The Standard Models of Particle Physics and Cosmology and Beyond

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University of Science and Technology of China

(2019年5月10日)

The Party of Particle Physics and Cosmology is NOT OVER YET!

粒子物理和宇宙学的盛宴还没有结束！

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Outline

- Introduction
- Some basic concepts
- Uniqueness of fermion representations and charges in the standard model of particle physics
- Family problem
- Broken symmetry and mass generation
- Neutrino masses
- Dark Matter and Dark Energy
- Gravitational waves
- Future prospectives

- # Introduction

Where Do We Come From?
我們從哪裡來？

What Are We?
我們是誰？

Where Are We Going?
我們到哪裡去？

Paul Gauguin （1848-1903）


（1942-2018）

Stephen Hawking: Questioning the universe

How did the universe begin?

How did the life begin?

Are we alone?

American Association for the Advancement of Science (AAAS)

July 1, 2005
Science Magazine
125th anniversary

THE QUESTIONS

The Top 25

Essays by our news staff on 25 big questions facing science over the next quarter-century.

- > What Is the Universe Made Of?
- > What is the Biological Basis of Consciousness?
- > Why Do Humans Have So Few Genes?
- > To What Extent Are Genetic Variation and Personal Health Linked?
- > Can the Laws of Physics Be Unified?
- > How Much Can Human Life Span Be Extended?
- > What Controls Organ Regeneration?
- > How Can a Skin Cell Become a Nerve

What is the Universe made of ? #1 ☜

宇宙是由什麼組成的？

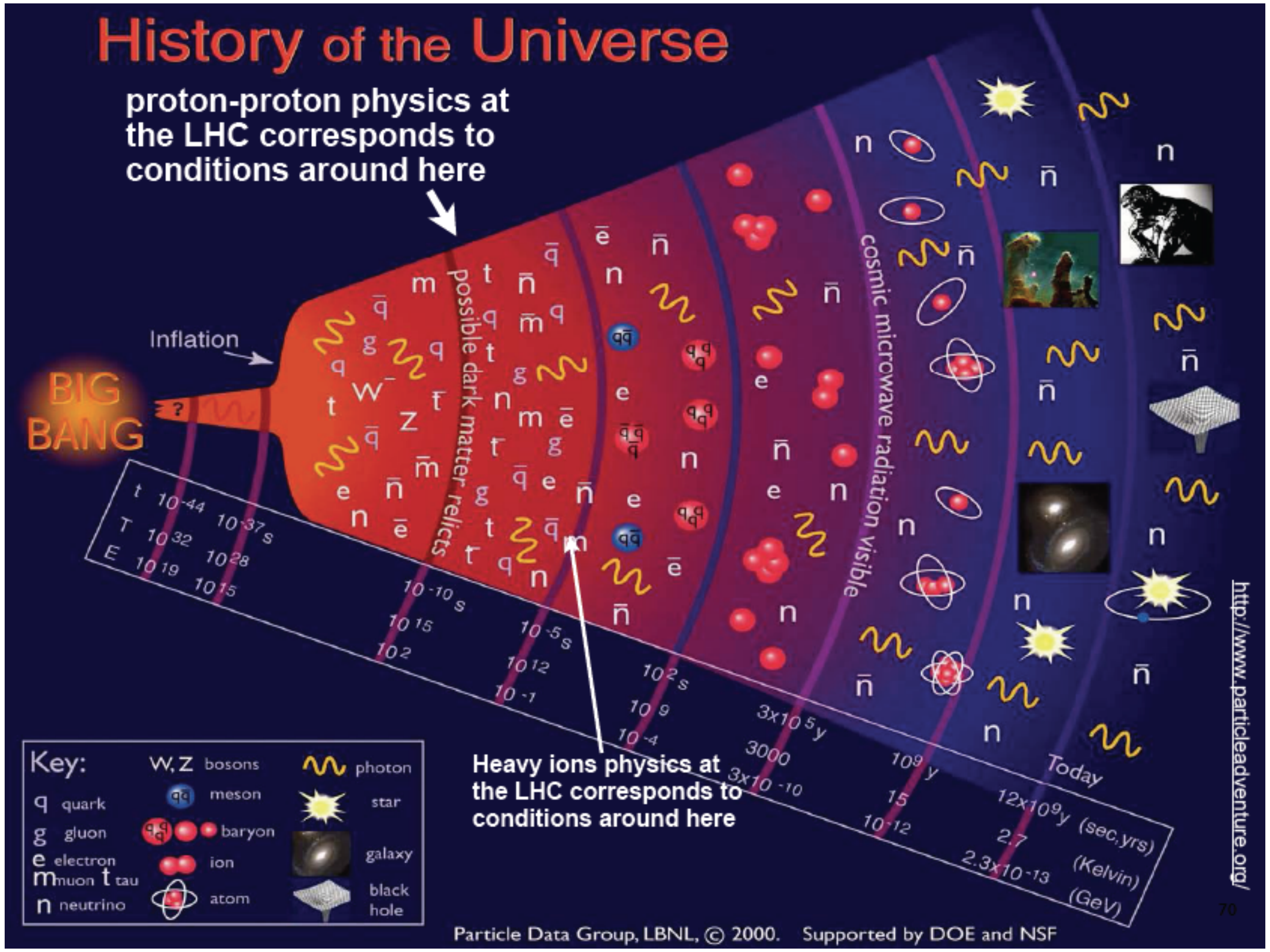
☞ #125

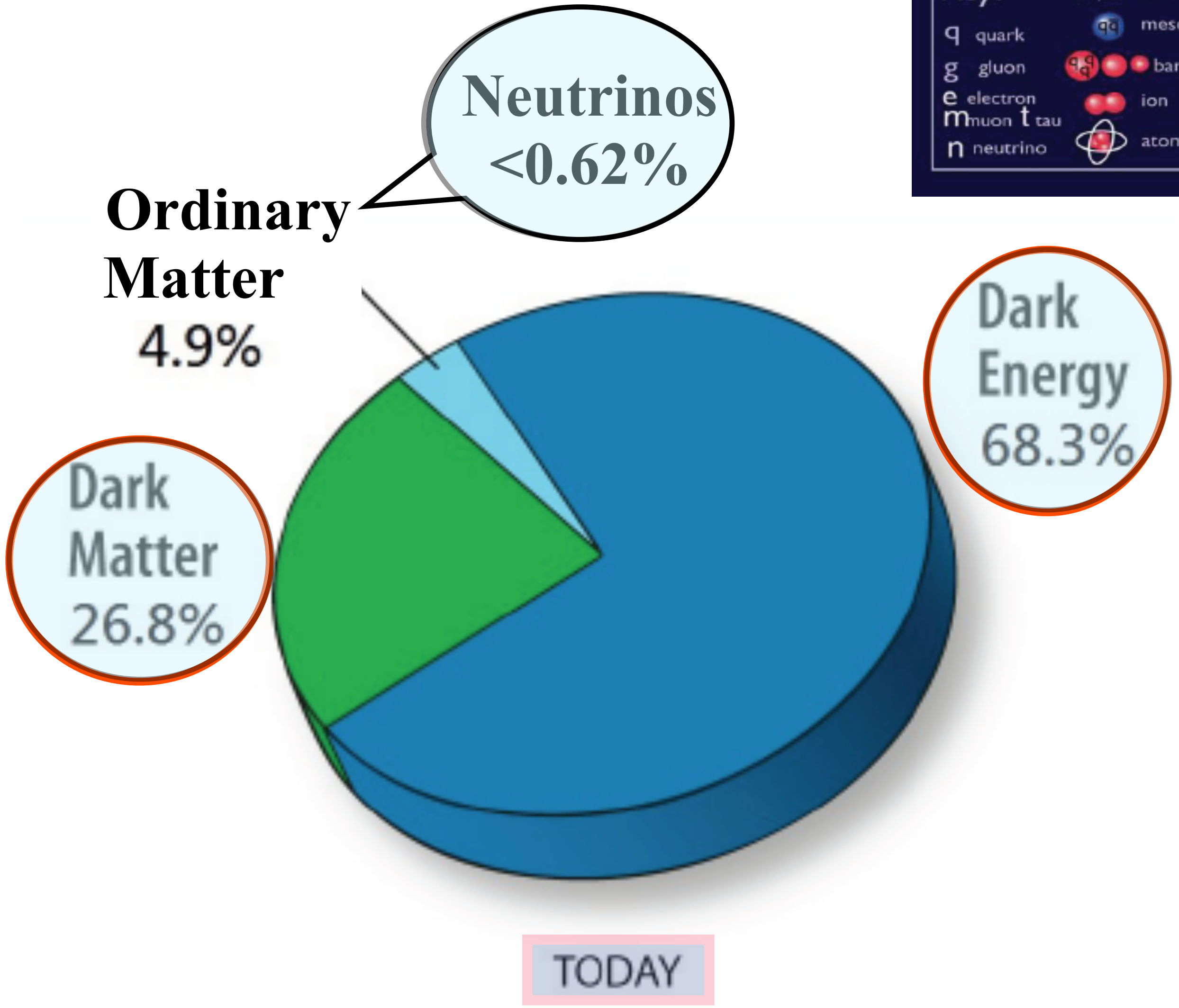
Does the Standard Model of particle physics rest on solid mathematical foundations?

粒子物理的標準模型是否
建構在堅固的數學基礎上？

對於宇宙
知道的很多
但了解的很少

We know much but
we understand very little



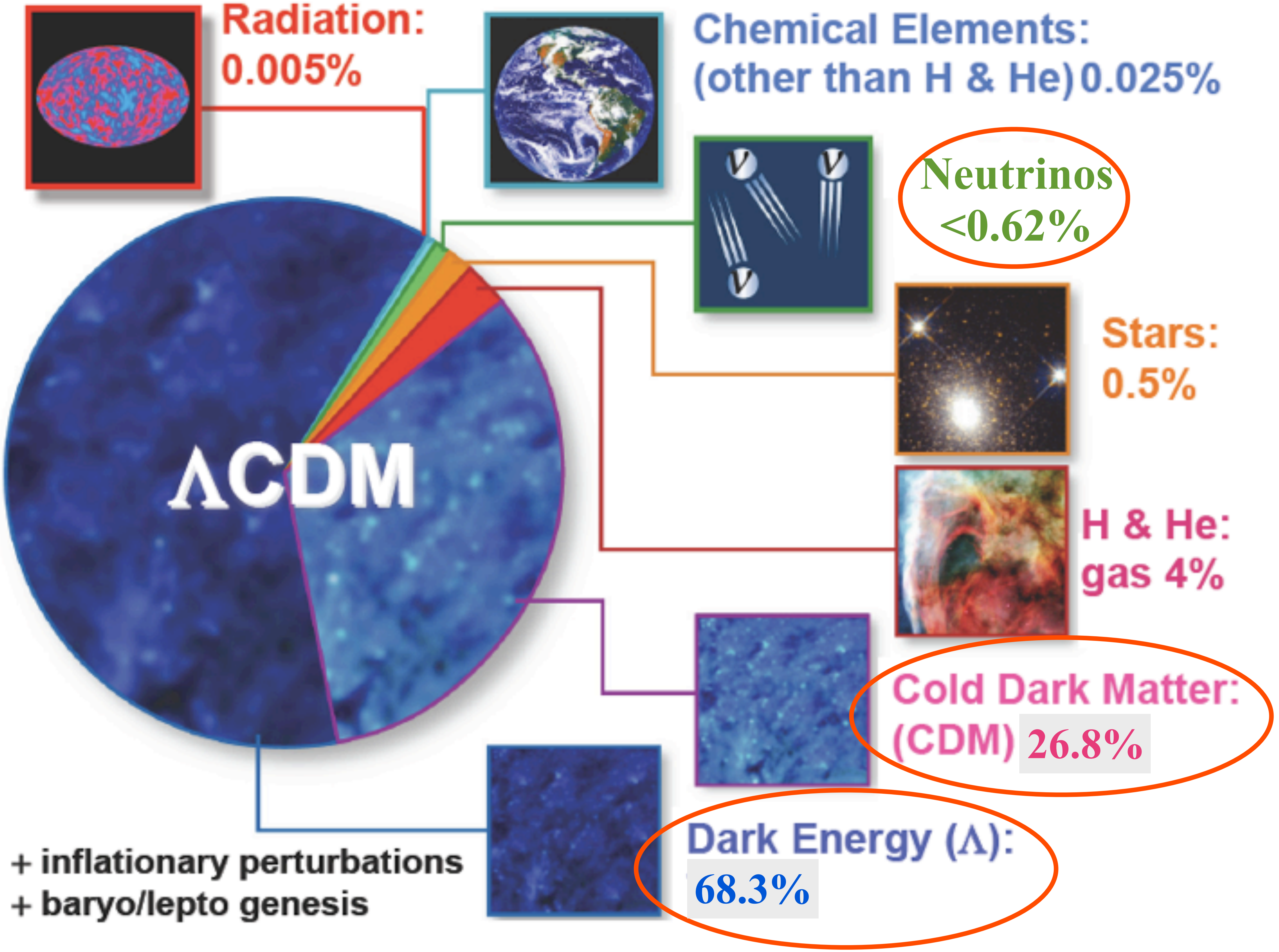


95%的宇宙物質/能量還是個謎。目前也無法在地球上最好的實驗室中觀測到。

95% of the cosmic matter/energy
is still a mystery.

宇宙學標準模型 The Standard Model in Cosmology

ΛCDM



Radiation:
0.005%

Chemical Elements:
(other than H & He) 0.025%

Neutrinos
<0.62%

Stars:
0.5%

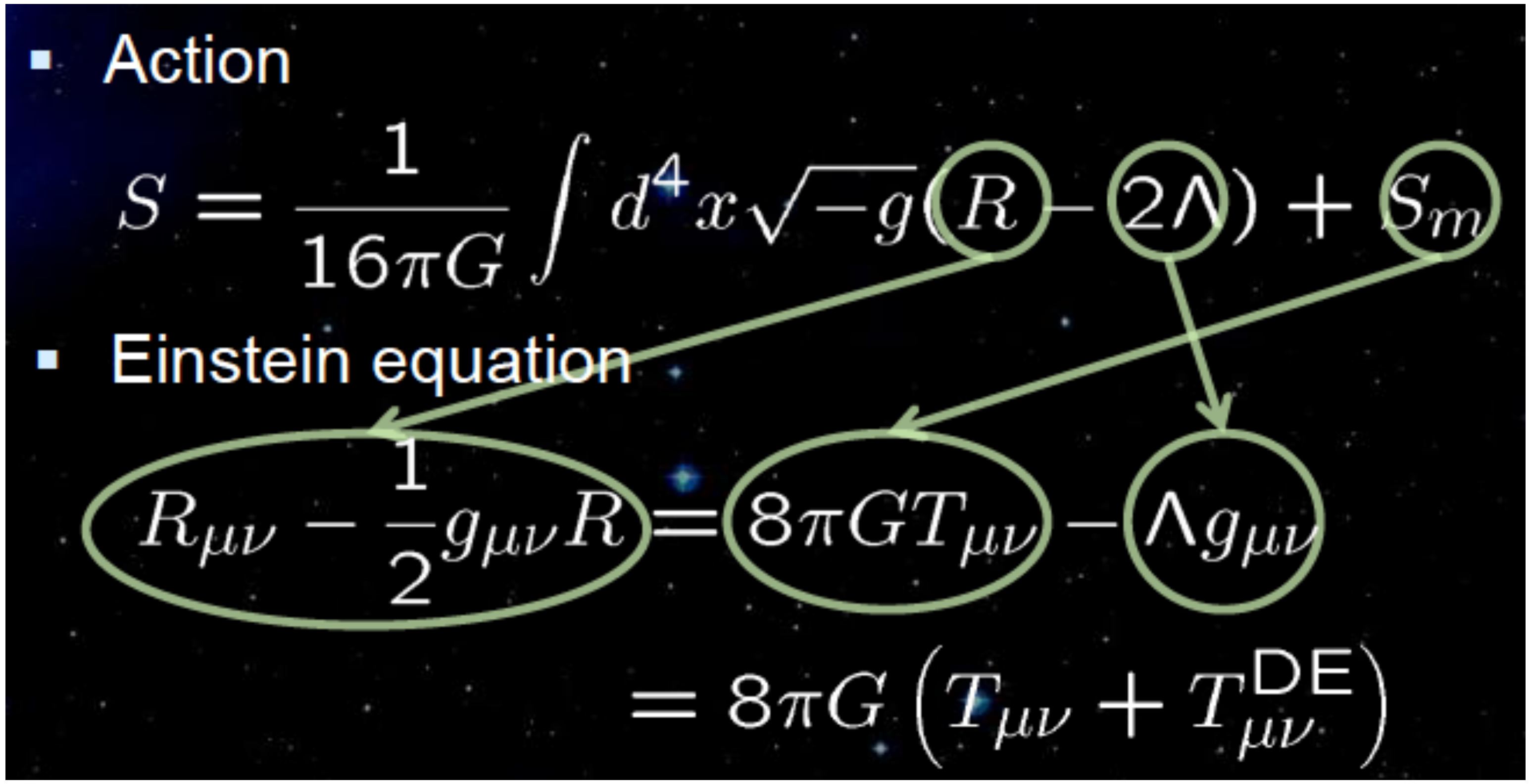
H & He:
gas 4%

Cold Dark Matter:
(CDM) 26.8%

Dark Energy (Λ):
68.3%

+ inflationary perturbations
+ baryo/lepto genesis

ΛCDM model



- Action

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,(R - 2\Lambda) + S_m$$

- Einstein equation

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G T_{\mu\nu} - \Lambda g_{\mu\nu}$$

$$= 8\pi G\left(T_{\mu\nu} + T^{\mathrm{DE}}_{\mu\nu}\right)$$

Friedmann–Lemaître–Robertson–Walker (FLRW) spacetime

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-\kappa r^2} + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)\right]$$

expansion rate

total energy

curvature

$$H^2 = 8\pi G\,(\rho_M + \rho_{DE})\,/\,3 - k\,/\,a^2$$

$$1 = \Omega_M + \Omega_{DE} - k\,/\,(a^2H^2)$$

G	Newton's constant
a	scale factor or radius
$H \equiv \dot{a}/a$	Hubble parameter
ρ	energy density
p	pressure
$k=1, 0, -1$	closed, flat, open

$\Omega \equiv 8\pi G\rho / 3H^2$

For the flat universe of k=0:

$$\Omega_{OM} + \Omega_{DM} + \Omega_{DE} = 1$$

$(\Omega_M = \Omega_{OM} + \Omega_{DM})$

where $\Omega_{OM} \sim 5\%$, $\Omega_{DM} \sim 27\%$ and $\Omega_{DE} \sim 68\%$

粒子物理標準模型 The Standard Model in Particle Physics

Fermion

Boson

Symmetry principle

Standard Matter

Higgs

Force

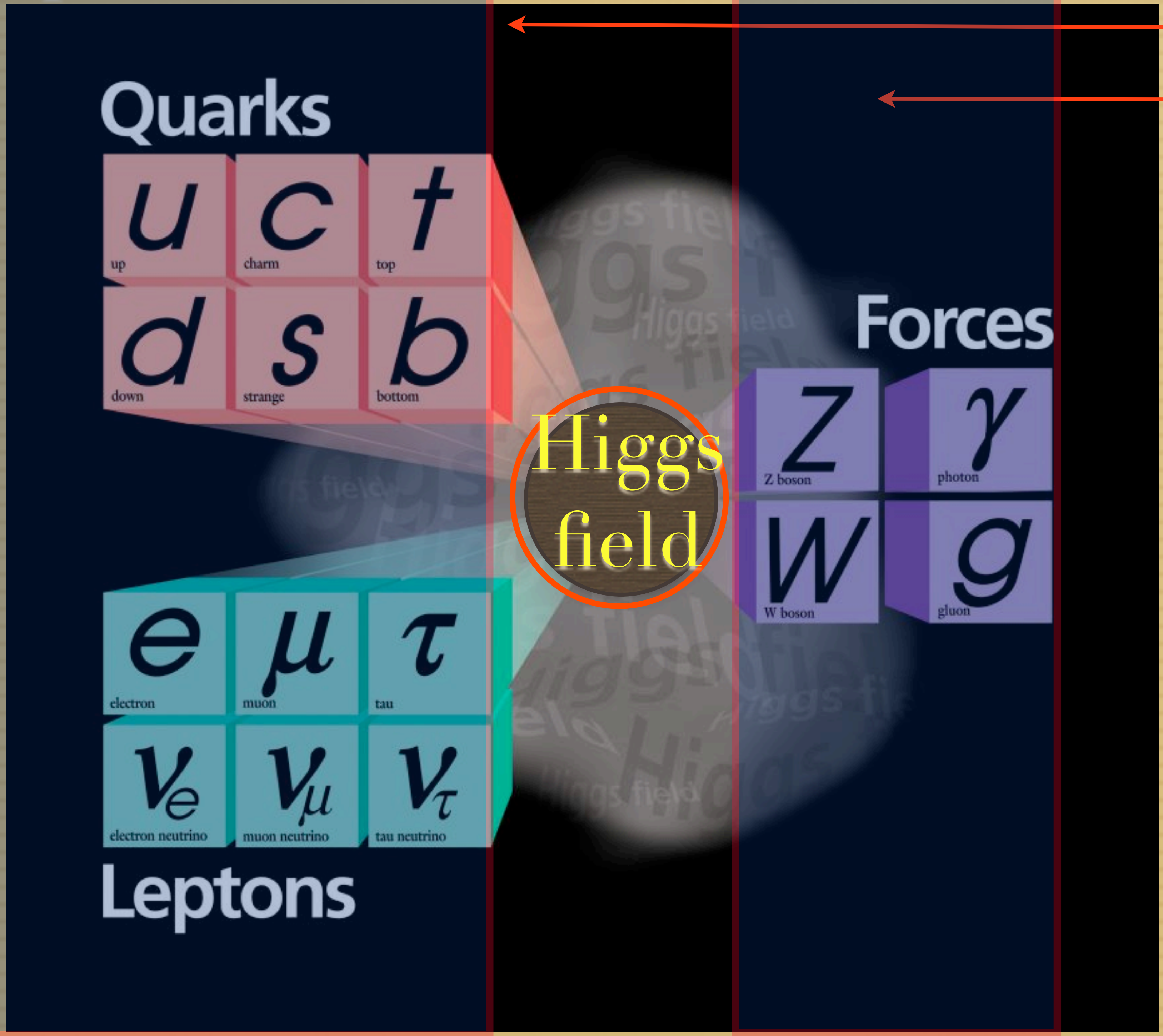
$SU(3)_c \times SU(2)_L \times U(1)_Y$

spin 1/2

0

1

massless



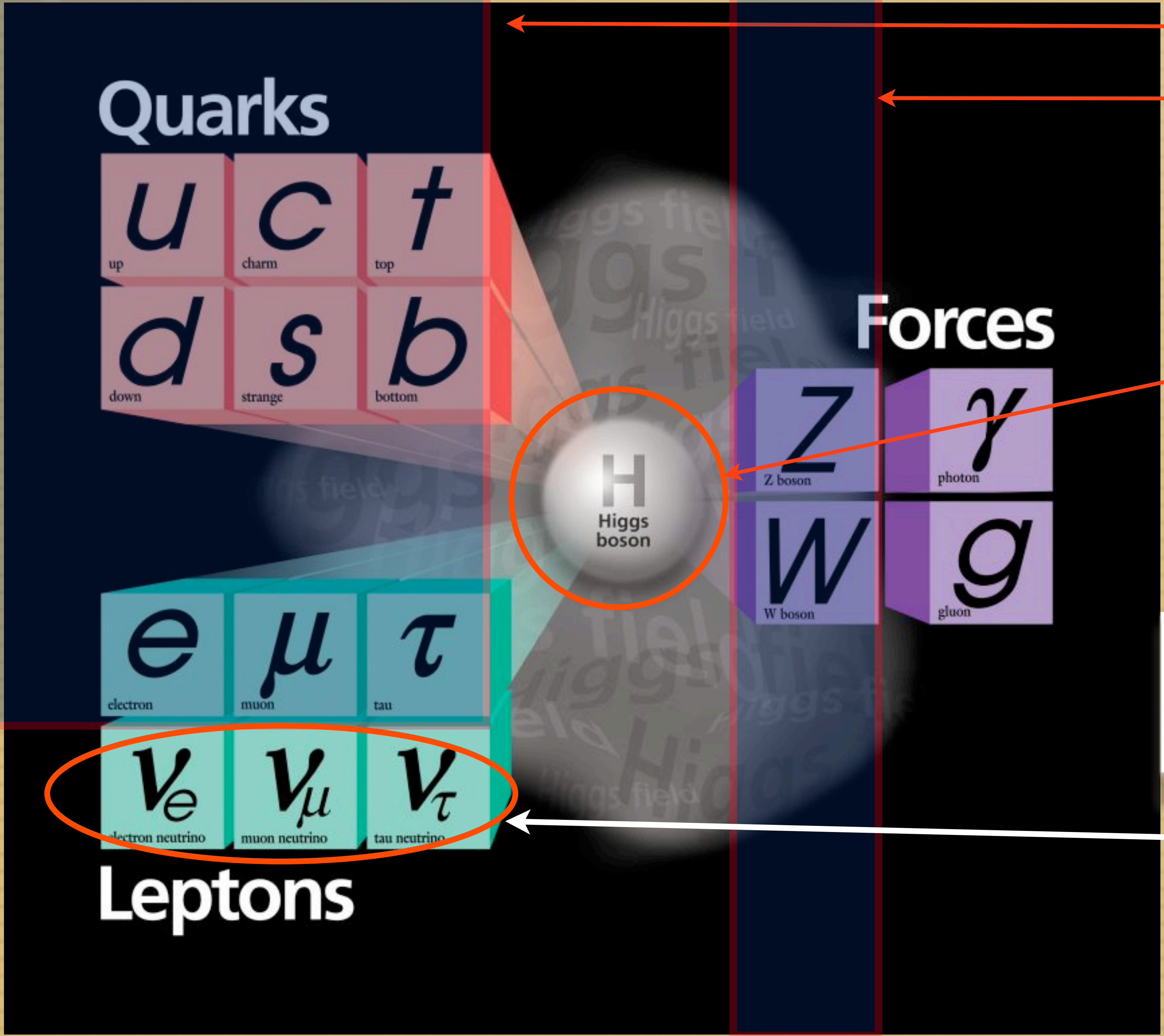
粒子物理標準模型 The Standard Model in Particle Physics

Fermion

Boson

Standard Matter **Higgs** **Force**

spin 1/2 0 1



Spontaneous symmetry breaking

masses

$SU(3)_c \times U(1)_{EM}$

Higgs Mechanism

$SU(3)_c \times SU(2)_L \times U(1)_Y$

Neutrino Oscillation
2015 Nobel: Kajita & McDonald

the SM cannot provides neutrino masses

☞ 超越標準模型的新物理

Standard Groups

☞ $SU(3)_C \times SU(2)_L \times U(1)_Y$

Strong Interaction

Electroweak Interaction

Gell-Mann–Nishijima formula

$Q = T_{3L} + \frac{Y}{2}$

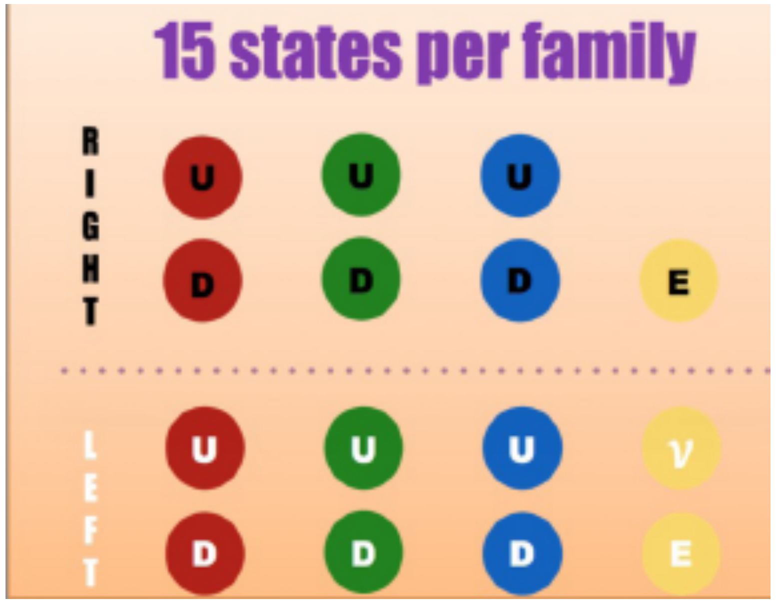
$SU(3)_C \times SU(2)_L \times U(1)_Y \xrightarrow{<H>} SU(3)_C \times U(1)_{EM}$

Higgs Mechanism

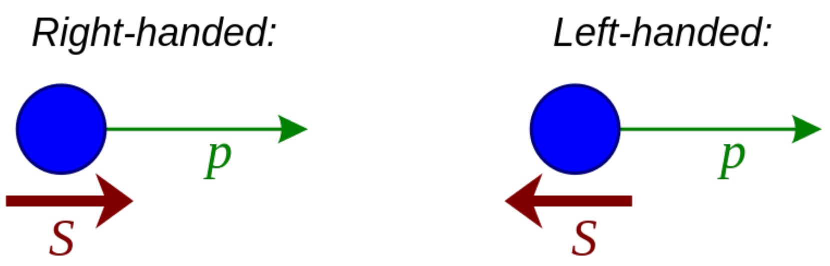
				$SU(3)_C \times SU(2)_L \times U(1)_Y$			$SU(3)_C \times U(1)_{EM}$	
Q_L :	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	$\begin{pmatrix} t \\ b \end{pmatrix}_L$	3	2	$\frac{1}{3}$	3 3	$\frac{2}{3}$ $-\frac{1}{3}$
U_R :	u_R	c_R	t_R	3	1	$\frac{4}{3}$	3	$\frac{2}{3}$
D_R :	d_R	s_R	b_R	3	1	$-\frac{2}{3}$	3	$-\frac{1}{3}$
L_L :	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	1	2	-1	1 1	0 -1
E_R :	e_R	μ_R	τ_R	1	1	-2	1	-1
		H		1	2	1	1 1	1 0

Questions:

1. Why are there 15 states of quarks and leptons?
2. Why are the electric charges of particles quantized?
3. Are these quantum numbers unique?
4. Why are there three fermion generations?
5. How to generate the fermion masses?
6. Is there any new physics beyond the SM?
7. What is the real nature of Dark Matter and Dark Energy?



- Some basic concepts



Chirality and Helicity 手征性和螺旋性

The chirality of a particle is determined by whether the particle is in a right- or left-handed.

The helicity of a particle is right-handed if the direction of its spin is the same as the direction of its motion. It is left-handed if the directions of spin and motion are opposite.

$$h_p \propto \vec{s} \cdot \vec{p}$$

For massless particles—such as photon, gluon, and graviton—chirality is the same as helicity; a given massless particle appears to spin in the same direction along its axis of motion regardless of point of view of the observer.

For massive particles, electrons, quarks and neutrinos, chirality and helicity must be distinguished. In the case of these particles, it is possible for an observer to change to a reference frame that overtakes the spinning particle, in which case the particle will then appear to move backwards, and its helicity (which may be thought of as 'apparent chirality') will be reversed.

Dirac Fermion and Majorana Fermion

Dirac Equation: $(i\gamma^{\mu}\partial_{\mu} - m)\Psi = (\gamma^{\mu} p_{\mu} - m)\Psi = 0$

在Dirac表象下：$\bar{\gamma}^{0} = \begin{pmatrix} \sigma_0 & 0 \\ 0 & -\sigma_0 \end{pmatrix}, \quad \bar{\gamma}^{i} = \begin{pmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{pmatrix}$

σ0 单位矩阵，σi 是泡利矩阵：$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$

Dirac Fermion

Dirac neutrino mass

$$\mathcal{L}_D = -m_D \overline{\nu_L} \nu_R + \text{h.c.}$$

在Majorana表象下：正反粒子等同的粒子 $\Psi^c(x) = \Psi(x)$

Majorana Fermion 天使粒子

Dirac 方程式为纯实的方程，因此方程和解都是实的。

$$\begin{cases} (i\partial_t - \boldsymbol{p}\cdot\boldsymbol{\sigma})\psi_R - i m_R \sigma_2 \psi_R^* = 0 \,, \\ (i\partial_t + \boldsymbol{p}\cdot\boldsymbol{\sigma})\psi_L + i m_L \sigma_2 \psi_L^* = 0 \,. \end{cases}$$

Majorana neutrino mass $\nu \leftrightarrow \bar{\nu}$

$$\mathcal{L}_M = -m_M \overline{\nu^c}\, \nu \quad + \text{h.c.}$$

Chiral symmetry 手征对称性

Massless Dirac fermion field ψ exhibits chiral symmetry

Dirac Equation: $(i\gamma^\mu\partial_\mu - m)\psi=0 \xrightarrow{m\to 0} \boxed{i\gamma^\mu\partial_\mu\,\psi=0} \xrightarrow{\gamma^5} \boxed{i\gamma^\mu\partial_\mu(\gamma^5\psi)=0}$

∴ both ψ and $\gamma^5\psi$ are solutions of Dirac equation.

