Cosmology

- Expanding Universe
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If the universe is infinite, then every line of sight should end on the surface of a star at some point. 

⇒ The night sky should be as bright as the surface of stars!

**Olbers’ Paradox:** Why is the sky dark at night?

If the universe had a beginning, then we can only see light from galaxies that have had time to travel to us since the beginning of the universe.

⇒ The visible universe is finite!

⇒ The universe is expanding
The Expanding Universe

Edwin Hubble’s study of the velocity of distant galaxies ⇒ on large scales, galaxies are moving apart, with velocity proportional to distance.

We now realize that it is not galaxies moving through space, it is space expanding, carrying the galaxies along!

The galaxies themselves are not expanding!
Expanding Space

Analogy:
Consider a loaf of raisin bread dough as the universe. As it is rising and expanding, it takes the raisins (galaxies) with it.
The Expanding Universe

This does not mean that we are at the center of the universe!

You have the same impression from any other galaxy as well.
Hubble’s Law

Distant galaxies are receding from us with a speed proportional to distance,

\[ v = H_0 d \]

The Doppler redshift is the result of an expanding universe and is called a cosmological redshift.
Cosmological Redshift

As the universe expands, wavelengths get longer
The Age of the Universe

Knowing the current rate of expansion of the universe, we can estimate the time it took for galaxies to move as far apart as they are today.

\[ t = \frac{d}{v} \]
\[ v = H_0 \, d \]
\[ t \approx \frac{d}{v} = \frac{1}{H_0} \]
~14 billion years

Light we see today left this galaxy when the universe was only ~1 billion years old!
Looking Back Towards the Early Universe

When we observe more distant objects, we are looking further back into the past of the universe.

The part of the universe that we are not able to see with existing telescopes

What we can see
The History of the Universe

“Big Bang” models

In “Big Bang” models, the universe begins as an extremely hot point and expands from there.

Universe cools down as time passes

Universe expands as time passes
The laws of physics (especially high-energy or particle physics) can be extrapolated to develop a scenario for the history of the early universe to about when the universe was $10^{-43}$ s old.

One of the hoped for results for the Large Hadron Collider is to learn enough about high-energy physics to push this time to even earlier.
When the universe cools to \(~10^{11}\) K, electrons, positrons, and gamma-rays will be in equilibrium between pair production and annihilation.
The Early History of the Universe

Almost no elements heavier than helium are produced. 25 % of mass in helium; 75 % in hydrogen

No stable nuclei with 5 – 8 nucleons

As the universe cools sufficiently, quarks form and they then form protons and neutrons. Protons and neutrons form some helium nuclei; the rest of the protons remain as hydrogen nuclei.

.: Almost no elements heavier than helium are produced.
The Early History of the Universe

Photons are incessantly scattered by free electrons; photons are in equilibrium with matter.

Radiation dominated era

Photons have a black body spectrum at the same temperature as matter.
Recombination

Protons and electrons recombine to form atoms \( \Rightarrow \) Universe becomes transparent to photons. Photons are no longer in equilibrium with matter.

\[ z \approx 1000 \]

Transition to matter dominated era
The Cosmic Background Radiation

The radiation from the very early phase of the universe should still be detectable today.

It was discovered in the mid-1960s as the Cosmic Microwave Background Radiation:

Black body radiation with a temperature of $T = 2.73 \text{ K}$
The Cosmic Background Radiation

After recombination, photons can travel freely through space.

Their wavelengths are only stretched (redshifted) by cosmic expansion.

Recombination: $z = 1000; T = 3000 \text{ K}$

This is what we observe today as the cosmic background radiation! The universe has cooled from 3000 K to 2.73 K.
After less than ~1 billion years, the first stars form. Ultraviolet radiation from the first stars re-ionizes gas in the early universe. Re-ionization leads to parts of the universe becoming opaque again.
The total energy of the Universe consists of radiation, matter and dark energy.

- The first era of the Universe was dominated by radiation.
- Then it became matter dominated after recombination.
- Now dark energy has become more important as the Universe expands.
The Cosmological Principle

Considering the largest scales in the universe, we make the following fundamental assumptions:

1) **Homogeneity**: On the largest scales, the local universe has the same physical properties throughout the universe.

   Every region has the same physical properties (mass density, expansion rate, visible vs. dark matter, etc.)

2) **Isotropy**: On the largest scales, the local universe looks the same in any direction that one observes.

   You should see the same large-scale structure in any direction.

