Introduction to Cosmology

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Early Universe
Seven Phases of Cosmic Evolution

14 billion years ago

Origin of Particles
Origin of Structure
Origin of Life
Origin of Consciousness

Katsushi Arisaka
History of Life and the Human beings

Time
10B years
1 Billion
100M
10M
1 Million
100,000
10,000
1,000
100
10
1 year
100 days
10 days
1 day
10 hours
1 hour
10 minutes
1 minute

Big Bang!
Solar System formed
First life on the Earth
Plants, Fish...
Mammals
Homo sapiens

Fossils
Written Documents
Videos, Pictures

You were born.
Jesus Christ was born.
Einstein was born.
You woke up this morning.
You saw this viewgraph.
Brief History of Universe and Life

- **Big Bang!**

- **First Galaxy formed**

- **Solar System formed**

- **First life on the Earth**

- **Plants, Fish...**

- **Homo sapiens**

- **You were born.**

- **Telescopes**

- **Fossils**
~100 Billions Stars in a Galaxy
Hubble Deep Field

~100 Billion Galaxies
Red shift up to \( \sim 10 \)
Hubble’s Law: Expansion of the Universe

Big Bang!

14 Billion Light Years

Moving Away at Speed of Light

Sun/Earth

Horizon of Universe
Expansion of Universe

Size

Size of Universe \( \propto \sqrt{\text{Time}} \)

Horizon \( \propto cT \)
Temperature of Universe

Temperature

\[
\text{Temperature} = \frac{1}{\text{Size}}
\]

2.7°K

Beginning  \hspace{2cm} Today  \hspace{2cm} Size
Relation between Temperature and Time

T: Temperature
t : time

\[ T = \frac{1.5 \times 10^{10}}{\sqrt{t(\text{sec})}}^{\circ K} \]
\[ = \frac{1.3}{\sqrt{t(\text{sec})}} \text{ MeV} \]

Temperature

130 GeV
130 MeV
1.3 MeV
130 keV

Time (sec)

10^{-10} 10^{-4} 1 100
Thermal Equilibrium

- If thermal energy is greater than twice the mass of particles, 
  \[ E > 2 \, m_c^2 \]
  Photon $\leftrightarrow$ Particle + Anti-particle

Example:

$m_e = 0.511$ MeV 
if $E > 1.022$ MeV 
$\gamma \leftrightarrow e^- + e^+$
Elementary Particles

Fermion

<table>
<thead>
<tr>
<th>Charge</th>
<th>Quarks</th>
<th>Leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>+2/3</td>
<td>u (up)</td>
<td>ν_e (electron neutrino)</td>
</tr>
<tr>
<td>-1/3</td>
<td>d (down)</td>
<td>ν_μ (muon neutrino)</td>
</tr>
<tr>
<td>0</td>
<td>c (charm)</td>
<td>ν_τ (tau neutrino)</td>
</tr>
<tr>
<td>-1</td>
<td>t (top)</td>
<td>W (W boson)</td>
</tr>
</tbody>
</table>

Boson

<table>
<thead>
<tr>
<th>Charge</th>
<th>Force Carriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>γ (photon)</td>
</tr>
<tr>
<td>0</td>
<td>g (gluon)</td>
</tr>
<tr>
<td>±1</td>
<td>Z (Z boson)</td>
</tr>
</tbody>
</table>

Three Families of Matter

+ Anti-particles
Elementary Particles and Forces

**Strong**
- Gluons (8)
- Quarks
- Mesons
- Baryons
- Nuclei

**Weak**
- Bosons (W, Z)
- Neutron decay
- Beta radioactivity
- Neutrino interactions
- Burning of the sun

**Electromagnetic**
- Photon
- Atoms
- Light
- Chemistry
- Electronics

**Gravitational**
- Graviton?
- Solar system
- Galaxies
- Black holes

$10^{-2}$ for Electromagnetic

$10^{-13}$ for Weak

$10^{-38}$ for Gravitational
Unification of Forces (1980)

The graph illustrates the relative strength of different forces (strong, electromagnetic, weak, and gravitational) as a function of temperature. At the Plank Epoch, all forces are unified.

