The Quest for Mass
--- 质量之谜

Tao Han (韩涛)
University of Pittsburgh / 清华大学物理系

KITS Public Lecture, Sept. 28, 2017

François Englert and Peter W. Higgs

"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

Is "the Quest for mass" completely resolved ?

质量起源问题完全解决了吗？

Outline

What Is Mass?（什么是质量？）

Ask a pedestrian, ask a physicist student, or ask a “theoretical physicist”...

The Mass Generation？（质量如何产生？）

The Mass Puzzle in the Universe（宇宙质量未解之谜）

What Is Mass?

Ask a pedestrian about it …

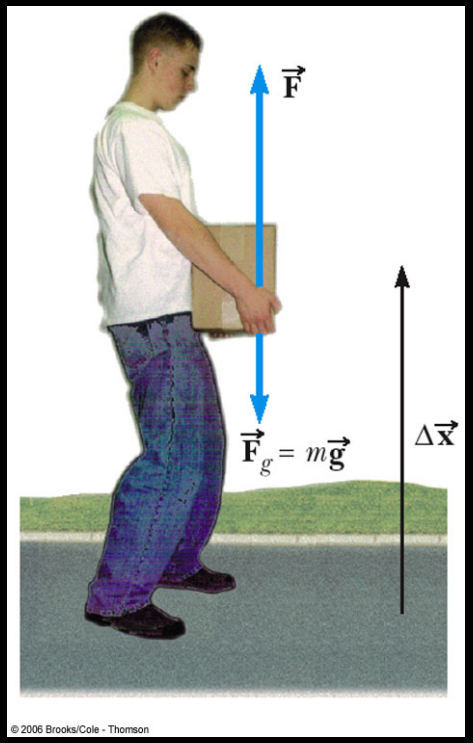
路边行人如何回答？

They are likely to think about the weight.

That's not too far off:

m = Weight / g

质量与重量的关系



T. Han

What Is Mass?

Ask a physicist …

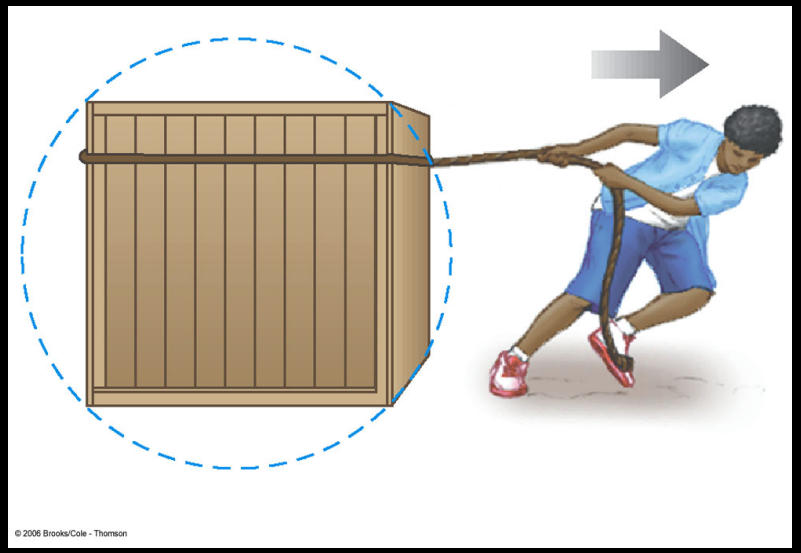
物理学家的定义？

- Based on Newton's 2nd Law:

  $m = F / a$

物理意义：惯性

Mass as Inertia: Mass (m) is the property of an object that measures how hard it is to change its motion.



- Based on Equivalence Principle :
  (Galileo/Newton/Einstein)

$$m_{init}\, a = F = m_{gravity}\, g$$

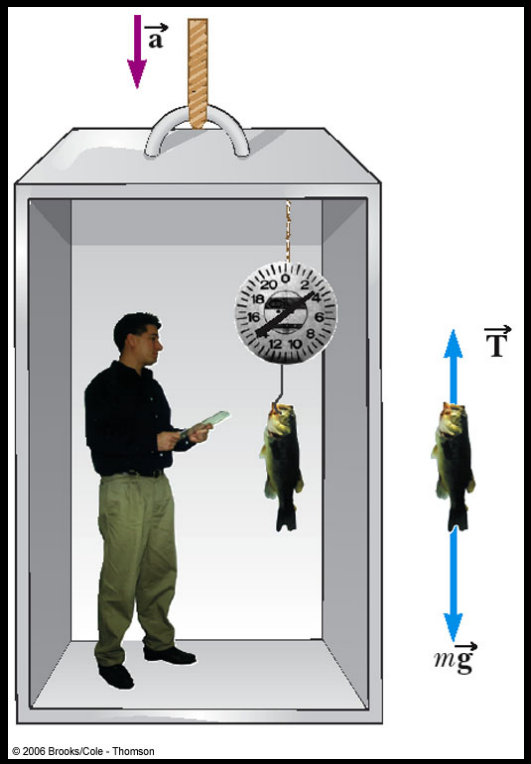
物理意义:等效原理

The inertia mass is equivalent to the gravitational mass :

$$m_{init} = m_{gravity}$$

Or acceleration is equivalent to gravity.

$$a = g$$



Some Basic Properties of Mass:

经典力学范畴:

(a) Mass conservation:

"… neither created, nor destroyed."

$(m1+m2+\ldots)_{initial} = (M1+M2+\ldots)_{final}$

"质量不能被产生, 也不能消失。"

(b) Simple additive:

$M = m1 + m2 + \ldots$

"质量可以简单相加。"

Einstein's Special Relativity (狭义相对论):

THE most celebrated equation:

物理学最著名的公式: $E = m c^2$

$m = m_0 /(1-v^2/c^2)^{1/2}$

This is profound:

E (joule) = m (kg) x 8.99 x 10^{16} $(m/s)^2$

just like

W (joule) = Q (cal) x (4.17)

Mechanical equivalent of heat: 热功当量

Mass-energy equivalence：能量质量等效

静止质量更基本: m_0 ＝ m(v=0)

Einstein's General Relativity (广义相对论):

This becomes even trickier !

Given the constituents of the Universe by Lagrangian *L*,

能量一动量张量:

$$T^{\mu\nu} = (2\, \delta/\delta\eta^{\mu\nu} - \eta^{\mu\nu})\, L_{matter}$$

The Einstein field equation (爱因斯坦方程):

$$G^{\mu\nu}(\text{space-time}) = T^{\mu\nu}(E, p, m) - \Lambda\, g^{\mu\nu}$$

- Energy-momentum, mass are the sources.
- Energy-momentum is conserved.
- May have additional contribution: Λ (宇宙常数)

In short :

Rest mass of "elementary particles",
that are the building blocks of the world.

基本粒子的静止质量具有基本意义！

Energy is rigorously conserved (能量守恒)

(a) Mass conservation ? Only approximate if

$m c^2 >> E_K \approx \frac{1}{2} m v^2$ (低速运动, 用动能)

(b) Simple additive ? Only approximate if

$m c^2 >> E_{potential}$ (弱关联, 弱作用)

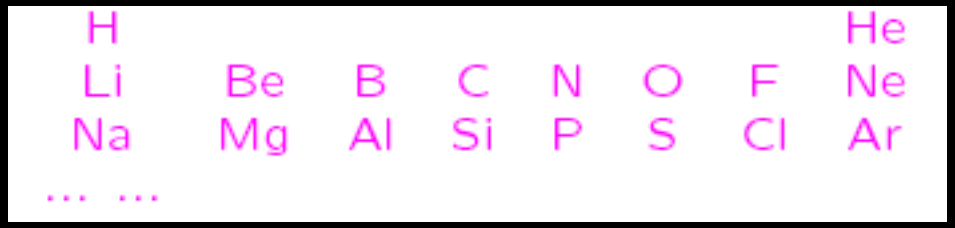
The Origin of Mass — 质量起源

The world is made of …

Ancient Chinese: 金，木，水，火，土
Ancient Greeks: *Four elements; Atoms*

E. Rutherford (1909): *Atom = Nucleus + Electrons*

All around us: Molecules → Elements → Atoms



We are in the atomic quantum world, mostly

Mass = M(nucleus) + small electrons

Because *nucleus non-relativistic, Coulomb force weak.*

The Origin of Mass

In nuclear physics:

Nucleus → bunch of nucleons: $p^+ + n^0$

M(nucleus) = M(p's, n's) - 1% binding energy
(binding energy：结合能
or mass deficit：质量亏损.)

Numerically,
M(p) ≈ M(n) ≈ 1 GeV =10^9 eV.
Binding energy ≈ O(few MeV / N)

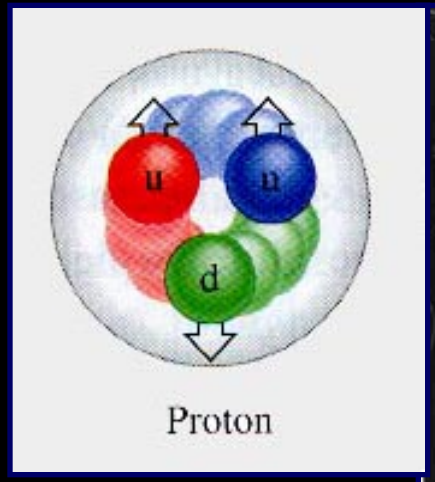
Nuclear transition to lower-mass to release *E ;*
You provide the mass deficit to release *p's, n's* .

