ANNOUNCEMENTS

MIDTERM III: Tuesday, Nov 24th

Midterm alternate day:
Fri, Nov 20th, 11am, ESS 450
At LAST: In the very Beginning…

Eras and Characteristics

Era of Galaxies
Stars, galaxies and clusters of galaxies (made of atoms and plasma)

Era of Atoms
Atoms and plasma (stars begin to form)

Era of Nuclei
Plasma of hydrogen and helium nuclei plus electrons

Era of Nucleosynthesis
Protons, neutrons, electrons, neutrinos (antimatter rare)

Particle Era
Elementary particles (antimatter common)

Electroweak Era
Elementary particles

GUT Era
Elementary particles?

Planck Era

Timeline and Events Since Big Bang

14 billion years:
Humans observe the cosmos.

1 billion years:
First galaxies form.

380,000 years:
Atoms form; photons fly free and become microwave background.

3 minutes:
Fusion creates; normal matter is 75% hydrogen, 25% helium, by mass.

0.001 second:
Matter annihilates antimatter.

$10^{-10}$ second:
Electromagnetic and weak forces become distinct.

$10^{-35}$ second:
Strong force becomes distinct, perhaps causing inflation of universe.

$10^{-43}$ second:
Gravity becomes distinct from other forces?

Key

neutron

proton

electron

neutrino

antiproton

antineutrion

antielectrons

quarks
BIG BANG: beginning of Time

Early times in the Universe were really Hot Stuff!!

- If the universe is cooling and expanding now...
  - The Universe was hotter at earlier times

- The temperature at the earliest times was more than the energy we create in even our largest particle accelerators

- Cosmology at the earliest times is explored via particle physics
Matter, Antimatter, and Energy

Photons converted into particle-antiparticle pairs and vice-versa (Matter and Energy are the same!!)

\[ E = mc^2 \]

Early universe was full of particles and radiation because of its high temperature.
Planck Era
0 - 10^{-43} sec

Before Planck time =???

- Things were so small and so dense...
  - modern physics fails
    - No theory of quantum gravity
The Four Known Forces in the Universe

- Gravity
- Electromagnetism
- Strong Force
- Weak Force
Four known forces in the universe:

- **Gravity**
- **Electromagnetism**
- **Strong Force**
- **Weak Force**

Do forces unify at high temperatures?
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Yes! (Electroweak)

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- Weak Force
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Four known forces in the universe:

- Gravity
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Yes! (Electroweak)

Maybe (Grand Unified Theories)
Four known forces in the universe:

- **Gravity**
- **Electromagnetism**
- **Strong Force**
- **Weak Force**

Do forces unify at high temperatures?

- Yes! (Electroweak)
- Maybe (GUT)
- Who knows? (String Theory?)
GUT Era
\(\sim 10^{-43} - 10^{-38}\) sec

Lasts from Planck time to end of GUT force
Inflation of the Universe

- As strong force becomes distinct (end of GUT era), a huge amount of energy is released

- Universe INFLATES:
  - Universe of atomic nucleus size becomes solar system size in $10^{-36}$ sec
Electroweak Era
\(~10^{-38}-10^{-10}\) sec

Lasts from end of GUT force to end of electroweak force

- Universe still made up of elementary particles (quarks)
Finally, temperatures low enough that quarks can combine to form subatomic particles (protons, antiprotons, neutrons, antineutrons, etc...)
The Particle Era

- Universe still hot: $10^{15}$ to $10^{12}$ K

- Particles now exist: electrons, protons, anti-protons, anti-electrons, neutrinos etc.

- Particle soup! Particles and photons/energy created and annihilated
At the end of the particle era, temperatures are low enough that photons cannot collide to create matter/anti-matter anymore. Nearly all the matter and antimatter that is in the universe at that time collides and forms photons. But a little bit of some type of matter remains... which type is it?

