Hubble flow

- Edwin Hubble was the first to find (using cepheids) that all external galaxies (except the ones in the Local Group) are receding, and that the velocity of recession is proportional to the distance.

$$v = H_0 D$$

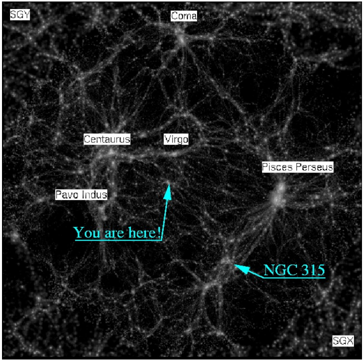
- H_0 is a constant, with units of km/s/Mpc, called the Hubble Constant. It is one of the most important numbers in astronomy.

Hubble flow

- Using all the distance indicators discussed eventually allows us to estimate the Hubble Constant. The generally accepted value is about 70 km/s/Mpc.
- Once it is known, then for very distant galaxies, measuring the redshift gives us an idea of the distance.

The distant universe

- Galaxies exist in clusters, clusters are members of super-clusters, super-clusters are members of filaments.
- Between the filaments - voids.



Cosmology

- *Cosmology* is the branch of astronomy concerned with the history and future of the universe
- What does it look like at the very largest scales?
- Where did the universe come?
- What is going to happen to it?

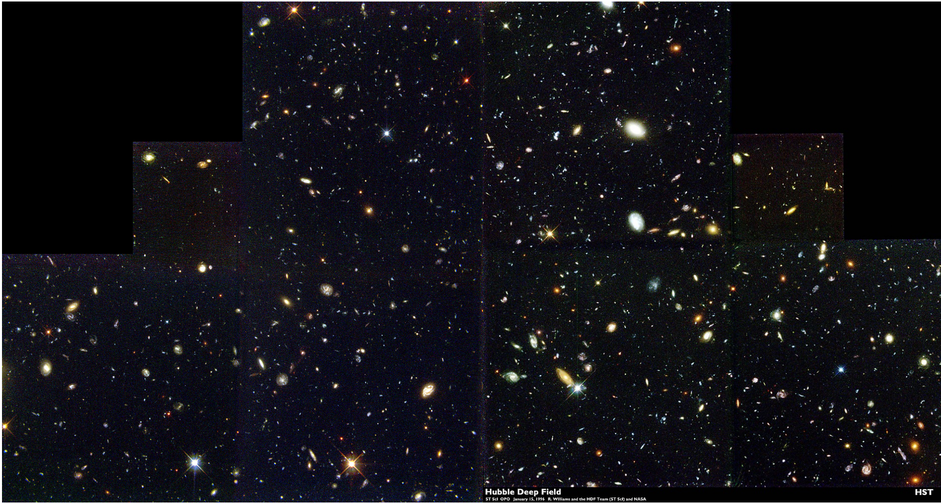
The cosmological principle

- At small scales, the universe is not at all uniform.

The cosmological principle

- But at the very largest scales the universe looks pretty uniform.
- It is generally thought that the universe at the very largest scales is **homogenous** and **isotropic** – that is, it looks the same in all directions and at all places.
- This is the **Cosmological Principle**.

The Hubble Deep Fields



The Hubble Deep Fields

- Extremely deep images of two very small patches of sky, each 2.5 arcminutes across.
- They look very similar, supporting the cosmological principle.
- About 3,000 galaxies in each.

The Big Bang

- In the 1920s, Edwin Hubble discovered that all galaxies were receding from Earth.

