Observational Astronomy - Lecture 12
Cosmology - II

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Remaining course logistics

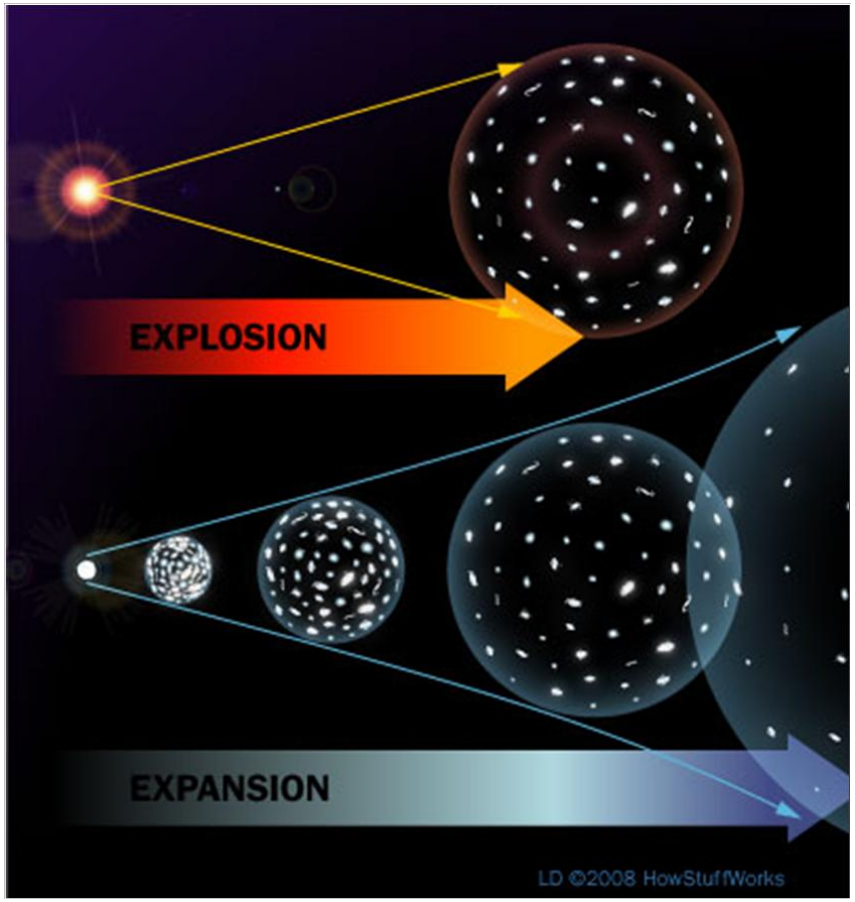
1. Today's lecture - Cosmology Part 2
2. Monday 5/12 lecture - Exoplanets and final review.
3. Final exam - Monday 5/19 4:00-5:50 PM, Meyer 102
   - Format similar to midterm and homework.
   - Mixture of short answers and calculations.
   - All formulae and constants needed will be provided.
   - All topics covered are "fair game" (except exoplanets).
4. Today's homework is the last homework.
5. Solutions to today's homework will be posted next Monday (5/12).
6. This week's lab is the last lab.
7. Tentatively planning an optional Saturn lab week of 5/12.
   - 10:00-11:00 PM - weather permitting.
   - Details will follow by E-Mail.

What do we mean by "The Big Bang"

1. Things we know:
   - The Universe is expanding from a state that was much hotter, denser and more uniform than today.

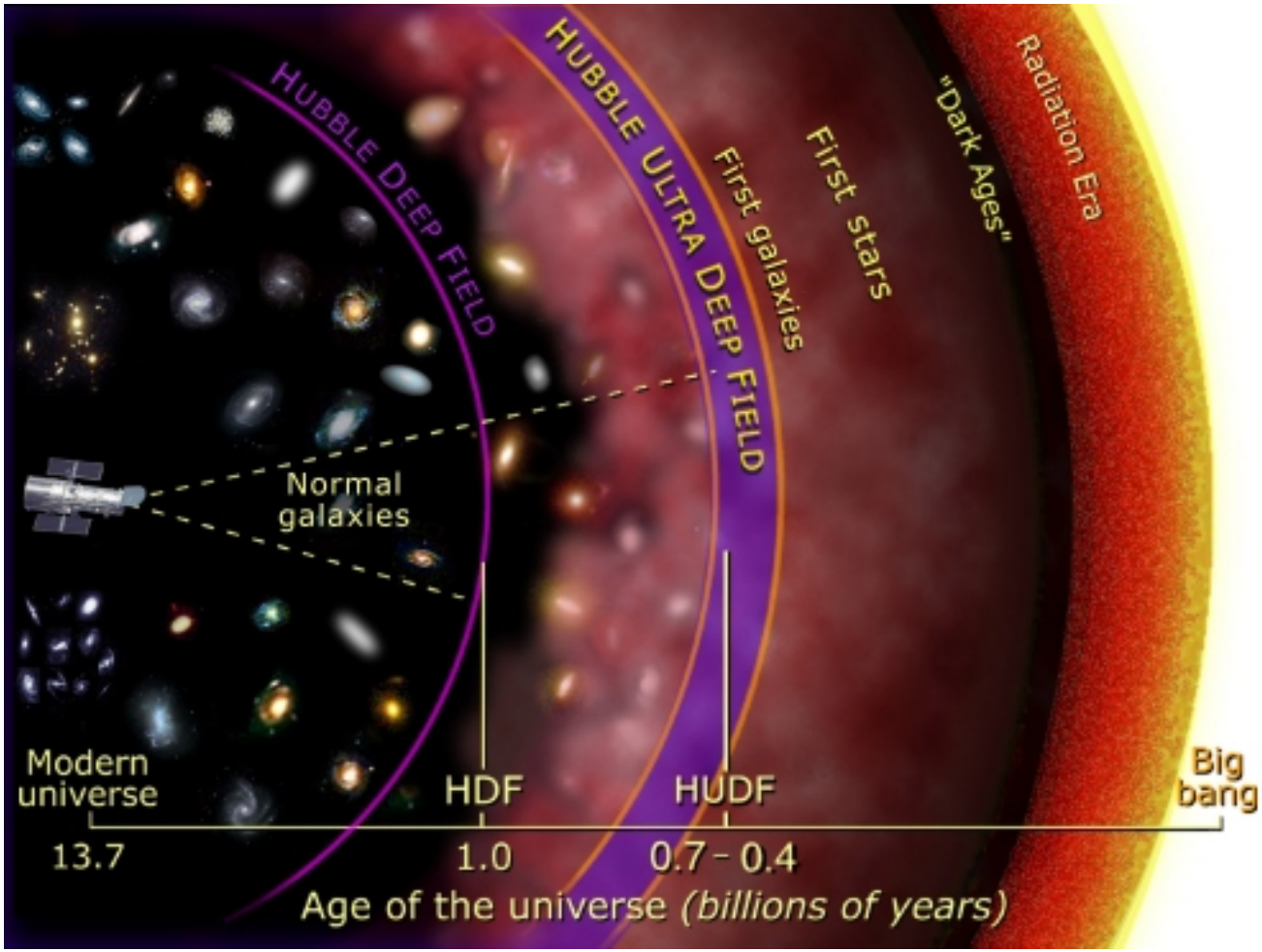
2. Things we don't know:
   - How the Universe came to be in this initial state.
   - What happened "before". This question may be meaningless.

The Big Bang was not an Explosion into Empty Space!!! There is no center!!!



