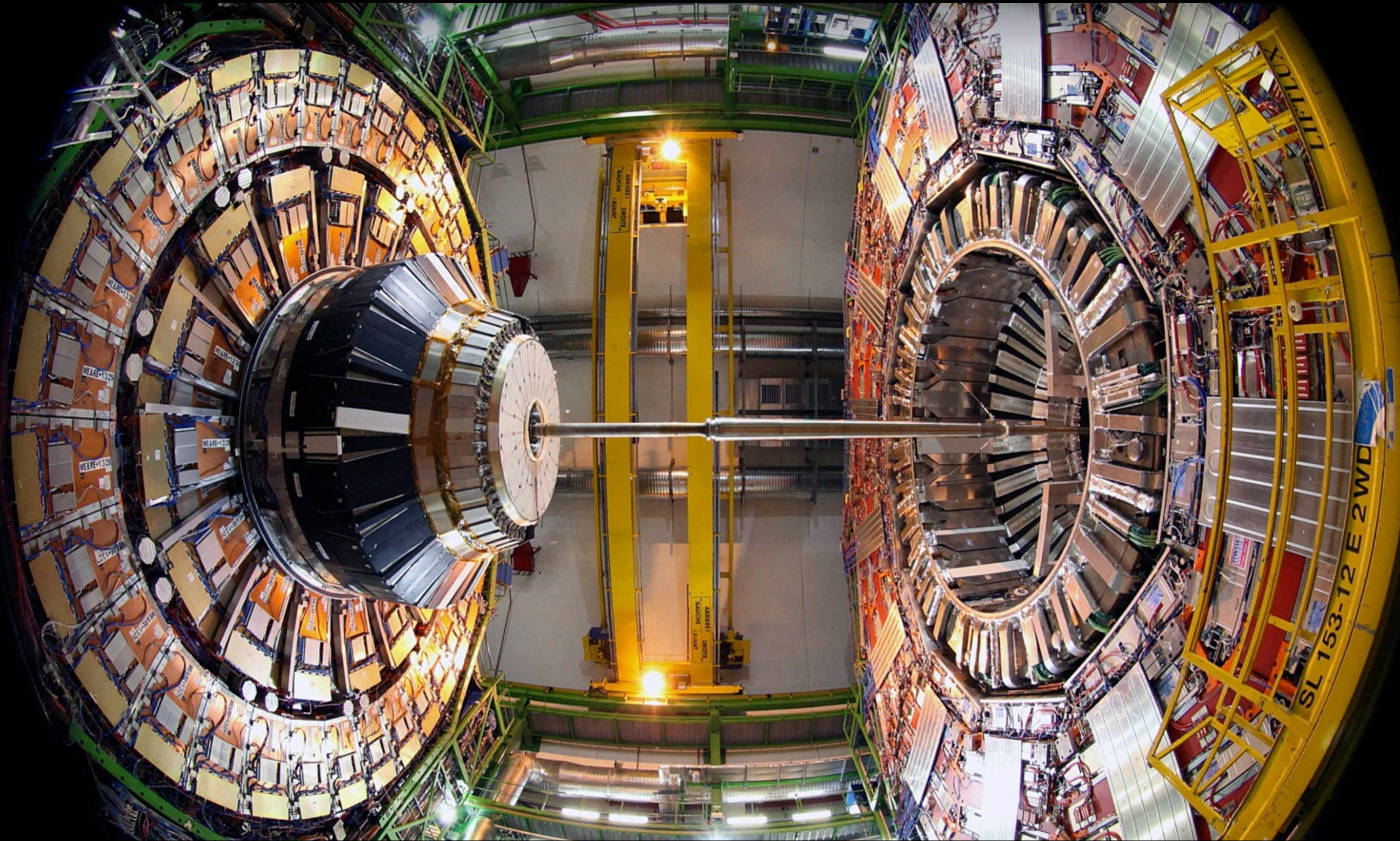


标准模型弱电理论和新物理



曹庆宏 (理论物理研究所)



“世界基本组成成分为何？”

和

“它们如何相互作用？”

粒子物理 和 宇宙学

研究自然界的
基本相互作用（力）

粒子物理:探测更深层次和更高能量

厘米:

流体 (经典流体力学)

10^{-5} 厘米:

分子 (分子运动学)

10^{-8} 厘米:

原子 (量子力学)

10^{-13} 厘米:

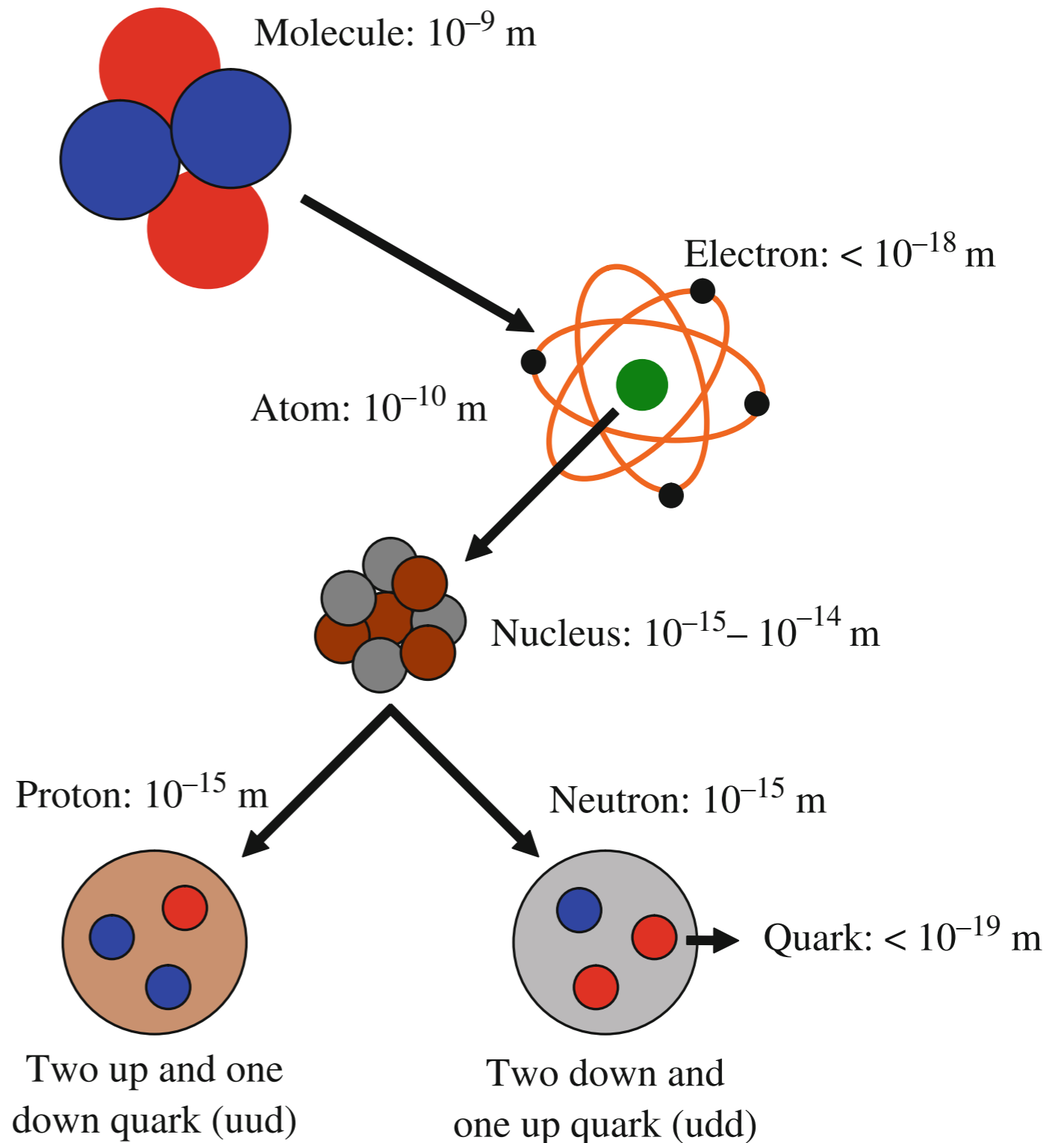
核子 (核物理)

$10^{-13} \sim 10^{-18}$ 厘米:

夸克 (量子色动力学)

10^{-33} 厘米:

弦理论



自然单位制：微观世界语言

高能物理中大部分情形下，基本粒子间的相互作用仅仅发生在极高能量和极短距离

$$\hbar = c = k_B = 1$$

$$[\text{长度}] = [\text{时间}] = [\text{质量}]^{-1} = [\text{温度}]^{-1} = [\text{能量}]^{-1}$$

\hbar 量子性质

c 相对论性质

k_B 热力学性质

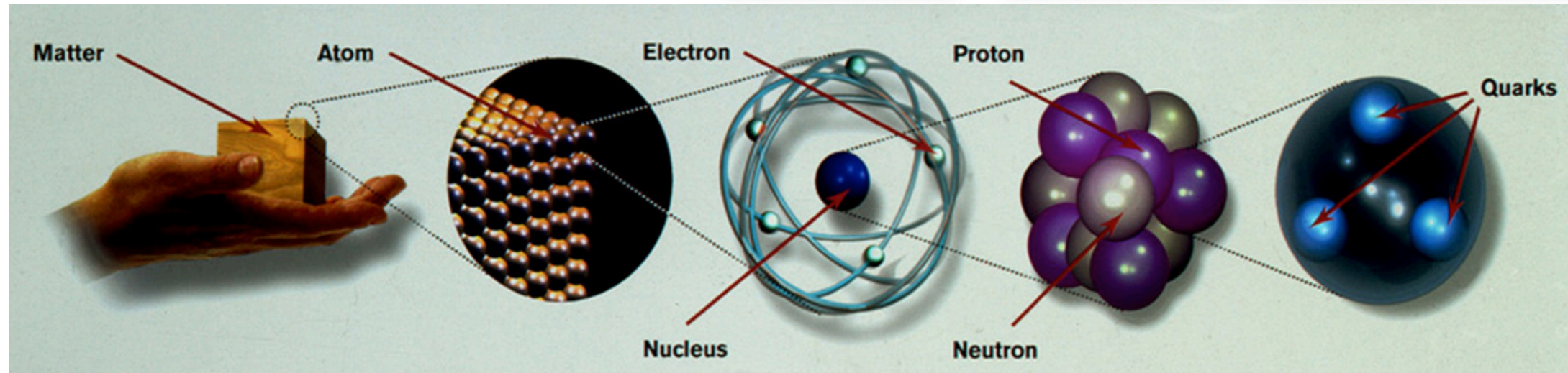
需要仔细处理
微观世界的理论结论
推广到
宏观世界的观测量

粒子物理:探测更深层次和更高能量

10^{-10} m

10^{-14} m

10^{-15} - 10^{-18} m



Motion of air atom
 $E = 0.04$ eV

Chemical reactions/atom
 $E = 1$ to a few eV

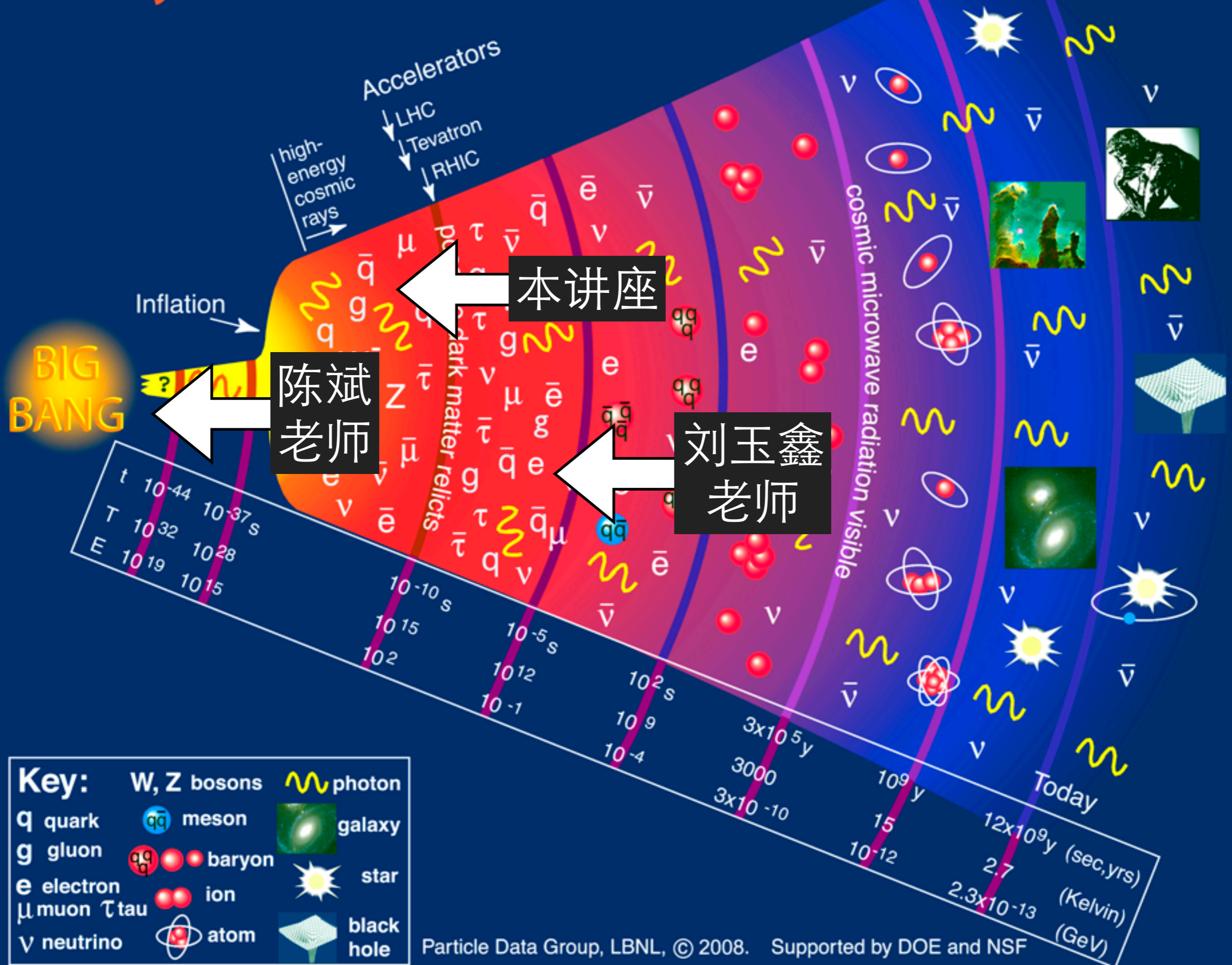
Nuclear reactions/atom
 $E = \text{Millions of eV (MeV)}$

Energy $E=mc^2$ of proton
 $E \sim 1 \text{ Billion eV (GeV)}$

大型强子对撞机可以探测 10^{-20} 米

每个质子的能量是4TeV (4×10^{12} eV)
相当于宇宙大爆炸后 10^{-12} 到 10^{-11} 秒的温度

History of the Universe



陈斌老师

本讲座

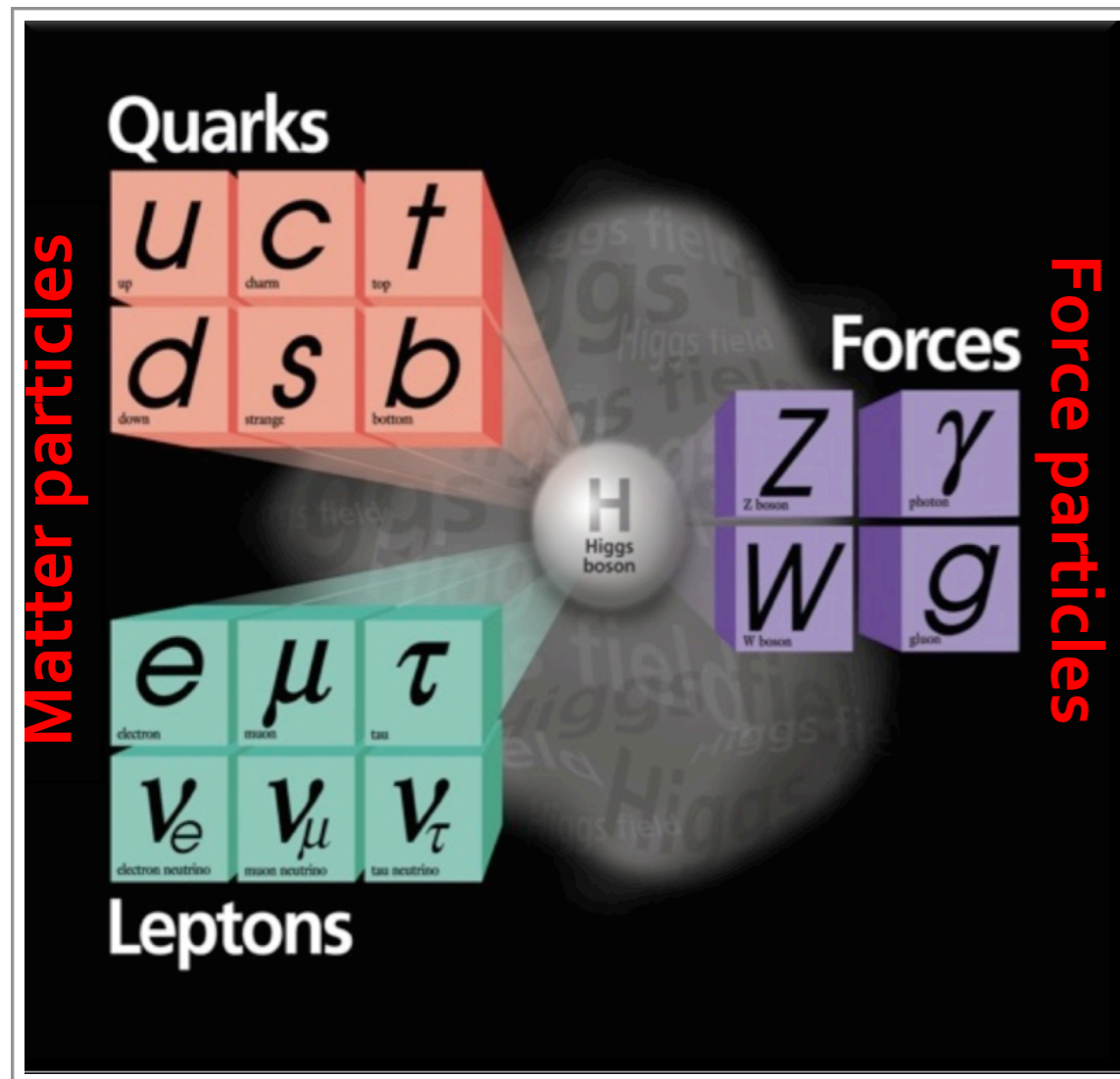
刘玉鑫老师

粒子物理的标准模型

集百年物理之大成

新“元素周期表”

20世纪自然科学
的卓越成就之一



宇宙万物可以用一个简单公式描述

$$\begin{aligned}
\mathcal{L}_{\text{SM}} = & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c \\
& -\partial_\nu W_\mu^+ \partial_\nu W_\mu^- - M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \Phi^+ \partial_\mu \Phi^- \\
& -M^2 \Phi^+ \Phi^- - \frac{1}{2}\partial_\mu \Phi^0 \partial_\mu \Phi^0 - \frac{1}{2c_w^2} M \Phi^0 \Phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \Phi^0 \Phi^0 + 2\Phi^+ \Phi^-) \right] + \frac{2M^4}{g^2} \alpha_h \\
& -igc_w \left[\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+) \right] \\
& -igs_w \left[\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+) \right] \\
& -\frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) \\
& +g^2 s_w c_w \left[A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^- \right] - g\alpha \left[H^3 + H\Phi^0 \Phi^0 + 2H\Phi^+ \Phi^- \right] \\
& -\frac{1}{8}g^2 \alpha_h \left[H^4 + (\Phi^0)^4 + 4(\Phi^+ \Phi^-)^2 + 4(\Phi^0)^2 \Phi^+ \Phi^- + 4H^2 \Phi^+ \Phi^- + 2(\Phi^0)^2 H^2 \right] - gM W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H \\
& -\frac{1}{2}ig \left[W_\mu^+ (\Phi^0 \partial_\mu \Phi^- - \Phi^- \partial_\mu \Phi^0) - W_\mu^- (\Phi^0 \partial_\mu \Phi^+ - \Phi^+ \partial_\mu \Phi^0) \right] + \frac{1}{2}g \left[W_\mu^+ (H \partial_\mu \Phi^- - \Phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \Phi^+ - \Phi^+ \partial_\mu H) \right] \\
& +\frac{1}{2}g \frac{1}{c_w} Z_\mu^0 (H \partial_\mu \Phi^0 - \Phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \Phi^- - W_\mu^- \Phi^+) + igs_w M A_\mu (W_\mu^+ \Phi^- - W_\mu^- \Phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\Phi^+ \partial_\mu \Phi^- \\
& -\Phi^- \partial_\mu \Phi^+) + igs_w A_\mu (\Phi^+ \partial_\mu \Phi^- - \Phi^- \partial_\mu \Phi^+) - \frac{1}{4}g^2 W_\mu^+ W_\mu^- \left[H^2 + (\Phi^0)^2 + 2\Phi^+ \Phi^- \right] - \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\Phi^0)^2 \\
& +2(2s_w^2 - 1)^2 \Phi^+ \Phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \Phi^0 (W_\mu^+ \Phi^- + W_\mu^- \Phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \Phi^- - W_\mu^- \Phi^+) + \frac{1}{2}g^2 s_w A_\mu \Phi^0 (W_\mu^+ \Phi^- + W_\mu^- \Phi^+) \\
& +\frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \Phi^- - W_\mu^- \Phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \Phi^+ \Phi^- - g^1 s_w^2 A_\mu A_\mu \Phi^+ \Phi^- - e^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \nu^\lambda \gamma \partial \nu^\lambda \\
& -\bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + igs_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] \\
& +\frac{ig}{4c_w} Z_\mu^0 \left[(\nu^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (e^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda) \right] \\
& +\frac{ig}{2\sqrt{2}} W_\mu^+ \left[(\nu^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa) \right] + \frac{ig}{2\sqrt{2}} W_\mu^- \left[(e^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda) \right] \\
& +\frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} \left[-\Phi^+ (\nu^\lambda (1 - \gamma^5) e^\lambda) + \Phi^- (e^\lambda (1 + \gamma^5) \nu^\lambda) \right] - \frac{g}{2} \frac{m_e^\lambda}{M} \left[H(e^\lambda e^\lambda) + i\Phi^0 (e^\lambda \gamma^5 e^\lambda) \right] \\
& +\frac{ig}{2M\sqrt{2}} \Phi^+ \left[-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) \right] + \frac{ig}{2M\sqrt{2}} \Phi^- \left[m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) \right] \\
& -\frac{g}{2} \frac{m_u^\lambda}{M} H(\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H(\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_u^\lambda}{M} \Phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_d^\lambda}{M} \Phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- \\
& +\bar{X}^0 \left(\partial^2 - \frac{M^2}{c_w^2} \right) X^0 + \bar{Y} \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + igs_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) \\
& +igs_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H \\
& +\frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} igM[\bar{X}^+ X^0 \Phi^+ - \bar{X}^- X^0 \Phi^-] + \frac{1}{2c_w} igM[\bar{X}^0 X^- \Phi^+ - \bar{X}^0 X^+ \Phi^-] + igM s_w [\bar{X}^0 X^- \Phi^+ - \bar{X}^0 X^+ \Phi^-] \\
& +\frac{1}{2}igM s_w [\bar{X}^0 X^- \Phi^+ - \bar{X}^0 X^+ \Phi^-]
\end{aligned}$$

麦克斯韦方程组

$$\oiint \mathbf{E} \cdot d\mathbf{S} = 4\pi Q$$

$$\oiint \mathbf{B} \cdot d\mathbf{S} = 0$$

$$\oint \mathbf{E} \cdot d\mathbf{r} = -\frac{1}{c} \frac{d}{dt} \iint \mathbf{B} \cdot d\mathbf{S}$$

$$\oint \mathbf{B} \cdot d\mathbf{r} = \frac{4\pi}{c} I$$

$$-\frac{1}{c} \frac{d}{dt} \iint \mathbf{E} \cdot d\mathbf{S}$$

Faraday

$$\nabla \cdot \mathbf{E} = 4\pi\rho$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{1}{c} \frac{\partial}{\partial t} \mathbf{B}$$

$$\nabla \times \mathbf{B} = \frac{4\pi}{c} \mathbf{j} + \frac{1}{c} \frac{\partial}{\partial t} \mathbf{E}$$