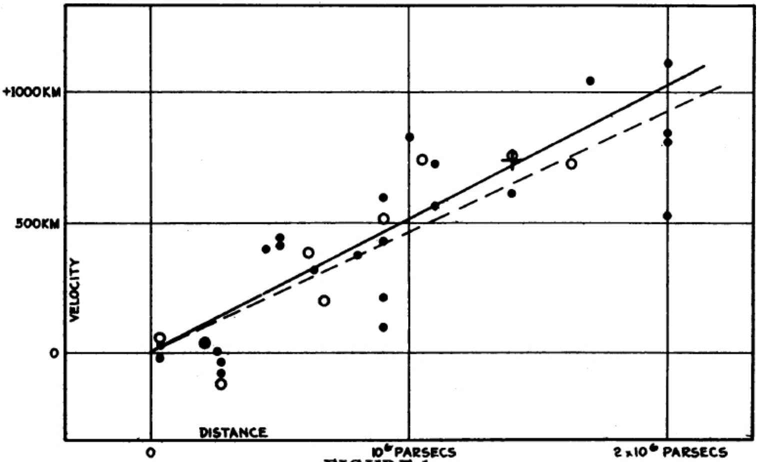


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

The Big Bang

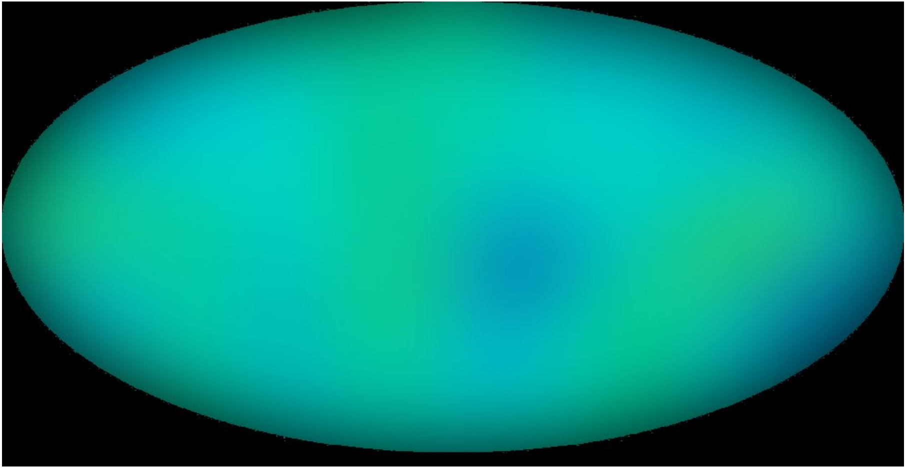
- Tracing the expansion back implies that the universe had a beginning, and that beginning was about 15 billion years ago.
- Fred Hoyle - strong proponent of ‘steady state theory’ - derisively referred to the notion as the ‘Big Bang theory’.
- The name stuck.

The Big Bang

- In 1964, Penzias and Wilson detected microwave emission that was coming from all parts of the sky with highly uniform intensity.
- It was characteristic of a black body with a temperature of 2.7K
- This Cosmic Microwave Background Radiation was exactly what the Big Bang theory had predicted

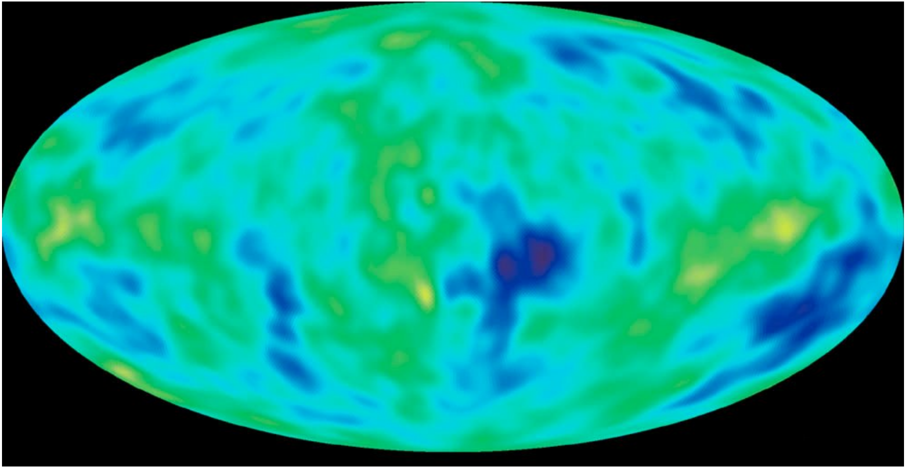
The Big Bang

- Successive experiments have revealed the CMBR in ever greater detail.



