[24] Cosmic Inflation (5/1/18)

Upcoming Items

- Homework #6 due in one week (hope you've started!).
- Read Ch. 23.1–23.2 for next class and do the self-study quizzes
- Final exam review: Fri, May 11, 1-3 PM, here.
- Course evaluations: http://CourseEvalUM.umd.edu **Open now; we appreciate your honest feedback!**

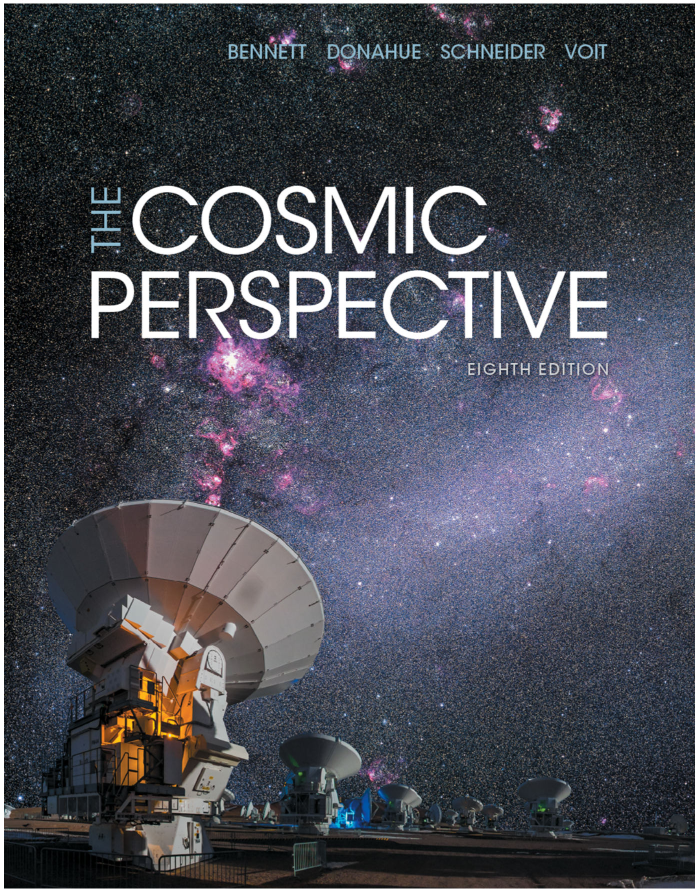
APOD 4/21/17: NGC 4302 & 4298

LEARNING GOALS

Chapter 22.3–22.4

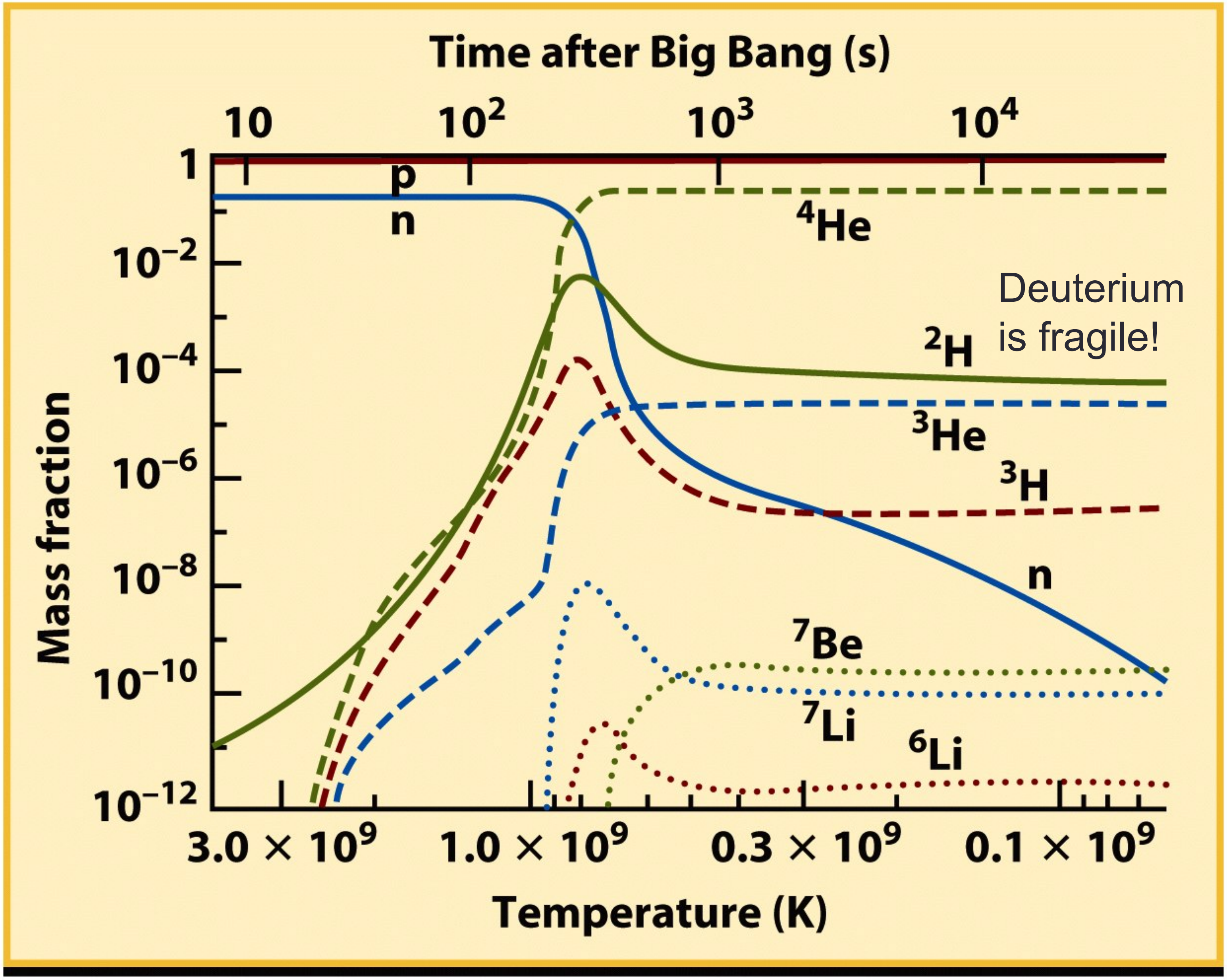
For this class, you should be able to…

- … *understand how the lightest nuclei were produced in the early universe, and how this constrains the total amount of ordinary matter;*
- … *describe how a period of inflation in the early universe can explain large-scale structure, the near-uniformity of the cosmic background radiation, and the apparent flat geometry of the universe*



