Lecture on
Cosmology

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National Center for Theoretical Sciences (NCTS)

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CONTENTS

- Modern Cosmology
- History of 20th-Century Cosmology
- Basic Questions about Expansion
- Summary
What is Cosmology?

- Evolution
  - Static?
  - Expansion?

- Structures
  - "ONE" Galaxy?
  - "\(\infty\)" Galaxies?

- Compositions

(One hundred years ago, ........)
Modern Cosmology

- 顧哲安 物理雙月刊2005年12月
  “宇宙學十大不可思議”
Thermal History of the Universe

Expansion

Decoupling

Reheating

Inflation

Structure Formation

Expansion

95% !

Accelerating!

Dark Energy?

Dark Matter?
Wrong:
The big bang was like a bomb going off at a certain location in previously empty space.

Right: It was an explosion of space itself.
Inflation (暴胀) : reset !?

- size $\uparrow$ $10^{26}$ times ($e^{60}$ times) in an exponential way
- driven by vacuum energy
- $\rho \downarrow_0$ (归零) (for particle number, energy, entropy, …)

BUT
After inflation,
- how can structures be generated?
- how can matter be generated?
Inflation (暴脹) → seeds of structures!!

generating initial perturbations (for physical quantities)

(инtrinsic) quantum fluctuations

inflation

classical fluctuations

Initial perturbations
(i.e. seeds of structures)

Forming structures later

Fine tuning: $(\delta \rho/\rho)_{early} \sim 10^{-5}$ ?)
Inflation (暴脹) → homogenous, isotropic, flat

- LSS & CMB → homog. & isotropic: similar $\rho$, $T$
  - Local region in equilibrium: OK
  - Non-causal regions: unnatural?

- CMB → flat (spatially) (not small curvature)
  - but $\frac{\rho_{\text{curvature}}}{\rho_{\text{matter}}} << 1$

- inflation
  - causal ← non-causal

Matter curves space-time.
Most of the effects of matter is to curve “time”
(i.e. metric changing with time) (very little for “space”).

\[ \begin{align*}
\frac{\rho_{\text{curvature}}}{\rho_{\text{matter}}} & \uparrow & \text{for decelerated expansion} \\
\downarrow_0 & \text{for accelerated expansion} & \text{inflation}
\end{align*} \]
Reheating (after inflation ended)

vacuum energy $\rightarrow$ matter / particles

$\Rightarrow$ **High-temperature Oven**

(cooking matter, e.g., p, n, e$^-$, γ, ν)

thermal equilibrium $\longleftrightarrow$ particle abundance

Standard Model of particle physics
$\oplus$ $\rho_{\text{CMB}}$ or $n_{\text{CMB}}$

❓ **Inflation then Reheating !! How ?**
Decoupling (退耦)

expansion $\Rightarrow$ $\rho \downarrow$ $T \downarrow$ $f_{\text{collision}} \downarrow$

- $f > H$
  - $T > T_{\text{de}}$
  - $t < t_{\text{de}}$

- $f < H$
  - $T < T_{\text{de}}$
  - $t > t_{\text{de}}$

\( T_{\text{de}} \approx 3000 \text{ K} \)
\( t_{\text{de}} \approx 380,000 \text{ years old} \)

$\Rightarrow$ relic photons: Cosmic Microwave Background (CMB)
Decoupling (退耦)

expansion ⇒ ρ \downarrow \ T \downarrow \ f_{\text{collision}} \downarrow

\begin{align*}
\text{decoupling} & \quad f > H \\
T > T_{\text{de}} & \quad t < t_{\text{de}} \\
T < T_{\text{de}} & \quad t > t_{\text{de}} \\
\text{decoupling} & \quad f < H
\end{align*}

\begin{align*}
(\frac{n_e}{n_\gamma}) & \quad T < 2m_e : \\
e^- + e^+ & \quad \longleftrightarrow \quad 2\gamma \\
\text{(cf. 10}^{-10} \text{ in reality)}
\end{align*}

\begin{align*}
(\frac{n_p}{n_\gamma}) & \quad T < 2m_p : \\
p + \bar{p} & \quad \longleftrightarrow \quad 2\gamma
\end{align*}

\begin{align*}
\text{until } T < T_{\text{de}} \sim 22 \text{ MeV} \quad \text{(then } N_p \sim \text{ const.)} & \Rightarrow \frac{n_p\bar{p}}{n_\gamma} \sim 10^{-19} \\
& \quad (\text{cf. } 10^{-10} \text{ in reality})
\end{align*}
Baryon Asymmetry (重子不對稱)

