# 太阳的奥秘：
# W玻色子、中微子与质量起源

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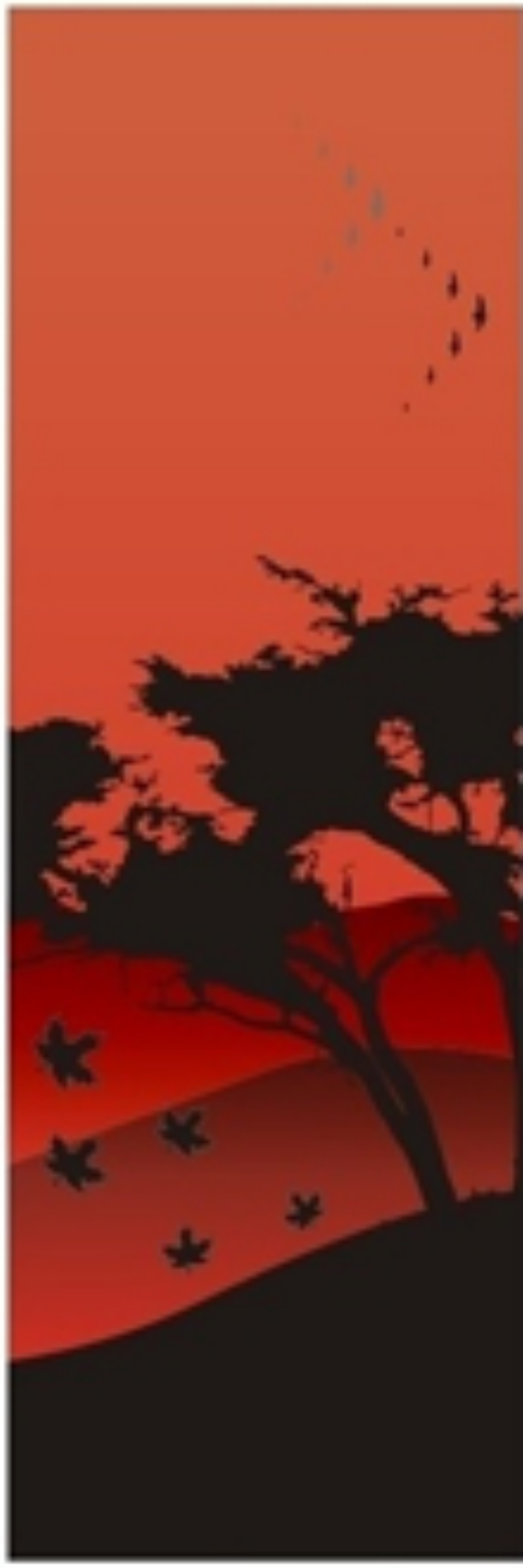
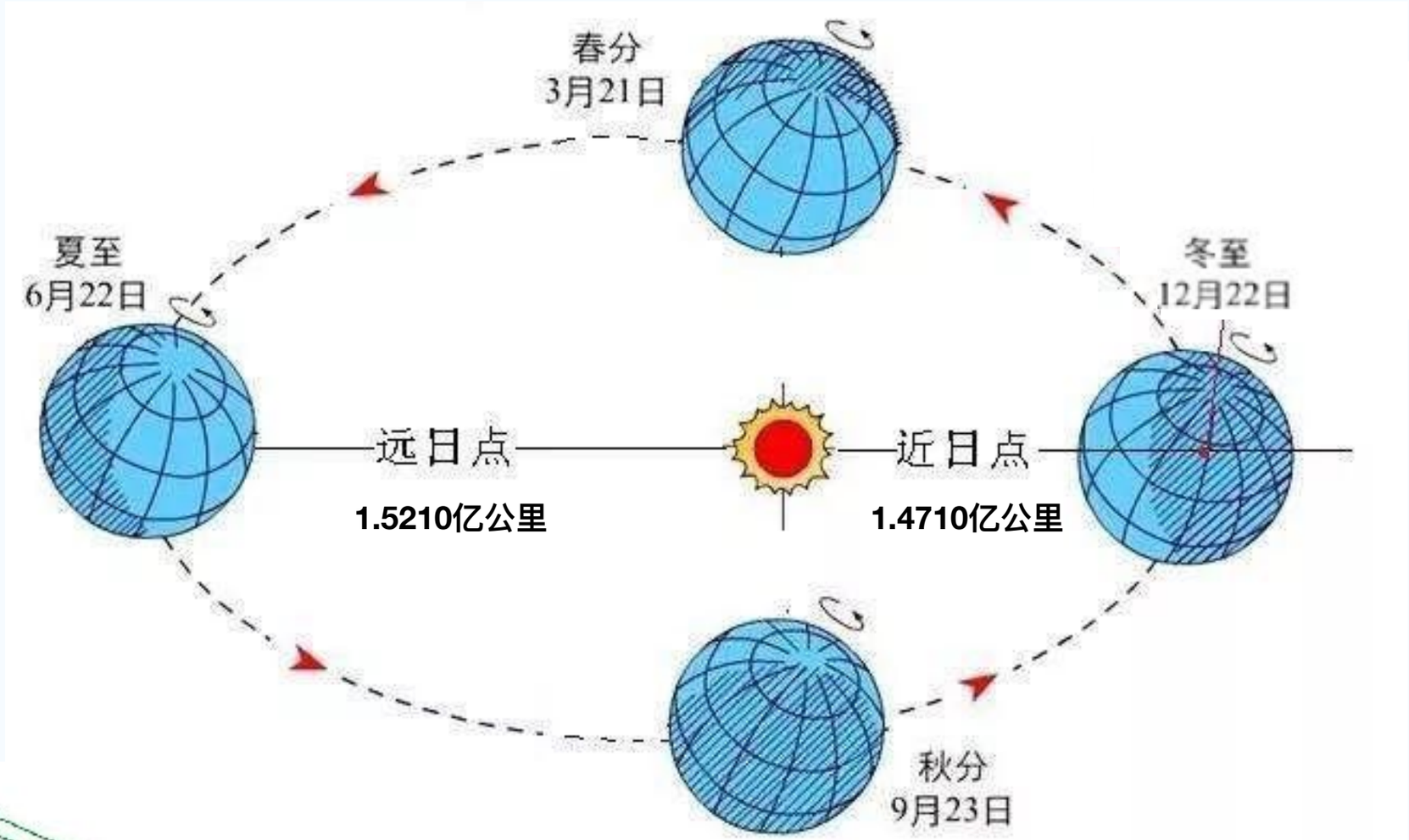
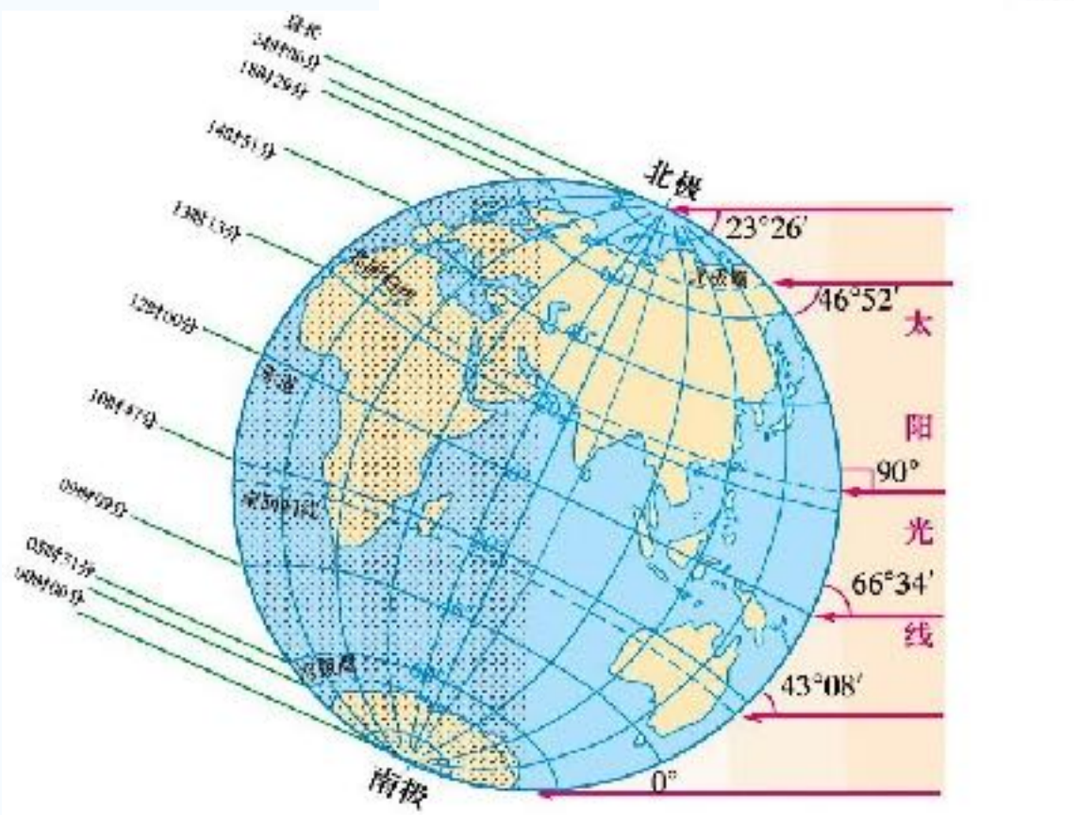
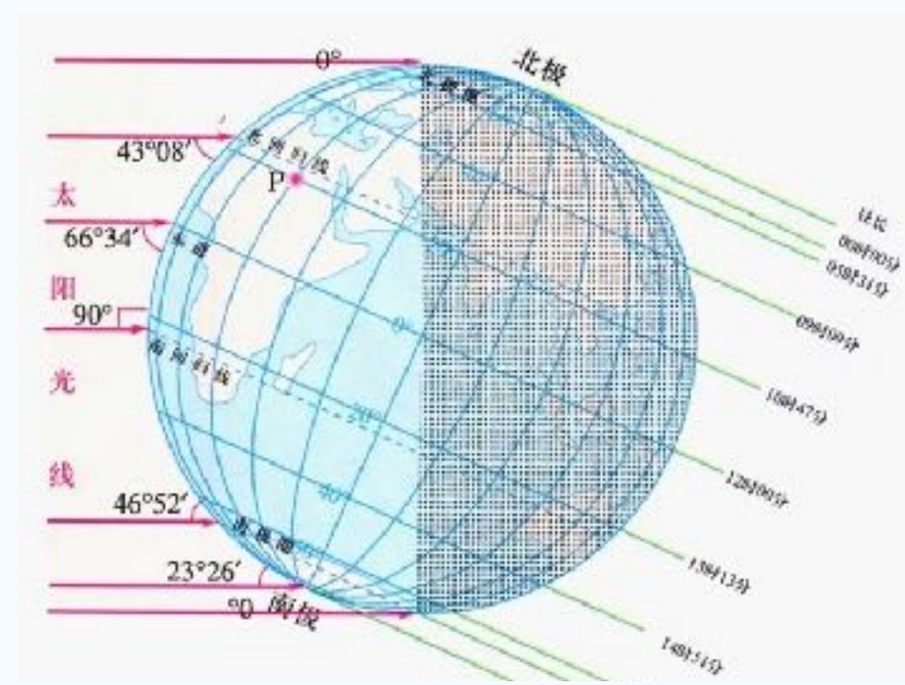
UCAS物院青年教师线上论坛 （2025年11月16日）

