Lecture 24

Inflationary Cosmology

Outline of Lecture 24

- Inflationary Cosmology and Its Motivation
  - Near-Isotropy of CMB (How can temperature be same on opposite sides of the sky?)
  - Lack of Magnetic Monopoles (Why are there no magnetic charges as there are electric charges?)
  - Flatness of Universe (Why is it so large?)
- Quantum Fluctuations → CMB Fluctuations → Large-Scale Structure → Galaxies
- Formation of Galaxies and Clusters of Galaxies by Gravitational Instability in the Universe – Bottom-Up Scenario

Limits to Current Physical Knowledge

- Planck mass, length, and time:

$$m_P \equiv \left(\frac{\hbar c}{G}\right)^{1/2} = 2.2 \times 10^{-8} \text{ kg},$$

$$L_P \equiv \left(\frac{G\hbar}{c^3}\right)^{1/2} = 1.6 \times 10^{-35} \text{ m},$$

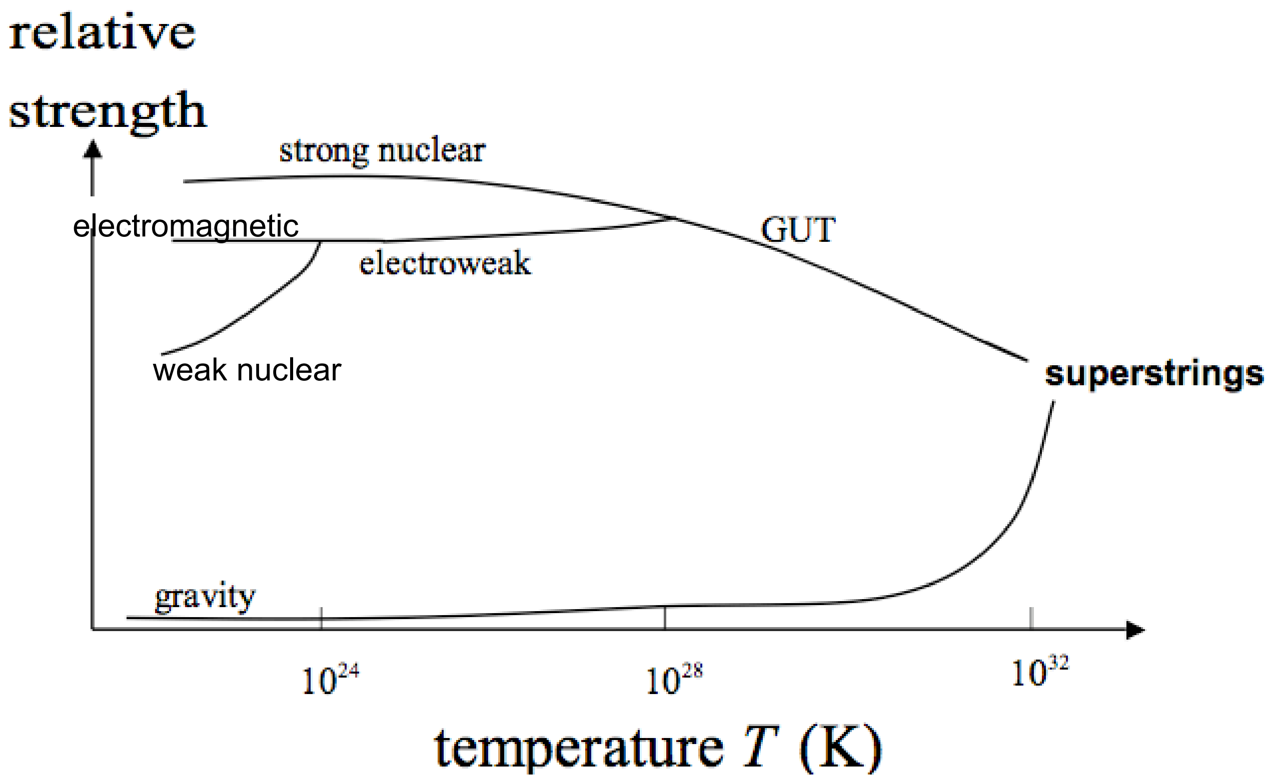
$$t_P \equiv \left(\frac{G\hbar}{c^5}\right)^{1/2} = 5.4 \times 10^{-44} \text{ s}.$$

- Corresponding temperature given through $kT_P = m_P c^2$,

$$T_P = 1.4 \times 10^{32} \text{ K is reached at } t \sim t_P.$$

- At Planck time, cosmic energy density is given roughly by $4\sigma T_P^{\,4} / c \sim m_P c^2 L_P^{\,-3}$, and spacetime is a quantum foam. Mass inside Planck volume is black hole of mass m_P, whose event horizon has size of order its Compton wavelength, a scale on which it is quantum-mechanically fuzzy: $Gm_P / c^2 = \hbar / m_P c$.
- To do physics in this regime, need to marry general relativity and quantum mechanics. Many physicists think this marriage produces superstring theory. We don't know how to do calculations in superstring theory, so the ideas presented here are tentative.

Unification of Forces



Analogy with phase transitions: At high temperature, water has a single phase: vapor. At lower temperatures, water vapor may separate into two phases, say, vapor plus liquid, releasing the binding energy of the liquid phase as latent heat. (This release provides the power behind hurricanes.) At even lower temperatures, liquid water may separate again into two phases, liquid plus ice. As the universe cooled to its present state, the single superforce at the origin of the universe might have also separated into the four disparate forces that we know as the gravitational, electromagnetic, weak, and strong interactions.

Inflation During GUT Era

- GUT (grand unified theory) era = when forces other than gravity (strong, weak, electromagnetism) were still unified until temperatures dropped below

$$T \sim 10^{29}\ \mathrm{K\ at}\ t \sim 10^{-38}\ \mathrm{s.}$$

- Following Alan Guth (1982), cosmologists assume that a false vacuum exists during this era whose vacuum density $\rho_{\rm v} \sim 10^{84}\ \mathrm{kg\ m^{-3}}$ is equal to the mass density $4\sigma T^4 / c^3$ associated with the thermal bath of particles at the GUT temperature $T \sim 10^{29}$ K.
- Prior to $t \sim 10^{-38}$ s, the universe is in normal (power-law) Friedmann expansion (see Lecture 23). After this time, the constant vacuum density $\rho_{\rm v}$ dominates over the declining density of matter and radiation, so the universe enters into exponential inflation, increasing its size by a factor of *e* = 2.7218… every 10^{-38} s. After, say, 200 *e*-foldings (when the cosmic age is only t ~ 2×10^{-36} s), the universe would have increased in size by an enormous factor of ~ 10^{86}. Such a huge increase has many salutary benefits.

Why Vacuum Energy Drives Exponential Inflation (extra material)

- With $\rho = \rho_{\text{rad}} + \rho_{\text{m}} + \rho_{\text{v}}$ where $\rho_{\text{rad}} = B / a^4$, $\rho_{\text{m}} = C / a^3$, and $\rho_{\text{v}} =$ const, Friedmann-Lemaitre equations become

$$\frac{1}{a^2}\left[\left(\frac{da}{dt}\right)^2 + kc^2\right] = \frac{8\pi G}{3}\left(\frac{B}{a^4} + \frac{C}{a^3} + \rho_{\text{v}}\right).$$

- If *a* can become large, dominant terms read:

$$\frac{1}{a^2}\left(\frac{da}{dt}\right)^2 \cong \frac{8\pi G}{3}\rho_{\text{v}} \equiv \omega^2 = \text{const},$$

which has the large *t* solution:

