Lecture 23

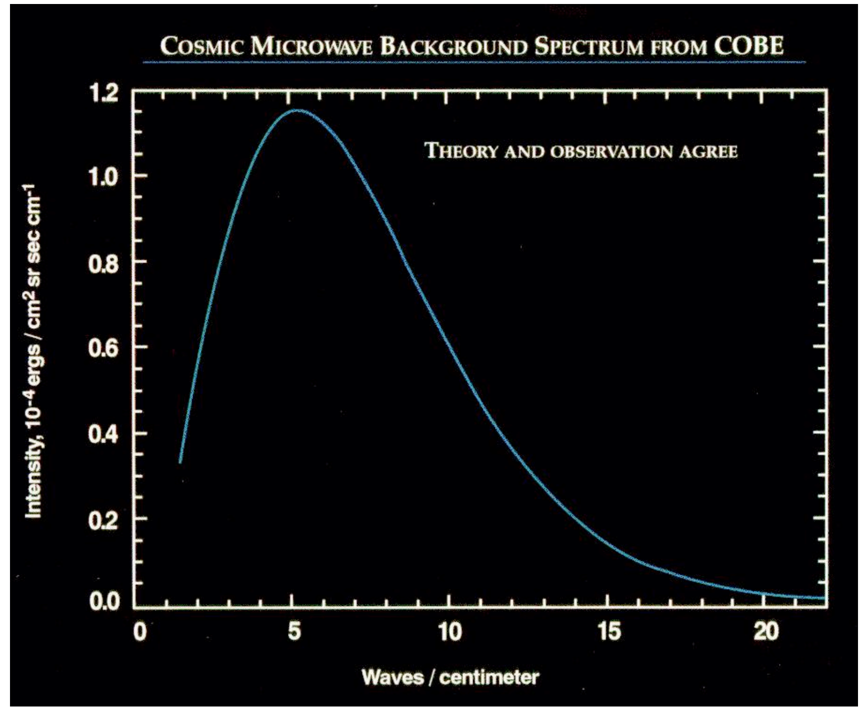
Creation of the Universe

Outline of Lecture 23

- Cosmic Microwave Background (CMB).
- Big-Bang Nucleosynthesis
- Very Early Universe
  - Creation of mass-energy (particle-antiparticle pairs from spacetime curvature.
  - Generation of spacetime curvature from mass-energy and stress (General Relativity)
  - Planck and GUT eras; unification of forces

Cosmic Microwave Background

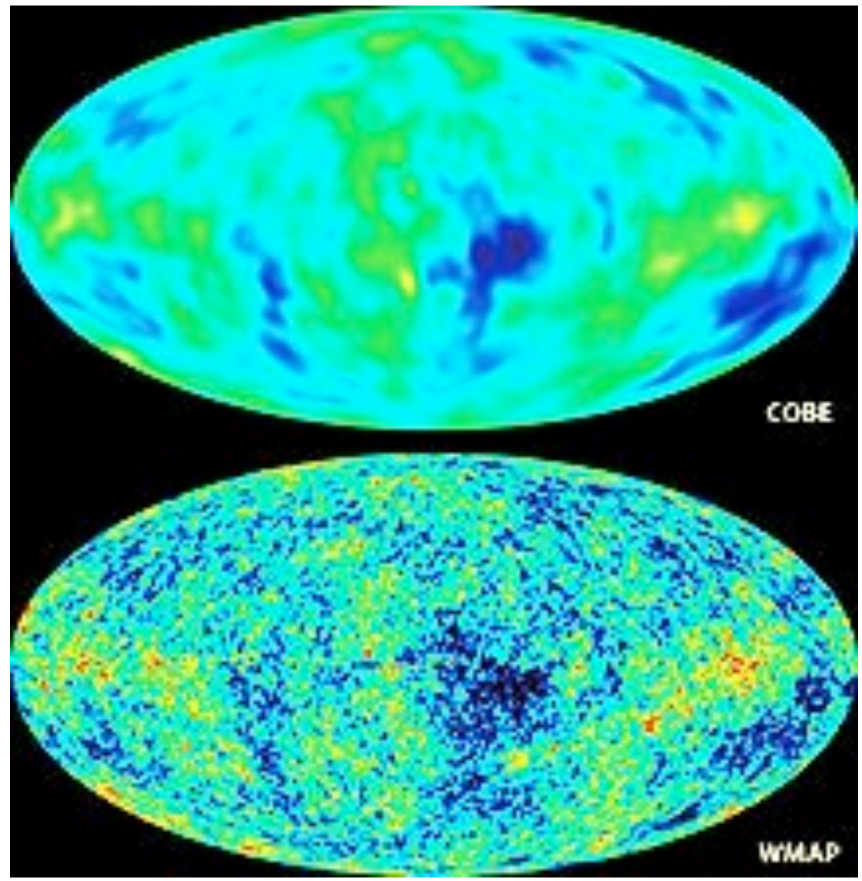
- Speculation of George Gamow (1904-1968) concerning Big Bang origin of the elements. Most made inside stars, but what about H and He? Early universe needs to be hot, but subsequent expansion would have cooled it off.
- Deduction by Gamow, Alpher, and Hermann that $T \sim 5$ K now. Story of Alpher, Bethe, Gamow.
- Above prediction largely forgotten until Arno Penzias (1933-) and Robert Wilson (1936-) discovered in 1965 the CMB, which was predicted by the Big Bang theory but not by the competing Steady State theory (which postulated "continuous creation" to offset the dilution of matter caused by the expansion of the universe).



