# Lecture on

# Cosmology

*Je-An Gu*（顧哲安）

National Center for Theoretical Sciences (NCTS)

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- Modern Cosmology
- History of $20^{th}$-Century Cosmology
- Basic Questions about Expansion
- Summary

# What is Cosmology ?

## Cosmology

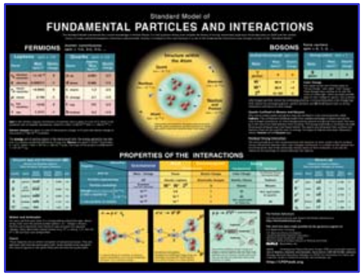
**Evolution**

- Static ?
- Expansion ?

**Structures**

- "ONE" Galaxy ?
- " ∞ " Galaxies ?

**Compositions**

- 

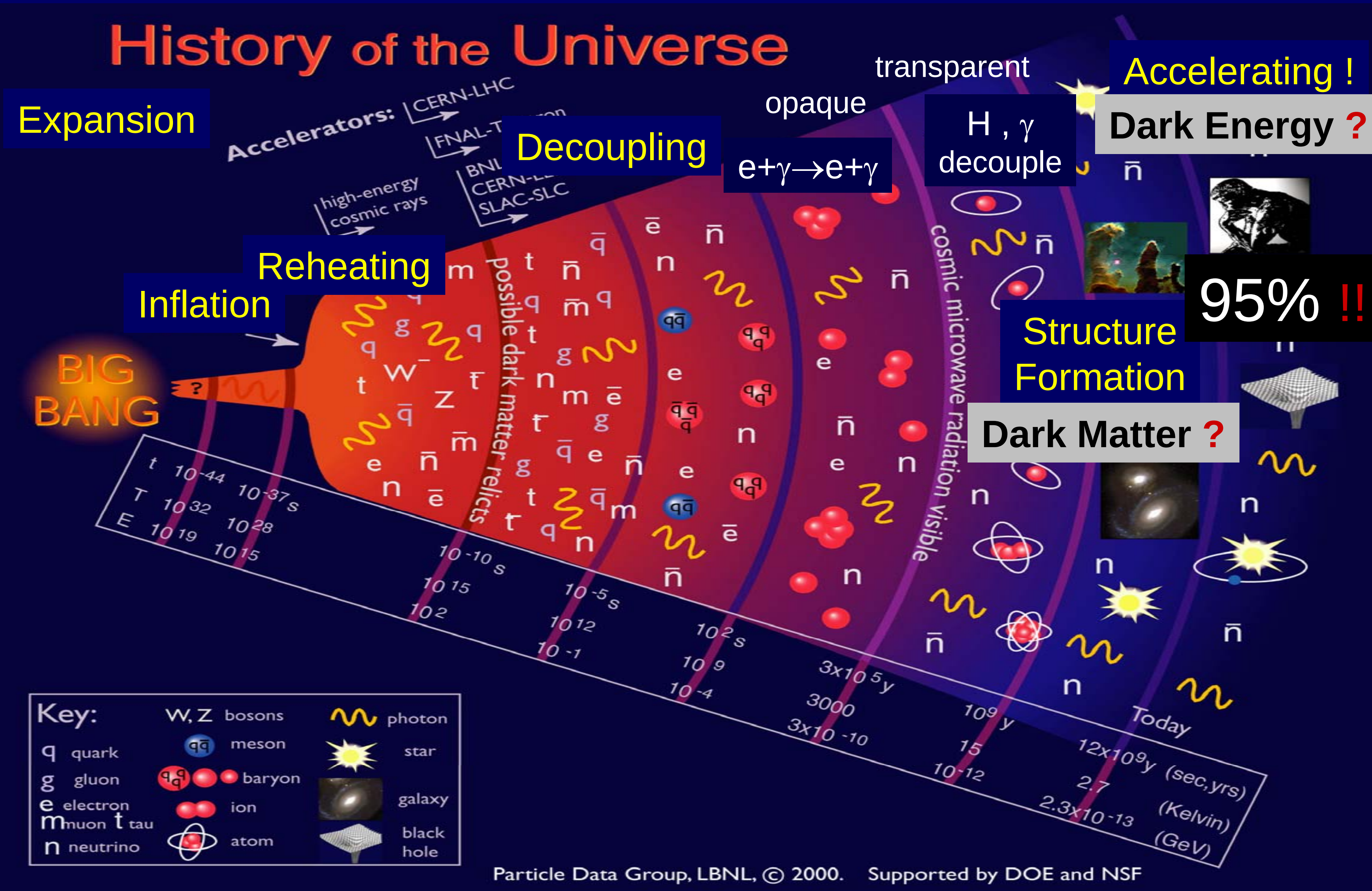
?
- 
?

(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

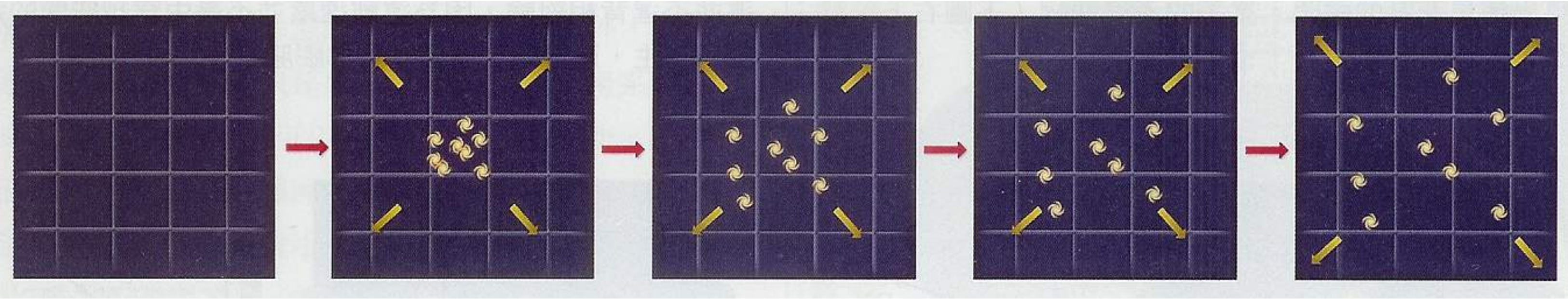


# What kind of explosion was the big bang ?

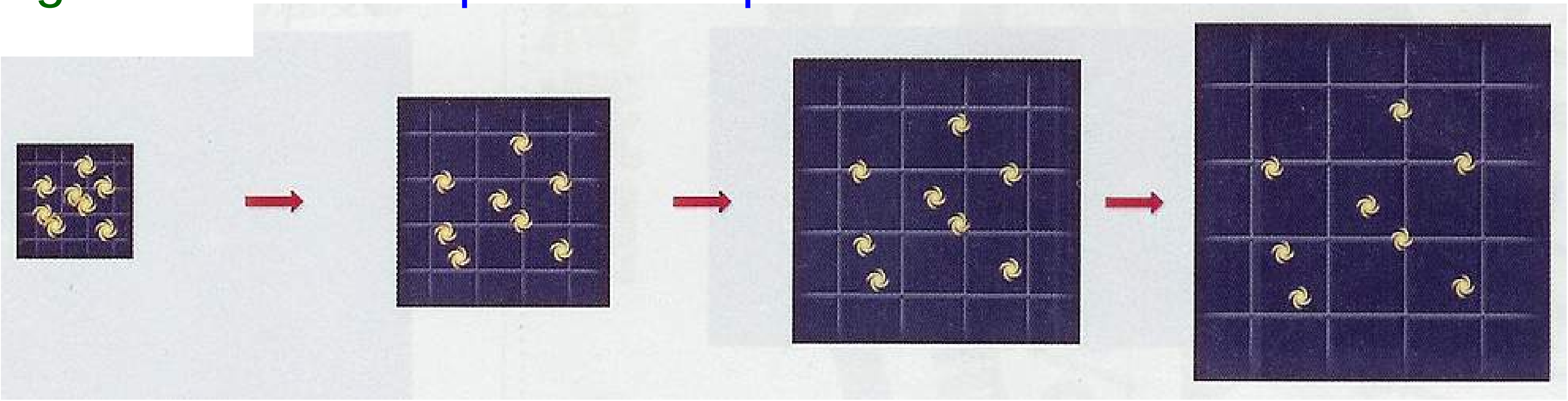
Lineweaver and Davis, Scientific American, March 2005
"*Misconceptions about the Big Bang*"

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.



# Inflation（暴脹）： reset !?

- size ⤴ $10^{26}$ times ($e^{60}$ times) in an exponential way
- driven by vacuum energy
- $\rho$ ⤵ 0 (歸零) (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)

本來無一物, 何處惹塵埃 ?

(intrinsic) 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 ρ , T

Local region in equilibrium: OK | Non-causal regions: unnatural ?

causal ←inflation→ non-causal

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

i.e. "curvature in space" << "curvature in time"

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

$\frac{\rho_{curvature}}{\rho_{matter}}$ ↗ for decelerated expansion

↘ 0 for accelerated expansion ← inflation

# **Reheating** (after inflation ended)

vacuum energy $\rightarrow$ matter / particles

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

(cooking matter, e.g., p, n, $e^-$, $\gamma$, $\nu$)

thermal equilibrium $\longleftrightarrow$ particle abundance

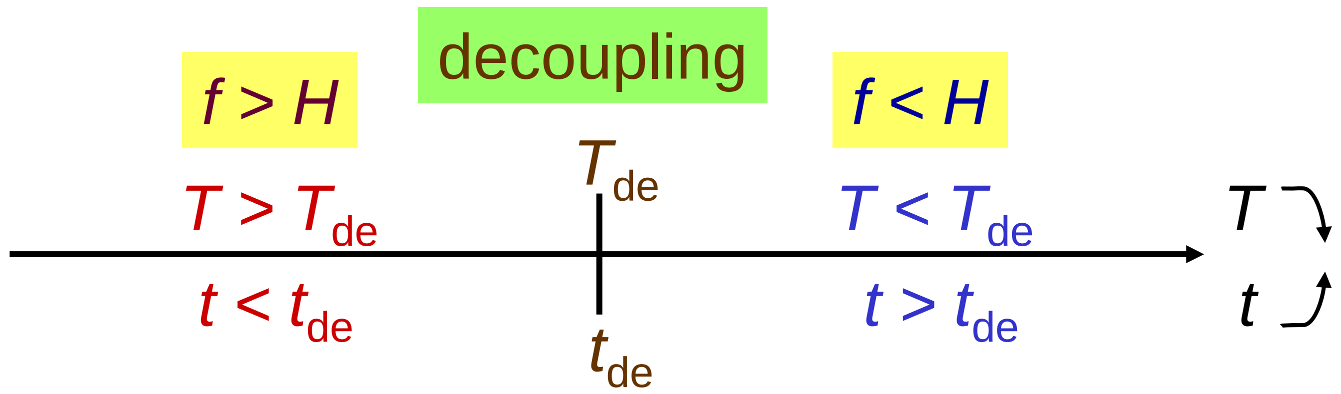
$\uparrow$

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

? **Inflation** then **Reheating !!** **How ?**

# Decoupling（退耦）

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




(example) $e^- + \gamma \longleftrightarrow e^- + \gamma$ : $T_{\text{de}} \sim 3000$ K

($t_{\text{de}} \sim$ 380,000 years old)

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

# Decoupling（退耦）

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

**decoupling**

| $f > H$ | $T_{de}$ | $f < H$ | |
|---|---|---|---|
| $T > T_{de}$ | | $T < T_{de}$ | $T \searrow$ |
| $t < t_{de}$ | $t_{de}$ | $t > t_{de}$ | $t \nearrow$ |

$e^- + e^+ \xleftrightarrow{(n_e \sim n_\gamma)} 2\gamma$  $T < 2m_e$ : $e^- + e^+ \longrightarrow 2\gamma$, $e^- + e^+ \not\longleftarrow 2\gamma$  $N_e \searrow$

$p + \bar{p} \xleftrightarrow{(n_p \sim n_\gamma)} 2\gamma$  $T < 2m_p$ : $p + \bar{p} \longrightarrow 2\gamma$, $p + \bar{p} \not\longleftarrow 2\gamma$  $N_p \searrow$

$N_p \searrow$ until $T < T_{de} \sim 22$ MeV (then $N_p \sim$ const.) $\Rightarrow \dfrac{n_{p,\bar{p}}}{n_\gamma} \sim 10^{-19}$

(cf. $10^{-10}$ in reality)

# Baryon Asymmetry（重子不對稱）

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

$p + \bar{p} \xleftrightarrow{(n_p \sim n_\gamma)} 2\gamma$ T < $2m_p$ : $p + \bar{p} \longrightarrow 2\gamma$, $p + \bar{p} \not\longleftarrow 2\gamma$ $N_p$ ⤵

If $n_p = n_{\bar{p}}$ initially,

$N_p$ ⤵ until $T < T_{de} \sim 22$ MeV (then $N_p \sim$ const.) $\Rightarrow \dfrac{n_{p,\bar{p}}}{n_\gamma} \sim 10^{-19}$

So, initially, $\dfrac{n_p - n_{\bar{p}}}{n_p} \sim 10^{-8}$ $\Leftarrow$ **Baryon Asymmetry**

? **How ?** **( initial condition? other mechanism? )**

# Structure Formation vs. Thermo. 2nd Law

s ⤵

entropy density

S ⤴

total entropy

**Expansion** ⇒ s ⤵ even if S ⤴

# Dark Matter : helping structure formation

- Structure formation : $\delta\rho/\rho$ ⤴ (gravitational instability)
- Visible matter: interaction with $\gamma$ $\Rightarrow$ $(\delta\rho/\rho)_{visible}$ ⤴ **X**

  after decoupling, $(\delta\rho/\rho)_{visible}$ ⤴
- Invisible matter: $(\delta\rho/\rho)_{invisible}$ ⤴ from $t << t_{de}$ (~ 380,000 years old)

**Dark Matter** Creating gravitational potential which would trapping baryons.

(before $t_{de}$) (after $t_{de}$)

■ initially proposed for **maintaining structures**.

➢ 1930 Fritz Zwicky : Coma cluster.

