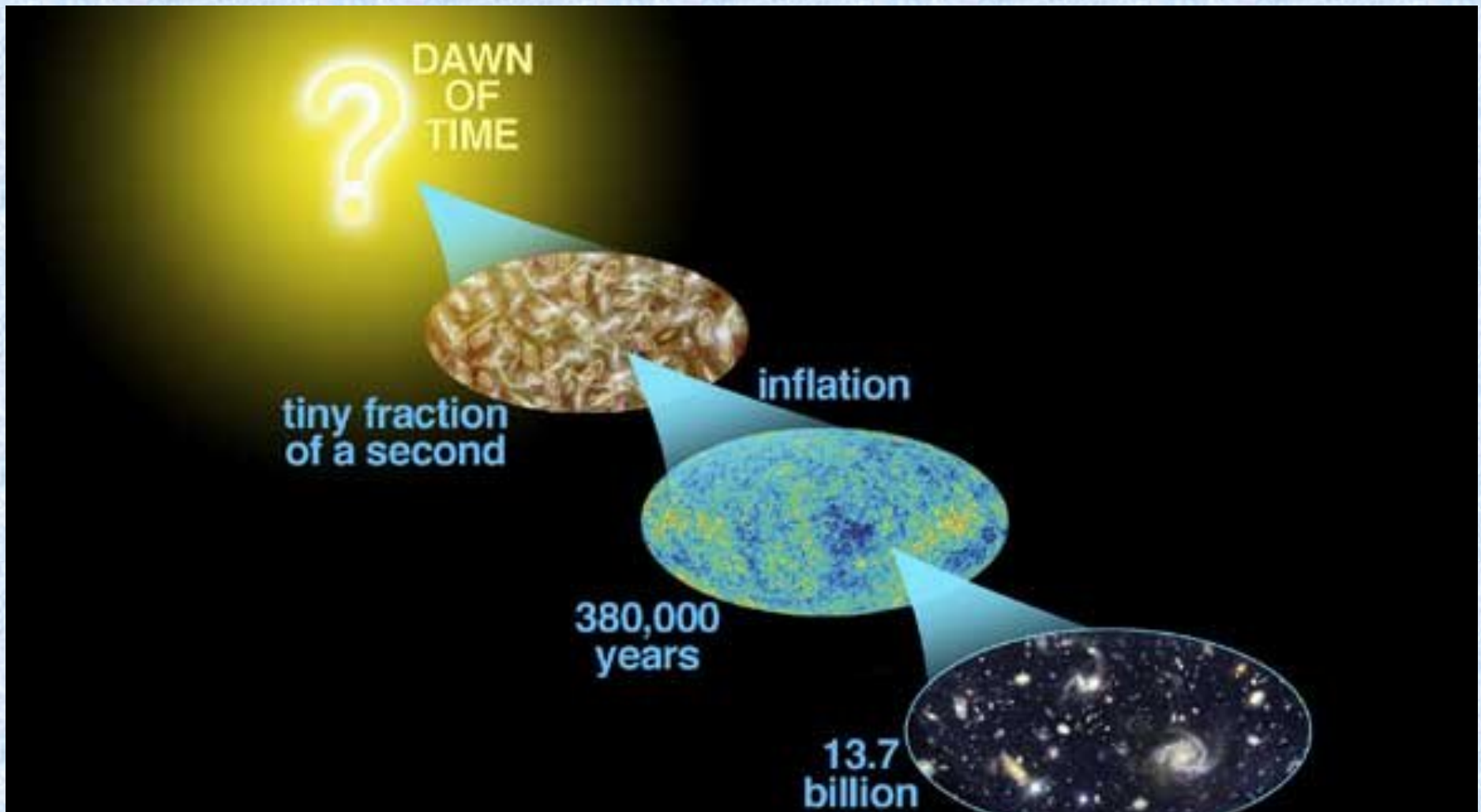


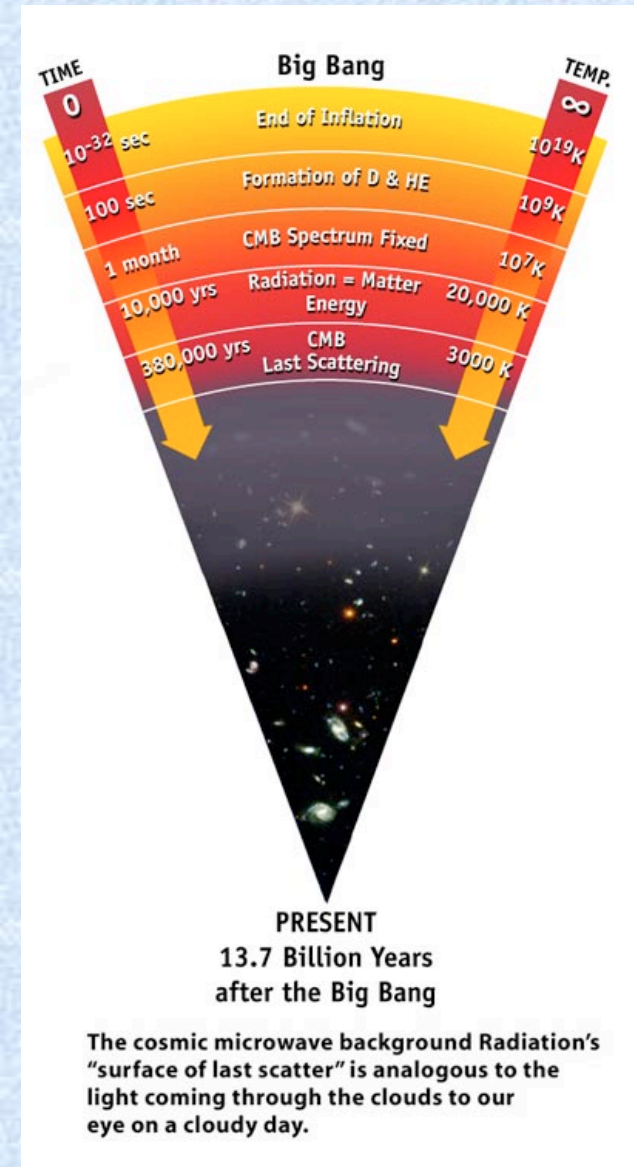
Physics 133: Extragalactic Astronomy and Cosmology



Week 8

Review Relevant Eras

- At $t \sim 1 \text{ ps}$, $kT \sim \text{TeV}$ scales (like LHC)
- At $t \ll 47,000 \text{ yr}$, scale factor $a \propto t^{1/2}$
 - $kT \sim 1 \text{ MeV} (t/1 \text{ s})^{-1/2}$
 - Scale of nuclear binding energies
 - Hot enough for nuclear reactions
- The universe undergoes a phase transition at temperatures near 3000 K, or $z \approx 1000$.
 - What form of mass/energy dominates? the
 - Why do we discuss a photon-baryon fluid?
- What do you think the term cosmic reionization means?