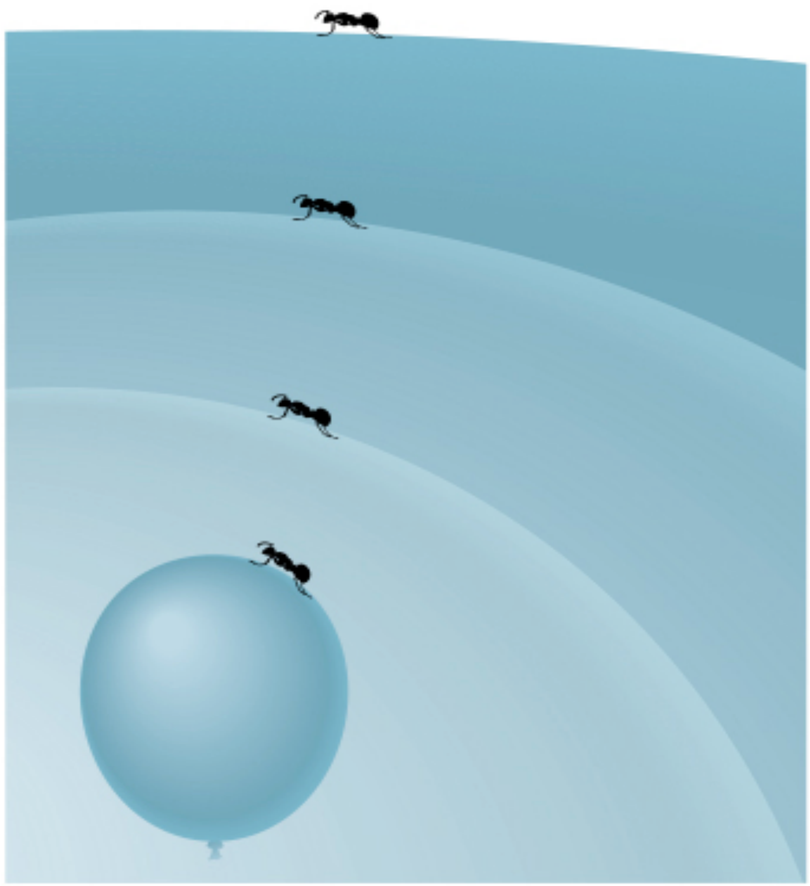
$$a = Ae^{\omega t}.$$

- The last conclusion holds even if $k = +1$ (closed universe); thus, closed universe is not synonymous with bound universe if there is a positive cosmological constant $\Lambda \equiv 8\pi G\rho_{\text{v}}$, and universe enters an exponential phase of expansion.

Exponential Inflation in Very Early Universe Solves Some Major Difficulties (Alan Guth 1982; extra material)

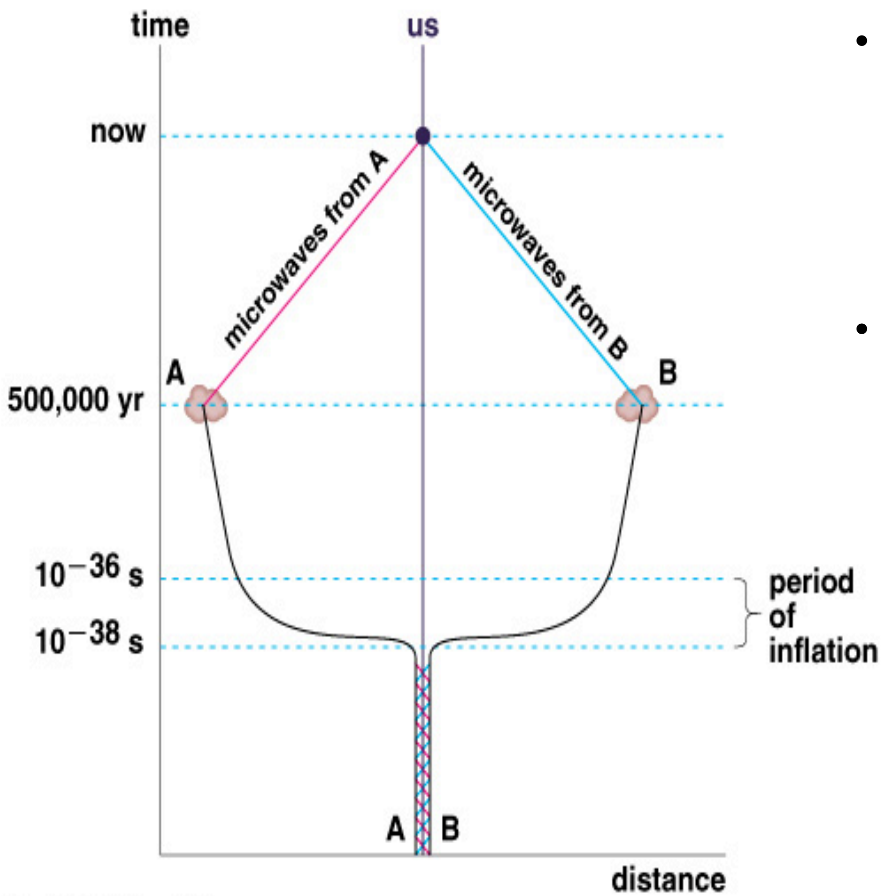
- Flatness problem:
  Once inflation sets in, the scale of universe $a = Ae^{\omega t}$ becomes very large for $t >> \omega^{-1} \sim 10^{-38}$ s, where $\omega = \sqrt{8\pi G\rho_v / 3} \sim 10^{38}$ s^{-1} when $\rho_v \sim 10^{84}$ kg m^{-3} during the GUT era.
- Horizon problem: *T* (now) = 2.725 K in every direction; regions that were originally causally connected regions and therefore could equilibrate their temperatures became causally disconnected when an exponentially large space was added between them.
- Magnetic monopole problem: Any heavy magnetic monopoles created prior to $t \sim 10^{-38}$ s were inflated to such large distances that the chances of finding them in the presently observable universe is nil.

Solution of Flatness Problem



- An ant on the surface of a rapidly expanding balloon would soon think that it lives on a flat world.
- Similarly, all our measurements, out to the very limits of the cosmic horizon, may lead us to conclude empirically that we live in a Euclidean cosmos even if inflation has made a closed universe, not infinite, but just immeasurably large.

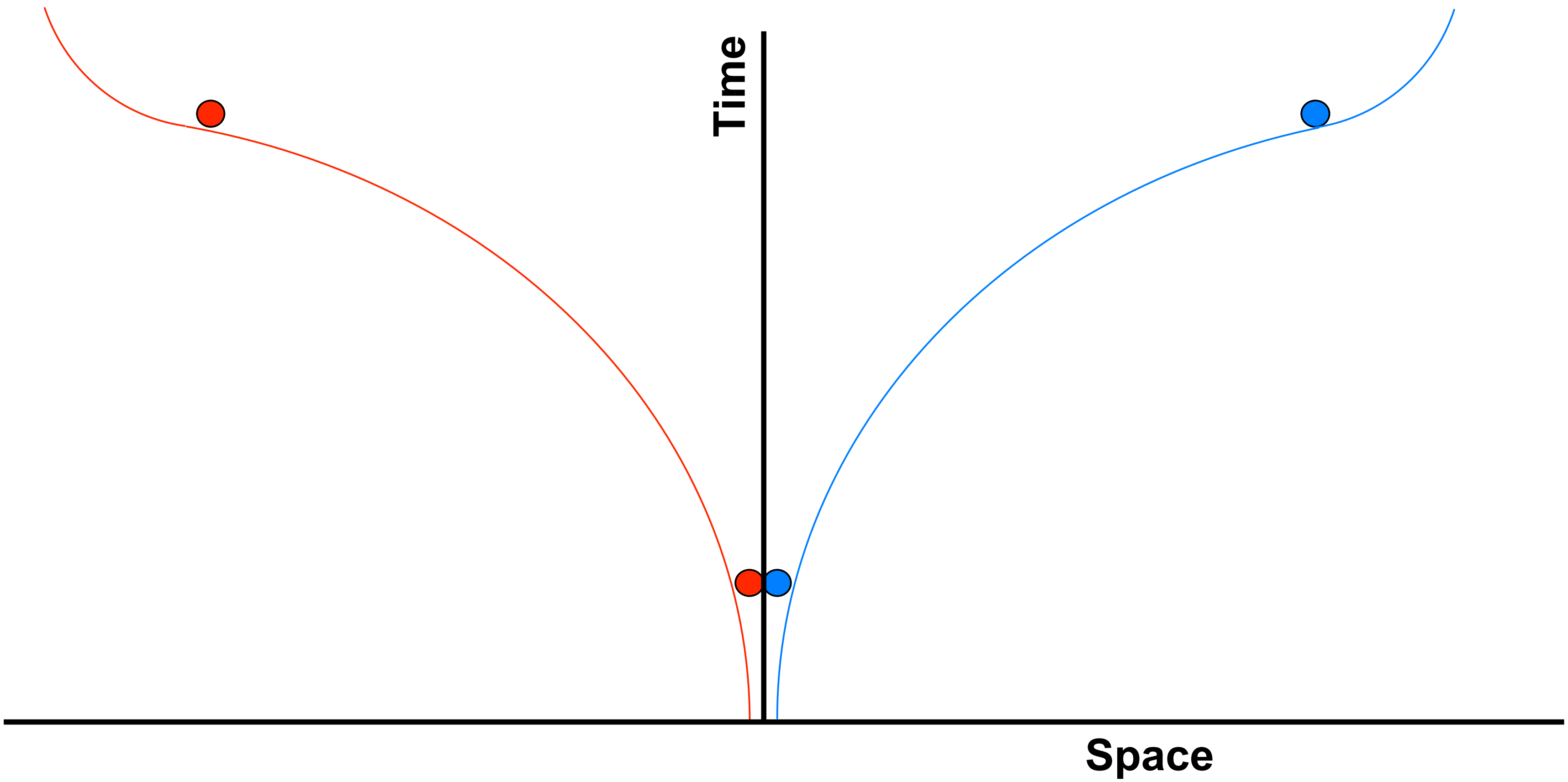
Solution of Horizon Problem
Equality of Temperature of CMB



