triple-star system called Alpha Centauri, which is approximately 4.35 light-years from Earth.

Your notes

Calculate the distance between the Earth and Alpha Centauri in:

a) Astronomical units

b) Parsecs

An astronomical unit is 1.496×10^{11} m

Answer:

Part (a)

Step 1: List the known quantities

- 1 light-year ≈ 9.5×10^{15} m (from data booklet)
- 1 AU = 1.496×10^{11} m
- Distance to Alpha Centauri = 4.35 ly

Step 2: Convert 4.35 light-years into metres

- 4.35 ly = $4.35 \times (9.5 \times 10^{15}) = 4.13 \times 10^{16}$ m

Step 3: Convert from metres into AU

- 4.13×10^{16} m = $\dfrac{4.13 \times 10^{16}}{1.496 \times 10^{11}}$ = 2.8×10^{5} AU (to 2 s.f)

Part (b)

Step 1: List the known quantities

- 1 parsec ≈ 3.1×10^{16} m (from data booklet)
- 4.35 ly = 4.13×10^{16} m (from part a)

Step 2: Convert from metres into parsecs

- 4.13×10^{16} m = $\dfrac{4.13 \times 10^{16}}{3.1 \times 10^{16}}$ = 1.3 pc (to 2 s.f)

Examiner Tips and Tricks

You do not need to learn all of the conversion factors for astronomical distances, you just need to know how to use them! The following are given in the data booklet:

1 light-year ≈ 9.5×10^{15} m

1 parsec ≈ 3.1×10^{16} m

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However, the astronomical unit (AU) is not, so this could be useful to learn by heart!

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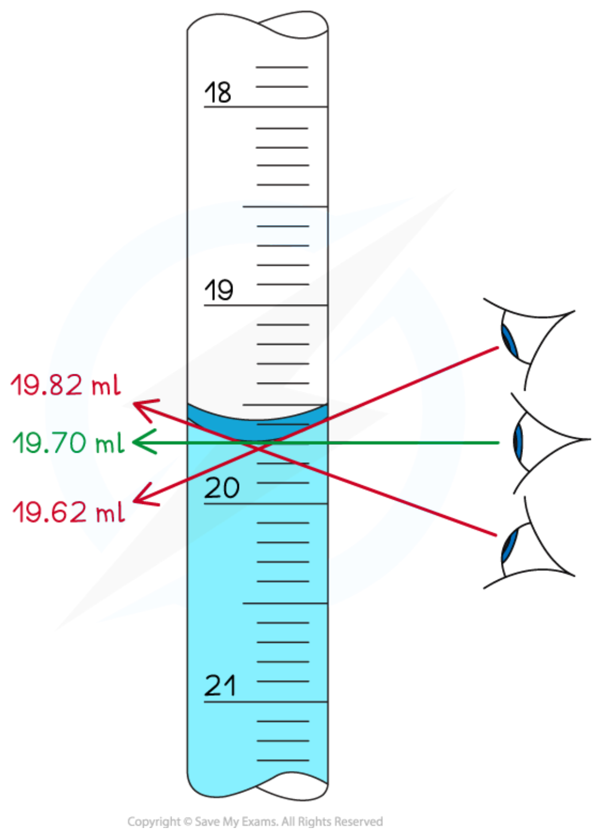
Stellar Parallax

Stellar Parallax

- The **principle of parallax** is based on how the position of an object appears to change depending on where it is observed from
  - When **observing** the volume of liquid in a measuring cylinder the parallax principle will result in the observer obtaining different values based on where they viewed the bottom of the meniscus from



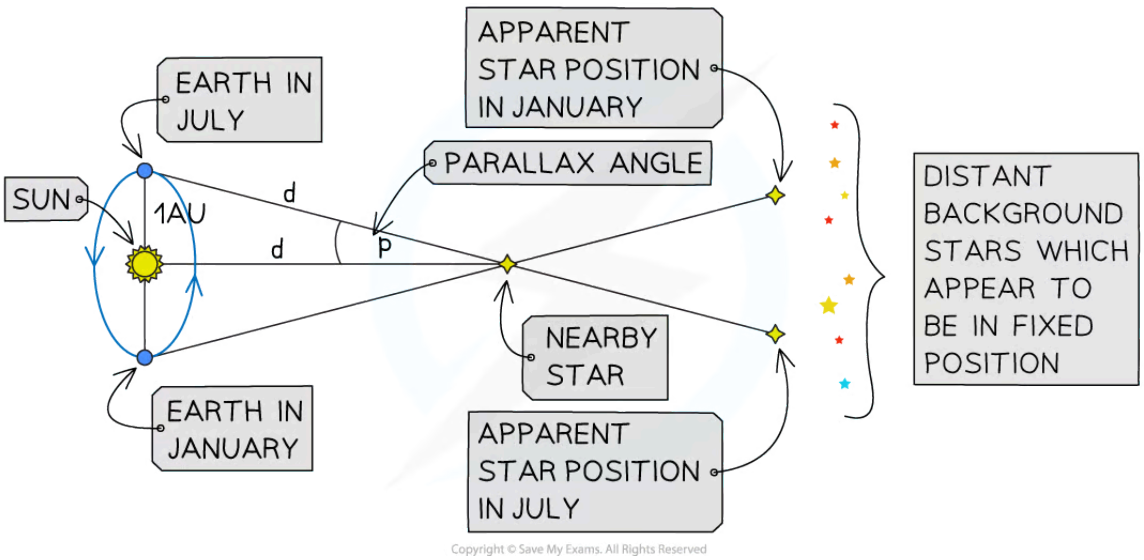
- **Stellar parallax** can be used to measure the distance to **nearby stars**
- Stellar Parallax is defined as:

  The apparent shifting in position of a nearby star against a background of distant stars when viewed from different positions of the Earth, during the Earth's orbit about the Sun

- It involves observing how the position of a nearby star changes over a period of time against a fixed background of distant stars

- To an **observer** the position of distant stars does not change with time

- If a **nearby star** is viewed from the Earth in January and again in July, when the Earth is at a **different position** in its orbit around the Sun, the star will appear in different positions against a backdrop of distant stars which will appear to not have moved
- This **apparent movement** of the nearby star is called the stellar parallax



The Parallax Equation

- Applying trigonometry to the parallax equation:
  - 1 AU = radius of Earths orbit around the sun
  - p = parallax angle from earth to the nearby star
  - d = distance to the nearby star
  - So, tan(p) = $\frac{1\ AU}{d}$
- For small angles, expressed in radians, tan(p) ≈ p, therefore: $p = \frac{1\ AU}{d}$
- If the distance to the nearby star is to be measured in parsec, then it can be shown that the relationship between the distance to a star from Earth and the angle of stellar parallax is given by

$$p = \frac{1}{d}$$

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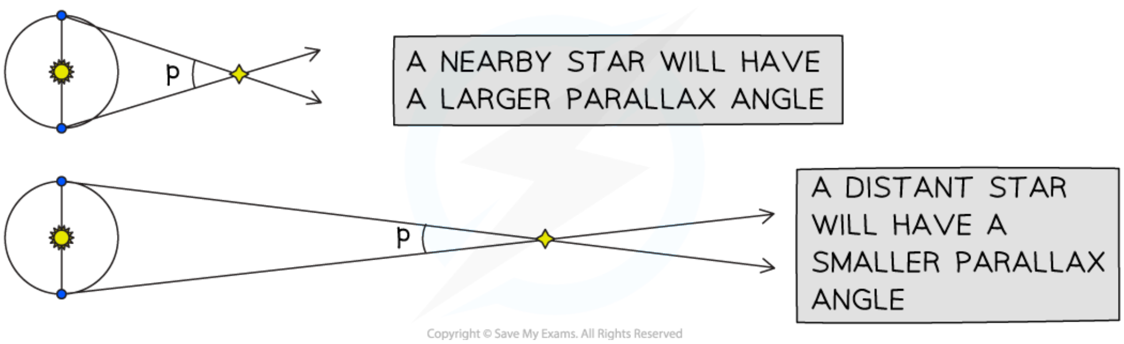
- Where:
  - p = parallax (")
  - d = the distance to the nearby star (pc)
- This equation is accurate for distances of up to 100 pc
  - For distances larger than 100 pc the angles involved are so small they are hard to measure accurately



Your notes

Worked Example

The nearest star to Earth, Proxima Centauri, has a parallax of 0.768 seconds of arc.