➢ Later : galactic rotational curves, gravitational lensing, …

? **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: $\Lambda$

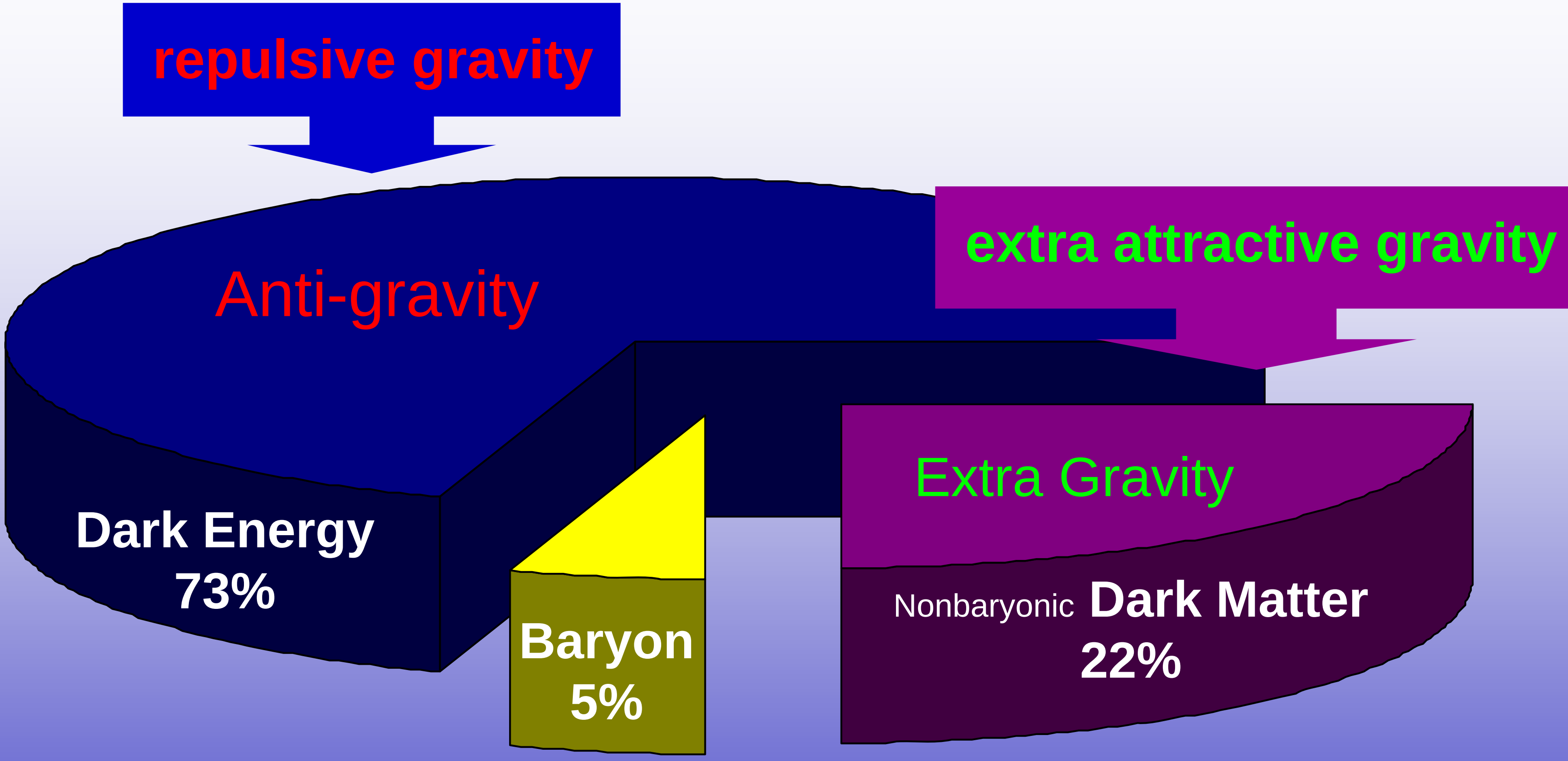
(cosmological constant)

Other candidates:

- modified gravity
- extra dimension
- inhomogeneity

….

? **What is Dark Energy ?**




? **Dark Energy , Cosmic Acceleration :**
**Purpose ? Effect ?**

# History of 20th-Century Cosmology

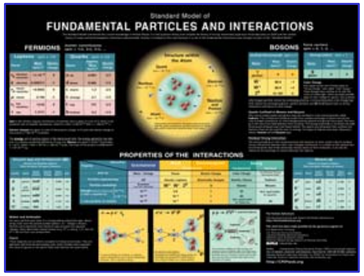
# One hundred years ago,

## Cosmology

**Evolution** | **Structures** | **Compositions**

- ☐ Static ?
- ☐ Expansion ?

- ☐ "ONE" Galaxy ?
- ☐ " ∞ " Galaxies ?

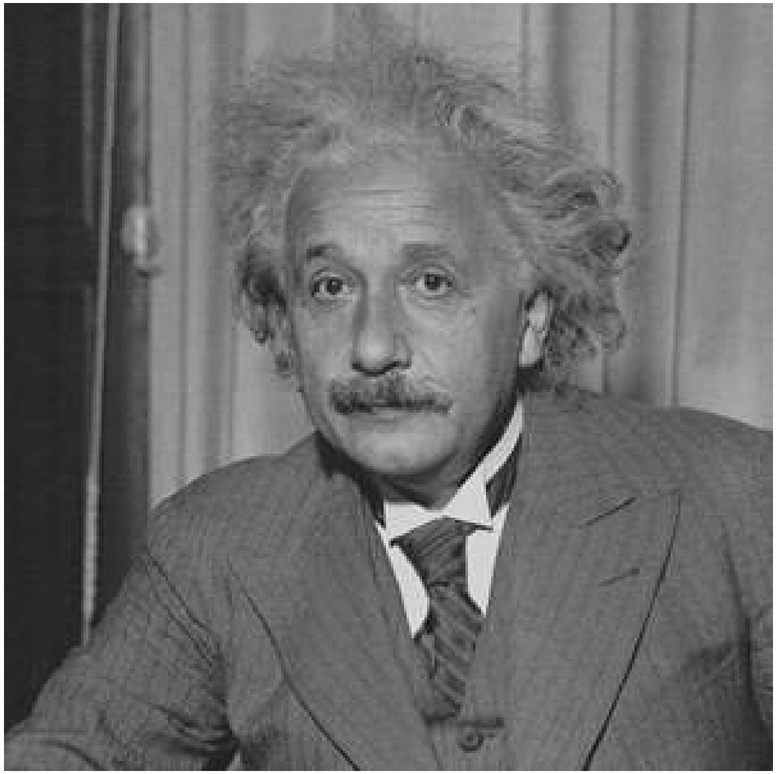
- ☐ 

?
- ☐  ?

# History of 20th-Century Cosmology

1916  Einstein: General Relativity (basic framework for cosmology)

1917  Einstein: cosmology constant ($\Lambda$) (for static cosmo. model)



Albert Einstein

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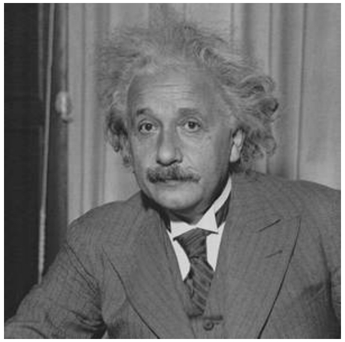


Albert Einstein

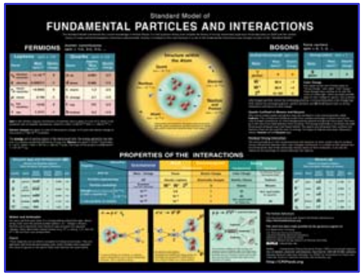
1924 Hubble: distance of Andromeda Nebula ~ 800,000 lyrs (galaxy)

(outside our Milky Way galaxy)

Edwin Hubble

# One hundred (– 20) years ago,

## Cosmology

| Evolution | Structures | Compositions |
|---|---|---|
| ☐ Static ? | ☐ "ONE" Galaxy ? | ☐  ? |
| ☐ Expansion ? | ☑ " ∞ " Galaxies ? | ☐  ? |

# History of 20th-Century Cosmology

1916 Einstein: General R

1917 Einstein: cosmolog

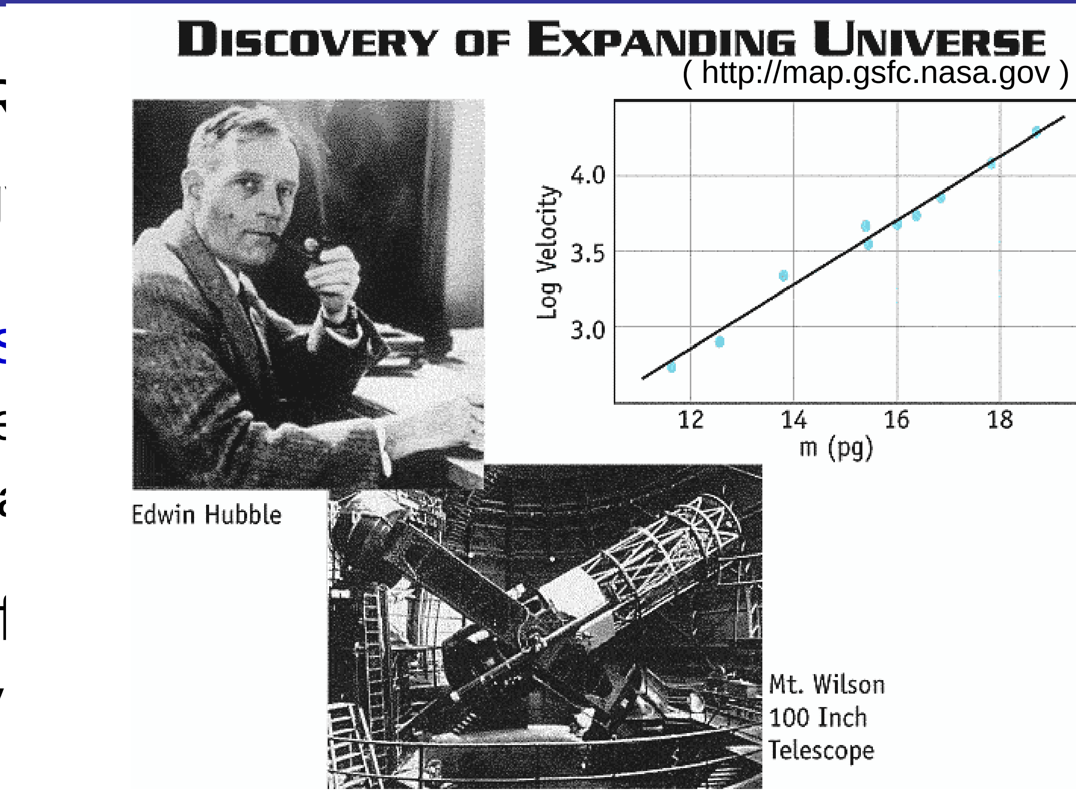
1910 Slipher (Lowell Obs

1913 Andromeda: blue

1913 – 1916 22 nebula

1924 Hubble: distance of

(outside our Milky Way




1920s Hubble: measure distance of nebulae

1929 Hubble's expansion law: $v = H d$ ($H$: Hubble constant)

# History of 20th-Century Cosmology

1916 Einstein: General Relativity (basic framework for cosmology)

1917 Einstein: cosmology constant ($\Lambda$) – biggest blunder

1910 Slipher (Lowell Observatory): redshift / blueshift of nebulae

1913 Andromeda: blueshift – 300 km/s

1913 – 1916 22 nebulae: redshift – 1000 km/s

1924 Hubble: distance of Andromeda Nebula ~ 800,000 lyrs (galaxy)

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(galaxy)

(outside our Milky Way galaxy)

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1927 – 1933 Lemaitre (priest @ Belgium): (prototype of Big Bang)

"Hypothesis of Primordial Atom" (quantum)

# One hundred (– 20) years ago,

## Cosmology

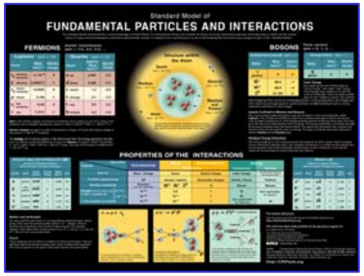
**Evolution** | **Structures** | **Compositions**

☐ Static ?

☑ Expansion ?

☐ "ONE" Galaxy ?

☑ " ∞ " Galaxies ?

☐ 

?

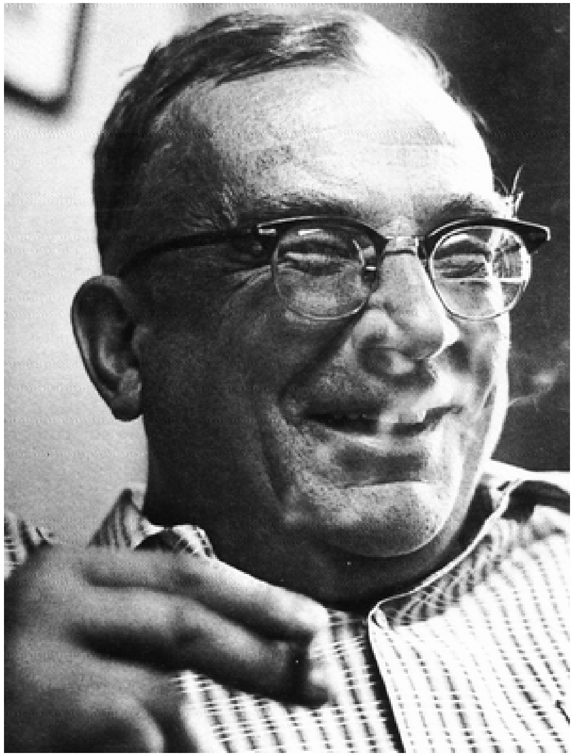
☐  ?

