Announcements

- Quiz#6 (last quiz) on Thursday
- Homework#5 due today!
  - Please turn it in NOW.

Lecture 22
Inflation – before the Big Bang

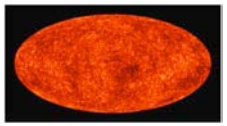
Reading: Chapter 23

Success of the Big Bang theory

- Expansion of the Universe
- Existence of the cosmic microwave background
  - The universe was hot in the past.
  - Thermal equilibrium
- Abundance of light elements
  - 75% Hydrogen, 25% Helium
  - A little bit of Deuterium and Lithium
- Is the Big Bang theory perfect?

Shortcomings of the Big Bang Model

- So far, we have considered the evidence which supports the Big Bang theory.
- Prior to 1980, cosmologists had identified **three major questions** which the theory was unable to answer:
  1. Where does structure come from?
  2. Why is the large-scale Universe so smooth?
  3. Why is the density of matter almost critical?

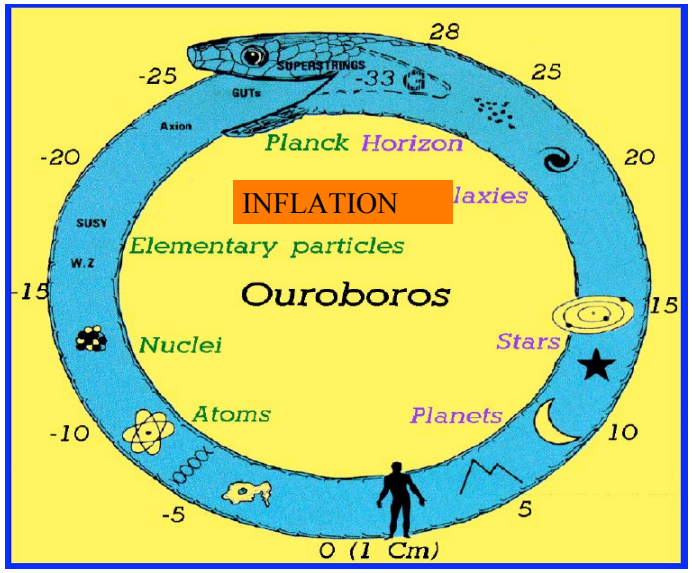


- In other words, the Big Bang theory does not tell us anything about initial conditions of the Universe. (How did it get started?)
- **What initiated the Big Bang??**

Birth of Inflationary Theory

- In 1981, physicist Alan Guth realized that the Grand Unified Theories could hold the answers to these questions.
- When the strong force froze out of the GUT force…
  - it should have released enough energy to expand the Universe 10^{30} times in less than 10^{-36} sec
  - we call this dramatic expansion ***INFLATION***
- Alan Guth unified the early universe physics with particle physics…

Ouroboros's Snake

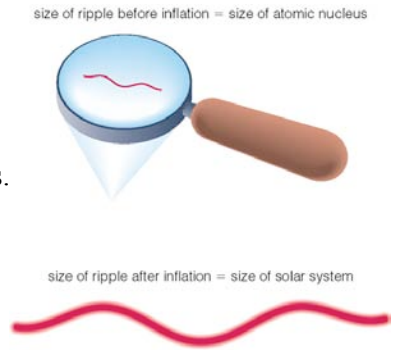


Quote from Alan Guth's Book

- After a few of the most productive hours I had ever spent at my desk, I had learned something remarkable… By 1:00am, I knew the answer: Yes, more than I could have ever imagined.
- The next morning I bicycled hurriedly to my office to start work, breaking my personal speed record with a time of 9 minutes and 32 seconds.
- My instincts were telling me that I might be on to something big.

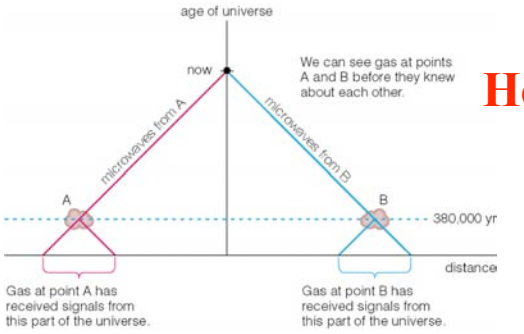
Where Does Structure Come from?

- The density of matter in the early Universe had to differ slightly from place to place.
  - otherwise, galaxies would never have formed
  - traditional Big Bang model does not tell what caused density enhancements
- Quantum Mechanics: energy fields must fluctuate at a given point.
- Energy distribution is irregular…
  - on microscopic spatial scales
- These quantum ripples would be greatly magnified by inflation.
- Large ripples in energy are the seeds for the density enhancements.
  - they imposed a pattern about which structure formed
- **Quantum Fluctuations**
  - Ultimate origin of everything!



Why is the Large-Scale Universe so Smooth?

