Introduction to Astronomy

Lecture 9:

Cosmology

the universe as a whole

University of Sydney
Centre for Continuing Education
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Outline

- The evolving universe
  - *the first clues that the universe is not eternal*
- The Big Bang
  - *what happened in the early universe*
- The fate of the Universe
  - *the discovery of dark energy*

The evolving universe

Is the universe infinite in extent and unchanging?
How can we find out?

Until recently, these questions were in the realm of philosophers. But some very basic questions and observations already give us a start.

Is the universe infinite in extent?

Archytas, a friend of Plato, posed the following riddle: If I am at the edge of the universe, can I stretch out my hand or my staff? If not, what is stopping it, since there is nothing outside the universe? If I can, then there must be space beyond the universe, and I can stretch my hand into that, and so on without limit.

So the Greeks concluded that *the universe has edge.*

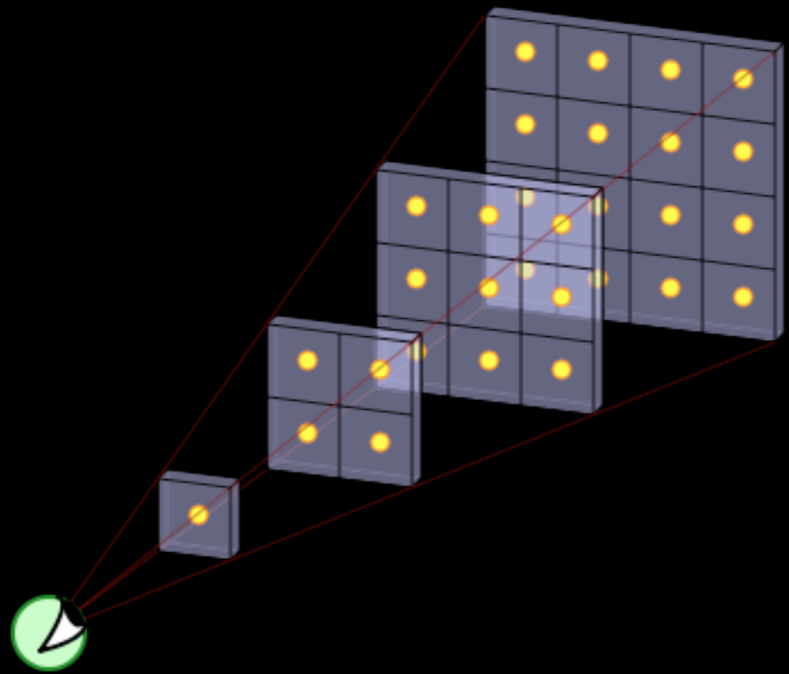
What about a beginning? Does the universe have a beginning or and end – an edge in time – or is it eternal?

One of the first pieces of evidence that it is *not* comes from a thought-experiment that is called "Olber's paradox", but was actually thought about by astronomers back to Halley and Kepler.

The question they asked is: why is the sky dark at night?

Suppose the universe is

- infinite in size
- infinite in age
- filled with stars



As you look out into space, the more distant stars are fainter; but you are looking at a larger volume, so the *number* of stars increases. The two effects cancel out, and each shell of stars contributes the *same amount of light*.

The entire sky should be as bright as the surface of a star.

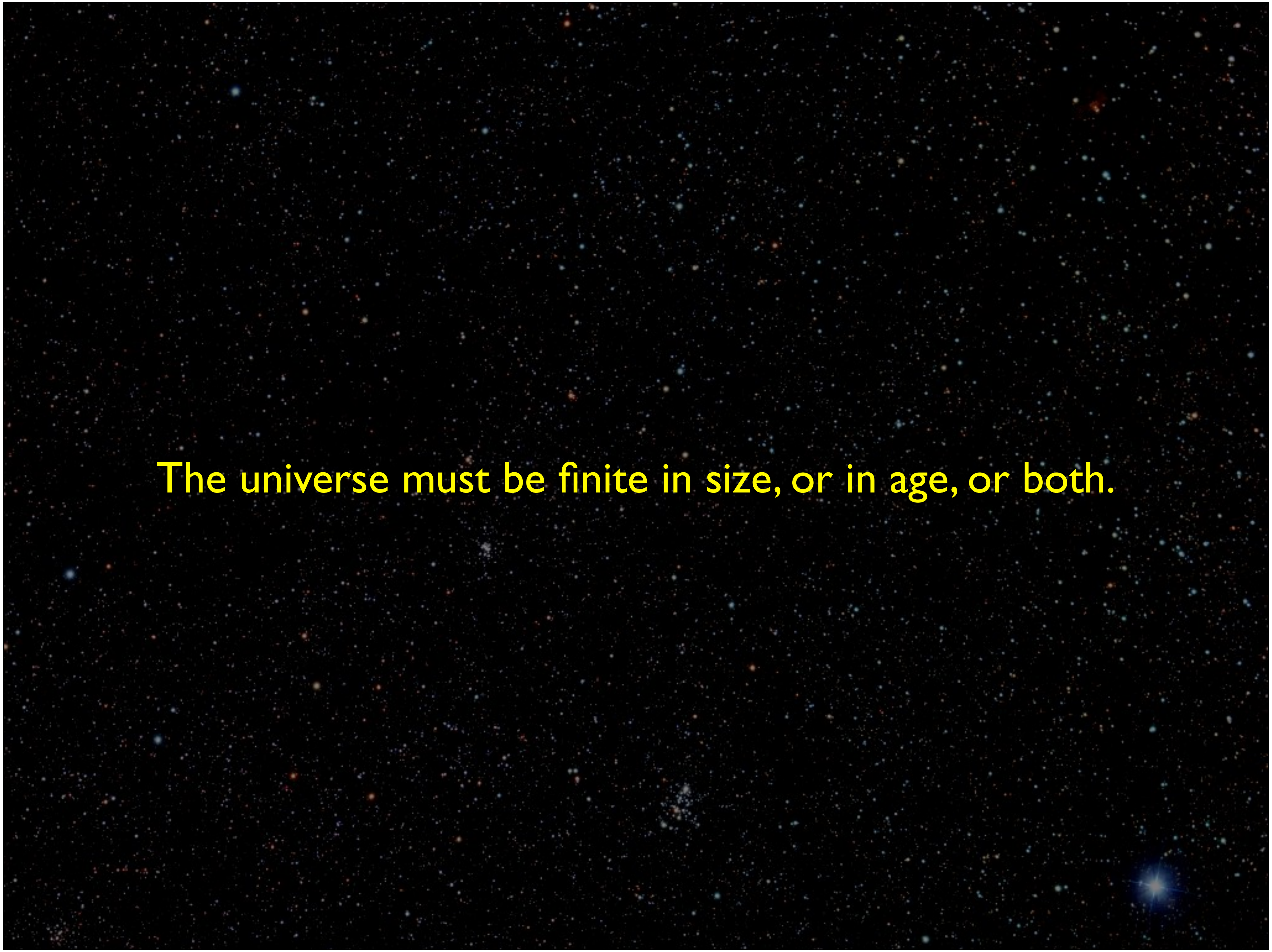
So (at least) one of the assumptions: that the universe is

- infinite in size
- infinite in age
- filled with stars

must be wrong.

Now, the universe is *not* filled with stars, because the Galaxy has an edge. But the same argument works for a universe filled with galaxies.

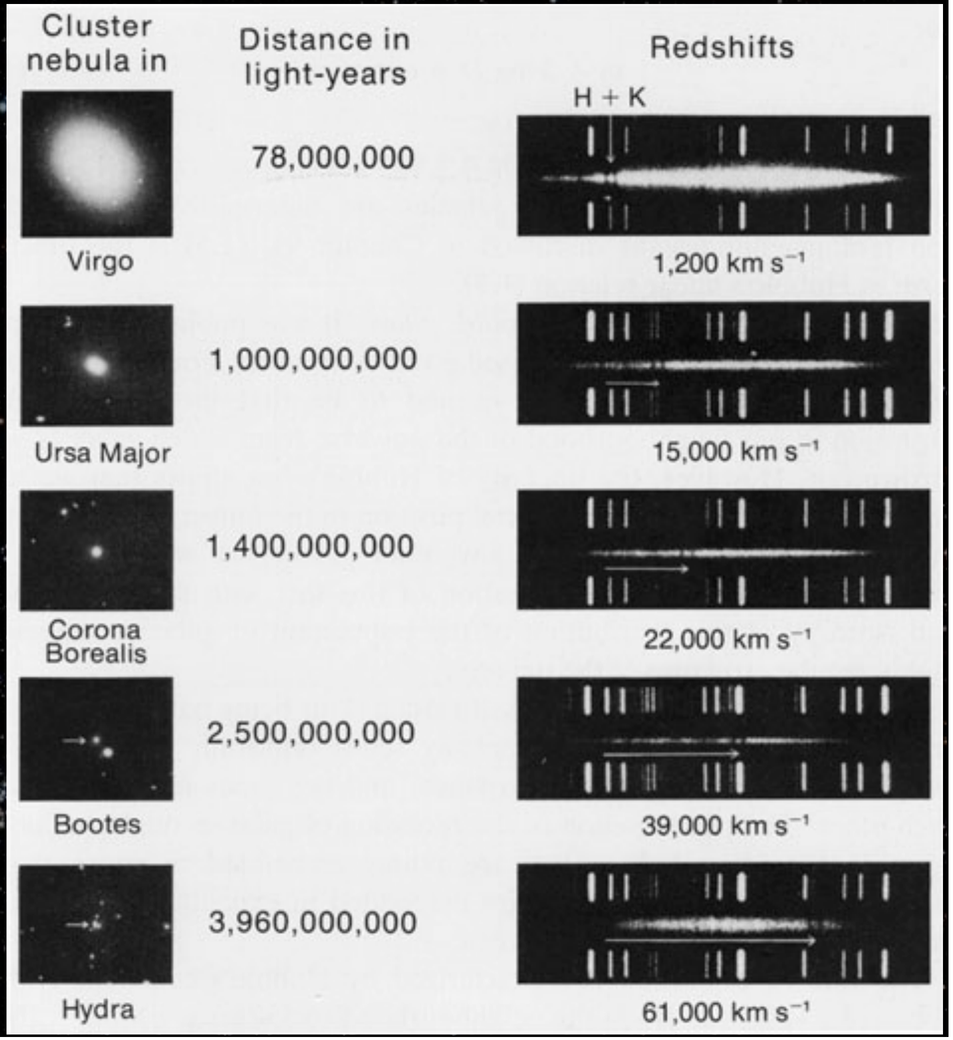

Part of the Hubble
Ultra-Deep Field


The universe must be finite in size, or in age, or both.

Direct evidence for a changing universe was found by Edwin Hubble. He measured the distances to a number of galaxies, and found that they were all *redshifted*: all galaxies are receding from the Milky Way.

What's more, the more distant the galaxy, the faster it is receding.

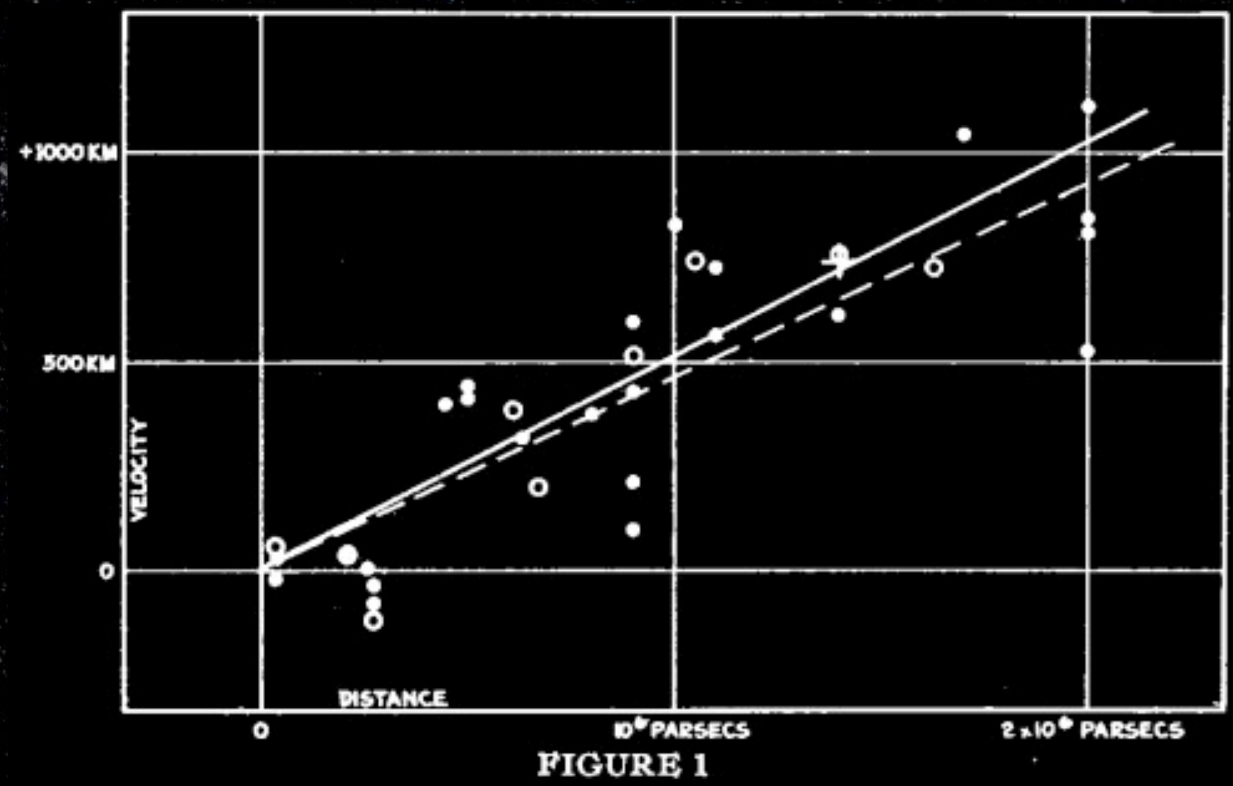
This relationship between redshift and distance is known as the *Hubble law*.



In every direction we look, galaxies are moving away from us.

Does this mean we are right in the middle of the universe?

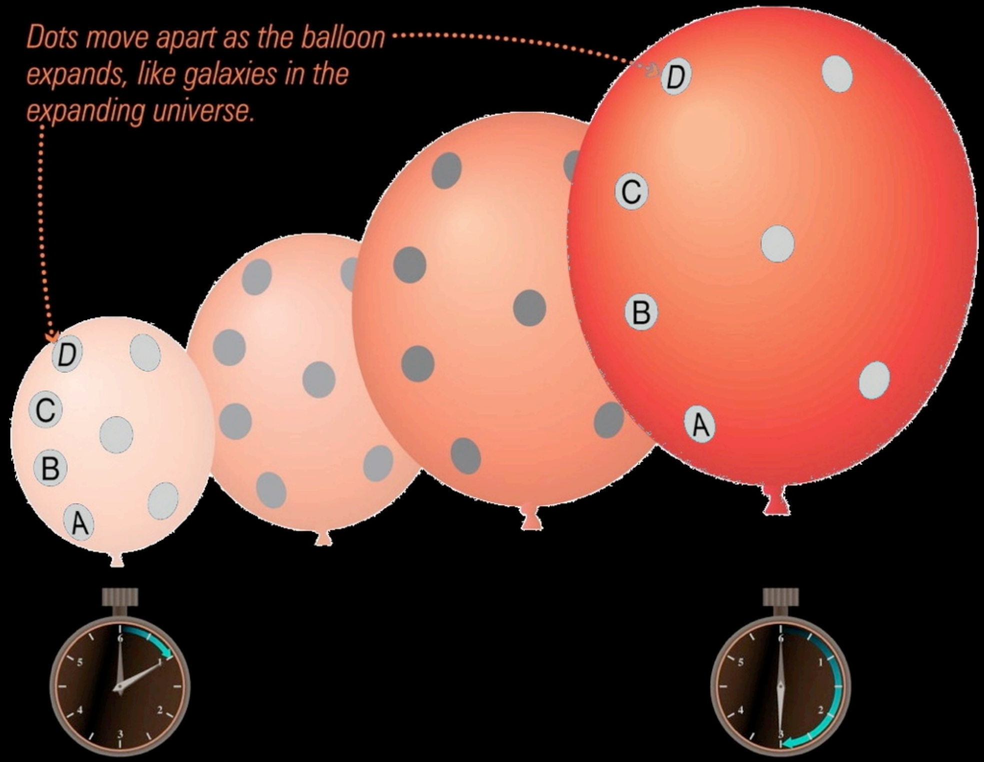
Hubble's original diagram showing the relationship between velocity and distance for galaxies.



