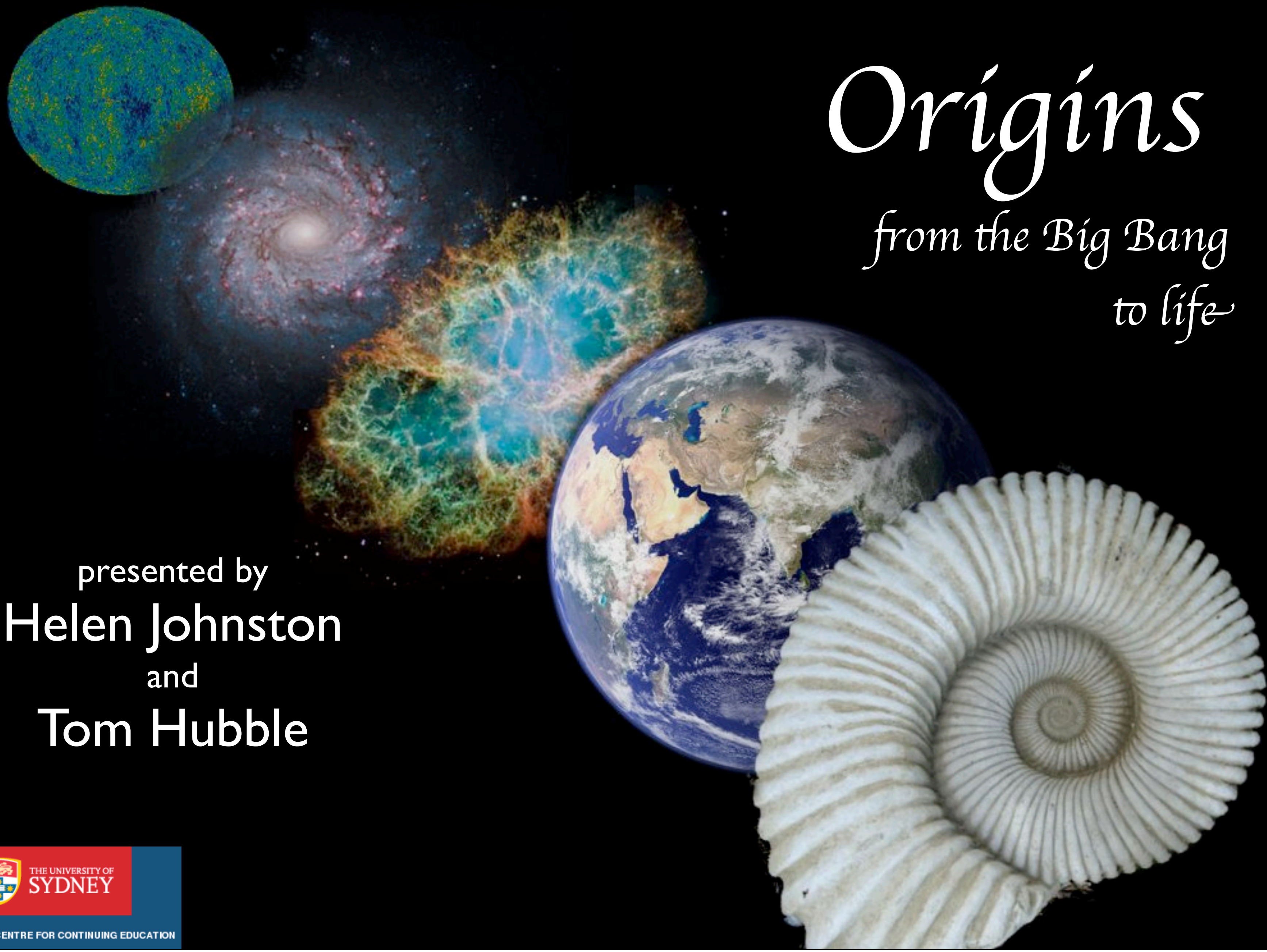
Origins

from the Big Bang to life



presented by

Helen Johnston

and

Tom Hubble

THE UNIVERSITY OF SYDNEY

CENTRE FOR CONTINUING EDUCATION

Course website

http://physics.usyd.edu.au/~helenj/Origins.html

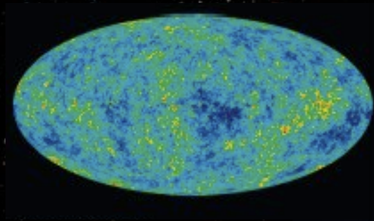
with copies of slides, recordings of lectures, suggestions for further reading.

The night viewing evening at Mt Wilson is on

Saturday 30 April

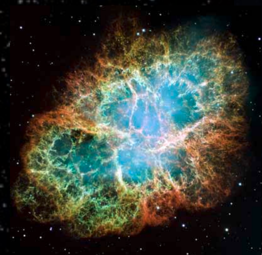
(the week after Easter), and there is a handout about it on the front bench.

1. The origin of the Universe



2. The origin of galaxies and stars

3. The origin of planets



4. The origin of the Earth

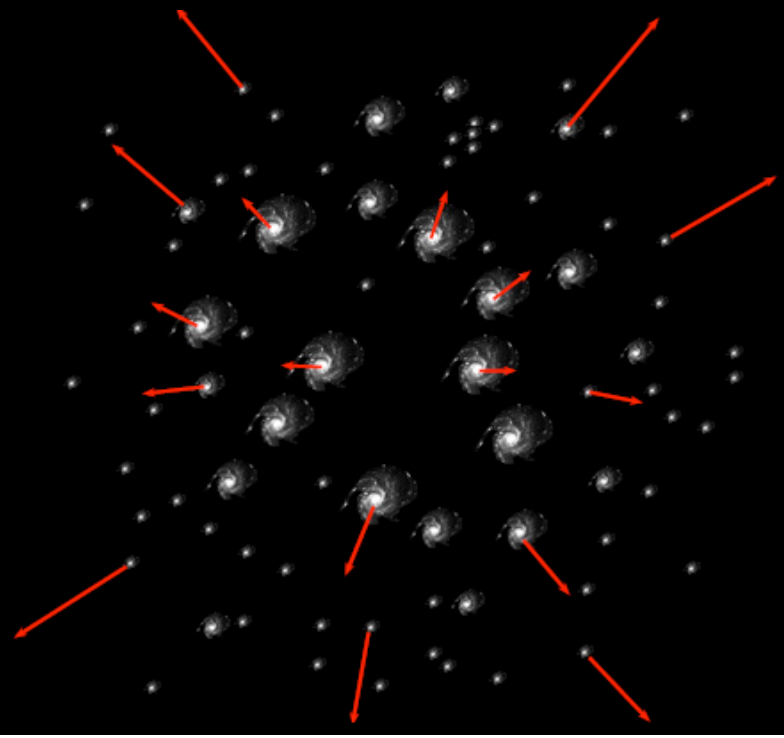
5. The origin of life

Prologue

When we look out into the universe, we make a startling discovery: every galaxy is receding from us, and the further away a galaxy is, the faster it is moving.

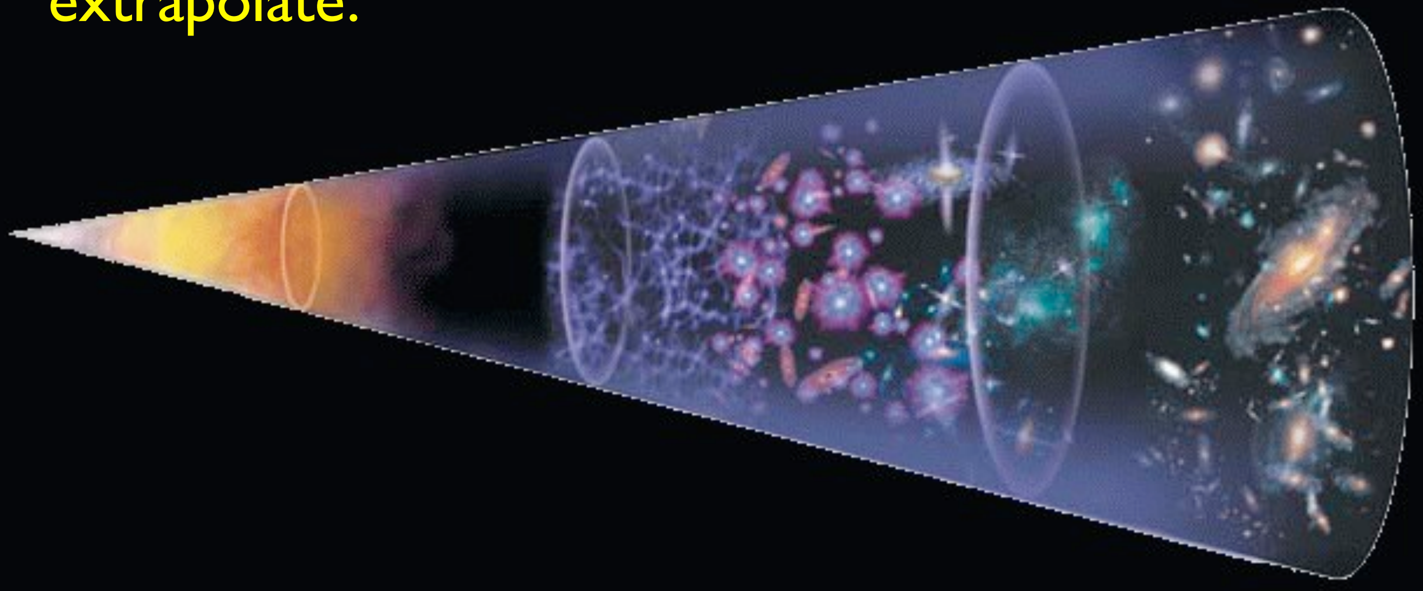
This must mean that the Universe is expanding.

As the Universe expands, galaxies get further away from each other, and the average density goes down.



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.

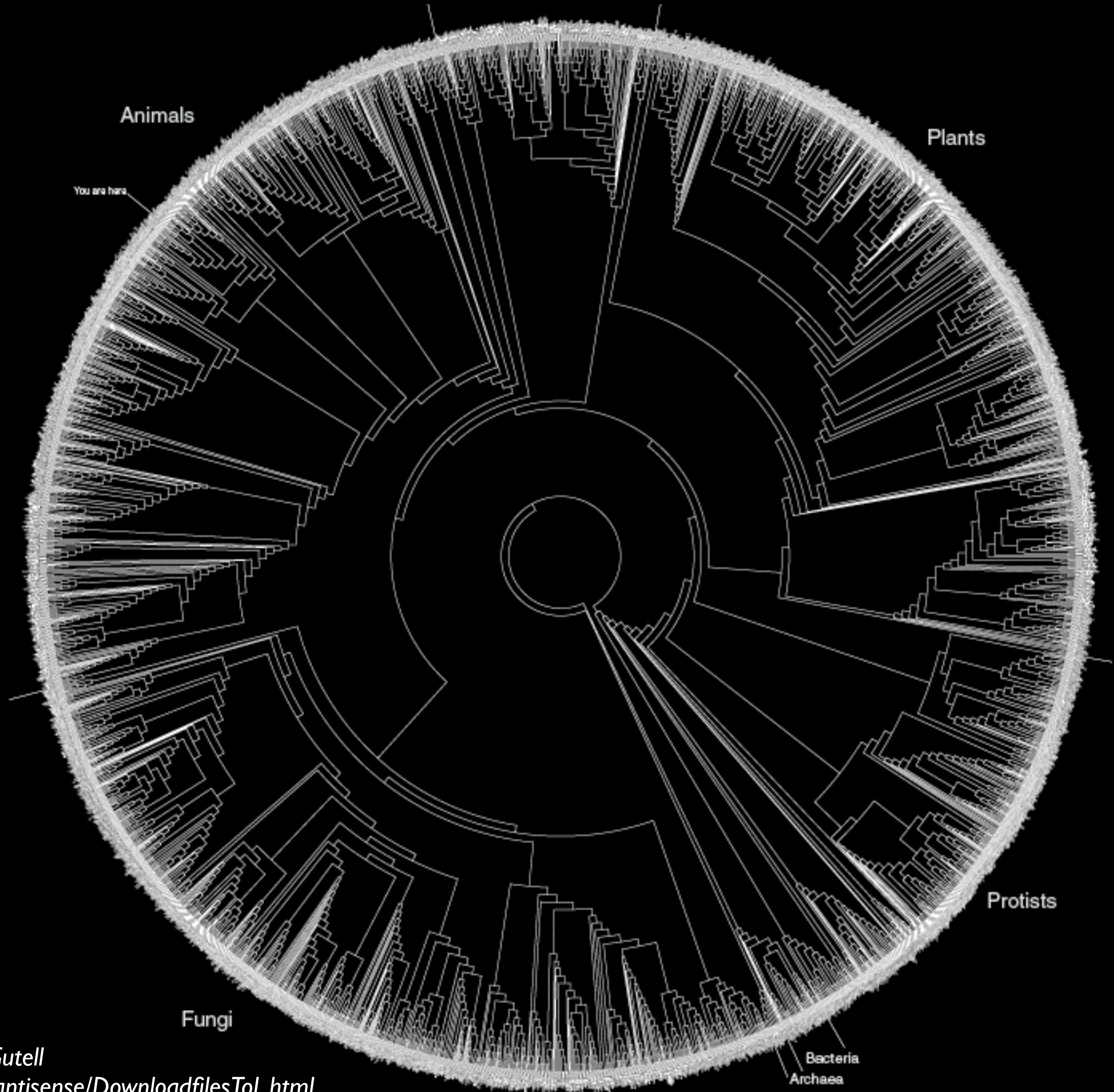


This in turn means there must have been a time when galaxies, stars, planets did not exist.

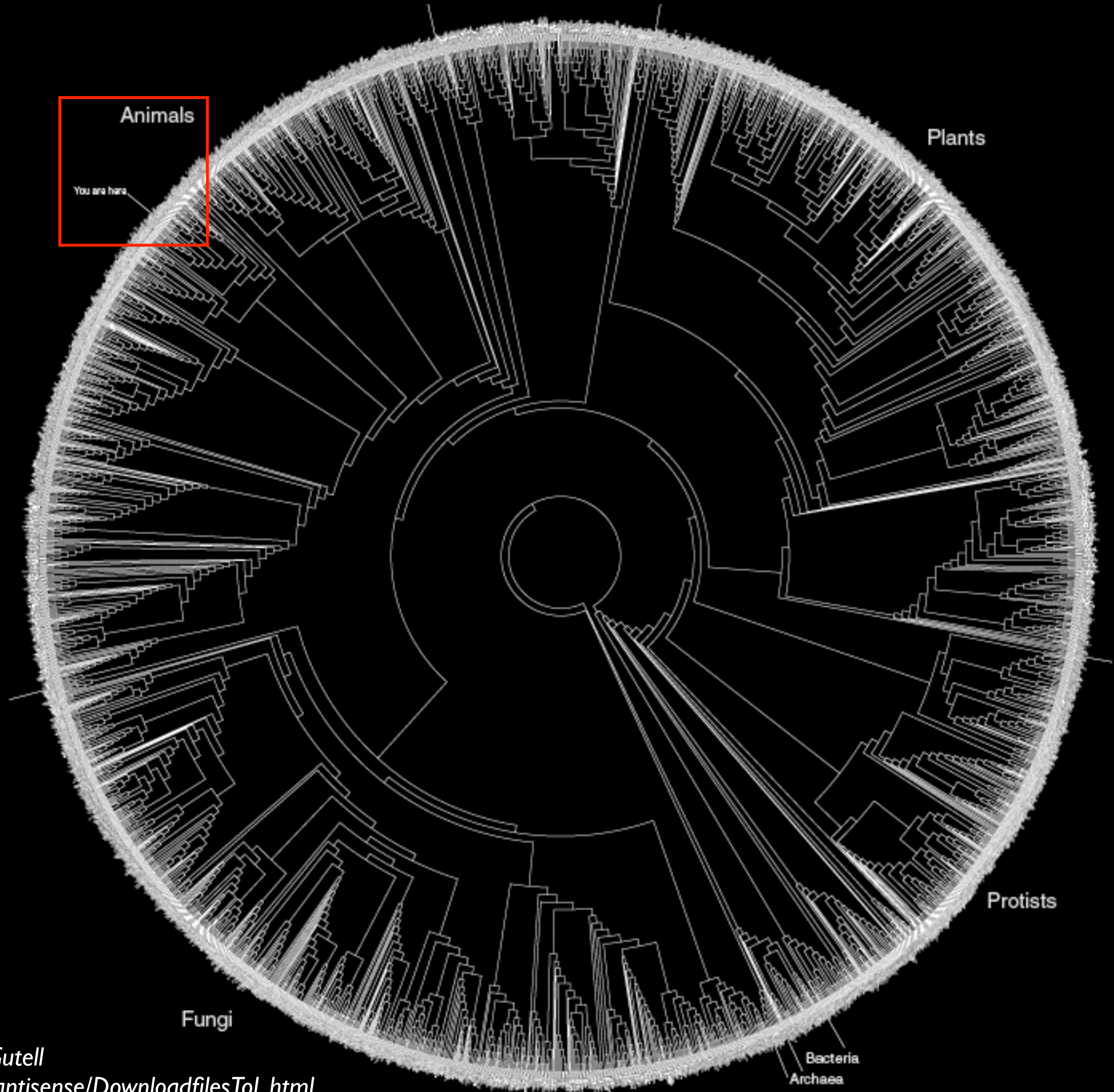
How did they come into being?

This course aims to show how we found the answer to that question.