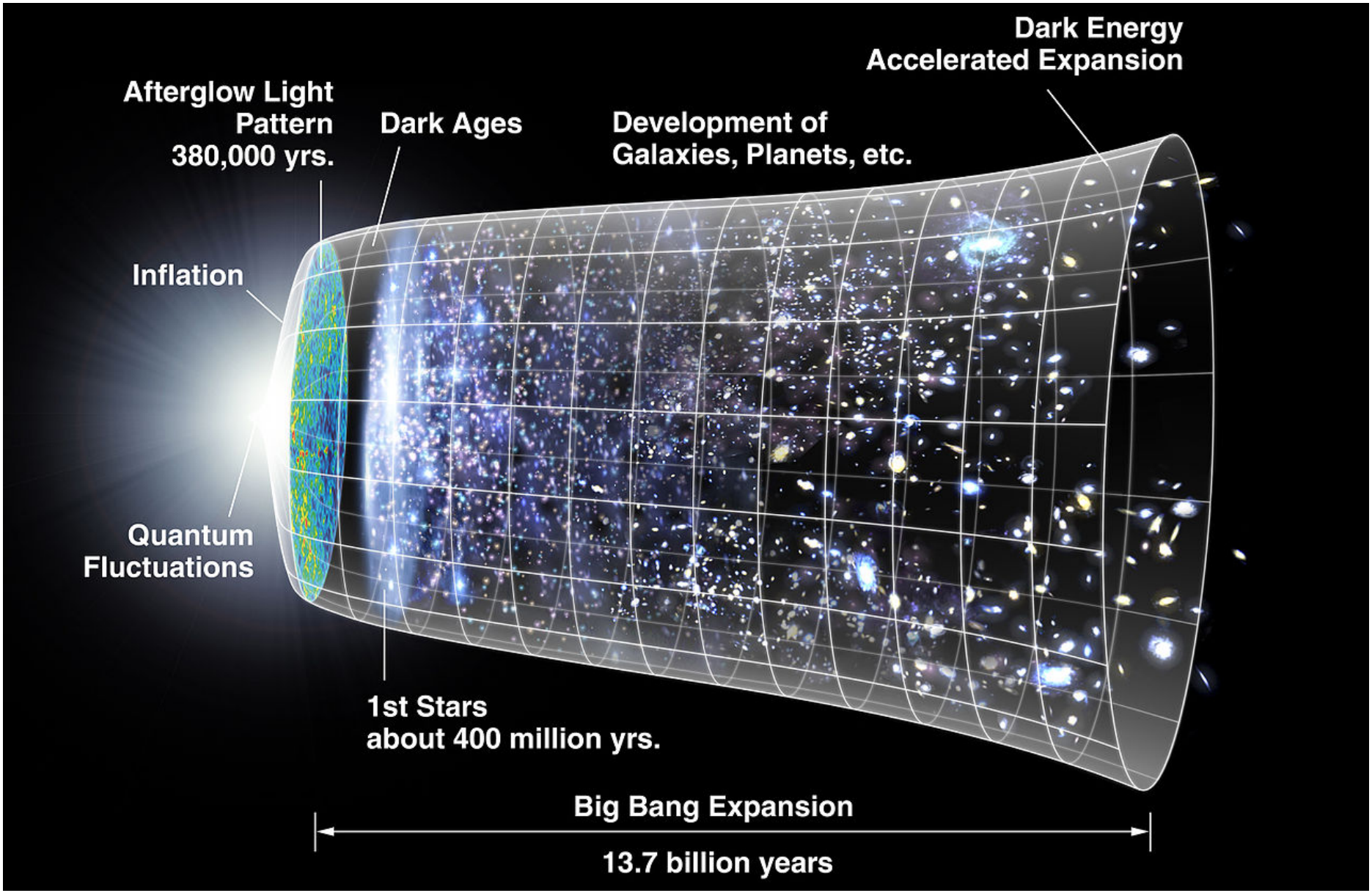
- Remember,"The whole universe was in a hot, dense state".

As we look out in Space, we look back in Time



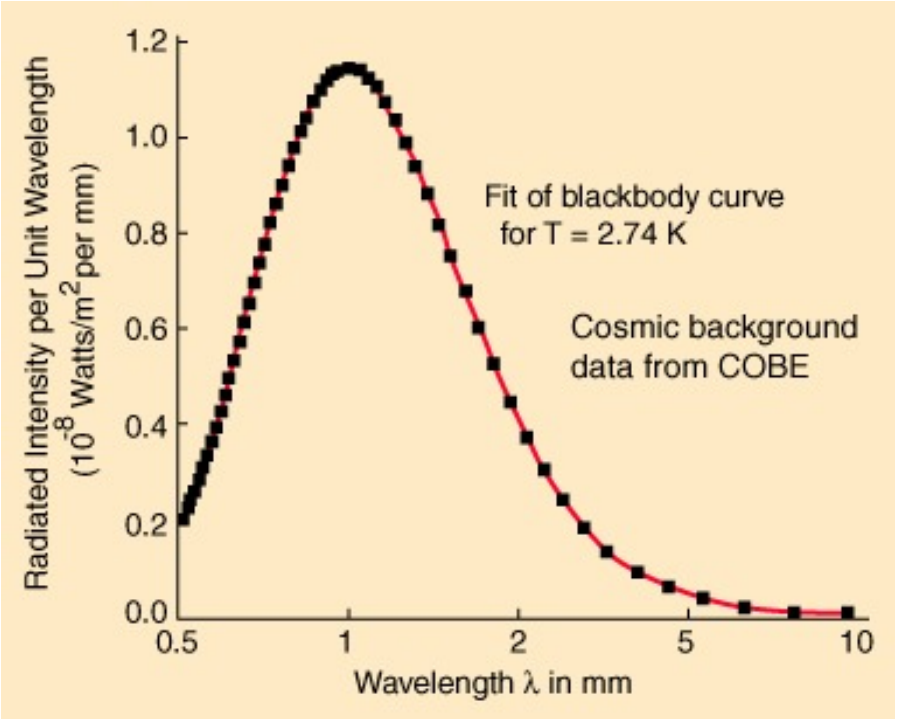
- We cannot see past the radiation dominated era, because the Universe was opaque before then.

Another view of the Evolution of the Universe



The Cosmic Microwave Background (CMB) - the "Flash" of the Big Bang

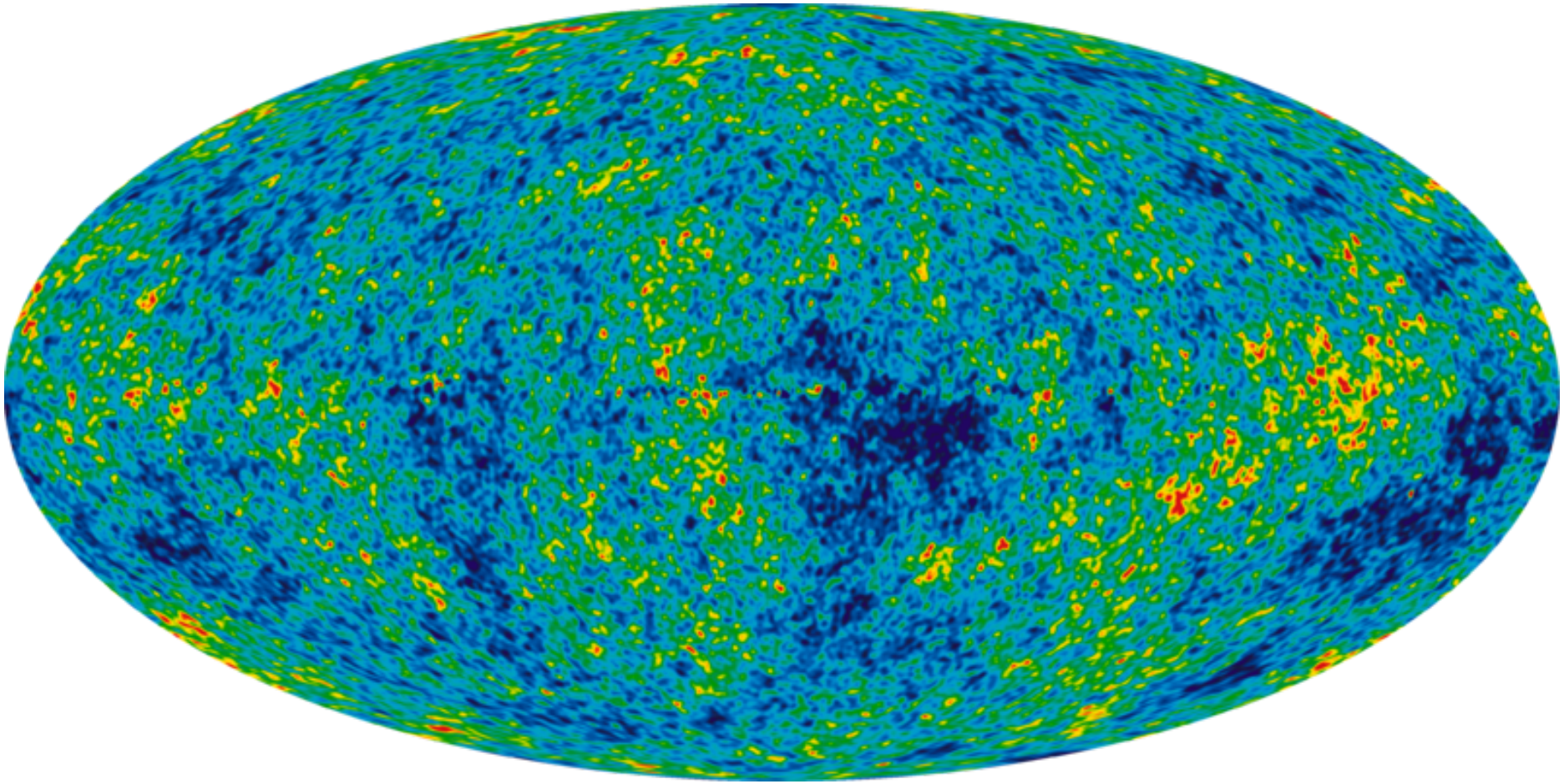
The CMB was discovered in 1964 by Penzias and Wilson.



