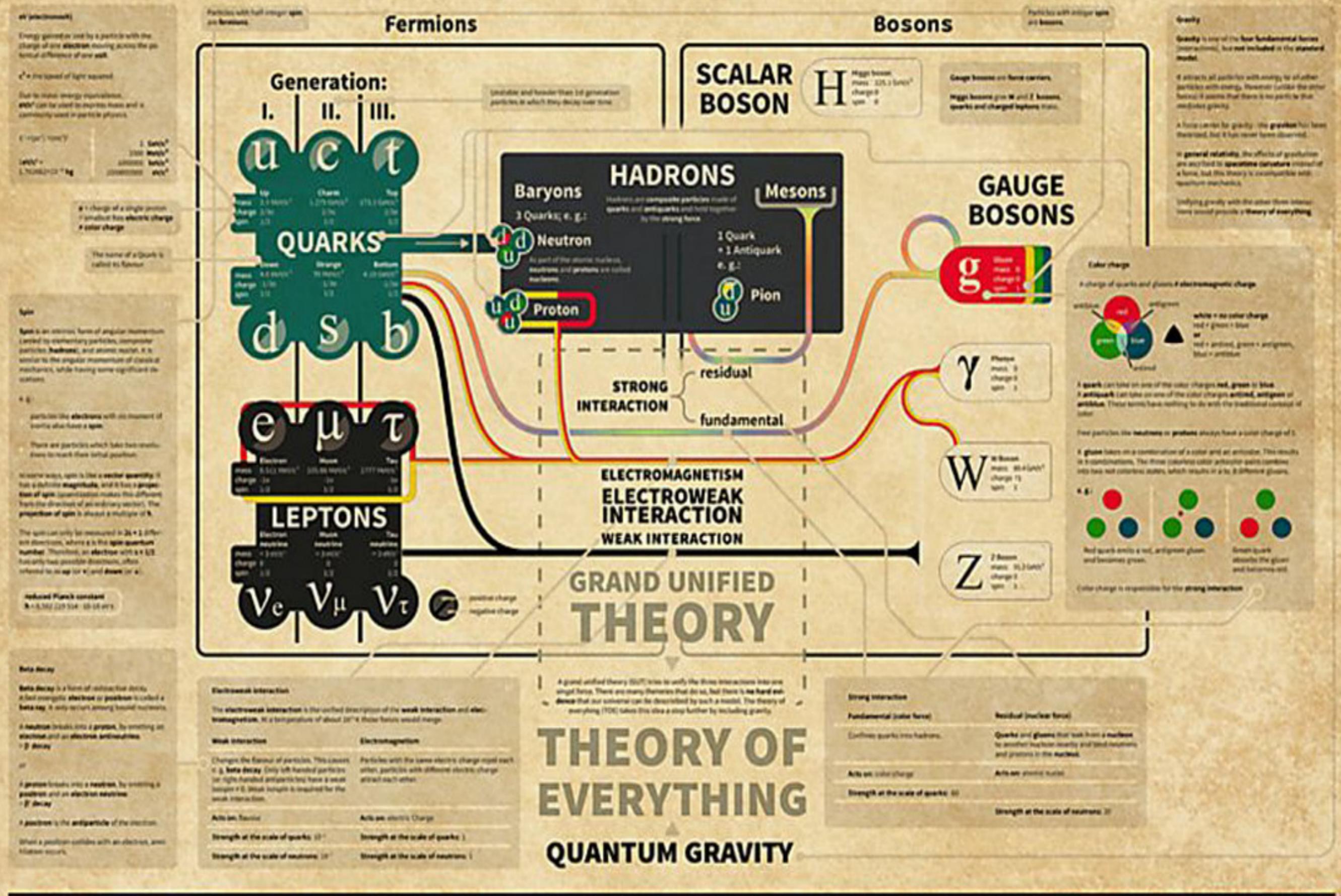


# 粒子物理电弱标准模型

张昊

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# THE STANDARD MODEL OF PARTICLE PHYSICS



# 什么是粒子物理标准模型？

- 基于平直时空相对论性量子场论、描述电弱能标尺度基本粒子组成及其相互作用的物理模型。

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  - 电弱能标——100GeV；
  - 基本粒子——展现为“点”结构、可重正相互作用。

# 标准模型中的“基本”粒子

QUARKS

**UP**  
mass  $2,3 \text{ MeV}/c^2$   
charge  $\frac{2}{3}$   
spin  $\frac{1}{2}$



**CHARM**  
mass  $1,275 \text{ GeV}/c^2$   
charge  $\frac{2}{3}$   
spin  $\frac{1}{2}$



**TOP**  
mass  $173,07 \text{ GeV}/c^2$   
charge  $\frac{2}{3}$   
spin  $\frac{1}{2}$



**DOWN**  
mass  $4,8 \text{ MeV}/c^2$   
charge  $-\frac{1}{3}$   
spin  $\frac{1}{2}$



**STRANGE**  
mass  $95 \text{ MeV}/c^2$   
charge  $-\frac{1}{3}$   
spin  $\frac{1}{2}$



**BOTTOM**  
mass  $4,18 \text{ GeV}/c^2$   
charge  $-\frac{1}{3}$   
spin  $\frac{1}{2}$



LEPTONS

**ELECTRON**  
mass  $0,511 \text{ MeV}/c^2$   
charge  $-1$   
spin  $\frac{1}{2}$



**MUON**  
mass  $105,7 \text{ MeV}/c^2$   
charge  $-1$   
spin  $\frac{1}{2}$



**TAU**  
mass  $1,777 \text{ GeV}/c^2$   
charge  $-1$   
spin  $\frac{1}{2}$



**ELECTRON NEUTRINO**  
mass  $<2,2 \text{ eV}/c^2$   
charge  $0$   
spin  $\frac{1}{2}$



**MUON NEUTRINO**  
mass  $<0,17 \text{ MeV}/c^2$   
charge  $0$   
spin  $\frac{1}{2}$



**TAU NEUTRINO**  
mass  $<15,5 \text{ MeV}/c^2$   
charge  $0$   
spin  $\frac{1}{2}$



**GLUON**  
mass  $0$   
charge  $0$   
spin  $1$



**PHOTON**  
mass  $0$   
charge  $0$   
spin  $1$



**Z BOSON**  
mass  $91,2 \text{ GeV}/c^2$   
charge  $0$   
spin  $1$



**W BOSON**  
mass  $80,4 \text{ GeV}/c^2$   
charge  $\pm 1$   
spin  $1$



GAUGE BOSONS

**HIGGS BOSON**  
mass  $126 \text{ GeV}/c^2$   
charge  $0$   
spin  $0$



# The Standard Model of particle physics

Years from concept to discovery

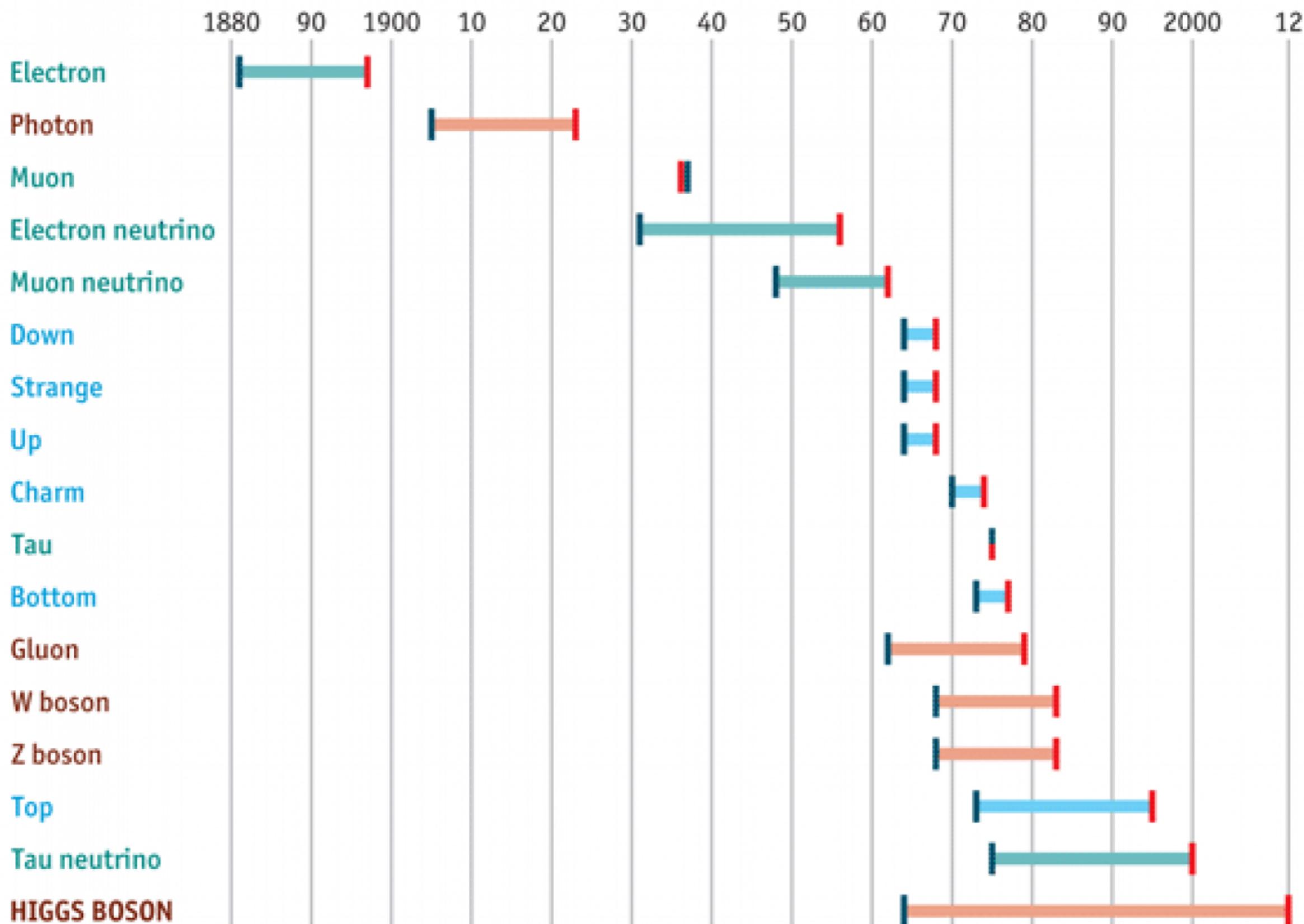
Leptons

Bosons

Quarks

Theorised/explained

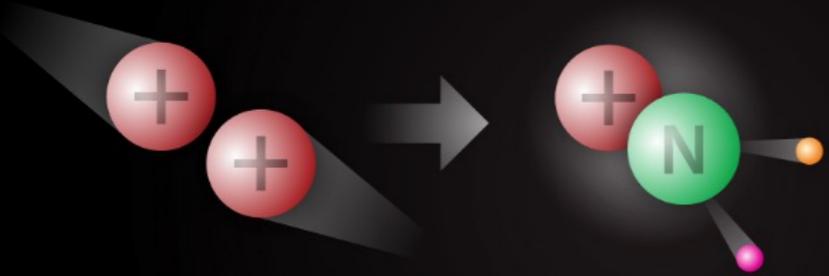
Discovered



Source: *The Economist*

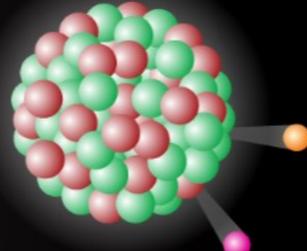
# 标准模型中的“基本”相互作用

## Weak Nuclear Force



### Converting protons into neutrons

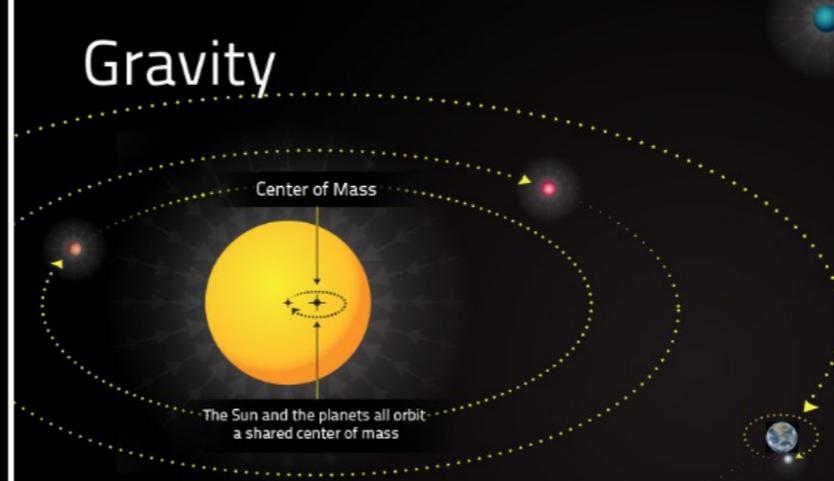
When two protons collide and fuse, a disruption in the weak nuclear force emits a positron and neutrino, which converts one of the positively charged proton to a neutrally charged Neutron. Without the weak nuclear force converting protons into neutrons, certain complex nuclei cannot form.



### Releasing radiation

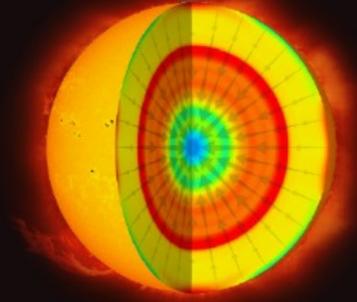
Heavy atoms have an imbalance of protons and neutrons, so the weak nuclear force converts protons to neutrons releasing radiation.

## Gravity



### Adding motion to the Universe

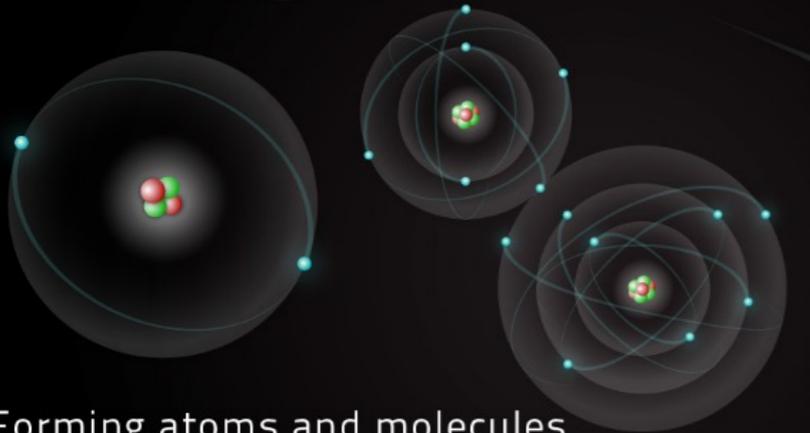
Gravity forms stars, planets, and moons, and forces these objects to spin on an axis and move along an orbital path. The planets appear to be orbiting the center of the Sun, but the Sun and planets all orbit a shared center of mass. Planets with enough mass can develop orbiting moons or rings of debris.



### Creating energy

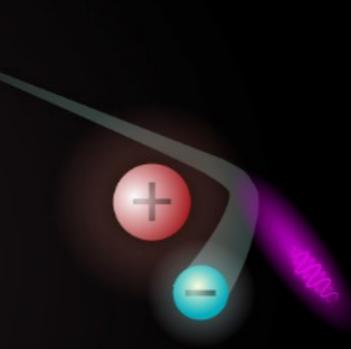
Gravity is the force that creates pressure and fusion energy in the core of stars allowing them to burn for millions of years.