3) **Universality**: The laws of physics are the same everywhere in the universe.
Cosmology and General Relativity

According to the theory of general relativity, gravity is caused by the curvature of space-time.

The effects of gravity on the largest cosmological scales should be related to the curvature of space-time!

The curvature of space-time, in turn, is determined by the distribution of mass and energy in the universe.

**Space-time tells matter how to move;**

**matter tells space-time how to curve.**
Deceleration of the Universe

- Expansion of the universe should be slowed down by mutual gravitational attraction of the galaxies.
- Fate of the universe depends on the matter density in the universe.
- Define "critical density", $\rho_c$, which is just enough matter density to slow the cosmic expansion to a halt at infinity.
The curvature of space time admits of just three geometric possibilities illustrated here.

- **Closed geometry** is like the surface of a sphere
- **Flat geometry** is a flat surface
- **Open geometry** is like a saddle.
The Geometry of Space

The sum of the angles of an equilateral triangle differ in each geometry:

- **Closed geometry**
  Sum \( > 180^\circ \)

- **Flat geometry**
  Sum \( = 180^\circ \)

- **Open geometry**
  Sum \( < 180^\circ \)
The Geometry of Space

These three possibilities also can be described by comparing the actual density of the universe to the critical density.

Astronomers refer to the present density of the universe as $\rho_0$ and to the critical density as $\rho_c$. This is sometimes expressed as $\Omega_0 = \rho_0/\rho_c$.

Then we can describe the three possibilities as:

- $\rho_0 < \rho_c$ or $\Omega_0 < 1$  Open geometry
- $\rho_0 = \rho_c$ or $\Omega_0 = 1$  Flat geometry
- $\rho_0 > \rho_c$ or $\Omega_0 > 1$  Closed geometry
If the density of matter equaled the critical density, then the curvature of space-time by matter would be just enough to make the geometry of the universe flat!
Dark Matter

Combined mass of all “visible” matter (i.e. emitting any kind of radiation) in the universe adds up to much less than the critical density.

Gravitational lensing shows that some clusters contain 10 times as much mass as is directly visible.
The Nature of Dark Matter

Can dark matter be composed of normal matter?

If so, then its mass would mostly come from protons and neutrons (baryons).

The density of baryons right after the “Big Bang” leaves a unique imprint in the abundances of deuterium ($^2$H) and lithium ($^7$Li).

The measured density of $^2$H and $^7$Li $\Rightarrow$ baryonic matter is only $\sim$4% of critical density.

Most dark matter must be non-baryonic!
Problems with the Classical, Decelerating Universe

The flatness problem:

The universe seems to be nearly flat.

Even a tiny deviation from perfect flatness at the time of the Big Bang should have been amplified to a huge deviation today.

⇒ Extreme fine tuning required!

The isotropy of the cosmic background:

If information can only travel through the universe at the speed of light, then the structure in the cosmic background should not be correlated over large angular scales!

⇒ Contradiction to almost perfect isotropy of the cosmic background!
The Solution: Inflation!

**Inflation** = period of sudden expansion during the very early evolution of the universe triggered by the sudden energy release from the decoupling of the strong and electroweak forces.
Measuring the “Deceleration” of the Universe …

By observing type Ia supernovae, astronomers can measure the Hubble relation at large distances:

Distance $\Rightarrow$ recession speed

Size scale of the universe $\Rightarrow$ rate of expansion

It was expected that this would measure the deceleration of the universe, but …
In fact, SN Ia measurements showed that the universe is accelerating!
The Cosmological Constant

Cosmic acceleration can be explained with the cosmological constant, $\Lambda$ (Lambda)

$\Lambda$ is a free parameter in Einstein’s fundamental equation of General Relativity; previously believed to be 0.

Energy corresponding to $\Lambda$ can account for the missing mass/energy ($E = mc^2$) needed to produce a flat space-time.

$\Rightarrow$ “dark energy”
Until ~6 billion years ago, gravity of matter was stronger than acceleration. Today, acceleration due to dark energy dominates.
If the universe was perfectly homogeneous on all scales at the time of reionization \((z = 1000)\), then the CMB should be perfectly isotropic over the sky.

Instead, it shows small-scale fluctuations.
Fluctuations in the Cosmic Microwave Background

Angular size of the CMB fluctuations allows us to probe the geometry of space-time!

CMB fluctuations have a characteristic size of 1 degree.
Analysis of the Cosmic Background Fluctuations

Analyze frequency of occurrence of fluctuations on a particular angular scale

⇒ Universe has a flat geometry