ASTR 1040 Recitation: Cosmology Part II

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April 28 & 30, 2014

This Week

- Final Exam: Wednesday May 7 (4:30 - 7:00 pm)
- Review Session: Wednesday April 30 (5:00 pm G125)

Today's Schedule

- Past/Current Homework or Lecture Questions?
- The Early Universe
- Fundamental Forces
- Big Bang: Era of GUT, Nuclei, Atoms, ...
- Inflation

What Do Cosmologists Study?

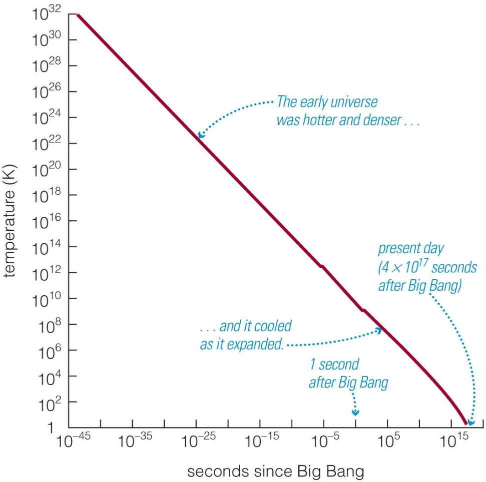
Early Universe: The Big Bang Theory

- What were conditions like in the early universe?

- How did the early universe change with time?

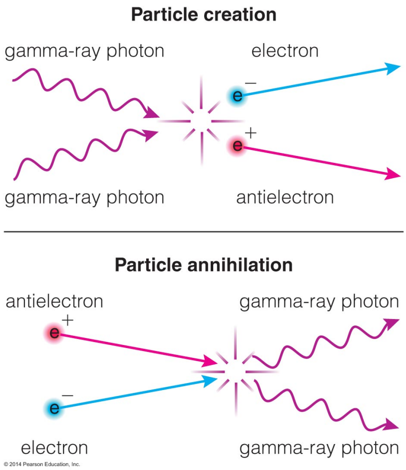
Early Universe

- Extremely hot
- Extremely dense
- Cooled as it expanded



Early Universe: Pair Creation

- Photons converted into particle-antiparticle pairs
- Particle-antiparticle pairs converted into photons
- $E = mc^2$
- High temp $\Rightarrow$ full of particles & radiation



Fundamental Forces

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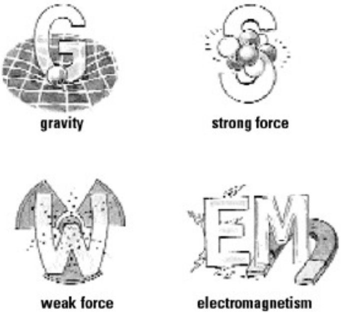
- Strong Force: holds quarks together to make hadrons
- Electromagnetism: deals with all things charged
- Weak Force: converts protons/neutrons into one another
- Gravity: deals with all massive things

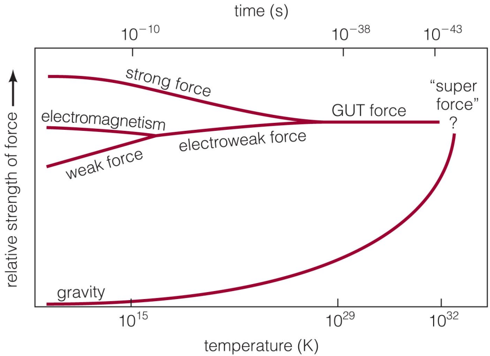


Thought Question

Which of the four forces keeps you from sinking to the center of the Earth?

(A) Gravity
(B) E & M
(C) Strong Force
(D) Weak Force
(E) Hopes and dreams of little children

Do the Forces Unify at High Temperatures?