No! We make the assumption that we are not in a special place: that the universe looks (approximately) the *same* to all observers: the *cosmological principle.*

According to this principle, if all galaxies are moving away from us, then they must all be moving away from each other.

This can happen if the whole universe is expanding: every galaxy moves away from every other galaxy, and the further away the galaxy is, the faster it seems to be moving.



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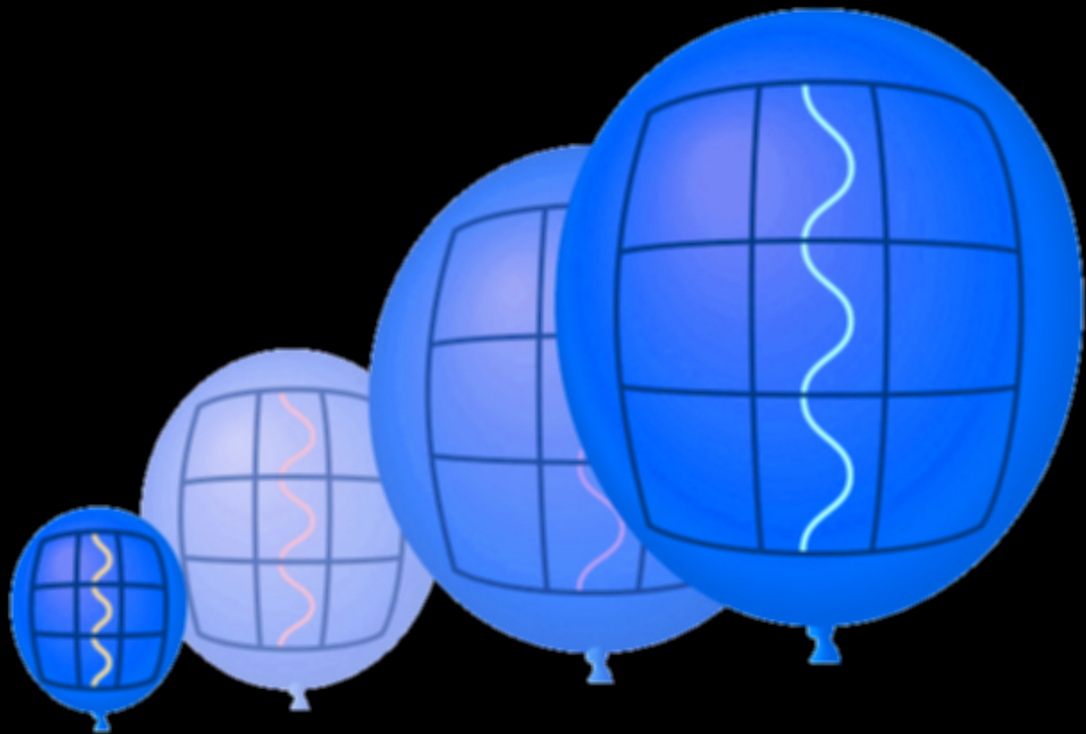
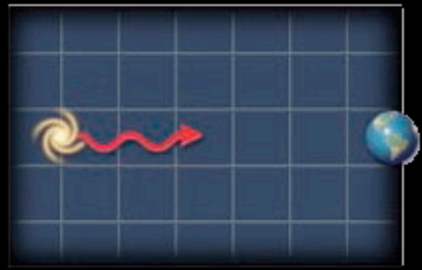
Note that the apparent velocity of galaxies is an illusion. The galaxies are not moving, the space between them is literally expanding. The galaxies are being *separated* from each other as space-time expands.

So a galaxy at a redshift of 2 is *not* moving faster than the speed of light; the space between us and the galaxy is getting larger.

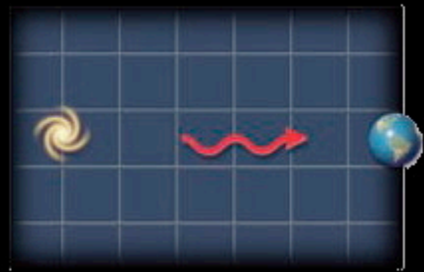
The photons of light from the distant galaxy are "stretched" as they travel across the universe. Their wavelength increases, and we measure a redshift.

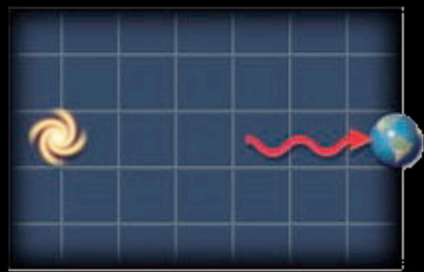


What's more, because the universe was smaller in the past, then we can receive light from objects from much further away than you would think.

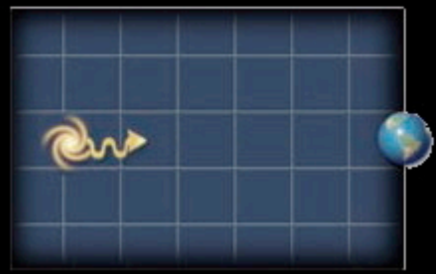


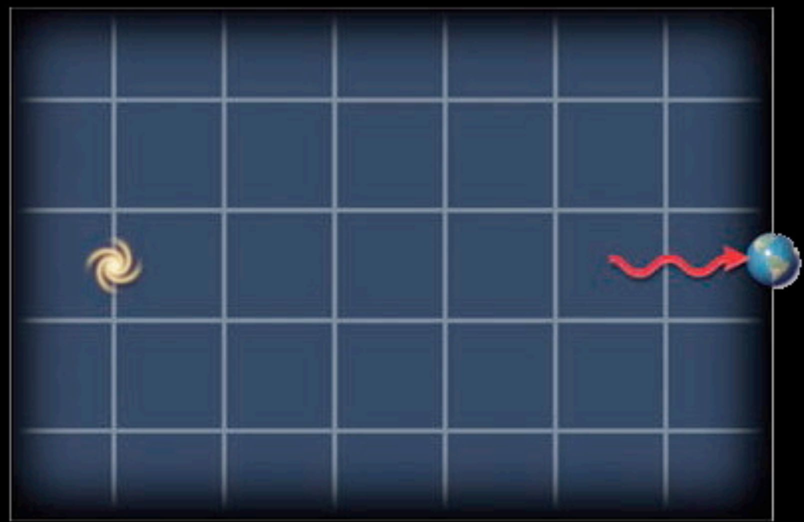
If space were not expanding, then since the universe is about 14 billion years old, the most distant object we could see would be 14 billion light years away.





But when the light from a very distant galaxy was emitted, the universe was much smaller, so as the light travelled towards us the space behind it expanded. The current distance to the most distant object we can see is about 50 billion light years.



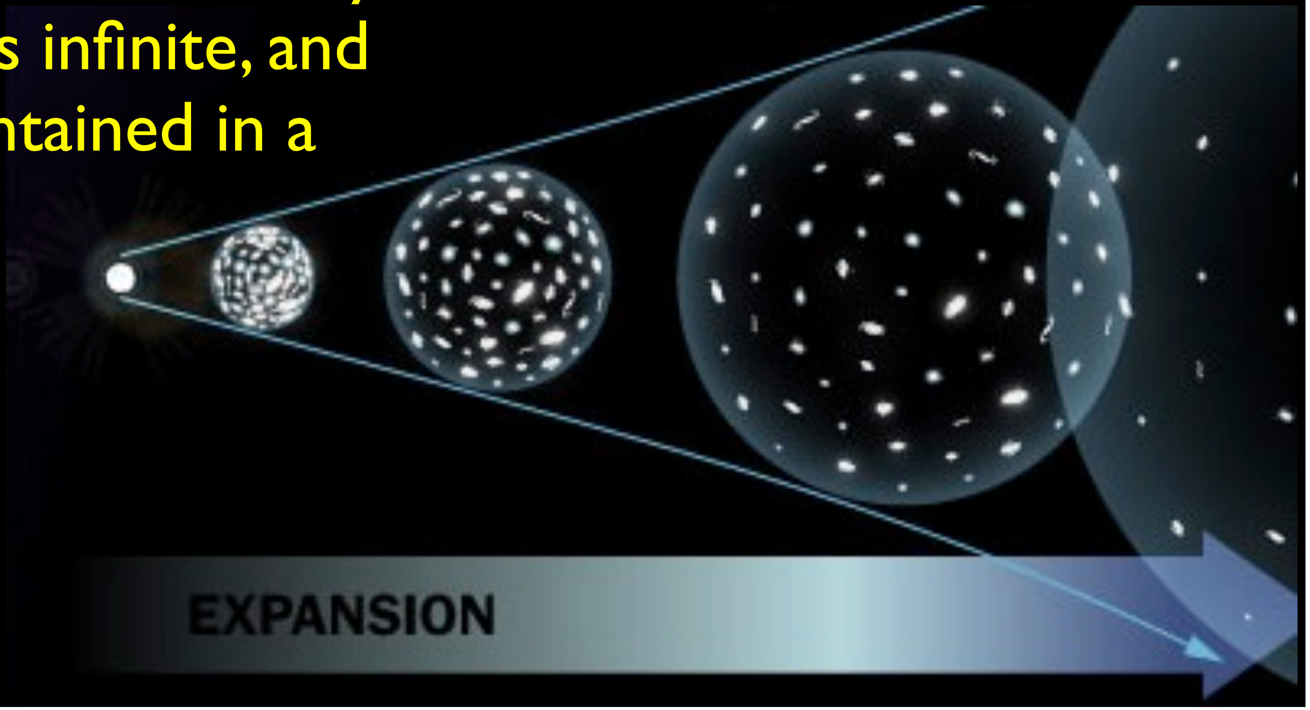


As a photon travels, space expands. By the time it reaches us, the distance to the galaxy where it started is larger than a simple calculation based on light travel-time might imply.

The Big Bang

If the galaxies are getting further apart now, then in the past they must have been closer together.

If we imagine playing the movie of the Universe in reverse, the density would *increase* as we went back in time, until we reach the time when the density of the Universe was infinite, and all of space was contained in a single point.



This instant – 13.7 billion years ago – is the "Big Bang", and represents the limit of what we can extrapolate.

The big bang model has essentially nothing to say about the big bang itself. It describes what happened afterwards.

At the instant of the Big Bang, the whole of the universe was in the same place.

The Big Bang was not an explosion *in* space, but an explosion *of* space. It did not happen at a particular location and spread out from there into some pre-existing void; it occurred *everywhere* at the same time.

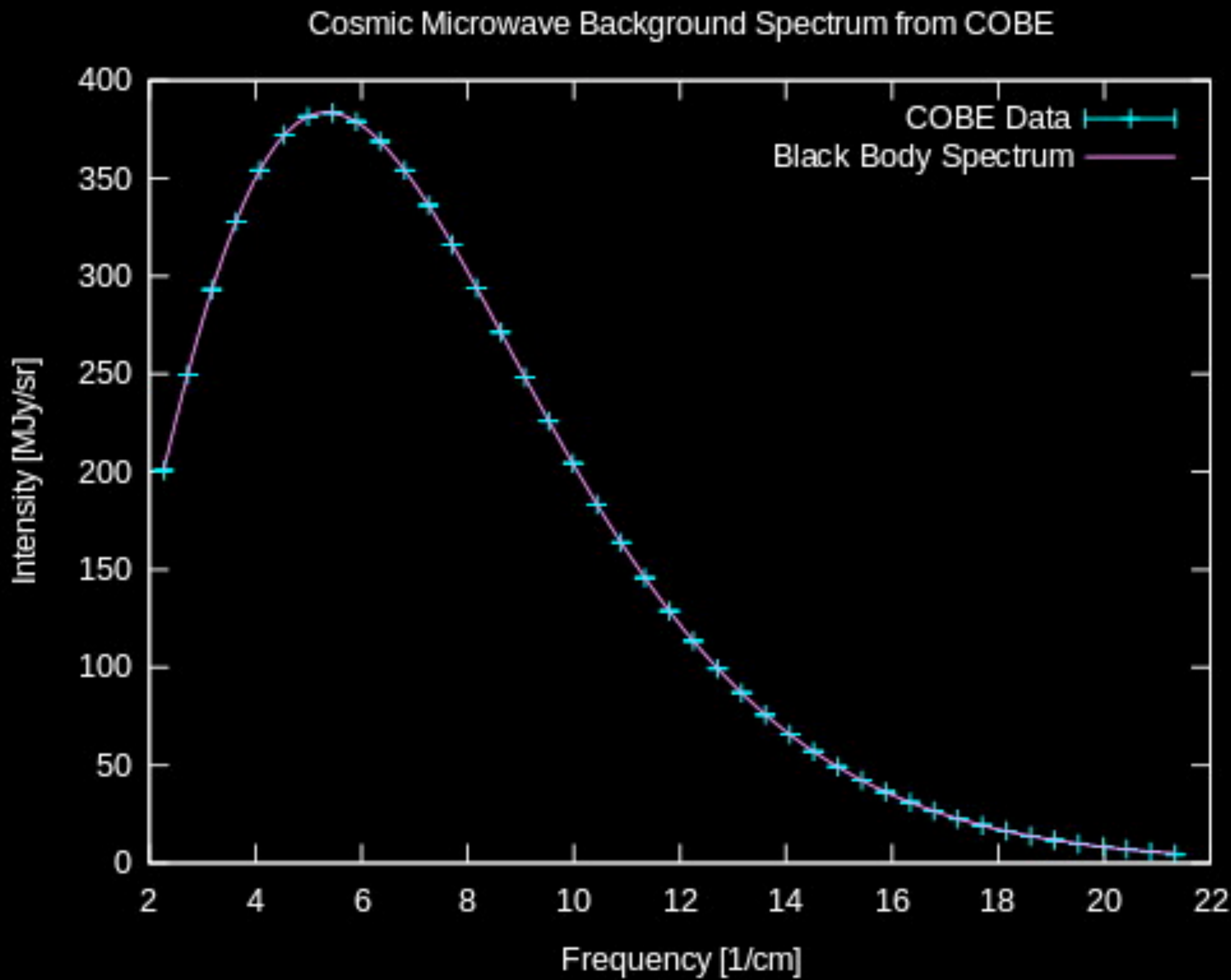
Evidence for the Big Bang was found in 1964 by Arno Penzias and Robert Wilson at Bell Laboratories. In trying to eliminate all sources of noise in their sensitive antenna, they discovered a steady source of noise coming from all directions, corresponding to a temperature of about 3K.

Theorists working at Princeton had predicted a few years earlier that there would be a residual microwave background radiation left over from the Big Bang.

Radiation from the hot early universe would have been redshifted by the expansion, so the original light would be visible as microwaves.

Further, because all the radiation was coming from a cool gas, the shape of the spectrum should be a blackbody curve.

