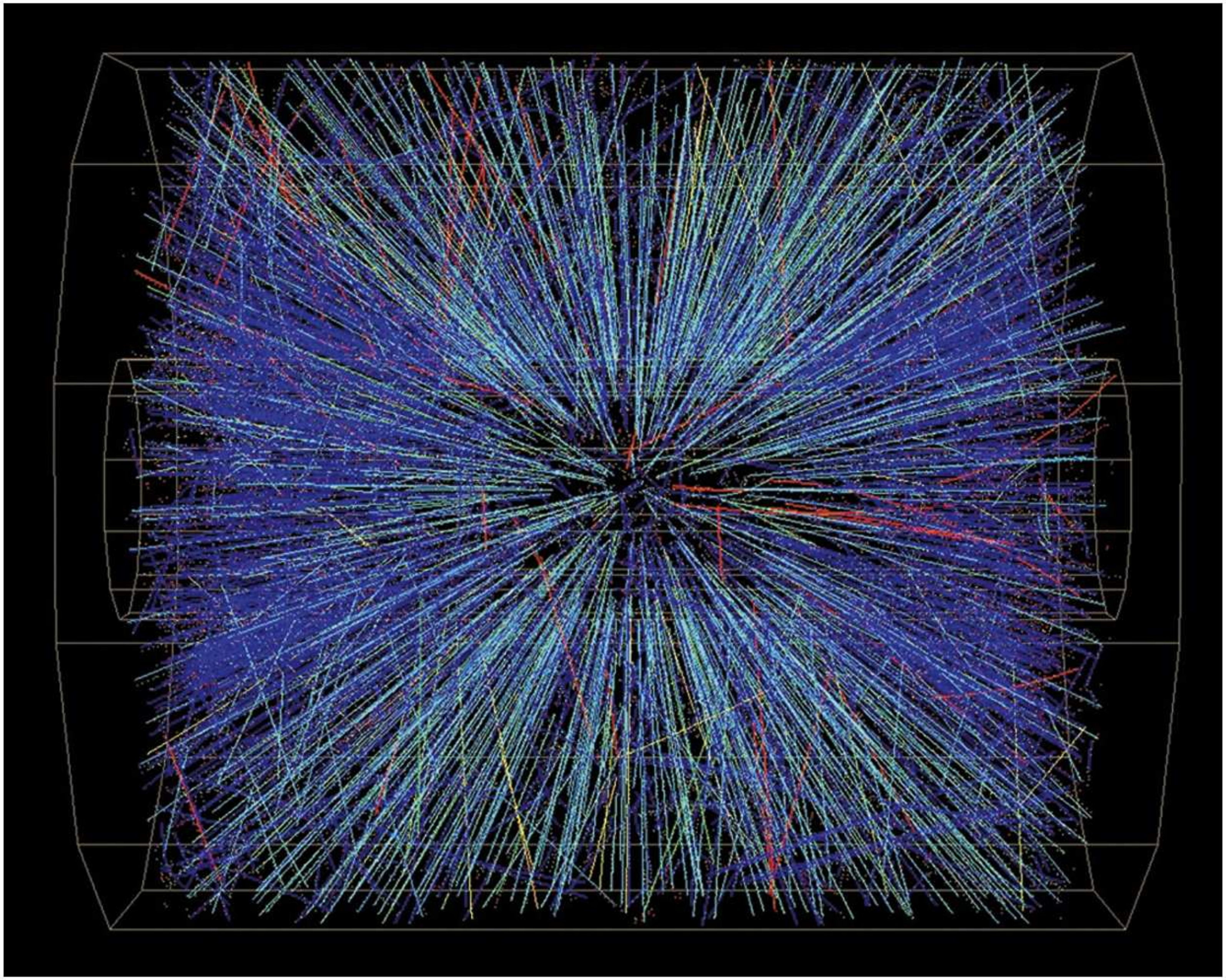
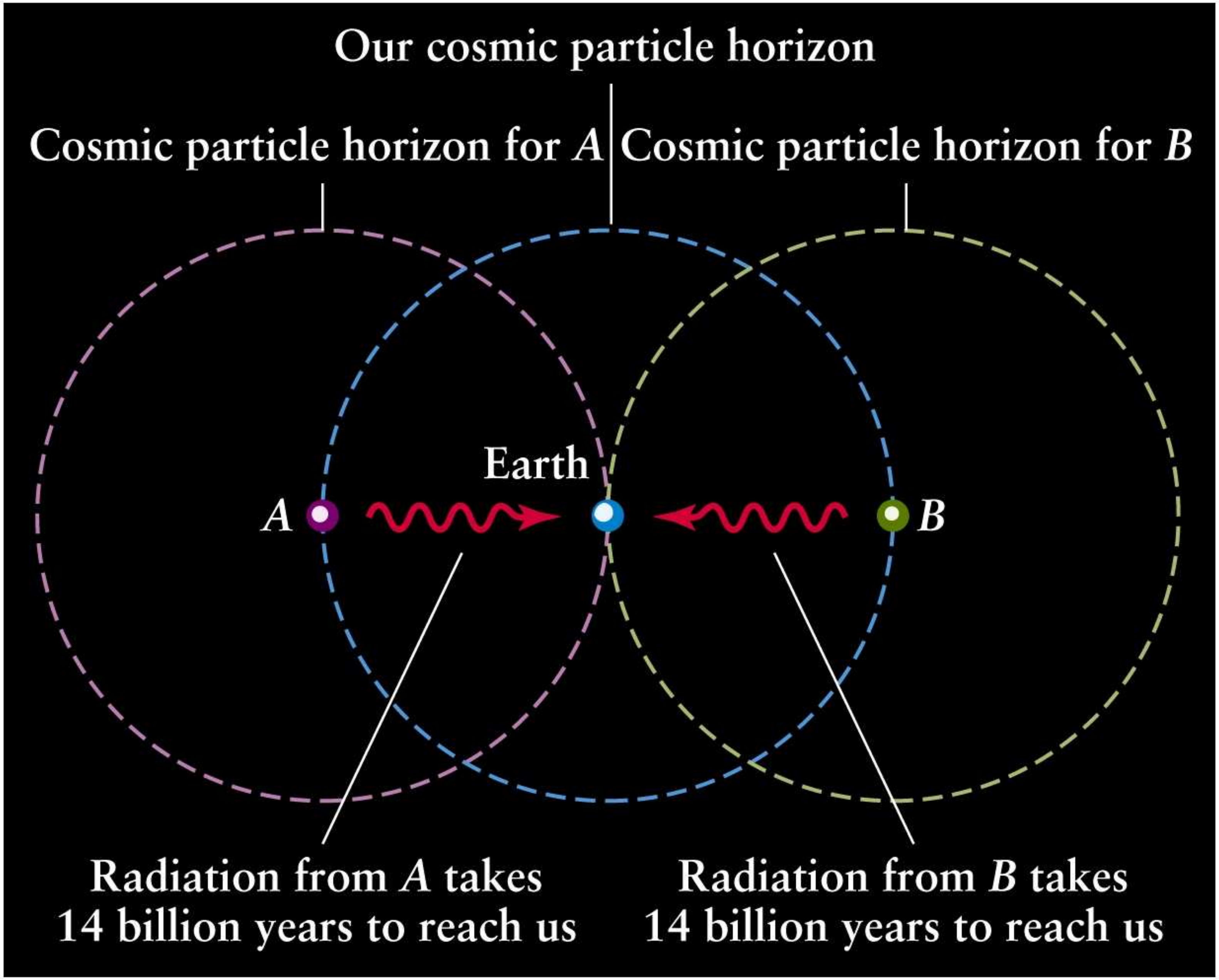


