Our Place in the Cosmos

The Science of Space:

‘A Physicists Guide to the Galaxy’

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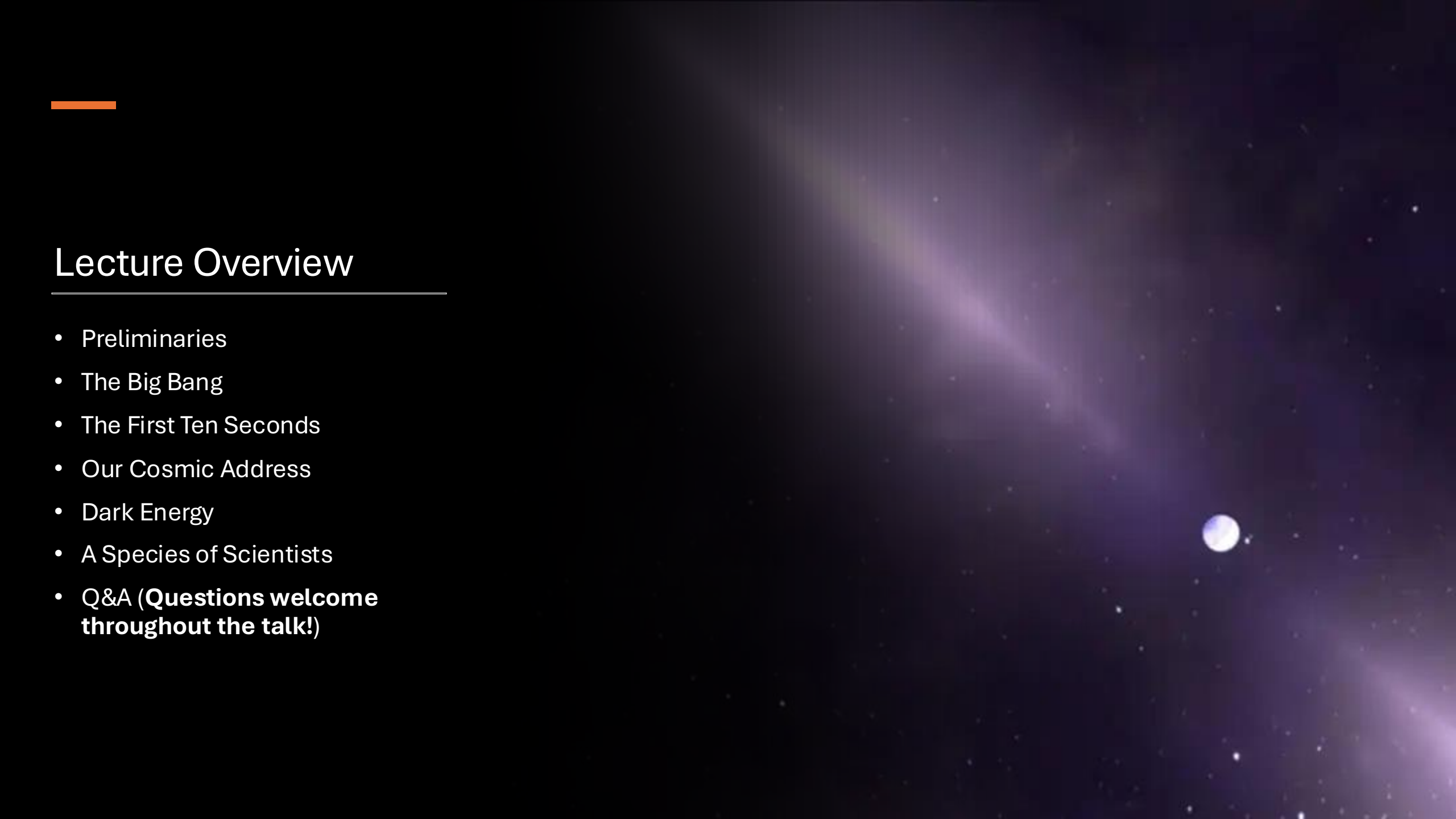
(Sussex U & Royal Holloway UoL)

Southend Planetarium – 04.05.2025

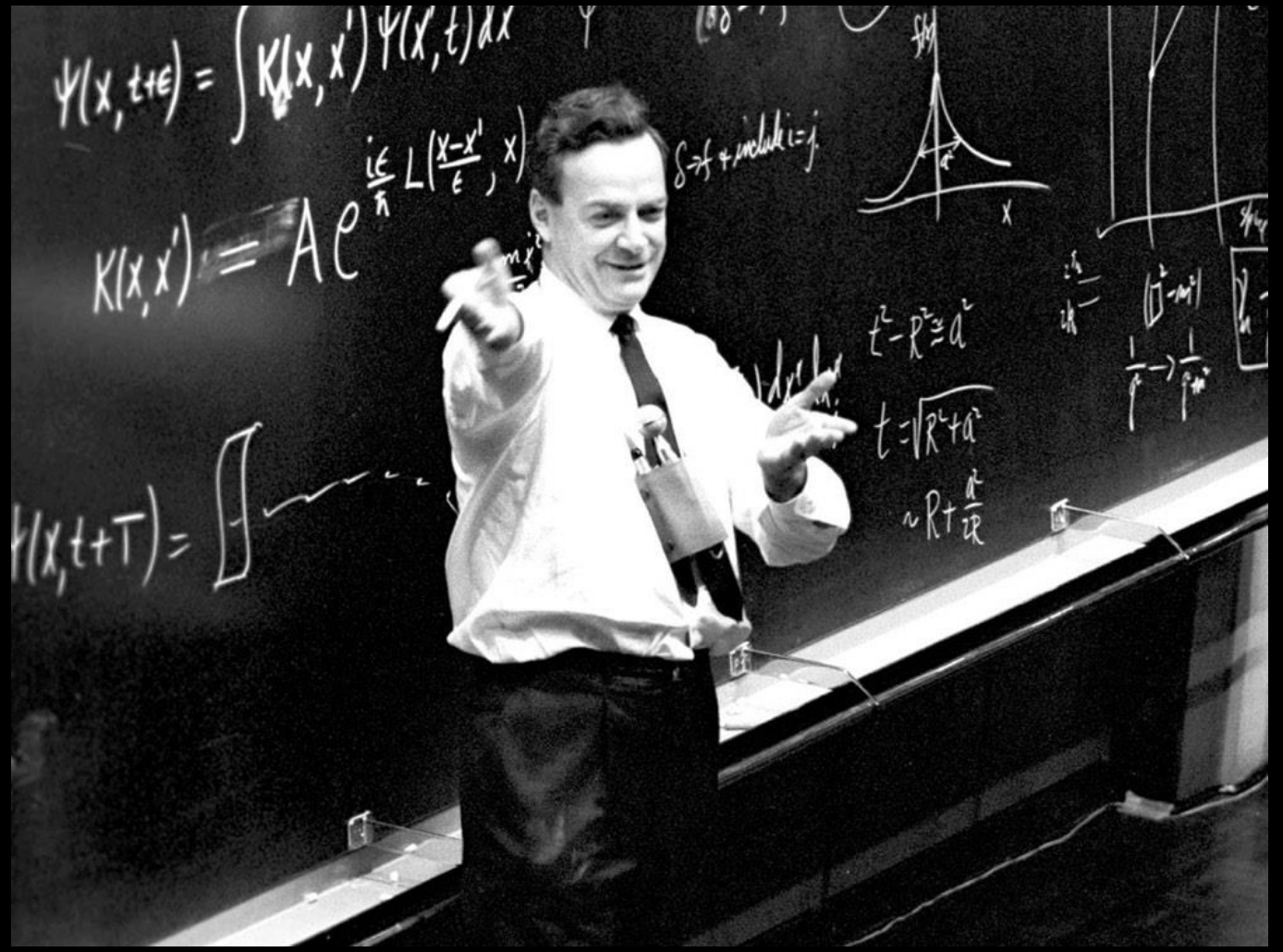
Lecture Overview

- Preliminaries
- The Big Bang
- The First Ten Seconds
- Our Cosmic Address
- Dark Energy
- A Species of Scientists
- Q&A (**Questions welcome throughout the talk!**)



Preliminary Lessons

1. What is Cosmology?
2. Very big numbers
3. Very small numbers
4. Distances in Cosmology
5. Matter and Anti-Matter

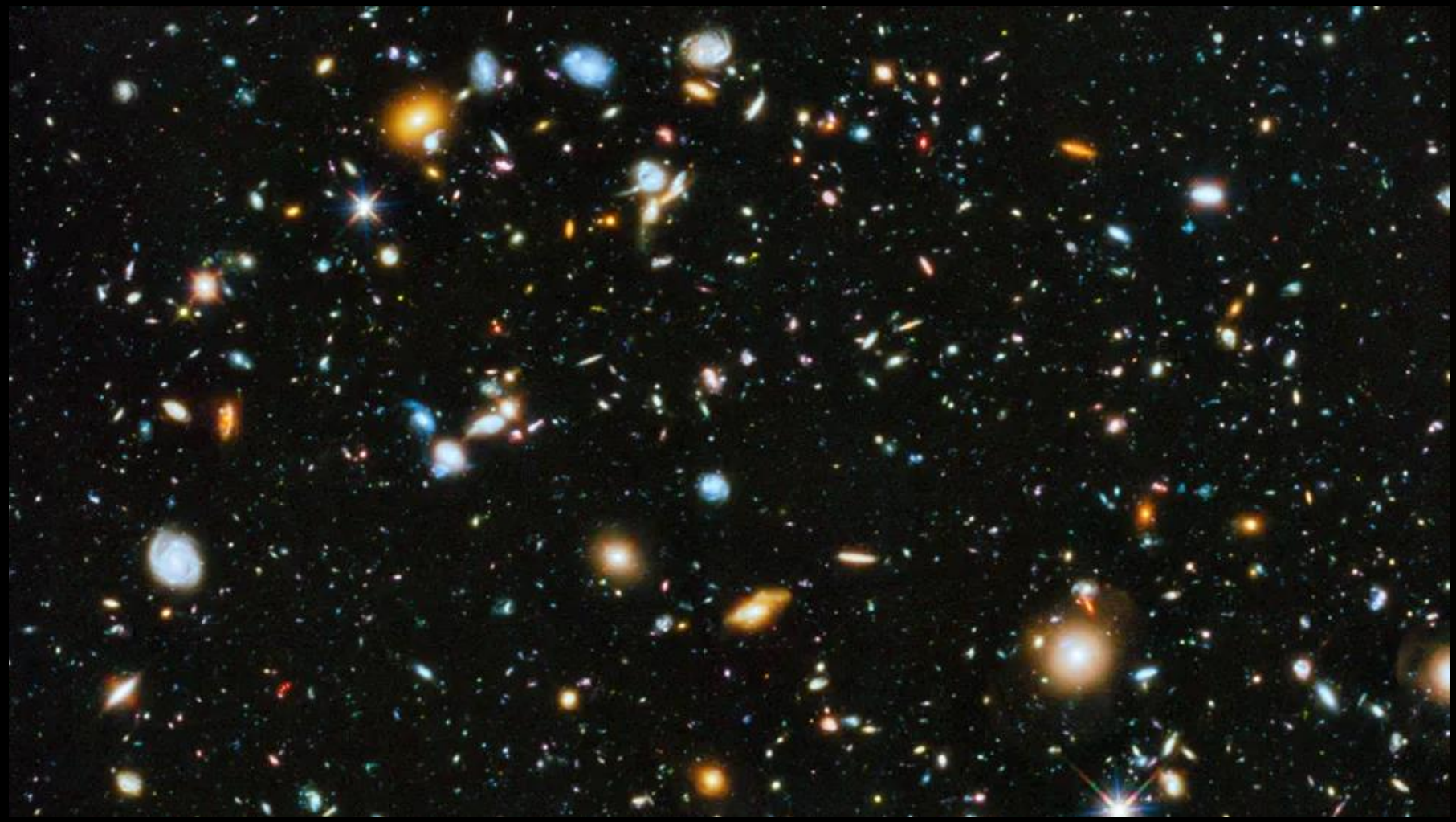


Richard Feynman. The ‘Physicists Physicist’, and teacher extraordinaire.

1. What is Cosmology?

Cosmology is the study of the Universe *as a whole*.

Cosmologists don’t study stars and galaxies at an individual level; instead considering the entire Universe as a single system.



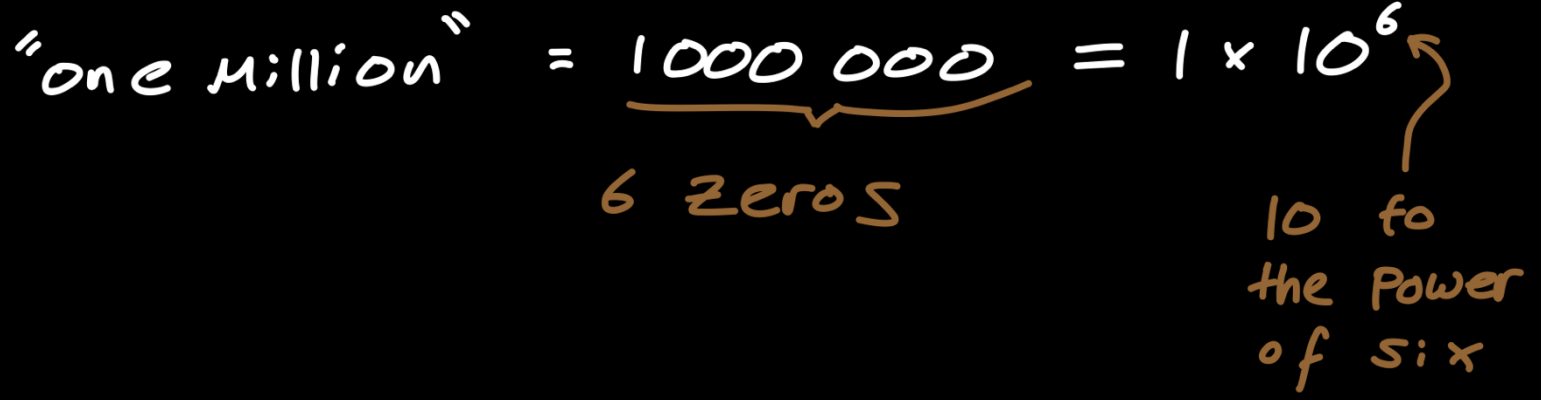
An image from the Hubble telescope’s *Ultra Deep Field*. An image of the sky, displaying nearly 10,000 galaxies in an area of the night sky no more than one tenth of a full moon, showing 12 billion years of the Universe’s history.

2. Very **Big** Numbers

Cosmology deals with the largest scaled imaginable.

It's therefore handy to have a way of writing very very big numbers, without using up all our chalk writing zeros.

The notation we use for writing very huge numbers is called '*Standard Form*'.



Count how many jumps to the **right** you make from where you would like to put the decimal point, and put that number as a power of ten.

3. Very **Small** Numbers

"one millionth" = 0.000001 = 1×10^{-6}

6 zeros

10 to the power of minus six

Surprisingly, we will also need a way to describe very tiny numbers.

This will be most useful for our discussion of the early Universe, tiny fractions of a second after the Big Bang.

This notation is still called standard form and works in much the same way.

"Zero point zero, zero, zero six two"

4 jumps left

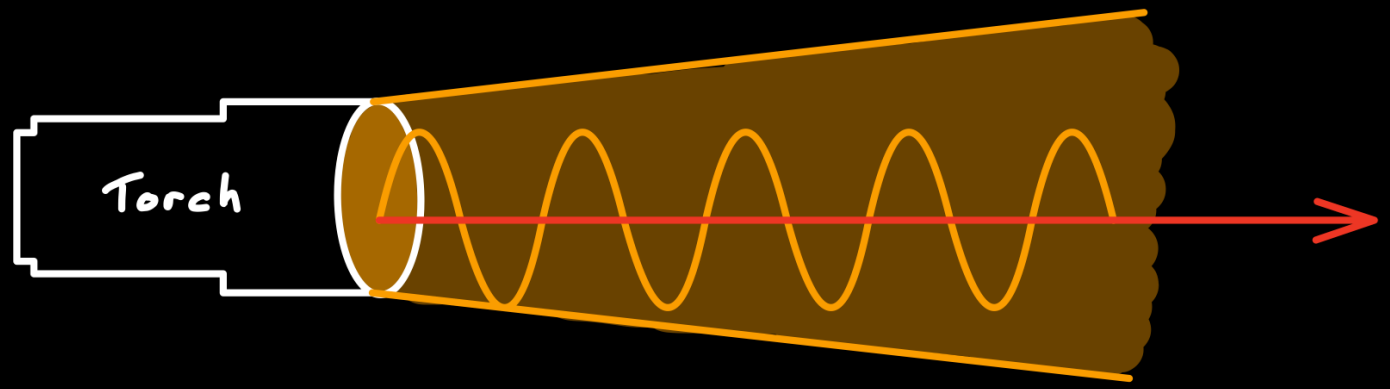
= 0.00062 = 6.2×10^{-4}

Count how many jumps to the **left** you make from where you would like to put the decimal point, and put minus that number as a power of ten.

4. Distances in Cosmology

Light is fast

A *light-year* is not a duration of time, but a unit of distance.



One light-year (abbreviated to LY) is the distance travelled by light moving through empty space in one year.

Speed = 300,000,000 Metres Per second

or 670,000,000 Miles Per hour

or 190,000 Miles Per hour

4. Distances in Cosmology

A *light-year* is not a duration of time, but a unit of distance.

One light-year (abbreviated to LY) is the distance travelled by light moving through empty space in one year.

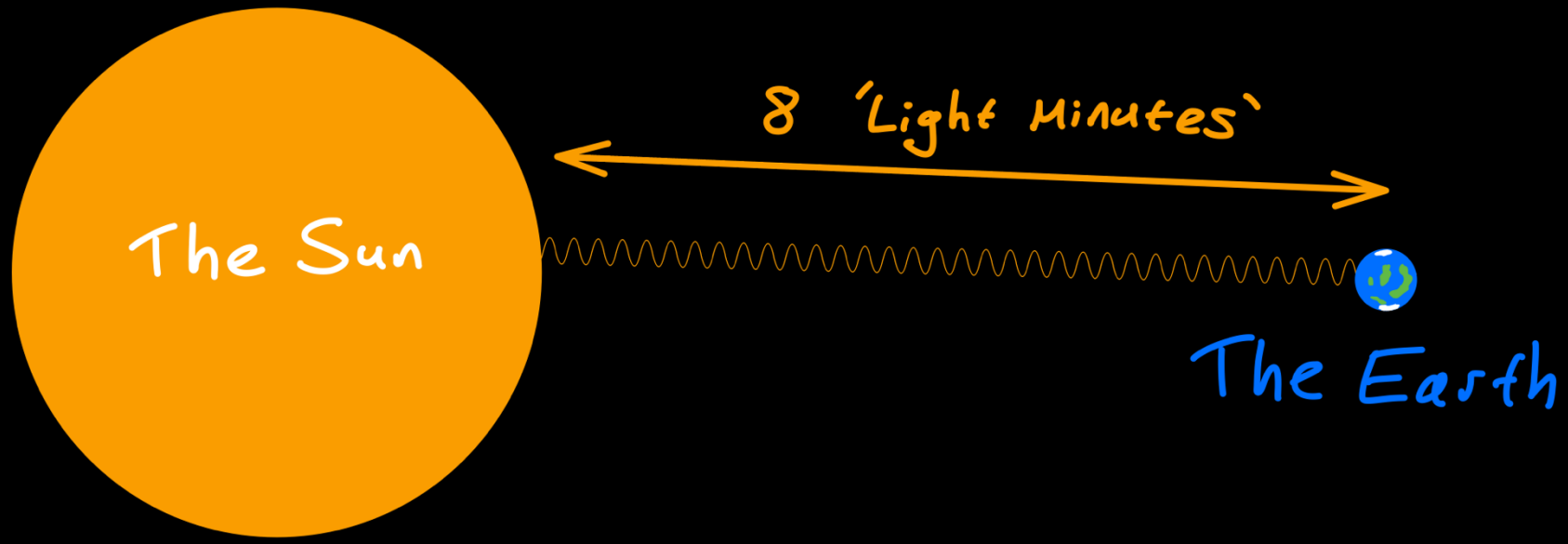
$$1\ LY = 300,000,000 \times (365 \times 24 \times 60 \times 60)$$

$$= 9,500,000,000,000,000 \text{ Metres}$$

or $5,900,000,000,000$ Miles

[590 Billion Miles]

4. Distances in Cosmology



A *light-year* is not a duration of time, but a unit of distance.

One light-year (abbreviated to LY) is the distance travelled by light moving through empty space in one year.

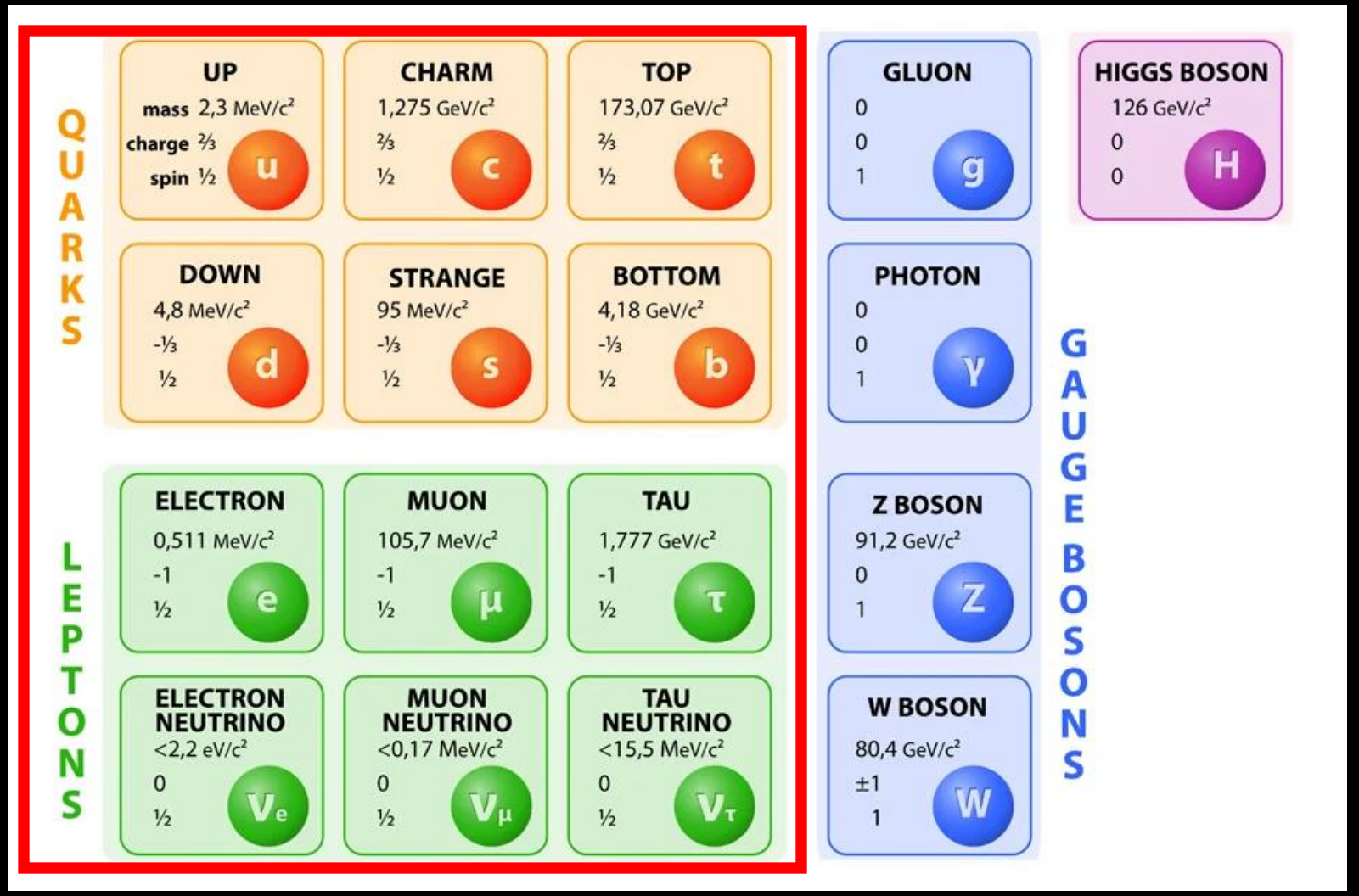
$\Delta t = 8$ minutes

Though not a common unit, a *light-minute* can be defined as the distance travelled by light in a single minute.

