The Uniqueness of the Standard Model and Beyond

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NCTS

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庆祝中科大60周年！

庆祝标准模型50周年！

庆祝中科大78级40周年！

Outline

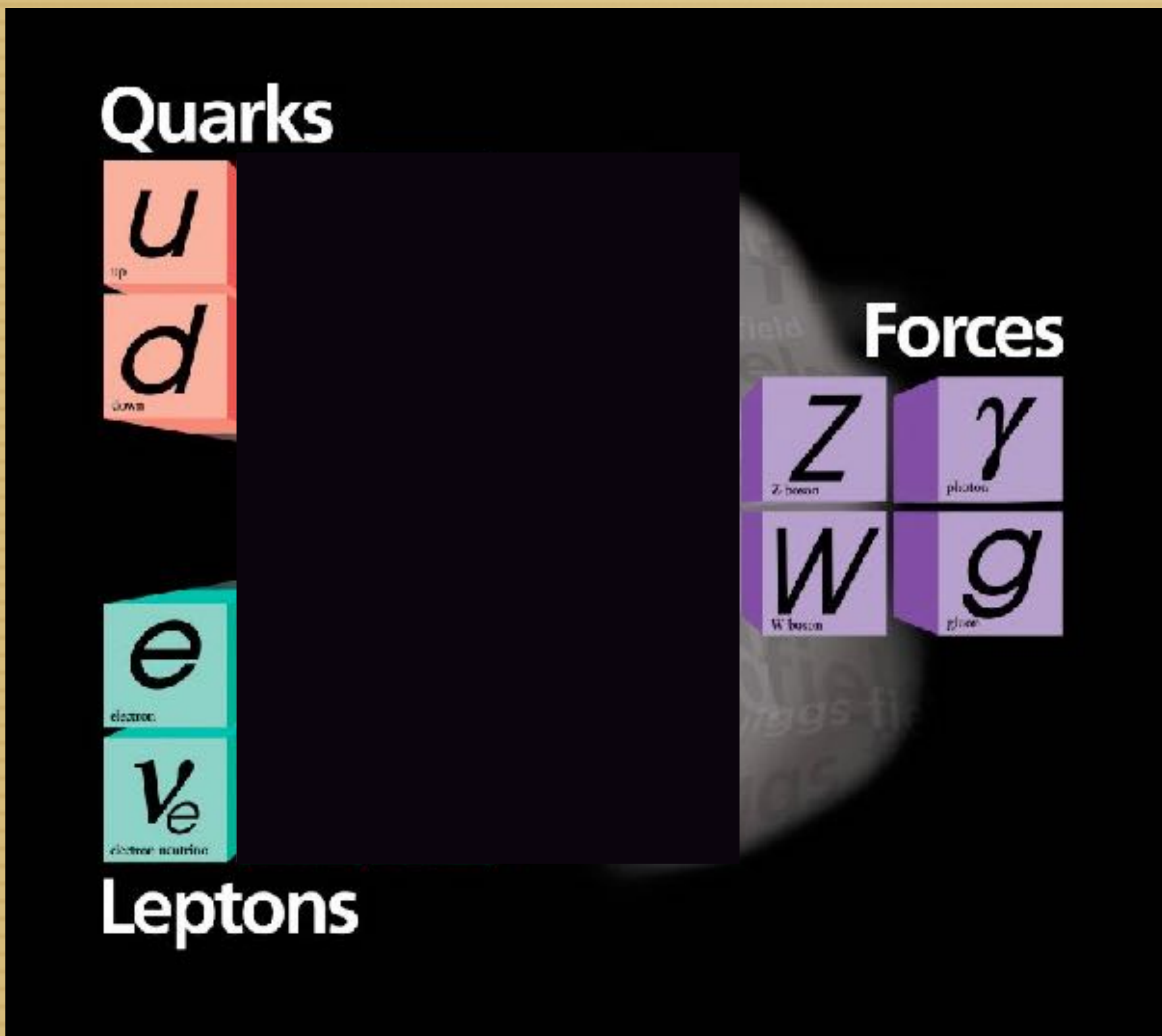
- Introduction
- Chiral symmetry
- Anomalies in four-dimension
- Uniqueness of fermion representations and charges in the standard model
- Family problem
- Broken symmetry and mass generation
- Future prospectives

