The Frontier

Matter and Antimatter

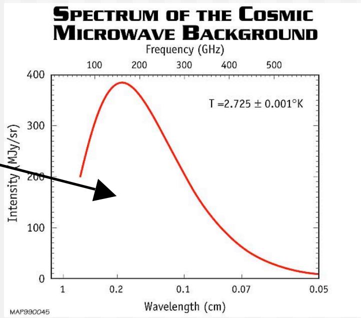
- One of elements driving cosmological evolution is the presence of radiation (photons)
- Early universe
  - Matter and antimatter
    - But we live in universe full of matter – where is the antimatter?
    - Would annihilate in early universe:
      - Produces photons
      - a slight imbalance of matter 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

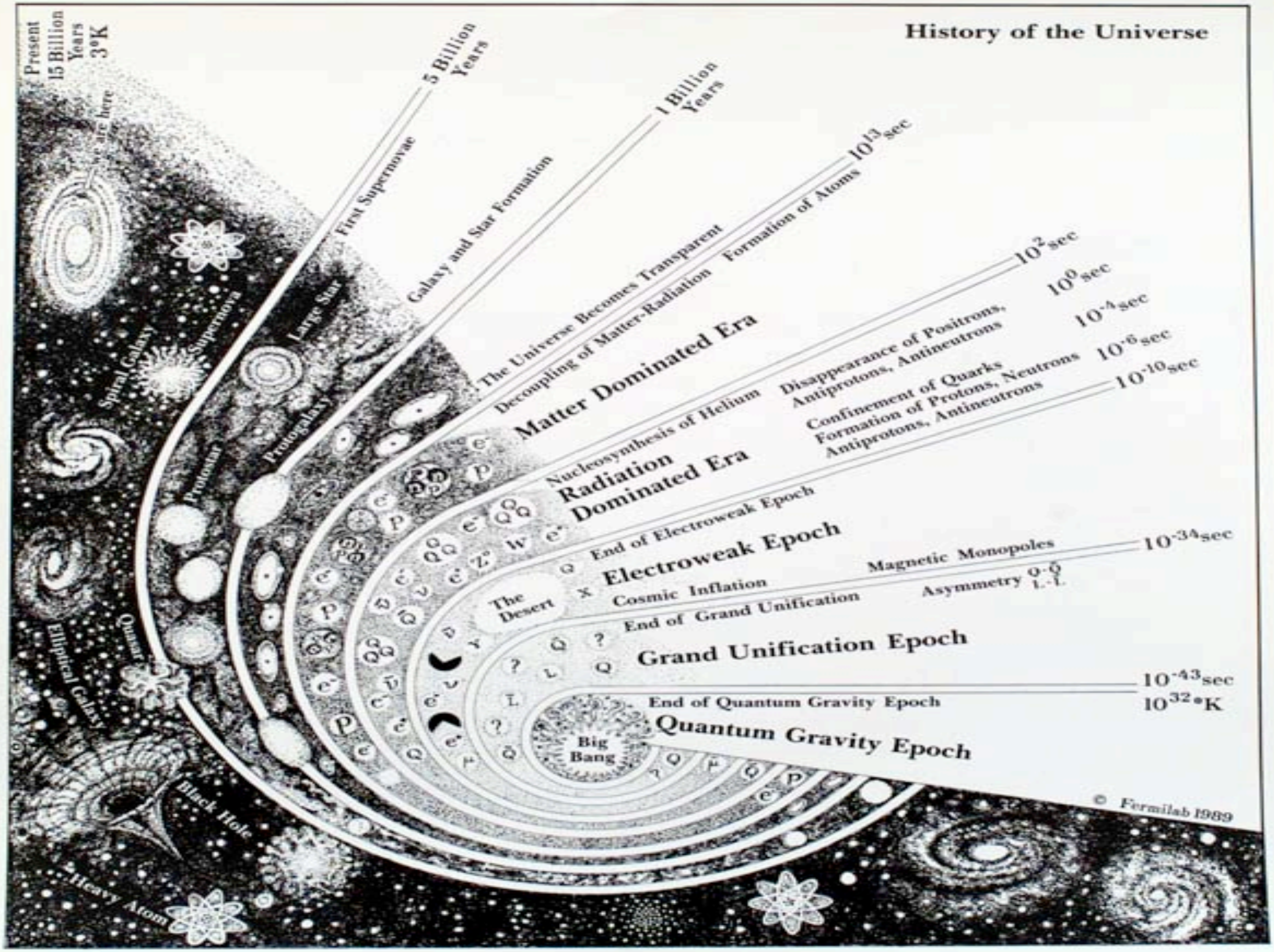
- Protons and neutrons
  - Prevented at first from combining into atomic nuclei
  - Ambient photons very energetic and tear incipient nuclei apart
- As universe expands
  - Light wavelengths get longer (I.e. are redshifted)
    - Each photon is less energetic
  - First, Hydrogen nuclei (1 proton, 0,1,2 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 tempurature 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, $\Omega_r \sim 10^{-4}$