## Electromagnetic Force



### Forming atoms and molecules

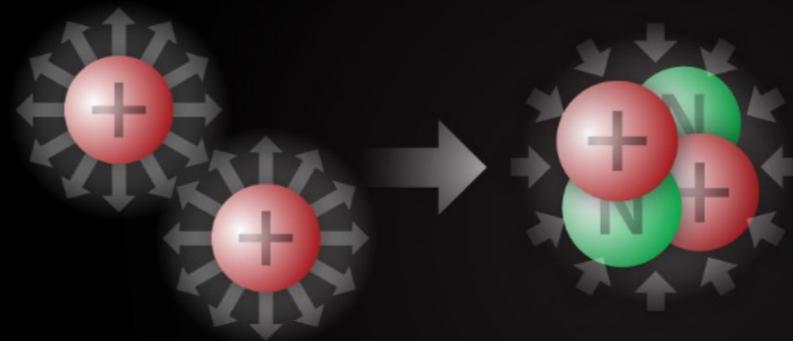
The electromagnetic force pulls negatively charged electrons into bound orbits around positively charged nuclei to form atoms and molecules. As a gas cools, electrons will find their way into the presence of atomic nuclei. Larger nuclei with a greater positive charge pull in more electrons until atoms and molecules have a balance of charges.



### Generating light

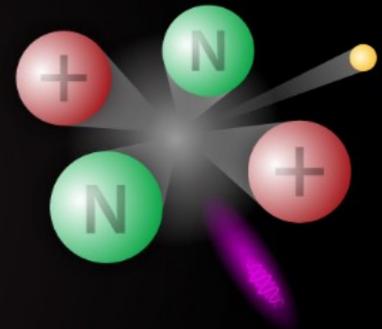
When a negative electron interacts with a positive proton, the electromagnetic force adds energy to the electron generating a photon.

## Strong Nuclear Force



### Binding protons in atomic nuclei

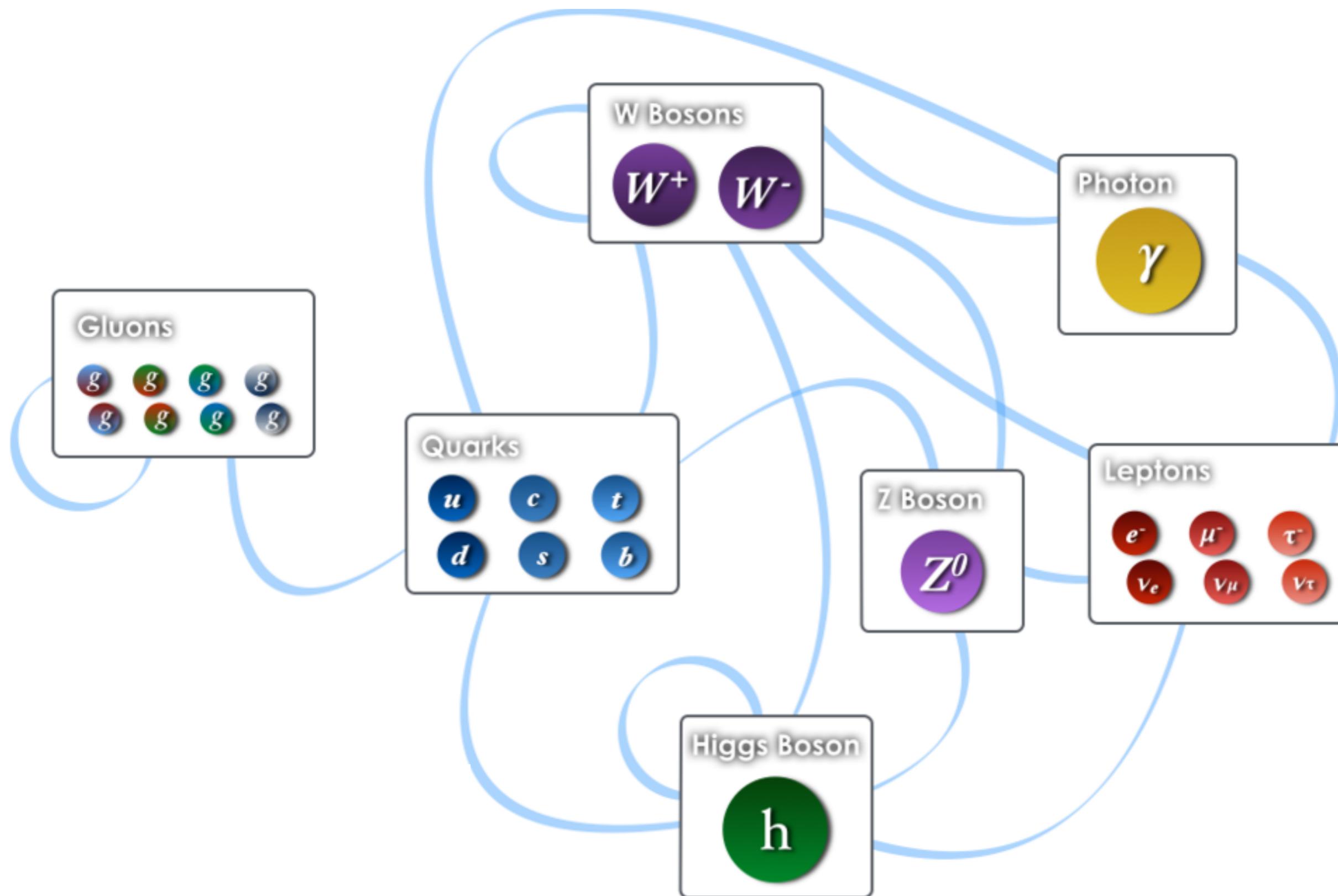
Positively charged particles naturally repel each other, it takes an extreme amount of force to hold protons together. The strong nuclear force overcomes the repulsion between protons to hold together atomic nuclei. Without the strong nuclear force, complex nuclei cannot form.



### Breaking the bond

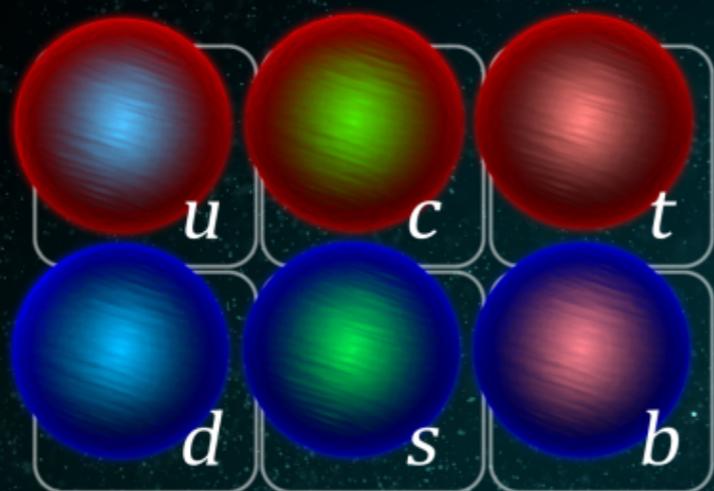
Enormous energy is released as gamma rays and neutrinos when the strong nuclear force is broken between protons and neutrons.

# 标准模型中的“基本”相互作用

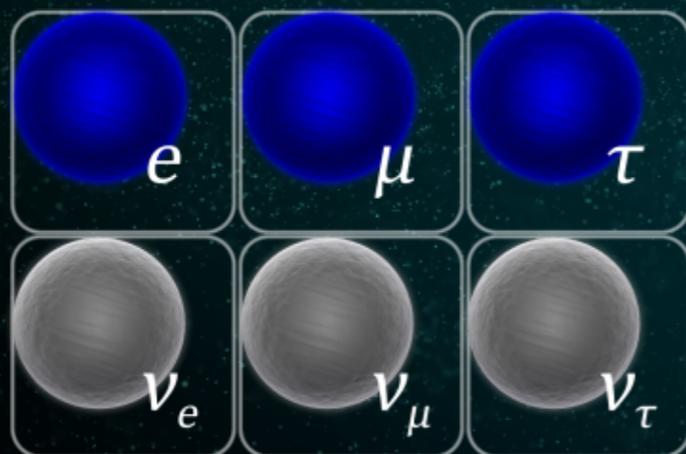


# 标准模型的理论结构

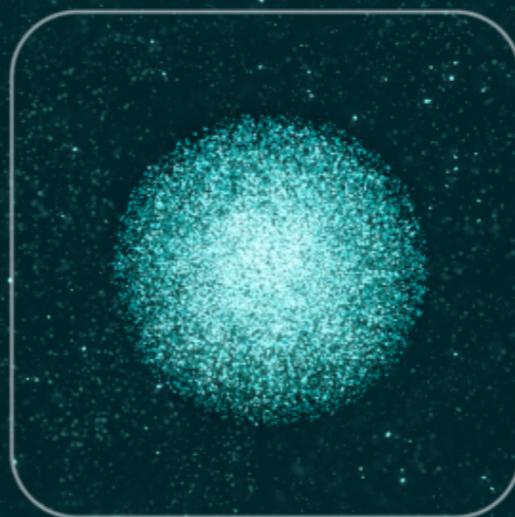
- 降服（轴）矢量流相互作用的历史
  - $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ 规范相互作用；
  - 弱电（部分）统一机制；
  - 产生弱规范玻色子质量的Higgs机制；
  - 产生费米子质量的整体对称性自发破缺机制；
  - 确保规范对称性的手征费米子反常相消机制；
  - 源自汤川相互作用的CP破坏机制；
  - .....



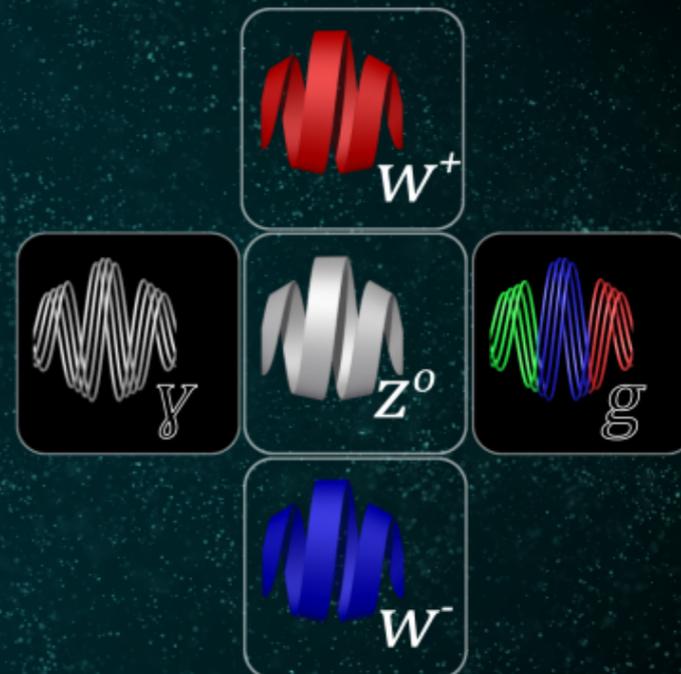
Quarks



Leptons



Higgs boson



Forces



ACCELERATING SCIENCE

# 从四费米子相互作用到电弱规范理论

# 四费米子相互作用的困难

- V-A型四费米子相互作用

$$\mathcal{H} = \frac{G_F}{\sqrt{2}} [\bar{\psi}_p \gamma^\mu (1 - \gamma_5) \psi_n] [\bar{\psi}_e \gamma^\mu (1 - \gamma_5) \psi_{\nu_e}]$$

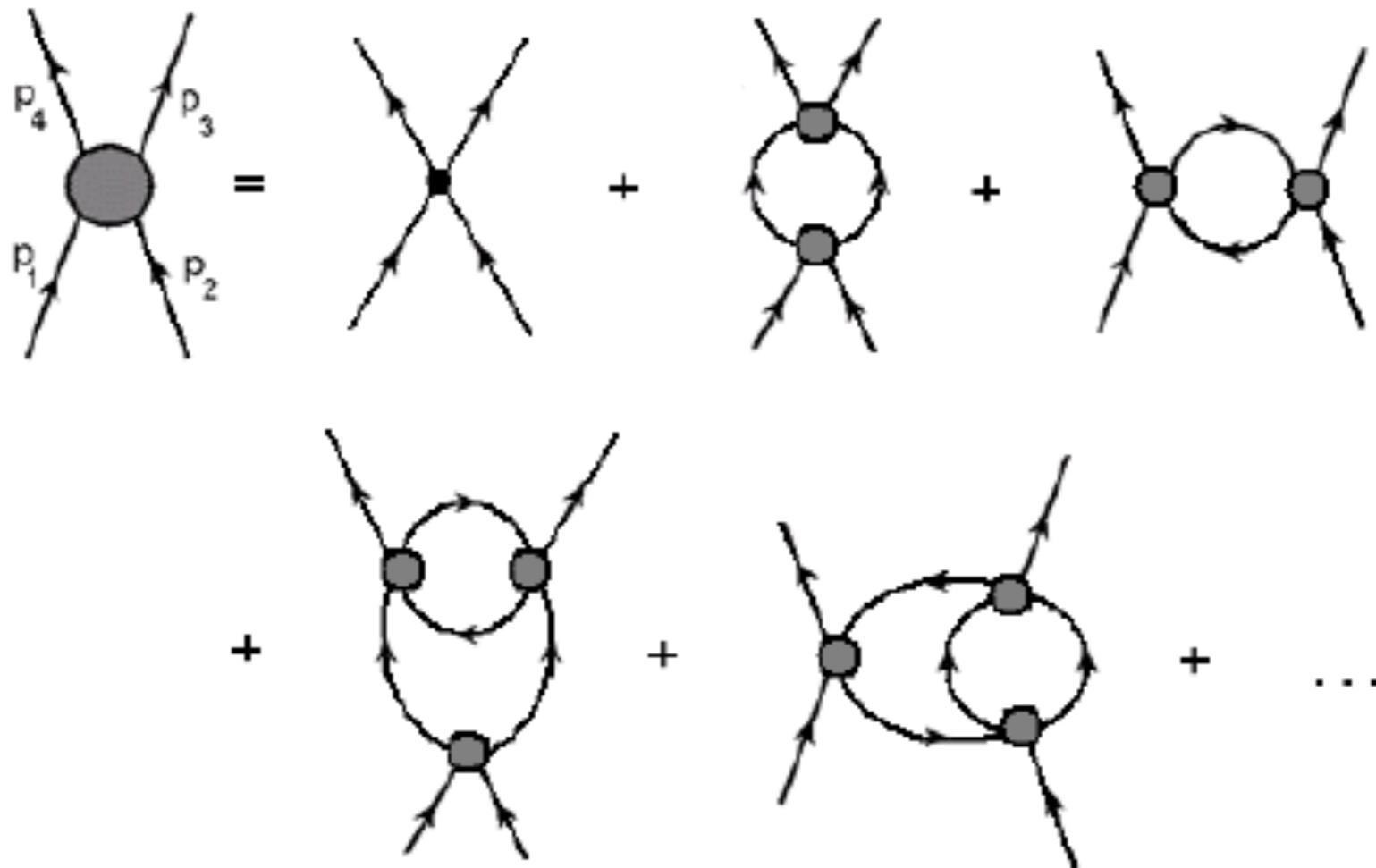
- 从强子到夸克

$$\mathcal{H} = \frac{G_F}{\sqrt{2}} [\bar{\psi}_u \gamma^\mu (1 - \gamma_5) \psi_d] [\bar{\psi}_e \gamma^\mu (1 - \gamma_5) \psi_{\nu_e}]$$