Measurement by the COBE satellite (1989) showed that the spectrum of CMB is in every direction of the sky a perfect blackbody with temperature $T = 2.725$ K.

CMB and Its Fluctuations from the Hot Big Bang

- Universe began as hot big bang.
- Universe cools with expansion.
- Current temperature T = 2.725 K as measured by cosmic microwave background ("relict radiation from the creation of the world").
- Equivalent mass density ≈ $5\times10^{-5}\,\rho_c$, a very small contribution to the critical density (today).
- Temperature is not completely uniform; small fluctuations that are precursors to large-scale structure formation (more later).
- These accomplishments, followed up with greater precision by the WMAP mission, resulted in the award of the 2006 Nobel Prize in Physics to 2 leaders of COBE project.



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Ratio of Matter & Radiation Through Cosmic Ages

- Cosmic stretching of each photon implies (Lecture 22):

$$\lambda_{\max} \propto D(t) \propto (1+z)^{-1}$$

- But $\lambda_{\max} T_{\text{rad}} = \text{constant} \Rightarrow$

$$T_{\text{rad}} \propto (1+z).$$

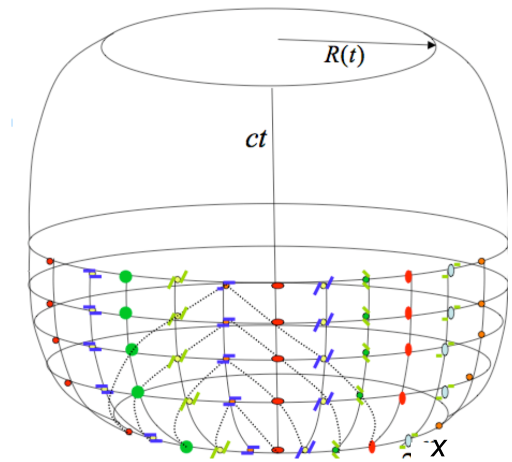
- Radiation energy or mass density

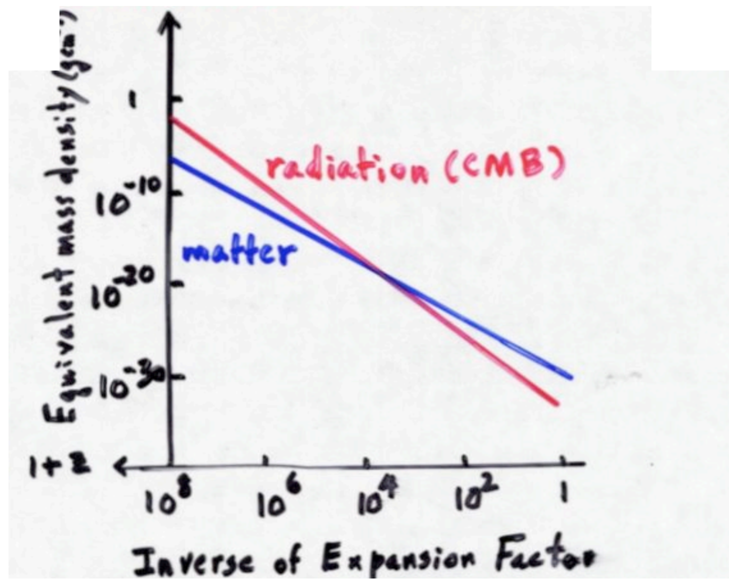
$$\propto T_{\text{rad}}{}^4 \propto (1+z)^4.$$

- In contrast, density of nonrelativistic (ordinary or dark) matter

$$\propto \text{fixed mass/volume} \ \propto D^{-3}(t) \propto (1+z)^3.$$

- Both increase toward past (small *D*, large 1+*z*) when universe was smaller, but radiation increases faster.
- Radiation small today, but it dominated in the distant past, in the early universe.





1+*z*

"In the beginning, God created the heaven and the earth. The earth was without form, and darkness was upon the deep, and the Spirit of God was moving upon the face of the waters. And God said 'Let there be light,' and there was light."