A. Regular matter
B. Anti-matter
C. There’s no way we can tell!
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Matter and Anti-matter

- **At end of particle era, universe contains matter!**

- **Protons must have slightly outnumbered anti-protons**

- **Universe ratio today:**
  - 1 billion photons (light) for every 1 proton (matter)

- **Universe ratio then:**
  - 1 billion and 1 protons for every 1 billion anti-protons
Era of Nucleosynthesis

0.001 sec-3 min

Begins when matter annihilates remaining antimatter
Era of Nucleosynthesis (Fusion)

- Matter particles are "frozen out"
  - no longer spontaneously generated to/from photons

- Temperatures hot enough to fuse protons (hydrogen nuclei) into helium nuclei
Nucleosynthesis stops after about 3 minutes

- Fusion ends because density drops
  - remember the universe has been expanding this whole time
  - Matter left as ~75% hydrogen, ~25% helium, with trace amounts of lithium, deuterium

- Amounts seen throughout the universe today (with slight enhancements of heavy elements from fusion in stars)
Era of Nuclei
3 min - 380,000 yrs
• Most matter was in the shape of hydrogen/helium nuclei, electrons
• Universe has become too cool to blast helium apart but too hot to allow electrons to combine with nuclei to make atoms
The era of nuclei created a lot of light but it couldn’t get anywhere!!

- Density was so high, photons would hit an electron or nuclei before getting anywhere
  - Just like the random walk inside the Sun!
• Finally, the temperature drops to about 3000 K and electrons all combine with nuclei to form the first atoms
Era of Atoms

- Finally cool enough (3000 K) for electrons combine with nuclei to form atoms (380,000 yrs)

- Photons now "decoupled" = free to fly away

- Universe becomes transparent to light
Era of Galaxies
1 billion years - now
Era of Galaxies

• About 1 billion years after Big Bang, first stars and galaxies start to form.
• We live in the Era of Galaxies now.
Big Bang evidence

Penzias & Wilson in 1965 discovered **Cosmic Microwave Background (CMB)** radiation
--> 2.73 K “black body”

Photons created when **hot** universe was only **380,000 yrs** old – as first atoms formed

Very uniform radiation from everywhere – 1 part in 100,000

severely redshifted by expansion of universe

1978 Nobel Prize
Spectrum of Cosmic Microwave Background (CMB)

2.73 K 'black body'

Penzias & Wilson
3.5 ± 1.0 K

Frequency [GHz]

Wavelength [cm]

Brightness L [erg cm⁻² s⁻¹ Hz⁻¹ ster⁻¹]

FIRAS, COBE satellite
DMR, COBE satellite
LBL - Italy, White Mtn & South Pole ground & balloon
Princeton
Cyanogen, optical
2.728 K blackbody
• This faint light looks like a solid glowing wall
• **Thermal spectrum at 3000 K, if redshifted by factor ~1000** → **microwaves!**
• Helps measure degree of isotropy in early Universe
Chemical abundances also confirm the Big Bang model

- **Big Bang Theory prediction:** $7:1$ proton-to-neutron ratio
  - Should lead to 75% H, 25% He (by mass)

- Matches observations of nearly primordial gas
Clicker Question

Which of these abundance patterns (by mass) is an unrealistic chemical composition for a star?

A. 70% H, 28% He, 2% other
B. 95% H, 5% He, less than 0.02% other
C. 75% H, 25% He, less than 0.02% other
D. 72% H, 27% He, 1% other
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Which of the following is not an evidence supporting the Big Bang theory?

