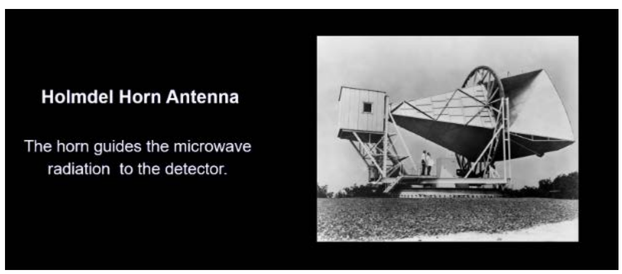
Big Bang ΛCDM Model

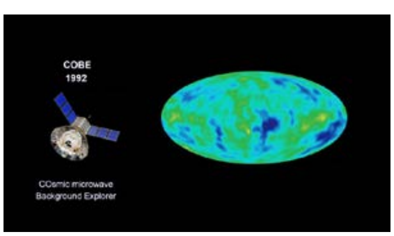
{**Abstract:** *We begin with the discovery of the Cosmic Microwave Background (CMB) radiation. We cover Recombination, Decoupling, and the Surface of Last Scattering that created the CMB. We examine the nature of the CMB temperature Anisotropy and how, through a process known as Caustics, it lead to galaxy filaments and great voids. This analysis includes Cold Dark Matter. We then cover Vacuum Energy, the Casimir Effect and Dark Energy. We then cover the observational evidence for an Accelerating expansion. We then go beyond the surface of last scattering to Neutrino Decoupling, Nucleosynthesis, Baryogenesis and Cosmic Inflation. We summarize with a review of the cosmic time line, and conclude with a look at current and future cosmology research.*}

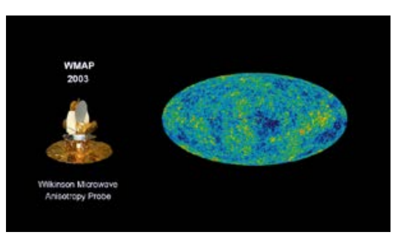
Cosmic Microwave Background (CMB) Discovery [Music - Bach - Sleepers Walk]

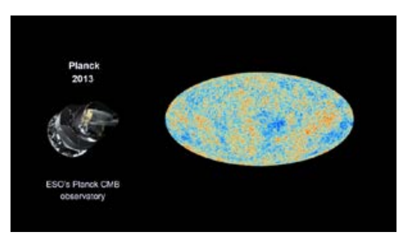
In 1965, Bell Labs engineers Arno Penzias and Robert Wilson discovered an isotropic background radiation in the microwave frequency range. [They were quickly put in touch with astronomers at Preston University who were looking for just this kind of background radiation to support their Big Bang theory.]



Over the years since then, ever more accurate technologies have increased our measurements of this key piece of evidence for a small hot beginning of the Universe. To understand how important this discovery is, we need a temperature history of the Universe.

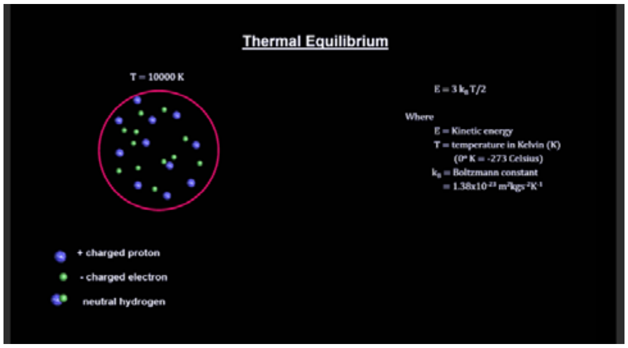




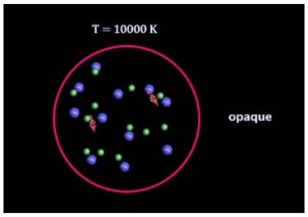


Recombination

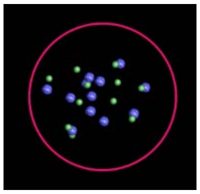
The Big Bang theory holds that there was a time when the Universe was very small and very hot. The contents of the Universe would have been in thermal equilibrium at that time. Particles in thermal equilibrium all have the same temperature. Roughly speaking, temperature is a measure of the kinetic energy of the particles. In this example, we have a small volume of protons and electrons in thermal equilibrium at 10000º Kelvin – the temperature at the surface of our Sun. At 10000º, the electrons and protons are too hot to combine into hydrogen.



If we add photons, they will scatter off these charged particles. Light cannot travel far through this space because it is constantly interacting with these free moving charged particles. The plasma is opaque. Calculations on the estimated matter density and Thompson cross section indicate that light could travel as much as several thousand light years before scattering.



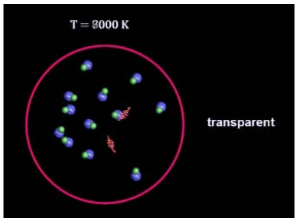
That might seem like a long way, but it is small in terms of cosmological distances. But it is enough for some to call this epoch 'foggy' instead of 'opaque'.

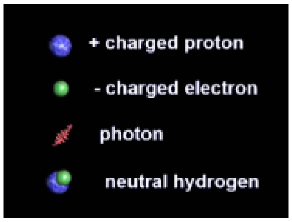


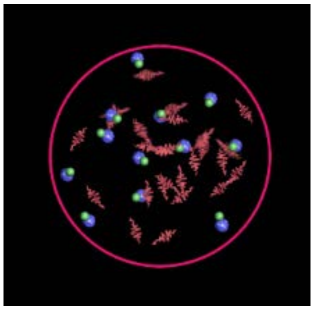
As the Universe expands, it cools. At some point, it cools enough for protons to capture electrons to form electrically neutral hydrogen. This will happen when the kinetic energy of the particles equals the ionization energy of hydrogen. This process is called Recombination.

Decoupling

Once the transformation to electrically neutral particles is complete, light will travel through space without any further interactions. This is called Decoupling. The radiation is said to have decoupled from the electrons and protons. The plasma becomes transparent.







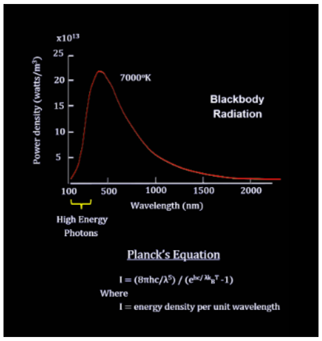
In addition to all the electrons and protons packed into this relatively small space, there are around 1.6 billion photons for every baryon in the Universe (baryons are the protons and neutrons in the plasma).

Being in thermal equilibrium, these photons' would be characterized by the blackbody radiation curve.

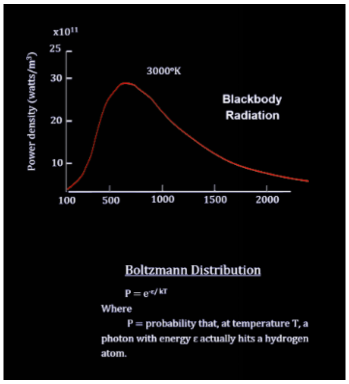
> [You may recall that we covered blackbody radiation in the "How far away is it" segment on "Distant Stars" to connect color to temperature to luminosity to distance as we built the cosmic distance ladder. [Blackbody Radiation].]

Knowing the energy that it takes to separate an electron from its proton in a hydrogen atom, we can calculate the temperature at which recombination and decoupling would occur.

[You can see from the blackbody curve that, for any given mean temperature, there is a small percentage of photons at higher energy levels. Given the very large number of photons per proton, at 7000 degrees, there would still be a significant number of photons with enough energy to ionize any hydrogen atom they happened to hit.



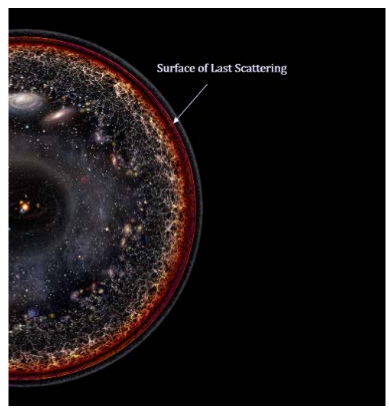
We can do the needed statistical math to find the mean temperature where there would no longer be enough photons with enough energy to prevent recombination and decoupling.] The current figure is around 3000° K - the surface temperature of a cool star like Proxima Centauri.



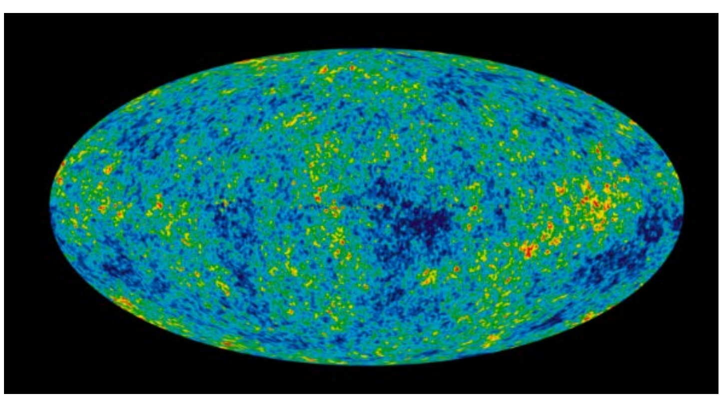
Surface of Last Scattering

As we observe the space around us, we see our solar system, our galaxy, and our local group of galaxies first. We then see significant numbers of large well-formed galaxies in our local supercluster and nearby superclusters. The further out we see, the further back in time we go. And the further back in time we go, the more we notice a reduction in the size and structure of the galaxies. Eventually, we reach as far as the first galaxies to ever form from the first stars that started to shine. Before that, there was just hydrogen and dark matter. No light was being created for us to see.