Radiation Dominated Early Universe (extra material)

- Relativistic (Friedmann-Lemaitre) equations for scale factor *a*:

$$\frac{1}{a^2}\left[\left(\frac{da}{dt}\right)^2 + kc^2\right] = \frac{8\pi G}{3}\rho \text{ with } k = +1, 0, -1 \text{ as closed, flat, open.}$$

First law of thermodynamics with zero entropy change: $\frac{d}{dt}\left(\rho c^2 a^3\right) = -P\frac{d}{dt}\left(a^3\right)$

- Special case:
  - Radiation dominated universe:

$$P = \frac{1}{3}\rho c^2 \Rightarrow \rho \propto T^4 \propto \frac{1}{a^4} \Rightarrow T \propto \frac{1}{a}$$

$$\text{because } \lambda_{\max} T = const \text{ and } \lambda_{\max} \propto a.$$

  - For small *a*, if radiation dominates, independent of *k*,

$$a \propto t^{1/2} \Rightarrow T \propto t^{-1/2}.$$

Model-Independent Temperature History of Early Universe

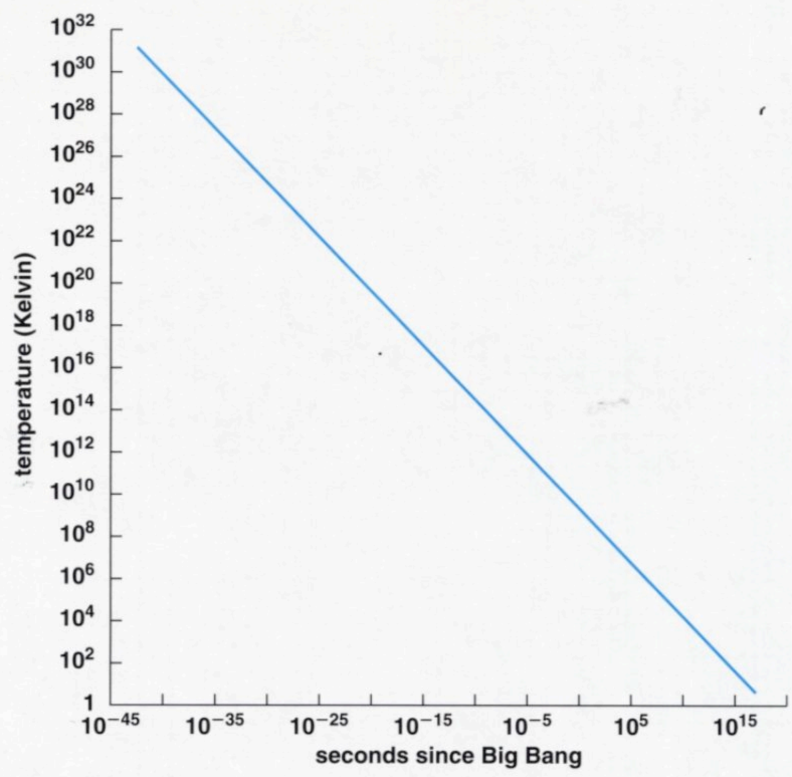
- If density and pressure of radiation dominates over all other forms (early times), solution for *T* in time *t* is given by

$$T = \left(\frac{3c^3}{128\pi Q G \sigma} \right)^{1/4} t^{-1/2}.$$

where *Q* is a correction for neutrinos, etc, and σ= Stefan-Boltzmann constant.

- Above formula gives $T = 10^{10}$ K at t = 1 s; $T = 10^9$ K at t = 100 s; $T = 10^8$ K at t = 10,000 s; etc. Important nucleosynthesis is over after first 15 minutes, with the formation of H and He.

Figure 19.1 Temperature of the universe from the big bang to the present (10^{10} years ≈ 3×10^{17} seconds)



Cosmic Matter Density

- For $t \gg 10^{-6}$ s, there is not enough energy in the photons to make proton and antiprotons (or neutrons and antineutrons). Thus, the number density of baryons (protons + neutrons) during big bang nucleosynthesis is the same as now, except compressed by $(1+z)^3$.
- For $T = 1\times10^9$ K, $(1+z) \sim 4\times10^8$; thus ρ at this time is 5×10^{25} times the density of ordinary matter today, 4×10^{-28} kg/m^3; i.e., $\rho \sim 2\times10^{-2}$ kg/m^3, which is much less than the densities inside the cores of stars.
- Charged-particle fusion reactions of the type inside stars have no time to proceed. Cosmic neutrons, if any, are all important.

Neutron/Proton Ratio (extra material)

- For t < 1 s, T > 10^{10} K, and there would be copious production of electron-positron pairs.
- Because of copious electrons, positrons, neutrinos, and antineutrinos, any nuclei would be in form of free protons and neutrons in thermodynamic equilibrium with each other:

$$\frac{\text{number of neutrons}}{\text{number of protons}} = e^{-(m_\mathrm{n} - m_\mathrm{p})c^2/kT},$$