Review:

Baryon-antibaryon asymmetry

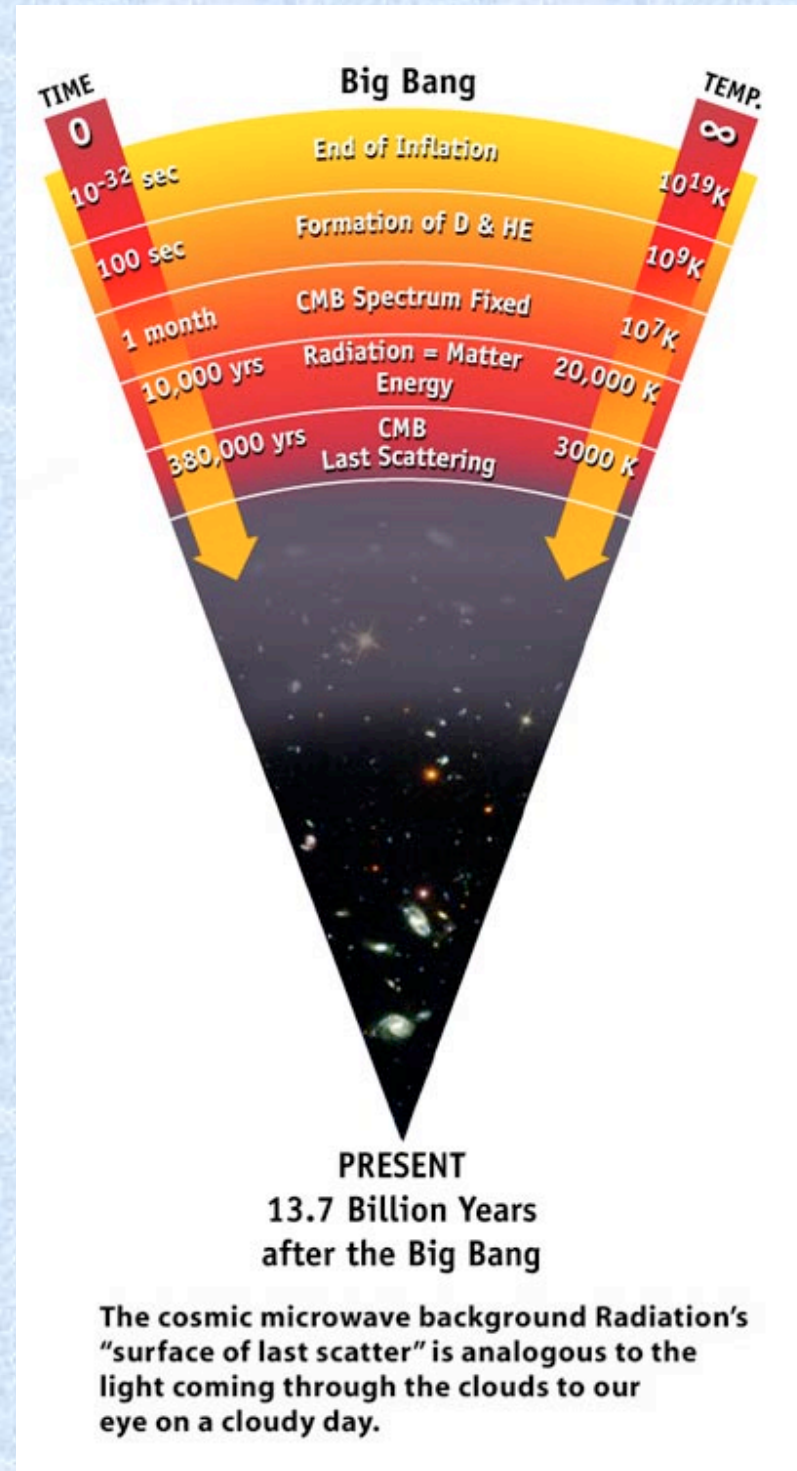
- There are many more photons than baryons
- There are many more baryons than antibaryons
- What happened?
 - Perhaps most of the baryons and antibaryons annihilated.
 - What's left is believed to reflect a small asymmetry between quarks and antiquarks in the early universe.