An apology



"Tree of Life" by Hillis, Zwicki & Gutell
http://www.zo.utexas.edu/faculty/antisense/DownloadfilesToL.html



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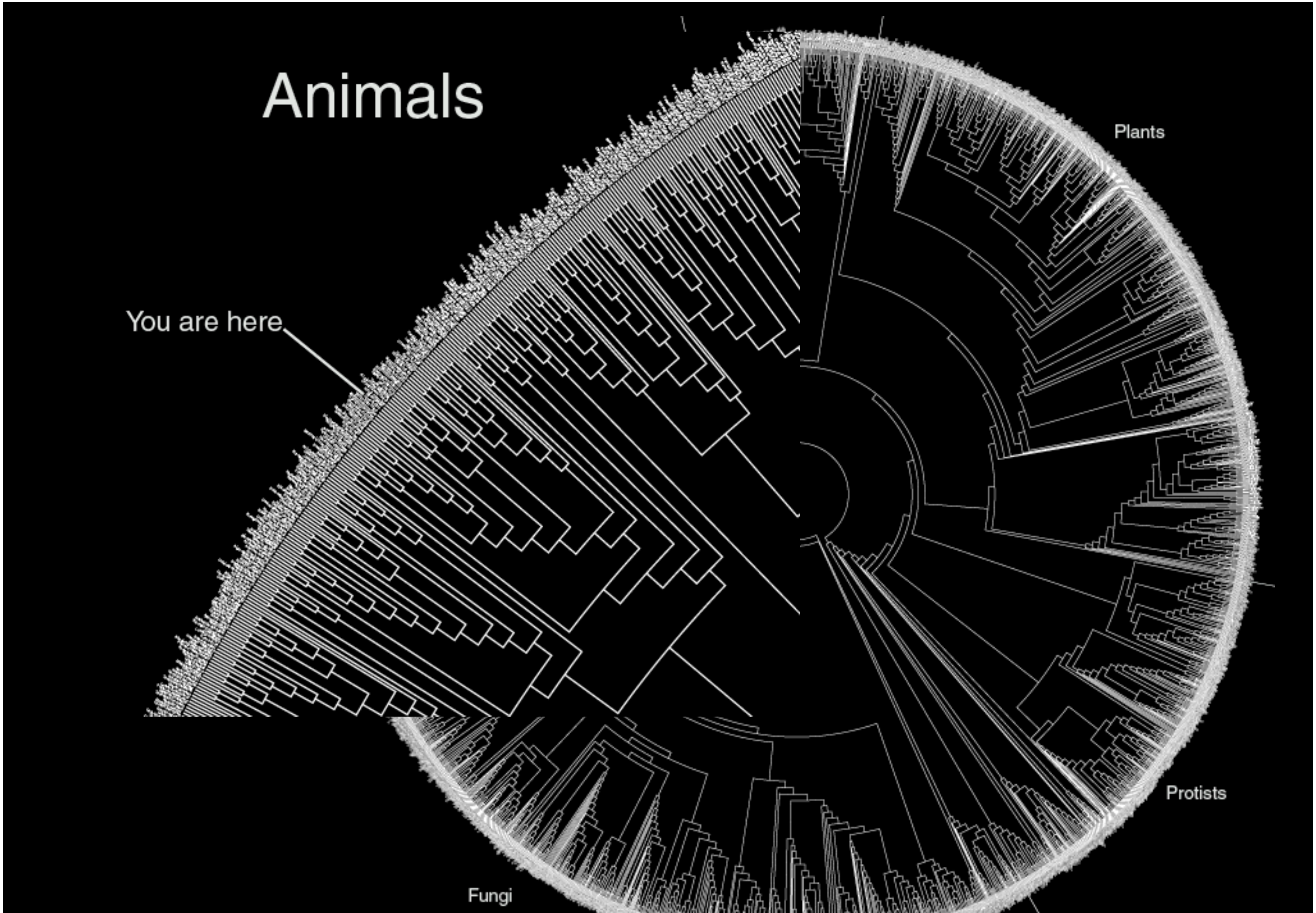

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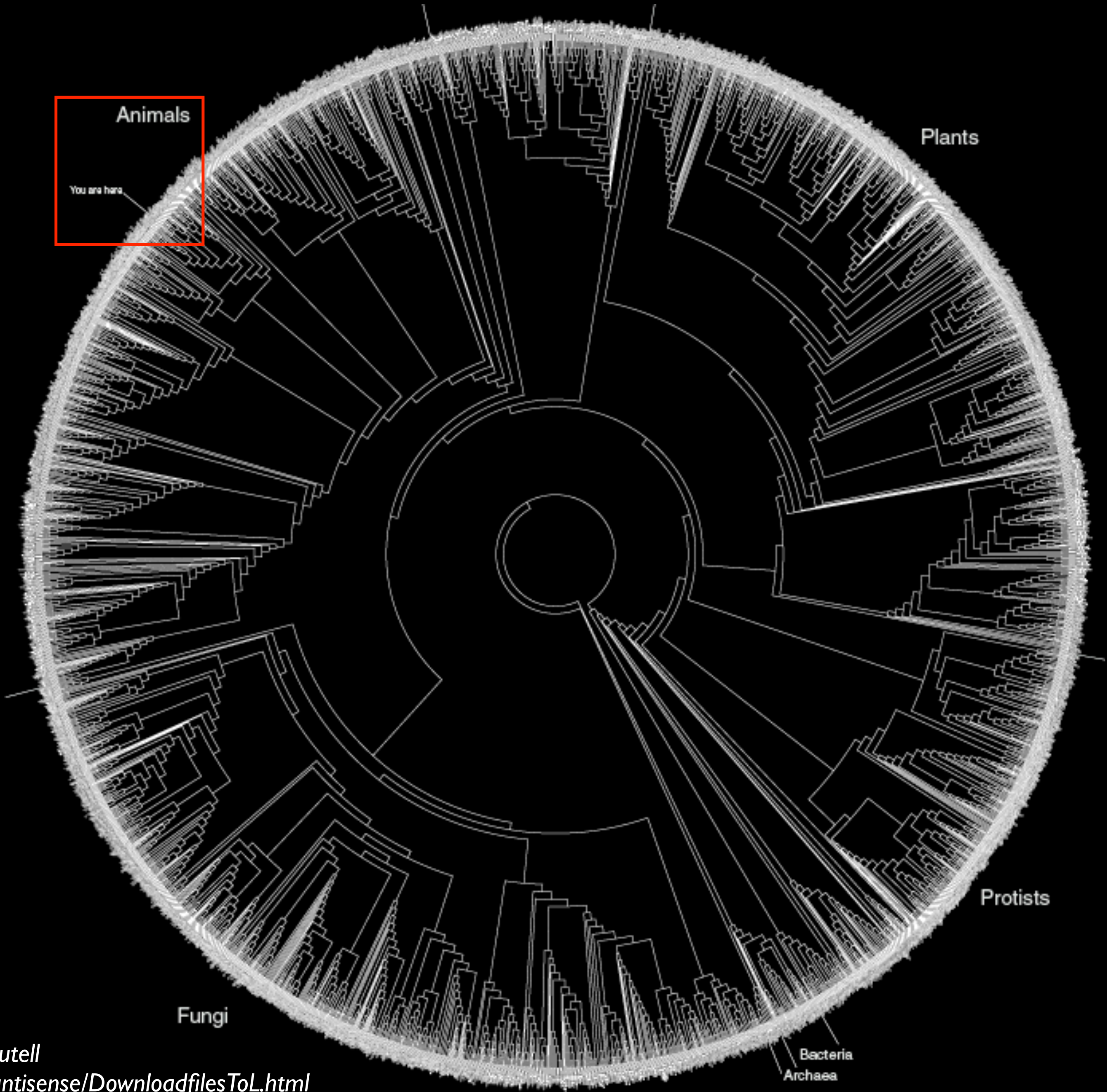

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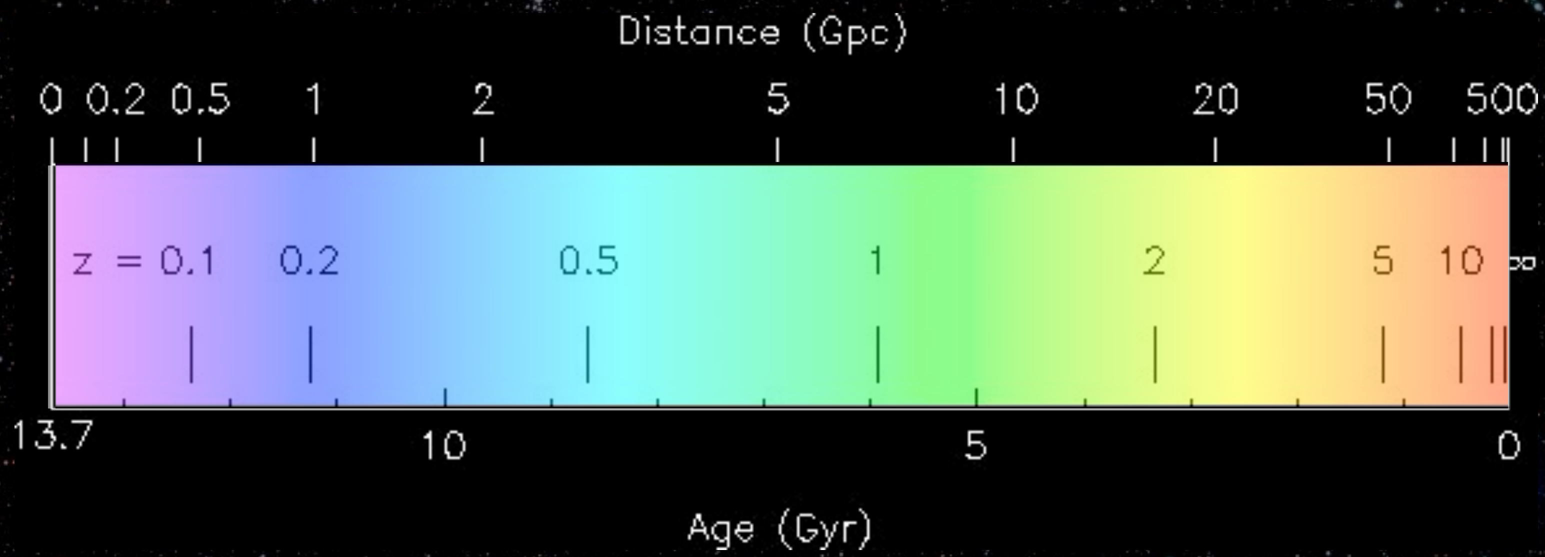
We have one advantage when trying to study the beginning of the Universe: because of the finite speed of light, the farther *away* we look, the farther *back in time* we are looking.

If we look at a galaxy which is a billion light years away, the light must have left the galaxy a billion years ago in order to be reaching us now, which means we are seeing it as it was a billion years ago.



We can say nothing about the actual instant of the Big Bang itself. Nor do we have any information about what came before the Big Bang.

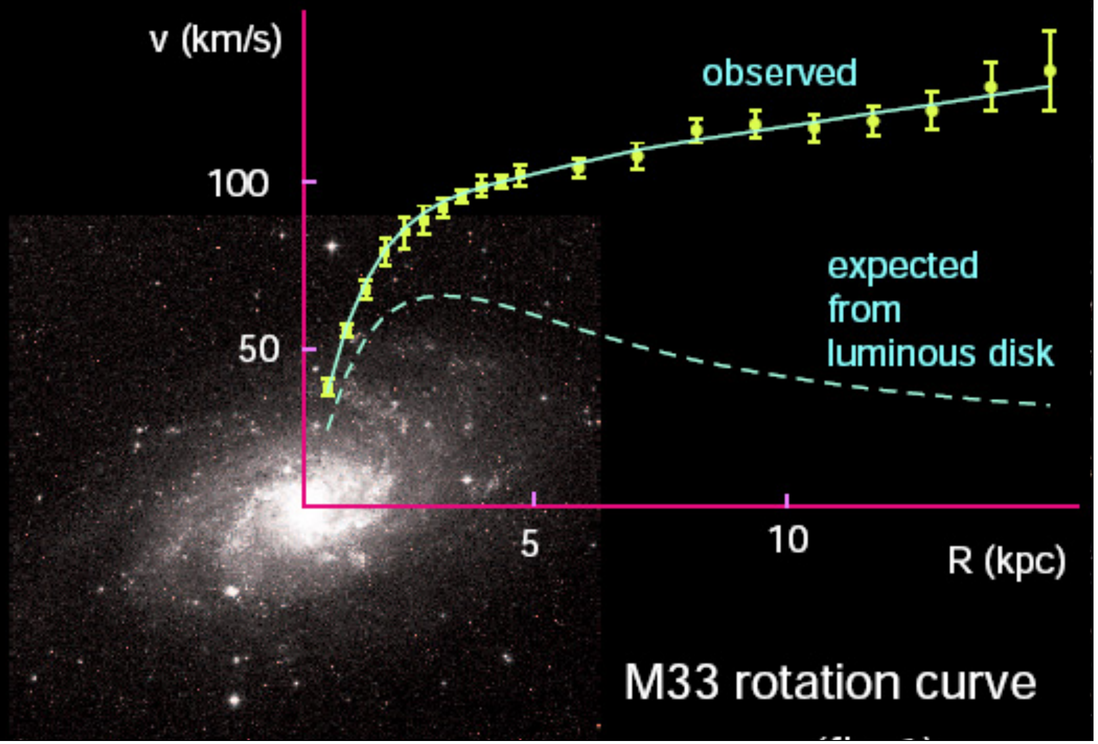
So our story starts a tiny moment after the instant the universe started to expand. As it expands, it cools.

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.

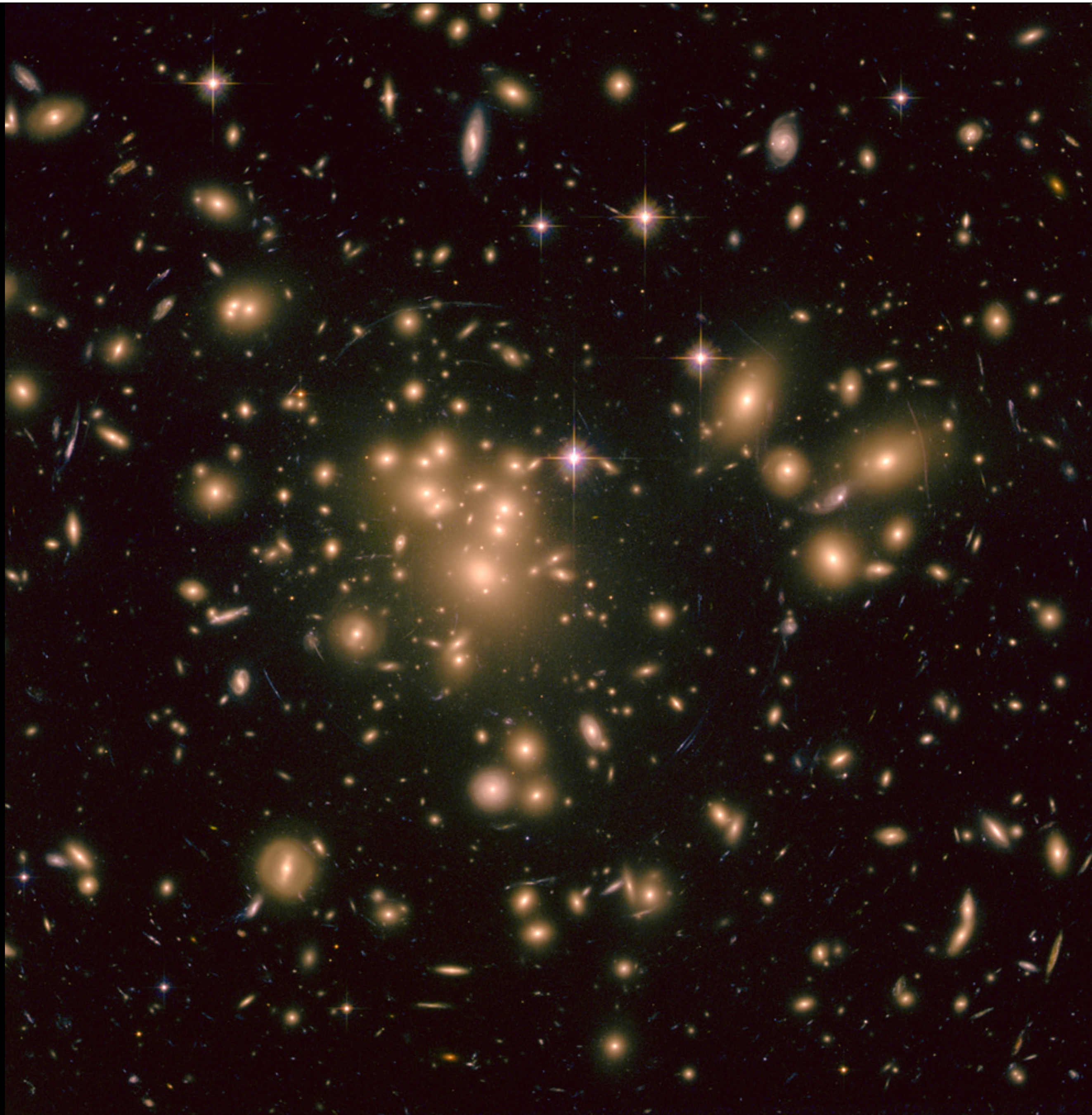
At first, the Universe consisted entirely of energy. As it expanded and cooled, particles materialised.

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”

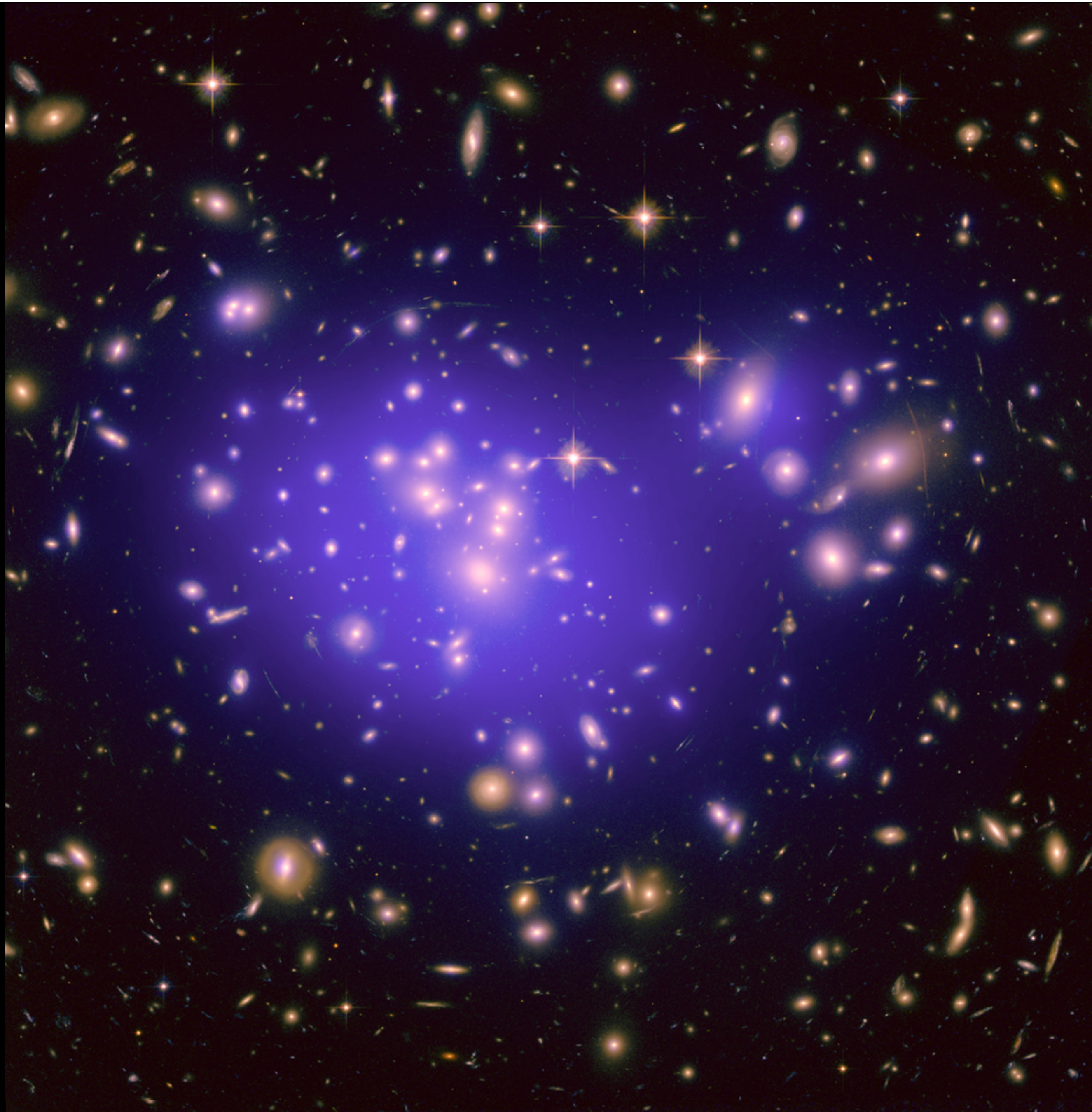
One other thing was created at this stage: *dark matter*. Observations of galaxies and clusters today indicate that something like 90% of mass in the Universe is dark. Galaxies and clusters of galaxies behave as though they were ~20 times more massive (or more!) than the amount of matter we can see.



