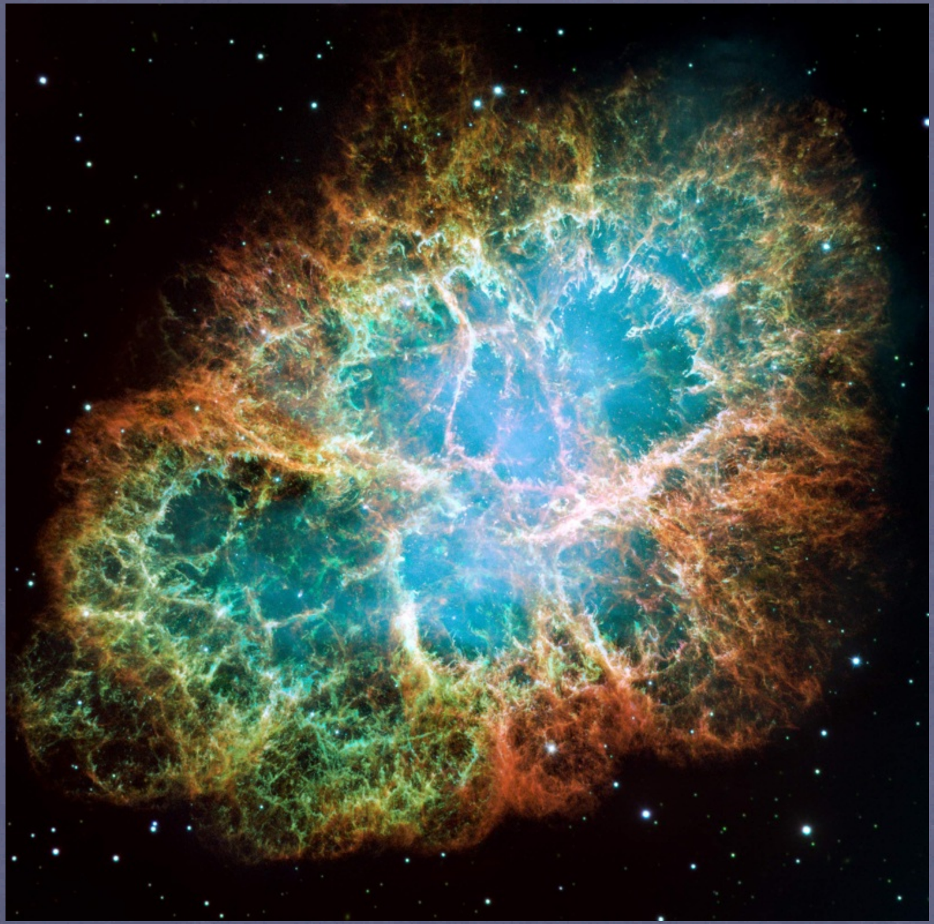
Crab Nebula



Hubble Telescope (optical)

Consists of Debris from 1054
Supernova in our Milky Way Galaxy

The Crab Nebula is the remnant of a star which, at the end of its lifespan, exploded in a supernova, as recorded by Chinese, Arab, and Native American astonomers in 1054AD. It was visible in the daytime for weeks and was a bright star in the night sky for two years.

Only about one supernova every 50 years happens in our galaxy, which contains more than 200 billion stars, and is about 80 thousand light years in diameter. The 1054 supernova exploded about 6500 light years away, with a light output that briefly rivaled the entire galaxy. The core of the star that was not ejected in the supernova collapsed into a neutron star.

Newton

Newton invented three of the foundations of modern science :

1. Calculus

   Which is part of the language of physics.

2. Mechanics

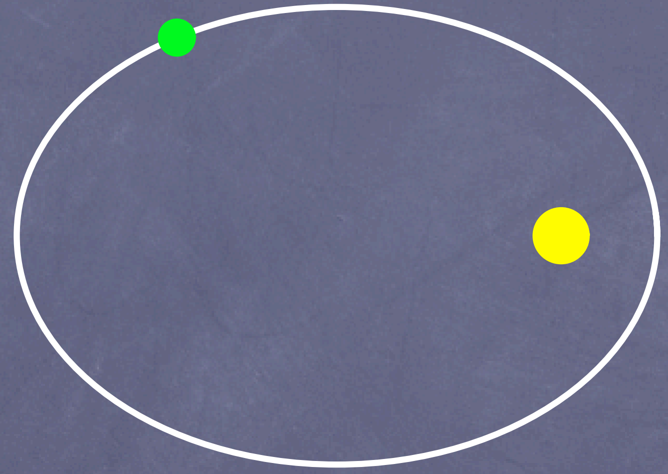
   Which is about how force leads to motion.

3. Gravitational force law

   Which governs how mass leads to force.

Newton's Gravity was a spectacular success.

It solved an ancient problem by precisely predicting closed elliptical planetary orbits :



Even today, virtually no engineering application requires corrections to Newton's theory of gravity. An exception is GPS.

Einstein

Einstein's most significant contributions are :

1. Early Quantum Reasoning

   One of the pioneers in understanding that nature has a quantum character.

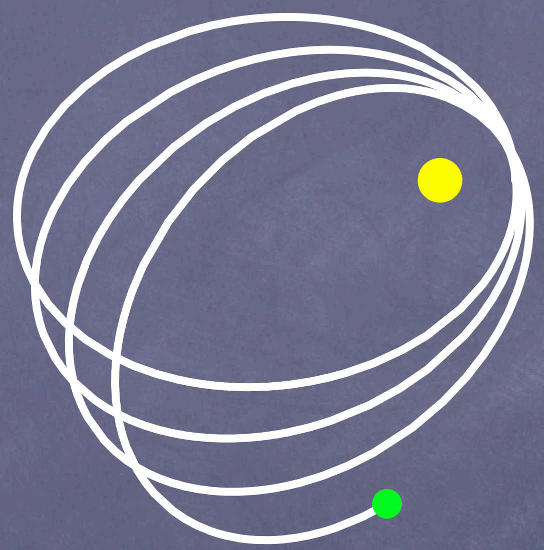
2. Special Relativity

   Modified Newton's Mechanics

3. General Relativity

   Gravitational force law and Mechanics

General Relativity predicts that planetary orbits precess, instead of following the closed ellipses predicted by Newton.



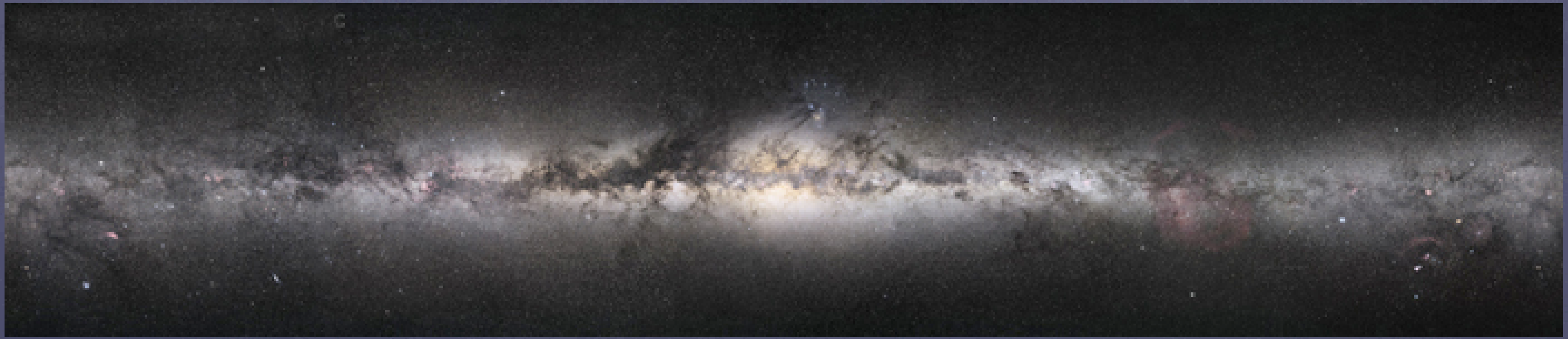
GR had immediate confirmation since it solved the unexplained problem of the precession of the orbit of Mercury.

In 1925, Edwin Hubble demonstrated that there are galaxies other than our own Milky Way. Today we know that there are more than 100 billion galaxies.

We dont have pictures like this of the Milky Way since we live inside it. Much of our view of the stars of our galaxy is obscured by stars and interstellar debris.

But if we look at the right part of the sky, the band of the Milky Way can be clearly made out.

Here is a panoramic view of the Milky Way.