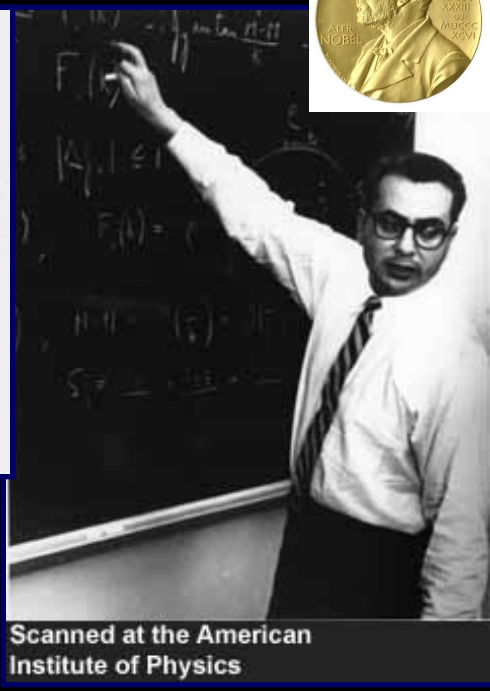
The Origin of Mass

Nucleon Structure: 核子结构

M. Gell-Mann (1963): 夸克

Nucleons (p, n) ≈ 3 quarks:
"up" quark (Q=+2/3),
"down" quark (-1/3)





M(p=uud) ≈ M(n=udd)
≈ M(3 quarks) - "binding energy"
??? ???

deep into relativistic quantum world:
相对论的量子世界 …

Elementary Particles: 基本粒子

Full chart of matter:

6 quarks (u,d…) 夸克; 6 leptons (e^-, μ …) 轻子

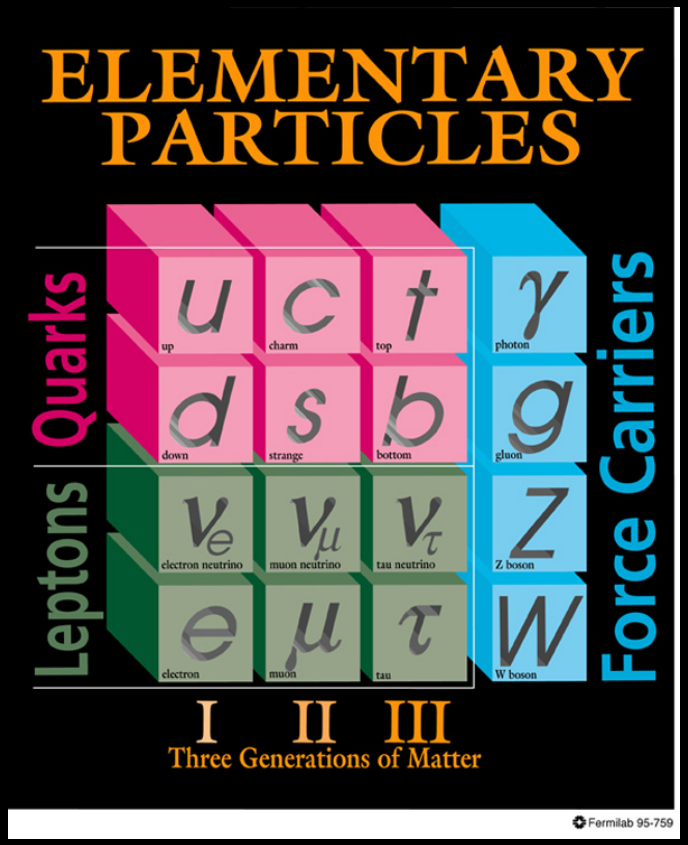
Matter Interactions
via force mediators:

g, W, Z, γ

The "Standard Model":
标准模型

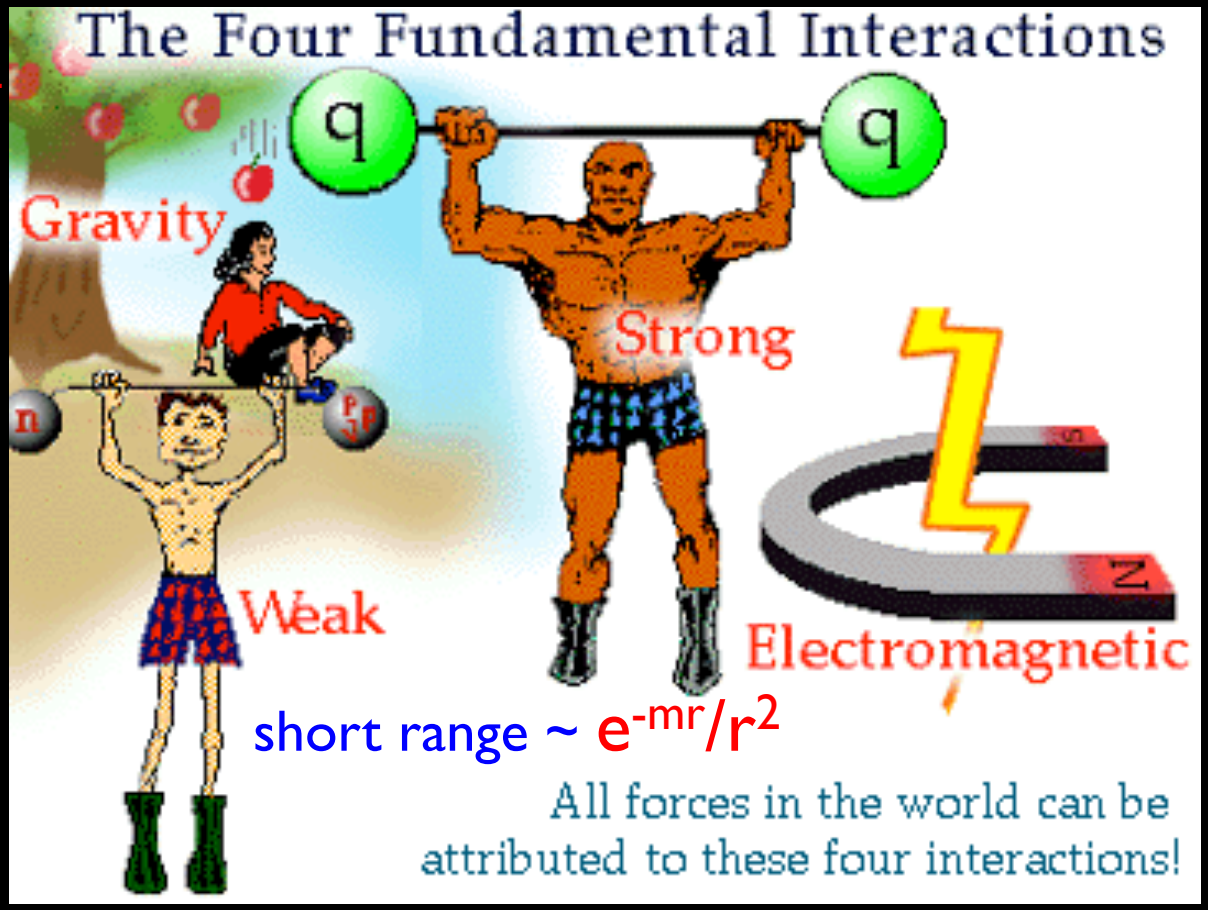
Observationally successful !

But, many free parameters.



The Nature of 4 Forces:

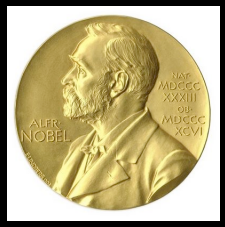
long range
$\sim(G_N m_1 m_2)/r^2$
→ GR



long range
$\sim(\alpha e_1 e_2)/r^2$
→E&M

Why are they so different? The mass!