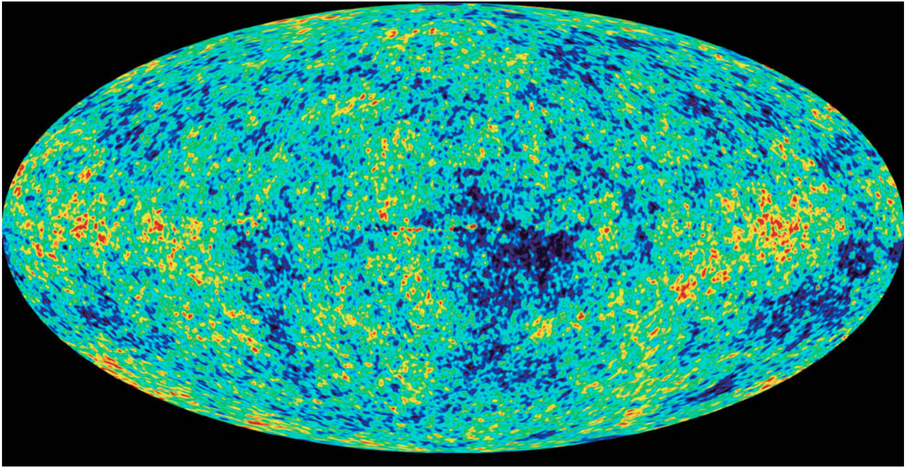
The Big Bang

- Successive experiments have revealed the CMBR in ever greater detail.



The Big Bang

- Successive experiments have revealed the CMBR in ever greater detail.



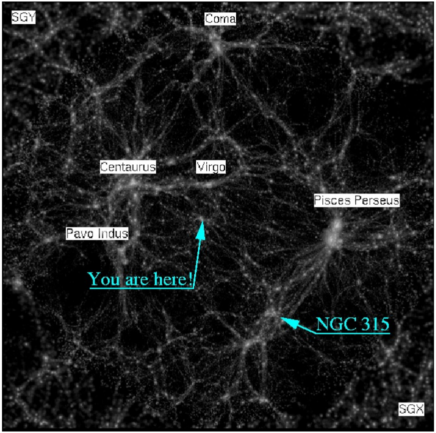
The Big Bang

- You can detect the CMBR as well...

- 10-25% of the static you see on an untuned TV is CMBR

The Big Bang

- Further evidence comes from the amounts of Helium and Lithium in the universe, which are well predicted by Big Bang theory, and also the large-scale structure of the universe.



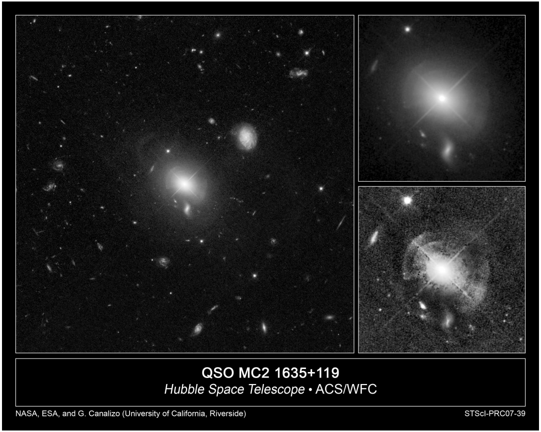
The Big Bang

- Large simulations of how a universe would evolve if it started with a Big Bang give results that look very much like what is observed.