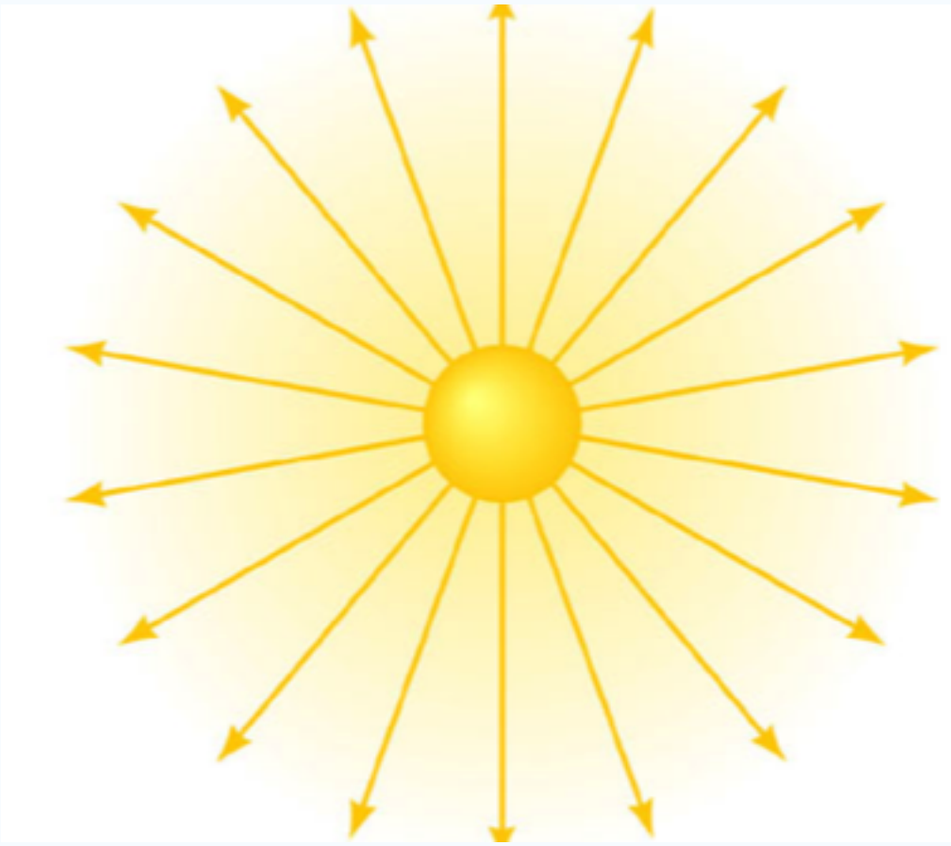


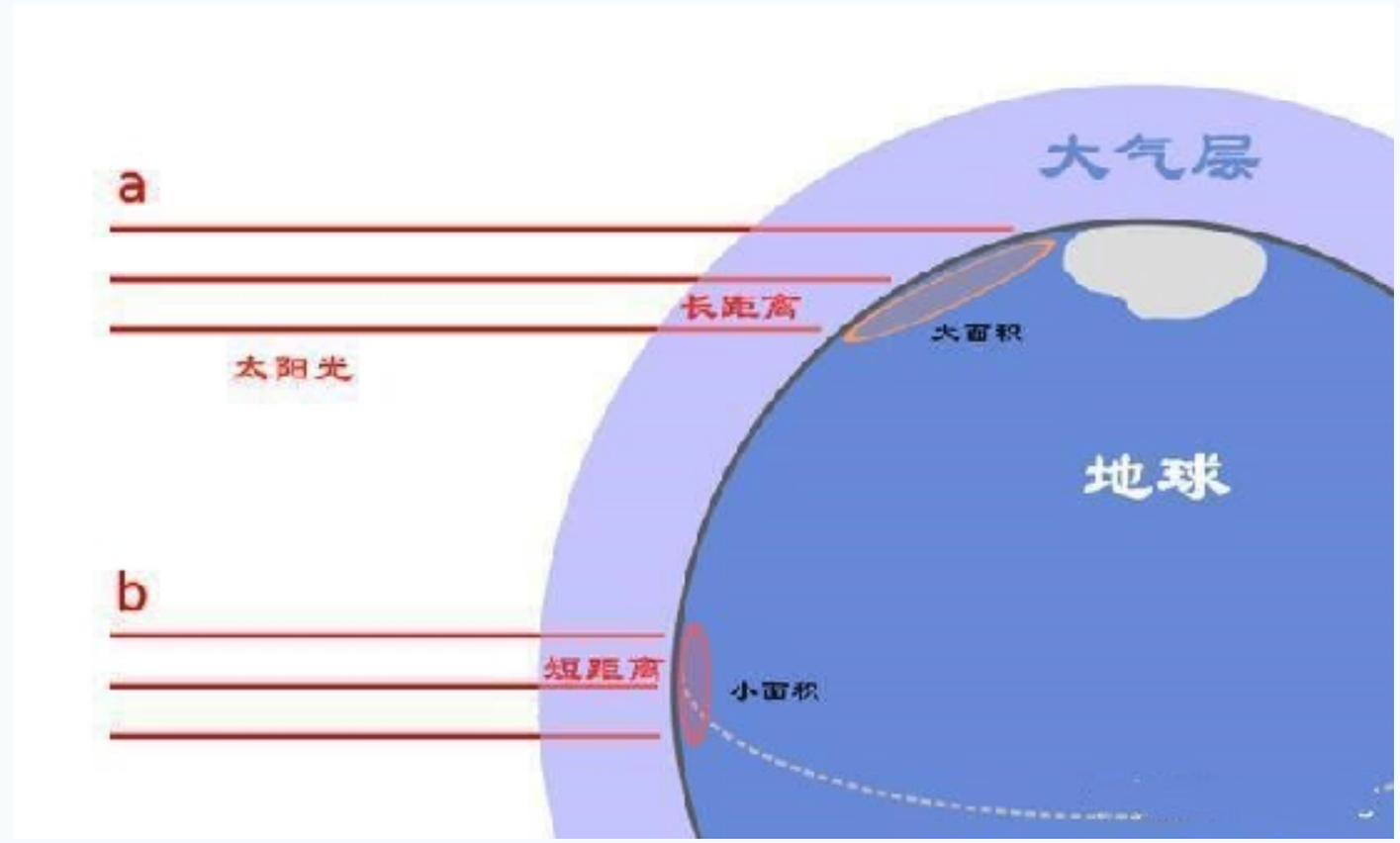

春分
3月21日
夏至
6月22日
冬至
12月22日
远日点
1.5210亿公里
近日点
1.4710亿公里
秋分
9月23日


北极
23°26′
46°52′
太
阳
90°
光
66°34′
线
43°08′
南极
0°

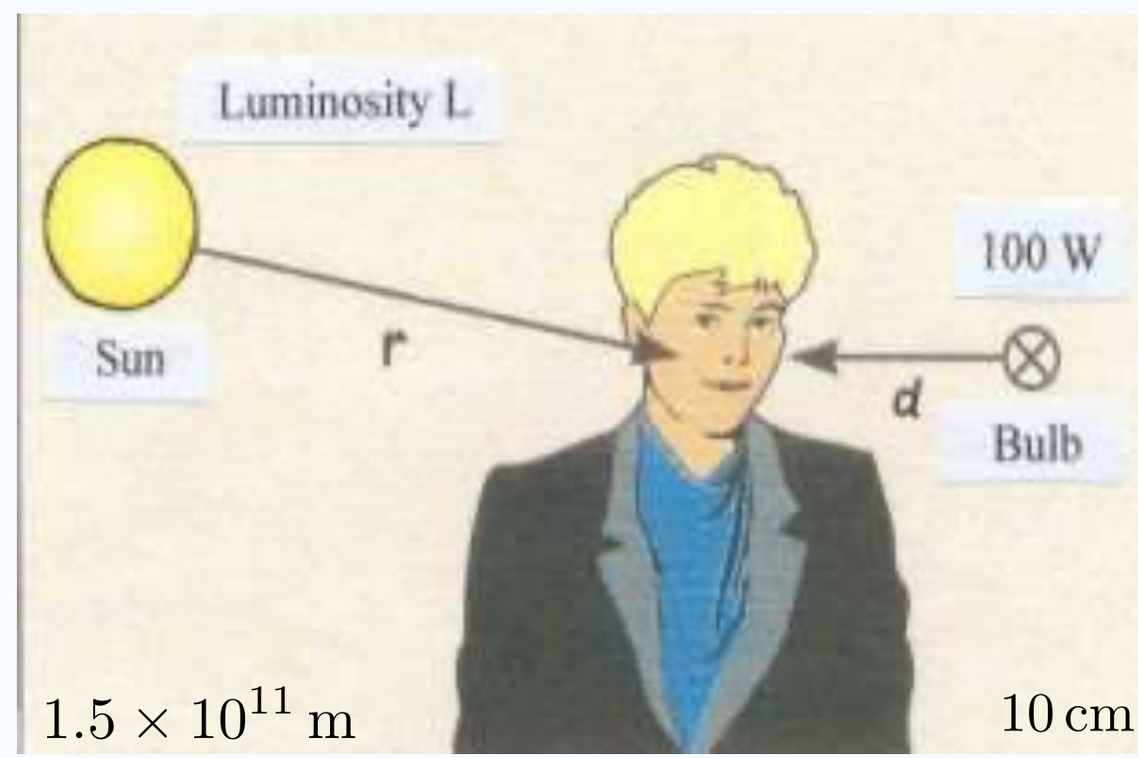

0°
北极
43°08′
P
太
66°34′
阳
90°
光
线
46°52′
23°26′
°0
南极

# 太阳的光照度

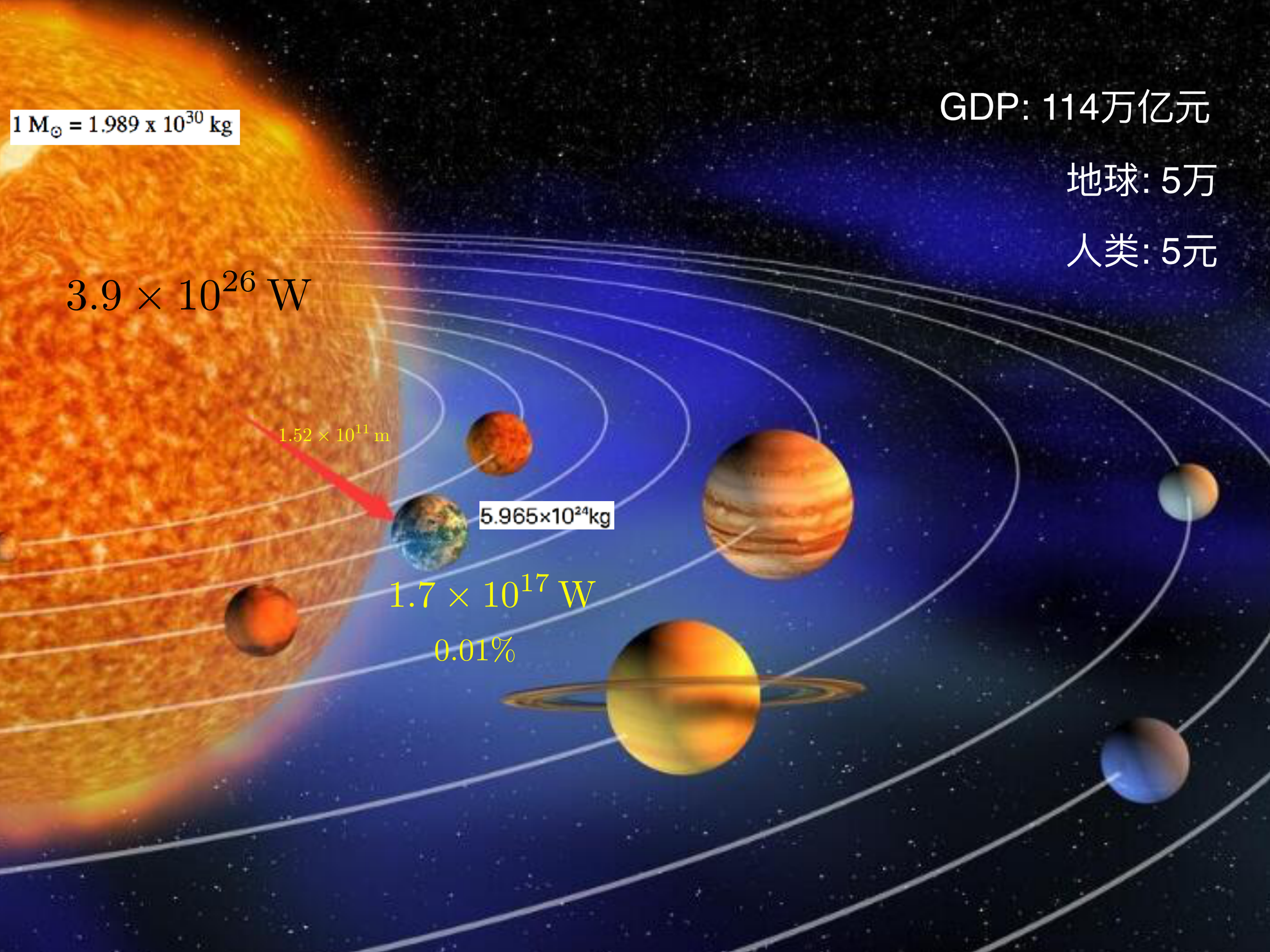





$$\text{光照度} = \frac{\text{光度 (W, J/s)}}{4\pi d^2\ (\mathrm{m}^2)}$$



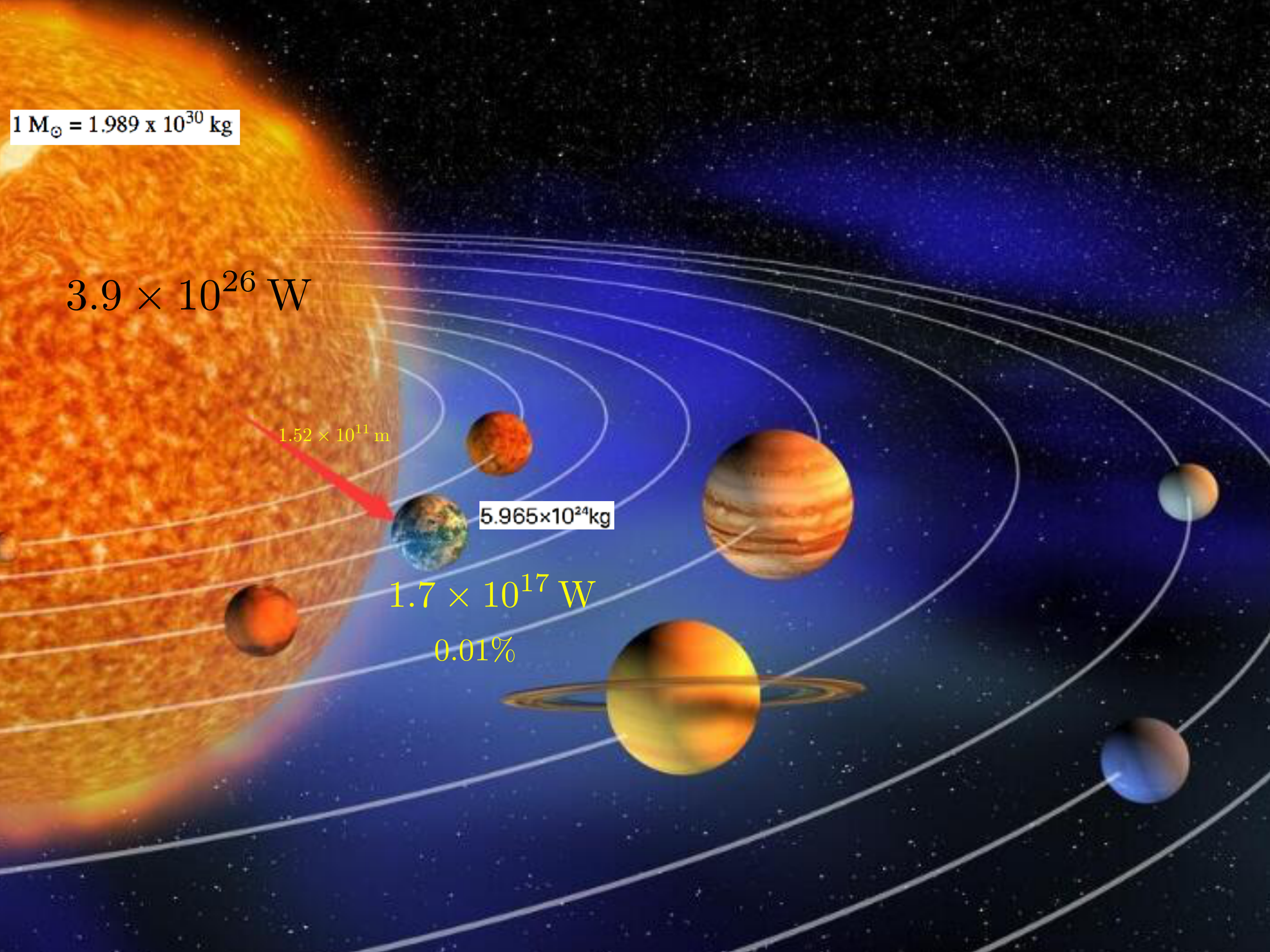

太阳光度/功率 = $3.9 \times 10^{26}$ W



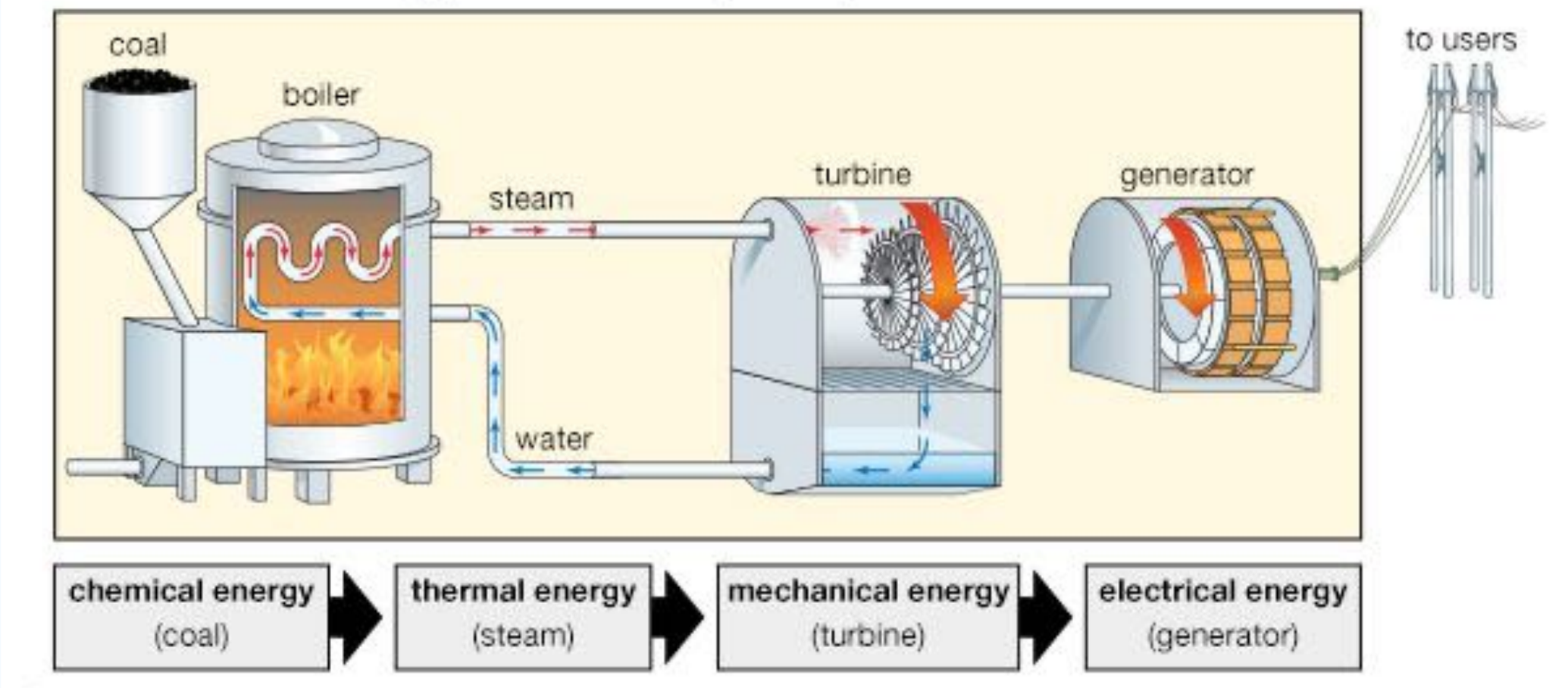

GDP: 114万亿元

地球: 5万

人类: 5元


1 M$_\odot$ = 1.989 x 10$^{30}$ kg
$3.9 \times 10^{26}$ W
$1.52 \times 10^{11}$ m
5.965×10$^{24}$kg
$1.7 \times 10^{17}$ W
0.01%