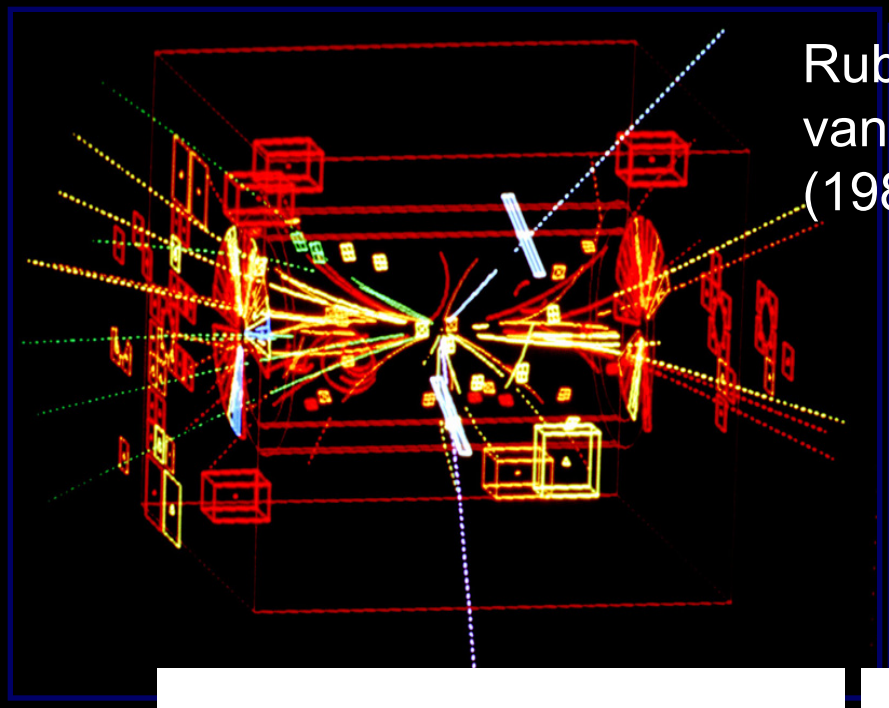
Electroweak Unification:
电-弱统一模型



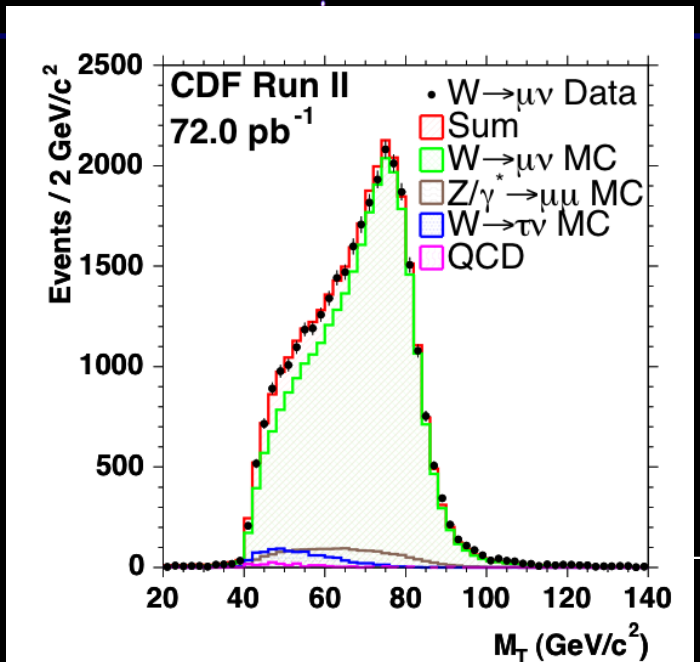
- Glashow, Salam, Weinberg realized that the field responsible for the electromagnetic force (the massless photon)
- And the fields responsible for the Weak force (the then undiscovered massive W^+ and W^-)
- Along with a then undiscovered massive neutral boson (Z) $\Rightarrow$ a single theory

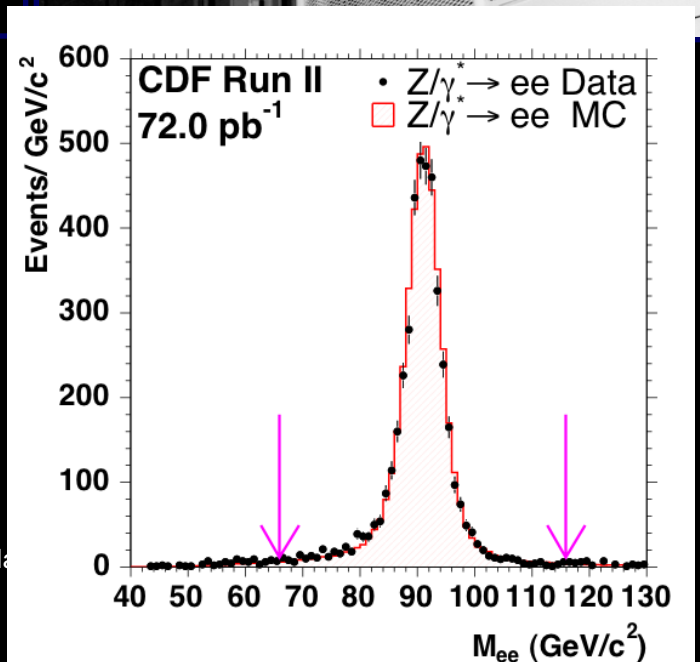
Plus a scalar sector, for the EW symmetry breaking (masses).

$W^{\pm}/Z$ Discovery in 1982:



Rubbia and van de Meer (1984)

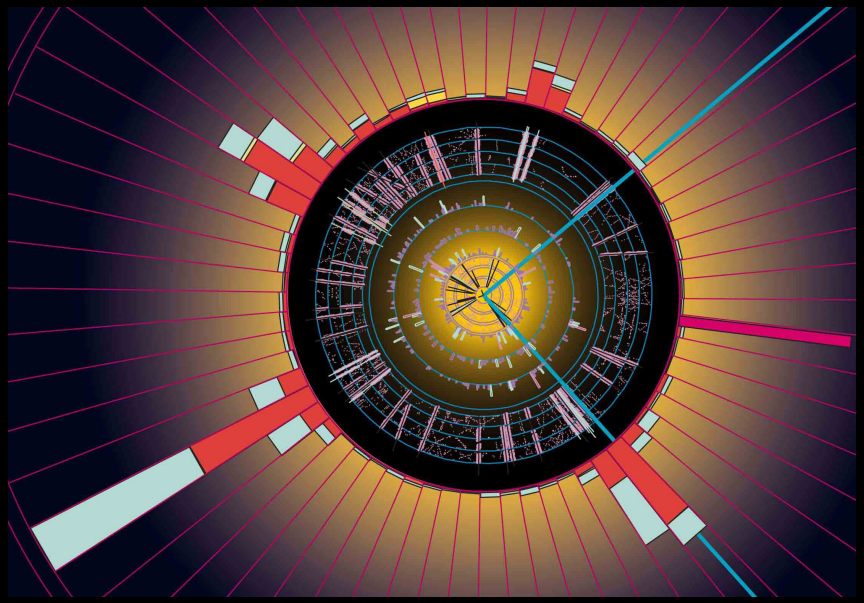




The Quest for Mass persists:

Why the photon is so different from $W^{\pm}/Z$?

$M_\gamma = 0$!
$M_W \approx 80$ GeV
$M_Z \approx 90$ GeV



Why the top quark is as heavy as a gold atom,

while neutrinos are nearly massless ?

M_t=173 GeV (Fermi Lab)

$m_\nu < 1$ eV

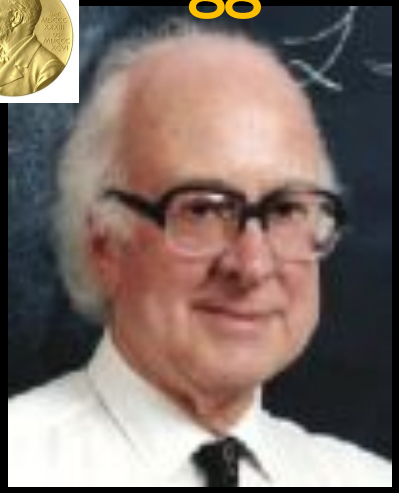
自发破缺对称性

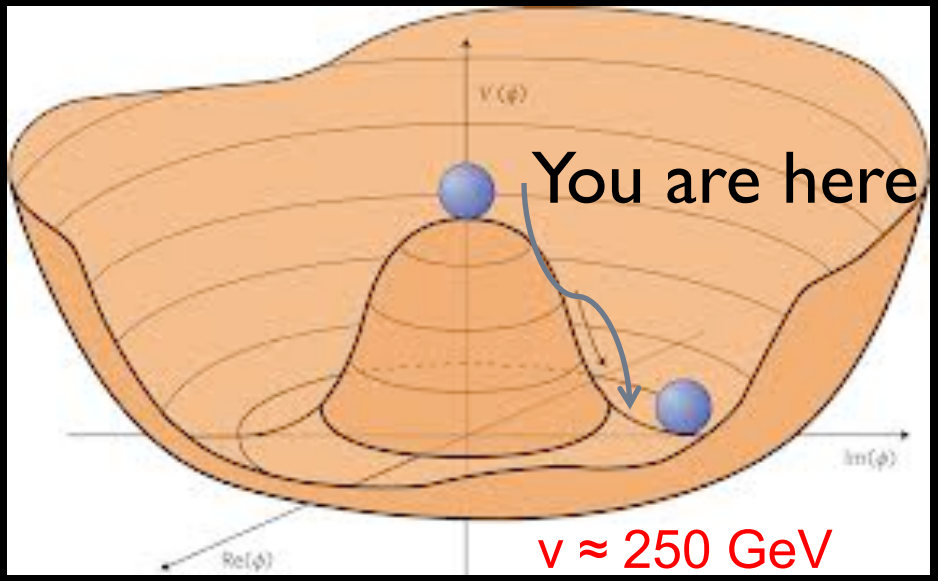
"Spontaneous symmetry breaking"

(known in Nature: QCD, condensed matter ...)