The rotation curve for the spiral galaxy M33. The points represent the measured rotation velocities and the dashed curve is the contribution due to the observed matter. The existence of dark matter is inferred by the discrepancy between the observed rotation curve and the one due to the luminous disk.



The galaxy cluster Abell 1689, which is acting as a gravitational lens, distorting background galaxies into strange arcs. The inferred dark matter distribution is shown in purple.

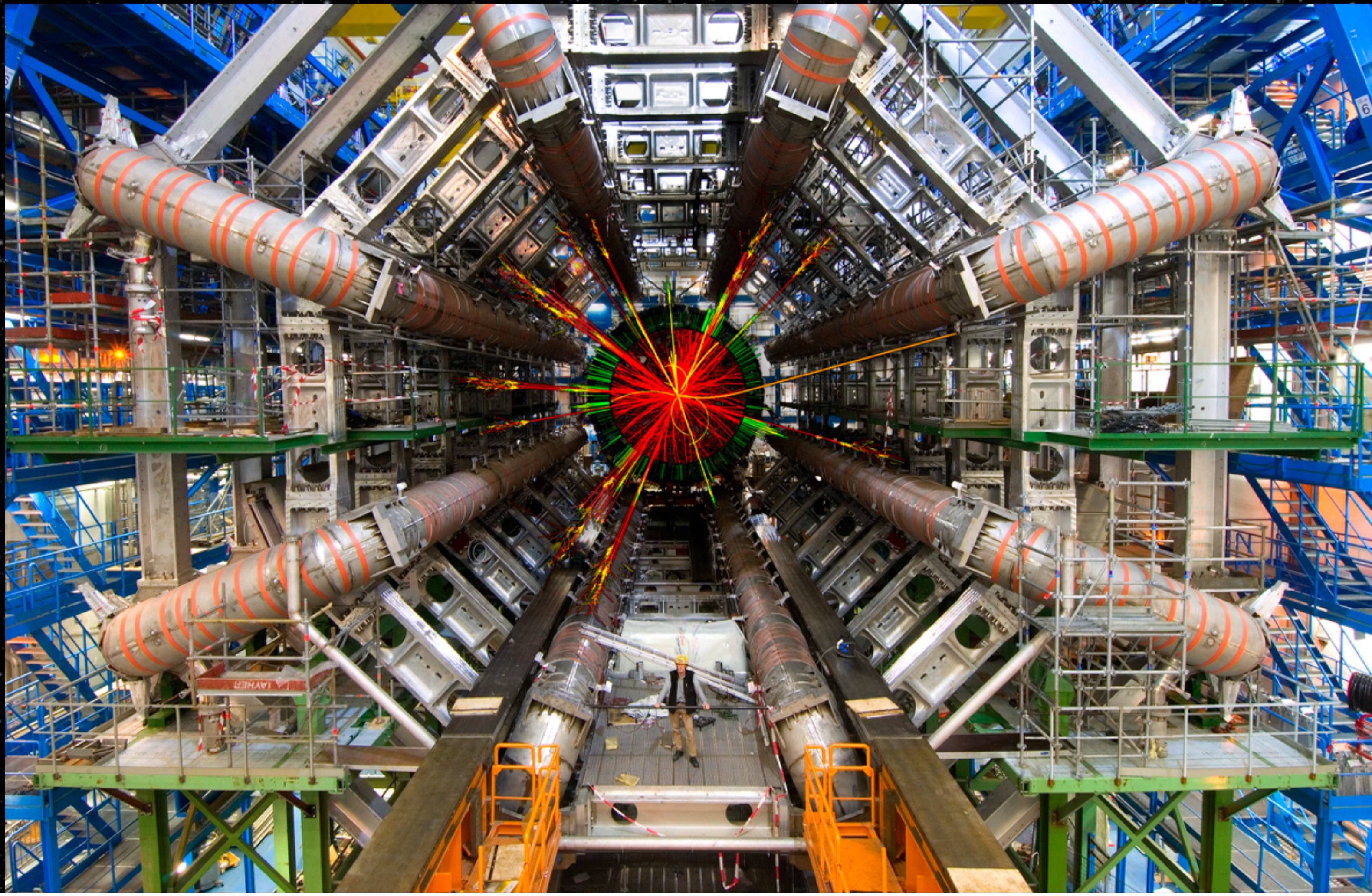


The galaxy cluster Abell 1689, which is acting as a gravitational lens, distorting background galaxies into strange arcs. The inferred dark matter distribution is shown in purple.

We still don't know what dark matter is. It is possible that it is ordinary matter but non-luminous, like black holes; or it could be some more exotic form of matter.

Evidence is growing that dark matter is most likely some sort of exotic particle, much heavier than the proton. It has mass, so is detectable via its gravity, but otherwise it doesn't interact with normal matter at all.

One of the aims for the Large Hadron Collider is identify the nature of dark matter.



Published online 28 February 2011 | *Nature* **471**, 13-14 (2011) | doi:10.1038/471013a

News

Beautiful theory collides with smashing particle data

Latest results from the LHC are casting doubt on the theory of supersymmetry.

Geoff Brumfiel

"Any squarks in here?" The ATLAS detector (above) at the Large Hadron Collider has failed to find predicted 'super partners' of fundamental particles.

C. MARCELLONI/CERN

"Wonderful, beautiful and unique" is how Gordon Kane describes supersymmetry theory. Kane, a theoretical physicist at the University of Michigan in Ann Arbor, has spent about 30 years working on supersymmetry, a theory that he and many others believe solves a host of problems with our understanding of the subatomic world.

Yet there is growing anxiety that the theory, however elegant it might be, is wrong. Data from the Large Hadron Collider (LHC), a 27-kilometre proton smasher that straddles the French–Swiss border near Geneva, Switzerland, have shown no sign of the 'super particles' that the theory predicts[1–3]. "We're painting supersymmetry into a corner," says Chris Lester, a particle physicist at the University of Cambridge, UK, who works with the LHC's ATLAS detector. Along with the LHC's Compact Muon Solenoid experiment, ATLAS has spent the past year hunting for super particles, and is now set to gather more data when the LHC begins a high-power run in the next few weeks. If the detectors fail to find any super particles by the end of the year, the theory could be in serious trouble.

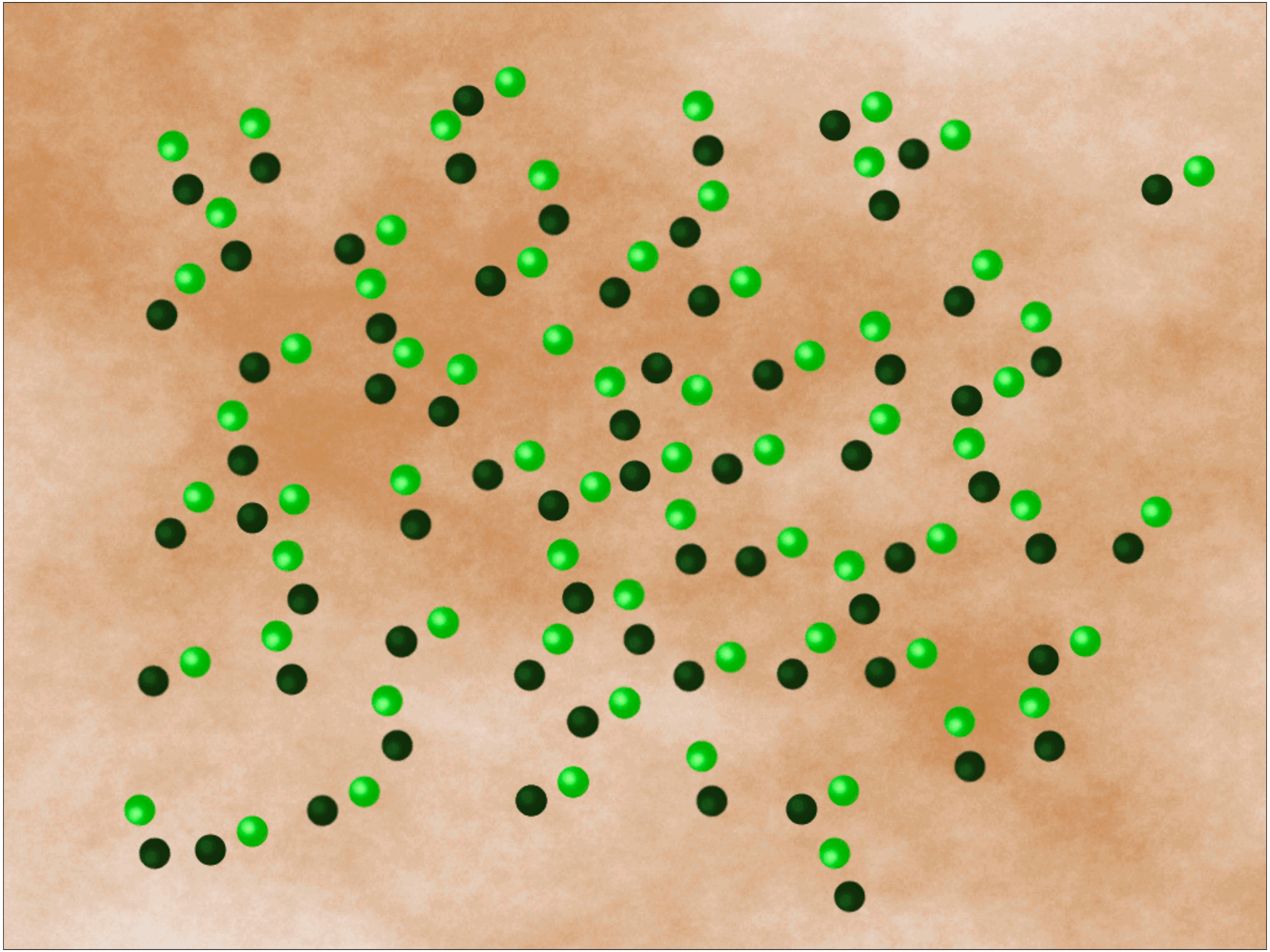
At about 0.01 s, the temperature had dropped to about a trillion degrees, and quarks could bind together to form protons and neutrons without instantly being ripped apart again.

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.

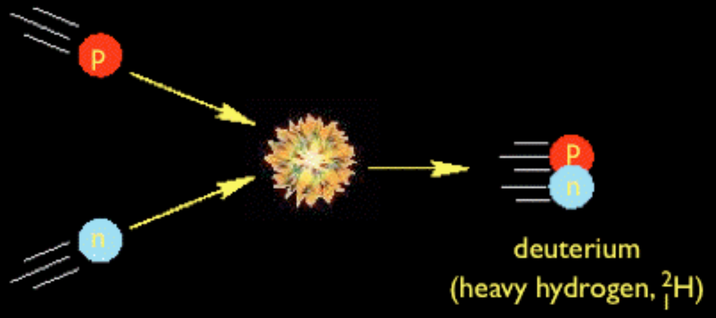
[redacted]

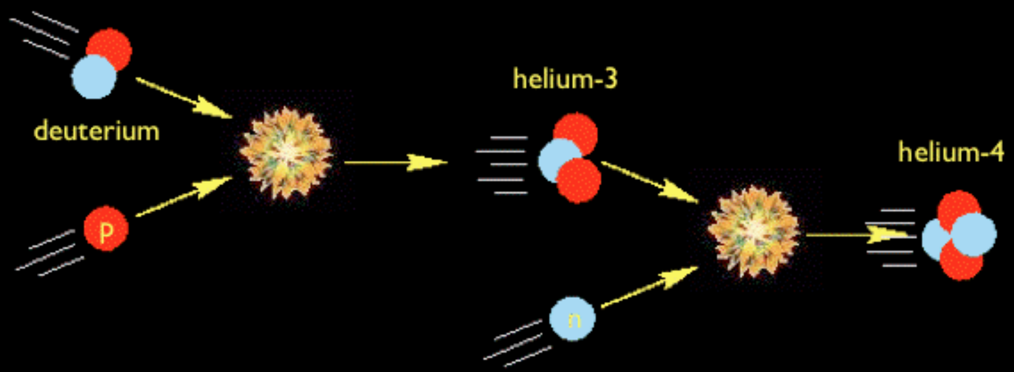


So about 1 second after the Big Bang, there was about one proton or neutron for every billion photons or electrons or neutrinos.

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.

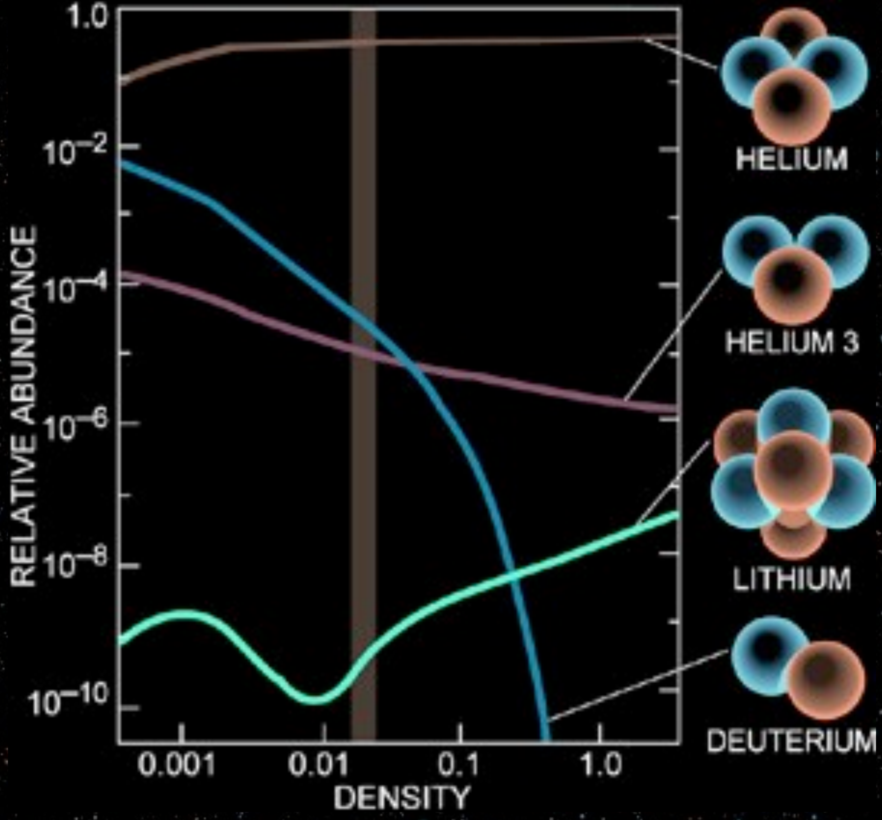




But nothing else. There is no stable nucleus containing 5 particles, so when a four-particle helium nucleus is struck by another particle, the whole lot is split apart again.

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.

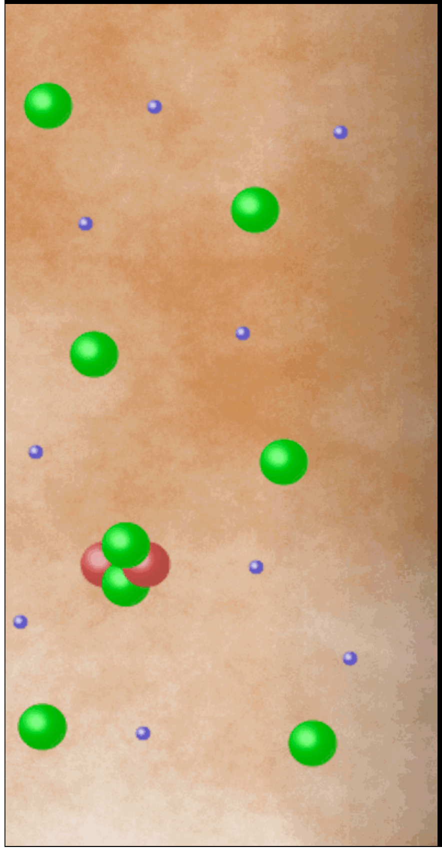
It turns out that the final composition of the universe depends only on the *baryon density*. By measuring the abundance of helium and deuterium in pristine gas, we can work out this density, and hence show that baryons make up only 4% of the Universe.



So the Universe continues to expand: hydrogen and helium in a fog of radiation that continues to cool. It was still to 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.