Light travels at the speed :

$$c = 300000 \text{ km/second}$$

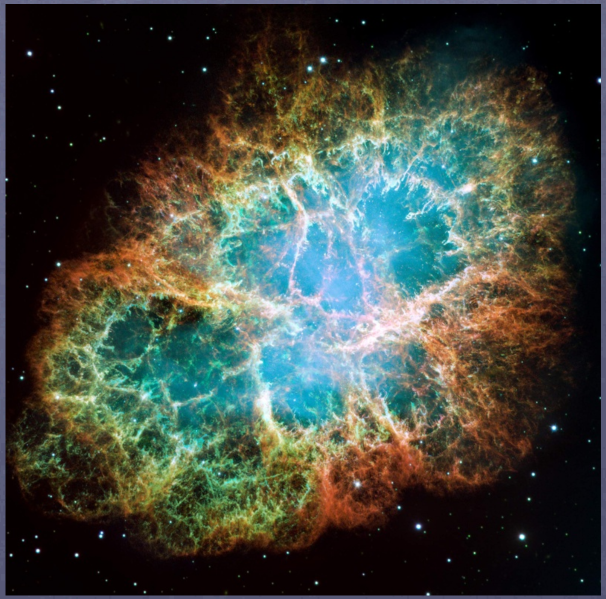
It takes light about 1/7 seconds to get around the earth. It takes about 1.2 seconds for light to get from the earth to the moon, and about 500 seconds to get from the sun to the earth.

$$1 \text{ lightyear} = 9.46 \times 10^{12} \text{ km}$$

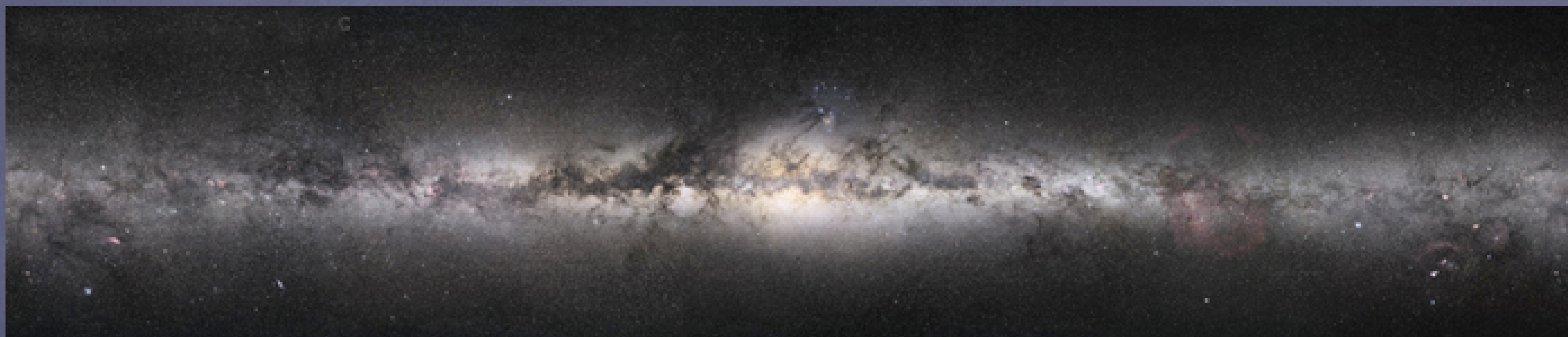
The solar system is about 10^{10} km or 1/1000 lightyear in radius.

The nearest star system to us is called Alpha Centauri. It is actually three stars orbiting one another. Its distance from the sun is 4.4 lightyears.

The Crab Nebula from 1054 Supernova is 6500 lightyears away.



The Milky Way, our galaxy of about 200 billion stars, is about 40000 lightyears in radius and about 2500 lightyears in thickness.



The nearest galaxy to us is Andromeda.

(Visible)

(UV)

Andromeda is 2.54 x 10^(6) lightyears away.

No one has any idea how large the universe is. However, the observable universe, that portion whose light has had time to reach us since the beginning of the universe, is about 45 billion light years in radius.

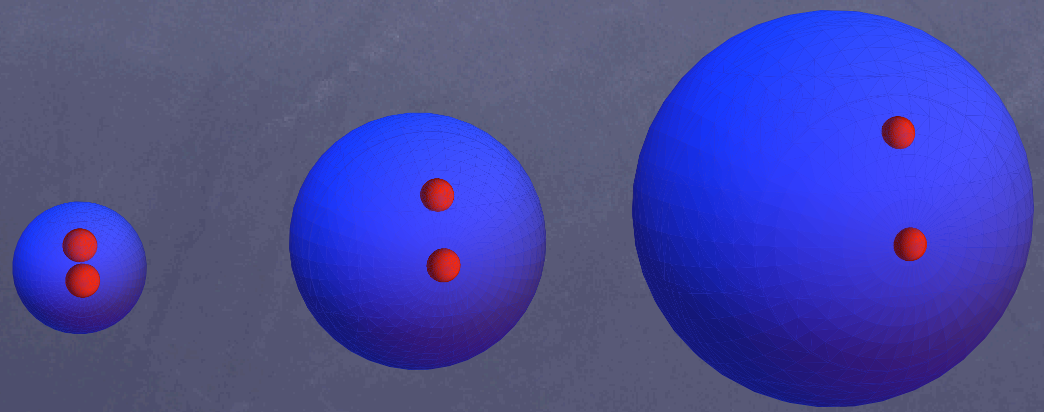
This represents about 10^20 earth radii.

It is interesting to note that the earth is about 10^22 proton radii. Thus “inner space” is in a sense more vast than outer space.

There are about 10^22 stars in the observable universe, but there are more than 10^26 atoms in the human body.

Hubble also compared the distances to each galaxy to the frequency of light coming from them. The Doppler effect is the blue shifting of light for oncoming objects and the redshifting of light for receding objects.

Hubble found that the farther a galaxy gets from another, the more redshifted the light. The universe was found to be expanding, with points separating much like those on an expanding balloon.



All of this is consistent with Einstein's theory of General Relativity, which makes two additional astonishing predictions.

1. The universe was once at incredibly high densities.

2. Depending on how much mass the universe has, the universe will either continue to expand indefinitely, or it will come to a halt and then begin to collapse, to return to incredibly high densities.

The Big Bang

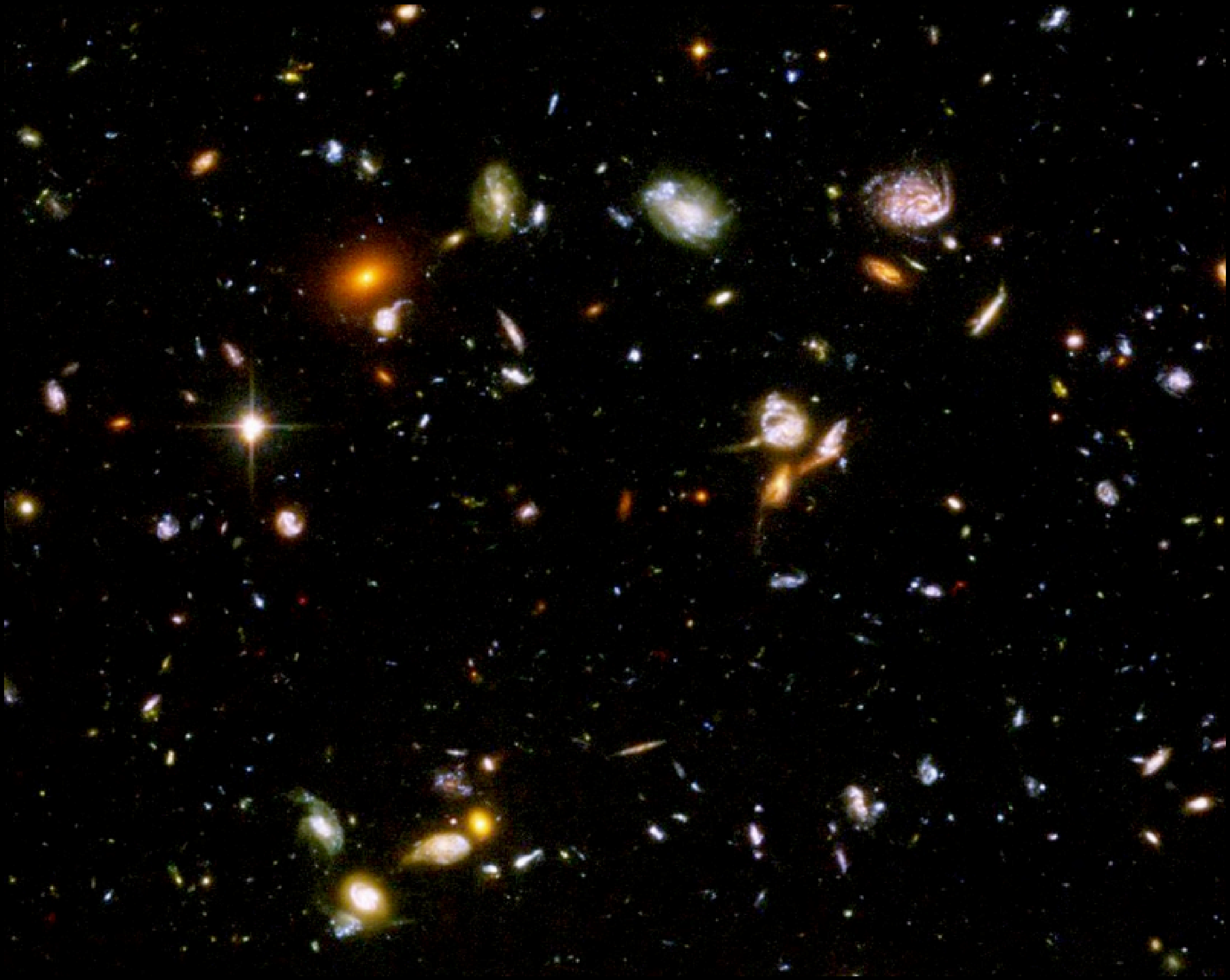
Central to the Big Bang model is that the Universe is both homogeneous and isotropic.