Outline for Week 8

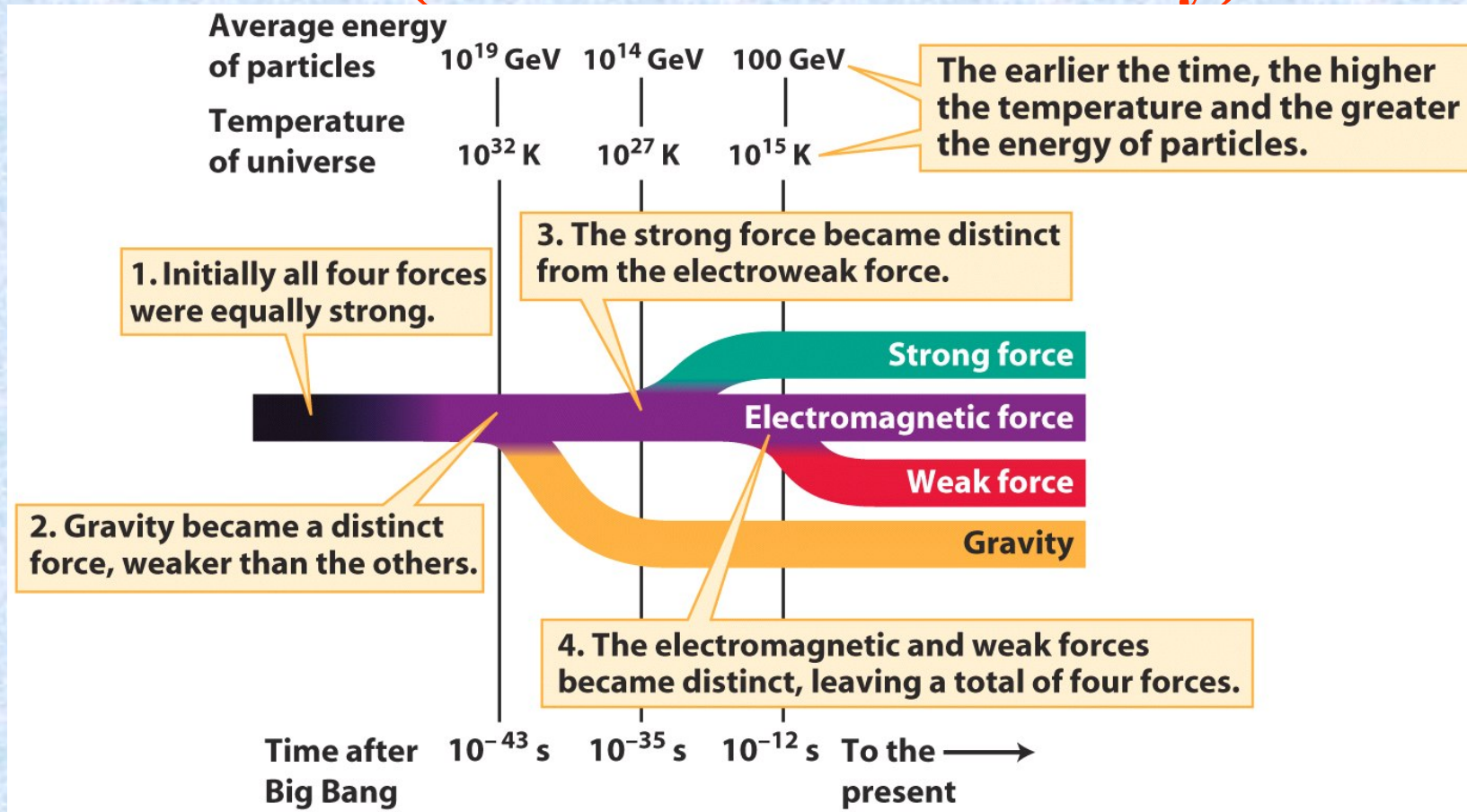
- The Flatness Problem [Ryden 10]
 - Measurement from the CMB (Ω_0 and Ω_b)
 - How departures from flatness evolve with time
 - The flatness problem
 - The inflation solution
- The Horizon Problem [Ryden 10]
 - The horizon at last scattering
 - The size of these structures today
 - The inflation solution
- *Tests of inflation*
 - *Power spectrum*
 - *Relics from symmetry breaking*
 - *Primordial gravitational waves*
- *Gravitational instability determines how structure grows.*
 - *Evolution of the Jeans mass*

Cosmic Inflation

- Planck Scale
- GUT Scale
- Electroweak Scale



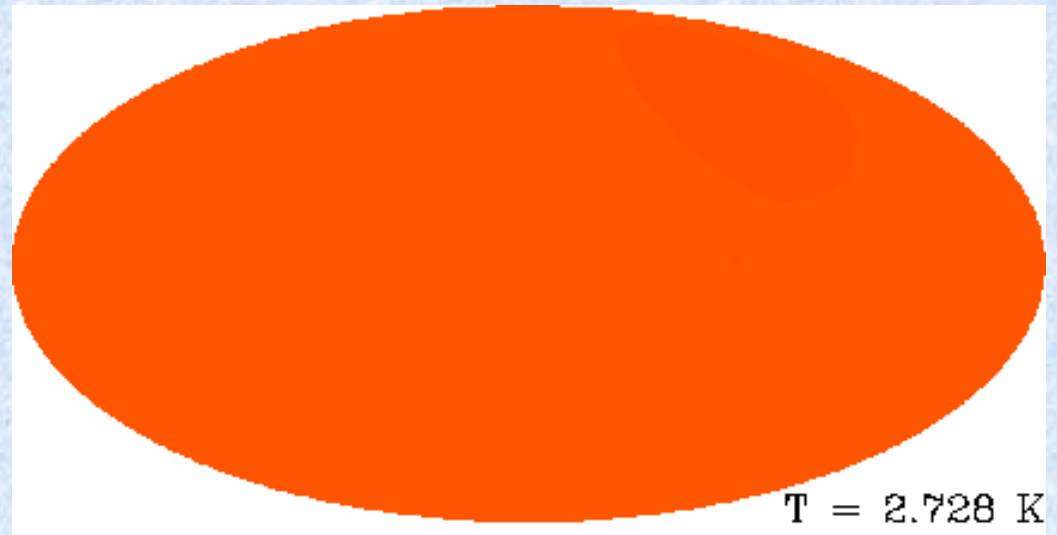
The GUT (Grand Unified Theory) Scale



- At about $\sim 10^{-36}$ s after the Big Bang the strong and electroweak forces separated.
- A quantity called the inflaton field found itself in a position of false vacuum, i.e. in a state that looked like a minimum but was not a minimum of energy.
- The decay to the true vacuum produced a cosmological constant.

Horizon Problem

- The CMB is VERY ISOTROPIC!
- Perhaps too isotropic?
- Regions too far away from each other on the sky are not causally connected, because their distance is larger than the horizon at the last scattering surface [blackboard]
- And there are 40,000 such patches.



The Flatness Problem

- At present time the universe is very close to flat, $|1 - \Omega_0| < 0.005$.
- You can consider this as a coincidence, but the Friedmann Eqn. suggests it was much flatter in the past.

[blackboard]

- Why is the density parameter so close to $\Omega(t) = 1$?

Quiz #13

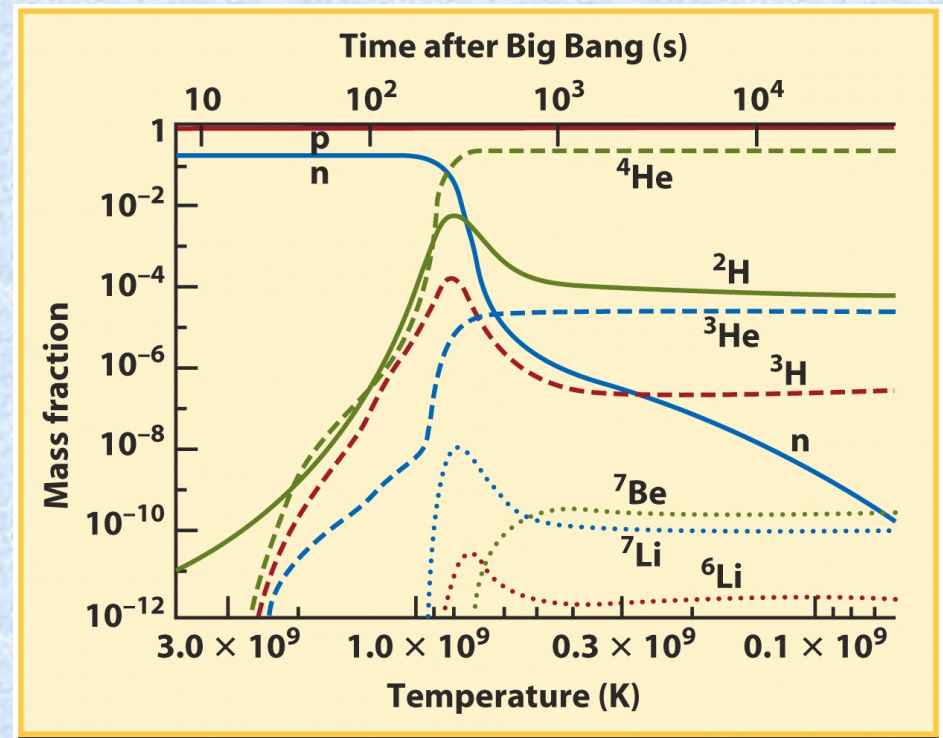
If $|1 - \Omega_0| < 0.005$, then what limit can you place on $|1 - \Omega(t_{\text{nuc}})|$ at the time of cosmic nucleosynthesis? Enter a value for X, where $|1 - \Omega(t_{\text{nuc}})| < 10^X$.

