BIG BANG LECTURE SUMMARY

TO DATE

Einstein, Hubble, and Hoyle

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu} \Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda c^2}{3} - \frac{\kappa c^2}{a^2}$$

$$\left(\frac{\ddot{a}}{a}\right) = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

In 1915, I came up with a set of equations that modelled Gravity, called The General Theory of Reality

In 1931 Edwin Hubble helped me correct a major misunderstanding, and showed me that the Universe was expanding, so I removed all terms with orange.

In 1922 Alexander Friedmann applied my equations to Cosmology and we call them The Friedman Equations.

A Catholic priest, Georges Lemaître, first proposed what that the entire cosmos was once compressed into a “primaeval atom” (his words) that then exploded and expanded, resulting in our modern-day universe. Fred Hoyle made fun of this new cosmology as it did not follow his believed Steady State Universe, and coined the phase Big Bang on March 28th, 1949, on a radio program to ridicule it.

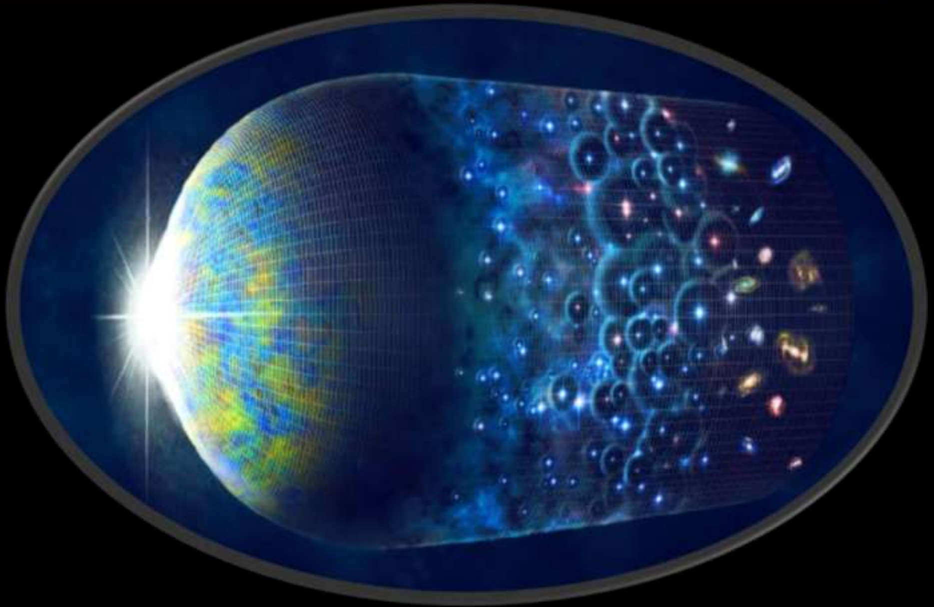
O.K., thanks for the History lesson. But still, what is it? and how does it explain our Universe?

The Internet

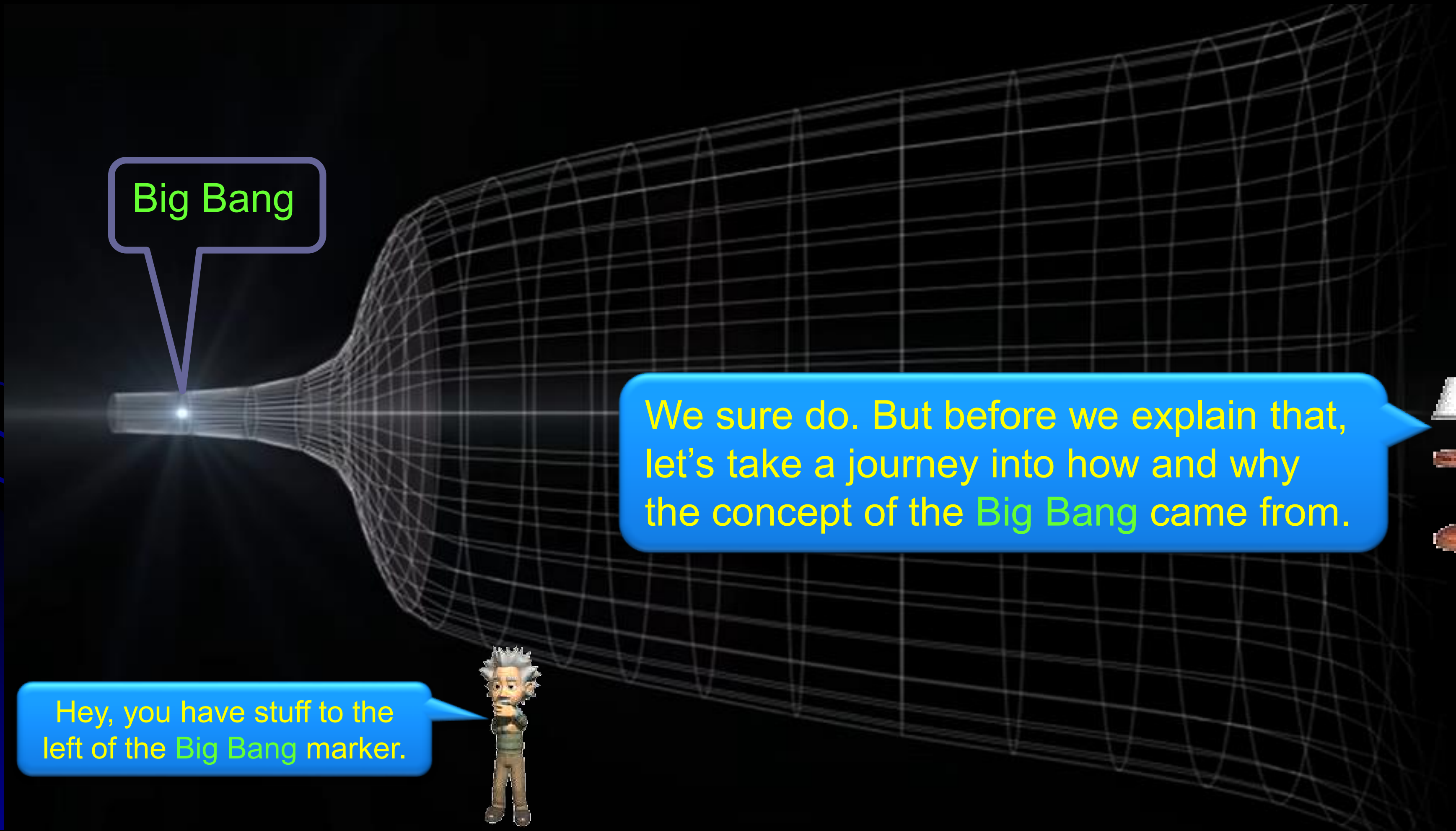
I decided to scan the internet and see what the Big Bang is defined as.

That said, most sources said that the Big Bang tells us that the entire Universe, including every atom, every planet, every star, every galaxy, and every physics property that currently spans over 90 billion light years across, was once compressed into a volume no bigger than a peach, or a golf ball, or a marble, or a pea, or an atom, or a singularity. And that this process took about 13.8 Billion years to occur. Usually, they included a cool looking image.

There is a lot of missing stuff, and even inconsistencies in that definition even though it relays an overall picture of the phrase, Big Bang.



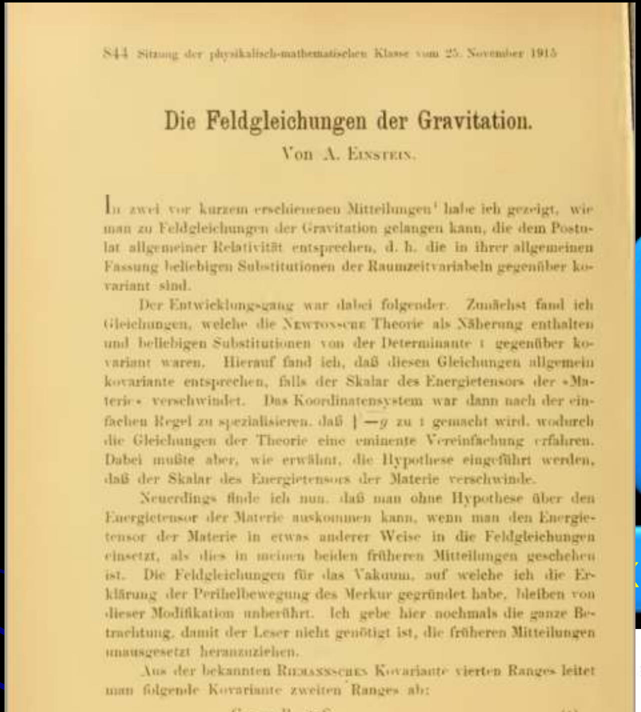
To better tell the story, let me draw a better diagram of the Big Bang. Notice how it differs from what most of you have come to think of the Big Bang.