The CMB is an almost perfect blackbody.

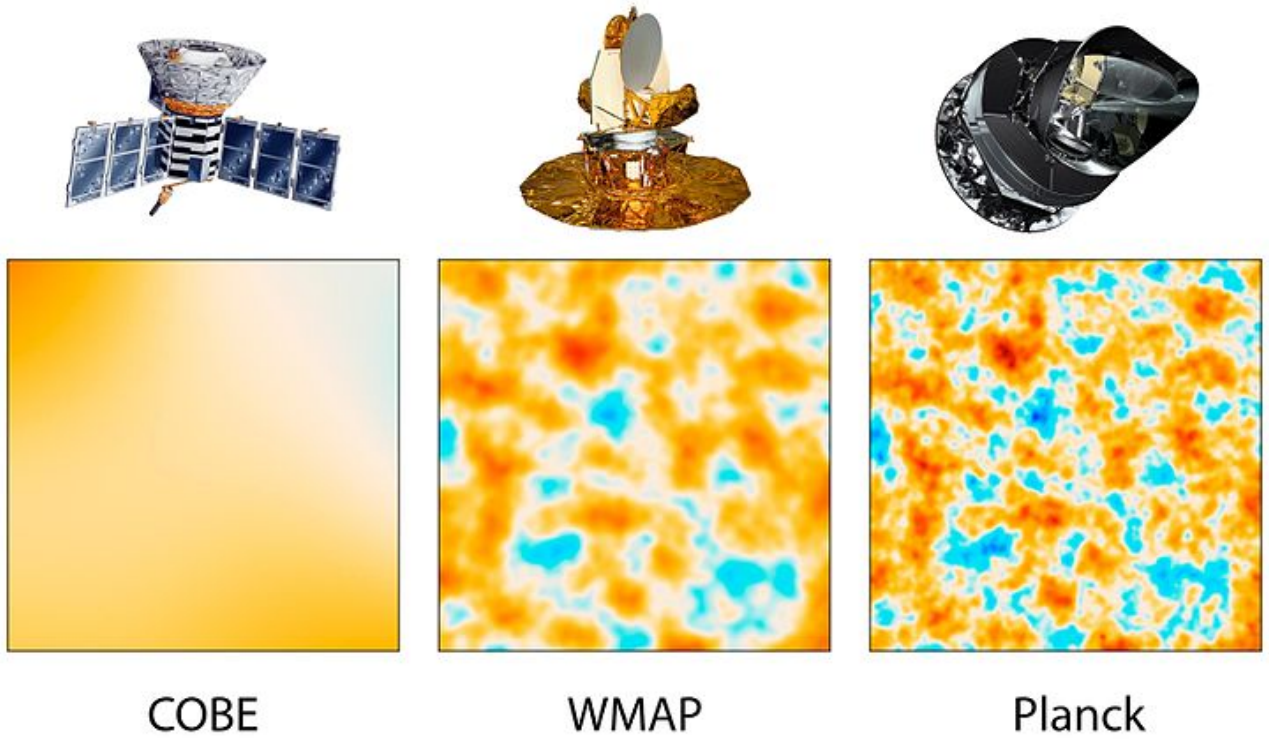
- The CMB radiation was emitted by hot gas at about 3000 K.
- The universe has cooled by about 1000 times since then, so today it is at about 3 K.

The Non-Uniformity of the CMB - WMAP



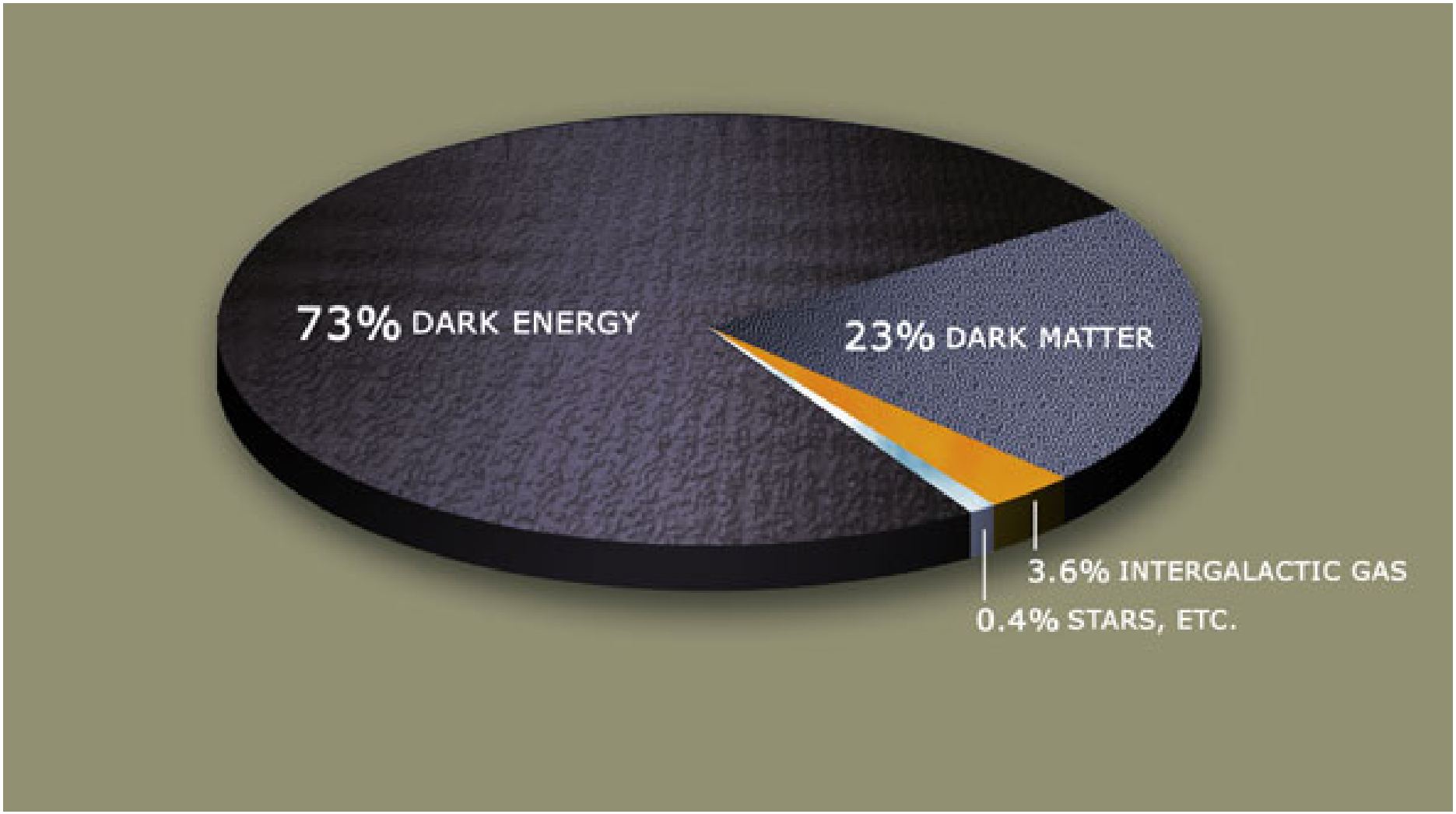
- This is an all-sky map of the CMB.
- It is uniform to about 50 ppm.