Reality: \( n_p >> n_{\bar{p}} \) \( n_p / n_\gamma \sim 10^{-10} \) now

\[ p + \bar{p} \overset{(n_p \sim n_\gamma)}{\rightarrow} 2\gamma \quad T < 2m_p: \quad p + \bar{p} \not\rightarrow 2\gamma \]

If \( n_p = n_{\bar{p}} \) initially,

\[ N_p \downarrow \quad \text{until } T < T_{de} \sim 22 \text{ MeV} \quad (\text{then } N_p \sim \text{const.}) \Rightarrow \frac{n_p \bar{p}}{n_\gamma} \sim 10^{-19} \]

So, initially, \( \frac{n_p - n_{\bar{p}}}{n_p} \sim 10^{-8} \) \( \leq \) Baryon Asymmetry

？？？（initial condition? other mechanism?）
Structure Formation vs. Thermo. 2nd Law

entropy density

Expansion $\Rightarrow$ $s \downarrow$ even if $s \uparrow$

total entropy
Dark Matter: helping structure formation

- Structure formation: $\frac{\delta \rho}{\rho}$ (gravitational instability)

- Visible matter: interaction with $\gamma \Rightarrow (\frac{\delta \rho}{\rho})_{\text{visible}}$ after decoupling, $(\frac{\delta \rho}{\rho})_{\text{visible}}$ is not created.

- Invisible matter: $(\frac{\delta \rho}{\rho})_{\text{invisible}}$ from $t << t_{\text{de}}$ (~380,000 years old)

  - Initially proposed for maintaining structures.
  - 1930 Fritz Zwicky: Coma cluster.
  - Later: galactic rotational curves, gravitational lensing, …

Creating gravitational potential which would trapping baryons.

What is Dark Matter?
Dark Energy (This is a dark age ….)

1998  Supernova Cosmology Project & High-z Supernova Search: discovery of Cosmic Acceleration!!

anti-gravity / repulsive gravity !?!

Dark Energy
e.g. Einstein’s biggest blunder: \( \Lambda \) (cosmological constant)

Other candidates:
- modified gravity
- extra dimension
- inhomogeneity
- ….

What is Dark Energy?
Anti-gravity

repulsive gravity

extra attractive gravity

Dark Energy
73%

Baryon
5%

Extra Gravity
Nonbaryonic
Dark Matter
22%

Dark Energy, Cosmic Acceleration:
Purpose? Effect?
History of 20th-Century Cosmology
One hundred years ago,

**Cosmology**

- **Evolution**
  - Static?  
  - Expansion?

- **Structures**
  - "ONE" Galaxy?

- **Compositions**
  - "∞" Galaxies?

...?
History of 20th-Century Cosmology

1916  Einstein: General Relativity (basic framework for cosmology)
1917  Einstein: cosmology constant ($\Lambda$) (for static cosmo. model)
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1917  Einstein: cosmology constant ($\Lambda$)  (for static cosmo. model)
1924  Hubble: distance of Andromeda Nebula ~ 800,000 lyrs  (outside our Milky Way galaxy)
One hundred (− 20) years ago, the concept of cosmology evolved as scientists debated whether the universe was static or expanding. The idea of an infinite number of galaxies also challenged the prevailing notions. Today, we continue to explore the compositions of the universe, questioning the very nature of the "ONE" galaxy.
1916  Einstein: General F
1917  Einstein: cosmology constant ($\Lambda$) – biggest blunder
1924  Hubble: distance of Andromeda Nebula ~ 800,000 lyrs (outside our Milky Way galaxy)
1910  Slipher (Lowell Observatory): redshift / blueshift of nebulae
1913  Andromeda: blueshift – 300 km/s
1913 – 1916  22 nebulae: redshift – 1000 km/s
1920s  Hubble: measure distance of nebulae
1929  Hubble’s expansion law: $v = Hd$ ($H$: Hubble constant)
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1916</td>
<td>Einstein: General Relativity (basic framework for cosmology)</td>
</tr>
<tr>
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</tr>
<tr>
<td></td>
<td>1913</td>
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<td></td>
<td>1913 – 1916</td>
</tr>
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1920s  Hubble: measure distance of nebulae
1929  Hubble’s expansion law: $v = H \, d$ ($H$: Hubble constant)

1927 – 1933 Lemaitre (priest @ Belgium): (prototype of Big Bang)
   “Hypothesis of Primordial Atom” (quantum)
One hundred (−20) years ago,

- **Cosmology**
  - **Evolution**
    - Static ?
    - Expansion ?
    - NOT YET (stay tuned)
  - **Structures**
    - "ONE" Galaxy ?
    - "∞" Galaxies ?
  - **Compositions**
    - ?

