The Cosmos

*{**Abstract** – In this final segment of our "How far away is it" video book, we cover the structure of the visible Universe as we currently know it.*

We start with some galaxy and galaxy clusters beyond our local superclusters, including: Abell 2029 with its supermassive galaxy IC 1101; Quasar Markarian; a massive cluster gravitationally lensing a more distant cluster; El Gordo; some distant supernovae remnants; gravitational lensing in giant galaxy clusters like Abell 1689, Abell 68, and more. We then cover dark matter discovery in the Coma cluster and evidence for it in the Bullet cluster. We see a gravitationally lensed supernova;

Next, we cover slowly expanding space and the impact that has on measuring distances using GN-z11, currently beyond the visible horizon, as an example. We also cover how recent redshift measurements from distant Type 1a Supernovas have provided evidence that the expansion is accelerating. We explain how this leads to the concept of 'Dark Energy' by examining the concept of a cosmic scale factor and how it changes over time. With this we introduce 'cosmological redshift' as a measure of the expansion.

We then cover the creation of the Cosmic Background Microwave (CMB) radiation and what that tells us about the formation of galaxy walls around great voids. We then cover some of the recent galaxy surveys that are helping us understand the fabric of the visible Universe. These include the 2dF Galaxy Redshift Survey of 52,000 galaxies out to 3 billion light years, and the Sloan Digital Sky Survey that mapped one million galaxies. We show the 3D supercomputer video that shows the fabric of the Universe is like a web of galaxies with massive voids. We show some of the galaxy surveys that show this web-like structure.

We conclude with a review of the cosmic distance ladder and our last adjustment based on cosmological redshift. And we end with Edwin Hubble's own words on the limits of our knowledge.}

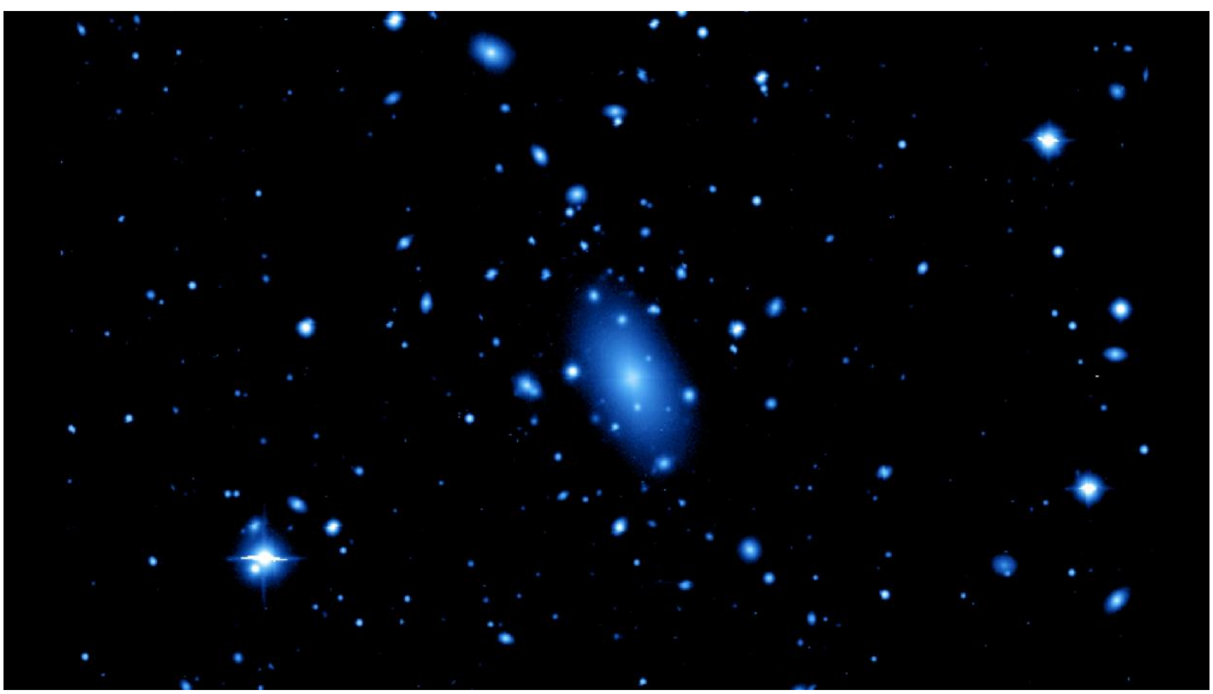
> ***[Music:** @00:00 Mendelssohn – "Violin Concerto in E Minor Op.64 Andante"; 101 Strings; from the album The Most Relaxing Classical Music, 1997**]***

Beyond the Local Superclusters

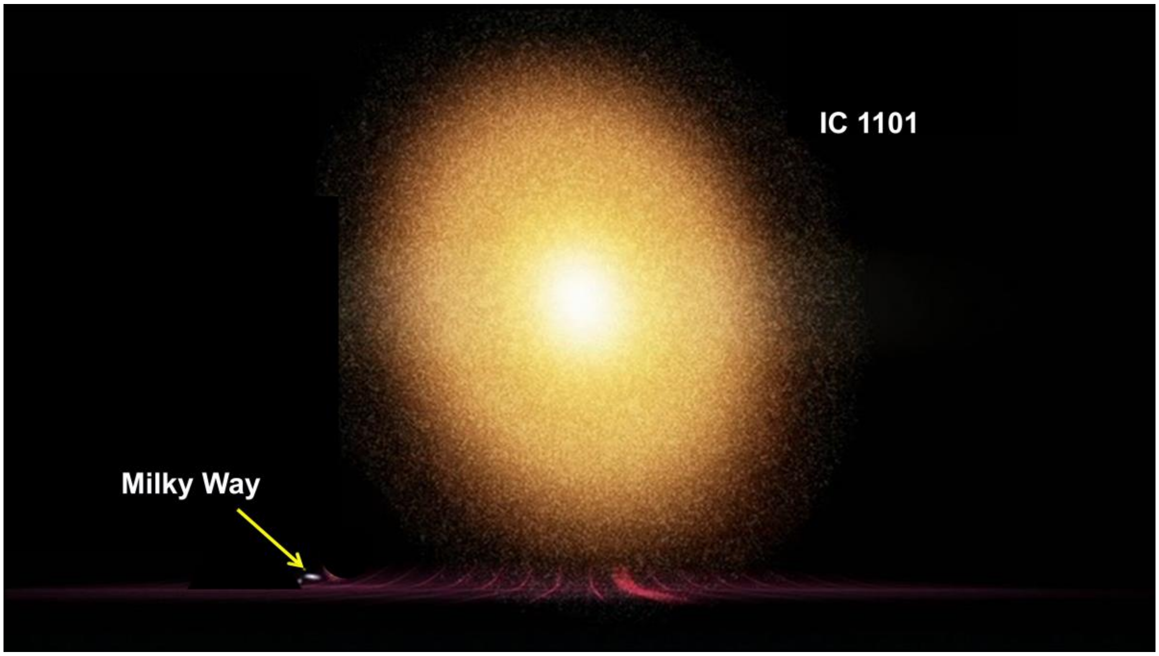
In this final segment, we'll go beyond the 7% covered by Local Superclusters, and examine the Universe as a whole. At the end, we'll quickly review all the territory we've covered since we began our journey exploring the dimensions of the Earth. So, let's start with a look at some of the objects photographed by Hubble that lay beyond our Local Supercluster.

Abell 2029 with IC 1101 – 1,000 mly

This optical image shows the massive galaxy cluster Abell 2029. This galaxy cluster has a Redshift that indicates that it is one billion light-years away.

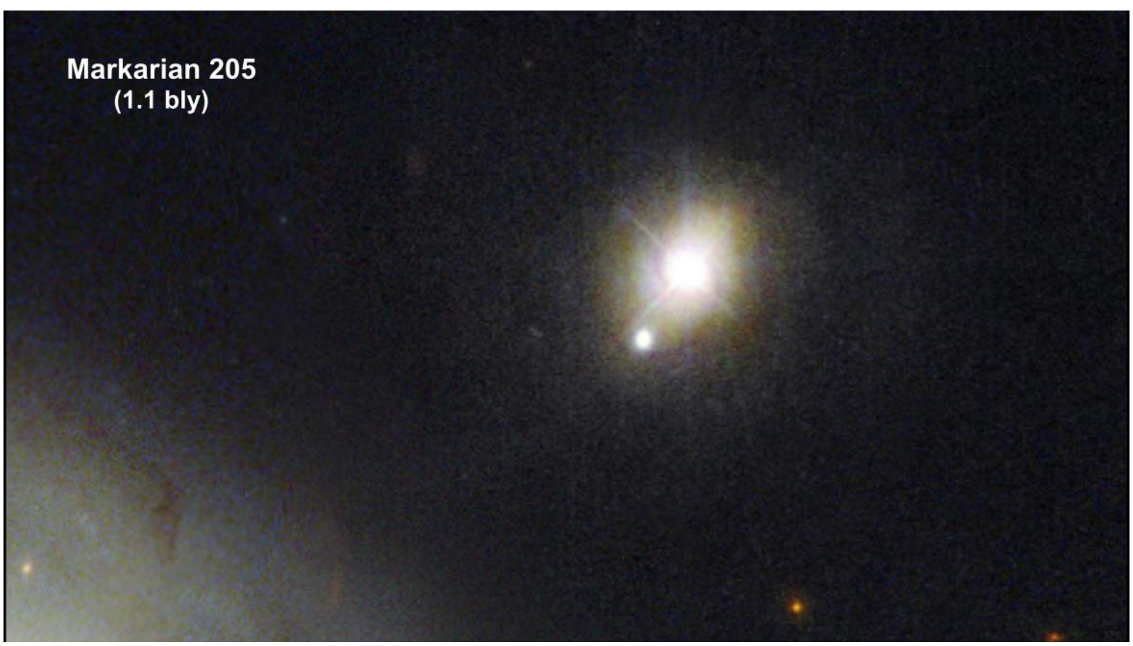


The large elliptical galaxy visible in the center of the image is IC 1101. It is the largest galaxy ever seen. It is 6 million light-years across – 60 times larger than our Milky Way, and it contains around 100 trillion stars!