5. Matter and Anti-Matter

Matter: Another word for 'stuff'. Matter is anything with a mass.

Anti-Matter: Anti-Matter is also stuff. Just stuff of a different kind. It still has mass, but many other properties are the reverse of matter.



The Standard Model of Elementary Particles. This is the most complete theory we have for describing matter in its most basic form, as indivisible (fundamental) particles.

To hear more about Particle Physics and Quantum Theory, come to next weeks lecture: '*Schrodinger's Cat in the Particle Zoo*'.

5. Matter and Anti-Matter

Matter and **Anti-Matter** particles weigh the same.

Illustration of an electron (a particular kind of matter particle), and its corresponding anti-particle, the anti-electron (also called a positron).

5. Matter and Anti-Matter

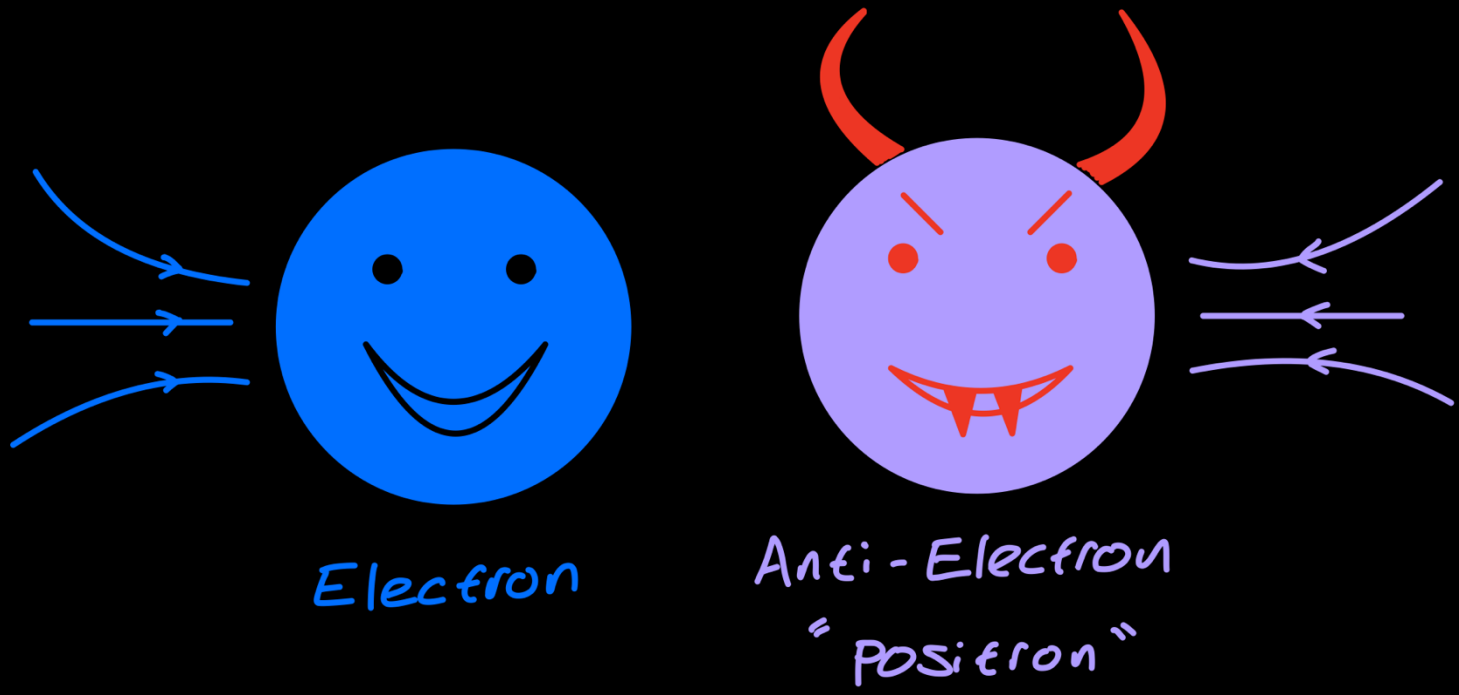
Some properties are reversed, such as charge.

Electron

Anti-Electron
"Positron"

5. Matter and Anti-Matter

When **Matter** **and** **Anti-Matter** collide they....

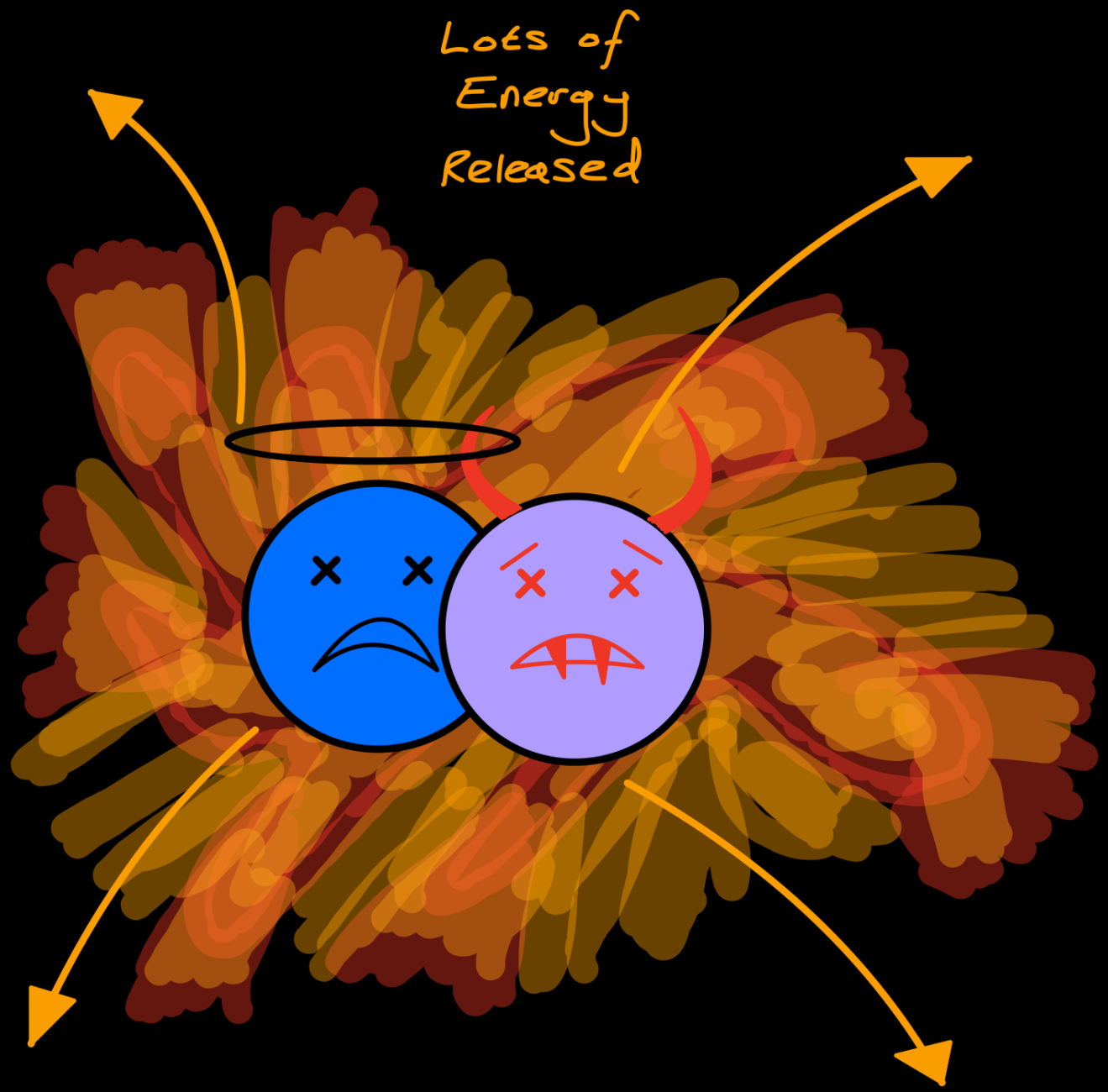


5. Matter and Anti-Matter

When **Matter** **and** **Anti-Matter** collide they....

ANNIHILATE

I.e. disappear and convert into pure energy.

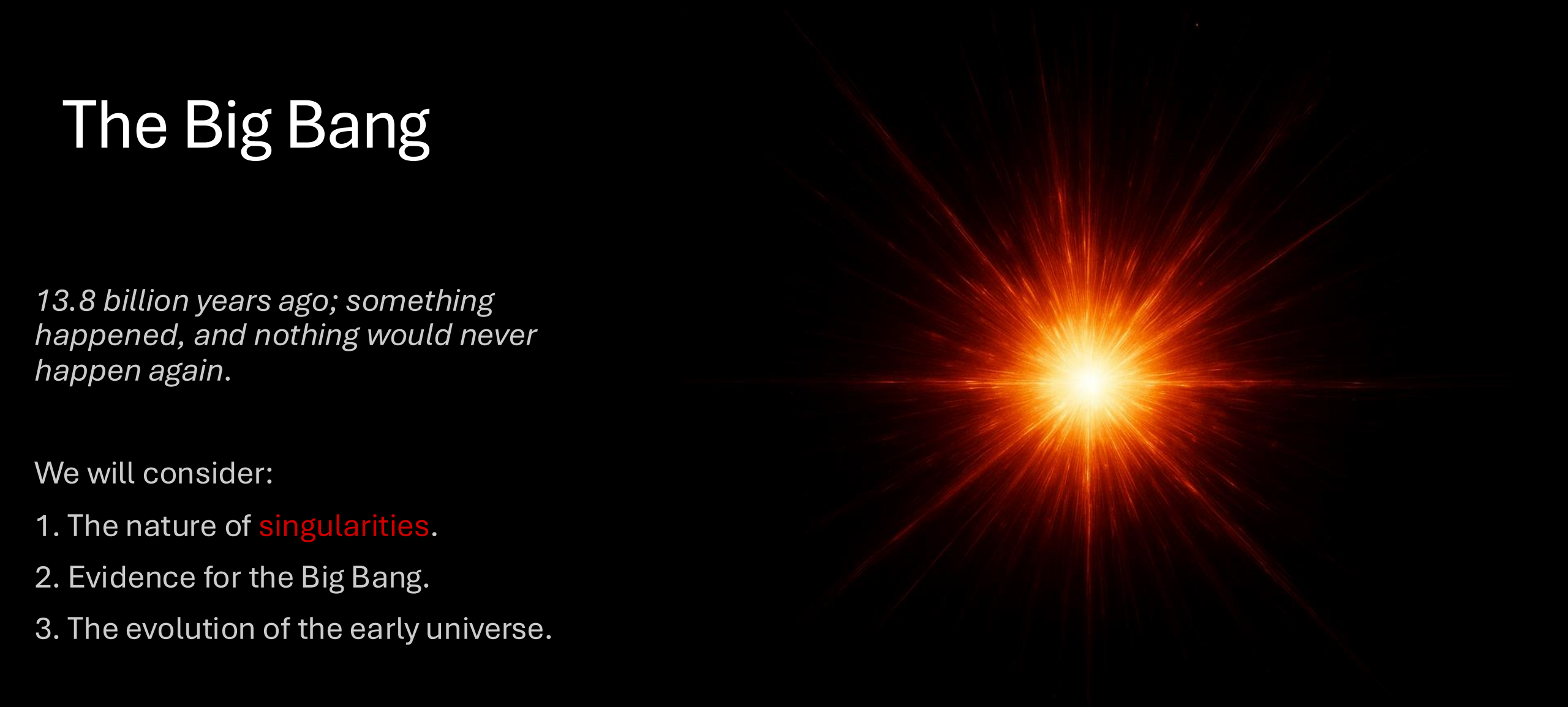


The Big Bang

13.8 billion years ago; something happened, and nothing would never happen again.

We will consider:

1. The nature of singularities.
2. Evidence for the Big Bang.
3. The evolution of the early universe.



In an instant, the entire Universe spawned from a single point, known as a space-time singularity.

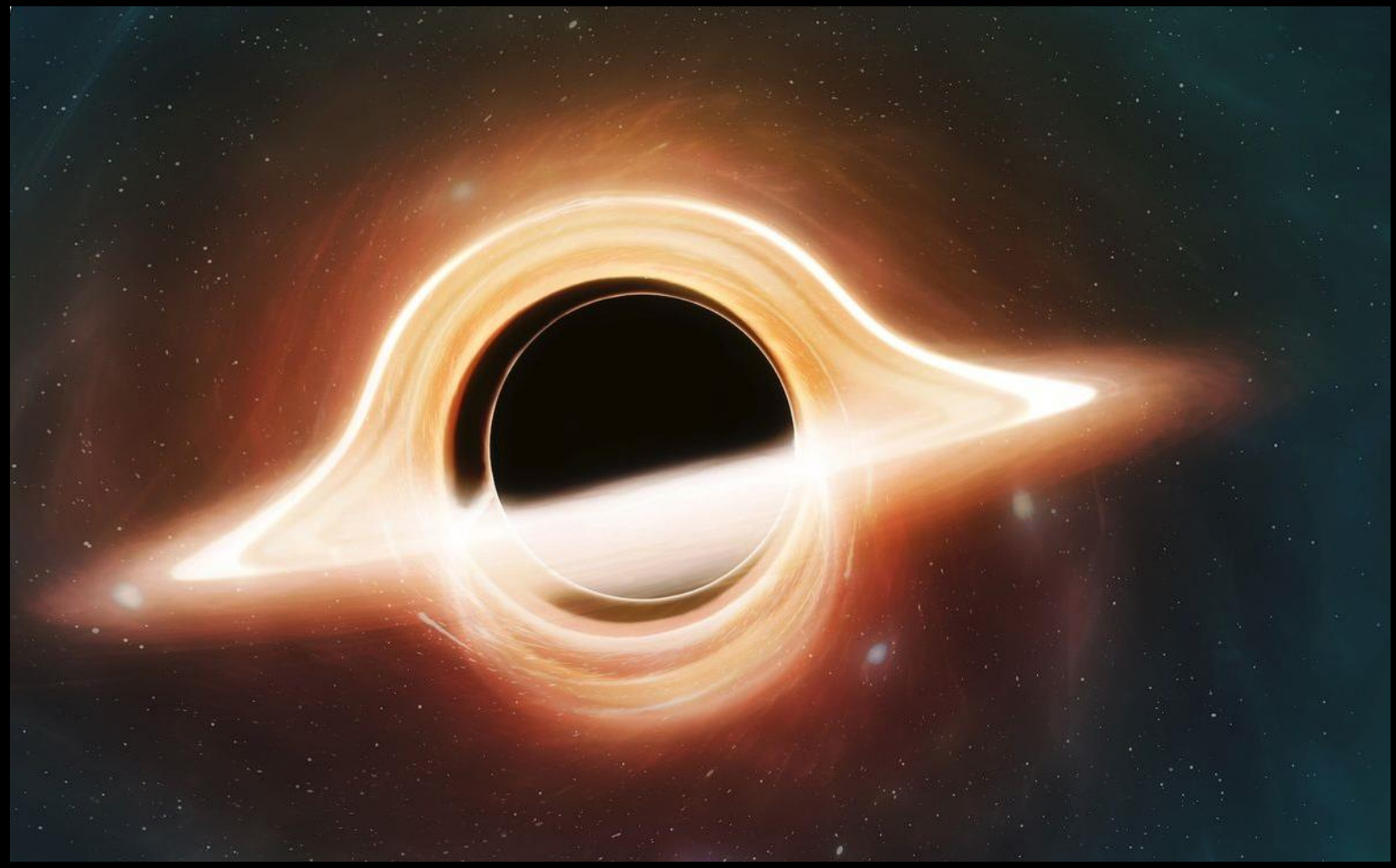
We call this moment in time, the Big Bang.

Space-time Singularities

‘Singularity’ is a term borrowed from Mathematics; used when a result ends up in a nonsensical expression, like:

$$\frac{1}{0}$$

“*Black Holes are where God Divided by Zero.*” – Stephen Wright



The only other place we believe space-time singularities exist, is at the center of a black hole.

Physically, a singularity can contain a huge amount of matter and energy, at a single infinitesimal point (infinite density, with zero size).

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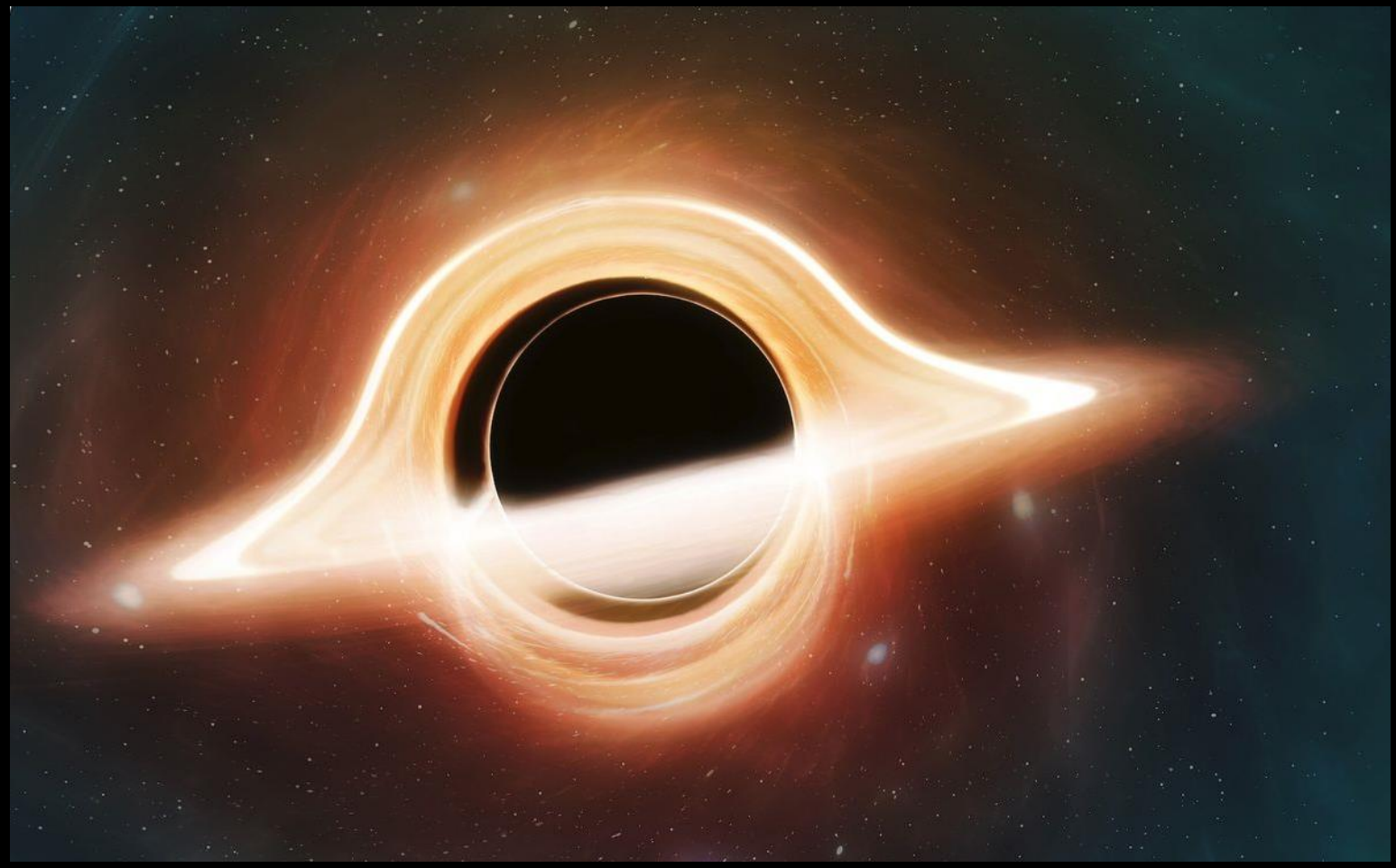

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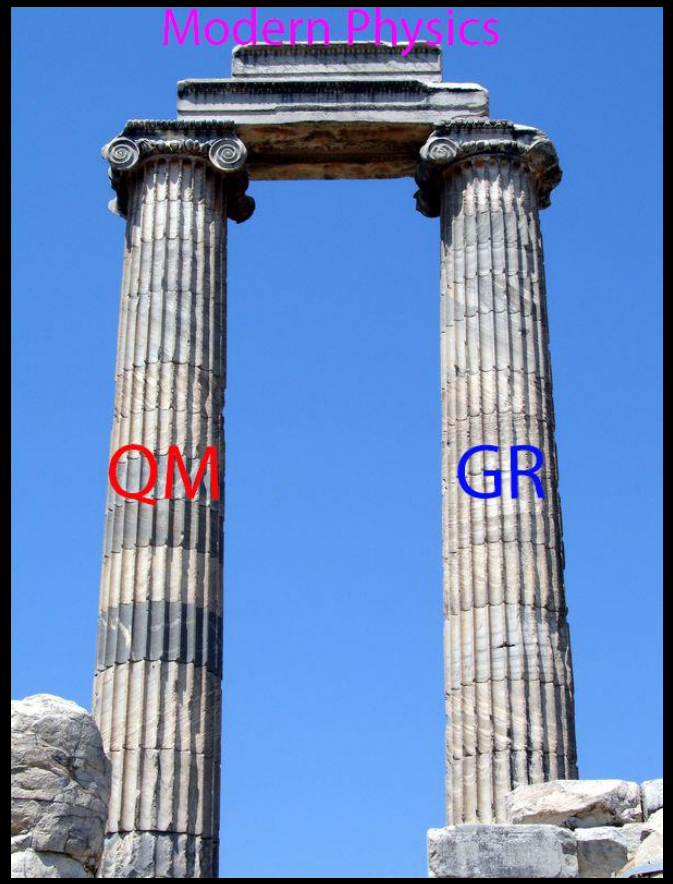
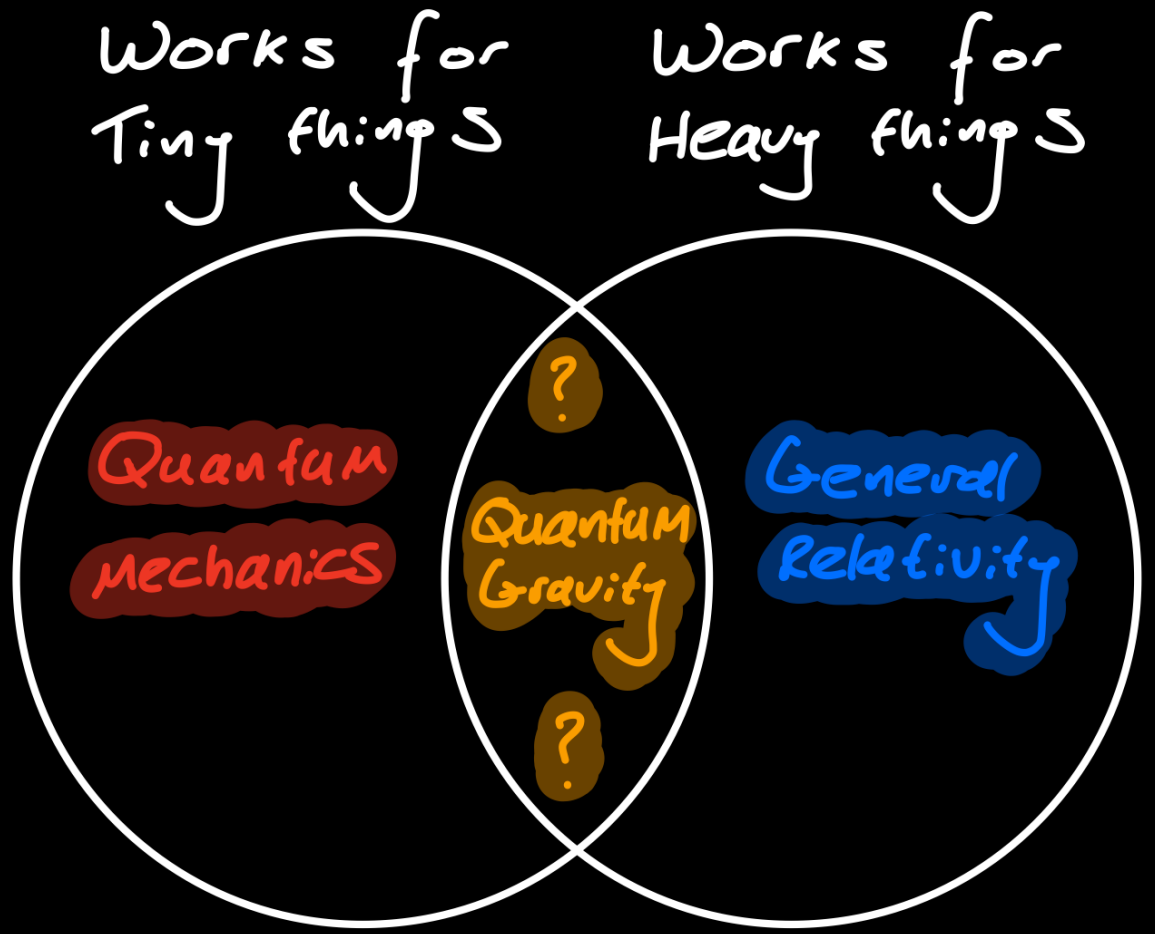
To hear more about Black Holes, come to the lecture on May 25th : ‘*Black Holes and Beyond*’.

