正负 电子对撞机上的新物理寻找

An introduction to High Energy Physics

我是谁？

我在哪？

我从哪来？

我要到哪去？

相对论

物理学已经解决了很多问题

量子论

并诞生了诸多学科

牛顿力学	理论力学	凝聚态物理学	粒子物理学
流体力学	声学	电子科学	原子核物理学
热力学	统计力学	通信科学	原子物理学
电磁学	电动力学	化学	分子物理学
量子力学	光学	介观物理学	…

还有更多、更严重的问题！

1. 暗物质 (what is dark matter)
2. 暗能量 (what is dark energy)
3. 宇宙演化 (how did the universe come into being)
4. 统一引力 (How does gravity fit into the big picture)
5. 基本粒子(Are quarks and leptons actually fundamental)
6. 多宇宙 (Is our universe unique, or are there many universes)
7. 终极真实 (Can we understand ultimate reality at all through science)
8. 其他(如时间本性，正反物质不对称，复杂动力系统，等等)……

关于这些问题的猜想和理论，大多数都要靠高能物理实验的手段进行验证(包括高能天体物理等交叉科学)

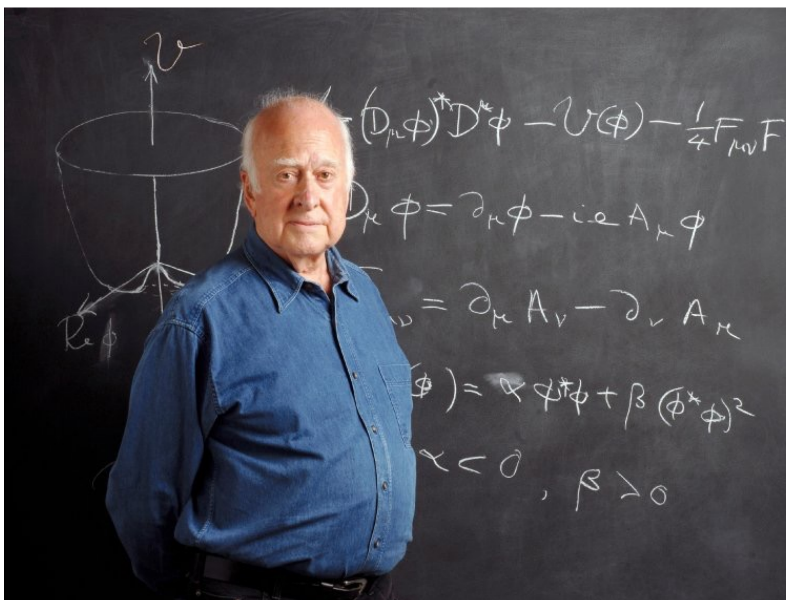
高能物理实验

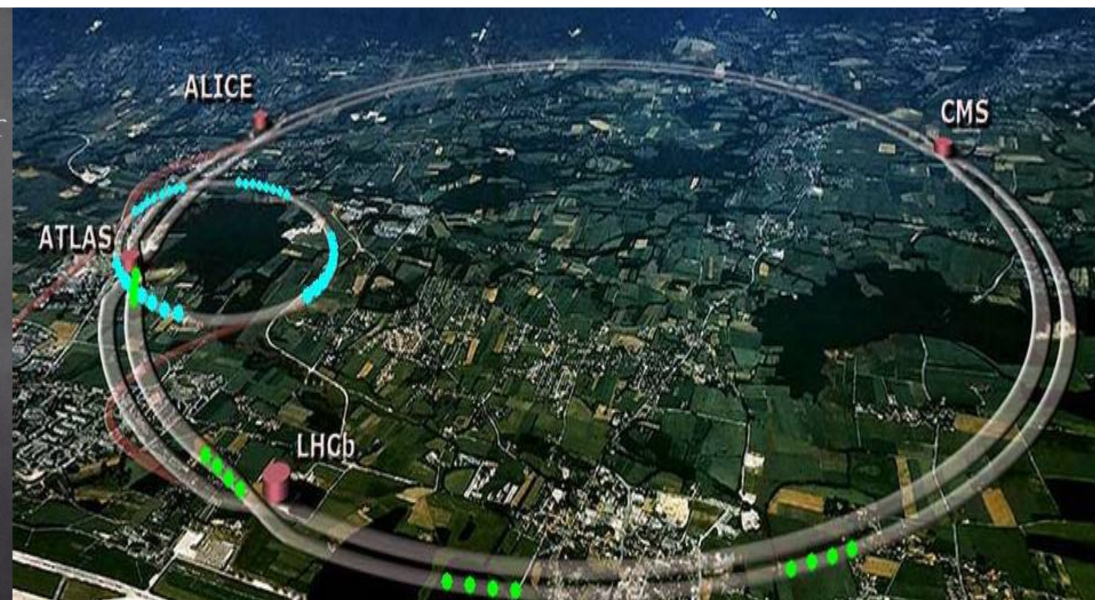
世界由什么组成？

世界如何组成？

世界如何演化？

我们如何知道！





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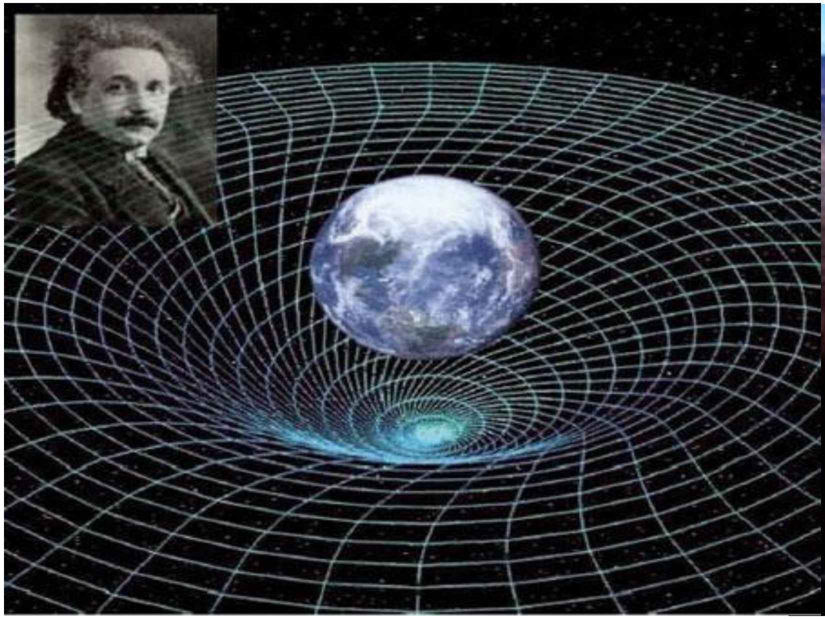

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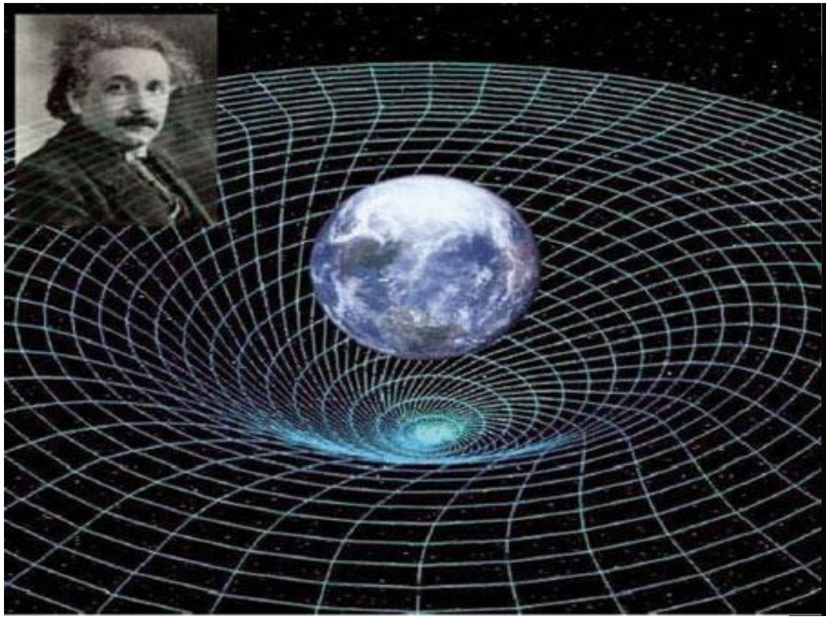
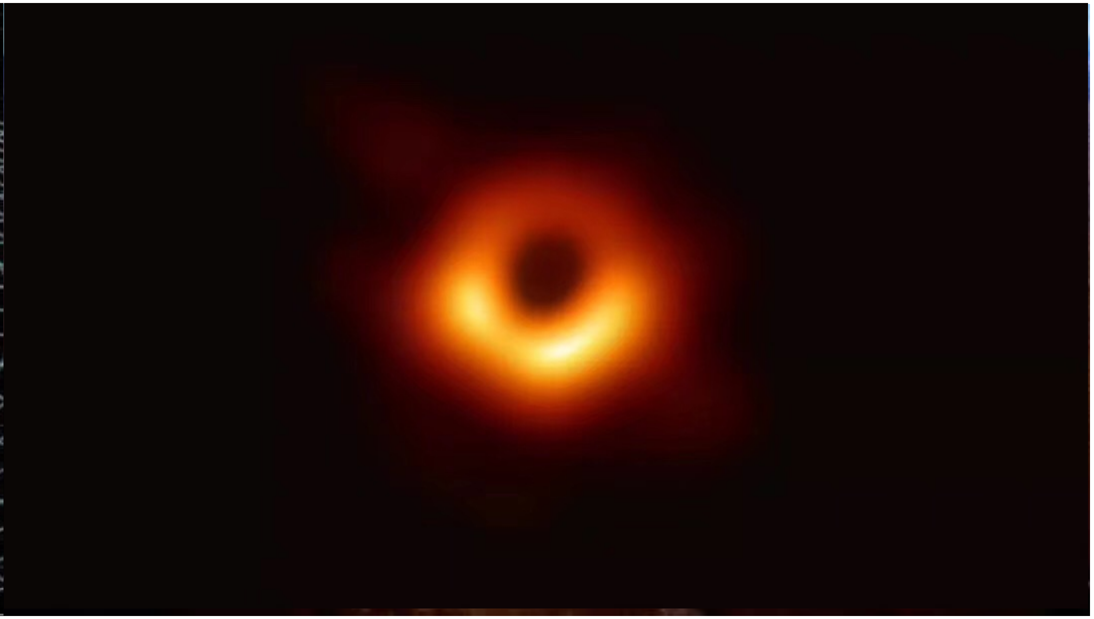




第一个问题：世界由什么组成?

世界由这些东西组成

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

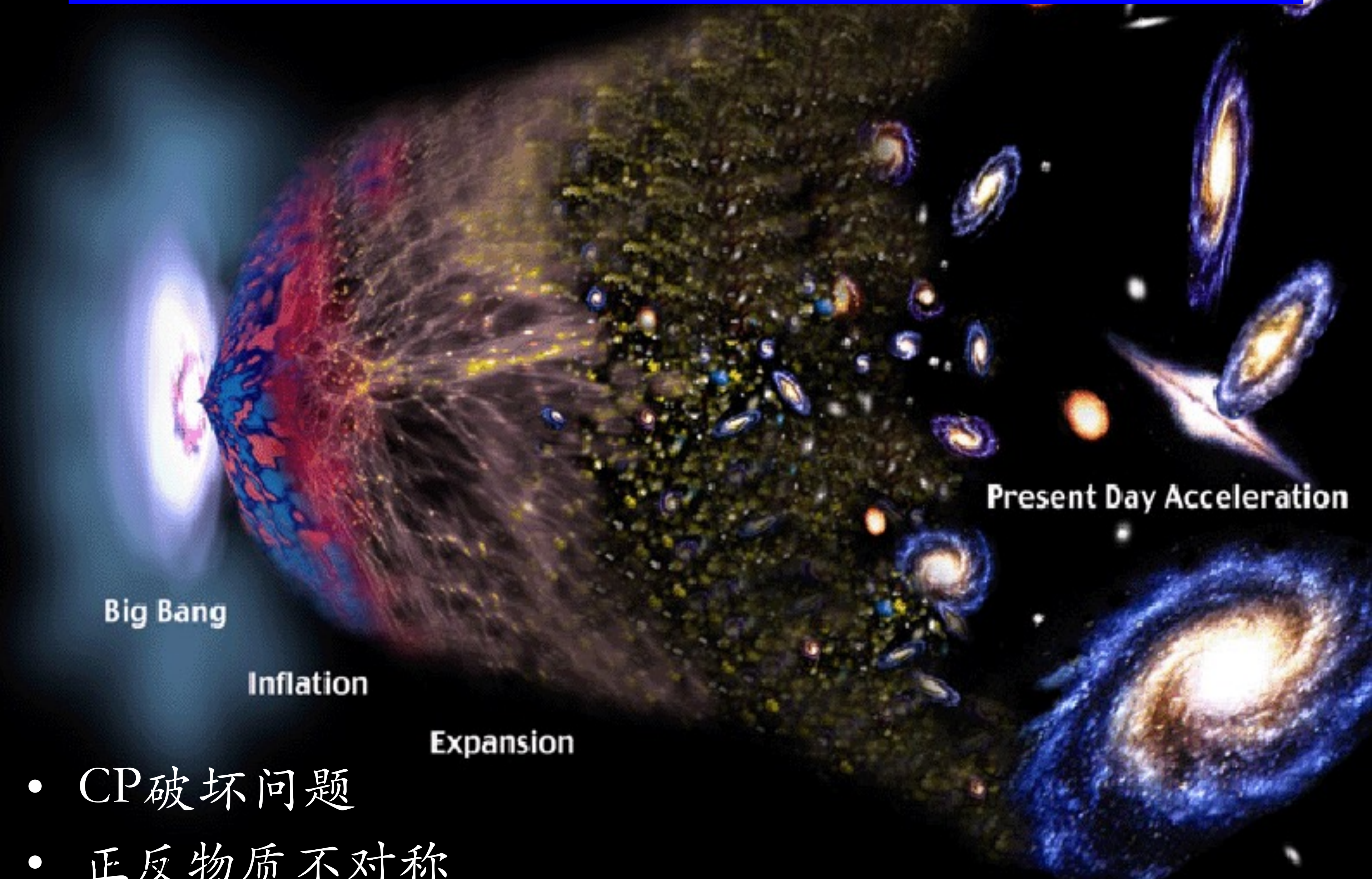
谁能料到真相如此简单？

道生一
一生二
二生三
三生万物！

续问1： 夸克和轻子是基本的吗？

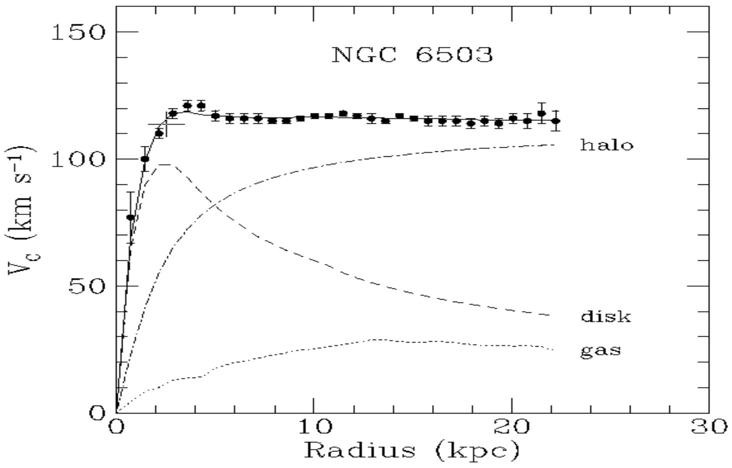
- 第二、三代费米子很快衰变为第一代，我们周围的物质均为第一代费米子构成。那么，其它两代费米子存在的意义是什么？
- 为什么是“三代”？有什么特殊含义？为什么质量相差那么大？
- 夸克和轻子是基本的吗？

