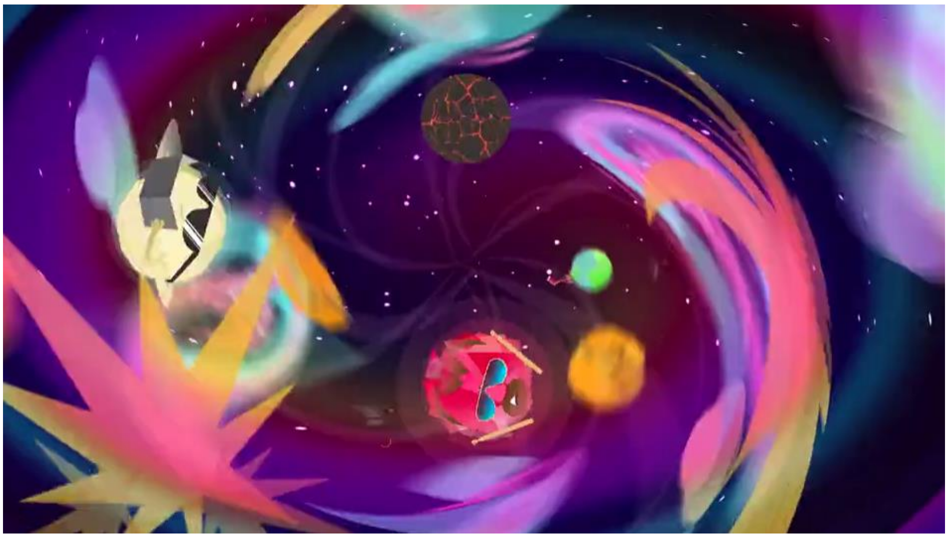
What did the early Universe look like?

Key Stage 5

Topics covered: Cosmic Microwave Background Radiation, Wien's displacement law, Doppler Effect

Watch the video "What makes the Universe colourful?"
https://vimeo.com/213990458



Scientists theorise that the Universe began with the Big Bang around 13.8 billion years ago. Space has been expanding ever since and the initial Big Bang energy has spread out. As a result the temperature of the Universe has fallen and the wavelength of light has stretched out.

The history of the Universe can be split into different epochs – see the handout 'TIMELINE OF THE UNIVERSE'. If we treat the Universe as a black body* then we can work out the peak wavelength of light travelling through the Universe at different epochs by using **Wien's law**:

$$\lambda_{max} = \frac{2.898 \times 10^{-3}}{T}$$

λ_{max} – peak wavelength emitted by the black body (m - metres)
T – temperature of the black body (K – Kelvin)

* A black body is an ideal case of an object or system which perfectly absorbs and emits radiation and light and does not reflect any of it.

1. Use the 'TIMELINE OF THE UNIVERSE' handout to help.

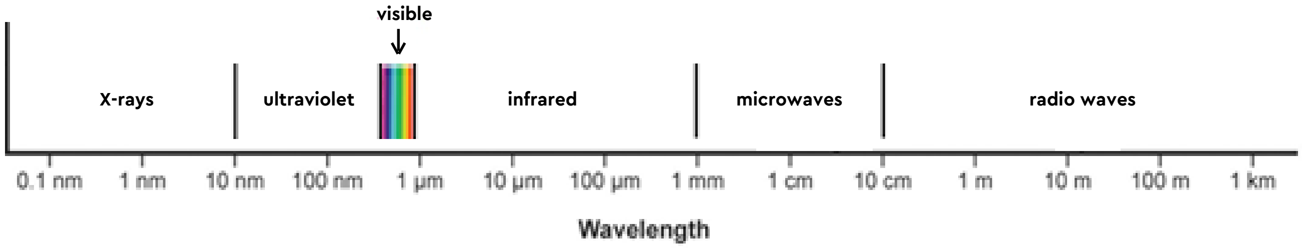
   For each of the following epochs:

   - **350,000 years** (t_1 - near the end of the photon epoch)
   - **380,000 years** (t_2 - at recombination)
   - **13.8 billion years** (t_3 - present day)

   a) Complete the table below to work out the peak wavelength (λ_{max}) of light that would be travelling through the Universe at that time.

	epoch	Temperature	Peak wavelength
t_1	**350,000 years**		
t_2	**380,000 years**		
t_3	**13.8 billion years**		

   b) Mark these three wavelengths (as vertical lines / arrows) on the diagram below as t_1, t_2 and t_3.