Nambu

Higgs





The theory is symmetric, but the background environment（vacuum－真空）is NOT.

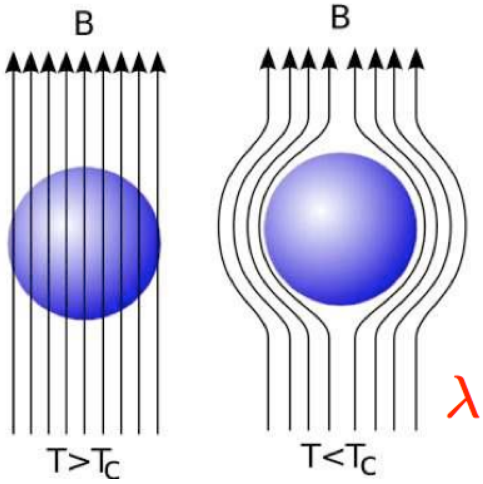
（真空就是能量最低的状态。）

A familiar example:

Normal phase⇒

$E^2 = p^2c^2$

Long-range force



⇐Superconducting phase

$E^2 = p^2c^2 + m^2c^4$

gap leads to $\sim exp(-r/\lambda)$

$\lambda \sim m^{-1}$ penetration depth

In "conventional" electro-magnetic superconductivity:

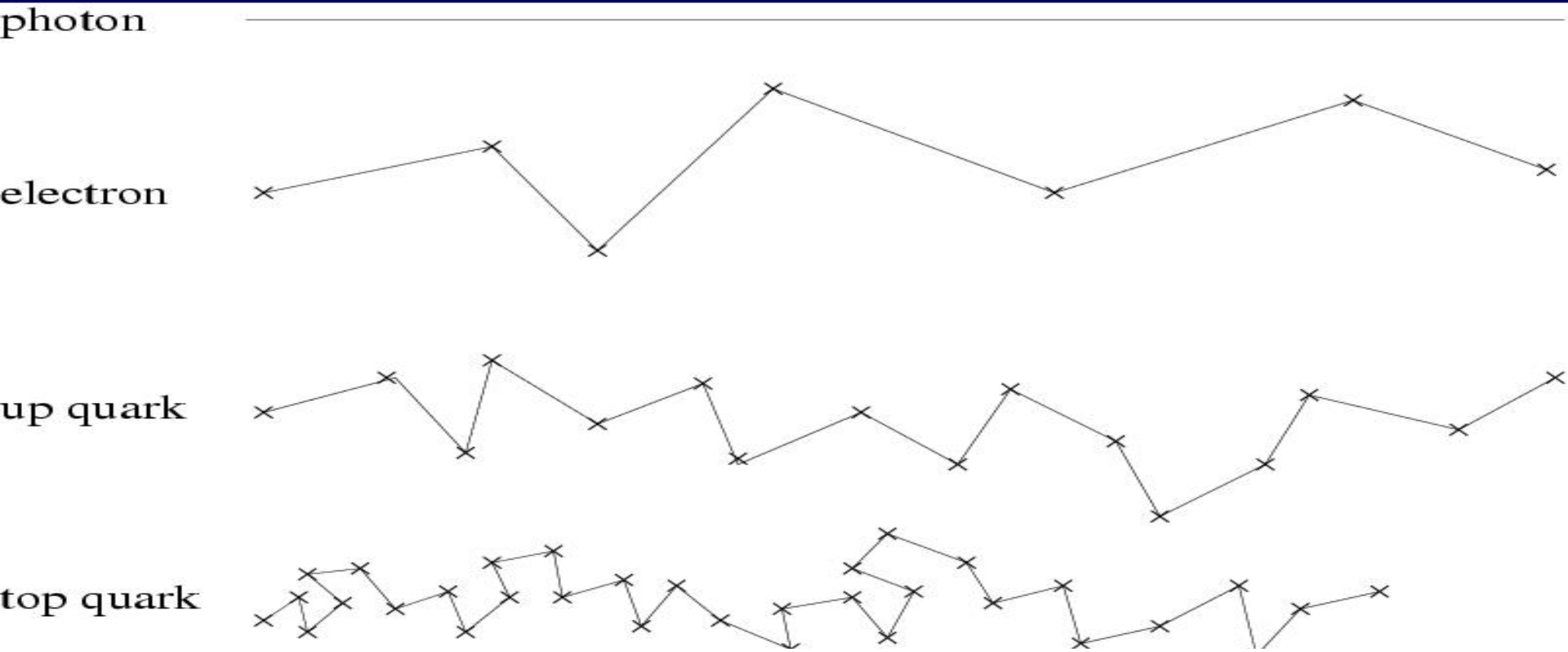
$m_\gamma \sim m_e/1000$, $T_c^{em} \sim \mathcal{O}(\text{few } K)$. BCS theory.

In "electro-weak superconductivity":

$m_w \sim G_F^{-\frac{1}{2}} \sim 100$ GeV, $T_c^w \sim 10^{15} K$!

我们就是生活在(EW)超导的环境里！

Masses determined by interactions with vacuum:
（质量来源于粒子同真空环境的相互作用）

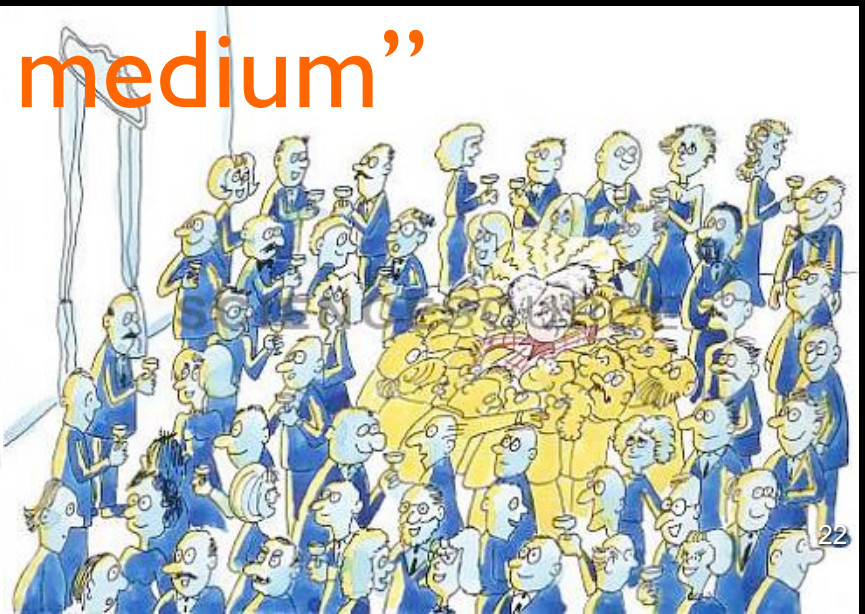


$$M_{W,Z} = \frac{1}{2} g_V v, \quad m_f = \frac{g_f}{\sqrt{2}}\, v, \quad v^{-2} = \sqrt{2}\, G_F.$$

Crucial prediction of SM: The Higgs boson H, $m_H = \sqrt{2\lambda}\, v$.

Masses determined by interactions with vacuum: It's like in a medium …

Or in a "social medium"



How to Study the Vacuum Property ?

如何研究真空性质？

Strike the vacuum hard for a signal !

The vacuum background is NOT empty: Particles can be excited, including the Higgs!

Large Hadron Collider: LHC
（大型强子对撞机）

At CERN, Geneva:

proton-proton collider:

27 km circumference;

1746 magnetic dipoles at *1.9 K*

Only 7 mph slower than *c*

Stored Energy of Beams as an aircraft carrier at 30 km/h !

Now operating at 13,000 GeV

Requires Detectors of Unprecedented Scale（大型探测器）

- Two detectors:

  3000 people each!