Animation - available in screen version

The Big Bang

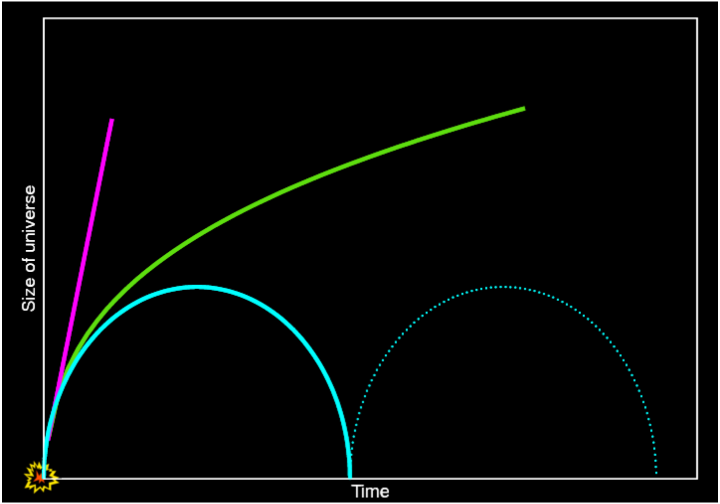
- Finally, some types of object are seen in the distant universe but not nearby, ruling out any kind of ‘steady state’ universe
- eg quasars



The future

- So, we have answered a major question. The universe started in a Big Bang.
- Next major question - what will happen to it?
  - Is it **closed** - will reach a maximum size then start contracting again?
  - Is it **open** - will expand forever?
  - Is it **flat** - contains just the right amount of mass that the expansion slows and never quite stops?

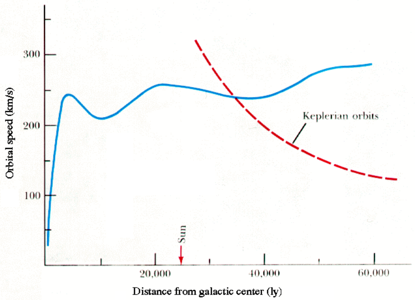
The future



- The answer depends on how much mass there is in the universe.

Dark matter

- Have mentioned galaxy rotation curves, and Type Ia supernovae. These have been the clue that the universe contains two extremely mysterious things – *dark matter* and *dark energy*.
- When looking at a distant galaxy, if you assume that its *luminosity* is a good tracer of its *mass* (ie the brighter a part of the galaxy, the more mass there is there), then you cannot understand its rotation curve. It should be *keplerian*, but is nothing like it.

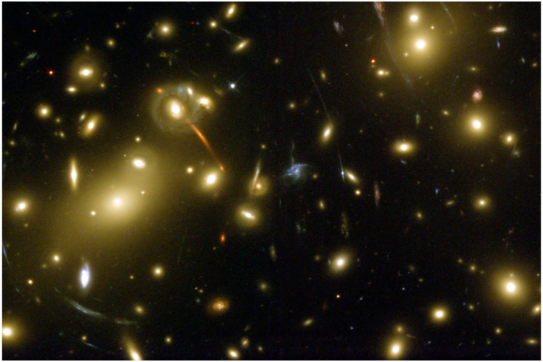


Dark matter

- Fritz Zwicky looked at the motions of galaxies in clusters in the 1930s
- He found they were moving extremely fast. The clusters should have dispersed billions of years ago - unless there was extra, invisible mass, holding them together

Dark matter

- Clusters of galaxies can bend and magnify the light of other clusters of galaxies which are much more distant along the same line of sight.
- Again, the amount the light is magnified implies that there is a lot of mass in the clusters that we can't see.

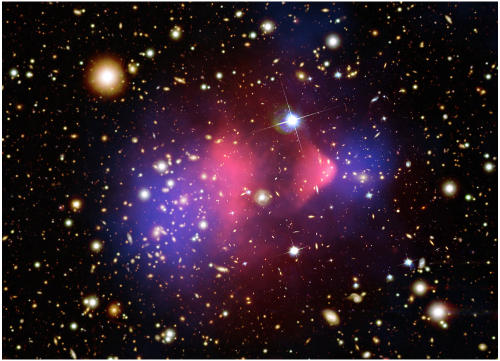


Dark matter

- There is not just a little bit of matter that we can't see
- 80-90% of the matter in the universe is not matter as we know it. It does not emit any electromagnetic radiation, it does not consist of atoms, and we only know it is there from its gravitational effect.
- What is this stuff? It could be *hot dark matter* – particles with a very small mass moving at speeds close to the speed of light. Neutrinos can be classed as hot dark matter, but our current understanding is that they can't possibly account for all the dark matter that is observed
- Dark matter could also be *cold dark matter* – Weakly Interacting Massive Particles (WIMPs), or non-emitting objects like black holes or neutron stars, described as Massive Compact Halo Objects (MACHOs).

