粒子物理标准模型电弱及真空破缺机制与高能实验前沿寻找新物理

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I. Introduction

近代科学的逻辑基础与粒子物理

What is "Science"?

- 要素：

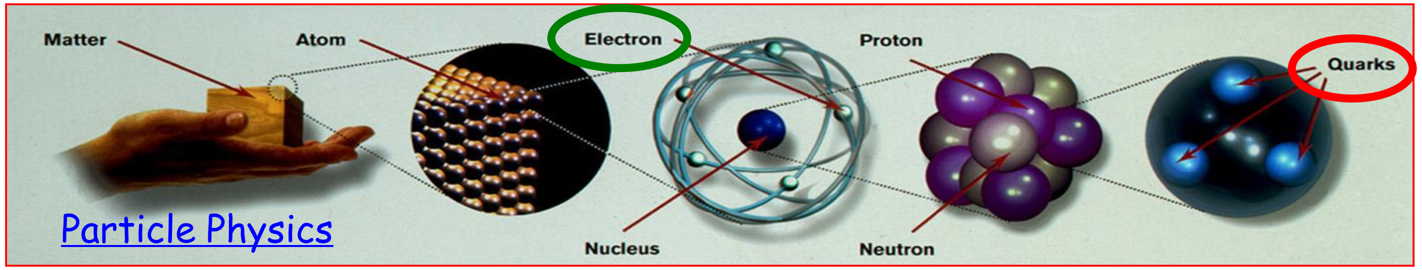
基于实验的、明确的概念与规律(!)

可重复性观测	严格的数学逻辑	公设⊕原理物理模型	明确条件下可预言性

- 方法：

简洁 Simplicity + 层级 Hierarchy + 自洽 Consistency → 统一 Unification?

- 粒子物理: 物质世界(时空)的最小基本构成、及其之间相互作用机制



经典时代的统一

Universal written in a piece of paper

天上的
地下的

Gravity
$\sim G_N M^2/r^2$
(Newton 1687)

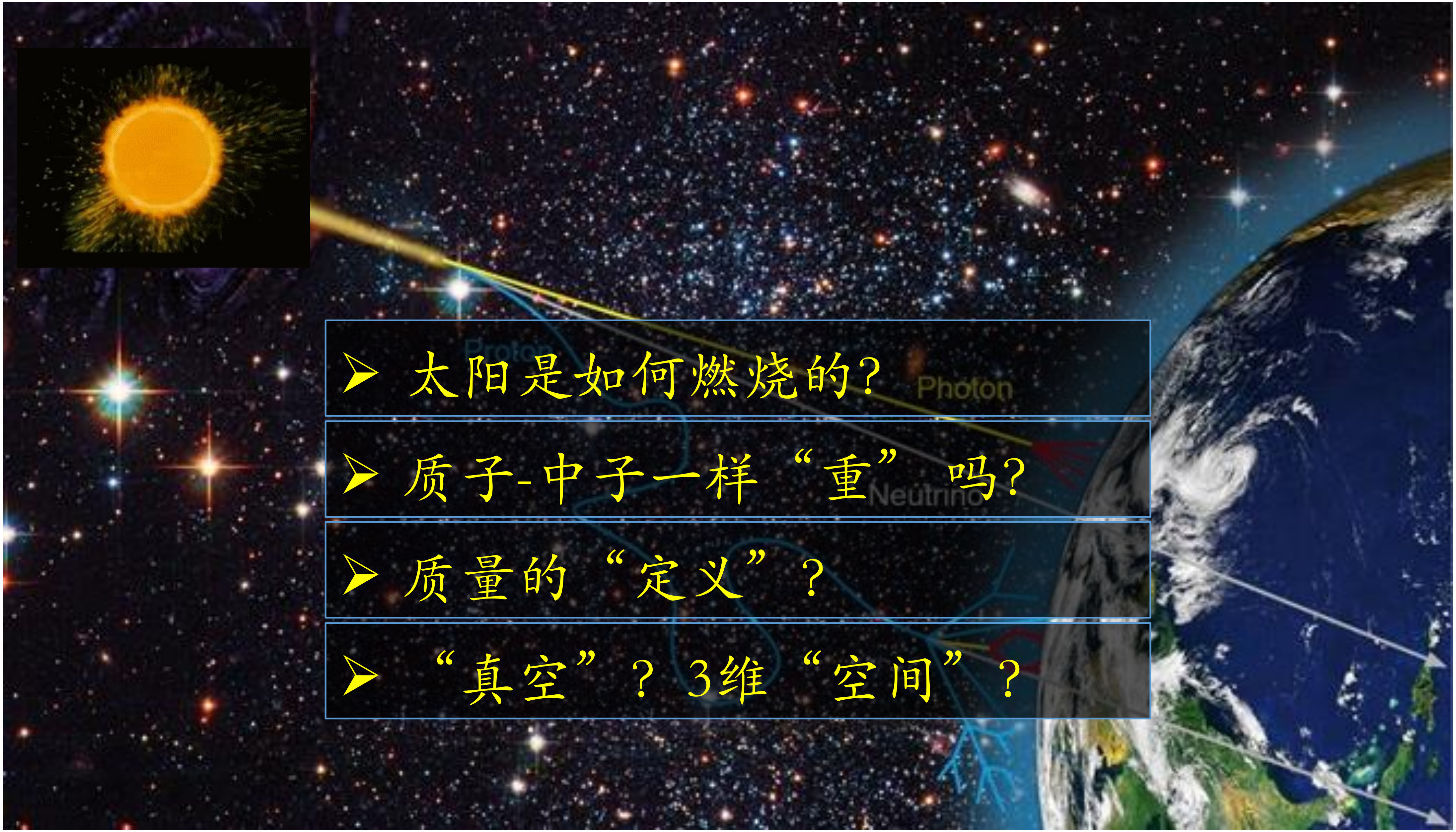
磁：磁石
电：1785 Coulomb
静电扭秤 $\sim e^2/r^2$
1789 → 1800
Galvani → Volta
青蛙腿 化学电池

1819
Oested
电流磁场

电磁学
Electro-Magnetic

伟大的时代 1867
Maxwell Equations
EM wave ＝光

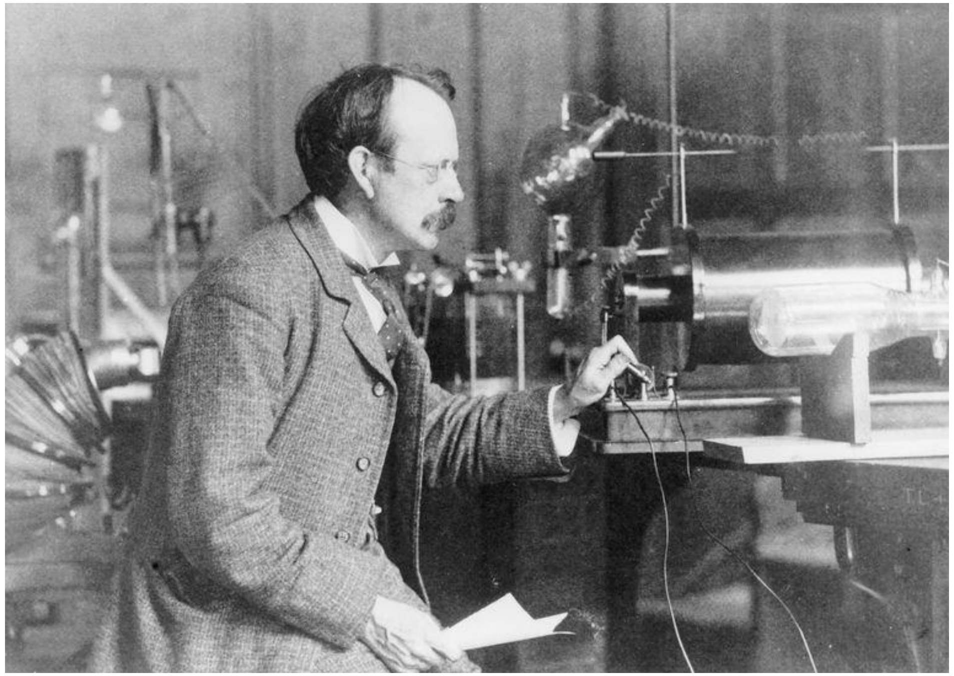
“日常问题”与“眼见为实”



- 太阳是如何燃烧的？
- 质子-中子一样“重”吗？
- 质量的“定义”？
- “真空”？3维“空间”？

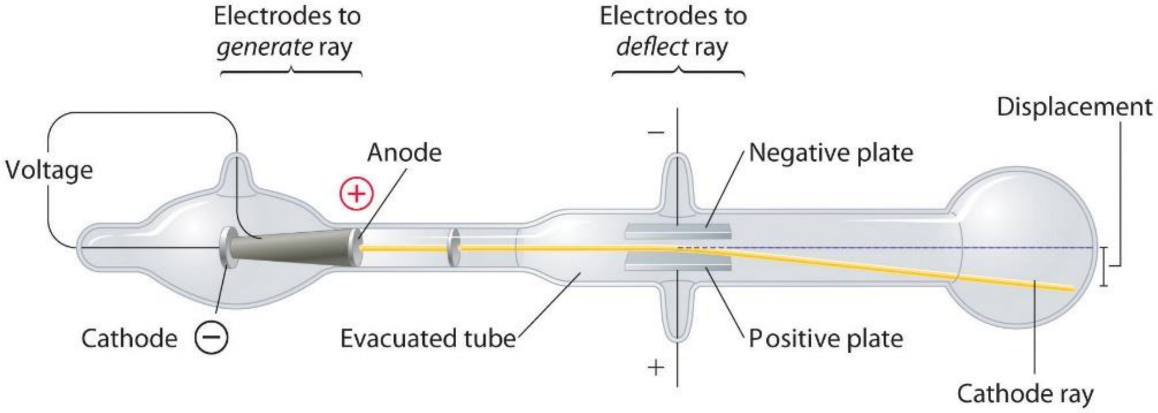
The discovery of Electron

- 1897年, J.J. Thomson在真空管中观测到阴极射线



(1856-1940)

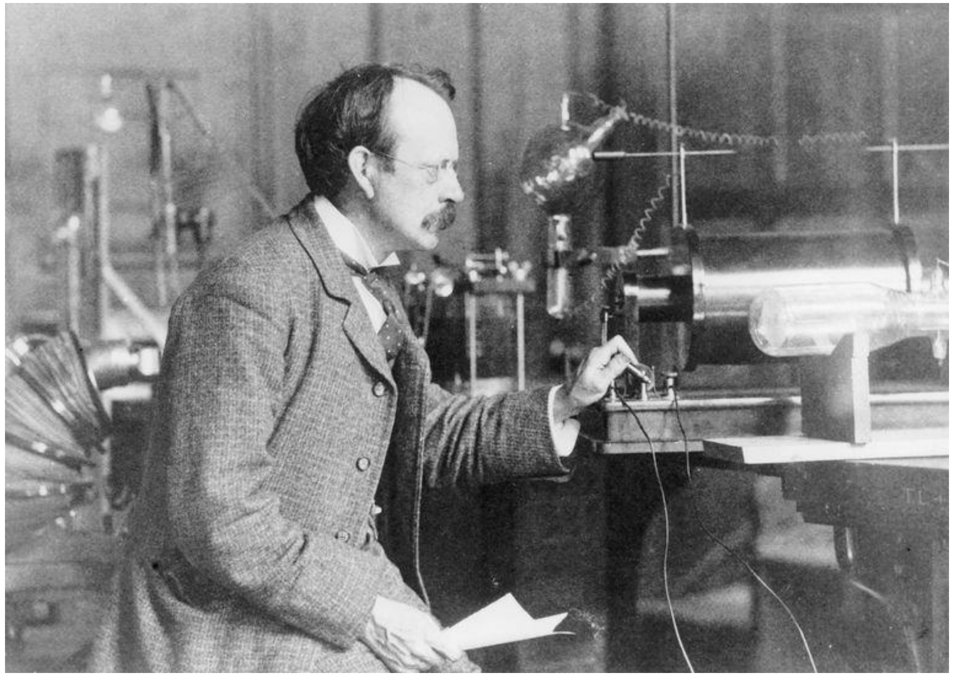
-- *"Excuse me … but how can you discover a particle so small that nobody has ever seen one?"*



The first discovery of a fundamental building block of matter, e^-

The discovery of Electron

- 1897年, J.J. Thomson在真空管中观测到阴极射线



(1856-1940)

-- *"Of course, you can not see it with naked eyes, but one can describe it as …"*

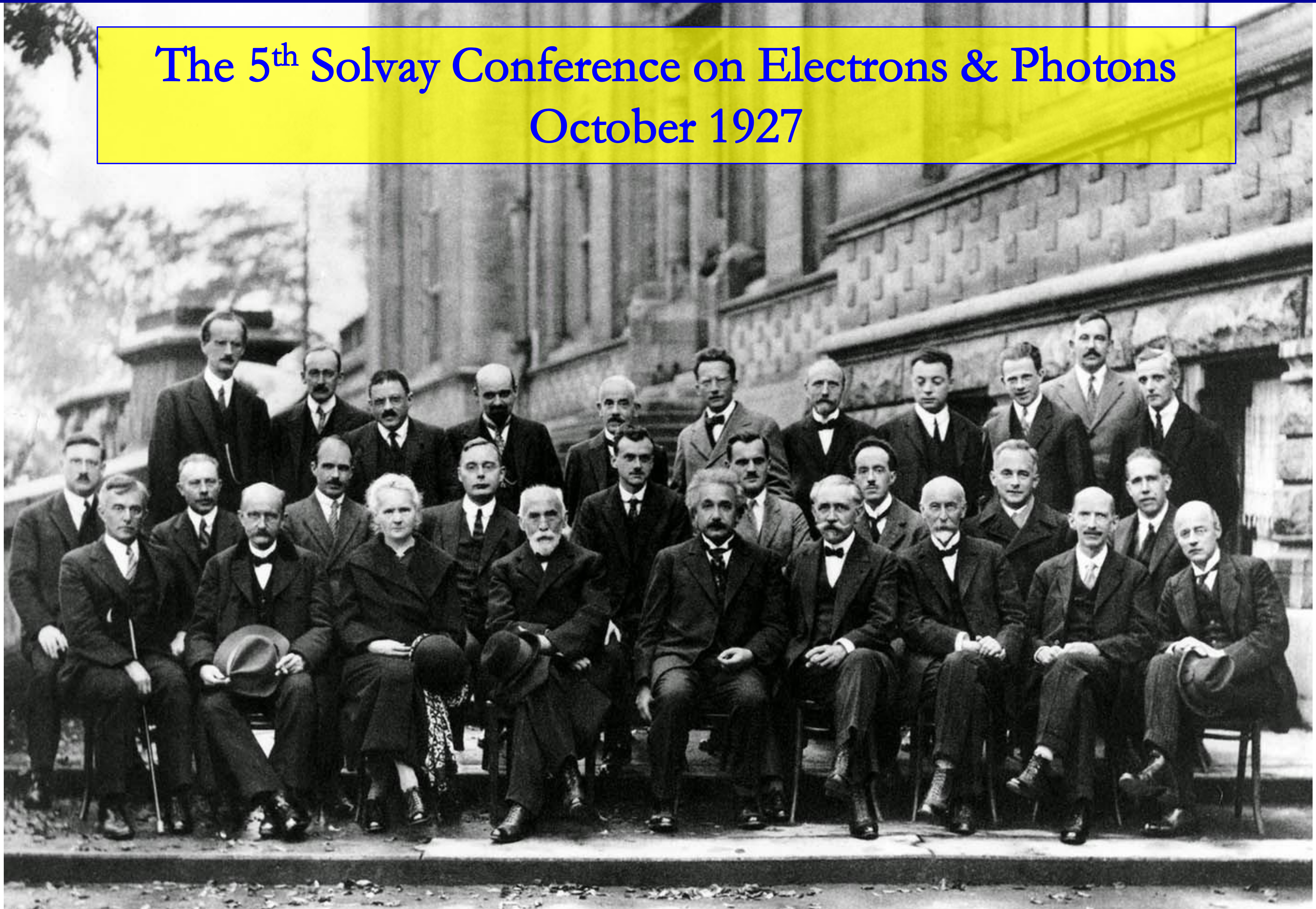
✓ 1897，阴极射线在电磁场中偏转 → 质谱仪 荷质比Q_e/m_e

✓ 1909，密立根(1868-1953)油滴 → 电子电量$|Q_e| \approx 1.6\times10^{-19}$ C

✓ 1925，G.乌伦贝克和S.古兹密特 → 反常塞曼效应 $s_e = 1/2$

The first discovery of a fundamental building block of matter, e^-

近代科学的奠基


The 5th Solvay Conference on Electrons & Photons
October 1927

To describe things moving very fast @ c=299 792 458 m·s^{-1} requires the theory of relativity.