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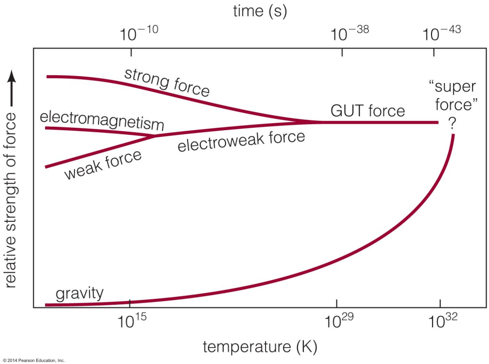

Electro-Weak

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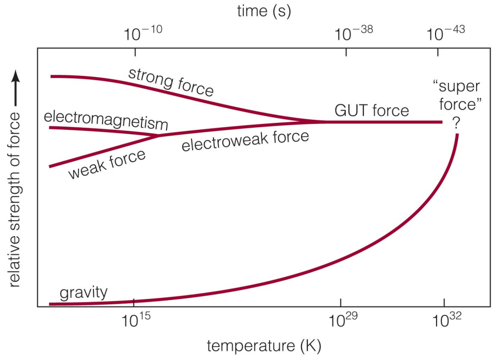

Electro-Weak

GUT

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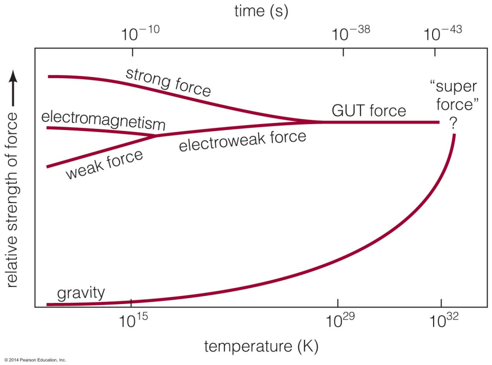

Electro-Weak

GUT

"super force" (little brother of Superman)

Hisotry of the World: Part I

- Planck Era:
  - $\lesssim 10^{-43}$ sec
  - $T \gtrsim 10^{32}$
  - no current theory can describe this

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- Planck Era:
  - $\lesssim 10^{-43}$ sec
  - $T \gtrsim 10^{32}$
  - no current theory can describe this
- GUT Era:
  - $10^{-43} \lesssim t \lesssim 10^{-38}$ sec
  - $T \approx 10^{32} - 10^{29}$
  - Only gravity and GUT

Hisotry of the World: Part I

- Electro-Weak Era:
  - $10^{-38} \lesssim t \lesssim 10^{-10}$ sec
  - $T \approx 10^{29} - 10^{15}$
  - GUT splits, inflation, elementary particles

Hisotry of the World: Part I

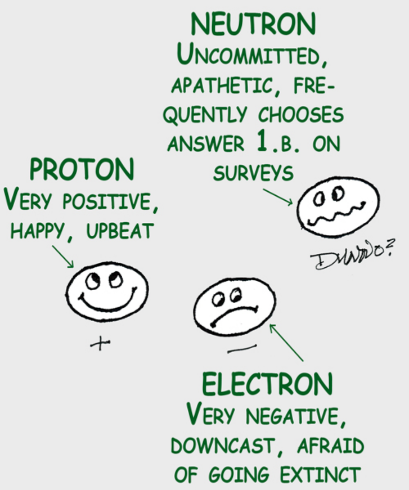
- Electro-Weak Era:
  - $10^{-38} \lesssim t \lesssim 10^{-10}$ sec
  - $T \approx 10^{29} - 10^{15}$
  - GUT splits, inflation, elementary particles
- Particle Era:
  - $10^{-10} \lesssim t \lesssim 10^{-3}$ sec
  - $T \approx 10^{15} - 10^{12}$
  - Full of elementary particles, quarks combine into protons

Hisotry of the World: Part I

- Era of Nucleosynthesis:
  - $0.001 \text{ sec} \lesssim t \lesssim 5 \text{ min}$
  - $T \approx 10^{12} - 10^{9}$
  - Fusion produces He

Hisotry of the World: Part I

- Era of Nucleosynthesis:
  - 0.001 sec $\lesssim t \lesssim$ 5 min
  - $T \approx 10^{12} - 10^{9}$
  - Fusion produces He
- Era of Nuclei:
  - 5 min $\lesssim t \lesssim$ 380000 yrs
  - $T \approx 10^{9} - 3000$
  - Plasma of free e^{-}, H, He nuclei, fusion stops



Hisotry of the World: Part I

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Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

R. A. ALPHER*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland
AND
H. BETHE
Cornell University, Ithaca, New York
AND
G. GAMOW
The George Washington University, Washington, D. C.
February 18, 1948

As pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,[2] the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.

Using these cross sections, one finds by integrating Eqs. (1) as shown in Fig. 1 that the relative abundances of various nuclear species decrease rapidly for the lighter elements and remain approximately constant for the elements heavier than silver. In order to fit the calculated curve with the observed abundances[3] it is necessary to assume the integral of $\rho_n dt$ during the building-up period is equal to 5×10^4 g sec./cm^3.