"ONE" Galaxy ?
"∞" Galaxies ?
NOT YET (stay tuned)
(Hot) Big Bang

**Gamow**

**Static Universe**

**Hoyle**

**Weakness**: Singularity
Beginning? Before Big Bang?
Physics of early universe?

(1950: create the name “Big Bang”)

1948 Hoyle; Bondi & Gold:
Model of static universe
One hundred (− 20) years ago,

**Cosmology**

- **Evolution**
  - Static ?
  - Expansion ?
- **Structures**
  - "ONE" Galaxy ?
  - "∞" Galaxies ?
- **Compositions**

**Issue**

**Origin and Abundance of Elements**

Not yet (stay tuned)
Issue  Origin and Abundance of Elements

1930s  Bethe & others: Sun heated by nuclear fusion

1938  Weizsacher: Stars NOT hot enough to cook up elements
      There must be a very-high-temperature “fire ball”.

1940s  Gamow, Alpher, Herman:
      model of cooking elements based on Big Bang
      (Alpher, Bethe and Gamow, Physical Review)

1940s  Alpher & Gamow: temperature of Universe ~ 5K (CMB)
      (Unfortunately, there was NO technique of detecting CMB.)
      (forgotten)
<table>
<thead>
<tr>
<th>(Hot) Big Bang</th>
<th>Static Universe</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age of Universe</strong></td>
<td>$\infty$</td>
</tr>
<tr>
<td>$1.8 \times 10^9$ years (too small)</td>
<td></td>
</tr>
<tr>
<td>$\rightarrow 1 \sim 2 \times 10^{10}$ years (Baade)</td>
<td></td>
</tr>
<tr>
<td><strong>Abundance of Elements</strong></td>
<td>(made by stars)</td>
</tr>
<tr>
<td>H: $\frac{3}{4}$, He: $\frac{1}{4}$ (heavier &lt; 1%)</td>
<td>(nonuniform distribution)</td>
</tr>
<tr>
<td>Uniform distribution</td>
<td></td>
</tr>
<tr>
<td><strong>Matter Distribution</strong></td>
<td>constant in time</td>
</tr>
<tr>
<td>The earlier, the denser.</td>
<td></td>
</tr>
<tr>
<td><strong>Temperature of Universe</strong></td>
<td>(NA)</td>
</tr>
<tr>
<td>$\sim 5K$</td>
<td></td>
</tr>
<tr>
<td>(1960s 3.5K)</td>
<td></td>
</tr>
<tr>
<td>(1990s 2.73K)</td>
<td></td>
</tr>
</tbody>
</table>

The profile of the present universe: not good enough.
How about the look/photo of the early universe?
1950s  Ryle: radio nebulae – the further, the denser

1960s (early) quasars (high redshift, even up to 3 or 4)  
-- indicating high-energy environment in the earlier time

Before mid-1960s  Static Universe: dying

1964  Arno Penzias and Robert Wilson: CMB – mercy stroke
3.5 K “noise” / microwave background (wavelength: 7.35 cm)
isotropy ; black body radiation
Winning of Big Bang

Discovery of Cosmic Background

AT&T Bell

(noise from “white insulator” ?)

Microwave Receiver

Robert Wilson

Arno Penzias

(http://map.gsfc.nasa.gov)
1964  Arno Penzias and Robert Wilson: CMB – mercy stroke
3.5 K “noise” / microwave background (wavelength: 7.35 cm)
isotropy ; black body radiation

The New York Times  May 21, 1965, Friday

Signals Imply a 'Big Bang' Universe

By WALTER SULLIVAN
Scientists at the Bell Telephone Laboratories have observed what a
group at Princeton University believes may be remnants of an
explosion that gave birth to the universe.
One hundred (−60) years ago,

**Cosmology**

- Evolution
- Structures
- Compositions

- □ Static ?
- □ "ONE" Galaxy ?
- □ "∞" Galaxies ?
- ✔ Expansion ?
- ✔ "∞" Galaxies ?

1964 Penzias & Wilson
Existence of CMB — relic photons along with expansion

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1964 Penzias & Wilson
Existence of CMB — relic photons along with expansion
CMB: so isotropic! (⇔ homogeneous density)

(issue)

How did structures form?
Where did structures come?

(solution) Looking for $\delta T/T$ ($\leftarrow \delta \rho/\rho$)
**Issue** Primeval density fluctuation $\delta \rho / \rho$

$\Rightarrow$ Temperature fluctuation $\delta T / T$ in CMB

1960s (late) $\delta T / T \sim 1/10$ ? (If yes, easy to find.)