In 1990, the COBE satellite confirmed the radiation has a temperature of 2.725 ± 0.002 K, with a perfect match to a blackbody spectrum.



Modern cosmology has combined these observations with modern physics. We now have a surprisingly good understanding of what happened in the very early universe.

Let's describe what happened, starting a tiny fraction of a second after time zero.

After that time, the universe began to expand, and as it did so, it cooled.

Initially there was nothing but energy. 10^{-47} s after the Big Bang, the Universe was trillions of times smaller than the size of a proton (10^{-24} m), and the temperature was 10^{32} degrees.

At first, the Universe consisted entirely of energy. As it expanded and cooled, particles materialised.

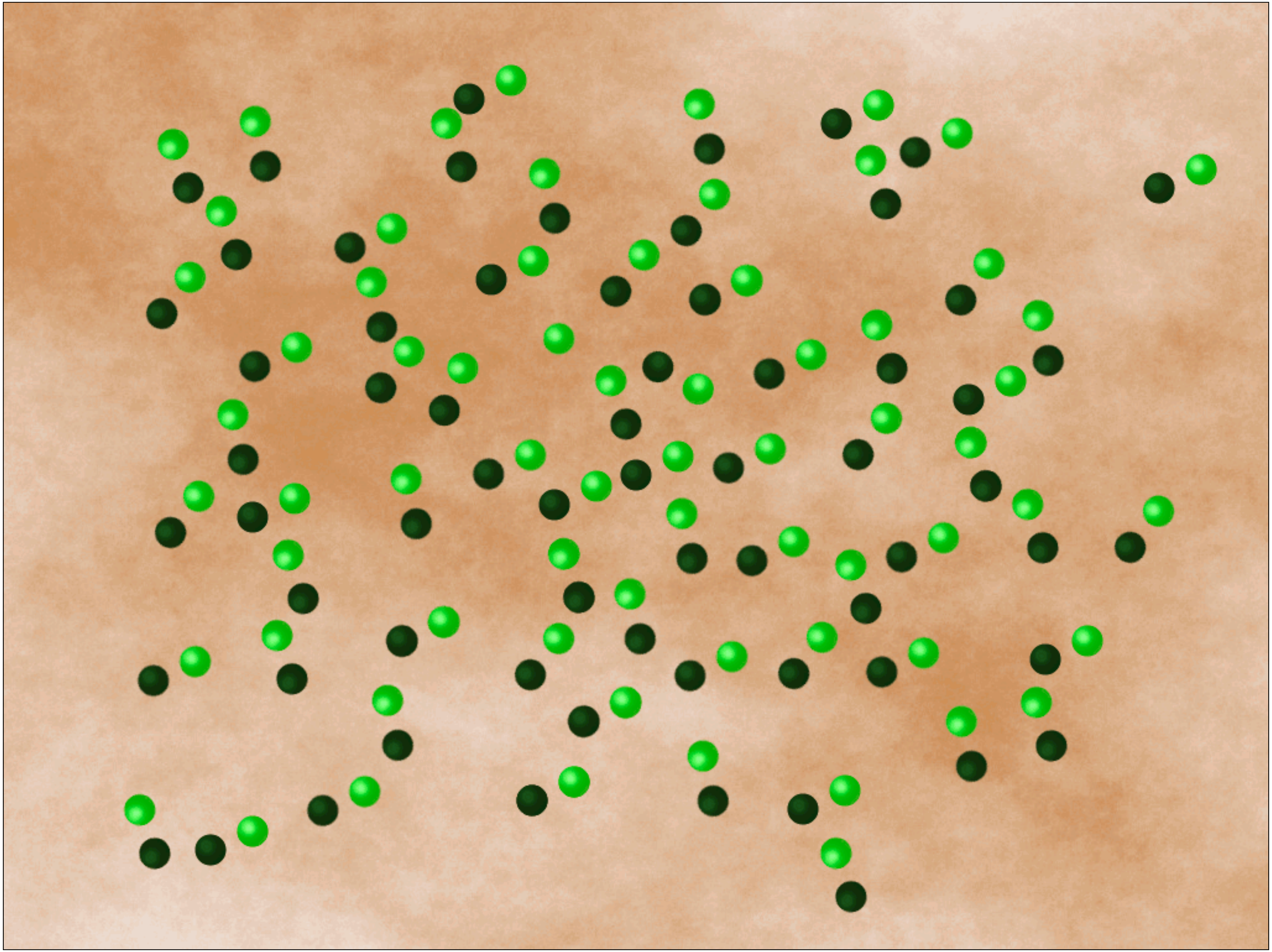
These were the consituents of matter as we know it – quarks and electrons – as well as neutrinos, antiparticles, and even weirder things. By about 1 microsecond the Universe was a seething mass of quarks and gluons, known as the “quark soup”

At about 0.01 s, the temperature had dropped to about a trillion degrees, and quarks could bind together to form protons and neutrons without instantly being ripped apart again.

However, antiprotons and antineutrons were also being formed, and whenever a particle met an antiparticle they would mutually annihilate, vanishing into a pair of photons. These photons would then spontaneously convert their energy back into mass, producing a new proton/anti-proton pair, which sped away from each other.

As the Universe kept cooling, eventually the temperature dropped enough that the photons don't have enough energy to make a a new pair of particles.

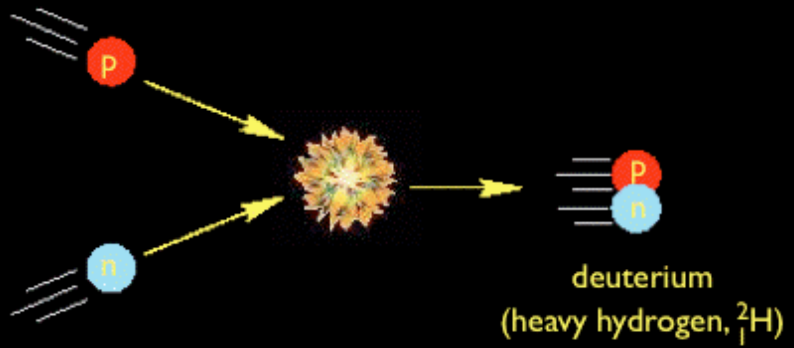
When that happens, the particles and antiparticles annihilate one last time. For reasons we still don't understand, there was a tiny imbalance of matter over antimatter – for every 30 million antiparticles there were 30 million and one particles. After the annihilation had finished, only this small amount of left-over matter remained: the rest had disappeared into radiation.

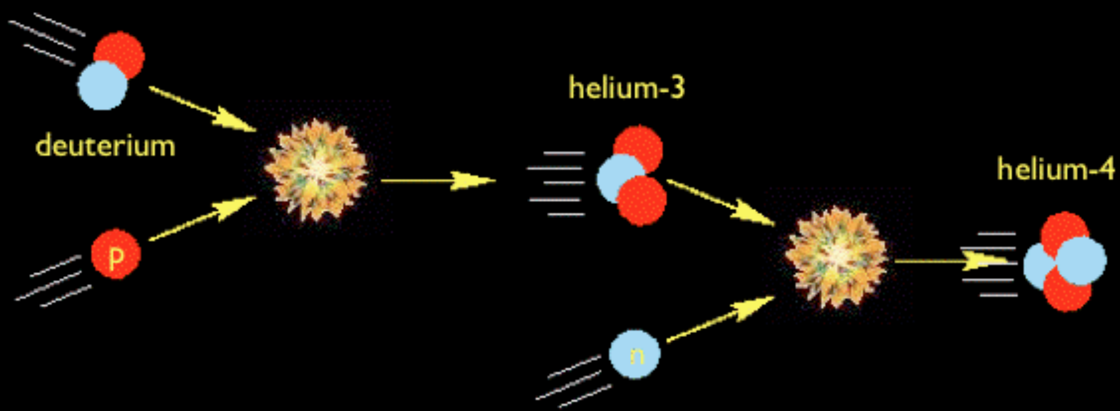


So about 1 second after the Big Bang, there was about one proton or neutron for every billion photons or electrons or neutrinos.

When the temperature dropped to about 10 billion degrees, the particles – protons and neutrons – could stick together when they meet. The strong nuclear force binds them together in the first atomic nuclei.

Protons and neutrons fuse to form deuterium, then helium-3 and helium-4.

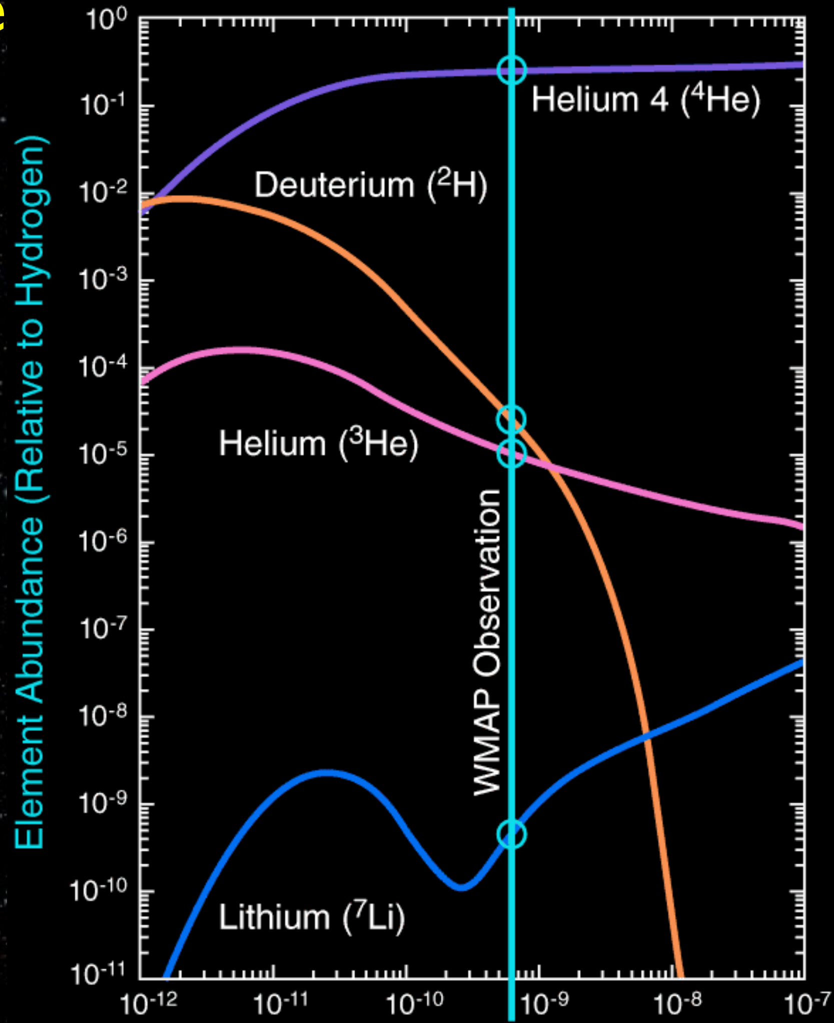




But nothing else. There is no stable nucleus containing 5 particles, so when a four-particle helium nucleus is struck by another particle, the whole lot is split apart again.

So by the time the Universe is three minutes old, nearly all the neutrons have been combined into nuclei, while most of the protons are still free. About 90% of the universe is hydrogen, with nearly all the rest made up of helium. There is some deuterium, and tiny amounts of lithium and beryllium, but nothing else.

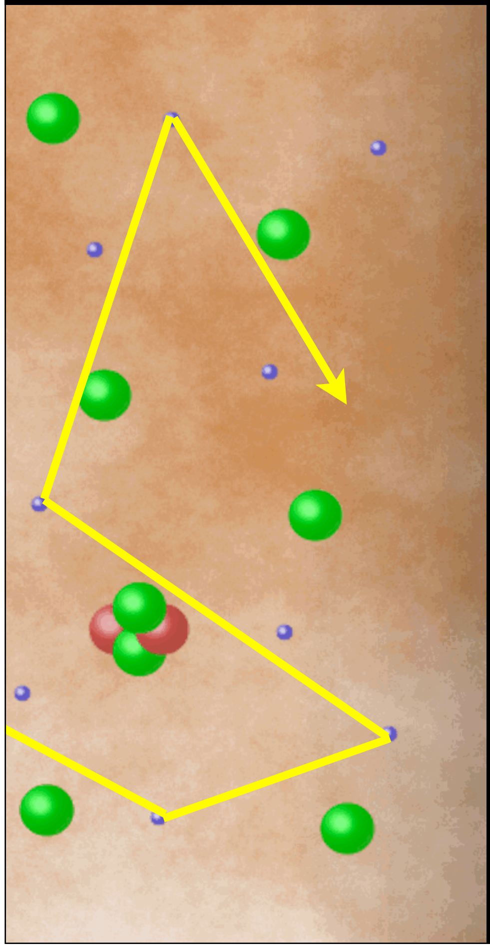
It turns out that the final composition of the universe depends only on the *baryon density*. By measuring the abundance of helium and deuterium in pristine gas, we can work out this density, and hence show that baryons make up only 4% of the Universe



So the Universe continues to expand: hydrogen and helium in a fog of radiation that continues to cool. It was still too hot for electrons to combine with the protons and nuclei to form atoms, so the whole Universe was filled with a glowing plasma.

After about 300,000 years, the temperature has cooled to about 3,000 degrees. Finally, it cooled enough for electrons to combine with nuclei to form stable atoms without being ripped apart again.

Hydrogen atoms are very poor scatterers of light, so instead of bouncing round, the photons started flying freely: the Universe was now transparent. The photons have been travelling freely every since, gradually increasing in wavelength as the Universe expands. Their temperature has dropped from 3000 degrees to just 3 degrees above absolute zero.

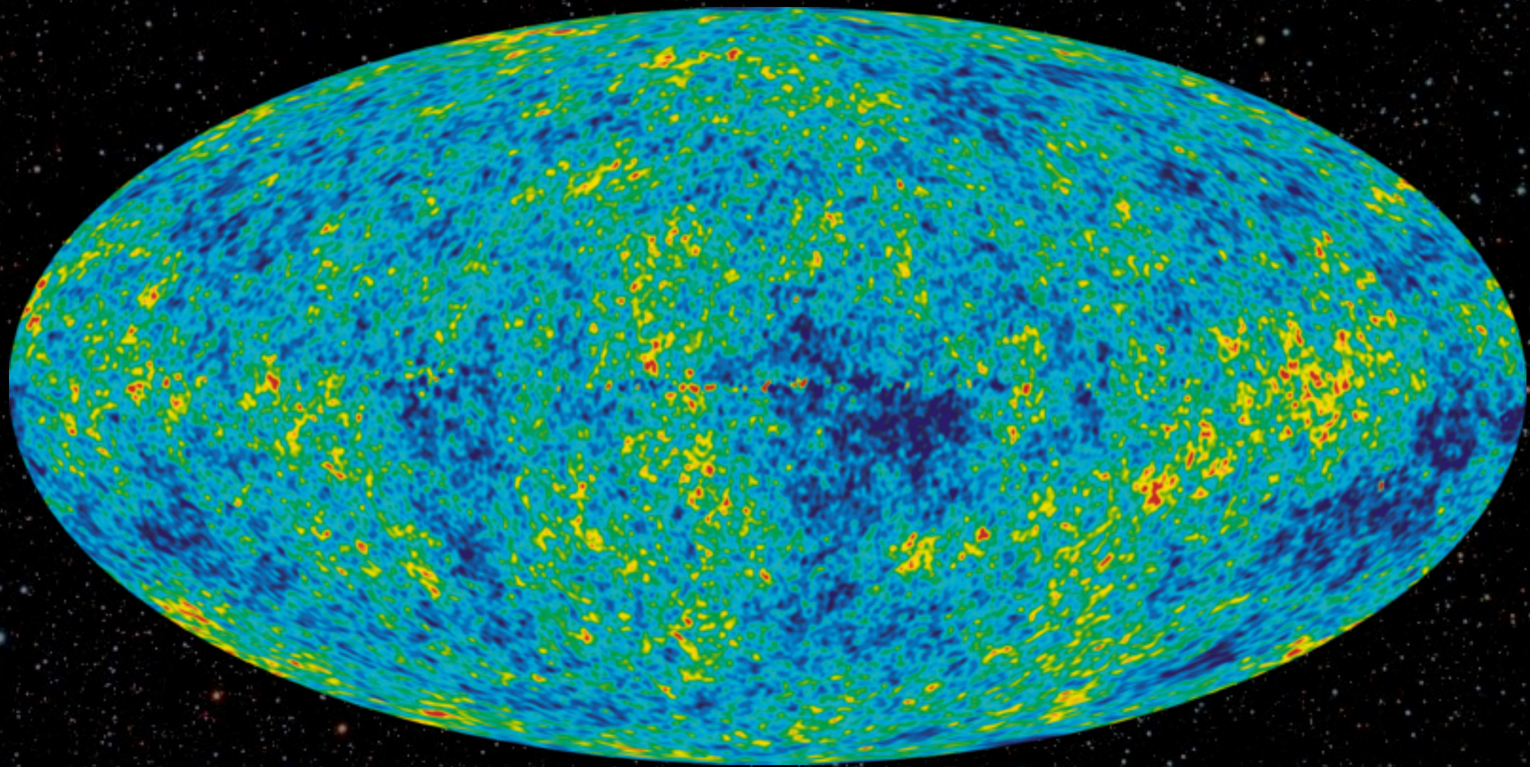


At the time of recombination, the entire universe was filled with orange-red light; those photons are now stretched so they are seen as microwaves, coming from all directions in space.