On the other hand, according to the relativistic theory of the expanding universe[4] the density dependence on time is given by $\rho \cong 10^6/t^2$. Since the integral of this expression diverges at $t=0$, it is necessary to assume that the building-up process began at a certain time t_0, satisfying the relation:

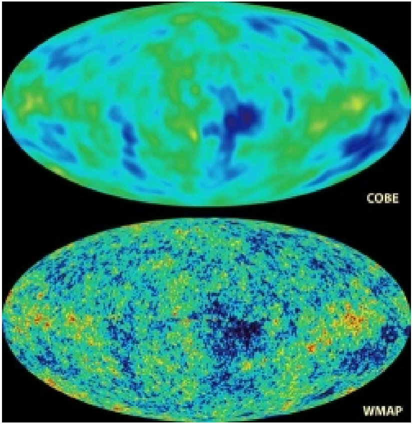
$$\int_{t_0}^{\infty} (10^6/t^2)dt \cong 5\times10^4, \qquad (2)$$

which gives us $t_0 \cong 20$ sec. and $\rho_0 \cong 2.5\times10^5$ g sec./cm^3. This result may have two meanings: (a) for the higher densities existing prior to that time the temperature of the neutron

Ralph Alpher, George Gamow & Hans Bethe

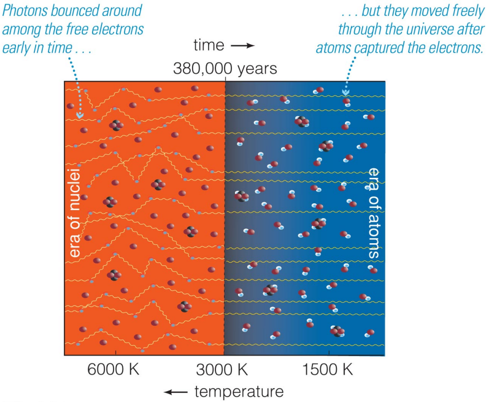
Hisotry of the World: Part I

- Era of Atoms
  - 380000 yrs $\lesssim t \lesssim$ ~1 billion yrs
  - $T \approx 3000 - 10$s
  - e^- recombine to form atoms



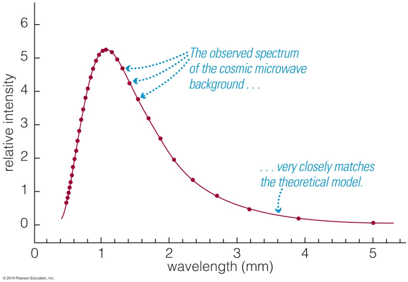
Cosmic Microwave Background

- Free e^- very good at scattering light
- Era of Atoms: not too many free e^- left
- Less e^- in the way of photon, it escapes $\Rightarrow$ CMB
- Freely streaming around since $T \approx 3000$K



Cosmic Microwave Background

- Perfect thermal radiation spectrum: T $= 2.725$ K
- Expansion of universe redshifted radiation, z ≈ 1100
- Now in microwaves



What Do We Know So Far?

- What were the conditions like in the early universe?
  - Very hot & dense
  - Radiation constantly produces particle-antiparticle pairs
  - Pairs constantly annihilate
- How did the early universe change with time?
  - Cooling universe, particle production stops
  - slightly more matter than antimatter
  - Fusion creates Helium (and Be, Li)
  - Atoms form, radiation travels freely

More Mysteries Need Explaining

- Where does structure come from?
- Why is the overall distribution of matter so uniform?
- Why is the density of the universe so close to the critical density?