- We think, "CMB photons from opposite sides of the sky, flying at the speed of light, have only had time to reach us, who are midway between the emitting regions. How could these regions know ahead of time to be at the same temperature?"
- We did not take into account the possible effect of cosmic inflation. If in the distant past (at cosmic time between 10^{-38} and 10^{-36} s!), these two regions were so close together that they could causally affect each other, then their temperatures could have equilibrated to the same value. Subsequently, torn apart by the violent insertion of a tremendous amount of space during inflation, they cooled by the same amounts from the expansion of the universe, until today they cross our horizon, and we see that their temperatures have the same universal value of 2.725 K.

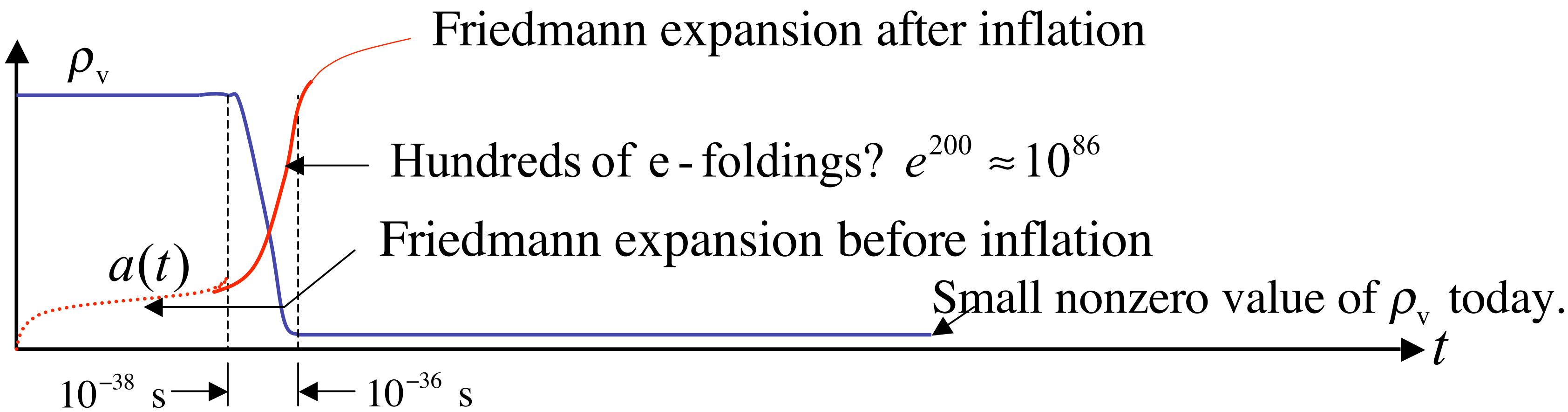
Solution of the Magnetic Monopole Problem

Monopoles separated by Compton length when created from quantum vacuum (Lecture 23) are pulled apart much beyond horizon by inflation.



Phase Transition to "Normal" Vacuum

- Clearly, $\rho_v \neq 10^{84}$ kg/m^3 today. Indeed, today, from the resurgent acceleration of the universe we know $\rho_v = 6 \times 10^{-27}$ kg/m^3 (Lecture 22). If ρ_v ever did = 10^{84} kg/m^3, it must have declined tremendously from a false vacuum to today's true vacuum. Speculation is that the release of the "latent heat" of the phase transition creates real particles out of the energy of the false vacuum and eventually leads to the end of the exponential expansion and the resumption of ordinary Friedmann expansion (until the present epoch when the universe is curiously re-entering exponential inflation at a greatly reduced rate).

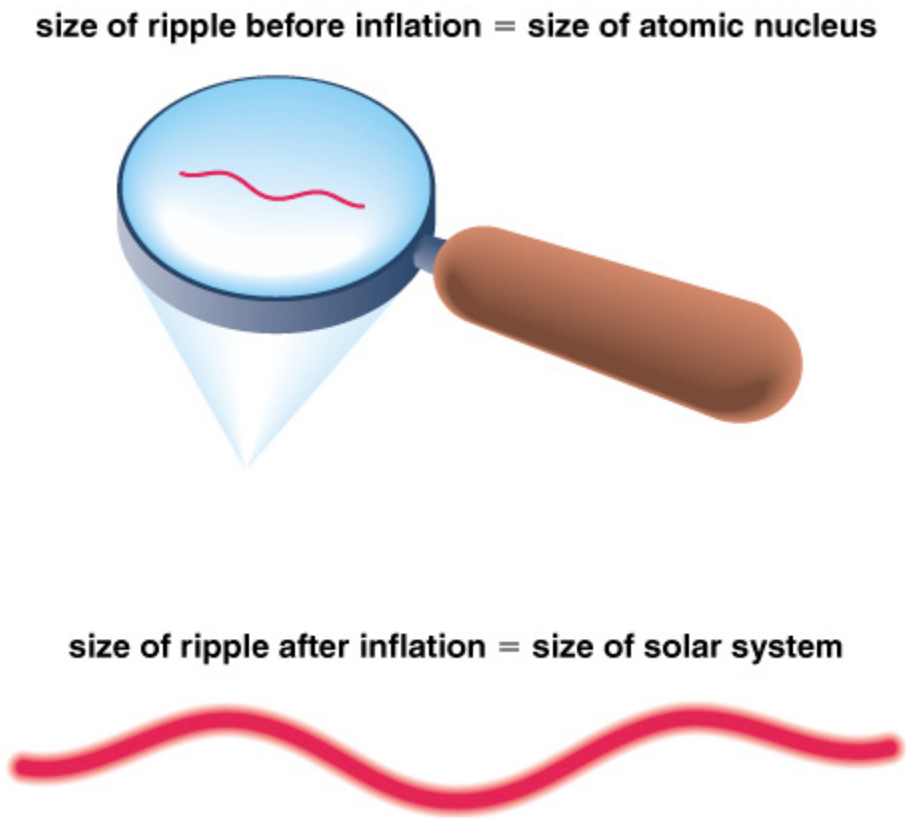


- Quantum fluctuations lead to slightly different expansion rates for different regions, which leads to CMB anisotropies, which leads to the development of large-scale structure through gravitational instabilities:

$$\frac{|\Delta\rho|}{\rho} = \varepsilon\left(\frac{ct}{\lambda}\right)^2 \quad \text{for small } t, \text{ with } \varepsilon = \text{const} << 1 \text{ not yet computable by theory.}$$

wavelength of ripple

Inflation of Quantum Fluctuations



CMB Fluctuations Peak at about 1° Consistent with Inflationary Prediction that Universe is Flat

