

clicker Quiz #14

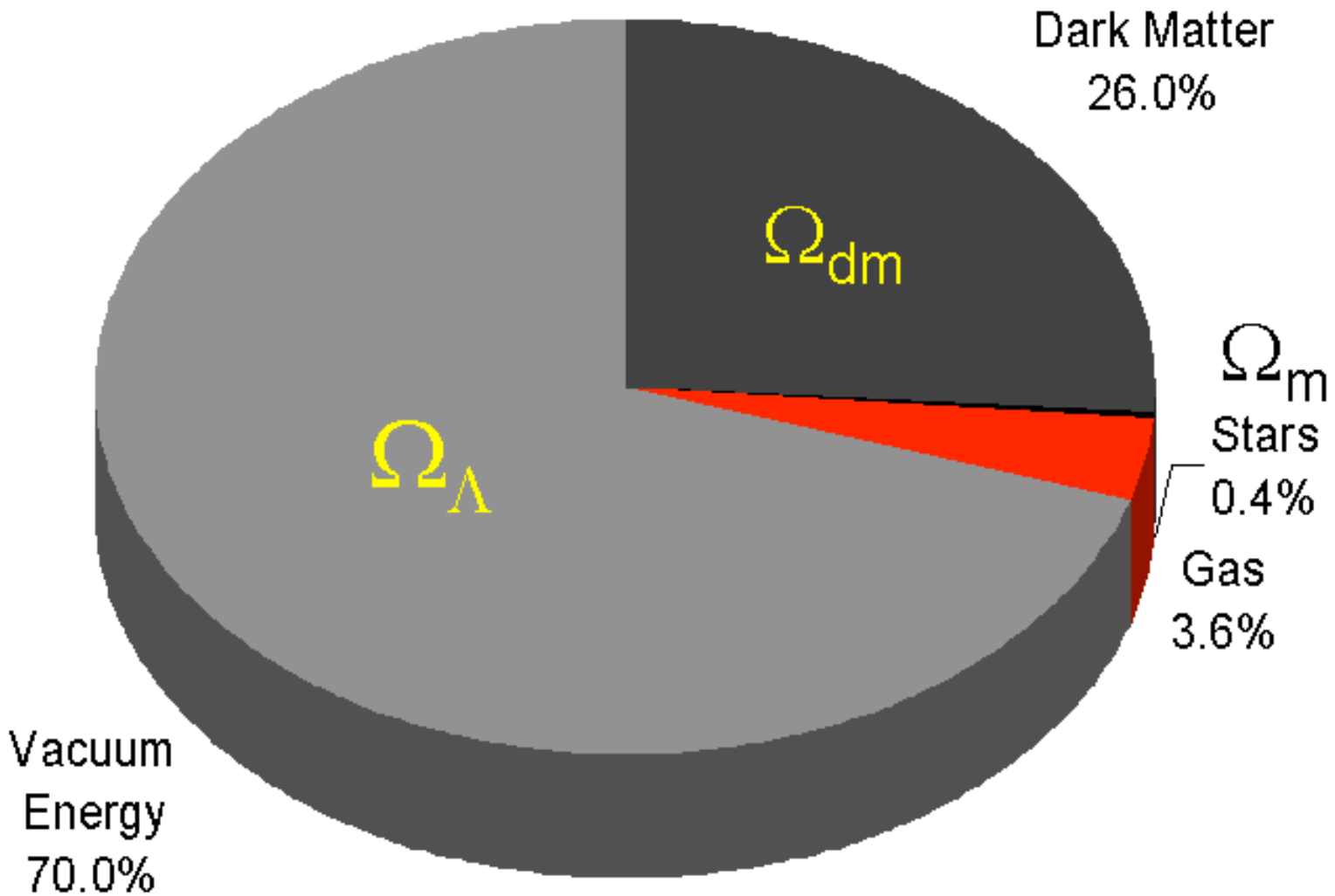
Which of the following statements is **TRUE**?