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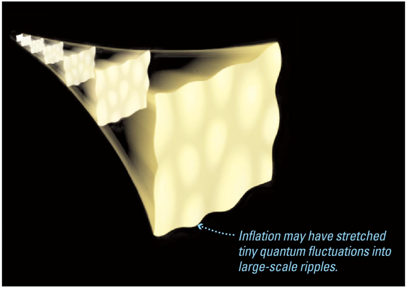
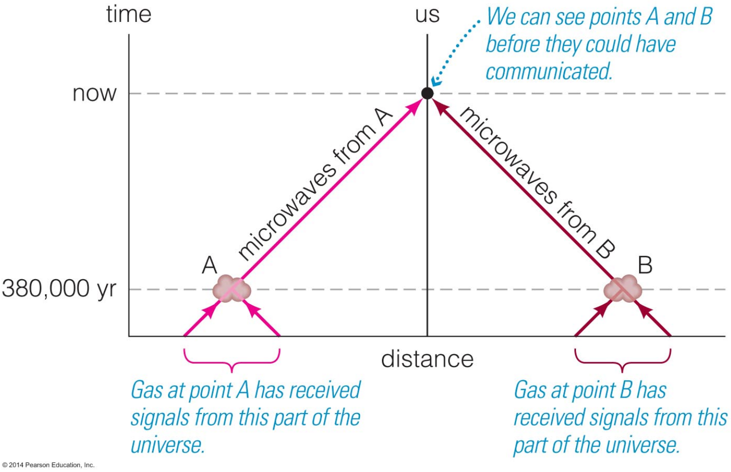
- Where does structure come from?
- Why is the overall distribution of matter so uniform?
- Why is the density of the universe so close to the critical density?
- Answer: Inflation

Inflation – Structure

- Stretching tiny quantum ripples to enormous size
- Ripples in density become seeds for structure in universe

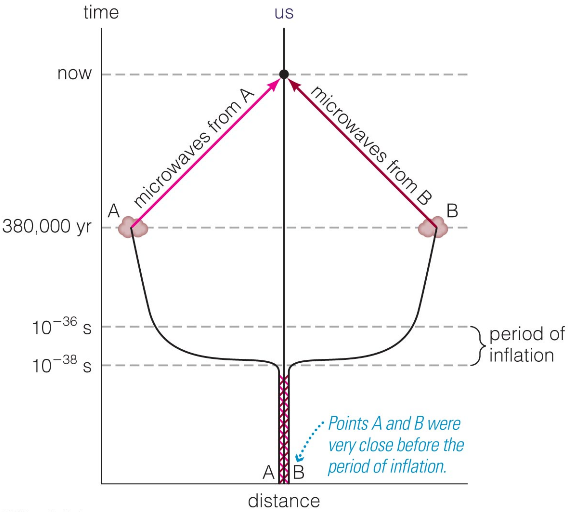


Inflation – Distribution of Matter



How can microwave temperature be nearly identical on opposite sides of the sky?

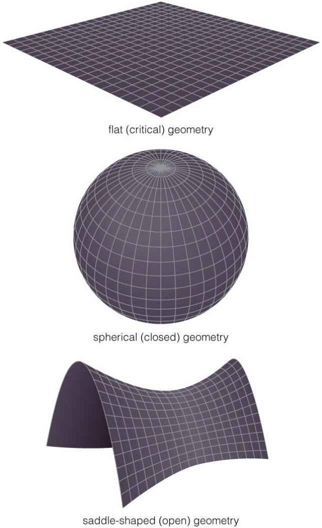
Inflation – Distribution of Matter



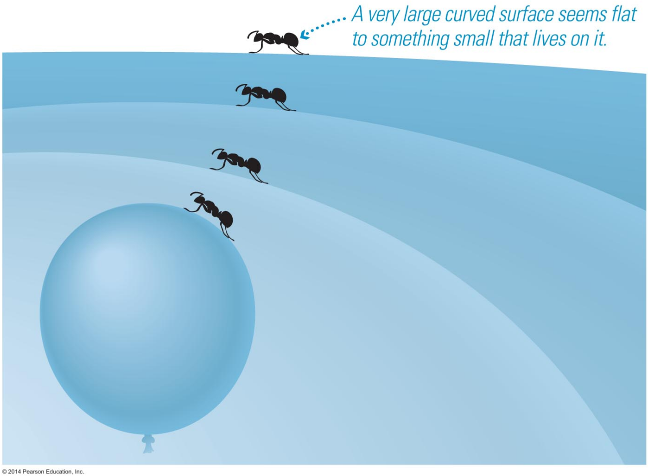
Regions now on opposite sides of the sky were close together before inflation pushed them far apart

Inflation – Critical Density

- Overall geometry of universe is closely related to matter and energy
- Real universe has these “shapes” in more dimensions than we can see



Inflation – Critical Density



Inflation flattens overall geometry ⇒ overall density closer to critical value

Condensed Inflation

- What key features of the universe are explained by inflation?
  - Origin of Structure: quantum ripples stretched into uniformity, i.e. universe becomes more smooth (Homogeneity)
  - Isotropy: stuff looks the same in all directions, e.g. CMB
  - Flat Geometry: expansion rate balances overall density of mass-energy