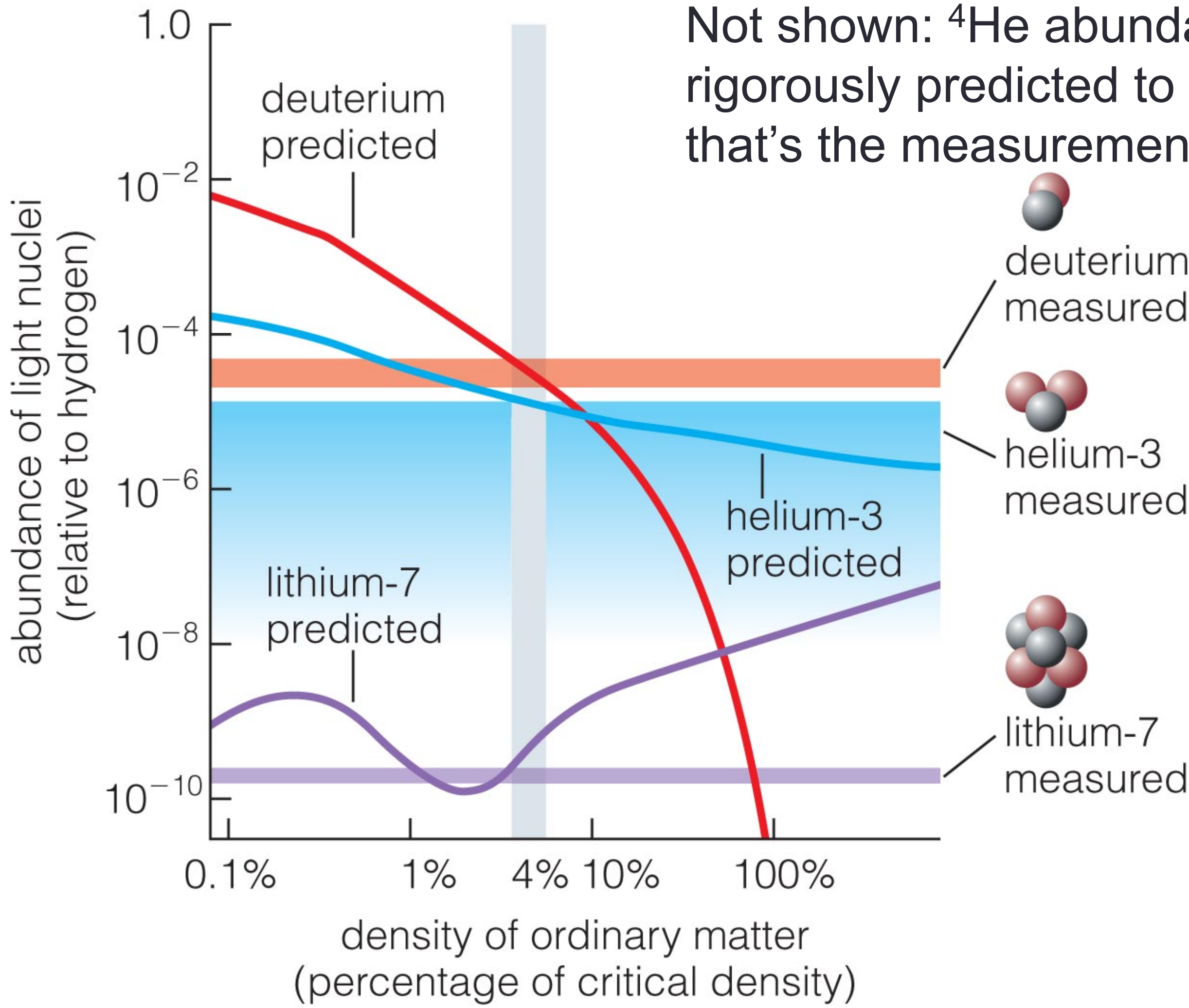
Any astro questions?

Big Bang Nucleosynthesis



How do the abundances of elements support the Big Bang theory?

Not shown: ^{4}He abundance is rigorously predicted to be 25%; that's the measurement as well!



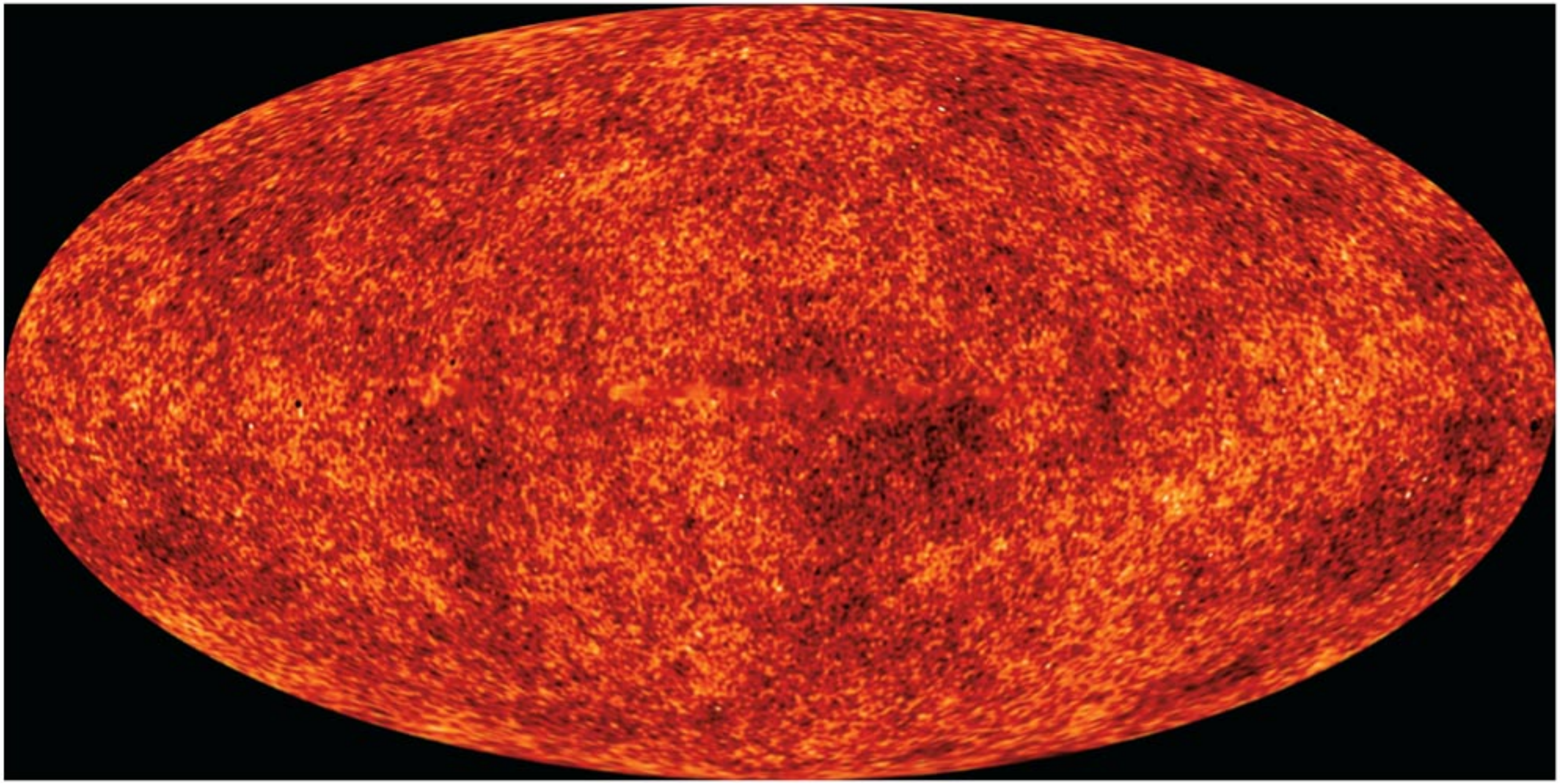
Measurements of light element abundances tell us the density of ordinary matter; e.g., higher than 4-5% and we wouldn't have enough deuterium.

Cosmic Inflation

1. Where does structure come from?
   - Quantum fluctuations inflated to be seeds of future formation.
2. Why are matter & temperature distributed so uniformly?
   - Universe reached equilibrium before inflated to large separations.
3. Why is the geometry of the universe so flat?
   - Inflation smoothed out any curvature so it is now nearly flat.

- Cosmology is now a precision science.
- Contemplations of infinity.
  - How can the sky be dark at night even if the universe is infinite?
  - What would it mean if the universe were truly “infinite” in extent?

What key features of the universe are explained by inflation?



Mysteries Needing Explanation

1. Where does structure come from?
2. Why is the overall distribution of matter so uniform?
3. Why is the density of the universe so close to the critical density (i.e., why is there such a flat geometry)?

An early episode of rapid inflation can solve all three mysteries!

Group Q: Why is it a Mystery?

- We say that the overall distribution of matter is uniform, and that this is a mystery.
- But let's think more deeply about why this is mysterious.
- We'll introduce the idea of causal contact; things are in causal contact if they could have sent light signals back and forth
- In a standard expanding universe, the universe expands slower than light, and slows down in its expansion
- This means that the region in causal contact with us (say) would increase all the time.
- So why is it mysterious that the CMB is so uniform? We need a pretty good reason to try inflation...