We sure do. But before we explain that, let's take a journey into how and why the concept of the Big Bang came from.

Hey, you have stuff to the left of the Big Bang marker.

Einstein's General Theory of Relativity



844 Sitzung der physikalisch-mathematischen Klasse vom 25. November 1915

Die Feldgleichungen der Gravitation.

Von A. Einstein.

In zwei vor kurzem erschienenen Mitteilungen[1] habe ich gezeigt, wie man zu Feldgleichungen der Gravitation gelangen kann, die dem Postulat allgemeiner Relativität entsprechen, d. h. die in ihrer allgemeinen Fassung beliebigen Substitutionen der Raumzeitvariabeln gegenüber kovariant sind.

Der Entwicklungsgang war dabei folgender. Zunächst fand ich Gleichungen, welche die Newtonsche Theorie als Näherung enthalten und beliebigen Substitutionen von der Determinante 1 gegenüber kovariant waren. Hierauf fand ich, daß diesen Gleichungen allgemein kovariante entsprechen, falls der Skalar des Energietensors der »Materie« verschwindet. Das Koordinatensystem war dann nach der einfachen Regel zu spezialisieren, daß $\sqrt{-g}$ zu 1 gemacht wird, wodurch die Gleichungen der Theorie eine eminente Vereinfachung erfahren. Dabei mußte aber, wie erwähnt, die Hypothese eingeführt werden, daß der Skalar des Energietensors der Materie verschwinde.

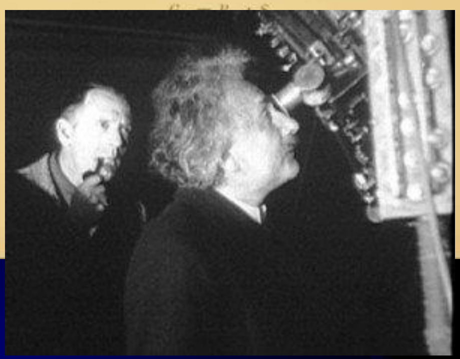
Neuerdings finde ich nun, daß man ohne Hypothese über den Energietensor der Materie auskommen kann, wenn man den Energietensor der Materie in etwas anderer Weise in die Feldgleichungen einsetzt, als dies in meinen beiden früheren Mitteilungen geschehen ist. Die Feldgleichungen für das Vakuum, auf welche ich die Erklärung der Perihelbewegung des Merkur gegründet habe, bleiben von dieser Modifikation unberührt. Ich gebe hier nochmals die ganze Betrachtung, damit der Leser nicht genötigt ist, die früheren Mitteilungen unausgesetzt heranzuziehen.

Aus der bekannten Riemannschen Kovariante vierten Ranges leitet man folgende Kovariante zweiten Ranges ab:

(1)

(1a)

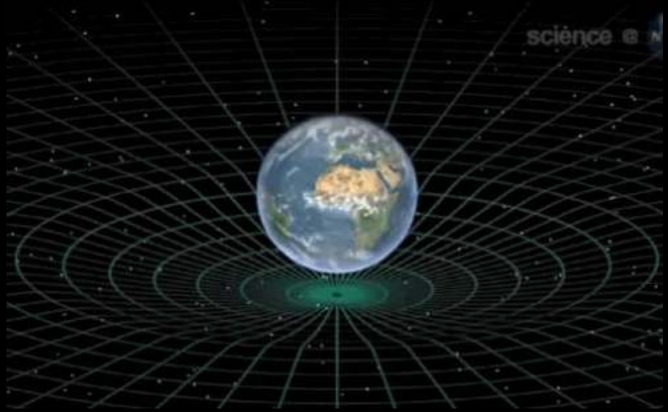
(1b)



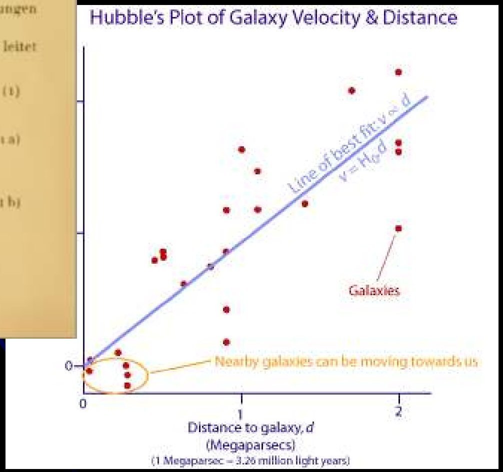
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G T_{\mu\nu}}{c^4}$$

As previously mentioned, in 1915 I published my work on General Relativity.

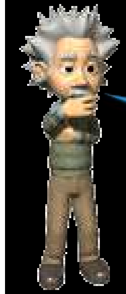
But I goofed. I made my Field Equations match the current Standard Model of the Universe.



panding, its not Static.



$$G_{\mu\nu} = \frac{8\pi G T_{\mu\nu}}{c^4}$$

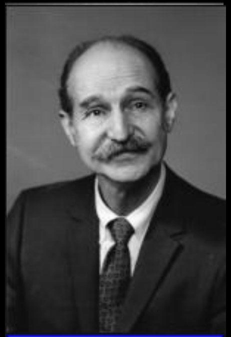


Thanks Hubbs, I can fix my blunder.

A Predicted After Glow

In 1948 an American cosmologist Ralph Alpher, working with Robert Herman and George Gamow, first predicted the after-glow from the Big Bang.

Alpher



Herman

Gamow

A precursor paper published by Alpher and Gamow in April 1, 1948 added the name of Bethe to pun the first 3 Greek letters.

Later the same year, collaborating with Herman, Alpher predicted the temperature of the residual radiation to be at about 5K.

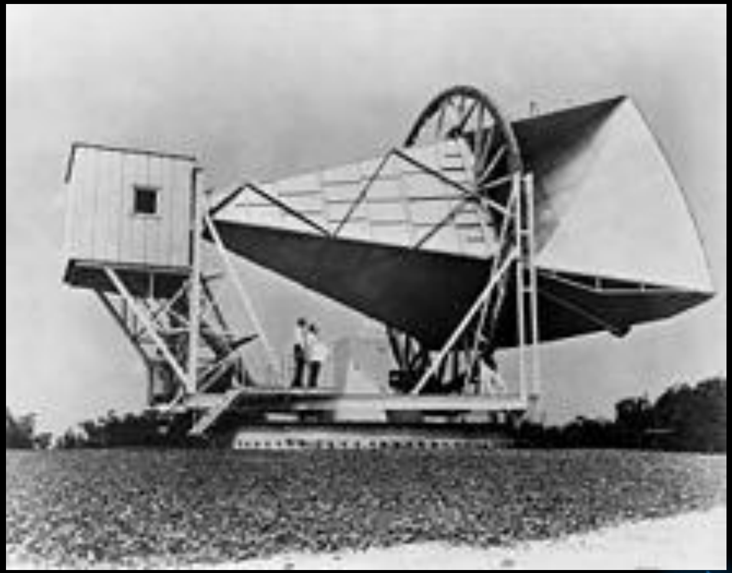
Sadly, their predictions faded into oblivion with time.