By homogeneous it is meant that the universe looks roughly the same as viewed from every point. By roughly, it is meant that above the galactic scale, there is little variation in density.

By isotropic it is meant that at any point the universe looks roughly the same when looking in different directions.

Powerful optical telescopes, such as the orbiting Hubble telescope, can look at such a small region of space that they can look between the close stars in the Milky Way. That is they look directly into the intergalactic space.

The results have been a stunning visual confirmation of the seeming uniformity of the universe. Galaxy densities are highly uniform on large scales.



Ultra Deep Field Hubble (optical)

At the very earliest times after the big bang, the densities and temperatures were so high that we dont understand enough about nature (quantum gravity) to make predictions.

It is unknown why matter predominated over anti-matter in the early universe.

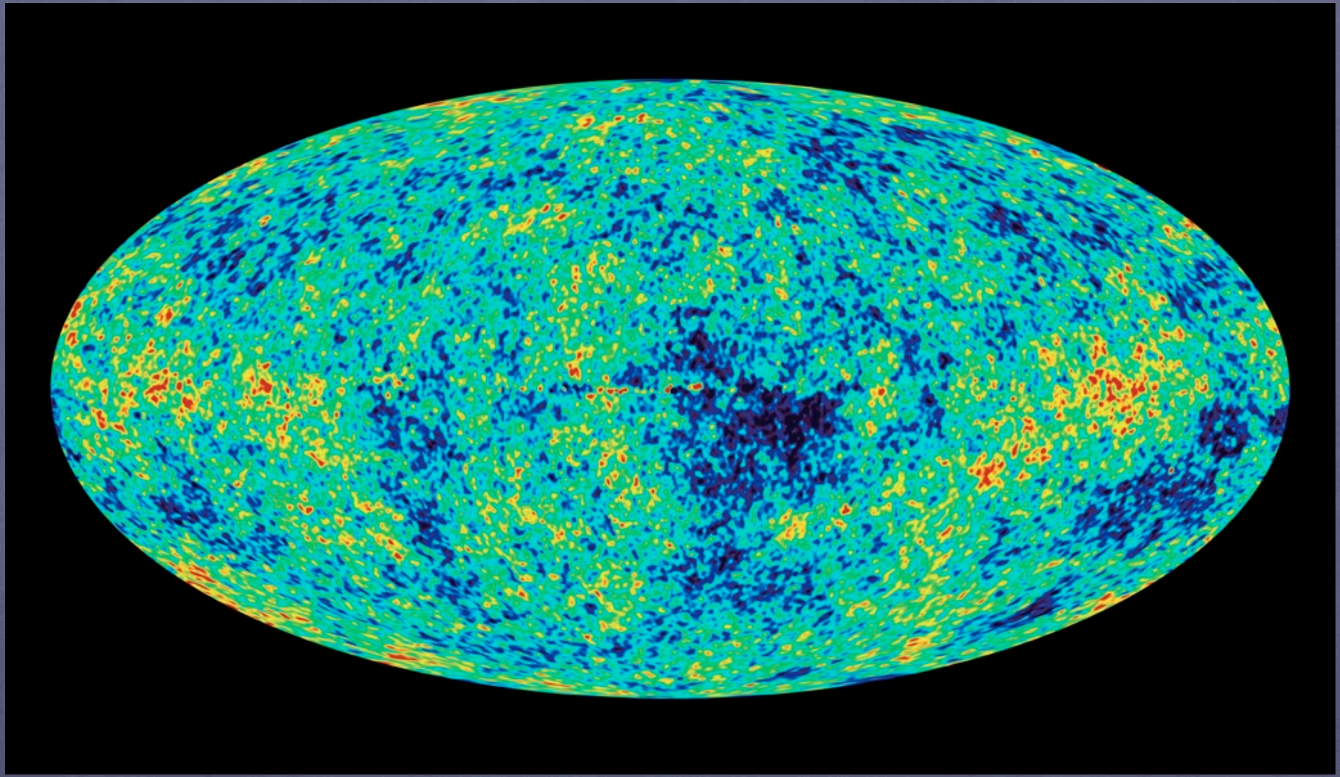
At some point, however, the universe expanded and cooled enough so that matter consisted of separated protons, neutrons, electrons, positrons, and photons.

Eventually some nuclei formed, and much later these captured enough electrons to make neutral atoms.

Once there was no free charge around, the photons had a much lower chance of scattering. Most of them havent struck matter since this “decoupling” time. They have since redshifted as the universe expanded.

In the late 1940s, George Gamow and others made the prediction that there should be a cosmic microwave background (CMB) radiation a few degrees above absolute zero.

In 1965, Penzias and Wilson, discovered the CMB after finding unexplained noise in their antennae at frequencies corresponding to a temperature of 2.7 degrees Kelvin.



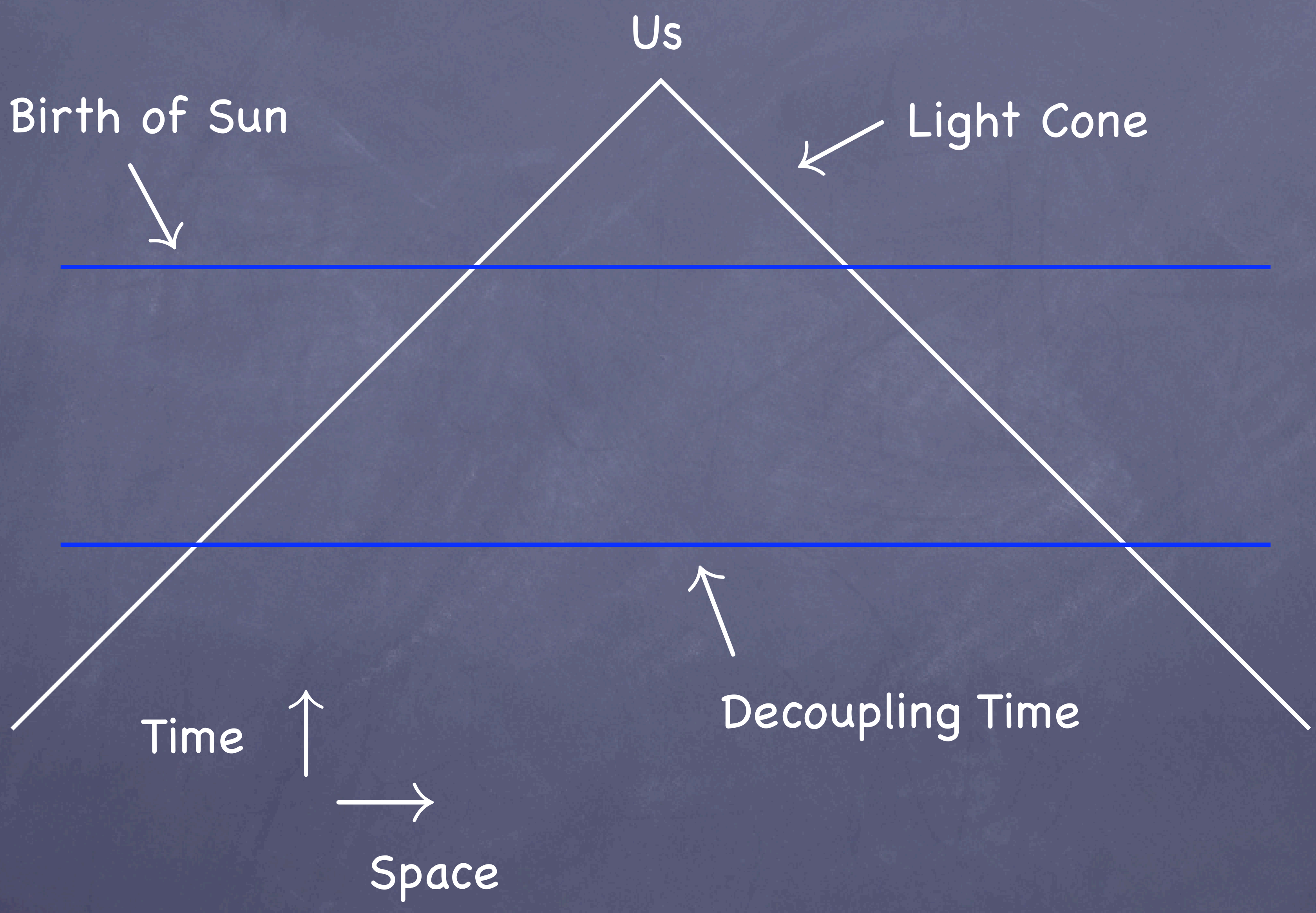
WMAP image of CMB over the earths sky.