- Strong force
- Electromagnetic force
- Weak force
- Electroweak force
- GUT force
- Gravity

Key points:
- Gravity at 100 GeV
- Temperature at 10^{15} K for 100 GeV
- Temperature at 10^{29} K for 10^{16} GeV
- Temperature at 10^{32} K for 10^{19} GeV

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Physicists’ View of Early Universe

Fiat lux

Let there be light
Physicists’ View of Early Universe

Lorentz Invariance

Local Gauge Invariance
Structure of DNA
Symmetry Breaking

Simple

Symmetry Break Down

Complex

Time
0
1B years
2
3
4
5
6
7
8
9
10
11
12
13
14

\[
\begin{align*}
\text{Z} & \quad \mu^- \\
\nu_e & \quad \gamma \\
\nu_{\mu} & \quad \nu_{\tau} \\
W^+ & \quad \nu_{\tau} \\
b & \quad \nu_e \\
d & \quad \nu_{\mu} \\
e^+ & \quad \nu_e \\
\tau^+ & \quad \nu_{\tau} \\
e^- & \quad \nu_e \\
d^+ & \quad \nu_{\mu} \\
u_e & \quad \nu_e \\
\end{align*}
\]
Everything was the same ⇔ Perfect symmetry.
- All the particles are the same as photons.
- All four forces are the same.

The Universe was 10 dimension.

Flattened

Compacitified

Space 3
Time 1

3 Strong Force
2 Weak
1 Electro-Magnetic
Cosmology
Expansion of Universe

Size

Size of Universe \( \propto \sqrt{\text{Time}} \)

Beginning

Today

Time
The Fate of the Cosmos

Low density—universe expands forever

High density—universe collapses

Big Bang

Present time

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Geometry of the Universe

Open $\Omega < 1$

Flat $\Omega = 1$

Closed $\Omega > 1$
Temperature of Universe

Temperature

Temperature = 1/Size

3,000°K
2.7°K

Beginning 300,000 years Today

Size
Time = 300,000 years, Temp. = 3000 °K

- All the electrons were bound by Hydrogen and Helium Nuclei. → **Atoms formed.**

- The Universe became transparent. Photons were released. → **Radiation decoupled.**

**Cosmic Microwave Background (CMB)**
Cosmic Microwave Background

Nuclei and free electrons

Universe opaque

Atoms

Universe transparent

14,000 Mpc

Earth

“Photosphere” at redshift of 1100
Cosmic Microwave Background (Discovered in 1964)

T = 300,000 years after the Big Bang

Temperature = 3,000°K

z = 1,100

Today: 3000°K / 1,100 = 2.7°K

Sun/Earth

Transparent

Opaque
The cosmic microwave background was discovered fortuitously in 1964, as two researchers tried to get rid of the last bit of “noise” in their radio antenna.

Instead they found that the “noise” came from all directions and at all times, and was always the same. They were detecting photons left over from the Big Bang.
Cosmological Redshift

$T = 300,000$ years
$3000^\circ K$

$T = 13.7$ B years (Today)
$3000^\circ K/1,100 = 2.7^\circ K$

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The CMB Spectrum by FIRAS

![Chart showing the CMB spectrum with wavelength on the x-axis and intensity on the y-axis. The data is marked with error bars, and a 2.725 K Blackbody line is superimposed.]
Inflation
Two Fundamental Problem of Big Bang Cosmology

- **Horizon Problem**
  - At early Universe, Size $\gg$ Horizon.
  - Why is CMB so uniform in every direction?

- **Flatness Problem**
  - $|\Omega - 1|$ grows proportional to the size of the Universe.
  - Why is $\Omega$ of today close to 1?
Expansion of Universe

Size

Time

Beginning  300k Years  Today

Horizon $\propto cT$

360°

Within 1°
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 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 $10^{15}$. 

$| \Omega - 1 | \propto \text{Size of Universe}$
Inflation in Early Universe

Size

Beginning

Today

Time

Horizon $\propto cT$

Inflation
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 flatness problem is solved as well – after the inflation the need to be exceedingly close to the critical density is much more easily met:
Universe is Flat. ⇒ Inflation
Geometry of the Universe

- **Open**: $\Omega < 1$
- **Flat**: $\Omega = 1$
- **Closed**: $\Omega > 1$
Dark Energy
Supernova as a Standard Candle
Two Types of Supernovae

(a) Type I Supernova
- Binary star system
- White dwarf
- Planetary nebula
- Accretion disk
- Red giant
- Growing white dwarf
- Detonation

(b) Type II Supernova
- Helium, carbon, Hydrogen
- Normal star fusion
- Heavy elements, Hydrogen
- Massive star imploding
- Iron core
- Core rebound
- Hydrogen
- Remnant core
- Shock wave

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When we look at the data, we see that it corresponds not to a decelerating universe, but to an accelerating one.

