Is nature natural?
(Where are we standing?)

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Dimensional Analysis

Physicists' view on nature

- Physical quantities are independent of the units
- Dimension of physical quantity : mass, length, time, …
- Derived quantity : $v = \frac{dx}{dt} \rightarrow [velocity] = \frac{[length]}{[time]}$,

$$F = ma \rightarrow [Force] = \frac{[mass][length]^2}{[time]^2}$$

Dimensional Analysis

Physicists' view on nature

- Physical quantities are independent of the units
- Thermal physics : $E = k_B T \;\&\; k_B = 1 \rightarrow [energy] = [temperature]$
- Special relativity : $x^2 - (ct)^2 = 0 \;\&\; c = 1 \rightarrow [length] = [time]$
- Quantum mechanics : $E = \hbar\omega \;\&\; \hbar = 1 \rightarrow [energy] = \frac{1}{[time]}$,

  ->

  $[energy] = [momentum] = [mass] = [temperature] = \frac{1}{[time]} = \frac{1}{[length]}$

Dimensional Analysis

Physicists' view on nature

- Physical quantities are independent of the units
- $[energy] = [momentum] = [mass] = [temperature] = \frac{1}{[time]} = \frac{1}{[length]}$
- Gravity : $F = G_N \frac{m^2}{r^2} \rightarrow [G_N] = \frac{1}{[mass]^2}$
- $G_N = 1 \rightarrow$ all quantities as numbers (natural unit)
- $[length] = L, [time] = T, [mass] = M$

Dimensional Analysis

Physicists' view on nature

- Physical quantities are independent of the units
- $[energy] = [momentum] = [mass] = [temperature] = \dfrac{1}{[time]} = \dfrac{1}{[length]}$
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- $[c] = LT^{-1} \sim 3 \times 10^{8} m/s$
- $[\hbar] = ML^2T^{-1} \sim 1.1 \times 10^{-34} kgm^2/s$
- $[G_N] = MLT^{-2} \times M^{-2}L^2 = M^{-1}L^3T^{-2} \sim 6.7 \times 10^{-11} kg^{-1}m^3/s^2$
- $[k_B] = ML^2T^{-2}K^{-1} \sim 1.4 \times 10^{-23} kgm^2s^{-2}K^{-1}$
- $[\hbar G_N] = L^5T^{-3} = L^2[c]^3 \rightarrow L_{\mathrm{Pl}} = \sqrt{\dfrac{\hbar G_N}{c^3}} = 1.6 \times 10^{-35} m$: Planck length
- $t_{\mathrm{Pl}} = \sqrt{\dfrac{\hbar G_N}{c^5}} = 5 \times 10^{-44} s$: Planck time
- $m_{\mathrm{Pl}} = \sqrt{\dfrac{\hbar c}{G_N}} = 2.2 \times 10^{-8} kg$: Planck mass
- $T_{\mathrm{Pl}} = \dfrac{m_{\mathrm{Pl}} c^2}{k_B} = 1.4 \times 10^{32}\ \mathrm{K} = 1.2 \times 10^{19}\ \mathrm{GeV}$: Planck temperature

A few exercises

natural size

- Age of the universe : $t_{\mathrm{Pl}} \sim 5 \times 10^{-44} s$ vs $t_U \sim 4.2 \times 10^{17} s \;\; \rightarrow \dfrac{t_U}{t_{\mathrm{Pl}}} \sim 10^{61}$
- Higgs mass : $m_{\mathrm{Pl}} \sim 1.2 \times 10^{19}\ \mathrm{GeV}$ vs $m_H \sim 125\ \mathrm{GeV} \;\; \rightarrow \dfrac{m_H}{m_{\mathrm{Pl}}} \sim 10^{-17}$
- Cosmic microwave b.g. temperature : $T_{\mathrm{cmb}} \sim 2.7K$ vs $T_{\mathrm{Pl}} \sim 1.4 \times 10^{32} K$

  $\rightarrow \dfrac{T_{\mathrm{cmb}}}{T_{\mathrm{Pl}}} \sim 10^{-32} \rightarrow n_\gamma \sim T^3 \sim 10^{-96}$

  $\rightarrow 10^{-96}/(10^{-33}\ cm)^3 \sim 1000\ cm^{-3}$ (more precisely, it is $310\ cm^{-3}$)

Simplication

&

Unification

Spherical Cow Approximation

Simplification

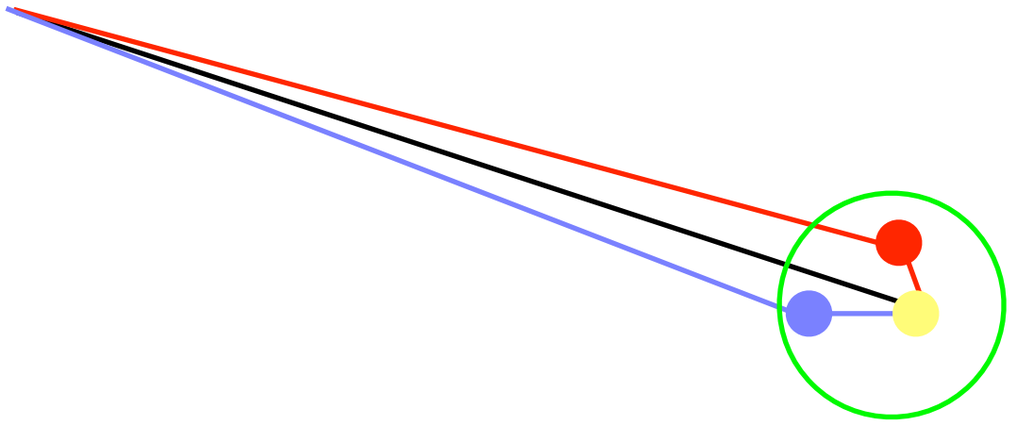
Effective Field Theory

Multipole expansion of electric potential

Legendre Polynomials

$$\Phi(\cos\theta) = \frac{1}{|\,r - r'\,|} = \frac{1}{r}\sum_{l=0}^{\infty} P_l(\cos\theta)(\frac{r'}{r})^l \simeq \frac{1}{r}\left(1 + \mathcal{O}(\frac{r'}{r})\right)$$

$$r' \ll r$$



Questions

&

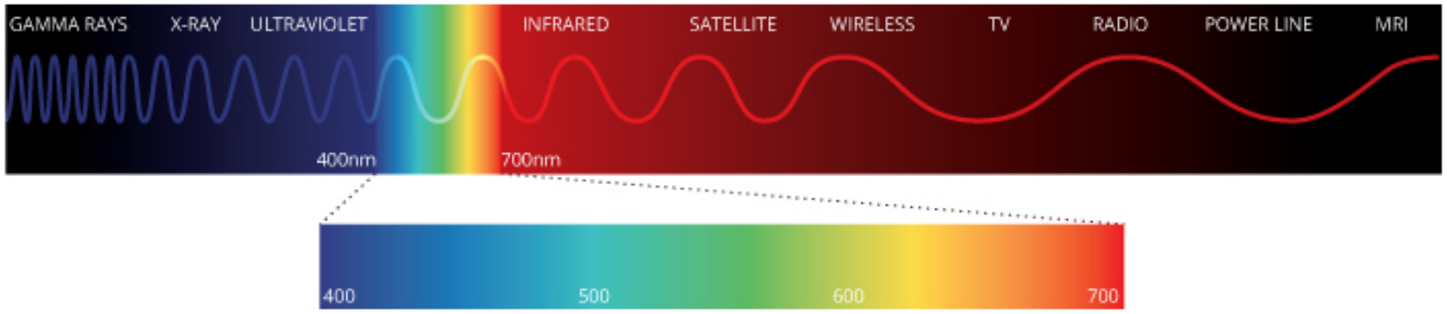
Answers

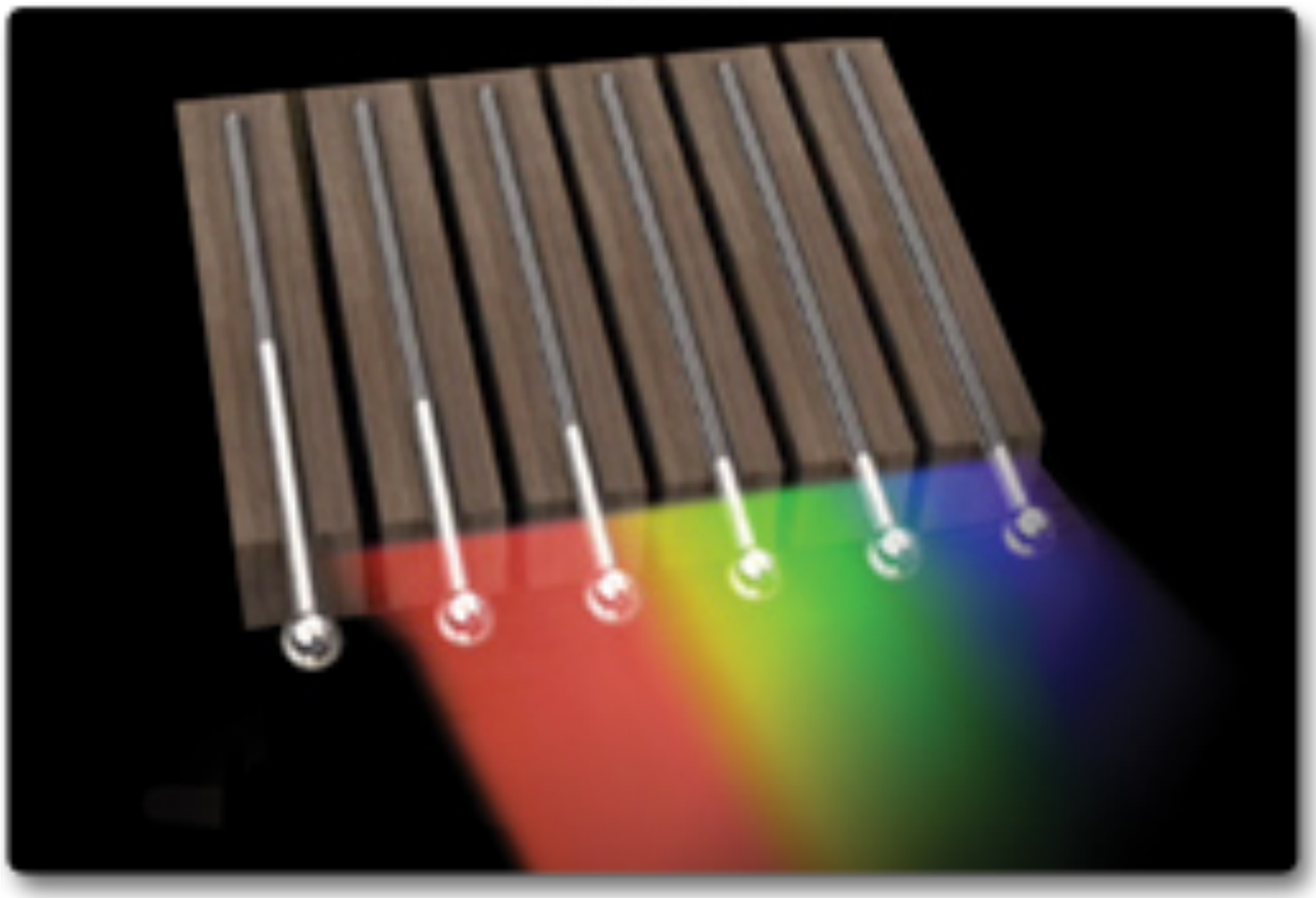
Why do we see visible light?