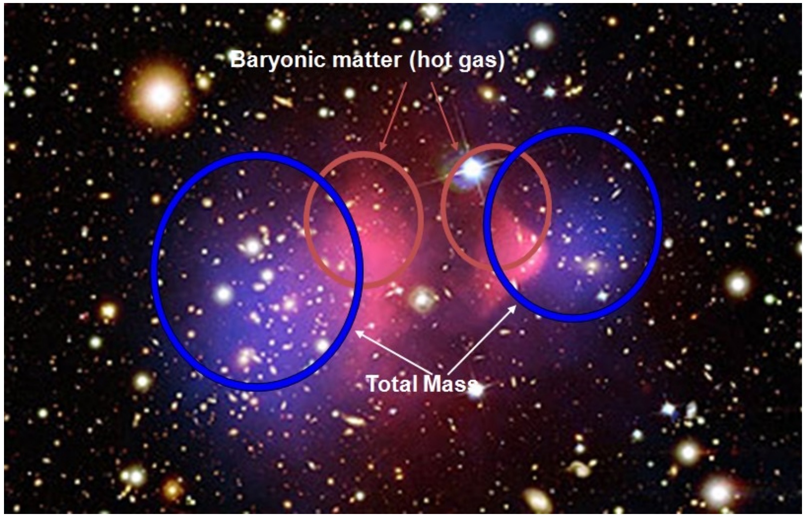
续问2：反物质宇宙存在吗？

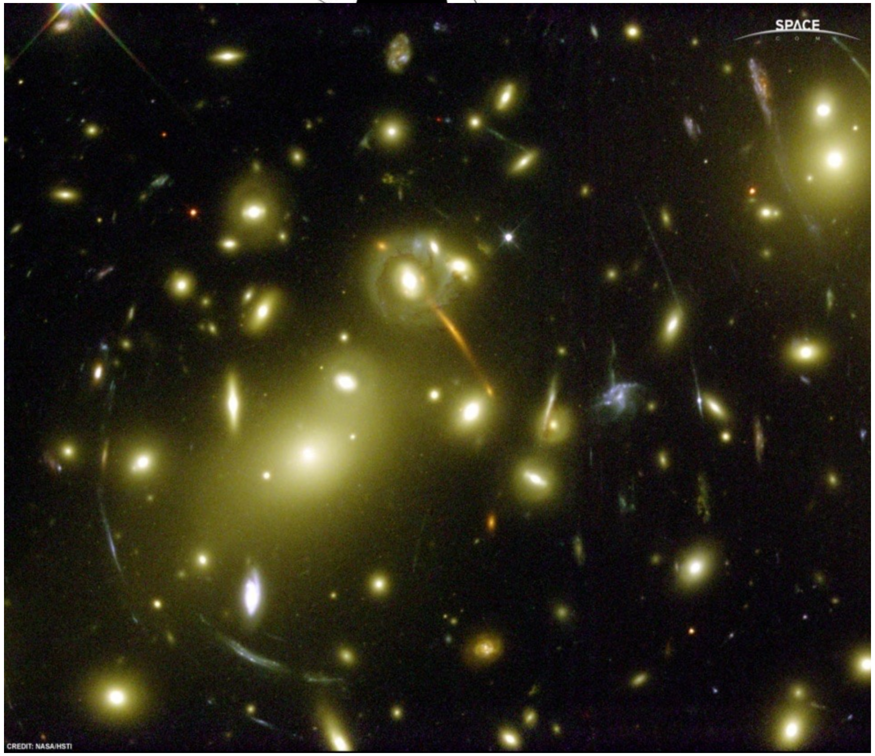


- CP破坏问题
- 正反物质不对称

续问3：暗物质是什么？

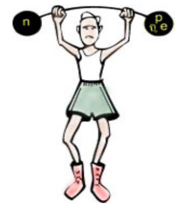

NGC 6503
150
100
50
0
0
10
20
30
V_c (km s^{-1})
Radius (kpc)
halo
disk
gas


Baryonic matter (hot gas)
Total Mass


SPACE
CREDIT: NASA/HST

第二个问题：世界如何组成？

四种相互作用

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

- 四种作用荷：引力只有吸引/弱力只有衰变/电磁力同斥异吸/强力如何吸引排斥？
- 强 力：跑动耦合常数！（尺度越小越小：渐进自由）
- 弱 力：跑动耦合常数！（尺度越小越大）
- 电 磁 力：跑动耦合常数！（尺度越小越大）
- 引 力：耦合常数？跑动否？怎么跑？

前两个问题解答了世界的构成

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matter constituents
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b bottom	4.2	−1/3

BOSONS
force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	−1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

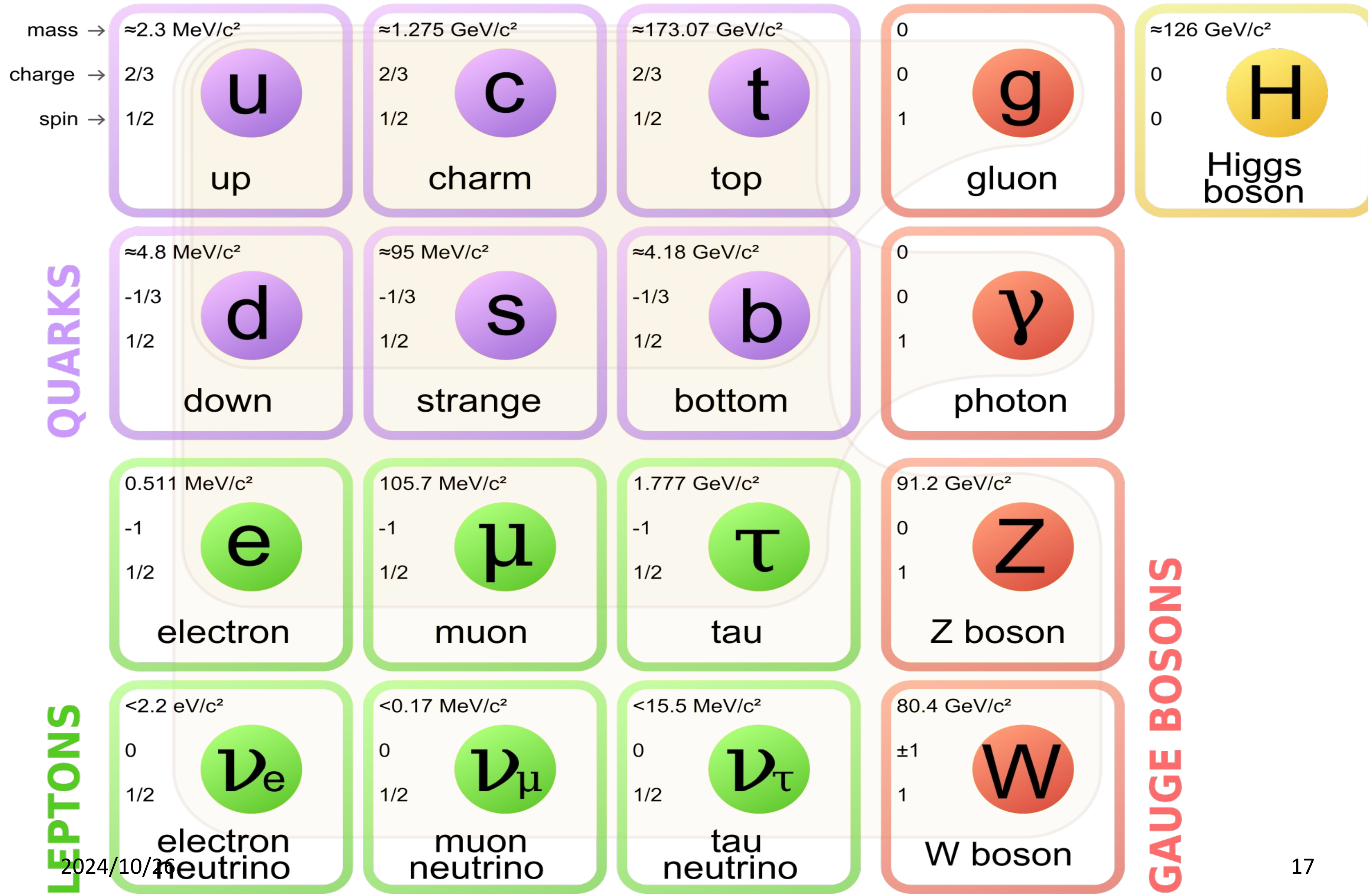
Color Charge
Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

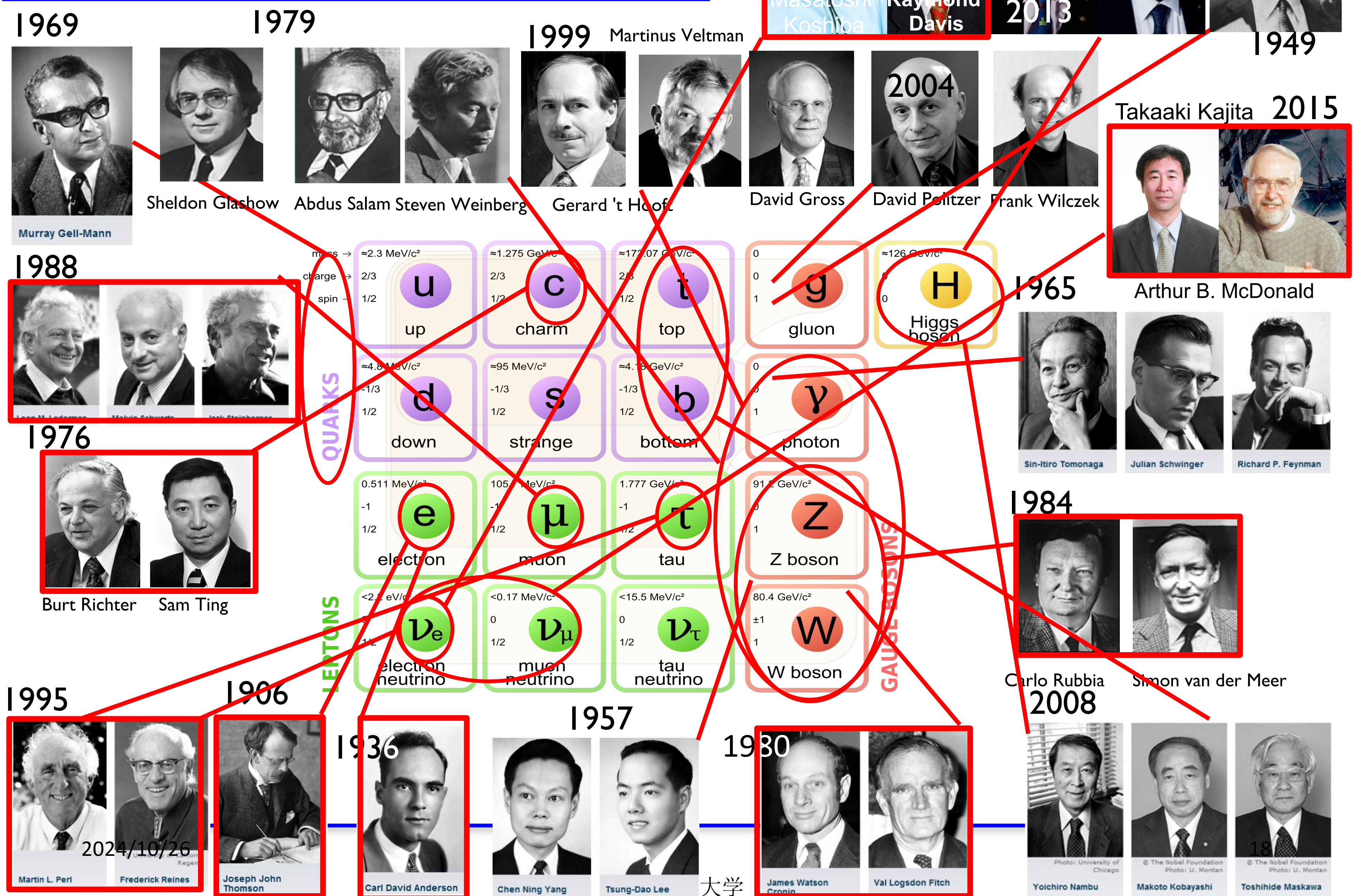
Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