Review:

- Recall, that the temperature of the universe was roughly 10^9 K during BBNS.
- What was the scale factor $a(t_{\text{nuc}})$?
- Which form of the Friedmann equation?

$$1 - \Omega(t) = \frac{a^2(1 - \Omega_0)}{\Omega_{r,0} + a\Omega_{m,0}}$$

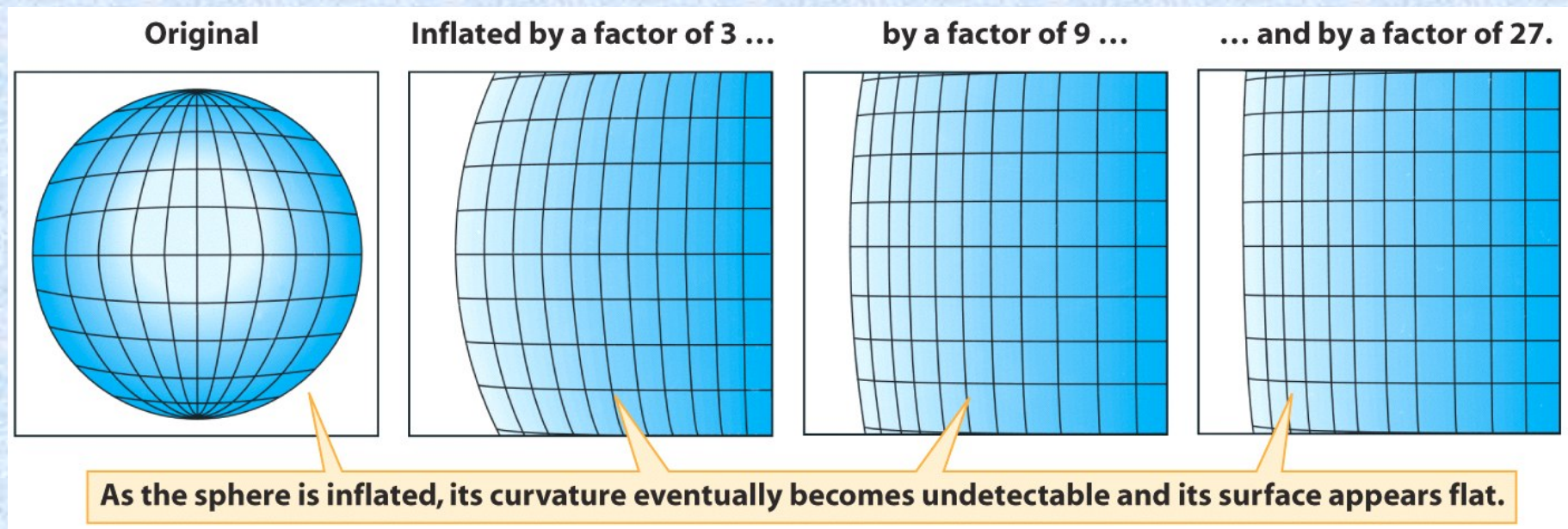
$$\Omega_{r,0} = 8.4 \times 10^{-5} \text{ and } \Omega_{m,0} = 0.3$$