This radiation was what Penzias and Wilson had found with their antenna, a relic from the time when the universe first became transparent: the *recombination era*.

This relic radiation is now known as the *Cosmic Microwave Background* (CMB).

The most recent measurements by the Wilkinson Microwave Anisotropy Probe (WMAP) have shown that the whole sky is emitting almost completely uniform radiation at a temperature of 2.725 K, with fluctuations of only 0.0001°.



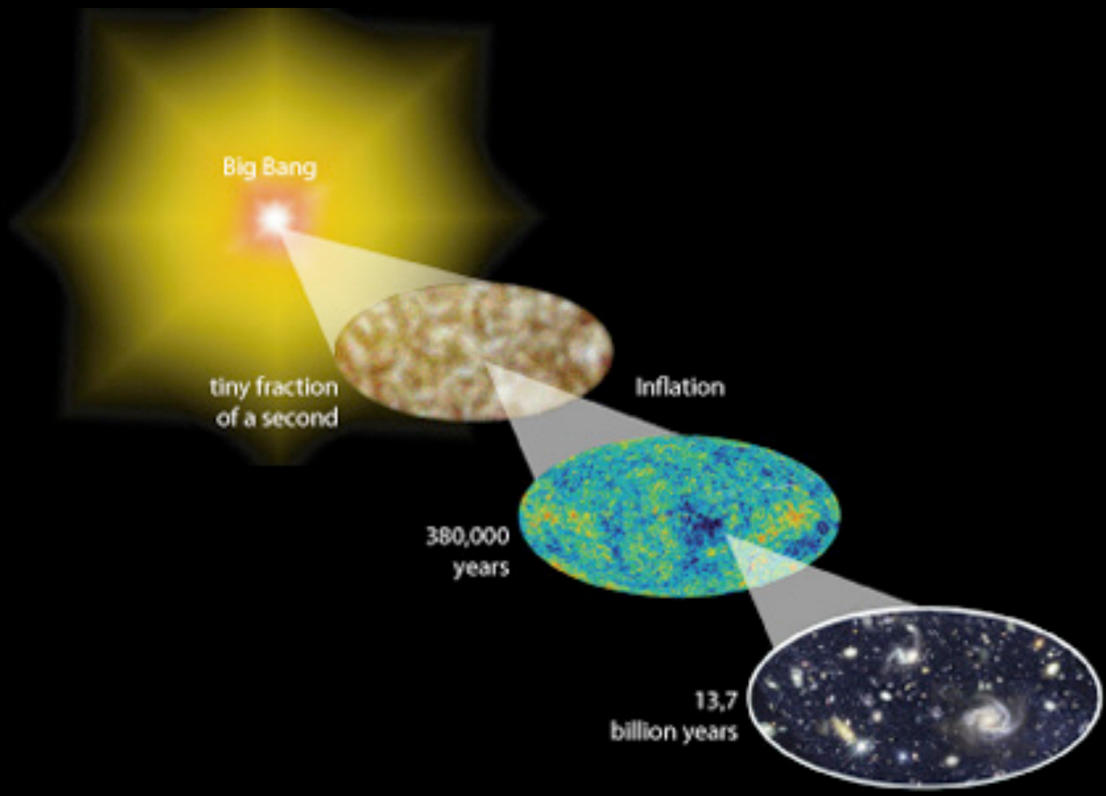
WMAP image of the microwave background radiation. The colours represent tiny fluctuations (0.0001 degrees) from the mean temperature of 2.725 K, with red regions warmer and blue regions colder.

Where did those fluctuations come from?

It appears that in the *very* early universe there must have been a period when the Universe was expanding at an enormous rate, called the *inflationary epoch*. Between 10^{-43} and 10^{-34} s the Universe doubled in size more than a hundred times, expanding in size from a trillionth the size of a proton to the size of a cricket ball. This enormous expansion smoothed out any irregularities an meant that the Universe was uniform on scales much larger than that of our horizon.

Tiny fluctuations in density were also inflated in size, and eventually resulted in the inhomogeneities in the density of the universe which eventually became the seeds for the formation of galaxies.

It is amazing to think that the galaxies of today originated from subatomic quantum-mechanical fluctuations at the dawn of time.

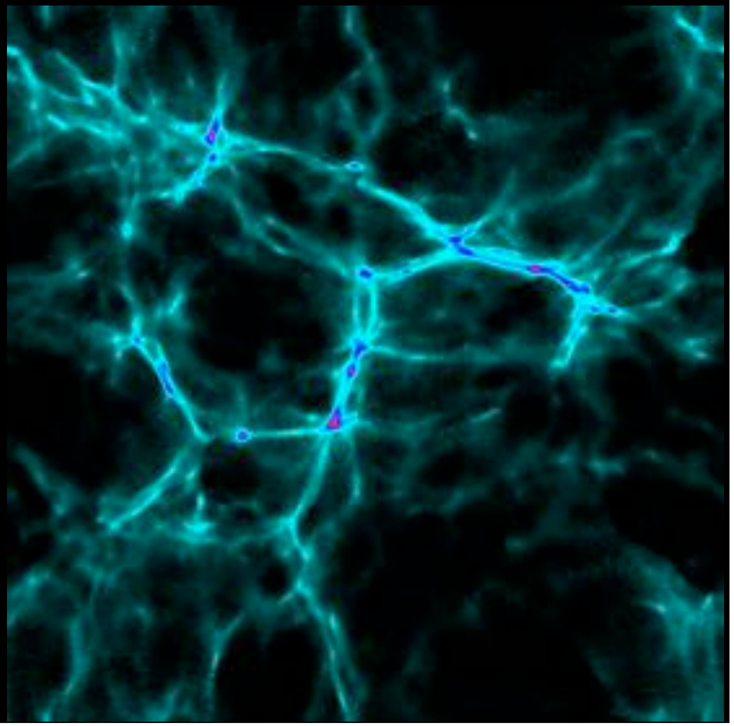


There was one more effect of the falling temperature. Once the temperature had fallen below a few thousand degrees, the radiation shifted into the infrared. Nothing in the Universe was hot enough to produce visible light. The Universe was completely dark.

This *cosmic dark age* lasted for perhaps a hundred million years.

However, as the expansion continues, the photons continue to lose energy while the matter does not. As matter starts to dominate, gravity starts becoming important.

Those tiny fluctuations in density now become the seeds around which clumps of matter grow. Regions which are slighty denser than their surrounds pull in more matter, which makes them denser still, which increases their gravity still more.



Gravity is starting to make structure.

The physics of how this happened is extremely

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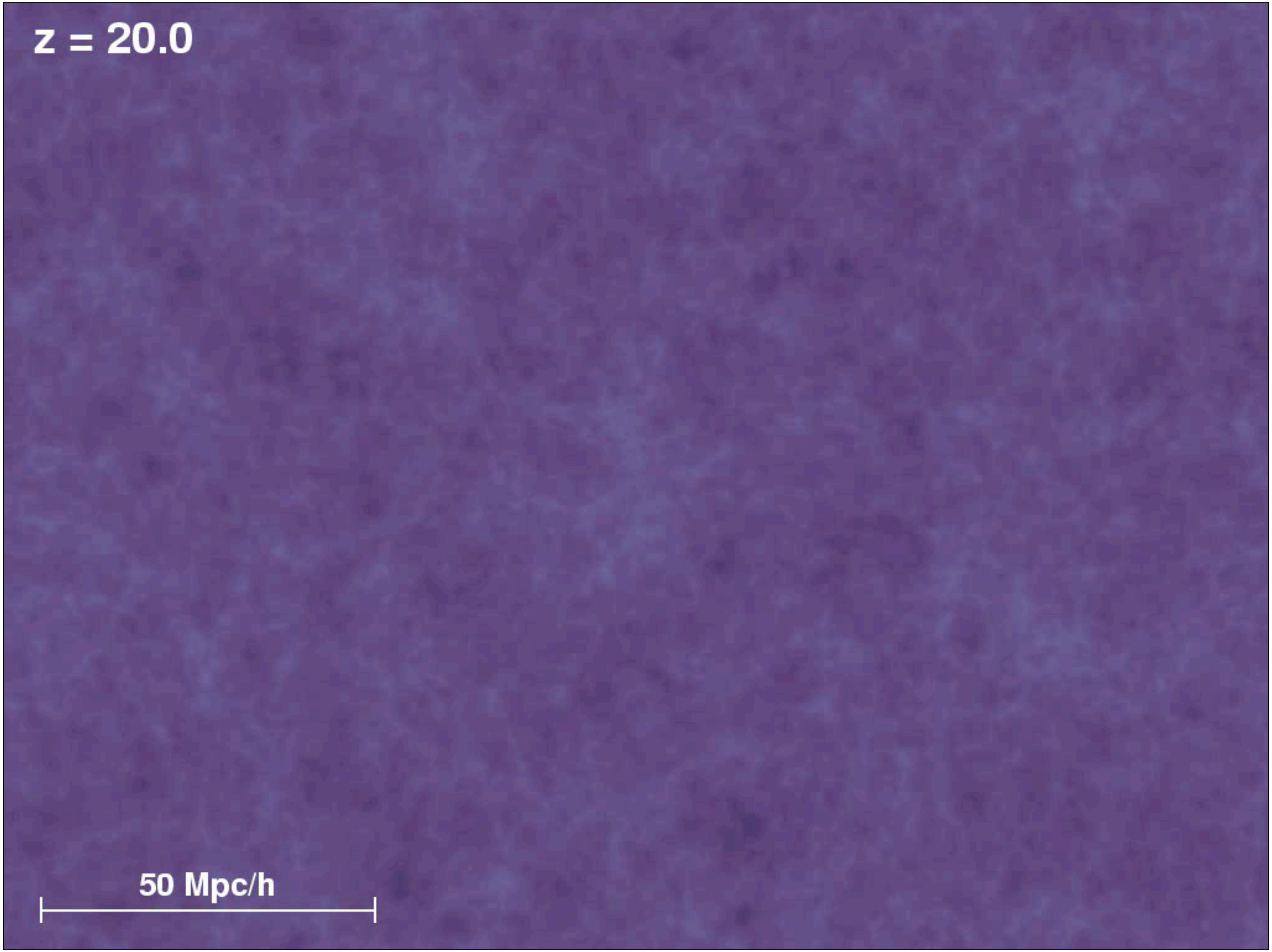
These simulations show that the wiggles in space-time cause dark matter to "fall in" to these dimples and form diffuse haloes. Since the DM particles are only weakly interacting, these haloes stay diffuse. However, ordinary matter is also pulled in, and it can form dense clouds of gas.

Eventually, the matter develops into a web of filaments, with voids separating the denser regions.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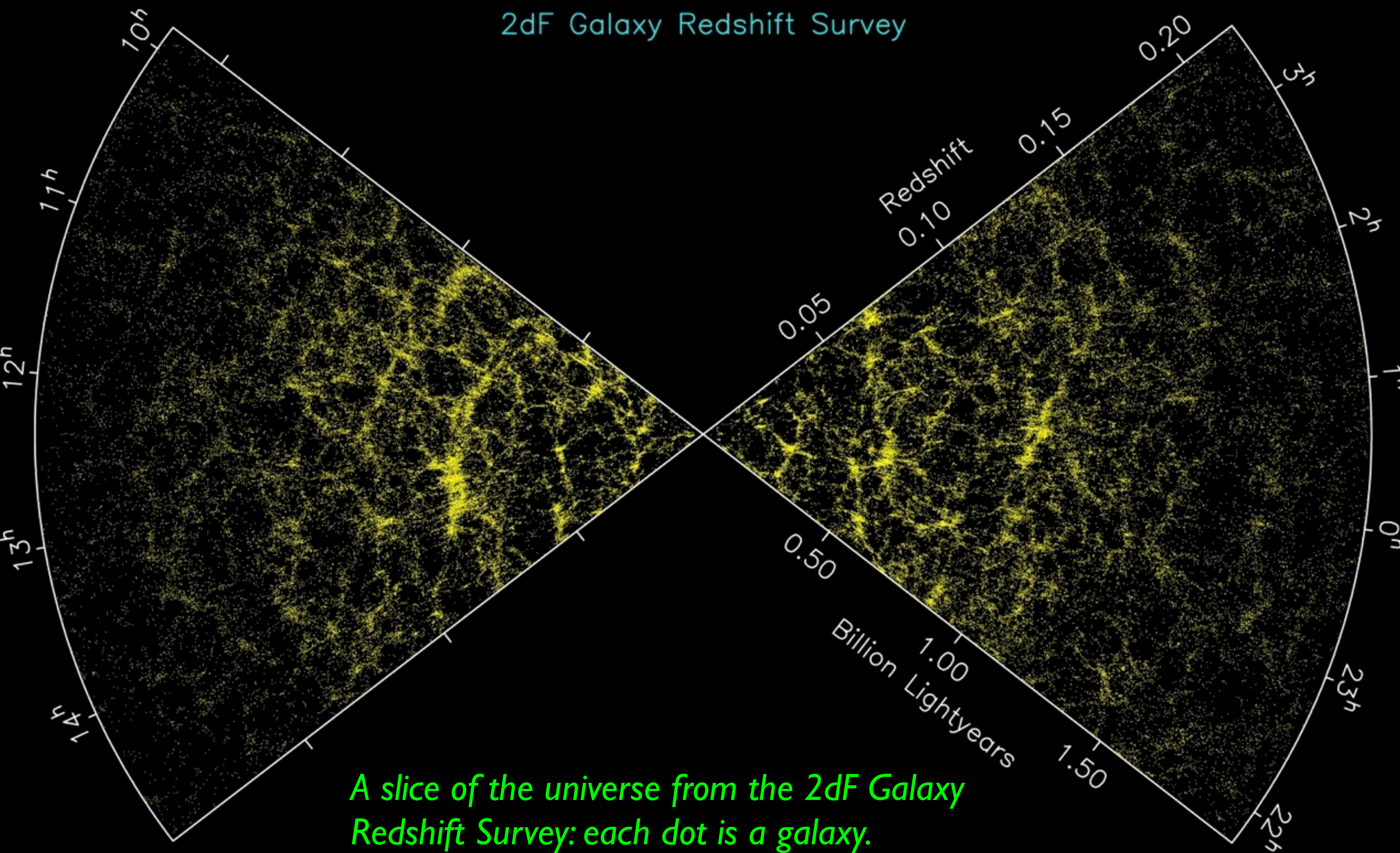
We see these filaments and voids today in the distribution of galaxies. The 2dF Galaxy Redshift Survey measured the distances to nearly a quarter of a million galaxies, enabling us to make a three-dimensional map of the universe.