# 太阳的能量的来源?




化学反应产生光和热（每克煤产生30 kJ能量）

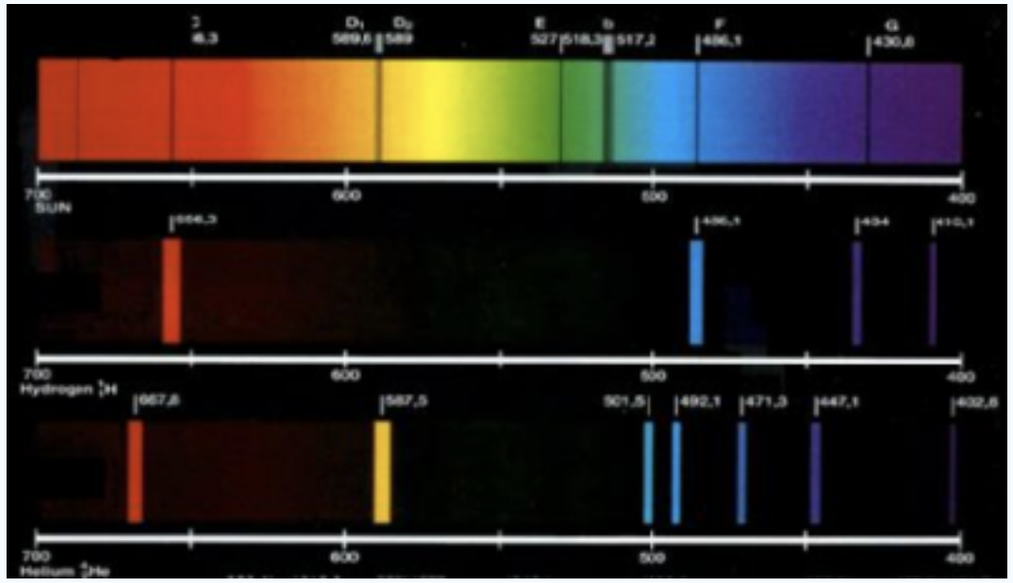
$$C + O_2 = CO_2 + 13.6\ eV$$

$$1\mathrm{eV} = 1.6 \times 10^{-19}\mathrm{J}$$

太阳由10^30千克煤组成

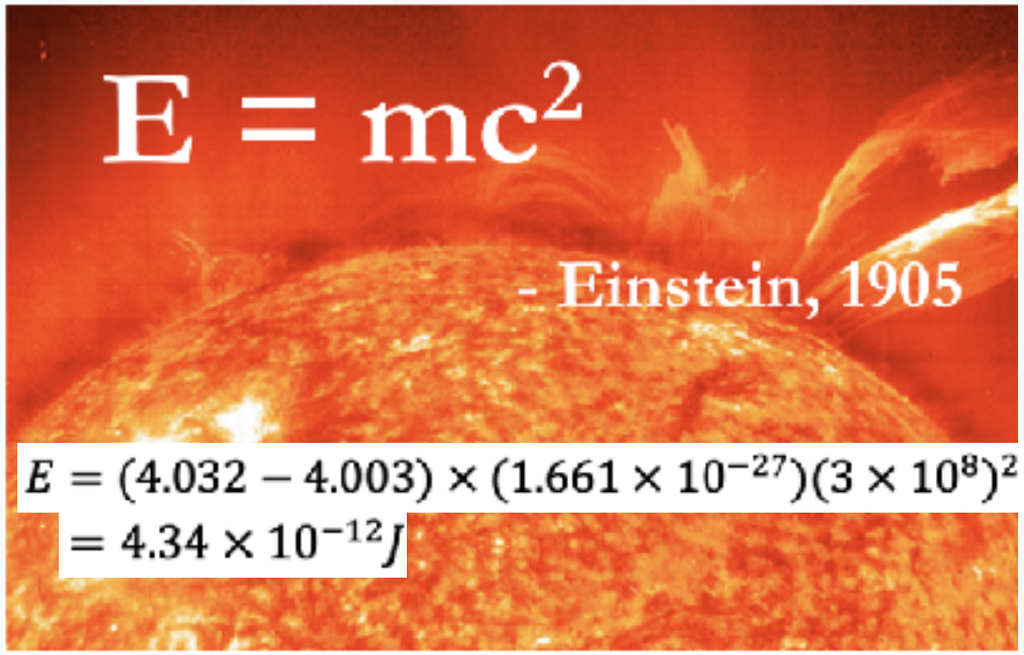
总化学能/光度 ～ 1万年

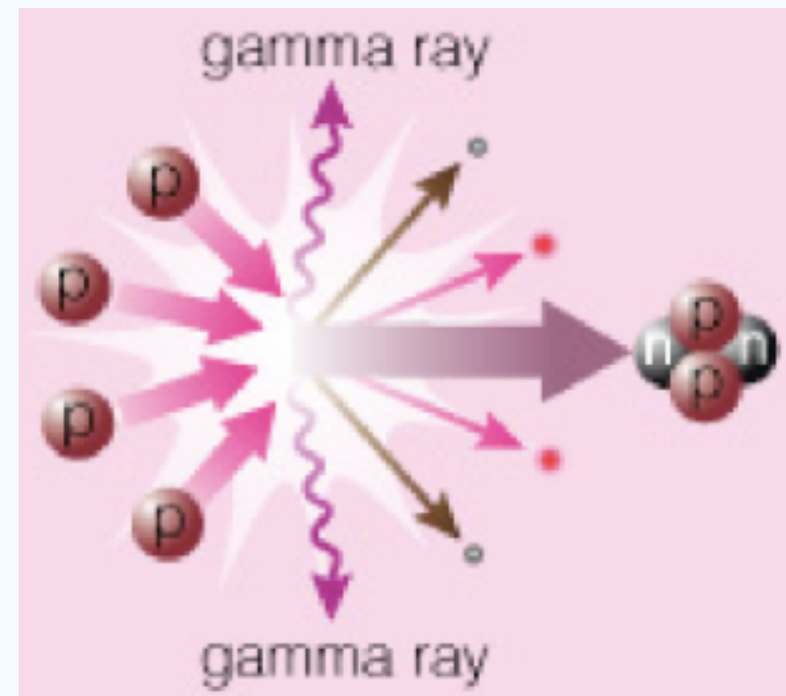
# 太阳的基本组分

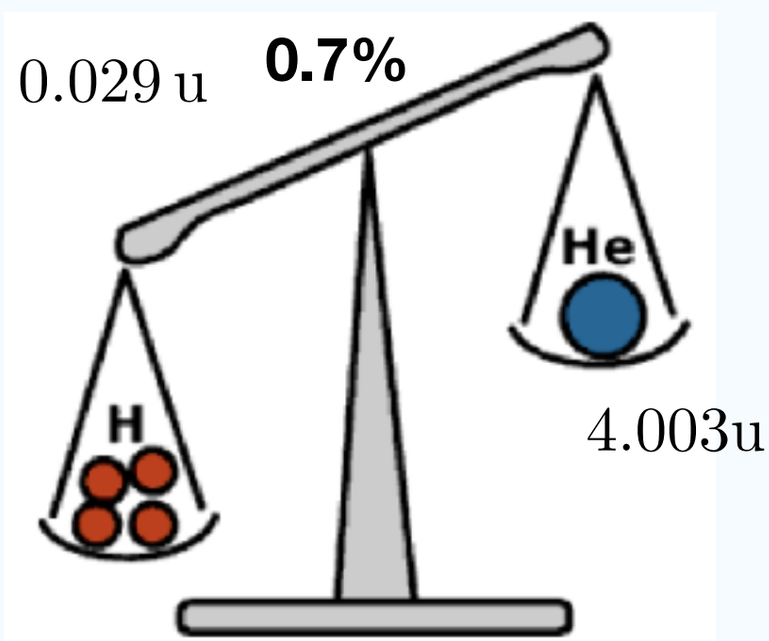



太阳主要是由氢和氦（太阳元素）组成

# 太阳能量的来源！




$1.008 \times 4 = 4.032\text{u}$

质量转化为能量（每克氢10^10 J能量）

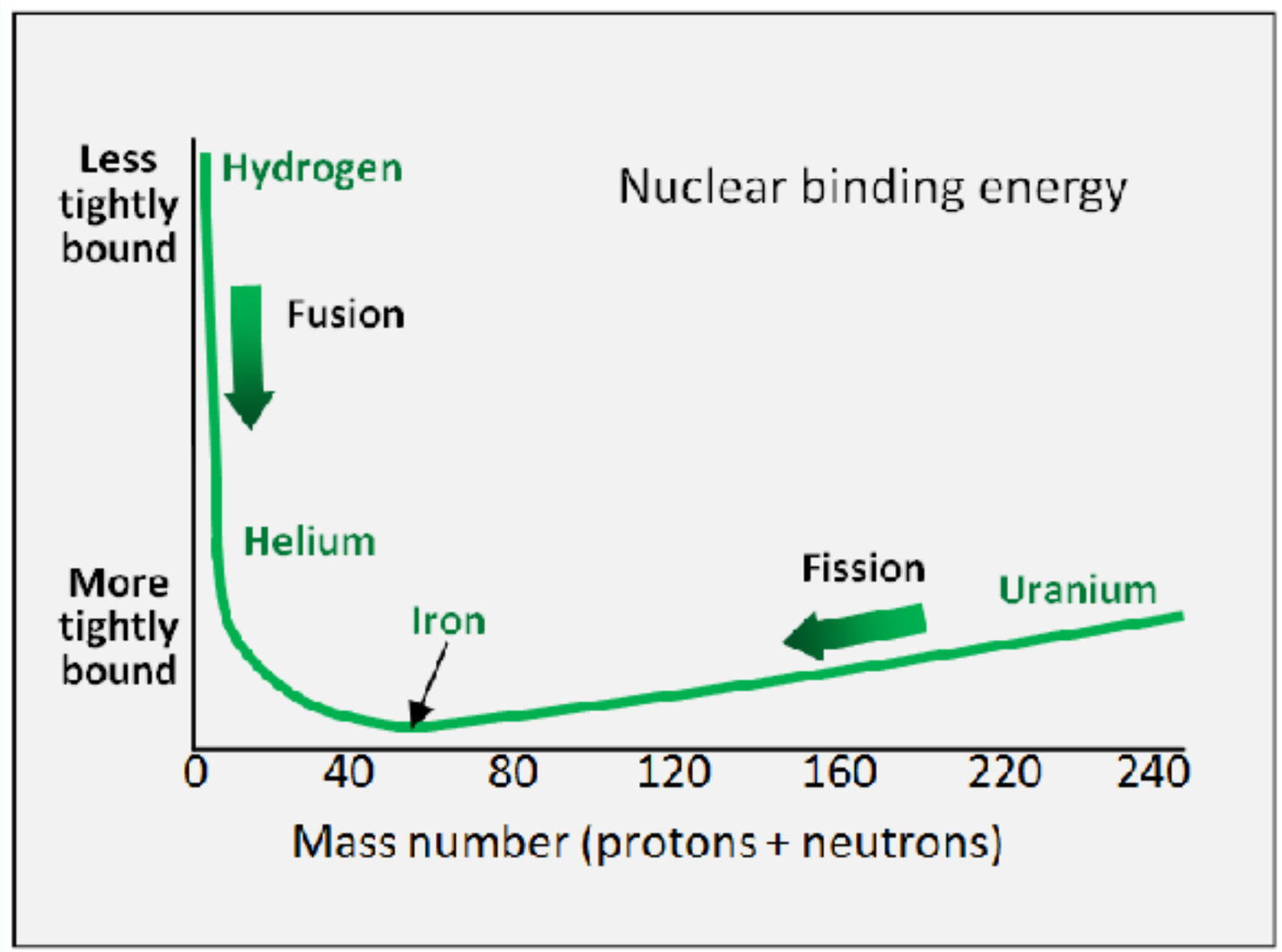
$4\ H \Rightarrow He^{4} + 4$ million eV.

太阳由约10^30千克氢组成

总能量/光度 ～ 100亿年

# 质能关系：核聚变/裂变

氢弹(0.7%)




原子弹(0.1%)

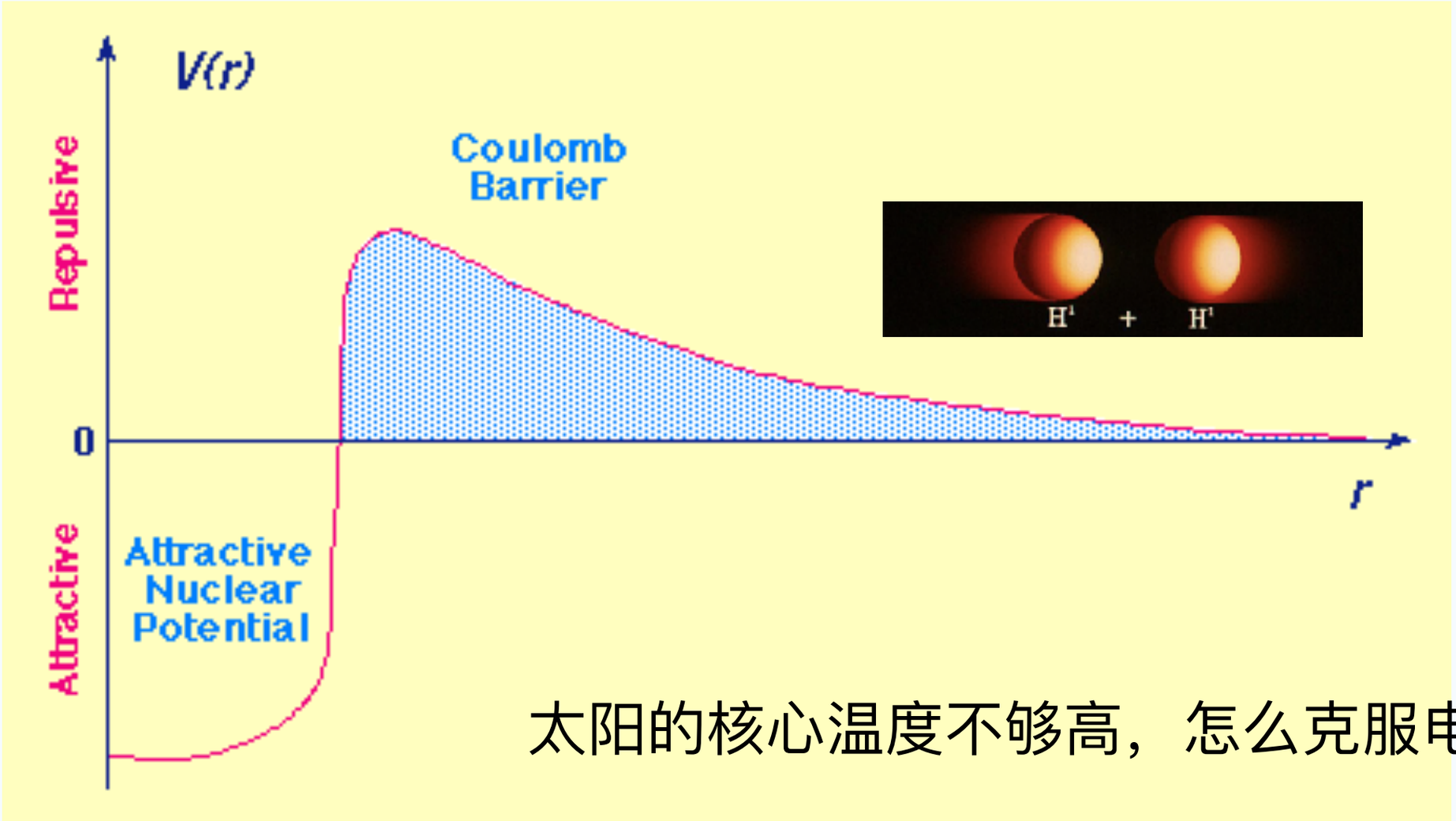
每秒钟太阳释放的能量 = 420万吨质量损失 = 910亿颗百万吨级的氢弹！

6亿吨的氢聚变成5.958亿吨的氦

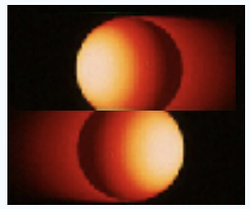
$$3.9 \times 10^{26}\ \mathrm{W}$$

# 从电磁排斥到强核力

质子/质子聚合成新的原子核

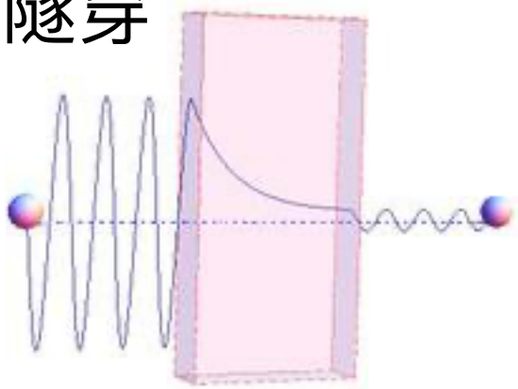



太阳的核心温度不够高，怎么克服电磁势垒?



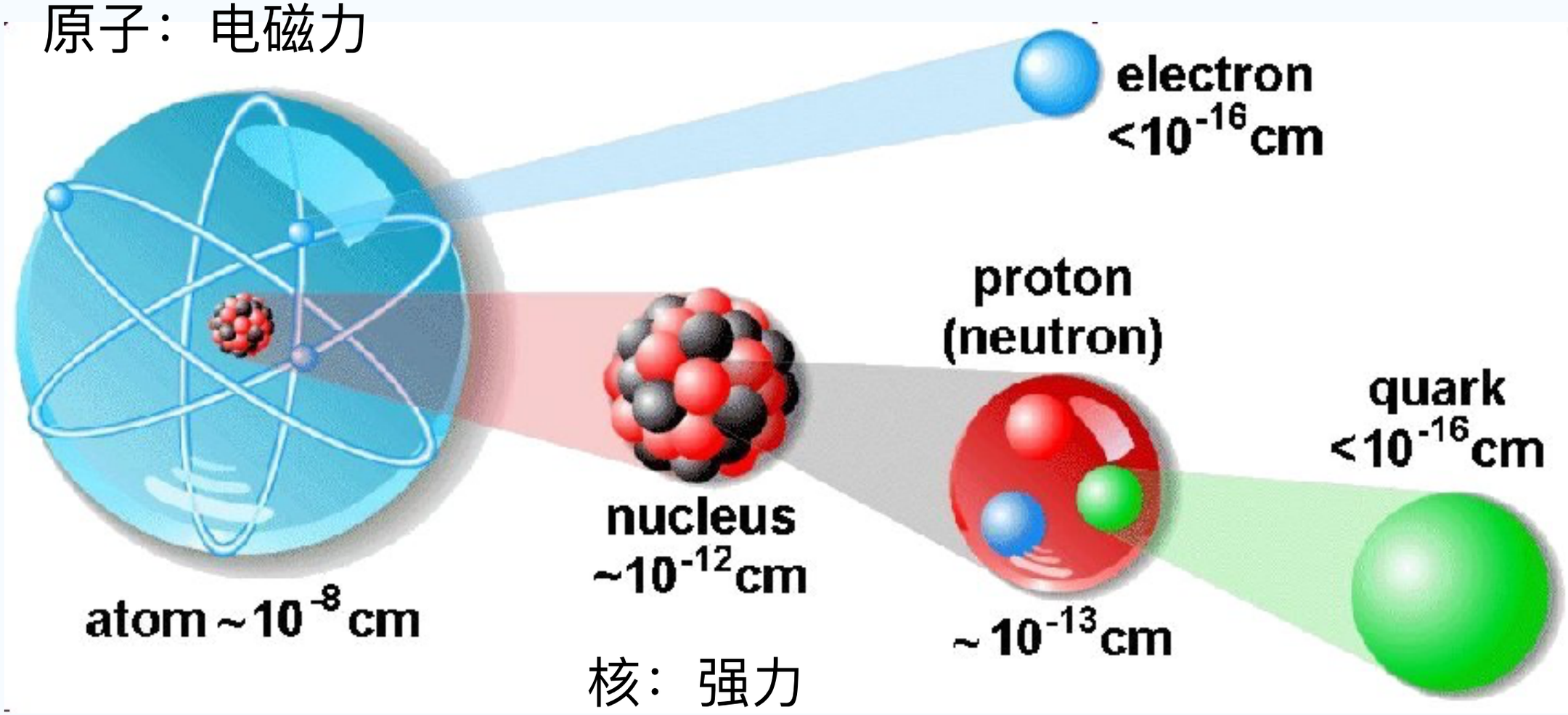
不稳定?

量子隧穿



# 原子和原子核

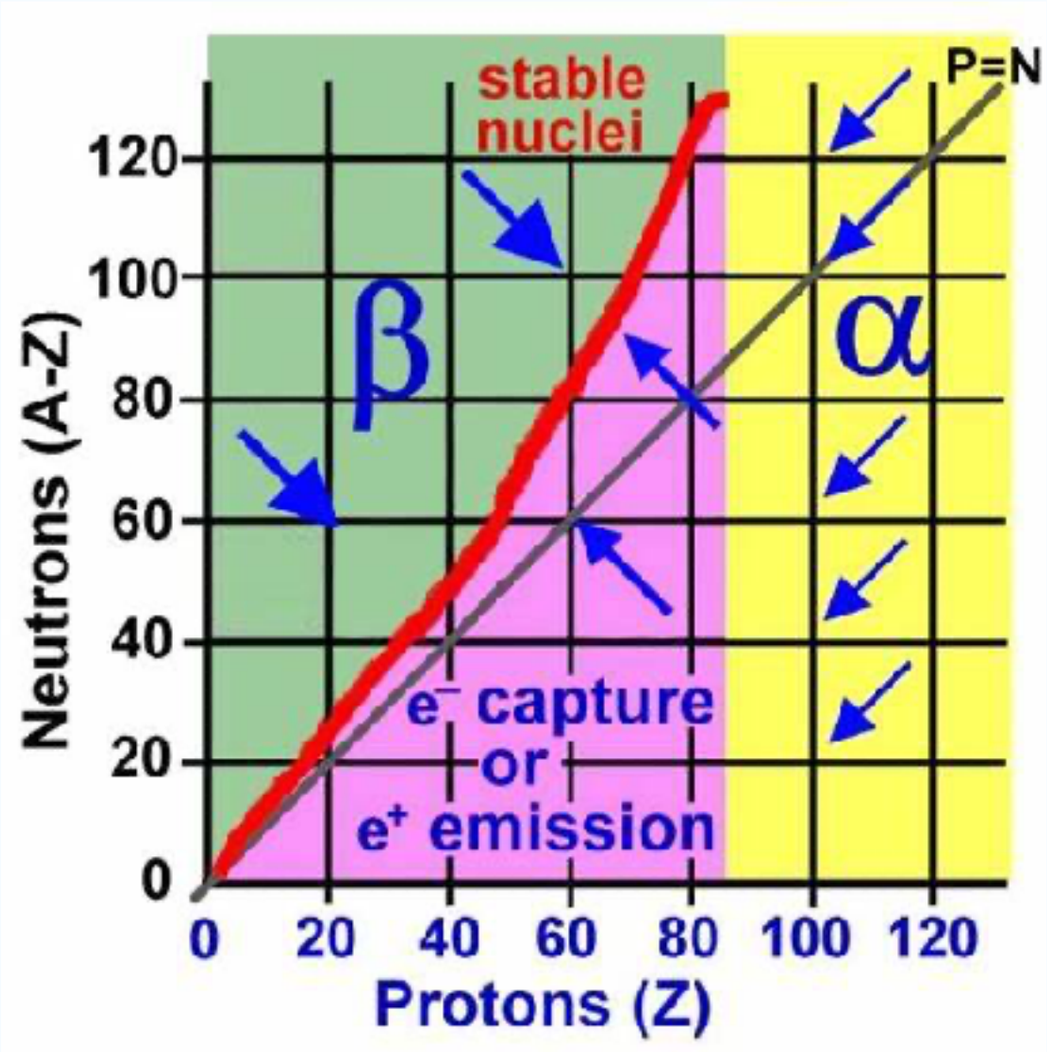
原子：电磁力

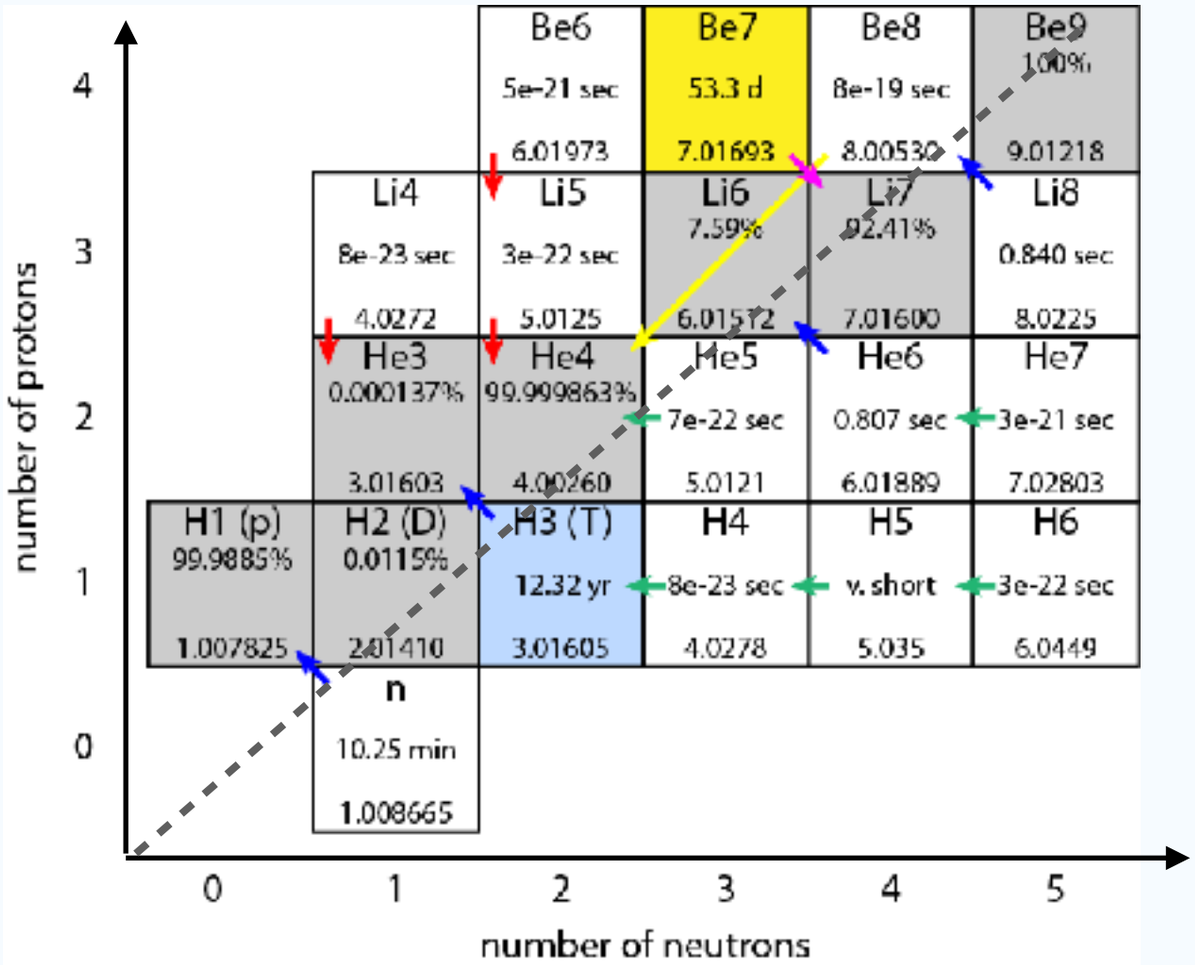



核：强力

什么样的原子核是稳定的?