As we look back in time, we are also looking back at an ever shrinking volume because the Universe was getting smaller. And its temperature was getting hotter. Eventually, it reached 3000^{o} K. At that point, hydrogen atoms began to disassociate into protons and electrons, and space became opaque. Coming back the other way, the surface where the transition from opaque to transparent occurred is called the Surface of Last Scattering. At that time, all the photons in the Universes were released.

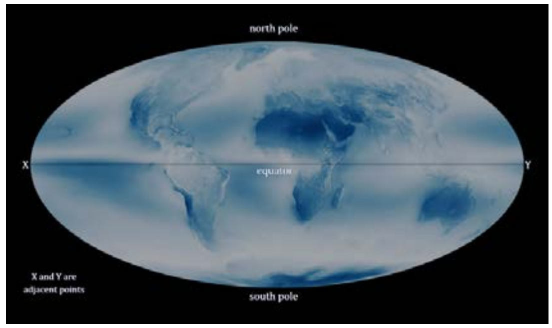


Those photons are still with us today. We see them all across the sky in tremendous numbers. They are the Cosmic Microwave Background (CMB) photons. And they tell us a great deal about the past, present and future of the Universe.

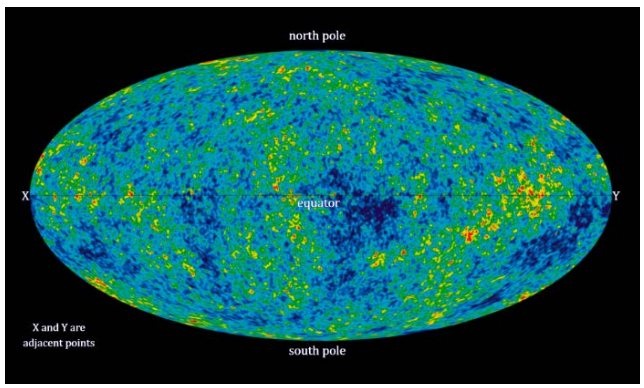


CMB Radiation **[Music - Offenbach - Barcarolle (from Tales Of Hoffman)]**

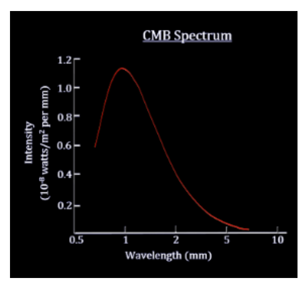
[Here's a projection of the spherical surface of our Earth down to a plane. The mapping preserves the relative sizes of the surface objects.]



Here's a projection of the celestial dome – the sky – as seen by the Planck satellite. It is the most detailed map ever created. [And it factors out our orbit around the Sun, the Sun's orbit around the center of the galaxy, and the orbital motion of our galaxy around the center of the Local Group, as well as the Local Group's motion in the direction of the Hydra cluster. It comes to 630 km/s. That's 0.2% of the speed of light (1.41 million miles per hour).]



The key observation is that the light fits the blackbody radiation curve almost perfectly. Its mean wavelength is around 2 mm, and its peak intensity has a wavelength of 1 mm. That's in the microwave range. [That's why we call it cosmic microwave background radiation.]



This gives us the temperature of the radiation today. It is 2.725 K. We know that at decoupling it was 3000 K. So the temperature has been reduced by a factor of 1,100.

Wien's Formula

$T = b/\lambda_{max} = b/1.0634 \text{ mm} = 2.725 \text{ K}$

Where

b = Wien's Constant

$= 2.8977685 \times 10^{-3}$ mK

We also know that the ratio of the current temperature to the temperature at decoupling is equal to the ratio of the current scale factor to the scale factor at decoupling. So the Universe has expanded by a factor of 1,100 times since decoupling.

$$\lambda_{today} / \lambda_{decoupling} = a_{today} / a_{decoupling} = T_{decoupling} / T_{today}$$

$$= 3000\,\mathrm{K} / 2.725\,\mathrm{K} = 1100$$

The blackbody radiation formula also gives us the number density of CMB photons. There are over 400 million of them in every cubic meter of space throughout the cosmos. This is a thousand times more than all the photons from all the starlight ever created by all the stars in all the galaxies for all the billions of years that stars have been shining.

$$n_{\gamma,0} = \varepsilon_{\gamma,0} / E_{mean}$$
$$= 0.2606\ \mathrm{MeV\ m^{-3}} / 6.34\mathrm{x}10^{-4}\mathrm{eV}$$
$$= 4.107\mathrm{x}10^{8}\ \mathrm{m^{-3}}$$

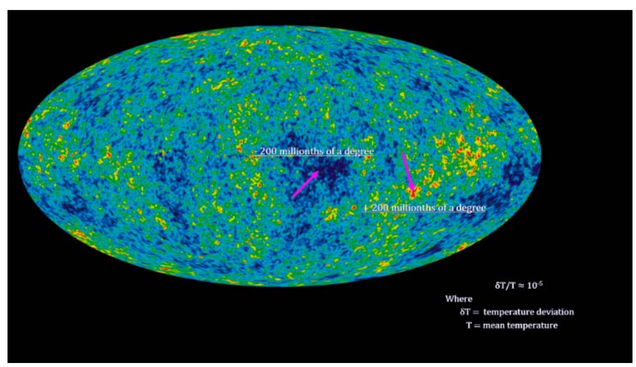
Where

$\varepsilon_{\gamma,0} =$ current energy density

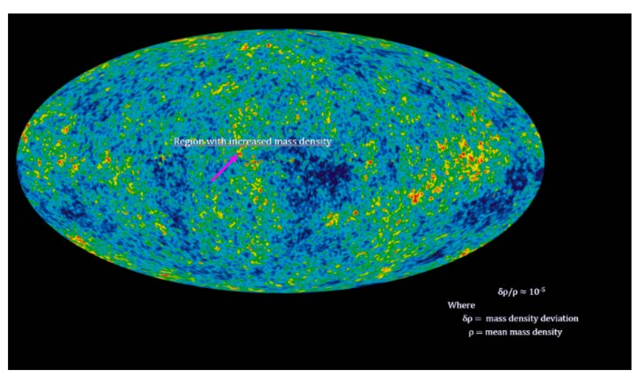
$E_{mean} =$ current mean photon energy

CMB Anisotropy

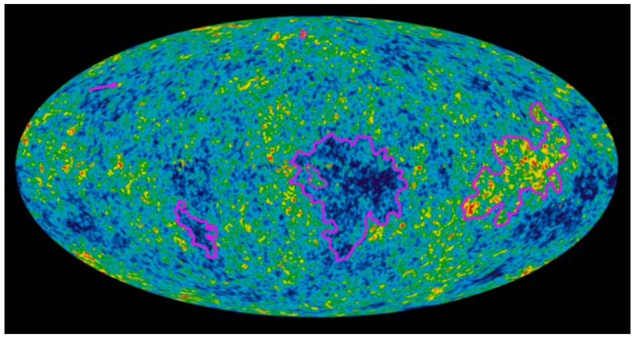
Earlier measurements of the CMB indicated that it was homogeneous. That would be a problem, because, if it were 100% homogeneous, the resulting Universe would be 100% homogeneous and it isn't. But our measurement technologies have improved dramatically over the past half century. The Planck satellite measurements detected small amounts of temperature deviation called anisotropy – meaning different in different directions (the opposite of isotropy – the same in all directions). The image uses color to show variations from the average with blue for -200 millionths of a degree through green and yellow to red for +200 millionths of a degree. That temperature deviation comes to 1 part in 100,000.



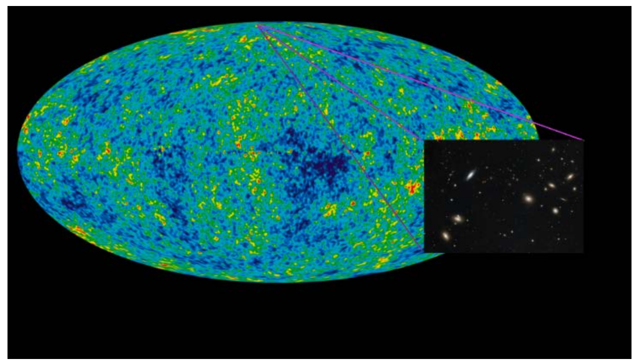
These temperature deviations come from small mass density deviations in the plasma at the time of decoupling. For example, suppose we had a small mass density excess in this region. Light from this region would be gravitationally redshifted from light from other regions that had the average mass density. These mass density deviations would be of the same magnitude as the temperature deviations – one in 100,000.



It is also important to note that these anisotropies have structure. We see large structures, small even tiny structures, and giant structures. We even see structures within structures at every scale. In other words, they're quite fractal in nature.



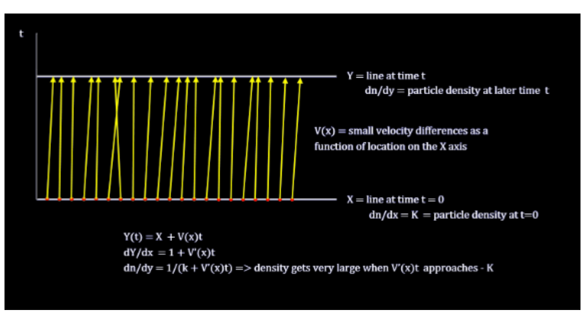
These small scale anisotropies in the CMB are what lead to the large scale structures such as galaxy clusters, filaments and voids that we see today. For example, a very tiny spot of red on the Surface of Last Scattering, representing a small decrease in mass density in that region, will have expanded 1,100 times to the size of the Coma Cluster today.