- Introduction

粒子物理標準模型
The Standard Model in Particle Physics

Ordinary Matter 5%

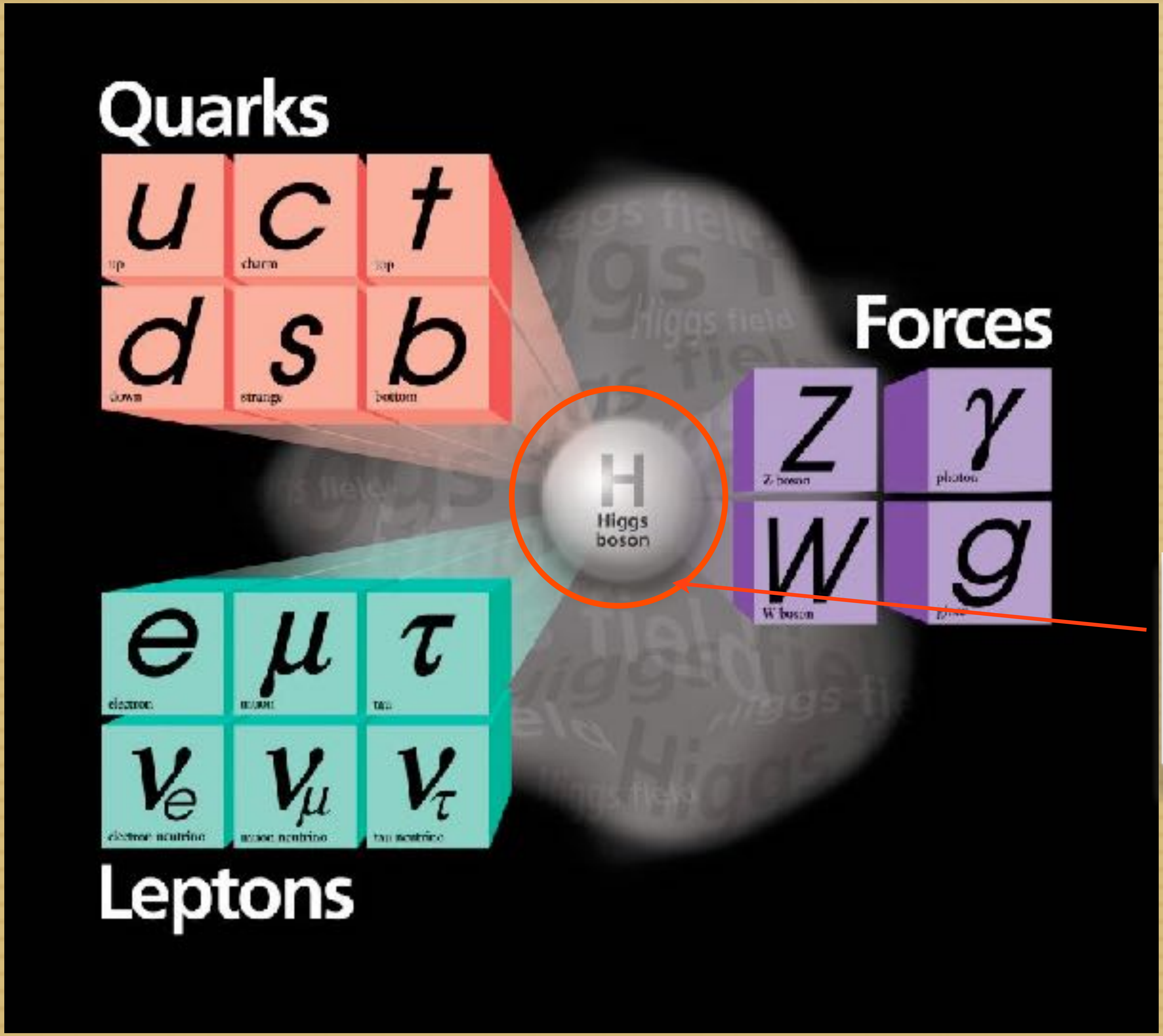
Force



- Introduction

粒子物理標準模型
The Standard Model in Particle Physics

Standard Matter Higgs Force



Higgs Boson:
observed at the LHC in 2012!
2013 Nobel: Englert & Higgs

- Introduction

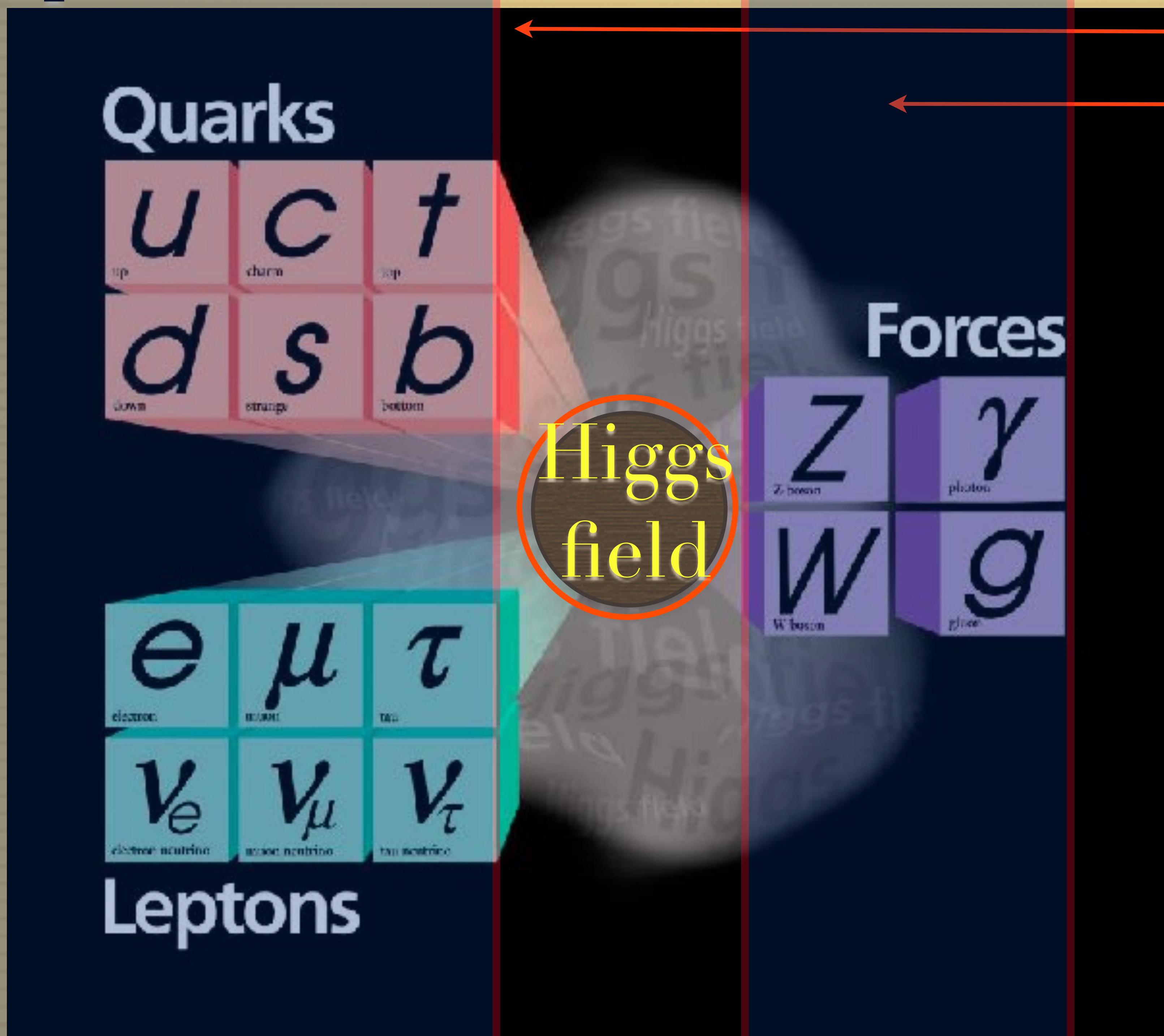
粒子物理標準模型
The Standard Model in Particle Physics