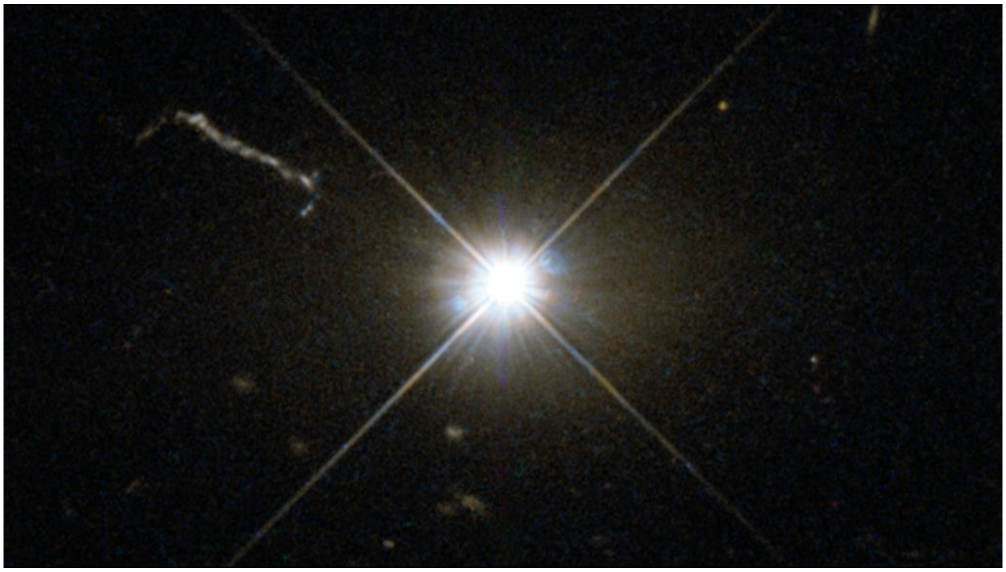
Markarian 205 – 1,100 mly

You might recognize NGC 4319. It is a galaxy in the Virgo Supercluster. Of interest now is the small light in the upper right. It's the quasar called Markarian 205. It's 1.1 billion light years away. Markarian 205 is a relatively nearby quasar. Many quasars reside much farther away. **[Additional info:** Markarian 205 has a companion, a compact galaxy just below it. The objects appear to be interacting. The compact galaxy may be responsible for the structure in Markarian 205's halo.**]**



Quasar 3C 273 – 2.5 bly

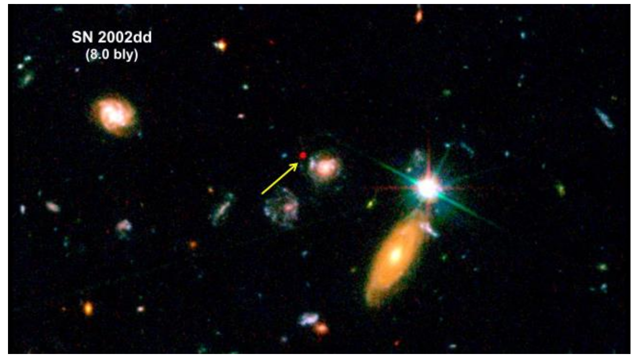
Quasars are the intensely powerful centers of distant, active galaxies, powered by a huge disc of particles surrounding a supermassive black hole. As material from this disc falls inwards, some quasars — including this one, have been observed to fire off super-fast jets into the surrounding space. In this picture, one of these jets appears as a cloudy streak, measuring some 200,000 light-years in length. Despite its great distance, 3C 273 is still one of the closest quasars to our home. It was the first quasar ever to be identified, and was discovered in the early 1960s. Quasars are capable of emitting hundreds or even thousands of times the entire energy output of our galaxy, making them some of the most luminous and energetic objects in the entire Universe. Of these very bright objects, 3C 273 is the brightest in our skies.



El Gordo – 7 bly
This is a combined ESO Very Large Telescope and Chandra image of the newly discovered galaxy cluster called El Gordo. It consists of two separate galaxy subclusters colliding are seeing what this cluster looked like when the Universe was only half its current age.

SN2002dd – 8,000 mly

Hubble is a 'supernova machine' for probing the early universe. Here's a type 1a it found that's approximately 8 billion light-years from Earth.

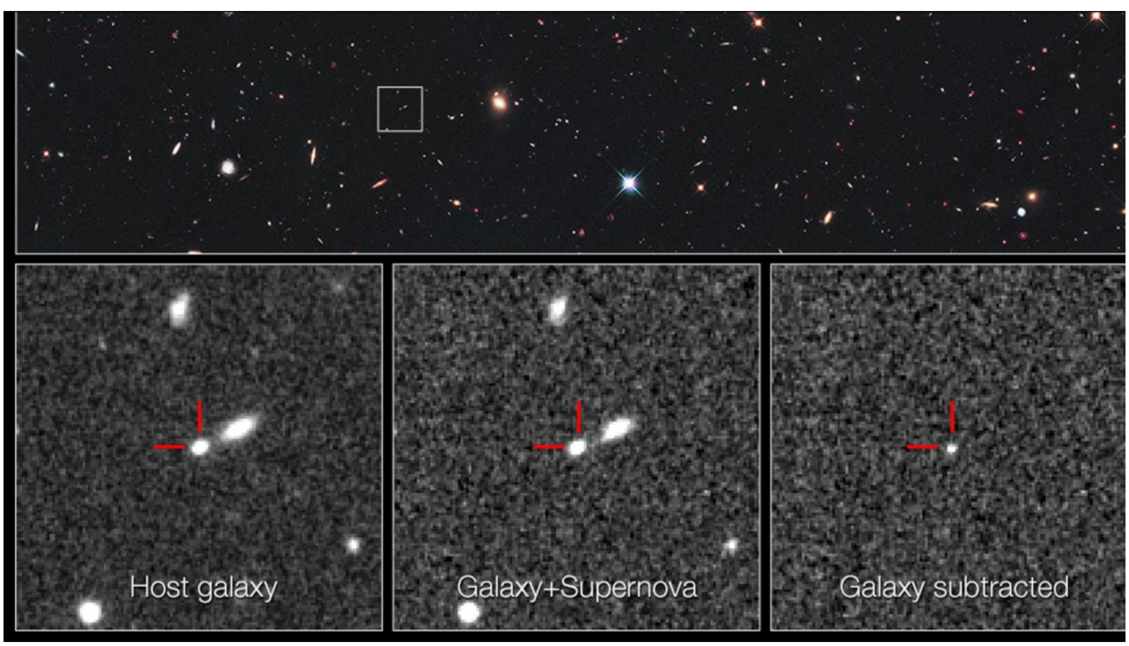


SN UDS10Wil – 10 bly

If you recall, type 1a supernova represent one of our most important standard candles because they are so bright, we can see them from very far away.

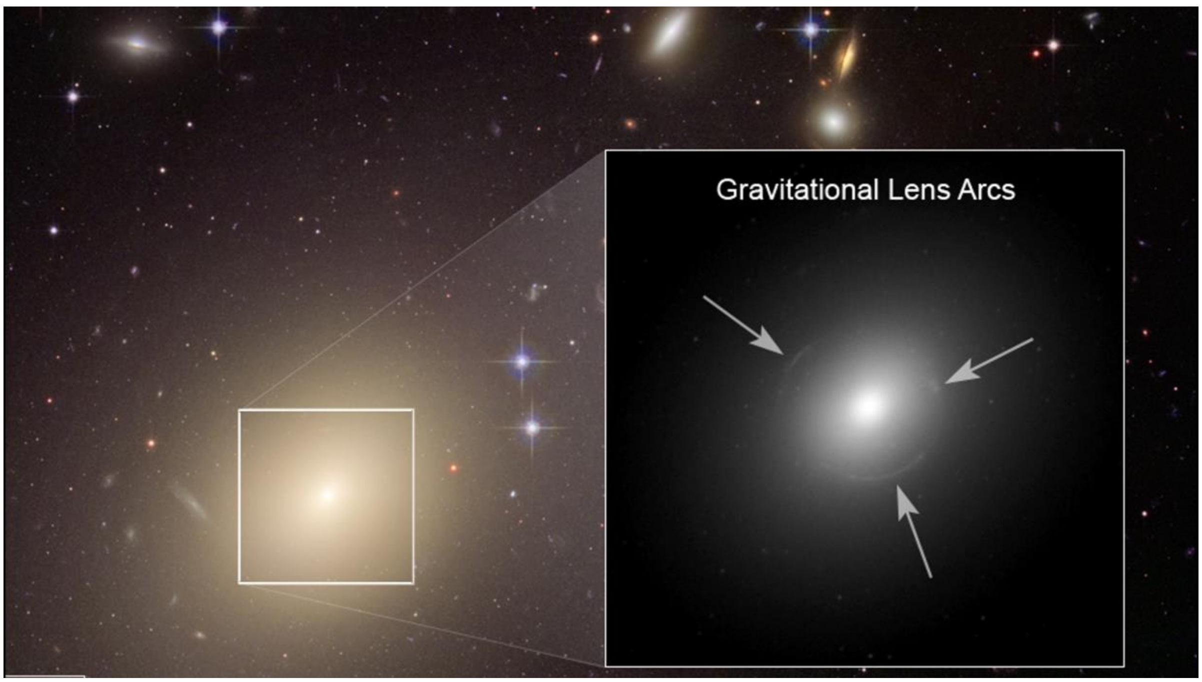
In 2013, Hubble broke the record in the quest to find the furthest type 1a with the discovery of SN UDS10Wil, a supernova that exploded more than 10 billion years ago at a time the Universe was in its early formative years and stars were being born at a rapid rate.

The image at the far left shows the host galaxy without the supernova. The middle image, taken a year later, reveals the galaxy with the supernova. The supernova cannot be seen because it is too close to the center of its host galaxy. To detect the supernova, astronomers subtracted the left image from the middle image to see the light from the supernova alone, shown in the image at far right.

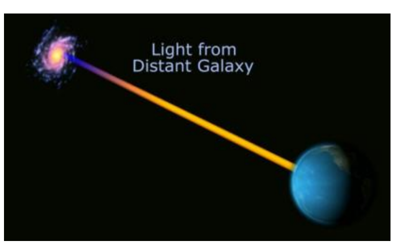


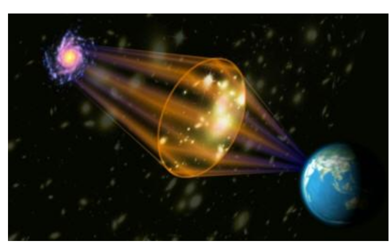
Gravitational Lensing

You'll remember the Einstein Ring we saw around ESO 325-G004 in our segment on Local Superclusters. The ring was the image of a more distant galaxy. The arc shape was created by the bending of the background galaxy's light by the gravity of the massive foreground galaxy. The process is called Gravitational Lensing because the mass between us and the background galaxy behaves just like an optical lens.



This same light bending leads to the warping of light from distant galaxies as the light encounters super-massive galaxies on their path to us. This is called gravitational lensing. Here's a clip that shows how this lensing works on a grand scale. A distant galaxy would be seen here on Earth directly if there were no intervening massive cluster to bend its light. But with such a cluster, the light from the distant galaxy gets bent into rings and arches that continue on to Earth.





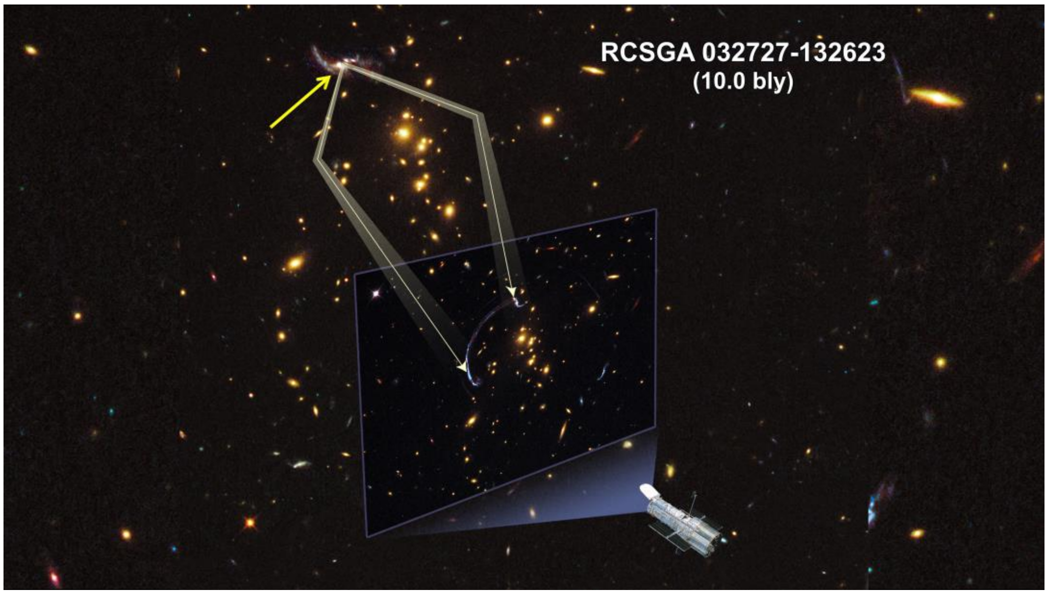
This is Abell 1689 [2.2 billion light years away]. It's one of the most massive galaxy clusters known. It's gravity acts like a 2-million-light-year-wide "lens" in space.

Abell 68 – 2.1 bly

Here again we see how the gravitational field surrounding this massive cluster of galaxies acts as a natural lens in space to brighten and magnify the light coming from very distant background galaxies. This galaxy is visible twice, because its light followed two separate paths around Abell 68 before reaching us.