At least until the 1960’s

The Search

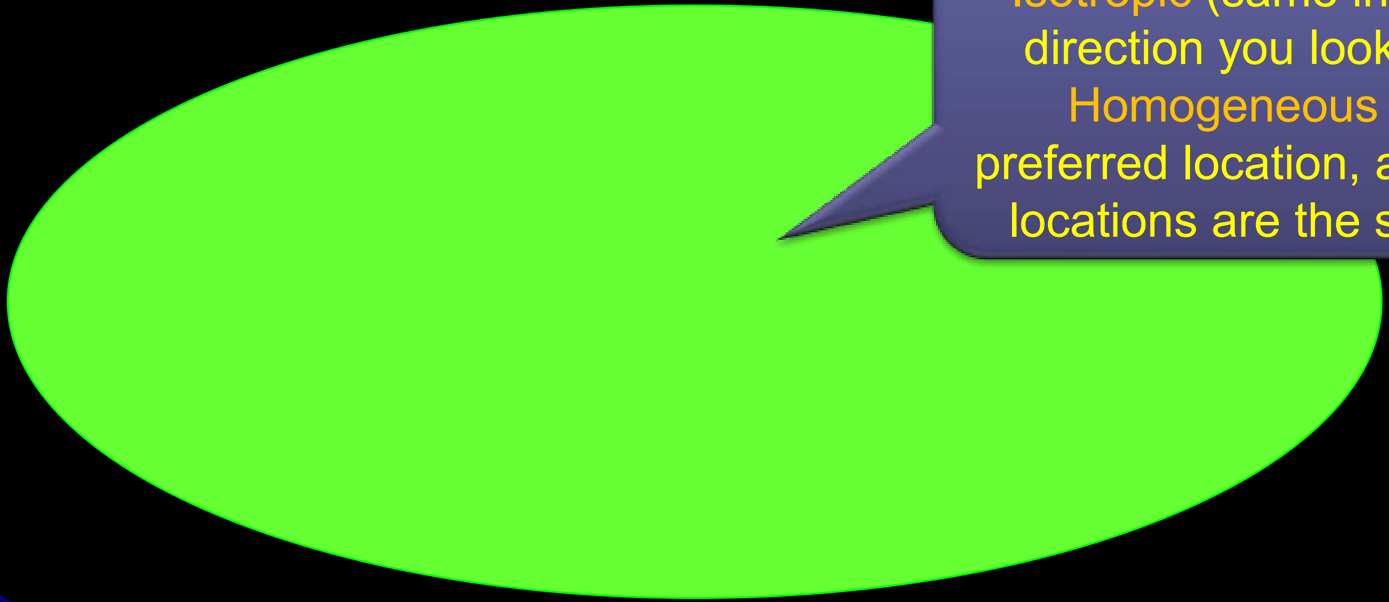
In 1964, Robert Dicke rediscovered the Alpher paper and with David Todd Wilkinson and Peter Roll, built a Dicke radiometer on the roof at Princeton University, and began trying to measure the cosmic microwave background.

Meanwhile down the road (37 Miles away) Arno Penzias and Robert Wilson at the Crawford Hill location of Bell Telephone Laboratories in nearby Holmdel Township, New Jersey had built a Dicke radiometer that they intended to use for satellite communication experiments.



What did they See?

A Uniform Cosmic Microwave Background energy that corresponded to 2.725K



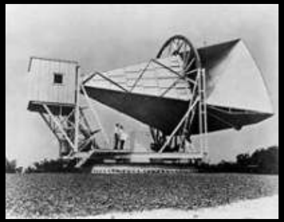
Isotropic (same in every direction you look) and Homogeneous (no preferred location, all home locations are the same).

Images of the CMB are drawn like ellipses because it is a map projection of a 3D object onto a 2D plane (this is called a Babinet or elliptical projection.

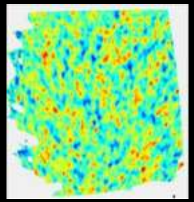
We need more and Better Data

To pull out more data from the CMB, we need higher resolution images with more data. So, time and technology came to our rescue.

Original Horn

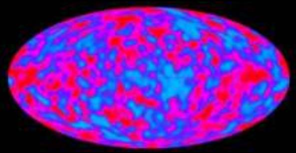


Boomerang



Balloon Observations Of Millimetric Extragalactic Radiation ANd Geophysics

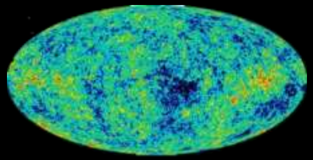
COBE



Cosmic Background Explorer

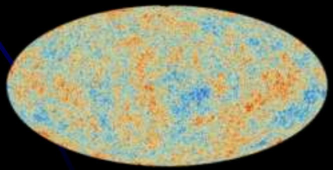
COBE team received Nobel Prize in 2006

WMAP



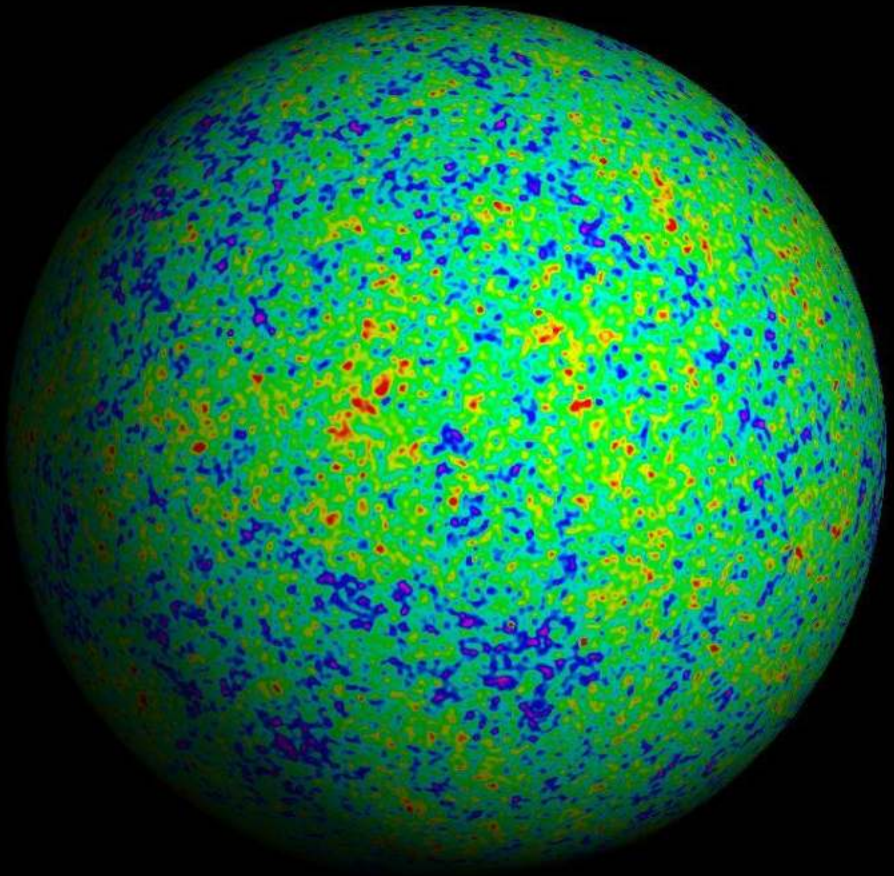
Wilkinson Microwave Anisotropy Probe

Planck



European Space Agency

So, what does this data indicate



Yes, what's all the fuss. Oh by the way, what are all these green , blue, red and yellow blotches all over the CMB?

In a Nut Shell

That the Universe on a large scale is Homogeneous and Isotropic.

That the Universe contains about 5% baryonic matter.

That the Universe contains about 25% Dark Matter.

Our model of baryogenesis was correct, specifically the Lambda CDM Model (75% hydrogen, 25% Helium).

Large scale galactic structure genesis.

We have an unusual odd parity problem (cosmic birefringence)

That the Universe contains about 70% Dark energy.

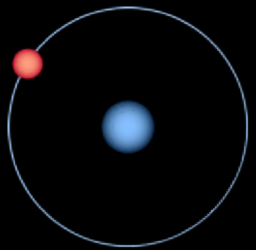
The hot Big Bang started our Universe some 13.8 billion years ago.

That the Universe is flat.

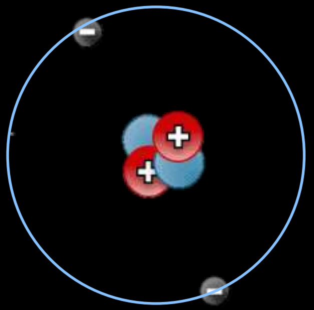
That the Universe is expanding.

Very high likely early moment of Inflation.

