ASTR 1120 – May 1

The Last Lecture

The Big Bang
The New Cosmology

Final Exam will be in this room 1:30-4:00, Wednesday May 7
Robyn will hold a review session in G131 Monday, May 5, from 5 to 6pm
I will be in my office by 11:30 on Wednesday.

Third Exam: Average 56       Standard Deviation: 15
Will multiply by 1.17 to bring into line with other two exams.

Last opportunity to get old problem sets.

Website
http://casa.colorado.edu/~wcash/APS1120/APS1120.html
The Origin of it All?

• Good Question

• Perhaps a bubble in a hyper-universe

• Perhaps its “unknowable”

• But it appears Universe started as a very tiny bubble. How small, we don’t know.
The “Planck Era”

- When quantum fluctuations exceed the radius of the universe our theories are definitely inadequate.
- \( R < 10^{-33}\text{cm} \)
- \( t < 10^{-44}\text{ seconds} \)
- Density of Universe > \( 10^{93}\text{ g/cc} \)
- \( T > 10^{32}\text{ K} \)

- Then it starts to expand and cool....
The Inflationary Universe

• Idea: Vacuum of space-time created with excess energy \( \rightarrow \) folded upon itself
• At \( t=10^{-37}\) s, \( T=10^{28}\) K, starts to relax
• From \( 10^{-37} \) to \( 10^{-33}\) s it expands by the creation of new space.
• Universe expands from \( 10^{-26}\) cm to 10 cm
• That’s 10 cm in \( 10^{-33}\) s = \( 10^{34}\) cm/s
  \( v = 3 \times 10^{23} \) c !!!
How Can It Expand Faster than Light?

• Einstein’s Law says nothing can travel faster than light.
• Particles in the inflationary universe aren’t traveling.
• More space comes into existence between them.
• Before inflation could see whole universe.
• Since then, can only see a small part.
Big! Very, Very Big

Because of inflation, universe gets much bigger → A factor of $10^{26}$!

Means now, universe is $10^{26}$ times larger than we can see.

$R_{\text{visible}} = 10^{28}\text{cm}$

$R_{\text{universe}} = 10^{54}\text{cm}$

We are connected to only one part in $10^{78}$ of the volume
Maps of Microwave Background

The size of lumps and blobs set before inflation.

Indicate residual gravity from parts of the universe we can no longer see.

Strong evidence that inflation is on the right track.
The Annihilation Era

• After inflation settles down and resumes normal expansion
• So hot that matter and anti-matter are in equilibrium.
• For every 100,000,000 antimatter particles, there are 100,000,001 matter particles.
• Basic Asymmetry From Planck era is not understood, but it’s why we’re made of matter.
.001 Seconds

- Jump from $10^{-33}$s to $10^{-3}$s
- $T = 10^{12}$K
- Neutrons and Protons now have cooled so that can annihilate with anti-neutrons and anti-protons.
- Leave mostly photons and an occasional particle of matter.
1 Second

- Electrons and Positrons have cooled to point where they are no longer in equilibrium. $T=10^{10}$K
- Create photons.
- One matter particle in hundred million is left.
- Those are today’s electrons.
Era of Nucleosynthesis

- $T = 10^9 \text{ K}$
- $t = 100\text{s}$
- Hydrogen and Helium form from neutrons and protons.
- Tiny amounts of Li and Be are created.
- No carbon: density too low for triple alpha

- This is when the initial elements form
The Plasma Era

- From 100s to 100,000 years universe is a soup of ionized hydrogen and helium
- But its expanding and cooling
- Ends at 100,000 years when the temperature falls below 3000K.
- Hydrogen and Helium nuclei combine with electrons to form neutral atoms
- At that moment, universe becomes transparent
Sky Aglow

- At moment of de-ionization, sky is glowing as blackbody at 3000K (M star)
- Photons released are no longer re-absorbed
- They travel into the universe and are travelling today
  - But they redshift.
  - Now 1000 times longer wavelength than then (makes them microwaves)
The Cosmic Microwave Background

- Microwave Antenna at Bell Labs – 1965
- Penzias and Wilson

- Microwaves coming from sky, but not Earth. Uniformly
- Predicted as part of a “Big Bang” by Gamov in the early 1950’s
- Inescapable proof of the “Big Bang”
- Killed all steady state theories
- Now we’re studying it.
At 100 Million Years

- No Galaxies yet – or perhaps protogalaxies
- Gas mostly smooth through universe
- Clumps cause gravitational spots that create even greater density fluctuations.
- Size:
- Remember: Dark matter dominates
Primordial Density Enhancements Grow

• Now (12.4 Billion years) we have structure
• Galaxies and clusters
Recap
Dark Energy

- Expansion of Universe is Accelerating!!!
- Implies New Inflationary Era (Why Now?)
- Acceleration takes energy
New Cosmology

• 70% of mass is Dark Energy (E=mc²)
• 25% of mass is Dark Matter
• 3.5% of mass is in Intergalactic Medium
• 1.5% of mass is regular matter in galaxies

• Together they add to exactly critical density.
• We’re right on the edge of open/closed

• Universe is either finite and very big, or infinite.