- In all directions, the Cosmic Microwave Background is uniform.
- Traditional Big Bang model can not explain…
  - how two disparate parts of the Universe, beyond each other's cosmological horizon, can have the same temperature



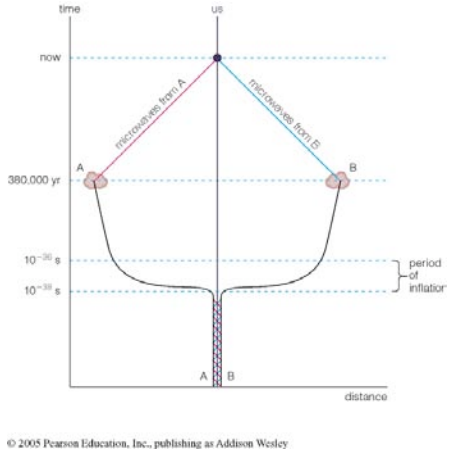
Horizon Problem

Quote from Alan Guth's Book

- Having learned about the horizon problem at lunch, I went home and thought about it.
- Eureka!
- The exponential expansion of inflation would obliterate this problem, too.

Solution to the Horizon Problem

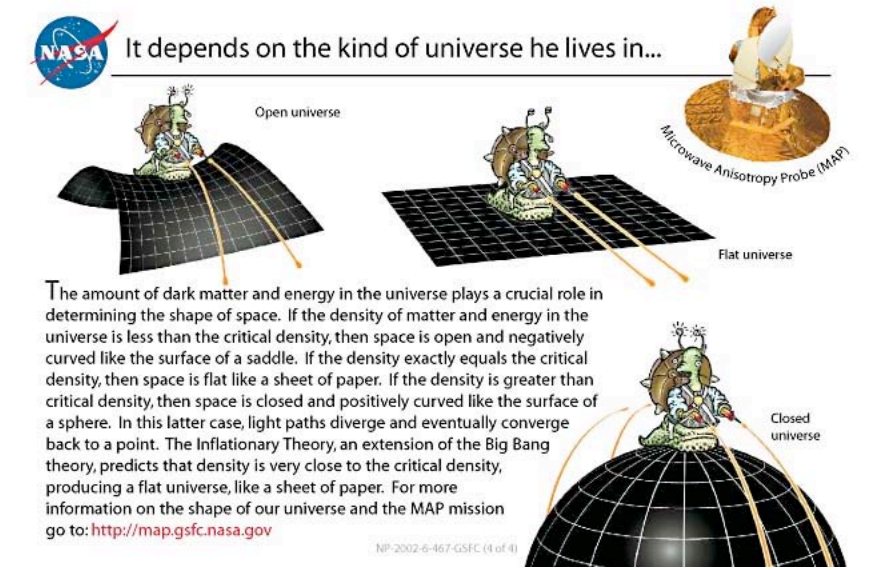
- Inflation can solve this problem.
  - the entire Universe was less than 10^{-38} light-second across
  - radiation signals could reach all points in the Universe
  - temperatures were equalized
  - then inflation expanded the Universe so quickly
  - that many points in the Universe went out of communication with each other

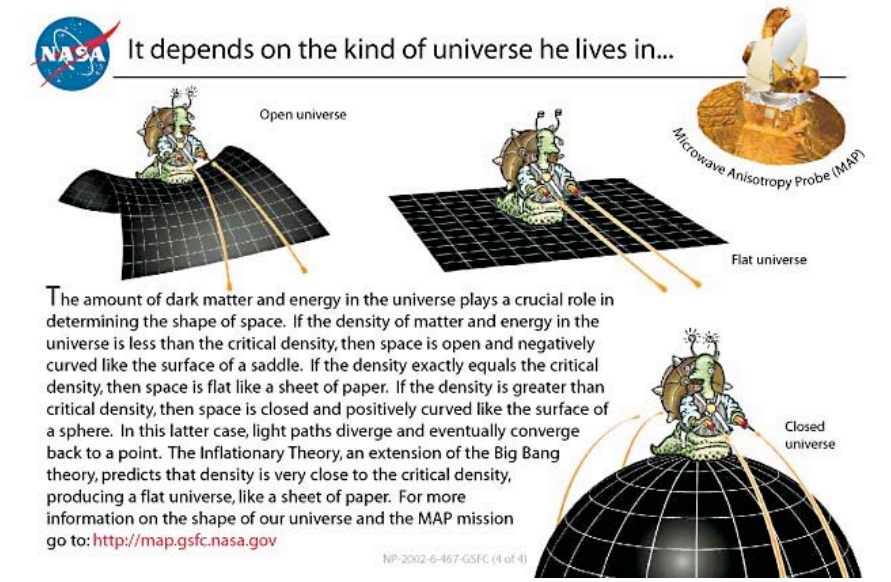


Why is the Density of Matter Almost Critical?