# 弱相互作用和稳定核

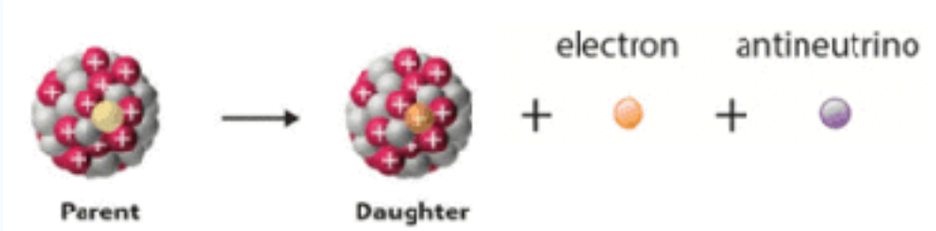


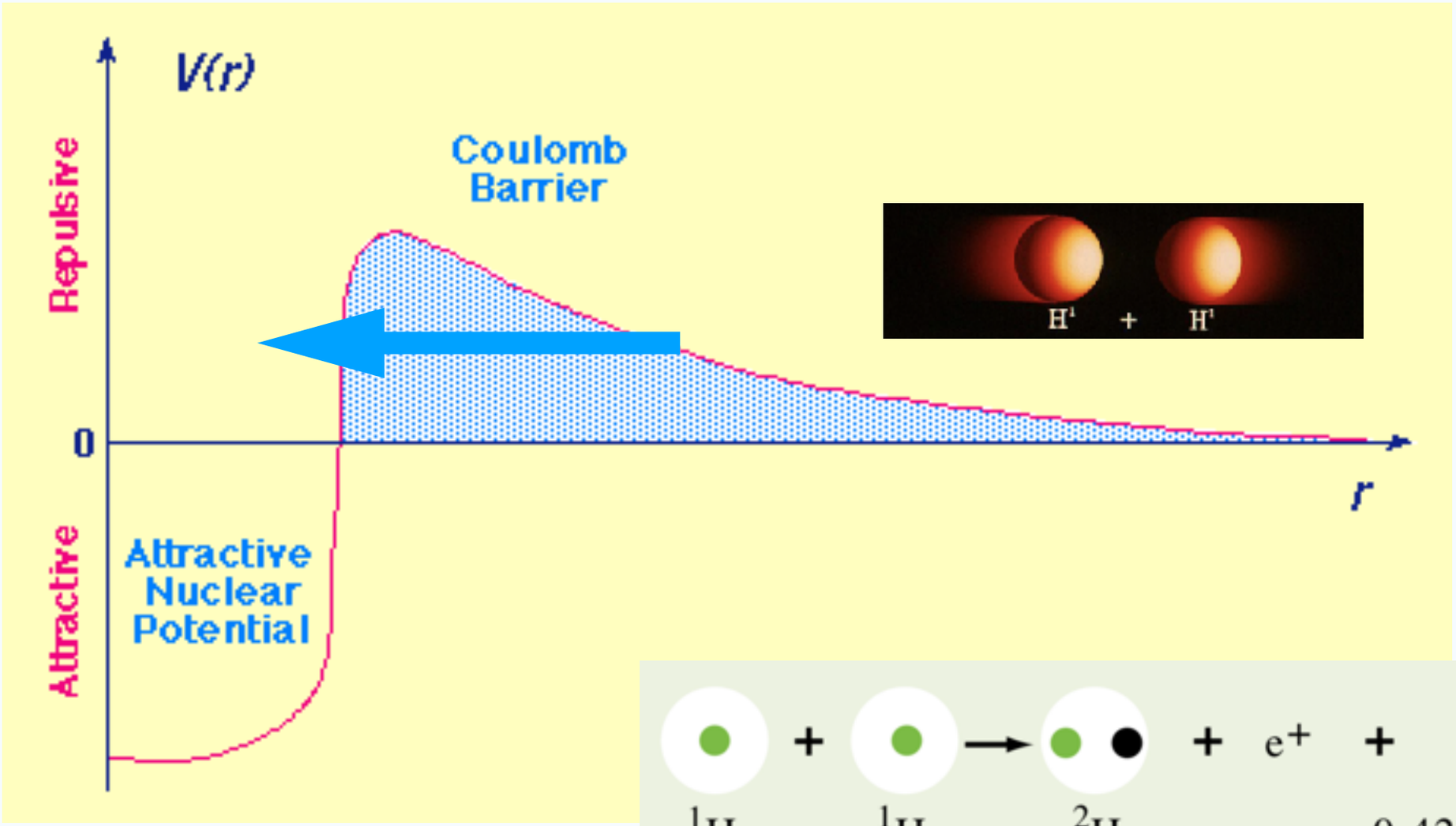

中子数～质子数

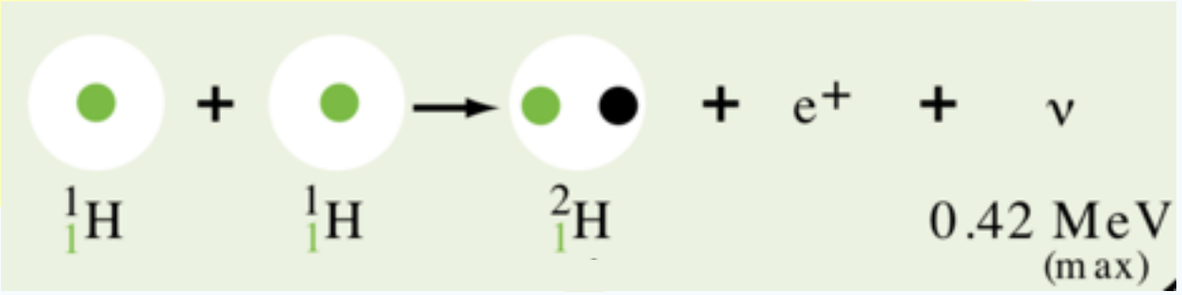
中和电磁力/泡利不相容

弱相互作用转化质子为中子：



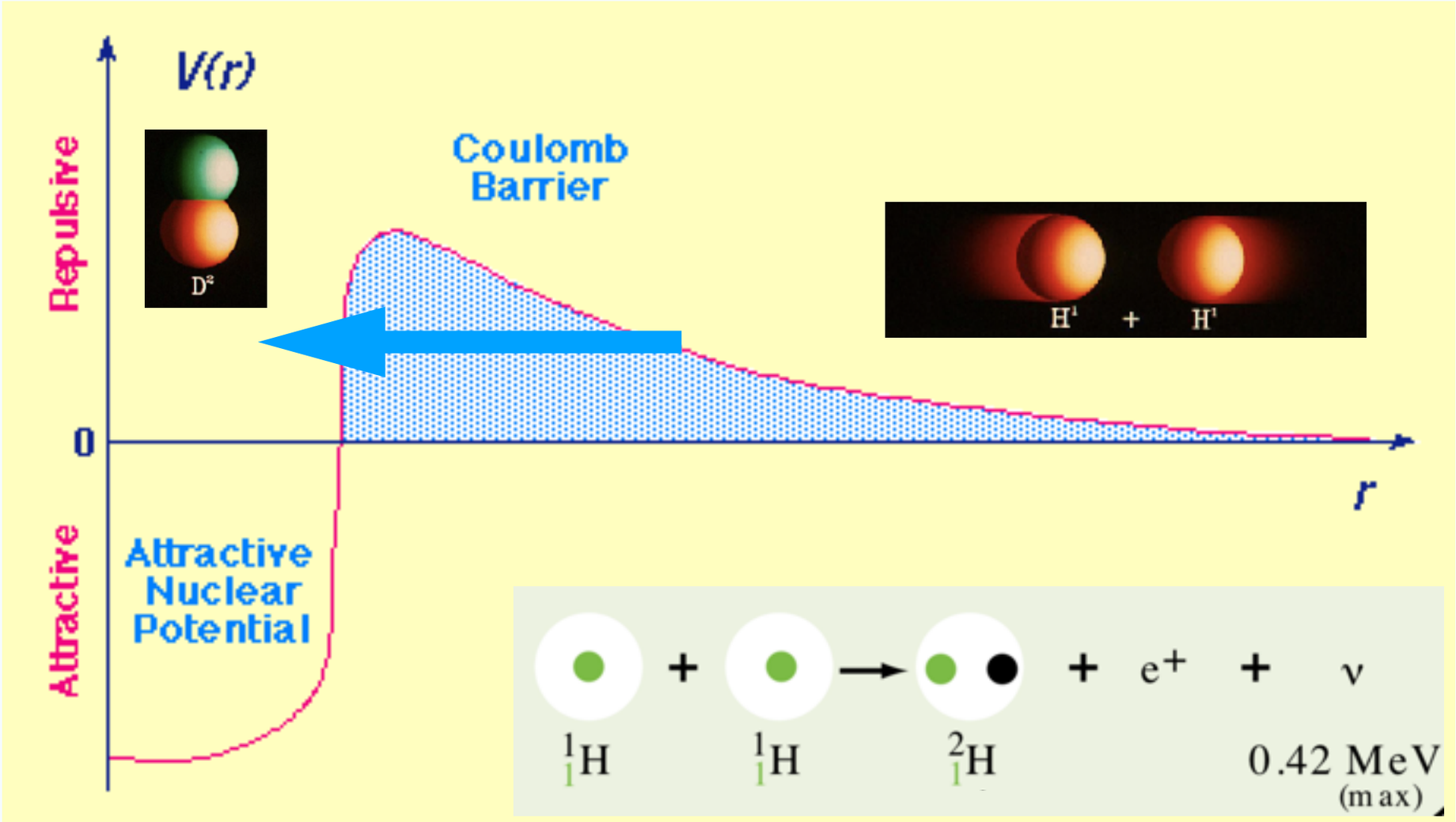
# 弱作用下形成稳定氘核



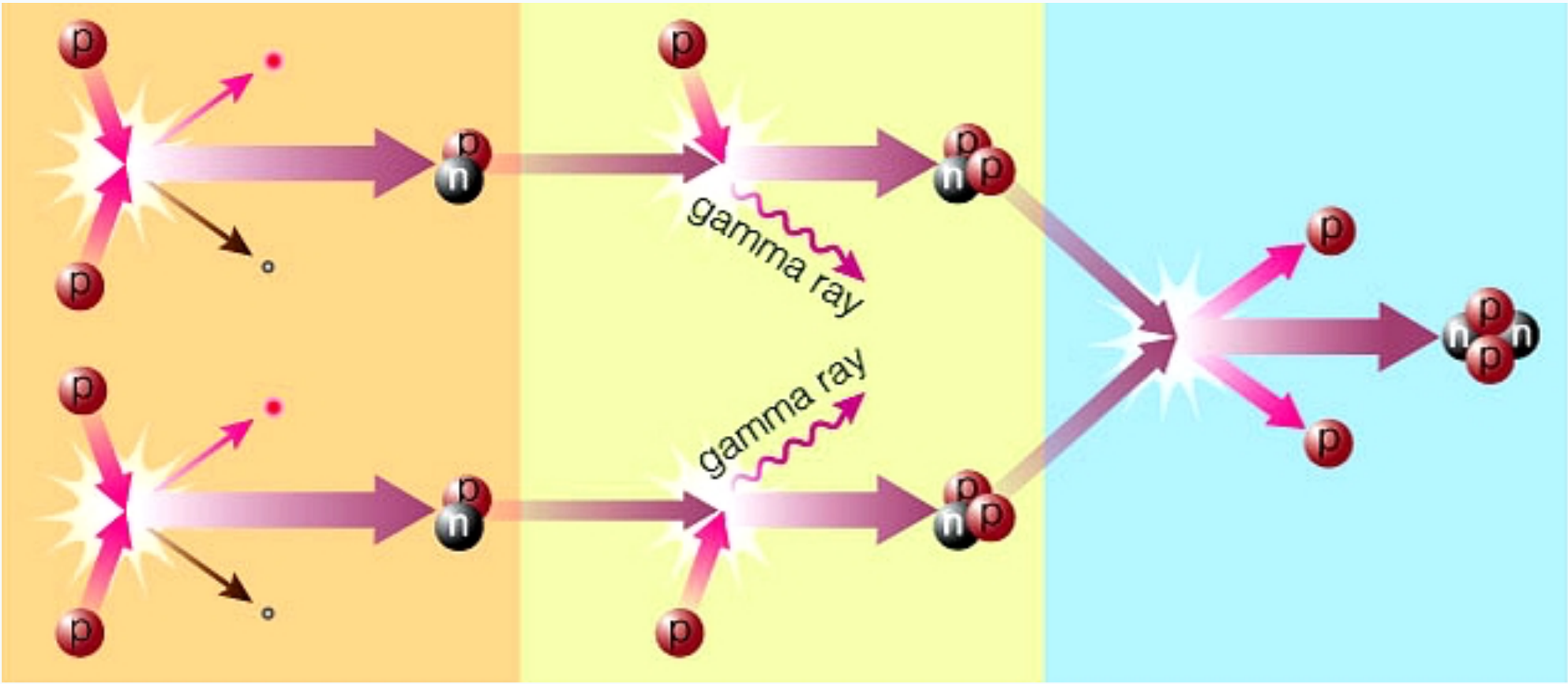
形成紧束缚氘核，释放能量！

# 弱作用下形成稳定氘核




形成紧束缚氘核，释放能量！

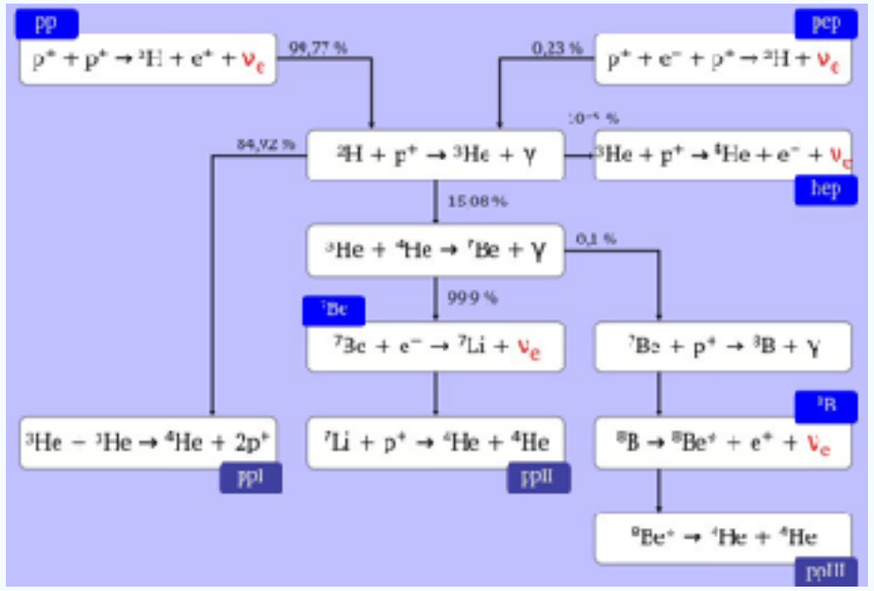
# 太阳发光发热的奥秘：聚变反应

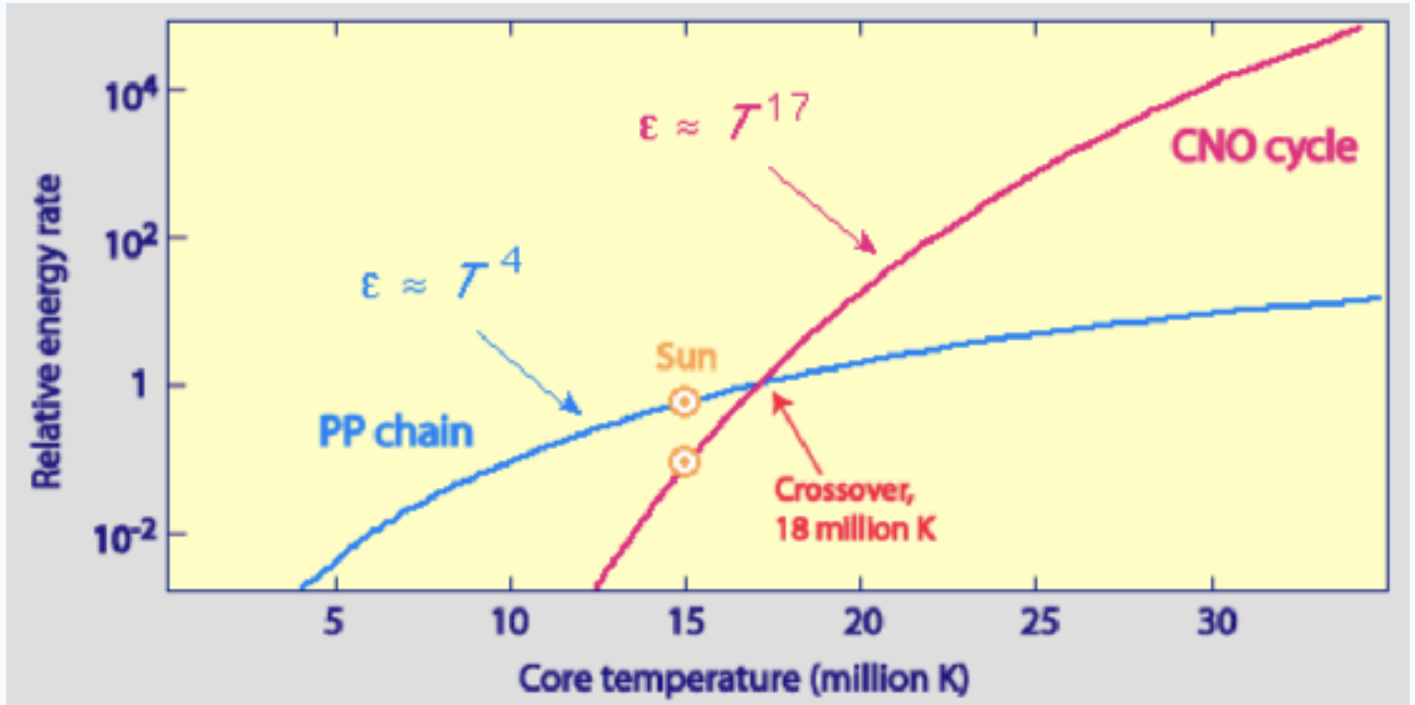


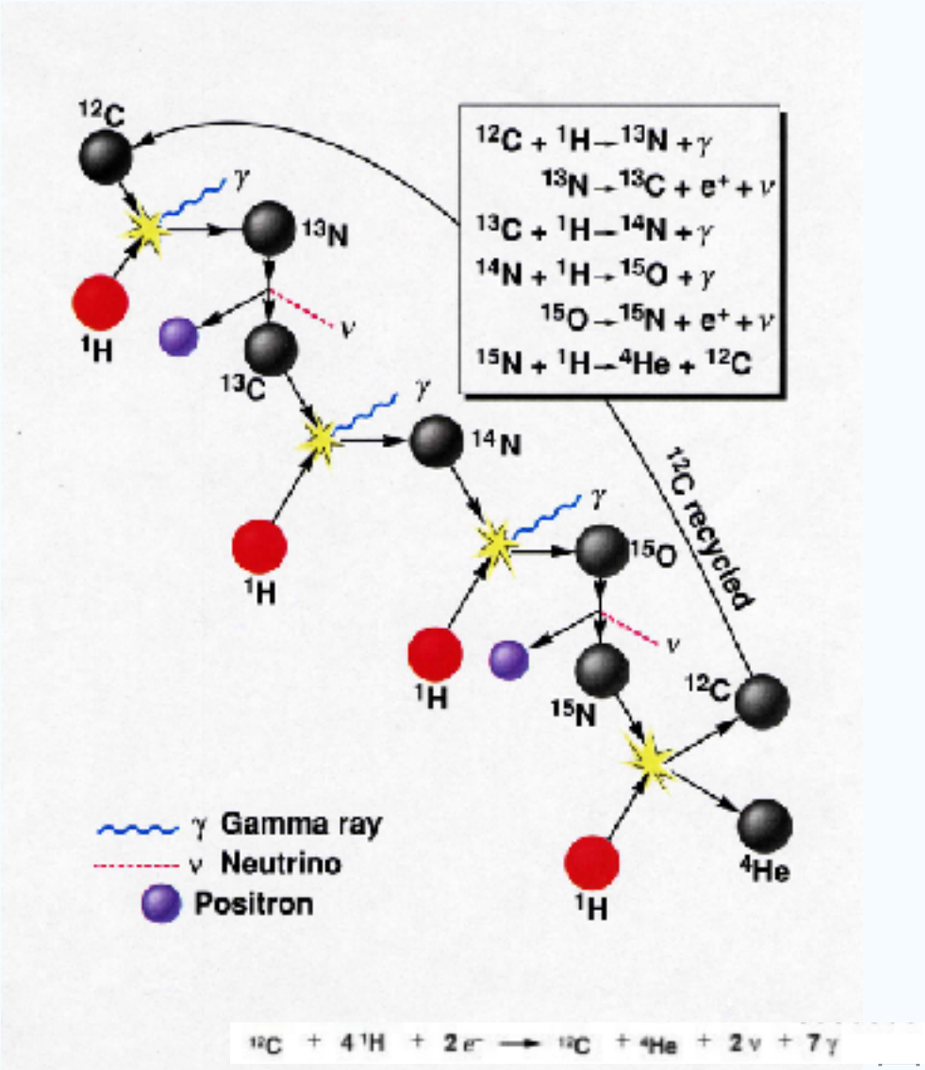

量子隧穿克服电磁排斥，进入强核力范围

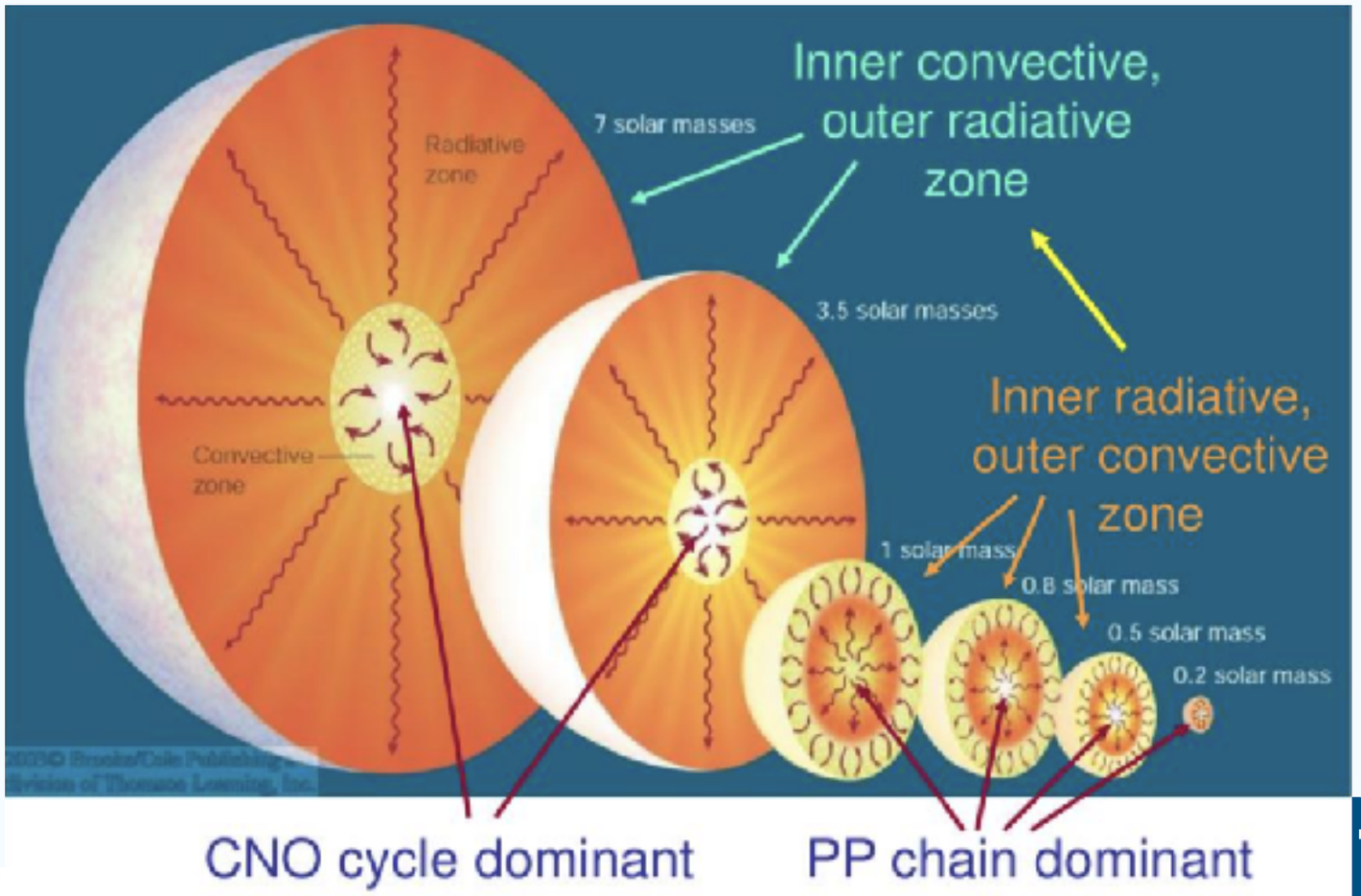
弱力使得核子间束缚成为稳定核

# 星星发光的奥秘


pp
pep
hep
ppI
ppII
ppIII
99,77 %
0,23 %
84,92 %
15.08 %
0,1 %
99.9 %


Relative energy rate
Core temperature (million K)
ε ≈ T^17
ε ≈ T^4
CNO cycle
PP chain
Sun
Crossover,
18 million K