Symmetry principle

Fermion	Boson	
Standard Matter	**Higgs**	**Force**
spin 1/2	**0**	**1**

$SU(3)_c \times SU(2)_L \times U(1)_Y$

massless



- Introduction

Spontaneous symmetry breaking

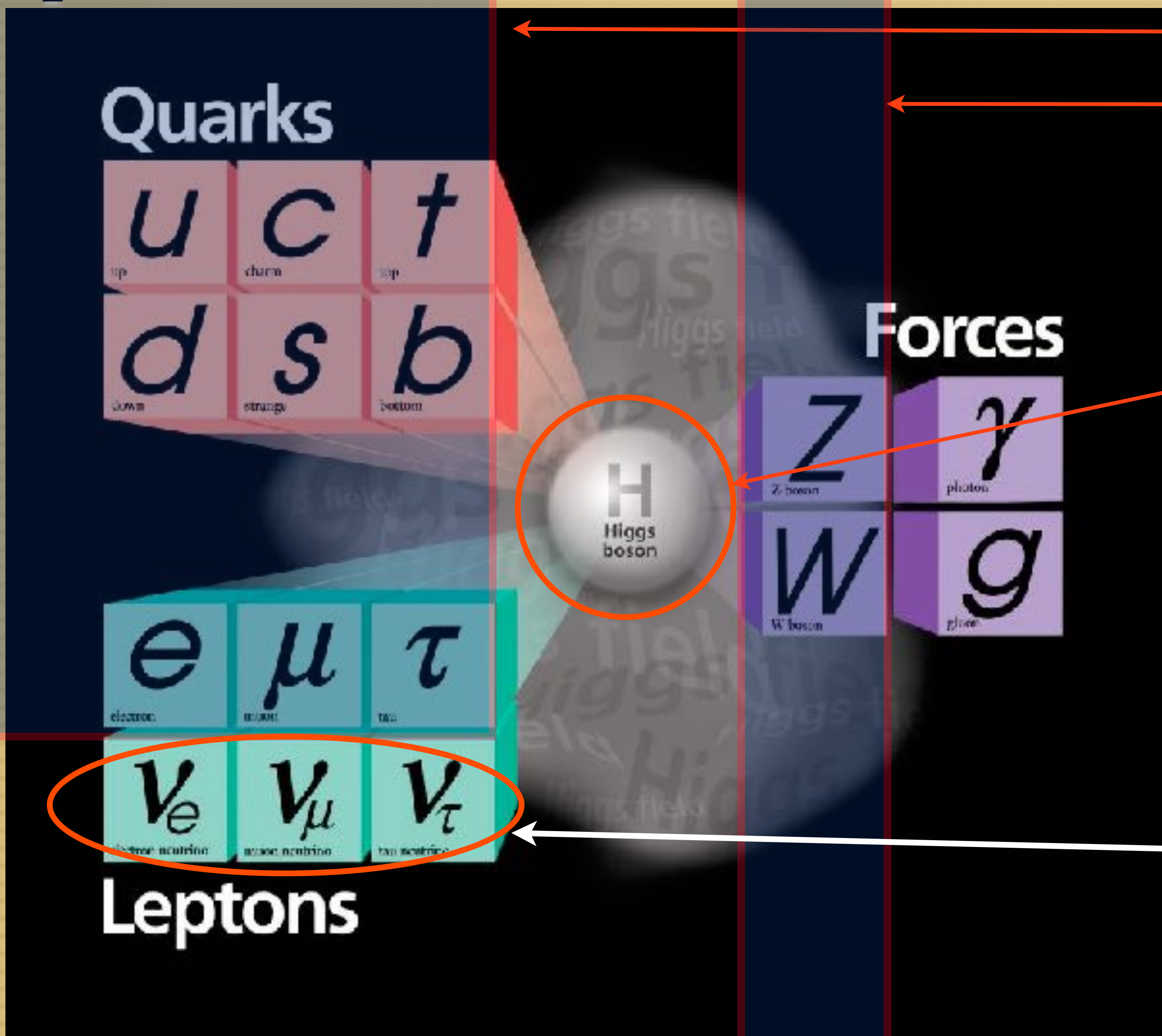
粒子物理標準模型

The Standard Model in Particle Physics

Fermion | Boson

Standard Matter | **Higgs** | **Force**

spin 1/2 | **0** | **1**

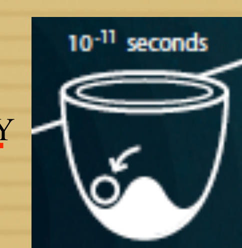


masses

$SU(3)_c \times U(1)_{EM}$

Higgs Mechanism

$SU(3)_c \times SU(2)_L \times U(1)_Y$



Neutrino Oscillation

2015 Nobel: Kajita & McDonald

the SM cannot provides neutrino masses

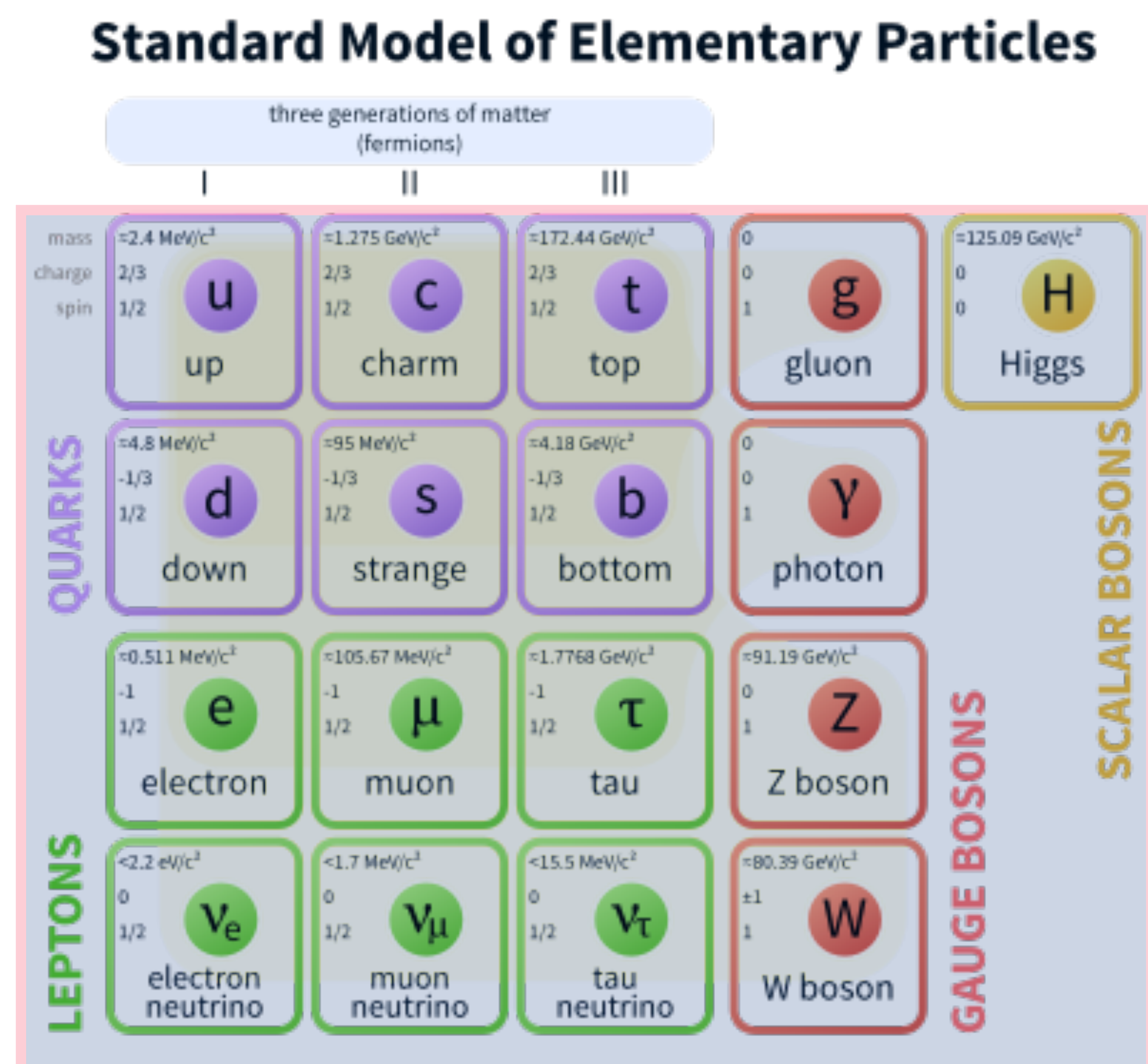
☞ New Physics beyond the SM

The Standard Model in Particle Physics

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

Strong Interaction   Electroweak Interaction

Particles $(i=1,2,3)$	$SU(3)_C$	$\times$	$SU(2)_L$	$\times$	$U(1)_Y$
$\begin{pmatrix} u \\ d \end{pmatrix}_L^i$	3		2		$\frac{1}{3}$
$u_L^{c\,i}$	$\overline{3}$		1		$-\frac{4}{3}$
$d_L^{c\,i}$	$\overline{3}$		1		$\frac{2}{3}$
$\begin{pmatrix} \nu \\ e \end{pmatrix}_L^i$	1		2		-1
$e_L^{c\,i}$	1		1		2



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

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

Standard groups

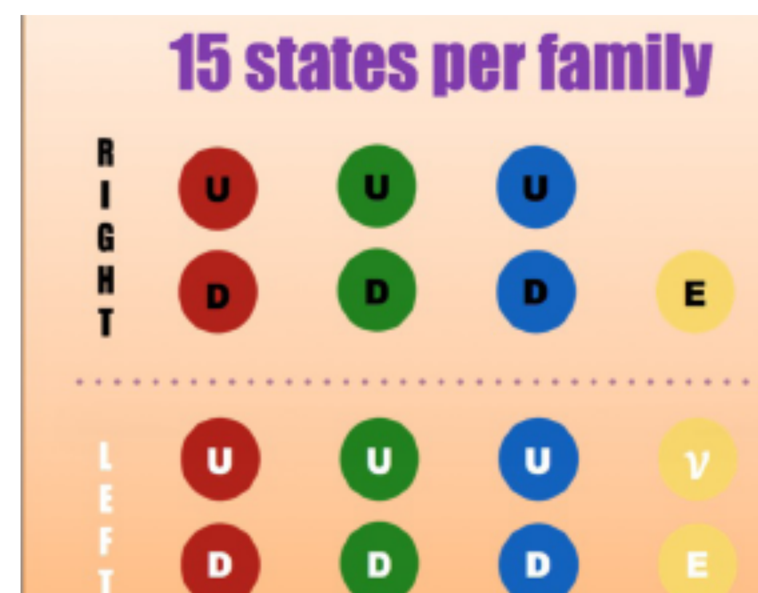
Strong Interaction — Electroweak Interaction

$$Q = T_{3L} + \frac{Y}{2}$$

$SU(3)_C \times SU(2)_L \times U(1)_Y$ $\xrightarrow{\langle H \rangle}$ $SU(3)_C \times U(1)_{EM}$

Higgs Mechanism

				$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$SU(3)_C$	$U(1)_{EM}$
Q_L :	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	$\begin{pmatrix} t \\ b \end{pmatrix}_L$	3	2	$\frac{1}{3}$	$\begin{pmatrix} 3 \\ 3 \end{pmatrix}$	$\begin{pmatrix} \frac{2}{3} \\ -\frac{1}{3} \end{pmatrix}$
U_R :	u_R	c_R	t_R	3	1	$\frac{4}{3}$	3	$\frac{2}{3}$
D_R :	d_R	s_R	b_R	3	1	$-\frac{2}{3}$	3	$-\frac{1}{3}$
L_L :	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	1	2	-1	$\begin{pmatrix} 1 \\ 1 \end{pmatrix}$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
E_R :	e_R	μ_R	τ_R	1	1	-2	1	-1
H				1	2	1		



Questions:

1. Why are there 15 states of quarks and leptons?
2. Why are the electric charges of particles quantized?
3. Are these quantum numbers unique?
4. Why are there three fermion generations?
5. How to generate the fermion masses?

Chiral symmetry

Massless Dirac fermion field ψ exhibits chiral symmetry

Dirac Equation: $(i\gamma^\mu\partial_\mu - m)\,\psi = 0 \xrightarrow{m\to 0}$ $i\gamma^\mu\partial_\mu\,\psi = 0 \xrightarrow{\gamma^5}$ $i\gamma^\mu\partial_\mu(\gamma^5\psi) = 0$

∴ both ψ and $\gamma^5\psi$ are solutions of Dirac equation.

Two linear combinations: $\psi_L = 1/2(1-\gamma^5)\,\psi$ and $\psi_R = 1/2(1+\gamma^5)\,\psi$ ⟵ $\psi = \psi_L + \psi_R$

In QED with one Dirac field:

$$\mathcal{L} = i\bar{\psi}\not{D}\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - m\bar{\psi}\psi \qquad (1)$$

$$F^{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu\,, \quad D_\mu = \partial_\mu - ieA_\mu$$

$$(1) \quad \Longrightarrow \quad U(1)_{\text{vector}} : \psi \longrightarrow e^{i\alpha}\psi$$

$$m \longrightarrow 0 \quad \Longrightarrow \quad U(1)_{\text{axial vector}} : \psi \longrightarrow e^{i\beta\gamma_5}\psi$$

Using $\psi_L = \frac{1}{2}(1-\gamma_5)\psi\,,\quad \psi_R = \frac{1}{2}(1+\gamma_5)\psi$ notations: ⟵ **Chiral Fermions**

$$(1) \implies \mathcal{L} = i\bar{\psi}_L\not{D}\psi_L + i\bar{\psi}_R\not{D}\psi_R - m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

$$m \longrightarrow 0 \qquad U(1)_L : \psi_L \longrightarrow e^{ia}\psi_L \qquad U(1)_R : \psi_R \longrightarrow e^{ib}\psi_R$$

☜ **Chiral symmetries**

$$U(1)_V = U(1)_{L+R}\,, \quad U(1)_A = U(1)_{L-R}$$

Chiral symmetry

- Anomalies in four-dimension

The triangular anomaly

In QED with one Dirac field:

$$\mathcal{L} = i\bar{\psi}\not{D}\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - m\bar{\psi}\psi \qquad (1)$$

$$F^{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \,, \quad D_\mu = \partial_\mu - ieA_\mu$$

$$(1) \quad \Longrightarrow \quad U(1)_{\text{vector}} \; : \; \psi \longrightarrow e^{i\alpha}\psi$$

$$m \longrightarrow 0 \quad \Longrightarrow \quad U(1)_{\text{axial vector}} \; : \; \psi \longrightarrow e^{i\beta\gamma_5}\psi$$

According to *Noether's Theorem*, gauge invariants imply the existence of conserved currents:

$$J_\mu = \bar{\psi}\gamma_\mu\psi \,, \qquad \partial_\mu J^\mu = 0 \,,$$

$$J_{5\mu} = \bar{\psi}\gamma_\mu\gamma_5\psi \,, \qquad \partial_\mu J_5^\mu = 2mJ_5 \xrightarrow{m \longrightarrow 0} 0$$

where $J_5 = i\bar{\psi}\gamma_5\psi$

The anomaly phenomenon is that

$$\partial_\mu J_5^\mu = \partial_\mu(\bar{\psi}\gamma_\mu\gamma_5\psi) = 2mJ_5 + \frac{\alpha_0}{2\pi}\tilde{F}^{\mu\nu}F_{\mu\nu}$$

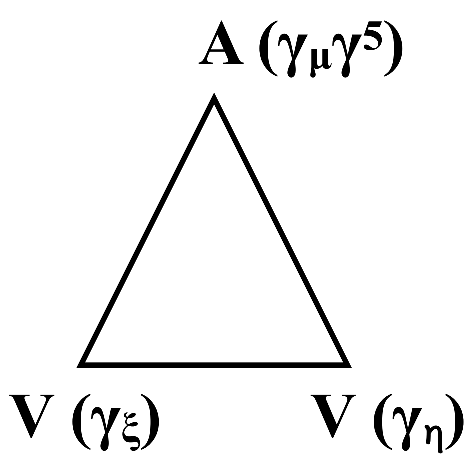
$$m \longrightarrow 0 \qquad \longrightarrow \frac{\alpha_0}{2\pi}\tilde{F}^{\mu\nu}F_{\mu\nu}$$

S.Adler,PR177,2426(1969);
J.S.Bell,R.Jackiw,Nuovo Cimen A60,47 (1969)

$(\tilde{F}_{\mu\nu} = \epsilon_{\mu\nu\alpha\beta}F^{\alpha\beta})$

Quantum Level

— Adler-Bell-Jackiw (ABJ) or axial *Anomaly*



— *Triangle Anomaly*

This anomalous result $\Longrightarrow$ an understanding of $\pi \to 2\gamma$

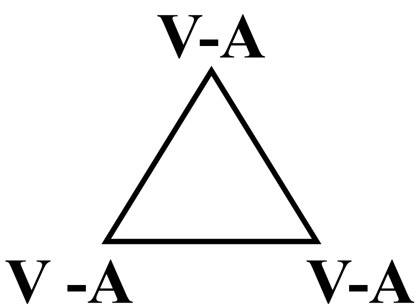
$U(1)$ problem in QCD

No problem in QED the axial-vector current doesn't couple to the photon (γ).

