Concepts in Theoretical Physics

Lecture 8: Cosmology

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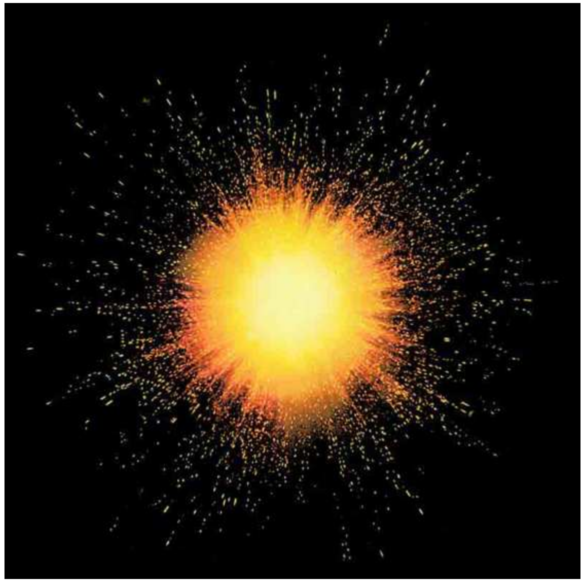
The Big Bang

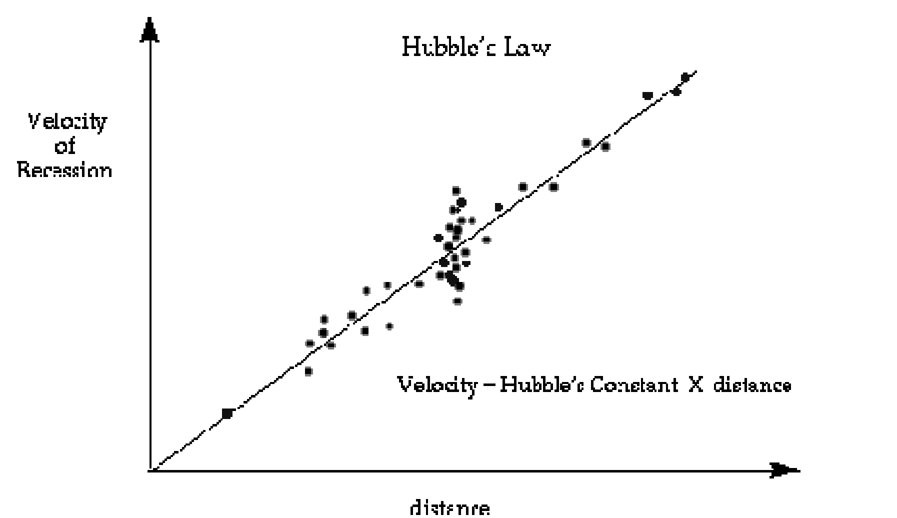
- This is not what the big bang looked like.