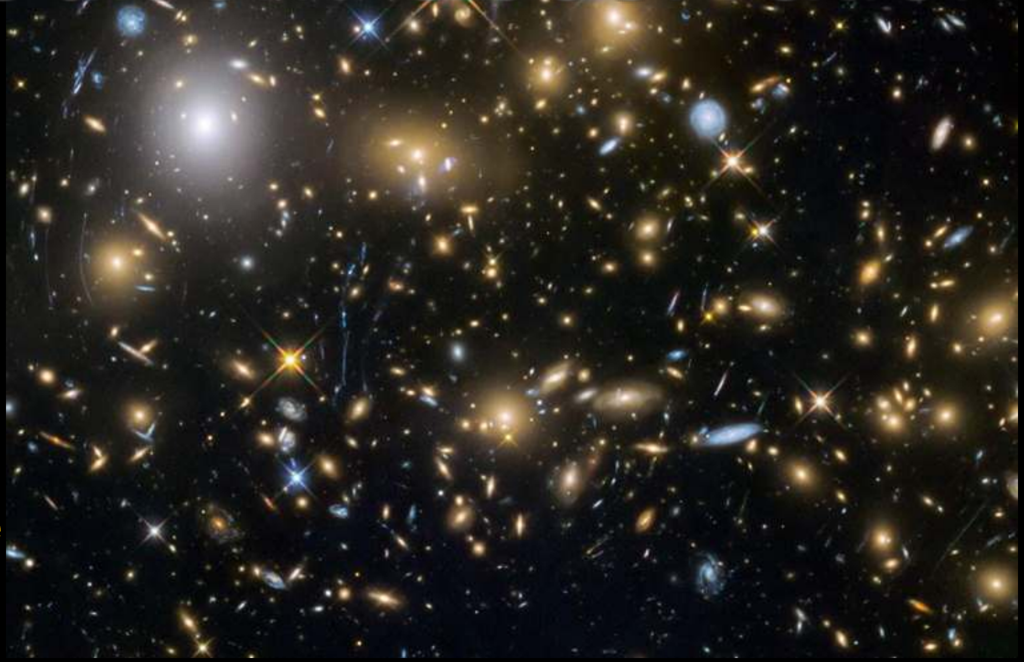
Current Observations



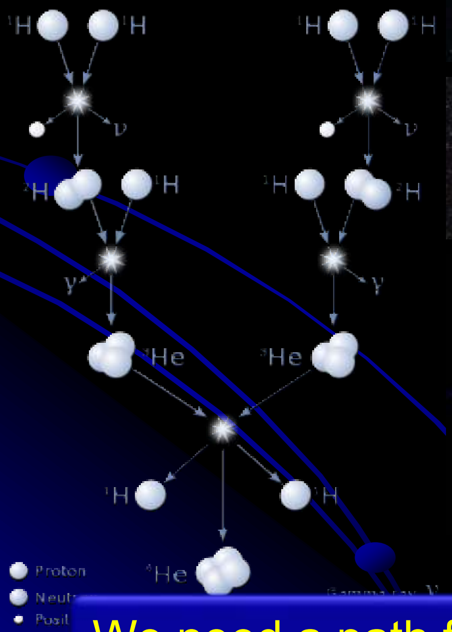
Hydrogen=74%

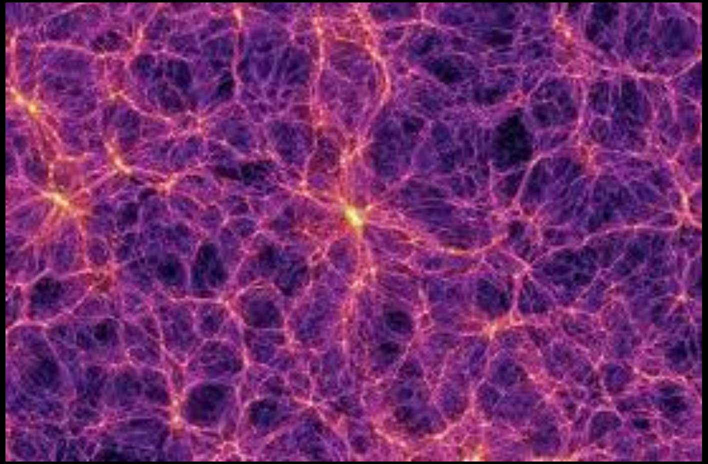


Helium = 24%



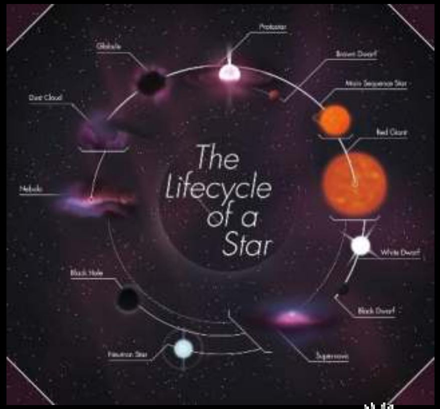
Proton-Proton Cycle





Homogenous and Isotropic

Star Life Cycle



We need a path from the past to the present that explains what we physically see.

Current Observations

In 1930’s Hubble observed that the Universe was expanding.

In 1960’s CMB was observed by Penzias and Wilson.

In 1970’s Dark Matter’s effect was observed.

In 1990’s Perlmutter and Schmidt observed that the Universe was accelerating.

The path, is the Big Bang Theory. This path must lead us to what we currently observe with the knowledge that with more data our model will be refined, but it must explain what we observe in all of the sciences, not just Cosmology.

Enough rambling, what does the Big Bang say about how we got here?

The Age of the universe

We already had a foundational formula: The Friedmann Equation

So, our models Stop at t=0, what do they say about the current age of the Universe?

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{\kappa c^2}{a^2}$$

You may of heard of this term. It is called the Hubble Constant

$$H \equiv \frac{\dot{a}(t)}{a(t)}$$

This equation relates the rate of change to the scale factor to the matter content of the Universe. Using this equation (with more complex math …. That calculus thing is needed), we can actually determine the change in time per the change in the Scale Factor and more accurately calculate the age of the Universe.

$$t = \frac{1}{H_o} f\left(\Omega_m, \Omega_r, \Omega_\Lambda, \Omega_k \ldots\right)$$

The Age of the Visible Universe

Sure, the Hubble Constant contains that number. Let's show you the power of Math

$$H_o$$

Is it possible for you to approximate the current age of the Universe?

$$v = H_o d$$

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

$$\frac{1}{H_o} = \frac{d}{v}$$

$$\frac{1}{H_o} = t$$

This tells us the time (age of the Universe) is just the reciprocal of the Hubble Constant, H_o

$$t = \frac{1}{71.5\,\frac{\frac{km}{s}}{Mpc}}$$

$$t = \frac{1}{71500\,\frac{\frac{m}{s}}{Mpc}}$$

$$t = \frac{1}{71500\,\frac{\frac{m}{s}}{Mpc \times \frac{3.09 \times 10^{22}\,m}{Mpc}}}$$

$$t = \frac{3.09 \times 10^{22}\,m}{71500\,\frac{m}{s}}$$

$$t = 4.32 \times 10^{17}\,s$$

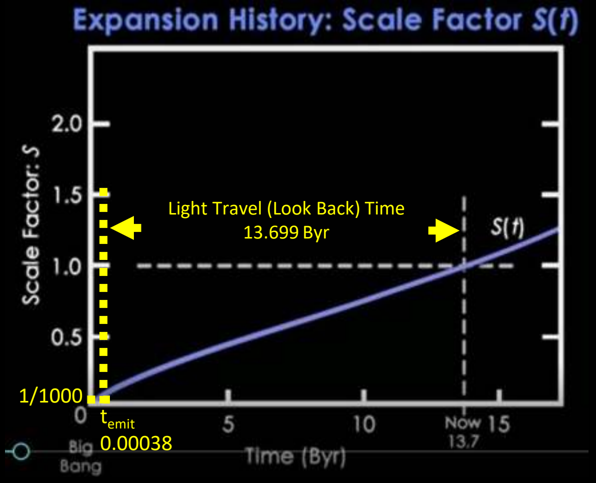
$$t = \frac{4.32 \times 10^{17}\,s}{31556926\,\frac{s}{yr}}$$

$$t = 13.7\ Billion\ Years$$

The Size of the Visible Universe

How about the size Universe?

Embedded in our Equations is a relationship between Scale, Time, and Size:



From the graph, the t_{emit} (CMB) was 380000 yr after the Big Bang. Therefore, the Light Travel Time was 13.7-0.00038 or 13.699 Byr. Then the d_{LT} must also be 13.699 Billion Light Years.