前两个问题解答了世界的构成



基本粒子的炸药奖

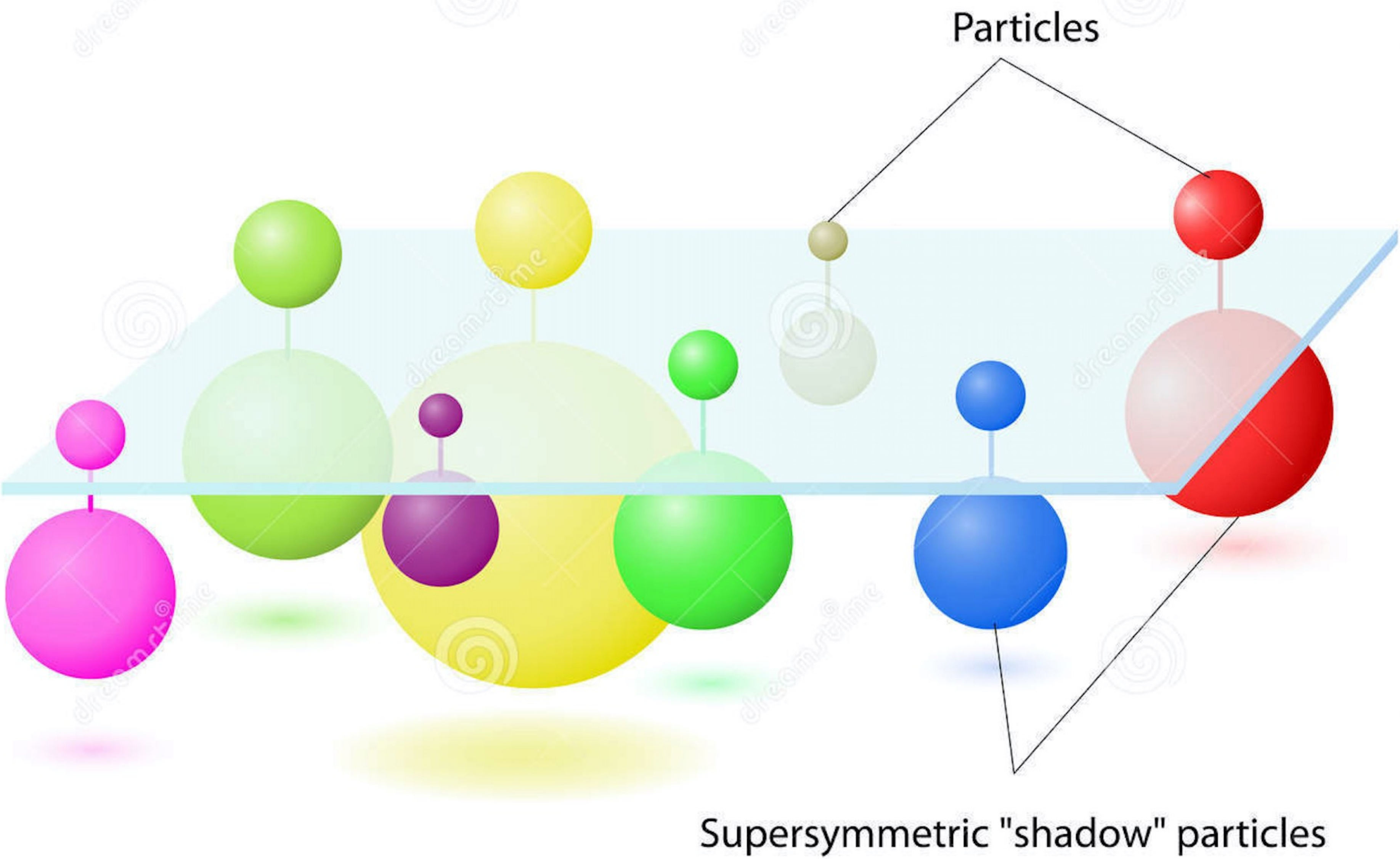

2002
Masatoshi Koshiba
Raymond Davis
2013
1949
Takaaki Kajita
2015
Arthur B. McDonald


1969
Murray Gell-Mann
1979
Sheldon Glashow
Abdus Salam
Steven Weinberg
1999
Martinus Veltman
Gerard 't Hooft
David Gross
2004
David Politzer
Frank Wilczek
1988
1976
Burt Richter
Sam Ting
1965
Sin-Itiro Tomonaga
Julian Schwinger
Richard P. Feynman
1984
Carlo Rubbia
Simon van der Meer
2008
Yoichiro Nambu
Makoto Kobayashi
Toshihide Maskawa
1995
Martin L. Perl
Frederick Reines
1906
Joseph John Thomson
1936
Carl David Anderson
1957
Chen Ning Yang
Tsung-Dao Lee
1980
James Watson Cronin
Val Logsdon Fitch
mass
charge
spin
QUARKS
LEPTONS
GAUGE BOSONS
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
c
charm
t
top
g
gluon
≈126 GeV/c²
H
Higgs boson
≈4.8 MeV/c²
-1/3
d
down
≈95 MeV/c²
s
strange
b
bottom
γ
photon
0.511 MeV/c²
-1
e
electron
1.777 GeV/c²
τ
tau
Z
Z boson
<2.2 eV/c²
νe
electron neutrino
<0.17 MeV/c²
νμ
muon neutrino
<15.5 MeV/c²
ντ
tau neutrino
80.4 GeV/c²
±1
W
W boson

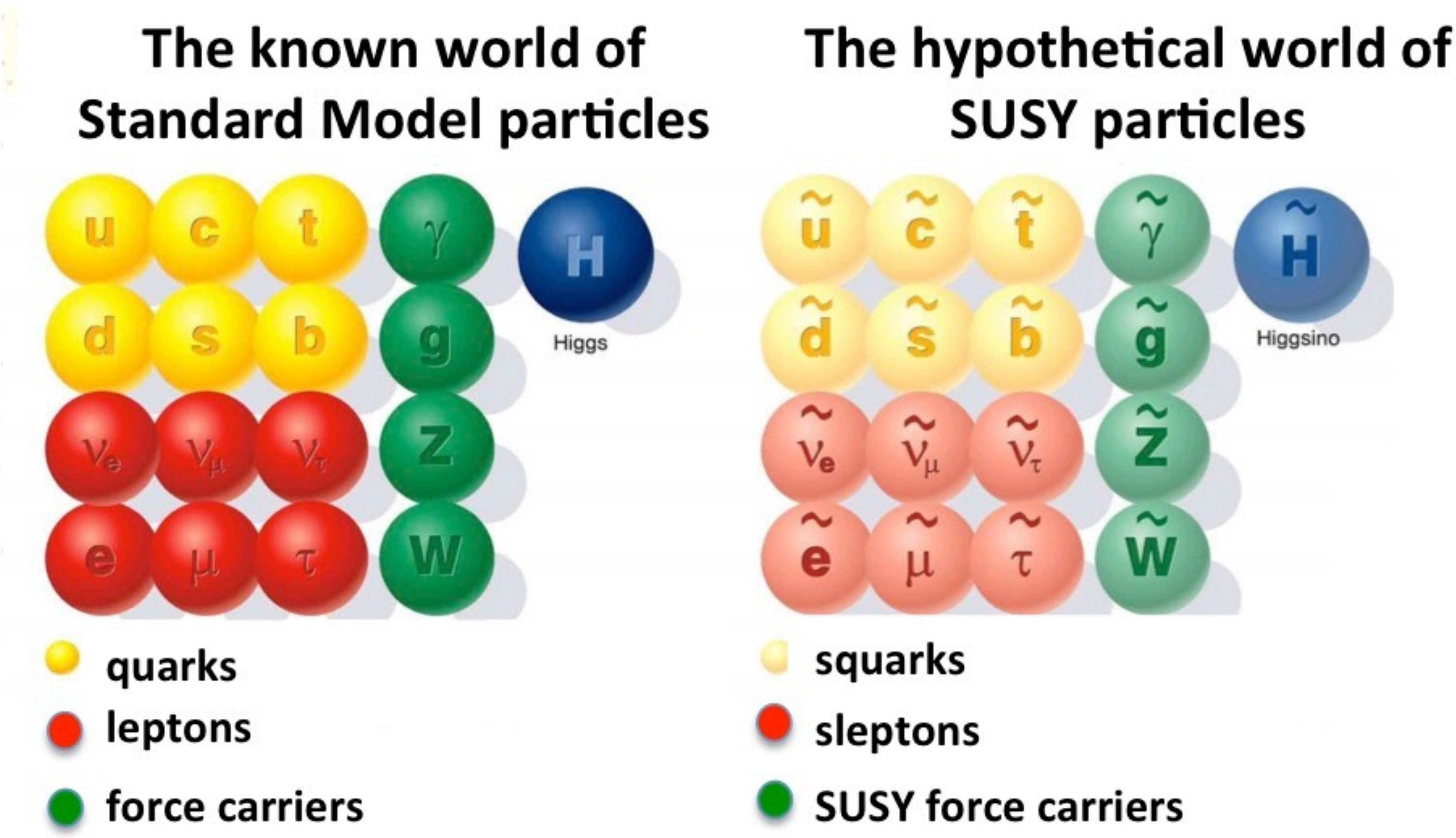
续问1：大统一理论？

- 大统一理论试图把强相互作用、弱相互作用、电磁相互作用—粒子物理学所有的力—统一到一个单一的理论之下。
- 以电弱统一理论为样板。电弱理论中，严格的规范不变性在一组Higgs标量作用下自发破缺，通过Higgs标量的适当选取，可赋予中间矢量玻色子以大质量同时让光子保持零质量。
- 大统一理论基于更大的规范群，其破缺方式为：保留光子和8个胶子为零质量粒子，同时给予中间矢量玻色子以适当质量。
- 但是，由于群结构问题，大统一理论必须纳入的规范矢量玻色子不只有这12个。例如SU(5)需要另外12个“X玻色子”。Higgs机制方面也必须经过适当选择才能使这些玻色子具有非常大的质量，以便产生已观测到的强作用与电弱作用的退耦效应。
- 直接预言：X玻色子。质量为质子质量的10^{15}倍！若在加速器上产生如此大的能量，常规质子加速器的半径有太阳系半径那么大！→ 宇宙线研究 → 宇宙起始时刻的大爆炸！
- 另一种寻找方式：低能遗迹。超弱现象，最著名的是“质子衰变”。