- A. Hubble's discovery that most distant galaxies are receding from us tells us that we are at the center of the Universe
- B. The Universe started with the Big Bang and will end in the Big Crunch
- C. The expansion rate of the Universe is speeding up because of a repulsive anti-gravity force
- D. The Andromeda galaxy is moving away from the Milky Way galaxy as a result of the expansion of the Universe

Dark Matter and Dark Energy

- Critical density of matter needed to barely halt the Universe's expansion: $\rho_{\text{crit}} \sim 10^{-30} \text{ g/cm}^3$
- Most of the matter in the Universe is **DARK** — total density of matter in the Universe ρ may or may not be equal to this critical density: $\Omega_{\text{matter}} \equiv \rho / \rho_{\text{crit}}$
- How much **DARK ENERGY** (anti-gravity) is present in the Universe?
- Determination of Ω_{matter} and Ω_{Λ} are major goals / achievements of modern cosmology
- Methods:
 - Density/dynamics of galaxies in the Universe
 - Geometrical properties of the Universe
 - Expansion rate in the Universe's past
 - Search for dark matter particles / physical origin of dark energy

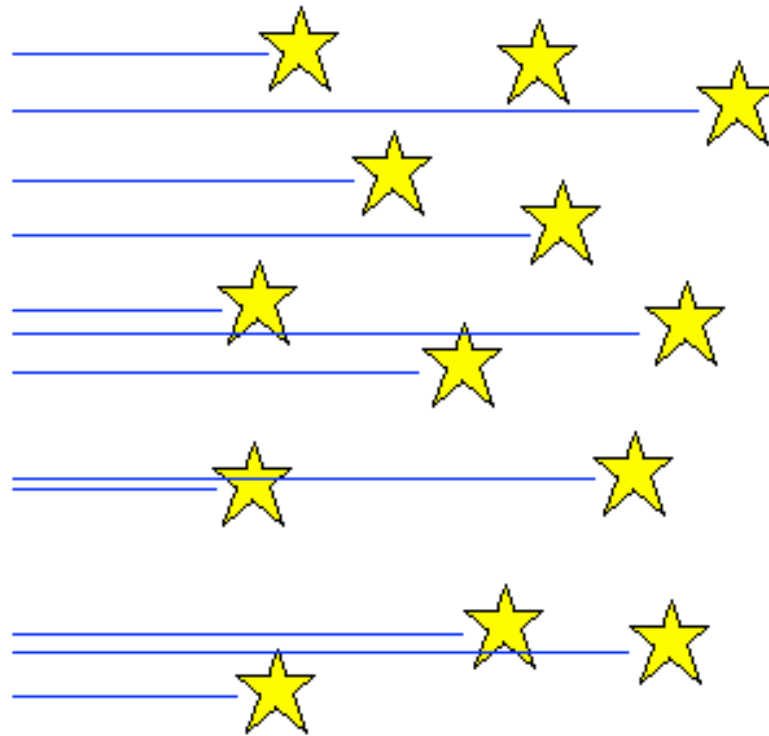
Matter & Energy Content of the Universe



Olbers' Paradox: Why is the Night Sky Dark?

- Assume uniform and infinite distribution of stars — night sky should be **infinitely bright(!)**, but is observed to be dark
- Paradox phrased by **Olbers** in 1823, though already well known for about a hundred years at the time
- Stars are distributed over a finite volume (our Galaxy, for example) but the argument can be extended to the distribution of individual galaxies
- Can absorption by dust in galaxies solve the paradox? **NO!** Dust would heat up and glow as a black body radiator
- Universe has **finite age t** → observable Universe has a **horizon** at a **finite distance ct** — this is the most important factor in solving Olbers' Paradox!

Olber's paradox



observer

Universe of stars

night sky

clicker Quiz #15

Which of the following statements is **FALSE**?