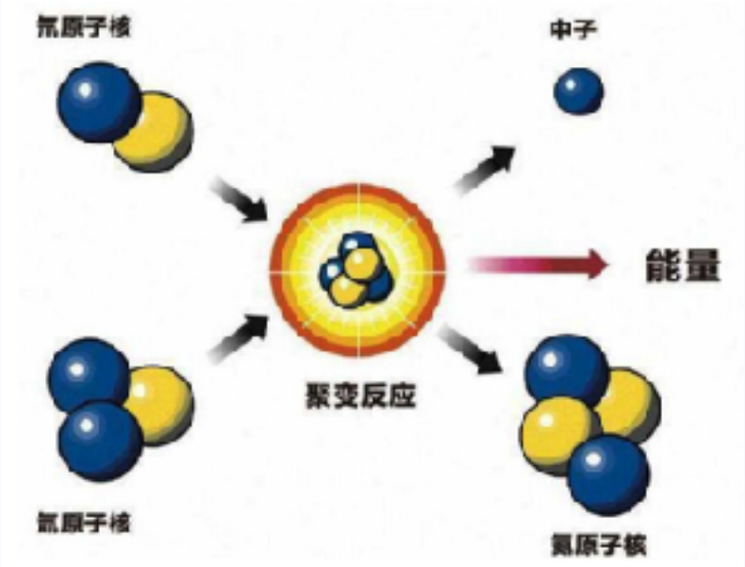

12C + 1H → 13N + γ
13N → 13C + e+ + ν
13C + 1H → 14N + γ
14N + 1H → 15O + γ
15O → 15N + e+ + ν
15N + 1H → 4He + 12C
12C recycled
γ Gamma ray
ν Neutrino
Positron
12C + 4 1H + 2e− → 12C + 4He + 2ν + 7γ


Inner convective,
outer radiative
zone
7 solar masses
Radiative zone
3.5 solar masses
Convective zone
Inner radiative,
outer convective
zone
1 solar mass
0.8 solar mass
0.5 solar mass
0.2 solar mass
CNO cycle dominant
PP chain dominant

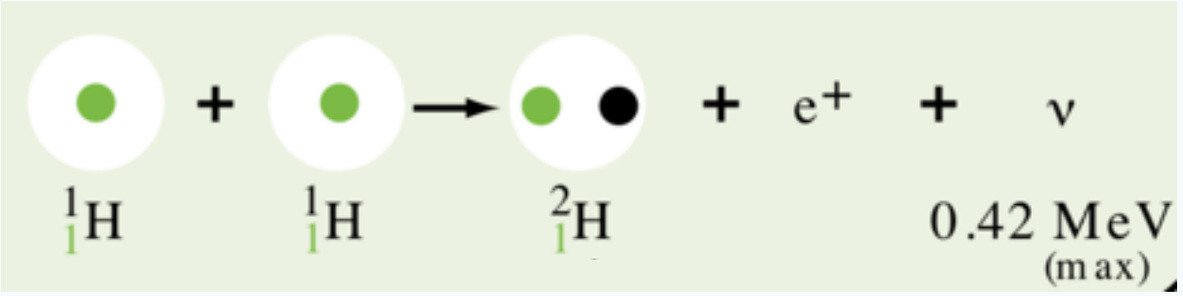
# 核反应的几率和太阳的寿命

氢弹瞬间爆炸，但为什么太阳燃烧百亿年?

原子弹点火（1亿度）氘氚融合




太阳中质子/质子相遇聚合成氘核的反应




隧穿及弱作用导致每10亿年才发生一次

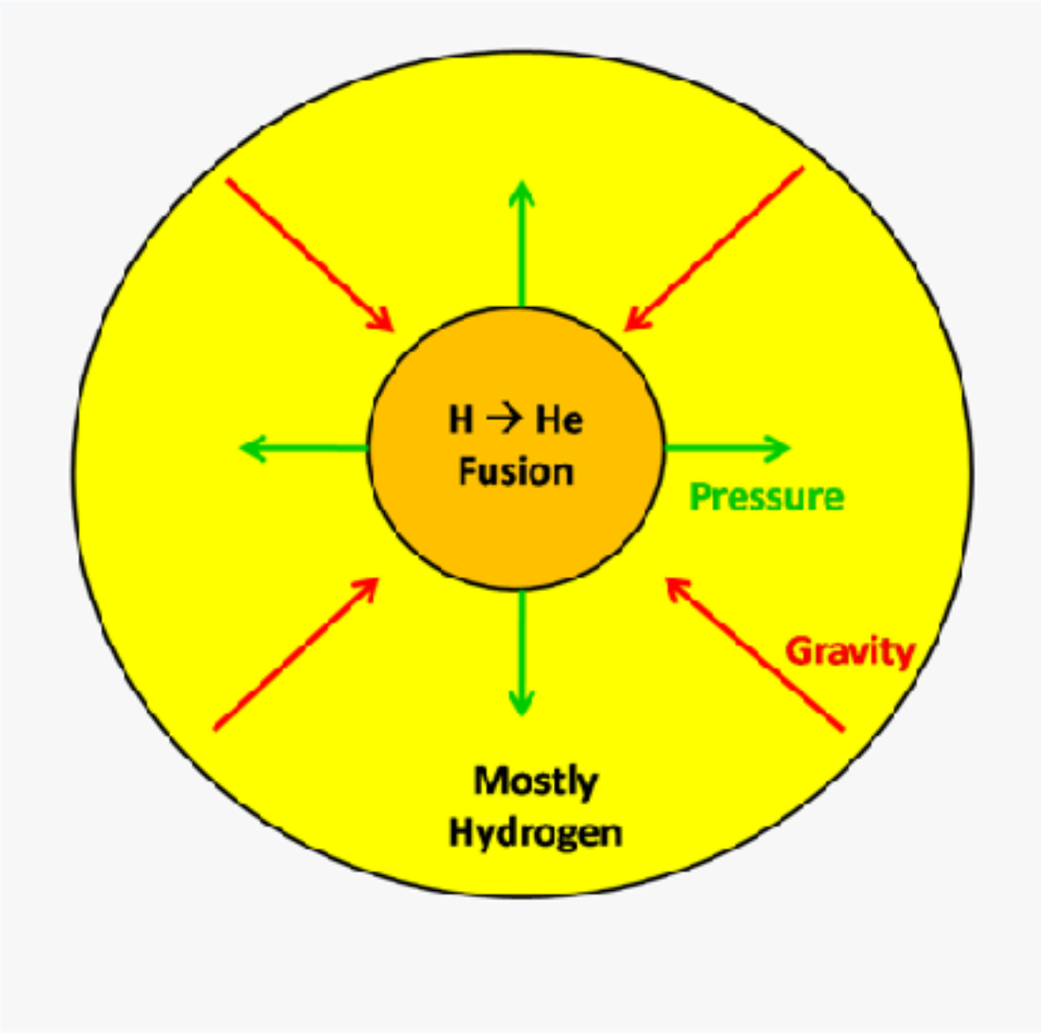
由于太阳核心大量的氢，反应得以持续进行几十亿年

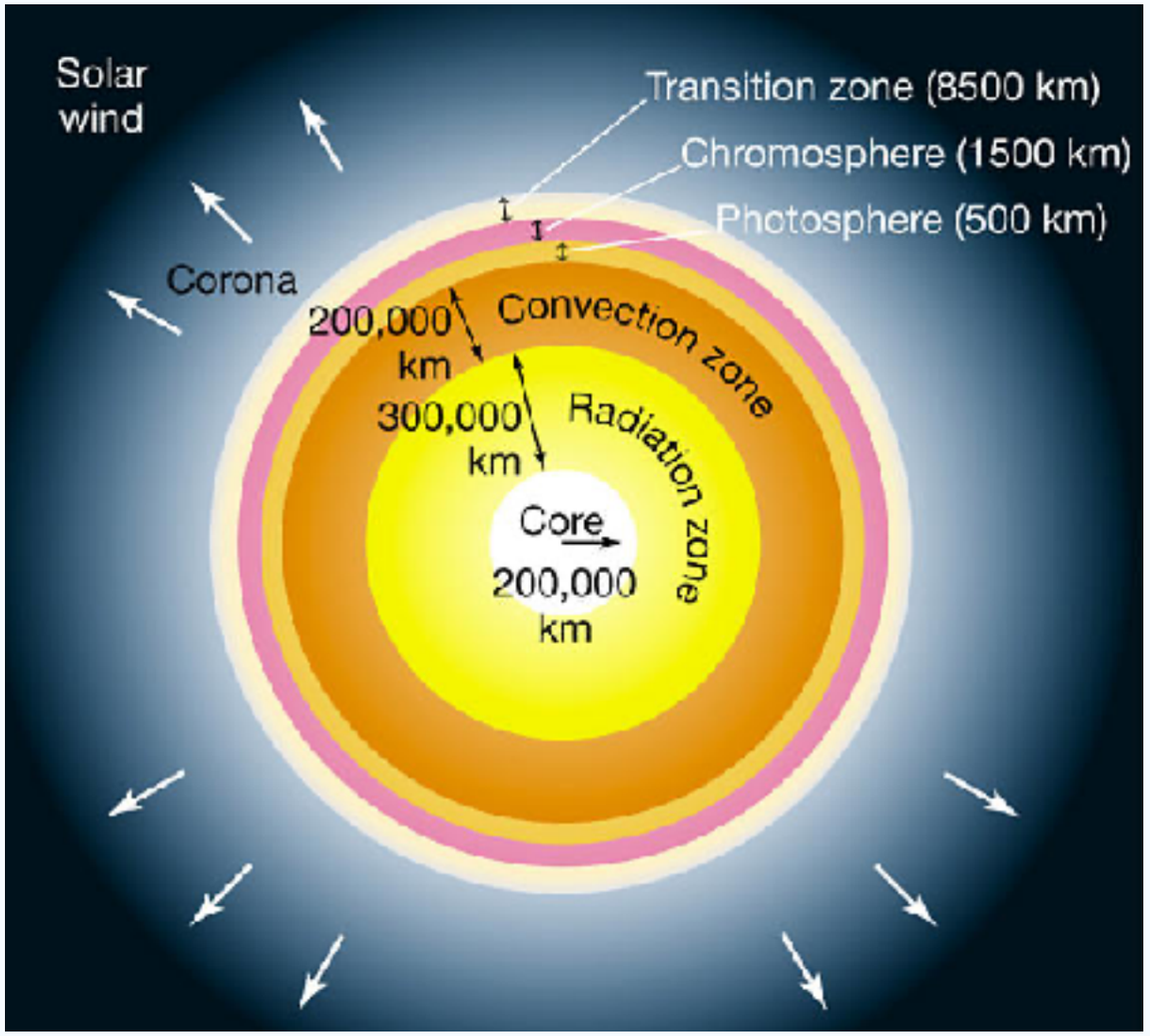
Solar mass: 1 $M_\odot$ = 1.989 x $10^{30}$ kg

