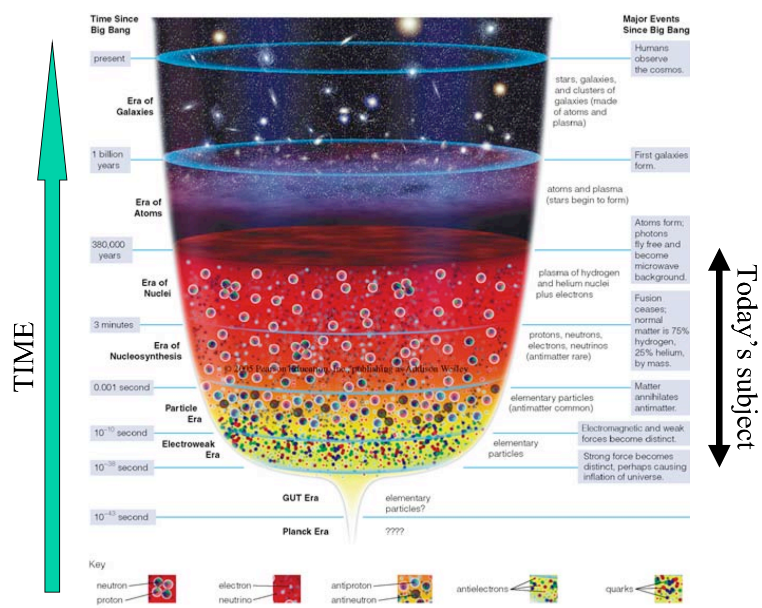
Announcements

- The last quiz on next Thursday (Nov 18)
  - Announced at the end of this lecture

Lecture 21
The Big Bang

Reading: Chapter 23



The Big Bang Theory

- The universe cools down as the universe expands.
- Therefore, as we go back in time, the universe contracts and gets hotter.
- When the universe contracts to a "point", both density and temperature would be infinite – The Big Bang.
- An physicist, George Gamow, is known to be a proposer of the Big Bang theory (1948).

The Steady State Theory

- The universe is expanding, but "steady".
- The universe looks the same at all times.
  - Temperature does not change
  - Galaxies do not evolve
- The theory has to assume continuous creation of matter out of vacuum.
- Fred Hoyle is one of the proposers of the Steady State Theory (1948).

Evidence for the Big Bang Theory

- A good scientific model should make predictions which can be verified.
- The Big Bang model makes two predictions which have been verified since the 1960s:
  - the existence and characteristics of the **cosmic microwave background**
  - the expected **Helium abundance** in the Universe
- The model predictions agree with current observations.
- The Steady State Theory has been ruled out.

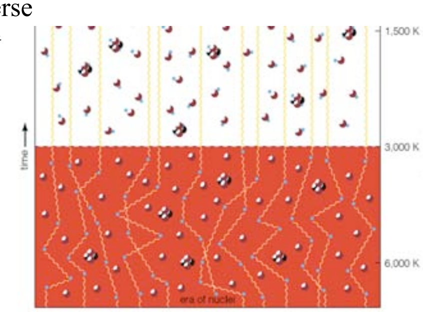
The Hot Universe

- At the end of inflation, the universe became extremely hot.
- High density and high temperature of the universe make it easy for radiation and matter to interact frequently.
- The universe is in "thermal equilibrium", emitting radiation with a thermal spectrum
  - Similar to radiation from stars.
- Can we see this radiation?
  - Yes!

Cosmic Microwave Background

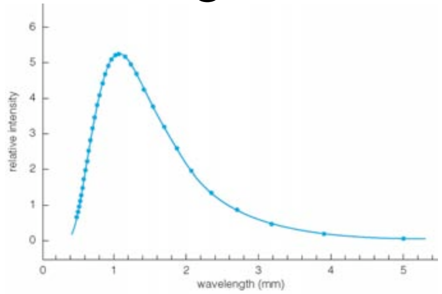
- The Universe is immersed in a sea of radiation.
- This is the same radiation which was emitted at the end of the Era of Nuclei.
  - 380,000 years after the Big Bang, the Universe had cooled enough for free electrons to become bound into atoms of H & He
  - without electrons to scatter them, photons were able to travel unhindered throughout the Universe
  - the Universe became *transparent*

The temperature of the Universe was 3,000 K at this time.



Cosmic Microwave Background

- The spectral distribution of this radiation was the same as radiation from a 3,000 K object.
  - like the surface of a red giant
- Since then, the Universe's size has expanded 1,000 times.
  - cosmological redshift has turned this radiation into microwaves.