Space-time Singularities

Why is the singularity so hard to understand?





"*Black Holes are where God Divided by Zero.*" – Stephen Wright

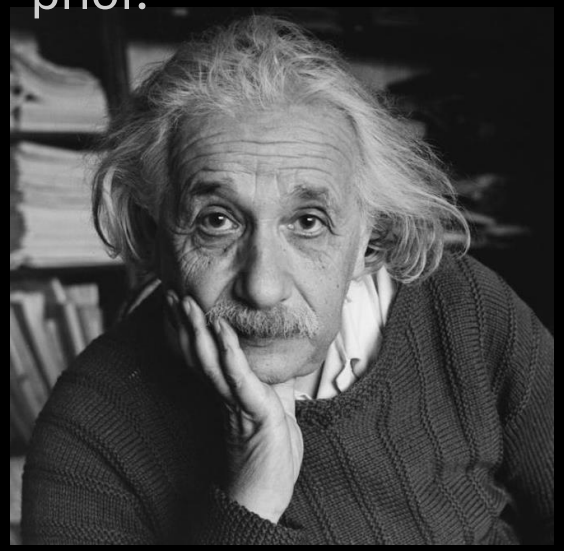
"***Quantum Gravity*** *is where such mathematical singularities, whether of human or divine origin, will be resolved.*" – Brian Greene

Slide recycled from 'Black Hole Basics' lecture, given on 01.03.2025.
Recording and full slides are on my website: CosmicConundra.com

The Big Bang Theory (no.. not that one...)

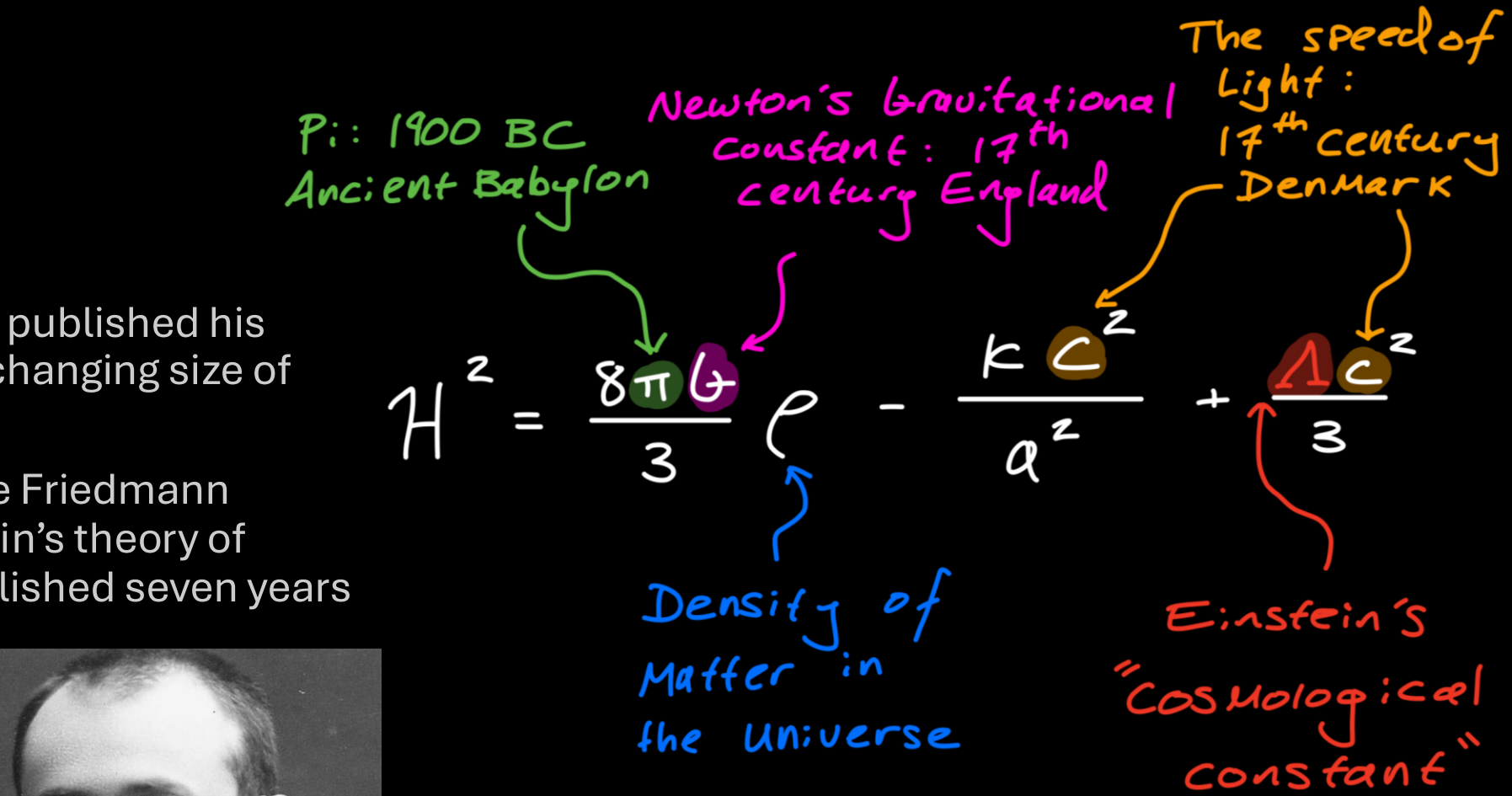
In 1922, Alexander Friedmann published his equations for calculating the changing size of the Universe.

His equations (now called 'The Friedmann Equations') spring from Einstein's theory of gravity (general relativity), published seven years prior.



Albert Einstein circa 1950

Alexander Friedmann circa 1920



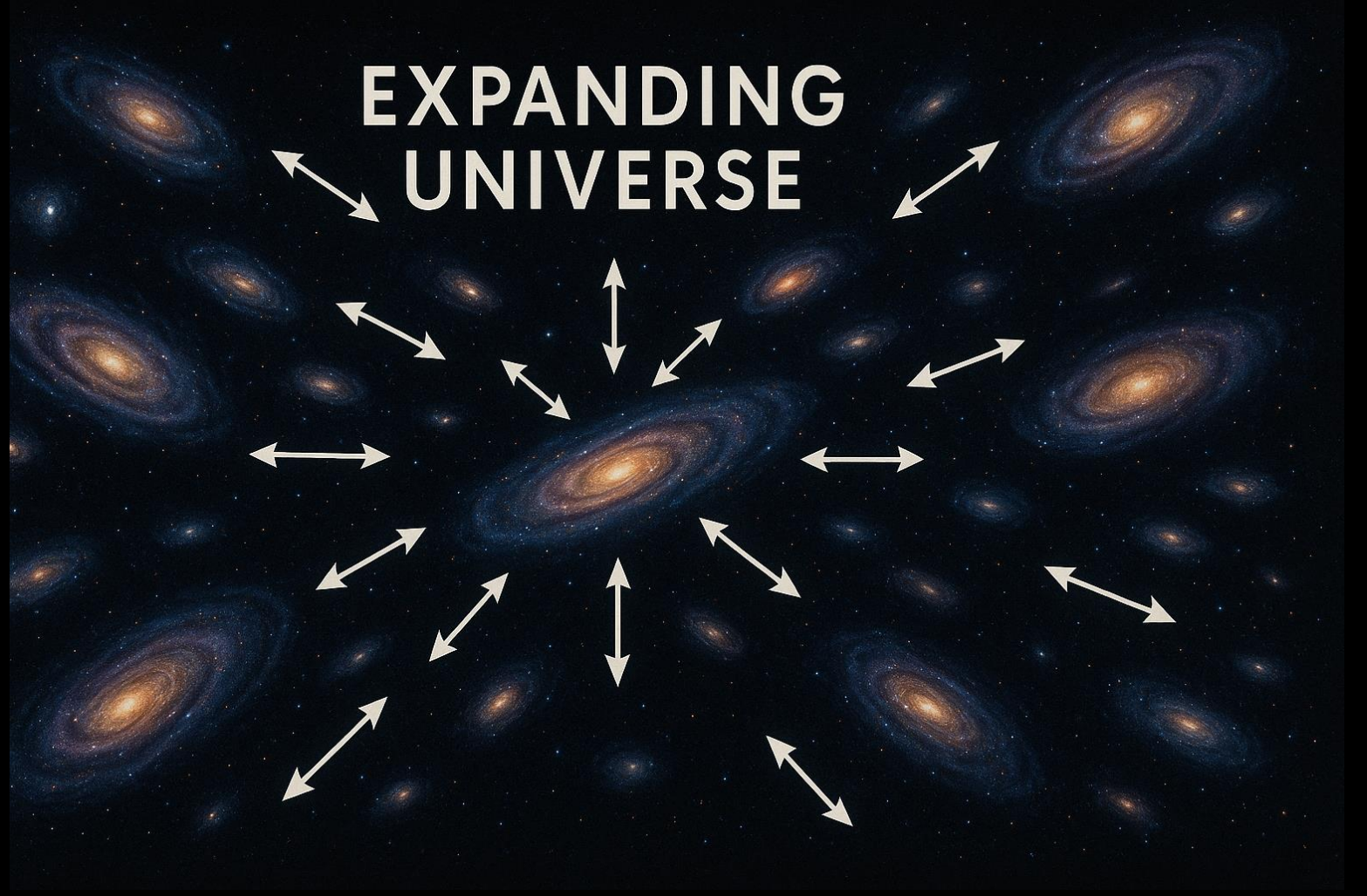
We will return to the Cosmological Constant later...

The Big Bang Theory (no.. not that one…)

Friedmann’s equation shows us that it is possible that the Universe could change in size.

This was puzzling, as the prevailing scientific theory in the 1920’s was the so called ‘Steady State Theory’.

Fred Hoyle circa 1955



In an expanding Universe, every Galaxy moves away from every other galaxy. There is no common center to the expansion.

So… Is the Universe expanding or not?

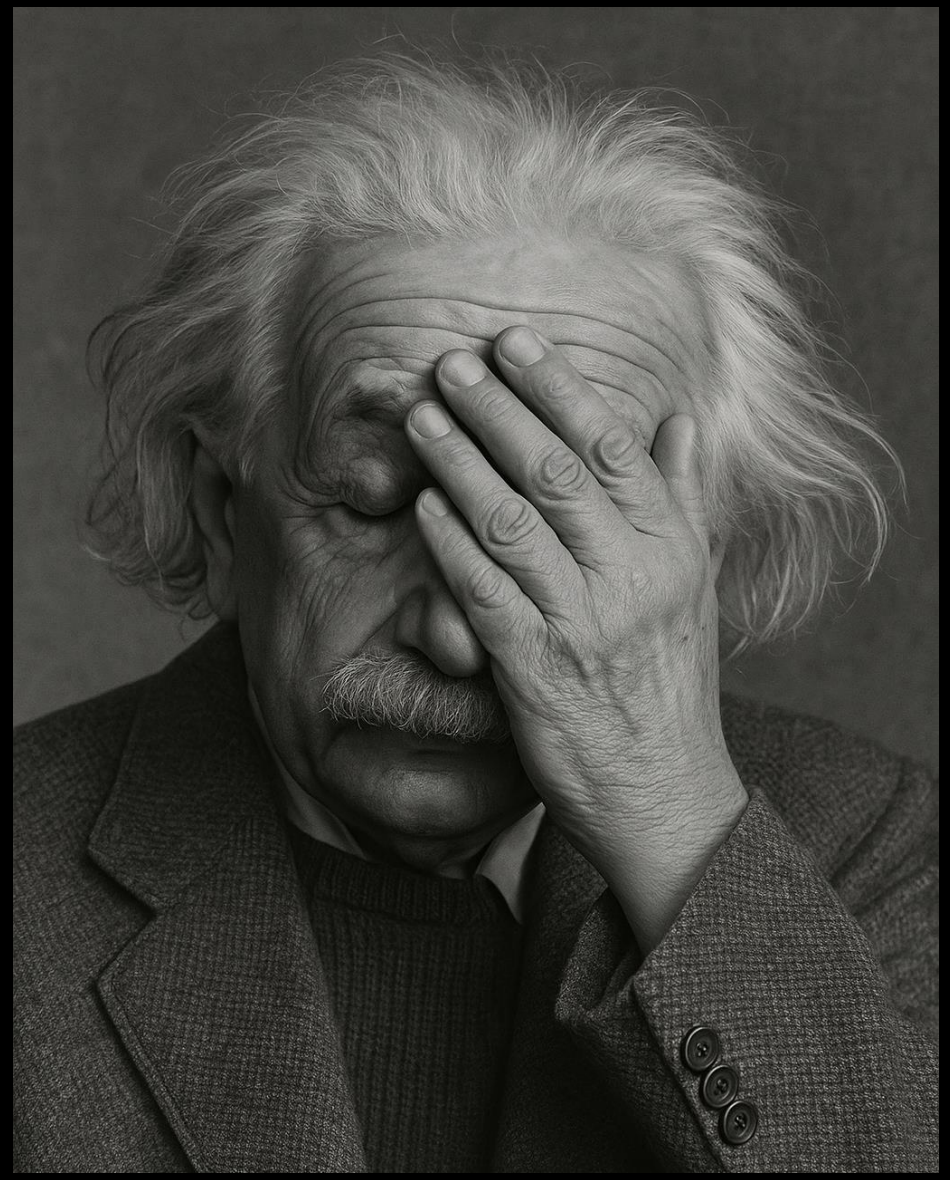
The Big Bang Theory (no.. not that one…)

The belief that the Universe is static in size first led Einstein to add a ‘Cosmological Constant’ into his equations of gravity.

This term acts to increase the density of energy in the Universe, to pull the galaxies back together and stop them from expanding away from one another.

He would later refer to his invention of this constant as his “biggest blunder”.

But was Einstein completely wrong?…. We will see later.



Note: This is an AI generated image.

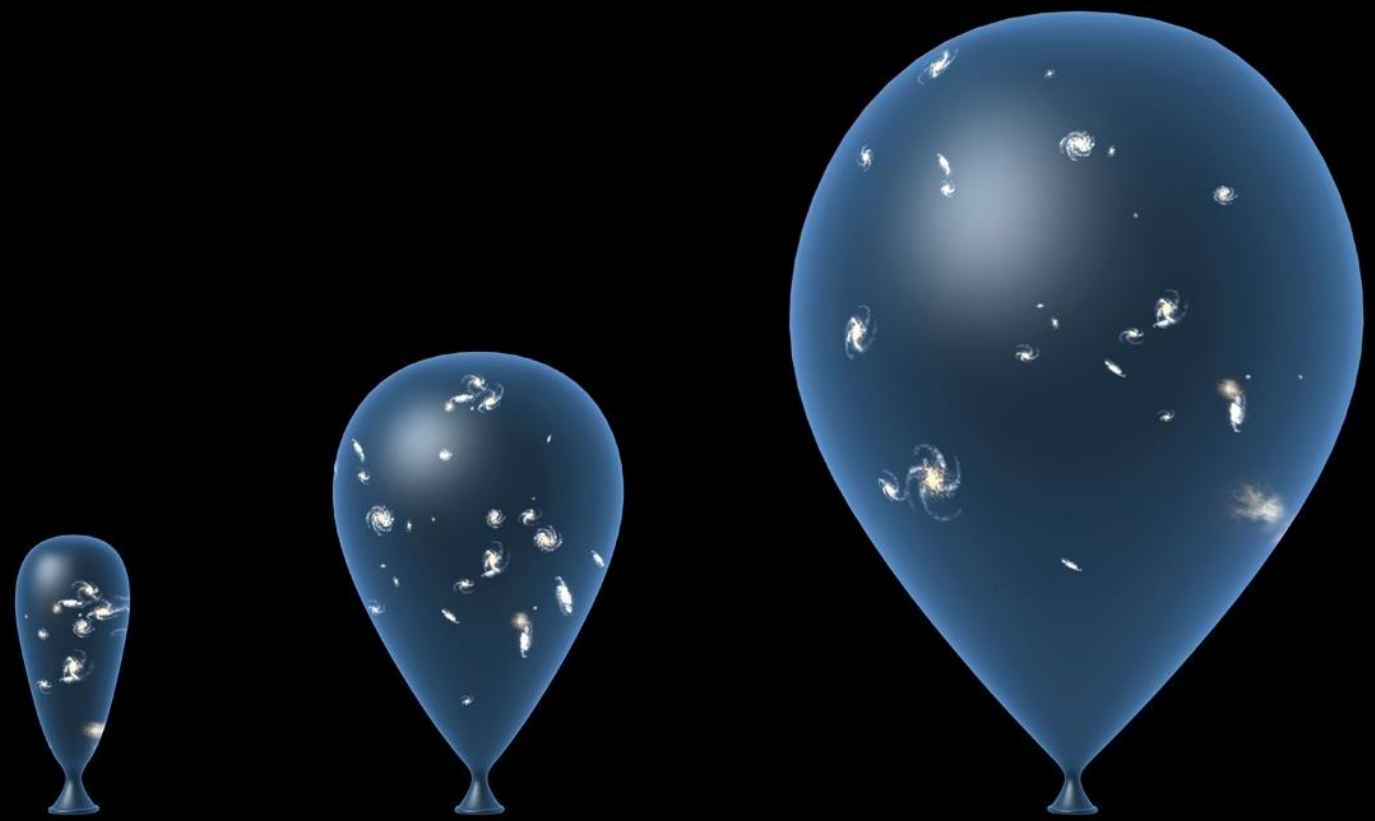
The Big Bang Theory (no.. not that one…)

In 1929, Edwin Hubble publishes his observations that distant galaxies are moving away from us, with the more distant galaxies moving away at higher speeds.

In 1931, Georges Lemaître proposes that the Universe might have begun from a single point that he called ‘the primeval atom’.

Georges Lemaître circa 1930

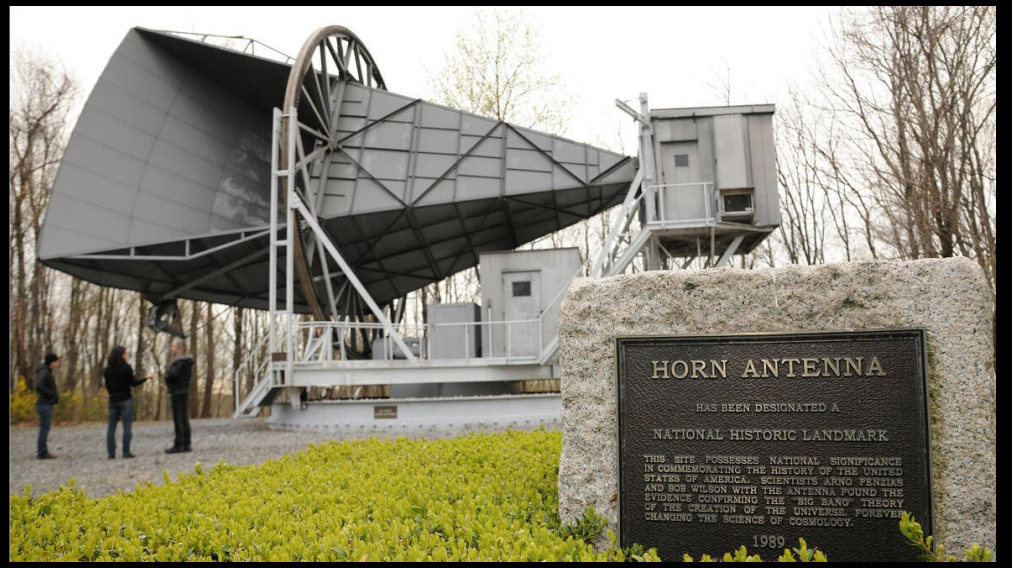
Edwin Hubbe circa 1930



In an expanding Universe, every galaxy moves away from every other galaxy, like points on an expanding balloon. There is no common center to the expansion.

The Big Bang Theory (no.. not that one…)

In 1964, Penzias & Wilson discovered (accidentally) a background of microwave radiation, that could only be due to a hot BIG BANG.

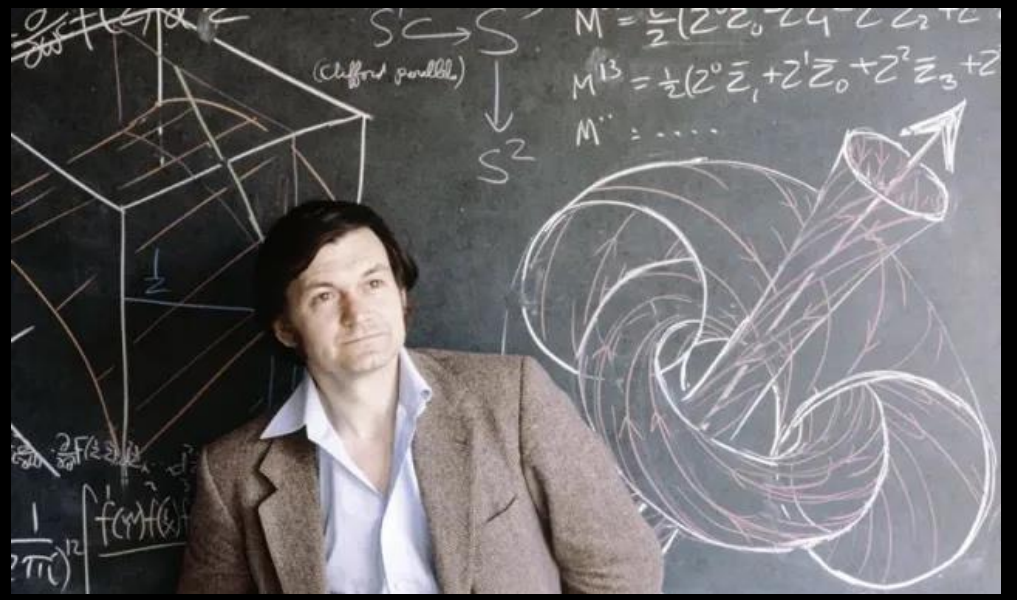


The Horn Antenna at Bell Labs in New Jersey.