NOT YET (stay tuned)

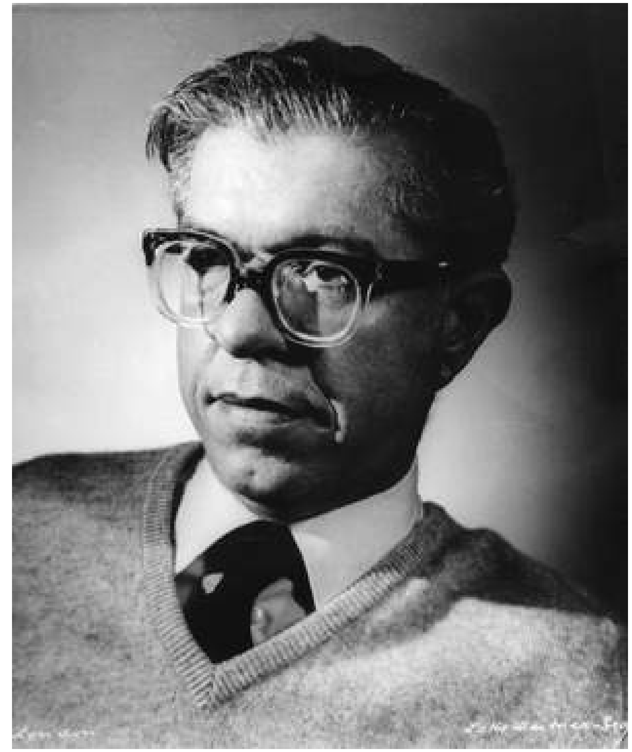
## (Hot) Big Bang

## Static Universe

Gamow



Hoyle



(1950: create the name "Big Bang")

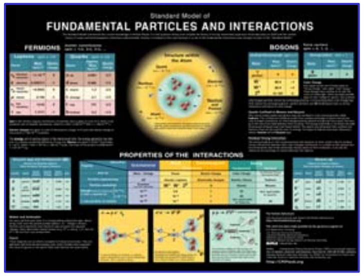
Weakness:

Singularity
Beginning? Before Big Bang?
Physics of early universe?

1948 Hoyle ; Bondi & Gold:
Model of static universe

# One hundred (– 20) years ago,

## Cosmology

| Evolution | Structures | Compositions |
|---|---|---|
| ☐ Static ? | ☐ "ONE" Galaxy ? | ☐   ? |
| √ Expansion ? | √ " ∞ " Galaxies ? | ☐  ? |

NOT YET (stay tuned)

**Issue**

**Origin and Abundance of Elements**

# History of 20th-Century Cosmology

## 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)

| | (Hot) Big Bang | Static Universe |
|---|---|---|
| Age of Universe | $1.8\times10^9$ years (too small)<br>→ $1\sim2\times10^{10}$ years (Baade) | ∞ |
| Abundance of Elements | H: ¾ , He: ¼ (heavier < 1%)<br>Uniform distribution | (made by stars)<br>(nonuniform distribution) |
| Matter Distribution | The earlier, the denser. | constant in time |
| Temperature of Universe | ~ 5K<br>(1960s 3.5K)<br>(1990s 2.73K) | (NA) |

The profile of the present universe: not good enough.
How about the look/photo of the early universe?

# Winning of Big Bang

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

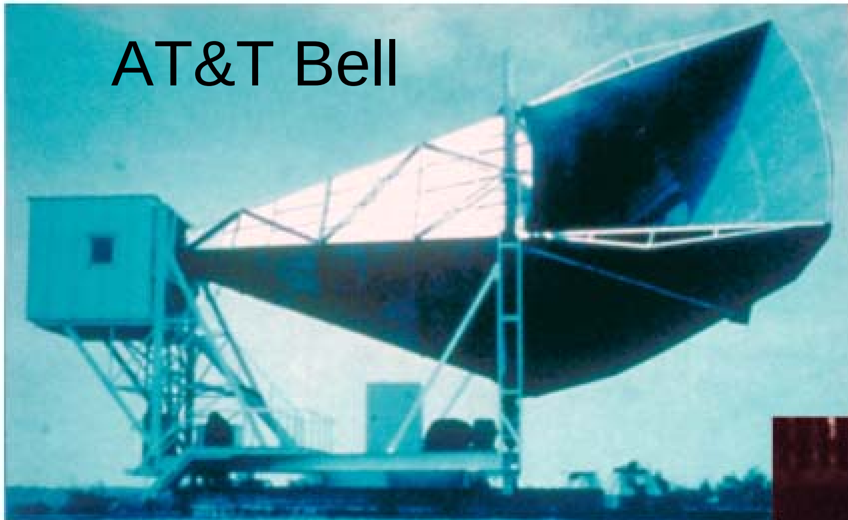
1964  Arno Penzias and Robert Wilson: CMB – mercy stroke

3.5 K “noise” / microwave background (wavelength: 7.35 cm)

isotropy ; black body radiation

# Winning of Big Bang

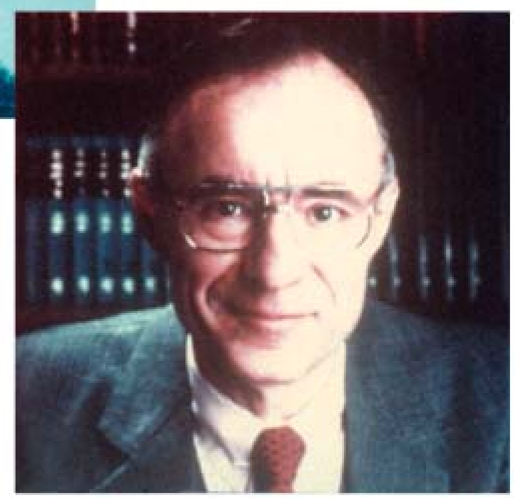
## DISCOVERY OF COSMIC BACKGROUND




(noise from “white insulator” ?)

Microwave Receiver

Robert Wilson



Arno Penzias

MAP990045

( http://map.gsfc.nasa.gov )

# Winning of Big Bang

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*

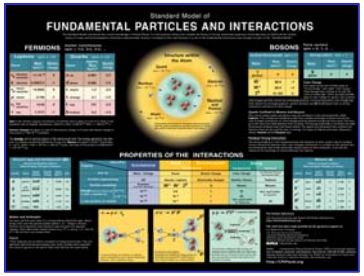
**Signals Imply a 'Big Bang' Universe**

***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 ? | ☐  ? |
| ☑ Expansion ? | ☑ " ∞ " Galaxies ? | ☐  ? |



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

# “泛黃” 宇宙太古照片

1965 AT&T Bell Penzias and Wilson

1978
Arno Penzias
Robert Wilson

Winning of Big Bang model

CMB : so isotropic ! ( ⇔ homogeneous density )

(issue)

How did structures form ?

Where did structures come ?

(solution) Looking for $\delta T/T$ ($\leftarrow \delta\rho/\rho$)

# History of 20th-Century Cosmology

**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 $<10^{-5}$

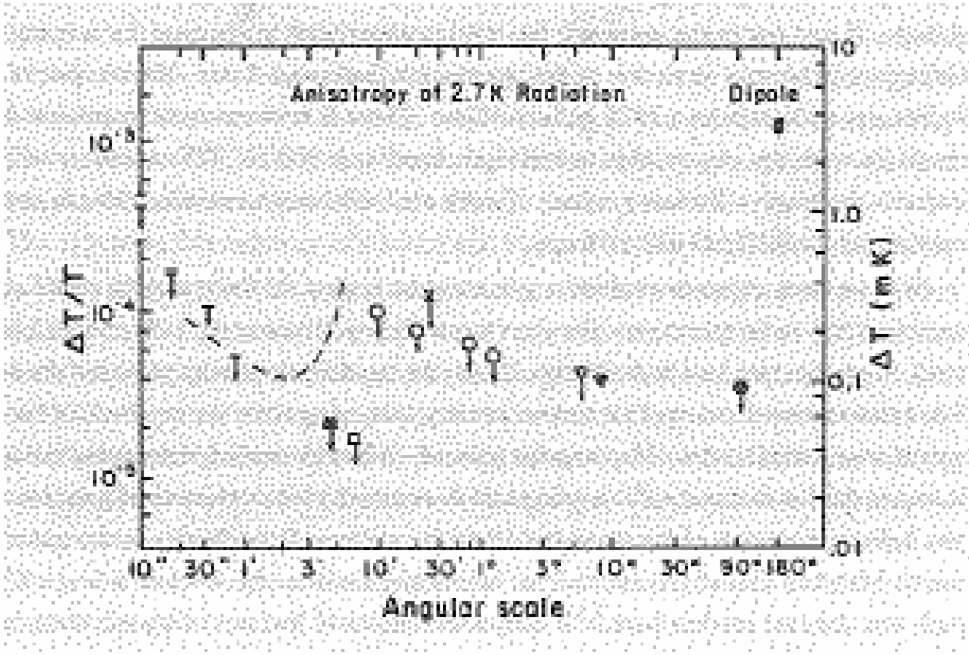
1980s regarding the origin of the density fluctuations (seeds)

models: Inflation vs. Topological Defect

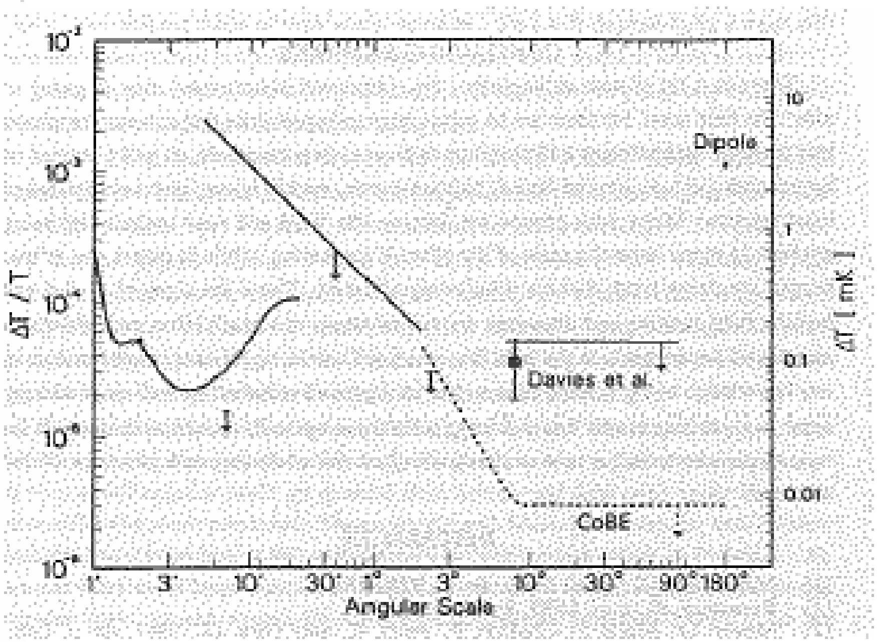
# History of 20th-Century Cosmology

(provided by Prof. K.W. Ng)

## 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)

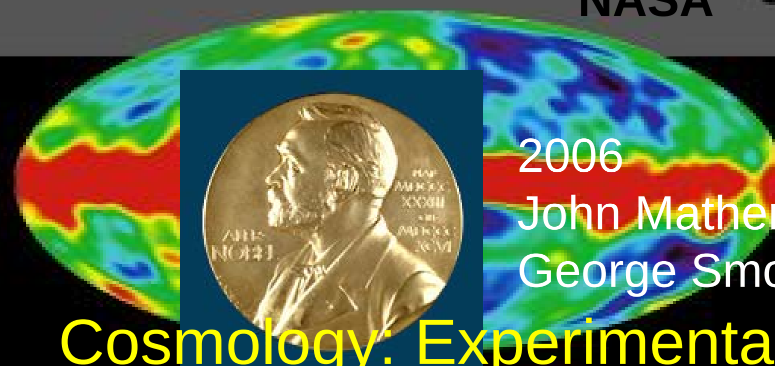
Supporting Big Bang !!

# “泛黃”宇宙太古照片 (CMB Milestones)

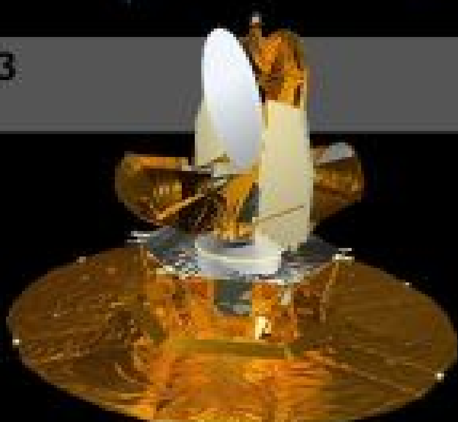
(edited by Prof. Ng)

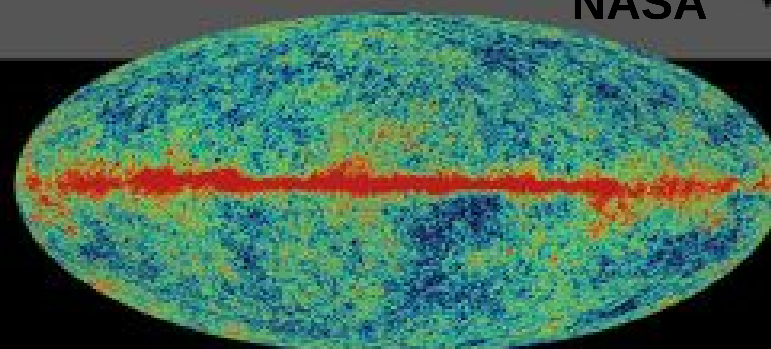
1965 AT&T Bell Penzias and Wilson


1992 NASA COBE




2003 NASA WMAP





(from: Nobelprize.org)