MYSTERIES

1. Where does structure come from?

Quantum Fluctuations

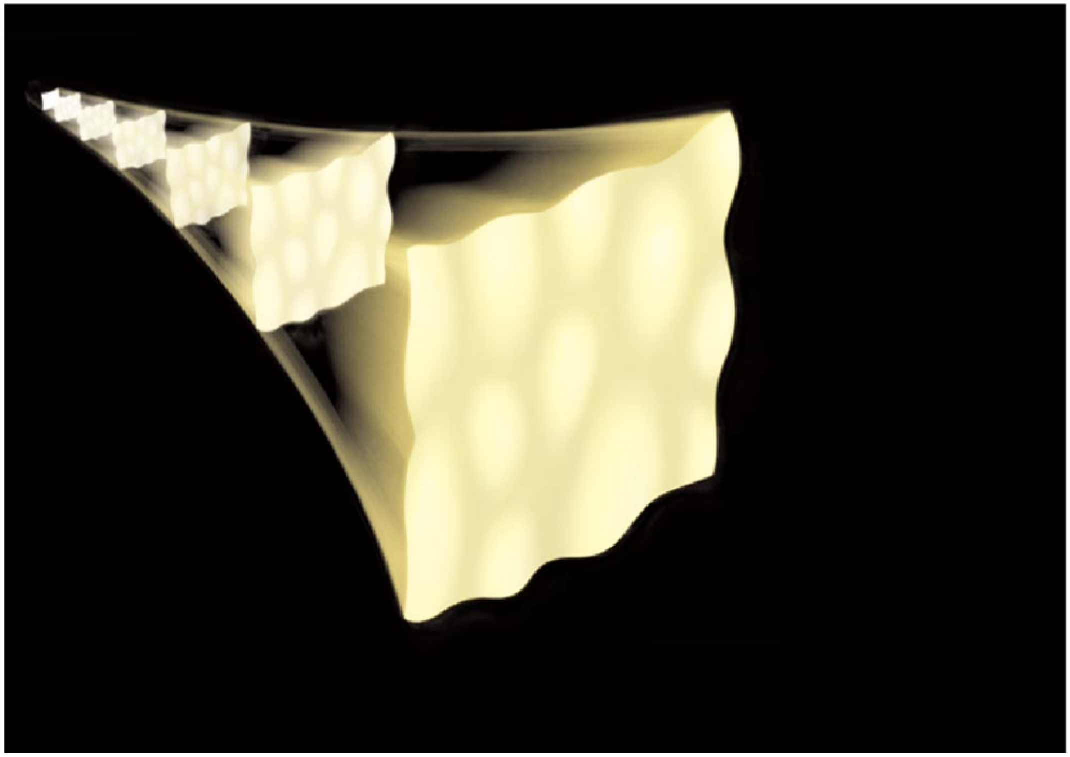
- The *Heisenberg Uncertainty Principle* states in part that you cannot know the energy of a system with infinite precision at every moment in time:

$$\Delta E \times \Delta t = \frac{h}{2\pi}. \qquad \text{(actually >=)}$$

- This energy uncertainty is equivalent to a mass uncertainty according to $E = mc^2$:

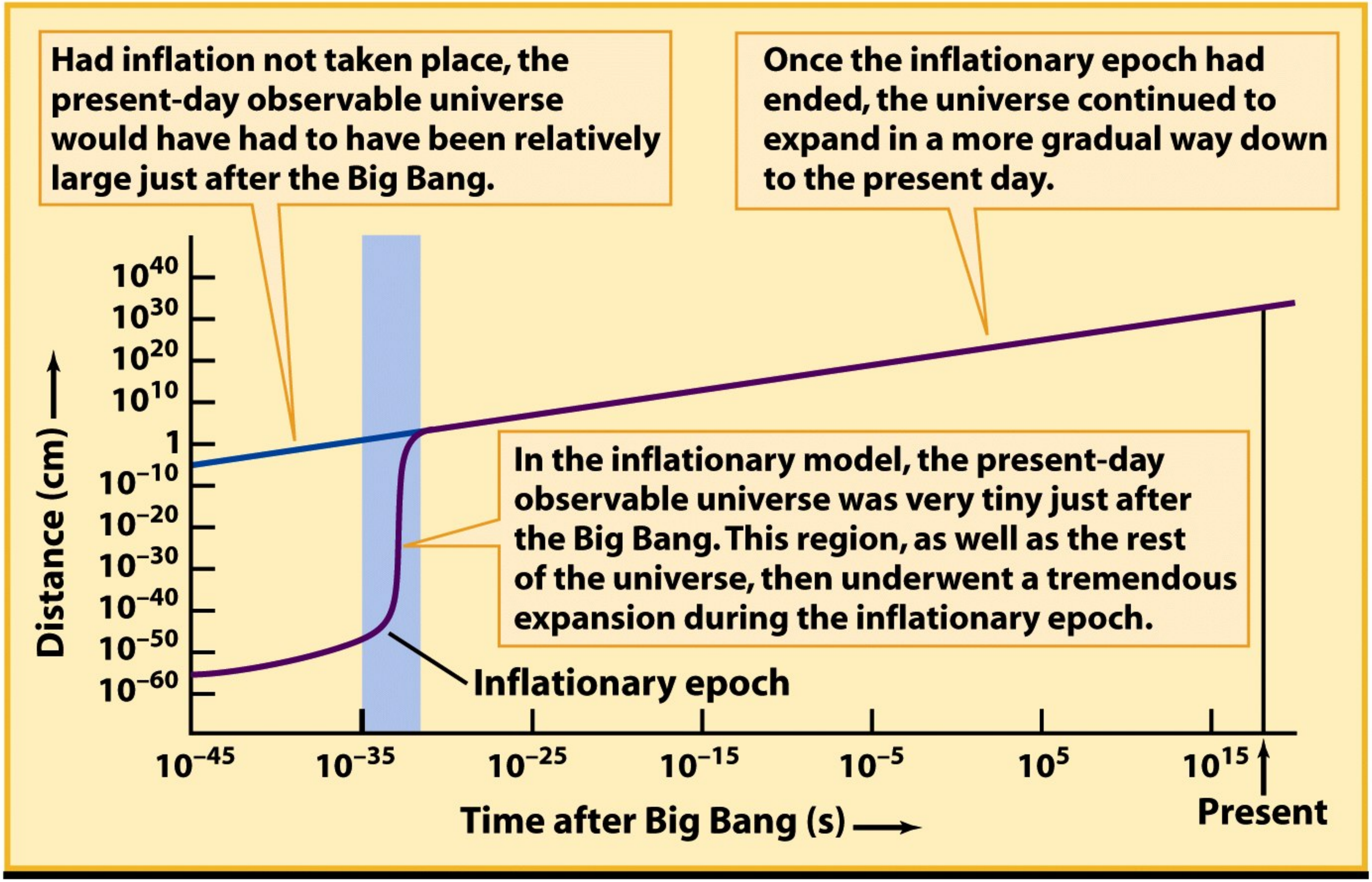
$$\Delta m \times \Delta t = \frac{h}{2\pi c^2}.$$

- These concepts lead to idea that *density fluctuations* were present during the very early universe.



Inflation theory predicts the universe grew by more than a factor of ~10^{30} in an instant!