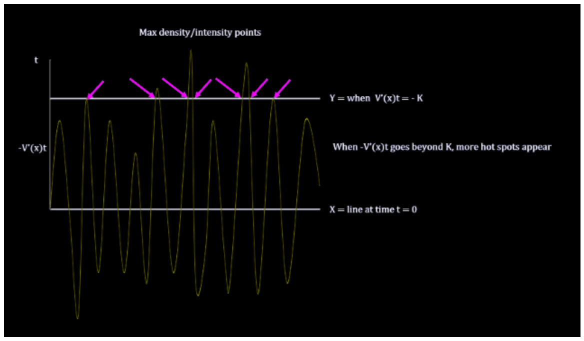
The fact that there is a Cosmic Microwave Background with all these characteristics, is one of the most important pieces of evidence we have that verifies and validates our current Big Bang model of the universe.

Cosmic Caustics **[Music - Strauss - Waltz on the Beautiful Blue Danube]**

Just how the Universe evolved from small scale matter deviations at the time of decoupling to filaments of superclusters and vast voids can be explained by a physical process called Caustics. Originally developed to explain light behavior, it works just as well for protons and dark matter. Picture a set of uniformly distributed particles on a line, each with slightly different velocities. They start out with a uniform particle density. But, because of the small velocity differences, the particle density will vary as time goes by. Areas of high and low density will develop. The density at a later time t is described by an equation. The equation has hot spots when the denominator approaches zero.

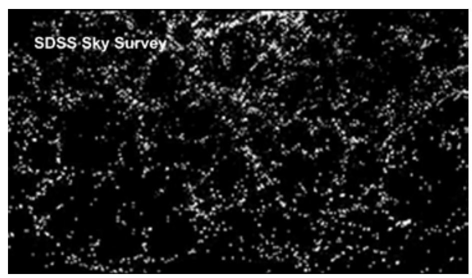


Here's a plot of the rate of change in velocity with respect to location on the x axis times time. Naturally, we get a very small curve when time is small. But as time goes on, the deviations grow. When they reach the critical time and beyond, we get hot-spots.

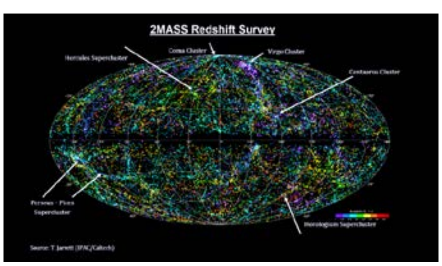


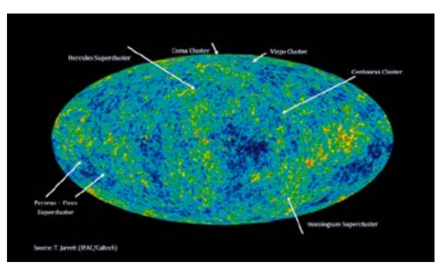
Extending this to two dimensions, we get density peaks along curved lines that themselves intersect at points with maximum intensity. I see this phenomenon in my own back yard. The lines at the bottom of a swimming pool are examples of caustics caused by small waves on the water's surface.

And, when we extend this to three dimensions, we get curved surfaces with increased density that intersect along lines that intersect at points. This is the web like pattern we see in the large scale Universe.



This is what you get from the initial conditions characterized by the Cosmic Microwave Background. No additional forces are involved. Gravity is the key to the formation of stars and galaxies within these filaments of dense accumulations of baryons and dark matter. But it is caustics that took the minor anisotropies that existed at the time of decoupling and turned them into giant walls around great voids.

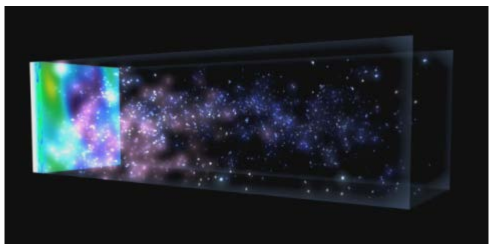




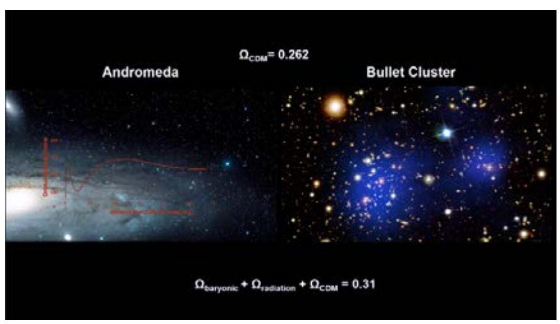
Cold Dark Matter

We've mentioned Dark Matter several times in reference to the CMB. It was the largest matter component of the opaque universe at the time of decoupling. And it is the dark matter density anisotropies that produced the filament structure we see in the Universe today. But this only works if the dark matter doesn't fly off at near the speed of light like neutrinos do. In this respect, it is said to be cold – cold dark matter – CDM for short.

> [We covered its discovery and role in galaxy rotation rates and galaxy cluster dynamics including its distribution across colliding galaxy clusters such as the Bullet Cluster in the 'How far away is it' video book. See Dark Matter.]



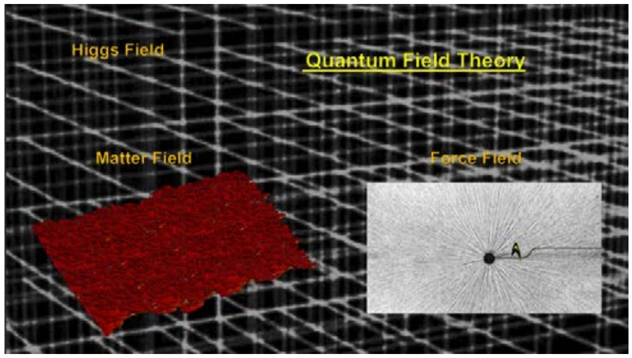
Using galaxy rotation rates, galaxy cluster dynamics, and gravitational lensing, the best estimate for the dark matter density parameter in the Universe is 0.262. The baryonic matter density parameter [from stars, stellar remnants, brown dwarfs, black holes, interstellar mediums, and intergalactic mediums] is measured to be around 0.048. Radiation, mostly from the CMB is significantly less than that. [Given that the number of non-CMB photons in the Universe is insignificant compared to the number of CMB photons, we can say that the radiation density parameter for the Universe is the radiation density parameter of the CMB, which is tiny compared to the baryonic matter.]



The problem is that this isn't enough matter to account for our flat Universe observations. But there is one component of the Universe that we have not yet taken into consideration. That is that empty space, the vacuum itself, has energy.

Casimir Effect

You may recall from our video on the Higgs Boson [Force Fields & Matter Fields], that empty space is not actually empty. It is filled with matter and energy fields.



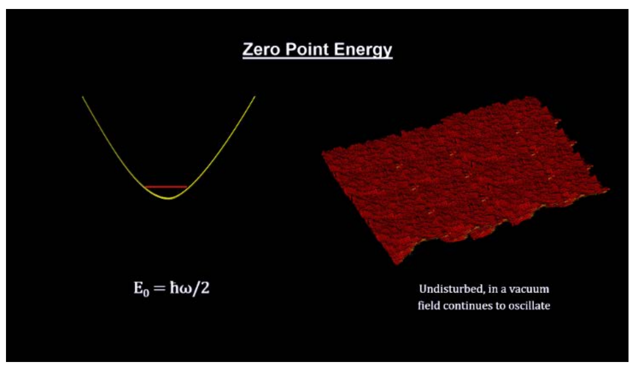
We model the waves in these fields as quantum harmonic oscillators. And, given the Heisenberg Uncertainty Principle, the Zero Point Energy for any wave in the field must be greater than zero.

Harmonic Oscillator Energy Levels

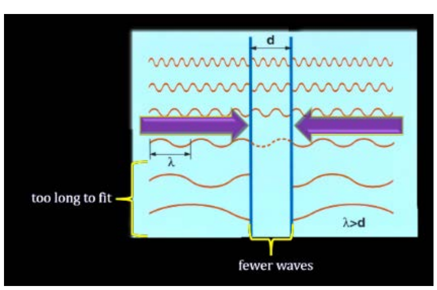
$E_n = (n + \hbar\omega/2)$

Where

E = energy
n = energy level
$\hbar$ = (Planck's constant)2π
$\omega = 2\pi$(frequency)



In the 1940s, a physicist named Hendrik Casimir proposed that this zero point energy was real and for the electromagnetic field, it could be measured. If you place two parallel low mass conducting surfaces close to each other, the fluctuations in the quantum field will be limited in between the surfaces, but not outside the surfaces. This will create a negative pressure on the surfaces and push them together. Negative pressure is called tension. This effect is called the Casimir Effect.