1980s Balloon exp’t, U-2 exp’t (e.g. Smoot): no $\delta T / T$ found

Sensitivity of $\delta T / T : 10^{-4}$

Baryon dominated: $\delta T / T \sim 10^{-4}$
Dark Matter dominated: $\delta T / T$ down to $<10^{-5}$

1980s regarding the origin of the density fluctuations (seeds) models: Inflation vs. Topological Defect
History of 20th-Century Cosmology

Before COBE (1965-1990)

David Wilkinson @ Princeton
George Smoot @ Berkeley

In Proceedings of the Workshop on Particle Astrophysics: Forefront Experimental Issues, December 1988, Berkeley, California
History of 20th-Century Cosmology

Baryon dominated: $\delta T/T \sim 10^{-4}$
Dark Matter dominated: $\delta T/T$ down to $<10^{-5}$

1989/11/18 COBE launched (sensitivity: $\delta T/T < 10^{-5}$)

1990 Jan. 1st Announcement (no $\delta T/T$ discovered)
FIRAS (Mather): black body nature
DMR (Smoot): dipole

<1992 no $\delta T/T$ discovery announced (down to $10^{-5}$)
(disappointment)
(crisis of Big Bang?)

1992/4/23 (Wed.) Announcement: $\delta T/T$ discovered (l=1~20)

Supporting Big Bang!!
2006
John Mather
George Smoot

1978
Arno Penzias
Robert Wilson

Cosmology: Experimental Science
Winning of Big Bang model

1992
NASA

1965
AT&T Bell

“泛黄”宇宙太古照片 (CMB Milestones)
(edited by Prof. Ng)
The Nobel Prize in Physics 2006

"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"

John C. Mather

1/2 of the prize

USA

NASA Goddard Space Flight Center
Greenbelt, MD, USA

b. 1946

George F. Smoot

1/2 of the prize

USA

University of California
Berkeley, CA, USA

b. 1945

Titles, data and places given above refer to the time of the award.
Diffuse InfraRed Background Experiment (DIRBE)

Launched on Nov 18, 1989 (Cosmic Background Explorer)

Far InfraRed Absolute Spectrophotometer (FIRAS)

Differential Microwave Radiometer (DMR)

(edited by Prof. Ng)
Fig. 6. The first FIRAS result (Mather et al. 1990). Data had been accumulated during nine minutes in the direction of the northern galactic pole. The small squares show measurements with a conservative error estimate of 1%. The unit along the vertical axis is erg (cm s sr)$^{-1}$. The relation to SI units is 1 MJy sr$^{-1} = 2.9979 \times 10^{-7}$ erg (cm s sr)$^{-1}$. The full line is a fit to the blackbody form.
Fig. **DMR results** (Smoot et al. 1992, http://lambda.gsfc.nasa.gov/product/cobe/) in galactic coordinates (horizontally longitude from +180° to -180°, vertically latitude from +90° to -90°, centre approximately on the Milky Way centre. The data from the 53 GHz band (6 mm wavelength) showing the near uniformity of the CMB (top), the dipole (middle) and the quadrupole and higher anisotropies with the dipole subtracted (bottom). The relative sensitivities from top to bottom are 1, 100 and 100,000. The background from the Milky Way, not following a blackbody spectrum (visible as a horizontal red band in the bottom panel), has not been subtracted.
One hundred (−85) years ago,

### Cosmology

- **Evolution**
  - Static ?
  - Expansion ?
    - 1990 FIRAS (Mather)
      - Blackbody of CMB — relic photons from
        - Expansion
        - Thermal equilibrium
        - Isolated.

- **Structures**
  - "ONE" Galaxy ?
  - "∞" Galaxies ?
    - 1992 DMR (Smoot)
      - Anisotropy of CMB
      - Origin of structures / Primordial seeds

- **Compositions**
  - / (some info)
One hundred (−85) years ago,

Cosmology

Evolution

Structures

Compositions

Static ?

"ONE" Galaxy ?

 Expansion ?

 "∞" Galaxies ?

(Δρ/ρ)$_{\text{present}}$ → evolution → (Δρ/ρ)$_{\text{decouple}}$ → composition → (ΔT/T)$_{\text{decouple}}$

(some info)
COBE Discovery of $\delta T/T$

1992/04/23 (Wed.) Announcement: $\delta T/T$ discovered ($l=1\sim20$)

Supporting Big Bang !!