Calculate the distance of Proxima Centauri from Earth

a) In parsec

b) In light-years

Answer:

Part (a)

Step 1: List the known quantities

- Parallax, p = 0.768"

Step 2: State the parallax equation

$$p = \frac{1}{d}$$

Step 3: Rearrange and calculate the distance d

$$d = \frac{1}{p} = \frac{1}{0.768} = 1.30\ pc$$

Part (b)

Step 1: State the conversion between parsecs and metres

- From the data booklet:

$$1 \text{ parsec} \approx 3.1 \times 10^{16} \text{ m}$$

Step 2: Convert 1.30 pc to m

$$1.30 \text{ pc} = 1.30 \times (3.1 \times 10^{16}) = 4.03 \times 10^{16} \text{ m}$$

Step 3: State the conversion between light–years and metres

- From the data booklet

$$1 \text{ light–year} \approx 9.5 \times 10^{15} \text{ m}$$

Step 4: Convert 4.03×10^{16} m into light–years

$$\frac{4.03 \times 10^{16}}{9.5 \times 10^{15}} = 4.2 \text{ ly (to 2 s.f)}$$

Examiner Tips and Tricks

Make sure you know the units for arc seconds (") and arc minutes (')

- 1 arcminute is denoted by 1'
- 1 arcsecond is denoted by 1"

Your notes

The Cosmological Principle

Your notes

The Cosmological Principle

The cosmological principle states that:

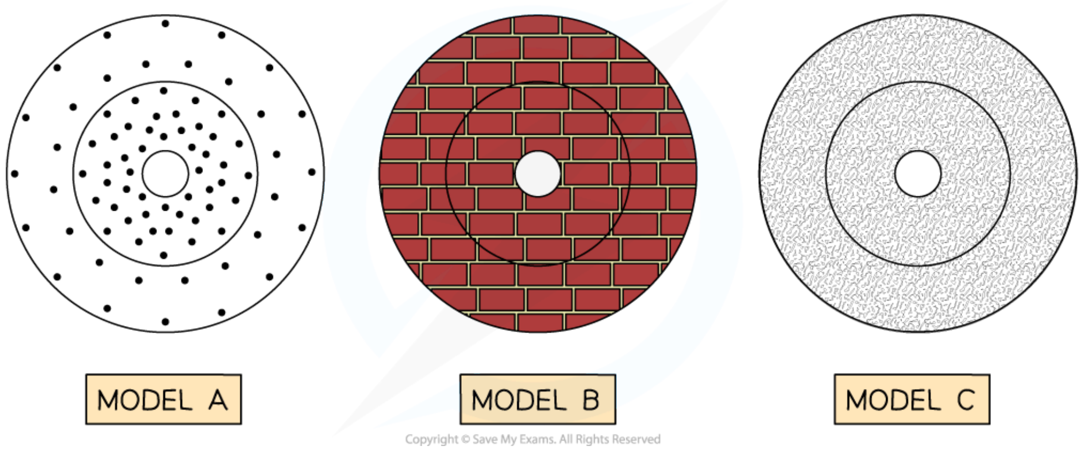
The universe is isotropic, homogenous and the laws of physics are universal

- **Isotropic** means that the universe is the same in all directions to every observer
  - Although specific regions of space may be completely empty and other regions may contain galaxies or clusters of galaxies which clump together, over the entire volume of space the distribution of matter appears to be uniform
- **Homogenous** means that matter is uniformly distributed, the universe has a uniform density
  - Although specific regions of space may contain more matter and other regions may contain less matter, over the entire volume of space the density appears uniform
- At every point in the universe the **laws of physics are universal**
  - This means that the same laws and models apply as here on Earth

The Cosmological Principle is demonstrated using the three models of the universe:

- Model A shows a universe that is **isotropic**, but not homogenous
  - The universe is the same in all directions to every observer
  - However, there is not a uniform distribution of matter (uniform density) in all regions
- Model B shows a universe that is **homogenous**, but not isotropic
  - The universe has a uniform distribution of matter (uniform density) in all regions
  - However, the universe is not the same in all directions to every observer due to the orientation of the bricks
- Model C illustrates the Cosmological Principle, it is both **isotropic** and **homogenous**
  - The universe is the same in all directions to every observer
  - The universe has a uniform distribution of matter (uniform density) in all regions

Your notes



Examiner Tips and Tricks

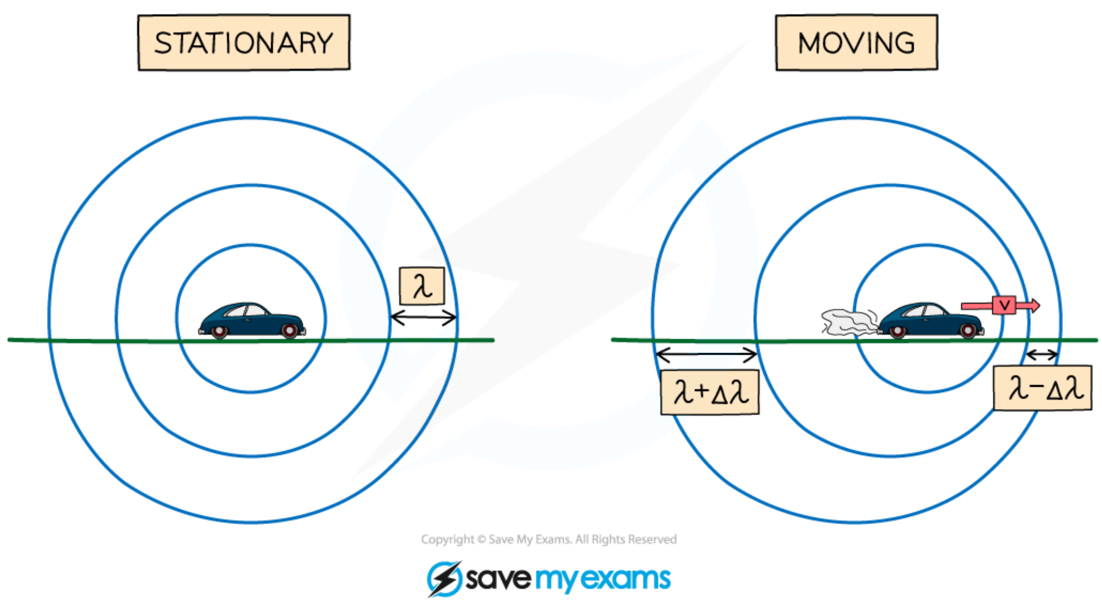
For the definition of 'homogenous' avoid saying the universe 'looks the same in all directions' - as this is a vague answer that will not be accepted in the exam!

Your notes

The Doppler Effect

The Doppler Effect

- If a wave source is stationary, the wavefronts spread out **symmetrically**
- If the wave source is moving, the waves can become **squashed** together or **stretched** out
  - If the wave source is moving **towards** an observer the wavefronts will appear **squashed**
  - If the wavefront is moving **away** from an observer the wavefronts will appear **stretched** out
- Therefore, when a wave source moves relative to an observer there will be a change in the observed **frequency** and **wavelength**



Wavefronts are even in a stationary object but are squashed in the direction of the moving wave source

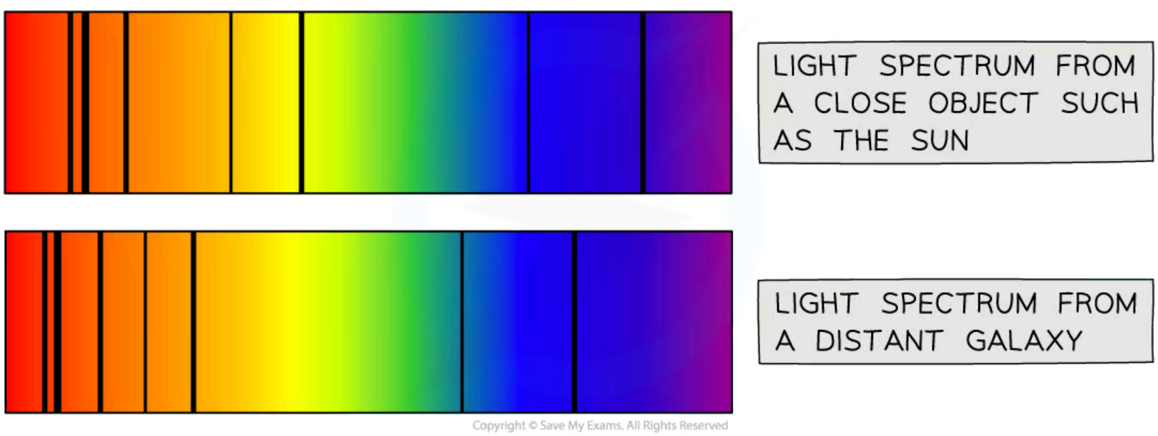
- A moving object will cause the **wavelength**, λ, (and frequency) of the waves to change:
  - The **wavelength** of the waves **in front** of the source **decreases** (λ – Δλ) and the **frequency increases**
  - The wavelength **behind** the source **increases** (λ + Δλ) and the **frequency decreases**
- Note: Δλ means '**change in wavelength**'

Your notes

- The actual wavelength emitted by the source remains the same
- It is only the wavelength that is received by the observer that appears to have changed
- This effect is known as the **Doppler effect** or **Doppler shift**
- The Doppler effect is defined as:

The apparent shift in wavelength occurring when the source of the waves is moving

- The Doppler effect, or Doppler shift, can be observed using any form of **electromagnetic radiation**
- It can be observed by comparing the light spectrum produced from a close object, such as our Sun, with that of a distant galaxy
    - The light from the distant galaxy is shifted towards the red end of the spectrum (There are more spectral lines in the red end)
    - This provides evidence that the universe is expanding



Comparing the light spectrum produced from the Sun and a distant galaxy

The Doppler Equation

- **Doppler shift** (Doppler effect) describes how the wavelength (or frequency) of waves change when the source of the waves and observer are moving relative to each other
- If the **relative speed** between the source of the waves and the observer, Δv, is **small** compared to the speed at which the wave is travelling, c, then the Doppler **wavelength shift**, $\Delta\lambda$, and **frequency shift**, Δf, is given by:

$$\frac{\Delta\lambda}{\lambda} \approx \frac{\Delta f}{f} \approx \frac{\Delta v}{c}$$

- Where:
  - Δv = relative speed between source and observer (m s^{-1})
  - c = speed of the wave (m s^{-1})
  - Δf = observed change in frequency between moving source and stationary source of wave (Hz)
  - f = unshifted frequency of the wave emitted (Hz)
  - $\Delta\lambda$ = observed change in wavelength between moving source and stationary source of wave (m)
  - λ = unshifted wavelength of the wave emitted (m)

- The **relative speed** between source and observer along the line joining them is give by:

$$\Delta v = v_s - v_o$$

- Where:
  - v_S = velocity of electromagnetic waves source
  - v_O = velocity of observer
- Usually, we are calculating the speed of the source of electromagnetic waves **relative** to an observer which we assume to be **stationary**
  - Therefore $v_O = 0$, hence $\Delta v = v_S = v$
  - Where v is the velocity at which the source of the electromagnetic waves is moving from the observer

- Hence, the Doppler shift equation can therefore be written as:

$$\frac{\Delta \lambda}{\lambda} \approx \frac{\Delta f}{f} \approx \frac{v}{c}$$

Worked Example

A stationary source of light is found to have a spectral line of wavelength 438 nm. The same line from a distant star that is moving away from us has a wavelength of 608 nm.