If we introduce a gauge boson which couples to the axial-vector current, such a theory will not be *renormalizable* since the gauge invariance – a necessary requirement for renormalizability — is lost due to $\partial_\mu J_5^\mu \neq 0$.

Electroweak theory: $V - A$ gauge coupling

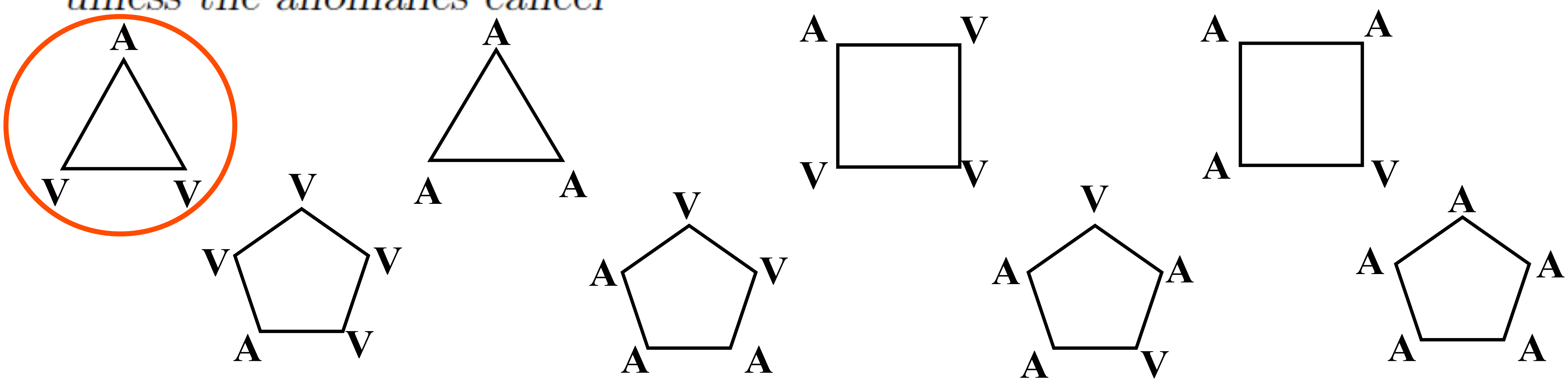
One must consider a fermion triangle with a $V - A$ current at each vertex.



This diagram is again anomalous.

Unless it cancels when summing over the fermion species running around the loop, the anomaly spoils conservation of the $V - A$ current.

- *Any gauge theory with non-vectorlike gauge coupling is inconsistent unless the anomalies cancel*



Two useful theorems:

- Once the AVV triangle anomaly is cancelled, then so are all the others.
- Radiative corrections do not renormalize the anomaly.

$\Longrightarrow$ *Only AVV triangle graph is needed to consider.*

For example: any gauge theory

$$
\begin{aligned}
J_a^\mu &= \bar{\psi}\gamma^\mu t_a \psi \\
&= \frac{1}{2}\bar{\psi}\gamma^\mu t_a^L (1-\gamma_5)\psi + \frac{1}{2}\bar{\psi}\gamma^\mu t_a^R (1+\gamma_5)\psi
\end{aligned}
$$

where t_a $(a = 1, 2, \cdots, N)$ are the generators of the gauge group.

$$
\begin{aligned}
Anomaly - free \Longleftrightarrow \mathcal{A} &\equiv Tr\left[\{t_a^L, t_b^L\}, t_c^L\right] - Tr\left[\{t_a^R, t_b^R\}, t_c^R\right] \\
&= 0
\end{aligned}
$$

△ Real representations are *safe*.

△ $SU(2)$, $SO(2k+1)$ $(k > 2)$, $SO(4k)$ $(k > 2)$, $Sp(2k)$, G_2, F_4, E_7, E_8 have only real reps. — *safe*.

△ $SO(4k+2)$ $(k > 2)$, E_6 have complex reps. — *safe*.

△ $SU(N)$ $(N > 2)$ are not *safe*.

For $(\square, Y)$ under SU(N)×U(1)$_Y$:
or $(\bar{\square}, Y)$

$$
\begin{aligned}
[SU(N)]^3 &: \mathcal{A}(\square) = 1\,, \quad \mathcal{A}(\bar{\square}) = -1 \\
[SU(N)]^2 U(1)_Y &: \mathcal{A}(\square) = Y\,, \quad \mathcal{A}(\bar{\square}) = Y \\
[U(1)_Y]^3 &: \mathcal{A} = Y^3
\end{aligned}
$$

Particles $(i=1,2,3)$	$SU(3)_C$	$\times$	$SU(2)_L$	$\times$	$U(1)_Y$
$\begin{pmatrix} u \\ d \end{pmatrix}_L^i$	3		2		$\frac{1}{3}$
$u_L^{c\,i}$	$\overline{3}$		1		$-\frac{4}{3}$
$d_L^{c\,i}$	$\overline{3}$		1		$\frac{2}{3}$
$\begin{pmatrix} \nu \\ e \end{pmatrix}_L^i$	1		2		-1
$e_L^{c\,i}$	1		1		2

Triangle anomalies in the standard model:

$$
\begin{aligned}
[SU(3)_C]^3 &= 2-1-1=0 \\
[SU(3)_C]^2\,U(1)_Y &= 2\cdot\frac{1}{3}+1\cdot(-\frac{4}{3})+1\cdot\frac{2}{3}=0 \\
[SU(2)_L]^3 &\equiv 0 \\
[SU(2)_L]^2\,U(1)_Y &= 3\cdot\frac{1}{3}-1=0 \\
[U(1)_Y]^3 &= TrY^3 \\
&= 3\cdot 2\cdot(\frac{1}{3})^3+3\cdot 1\cdot(-\frac{4}{3})^3+3\cdot 1\cdot(\frac{1}{3})^3 \\
&\quad +2\cdot(-1)^3+1\cdot(2)^3=0
\end{aligned}
$$

Particles $(i=1,2,3)$	$SU(3)_C$	$\times$	$SU(2)_L$	$\times$	$U(1)_Y$	重子數 $\times\ U(1)_B$	輕子數 $\times\ U(1)_L$	$=\ U(1)_{B+L}$	$\times\ U(1)_{B-L}$
$\begin{pmatrix} u \\ d \end{pmatrix}_L^i$	3		2		$\frac{1}{3}$	1/3	0	1/3	1/3
$u_L^{c\,i}$	$\overline{3}$		1		$-\frac{4}{3}$	-1/3	0	-1/3	-1/3
$d_L^{c\,i}$	$\overline{3}$		1		$\frac{2}{3}$	-1/3	0	-1/3	-1/3
$\begin{pmatrix} \nu \\ e \end{pmatrix}_L^i$	1		2		-1	0	1	1	-1
$e_L^{c\,i}$	1		1		2	0	-1	-1	1

Global Symmetries

Global Symmetries

U(1)B : $q_i \to \exp\left[\frac{i}{3}\alpha_B\right] q_i$ $\quad J_B^\mu = \frac{1}{3}\sum_i \bar{q}_i\gamma^\mu q_i$ $\quad \mathcal{L}_{SM} \xrightarrow{U(1)_B} \mathcal{L}_{SM}$ 重子數守恆

U(1)L : $\ell_i \to \exp(i\alpha_L)\ell_i$ $\quad J_L^\mu = \sum_i \bar{\ell}_i\gamma^\mu \ell_i$ $\quad \mathcal{L}_{SM} \xrightarrow{U(1)_L} \mathcal{L}_{SM}$ 輕子數守恆

At the quantum level, however, neither U(1)L or U(1)B are good symmetries, because of the chiral nature SU(2)L.

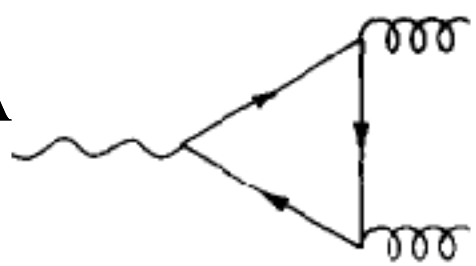
$$[SU(2)_L]^2\, U(1)_B = 3 \times \frac{1}{3} + 1 \times 0 = 1 \qquad [SU(2)_L]^2\, U(1)_L = 3 \times 0 + 1 \times 1 = 1$$

$$[SU(2)_L]^2\, U(1)_{B+L} = 3 \times \frac{1}{3} + 1 \times 1 = 2 \qquad [SU(2)_L]^2\, U(1)_{B-L} = 3 \times \frac{1}{3} - 1 \times 1 = 0$$

$$\mathcal{L}_{SM} \xrightarrow{U(1)_{B-L}} \mathcal{L}_{SM}$$

（重子－輕子）數守恆

- The mixed gauge-gravitational anomaly



The triangle with one axial-current and two energy-momentum tensors is anomalous

$$D_\mu J_5^\mu = -\frac{1}{384\pi^2}(TrQ)\, R_{\mu\nu\sigma\tau}\tilde{R}^{\mu\nu\sigma\tau}$$

R.Delbourgo,A.Salam,PLB40,381(72); T.Eguchi,P.Freund,PRL37,1251(76)

$R_{\mu\nu\sigma\tau}$ is the Riemann curvature tensor and $\tilde{R}^{\mu\nu\sigma\tau} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}R^{\sigma\tau}_{\alpha\beta}$.

