14. A History of the Universe

1. Dark Matter and Energy
2. The Microwave Background
3. The Early Universe
Looking back in time, we see signs that the expansion of the universe is accelerating, and clear evidence that the early universe was hot, dense, and *almost* perfectly smooth. The tiny variations in density we detect naturally explain the large-scale structure of the present universe. Extrapolating events even further back we come to the formation of light elements, the origin of matter itself, and finally to hints of an initial phase of violent expansion which may forever hide the events giving rise to our universe.
Expansion of the Universe

The two drawings below represent the same group of galaxies at two different points in time during the history of the universe.

Early Universe

Universe Some Time Later

1) Examine the distance between the galaxies labeled A–E in the Early Universe. Are all the galaxies the same distance from each other?

2) Describe how the universe changed in going from the Early Universe to the Universe Some Time Later.

3) Do the galaxies appear to get bigger?

4) Based on your answer to Question 3, do you think the stars within a galaxy move away from one another due to the expansion of the universe? Explain your reasoning.

5) Compare the amount that the distance between the D and C galaxies changed in comparison to the amount that the distance between the D and E galaxies changed. Which galaxy, C or E, appears to have moved farther from D?

6) If you were in the D galaxy, how would the A, B, C, and E galaxies appear to move relative to your location?

7) If you were in the D galaxy, would the A, B, C, and E galaxies all appear to move by the same amount in the time interval from the Early Universe to the Universe Some Time Later?

8) Imagine that you are still in Galaxy D. Rank the A, B, C, and E galaxies in terms of their relative speeds away from you, from fastest to slowest.

9) Now imagine that you are in the E galaxy. Rank the A, B, C, and D galaxies in terms of their relative speeds away from you, from greatest to smallest.

10) Is there a relationship between an object’s distance away from you in the universe and the speed it would appear to be moving away from you? If so, describe this relationship.

11) Would your answer to Question 10 be true in general for all locations in the universe?

12) Consider the following discussion between two students regarding the possible location of the center of the universe.

Student 1: Since all the galaxies we observe are moving away from us, we must be at the center of the universe.

Student 2: If you look at the drawing on the first page its pretty clear that all the galaxies move away from each other, so I think each galaxy must be at the center of the universe.

Do you agree or disagree with either or both of the students? Explain your reasoning.
I. DARK MATTER AND ENERGY

a. Dark Matter in Galaxy Clusters

b. Dark Energy and Expansion
The Milky Way’s Dark Halo

The Milky Way’s total mass is at least $5 \times 10^{11} M_\odot$. More than 80% of this mass is dark.
Other spiral galaxies have ‘flat’ rotation curves like the Milky Way’s. It appears that all galaxies have dark halos!
Dark Matter in Galaxy Clusters

Orbital speeds of galaxies in clusters are ~1000 km/s; about 7 times speed expected from known stellar mass.

Total cluster mass ~50 times mass in stars!
Hot Gas in Galaxy Clusters
Hot Gas in Galaxy Clusters: X-Ray Emission

Temperature: $10^8$ K (nuclei move at ~1000 km/s)

Gas mass: ~6 times visible mass in stars!

Total cluster mass ~7 times mass in stars and gas.
Gravitational fields can bend light.
Gravitational Lensing
Gravitational Lensing Observed

Mass is much more smoothly distributed than galaxies.

Total mass required agrees with previous estimates.
Dark Matter in Galaxy Clusters: Summary

Three different measurements agree:

— orbital velocities of galaxies
— hot gas detected in X-rays
— gravitational lensing effects

\[ \text{dark matter exists} \]

Cluster mass budget and structure:

85% dark matter — giant cluster halo
13% hot gas — pressure equilibrium
2% stars — associated with galaxies
Direct Proof of Dark Matter

Dark Matter in Action

Hot Gas

Dark Matter

(Lensing)

(X-Rays)
Galaxy Cluster Collision

Animation of Cluster Collision
Dark Matter

**Dark Matter** is our name for the unknown material whose gravity holds galaxies and clusters together.

- only known effect is through gravity $\Rightarrow$ dark
- has momentum in addition to gravity $\Rightarrow$ matter

Possible candidates:

- dead stars, hydrogen snowballs, interstellar trash
- unknown subatomic particle (a.k.a. ‘WIMP’)
The Expansion of the Universe: Non-Linear?

Plotting galaxy velocities, $v$, against their distances, $d$, revealed a relationship:

$$v \approx H_0 \cdot d,$$

where $H_0$ is **Hubble's "constant"**:

$$H_0 \approx 22 \text{ km/s/Mly.}$$

A break-down of this linear relationship would tell us something about the history and fate of the universe.
White Dwarf Supernovae: Standard Bombs

White-dwarf supernovae are good standard candles for testing Hubble's law at very large distances.

— very luminous; visible at large distances
— easy to recognize in distant galaxies
— well-standardized peak luminosities
White Dwarf Supernovae in Distant Galaxies

Galaxies before supernova explosions

Galaxies after supernova explosions
White Dwarf Supernovae: Results

We expected to see that the expansion was slowing down due to gravity. not . . .