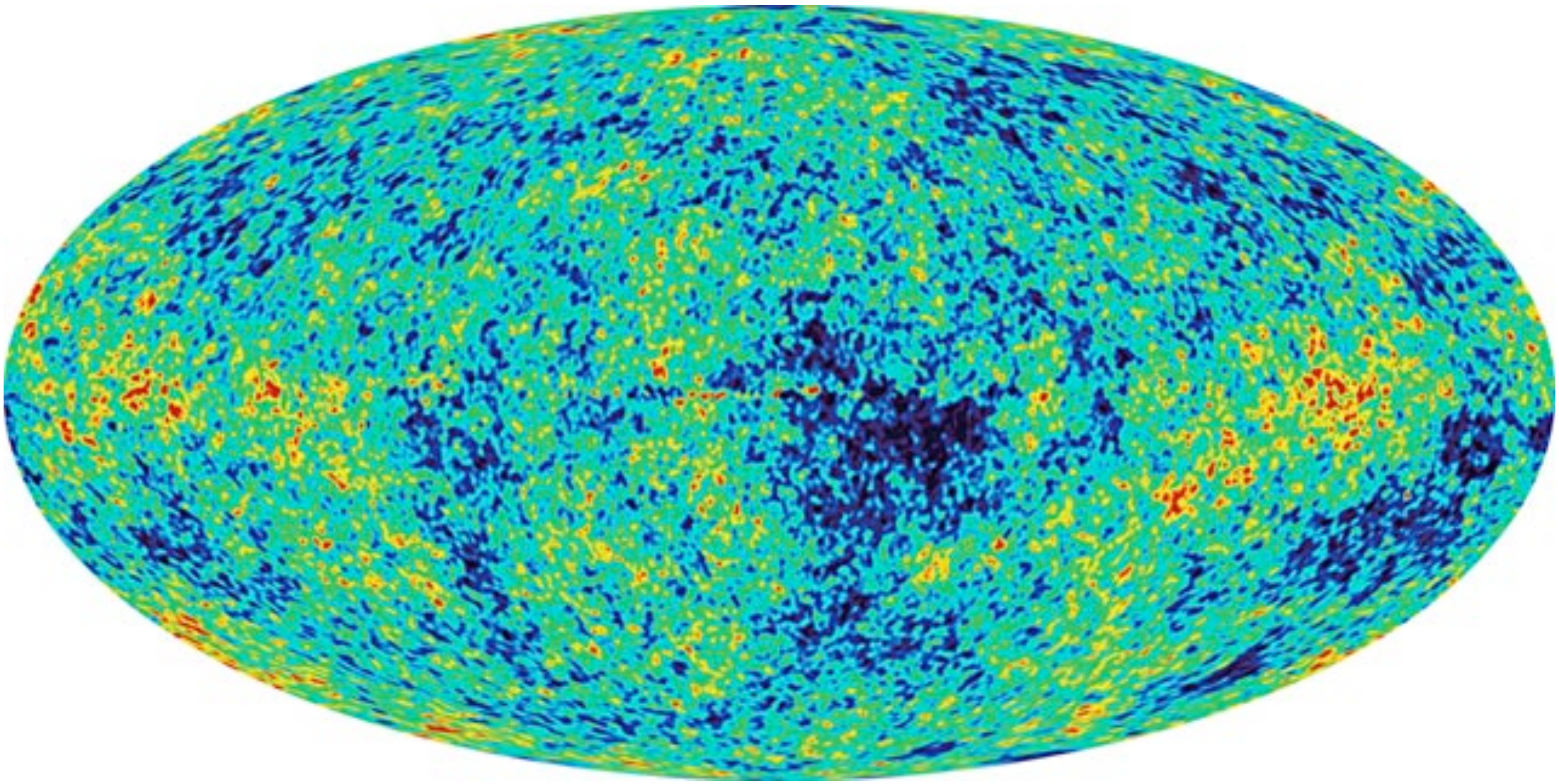
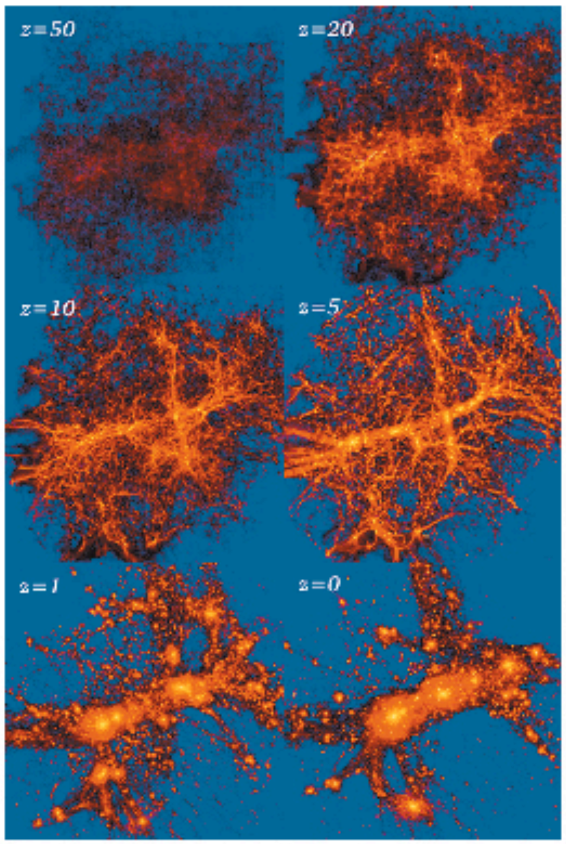


Photo Credit: WMAP Science Team/NASA

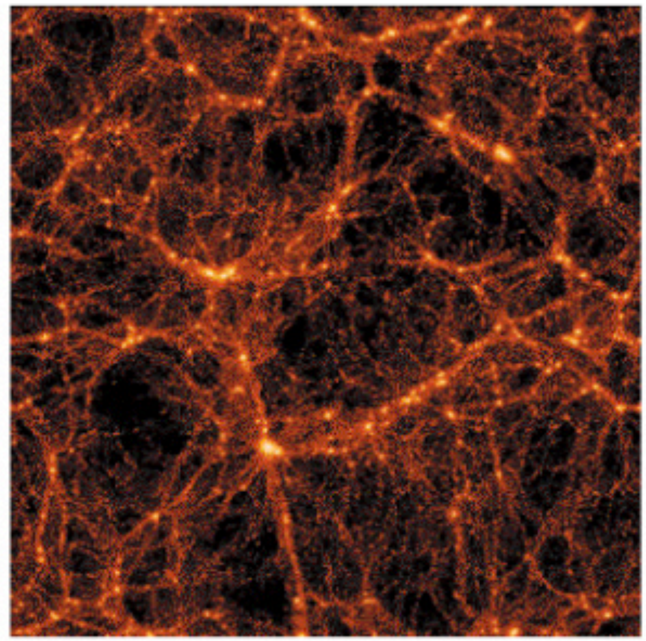
Eternal inflation?

Multiverses?

Formation of Large-Scale Structure

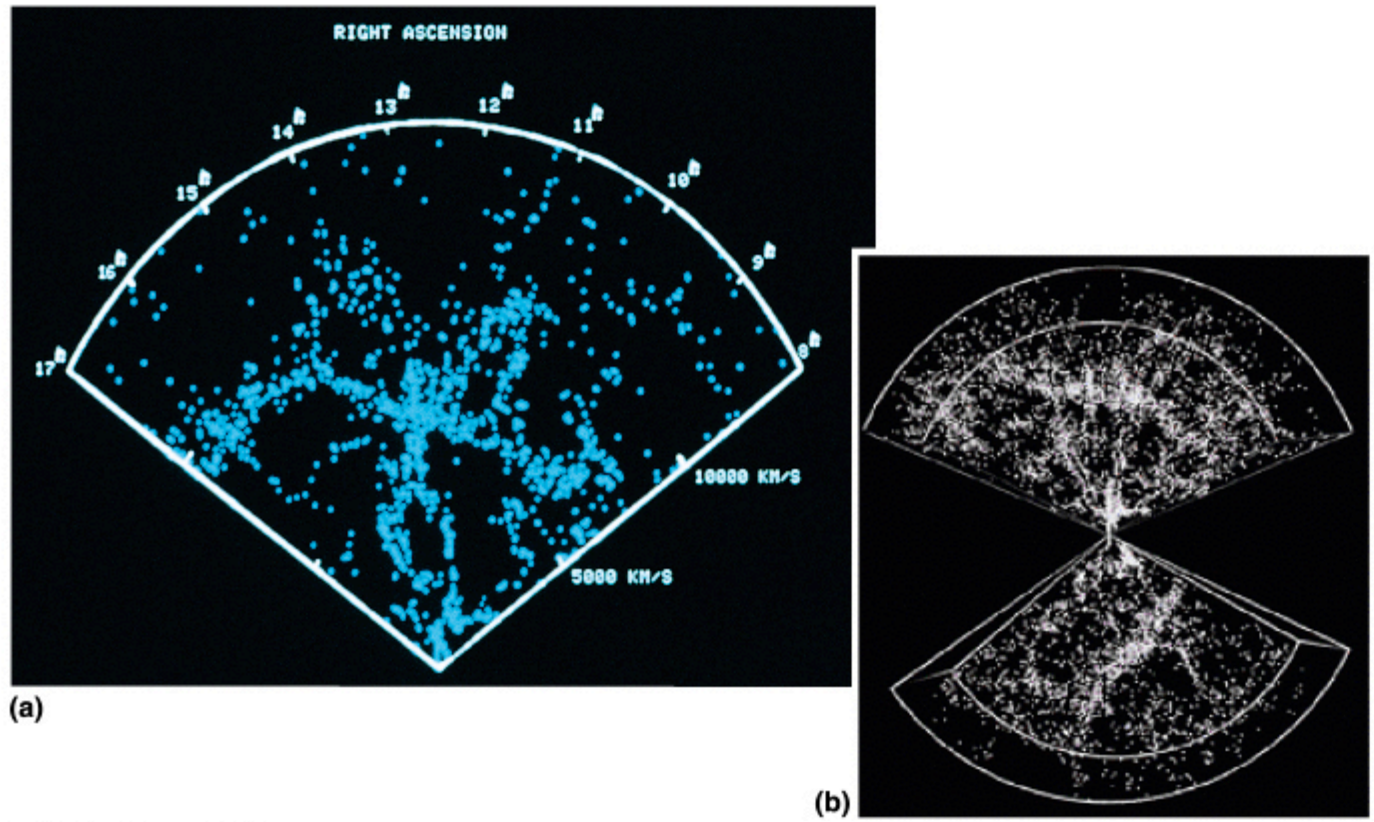


(a)