- Surface temperature of the sun ~ 6,000 K and the sun emits visible lights dominantly

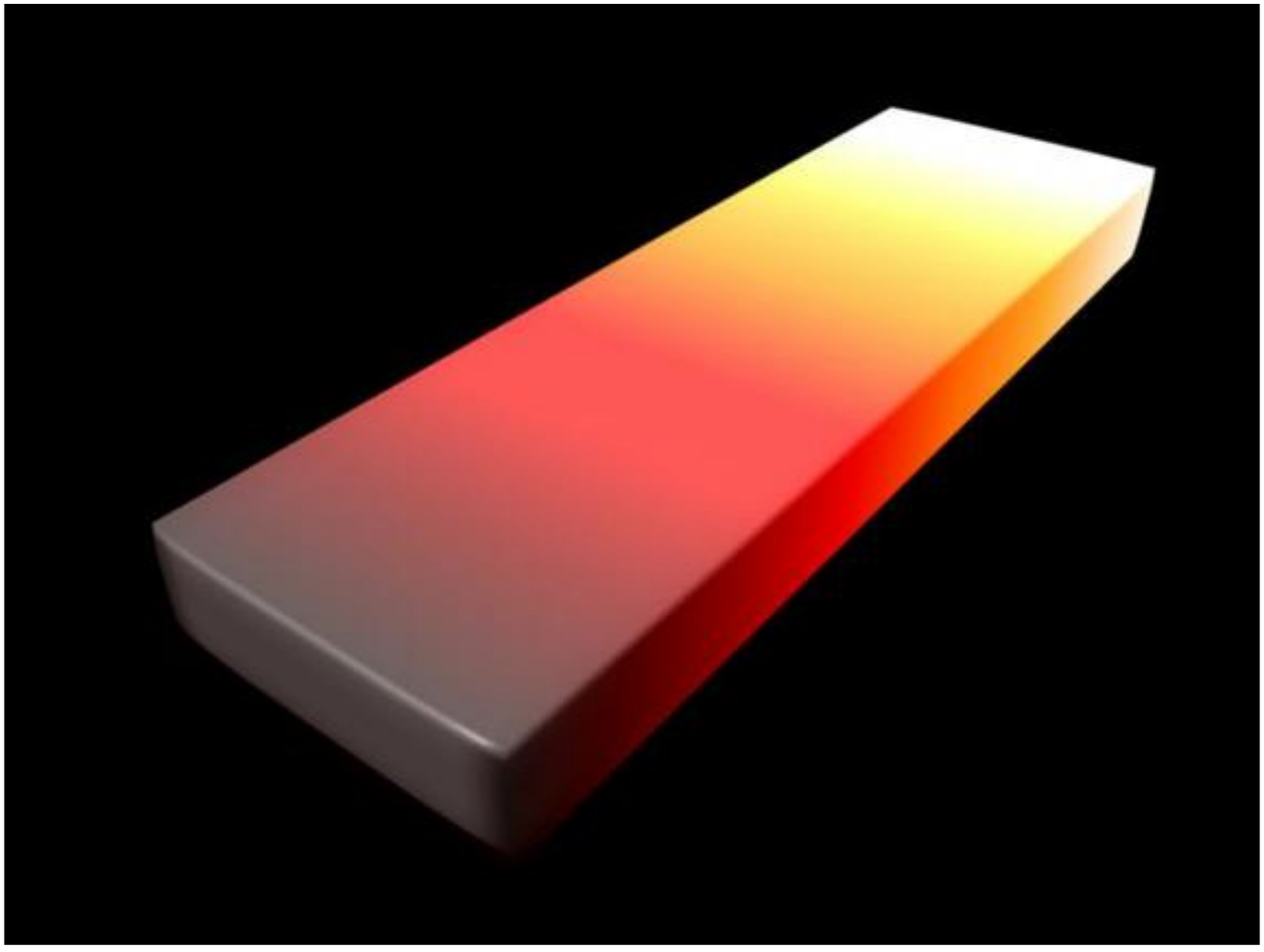
- Life evolving in the solar system would get benefits by detecting the dominant EM fields the sun emits

- How to verify it? Stars with different surface temperatures and the planetary systems with different light detection would do it

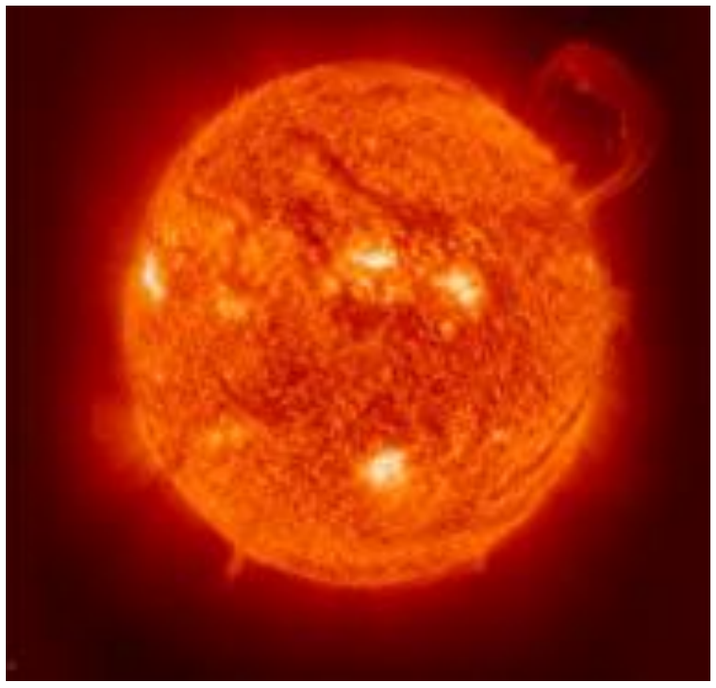

GAMMA RAYS
X-RAY
ULTRAVIOLET
INFRARED
SATELLITE
WIRELESS
TV
RADIO
POWER LINE
MRI
400nm
700nm
400
500
600
700
VISIBLE LIGHT

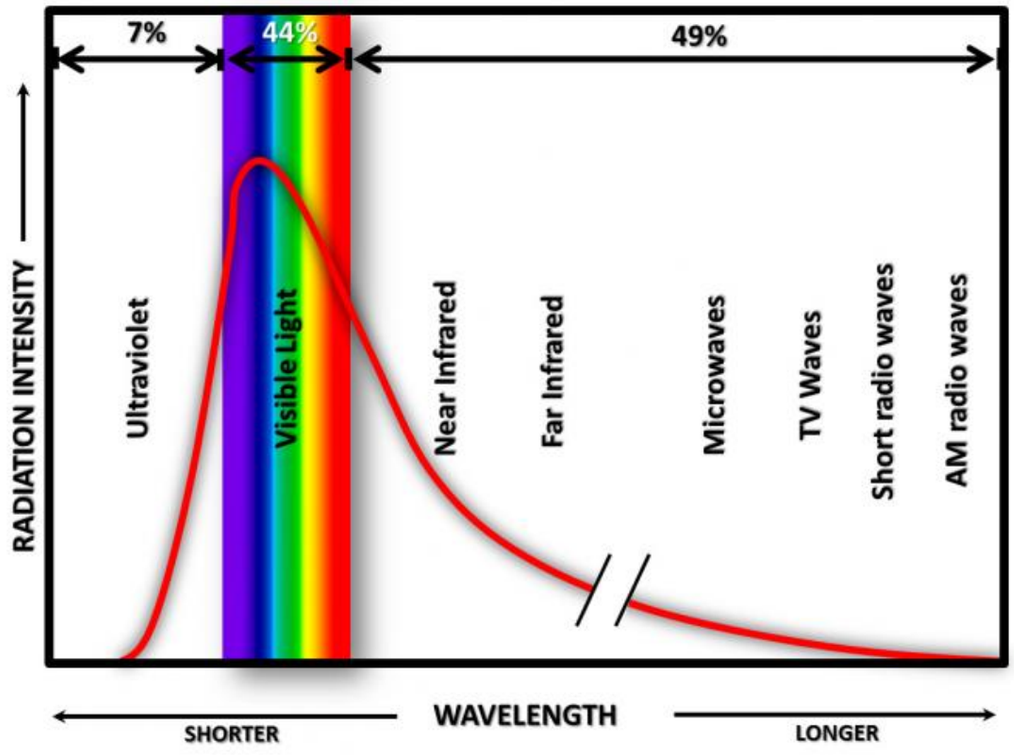


Color Temperature



sun light = visible light?



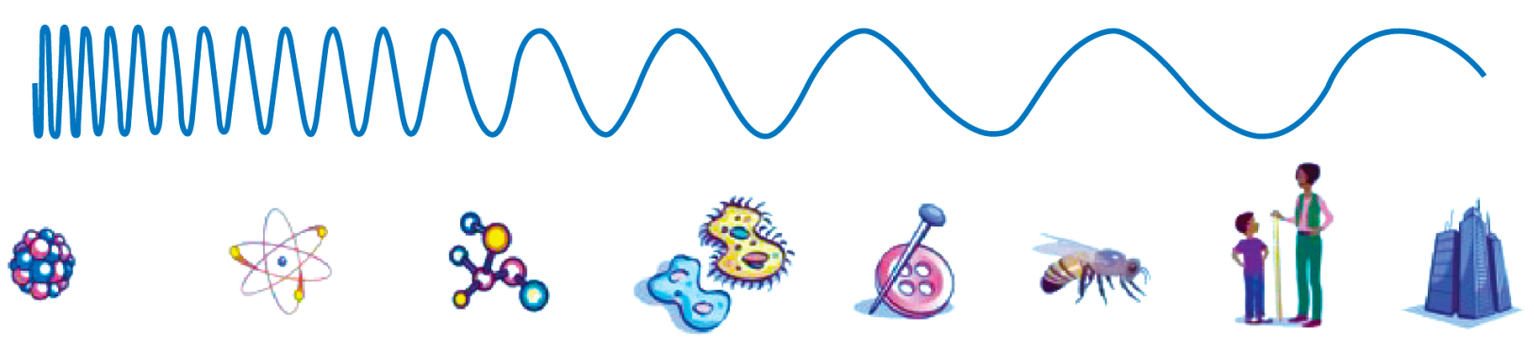


Over the Rainbow

THE ELECTROMAGNETIC SPECTRUM

Penetrate Earth's Atmosphere

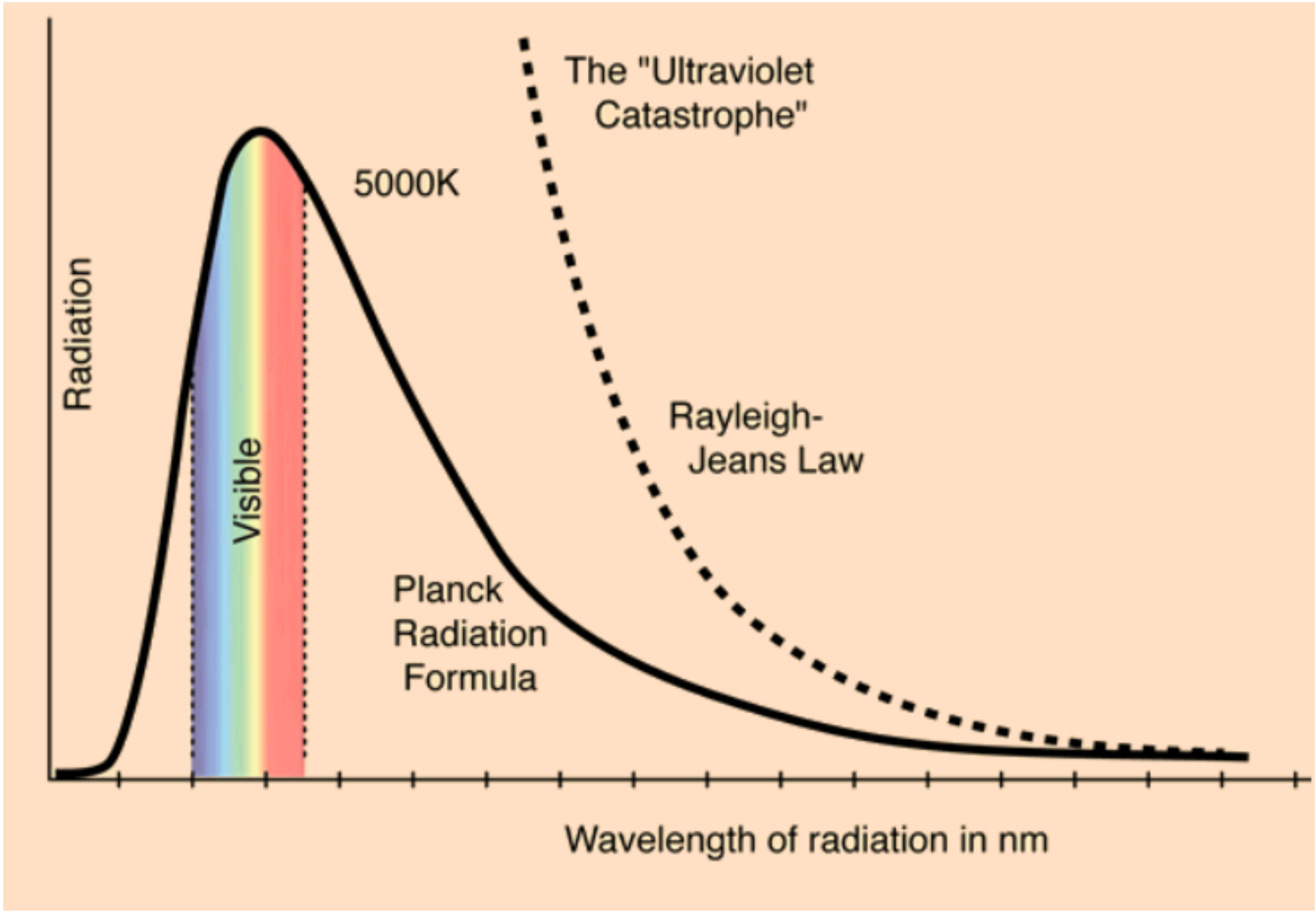
Radiation Type	**Gamma Ray**	**X-ray**	**Ultraviolet**	**Visible**	**Infrared**	**Microwave**	**Radio**
Wavelength (m)	10^{-12}	10^{-10}	10^{-8}	5×10^{-6}	10^{-5}	10^{-1}	10^{3}