- A. Galaxies are generally moving away from one another because of the expansion of the Universe, but there are exceptions to this rule where collections of galaxies are bound together by their mutual gravity
- B. Most galaxies harbor massive black holes at their centers and these used to be active galactic nuclei in the past
- C. Spiral arms in disk galaxies are thought to be related to the fact that disks rotate differentially
- D. The center of the Universe is marked by a supermassive black hole at the nucleus of a giant elliptical galaxy

Alternative to Big Bang theory: Steady State Cosmology

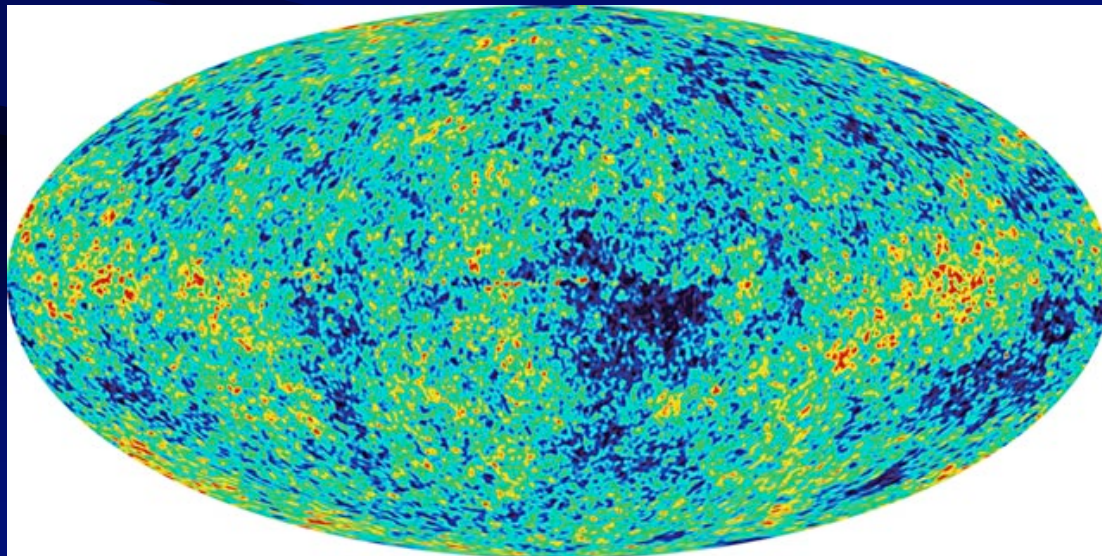
- Cosmological Principle: Universe is homogenous and isotropic — the **same** everywhere in **space**
- Perfect Cosmological Principle: Universe is the same at all **times** also — our Universe probably does **not** obey the Perfect Cosmological Principle
- **Steady State** theory proposed as alternative to Big Bang by Bondi, Gold, & Hoyle in 1940s — a theory is based on Perfect Cosmological Principle
- Requires that galaxies constantly be **created** at the expense of energy out of the so-called C-field
- Not widely believed — discovery of the **Cosmic Microwave Background Radiation** is considered definitive evidence **against** Steady State cosmology

Cosmic Microwave Background Radiation (CMBR)

- Relic of the Big Bang (“**afterglow**” of initial fireball) predicted in late 1940s
- Discovered by **Penzias & Wilson** in 1965 — they won the Nobel Prize for this discovery
- CMBR studied in detail by satellites (COBE, WMAP)
- Radiation comes from era of **decoupling of matter and radiation** in the early Universe (~300,000 years old) when neutral H atoms first formed

Observations of the CMBR

- CMBR very smooth — photons from different directions have the same properties
- Earth's motion with respect to the CMBR is detectable — one half of sky hotter by one part in 1000
- Satellite observations detected tiny fluctuations in CMBR (1 part in 100,000) that represent seeds of density fluctuations from which galaxies arose



clicker Quiz #16

Which of the following statements is **FALSE**?

- A. The Cosmic Microwave Background Radiation is considered to be strong evidence in favor of the Big Bang theory
- B. The Steady State theory is founded on the Cosmological Principle
- C. Most astronomers believe that the Universe satisfies the Cosmological Principle but not the Perfect Cosmological Principle
- D. The Steady State theory postulates that, as the Universe expands, matter in the form of galaxies is created out of the energy in the C-field (“Creation” field)