Improving Measurements of the Non-uniformity of the CMB

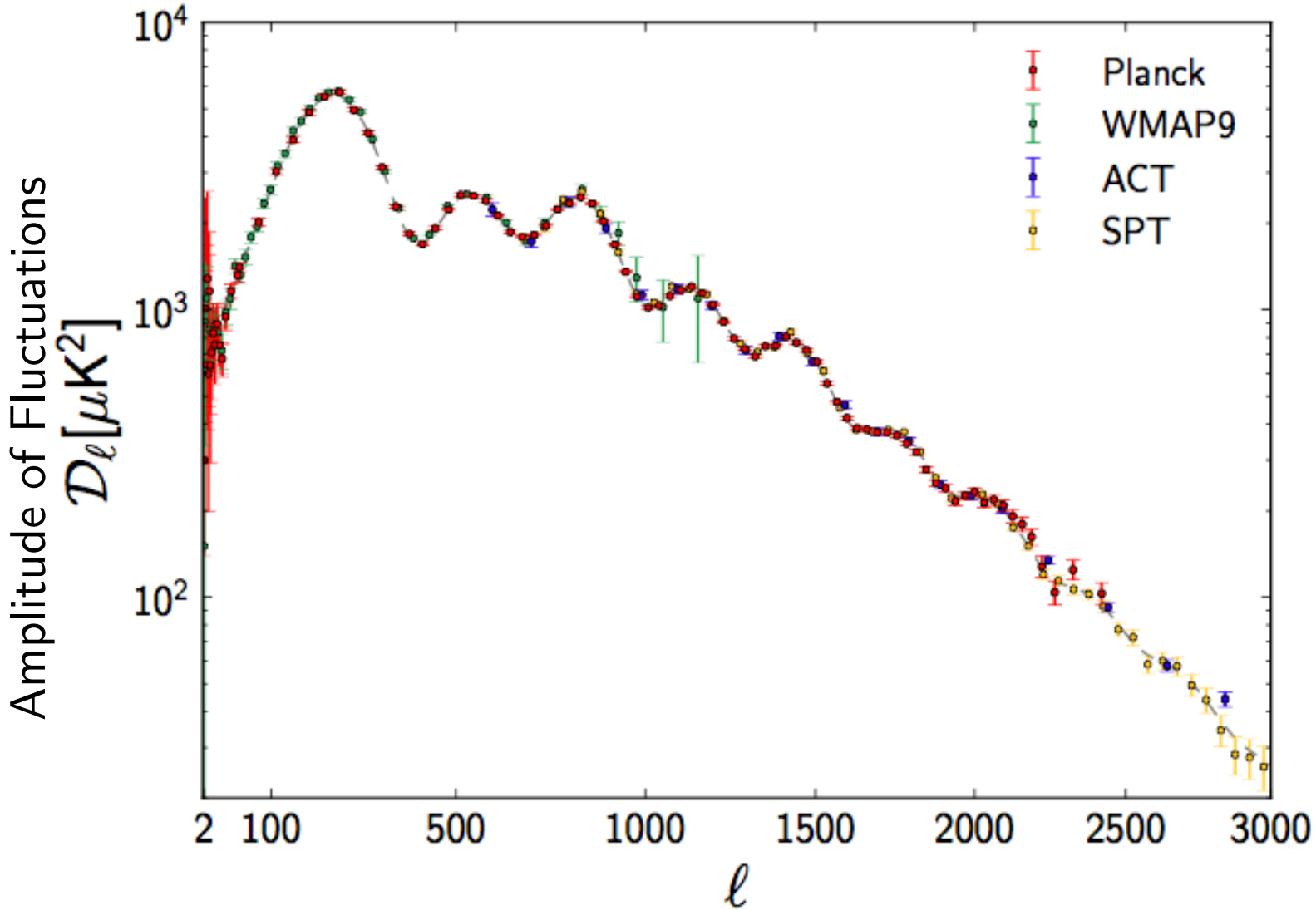


- The CMB is uniform to about 50 ppm.
- However, these small non-uniformities carry a great deal of information.