Hawking: “the most important discovery”

Smoot in 1992:

Seeing a dust on a skating rink
Seeing the oldest, largest structures
Cosmo-Archeologist

Smoot in “Wrinkles in Time”:

“我們在時間的組織中發現的皺紋是這永恆追尋過程中的一部份，而這個發現也是人類邁入宇宙學黃金年代的重要一步。忽然之間，一幅巨大拼圖的碎片開始合併了，暴脹理論愈形成立，而黑暗物質也呼之欲出了。我們對大爆炸理論的信念又重新點燃了，在漆黑的夜空、元素的組成和宇宙膨脹現象之外，這種萬物創始時留下的餘暈成了另一個我們所知構成今日宇宙之方法。宇宙的創造力就是它最強而有力的力量，他隨著時間創造出星球和星雲之類的結構，到最終，創造了我們。皺紋就是這創造力的核心，它能從一片均勻中創造出結構來。”
### NASA WMAP Data & Cosmological Parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
<th>+ uncertainty</th>
<th>− uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total density</td>
<td>$\Omega_m$</td>
<td>1.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Equation of state of quintessence</td>
<td>$w$</td>
<td>$-0.78$</td>
<td>95% CL</td>
<td>—</td>
</tr>
<tr>
<td>Dark energy density</td>
<td>$\Omega_{de}$</td>
<td>0.73</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Baryon density</td>
<td>$\Omega_b h^2$</td>
<td>0.0224</td>
<td>0.0009</td>
<td>0.0009</td>
</tr>
<tr>
<td>Baryon density</td>
<td>$\Omega_b$</td>
<td>0.0441</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>Baryon density (cm$^{-3}$)</td>
<td>$n_b$</td>
<td>$2.5 \times 10^{-7}$</td>
<td>0.1 $\times 10^{-7}$</td>
<td>0.1 $\times 10^{-7}$</td>
</tr>
<tr>
<td>Matter density</td>
<td>$\Omega_m h^2$</td>
<td>0.135</td>
<td>0.008</td>
<td>0.009</td>
</tr>
<tr>
<td>Matter density</td>
<td>$\Omega_m$</td>
<td>0.27</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Light neutrino density</td>
<td>$\Omega_{\nu} h^2$</td>
<td>$&lt;0.0073$</td>
<td>90% CL</td>
<td>—</td>
</tr>
<tr>
<td>CMB temperature (K)$^a$</td>
<td>$T_m$</td>
<td>2.725</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>CMB photon density (cm$^{-1})^b$</td>
<td>$n_\gamma$</td>
<td>410.4</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Baryon-to-photon ratio</td>
<td>$\eta$</td>
<td>$8.1 \times 10^{-10}$</td>
<td>0.3 $\times 10^{-10}$</td>
<td>0.2 $\times 10^{-10}$</td>
</tr>
<tr>
<td>Baryon-to-matter ratio</td>
<td>$\Omega_b/\Omega_m$</td>
<td>0.17</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Power spectrum normalization (at $k_0 = 0.05$ Mpc$^{-1})^p$</td>
<td>$A$</td>
<td>0.833</td>
<td>0.088</td>
<td>0.088</td>
</tr>
<tr>
<td>Power spectrum index (at $k_0 = 0.05$ Mpc$^{-1})^p$</td>
<td>$n_g$</td>
<td>0.93</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Tensor-to-scalar ratio (at $k_0 = 0.002$ Mpc$^{-1})^p$</td>
<td>$\sigma_8$</td>
<td>0.84</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Power spectrum index (at $k_0 = 0.05$ Mpc$^{-1})^p$</td>
<td>$\sigma_8/\sigma_{*}$</td>
<td>0.44</td>
<td>0.04</td>
<td>0.04</td>
</tr>
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<td>Power spectrum index (at $k_0 = 0.05$ Mpc$^{-1})^p$</td>
<td>$A$</td>
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<td>0.088</td>
<td>0.088</td>
</tr>
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<td>Tensor-to-scalar ratio (at $k_0 = 0.002$ Mpc$^{-1})^p$</td>
<td>$r$</td>
<td>$&lt;0.90$</td>
<td>90% CL</td>
<td>—</td>
</tr>
<tr>
<td>Redshift of decoupling</td>
<td>$z_{dec}$</td>
<td>1089</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Thickness of decoupling (FWHM)</td>
<td>$\Delta z_{dec}$</td>
<td>195</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Hubble constant</td>
<td>$h$</td>
<td>0.71</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>Age of universe (Gyr)</td>
<td>$t_0$</td>
<td>14.7</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Age at decoupling (Gyr)</td>
<td>$t_{dec}$</td>
<td>379</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Age at recombination (Mry, 95% CL)</td>
<td>$t_r$</td>
<td>150</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>Decoupling time interval (Gyr)</td>
<td>$\Delta t_{dec}$</td>
<td>118</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Redshift of matter-energy equality</td>
<td>$z_{eq}$</td>
<td>3233</td>
<td>194</td>
<td>210</td>
</tr>
<tr>
<td>Redshift of optical depth</td>
<td>$\tau$</td>
<td>0.17</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Redshift of recombination (95% CL)</td>
<td>$z_r$</td>
<td>20</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Sound horizon at decoupling ($c$)</td>
<td>$d_A$</td>
<td>0.908</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Angular size distance to decoupling (Gpc)</td>
<td>$d_A$</td>
<td>14.0</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Sound horizon at decoupling (Mpc)$^c$</td>
<td>$\ell_A$</td>
<td>201</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Sound horizon at decoupling (Mpc)$^c$</td>
<td>$r_s$</td>
<td>147</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>
Ongoing CMB Experiments