Proton mass: 1 $m_p$ = 1.6726 x $10^{-27}$ kg = 0.938 GeV $c^{-2}$

# 太阳标准模型

太阳发生热核反应和引力达到稳态平衡（可控核聚变）

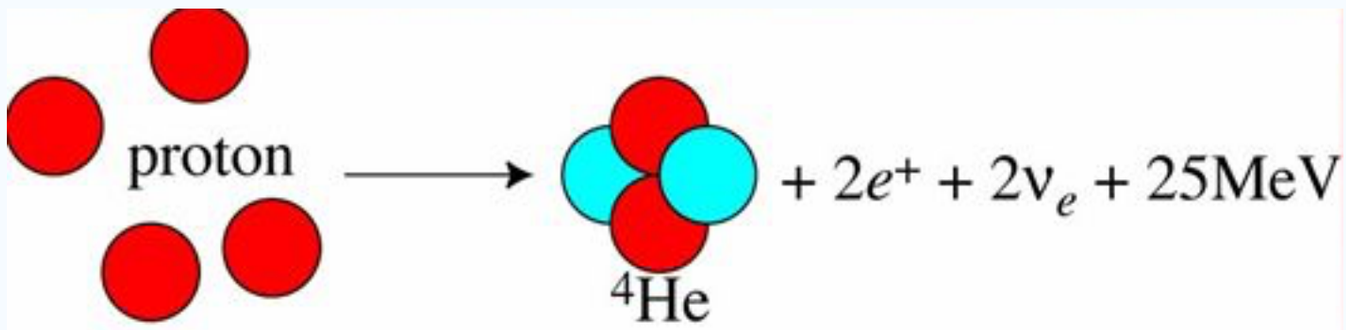


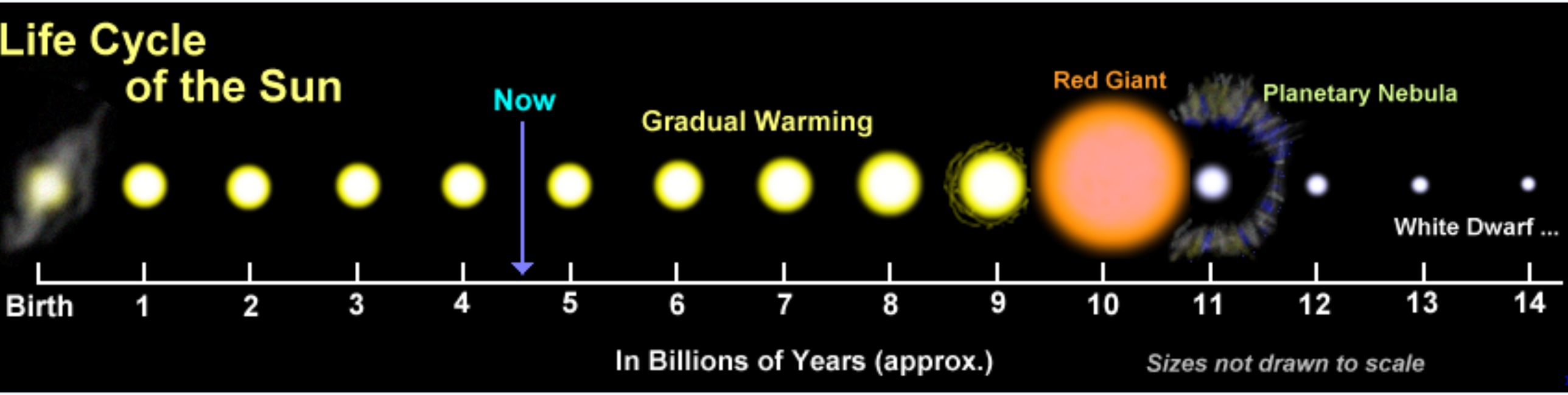




能量从核心区传递到辐射区和对流区

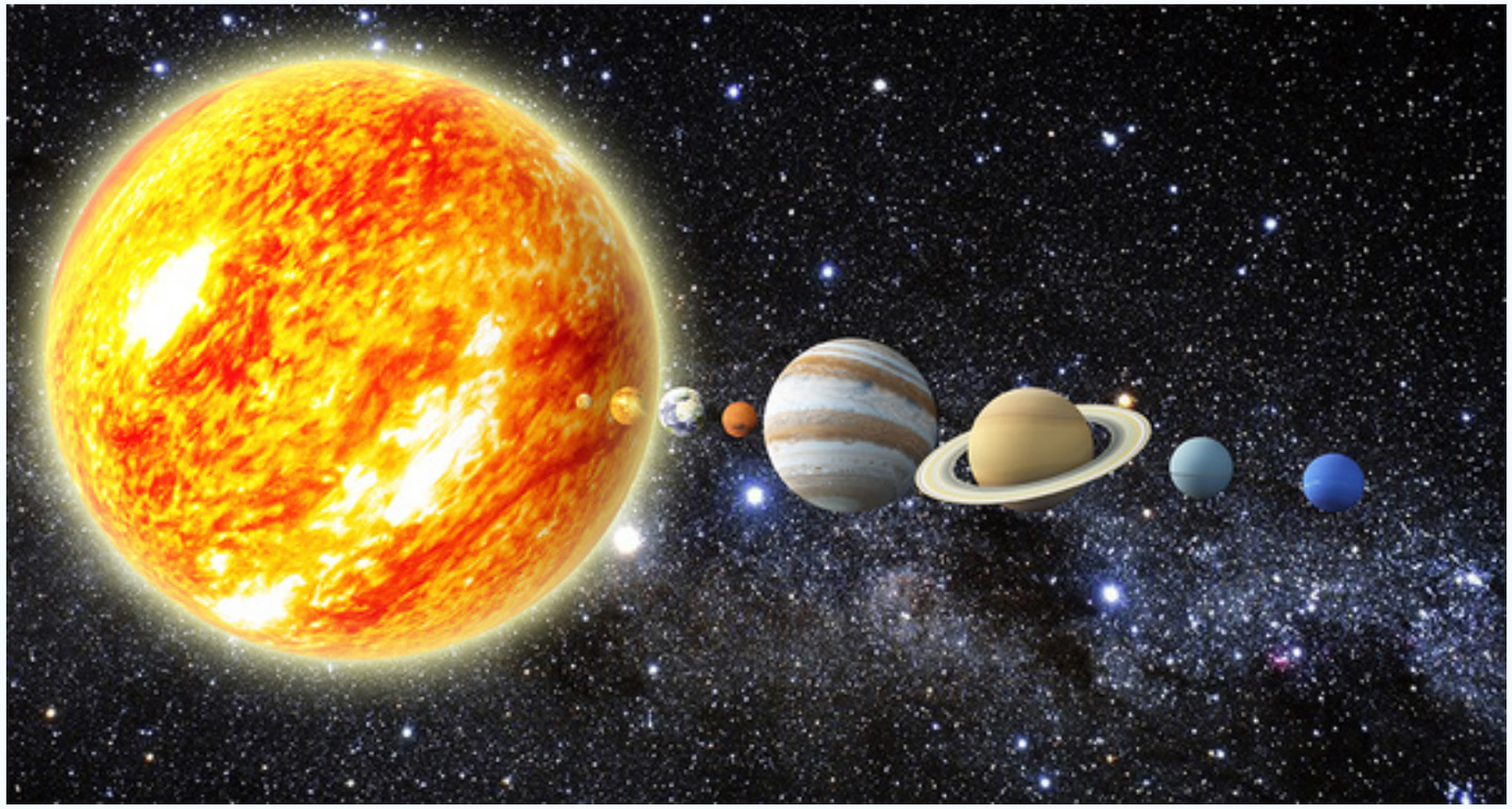
# 太阳的寿命有多长?

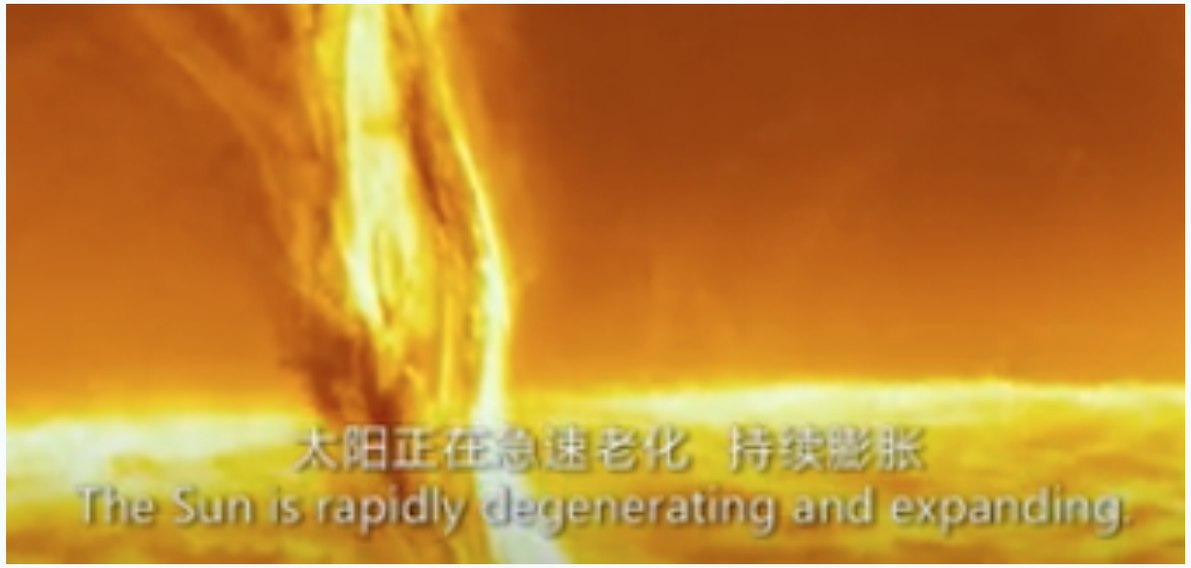
核聚变计算：太阳已经燃烧了47亿年，正处于中年

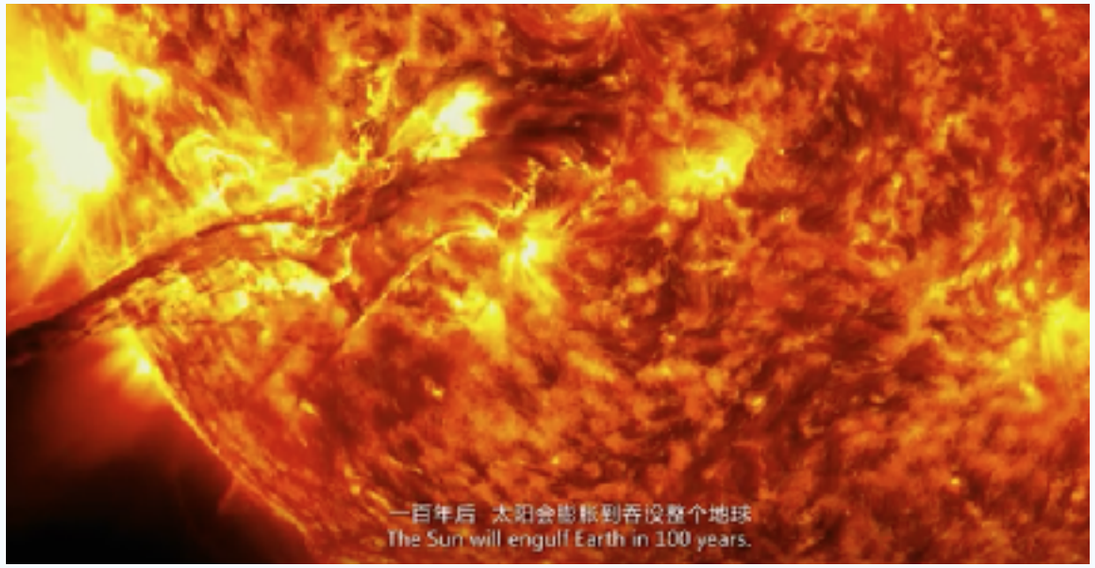


# 流浪地球：太阳在一百年后老去?

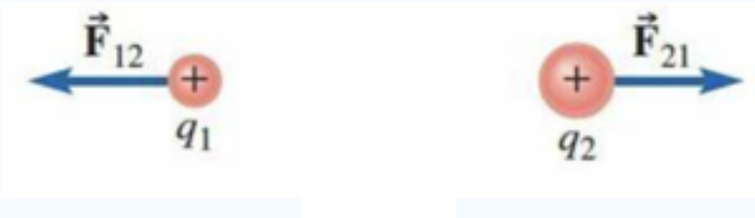




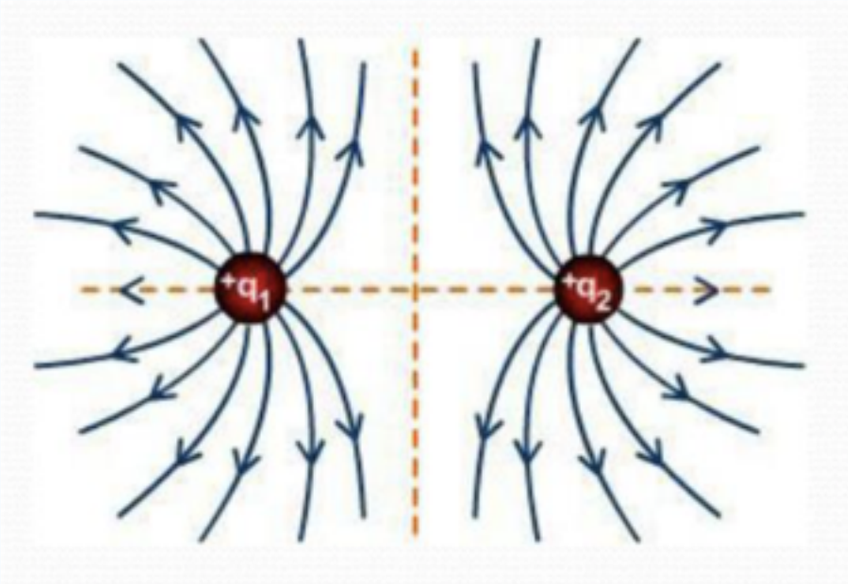



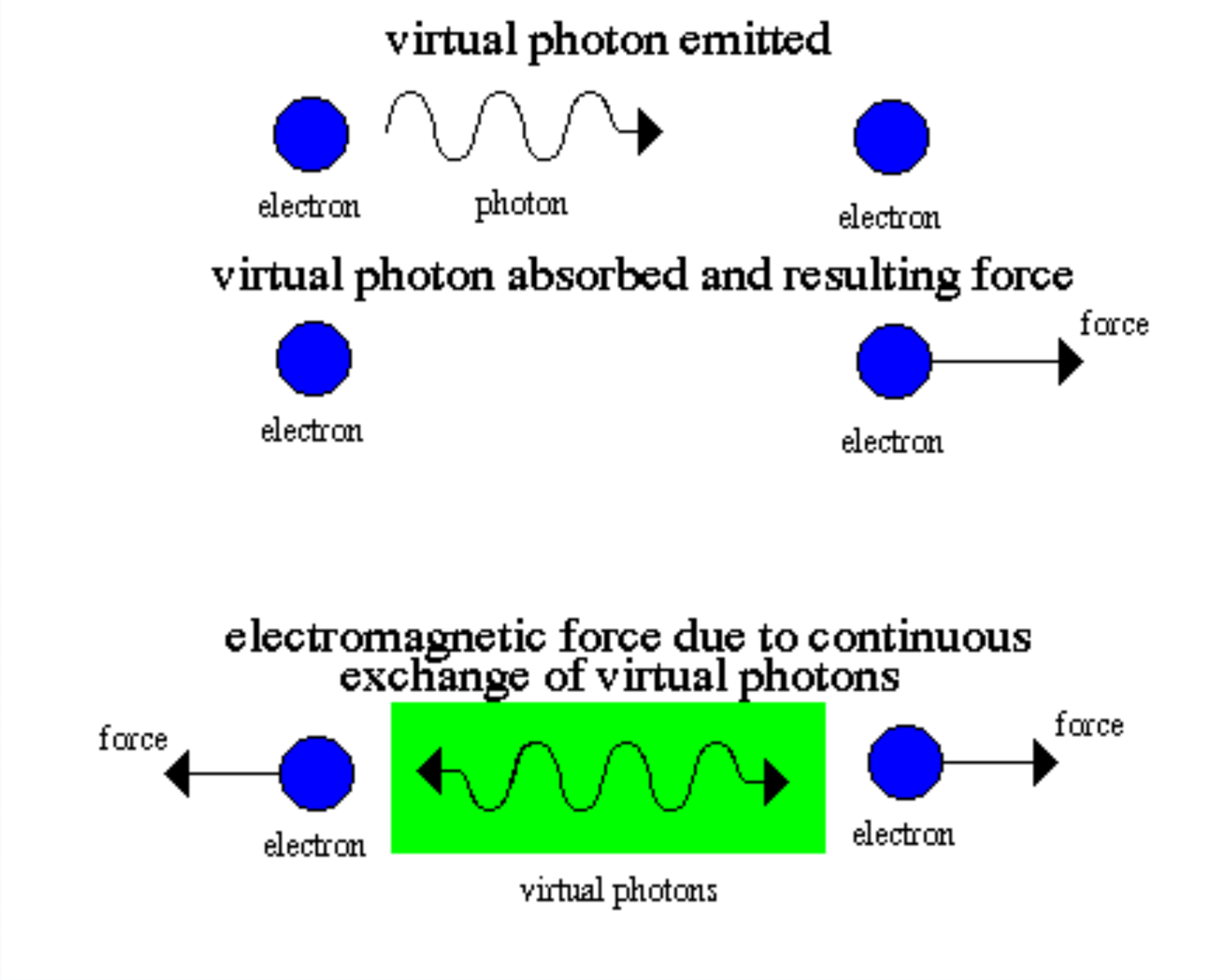
# 相互作用力 = 媒介粒子

电磁力需要媒介粒子(光子)，而不是瞬时相互作用的



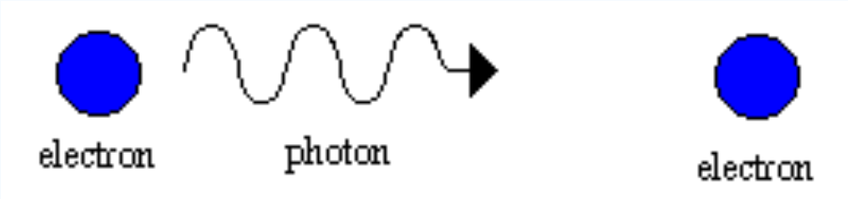

$$F_e = k\frac{q_1 q_2}{r^2}$$

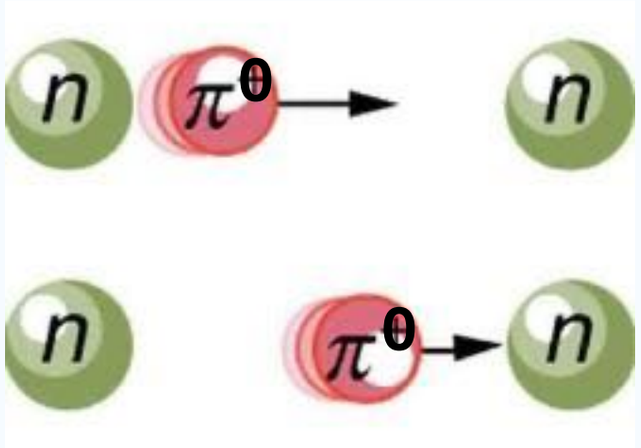


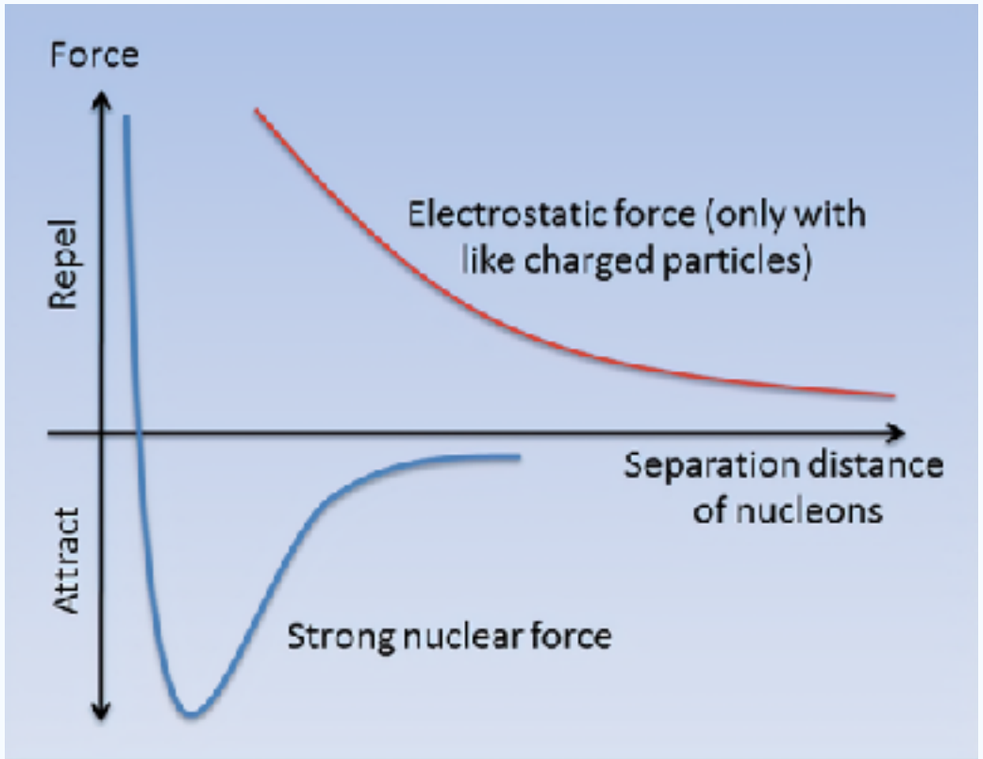



# 强相互作用力 = 派介子

强力类似于电磁力，交换派介子粒子




$$V(r) = -\frac{e^2}{4\pi}\frac{1}{r}$$

光子无质量

$$V(r) = -\frac{g^2}{4\pi}\frac{1}{r}e^{-m_\phi r}$$

$1\ \mathrm{fm}^{-1} = 197.3\ \mathrm{MeV}$

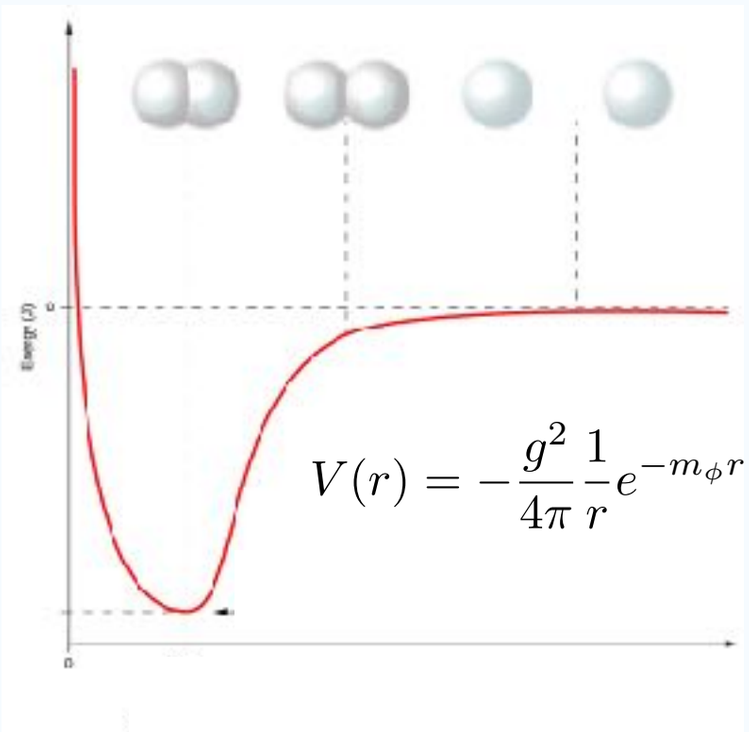
强力是有力程范围的

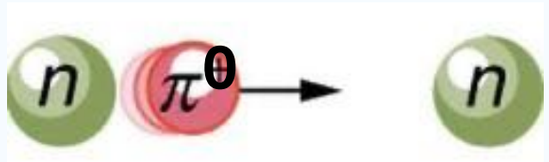
$10^{-15}$
(diameter of a medium sized nucleus)

