The Frontier
Matter and Antimatter

- One of elements driving cosmological evolution is the presence of radiation (photons)
- Early universe
  - Matter and antimatter
    - But we live in universe full of matter – where is the antimatter?
    - Would annihilate in early universe:
      - Produces photons
      - A slight imbalance of matter over antimatter would produce the matter we see
- There are $10^9$ more photons than baryons (protons and neutrons) in universe
  - Indicates that for every 1 billion antibaryons, there were 1 billion + 1 baryons
    - Why the asymmetry?
    - Why is it the value that we measure?
Creation of the First Elements

- Protons and neutrons
  - Prevented at first from combining into atomic nuclei
  - Ambient photons very energetic and tear incipient nuclei apart
- As universe expands
  - Light wavelengths get longer (i.e. are redshifted)
    - Each photon is less energetic
  - First, Hydrogen nuclei (1 proton, 0,1,2 neutrons) form
    - Then Helium nuclei (2 protons, 0,1,2 neutrons)
    - 75% of matter Hydrogen, 25% Helium
      - This ratio can be ‘predicted’ based on models of the early universe
      - No baryons left to form heavier nuclei
  - Electrons still cannot bind with nuclei to form neutral atoms until expansion further redshifts the photons
Microwave Background & Inflation

An early prediction of the Big Bang model of the expanding universe
- There must be some ‘afterglow’ of the explosion
- Nuclear physics calculations suggest 3 degrees K microwaves
- Expansion of universe reduces temperature to 3 degrees K

Observation
- Two engineers for AT&T working with radar notice a noise in all directions
- determined it was cosmic in origin, and corresponds to 2.7 K microwaves
- A perfect black-body spectrum

Apparent uniformity
- Observed to be homogeneous to one part in 10,000
- This implies that there was a very early phase in the universe where the expansion was much faster than it is now
  • Called ‘inflation’
  • Would smooth out variations

Expansion keeps redshifting photons
- Reduces current energy density in the universe due to photons, $\Omega_r \sim 10^{-4}$
**Dark Matter**

- Look at how fast stars move around center of our Milky Way galaxy
  - Velocity should decrease as get further out from center
    - Because gravity is weaker there
  - But observe that velocities stay constant
    - Indicates presence of more matter than we see
    - What we see is dominated by baryons (protons and neutrons)

- Look at large structures in universe: galaxy clusters and superclusters
  - Study motion of galaxies within these: like orbital motion in solar system, this indicates strength of gravity
    - If a lot of mass $\rightarrow$ fast velocities
    - If there is little mass $\rightarrow$ slow velocities
    - Evidence for a lot (20x) more mass than we see
  - Study level of clumpiness of galaxies, which tells something about how the unseen (‘dark’) matter is distributed
    - Dark matter appears only to interact via gravity and the weak interaction

- Appears there is much more matter than baryons can account for
  - Neutrinos not able to account for this
  - $\Omega_m$ is large $\sim 0.3$, but 95% of this matter is of a type we have never seen!
Dark Energy

- Look at distant supernovae to see how fast universe expanding at very large distances (i.e. the early universe)
- Use Type 1a supernovae
  - Since they detonate when get to 1.4 solar mass, the luminosity of the explosion is always the same
  - Get recession velocity from redshift, and distance from peak brightness

\[ \Omega_m = 0.3, \quad \Omega_\Lambda = 0.7 \]

Supernovae receding more slowly in early universe

Expansion of universe is accelerating!!

Like would expect from cosmological constant!

- Energy associated with this accelerating expansion,
  - \( \Omega_\Lambda \approx 0.7 \) (i.e. equals 70% of critical mass/energy to close universe
  - total energy density, \( \Omega = \Omega_r + \Omega_m + \Omega_\Lambda = 1.0 \) (so we live in a flat universe!)
Some Questions

- Why is there matter in the universe?
- Why is the universe a flat geometry?
- What is the dark matter?
- What is the dark energy?

- To answer these questions, we seem to need to think further about fundamental (particle) physics
  - Probing smaller distances like probing earlier universe
  - Are there other types of particles out there, other interactions?
    - Electroweak and strong interactions
      - Governed by many of same principles:
        - quantum field theories
        - Probabilistic, small scale, discrete universe
      - Somewhat different strengths
    - Gravity
      - Understood by very different mechanism
        - General relativity
        - Deterministic, large scale, continuous geometry
      - Entirely different strength than other forces
Further Unification?

- **Supersymmetry**
  - A generalization of the quantum electroweak and strong approaches
  - may produces energy density like $\Lambda$ (i.e. dark energy)
  - Some variants predict matter-antimatter asymmetry
  - Some variants predict undiscovered weakly interacting massive particles (i.e. dark matter)

- **Extra dimensions**
  - Expansion of the geometric idea in general relativity
    - Consider geometry as integral to forces observed
    - Gravity is weak because it is spread over several more dimensions
  - Can unify interactions and get dark matter

- **Superstrings (now M-theory)**
  - Resolve ‘choppiness’ of quantum perspective with ‘smoothness’ of relativistic perspective by replacing quantum particles with complex geometry
    - Different shapes for particles give different properties (charge, baryon #…)
  - Extremely challenging calculations
Where do we go from here?

- While theorists are working on the math and models, experimentalists are working on new experiments and observations.

- Large Hadron Collider (LHC) in Geneva, Switzerland
  - 7x more energy than existing accelerator at Fermilab, IL
  - We start running Fall 2007
  - If supersymmetry exists, there is a good chance it will be found by the end of the decade.
Questions

- Describe the matter-antimatter problem. [10 pts]
- Explain why the universe is primarily made up of Hydrogen and Helium. [7 pts]
- What is the cosmic microwave background? Explain its origin [10 pts]
- What observations support the presence of dark matter in the universe? [10 pts]
- Dark matter is 5% of all matter. (T or F) [2 pts]
- Why are type 1a supernovae used to probe the universe’s expansion in the early universe? [10 pts]
- The universe is closed. (T or F) [2 pts]