- 带有质量负幂次量纲的耦合常数。
- 不可重整问题。
- 么正性破坏问题。

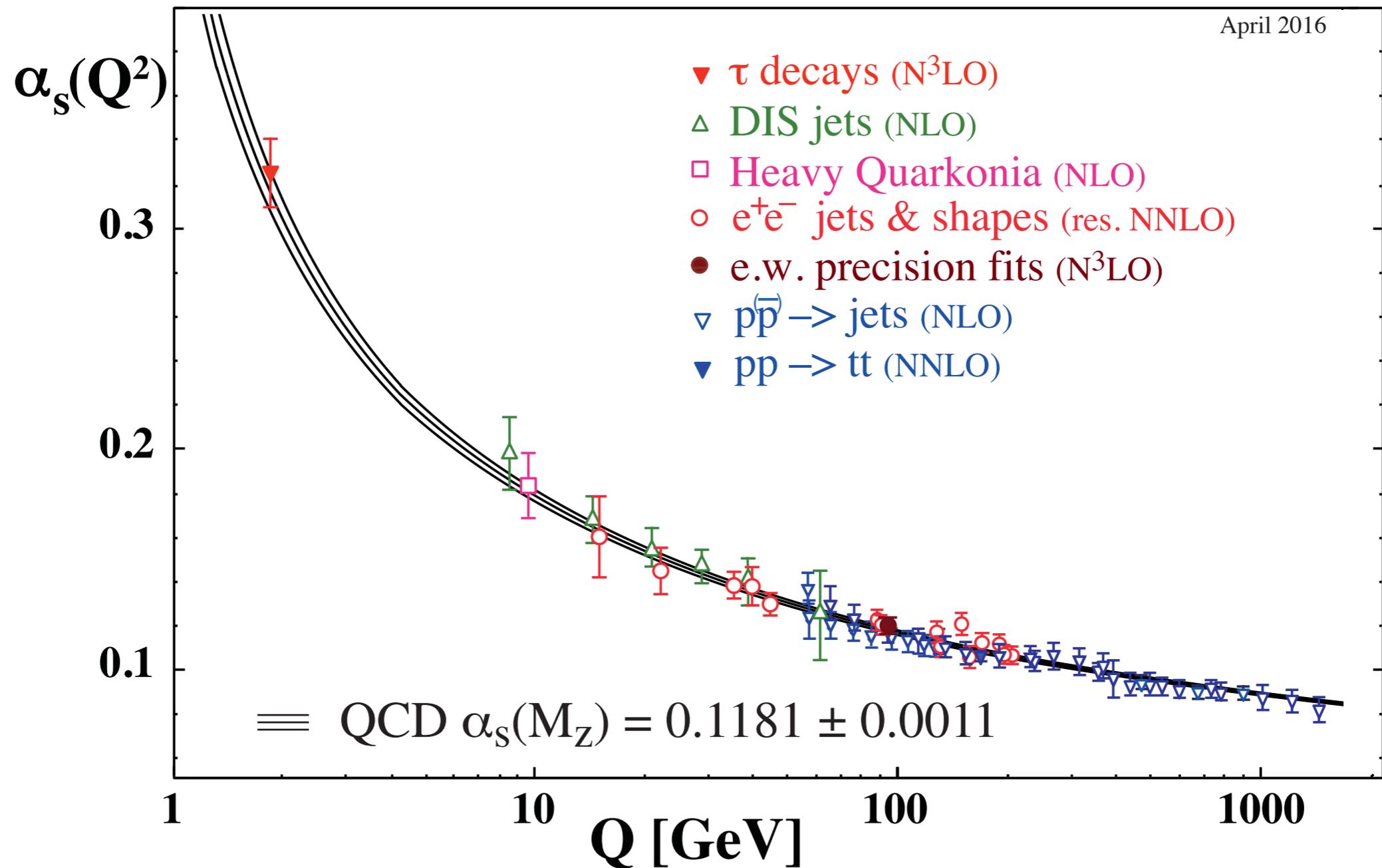
# 四费米子相互作用的困难

- 量子场论的紫外发散与重整化



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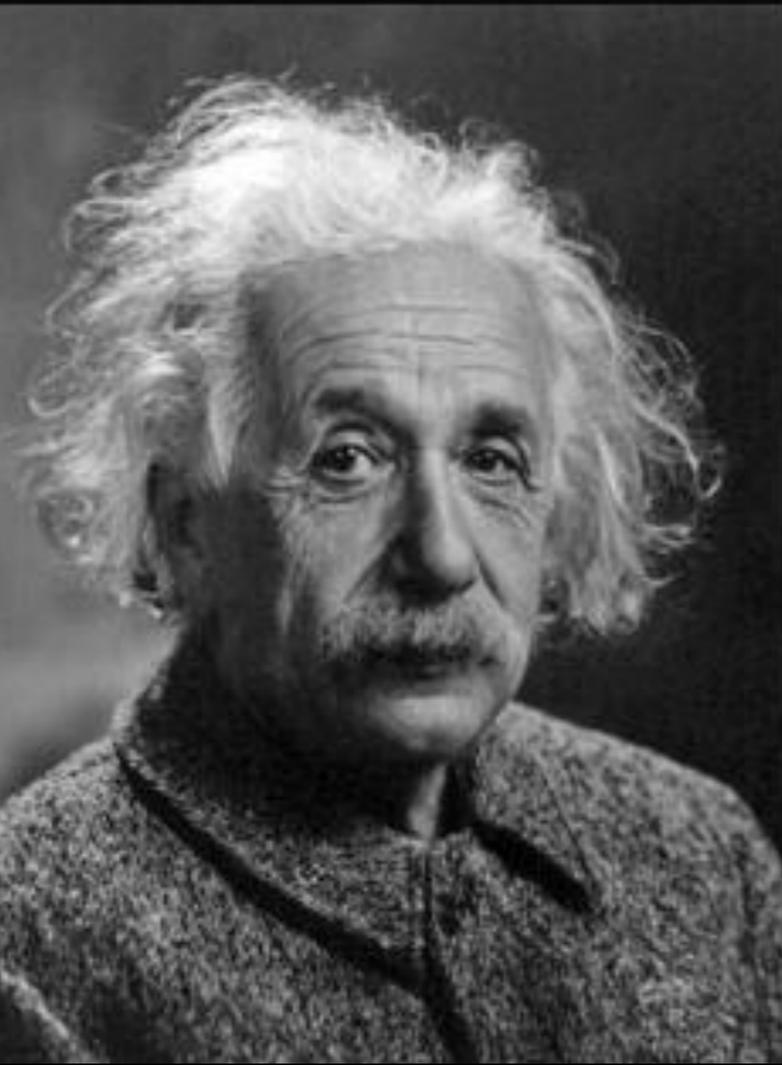


# 四费米子相互作用的困难

- 量子场论的紫外发散与重整化
- 带有质量量纲的耦合常数的出现及其物理意义
- 有效场论观点

# 四费米子相互作用的困难

- 么正性与么正性破坏



At any rate, I am convinced that He [God] does not play dice.

(Albert Einstein)

# 四费米子相互作用的困难

- 么正性与么正性破坏

**GOD**

not only plays dice,  
he also sometimes

**THROW**

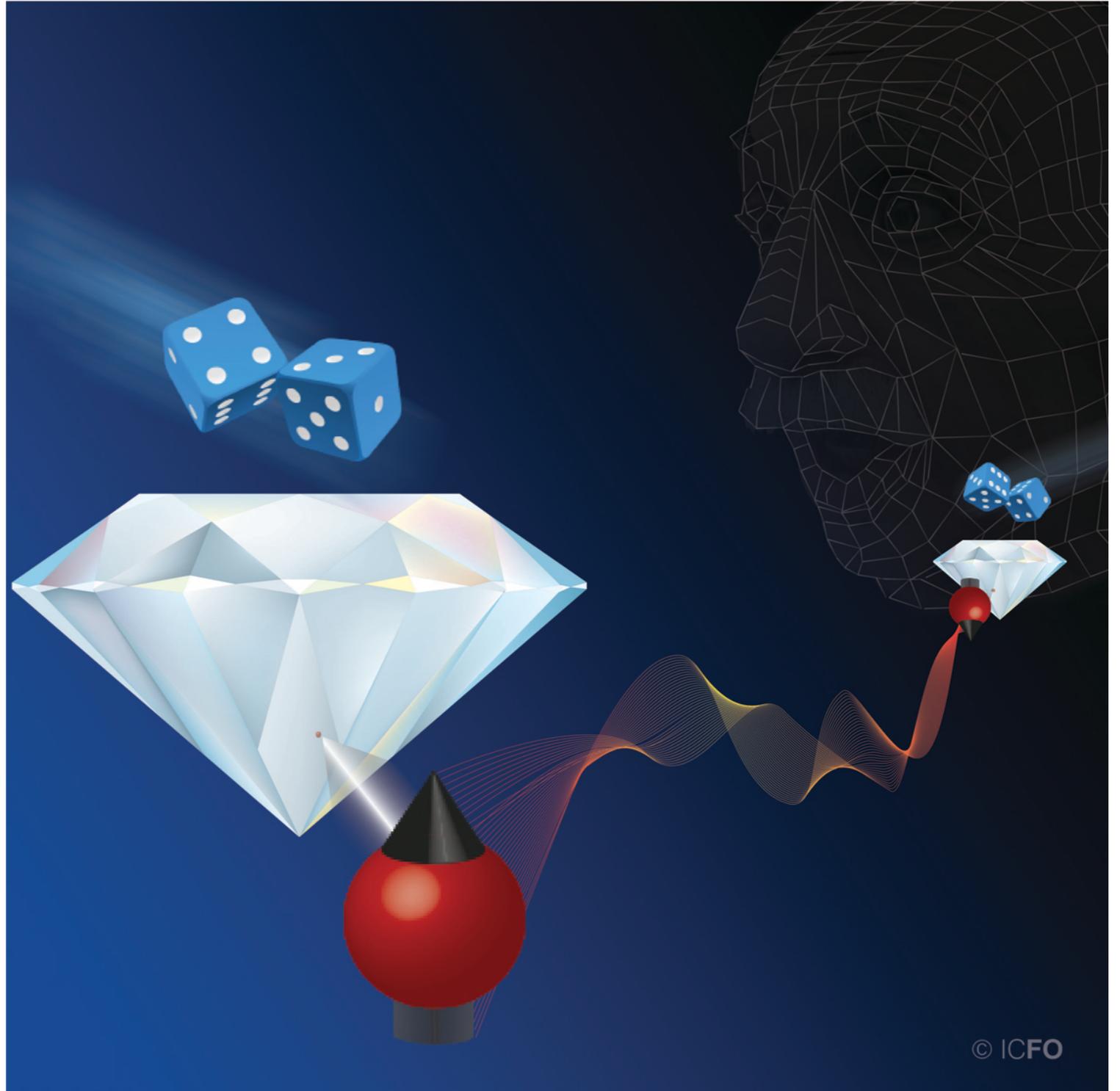
the dice where  
they cannot be seen



*Stephen Hawking via Gecko&Fly*

# 四费米子相互作用的困难

- 么正性与么正性破坏
- 系统处在所有可能状态上的概率的总和，是否始终等于1？



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- 么正性与分波振幅的高能行为

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$$i\langle p_1 p_2 | \mathcal{T}^\dagger | p_1 p_2 \rangle - i\langle p_1 p_2 | \mathcal{T} | p_1 p_2 \rangle = \sum_n \int d\Pi(p) |\langle \Psi_n(p) | \mathcal{T} | p_1 p_2 \rangle|^2.$$

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$$i\langle p_1 p_2 | \mathcal{T}^\dagger | p_1 p_2 \rangle - i\langle p_1 p_2 | \mathcal{T} | p_1 p_2 \rangle \geq \int d\Pi_X |\langle X | \mathcal{T} | p_1 p_2 \rangle|^2.$$

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$$\text{Im}\mathcal{M}(p_1p_2 \rightarrow p_1p_2) = 2E_{\text{CM}}|\mathbf{p}_i| \sum_X \sigma(p_1p_2 \rightarrow X).$$

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光学定理 (Optical Theorem)

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$$\mathcal{M}(\theta) = 16\pi \sum_{\ell=0}^{+\infty} a_{\ell} (2\ell + 1) P_{\ell}(\cos \theta)$$

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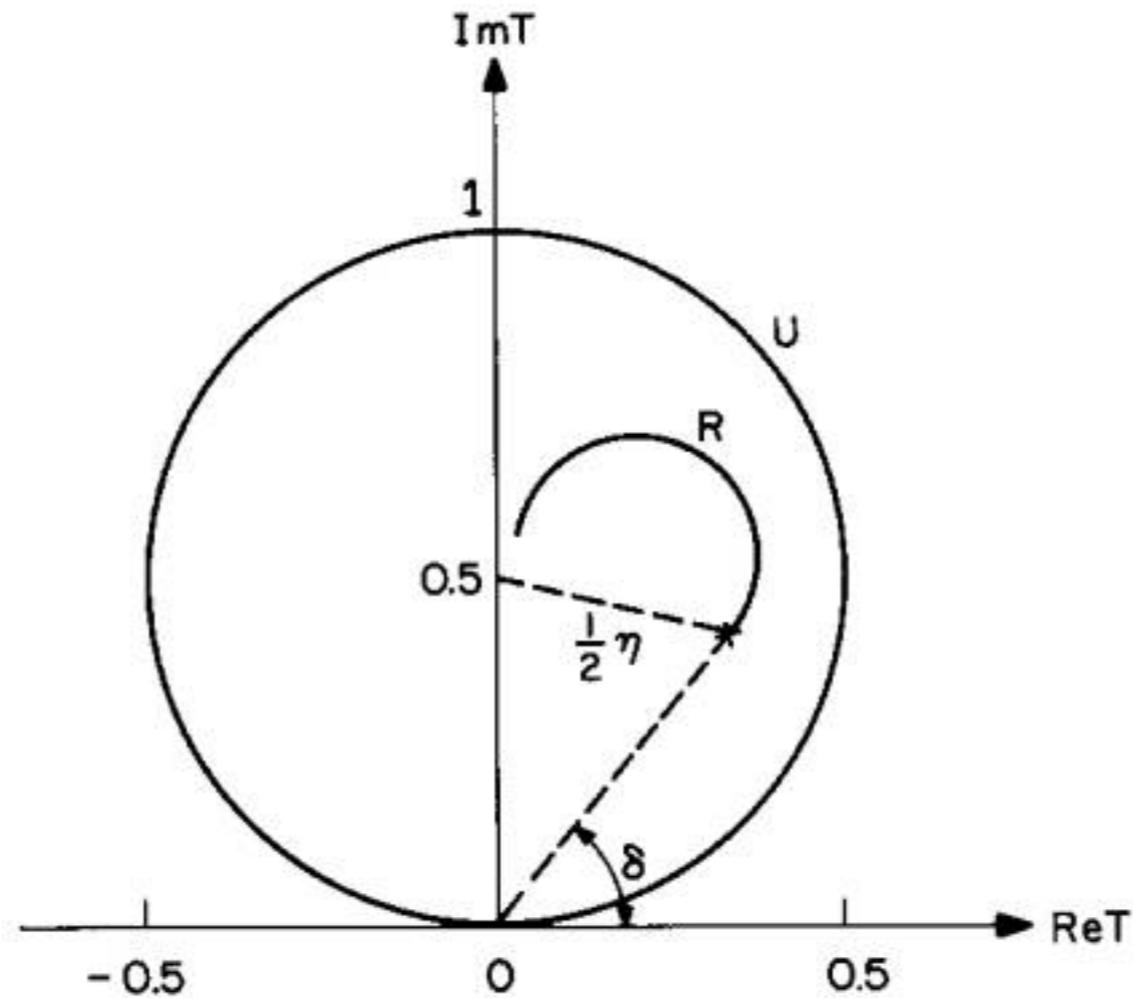
$$\mathcal{M}(\theta) = 16\pi \sum_{\ell=0}^{+\infty} a_{\ell} (2\ell + 1) P_{\ell}(\cos \theta)$$

$$\sum_{\ell=0}^{+\infty} (2\ell + 1) \operatorname{Im}(a_{\ell}) \geq \frac{2|\mathbf{p}_i|}{E_{\text{CM}}} \sum_{\ell=0}^{+\infty} (2\ell + 1) |a_{\ell}|^2.$$

$$\operatorname{Im}(a_{\ell}) \geq |a_{\ell}|^2, \quad \operatorname{Im}(a_{\ell}) \geq |b_{\ell}|^2.$$