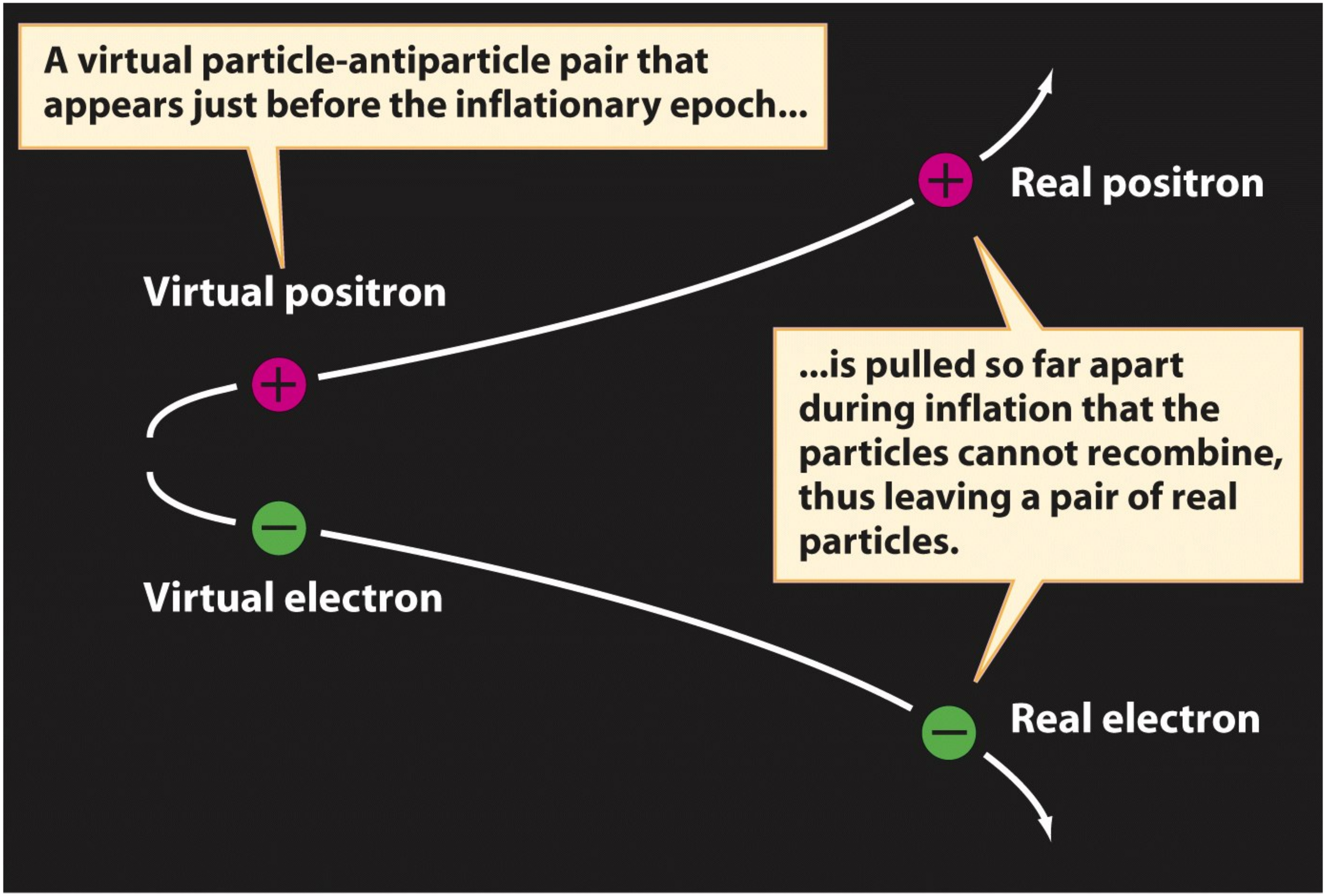
- Inflation would stretch density fluctuations to enormous size.
- These ripples in density then become the seeds for all structures in the universe.


Had inflation not taken place, the present-day observable universe would have had to have been relatively large just after the Big Bang.
Once the inflationary epoch had ended, the universe continued to expand in a more gradual way down to the present day.
In the inflationary model, the present-day observable universe was very tiny just after the Big Bang. This region, as well as the rest of the universe, then underwent a tremendous expansion during the inflationary epoch.
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}
Present
Time after Big Bang (s)

What caused inflation?

- Negative-pressure vacuum density!
- Huh?

- Many details not understood, but basic idea is that when the strong force decoupled from the electroweak force, *vacuum energy* (the energy of empty space, related to the cosmological constant) caused *exponential* expansion.
- Inflation stopped a brief instant later when space filled with particles and antiparticles (pulled-apart virtual pairs).
- Self-annihilation raised the temperature close to pre-inflation levels, with pair production at equilibrium.

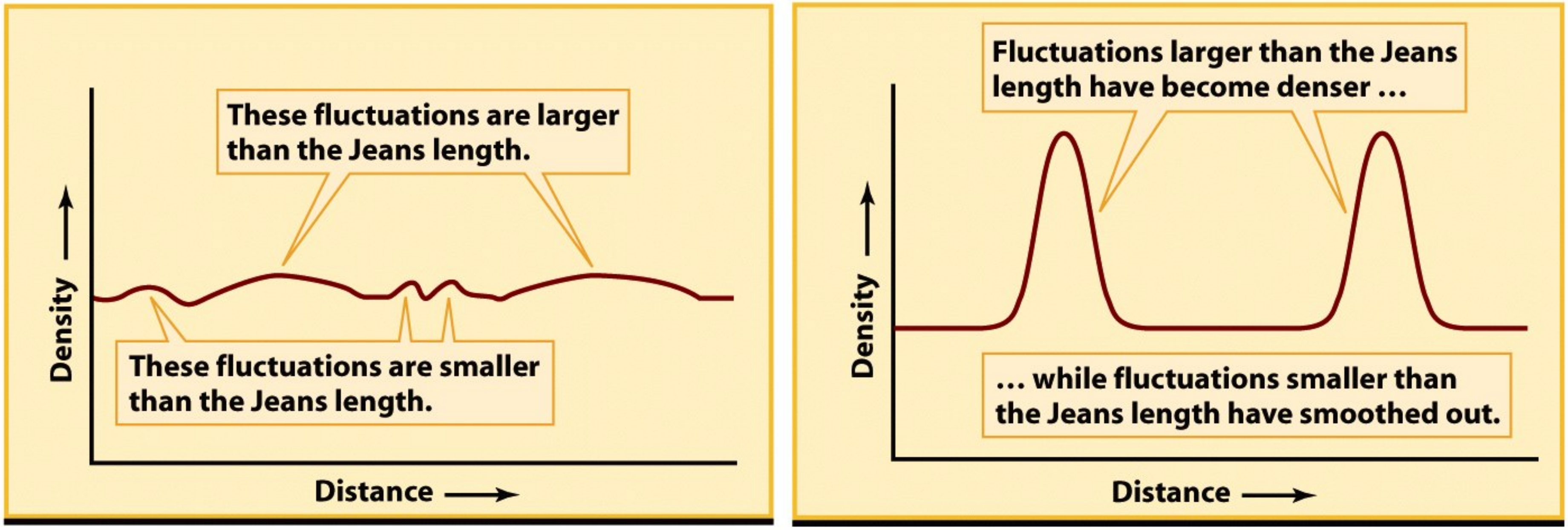

A virtual particle-antiparticle pair that appears just before the inflationary epoch...
Virtual positron
Virtual electron
Real positron
...is pulled so far apart during inflation that the particles cannot recombine, thus leaving a pair of real particles.
Real electron

Reminder: The Jeans Mass/Length

- An object will grow from a density fluctuation if the latter is larger than the *Jeans length*

$$L_J \sim \sqrt{\frac{15 k_B T}{\pi G \rho_m m_H}}.$$

- E.g., after recombination, $T \sim 3{,}000\ \mathrm{K}$, $\rho_m \sim 2 \times 10^{-18}\ \mathrm{kg/m^3}$, so $L_J \sim 100\ \mathrm{ly}$, the diameter of a typical globular cluster!
- Larger structures form from the bottom up (see cold dark matter), leading to galaxies, clusters, and superclusters.