- The gravitational pull of the Universe almost balances the kinetic energy of its expansion…Why?
  - if matter were at least 10% denser, Universe would have already collapsed
  - if matter were at least 10% less dense, galaxies would have never formed
- According to General Relativity, an imbalance of these energies imposes a curvature of spacetime.
  - but when they balance, we say that spacetime is "flat"

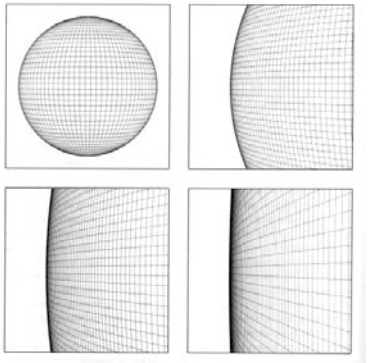
Flatness Problem





Solution to the Flatness Problem

- The effect of rapid inflation is to flatten spacetime.
  - thus, inflation imposed the balance of these energies
- Imagine surface of an expanding balloon.



Steven Weinberg's response

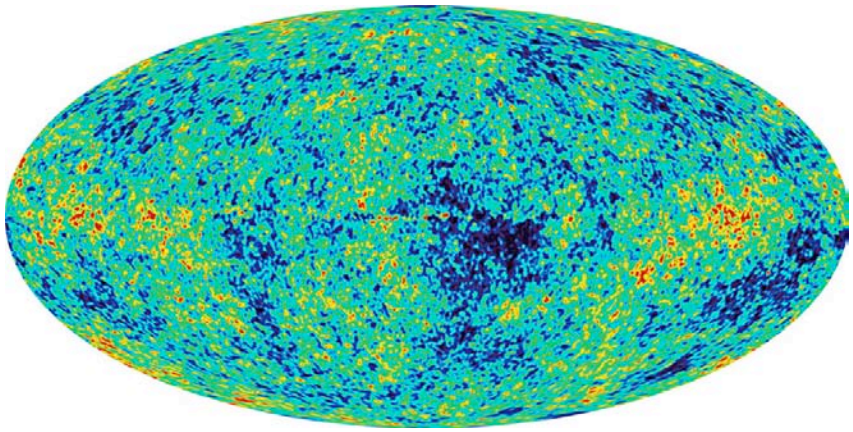
- Sheldon Glashow (another Novel laureate in Physics) told Alan Guth that he had decided inflation must be a good idea when he explained it to Steven Weinberg, who became "furious".
- "Did Steve have any objections to it?", Alan asked.
- "No," replied Sheldon, who enjoyed poking fun at his colleague.
- "He just didn't think of it himself."

Then, "Bang!"

- A very rapid expansion of the universe (inflation) will make the universe extremely cold.
  - Temperature will reach absolute zero.
- How did the universe become hot?
- When inflation ended, the energy which had driven inflation was converted into heat (energy conservation again).
  - This is the moment when the univese became extremely hot.
  - The beginning of the hot universe --- the Big Bang.
- Note that there was no explosion.
  - In that sense, the popular picture of the Big Bang as a big explosion is not quite correct.

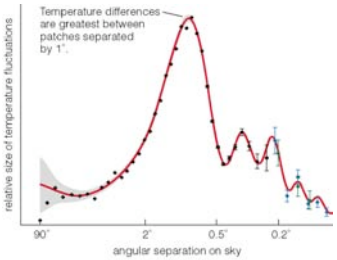
New Evidence for Inflation

- In 2002, the *Wilkinson Microwave Anisotropy Probe* (WMAP) measured the Cosmic Microwave Background with much more precision than COBE.
- It detected far more subtle, small-scale temperature variations.



New Evidence for Inflation

- A Big Bang model with inflation was fitted to:
  - temperature variations plotted as angular separation on the sky
  - the data are shown here



- Overall geometry of the Universe is flat.
- Total matter density is 27% of the critical density.
  - in agreement with M/L in clusters of galaxies
- Density of baryonic (ordinary) matter is 4.4% of critical density.
  - in agreement with observed abundance of Deuterium
- Flat geometry + matter density < critical implies dark energy.
  - in agreement with accelerating expansion from white dwarf supernovae
- Age of the Universe is 13.7 billion years.

Message

- Inflation has changed the way we think about the universe *completely*.
  - It was proposed more than 20 years ago, and it has become the standard theory of the early universe.
- This theory provides us with a picture of the universe before the Big Bang.
  - And, we can even "see" this epoch by observations. (although not directly.)
- Inflation gave us a great stride toward understanding the complete history of the universe.

Next Lecture: The Fate of the Universe

- The last quiz on Thursday (Nov 18)
- Multiple choices
  - *All* of "True Statements?" in Chapter 23
  - 3 additional multiple choices regarding
    - The Big Bang (Problem 10)
    - The Earliest Moment (Problem 12)
    - Nucleosynthesis (Problem 13)
- Short Answer Questions
  - Cosmic Microwave Background