We are really talking about the distance to the visible horizon. You may read about words like coordinate distance, conformal distance, radial distance or even conformal time. Don't worry, cosmologists are ensuring that they are calculating the distance/time that light (photon) covers.

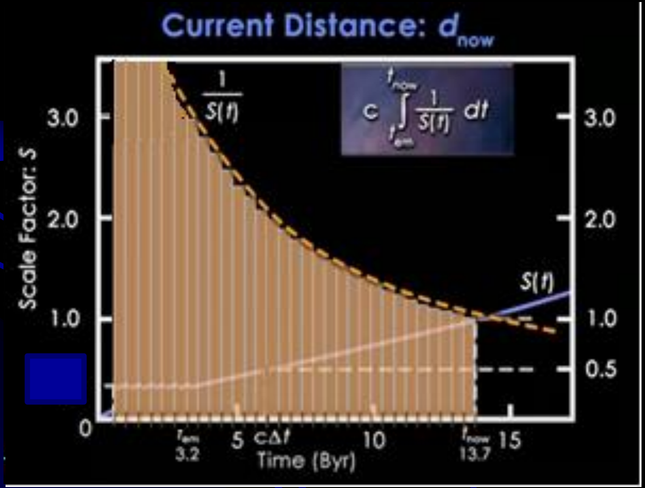
We discovered a fundamental relationship between a measurement (redshift) and the scale factor that provides with the size, time, and distance parameters:

$$1 + z = \frac{\lambda_O}{\lambda_e} = \frac{1}{a}$$

The Size of the Visible Universe

Now it is time to determine d_{now}. This is going to get a lot tricky. We will need to start with our Scale Factor vs Time diagram. What we need to take into consideration, is that between any two intervals of time , we can calculate the distance light moves in that interval (d=ct).

So, if we graph the reciprocal of S(t), then the area underneath this curve between any to times will provides us with a number (time stretched), that we need only to multiply by the velocity of light to determine the current distance, d_{now}., the current radius of the visible Universe.



$$d_{now} = c\int_{t_{emit}}^{t_{now}} \frac{1}{S(t)}\,dt$$

$$d_{now} = \frac{c}{H_o}\int_0^1 \frac{1}{a^2\sqrt{\Omega_{R,o}a^{-4} + \Omega_M a^{-3} + \Omega_K a^{-2} + \Omega_\Lambda}}\,da$$

$$d_{now} \approx c d_{LT}(3.353)$$

$$= \left(3.0\times10^8\frac{m}{s}\right)(13.7\,Bly)(3.353)$$

$$= \left(3.0\times10^8\frac{m}{s}\right)(4.355\times10^{17}s)(3.353)$$

$$= 4.4\times10^{26}\,m$$

$$= \frac{4.4\times10^{26}\,m}{9.46\times10^{15}\,m/ly}$$

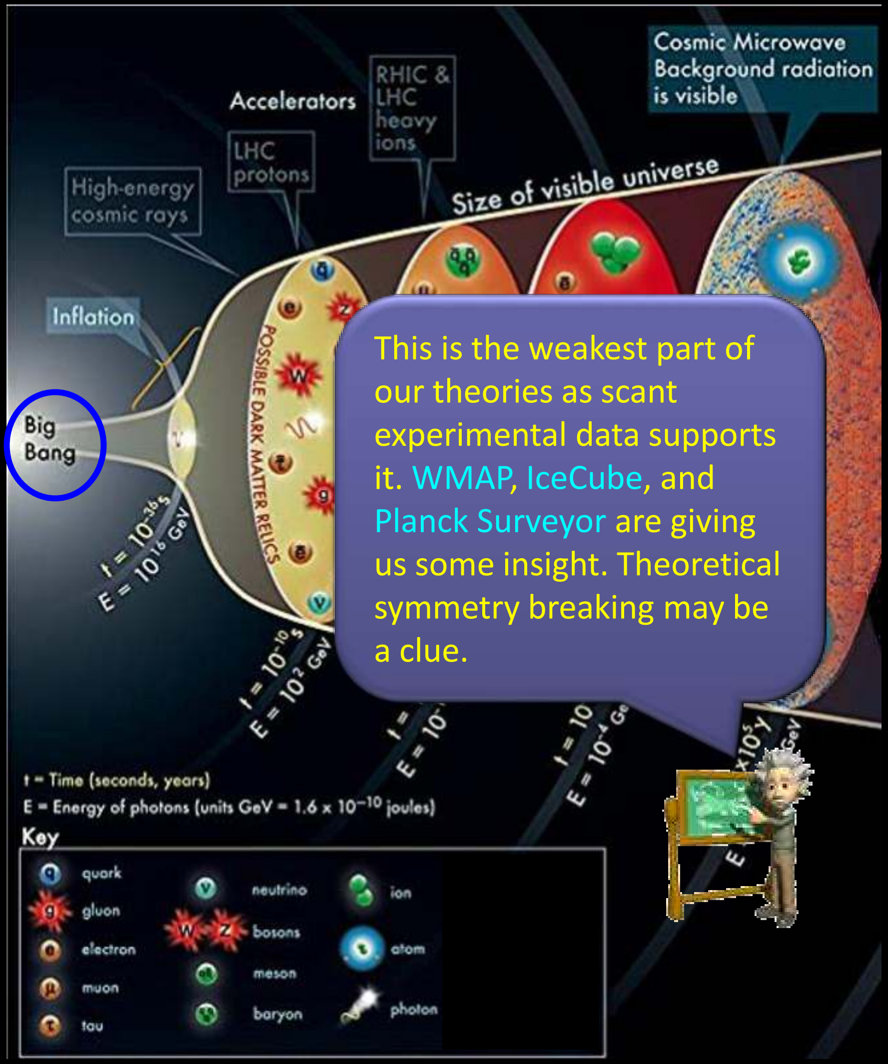
$$= 46.5\,Bly$$

Early History of the Universe

Let's look at what our Theory says about the early Universe. We will call t=0, the Big Bang as this is when our equations fail (divide by zero).

Name: Planck epoch
Time: $<10^{-43}$s
Temperature: $>10^{34}$K
Size: $< 10^{-35}$ m – 0.17 m ????
Effects: Quantum Dominated?

The moment immediately after the Big Bang, typically viewed at around one Planck Time (time it takes light to travel one Planck Length (1.6×10^{-35}m)). It is here where all forces were unified. It is the triggering event when the Visible Universe went from being small and dense, to growing and become less dense.



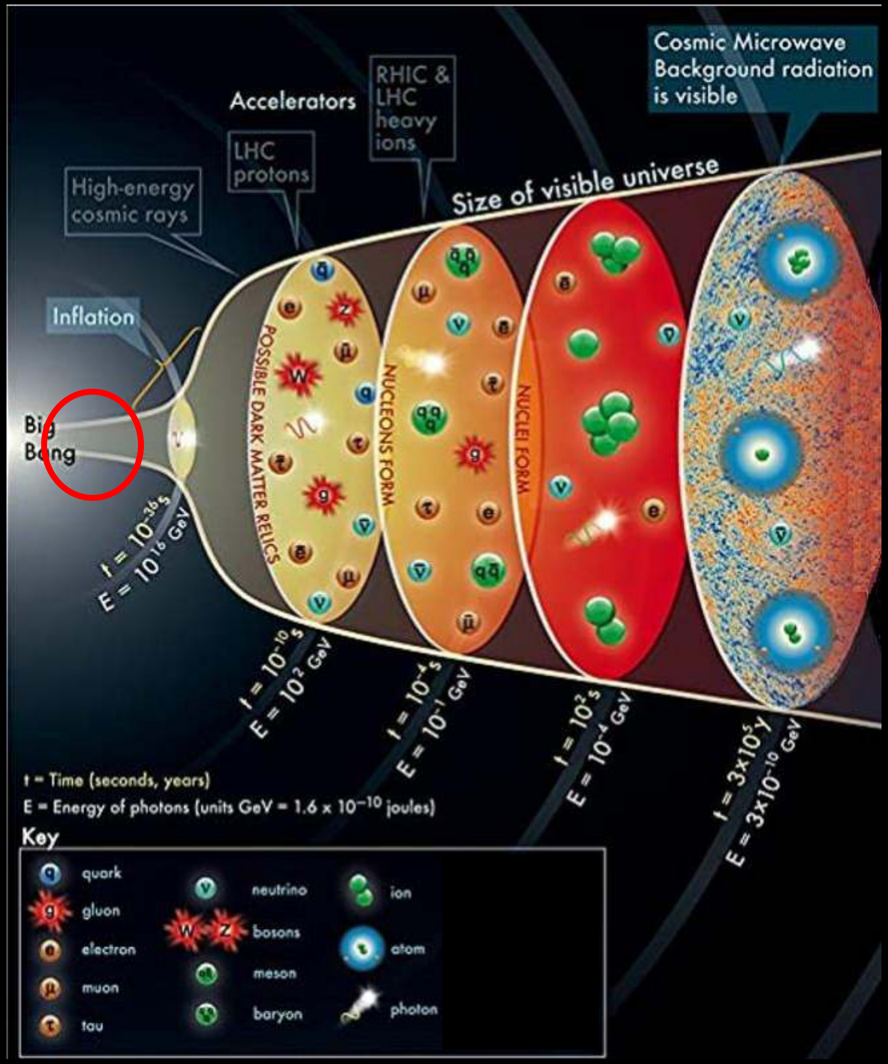
This is the weakest part of our theories as scant experimental data supports it. WMAP, IceCube, and Planck Surveyor are giving us some insight. Theoretical symmetry breaking may be a clue.