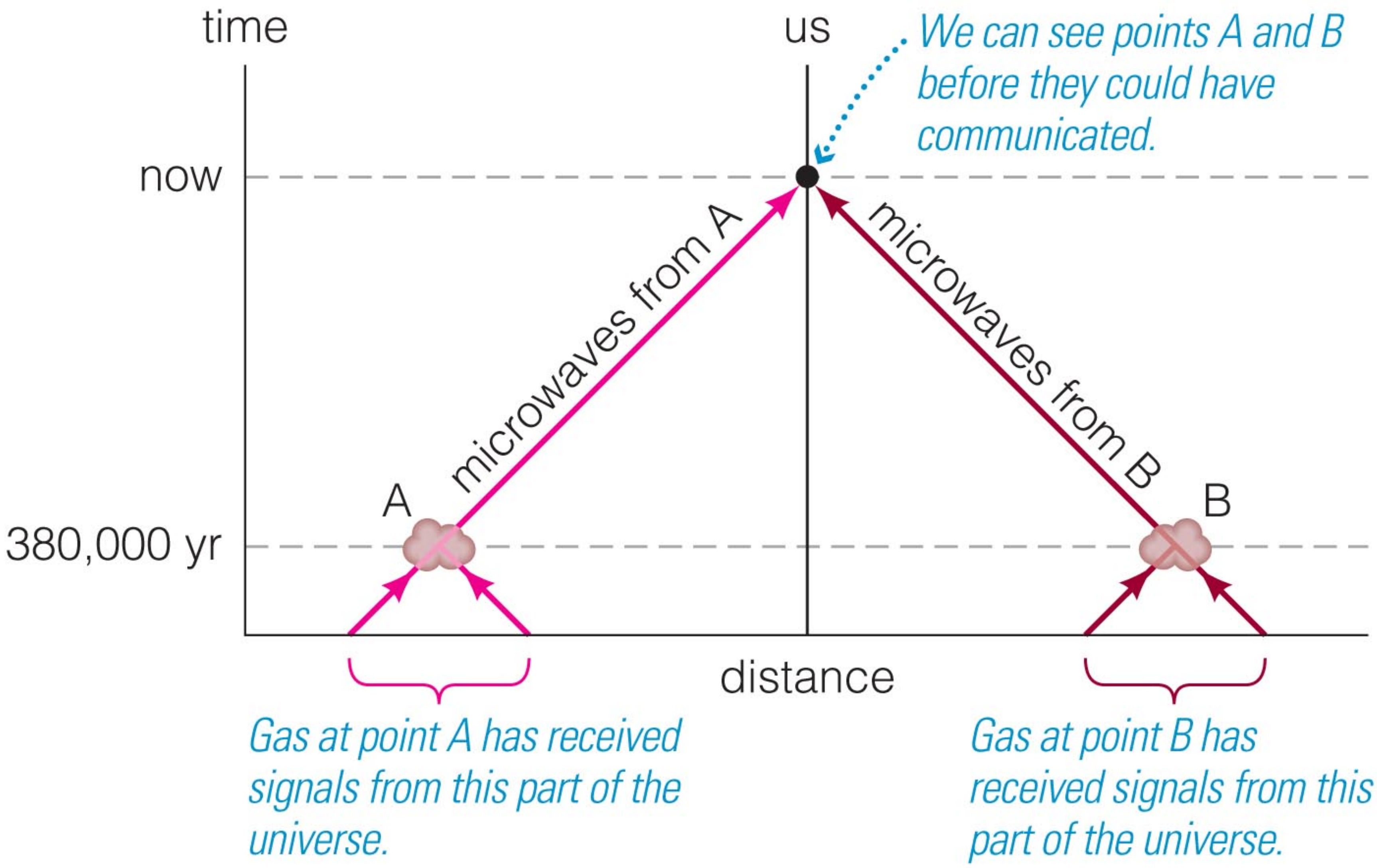


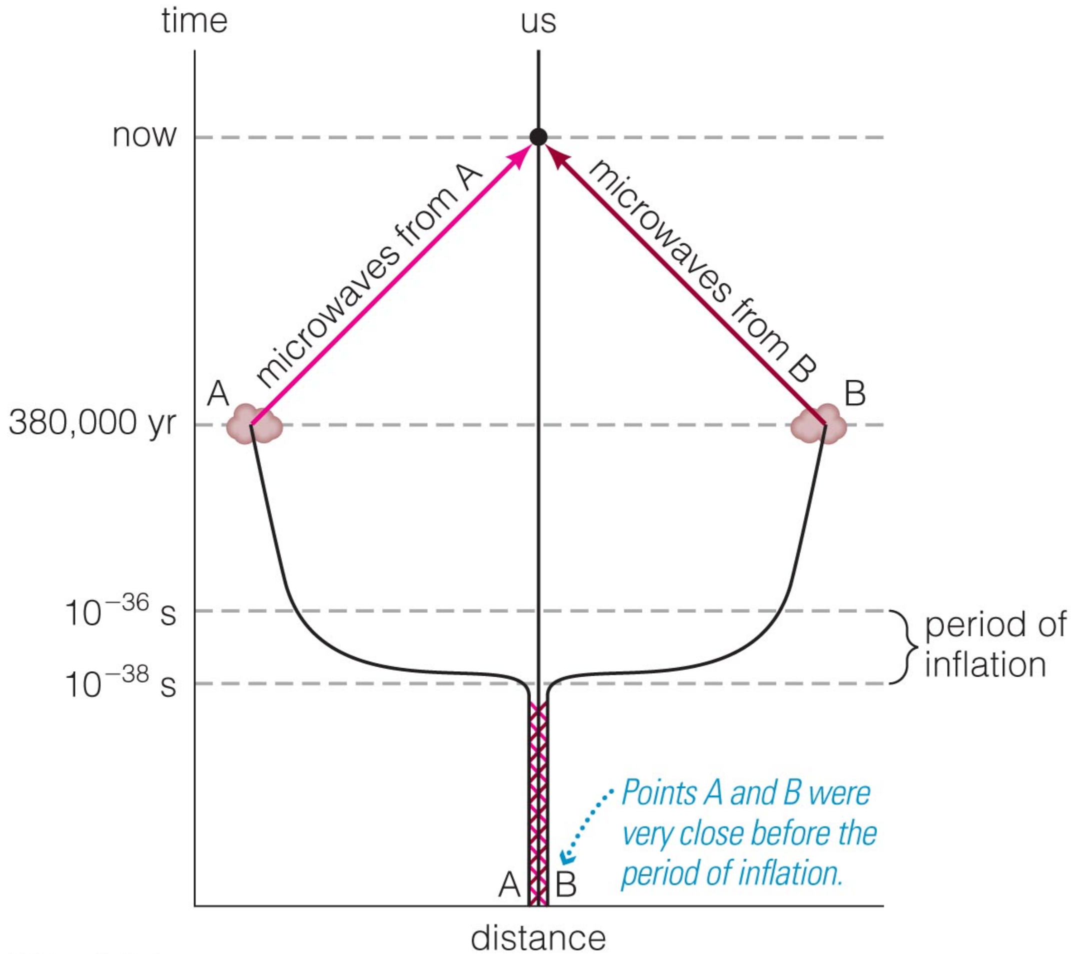
(a) At an early time (b) At a later time

MYSTERIES

2. Why is the distribution of matter so uniform?

How can the temperature be nearly identical on opposite sides of the sky?



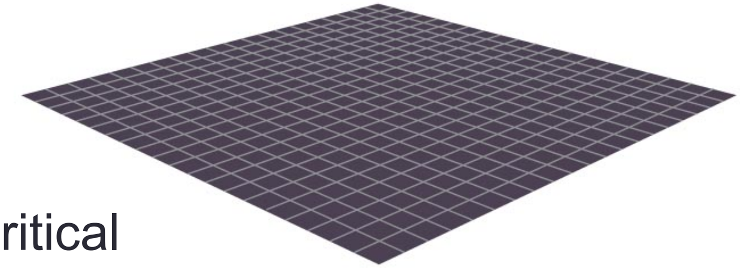


- Regions now on opposite sides of the sky were close together before inflation pushed them far apart.
- These regions were in *thermal equilibrium* until they were separated.