Special Relativity :

- One cannot catch up with light.

  实验观测: **光速不变**

- Time-Space

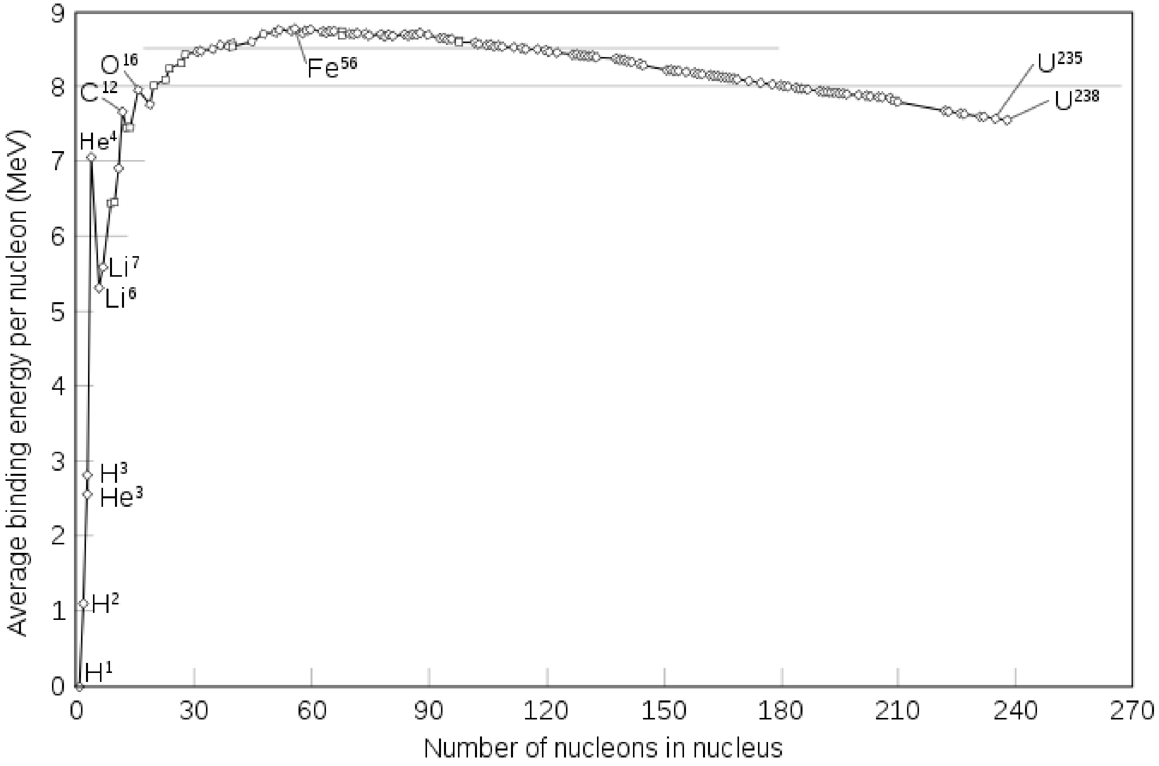
  时空一致 $(t, \vec{x})$

- Mass is a form of energy.

  质能关系 $E = mc^2$

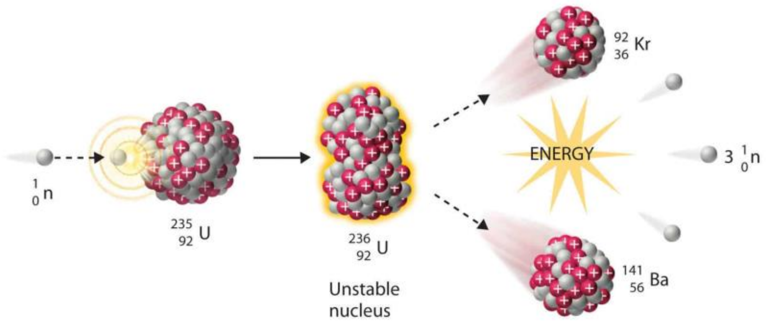
Albert Einstein
(1879 - 1955)

质量亏损与裂变



$$\sum M_i - \sum M_f = \Delta E \geq 0$$

$$^{235}_{92}U + n \rightarrow ^{236}_{92}U \rightarrow ^{92}_{36}Kr + ^{141}_{56}U + 3n$$



To describe things very small @ ***h*** =6.626070040(81)×10^{-34} J·s requires quantum mechanics.

Wave function :

$$\Psi(\vec{r},t) \sim e^{i(\vec{p}\cdot\vec{r}-E\cdot t)/h}$$

– Atom never collapses

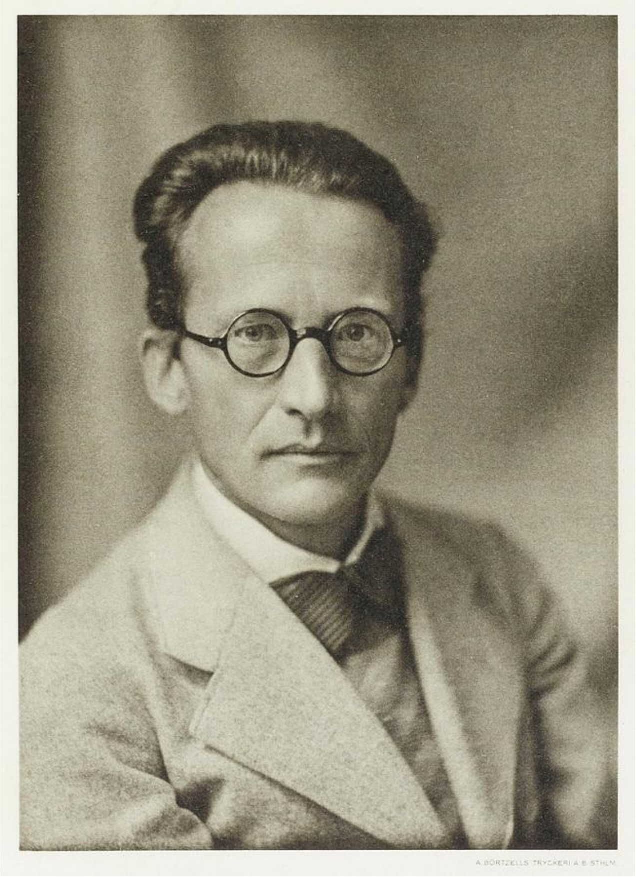
实验观测: 原子定态与光谱

– 理论: Schrodinger Equation $\hat{E}\Psi = \left[\hat{\vec{p}}^2/m + \mathrm{V}\right]\Psi$

Time-dependent Schrödinger equation in position basis

(single nonrelativistic particle)

$$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},t) = \left[\frac{-\hbar^2}{2\mu}\nabla^2 + V(\mathbf{r},t)\right]\Psi(\mathbf{r},t)$$

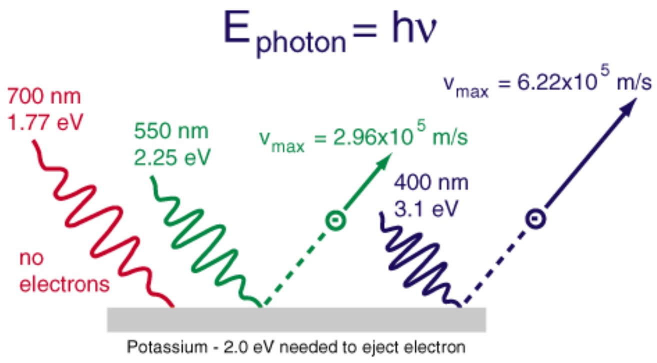


Erwin Schrödinger
(1887 - 1961)

近代科学柱石(II)：Quantum Mechanics量子力学

In subatomic world, to be a particle or wave? That is a question

- Photon as particle



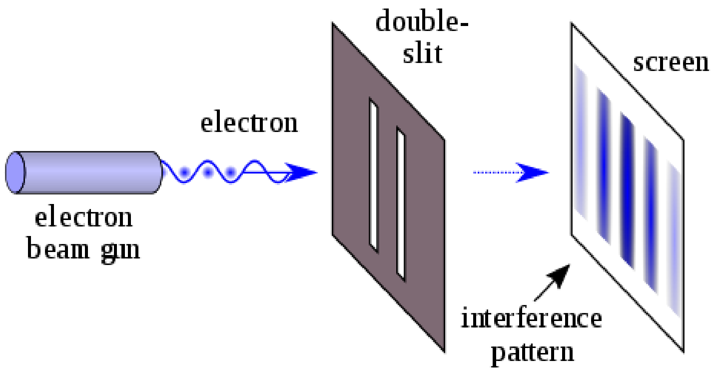
Photoelectric effect

$\mathrm{E} = \hbar\omega$

光的能量量子化

Louis de Broglie
(1891 - 1987)

- Electron as wave



Double-slit interference

$\lambda = h/p$

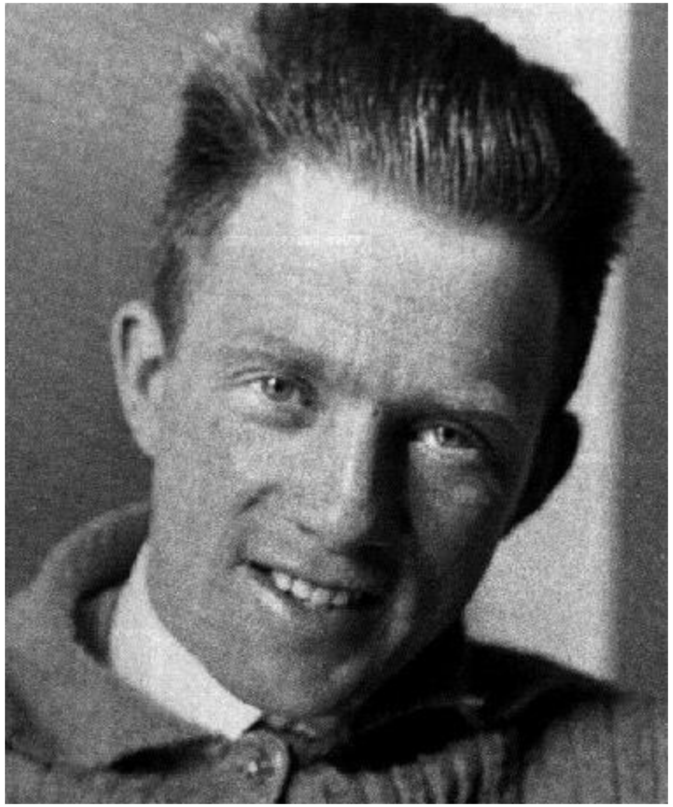
电子的空间概率分布

波粒二相性 Particle-wave duality

The uncertainty principle:

– The more precisely we know the position $\vec{x}$ of an object, the worse we know its momentum $\vec{p}$.

$$\Delta p \cdot \Delta x \sim \Delta E \cdot \Delta t \sim h$$



Werner Karl Heisenberg
(1901 - 1976)

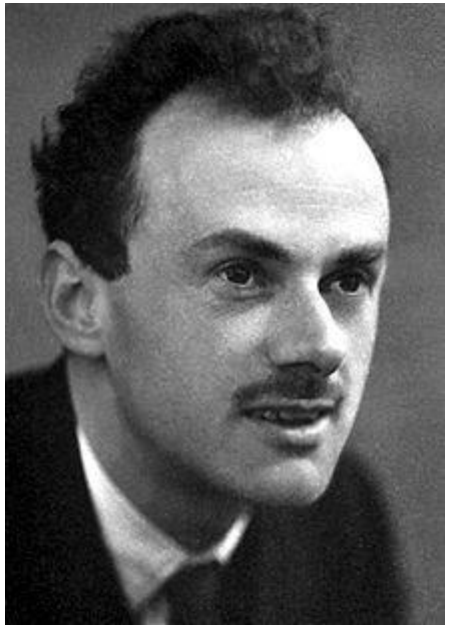
量子力学:

✓波函数概率解释

✓波粒二相性

✓Principle of Uncertainty 测不准原理

- 狄拉克方程： 自旋1/2自由粒子的旋量空间spinor相对论量子力学波动方程



Paul Dirac (1902 - 1984)

Dirac equation *(original)*

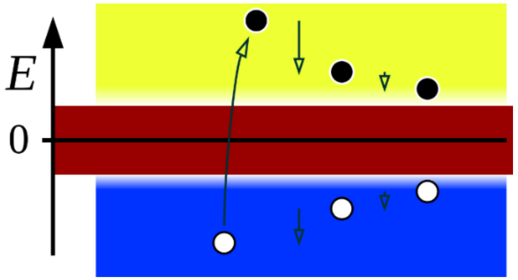
$$\left(\beta mc^2 + c\left(\sum_{n=1}^{3}\alpha_n p_n\right)\right)\psi(x,t) = i\hbar\frac{\partial\psi(x,t)}{\partial t}$$

能量解：

$$E = c\sqrt{p^2 + m^2c^2} \longrightarrow \begin{cases} E > 0,\ \text{自由粒子动能} \\ E < 0,\ ? \rightarrow \text{反粒子假说 (1928)} \end{cases}$$

Dirac费米子:

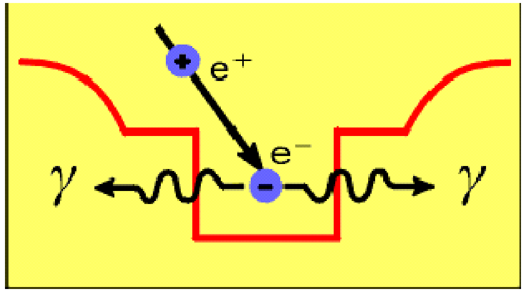
- ✓ Dirac Sea：正-**反**物质，电子-空穴对
- ✓ 阈值效应 $E > 2\ m_e$



相对论量子力学 －positron的实验发现

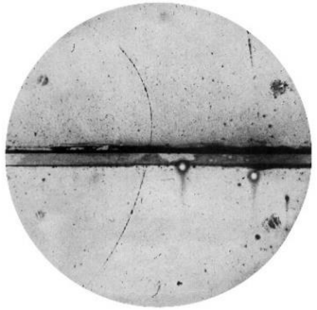
- 理论对实验的推动：反物质粒子 → 正电子e^+

赵忠尧 (1902 -1998)



1930, 硬γ射线-铊
反常吸收、及特殊辐射
(0.511MeV γ)

C.D.Anderson (1905-1991)



1932, 宇宙线中发现e^+径迹
in Cloud Chamber

正反电子$e^{\pm}$：质量m/自旋s 相同，电荷q_e /轻子数L_e 相反

相对论量子场论

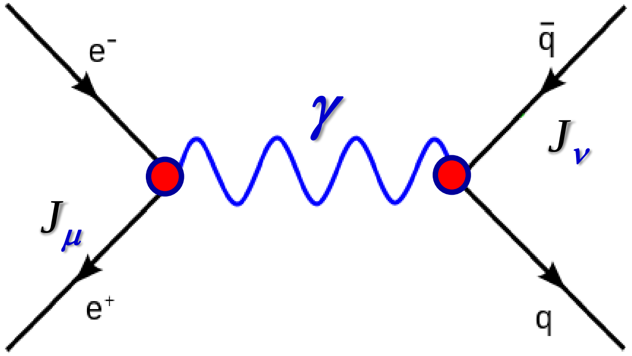
规范理论：U(1)不变

$$\Psi \rightarrow \Psi\, e^{-ie\cdot\theta(x)}$$

- 量子电动力学Quantum electro dynamics QED

光γ-规范场 传播带电基本粒子之间的电磁相互作用

流-流相互作用：

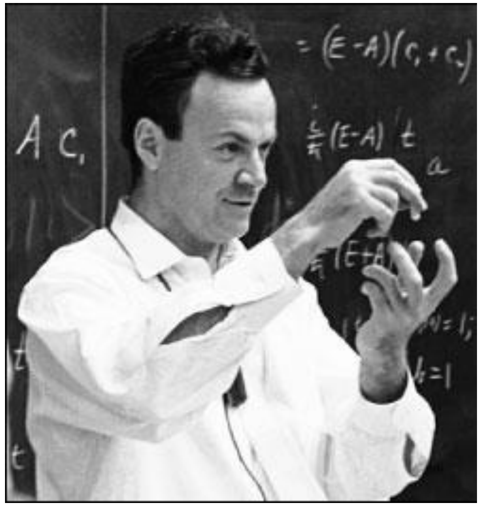


散射振幅：$A \sim (eJ_\mu)\cdot\frac{-i}{E_{ee}^2}g^{\mu\nu}\cdot(eQ_fJ_\nu)$

散射截面：$\sigma \propto |A|^2 \approx \alpha^2 Q_f^2/E_{ee}^2$

- 精细结构常数：

$$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c} = 0.007\,297\,352\,5664(17).$$



Richard Feynman(1918-1988)

Julian Schwinger (1918-1994)

统一：新物质观+新时空观

天上的
地下的

Gravity
$\sim G_N M^2/r^2$
(Newton 1687)

新时空观 →

General Relativity
(Einstein 1916)
$\sim\sqrt{g}\cdot G^{-1}R$?