$F = (\pi^2 \hbar c/240d^4)(A)$

Where

F = the Casimir force
A = area of each plate
d = distance between plates

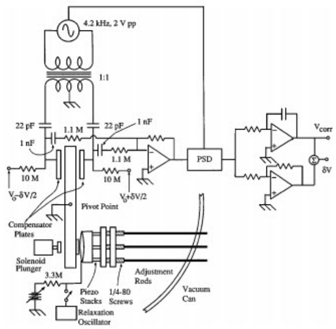
if

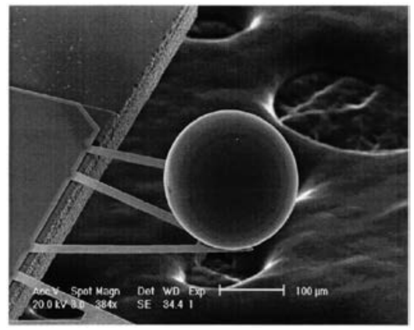
$A = 1\ cm^2$
$d = 1$ micron

Then

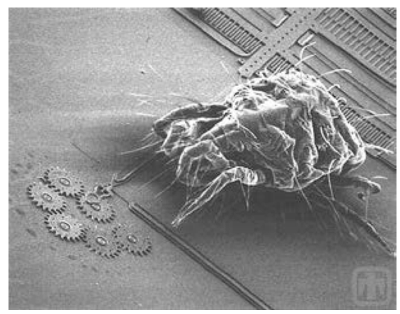
$F = 1.3 \times 10^{-7}$ N

It wasn't until the late 1990s that instruments sensitive enough to reproduce the situation and register the very small amount of force involved were available. Here we see that the force on 1 square cm plates placed one micron apart is equivalent to 1/100th the weight of an average mosquito.



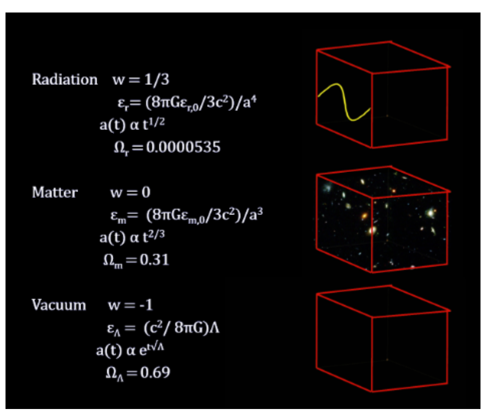


The Casimir Effect shows that the Vacuum Energy is real, it's small, it is useful, and it has negative pressure. But this is only for the Electromagnetic Force Field. It's only one of a number of fields filling empty space. We do not know how many there are, so we can't predict the total amount of vacuum energy.



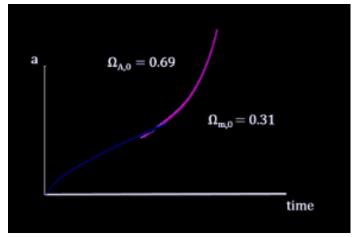
Dark Energy **[Music - Bach - Concerto for Violin, Strings and Continuo]**

Vacuum energy has a key implication for our flat cosmological model. We have seen that radiation, with w equal to 1/3, dilutes by the cosmic scale factor raised to the 4th power. [It was significant in the early times, but is now an insignificant component.] Relatively still matter that exerts no pressure and has w equal to 0, and dilutes with the scale factor cubed. But vacuum energy density, with w equal to -1 is a constant. It does not dilute. Therefore, the total amount of vacuum energy increases with the volume of the Universe.



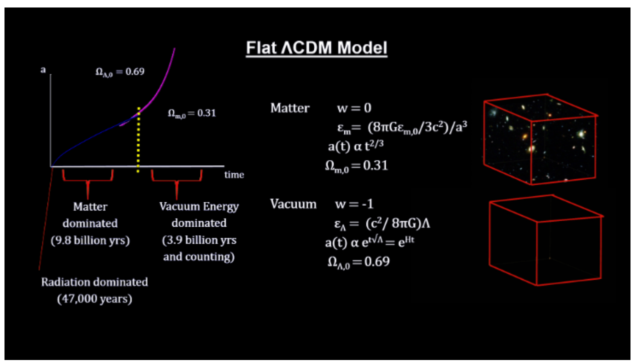
In a small Universe, it would have little impact. But today, it is almost 70% of the energy density of the Universe, filling the gap left by the matter/radiation only numbers.

[According to current estimates, the vacuum energy component of our Universe is dominating the expansion. Here we see the curve shift as the universe moved from matter domination to vacuum energy domination.



]

Under this model, the Universe was matter dominated for most of its existence since the Big Bang. It was radiation dominated for a mere 47,000 years; matter dominated for 9.8 billion years; and currently in transition to complete vacuum energy domination. The name we use for this zero point quantum vacuum energy is 'Dark Energy'.



We use the symbol lambda to represent this component of the Universe. The symbol was first used by Einstein as a **Cosmological Constant** to account for a static Universe. It went by the wayside when Edwin Hubble discovered that the Universe was not static. But it has now been repurposed to represent this vacuum energy.

Einstein Field Equations

$$\mathbf{G}_{\mu\upsilon} = \frac{8\pi G}{c^4}\mathbf{T}_{\mu\upsilon} + \Lambda$$

Friedmann Equation

$$(\dot{a}/a)^2 = 8\pi G\varepsilon(t)/3c^2 - \kappa c^2/R_0^2 a(t)^2 + \Lambda/3$$

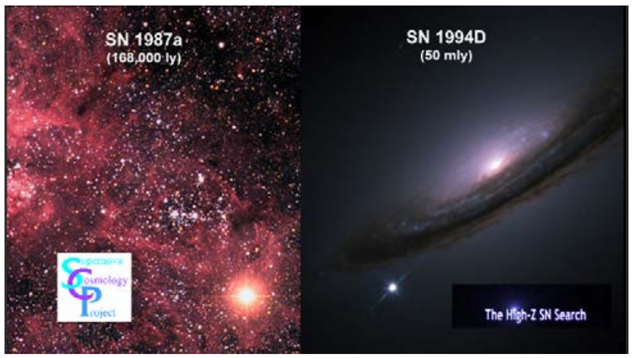
Equation of State

$$\varepsilon_\Lambda = \varepsilon_{\Lambda,0}/a^{3(1+w)} = \varepsilon_{\Lambda,0} \Rightarrow w = -1$$

Accelerating Expansion Supernovae

Well before the major role played by vacuum energy was understood, it was assumed that the universe was matter dominated and that the matter was slowing the expansion of the Universe. Two major efforts were started in the late 1990s to prove that the Universe's expansion was decelerating. Both groups used distant Type 1a Supernova as their standard candles.

> [We covered Type 1a Supernova in our 'How far away is it' video book as the last rung in our cosmic distance latter. Type 1a Supernova]



Supernovae provide a luminosity reading that enables us to determine their luminosity distance via the inverse square law.

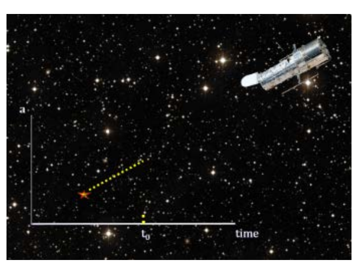
Let
d_L = luminosity distance to SN
L = intrinsic luminosity of Type Ia
f = observed luminosity

From inverse square law
$d_L = (L/4\pi f)^{1/2}$

And
$f = L/(4\pi\, d_L^2)$

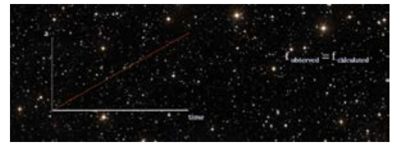
And they provide a redshift reading that gives us the cosmic scale factor at the time the light was emitted. The redshift also enables a correction for the expected luminosity due to the expansion of space. Luminosity and redshift combined can tell us if the expansion is constant, decelerating or accelerating.

Let
d_L = luminosity distance to SN
d_p = proper distance to SN
λ_e = wavelength emitted
λ_o = wavelength observed
E_0 = light energy at time light observed
E_e = light energy at time light emitted
z = redshift at time light observed
a = scale factor at time light emitted
$= 1/(1+z)$

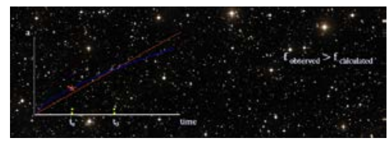


For flat space
$\lambda_o = \lambda_e/a = (1+z)\,\lambda_e$
$E_0 = E_e/(1+z)$
$d_L = d_p(1+z)$

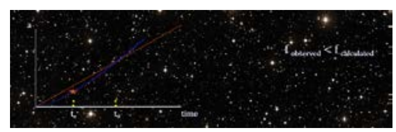
Here's how it works. If the expansion rate is constant, the relationship between the luminosity distance and the redshift will be constant. Given a redshift, we can compute the expected luminosity distance and therefore the expected observed luminosity. Comparing this to the actual observed luminosity would find them equal.



But if the expansion is slowing down, the expansion rate in the past would have been greater than what we see now. Which means, it took a shorter time to expand from its size at light emission time to its present size compared to a non-accelerating universe. This results in a shorter light-travel time, shorter distance and brighter supernovae.

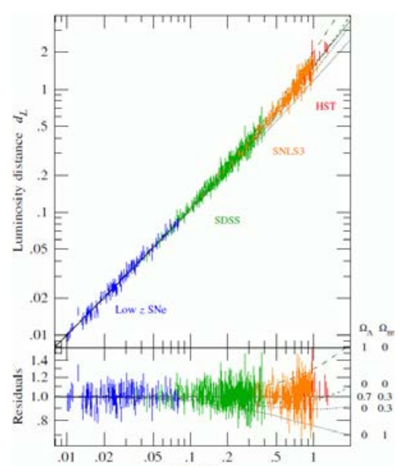


By the same token, if the expansion is speeding up, the universe was expanding more slowly in the past than it is today, which means it took a longer time to expand from its size at light emission time to its present size compared to a non-accelerating universe. This results in a larger light-travel time, larger distance and fainter supernovae. This is what both of the supernovae study teams found.