Short wavelength
High energy
High frequency

Long wavelength
Low energy
Low frequency

UV Catastrophe:unnatural



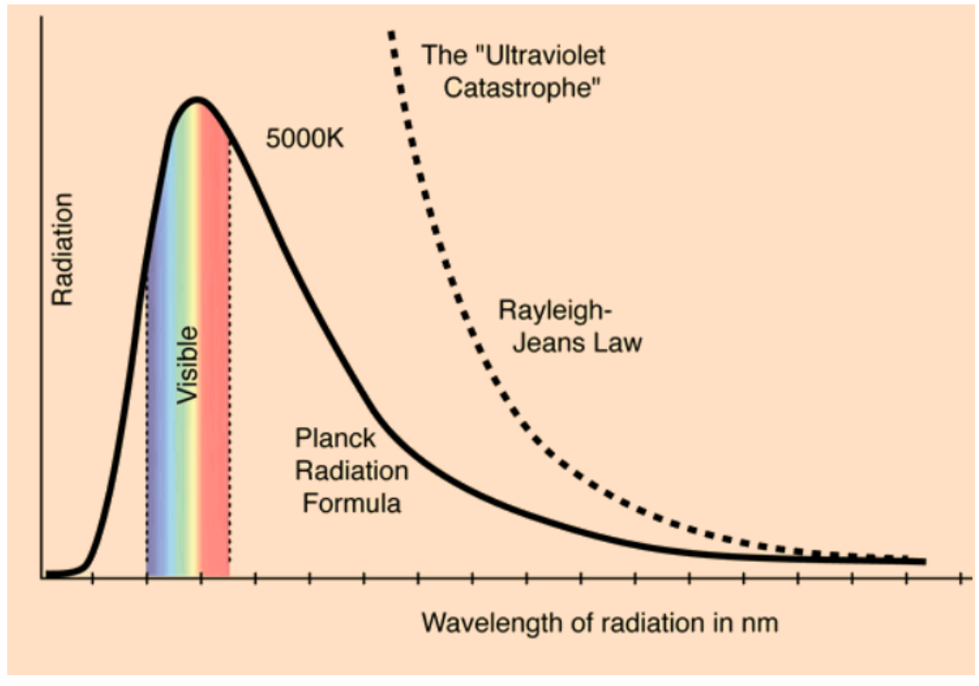
Light Quanta by Planck

$$n_\nu(T) = \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

$$E_\nu = h\nu n_\nu(T) \simeq kT \quad (h\nu \ll kT)$$

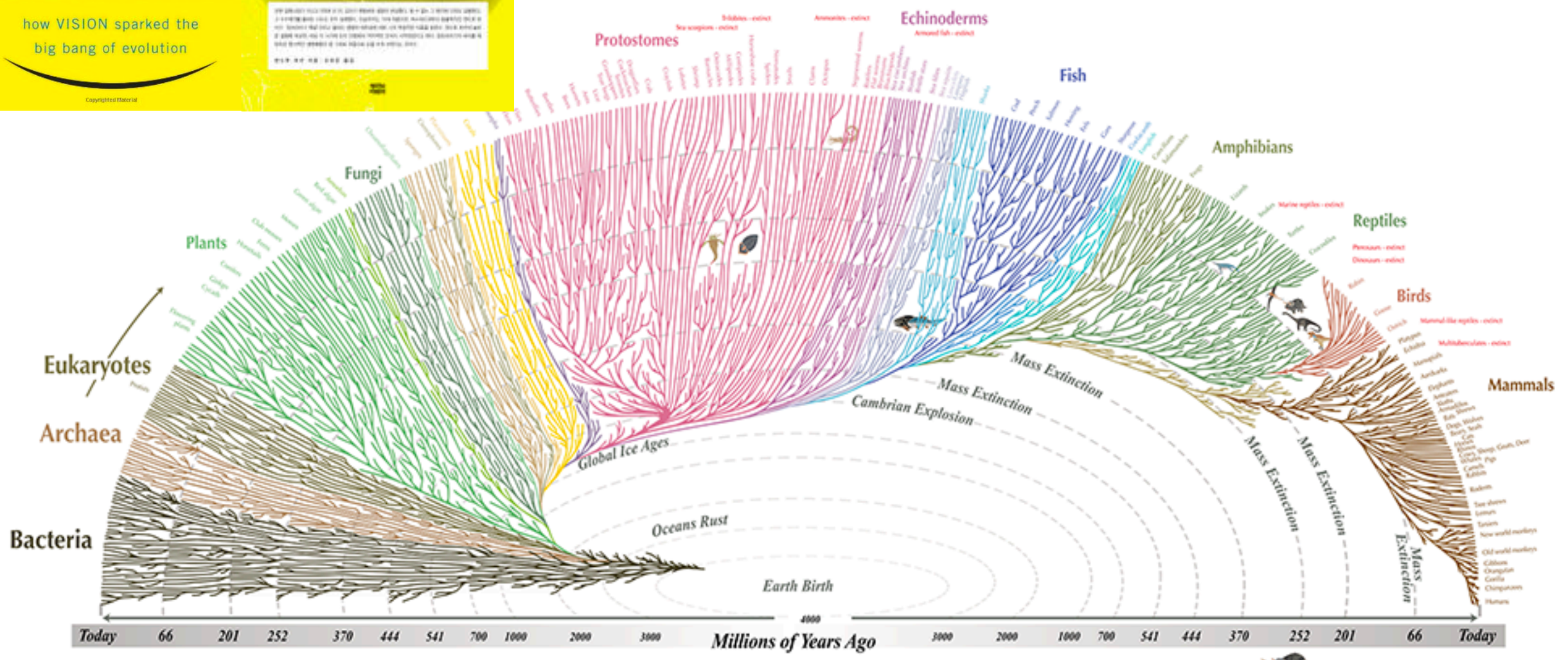
$$E_\nu \simeq h\nu e^{-\frac{h\nu}{kT}} \quad (h\nu \gg kT)$$