- ATLAS has 8 times the volume of CMS
- CMS is 12,000 tons (2 x's ATLAS)

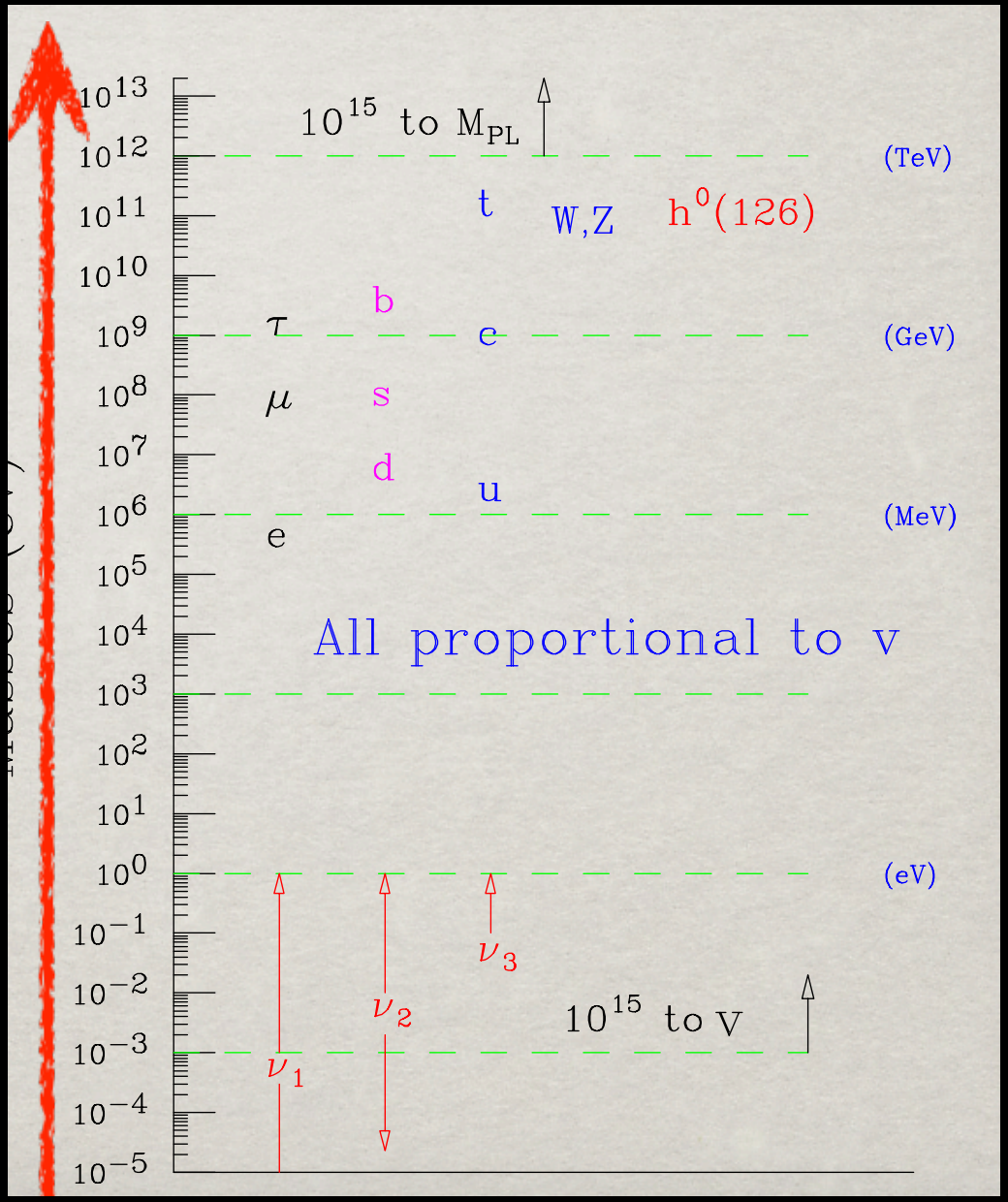
The experiments are extremely difficult !

寻找Higgs是大海捞针 !

It is not a needle in a haystack ---
It is much worse than a needle in a haystack!
--- Joe Lykken, FNAL

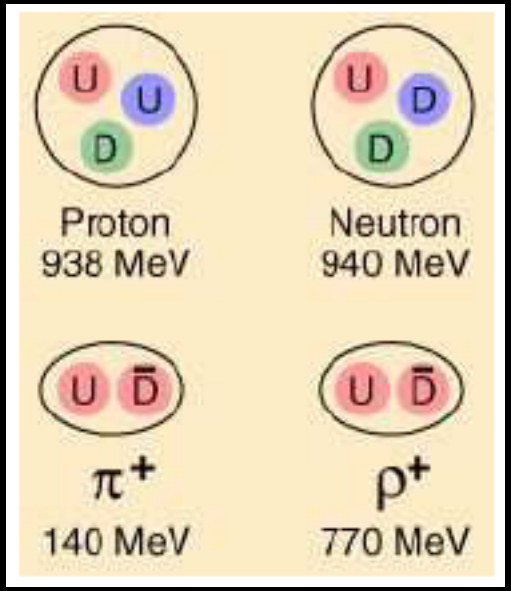
The discovery of the Higgs boson is monumental:
most exciting discovery for decades!
It is a true triumph in HE physics, and in science!

“Mass hierarchy” remains a great puzzle !



The Dynamical Origin of Mass
核子质量的动力学起源

Nucleons (p, n), mesons (π,ρ,K)
Called "hadrons"
← (valence) quarks: "up, down, …"



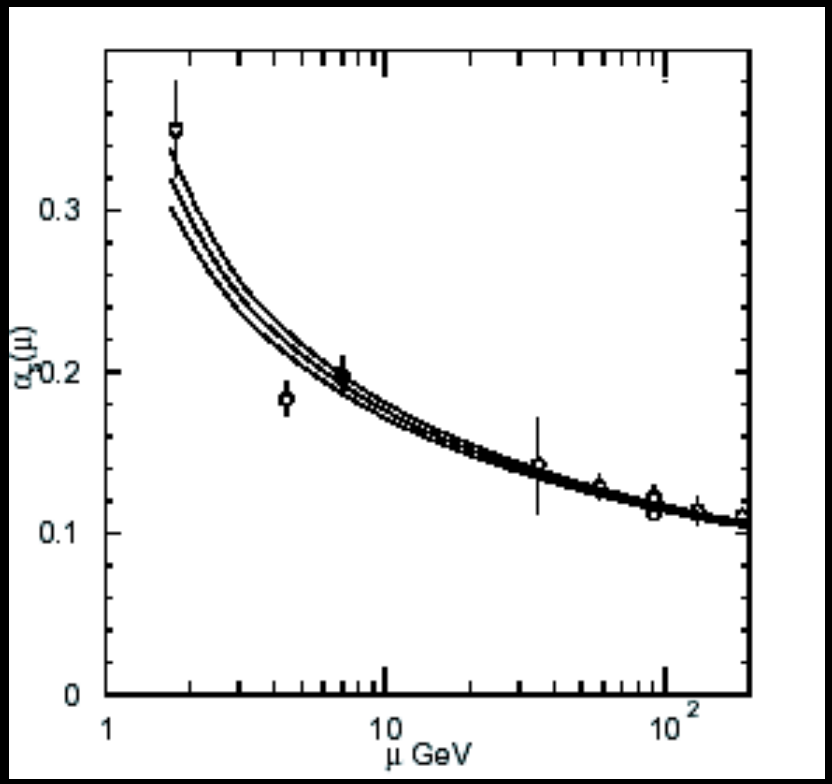
M(hadrons) >> M(a few quarks) !
100-1000 MeV a few MeV

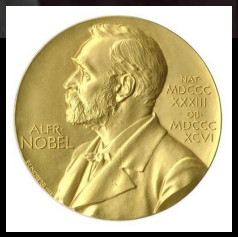
"Simple additive" totally wrong !
Because kinetic/potential energy dominant.

Quantum-Chromodynamics (QCD)

Remarkable feature:

Interaction strength changes fast with energy/distance scale:



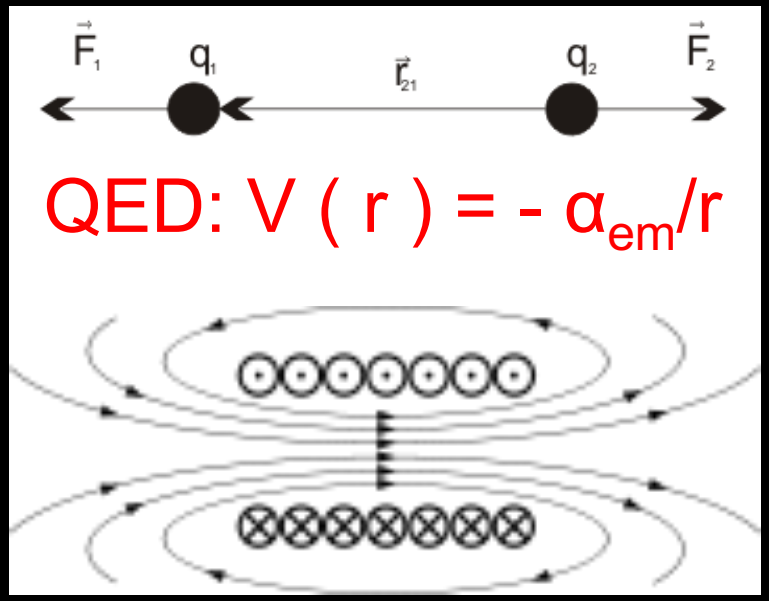


D. Gross,
F. Wilczek,
D. Politzer
(2004)

T. Han

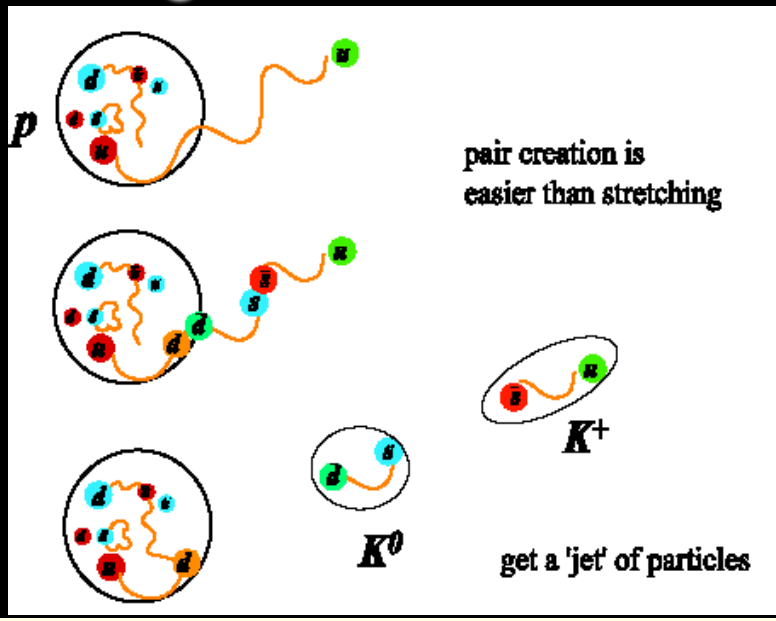
QED（电动力学）versus QCD（色动力学）

Electromagnetism vs. Strong force

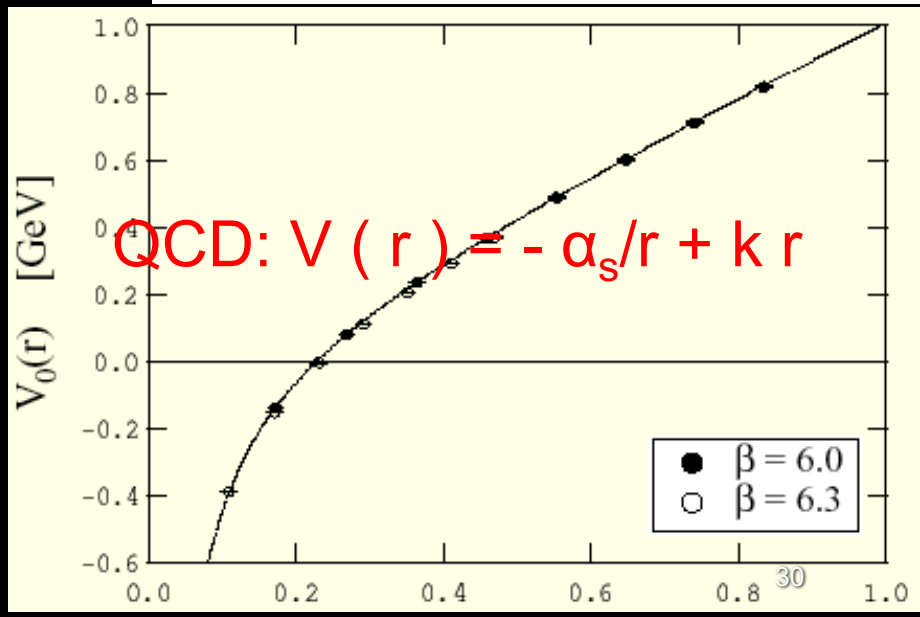


QED: $V(r) = -\alpha_{em}/r$

Photons vs. gluons



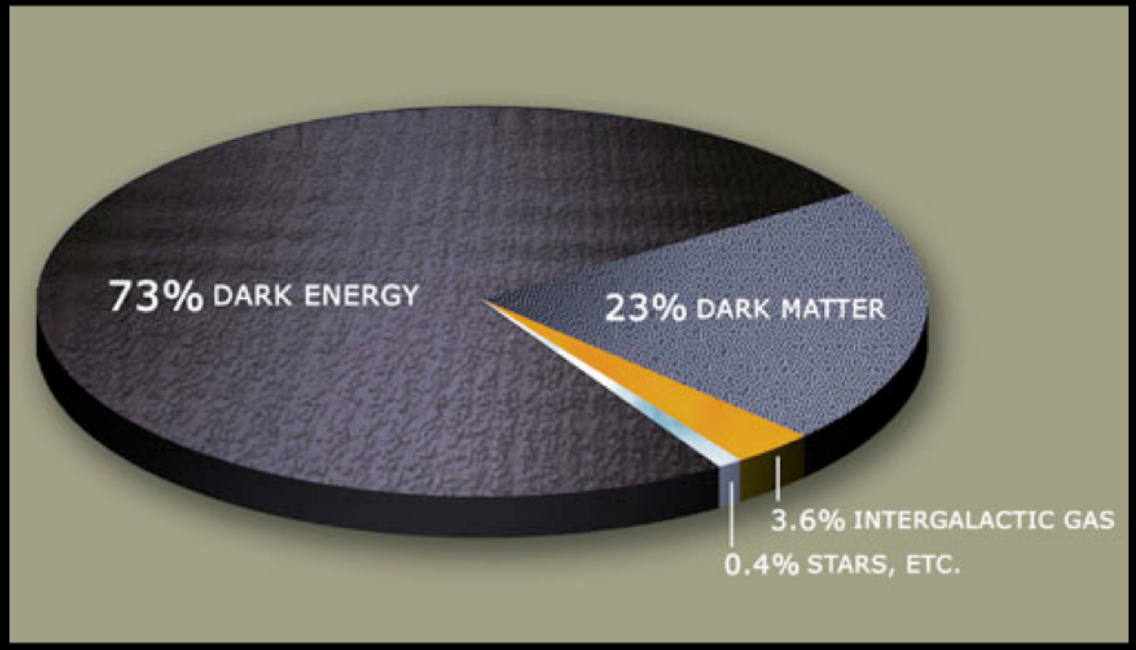
Majority of the (luminous) mass around us （你和我） is of dynamical origin, from strong interactions (u, d quarks + gluons).



T. Han

The Mass Puzzle in the Universe

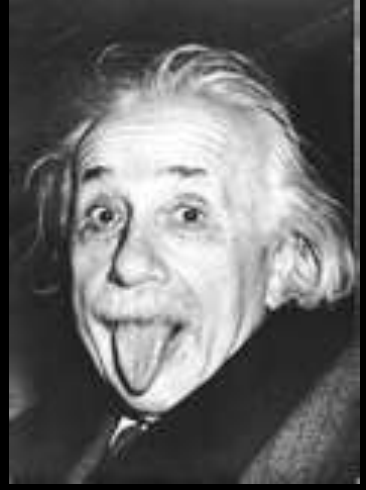
宇宙质量之谜！



- What is Dark Energy ? 暗能量
- What is Dark Matter ? 暗物质
- New sources of CP violation

物质－反物质的不对称性

What is the "Dark Energy" ?



Could it be just Λ ?

$G^{\mu\nu}$(space-time) = $T^{\mu\nu}$(E, p, m) - $\Lambda\, g^{\mu\nu}$

"… greatest blunder of my life!"

Any vacuum energy counts,

but why is it so small ? $(10^{-3}\ eV)^4$

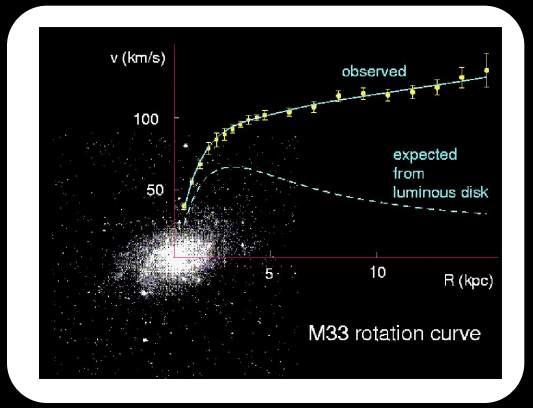
Below M_{Pl} by 120 orders, Λ_{QCD} by 40 orders

Could it be dynamical (time-dependent) ?