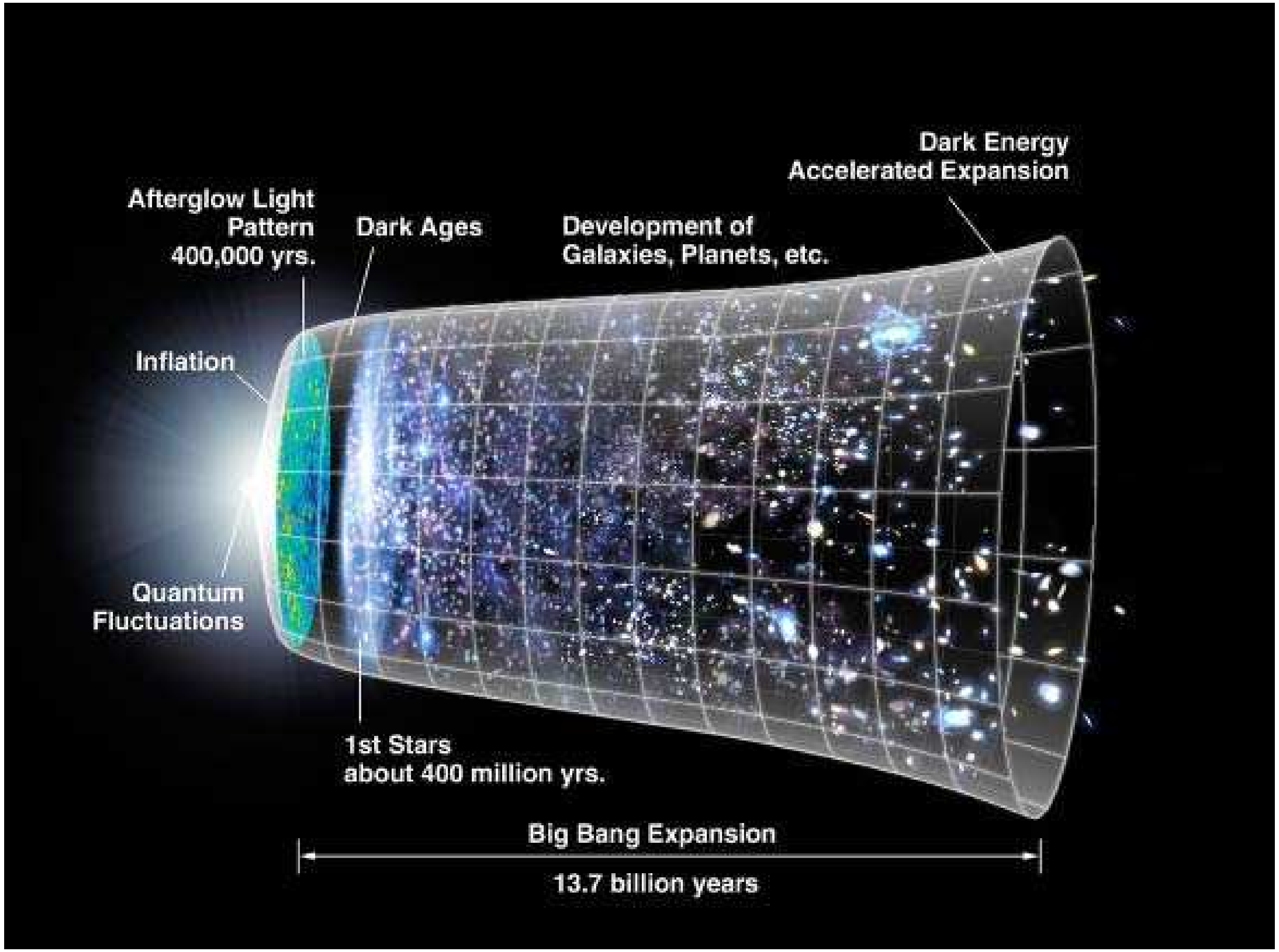
- There is no bang in the big bang. There is no explosion.
- Big bang theory has *nothing* to say about how the universe started. We don’t know the answer to that question

Big Bang Theory

- The theory simply tells us what the universe looked like when it was younger. This follows from a simple observation:
  - The universe is expanding. Everything is getting further apart
  - In the past, everything was closer together
  - That’s it!



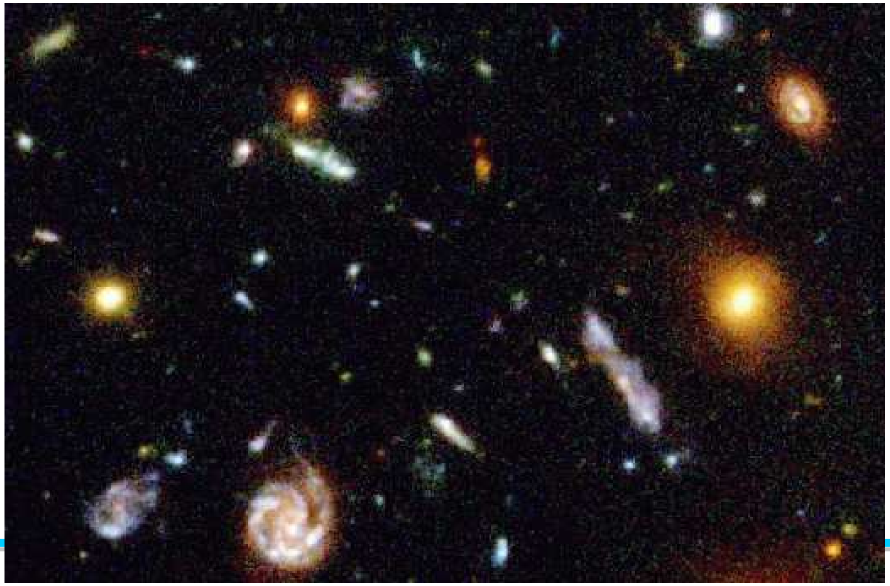
History of the Universe



History of the Universe

- 13.7 billion years: Today
- 9.3 billion years: Solar system forms
- 2.6 billion years: Milky way forms
- 1 billion years: First galaxies
- 500 million years: First stars

…



History of the Universe

- 400,000 years: Atoms form
- 10^{-2} seconds: Nuclei form
- 10^{-6} seconds: Protons/neutrons form (quark-gluon plasma)
- 10^{-11} seconds: Electro-weak phase transition
- 10^{-34} seconds: Inflation?

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<u>Big Bang Nucleosynthesis</u>

This is understood with glorious precision, and depends crucially on details of particle physics.

If you have a crazy theory about the early universe, this is a loophole that it has to jump through.