磁：磁石
电：1785 Coulomb
静电扭秤
$\sim e^2/r^2$
1789 Galvani → 1800 Volta
青蛙腿　化学电池

1819
Oested
电流磁场

电磁学
Electro-Magnetic

伟大的时代
✓1867
Maxwell Equations
EM wave ＝光

✓1905 Einstein @ *C*
新时空观 → **Special Relativity**

✓1925 @ h
Quantum Mechanics
(新物质观:波粒2象性)

量子电动力学
QED U1
(1948)
正反物质
量子场论
规范对称性

基本粒子
（“最小时空结构”）
相互作用力学
及其统一

自然单位制Natural Units

- 物理能标单位制(千克/米/秒) vs 基本粒子物理:

量子力学 Quantum Mechanics + 相对论 Relativity → 量子场论 Quantum Field Theory

$h \sim 6.63\times10^{-34}\mathrm{J\cdot s}$ 　　 $c \sim 3\times10^{8}\ \mathrm{m\cdot s^{-1}}$ 　　 Natural Units

- 引入自然单位制: $[h] = [c] \equiv 1$

$v = x/t \rightarrow \quad [L] = [T]$ 时空一致

$E = \hbar\omega \rightarrow \quad [E] = [T]^{-1}$

$E = mc^2 \rightarrow \quad [E] = [M] = [\vec{p}]$

$[E] = [M] = [\vec{p}] = [T]^{-1} = [L]^{-1}$

$$\hbar c = 197.326\ 9788(12)\ \mathrm{MeV\ fm}$$

- $1\mathrm{eV}=1.6\times10^{-19}\mathrm{J}$, $1\mathrm{MeV}=10^{6}\mathrm{eV}$, $1\mathrm{GeV}=10^{3}\mathrm{MeV}$, $1\mathrm{TeV}=10^{3}\mathrm{GeV}$
- $m_e=0.511\mathrm{MeV}$, $m_p=1.0073\mathrm{u}=938.3\mathrm{MeV}$, $m_n=1.0087\mathrm{u}=939.6\mathrm{MeV}$
- 普适性 e.g. $[\vec{F}] = [m\vec{a}] = [\nabla U] = [M^2] \rightarrow$ 问: 电子电荷 $[e]=?$
  引力常数 $[G_N]=?$

物理过程能标与高能加速器

- 物理能标：

太阳表面(6000K) ~ 0.5 eV → 太阳核心(10^7K) ~ keV

热核聚变(氢弹) ~ 10 keV

电子质量m_e ~ 0.511 MeV → 质子质量m_p ~ 1 GeV

电弱真空破缺与Higgs ~ O(100) GeV

New Physics BSM ~ 1 -10 TeV ?

大统一GUT能标 ~ 10^{19} TeV !

- 粒子物理：

+ 探测“最小”时空结构

Heisenberg： $\lambda \sim h/E$

↓

带电粒子高能加速器

TeV accelerator & collider

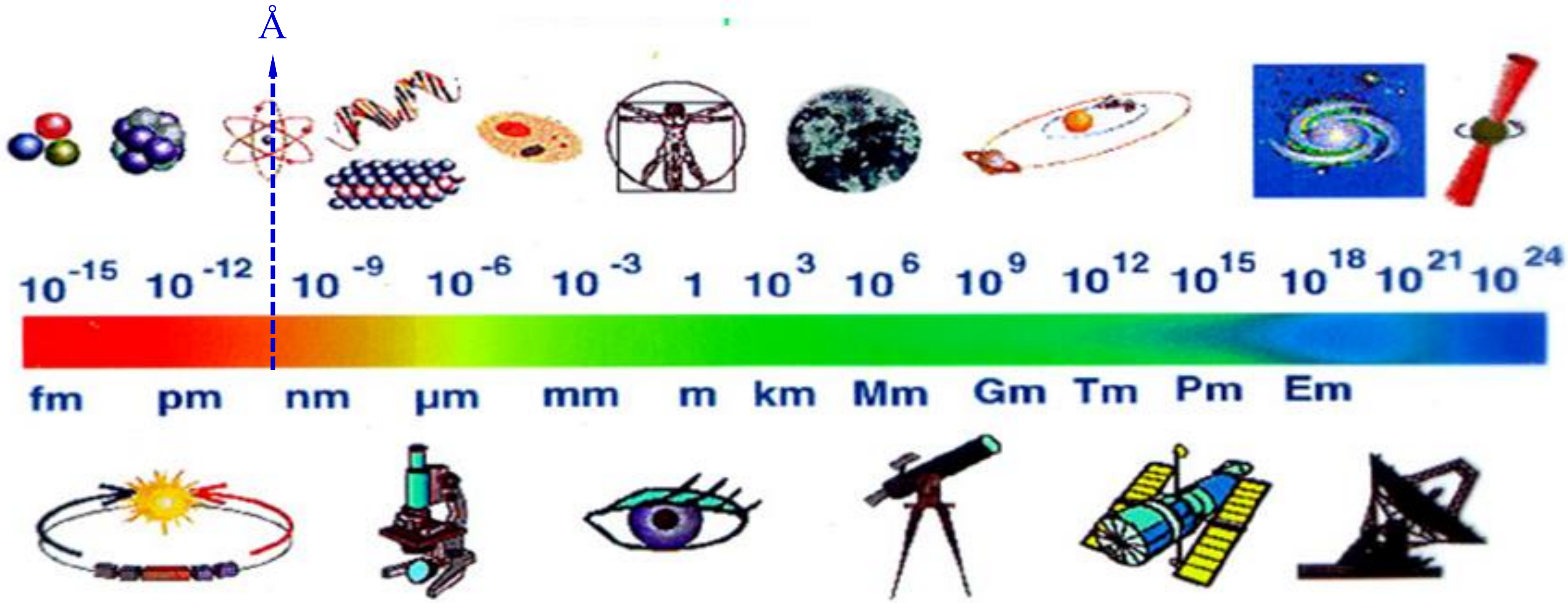
↑

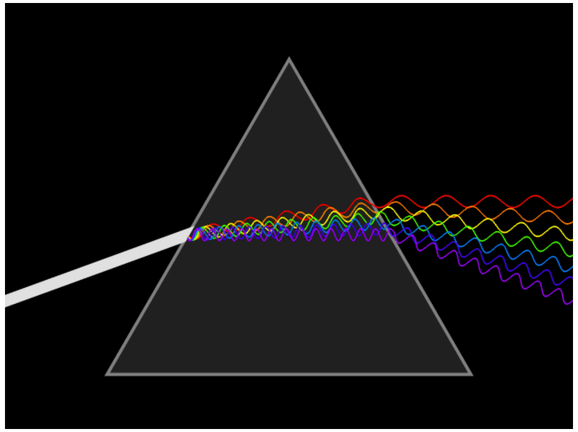
Einstein： $m = E/c^2$

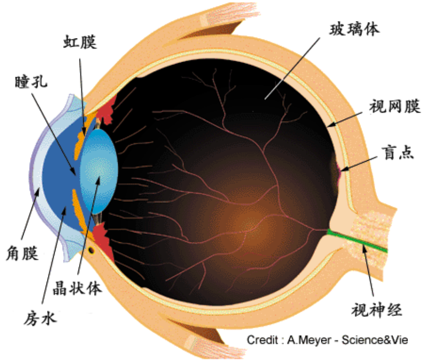
+ 产生大质量“重”新粒子

如何“看见”？

- 测量：尺子与物体必须相匹配，“光源”＋待测对象＋“眼睛”

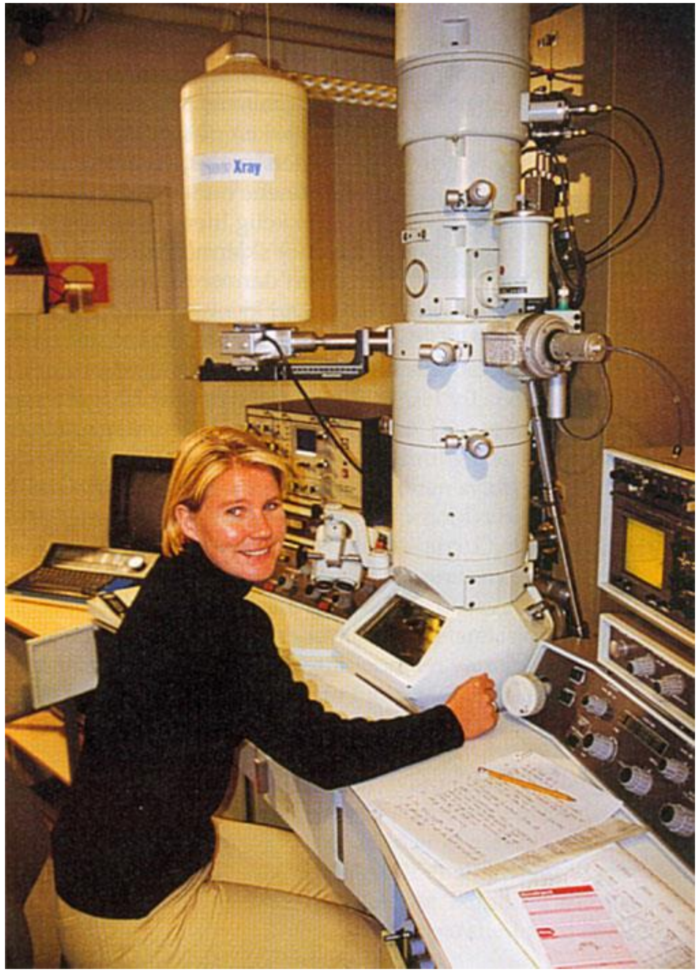






如何“看见”？

- 如何“看见”原子？ → 电子扫描隧道显微镜STM



+ “光源”：

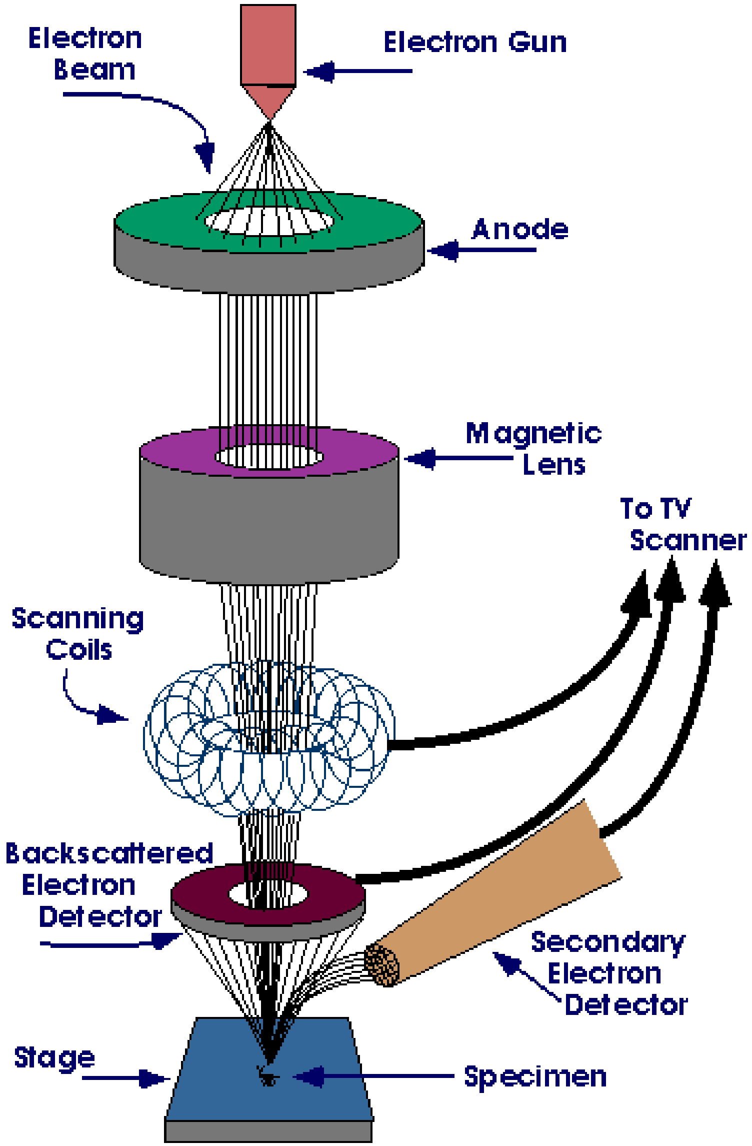
  电子加速电压~100kV

  物质波长λ ~ h/E ~ 0.005纳米

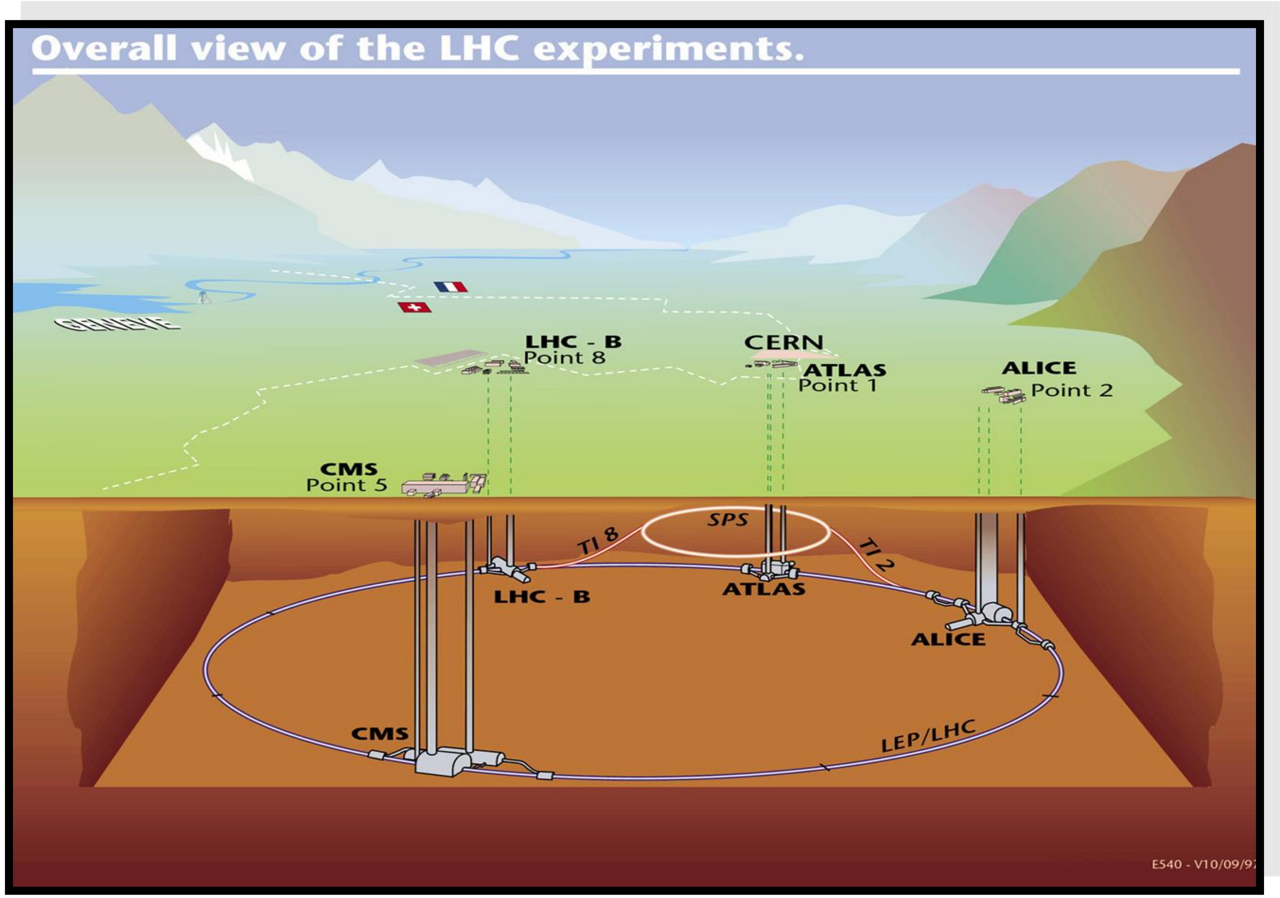
+ “眼睛”：

  背散射电子探测器, e.g. CCD

  二次散射电子探测器



欧洲核子中心Large Hadron Collider (LHC)对撞机

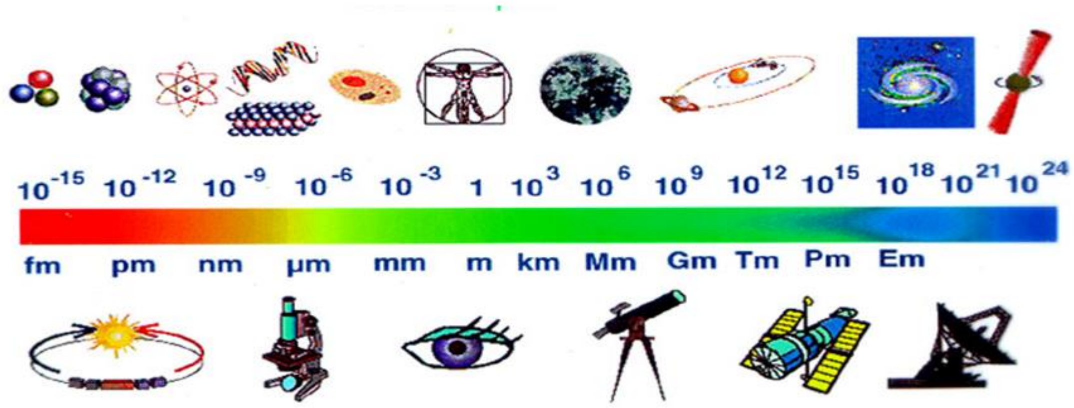


- 大型强子对撞机LHC
  + 实验设置：环形加速器周长~27 km，地下~140m
  + 高能前沿：7+7 TeV pp对撞 @ 2×10^{34} $cm^{-2}s^{-1}$