续问2：超对称？

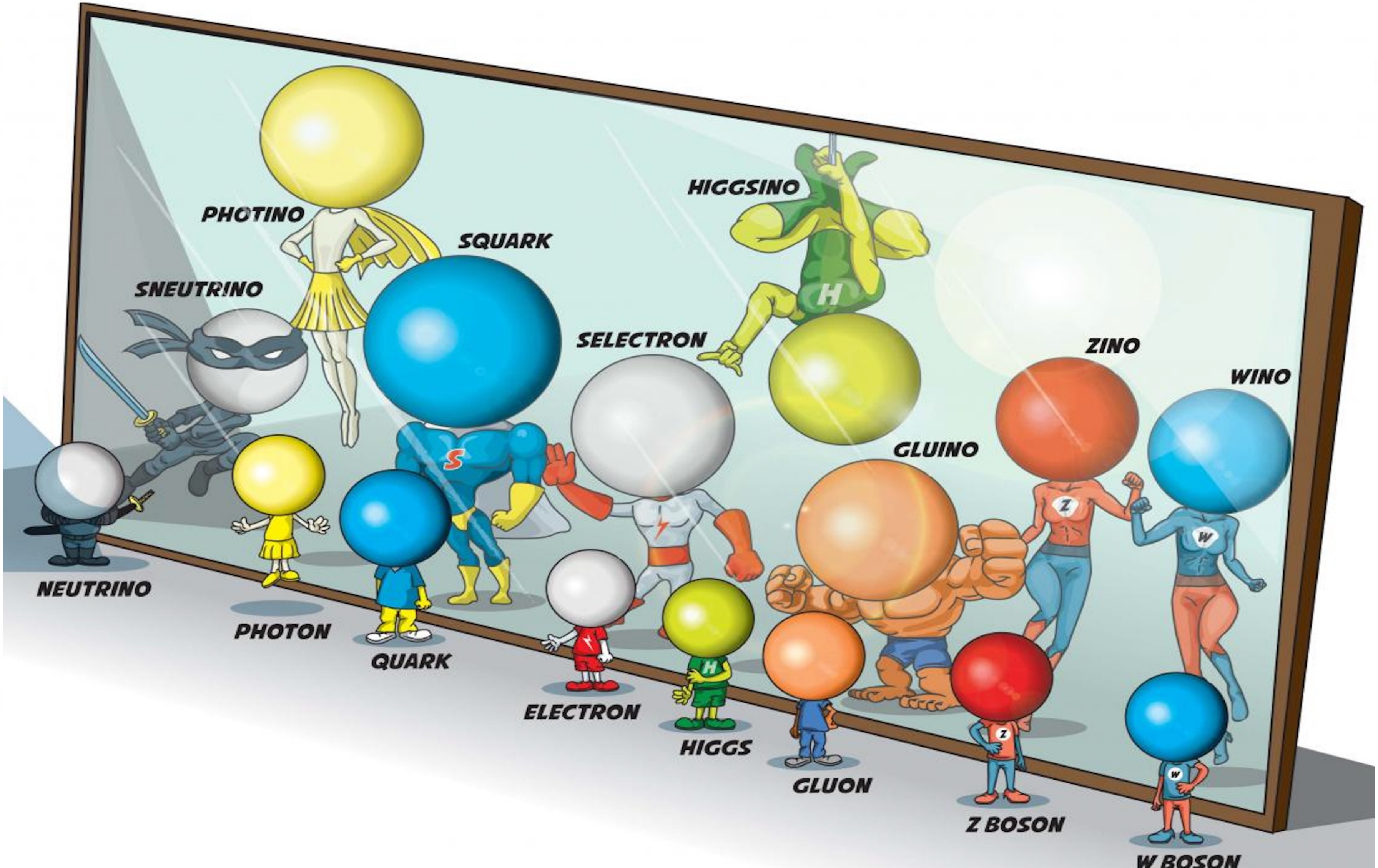


续问2：超对称？



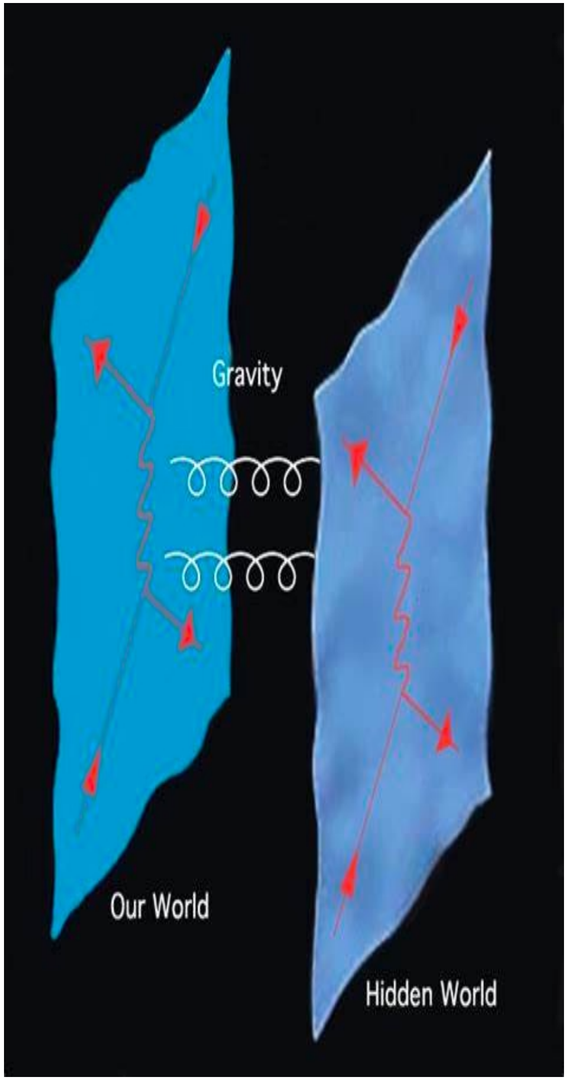
The known world of Standard Model particles
u c t γ
d s b g
νe νμ ντ Z
e μ τ W
H
Higgs
quarks
leptons
force carriers
The hypothetical world of SUSY particles
ũ c̃ t̃ γ̃
d̃ s̃ b̃ g̃
ν̃e ν̃μ ν̃τ Z̃
ẽ μ̃ τ̃ W̃
H̃
Higgsino
squarks
sleptons
SUSY force carriers

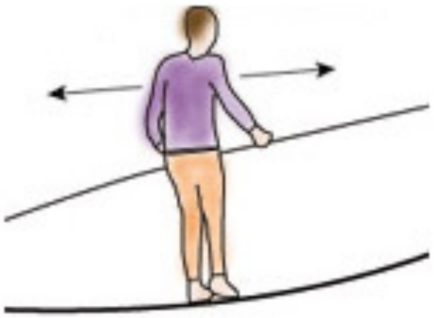
续问2：超对称？



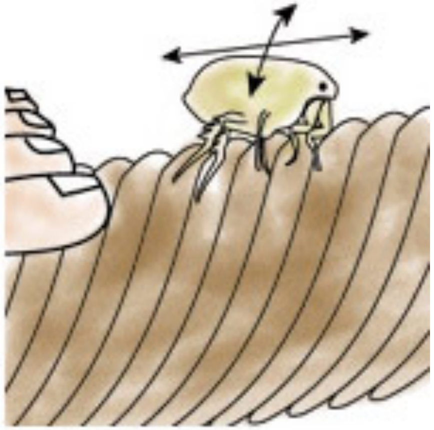
PHOTINO
SQUARK
SNEUTRINO
HIGGSINO
SELECTRON
ZINO
WINO
GLUINO
NEUTRINO
PHOTON
QUARK
ELECTRON
HIGGS
GLUON
Z BOSON
W BOSON

续问3：额外维空间/多宇宙？

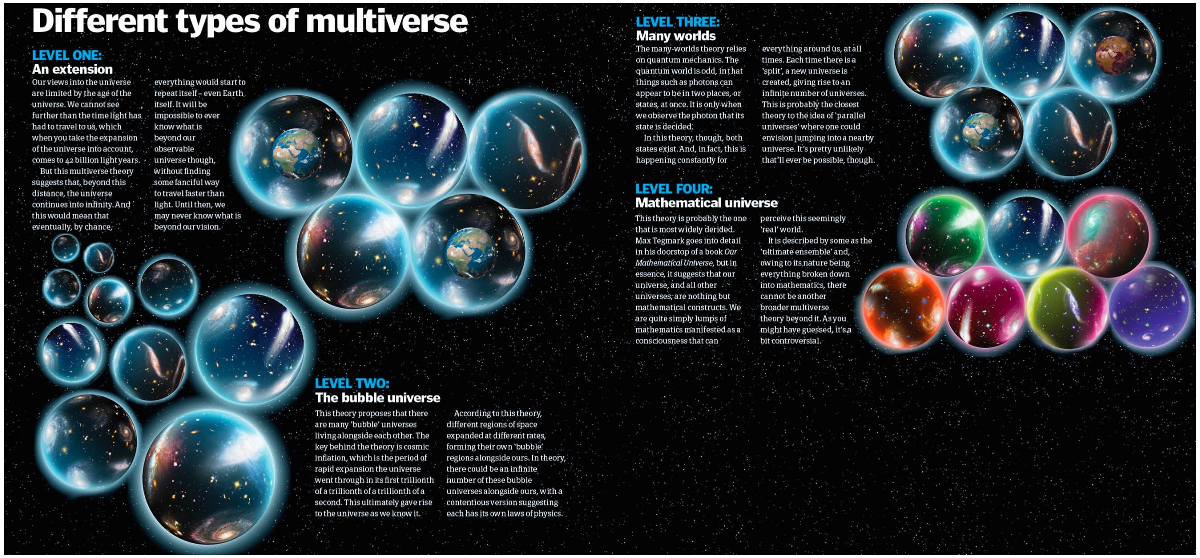




An acrobat can only move in one dimension along a rope..



...but a flea can move in two dimensions.



Different types of multiverse

LEVEL ONE:
An extension

Our views into the universe are limited by the age of the universe. We cannot see further than the time light has had to travel to us, which when you take the expansion of the universe into account, comes to 42 billion light years.

But this multiverse theory suggests that, beyond this distance, the universe continues into infinity. And this would mean that eventually, by chance, everything would start to repeat itself – even Earth itself. It will be impossible to ever know what is beyond our observable universe though, without finding some fanciful way to travel faster than light. Until then, we may never know what is beyond our vision.

LEVEL TWO:
The bubble universe

This theory proposes that there are many 'bubble' universes living alongside each other. The key behind the theory is cosmic inflation, which is the period of rapid expansion the universe went through in its first trillionth of a trillionth of a trillionth of a second. This ultimately gave rise to the universe as we know it.

According to this theory, different regions of space expanded at different rates, forming their own 'bubble' regions alongside ours. In theory, there could be an infinite number of these bubble universes alongside ours, with a contentious version suggesting each has its own laws of physics.

LEVEL THREE:
Many worlds

The many-worlds theory relies on quantum mechanics. The quantum world is odd, in that things such as photons can appear to be in two places, or states, at once. It is only when we observe the photon that its state is decided.

In this theory, though, both states exist. And, in fact, this is happening constantly for everything around us, at all times. Each time there is a 'split', a new universe is created, giving rise to an infinite number of universes. This is probably the closest theory to the idea of 'parallel universes' where one could envision jumping into a nearby universe. It's pretty unlikely that'll ever be possible, though.

LEVEL FOUR:
Mathematical universe

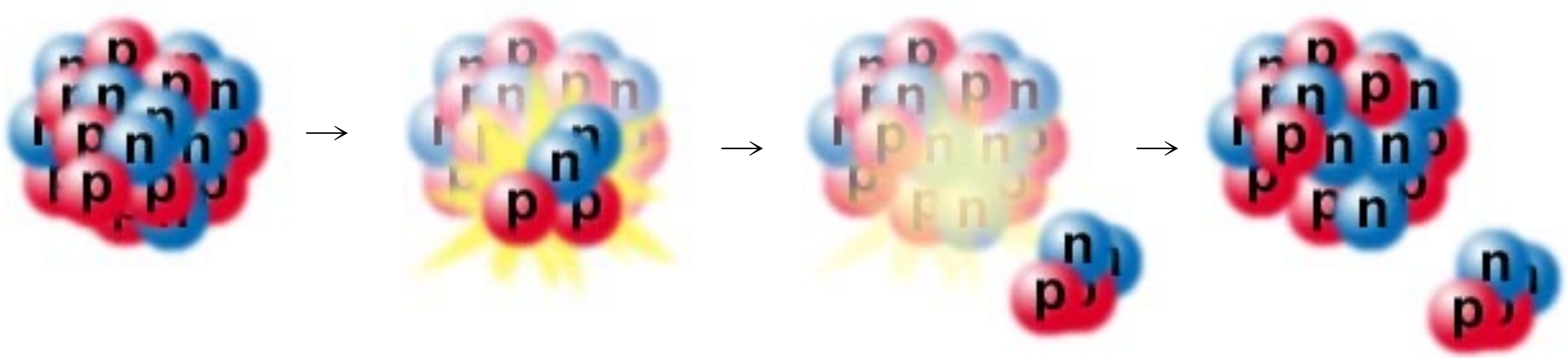
This theory is probably the one that is most widely derided. Max Tegmark goes into detail in his doorstop of a book *Our Mathematical Universe*, but in essence, it suggests that our universe, and all other universes, are nothing but mathematical constructs. We are quite simply lumps of mathematics manifested as a consciousness that can perceive this seemingly 'real' world.

It is described by some as the 'ultimate ensemble' and, owing to its nature being everything broken down into mathematics, there cannot be another broader multiverse theory beyond it. As you might have guessed, it's a bit controversial.