Calculate the speed at which the star is travelling away from Earth.

Your notes

Answer:

Step 1: List the known quantities

- Unshifted wavelength = λ = 438 nm = 438 × 10^{-9} m
- Shifted wavelength = 608 nm = 608 × 10^{-9} m
- Change in wavelength = $\Delta\lambda$ = (608 – 438) × 10^{-9} = 170 × 10^{-9} m
- Speed of light = c = 3.00 × 10^{8} m s^{-1}

Step 2: State the Doppler shift equation

$$\frac{\Delta\lambda}{\lambda} \approx \frac{\Delta v}{c}$$

Step 3: Substitute values to calculate v

$$v = \frac{c\Delta\lambda}{\lambda} = \frac{(3.00 \times 10^{8})(170 \times 10^{-9})}{438 \times 10^{-9}} = 1.16 \times 10^{8} \text{ m s}^{-1}$$

Examiner Tips and Tricks

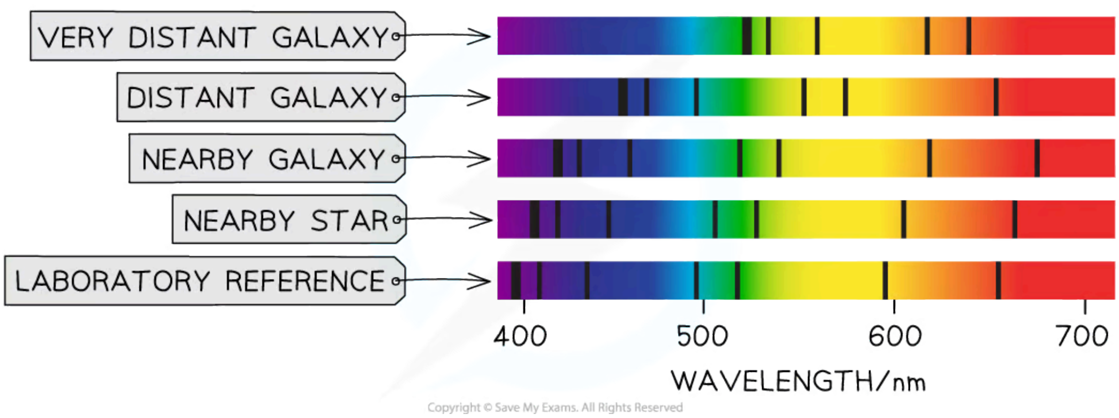
You need to know that in the visible light spectrum **red light** has the **longest wavelength** and the **smallest frequency** compared to **blue light** which has a **shorter wavelength** and **higher frequency**.

Your notes

Hubble's Law

Hubble's Law

- In 1929, the astronomer Edwin Hubble showed that the universe was **expanding**
  - He did this by observing that the absorption line spectra produced from the light of distant galaxies was shifted towards the **red** end of the spectrum
  - This **doppler shift** in the wavelength of the light is evidence that distant galaxies are moving away from the Earth



- Hubble also observed that light from more distant galaxies was **shifted further** towards the red end of the spectrum compared to closer galaxies
  - From this observation he concluded that galaxies or stars which are **further away** from the Earth are **moving faster** than galaxies which are closer
- Hubble's law states:

The recessional velocity, v, of a galaxy is proportional to its distance from Earth

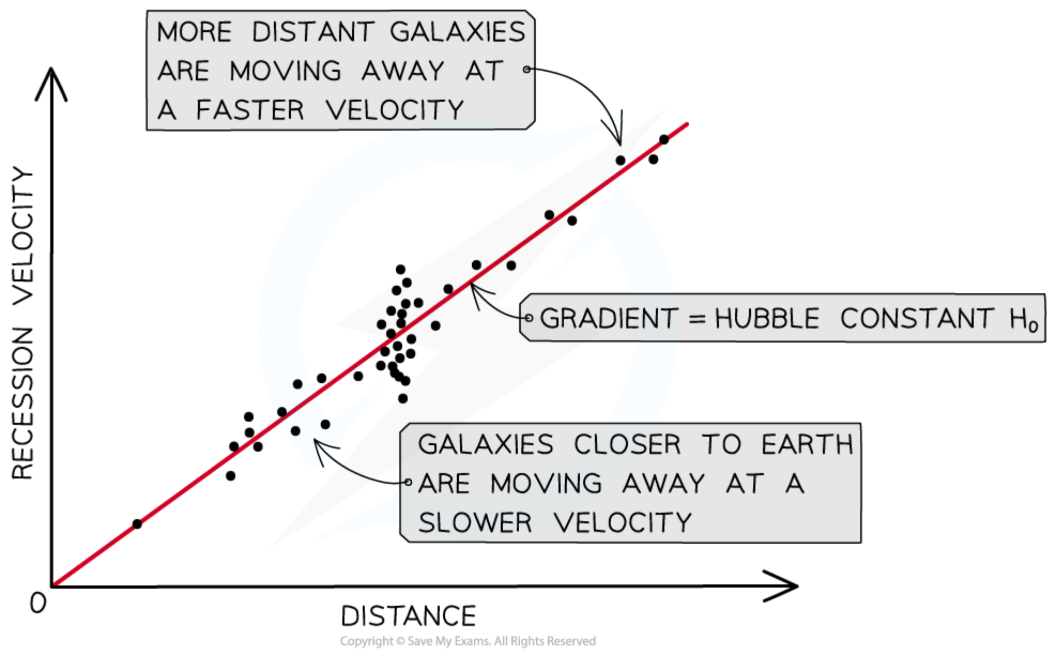
- Hubble's law can be expressed as an equation:

$$v \approx H_0 d$$

- Where:
  - v = recessional velocity of an object, the velocity of an object moving **away** from an observer (km s^{-1})

- H_0 = Hubble constant, this will be provided in your examination along with the correct units (km s^{-1} Mpc^{-1})
- *d* = distance between the object and the Earth (Mpc)

- Alternatively, if the velocity of the receding object was measured in km s^{-1} and the distance from the earth to the object was measured in km, then then unit for the Hubble constant would be s^{-1}
- This Hubble's law shows:
  - The further away a star is from the Earth, the faster it is moving away from us
  - The closer a star is to the Earth, the slower it is moving away from us



A key aspect of Hubble's law is that the furthest galaxies appear to move away the fastest

Worked Example

A distant galaxy is 20 light-years away from Earth.

Use Hubble's Law to determine the velocity of the galaxy as it moves away from Earth.

The Hubble constant is currently agreed to be 2.2×10^{-18} s^{-1}.

Answer:

Your notes

Step 1: List the known quantities

- d = 20 light years
- $H_0 = 2.2 \times 10^{-18}$ s^{-1}

Step 2: Convert 20 light-years to m

- From the data booklet: 1 ly ≈ 9.5×10^{15} m
- So, 20 ly = 20 x (9.5×10^{15}) = 1.9×10^{17} m

Step 3: Substitute values into Hubble's Law

- From the data booklet: $v \approx H_0 d$
- So, $v \approx (2.2 \times 10^{-18}\ \text{s}^{-1}) \times (1.9 \times 10^{17}\ \text{m}) = 0.418$ m s^{-1}

Step 4: Confirm your answer

- The velocity of the galaxy as it moves away from Earth 0.42 m s^{-1}

The Hubble Constant

- By rearranging the equation for Hubble's law, we can determine that the Hubble constant, H_0, is:

$$H_0 \approx \frac{v}{d}$$

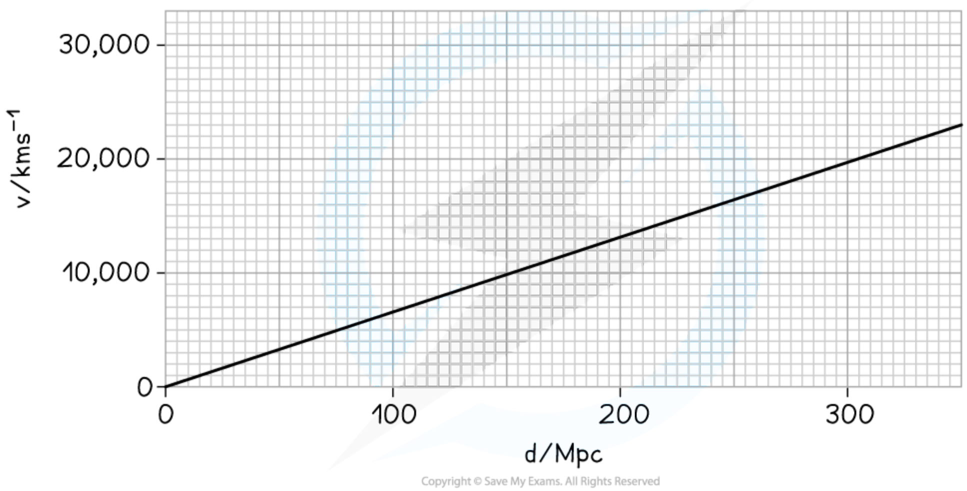
- v = recessional velocity of an object (km s^{-1})
- d = distance between the object and the Earth (Mpc)
- H_0 = Hubble constant (km s^{-1} Mpc^{-1})

- The value for the Hubble constant has been estimated using data for thousands of galaxies
- The latest estimate of the Hubble constant based on CMB observations by the Planck satellite is:
  - $\boldsymbol{H_0 = 67.4 \pm 0.5}$ **km s^{-1} Mpc^{-1}** (Planck Collaboration VI 2020)
- It is difficult to be certain about just how accurate the values for the Hubble constant are
  - This is due to the random and systematic errors involved when calculating the distance to a galaxy or star

Worked Example

The graph shows how the recessional velocity, v, of galaxies varies with their distance, d, measured from the Earth.