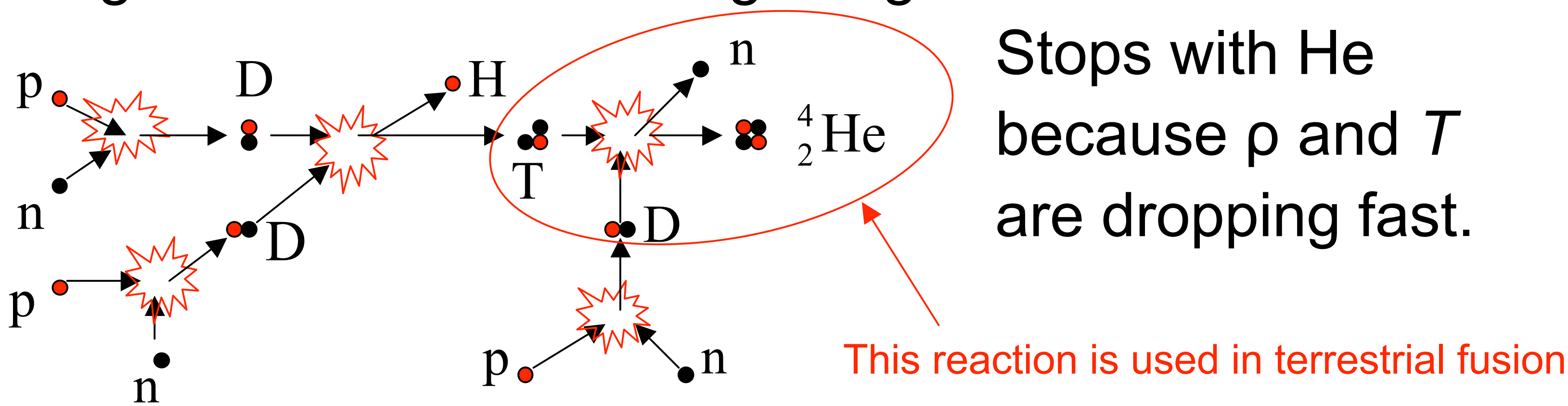
  where k = Boltzmann's constant.
- With $m_\mathrm{n} - m_\mathrm{p} = 0.0014 m_\mathrm{p}$ and T = 10^{10} K,

$$\frac{\#\,\mathrm{n}}{\#\,\mathrm{p}} = 0.22 \approx \frac{3}{13}, \quad \text{i.e., } 3\mathrm{n} \text{ for every } 13\ \mathrm{p}.$$

- When t > 100 s and T < 10^9 K, most of electrons and positrons annihilate, and p and n drop out of equilibrium. The n will begin to decay into p (and electrons and antineutrinos) with a half-life of about 10 min. Over next several minutes, about 1 in 3 n become p. The rest participate in neutron capture and other nuclear reactions. Thus, consider reactions with 2 n and 14 p

Synthesis of Light Elements

- During first few minutes of big bang:



Stops with He because ρ and *T* are dropping fast.

- Net reaction: 2 n + 2 p → $^4_2\mathrm{He}$.
  Similar reactions produce same net result →
  14 p + 2 n → 12 H + 1 He nuclei and compensating number of electrons (14).
- Mass fractions: Hydrogen: $X = \frac{12}{16} = 75\% + \text{ trace of D}$

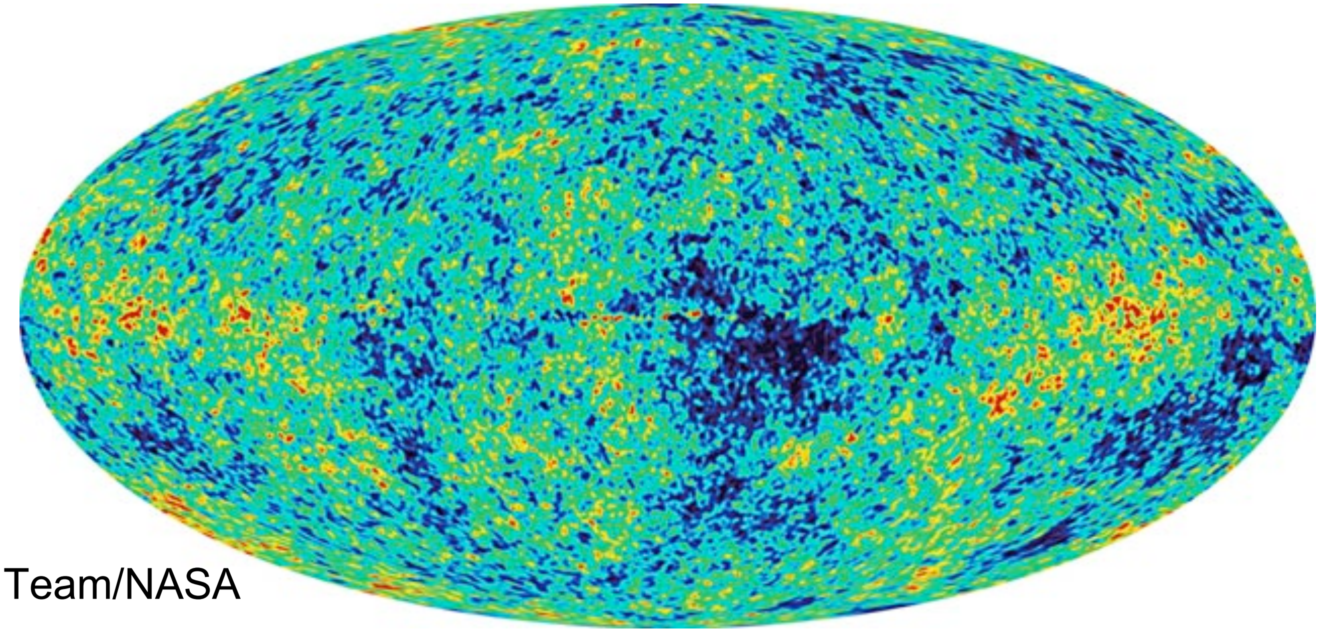
  Helium: $Y = \frac{4}{16} = 25\%$

  This result is exactly what we see in oldest stars!