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# 四费米子相互作用的困难

- 么正性与分波振幅的高能行为

$$\begin{aligned}\sigma_\ell &= \frac{1}{32\pi s} \int |\mathcal{M}_{X,\ell}(\theta)|^2 d\cos\theta \\ &= \frac{8\pi}{s} \int |b_\ell|^2 (2\ell + 1)^2 P_\ell(\cos\theta)^2 d\cos\theta \\ &= \frac{16\pi (2\ell + 1)}{s} |b_\ell|^2 \\ &\leq \frac{16\pi (2\ell + 1)}{s} \text{Im}(a_\ell) \\ &\leq \frac{16\pi (2\ell + 1)}{s}.\end{aligned}$$

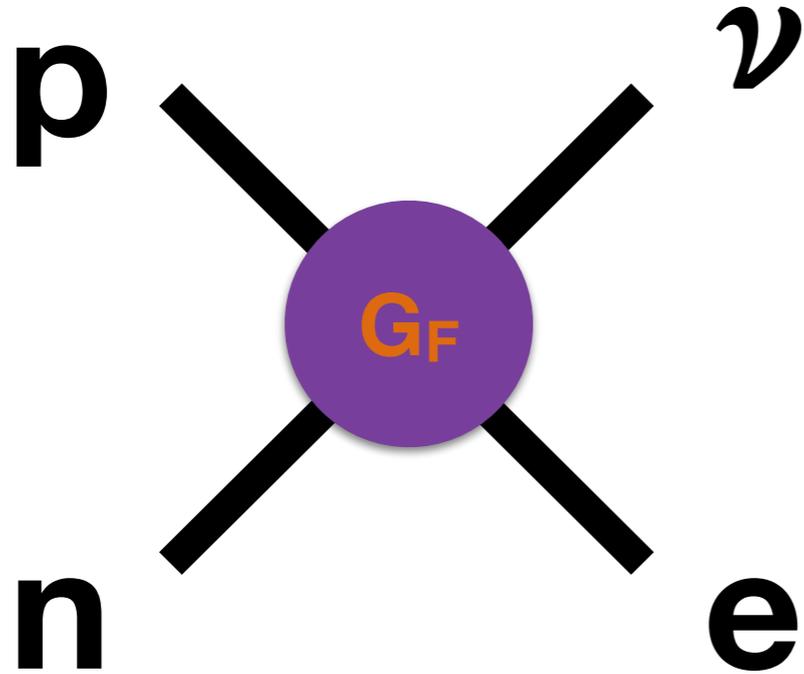
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- 么正性与分波振幅的高能行为
- 四费米子相互作用振幅的高能行为

$$\mathcal{M}(s) = \mathcal{M}_{\text{loop}} + \mathcal{M}_{\text{tree}} + \mathcal{M}_{\text{c.t.}} \sim G_F + sG_F^2 \left( a_1 - b_2 \ln \frac{s}{s_0} \right) + a_2 s^2 G_F^3 + \dots$$

# 带电矢量玻色子的引入

- 带电流与矢量玻色子 $W^\pm$

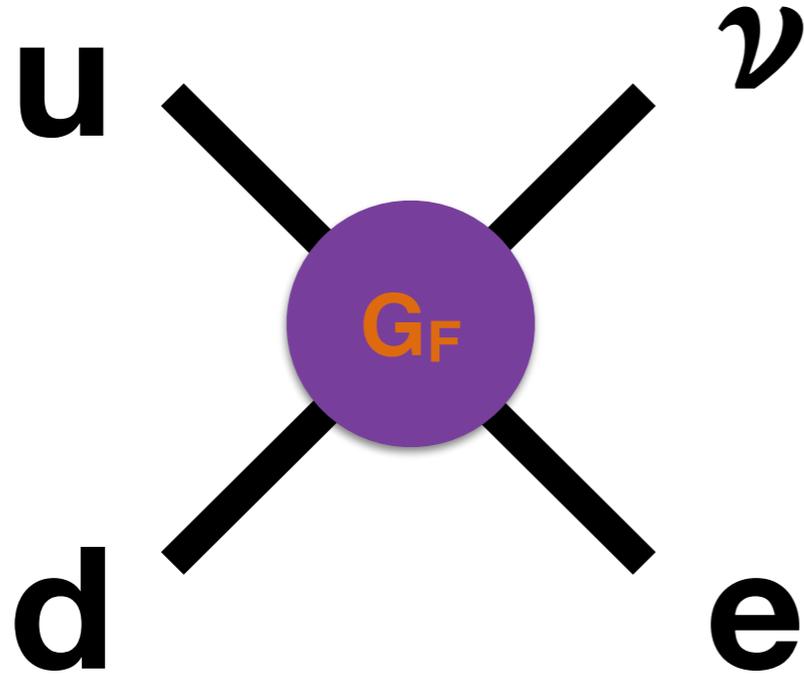


$$\mathcal{H} \sim G_F (\bar{e} \gamma^\mu P_L \nu) (\bar{p} \gamma^\mu P_L n)$$

$$G_F \approx 0.00001 \text{ GeV}^{-2}$$

# 带电矢量玻色子的引入

- 带电流与矢量玻色子 $W^\pm$

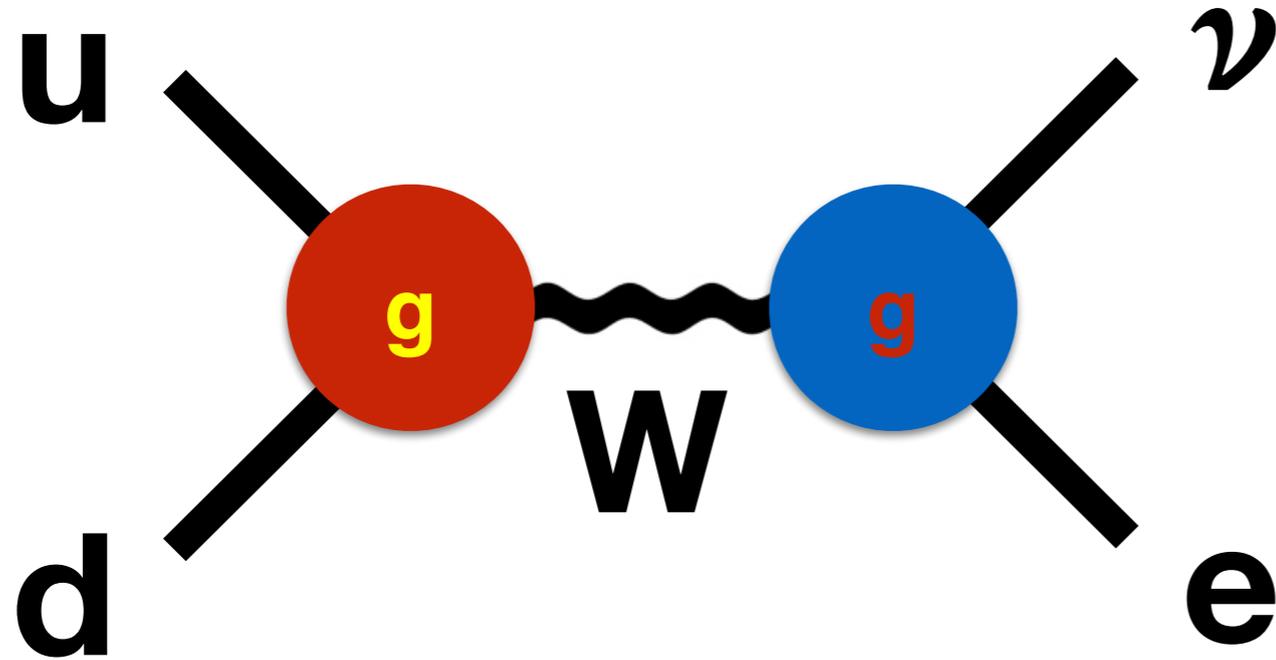


$$\mathcal{H} \sim G_F (\bar{e} \gamma^\mu P_L \nu) (\bar{u} \gamma^\mu P_L d)$$

$$G_F \approx 0.00001 \text{ GeV}^{-2}$$

# 带电矢量玻色子的引入

- 带电流与矢量玻色子 $W^\pm$



$$\mathcal{H} \sim gW_\mu^- (\bar{e}\gamma^\mu P_L \nu) + gW_\mu^+ (\bar{u}\gamma^\mu P_L d)$$

$$m_W/g \approx (G_F)^{-1/2} \approx 100\text{GeV}$$

# 带电矢量玻色子的引入

- 标准模型费米子与矢量玻色子的相互作用

$$\mathcal{H} = \frac{g_w}{2\sqrt{2}} (\bar{u} \quad \bar{d}) \gamma^\mu (1 - \gamma_5) \begin{pmatrix} 0 & W_\mu^+ \\ W_\mu^- & 0 \end{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix} \\ + \frac{g_w}{2\sqrt{2}} (\bar{e}^- \quad \bar{\nu}_e) \gamma^\mu (1 - \gamma_5) \begin{pmatrix} 0 & W_\mu^+ \\ W_\mu^- & 0 \end{pmatrix} \begin{pmatrix} e^- \\ \nu_e \end{pmatrix}$$

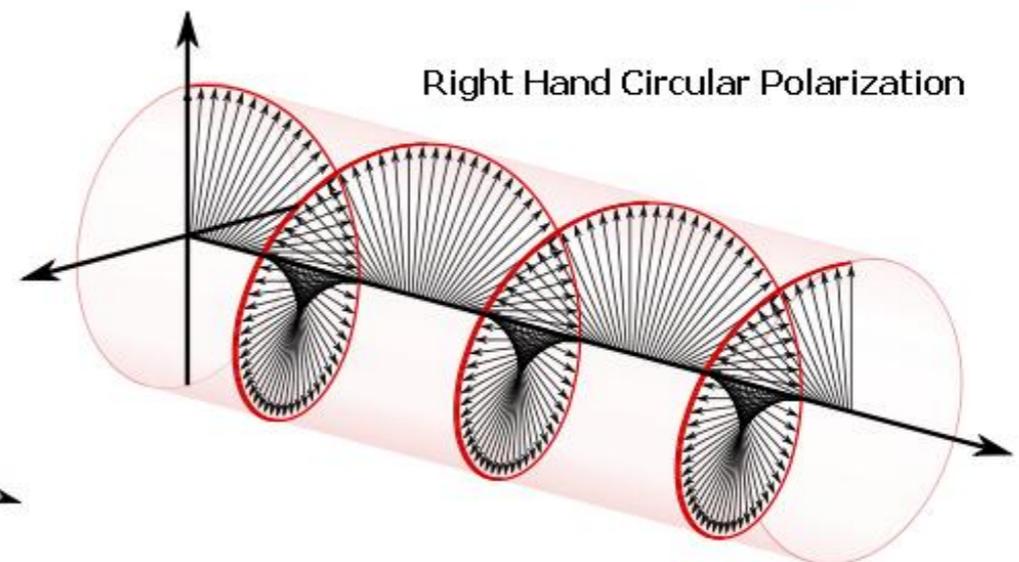
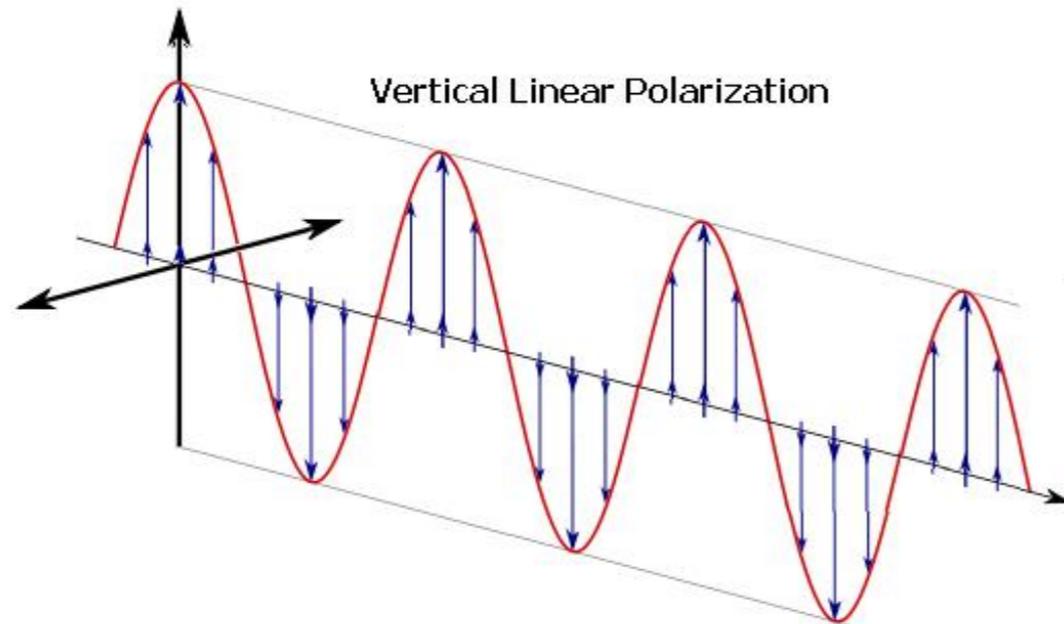
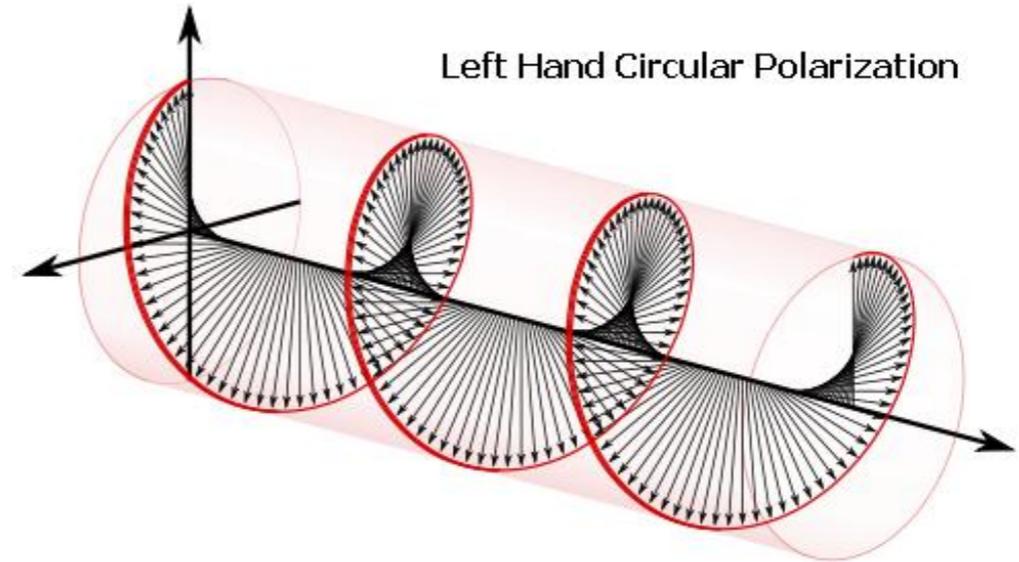
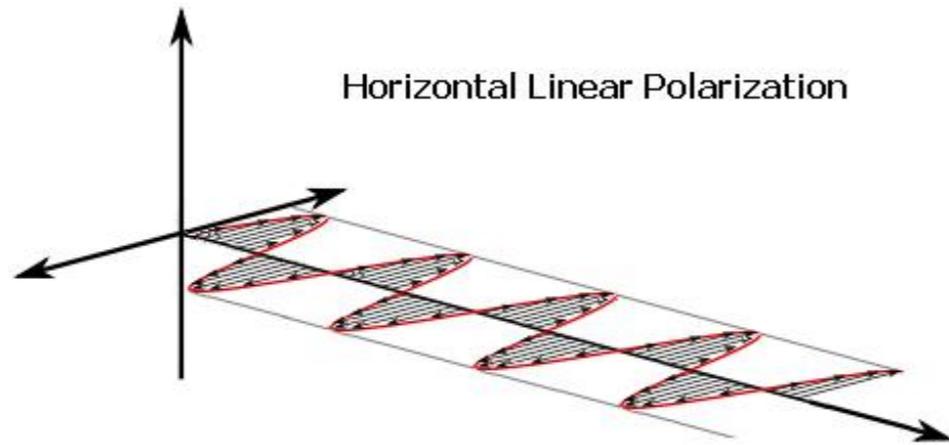
$$g_w = 0.65 > e (= 0.31)$$

