# Broken Symmetry
# 破缺的對稱性

## The Nobel Prize in Physics 2008

「發現對稱破缺的起源，預測自然界存在三代夸克」

*Why is there something instead of nothing? Why are there so many different elementary particles? This year's Nobel Laureates in Physics have presented theoretical insights that give us a deeper understanding of what happens far inside the tiniest building blocks of matter.*


耿朝強
國立清華大學物理系


(2009年12月23日)

# The Nobel Prize in Physics 2008

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Photo: SCANPIX

Photo: Kyodo/Reuters

Photo: Kyoto University

**Yoichiro Nambu**

1/2 of the prize

USA

Enrico Fermi Institute, University of Chicago
Chicago, IL, USA

b. 1921

**Makoto Kobayashi**

1/4 of the prize

Japan

High Energy Accelerator Research Organization (KEK)
Tsukuba, Japan

b. 1944

**Toshihide Maskawa**

1/4 of the prize

Japan

Yukawa Institute for Theoretical Physics (YITP), Kyoto University
Kyoto, Japan

b. 1940

# *Outline*

引言

對稱性

- 連續對稱性之破缺 ⟵ Nambu
- 分立對稱性之破缺 ⟵ Kobayashi+Maskawa

尚未解決之問題

未來展望與結束語

引言

Science
AAAS

*American Association for the Advancement of Science*


**July 1, 2005**
**Science Magazine**
**125th anniversary**

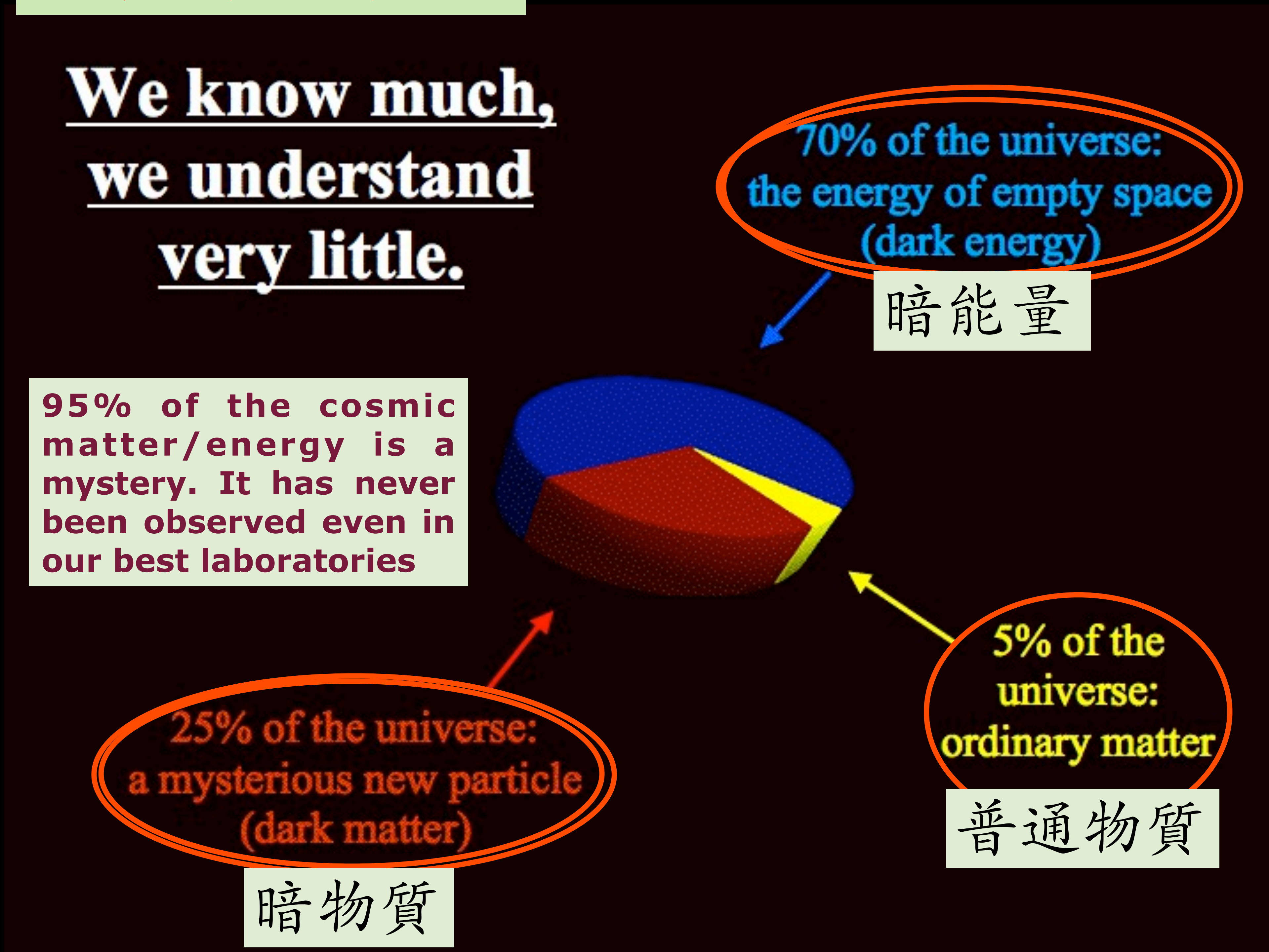
**THE QUESTIONS**

**The Top 25**

Essays by our news staff on 25 big questions facing science over the next quarter-century.

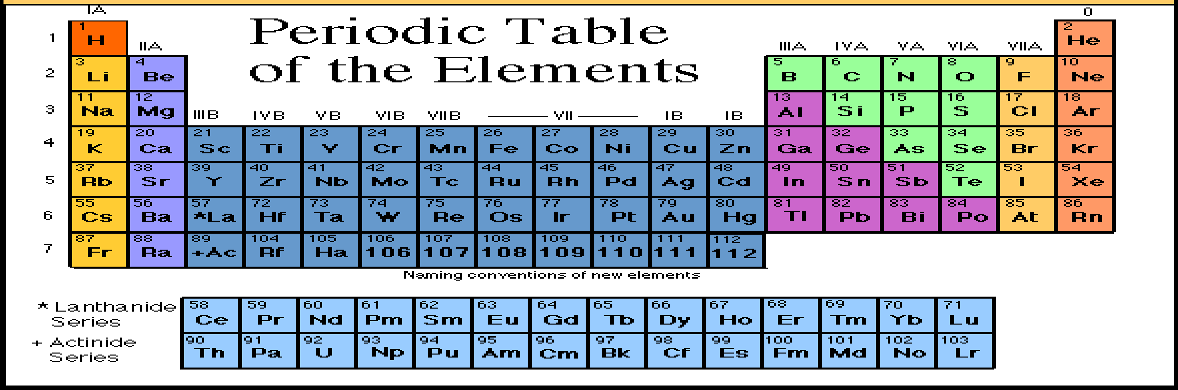
- What Is the Universe Made Of? #1
- What is the Biological Basis of Consciousness?
- Why Do Humans Have So Few Genes?
- To What Extent Are Genetic Variation and Personal Health Linked?
- Can the Laws of Physics Be Unified? #5
- How Much Can Human Life Span Be Extended?
- What Controls Organ Regeneration?
- How Can a Skin Cell Become a Nerve Cell?
- How Does a Single Somatic Cell Become a Whole Plant?
- How Does Earth's Interior Work?
- Are We Alone in the Universe?
- How and Where Did Life on Earth Arise?
- What Determines Species Diversity?
- What Genetic Changes Made Us Uniquely Human?
- How Are Memories Stored and Retrieved?
- How Did Cooperative Behavior Evolve?
- How Will Big Pictures Emerge from a Sea of Biological Data?