A slice of the universe from the 2dF Galaxy Redshift Survey: each dot is a galaxy.

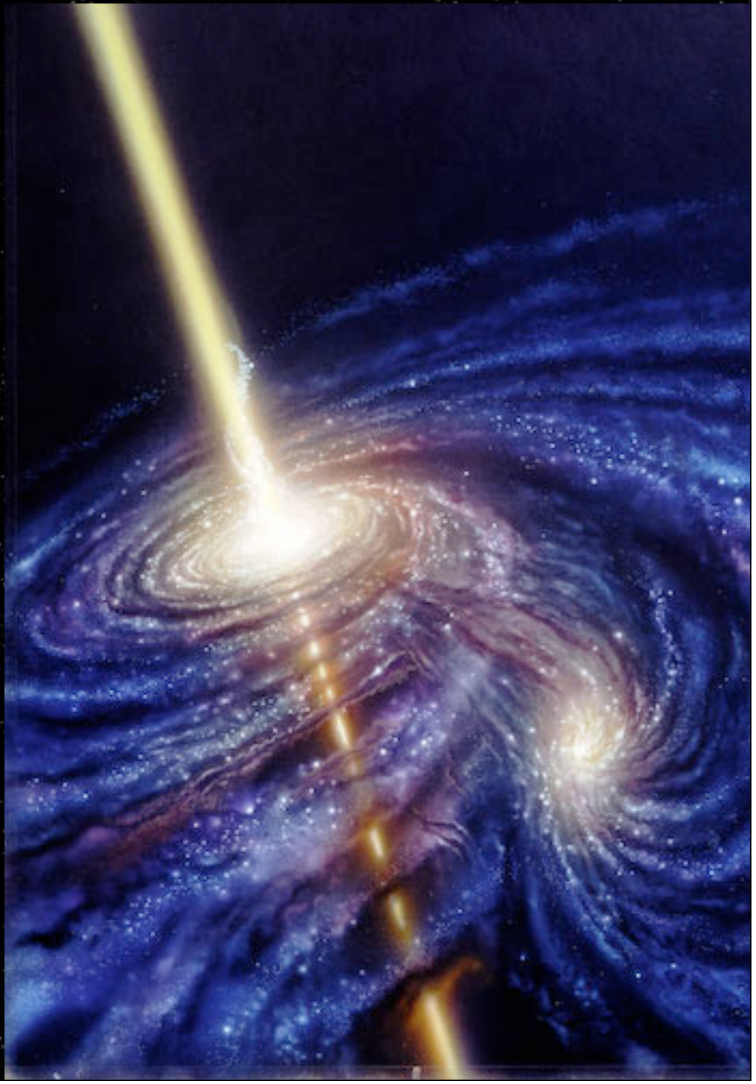
Meanwhile, in the dark, the matter continues to collect and become denser. Eventually, the densest regions contract and heat up so much that hydrogen can start fusing to helium. The first stars in the Universe have been born, and the cosmic dark age is at an end.

The first stars were quite different to stars in the Universe today. Because the only elements were hydrogen and helium, they contained none of the heavier elements present in all stars today. Models show that such stars would be much brighter and much more massive than heaviest stars today.

from Larson & Bromm, SciAm, Dec 2001

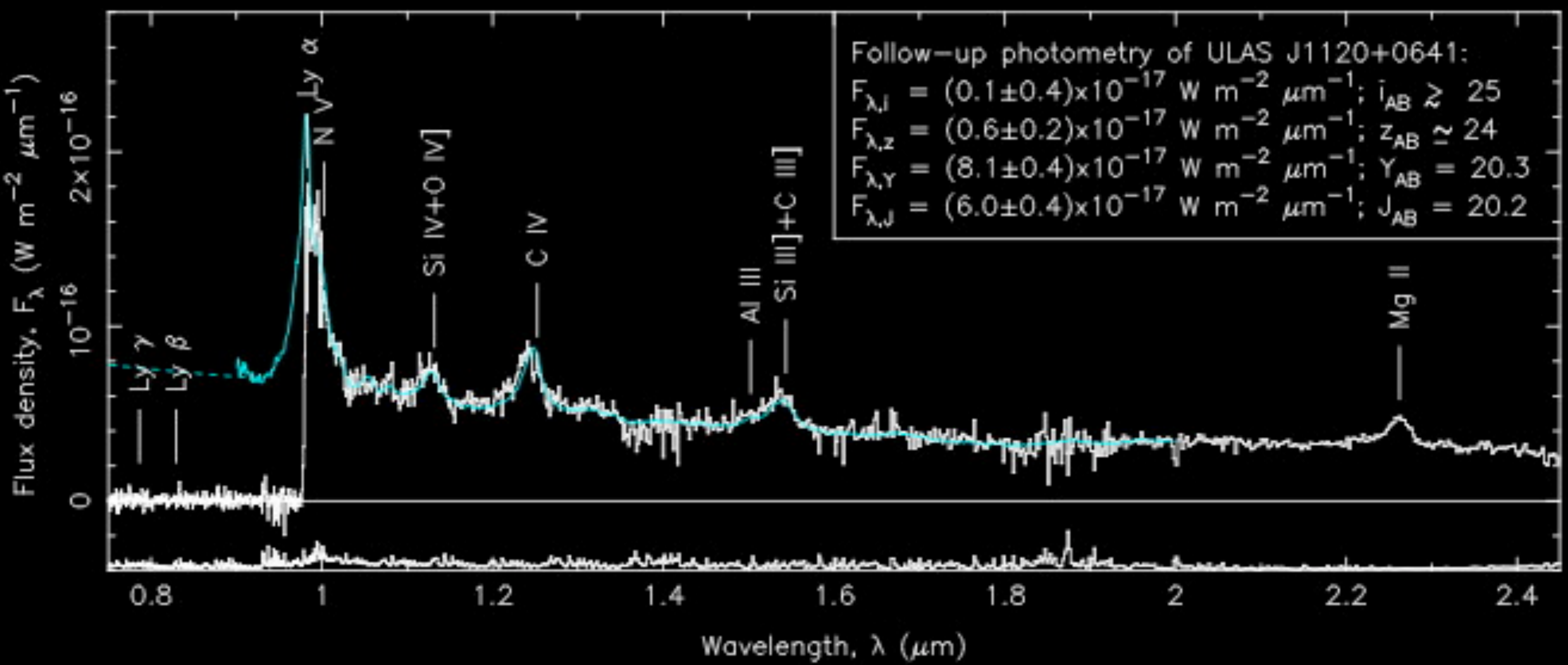
The death of the first stars also had major consequences, in two ways. When they went supernova, they scattered heavy elements throughout their surroundings, which then got incorporated into subsequent generations of stars.

In addition, the collapsing cores of these stars probably left behind black holes, which may have provided the seeds which grew into the massive black holes we see at the centres of quasars and galaxies today.



painting by Don Dixon

The fact that we see quasars at high redshift means that massive black holes already existed and were growing less than a billion years after the Big Bang. The most distant quasar known has a redshift of 7.08, so it was formed when the universe was only 0.77 Gy old.

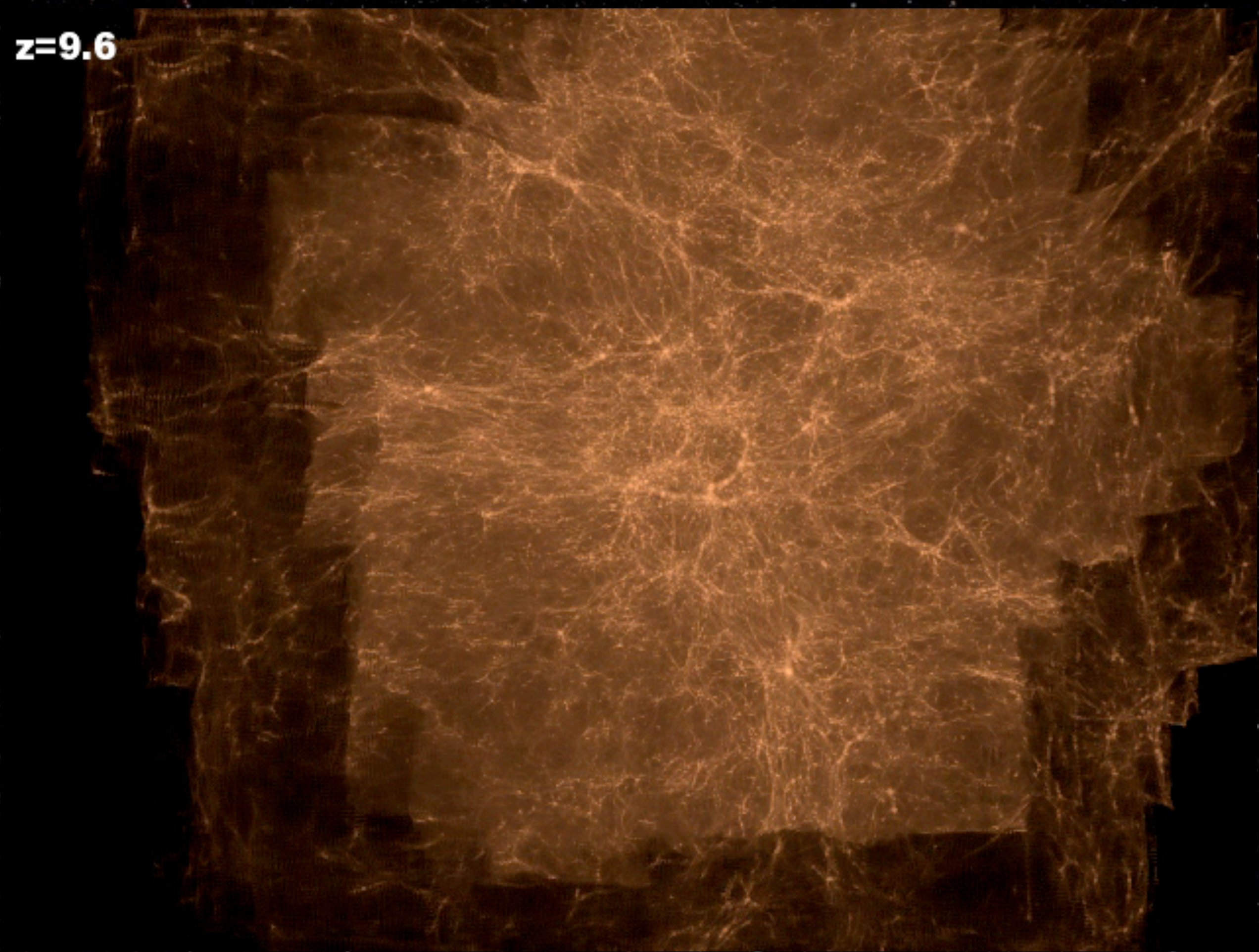


Spectrum of the highest redshift quasar known, ULAS J1120+0641, at redshift 7.08

Last week, we talked about how both galaxies and black holes grow through collisions of galaxies. The further back we look, the more common these collisions seem to be.

The "Spiderweb galaxy", a large galaxy under assembly by the merging of smaller galaxies.

This suggests that gas falls in to build the galaxy, and at the same time some gets funnelled in to the centre where it feeds and grows the black hole.



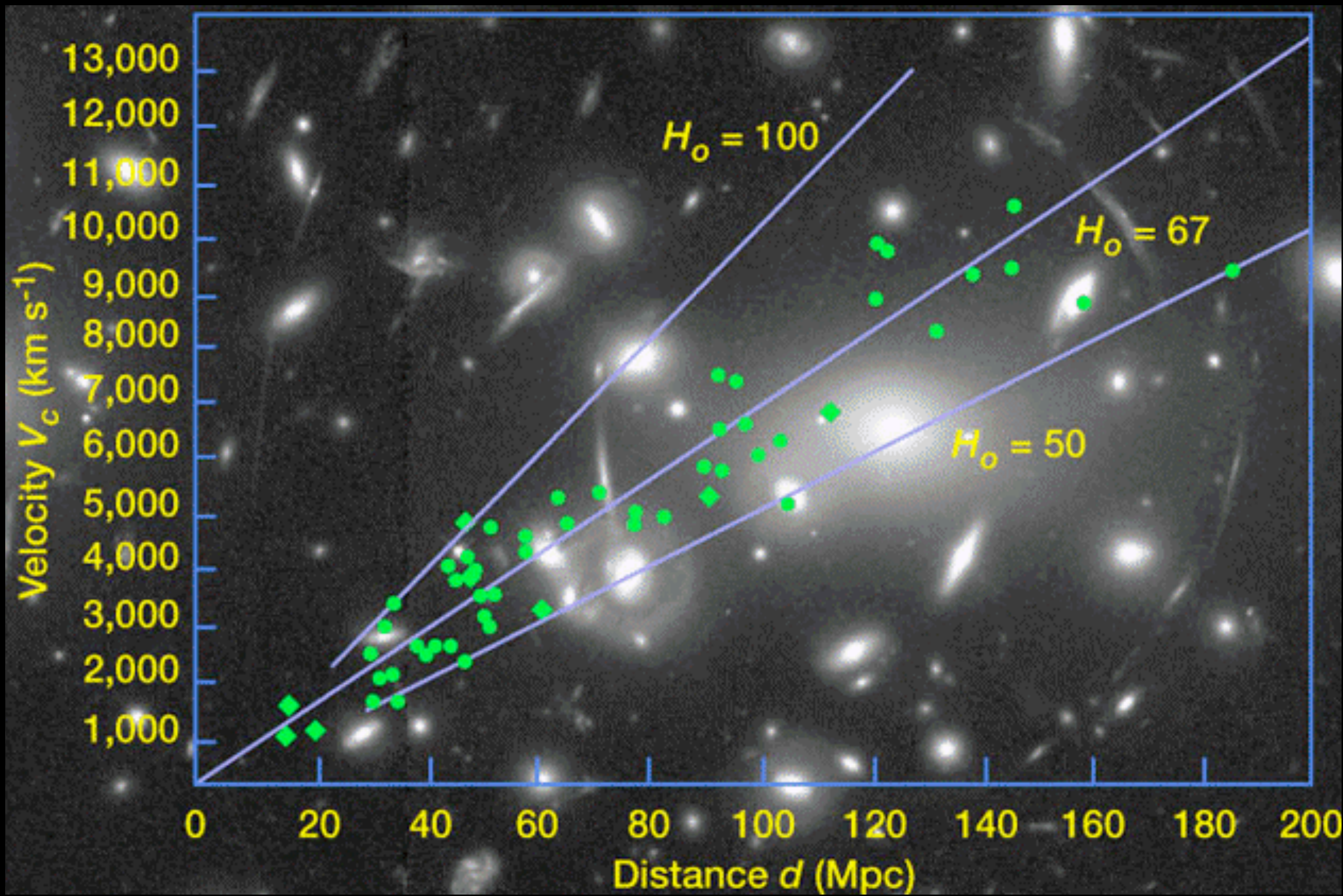
Evidence for the Big Bang

There are four main pieces of observational evidence for the Big Bang theory.

Any competing theory must be able to explain these observations.