In 1970, Hawking & Penrose publish their ‘singularity theorems’, showing mathematically that the Universe must have begun as a space-time singularity.

Arno Penzias & Robert Wilson

Stephen Hawking & Roger Penrose



Roger Penrose in the 1970’s.


The Big Bang is Science!

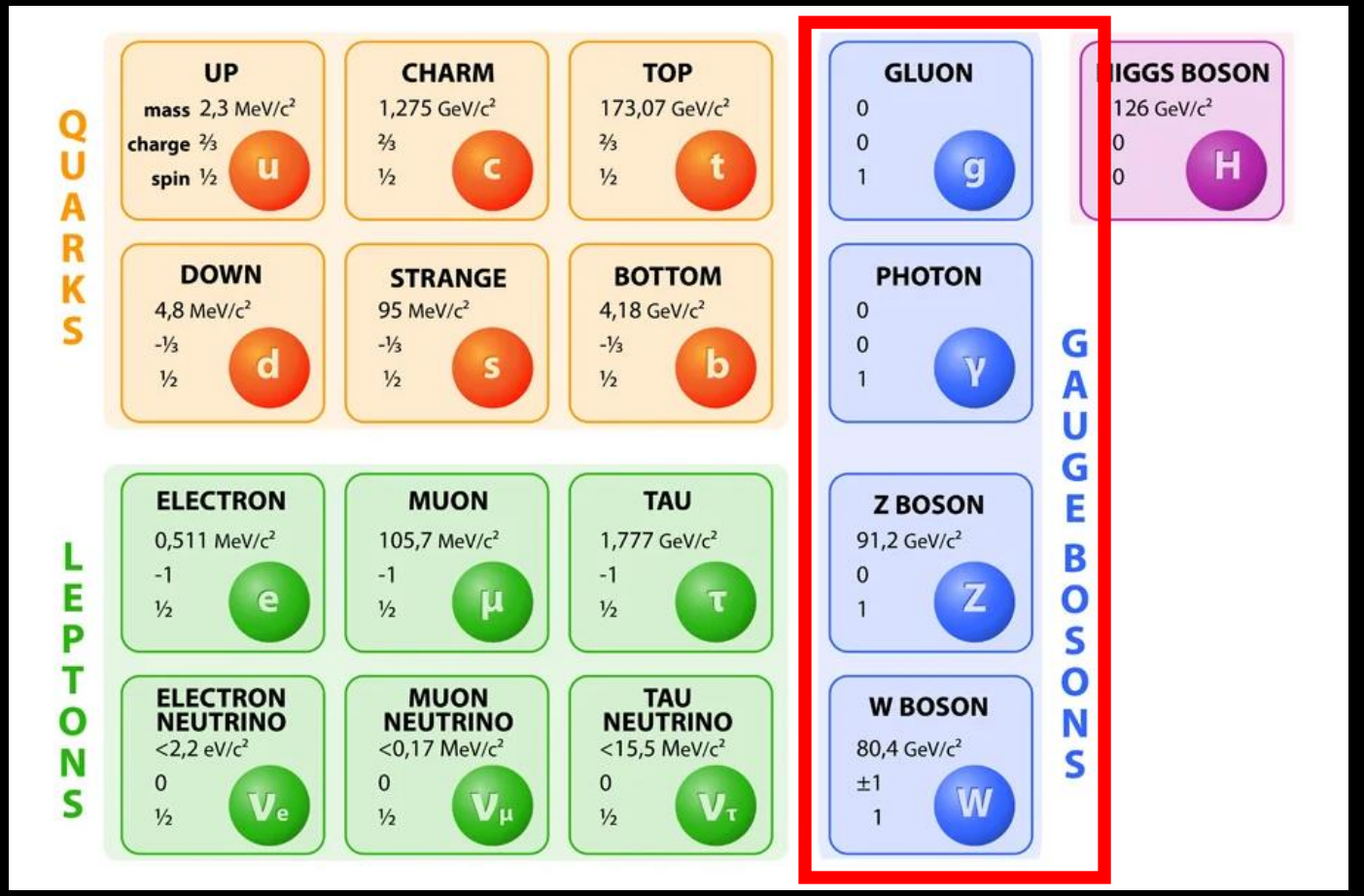
The First Ten Seconds

$$t = 0 \rightarrow 10^{-43}$$

Planck Epoch

Immediately after the Big Bang, we think that the four fundamental forces of nature were unified as a single force.

This epoch is so close to the singularity at the beginning of the Universe, that our present understanding of the laws of physics does not allow us to make many concrete predictions.



The Standard Model of Elementary Particles. The Gauge Bosons are the particles responsible for the fundamental forces of nature.

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Four Fundamental Forces

The Strong Force:
Binds the atomic nucleus.

The ElectroMagnetic force:
Electrical and Magnetic Phenomena

The Weak Nuclear force:
Nuclear decay and radioactivity.

The Gravitational force:

The Standard Model of Elementary Particles. The Gauge Bosons are the particles responsible for the fundamental forces of nature.

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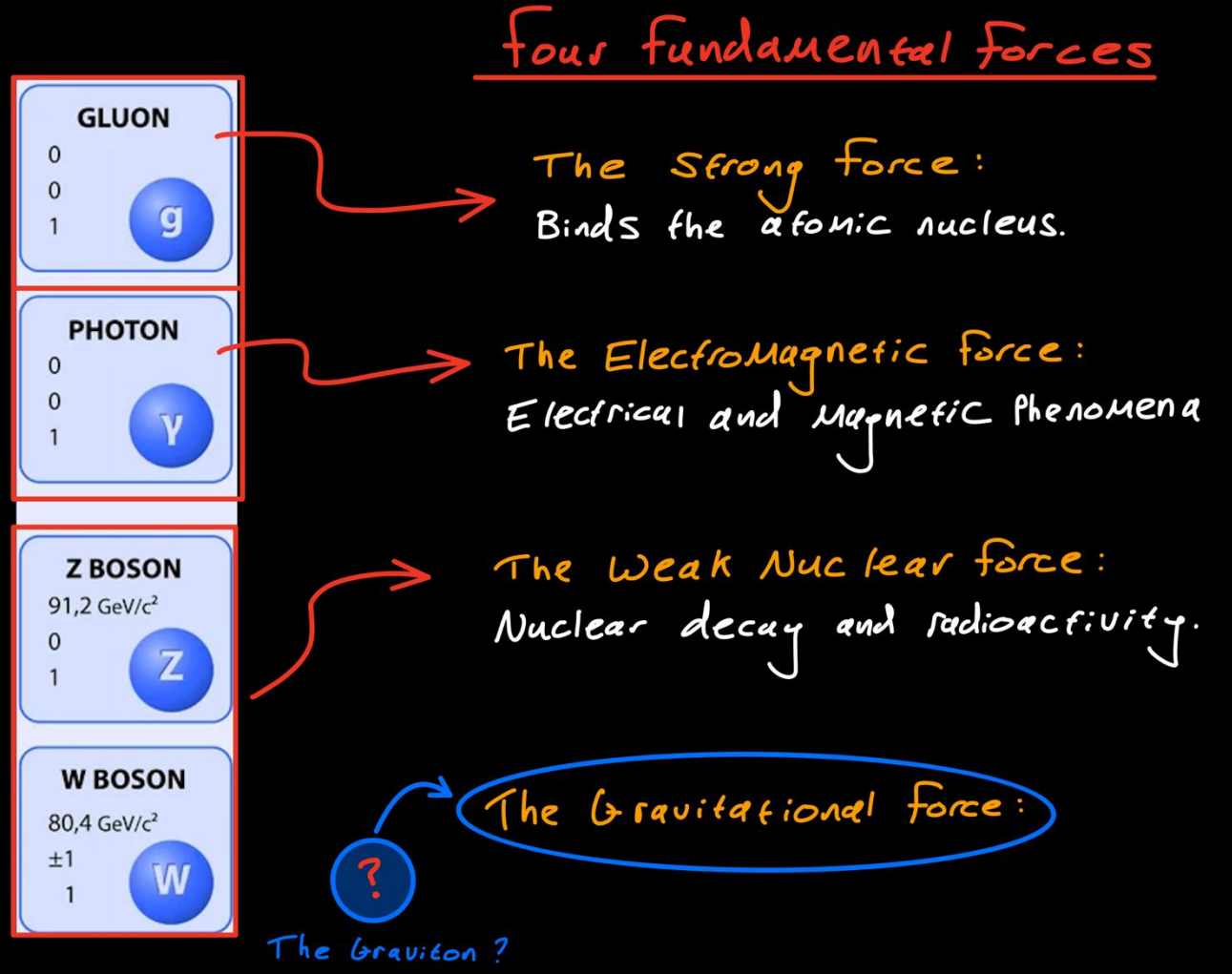

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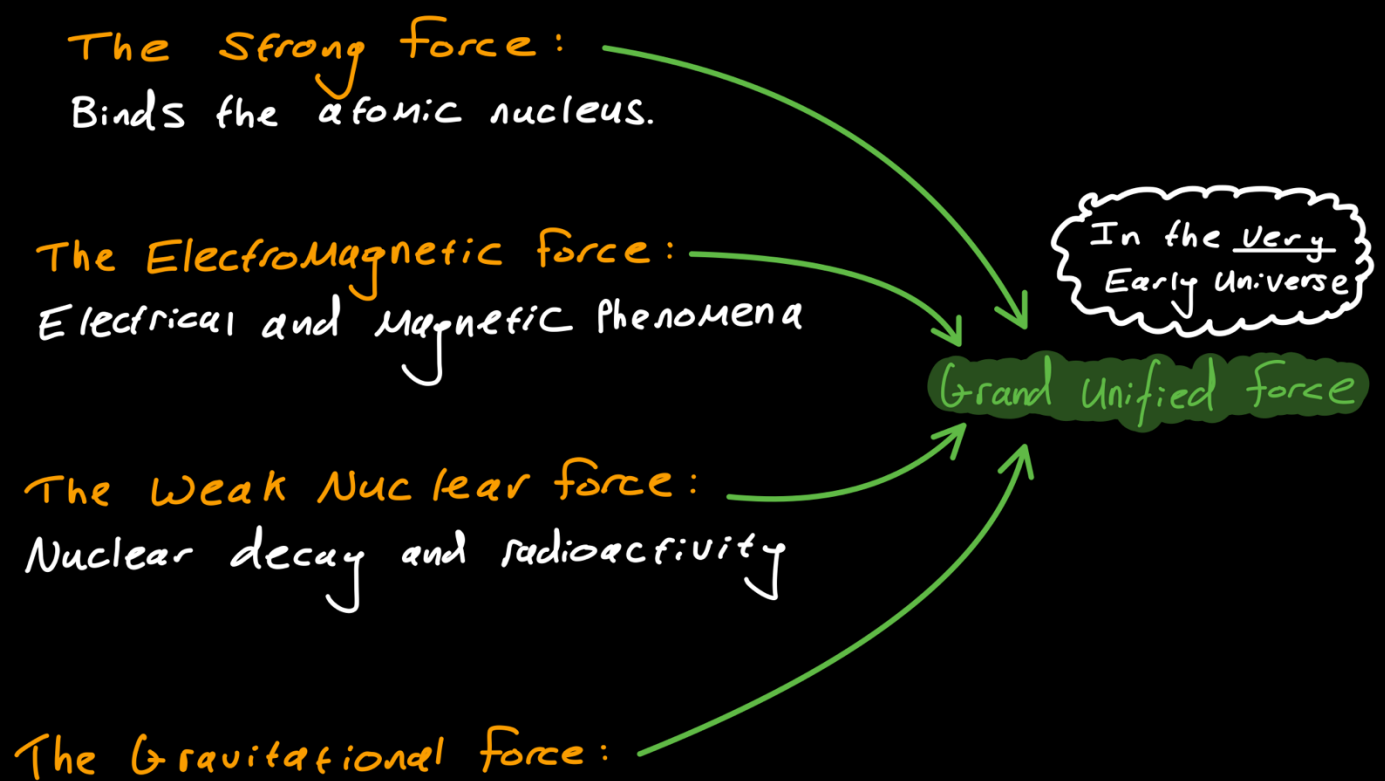


All the fundamental forces unify in the very early Universe.

To study the Universe at this young age, we need a theory of Quantum Gravity that bridges the gap between Quantum Theory and Einsteins theory of Gravity.

The First Ten Seconds

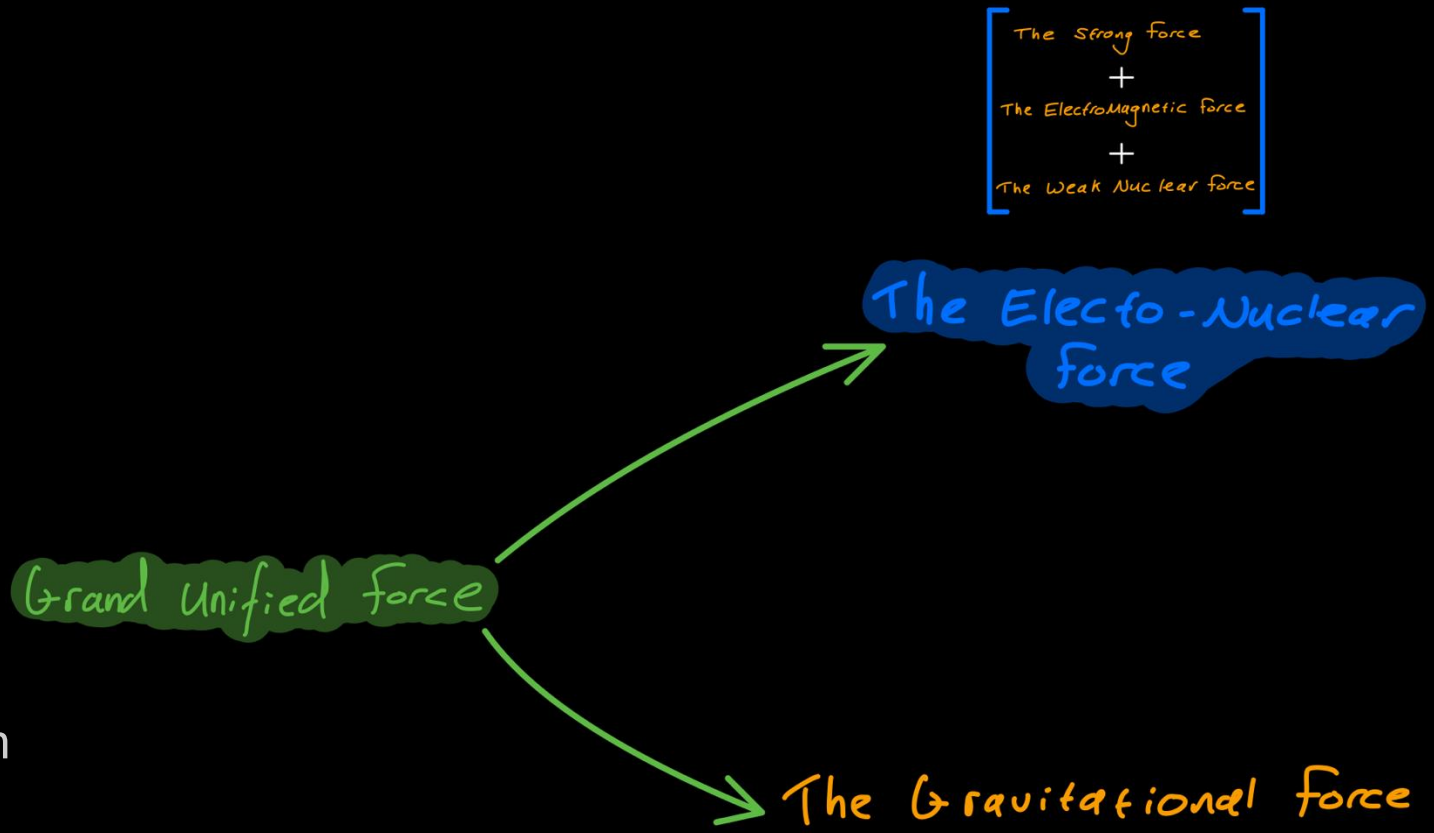
$$t = 10^{-43} \rightarrow 10^{-37}$$

Grand Unification Epoch

Between 10^{-43} and 10^{-37} seconds after the Big Bang, the single Unified Force splits in two; with gravity separating.

This transition from one fundamental force to two fundamental forces is described as a *phase transition*. Similar in many ways to the freezing of water to ice.

We will talk more about phase transitions in a few trillionths of a second.



The First Ten Seconds

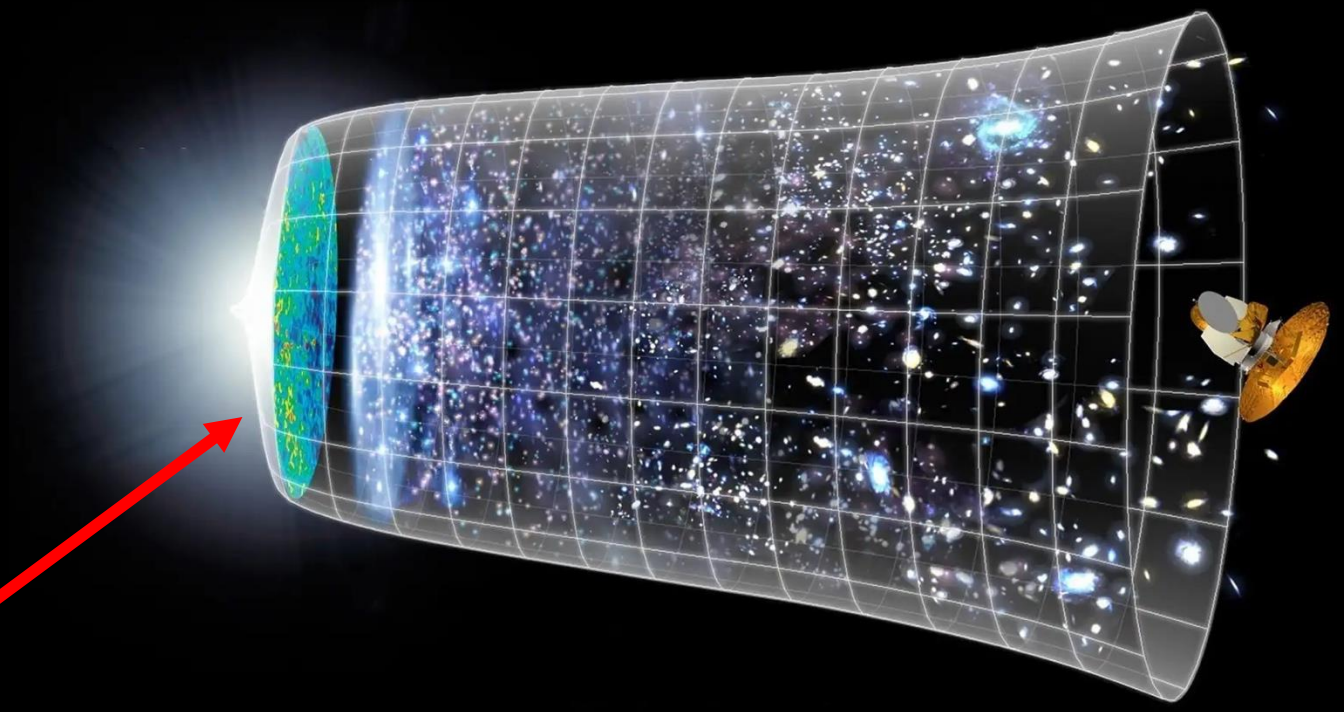
$t = 10^{-37} \rightarrow 10^{-32}$

Inflationary Epoch

After 10^{-43} seconds, we are able to apply the known laws of physics with *slightly* more certainty.

Between 10^{-37} and 10^{-33} seconds after the Big Bang, the Universe underwent a brief period of extremely rapid growth.

In this period the, the size of the Universe increased by a factor of roughly 10^{24}. Equivalent to expanding from the size of a grain of sand, to size of our Galaxy.



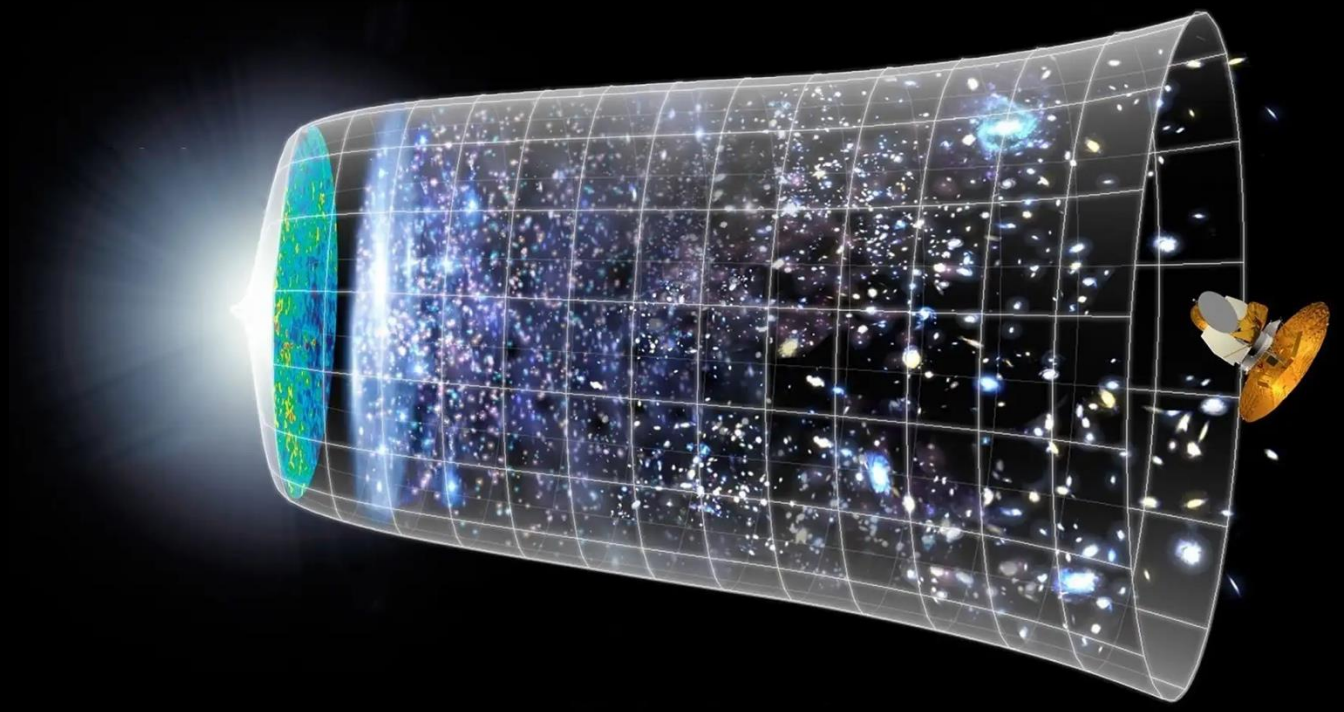
The First Ten Seconds

$t = 10^{-37} \rightarrow 10^{-32}$

Inflationary Epoch

In this early period, the Universe is still dominated by Quantum Theory (the theory of subatomic particles).

This faster than light expansion blew quantum fluctuations of the vacuum up to macroscopic sizes, where they would seed the formation of stars and galaxies later on.



The First Ten Seconds

$t = 10^{-32} \rightarrow 10^{-12}$

Electroweak Epoch

The Electromagnetic Force and the Weak Nuclear Force separate. We think that this phase transition occurs via Bubbles.