Major Epochs in the Early Universe

- $t < 3 \times 10^5$ years: Universe radiation dominated
- $t > 3 \times 10^5$ years: Universe matter dominated
- Why?
- Let R be the scale length of the Universe (the separation between your favorite pair of galaxies, say).
- Energy density of matter $\propto 1/R^3$ since volume $\propto R^3$
- Energy density of radiation $\propto 1/R^4$ since λ “stretched out” $\propto R$. By Wien's Law, T decreases as $1/R$, and by the blackbody eqn. energy density decreases as $T^4 \propto 1/R^4$

Unification of Forces

- All four fundamental forces of Nature unified at $t < 10^{-43}$ s, the **Planck time**.
- Gravity 'froze' out separate from the other three forces at this time.
- Next the strong nuclear force froze out at $t = 10^{-35}$ s
- Weak and electromagnetic forces unified until $t = 10^{-12}$ s
- Electroweak unification confirmed in the laboratory during the 1980s at CERN particle accelerator in Europe.

Planck Epoch { **Big Bang**

GUTs Epoch

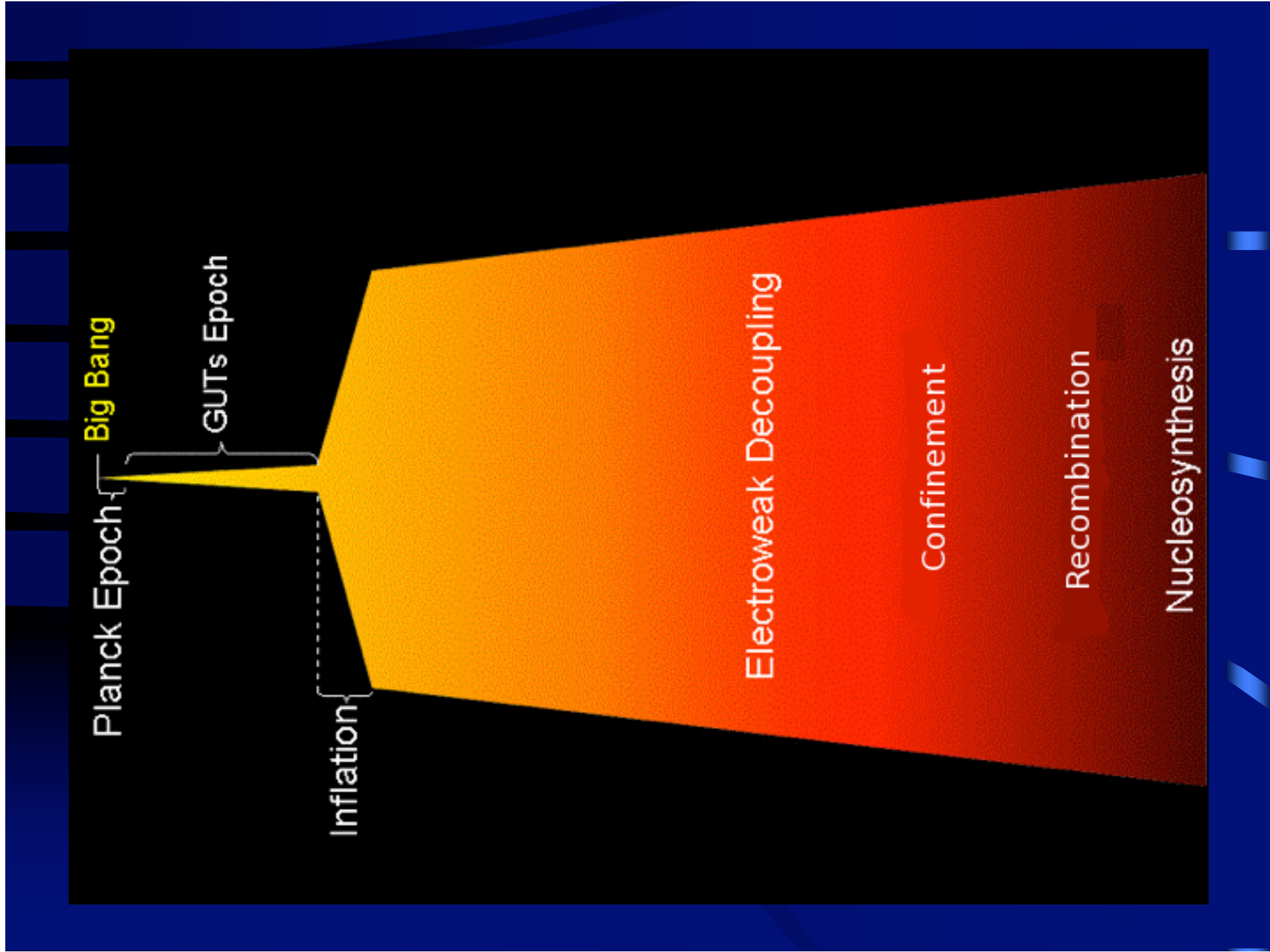
Inflation {

Electroweak Decoupling

Confinement

Recombination

Nucleosynthesis



i>clicker Quiz #17

Which of the following statements is **FALSE**?

- A. Most of the mass in the Milky Way galaxy is thought to be in the form of non-luminous “dark matter” whose exact nature is unknown
- B. Albert Einstein introduced the Cosmological constant Λ to obtain a static solution to the field equations of General Relativity because he believed at that time that the Universe was not expanding
- C. Hubble’s law: $v = H_0 d$ indicates that the Universe is expanding uniformly
- D. Edwin Hubble discovered that the expansion rate of the Universe is speeding up because of a repulsive anti-gravity force associated with “dark energy”

Baryon Asymmetry

- Extremely hot radiation in the few seconds after the Big Bang
- Very energetic photons → continuous interchange of radiation into matter and vice versa (via pair production and pair annihilation).
- Observable Universe is made up of mostly matter (as opposed to anti-matter)
- Implies a slight asymmetry between matter and anti-matter in the very early Universe (a little more matter than antimatter)
- This is referred to as the '**baryon asymmetry**' of the Universe..