Your notes



Use the graph to determine a value for the Hubble constant and state the unit for this constant.

Answer:

Step 1: From the data booklet

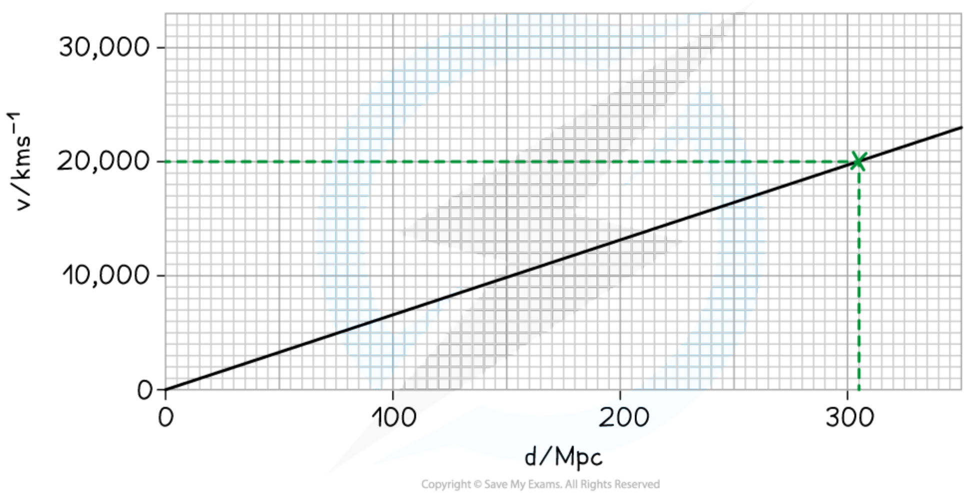
$$\text{Hubble's Law: } v \approx H_0 d$$

Step 2: Determine the Hubble constant, H_0, from the graph

- y–axis = v = 20, 000
- x–axis = d = 305
- gradient = H_0

Step 3: Calculate the gradient of the graph

Your notes



- $H_0 = \dfrac{Y_2 - Y_1}{X_2 - X_1} = \dfrac{20000 - 0}{300 - 0}$ = 66 km s^{-1} Mpc^{-1}

Step 4: Confirm your answer

- The Hubble Constant = 66 km s^{-1} Mpc^{-1}

Examiner Tips and Tricks

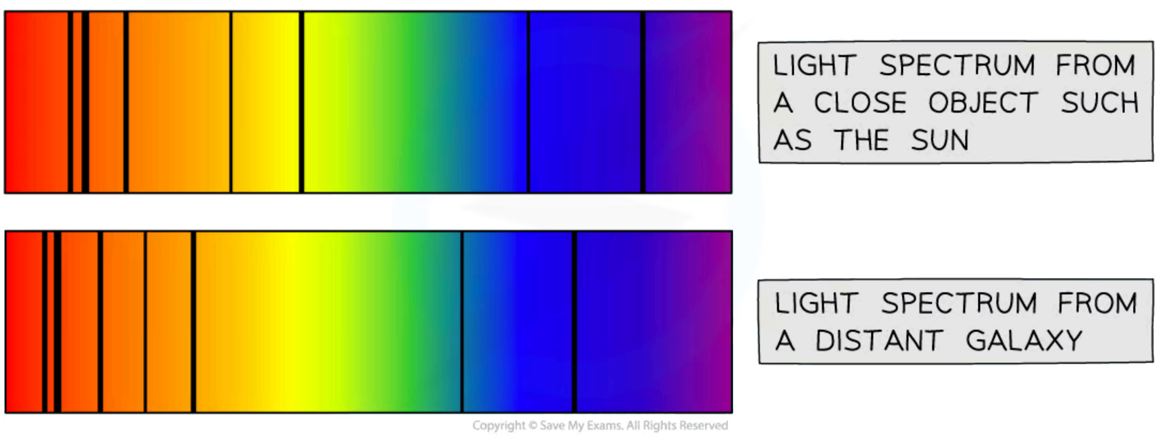
The units for the quantities in Hubble's Law and for the Hubble Constant can change depending on the situation, Make sure you convert them to appropriate units and express your final answer correctly.

Your notes

An Expanding Universe

An Expanding Universe

- Hubble provided evidence from galactic redshift data that the universe is expanding
- Astronomers have concluded that:
  - All galaxies are moving away from the Earth
  - Galaxies are moving away from each other
  - Distant galaxies are receding faster than closer galaxies
- The diagram below shows:
  - **Light** coming to the Earth from a **close object**, such as the Sun,
  - Light coming to the Earth from a **supernovae i**n a **distant galaxy**

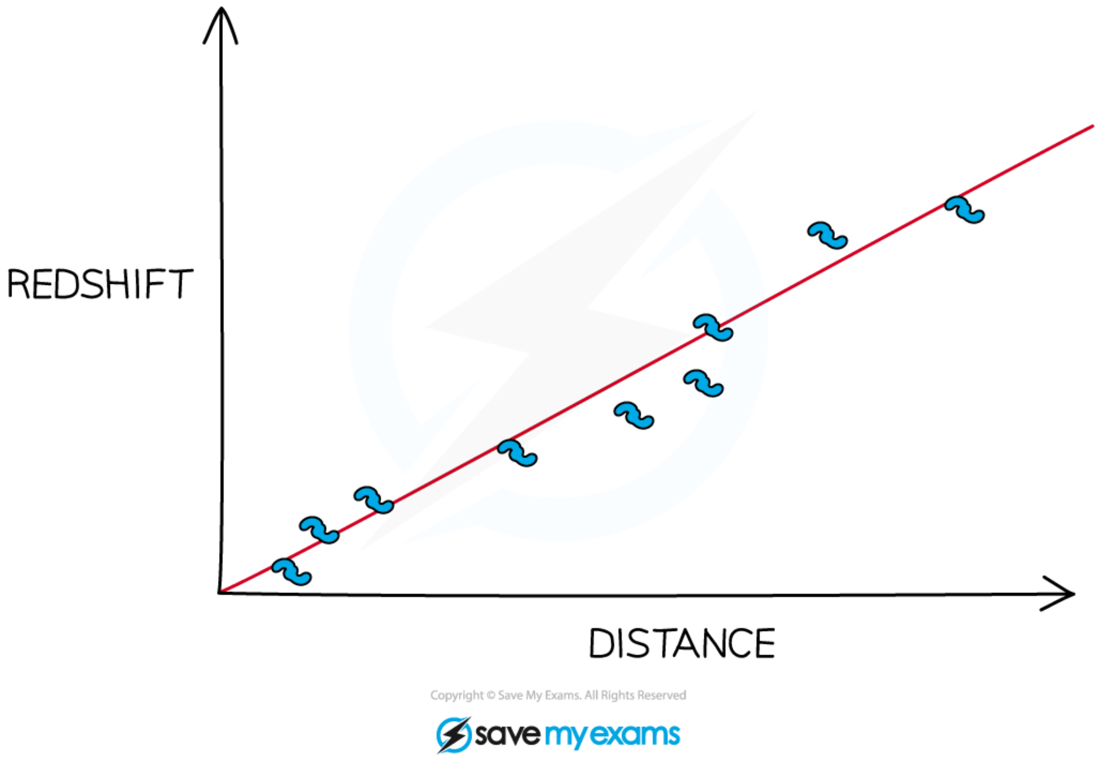


Comparing the light spectrum produced from the Sun and a distant galaxy

- Red-shift is observed when the spectral lines from the distant galaxy move closer to the **red** end of the spectrum
  - This is because light waves are **stretched** by the expansion of the universe so the wavelength increases (or frequency decreases)
  - This indicates that the galaxies are **receding** (moving **away**) from us
- Light spectra produced from **distant** galaxies are red-shifted **more** than **nearby** galaxies
  - This shows that the **greater** the **distance** to the galaxy the **greater** the **redshift**

Your notes

- This means, that the **further away** a galaxy is, the **faster** it is **receding (**moving away) from the Earth