RCS2 032727-132623 - 10,000 mly RCSGA 032727-132609 – 5,000 mly

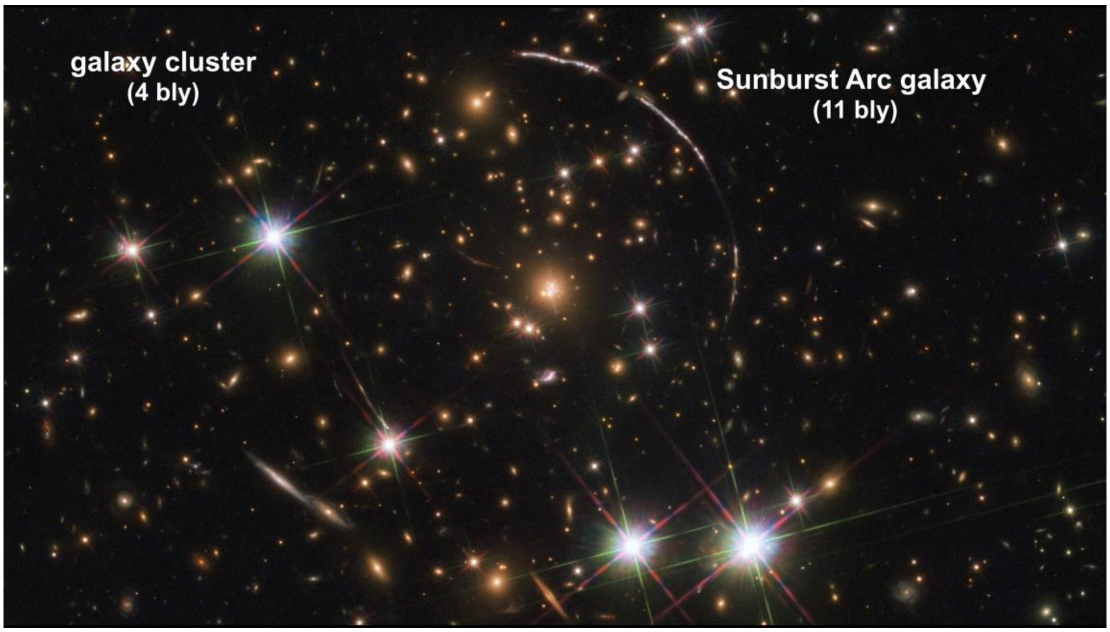
This is a close-up look at the brightest distant "magnified" galaxy in the universe known to date. It is one of the most striking examples of gravitational lensing. In this image the light from a distant galaxy, nearly 10 billion light-years away, has been warped into a nearly 90-degree arc of light in the galaxy cluster. The galaxy cluster that is bending the light lies 5 billion light-years away.



And here's MACS J0416.1–2403, 5.47 billion light years away. These foreground galaxy clusters are magnifying the light from the faint galaxies that lie far behind the clusters themselves. These faint lensed galaxies are around 12 billion lightyears away. It's the gravitational lensing that allows us to see that far back in time. Without the magnification, these galaxies would be invisible for us.

PSZ1 G311.65-18.48 Sunburst Arc galaxy – 11 bly

This Hubble image shows a massive galaxy cluster, about 4.6 billion light years away. Along its borders, four bright arcs are visible; these are copies of the same distant galaxy, nicknamed the Sunburst Arc. It's almost 11 billion light-years away. It's light is being lensed into multiple images by strong gravitational lensing. The Sunburst Arc is among the brightest lensed galaxies known and its image is visible at least 12 times within the four arcs.

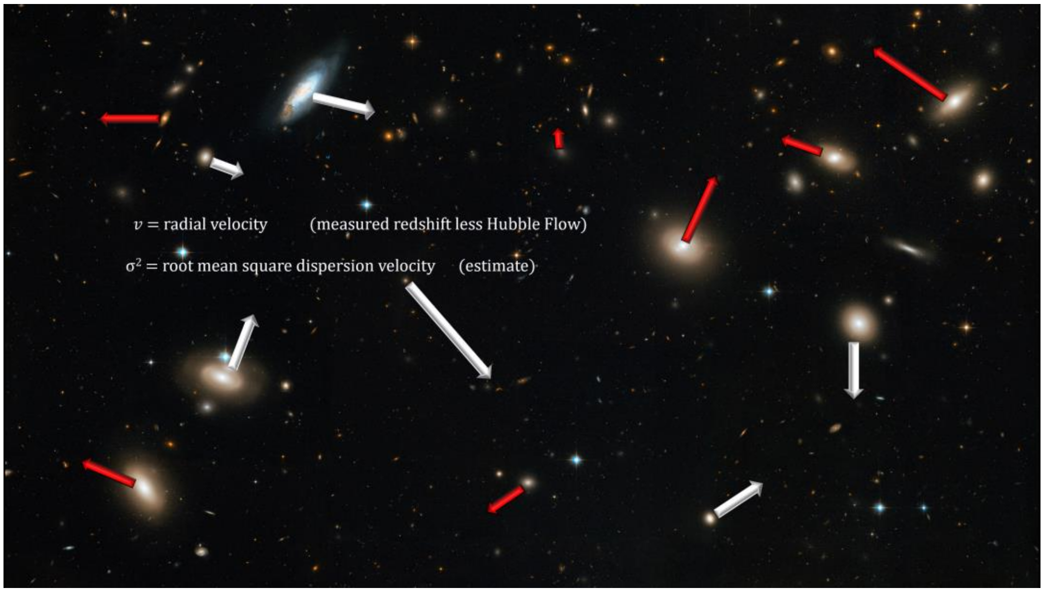


Here's a closer look at three of them. The lens makes various images from 10 and 30 times brighter. This allows Hubble to view structures as small as 520 light-years across — a rare detailed observation for an object that far away.

Dark Matter Discovery

Until the early part of the 20th century it went without saying that the matter we see is most of the matter there is. That would be protons and neutrons with accelerating electrons creating the light we "see". But that came into question in the early 1930s when Fritz Zwicky, a Swiss astronomer out of Caltech, studied the Coma galaxy cluster 321 mly away with a thousand galaxies spanning 25 mly in diameter. He looked at it in a number of ways – two of which are very revealing. In one he used galaxy motion to calculate mass and in the other he used galaxy luminosity.

His processes are not precise, but they do provide ballpark figures for the mass of the cluster. For motion, he had the cluster galaxy's radial velocities from the Doppler shifts in the light we see. He then generalized them into their three-dimensional velocity dispersion statistical equivalent.



This galaxy motion gives us the kinetic energy of the cluster. Zwicky used the well understood virial theorem that has the kinetic energy of a system equal to ½ its gravitational potential energy. This allows us to solve for the mass of the cluster. This is the mass as measured by its gravitational effects.

Gravitational Based Mass

$$E_K = -\left(\frac{1}{2}\right) E_P$$

$$E_K = \left(\frac{1}{2}\right) M\langle v^2\rangle$$

$$E_P = \left(\frac{1}{2}\right) GM^2/R$$

$$M = 6\sigma^2 R/G$$

Where

v = radial velocity (measured redshift less Hubble Flow)

$\langle v^2\rangle$ = root mean square velocity

σ^2 = root mean square dispersion velocity (estimate)

$\langle v^2\rangle = 3\sigma^2$ (for galaxy clusters)

E_K = kinetic energy

E_P = potential energy

M = mass of the cluster

R = radius of the cluster

G = gravitational constant = 6.67×10^{-11} $m^3kg^{-1}s^{-2}$

$M_\odot$ = Mass of the Sun = 1.99 x 1030 kg

And for the Coma Cluster $M_\odot$

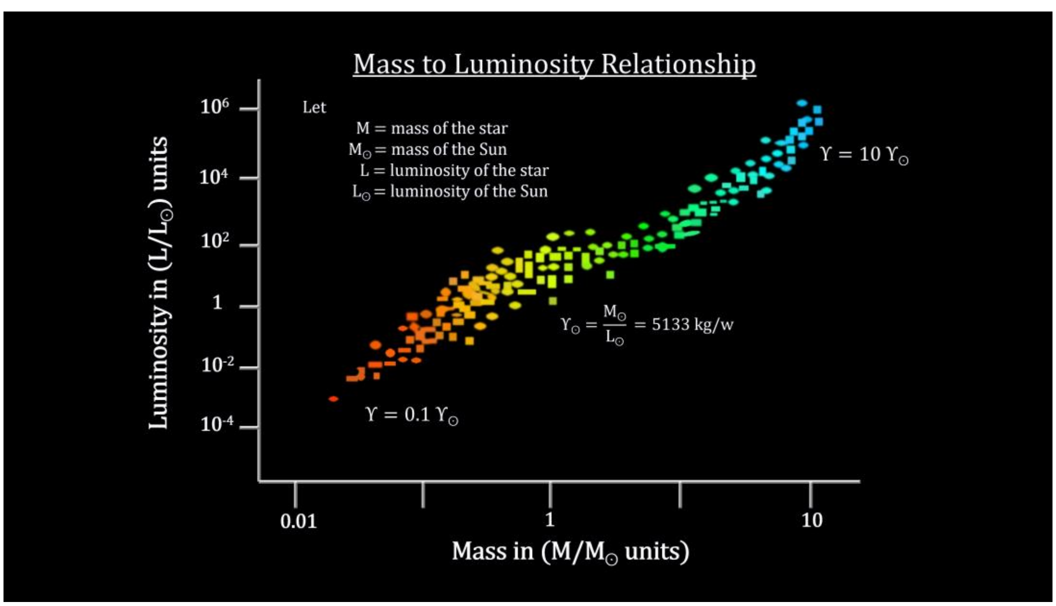
$\sigma^2 = 10^{12} m^2 s^{-2}$

R = 9.78×10^6 ly

We get

M = 4.18×10^{15} $M_\odot$

The second way he calculated the cluster's mass was to use the cluster's luminosity. You may recall from our discussion of the Hertzsprung-Russel diagram in our "How Far Away is it" segment on "Distant Stars" that there is a relationship between a star's mass and its luminosity. We can use that relationship to estimate the mass of groups of stars by measuring their luminosity.



We use the mass to light ratio of the sun as the base for comparisons.

Luminosity Based Mass

Let

L_G = measured luminosity of analyzed galaxy

= $1.2 \times 10^{10}\ L_\odot$

$L_\odot$ = luminosity of the Sun

L = luminosity of the Coma cluster

M_G = mass of analyzed galaxy

$M_\odot$ = mass of the Sun

M = mass of the Coma cluster

N = number of galaxies in cluster

= 1000

Assume

$M/L = \Upsilon = 3M_\odot/L_\odot$

Then

$L = 1000\ L_G = 1.0 \times 10^{13}\ L_\odot$

$M/(1.2 \times 10^{13}\ L_\odot) = 3M_\odot/L_\odot$

$M = 3.6 \times 10^{13}\ M_\odot$

Zwicky measured the luminosity of the average galaxy in the Coma Cluster. Using a mass to light ratio of 3, he calculated its mass.

When he multiplied the average times the 1,000 galaxies in the cluster, he came out with a number that was over a 100 time less than the mass calculated via the virial theorem based on gravity. In other words, the motion of the galaxies in the cluster indicated a mass that was over 100 times the mass from luminous matter.

