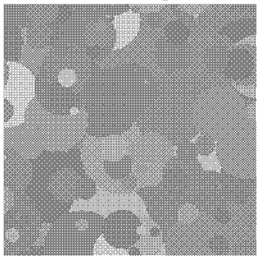
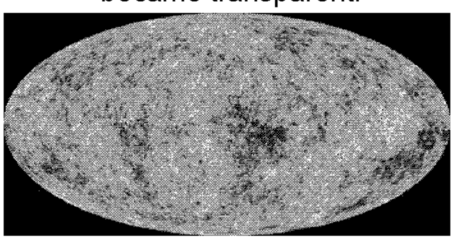
The Inflationary Universe



Wednesday, November 25

Please hand in Problem Set #7,
pick up Problem Set #8

The universe is very lumpy today because it was slightly lumpy when the universe became transparent.



But why was it slightly lumpy then instead of being perfectly smooth?

(1) Why is the average density so close to the critical density?

? Why is the universe **flat** on large scales? ?

(2) Why isn't the density equal to the average density everywhere?

? Why is the universe **lumpy** on small scales? ?

The answers to these two questions are actually linked!!

By explaining why the average density is close to critical, we can also explain why there are deviations from the average.

1st question first…

Why should the average density of the universe (ρ) be so close to the theoretical critical density (ρ_{crit})?

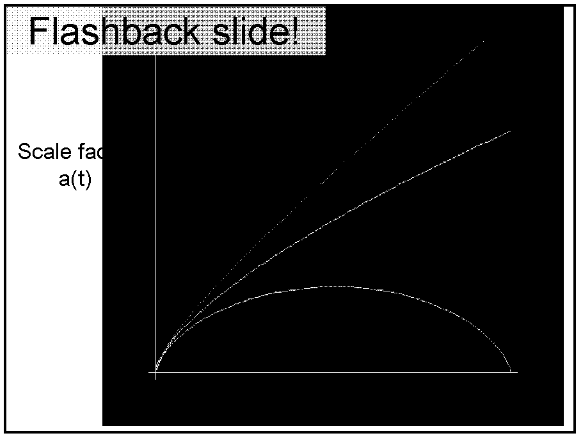
There's no law of nature that says **Ω** (= ρ/ρ_{crit}) must be equal to one.

Why not $\Omega = 0.01$ or $\Omega = 100$?

Maybe it's just a coincidence that Ω is close to one, and space is nearly flat.

The coincidence becomes **harder to explain** as you look into the past.

Why? When the universe is matter-dominated, deviations of Ω from one **increase with time**.



If Ω is slightly less than 1, we expect a **Big Chill** ($\Omega \rightarrow$ zero).

If Ω is slightly greater than 1, we expect a **Big Crunch** ($\Omega \rightarrow$ infinity).

What we observe today:
$0.9 < \Omega < 1.1$

Today (t = 13.7 billion years):
$0.9 < \Omega < 1.1$

Transparency (t = 400,000 years):
$0.9997 < \Omega < 1.0003$

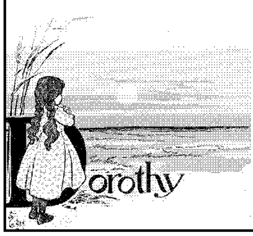
Nucleosynthesis (t = 3 minutes):
$1 - 10^{-14} < \Omega < 1 + 10^{-14}$

At the time of Big Bang Nucleosynthesis, the density differed from the critical density by **one part in 100 trillion - or less**!

Our **existence** depends on this close agreement – otherwise the universe would have Crunched or Chilled before stars could form.

Flatness Problem:

Since the universe is **fairly** close to flat today, it must have been **insanely** close to flat in its early history.

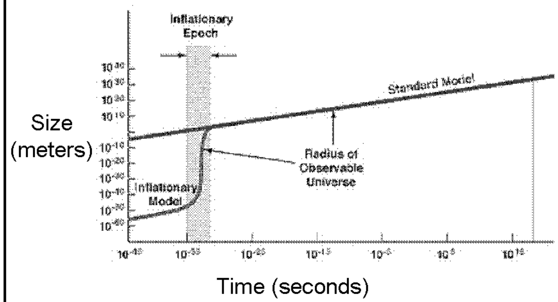


What flattened the early universe?

Until the 1980s, cosmologists were baffled by the flatness problem.

1981: Alan Guth proposes the idea of **inflation**.

Inflation = a brief period of highly accelerated expansion, early in the history of the universe.



Highly relevant questions:

How does inflation solve the flatness problem?

Why did the universe start inflating exponentially (& why did it stop)?

According to the current model of inflation:

At $t \approx 10^{-34}$ seconds, the universe started expanding exponentially, doubling in size every 10^{-34} seconds.

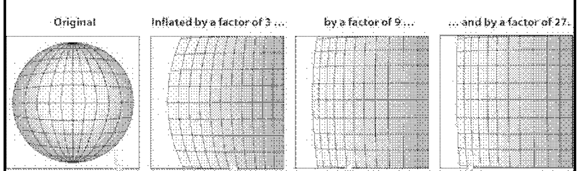
Inflation ended at $t \approx 10^{-32}$ seconds, after expansion by a factor 10^{30}.

Today, the observable universe has a radius $r \approx c/H_0$ ≈ 4300 Mpc $\approx 10^{26}$ meters

At the end of inflation, it had a radius $r \approx 1$ meter!

At the beginning of inflation, it had a radius $r \approx 10^{-30}$ meter!!!

How does inflation solve the flatness problem?