# The Nobel Prize in Physics 2006

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

Photo: NASA

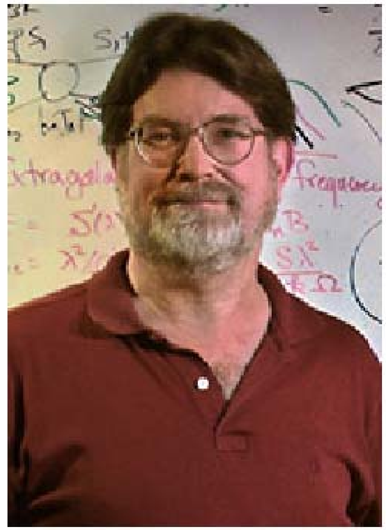


Photo: R. Kaltschmidt/LBNL

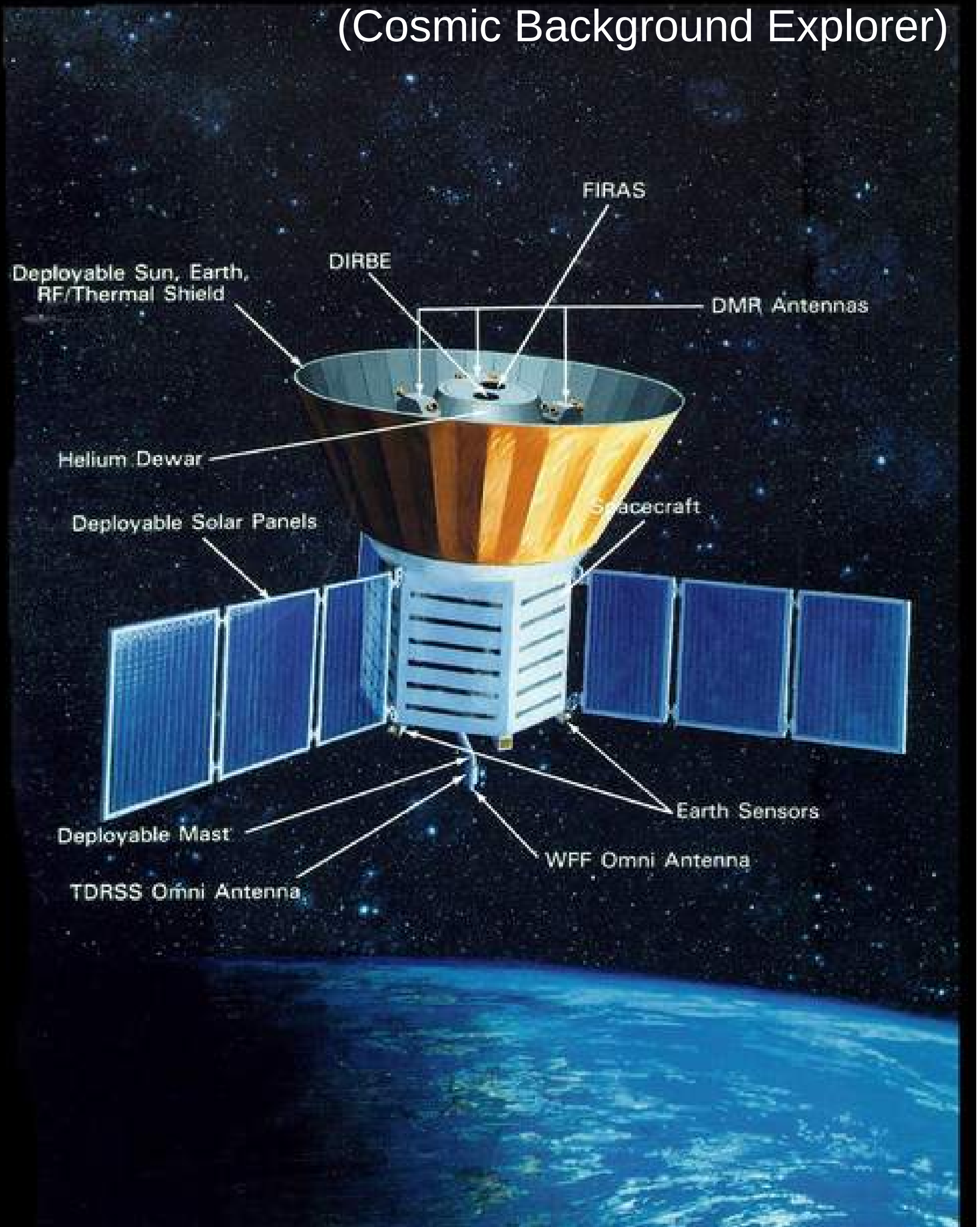
| John C. Mather | George F. Smoot |
|---|---|
| 1/2 of the prize | 1/2 of the prize |
| USA | USA |
| NASA Goddard Space Flight Center Greenbelt, MD, USA | University of California Berkeley, CA, USA |
| b. 1946 | b. 1945 |

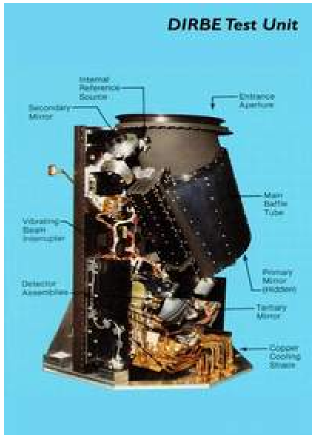
Titles, data and places given above refer to the time of the award.

(edited by Prof. Ng)

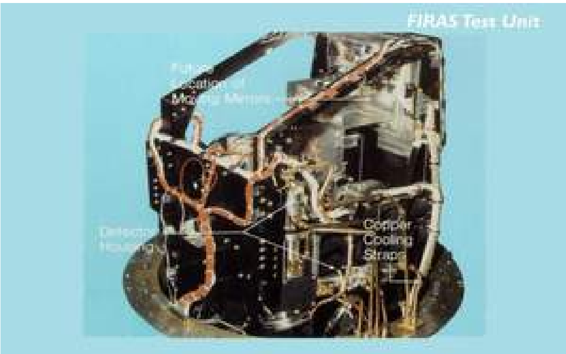
# The COBE Satellite

(Cosmic Background Explorer)

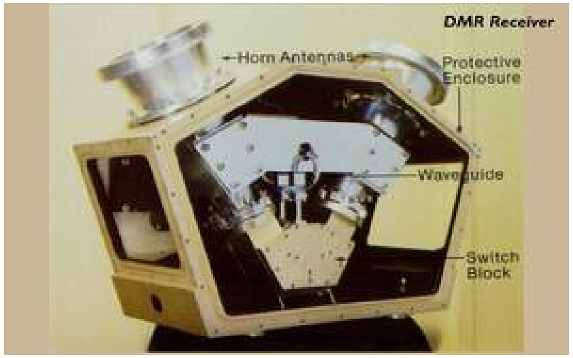



Diffuse InfraRed Background Experiment (DIRBE)

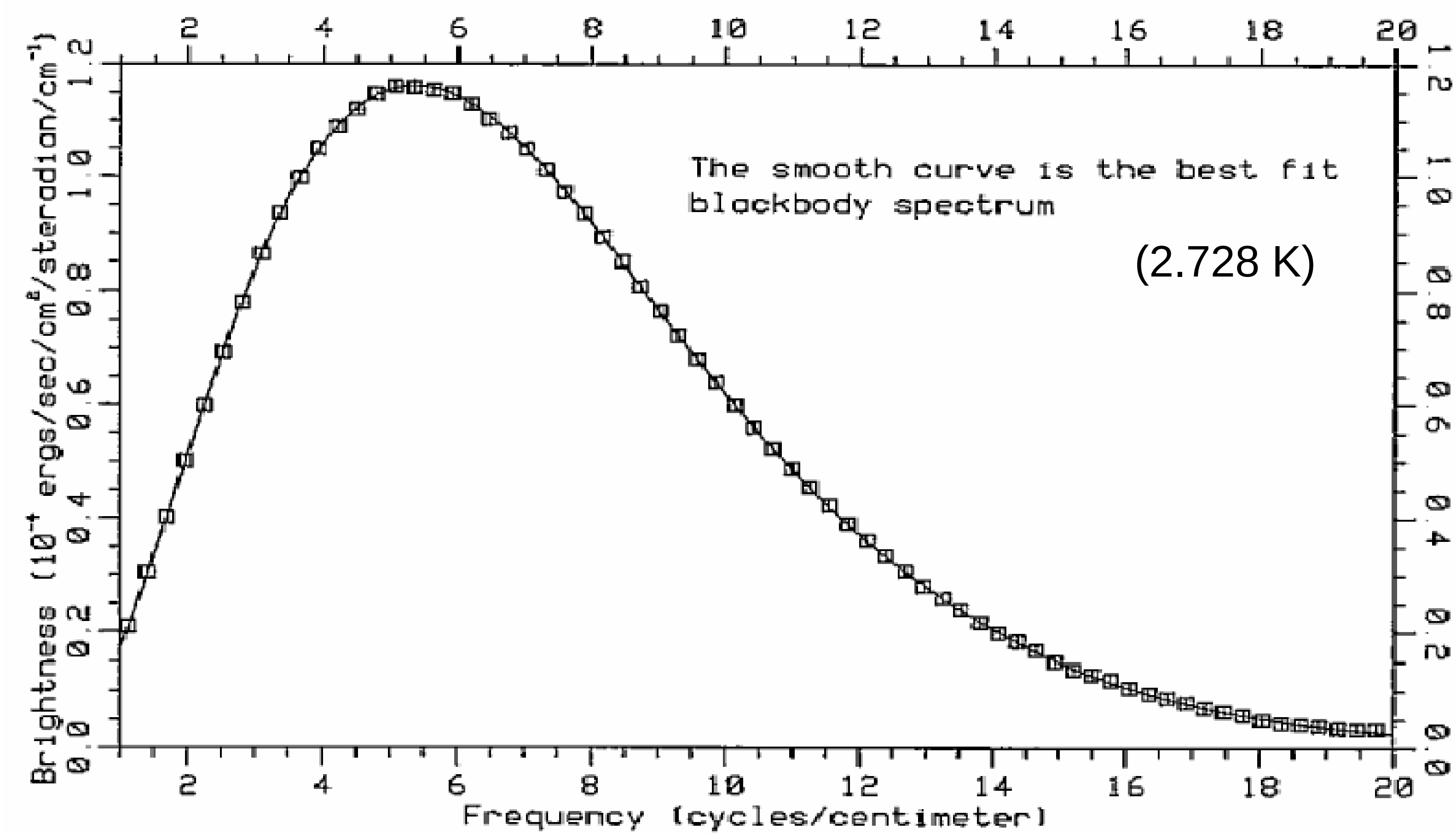



Far InfraRed Absolute Spectrophotometer (FIRAS)




(DMR)

Differential Microwave Radiometer




( wavelength: 0.05 cm – 1 cm )

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 $^{-1}$ = 2.9979.10$^{-7}$ erg (cm s sr) $^{-1}$. The full line is a fit to the blackbody form.

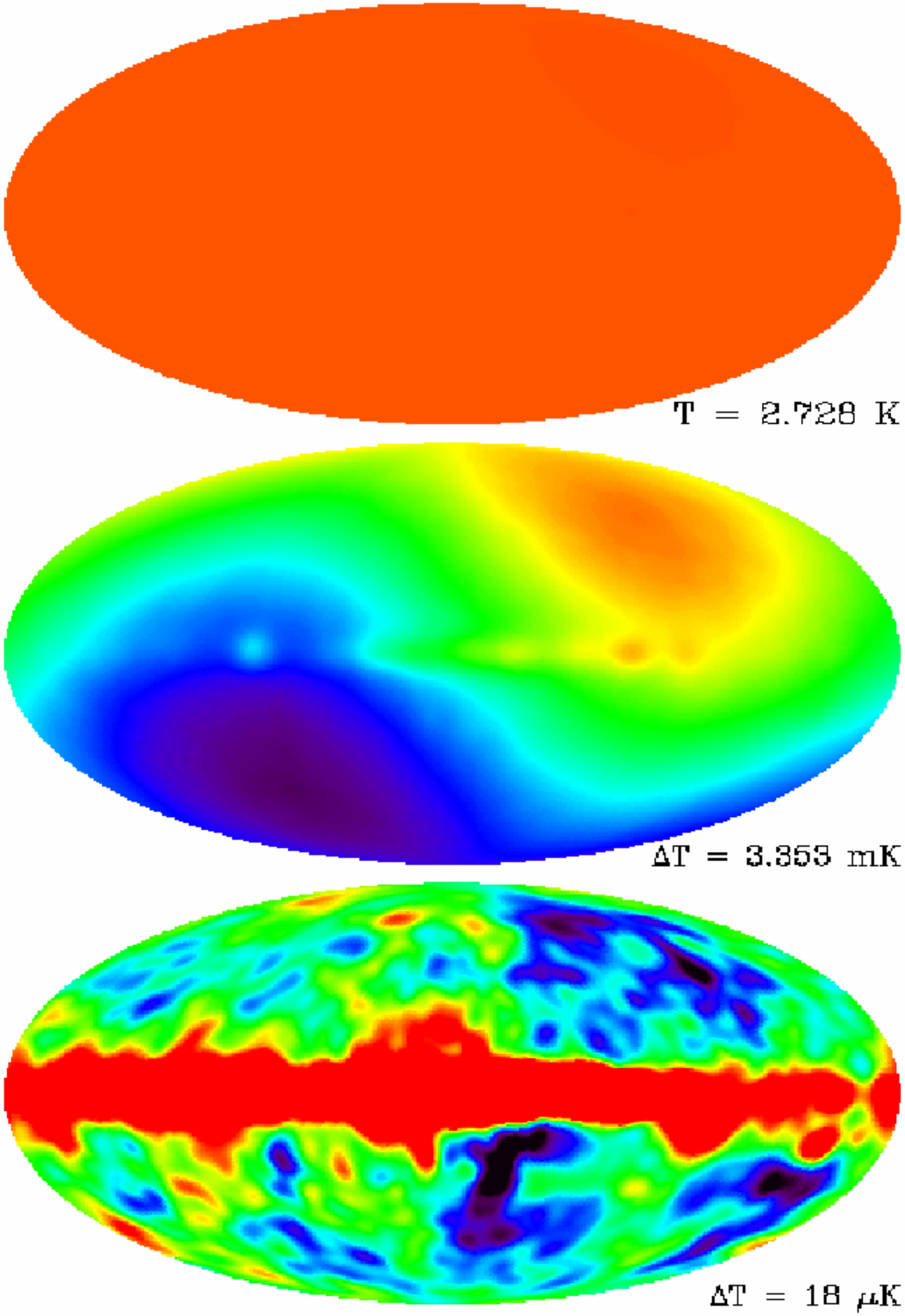
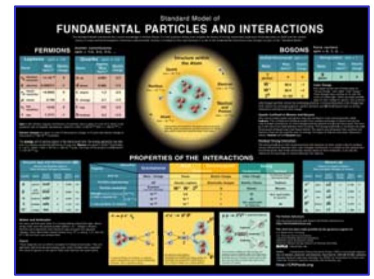
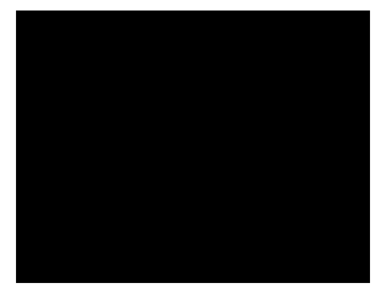



Fig. **DMR results** (**Smoot** et al. **1992**, http://lambda.gsfc.nasa.gov/product/cobe/ ) in galactic coordinates (horizontally longitude from + 180° to -180°, vertically latitude from +90° to -90°, centre approximately on the Milky Way centre. The data from the 53 GHz band (6 mm wavelength) showing 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 | Structures | Compositions |
|---|---|---|
| ☐ Static ? | ☐ "ONE" Galaxy ? | ☐  ? |
| ☑ Expansion ? | ☑ " ∞ " Galaxies ? | ☐  ? |



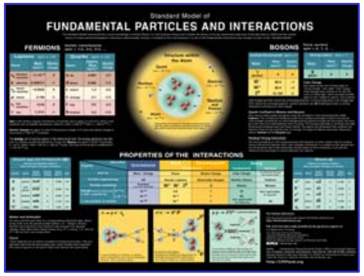
1990 FIRAS (Mather)
Blackbody of **CMB** —
relic photons from
- Expansion ;
- Thermal equilibrium ;
- Isolated .