It is out of the non-uniformities displayed in this image that the galaxies eventually coalesced.

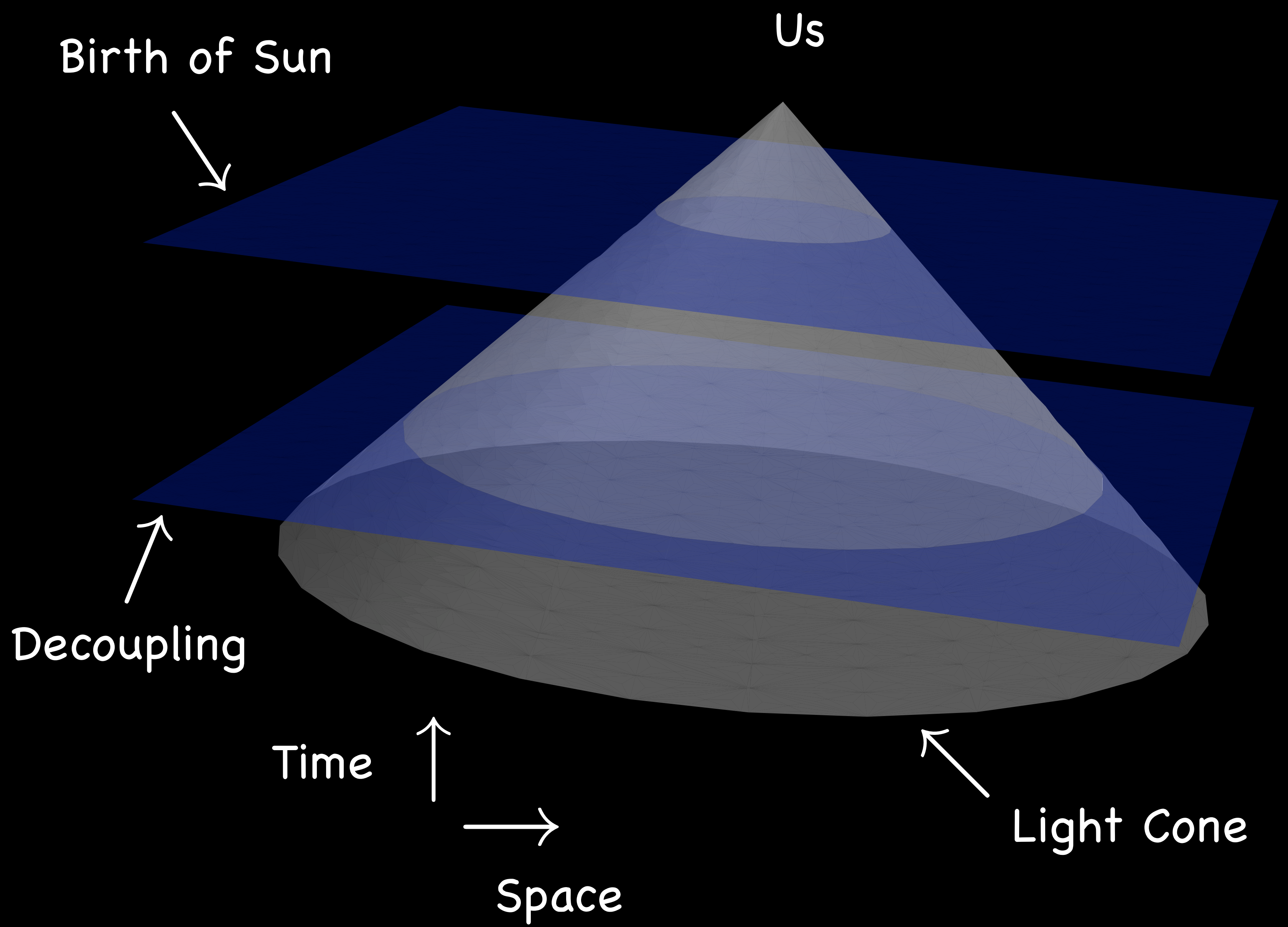
The stars that formed in the early universe have since gone through their lifecycles, although we still see the most distant of them through instruments since the light takes so long to get here.

It is out of the material (heavier nuclei) that these stars made over their lifetimes that complex molecules, and thus life, were formed.

When we view the universe, we are looking backwards along a light cone.



The Backward Light Cone.



Decoupling Time

The decoupling time refers to the relative decoupling of the photon from interacting with matter when the universe cooled enough for free electrons to combine with nuclei to form neutral atoms.

Decoupling took place about 370000 years after the Big Bang, which occured about 13.7 billion years ago.

We cannot view photons which originated before decoupling since there was so much charged matter around that they would have been absorbed or scattered before they could reached our eyes.

At the time of decoupling the universe was at a temperature of about 3000 degrees Kelvin.

Because of the expansion of the universe, photons produced at this temperature have been greatly redshifted over the last 13 billion years.

Gamow made the prediction in the late 1940s that these photons should still be around in a cosmic microwave background (CMB) radiation a few degrees above absolute zero.

Effect of Decoupling on Inhomogeneities

Prior to decoupling the photon pressure was so high that it inhibited the gravitational formation of inhomogeneities smaller than 10^{17} solar masses. Following decoupling, inhomogeneities could form that were as small as 10^{5} solar masses.

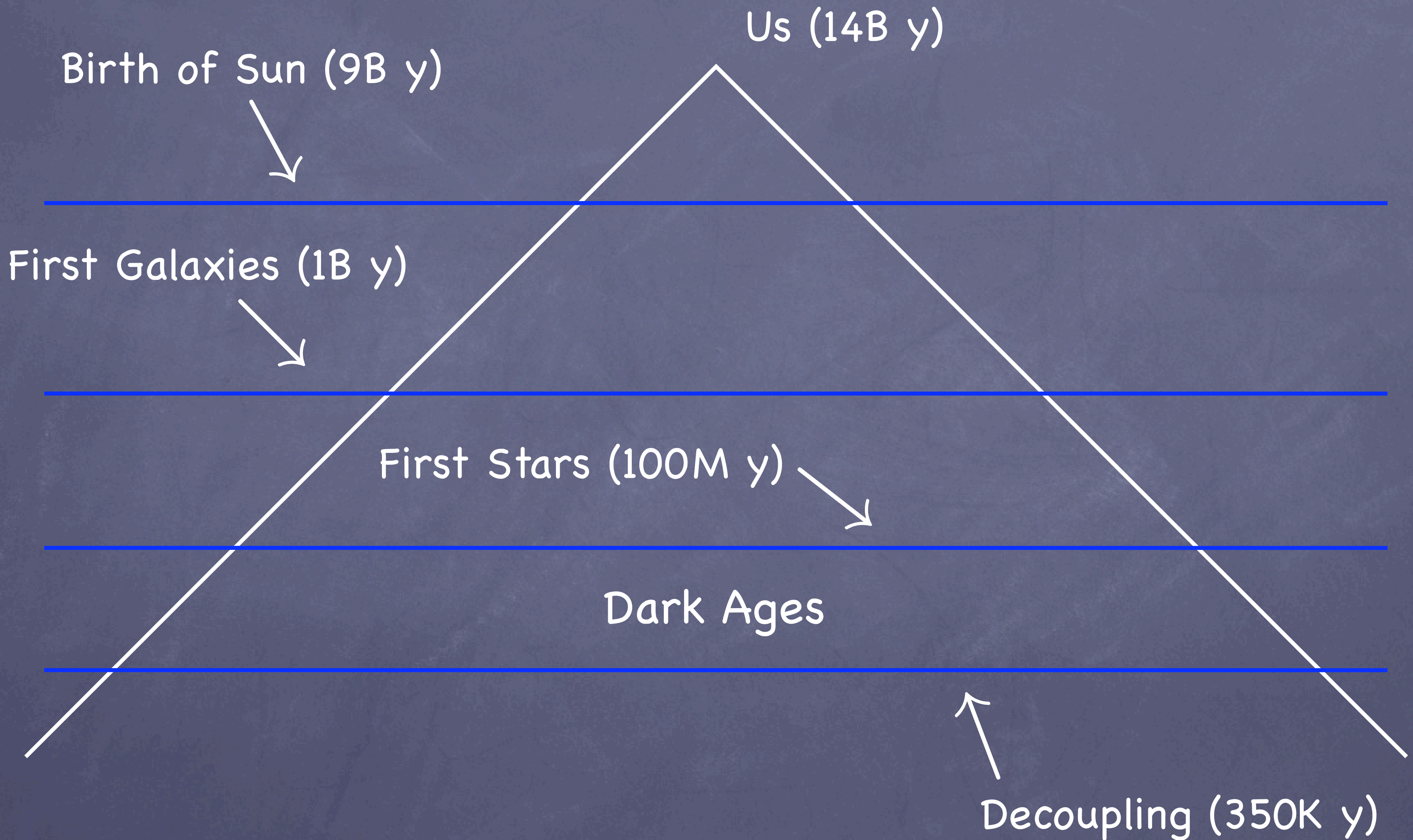
Since a typical galaxy is about 10^{11} solar masses, we can say that all but the largest structures in the universe formed after decoupling, sometime in what is known as the Dark Ages.