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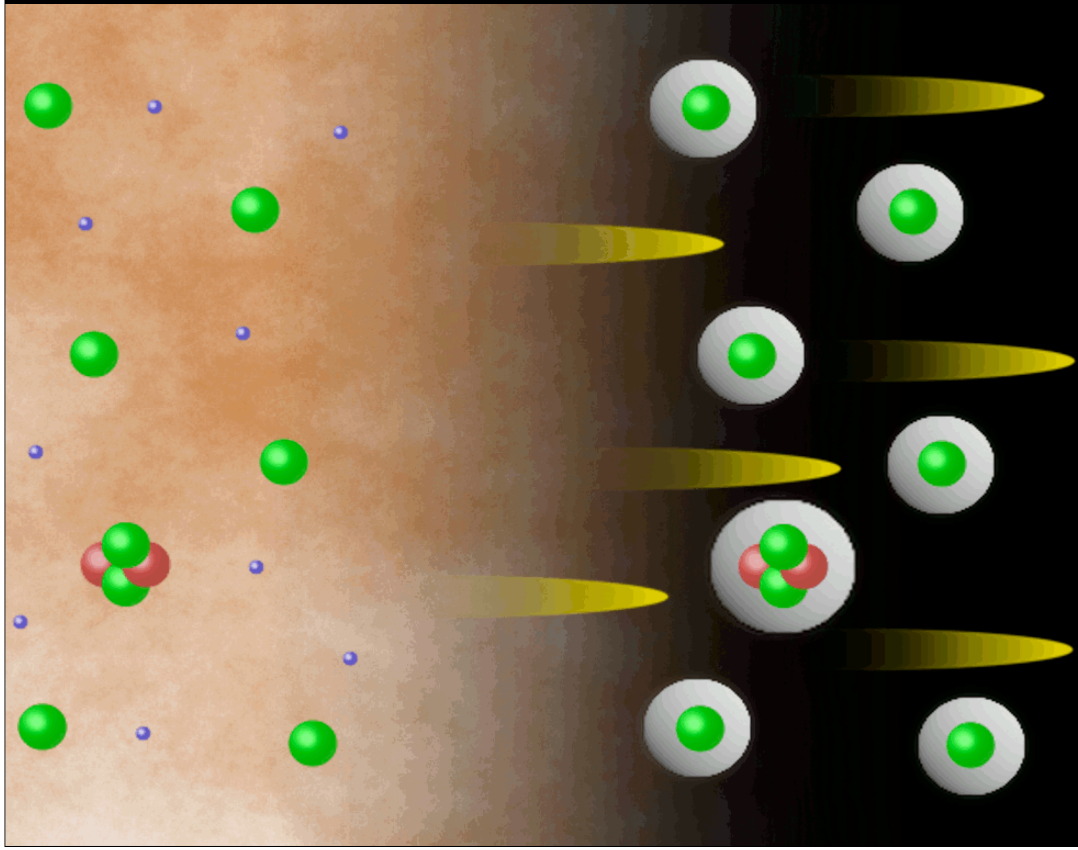
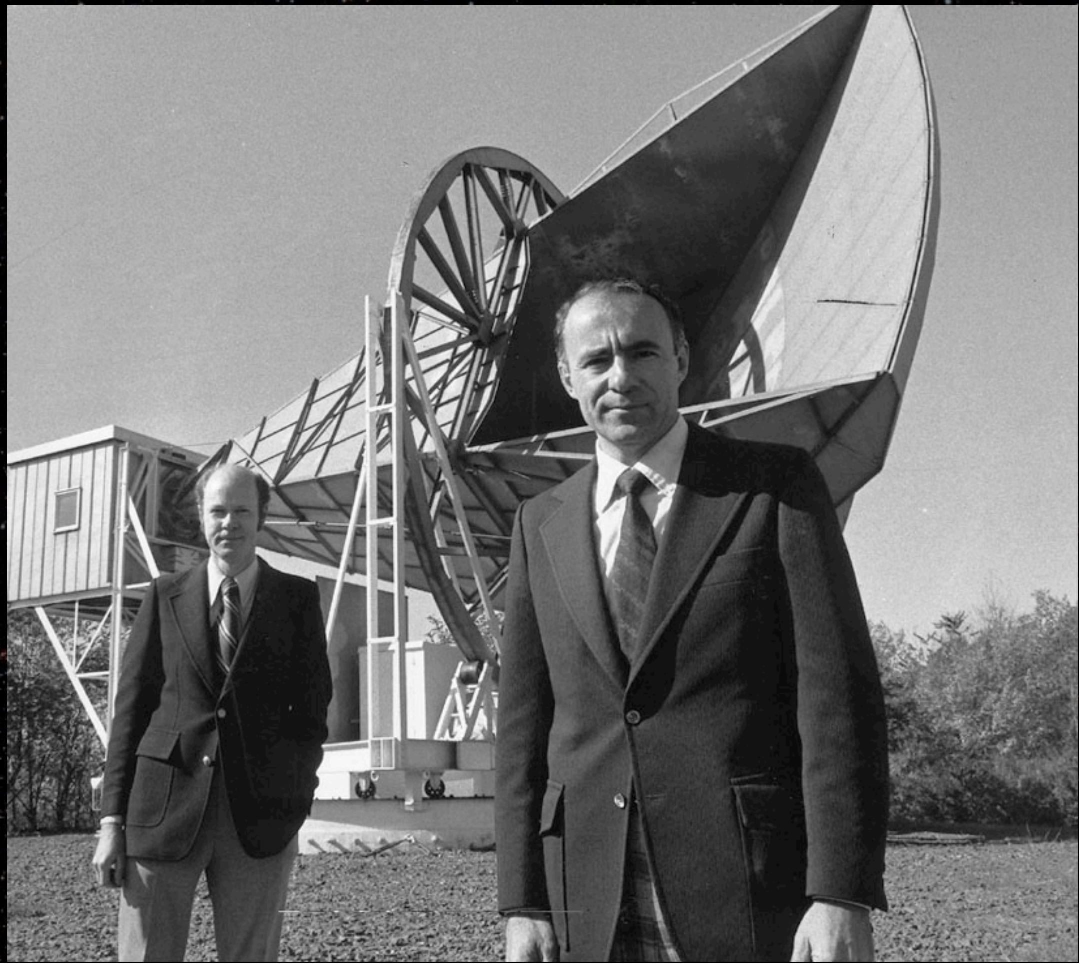
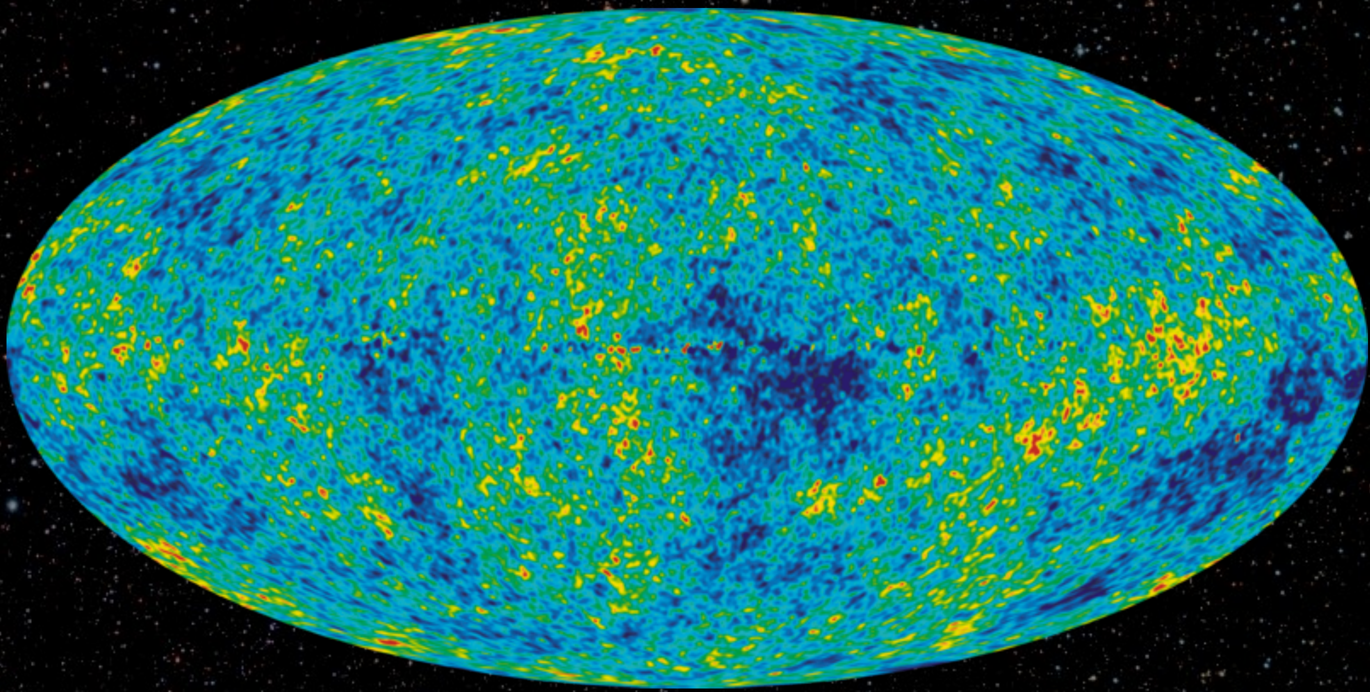


This sea of radiation, coming from all directions, was discovered in 1964 by Arno Penzias and Robert Wilson at Bell Laboratories: the *Cosmic Microwave Background* (CMB)



Penzias and Wilson in front of the horn antenna at Bell Labs

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°.



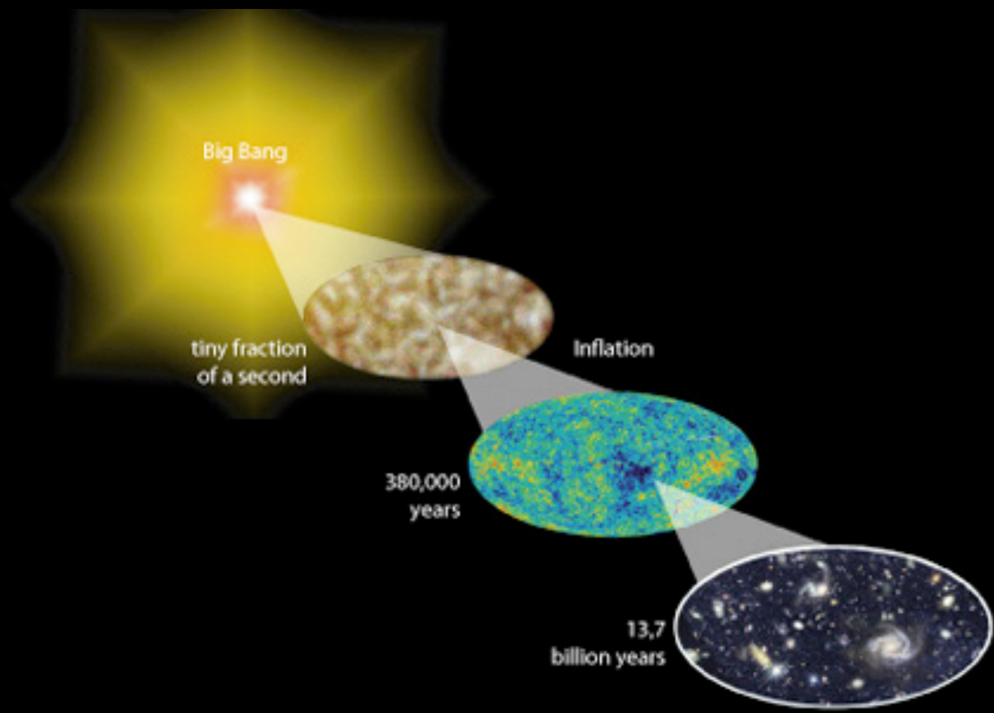
WMAP image of the microwave background radiation. The colours represent tiny fluctuations (0.0001 degrees) from the mean temperature of 2.725 K, with red regions warmer and blue regions colder.

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.



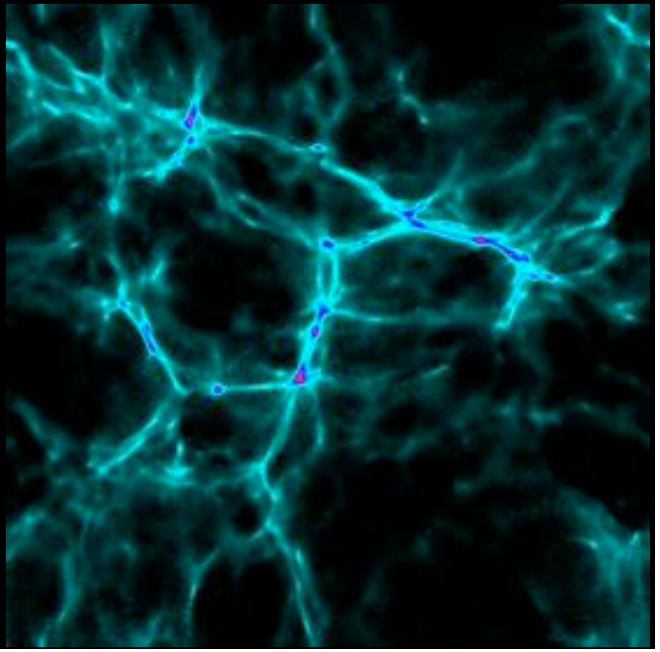
There was one more effect of the falling temperature. Once the temperature had fallen below a few thousand degrees, the radiation shifted into the infrared. Nothing in the Universe was hot enough to produce visible light. The Universe was completely dark.

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 complicated: we need supercomputer simulations to understand how structures grew.

The *Millennium Simulation* was the largest such simulation to date. It was run on a supercomputer in Garching, Germany in 2005. It took 350,000 processor hours of CPU time, or 28 days of wall-clock time. It followed the evolution of 10 billion particles, each representing a billion solar masses of dark matter. The volume was a cube 700 Mpc in length, containing 20 million galaxies.

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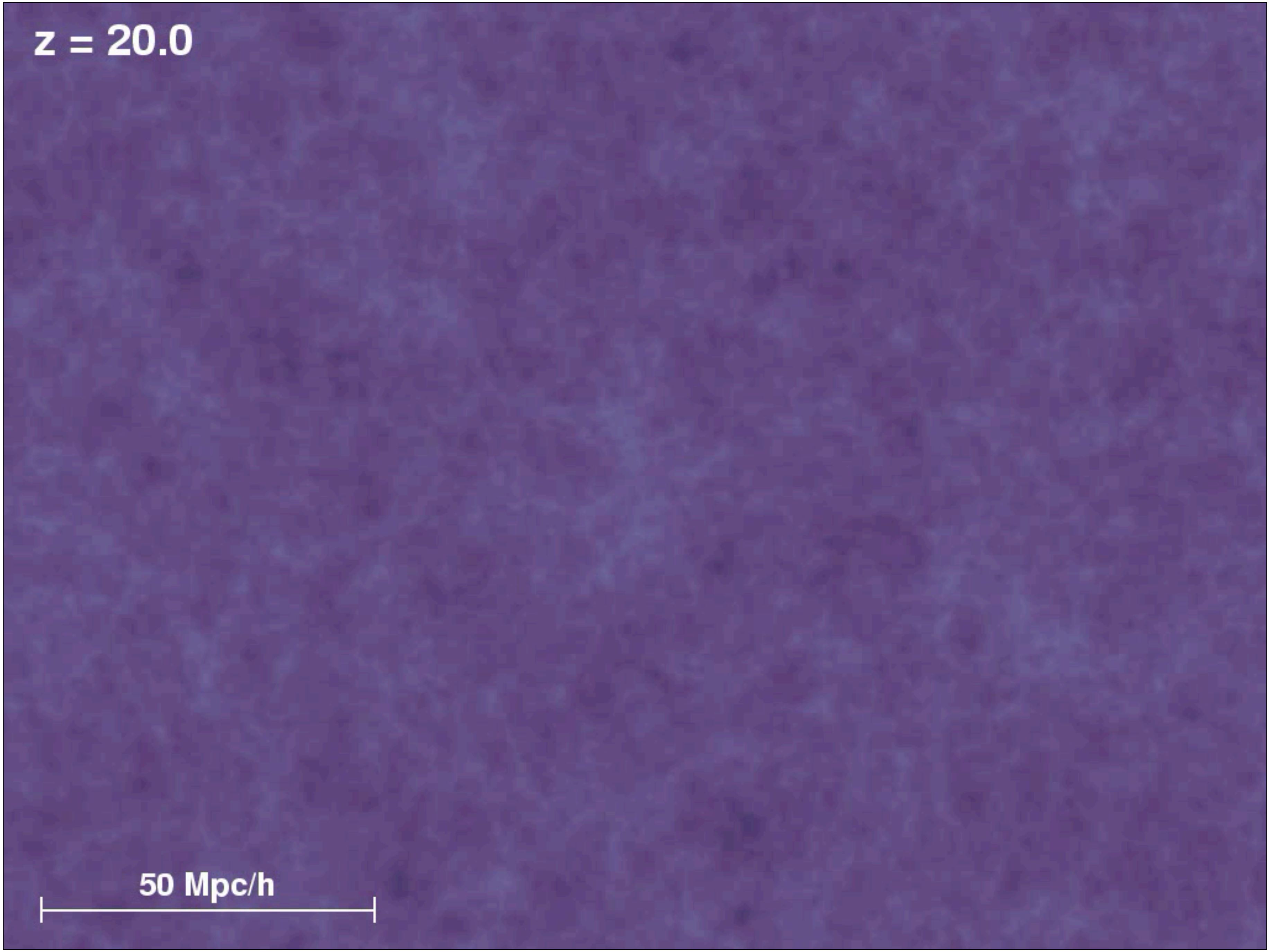
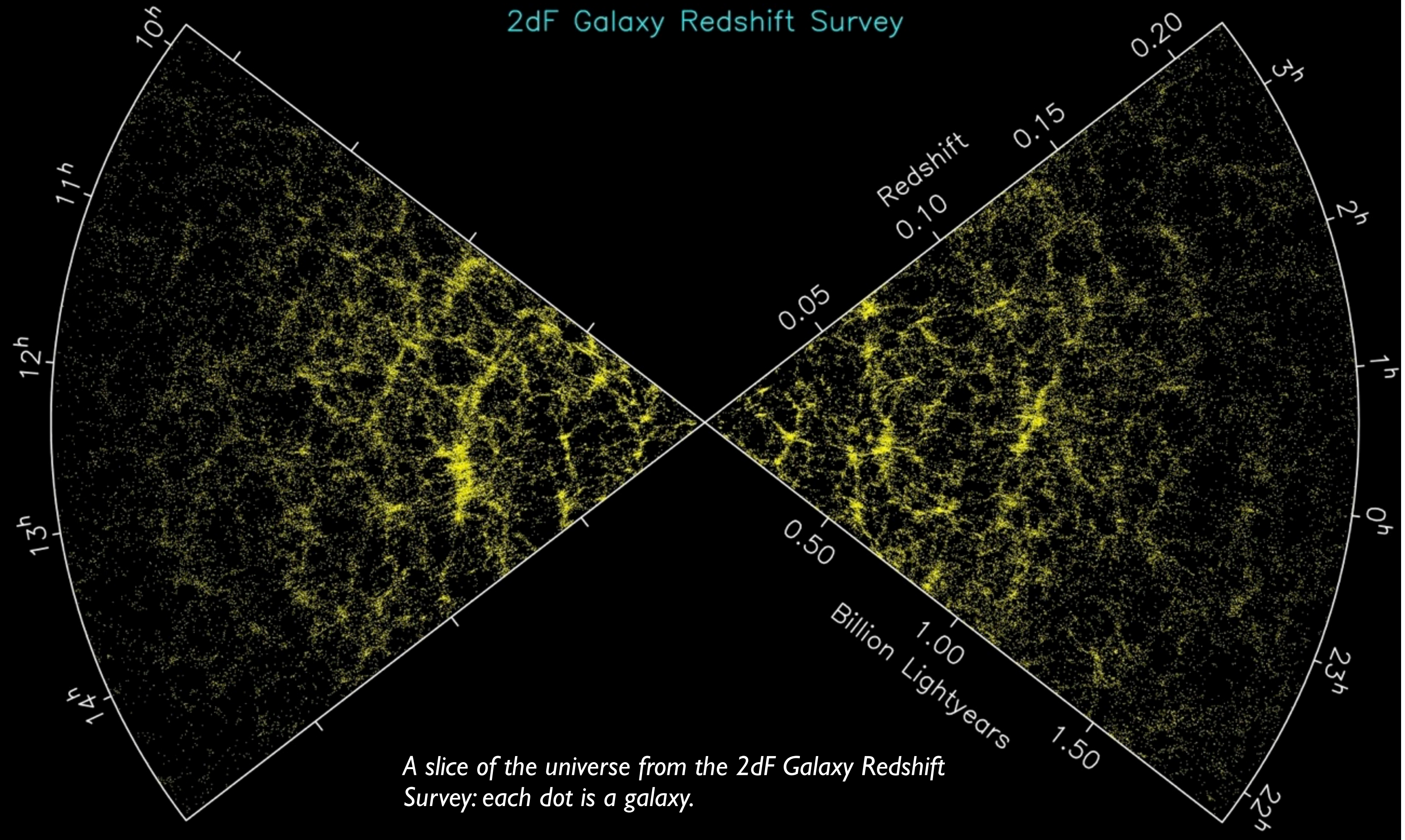
These simulations show that the wiggles in space-time cause dark matter to “fall in” to these dimples and form diffuse haloes. Since the DM particles are only weakly interacting, these haloes stay diffuse. However, ordinary matter is also pulled in, and it can form dense clouds of gas.