MYSTERIES

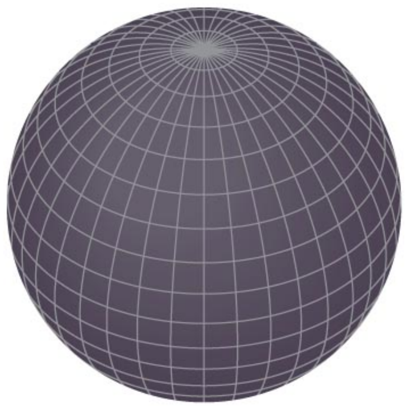
3. Why is the universe so “flat”?

Density = Critical
$(\Omega = 1)$



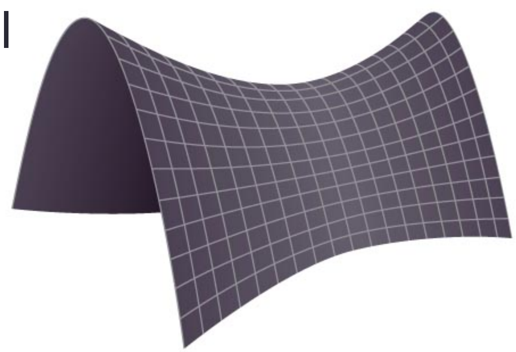
flat (critical) geometry

Density > Critical
$(\Omega > 1)$



spherical (closed) geometry

Density < Critical
$(\Omega < 1)$



saddle-shaped (open) geometry

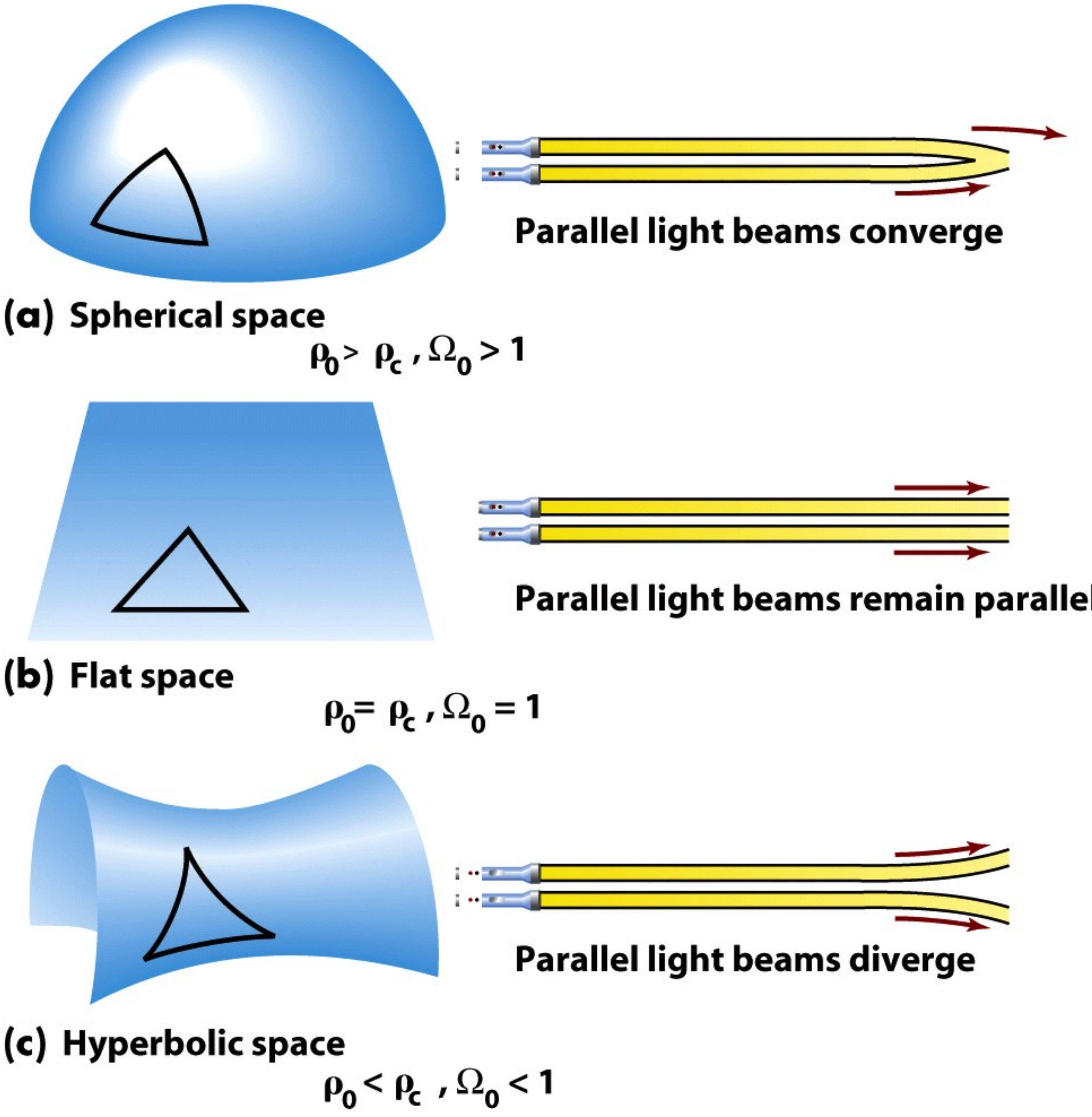
Overall geometry of the universe is closely related to total density of matter and energy.

$$\Omega = \frac{\rho}{\rho_{\mathrm{crit}}},$$

$$\rho_{\mathrm{crit}} = \frac{3H^2}{8\pi G}$$

Measuring the Geometry of the Universe

- We can study the geometry of the universe using the properties of triangles.
- Suppose that we draw a giant triangle in space and then add up the angles inside the triangle…
  - Sum of angles = 180° $\Rightarrow$ flat geometry.
  - Sum of angles < 180° $\Rightarrow$ hyperbolic geometry.
  - Sum of angles > 180° $\Rightarrow$ spherical geometry.