Thus decoupling has profound observational significance as well as having had a very significant impact on how structure formed in the universe.

The CMB is a crucial piece of evidence confirming the basic correctness of the Big Bang model.

Its remarkable uniformity, one part in 10000, was precisely observed by the COBE satellite. The COBE project led to two Nobel prizes.

Since Decoupling



Dark Era

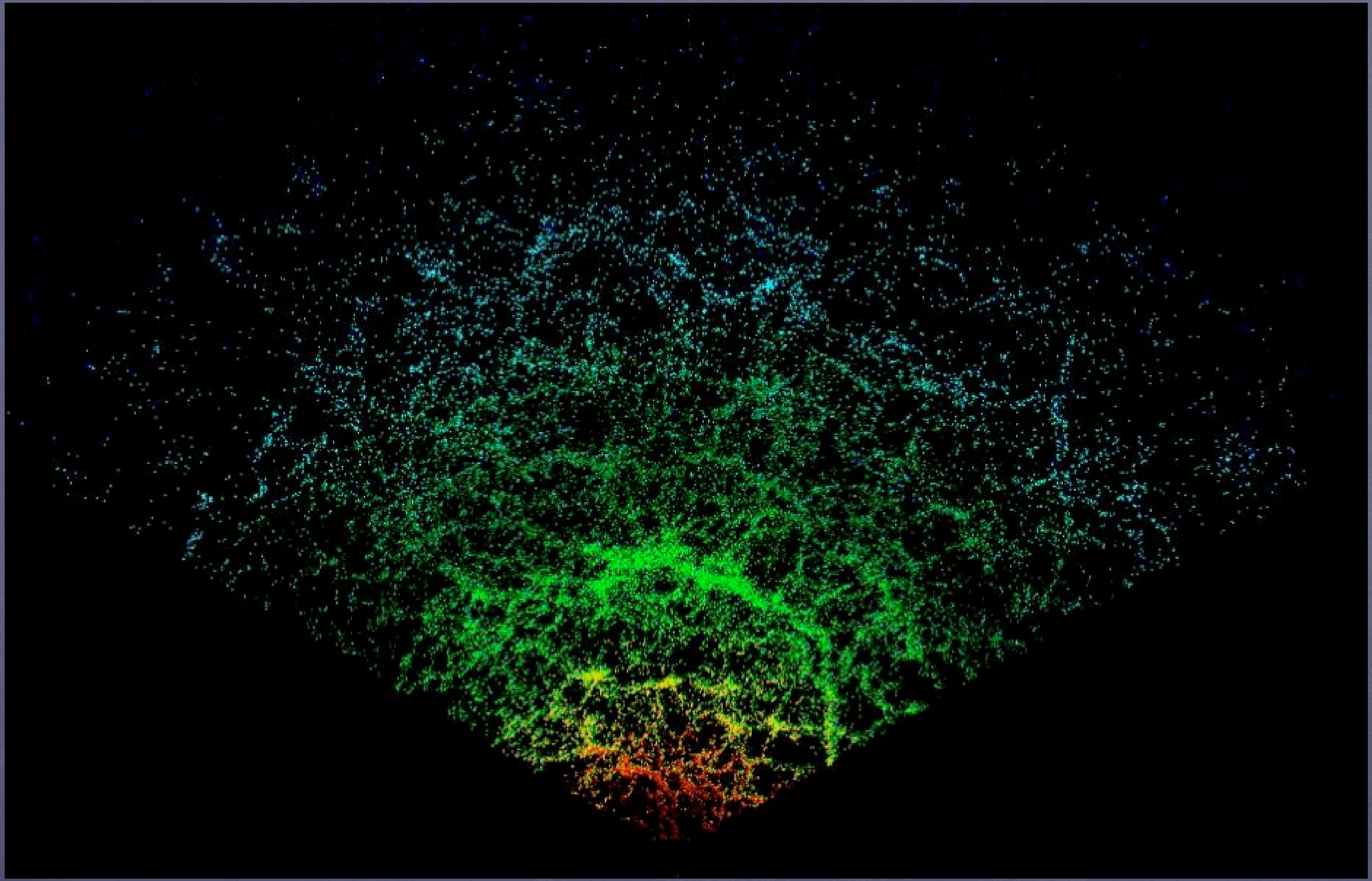
After the decoupling time came an era known as the Dark Era. The universe at this time was extremely uniform and was filled with light atoms and photons of the CMB. No new light was produced until stars slowly formed out of the coalescing inhomogeneities.

The Dark Era lasted until about 10^8 years after the Big Bang, when the universe was about 1/10 the size it is today.

Often the Dark Era is referred to as the era of atoms. The universe at this time consisted of an extremely uniform and diffuse mixture of hydrogen and Helium atoms, as well as the free photons which we view in the (redshifted) CMB today.

The non-uniformities in the original matter distribution, thought to closely follow those in the CMB, as well as additional non-uniformities which slowly developed at smaller scale after decoupling, ultimately led to the distribution of matter we see today.

Galaxies distribution with respect to distance in a section of sky from the Sloan Digital Sky Survey

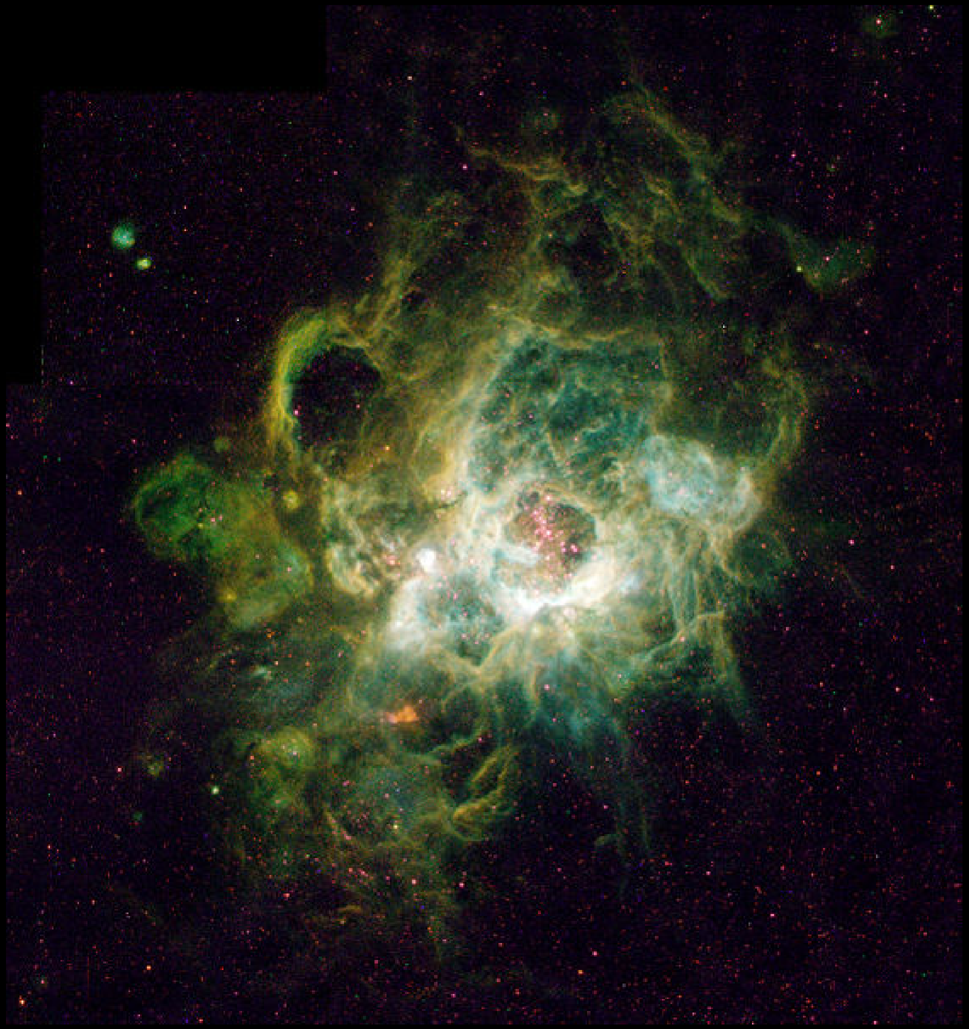


Distance from Sun ↑

First Stars and Galaxies

The first stars are thought to have been born about 100M years after the big bang, toward the end of the so-called dark ages which followed decoupling. These stars began assembling themselves into galaxies about 1 billion years after the big bang.