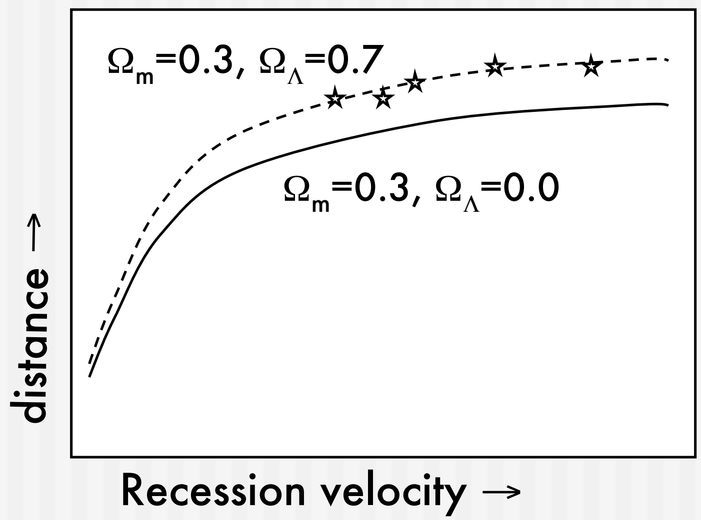
History of the Universe
Present
15 Billion
Years
3°K
5 Billion
Years
1 Billion
Years
10^13 sec
10^2 sec
10^0 sec
10^-4 sec
10^-6 sec
10^-10 sec
10^-34 sec
10^-43 sec
10^32 °K
We are here
First Supernovae
Galaxy and Star Formation
The Universe Becomes Transparent
Decoupling of Matter-Radiation
Formation of Atoms
Matter Dominated Era
Nucleosynthesis of Helium
Disappearance of Positrons, Antiprotons, Antineutrons
Confinement of Quarks
Formation of Protons, Neutrons
Antiprotons, Antineutrons
Radiation
Dominated Era
End of Electroweak Epoch
Electroweak Epoch
Magnetic Monopoles
Cosmic Inflation
Asymmetry
End of Grand Unification
The Desert
Grand Unification Epoch
End of Quantum Gravity Epoch
Quantum Gravity Epoch
Big Bang
Spiral Galaxy
Supernova
Large Star
Protogalaxy
Protostar
Quasar
Elliptical Galaxy
Black Hole
Heavy Atom
© Fermilab 1989

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 –> fast velocities
    - If there is little mass –> 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
  - Ω_m is large ~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



Supernovae receding more slowly in early universe

Expansion of universe is **accelerating**!!

Like would expect from cosmological constant!

- Energy associated with this accelerating expansion,
  - Ω_Λ ~ 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?

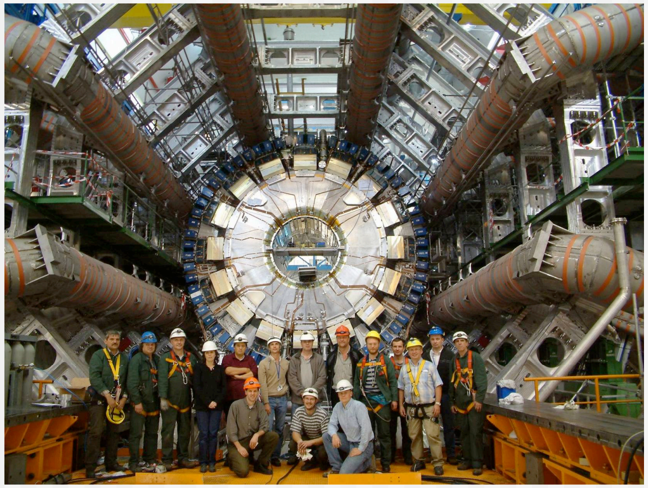
- To answer these questions, we seem to need to think further about fundamental (particle) physics
  - Probing smaller distances like probing earlier universe
  - Are there other types of particles out there, other interactions?
  - Electroweak and strong interactions
    - Governed by many of same principles:
      - 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

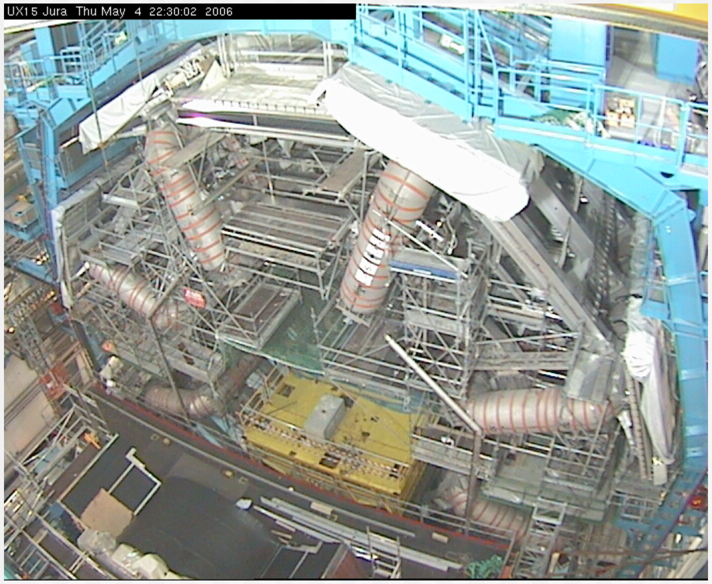
Further Unification?

- Supersymmetry
  - A generalization of the quantum electroweak and strong approaches
  - may produces energy density like Λ (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]