The Early Universe
Back to the Big Bang

The total energy of the universe consists of both radiation and matter.

As the Universe cooled, it went from being radiation dominated to being matter dominated.

Dark energy becomes more important as the Universe expands.
In the very early Universe, one of the most important processes was pair production: The upper diagrams show how two gamma rays can unite to make an electron–positron pair, and vice versa.

The lower picture is of such an event occurring at a high-energy particle accelerator.
In the very early Universe, the pair production and recombination processes were in equilibrium. When the temperature had decreased to about 1 billion K, the photons no longer had enough energy for pair production, and were “frozen out”.

We now see these photons as the cosmic background radiation.
The Evolution of the Universe

This table lists the main events in the different epochs of the Universe

<table>
<thead>
<tr>
<th>Era</th>
<th>Epoch</th>
<th>Time</th>
<th>Density</th>
<th>Temperature</th>
<th>Main Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation</td>
<td>0 s</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td></td>
<td>Unknown physics; quantum gravity.</td>
</tr>
<tr>
<td></td>
<td>Planck</td>
<td>$10^{-43}$ s</td>
<td>$10^9$</td>
<td>$10^{12}$</td>
<td>Strong, weak, and electromagnetic forces unified.</td>
</tr>
<tr>
<td></td>
<td>GUT*</td>
<td>$10^{-35}$ s</td>
<td>$10^{75}$</td>
<td>$10^{27}$</td>
<td>Strong force frozen out. Heavy and light particles all in thermal equilibrium. Electroweak force freezes out at $10^{15}$ K.</td>
</tr>
<tr>
<td></td>
<td>Quark</td>
<td>$10^{-4}$ s</td>
<td>$10^{16}$</td>
<td>$10^{12}$</td>
<td>Only low-mass particles still in thermal equilibrium; neutrinos decouple at $10^{10}$ K.</td>
</tr>
<tr>
<td></td>
<td>Lepton</td>
<td>$10^3$ s</td>
<td>$10^7$</td>
<td>$10^0$</td>
<td>Deuterium and helium formed by fusion of protons and neutrons during first 1000 s.</td>
</tr>
<tr>
<td></td>
<td>Nuclear</td>
<td>$5 \times 10^4$ yr ($2 \times 10^{12}$ s)</td>
<td>$6 \times 10^{-16}$</td>
<td>16,000</td>
<td></td>
</tr>
<tr>
<td>Matter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Atomic</td>
<td>$5 \times 10^6$ yr ($2 \times 10^{12}$ s)</td>
<td>$6 \times 10^{-16}$</td>
<td>16,000</td>
<td>Matter begins to dominate; atoms form; electromagnetic radiation decouples.</td>
</tr>
<tr>
<td></td>
<td>Galactic</td>
<td>$2 \times 10^8$ yr ($5 \times 10^{15}$ s)</td>
<td>$10^{-22}$</td>
<td>60</td>
<td>Large-scale structure forms; first stars and quasars shine; galaxies form and grow.</td>
</tr>
<tr>
<td></td>
<td>Stellar</td>
<td>$3 \times 10^9$ yr ($10^{17}$ s)</td>
<td>$2 \times 10^{-25}$</td>
<td>10</td>
<td>Galaxies merge and evolve; star formation peaks. Dark energy begins to dominate.</td>
</tr>
</tbody>
</table>

*Grand Unified Theory, or More Precisely 27-1.
The Evolution of the Universe

Current understanding of the forces between elementary particles is that they are accomplished by exchange of a third particle. Different forces “freeze out” when the energy of the Universe becomes too low for the exchanged particle to be formed through pair production.
The Evolution of the Universe

If we extrapolate the Big Bang back to the beginning, it yields a singularity—infinite density and temperature.

This may or may not be accurate; we can only understand what happens back to $10^{-43}$ seconds after the Big Bang.

Before that, we need physics of which we know very little right now.
The Evolution of the Universe

Therefore, we cannot predict anything about what happened before the Big Bang.

Indeed, the question may be meaningless.

This first $10^{-43}$ seconds after the Big Bang are called the Planck era.

At the end of that era, the gravitational force “freezes out” from all the others.

The next era is the GUT (Grand Unified Theory) era.

Here, the strong nuclear force, the weak nuclear force, and electromagnetism are all unified.
The Evolution of the Universe

The next era is called the quark era

During this era all the elementary particles were in equilibrium with radiation

About $10^{-4}$ s after the Big Bang, the Universe had cooled enough that photons could no longer produce the heavier elementary particles

The only ones still in equilibrium were electrons, positrons, muons, and neutrinos

This is called the lepton era
The Evolution of the Universe

About 1 second after the Big Bang, the Universe became transparent to neutrinos.

After 100 seconds, photons became too low in energy for electron–positron pair creation.

This marks the end of the radiation era.
The Evolution of the Universe

The next major era occurs when photons no longer are able to ionize atoms as soon as they form.

This allows the formation of hydrogen and helium atoms, which can then form larger structures.

For the next 3 billion years, galaxies and quasars begin to form.

After that, they merge.

Galaxies evolve into the ones we see now, and star formation goes through many generations.
More on Fundamental Forces

Table 27-2 lists the four fundamental forces and the particles on which they act.

There are six types of quarks (up, down, charm, strange, top, bottom) and six types of leptons (electron, muon, tau, and neutrinos associated with each).