Two linear combinations: $\psi_L = 1/2(1-\gamma^5)\,\psi$ and $\psi_R = 1/2(1+\gamma^5)\,\psi \longleftarrow \boxed{\psi = \psi_L+\psi_R}$

In QED with one Dirac field:

$$\mathcal{L} = i\bar{\psi}\not{D}\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - m\bar{\psi}\psi \qquad (1)$$

$$F^{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu\,, \quad D_\mu = \partial_\mu - ieA_\mu$$

$$(1) \quad \Longrightarrow \quad U(1)_{\text{vector}} \;:\; \psi \longrightarrow e^{i\alpha}\psi$$

$$m \longrightarrow 0 \quad \Longrightarrow \quad U(1)_{\text{axial vector}} \;:\; \psi \longrightarrow e^{i\beta\gamma_5}\psi$$

Using $\psi_L = \frac{1}{2}(1-\gamma_5)\psi\,, \quad \psi_R = \frac{1}{2}(1+\gamma_5)\psi$ notations: ⟵ **Chiral Fermions**

$$(1) \quad \Longrightarrow \quad \mathcal{L} = i\bar{\psi}_L\not{D}\psi_L + i\bar{\psi}_R\not{D}\psi_R - m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

$$m \longrightarrow 0 \qquad U(1)_L \;:\; \psi_L \longrightarrow e^{ia}\psi_L \qquad U(1)_R \;:\; \psi_R \longrightarrow e^{ib}\psi_R$$

☜ **Chiral symmetries**

$$U(1)_V = U(1)_{L+R}\,, \quad \boxed{U(1)_A = U(1)_{L-R}}$$

Chiral symmetry

The anomaly phenomenon is that

$$\begin{aligned}\partial_\mu J_5^\mu &= \partial_\mu(\bar{\psi}\gamma_\mu\gamma_5\psi)\\ &= 2mJ_5 + \frac{\alpha_0}{2\pi}\tilde{F}^{\mu\nu}F_{\mu\nu}\\ \boxed{m \longrightarrow 0} \quad &\longrightarrow \frac{\alpha_0}{2\pi}\tilde{F}^{\mu\nu}F_{\mu\nu}\end{aligned}$$

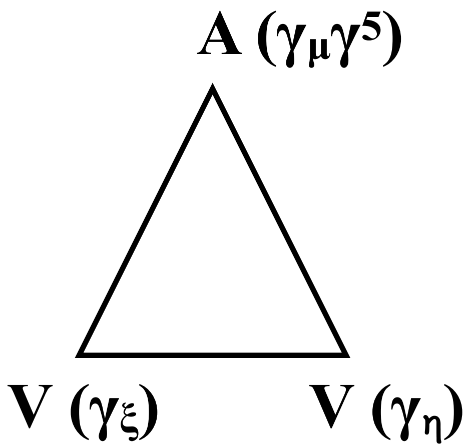
S.Adler, PR177, 2426 (1969);
J.S.Bell, R.Jackiw, Nuovo Cimen A60,47 (1969)

$(\tilde{F}_{\mu\nu} = \epsilon_{\mu\nu\alpha\beta}F^{\alpha\beta})$

Quantum Level

— Adler-Bell-Jackiw (ABJ) or axial *Anomaly*

— *Triangle Anomaly*



This anomalous result $\Longrightarrow$ an understanding of $\pi \to 2\gamma$

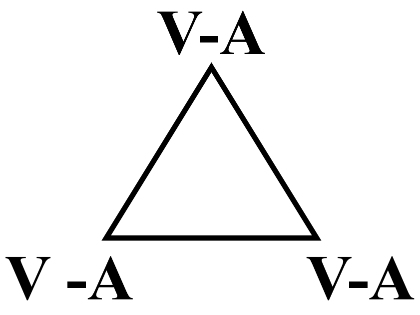
$U(1)$ problem in QCD

No problem in QED the axial-vector current doesn't couple to the photon (γ).

If we introduce a gauge boson which couples to the axial-vector current, such a theory will not be *renormalizable* since the gauge invariance – a necessary requirement for renormalizability — is lost due to $\partial_\mu J_5^\mu \neq 0$.

Electroweak theory: $V - A$ gauge coupling

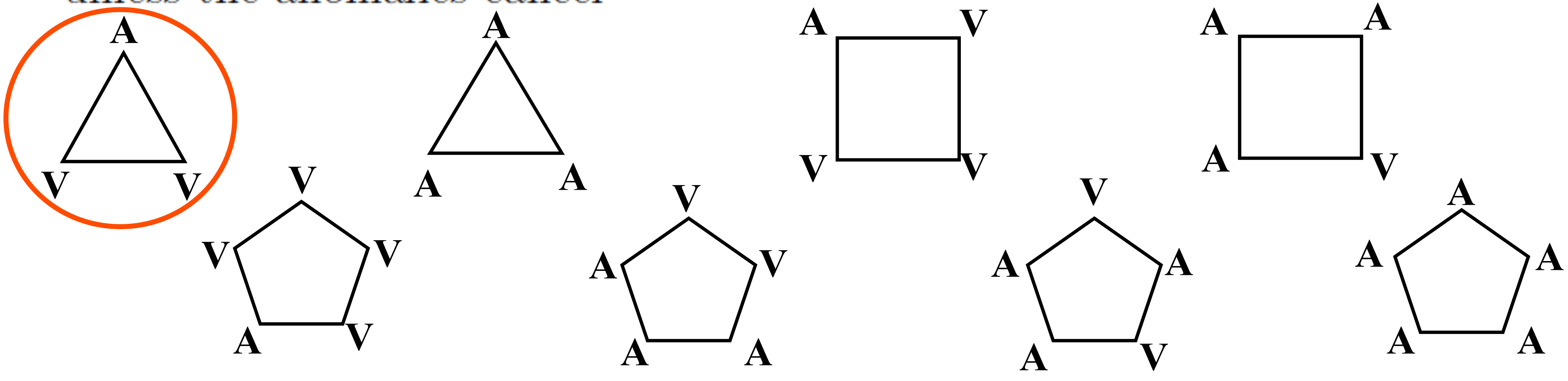
One must consider a fermion triangle with a $V - A$ current at each vertex.



This diagram is again anomalous.

Unless it cancels when summing over the fermion species running around the loop, the anomaly spoils conservation of the $V - A$ current.

- *Any gauge theory with non-vectorlike gauge coupling is inconsistent unless the anomalies cancel*



Two useful theorems:

- Once the AVV triangle anomaly is cancelled, then so are all the others.
- Radiative corrections do not renormalize the anomaly.

$\Longrightarrow$ *Only AVV triangle graph is needed to consider.*

For example: any gauge theory

$$
\begin{aligned}
J^{\mu}_{a} &= \bar{\psi}\gamma^{\mu}t_{a}\psi \\
&= \frac{1}{2}\bar{\psi}\gamma^{\mu}t^{L}_{a}(1-\gamma_5)\psi + \frac{1}{2}\bar{\psi}\gamma^{\mu}t^{R}_{a}(1+\gamma_5)\psi
\end{aligned}
$$

where t_a $(a = 1, 2, \cdots, N)$ are the generators of the gauge group.

$$
\begin{aligned}
Anomaly - free \Longleftrightarrow \mathcal{A} &\equiv Tr\left[\{t^{L}_{a}, t^{L}_{b}\}, t^{L}_{c}\right] - Tr\left[\{t^{R}_{a}, t^{R}_{b}\}, t^{R}_{c}\right] \\
&= 0
\end{aligned}
$$

△ Real representations are *safe*.

△ $SU(2)$, $SO(2k+1)$ $(k > 2)$, $SO(4k)$ $(k > 2)$, $Sp(2k)$, G_2, F_4, E_7, E_8 have only real reps. — *safe*.

△ $SO(4k+2)$ $(k > 2)$, E_6 have complex reps. — *safe*.

△ $SU(N)$ $(N > 2)$ are not *safe*.

For ($\Box$, Y) under SU(N)×U(1)$_Y$:
or ($\bar{\Box}$, Y)

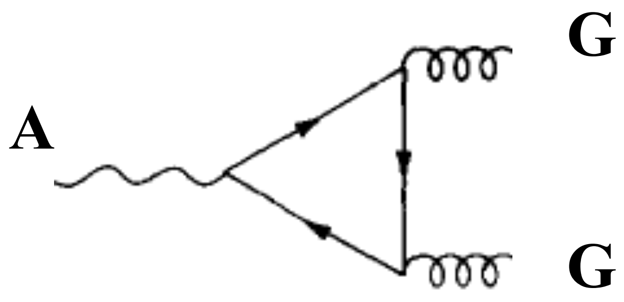
$$
\begin{aligned}
[SU(N)]^3 &: \mathcal{A}(\Box) = 1\,, \quad \mathcal{A}(\bar{\Box}) = -1 \\
[SU(N)]^2\,U(1)_Y &: \mathcal{A}(\Box) = Y\,, \quad \mathcal{A}(\bar{\Box}) = Y \\
[U(1)_Y]^3 &: \mathcal{A} = Y^3 \mathrm{N}
\end{aligned}
$$

Particles $(i=1,2,3)$	$SU(3)_C$	$\times$	$SU(2)_L$	$\times$	$U(1)_Y$
$\begin{pmatrix} u \\ d \end{pmatrix}_L^i$	3		2		$\frac{1}{3}$
$u_L^{c\,i}$	$\overline{3}$		1		$-\frac{4}{3}$
$d_L^{c\,i}$	$\overline{3}$		1		$\frac{2}{3}$
$\begin{pmatrix} \nu \\ e \end{pmatrix}_L^i$	1		2		-1
$e_L^{c\,i}$	1		1		2

Triangle anomalies in the standard model:

$$
\begin{aligned}
[SU(3)_C]^3 &= 2-1-1=0 \\
[SU(3)_C]^2\,U(1)_Y &= 2\cdot\frac{1}{3}+1\cdot(-\frac{4}{3})+1\cdot\frac{2}{3}=0 \\
[SU(2)_L]^3 &\equiv 0 \\
[SU(2)_L]^2\,U(1)_Y &= 3\cdot\frac{1}{3}-1=0 \\
[U(1)_Y]^3 &= TrY^3 \\
&= 3\cdot 2\cdot(\frac{1}{3})^3+3\cdot 1\cdot(-\frac{4}{3})^3+3\cdot 1\cdot(\frac{1}{3})^3 \\
&\quad +2\cdot(-1)^3+1\cdot(2)^3=0
\end{aligned}
$$

- The mixed gauge-gravitational anomaly



The triangle with one axial-current and two energy-momentum tensors is anomalous

Toshiei Kimura, Progress of Theoretical Physics,1191 (1969)

$$D_\mu J^\mu_5 = -\frac{1}{384\pi^2}(TrQ)\; R_{\mu\nu\sigma\tau}\tilde{R}^{\mu\nu\sigma\tau}$$

R.Delbourgo,A.Salam,PLB40,381(72); T.Eguchi,P.Freund,PRL37,1251(76)

$R_{\mu\nu\sigma\tau}$ is the Riemann curvature tensor and $\tilde{R}^{\mu\nu\sigma\tau} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}R^{\sigma\tau}_{\alpha\beta}$.

In four dimensions, the standard $SU(2)_L \times U(1)_Y$ theory cannot be coupled to gravity unless the sum of hypercharges (Y) of the Weyl fermions vanishes:

$$Tr\,Y = 0$$

L.Alvarez-Gaume, E.Witten, NPB234 (1983) 269

In the SM: $TrY = 3\cdot 2\cdot(\frac{1}{3}) + 3\cdot 1\cdot(-\frac{4}{3}) + 3\cdot 1\cdot(\frac{2}{3}) + 1\cdot 2\cdot(-1) + 1\cdot 1\cdot 2 = 0.$

Remarks:

- $U(1)$ — *unsafe*, unless $TrQ = 0$.
- G — *safe*. $\quad G \longrightarrow U(1)\times g\,, \quad TrQ \equiv 0$

- The global Witten $SU(2)$ anomaly

E.Witten,PLB117(1982)324

Any $SU(2)$ gauge theory with an odd number of left-handed fermion doublets is mathematically inconsistent.

The fermion integration for N massless Weyl fermion doublets, ψ:

$$\begin{aligned}\int(\mathcal{D}\psi\mathcal{D}\bar{\psi})_{\text{Weyl}}\, e^{\bar{\psi}iD\psi} &= det^{N/2} iD(A)\\ &\longrightarrow (-1)^N det^{N/2} iD(A^U)\end{aligned}$$

a topologically nontrivial gauge transformation U

where $A_\mu^U = U^{-1}A_\mu U - iU^{-1}\partial_\mu U$.

The number of the doublets, N, has to be *even*, otherwise the theory is ill-defined.

In the SM, for each family, $N = 3$ (quark) $+$ 1 (lepton) $= 4$ — even.

Remarks:

- $\Pi_4(G) = Z_2\,,\ G = Sp(2N), SU(2) = Sp(2)$ — *unsafe*.
- $\Pi_4(G) = 0$, G: all the simple compact Lie groups except $Sp(2N)$ — *safe*.

Π_4(G) is the 4th homotopy group

Question: For $G \longrightarrow SU(2) \times g$, is Witten $SU(2)$ anomaly free?

Triangle Anomaly-free of $G \implies$ Witten $SU(2)$ Anomaly-free

CQG, Zhao,Marshak,OKubo PRD(RC)36(1987)1953

(a) $SO(10)$	$\rightarrow$ $SU(4)_C$	$\times$ $SU(2)_L$	$\times$ $SU(2)_R$
16	4	2	1
	$\bar{4}$	1	2

N= even

(b) $SU(3)$	$\rightarrow$ $SU(2)$	$\times$ $U(1)$
3	2	1
	1	-2

N= odd

- Uniqueness of fermion representations and charges in the SM

$SU(3)$	×	$SU(2)$	×	$U(1)$
3		2		$Q_i\,,\ i=1,\cdots,j$
3		1		$Q'_i\,,\ i=1,\cdots,k$
$\overline{3}$		1		$\overline{Q}_i\,,\ i=1,\cdots,l$
$\overline{3}$		2		$\overline{Q}'_i\,,\ i=1,\cdots,m$
1		2		$q_i\,,\ i=1,\cdots,n$
1		1		$\overline{q}_i\,,\ i=1,\cdots,p$
$\cdots$		$\cdots$		$\cdots$

☜ ***arbitrary***

The triangular anomaly-free conditions:

$$[SU(3)]^3 \ : \ \sum_{i=1}^{j} 2 + \sum_{i=1}^{k} 2 - \sum_{i=1}^{l} 1 - \sum_{i=1}^{m} 2 = 0\,, \tag{1}$$

$$[SU(3)]^2 U(1) \ : \ 2\sum_{i=1}^{j} Q_i + \sum_{i=1}^{k} Q'_i + \sum_{i=1}^{l} \overline{Q}'_i + 2\sum_{i=1}^{m} \overline{Q}'_i = 0\,, \tag{2}$$

$$[SU(2)]^2 U(1) \ : \ 3\sum_{i=1}^{j} Q_i + 3\sum_{i=1}^{m} \overline{Q}'_i + \sum_{i=1}^{n} q_i = 0\,, \tag{3}$$

$$[U(1)]^3 \ : \ 6\sum_{i=1}^{j} Q_i^3 + 3\sum_{i=1}^{k} Q_i'^3 + 3\sum_{i=1}^{l} \overline{Q}_i^3 + 6\sum_{i=1}^{m} \overline{Q}_i'^3 + 2\sum_{i=1}^{n} q_i^3 + \sum_{i=1}^{p} \overline{q}_i^3 = 0. \tag{4}$$

The global Witten $SU(2)$ anomaly-free condition:

$$3j + 3m + n = 0 \mod 2 \tag{5}$$

The mixed anomaly-free condition:

$$[U(1)] : 6\sum_{i=1}^{j} Q_i + 3\sum_{i=1}^{k} Q'_i + 3\sum_{i=1}^{l} \overline{Q}_i + 6\sum_{i=1}^{m} \overline{Q}'_i + 2\sum_{i=1}^{n} q_i + \sum_{i=1}^{p} \overline{q}_i = 0\,. \tag{6}$$

Minimality Condition with Chiral Fermions!

CQG&R.Marshak, PRD39(1989)693

The minimal solusions are: ☜

- $j = k = l = m = n = p = 0$ <u>NO *fermions*</u>
- $j = 1\,,\ k = 0\,,\ l = 2\,,\ m = 0\,,\ n = 1\,,\ p = 1$

$SU(3)_C$	$\times$	$SU(2)_L$	$\times$	$U(1)_Y$
3		2		Q_1
$\bar{3}$		1		$\bar{Q}_1$
$\bar{3}$		1		$\bar{Q}_2$
1		2		q_1
1		1		$\bar{q}_1$

15 states !

The minimal solusions are: ☜

Minimality Condition with Chiral Fermions!

CQG&R.Marshak, PRD39(1989)693

- $j = k = l = m = n = p = 0$ NO *fermions*
- $j = 1\,,\ k = 0\,,\ l = 2\,,\ m = 0\,,\ n = 1\,,\ p = 1$

(a) $Q_1 = 0\,,\quad \bar{Q}_1 = -\bar{Q}_2\,,\quad q_1 = \bar{q}_1 = 0$ No *electroweak forces!*

(b) $Q_1 = -\frac{q_1}{3}\,,\ \bar{Q}_1 = \frac{4q_1}{3}\,,\ \bar{Q}_2 = -\frac{2q_1}{3}\,,\ \bar{q}_1 = -2q_1$

$q_1 = -1$ in unit of e → The *standard model* with *one family*

Table 1. The quantum numbers of quark and lepton representations under $SU(3)_C \times SU(2)_L \times U(1)_Y$ and $SU(3)_C \times U(1)_{EM}$

Particles $(i = 1, 2, 3)$	$SU(3)_C$ ×	$SU(2)_L$ ×	$U(1)_Y$ →	$SU(3)_C$ ×	$U(1)_{EM}$
$\begin{pmatrix}u\\d\end{pmatrix}_L^i$	3	2	$\frac{1}{3}$	$\begin{pmatrix}3\\3\end{pmatrix}$	$\begin{pmatrix}2/3\\-1/3\end{pmatrix}$
$u_L^{c\,i}$	$\bar{3}$	1	$-\frac{4}{3}$	$\bar{3}$	$-2/3$
$d_L^{c\,i}$	$\bar{3}$	1	$\frac{2}{3}$	$\bar{3}$	$1/3$
$\begin{pmatrix}\nu\\e\end{pmatrix}_L^i$	1	2	-1	$\begin{pmatrix}1\\1\end{pmatrix}$	$\begin{pmatrix}0\\-1\end{pmatrix}$
$e_L^{c\,i}$	1	1	2	1	1

Why the three anomaly cancellations, especially the global Witten $SU(2)$ and mixed gauge-gravitational ones, should be satisfied?

→ **New Physics!**

Unified Theory: G —— Triangle $\mathcal{A}$nomaly free

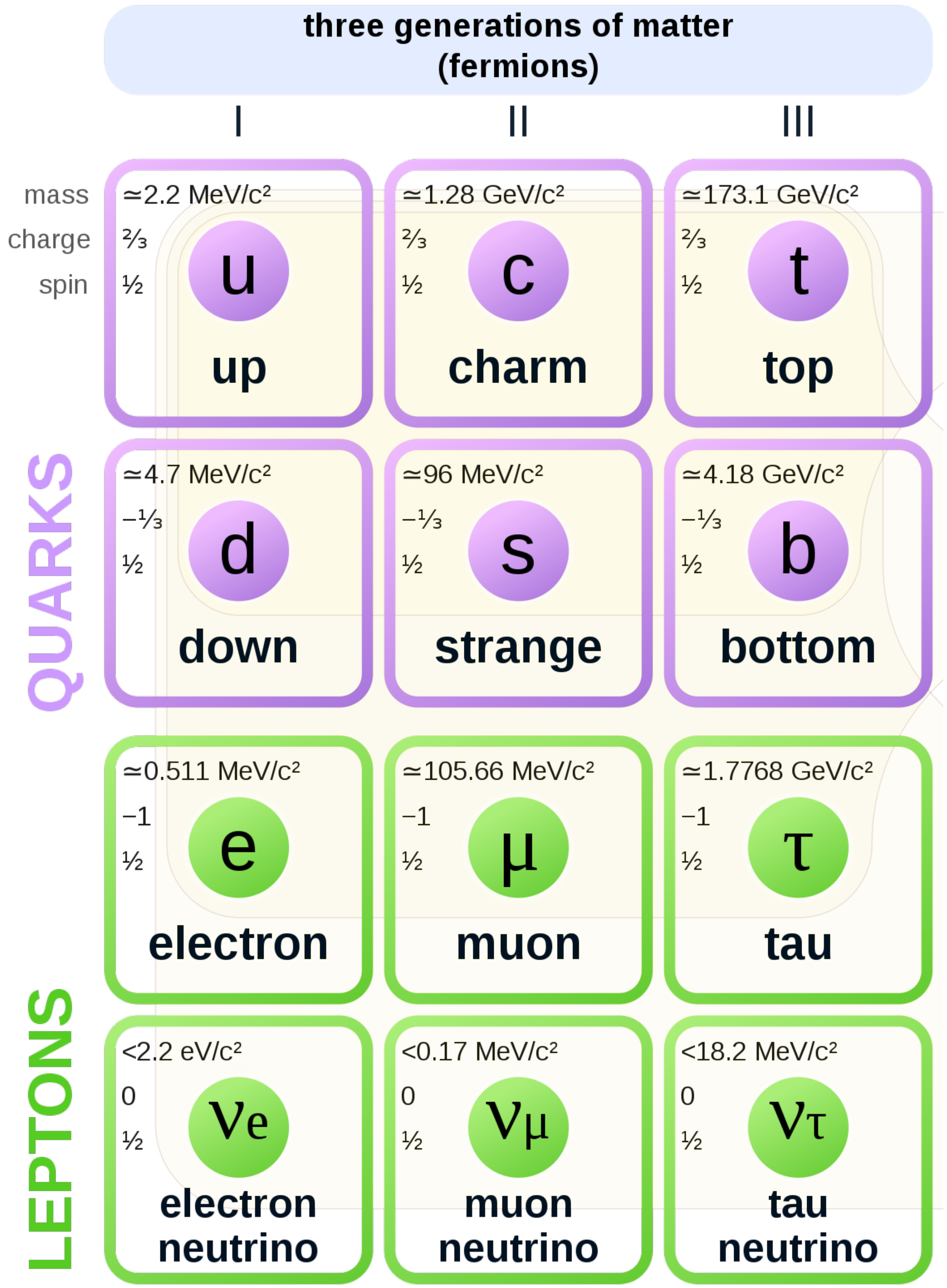
⬇

No global Witten $SU(2)$ and
mixed gauge-gravitational anomalies
when G breaks down $SU(3)_C \times SU(2)_L \times U(1)_Y$

It is very natural to think that the standard model comes from some form of New Physics unless the $\mathcal{A}$nomaly Cancellations are ACCIDENTS.

- **Family problem**

Why are there three fermion generations?



three generations of matter (fermions)

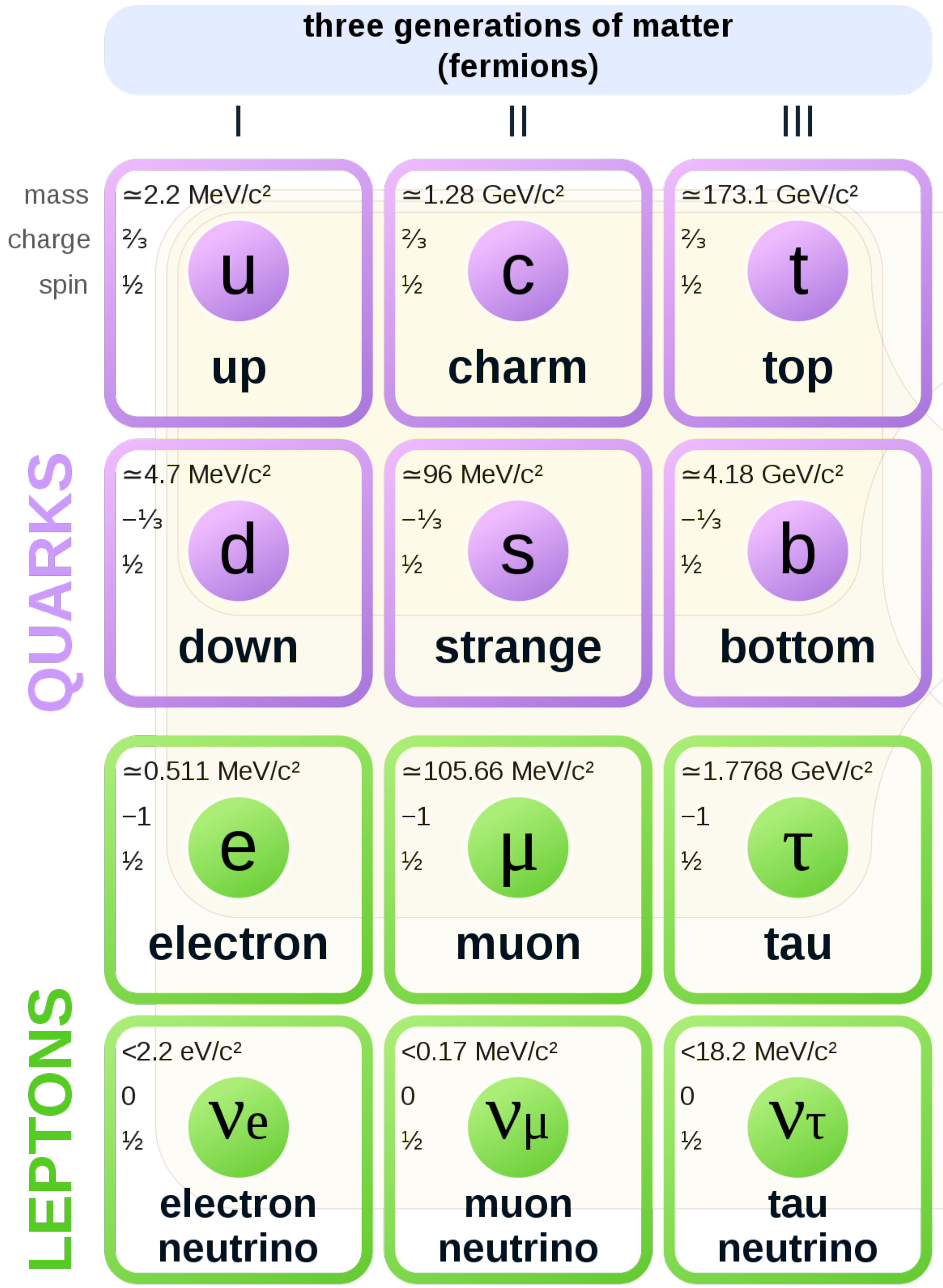
		I	II	III
QUARKS	mass charge spin	≃2.2 MeV/c^2 ⅔ ½ u up	≃1.28 GeV/c^2 ⅔ ½ c charm	≃173.1 GeV/c^2 ⅔ ½ t top
		≃4.7 MeV/c^2 −⅓ ½ d down	≃96 MeV/c^2 −⅓ ½ s strange	≃4.18 GeV/c^2 −⅓ ½ b bottom
LEPTONS		≃0.511 MeV/c^2 −1 ½ e electron	≃105.66 MeV/c^2 −1 ½ μ muon	≃1.7768 GeV/c^2 −1 ½ τ tau
		<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<18.2 MeV/c^2 0 ½ ν_τ tau neutrino

三代物质粒子（费米子）

		I	II	III
夸克	质量 电荷 自旋	≃2.2 MeV/c^2 2/3 1/2 u 上	≃1.28 GeV/c^2 2/3 1/2 c 粲	≃173.1 GeV/c^2 2/3 1/2 t 顶
		≃4.7 MeV/c^2 -1/3 1/2 d 下	≃96 MeV/c^2 -1/3 1/2 s 奇	≈4.18 GeV/c^2 -1/3 1/2 b 底
轻子		≈0.511 MeV/c^2 -1 1/2 e 电子	≃105.66 MeV/c^2 -1 1/2 μ μ子	≈1.7768 GeV/c^2 -1 1/2 τ τ子
		<2.2 eV/c^2 0 1/2 ν_e 电中微子	<1.7 MeV/c^2 0 1/2 ν_μ μ中微子	<15.5 MeV/c^2 0 1/2 ν_τ τ中微子

• Family problem

Why are there three fermion generations?



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		<2.2 eV/c^2 0 1/2 ν_e 电中微子	<1.7 MeV/c^2 0 1/2 ν_μ μ中微子	<15.5 MeV/c^2 0 1/2 ν_τ τ中微子

Charm quark： 粲 → 媚

LEP experiments ALEPH, DELPHI, L3, and OPAL

The invisible width Γ_{inv} is assumed to be due to N_ν light neutrino species each contributing the neutrino partial width Γ_ν as given by the Standard Model.

$$N_\nu = \frac{\Gamma_{\text{inv}}}{\Gamma_\ell}\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{\text{SM}}$$

☞ $N_\nu = 3.00 \pm 0.08$

Other experiments supporting 3 families

LHC: Higgs mass

Planck: Active neutrino number

CP violation in the SM

M. Kobayahsi and K. Maskawa,
“CP Violation in the Renormalizable Theory of Weak Interactions”, Progr. Theor. Phys. **49** (1973) 652.

→ observable or physical phases : $\frac{n(n+1)}{2} - (2n-1) = \frac{(n-1)(n-2)}{2}$

For two generations ($n = 2$) → **no phase** + 1 angle

For three generations ($n = 3$) → one phase + 3 angles

Observation of CP Violation at B-factories ☞ 三代夸克之存在

Nobel Physics Prize 2008

Broken Symmetry

破缺的對稱性

「發現對稱破缺的起源，預測自然界存在三代夸克」

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Photo: SCANPIX

Yoichiro Nambu

Photo: Kyodo/Reuters

Makoto Kobayashi

Photo: Kyoto University

Toshihide Maskawa

● Broken symmetry and mass generation

對稱性破缺相關的兩大問題 → 機會

I. 手征規范對稱性之破缺

連續對稱性

$$SU(3)_c\times\underline{SU(2)_L\times U(1)_Y}\xrightarrow{\text{Higgs Mechanism}}SU(3)_c\times\underline{U(1)_{EM}}$$

The Higgs Particle (2012) ← **LHC大強子對撞機**

II.宇宙物質與反物質之不對稱性

為什麼普通物質是由物質構成？

分立對稱性

1. *Baryon number violation*
2. *C and CP violation*
3. *A departure from thermal equilibrium*

1967: Sakharov (the Nobel Peace Prize 1975)

但是，**CKM**之**CP**破缺機制不能解識
「宇宙物質與反物質之不對稱性」

連續對稱性之破缺

Nambu was the first to introduce spontaneous symmetry violation into elementary particle in 1960s.