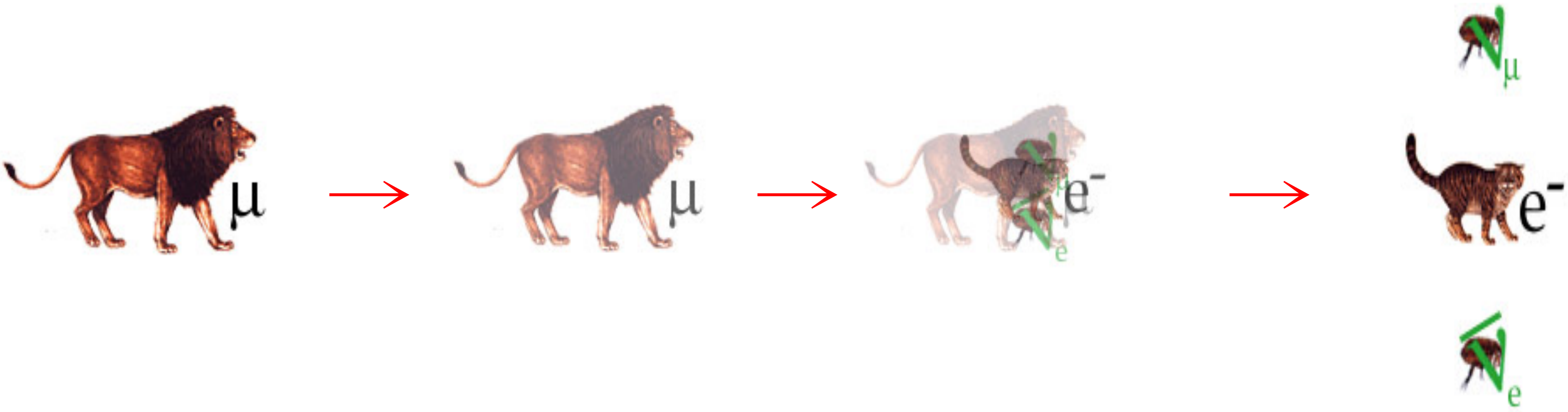
第三个问题：世界如何演化？

演化方式-I：粒子的衰变

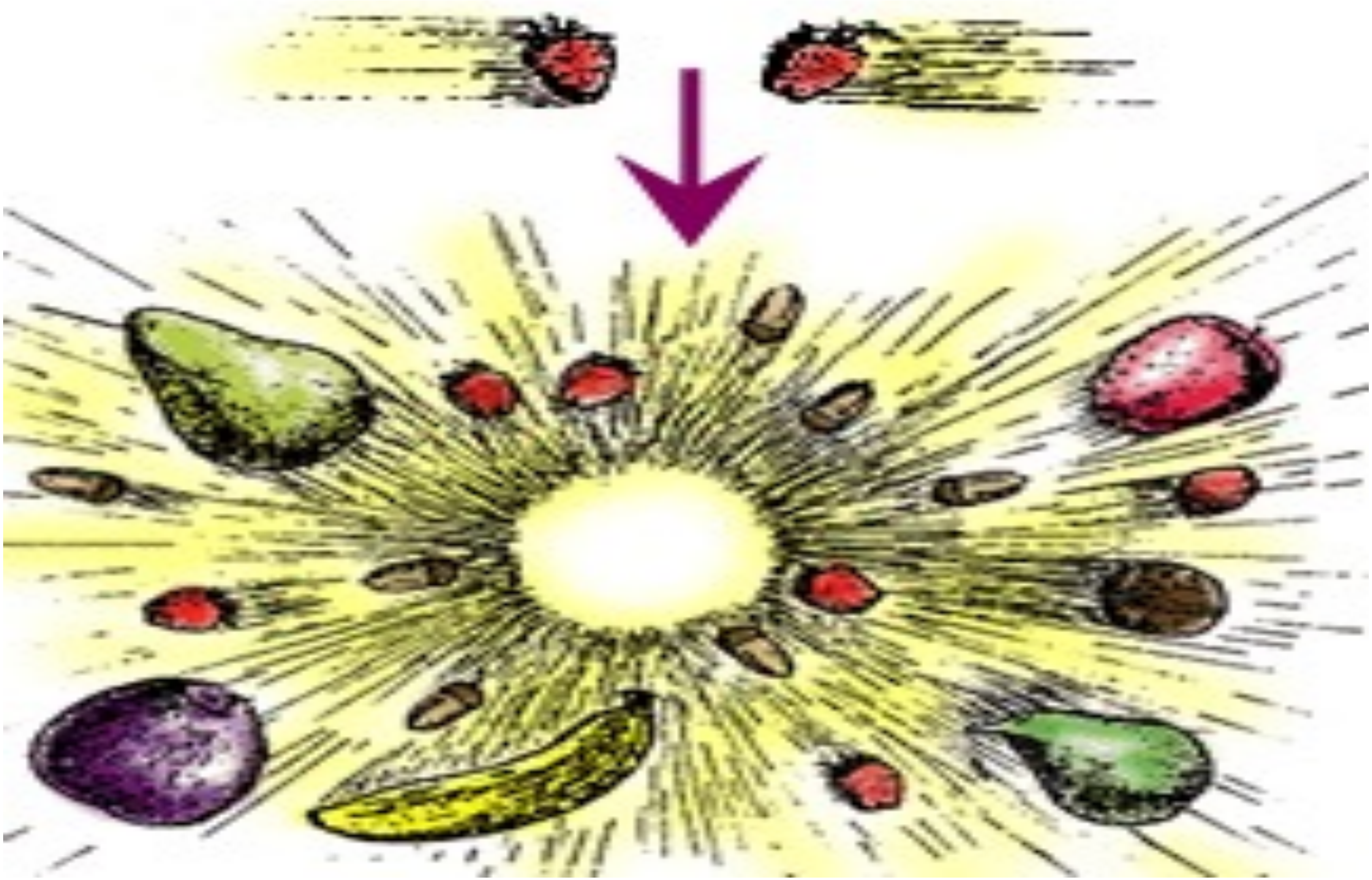
- 原子核的衰变：一个大原子核变成几个小原子核

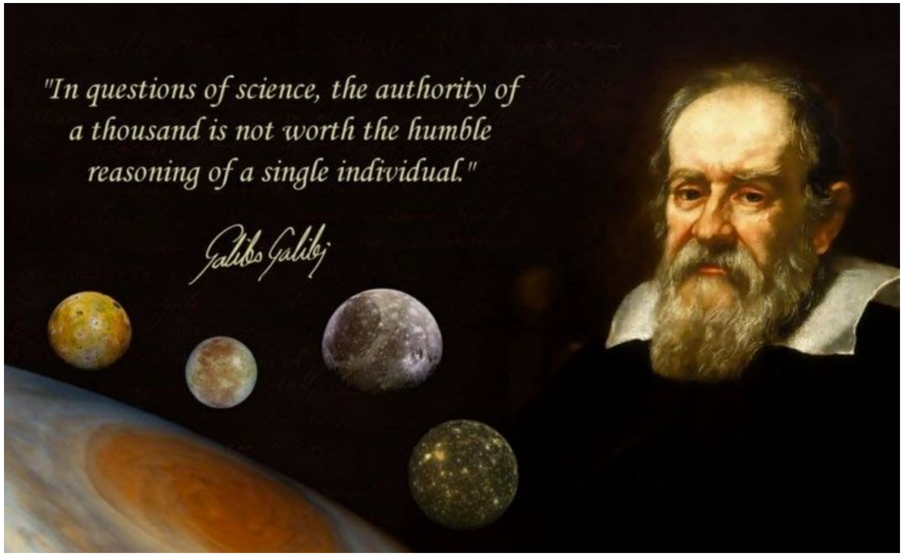


- 基本粒子的衰变：一个基本粒子变成几个较轻的基本粒子



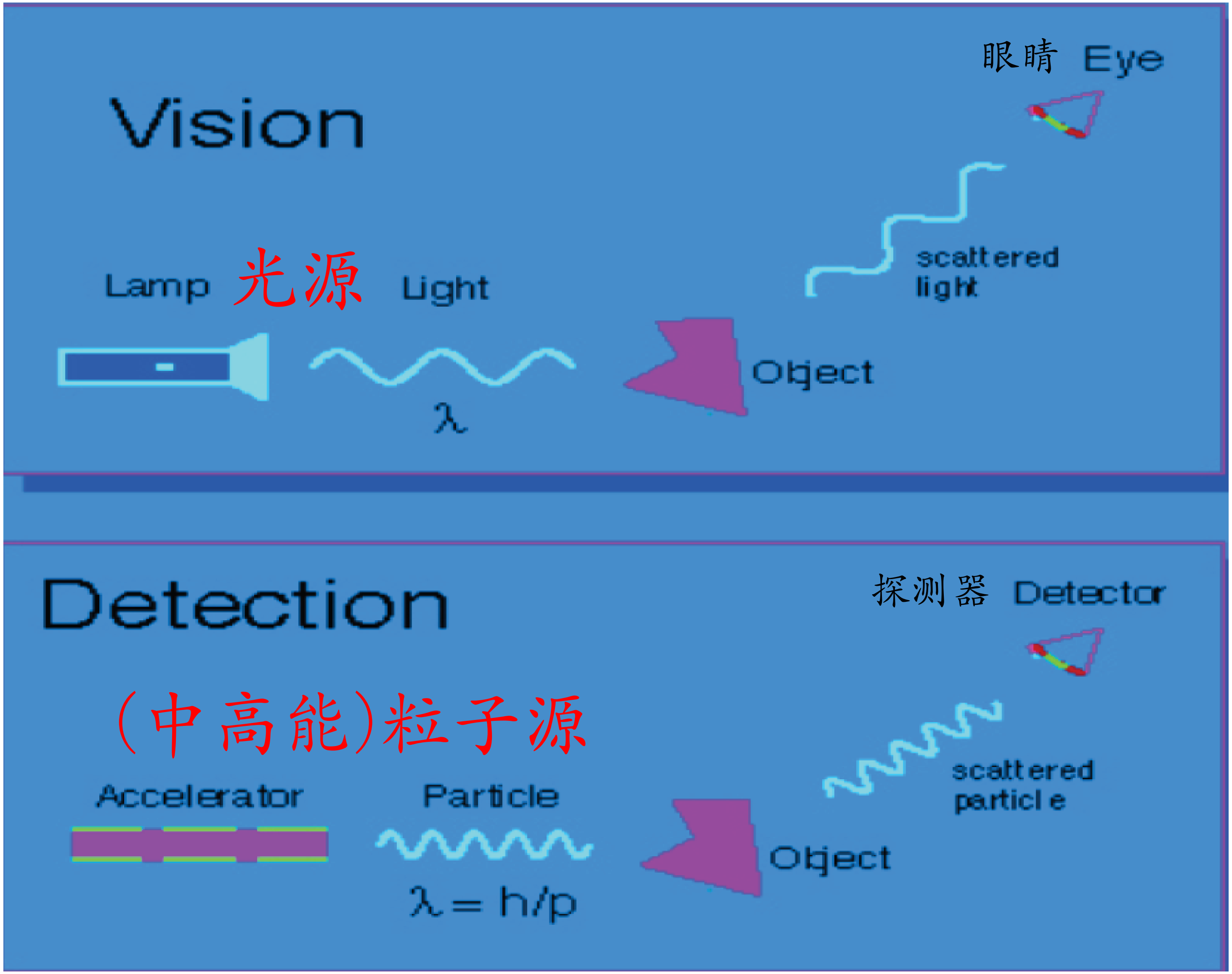
演化方式-II：正反粒子湮灭





最关键的问题：我们如何知道？

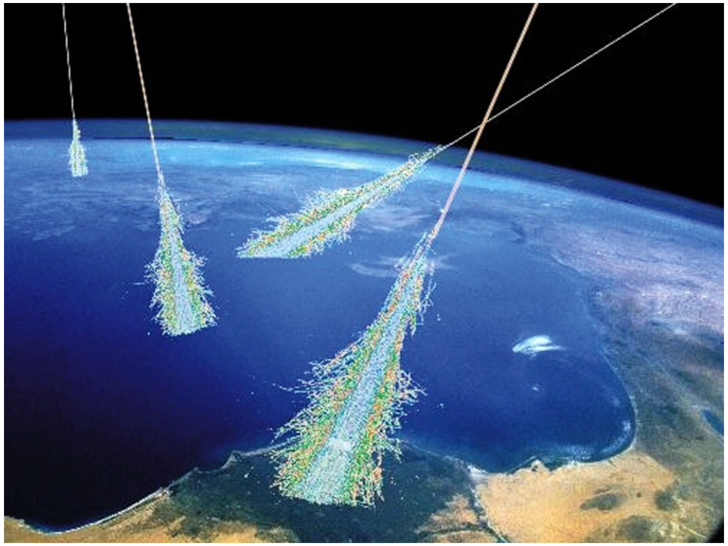
通过实验进行研究



眼睛 Eye
Vision
scattered
light
Lamp 光源 Light
Object
λ
探测器 Detector
Detection
(中高能)粒子源
scattered
particl e
Accelerator
Particle
Object
λ = h/p

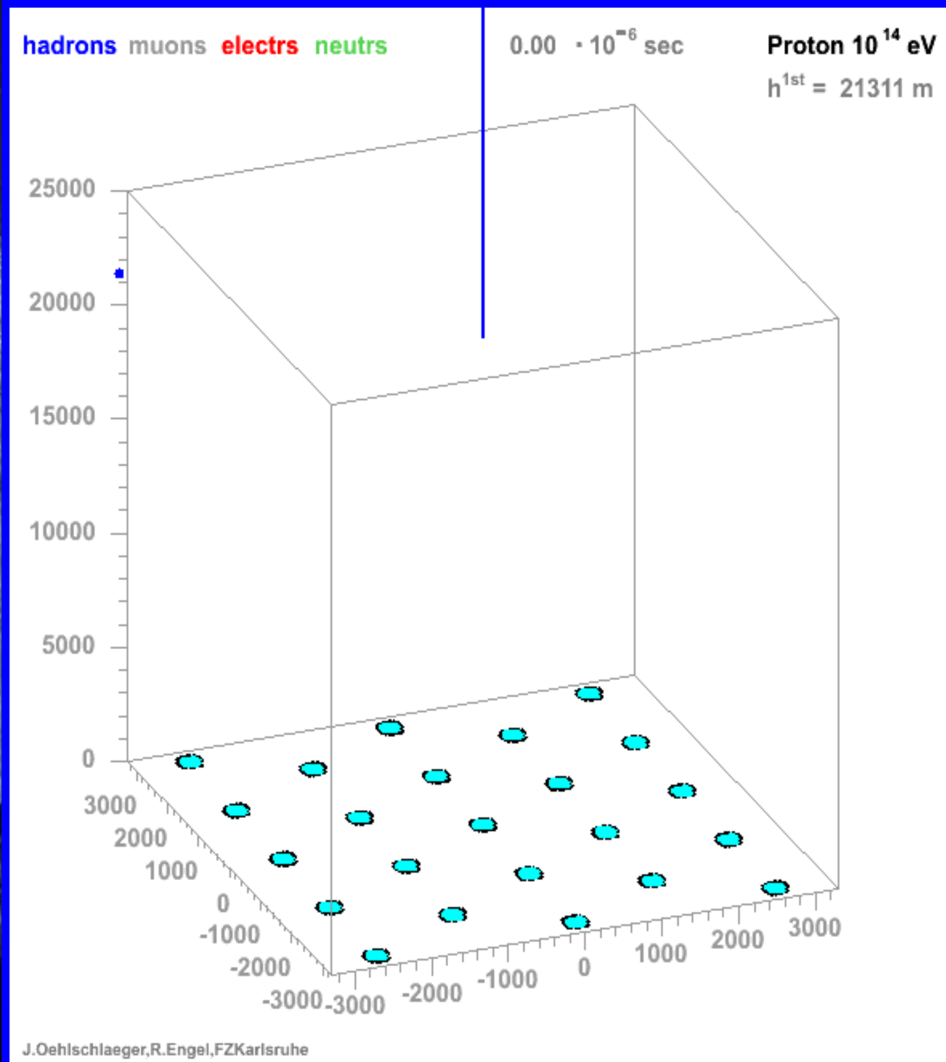
粒子源

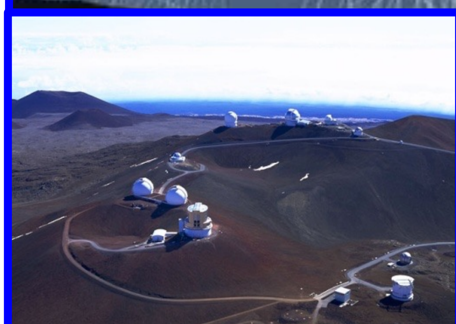
- 放射源（反应堆）
- 宇宙线
  - 可获超高能量粒子
  - 统计量低
  - 随机性强
- 粒子加速器
  - 能量较宇宙线低
  - 能量可调节
  - 统计量高
  - 可控制与可重复性强
  - 回旋加速器
  - 同步回旋加速器