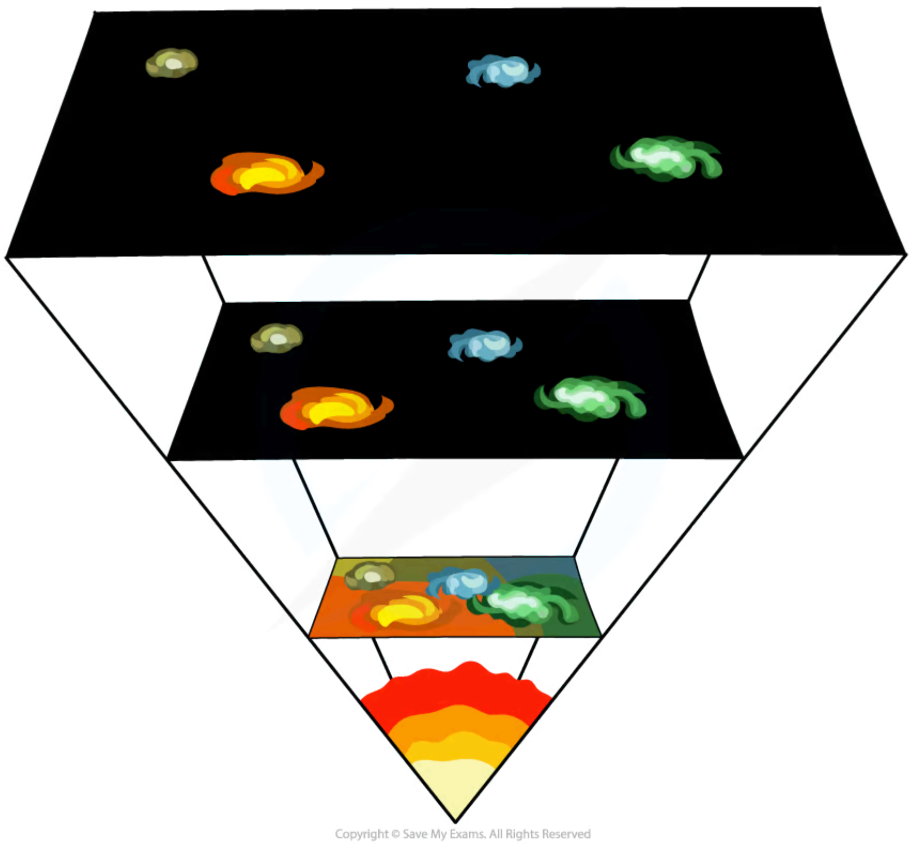


Graph showing the greater the distance to a galaxy, the greater the redshift

- The fact the galaxies are moving further apart is what we would expect after an **explosion**
  - Matter is first **densely packed** and as it explodes it moves out in **all** directions getting further and further from the source of the explosion
  - Some matter will be **lighter** and travel at a **greater** speed, **further** from the source of the explosion
  - Some matter will be **heavier** and travel at a **slower** speed, **closer** to the source of the explosion
- If someone were to **travel back in time** and compare the separation distance of the galaxies:
  - It would be seen that galaxies would become **closer and closer together** until the entire universe was a **single point**
- If **galaxies** were originally all grouped together at a single point and then there was an explosion a similar effect would be observed:
  - The galaxies that are the **furthest** are moving the **fastest**

Your notes

- Their distance, *d*, is proportional to their speed, *v*, as shown by Hubble's law, $v = H_0 d$
- The galaxies that are **closer** are moving **slower**



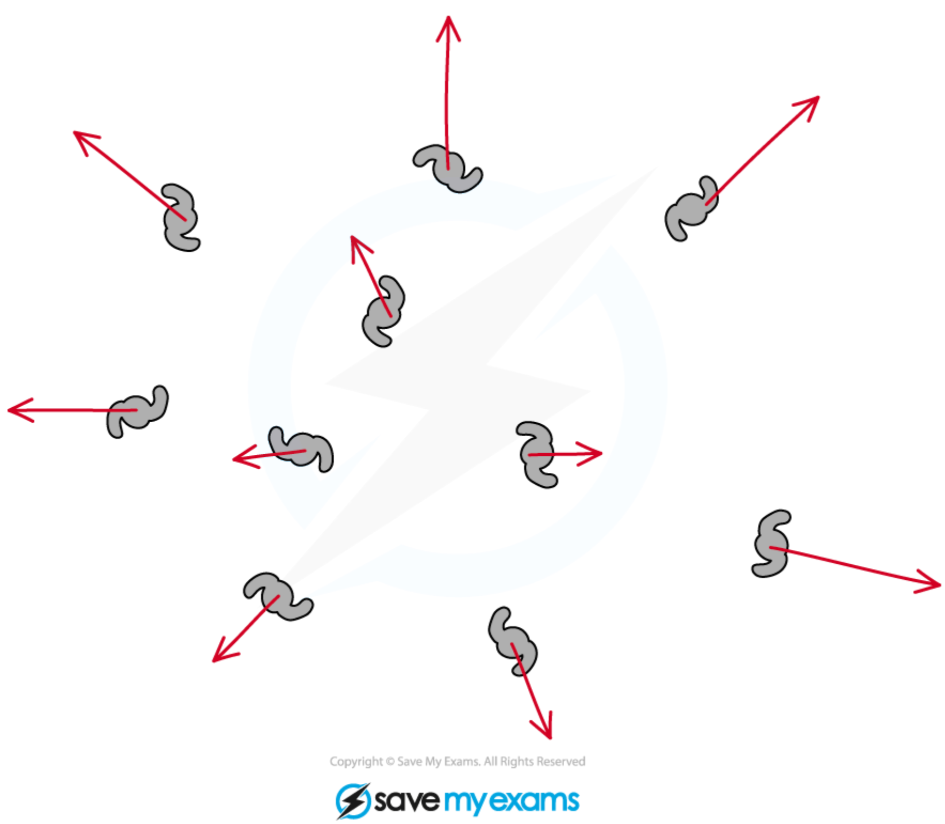
Tracing the expansion of the universe back to the beginning of time leads to the idea the universe began with a "big bang"

Your notes

The Big Bang

The Big Bang Theory

- Around **13.7 billion years ago** the universe was created from a **hot singularity** (a single point) which was infinitely dense, hot and small
- There was a **giant explosion**, which is known as the **Big Bang**
  - Both **space** and **time** were created at this instant
- This caused the universe to **expand** and **cool** from a single point, to form the universe today
- Each point **expands away** from the others
  - This is seen from galaxies moving away from each other
  - The further away they are, the faster they are moving
- As a result of the initial explosion, the Universe **continues to expand**

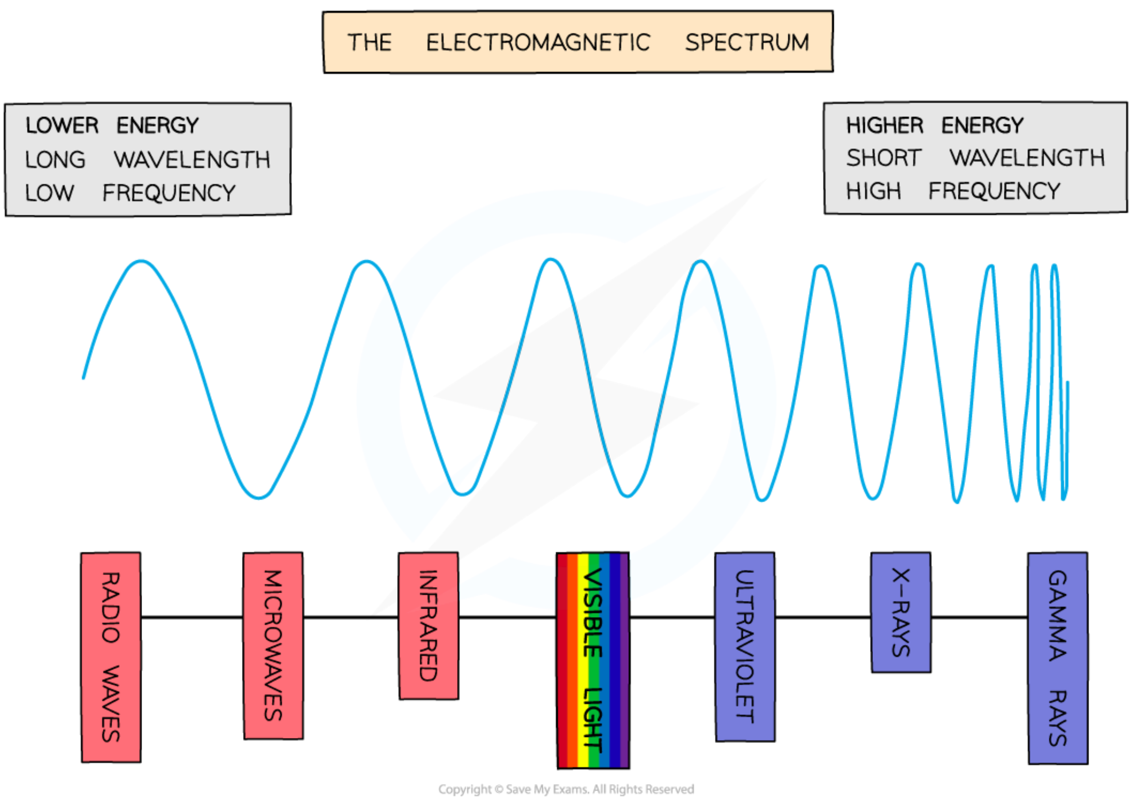


All galaxies are moving away from each other, indicating that the universe is expanding