Timbie 02

Interferometer
- AMiBA
- CBI
- DASI
- VSA
- CAPMAP
- Boomerang
- Maxipol
- QUAD

Radiometer
- Bolometer
- Mauna Loa
- Chile
- South Pole
- Princeton
- Tenerife
- New Mexico
- South Pole
- South Pole

Balloon-borne bolometer
- NASA WMAP
  - launched in 6/2001
  - 1st year data 2/2003
  - 3rd year data 3/2006
  - 0.2° l<1000

AMiBA at Mauna Loa
Taiwan, Australia, USA
SPOrt aboard the International Space Station $7^\circ \ 1<20$

Large-format radiometer arrays

Large-format bolometer arrays:
South Pole Telescope
Atacama Cosmology Telescope
Polarbear

ESA Planck 2007 $0.2^\circ \ 1<1000$

NASA Inflation Probe (Beyond Einstein Program)
Winning of Big Bang model

Cosmology: Experimental Science

Cosmology → Precision Cosmology

Plus many other observations

edited by
Prof. K.-W. Ng
Basic Questions about Expansion

Scientific American, March 2005
“Misconceptions about the Big Bang”
-- Lineweaver and Davis
Expansion

Scientific American, March 2005
“Misconceptions about the Big Bang”
-- Lineweaver and Davis

(6 common errors about the expanding universe)

• What kind of explosion was the Big Bang?
• Can galaxies recede faster than light?
• Can we see galaxies receding faster than light?
• Why is there a cosmic redshift?
• How large is the observable universe?
• Do objects inside the universe expand, too?
What kind of explosion was the big bang?

Wrong:
The big bang was like a bomb going off at a certain location in previously empty space.

Right: It was an explosion of space itself.
Wrong: Of course not. Einstein’s special theory of relativity forbids that.

Right:
Sure they can. Special relativity does not apply to recession velocity.
Can we see galaxies receding faster than light?

Wrong: Of course not. Light from those galaxies never reaches us.

Right: Sure we can, because the expansion rate changes over time.

For decelerating expansion, YES.

But, ....

Accelerating expansion $\rightarrow$ HORIZON ($\ddot{a} > 0$)

We can never see the galaxies outside the HORIZON.
Wrong:
Because receding galaxies are moving through space and exhibit a Doppler shift.
(Doppler effect)

Right:
Because expanding space stretches all light waves as they propagate.
(Gravitational Redshift)
(The energy of particles is transferred to the energy of the gravitational field.)
Do objects inside the universe expand, too?

Wrong: Yes. Expansion causes the universe and everything in it to grow.

Right: No. The universe grows, but coherent objects inside it do not.
How to distinguish expansion & outgoing motion?

• How to distinguish between the expansion of the universe and the outgoing motion of particles (or galaxies)?

• Is it possible to describe the phenomenon of expansion via outgoing motion?
  (In principle, they are different and cannot be equivalent.)
  (e.g. \( v > < c \) ? Horizon ?)

• Phenomenologically, how much can we distinguish them?

• Does “expansion + outgoing motion” make sense?
  (While none of them is dominant over the other.)
  Can the observational data rule out this possibility?

Note  momentum \( \sim \frac{1}{a} \)
Summary
Thermal History of the Universe

History of the Universe

Expansion
Decoupling
Reheating
Baryon Asymmetry
Accelerating!
Structure Formation
Dark Matter?