The Early Universe

- **Goals**
  - Determine how the Universe expanded.
  - Understand the formation of H, He.
  - Define the mass of structures that could collapse to form superclusters.
- **Inflation**
  - The Horizon problem
    - The isotropy of the CMB provides a major challenge for standard cosmology. CMB is isotropic over <u>all</u> the sky with $\Delta T/T \sim 10^{-6}$.
    - For regions to have the same temperature they must have been in <u>causal contact</u>. The size of the region that can pass information is determined by the speed of light.
    - The maximum region over which light can travel is called the <u>horizon</u>.
    - It would take photons from either side of the sky 2x age of the Universe for them to pass information. At last scattering the Horizon corresponds to about 2 degrees.
    - The sky should not be so isotropic.

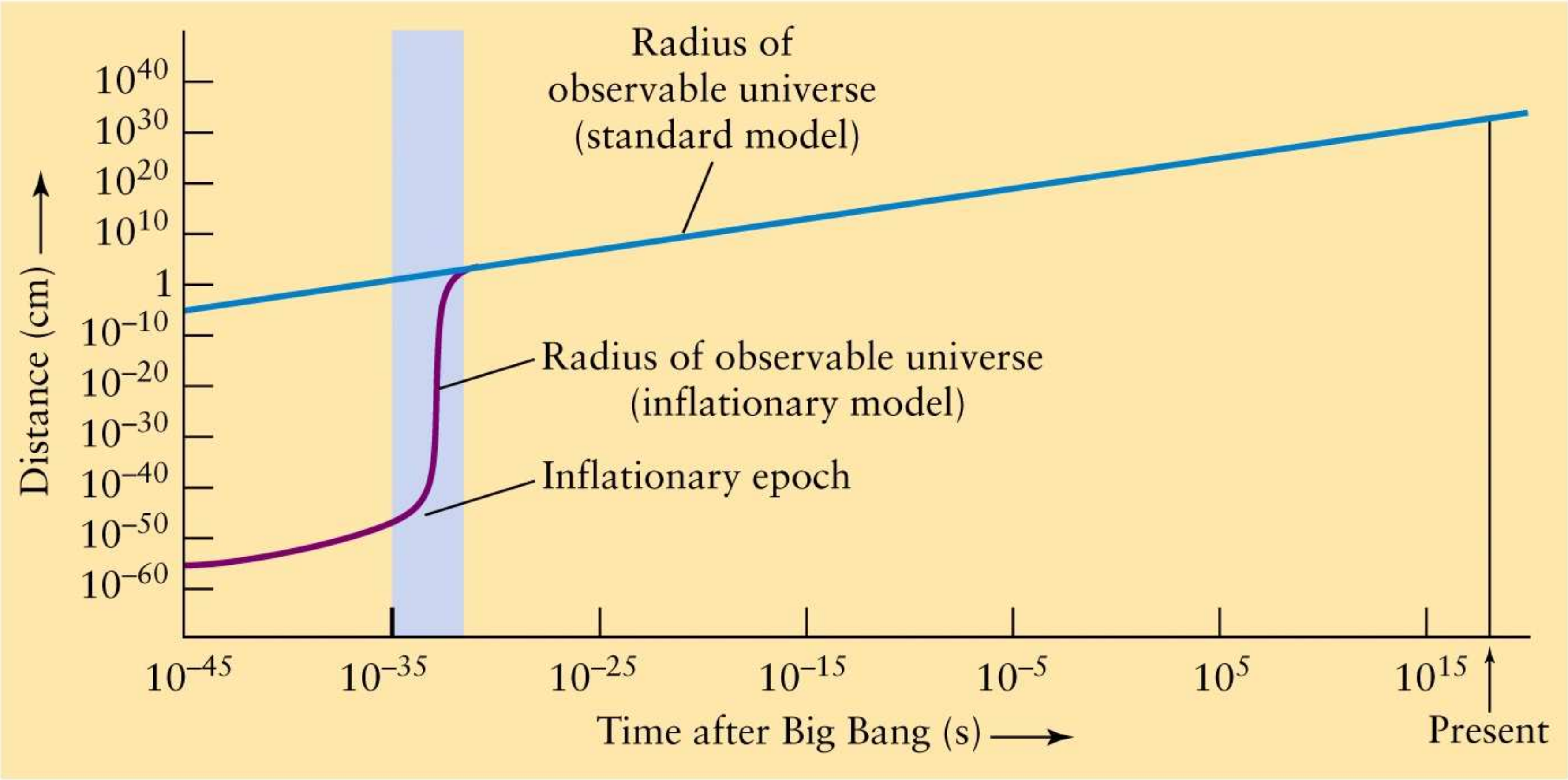

Our cosmic particle horizon
Cosmic particle horizon for A
Cosmic particle horizon for B
Earth
A
B
Radiation from A takes 14 billion years to reach us
Radiation from B takes 14 billion years to reach us

– The Flatness problem

- **A second problem is posed by the density (Ω) of the Universe.**
- **If $\Omega<1$ the Universe expands forever if $\Omega>1$ it collapses. Why is Ω so close to one.**
- **For Ω„ 1 the deviation from a critical density changes rapidly with time (expansion).**
- **For Ω to be $0.3 \rightarrow 1$ at the present time it must have been within 1 part in 10^{24} at 1ns after the Big Bang.**
- **If it was this close why isnt it 1?**