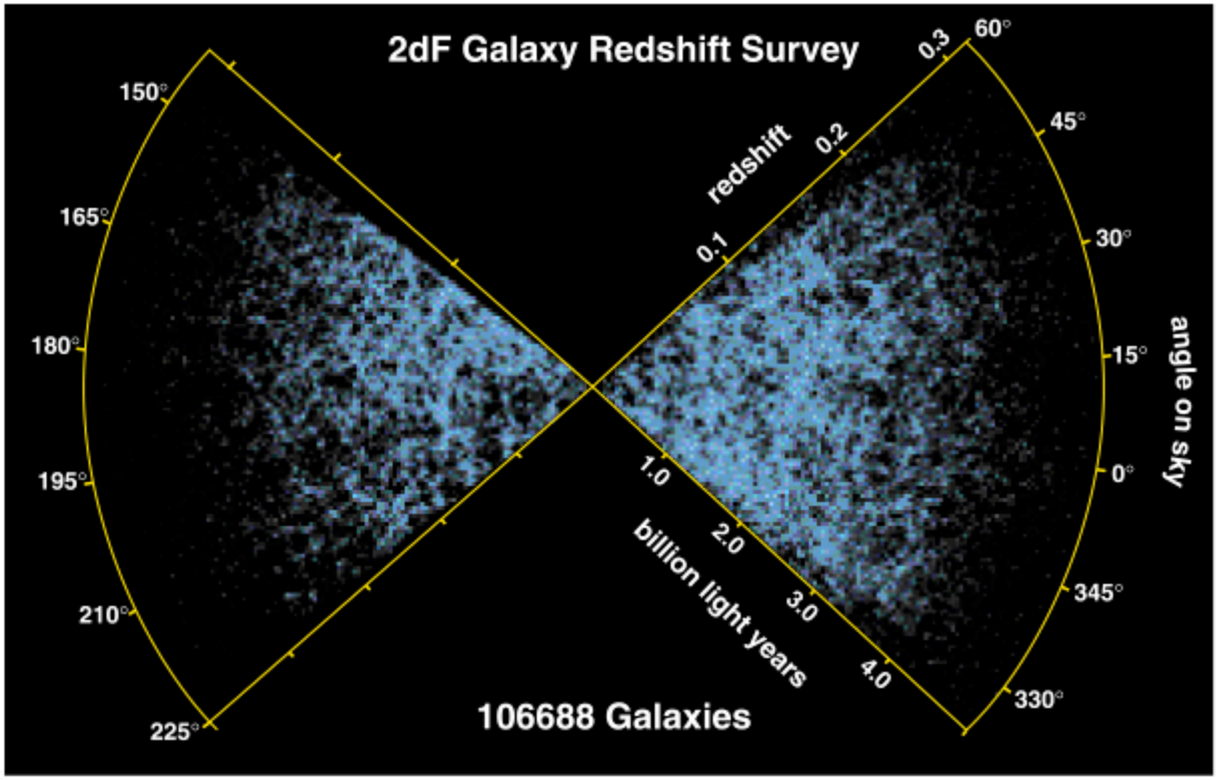


(b)