Maxwell

$$\partial_\mu F^{\mu\nu} = -\frac{4\pi}{c} j^\nu$$

$$\partial_\mu \tilde{F}^{\mu\nu} = 0$$

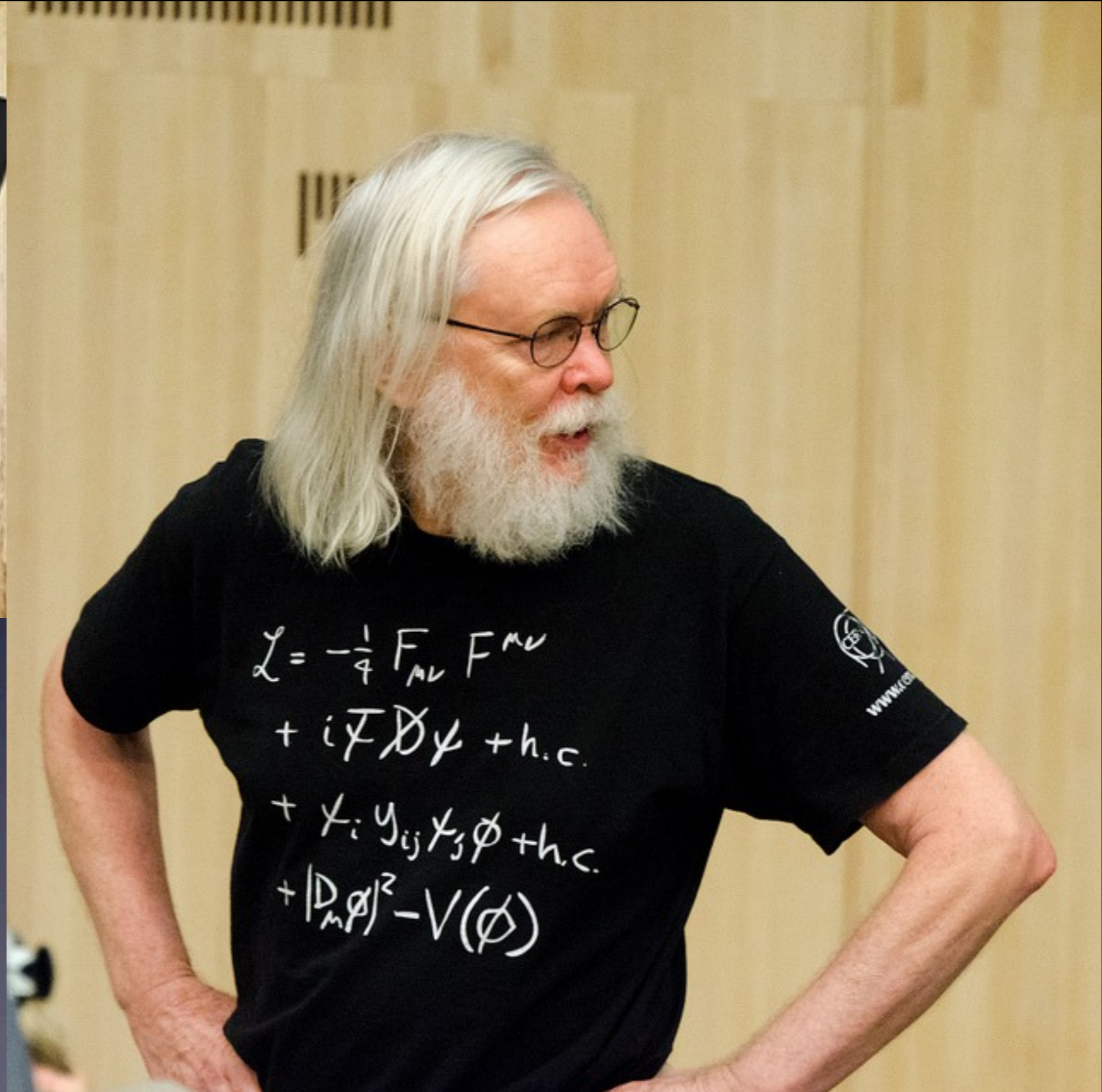
Einstein

1864年10月27日，麦克斯韦写下方程组：
283种符号，20个变量，20个方程

粒子物理的标准模型



John
Ellis



粒子物理的 标准模型

(集百年物理之大成)

费米子和玻色子

费米子：

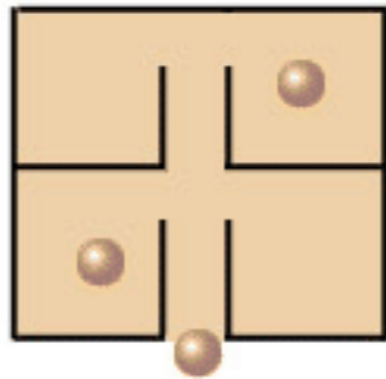
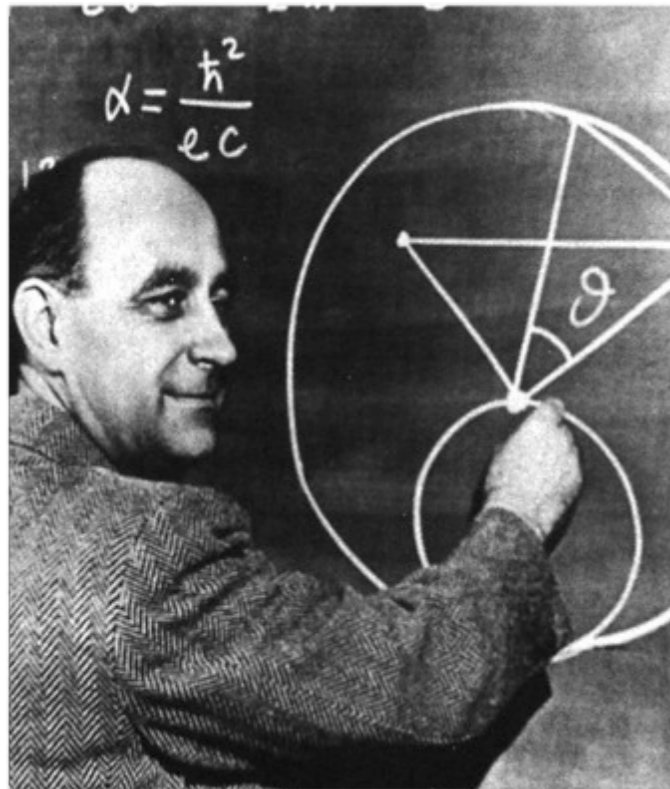
遵守**Pauli**不相容原理

自旋为半整数

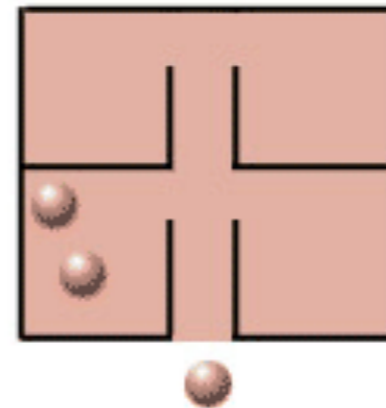
玻色子：

不遵守**Pauli**不相容原理

自旋为整数



Enrico
Fermi



Satyendra
N. Bose



物质场粒子：轻子

- 不参与强相互作用
- 整数或零电荷
- 味:

e^-	“电子”	(1897)	在原子中
μ^-	“Muon” ($206 m_e$)	(1937)	在宇宙射线中首次观测到
τ^-	“Tau” ($17 m_\mu$)	(1975)	在SLAC观测到 (Stanford Linear Accelerator Center)
ν_e	“Electron 中微子”	(1956)	泡利以之解释Beta衰变中能动量不守恒 (1930)
ν_μ	“Muon 中微子”	(1962)	
ν_τ	“Tau 中微子”	(2000)	

物质场粒子：夸克

- 参与强相互作用
- 带分数电荷

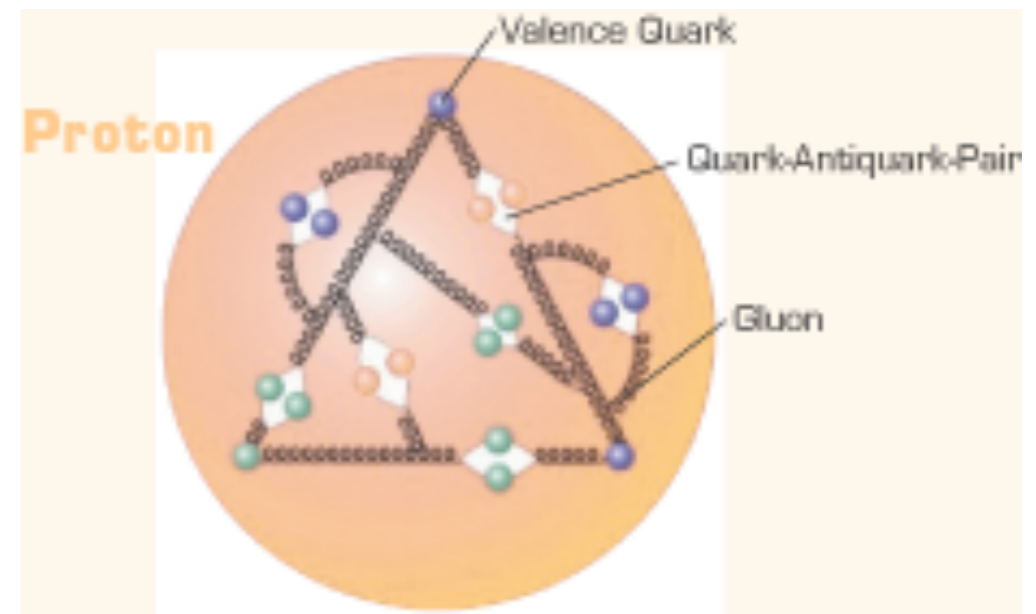
$$Q = \left\{ \begin{array}{l} 2/3 \\ -1/3 \end{array} \right\} \times \text{Proton charge}$$

- 质子和中子的组成成分
(udd) (uud)

(u) “up”
 (d) “down”

- 味:

u “up”
d “down”
s “strange”
c “charmed”
b “bottom”
t “top”



第一次实验证据:

Stanford Linear Accelerator Center
(Giant Electron Microscope)

(1974)

(1977)

1995

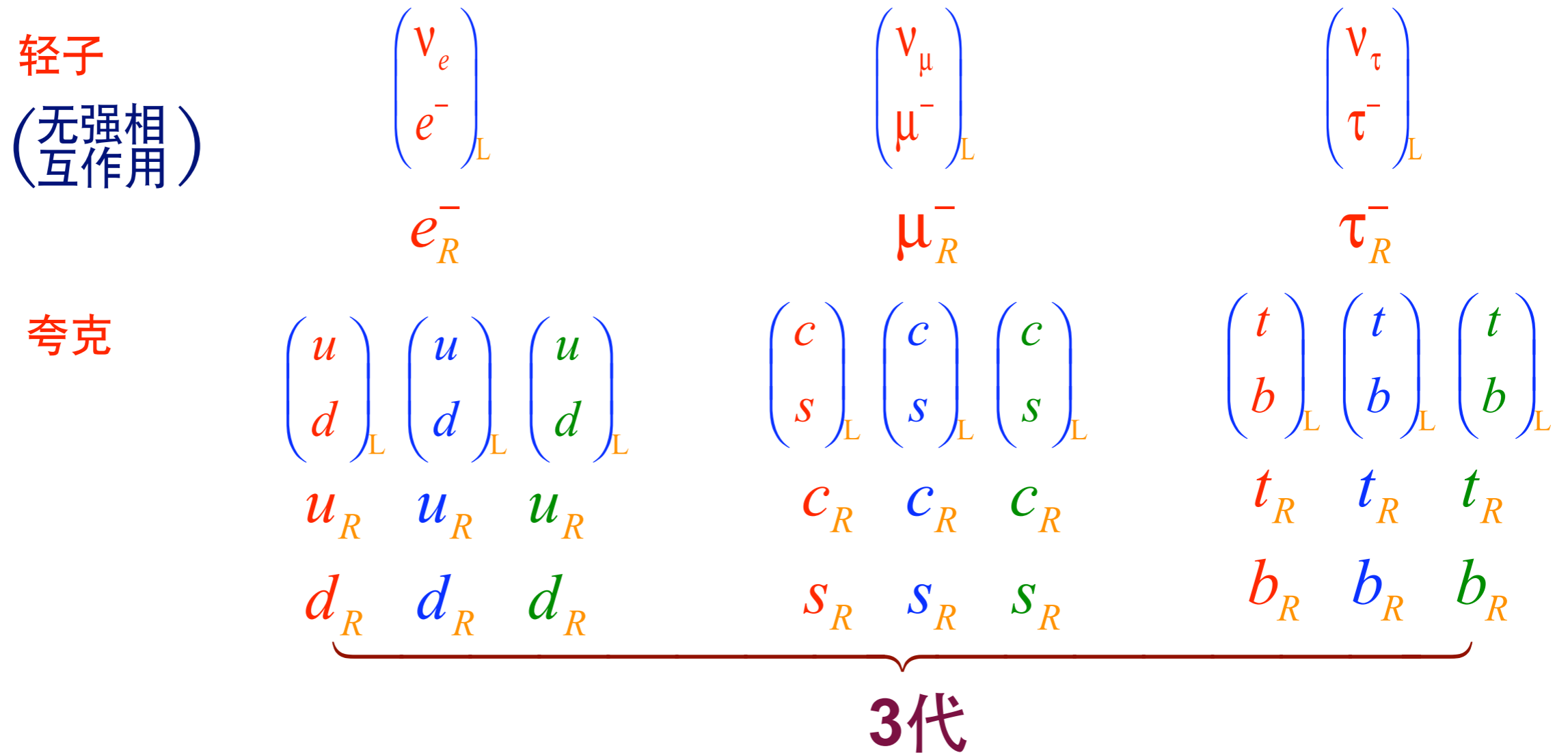
@ Fermilab (Tevatron)

“Beauty”

“Truth”

标准模型的物质场

- 费米子 (自旋 1/2)



- 标量场 (自旋为 0)

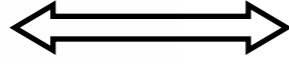
希格斯玻色子：唯一知道不同代的粒子间不同之处的粒子
(希格斯机制 —— 对称性自发破缺)

自然界中四种力

1 重力



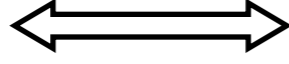
牛顿



2 电磁

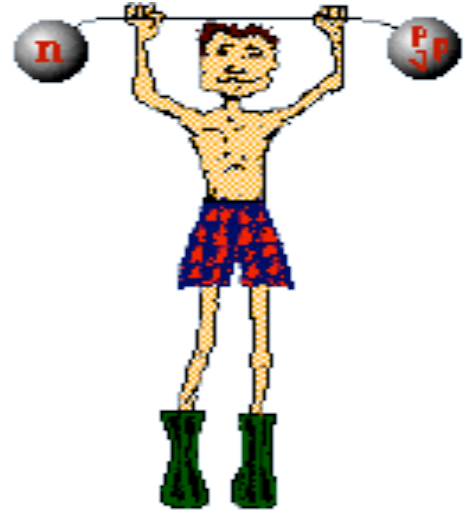


法拉第



3 弱相互作用

Beta 衰变
Muon 衰变



时间尺度: $10^{-12} \sim 10^3$ 秒

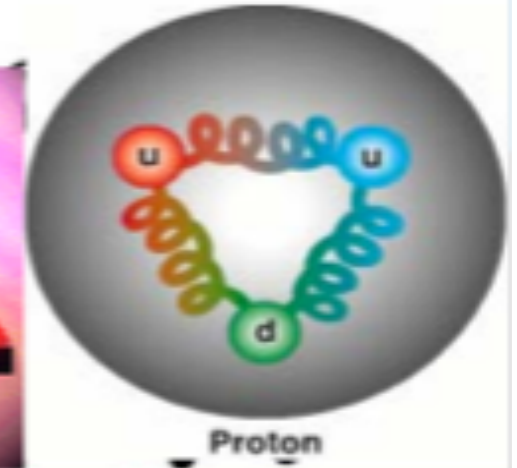
4 强相互作用

将核子紧紧
结合起来

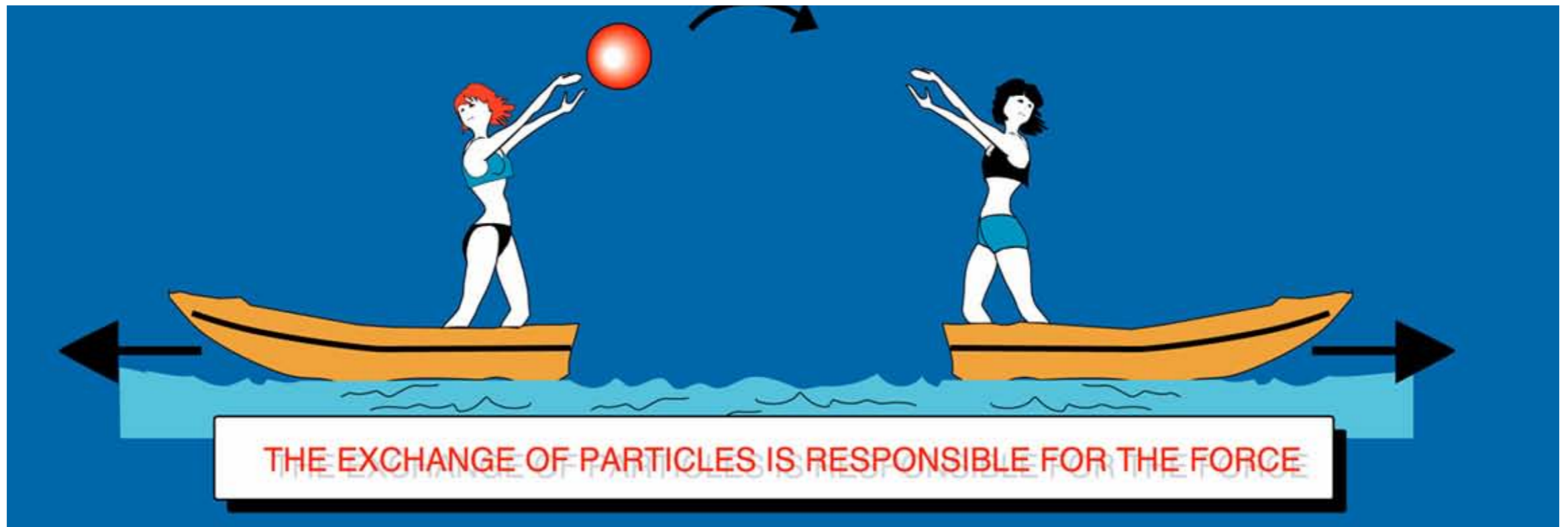


时间尺度: 10^{-23} 秒

相互作用传播子



	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



相互作用传播子

相互作用 (通过交换自旋为1的规范玻色子)

电磁相互作用 (QED)

光子 (无质量)

强相互作用 (QCD)

胶子 (无质量) (1979)

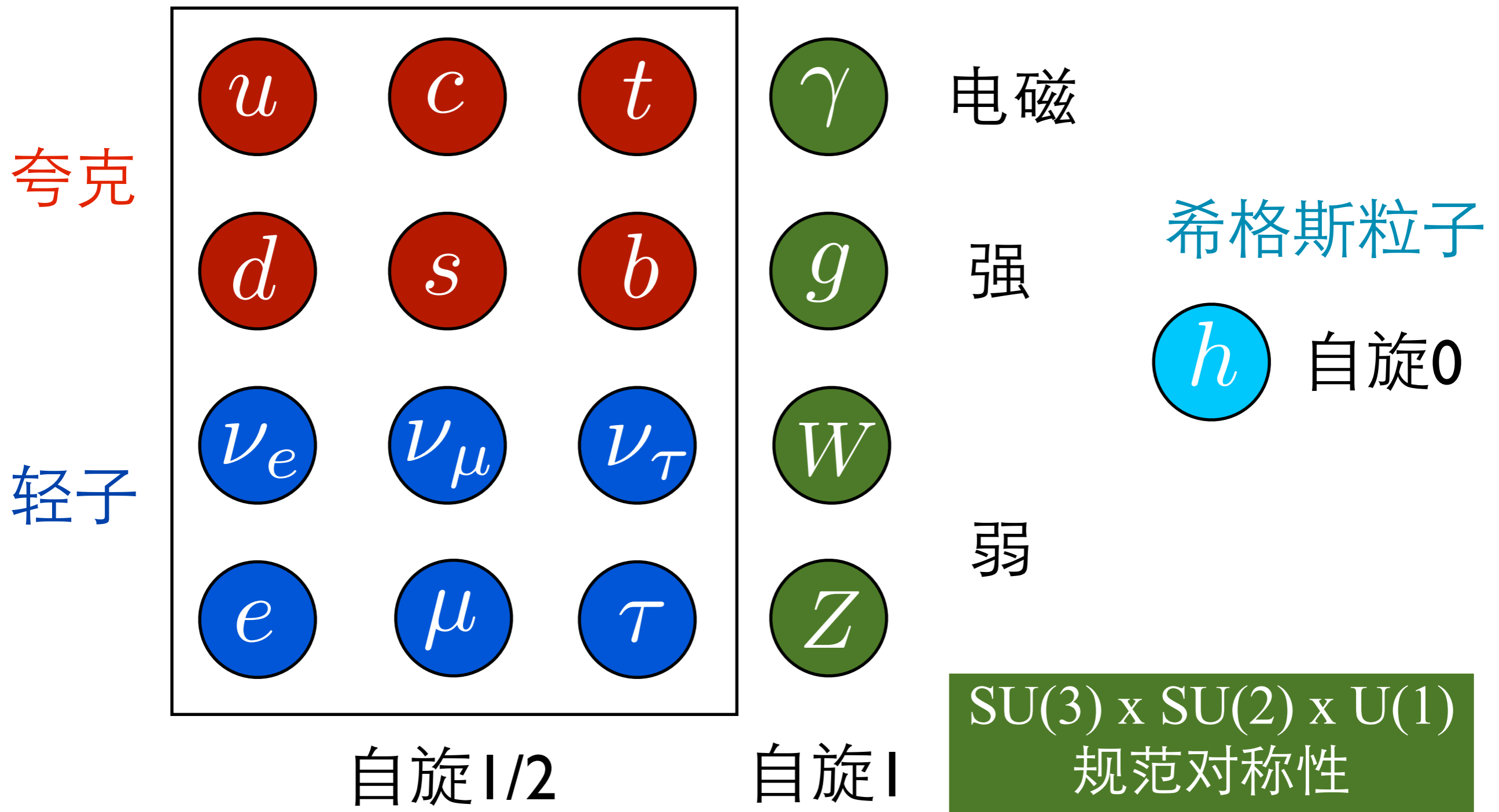
弱相互作用

W^\pm 和 Z 规范玻色子 (1983)

(有质量 $M_W = 80.4 \text{ GeV}$ $M_Z = 91.187 \text{ GeV}$ $1 \text{ GeV} = 10^9 \text{ eV}$)

粒子物理的标准模型

新“元素”周期表



规范统一之路

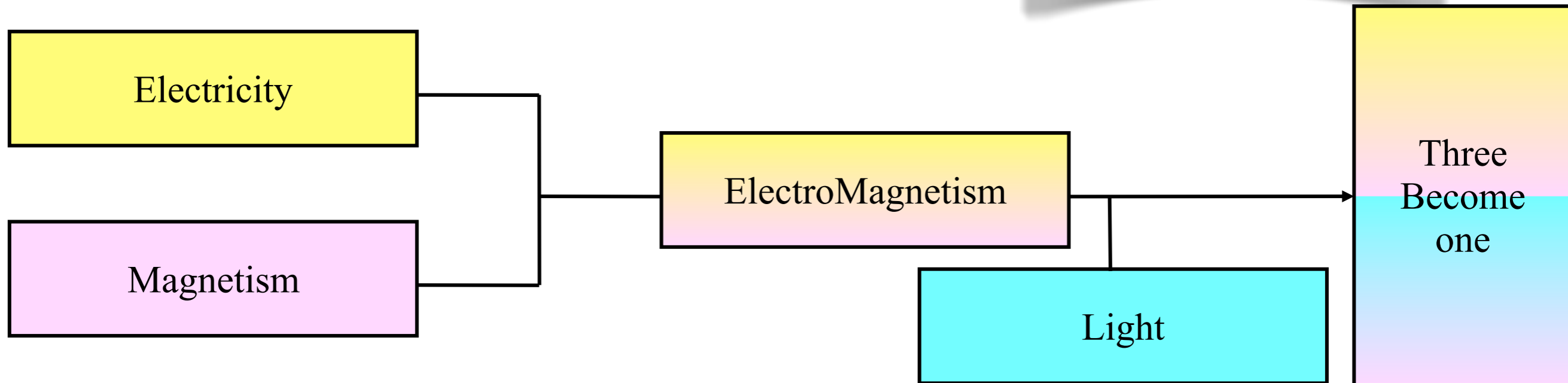
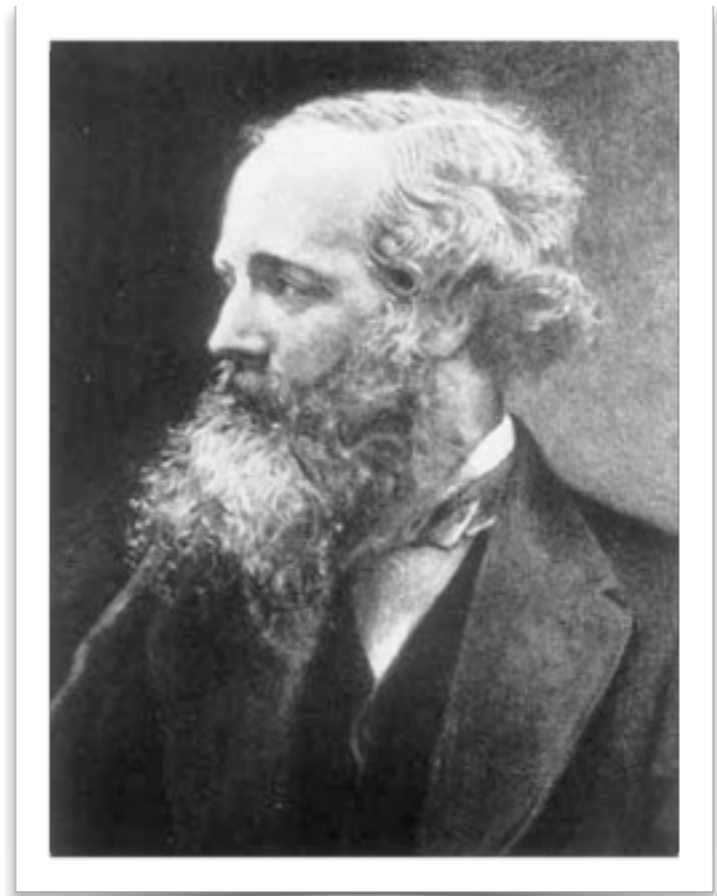
*Is there an underlying simplicity
behind vast phenomena in Nature?*