Virtually all of the visible matter in the universe is contained in the more than 100 billion galaxies in the visible universe.



Stellar Formation

The Sun

The Sun was born about 5 billion years ago from a ball of accumulated hydrogen which underwent thermonuclear ignition when temperatures and pressures allowed the fusing of hydrogen and deuterium into helium in the new star's core.

It is now believed that when the Sun was born the universe was about 9 billion years old. The sun and the planets are thought to have formed from debris from the death of the second generation of stars since the big bang.

Galactic Rotation

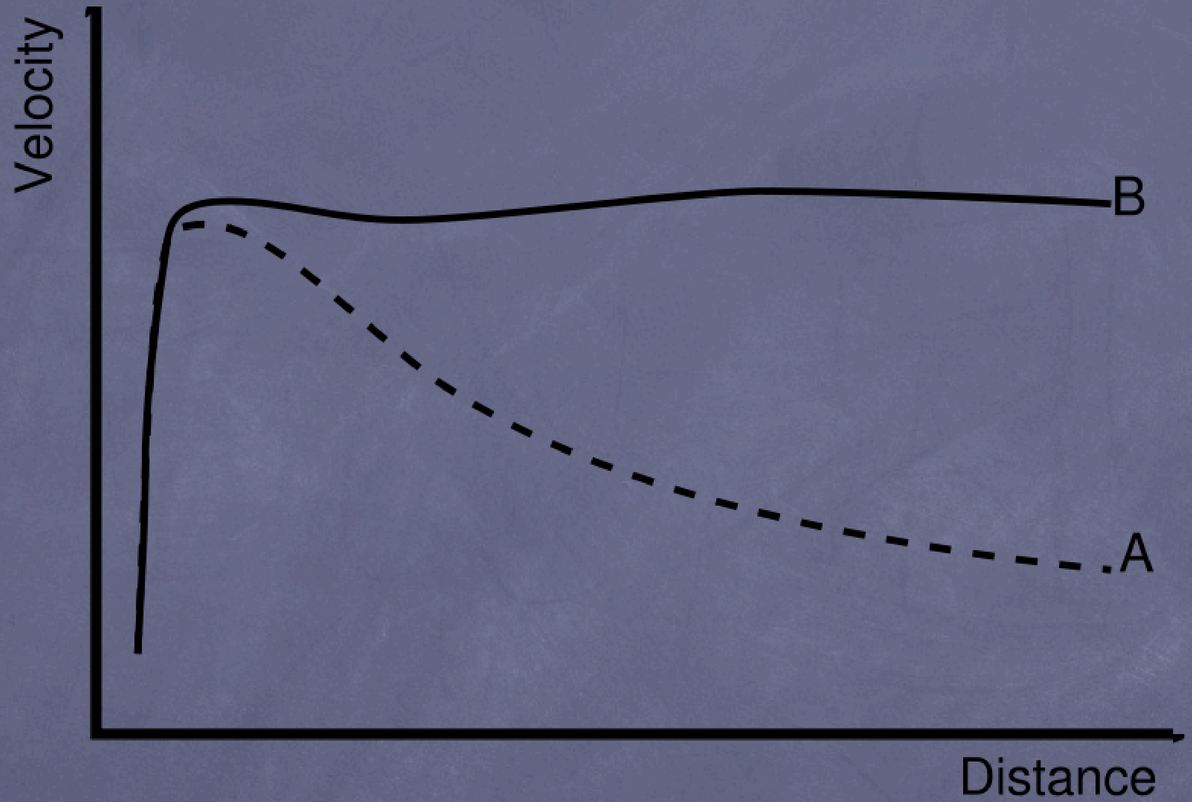
Based on the amount of visible matter we can use Einstein's equations to give us the distribution of velocities in a rotating galaxy.

Dark Matter

To account for the motion and rotation of galaxies it must be concluded that there is a great deal more matter in the universe than we can see by measuring visible or non-visible light. This must be so if Einstein's theory of gravity and motion, General Relativity, is correct.

It is now widely believed that ordinary matter, say very cold interstellar particles and dust, cannot account for this unseen extra matter. It is believed that this "Dark Matter" is made up of presently undiscovered particles which interact very weakly, perhaps only gravitationally, with ordinary matter.

Velocity versus Distance



Curve A is predicted using visible matter.
Curve B is actual measured velocity curve, accounted for by including Dark Matter.

Dark Energy

In 1998, following a series of precision redshift experiments of supernovae explosions, it was discovered that the expansion of the universe is accelerating.

Regions of the universe appear to be moving away from each other at an increasing rate, thus ultimately falling out of causal contact.

This suggests a future for the universe of increasingly separated galaxies which grow increasingly cold and dark.

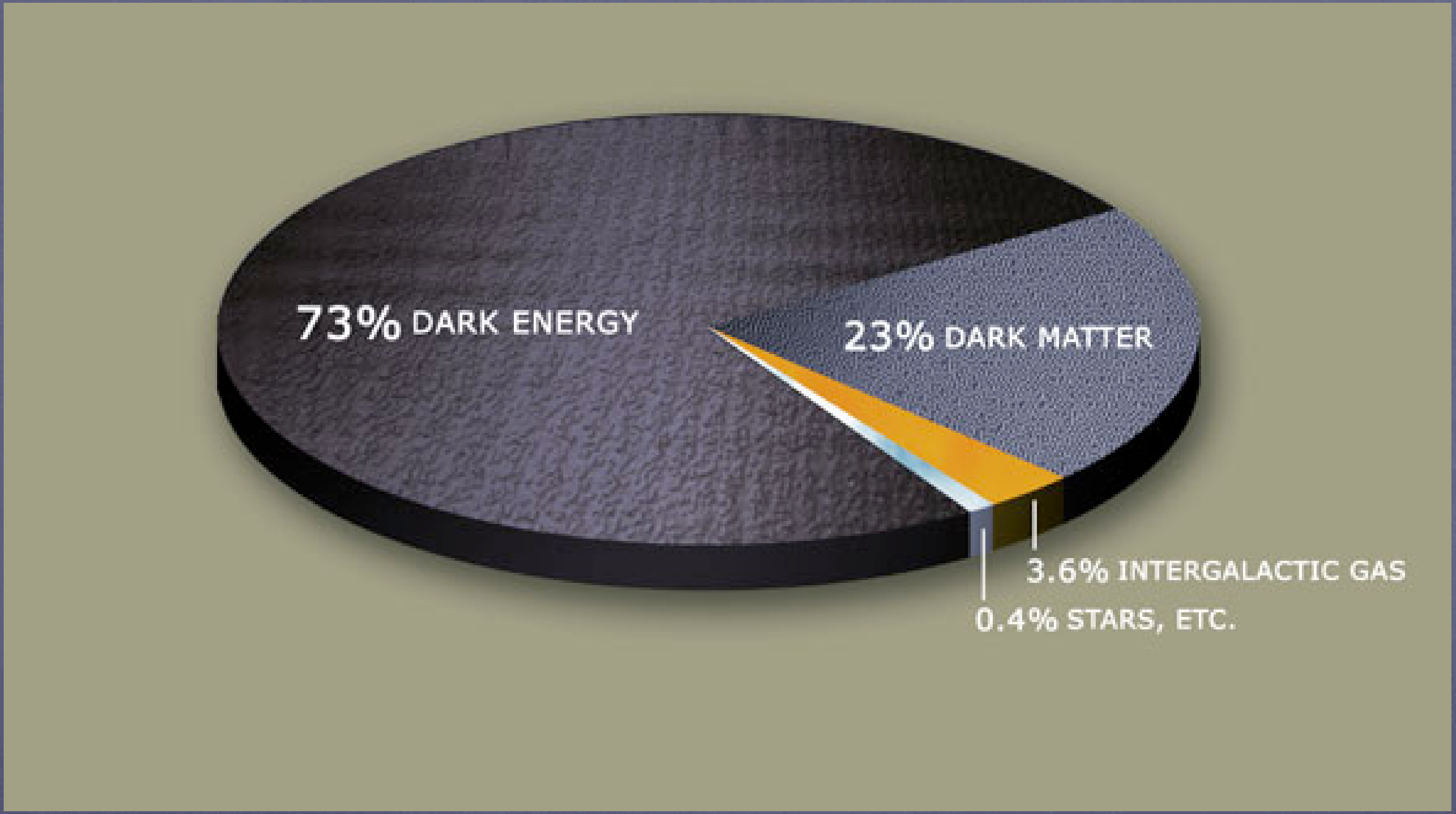
Cosmological Constant

One candidate for Dark Energy is what is known as a cosmological constant. In this case this constant is positive (repulsive).