1992 DMR (Smoot)
Anisotropy of **CMB**
↓
Origin of **structures** /
Primordial **seeds**

(some info)

# One hundred (– 85) years ago,

## Cosmology

| **Evolution** | **Structures** | **Compositions** |
|---|---|---|
| ☐ Static ? | ☐ "ONE" Galaxy ? | ☐  ? |
| ☑ Expansion ? | ☑ " ∞ " Galaxies ? | ☑ (dotted check)  ? |



(some info)

evolution — composition

$(\Delta\rho/\rho)_{present} \leftarrow (\Delta\rho/\rho)_{decouple} \leftarrow (\Delta T/T)_{decouple}$

# COBE Discovery of $\delta T/T$

1992/04/23 (Wed.) Announcement: $\delta T/T$ discovered (l=1~20)

Supporting Big Bang !!

Hawking: “the most important discovery”

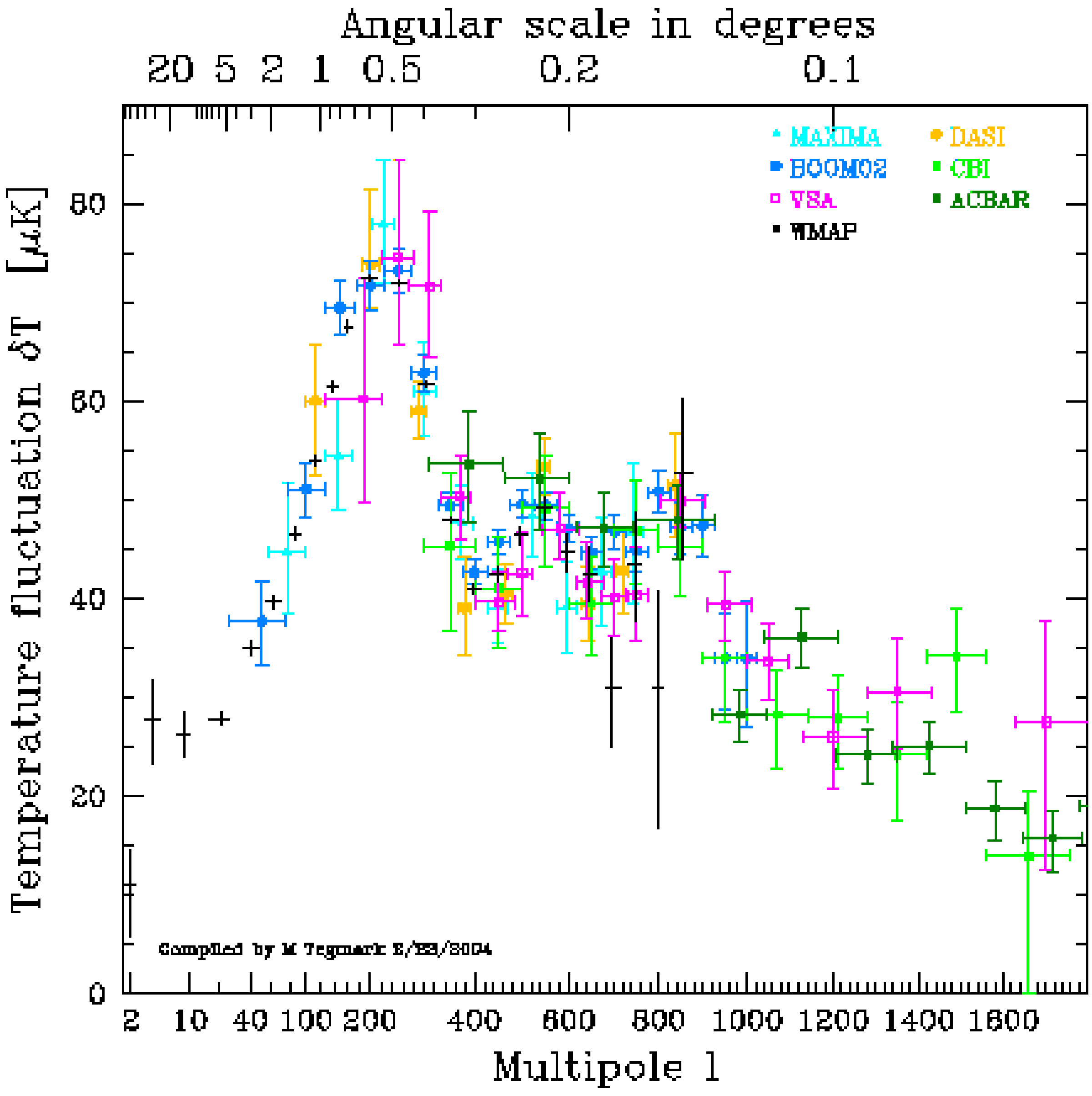
Smoot in 1992:

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暉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。”

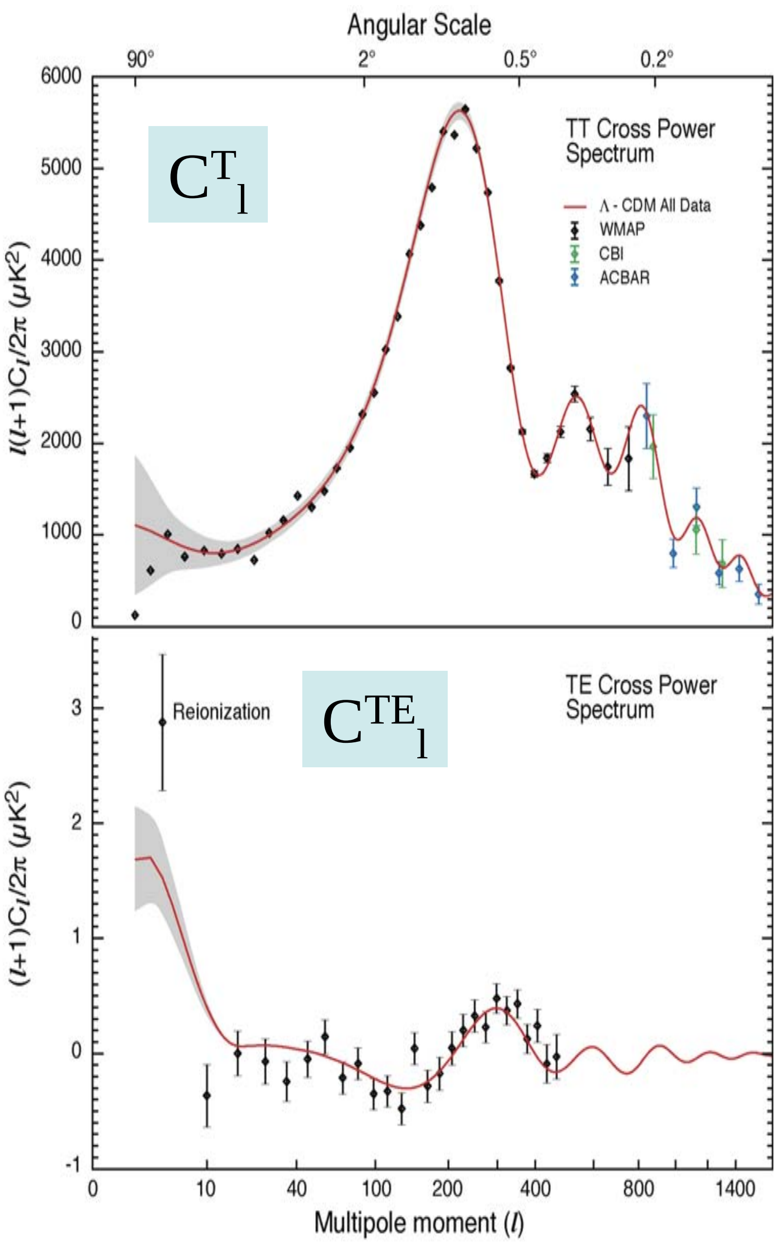
# Post-COBE



Angular scale in degrees
20 5 2 1 0.5 0.2 0.1
MAXIMA
DASI
BOOM02
CBI
VSA
ACBAR
WMAP
Temperature fluctuation δT [μK]
0
20
40
60
80
2 10 40 100 200 400 600 800 1000 1200 1400 1600
Multipole l
Compiled by M Tegmark 2/23/2004

# NASA WMAP Data & Cosmological Parameters

2002

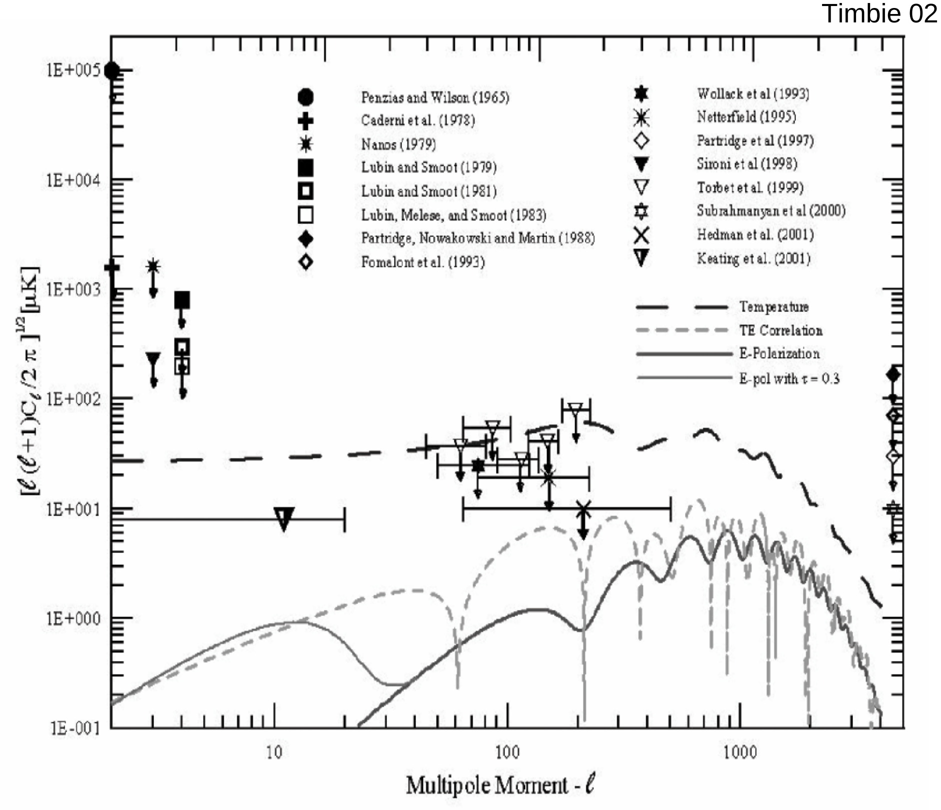


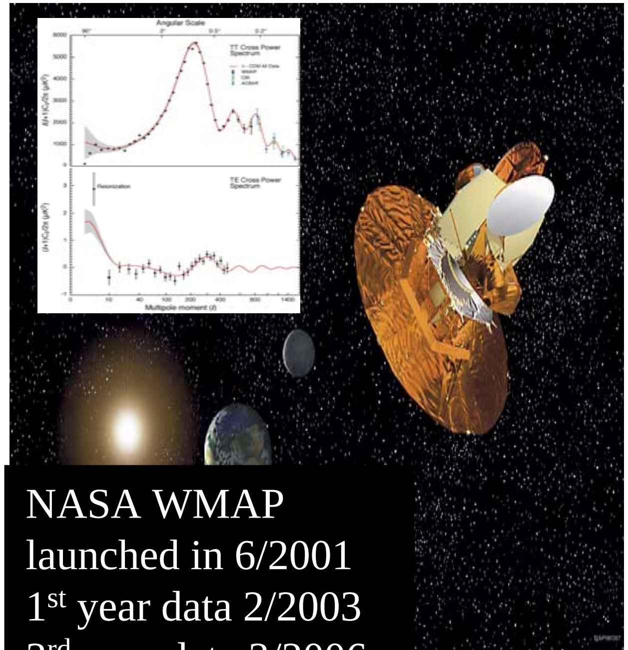

| Description | Symbol | Value | + uncertainty | − uncertainty |
|---|---|---|---|---|
| Total density | $\Omega_{tot}$ | 1.02 | 0.02 | 0.02 |
| Equation of state of quintessence | $w$ | $< -0.78$ | 95% CL | — |
| Dark energy density | $\Omega_\Lambda$ | 0.73 | 0.04 | 0.04 |
| Baryon density | $\Omega_b h^2$ | 0.0224 | 0.0009 | 0.0009 |
| Baryon density | $\Omega_b$ | 0.044 | 0.004 | 0.004 |
| Baryon density (cm$^{-3}$) | $n_b$ | $2.5 \times 10^{-7}$ | $0.1 \times 10^{-7}$ | $0.1 \times 10^{-7}$ |
| Matter density | $\Omega_m h^2$ | 0.135 | 0.008 | 0.009 |
| Matter density | $\Omega_m$ | 0.27 | 0.04 | 0.04 |
| Light neutrino density | $\Omega_\nu h^2$ | $< 0.0076$ | 95% CL | — |
| CMB temperature (K)[a] | $T_{cmb}$ | 2.725 | 0.002 | 0.002 |
| CMB photon density (cm$^{-3}$)[b] | $n_\gamma$ | 410.4 | 0.9 | 0.9 |
| Baryon-to-photon ratio | $\eta$ | $6.1 \times 10^{-10}$ | $0.3 \times 10^{-10}$ | $0.2 \times 10^{-10}$ |
| Baryon-to-matter ratio | $\Omega_b \Omega_m^{-1}$ | 0.17 | 0.01 | 0.01 |
| Fluctuation amplitude in $8h^{-1}$ Mpc spheres | $\sigma_8$ | 0.84 | 0.04 | 0.04 |
| Low-$z$ cluster abundance scaling | $\sigma_8 \Omega_m^{0.5}$ | 0.44 | 0.04 | 0.05 |
| Power spectrum normalization (at $k_0 = 0.05$ Mpc$^{-1}$)[c] | $A$ | 0.833 | 0.086 | 0.083 |
| Scalar spectral index (at $k_0 = 0.05$ Mpc$^{-1}$)[c] | $n_s$ | 0.93 | 0.03 | 0.03 |
| Running index slope (at $k_0 = 0.05$ Mpc$^{-1}$)[c] | $dn_s/d\ln k$ | $-0.031$ | 0.016 | 0.018 |
| Tensor-to-scalar ratio (at $k_0 = 0.002$ Mpc$^{-1}$) | $r$ | $< 0.90$ | 95% CL | — |
| Redshift of decoupling | $z_{dec}$ | 1089 | 1 | 1 |
| Thickness of decoupling (FWHM) | $\Delta z_{dec}$ | 195 | 2 | 2 |
| Hubble constant | $h$ | 0.71 | 0.04 | 0.03 |
| Age of universe (Gyr) | $t_0$ | 13.7 | 0.2 | 0.2 |
| Age at decoupling (kyr) | $t_{dec}$ | 379 | 8 | 7 |
| Age at reionization (Myr, 95% CL)) | $t_r$ | 180 | 220 | 80 |
| Decoupling time interval (kyr) | $\Delta t_{dec}$ | 118 | 3 | 2 |
| Redshift of matter-energy equality | $z_{eq}$ | 3233 | 194 | 210 |
| Reionization optical depth | $\tau$ | 0.17 | 0.04 | 0.04 |
| Redshift of reionization (95% CL) | $z_r$ | 20 | 10 | 9 |
| Sound horizon at decoupling (°) | $\theta_A$ | 0.598 | 0.002 | 0.002 |
| Angular size distance to decoupling (Gpc) | $d_A$ | 14.0 | 0.2 | 0.3 |
| Acoustic scale[d] | $\ell_A$ | 301 | 1 | 1 |
| Sound horizon at decoupling (Mpc)[d] | $r_s$ | 147 | 2 | 2 |