Instead, the expansion of the universe is **speeding up**!
What’s Making the Universe Do That?

We Dunno!
Dark Energy

Dark Energy is our name for the anti-gravitational force which is speeding up the expansion.

— only known effect is through gravity
— very smoothly distributed in space

Possible candidates:

— ‘cosmological constant’: energy of empty space
— ‘quintessence’: variable energy density
74% DARK ENERGY
22% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.
2. THE MICROWAVE BACKGROUND

a. Signals From the Early Universe
b. Microwave Background Features
c. Formation of Cosmic Structure
Redshift and Expansion

Recall this relationship:

\[ 1 + z = \frac{d_{\text{today}}}{d_{\text{then}}} = \frac{\lambda_{\text{shift}}}{\lambda_{\text{rest}}} \]

So photon wavelengths $\lambda$ expand by the *same factor* as the universe.

We’ve observed *galaxies* out to $z \approx 7$, but the oldest *light* comes all the way from $z \approx 1000$!
Discovery of the Microwave Background

Signals from the early universe, or pigeon droppings?
Microwave Background Radiation

Very uniform microwave energy reaching us from all directions.

The observed spectrum is a perfect match to a black-body at $T = 2.73$ K.
Any opaque object (black body) with a temperature $T > 0 \text{ K}$ emits light (radiation). As the temperature goes up, this light gets brighter and bluer.
Microwave Background Radiation

Very uniform microwave energy reaching us from all directions.

The observed spectrum is a **perfect** match to a **black-body** at $T = 2.73 \text{ K}$.

*Nothing* in the present universe explains this radiation. It’s a relic of a time when the **entire universe** was a black body with a temperature $T \approx 3000 \text{ K}$. 
Origin of the Microwave Background

Back at \( z > 0 \), microwave background photons had proportionately shorter wavelengths, and the radiation’s temperature was \( T = (1+z) \times 2.73 \text{ K} \).

Before \( z \approx 10^3 \), the temperature was \( T > 3000 \text{ K} \), and atoms were *ionized*. Free electrons scatter photons, so the universe was a very good black body.

After \( z \approx 10^3 \) it was cool enough for atoms to form, the electron ‘fog’ lifted, and photons could travel freely.
The universe became transparent at an age of 0.38 Myr ($z \approx 10^3$).

IR photons ($\lambda \sim 1 \mu m$) were very common.

By the present ($z = 0$), they’ve been redshifted to microwaves ($\lambda \sim 1 \text{mm}$).

Looking in all directions, we see back to the time when the fog lifted, 13.7 Gyr ago and 13.7 Gly away.
The microwave background looks almost featureless, implying that *conditions were very similar everywhere* on the last scattering surface.
A closer look reveals (a) emission from the MW, and (b) slightly hotter and cooler spots due to our motion with respect to the microwave background.
Microwave Background Features

Subtracting the MW and the effects of our motion reveals *tiny* variations in density and temperature on the last scattering surface.
Background Fluctuations

The texture of these variations depends on properties of the universe. For example, ‘lumps’ have typical sizes of $\sim 1^\circ$; this implies that space has no overall curvature.

A ‘best bet’ model assumes
• no overall curvature
• 4% ordinary matter
• 23% dark matter
• 72% dark energy
• age of 13.7 Gyr

Good agreement with other measurements!
Charting the large-scale distribution of galaxies reveals a web-like structure interconnecting clusters and super-clusters of galaxies.
The Web From Above

Using redshifts to plot galaxy distances shows a pattern like a slice of foam.

The largest structures in this map are chains of galaxy super-clusters \( \sim 10^9 \text{ ly long!} \)
Simulated Clustering of ‘Cold’ Dark Matter

This foamy structure can be produced by gravity acting on dark matter, provided (a) the matter has no random motion, and (b) small density variations exist initially.
Formation of Cosmic Structure

Gravitational clustering of dark matter creates the basic pattern of structure for galaxies, groups, clusters, and super-clusters.

Ordinary matter, a minor ingredient, is carried along as it falls into the gravitational field of the dark matter, and cools to form galaxies and eventually stars.

The initial density variations which start the clustering process are consistent with those detected in maps of the microwave background.
THE MICROWAVE BACKGROUND: SUMMARY

1. The early universe appears to have been an almost perfectly smooth blend of matter and radiation.

2. Going back in time, we find higher temperatures and an ever-larger role for radiation compared to matter.

3. Small variations in density at early times eventually collapsed due to gravity to form cosmic structures.
3. THE EARLY UNIVERSE

a. Big Bang Nucleosynthesis
b. The Origin of Matter
c. The Universe as a Free Lunch
The universe started hot and cools as it expands.
Particle Creation and Annihilation

At high temperatures, matter and radiation can be transformed into each other, obeying \( E = mc^2 \).