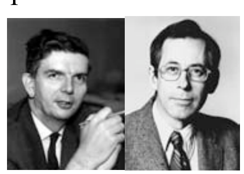
- This Cosmic Microwave Background, predicted by theory…
  - was accidentally discovered in 1965 by Arno Penzias & Robert Wilson
  - appeared to come from every direction
  - had a perfectly thermal spectrum with a temperature of 2.73 K
  - this is the temperature one expects after expanding the Universe 1,000 times
  - The discovery killed the steady state theory

Penzias and Wilson (1965)

- They were working at Bell Laboratories in NJ
  - Company for communication and technology
- While they were calibrating a telescope by measuring temperature of the sky, they recorded **mysterious excess noise** from every direction on the sky.
- They thought that the noise was coming from some contamination.
  - Including pigeon's excrement
- But, they failed to explain the excess noise by any known contaminations or signals.
- What is this noise?

At the same time…

- Robert Dicke and Jim Peebles were calculating the spectrum of the thermal radiation from the Big Bang.
  - Calculations originally done by Gamow and his students in 1948, but Dicke and Peebles did not know their work.
- Their collaborators were building an instrument to detect this fossil radiation.
- Then phone rang…
  - A phone call from Penzias!
  - Dicke was notified that Penzias and Wilson found some excess noise whose characteristics match theoretical expectations of the fossil radiation.
  - He immediately realized that they found it.
  - "Guys, we are scooped!"
- Penzias and Wilson received Novel Prize

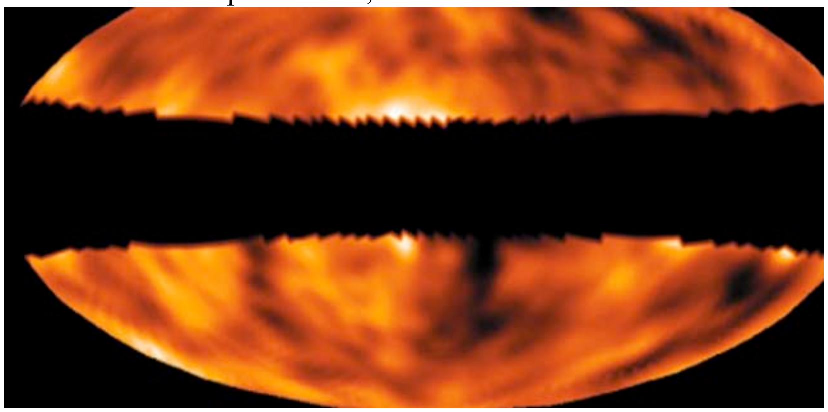


Why not the Steady State?

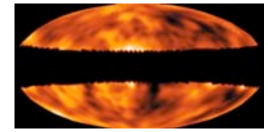
- According to the Steady State Theory, the universe was never hot.
  - Therefore, no thermal equilibrium between radiation and matter – no cosmic microwave background
- Supporters of the Steady State Theory tried to explain CMB by light from stars and galaxies.
  - However, the shape of the spectrum does not quite match.
- There is no doubt that the Steady State Theory is ruled out.

Cosmic Microwave Background…

- …was mapped by the *COsmic Background Explorer* (COBE) in 1990s
- While very smooth and uniform across the sky…
- COBE did find slight temperature variations from place to place on the level of a few parts in 100,000.



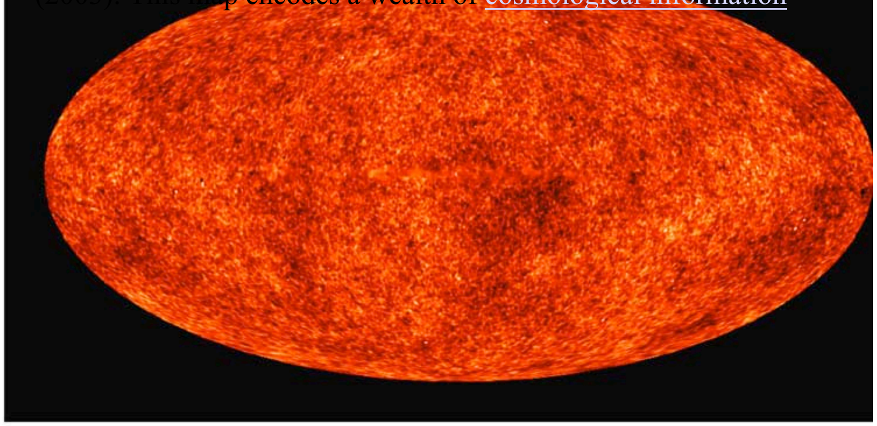
CMB Fluctuations



- Fluctuations (or ***anisotropies***) of the cosmic microwave background represent tiny irregularities in density in the early universe.
- Cold spots represent places where gravity is slightly (1 part in 100,000) stronger.
- Matter will be gravitationally attracted to cold spots – eventually, galaxies will form there.
- We are seeing *seeds* of galaxies (or us!) directly.
  - CMB is a very powerful probe of the early universe.
- Where did CMB fluctuations come from?
  - The Big Bang theory does not tell where they came from.
  - We need to know how the Big Bang happened.
  - That's a theory of ***cosmic inflation***.