Our Current Picture of the Composition of the Universe

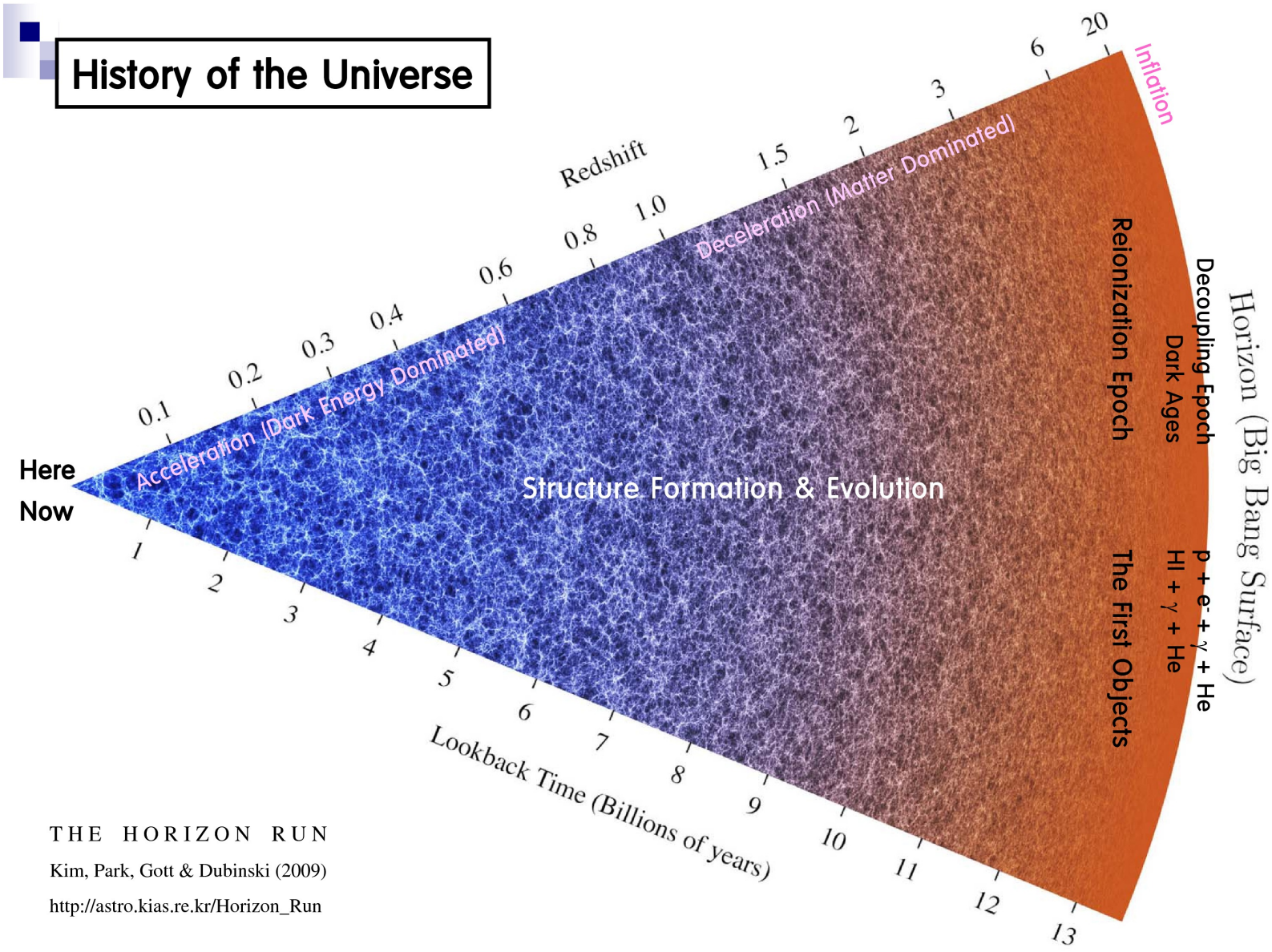


Measured CMB Non-Uniformities vs Theory

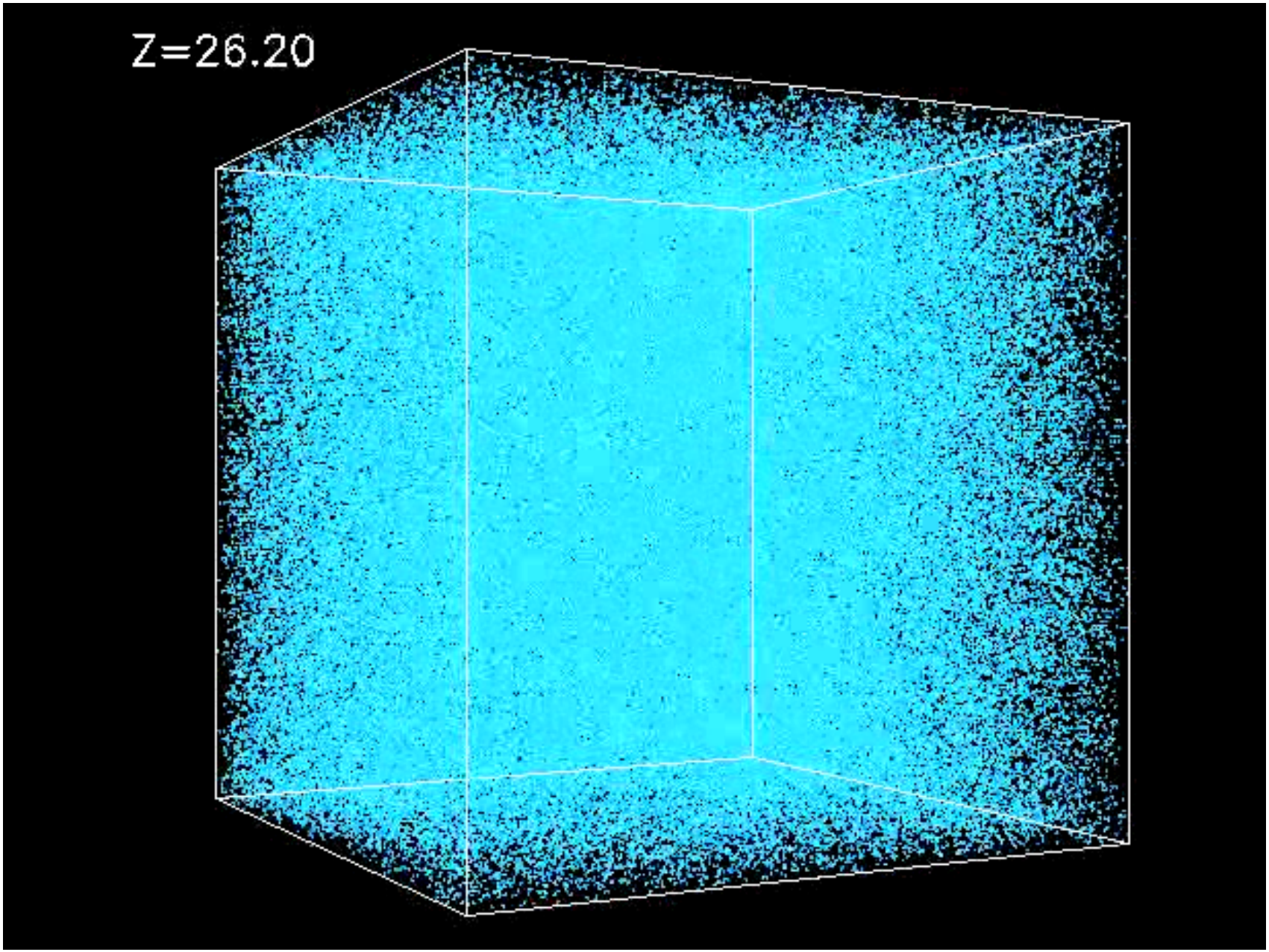


$\Leftarrow$ Large Scale Fluctuations – Small Scale Fluctuations$\Rightarrow$

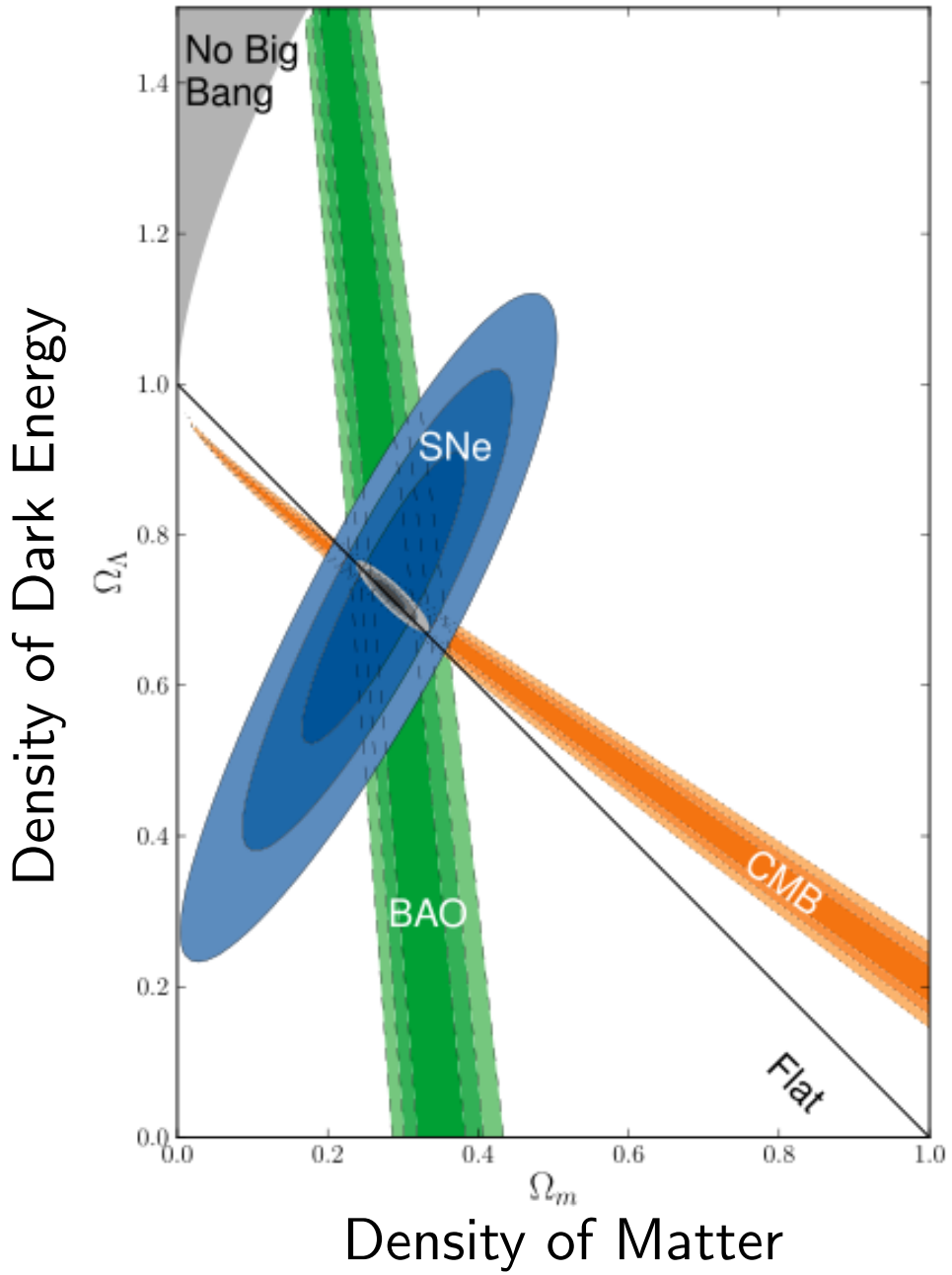
A Simulation of the Evolution of the Universe