Slice of the Universe

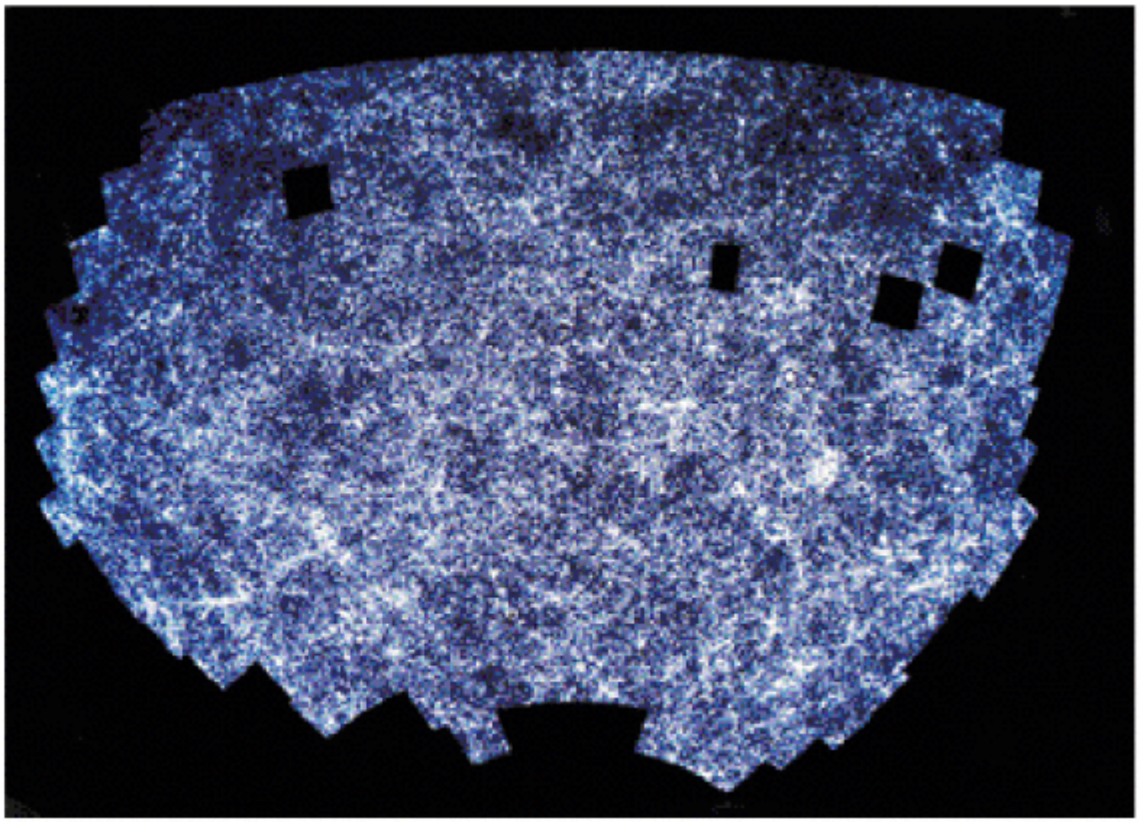


2dF Galaxy Redshift Survey

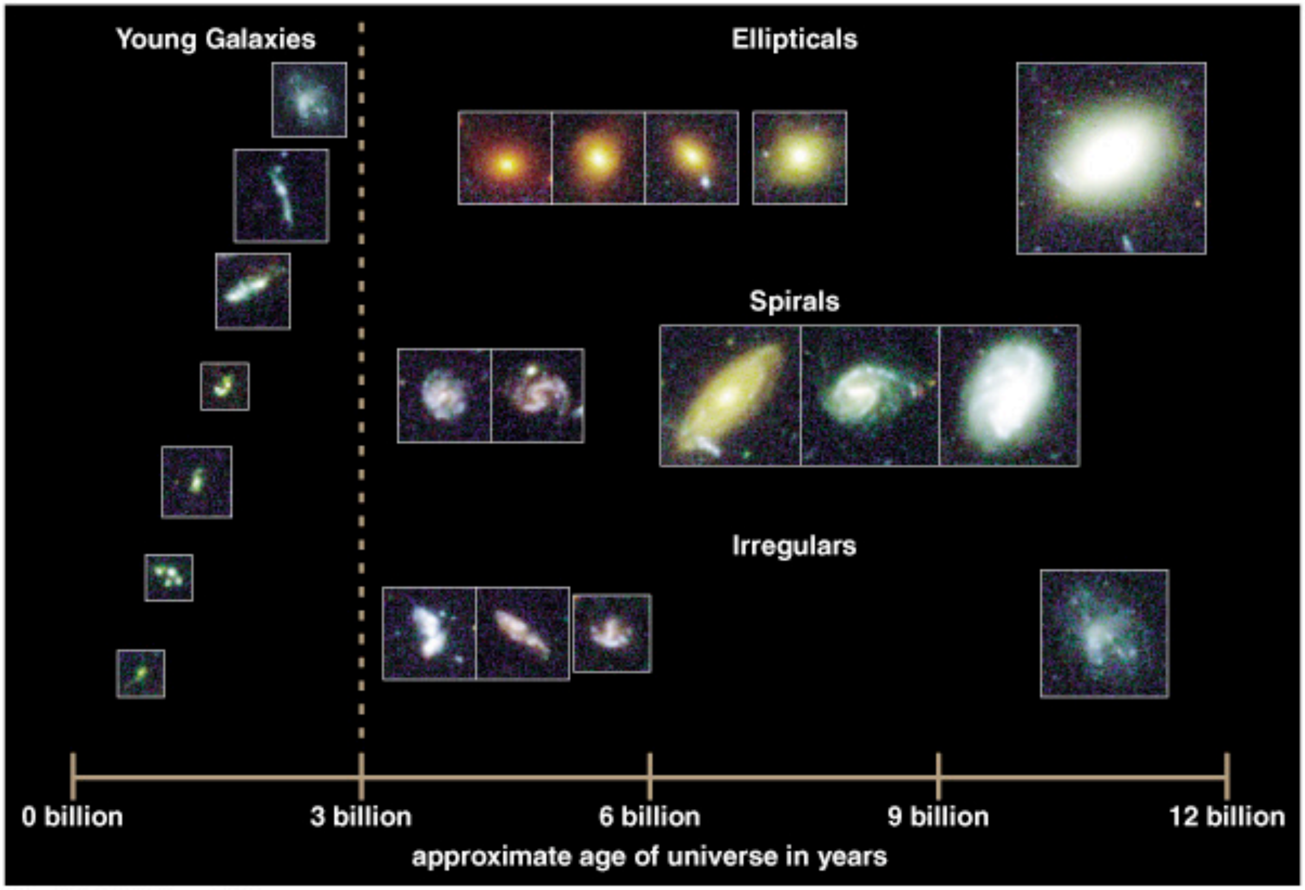


(c)

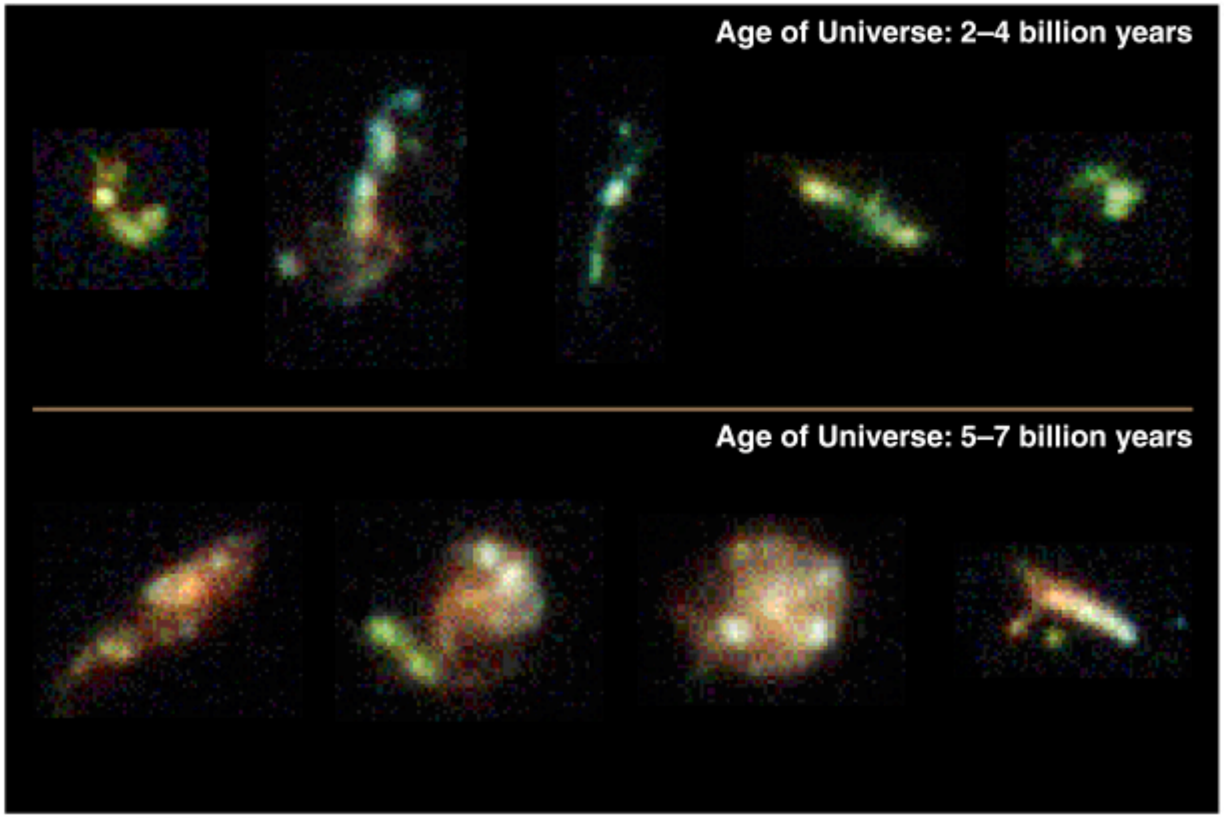
APM Galaxy Survey



Evolution of Galaxies

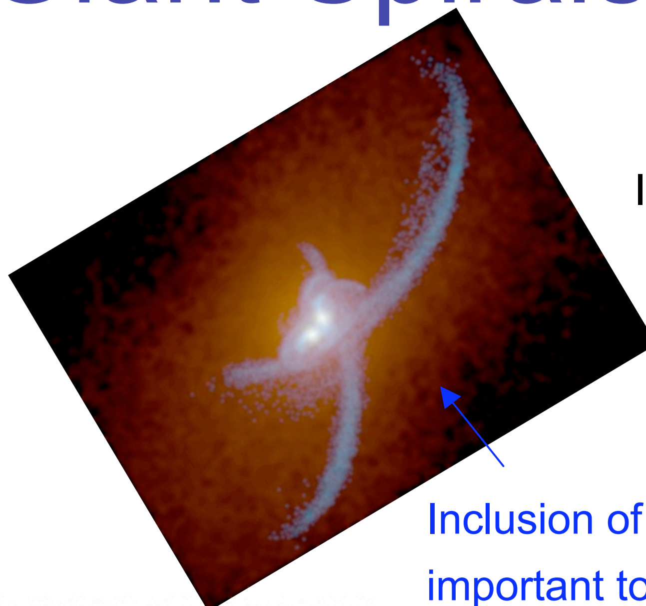


Galaxy Interactions More Important in Past When They Were Smaller, More Numerous, and Closer to Each Other