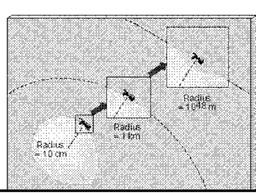


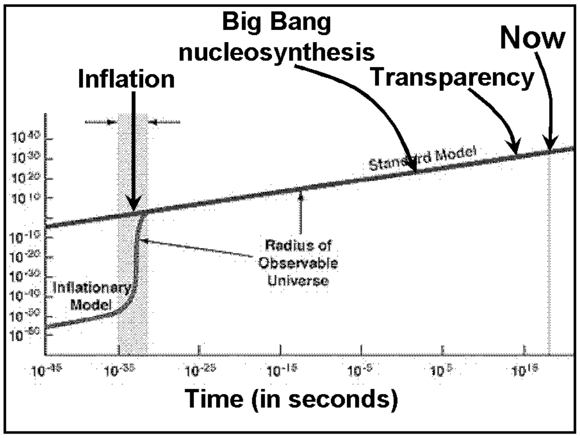
As the sphere is inflated, its curvature eventually becomes undetectable and its surface appears flat.

Inflation greatly increases the radius of curvature of the universe.

Suppose the radius of the universe was only one nanometer (10^{-9} meter) before inflation.

After inflation, the radius would be 30,000 parsecs; today, 3 trillion trillion megaparsecs.



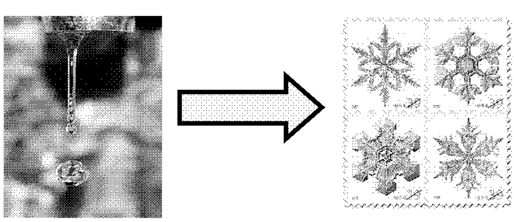


Why did the universe start inflating exponentially (& why did it stop)?

According to the particle physicists: universe underwent a phase transition at t ≈ 10^{-35} seconds.

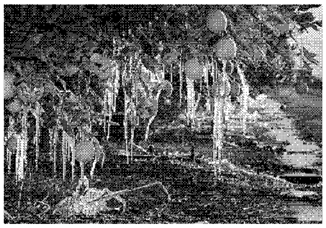
Example of a modern phase transition: water freezes.

When water goes from liquid to solid, it goes from a random state to an ordered state.



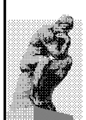
Energy is released.

During a freeze in Florida, orange trees are sprayed with water.



Why? The energy released by freezing water warms the leaves & fruit.

The energy released by the phase transition at $t \approx 10^{-35}$ sec acts (temporarily) like **dark energy**.



Expansion of the universe is accelerating **now**, just as it was at $t \approx 10^{-35}$ sec. Is the universe **now** undergoing a phase transition?

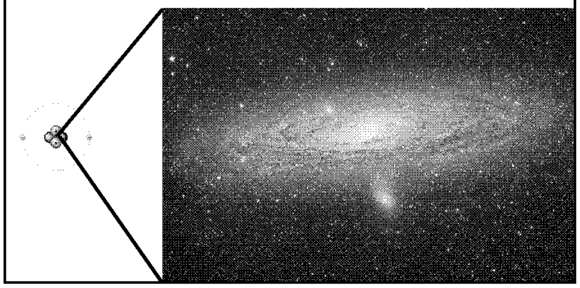
Why is the universe **flat** on large scales?

Because it underwent **inflation** early in its history.

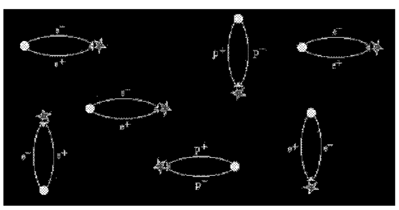
Why is the universe **lumpy** on small scales?

Because it underwent **inflation** early in its history.

Inflation increases a length of 1 nanometer (the size of an atom) to 30,000 parsecs (the size of a galaxy).



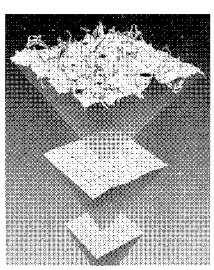
On subatomic scales, the universe is full of quantum fluctuations.



A vacuum looks empty, but it's full of particles & antiparticles being created & destroyed.

This is a result of Heisenberg's Uncertainty Principle: we can't specify exactly the energy of a subatomic patch of the universe.

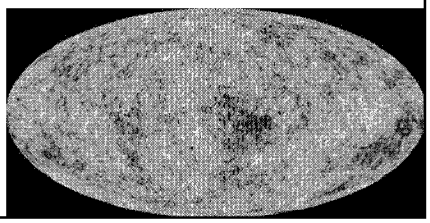
Some patches are higher in energy: some are lower.



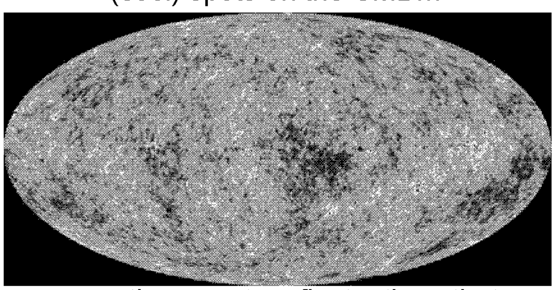
Ordinarily, these quantum fluctuations are on tiny scales.

However, inflation increased tiny scales (1 nanometer) to galaxy-sized scales (30,000 parsecs)!

Cosmic
Microwave
Background



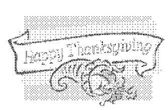
The high-density (warm) and low-density (cool) spots on the CMB…



…are tiny quantum fluctuations that have been blown up in scale.

Monday's Lecture:

Planets



Reading:

Chapters 13 & 14