Eventually, the matter develops into a web of filaments, with voids separating the denser regions.


z = 20.0
50 Mpc/h

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.

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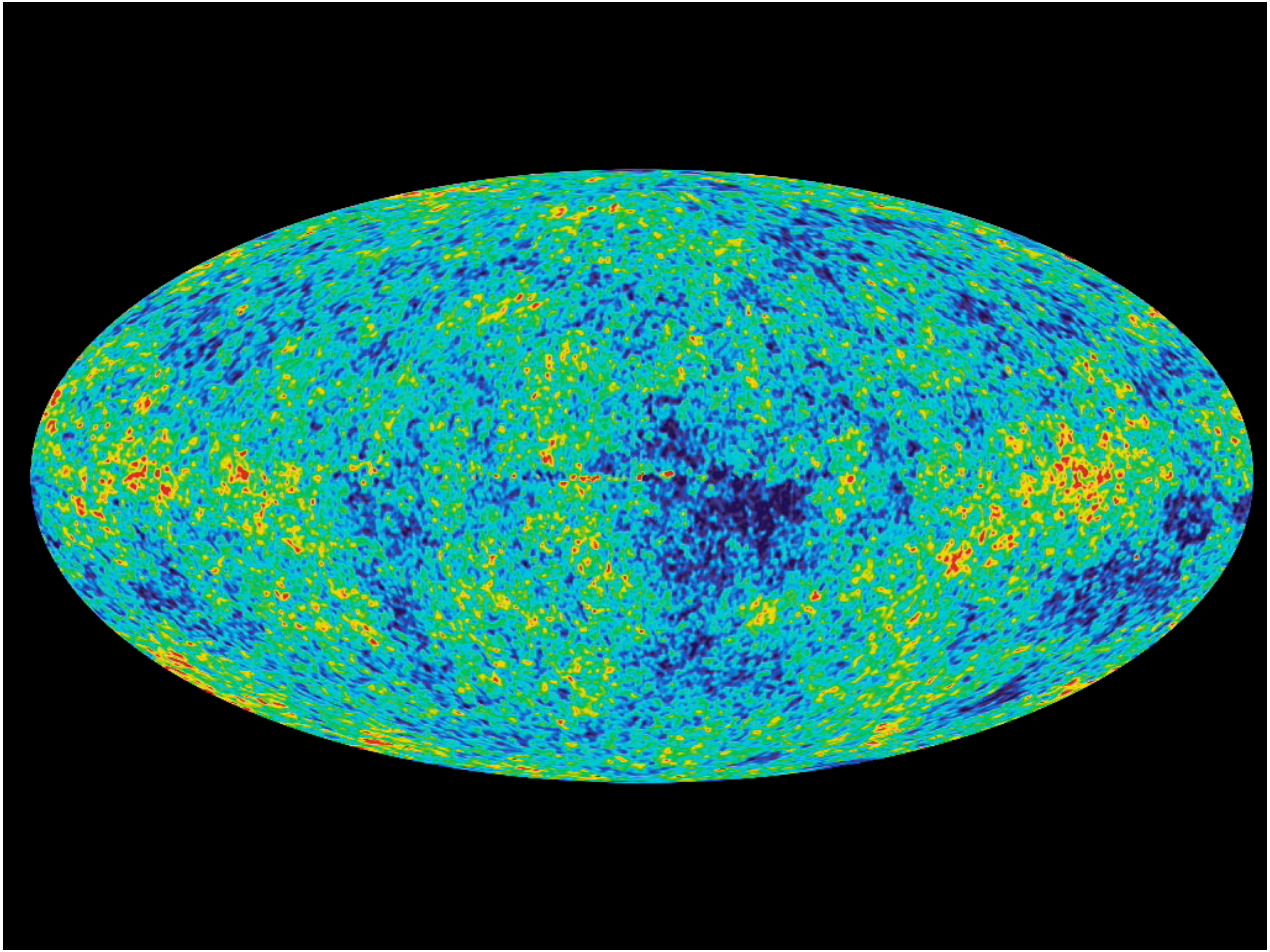
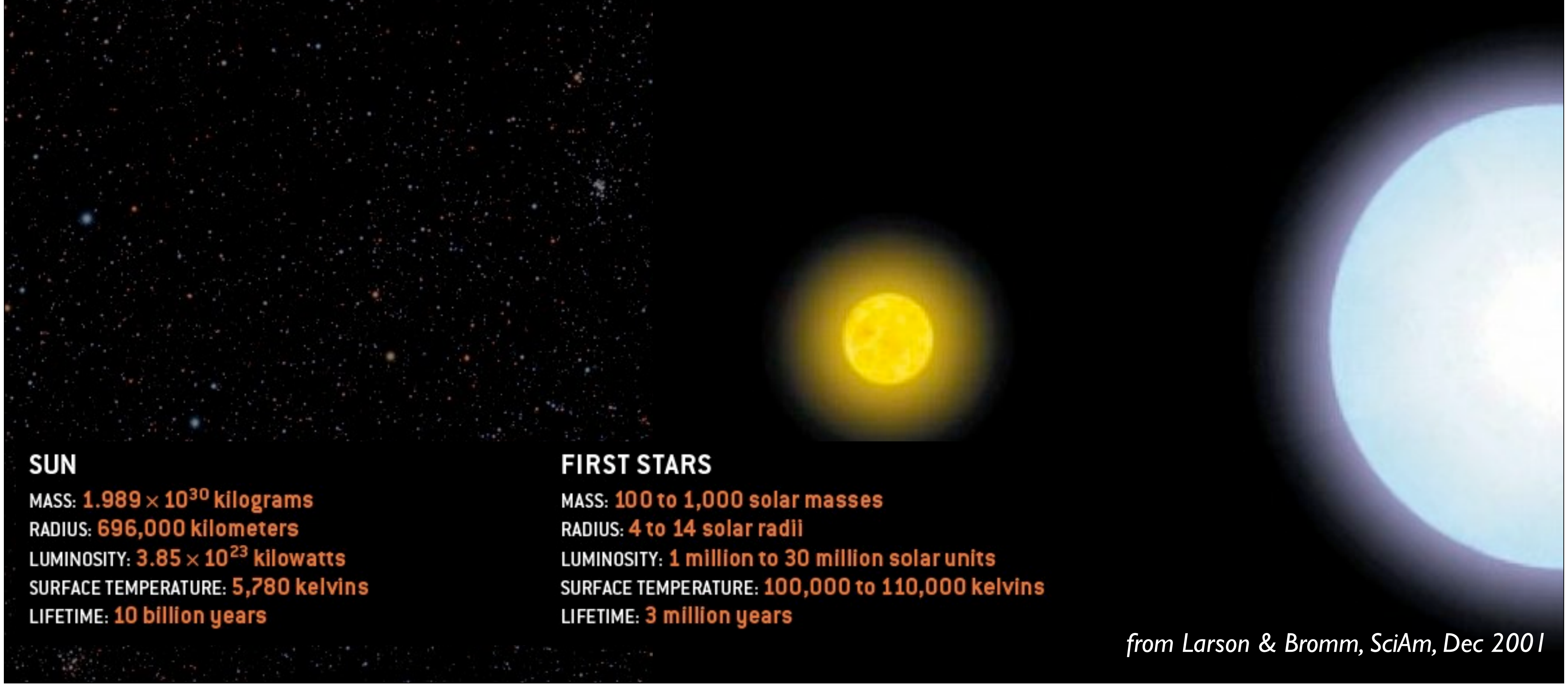
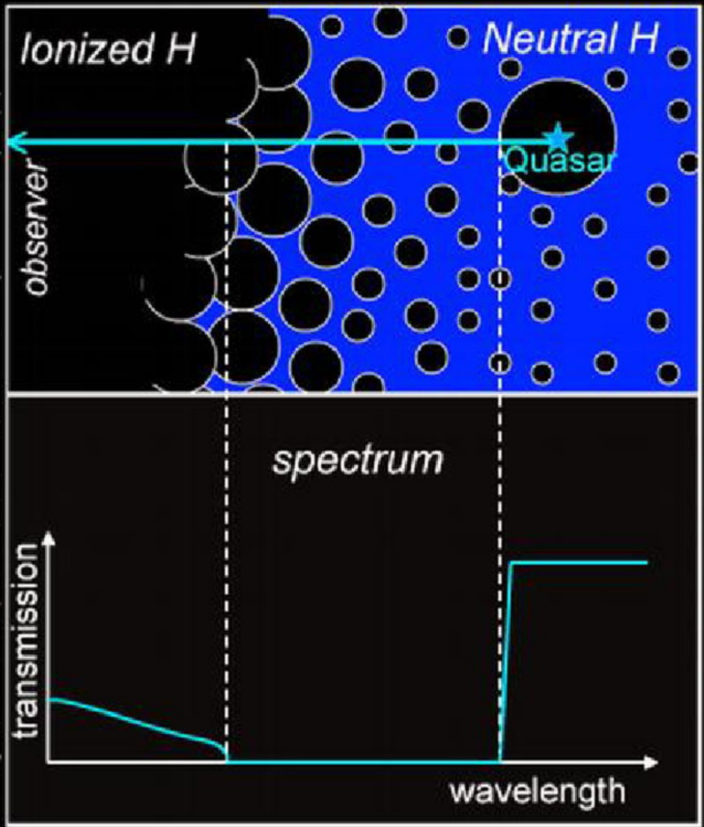


The first stars were quite different to stars in the Universe today. Because the only elements were hydrogen and helium, they contained none of the heavier elements present in all stars today. Models show that such stars would be much brighter and much more massive than heaviest stars today.

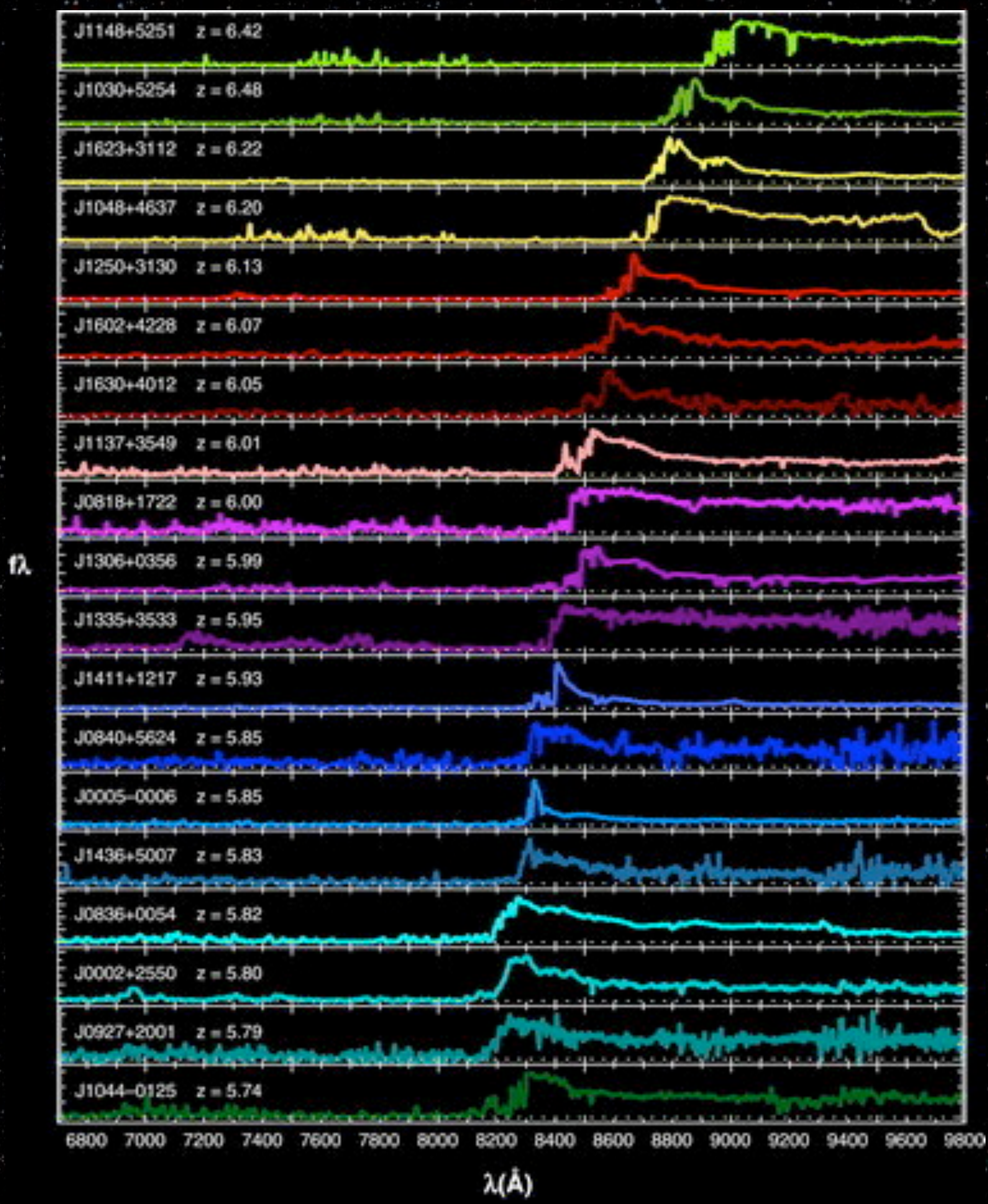


from Larson & Bromm, SciAm, Dec 2001

The first stars did more than just light up the Universe: they *re-ionised* it. Energetic photons of ultraviolet light strip the electrons off hydrogen atoms, which means that the blue light can now travel freely. The onset of reionisation can be seen in quasar spectra: at high redshift all the blue light is absorbed, while at lower redshift some of it gets through.

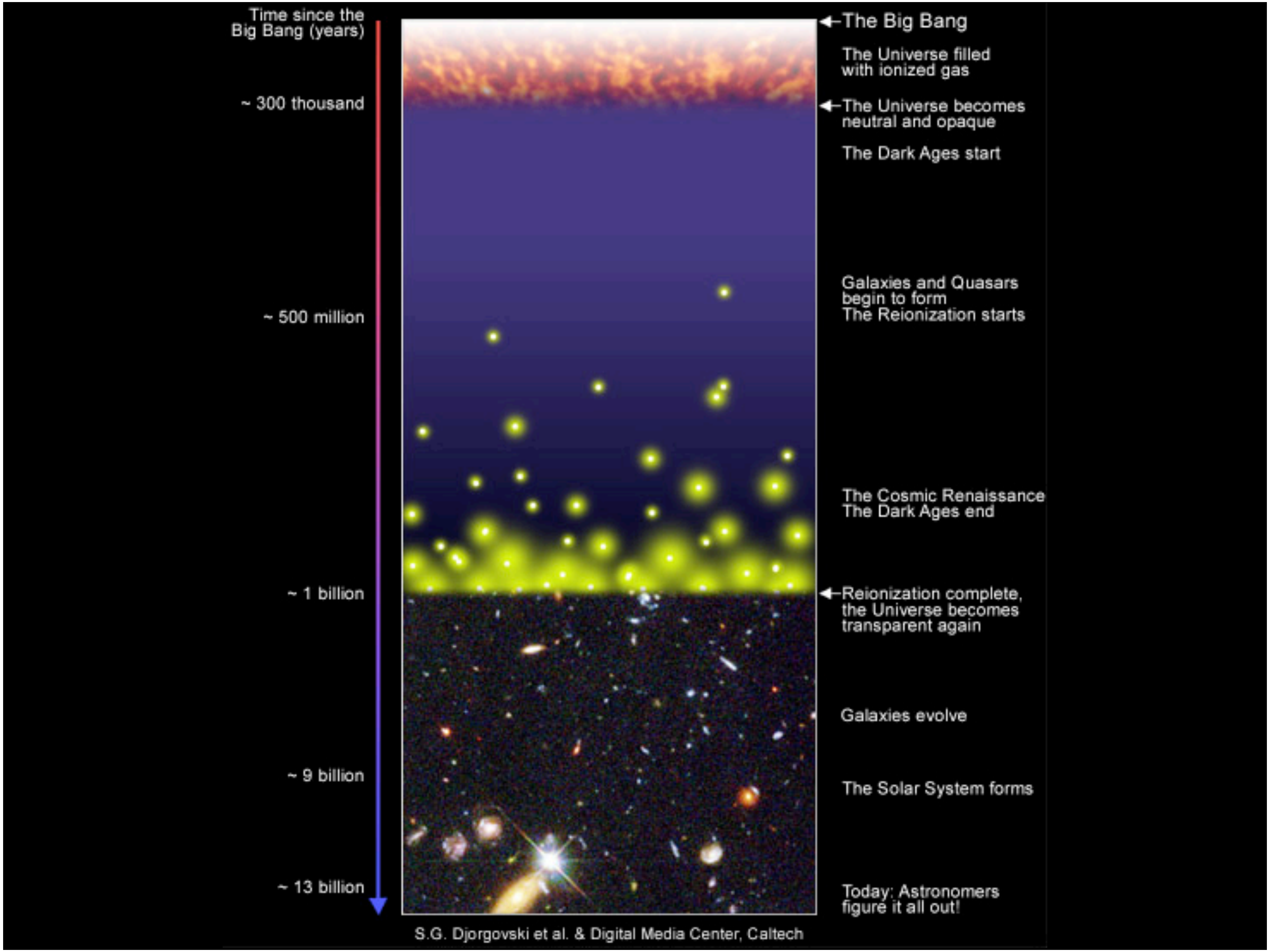


Quasars can be used to measure the redshift at which the intergalactic gas started to transmit blue light. When the gas is still partly neutral, every photon is absorbed, but when the gas is completely ionised the blue light can reach us.