- There are 2 key pieces of evidence to support the Big Bang theory:
  1. **Hubble's Law** shows the universe is expanding, through the red shift of light from distant galaxies
  2. **Microwave background radiation** provides evidence that the universe has expanded from a **single point** and cooled significantly during the time it has been expanding

Microwave Background Radiation

- After space flight was developed astronomers were able to send telescopes into orbit above the atmosphere
- In 1964, this led to the discovery of radiation in the **microwave** region of the electromagnetic spectrum
  - A microwave has a wavelength of about **1 mm**

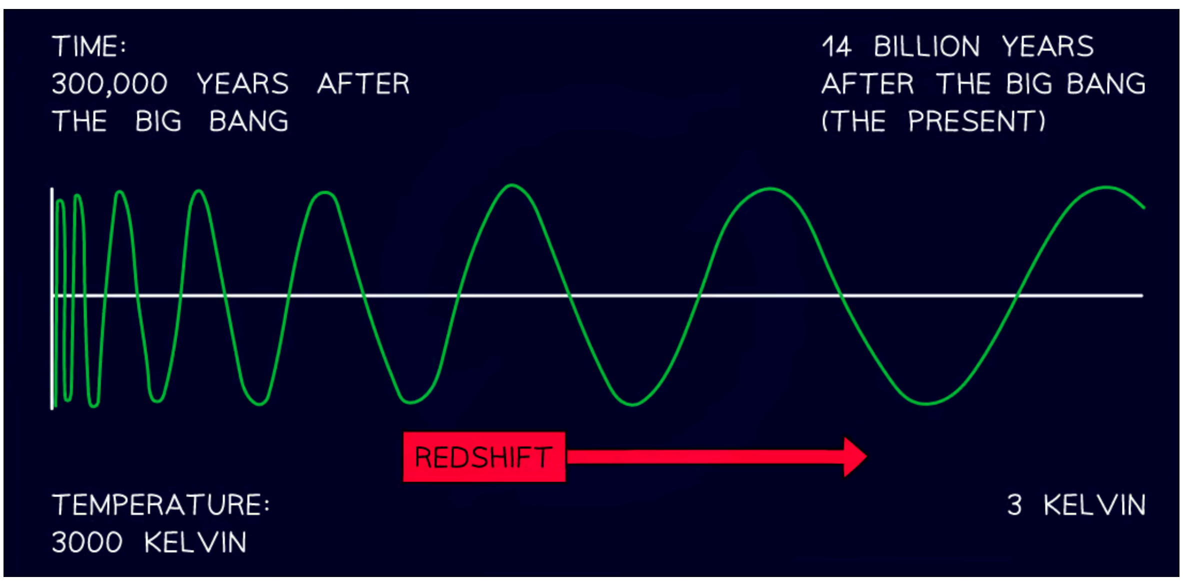


Microwaves have the second-longest wavelength in the electromagnetic spectrum

Your notes

Your notes

- Astronomers were unable to detect these microwaves before the development of space flight since microwaves are **absorbed** by the atmosphere
- The microwave radiation detected came from **all directions** and at a generally **uniform temperature** of **2.73 K**
- Microwave background radiation is a type of electromagnetic radiation which is a remnant from the early stages of the Universe
- According to the Big Bang theory, the early Universe was an extremely **hot** and **dense** environment
  - As a result of this, it must have emitted **thermal radiation**
- This radiation has expanded with the expansion of the universe and is now in the **microwave** region of the EM spectrum
  - Initially, this would have been **high energy** radiation, towards the gamma end of the spectrum
  - This is because over the past 13.7 billion years the radiation initially from the Big Bang has become redshifted as the Universe has expanded
  - As the Universe expanded, the wavelength of the radiation **increased**
  - It has increased so much that it is now in the **microwave** region of the spectrum

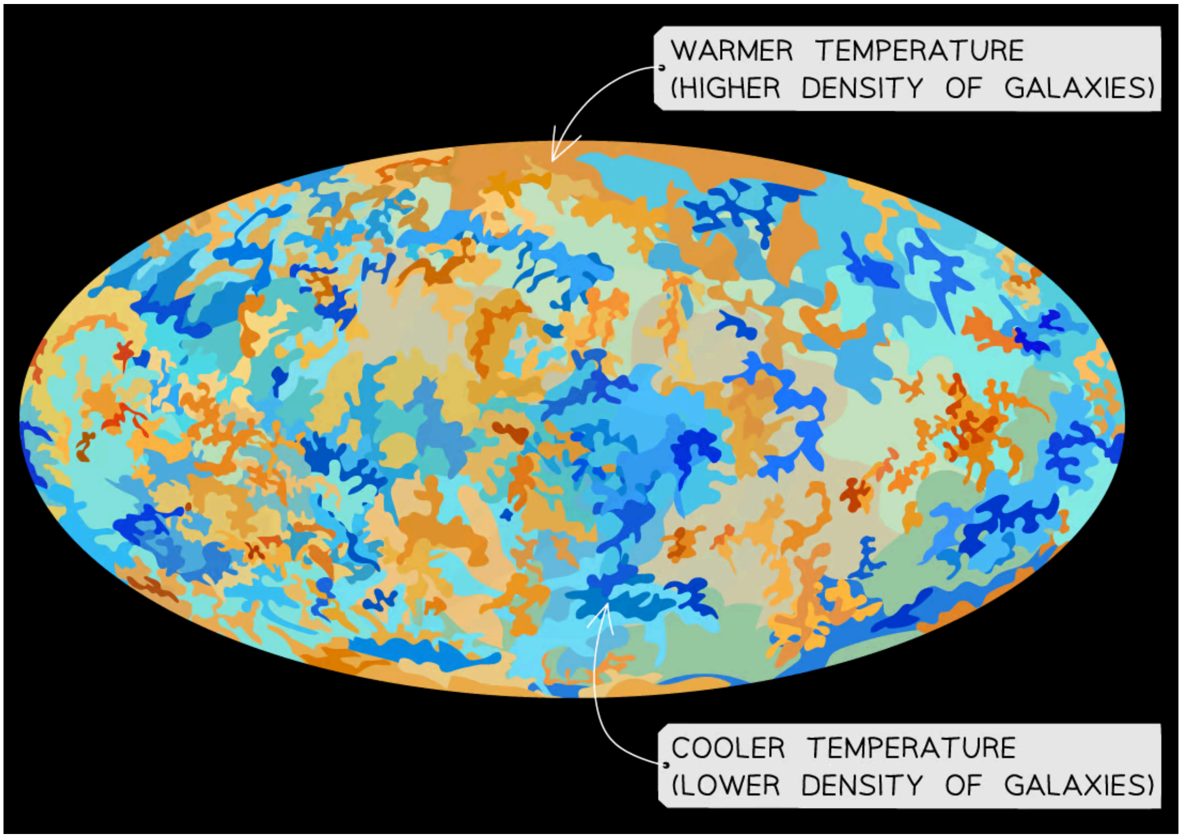


The Microwave Background Radiation is a result of high energy radiation being redshifted over billions of years

- Microwave background radiation is **uniform** and has the exact profile expected to be emitted from a **hot body** that has cooled down over a very long time

Your notes

    - This phenomenon is something that other theories (such as the Steady State Theory) **cannot** explain
- **Microwave background radiation** is represented by a map of the universe



The Microwave Background Radiation map with areas of higher and lower temperature.

- This is the closest image that exists to a map of the Universe
- The different colours represent different temperatures
    - The **red**/orange/brown regions represent **warmer** temperatures indicating a **higher density** of galaxies
    - The **blue** regions represent **cooler** temperatures indicating a **lower density** of galaxies
- The temperature of the microwave background radiation is mostly uniform
    - It has a value of 2.7 ± 0.00001 K
    - This implies that all objects in the Universe are uniformly **spread out**

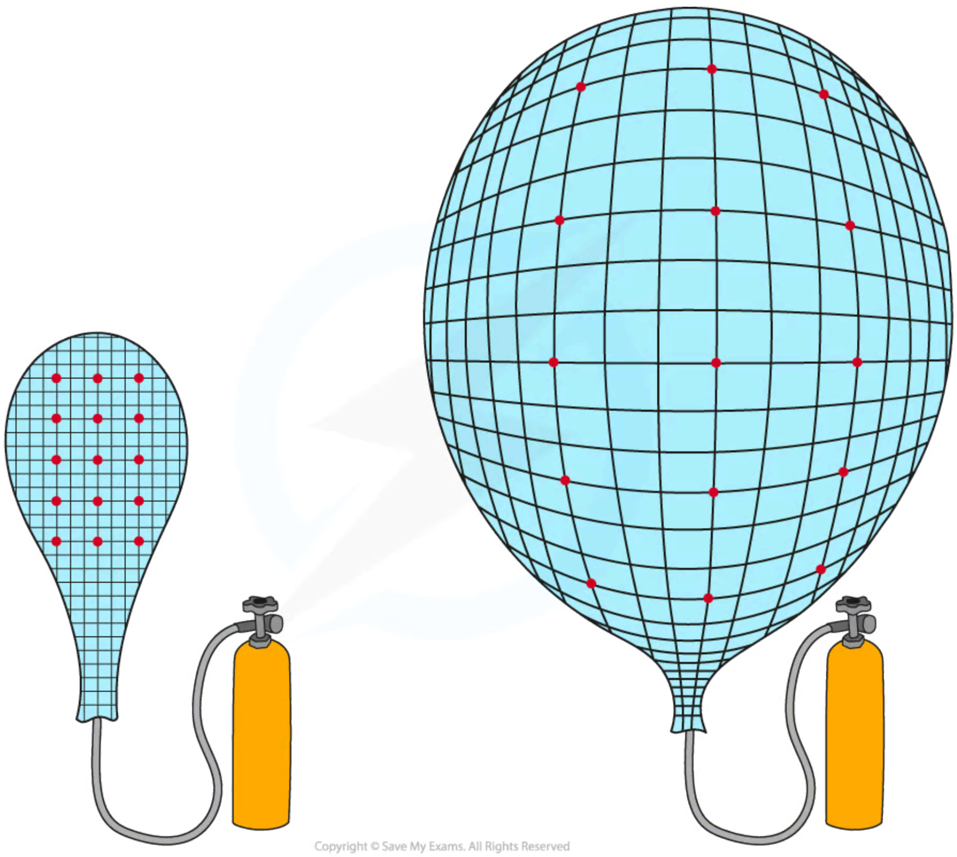
- The discovery of the **microwave background radiation** led to the Big Bang theory becoming the currently accepted model
  - If the universe had not started in a Big Bang then there would be no microwave background radiation
  - If the universe was younger than 13.7 billion years then the temperature would be higher than 2.7 K