# 物質是由什麼組成的？

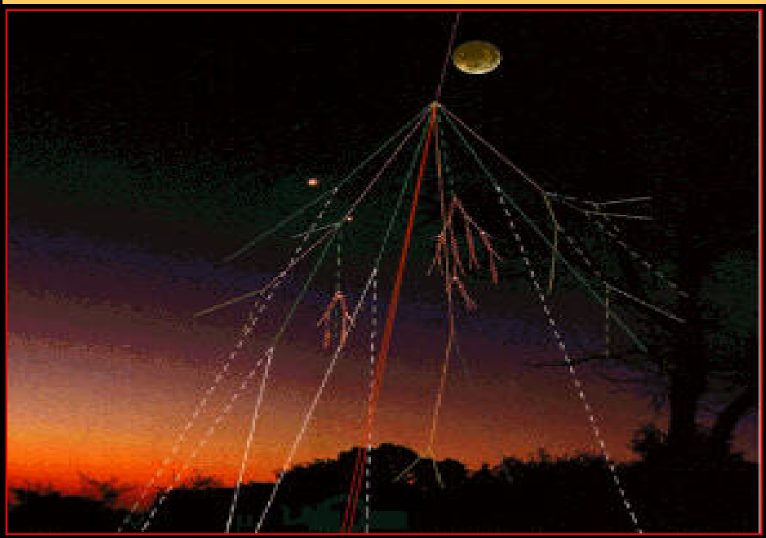

We know much,
we understand
very little.
70% of the universe:
the energy of empty space
(dark energy)
暗能量
95% of the cosmic matter/energy is a mystery. It has never been observed even in our best laboratories
5% of the
universe:
ordinary matter
普通物質
25% of the universe:
a mysterious new particle
(dark matter)
暗物質

# 已知（標準）物質：

## *ordinary matter* 普通物質

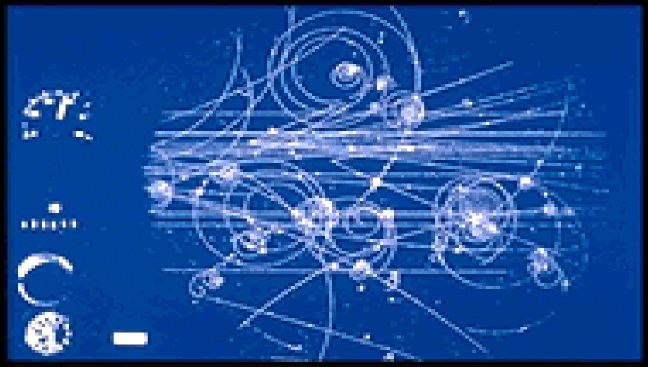



## *cosmic matter* 宇宙物質



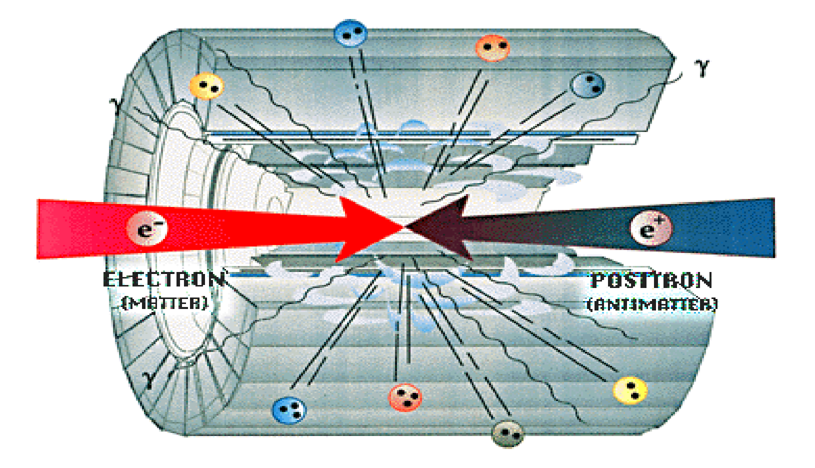
*So to understand the matter that exists as cosmic rays, we need more components than we need to make atoms. In addition to the electron, electron-neutrino, up quark and down quark, we need the muon, the muon-neutrino and the strange quark.*

## *High-energy matter* 高能物質



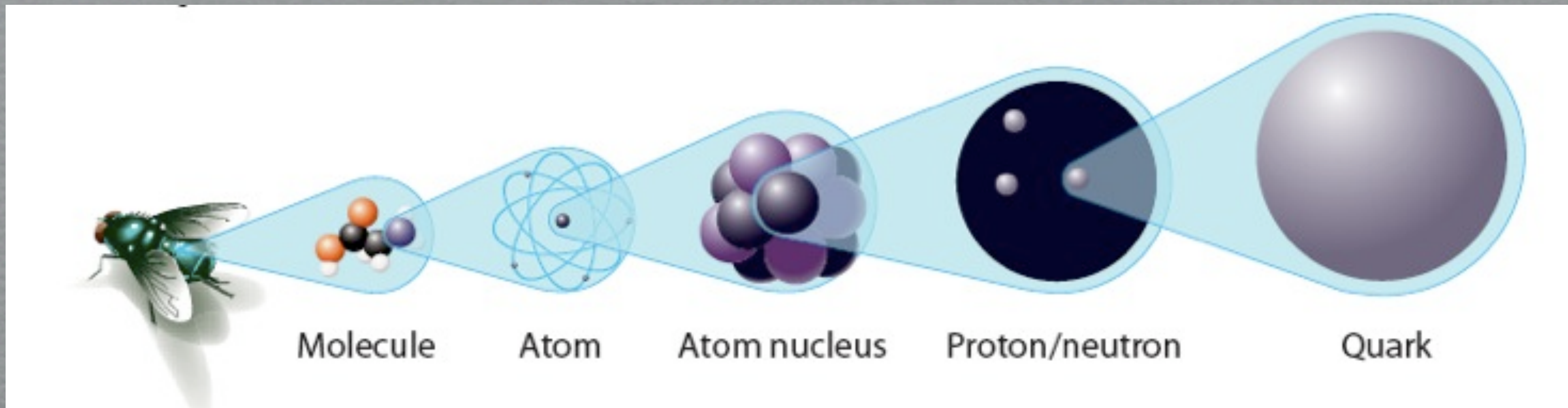
*To study high energy particle collisions under more controlled conditions, particle physicists use laboratories such as CERN, where high-energy particle colliders mimic the actions of cosmic rays in the atmosphere. Nowadays, these experiments reach energies that were common in the Universe only in the first instants of its existence.*

## *Antimatter* 反物質




*For each of the basic particles of matter, there also exists a "mirror" version - or antiparticle - in which properties such as electric charge are reversed.*