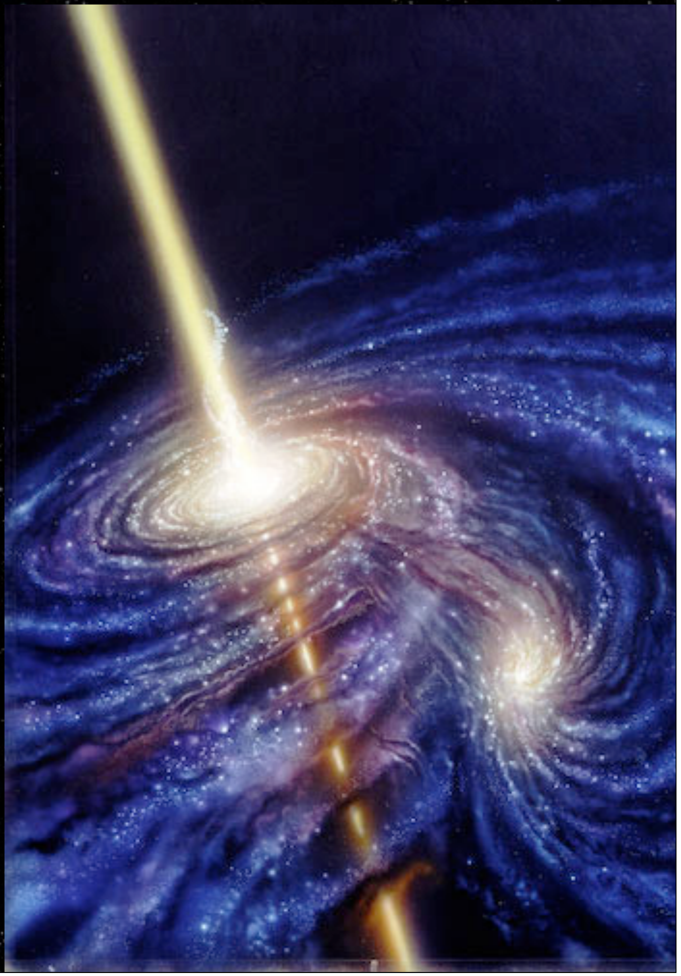
Spectra of quasars from the Sloan Digital Sky Survey show that reionisation happened at a redshift of about 6

Fan X, et al. 2006.
Annu. Rev. Astron. Astrophys. 44:415–62


Time since the Big Bang (years)
~ 300 thousand
~ 500 million
~ 1 billion
~ 9 billion
~ 13 billion
The Big Bang
The Universe filled with ionized gas
The Universe becomes neutral and opaque
The Dark Ages start
Galaxies and Quasars begin to form
The Reionization starts
The Cosmic Renaissance
The Dark Ages end
Reionization complete, the Universe becomes transparent again
Galaxies evolve
The Solar System forms
Today: Astronomers figure it all out!
S.G. Djorgovski et al. & Digital Media Center, Caltech

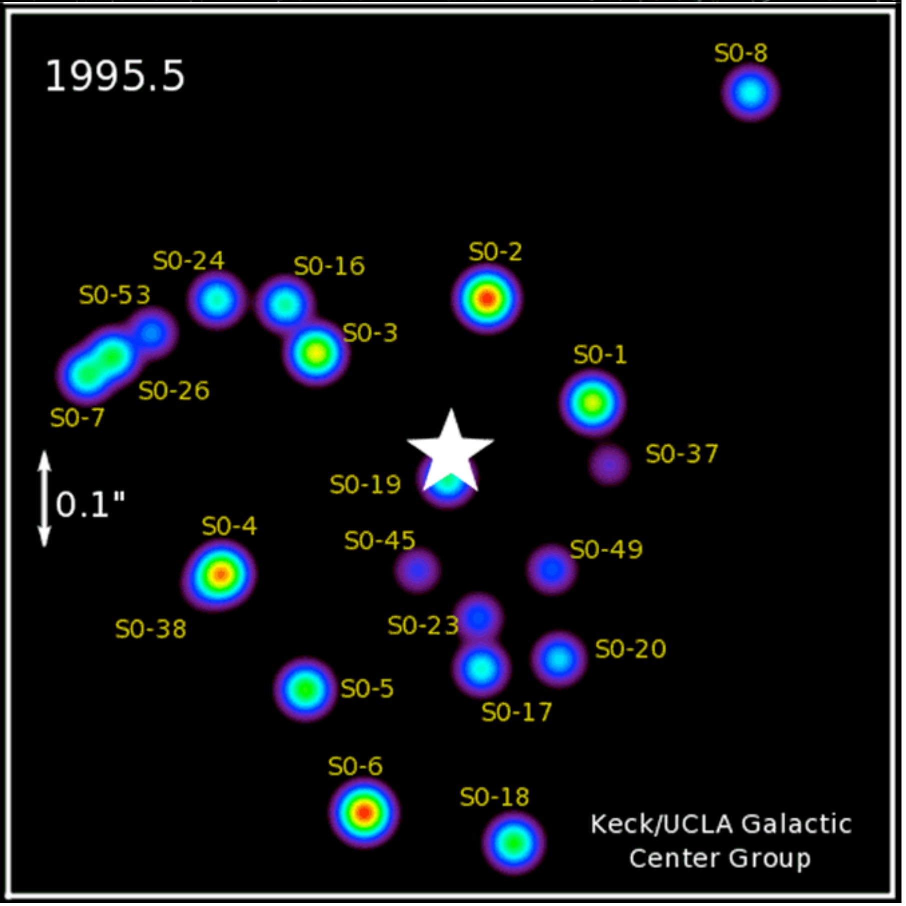
The death of the first stars also had major consequences, in two ways. When they went supernova, they scattered heavy elements throughout their surroundings, which then got incorporated into subsequent generations of stars.

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.



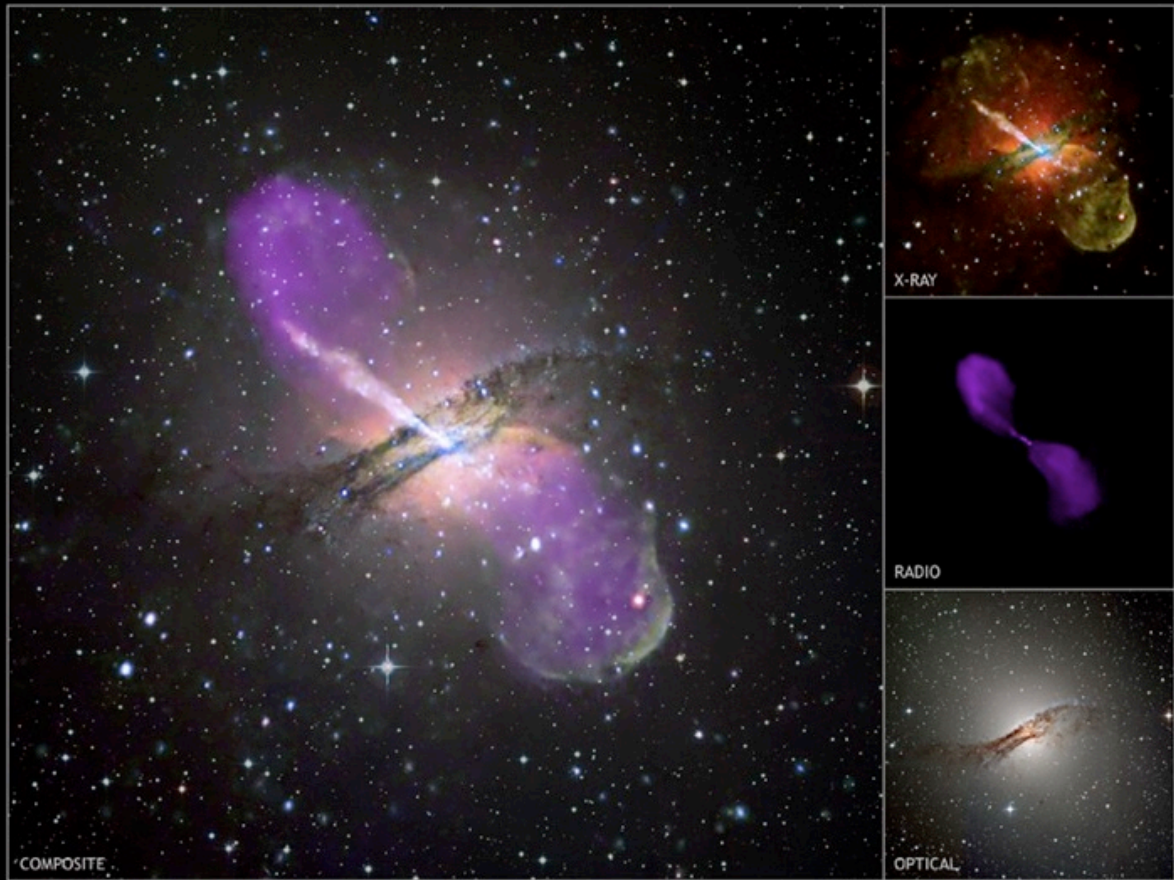
painting by Don Dixon

It now appears that every galaxy has a black hole at its centre. In some, like our own Milky Way, the black hole is currently quiescent, and we can only detect it by its influence on the orbits of stars in its vicinity.



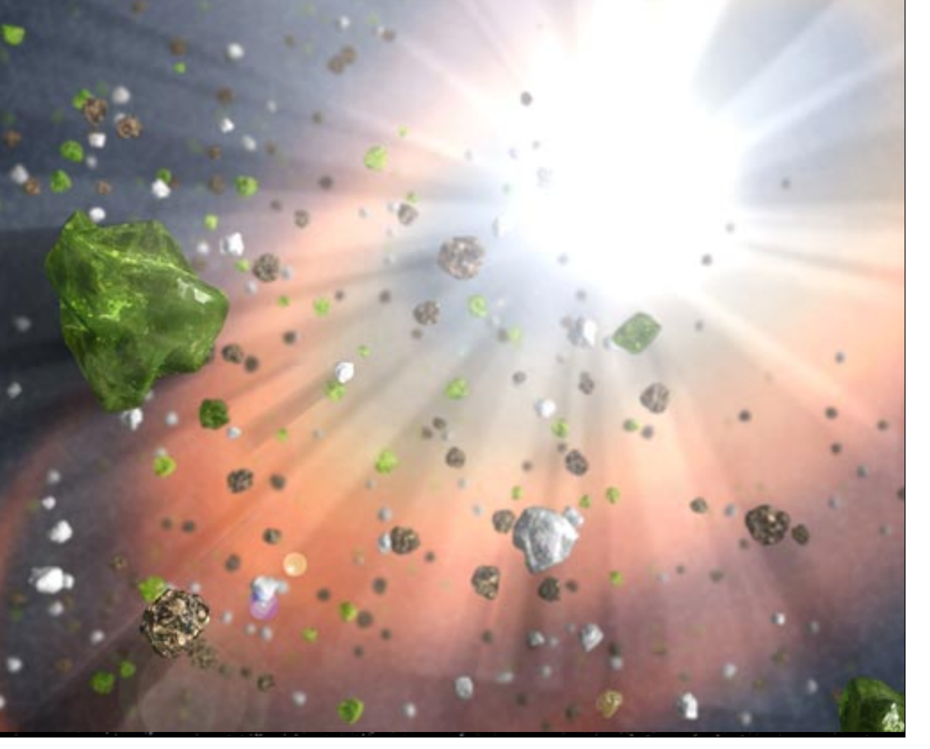
Animation of the stellar orbits in the central pc of the Galaxy. These orbits, and a simple application of Kepler's Laws, provide the best evidence yet for a supermassive black hole, which has a mass of 4 million times the mass of the Sun. Especially important are the stars S0-2, which has an orbital period of only 15.78 years, and S0-16, which comes a mere 90 AU from the black hole.

In other galaxies, the black holes are being fed by material falling in. Some of this material is squirted out in twin jets at nearly the speed of light; we see these objects as *radio galaxies*, with lobes of radio-bright emission stretching well outside the host galaxy.

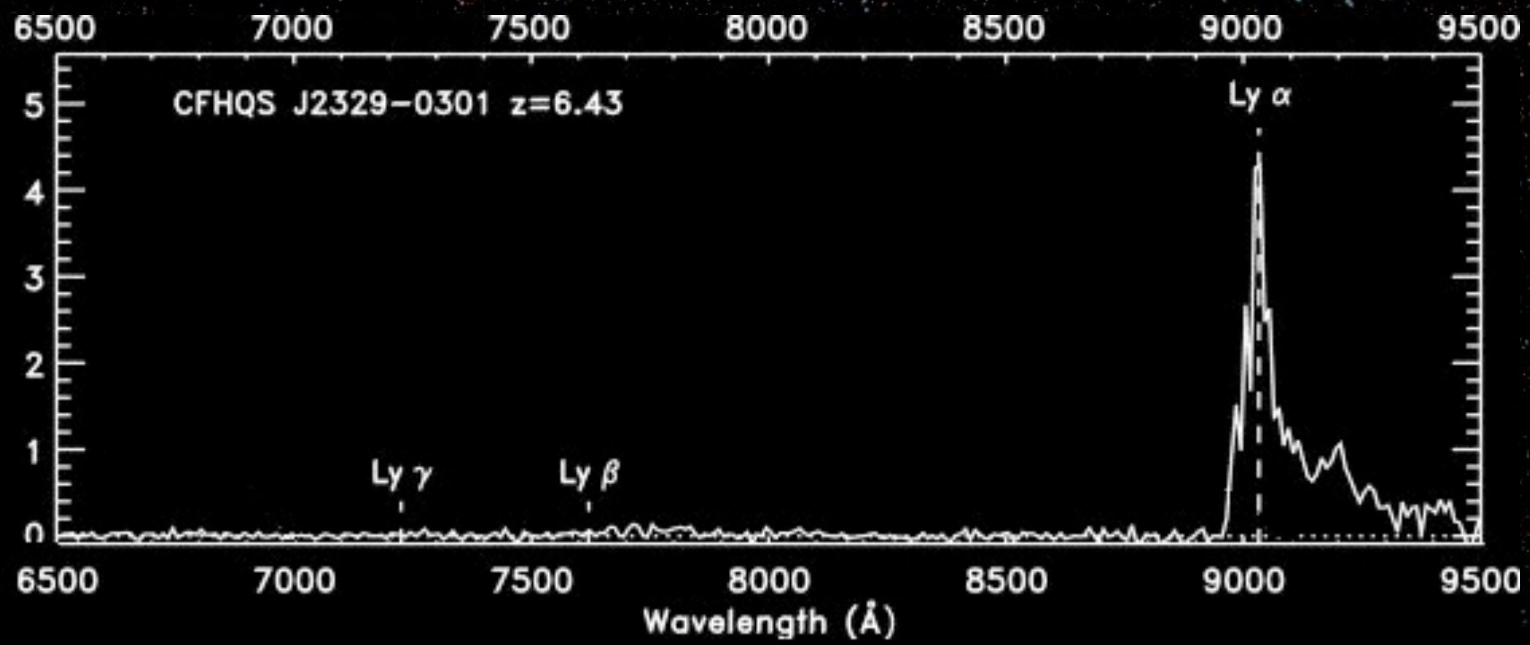


The radio galaxy Centaurus A, showing twin jets of matter being ejected from the central black hole. These jets can be seen at X-ray and radio wavelengths.

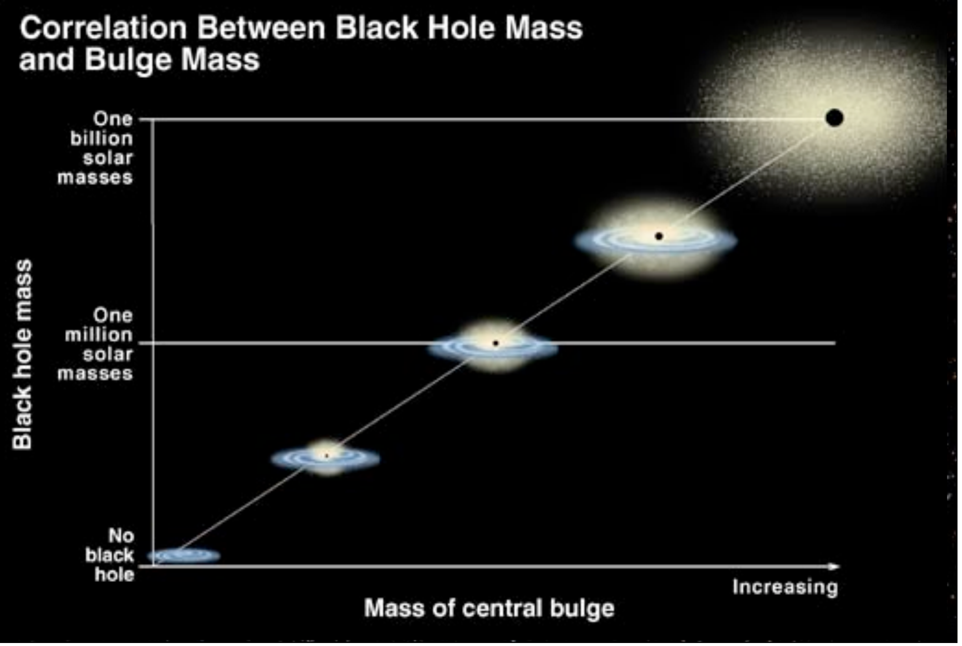
When the jet from the black hole is pointed directly at us, we can't see the galaxy at all, and all we can see is a very bright star-like object: a *quasar*. They differ from radio galaxies only in the direction we see them from: both are an explosive result of the overfeeding of the black holes at their centres.



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 6.43, so it was formed when the universe was only 0.87 Gy old.