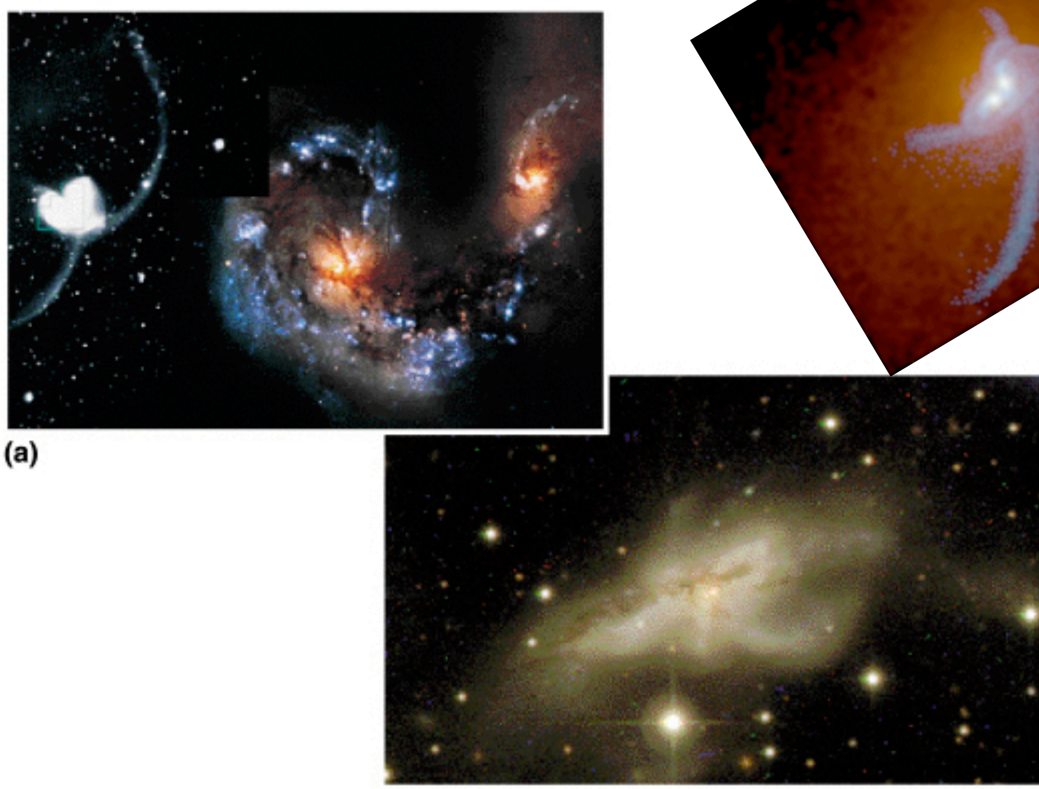
Young galaxies seen at cosmological distances look appreciably different from The mature, giant spirals and ellipticals we see at low redshifts (local universe).

Remnant Interactions Today Between Giant Spirals



IfA/J. Barnes

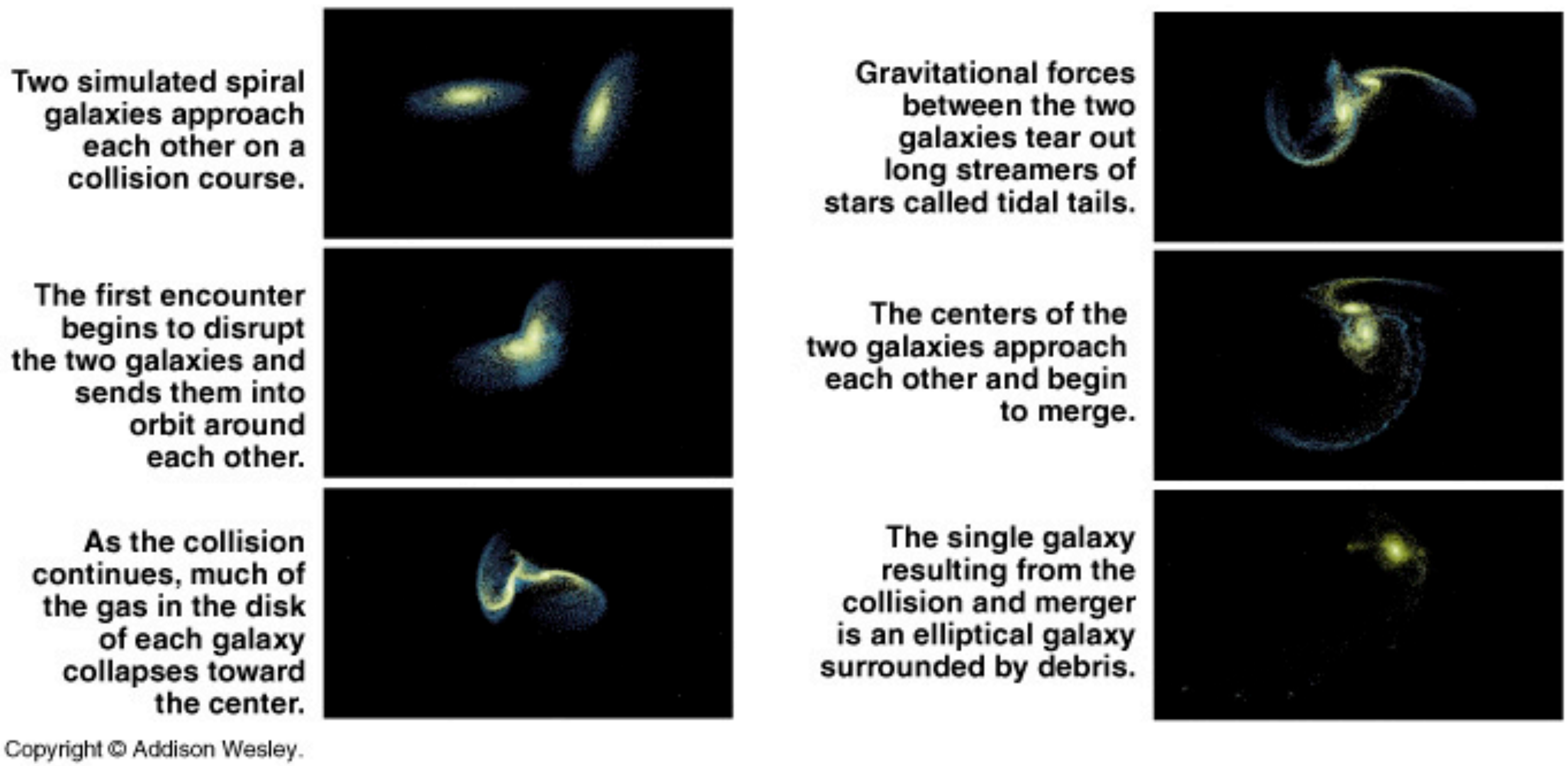
Inclusion of dark matter halos important to getting detailed shapes and merger rates right in the numerical simulations. Doing interstellar gas dynamics correctly is much harder.



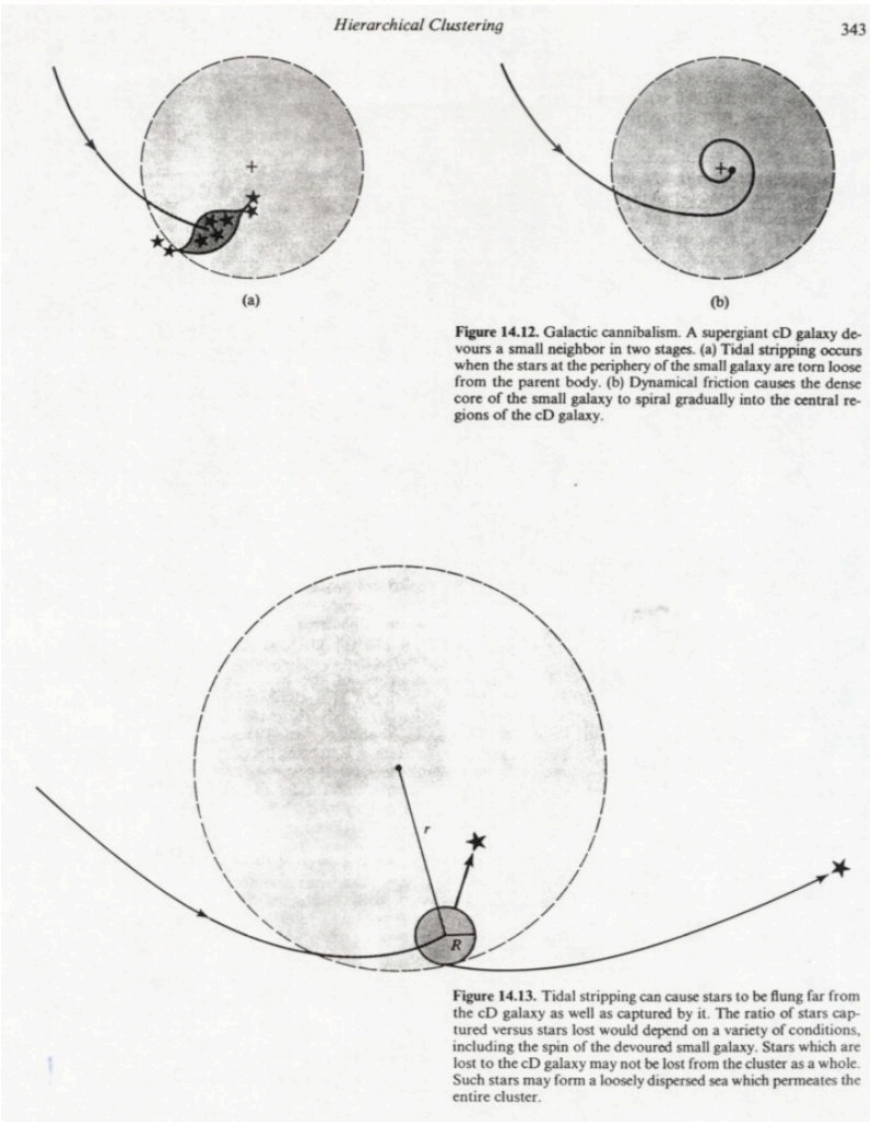
(a)