A. Cosmic microwave radiation
B. The Hubble expansion of the universe
C. Helium is 25% of all matter
D. Gamma ray bursts
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Today:
REVIEW FOR MIDTERM III
Disk, Bulge & Halo

- **Disk:** includes spiral arms -- young, new star formation
- **Bulge & Halo:** older stars, globular clusters

*Artist's sketch*
Disk is very thin!
halo star orbits (green)

bulge star orbits (red)

disk star orbits (yellow)
Galaxies: Ultimate Recycling Plants

**Star–Gas–Star Cycle**

- Atomic-hydrogen clouds
  - Fig. 19.12a
- Molecular clouds
  - Fig. 19.10
- Star formation
  - Fig. 19.11
- Stellar lives: nuclear fusion/heavy-element formation
  - Fig. 19.13
- Returning gas: supernovae and stellar winds
  - Fig. 19.5
- Hot bubbles
  - Fig. 19.6
Summary of Galactic Recycling

From **HOT** to **COLD**

- Stars make new elements by fusion
- Dying stars expel gas and new elements, producing hot bubbles (~$10^6$ K)
- Hot gas cools, allowing atomic hydrogen clouds to form (~100-10,000 K)
- Further cooling permits molecules to form, making molecular clouds (~30 K)
- Gravity forms new stars (and planets) in molecular clouds
We observe star-gas-star cycle operating in Milky Way’s disk using many different wavelengths of light.

a) 21-cm radio emission from atomic hydrogen gas.
b) Radio emission from carbon monoxide reveals molecular clouds.
c) Infrared (60–100 μm) emission from interstellar dust.
d) Infrared (1–4 μm) emission from stars that penetrates most interstellar material.
e) Visible light emitted by stars is scattered and absorbed by dust.
f) X-ray emission from hot gas bubbles (diffuse blobs) and X-ray binaries (pointlike sources).
g) Gamma-ray emission from collisions of cosmic rays with atomic nuclei in interstellar clouds.
Dark matter halo for galaxies

- Dark matter extends beyond visible part of the galaxy -- mass is \( \sim 10x \) stars and gas!

- Probably not normal mass that we know of (protons, neutrons, electrons).

- Most likely subatomic particles, as yet unidentified (weakly interacting massive particles – WIMPs?)
Stars appear to be orbiting something massive but invisible ... a black hole!

Orbits of stars indicate a mass of about 3-4 million $M_{\text{sun}}$ within 600 $R_{\text{Schwarzchild}}$. 

Keck/UCLA Galactic Center Group 1995-2006
Summary

“Distance Ladder” to measure universe

Different standard candles are useful for different distances
"Hubble’s Law"

\[ v = H_0 \times d \]

Velocity of Recession (Doppler Shift) \((\text{km/sec})\)

Hubble’s Constant \((\text{km/sec/Mpc})\)

Distance \((\text{Mpc})\)

**Best current values for expansion**

\[ H_0 = 71 \pm 4 \text{ km/s/Mpc} \]
Balloon analogy for expanding universe

- Each dot on the balloon can be thought of as a galaxy.

As the balloon expands, galaxies move farther away from each other.
Forming a disk with spiral

- As more material collapses, *angular momentum* spins it into a disk

- Stars now formed in *dense spiral arms* – disk stars are younger!

Angular momentum of protogalactic cloud important in spiral galaxy formation
Making ellipticals

1. Higher density: much faster star formation uses up all the gas
   - Nothing left to make a disk

or

2. Lower spin
   - Gas used up before angular momentum took over

• Now we see a sphere of old stars
Or perhaps a different scenario....

- **Spiral galaxy collisions** destroy disks, leave behind **elliptical**

- **Burst of star formation** uses up all the gas

- **Leftovers:** *train wreck*

- **Ellipticals** more common in dense galaxy clusters (centers of clusters contain **central dominant galaxies**)

NGC 4038/39 Antennae
“Active Galactic Nuclei” -- artist’s conception

- Accretion disk around supermassive black hole
- Disk itself may or may not be obscured by dust
- If bright nucleus is visible, looks like a quasar, if not, then it’s a radio galaxy
Prototypical "radio galaxy"

**Giant elliptical galaxy** NGC 5128 with dust lane (from spiral galaxy?)

+ **Centaurus A** radio source (color lobes)
Supermassive Black Holes and galaxies grow together

Galaxies with large bulges have large black holes…

…while those with smaller bulges have smaller black holes.