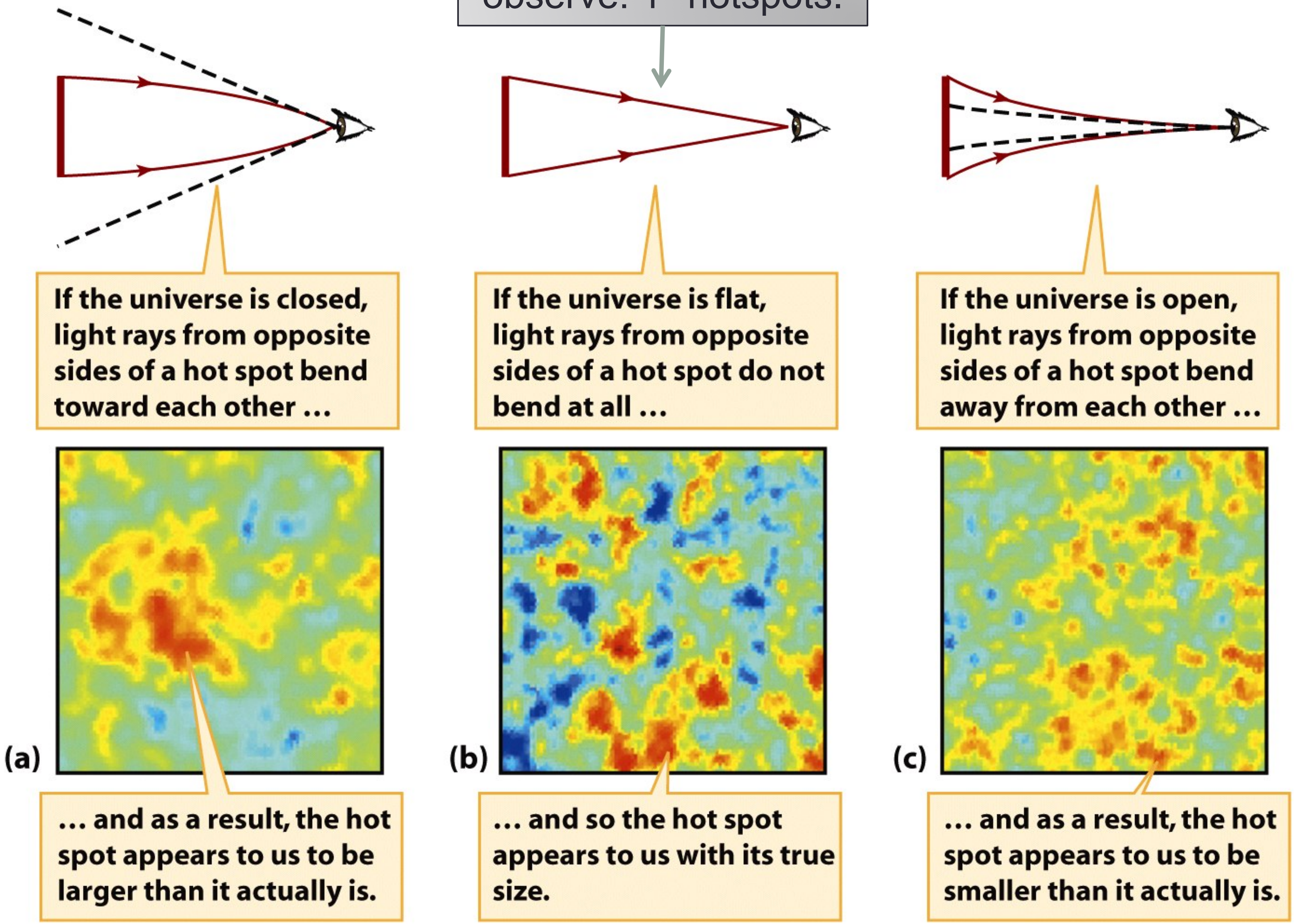

Parallel light beams converge
(a) Spherical space
$\rho_0 > \rho_c , \Omega_0 > 1$
Parallel light beams remain parallel
(b) Flat space
$\rho_0 = \rho_c , \Omega_0 = 1$
Parallel light beams diverge
(c) Hyperbolic space
$\rho_0 < \rho_c , \Omega_0 < 1$

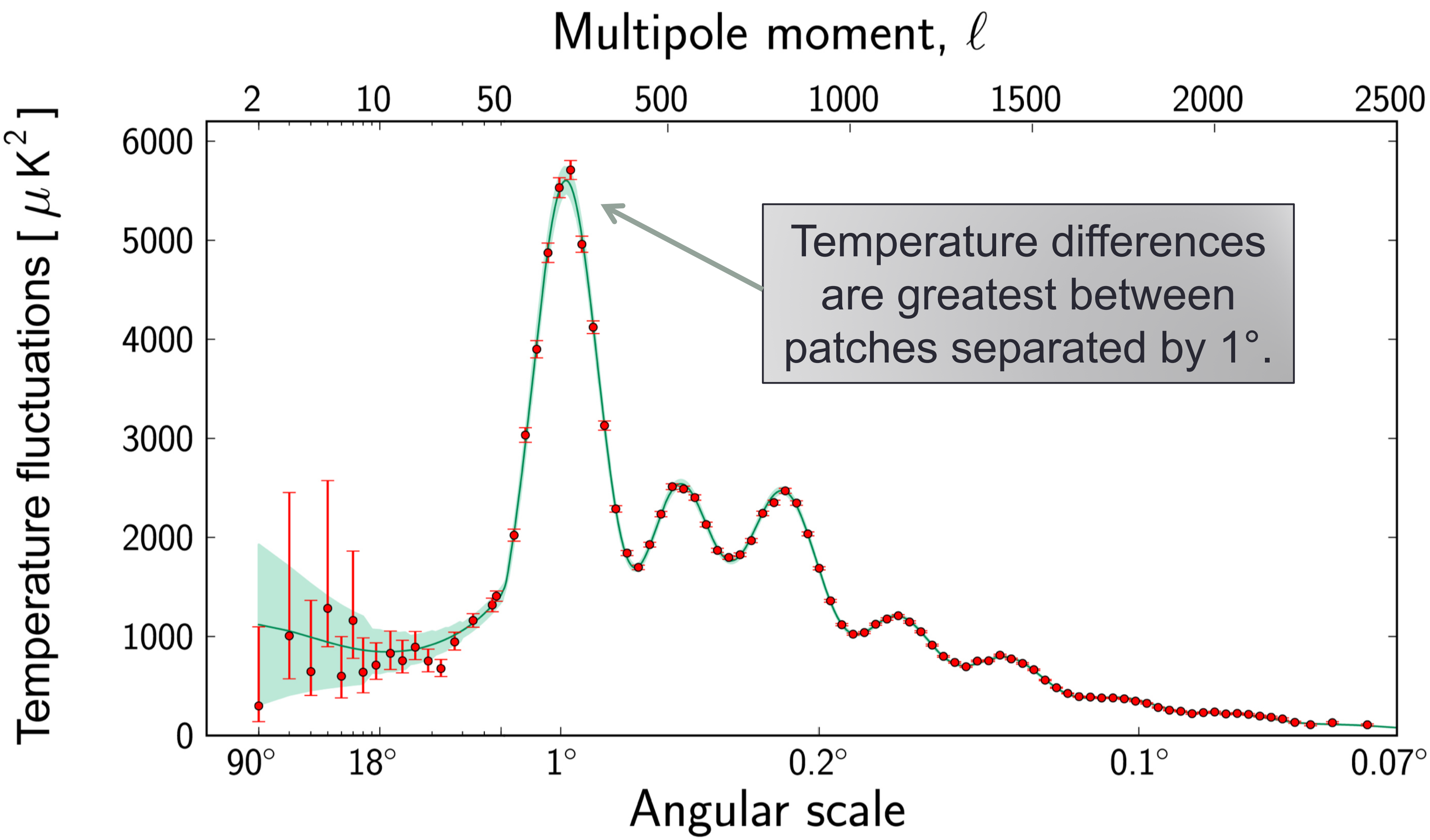
Fluctuations in the CMB reveal the geometry of the universe

- We can study these “triangles” by looking at the CMB fluctuations…
  - Recall, many of these fluctuations are due to oscillations (sound waves) that were present in the early universe.
    - Compression ➔ higher density ➔ more gravitational redshift ➔ colder.
    - Rarefaction ➔ lower density ➔ less gravitational redshift ➔ warmer.
  - An “image” of these sound waves was frozen into the CMB at the time that radiation and matter decoupled.
  - We can calculate the physical size (about 150 Mpc) of these fluctuation peaks from theory, and we know how far this “image” of the CMB is from us (about 15 Gpc comoving distance).
  - Thus, we have our triangle: all we need to do is measure the angle subtended by these fluctuations as seen from Earth (about 1°).

