Notes about the final exam:
• Saturday May 17th, 7:45 AM-9:45 AM
• Chamberlain 2103
• If you have a CONFLICT email me or Ella before the end of this week. No excuses accepted after exam.
• Comprehensive, covering all material in the course.
• Focus (at least half) on new material since last exam.
• 50 questions, multiple choice
• Some fraction will be questions you have seen in quizzes or class.
• 25% of your grade

The best evidence so far in support of the Big Bang theory is:

a) Hubble’s discovery that the universe is expanding.
b) The cosmic microwave background radiation discovery of Penzias and Wilson.
c) The measured age of the oldest stars at 13.7 billion years.
d) The discovery of Dark Matter
e) The discovery of Dark Energy
Light from the Early Universe

- So what should light from 400,000 years after the Big Bang look like?
  - It should have a spectrum that corresponds to the temperature of the Universe at that time, 3000 K.
  - Expansion of space will stretch this light, however
    - The Universe has expanded by a factor of 1000 since this time, so the wavelength will have stretched by the same amount
    - Spectrum will correspond to a temperature of 3K.
- This light from the early Universe has been found, and is called the *Cosmic Microwave Background*

Clumpiness in the CMB
The Curvature of the Universe

- Remember that mass and energy can curve the space around it.
- As the Universe expands, the distances between the galaxies increases, like galaxies painted on the surface of an inflating balloon.
- If the universe was like an expanding balloon (but with the galaxies distributed in three dimensions), travel in any direction would eventually bring you back to your starting place (*a closed universe*).
- No Center, No Edge!
Other Possible Curvatures of Space

- In addition to a closed, or positive curvature of space, there are two other options
  - Space could be flat, or have zero curvature
  - Space could be curved away from itself, or have negative curvature
  - Geometry behaves differently with each curvature!

Expansion Forever? Or Collapse?

- The fate of the universe is ultimately controlled by its total amount of energy
  - Energy of expansion (positive)
  - Gravitational energy that can slow the expansion (negative)
  - Binding energy
- If the total energy is positive or zero, the expansion continues forever
- If the total energy is negative, the expansion will halt, and the universe will contract and eventually collapse.
• If we can measure the density of the universe, we can predict how much gravitational energy the universe has, and therefore whether it will collapse or keep expanding.

• The critical density of the universe, $\rho_C$, is the density at which the total energy of the universe is zero.

\[ \Omega_M = \frac{\rho}{\rho_C} \]

• If $\Omega_M > 1$, the universe will recollapse.

• If $\Omega_M < 1$, the universe will expand forever.

• If $\Omega_M = 1$, the universe is exactly at the critical density.

If the Big Bang theory is correct, and there is not enough mass to close the universe, then

a) more Big Bangs will occur.

b) there is no "dark matter".

c) the universe will eventually be entirely cold.

d) the expansion will slow to a halt.
SANP
Super Novae Acceleration Probe
Measure distant supervovae
2000 per year
3 year lifetime starting 2013

SNAP
Super Novae Acceleration Probe
Measure distant supervovae
2000 per year
3 year lifetime
Supernova Type Ia Findings

- We also need to know how the universe is expanding – this can help us determine the value of $\Omega_M$.
- We can measure the recession velocity of distant galaxies using Type Ia supernovae as standard candles.
- It appears that the expansion rate at a time when the universe was half its current size ($z=1$) was slower than it is today.
- This shows that the expansion rate is increasing with time! Very puzzling!

Dark Energy!

- Dark energy may provide the solution to the mystery.
- Dark energy remains constant everywhere, regardless of the universe’s expansion.
- Provides an outward push to accelerate expansion: antigravity!
- In order for dark energy to balance the equation, it must make up around 70% of all of the energy in the universe.
- Much work remains to be done on this frontier…
If the universe is expanding, won't the solar system eventually expand apart?
   a) The solar system may actually be shrinking now, which makes the Universe LOOK like it's expanding.
   b) No, its gravity holds it together.
   c) No, because there is no planetary redshift.
   d) Eventually, but only after a very long time.
The Origin of Helium

- Immediately after the Big Bang, only protons and electrons existed.
- Shortly after the Big Bang, temperature and density were high enough for deuterium to form by fusion.
- After 100 seconds or so, temperature cooled enough so that deuterium could fuse into helium nuclei.
- The temperature continued to cool, and fusion stopped after a few minutes.
- Big Bang theory predicts that around 24% of the matter in the early universe was helium, which matches what we see.

Radiation, Matter and Antimatter

- In the first second of the early universe, matter did not really exist; rather, everything was radiation or *energy*. Cosmologists call this time period the *early universe*.
- When energy is converted into matter, antimatter is formed as well.
- For a proton-antiproton pair to form, the temperature must be more than $10^{13}$ K!
- Matter and antimatter annihilate on contact, releasing energy.
- There must have been an asymmetry in the amount of matter and antimatter formed in order for there to be a predominance of ordinary matter today.
The Epoch of Inflation

• Modern technology allows us to test theories back to a time $10^{-33}$ seconds after the Big Bang.
• Physics as we know it ceases to function at $10^{-43}$ seconds after the BB, called the Plank Time
• Using particle colliders, scientists have uncovered a number of clues about what happened in the early universe, after the Plank time
• The early universe underwent a period of very rapid expansion

• By $10^{-33}$ seconds, the universe expanded from the size of a proton to the size of a basketball
• This expansion is called inflation