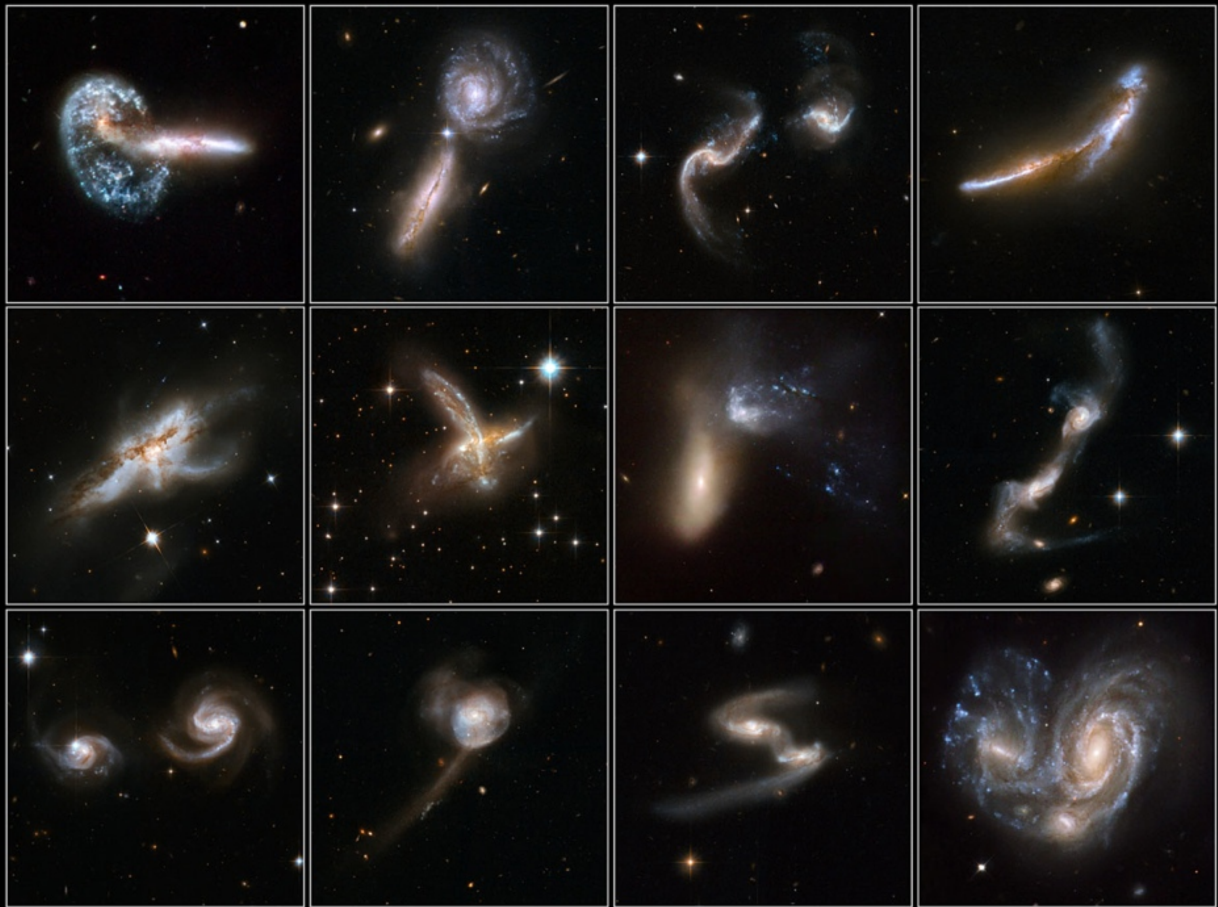


So the black holes must have been formed very early on in the universe. Did they exist first and then galaxies grew around them? Or did the galaxy and the black hole both form together? We still don't know. We do know, however, that almost every galaxy has a massive black hole at its heart, and that the bigger the galaxy, the bigger the black hole. This suggests that the growth of the galaxy and the black hole are somehow intimately linked.



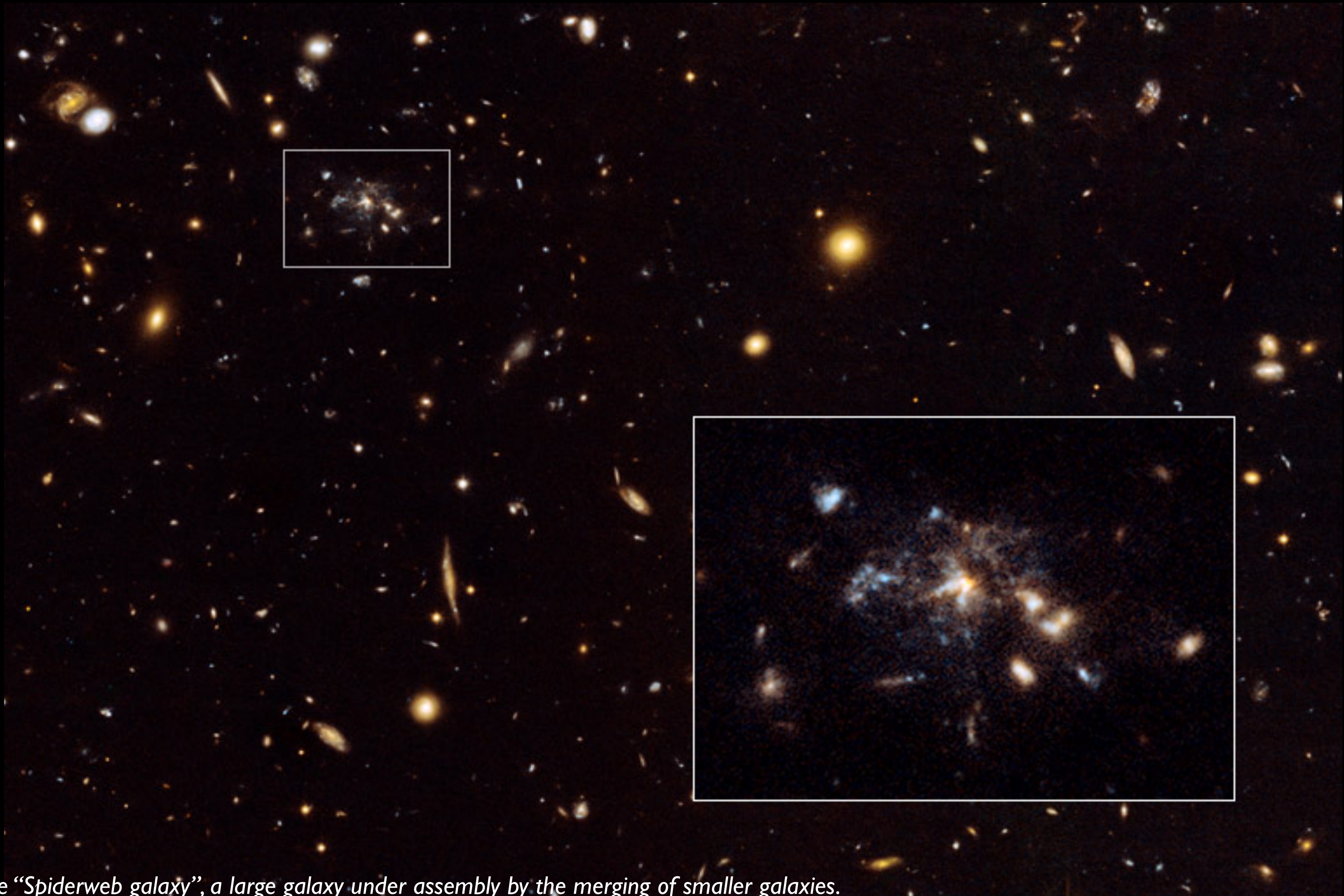
The size of the black hole in the centre of galaxies is related to the size of the galaxy itself.

We think that the link is that both galaxies and black holes grow through the merging of galaxies. Everywhere we look, we see signs of galaxies in the process of colliding, or showing evidence of collisions in the not-too-distant past.

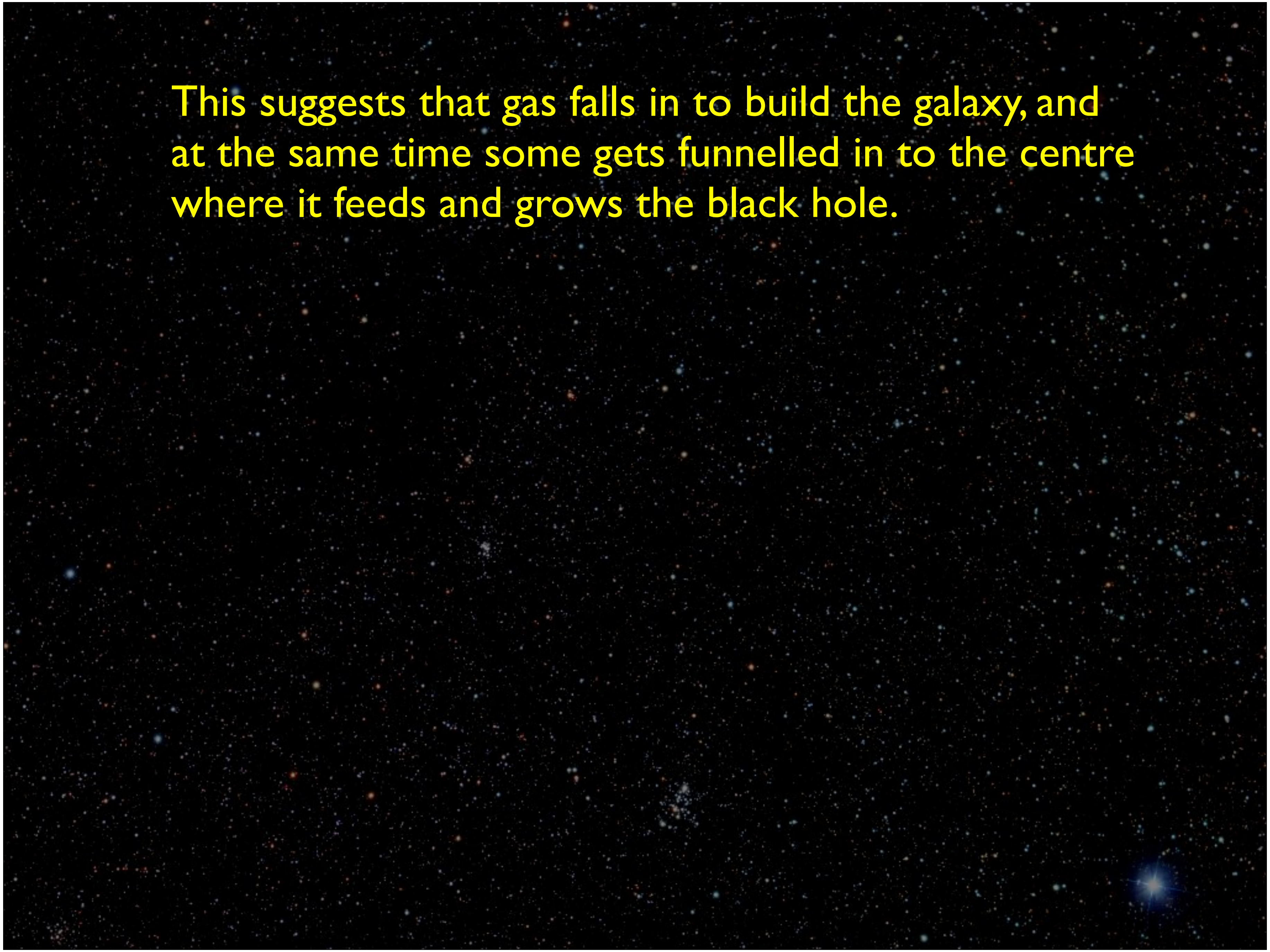


A collection of colliding galaxies seen by Hubble.

What's more, 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.

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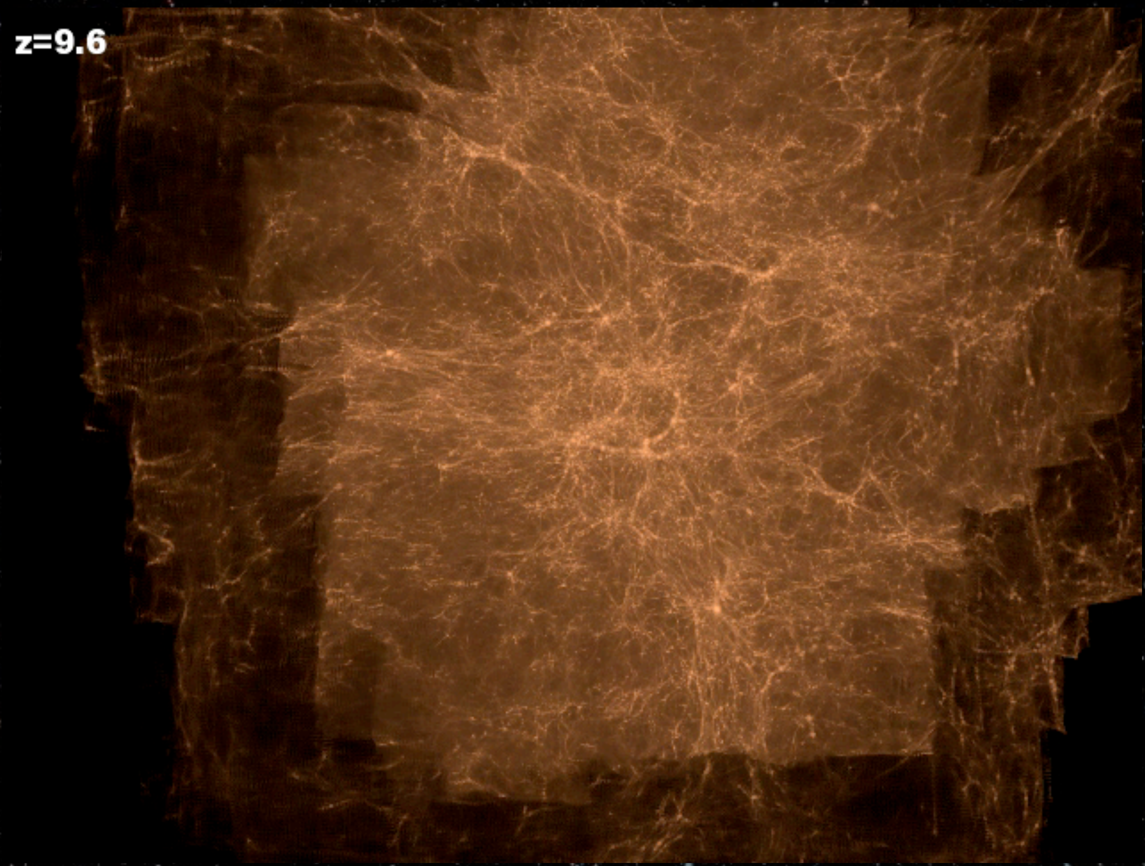
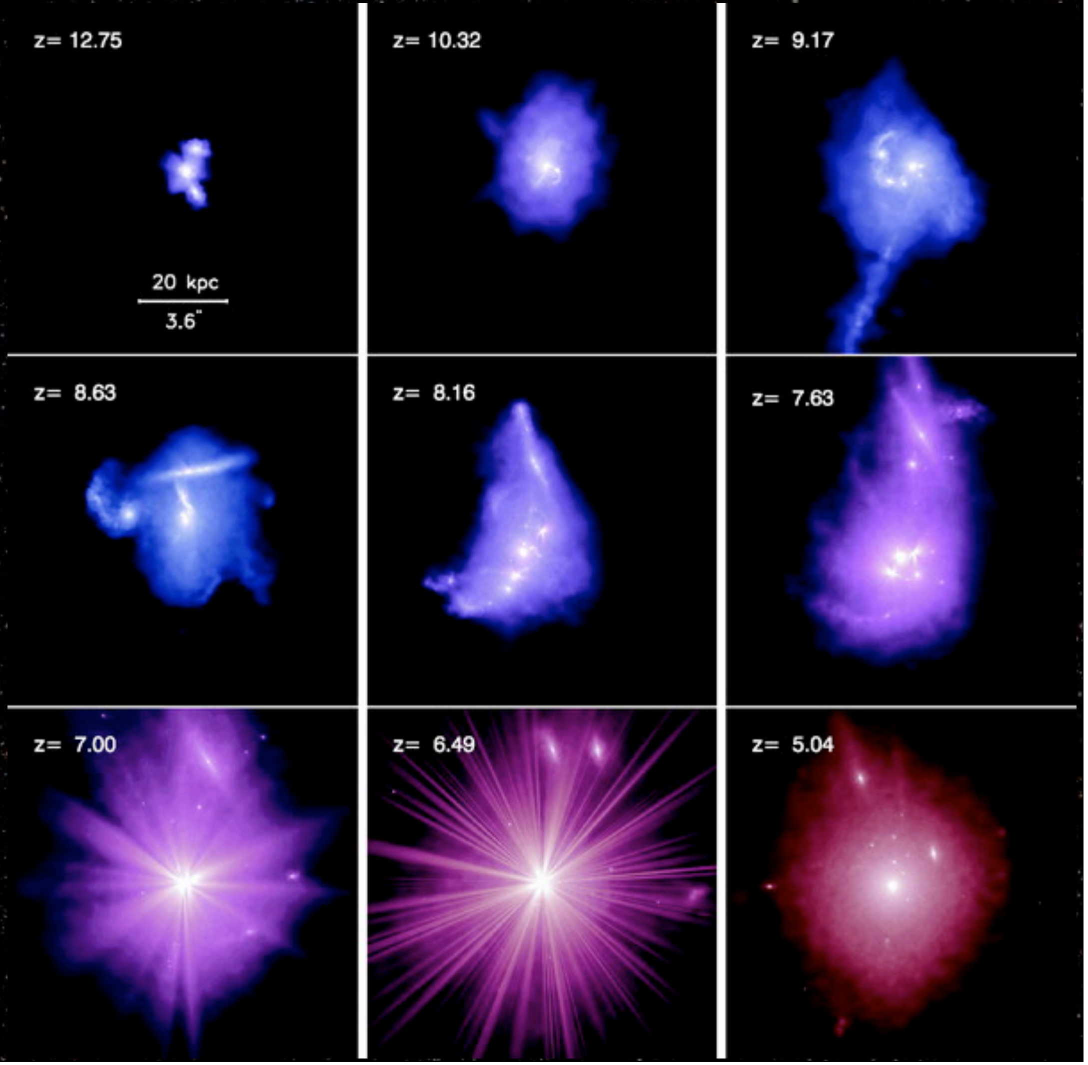
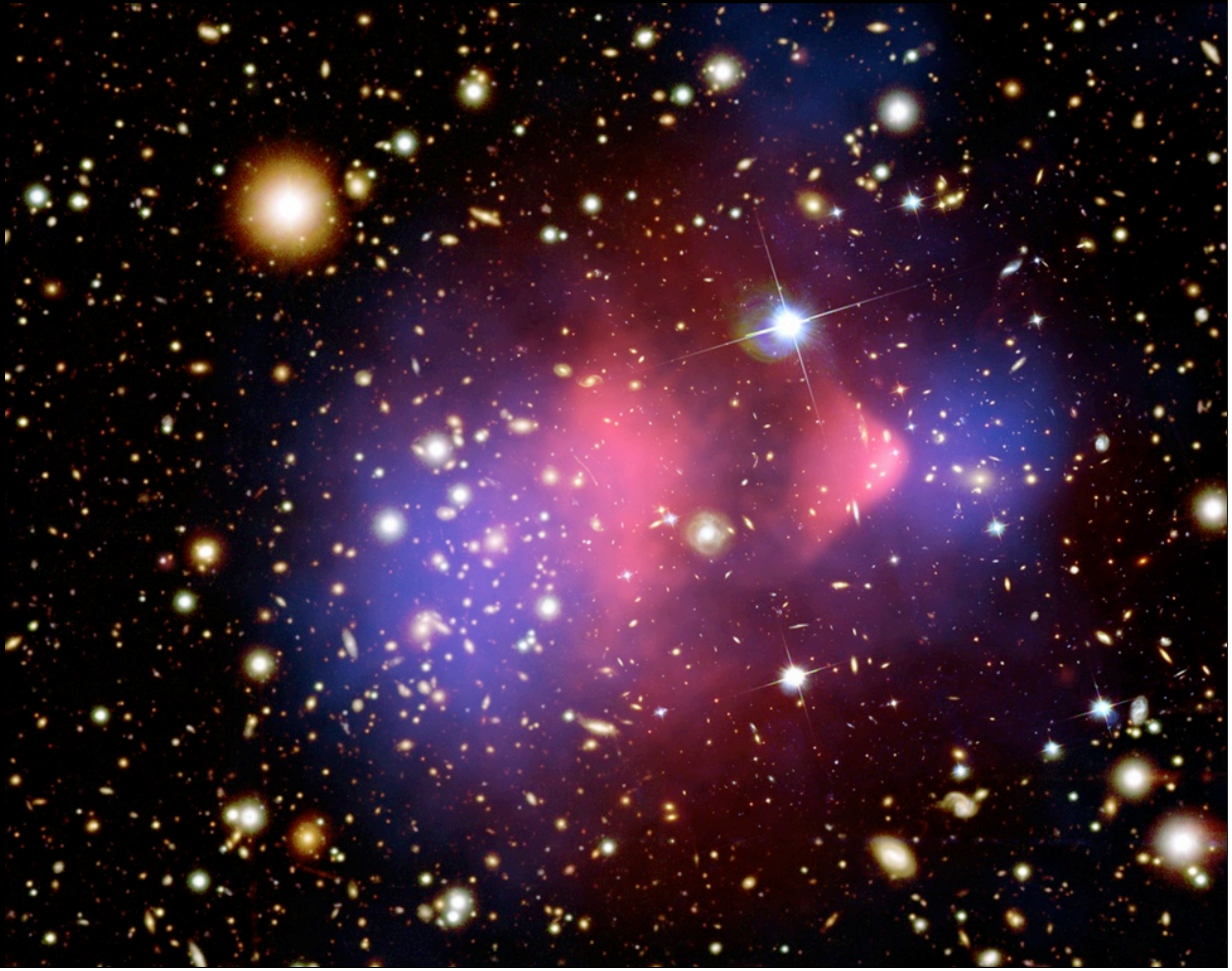