Mass Ratio

$$\frac{M_{gravitational}}{M_{luminosity}} = \frac{(4.18 \times 10^{15}\ M_\odot)}{(3.6 \times 10^{13}\ M_\odot)}$$

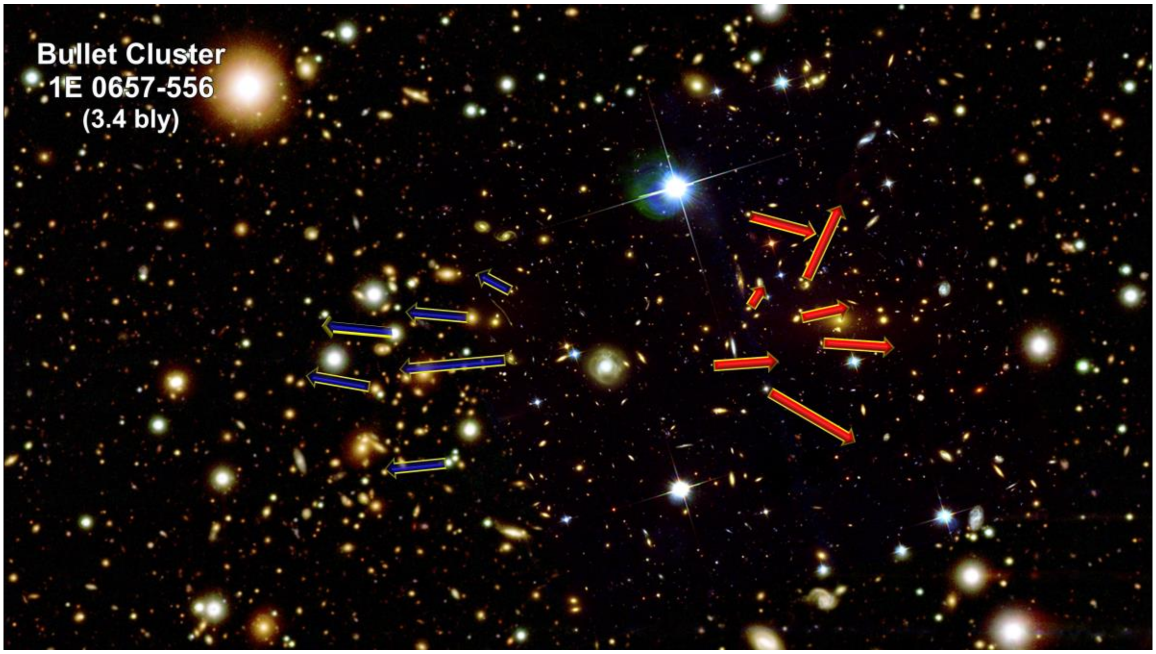
$$= 116$$

Zwicky concluded that either the laws of gravity as we know them (Newton's and Einstein's) did not work for volumes as large as the Coma Cluster, or the luminous matter is only a very small part of the total matter in the cluster. He called the rest of the matter – 'dark matter', and suggested that gravitational lensing would help quantify this dark matter. In the 1930s, nobody believed him.

*[**Music:** @11:55 Mozart - Piano Concerto No.21 in C 'Elvira Madigan' K.467 - Andante; from the album The Most Relaxing Classical Music, 1997]*

Bullet cluster - 3.4 bly

With this new understanding about the possibility and impact of dark matter, astronomers turned their attention-to galaxy clusters like the one studied by Zwicky in 1936. Our case in point is the galaxy cluster is known as the "bullet cluster." The virial motion of its galaxies indicates that a collision has occurred. Two massive clusters have passed through each other millions of years ago and the member galaxies are now flying apart.



If we zoom in a bit closer, we can see the telltale arcs of more distant galaxies lensed by the gravity of the bullet cluster. Counting the lensed objects and the estimated amount of light bending involved for each one, a map of the areas containing most of the mass of the cluster can be superimposed on the visible image. We have used blue to indicate the locations where the vast majority of the matter must be located in order to get the observed lensing.

Here we have the cluster's hot x-ray emitting gas detected by the Chandra X-ray observatory. The two pink clumps contain most of the "normal," matter – sometimes referred to as baryonic matter or matter made up of protons and neutrons. The bullet-shaped clump on the right is the hot gas from one cluster, which passed through the hot gas from the other larger cluster during the collision.

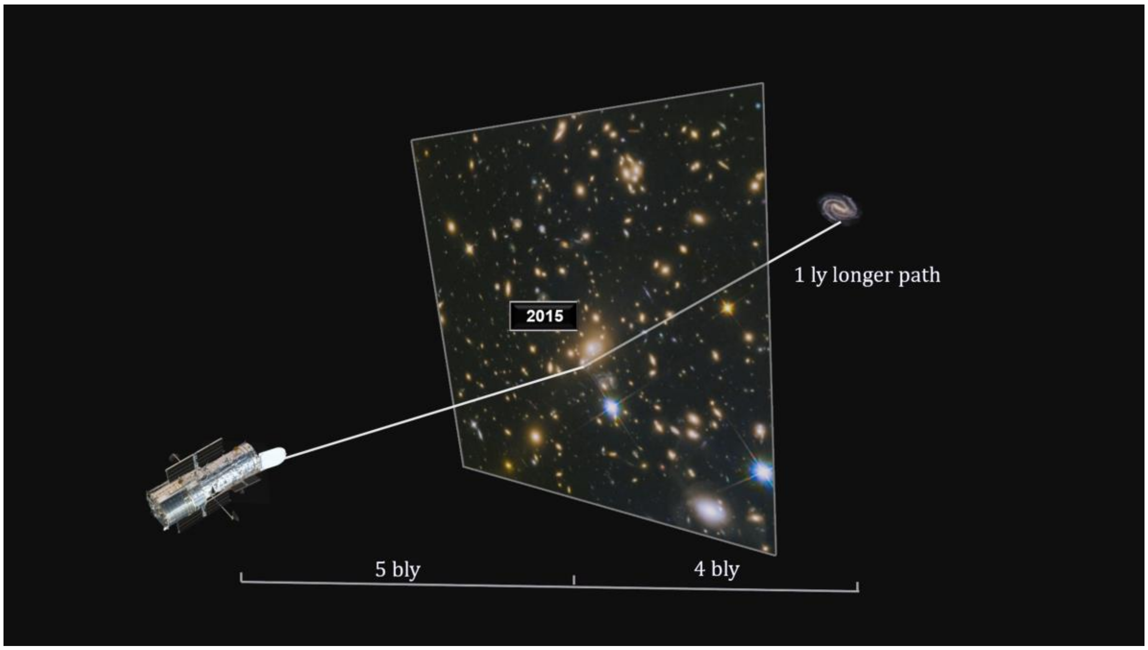
When we superimpose the dark, baryonic and visible components of the cluster's mass we get the full picture. The galaxies and the dark matter have traveled a great deal further than the gas. This indicates that the galaxies and dark matter in the two colliding clusters did not interfere with each other. In other words, they passed through each other without slowing down. On the other hand, during the collision, the gas clouds were slowed by a drag force, similar to air resistance. This combination had the effect of separating the gas from the dark matter. This separation is considered to be direct evidence that dark matter exists. Measurement indicate that galaxy clusters on average have 85% dark matter, 14% intergalactic gas, and only 1% stars.

Dark Matter Gravitational lensing

In 2014, a team of astronomers found a supernova in this galaxy cluster [MACS J1149+2223] over 5 billion light years away.

The supernova actually happened in a galaxy 4 billion light years behind this cluster – making it 9 billion light years away. The huge mass of the foreground galaxy and the cluster bent the light from the distant supernova - creating four separate images of the same explosion. The images are arranged around an elliptical galaxy in a formation known as an Einstein cross – because he was the one who predicted these phenomena.

Following this discovery, astronomers modeled several possible gas and dark matter distributions in the galaxy cluster. Each model predicted that another image of this supernova will appear in the cluster, but they had different time estimates ranging from 2015 through 2025. In December 2015 it appeared. For the first time in history, the time and location of a supernova was accurately predicted. We actually saw the supernova happen. Instead of detecting a flash in the sky and turning telescopes to its location, we had the telescopes already focused on the correct area and recorded the event from beginning to end. This was powerful evidence for dark matter.

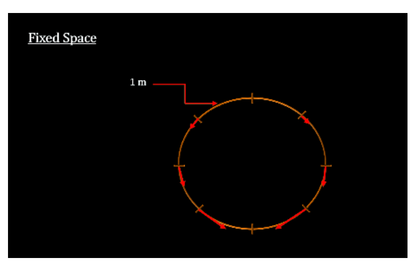


Expanding Space

In the 1920s, Edwin Hubble discovered that, except for a few nearby galaxies, all galaxies were moving away from us, and the further away they are, the faster they are moving. Along with the assumptions that there are no preferred places and directions in space, this means that all galaxies (not bound together by gravity) are moving away from each other.

The flow of all galaxies away from each other, with faster velocities the further away from each other they are, cannot happen in a fixed volume because, in a fixed volume, some reference frames would have to have distant objects heading towards them for others to have them moving away. It can only be explained if the space that these galaxies exist in is itself expanding. Here's a one-dimensional example to illustrate why this is the case.

Consider an 8 meter circle with marks one meter apart. If we are the top mark, and all the other marks are moving away from us, then from other points of view, marks are getting closer. The system is not homogenous.



But if the apparent motion is due to the amount of space expanding, we get a different picture. Here the marks hold their position on the line, but the line grows. Let's say each meter on the line expands to 2 meters over the course of a minute. We see that the distance between adjacent marks goes up one meter and their apparent velocity as seen by each other is 1 meter per minute. But more distant marks have increased their distance and velocity by more than that. And the further away any two marks are, the more their distance and velocity have increased. And most importantly, this will be the same no matter which mark is used for the reference frame.

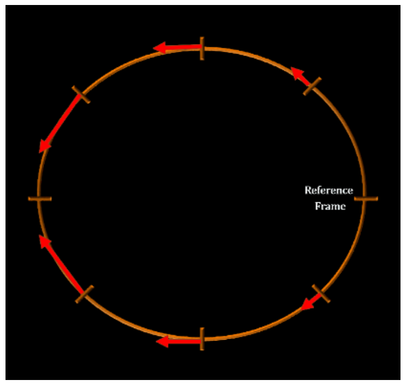
Expanding Space

If expansion = 1 m/min , then

$$K = V/R = (1\text{m/min})/1\text{m} = 1/\text{m} = 1/60\text{s} = 1.67 \times 10^{-2}\text{s}^{-1}$$

Where

V = velocity of a mark
R = distance to the mark
K = constant of proportionality



Velocity Formula

$$V = K R$$

V = mark velocity
R = mark distance
$K = 1.67 \times 10^{-2}\text{s}^{-1}$

In order to illustrate the point, this example used an expansion rate that is 74 thousand trillion times greater than the actual expansion rate as determined by the Hubble constant.

$$\frac{K = 1.67 \times 10^{-2}\text{s}^{-1}}{H = 2.27 \times 10^{-18}\text{s}^{-1}} = 0.74 \times 10^{20}$$

]

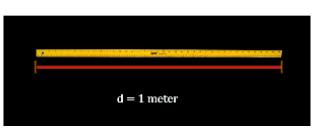
The real expansion is very slow. If we take a look at what the expansion does to one meter, we see that it would take a million years to expands by just 7 millionths of a meter. That's way too slow to ever notice or even measure in a lab in a lifetime. And it is why it's so easy to overcome it with local gravity out to the Andromeda galaxy.

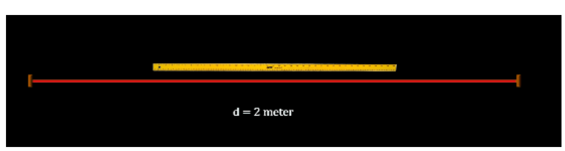
$$V = HR$$
$$V = 2.2 \times 10^{-18}\,\text{m/s}$$
$$\delta d = Vt = 6.94 \times 10^{-6}\,\text{m}$$

Where

V = expansion velocity
R = 1 meter
$H = 2.2 \times 10^{-18}\,\text{s}^{-1}$
δd = meter expansion
t = 1 million years
$= 3.145 \times 10^{12}$ s

It should be noted that this expansion of space itself does not pull apart objects that exist in that space. A meter stick does not expand. That's because the size of the meter stick is determined by the forces that hold it together, and these forces are not changing.