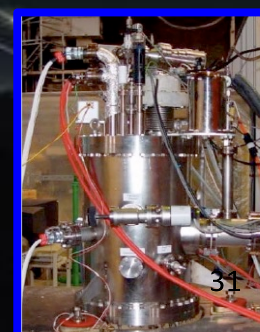


加速方式：靠天吃饭的宇宙线

加速方式：靠天吃饭的宇宙线







加速方式：直线 vs 回旋

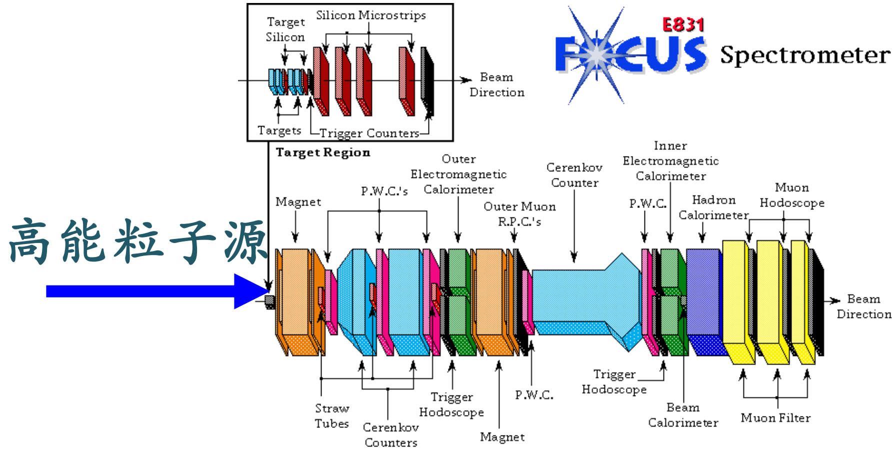
直线加速

回旋加速

反应方式：打靶 vs 对撞

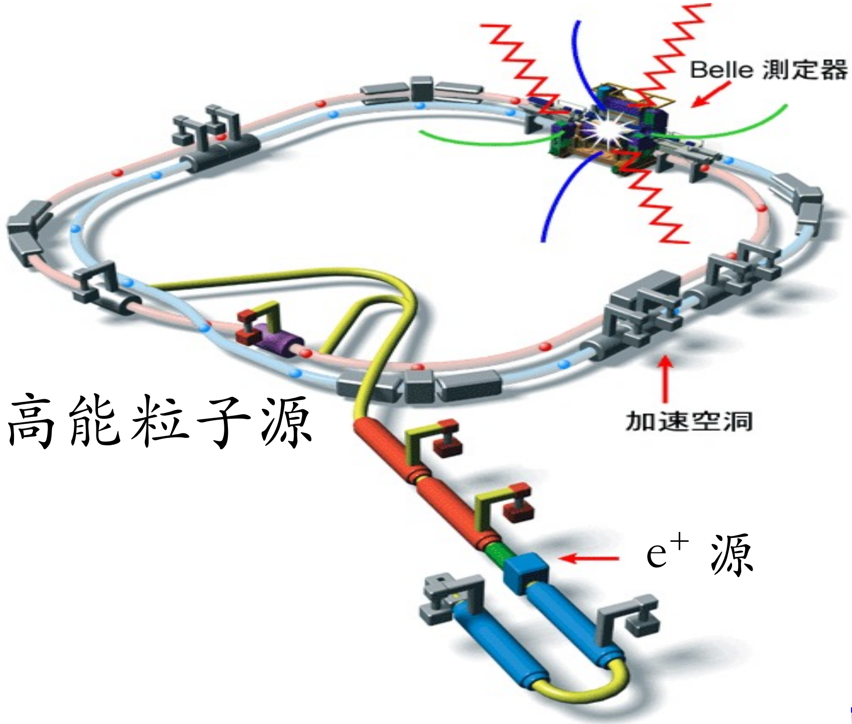
- 固定靶
  - 高能粒子束(m_1)轰击静止的粒子(m_2)靶

$$E_{cm}^2 \approx 2E_1 m_2$$



- 移动靶（对撞机）
  - 两束高能粒子对头碰撞

$$E_{cm}^2 = 4E_1 E_2$$



测量方法：探测器

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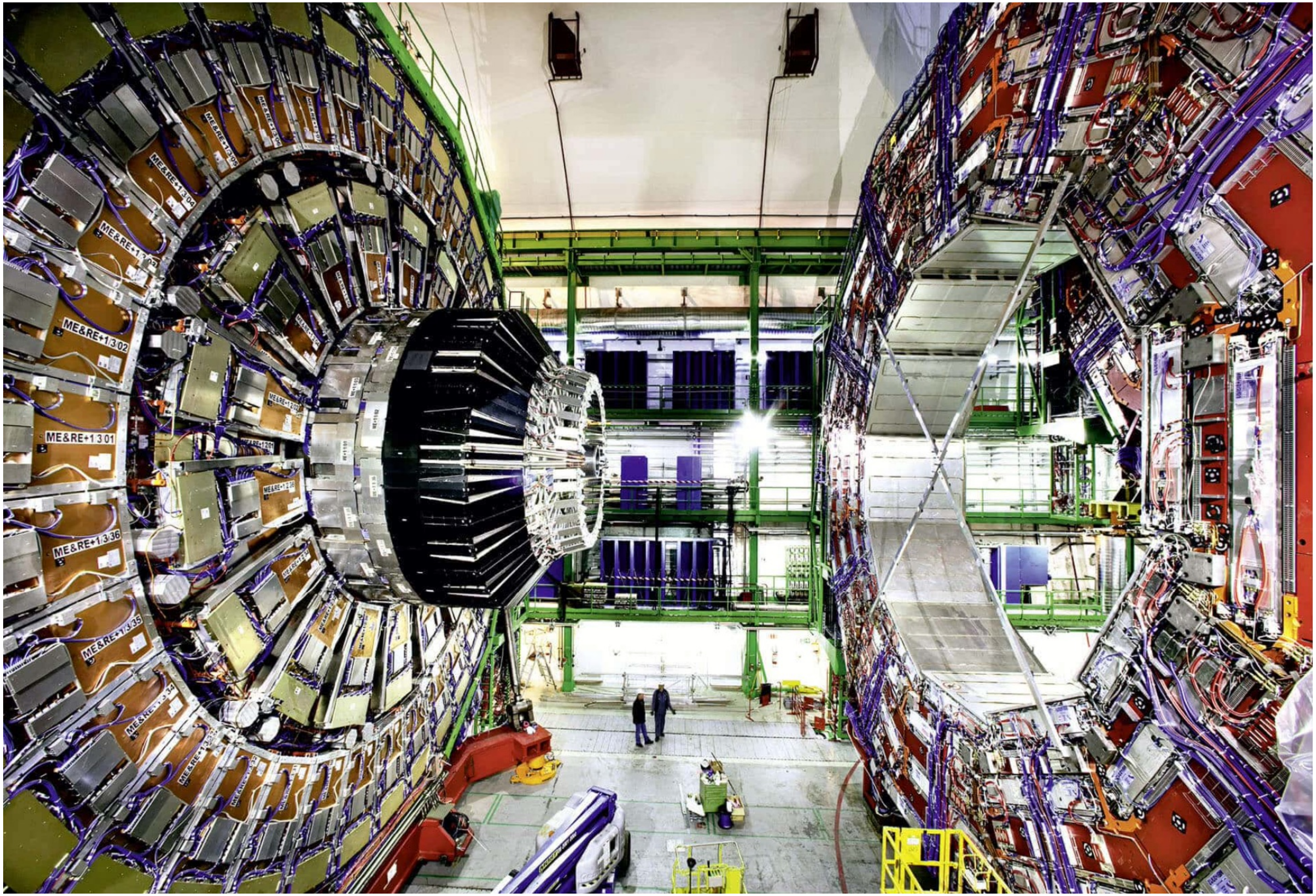
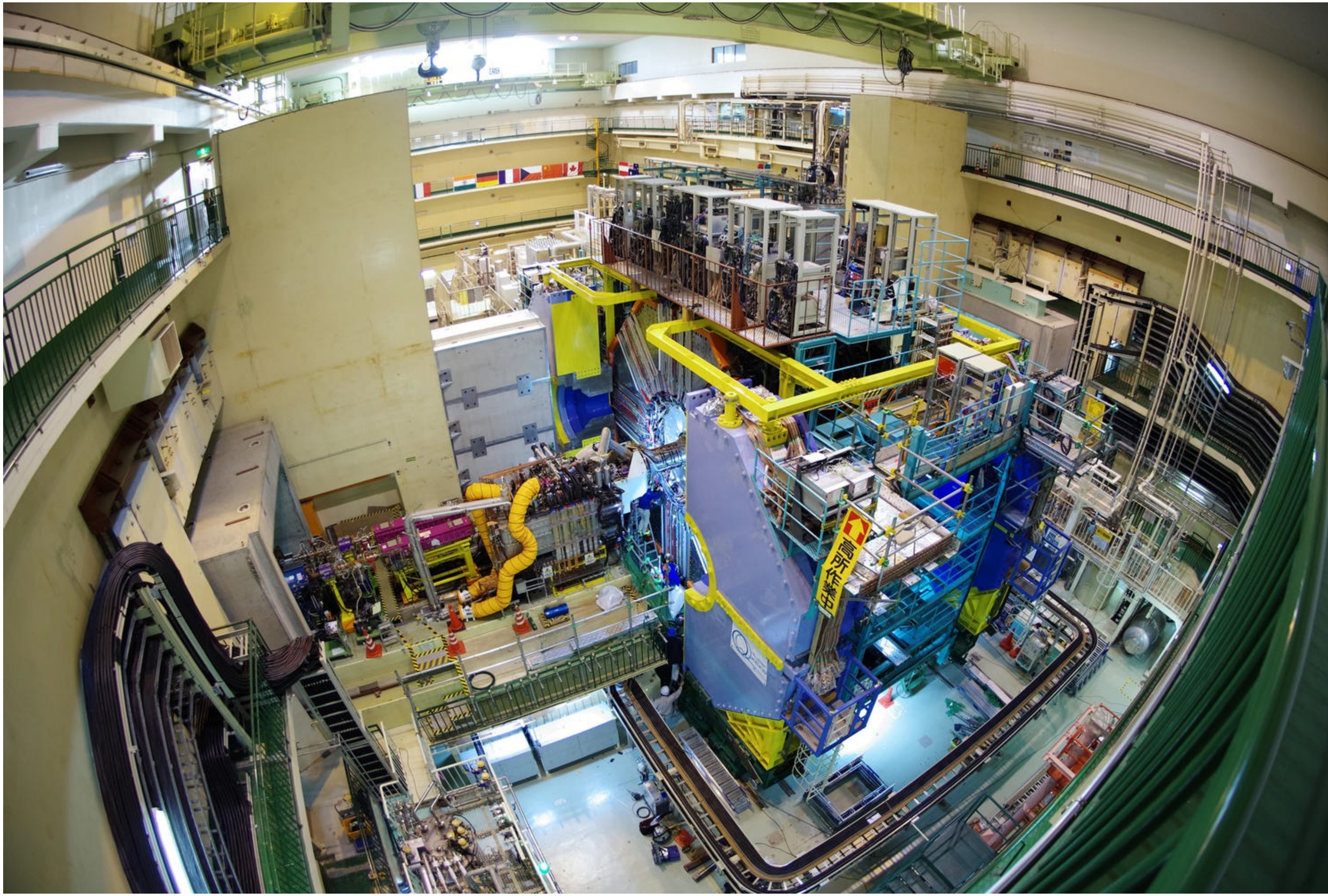
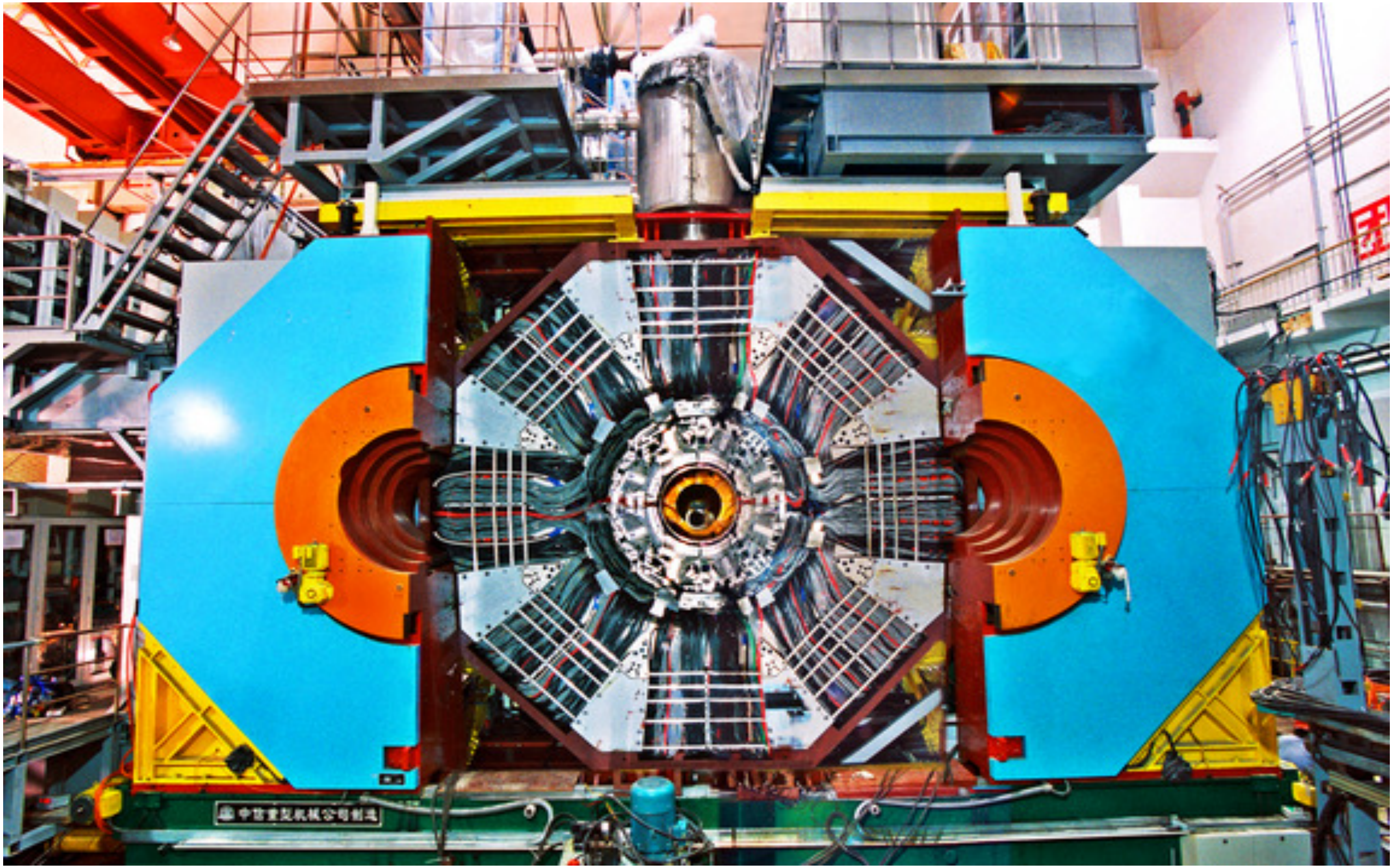


