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.
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

- Inflation
- Quantum Fluctuations
- Afterglow Light Pattern 400,000 yrs.
- Dark Ages
- Development of Galaxies, Planets, etc.
- Dark Energy Accelerated Expansion
- 1st Stars about 400 million yrs.
- Big Bang Expansion 13.7 billion years
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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**Big Bang Nucleosynthesis**

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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Recombination

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 \( \rho \) 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.

    \[ \rho_M(t) \sim \frac{1}{a(t)^3} \quad \Rightarrow \quad a(t) \sim t^{2/3} \]

  - Radiation: This dilutes, but also redshifts.

    \[ \rho_R(t) \sim \frac{1}{a(t)^4} \quad \Rightarrow \quad a(t) \sim t^{1/2} \]
Types of Energy

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

\[
\rho_\Lambda(t) \sim \text{constant} \quad \implies \quad a(t) \sim e^t
\]

- 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 disappear 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 comparison: 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.