- pre-LHC era: Large Electron-positron collider (LEP 1989-2000)
  + 实验设置：占据LHC同一加速、存储、对撞环
  + 正负电子对撞：LEP e^+e^- 100+100GeV @ 10^{32} $cm^{-2}s^{-1}$

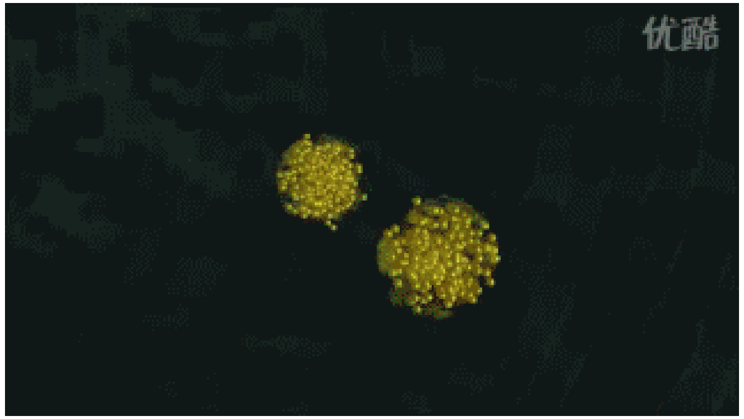
LHC之看见：“要有光!”

- “光源”：质子束流 $E_p = 7\text{TeV}$，波粒二象性，物质波探测时空结构

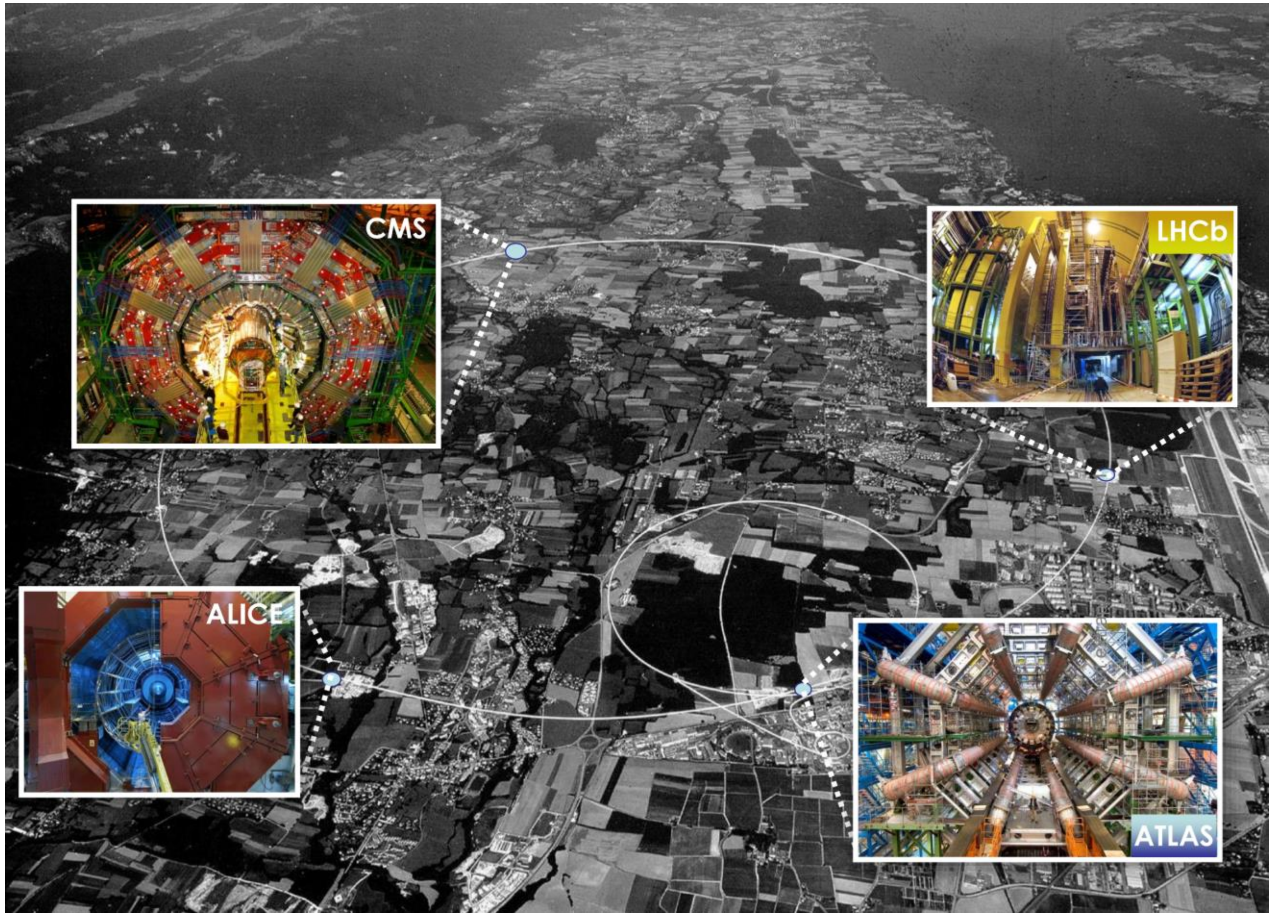


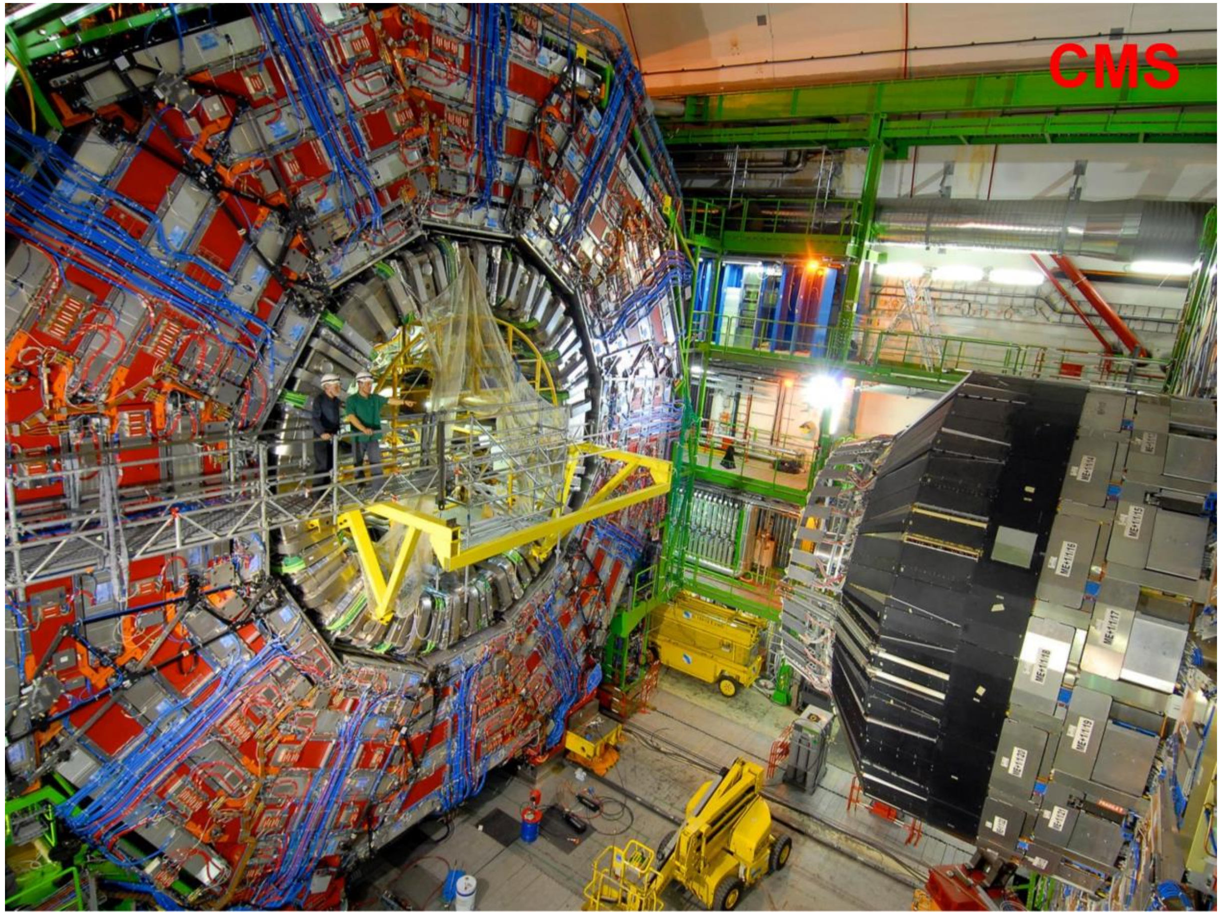
$$\lambda = hc/E \sim 197\text{MeV}\,fm\,/\,7\text{TeV}$$
$$\sim 1 \times 10^{-19}\,\text{m}$$

- “能量”：
  - 单质子能量 $E_p = 7\ \text{TeV} = 7 \times 10^{12}\ \text{eV} \times 1.6 \times 10^{-19}\ \text{J/eV} \sim 1 \times 10^{-6}\ \text{J}$
  - 瞬时束流亮度 $L_{ins} = 2\times10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
  - 束团功率 $W = E_p \times L_{ins} \sim 2\times10^{28}\ \text{J}\cdot\text{cm}^{-2}\text{s}^{-1}$



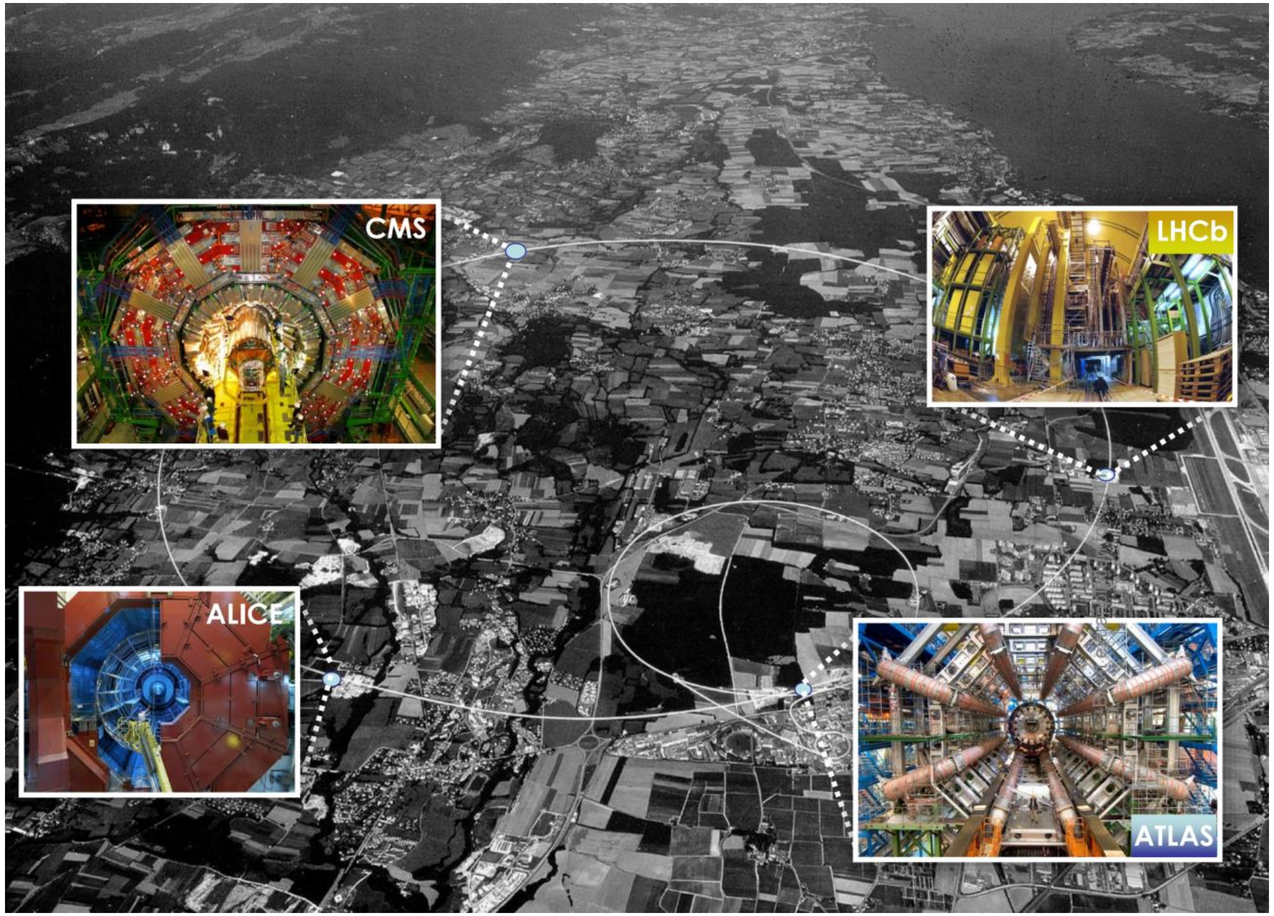
LHC之看见：“眼睛”