This acceleration cannot be explained by current theories of the universe, although we do know it is not caused by either matter or radiation.

\[ \Omega_\Lambda = 0.7 \]
The Accelerating Universe (1998)

After inflation, the expansion either...

\[ \Omega_\Lambda = 0.7 \]
Density of Our Universe

- $\Omega_{\text{Total}} = \Omega_{\Lambda} + \Omega_{\text{Matter}} = 1.0$

- Universe is Flat.  $\Rightarrow$ Inflation

- 73% is Dark Energy.  $\Rightarrow$ Accelerating
Density Fluctuations

![Graph showing density fluctuations vs scale (millions of lightyears). The graph includes data points and labels for Intergalactic hydrogen clumping, Gravitational lensing, Cluster abundance, SDSS galaxy clustering, Cosmic microwave background.]
Abundance vs. Density

$H_0 = 65 \text{ km/s/Mpc}$, $T_{\text{cmb}} = 2.73 \text{ K}$, $N_v = 3.0$, $\tau_{\text{neutron}} = 886.7 \text{ s}$

$0.03 < \Omega_{\text{Baryon}} < 0.06$
Cosmic Pyramid

Baryonic Matter

Metal

Star

Gas, Dust

Dark Matter

Dark Energy

0.01%
0.5%
5%
25%
70%
Dark Energy and Cosmology

This graph now includes the accelerating universe.

Given what we now know, the age of the universe works out to be 13.7 billion years.
Dark Matter
What is Dark Matter?

- Must be a heavy particle
  - Only weakly interacting.
  - Gravitationally attracted.

- Candidates
  - “MACHO” (Massive Compact Halo Objects) ×
    - → Baryonic Dark Matter
  - Heavy Neutrino ×
    - → Hot Dark Matter
  - “WIMP” (Weakly Interacting Massive Particle”
    - → Cold Dark Matter
Candidate of “WIMP”

- A leading candidate of WIMP is “Neutralino”
  - Least-massive Super-Symmetric Particle.

- Super-Symmetry is the symmetry between Fermion ↔ Boson

- This symmetry was broken
  - at energy around 100 GeV – 1 TeV
  - at time around $10^{-10} – 10^{-11}$ second.

- Neutralinos were decoupled.

- Started to be attracted each other gravitationally.
Formation of Structure by Dark Matter

(a) Time = 1 second

(b) Time = 1000 years

(c) Time = $10^8$ years
Formation of Structure in the Universe

Dark Matter is required!
Dark Matter is required!

ANDROMEDA GALAXY
SUSY Particles and Neutralino

Super Symmetry

Neutralino

Standard particles

SUSY particles

Spin 1/2 1 0 0 1/2 1/2

Quarks Leptons Force particles Squarks Sleptons SUSY force particles

Higgs Higgsino
Katsushi Arisaka, UCLA

KK Photon

Our 3D Space (= Brane)

Extra Dimensions

Bulk

Photon

KK Photon
Origin of Mass in Extra Dimensions

\[ E = mc^2 \implies m = \frac{E}{c^2} \]

- Mass can be generated as kinetic energy in extra dimensions.
  - Origin on mass
  - Dark matter is running in the extra dimensions

- Gravity can escape into the extra dimensions.
  - Why gravity is so small
  - Origin of dark energy
Early Universe & Unsolved Problems

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Temp. (°K)</th>
<th>Energy (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10^{-45}) sec</td>
<td>(10^{30})</td>
<td>(10^{18})</td>
</tr>
<tr>
<td>(10^{-40})</td>
<td>(10^{25})</td>
<td>(10^{15})</td>
</tr>
<tr>
<td>(10^{-35})</td>
<td>(10^{20})</td>
<td>(10^{12})</td>
</tr>
<tr>
<td>(10^{-30})</td>
<td>(10^{15})</td>
<td>(10^{9})</td>
</tr>
<tr>
<td>(10^{-25})</td>
<td>(10^{10})</td>
<td>(1 PeV)</td>
</tr>
<tr>
<td>(10^{-20})</td>
<td>(10^{5})</td>
<td>(1 TeV)</td>
</tr>
<tr>
<td>(10^{-15})</td>
<td>(10^{0})</td>
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<td>(10^{-10})</td>
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<td>(10^{-5})</td>
<td>(10^{5})</td>
<td>(1 KeV)</td>
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<tr>
<td>(1) year</td>
<td>(10^{5})</td>
<td>(1 eV)</td>
</tr>
<tr>
<td>(10^{5}) sec</td>
<td>(10^{1})</td>
<td>(10^{-3} eV)</td>
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<tr>
<td>(10^{9}) year</td>
<td>1</td>
<td>Now</td>
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The Beginning

Plank Epoch

Inflation

Grand Unification

Dark Matter

Electro-Weak Unification

Matter-Radiation Decoupling

Dark Energy