In four dimensions, the standard $SU(2)_L \times U(1)_Y$ theory cannot be coupled to gravity unless the sum of hypercharges (Y) of the Weyl fermions vanishes:

$$Tr\,Y = 0$$

L.Alvarez-Gaume, E.Witten, NPB234 (1983) 269

In the SM: $TrY = 3\cdot 2\cdot(\frac{1}{3}) + 3\cdot 1\cdot(-\frac{4}{3}) + 3\cdot 1\cdot(\frac{2}{3}) + 1\cdot 2\cdot(-1) + 1\cdot 1\cdot 2 = 0.$

Remarks:

- $U(1)$ — *unsafe*, unless $TrQ = 0$.
- G — *safe*. $\quad G \longrightarrow U(1)\times g\,, \quad TrQ \equiv 0$

Example:

$SU(3)_C$	$\times SU(2)_L$	$\times U(1)_Y$
3	2	1/3
$\overline{3}$	1	−4/3
$\overline{3}$	1	2/3
1	2	−1
1	1	2
1	1	y_i

$i = 1, \cdots, n$

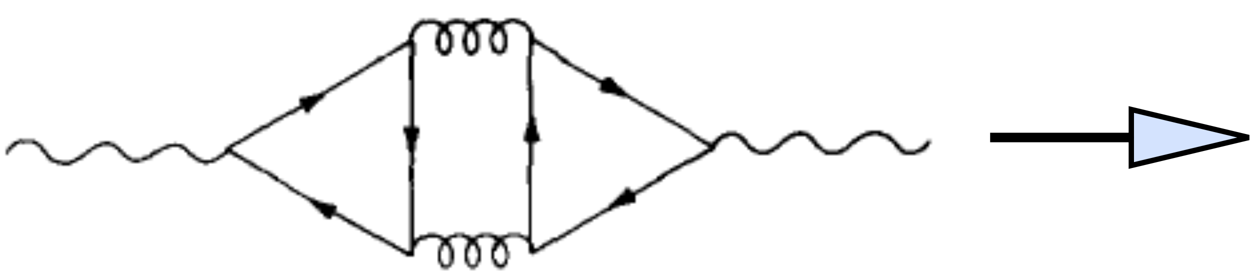
$$\Sigma_{i=1}^{n} y_i^3 = 0$$

$$\Sigma_{i=1}^{n} y_i \neq 0$$

$$Q = T_{3L} + \frac{Y}{2} \Longrightarrow Tr\, Q \neq 0$$

Existing massless electrically charged fermions:

L.Alvarez-Gaume, E.Witten, NPB234 (1983) 269



$$m_\gamma^2 \sim \alpha G_N^2 \Lambda^6 (Tr\, Q)^2$$

G_N — Newton's constant

Λ — an ultraviolet cut off

$$m_\gamma \leq (10^6\, km)^{-1} \sim 10^{-25}\, GeV \Longrightarrow \Lambda \leq 10^5\, GeV$$

- The global Witten $SU(2)$ anomaly

E.Witten,PLB117(1982)324

Any $SU(2)$ gauge theory with an odd number of left-handed fermion doublets is mathematically inconsistent.

The fermion integration for N massless Weyl fermion doublets, ψ:

$$\int (\mathcal{D}\psi\mathcal{D}\bar{\psi})_{\text{Weyl}}\, e^{\bar{\psi}iD\psi} = det^{N/2} iD(A) \longrightarrow (-1)^N det^{N/2} iD(A^U)$$

a topologically nontrivial gauge transformation U

where $A^U_\mu = U^{-1}A_\mu U - iU^{-1}\partial_\mu U$.

The number of the doublets, N, has to be *even*, otherwise the theory is ill-defined.

In the SM, for each family, $N = 3$ (quark) $+$ 1 (lepton) $= 4$ — even.

Remarks:

- $\Pi_4(G) = Z_2$, $G = Sp(2N), SU(2) = Sp(2)$ — *unsafe*.
- $\Pi_4(G) = 0$, G: all the simple compact Lie groups except $Sp(2N)$ — *safe*.

$\Pi_4(G)$ is the 4th homotopy group

Question: For $G \longrightarrow SU(2) \times g$, is Witten $SU(2)$ anomaly free?

Triangle Anomaly-free of $G \Longrightarrow$ Witten $SU(2)$ Anomaly-free

CQG, Zhao,Marshak,OKubo PRD(RC)36(1987)1953

(a) $SO(10)$ $\rightarrow$	$SU(4)_C$ $\times$	$SU(2)_L$ $\times$	$SU(2)_R$
16	4	2	1
	4	1	2

N= even

(b) $SU(3)$ $\rightarrow$	$SU(2)$ $\times$	$U(1)$
3	2	1
	1	-2

N= odd

- Uniqueness of fermion representations and charges in the SM

$SU(3)$	$\times$ $SU(2)$	$\times$ $U(1)$
3	2	$Q_i\,,\ i=1,\cdots,j$
3	1	$Q'_i\,,\ i=1,\cdots,k$
$\overline{3}$	1	$\overline{Q}_i\,,\ i=1,\cdots,l$
$\overline{3}$	2	$\overline{Q}'_i\,,\ i=1,\cdots,m$
1	2	$q_i\,,\ i=1,\cdots,n$
1	1	$\overline{q}_i\,,\ i=1,\cdots,p$
$\cdots$	$\cdots$	$\cdots$

☜ ***arbitrary***

The triangular anomaly-free conditions:

$$[SU(3)]^3 \ : \ \sum_{i=1}^{j} 2 + \sum_{i=1}^{k} 2 - \sum_{i=1}^{l} 1 - \sum_{i=1}^{m} 2 = 0\,, \tag{1}$$

$$[SU(3)]^2 U(1) \ : \ 2\sum_{i=1}^{j} Q_i + \sum_{i=1}^{k} Q'_i + \sum_{i=1}^{l} \overline{Q}'_i + 2\sum_{i=1}^{m} \overline{Q}'_i = 0\,, \tag{2}$$

$$[SU(2)]^2 U(1) \ : \ 3\sum_{i=1}^{j} Q_i + 3\sum_{i=1}^{m} \overline{Q}'_i + \sum_{i=1}^{n} q_i = 0\,, \tag{3}$$

$$[U(1)]^3 \ : \ 6\sum_{i=1}^{j} Q_i^3 + 3\sum_{i=1}^{k} Q_i'^3 + 3\sum_{i=1}^{l} \overline{Q}_i^3 + 6\sum_{i=1}^{m} \overline{Q}_i'^3 + 2\sum_{i=1}^{n} q_i^3 + \sum_{i=1}^{p} \overline{q}_i^3 = 0. \tag{4}$$

The global Witten $SU(2)$ anomaly-free condition: $3j + 3m + n = 0 \mod 2$ (5)

The mixed anomaly-free condition:

$$[U(1)] : 6\sum_{i=1}^{j} Q_i + 3\sum_{i=1}^{k} Q'_i + 3\sum_{i=1}^{l} \overline{Q}_i + 6\sum_{i=1}^{m} \overline{Q}'_i + 2\sum_{i=1}^{n} q_i + \sum_{i=1}^{p} \overline{q}_i = 0\,. \tag{6}$$

The minimal solusions are: ☜ ***Minimality Condition with Chiral Fermions!***

- $j = k = l = m = n = p = 0$ NO *fermions*
- $j = 1\,,\; k = 0\,,\; l = 2\,,\; m = 0\,,\; n = 1\,,\; p = 1$

(a) $Q_1 = 0\,,\;\; \bar{Q}_1 = -\bar{Q}_2\,,\;\; q_1 = \bar{q}_1 = 0$ No *electroweak forces!*

(b) $Q_1 = -\frac{q_1}{3}\,,\; \bar{Q}_1 = \frac{4q_1}{3}\,,\; \bar{Q}_2 = -\frac{2q_1}{3}\,,\; \bar{q}_1 = -2q_1$

CQG&R.Marshak, PRD39(1989)693

P.Ramond et al., PRD41(1990)715

CQG&R.Marshak, PRD91(1990)717

$SU(3)_C$	$\times$ $SU(2)_L$	$\times$ $U(1)_Y$
3	2	Q_1
$\bar{3}$	1	$\bar{Q}_1$
$\bar{3}$	1	$\bar{Q}_2$
1	2	q_1
1	1	$\bar{q}_1$

The minimal solusions are: ☜ **_Minimality Condition with Chiral Fermions!_**

- $j=k=l=m=n=p=0$ NO *fermions*
- $j=1\,,\ k=0\,,\ l=2\,,\ m=0\,,\ n=1\,,\ p=1$

(a) $Q_1=0\,,\ \ \bar{Q}_1=-\bar{Q}_2\,,\ \ q_1=\bar{q}_1=0$ No *electroweak forces!*

(b) $Q_1=-\frac{q_1}{3}\,,\ \bar{Q}_1=\frac{4q_1}{3}\,,\ \bar{Q}_2=-\frac{2q_1}{3}\,,\ \bar{q}_1=-2q_1$

$q_1=-1$ in unit of e → The *standard model* with *one family*

CQG&R.Marshak, PRD39(1989)693

P.Ramond et al., PRD41(1990)715

CQG&R.Marshak, PRD91(1990)717

Table 1. The quantum numbers of quark and lepton representations under $SU(3)_C\times SU(2)_L\times U(1)_Y$ and $SU(3)_C\times U(1)_{EM}$

Particles $(i=1,2,3)$	$SU(3)_C$	$\times$	$SU(2)_L$	$\times$	$U(1)_Y$	$\rightarrow$	$SU(3)_C$	$\times$	$U(1)_{EM}$
$\begin{pmatrix}u\\d\end{pmatrix}^i_L$	3		2		$\frac{1}{3}$		$\begin{pmatrix}3\\3\end{pmatrix}$		$\begin{pmatrix}2/3\\-1/3\end{pmatrix}$
$u^{c\,i}_L$	$\overline{3}$		1		$-\frac{4}{3}$		$\overline{3}$		$-2/3$
$d^{c\,i}_L$	$\overline{3}$		1		$\frac{2}{3}$		$\overline{3}$		$1/3$
$\begin{pmatrix}\nu\\e\end{pmatrix}^i_L$	1		2		-1		$\begin{pmatrix}1\\1\end{pmatrix}$		$\begin{pmatrix}0\\-1\end{pmatrix}$
$e^{c\,i}_L$	1		1		2		1		1

Why the three anomaly cancellations, especially the global Witten $SU(2)$ and mixed gauge-gravitational ones, should be satisfied?