The Constraint from Deuterium

- The number fraction of D left unreacted (into He) with respect to H has been measured in the absorption lines of D in QSOs by the Keck telescope (by David Tytler at UCSD) and is about
$$4\times10^{-5}$$
- The concentration of D in interstellar space has been reduced by about a factor less than 2 from primordial values by cycling inside stars, whereas the concentration of D in seawater has been enhanced by a factor of about 5 by chemical fractionation.
- To produce a D/H level of 4×10^{-5} the models of primordial nucelosynthesis requires that baryons not be more than about 4-5% of the critical density today, a value consistent with astronomical estimates of ordinary matter in the universe.

Fluctuations in CMB at Level of 1 part in 10^5 Peak at Angular Scale of about 1^o

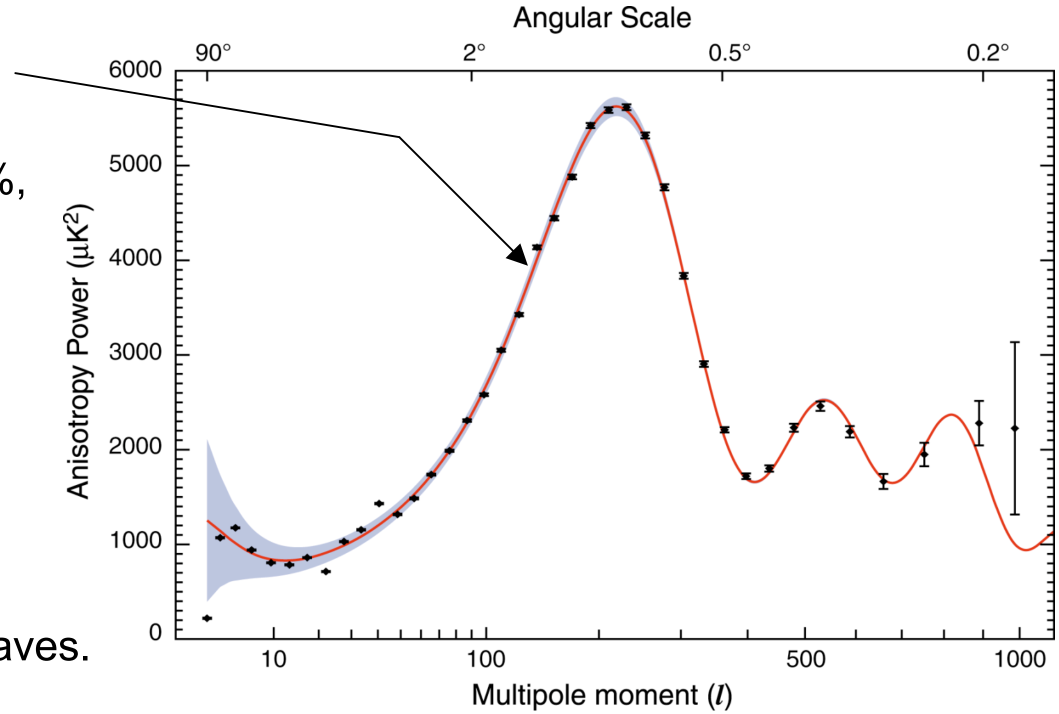


WMAP Science Team/NASA

Random fluctuations create sound waves in cosmic plasma. These sound waves can reinforce each other coherently if they satisfy certain integer relations (analogous to de Broglie's argument in wave mechanics) as they criss-cross the universe in the time available to them. The most robust coherent structures that survive from the era of recombination at an age of about 400,000 years (when the CMB photons can fly straight to us in a transparent universe) now subtend an angle of about 1^o when we look in any direction, if the universe is flat with the properties in the next slide.