## ordinary matter 普通物質




***Only four kinds of building block are needed to account for all of ordinary matter.***

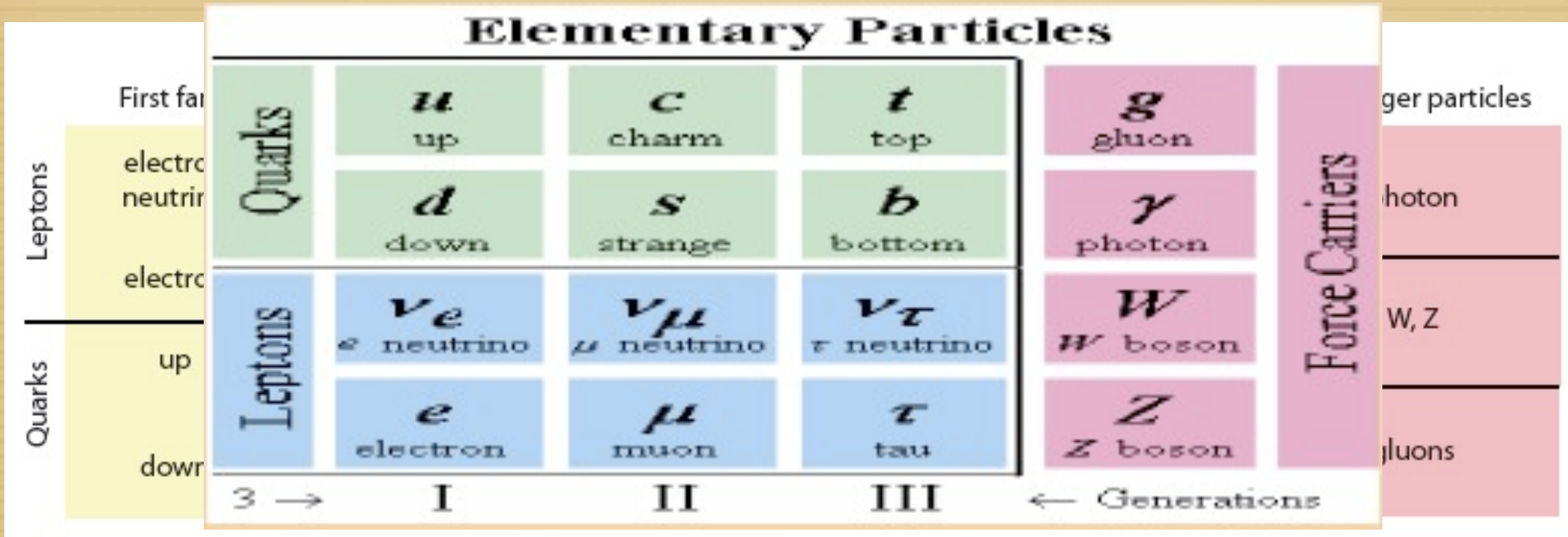
up-quarks and down-quarks 上和下夸克
electrons 電子 和 electron-neutrinos 電子中微子

是什麼結合它在一起？

***Particles are stuck together by forces: four kinds of forces***
gravity 重力
weak 弱作用力
electromagnetic 電磁作用力
strong 強作用力

| | Gravity | Weak (Electroweak) | Electromagnetic | Strong |
|---|---|---|---|---|
| Carried By | Graviton (not yet observed) | $W^+$ $W^-$ $Z^0$ | Photon | Gluon |
| Acts on | All | Quarks and Leptons | Quarks and Charged Leptons and $W^+$ $W^-$ | Quarks and Gluons |

# The Standard Model




**The Standard Model is a good theory. Experiments have verified its predictions to incredible precision.**

• 兩大問題? → 機會

I. 手征規范對稱性之破缺 ← The Higgs Particle? ← LHC大強子對撞機

連續對稱性

12/09/2009:能量 2.36 TeV

II.宇宙物質與反物質之不對稱性

為什麼普通物質是由物質構成?

物質

反物質

分立對稱性

1. *Baryon number violation*
2. *C and CP violation*
3. *A departure from thermal equilibrium*

1967: Sakharov (the Nobel Peace Prize 1975)

# 對稱性

"I aim at two things: On the one hand to clarify, step by step, the philosophic-mathematical significance of the idea of symmetry and, on the other, to display the great variety of applications of symmetry in the arts, in inorganic and organic nature." And "*Symmetry*….is an idea which has guided man through the centuries to the understanding and the creation of order, beauty and perfection. "

對稱性是一種觀念，這種觀念在幾千年來一直引導人類理解和創造世界上各種事物之規律，美妙，及完善。

***Hermann Weyl ( in his book "Symmetry")***

**"I heave the basketball; I know it sails in a parabola, exhibiting perfect *symmetry*, which is interrupted by the basket. Its funny, but it is always interrupted by the basket."** *Michael Jordan ( former Chicago Bull)*

**Noether's Theorem** Symmetries ⟷ Conservation Laws

| Symmetry Transformation | Conserved Charge |
|---|---|
| time translation $t \to t + a$ | Energy |
| space translation $\vec{x} \to \vec{x} + \vec{b}$ | Momentum |
| rotation | Angular momentum |
| $\cdots$ | $\cdots$ |