Einstein originally introduced the cosmological constant to keep the universe from collapsing (positive) or expanding forever.

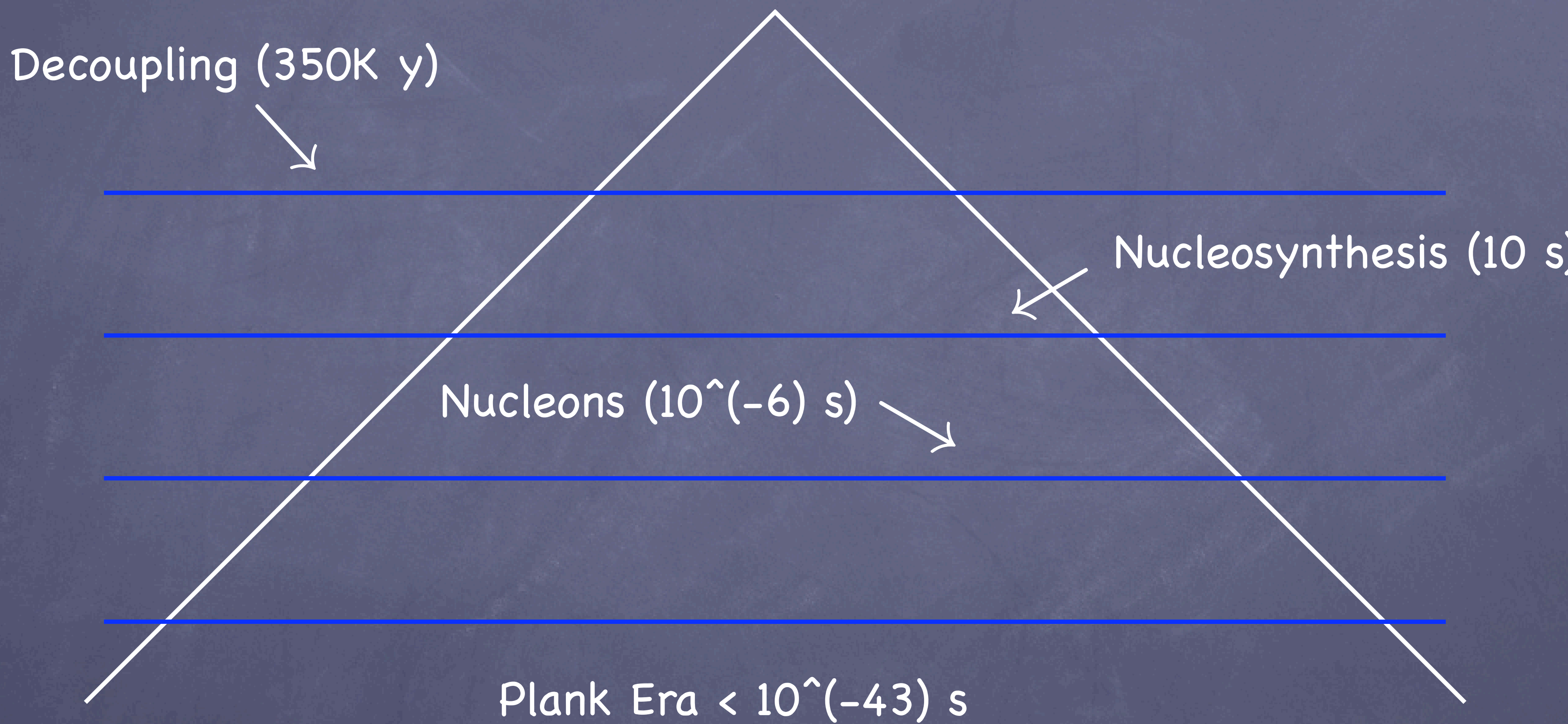
When it became clear that the universe was expanding, Einstein called the cosmological constant his greatest mistake.

Relative Abundance of Matter/Energy



No one knows what Dark Energy is.

Before Decoupling



Primordial Nucleosynthesis

At about 10 seconds after the Big Bang, the universe cooled enough for protons and neutrons to fuse into nuclei.

However this period only lasted long enough and had the temperatures and pressures necessary to form Deuterium, Helium, and Lithium. All other nuclei have been formed by fusion in the stars.

Helium Abundance

The known abundance of helium in the universe cannot be explained through stellar nucleosynthesis.

The accurate prediction of this abundance through primordial nucleosynthesis has been a big success of the Big Bang model.

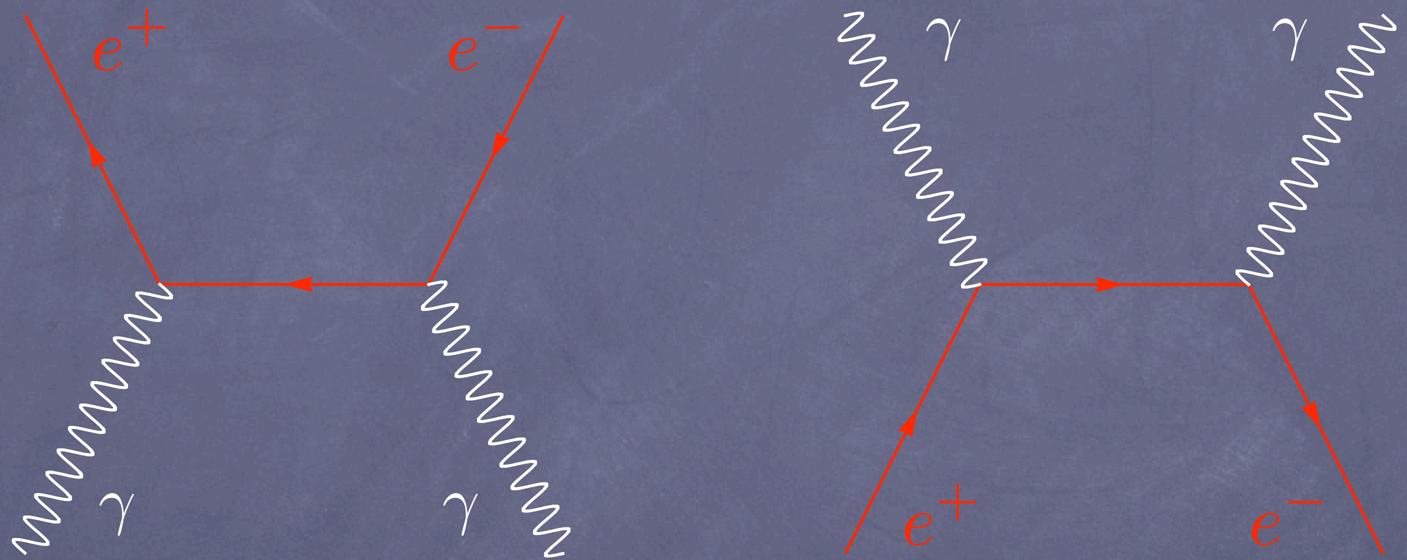
Results like the prediction of Helium abundance allow tests of the big bang model for times earlier than can be explored through measuring photons, for which the CMB is the earliest evidence available.

Condensation of Quark/Gluon Plasma

About $10^{(-6)}$ seconds after the Big Bang the temperature of the universe was low enough for quarks and gluons to bind into protons and neutrons. This was the original confinement.

At this point matter became neutral with respect to the "color" charge of the strong force. The strong force only has a residual impact on the world above $10^{(-15)}$ m.

Matter/Antimatter creation and annihilation was going on constantly in the early universe.