Quantum Mechanics



Cambrian Explosion

4 billion years vs 0.5 billion years
Pre-cambrian vs Cambrian explosion



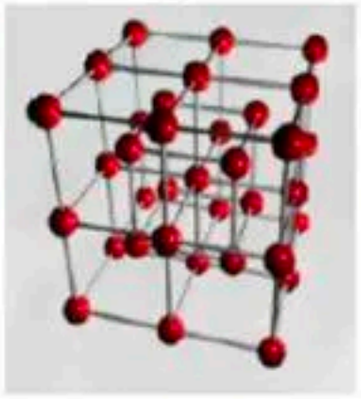
Nuclear scale

MAGDALENA KOWALSKA / CERN / ISOLDE TEAM

Matter

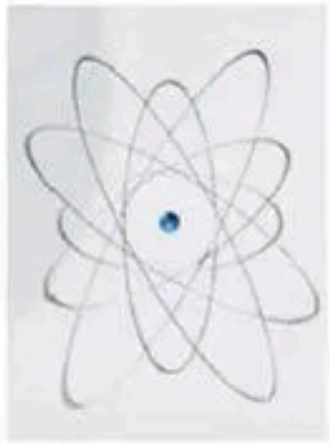
Macroscopic

Crystal



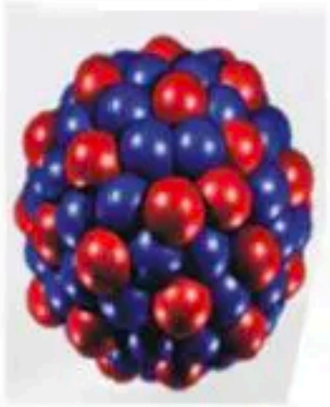
10^{-9} m

Atom



10^{-10} m

Atomic nucleus



10^{-14} m

Nucleon

10^{-15} m

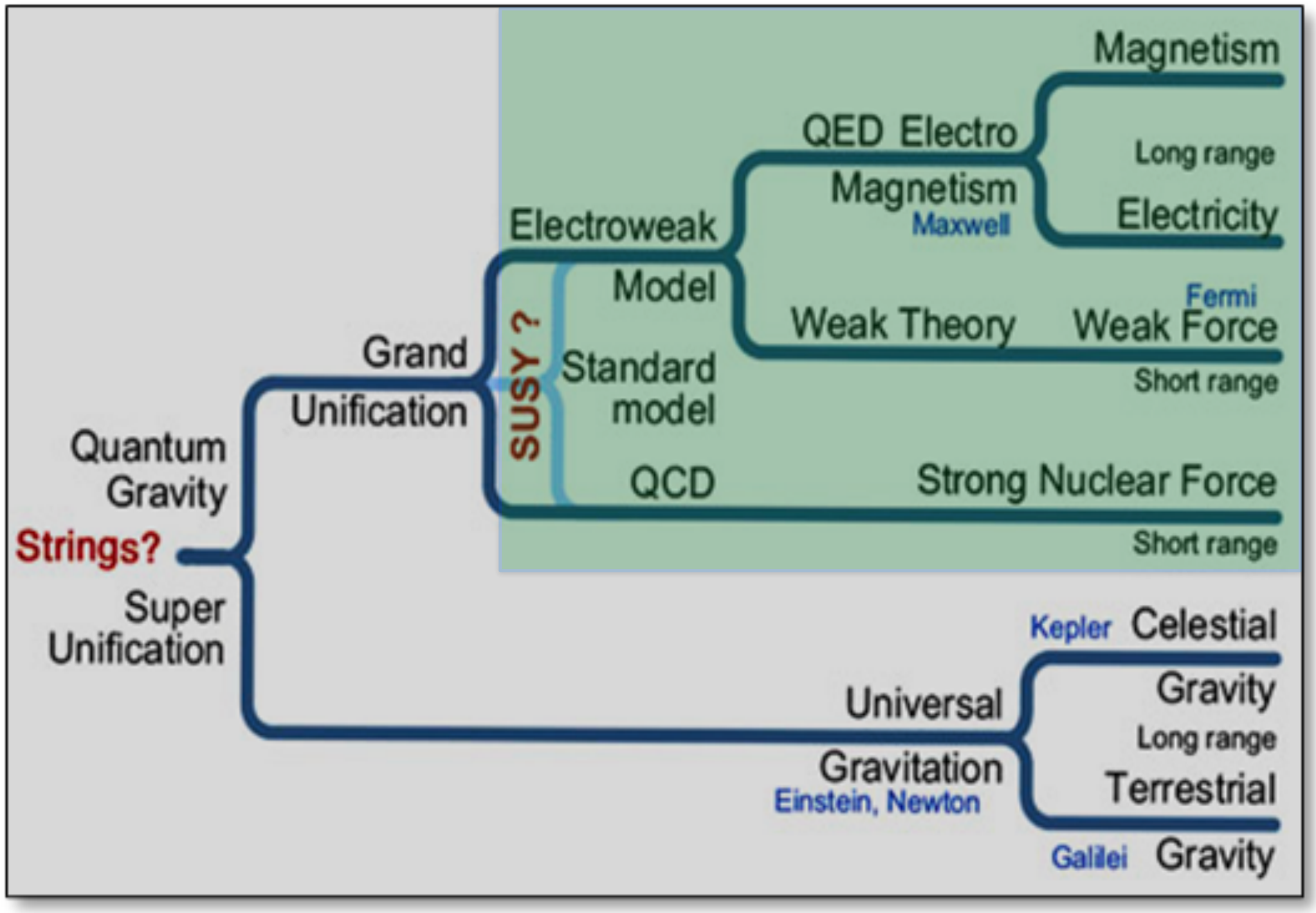
Quark

$< 10^{-18}$ m

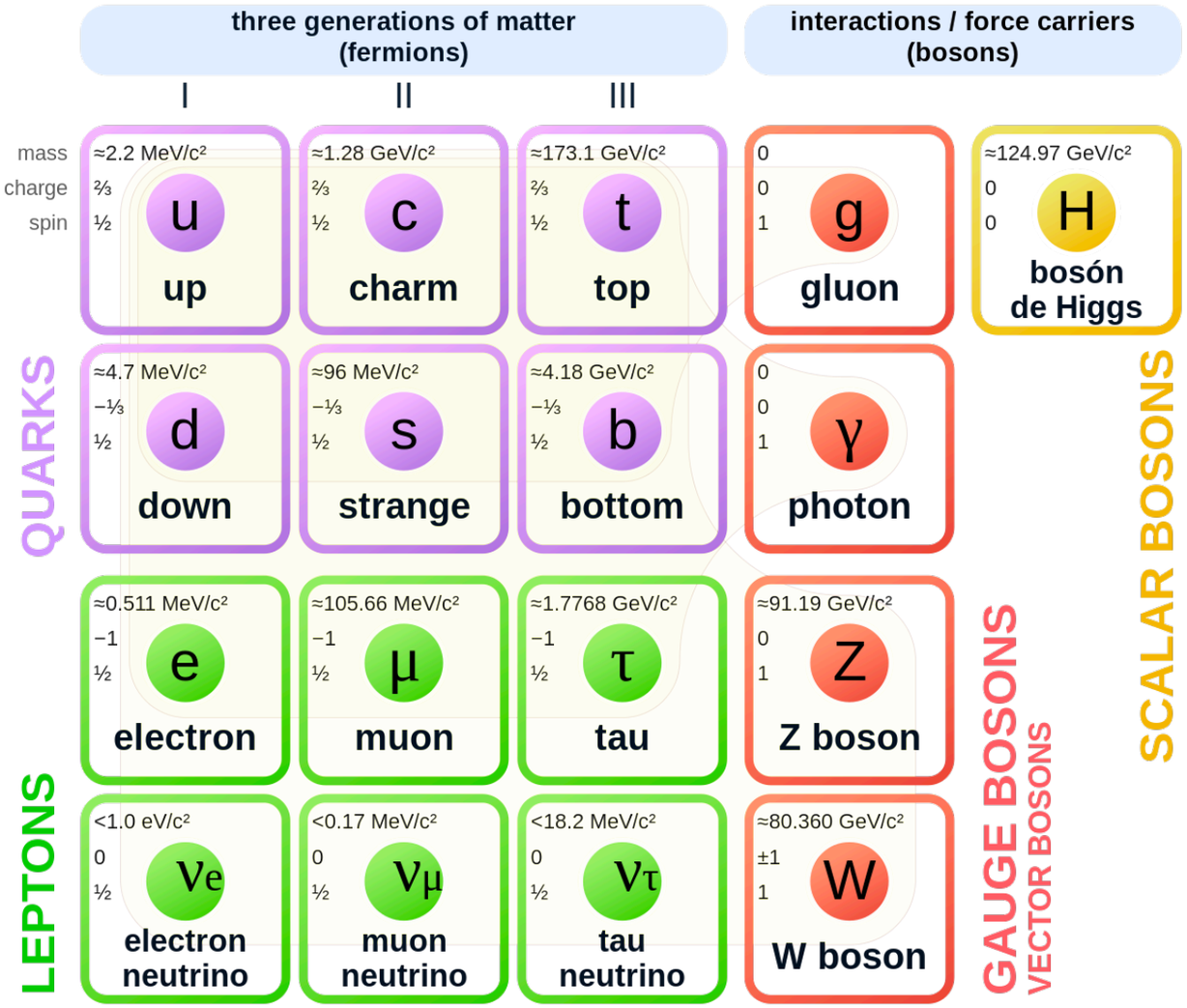
Nuclear physics:
studies the properties of nuclei and
the interactions inside and between them

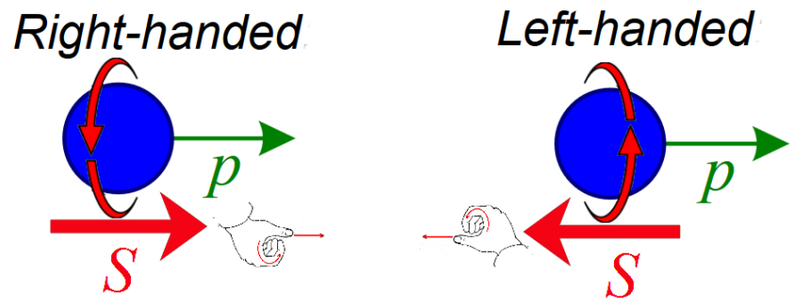
Standard Model

The Standard Model

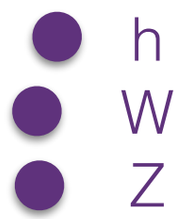


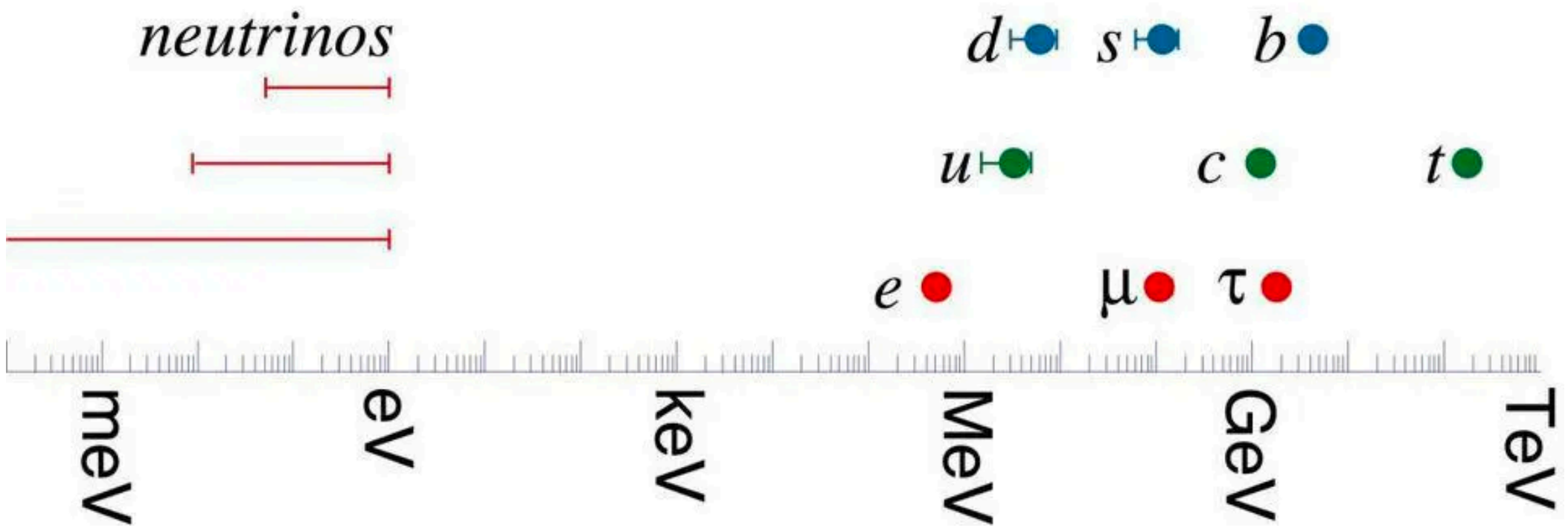
Standard Model of Elementary Particles





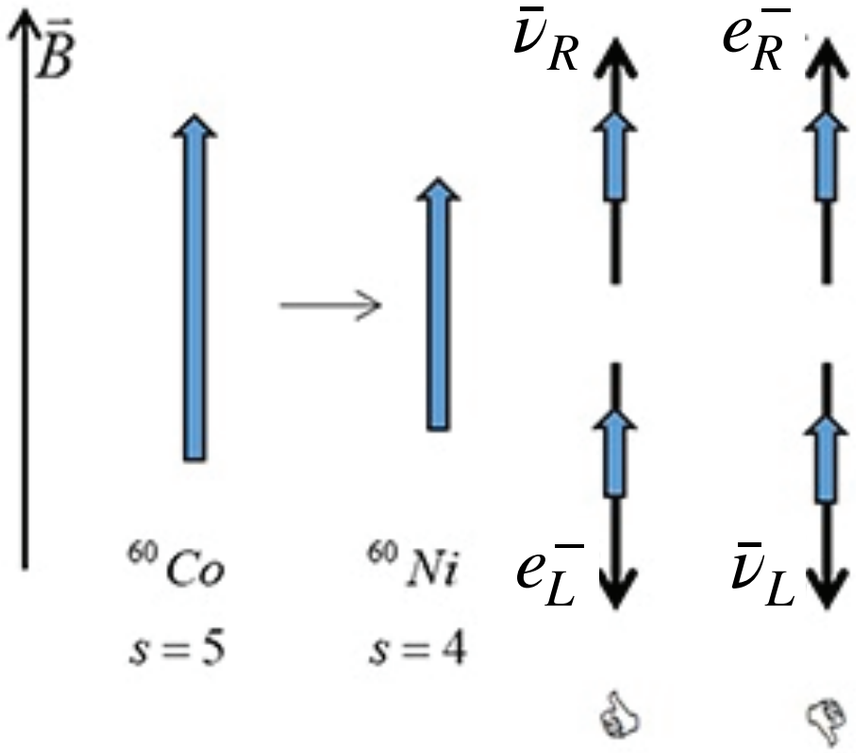
Fermions in chiral rep. are massless



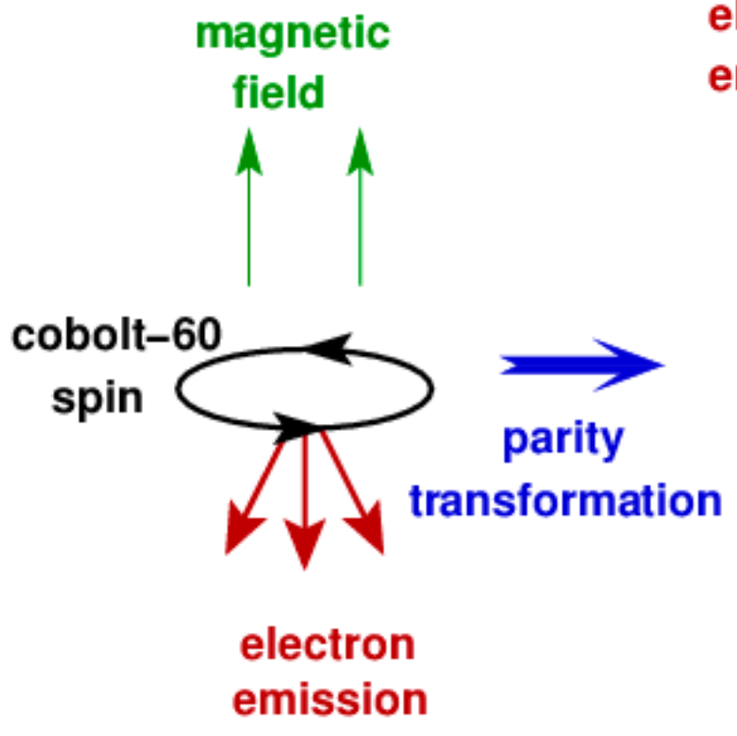


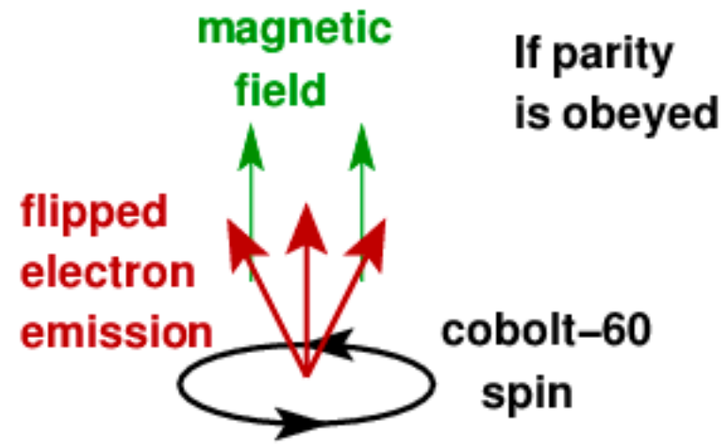
Parity violation of weak interaction

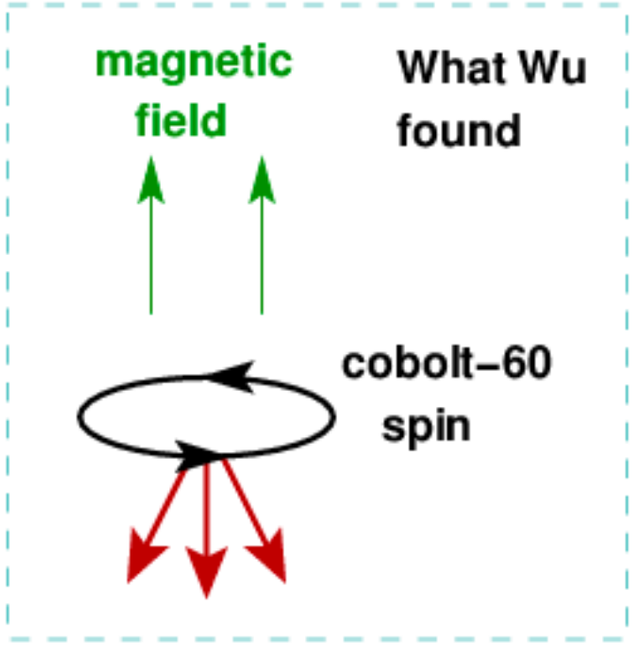
C.S.Wu(1956)