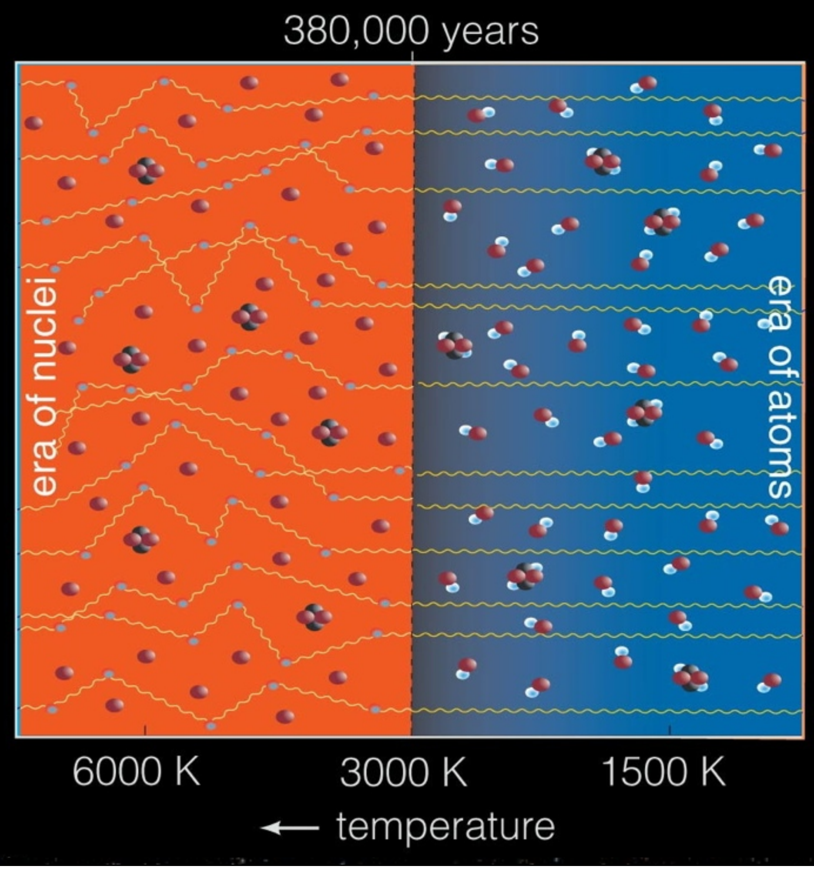
1. *Cosmic expansion*

All objects (galaxies and quasars) in deep space are observed to be redshifted, i.e. they are receding from us.



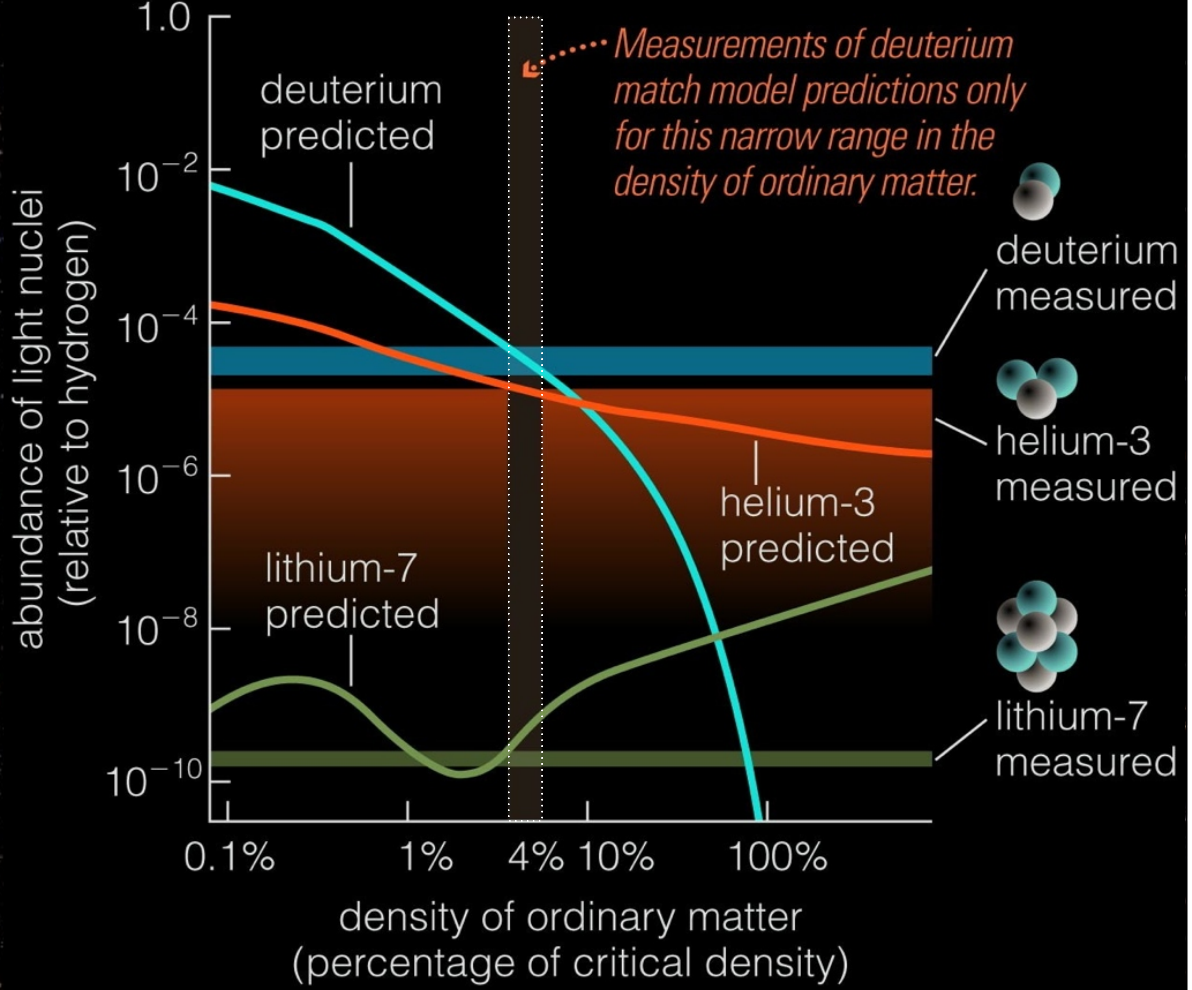
2. *The cosmic microwave background*

Everywhere we look in the sky, there is a signal with a temperature of 2.75 K. This is what we expect to see from the hot plasma before hydrogen atoms first became stable. The initial temperature of 3000 K has been redshifted to the current ~3 K.



3. *The abundance of light elements*

When the universe had cooled enough for elements to be formed, the low-mass elements of deuterium, helium and lithium were formed. The proportions of each depend only on a single number: the *baryon density*.



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4. *The evolution of galaxies*

When we look at galaxies and quasars at different redshifts, they look very different. At high redshift, all the galaxies are highly distorted, not the nice symmetric objects we see at low redshift.

Plus the numbers of e.g. quasars changes with redshift; quasars were significantly more common at redshift of 2 than they are at higher or lower redshift.

Close-up of galaxies from the Hubble Ultra Deep Field image.

"... It does not seem to be universally recognised that these observations stand for themselves – that they are *independent of any theory*. Very often those who, for some reason, take issue with relativity, appear to forget that the ultimate theory (whether it be Einstein's or not) must be able to explain these observational results. That relativity does so is a strong argument for its reality; that it predicted many of them before any study had been made is even more proof of its correctness."

– Donald Menzel, 1929

The fate of the Univsere

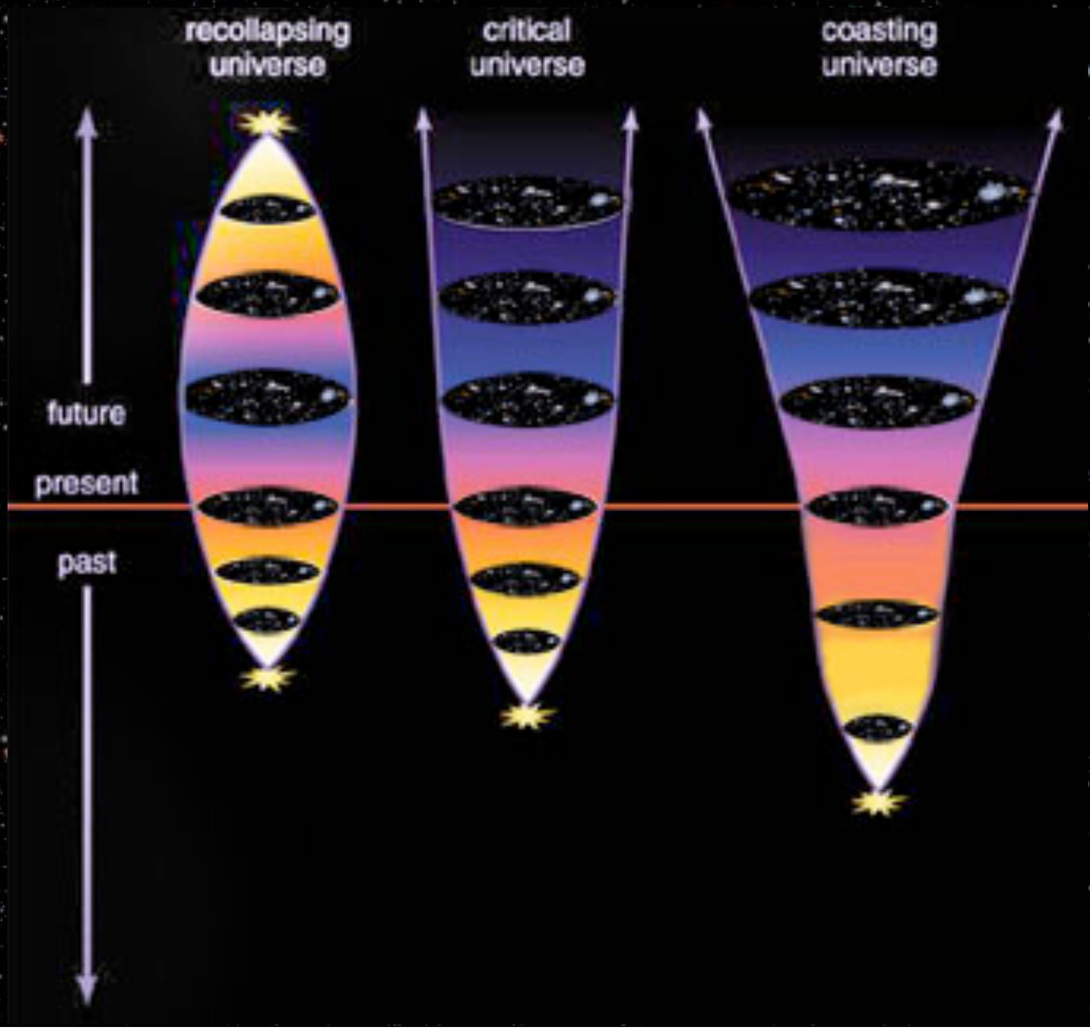
What is the ultimate fate of the universe? Will it go on expanding forever, with stars burning out, galaxies becoming cold, and dark remnants expanding forever through an endless dark?

Or will gravity slow the expansion down and reverse it, so the universe contracts, galaxies get closer and closer, and eventually it all ends in an inverse Big Bang – a *gnab gib*?

What will happen depends on the *density* of the universe. If the average density of the universe is large, then gravity will eventually win over the expansion, and everything will recollapse.

If the average density is too low, then the universe will expand forever.

If we have just the right amount of matter per unit volume (the *critical density*), the expansion slows down to zero.



Counting all the matter we can see, we get a density only 10% of the critical density.

However, we have already seen how the rotation curves of galaxies tell us that much of the mass in galaxies is dark.

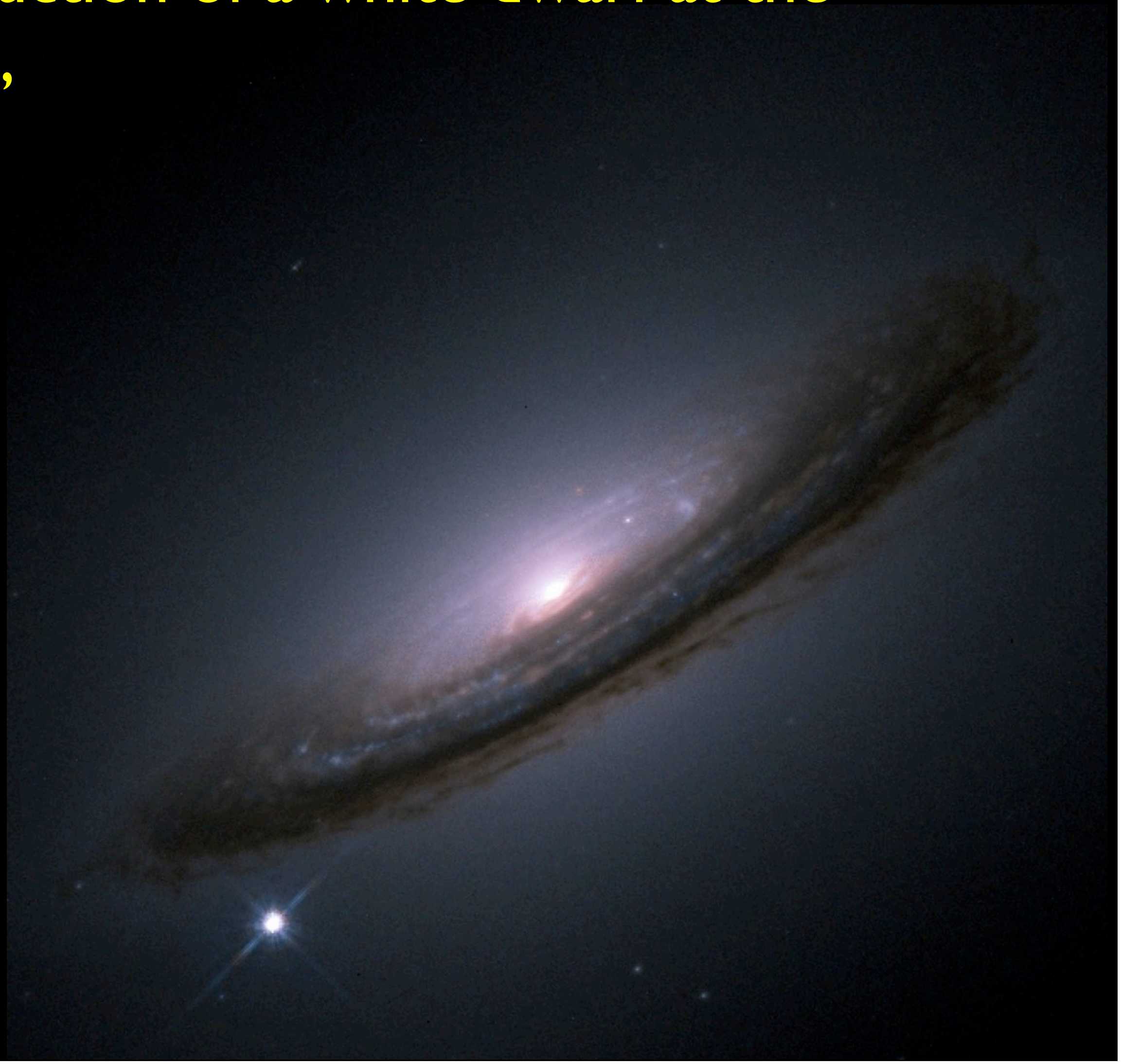
Observations of gravitational lensing in clusters of galaxies has given strong evidence of the existence of dark matter.