The action for a meson field φ interacting with a Dirac fermion field ψ is

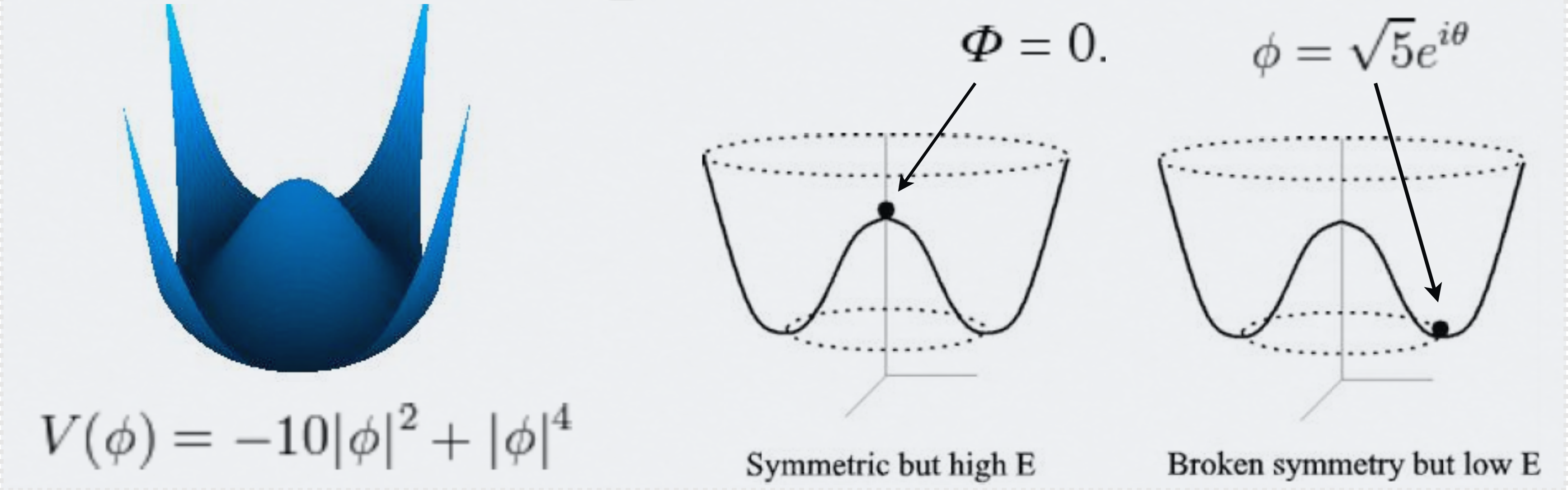
$$S[\phi,\psi] = \int d^dx\ [\mathcal{L}_{\text{meson}}(\phi) + \mathcal{L}_{\text{Dirac}}(\psi) + \mathcal{L}_{\text{Yukawa}}(\phi,\psi)]$$
$$= \int d^dx \left[\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi) + \bar{\psi}(i\partial\!\!\!/ - m)\psi - g\bar{\psi}\phi\psi\right]$$

For a (renormalizable) self-interacting field:

$$V(\phi) = \mu^2\phi^2 + \lambda\phi^4$$

Lagrangian exhibits spontaneous symmetry breaking (SSB) when $\mu^2<0$

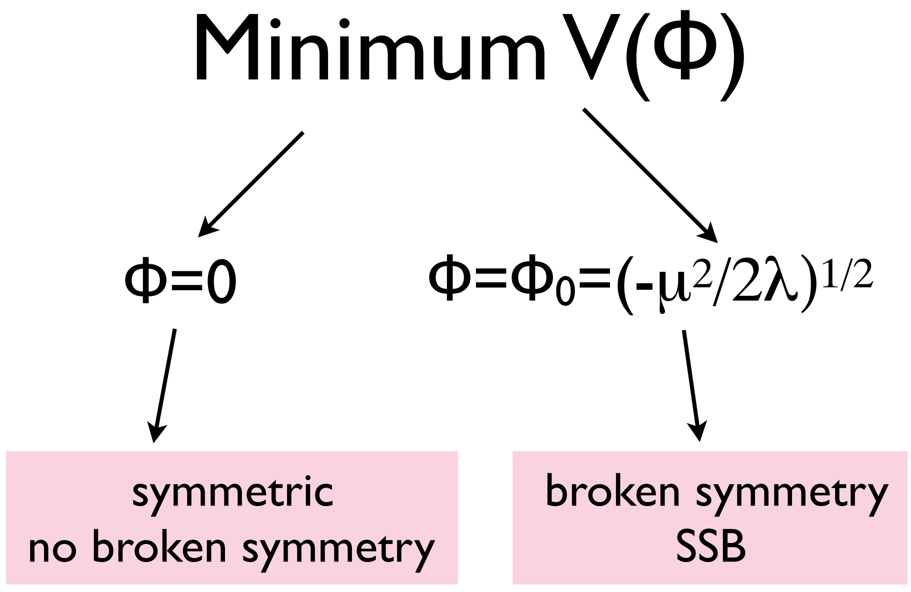
the Mexican hat potential



$$V(\phi) = -10|\phi|^2 + |\phi|^4$$

Symmetric but high E

Broken symmetry but low E



Minimum V(Φ)

$\Phi=0$

$\Phi=\Phi_0=(-\mu^2/2\lambda)^{1/2}$

symmetric
no broken symmetry

broken symmetry
SSB

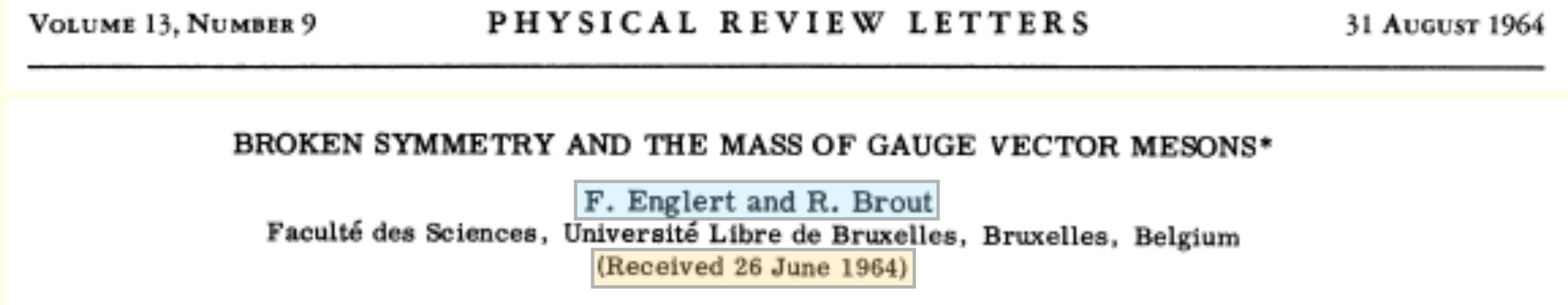
In the Standard Model, Φ_0 is responsible for the fermion masses: $g\phi_0\bar{\psi}\psi$

$\tilde{\phi} = \phi - \phi_0$ ***is known as the Higgs field.***

The story begins in 1964 . . .

with Englert and Brout; Higgs; Hagen, Guralnik and Kibble

page 321-323



VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

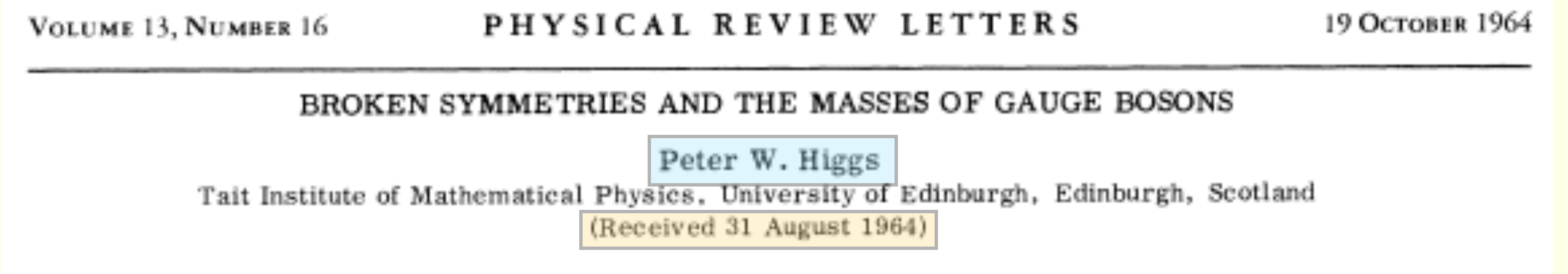
BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout

Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium

(Received 26 June 1964)

page 508-509



VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

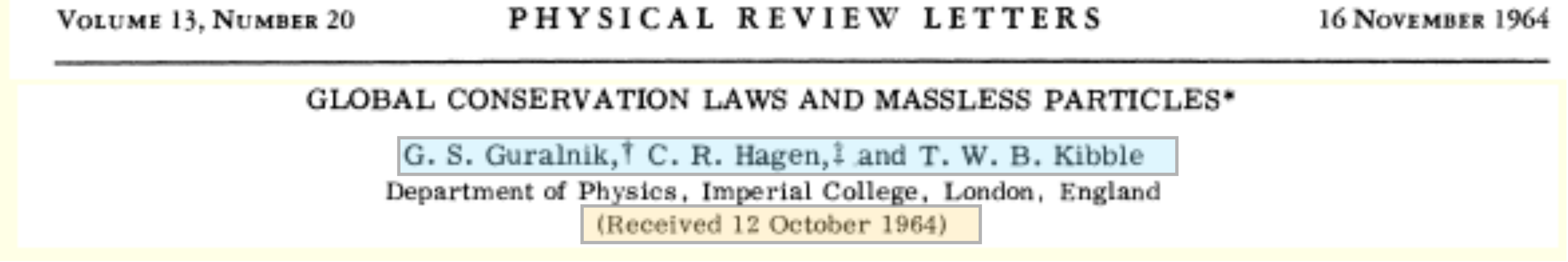
BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs

Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland

(Received 31 August 1964)

page 585-587



VOLUME 13, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1964

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble

Department of Physics, Imperial College, London, England

(Received 12 October 1964)

J. J. Sakurai Prize in 2010

Higgs

81

Kibble, *Guralnik*, *Hagen*, *Englert*, *Brout*

78 74 73 78 82

deceased at age 84 (2016)

deceased at age 78 (2014)

deceased at age 83 (2011)

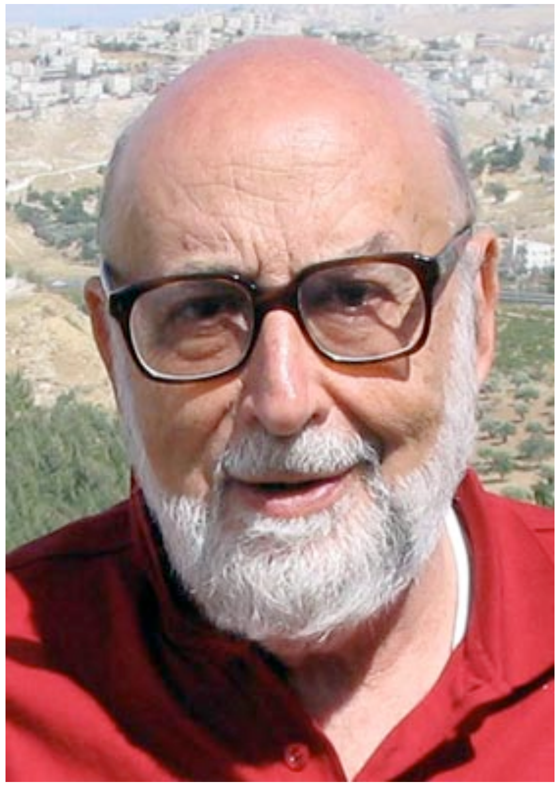
The Nobel Prize in Physics 2013

發現一個理論機制（希格斯機制）：

亞原子粒子質量起源 預測希格斯玻色子

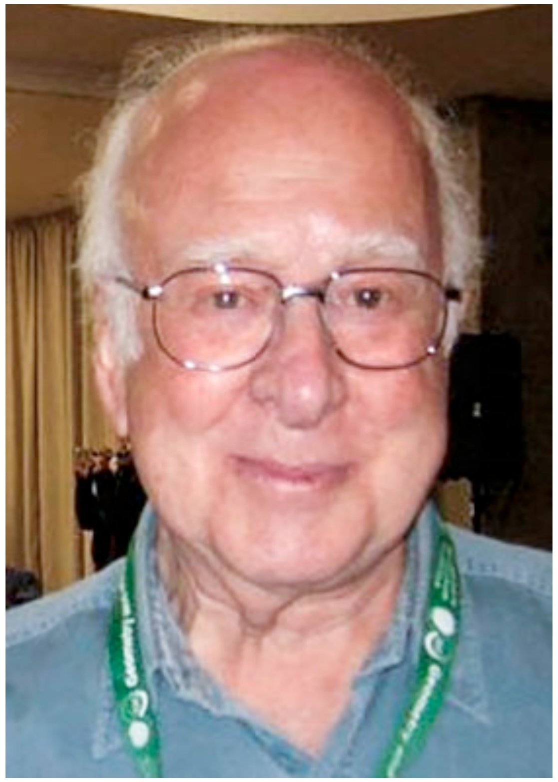
"For the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

François Englert



Born: November 6, 1932
Etterbeek, Belgium

Peter W. Higgs



Born: May 29, 1929
Newcastle upon Tyne, United Kingdom

The Nobel Prize in Physics 2013

發現一個理論機制（希格斯機制）：

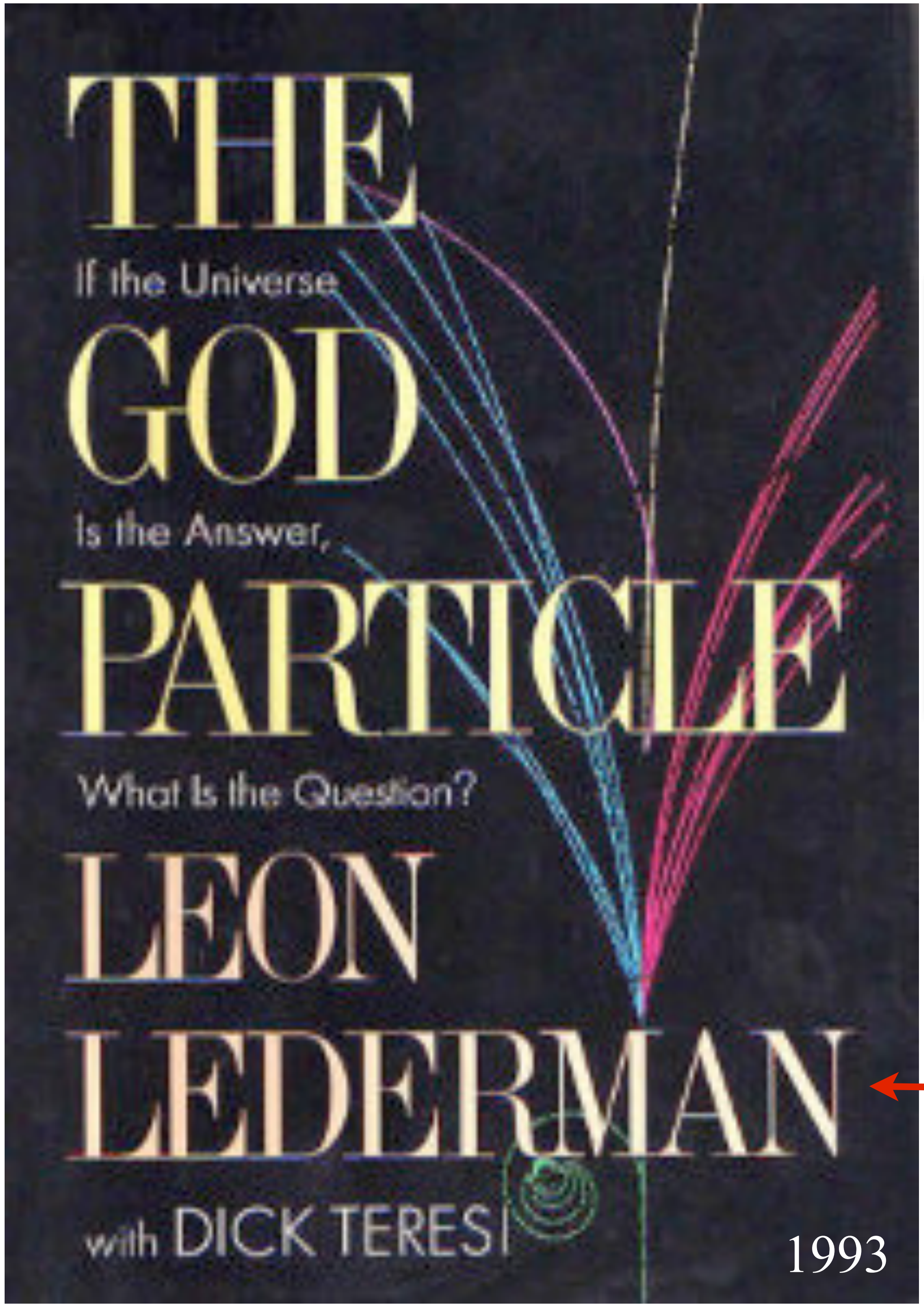
亞原子粒子質量起源

預測希格斯玻色子

"For the theoretical discovery of a mechanism that contributes to our underst ch recently was con al particle, by the A lider"

July 4, 2012

The God Particle: Higgs Boson
上帝粒子：希格斯玻色子



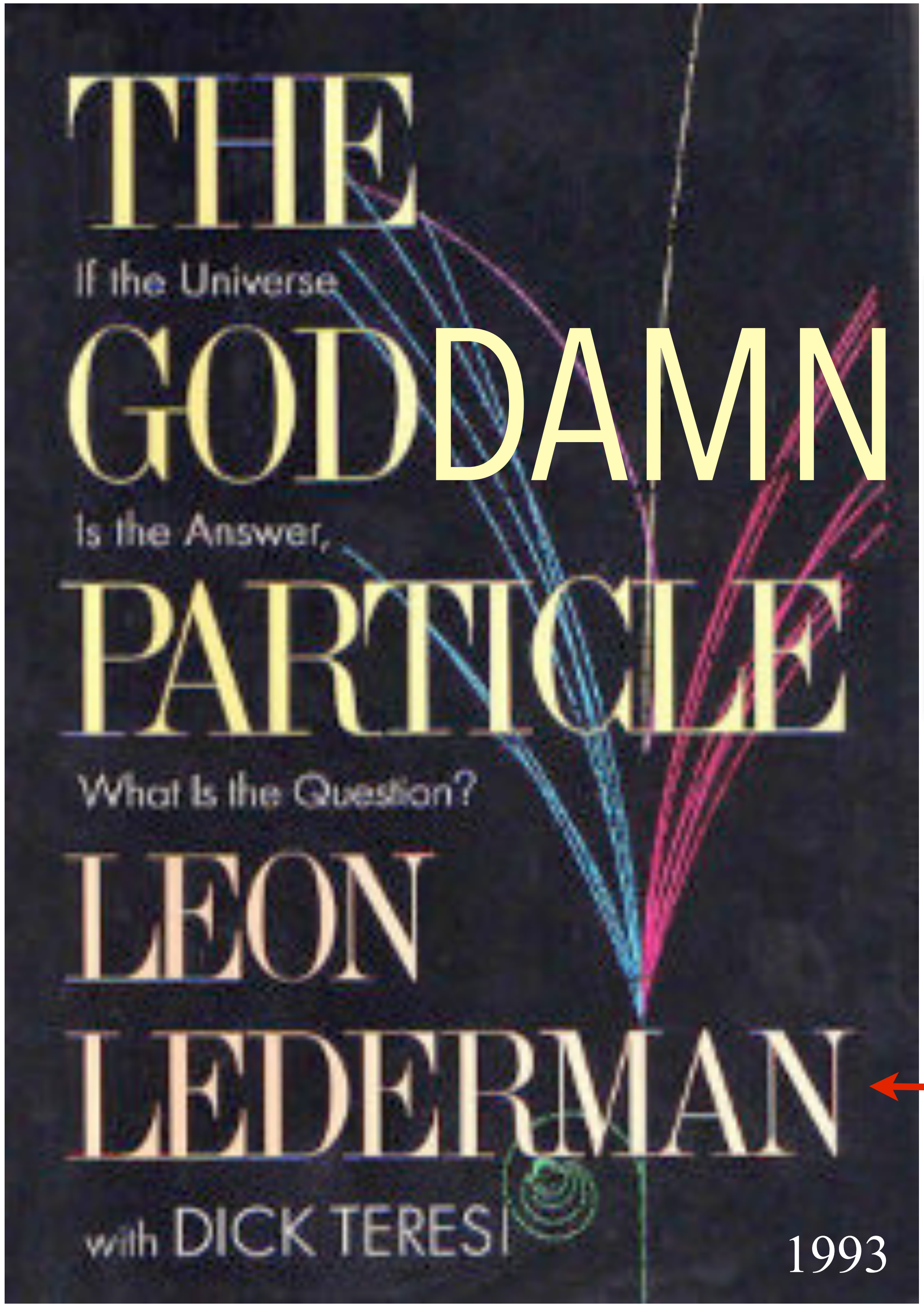
THE
If the Universe
GOD
Is the Answer,
PARTICLE
What Is the Question?
LEON
LEDERMAN
with DICK TERESI

1993

如果宇宙
是答案，
它的問題是什麼？

1988年Nobel
物理學獎

The *Goddamn* Particle: Higgs Boson
上帝詛咒的粒子：希格斯玻色子



THE

If the Universe

GODDAMN

Is the Answer,

PARTICLE

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LEON LEDERMAN

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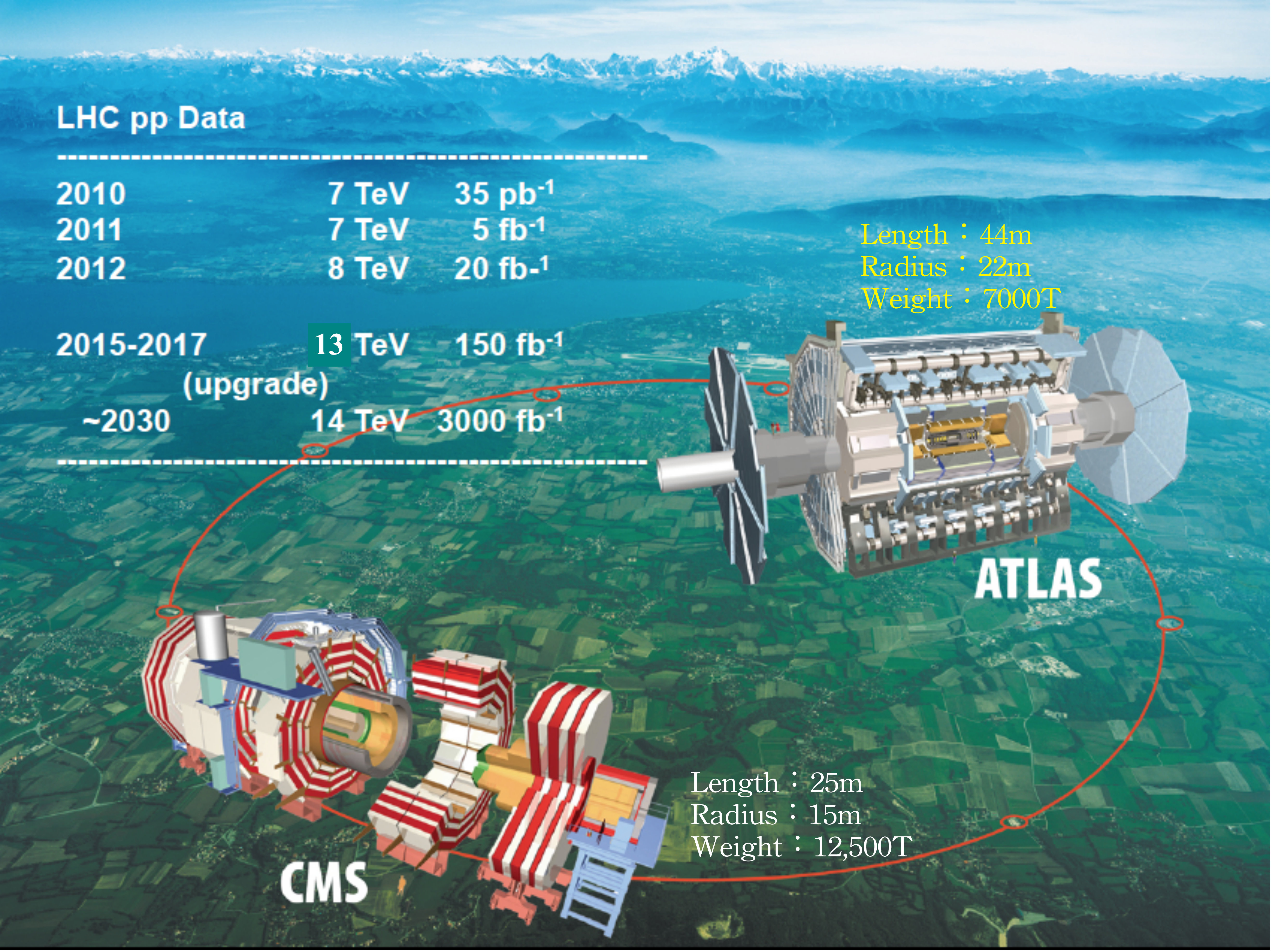
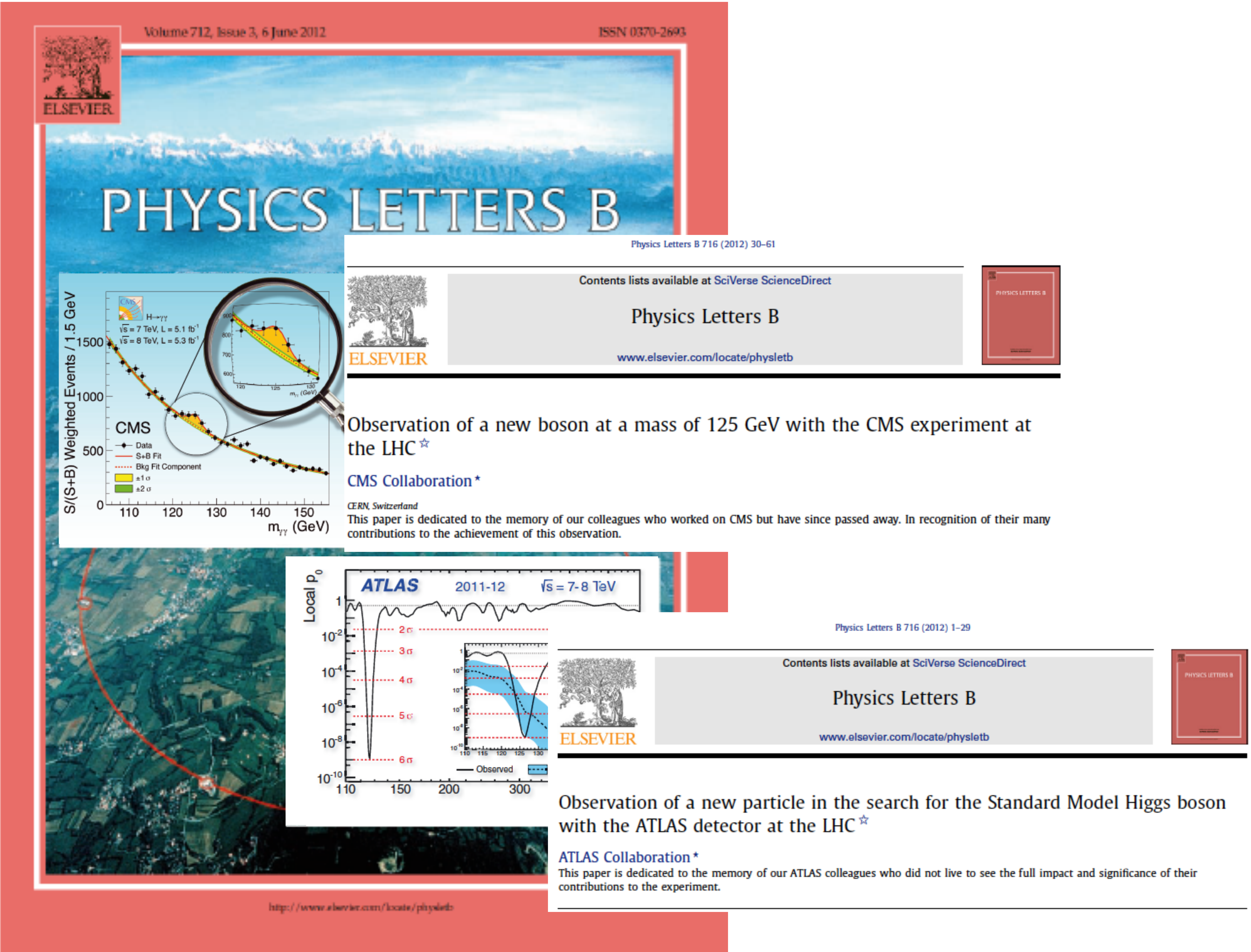


LHC pp Data

2010	7 TeV	35 pb^{-1}
2011	7 TeV	5 fb^{-1}
2012	8 TeV	20 fb-1
2015-2017 (upgrade)	13 TeV	150 fb^{-1}
~2030	14 TeV	3000 fb^{-1}

Length：44m
Radius：22m
Weight：7000T

Length：25m
Radius：15m
Weight：12,500T



Volume 712, Issue 3, 6 June 2012

ISSN 0370-2693

ELSEVIER

PHYSICS LETTERS B

http://www.elsevier.com/locate/physletb

Physics Letters B 716 (2012) 30–61

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

Physics Letters B 716 (2012) 1–29

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

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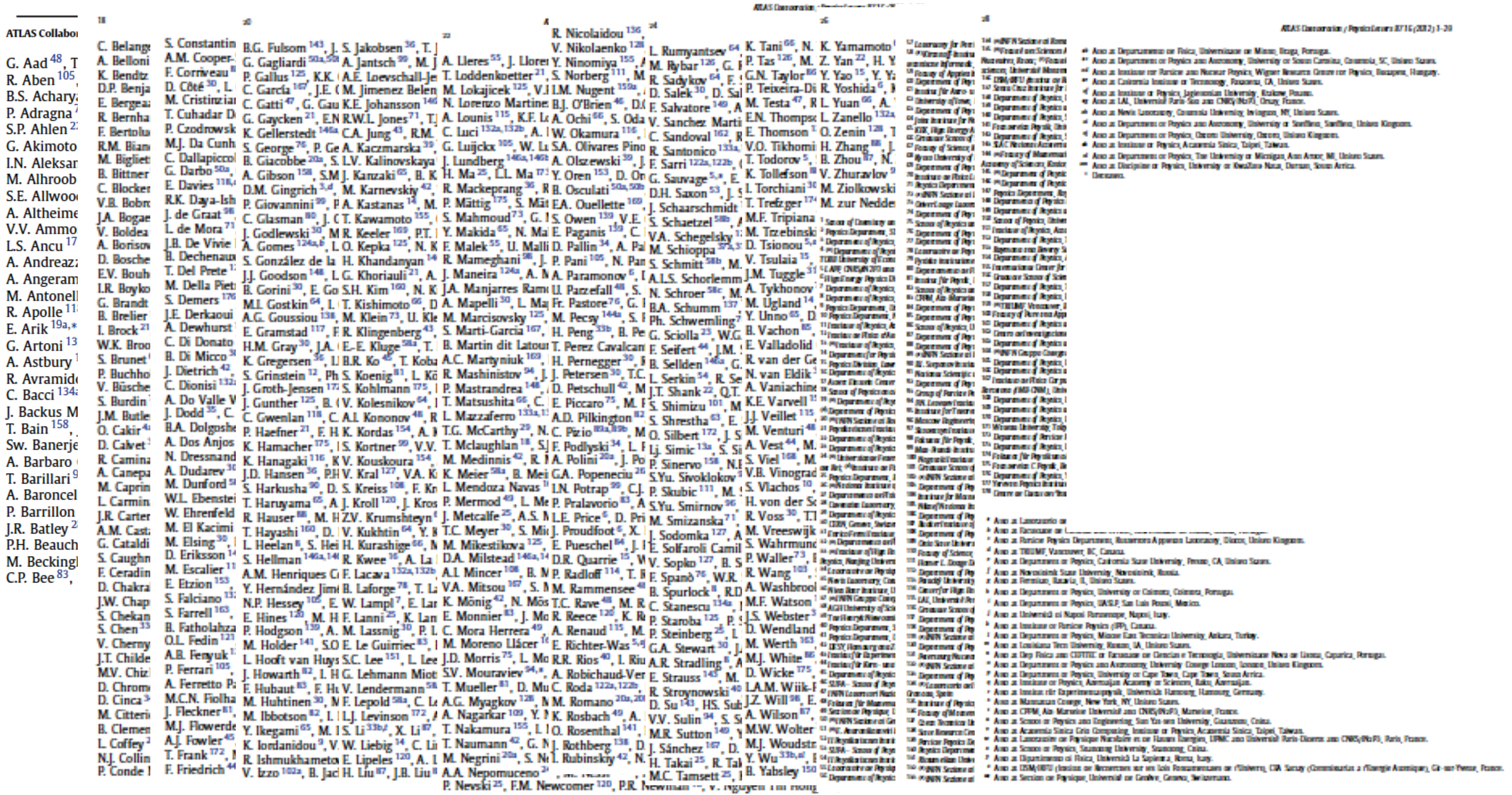


Why is the Higgs boson so important?

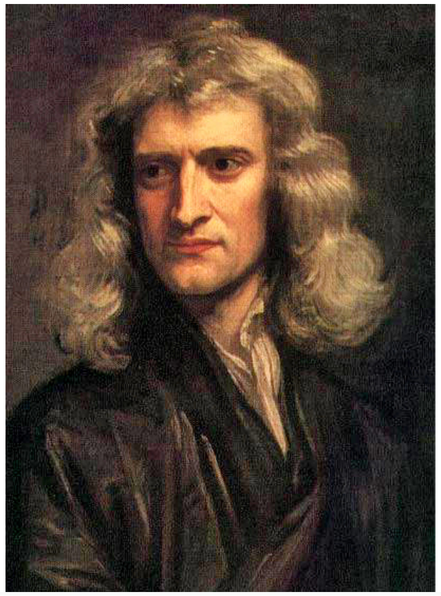
ATLAS Spokesperson

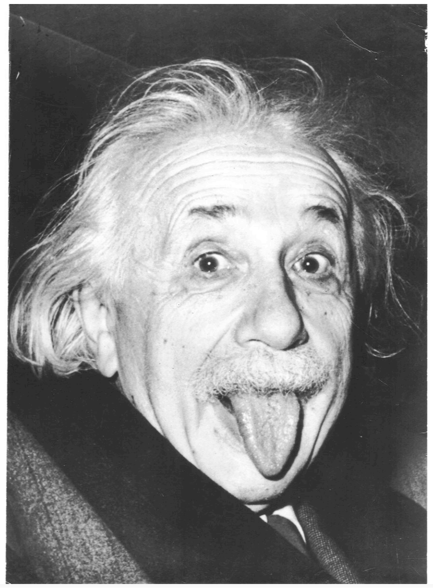
Current CERN Director-General


21 December 2012

Origin of Mass:
(質量的來源)

What is Mass?



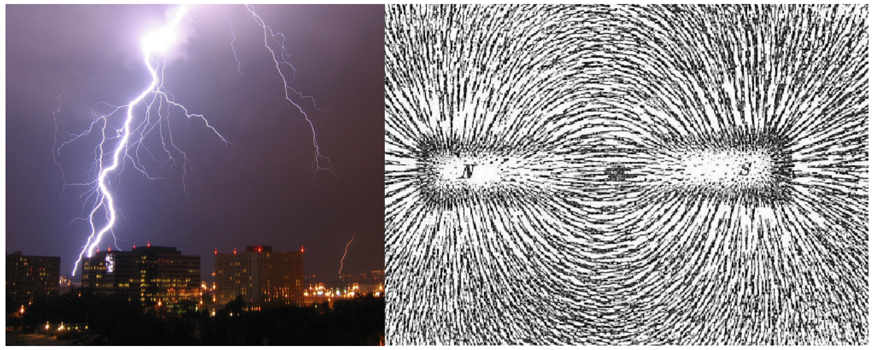


Newton: F=ma

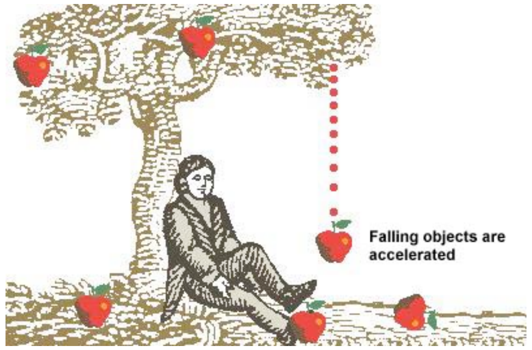
Einstein: $E=mc^2$

但是，他們兩位都忘記告訴我們粒子是如何得到質量的!

Electro-Magnetic Field



Gravitation Field



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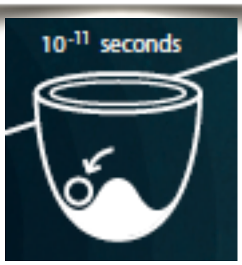
Higgs field

Mass

Matter

$W^{\pm}$, Z

Higgs Mechanism
希格斯機制



Higgs Boson: H

中微子質量=?

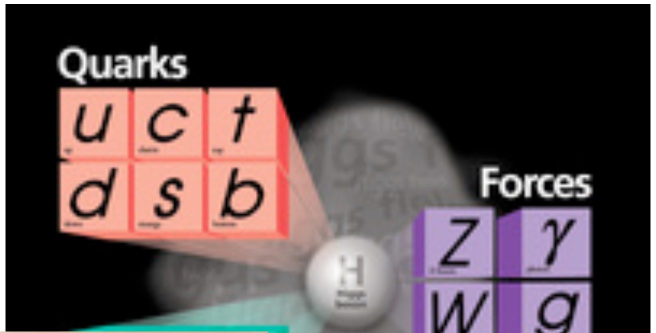
- **The standard model:** $SU(3)_C \times SU(2)_L \times U(1)_Y$

Q_L : $\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L$ L_L : $\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$

U_R : u_R c_R t_R

D_R : d_R s_R b_R E

Higgs : H^0 Gauge Bosons : W



Yukawa interactions: $\mathcal{L}_{\text{Yukawa}}$ $+ \text{h.c.}$.