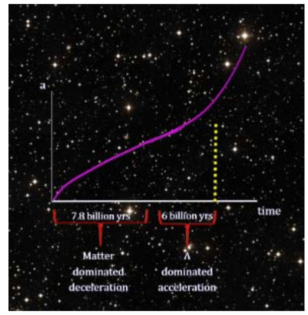


ΛCDM Benchmark Model

The supernovae observations that discovered the acceleration of our Universe's expansion also provided key missing information for our benchmark model. What astronomers do is to plot the expected luminosity distances for a variety of scenarios concerning the contents and curvature of the Universe. Then lay the actual observed luminosity distances over the graph to see which scenario is the best fit. Here we see that the lambda cold dark matter scenario with matter accounting for 30% and vacuum energy accounting for 70% is the current best fit. It is the current 'Benchmark Model'.

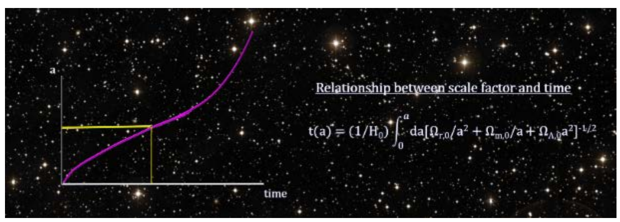


[In the Benchmark Model, the early universe was dominated by matter whose gravity was slowing down the universe's expansion rate. Hubble observations confirm that the expansion rate began speeding up about five to six billion years ago. This is when vacuum energy began to overtake gravity's attractive grip.

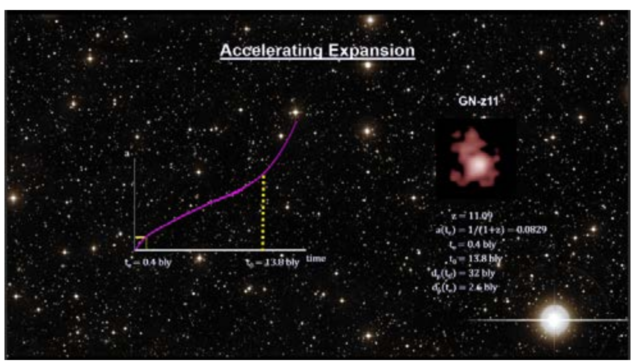


It's important to note that actually calculating the time for a given scale factor depends on the model of expansion used. Plus it is quite complex – requiring computer assistance. But once we have a benchmark model, a graph like this can be used to find the time for any given scale factor, or find the scale factor for any given time.]

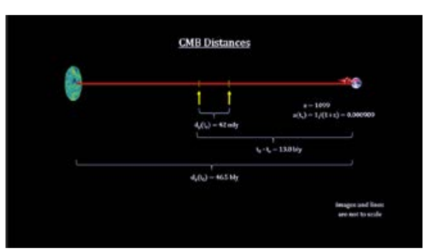
With this Benchmark Model, we can map the expansion history of the Universe from decoupling to the present and on into the future.



To illustrate, let's take a final look at GN-z11's numbers. Its redshift of 11.09 gives us the scale factor at emission time. Which gives us the time the light was emitted. All the other numbers follow.

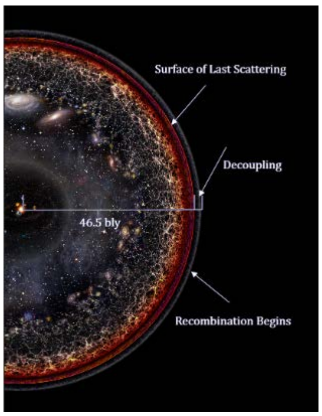


For the CMB radiation, the redshift tells us that the light we see now was only 42 million light years away from our location when it was emitted. It traveled for just under 13.8 billion years to reach us, and its starting location is now 46.5 billion light years away – making the diameter of the visible universe 93 billion light years.



Beyond the Surface of Last Scattering [Music - Beethoven - The Emperor]

Type 1a Supernovae redshifts provide a measure of the scale factor back to near the earliest galaxies. The Cosmic Microwave Background radiation provides the scale factor for the Surface of Last Scattering. We can tie scale factor and time together given the vacuum energy, radiation, baryonic and cold dark matter contents of the Universe. So we can say, with a fair degree of accuracy that decoupling started around 250 thousand years into the expansion and the Surface of Last Scattering occurred around 370 thousand years into the expansion.



$$t(a) = (1/H_0)\int_0^a da[\Omega_{r,0}/a^2 + \Omega_{m,0}/a + \Omega\Lambda_{,0}a^2]^{-1/2}$$

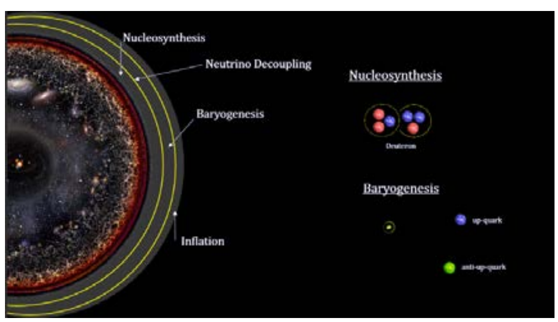
$H_0 = 20.86$ km/s/mly
$\Omega_{r,0} = 0.0000535$
$\Omega_{m,0} = 0.31$
$\Omega_{\Lambda,0} = 0.69$

$\lambda_{observed} / \lambda_{emitted} = a_{today} / a_{emitted} = T_{emitted} / T_{today}$

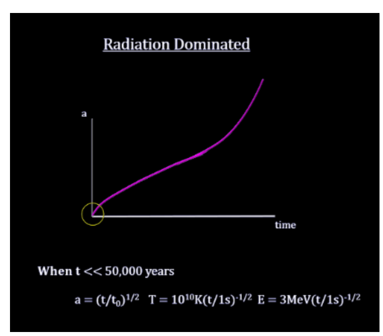
<u>Recombination Begins</u>
$T = 3760$ K
$a(t_{rb}) = .0007247$
$t_{rb} = 250{,}000$ years

<u>Last Scattering</u>
$T = 2970$ K
$a(t_{ls}) = .000909091$
$t_{ls} = 370{,}000$ years

But how did we get to the Cosmic Microwave Background? Where did the matter come from? Why is there no anti-matter? And how did a fractal landscape form? To address these questions, we need to go beyond the Surface of Last Scattering - back to the time when atomic nuclei formed (called Nucleosynthesis) kicked off by Neutrino Decoupling. And back further still to the time when quarks and protons were created from radiation (called Baryogenesis). It is in this timeframe that cosmologists propose that a super rapid increase in the size of the Universe happened (called Inflation).

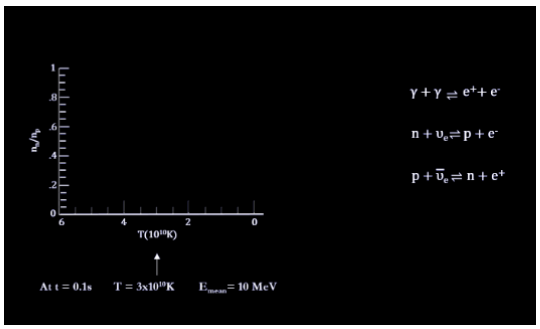


In these earliest times, the Universe was radiation dominated. The transition from matter dominated would have stared when the percentage of the energy density from radiation equaled that from matter. That happened when the universe was around 50 thousand years old. At times much much less than this, we have a fairly simple relationship between time, scale factor, temperature and energy that we can use as we cover each of these key areas.

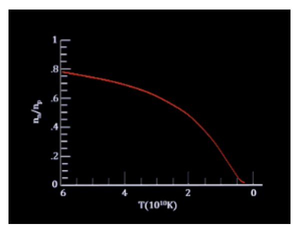


Neutrino Decoupling

Neutrino decoupling triggered the start of Nucleosynthesis. Both processes happened in the unobservable realm, so we have to rely entirely on theory. But the theory is well established in nuclear physics laboratories. When the Universe was just 1 tenth of a second old, its temperature was around 30 billion degrees (3×10^{10} K) – that's about twice the temperature of the interior of our Sun. At this temperature, photons can create electrons and positrons, and neutrinos are coupled to protons and neutrons. That coupling enables a fluid flow of protons to neutrons and neutrons to protons. That puts the entire mix of photons, neutrinos, electrons, positrons, protons, and neutrons in thermal equilibrium.



Given the mass difference between neutrons and protons, we can calculate the expected ratio of neutrons to protons for any given temperature. Note that the number of neutrons decreases exponentially as the temperature cools. Left unchecked, the universe would have had only one neutron left for every million protons by the time it was only six minutes old.



Let

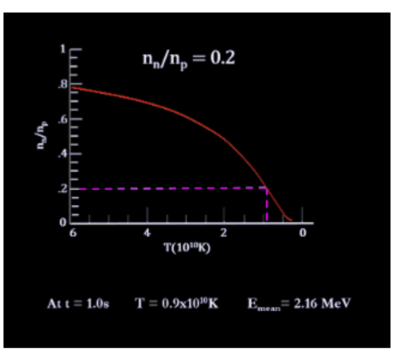
$Q_n = (m_n - m_p)c^2 = 1.29$ MeV

Then

$n_n/n_p = e^{(-Q_n/kT)}$

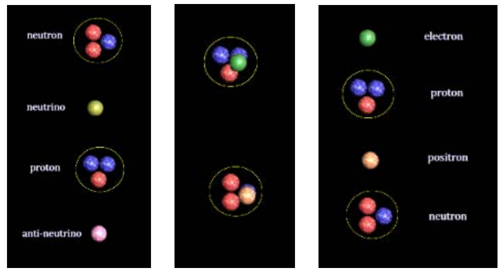
Where

n_n = number of neutrons
m_n = mass of a neutron
n_p = number of protons
m_p = mass of a proton

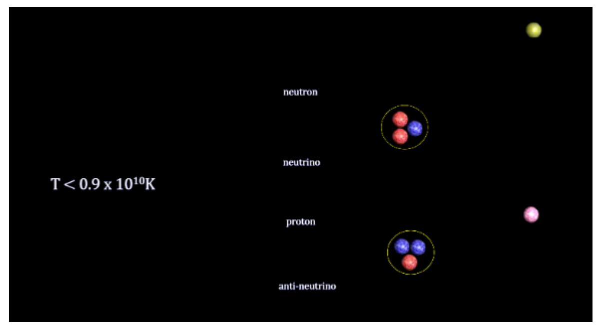


But, as the universe continued to expand and cool, the neutrinos decoupled from the protons and neutrons. Using the best available laboratory information, this would have occurred when the temperature cooled to 9 billion degrees when the Universe was around 1 second old. At that point, two things happened. One, without neutrino interactions, the ratio of neutrons to protons froze. Computations show that, at the time of neutrino decoupling, the ratio would have been one neutron for every five protons. This neutrino decoupling process would have lasted around 1 second.