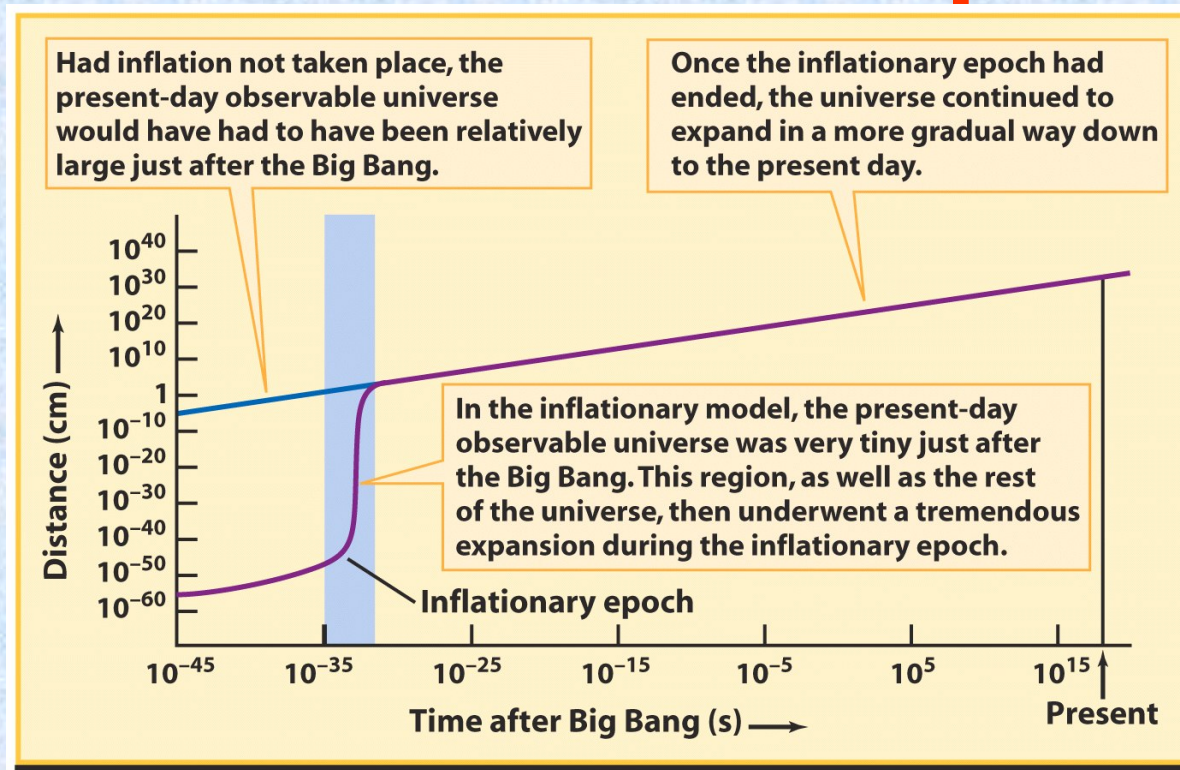
$$T(a) = T_0 (1+z) = T_0 / a$$

Inflation Solves the Flatness Problem

- Exponential expansion requires $w = -1$.
- When $w < -1/3$, the expansion accelerates and $|1 - \Omega(t)|$ becomes closer to unity with increasing t .



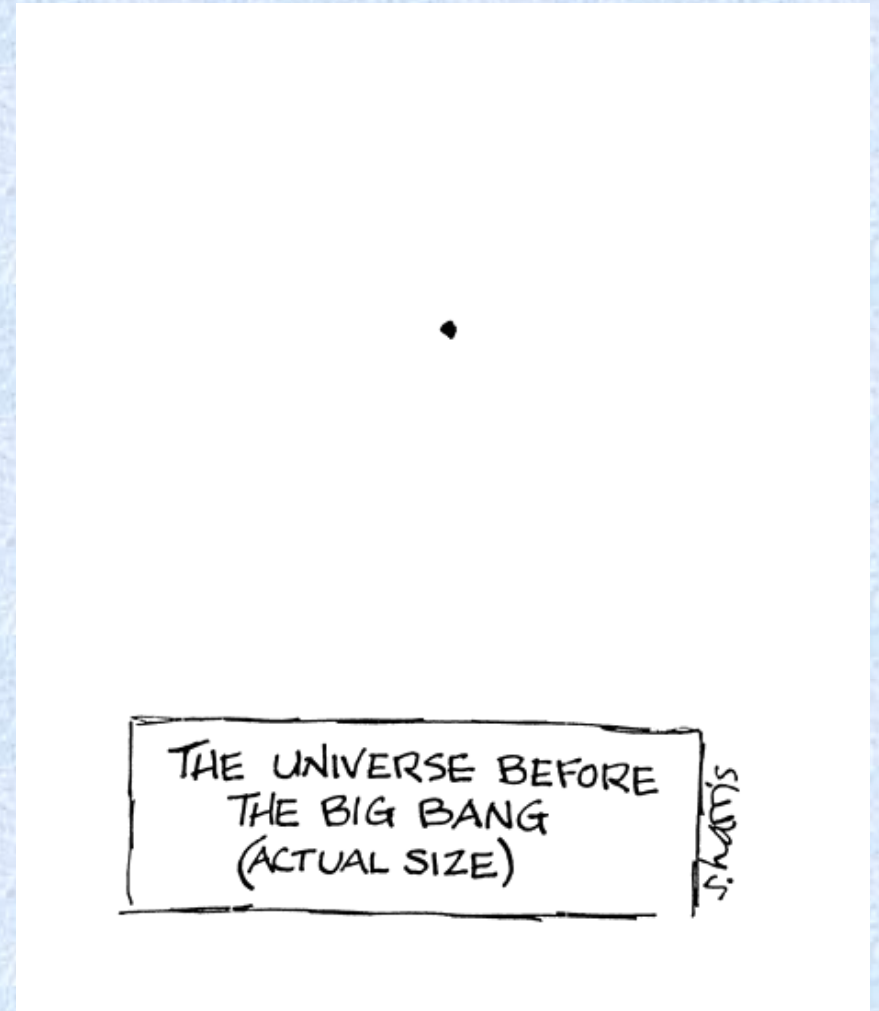
Inflation. The universe expands fast!



- The size of the horizon was just 10^{-43} m before inflation. Quantum mechanics ensures that the universe is very inhomogeneous on this scale!
- Ultra-rapid expansion means that our present horizon was tiny before inflation. It was a small fraction of the causally connected region, so it could be homogeneous.

Solution to the Horizon Problem

- The entire universe that we see today was crammed into a region just a meter in radius after inflation.
- This explains why the CMB properties are the statistically the same in different regions of the sky.
- Note - as used here 'universe' means the observable universe today.



Summary:

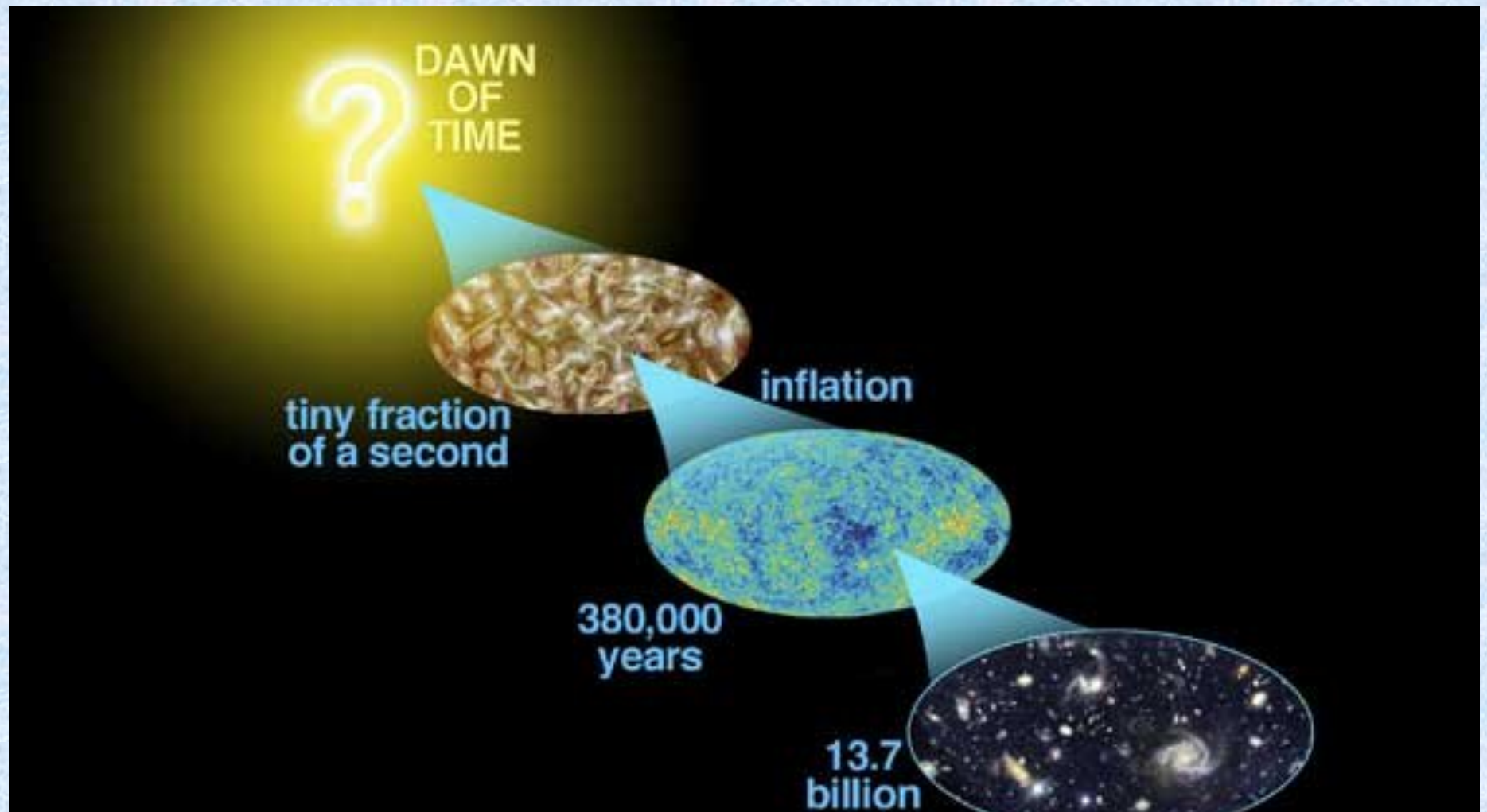
Why Inflation Solves the Horizon Problem