Initially, every part of the Universe is in the Electroweak Phase.

The First Ten Seconds

$t = 10^{-32} \rightarrow 10^{-12}$

Electroweak Epoch

Tiny pockets of space begin to transition into a new phase.

The points where this begins are called nucleation sites.

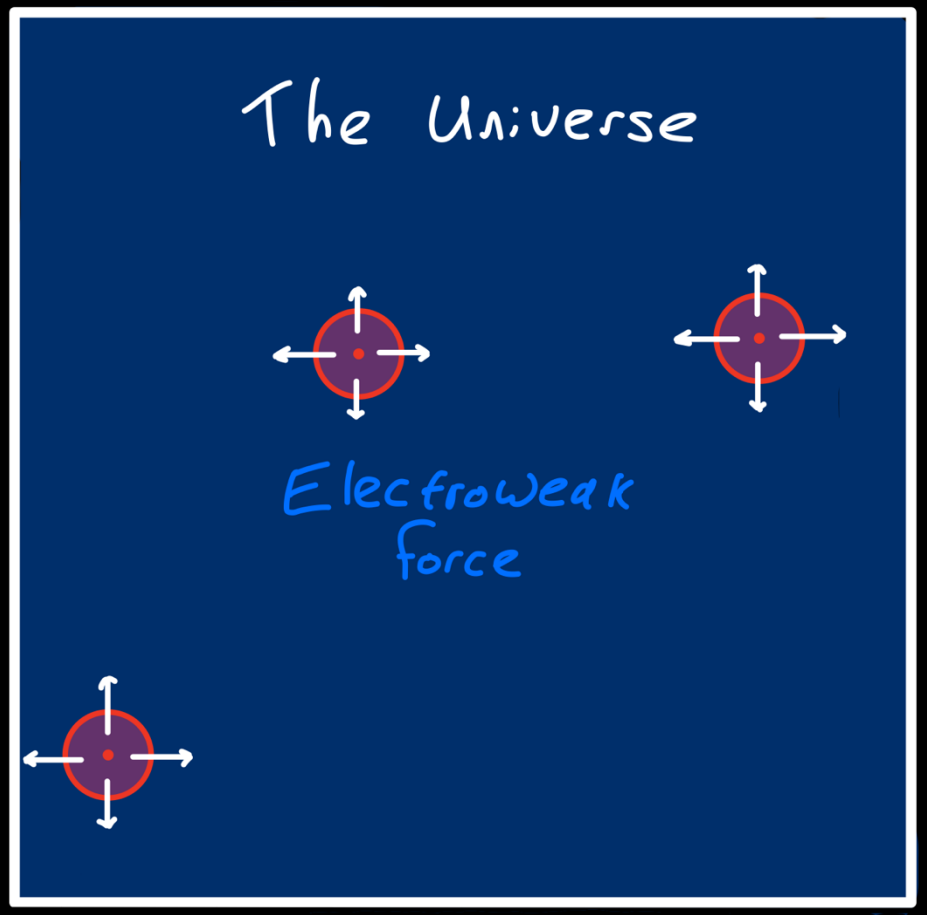
The First Ten Seconds

$t = 10^{-32} \rightarrow 10^{-12}$

Electroweak Epoch

Expanding from these nucleation sites at the speed of light, ‘Bubbles’ form.

Inside of each Bubble, the phase transition has occurred (i.e. the Electroweak force has split).



The First Ten Seconds

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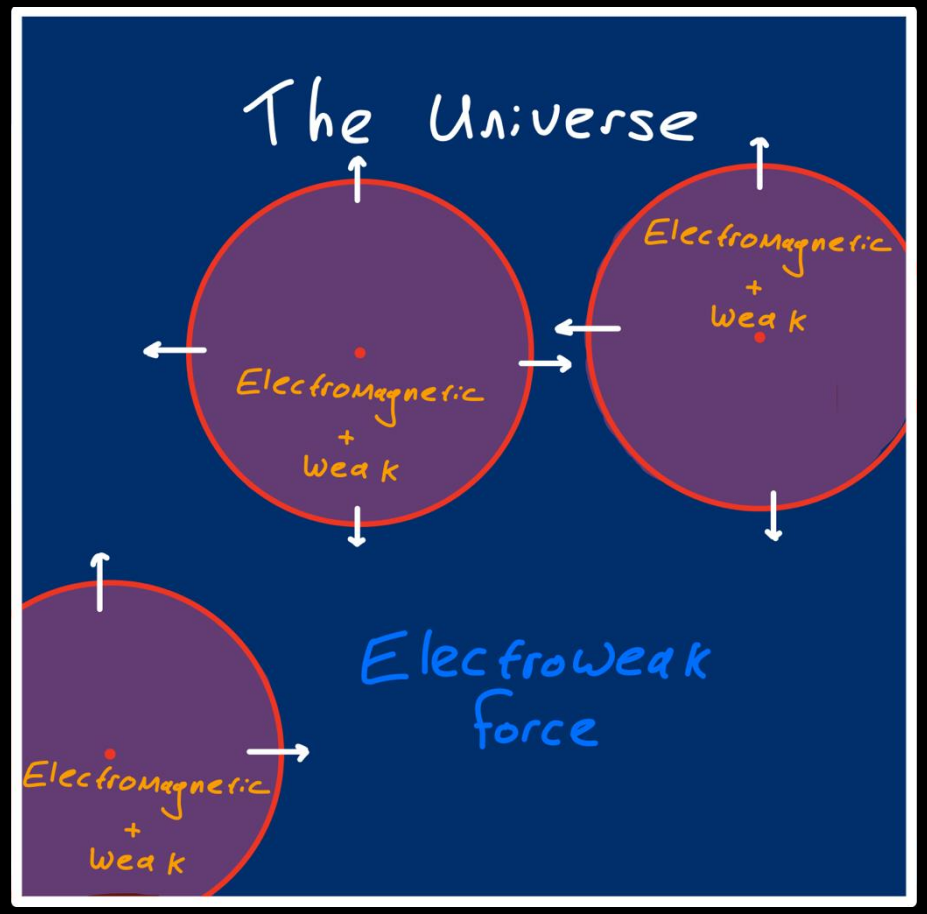
Electroweak Epoch

As the Bubbles fill more and more of the Universe, they collide and release Gravitational Waves (ripples in space).



The First Ten Seconds

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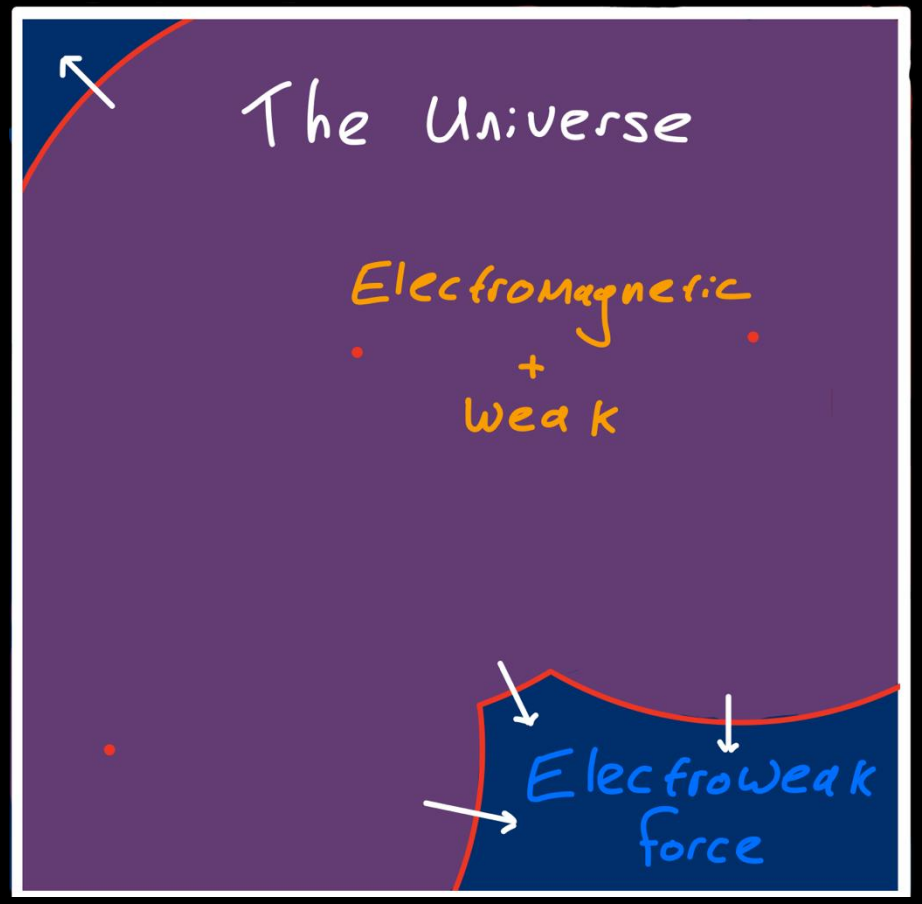
Electroweak Epoch

Detecting these gravitational waves would provide evidence of this phase transition, and teach us more about the physics of the very early Universe.



The First Ten Seconds

$$t = 10^{-32} \rightarrow 10^{-12}$$

Electroweak Epoch

Once the transition has completed, the Universe exists in a state fundamentally quite similar to today.

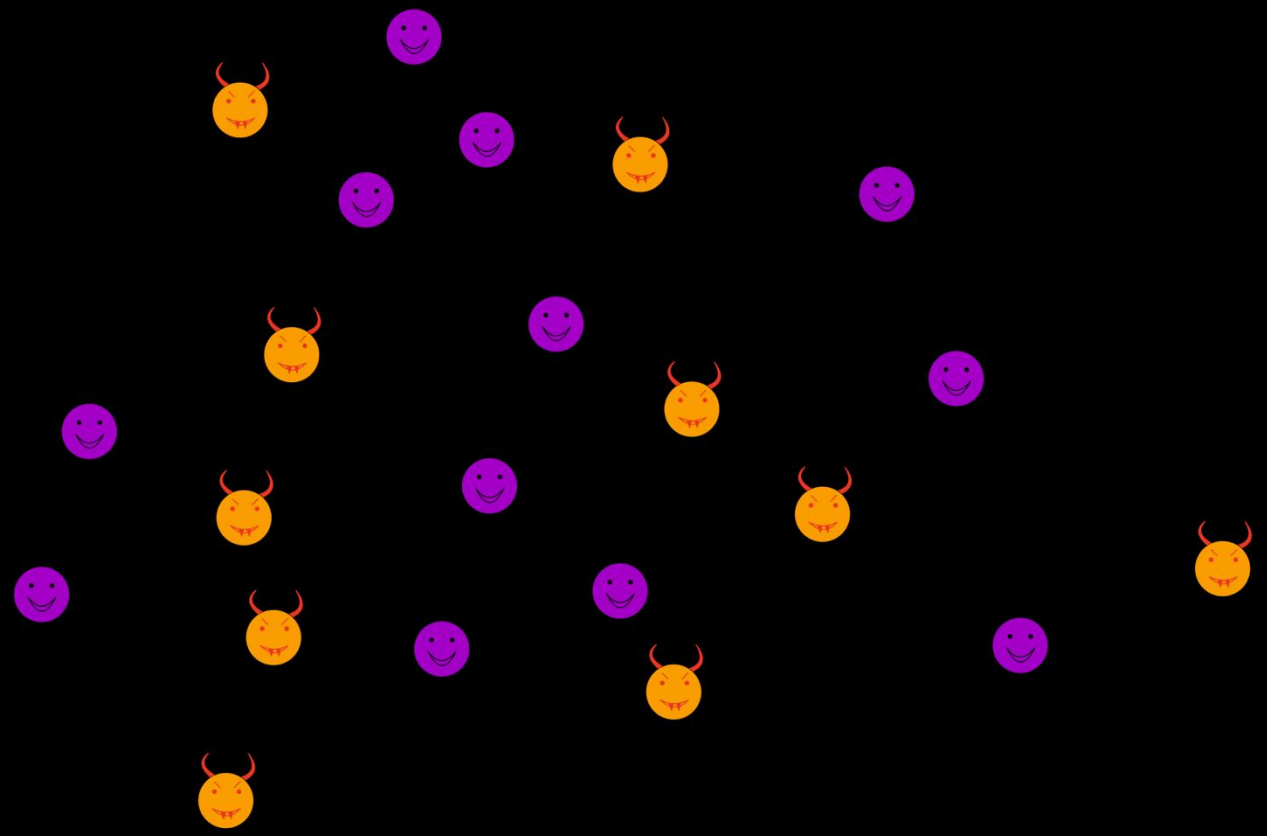
With all four Fundamental Forces fully separated.

1. The Strong Nuclear Force
2. The Electromagnetic Force
3. The Weak Nuclear Force
4. The Gravitational Force

The First Ten Seconds

$$t = 10^{-32} \rightarrow 10^{-12}$$

Electroweak Epoch



In this period, matter particles (specifically quarks) begin to form, in a process called *Baryogenesis*.

The laws of physics, as we understand them, tell us that Matter and Anti-Matter can only form in equal amounts.

However… There is still Matter in the Universe. It has **not** annihilated away

This is still an open problem. A number of theories have been proposed, but there is a great deal of uncertainty.

The First Ten Seconds

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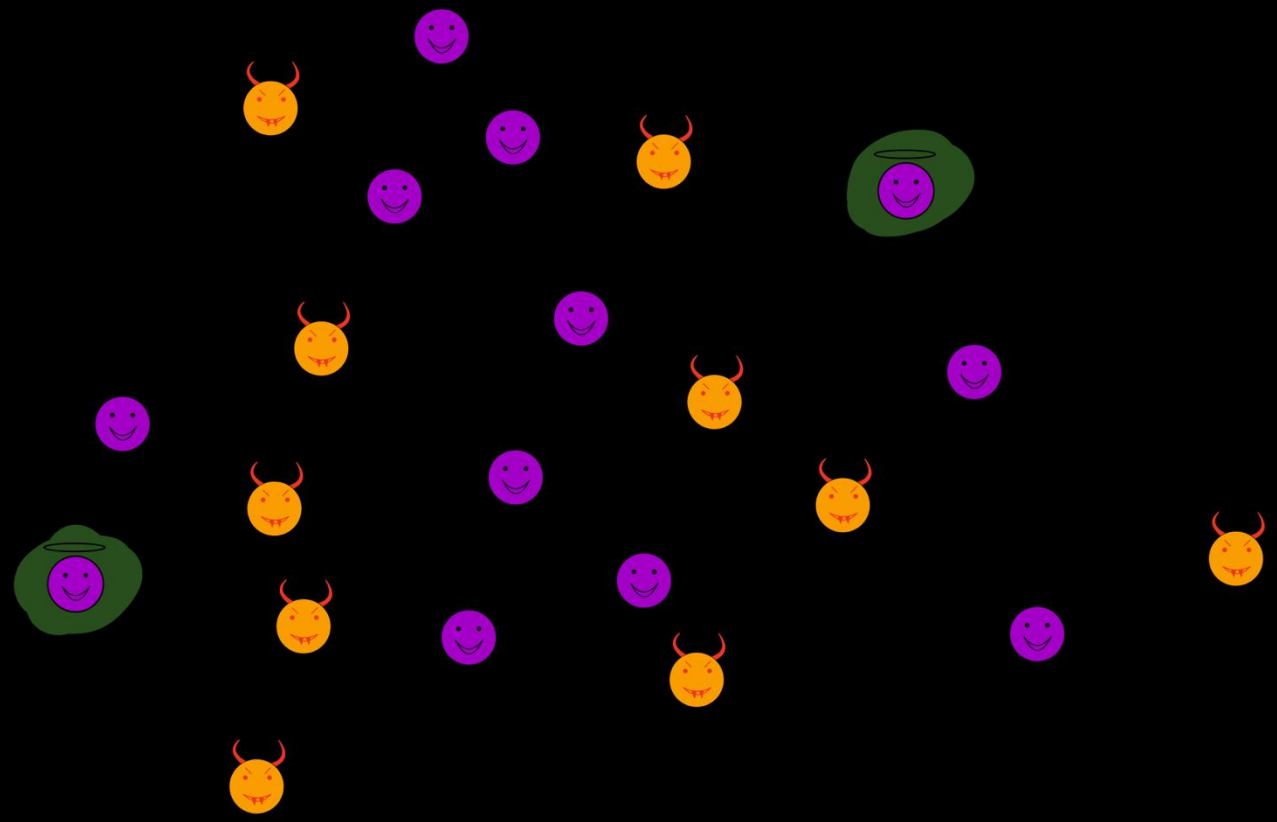
Electroweak Epoch



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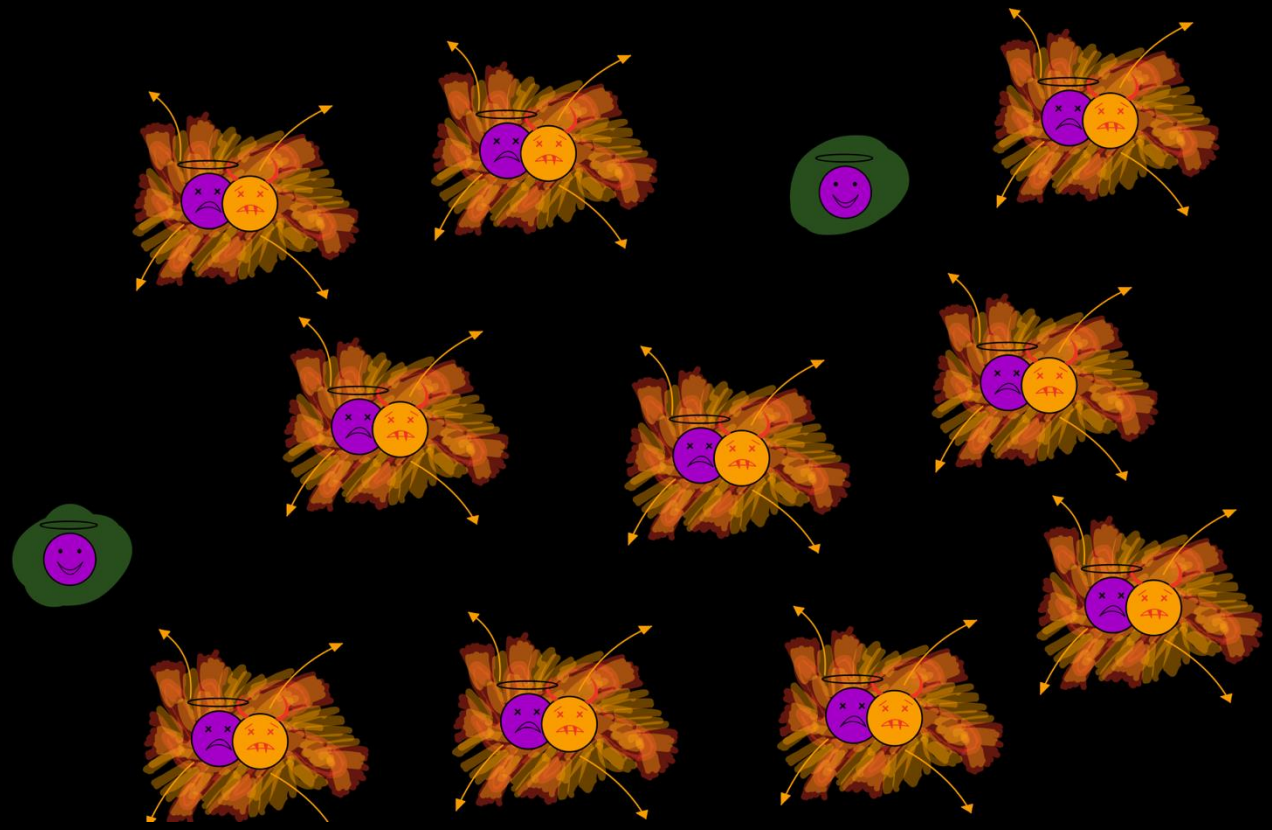

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In this period, matter particles (specifically quarks) begin to form, in a process called *Baryogenesis*.

The laws of physics, as we understand them, tell us that Matter and Anti-Matter can only form in equal amounts.

However… There is still Matter in the Universe. It has **not** annihilated away

This is still an open problem. A number of theories have been proposed, but there is a great deal of uncertainty.

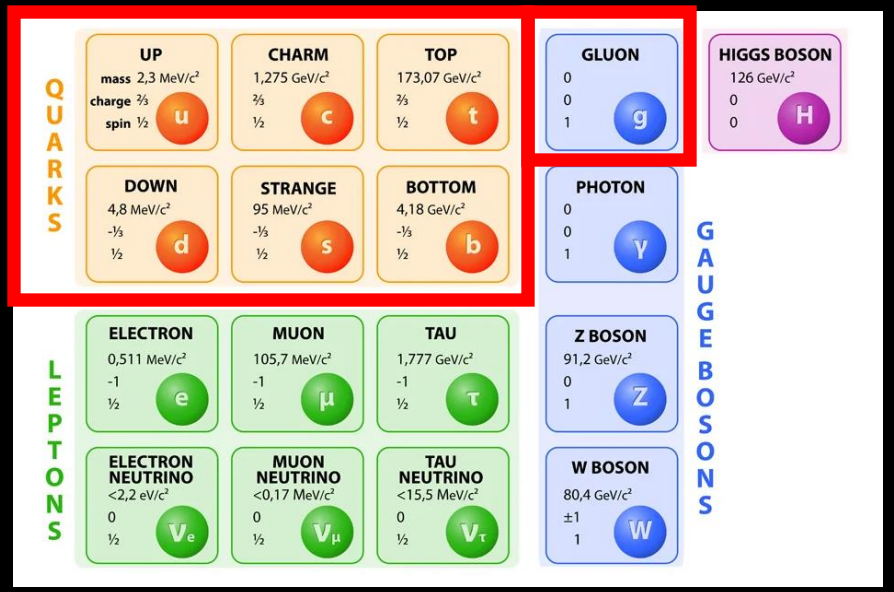
The First Ten Seconds

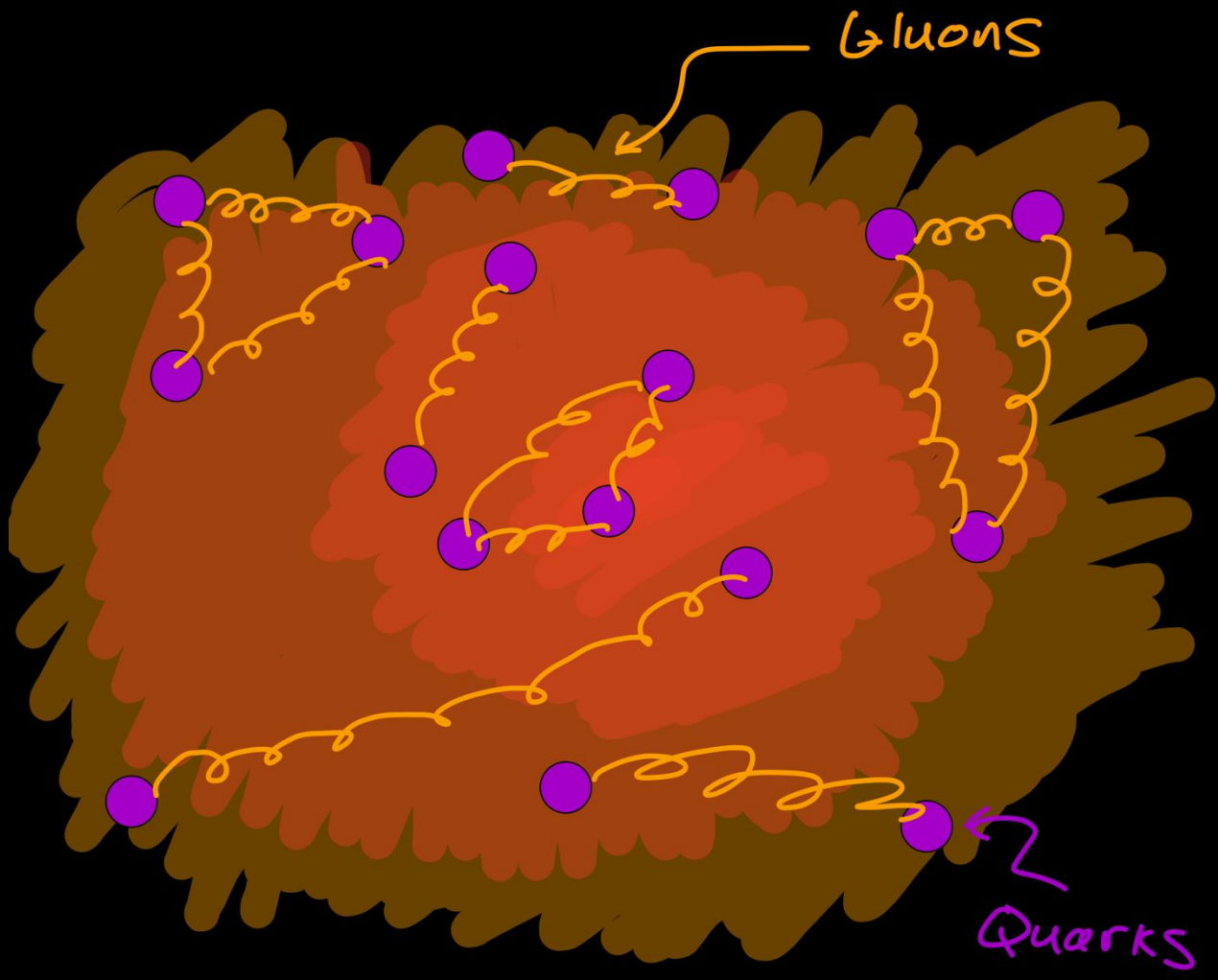
$$t = 10^{-12} \rightarrow 10^{-6}$$

Quark Epoch

During the Quark Epoch, only Quarks have formed.