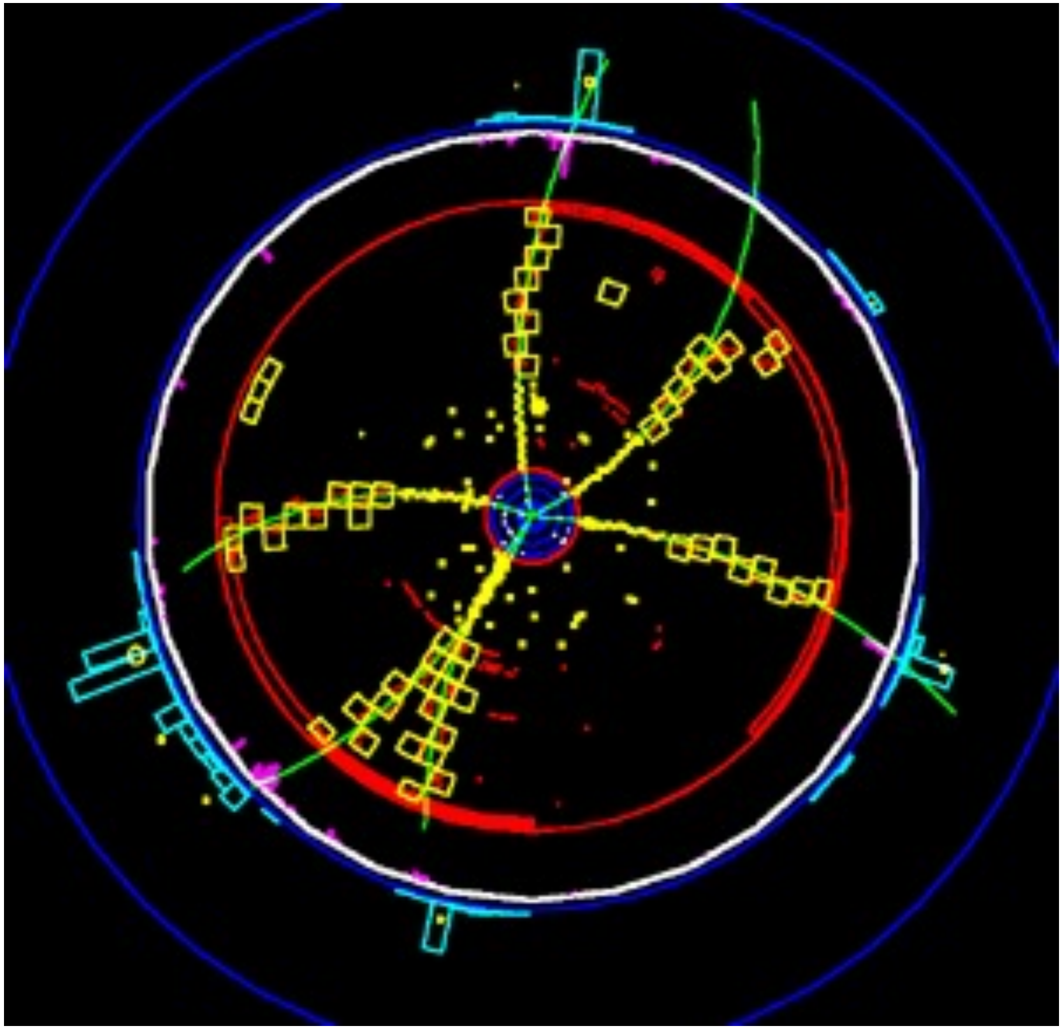
测量方法：探测器



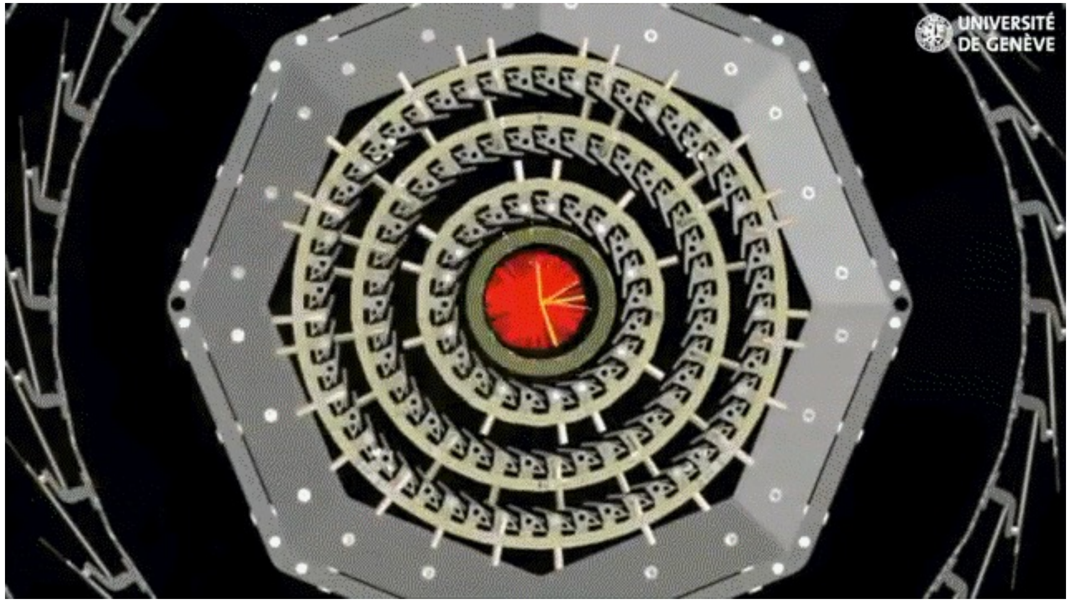
测量方法：探测器



正负电子对撞机的典型事例



对比：强子对撞机的典型事例



高能物理实验：特点

- 大型科学装置
  - 软件、硬件、触发与数据采集（电子学）
  - 大数据分析
  - 大科学工程的协调与管理
- 大型国际合作
  - 大型化：几百～几千成员，包括物理学家、工程师、技术员以及合同人员
  - 国际化：几十个国家、几百个大学或研究所
  - 规范化：严格的科学规范

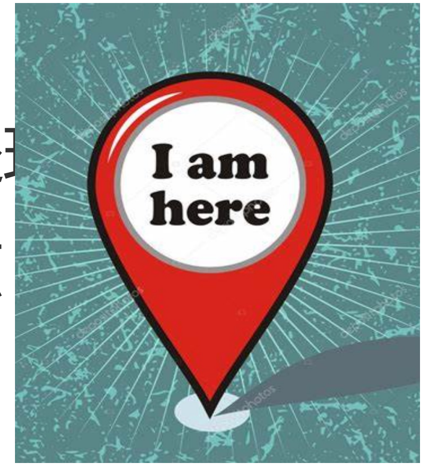
高能物理实验：四大方向

①**硬件**：研发和制造粒子物理实验的仪器设备；（缺点：文章少；优点：去企业收入高）

②**电子学**：研发和制造沟通仪器设备和软件的集成电路；（缺点：文章少；优点：去企业收入高）

③**软件**：开发粒子物理实验的软件平台以及各种软件包；（缺点：文章少；优点：去企业收入高）

④**物理**：挖掘实验数据中的物理内容（大数据处理）物理文章（优点：文章多，高校职位多；缺点



高能物理实验：人才培养

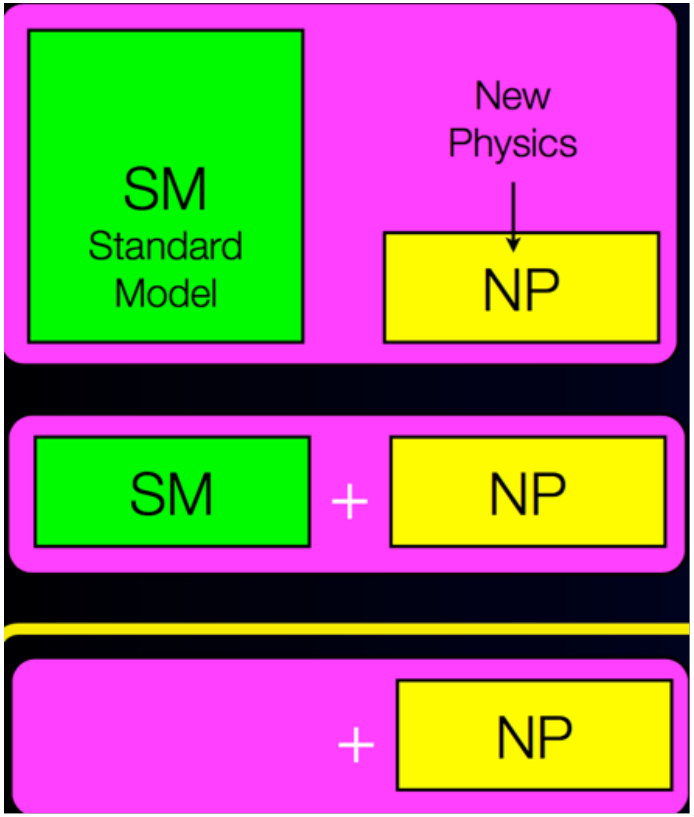
- ✓ 一技之长：硬件、电子学、软件、模拟
- ✓ 基本技能：C++、Linux、英文、大数据处理
- ✓ 交流能力：全英文email沟通、讲报告
- ✓ 独立思考
- ✓ 大局观

前途 & 钱途

- 学术界
  - 高校教师(粒子物理与原子核物理、生物物理、医学物理)
  - 研究所科研人员
- 企业界
  - 金融分析师(物理分析背景的博/硕)
  - 工业用(医用)探测器研发(探测器硬件背景的博/硕)
  - 技术医生(探测器模拟背景的博/硕)
  - 电子工程师(电子学背景的博/硕)
  - 软件架构师(软件背景的博)
  - 高级程序员(软件或物理分析背景的硕及以上)
  - 咨询公司
  - 核电站
  - 。。。

新物理 vs 稀有衰变

利用BESIII采集的大统计量、高质量数据，特别是含有100亿 J/ψ 粒子和独特的粲介子和粲重子近阈样本，在极高的实验精度下研究各种稀有或禁戒的过程，从而对各种BSM的理论进行检验。