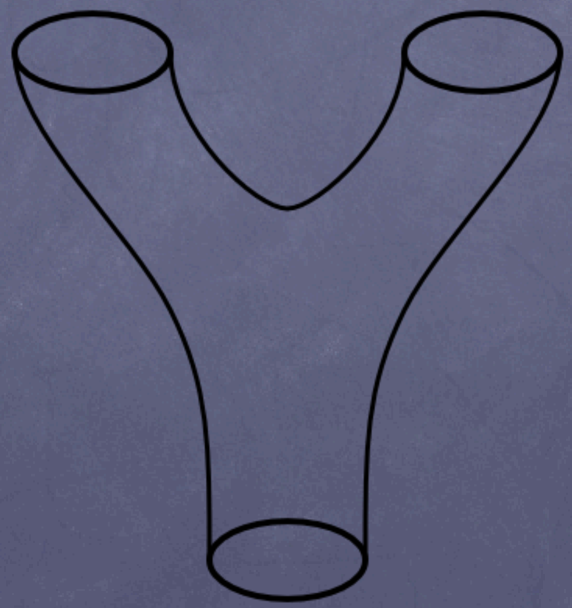
It is unknown why matter predominated over anti-matter soon after the Planck Era.

Planck Era

The earliest epoch in the universe is often known as the Planck era. It lasted for about 10^(-43) seconds after the big bang, when the universe was 10^(-30) of its present scale. This corresponds to an observable universe 1 mm in diameter.

We know very little about the Planck era since we dont have a sufficient understanding of quantum gravity. In particular, it is unknown whether the universe ever reached infinite density, as predicted by Einstein's General Relativity.

A great deal of the work in modern theoretical physics is concentrated on the nature of the Planck era. These studies are also closely associated with studies of quantum phenomena in black holes. Perhaps the most ambitious and successful of the theories that have been developed is the Superstring Theory.



Endpoint of Stellar Evolution

Stars begin to burn out when they have fused most of the lighter elements, like Hydrogen and Helium, into more stable heavier elements, the most stable being Iron and Nickel.

Stars of a sufficient size will end their lifecycle in a supernova which ejects a significant amount of their original material.

Neutron Stars

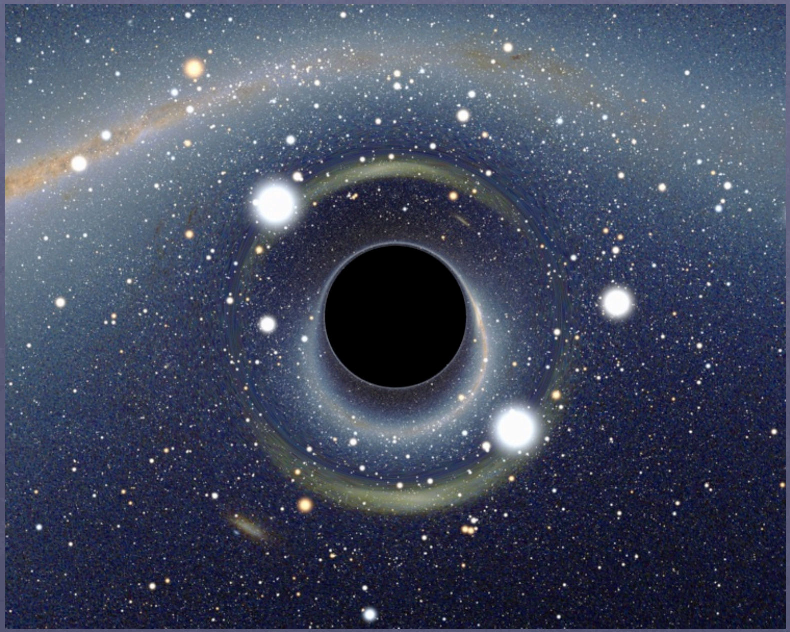
One possibility for the remnant object left behind by the supernova is a neutron star.

A Neutron Star is formed when gravity becomes so strong that all of the electrons bind with all of the protons to form one object of nuclear density consisting entirely of neutrons.

A neutron star of the mass of the earth would be 300 meters in diameter. Its surface gravity would be 1 billion times earths gravity.

Collapse to Black Hole

Another possibility is for the remaining matter to collapse into a black hole. A Black Hole the mass of the earth would be 2 centimeters in diameter. A Black Hole the mass of the sun would be 6 kilometers in diameter.



Chandrasekhar Limit

In 1939, Subrahmanyan Chandrasekhar, working at the University of Chicago, proved that stars of sufficient mass must collapse to form a black hole.

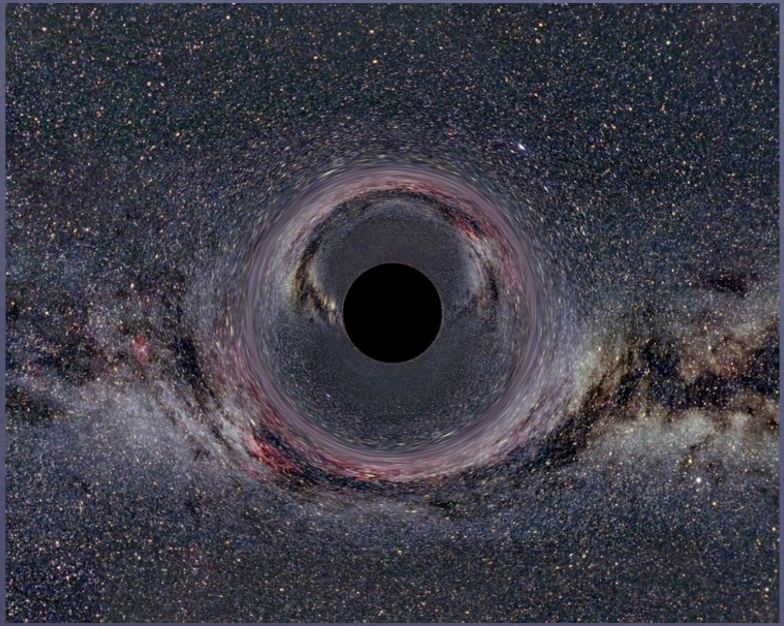
The so-called Chandrasekhar limit is about twice the mass of the sun. Stars larger than this are expected to form Black Holes after they die.

Chandrasekhar's result was strongly disputed at the time, but he received the Nobel prize in 1983 and he is now considered to be the father of the study of Black Hole physics.

Supermassive Black Holes

It is now believed that each galaxy has at its center a supermassive black hole, of perhaps billions of solar masses. It is very likely that these Black Holes have played a large role in the evolution of the universe.

Black Hole



Galaxy

Facts about Black Holes

It is believed that every Galaxy has a supermassive ($> 10^5 M_\odot$) black hole at its center.

Black holes formed by stellar collapse following supernovae are expected to be a few solar masses.

Radius of Event Horizon : $$R_h = \frac{2GM}{c^2} \sim 3\,\frac{M}{M_\odot}\,\mathrm{km}$$

Maximum time from Horizon to Singularity : $$T_s = \frac{\pi GM}{c^3} \sim 10^{-5}\,\frac{M}{M_\odot}\,\mathrm{s}$$

Hawking Temperature

Stephen Hawking (1974) discovered that quantum mechanics implies that black holes radiate as black bodies at the temperature :

$$T_H = \frac{\hbar c^3}{8\pi G M} \sim 10^{-7}\,\frac{M_\odot}{M}\,{}^\circ\mathrm{K}$$

This implies an evaporation process and the following lifetime for a black hole :

$$\tau_L \propto \frac{M^3 G^2}{\hbar c^4} \sim 10^{71}\,\frac{M^3}{M_\odot^3}\,s$$

Microscopic Black Holes

Thus Black Holes larger than about 10^(-8) solar masses have temperatures lower than the Cosmic Microwave background. They would thus not evaporate at all, but would consume the CMB and get more massive.

It is unknown whether smaller black holes can completely "evaporate", but it is believed that it can radiate down to microscopic size. For example, for a proton diameter black hole :

$$R_h = 10^{-15}\,\mathrm{m} \qquad M = 6.7 \times 10^{11}\,\mathrm{kg}$$

$$T_H = 1.8 \times 10^{11}\,^{\circ}\mathrm{K} \qquad \tau_L = 1.6 \times 10^{15}\,\mathrm{s}$$

Evidence for BH's : Jets

Jets consist of matter that comes very close to entering the black hole but is ejected at extremely high velocities.

This (relativistic) jet of matter comes from a supermassive black hole.

Stellar Orbits Near Galactic Center

In the last decade astronomers and physicists have carefully examined the orbits of stars close to the galactic center. What they have found is that there is an object of enormous mass (millions of solar masses) that accelerate some stars to enormous velocities.

Since we cannot see the object, it seems increasingly hard to dispute that this is a supermassive Black Hole.