$$Co^{60} \rightarrow Ni^{60} + e^- + \bar{\nu}_e$$







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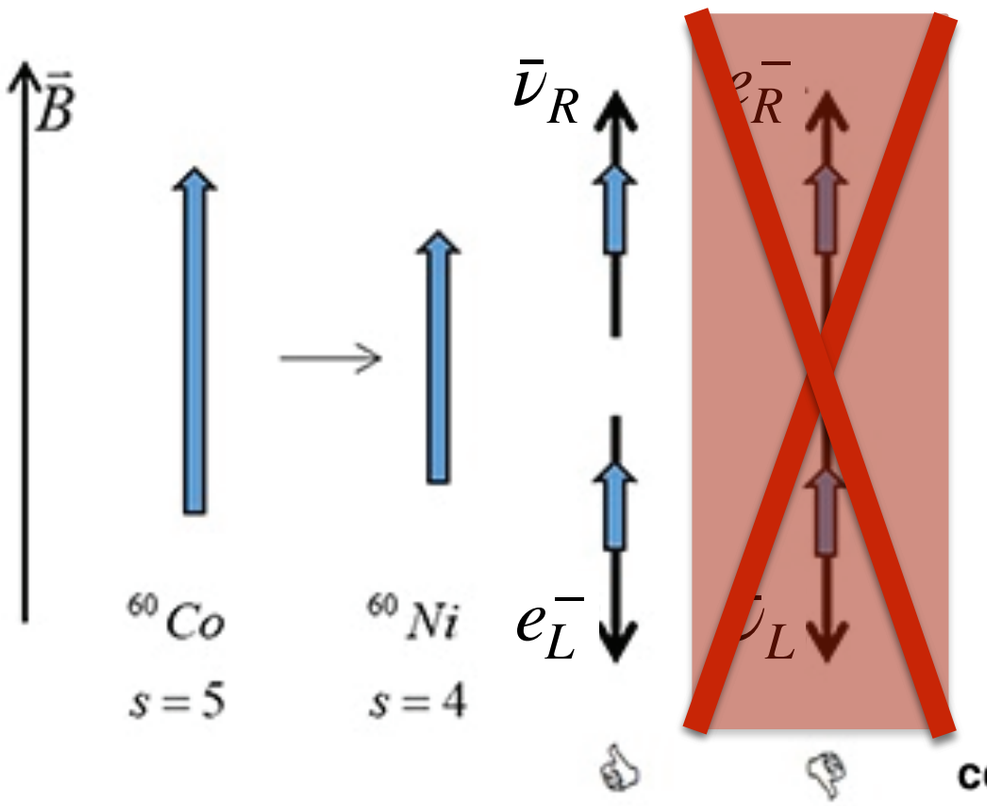

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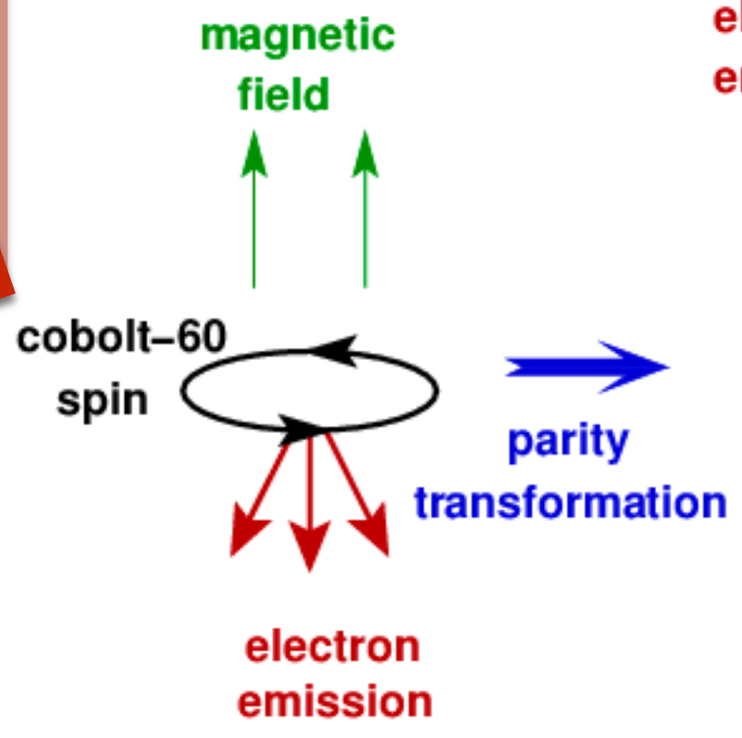

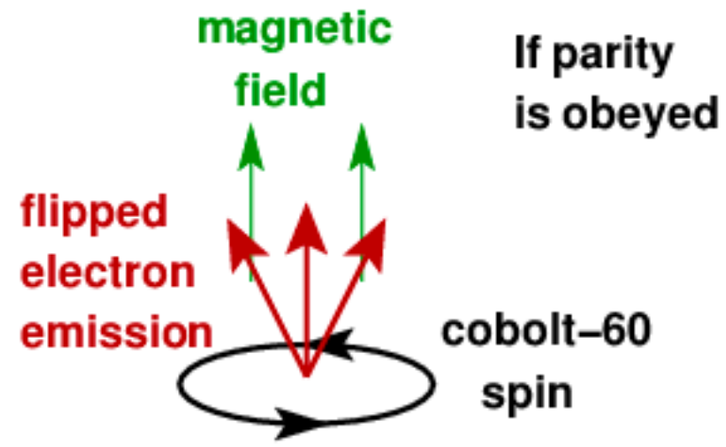

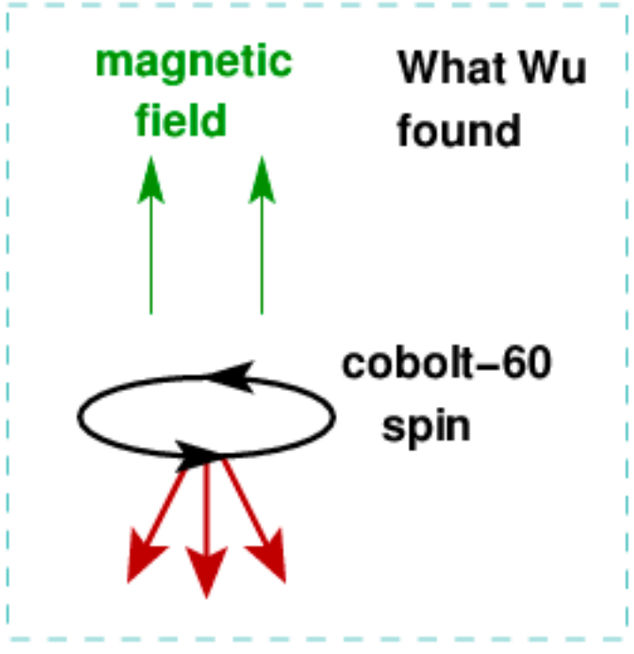

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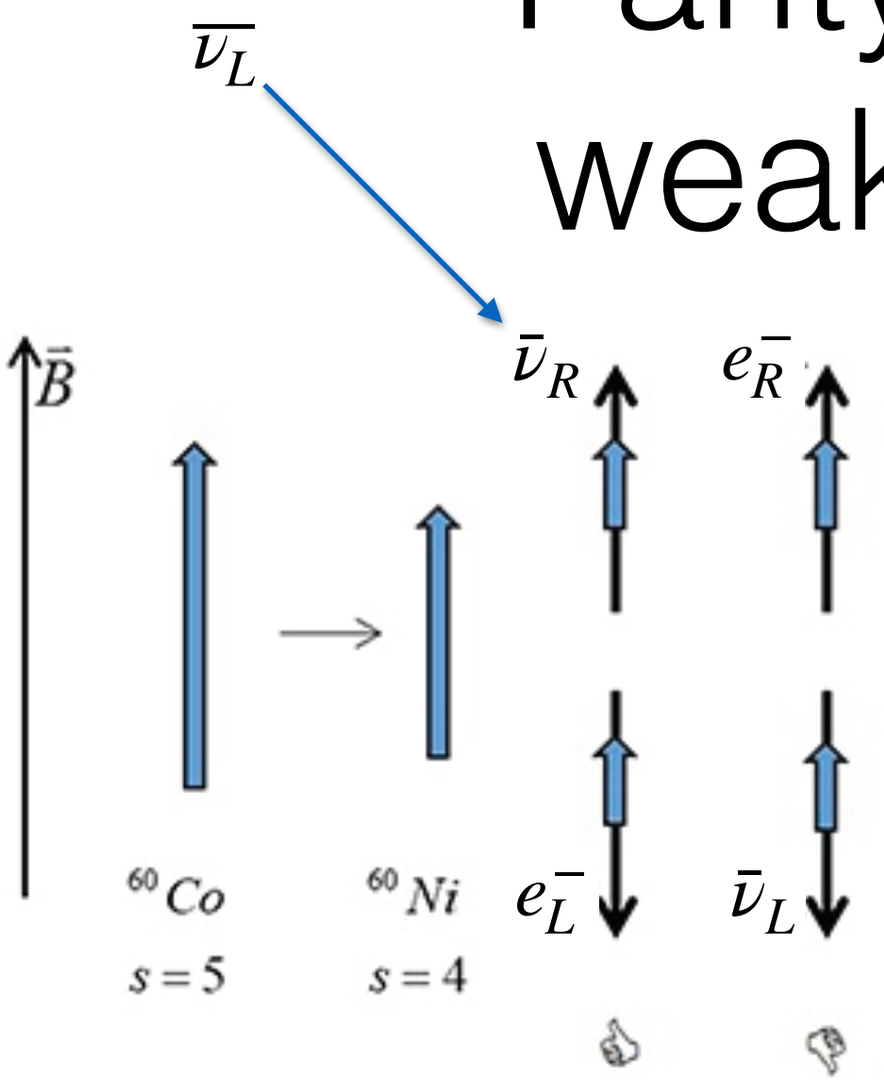


$$\mathrm{Co}^{60} \rightarrow \mathrm{Ni}^{60} + e^- + \bar{\nu}_e$$

$$\nu_L \xleftrightarrow{\text{CPT}} \overline{(\nu_L)} = (\bar{\nu})_R$$

$$\nu_R \longleftrightarrow \overline{(\nu_R)} = (\bar{\nu})_L$$

$$e_L^- \longleftrightarrow \overline{(e_L^-)} = (e^+)_R$$

$$e_R^- \longleftrightarrow \overline{(e_R^-)} = (e^+)_L$$

No right-handed neutrino!
(no flip for the massless neutrino)

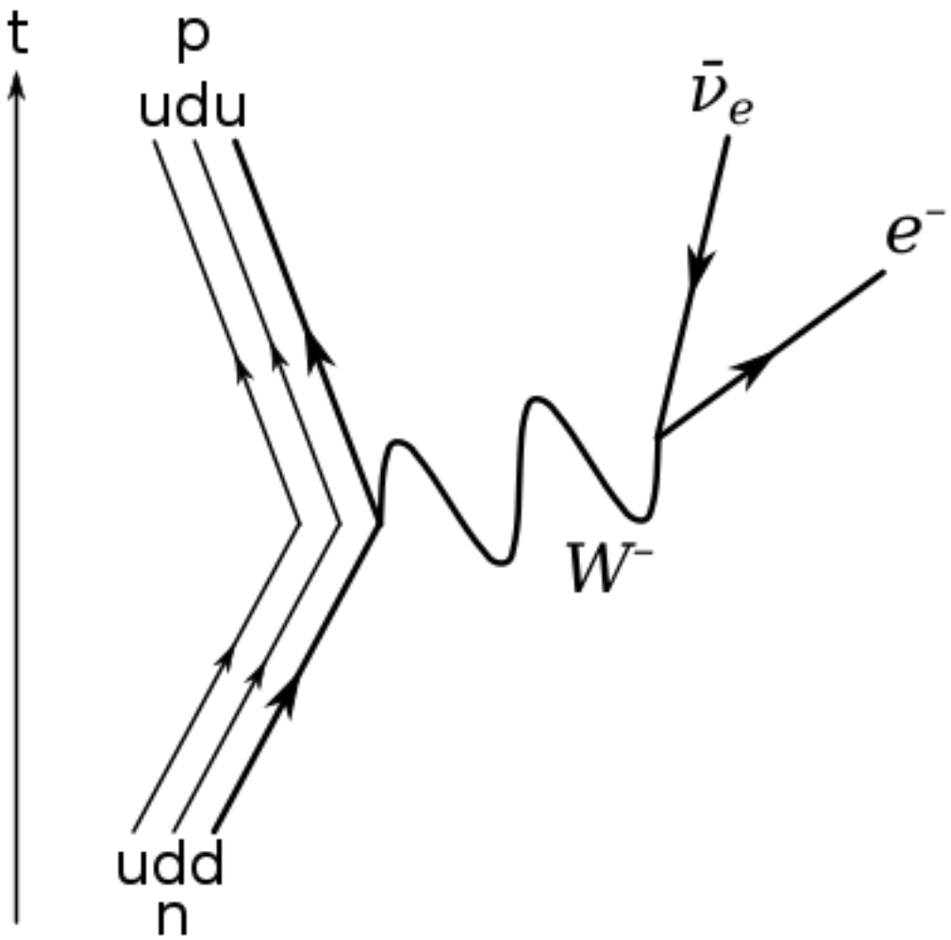
Weak interaction

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \qquad \begin{matrix} u_R \\ d_R \end{matrix}$$