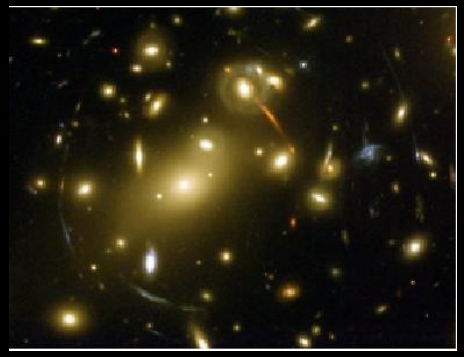
对理论的挑战！最大的未解之谜！

Evidence For Dark Matter

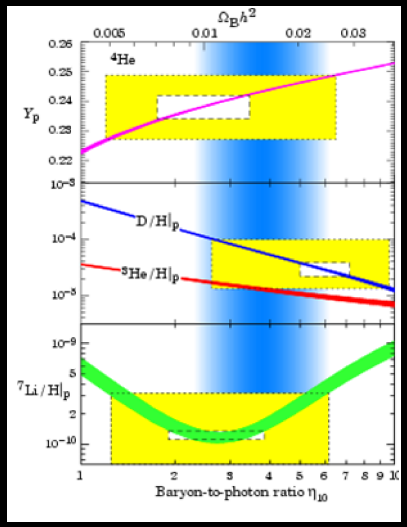
- Galactic rotation curves



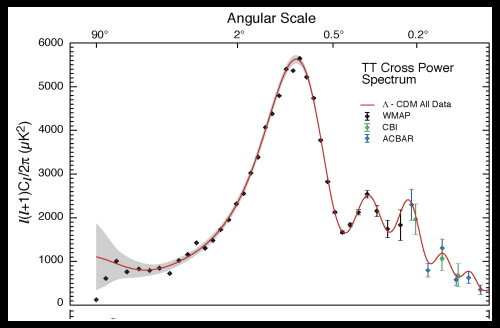
- Gravitational lensing



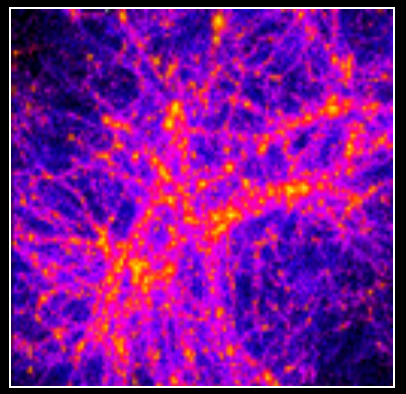
- Light element abundances



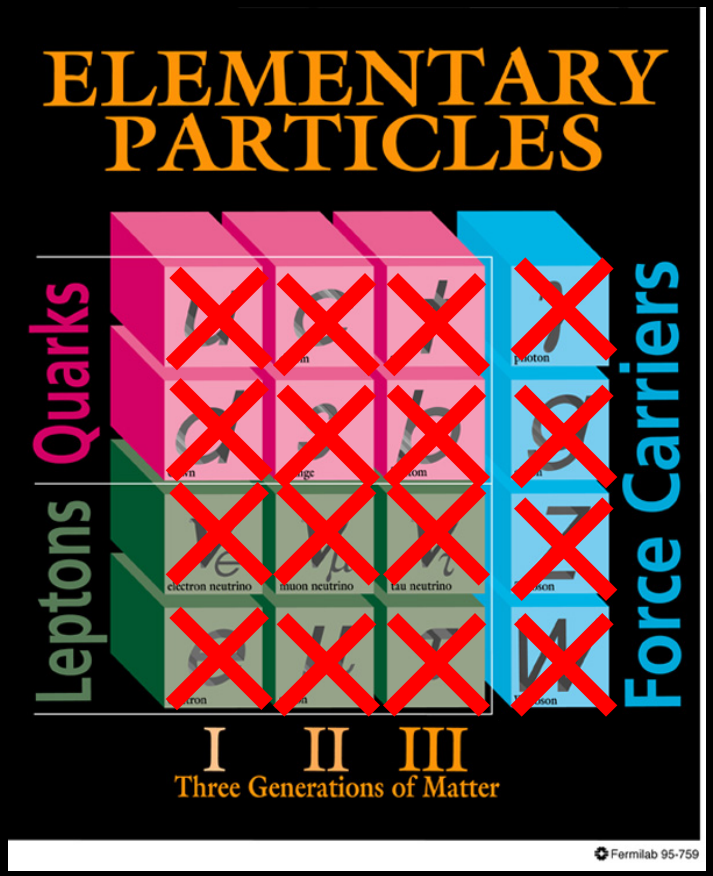
- Cosmic microwave background anisotropies



- Large scale structure



Dark Matter in the SM?



- Gravitationally interacting
- Not short-lived
- Not hot, relativistic
- Not baryonic (p,n)

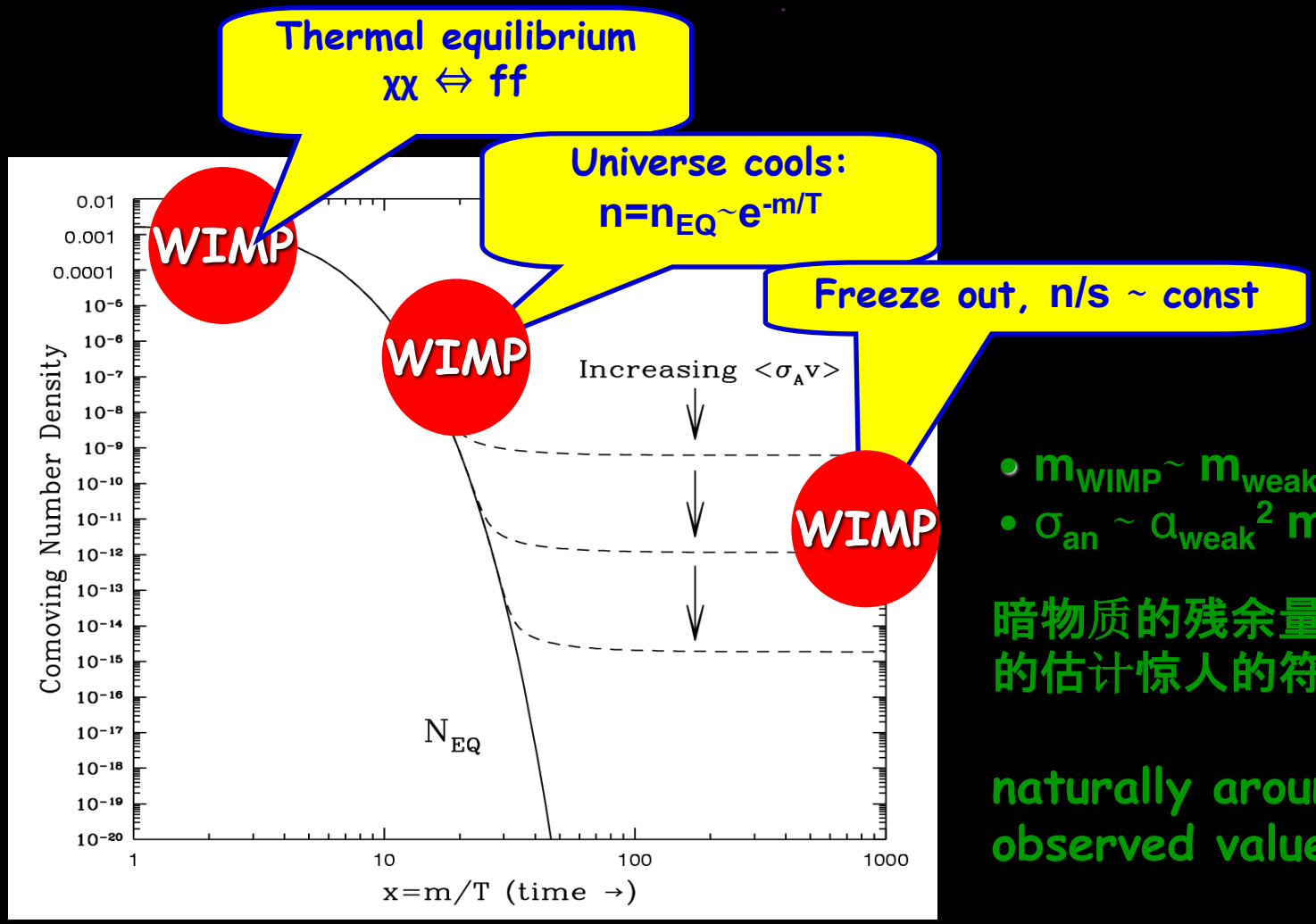
标准模型中没有“暗物质”的选择？！

Unambiguous evidence for new particles!