Key:
- W, Z bosons
- photon
- quark
- meson
- gluon
- baryon
- electron
- ion
- muon
- tau
- neutrino
- star
- galaxy
- black hole
- atom
- dark matter
- dark energy

Particle Data Group, LBNL, © 2000. Supported by DOE and NSF
\( \Omega_i \equiv \rho_i / \rho_{\text{CRITICAL}} \)

\( \Omega_{\text{TOTAL}} = 1 \)

**Cosmic Pie**

- **\( \Lambda CDM \)**
- **Heavy Elements:**
  - \( \Omega = 0.0003 \)
- **Neutrinos (\( \nu \)):**
  - \( \Omega = 0.0047 \)
- **Stars:**
  - \( \Omega = 0.005 \)
- **Free H & He:**
  - \( \Omega = 0.04 \)
- **Cold Dark Matter:**
  - \( \Omega = 0.22 \)
- **Dark Energy (\( \Lambda \)):**
  - \( \Omega = 0.73 \)
The 95% of the energy in our universe is beyond our understanding!!

What we understand contributes only 5%!!
Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS

**Part 1: FERMIONS**

**Leptons** |
<table>
<thead>
<tr>
<th><strong>Flavor</strong></th>
<th><strong>Mass GeV/c²</strong></th>
<th><strong>Electric Charge</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>ν_e</td>
<td>&lt;10⁻³⁰</td>
<td>0</td>
</tr>
<tr>
<td>ν_μ</td>
<td>&lt;0.0002</td>
<td>0</td>
</tr>
<tr>
<td>ν_τ</td>
<td>&lt;0.02</td>
<td>0</td>
</tr>
<tr>
<td>e⁺</td>
<td>0.000511</td>
<td>1</td>
</tr>
<tr>
<td>μ⁺</td>
<td>0.106</td>
<td>1</td>
</tr>
<tr>
<td>τ⁺</td>
<td>1.7771</td>
<td>1</td>
</tr>
</tbody>
</table>

**Quarks** |
<table>
<thead>
<tr>
<th><strong>Flavor</strong></th>
<th><strong>Approx. Mass GeV/c²</strong></th>
<th><strong>Electric Charge</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>0.003</td>
<td>2/3</td>
</tr>
<tr>
<td>d</td>
<td>0.006</td>
<td>-1/3</td>
</tr>
<tr>
<td>c</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>s</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>t</td>
<td>175</td>
<td>2/3</td>
</tr>
<tr>
<td>b</td>
<td>4.3</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

**Properties of the Interactions**

**Gravitational** |
- Acts on: Particles experiencing: Mass-Energy
- Particles mediating: Graviton (massless, massless)
- Strength relative to electromagnetic: 10⁻³⁶ m⁻¹

**Weak** |
- Acts on: All quarks, leptons
- Particles mediating: W⁺, W⁻, Z⁰
- Flavor: 0.8
- Electric Charge: 1

**Electromagnetic** |
- Acts on: All leptons, quarks
- Particles mediating: Photon (massless, massless)
- Strength relative to electromagnetic: 10⁻²² m⁻¹

**Strong** |
- Acts on: Quarks, Gluons
- Particles mediating: Gluons (massless, massless)
- Strength relative to electromagnetic: 10⁻¹⁰ m⁻¹

**Bosons**

**Unified Electroweak** |
<table>
<thead>
<tr>
<th><strong>Name</strong></th>
<th><strong>Mass GeV/c²</strong></th>
<th><strong>Electric Charge</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>γ</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Z⁰</td>
<td>91.187</td>
<td>0</td>
</tr>
</tbody>
</table>

**Strong (color)** |
<table>
<thead>
<tr>
<th><strong>Name</strong></th>
<th><strong>Mass GeV/c²</strong></th>
<th><strong>Electric Charge</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>g</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Residual Strong Interaction**

**Properties of the Interactions**

**Fermions** |
- Matter and antimatter |
- Every particle type has a corresponding antiparticle type.

**Baryons** |
<table>
<thead>
<tr>
<th><strong>Symbol</strong></th>
<th><strong>Name</strong></th>
<th><strong>Charge</strong></th>
<th><strong>Mass</strong></th>
<th><strong>Spin</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>proton</td>
<td>1</td>
<td>938</td>
<td>1/2</td>
</tr>
<tr>
<td>n</td>
<td>neutron</td>
<td>0</td>
<td>940</td>
<td>1/2</td>
</tr>
<tr>
<td>Λ</td>
<td>lambda</td>
<td>1</td>
<td>1116</td>
<td>1/2</td>
</tr>
<tr>
<td>Ω⁻</td>
<td>omega bar</td>
<td>-1</td>
<td>1672</td>
<td>3/2</td>
</tr>
</tbody>
</table>