派介子有质量

# 弱相互作用力 = W玻色子

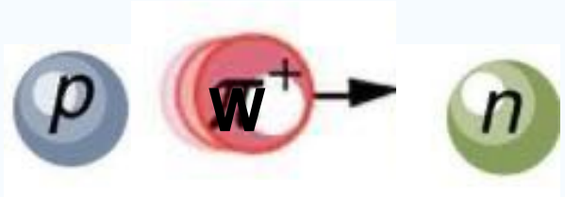
弱力类似于强力，但是力程范围更短




$10^{-15}$
(diameter of a medium sized nucleus)

$1\ \mathrm{fm}^{-1} = 197.3\ \mathrm{MeV}$

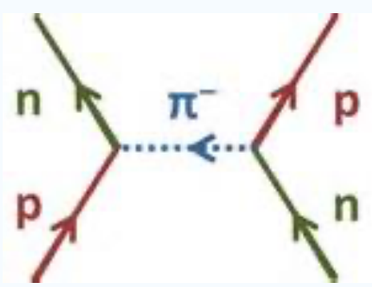



Range (m)

$10^{-18}$
(0.1% of the diameter of a proton)

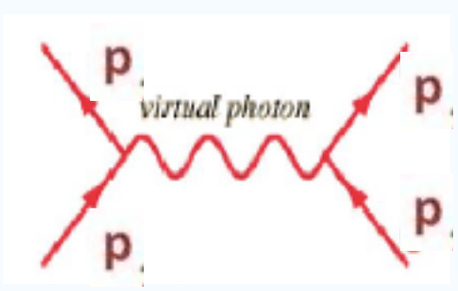
$10^{-3}\ \mathrm{fm}^{-1} \simeq 100\ \mathrm{GeV}$

质子和中子存在四种相互作用，因此存在四种玻色子媒介粒子



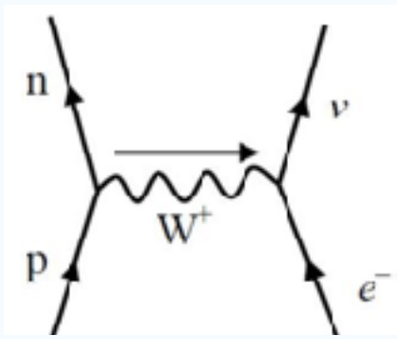

Strength

1



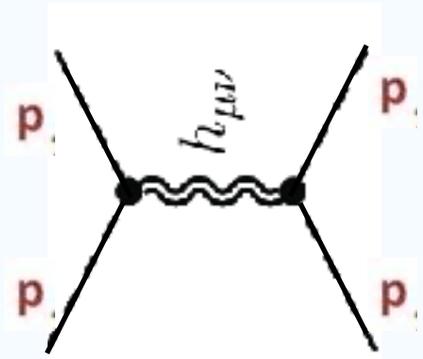

Strength

$\frac{1}{137}$




Strength

$10^{-6}$




Strength

$6 \times 10^{-39}$

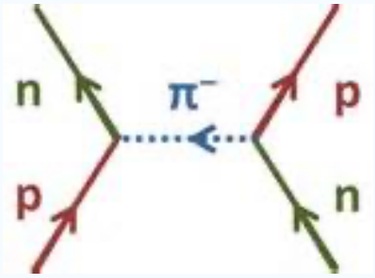
# 电弱统一理论

电　　磁

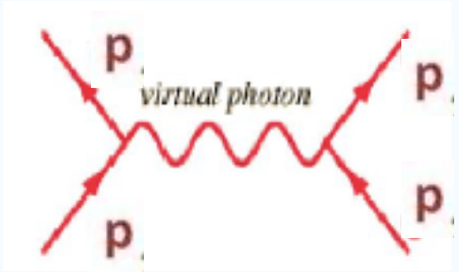
麦克斯韦电磁学

万有引力

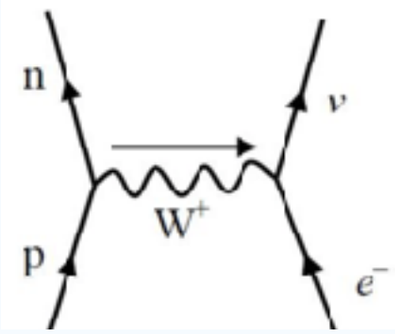
广义相对论



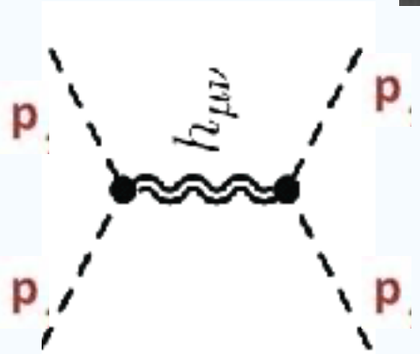

强相互作用



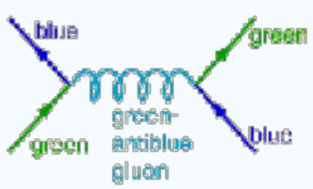

电磁相互作用




弱相互作用




引力相互作用

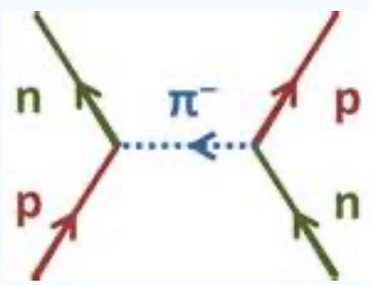



电弱相互作用（1967）

大统一理论?

弦论?