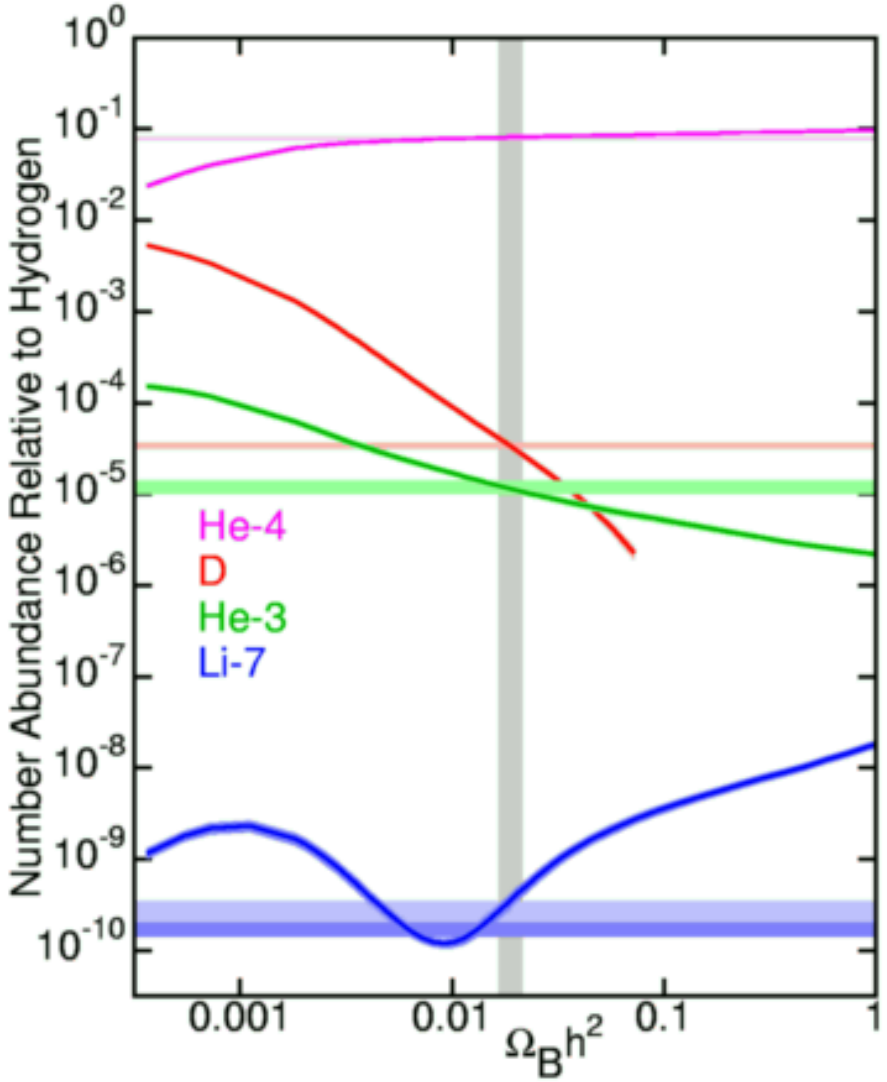
Movie of Structure Growth



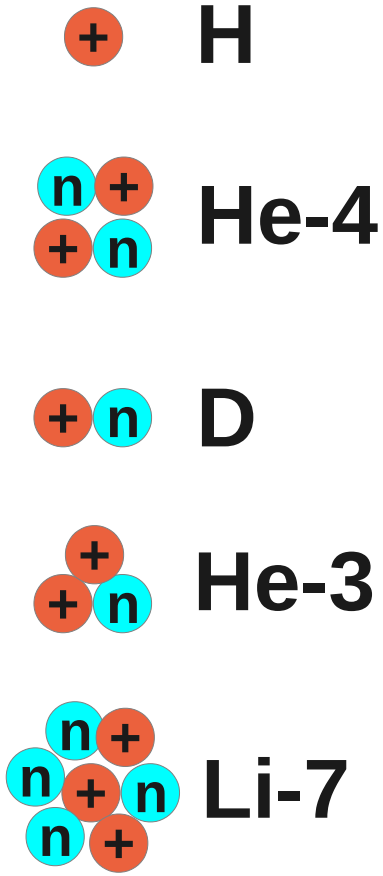
Overlap of Different Measurements



Agreement of CMB with Elemental Abundances



Density of Ordinary Matter (Atoms)



Excellent Agreement of Different Measurements

- Four completely different types of measurements all agree very well:
  - Measurements of the CMB using microwave satellites.
  - Measurements of Baryon Acoustic Oscillations by counting galaxies in different areas of the sky.
  - Measurements of abundances of hydrogen, deuterium, helium, and lithium in the oldest stars.
  - Measurements of expansion rate using Type 1A supernovae.
- The fact that all of these measurements overlap in a small region gives us great confidence that the baseline model of cosmology is correct.
  - This model is called the $\Lambda\mathrm{CDM}$ model.
  - It is based on Einstein's General Theory of Relativity applied to the universe as a whole.

Dark Energy - The Story of Λ - 1

- 1915 - Einstein publishes the equations of General Relativity:

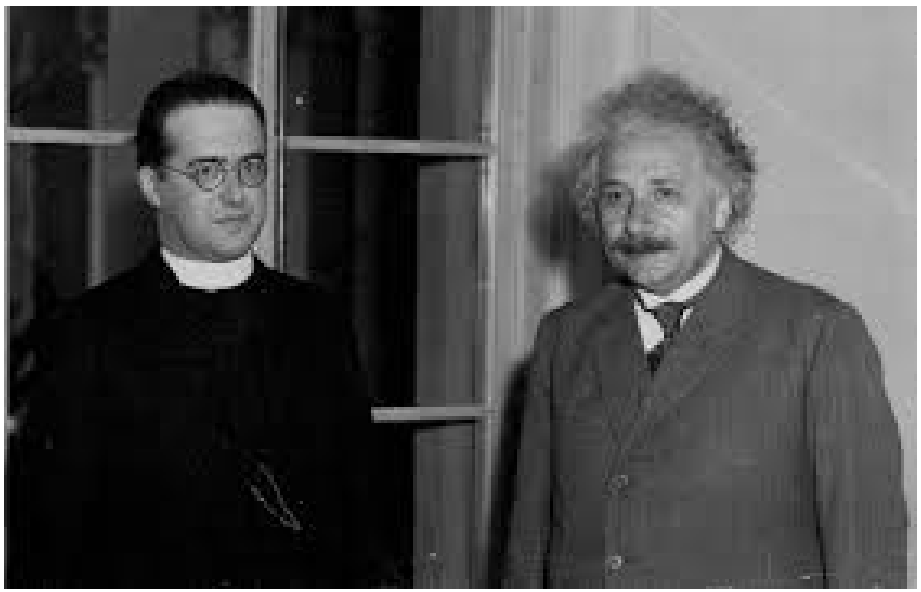
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- 1917-1927 - Einstein, Lemaitre, Friedmann and others apply these equations to the Universe as a whole and realize they imply that the universe is expanding.
- 1917 - Einstein adds the "Cosmological Constant" - Λ to the equations in an effort to have a static Universe.