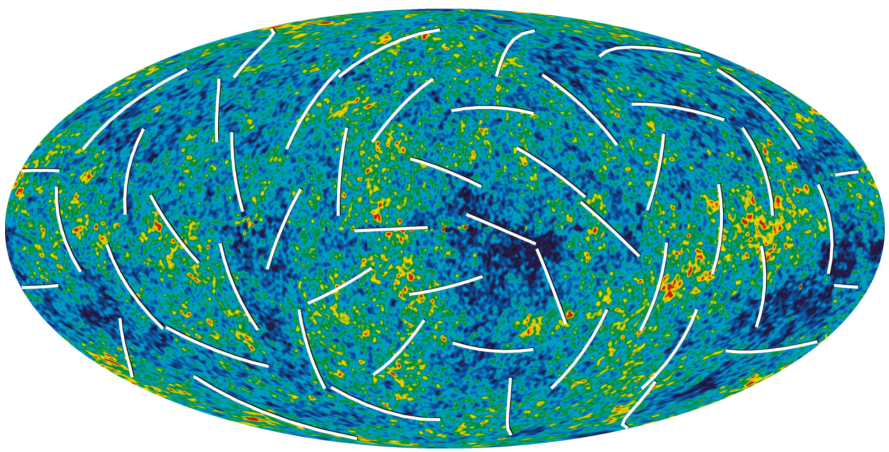
CMB Anisotropy

Red curve is prediction if universe is flat, with ordinary matter 4%, dark matter 22%, and dark energy 74% the critical density. In particular, relative ratio of heights of successive "acoustic peaks" depends sensitively on the amount of ordinary matter, which is the only component that can interact electromagnetically with the CMB to provide the damping of sound waves.



CMB Polarization

Pattern of white lines showing directions of excess polarization are consistent with the predictions of the Sachs-Wolfe effect.
(Art Wolfe is a Professor at UCSD.)



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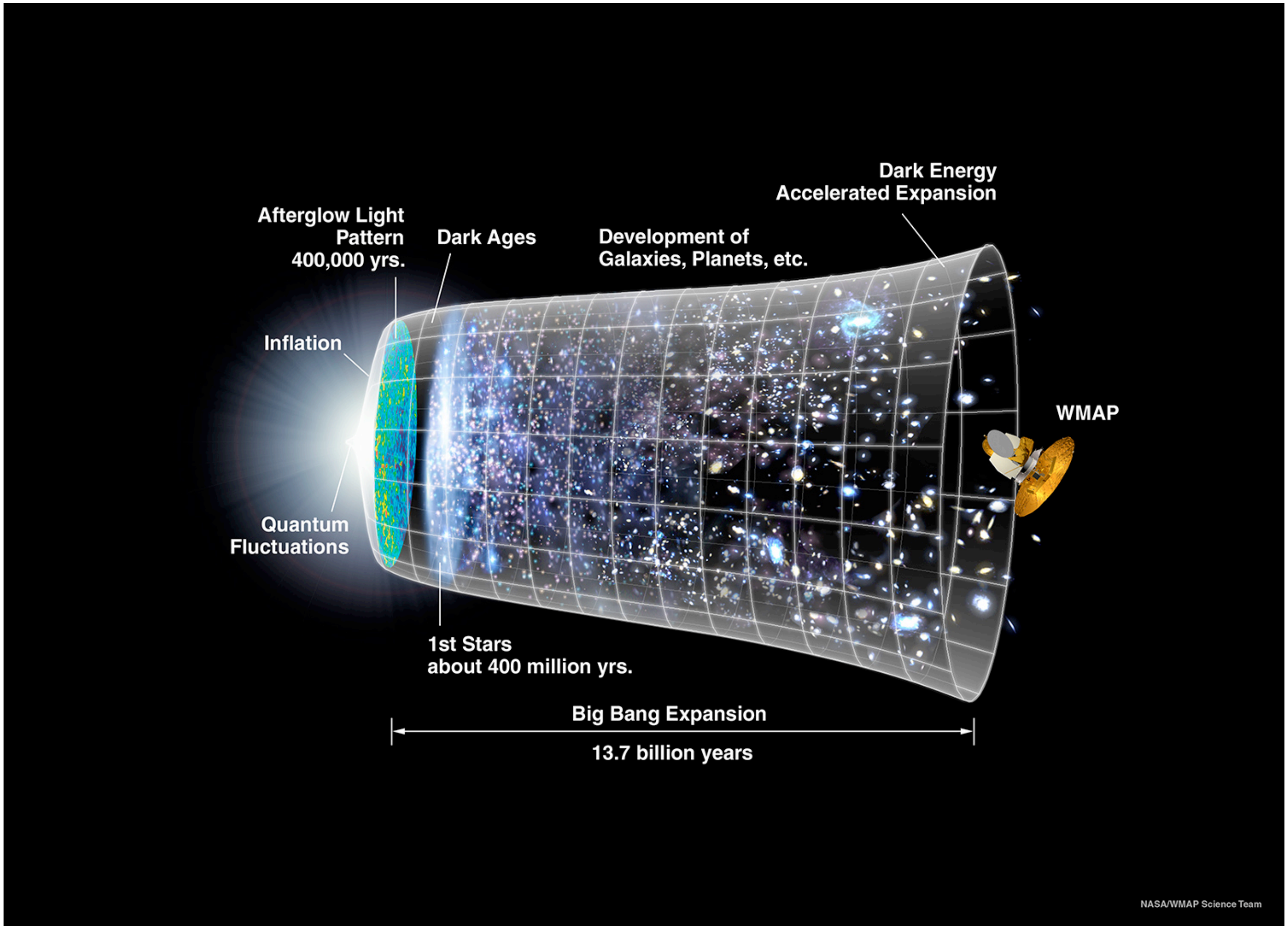
Timeline for Cosmic Evolution



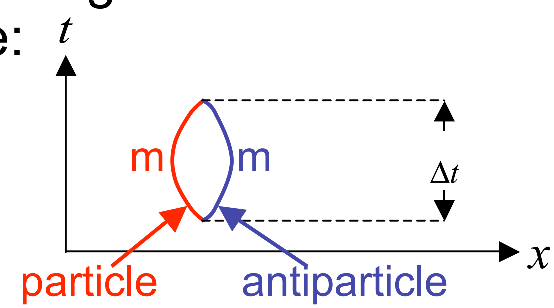
Lecture 24 will discuss earliest epochs of quantum fluctuations and inflation.