H. Yukawa

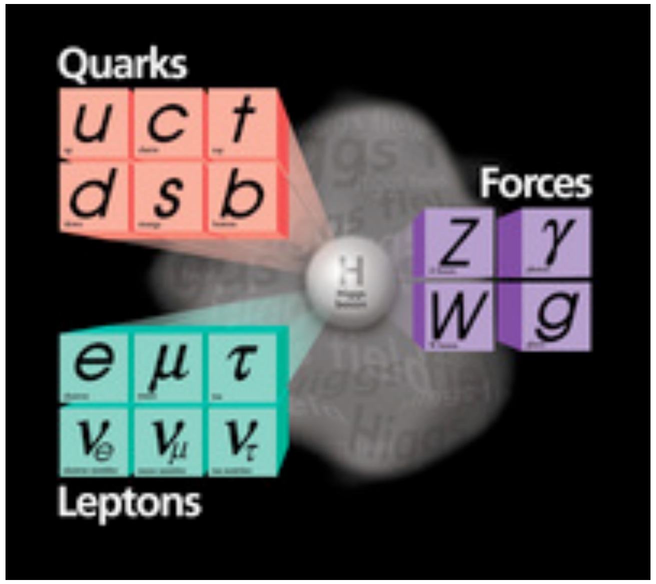
R.E. Marshak

1907-1981
Nobel Prize in Physics 1949

- **The standard model:** $SU(3)_C \times SU(2)_L \times U(1)_Y$

$$\begin{array}{lcccccclccccc} Q_L & : & \begin{pmatrix} u \\ d \end{pmatrix}_L & \begin{pmatrix} c \\ s \end{pmatrix}_L & \begin{pmatrix} t \\ b \end{pmatrix}_L & & & L_L & : & \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L & \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L & \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \\ U_R & : & u_R & c_R & t_R & & & & & & & \\ D_R & : & d_R & s_R & b_R & & & E_R & : & e_R & \mu_R & \tau_R \end{array}$$

Higgs : H^0 Gauge Bosons : $W^\pm, \quad Z\,, \ \gamma\,, \ g$



Yukawa interactions: $\mathcal{L}_{\text{Yukawa}} = -\Gamma^u_{ij} (\bar{u}, \bar{d})_{\text{L}i} \Phi u_{\text{R}j} - \Gamma^d_{ij} (\bar{u}, \bar{d})_{\text{L}i} \tilde{\Phi} d_{\text{R}j} + \text{h.c.}\ .$

1907-1981
Nobel Prize in Physics 1949

$$\Phi \to \frac{1}{\sqrt{2}} \begin{pmatrix} v + H \\ 0 \end{pmatrix} \longrightarrow M^{u,d}_{ij} = \frac{1}{\sqrt{2}} \Gamma^{u,d}_{ij} v\ .$$

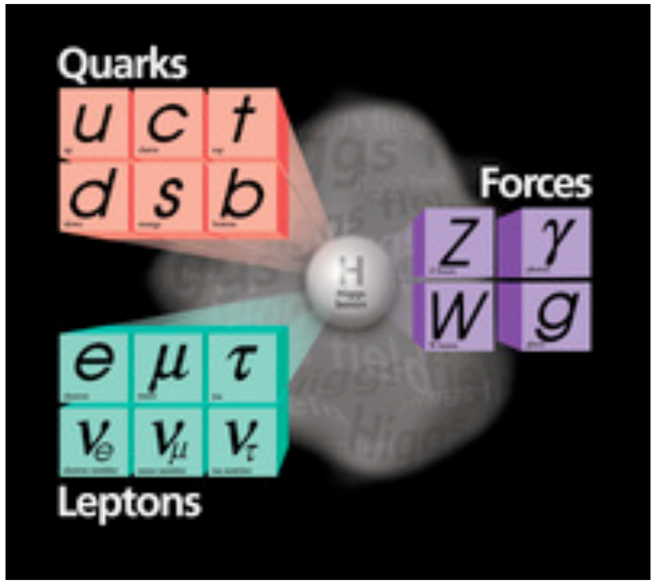
$$(U^{u,d}_{\text{L}})^\dagger M^{u,d} U^{u,d}_{\text{R}} = \mathcal{M}^{u,d}$$

$$\mathcal{L}^{\text{eff}}_{\text{Yukawa}} = -\sum_i m_i \bar{q}_i(x) q_i(x) \left[1 + \frac{H(x)}{v} \right]$$

- **The standard model:** $SU(3)_C \times SU(2)_L \times U(1)_Y$

$$
\begin{array}{lclllclll}
Q_L & : & \begin{pmatrix} u \\ d \end{pmatrix}_L & \begin{pmatrix} c \\ s \end{pmatrix}_L & \begin{pmatrix} t \\ b \end{pmatrix}_L & L_L & : & \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \; \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \; \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \\
U_R & : & u_R & c_R & t_R & & & \\
D_R & : & d_R & s_R & b_R & E_R & : & e_R \quad \mu_R \quad \tau_R
\end{array}
$$

Higgs : H^0 Gauge Bosons : $W^\pm, \quad Z\,,\ \gamma\,,\ g$



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1907-1981
Nobel Prize in Physics 1949

$$
\Phi \to \frac{1}{\sqrt{2}} \begin{pmatrix} v + H \\ 0 \end{pmatrix} \longrightarrow M^{u,d}_{ij} = \frac{1}{\sqrt{2}} \Gamma^{u,d}_{ij} v\ .
$$

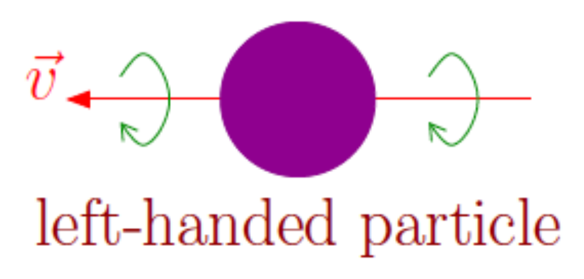
$$
(U^{u,d}_{\text{L}})^\dagger M^{u,d} U^{u,d}_{\text{R}} = \mathcal{M}^{u,d}
$$

$$
\mathcal{L}^{\text{eff}}_{\text{Yukawa}} = -\sum_i m_i \bar{q}_i(x) q_i(x) \left[1 + \frac{H(x)}{v} \right]
$$

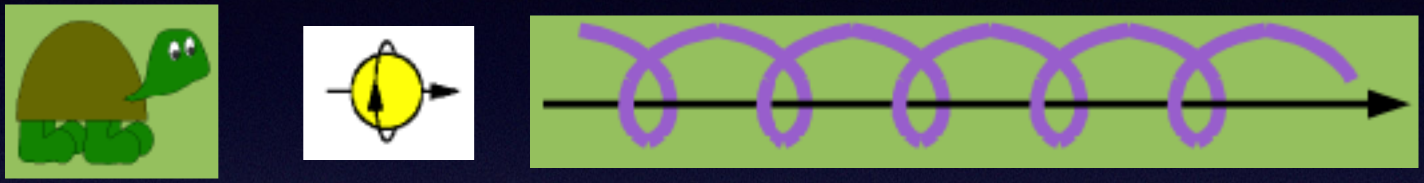
- **What are about neutrinos?**
- **Do neutrinos get their masses like charged fermions?**
- **In the standard model, neutrino masses must be zero !**

Why does the Standard Model require MASSLESS neutrinos?

All neutrinos are left-handed $\Longrightarrow$ massless



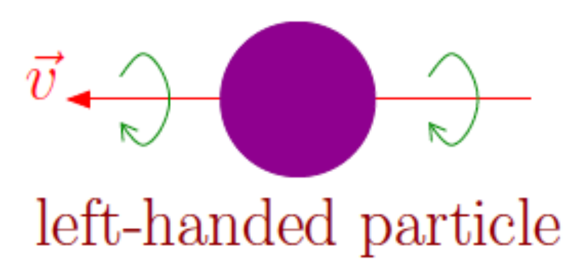
left-handed



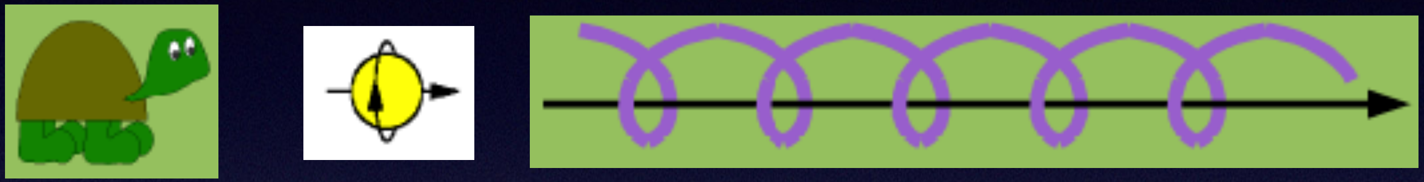
A massless particle moves with c, so a real observer (who must always travel at less than c) cannot be in any reference frame where the particle appears to reverse its relative direction, meaning that all real observers see the same chirality.

Why does the Standard Model require MASSLESS neutrinos?

All neutrinos are left-handed



left-handed



A massive particle

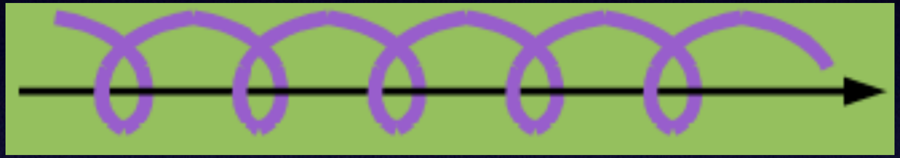
If they have mass, cannot go at speed of light.

For massive particles, it is possible for an observer to change to a reference frame that overtakes the spinning particle, in which case the particle will then appear to move backwards, and its helicity will be reversed.

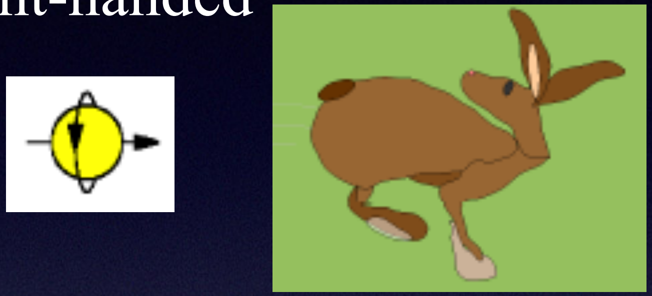
Why does the Standard Model require MASSLESS neutrinos?

All neutrinos are left-handed

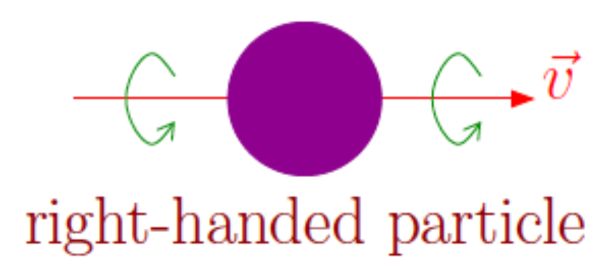
right-handed



A massive particle



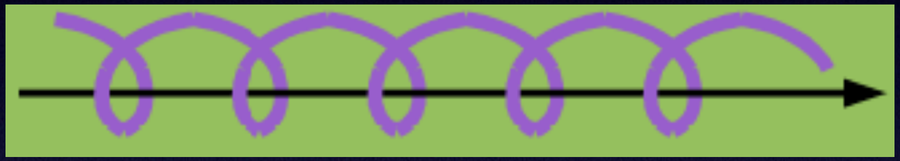
If they have mass, cannot go at speed of light.
They are right-handed in a Lorentz boost frame,



For massive particles, it is possible for an observer to change to a reference frame that overtakes the spinning particle, in which case the particle will then appear to move backwards, and its helicity will be reversed.

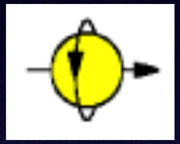
Why does the Standard Model require MASSLESS neutrinos?

All neutrinos are left-handed ⟹ massless

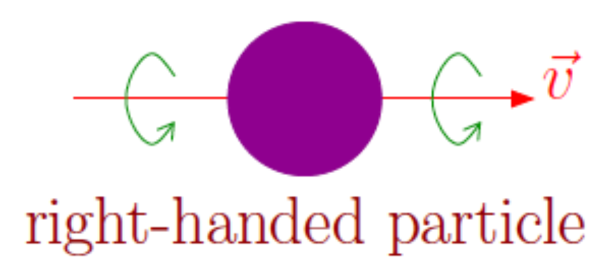


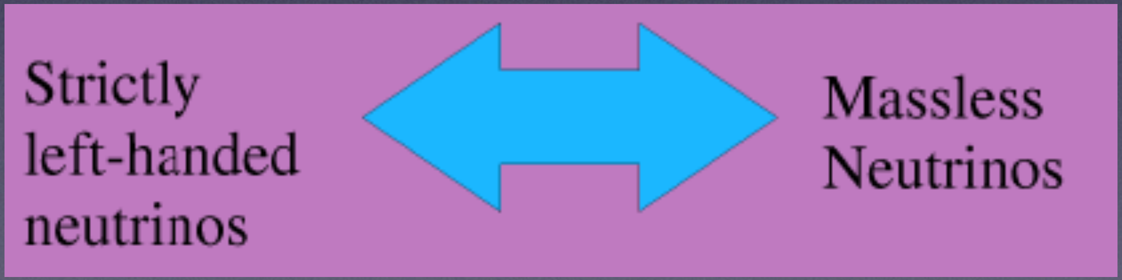
A massive particle

right-handed



If they have mass, cannot go at speed of light.
They are right-handed in a Lorentz boost frame,
contradicting "all neutrinos: left-handed."





Strictly left-handed neutrinos ⟺ Massless Neutrinos

$m_\nu \neq 0$ ☞ New Physics beyond the SM

- Neutrino masses

Neutrino Oscillations

中微子振盪

The Nobel Prize in Physics 2015

Takaaki Kajita

Arthur B. McDonald

「發現中微子振盪, 顯示中微子有質量」

``for the discovery of neutrino oscillations, which shows that neutrinos have mass”

這項發現改變了我們對物質最內部運作方式的了解，證實了標準模型理論已無法成為解釋宇宙基本構成的完整理論。

This discovery has changed our understanding of the innermost workings of matter and showed that the Standard Model cannot be the complete theory of the fundamental constituents of the universe.

- Neutrino masses

Neutrino Oscillations

中微子振盪

The Nobel Prize in Physics 2015

Takaaki Kajita
Born 1959, Japan

Arthur B. McDonald
Born 1943, Canada

- Neutrino masses

Neutrino Oscillations

中微子振盪

The Nobel Prize in Physics 2015

Takaaki Kajita
Born 1959, Japan
Prize share: 1/2

Arthur B. McDonald
Born 1943, Canada
Prize share: 1/2

Prize amount:
SEK 8 million
(1USD=8.5SEK;
1SEK=3.83NT)
～3100NTD

Fajita

McDonald

2016 Breakthrough Prize in Fundamental Physics

7 leaders and 1370 members of 5 experiments on

Neutrino Oscillation

splitting 3 million USD (Nov. 8, 2015)

Daya Bay (China): Yifang Wang 王贻芳 and Kam-Biu Luk 陸錦標

KamLand (Japan): Atsuto Suzuki

K2K/T2K (Japan): Koichiro Nishikawa

Sudbury Neutrino Observatory (Canada): Arthur B. McDonald

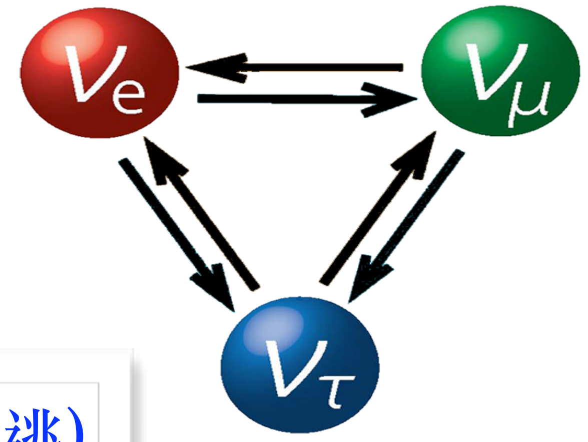
Super-Kamiokande (Japan): Takaaki Kajita and Yoichiro Suzuki

2015 Noble Physics Prize (Oct. 6, 2015)

Highlights of Neutrino History

	1930	ν existence postulated (Pauli)
	1953	ν_e interaction observed (Reines & Cowan)
	Nobel 1995	Reines (Cowan died in 1974)
	1957	ν oscillation predicted (Pontecorvo)
	1962	ν_μ observed (Lederman, Schwartz & Steinberger)
	Nobel 1988	Lederman, Schwartz & Steinberger
	1968	Solar ν observed (Davis)
	1987	Supernova ν observed (Koshiba)
	Nobel 2002	Davis & Koshiba
	1989	Only three light ν generations (LEP experiments)
	1998	ν_{atm} oscillation observed by Super-K (Kajita)
	2001	ν_{sol} oscillation observed by SNO (MaDonald)
	Nobel 2015	Kajita & MaDonald
	2000	ν_τ observed (DONUT experiment)

Solution to Solar and Atmospheric Neutrino Problems



Neutrino Oscillations

中微子振盪

1957年: 義大利物理學家龐蒂科夫
(Bruno Pontecorvo1913-1993)

1950年失蹤，1955年出現在前蘇聯(叛逃)

Бруно Понтекорво

The Atlantic

SCIENCE

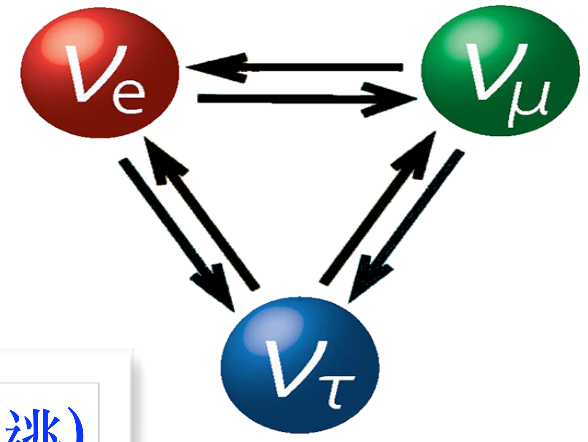
The Communist Spy (Maybe) Behind This Year's Nobel Prize in Physics

How neutrino research stems from—and validates—a physicist who defected to the Soviet Union in the 1950s

Solution to Solar and Atmospheric Neutrino Problems

Neutrino Oscillations

中微子振盪



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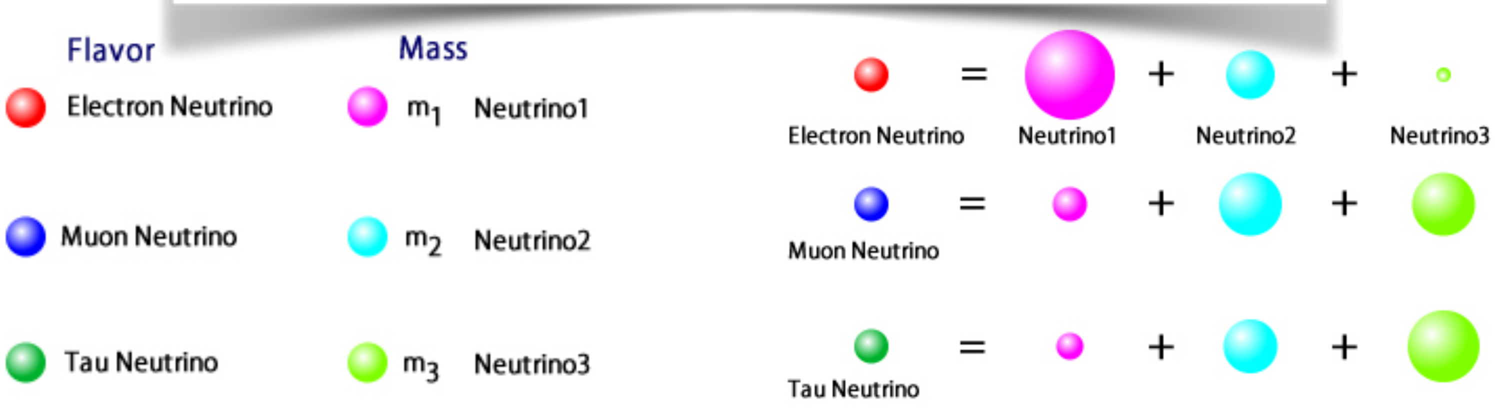
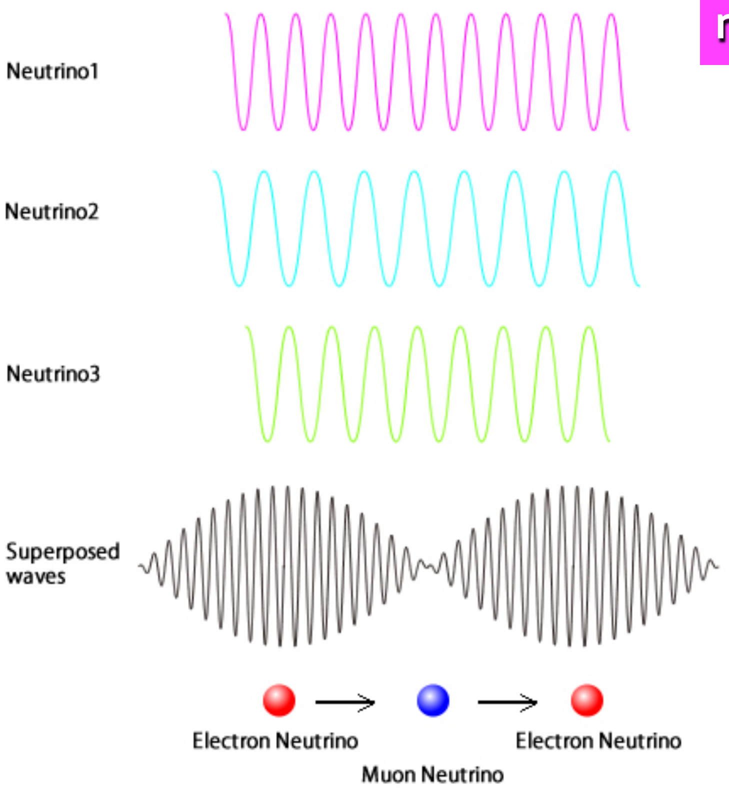
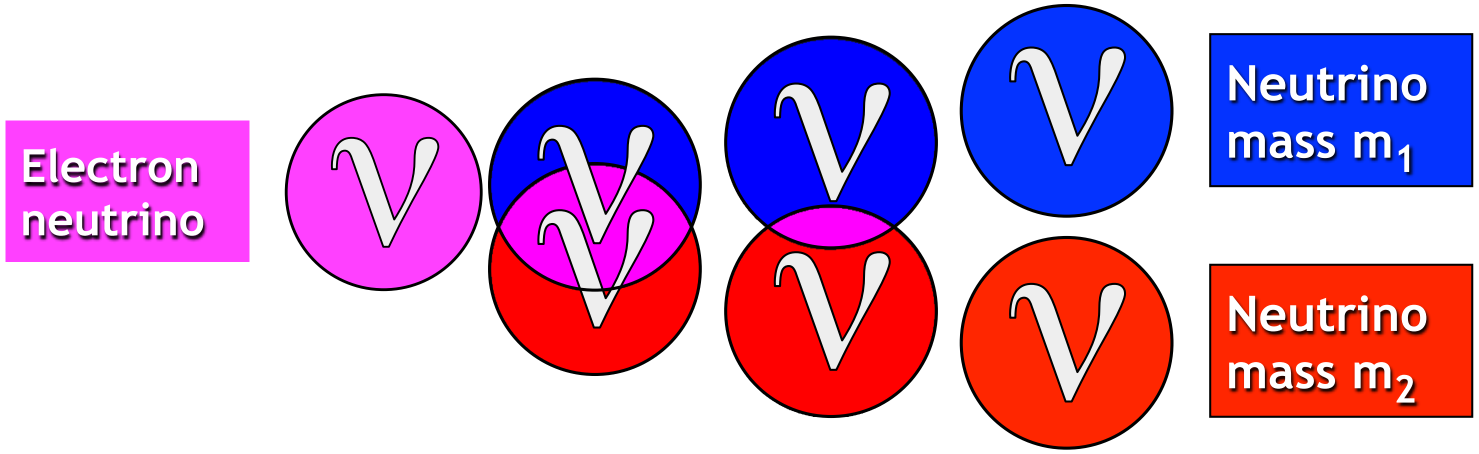
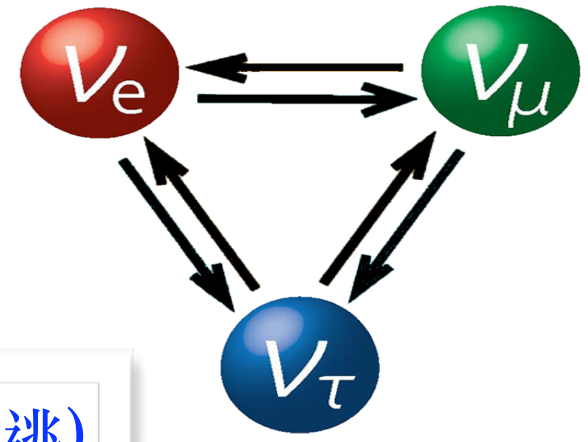






Neutrino propagation as a wave phenomenon

Solution to Solar and Atmospheric Neutrino Problems



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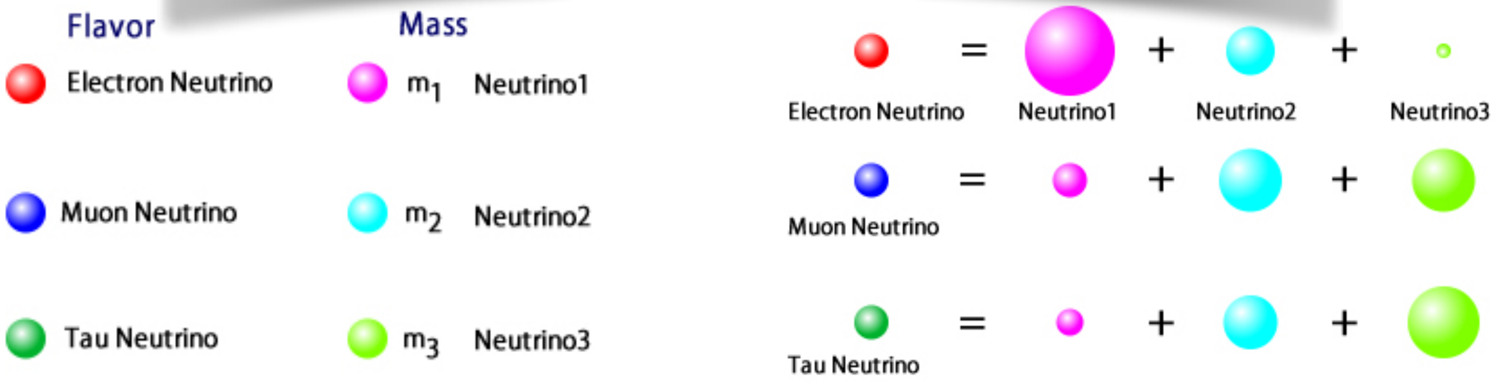
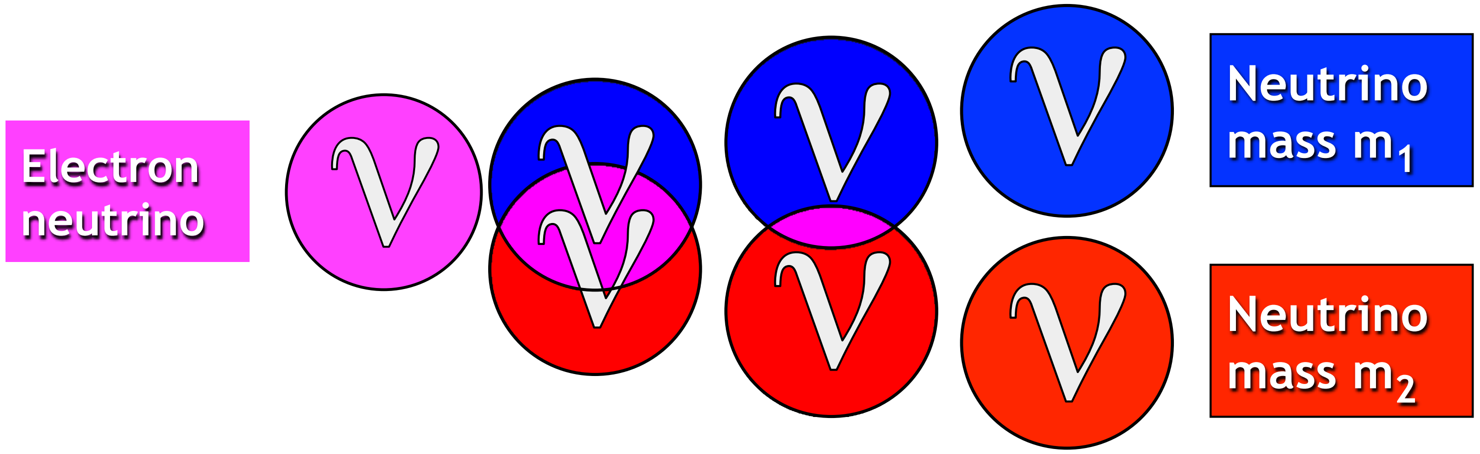
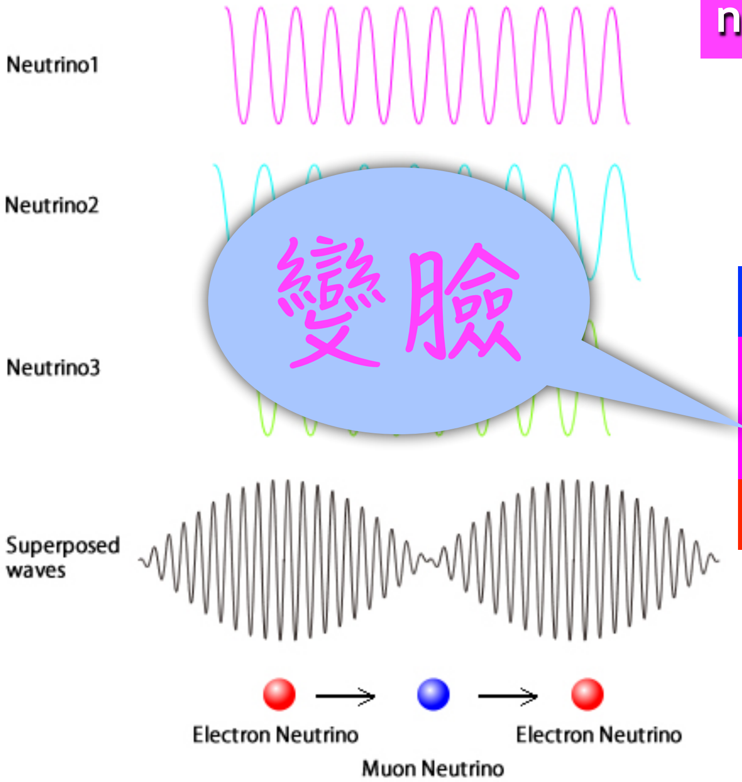






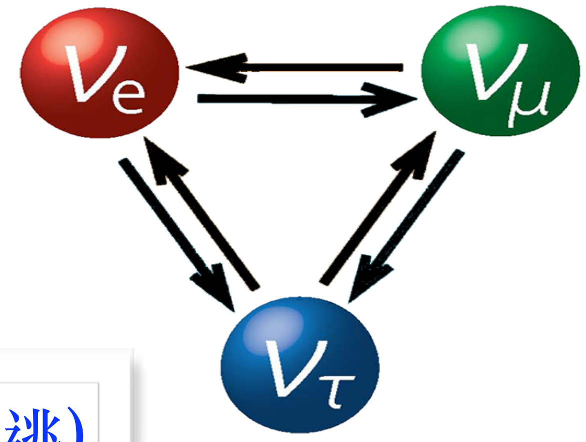
Neutrino propagation as a wave phenomenon

Neutrinos have mass!