– An Inflationary Period

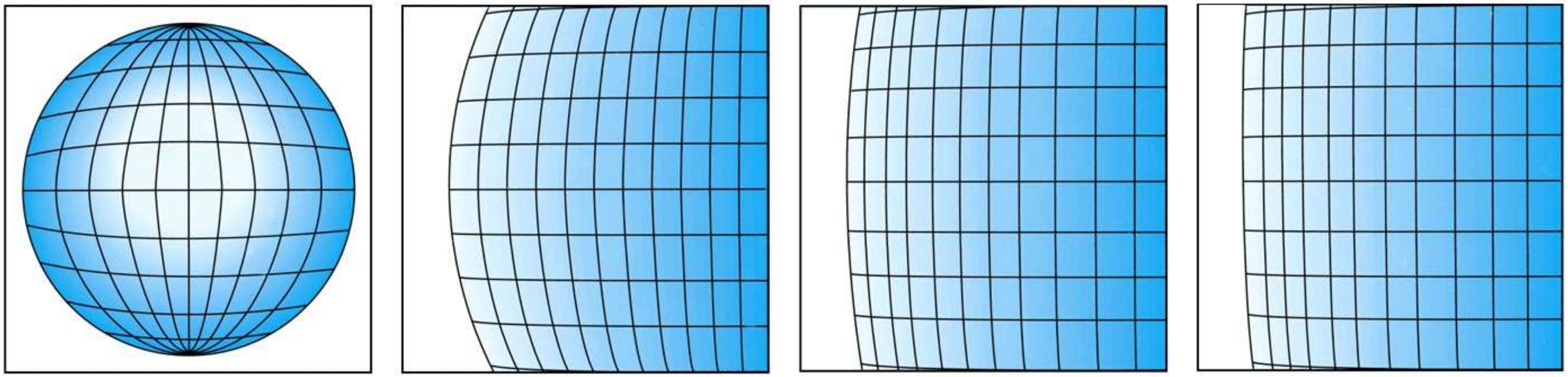
- **Alan Guth (MIT) came up with a solution for the Horizon and Flatness problems called <u>inflation</u>.**
- **He proposed that there was a rapid period of growth in the Universe such that regions on the sky today were much closer in the past than the current expansion rate would suggest.**
- **At early times all the sky was in causal contact.**


Radius of
observable universe
(standard model)
Radius of observable universe
(inflationary model)
Inflationary epoch
Distance (cm)
10^40
10^30
10^20
10^10
1
10^−10
10^−20
10^−30
10^−40
10^−50
10^−60
10^−45
10^−35
10^−25
10^−15
10^−5
10^5
10^15
Time after Big Bang (s)
Present

– An Inflationary Period

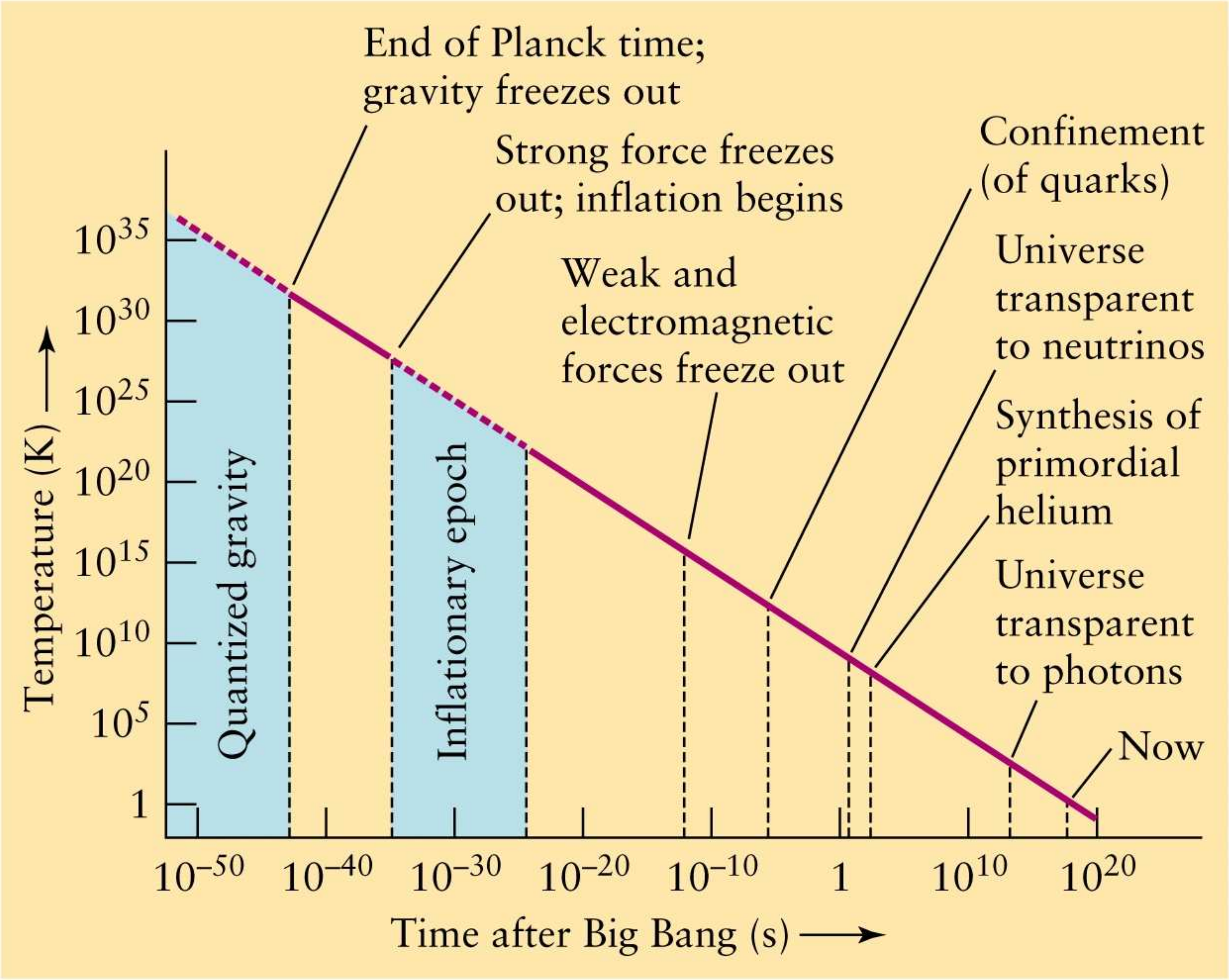
- Universe expands exponentially
- For the Universe to be isotropic it must have expanded by about e^{60} or 10^{26}.
- One question is that how do we stop inflation once it has started (and return to the normal expansion).
- This rapid expansion solves the horizon and flatness problems.

$$R(t) = R_0 e^{Ht}$$



• The Early Universe and Beyond

- **When considering processes in the Universe which occurred when the Universe was less than a few seconds old, we say we are studying the `early Universe.' Our current understanding of the laws of physics suggests that we can understand what physical processes happened in the Universe back to a time when it was only 10^{-43} seconds old.**
- **Prior to 10^{-43} seconds, there is no agreement on what the correct laws of physics are.**
- **As we go back in time, and approach the "beginning" of the Universe the density and temperature increases rapidly. As a consequence the nature of the Universe continually changes.**


End of Planck time; gravity freezes out
Strong force freezes out; inflation begins
Weak and electromagnetic forces freeze out
Confinement (of quarks)
Universe transparent to neutrinos
Synthesis of primordial helium
Universe transparent to photons
Now
Quantized gravity
Inflationary epoch
Temperature (K)
10^{35}
10^{30}
10^{25}
10^{20}
10^{15}
10^{10}
10^{5}
1
10^{-50} 10^{-40} 10^{-30} 10^{-20} 10^{-10} 1 10^{10} 10^{20}
Time after Big Bang (s)