Extra Material: Prelude to Force Unification
Quantum Vacuum & Bare Charge

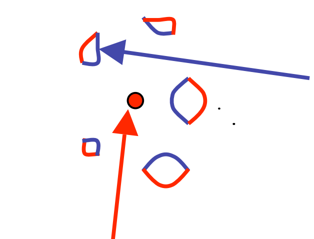
- Quantum vacuum is not uninteresting state of Galileo. Virtual pairs that blink in and out of existence:

  Pair is unobservable (by Heisenberg's uncertainty principle) if

  $$\Delta t < \frac{\hbar}{\Delta E} \quad \text{where} \quad \Delta E = 2mc^2.$$



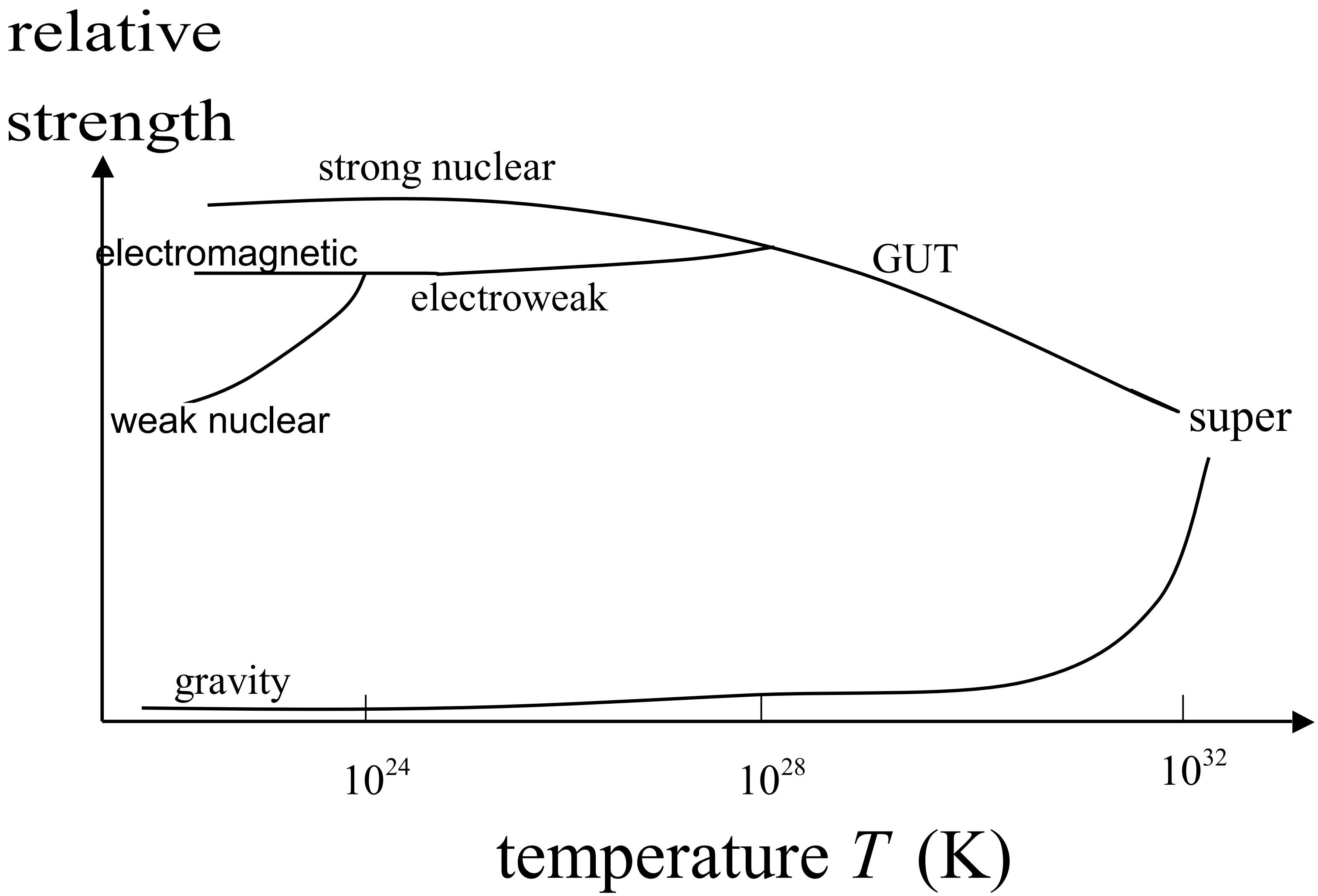
- Implication: charge of electron is not what is measured, -*e*, at macroscopic distance.