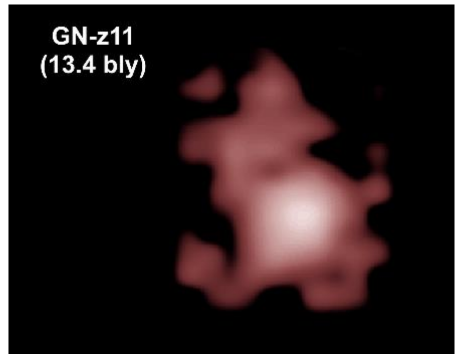




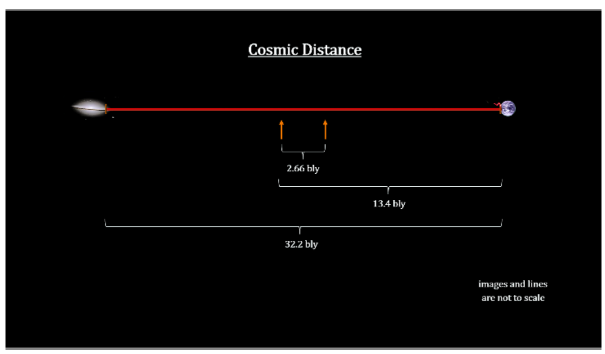
Cosmic Distance

Expanding space has significant implications for measuring distance.

Here we are zooming into GN-z11, the most distant object ever found. The galaxy's redshift combined with Hubble's law gives us the distance the light traveled – 13.4 billion light-years. And we know the speed of light so the time traveled was 13.4 billion years. We normally say that the galaxy is therefore 13.4 billion light years away.



But, during its long travel time, space expanded considerably. In fact, GN-z11 was less than 2.7 billion light years away from us when the light started its journey. And the galaxy is now over 30 billion light years away. In order to calculate these distances, we need to know how the Universe expanded during the light's journey.

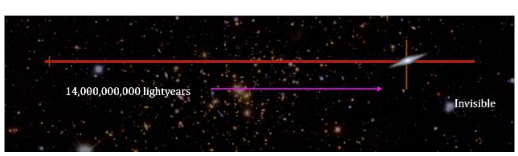


Visible Horizon

Note that, if a galaxy is far enough away, its apparent velocity will be faster than the speed of light – and its light would never reach us. It would be beyond the physical visible horizon for the Universe. It's not that it is moving through space that fast, it's just that more space is being created per second between us and them than light can travers in one second. Plugging in the numbers, we find that all galaxies beyond 14 billion light years could never be seen here. GN-z11 is now 32 billion lightyears away, so the light that is leaving GN-z11 now, can never reach us.

Let

V_c = speed of light = 3×10^8 m/s
$H = 2.27 \times 10^{-18} s^{-1}$
R_h = visible horizon



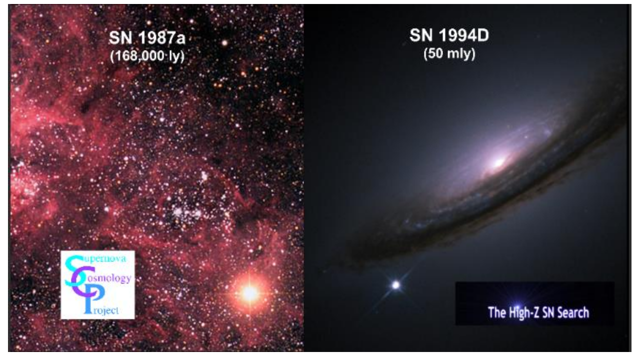
Then

$V_c = H R_h$
$R_h = V_c / H$
$= (3 \times 10^8 ms^{-1}) / 2.27 \times 10^{-18} s^{-1}$
$= 1.32 \times 10^{26}$ m $= 14 \times 10^9$ ly

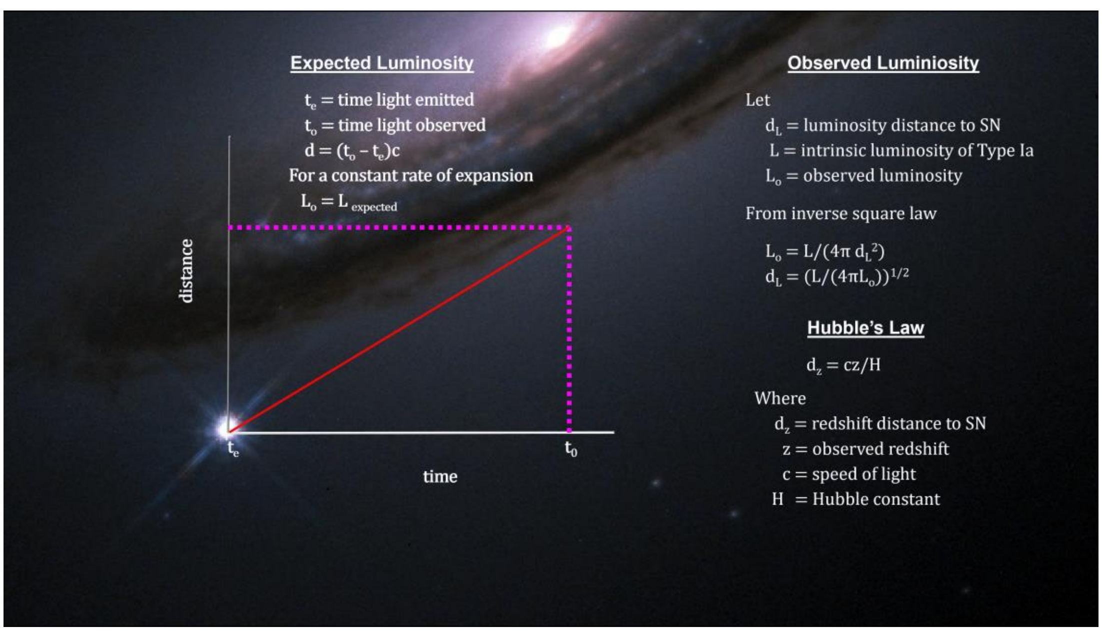
[Music:** @21:34 Rachmaninov - Piano Concerto No 2 in C minor; from the album The Most Relaxing Classical Music, 1993**]

Accelerating Expansion

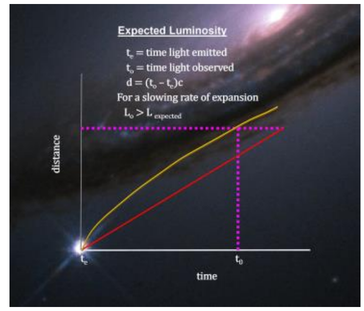
After Hubble discovered that the Universe was expending, it was assumed that it started off with a tremendous expansion rate and because of the gravitational attraction of all the matter in the Universe, the expansion would be slowing down. Two major efforts were started in the late 1990s to prove that the Universe's expansion was decelerating. Both groups used distant Type 1a Supernova as their standard candles. One examined SN 1987A and the other examined SN 1994D.



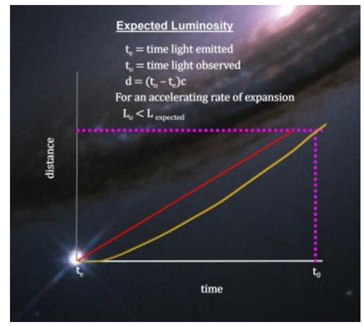
Supernovae provide a luminosity reading that enables us to determine their distance via the inverse square law. This distance is called the luminosity distance. Type 1a Supernova also provide a redshift reading that gives us the distance via Hubble's Law [$d_z = cz/H$]. Luminosity and redshift combined can tell us if the expansion is constant, decelerating or accelerating. Here's how it works. First, we measure the luminosity of a distant type 1a SN like SN 1994D and measure its redshift. Second, we calculate the luminosity distance via the inverse square law, and the redshift distance via Hubble's Law. Then we map the distance between us and the SN over time. If the expansion rate is constant, the luminosity distance and the redshift distance will be the same.



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 would have taken a shorter time to expand from its size at light emission time to its present distance compared to a non-accelerating universe. This would result in a shorter light-travel time, shorter distance traveled and a brighter observed supernova compared to a non-accelerating universe.



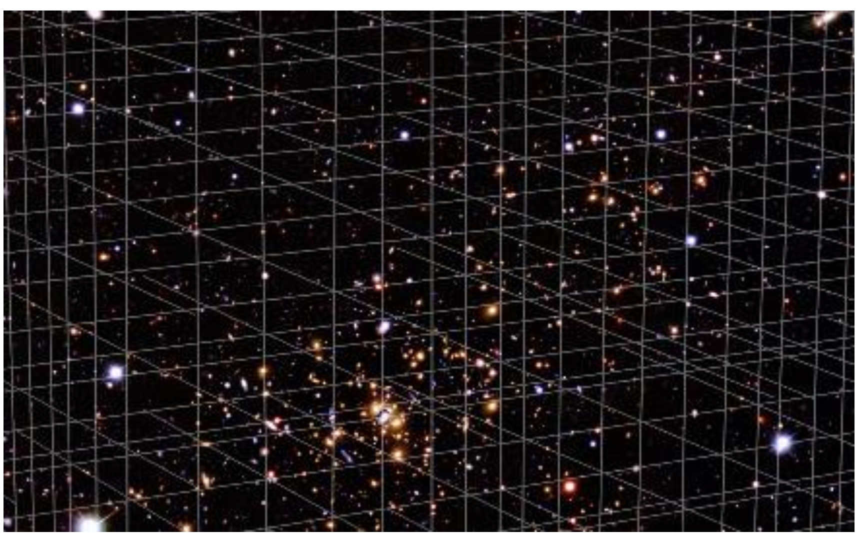
By the same token, if the expansion is speeding up, the expansion rate in the past would have been smaller than what we see now. Which means, it would have taken a longer time to expand from its size at light emission time to its present distance compared to a non-accelerating universe. This would result in a longer light-travel time, larger distance traveled and a dimmer observed supernova compared to a non-accelerating universe. This is what both studies found.

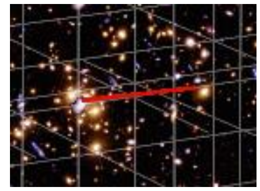


The universe is expanding and the expansion is accelerating! [This also means that the Hubble Constant is not constant. It is changing over time. We call it the Hubble parameter with H_0 used to identify the value at the current time.]

The Cosmic Scale Factor

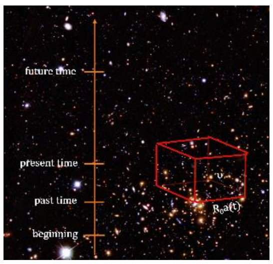
In order to more precisely analyze our expanding Universe, modern cosmology places a grid over our three-dimensional space.

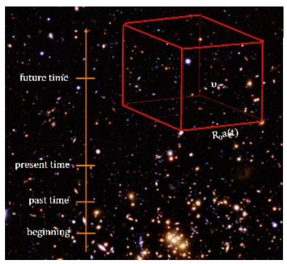




We treat the distance between two galaxies (R) as a constant. Then, we set the grid's scale factor 'a' equal to one at the present time, and vary it, to account for changes in distances over time instead of changing R.

Now consider a cube inclosing a volume of space containing some number of galaxies. With our scale factor approach, the amount of matter inside the volume remains the same as the volume increases or decreases. But the matter density goes down when the scale factor increases, and it goes up when the scale factor decreases. We see that matter density depends on the scale factor.