These are present in a hot Quark-Gluon plasma.





The First Ten Seconds

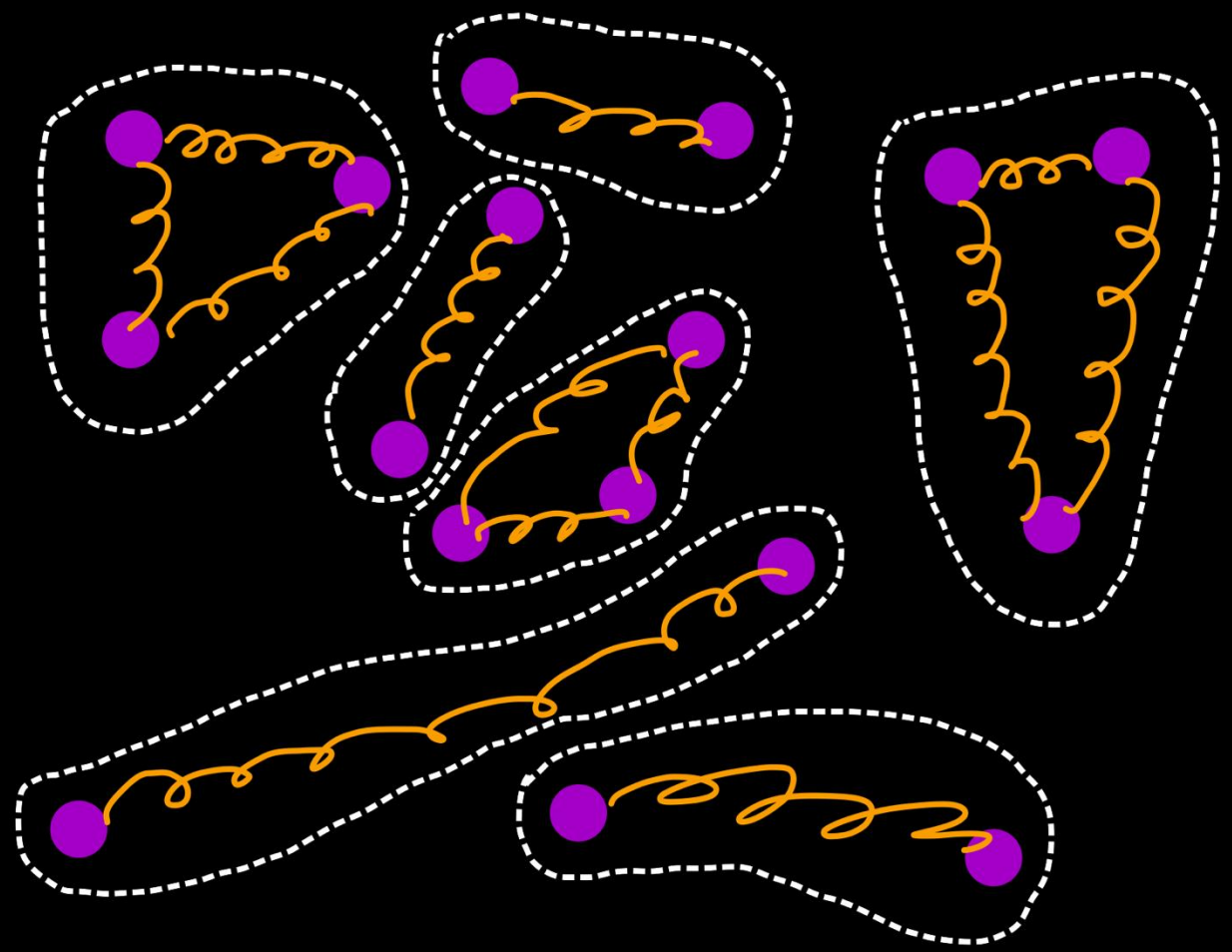
$$t = 10^{-6} \rightarrow 1$$

Quark-Hadron Transition

As the Universe expands and cools, the Quark gluon plasma changes phase, and forms *composite particles*, called *Hadrons*.

Hadrons divide into two families:

1. Baryons – Made of three quarks.
2. Mesons – Made of two quarks*.



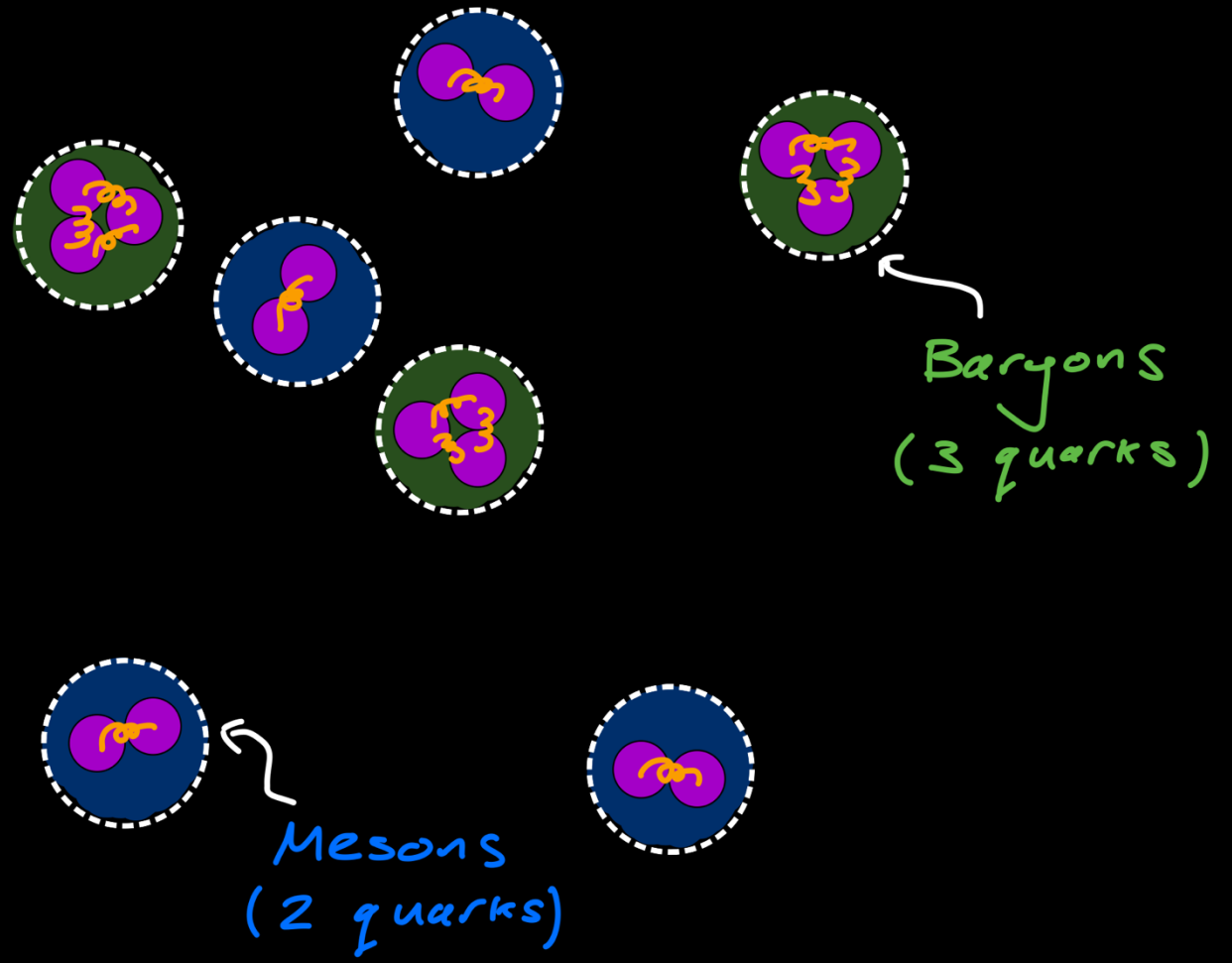
*One of these is always an anti-quark

The First Ten Seconds

$$t = 10^{-6} \rightarrow 1$$

Quark-Hadron Transition

As the Universe expands and cools, the Quark gluon plasma changes phase, and forms *composite particles*, called *Hadrons*.



Hadrons divide into two families:

1. Baryons – Made of three quarks
2. Mesons – Made of two quarks*

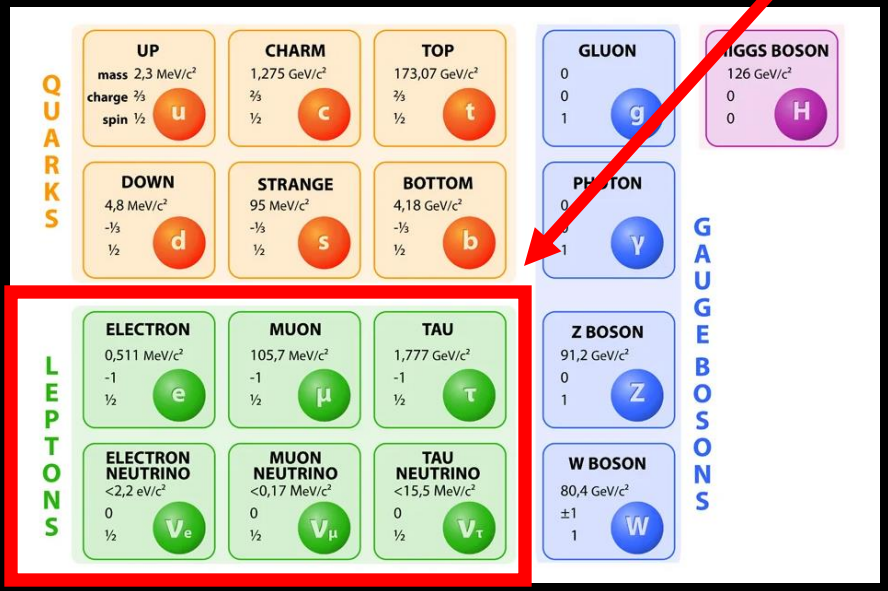
*One of these is always an anti-quark

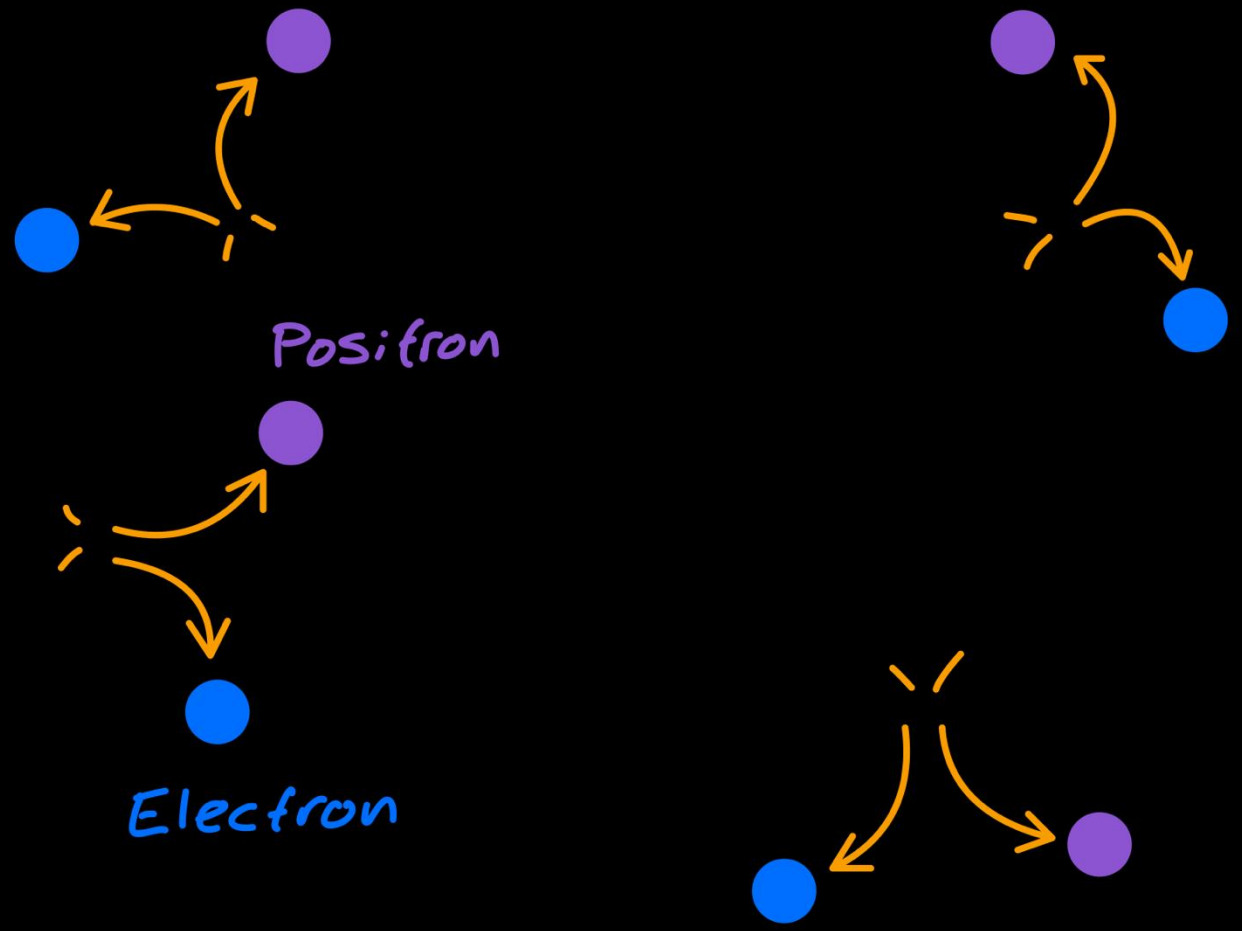
The First Ten Seconds

$$t = 1 \rightarrow 10$$

Lepton Epoch

As the Universe cools further, the residual energy from the annihilation of Baryons and Anti-Baryons creates pairs of Leptons and Anti-Leptons, in a process called *Leptogenesis*.



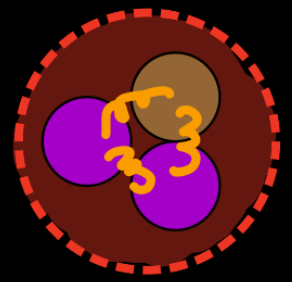


After Ten Seconds

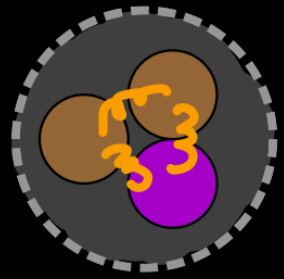
After ten seconds, we have created the basic components that make up all of the matter we can see in the Universe.

Two kinds of Baryon: Protons and Neutrons.

One kind of Lepton: the Electron.



Protons



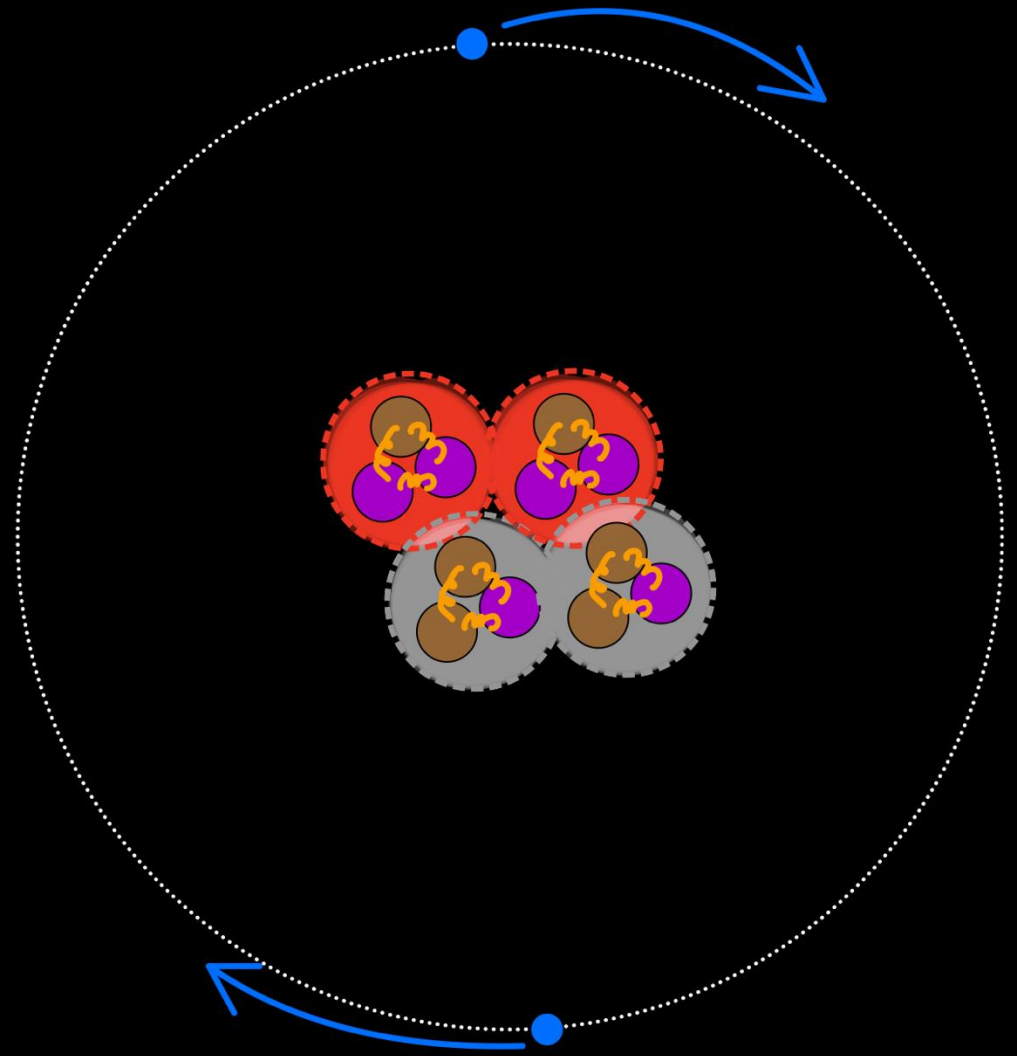
Neutrons

Electrons

After Ten Seconds

These three particles (Protons, Neutrons and Electrons) are all that is required to make everything we see on Earth, every other planet, moon and star in the sky.

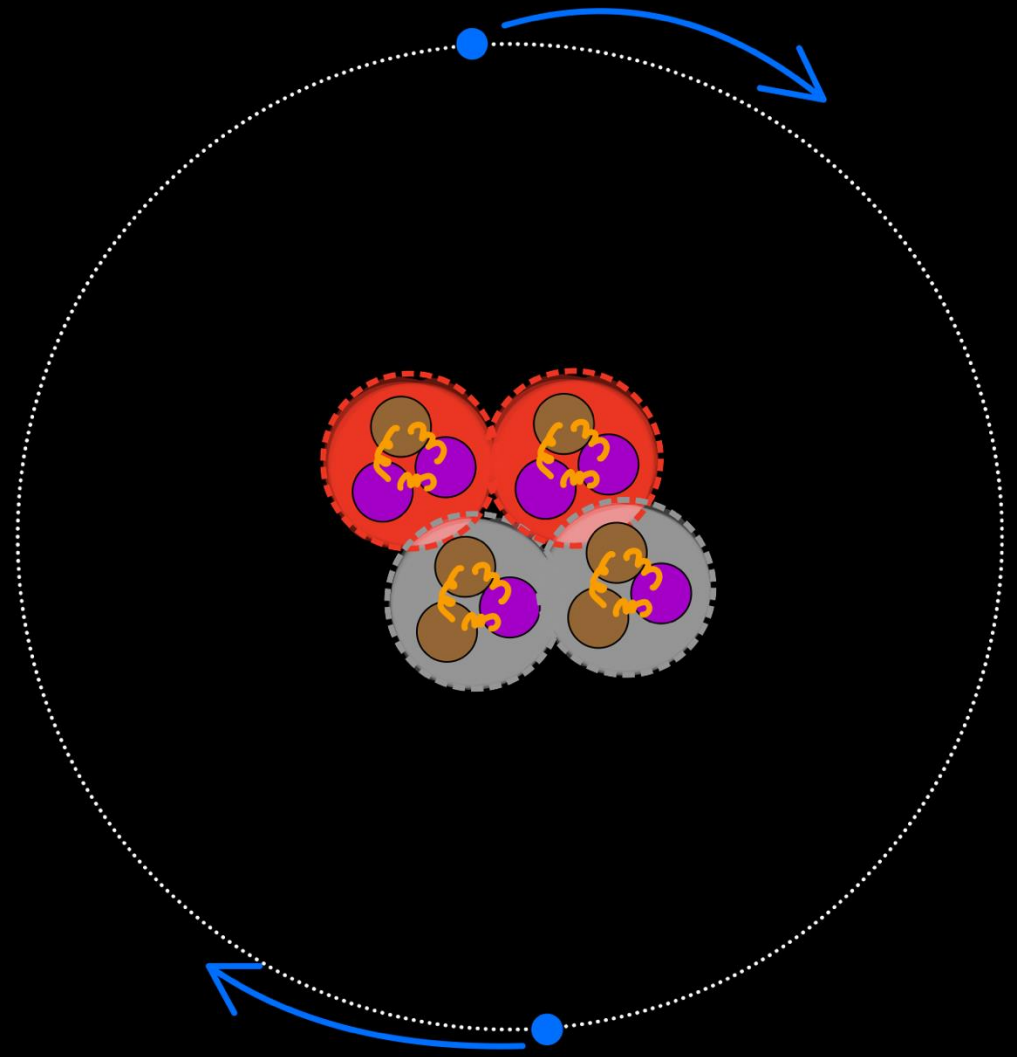
But this isn't all that's out there...



It would be nearly another 400,000 years until the first atoms formed.