台北市音樂季

中國文學：

# 舉頭望明月

# 低頭思故鄉

英文：*palindromes* 回文

**"Madam, I'm Adam"**

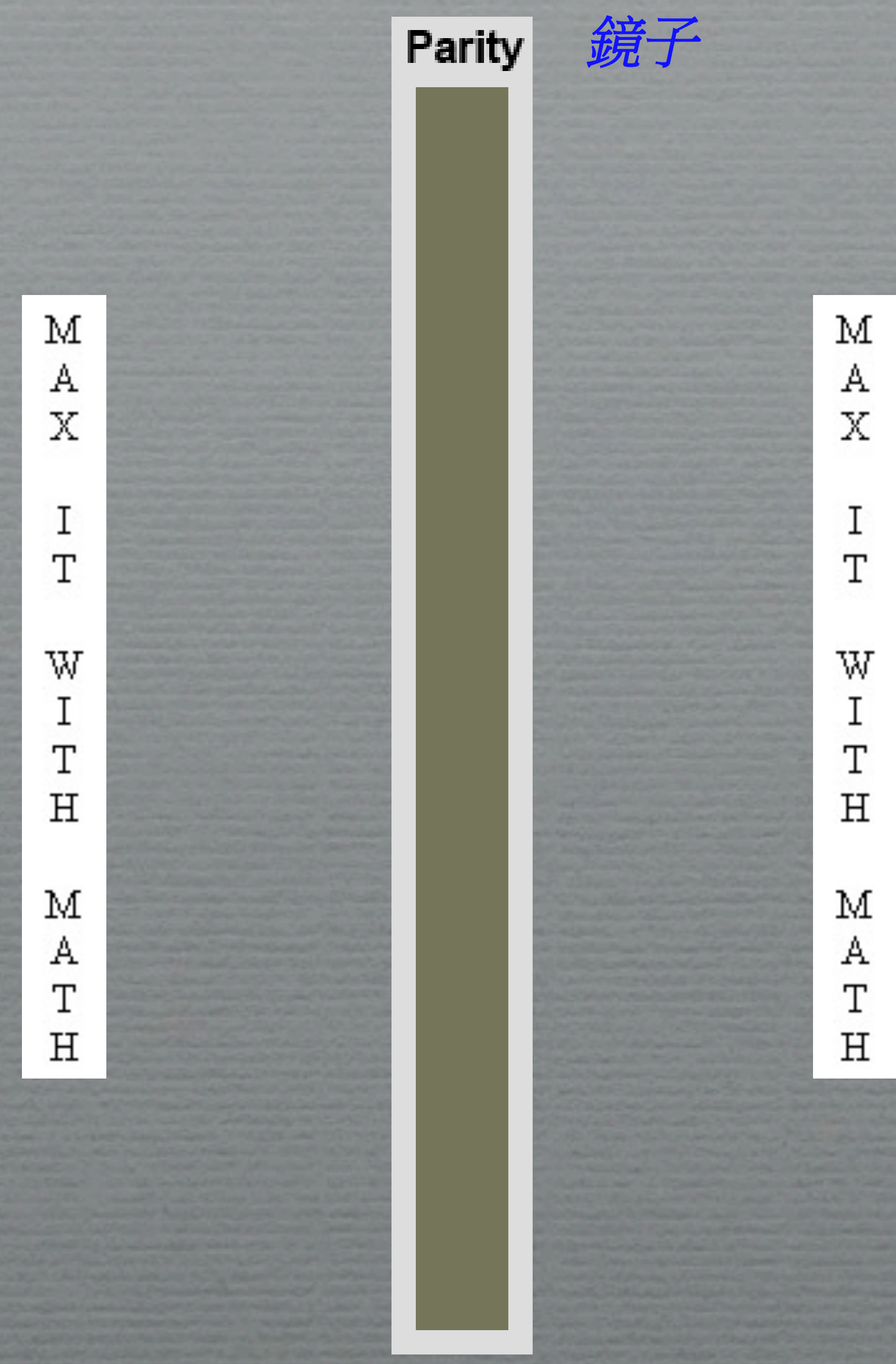
生物：基因 ***the male-defining Y*** – 染色體

**About 6 million (out of 50 million) of the Y's DNA letters from palindromic sequences.**

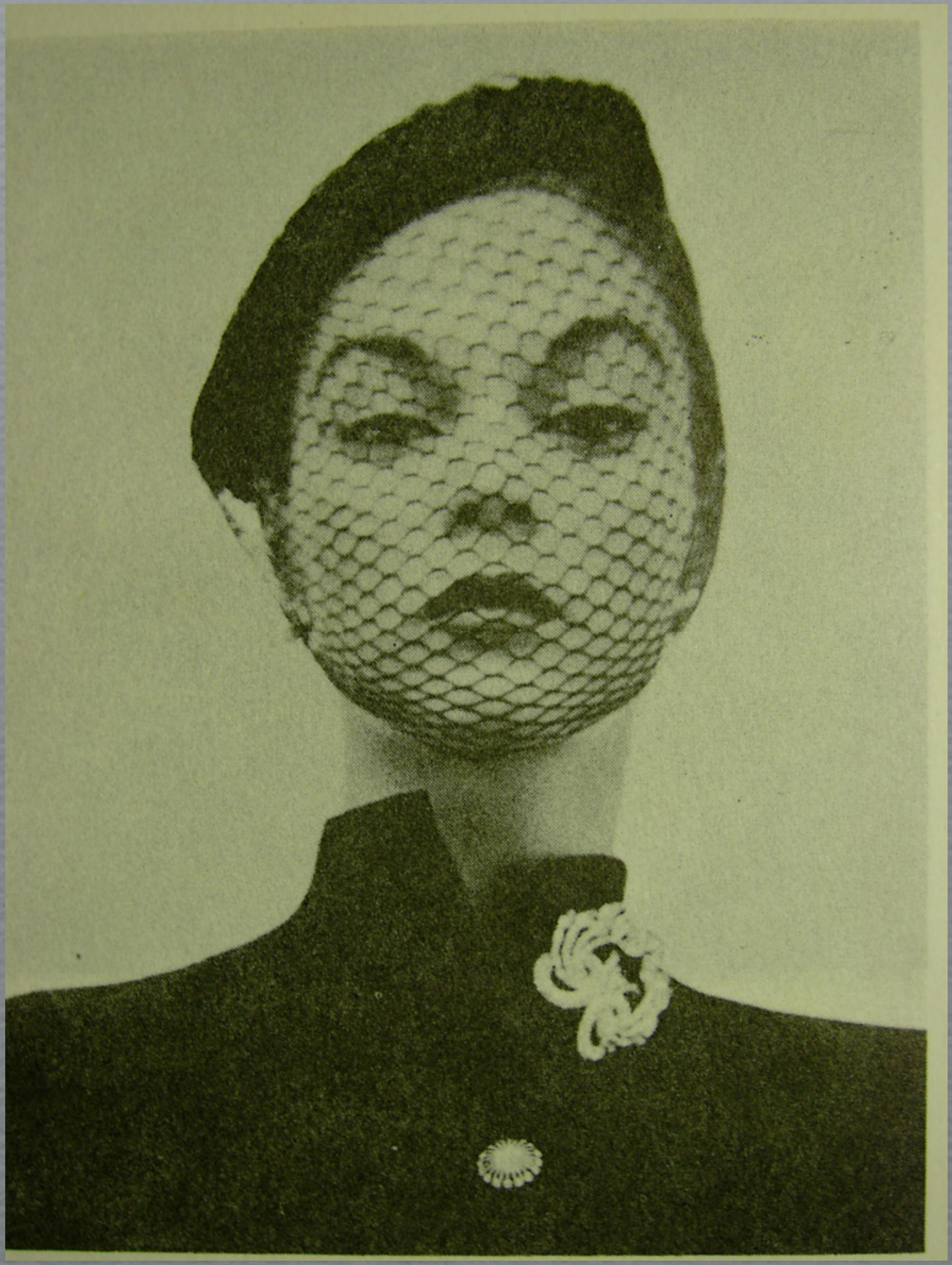
***Does this look right to you?***

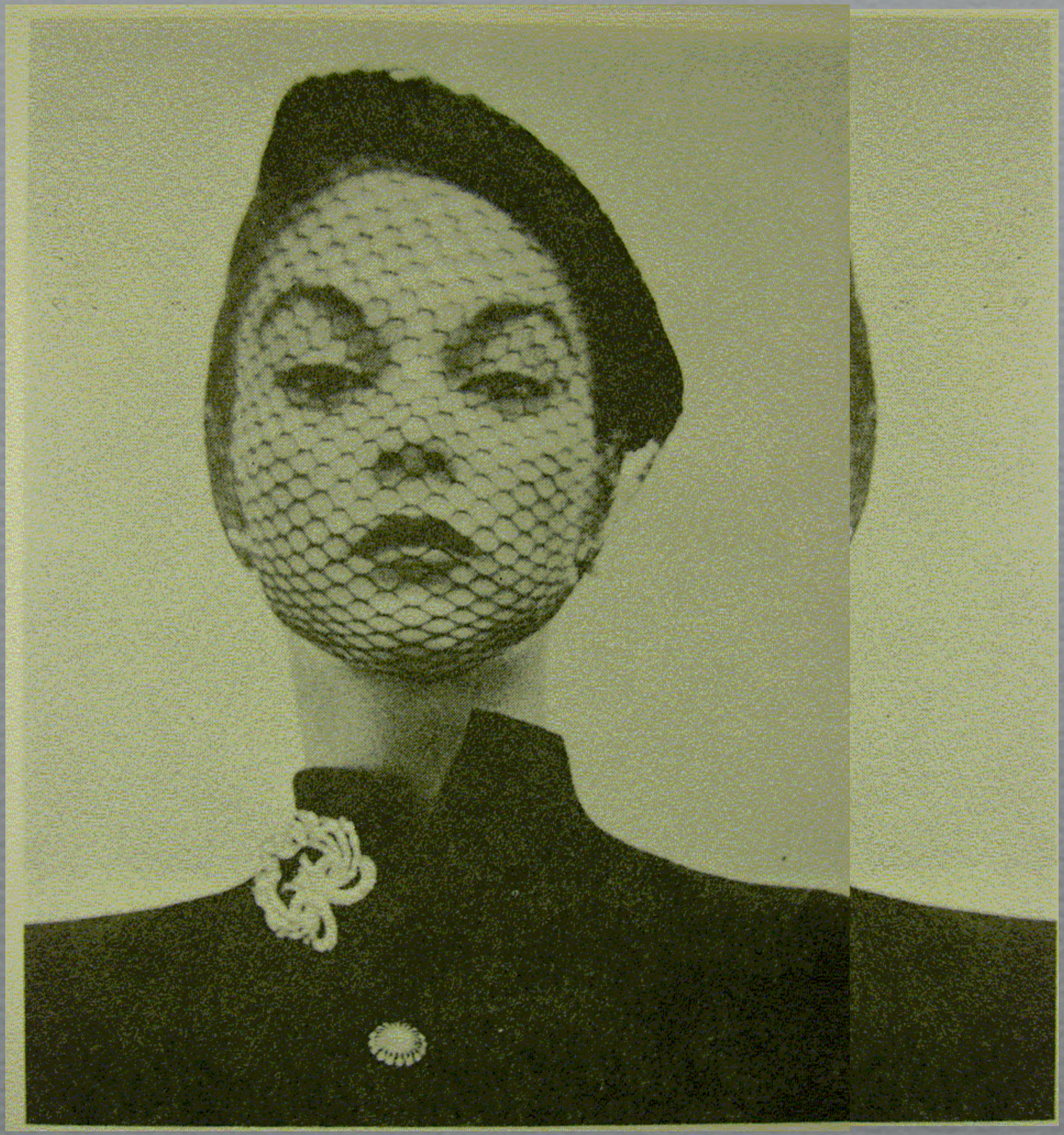
A disconcerting experience for even the harshest critic.