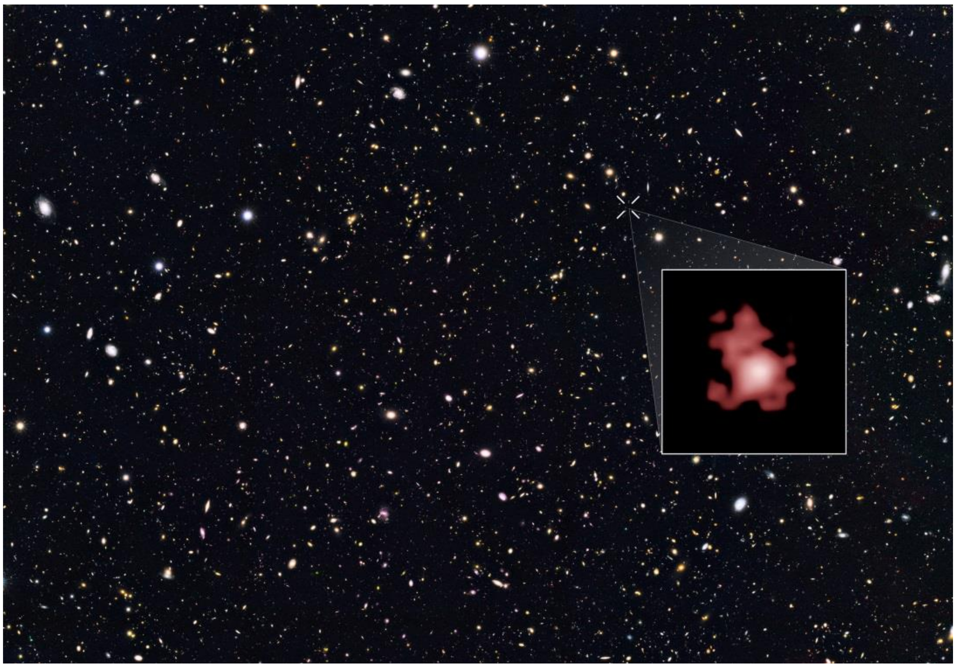


2. "Billions of years ago when the Universe was much smaller, this Big Bang energy would have been in the visible range and for a short time the Universe would have been filled with colour, it's a shame we weren't around to see it! "
   (Video - What makes the Universe Colourful? at 3:00 mins).

   Even if we had existed in the very early Universe why would we still not have been able to see the Universe filled with colour?

HINT – Which epoch came before recombination – what was this epoch like?
What's the difference between opaque and transparent?

The most distant galaxy seen is GN-Z11. It was discovered in 2016 by the Hubble Space Telescope's wide field camera 3. Looking at a part of the sky known as the GOODS North Field, it collected spectroscopic data from this extremely distant galaxy.



Credit: NASA/ESA/G. Bacon (STScI) GN-Z11

3. The hydrogen gas in this galaxy is absorbing a particular wavelength of light. This is happening because electrons in the hydrogen atoms are absorbing energy from nearby stars and so they transition to a higher energy state before falling back to a lower energy state. Due to this absorption, a dark line appears on the continuous spectrum of light from the galaxy.

   The electronic transition in this galaxy is known as the Lyman-alpha transition. Hydrogen atoms absorb light with a wavelength of 121nm. But, because the galaxy is receding (moving away from us), scientists measured the wavelength to be 1470nm instead.

$$z = \frac{v}{c} = \frac{\lambda - \lambda_{obs}}{\lambda}$$

z – redshift
c – speed of light (3 x 10^8 ms^{-1})
v – recessional velocity of the galaxy (ms^{-1} – metres per second)
λ – rest wavelength (m – metres)
λ_{obs} – observed wavelength (m – metres)

3. a) Use the Doppler equation to work out the redshift of this galaxy. What are the units?

   b) How do you think GN-Z11 got its name?

4. This redshift corresponds to a distance of 13.4 billion light years. This is the time it has taken its light to reach us. However the proper distance to this galaxy is actually 32 billion light years. Why is this?

5. This galaxy was around just 400 million years after the Big Bang. Use the 'TIMELINE OF THE UNIVERSE' handout to help you answer the following questions.

   a) Which epoch would this galaxy have been observed in?

   b) Why were astronomers surprised by the observation of this galaxy?