Map of the dark matter in the galaxy cluster Abell 1689 from gravitational lensing

We need to measure the history of the expansion of the universe. We have measured this locally using the Hubble constant, which tells us the age of the universe: 13.7 billion years.

In 1998, two teams of astronomers, one led by Brian Schmidt, announced the results of the study of high-redshift supernova explosions.

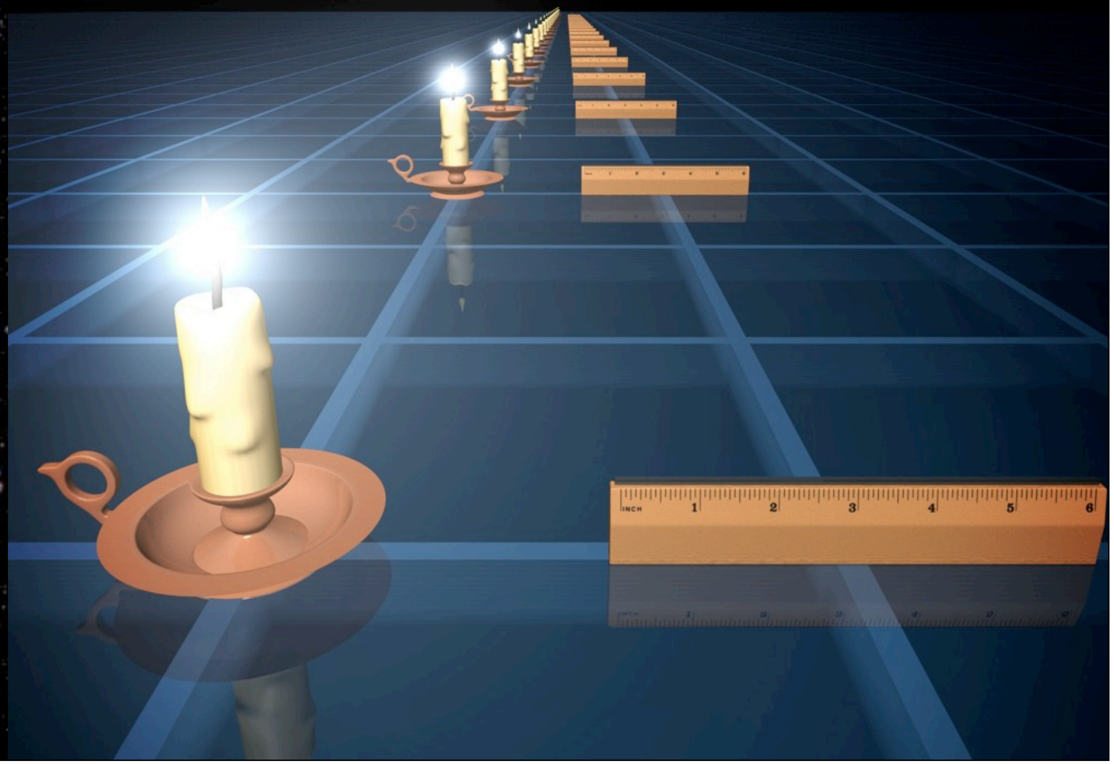
Both teams went looking for thermonuclear supernovae in distant galaxies. These supernovae result from the destruction of a white dwarf at the Chandrasekhar limit*,
so all have exactly
the same luminosity.



* see lecture 6

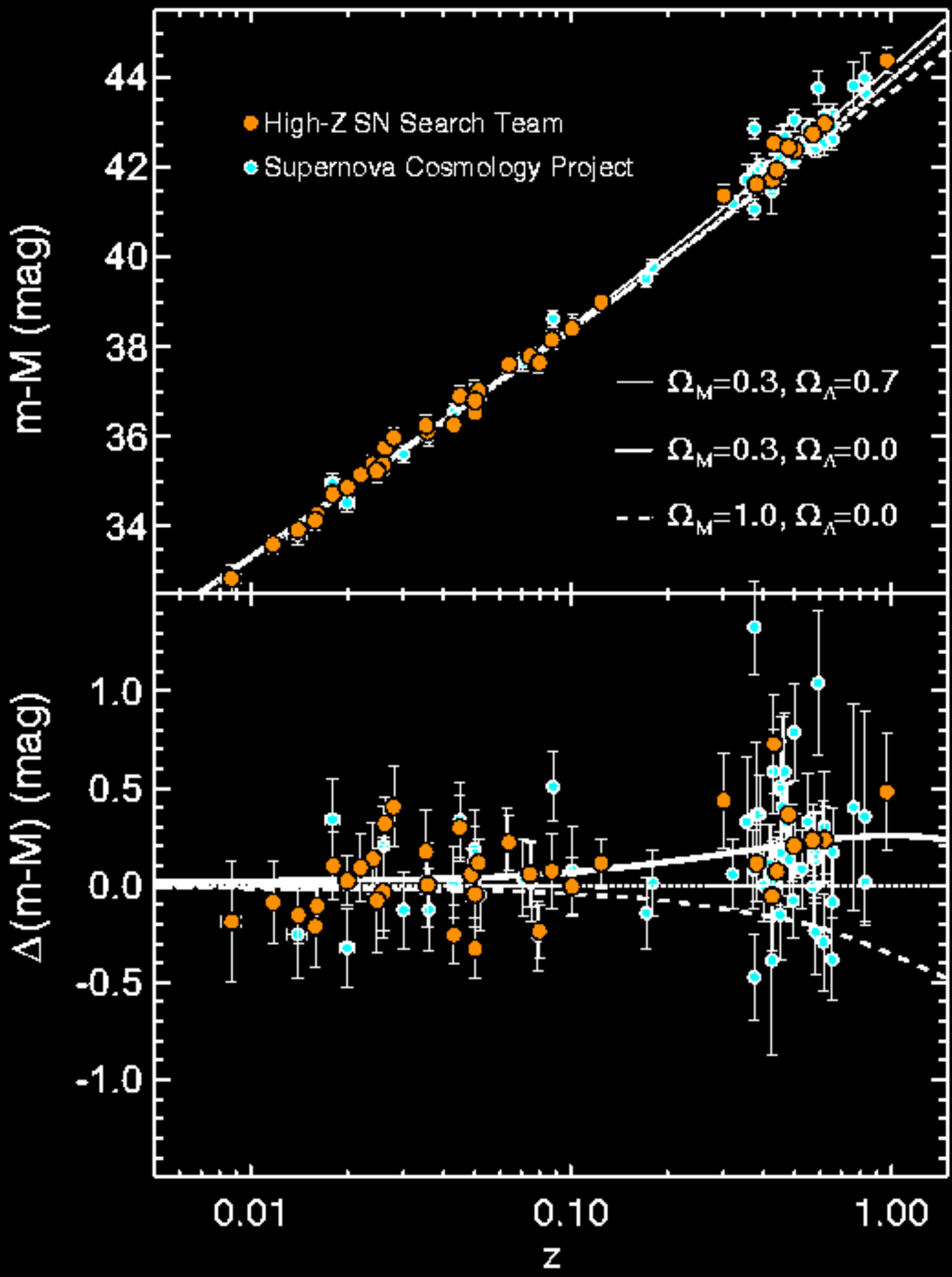
By measuring how bright a supernova appears to be, we can find the distance; and we can measure its redshift from its spectrum.

This means we know both how far away it is and how fast it's moving. Combine those two pieces of information for enough supernovae, and you learn the expansion history of the Universe.

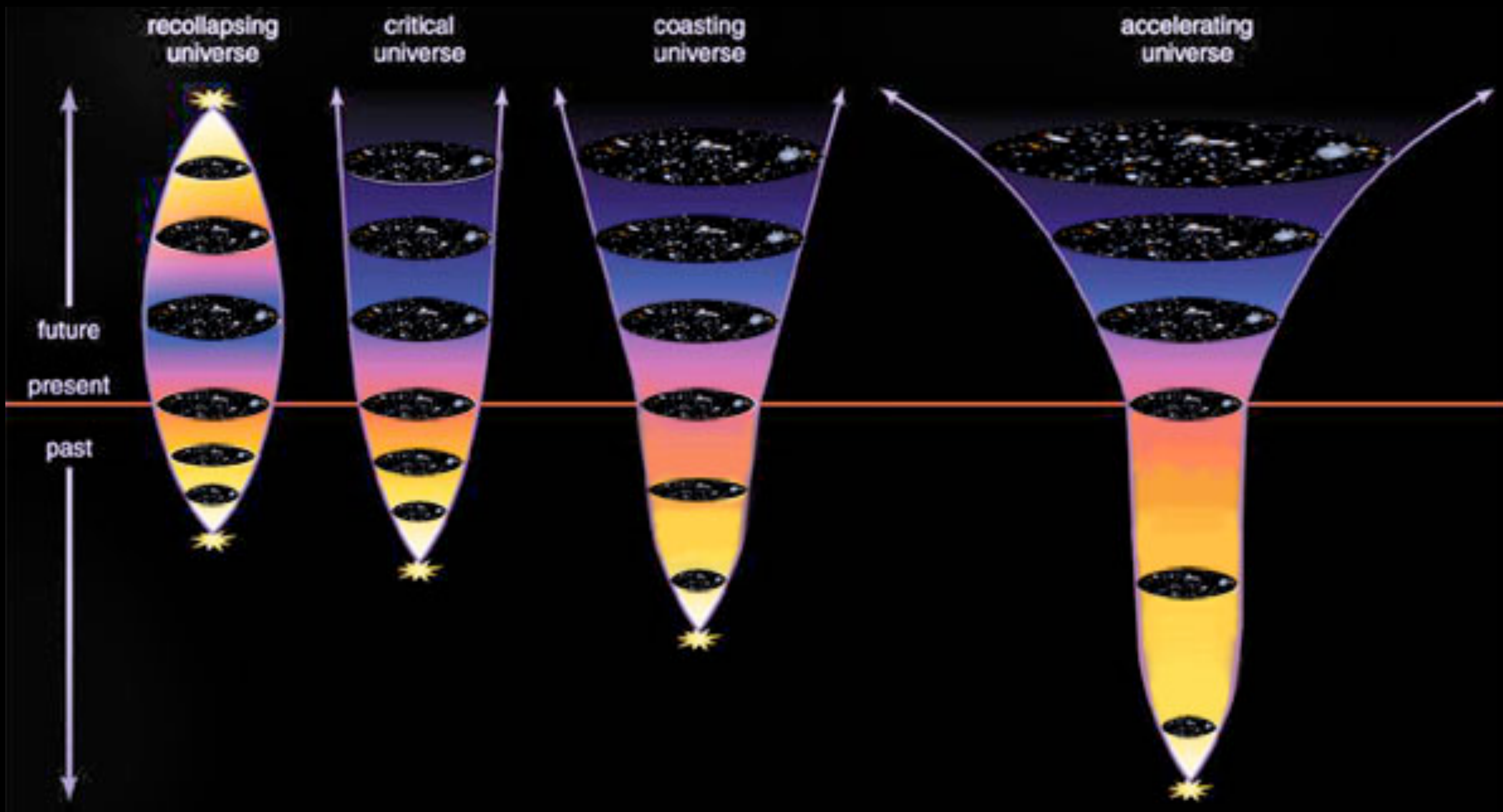


Both teams found that supernovae at high redshift were *dimmer* than expected.

This means that instead of re-collapsing, slowing down or coasting, the expansion of the universe was *accelerating*!



So the universe will not end with a crunch; instead, galaxies will move away faster and faster. Eventually, everything will disappear from our observable universe, until we are left alone with no other galaxies except the ones in the Local Group.

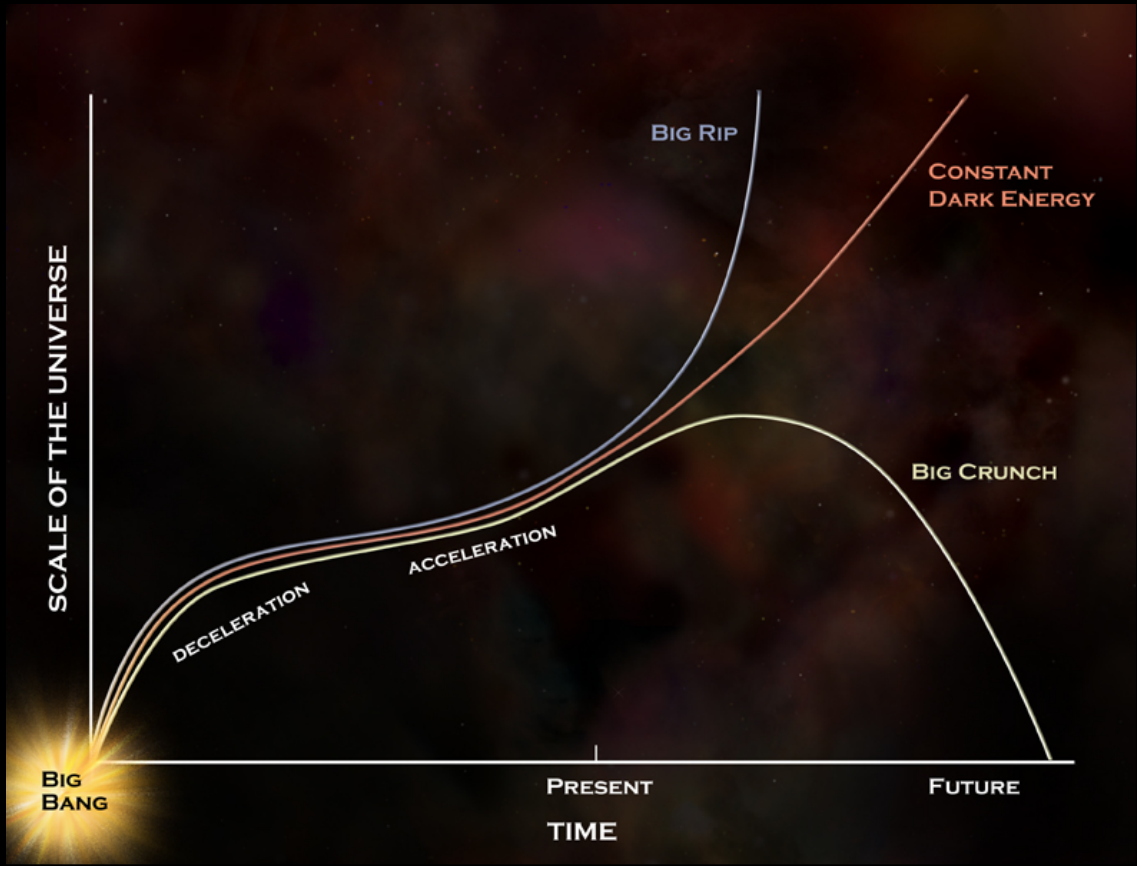


What is causing the expansion of the universe to accelerate?

We don’t have the answer yet, but we have a name: *dark energy*. Dark energy acts like something filling space, that pushes instead of pulls.