Early History of the Universe

Let's look at the next epoch

Name: Grand Unification epoch
Time: 10^{-36}s
Temperature: >10^{27}K
Size: < 10^{-30} m – 0.17m ????
Effects: 3 forces of Standard Model
Electromagnetism, Strong, and Weak are unified,
Gravity remains separate

As the Universe expands, the temperatures necessary to maintain the superforce decrease. As a result, gravity separates, leaving the electroweak and strong nuclear forces together (electronuclear force). At this time, the electromagnetic, weak, and strong forces are identical, matching the conditions requested in the Grand Unification Theory. Beginning of an asymmetry?

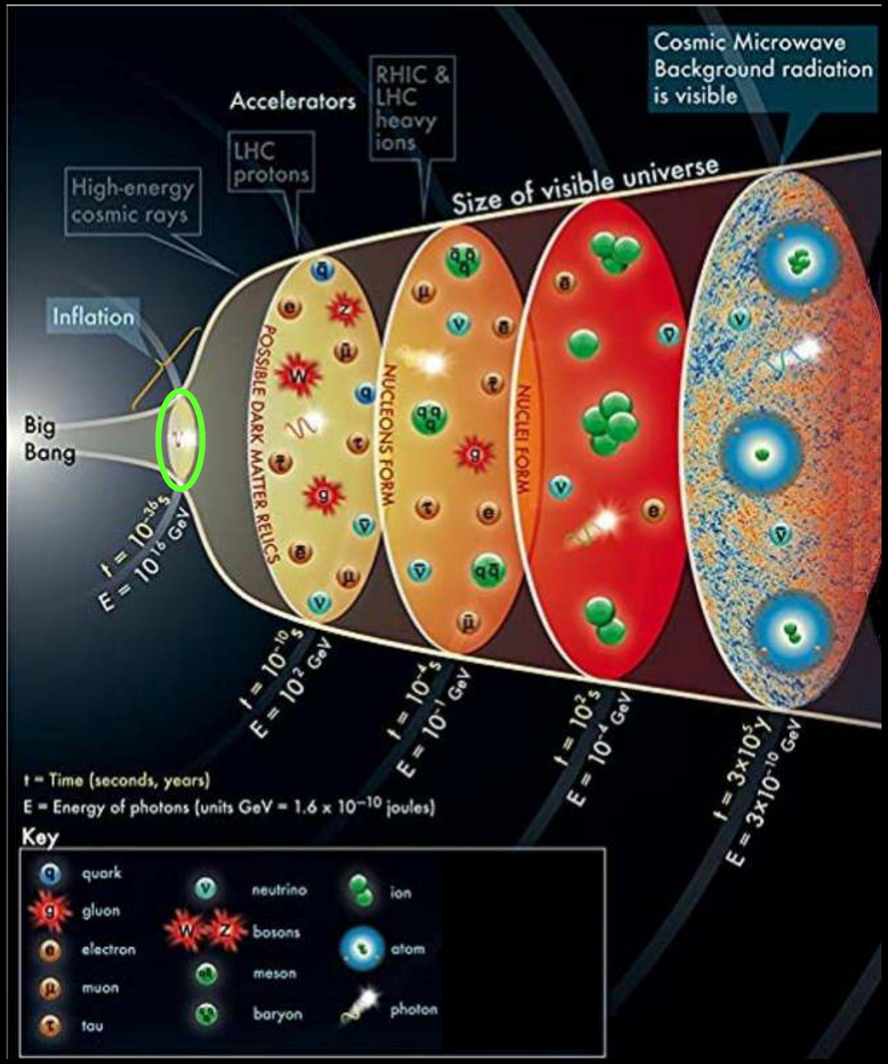


Early History of the Universe

This epoch explain why the Universe is Homogenous and Isotropic. The Universe underwent rapid grown where its volume increased more than 10^{78}.

Name: Inflationary epoch
Time: $>10^{-36}$s to 10^{-32}
Temperature: $>10^{27}$K down to 10^{22}K then back to 10^{27}K
Size: Each axis increase by 10^{26}
Effects: The Flatness of our CMB measurements (angles add to 180°). Explain why two ends of the visible Universe could have shared properties , i.e. causally connected.

After the Big Bang, vacuum state of the Universe was different from the one seen at the present time: the inflationary vacuum had a much higher energy density. According to General Relativity, any vacuum state with non-zero energy density generates a repulsive force that leads to an expansion of space. In inflationary models, early high-energy vacuum state causes a very rapid expansion (inflaton, scaler (inflaton) field).

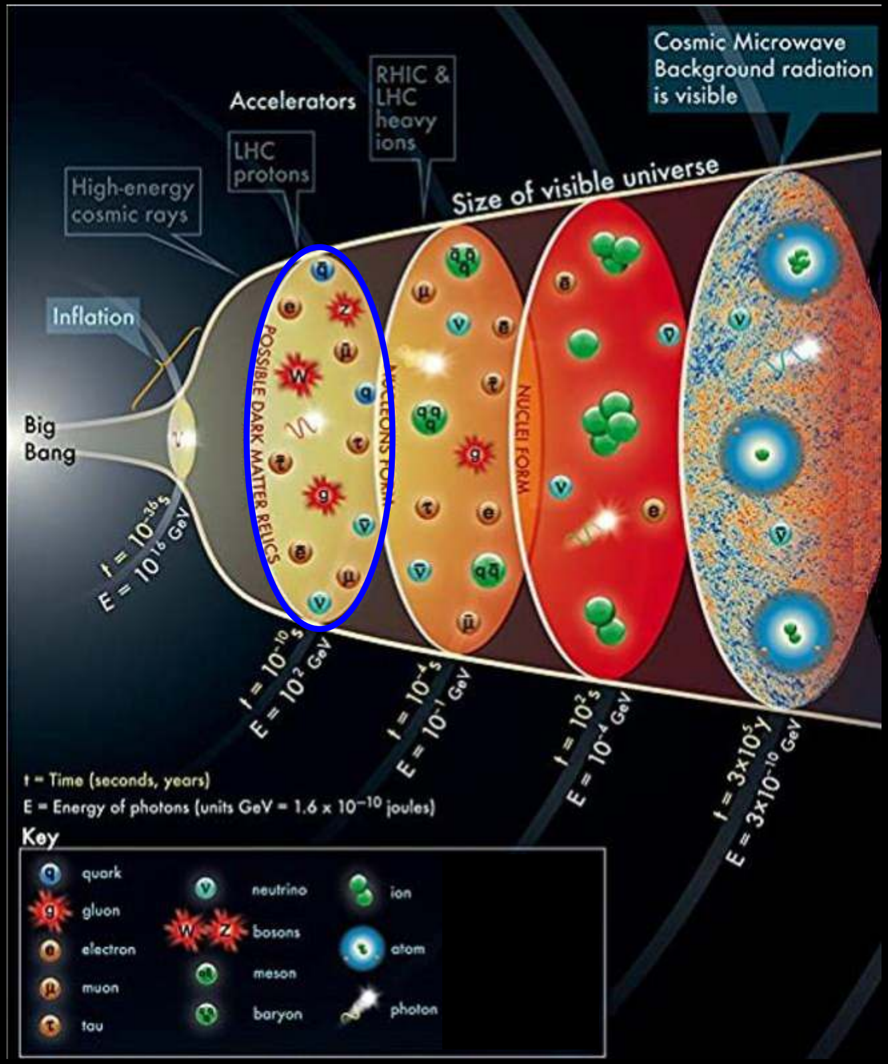


Early History of the Universe

The Quark epoch was the period in the evolution of the early Universe when the 4 fundamental forces (gravitation, electromagnetism, strong and weak) had taken their present forms, but the temperature of the Universe was still too high to allow Quarks to bind together to form Hadrons.