- Unification of the Fundamental Forces of Nature

- **Modern physics is struggling to reconcile the various laws of physics with each other. For example General Relativity, the modern theory of gravity, is not consistent with Quantum Mechanics.**

- **Quantum Mechanics is a theory which provides a description of behavior on small (microscopic) scales.**
    - **It provides a theory for atomic structure.**

- **General Relativity also predicts singularities (infinitely small points of infinite density), which suggests the theory is incomplete.**

- **There are 4 fundamental forces in nature. Physicists hope to develop a** SINGLE **theory which can explain all 4 forces of nature. Attempts to do this are called Grand Unification Theories (GUTs).**

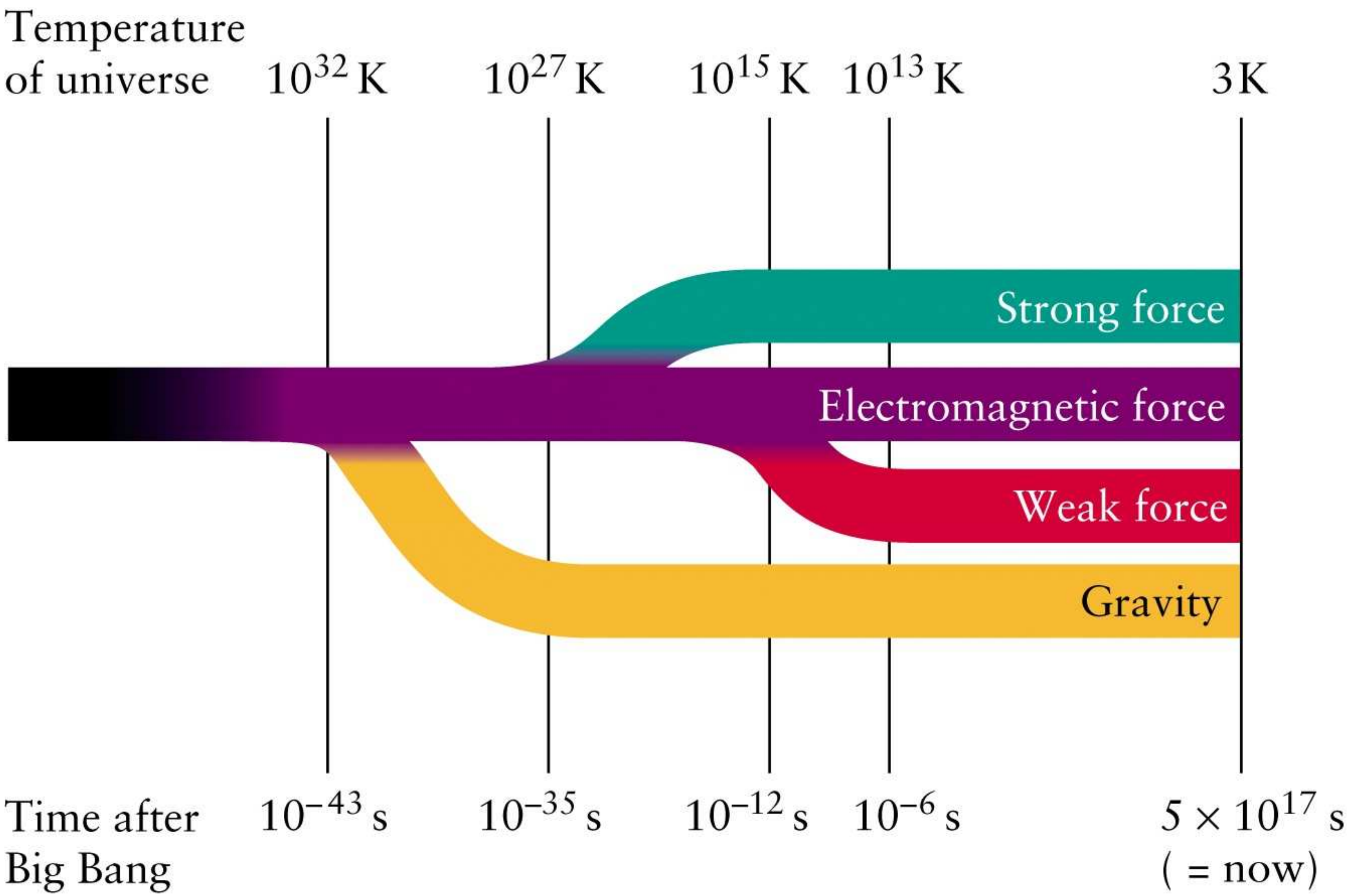
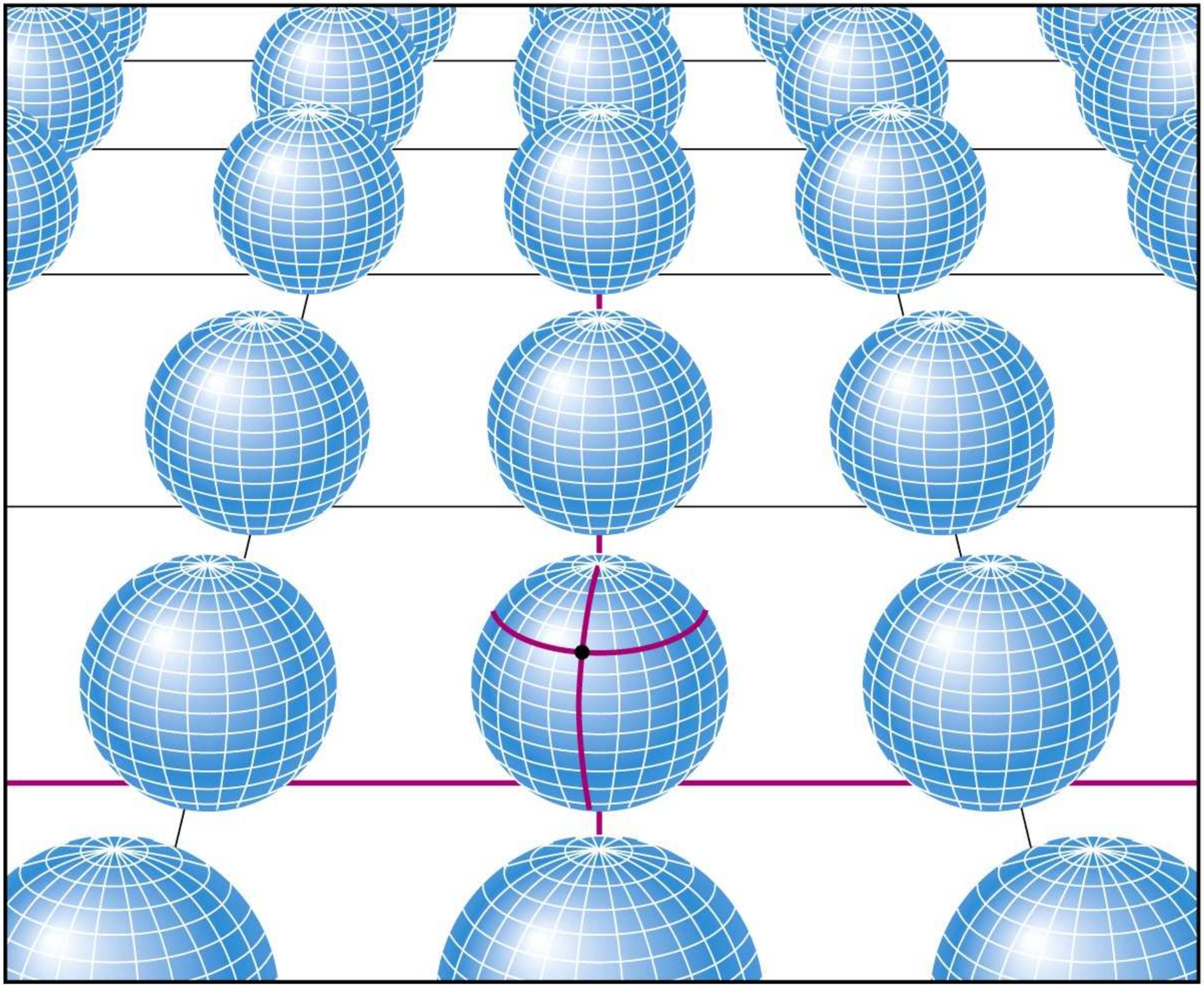
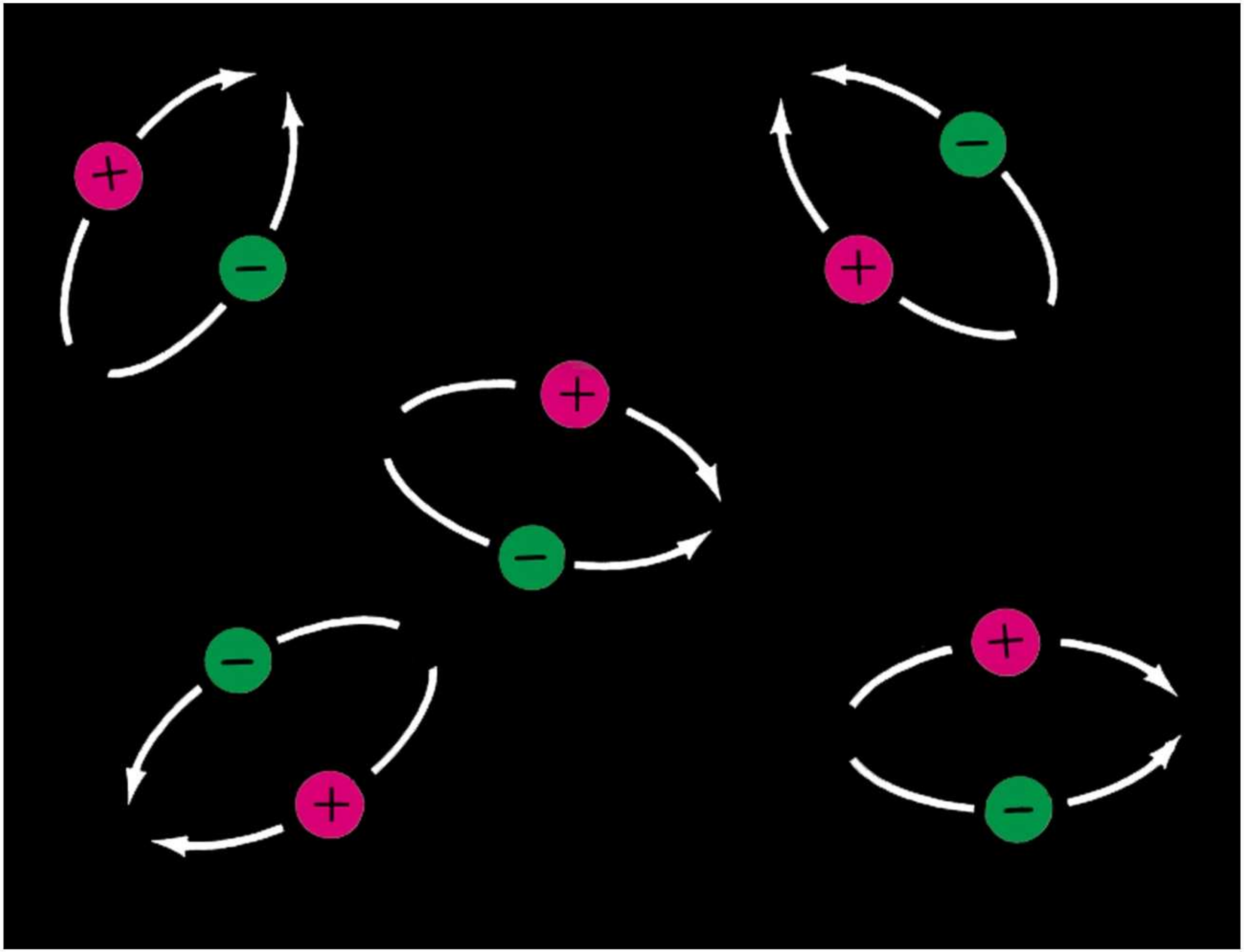