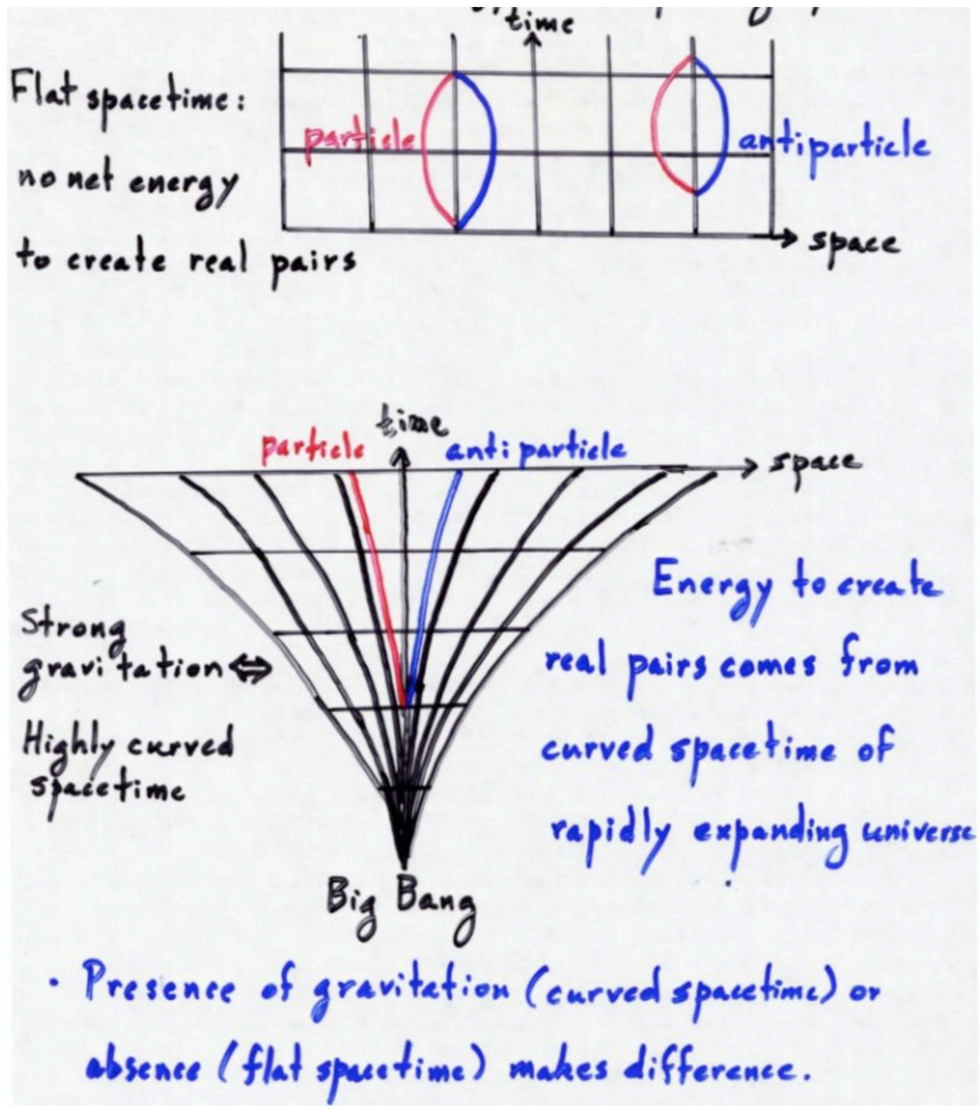
If penetrate cloud of shielding by virtual positrons, bare charge of electron is much greater negatively than –*e.* Thus, at high *E* or *T*, strength of electromagnetic interaction rises faster than Qq / r^2 with fixed *Qq* as *r* decreases.

In contrast, strength of strong force decreases with increasing energy. Thus, as we increase the temperature *T* of the universe by going into the past, the electromagnetic and strong interactions acquire the same strength and may merge into the same force.

Unification of Forces at High *T*



Creation of Mass-Energy from Expanding Spacetime



Creation of Everything from Nothing

- Can everything that exists in the natural world have arisen from a state of absolute nothing. A motivation: total charge = 0.
- We think today that everything consists of a lot. And so it does, lots of electrons, lots of protons, lots of space, etc., but in reality, they may all add to nothing. No charge, no total energy (positive plus negative), no baryons minus leptons, … Why? Because everything may have arisen out of nothing.
- Truly nothing: no matter, no energy, no space, no time – nothing.
- Need mass-energy to produce spacetime curvature; need spacetime curvature to produce mass-energy. Which came first, mass-energy or spacetime curvature?
- Analogous question: Which came first, chicken or egg?
- Answer: Neither, they both arose from something yet more simple.
- But what is more fundamental and simple than mass-energy and spacetime? Physics is struggling to find an answer to this question. Superstrings? Need another Einstein? Or God? (Prime Mover)