Solution to Solar and Atmospheric Neutrino Problems

Neutrino Oscillations

中微子振盪



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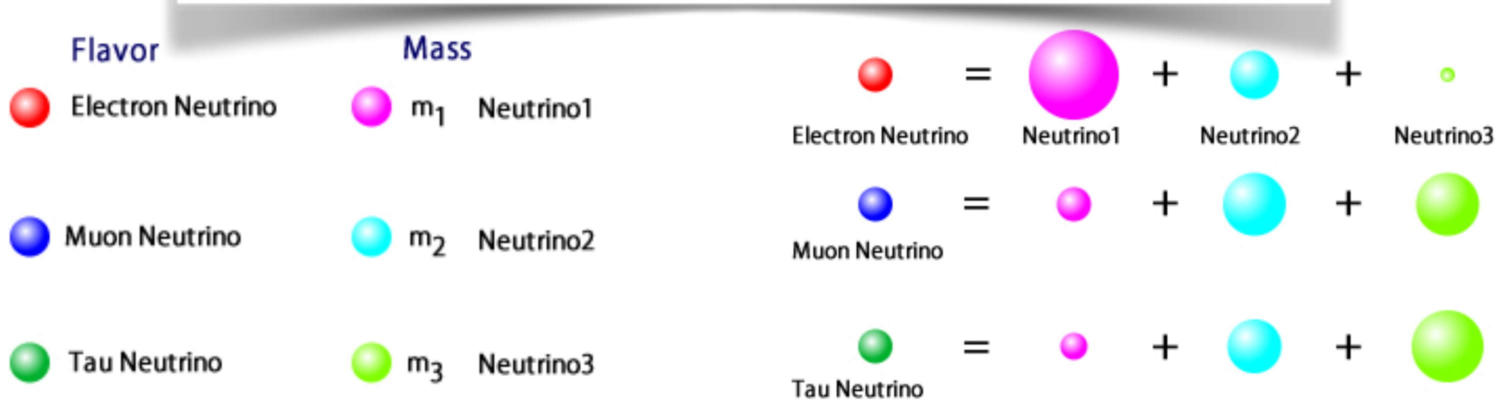
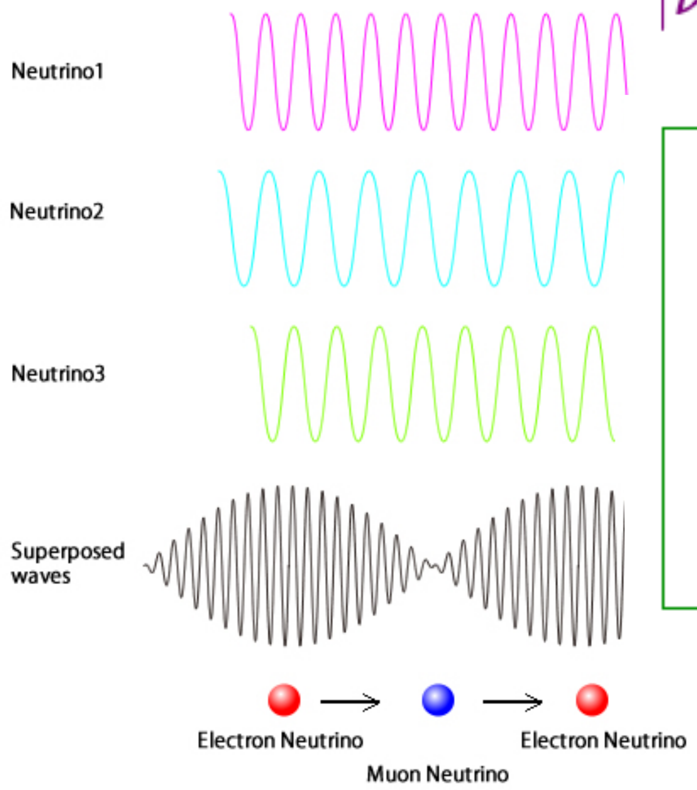
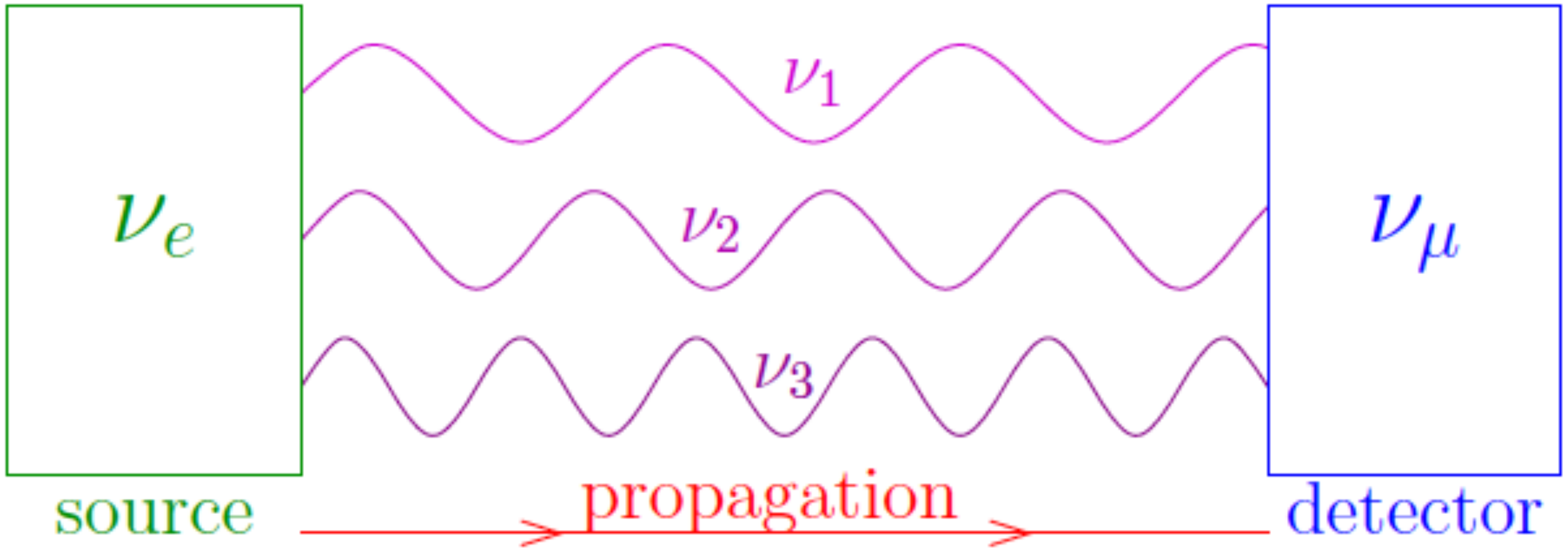


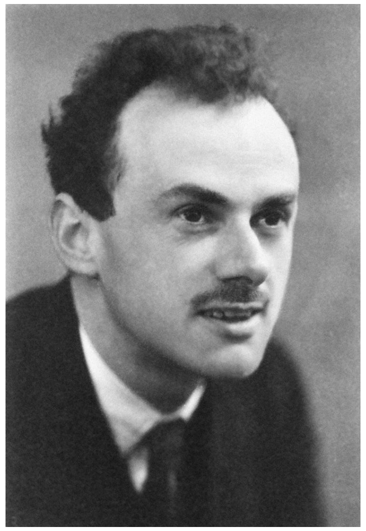
$$|\nu(t=0)\rangle = |\nu_e\rangle = U_{e1}\,|\nu_1\rangle + U_{e2}\,|\nu_2\rangle + U_{e3}\,|\nu_3\rangle$$

$$|\nu(t>0)\rangle = U_{e1}\,e^{-iE_1 t}\,|\nu_1\rangle + U_{e2}\,e^{-iE_2 t}\,|\nu_2\rangle + U_{e3}\,e^{-iE_3 t}\,|\nu_3\rangle \neq |\nu_e\rangle$$





Origin of the neutrino masses: Dirac or Majorana?



Paul Dirac (1902-1984)

$$\begin{pmatrix} \nu_{\uparrow} \\ \nu_{\downarrow} \\ \overline{\nu}_{\downarrow} \\ \overline{\nu}_{\uparrow} \end{pmatrix} \quad \text{or} \quad \begin{pmatrix} \nu_{\uparrow} \\ \nu_{\downarrow} \end{pmatrix}$$

Ettore Majorana (1906-???)

Disappeared in 1938 during a boat trip from Palermo to Naples without his body found

天使粒子

張首晟 1964-2018

Dec. 1 突然去世!

Dirac neutrino r

$\mathcal{L}_D = -m_D \overline{\nu_L} \nu$

> *There are several categories of scientists in the world; those of second or third rank do their best but never get very far. Then there is the first rank, those who make important discoveries, fundamental to scientific progress. But then there are the geniuses, like Galilei and Newton. Majorana was one of these.*
>
> *— (Enrico Fermi about Majorana, Rome 1938)*

geniuses, like Galilei and Newton

☺the lepton number L is conserved

- the lepton number L is violated

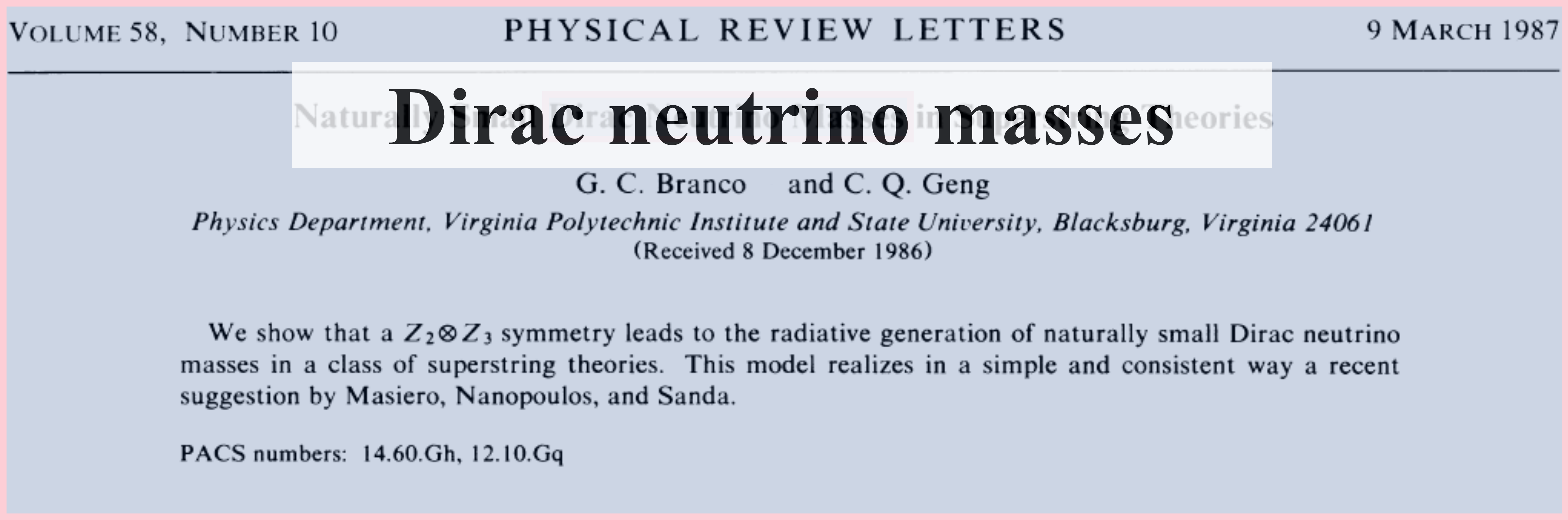
Introduce ν_R (not in the SM)

FORBIDDEN IN THE SM.

(ν_L is an SU(2) doublet).

New Physics beyond the SM

本人發表的第一篇學術論文(32多年前)。



VOLUME 58, NUMBER 10 PHYSICAL REVIEW LETTERS 9 MARCH 1987

Dirac neutrino masses

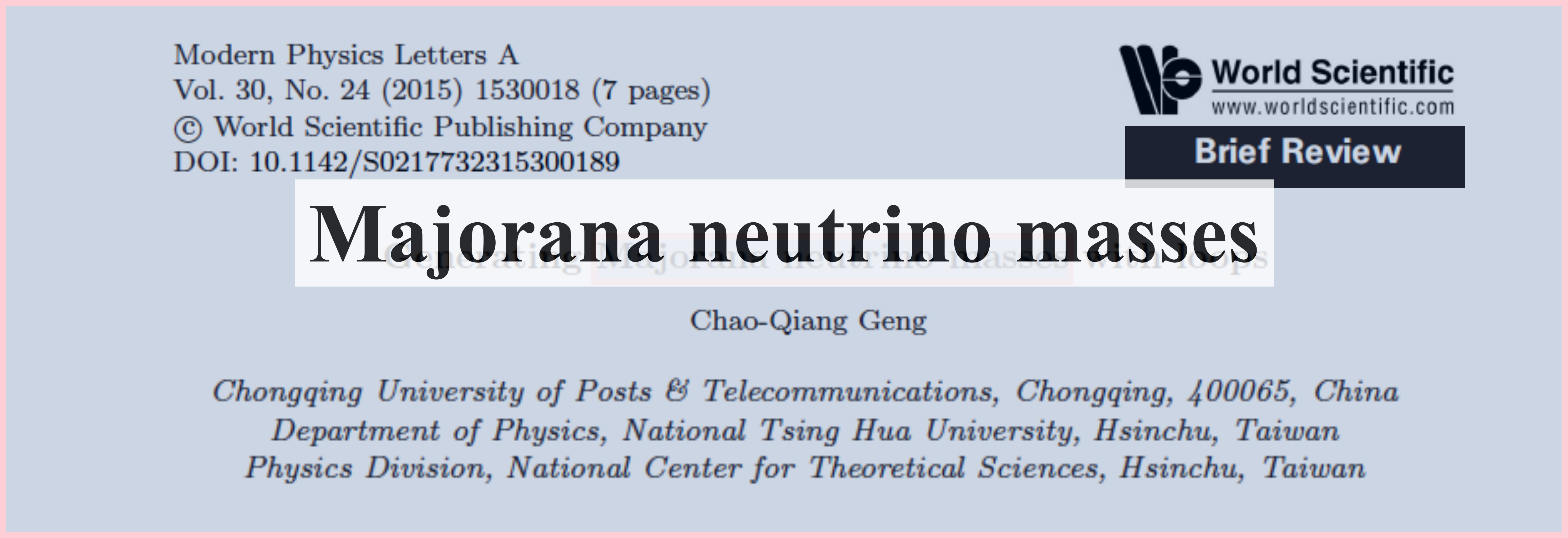
G. C. Branco and C. Q. Geng

Physics Department, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

(Received 8 December 1986)

We show that a $Z_2 \otimes Z_3$ symmetry leads to the radiative generation of naturally small Dirac neutrino masses in a class of superstring theories. This model realizes in a simple and consistent way a recent suggestion by Masiero, Nanopoulos, and Sanda.

PACS numbers: 14.60.Gh, 12.10.Gq



Modern Physics Letters A
Vol. 30, No. 24 (2015) 1530018 (7 pages)
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DOI: 10.1142/S0217732315300189

World Scientific
www.worldscientific.com

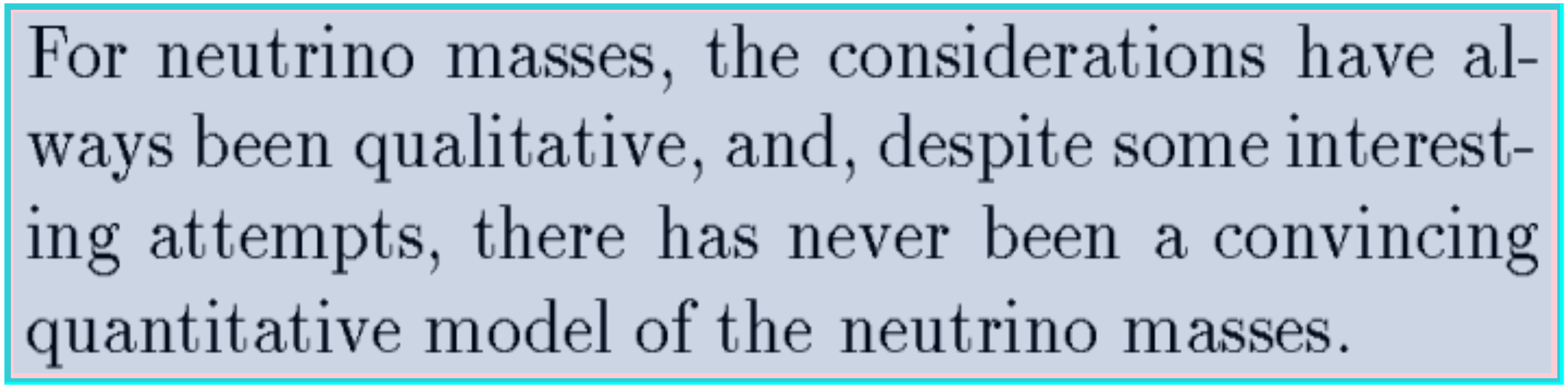
Brief Review

Majorana neutrino masses

Chao-Qiang Geng

Chongqing University of Posts & Telecommunications, Chongqing, 400065, China
Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
Physics Division, National Center for Theoretical Sciences, Hsinchu, Taiwan

E. Witten—Opening Talk at *Neutrino 00* [hep-ph/0006332]

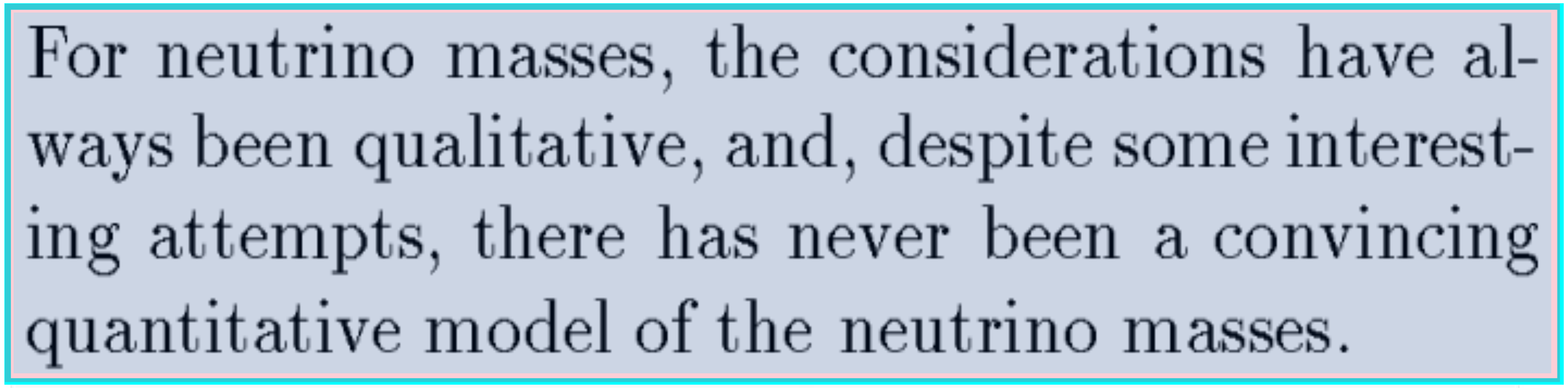


For neutrino masses, the considerations have always been qualitative, and, despite some interesting attempts, there has never been a convincing quantitative model of the neutrino masses.

當今公認的

genius

E. Witten—Opening Talk at *Neutrino 00* [hep-ph/0006332]



For neutrino masses, the considerations have always been qualitative, and, despite some interesting attempts, there has never been a convincing quantitative model of the neutrino masses.

當今公認的
genius

What was said in 2000 by Witten is also true TODAY (2019)

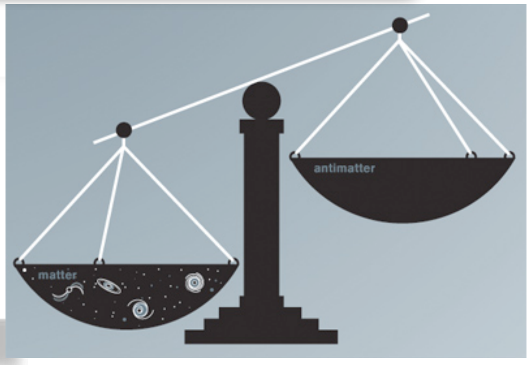
如同2000年，19年後的今天(2019年)也是如此：

至今也還沒有一個令人信服的定量微中子質量模型

Neutrino Masses?

Matter-antimatter asymmetry

物質－反物質不對稱性



Dark Matter

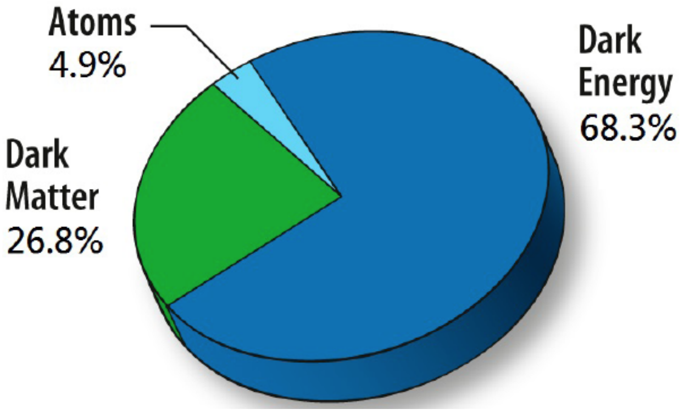
暗物質

Family problem

為什麼自然界僅有三代

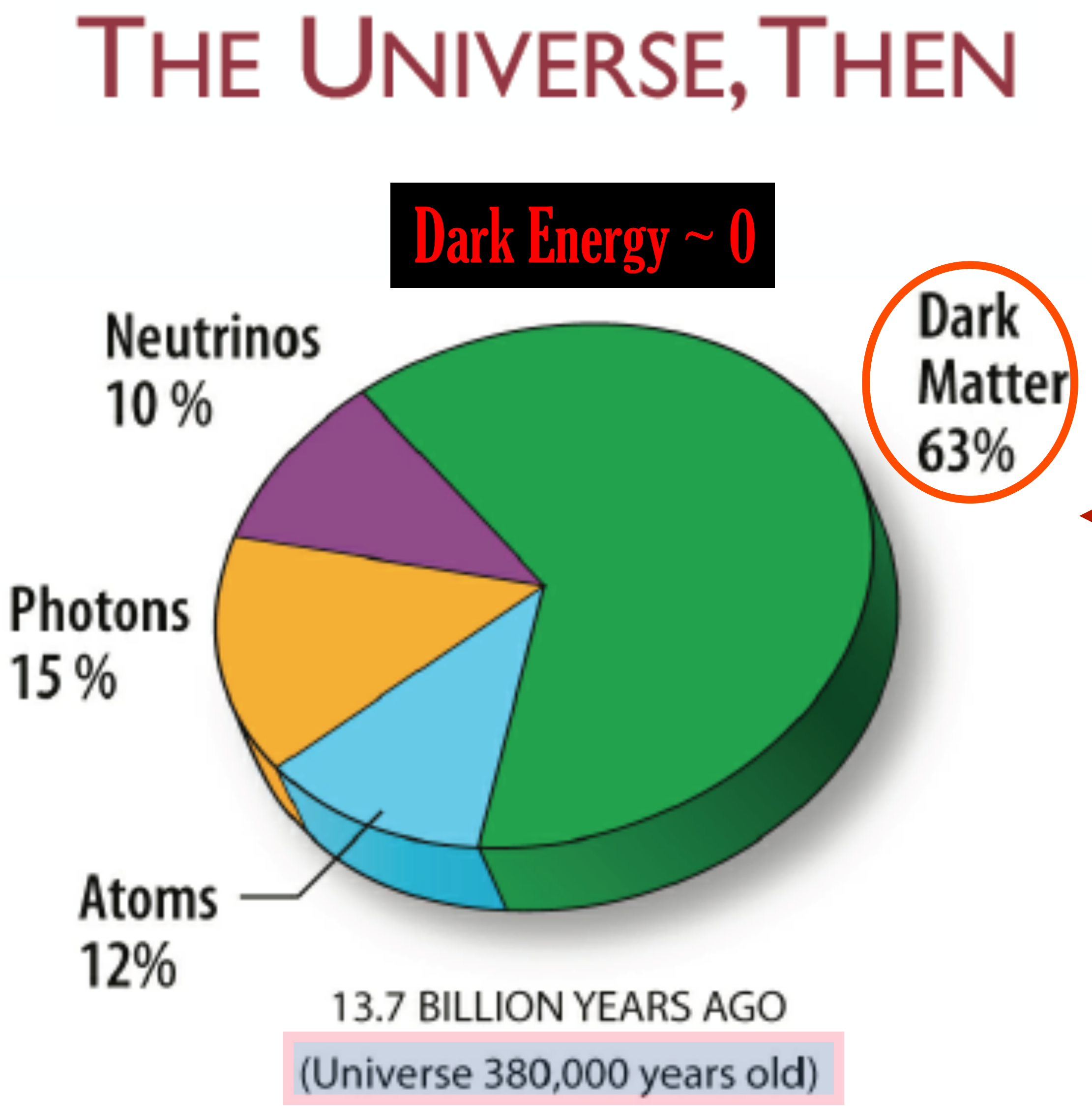
Dark Energy

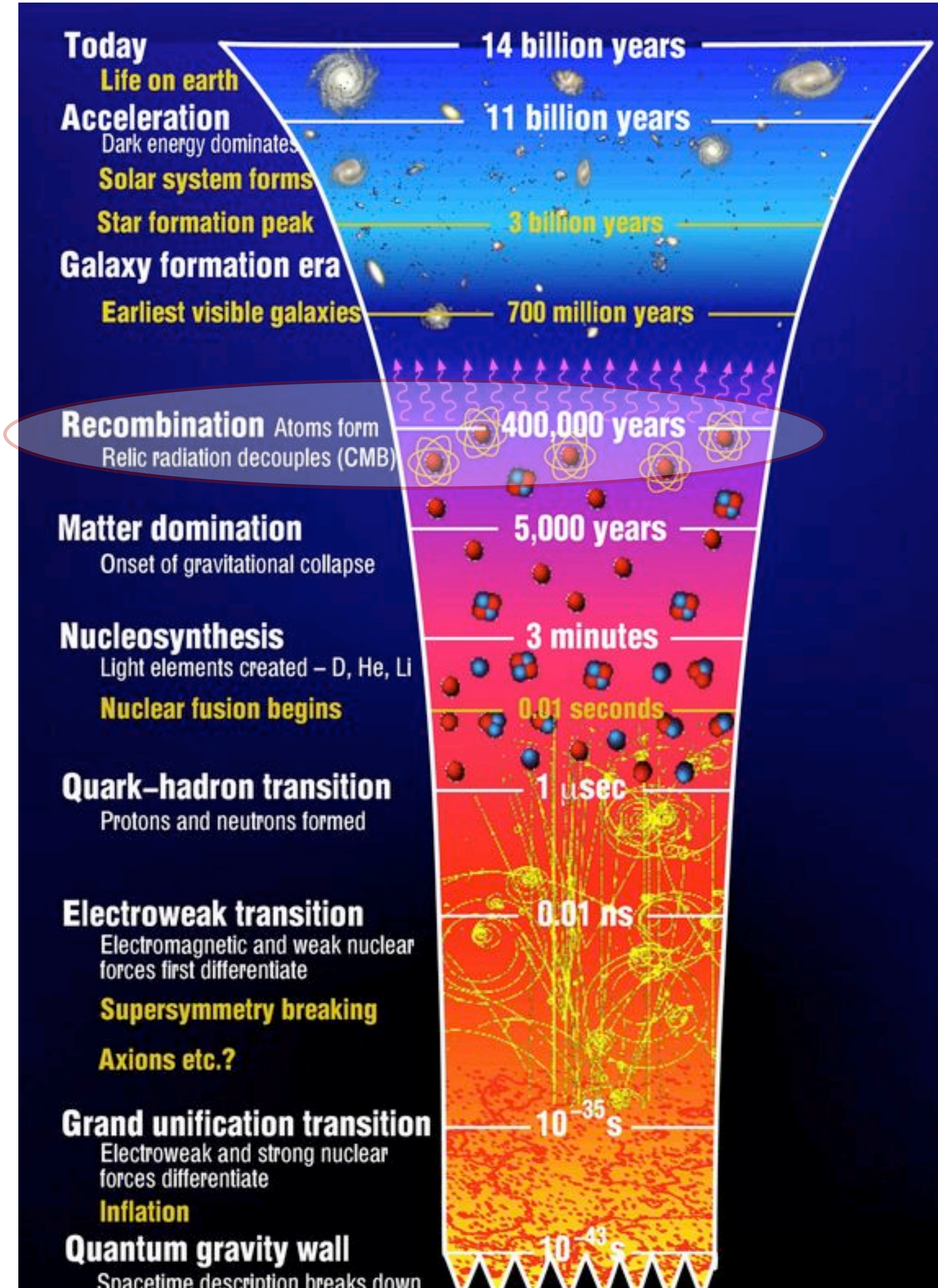
暗能量



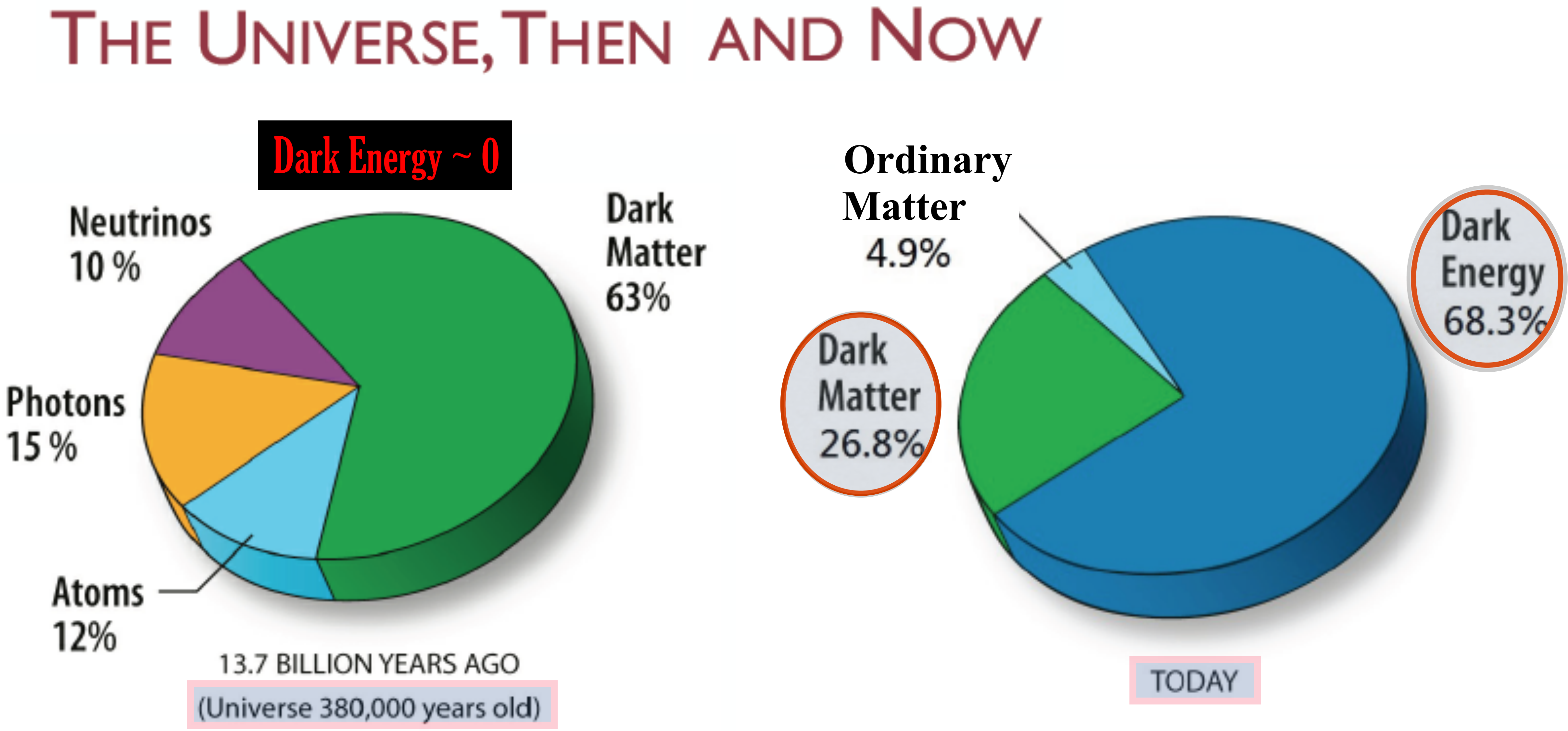
☞ New Physics beyond the SM

- **Dark Matter and Dark Energy**





- Dark Matter and Dark Energy



What is the real nature of Dark Matter and Dark Energy?

95% of the cosmic matter/energy is a mystery.

Dark Energy

The Accelerating Universe

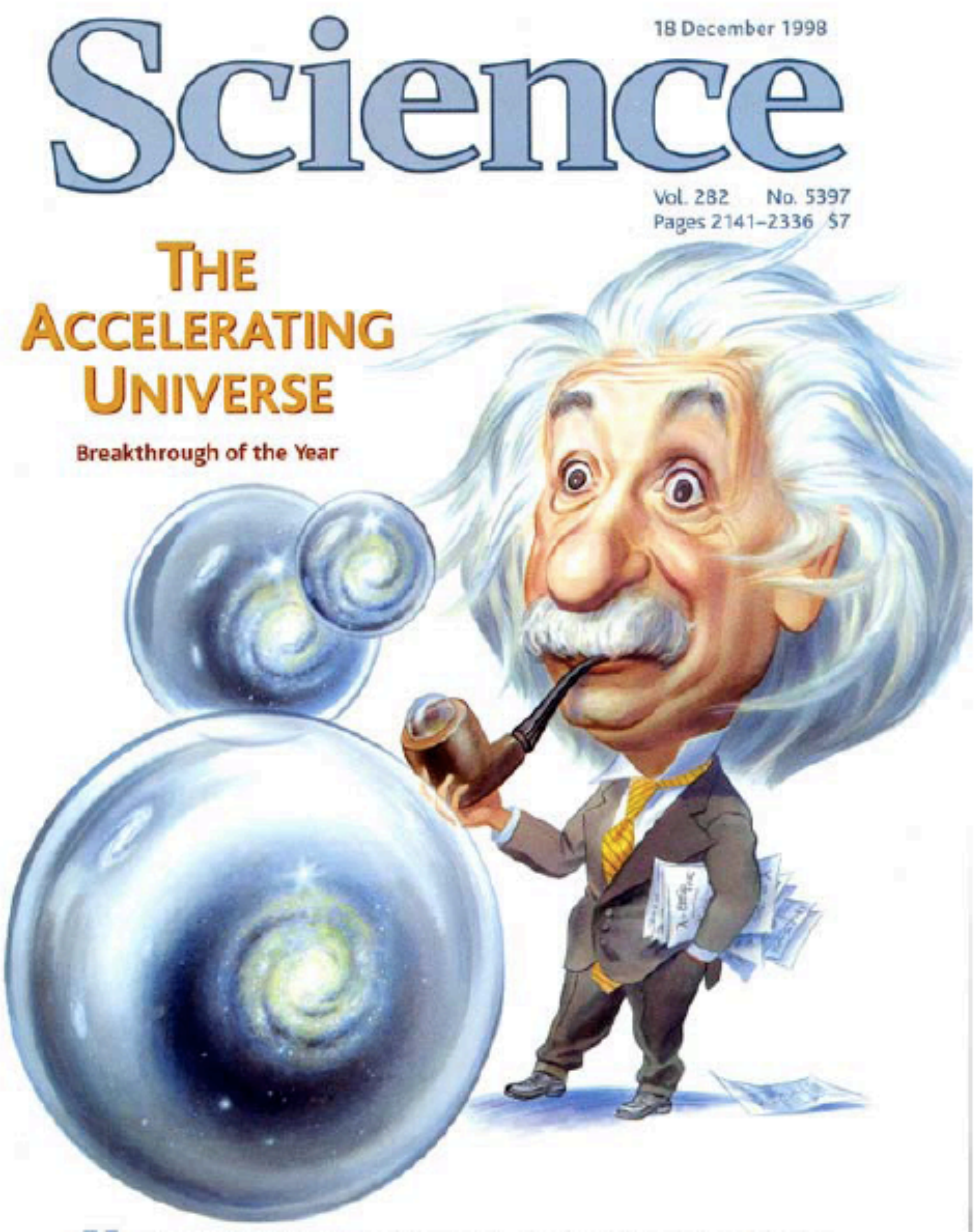
Big News in 1998!