太阳、地球和苹果

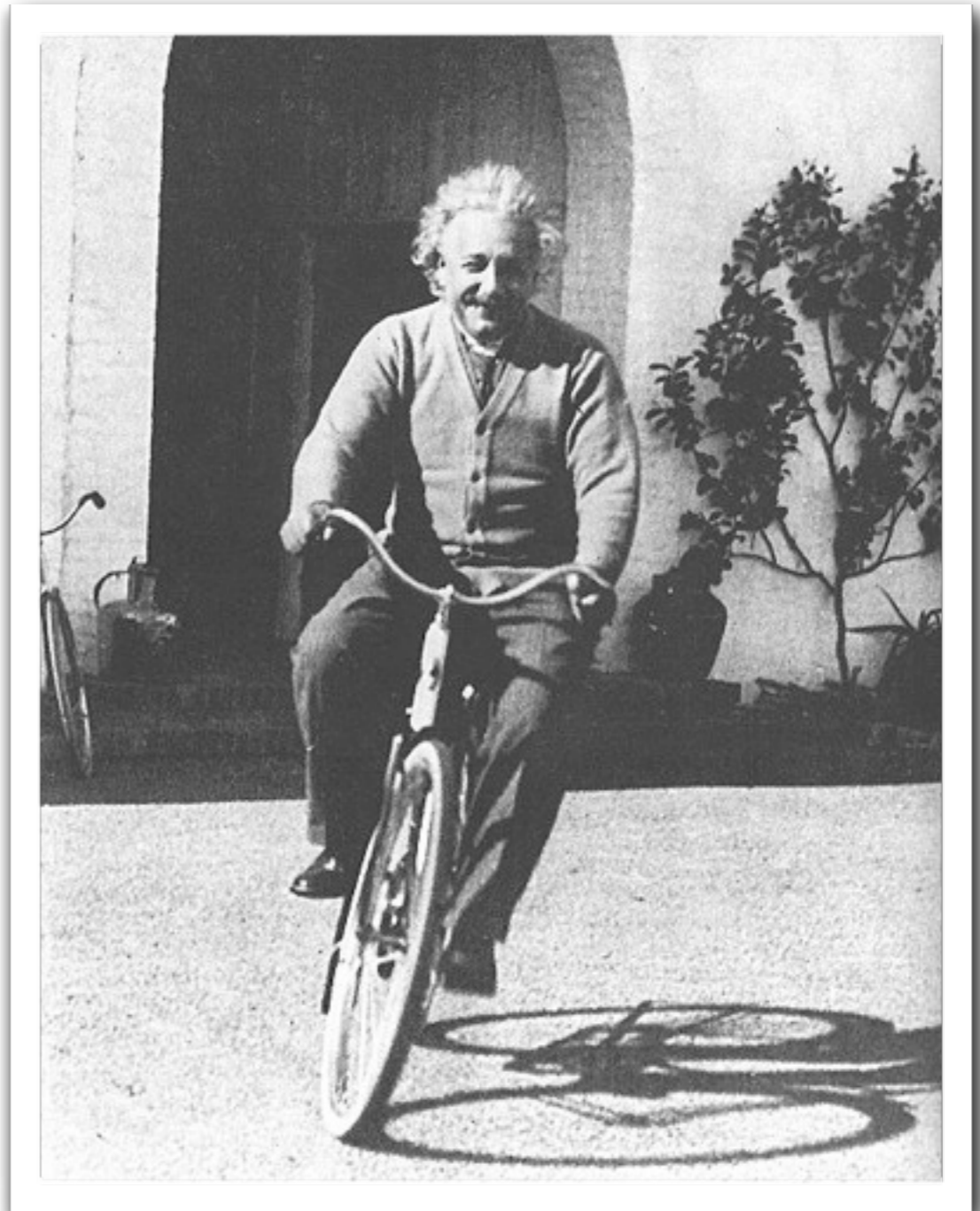
麦克斯韦：电磁学

$$\begin{aligned}\vec{\nabla} \times \vec{D} &= \rho & \vec{\nabla} \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\ \vec{\nabla} \times \vec{B} &= 0 & \vec{\nabla} \times \vec{H} &= \vec{j} + \frac{\partial \vec{D}}{\partial t}\end{aligned}$$

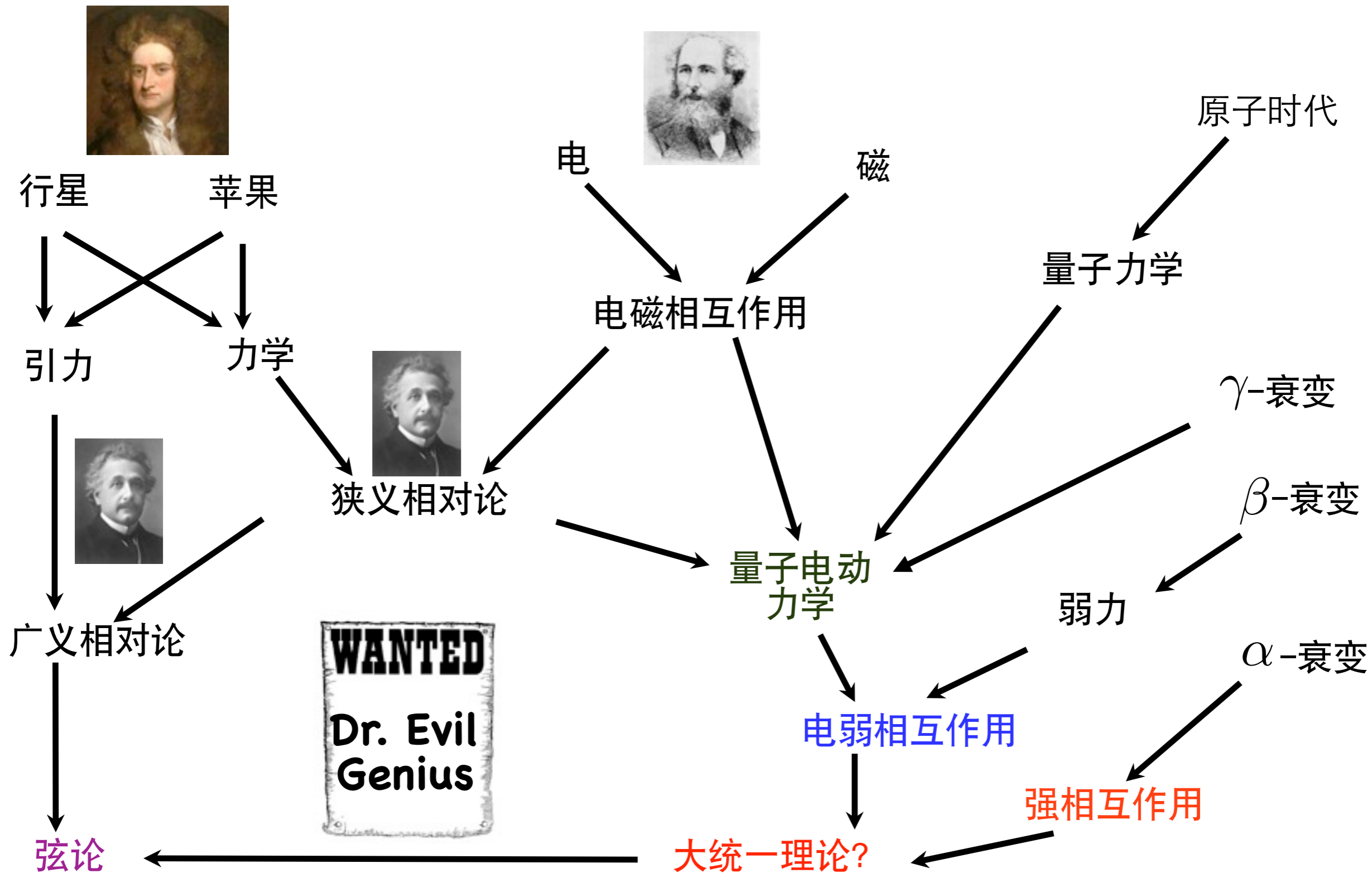


爱因斯坦的统一之梦

- *Einstein dreamed to come up with a unified description*
- *But he failed to unify electromagnetism and gravity (GR)*



物理统一之路



工具：对称性

1) 不可观测

无法观测的物理量

绝对位置 \vec{p}

绝对时间 E

绝对方位 $\vec{L} = \vec{r} \times \vec{p}$

绝对左右 P

绝对未来 T

绝对电荷 C

2) 无法区分

一个物体变换为另一个物体

整体对称性：同位旋

时空对称性

→ 等价性

→ 完美但却无聊的世界



在微观世界中，
等价的相互作用，力的载体为**无质量**的粒子

标准模型的规范对称性

$SU(3)_{\text{Color}}$

QCD

(Strong Interaction)

$\otimes SU(2)_{\text{Left}} \otimes U(1)_{\text{Hyper charge}}$

WEAK \oplus QED

(Unification of
Weak and Electromagnetic)

对称性自发破缺

(希格斯机制)



$U(1)_{\text{E.M.}}$

量子电动力学
(电磁相互作用)



Brout



Englert



Higgs

(1964)

对称性意味着“力”

电磁相互作用 (Abelian gauge symmetry)

规范变换

$$\psi(x) \rightarrow e^{iq\alpha(x)}\psi(x)$$

$$A_\mu(x) \rightarrow A_\mu(x) - \partial_\mu\alpha(x)$$

$$D_\mu \equiv \partial_\mu + iqA_\mu(x)$$

QED

$$\mathcal{L} = \bar{\psi} (i\gamma^\mu D_\mu - m) \psi$$

$$= \bar{\psi} (i\gamma^\mu \partial_\mu - m) \psi - qA_\mu \bar{\psi} \gamma^\mu \psi$$

$$= \mathcal{L}_{\text{free}} - J^\mu A_\mu$$

规范对称性要求光子的质量为零

$$\frac{1}{2} m_\gamma^2 A^\mu A_\mu$$

对称性意味着“力”

杨振宁和米尔斯 (1954)

定域同位旋对称性
意味着有3个无质量的
规范波色子和同
位旋耦合

$$\begin{pmatrix} p \\ n \end{pmatrix}$$

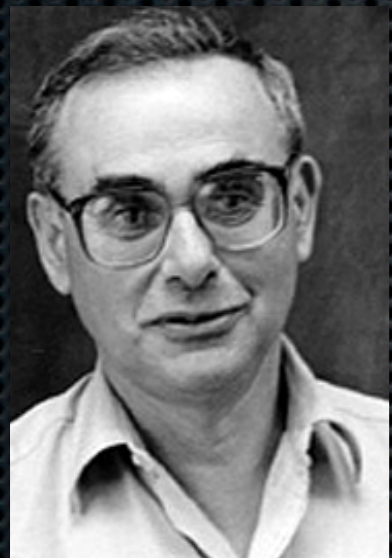


Nambu-Goldstone boson

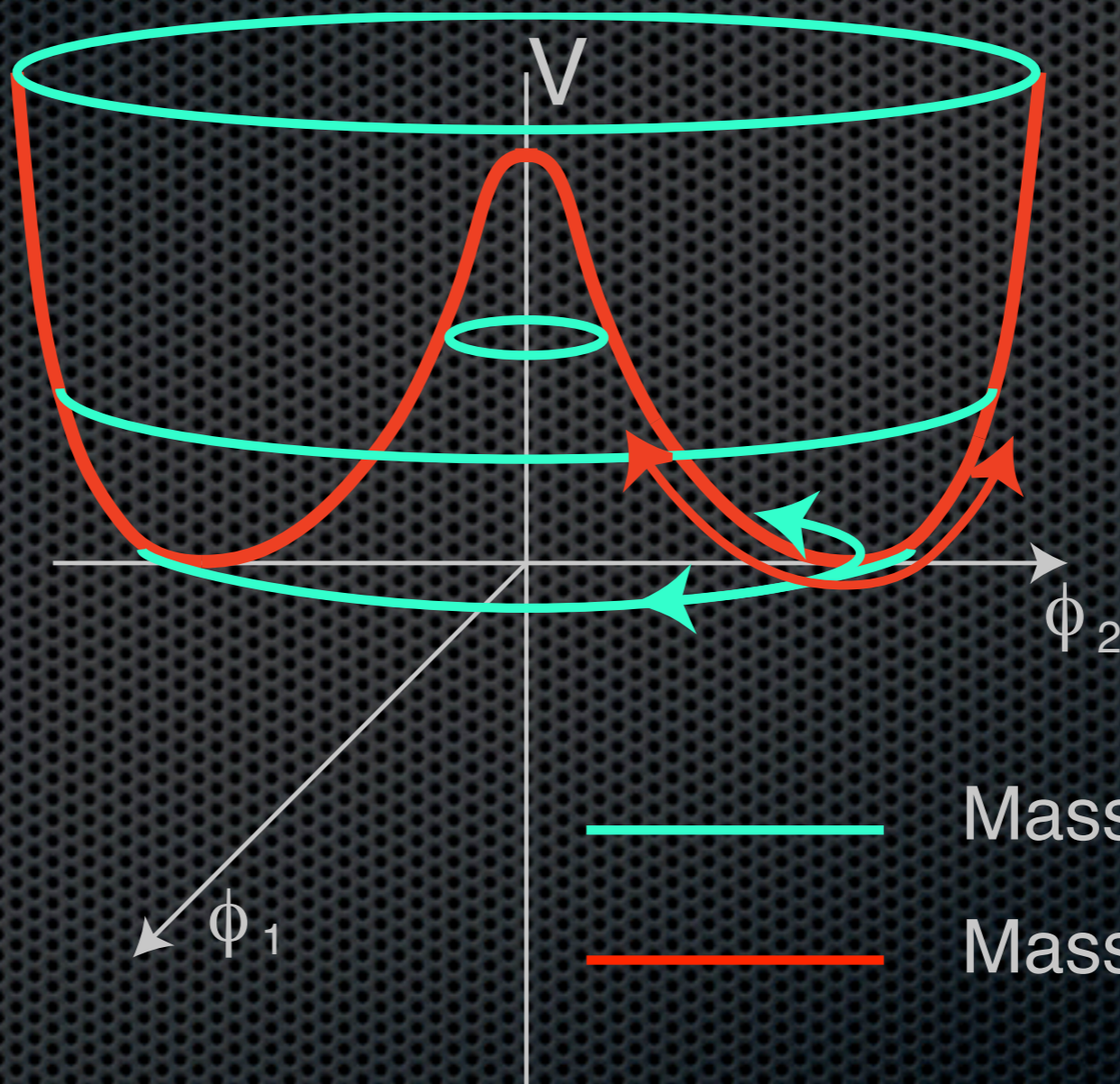


Yoichiro
Nambu

(1960)
2008
Nobel
Prize



Jeffrey
Goldstone (1961)



Goldstone, Salam, Weinberg (1962)

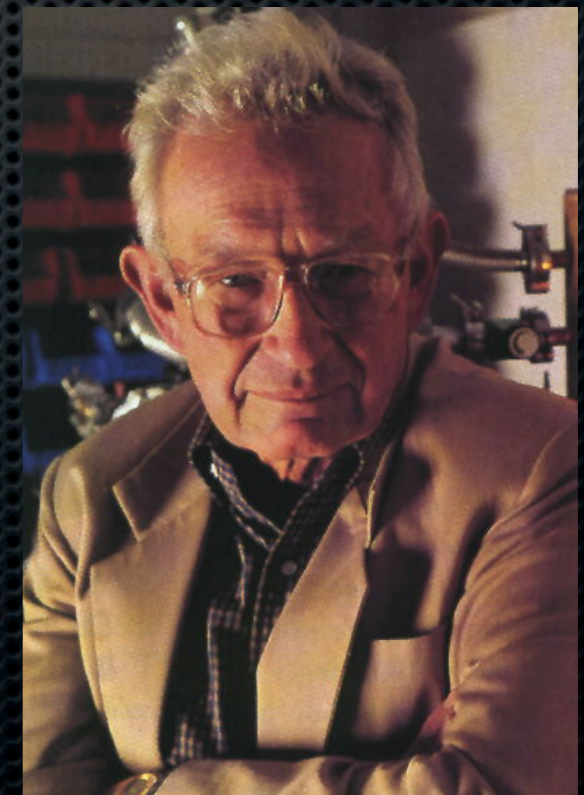
Anderson (1963)

指出超导中的Goldstone模式会因其电磁耦合获得质量，并且产生一个纵向极化模式。

- “the Goldstone zero-mass difficulty is not a serious one, because we can **probably** cancel it off against an equal Yang-Mills zero-mass problem”

没有指出Goldstone定理的瑕疵，
也没有探讨相对论性的理论模型

Phys. Rev. 130 (1963) 439



对称性自发破缺



Higgs Kibble Guralnik Hagen Englert Brout

1964年：Goldstone定理并不适用于规范理论

每个无质量的Goldstone玻色子和一个无质量的规范玻色子组成一个有质量的玻色子，同时还产生有质量的标量粒子

1964年3组人不约而同地...

VOLUME 13, NUMBER 9

PHYSICAL REVIEW LETTERS

31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout

Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium

(Received 26 June 1964)

Volume 12, number 2

PHYSICS LETTERS

15 September 1964

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS

Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16

PHYSICAL REVIEW LETTERS

19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs

Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland

(Received 31 August 1964)

VOLUME 13, NUMBER 20

PHYSICAL REVIEW LETTERS

16 NOVEMBER 1964

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,[†] C. R. Hagen,[‡] and T. W. B. Kibble

Department of Physics, Imperial College, London, England

(Received 12 October 1964)

电弱理论 (1967)

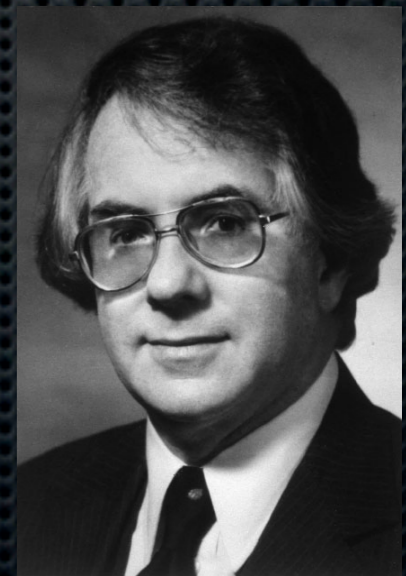
1979
Nobel
Prize

Steven
Weinberg



Abdus
Salam

将希格斯机制引入到Glashow的轻子电弱理论
Shelton Glashow, Nucl. Phys. 22 (1961) 579



使用真空隐藏电弱对称性

3个有质量的规范玻色子 $W^+ W^- Z^0$ (1983)

1个无质量的规范玻色子 γ

1个有质量的希格斯粒子

为何叫“希格斯机制”？

Weinberg乌龙引用

VOLUME 19, NUMBER 21

PHYSICAL REVIEW LETTERS

20 NOVEMBER 1967

¹¹ In obtaining the expression (11) the mass difference between the charged and neutral has been ignored.

¹² M. Ademollo and R. Gatto, *Nuovo Cimento* 44A, 282 (1966); see also J. Pasupathy and R. E. Marshak, *Phys. Rev. Letters* 17, 888 (1966).

¹³ The predicted ratio [eq. (12)] from the current alge-

bra is slightly larger than that (0.23%) obtained from the ρ -dominance model of Ref. 2. This seems to be true also in the other case of the ratio $\Gamma(\eta \rightarrow \pi^+\pi^-\gamma)/\Gamma(\gamma\gamma)$ calculated in Refs. 12 and 14.

¹⁴ L. M. Brown and P. Singer, *Phys. Rev. Letters* 8, 460 (1962).

A MODEL OF LEPTONS*

Steven Weinberg†

Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received 17 October 1967)

³ P. W. Higgs, *Phys. Letters* 12, 132 (1964), *Phys. Rev. Letters* 13, 508 (1964), and *Phys. Rev.* 145, 1156 (1966); F. Englert and R. Brout, *Phys. Rev. Letters* 13, 321 (1964); G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, *Phys. Rev. Letters* 13, 585 (1964).

温伯格的再次乌龙

VOLUME 27, NUMBER 24

PHYSICAL REVIEW LETTERS

13 DECEMBER 1971

Physical Processes in a Convergent Theory of the Weak and Electromagnetic Interactions*

Steven Weinberg

Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 20 October 1971)

²P. W. Higgs, *Phys. Rev. Lett.* 12, 132 (1964), and 13, 508 (1964), and *Phys. Rev.* 145, 1156 (1966); F. Englert and R. Brout, *Phys. Rev. Lett.* 13, 321 (1964); G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, *Phys. Rev. Lett.* 13, 585 (1965); T. W. B. Kibble, *Phys. Rev.* 155, 1554 (1967). Also see A. Salam, in *Elementary Particle Physics*, edited by N. Svartholm (Almqvist and Wiksells, Stockholm, 1968), p. 367.

匪夷所思的巧合

Phys. Rev. Lett. 12, 132–133 (1964)

Large Angle p - p Elastic Scattering at 30 bev

Abstract

References

Citing Articles (346)

Page Images

Download: PDF (196 kB) Export: [BibTeX](#) or [EndNote](#) (RIS)

W. F. Baker, E. W. Jenkins, and A. L. Read

Brookhaven National Laboratory, Upton, New York

G. Cocconi^{*}, V. T. Cocconi^{*}, A. D. Krisch, J. Orear, R. Rubinstein, D. B. Scarl, and B. T. Ulrich

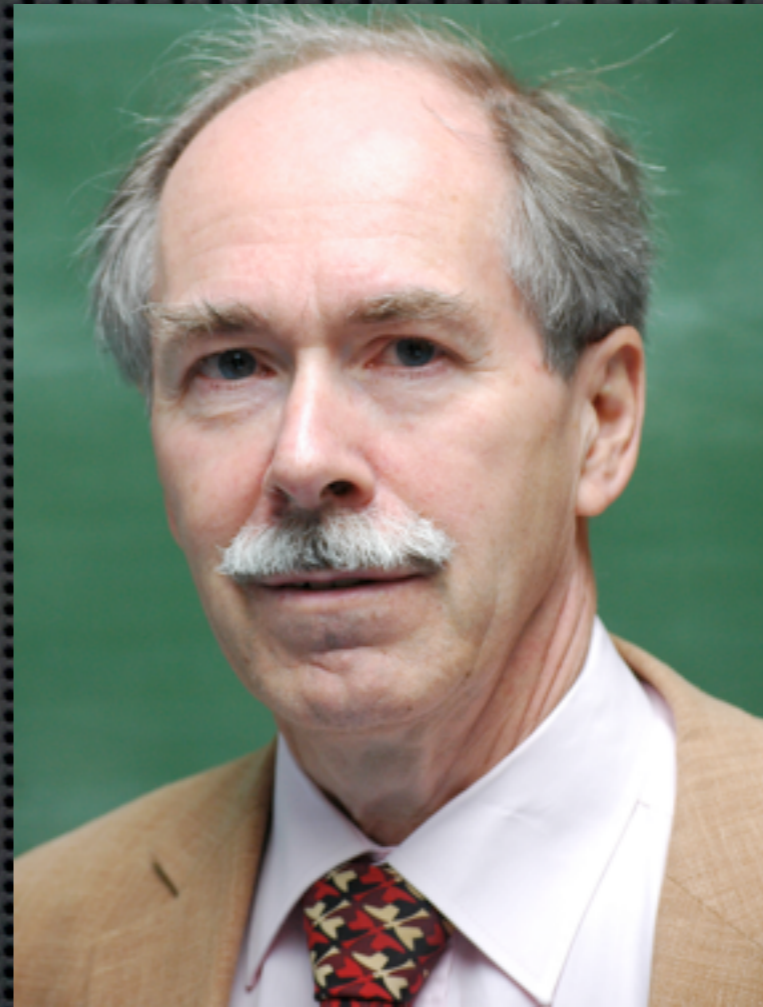
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York

Received 13 January 1964; published in the issue dated 3 February 1964

时间提前到1964年1月份!!!