# 带电矢量玻色子的问题

- 非零质量矢量玻色子的横向极化自由度

$$m_W \ll E \rightarrow +\infty$$

$$\vec{e}_{L(R)} \perp \vec{p}$$

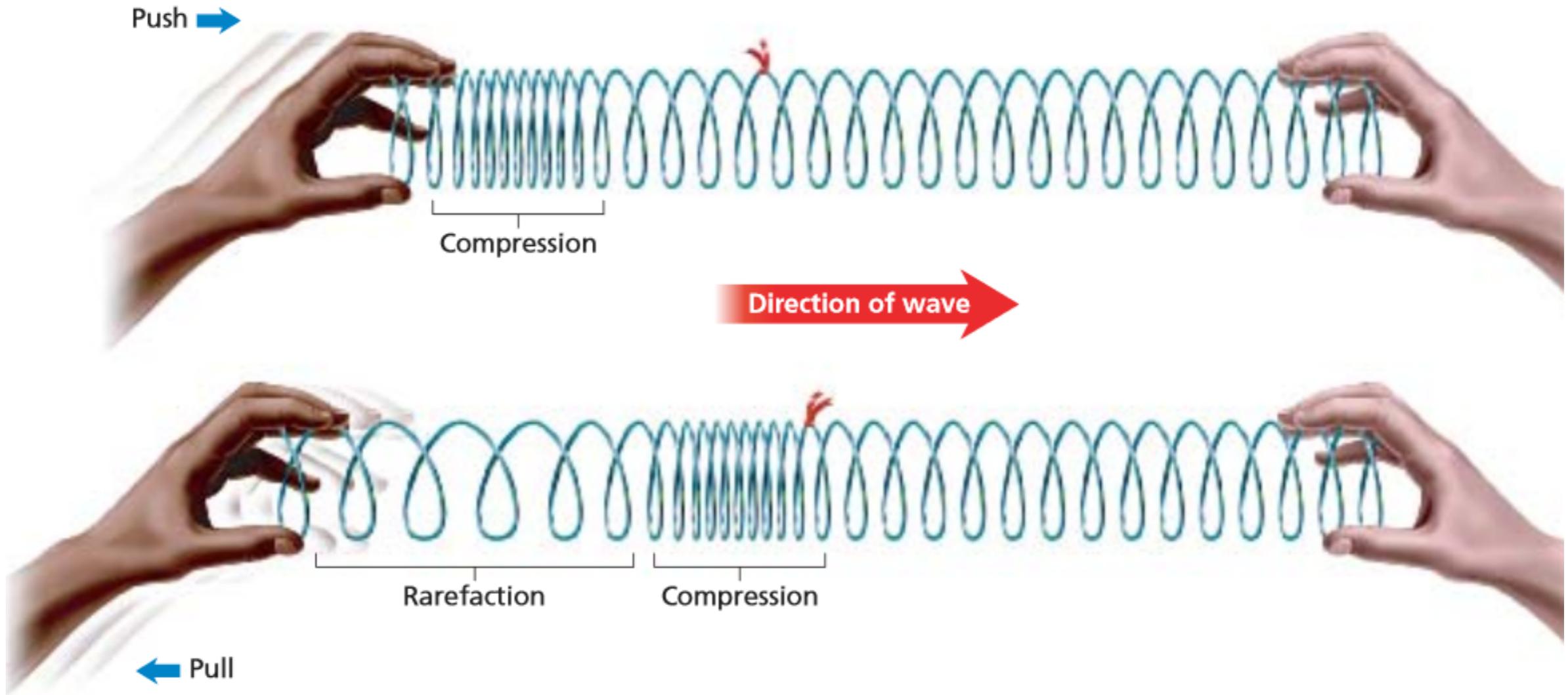


# 带电矢量玻色子的问题

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$$m_W \ll E \rightarrow +\infty$$

$$\vec{e} // \vec{p}$$

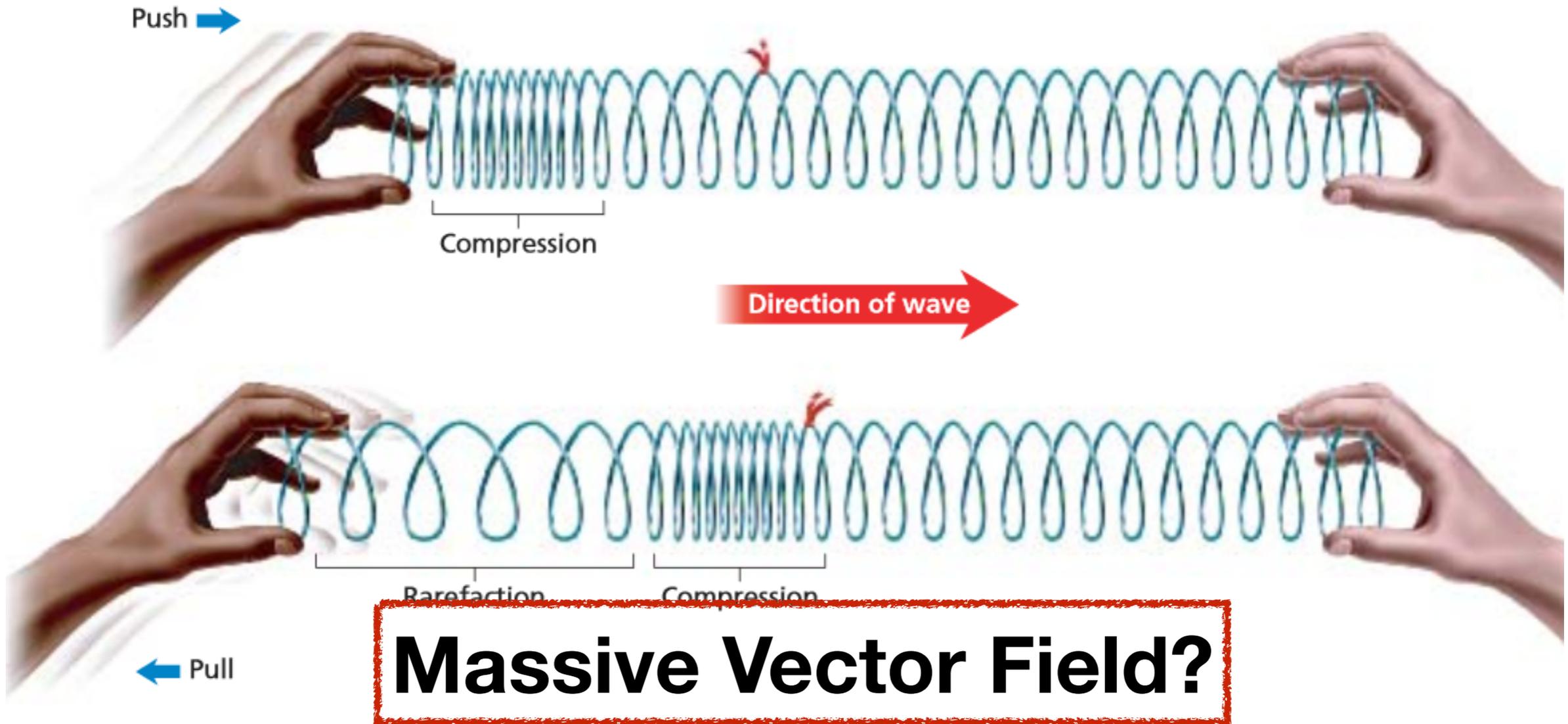


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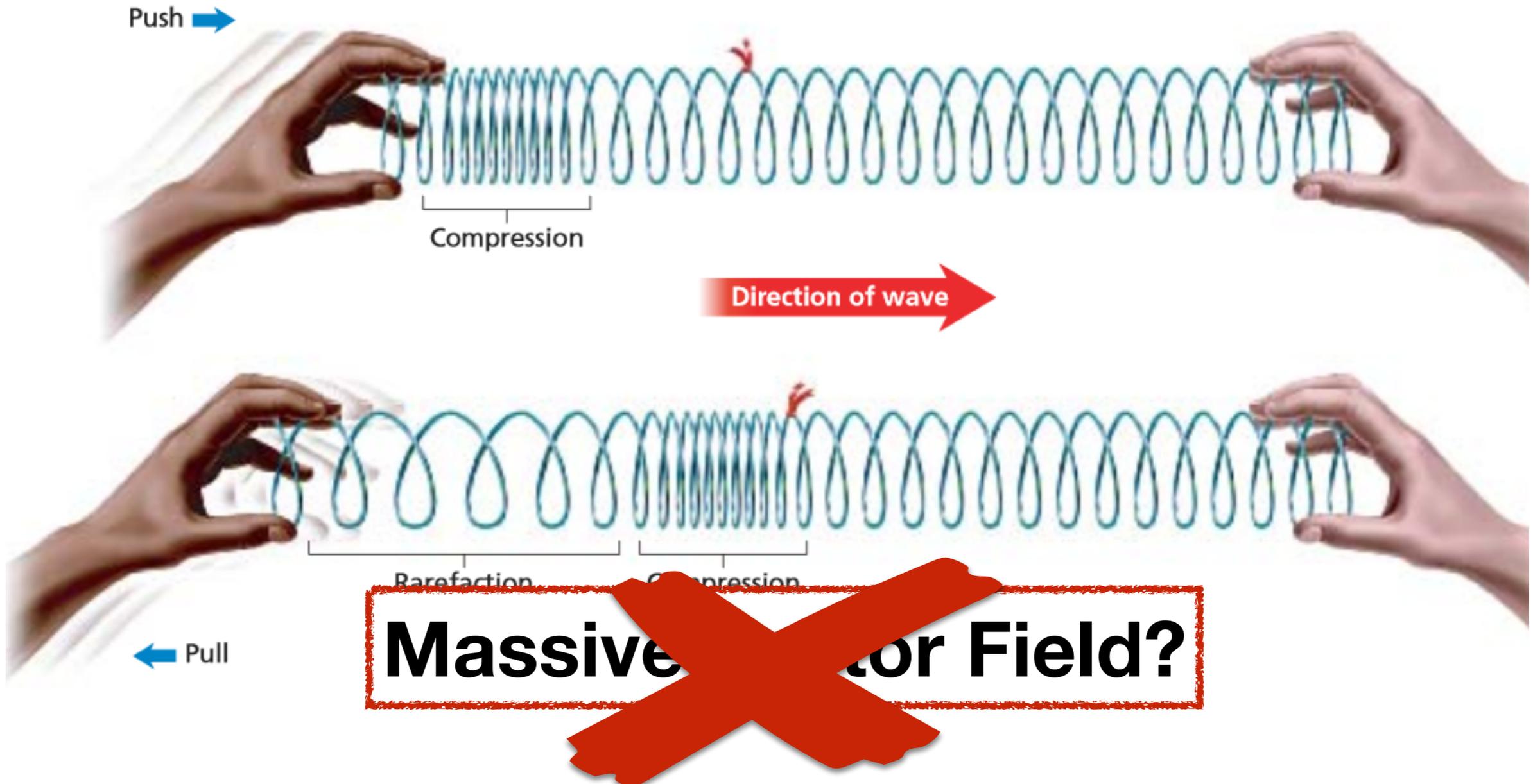


# 带电矢量玻色子的问题

- 非零质量矢量玻色子的纵向极化自由度

$$m_W \ll E \rightarrow +\infty$$

$$\vec{e} \parallel \vec{p}$$



# 带电矢量玻色子的问题

- 纵向极化自由度的病态高能行为  $\lim_{E \rightarrow +\infty} e_\mu \rightarrow p_\mu$

$$\mathcal{M}(X_1 \dots X_n \rightarrow V + Y_1 \dots Y_m) \propto \mathcal{J}^\mu e_\mu^V$$