After Ten Seconds

These three particles (Protons, Neutrons and Electrons) are all that is required to make everything we see on Earth, every other planet, moon and star in the sky.



But this isn't all that's out there...

Come to next weeks lecture, where we will discuss the mysterious nature of **Dark Matter**.

It would be nearly another 400,000 years until the first atoms formed.

After Ten Seconds

- Formation of First Atoms: $t \approx 400{,}000$ years
- Formation of First Stars: $t \approx 200$ million years
- Formation of First Galaxies: $t \approx 300$ million years
- First Stars in our Galaxy form: $t \approx 1$ billion years
- Our Sun first shines: $t \approx 9$ billion 231 million and 8 hundred thousand years
- The Earth forms: $t \approx 9$ billion 257 million years
- Life on Earth emerges: $t < 10$ billion 400 million years

Our Cosmic Address

- Where do we fit into the *big picture* of the cosmos? What are the larger structures of which we are a part?

- What else is there in the Universe?

Lines 1, 2, 3:

The Beecroft Gallery,

The United Kingdom,

Earth,

The Solar System,

The Milky Way,

~~The Virgo Supercluster,~~

The Universe

(Lines 1 and 2 are a bit too small for our discussion today)

Line 3: The Earth

History before Humans

- 4.6 billion years ago - Earth forms from leftover gas and dust in the early solar system.
- 4.5 billion years ago – Our Moon forms from debris, raised by a collision with another proto-planetary object.
- The Earth cools, the atmosphere clears, water oceans form. Volcanic activity slows.
- 3.7 billion years ago – Life!

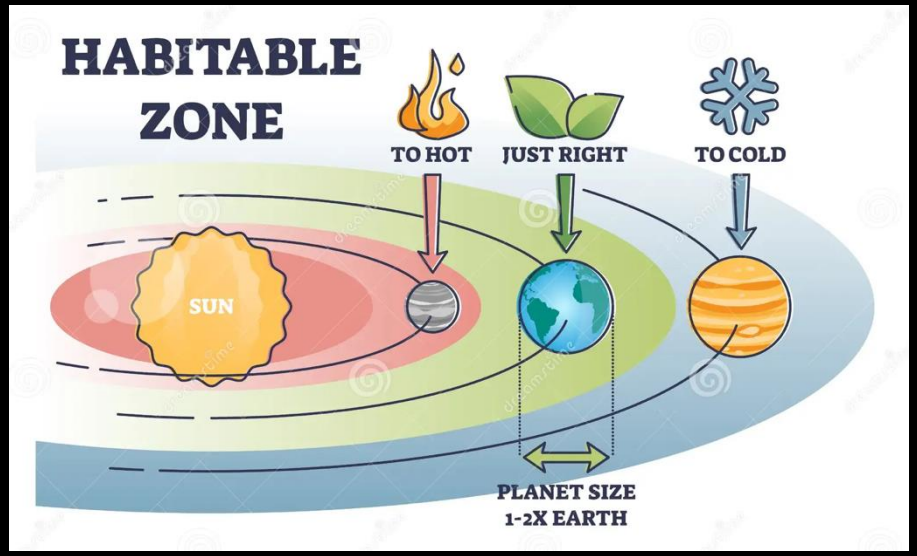
Formation of the Earth.

Formation of the Moon.

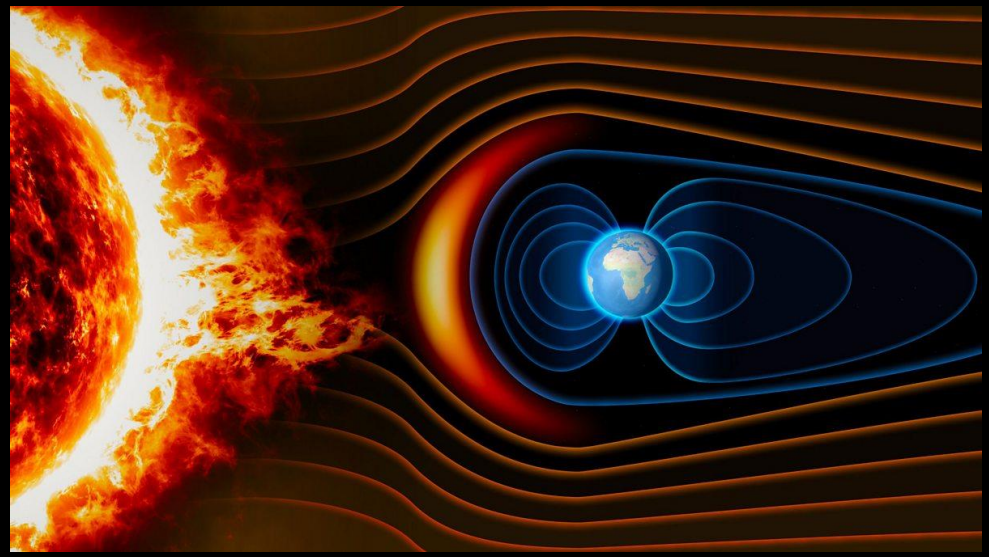
Line 3: The Earth

<u>What makes the Earth special?</u>

- Goldilocks / Habitable Zone – The region around the Sun, in which liquid water (a necessity for life) can exist.
- The Moon – Maintains our stable seasons and gives us the tides needed for much life on Earth.
- The Geomagnetic Field – Prevents the deadly stream of high energy particles from the sun (mostly protons and electrons) from stripping our Atmosphere



The Goldilocks / Habitable Zone.



The Geomagnetic Field, and Solar Winds.

Line 4:

The Beecroft Gallery,

The United Kingdom,

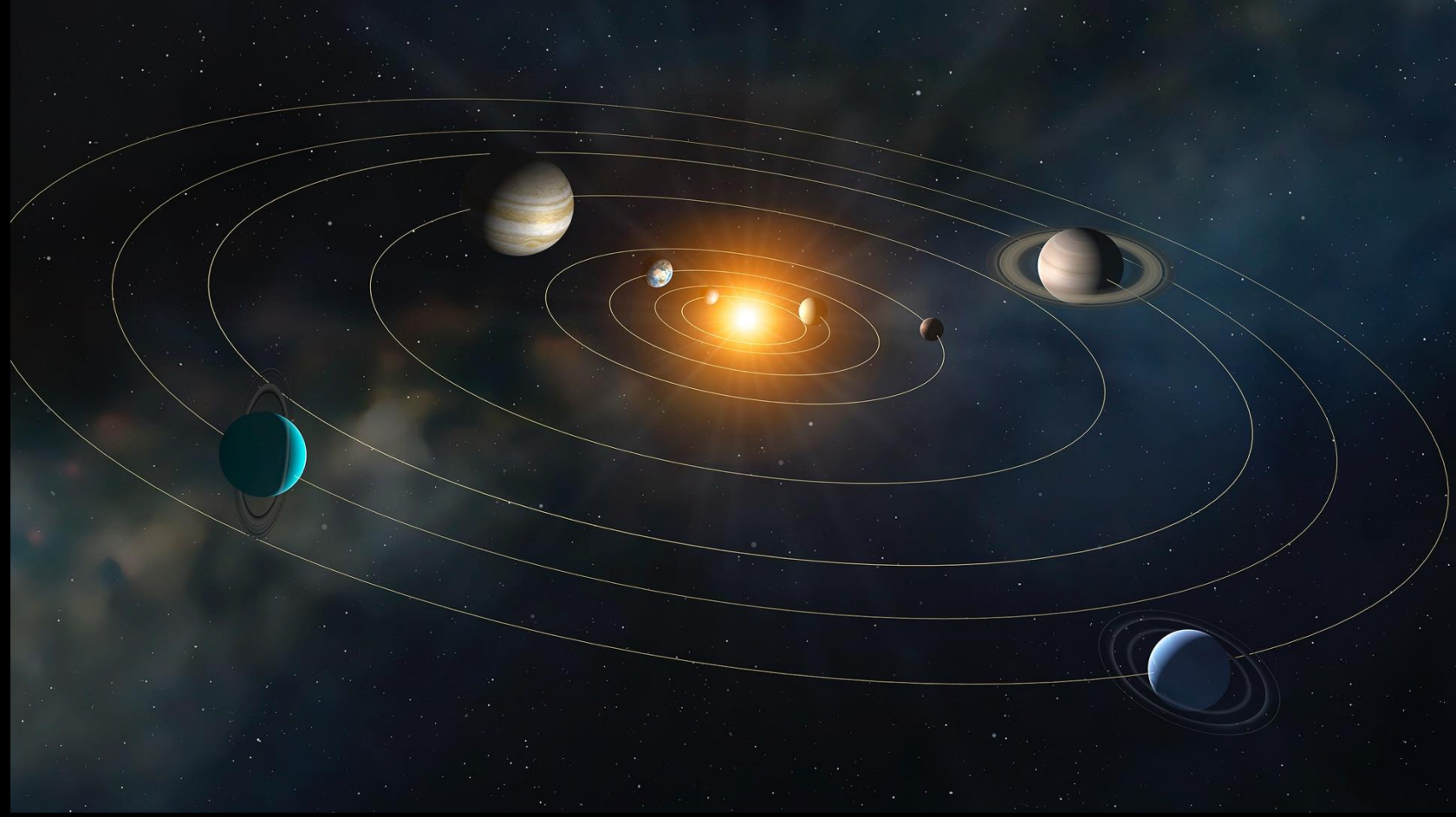
Earth,

The Solar System,

The Milky Way,

~~*The Virgo Supercluster,*~~

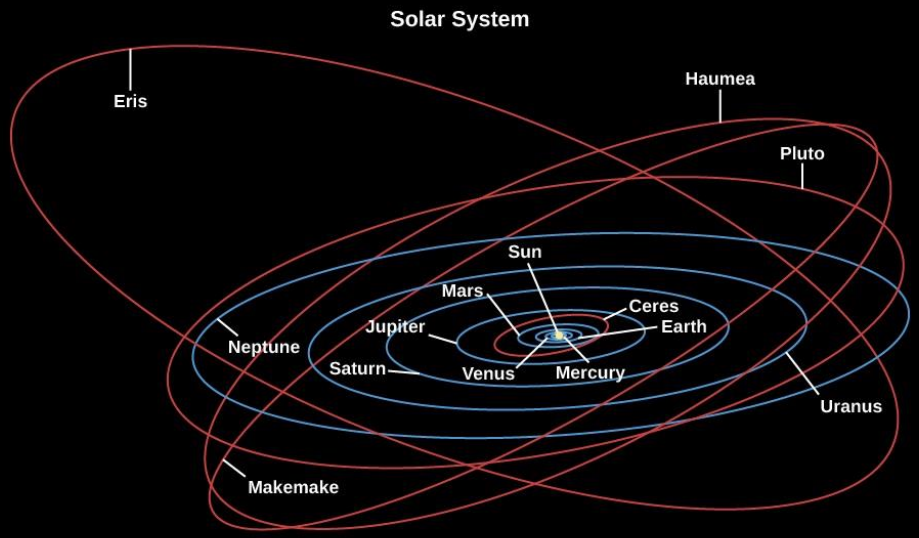
The Universe



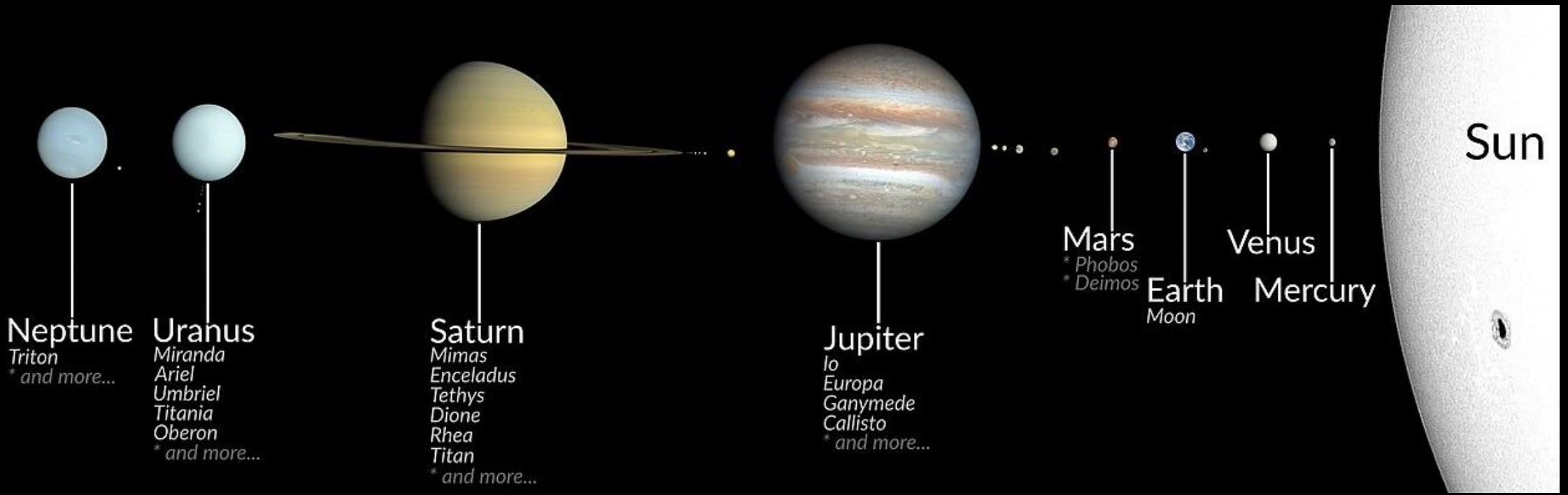
(Not remotely to scale…)

Line 4: The Solar System

Structure of the Solar System



Orbits of bodies in the solar system.

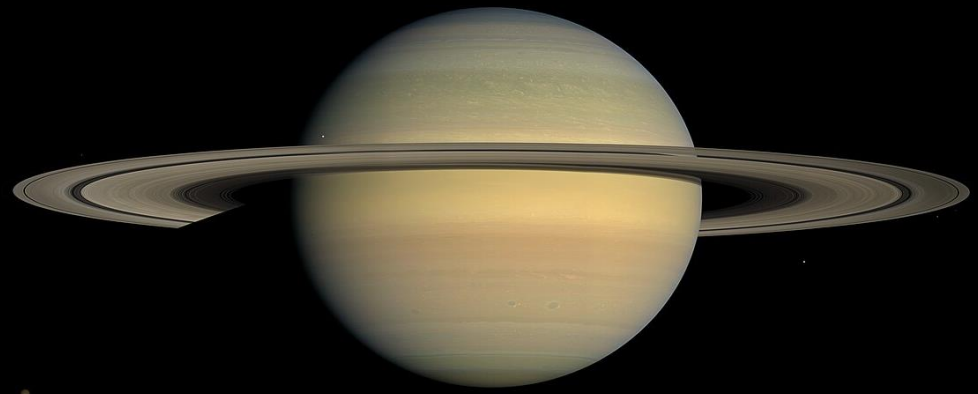


The Solar System (Planet sizes to scale, distances not to scale)

Line 4: The Solar System

<u>Planets in Focus</u>

- Saturn – A many mooned gas giant with an impressive ring system.



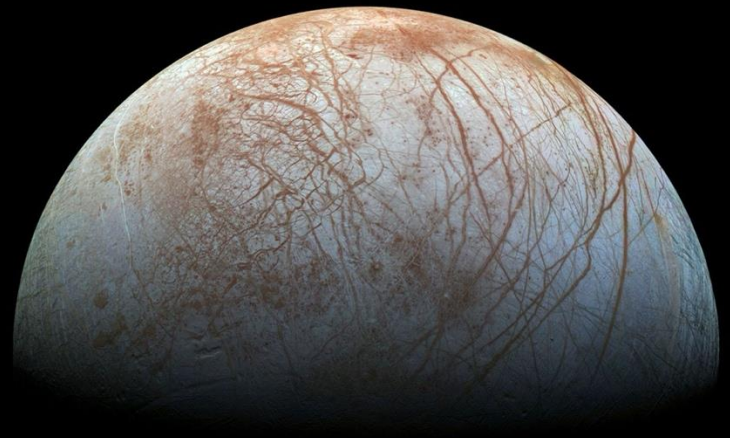
Saturn – The Ringed Planet

- Jupiter – The largest planet in our solar system, over 300 times the mass of the Earth.

Jupiter's 'great spot' is an anticyclonic storm system that has been raging for at least the last 190 years. The storms diameter is wider than the diameter of the EARTH.

Jupiter – Note the aurora at the North Pole.

Line 4: The Solar System



Jupiter's moon Europa.

Subsurface Oceans

- Europa is the smallest of Jupiter's four Galilean moons, and is believed to have a liquid ocean beneath a thick crust of ice. This ocean is prevented from freezing by *tidal heating*. It is thought that Europa ejects plumes of water into space from beneath its surface, much like Saturn's moon Enceladus.

- In October 2024, NASA launched the Europa Clipper Spacecraft. Due to reach Europa in April 2030, this probe hopes (among other things) to capture material from these plumes and investigate whether they contain the ingredients required for life.

The Europa clipper spacecraft.

Line 4: The Solar System

The Sun

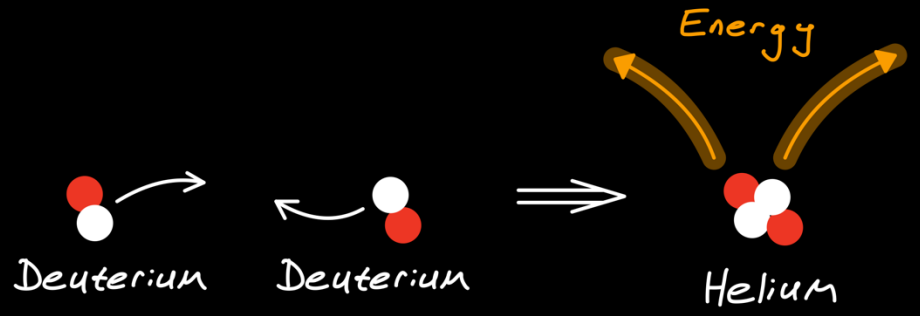
- The sun is the heart of our solar system. Its gravity holds the solar system together, it's heat and light allow life to exist on the Earth.

- The sun produces heat and light by nuclear fusion. Hydrogen nuclei combine to form Helium nuclear, and release energy in the process.

$$\Delta E = \Delta m c^2$$

- Stars move through several evolutionary stages in their life-times. Our sun is in its *Main Sequence* phase.

The Sun (taken by me)



Nuclear Fusion within the Sun

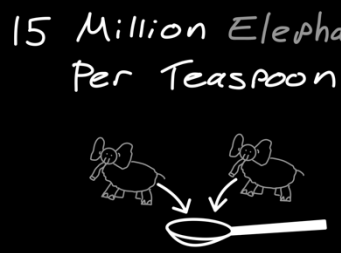
To hear more about stellar evolution, you can watch the lecture on Pulsars I gave on April 16th. Recording and full slides are on my website: CosmicConundra.com

Line 4: The Solar System

Stellar Evolution – Exotic End States

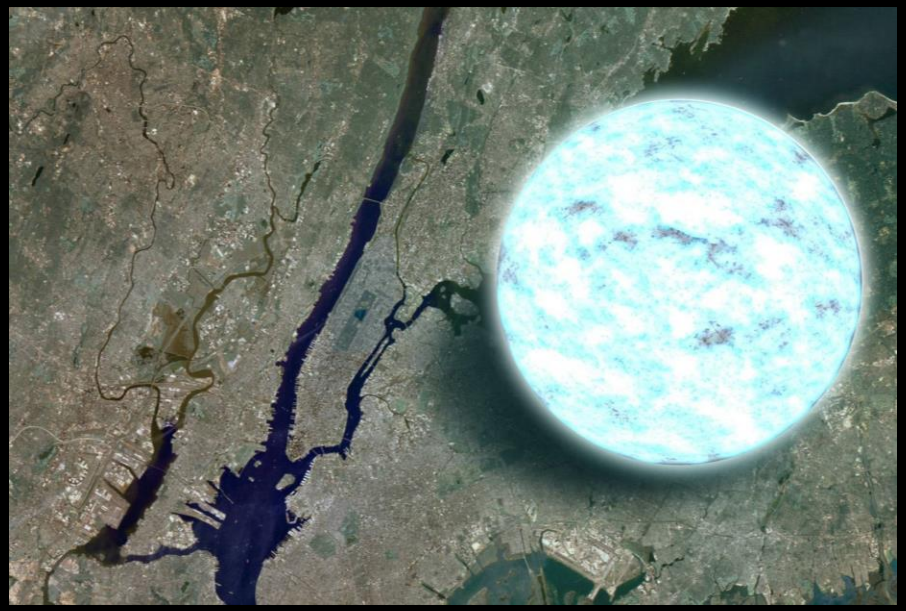
- White Dwarf Stars: The end state of stars with masses between 80% and 10x the mass of our sun.

- Neutron Stars: The end state of stars with masses over 8x the mass of our sun. Composed almost entirely of neutrons, with a density of around $5 \times 10^{17} \mathrm{kg\ m^{-3}}$ (or 15 million elephants per teaspoon).

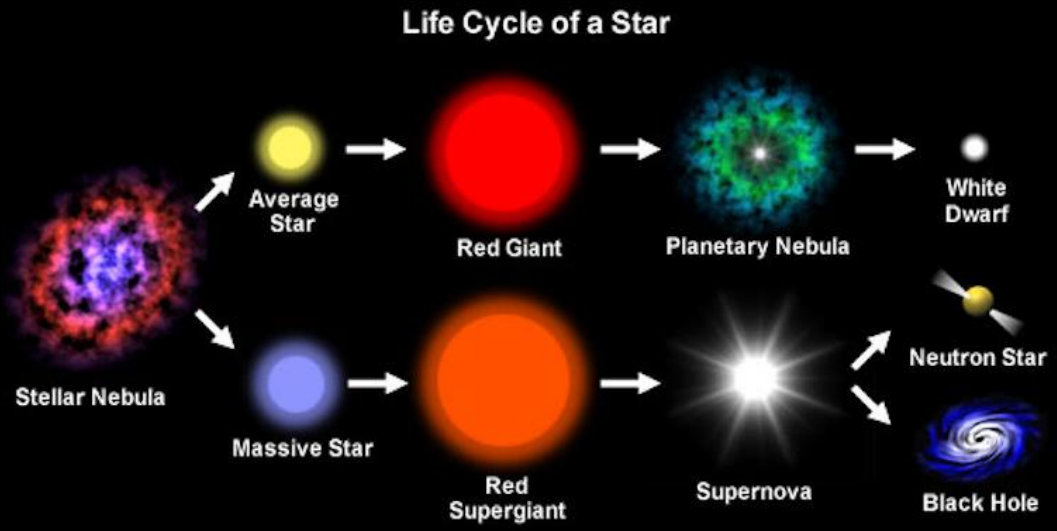


- Black Holes: We will come back to these on May 25th…

To hear more about stellar evolution, you can watch the lecture on Pulsars I gave on April 16th. Recording and full slides are on my website: CosmicConundra.com



A Neutron Star compared to New York City.



The Life Cycle of a Star.

Line 5:

The Beecroft Gallery,

The United Kingdom,

Earth,

The Solar System,

The Milky Way,

~~*The Virgo Supercluster,*~~

The Universe

The Milky Way (Well… Not really… Who could have taken the picture?)