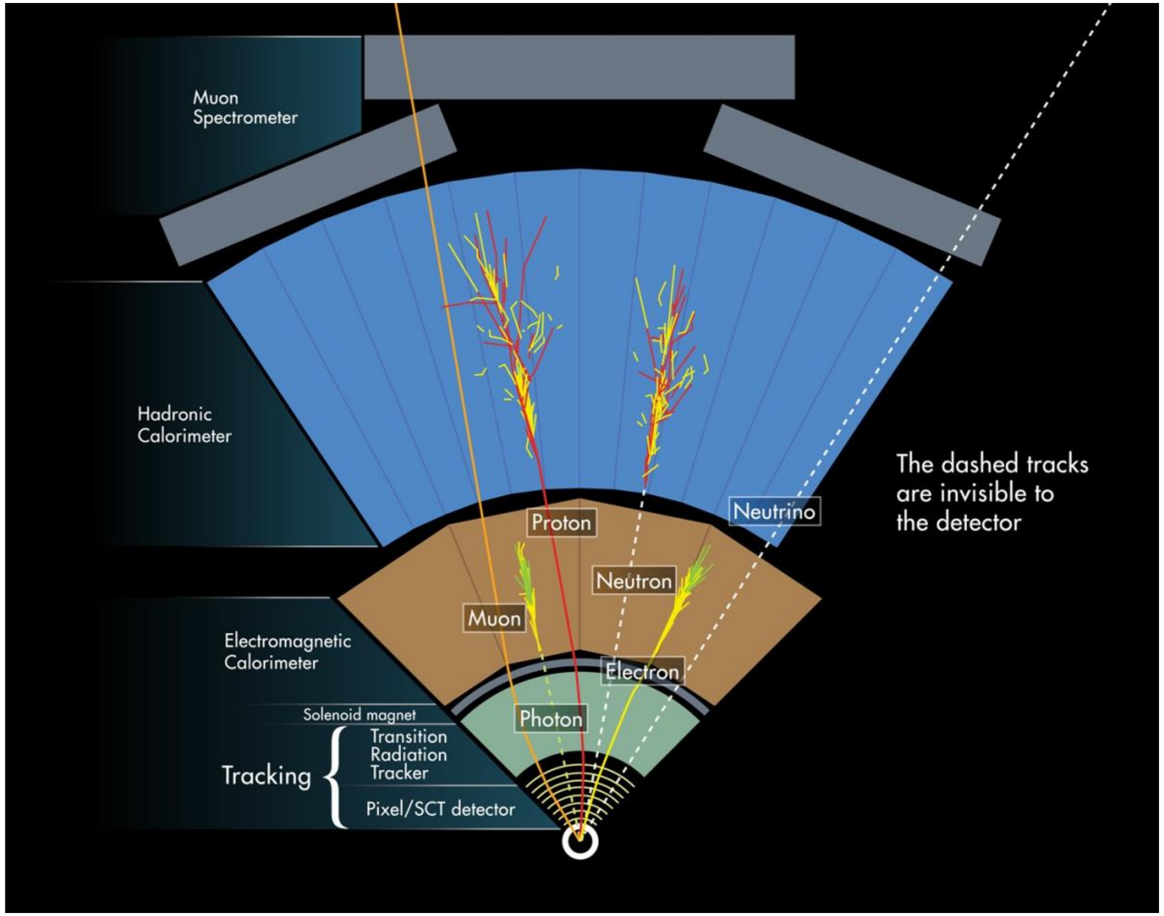




	全覆盖普适型探测系统	大科学装置国际合作
ATLAS	重量7000吨，长46m × 直径25m	~5500人，245研究单位，42国家
CMS	重量14000吨，长21m × 直径15m	~5500人，241研究单位，54国家

LHC之看见：“眼睛”





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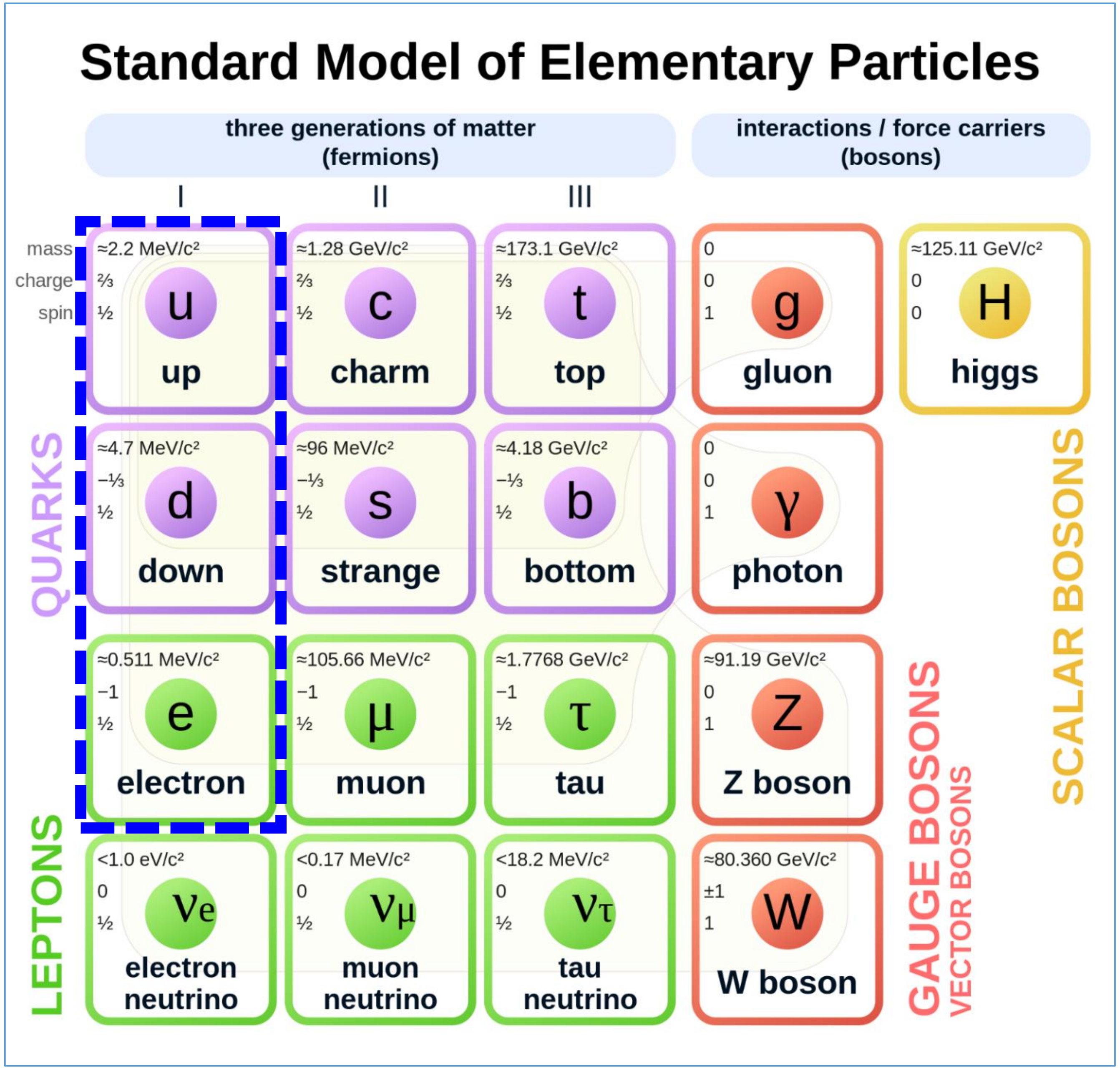
IIa. Standard Model(1-费米子)

基本粒子及其相互作用

基本粒子“元素表”



- 基本粒子：“点”粒子，无内部结构

  - 自旋J=1/2费米子：“两类三代”物质场

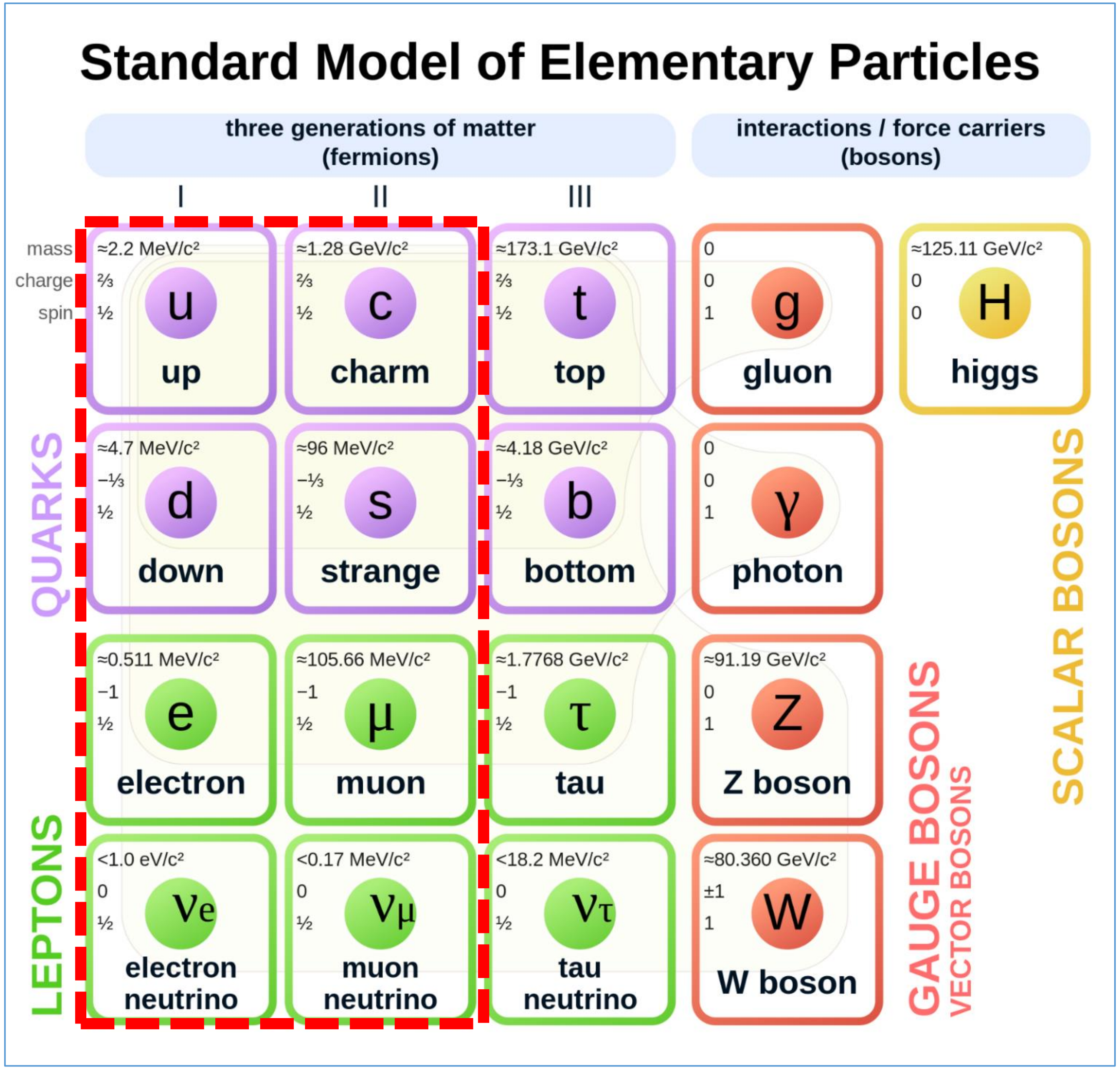
    夸克 Quark $\begin{pmatrix} u_i \\ d_i \end{pmatrix}$　　轻子 Lepton $\begin{pmatrix} e_i \\ \nu_i \end{pmatrix}$　　i=1,3

  - 自旋J=1规范场：相互作用传播子

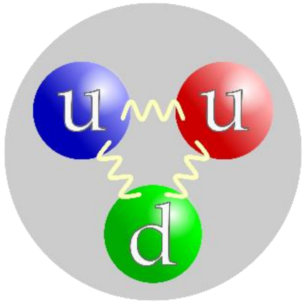
强相互作用 g_s	胶子gluon g
电磁相互作用 e	光子photon γ
弱相互作用 $\sin^2\theta_W$	弱矢量玻色子$W^\pm/Z^0$

  - 自旋J=0标量场：Higgs粒子

基本粒子“元素表”



- 自旋J=1/2费米子(三代):
  - 夸克Quark: 分数电荷 + 色禁闭



质子$p(uud)$

中子$n(udd)$

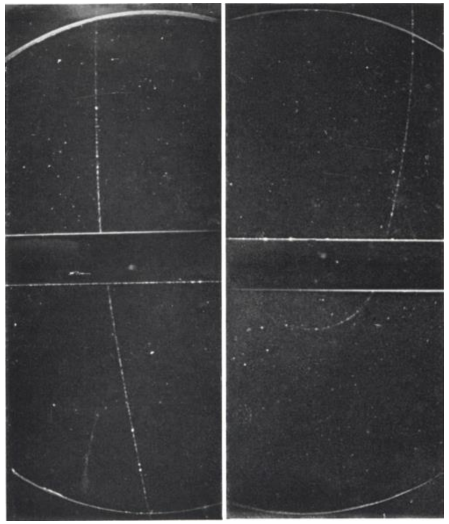
  - 轻子Lepton: “电子” + 中微子

$$n \to p + e^- + \bar{\nu}_e$$

轻子数$L_e/L_\mu/L_\tau$代间守恒

第二代轻子μ与轻子数$L_{e/\mu/\tau}$代间守恒

- 宇宙线观测：$\pi^+ \to \mu^+ + \nu_\mu$，“μ介子”海平面 ~ 10^4 /(米^2 分钟)

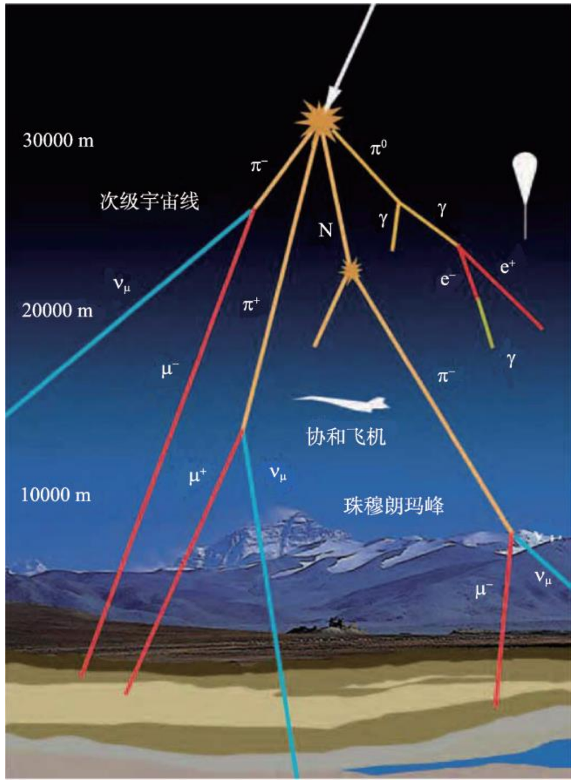


第二代轻子μ^-

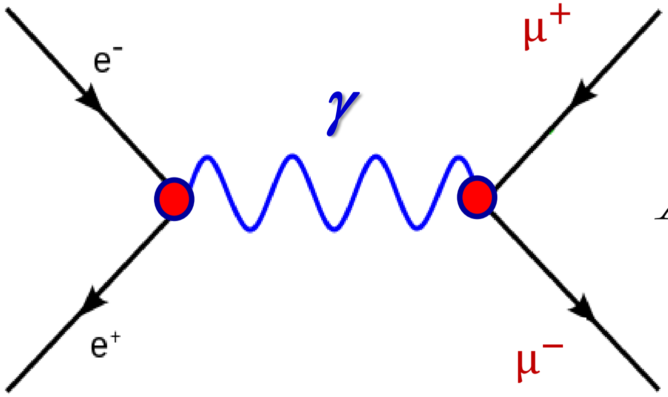
$Q_\mu = -e$，m_μ~105.66 MeV，L_e=0/L_μ=1/L_τ=0

C.D.Anderson, strange track @ balloon, 1936

J.C.Street & E.C.Stevenson, q/m ratio @ ground , 1937



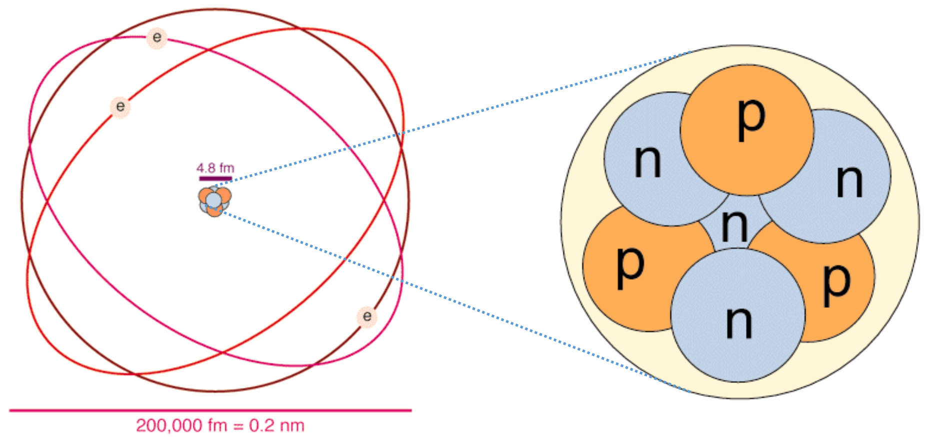
- 正负电子对撞机实验：

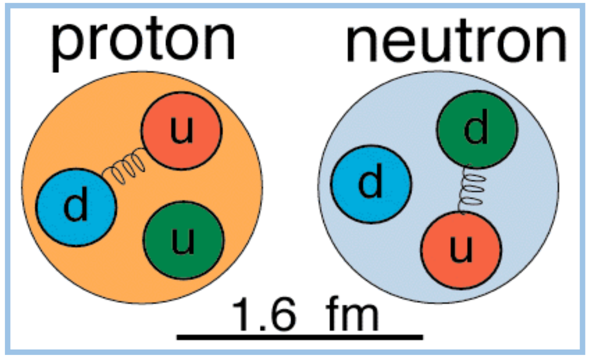


$$A \sim (e\, j_e) \cdot \frac{-i}{E_{ee}^2} \cdot (e Q_\mu\, j_\mu)$$

- ✓ 反应阈值：质能关系$E_{ee} > 2\, m_\mu$
- ✓ 产生截面：测量μ电荷 $\sigma \propto \alpha^2 Q_\mu^2 / E_{ee}^2$
- ✓ 初末态轻子数守恒 $\sum L_e = \sum L_\mu = 0$