High-Z Team

Riess et al. (1998)

Supernova Cosmology Project

Perlmutter et al. (1999)



The Nobel Prize
in Physics 2011

"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

Brian P. Schmidt

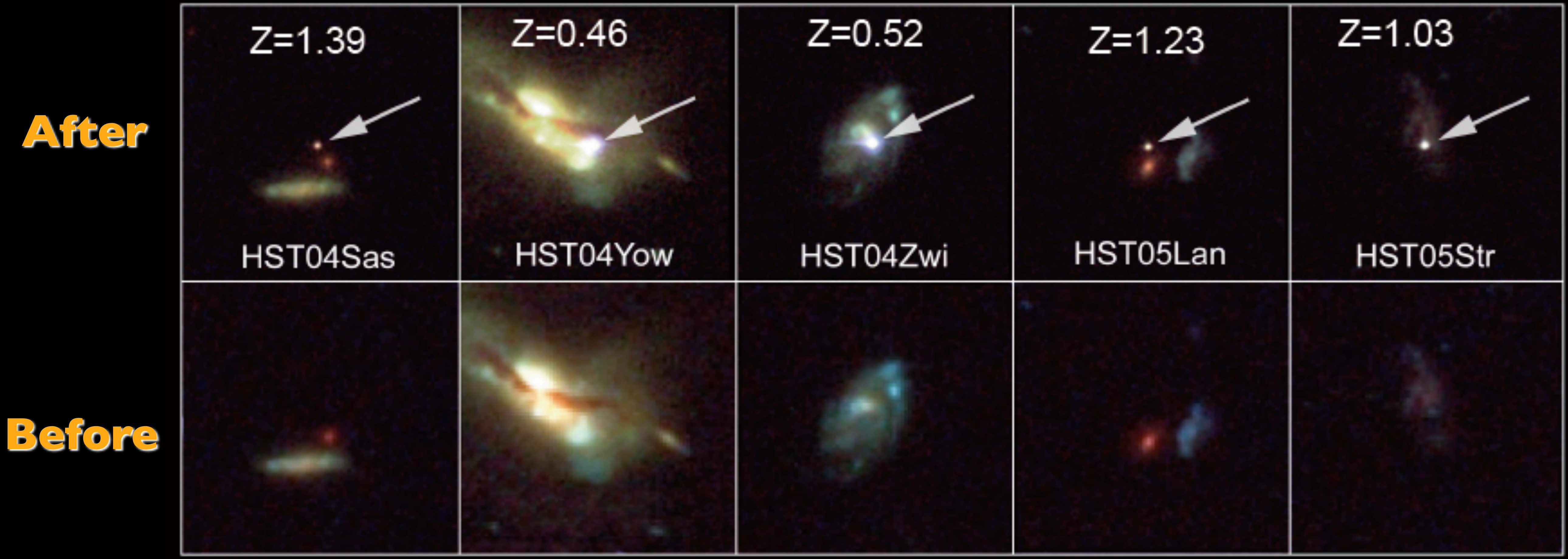
Photo: Homewood Photography

Adam G. Riess

2015 Breakthrough Prize in Fundamental Physics: 51 members splitting the $3 million

Distant supernovae 遥远的超新星

Higher-z SNe Ia from HST



Host Galaxies of Distant Supernovae

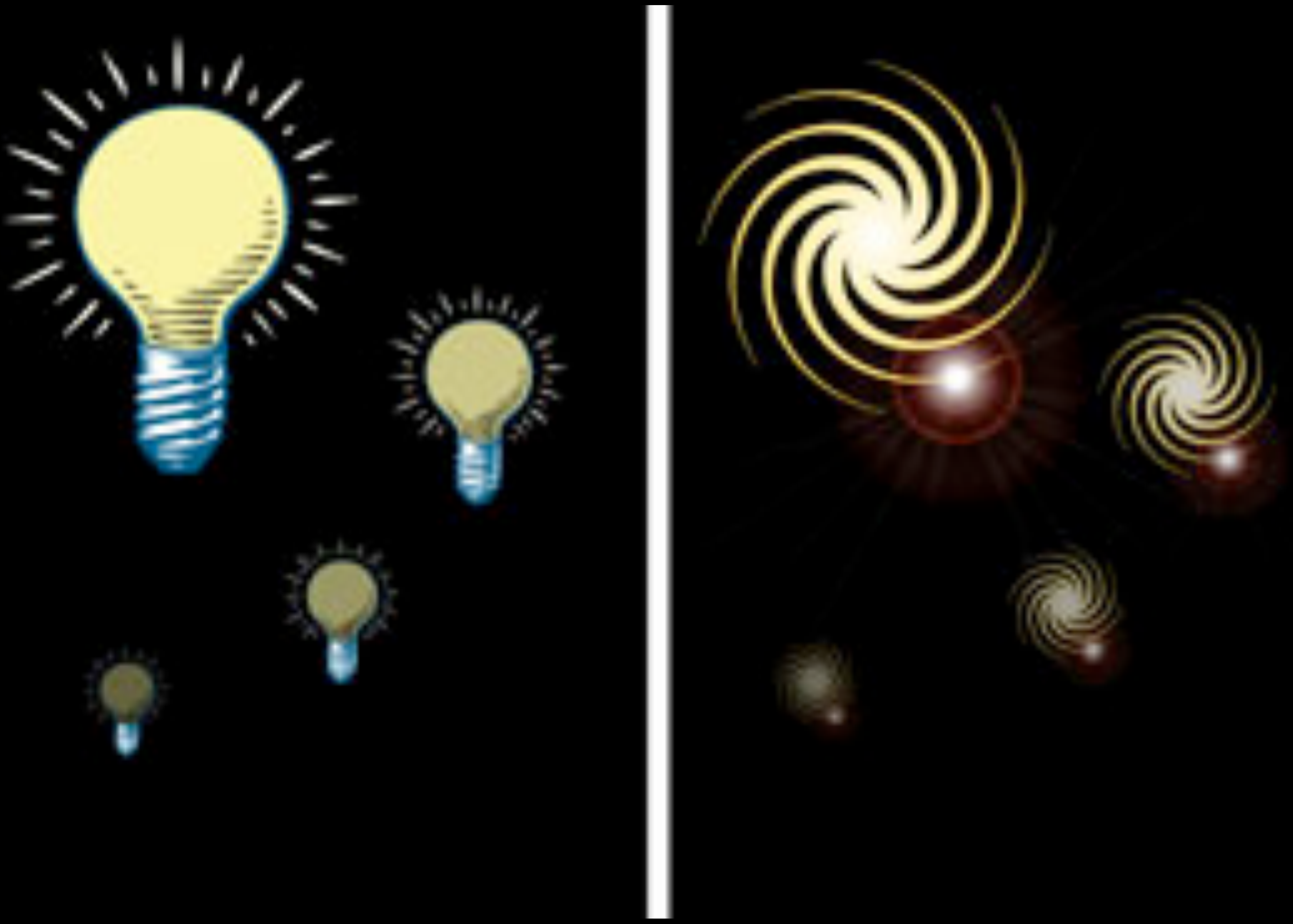
Hubble Space Telescope ▪ Advanced Camera for Surveys

50 SNe Ia, 25 at $z>1$

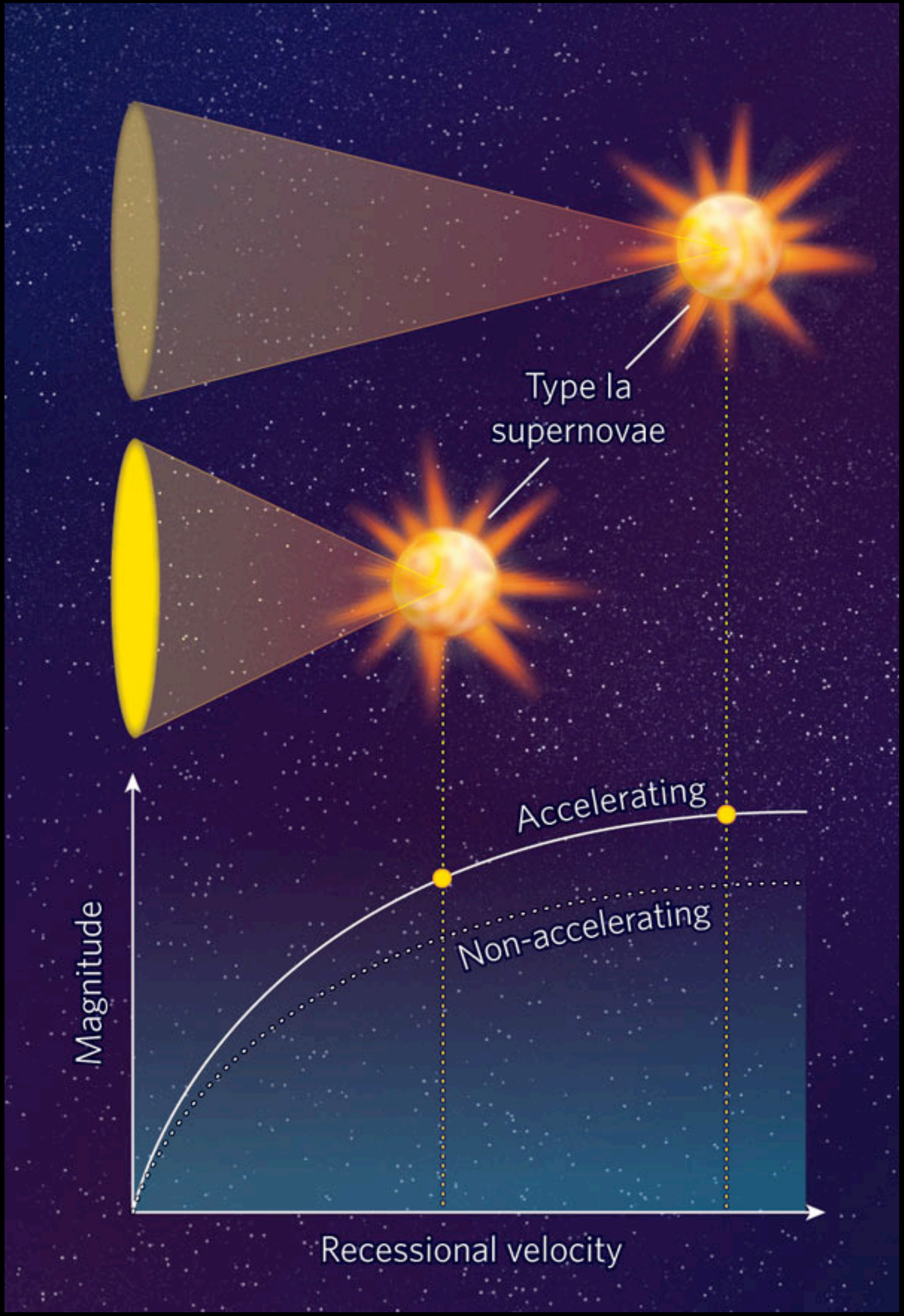
Riess, etal

Distant supernovae

Standard candles:
Their intrinsic luminosity is known
Their apparent luminosity can be measured



Distant SN as standard candles



Luminosity distance:

$$d_L^2 = \frac{L_s}{4\pi\mathcal{F}}$$

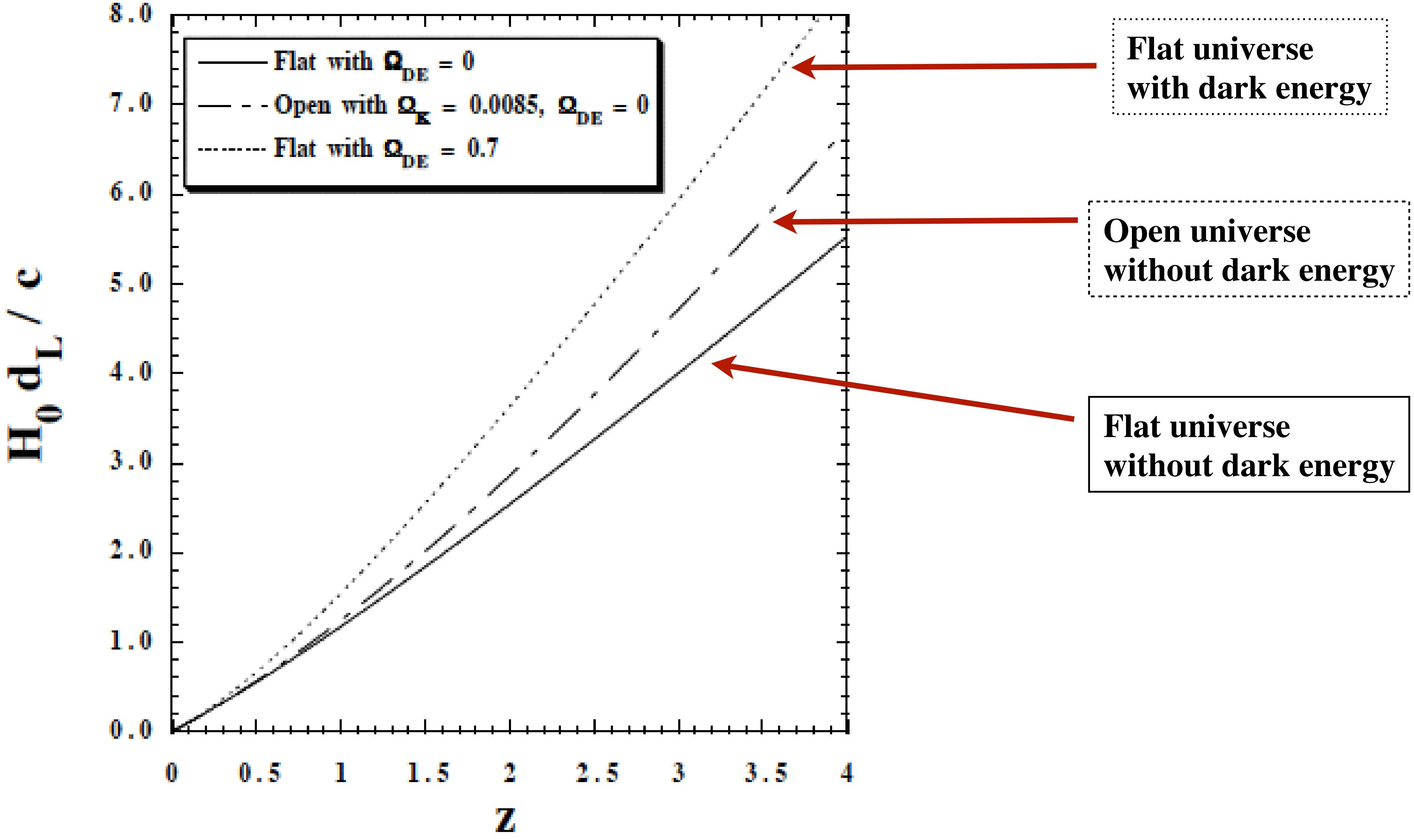
L_s the absolute luminosity of the source
F observed flux

$$d_L = \frac{c(1+z)}{H_0\sqrt{-K_0}}\sinh\left(\sqrt{-K_0}\int_0^z \frac{\mathrm{d}z'}{E(z')}\right)$$

K>0: closed
K=0: flat
K<0: open

$$K_0 = Kc^2/a_0^2H_0^2$$

$$E(z) = \left[\Omega_m^{(0)}(1+z)^3 + \Omega_K^{(0)}(1+z)^2 + \Omega_{\mathrm{DE}}^{(0)}\exp\left\{\int_0^z \frac{3(1+w_{\mathrm{DE}})}{1+z'}\mathrm{d}z'\right\}\right]^{1/2}$$

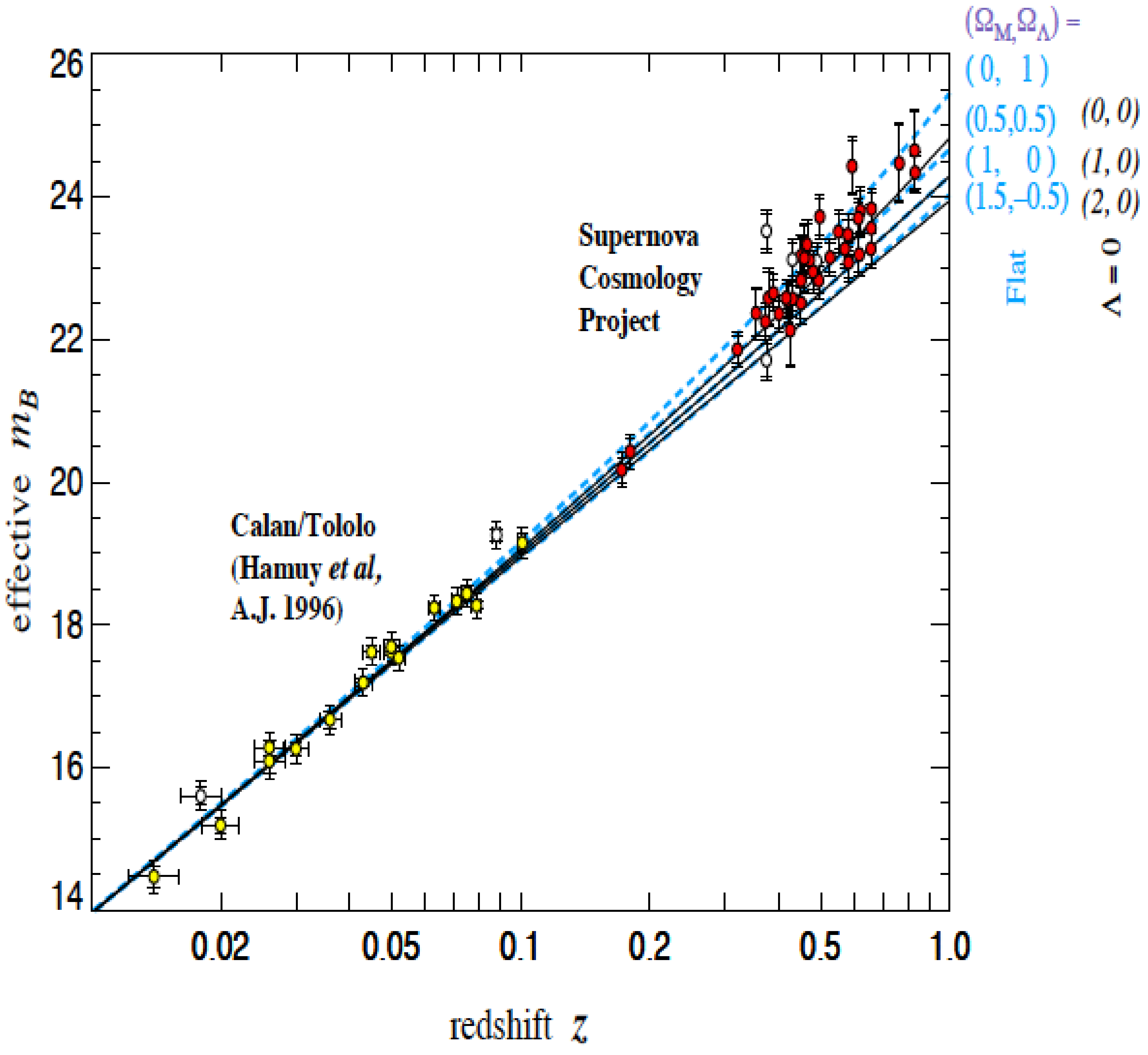


Flat universe with dark energy

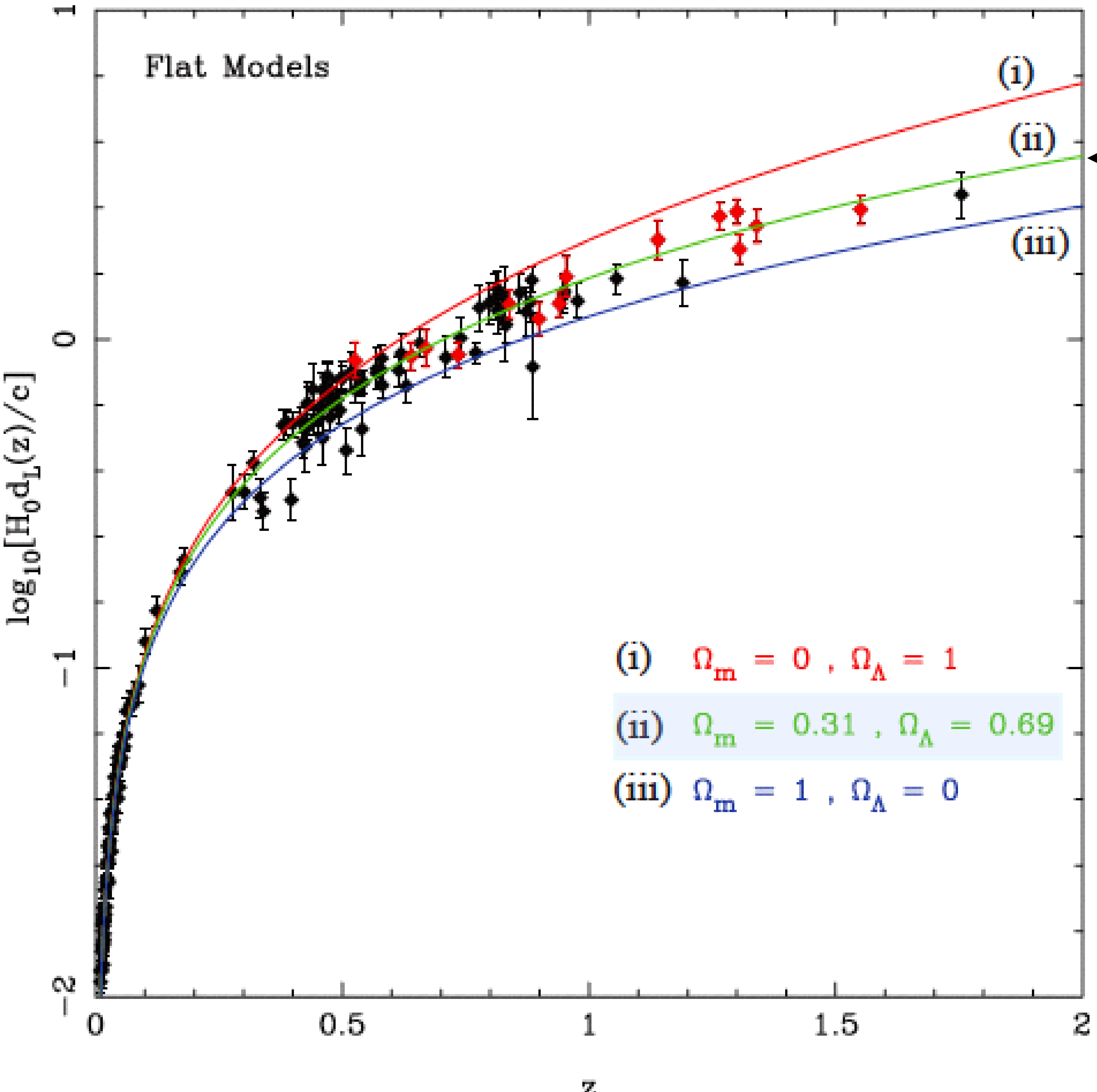
Open universe without dark energy

Flat universe without dark energy

Perlmutter et al and Riess et al (1998)



More data over the past 20 years

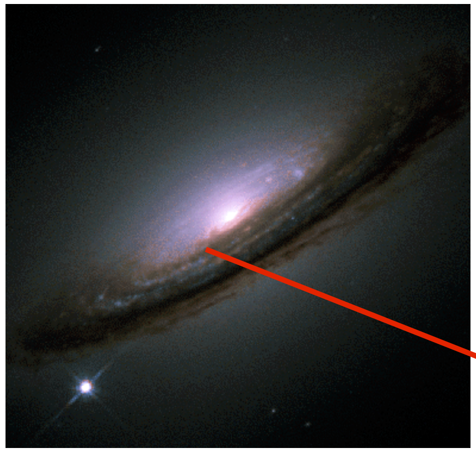


~ 70%
Dark Energy

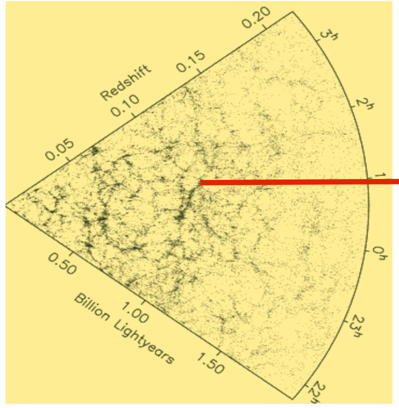
Dark Energy (DE)

Concordance region:
68% dark energy
27% dark matter
5% atoms

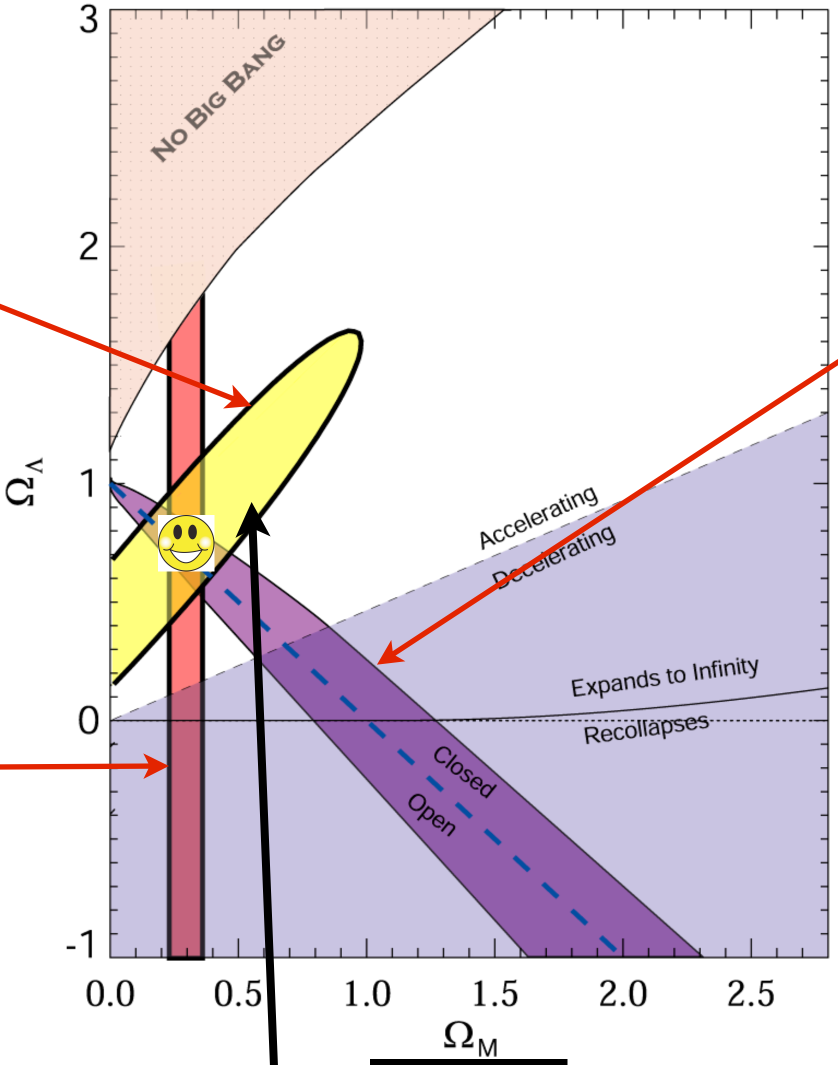
SNe Ia



LSS

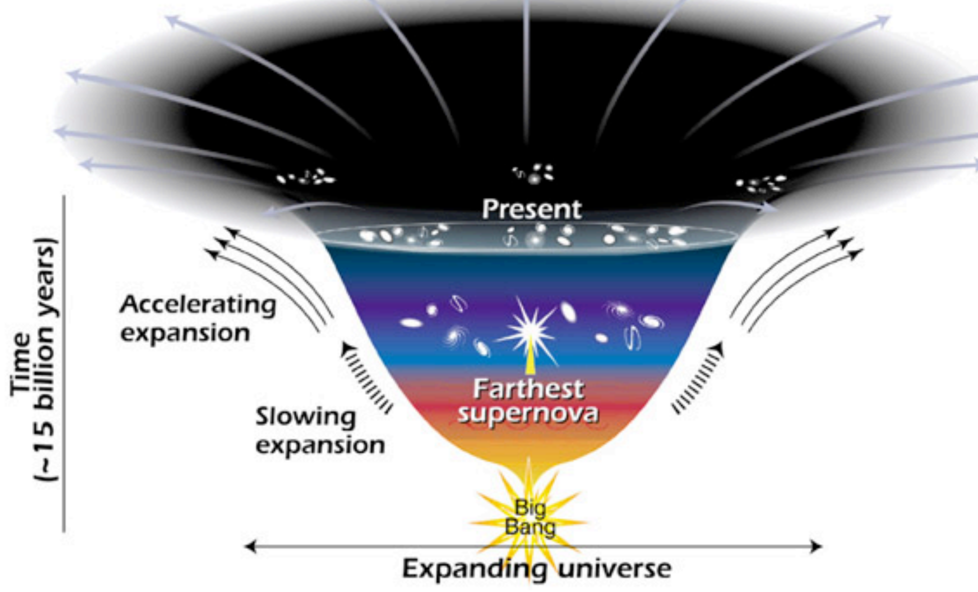


DE



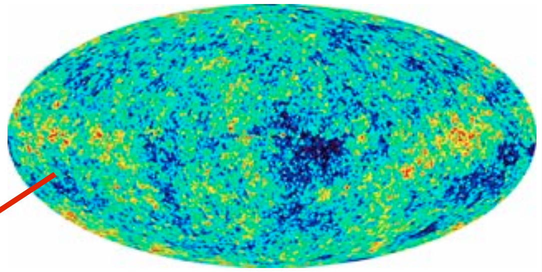
Matter

2011 N.P. in Physics



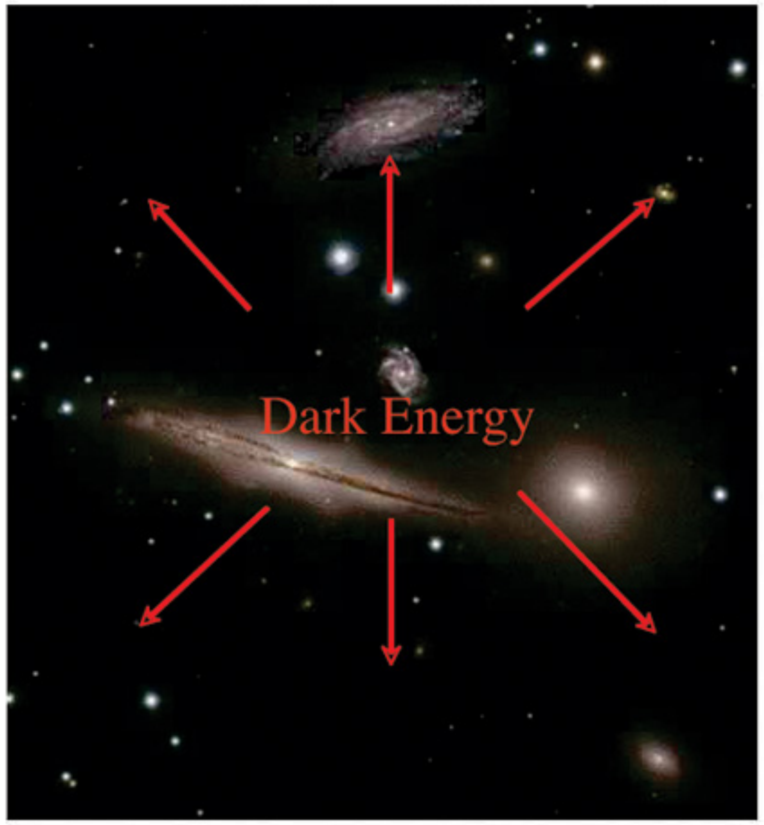
This diagram reveals changes in the rate of expansion since the universe's birth 15 billion years ago. The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart at a faster rate. Astronomers theorize that the faster expansion rate is due to a mysterious, dark force that is pushing galaxies apart.

CMB

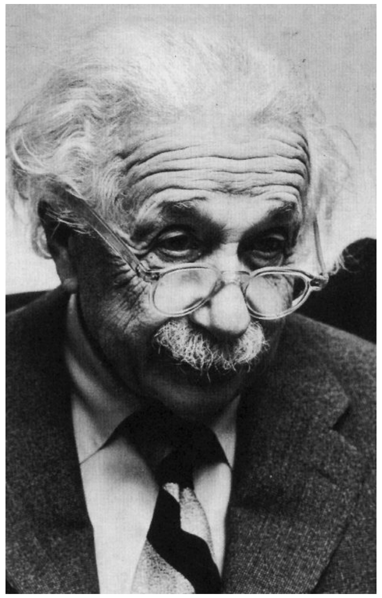


The current universe is accelerating!

Dark energy is pushing galaxies apart.