→ New Physics!

Unified Theory: G —— Triangle $\mathcal{A}$nomaly free

⬇

No global Witten $SU(2)$ and mixed gauge-gravitational anomalies when G breaks down $SU(3)_C \times SU(2)_L \times U(1)_Y$

It is very natural to think that the standard model comes from some form of New Physics unless the $\mathcal{A}$nomaly Cancellations are ACCIDENTS.

• Family problem

Why are there three fermion generations?

1. Family Symmetry (gauged)?

$$SU(3) \times SU(2) \times U(1) \times SU(2)$$

$$\Downarrow$$ Anomaly free + minimality

Left-right symmetric model

$SU(3)_C$	$SU(2)_L$	$SU(2)_R$	$U(1)$
3	2	1	$\frac{1}{3}$
$\bar{3}$	1	2	$-\frac{1}{3}$
1	2	1	-1
1	1	2	1

1 family: quarks & leptons

$$SU(3) \times SU(2) \times U(1) \times SU(3)$$

CQG,PRD39(1989)2402

$$\Downarrow$$ Anomaly free + minimality

Chiral-color model

P.Frampton,S.Glashow, PRL58(1987)2168

$SU(3)_L$	$SU(3)_R$	$SU(2)_L$	$U(1)$
3	1	2	$\frac{1}{3}$
1	$\bar{3}$	1	$-\frac{4}{3}$
1	$\bar{3}$	1	$\frac{2}{3}$
1	1	2	-1
1	1	1	2
$\bar{3}$	1	1	q
1	3	1	$-q$
$\bar{3}$	1	1	$-q-\frac{2}{3}$
1	3	1	$q+\frac{2}{3}$

one family of quarks and leptons

exotic fermions

2. Preon models

	$SU(N)_{MC}$	×	$SU(N+4)_F$	×	$U(1)_F$
F^{ia}	$\square$		$\square$		$(N+2)$
$\bar{S}_{ij}$	$\overline{\square\square}$		1		$-(N+4)$

CQG&R.Marshak, PRD(RC)35(1987)2278

In the Higgs phase: the most attractive channel (MAC)

$$F^{ia}\bar{S}_{ij}=(\square;\square,(N+2))\times(\overline{\square\square};1,-(N+4))\longrightarrow(\bar{\square};\square,-2)$$

$$SU(N)_{MC}\times SU(N+4)_F\times U(1)_F\longrightarrow \widetilde{SU}(N)_F\times SU(4)_F\times\tilde{U}(1)_F$$

$$\left(\begin{smallmatrix}\square\\\square\end{smallmatrix},1,2(N+4)\right),\ (\square,\square,N+4)$$

complementarity

In the confining phase: the t'Hooft anomaly-free conditions

	Preons	$SU(N)_{MC}$	× $SU(N)_F$	× $SU(4)_F$	× $\tilde{U}(1)_F$
$F^{ia}\rightarrow$	p_1'	$\square$	$\square$	1	$2(N+4)$
	p_1''	$\square$	1	$\square$	$N+4$
$\bar{S}_{ij}\rightarrow$	p_2	$\overline{\square\square}$	1	1	$-2(N+4)$

Composites					Indices	
$p_1'p_1''p_2$	1	$\square$	$\square$	$N+4$	l_1	$\rightarrow l_1=1$
$p_1'p_1'p_2$	1	$\square\square,\begin{smallmatrix}\square\\\square\end{smallmatrix}$	1	$2(N+4)$	l_2,l_2'	$\rightarrow l_2=0,\ l_2'=1$
$p_1''p_1''p_2$	1	1	$\square\square,\begin{smallmatrix}\square\\\square\end{smallmatrix}$	0	l_3,l_3'	$\rightarrow l_3=l_2'=0$

For N=15, $\left(\begin{smallmatrix}\square\\\square\end{smallmatrix},1,38\right)$ and $(\square,\square,19)$ under $SU(15)_F\times SU(4)_F\times\tilde{U}(1)_F$.

Gauging the subgroup SU(5) of $SU(15)_F$:

$$\square\rightarrow\bar{5}+10\ ,$$

$$\begin{smallmatrix}\square\\\square\end{smallmatrix}\rightarrow 5+\overline{10}+\overline{45}+45$$

☞ **N_g=3 of chiral fermions**

$$\bar{5}+10$$

3. High-dimensional spacetime

In an extra dimensional theory, there are many types of chiral anomalies

M.Bershadsky, C.Vafa hep-th/9703167

For D spacetime dimensions:

$$\Pi_D(G)=Z_n \rightarrow c_D[N(p_{LD})-N(p_{RD}) = 0 \text{ mod } n$$

where $\Pi_D(G)$ is the D-th homotopy group, similar to the Witten SU(2) global anomaly in D=4:

$\Pi_4(SU(2))=Z_2$; $N(2_{L4})-N(2_{R4})=0$ mod 2 $(c_4=1)$

For D=6: Global gauge anomalies

$$\Pi_6(SU(3))=Z_6 \rightarrow N(3_{L6})-N(3_{R6}) = 0 \text{ mod } 6 \ (c_6=1)$$

$$\Pi_6(SU(2))=Z_{12} \rightarrow N(2_{L6})-N(2_{R6}) = 0 \text{ mod } 6 \ (c_6=2)$$

In the SM: $N(3_{L6})=N(3_{R6})$; $N(2_{L6})=4$, $N(2_{R6})=0$

B.A.Dobrescu, E.Poppitz, PRL87(2001)031801

$\rightarrow$ $N_g = 0$ mod 3 ☞ $N_g = 3$ (minimal value)

4. Toy models

$\mathcal{A}$-free + $\mathcal{M}$inimality: $SU(N) \times SU(2) \times U(1)$

$N = 2k$

$SU(N)$	$\times SU(2)$	$\times U(1)$
N	2	0
$\overline{N}$	1	-1
$\overline{N}$	1	1

$N = 2k + 1$

$SU(N)$	$\times SU(2)$	$\times U(1)$
N	2	$1/N$
$\overline{N}$	1	$-1/N - 1$
$\overline{N}$	1	$-1/N + 1$
1	2	-1
1	1	2

$SU(N)_C$	$\times SU(2)_L$	$\times SU(2)_R$
N	2	1
$\overline{N}$	1	2

N=12 →

$SU(12)_C$	$\times SU(2)_L$	$\times SU(2)_R$
12	2	1
$\overline{12}$	1	2

CQG,hep-ph/0101329

$$\downarrow$$

$$SU(12)_C \times SU(2)_L \times SU(2)_R$$

$$\downarrow$$

$$SU(8)_C \times SU(4)_{C1} \times SU(2)_L \times SU(2)_R \times U(1)$$

$$\downarrow$$

$$SU(4)_{C3} \times SU(4)_{C2} \times SU(4)_{C1} \times SU(2)_L \times SU(2)_R \times U(1) \times U(1)$$

$$\downarrow$$

$$\downarrow$$

$$SU(4)_C \times SU(2)_L \times SU(2)_R$$

$$\downarrow$$

$$\downarrow$$

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

three quark and lepton families

with right-handed neutrinos

A note on the color number: N_c

Particles $(i=1,2,3)$	$SU(N)_C \times$	$SU(2)_L \times$	$U(1)_Y$	$\rightarrow$ $SU(N)_C \times$	$U(1)_{EM}$
$\begin{pmatrix} u \\ d \end{pmatrix}_L^i$	N	2	$\frac{1}{N}$	$\begin{pmatrix} N \\ N \end{pmatrix}$	$\begin{pmatrix} \frac{N+1}{2N} \\ -\frac{N-1}{2N} \end{pmatrix}$
$u_L^{c\ i}$	$\overline{N}$	1	$-\frac{N+1}{N}$	$\overline{N}$	$-\frac{N+1}{2N}$
$d_L^{c\ i}$	$\overline{N}$	1	$\frac{N-1}{N}$	$\overline{N}$	$\frac{N-1}{2N}$
$\begin{pmatrix} \nu \\ e \end{pmatrix}_L^i$	1	2	-1	$\begin{pmatrix} 1 \\ 1 \end{pmatrix}$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
$e_L^{c\ i}$	1	1	2	1	1

$\leftarrow Q_u = e(N+1)/(2N)$

$\leftarrow Q_d = -e(N-1)/(2N)$

C.Chow,T.M.Yan,PRD53,5105(1996); R.Shrock,PRD53,6465(1996)

V.A.Kovalchuk, JETP Lett. 48 (1988) 11

R.Marshak,``Conceptual foundations of modern particle physics," Singapore, WS (1993)

For $\pi^0 \rightarrow \gamma\gamma$, the decay width:

$$\Gamma_{\pi^0 \rightarrow \gamma\gamma} \propto N(Q_u^2 - Q_d^2) \xrightarrow{Q_u^2 - Q_d^2 = e^2/N} e^2$$

☞ independent on the color number N!

The result is true for any anomalous process.

BUT: $\boldsymbol{R} \equiv \sigma(e^+e^- \rightarrow \text{hadron})/\sigma(e^+e^- \rightarrow \mu^+\mu^-) = N\,\Sigma Q_u^2 \propto N$ ☞ dependent on the color number N!