# 對稱一定會美嗎？



左 ↔ 右





完全左右對稱

美麗嗎?

# 王菲


NO.156
2000年10月28日~11月03日
每套100元
精采生活
八卦糾紛特集
李靖
打官
明星跑法院高人
演唱會
主辦單位要
謝霆
全裸

# 對稱的王菲

# 張柏芝


張柏芝＝林青霞＋張曼玉

# 對稱的張柏芝


還美麗嗎？

右

右

`右’

左

左

對稱性 → 不可區分性

對稱性破壞 → 可區分性

# 連續對稱性之破缺：

Symmetry lies hidden under spontaneous violations

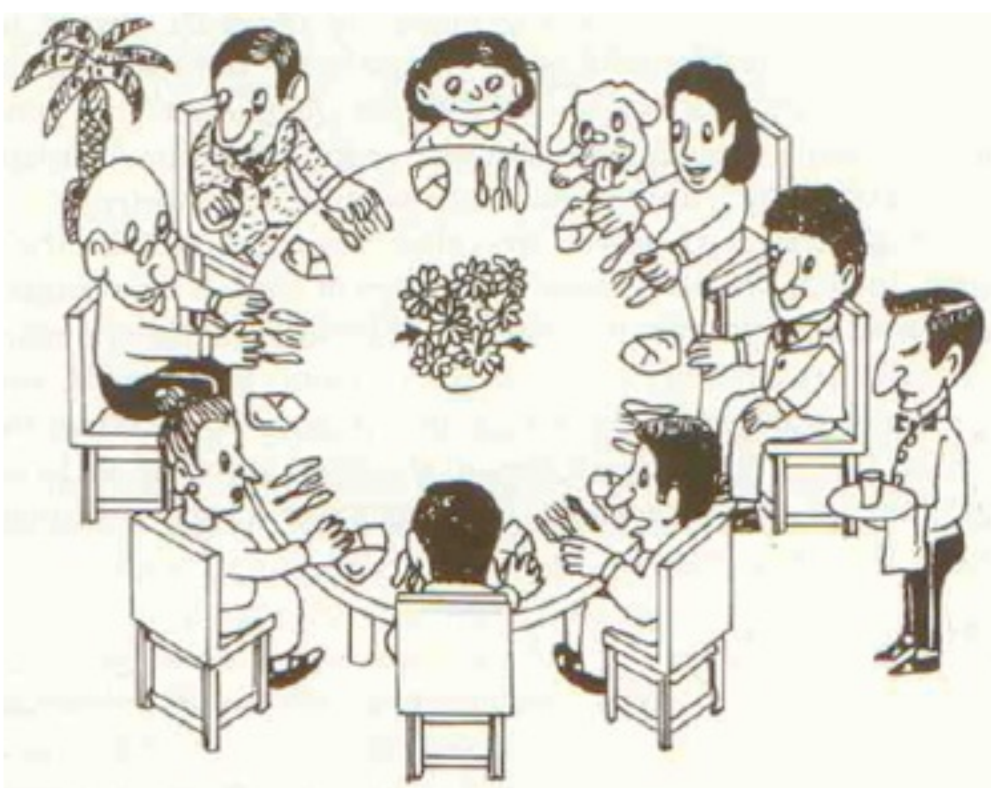
Pencil balanced on end has rotational symmetry about vertical axis.

Symmetry is broken when pencil falls over.

自發對稱性破缺

Special direction is specified.

**But, underlying law of gravity is still symmetrical.**



Spontaneous symmetry breaking — Salam's analogy.

From ``Quarks”, by Y. Nambu 1981 (Japanese); 1985(English)

# In the 1960s, Yoichio Nambu pioneered a radical idea:

***the symmetry of a beautiful theory could be subtly broken.***

***Nambu*** **showed that even if a theory appears symmetrical, it could actually be unstable if a lower energy state exists in which that symmetry is broken. Perhaps, he said, our infant universe was originally symmetrical but was also unstable. Suddenly, this symmetry broke, and the universe burst into a lower energy state,unleashing a tidal wave of energy.This could be the origin of the Big Bang.**

***Nambu was the first to introduce spontaneous symmetry violation into elementary particle physics.***

Y. Nambu, "A 'Superconductor' Model of Elementary Particles and its Consequencies", Talk given at a conference at Purdue (1960), reprinted in "Broken Symmetries, Selected Papers by Y. Nambu", ed:s T. Eguchi and K. Nishijima, World Scientific (1995).

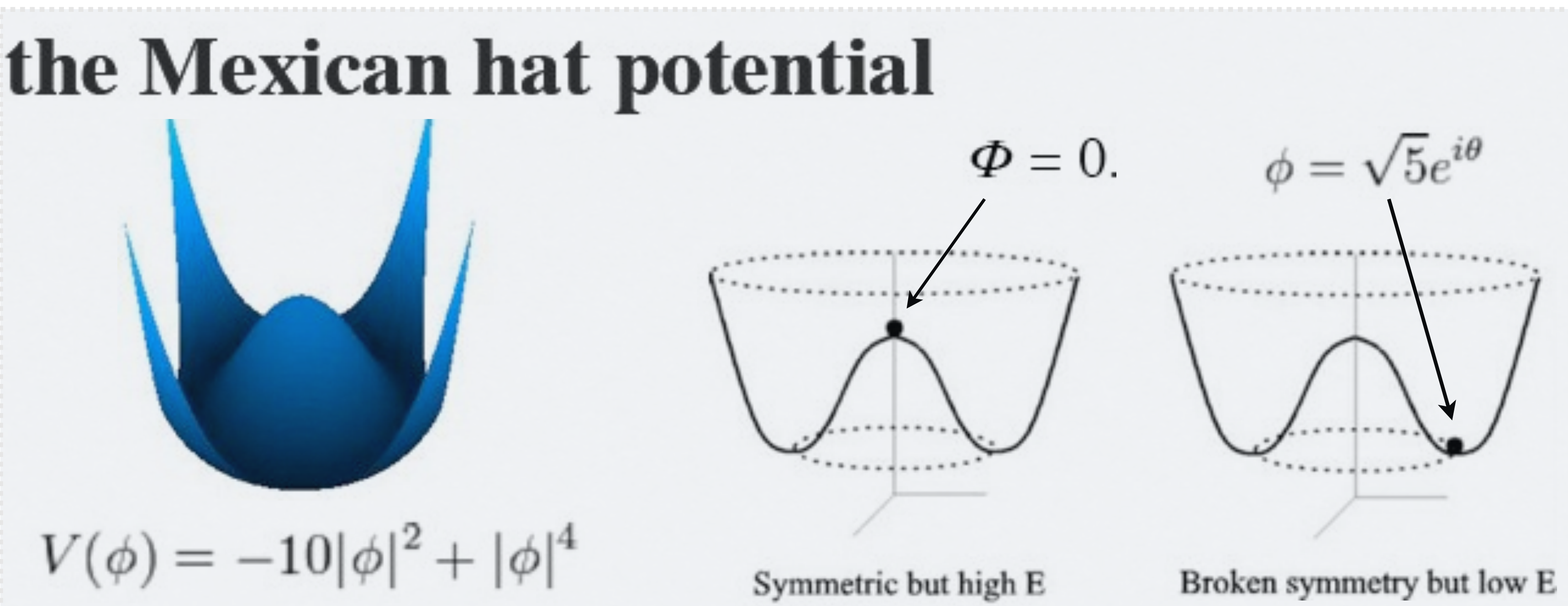
Y. Nambu and G. Jona-Lasinio, "A Dynamical Model of Elementary Particles based on an Analogy with Superconductivity I", Phys. Rev. **122** (1961) 345;
Y. Nambu and G. Jona-Lasinio, "A Dynamical Model of Elementary Particles based on an Analogy with Superconductivity II", Phys. Rev. **124** (1961) 246;