Name: Quark epoch
Time: 10^{-12} s to 10^{-6} s
Temperature: $>10^{15}$ K
Size: Each axis increases
Effects: The forces of the Standard Model have separated.

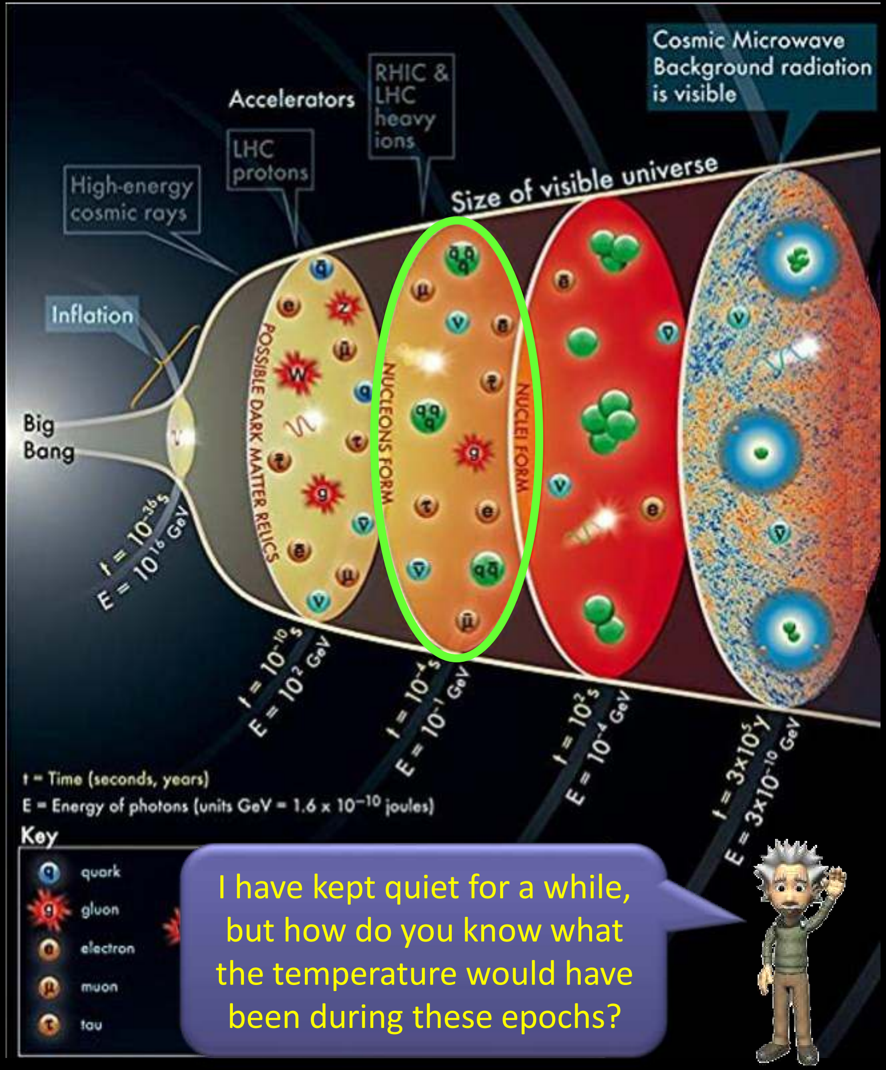
During the Quark epoch, the Universe was filled with a dense, hot quark–gluon plasma, containing quarks, leptons and their antiparticles. The Quark epoch ended when the Universe was about 10^{-6} s old.



Early History of the Universe

The temperature of the Universe had fallen sufficiently to allow the Quarks from the preceding Quark epoch to bind together into Hadrons

Name: Hadron epoch
Time: 10^{-6} s to1 s
Temperature: 10^{15}K down to about 10^{10}K
Effects: Quarks can form Hadrons, matter to anti-matter asymmetry is formed.



I have kept quiet for a while, but how do you know what the temperature would have been during these epochs?

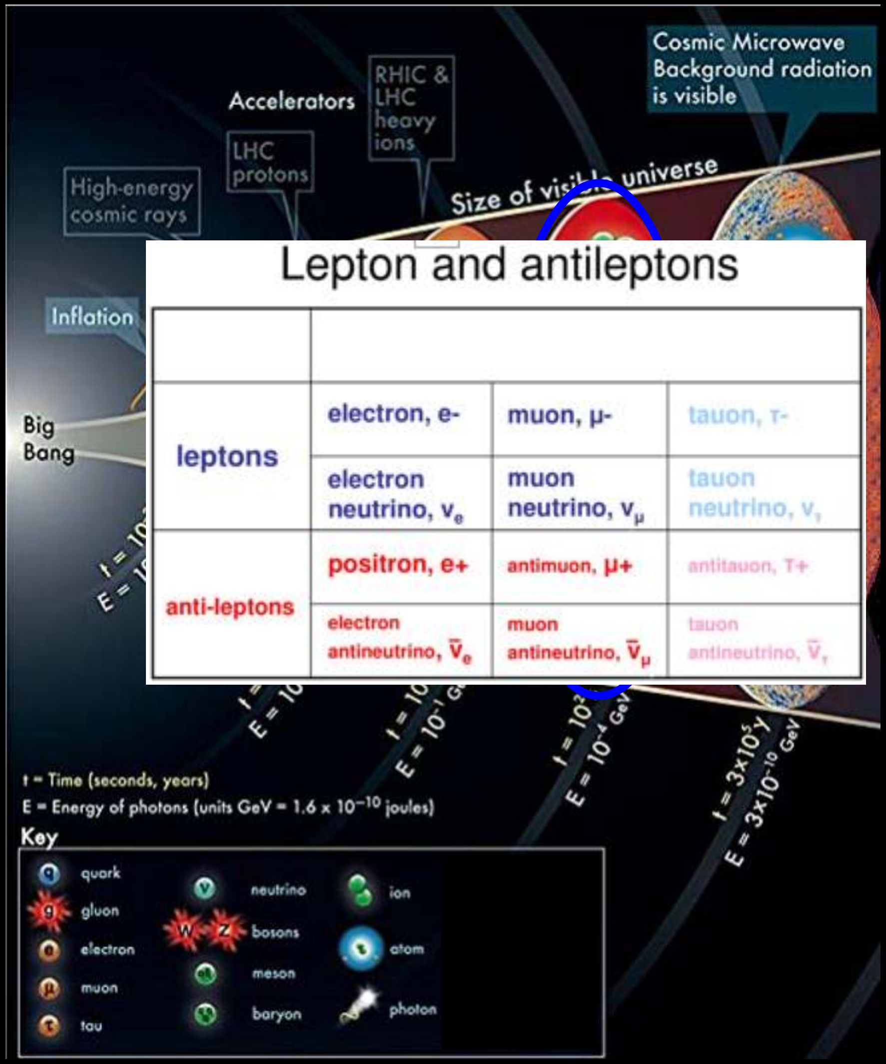
Upon elimination of anti-hadrons, The protons began to collide with electrons at extremely high speeds which formed neutrons and neutrinos. Hadrons (3 Quarks), Mesons (2 Quarks). You can think of this epoch as the beginning of Baryogenesis.

Early History of the Universe

The temperature in this next epoch drops enough to stop hadron production (part of our baryogenesis), but high enough to create smaller particles

Name: Lepton epoch
Time: 1 second to 10 s
Temperature: 10^{10}K down to about 10^{9}K
Effects: This was the period in the evolution of the early Universe in which the leptons dominated the mass of the universe.

After the majority (but not all) of hadrons and antihadrons annihilate each other at the end of the Hadron Epoch, leptons (such as electrons) and antileptons (such as positrons) dominate the mass of the universe.