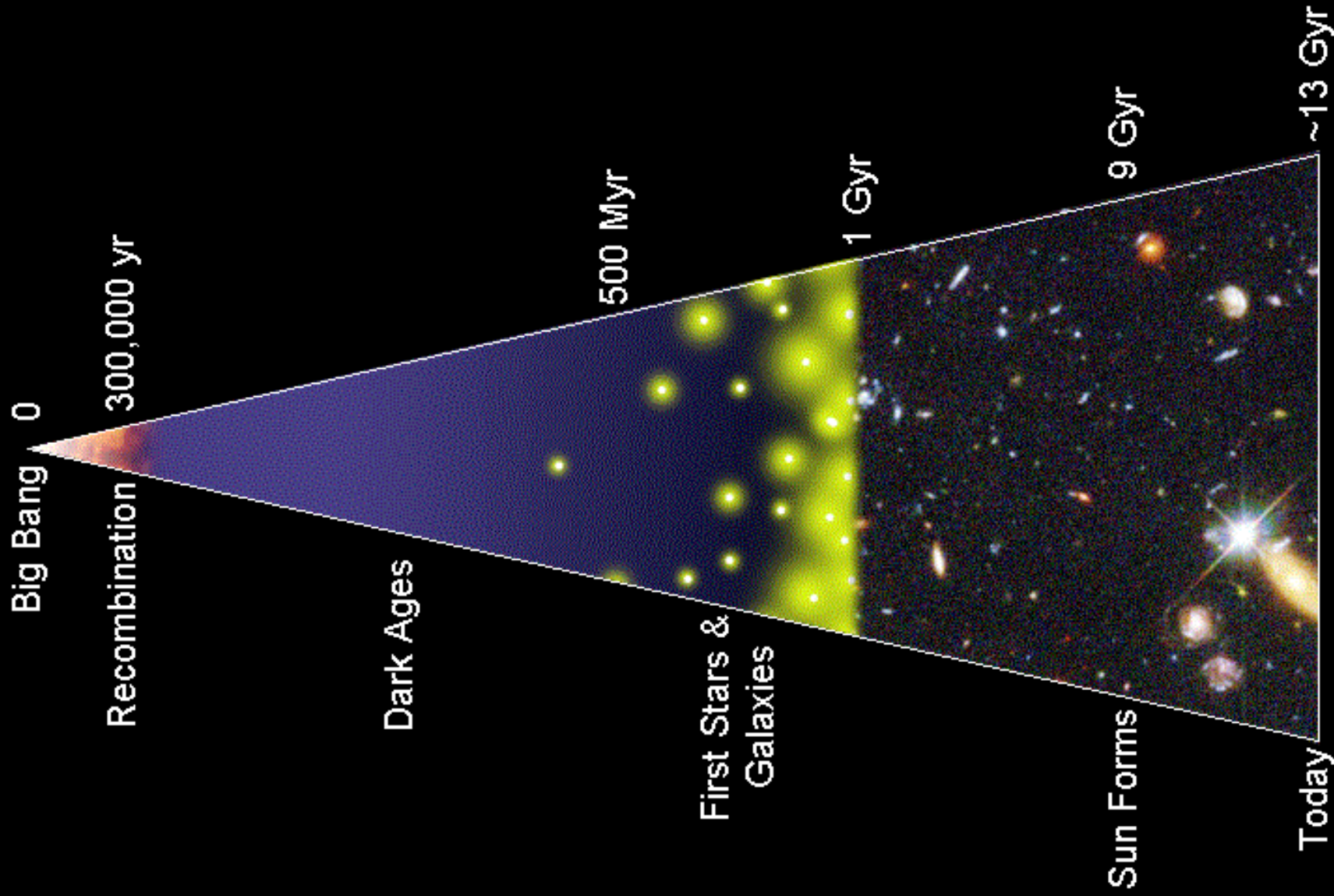
Confinement and Recombination

- Quarks are the basic particles that protons and neutrons are thought to be composed of.
- $t=10^{-6}$ sec ($T=10^{13}$ K), quarks were able to combine to form protons and neutrons → the epoch of confinement.
- After $t=3 \times 10^5$ years the temperature dropped to $T=3000$ K
- Protons and electrons (and neutrons) were able to combine to form neutral atoms.
- Matter and radiation practically ceased to interact with each other (i.e., the Universe became transparent to radiation → CMBR).
- The epoch of decoupling of matter and radiation or the epoch of recombination.

clicker Quiz #18

Which of the following statements is **FALSE**?

- A. Black holes emit Hawking radiation which can be characterized as thermal radiation and it is related to pair-production/annihilation from vacuum energy near the Schwarzschild radius or event horizon
- B. The event horizon or Schwarzschild radius of a black hole, the region over which it is capable of trapping light (radiation), is proportional to the black hole's mass
- C. "A black hole has no hair" is a statement that describes the loss of identity of matter when it is swallowed by a black hole
- D. The gravitational field of a black hole extends only out to its event horizon or Schwarzschild radius



Big Bang Nucleosynthesis

- Almost all the hydrogen we see in the present Universe was formed at the epoch of recombination
- Most of the light elements (helium, deuterium, lithium, etc.) were formed shortly thereafter
- The efficiency with which these light elements were formed depends on what the density of protons and neutrons was (baryonic matter).
- Studying the abundance of light elements (relative to hydrogen) is a good way of determining the baryon content of the Universe.
- There is a fairly strong indication that most of the matter in the Universe is non-baryonic, in addition to being non-luminous.

The CMBR Horizon Problem

- The CMBR has the same properties in all directions.
- Consider two portions of the Universe from opposite ends of the sky.
- These two portions are within our observable Universe (horizon), but they are outside each other's horizons.
- Light has not yet had time to travel from one of these portions to the other.
- If they have never been in communication, how do they know to be at the same temperature?

Inflation

- Very early phase of extremely rapid expansion (Guth, Linde, 1980s).
- During this inflationary phase, the Universe expands by a factor of 10^{50} in the time span $t= 10^{-35}$ sec to $t= 10^{-24}$ sec.
- Inflationary phase is immediately after the epoch at which the strong nuclear force froze out, and before the weak nuclear force and electromagnetic force froze apart from each other.
- All of our observable Universe was an infinitesimally small volume $10^{50} \times 10^{50} \times 10^{50} = 10^{150}$ times smaller than we would have guessed from a simple extrapolation of the expansion we observe today.