C.Q. Geng and H. Okada, ``Neutrino masses, dark matter and leptogenesis with $U(1)_{B-L}$ gauge symmetry," Phys. Dark Univ. 20, 13 (2018).

Gauge $U(1)_{B-L}$ Symmetry

				$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
Q_L :	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	$\begin{pmatrix} t \\ b \end{pmatrix}_L$	3	2	$\frac{1}{3}$	1/3
U_R :	u_R	c_R	t_R	3	1	$\frac{4}{3}$	1/3
D_R :	d_R	s_R	b_R	3	1	$-\frac{2}{3}$	1/3
L_L :	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	1	2	-1	-1
E_R :	e_R	μ_R	τ_R	1	1	-2	-1
N_{R1}				1	1	0	-4
N_{R2}				1	1	0	-4
N_{R3}				1	1	0	5

5. A geometrical origin

One starts with a theory in d > 4 dimensions but then assumes that the extra dimensions somehow compactify, leaving a 4-dimensional theory.

The d = 10 heterotic superstring

This string theory has an associated $E_8 \times E_8$ gauge symmetry and is supersymmetric. The chiral fermions in the d = 10 theory are gauginos of one of the E_8 groups (the other E_8 acts as a hidden sector), sitting in the 248 dimensional adjoint representation.

A. Candelas, G. Horowitz, A. Strominger, and E. Witten, Nucl. Phys. B258, 46 (1985).

D. Gross, J. Harvey, E. Martinec, and R. Rohm, Nucl. Phys. B255, 257 (1985); B267, 75 (1986).

The 10-dimensional space of the theory compactifies down to d = 4 Minkowski space times a 6-dimensional Calabi-Yau space.

$$E_8 \longrightarrow E_6 \times SU(3)$$

$$248 = (78, 1) \oplus (27, 3) \oplus (\bar{27}, \bar{3}) + (1, 8)$$

After Calabi-Yau compactification, the 4-dimensional chiral matter E_6.

☞ The 27-dimensional representation of E_6 when decomposed in terms of its SO(10) subgroup contains the 16-dimensional representation, appropriate for a family of quarks and leptons, plus a 10 and a singlet.

6. LEP experiments

ALEPH, DELPHI, L3, and OPAL

The invisible width Γ_{inv} is assumed to be due to N_ν light neutrino species each contributing the neutrino partial width Γ_ν as given by the Standard Model.

$$N_\nu = \frac{\Gamma_{\rm inv}}{\Gamma_\ell}\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{\rm SM}$$

$$N_\nu = 3.00 \pm 0.08$$

Other experiments supporting 3 families

- LHC: Higgs mass
- Planck: Active neutrino number

7. CP violation in the SM

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

→ 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

Nobel Physics Prize 2008

Broken Symmetry

破缺的對稱性

「發現對稱破缺的起源，預測自然界存在三代夸克」

"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

Yoichiro Nambu

Photo: Kyodo/Reuters

Makoto Kobayashi

Photo: Kyoto University

Toshihide Maskawa

• Broken symmetry and mass generation

對稱性破缺相關的兩大問題 → 機會

Higgs Mechanism

I. 手征規范對稱性之破缺

$SU(3)_c \times SU(2)_L \times U(1)_Y \longrightarrow SU(3)_c \times U(1)_{EM}$

連續對稱性

The Higgs Particle ← LHC大強子對撞機

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？

分立對稱性

物質

反物質

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

1967: Sakharov (the Nobel Peace Prize 1975)

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」

連續對稱性之破缺

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

The action for a meson field ϕ interacting with a Dirac fermion field ψ is

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

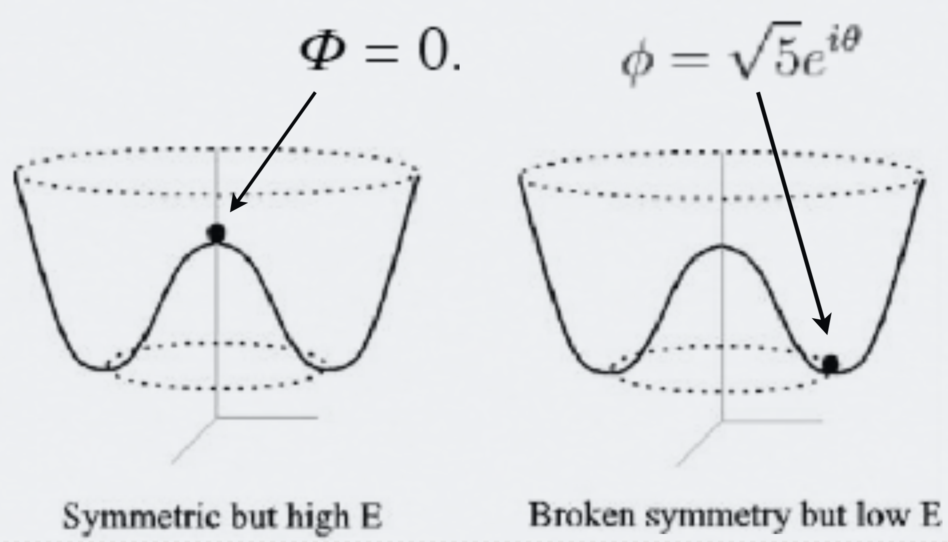
For a (renormalizable) self-interacting field:

$$V(\phi) = \mu^2\phi^2 + \lambda\phi^4$$

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

the Mexican hat potential

$$V(\phi) = -10|\phi|^2 + |\phi|^4$$



Minimum V(Φ)

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

In the Standard Model, Φ_0 is responsible for the fermion masses: $g\phi_0\bar{\psi}\psi$

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

The Nobel Prize in Physics 2013

發現一個理論機制（希格斯機制）：

亞原子粒子質量起源 | 預測希格斯玻色子

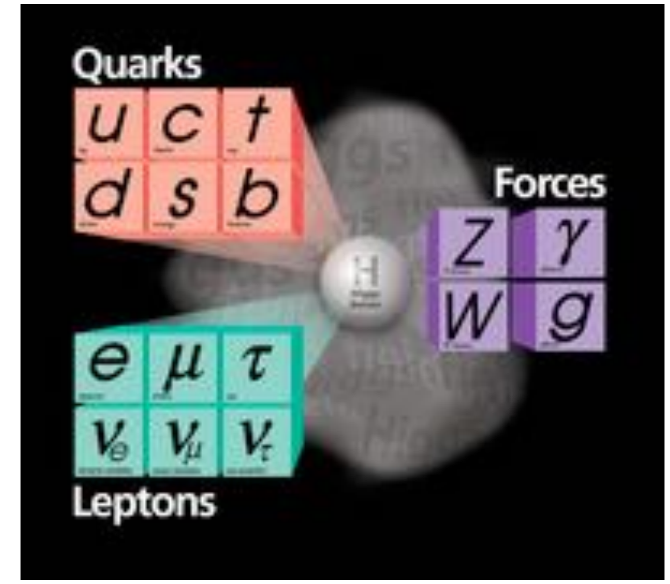
"For the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

July 4, 2012

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

Q_L :	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	$\begin{pmatrix} t \\ b \end{pmatrix}_L$	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	c_R	t_R				
D_R :	d_R	s_R	b_R	E_R :	e_R	μ_R	τ_R

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



Yukawa interactions: $\mathcal{L}_{\text{Yukawa}} = -\Gamma^u_{ij}(\bar{u},\bar{d})_{\text{L}i}\Phi u_{\text{R}j} - \Gamma^d_{ij}(\bar{u},\bar{d})_{\text{L}i}\tilde{\Phi} d_{\text{R}j} + \text{h.c.}\ .$

$$\Phi \to \frac{1}{\sqrt{2}}\begin{pmatrix} v+H \\ 0 \end{pmatrix} \longrightarrow M^{u,d}_{ij} = \frac{1}{\sqrt{2}}\Gamma^{u,d}_{ij} v\ .$$

$$(U^{u,d}_{\text{L}})^\dagger M^{u,d} U^{u,d}_{\text{R}} = \mathcal{M}^{u,d}$$

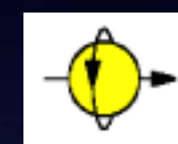
$$\mathcal{L}^{\text{eff}}_{\text{Yukawa}} = -\sum_i m_i \bar{q}_i(x) q_i(x)\left[1 + \frac{H(x)}{v}\right]$$

- **What about neutrinos?**
- **Do neutrinos get their masses like charged fermions?**
- 在標準模型中，微中子質量必須是零。

Why does the Standard Model require MASSLESS neutrinos?

- All neutrinos left-handed ⇒ massless
- If they have mass, can't go at speed of light.

right-handed



A massive particle

- Now neutrino right-handed??

  ⇒ contradiction ⇒ can't have a mass

Strictly left-handed neutrinos ⟺ Massless Neutrinos

微中子質量 ☞ New Physics beyond the SM

Origin of the neutrino masses: Dirac or Majorana?

Paul Dirac (1902-1984)

$$\begin{pmatrix} \nu_\uparrow \\ \nu_\downarrow \\ \overline{\nu}_\downarrow \\ \overline{\nu}_\uparrow \end{pmatrix} \quad \textbf{or} \quad \begin{pmatrix} \nu_\uparrow \\ \nu_\downarrow \end{pmatrix}$$

Ettore Majorana (1906-???)

Dirac neutrino mass (1928):

$$\mathcal{L}_D = -m_D \overline{\nu_L} \nu_R + \text{h.c.}$$

☺ the lepton number L is conserved

☞ **Introduce ν_R (not in the SM)**

Majorana neutrino mass (1937):

$$\mathcal{L}_M = -m_M \overline{\nu^c} \nu \quad + \text{h.c.} \qquad \nu \leftrightarrow \bar{\nu}$$

- the lepton number L is violated

☞ **FORBIDDEN IN THE SM.**
(ν_L is an SU(2) doublet).