(b)

Formation of Ellipticals Through Mergers When There is Not Much Gas Left



Galactic Cannibalism of Small Satellite Galaxies by Host Galaxy



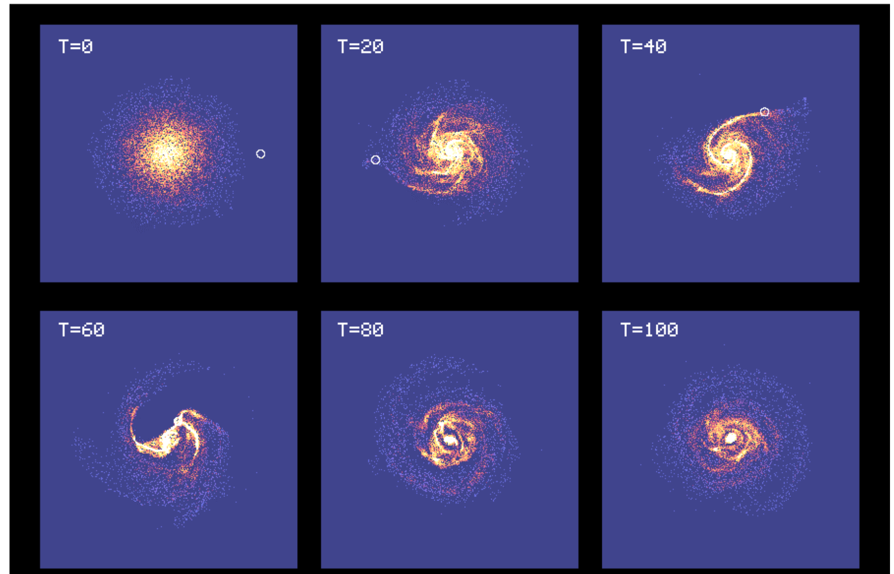
Hierarchical Clustering 343

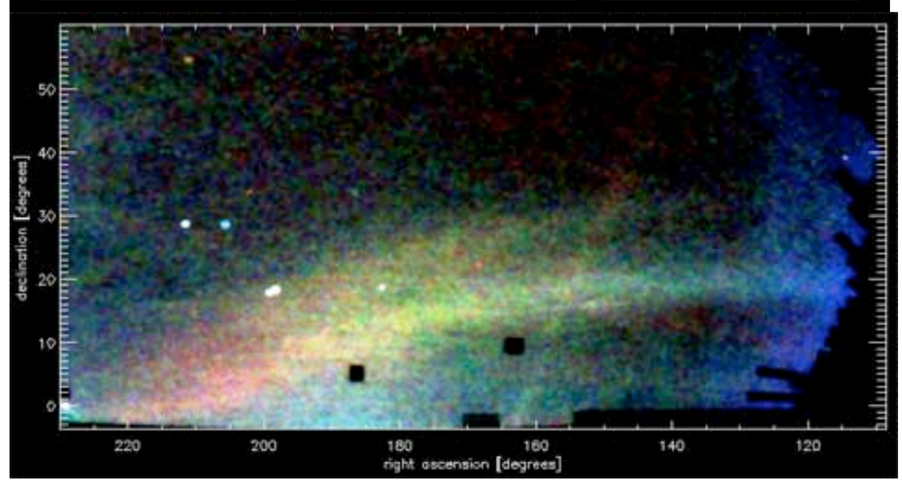
(a) (b)

Figure 14.12. Galactic cannibalism. A supergiant cD galaxy devours a small neighbor in two stages. (a) Tidal stripping occurs when the stars at the periphery of the small galaxy are torn loose from the parent body. (b) Dynamical friction causes the dense core of the small galaxy to spiral gradually into the central regions of the cD galaxy.

Figure 14.13. Tidal stripping can cause stars to be flung far from the cD galaxy as well as captured by it. The ratio of stars captured versus stars lost would depend on a variety of conditions, including the spin of the devoured small galaxy. Stars which are lost to the cD galaxy may not be lost from the cluster as a whole. Such stars may form a loosely dispersed sea which permeates the entire cluster.

Mihos &Hernquist (1994)





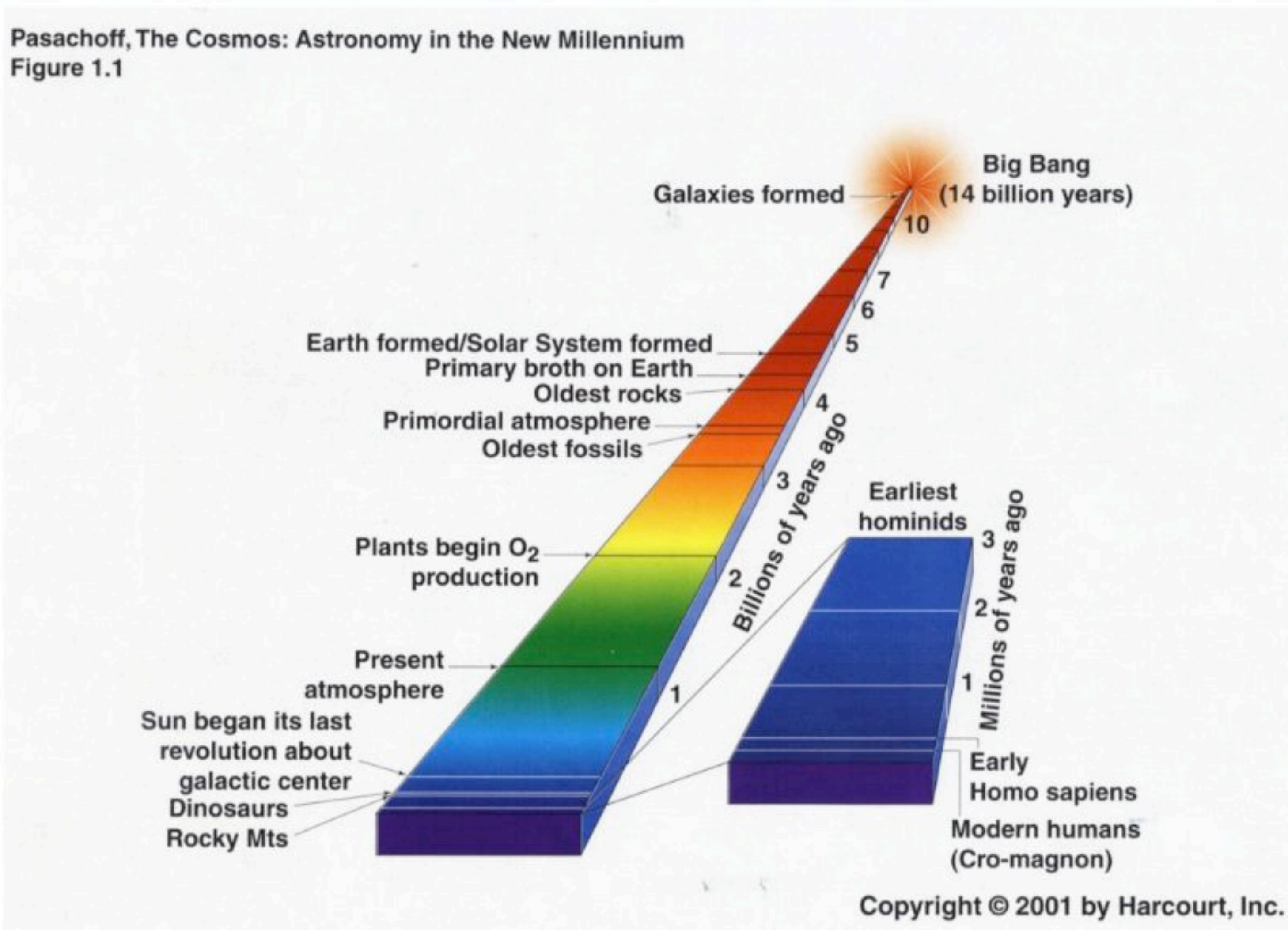
Milky Way Field of Streams

SDSS

Giant Elliptical Galaxies that Have Cannibalized their Neighbors Dominate the Centers of Rich Clusters

Massive cluster acts as gravitational lens for background galaxies

From the Big Bang to Now



Cosmic Landscape, Cosmic Calendar