**Antibaryons** |
<table>
<thead>
<tr>
<th><strong>Symbol</strong></th>
<th><strong>Name</strong></th>
<th><strong>Charge</strong></th>
<th><strong>Mass</strong></th>
<th><strong>Spin</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>¯p</td>
<td>antiproton</td>
<td>-1</td>
<td>938</td>
<td>1/2</td>
</tr>
<tr>
<td>¯n</td>
<td>antineutron</td>
<td>0</td>
<td>940</td>
<td>1/2</td>
</tr>
<tr>
<td>¯Λ</td>
<td>antibarriomen</td>
<td>-1</td>
<td>1116</td>
<td>1/2</td>
</tr>
<tr>
<td>¯Ω⁻</td>
<td>antomega</td>
<td>1</td>
<td>1672</td>
<td>3/2</td>
</tr>
</tbody>
</table>

**Mesons** |
<table>
<thead>
<tr>
<th><strong>Symbol</strong></th>
<th><strong>Name</strong></th>
<th><strong>Charge</strong></th>
<th><strong>Mass</strong></th>
<th><strong>Spin</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>p⁺</td>
<td>pion plus</td>
<td>+1</td>
<td>247</td>
<td>0</td>
</tr>
<tr>
<td>K⁺</td>
<td>kaon plus</td>
<td>+1</td>
<td>493</td>
<td>0</td>
</tr>
<tr>
<td>η⁺</td>
<td>eta plus</td>
<td>+1</td>
<td>650</td>
<td>0</td>
</tr>
<tr>
<td>η₀</td>
<td>eta zero</td>
<td>0</td>
<td>527</td>
<td>0</td>
</tr>
<tr>
<td>η⁻</td>
<td>eta minus</td>
<td>-1</td>
<td>208</td>
<td>0</td>
</tr>
</tbody>
</table>

**The Particle Adventure**
Visit: Visit the Particle Adventure at: http://ParticleAdventure.org

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Great Achievement!!

BUT
### Standard Model of

#### FUNDAMENTAL PARTICLES AND INTERACTIONS

**Fermions**

<table>
<thead>
<tr>
<th>Lepton</th>
<th>Mass (GeV/c²)</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>0.000511</td>
<td>0</td>
</tr>
<tr>
<td>μ electron</td>
<td>&lt;0.0002</td>
<td>0</td>
</tr>
<tr>
<td>τ electron</td>
<td>1.7771</td>
<td>-1</td>
</tr>
</tbody>
</table>

**Quark**

<table>
<thead>
<tr>
<th>Quark</th>
<th>Mass (GeV/c²)</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>0.003</td>
<td>2/3</td>
</tr>
<tr>
<td>d</td>
<td>0.006</td>
<td>-1/3</td>
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</tr>
<tr>
<td>b</td>
<td>4.3</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

**Bosons**

<table>
<thead>
<tr>
<th>Boson</th>
<th>Mass (GeV/c²)</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>W⁺</td>
<td>80.4</td>
<td>+1</td>
</tr>
<tr>
<td>W⁻</td>
<td>80.4</td>
<td>-1</td>
</tr>
<tr>
<td>Z⁰</td>
<td>91.187</td>
<td>0</td>
</tr>
</tbody>
</table>

**Structure within the Atom**

- **Nucleus** (Size = 10⁻¹⁵ m)
- **Electron** (Size = 10⁻¹⁸ m)

#### Properties of the Interaction

<table>
<thead>
<tr>
<th>Force</th>
<th>Short Range</th>
<th>Long Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weak</strong></td>
<td>γ, Z⁰</td>
<td>Gluon</td>
</tr>
<tr>
<td><strong>Strong</strong></td>
<td>Quarks, Gluons</td>
<td>Hadrons</td>
</tr>
<tr>
<td><strong>Electromagnetic</strong></td>
<td>Quarks</td>
<td>Photons</td>
</tr>
</tbody>
</table>

#### Quarks Confined in Mesons and Baryons

Mesons and baryons are composite particles consisting of quarks. There are 6 quark flavors and 6 antiquark flavors, allowing for the formation of mesons and baryons.

### Matter and Antimatter

Matter and antimatter are defined by their antiparticle type, denoted by a bar over the particle symbol (e.g., $\bar{e}$). The charge is opposite in sign. Quarks and antiquarks have identical mass but opposite charges.

#### Figures

- `n→p+e⁻+ν_e`
- `e⁻+p→B^0+\bar{B}^0`
- `p+p→Z⁰+assorted hadrons`
- `γ or Z→hadrons`

---

This document is a summary of the current knowledge in Particle Physics. It includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is not included in this list because it is one of the fundamental interactions even though part of the "Standard Model."
Known? Unknown!
5% 95%

知之為知之，不知為不知，是知也。

— 論語為政篇
— By Confucius

(Analects of Confucius)
Known?  Unknown!

Great Puzzles

New Revolution!!