☞ New Physics beyond the SM

Origin of the neutrino masses: Dirac or Majorana?

Paul Dirac (1902-1984)

$$\begin{pmatrix} \nu_{\uparrow} \\ \nu_{\downarrow} \\ \overline{\nu}_{\downarrow} \\ \overline{\nu}_{\uparrow} \end{pmatrix} \quad \text{or} \quad \begin{pmatrix} \nu_{\uparrow} \\ \nu_{\downarrow} \end{pmatrix}$$

Ettore Majorana (1906-???)

Disappeared in 1938 during a boat trip from Palermo to Naples without his body found

There are several categories of scientists in the world; those of second or third rank do their best but never get very far. Then there is the first rank, those who make important discoveries, fundamental to scientific progress. But then there are the geniuses, like Galilei and Newton. Majorana was one of these.

— (Enrico Fermi about Majorana, Rome 1938)

geniuses, like Galilei and Newton

Dirac neutrino m

$\mathcal{L}_D = -m_D \overline{\nu_L} \nu$

☺ the lepton number L is conserved

• the lepton number L is violated

Introduce ν_R (not in the SM)

FORBIDDEN IN THE SM. (ν_L is an SU(2) doublet).

New Physics beyond the SM

本人發表的第一篇學術論文(30多年前)。

VOLUME 58, NUMBER 10 PHYSICAL REVIEW LETTERS 9 MARCH 1987

Naturally Small Dirac Neutrino Masses in Superstring Theories

G. C. Branco and C. Q. Geng
Physics Department, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
(Received 8 December 1986)

We show that a $Z_2 \otimes Z_3$ symmetry leads to the radiative generation of naturally small Dirac neutrino masses in a class of superstring theories. This model realizes in a simple and consistent way a recent suggestion by Masiero, Nanopoulos, and Sanda.

PACS numbers: 14.60.Gh, 12.10.Gq

Generating Majorana Neutrino Masses with Loops

本人發表的第一篇學術論文(30多年前)。

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Dirac neutrino masses

G. C. Branco and C. Q. Geng

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Modern Physics Letters A
Vol. 30, No. 24 (2015) 1530018 (7 pages)

DOI: 10.1142/S0217732315300189

World Scientific
www.worldscientific.com

Brief Review

Majorana neutrino masses

Chao-Qiang Geng

Chongqing University of Posts & Telecommunications, Chongqing, 400065, China
Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
Physics Division, National Center for Theoretical Sciences, Hsinchu, Taiwan

E. Witten—Opening Talk at *Neutrino 00* [hep-ph/0006332]

For neutrino masses, the considerations have always been qualitative, and, despite some interesting attempts, there has never been a convincing quantitative model of the neutrino masses.

當今公認的
genius

E. Witten—Opening Talk at *Neutrino 00* [hep-ph/0006332]

For neutrino masses, the considerations have always been qualitative, and, despite some interesting attempts, there has never been a convincing quantitative model of the neutrino masses.

當今公認的
genius

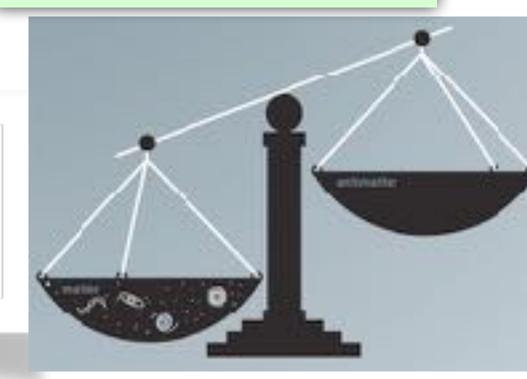
What was said in 2000 by Witten is also true TODAY (2017)

如同2000年，18年後的今天(2018年)也是如此：

至今也還沒有一個令人信服的定量微中子質量模型

Neutrino Masses?

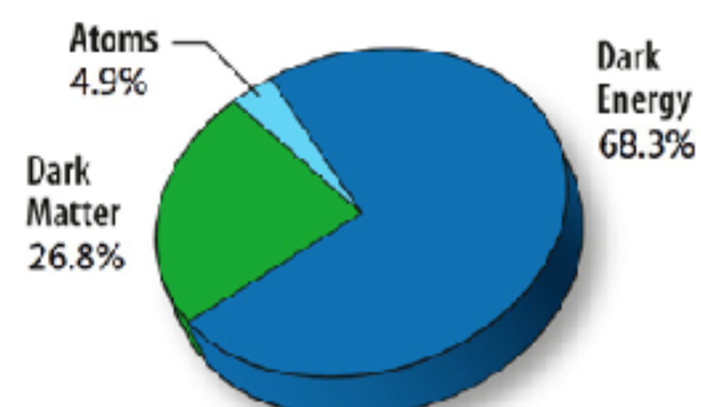
Matter-antimatter asymmetry
物質－反物質不對稱性



Family problem
為什麼自然界僅有三代

Dark Matter
暗物質

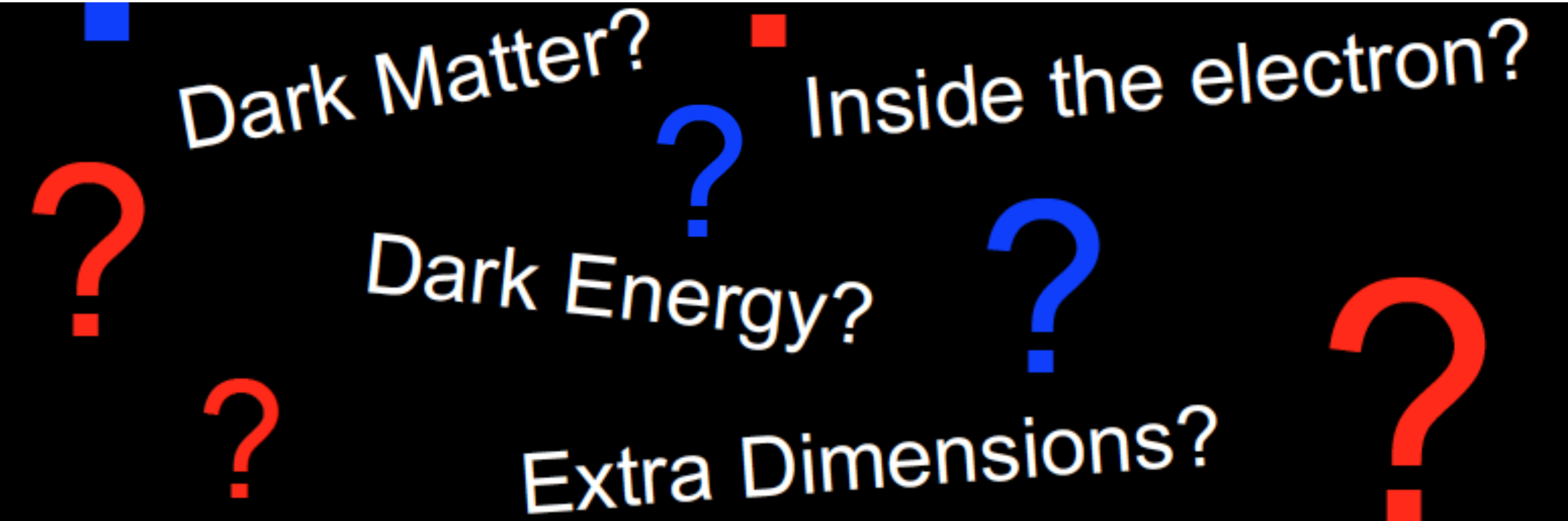
Dark Energy
暗能量



New Physics beyond the SM

很多尚未解決之問題

- *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?*



Future Perspectives

Modern Particle Physics: 7 Periods

1. **< 1945** ***-- Pre-Modern Particle Physics Period***
2. ***Startup Period (1945 -- 1960)：Early contributions to the basic concepts of modern particle physics.***
3. ***Heroic Period (1960 -- 1975):Formulation of the standard model of strong and electroweak interactions.***
4. ***Period of Consolidation and Speculation (1975 -- 1990): Precision tests of the standard model and theories beyond the standard model.***
5. ***"Frustration" and "Waiting" Period (1990 -- 2005)***
6. ***Preparation Period (2005--2020)***
7. ***Super-Herioic Period (2020--2035)***

英雄歲月

3 Dark Clouds 三朵烏雲

Cosmic microwave fluctuations (2006 Nobel Prize)
Dark energy (2011 Nobel Prize)
Neutrino oscillations (2015 Nobel Prize)

超英雄歲月

LHC: ...
GW: LISA *2030*
100 TeV Collider *2030*

+ something unexpected?

Great Collider

How many Nobel Prizes in Particle Physics & Cosmology for the Super-Heroic Period (超英雄歲月) ?

- **Future Perspectives**

Heroic Period 英雄歲月(1960 -- 1975):

Nobel Prizes in Particle Physics & Cosmology: [work done]

20xx: ?

2013: Englert, Higgs – Higgs particle [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]

1993: Hulse,Taylor – pulsar (indirect detection of GW [1974]

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]

1978: Penzias,Wilson – cosmic microwave background radiation [1965]

1976: Richter,Ting–charm quark (J/Psi) [1974]

1969: Gell-Mann–classification of elementary particles [1964]

more?

=13

7. Super-Herioic Period (2020--2035)

超英雄歲月

LHC: ...
GW: LISA *2030*
100 TeV Collider *2030*

+ something unexpected?

Great Collider

How many Nobel Prizes in Particle Physics & Cosmology for the Super-Heroic Period (超英雄歲月) **?**

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5th International Workshop on

Dark Matter, Dark Energy and Matter-Antimatter Asymmetry

暗物質，暗能量及物質-反物質不對稱

Dec. 28-31, 2018 佛光山，高雄，台灣

謝謝！