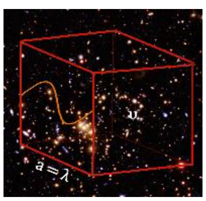
Let

D = distance
V = velocity
A = acceleration
R_0 = current distance
a(t) = scale factor
υ = mass in unit volume
ρ = mass density

Then

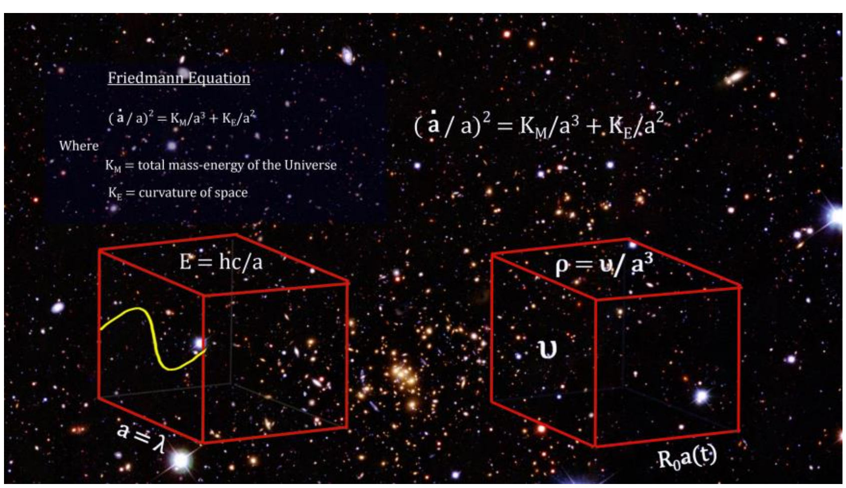
$D = R_0\, a(t)$
$V = R_0\, \dot{a}$
$A = R_0\, \ddot{a}$
$\rho = \upsilon / a^3$

Unlike matter that moves through space, photons are attached to the space they propagate through. So, an expanding space will impact photons in a way that does not affect matter.



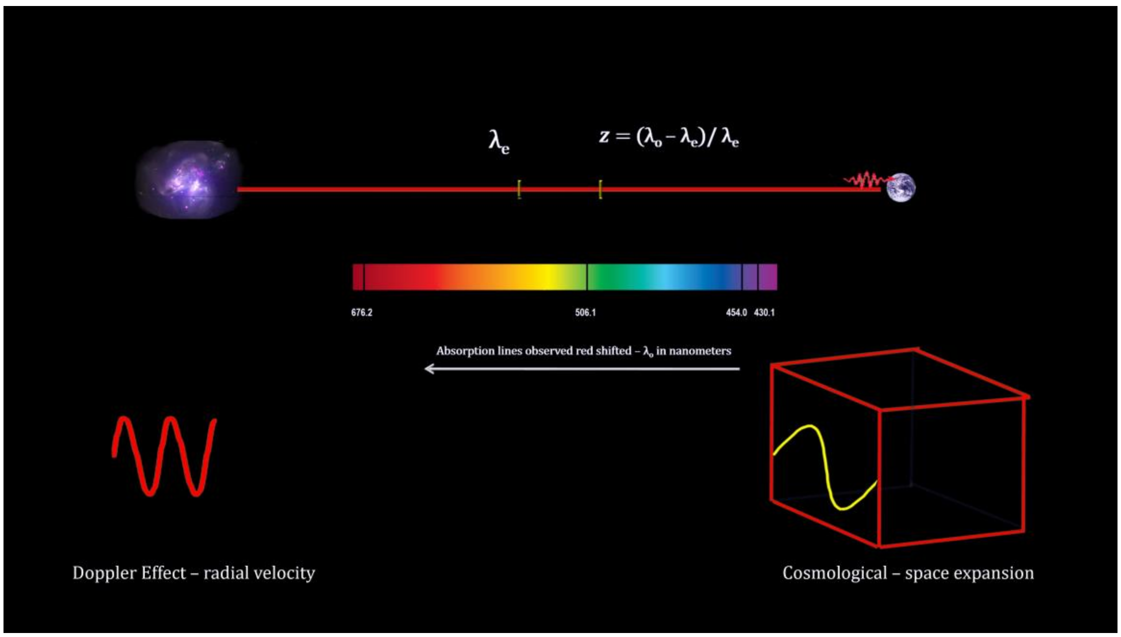
Here's a cubic volume of space with a photon inside. The photon's wavelength (λ) is equal to the length of the cube (a). Its energy is equal to Planck's constant time the speed of light divided by the wavelength (E = hc/λ).

As the wavelength increases with an increase in the scale factor, the energy decreases - unlike matter where it remained constant. We see that the energy density also depends on the scale factor. In fact, we find that the scale factor 'a' is the only variable. In other words, the history of the Universe comes down to the history of the scale factor. And the history of the scale factor depends completely the contents of the Universe and how that content effects the space it exists in.



Cosmological Redshift

When we observe light from distant galaxies, we are seeing the light from the stars in those galaxies. And that light has absorption lines. The same lines measured in a lab give us the wavelength of the light at the time it was emitted. A stretching of the wavelength creates a shift in the spectral lines to the red. For our nearby galaxies, light travels for a relatively short period of time, so the stretching due to space expansion is small. Our use of the doppler effect that shifts spectral lines as the basis for determining radial velocities provides excellent measurements. But as the distance increases to hundreds of millions and billions of light years, space expansion becomes the dominant factor. In either case, we continue to measure redshift z as the difference between the wavelength emitted and the wavelength observed divided by the wavelength emitted. In this hypothetical example, we have an object with a redshift equal to 6.



Once a model for the change in the cosmic scale factor over time is specified, redshift gives us a great deal of information. For now, we'll assume a flat, matter dominated universe.

Matter Dominated flat model

$$H_0 = 2.2 \text{ x } 10^{-18} s^{-1}$$
$$\Omega_r = 0$$
$$\Omega_m = 1$$
$$a(t) = \left({}^{t}/_{t_0} \right)^{2/3}$$

First, redshift gives us an object's receding velocity. With our model, we have the object moving away at 6 times the speed of light. Redshift also gives us the actual cosmic scale factor at the time the light was emitted. When the light we see from this object started, the Universe was a little over a tenth of its current size.

Z Scale Factor & Time

$$V_r = zc = 6c$$
$$a(t_e) = 1/(z+1) = 0.14$$

It gives us the age of the universe at the time the light was emitted, and the amount of time the light was traveling. We're seeing it as it looked almost 8 billion years ago when our Universe was only 2 billion years old.

$t_0 = 2/3H_0 = 9.6$ billion years
$t_e = t_0 a(t_e)^{2/3} = 1.9$ billion years

Light travel time $= t_0 - t_e = 7.7$ billion years

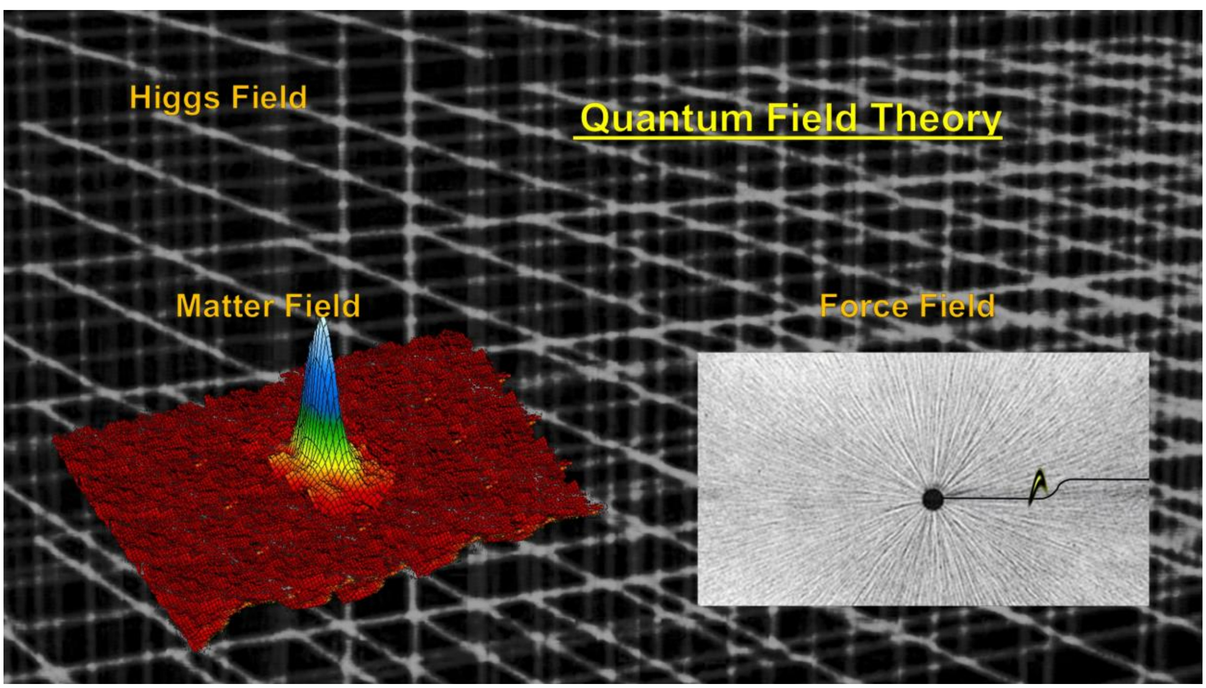
Redshift gives us the distance to the object at the current time. And it gives us the distance to the object at the time the light was emitted. You can see why astronomers rely so heavily on redshift measurements.

$$d_p(t_0) = c\int_{t_e}^{t_0} \frac{dt}{a(t)^{2/3}} = c\int_{t_e}^{t_0} \frac{dt}{\left(t/t_0\right)^{2/3}} = \frac{2c}{H_0}\left[1 - \frac{1}{(1+z)^{1/2}}\right] = 18 \text{ bly}$$

$$d_p(t_e) = \frac{d_p(t_0)}{(1+z)} = 2.6 \text{ bly}$$

Dark Energy

We now ask, what could be accelerating the expansion of the Universe. In the How Small Is It video book chapter on the Higgs Boson, we covered how so-called empty space is actually 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

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

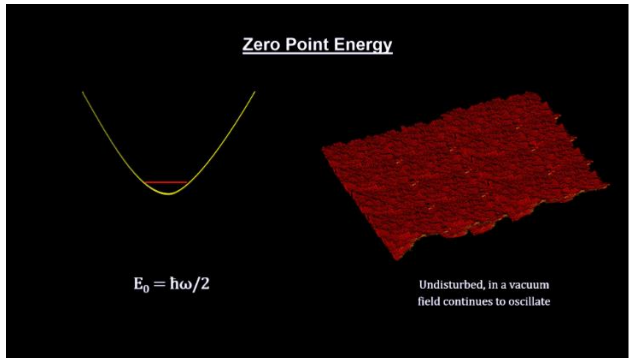
Where

E = energy

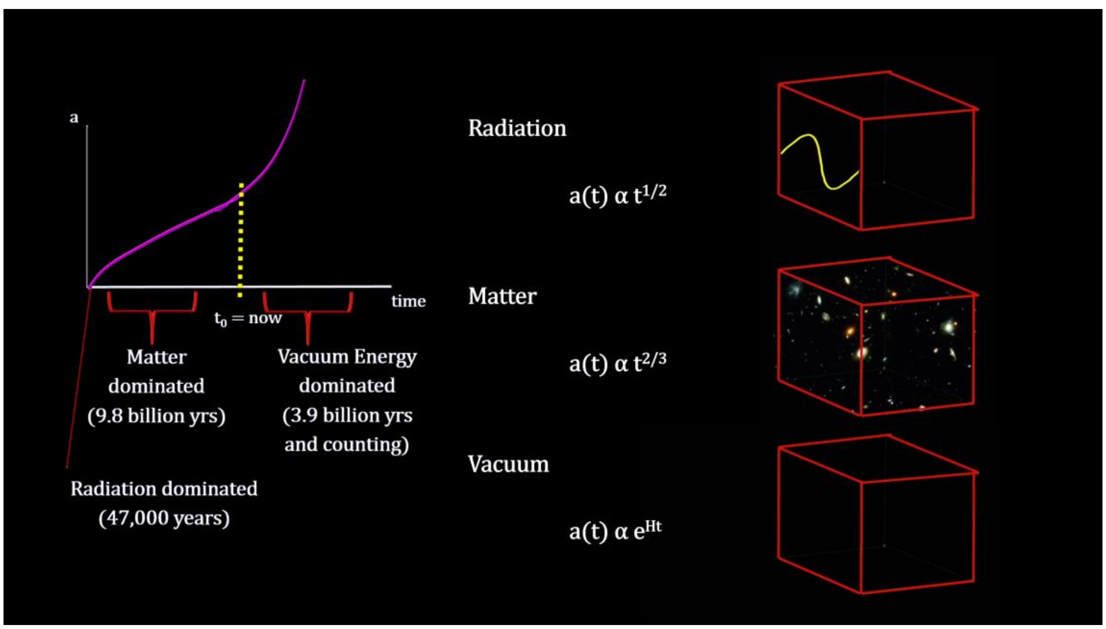
n = energy level

$\hbar$ = (Planck's constant)2π

ω = 2π(frequency)



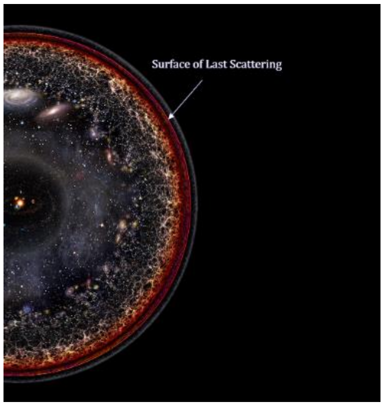
We have seen that radiation and matter in the universe are diluted as space expands. But zero-point vacuum energy does not dilute. In fact, the total amount of vacuum energy increases with the volume of the Universe. In a small Universe, it would have little impact. But today, it is estimated to be almost 70% of the energy density of the Universe. This zero-point quantum vacuum energy is called 'Dark Energy'. And it is enough to force the Cosmos into its accelerating expansion.