- 例:  $e^+ e^- \rightarrow W^+ W^-$

# 带电矢量玻色子的问题

- 纵向极化自由度的病态高能行为  $\lim_{E \rightarrow +\infty} e_\mu \rightarrow p_\mu$

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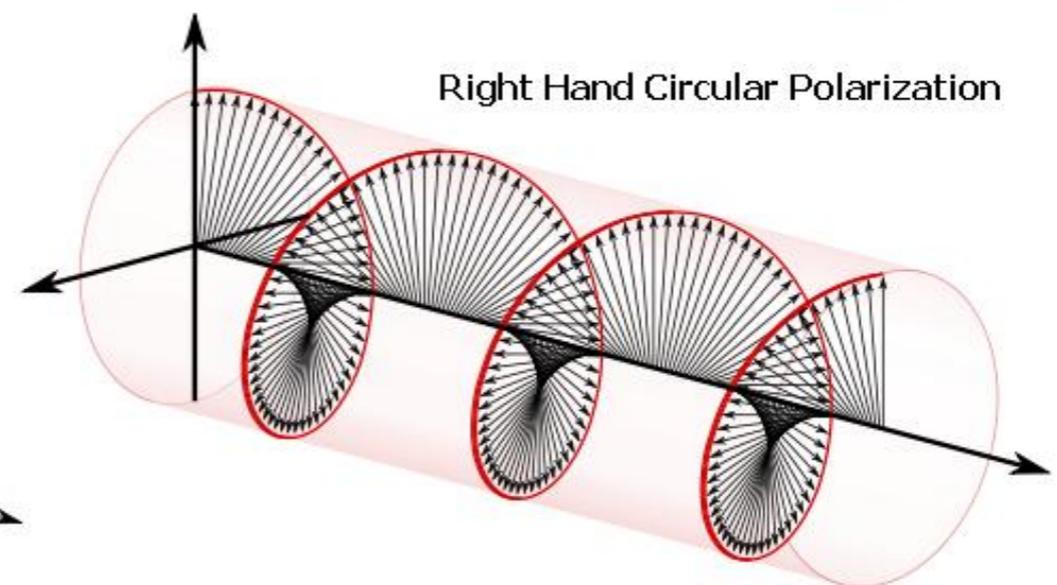
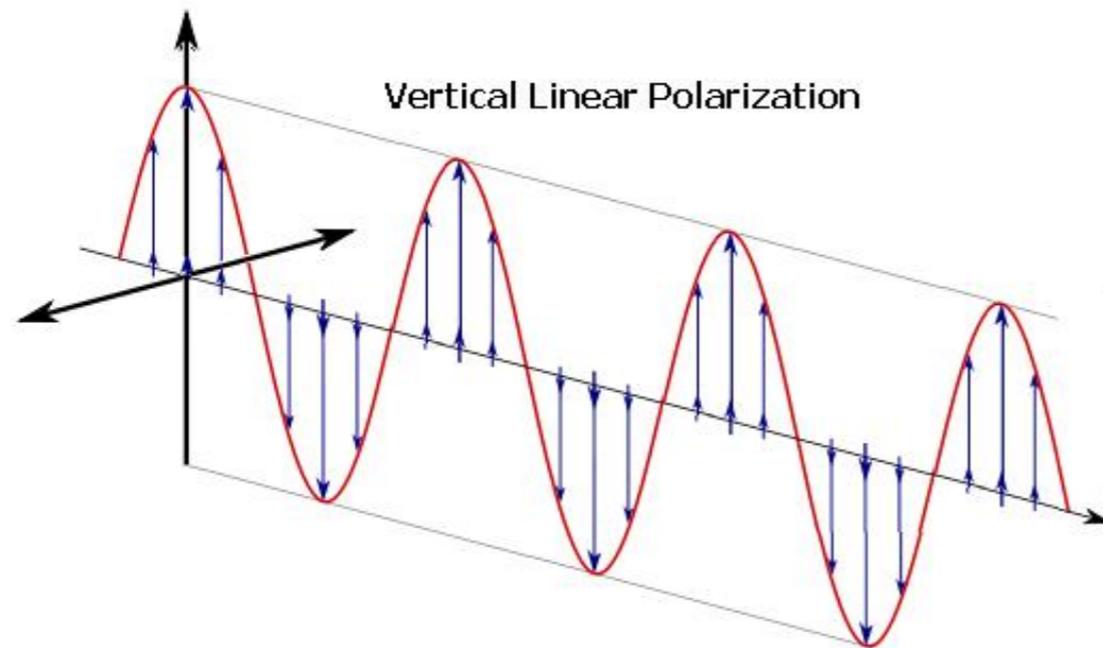
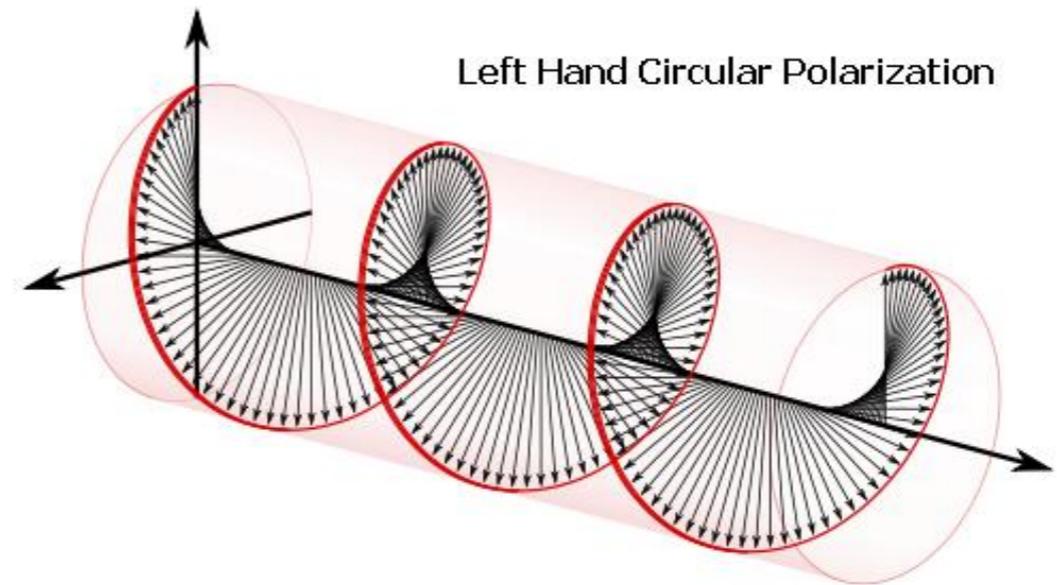
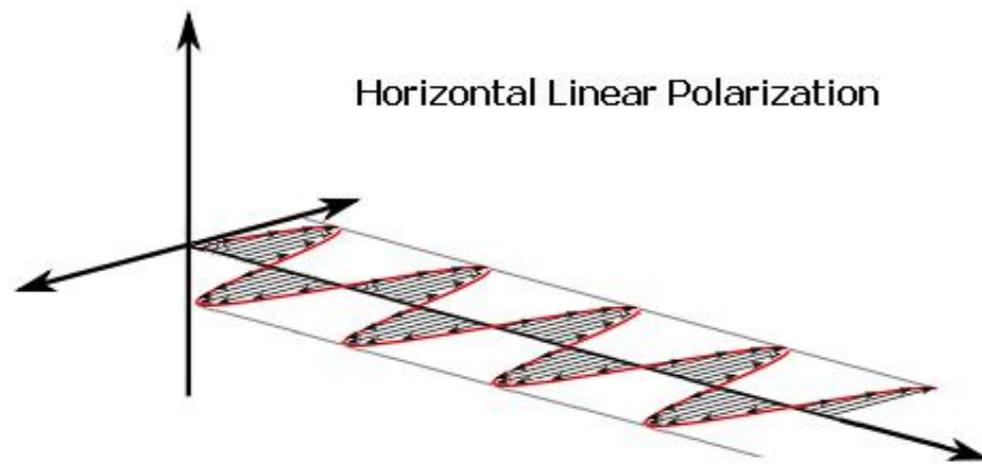
- 解决的方案

$$\partial_\mu \mathcal{J}^\mu = 0$$

- 流守恒、规范相互作用？
- 为什么？

# 带电矢量玻色子的问题

- 电磁波极化自由度与狭义相对论的不相容之处



# 带电矢量玻色子的问题

- 电磁波极化自由度与狭义相对论的不相容之处。
- 横波极化矢量“垂直于”波矢方向。
- 考虑沿波矢方向的Lorentz boost, 极化矢量不可能是Lorentz协变的4矢量!

$$S(a, b)\varepsilon_x^\mu = \begin{pmatrix} 1 + \frac{a^2+b^2}{2} & a & b & -\frac{a^2+b^2}{2} \\ a & 1 & 0 & -a \\ b & 0 & 1 & -b \\ \frac{a^2+b^2}{2} & a & b & 1 + \frac{a^2+b^2}{2} \end{pmatrix} \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} a \\ 1 \\ 0 \\ a \end{pmatrix} = \varepsilon_x^\mu + ak^\mu$$

# 带电矢量玻色子的问题

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怎么办???

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- 现实世界中任何包含电磁波的理论, 除满足狭义相对论协变外, 必须在上述变换下给出相同的结果——

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# 带电矢量玻色子的问题

- 无论是带质量的矢量玻色子，还是零质量的矢量玻色子，当它们参与相互作用时，流守恒和规范冗余是理论完备性的物理要求。
- 一个理论上自治的模型，不仅要在树图水平满足上述条件，还要确保量子修正不会破坏上述要求。

# 带电矢量玻色子的问题

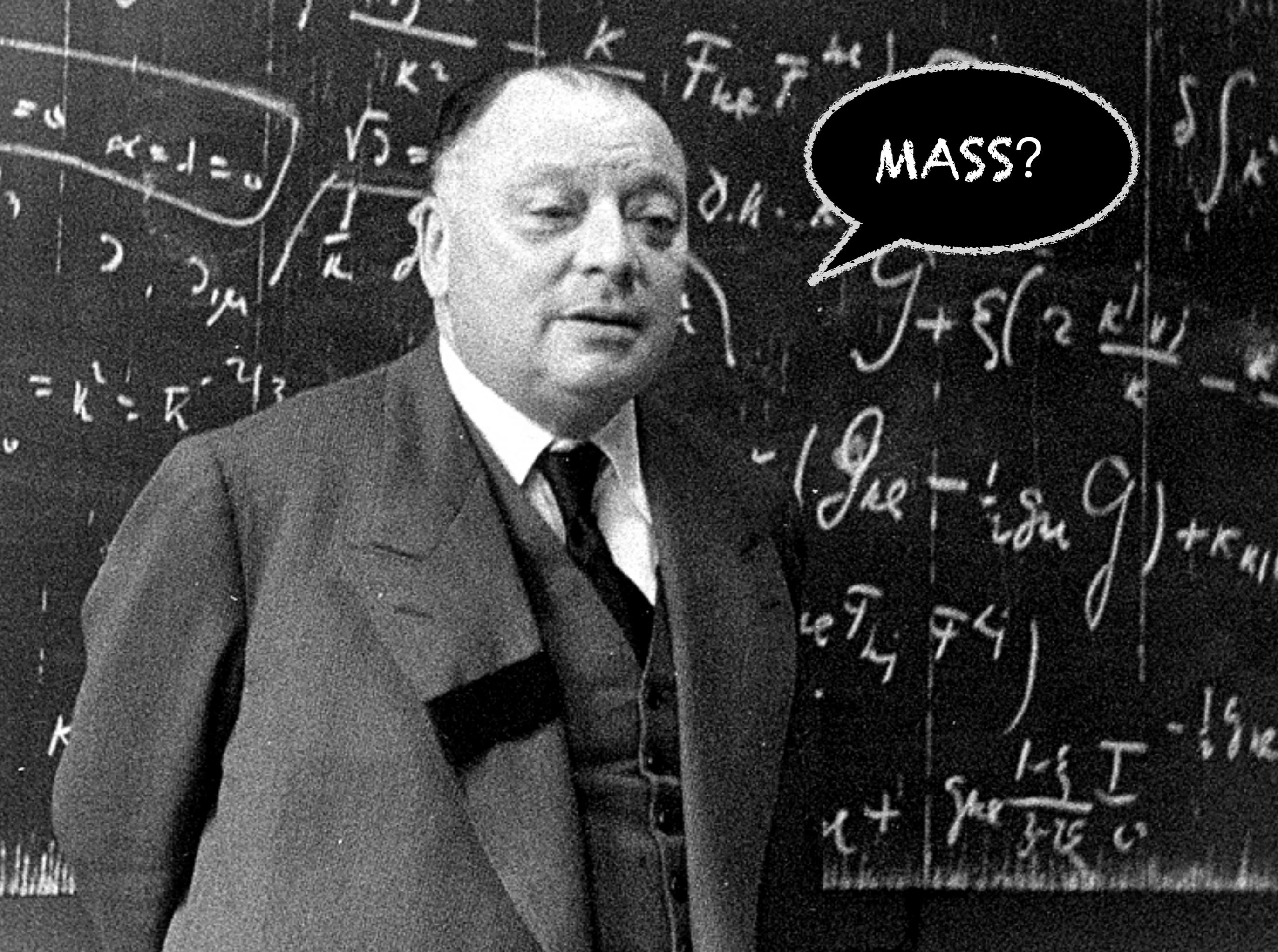
- 将弱SU(2)对称性规范化 (副产物: 中性流——Z。思考: 如何检验? )
- 严重的后果:

$$m_W^2 W^\mu W_\mu$$

**Unitarity (Gauge symmetry) Violation**

$$m\bar{\psi}_L\psi_R + h.c.$$

**Vector  $\times$  scalar  $\neq$  scalar**



MASS?

$\alpha = 1 = 0$

$\sqrt{5} =$

$\frac{1}{\kappa}$

$\frac{\kappa}{F_{\mu\nu} F^{\mu\nu}}$

$\partial_\mu A^\mu$

$\int + \int (2 \frac{\kappa'}{\kappa})$

$-(g_{\mu\nu} - \frac{1}{2} g_{\mu\nu} g) + \kappa_{\mu\nu}$

$\int F_{\mu\nu} F^{\mu\nu}$

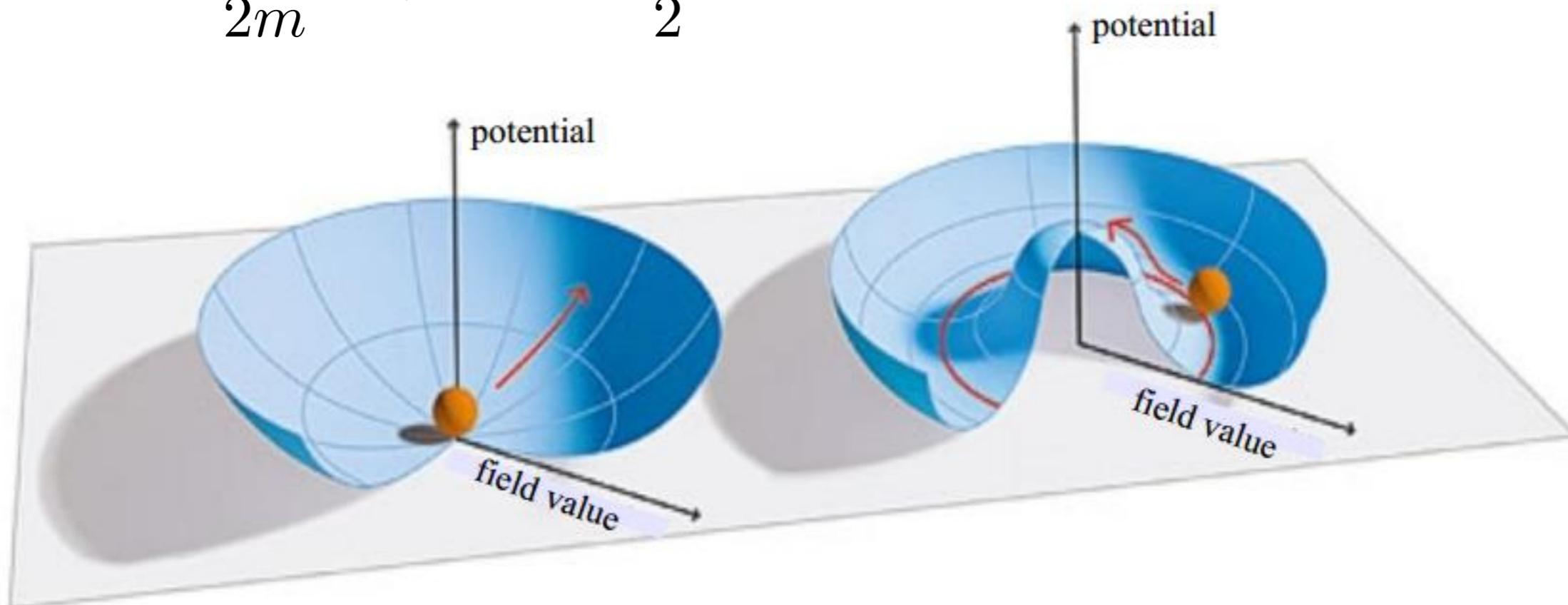
$\kappa + \frac{1-\epsilon}{375} \frac{T}{c}$