# Ongoing CMB Experiments

(edited by Prof. Ng)

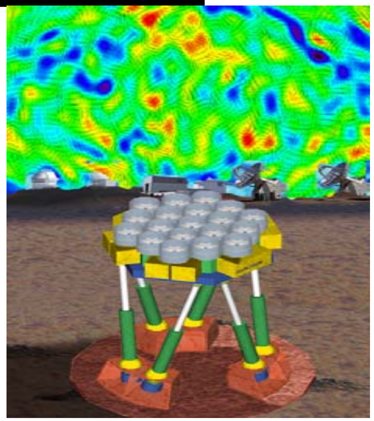
Timbie 02



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

| | | |
|---|---|---|
| Interferometer | AMiBA | Mauna Loa |
| | CBI | Chile |
| | DASI | South Pole |
| | VSA | Tenerife |
| Radiometer | CAPMAP | Princeton |
| Balloon-borne bolometer | Boomerang | South Pole |
| | Maxipol | New Mexico |
| Bolometer | BICEP | South Pole |
| | QUAD | South Pole |

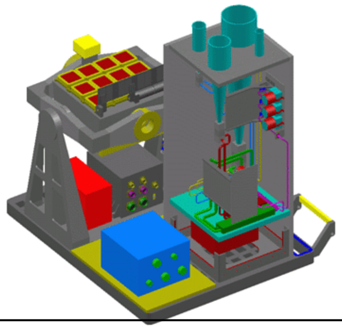


AMiBA at Mauna Loa
Taiwan, Australia, USA

# Future CMB Space Missions & Experiments

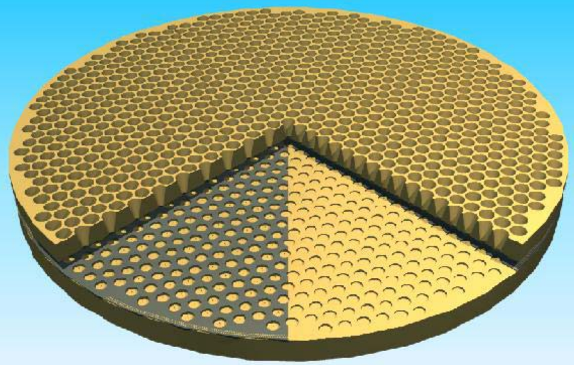
(edited by Prof. Ng)

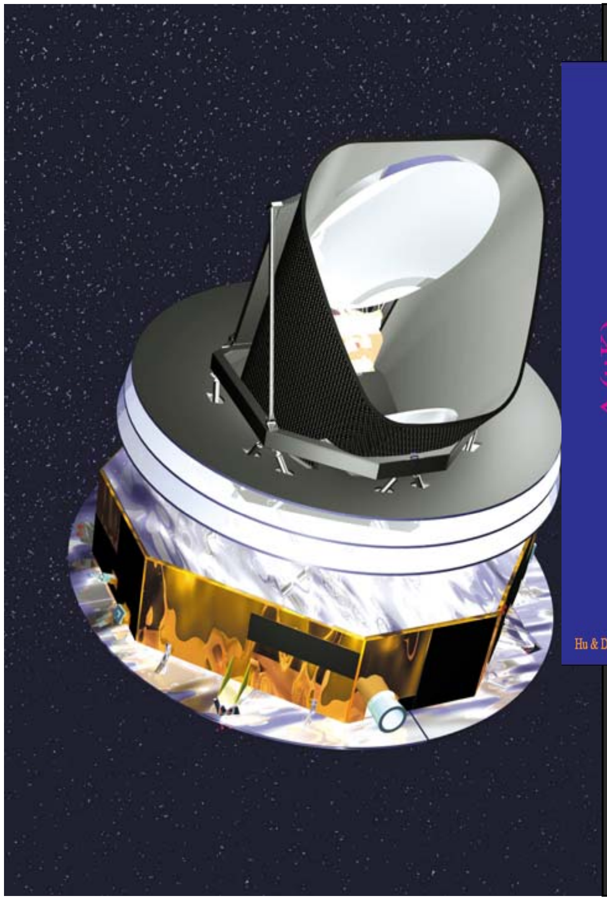
**SPOrt aboard the International Space Station**
**$7^o$ l<20**

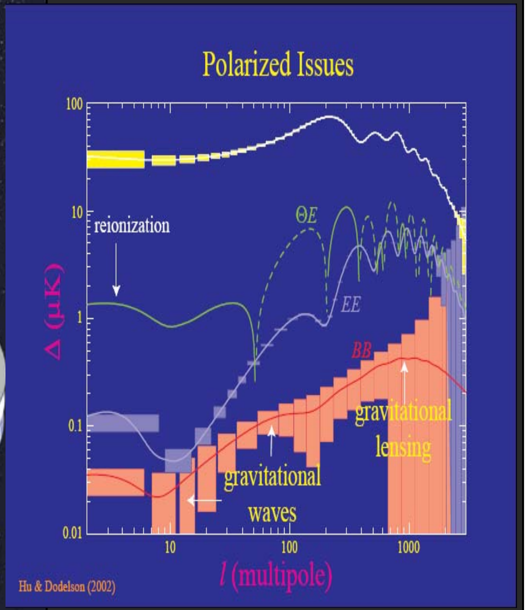


**Large-format radiometer arrays**

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








ESA Planck 2007
$0.2^o$ l<1000

NASA Inflation Probe
(Beyond Einstein Program)

# "泛黃"宇宙太古照片 (CMB Milestones)

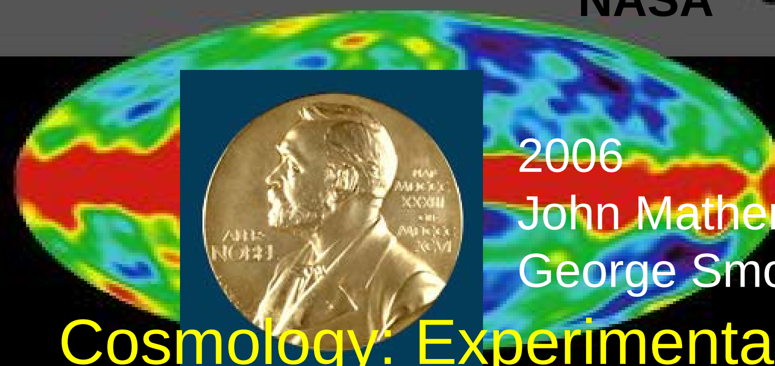
edited by Prof. K.-W. Ng

1965 AT&T Bell Penzias and Wilson

1978
Arno Penzias
Robert Wilson

Winning of Big Bang model

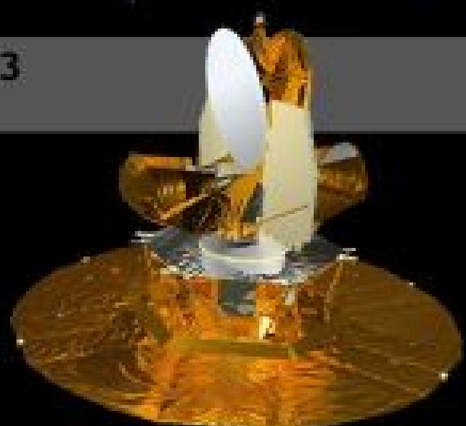
1992 NASA COBE



2006
John Mather
George Smoot

Cosmology: Experimental Science

2003 NASA WMAP




Plus r… bservations

Cosmology → Precision Cosmology

# 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

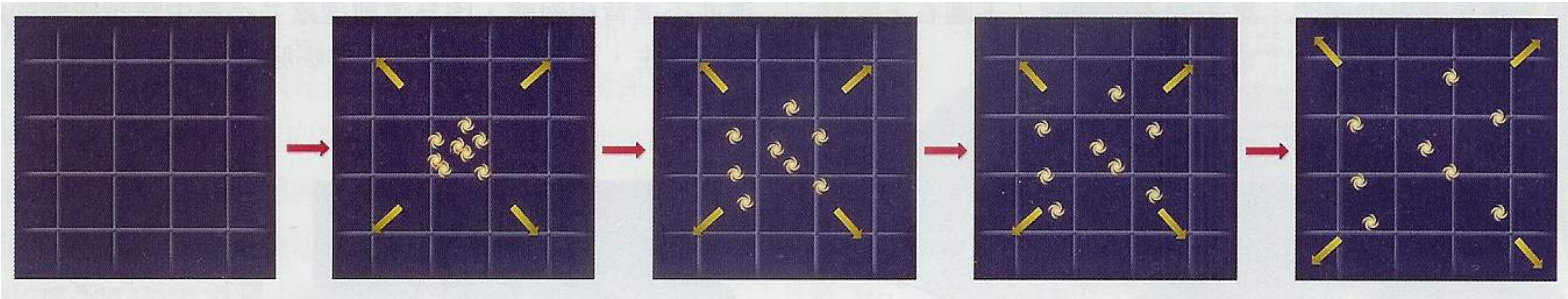
(6 common errors about the expanding universe)

- 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 ?

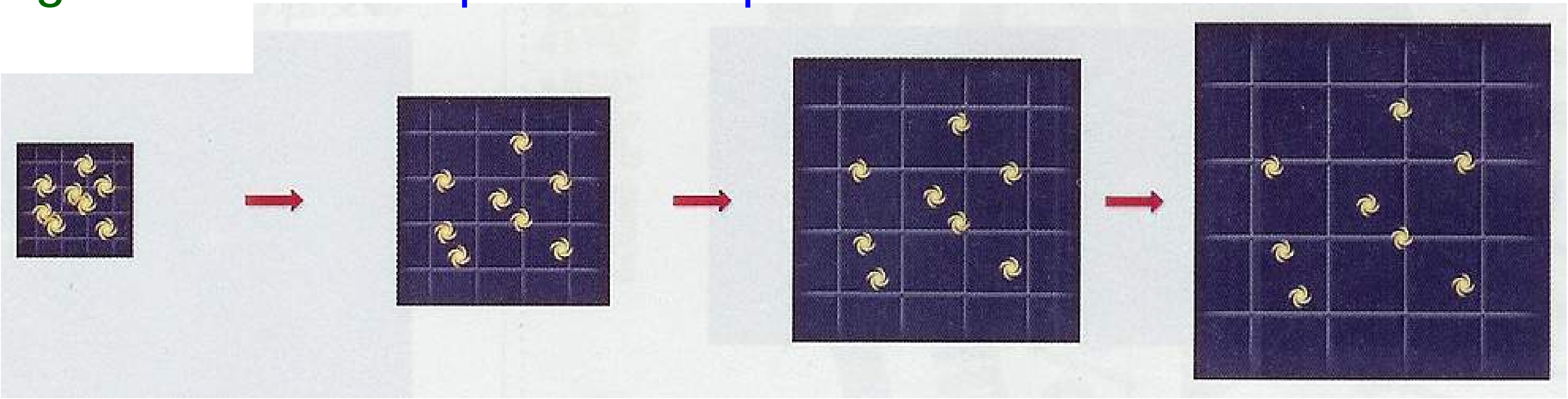
# What kind of explosion was the big bang ?

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.



# Can galaxies recede faster than light ?

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 → HORIZON $(\ddot{a} > 0)$

We can never see the galaxies outside the HORIZON.

# Why is there a cosmic redshift ?

Wrong :

Because receding galaxies are moving through space and exhibit a Doppler shift.

(Doppler effect)

Right :

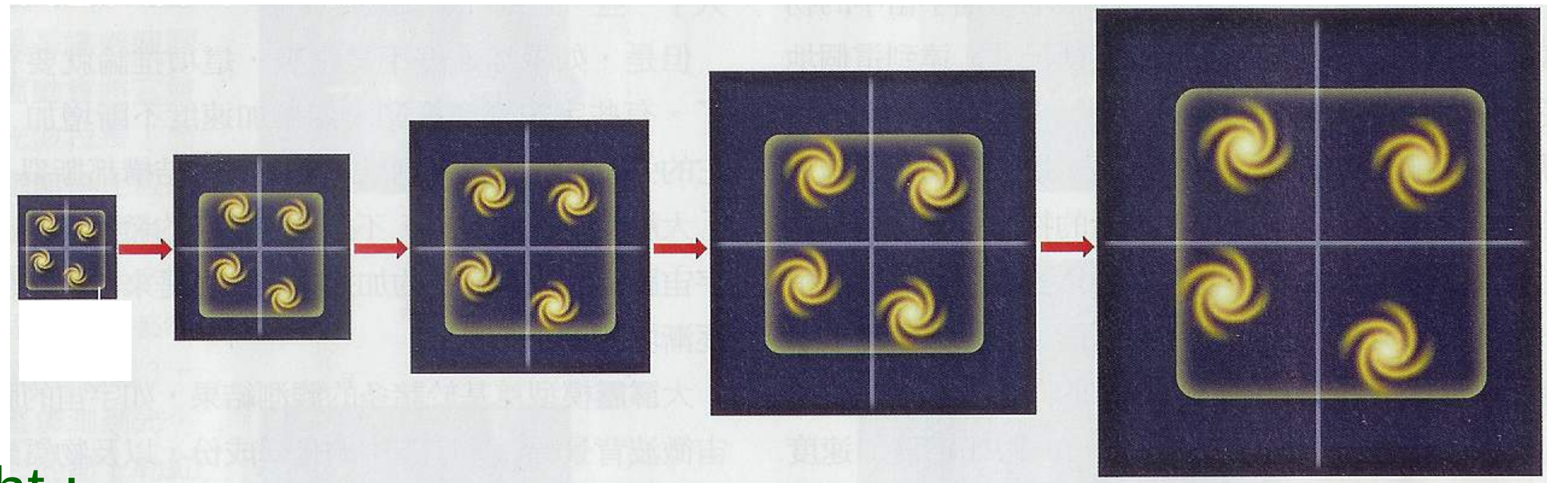
Because expanding space stretches all light waves as they propagate.