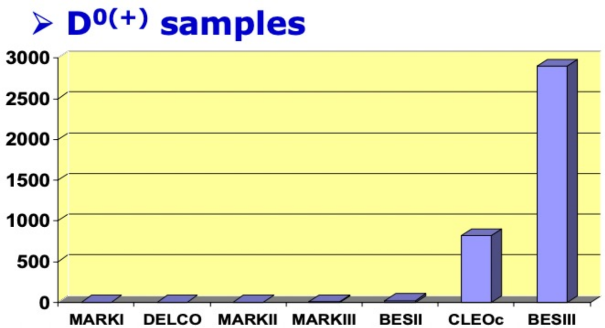
SM contribution is dominant

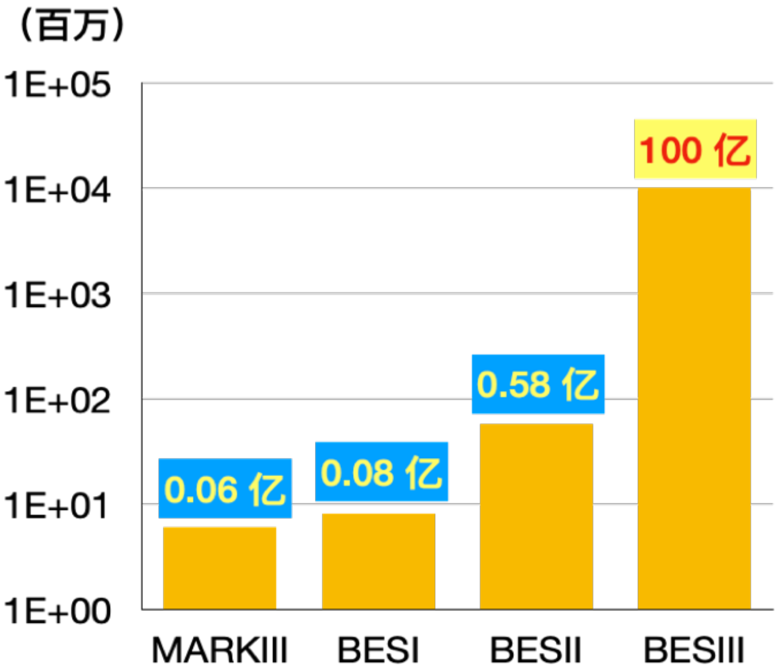
SM contribution is highly suppressed

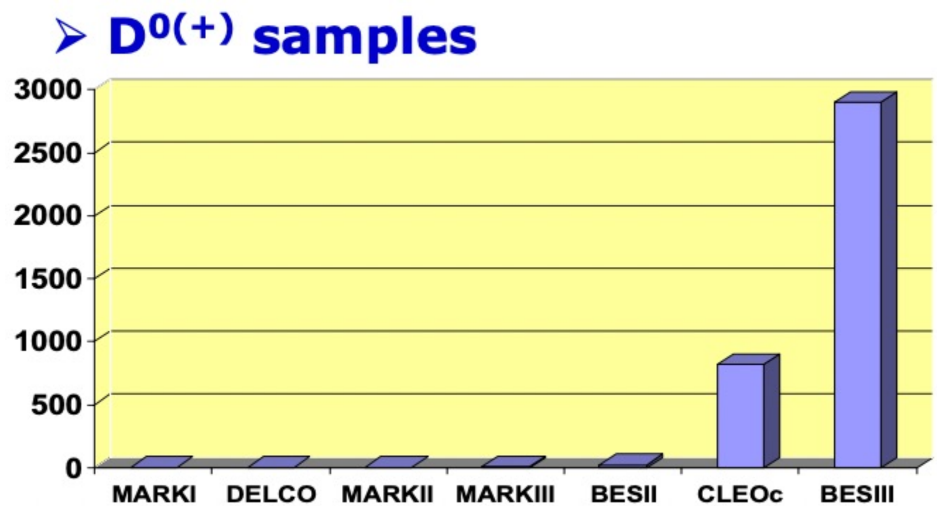
SM contribution is forbidden

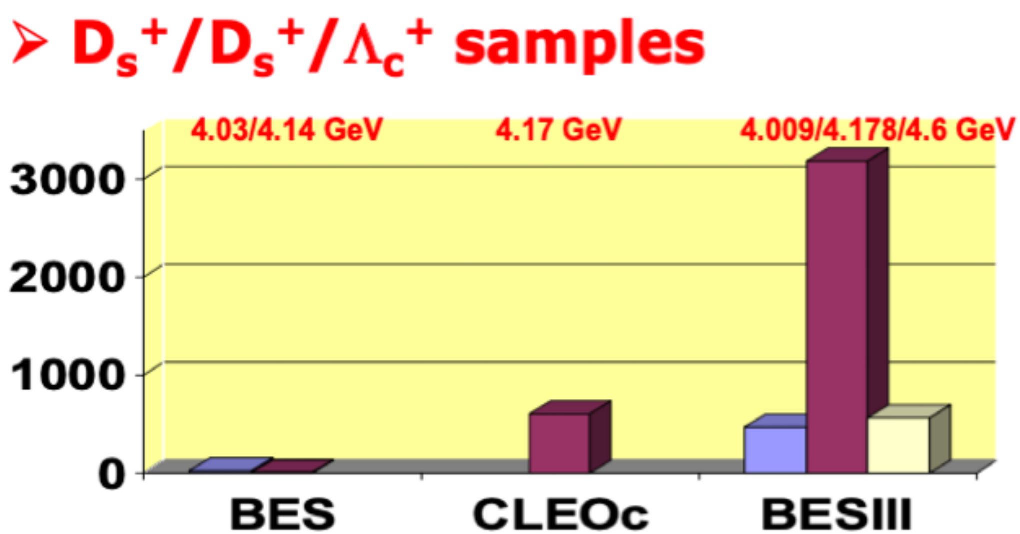
From D.Y. Wang

最大的tau-charm数据

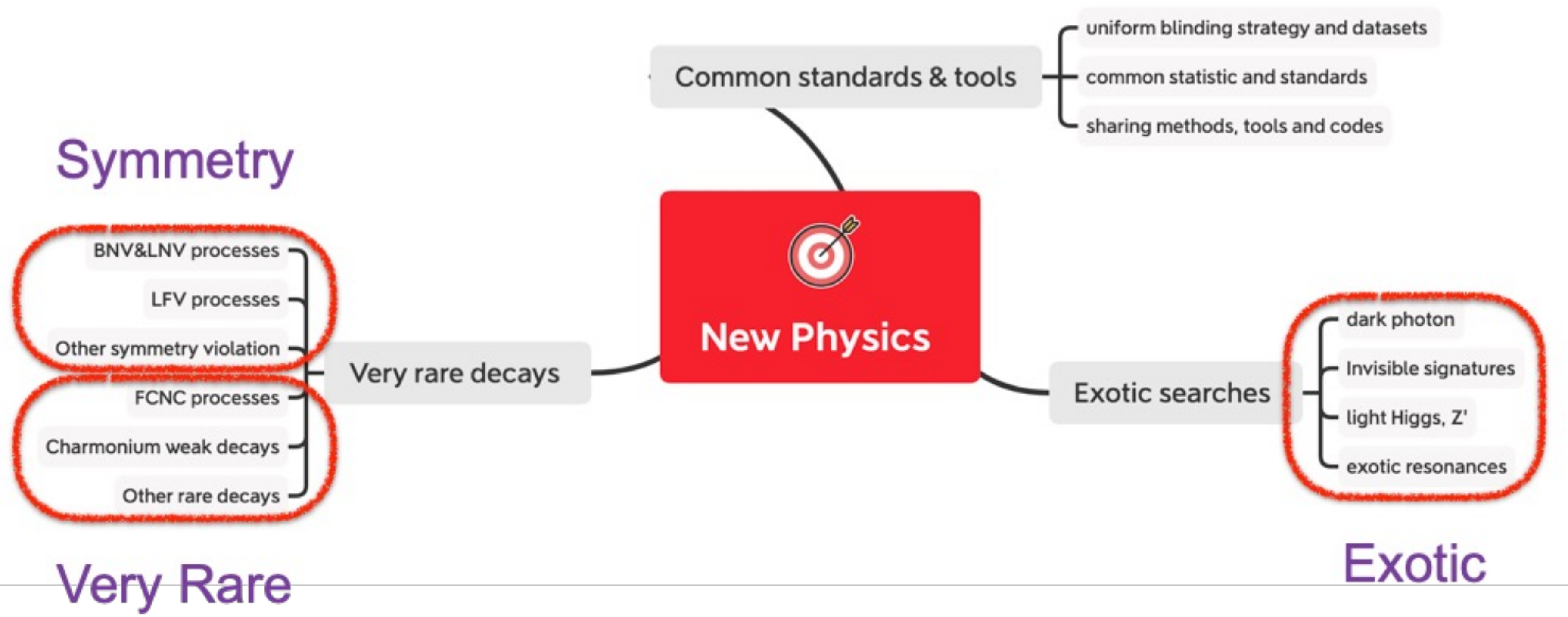






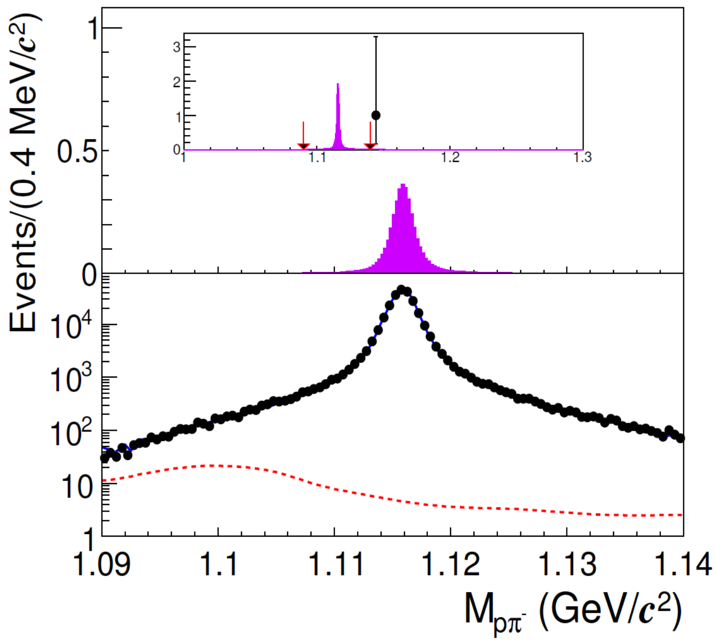


BESIII 的新物理研究

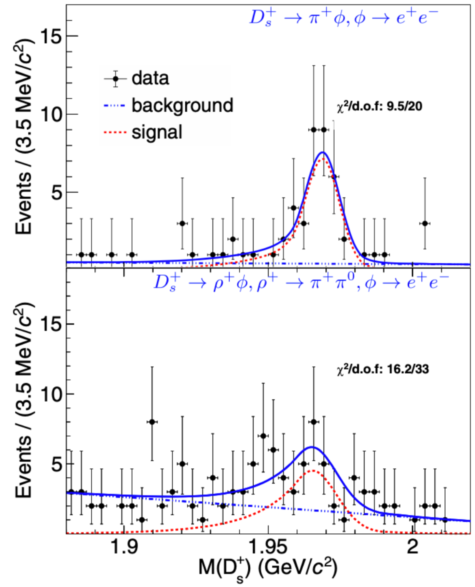


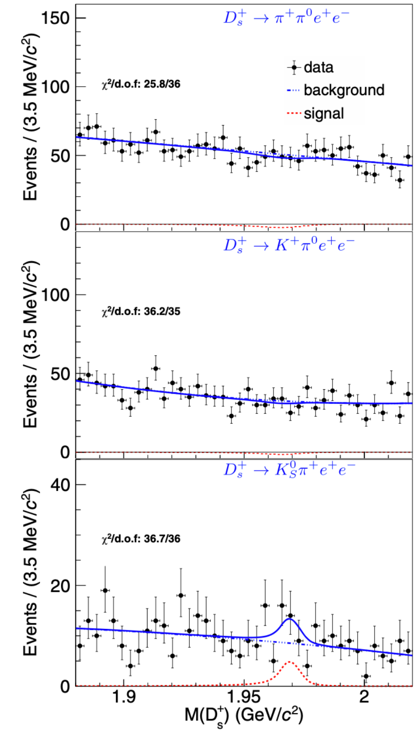
BESIII 的新物理研究

PRL131 (2023) 121801



PRL133 (2024) 121801





Search for $\bar{\Lambda} - \Lambda$ oscillations

$$P(\Lambda) = \frac{\mathcal{B}(J/\psi \to pK^-\Lambda + c.c.)}{\mathcal{B}(J/\psi \to pK^-\bar{\Lambda} + c.c.)}$$

$< 4.4\times10^{-6}$ @ 90%C. L.

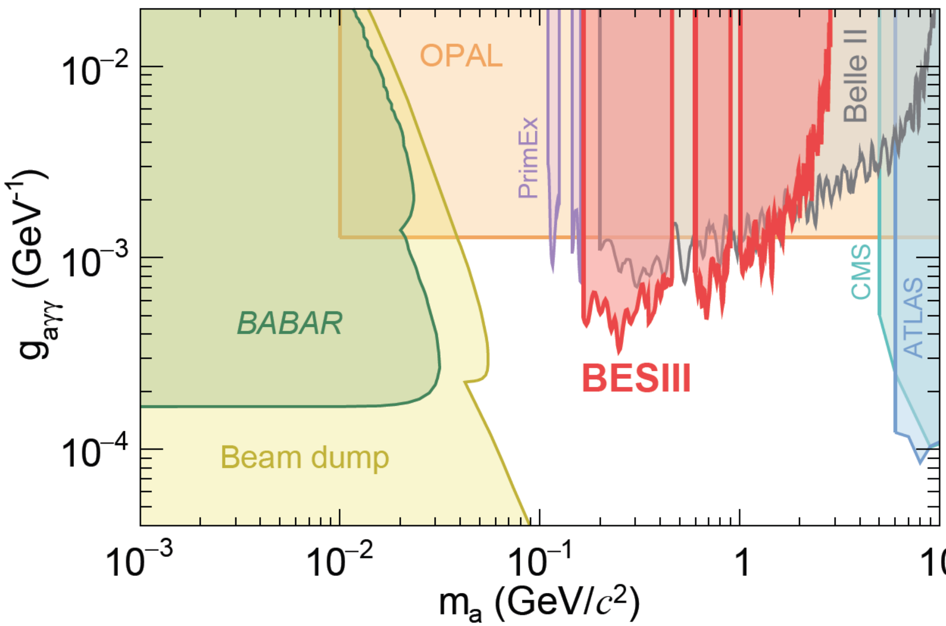
$\delta m_{\Lambda\bar{\Lambda}} < 3.8\times10^{-15}$ MeV/c² @ 90%C. L.

Search for FCNC processes

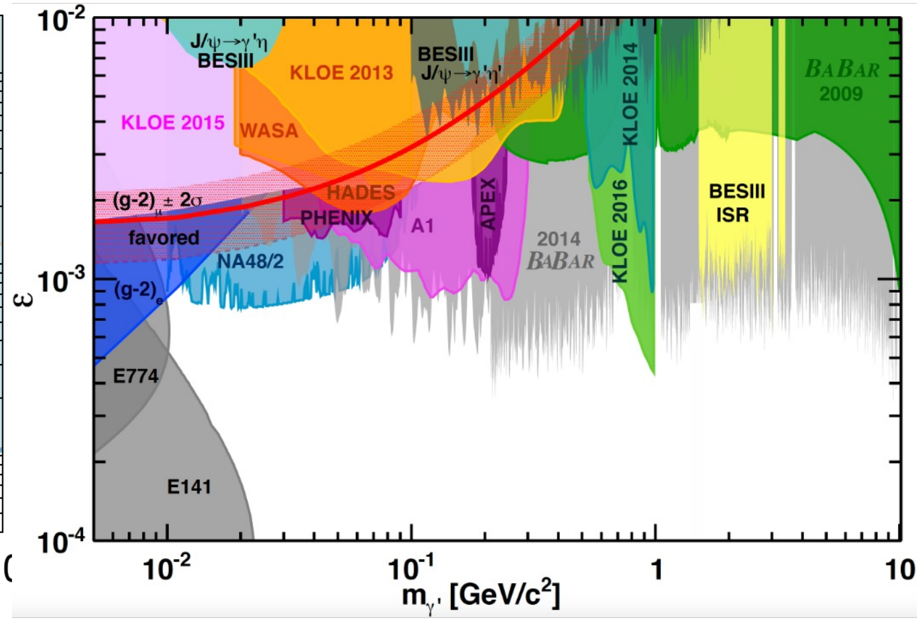
Decay	$N_{\rm sig}$	ϵ (%)	$\mathcal{B}(\times10^{-5})$
$D_s^+ \to \pi^+\phi,\ \phi \to e^+e^-$	$38.2^{+7.8}_{-6.8}$	25.1	$1.17^{+0.23}_{-0.21} \pm 0.03$
$D_s^+ \to \rho^+\phi,\ \phi \to e^+e^-$	$37.8^{+10.3}_{-9.6}$	12.1	$2.44^{+0.67}_{-0.62} \pm 0.16$
$D_s^+ \to \pi^+\pi^0e^+e^-$	$\cdots$	7.4	<7.0
$D_s^+ \to K^+\pi^0e^+e^-$	$\cdots$	5.3	<7.1
$D_s^+ \to K_S^0\pi^+e^+e^-$	$\cdots$	6.7	<8.1

BESIII 的新物理研究

Search for Axion-Like-Particle



Search for Dark Photon



文章产出越来越多、越来越快

- 2015-2019: 13 papers
- 2019-2022: 18
- 2023-2024: 11 (2 PRL)

Backup