1971-72年

- t'Hooft 和 Veltman证明电弱理论的可重整化性



1999
Nobel
Prize

- 1972年在费米实验室举办的高能物理会议上，电弱理论部分的报告人B. W. Lee，首次提出“**Higgs meson**”。

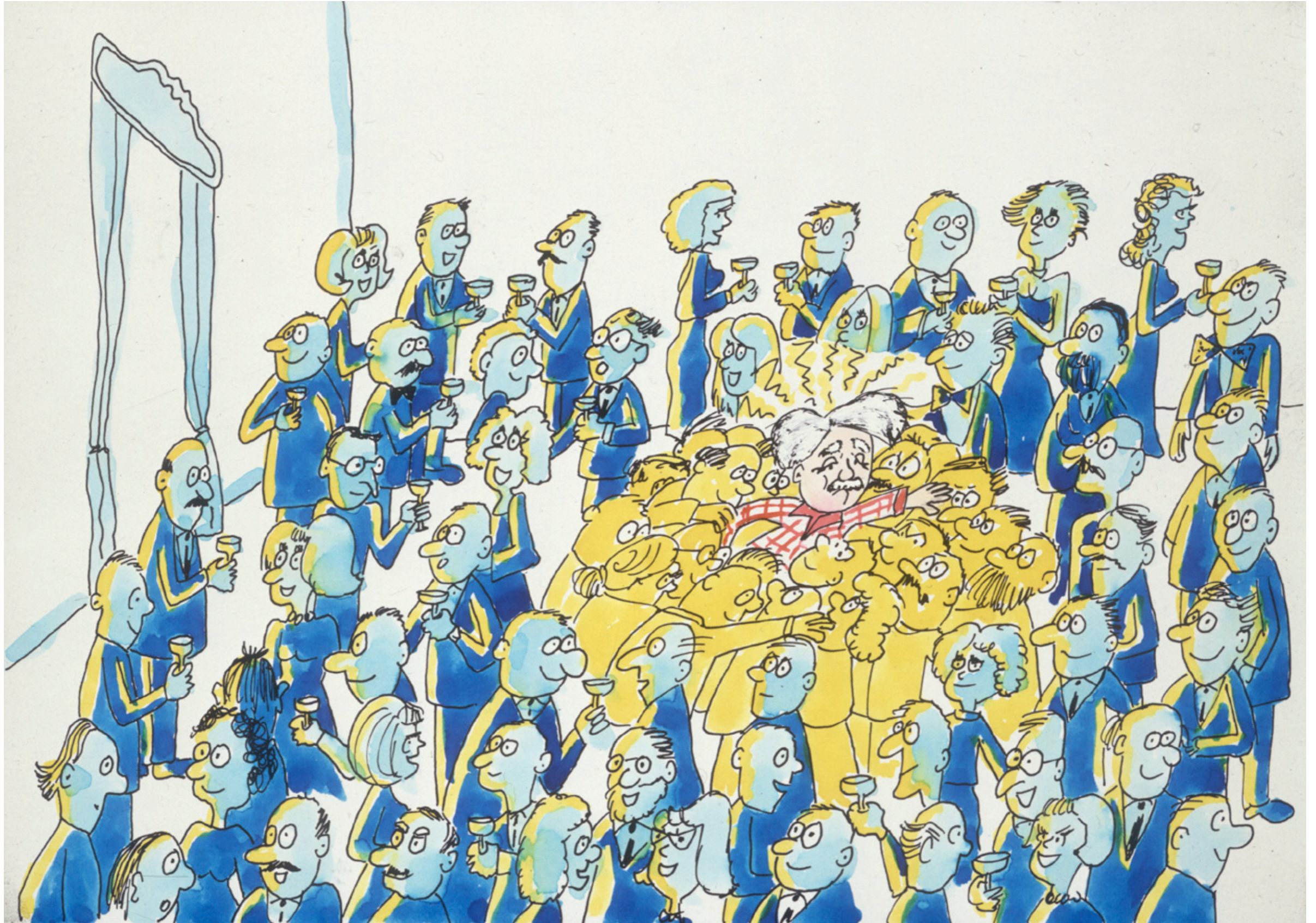
标准模型的希格斯机制



标准模型的希格斯机制



标准模型的希格斯机制

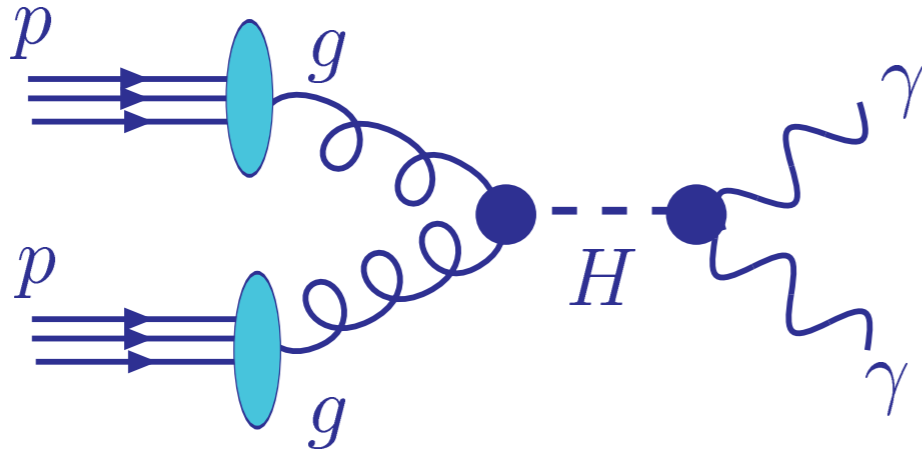


见证奇迹的历史时刻

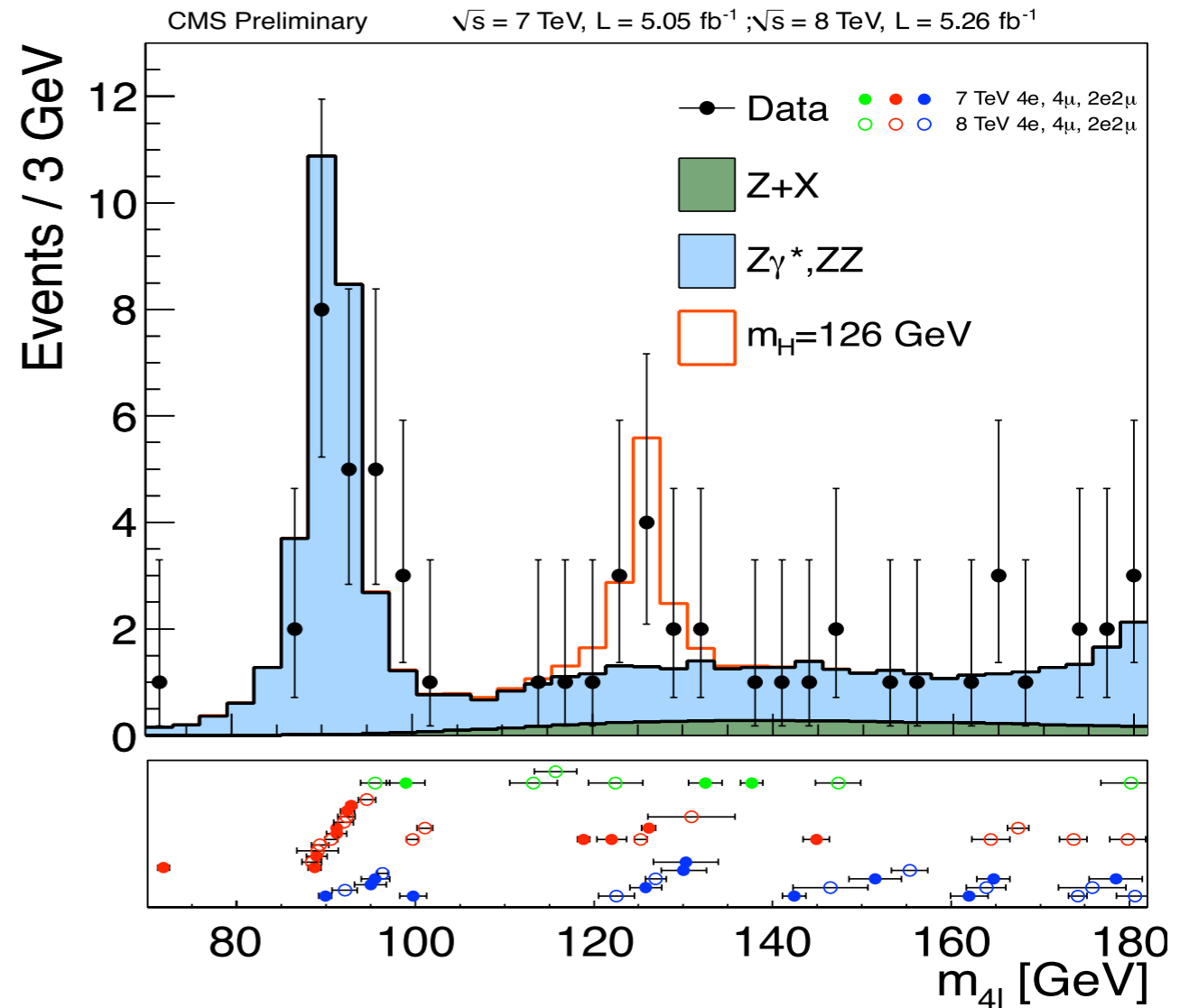
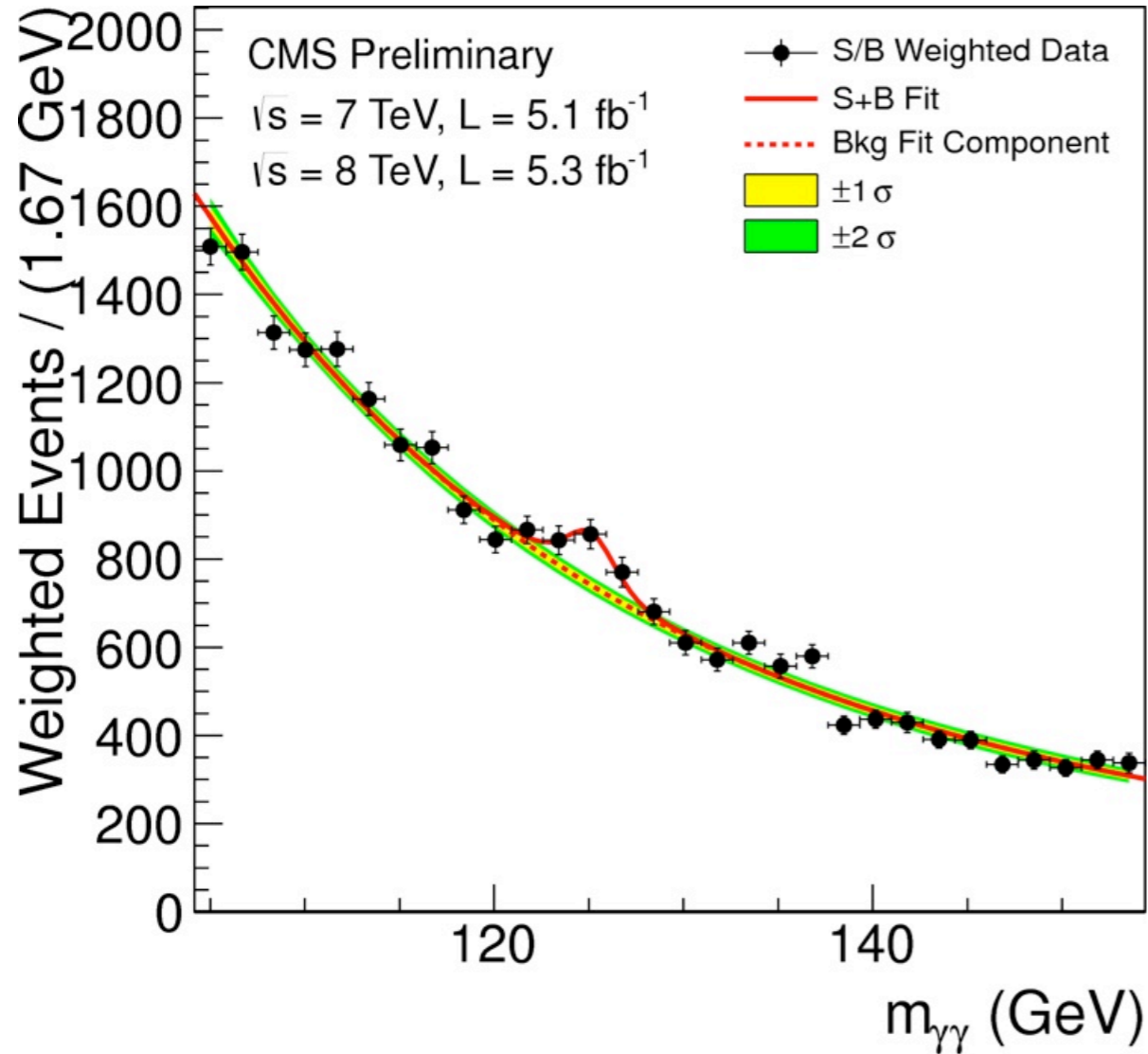
July 4th, 2012



希格斯信号



实验信号寻找
末态两个光子的
共振峰



我们终于验证
基本粒子的
质量起源
(1964 - 2012)



2013 NOBEL PRIZE IN PHYSICS

François Englert Peter W. Higgs



© The Nobel Foundation. Photo: Lovisa Engblom.

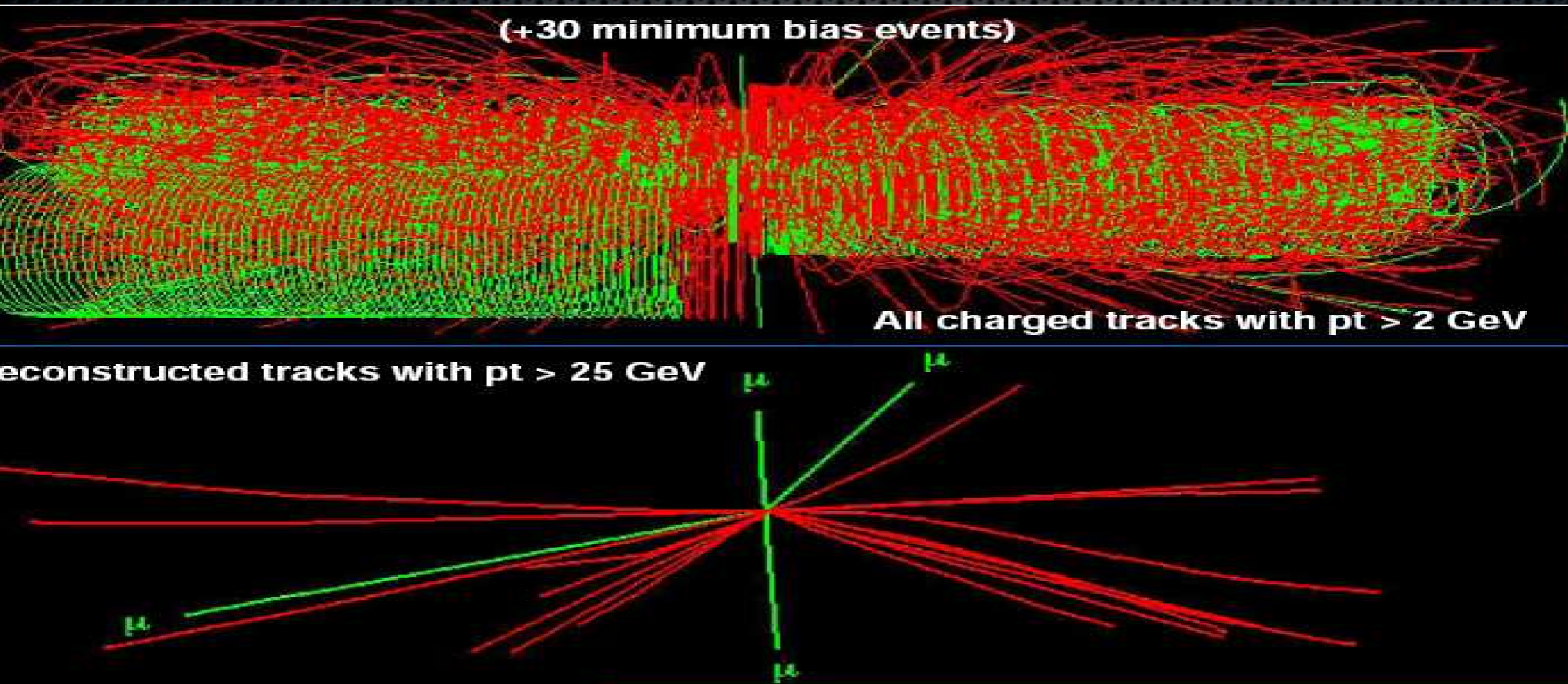
'for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider'



不幸的是，
Brout 于2011年5月
去世，享年83岁



发现希格斯粒子是理论+实验 共同不懈的努力完成的



$$h \rightarrow ZZ \rightarrow \mu^+ \mu^- \mu^+ \mu^-$$

Higgs decay in 4 muons
1 in 10^{13} events

高能物理的 实验手段

高能理论研究的数次革命都是基于
实验物理技术的革命性突破，
特别是加速器和探测器技术的成熟。

能量和空间尺度

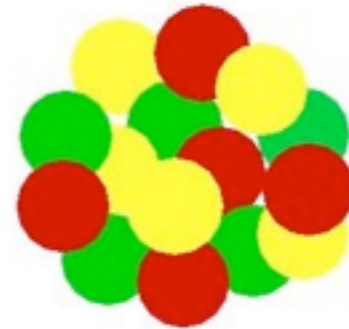
加速器： 强力的“显微镜”

高能加速的粒子束，帮助我们看清细微的结构

$$E \sim \frac{1}{x}$$



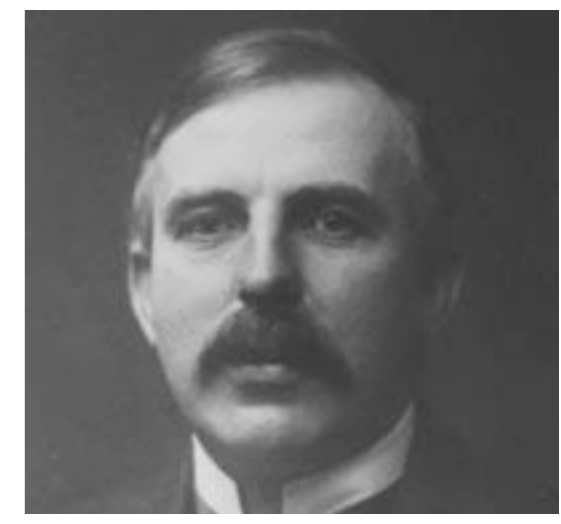
低能量粒子束



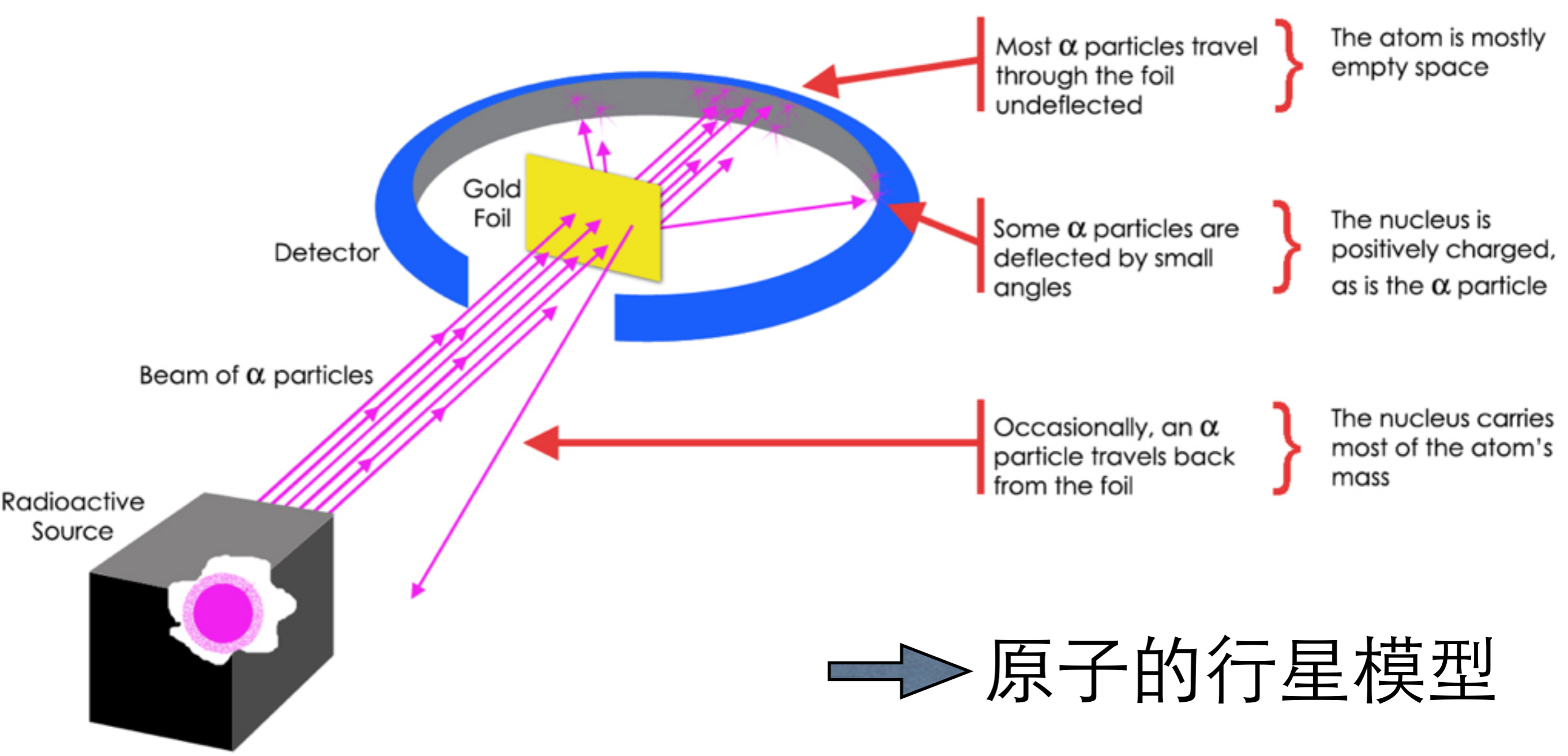
高能量粒子束

卢瑟福散射实验

对撞实验鼻祖

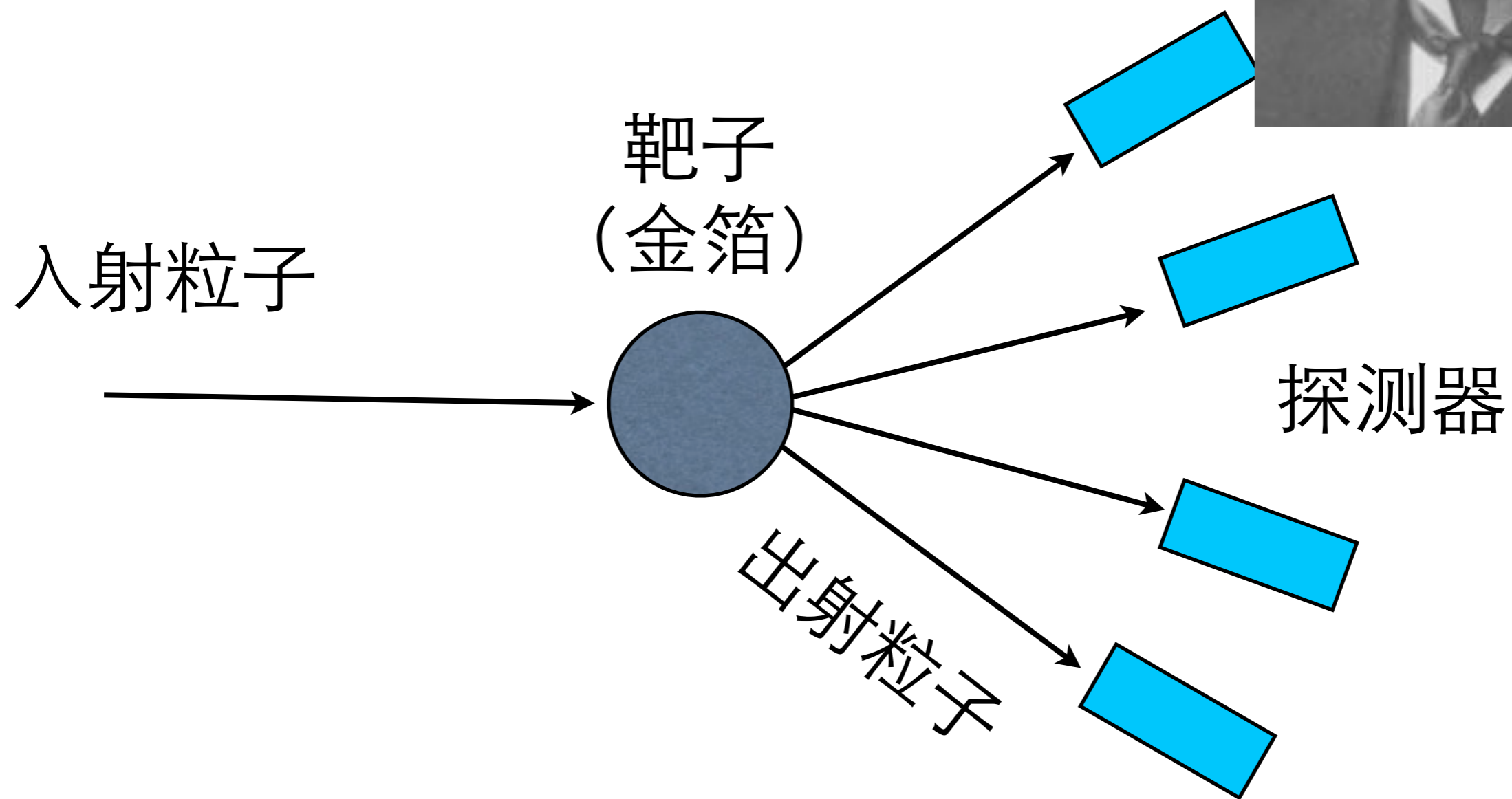
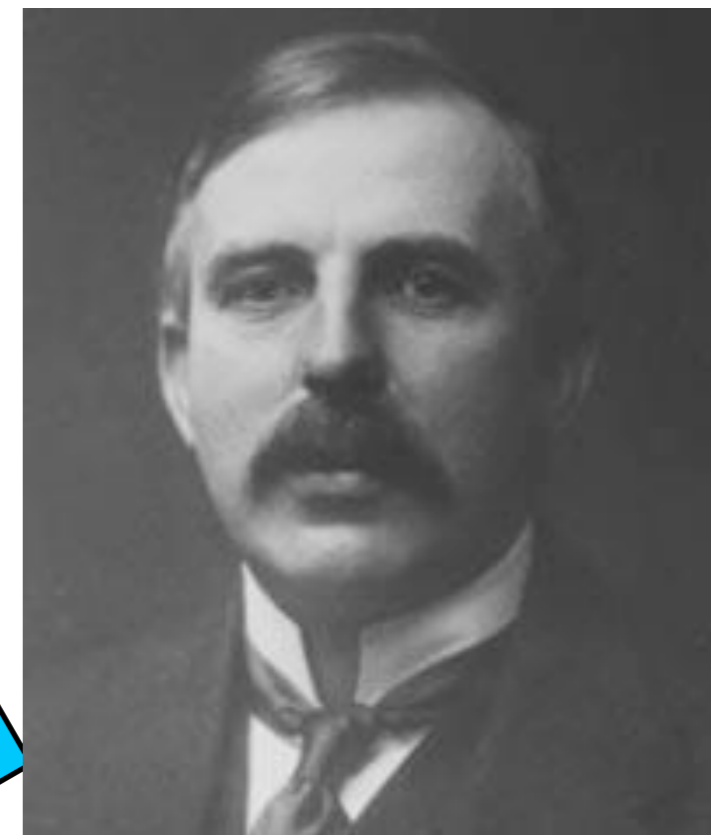