And two, while the neutrinos were coupled to the protons and neutrons, they could not travel far.

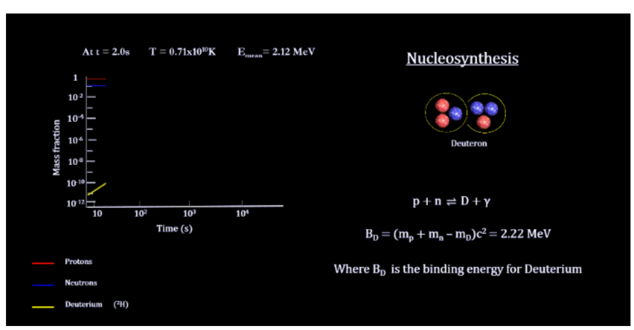


But once decoupled, they were freed to travel across the universe like photons did at their decoupling. [If we could detect these neutrinos, we'd have a tool that could take us back to the time when the Universe was just 2 second old.]



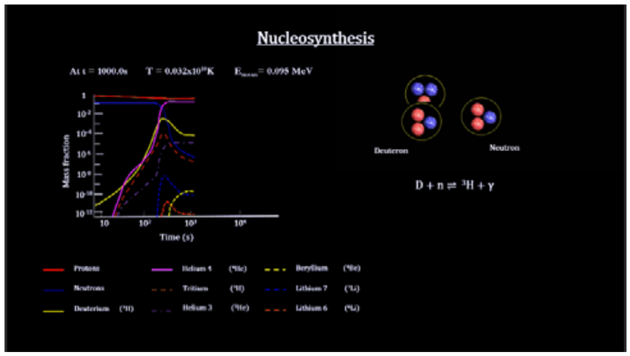
Nucleosynthesis

[The epoch of Nucleosynthesis was an era of nuclear fusion. Where Recombination was about the binding energy of an atom (around 10 eV), Nucleosynthesis is about the much greater binding energy of an atomic nucleus (measured in MeV).] The end of neutrino decoupling marked the beginning of nucleosynthesis. The universe was around 2 seconds old with 5 protons for each neutron. At the start, there was sufficient energy for protons and the remaining neutrons to combine into Deuterons – the nucleus of Deuterium. Here we track the ratios of each kind of nuclei as these processes evolved.



As the Deuterium density climbed, significant amounts of Helium and Hydrogen isotopes were formed along with lots of tightly bound Hydrogen. The diagram illustrates the various nuclear interactions along the way.

Hydrogen resists combinations with protons and neutrons, so the creation of Beryllium and Lithium went more slowly producing far less of these elements than Helium. By the time the temperature of the universe had fallen to 300 million degrees (when it was around 1000 seconds old), the nucleosynthesis energies were no longer available and the epoch was over.

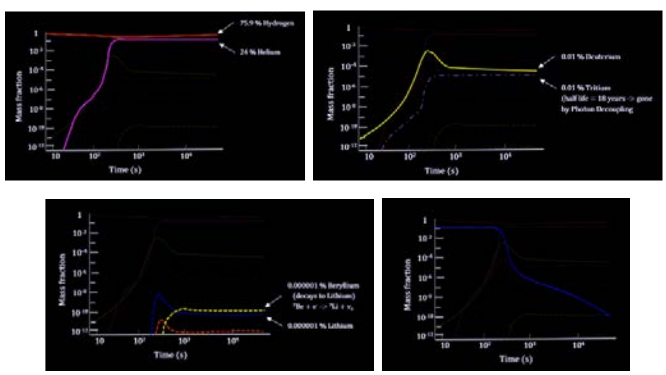


The vast majority of the baryonic matter wound up in the form of hydrogen and helium nuclei.

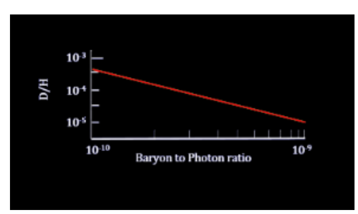
The percentages of deuterium and tritium are much smaller.

There were just traces of beryllium and lithium.

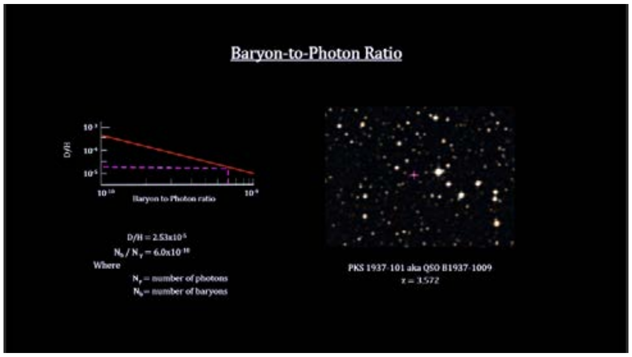
The remaining free neutrons decayed over time into protons.



[As you can see, Nucleosynthesis was a race against time. Once started, its duration was fixed. So the length of time it lasted depended on how early it started fusing Deuterium nuclei. And that depended heavily on how many high energy photons were present. Here we see the possibilities, given an amount of deuterium. [i.e. deuterium-to-hydrogen ratios for different values of the baryon-to-photon ratio.]

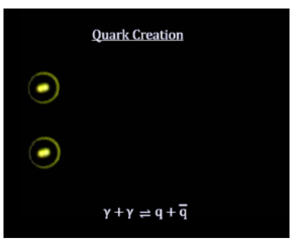


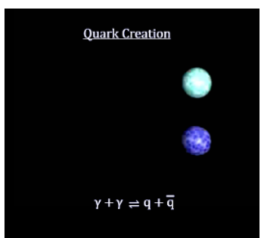
The best way to measure the primordial percentages of these elements, is to look at the spectra of distant quasars like this one. The actual amounts of Hydrogen, Helium, Beryllium and Lithium in the early universe, does match predicted levels. This represents significant evidence that the Big Bang Nucleosynthesis process did occur.

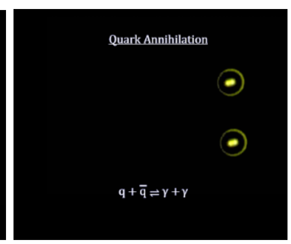


Baryogenesis **[Music - Mozart - Symphony No 8]**

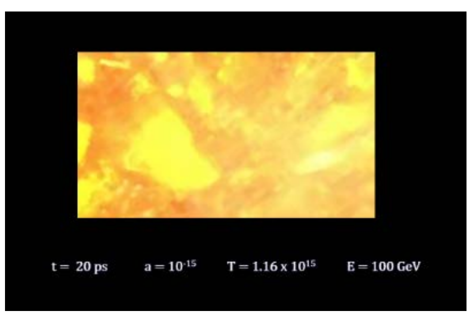
The inputs to Nucleosynthesis were baryons (protons and neutrons). Baryogenesis is the process that created these baryons. Quantum Chromodynamics shows how photons can create matter-antimatter pairs and how matter-antimatter pairs can create photons. [Quantum Chromodynamics QED]



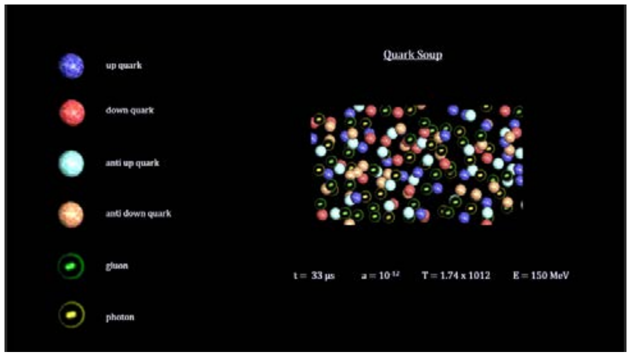




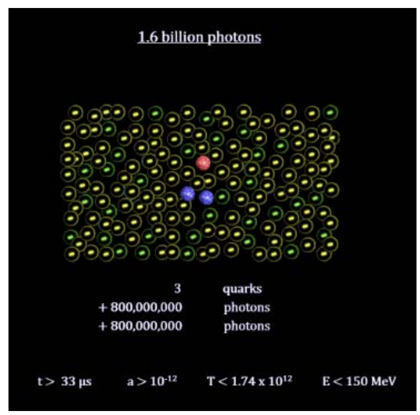
If we go back in time to when the universe was only 20 trillionths of a second old, its temperature was over a thousand trillion degrees and photon energy was around 100 GeV. At that level, no baryonic matter could survive, and all of space would have been filled with pure radiation.