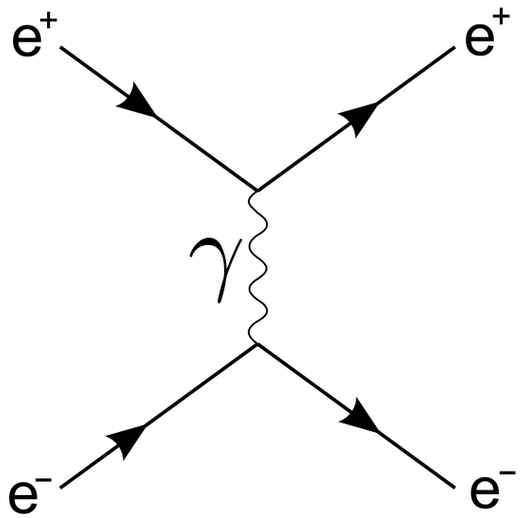
$$L_L = \begin{pmatrix} \nu \\ e^- \end{pmatrix}_L \qquad \overline{e_R}$$

Mass term is forbidden

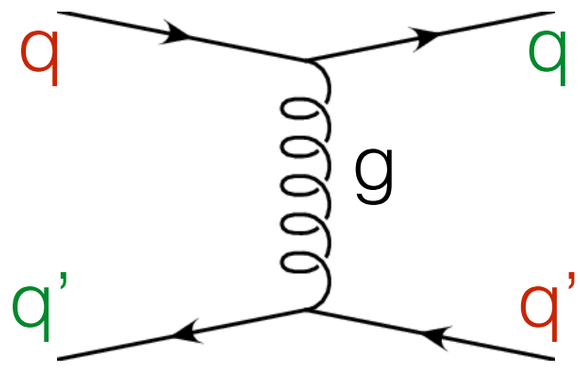
$$\cancel{Q_L \overline{u_R}}$$



electromagnetic interaction



strong interaction



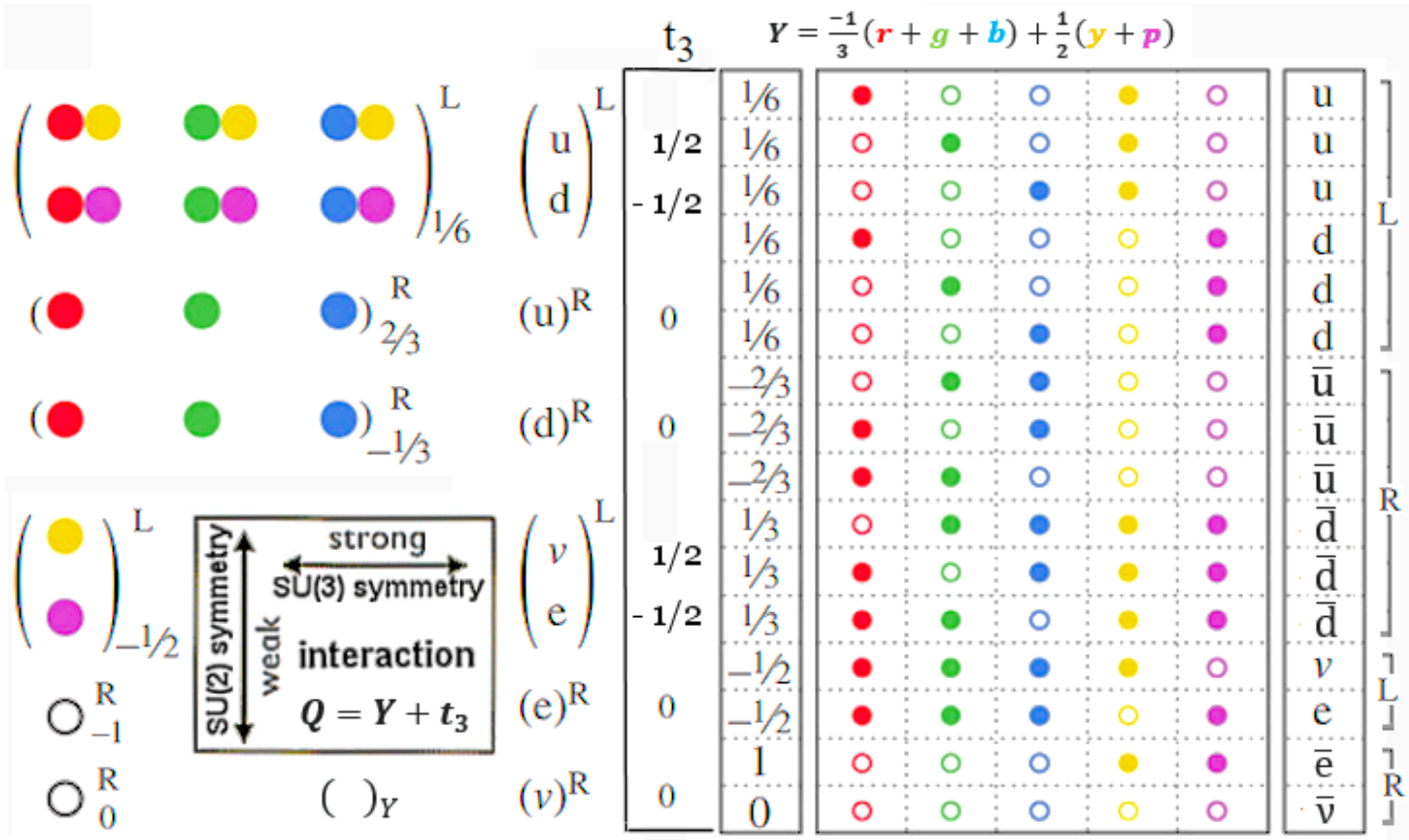
Grand Unified Theory

The Standard Model in SU(5)

$$10 = \begin{bmatrix} 0 & u_3^c & -u_2^c & -u_1 & -d_1 \\ -u_3^c & 0 & u_1^c & -u_2^c & -d_2 \\ u_2^c & -u_1^c & 0 & -u_3 & -d_3 \\ u_1 & u_2 & u_3 & 0 & -e^c \\ d_1 & d_2 & d_3 & e^c & 0 \end{bmatrix} \qquad (Q, u^c, e^c)$$

$$\bar{5} = \begin{bmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e \\ -\nu_e \end{bmatrix} \qquad (d^c, L)$$

The Standard Model in SO(10)



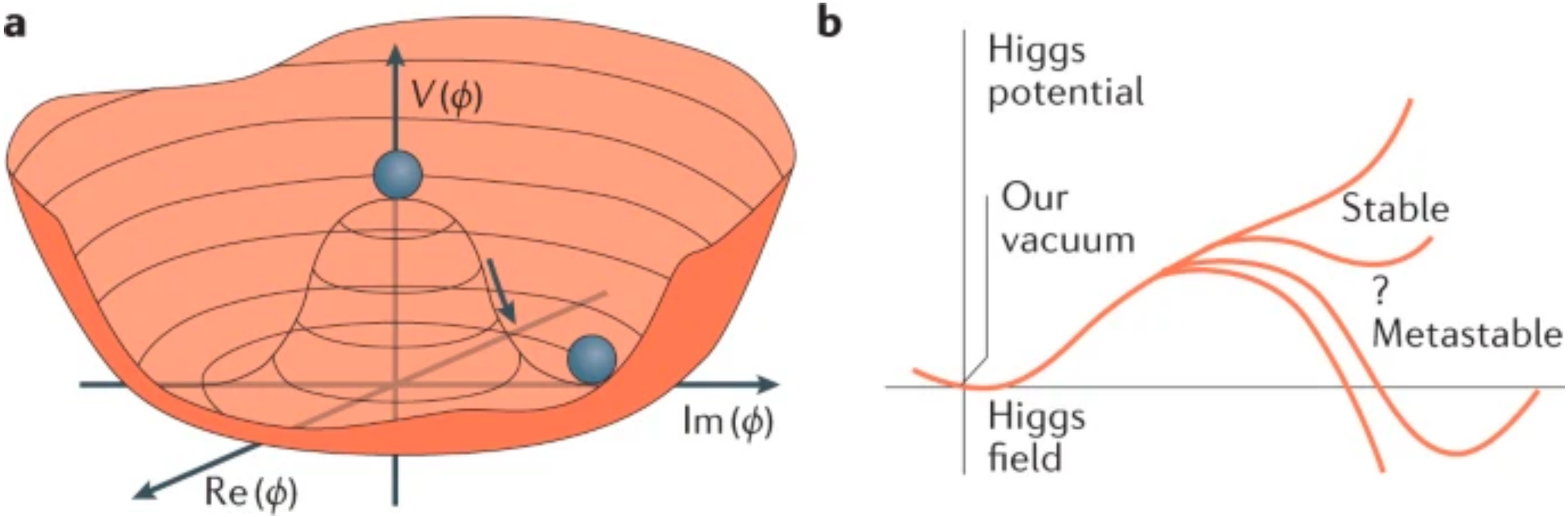
(a) 5 Colored Charges of SO(10) (b) 16 Fermions in SO(10)

Higgs Mechanism

Higgs mechanism

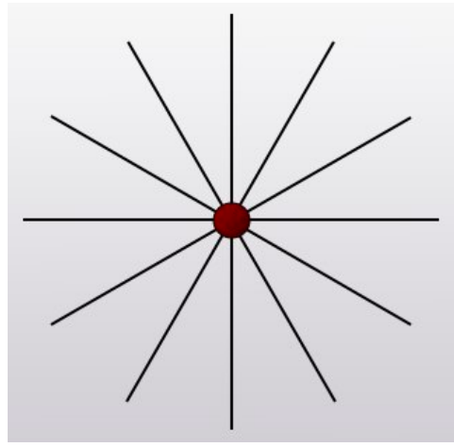
$$D_\mu = \frac{\partial}{\partial x^\mu} + igA_\mu$$

$$D_\mu \phi D^\mu \phi \rightarrow g^2 \langle \phi \rangle^2 A_\mu A^\mu$$



Higgs mechanism

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4 \qquad \mathscr{L} = y_f \Psi_L \phi \bar{\Psi}_R + c\,.\,c\,.$$

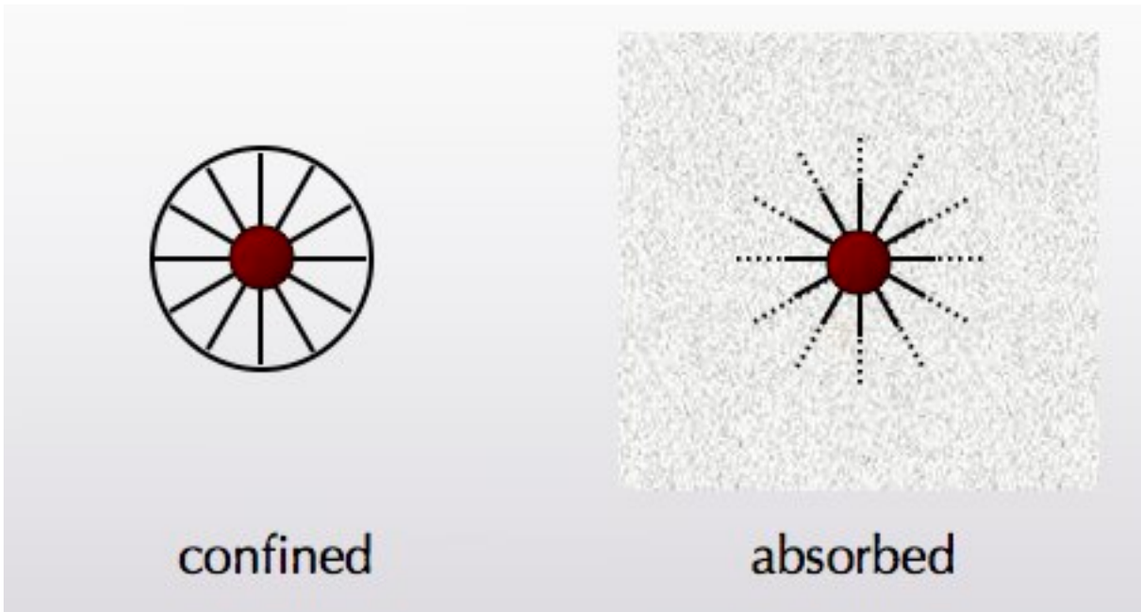


When $\mu^2 < 0$ the potential has a minimum at: $|\phi| \equiv \frac{v}{\sqrt{2}} = \sqrt{-\frac{\mu^2}{2\lambda}}$

$$D_\rho \phi = [\partial_\rho + \mathrm{i}g\mathbf{A}_\rho]\phi$$

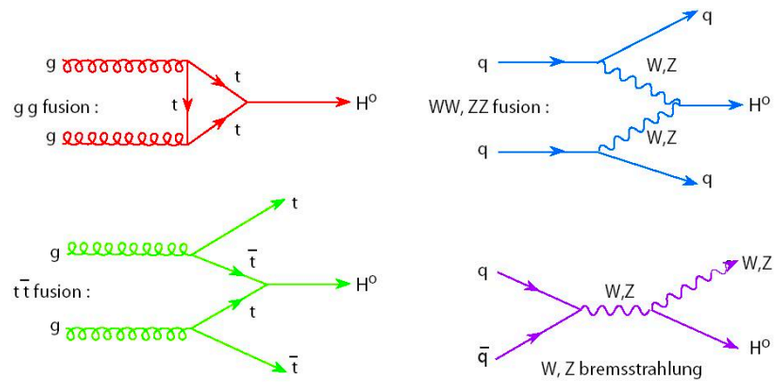
$$m_{\mathrm{W}}^2 = \frac{1}{4}g^2v^2, \quad m_{\mathrm{Z}}^2 = \frac{1}{4}(g^2 + g'^2)v^2,$$