Temperature of universe
10^32 K
10^27 K
10^15 K
10^13 K
3K
Strong force
Electromagnetic force
Weak force
Gravity
Time after Big Bang
10^−43 s
10^−35 s
10^−12 s
10^−6 s
5 × 10^17 s
(= now)

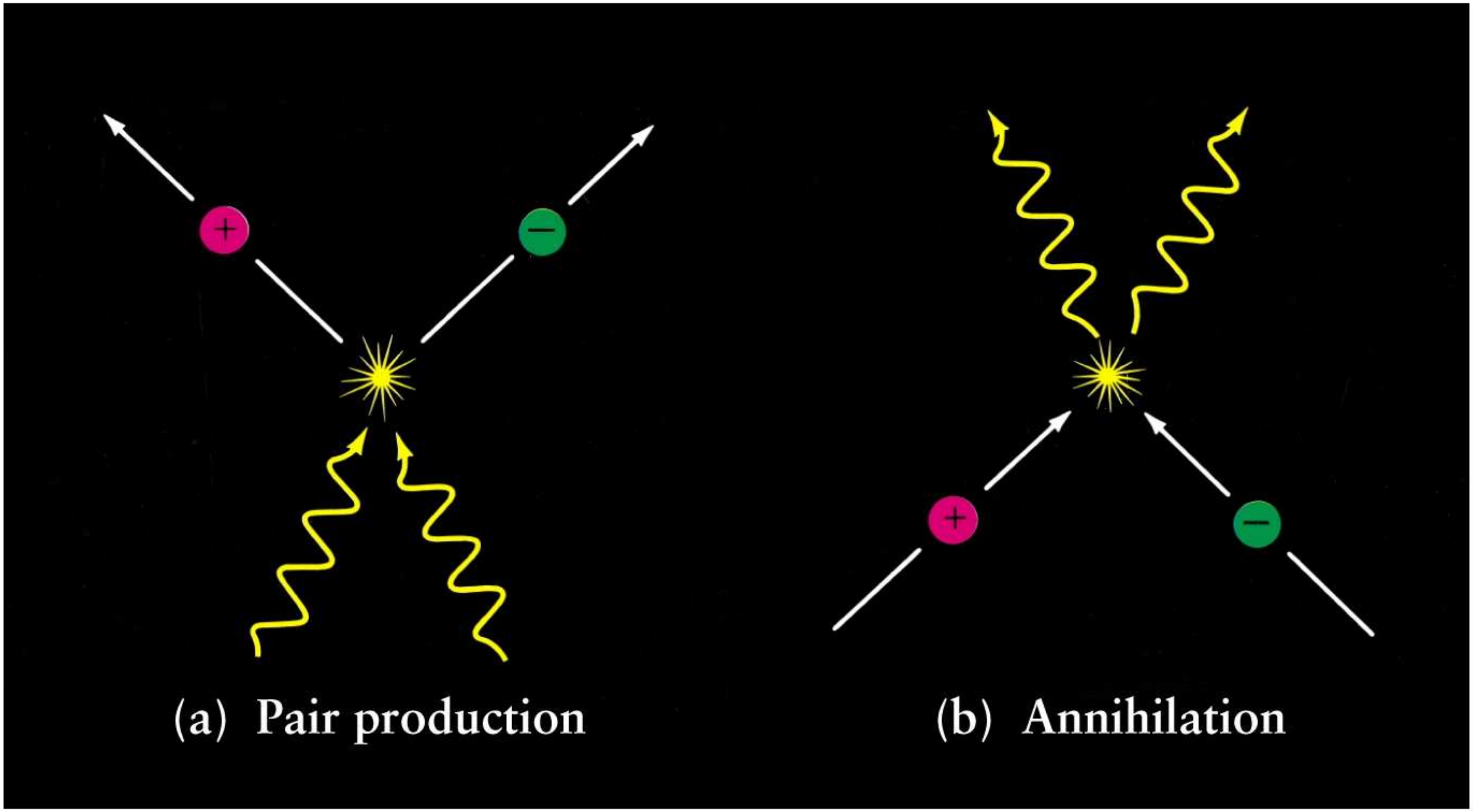
table 29-1 The Four Forces

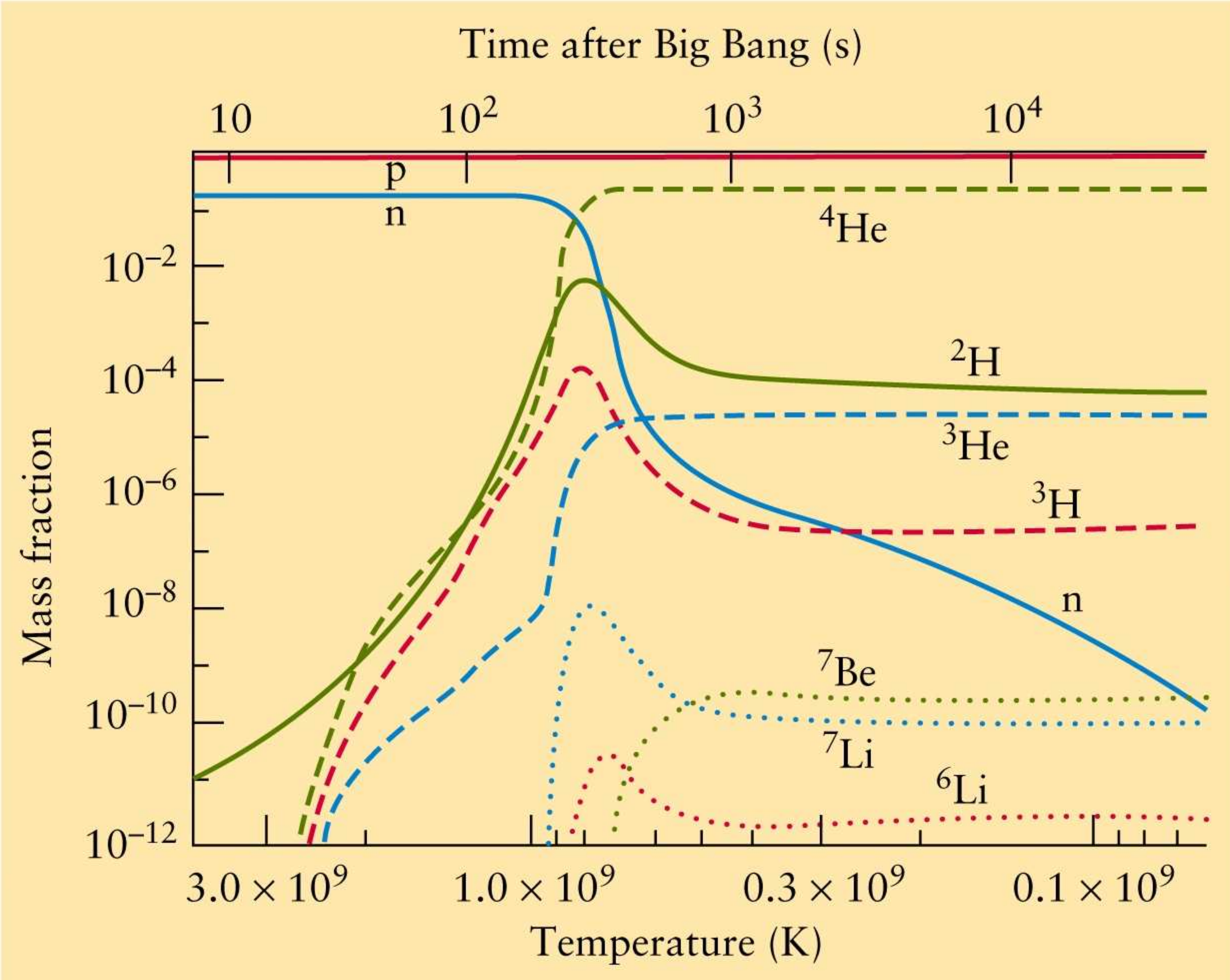
Force	Relative strength	Particles exchanged	Particles on which the force can act	Range	Example
Strong	1	gluons	quarks	10^{-15} m	holding protons, neutrons, and nuclei together
Electromagnetic	$1/137$	photons	charged particles	infinite	holding atoms together
Weak	10^{-4}	intermediate vector bosons	quarks, electrons, neutrinos	10^{-16} m	radioactive decay
Gravitational	6×10^{-39}	gravitons	everything	infinite	holding the solar system together