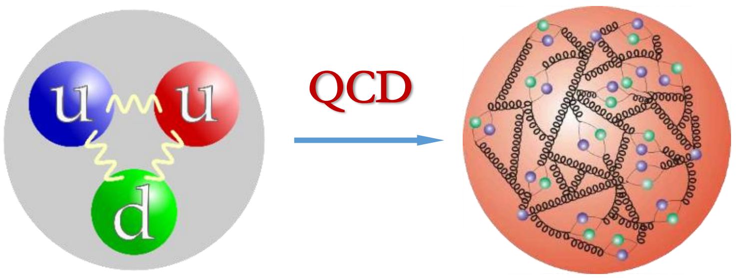
夸克quark与色禁闭Color confinement

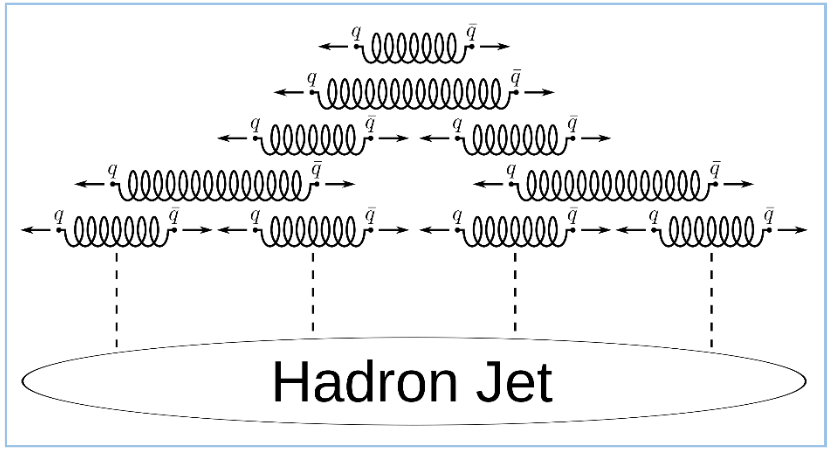




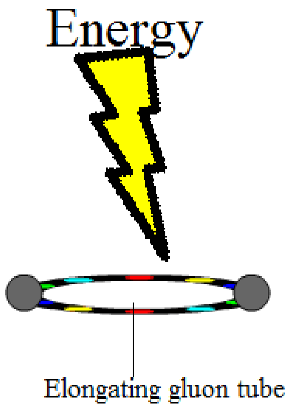
"Hadron Jail" :
no free quark,
gluon as color strain to
bond neutral hadrons

- 特征尺度： "力程" ~ 1 fm





- 特征能标： Λ_{QCD} ~ 200 MeV

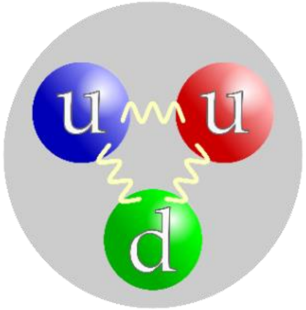


强相互作用：Quantum Chromodynamics (QCD)

- 基本假设：quark模型，自旋1/2，分数电荷，带“色”荷 → “色紧闭”不存在自由夸克

- 低能情况：O(1)MeV $\ll \Lambda_{QCD}$，非微扰 npQCD → 价夸克valence重子模型

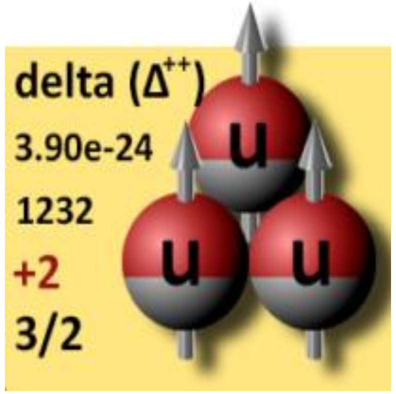
质子：J_p=1/2, m_p~ 1GeV，Q_p=+1



价夸克：$J_u = J_d = 1/2$，$m_u \sim m_d \sim 0$, Q_u=+2/3, Q_d=-1/3

→

双电荷重子：J_Δ=3/2，m_Δ ~ 1.2 GeV，Q_Δ=+2



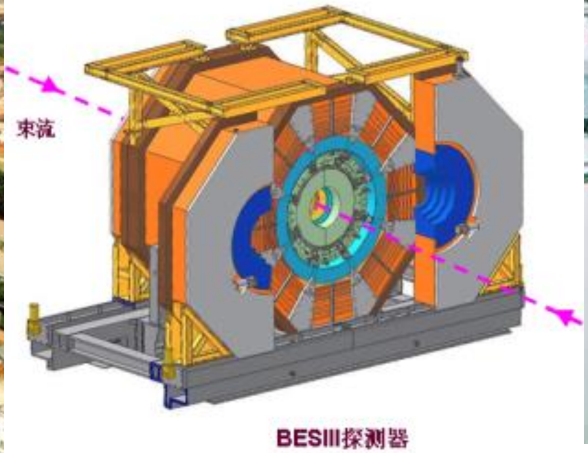
$$\Delta^{++} = \frac{1}{\sqrt{6}} \varepsilon^{\alpha\beta\gamma} \left| u_\alpha u_\beta u_\gamma \right\rangle$$

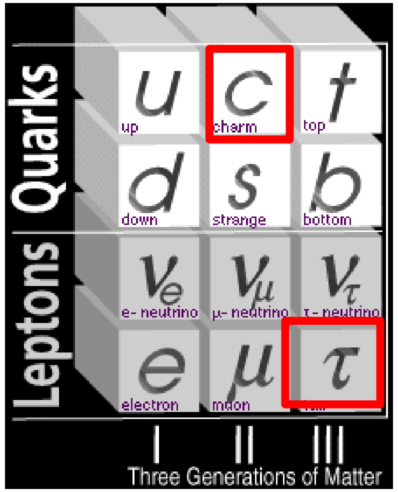
“三重色”自由度

- 高能情况：O(10)GeV $\gg \Lambda_{QCD}$，微扰 pQCD → 强子喷注jet模型
  - + 极端相对论情况下，轻夸克u/d/s质量可忽略 → 难以鉴别轻quark强子类型
  - + 在重核物质中，强子簇射能量损失形成jet喷注 → i.e. 强子jet探测器中行为可区别于e/γ电磁信号

北京正负电子对撞机BES强子物理研究

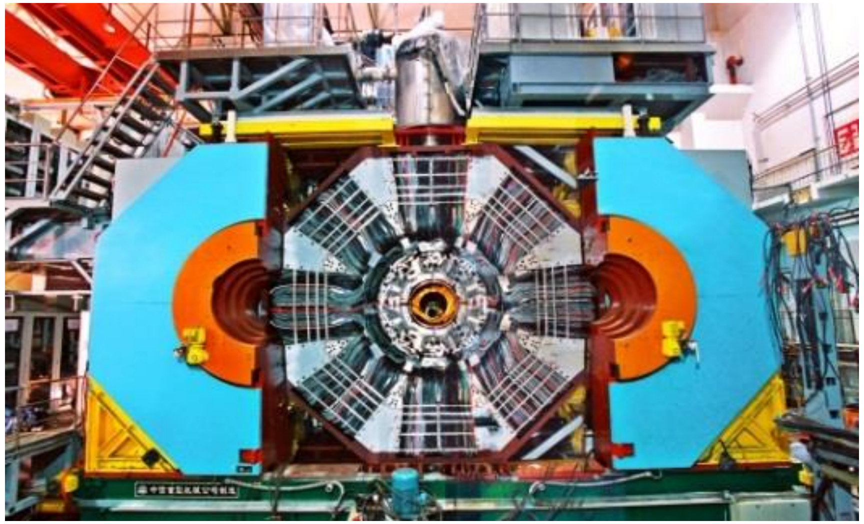
世界上唯一运行在τ-c能区e^+e^-对撞机!





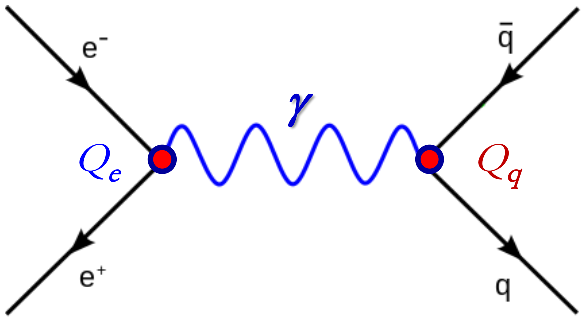
E_{beam} = 1.0-2.1 (2.3) GeV

$L_{BES} = 6.5\times 10^{32}\ cm^{-2}s^{-1}$ @ 3770

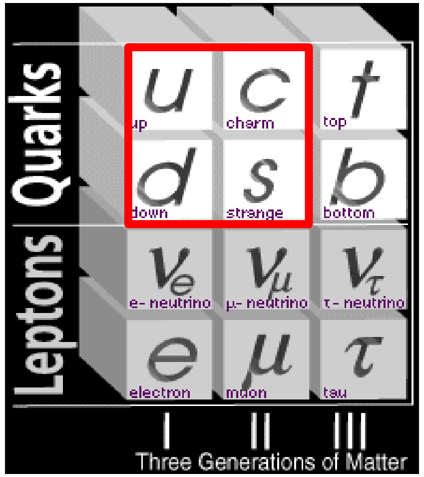


QCD实验检验(1)：夸克模型

- 北京谱仪BSE全强子末态过程：



夸克 *i*@BES	电荷	质量(GeV)
u/c	$+2/3$	$\sim 0\ /\ 1.28$
d/s	$-1/3$	$\sim 0\ /\ 0$

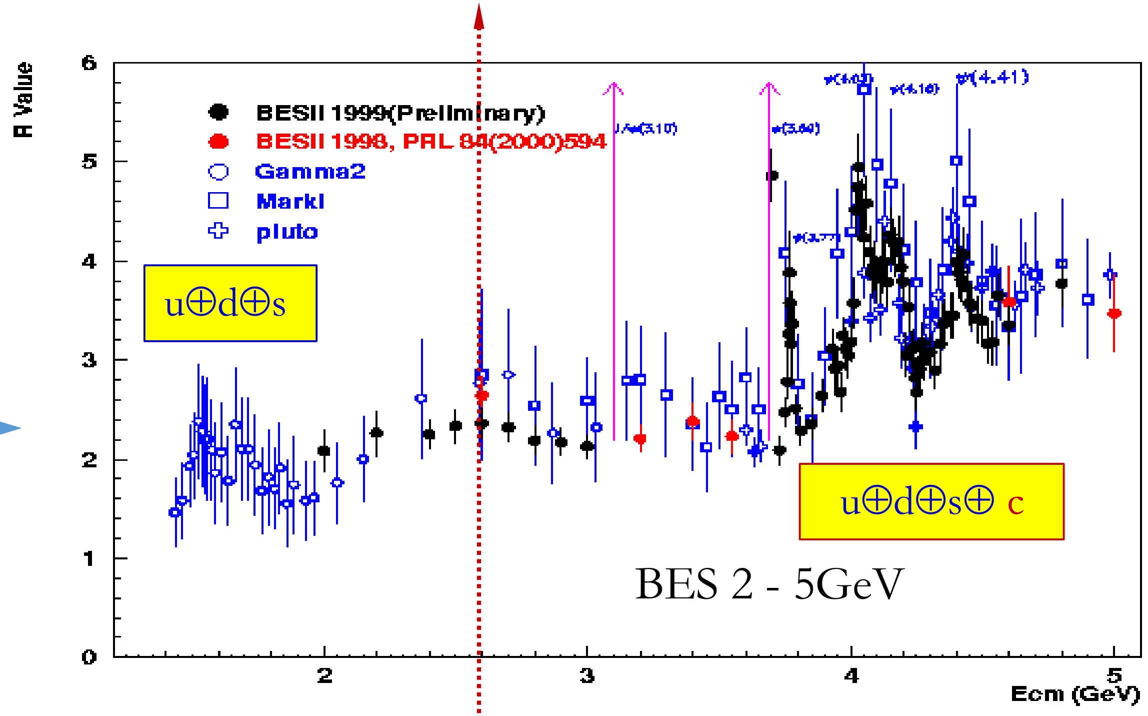


- 北京谱仪BSE强子R值实验测量：

$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

$$= \frac{\sum \sigma_i(e^+e^- \to q_i\bar{q}_i)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

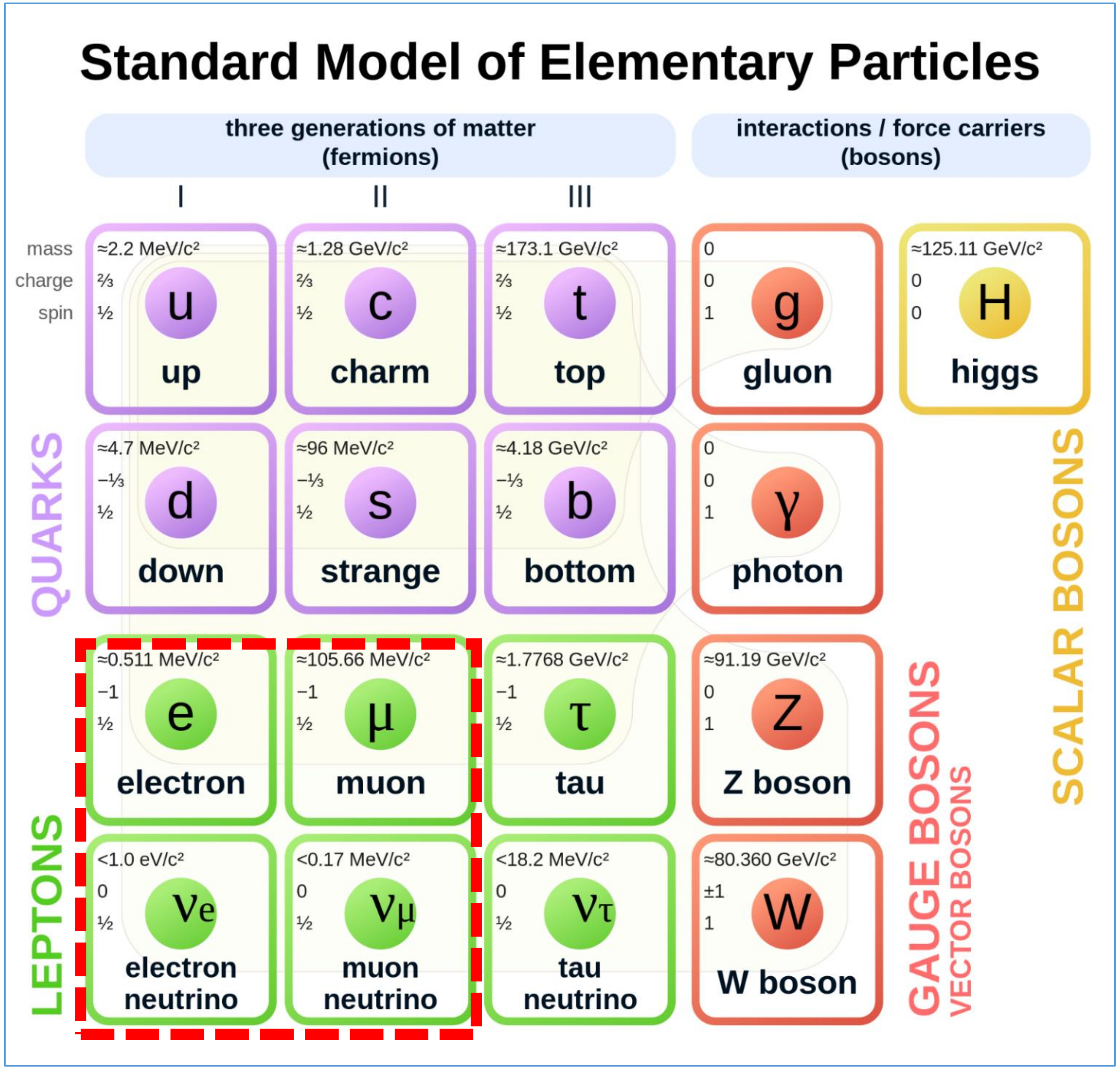
Colors and fractional charge of quarks



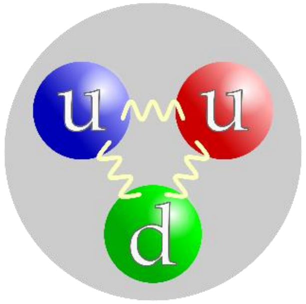
R ~ [(2/3)²+2×(1/3)²]×3 = 2

[2×(2/3)²+2×(1/3)²]×3 = 3

基本粒子“元素表”