Your notes

The Big Bang & Space Time

- Albert Einstein helped develop the idea of space-time as part of his theory of relativity
- **General relativity** states that space and time are connected by a property known as **space-time**
  - Space-time connects the three dimensions of space (the x, y and z-axis) to a fourth dimension, which is time
- The evidence suggests that the Big Bang gave rise to the expansion of space-time about 13.7 billion years ago
- An analogy of this is to draw points on a balloon
  - The balloon represents space and the points represent galaxies
- When the balloon is deflated, all the points are close together and an equal distance apart
- As the balloon expands, all the points become further apart **by the same amount**
- This is because the **space** between the galaxies has expanded
  - The galaxies are not actually moving through space but being carried along as space itself expands

Your notes



A balloon inflating is similar to the stretching of the space between galaxies

- Regardless of which galaxy you observe the universe from, the other galaxies all appear to be moving away from one another by the same amount
- This agrees with the **cosmological principle** which states that the Universe is
  - **Homogeneous** (i.e. matter is uniformly distributed)
  - **Isotropic** (i.e. the Universe is the same in all directions to every observer)

The Age of the Universe

Your notes

Estimating the Age of the Universe

- **Hubble's law** can be used to estimate the age of the universe
- The equation for Hubble's law is:

$$v = H_0 d$$

- **Assuming** the **recessional speed of a galaxy** is **constant** over the history of the universe, we can find the **time** since the expansion began, and hence the age of the universe
  - o We must assume that all points in the universe were initially together
  - o If we know how **far away** a galaxy is from Earth and its **recessional speed**
  - o We can calculate the time taken to get to reach that distance from the Earth
  - o Using the equation:

$$\text{time} = \frac{distance}{speed} = \frac{d}{v}$$

- o We can also rearrange the Hubble equation to give:

$$H_0 = \frac{v}{d}$$

- Therefore:

$$\text{time} = \frac{1}{H_0}$$

- If we say that all matter was at the same point at the very start of the Big Bang (t = 0), then the time taken for the galaxy to move to its current position will be equal to the age of the universe

- Astronomers believe that the universe has been expanding for around **13.7 billion years**

Worked Example

In 2020, the best estimate for the Hubble constant, H_0 was 67.4 km s^{-1} Mpc^{-1}. Use this value to calculate the age of the universe.

Answer:

Step 1: List the known quantities

- H_0 = 67.4 km s^{-1}Mpc^{-1}

Step 2: Use data booklet

- 1 parsec ≈ 3.1 x 10^{16} m
- 1 year = 3.16 x 10^{7} s
- t = H$_0^{-1}$

Step 3: Convert 67.4 km s^{-1} Mpc^{-1} to m s^{-1} Mpc^{-1}

- 67.4 km s^{-1}Mpc^{-1} = 67.4 x 1000 = 6.74 x 10^{4} m s^{-1} Mpc^{-1}

Step 4: Convert 1 Mpc to m

- 1 Mpc = (3.1 x 10^{16}) x (1 x 10^{6}) = 3.1 x 10^{22} m

Step 5: Convert 6.74 x 10^{4} m s^{-1} Mpc^{-1} to s^{-1}

- 6.74 x 10^{4} m s^{-1} Mpc^{-1} = $\frac{6.74 \times 10^4}{3.1 \times 10^{22}}$ = 2.17 x 10^{-18} s^{-1}
- Hence, H$_0$ = 2.17 x 10^{-18} s^{-1}

Step 6: Calculate the age of the universe

- t = $\frac{1}{H_0}$ = $\frac{1}{2.17 \times 10^{-18}}$ = 4.60 x 10^{17} s

Step 7: Convert 4.60 x 10^{17}s to years

- Age of the universe = $\frac{4.60 \times 10^{17}}{3.16 \times 10^{7}}$ = 1.46 x 10^{10} years = 14.6 billion years

Your notes

Your notes

Evolution of the Universe

The Evolution of the Universe

- There are many different stages in the evolution of the universe
  - As the **time** from the Big Bang **increases** the **temperature** of the universe **decreases**
- The key stages of evolution are:
  - **Stage 0:** The Big Bang
  - **Stage 1:** Big Bang → 10^{-35} s after the Big Bang
  - **Stage 2:** 10^{-35} s after the Big Bang → 10^{-6} s after the Big Bang
  - **Stage 3:** 10^{-6} s after the Big Bang → 225 s after the Big Bang
  - **Stage 4:** 225 s after the Big Bang → 1000 years after the Big Bang
  - **Stage 5:** 1000 years after the Big Bang → 3000 years after the Big Bang
  - **Stage 6:** 3000 years after the Big Bang → 300 000 years after the Big Bang
  - **Stage 7:** 300 000 years after the Big Bang → Present

Stage 0

- This is when the Big Bang occured
- At this point, time and space are created
- The universe is infinitely dense, hot and small, a **hot singularity**

Stage 1

- Just after the Big Bang → 10^{-35} s after the Big Bang
- The universe expands **rapidly**
  - This is known as **inflation**
- There is **no matter**, only **high energy gamma photons** and electromagnetic radiation

Stage 2

- This is from 10^{-35} s after the Big Bang → 10^{-6} s after the Big Bang
- Building block particles come into existence (**quarks**, leptons, photons, and their antiparticles)

Your notes

- These particles cannot form heavier particles (protons and neutrons) because of the **high temperatures** present
- There is slightly more **matter** than **antimatter**
  - As matter and antimatter **annihilate**, they leave a matter-dominated universe made from particles and not antiparticles

Stage 3

- This is from 10^{-6} s after the Big Bang → 225 s after the Big Bang
- As the universe cools **protons** and **neutrons** begin to form from quarks
- Matter and antimatter continue to collide and **annihilate**
  - Producing enormous quantities of **high-energy photons**
  - These are continually absorbed and re-emitted as they interact with charged particles

Stage 4

- This is from 225 s after the Big Bang → 1000 years after the Big Bang
- As the universe continues to **cool** it behaves in the same way as the core of a star
- Nuclear **fusion** begins
  - Protons and neutrons fuse to form light nuclei like deuterium, helium and lithium
- Matter is in **plasma** form
  - A state in which protons and electrons are not bound to one another because of high temperatures
- **Rapid expansion** of the universe continues until 25% of matter is helium nuclei

Stage 5

- This is from 1000 years after the Big Bang → 3000 years after the Big Bang
- At this time, nuclear fusion ends
- **Electrons** are formed

Stage 6

- This is from 3000 years after the Big Bang → 300 000 years after the Big Bang
- The universe continues to cool and electrons combine with nuclei to form hydrogen and helium **atoms**
- In **decoupling** more electrons become attached to protons
  - Radiation and matter separate from each other

Your notes

- Photons travel freely through space
- The universe becomes transparent
- Photons now become the **microwave background radiation** that we detect today