$-\frac{1}{2} g_{\mu\nu}$

# 对称性自发破缺

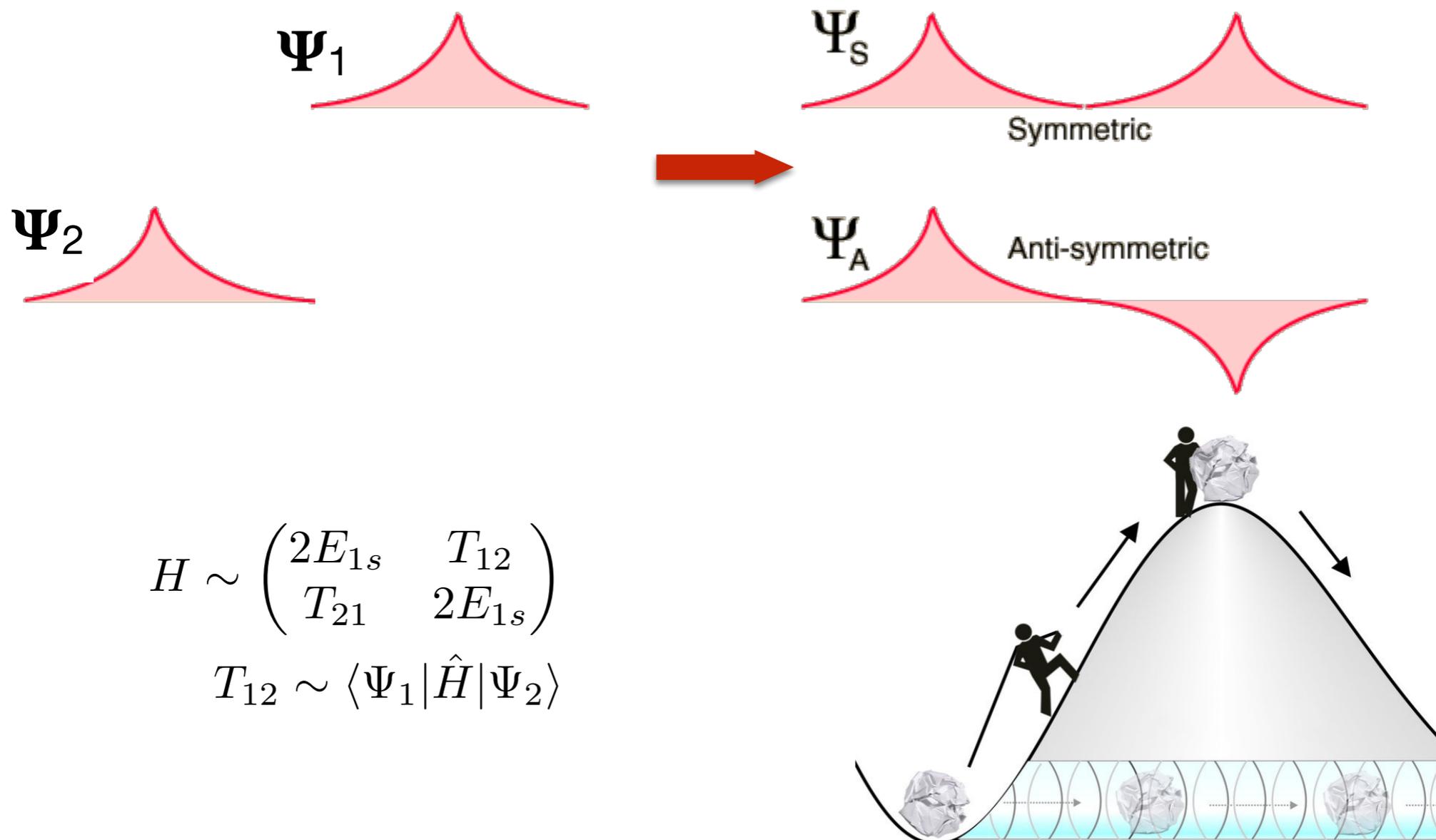
- 经典物理中的对称性自发破缺。
- 小振动：

$$H = \frac{p_x^2 + p_y^2}{2m} + \frac{k(x^2 + y^2 - r_0^2)^2}{2}$$



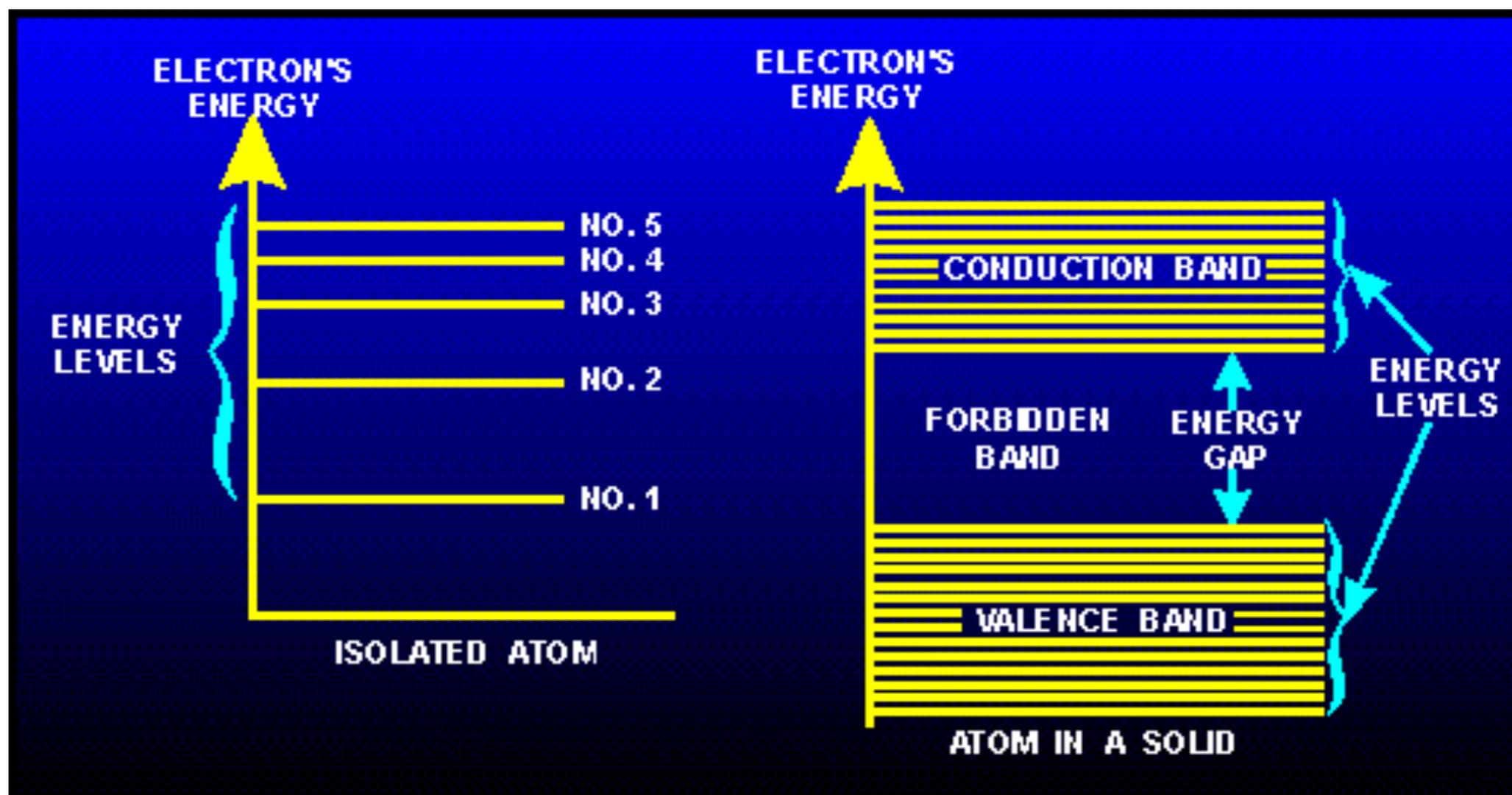
# 对称性自发破缺

- 量子力学中的对称性自发破缺。(X)
- 例子：从氢分子到能带。



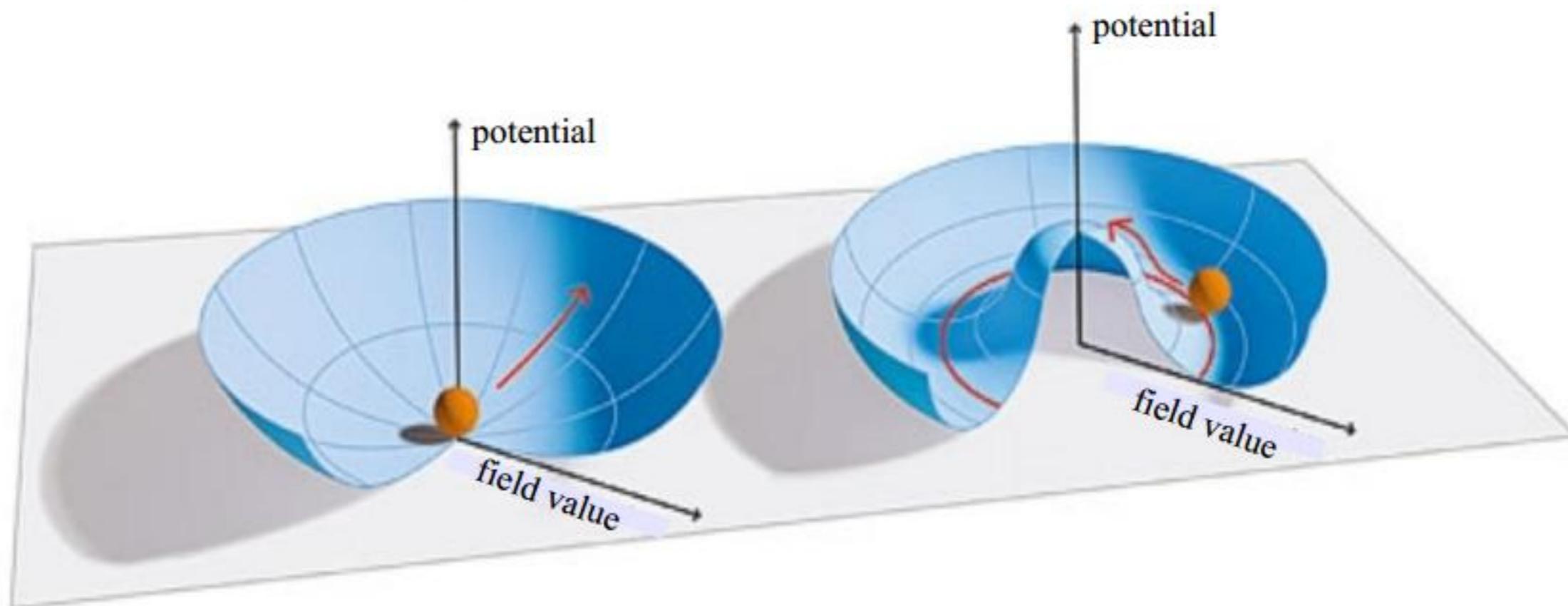
# 对称性自发破缺

- 量子力学中的对称性自发破缺。(X)
- 例子：从氢分子到能带。



# 对称性自发破缺

- 量子场论中的对称性自发破缺。
- 无穷自由度系统， $T_{SA}$ 可以等于0。



$$S = \int d^4x \left[ (D_\mu \Phi)^\dagger D^\mu \Phi - \frac{\lambda}{4} (\Phi^\dagger \Phi - v^2)^2 \right]$$

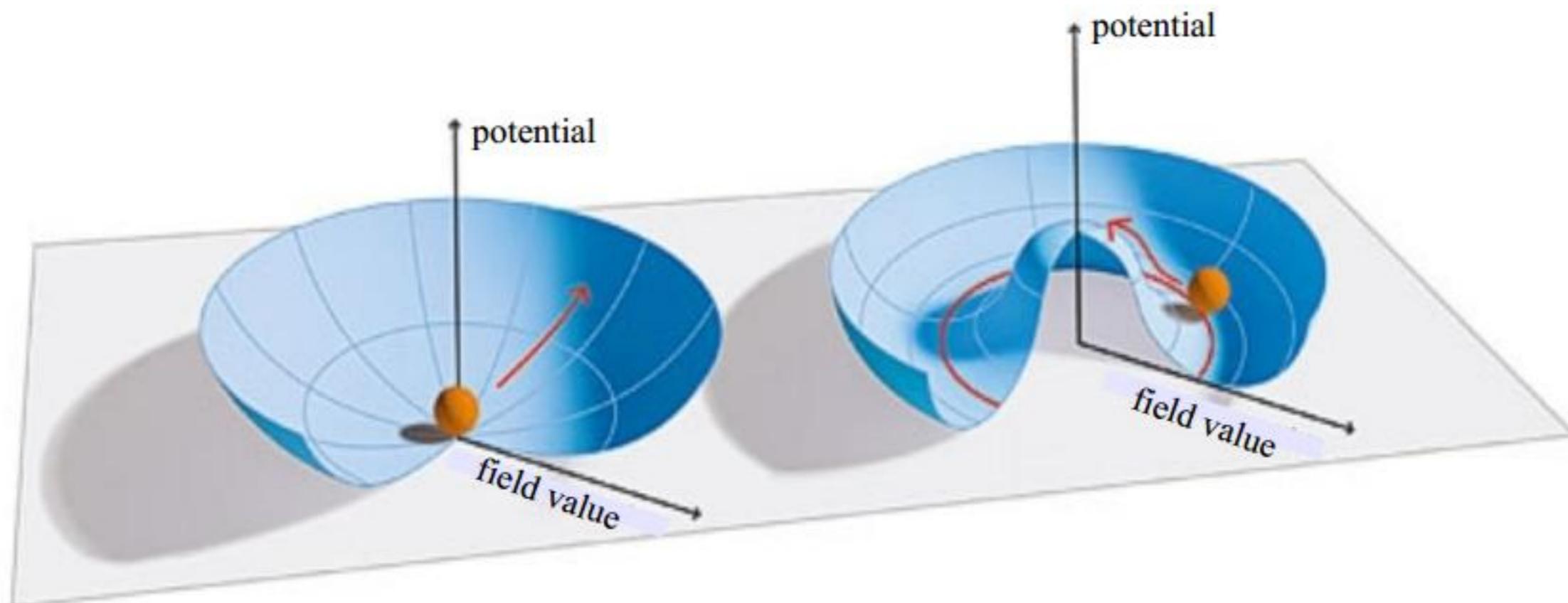
# 对称性自发破缺

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$$S = \int d^4x \left[ (D_\mu \Phi)^\dagger D^\mu \Phi - \frac{\lambda}{4} (\Phi^\dagger \Phi - v^2)^2 \right]$$

$$\langle \Phi \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\Phi = \begin{pmatrix} G^+ \\ v + \frac{1}{\sqrt{2}}(h + iG^0) \end{pmatrix}$$