Wilkinson Microwave Anisotropy Probe

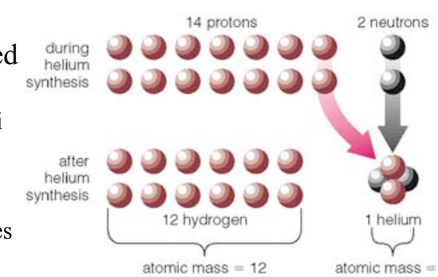
- Very accurate measurements of the cosmic microwave background (2003): This map encodes a wealth of cosmological information



Cosmic Helium Abundance

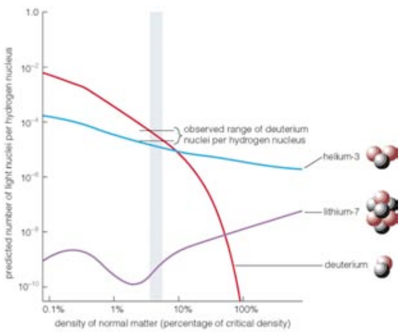
- In the Era of Nucleosynthesis, i.e. the first three minutes
  - number of protons & neutrons roughly equal as long as $T > 10^{11}$ K
  - below 10^{11} K, proton-to-neutron reactions no longer occur
    - neutrons still decay into protons
  - protons begin to outnumber neutrons
- At $T < 10^{10}$ K, the products of fusion reactions no longer break up.
  - Helium, Deuterium, & Lithium remain stable
- At this time, Big Bang model predicts a 7-to-1 proton:neutron ratio.

- For every 2 n & 2 p^+ which fused into a Helium nucleus…
  - there are 12 p^+ or Hydrogen nuclei
- Model predicts a 3-to-1 H:He
- This what we observe:
  - minimum of 25% He in all galaxies



Abundances of Other Light Nuclei

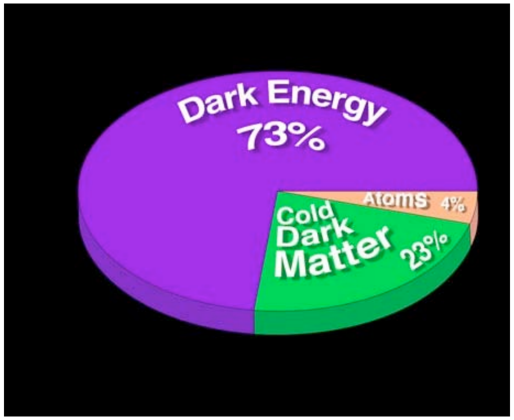
- By the time stable ^{4}He formed…
  - the Universe was too cool for He to fuse into C or other heavier nuclei
  - ^{4}He could fuse with ^{3}H to form stable ^{7}Li
- Deuterium (^{2}H) is a "leftover" isotope.
  - if densities had been greater, fusion would have gone faster, and more neutrons would have ended up in ^{4}He instead of ^{2}H
  - nucleosynthesis models predict the amount of leftover ^{2}H for each density



- The measured abundance of ^{2}H is
  - one for every 40,000 H atoms
- Compared to the model calculations
  - the density of ordinary matter is 4% of the critical density.
- Density of matter appears to be more like 30% of the critical density.
- Majority of mass in the Universe is extraordinary, such as WIMPs.

Cosmic Pie

- This is our Universe
  - Atoms (Hydrogen, Helium, etc…) comprise only 4% of the total energy in the universe.
  - Dark matter is 23%
  - Vast majority is occupied by Dark energy – 73%.
- These values are determined by combining measurements of CMB and galaxies.



Olber's Paradox

- If the Universe is infinite and filled with stars, then why is the night sky **black**?
  - in every direction we look, we should eventually see a star
  - the sky should be ablaze with light
- This paradox can be solved with an expanding Universe.
  - Starlight gets redshifted out of the visible range
  - Since light travels at a finite speed, if the Universe had a beginning, then there would be a limit on the number of visible stars

Next Lecture: The Fate of the Universe

- The last quiz on next 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