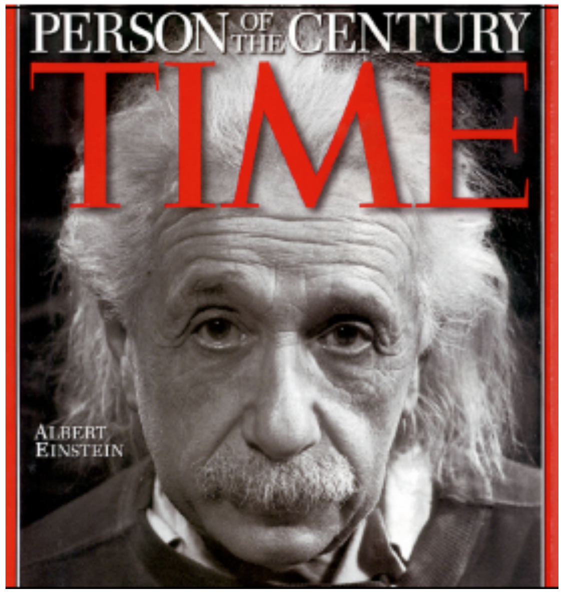
Two main approaches to Dark Energy



$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$ **(Einstein equations)**

Modified Gravity ↑ $G_{\mu\nu}$

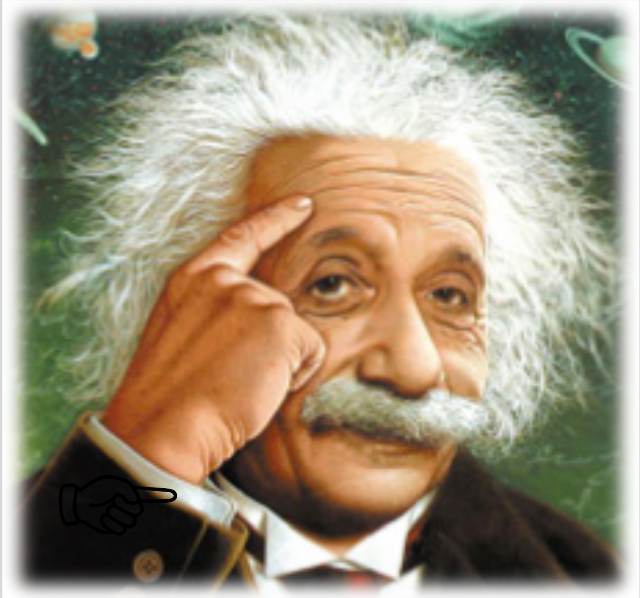
Modified Matter ↑ $T_{\mu\nu}$



→ **The simplest model: cosmological constant Λ**

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} \boxed{- \Lambda g_{\mu\nu}}$$

1917~2019
102週年



Energy Density

$$\rho_\Lambda = \frac{3H_0^2}{8\pi G} = 10^{-47}\ GeV^4$$

$$\rho_{vac} \sim m_{pl}^4 = 10^{76}\ GeV^4$$

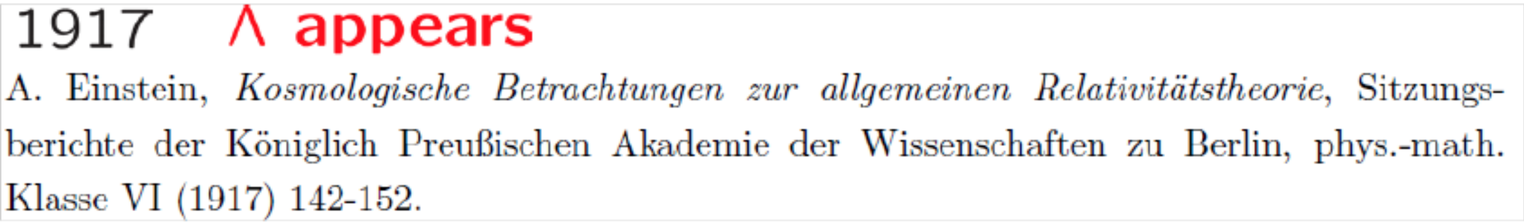
$$\frac{\rho^{obs}}{\rho^{th}} = 10^{-120}$$

A difference of 120 orders of magnitude

Cosmological constant problem

Cosmological constant:
``biggest blunder”

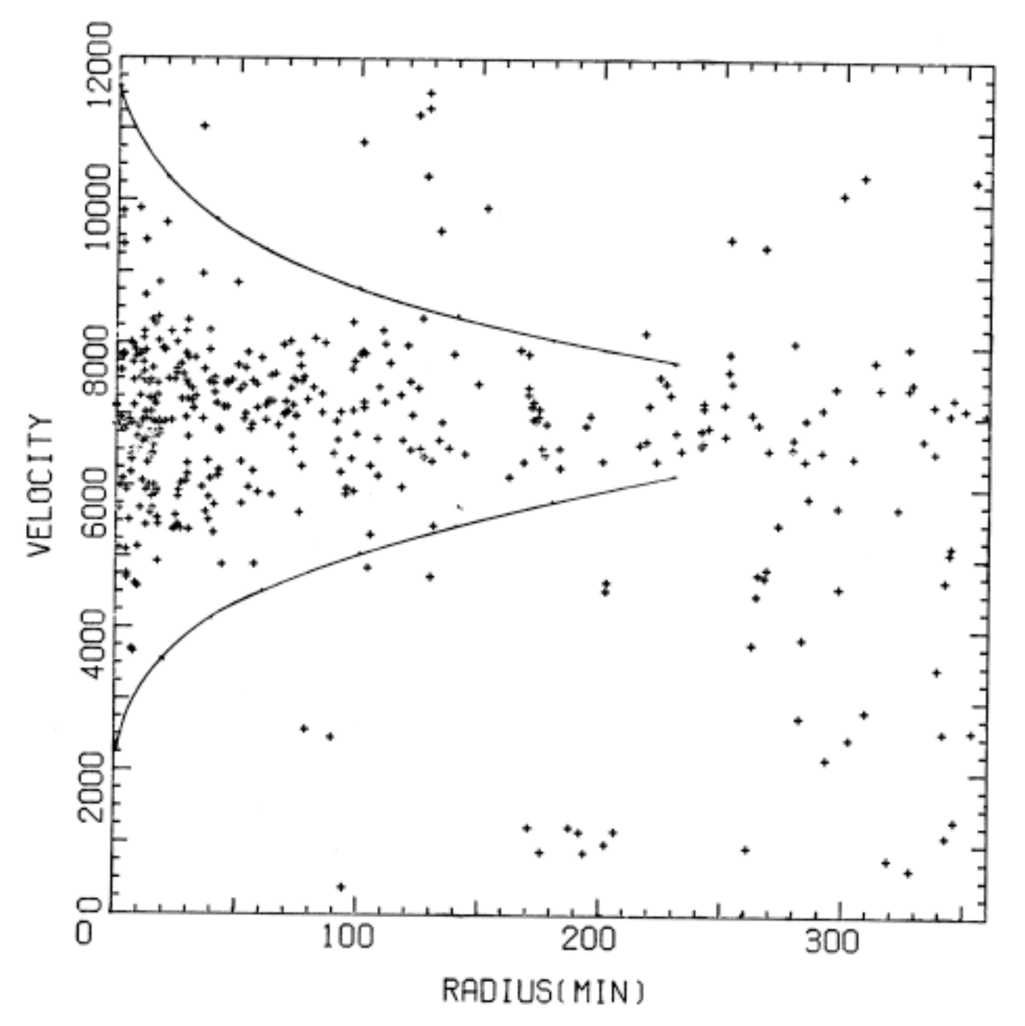
一生最大的錯誤



1917 Λ appears

A. Einstein, *Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie*, Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften zu Berlin, phys.-math. Klasse VI (1917) 142-152.

暗物質



COMA cluster

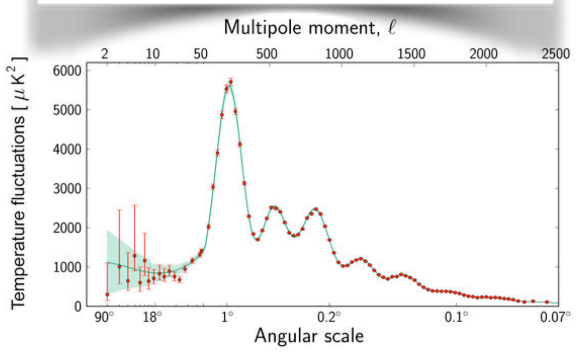
Zwicky (1933) used the radial velocity dispersion in the Coma cluster to conclude that the mass of luminous matter ~ 10% Gravitational mass .

F. Zwicky 1933

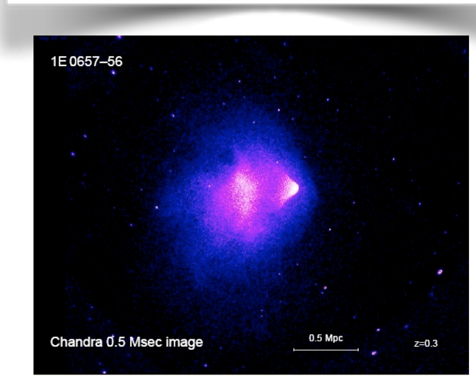
Cluster would be unstable if there were only luminous matters

Observations support Dark Matter at

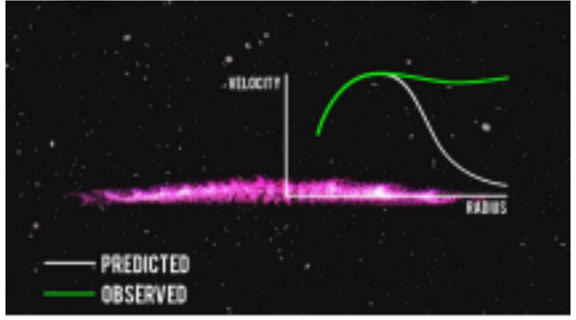
Cosmological scale



Galaxy cluster scale



Galactic scale



Dark matter cannot be the particle in the standard model, which has to be:

$$\Omega_{\rm DM} h^2 = 0.1196 \pm 0.0031$$

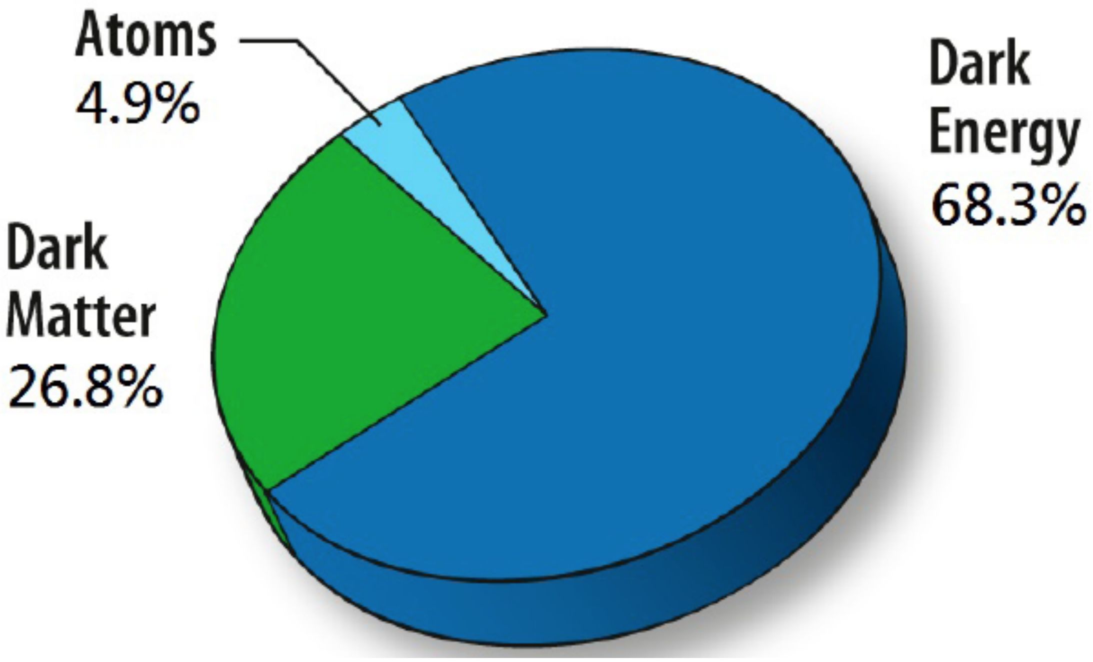
- Massive
- Non baryonic
- No charge (electric or color)
- Stable ($\tau > 10^{26}$ s, $\tau_{\rm universe} \sim 10^{17}$ s)

WIMP

Weakly Interacting Massive Particles

Axion

Sterile neutrino



What is the real nature of Dark Matter ?

The Standard Model

[redacted]

[redacted]

Beyond the SM

DARK MATTER

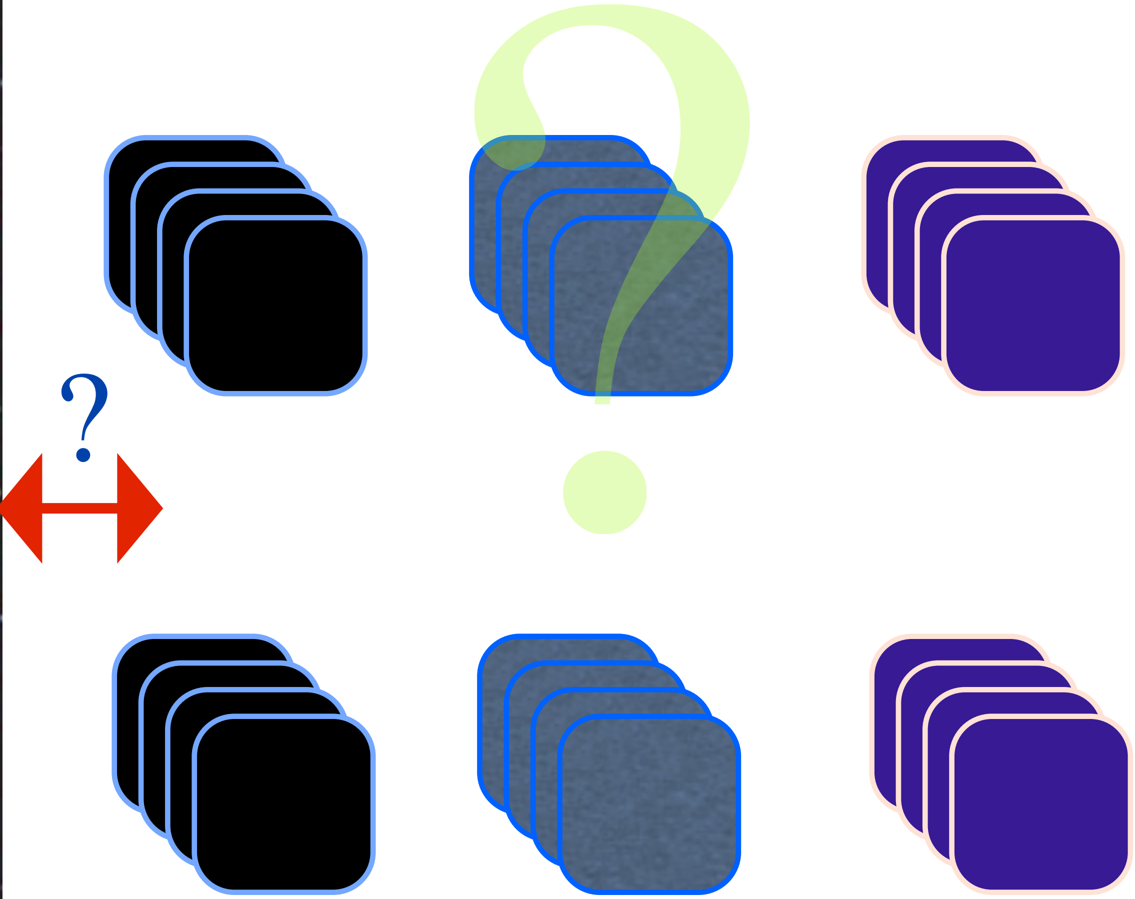
?

What is the real nature of Dark Matter ?

The Standard Model

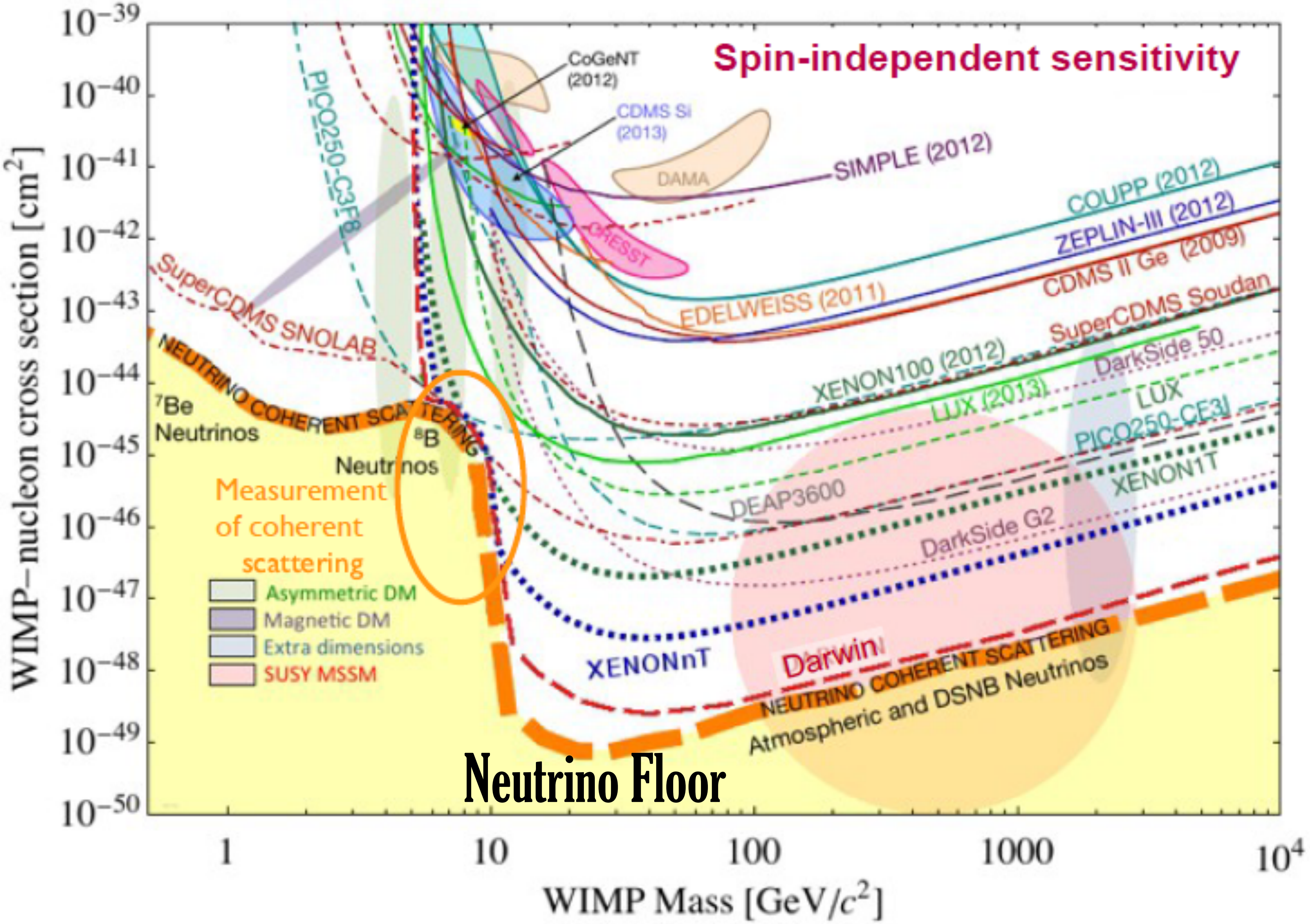
Beyond the SM

DARK MATTER

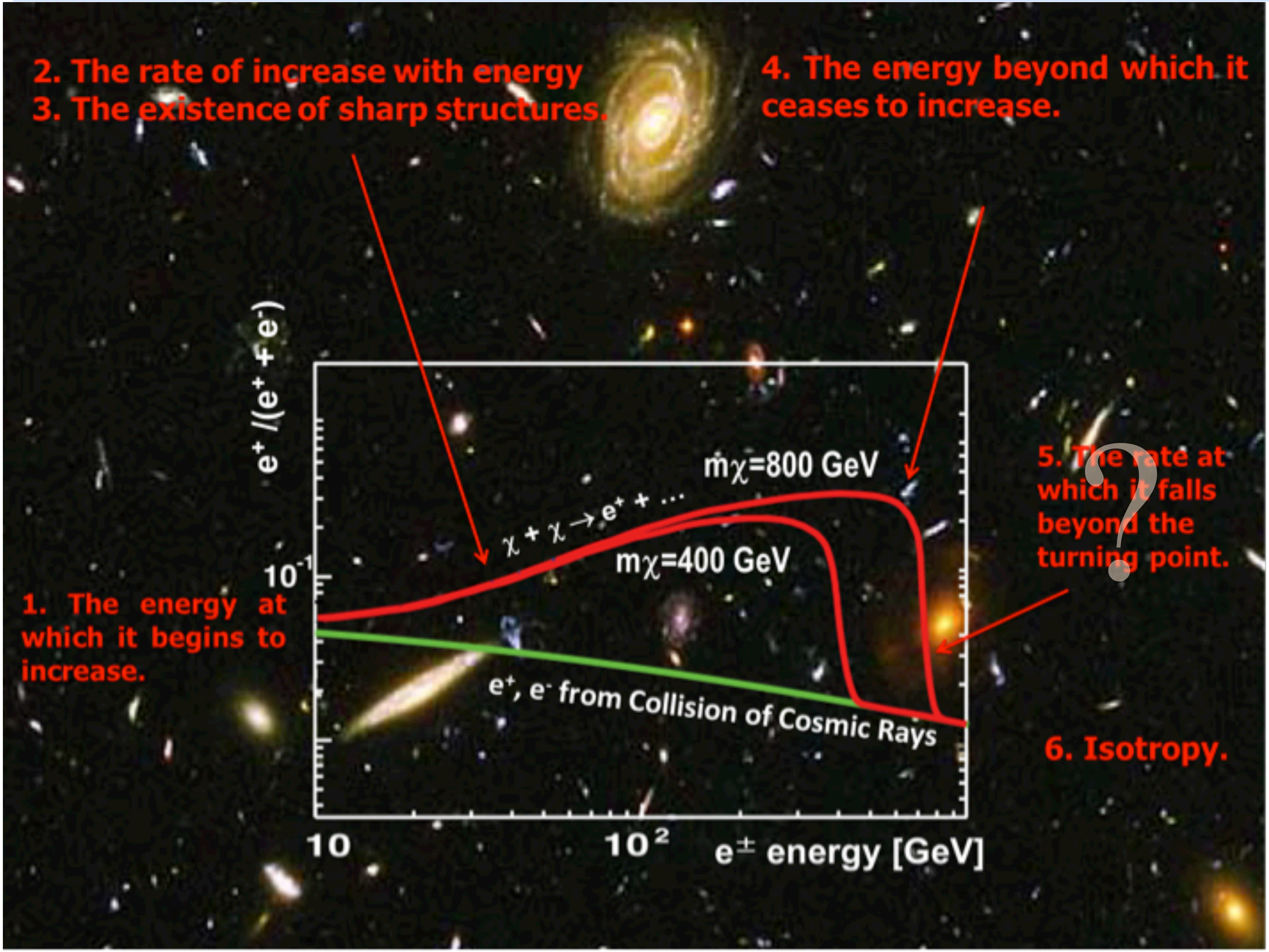


Current Status and Future Goal

Credit: Uwe Oberlack @ Darwin 2015



***AMS-02: six conditions for Dark Matter** with five seen!*



1. The energy at which it begins to increase.

2. The rate of increase with energy

3. The existence of sharp structures.

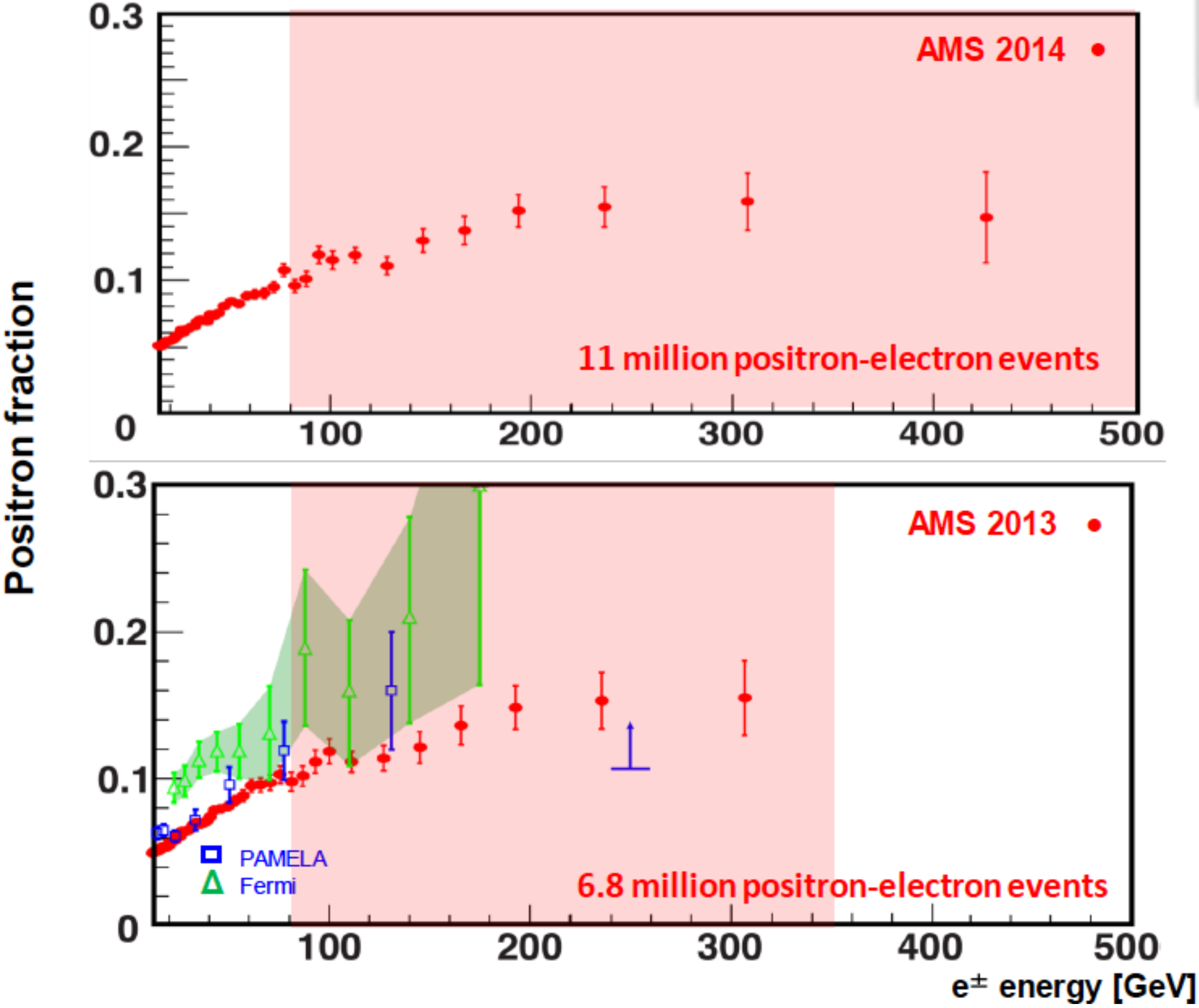
4. The energy beyond which it ceases to increase.

5. The rate at which it falls beyond the turning point. ?

6. Isotropy.

***AMS-02: six conditions for Dark Matter** with five seen!*

2. With much higher statistics



2016

?

It would be observed in 2024!

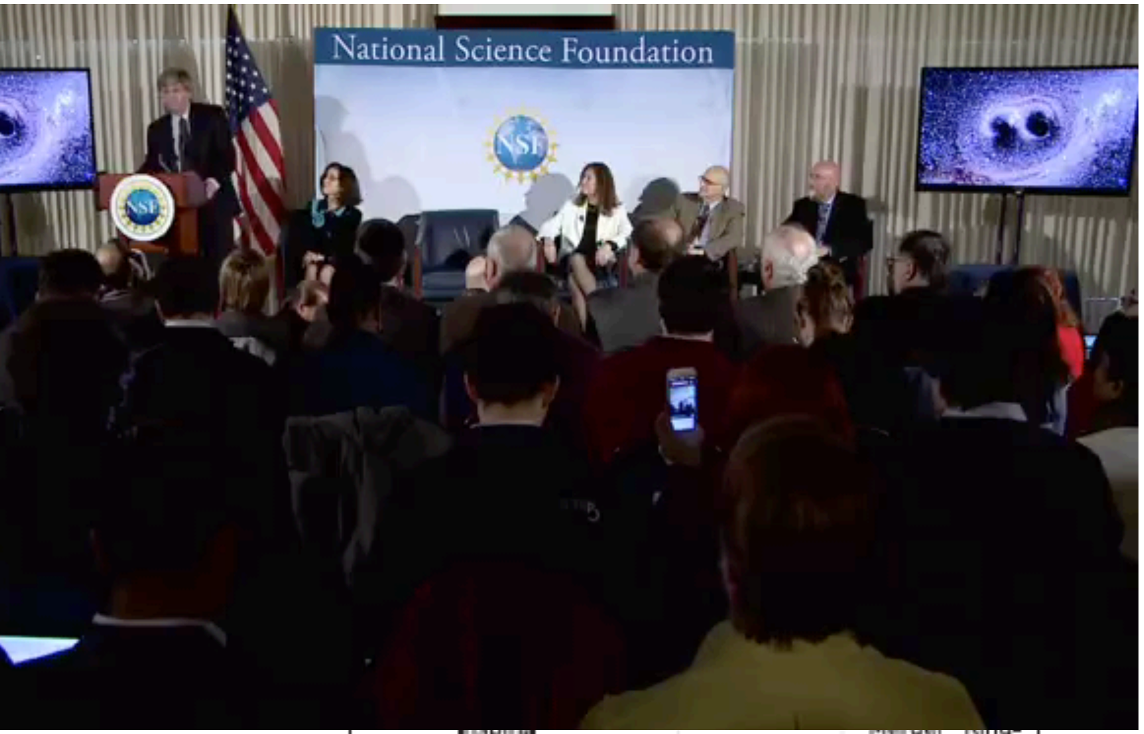
丁肇中
Talk at CERN
on Dec. 8, 2016

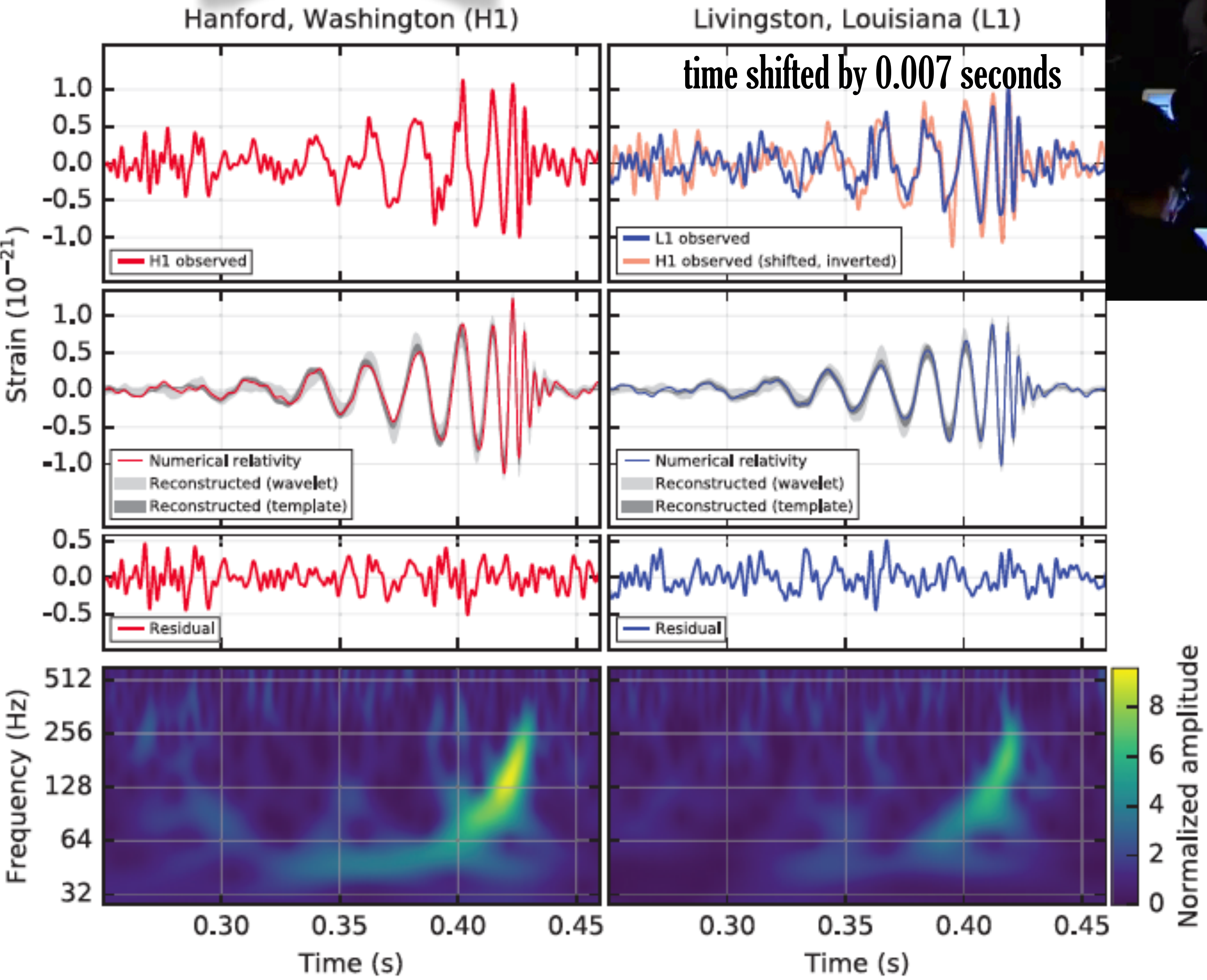
中國
“悟空”衛星

- *Gravitational Waves* Feb. 11, 2016

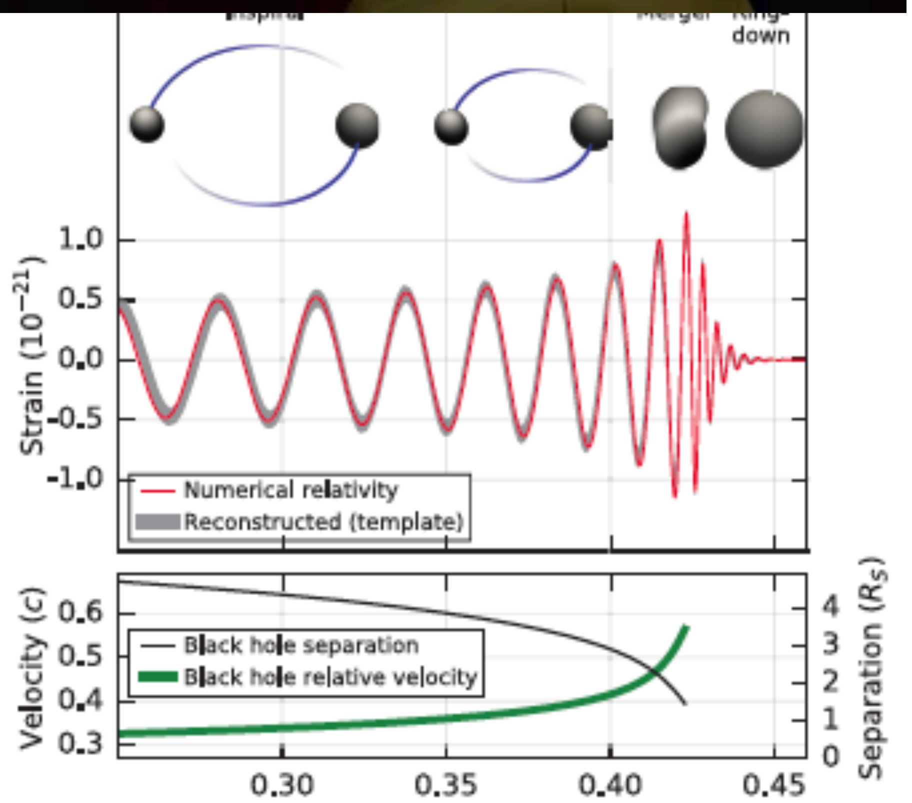
Sept. 15, 2015

GW150914





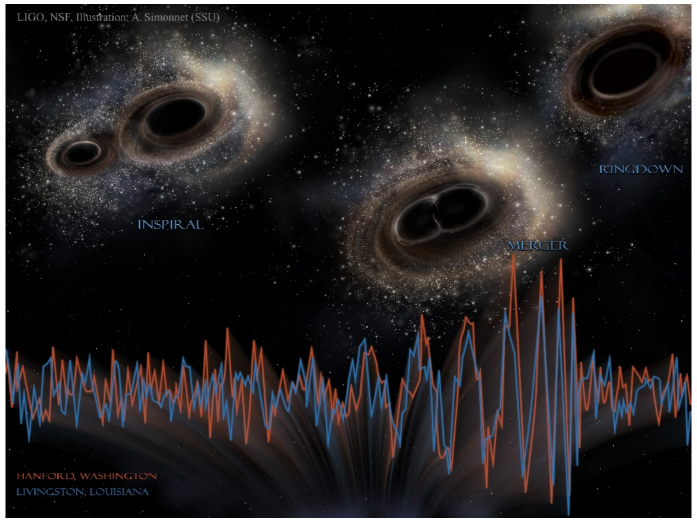
time shifted by 0.007 seconds

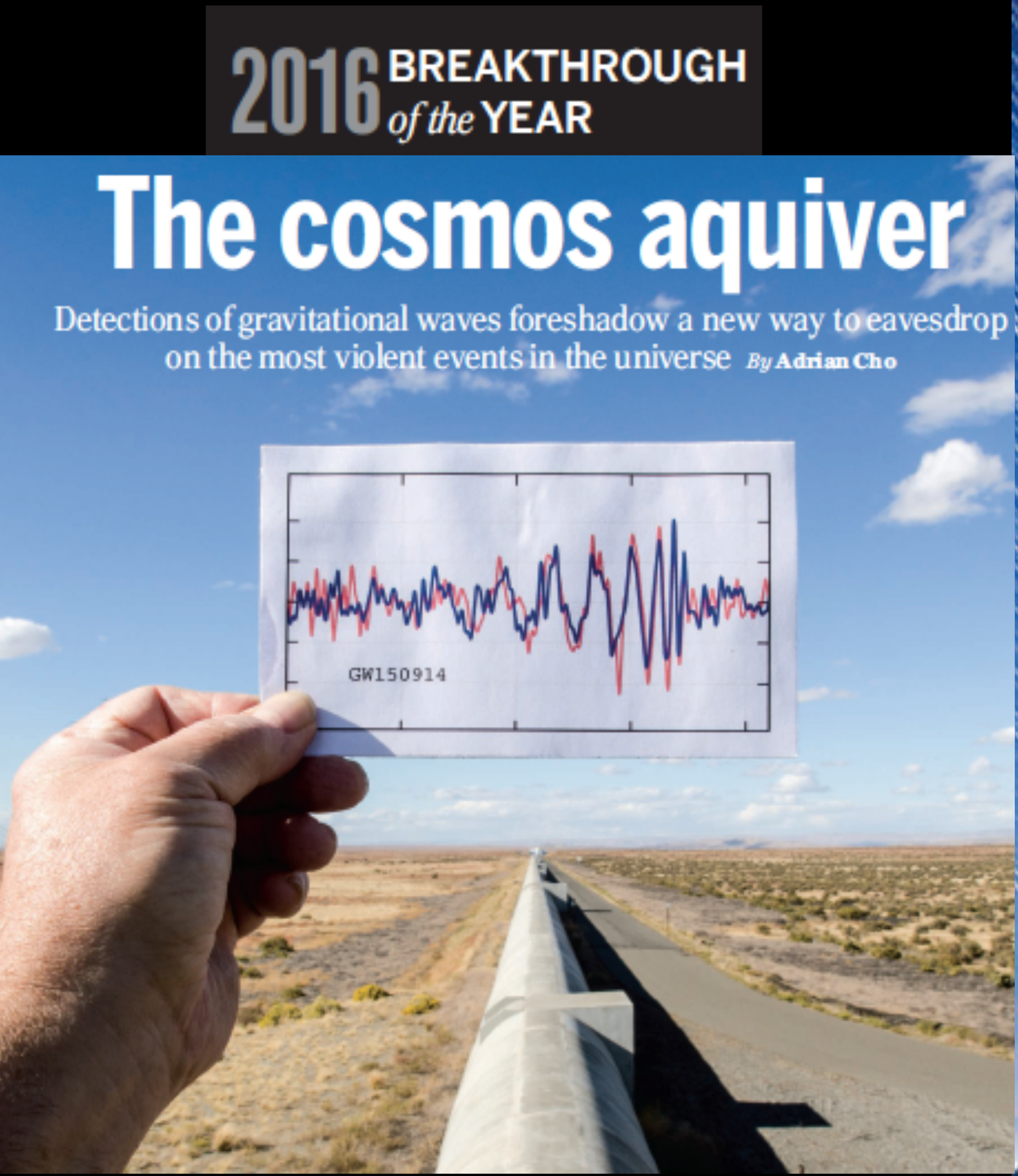


GW150914: What was seen?