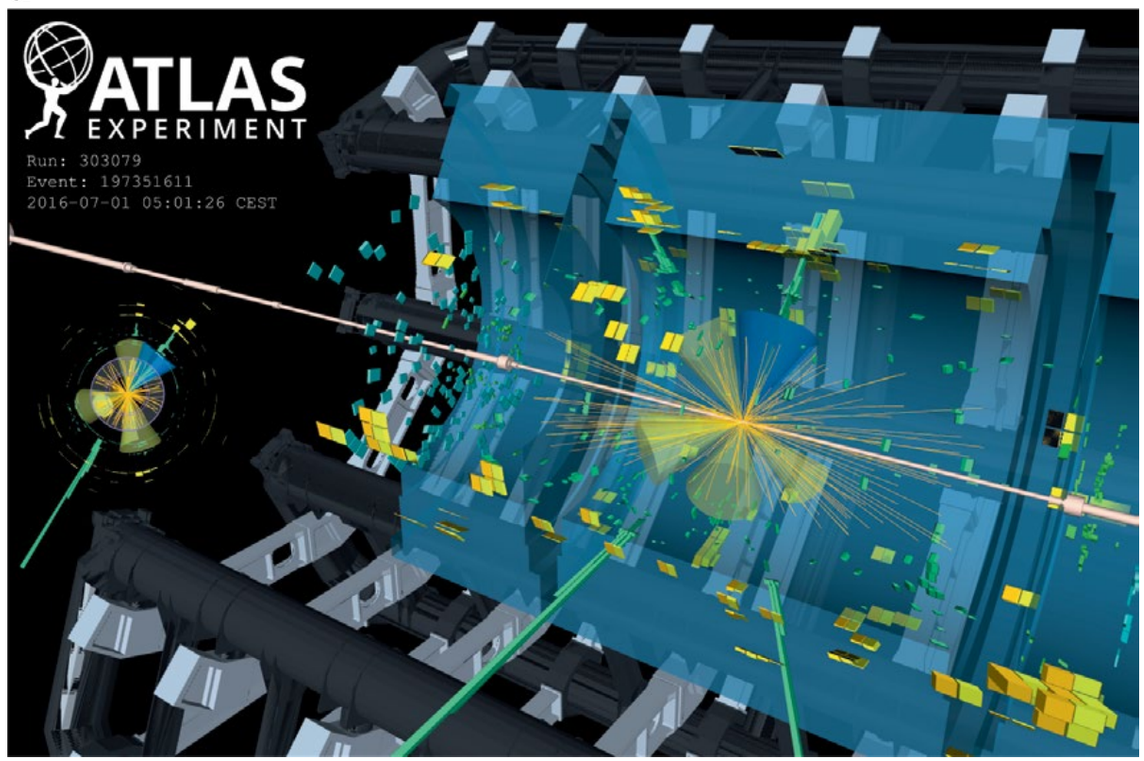
$$m_{\mathrm{f}} = y_{\mathrm{f}}\frac{v}{\sqrt{2}}, \quad m_{\mathrm{H}}^2 = 2\lambda v^2.$$

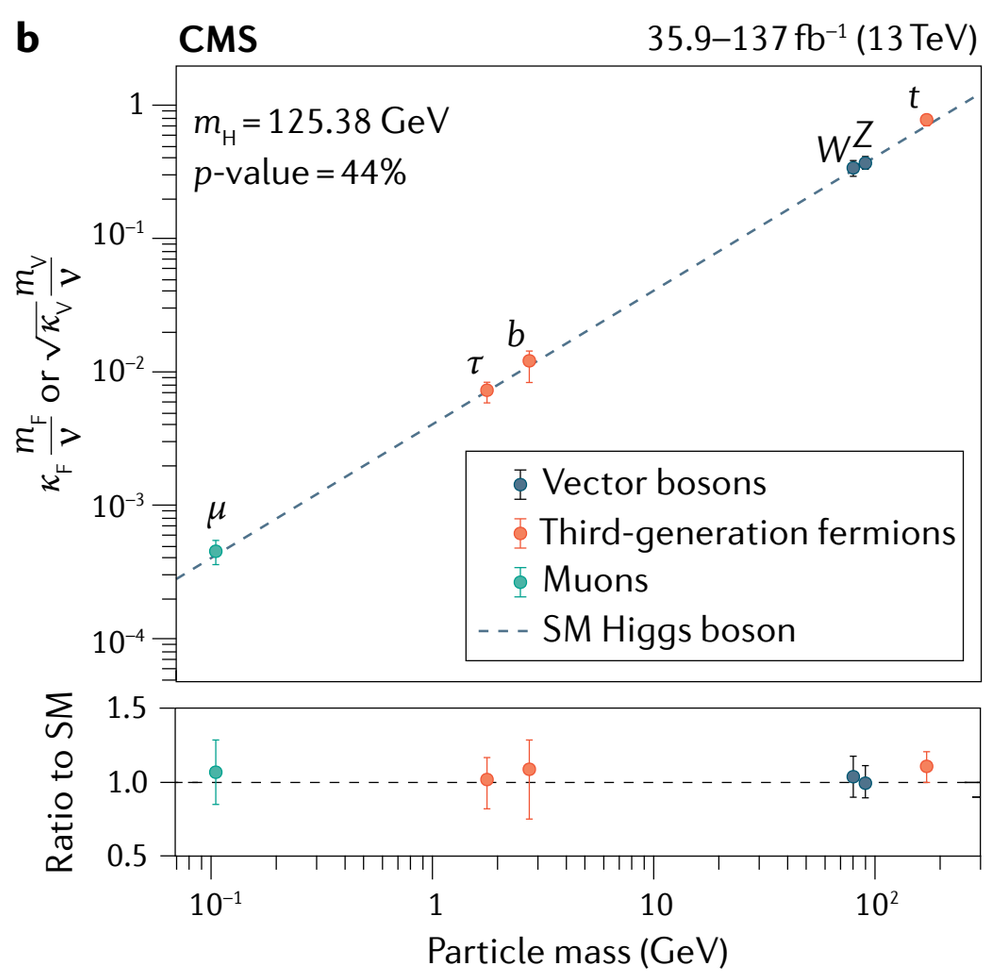


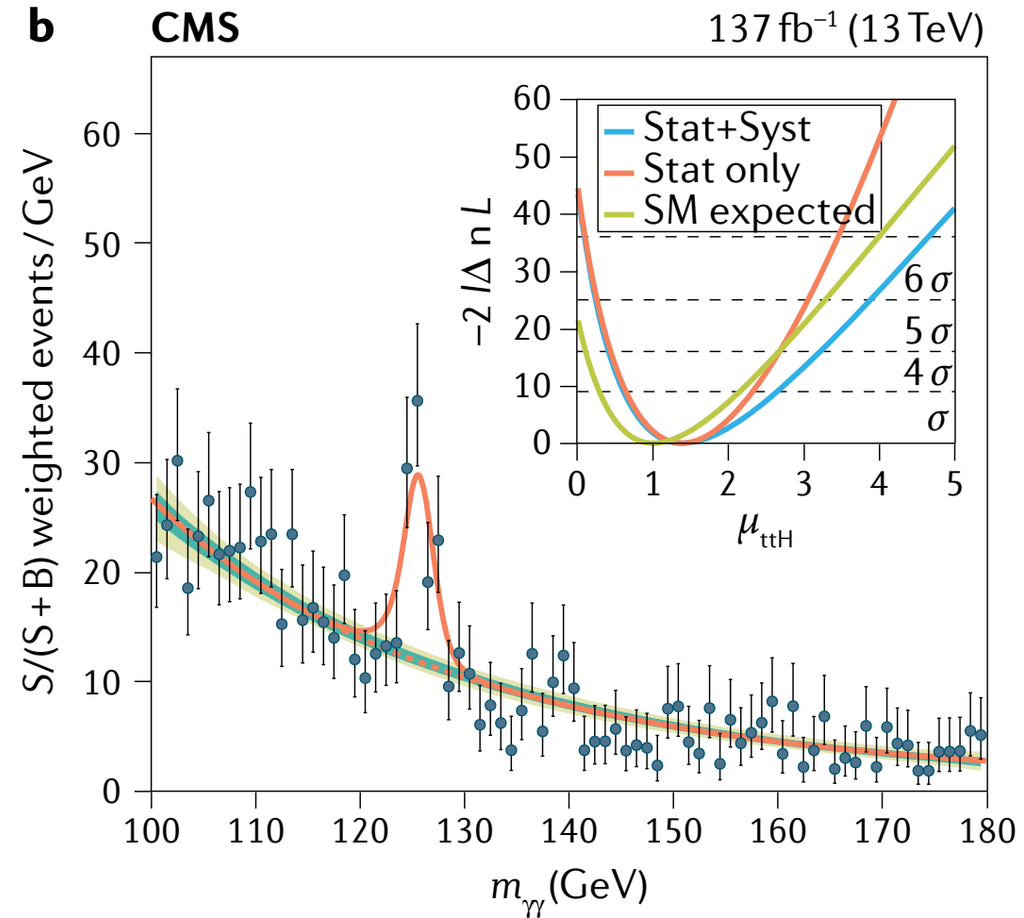
gluons W, Z

Higgs physics

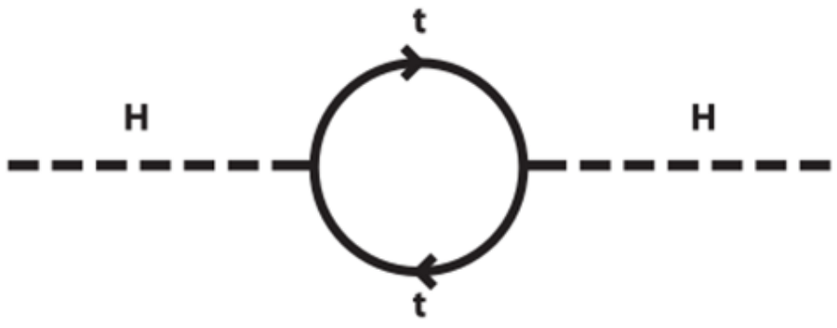








Higgs mechanism



$$\delta m_h^2 = \frac{3m_t^2}{2\pi^2 v^2}\,\Lambda^2 \qquad\qquad m_h^2 = m_{h0}^2 + \delta m_h^2$$

It is unnatural to have $m_h^2 \ll \Lambda^2$

It implies new effective theory at TeV scale

supersymmetry, composite Higgs, technicolor, etc.

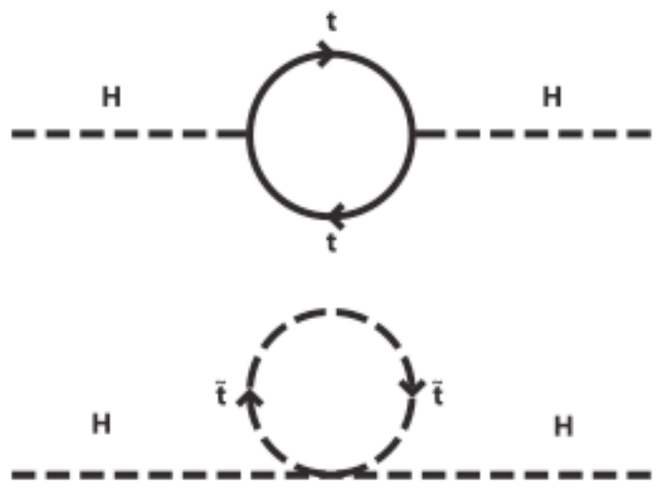
Why gravity is so weak compared to the others?

$$F_{\text{Gravity}} = G_N \frac{m^2}{r^2} \qquad F_{\text{Coulomb}} = k \frac{q^2}{r^2}$$

For the electron,

$$\frac{F_{\text{Gravity}}}{F_{\text{Coulomb}}} = \frac{G_N m_e^2}{k q_e^2} \sim 10^{-48}$$

Why is Higgs so light?