time	t_initial	t_final	t_LS	today
Growth of the region in causal contact	Horizon distance = 6e-28 m	15 m	~200 Mpc (>> 0.25 Mpc)	
Entire universe directly visible to us today	4e-29 m	0.9 m		14000 Mpc

- The universe that is visible to us today was all within the horizon distance at the time inflation began. That's why it can all look so similar.
- At the beginning of inflation, the region that becomes the visible universe is submicroscopic. Quantum mechanics guarantees some 'energy fluctuations', or structure, so the universe is not completely homogeneous.

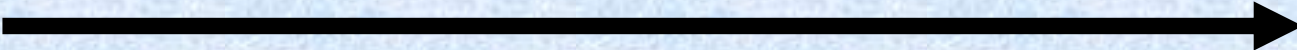
Quantum Origin of Energy Fluctuations

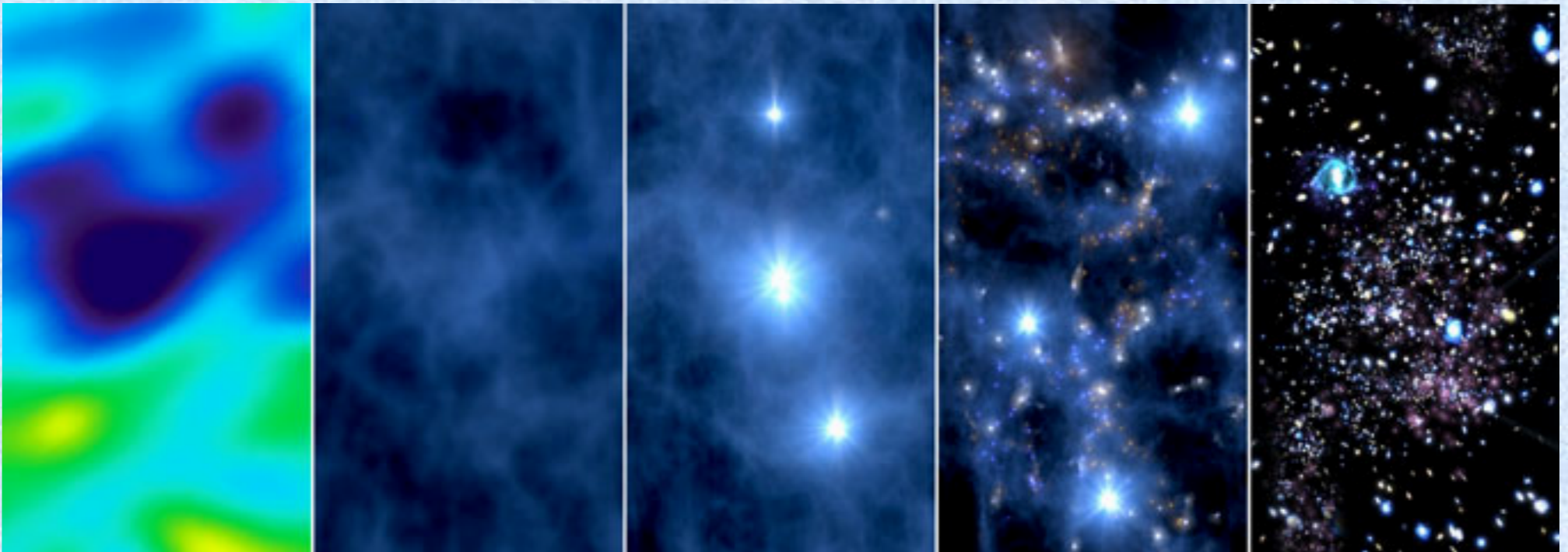
These perturbations in the potential at last scattering are believed to arise from quantum fluctuations present during the Planck era.



Growth of Overdense Regions

- The temperature fluctuations reflect small perturbations in the gravitational potential of the non-baryonic dark matter at the time of last scattering.
- The deepest gravitational potentials become even deeper as matter flows into them from less dense regions.
- Tiny perturbations give rise to the luminous objects.

time 



Inflation makes a testable prediction

- Inflationary models predict the power spectrum index is close to 1, but not exactly one.
 - The measured large-scale structure (defined by galaxies and the IGM) is consistent with $n \sim 1$.
 - More about this next week
- Inflationary models can predict the amount of polarization of the CMB .
- Inflationary models predict fossil gravitational waves, like the CMB but for gravitons.