All matter is made of quarks and leptons.

<table>
<thead>
<tr>
<th>TABLE 27.2 Fundamental Forces and Particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>strong</td>
</tr>
<tr>
<td>electromagnetic</td>
</tr>
<tr>
<td>weak</td>
</tr>
<tr>
<td>gravity</td>
</tr>
</tbody>
</table>
More on Fundamental Forces

The theories of the weak and electromagnetic forces have been successfully unified in what is called the electroweak theory.

At a temperature of $10^{15}$ K, these forces should have equal strength.

Considerable work has been done on unifying the strong and electroweak theories.

These forces should have equal strength at a temperature of $10^{28}$ K.

One prediction of many such theories is supersymmetry - the idea that every known particle has a supersymmetric partner.
More on Fundamental Forces

Unification of the other three forces with gravity has been problematic.

One theory that showed early promise is string theory—the idea that elementary particles are oscillations of little loops of “string,” rather than being point particles.

This avoids the unphysical results that arise when point particles interact.

It does, however, require that the strings exist in 11-dimensional space.

The extra seven dimensions are assumed to be very small.
The Formation of Nuclei and Atoms

Hydrogen will be the first atomic nucleus to be formed, as it is just a proton and an electron.

Beyond that, helium can form through fusion:

\[ ^2\text{H} + ^1\text{H} \rightarrow ^3\text{He} + \text{energy} \]

\[ ^2\text{H} + ^2\text{H} \rightarrow ^3\text{He} + \text{neutron} + \text{energy} \]

\[ ^3\text{He} + \text{neutron} \rightarrow ^4\text{He} + \text{energy} \]
The Formation of Nuclei and Atoms

This diagram illustrates the fusion process.

Note that it is not the same as the fusion process that now goes on in the Sun’s core.
The Formation of Nuclei and Atoms

This would lead one to expect that \( \frac{1}{4} \) of the atoms in the universe would be helium, which is consistent with observation (remembering that nucleosynthesis is ongoing in stellar cores).

\[
\frac{1 \text{ helium nucleus}}{12 \text{ protons} + 1 \text{ helium nucleus}} = \frac{4 \text{ mass units}}{12 \text{ mass units} + 4 \text{ mass units}}
\]

\[
= \frac{4}{16} = \frac{1}{4}.
\]
The Formation of Nuclei and Atoms

Most deuterium fused into helium as soon as it was formed, but some did not.

Deuterium is not formed in stars, so any deuterium we see today must be primordial.

This gives us a very sensitive way to estimate the present-day matter density of the universe.
As with galaxy measurements, the total matter density determined by deuterium abundance shows that the matter density is only a few percent of the critical density.
The time during which nuclei and electrons combined to form atoms is referred to as the decoupling epoch. This is when the cosmic background radiation originated.
The Inflationary Universe

The horizon problem

When observed in diametrically opposite directions from Earth, cosmic background radiation appears the same even though there hasn’t been enough time since the Big Bang for them to be in thermal contact.
The Inflationary Universe

The flatness problem

In order for the Universe to have survived this long, its density in the early stages must have differed from the critical density by no more than 1 part in $10^{15}$. 
The Inflationary Universe

Between the GUT epoch and the quark epoch, some parts of the Universe may have found themselves stuck in the unified condition longer than they should have been.

This resulted in an extreme period of inflation, as shown on the graph.

Between $10^{-35}$ s and $10^{-32}$ s, this part of the Universe expanded by a factor of $10^{50}$!
The Inflationary Universe

Inflation, if correct, would solve both the horizon and the flatness problems

This diagram shows how the horizon problem is solved

The points diametrically opposite from Earth were, in fact, in contact at one time
The Inflationary Universe

The flatness problem is solved as well

After the inflation, the need to be exceedingly close to the critical density is much more easily met
The Formation of Structure in the Universe

Cosmologists realized that galaxies could not have formed just from instabilities in normal matter:

• **Before decoupling, background radiation** kept clumps from forming.

• **Variations in the density of matter** before decoupling would have led to variations in the cosmic microwave background.

• **Galaxies, or quasars, must have begun forming** by a redshift of 6, and possibly as long ago as a redshift of 10 to 20.
The Formation of Structure in the Universe (cont.)

- Because of the overall expansion of the universe, any clumps formed by normal matter could only have had 50 – 100 times the density of their surroundings.

Dark matter, being unaffected by radiation, would have started clumping long before decoupling.
Galaxies could then form around the dark-matter clumps, resulting in the Universe we see.
The Formation of Structure in the Universe

This figure is the result of simulations, beginning with a mixture of 4% normal matter, 23% cold dark matter, and 73% dark energy:
Cosmic Structure and the Microwave Background

Although dark matter does not interact directly with radiation, it will interact through the gravitational force, leading to tiny “ripples” in the cosmic background radiation.

These ripples have now been observed.
Cosmic Structure and the Microwave Background

This is a much higher-precision map of the cosmic background radiation:
Cosmic Structure and the Microwave Background

Here, the red dots are measurements derived from the data in the last image, and the blue curve is a prediction for a universe with $\Omega_0 = 1$, showing excellent agreement. The placement of the large peak is particularly sensitive to $\Omega_0$. 

\[ \text{Angular scale} \]