Photons with \(~200,000\) times the energy of visible light make electron-positron pairs:

\[
\gamma + \gamma \leftrightarrow e^- + e^+
\]

Even more energetic photons make proton-antiproton pairs:

\[
\gamma + \gamma \leftrightarrow p + \bar{p}
\]
Fundamental Forces of Nature

At very high temperatures the forces become unified.
Big Bang Nucleosynthesis: Main Characters

The **proton** \( (p) \), a heavy, positively charged particle; the nucleus of ordinary hydrogen.

The **neutron** \( (n) \), a heavy, uncharged particle; found in the nuclei of all atoms other than ordinary hydrogen.

- Hydrogen \( (p) \)
- Deuterium \( (^2\text{H}) \)
- Hydrogen-3 \( (^3\text{H}) \)
- Light Helium \( (^3\text{He}) \)
- Helium \( (^4\text{He}) \)
- Lithium \( (^7\text{Li}) \)
Preamble

At $t < 1 \text{s}$ after the big bang, weak-force reactions kept protons ($p$) and neutrons ($n$) in balance:

\[
 n + \nu \rightleftharpoons p + e^- \quad \text{and} \quad n + e^+ \rightleftharpoons p + \bar{\nu}
\]

By $t \approx 1 \text{s}$, the universe had cooled to $T < 10^{10}\text{K}$, and these reactions ceased. The $p:n$ ratio was 6:1.

Up to $t \approx 100\text{s}$, the universe continued to cool down, while $n$ slowly decayed into $p$ (half-life is 886s).

\[
 n \rightarrow p + e^- + \bar{\nu}
\]

At this point, the $p:n$ ratio was 7:1.
Helium Production

By $t \approx 100s$, the universe had cooled to $T < 10^9K$, and deuterium ($^2H$) could survive long enough to react:

The net reaction is $2p + 2n \rightarrow {}^4\text{He}$. This reaction locked up *almost all* existing $n$ in helium ($^4\text{He}$) nuclei.
A robust prediction of the hot big bang: the universe contains 75% hydrogen and 25% helium (by mass).
A *trace* of $^2\text{H}$ is left when reactions stop at $t \approx 1000\text{s}$ ($T \approx 3 \times 10^8 \text{K}$).

Some $^3\text{He}$ is made by reactions like $d + p \rightarrow ^3\text{He}$ and $d + d \rightarrow ^3\text{He} + n$.

Some $^7\text{Li}$ is made by reactions like $^4\text{He} + ^3\text{H} \rightarrow ^7\text{Li}$.

No other stable elements can be produced.
Light Element Abundances

Abundances of $^2$H, $^3$He, and $^7$Li depend on the density of ordinary matter.

Eg, at higher densities, $^2$H is used up faster before reactions cease.

(The $^4$He abundance is fixed by the p:n ratio.)

Predicted abundances match observations if ordinary matter is 4% to 5% of the total density.
The Origin of Matter

At early times, it would have been too hot for ps and ns to survive — instead, the universe contained a ‘soup’ of quarks (q), antiquarks (\(\bar{q}\)), and other particles.

Quark-antiquark pairs were made by energetic photons:

\[
\gamma + \gamma \leftrightarrow q + \bar{q}
\]

This reaction doesn’t favor quarks or antquarks; both were made together, so there were equal amounts of matter and antimatter — unlike today!
Baryogenesis

At some stage as the universe cooled, a *slight* imbalance between $q$ and $\bar{q}$ somehow developed.

Below $T \approx 3 \times 10^{12} \text{ K}$ ($t \approx 10^{-6} \text{s}$), $p$s and $n$s (*baryons*) could form, and so could antibaryons:

$$3q \rightarrow n \text{ or } p \quad 3 \bar{q} \rightarrow \bar{n} \text{ or } \bar{p}$$

Due to the $q$ vs $\bar{q}$ imbalance, baryons had a *tiny* edge over antibaryons: a billion and one to a billion.

After all antibaryons annihilated baryons, those few extra baryons went on to form the visible universe.
Inflation

The model of the universe presented so far has several important features put in ‘by hand’:

• Cosmological principle: things are similar everywhere.
• Euclidean geometry on large scales: no curvature.
• Density fluctuations: just right to make galaxies, etc.

Inflation — the hypothesis that the universe went through a phase of extremely rapid expansion very early in its history — explains these features.
The Horizon

We are here now

Events inside here influence us

13.7 Gly
The Horizon Problem

How can A and B have similar conditions?
The Horizon Solution

A and B were in touch before inflation!

we are here now
Cosmological Principle

Every part of the visible universe was in touch before inflation.
The Curvature Solution

The universe had curvature before inflation.

After inflation, what we see looks nearly flat.
The Fluctuation Solution

Small quantum fluctuations before inflation...

are stretched to huge scales after.
When and How?

Inflation must have happened well before the other events described so far. One possible time is the ‘Grand Unification’ era at $10^{-38}$s to $10^{-36}$s.

The energy powering inflation could be released when the strong and electroweak forces separated.

Once inflation was over, this energy would be available to reheat the universe, filling it with matter and energy.

“The universe is a free lunch” — Alan Guth.
Thermal History of the Universe

The universe becomes more complex as it cools.