Summary for Inflation

- Cosmic microwave background temperature fluctuations
 - Implications for cosmological parameters [R 8.4]
 - Origin of the temperature fluctuations [R 8.5]
 - Relic of inhomogeneities in the very early universe
- Problems of the standard Big Bang model
 - **It's too flat**
 - **It's too isotropic**
 - Low density of domain walls (relics from symmetry breaking)
- **The currently favored solution is called “inflation”**
 - How inflation solves the above problems.
 - Physics of inflation (on your own in 10.5)
 - Predictions of inflation

Things to Think About...

[R] 10.1 – **How small does Ω_p need to be to avoid a big crunch?**

Motivation:

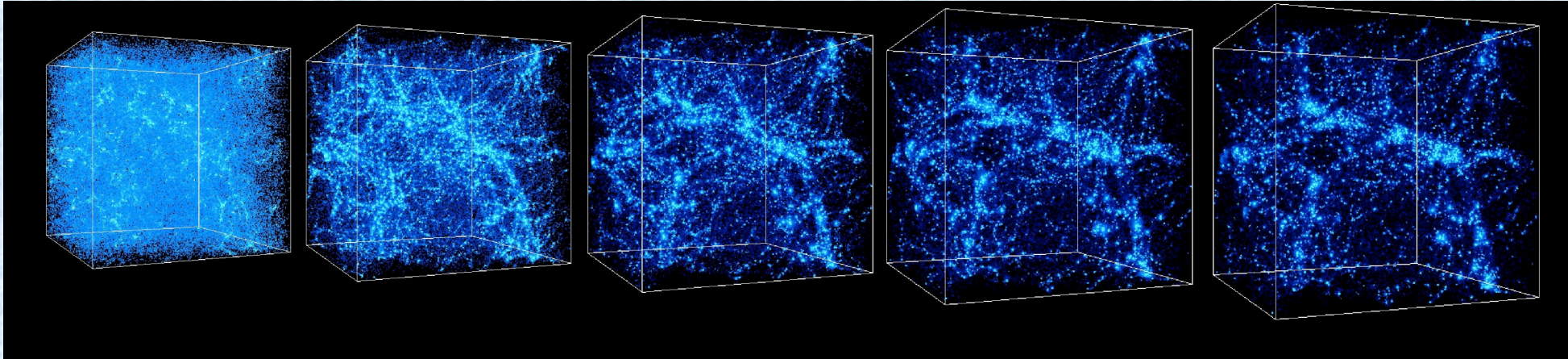
This problem illustrates why inflation requires Ω very close to 1.

1. How do you write the Friedmann Eqn?
2. What does the solution look like?
3. How does the time of the big crunch depend on Ω_p ?
4. Require that $t(\text{crunch}) > t(\text{inflation})$.

Things to Think About...

[R] 10.3 - What will the decay of the vacuum energy associated with Dark Energy today do to the universe?

Gravitational Instability



- Density fluctuations are measured relative to the mean density over a large volume.
 - Define $\delta(\mathbf{r},t)$
- Gravity makes the amplitude of density fluctuations grow.
- Let's first consider the growth of density fluctuations in a static medium.
- Then, next week, we will show how the expansion of the universe changes the growth rate.

Jeans Length I. Static Medium

- Pressure prevents the collapse of the gas in this room, the Sun, etc.
- Hydrostatic equilibrium can only be obtained when sound waves travel fast enough to set up a pressure gradient and halt the collapse
- Overdense regions larger than the Jeans length collapse under their own gravity
- Overdense regions smaller than the Jeans length merely oscillate in density -- i.e. sound waves.
- [blackboard]
- Linear perturbation theory shows that fluctuations of small amplitude grow exponentially with time in a static, pressureless medium.
- **The collapse timescale, $t_{\text{dyn}} \sim (G\rho)^{-1/2}$ depends only on average density and not the size of the region.**

Quiz 14 – Dynamical Timescale

The average density of the Sun is 1 g/cm^3 .
Suppose all pressure support within the Sun were suddenly switched off.

Estimate the timescale for the Sun to collapse under its own weight.

Enter your answer in seconds.

Sound Speed in Photon-Baryon Fluid

- Photon gas determines how the baryons move up until decoupling because $\epsilon_m > \epsilon_\gamma > \epsilon_b$.
- We can find the sound speed in the photon-baryon fluid.

$$\epsilon = \epsilon_\gamma + \epsilon_b \text{ and } P = \frac{1}{3}\epsilon_\gamma$$

[Blackboard]

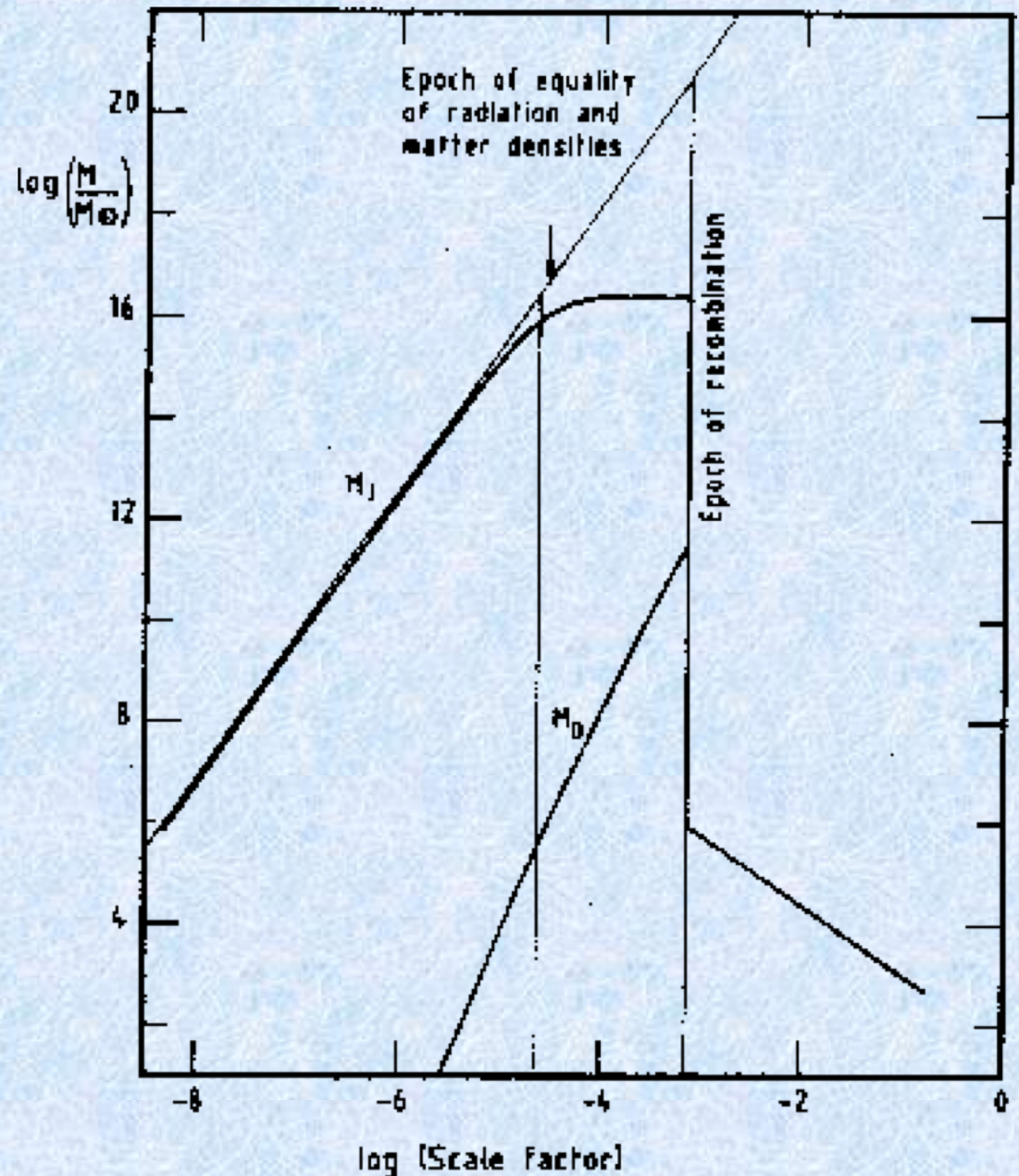
$$c_s^2 = \frac{dP}{d\rho} = \frac{dP}{d\epsilon} c^2$$