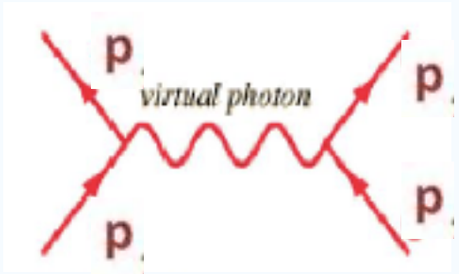
# 电弱统一理论




强相互作用

Strength

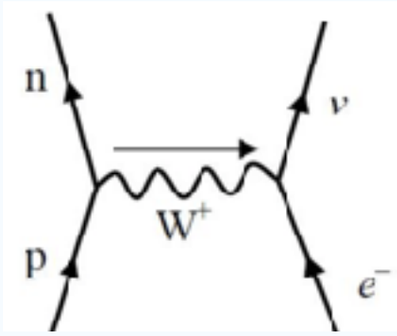
1




电磁相互作用

Strength

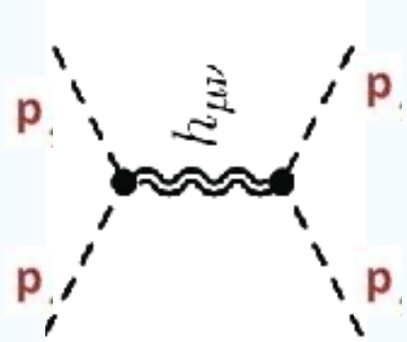
$\frac{1}{137}$




弱相互作用

Strength

$10^{-6}$



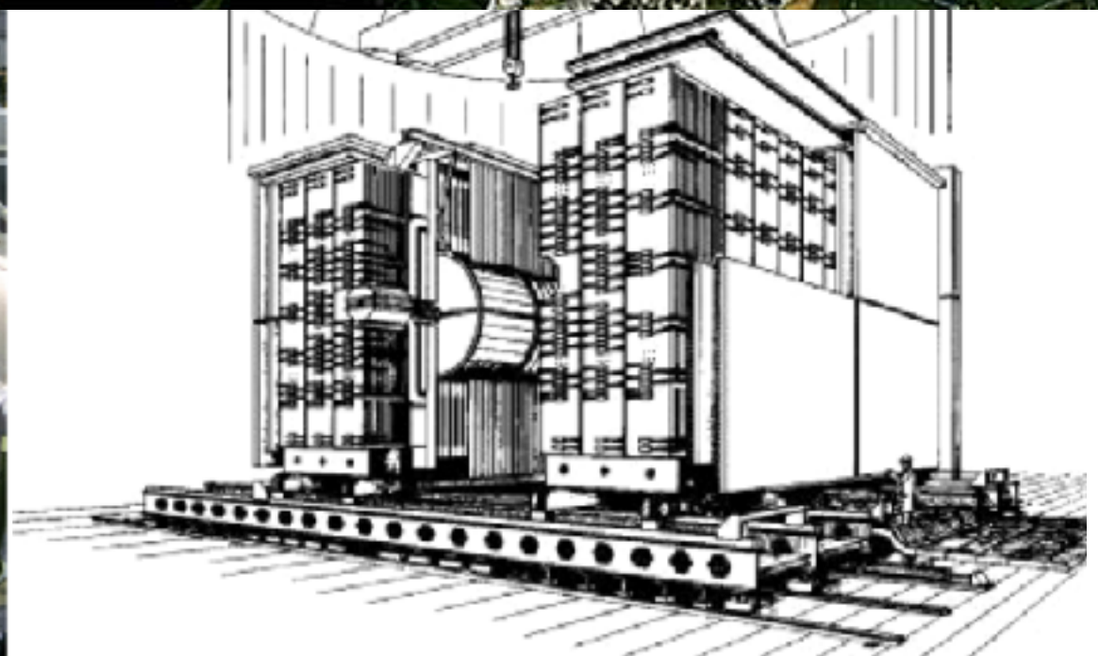

引力相互作用

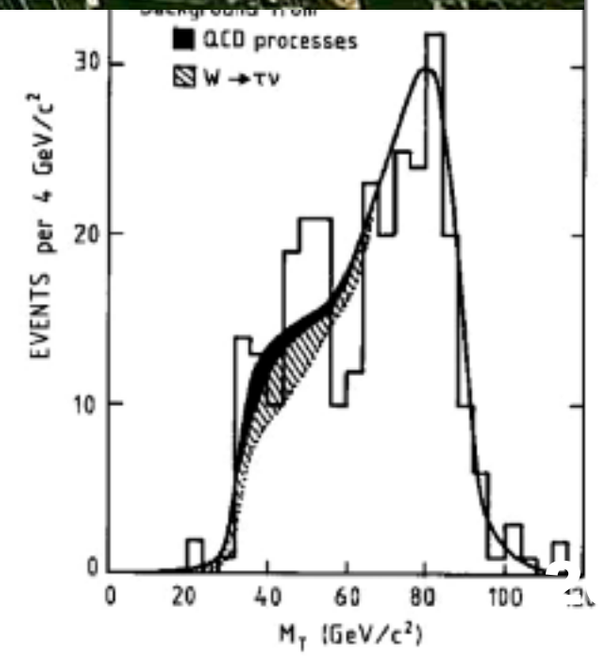
Strength

$6 \times 10^{-39}$

# W玻色子发现

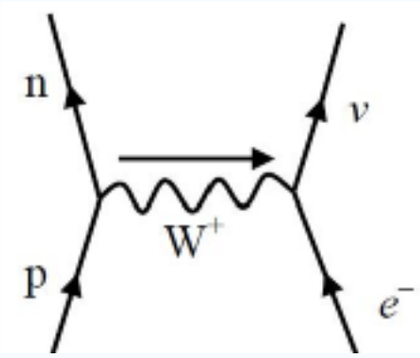
1967年电弱统一理论预测其质量，1983年在SPS发现

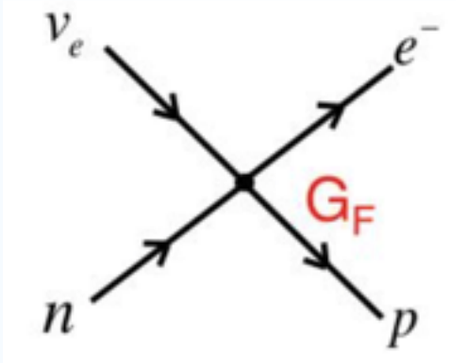




# 太阳寿命的奥秘：W玻色子质量

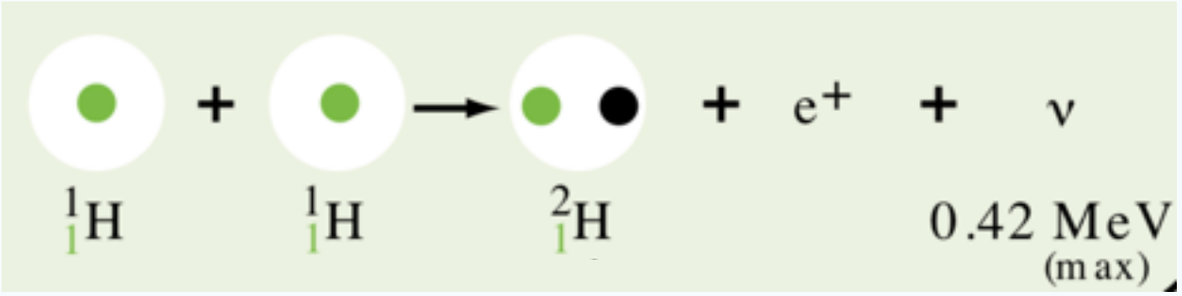
W玻色子质量控制着弱相互作用的强度




$$\frac{G_F}{\sqrt{2}} = \frac{g_w^{\,2}}{8M_w^{\,2}}$$

如果弱力比现在大10%，W质量减少5%



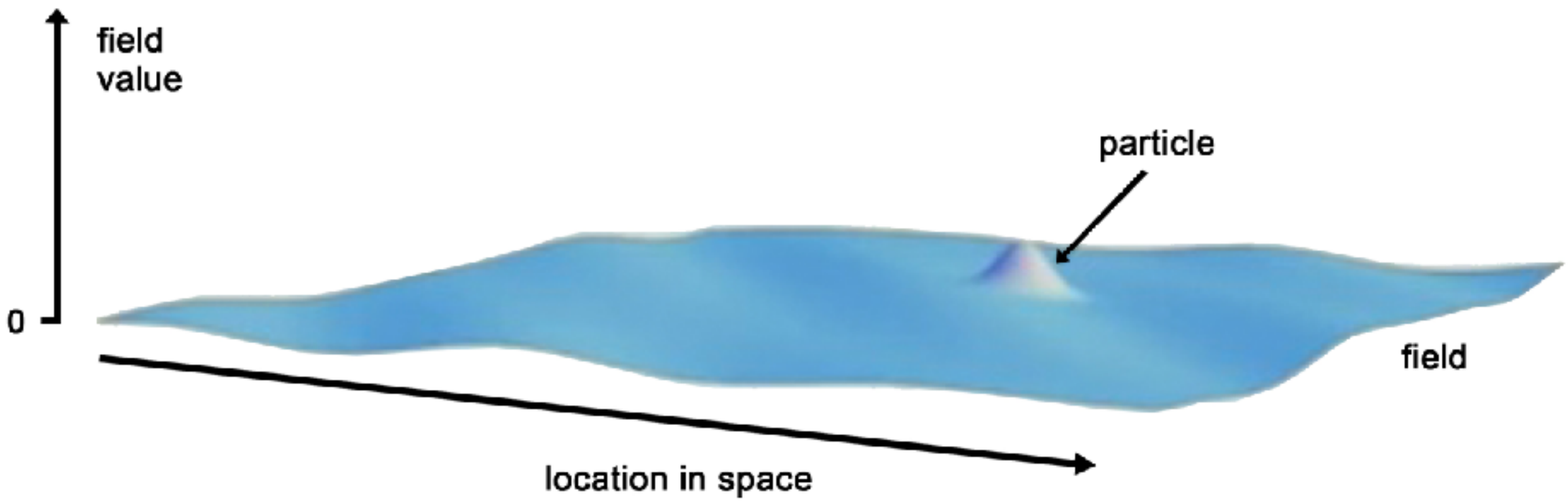

热核反应率变大，太阳的寿命缩短20%

如果W玻色子没有质量，太阳早就燃烧殆尽

# W质量的起源：量子场论

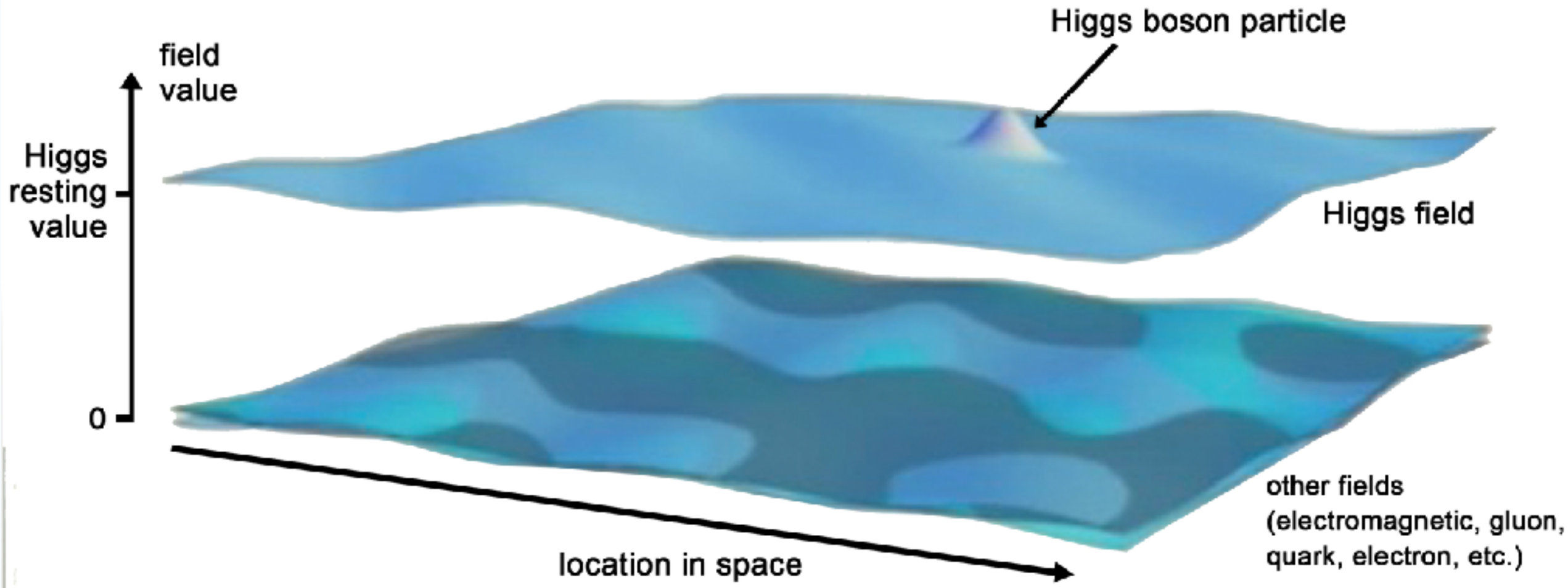
每一个粒子都对应一个场（不只是媒介粒子场），粒子是场的激发

真空不空：存在场，没有粒子激发而已



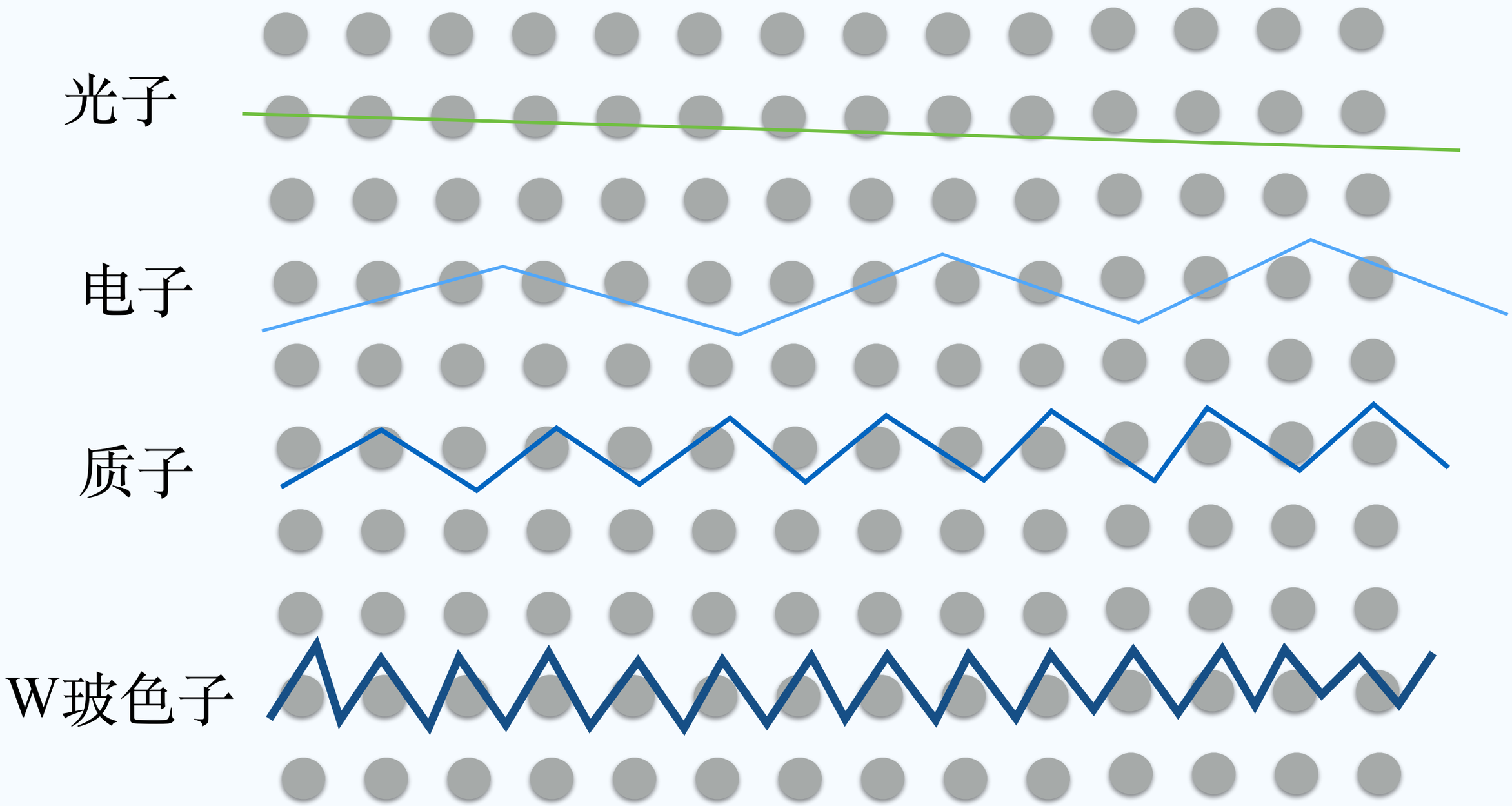
# W质量的起源：希格斯场

希格斯场很特殊：即使没有粒子激发，真空中的场值可以不为零

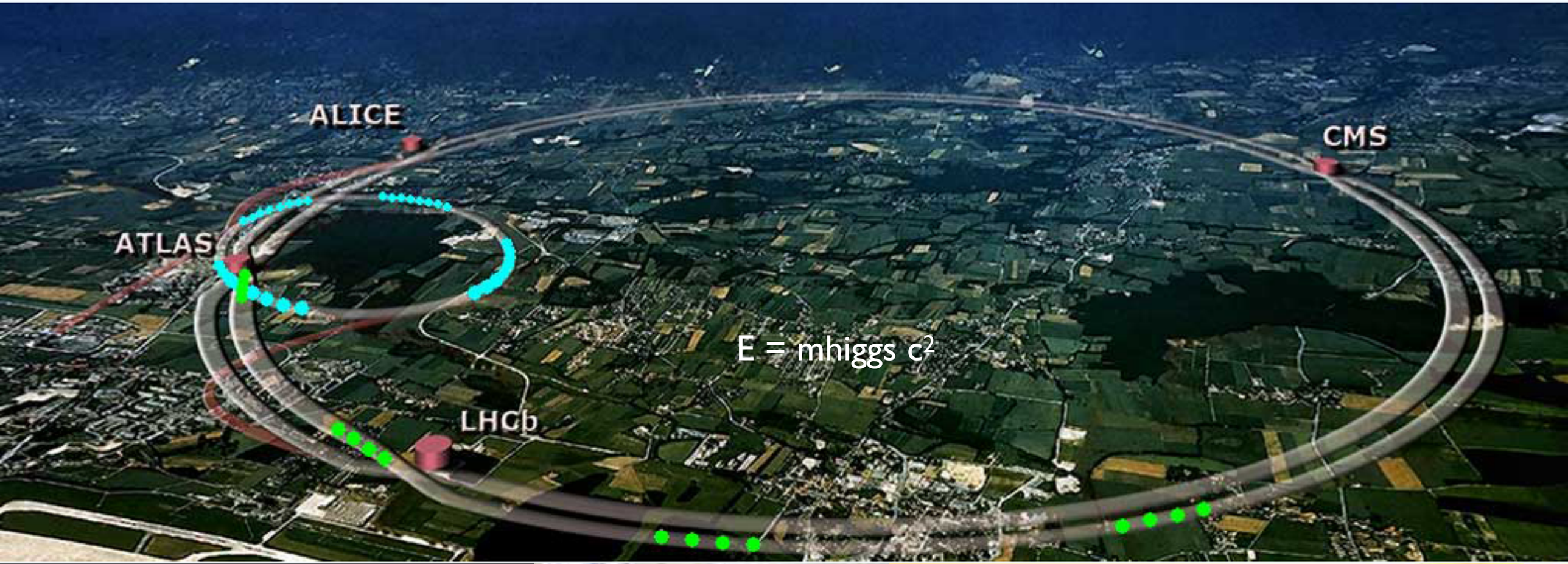


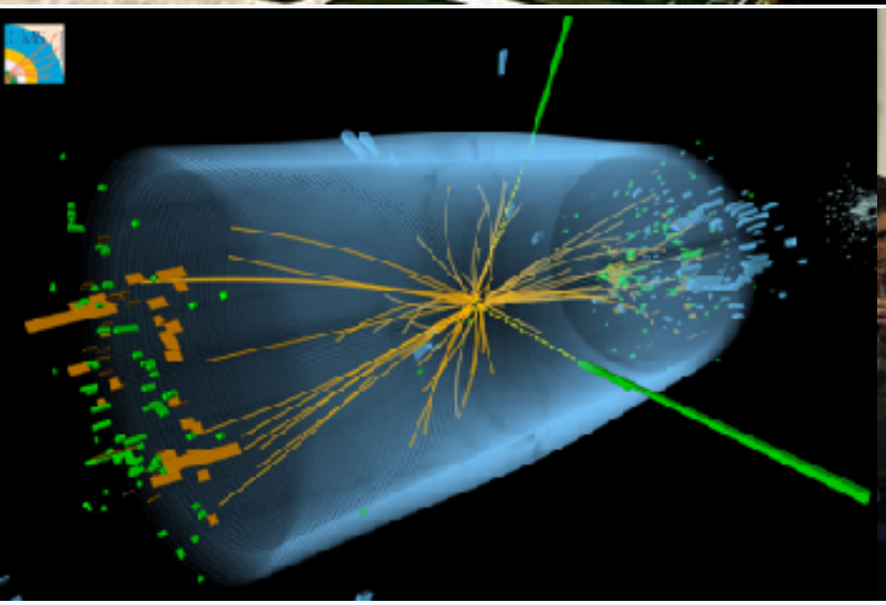
# W质量的起源：希格斯机制

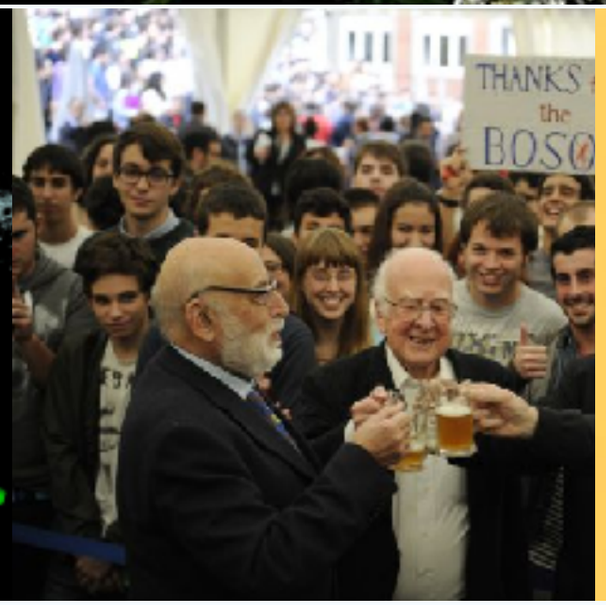
基本粒子的质量和希格斯的场的值成正比

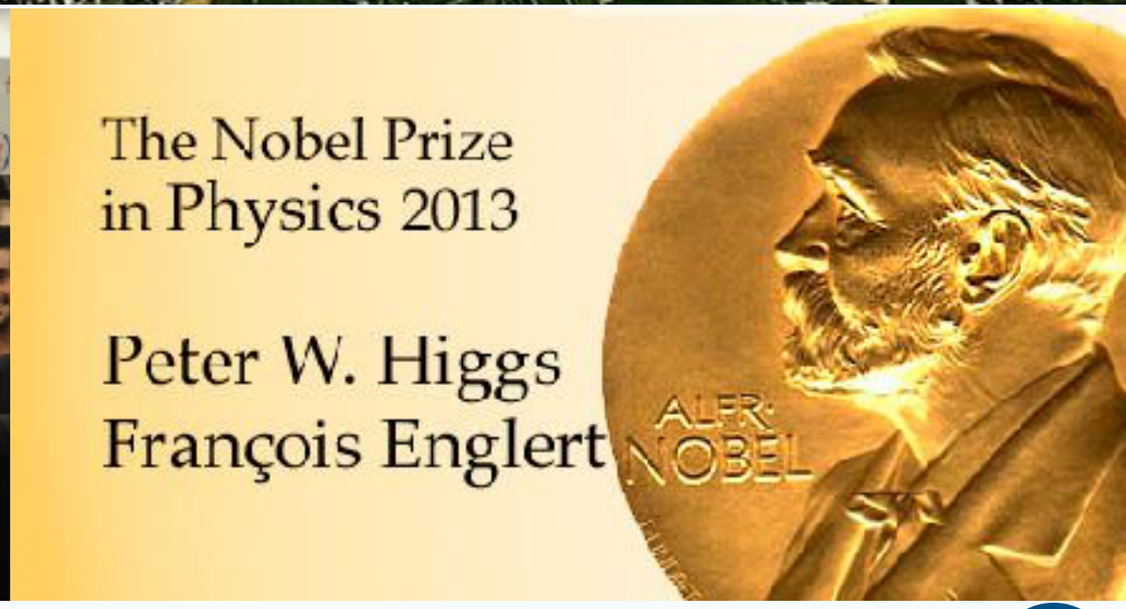


# 希格斯粒子发现

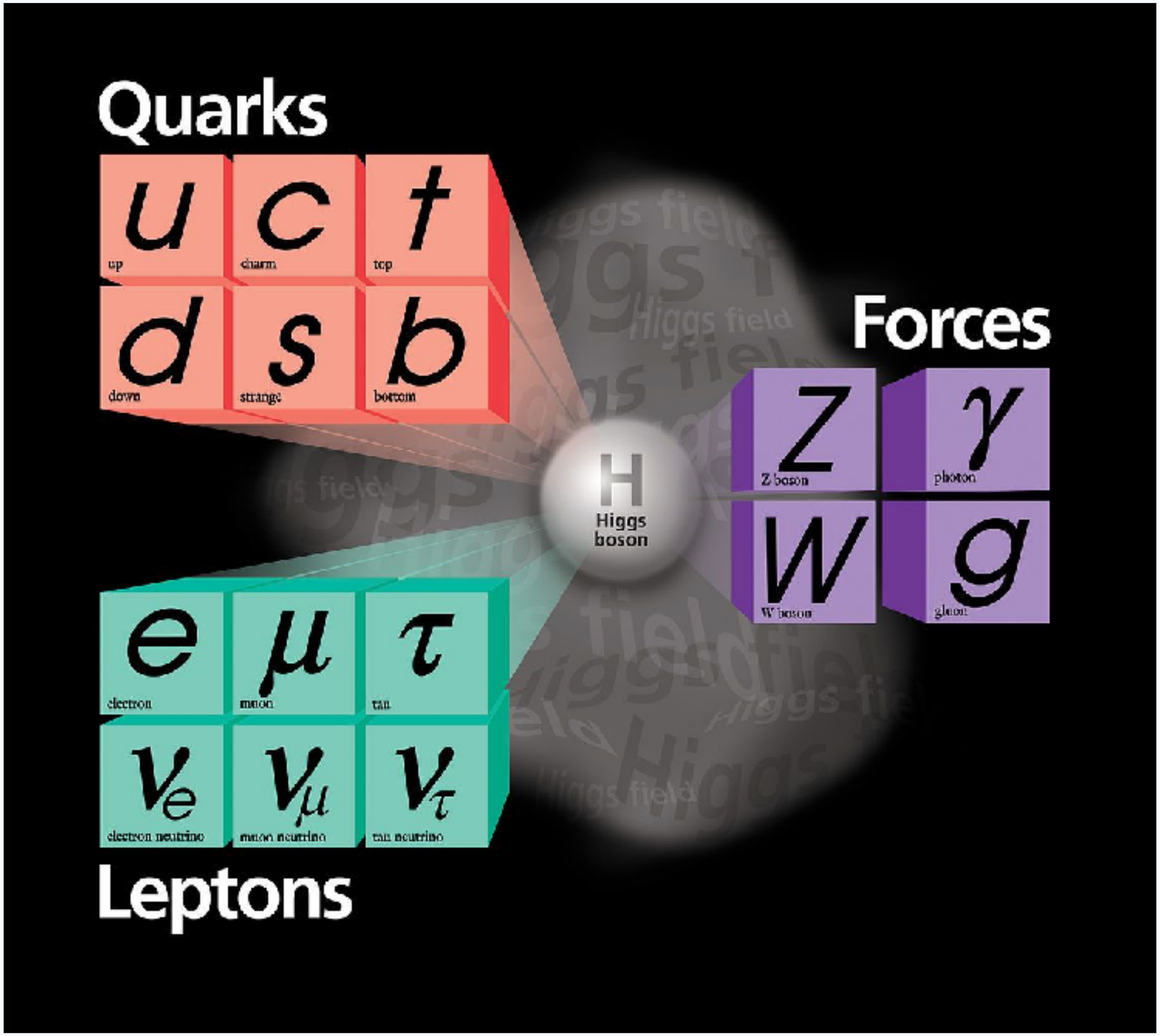

ALICE
CMS
ATLAS
LHCb
E = mhiggs c²




THANKS
the
BOSO

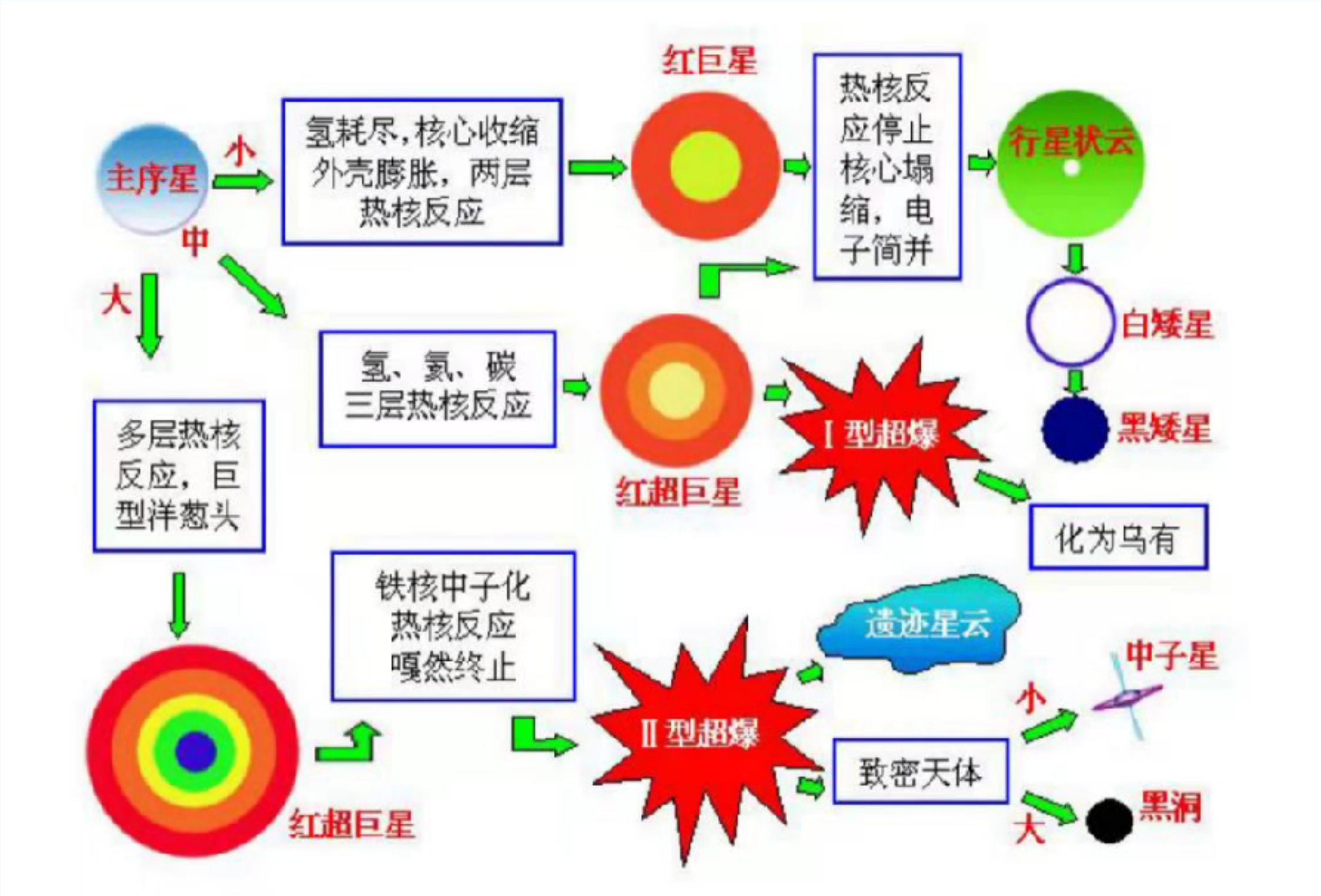

The Nobel Prize
in Physics 2013
Peter W. Higgs
François Englert
ALFR.
NOBEL

# 粒子物理标准模型


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs boson
e
electron
μ
muon
τ
tau
$\nu_e$
electron neutrino
$\nu_\mu$
muon neutrino
$\nu_\tau$
tau neutrino
Leptons

谢谢大家！

# 太阳（恒星）的宿命


主序星
小
中
大
氢耗尽，核心收缩
外壳膨胀，两层
热核反应
红巨星
热核反应停止
核心塌缩，电子简并
行星状云
白矮星
黑矮星
氢、氦、碳
三层热核反应
红超巨星
Ⅰ型超爆
化为乌有
多层热核反应，巨型洋葱头
铁核中子化
热核反应
嘎然终止
遗迹星云
Ⅱ型超爆
致密天体
中子星
小
大
黑洞
红超巨星