Rutherford's Gold Foil Experiment



卢瑟福散射实验

对撞实验鼻祖



加速器和对撞机

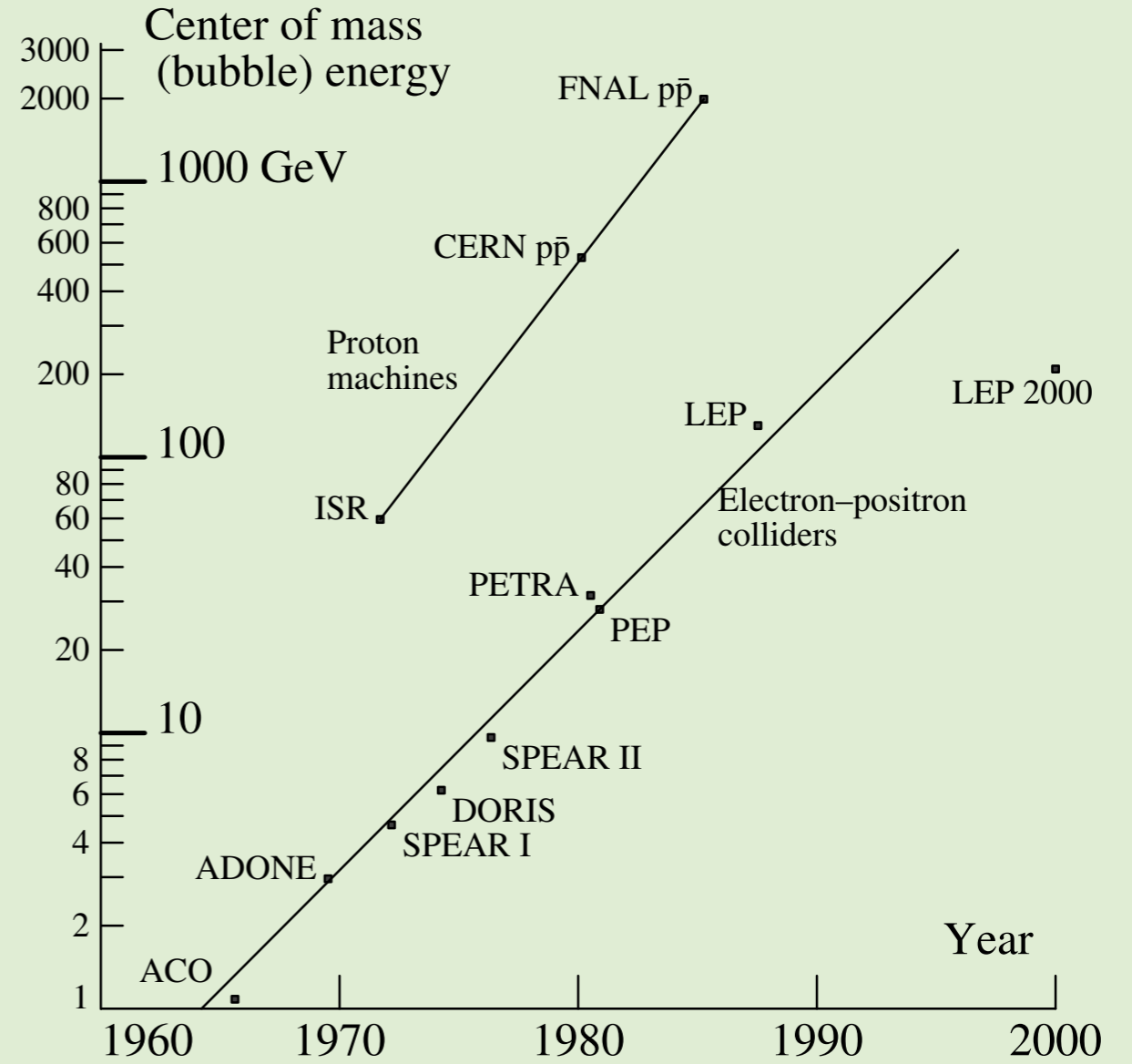
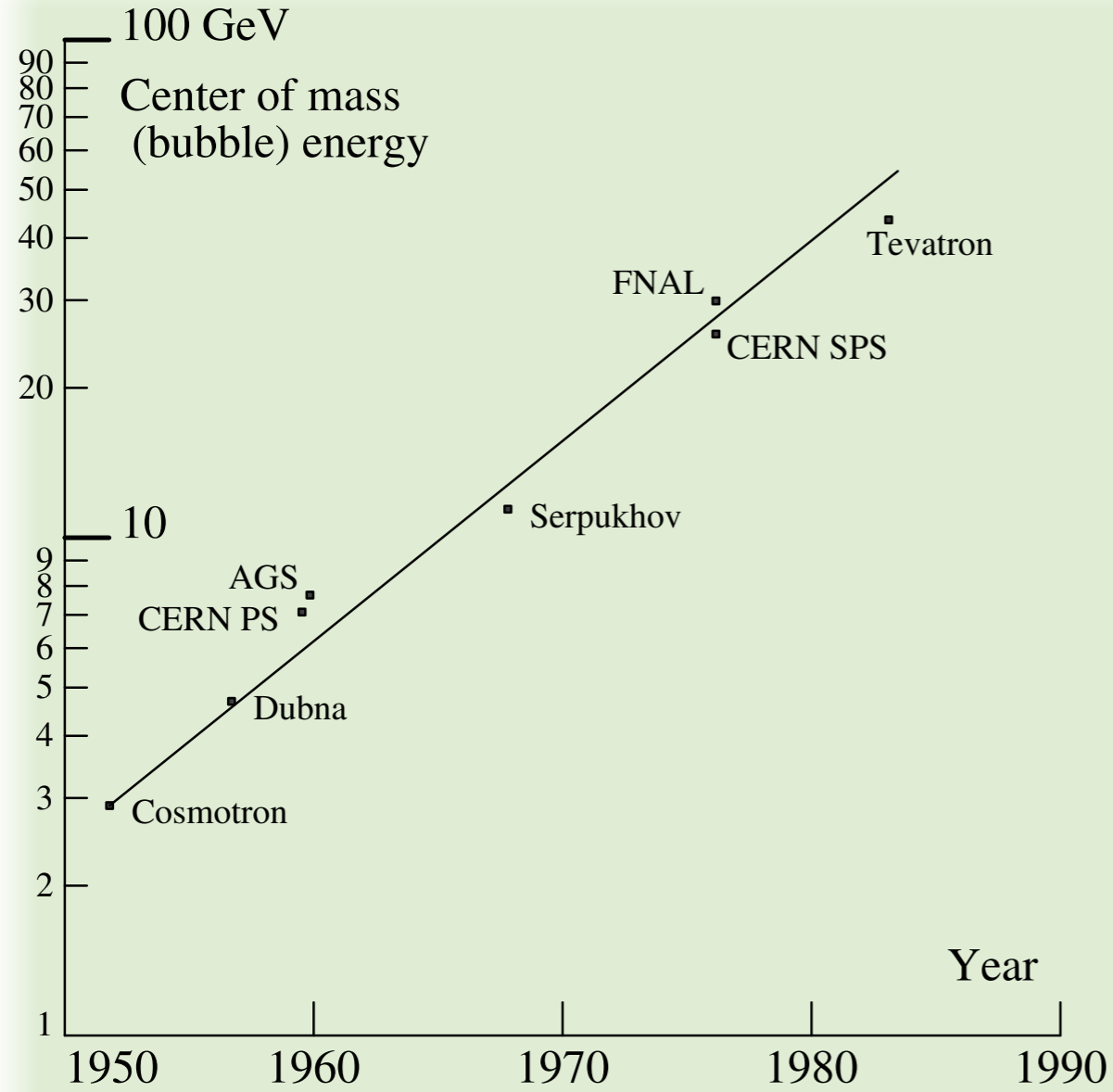
二战之后高能物理才成为一门公认的学科
(富人的游戏)

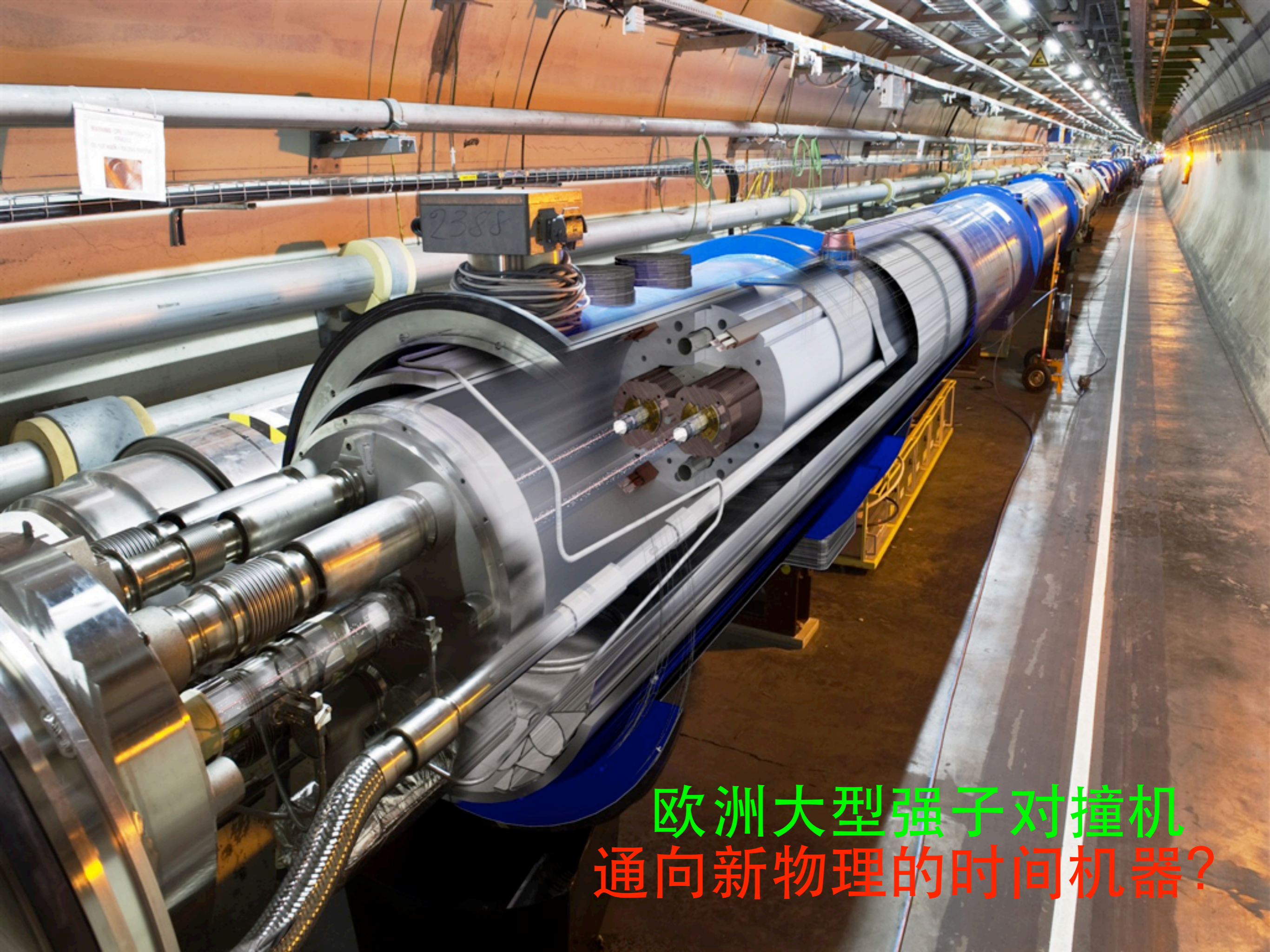
能量上限由机器的环半径和磁场强度决定

- ▶ 上世纪50年代, 半径~10-20米 (房子中)
- ▶ 上世纪60年代, 半径~100米 (地下)
- ▶ 上世纪70年代, 半径~1000米 (地下)
- ▶ 上世纪80年代, 半径~4000米 (地下)



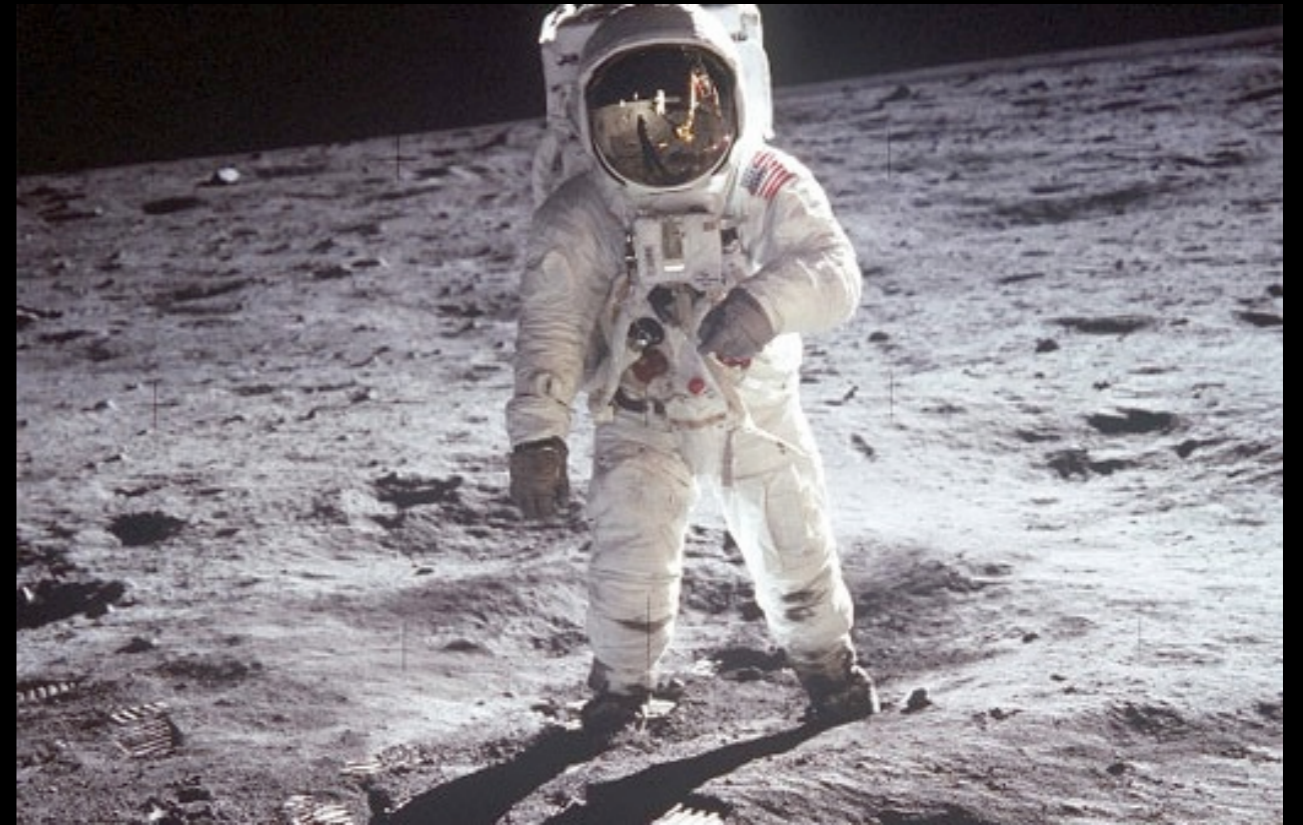
对撞机年表





欧洲大型强子对撞机
通向新物理的时间机器？

Inside the LHC



Largest cryogenic system in the world

- Air pressure (inside two 16 mile-long vacuum pipes)
 - lower than on the moon!
- Magnets cooled by 100 metric tons of superfluid helium
 - Colder than outer space!

大型强子对撞机

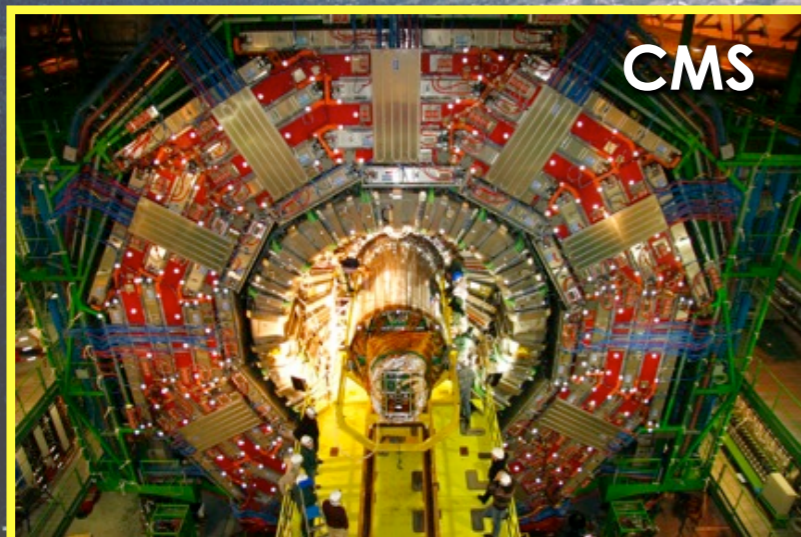
质心系能量 **14TeV**



LHC ring:
27 km circumference

大型强子对撞机

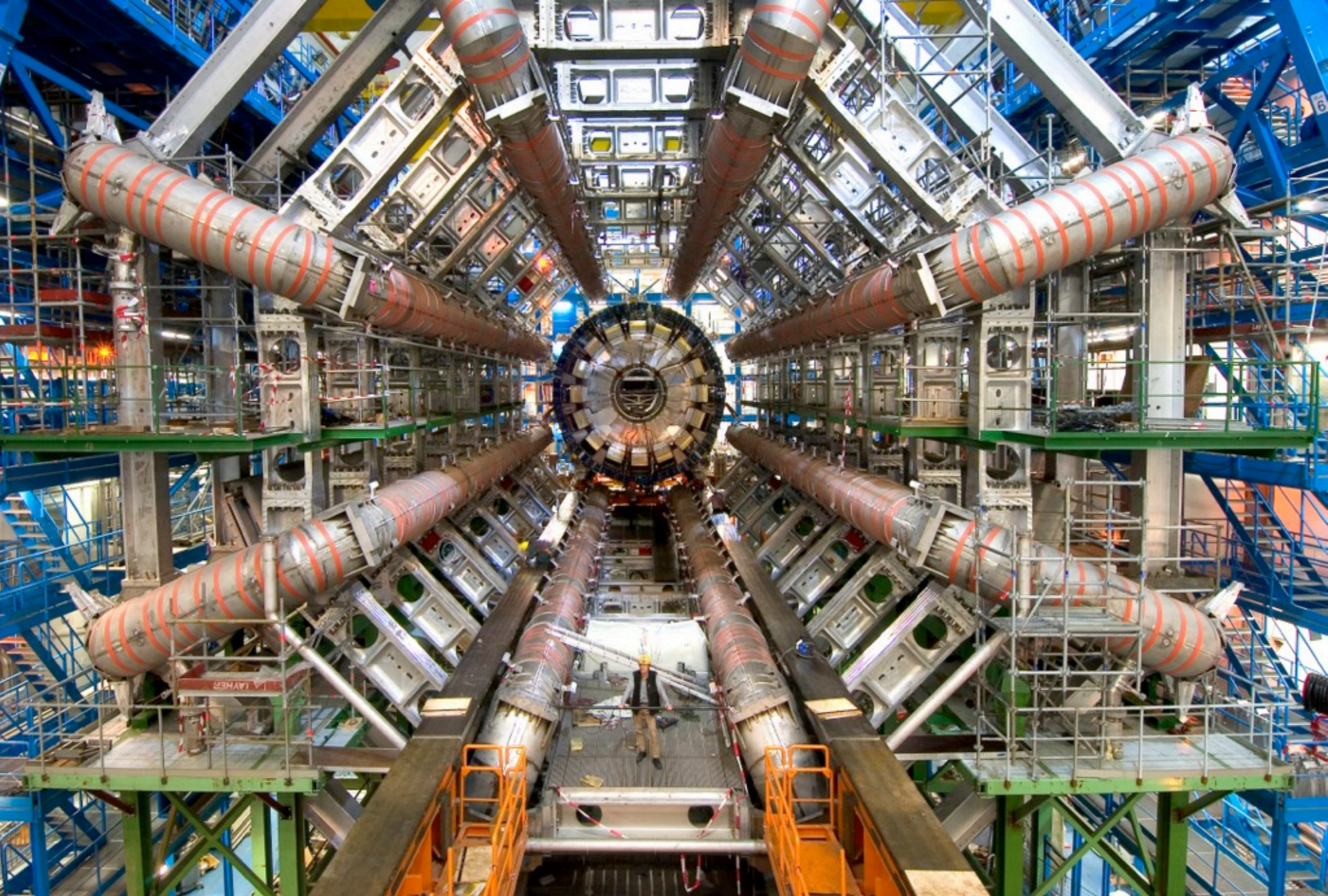
质心系能量 **14TeV**



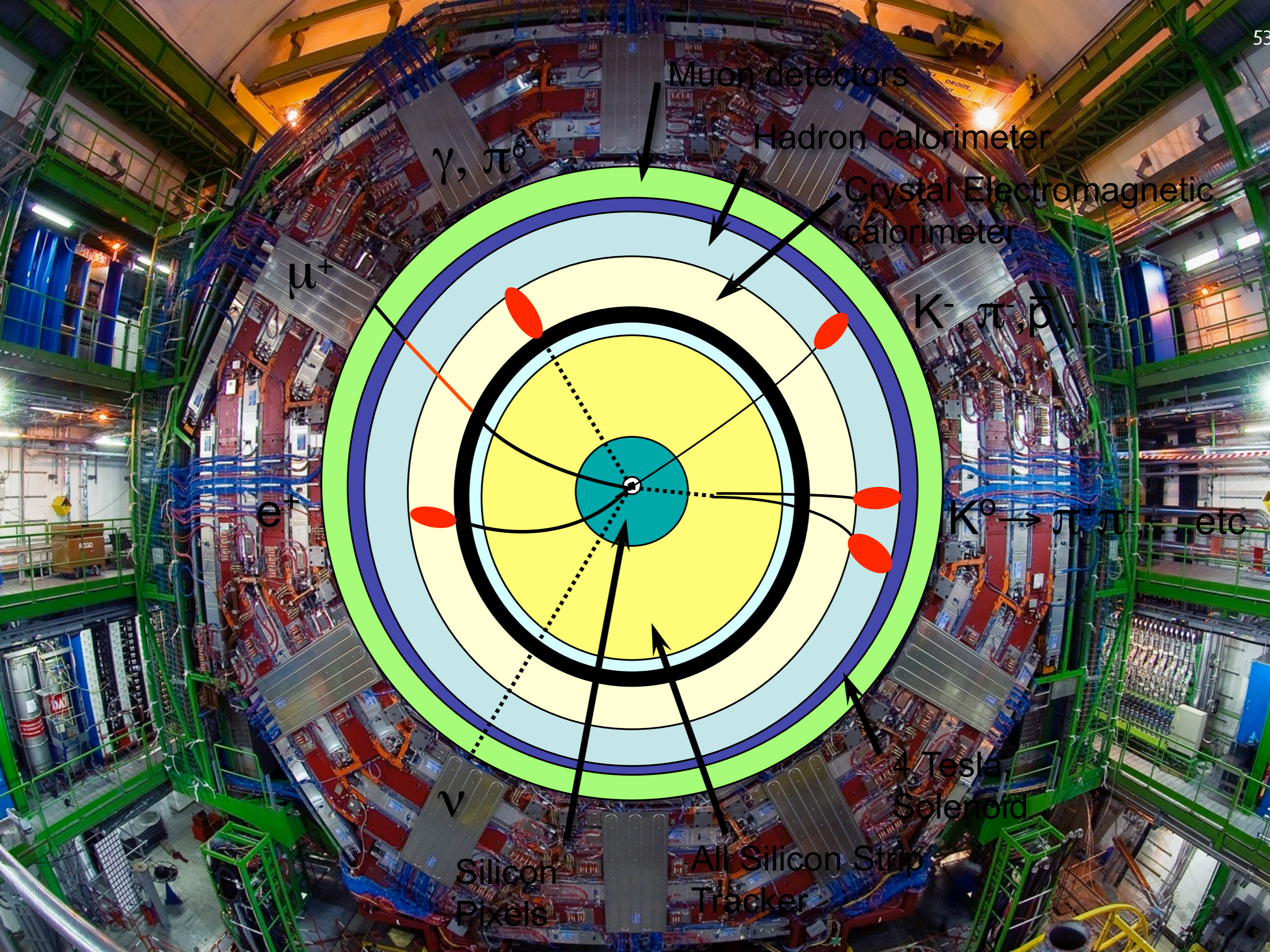
LHC ring:
27 km circumference



CMS: 长21米, 高15米, 宽15米, 12.5千吨



ATLAS: 长46米, 高25米, 宽25米, 7千吨



Muon detectors

Hadron calorimeter

Crystal Electromagnetic calorimeter

K^- , π , p , ...