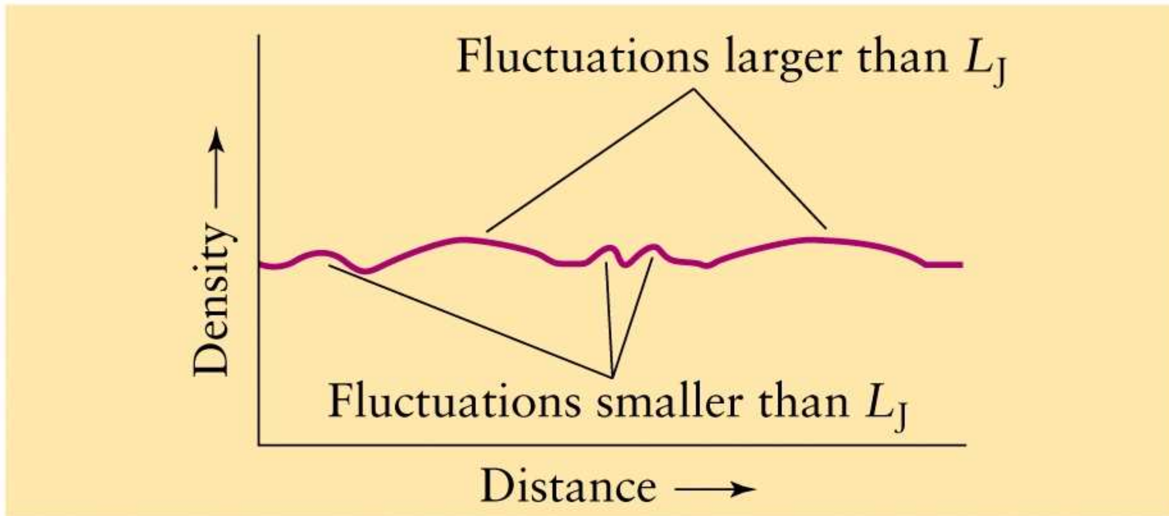


- At times earlier than 10^{-6} seconds, the temperatures (greater than 10^{13} K) and densities were sufficiently high (Visible Universe in a volume the size of Earth) that neutrons and protons broke into their constituent components called quarks.
- At times less than 10 seconds, positrons and electrons were continually being created out of gamma rays. The positrons and electrons would immediately annihilate each other, establishing an equilibrium with the radiation field.
- Very early in the evolution of the Universe it was filled with both matter and anti-matter. As the Universe cooled, all the anti-matter was annihilated by the matter. Fortunately, there was a slight excess of matter which is what we see today.

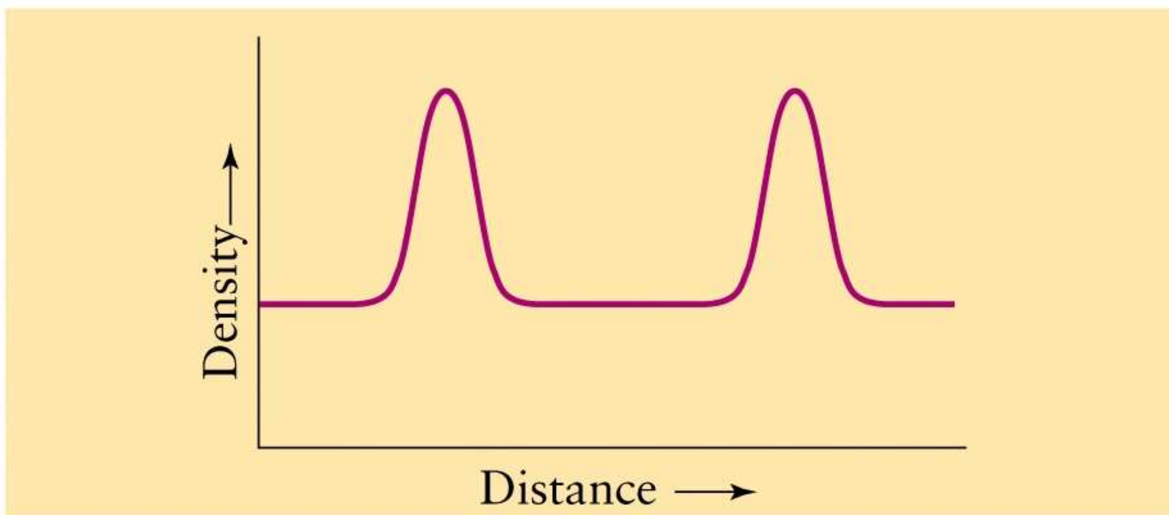



+
−
(a) Pair production
(b) Annihilation


Time after Big Bang (s)
10
10^2
10^3
10^4
p
n
^{4}He
^{2}H
^{3}He
^{3}H
n
^{7}Be
^{7}Li
^{6}Li
Mass fraction
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
3.0×10^9
1.0×10^9
0.3×10^9
0.1×10^9
Temperature (K)