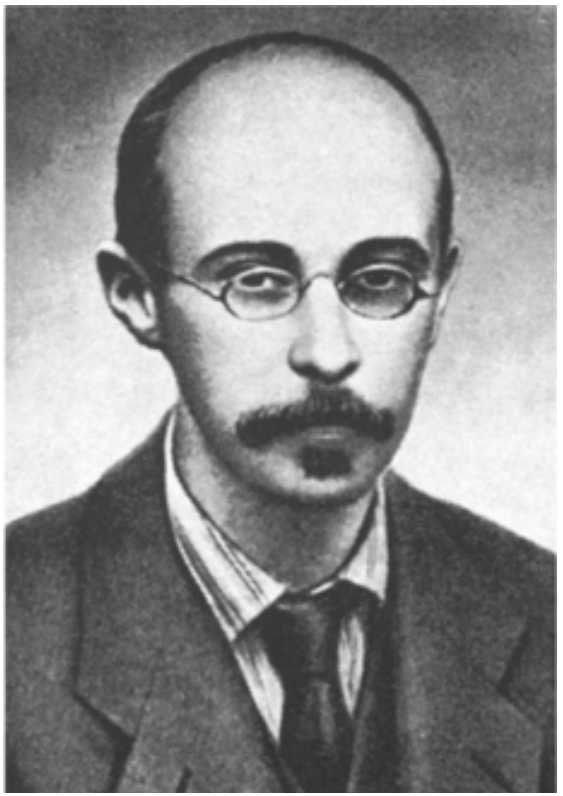
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- 1929 - Hubble discovers that the universe is expanding.
- ca 1940 - Einstein calls Λ his "greatest blunder".
- 2011 - Perlmutter, Riess, and Schmidt receive the Nobel Prize for showing that Λ is present in our universe.