In this view, a quasar is just a particularly violent stage in the life of a galaxy, one that many (most?) galaxies have gone through.



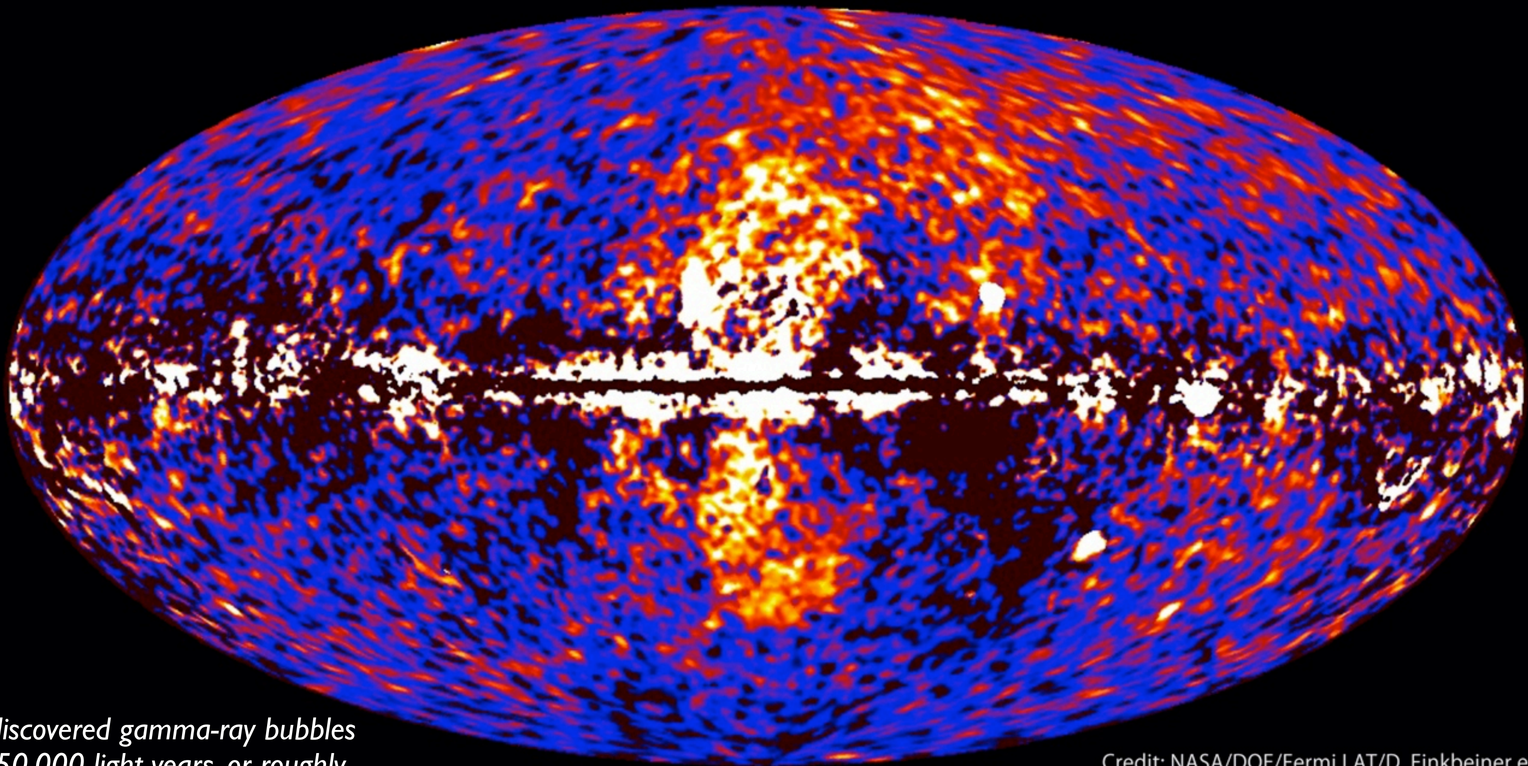
Simulation of the history of a quasar host galaxy as it undergoes several mergers. When the gas from the merger reaches the central black hole, it "switches on" as a quasar.

So galaxies grow by merging from the bottom up, all the while feeding the black hole at their centre, which grows in bursts of activity.



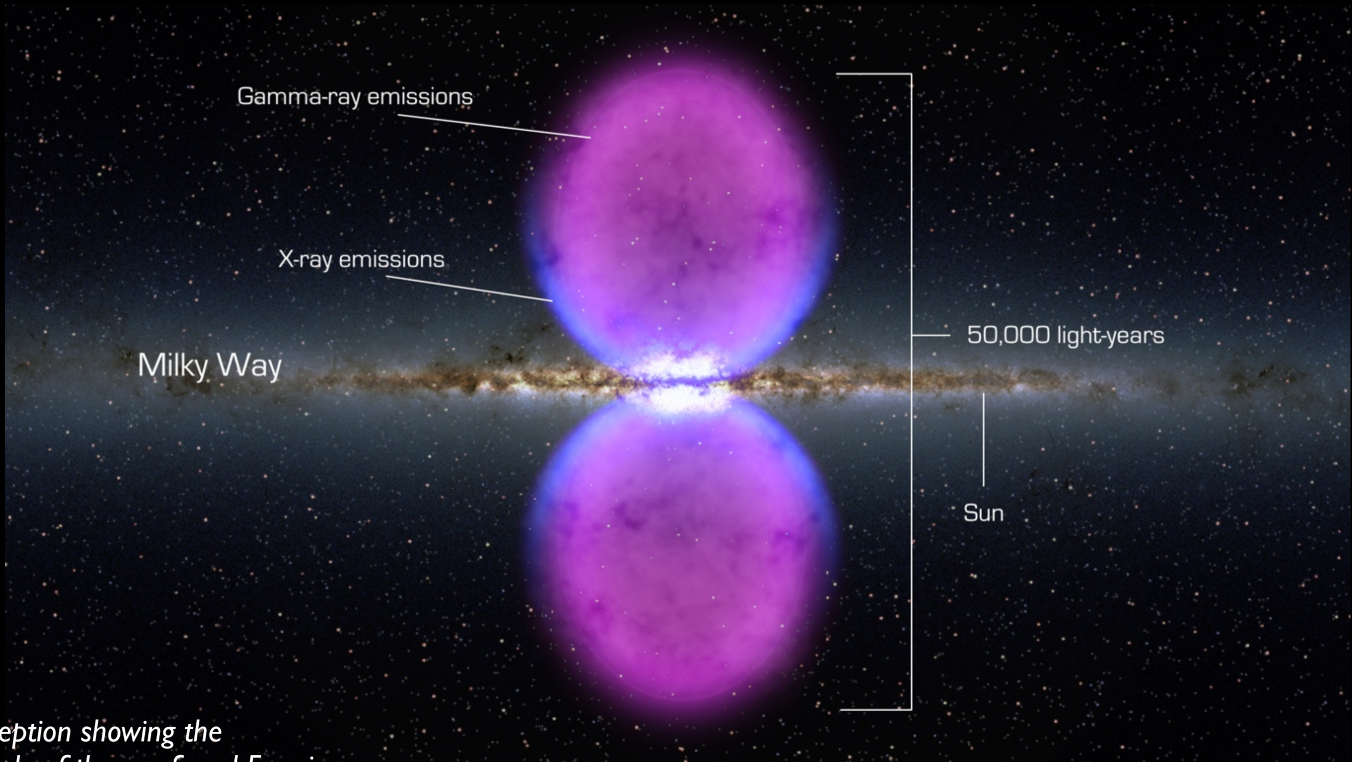
Combined Chandra/HST picture of two colliding clusters of galaxies, called the "Bullet cluster". The X-ray gas (shown in red) has been heated by the collision, but the mass in the cluster (in blue) is in a quite different place, and shows that the dark matter is not interacting with the cluster gas.

Late last year, the *Fermi* gamma-ray satellite discovered two giant gamma-ray bubbles extending above and below the Galactic plane.



Newly discovered gamma-ray bubbles extend 50,000 light-years, or roughly half of the Milky Way's diameter

These could be the result of recent activity of the central black hole, some time in the past few million years.



An artist's conception showing the approximate scale of the newfound Fermi bubbles above and below the Milky Way.

The problems

This is the generally accepted view of how the Universe and galaxies formed. Needless to say, we don't have all the answers yet. Here are some of the big unanswered questions, and what we're doing about them.

1. *What is dark matter?*

We still have very little idea. All sorts of experiments are being done to try to find and understand it. *Particle cosmology* is field which describes the behaviour of matter at very high energies, and is where particle physics intersects with cosmology. All sorts of experiments are looking for the very rare instances where WIMPs interact with regular matter.

2. *How did the supermassive black holes form?*

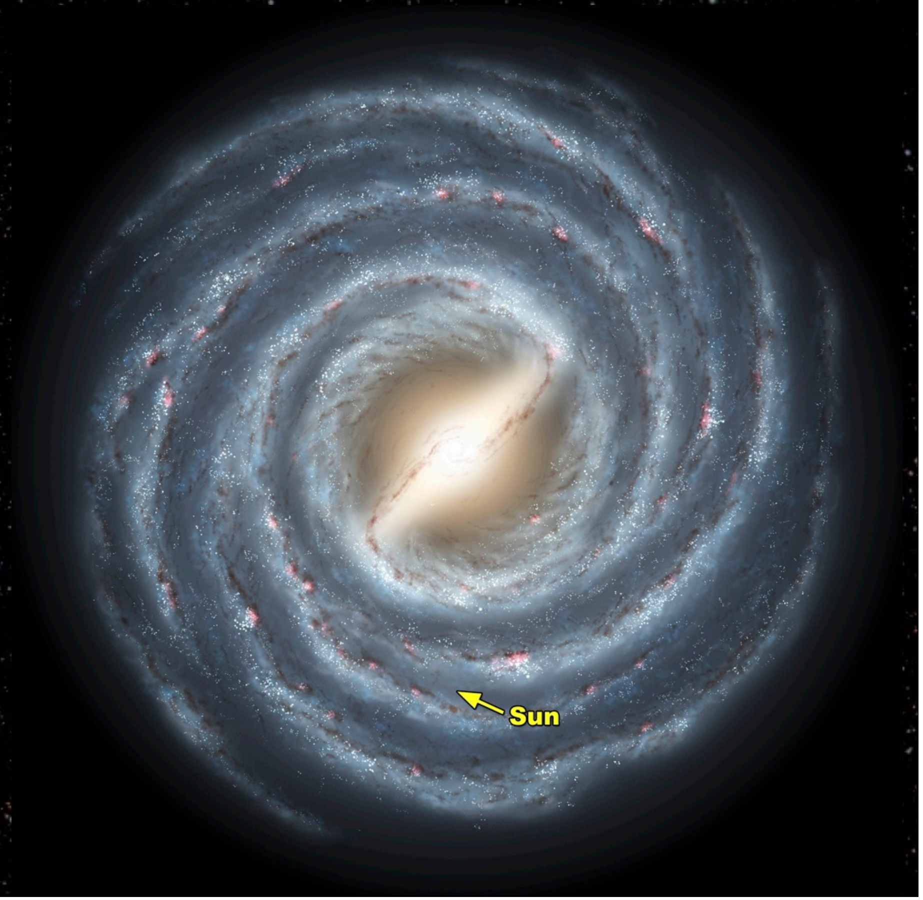
We still don't know where the first black holes came from. We know they existed very early, but where did they come from? And how did they grow? Theorists have difficulty explaining how a black hole left over from a star can grow to a billion solar masses in less than a billion years. But where else can they have come from?

Suggestions: Perhaps they were formed directly in the Big Bang? Or perhaps an early cloud of gas could collapse directly to a black hole without becoming a star? This is in the realm of theorists with their computer models.

3. *How did spiral galaxies form?*

Our model of merging galaxies ("hierarchical formation") works beautifully for elliptical galaxies, but fails badly on explaining spiral galaxies. The problem is that the merger of two galaxies is almost bound to destroy the fragile thin disk of a galaxy with its beautiful spiral arms. So how do you grow the Milky Way?

Comparing the Milky Way with Andromeda is interesting: both are spiral galaxies with very similar sizes, but the black hole at the centre of Andromeda is nearly 100 times as large as the black hole at the centre of our galaxy.



Next week...

... we'll talk some more about spiral galaxies. We'll talk about the formation of the Milky Way, how stars form, and the beginnings of our own Sun.

Further reading

Books:

There are several good books about cosmology and the creation of the Universe.

- "**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 Infinite Cosmos:** Questions from the frontiers of cosmology" by Joseph Silk (Oxford UP, 2006) covers everything, but the organisation leaves a bit to be desired.

Websites:

- 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.

- You can read about the Planck scale at http://www.phys.unsw.edu.au/einsteinlight/jw/module6_Planck.htm

- 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

- Scientific American had a cover story devoted to dark matter in November 2010: "Dark Worlds" by Jonathan Feng and Mark Trodden. It does a very good job of explaining the various candidates for dark matter and how experimenters are looking for them. There's a copy available at Jonathan Feng's website at http://www.ps.uci.edu/~jlf/research/press/dm_1011sciam.pdf

- For a bit of silliness, take a look at the "Universe Simulator" video by Andrew Pontzen http://www.youtube.com/watch?v=7E4Owc5gdRc

Sources for images used:

- Timeline of the Universe: painting by Don Dixon http://www.cosmographica.com/gallery/portfolio2007/content/389_UniverseTimeline_large.html
- Spiral galaxy rotation curve: from IceCUBE, "Searching for neutralino dark matter" http://w3.iihe.ac.be/icecube/3_Activities/1_WIMPs%20Analysis/
- Dark matter in Abell 1689: from Hubble news release 2010-26 http://hubblesite.org/newscenter/archive/releases/2010/26/
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- Baryon fraction: from Martin White. "Big Bang nucleosynthesis", http://astro.berkeley.edu/~mwhite/darkmatter/bbn.html
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- 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
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- 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
- Effect of reionisation on quasar spectrum: from Abraham Loeb, "First Light", http://nedwww.ipac.caltech.edu/level5/Sept06/Loeb/Loeb6.html
- Reionisation: from George Djorgovski, "Discovery of the cosmic reionization era" http://www.astro.caltech.edu/~george/reion/
- 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.
- Black hole at the centre of the Milky Way: from Andrea Ghez http://www.astro.ucla.edu/~ghezgroup/gc/pictures/orbitsMovie.shtml
- Radio galaxy Centaurus A; from APOD 2008 Jan 10 http://apod.nasa.gov/apod/ap080110.html
- Quasar: artist's impression from Universe Today http://www.universetoday.com/30275/quasars/. The quote about overfeeding black holes is from Peebles 2011, "How galaxies got their black holes" Nature 469 305

- Highest redshift quasar spectrum: from Willott et al. 2007, "Four Quasars above Redshift 6 Discovered by the Canada-France High-z Quasar Survey", AJ, 134, 2435 http://adsabs.harvard.edu/abs/2007AJ....134.2435W
- Black hole-galaxy mass correlation: from "Correlation of Black Hole Mass and Bulge Mass/Brightness", http://www.spacetelescope.org/images/opo0022b/
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- Colliding galaxies: from Hubble press release, 24 April 2008: Galaxies gone wild! http://www.spacetelescope.org/news/heic0810/
- Spiderweb galaxy: from HubbleSite news release STScI-2006-45, "Hubble captures galaxy in the making" http://hubblesite.org/newscenter/archive/releases/2006/45/
- Quasar episode: from Li et al. 2007, "Formation of z~6 Quasars from Hierarchical Galaxy Mergers", ApJ, 665, 187 http://adsabs.harvard.edu/abs/2007ApJ...665..187L
- Bullet cluster: from APOD 2008 August 23 http://apod.nasa.gov/apod/ap080823.html
- Fermi bubble: from NASA, "NASA's Fermi Telescope Finds Giant Structure in our Galaxy" http://www.nasa.gov/mission_pages/GLAST/news/new-structure.html
- Andromeda: from APOD 2002 October 21 http://apod.nasa.gov/apod/ap021021.html. Artist's impression of the Milky Way: from http://www.news.wisc.edu/newsphotos/milkyway.html