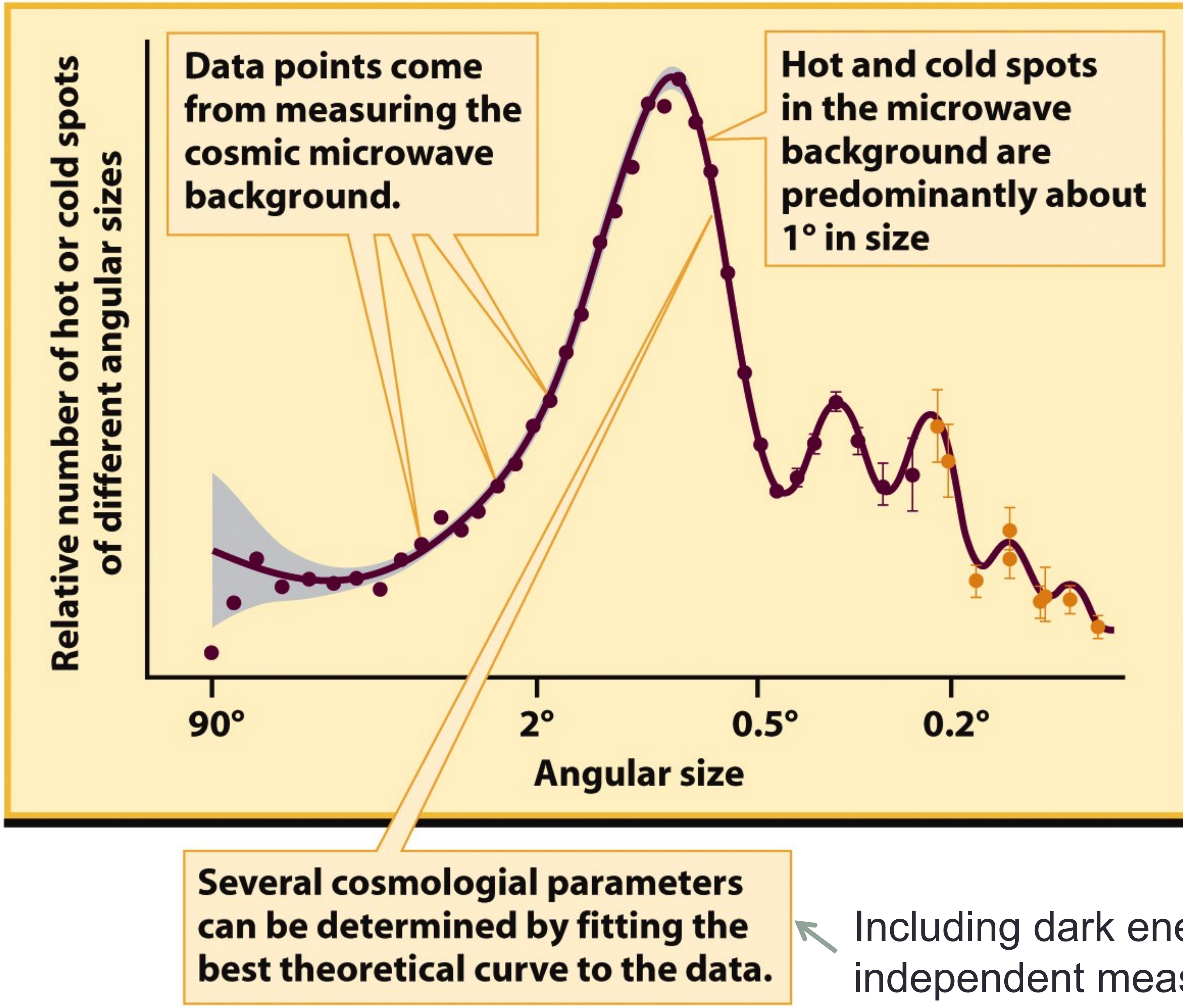
“Standard ruler.”

This is what we observe: 1° hotspots.





Observed patterns of structure in universe agree (so far) with the "seeds" that inflation would produce.



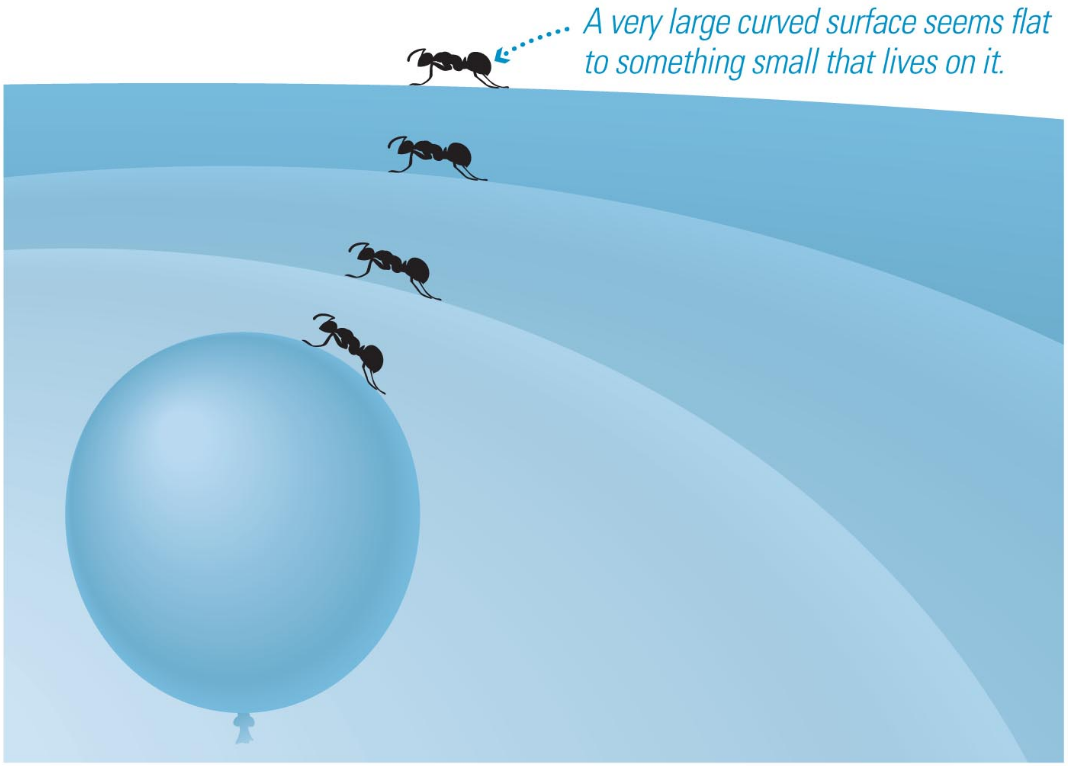
Including dark energy (Ω_Λ)… independent measure!

Result: The universe is flat!

- If phrased in terms of the density parameter, the geometry of the universe suggests that $\Omega = 1.00 \pm 0.02$.

Flat universe: amazing coincidence?

- If $\Omega < 1$ (subcritical) in the early universe, expansion would not halt, so $\Omega_0 << 1$ now.
- But if $\Omega > 1$ early on, expansion would slow down and reverse, so $\Omega_0 >> 1$ now (Big Crunch—never happened).
- To get $\Omega_0 \sim 1$ now requires incredible fine tuning of Ω in early universe, i.e., $\Omega = 1 \pm \varepsilon$, $\varepsilon << 1$ (like 1 part in 10^{50}!).
- Easier to believe something forced $\Omega = 1 \ldots$



Inflation of the universe flattens its overall geometry like the inflation of a balloon, causing the overall density of matter plus energy to be very close to the critical density.

“Seeds” Inferred from CMB

- Overall geometry is flat.
  - Total mass + energy has critical density.
- Total matter is ~31% of total.
  - Ordinary matter is ~4.9% of total.
  - Dark matter is ~26% of total.
- Dark energy is ~69% of total.
- Age is 13.80 billion years.

In excellent agreement with observations of the present-day universe and models involving inflation and WIMPs!

Summary

- The Big Bang explains:
  - The expansion of the universe.
  - The presence of a cosmic microwave background (CMB).
  - Why the universe is about 75% H and 25% He.
- Inflation explains:
  - The cosmological principles.
  - Why the universe is flat ($\Omega_0 \sim 1$).
  - The source of density fluctuations that grow into galaxies.
- Outstanding issue:
  - Where is all the antimatter?