The action for a meson field $\phi$ interacting with a Dirac fermion field $\psi$ is

$$S[\phi,\psi] = \int d^d x\ [\mathcal{L}_{\text{meson}}(\phi) + \mathcal{L}_{\text{Dirac}}(\psi) + \mathcal{L}_{\text{Yukawa}}(\phi,\psi)]$$
$$= \int d^d x \left[\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi) + \bar{\psi}(i\partial\!\!\!/ - m)\psi - g\bar{\psi}\phi\psi\right]$$

For a (renormalizable) self-interacting field: $V(\phi) = \mu^2\phi^2 + \lambda\phi^4$

Lagrangian exhibits spontaneous symmetry breaking (SSB) when $\mu^2<0$




Minimum $V(\Phi)$

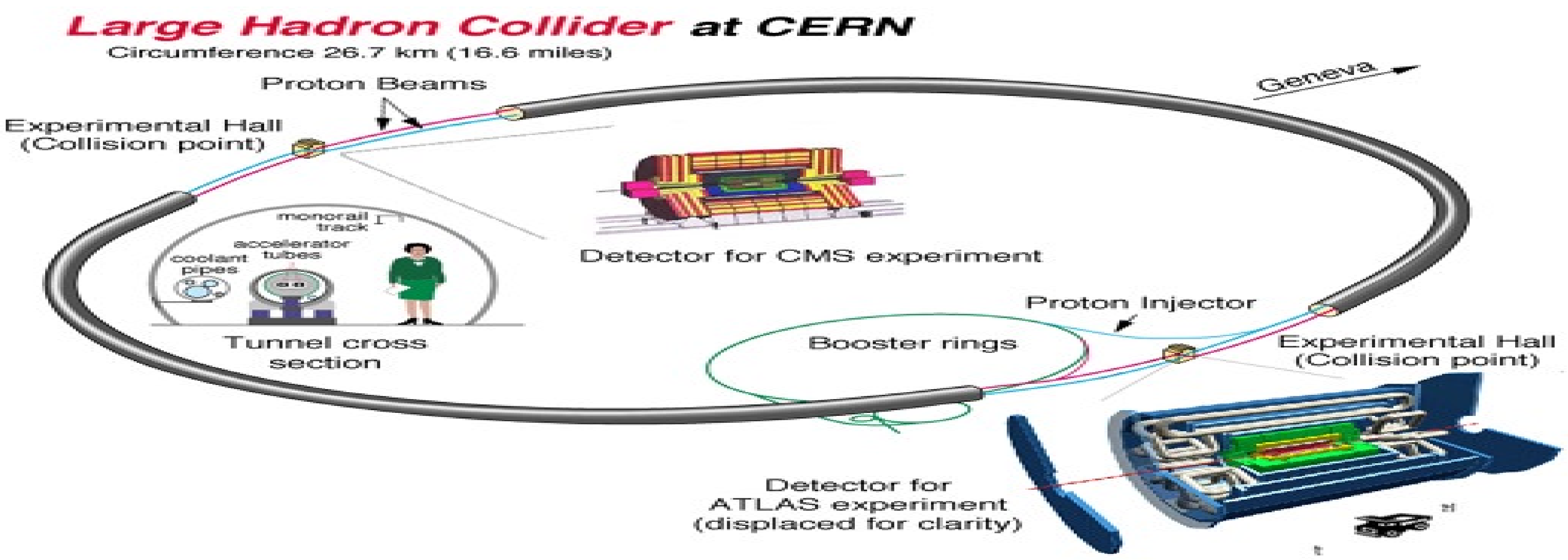
- $\Phi=0$ → symmetric, no broken symmetry
- $\Phi=\Phi_0=(-\mu^2/2\lambda)^{1/2}$ → broken symmetry, SSB

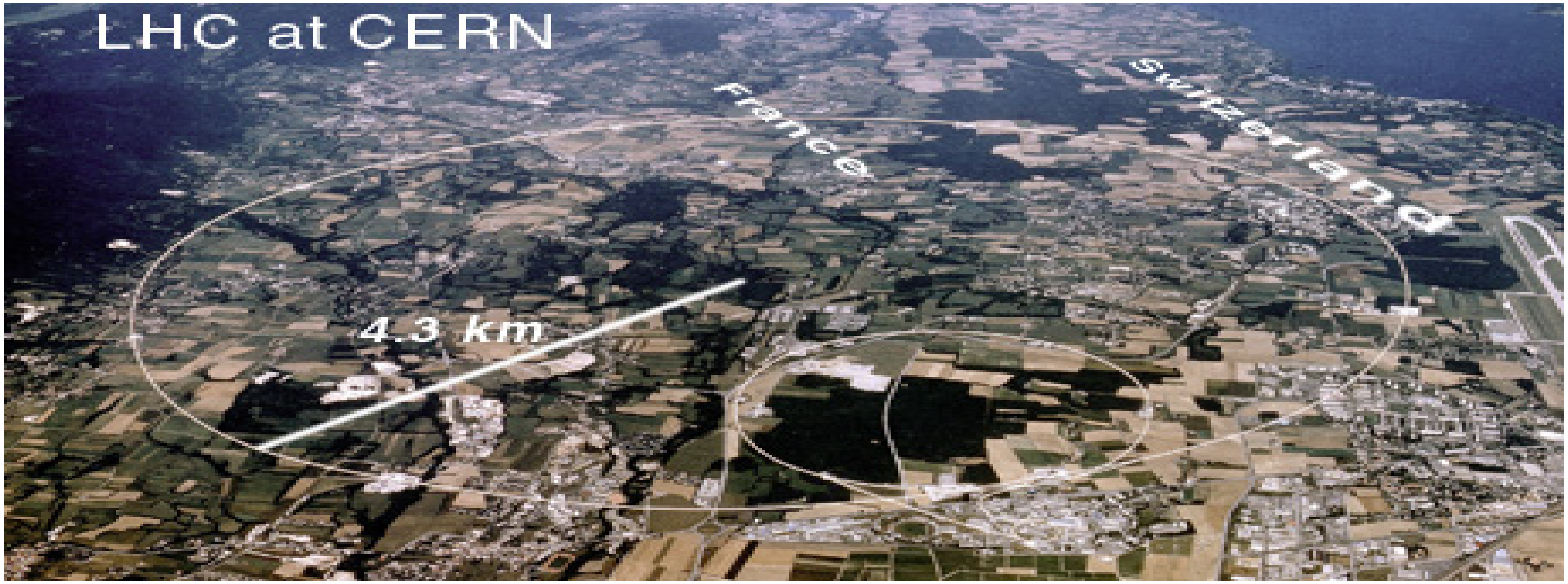
In the Standard Model, $\Phi_0$ is responsible for the fermion masses: $g\phi_0\bar{\psi}\psi$

$\tilde{\phi} = \phi - \phi_0$ ***is known as the Higgs field.***

# Search for the Higgs Particle at the LHC

One of the main goals of the LHC program is to discover and study the Higgs particle. The Higgs particle is of critical importance in particle theories and is directly related to the concept of particle mass and therefore to all masses.