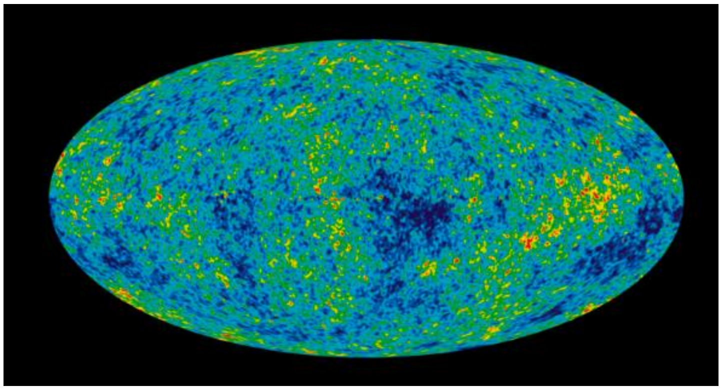
Surface of Last Scattering

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 3000º 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.



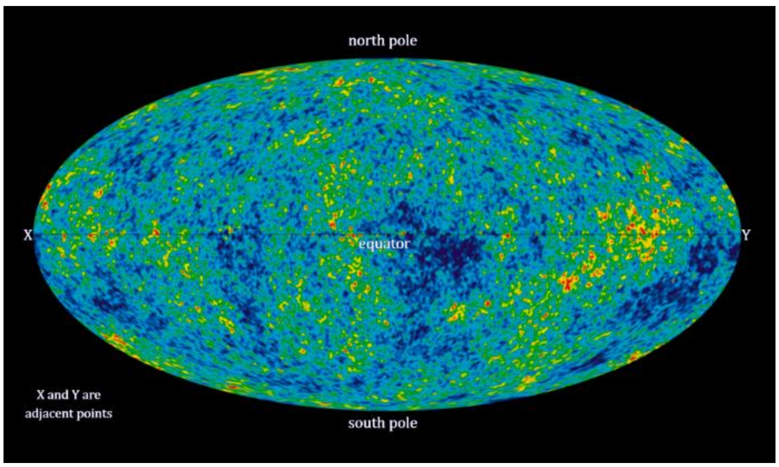
Those photons are still with us today. We see them all across the sky in tremendous numbers. They are the Cosmic Microwave Background (CMB) photons. And they tell us a great deal about the past, present and future of the Universe.



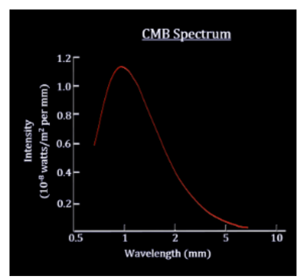
[Music:** @32:18 Mozart - Clarinet Concerto in A from the album The Most Relaxing Classical Music, 1997**]

CMB Radiation

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.

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

$$= 3000\text{ K}/2.725\text{ K} = 1100$$

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.

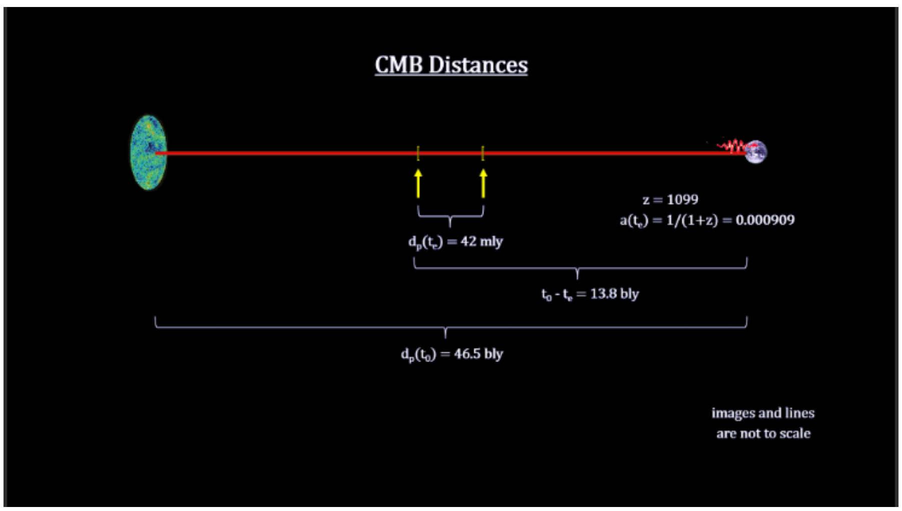
$$n_{\gamma,0} = \varepsilon_{\gamma,0} / E_{mean}$$
$$= 0.2606 \text{ MeV m}^{-3} / 6.34\text{x}10^{-4}\text{eV}$$
$$= 4.107\text{x}10^{8} \text{ m}^{-3}$$

Where

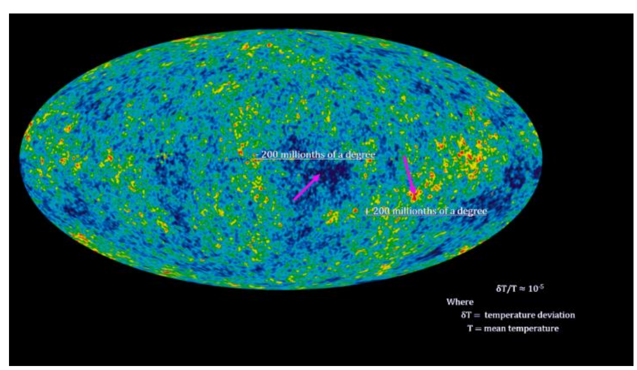
$\varepsilon_{\gamma,0}$ = current energy density

E_{mean} = current mean photon energy

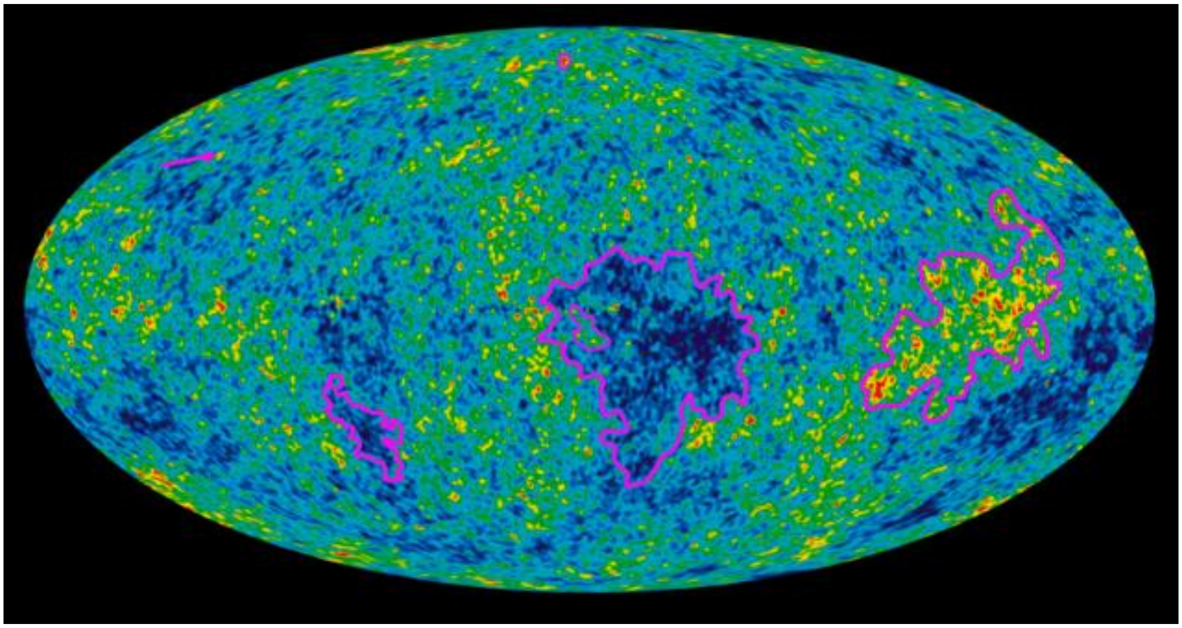
The CMB redshift tells us that the light we see now was only 42 million light years away from our location when it was emitted. It traveled for just under 13.8 billion years to reach us, and its starting location is now 46.5 billion light years away – making the diameter of the visible universe 93 billion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

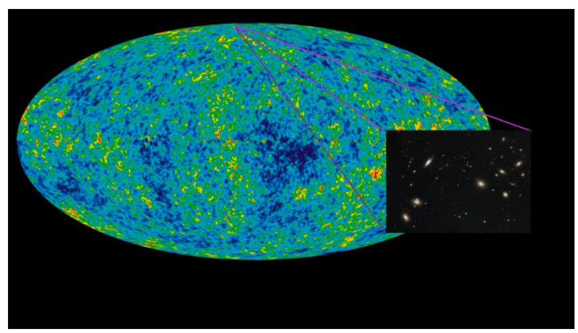


The Planck satellite measurements detected small amounts of temperature deviation. The image uses color to show variations from the average with blue for -200 millionths of a degree through green and yellow to red for +200 millionths of a degree. That temperature deviation comes to 1 part in 100,000. These temperature deviations come from equally small mass density deviations in the plasma at the time of decoupling.



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.