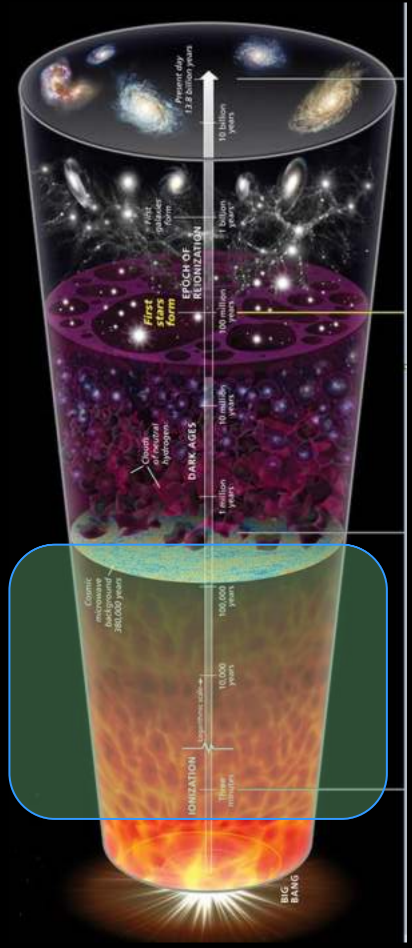
Lepton and antileptons

leptons	electron, e-	muon, μ-	tauon, τ-
	electron neutrino, ν_e	muon neutrino, ν_μ	tauon neutrino, ν_τ
anti-leptons	positron, e+	antimuon, μ+	antitauon, τ+
	electron antineutrino, $\bar{\nu}_e$	muon antineutrino, $\bar{\nu}_\mu$	tauon antineutrino, $\bar{\nu}_\tau$

Early History of the Universe

As the name implies, this is the period in the evolution of the early Universe in which photons dominated the energy of the Universe. The Photon epoch started after most leptons and anti-leptons were annihilated at the end of the Lepton epoch, producing photons.

Name: Photon epoch
Time: 10 second to < 380000 years
Temperature: 10^{10}K down to 3000K
Effects: This All radiation energy was thus “trapped” and plasma was opaque to radiation.

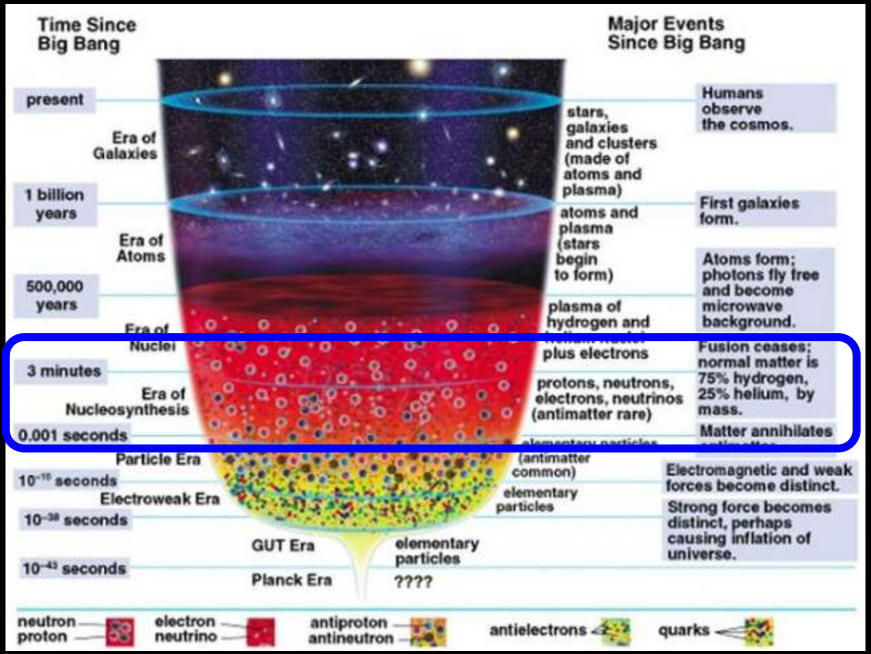


At the start of this period, many photons had sufficient energy to break apart deuterium, so those atomic nuclei that formed were quickly separated back into protons and neutrons. After the ten second mark, fewer high energy photons were available to photodissociate deuterium, and thus the abundance of these nuclei began to increase. As we shall see, this epoch spans other epochs.

Early History of the Universe

The next stage is not normally referred to an epoch but rather an era. This is known as the Big Bang Nuclear Synthesis era (BBN).

Name: Nucleosynthesis epoch
Time: 10s to 20 minutes
Temperature: 10^9K to 10^7K
Size (Visible): 300 light-years in radius
Effects: Protons and Neutrons are bound into primordial atomic nuclei, Hydrogen and Helium (75% to 25% ratio by mass, or about 92% to 8% by quantity).



The Universe was very close to homogeneous at this time, and strongly radiation-dominated. The fusion of nuclei is occurring. The temperature range in the Universe was cool enough (photon energy decreasing) for deuterium to survive, but hot and dense enough for fusion reactions to occur at a significant rate.

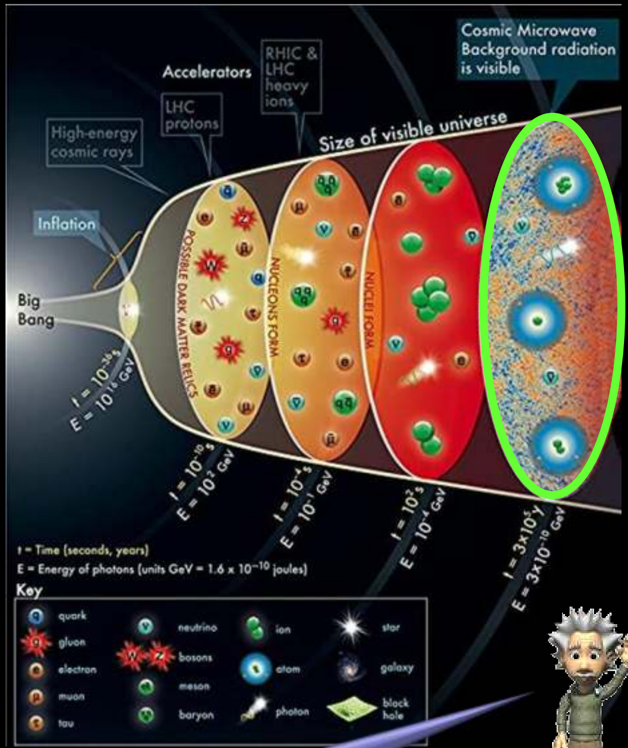
$$\mathrm{n} + e^{+} \rightleftharpoons \bar{\nu}_e + \mathrm{p}$$
$$\mathrm{n} + \nu_e \rightleftharpoons \mathrm{p} + e^{-}$$

$$\mathrm{p} + \mathrm{n} \longrightarrow {}^2\mathrm{H} + \gamma$$
$$\mathrm{p} + {}^2\mathrm{H} \longrightarrow {}^3\mathrm{He} + \gamma$$
$${}^2\mathrm{H} + {}^2\mathrm{H} \longrightarrow {}^3\mathrm{He} + \mathrm{n}$$
$${}^2\mathrm{H} + {}^2\mathrm{H} \longrightarrow {}^3\mathrm{H} + \mathrm{p}$$
$${}^3\mathrm{He} + {}^2\mathrm{H} \longrightarrow {}^4\mathrm{He} + \mathrm{p}$$
$${}^3\mathrm{H} + {}^2\mathrm{H} \longrightarrow {}^4\mathrm{He} + \mathrm{n}$$

Early History of the Universe

As the Universe expanded, its density and temperature dropped until the conditions were such that ions and electrons could ‘recombine’ to form atoms (mostly hydrogen and helium). The presence of a cosmic background of photons were now free.

Name: Recombination epoch
Time: 380,000 years
Temperature: 3000K
Size (Visible): 84 million light-years across
Effects: Electrons and atomic nuclei first become bound to form neutral atoms. Photons are no longer in thermal equilibrium with matter and the universe first becomes transparent.



The baryonic matter density at this time is about 500 million hydrogen and helium atoms per m^3, approximately a billion times higher than today. This density corresponds to pressure on the order of 10^{-17} atm and produces affect like sound waves

Hey, I see those coloured splotches?