- 自旋J=1/2费米子(三代)：
  - 夸克Quark: **分数电荷** + **色禁闭**



质子$p(uud)$

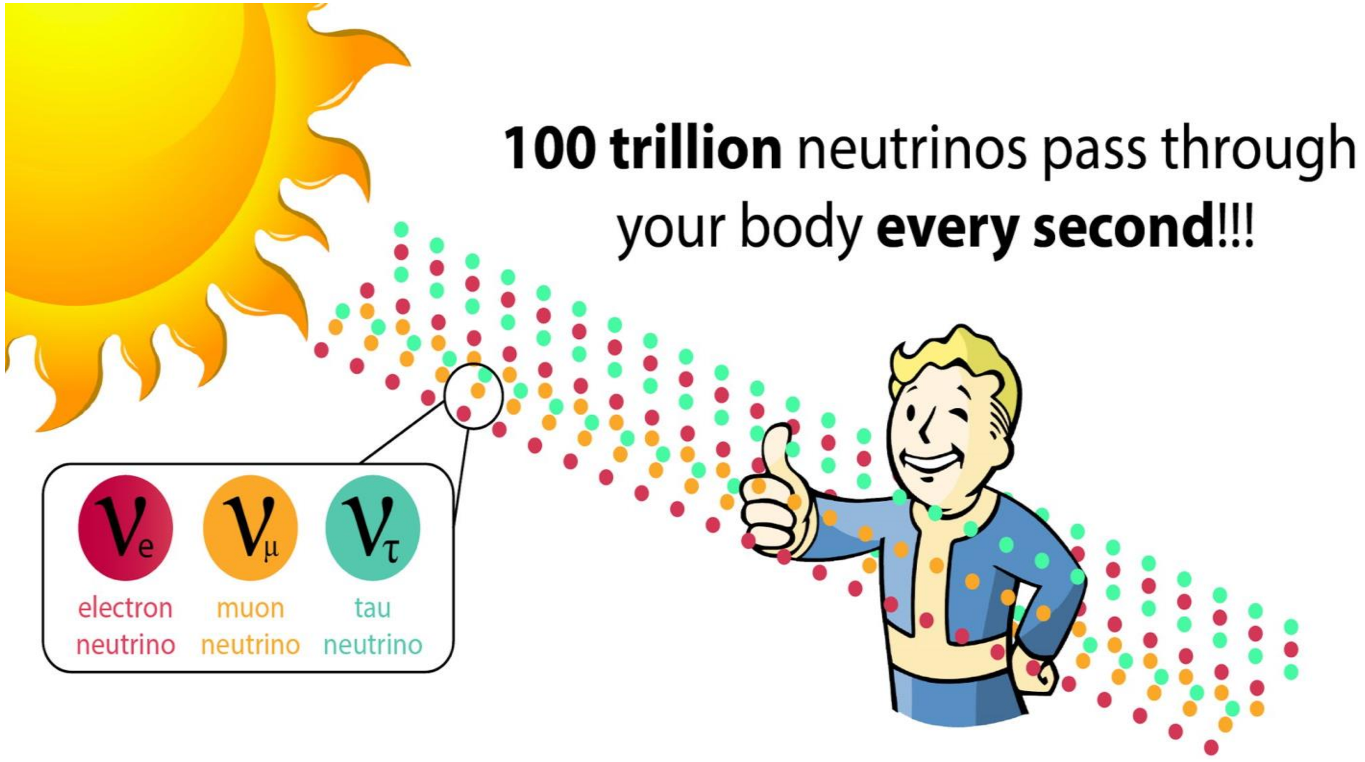
中子$n(udd)$

  - 轻子Lepton: “**电子**” + **中微子**

$$n \to p + e^{-} + \bar{\nu}_e$$

轻子数$L_e/L_\mu/L_\tau$代间守恒

- 中微子：电中性$Q_\nu = 0$，极小质量$m_\nu \neq 0$，大量存在，仅与物质发生极其微弱的反应



- Your body will stop 1 neutrino passing through in a lifetime!

- Human body contains ~20 mg of Potassium ^{40}K, which is emitting 340 million neutrinos per day!

$$^{40}_{19}K \rightarrow ^{40}_{20}Ca + \beta^- + \bar{\nu}_e$$

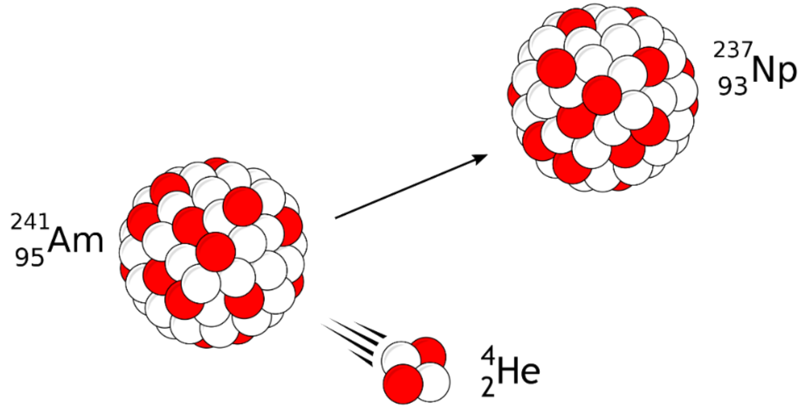
自然丰度：0.01171(1)%

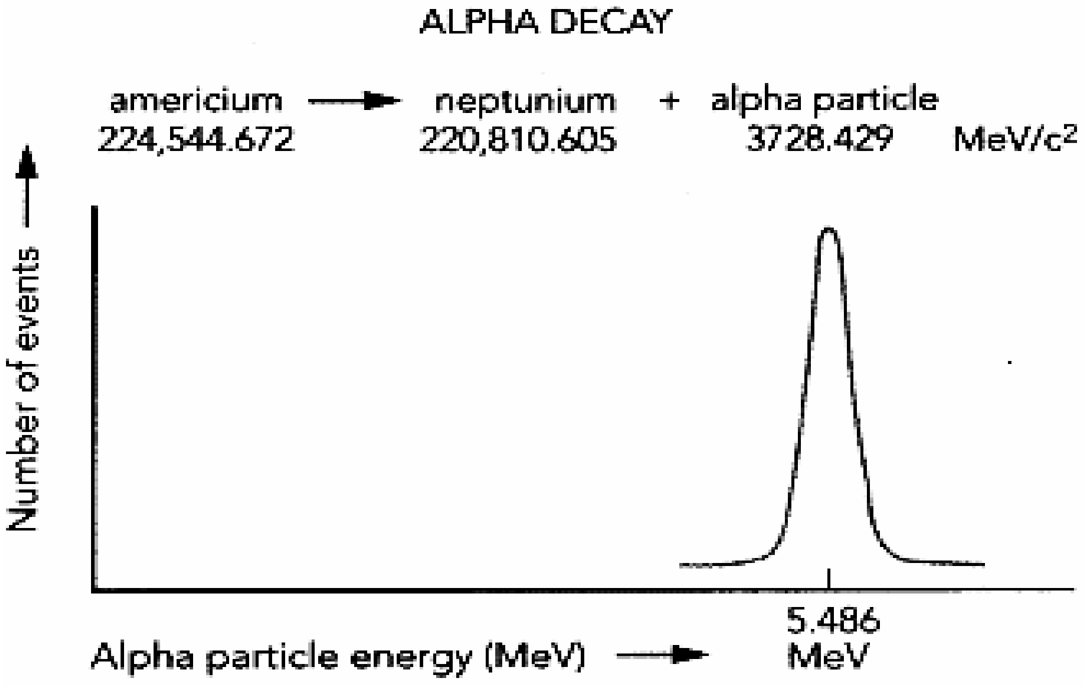
半衰期：1.251(3)×10^9 y

放射性α衰变

➢ 人工同位素镅Am-镎Np放射性α衰变：

$$^{241}_{95}Am \rightarrow ^{237}_{93}Np + ^{4}_{2}He$$





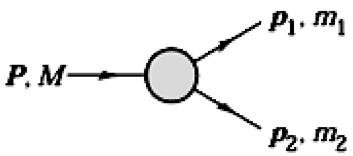


Figure 38.1: Definitions of variables for two-body decays.

38.4.2. ***Two-body decays:***

In the rest frame of a particle of mass M, decaying into 2 particles labeled 1 and 2,

$$E_1 = \frac{M^2 - m_2^2 + m_1^2}{2M}, \qquad (38.15)$$

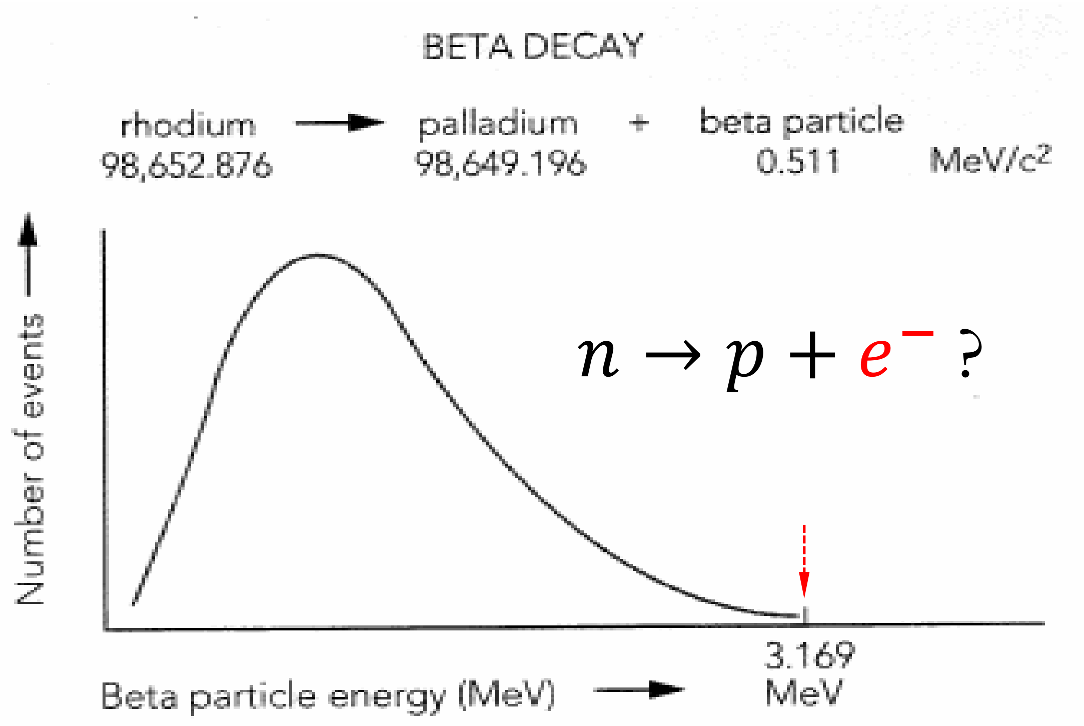
$$|\mathbf{p}_1| = |\mathbf{p}_2|$$

镅^{241}Am两体α衰变，末态氦核^{4}He出射动能谱单峰结构，可精确测量。

放射性β衰变

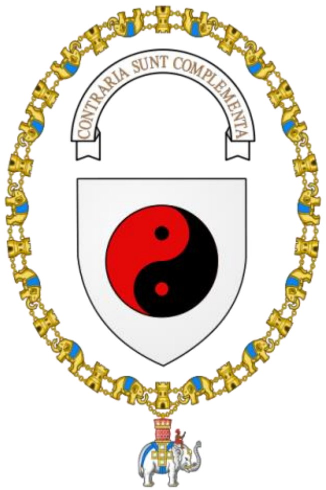
- 1913-1930: 铑Rh-钯Pd β decay → “可探测末态” 出射电子continuous spectrum of E ?!

$$^{107}_{45}Rh \rightarrow ^{107}_{46}Pd + e^{-}$$



$$n \rightarrow p + e^{-}\ ?$$

(1885-1962)



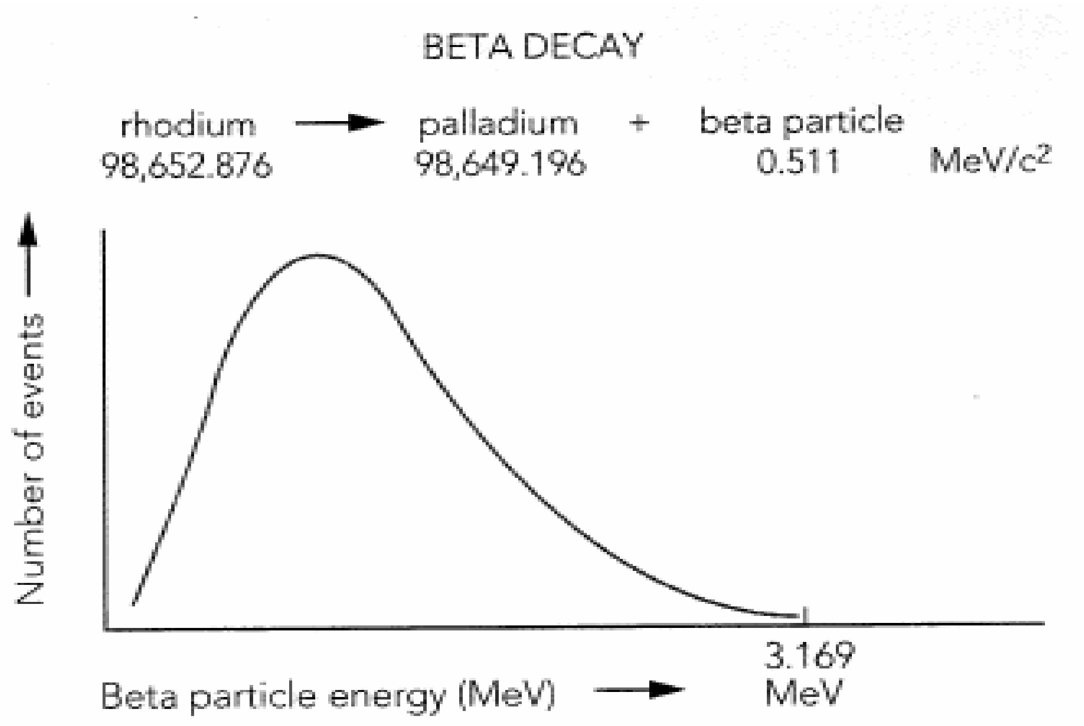
“E or P not conserved in Sub-Atom World ? ”

(Niels Bohr)

放射性β衰变

- 1913-1930: 铑Rh-钯Pd β decay → “可探测末态”出射电子continuous spectrum of E ?!

$$^{107}_{45}Rh \rightarrow {}^{107}_{46}Pd + e^-$$




(1900-1958)

Wolfgang E Pauli (1930)

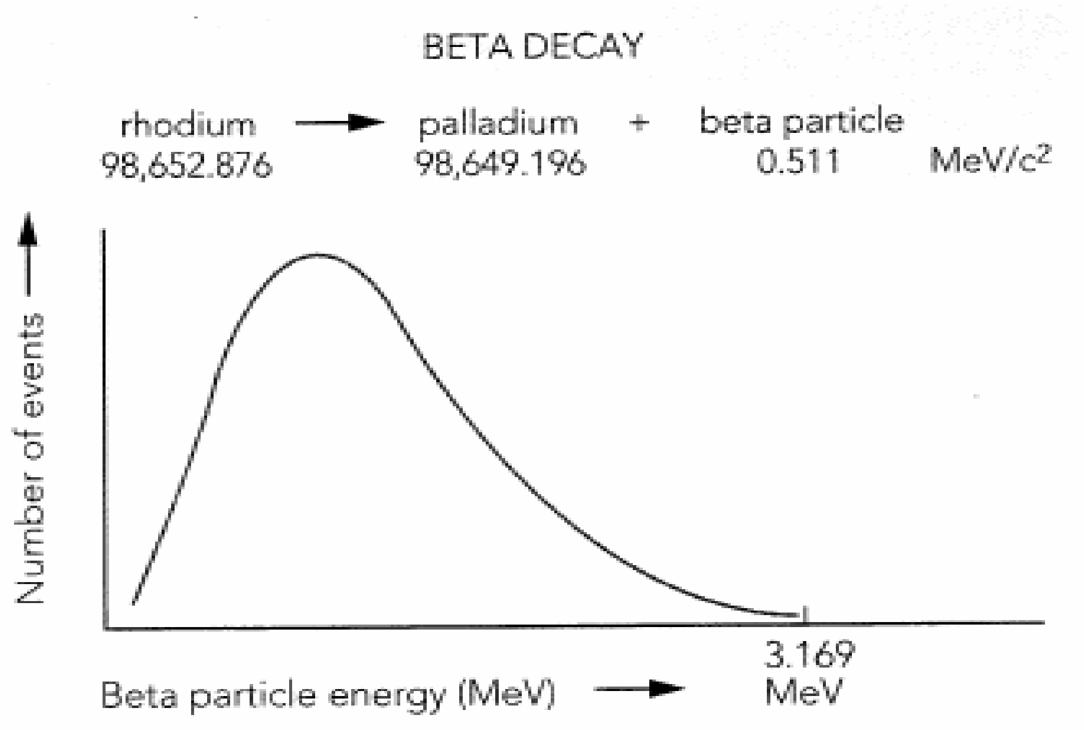
$$n \rightarrow p + e^- + \mathrm{X}\,?$$

- Hypothesis of Neutrino (1930):
  - ✓ Massless, $m_\nu = \mathbf{0}$
  - ✓ No or very weak interaction → undetectable

放射性β衰变

- 1913-1930: 铑Rh-钯Pd β decay → “可探测末态”出射电子continuous spectrum of E ?!

$$^{107}_{45}Rh \rightarrow {}^{107}_{46}Pd + e^-$$



(1900-1958)

"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do."