- 75 % H
- 25 % He
- 10^{-5} % D
- 10^{-10} % L

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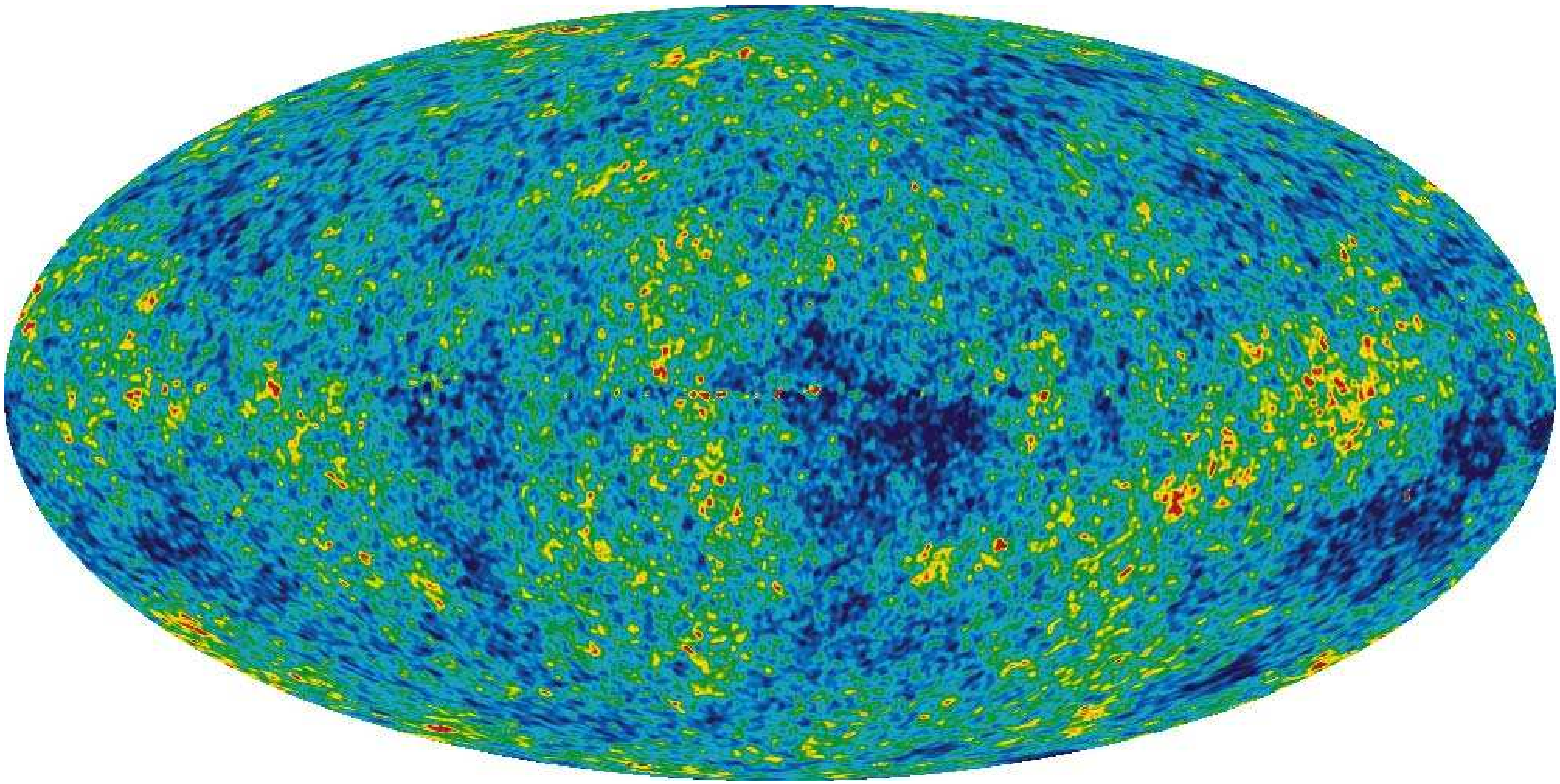
<u>Recombination</u>

This is the earliest that we can see. Before this time, the universe was filled with a charged plasma. Light cannot pass.