a At an early time

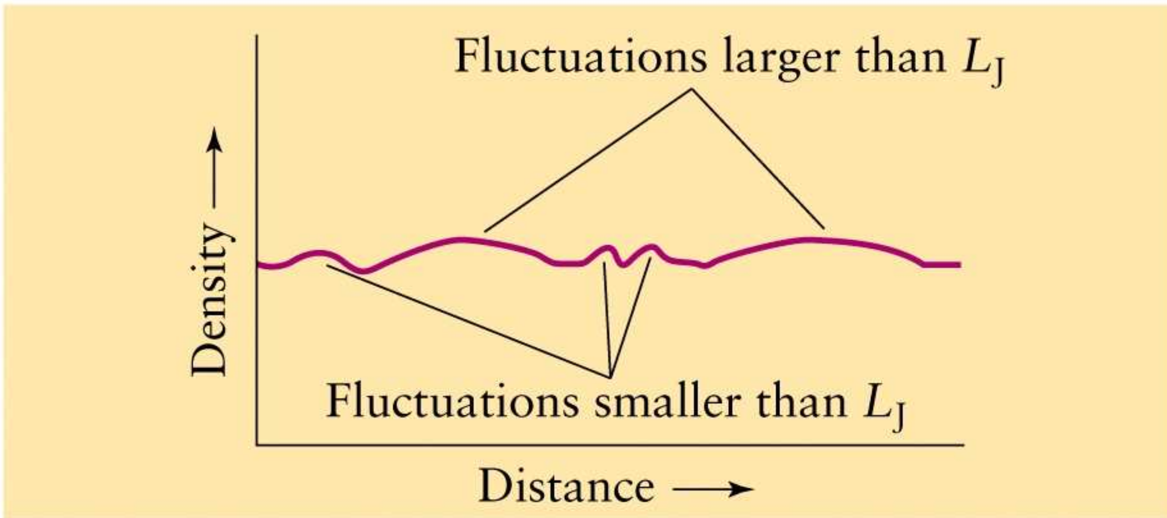


b At a later time

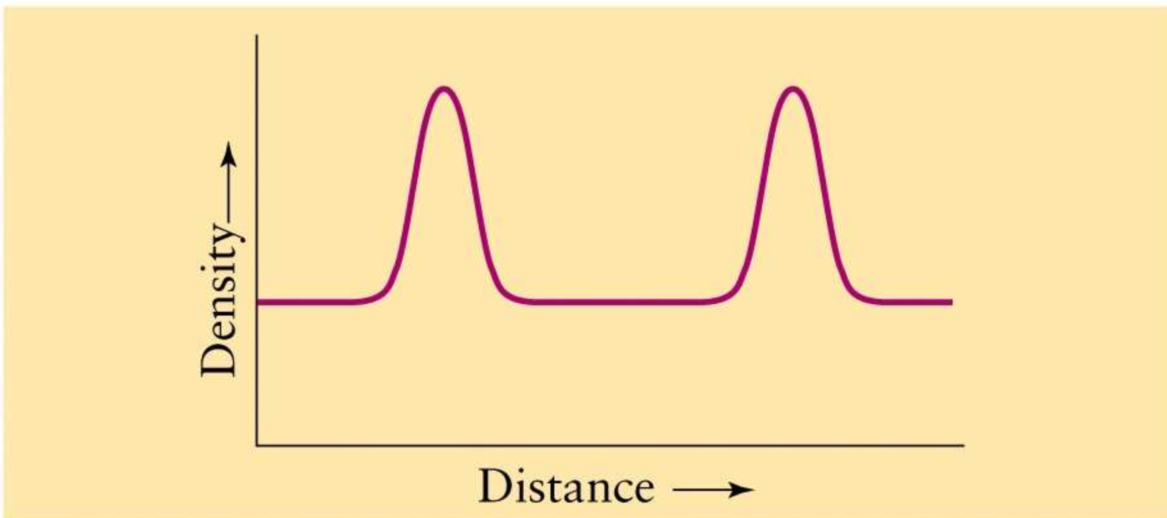
- # Growth of Structure
  - ## From the CMB to Superclusters
    - The overdensities in the mass (as seen in the CMB) grow through gravity.
    - As they grow the pressure of the gas within the overdensity can suppress the collapse.
    - Whether a density fluctuation will grow or dissipate is determined by its Jeans length or Jeans mass.
  - ## Jeans Length

$$L = \sqrt{\frac{\pi \, kT}{mG \, \rho_m}}$$

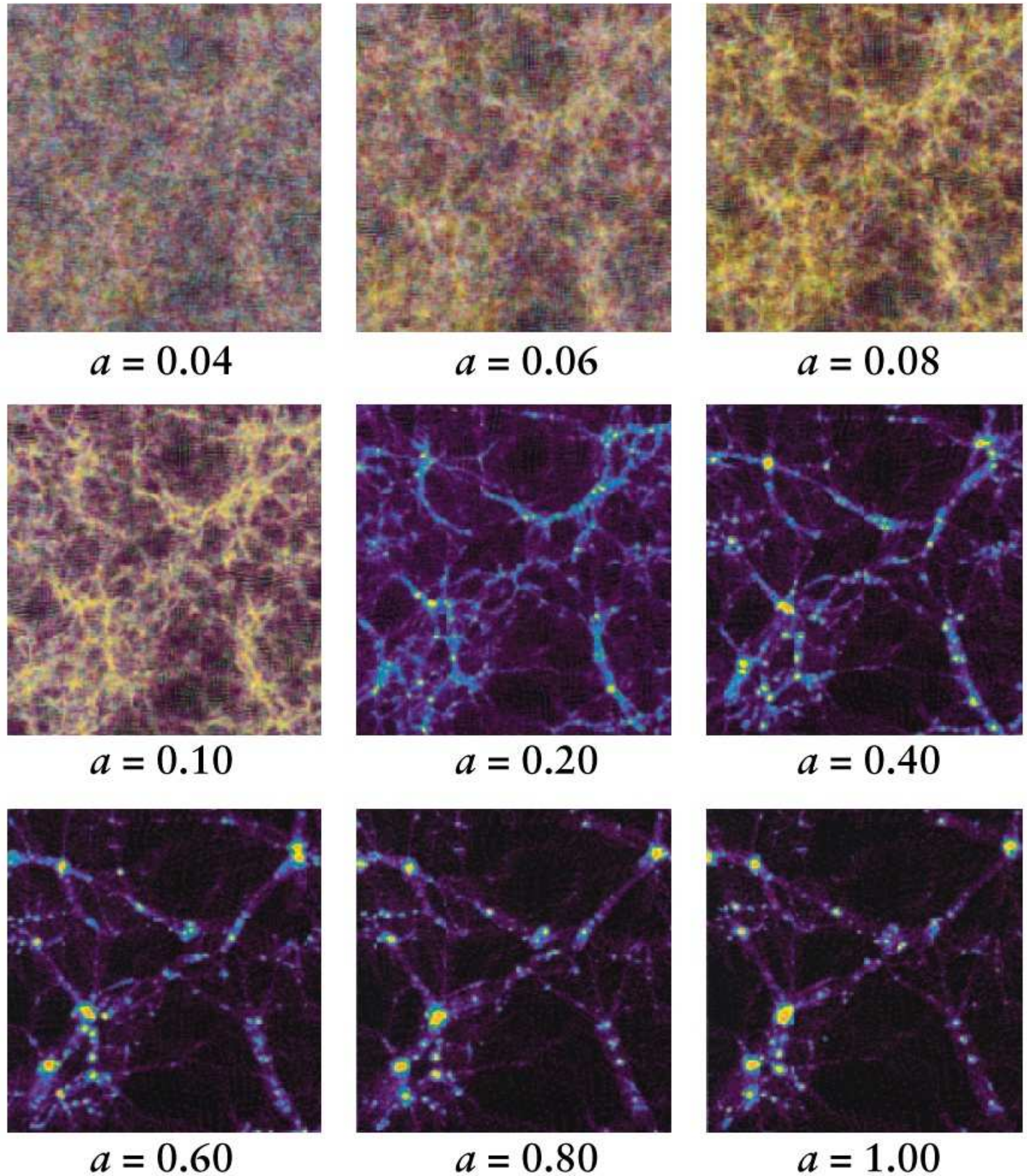
    - L: size of the fluctuation (Jeans length)
      k: Boltzmann's constant
      T: temperature
      m: mass of a single particle of gas
      ρ_m: density of matter in gas
    - Fluctuations larger than Jeans length tend to grow. Those less than L tend to dissipate.
    - At recombination (T=3000 K, $\rho_m = 10^{-18}$ kg m^{-3}) L= 30 pc (size of a globular cluster).
    - The mass within the Jeans Length is about 5×10^5 $M_{/}$ (globular cluster mass)
    - The minimum size of structures that can form are probably globular clusters.



a At an early time



b At a later time


$a = 0.04$
$a = 0.06$
$a = 0.08$
$a = 0.10$
$a = 0.20$
$a = 0.40$
$a = 0.60$
$a = 0.80$
$a = 1.00$