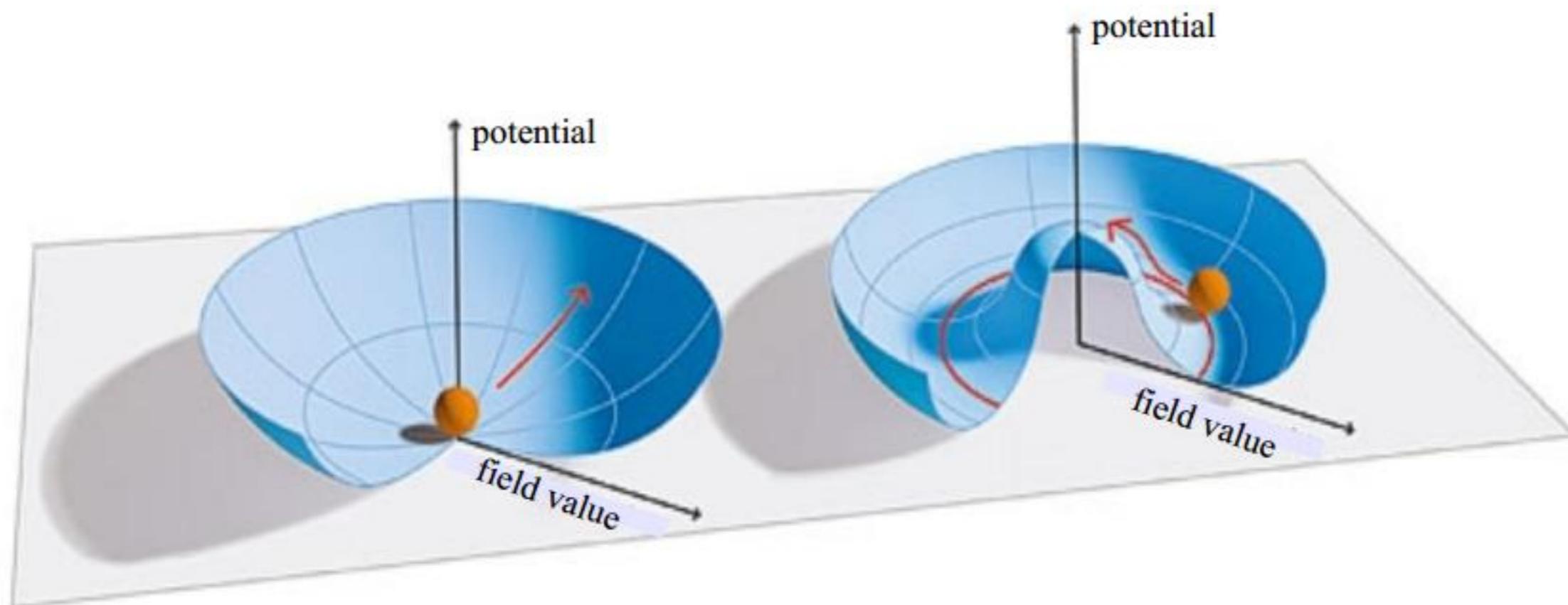


# 对称性自发破缺

- 整体对称性的自发破缺（Goldstone定理：0质量赝标量粒子的存在）。

$$y (\bar{\psi}_L \cdot \Phi) \psi_R \rightarrow y(\bar{\psi}_{L,1}, \bar{\psi}_{L,2}) \begin{pmatrix} 0 \\ v \end{pmatrix} \psi_R \rightarrow yv\bar{\psi}_{L,2}\psi_R$$

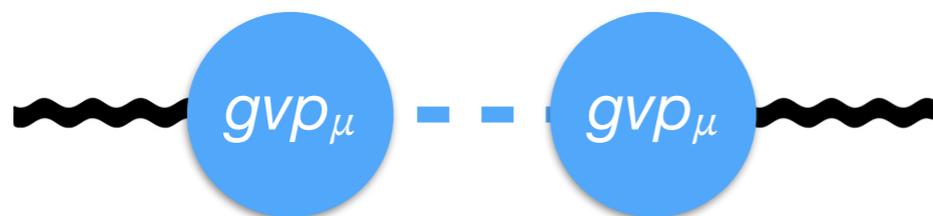
**Spontaneous Symmetry Breaking**



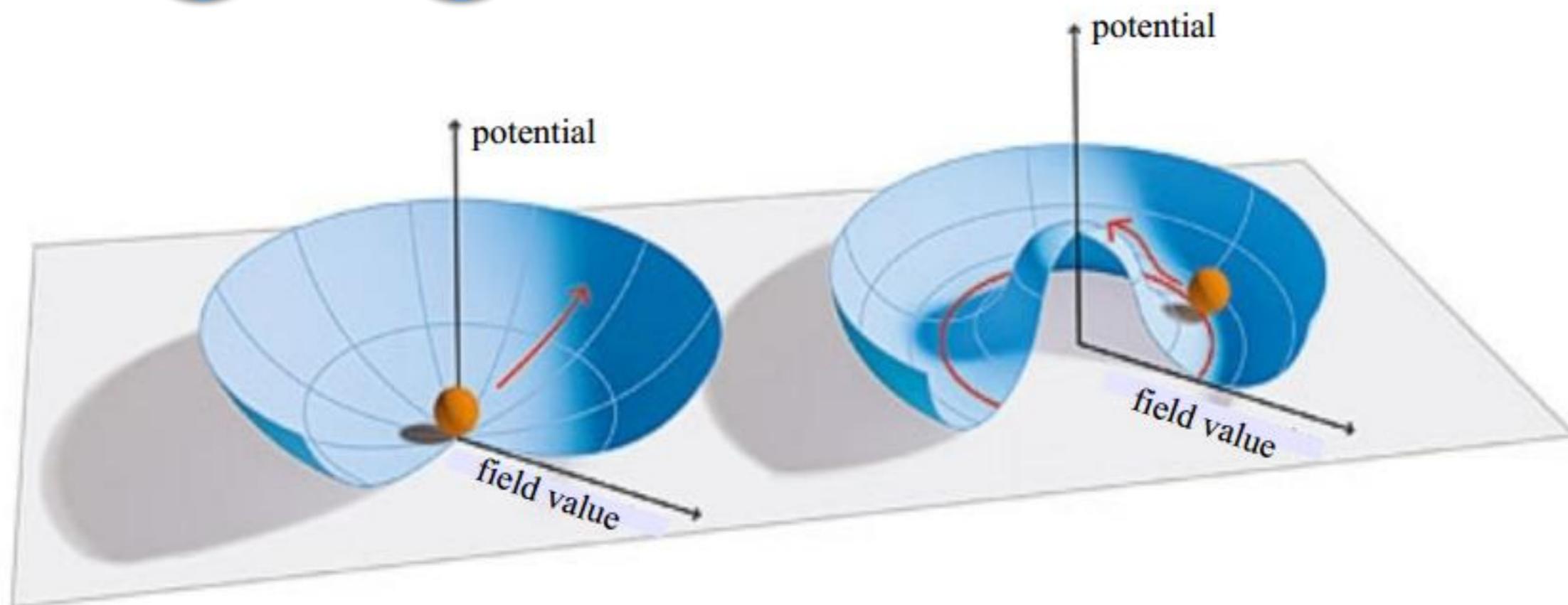
# 对称性自发破缺

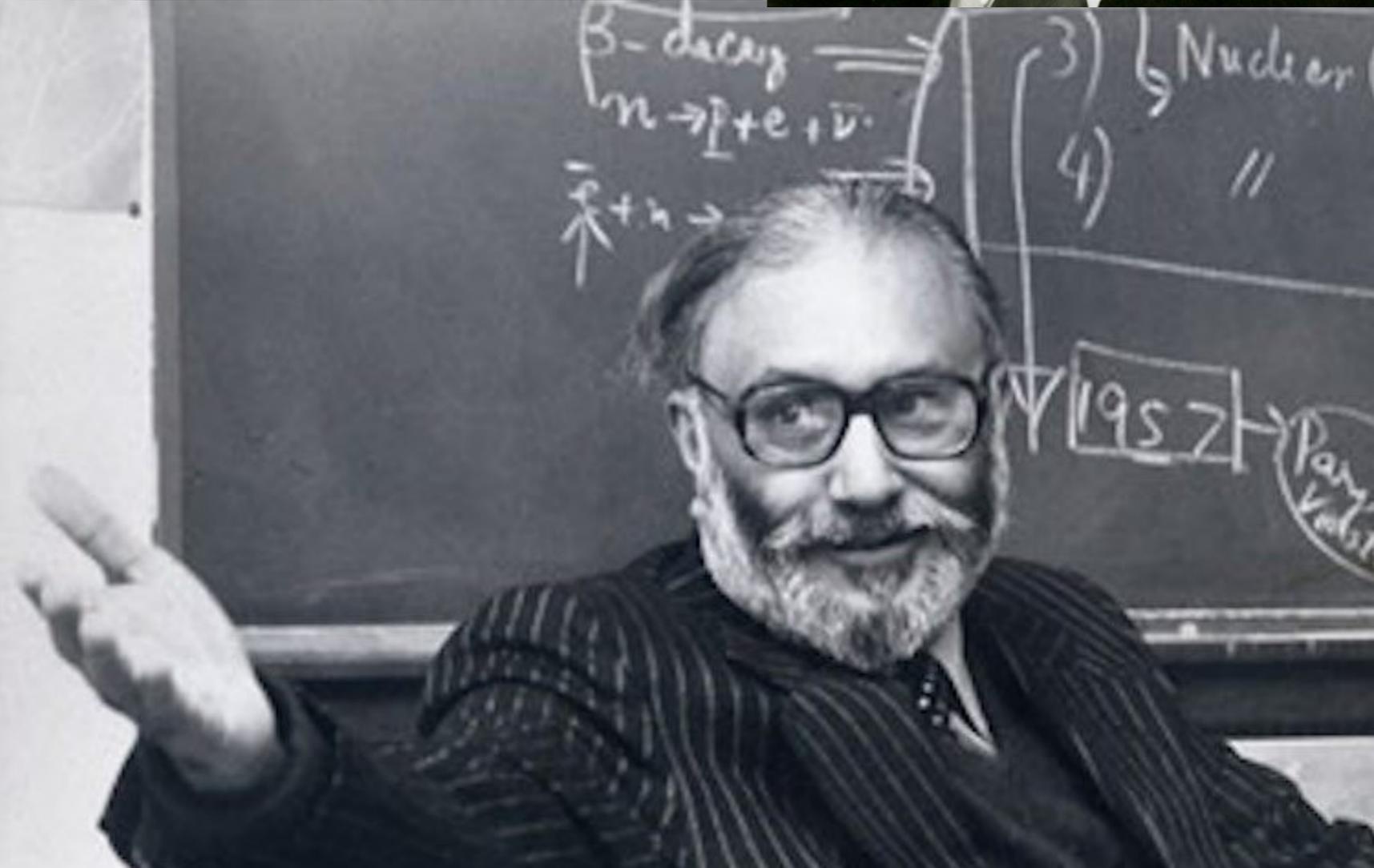
- 规范对称性的自发破缺（Higgs机制：0质量规范玻色子自由度被规范玻色子“吃掉”，成为其纵向极化自由度）。

$$\sim g^2 v^2 \left( W_{\mu}^{+} + \partial_{\mu} G^{+} \right) \left( W^{-,\mu} + \partial^{\mu} G^{-} \right)$$



**Higgs Mechanism**





# 希格斯机制

- 标准模型电弱对称性自发破缺（树图）。

$$V(\varphi) = \mu^2 (\varphi^\dagger \varphi) + \lambda (\varphi^\dagger \varphi)^2$$

$$\varphi = \begin{pmatrix} G^+ \\ v + \frac{1}{\sqrt{2}} (H^0 + iG^0) \end{pmatrix} \quad \langle \varphi \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\begin{aligned} D_\mu \varphi &= \begin{pmatrix} \partial_\mu G^+ + \frac{i}{2} (gW_\mu^3 + g'B_\mu) G^+ + \frac{ig}{2} W_\mu^+ (\sqrt{2}v + H^0 + iG^0) \\ \frac{1}{\sqrt{2}} \partial_\mu H^0 + \frac{i}{\sqrt{2}} \partial_\mu G^0 + \frac{ig}{\sqrt{2}} W_\mu^- G^+ + \frac{i}{2\sqrt{2}} (-gW_\mu^3 + g'B_\mu) (\sqrt{2}v + H^0 + iG^0) \end{pmatrix} \\ &= \begin{pmatrix} \partial_\mu G^+ + ieA_\mu G^+ + \frac{ie(c_W^2 - s_W^2)}{2s_W c_W} Z_\mu G^+ + \frac{ie}{2s_W} W_\mu^+ (\sqrt{2}v + H^0 + iG^0) \\ \frac{1}{\sqrt{2}} \partial_\mu H^0 + \frac{i}{\sqrt{2}} \partial_\mu G^0 + \frac{ie}{\sqrt{2}s_W} W_\mu^- G^+ - \frac{ie}{2\sqrt{2}s_W c_W} Z_\mu^0 (\sqrt{2}v + H^0 + iG^0) \end{pmatrix} \end{aligned}$$

$$\begin{pmatrix} A^0 \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} B \\ W^3 \end{pmatrix} \quad \frac{e^2 v^2}{2s_W^2} W_\mu^- W^{+\mu} + \frac{e^2 v^2}{4s_W^2 c_W^2} Z_\mu^0 Z^{0\mu}$$

# 希格斯机制

- 标准模型电弱对称性自发破缺（树图）。

$$\mathcal{L}_{\text{Yukawa}} = -Y_u^{ij} \epsilon_{ab} \bar{Q}_i^a \varphi^{b*} u_{Rj} - Y_d^{ij} \bar{Q}_i^a \varphi_a d_{Rj} - Y_e^{ij} \bar{L}_i^a \varphi_a e_{Rj} + \text{h.c.}$$

$$Y_u^{ij} v \bar{u}_{Li} u_{Rj} + Y_d^{ij} v \bar{d}_{Li} d_{Rj} + Y_e^{ij} v \bar{e}_{Li} e_{Rj} + \text{h.c.}$$

**Polar decomposition theorem:**

$$u_L \rightarrow U_L^u u_L, \quad u_R \rightarrow U_R^u u_R, \quad d_L \rightarrow U_L^d d_L, \quad d_R \rightarrow U_R^d d_R$$

$$\mathcal{L}_{\text{Yukawa}} = -\frac{m_{ui}}{v} \epsilon_{ab} \bar{Q}_i^a \varphi^{b*} u_{Ri} - \frac{m_{di}}{v} \bar{Q}_i^a \varphi_a d_{Ri} - \frac{m_{ei}}{v} \bar{L}_i^a \varphi_a e_{Ri} + \text{h.c.}$$

$$V_{CKM} = U_L^{u\dagger} U_L^d$$

