Plan of Lecture
The Very Early Universe

Redshift dependence of matter, energy, etc.

Big Bang nucleosynthesis.

Phase transitions and primordial black holes.

The inflationary epoch and before.

Earlier and Earlier

What happens to the average state of the universe as we go back in time?

Volume decreases.

Density increases.

Temperature increases.

These have many consequences that we will explore.

Tighter coupling.

Higher energy processes.

At very early times, energies are high enough that particle physics is important.

Evolution of Components

Consider fraction of critical density in matter, radiation, dark energy, and curvature.

Ω_m, Ω_r, Ω_Λ, Ω_R.

How do they change with redshift?

Consider Ω_m: volume shrinks by factor $(1+z)^3$, so density increases by $(1+z)^3$.

$\Omega_m \propto (1+z)^3$.

For radiation, $\Omega_r \propto (1+z)^4$ (why?).

Less obviously: $\Omega_\Lambda \propto (1+z)^0$ (const), and $\Omega_R \propto (1+z)^2$.

Changing State of Universe

What do the different redshift dependences mean?

At higher z, higher powers of $(1+z)$ dominate.

Matter and radiation.

In particular, at higher redshift, since $\Omega_m + \Omega_r + \Omega_\Lambda + \Omega_R$ *always* equals 1, $\Omega_\Lambda \to 0$ and $\Omega_R \to 0$.

Insignificant dark energy.

Flat universe.

But a slight deviation from flat at high redshift would mean a large deviation now. Why so close???

Radiation-Dominated Era

Since $\Omega_r \propto (1+z)^4$ whereas $\Omega_m \propto (1+z)^3$, radiation dominates at high z.

$z \gtrsim 10^4$**.**

What consequences does this have?

Remember the process of structure formation.

Density perturbation is produced.

Gravity enhances the perturbation.

However, radiation doesn't collect.

Prevents matter from clustering.

Above decoupling redshift $z \approx 1100$, matter and radiation temperatures are same.

Below, T_m drops faster.

Big Bang Nucleosynthesis

How did the elements form?

Hydrogen's easy; you just need spare protons and electrons.

For the rest, however, you need fusion.

In the early universe ($\lesssim$ few minutes), you have high density and temperature.

Gamow thought all elements could be formed then.

No! Two bottlenecks.

No stable element of mass 5, 8.

Need longer duration.

Form all heavy elements in stars.

But light elements *can* be formed early...

Constraints on Baryons

Baryons: protons and neutrons.

When $T > 10^{10}$ K, have both.

$T \gg 10^{10}$ **K; nuclei shatter.**

$T \ll 10^{10}$ **K; free neutrons decay.**

Only a few minutes for formation.

Suppose you have very few baryons.

p, n don't meet!

Little formation of d, He, etc.

With a lot, most hydrogen becomes helium.

Ratios of d, He, etc. to H constrain baryon fraction Ω_b.

$\Omega_b \approx 0.04$**.**

Most dark matter isn't baryons!

Phase Transitions

We now go into energies so high the physics is uncertain...

The universe is thought to have undergone several "phase transitions".

This is a transition from one state to another.

Like liquid water to ice.

Here, however, we are talking about tremendous densities and temperatures.

The physics can differ depending on how the transition happens.

Abruptly? First-order.

Smoothly? Higher-order.

First-order transitions can create discontinuities.

Quark-Hadron Transition

One transition is expected to have happened $\sim 10^{-5}$ s after the Big Bang.

In current universe, quarks are all bound up in particles.

E.g., proton has three quarks.

Therefore, we are in an era of heavy particles, or "hadrons".

At a very high energy, expect quarks to be in a soup with each other and with "gluons".

Quark-gluon plasma.

Being seen in accelerators.

This transition might have had some very interesting effects...

Primordial Black Holes

Hypothesized; not yet seen.

In very early universe, imagine excess density.

Enough matter, collapses to BH.

Wouldn't interrupt BBN.

Perhaps produced at many scales (i.e., wide range of masses).

Squeezing is easier during density-induced phase transition.

Less pressure to resist.

Quark-hadron: $M \sim 1\, M_{\odot}$**.**

Many could be floating around.

See by microlensing?

Can't be most of dark matter.

Inflation

Horizon problem: CMB patches $> 7^\circ$ apart not in contact at $z = 1100$; why same T?

Flatness problem: why is $\Omega_R \approx 0$ today? Need $< 10^{-50}$ in early universe!

In early 1980s, solution proposed: inflation.

Start $\sim 10^{-35}$ s after BB.

Universe expands by factor $\gtrsim 10^{50}$.

How? Mechanisms similar to dark energy!

Spacetime expands faster than speed of light.

Doesn't violate relativity.

Pre-inflation, patches in contact with each other. Same T.

Flatness comes from stretching out spacetime.

Unification of Forces

Now we go to the *really* early universe...

Currently, four fundamental forces: gravity, electromagnetism, and strong and weak nuclear.

At high enough energies, EM and weak "merge" into single force.

At higher energies yet, expected that these merge with strong force.

At highest energies, gravity is thought to join.

One single force!

Expected $\sim 10^{-43}$ s after BB!!!

Other than electroweak, accelerators can't probe high enough energies.

Before the Big Bang

Wild speculation!

What caused the Big Bang? Several possible answers.

Hawking: maybe no cause!

Time began at BB.

What's north of the North Pole?

Rupture of infinite spacetime?

Collision of higher-dimensional "branes"???

How could any of this be tested?

Only gravitational waves can come to us from that epoch.

Potentially, discriminate between models.

Summary

Earlier, denser, hotter!

At $z \gtrsim 10^4$, radiation dominated.

Hydrogen, deuterium, helium (and a little lithium, beryllium) synthesized in first few minutes.

Primordial black holes might have formed early!

Inflation solves flatness, horizon problems.

Very early universe is a mystery...

Challenge: could we measure neutrinos from the very early universe?