Dark matter

- One recent interesting observation was of the Bullet Cluster – colliding galaxies in which the dark matter appears to have been separated from the visible matter by the collision.
- This argues strongly against some other theories which involve very slight modifications to the laws of gravity.



Dark energy

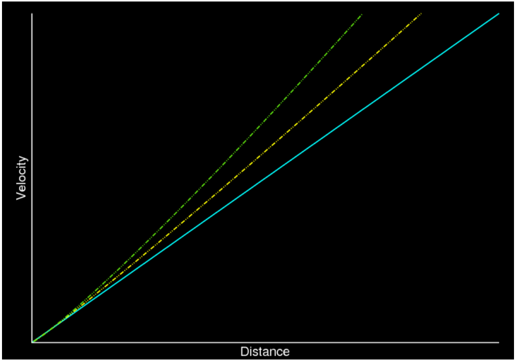
- By 1998 it appeared that the universe was **flat**. The total amount of mass was very close to the value required to just halt the expansion of the universe.
- Problem was, most of that mass was made of something completely unknown to science.
- And then things got suddenly worse.

Dark energy

- Type Ia supernova are a very reliable standard candle. By observing very distant Type Ia supernovae, astronomers hoped to find out what the ultimate fate of the universe was
- Would it expand for ever, would it eventually stop expanding and contract, or did it have the critical mass required to just halt its expansion?

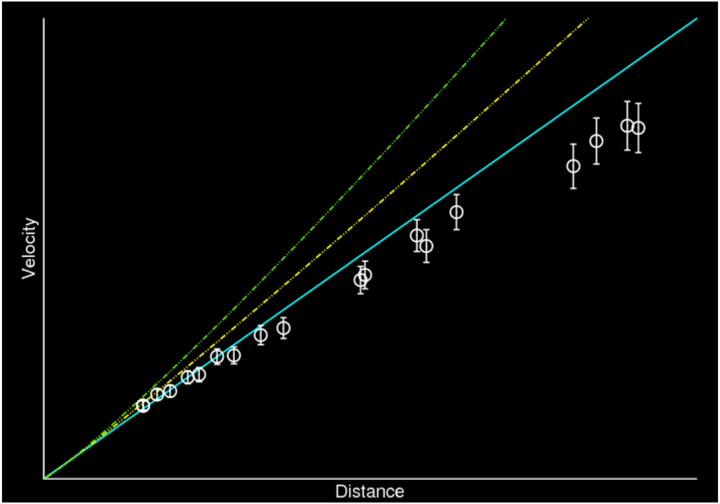
Dark energy

- Plotting velocity v. distance out into the extremely distant universe allows us to measure how the universe's expansion has changed with time.
- If it has slowed down, then very distant things were moving *faster*.
- They will fall above the line that correponds to the present-day Hubble Constant.



Dark energy

- Astronomers in the 1990s measured distant enough galaxies to find the answer.



Dark energy

- The universe's expansion is not slowing down – it is accelerating. Very distant supernovae are always moving more slowly than can be explained by a non-accelerating universe.
- The observed acceleration implies that about 74 per cent of the *mass-energy* of the universe is in the form of something that is neither normal matter or dark matter

Dark energy

- If you thought dark matter was weird and mysterious...
- The nature of dark energy is as yet unknown. But it almost certainly means that the universe is **open**.
- It will expand forever, at an ever-increasing rate.

Summary

- 96% of the universe is completely mysterious.
- Good job – otherwise this course would have lasted 25 times as long!
- Hope you've enjoyed it :)