TIMELINE OF THE UNIVERSE

The Big Bang → Today

Epoch	Description	Time	Temperature
Planck epoch	The time when quantum effects dominated over classical physics. Before this time any measurement would be so small it would have no meaning. The closest we can get to the beginning of time.	$< 10^{-43}$ s	$> 10^{32}$ K
Inflationary epoch	Cosmic inflation occurs – expanding space very rapidly causing the Universe to supercool.	$< 10^{-32}$ s	$10^{28} \rightarrow 10^{22}$ K
Quark epoch	Quarks, electrons and neutrinos form. Quarks and antiquarks annihilate but a surplus of quarks is left (one remains for every billion annihilations).	$> 10^{-12}$ s	10^{12} K
Hadron epoch	Quarks can now combine to form hadrons (like protons and neutrons).	$10^{-6} \rightarrow 1$ s	10^{11} K
Big Bang nucleosynthesis	Protons and neutrons combine to form nuclei of hydrogen, helium and lithium.	$10 \rightarrow 10^{3}$ s	$10^{11} \rightarrow 10^{9}$ K
Photon epoch	It's still too hot for electrons to bind to nuclei so the Universe is a 'sea' or plasma of nuclei, electrons and photons – it is opaque.	10^{3} s → 380,000 yrs.	$10^{9} \rightarrow 10^{4}$ K
Recombination	Electrons and atomic nuclei can now combine to form neutral atoms. The Universe becomes transparent to photons – light was finally free to move through space. This is the earliest epoch observable today and the photons of the CMBR originate from this time.	380,000 yrs.	4000 K
Dark ages	The time between recombination and the formation of the first stars that would light up the dark Universe.	380,000 → 150 million yrs.	4000 → 60 K
Reionisation	The first quasars (very luminous active galaxies) form from gravitational collapse and the strong radiation they emit reionises the material in the surrounding Universe.	150 million → 1 billion yrs.	60 K → 19 K
Galaxy formation and evolution	Galaxies form and coalesce eventually forming galaxy clusters and superclusters.	1 → 10 billion yrs.	19 K → 4 K
Dark energy dominated era	The density of matter falls below the density of dark energy leading to the acceleration of the expansion of space.	> 10 billion yrs.	< 4 K
Present time	The expansion of the Universe means that the observable Universe is 46 billion light-years in radius. It's defined by the farthest observable photons (CMBR photons) which originated at recombination.	13.8 billion yrs.	2.7 K

What did the early Universe look like: ANSWERS

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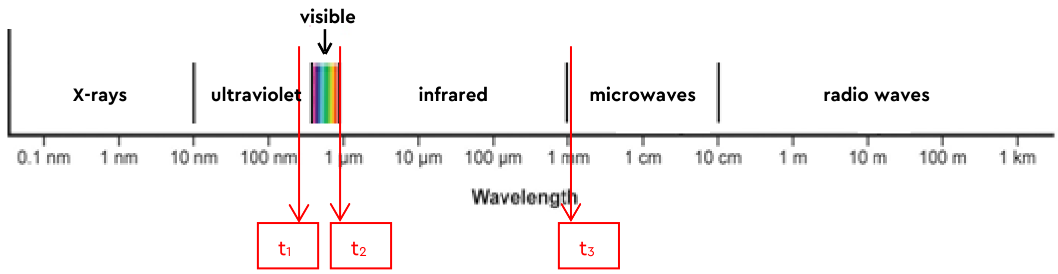
1. a)

	epoch	Temperature (K)	Peak wavelength	
t_1	**350,000 years**	$10^4\ K$	289.8 nm	$289.8 \times 10^{-9}\ m$
t_2	**380,000 years**	$4000\ K$	0.7 µm	$0.7 \times 10^{-6}\ m$
t_3	**13.8 billion years**	$2.7\ K$	1.1 mm	$1.1 \times 10^{-3}\ m$

b)



2. - After the Big Bang, radiation (light) stretched out from shorter to longer wavelengths as the Universe expanded and cooled.
   - It took time for the Universe to cool enough for neutral atoms to form.
   - When neutral atoms formed (recombination) light could finally travel through space freely.
   - Humans can only detect visible light (400 – 700 nm).
   - The early Universe was opaque because light could not travel freely.
   - Once light was able to travel freely it had stretched to longer wavelengths (infrared) which can't be detected by humans.

3. a) Z = 11.1
   Redshift has no units.

   b) This galaxy was observed in a part of the sky known as the **G**OODS **N**orth Field and its redshift was calculated as **Z** = **11**.1.
   It was therefore named **GN-Z11.**

4. The light we are observing set off from this galaxy 13.4 billion years ago. But the Universe is expanding. GN-Z11 has therefore been moving away from us (as space expands) over the past 13.4 billion years while its light was travelling towards us. The galaxy <u>is now</u> 32 billion light years away and may not even exist anymore.

5. a) Near the beginning of the reionisation era.

   b) They were surprised because this galaxy existed just after the first stars formed. It was thought that galaxies began forming about 1 billion years after the Big Bang. Finding galaxies forming so soon after the Big Bang challenges our current theoretical models of how galaxies form and the evolution of the Universe.