- Chirp: 35 Hz to 250 Hz
- Initial masses: $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$
- Final mass: $62^{+4}_{-4} M_\odot$
- Energy output: $3^{+0.5}_{-0.5} M_\odot$

1.3 billion light year away (10^{17}m)


LIGO, NSF, Illustration: A. Simonnet (SSU)



2016 BREAKTHROUGH *of the* YEAR

The cosmos aquiver

Detections of gravitational waves foreshadow a new way to eavesdrop on the most violent events in the universe *By* **Adrian Cho**

Watching bacteriorhodopsin pump protons *p. 1552*

Boron nitride paves a path to propylene *p. 1570*

Trillions of insects migrate over our heads *p. 1584*

Science

$15
23 DECEMBER 2016
sciencemag.org

AAAS

2016
BREAKTHROUGH
of the YEAR

Science
AAAS

2017
BREAKTHROUGH
of the YEAR

How will AI impact jobs and the economy?

The catalog of New World plants

Minor recurrent infections and colitis

Science

$15
22 DECEMBER 2017
sciencemag.org

AAAS

2017
BREAKTHROUGH
of the YEAR

Nobel Physics Prize 2017

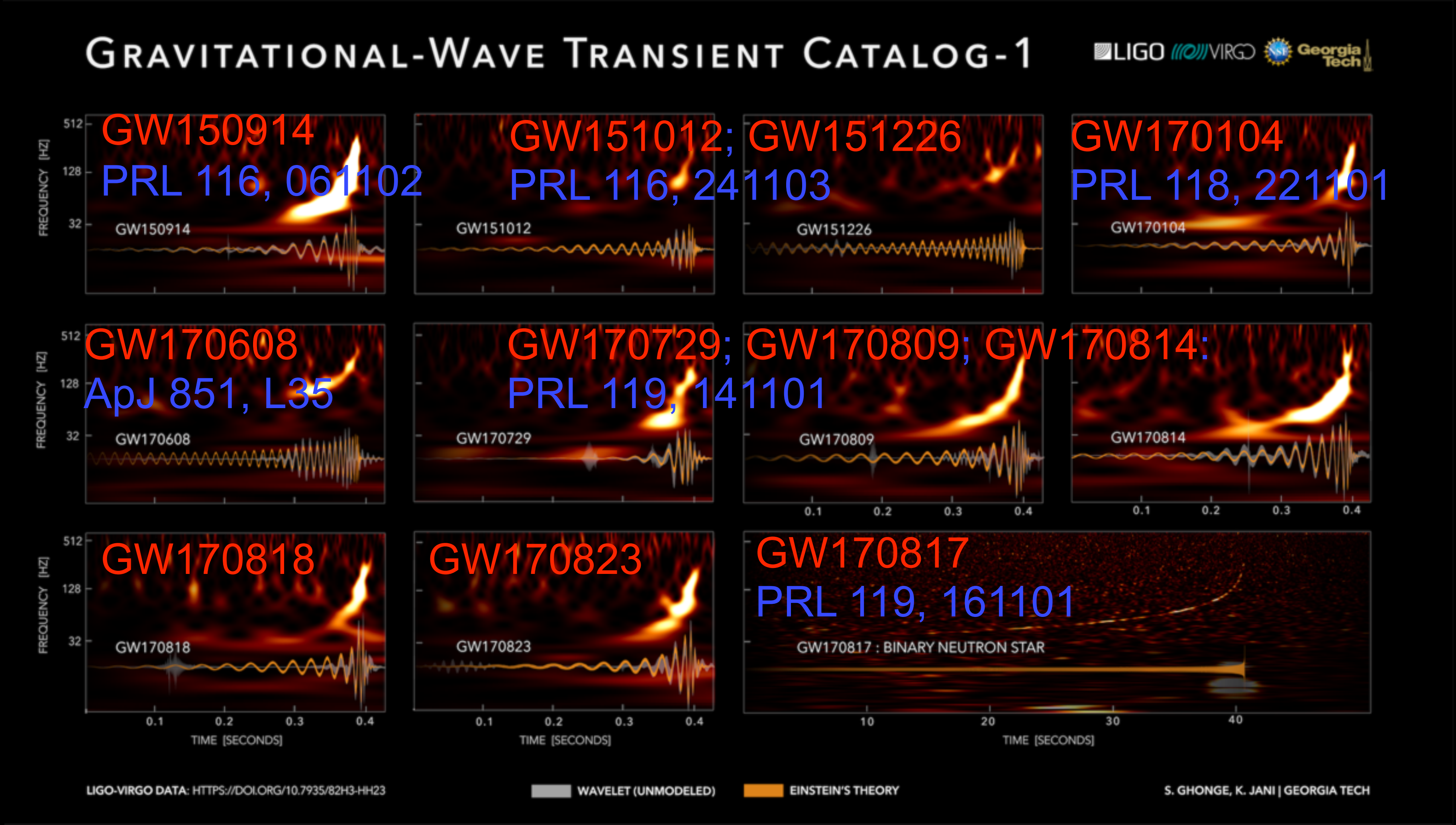
Gravitational Waves

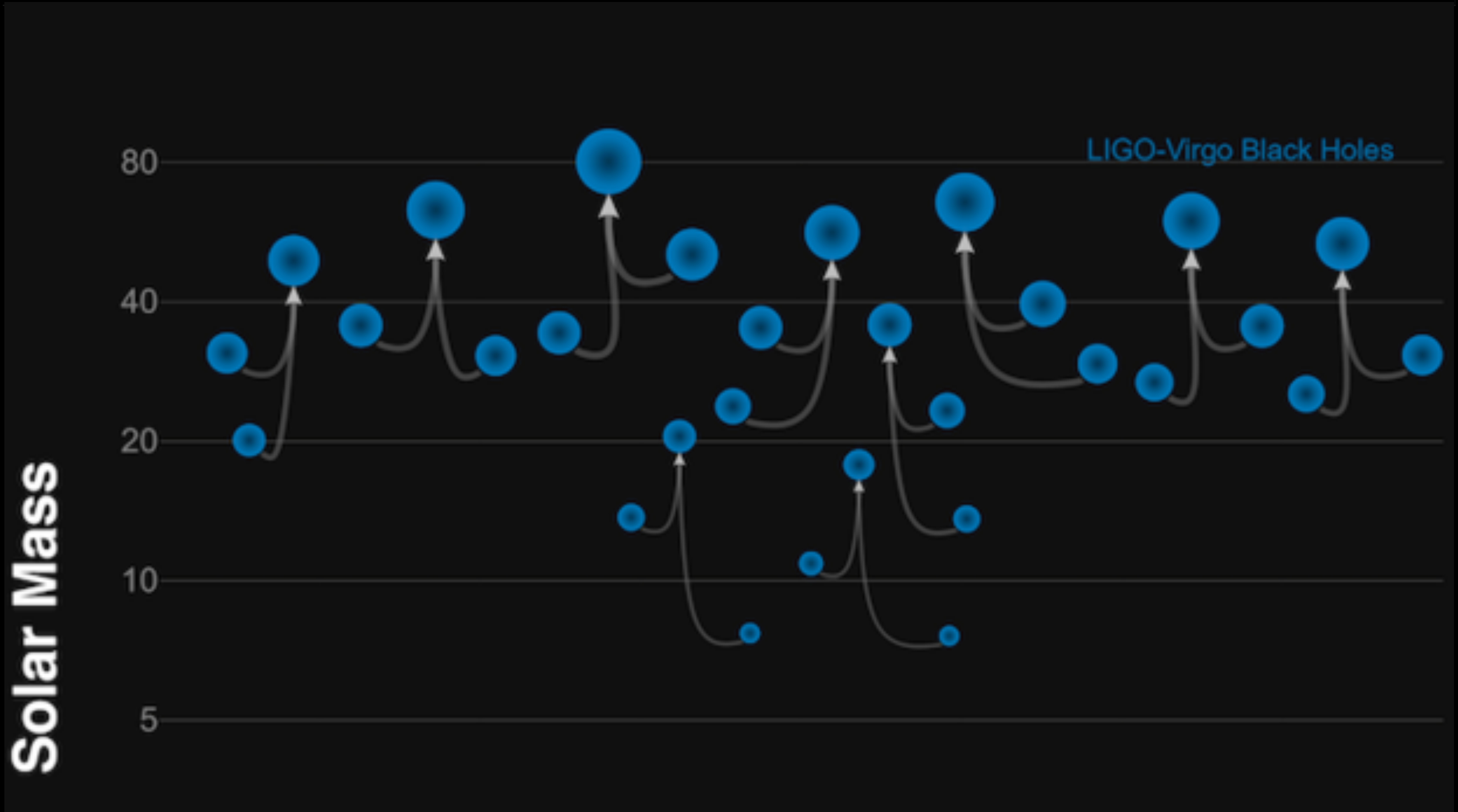
"for decisive contributions to the LIGO detector and the observation of gravitational waves".

"For the greatest benefit to mankind"
Alfred Nobel

2017 NOBEL PRIZE IN PHYSICS
Rainer Weiss
Barry C. Barish
Kip S. Thorne

85 **77** **81**





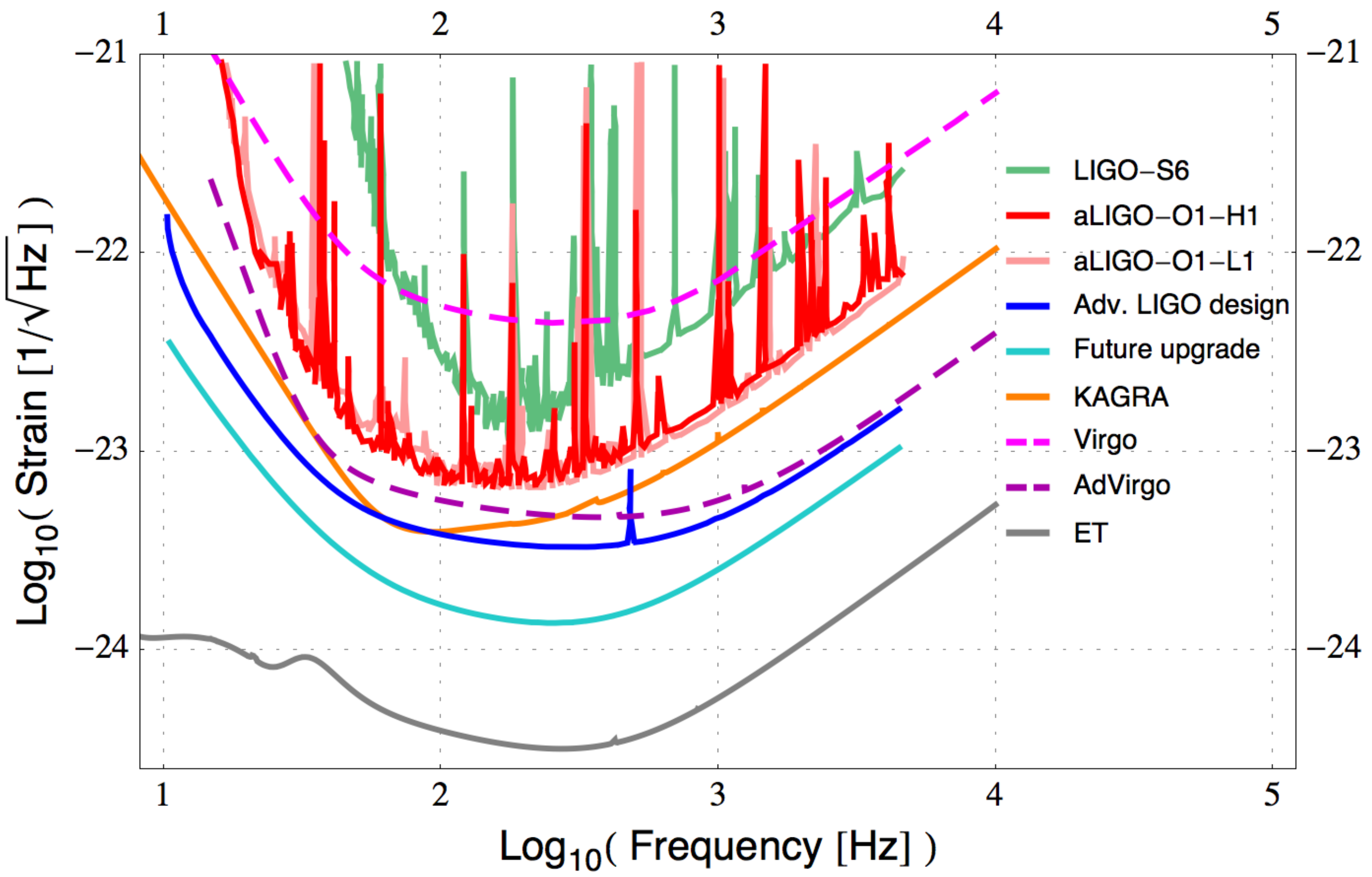
10 (B-B)+1 (N-N)

2019.4.1-5.3 : 4 (B-B)

2019.4.25: 1 (N-N)

2019.4.26: 1 (B-N)

Advanced LIGO has detected GWs from stellar-mass binary black hole mergers. We now have a global network of second generation km-size interferometers for the GW detection. Scaling with the achieved detection, third generation detectors would be to detect more than 100,000 5σ-GW events per year.



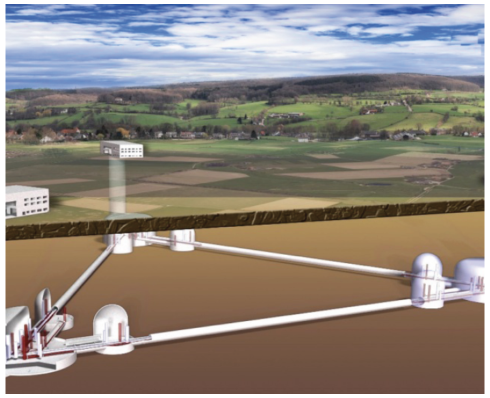
aLIGO sensitivity: ~1event/3 months (5σ)

2nd generation: ~100 events/yr (5σ)

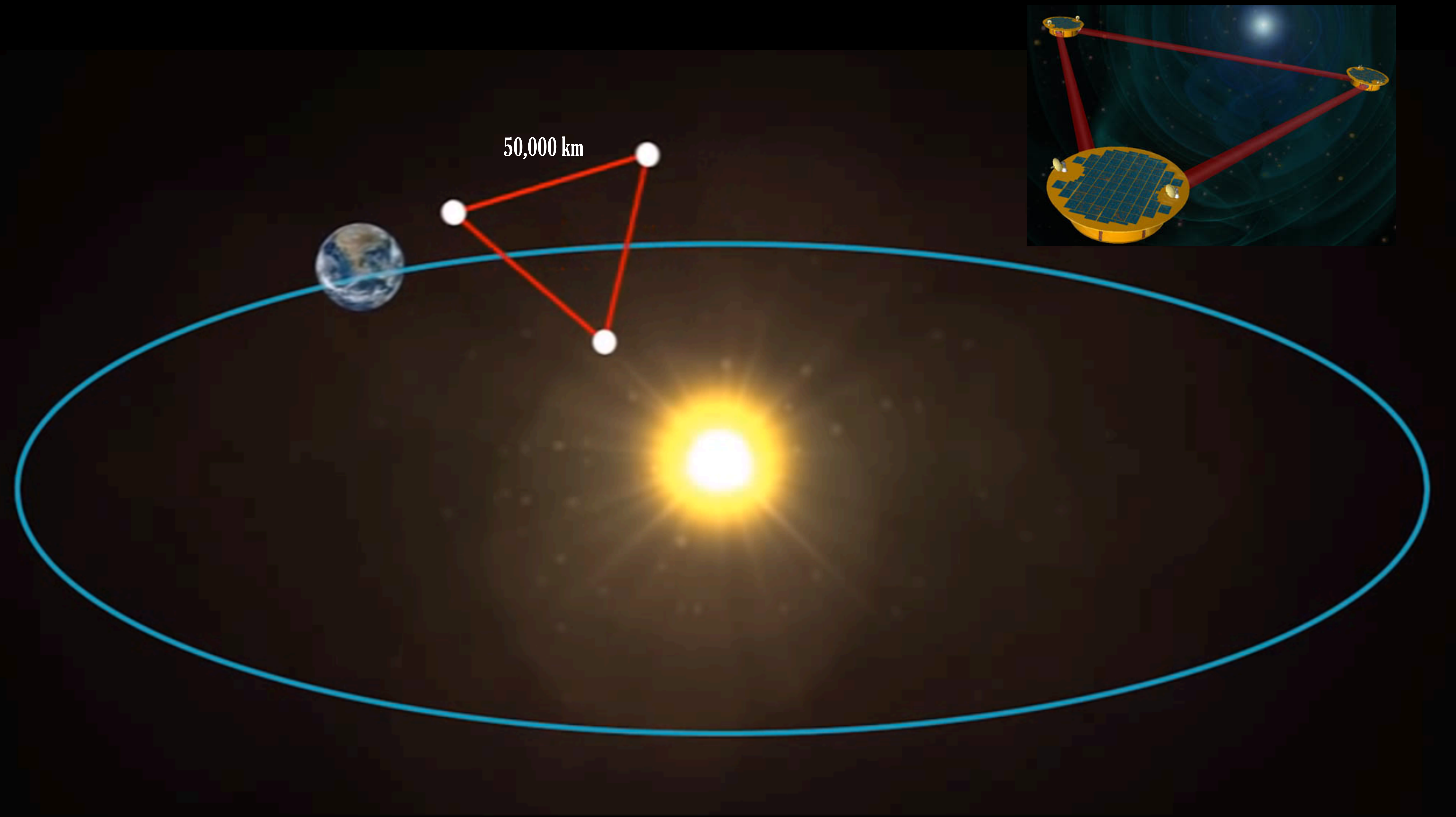
3rd generation: ~100,000 events/yr (5σ)

☞ >10 events/hour (5σ)

ET EINSTEIN TELESCOPE



- ET 10 km arms 2030+
- Cosmic Explorer 2030+
  10 km, 20 km or 40 km



In the future, there will also be gravitational wave detectors in space, like LISA.

中國的四個引力波探測實驗計劃：

太極（中國科學院）

天琴（中山大學）

阿里（中國科學院）

FAST（中國科學院）

中國的四個引力波探測實驗計劃：

Taiji Program in Space
ravitational wave physics
空间太极计划

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2016—2020年进行预研和关键技术突破；

2020—2025年进行关键技术应用和验证；

2025—2033年进行测试和发射。

太極計劃首席科學家

吴岳良，男，1962年生于江苏宜兴，中共党员。理论物理学家。中国科学院院士。现任中国科学院大学副校长。1982年毕业于南京大学物理系。同年，考入中国科学院理论物理研究所。1987年获博士学位。

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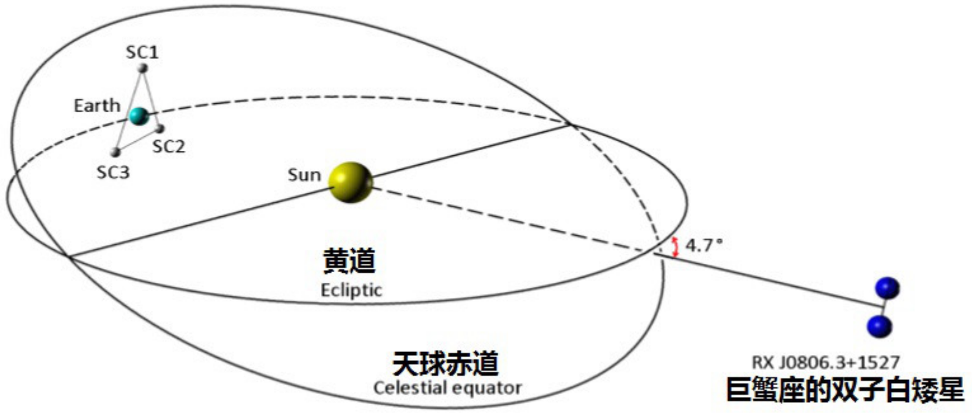

ChinaSpaceflight.com

天琴計劃首席科學家

罗俊，男，1956年11月生于湖北仙桃，理学博士，中国科学院院士。现任中山大学大学校长。长期从事引力实验与精密测量物理研究，开展了牛顿万有引力常数G的精确测量。

“世界引力中心”

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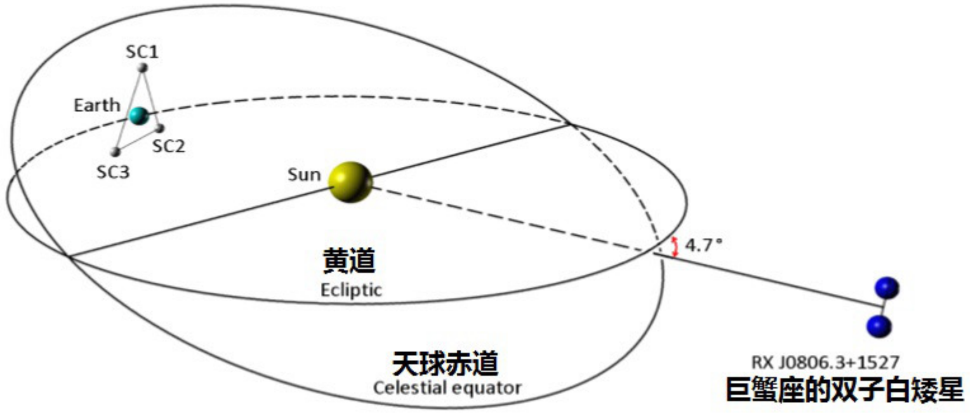

ChinaSpaceflight.com

阿里（中國科學院）

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Search for low-f primordial GW
原初引力波

阿里計劃首席科學家

张新民，男，1959年1月生于河南省温县，1981年获河南师范大学学士学位。1991年获美国洛杉矶加州大学(UCLA)博士学位。1991-1993 年美国马里兰大学和1993-1996年依阿华州立大学作博士后。1996年8月回国在高能所理。1997年中国科学院“百人计划”入选者，1999年获国家“杰出青年”。

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in Space
hysics

星

Sea

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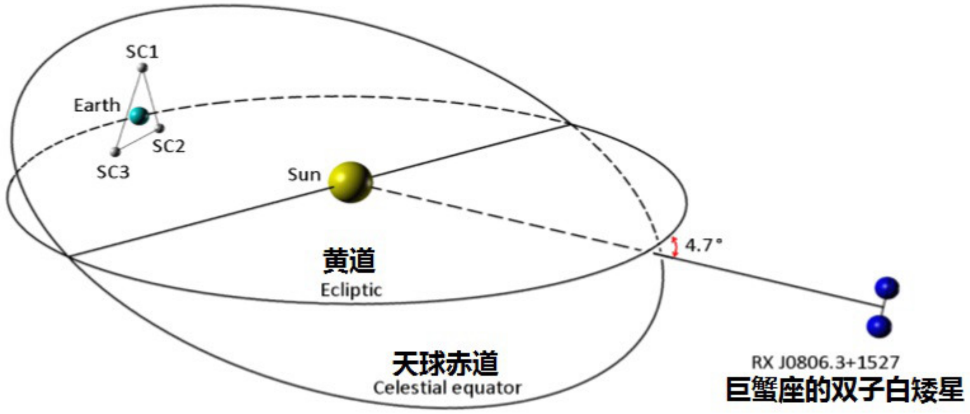

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Search for low-f primordial GW
原初引力波

FAST（中國科學院）

在中國貴州省平塘縣 大窩凼窪地，2016年9月建成

Five hundred meter Aperture Spherical Telescope

观测到全天的脉冲星或者某一方向上的多个脉冲星周期发生变化，探测到引力波。

Future Perspectives

Modern Particle Physics: 7 Periods

1. < 1945 -- *Pre-Modern Particle Physics Period*
2. *Startup Period (1945 -- 1960)：Early contributions to the basic concepts of modern particle physics.*
3. *Heroic Period (1960 -- 1975):Formulation of the standard model of strong and electroweak interactions.*
4. *Period of Consolidation and Speculation (1975 -- 1990): Precision tests of the standard model and theories beyond the standard model.*
5. *"Frustration" and "Waiting" Period (1990 -- 2005)*
6. *Preparation Period (2005--2020)*
7. *Super-Herioic Period (2020--2035)*

英雄歲月

3 Dark Clouds 三朵烏雲

Cosmic microwave fluctuations (2006 Nobel Prize)
Dark energy (2011 Nobel Prize)
Neutrino oscillations (2015 Nobel Prize)

超英雄歲月

LHC: ...
GW: LISA 2030
100 TeV Collider 2030

+ something unexpected?

Great Collider

How many Nobel Prizes in Particle Physics & Cosmology for the Super-Heroic Period (超英雄歲月) ?

Future Perspectives

Heroic Period 英雄歲月(1960 -- 1975):

Nobel Prizes in Particle Physics & Cosmology: [work done]

20xx: ?

2013: Englert, Higgs – Higgs particle [1964]

2008: Nambu,Kobayashi,Maskawa–broken symmetry [1961,1973]

2004: Gross, Politzer, Wilczek–asymptotic freedom [1973]

1999: 't Hooft, Veltman–electroweak force [1972]

1995: Perl,Reines–tau lepton [1975], electron neutrino [1953]

1993: Hulse,Taylor – pulsar (indirect detection of GW [1974]

1990: Friedman, Kendall, Taylor–quark model [1972]

1988: Lederman,Schwartz,Steinberger -muon neutrino [1962]

1980: Cronin, Fitch–symmetry breaking (CP violation) [1964]

1979: Glashow, Salam, Weinberg–electroweak theory [1961,67]

1978: Penzias,Wilson – cosmic microwave background radiation [1965]

1976: Richter,Ting–charm quark (J/Psi) [1974]

1969: Gell-Mann–classification of elementary particles [1964]

more?

=13

7. Super-Herioic Period (2020--2035)

超英雄歲月

LHC: ...
GW: LISA *2030*
100 TeV Collider *2030*

+ something unexpected?

Great Collider

How many Nobel Prizes in Particle Physics & Cosmology for the Super-Heroic Period (超英雄歲月) ?

>10

2019 Nobel Prize in Physics?

S.Adler, PR177,2426(1969);
J.S.Bell, R.Jackiw, Nuovo Cimen A60,47 (1969).

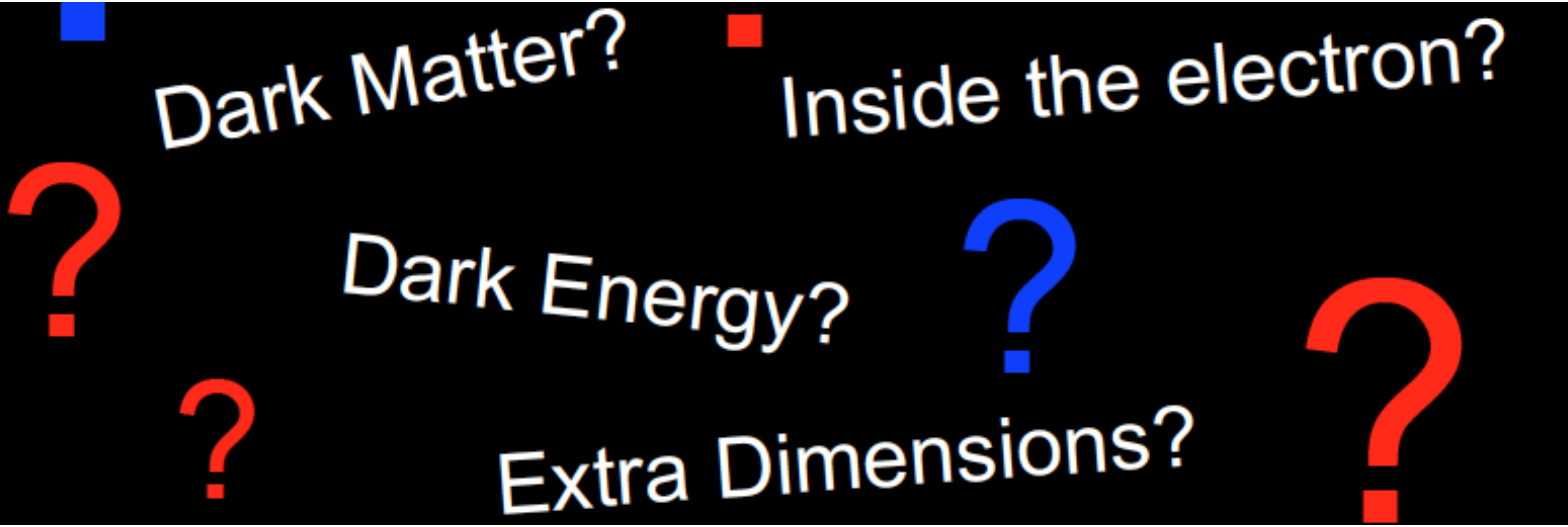
deceased at age 62
(Jun. 28, 1928-Oct. 1, 1990)

1960-1975
Heroic Period

50th Anniversary of ABJ Anomaly ！

尚未解決之問題

- *Why are there three types of quarks and leptons?*
- ***Is there some pattern to their masses?***
- *Are there more types of particles and forces to be discovered at yet higher energy accelerators?*
- *Are the quarks and leptons really fundamental, or do they, too, have substructure?*
- *How to include the gravitational interactions in the SM?*
- *How to understand dark matter and dark energy in the universe?*



Key to the Universe

中微子，暗物質，暗能量和引力波
等問題或許是人類了解
宇宙歷史、結構和未來的鑰匙

Just the beginning of the story

The Party of Particle Physics and Cosmology
is NOT OVER YET!

高能物理的超级新盛宴即將開始
2020—2035 超英雄歲月！

謝謝！