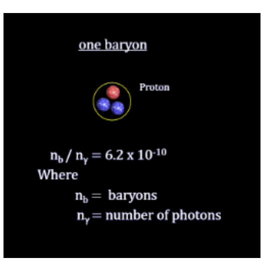


Then, when the temperature of the Universe cooled to around 1.74 trillion degrees, 33 microseconds into its expansion, created quarks and anti-quarks could survive. These quarks were not confined within baryons as they are today. Instead, they formed a sea of free quarks, a "quark soup". During this period of quark – antiquark production, the number of quarks, antiquarks and photons were in thermal equilibrium and therefore present in equal numbers. But the universe today has almost no antimatter at all.



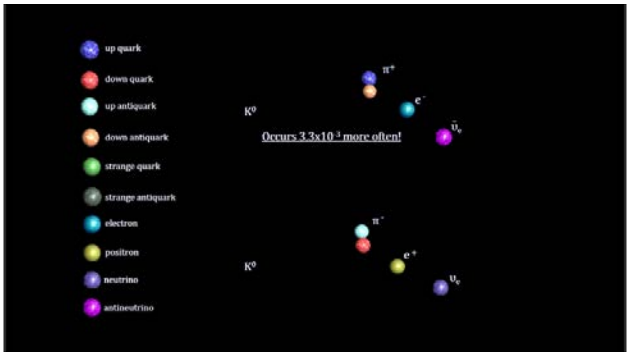
Now suppose nature had a very tiny tilt in favor of quarks over antiquarks. For example, let's say that for every 800,000,003 quarks, there were only 800,000,000 anti-quarks. Then when the universe cooled to the point that quark – antiquark pairs were no longer being produced, all the existing quarks and antiquarks would annihilate each other. In our example, only 3 quarks would remain. And these three quarks would be surrounded by 1.6 billion photons – the product of the annihilations.





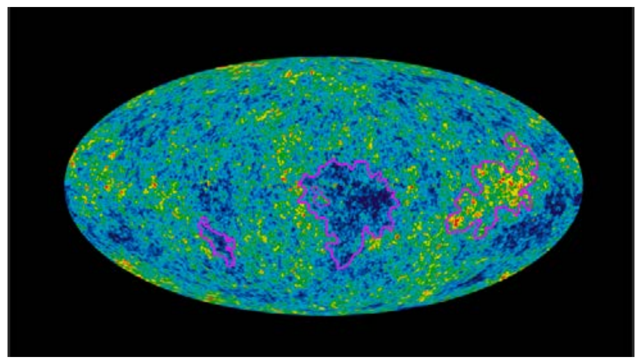
As the expansion continues and temperatures continue to cool, the free quarks were bound into protons and neutrons with the resulting baryon-to-photon ratio equal to our familiar 6 x 10^{-10}. Baryogenesis was over.

Before the 1960s, elementary particle theory held that the laws of physics were exactly the same for matter and anti-matter. Theorizing a processes that selects one over the other to create a small imbalance, like the one we just proposed, was at odds with this equality premise. But in the1960s small differences in Kaon decay showed that nature does treat them differently. [For example, these two decay modes should have equal probabilities. But measurements show that the production of electrons happens more often than the production of positrons (the electron's anti-particle).**]** But so far, no good explanation for how things happened during Baryogenesis has been developed. [Muons Pions and Kaons]

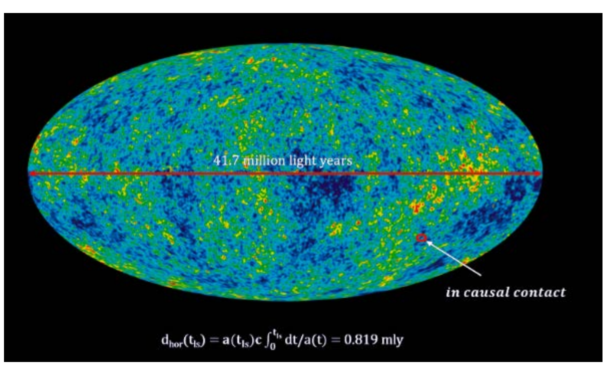


Inflation

We have taken the history of the Universe back to the first few microseconds of its expansion. At each stage, from Baryogenesis, through Nucleosynthesis to Recombination and Decoupling, we had the Universe in thermal equilibrium. At this point, there are two notable issues with the Flat Lambda Cold Dark Matter theory. One is that nothing we have covered so far gives us the anisotropy we see in the CMB radiation.

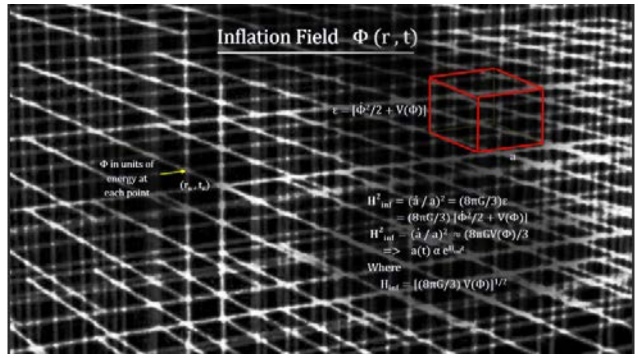


And two, the Universe appears to have been too large to be in thermal equilibrium during recombination. This one is called the "horizon problem" and it's a showstopper. You'll recall that the horizon distance is the furthest distance that light could have traveled in the time available. Assuming a matter and radiation dominated universe, appropriate for that time, we get a horizon distance that is less than 2% of the distance across the region. In other words, there is no way for the vast majority of the particles in recombination to be in causal contact as required for thermal equilibrium.

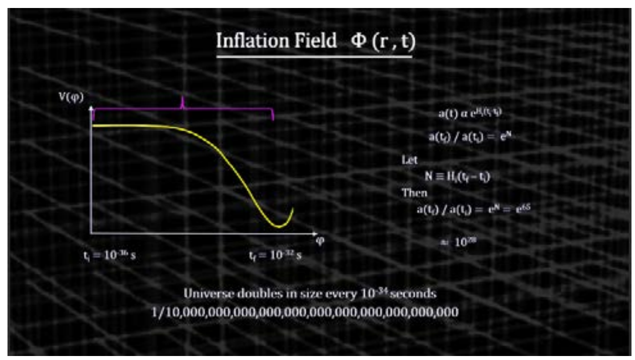


To solve this problem, a theory of cosmic inflation was suggested by cosmologist Alan Guth in 1982. We know from Quantum Field Theory, that the universe is permeated with any number of matter and force fields.

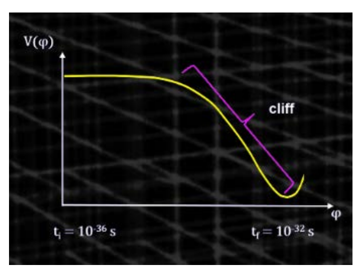
Like Higgs proposed a new field to explain W and Z boson behavior, Guth proposed that the universe contains a scalar energy field with a very large vacuum energy – much larger than today's cosmological constant. The field is called the Inflation field and its force particle is called an inflaton. If we assume that this large potential energy isn't changing appreciably, the large Hubble parameter would be constant and as we have seen before, the universe would expand exponentially.



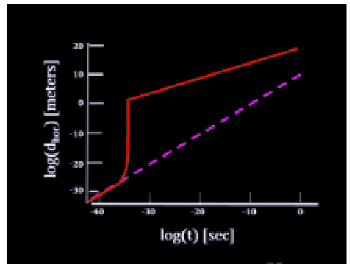
Here's a graph that relates the potential energy density of space against the changes in the energy of the field. [During a very short period of time, we see that the scale factor increases dramatically.] A large enough vacuum energy density would cause the universe to double in size once every10 billion trillion trillionths of a second.



At the end of the plateau, there is a sharp fall in the potential energy. We don't know what triggered the start of inflation, and we don't know what triggered this end. But during this split second fall, the inflation theory has it that all the potential energy and all the inflatrons in a rather cool universe following the inflation expansion were converted into all the heat, matter and energy in the universe. This was the fiery big bang we had entering the Baryogenesis epoch.



The horizon distance at the start of inflation would have been sub-microscopic. The horizon distance at the end of inflation (a tiny fraction of a second later) would have been the size of a whale. And the horizon distance at the time of last scattering would have been 652 million light years – 800 times larger than without inflation. This puts every particle in the decoupling process that created the CMB into causal contact with every other particle – easily enabling thermal equilibrium.



$d_{hor}(t_i) = 2ct_i \approx 6 \times 10^{-28}$ m

$d_{hor}(t_f) \approx e^N 3ct_f \approx 15$ m

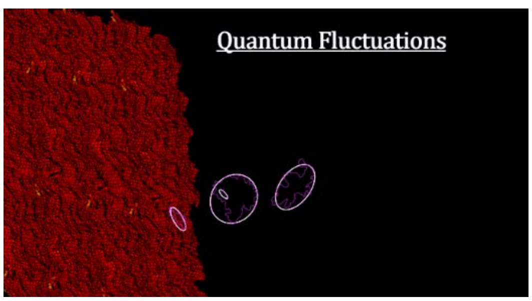
$a(t_f) \approx 2 \times 10^{-27}$

$a(t_{ls}) = 9.1 \times 10^{-4}$

$d_{hor}(t_{ls}) = a(t_{ls}) / a(t_{ls}) = 652$ mly

The zero point energy quantum fluctuations are short, small and create localized deviations in energy density. Under normal circumstances, the restorative force returns the deviation to normal almost instantly. But an exponentially expanding space weakens the restorative force. Each wave stretches with the expansion and freezes once it reaches the size of the horizon.