$K^0 \rightarrow \pi^+ \pi^-$, ... etc

4 Tesla Solenoid

All Silicon Strip Tracker

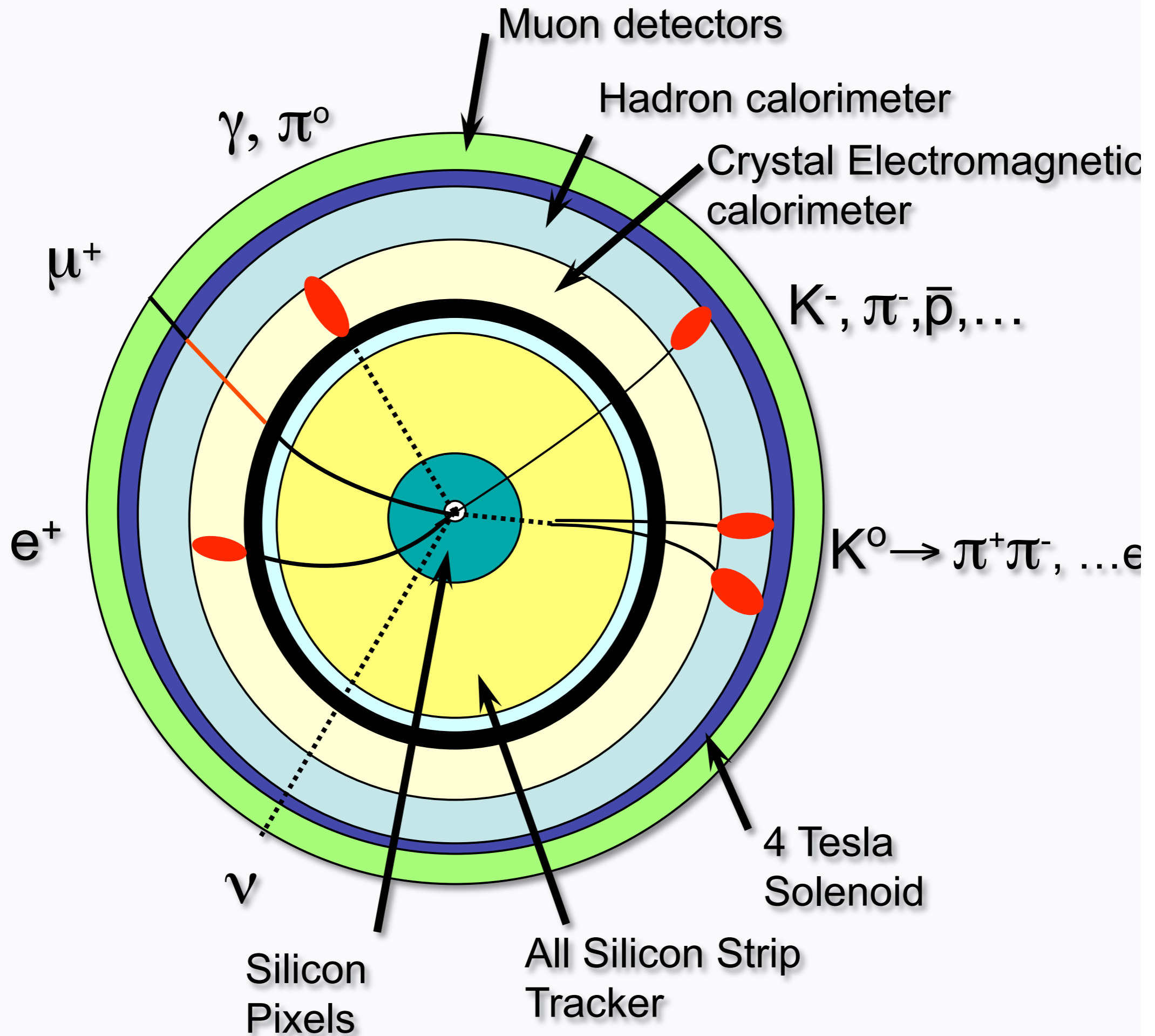
Silicon Pixels

γ , π^0

μ^+

e^+

ν



超出标准模型
之外的新物理

新物理探索：盲人摸象

It's a Fan!

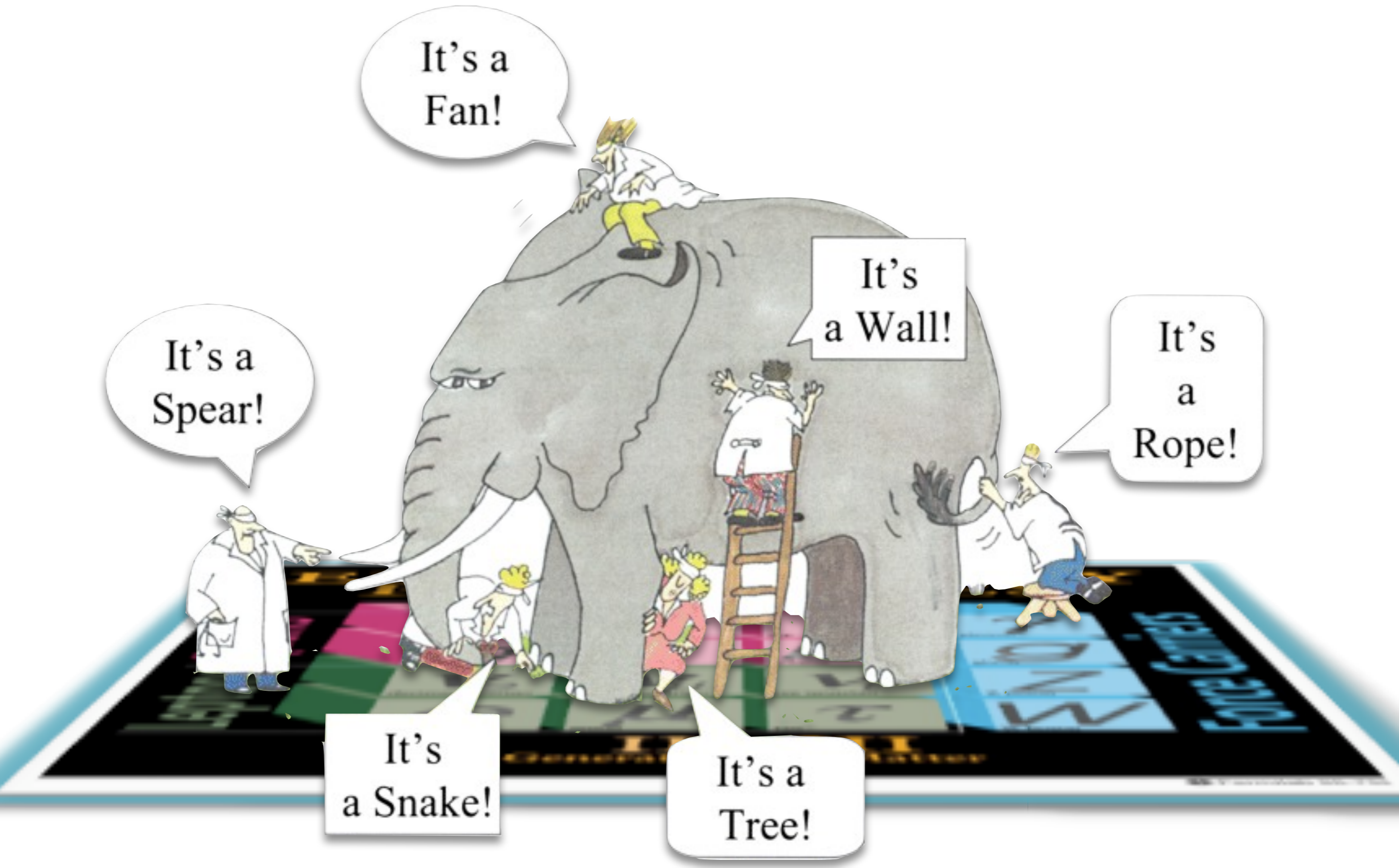
It's a Wall!

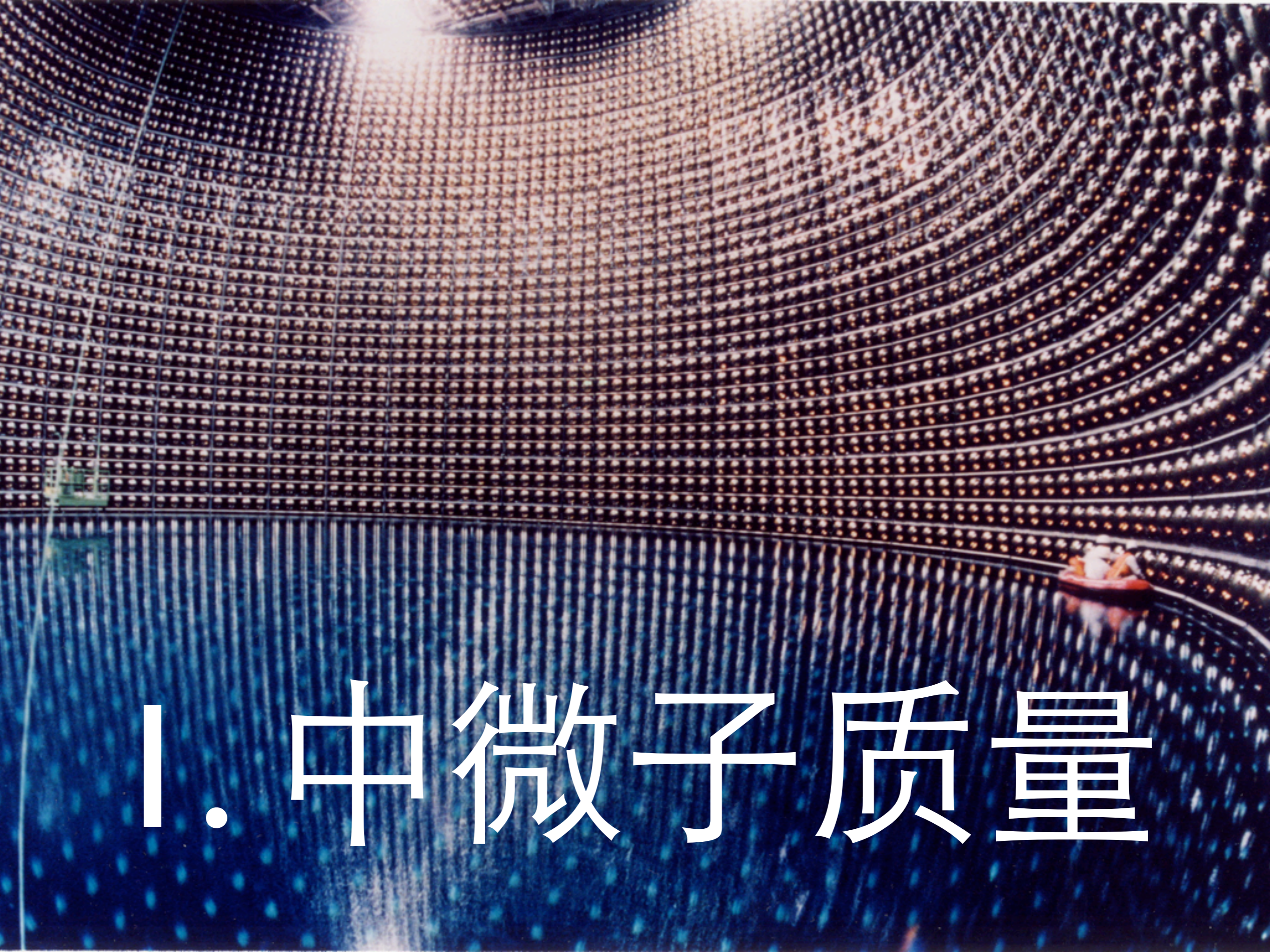
It's a Rope!

It's a Spear!

It's a Snake!

It's a Tree!





I. 中微子质量

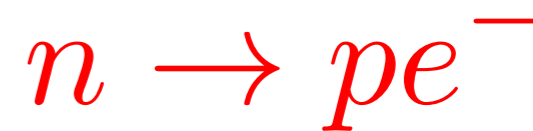
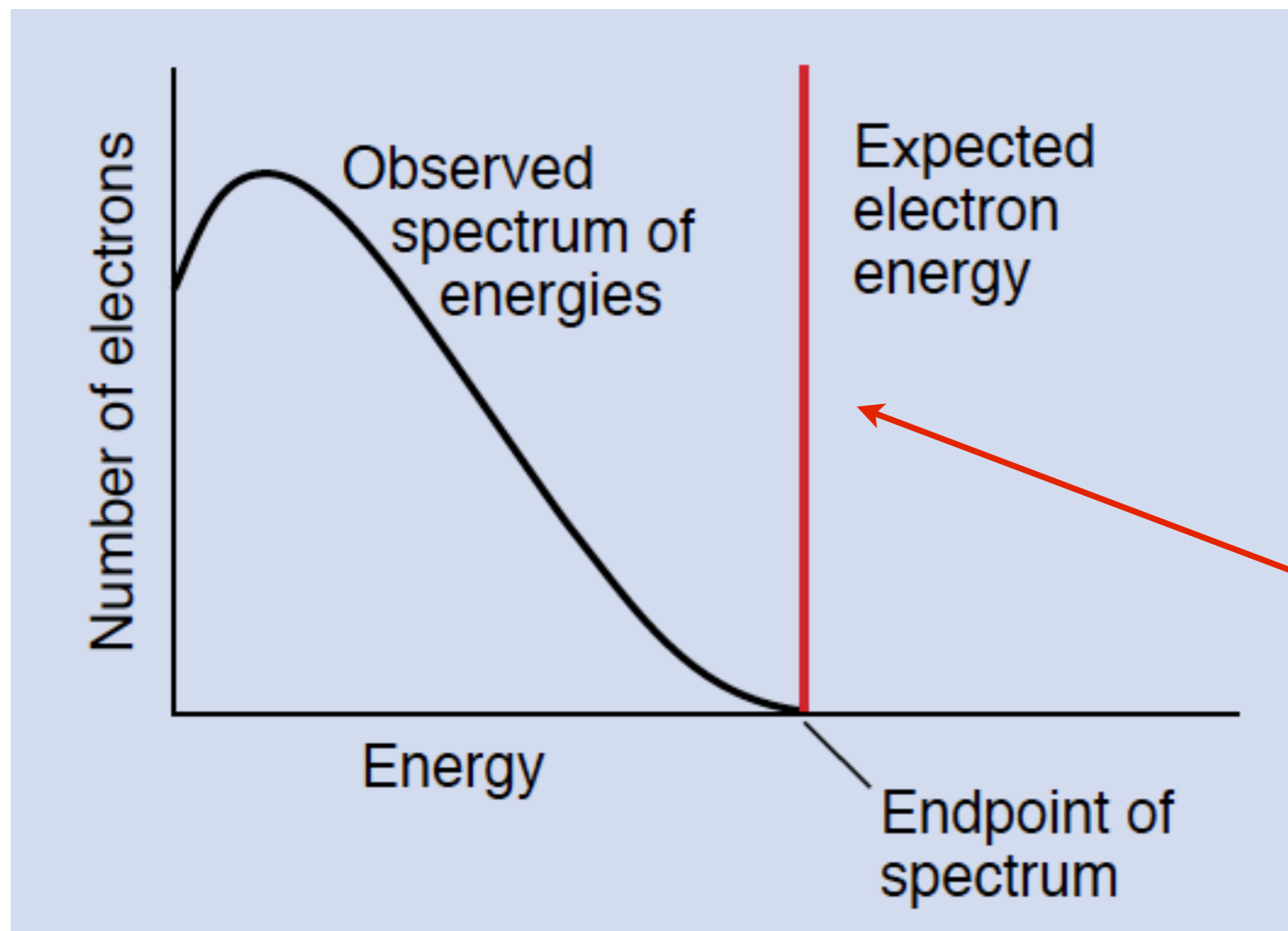
泡利和中微子



Beta-衰变



(1930)

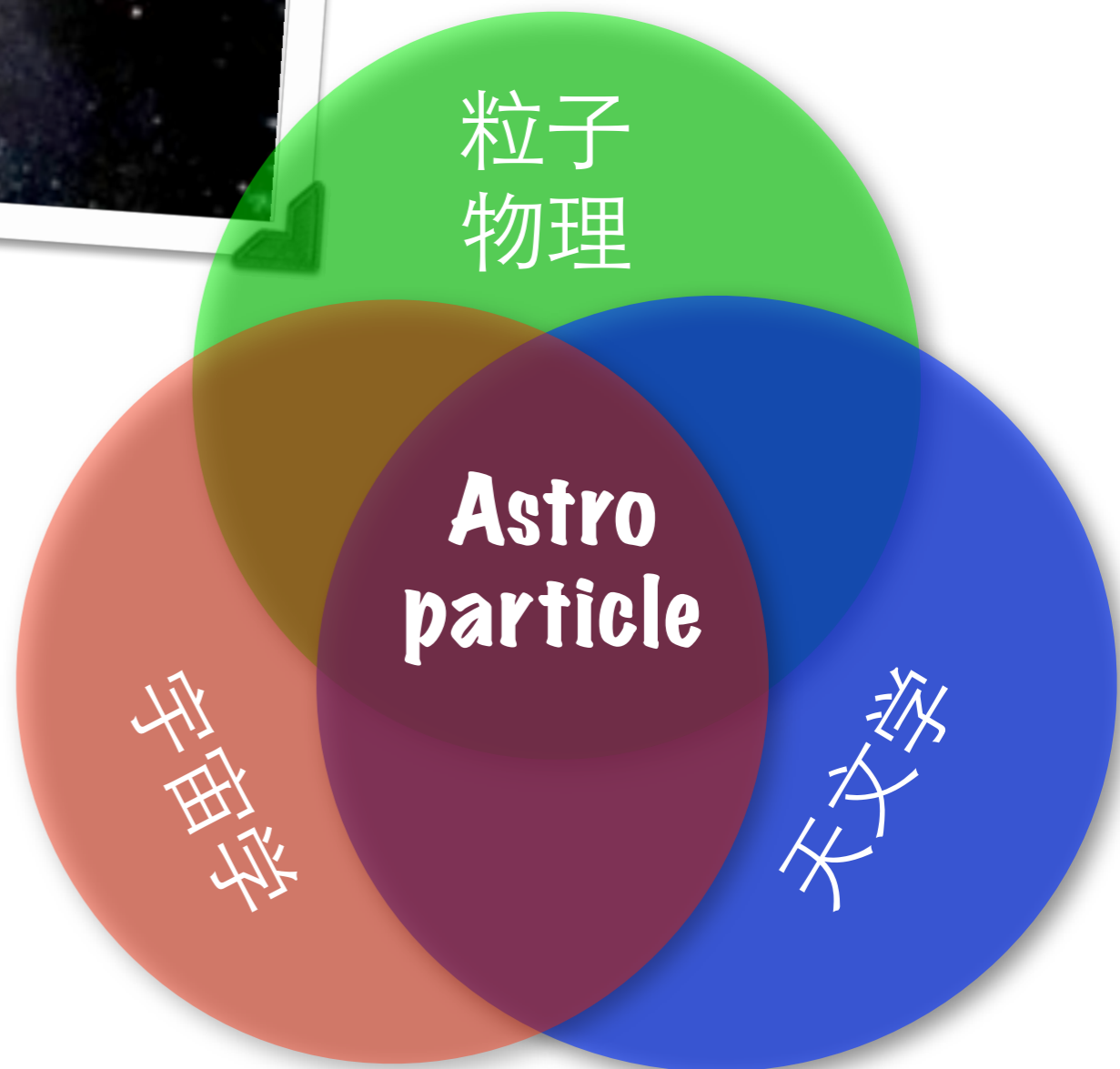




粒子
物理

2. 暗物质

(粒子宇宙学)



暗物质

已知信息:

不发光物质 (无电磁相互作用)

寿命非常长或绝对稳定

非重子

大质量

未知信息:

质量和自旋

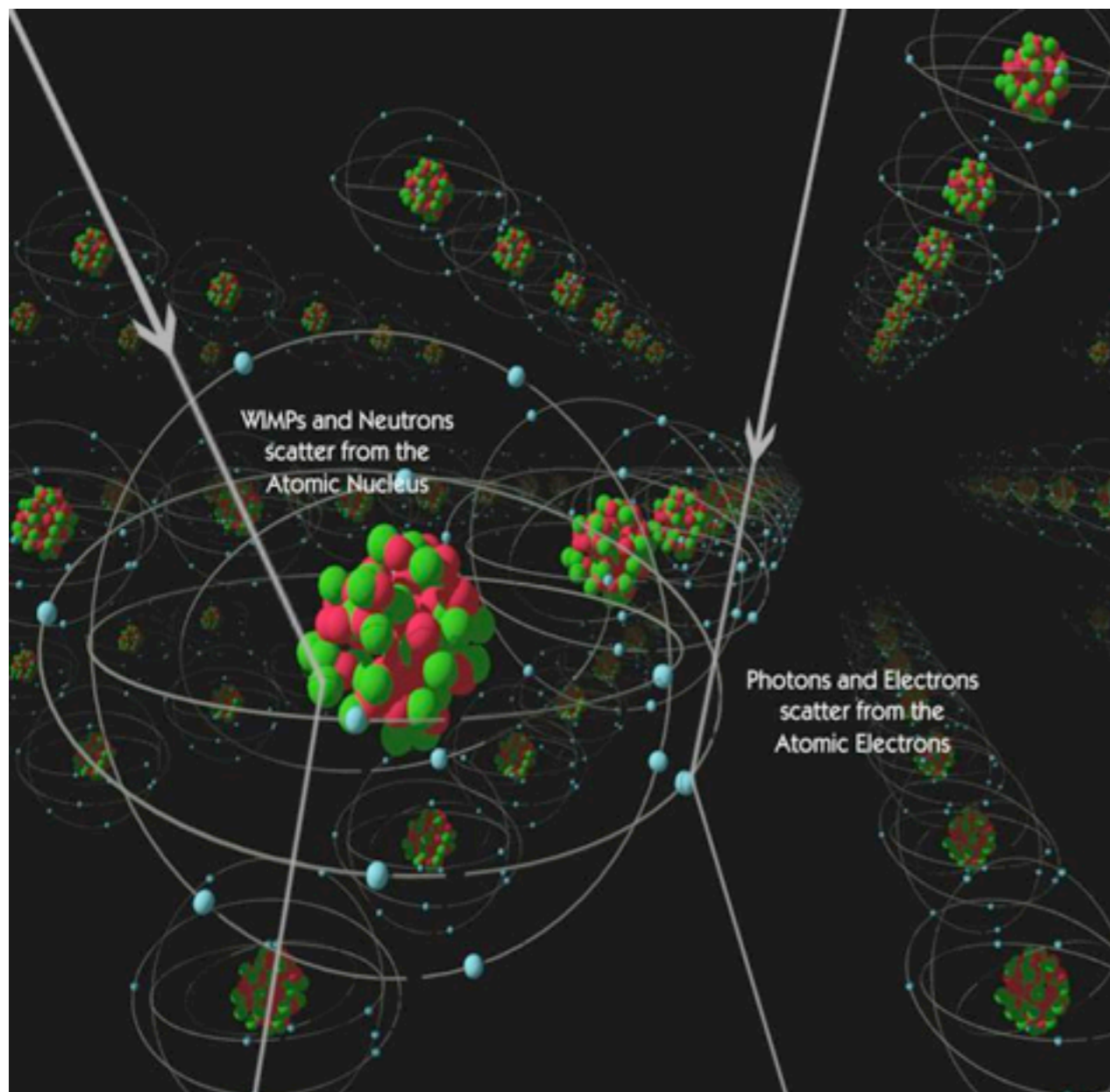
相互作用形式

种类和数目



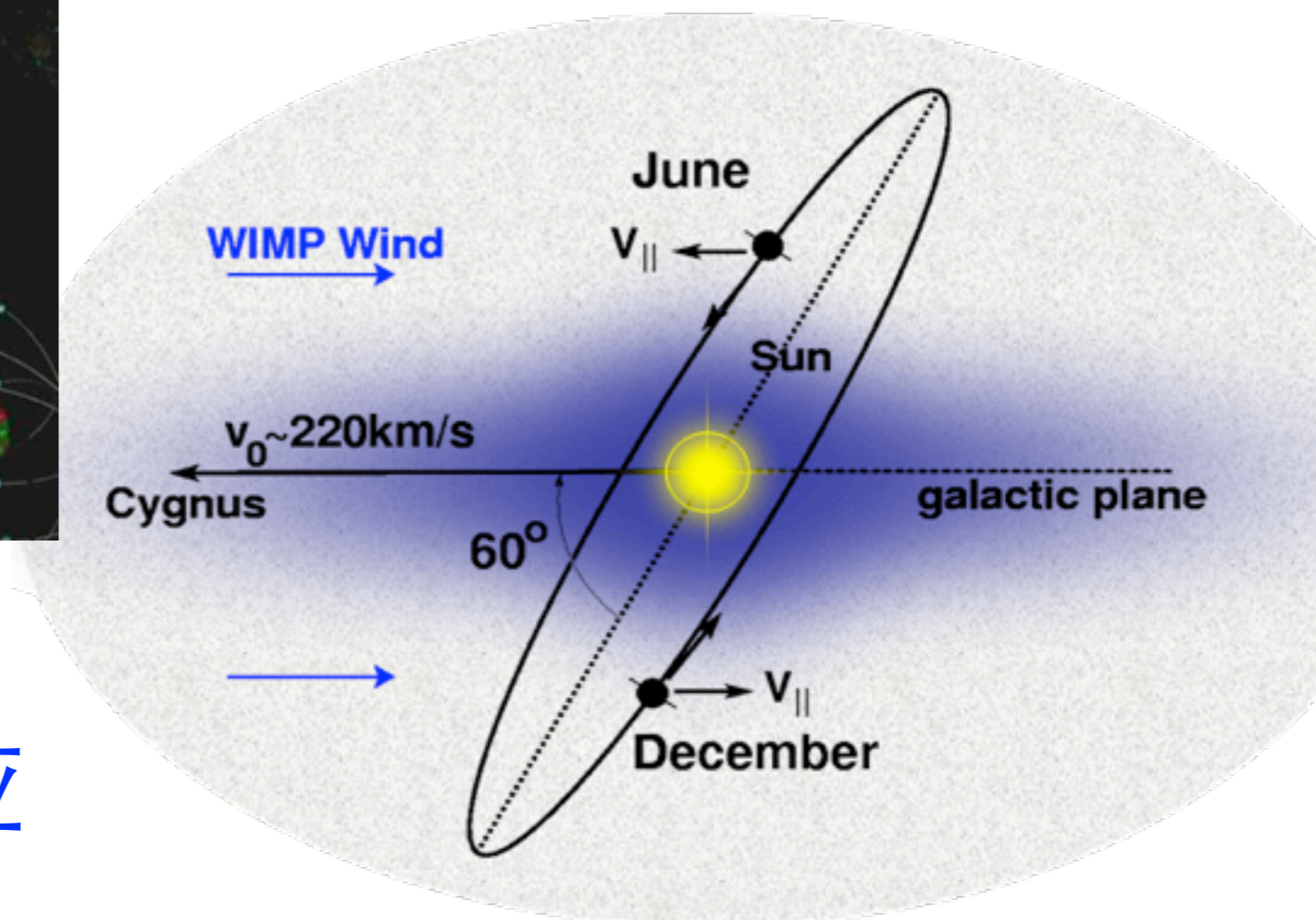
**更糟的是，我们甚至不知道
“什么是我们不知道的”**

暗物质直接探测

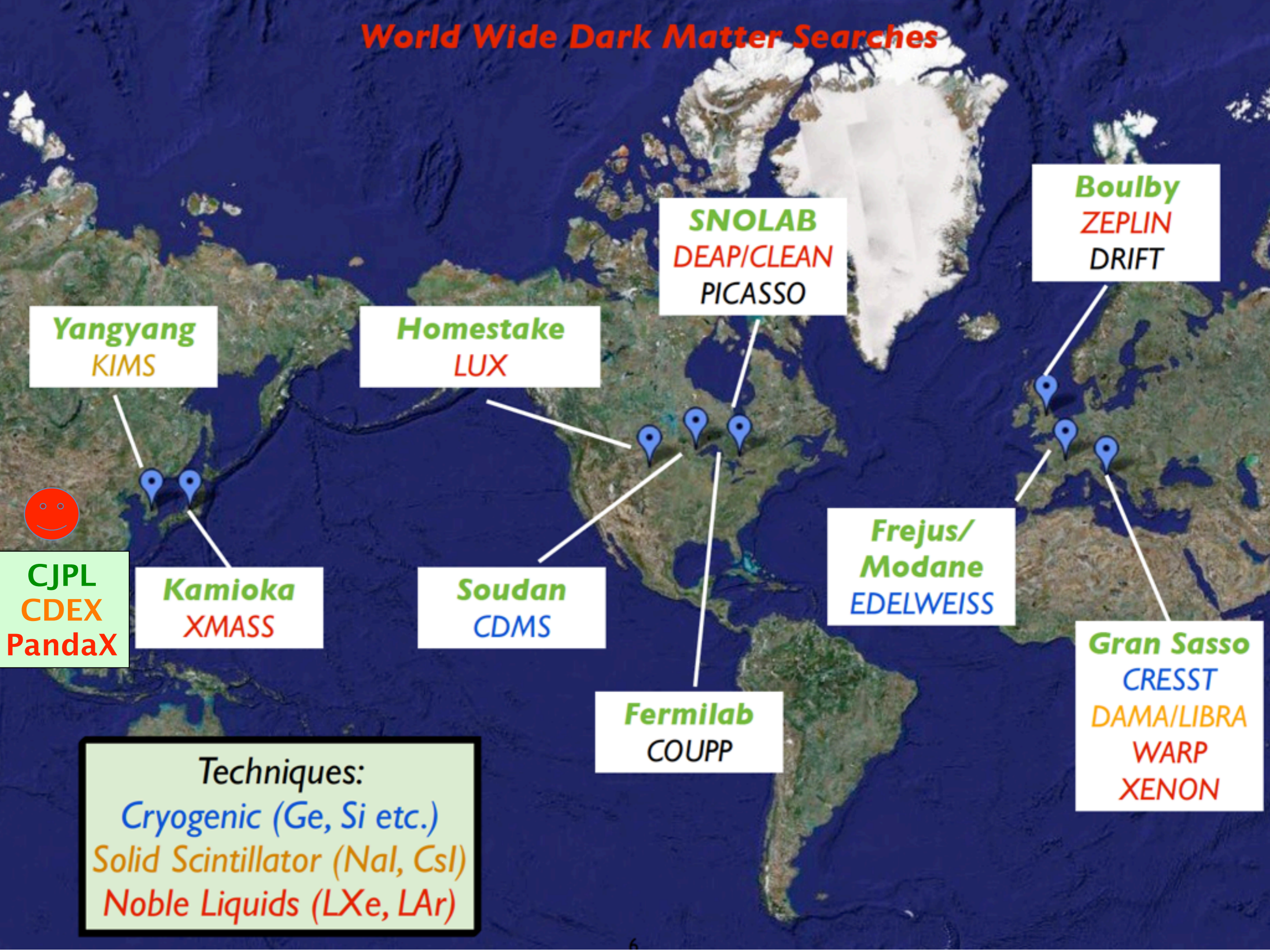


- 直接探测暗物质和原子的弹性散射。
- 信号：热，光，电

年调制效应



World Wide Dark Matter Searches



Yangyang
KIMS

Homestake
LUX

SNOLAB
DEAP/CLEAN
PICASSO

Boulby
ZEPLIN
DRIFT

Kamioka
XMASS

Soudan
CDMS

**Frejus/
Modane**
EDELWEISS

Fermilab
COUPP

Gran Sasso
CRESST
DAMA/LIBRA
WARP
XENON

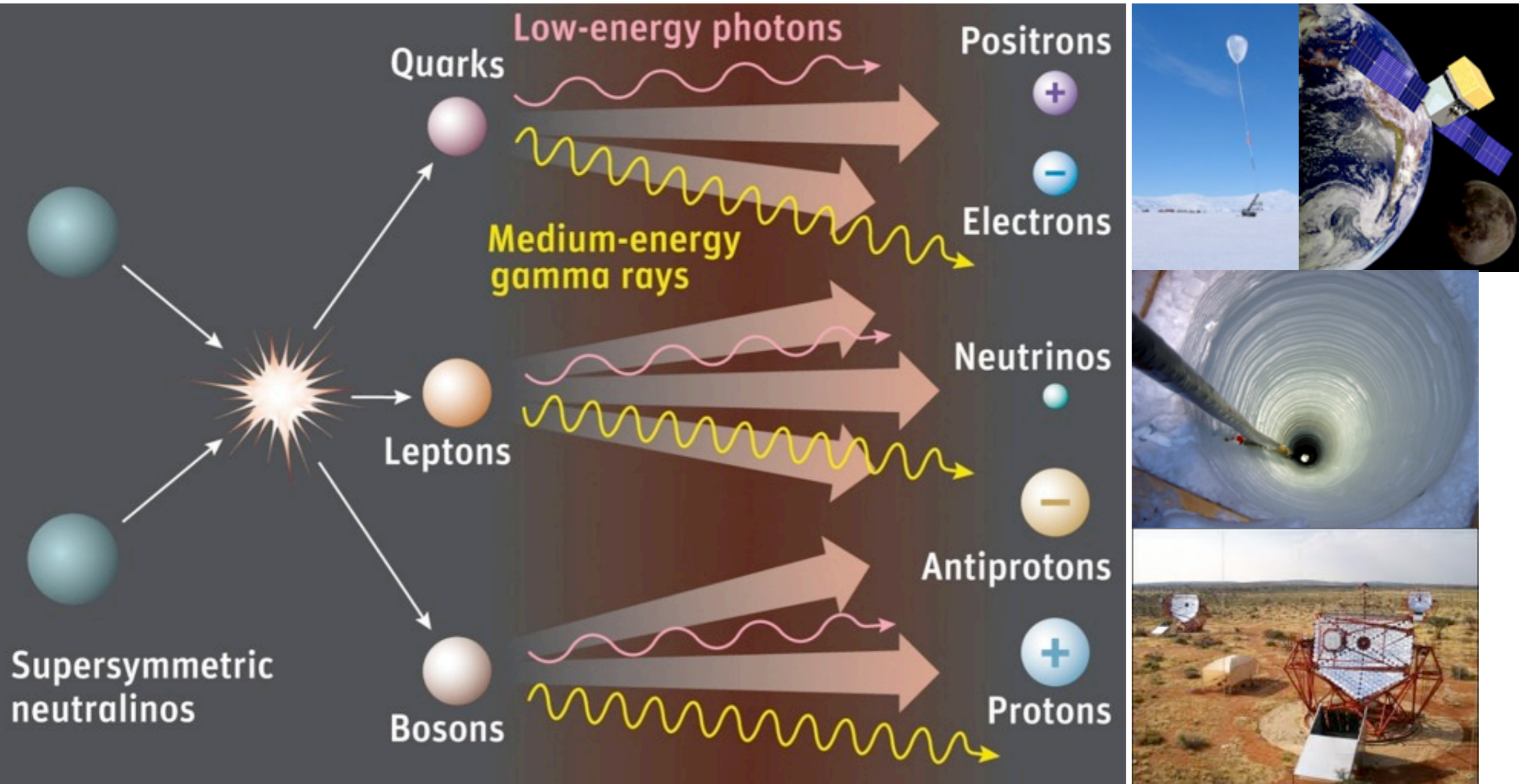
CJPL
CDEX
PandaX

Techniques:
Cryogenic (Ge, Si etc.)
Solid Scintillator (NaI, CsI)
Noble Liquids (LXe, LAr)



暗物质间接测量

暗物质在宇宙中湮灭产生正反电子，正反质子，光子，中微子



An illustration depicting the annihilation of matter and antimatter. On the left, a blue silhouette of a human figure contains three gold circles with plus signs (+), representing matter. On the right, an orange silhouette of a human figure contains three green circles with minus signs (-), representing antimatter. Both figures have their arms extended towards a central point where a bright, fiery red and orange explosion occurs, emitting a large burst of white and grey energy rays. The background is dark, making the central explosion and the figures stand out.

3. 物质和反物质 不对称之谜

早期宇宙中物质和反物质

10,000,000,001

物质

10,000,000,000

反物质

目前宇宙中物质和反物质

10,000,000,001

物质

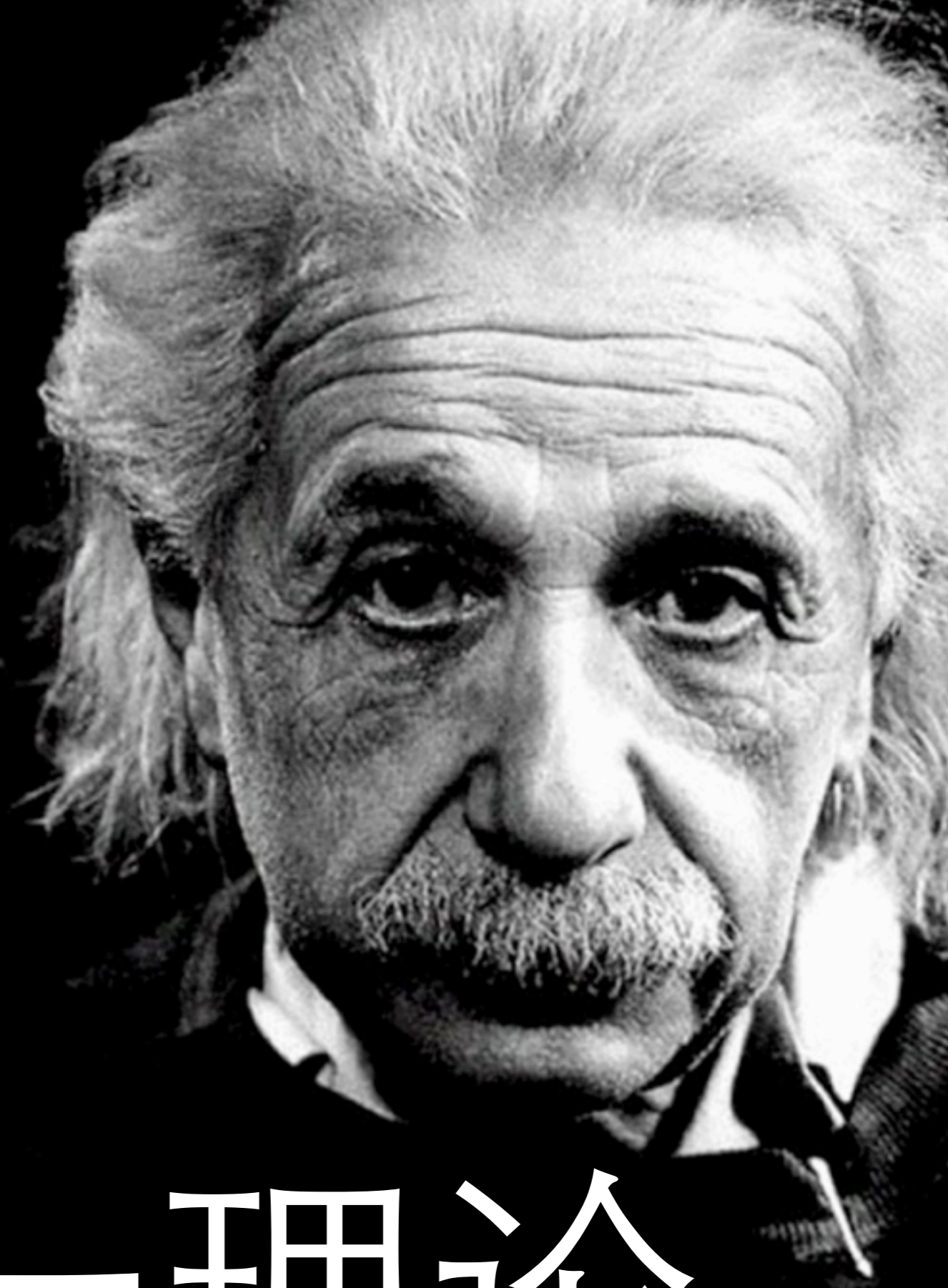
难以置信的
精确相消
(0.00000000000001)
10,000,000,000

反物质

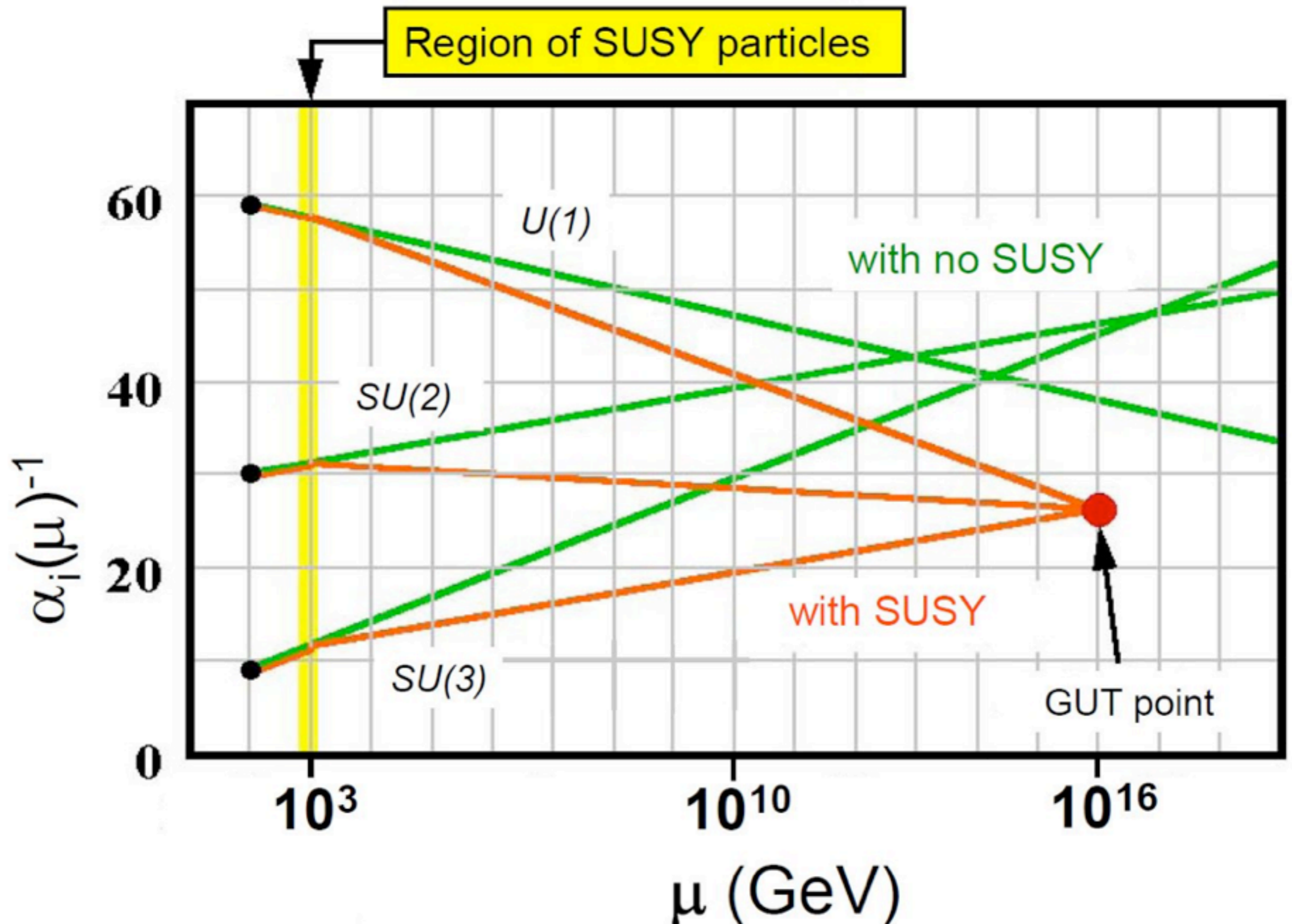
Two things are
infinite. The Universe
and human stupidity.

... and I'm not sure
about the Universe.