Dark Energy - The Story of Λ - 2

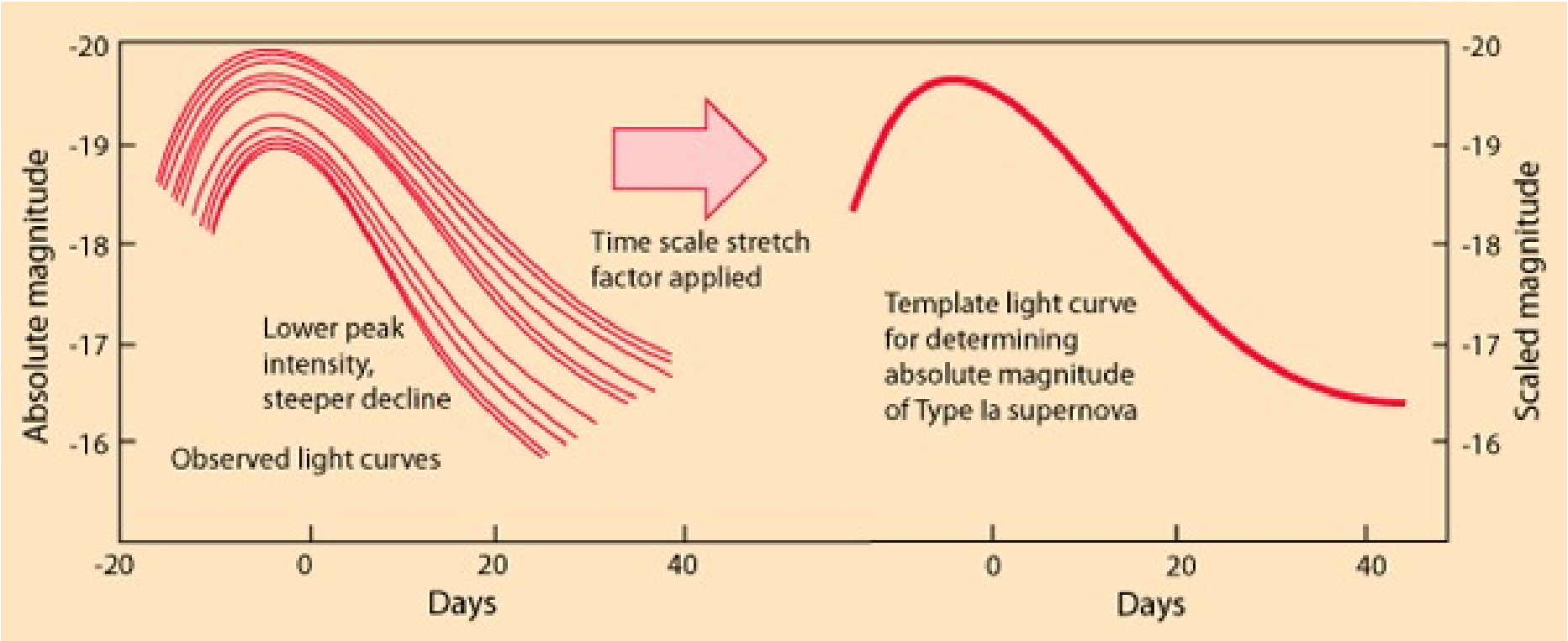


Einstein and Lemaitre



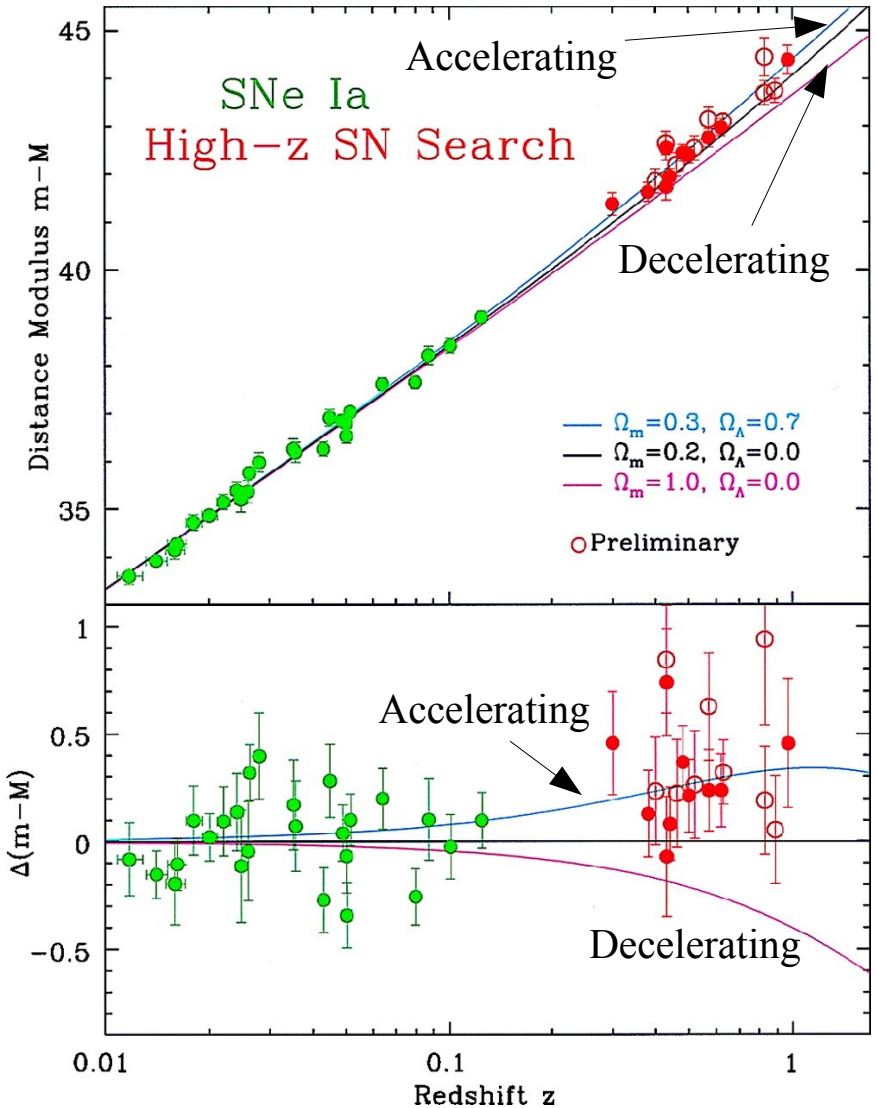
Friedmann

Type 1A Supernovae as Standard Candles



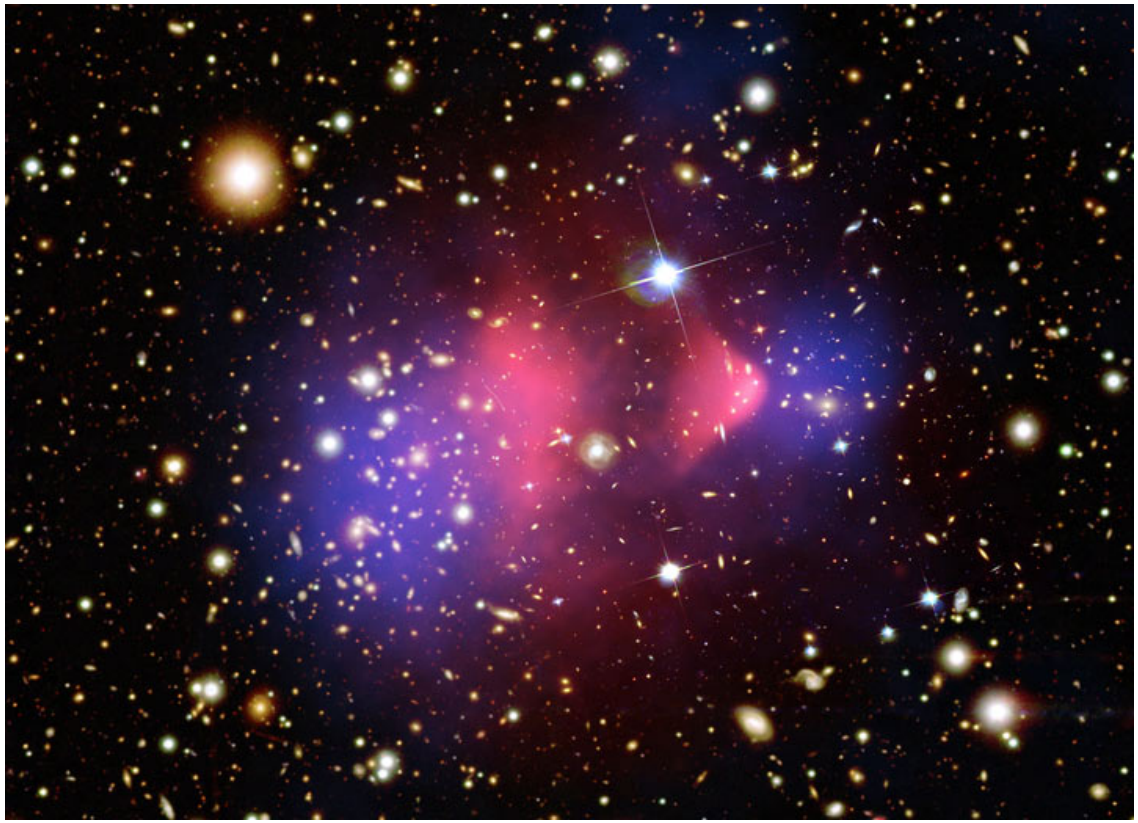
- Type 1A supernovae are exploding white dwarf stars.
- They all have a similar intrinsic peak brightness.
- We can use them as standard candles.

Type 1A Supernovae show the Expansion of the Universe is Accelerating



Kirshner R P PNAS 1999;96:4224-4227

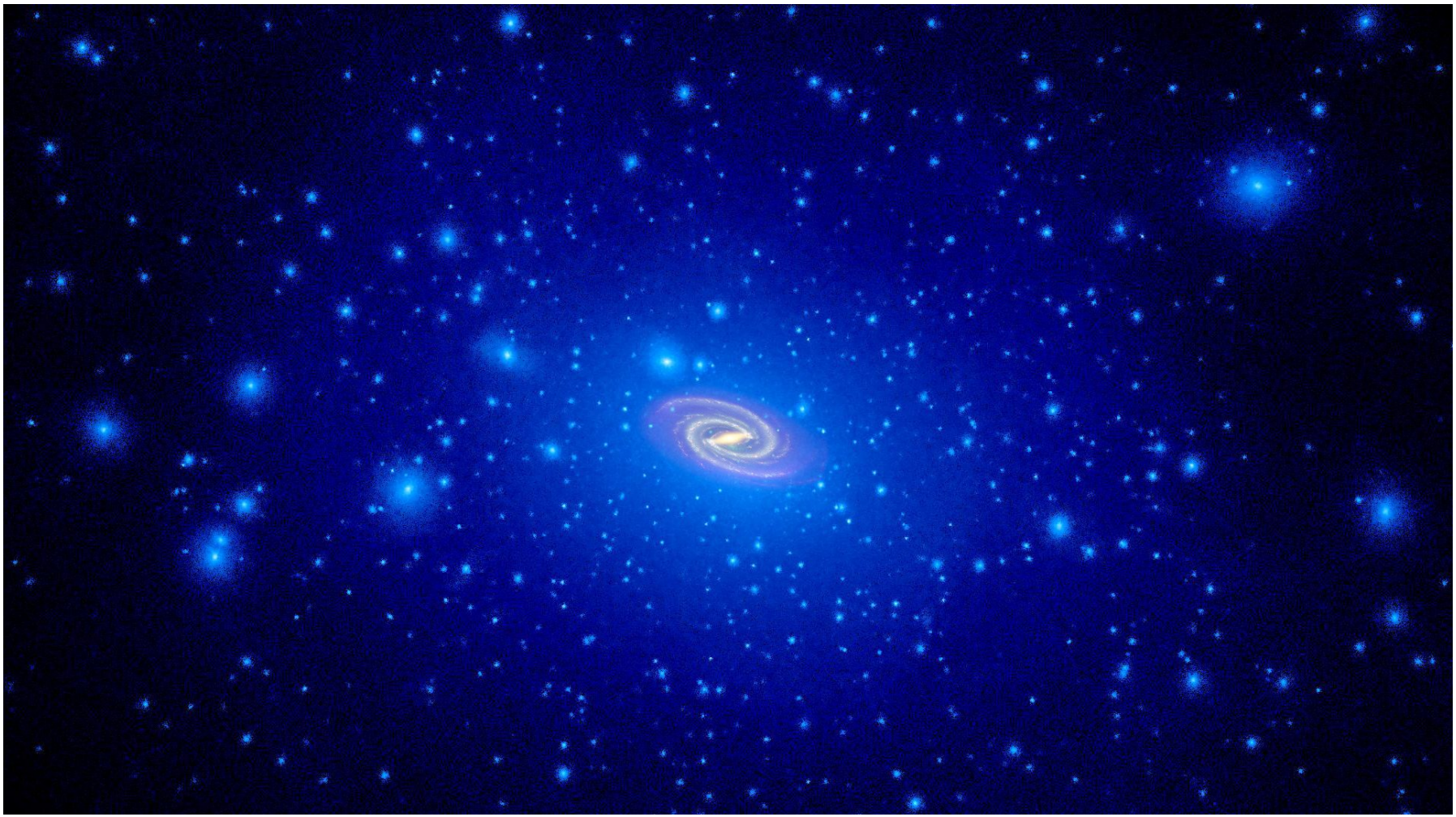
The Bullet Cluster



Clowe - 2006

- Ongoing collision of two massive galaxy clusters
- Distance $\approx 1.2\mathrm{Gpc}$ (z = 0.296)
- Considered the best "proof" of the existence of dark matter.
  - Separation of the dark matter (blue) from the ordinary matter(pink) indicates that dark matter is "real".

The Milky Way Dark Matter Halo (Artist's Conception)



What *ARE* Dark Energy and Dark Matter

- Dark Energy:
  - Completely described by Λ - constant in space and time.
  - We believe it represents the energy density of empty space.
  - Experiments are testing whether it varies.
- Dark Matter:
  - It appears to be a form of matter in that some regions have a lot of it and others nearly none.
  - So far, we have only seen it to interact through gravity.
  - It doesn't interact with electromagnetism - that's why it is "dark".
  - We think it is an undiscovered type of particle.
  - Many people are trying to find it, but so far - no success.

Summary

1. The Universe is expanding from an initial state that was much hotter, denser, and more uniform than today.
2. We see the evidence of the early hot phase of the universe as the Cosmic Microwave Background (CMB).
3. The current model of the Universe - called the $\Lambda\mathrm{CDM}$ model, describes the observations with great accuracy.
4. The main features of this model are:
   - The expansion started about 13.7 billion years ago.
   - About 70% of the energy density of the Universe is in the form of "Dark Energy" - an apparently uniform energy density in empty space.
   - About 26% of the energy density of the universe is in the form of "Cold Dark Matter" - believed to be an undiscovered type of sub-atomic particle.
   - About 4% of the energy density of the universe is in the form of ordinary atoms.