So we have a large ambient population of waves of every wavelength undergoing this expansion. This way, large numbers of small short localized energy deviations become small long lived extended deviations. In fact, these quantum fluctuations persist long after the inflation ends.



Wave Equation in expanding space

$$\partial^2\varphi/\partial t^2 + 3H\partial\varphi/\partial t - (k^2/a^2)\partial^2\varphi/\partial x^2 = 0$$

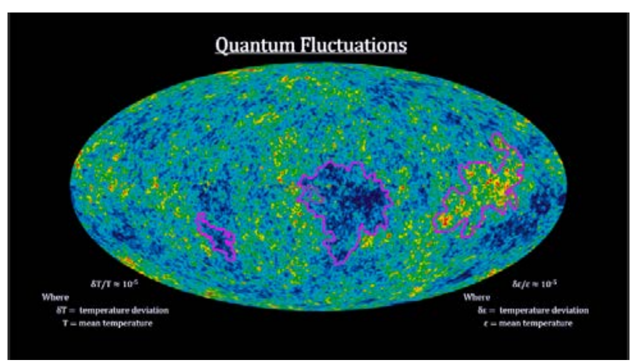
Freeze point $a_{freeze} = 2k/3H_{inf}$

Crossover wavelength $\lambda = (3\pi/4)/H_{inf}$

Where

k = wave number

We can tweak the variables to produce an energy density deviation on the order of 10^{-5} – the amount of temperature deviation we found in the CMB. These tiny quantum fluctuations are the origin of the anisotropy in the CBM that eventually lead to the huge galaxy superclusters and the great voids we see across the Universe today.



The ability to solve big bang problems like the horizon, CMB anisotropy and others have given the Theory of Inflation a great deal of credibility among cosmologists.

Cosmic Time Line **[Music - Puccini -Turandot - Nessun dorma - none shall sleep]**

Here's a summary of the Big Bang time line, according to the ΛCDM benchmark model with Inflation.

Planck Epoch (from 10^{-43} seconds to 10^{-36} seconds): Quantum mechanics has a notion of a smallest length called the Planck length (10^{-35} meters). It's theoretically impossible to determine the difference between two locations less than one Planck length apart. This gives us a smallest possible time interval called Planck time (10^{-43}seconds). It's the time it would take light to cover the Planck length. And it gives us the highest possible temperature called Planck Temperature (10^{32}°K). We'll start here.

Cosmic Inflation (from 10^{-36} seconds to 10^{-32} seconds) created a radiation only universe that cooled into a quark plasma following an exponential expansion.

Baryogenesis (from 10^{-32} seconds to 1 second) turned the quark plasma into baryons, eliminating anti-matter.

Neutrino decoupling (from 1 second to 3 minutes) freed neutrinos to travel across the universe.

Nucleosynthesis (from 3 minutes to 20 minutes) filled the universe with Hydrogen and Helium.

The Photon Epoch (from 20 minutes to 240,000 years) during the long photon epoch that followed nucleosynthesis, the universe was filled with a hot, opaque plasma of photons, atomic nuclei, electrons and dark matter.

Recombination (from 240,000 to 300,000 years) united electrons with protons creating a sea of Hydrogen and Helium atoms filling the Universe.

Photon Decoupling (from 300,000 to 370,000 years) freed photons to travel across the universe. At this time, the entire sky was as bright as the surface of the Sun.

Dark Ages (from 370,000 to 150 million years): The sky darkened as the expanding universe stretched the bright surface of last scattering radiation into the infrared range. With no stars having formed to give off light, the universe literally went dark. During this time, the caustic process worked the dark matter into filaments with the baryonic matter (Hydrogen and Helium) tagging along. At this time, the Universe left thermal equilibrium.

Star and Galaxy Formation (150 million years onwards): Eventually, the dense clouds of cosmic gas in the filaments started to collapse under their own gravity, becoming hot enough to trigger nuclear fusion reactions between hydrogen atoms, creating the very first stars.
[Larger stars burned out quickly and explode in massive supernova events, ejecting heavier elements used in the formation of subsequent star generations.] Galaxies of stars formed and gravitational attraction pulled these galaxies towards each other to form groups, clusters and galaxy superclusters.

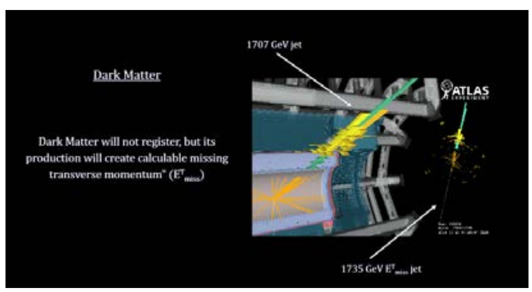
Solar System Formation (8.5 - 9 billion years): Our Sun is a late-generation star, incorporating the debris from many generations of earlier stars. It and its Solar System, form roughly 4.5 to 5 billion years ago (8.5 to 9 billion years after the Big Bang). [Around this time, as the universe expanded, the energy density contribution from matter diluted to the point where it was equal to the contribution from Vacuum Energy. From this point on, the universe moved into vacuum energy domination (aka dark energy).]

Today and beyond (13.7 billion years and counting): Today, the universe is dominated by vacuum energy and is expanding at an accelerating rate. Eventually everything gravitationally bound will be in a galaxy and all other galaxies will be beyond the visible horizon. CMB radiation will disappear. No intelligent species will be able to detect that they exist in a Universe bigger than their own galaxy. In addition, all star fuel will eventually run out, and the universe will go dark forever.

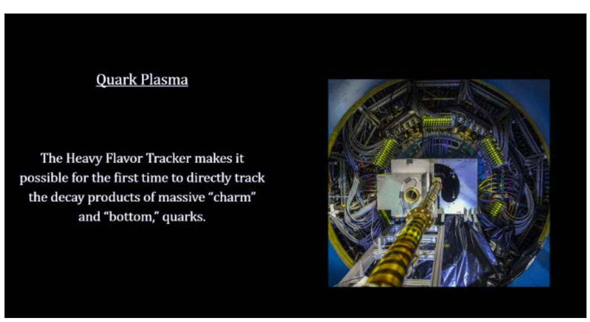
Futures [Music - Nicolai - Moon Choir (from The Merry Widows Of Windsor)]

When it comes to the cosmos as a whole, there is far more that we don't know than the little bit we do know. Based on new information and discoveries, the Benchmark Model is changing all the time. Sometimes the change are quite dramatic, like the discovery that the Universe's expansion is accelerating. Some of the key unknowns are being investigated via intensive efforts across a spectrum of scientific projects. Here are just a few.

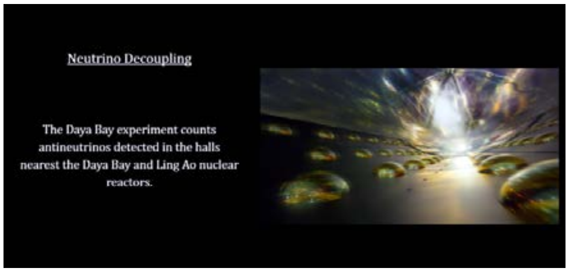
Dark Matter: There's a hunt for the nature of dark matter. For example, the LHC at CERN the ATLAS project now reaches 13 TeV. That's enough energy to find support for, limit, or eliminate various dark matter theories. [This is done by measuring the magnitude of missing transverse momentum.]



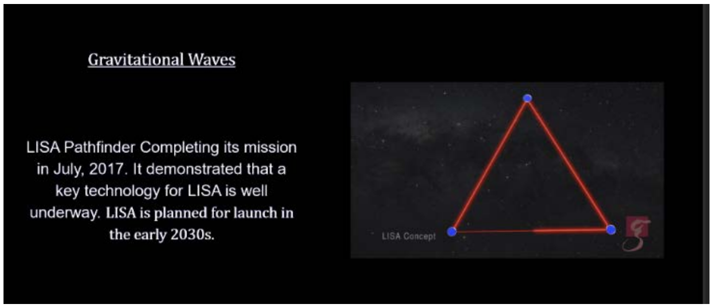
Quark Plasma: There's a hunt for the behavior of the hot quark plasma in existence during Baryogenesis. For example, thousands of times a second the Brookhaven National Laboratory's Relativistic Heavy Ion Collider (RHIC) creates a quark-gluon plasma. This research can reveal subtle details about the quark-gluon plasma, and by extension, the origins of matter.



Neutrinos: There's a hunt for neutrinos with new detectors like Daya Bay in South China. They hope to detect neutrinos from the Neutrino Decoupling epoch and may eventually solve the riddle of why so little antimatter survived Baryogenesis.

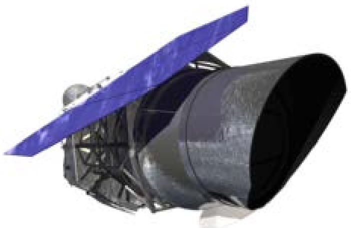


Gravitational Waves: There's a hunt for early gravitational waves, with projects like the Laser Interferometer Space Antenna (LISA). The laser arms will be millions of kilometers long, making it sensitive enough to register weak gravitational waves like the remnants of waves created in the earliest moments of the big bang.



Type 1a Supernovae: And the hunt for more type 1a supernovae continues along with deeper analysis of each and every one of them. This will provide a more exact measure of the scale factor dynamics since the end of the Dark Ages.

To further our knowledge, a new space telescope called the Wide Field Infrared Survey Telescope (WFIRST) is in design and scheduled for launch in the early 2020s. This telescope is specifically designed to further our understanding of these key standard candles.



As these researchers uncover more of nature's secrets, we can expect significant changes to the Benchmark Model. So stay tuned.