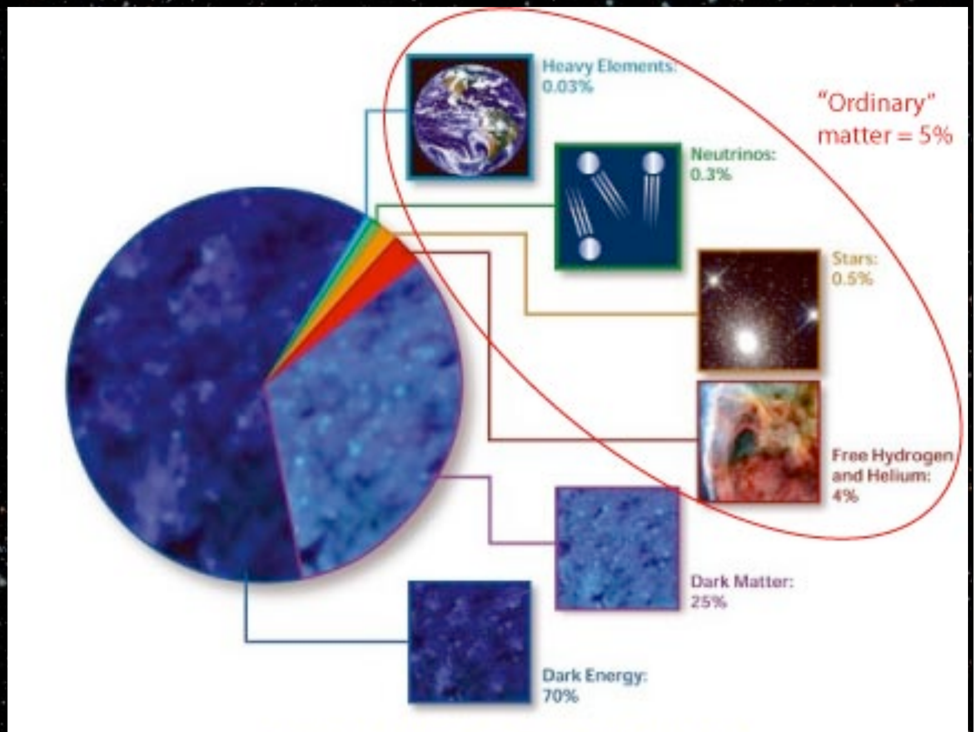
General relativity suggests that "empty space" can possess its own energy. Because this energy is a property of space itself, it would not be diluted as space expands. As more space comes into existence, more of this energy-of-space would appear. As a result, this “vacuum energy” would cause the Universe to expand faster and faster.

Or perhaps the vacuum contains energy that drives the acceleration: a property known as *quintessence*. This is not necessarily constant with time. If there is enough dark energy in the universe, the rate of acceleration would increase over time, and everything, even atoms, would eventually get torn apart: the “Big Rip”.



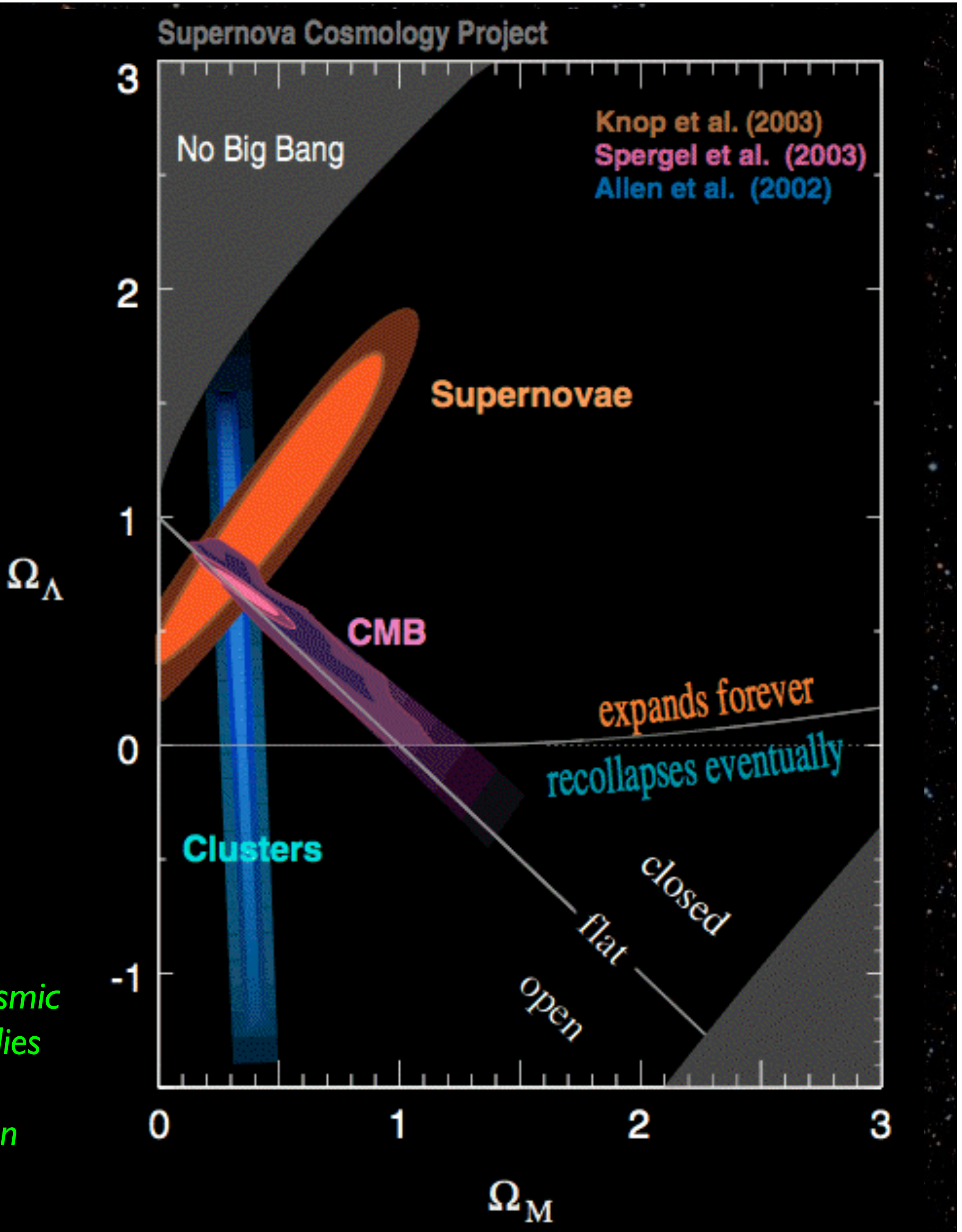
A large number of different observations have led to the our best guess for the parameters of the universe: the "Λ-CDM" model.

- Λ (lambda) stands for the cosmological constant, or dark energy, which makes up 70% of the energy density
- CDM stands for cold dark matter, which makes up 25%
- The remaining 5% comprises all normal matter
- The current age of the universe is 13.7 ± 0.2 billion years



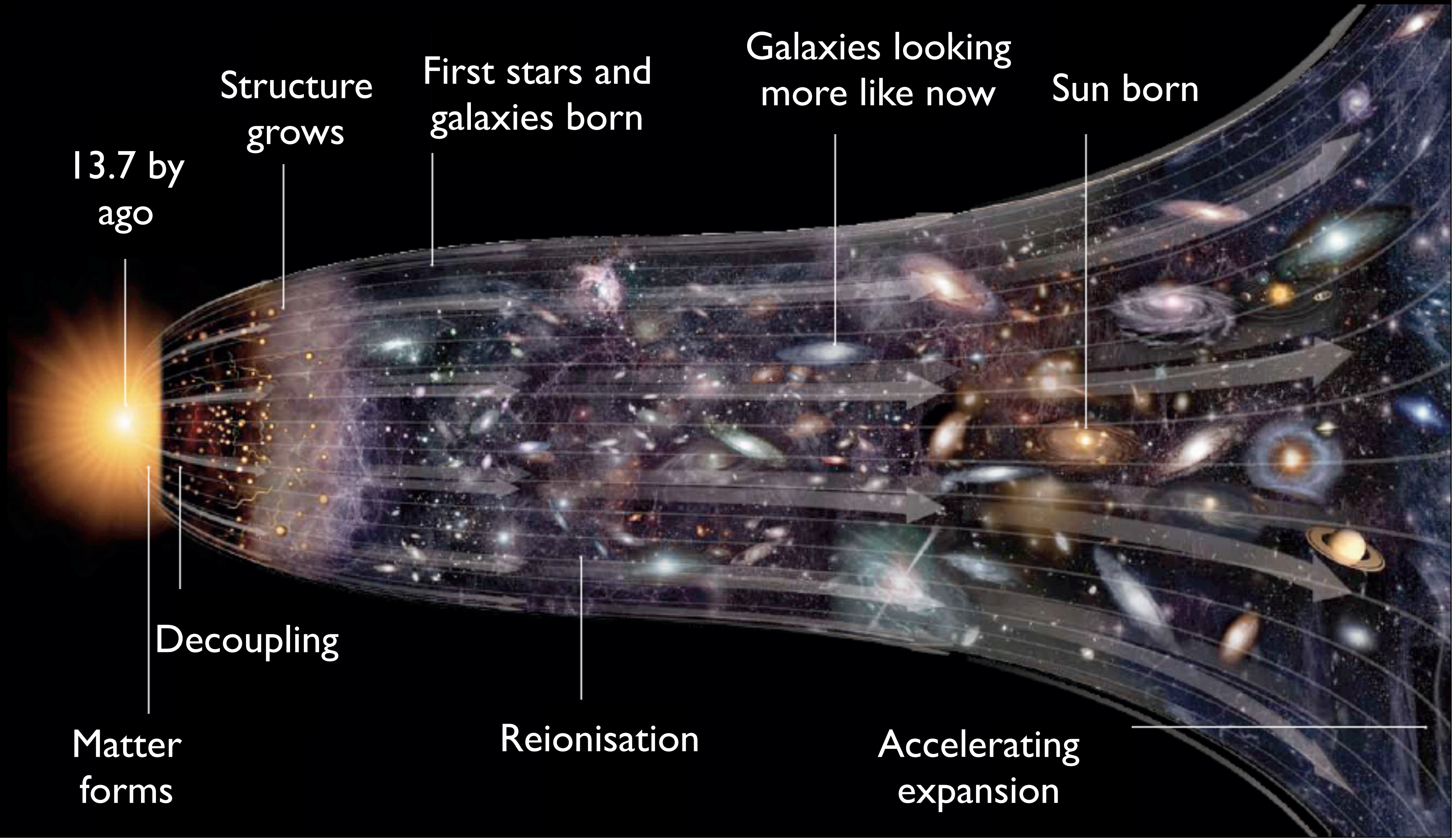
Composition of the Universe

We are going to need new surveys looking for 10 billion year old supernovae to improve our estimates.



Combining all the measurements from the cosmic microwave background, supernovae, and studies of galaxy clusters, all estimates for the energy densities of mass and dark energy converge on the same values: $\Omega_\Lambda \simeq 0.7$ and $\Omega_M \simeq 0.3$.

So, astonishingly, from our fixed vantage point here on Earth, we have untangled not only the origin of our Universe but also its ultimate fate.



Next week...

... we’re going to look at some new and exciting results in modern astronomy, particularly the brand new field of exoplanets.

Further reading

- "**The First Three Minutes:** A Modern View Of The Origin Of The Universe" by Steven Weinberg (Basic Books, 1993) is getting on a bit, and is not a particularly easy read, but is still a fantastic explanation of the very beginning of everything.
- "**Big Bang**" by Simon Singh (Fourth Estate, 2004) is a good description of how the Big Bang model came to be accepted. A very good read.
- The relationship between redshift, distance, and age of the universe is not simple. Ned Wright's Cosmology Calculator http://www.astro.ucla.edu/~wright/CosmoCalc.html allows you to work out the age and distance at a given redshift. The default values (H_0 = 71 km/s/Mpc, Ω_M = 0.27, Ω_{vac} = 0.73) are the generally accepted values from WMAP.
- The Millennium Simulation animations are available at http://www.mpa-garching.mpg.de/galform/millennium/
- *Via Lactea* movies of the formation of the Galaxy: http://www.ucolick.org/~diemand/vl/movies.html
- Brian Schmidt's page on the High-z Supernova Search is at http://www.mso.anu.edu.au/~brian/PUBLIC/public.html

- The Nobel lectures for the 2011 Nobel prize are available at http://www.nobelprize.org/nobel_prizes/physics/laureates/2011
- HubbleSite has a nice page about dark energy at http://hubblesite.org/hubble_discoveries/dark_energy/. There's another good description at http://science.nasa.gov/astrophysics/focus-areas/what-is-dark-energy/
- There's a must-read article by Charlie Lineweaver and Tamarra Davis, called **"Misconceptions about the Big Bang"**, published in Scientific American Feb 21, 2005. It's available online at http://www.mso.anu.edu.au/~charley/papers/LineweaverDavisSciAm.pdf

Sources for images used:

- Olber's paradox: from https://commons.wikimedia.org/wiki/File: Olbers'_Paradox.svg
- Hubble ultra-deep field: from http://www.hubblesite.org/newscenter/archive/releases/2004/07/
- Redshift: from James Schombert, Galaxies and the Expanding Universe, http://abyss.uoregon.edu/~js/ast123/lectures/lec14.html
- Hubble's diagram: from http://www.astro.rug.nl/~hidding/ao/hubble.png
- Size of the observable universe: from Lineweaver and Davis, "Misconceptions about the Big Bang", Scientific American Feb 21, 2005 http://www.mso.anu.edu.au/~charley/papers/LineweaverDavisSciAm.pdf
- Redshifted photons: from http://eppursimuov3.wordpress.com/2010/02/25/reflections-in-cosmology-15-where-have-all-the-energy-gone/
- Expansion: from "Fare thee well, Allan Sandage" by Ethan Siegel http://scienceblogs.com/startswithabang/2010/11/19/fare-thee-well-allan-sandage
- Big bang: from Ethan Siegel http://scienceblogs.com/startswithabang/2011/10/04/discover-the-fate-of-the-unive/
- Baryon fraction: from "Test of big bang: The light elements" http://map.gsfc.nasa.gov/universe/bb_tests_ele.html
- Penzias and Wilson: from http://en.wikipedia.org/wiki/Robert_Woodrow_Wilson
- COBE blackbody curve: from http://en.wikipedia.org/wiki/Cosmic_Background_Explorer
- WMAP image of the CMB: from WMAP 5 year release http://map.gsfc.nasa.gov/news/5yr_release.html
- Inflation: from Physics World http://physicsworld.com/cws/article/news/21330
- Millennium smulation: from http://www.mpa-garching.mpg.de/galform/millennium/
- Universe Simulator: from the video by Andrew Pontzen http://www.ast.cam.ac.uk/~app26/?page=experience
- 2dF Galaxy Redshift Survey: from http://www2.aao.gov.au/2dFGRS/2dFzcone_big.gif
- First stars: from WMAP Concept Animations: Universe evolution http://wmap.gsfc.nasa.gov/media/030651/index.html
- Quasar: painting by Don Dixon http://cosmographica.com/gallery/portfolio/portfolio301/pages/326-QuasarB.htm . Artwork copyright 2003 by Don Dixon/cosmographica.com, used with permission.
- Highest redshift quasar spectrum: from ESO press release 1122, www.eso.org/public/news/eso1122/
- Spiderweb galaxy: from HubbleSite news release STScI-2006-45, "Hubble captures galaxy in the making" http://hubblesite.org/newscenter/archive/releases/2006/45/
- Formation of the Galaxy: from the Via Lactea project http://www.ucolick.org/~diemand/vl/movies.html

- Composition of the universe: from outreach.atnf.csiro.au/education/senior/cosmicengine/bigbang.html
- Close-up of galaxies from the HUDF: from hubblesite.org/newscenter/archive/releases/2004/07/
- Dark matter in Abell 1689: from Hubblesite hubblesite.org/newscenter/archive/releases/2010/26/
- Fate of the universe: from Ethan Siegel http://scienceblogs.com/startswithabang/2011/10/04/discover-the-fate-of-the-unive/
- Supernova 1994D: from http://www.spacetelescope.org/images/opo9919i/
- Supernova results: from http://www.cfa.harvard.edu/supernova/HighZ.html
- Dark energy models: from Chandra field guide: Dark energy http://chandra.harvard.edu/xray_astro/dark_energy/
- Best value for cosmic parameters: from http://supernova.lbl.gov/Union/