4. 大统一理论

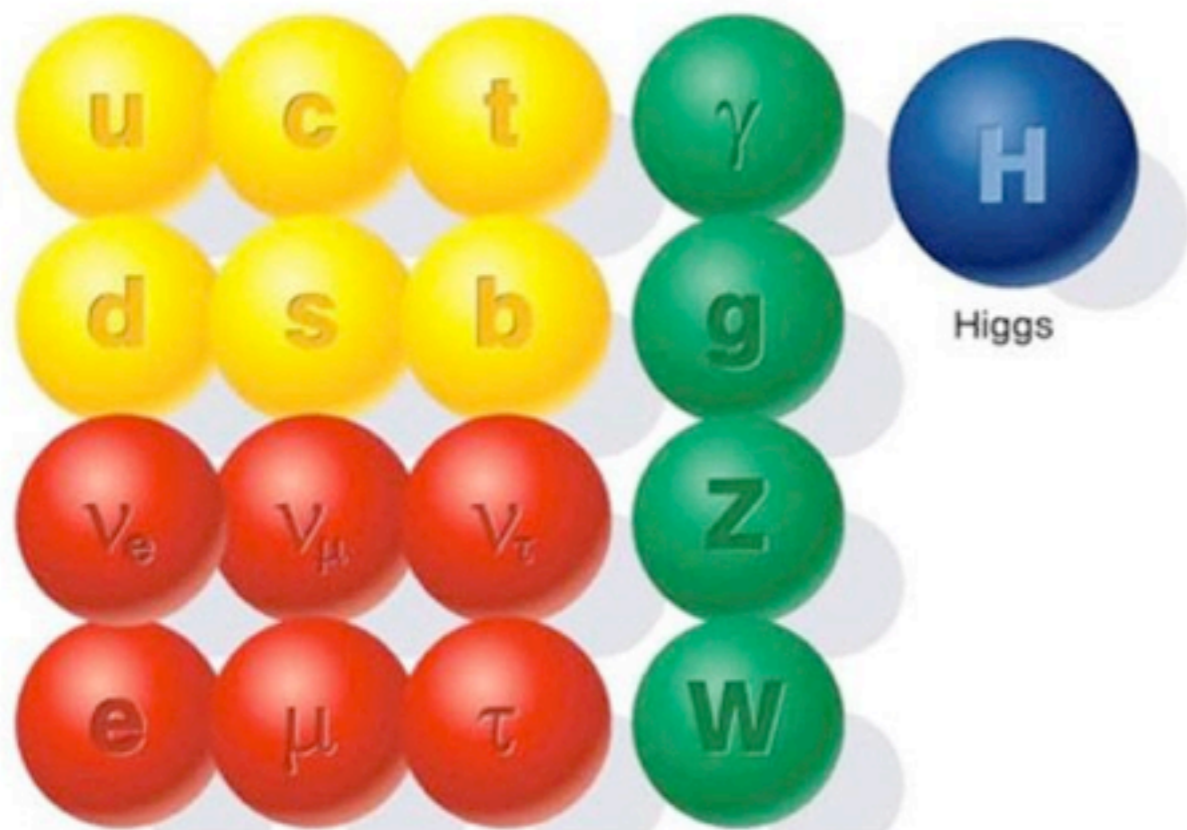


强-弱-电磁相互作用统一



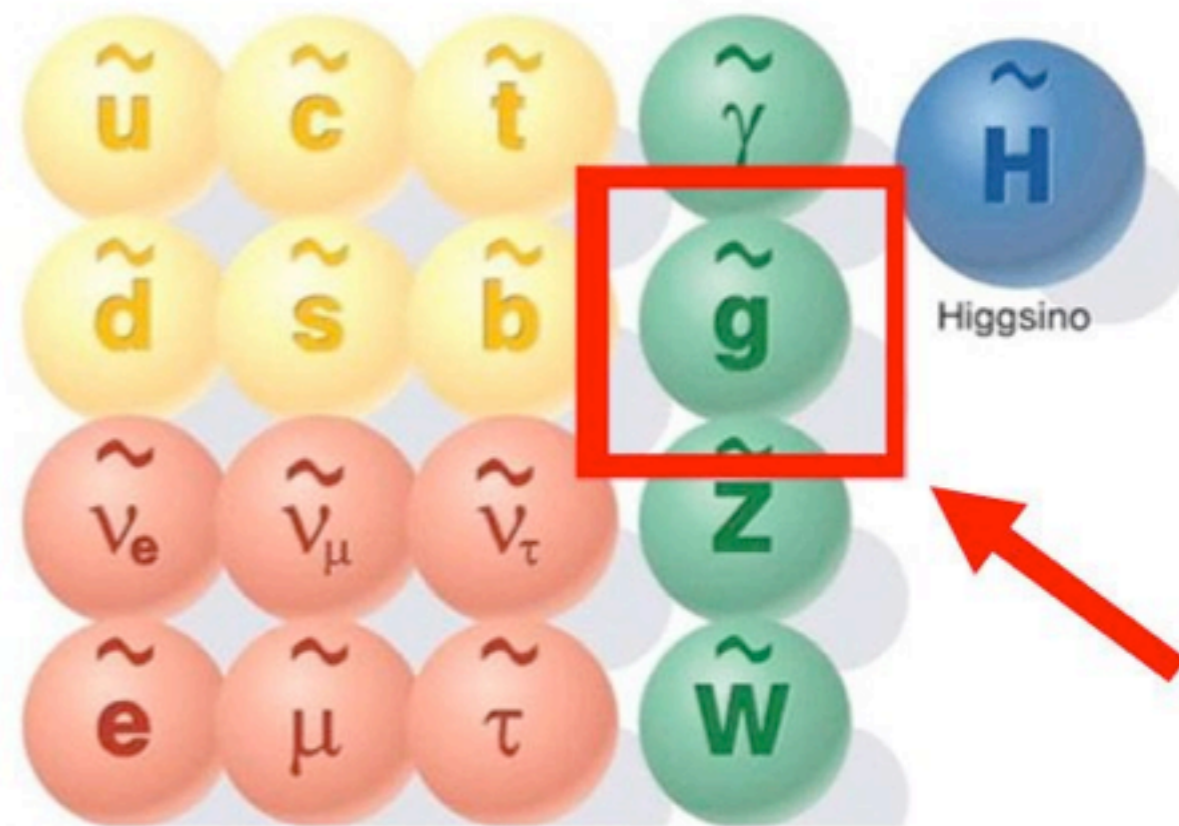
超对称模型

The known world of Standard Model particles



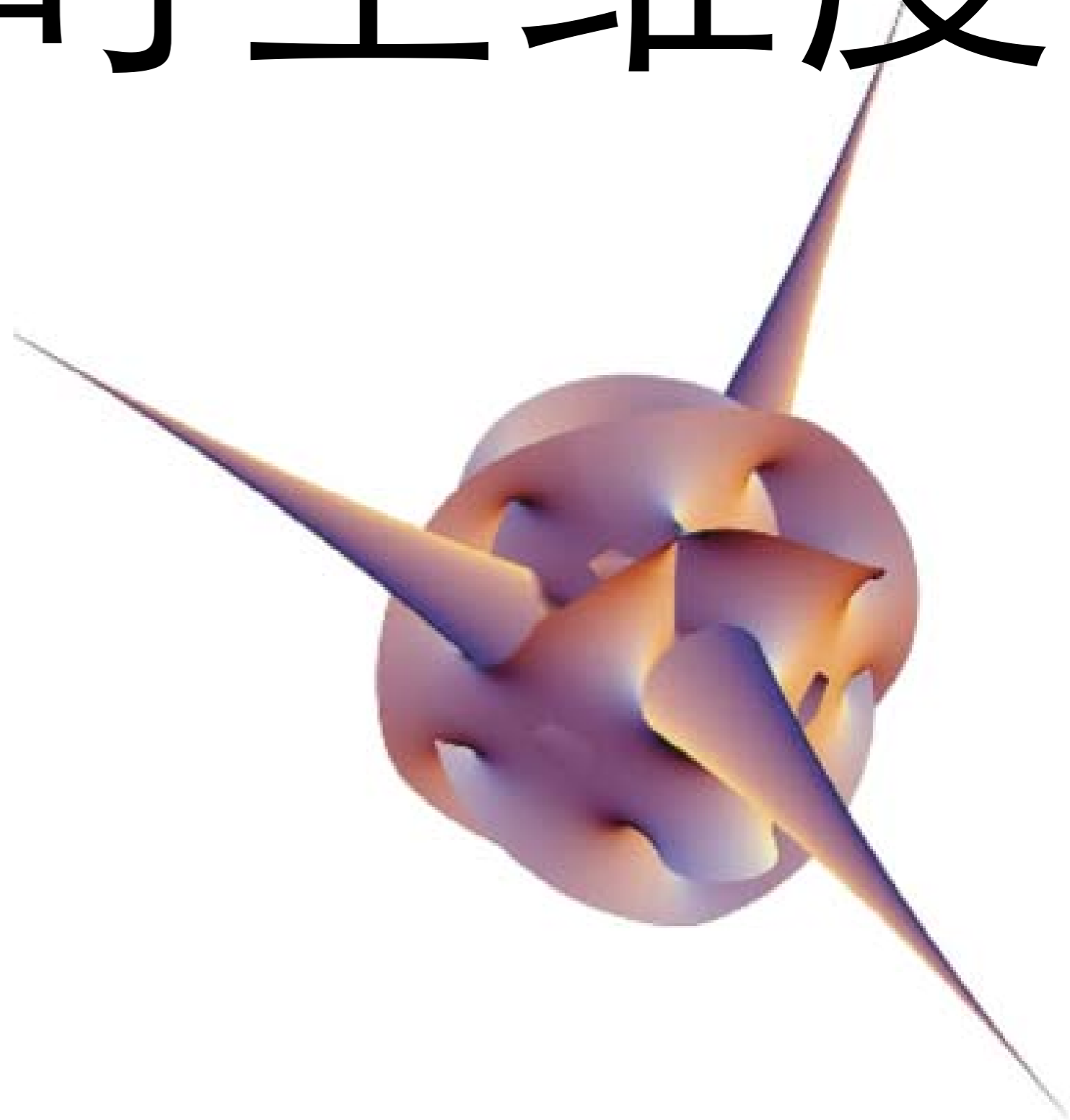
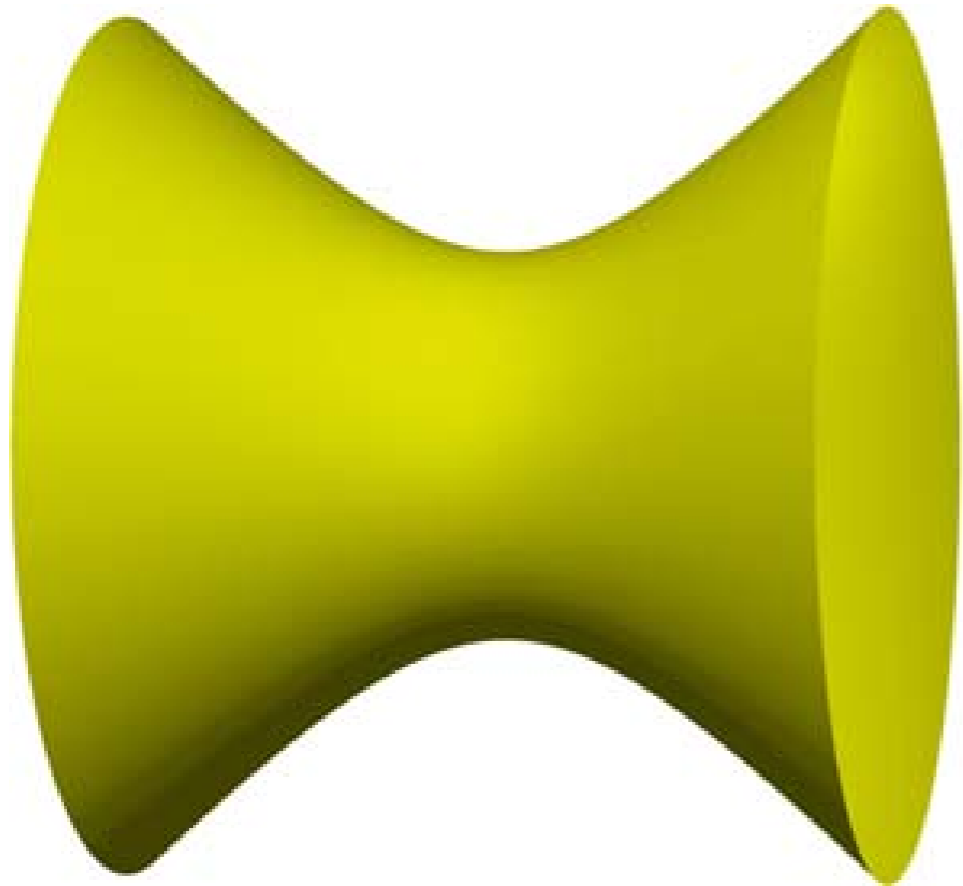
- quarks
- leptons
- force carriers

The hypothetical world of SUSY particles

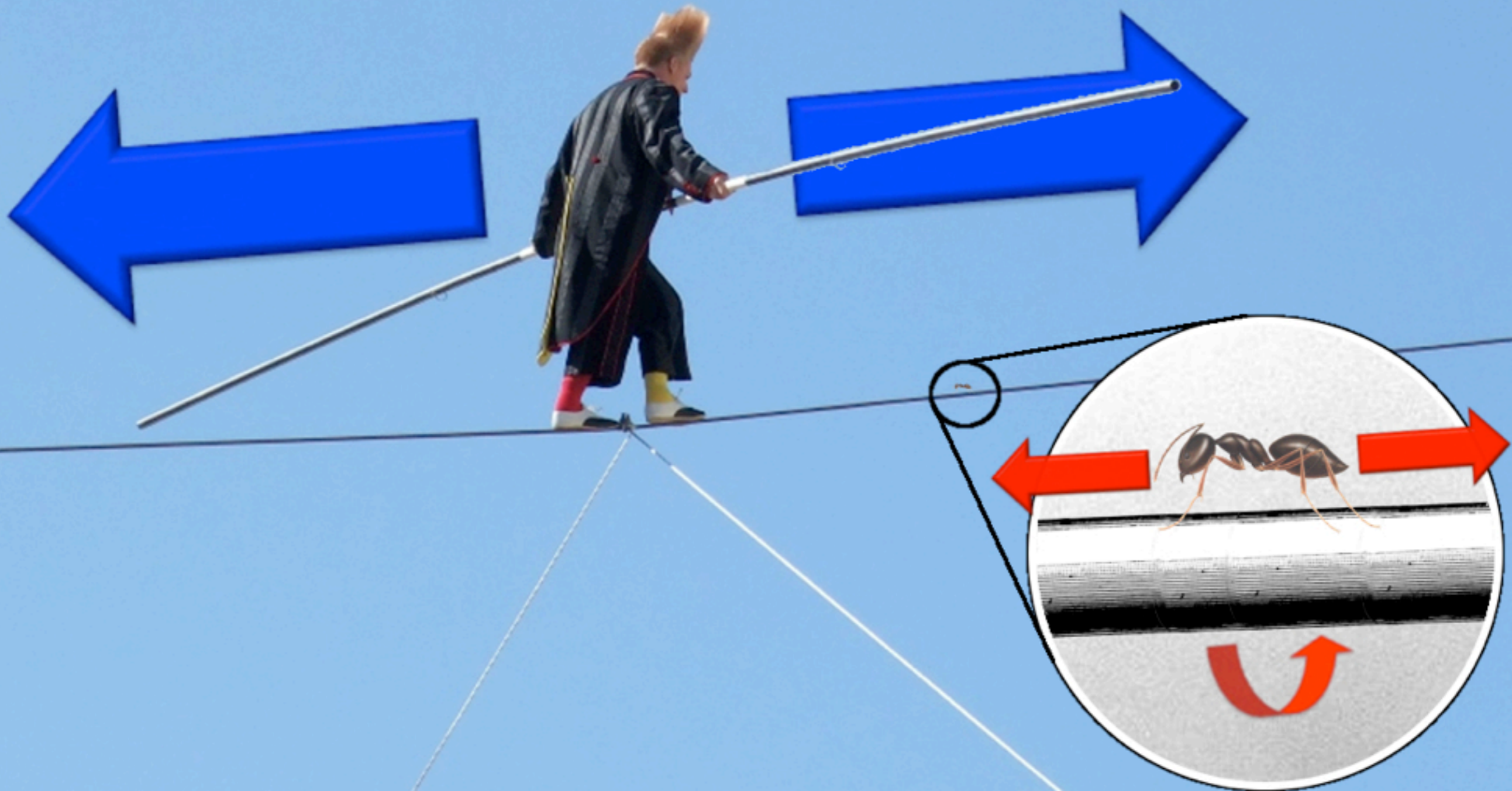


- squarks
- sleptons
- SUSY force carriers

5. 额外时空维度



时空：最熟悉也最陌生



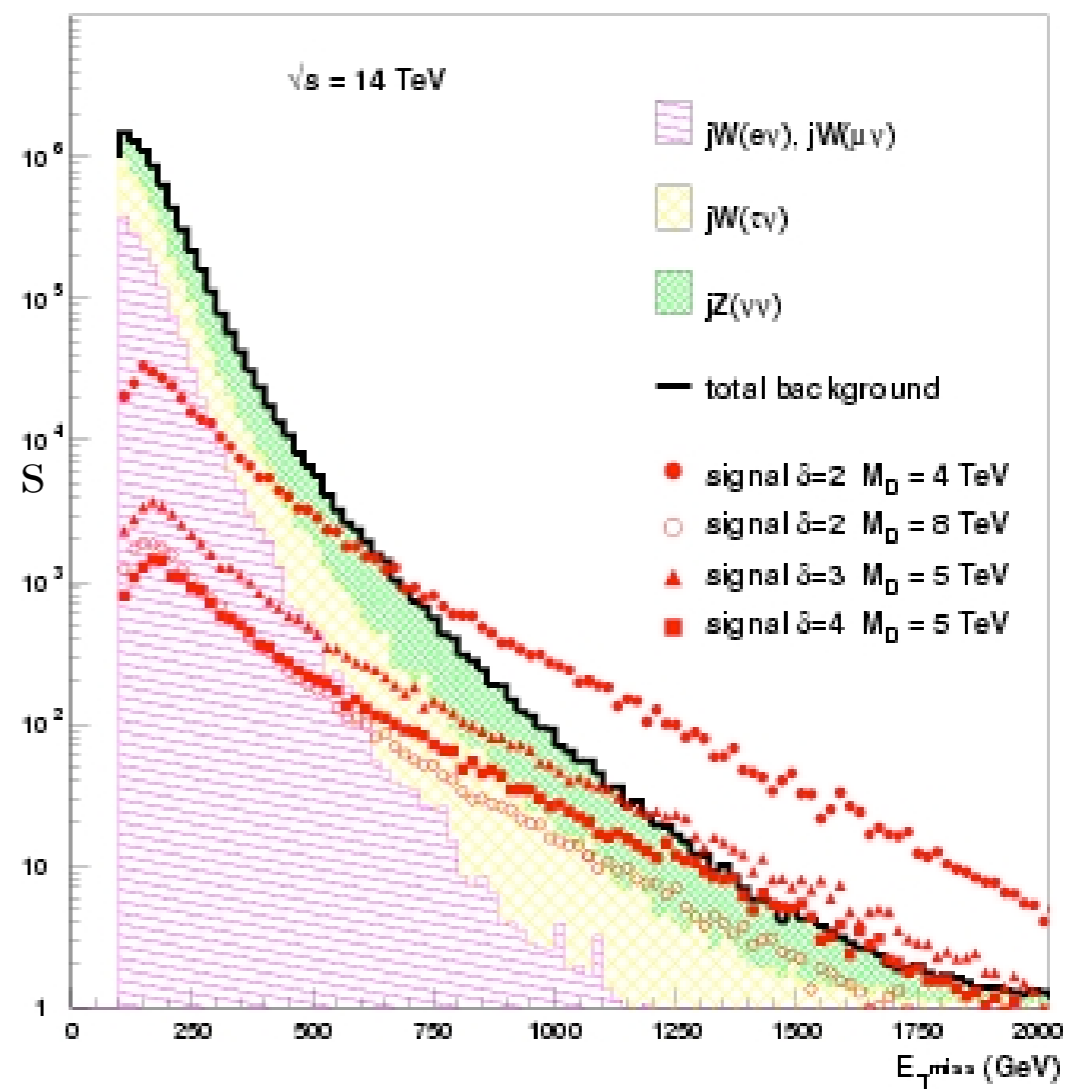
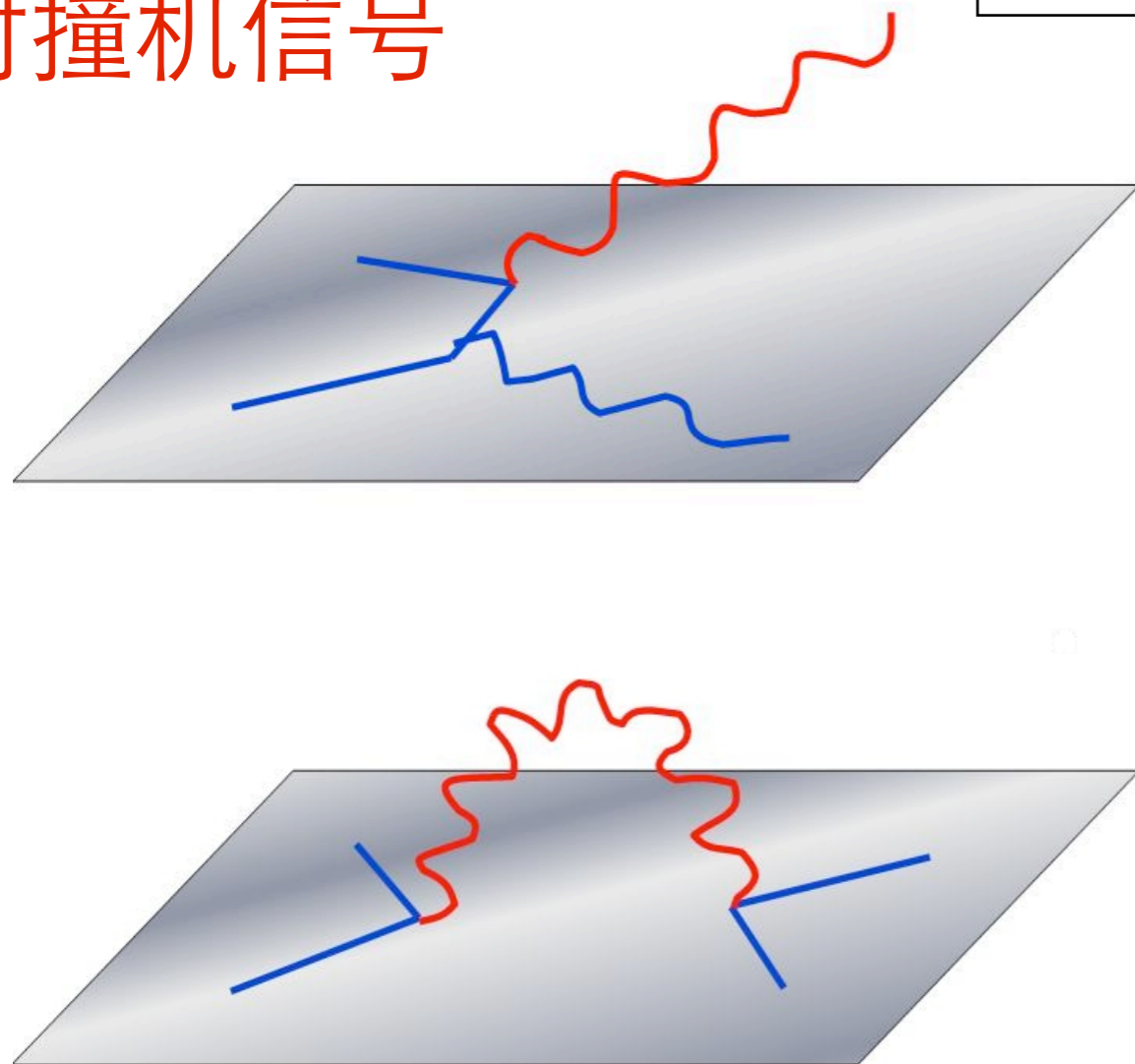
大型强子对撞机信号

大额外维模型 (Large Extra Dimensions)

已知的基本粒子都生活在平常的(3+1)维时空中，
仅有引力可以在额外维空间中传播

对撞机信号

$$p\bar{p} \rightarrow g G_N (G_N \rightarrow \cancel{E}_T) \longrightarrow \text{jet} + \cancel{E}_T$$



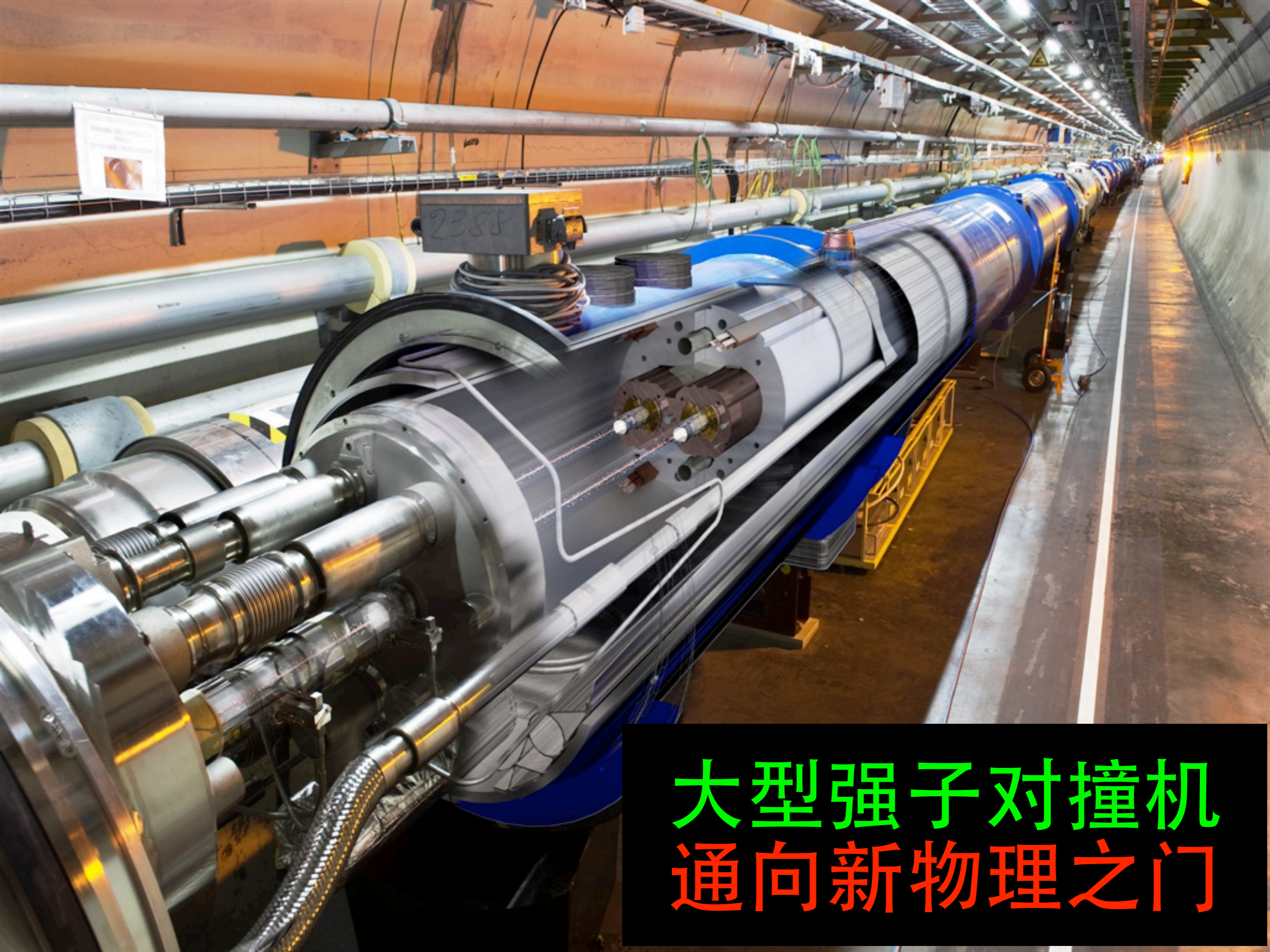
总结

天问



为什么希格斯粒子质量为 125GeV ?
费米子和玻色子质量起源是否相同?
大CP破坏产生机制?
为何仅有3代夸克和轻子?
是否有4代物质场粒子?
能否把自然界中所有力统一?
是否存在新相互作用?
夸克和轻子是否有内部结构?
暗物质的内禀属性及其相互作用?
什么是暗能量?
是否有额外的空间维度?

.....



大型强子对撞机
通向新物理之门