# 分立對稱性之破缺

- P： 宇稱 或 空間反演　$x \longleftrightarrow -x$
- T： 時間反演　$t \longleftrightarrow -t$
- C： 粒子和反粒子交換 或 電荷共軛

粒子 ⟷ 反粒子

粒子物理：三種非常重要的分立對稱性 -- C, P, 和 T 宇稱

很多年來,物理學的規律被認為是 P, C,和 T,守恆的

在電磁作用中, P , C 和 T 是守恆的！
同樣在強作用中,P, C 和 T 也是守恆的！

在弱作用中,它們是守恆的嗎？

眾所周知, 美國著名華人物理學家李政道和楊振寧博士在1956年指出：在弱作用力中, P 和 C是極大破壞的！
為此他們榮獲1957年的NOBEL物理學獎

1964年，在美國BNL國家實驗室，Fitch和Cronin等人發現了 反常的中性 K介子弱衰變 ：→ CP 破壞。

--Fitch和Cronin榮獲了1980年的NOBEL物理學獎

1998年，在FNAL (KTeV) 和CERN (CPLEAR)分別觀測到了在弱作用T破壞現象。

弱交互作用力：**P**，**C**，**CP** 和 **T** 都是破壞的


Is the weak interaction God’s mistake?

Creation of Adam (Michelangelo, in Sistine Ceiling)

上帝創造的第一個男人：亞當

God’s right hand, on the right, touches life into Adam’s left.

Right=對, Left 拉丁文 Sinister = Evil 邪惡，罪過

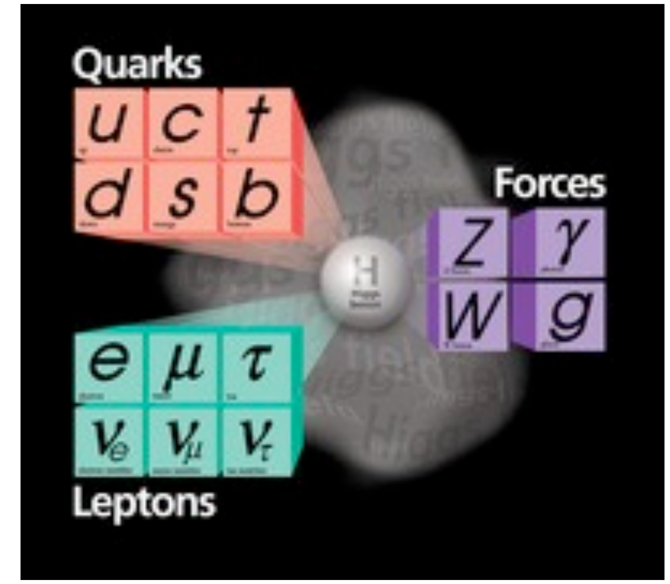
- **The standard model:** $SU(3)_C \times SU(2)_L \times U(1)_Y$

$$Q_L : \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L \quad L_L : \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

$$U_R : u_R \quad c_R \quad t_R$$

$$D_R : d_R \quad s_R \quad b_R \quad E_R : e_R \quad \mu_R \quad \tau_R$$

Higgs : $H^0$ Gauge Bosons : $W^\pm$, $Z$, $\gamma$, $g$

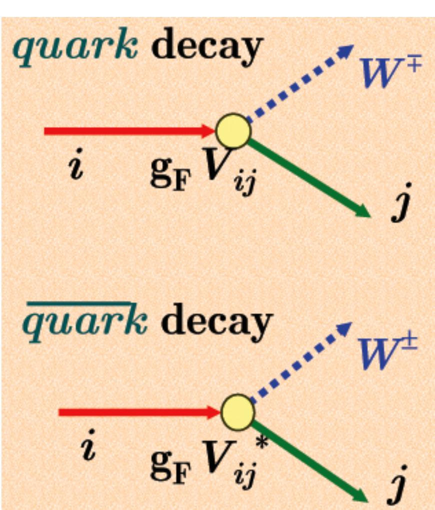



Yukawa interactions: $$Y = \sum_{i,j} h^d_{ij} \bar{Q}_L \phi D_R + h^u_{ij} \bar{Q}_L \tilde{\phi} U_R + h^e_{ij} \bar{L}_L \phi E_R + h.c.$$

$\Phi=\Phi_0=(-\mu^2/2\lambda)^{1/2}$
SSB

$$V_L^{d+} M_d V_R^d = M_d^{diag.} \; , \; D_{L(R)_j} = (V^d_{L(R)})_{ji} D'_{L(R)_i}$$
$$V_L^{u+} M_u V_R^u = M_u^{diag.} \; , \; U_{L(R)_j} = (V^u_{L(R)})_{ji} U'_{L(R)_i}$$

Gauge couplings $W^\pm$ : $$\sum_i \bar{U}_{Li} \gamma_\lambda D_{Li} \longrightarrow \sum_{ij} \bar{U}'_{Lj} \gamma_\lambda V_{ji} D'_{Li}$$




$$V = (V_L^u)^+ V_L^d \, , \; (V^+ V = 1)$$

– Kobayashi-Maskawa (KM) matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

M. Kobayahsi and K. Maskawa, "CP Violation in the Renormalizable Theory of Weak Interactions", Progr. Theor. Phys. **49** (1973) 652.

$V = (V_L^u)^+ V_L^d$ , $(V^+ V = 1)$

Unitary matrix:

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Counting the parameters:

$n \times n$ complex matrix : $2n^2$

$n \times n$ unitary matrix : $n^2$

rot. angles : $\frac{n(n-1)}{2}$

phases : $n^2 - \frac{n(n-1)}{2} = \frac{n(n+1)}{2}$

Some of the phases in $V$ can be removed by choosing the $(2n-1)$ phase differences $\theta_j - \phi_i$ appropriately.

$u_L^i \to e^{i\phi_i} u_L^i$ , $d_L^i \to e^{i\theta_i} d_L^i$ ⟶ $V_{ij} \to V_{ij}\, e^{i(\theta_j - \phi_i)}$

⟹ observable or physical phases : $\frac{n(n+1)}{2} - (2n-1) = \frac{(n-1)(n-2)}{2}$

For two generations $(n=2)$ ⟶ **no phase** + 1 angle

For three generations $(n=3)$ ⟶ one phase + 3 angles

三代夸克之存在 ⟶ CP對稱性破缺

$$V_{CKM} = \begin{pmatrix} c_1 & -s_1c_3 & -s_1s_3 \\ s_1c_2 & c_1c_2c_3 - s_2s_3e^{i\delta} & c_1c_2s_3 + s_2c_3e^{i\delta} \\ s_1s_2 & c_1s_2c_3 + s_2s_3e^{i\delta} & c_1s_2s_3 - c_2c_3e^{i\delta} \end{pmatrix},$$

CKM=Cabibbo, Kobayashi, Maskawa

where $s_1 = \sin\theta_1, c_1 = \cos\theta_1$, etc. and the explicit phase $\delta$ is seen.