T. Han

Beyond SM: Many theories lead to

WIMP: Weak Interacting Massive Particle



- $m_{WIMP} \sim m_{weak}$
- $\sigma_{an} \sim \alpha_{weak}^2 \, m_{weak}^{-2}$

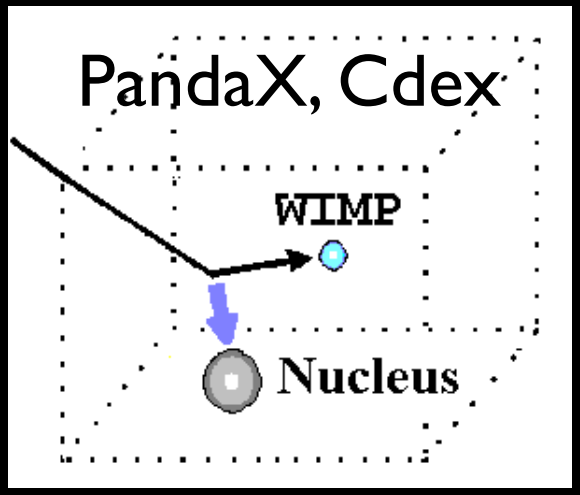
暗物质的残余量与电弱理论的估计惊人的符合！

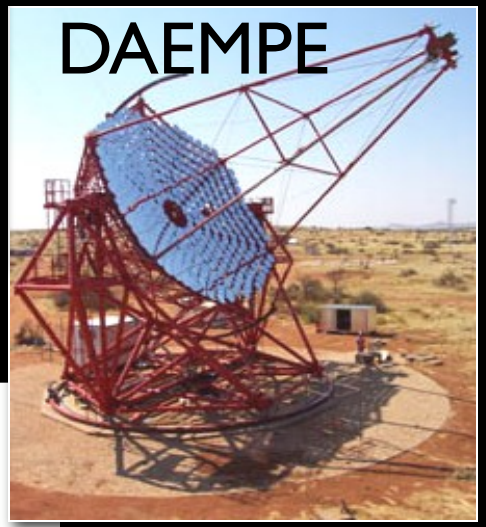
naturally around the observed value

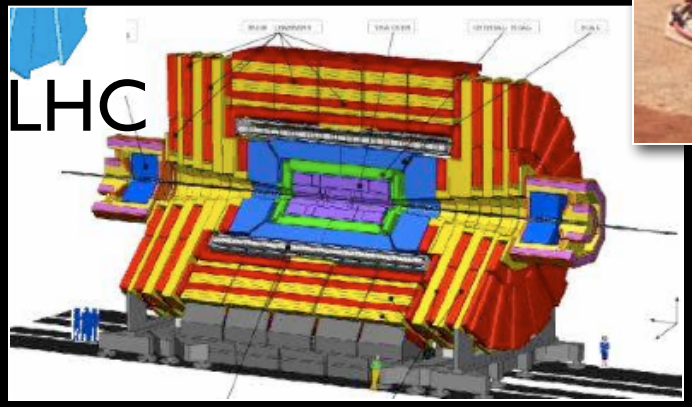
Hard to find something dark!

"在一间漆黑的屋子里很难找到那只黑猫,
特别是, 它也可能没在屋里."

- **Direct Detection**
- **Indirect Detection**
- **Collider Searches**







Summary：总结

What Is Mass？

The Mass，you and me：强相互作用能

Mass for “all of us”: Strong interaction in QCD

The Mass for elementary particles …

Spontaneous symmetry breaking,

and the Higgs mechanism：

源于希格斯机制

Dark Matter, dark energy:

暗物质，暗能量 … 仍然是深奥的迷！

Please join to seek for the answers!

答案还要靠你们新一代的探索！

Largest scientific project ever !

迄今为止最大的科学装置！

- *Only 7 mph* slower than the speed of light
- Stored Energy of Beams unprecedented :
  E_{beam}=*1.5* Giga Joule (N m)

  → same kinetic energy as aircraft carrier at 15 knots ≈ 30 km/h !

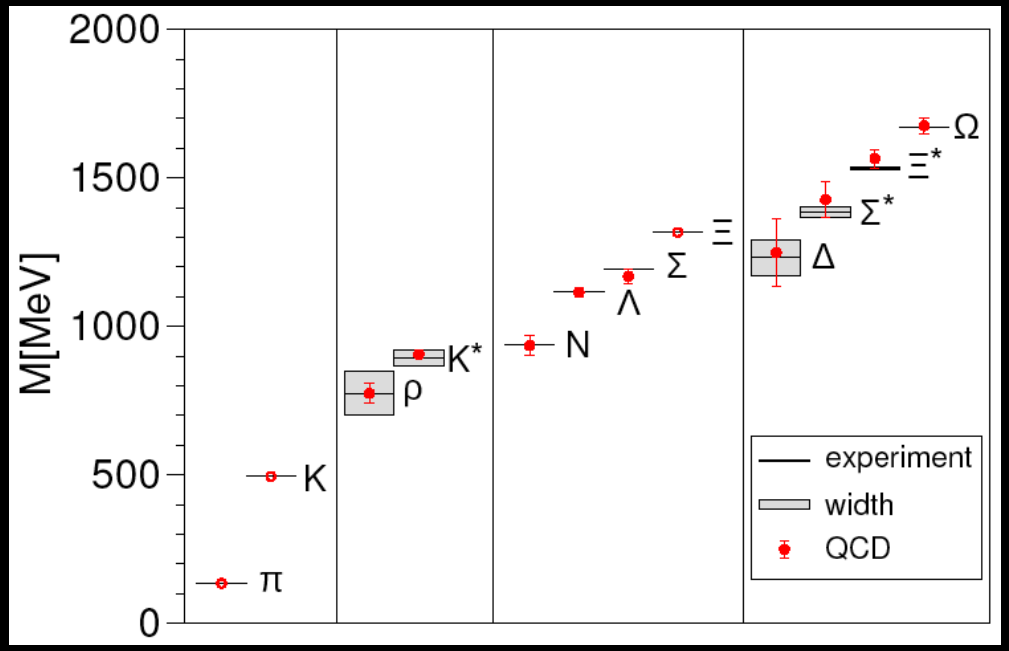
Highest energy, probing smallest scale at

10^{-17} cm (10^{-10} nm) !

T. Han

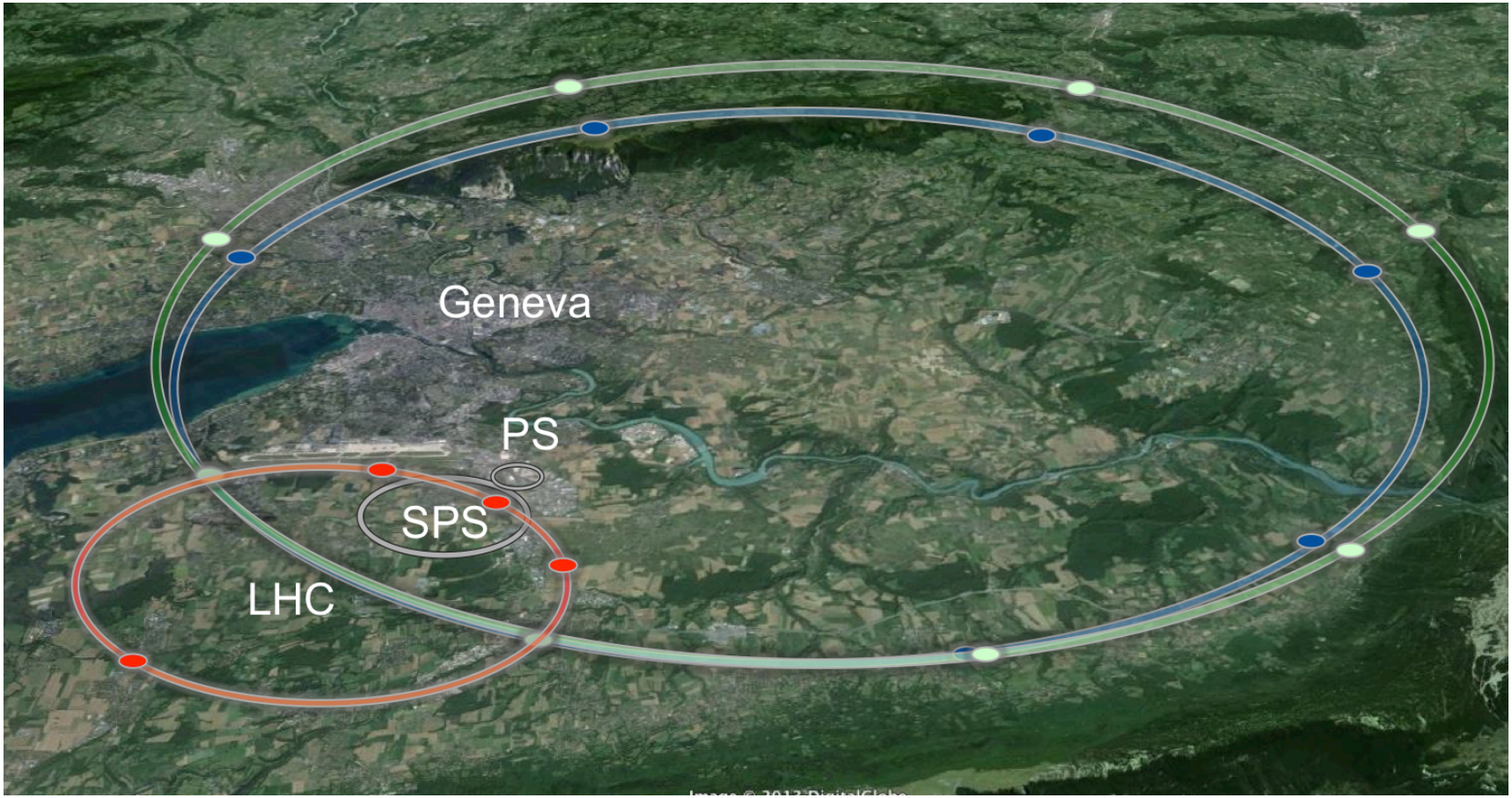
Mass due to QCD:

From quark constituents to hadrons:
(From PDG, based on lattice QCD)



Majority of the (luminous) mass around us is of dynamical origin, from strong interactions (u, d quarks + gluons).
It is not very meaningful to think about quark rest mass .

FCC (future circular collider): CERN



HE-LHC	FCC-ee	FCC-hh
27 km, 20T	80/100 km	80 /100 km, 16/20T
33 TeV	90 - 400 GeV	100 TeV

CEPC (circular e^-e^+)/SppC: China

FHEP

Center for Future High Energy Physics

高能物理前沿研究中心

The Mass Puzzle in the Universe