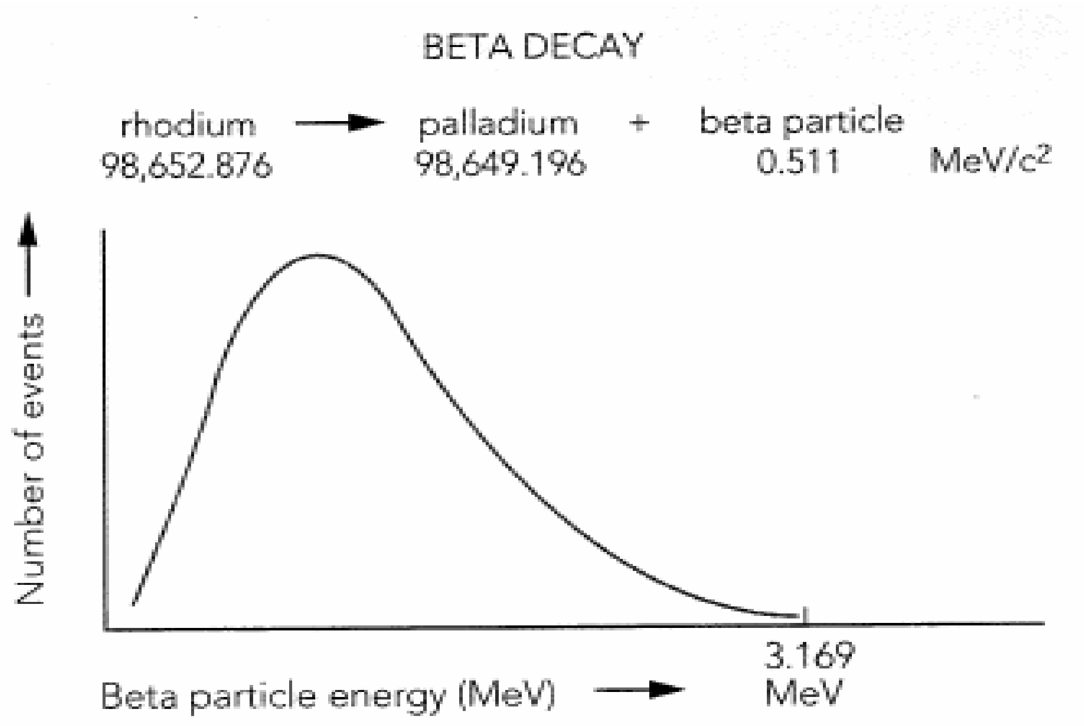
- Hypothesis of Neutrino (1930):

$$n \rightarrow p + e^- + \bar{\nu}_e$$

中微子neutrino

- 1913-1930: 铑Rh-钯Pd β decay → "可探测末态"出射电子continuous spectrum of E ?!

$$^{107}_{45}Rh \rightarrow {}^{107}_{46}Pd + e^-$$



(1900-1958)

"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do."

- Reines-Cowan反应堆中微子实验 (1956):

$$\bar{\nu}_e + p \rightarrow n + e^+$$

To Pauli: "We are happy to inform you that we have definitively detected neutrinos."

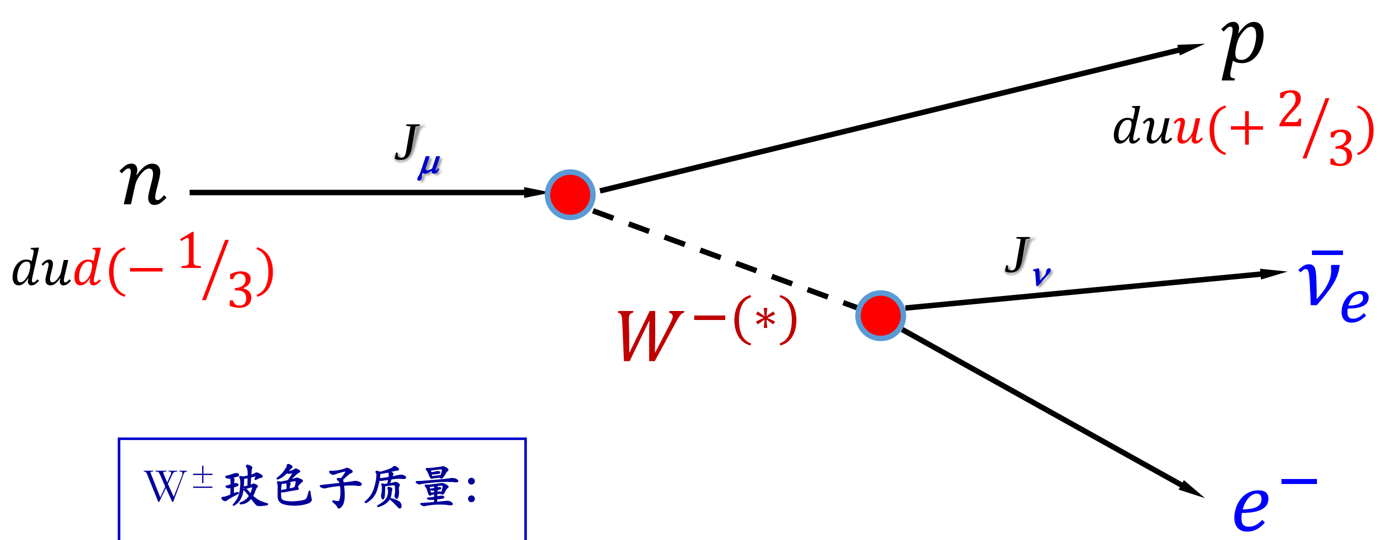
电弱相互作用(1): Electro-Weak弱荷电流

规范理论：SU(2)不变

$$\Psi \rightarrow \Psi e^{-ig\vec{\tau}\cdot\vec{\theta}\,(x)}$$

➢ 放射性核素 β-衰变：矢量玻色子$W^{\pm}$ -规范场 传播带弱带电流相互作用

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$



$W^{\pm}$玻色子质量：
M_W

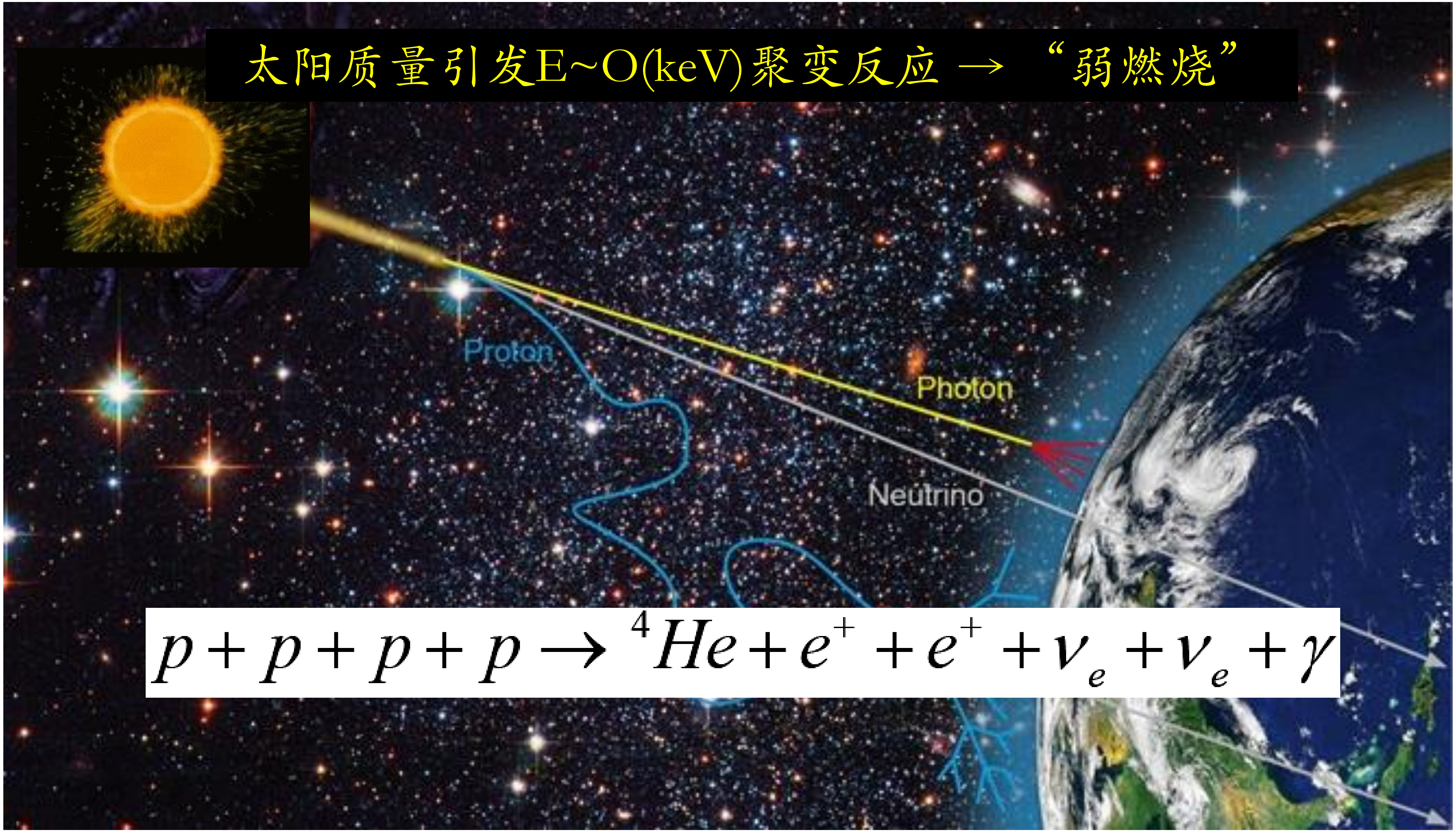
中微子末态弱过程：散射振幅

$$A \sim (gJ_\mu)\cdot\frac{-i}{E^2-M_W^2}g^{\mu\nu}\cdot(gJ_\nu)$$

- ✓ 弱-电耦合强度相当 $g \approx e$
- ✓ 弱作用传播子 $M_W \sim 80$GeV
- ✓ 低能衰变 $E=(m_n - m_p) \sim O(1)$MeV
- ✓ 低能 $E \ll M_W$反应被M_W极大压低

太阳燃烧“标准模型”

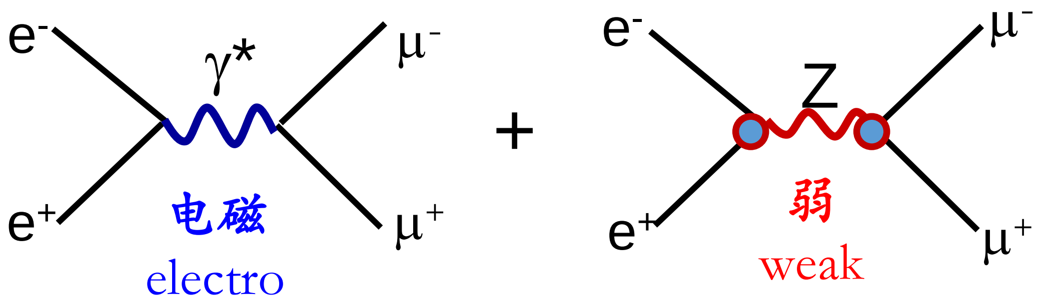
太阳质量引发E~O(keV)聚变反应 → “弱燃烧”



$$p+p+p+p \rightarrow {}^4He+e^++e^++\nu_e+\nu_e+\gamma$$

电弱相互作用(2): Electro-Weak弱中性流

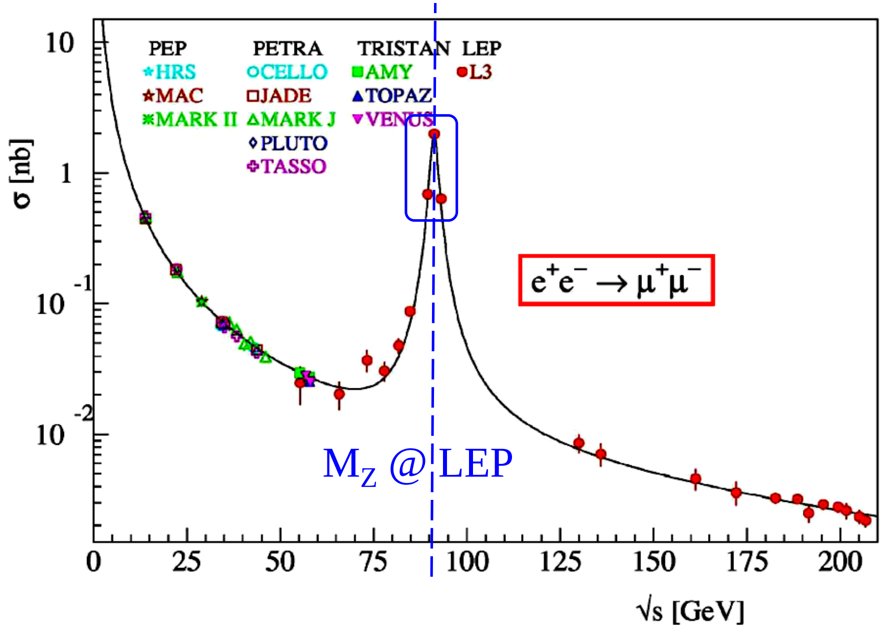
矢量玻色子Z^0 -规范场 传播带弱中性流相互作用



Z^0玻色子质量:

M_Z

- 1980年代LEP 对撞机$e^+e^- \to \mu^+\mu^-$能量扫描Z-pole标准测量



- 对撞实验反应截面 $\sigma \propto \dfrac{1}{E^2 - M^2 + i\Gamma \cdot M}$
- Breit-Wigner共振峰 @ $M_Z \sim 90$GeV
- 低能~1GeV区域，电弱反应强度比 $1 : 10^{-4}$

电弱相互作用统一

天上的
地下的

Gravity
$\sim G_N M^2/r^2$
(Newton 1687)

新时空观

General Relativity
(Einstein 1916)
$\sim\sqrt{g}\cdot G^{-1}R$?

磁： 磁石
电： 1785 Coulomb
静电扭秤
$\sim e^2/r^2$
1789 1800
Galvani → Volta
青蛙腿 化学电池

1819
Oested
电流磁场

电磁学
Electro-Magnetic

伟大的时代
✓1867
Maxwell Equations
EM wave ＝光

✓1905 Einstein @ *C*
新时空观 → **Special Relativity**

✓1925 @ h
Quantum Mechanics
(新物质观:波粒2象性)

量子电动力学
QED U1
(1948)
正反物质
量子场论
规范对称性

弱作用
Weak SU2
(1958)
eg 太阳反应 4p→α+2e+2ν

Great Achievement

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

@ 100GeV

W/Z/γ
mass ?

强作用
Strong SU3
(1930)
eg 核子聚合作用

$SU_c(3)$

基本粒子
（“最小时空结构”）
相互作用力学
及其统一