(Gravitational Redshift)

(The energy of particles is transferred to the energy  of the gravitational field.)

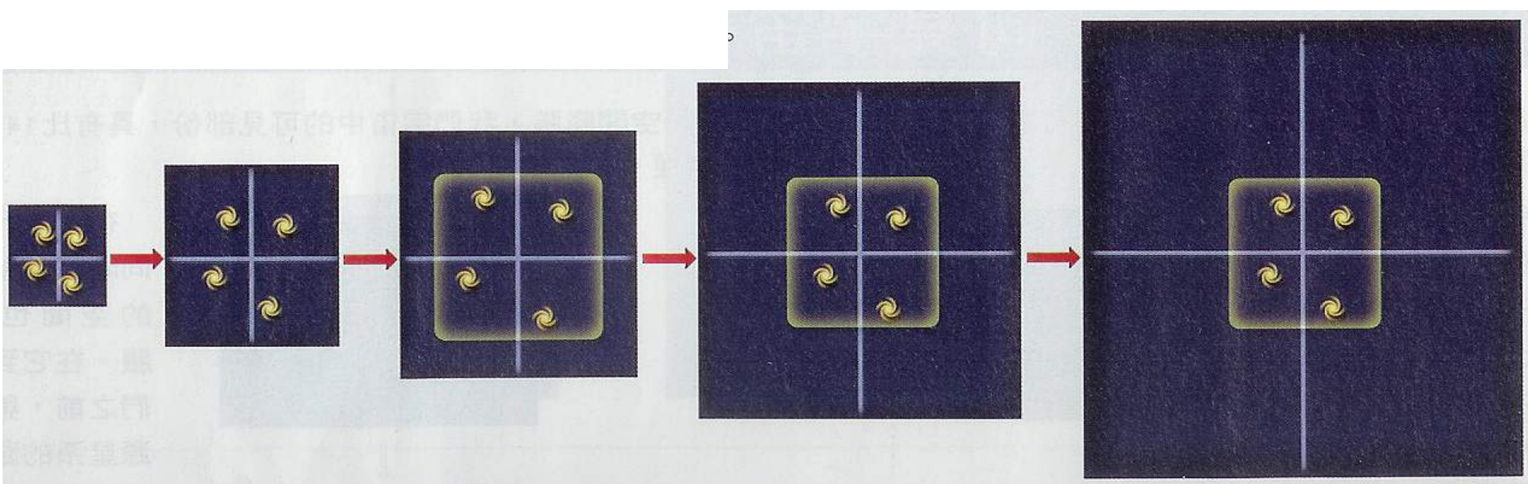
# Do objects inside the universe expand, too ?

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 ?

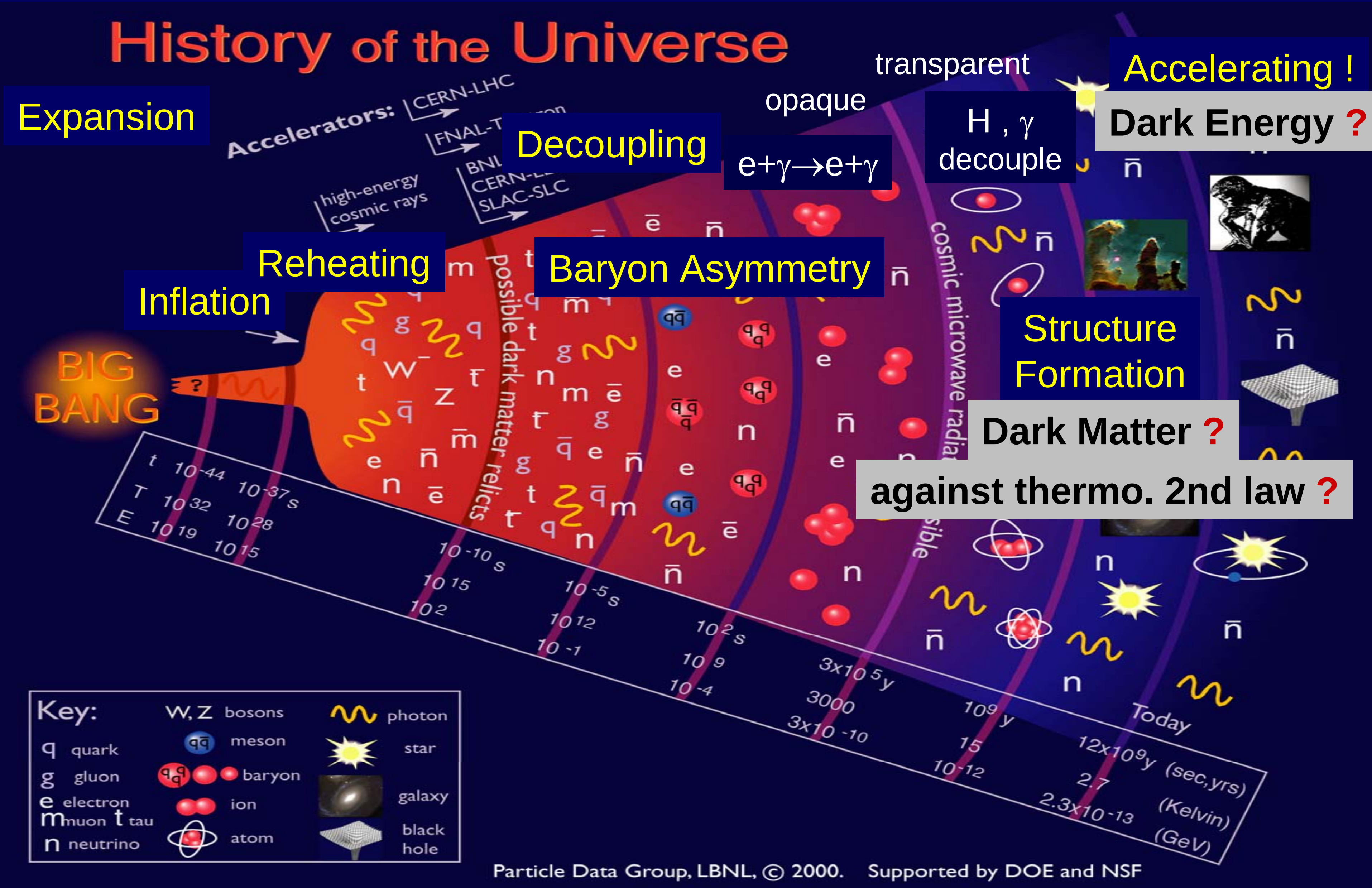
  (While none of them is dominant over the other.)

  Can the observational data rule out this possibility ?

  Note momentum ~ 1/a

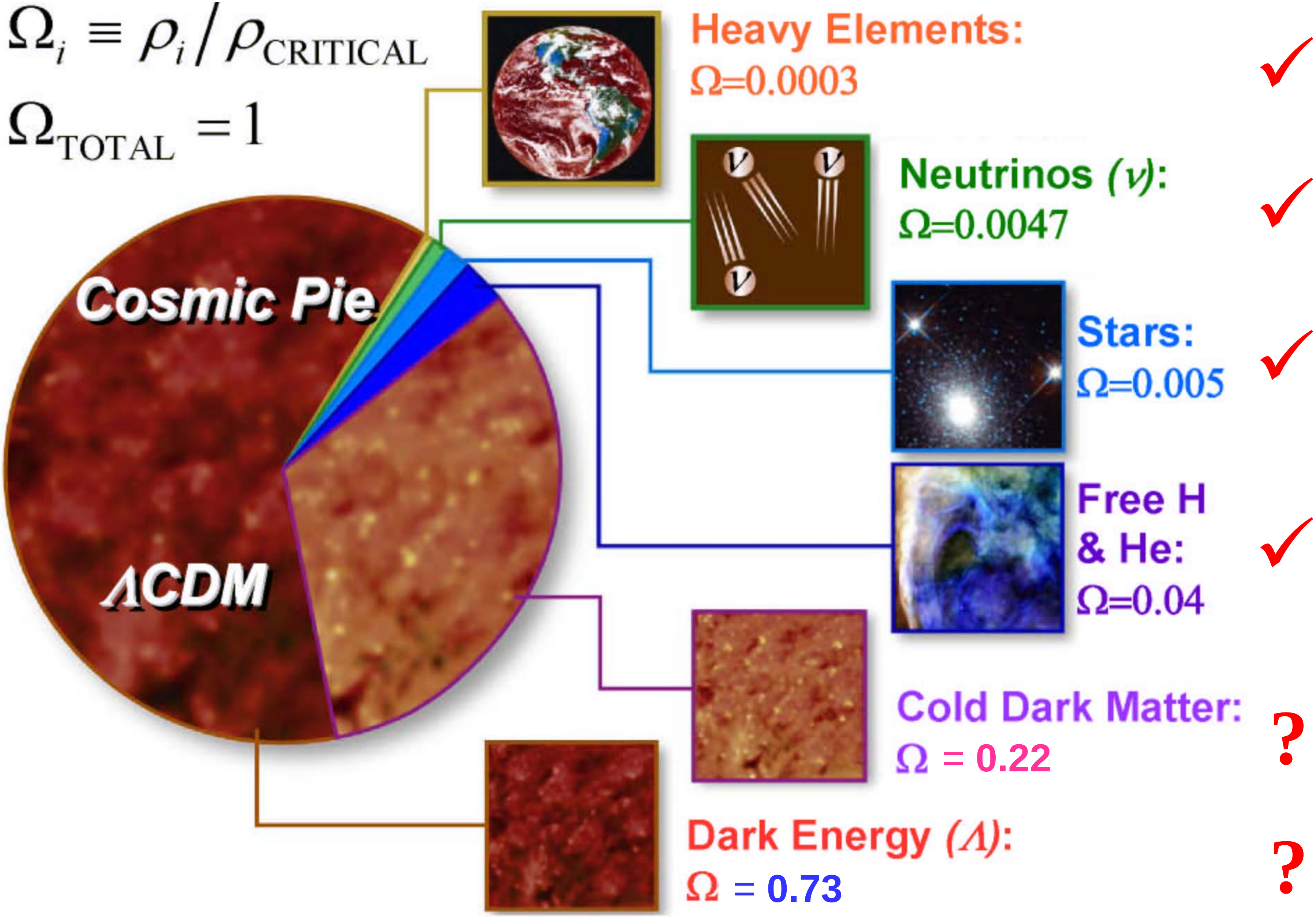
# Summary

# Thermal History of the Universe



$$\Omega_i \equiv \rho_i / \rho_{\mathrm{CRITICAL}}$$

$$\Omega_{\mathrm{TOTAL}} = 1$$



# Known? Unknown!

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

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

## FERMIONS

**matter constituents**
**spin = 1/2, 3/2, 5/2, ...**

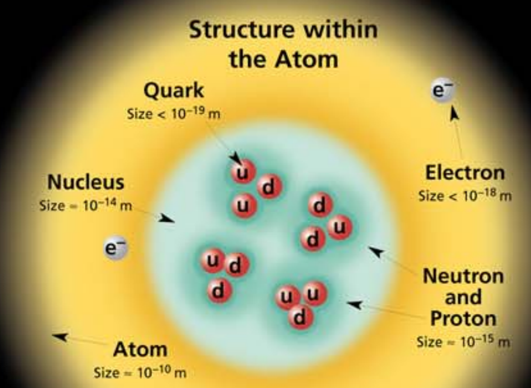
| Leptons spin = 1/2 | | |
|---|---|---|
| Flavor | Mass GeV/$c^2$ | Electric charge |
| $\nu_e$ electron neutrino | $<1\times10^{-8}$ | 0 |
| e electron | 0.000511 | –1 |
| $\nu_\mu$ muon neutrino | <0.0002 | 0 |
| $\mu$ muon | 0.106 | –1 |
| $\nu_\tau$ tau neutrino | <0.02 | 0 |
| $\tau$ tau | 1.7771 | –1 |

| Quarks spin = 1/2 | | |
|---|---|---|
| Flavor | Approx. Mass GeV/$c^2$ | Electric charge |
| u up | 0.003 | 2/3 |
| d down | 0.006 | –1/3 |
| c charm | 1.3 | 2/3 |
| s strange | 0.1 | –1/3 |
| t top | 175 | 2/3 |
| b bottom | 4.3 | –1/3 |

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

**Electric charges** are given in units of the proton's charge. In SI units the electric charge of the proton is $1.60\times10^{-19}$ coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/$c^2$ (remember $E = mc^2$), where 1 GeV $= 10^9$ eV $= 1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/$c^2$ $= 1.67\times10^{-27}$ kg.




If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

## BOSONS

**force carriers**
**spin = 0, 1, 2, ...**

| Unified Electroweak spin = 1 | | |
|---|---|---|
| Name | Mass GeV/$c^2$ | Electric charge |
| $\gamma$ photon | 0 | 0 |
| $W^-$ | 80.4 | –1 |
| $W^+$ | 80.4 | +1 |
| $Z^0$ | 91.187 | 0 |

| Strong (color) spin = 1 | | |
|---|---|---|
| Name | Mass GeV/$c^2$ | Electric charge |
| g gluon | 0 | 0 |

### Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

### Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** $qqq$.

### Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

## PROPERTIES OF THE INTERACTIONS

| Property \ Interaction | Gravitational | Weak (Electroweak) | Electromagnetic (Electroweak) | Strong: Fundamental | Strong: Residual |
|---|---|---|---|---|---|
| Acts on: | Mass – Energy | Flavor | Electric Charge | Color Charge | See Residual Strong Interaction Note |
| Particles experiencing: | All | Quarks, Leptons | Electrically charged | Quarks, Gluons | Hadrons |
| Particles mediating: | Graviton (not yet observed) | $W^+$ $W^-$ $Z^0$ | $\gamma$ | Gluons | Mesons |
| Strength relative to electromag for two u quarks at: $10^{-18}$ m | $10^{-41}$ | 0.8 | 1 | 25 | Not applicable to quarks |
| Strength relative to electromag for two u quarks at: $3\times10^{-17}$ m | $10^{-41}$ | $10^{-4}$ | 1 | 60 | |
| for two protons in nucleus | $10^{-36}$ | $10^{-7}$ | 1 | Not applicable to hadrons | 20 |

**Baryons $qqq$ and Antibaryons $\bar{q}\bar{q}\bar{q}$**
Baryons are fermionic hadrons.
There are about 120 types of baryons.

| Symbol | Name | Quark content | Electric charge | Mass GeV/$c^2$ | Spin |
|---|---|---|---|---|---|
| p | proton | uud | 1 | 0.938 | 1/2 |
| $\bar{p}$ | anti-proton | $\bar{u}\bar{u}\bar{d}$ | –1 | 0.938 | 1/2 |
| n | neutron | udd | 0 | 0.940 | 1/2 |
| $\Lambda$ | lambda | uds | 0 | 1.116 | 1/2 |
| $\Omega^-$ | omega | sss | –1 | 1.672 | 3/2 |

**Mesons $q\bar{q}$**
Mesons are bosonic hadrons.
There are about 140 types of mesons.

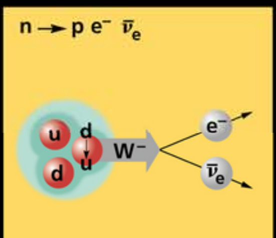
| Symbol | Name | Quark content | Electric charge | Mass GeV/$c^2$ | Spin |
|---|---|---|---|---|---|
| $\pi^+$ | pion | $u\bar{d}$ | +1 | 0.140 | 0 |
| $K^-$ | kaon | $s\bar{u}$ | –1 | 0.494 | 0 |
| $\rho^+$ | rho | $u\bar{d}$ | +1 | 0.770 | 1 |
| $B^0$ | B-zero | $d\bar{b}$ | 0 | 5.279 | 0 |
| $\eta_c$ | eta-c | $c\bar{c}$ | 0 | 2 .980 | 0 |

### Matter and Antimatter

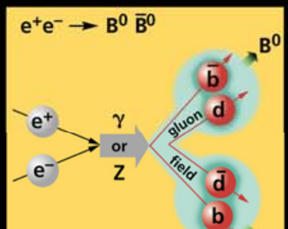
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., $Z^0$, $\gamma$, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

### Figures

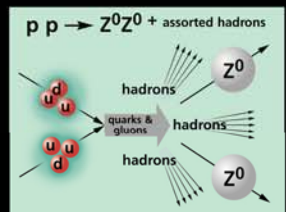
These diagrams are an artist's conception of physical processes. They are *not* exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.




A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.




An electron and positron (antielectron) colliding at high energy can annihilate to produce $B^0$ and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.




Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

### The Particle Adventure

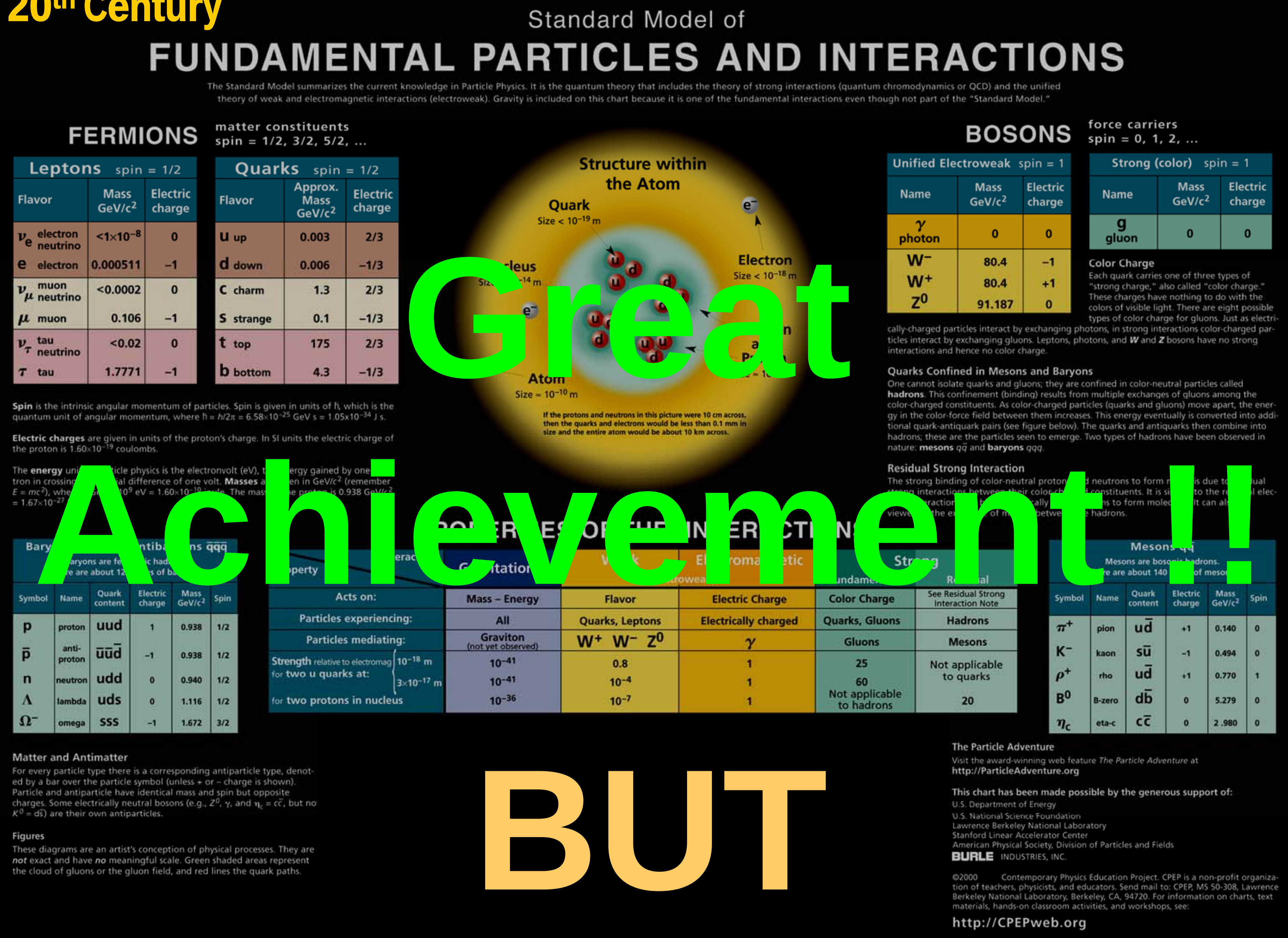
Visit the award-winning web feature *The Particle Adventure* at
**http://ParticleAdventure.org**


**This chart has been made possible by the generous support of:**
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.



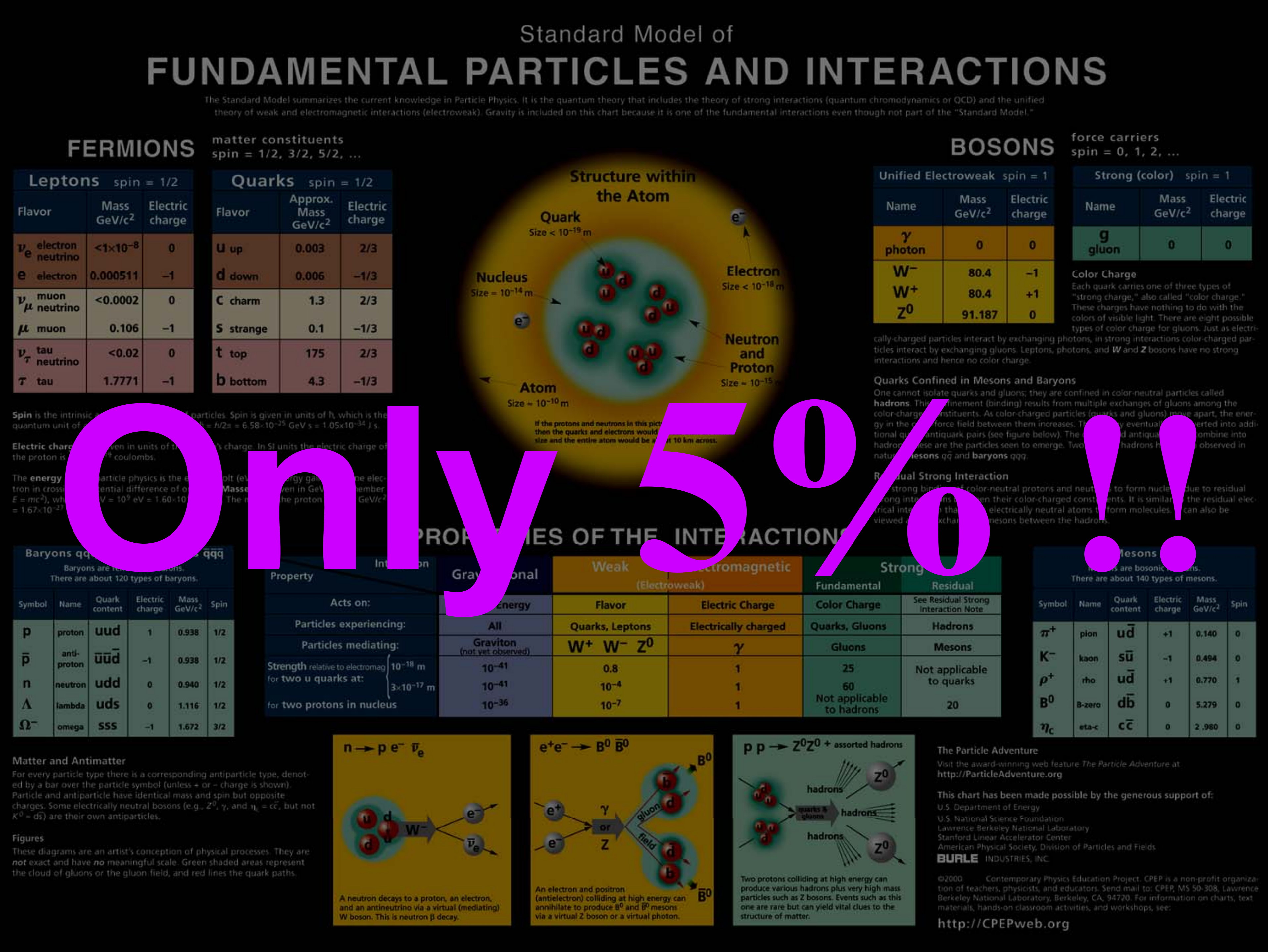

**http://CPEPweb.org**

## 20th Century




# Great Achievement !!

# BUT


Only 5%!!
Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS
The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."
FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...
Leptons spin = 1/2
Flavor
Mass GeV/c²
Electric charge
electron neutrino <1×10⁻⁸ 0
e electron 0.000511 −1
muon neutrino <0.0002 0
μ muon 0.106 −1
tau neutrino <0.02 0
τ tau 1.7771 −1
Quarks spin = 1/2
Flavor
Approx. Mass GeV/c²
Electric charge
u up 0.003 2/3
d down 0.006 −1/3
c charm 1.3 2/3
s strange 0.1 −1/3
t top 175 2/3
b bottom 4.3 −1/3
Structure within the Atom
Quark
Size < 10⁻¹⁹ m
Nucleus
Size ≈ 10⁻¹⁴ m
Electron
Size < 10⁻¹⁸ m
Neutron and Proton
Atom
Size ≈ 10⁻¹⁰ m
BOSONS
force carriers
spin = 0, 1, 2, ...
Unified Electroweak spin = 1
Name
Mass GeV/c²
Electric charge
γ photon 0 0
W⁻ 80.4 −1
W⁺ 80.4 +1
Z⁰ 91.187 0
Strong (color) spin = 1
Name
Mass GeV/c²
Electric charge
g gluon 0 0
Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and W and Z bosons have no strong interactions and hence no color charge.
Quarks Confined in Mesons and Baryons
PROPERTIES OF THE INTERACTIONS
Property
Gravitational
Weak (Electroweak)
Electromagnetic
Strong
Fundamental
Residual
Acts on:
Flavor
Electric Charge
Color Charge
See Residual Strong Interaction Note
Particles experiencing:
All
Quarks, Leptons
Electrically charged
Quarks, Gluons
Hadrons
Particles mediating:
Graviton (not yet observed)
W⁺ W⁻ Z⁰
γ
Gluons
Mesons
Strength relative to electromag for two u quarks at:
10⁻¹⁸ m
3×10⁻¹⁷ m
for two protons in nucleus
10⁻⁴¹ 0.8 1 25
10⁻⁴¹ 10⁻⁴ 1 60
10⁻³⁶ 10⁻⁷ 1
Not applicable to quarks
Not applicable to hadrons
20
Baryons qqq and q̄q̄q̄
There are about 120 types of baryons.
Symbol Name Quark content Electric charge Mass GeV/c² Spin
p proton uud 1 0.938 1/2
p̄ anti-proton ūūd̄ −1 0.938 1/2
n neutron udd 0 0.940 1/2
Λ lambda uds 0 1.116 1/2
Ω⁻ omega sss −1 1.672 3/2
Mesons
There are about 140 types of mesons.
Symbol Name Quark content Electric charge Mass GeV/c² Spin
π⁺ pion ud̄ +1 0.140 0
K⁻ kaon sū −1 0.494 0
ρ⁺ rho ud̄ +1 0.770 1
B⁰ B-zero db̄ 0 5.279 0
ηc eta-c cc̄ 0 2.980 0
Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or − charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z⁰, γ, and ηc = cc̄, but not K⁰ = ds̄) are their own antiparticles.
Figures
These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.
n → p e⁻ ν̄e
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.
e⁺e⁻ → B⁰ B̄⁰
An electron and positron (antielectron) colliding at high energy can annihilate to produce B⁰ and B̄⁰ mesons via a virtual Z boson or a virtual photon.
p p → Z⁰Z⁰ + assorted hadrons
Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.
The Particle Adventure
Visit the award-winning web feature The Particle Adventure at
http://ParticleAdventure.org
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# Known? Unknown!

5% 95%

知之為知之， ← 5% → Present your understanding when you understand;

不知為不知， ← 95% → recognize your not understanding when you don't understand;

是知也。 that's the true meaning of understanding.

—論語為政篇

— By Confucius

(Analects of Confucius)

# Known?    Unknown!

Great Puzzles

?

New Revolution !!