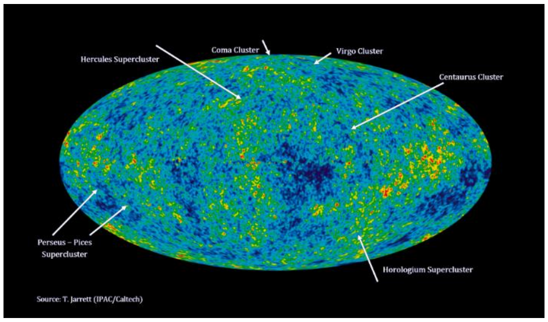


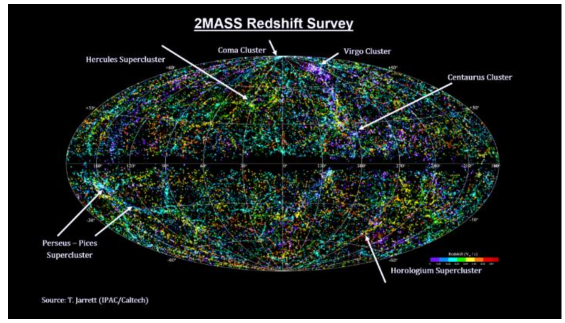
These small-scale differences in the CMB are what lead to the large-scale structures such as galaxy clusters, filaments and voids that we see today. For example, a very tiny spot of red on the Surface of Last Scattering, representing a small decrease in mass density in that region, will have expanded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

Fabric of the Cosmos

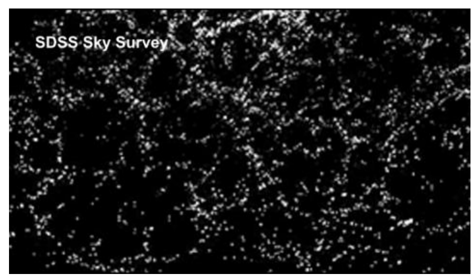
Just how the Universe evolved from small scale matter deviations at the time of decoupling to filaments of superclusters and vast voids can be explained by a physical process called Caustics. Originally developed to explain light behavior, it works just as well for protons and dark matter.



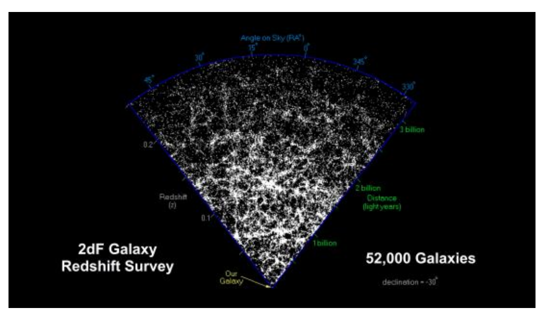


I see this phenomenon in my own back yard. The lines at the bottom of a swimming pool are examples of caustics caused by small waves on the water's surface.

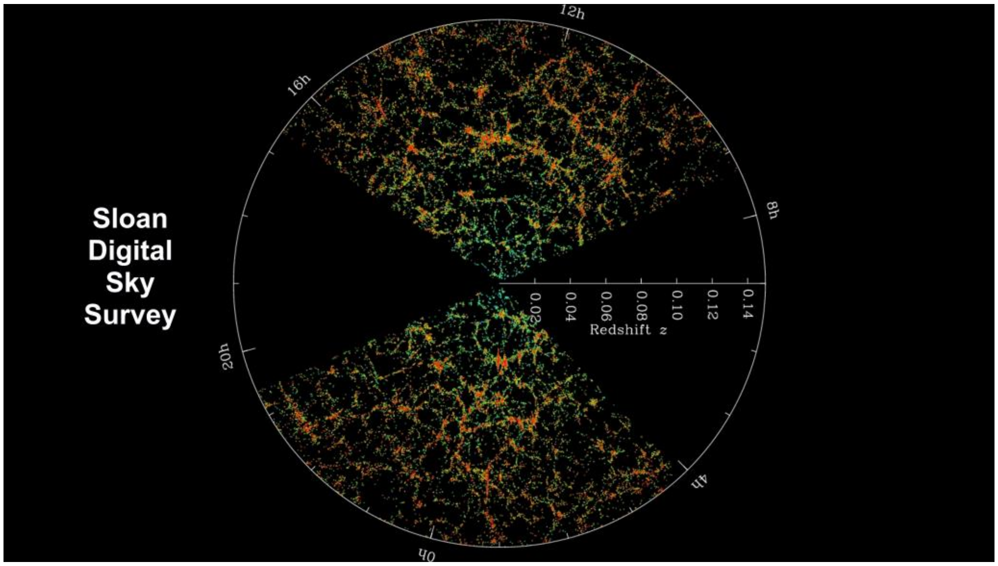
And, when we extend this to three dimensions, we get curved surfaces with increased density that intersect along lines that intersect at points. This is the web like pattern we see in the large-scale Universe.



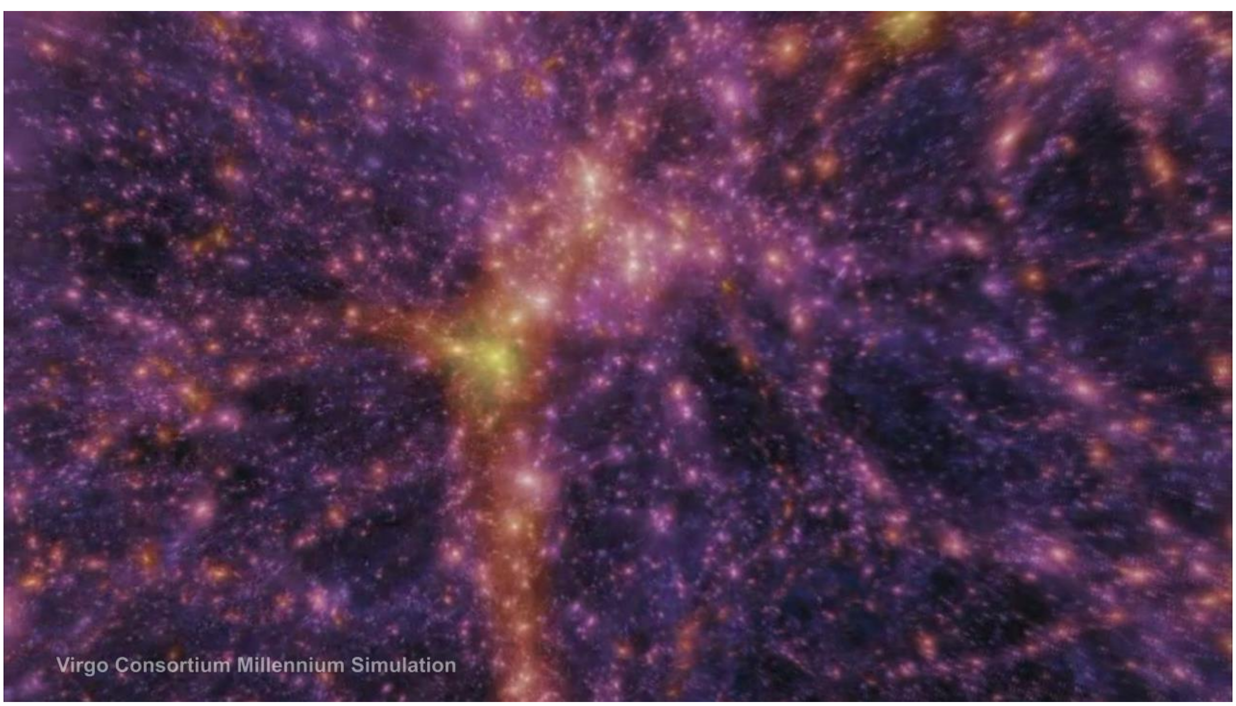
By collecting distances to thousands of galaxies in a narrow strip of the sky, it is possible to produce a slice of the universe, like this one from the 2dF Galaxy Redshift Survey. In 2003, this survey looked out into the universe to 3.5 billion light years.



Between 2000 and 2008, the Sloan Digital Sky Survey (SDSS) conducted one of the most ambitious and influential surveys in the history of cosmology. Over eight years of operations it obtained deep, multi-color images covering more than a quarter of the sky and created a 3-dimensional map containing more than 1 million galaxies. These are the color enhanced slices through the SDSS 3-dimensional map of the distribution of galaxies. Earth is at the center, and each point represents a galaxy. Galaxies are colored according to the ages of their stars, with the redder, more strongly clustered points showing galaxies that are made of older stars. The outer circle is at a distance of two billion light years. The region between the wedges was not mapped by the SDSS because dust in our own Galaxy obscures the view of the distant universe in these directions.

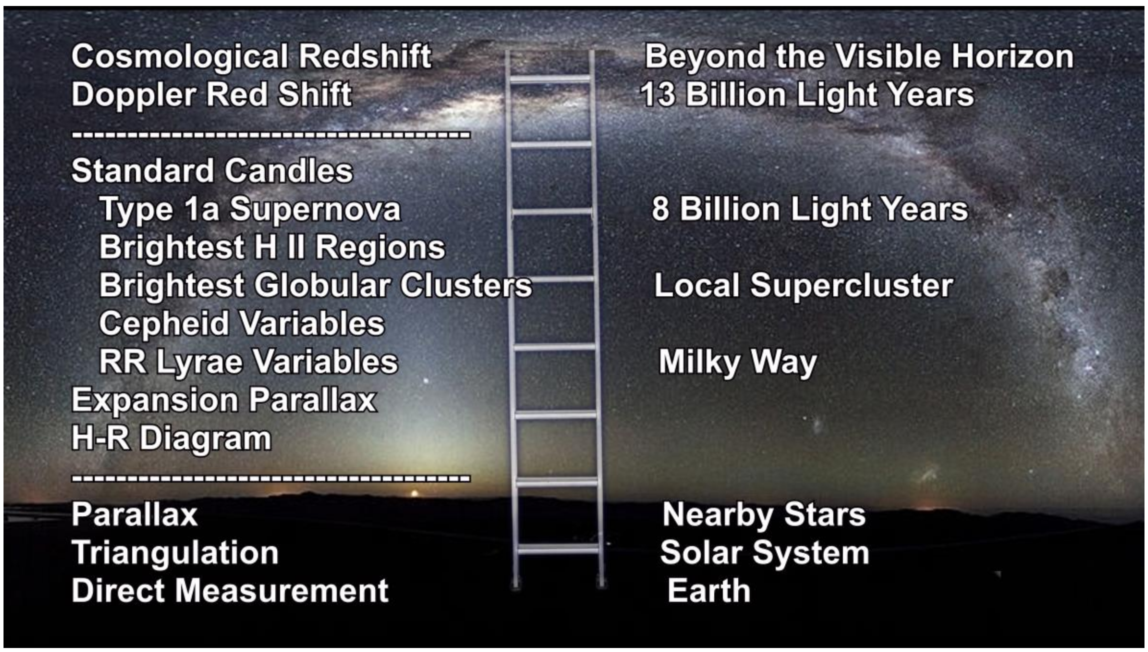


Working with the Virgo Consortium of scientists and the Max-Planck Institute in Germany, SDSS put every data point into a supercomputer and created the largest 3D image ever created. Here we are zooming into and panning across that image. Here you cannot see individual galaxies or even galaxy clusters. What we can see are superclusters linked together in filaments or walls in a gigantic cosmic web. In this view to the cosmos, the great Virgo Supercluster is just a dot. There are more stars in the universe than there are grains of sand on all the beaches of Earth. This is the big picture of our universe as we understand it today.



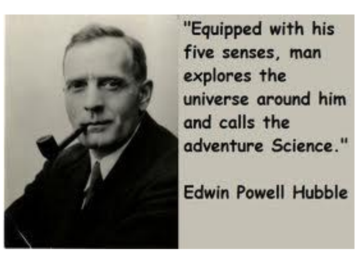
Cosmic Distance Ladder Review

We've come a long way from our start triangulating and directly measuring sizes in my backyard in our segment on the Earth. In this segment, we split 'redshift', our final rung of the cosmic distance ladder, into two parts. The original was based on the doppler effect. The second is cosmological redshift based on the expansion of the universe. (It is important to remember that this kind of redshift can only provide distance information if we have a cosmological model for the expansion. And we do. It's called the lambda cold dark mater benchmark model. It is covered in depth in the "How Old Is It" video book.)



How far away is it - Conclusion

All this reminds me of Edwin Hubble's own words in 1936. They are still appropriate today:



"Thus, the explorations of space end on a note of uncertainty - and necessarily so. We are, by definition, in the very center of the observable region. We know our immediate neighborhood rather intimately. With increasing distance, our knowledge fades, and fades rapidly. Eventually, we reach the dim boundary – the utmost limits of our telescopes. There we measure shadows, and we search among ghostly errors of measurement for landmarks that are scarcely more substantial. The search will continue. Not until the empirical resources are exhausted, need we pass on to the dreamy realms of speculation."