This plasma is now cold: 2.7K. It is called the cosmic microwave background radiation. It contains ripples at the level of 1 part in 10^5…

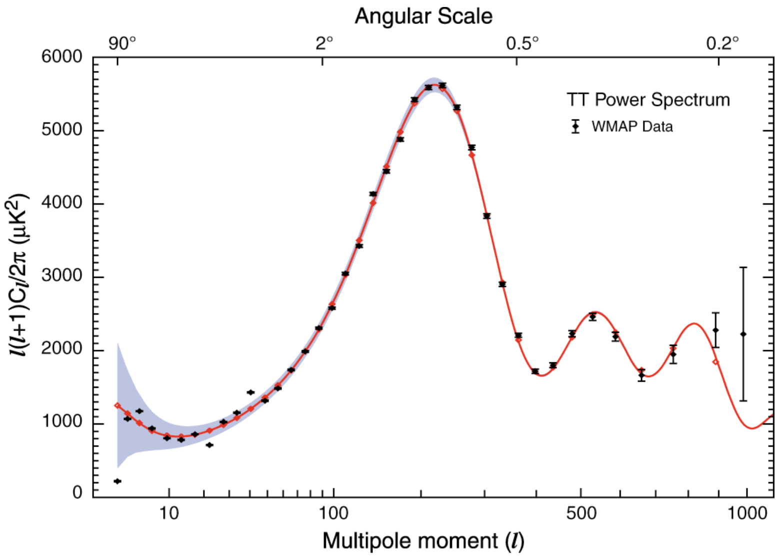
Cosmic Microwave Background



WMAP: 5 year data

Cosmic Microwave Background

- These fluctuations define a function on the sky
- We can look at spherical harmonics.
- The line is theory; the dots are data points (with error bars!)
  - This is how well we understand the universe almost 14 billion years ago



- Best understanding: galaxies formed by matter falling into cold spots formed by quantum fluctuations in the early universe.

The Expanding Universe

- Work with spacetime intervals (like in special relativity).
  - Assume isotropic, homogeneous and flat.

$$ds^2 = dt^2 - a(t)^2\, d\vec{x}^2$$

- Einstein's equations tell us how *a(t)* changes.
  - This depends on the energy density ρ in the universe
  - This is known as the Friedmann equation

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\,\rho$$

Types of Energy

- Three important types of energy density
- Matter: This dilutes as the universe expands.

$$\rho_M(t) \sim \frac{1}{a(t)^3} \quad \Longrightarrow \quad a(t) \sim t^{2/3}$$

- Radiation: This dilutes, but also redshifts.

$$\rho_R(t) \sim \frac{1}{a(t)^4} \quad \Longrightarrow \quad a(t) \sim t^{1/2}$$

Types of Energy

- Vacuum Energy: This remains constant as the universe expands
  - a.k.a. cosmological constant or dark energy

$$\rho_\Lambda(t) \sim \text{constant} \quad \Longrightarrow \quad a(t) \sim e^{t}$$

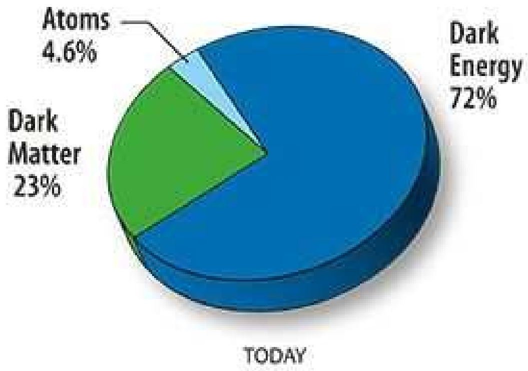
- Unlike matter and radiation, this leads to an expanding and *accelerating* universe.
  - Vacuum energy is like an anti-gravitational force field
  - Current universe contain dark energy: galaxies will dissapear from view in 150 billion years.

What is our Universe Made of?

- Current observations tell us:

$$\rho = 0.72\rho_\Lambda + 0.28\rho_M + 10^{-5}\rho_R$$

- Moreover, the matter energy density is:
  - 0.23 dark matter
  - 0.05 visible matter.

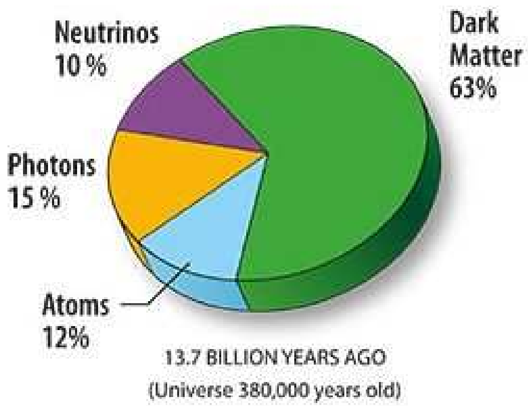


- Dark matter does probably not need a conceptual leap.
  - Nearly all models of particle physics predict new neutral particles which could play the role of dark matter

What was our Universe Made of?

- Because the different energy densities dilute in different ways, the composition of the universe was different in the past

- e.g. At recombination, the energy budget looked like this:



- Question: when was $\rho_\Lambda = \rho_M$?
- Answer: 11 billion years after big bang
  - For comparision: life on earth started 10.5 billion years after the big bang

- Homework: Write down a natural theory of particle physics with vacuum energy which does nothing for 11 billion years and then takes over the universe.