Line 5: The Milky Way

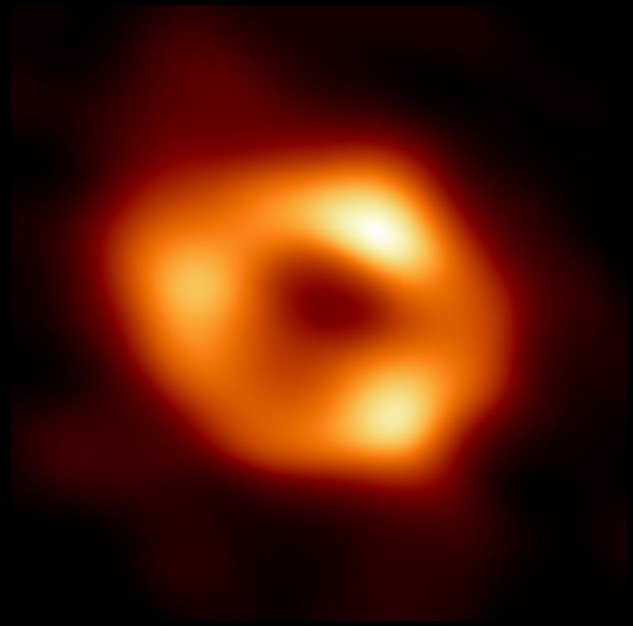
<u>Structure of the Galaxy</u>

- The Milky Way contains around 100 billion stars.

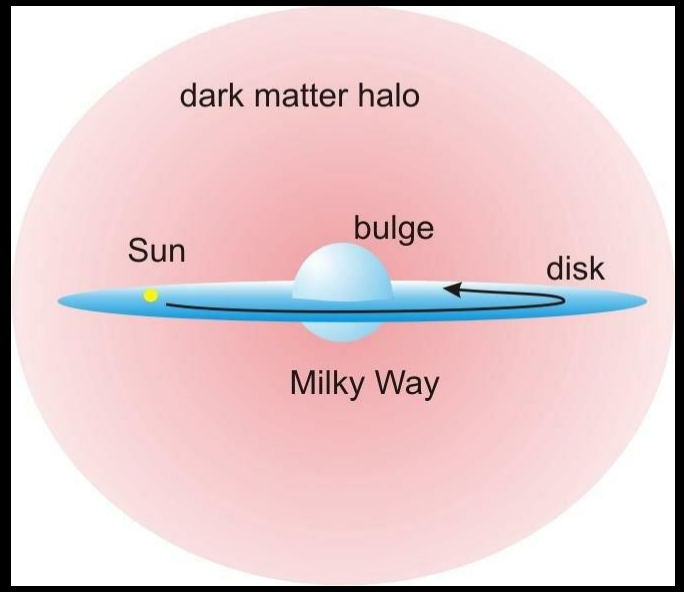
- Notice the bright center, and spiral arms. Sat at the center of our galaxy is a Supermassive Blackhole (Sagittarius A*).

- About 95% of the mass of the Galaxy is invisible '*Dark Matter*'

We will come back to Dark Matter next week…



EHT image of Sagittarius A*.



The Milky Way's Dark Matter Halo

Line 7:

The Beecroft Gallery,

The United Kingdom,

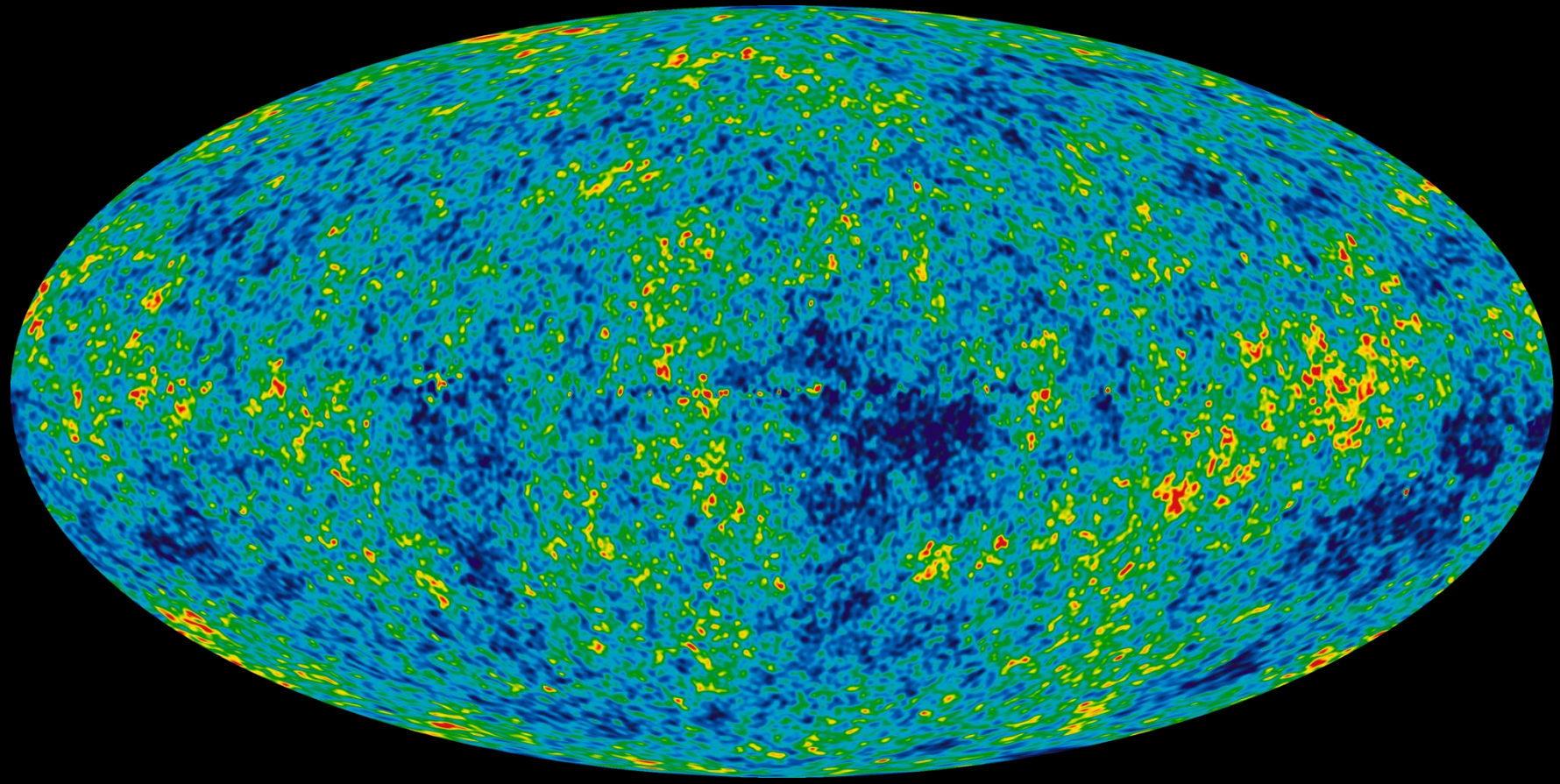
Earth,

The Solar System,

The Milky Way,

~~*The Virgo Supercluster,*~~

The Universe



The Cosmic Microwave Background

Line 7: The Universe

"The Observable Universe"

- When physicists say 'The Universe', this is typically shorthand for 'The Observable Universe'.

- This distinction has two causes:

1. The finite speed of light. ***Nothing**** in the Universe can travel faster than the speed of light (three hundred million meters per second).
2. The expansion of the Universe. The Universe is expanding, with the parts furthest from us receding away from us at the greatest speed.

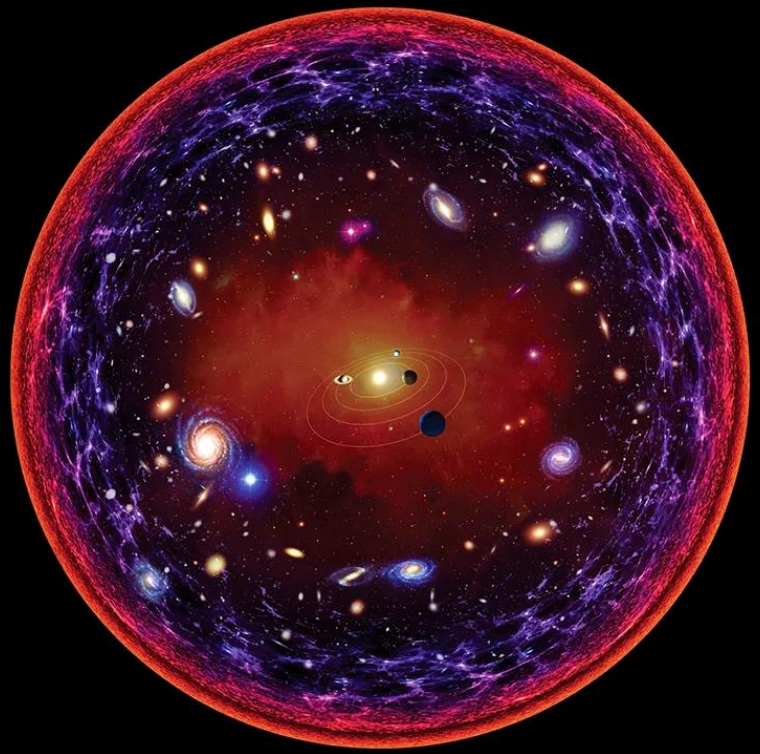


Illustration of the observable Universe.

*There is a get around clause here...

Interlude: Dark Energy

Earlier we discussed Einstein's 'biggest blunder', his Cosmological Constant.

Einstein added this term in to his equations as a mathematical fudge, so prevent the Universe from expanding.

Physically, this term can only arise from a constant (non-diluting) energy density.

Such energy densities would not be found until decades later, with our improved understanding of Quantum Theory.

Einstein's Cosmological constant

$$H^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

$\Lambda > 0 \longrightarrow$ Needed for a static Universe

$\Lambda < 0 \longrightarrow$ Leads to an accelerating Expanding Universe

Interlude: Dark Energy

The Accelerating Universe

In 1998, Astronomers looking at type 1a supernovae were able to establish that the Universe is indeed accelerating its expansion.

The supernovae occur when a White Dwarf leachers material from a companion star sharing its orbit, leading to a runaway flash of nuclear fusion.

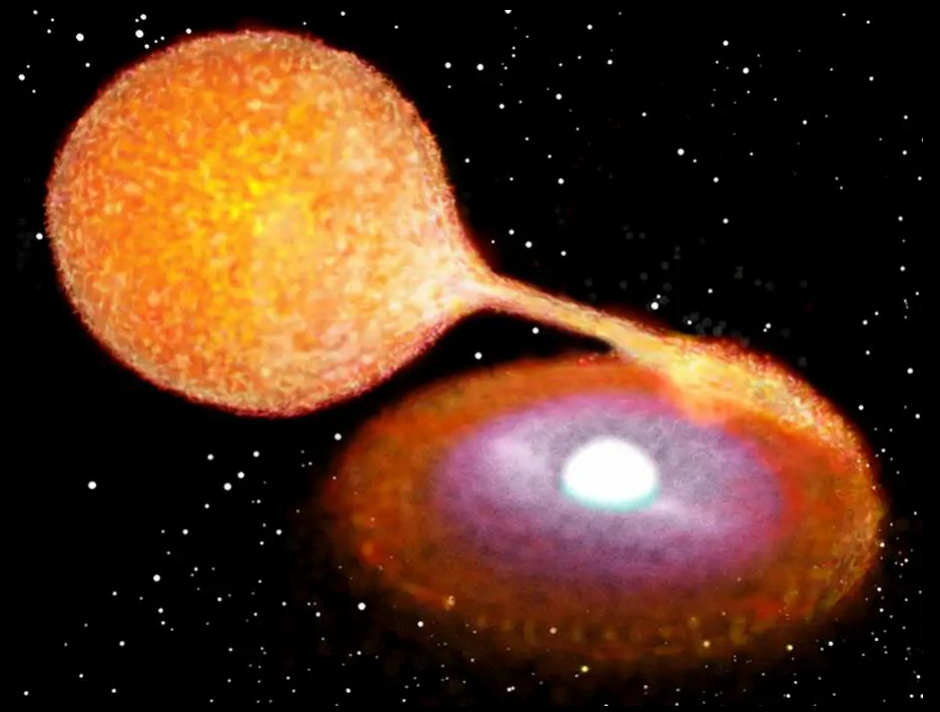


Illustration of a binary Red Giant-White Dwarf system.

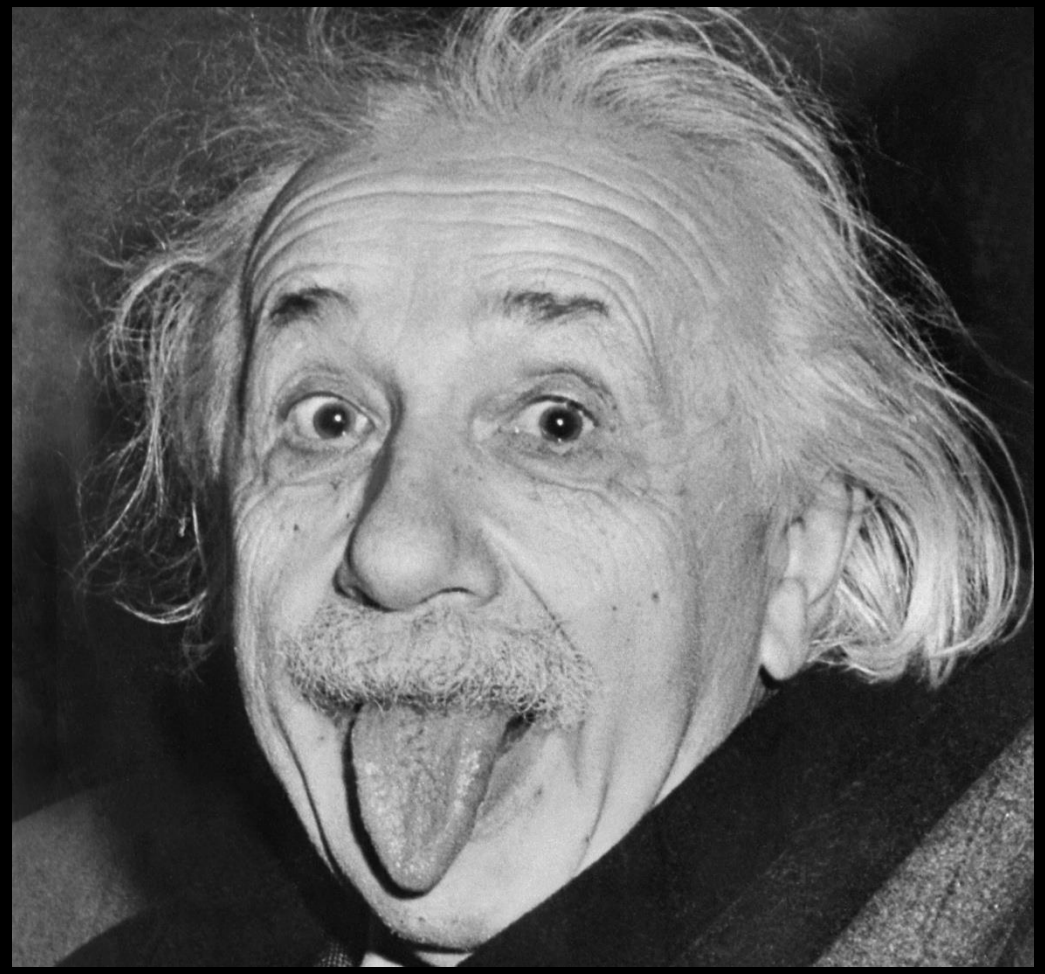
Tycho's Nova, the remnant of a type 1a supernova.

Interlude: Dark Energy

Einstein was right in the end! (Well.. Sort of…).

He introduced a positive cosmological constant to try and halt the expansion of the Universe, but we see some evidence for a negative cosmological constant, leading to an accelerating Universe.

Understanding where the cosmological constant originates, and how to calculate its value at a theoretical level is an open problem in physics (the cosmological constant problem).



Beyond the Universe?

<u>“The Multiverse”</u>

- There are different kinds of **hypothetical** multiverses described by theoretical physicists.

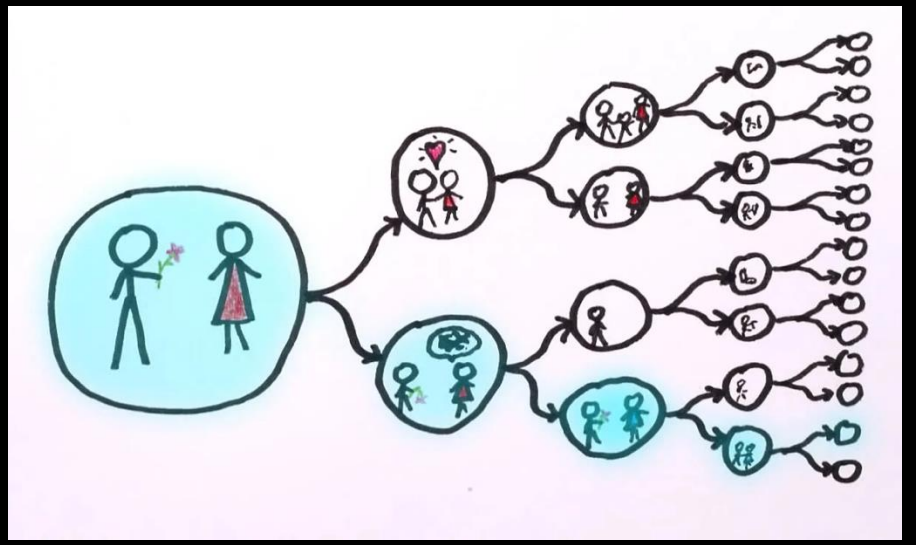
- Level 1: ‘Eternal Inflation Multiverse’.

A consequence of the hypothetical rapid expansion of the Universe (inflation), which leads to pockets of space causally disconnected from out own Universe. This type of Multiverse is basically just ‘more Universe’.

- Level 3: The ‘Everett Multiverse’.

Named for Hugh Everett’s ‘Many Worlds Interpretation’ of quantum mechanics. (We will come back to this next week)

Illustration of ‘the Multiverse’.



Fissioning in an Everett Multiverse

The Carina Nebula. A vast and varied amalgam of stellar nurseries, supergiant stars, and globular structures. 230 lightyears across and nearly 8500 lightyears from the Earth

Westerlund 2 is a 3000 strong cluster of young start stars in the Whirling Dervish Nebula, near the constellation of Carina.

The Bubble Nebula. An emission nebula in the constellation of Cassiopea. The characteristic bubble shape is a result of the stellar wind from a bright star located at its center, ‘blowing’ up the bubble.

Questions!

Coming Up…

The Science of Space: A Physicists Guide to the Galaxy

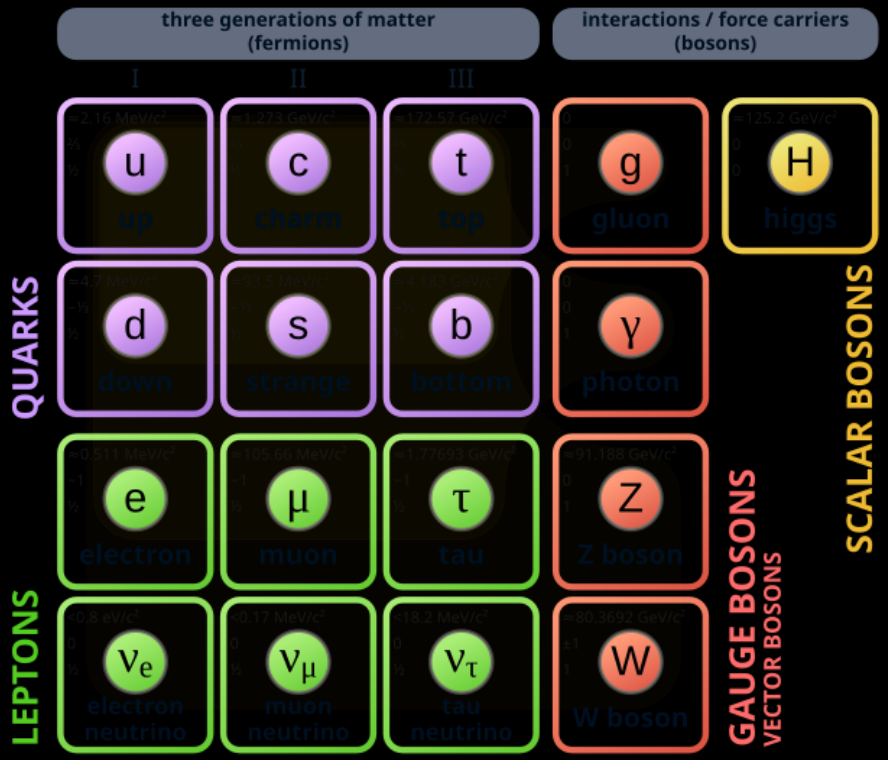
Every Sunday 11:30am in May @ The Beecroft Gallery Lecture Theatre

~~*'Our Place in the Cosmos' (04/05)*~~

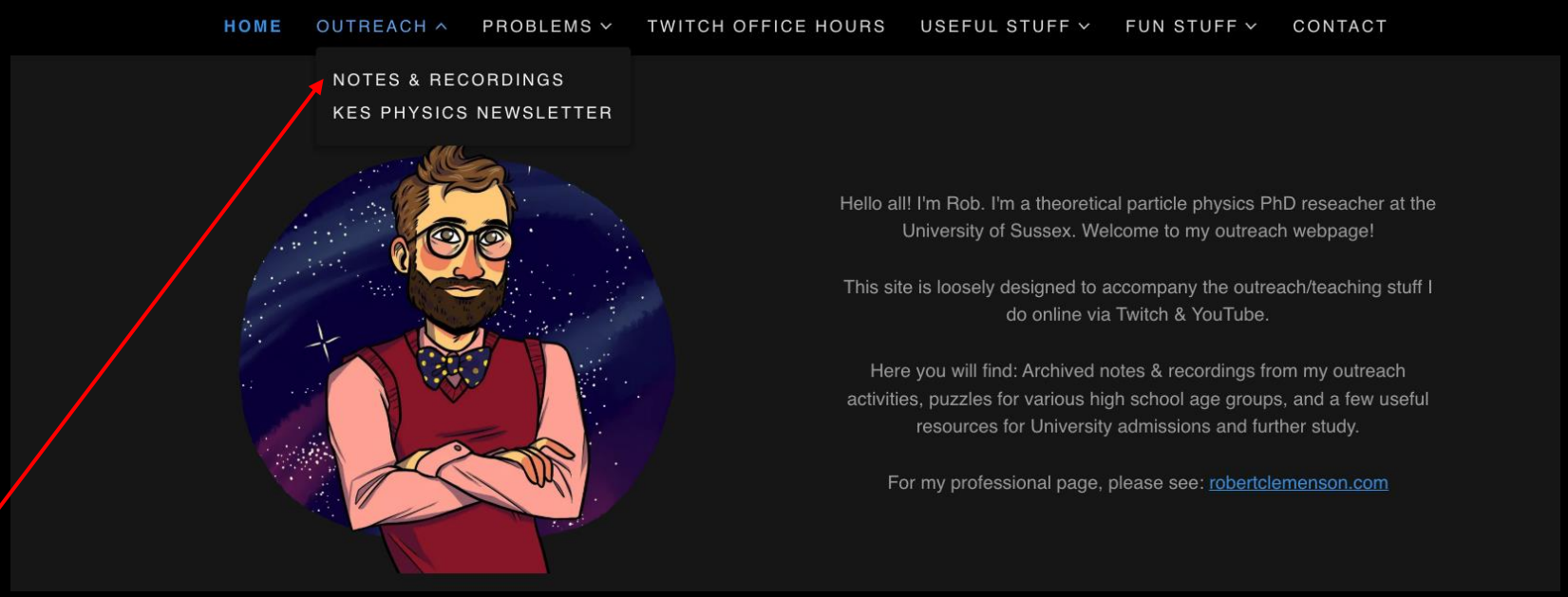
'Schrodinger's Cat in the Particle Zoo' (11/05)

'Time Travel 101' (18/05)

'Black Holes and Beyond' (25/05)



Lecture Slides



These lecture slides are available on my outreach website:

CosmicConundra.com