$$c_s^2 = \frac{4}{3} \frac{\Omega_{\gamma,0}}{4\Omega_{\gamma,0} + 3a\Omega_{b,0}} c^2$$

(Apply in HW8
[R] 11.3)

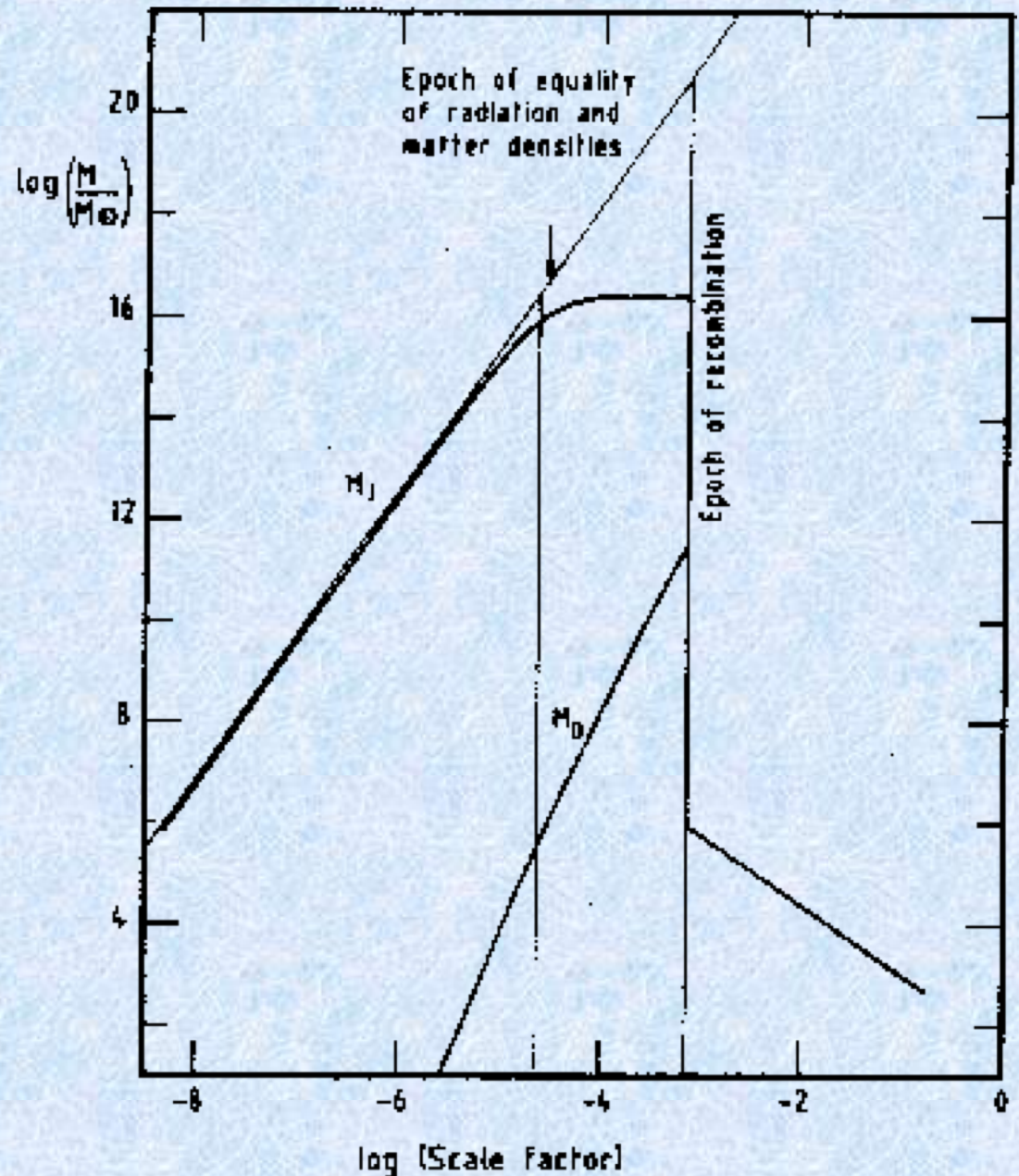
Jeans Length. II. Temporal Evolution

- How large was λ_J when large scale structure began to form?
- The Jeans length depends on the equation of state
- A relativistic gas has a fast sound speed and a large Jeans length.
- Prior to photon-baryon decoupling density fluctuations simply create sound waves if they are smaller than $3c/H$



Jeans Length. II. Temporal Evolution (cont'd)

- After decoupling the Jeans length drops by a factor $\sim 10^5$.
- And the minimum mass scale of an unstable region drops to that of large star clusters or small galaxies



Summary

- Gravitational instability determines how structure grows.
- Results for static medium
 - Know how gravitational timescale depends on density
 - Matter fluctuations grow when the structure is big enough, i.e., larger than Jeans mass or Jeans radius
- Understand how the Jeans mass evolves up to and through the epoch of last scattering