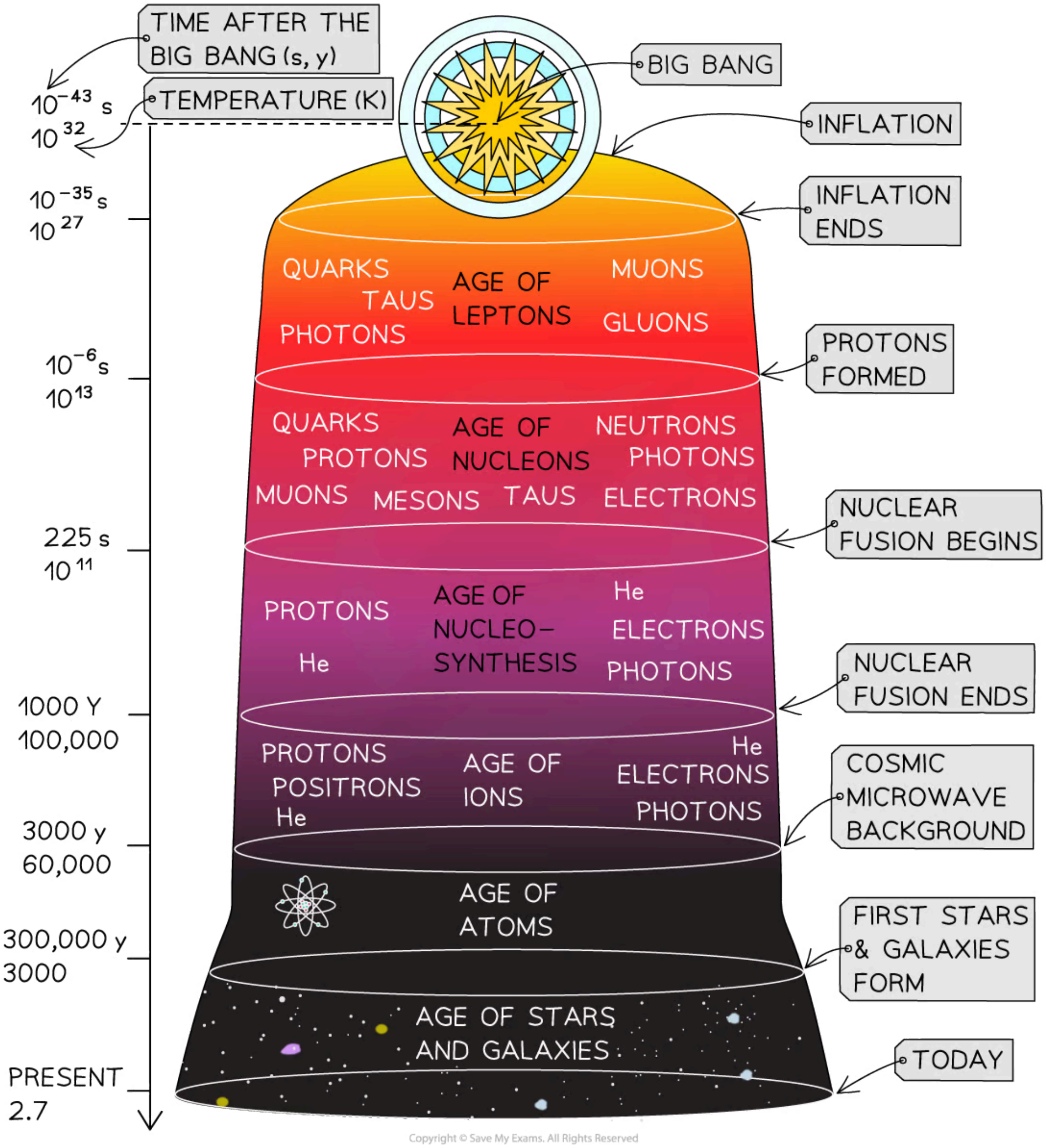
Stage 7

- This is from 300 000 years after the Big Bang → Present
- After about 30 million years, the first **stars** form
- **Galaxies** begin to form from tiny density fluctuations because of gravitational forces pulling together clouds of hydrogen and existing stars
- Billions of years later, heavy elements form from the gravitational collapse of stars
- After approximately 9 billion years the **solar system** forms from a supernova nebula
  - Our **Sun** is formed at the centre of the nebula
  - **Earth** is formed almost 1 billion years later
- Approximately 11 billion years after the Big Bang, **primitive life** begins on Earth
- **13.7 billion** years after the Big Bang, the first modern humans evolve

Your notes

	Time after the Big Bang	Nature of the Universe
DECREASING TEMPERATURE	The Big Bang	Time and space are created. The Universe is a singularity – it is infinitely dense and hot.
	10^{-35} s	The Universe expands rapidly, including a phase of incredible acceleration known as inflation. There is no matter in the Universe – instead it is full of electromagnetic radiation in the form of high – energy gamma photons. The temperature is about 10^{28} K.
	10^{-6} s	The first fundamental particles (quarks, leptons, etc.) gain mass through a mechanism that is not fully understood but involves the Higgs boson (discovered in 2013).
	10^{-3} s	The quarks combine to form the first hadrons, such as protons and neutrons. Most of the mass in the Universe was created within the first second through the process of pair production (high–energy photons transforming into particle–antiparticle pairs).
	1 s	The creation of matter stops after about 1 s, once the temperature has dropped to about 10^{9} K.
	100 s	Protons and neutrons fuse together to form deuterium and helium nuclei, along with a small quantity of lithium and beryllium. The expansion of the Universe is so rapid that no heavier elements are created. During this stage, about 25% of the matter in the Universe is helium neclei (known as primordial helium).
DECREASING TEMPERATURE	380 000 years	The Universe cools enough for the first atoms to form. The nuclei capture electrons. The electromagnetic radiation from this stage of the Universe is what can be detected as microwave background radiation.
	30 million years	The first stars appear. Through nuclear fusion in these stars the first heavy elements (beyond lithium) begin to form.
	200 million years	Our galaxy, the Milky Way, forms, as gravitational forces pull clouds of hydrogen and existing stars together.
	9 billion years	The Solar System forms from the nebula left by the supernova of a larger star. After the Sun forms the remaining material forms the Earth and other planets (around 1 billion years later). It is thought that around 1 billion years after the formation of the Earth (11 billion years after the Big Bang) primitive life on Earth begins.
	13.7 billion years (now)	Around 200 000 years ago the first modern humans evolve, and eventually study physics. The temperature of the Universe is 2.7 K.

Your notes


TIME AFTER THE BIG BANG (s, y)
TEMPERATURE (K)
10^{-43} s
10^{32}
10^{-35} s
10^{27}
10^{-6} s
10^{13}
225 s
10^{11}
1000 Y
100,000
3000 y
60,000
300,000 y
3000
PRESENT
2.7
BIG BANG
INFLATION
INFLATION ENDS
PROTONS FORMED
NUCLEAR FUSION BEGINS
NUCLEAR FUSION ENDS
COSMIC MICROWAVE BACKGROUND
FIRST STARS & GALAXIES FORM
TODAY
QUARKS
TAUS
PHOTONS
AGE OF LEPTONS
MUONS
GLUONS
QUARKS
PROTONS
AGE OF NUCLEONS
NEUTRONS
PHOTONS
MUONS
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ELECTRONS
PHOTONS
AGE OF ATOMS
AGE OF STARS AND GALAXIES
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Your notes

Dark Energy & Dark Matter

Dark Energy & Dark Matter

Dark Energy

- Scientists know that the universe is **accelerating** as it expands
- **Dark Energy** is a hypothetical form of energy which is used to try and explain the accelerating expansion
- Dark energy is defined as:

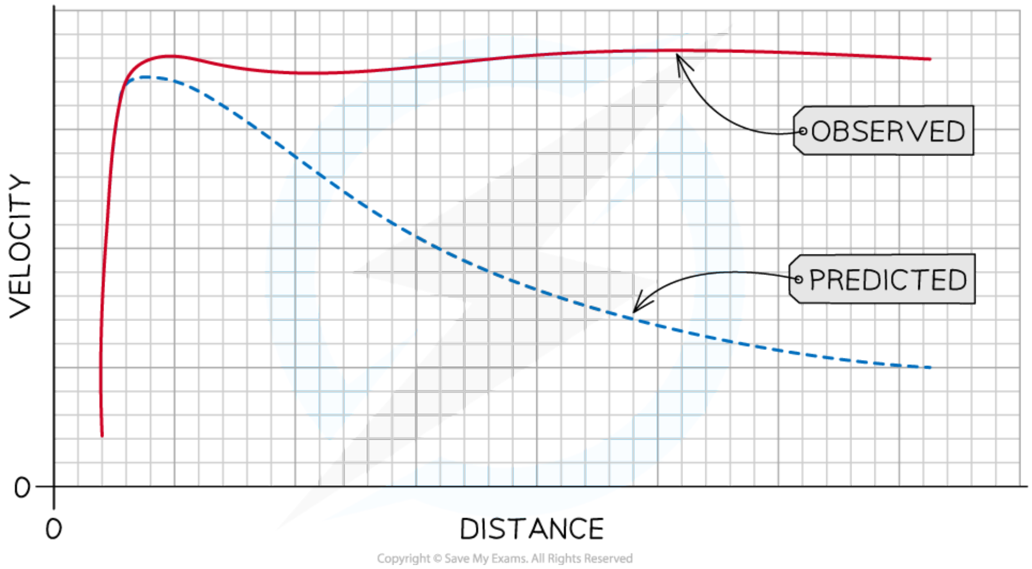
  A type of energy that permeates the whole universe and opposes the attractive gravitation force between galaxies via the exertion of a negative pressure

- Dark energy cannot be detected directly
  - It should make up 68% of the total energy in the universe
  - So far experiments have not been able to find the form of the energy

Dark Matter

- Astronomers expect to observe the **velocity** of an object within a galaxy **decrease** as it moves away from the galaxy's centre
  - This is thought to be the case because of weakening gravitational field strength further from the centre
- This is observed in smaller mass systems, such as the in the solar system, where planets orbiting **furthest** from the Sun have the **slowest orbital velocity**
  - This is not the case in larger mass systems, such as entire galaxies

Your notes



- In fact, mass is not concentrated in the centre of galaxies - it is **spread out**
- However, all the observable mass of a galaxy is observed to concentrate in the centre of galaxies
  - Therefore, there must be another type of matter that can't be observed
  - This is known as **Dark Matter**
- Dark matter is defined as:

  Matter which cannot be seen and that does not emit or absorb electromagnetic radiation
- Dark matter cannot be detected directly through telescopes
  - It is estimated to make up 27% of the mass in the universe
  - It is detected based on its gravitational effects relating to either the **rotation of galaxies** or by the **gravitational lensing** of starlight