Paticle Data Group:

$$V_{CKM} = = \begin{pmatrix} c_1c_3 & s_1c_3 & s_3e^{-i\delta} \\ -s_1c_2 - c_1s_2s_3e^{i\delta} & c_1c_2 - s_1s_2s_3e^{i\delta} & s_2c_3 \\ s_1s_2 - c_1c_2s_3e^{i\delta} & -c_1s_2 - s_1c_2s_3e^{i\delta} & c_2c_3 \end{pmatrix}$$

CKM=Chau, Keung, Matrix

$$V = \begin{pmatrix} Vud & Vus & Vub \\ Vcd & Vcs & Vcb \\ Vtd & Vts & Vtb \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{pmatrix} + o(\lambda^4)$$

$\lambda = 0.2235 \pm 0.0033$ $A = 0.81 \pm 0.08$ $|\rho - i\eta| = 0.36 \pm 0.09$ $|1-\rho-i\eta| = 0.79 \pm 0.19$

~~CP~~

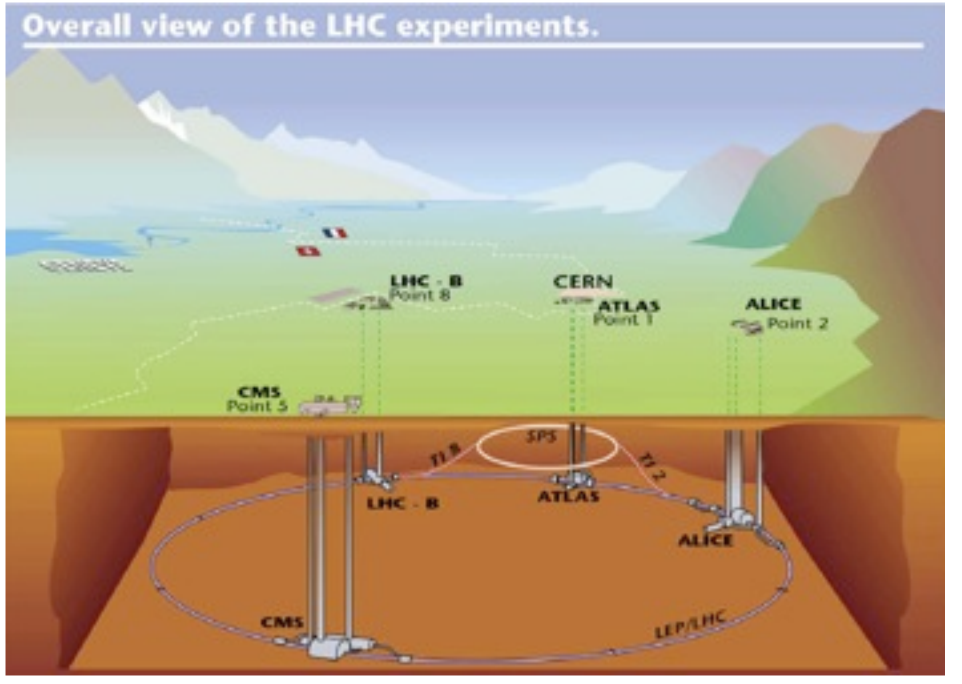
**Large in B decays**

**BaBBa and Belle**

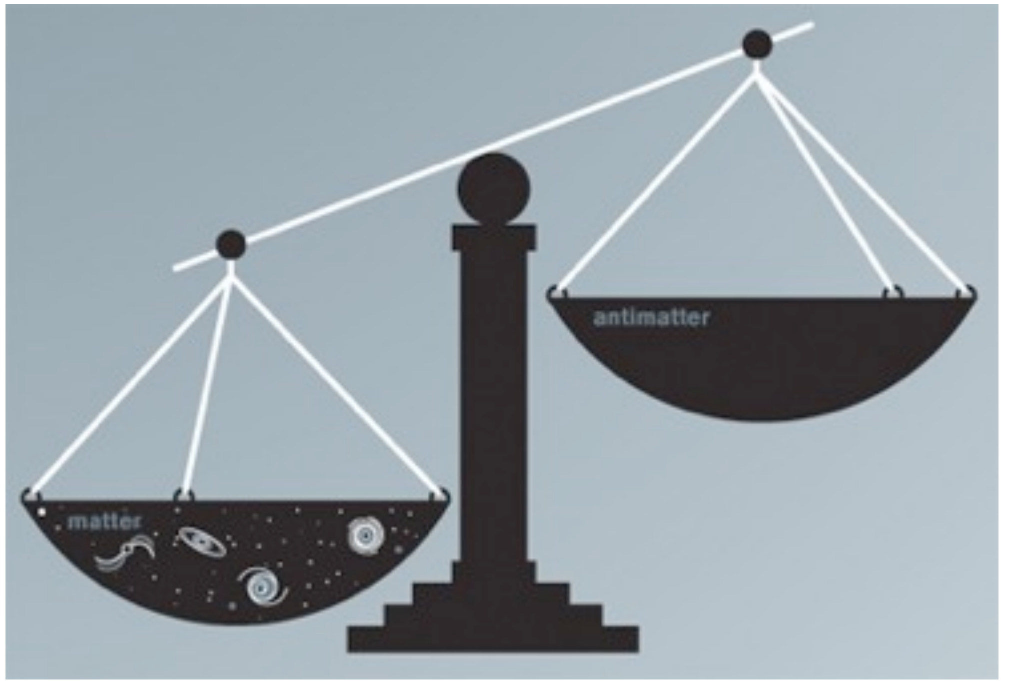
但是，**CKM**之**CP**破缺機制不能解識「宇宙物質與反物質之不對稱性」

尚未解決之問題

*The Higgs particle at the LHC??*




*Matter and Anti-matter asymmetry?*




- *Why are there three types of quarks and leptons?*
- *Is there some pattern to their masses?*
- *Are there more types of particles and forces to be discovered at yet higher energy accelerators?*
- *Are the quarks and leptons really fundamental, or do they, too, have substructure?*
- *How to include the gravitational interactions in the SM?*
- *How to understand dark matter and dark energy in the universe?*

未來展望與結束語

*Heroic Period (1960 -- 1975):*

Nobel Prizes in Particle Physics: [work done]
20xx: ?
20xx: Goldstone, Higgs – Higgs particle [1961,1964]
2008: Nambu,Kobayashi,Maskawa–broken symmetry [1961,1973]
2004: Gross, Politzer, Wilczek–asymptotic freedom [1973]
1999: 't Hooft, Veltman–electroweak force [1972]
1995: Perl,Reines–tau lepton [1975], electron neutrino [1953]
1990: Friedman, Kendall, Taylor–quark model [1972]
1988: Lederman,Schwartz,Steinberger -muon neutrino [1962]
1980: Cronin, Fitch–symmetry breaking (CP violation) [1964]
1979: Glashow, Salam, Weinberg–electroweak theory [1961,67]
1976: Richter,Ting–charge quark (J/Psi) [1974]
1969: Gell-Mann–classification of elementary particles [1964]

**more?**

**=10**

*6. Super-Heroic Period (2005 –2020)*

**How many Nobel Prizes in Particle Physics for the Super-Heroic Period?**

**>10**

# Thank you!

謝謝！