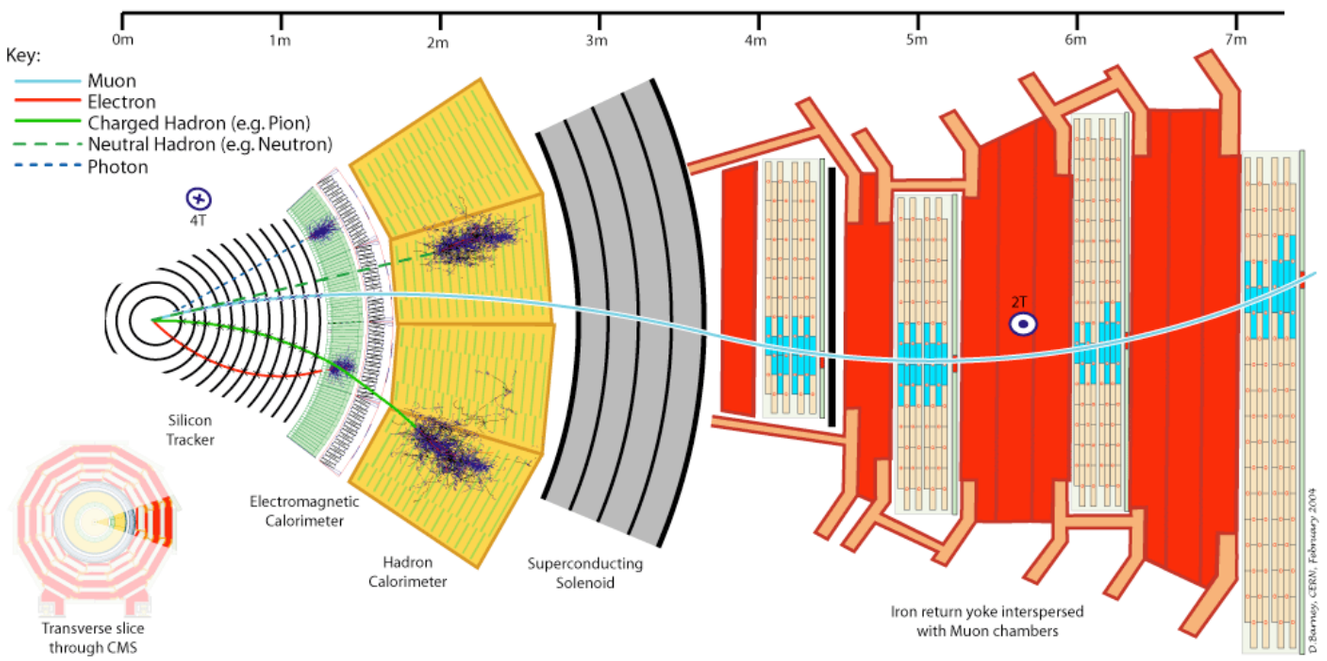


Large Hadron Collider

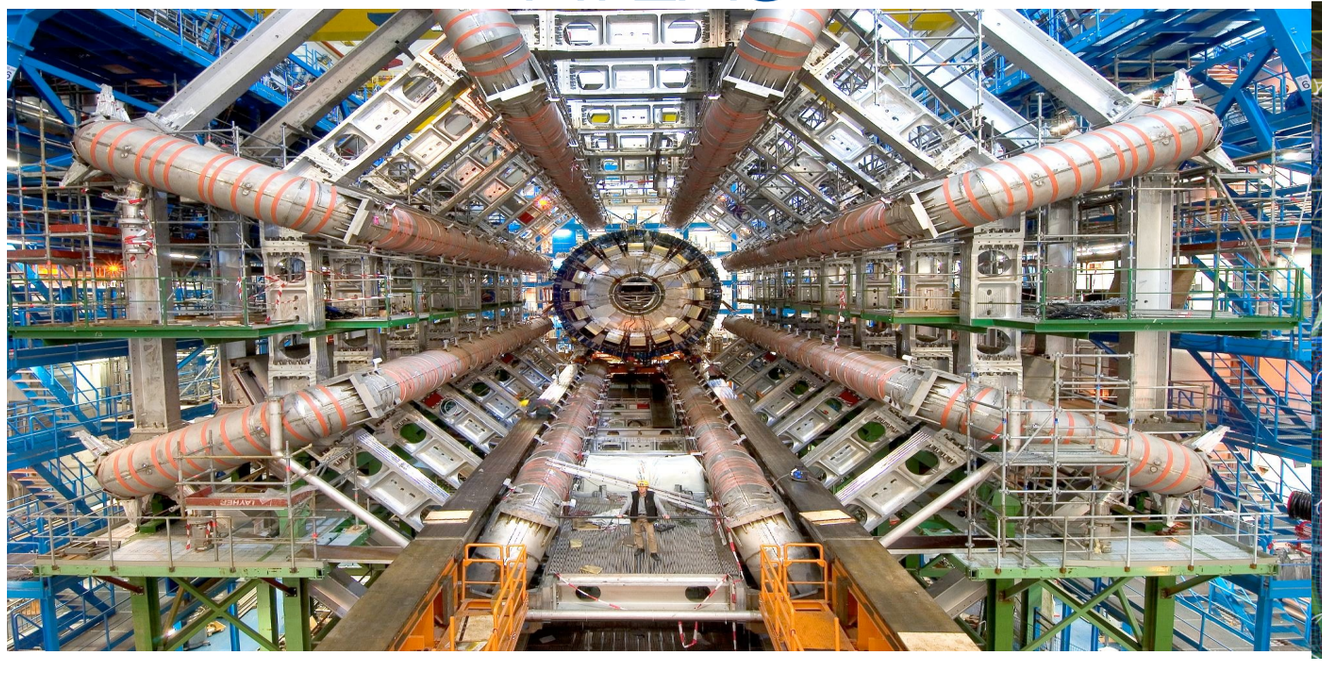
Higgs discovery machine :
Large Hadron Collider

CERN at Geneva, Swiss
27km, 100m deep, 14 TeV
~1983, first collision at 2010
Higgs discovery at 2012

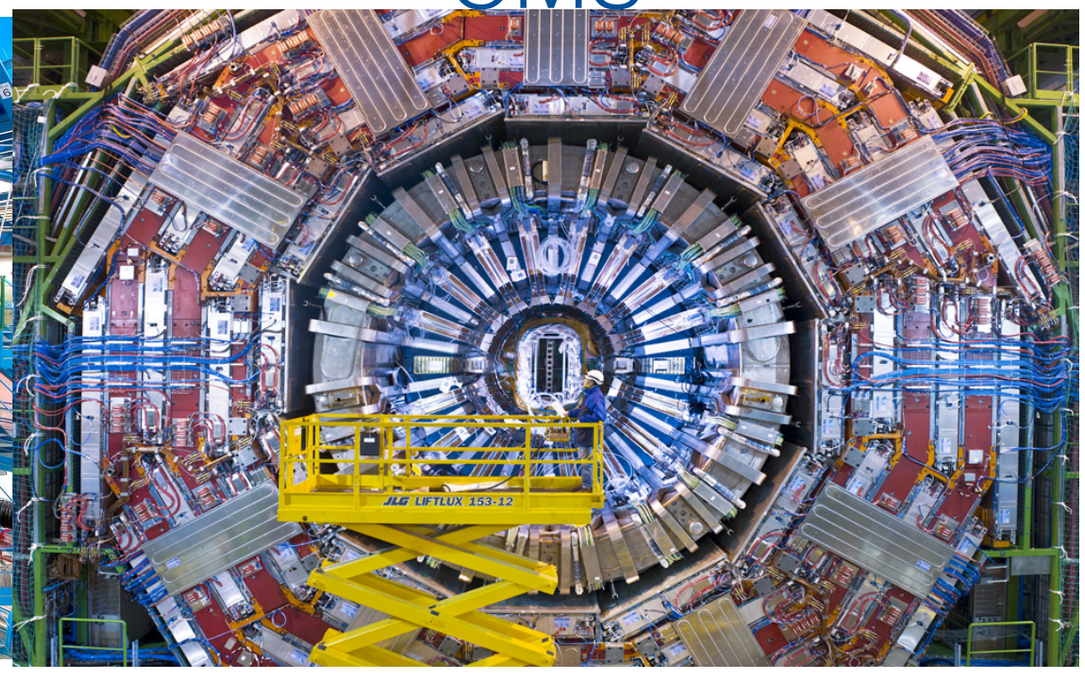
Large Hadron Collider

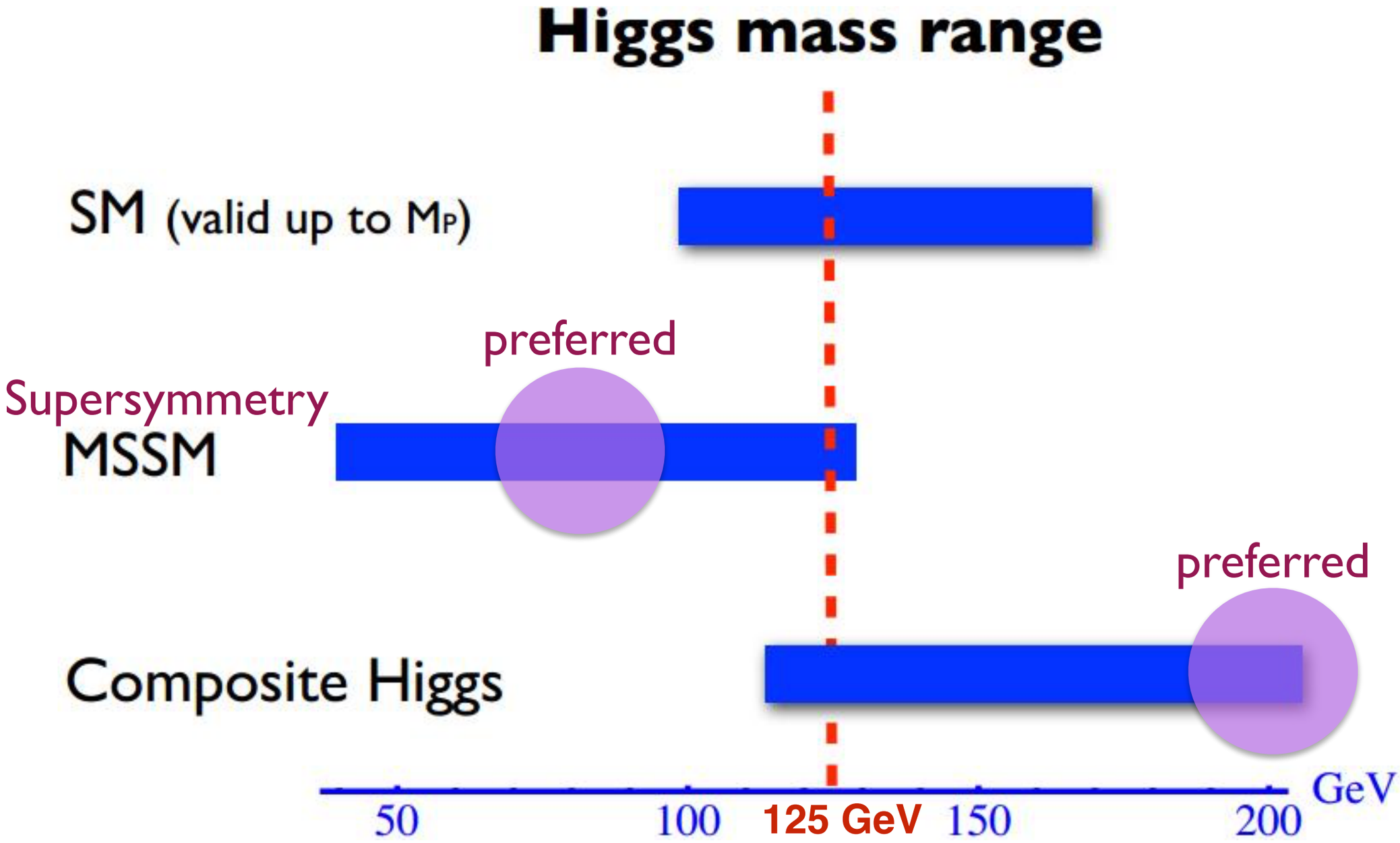


ATLAS



CMS





From the talk of Alex Pomarol

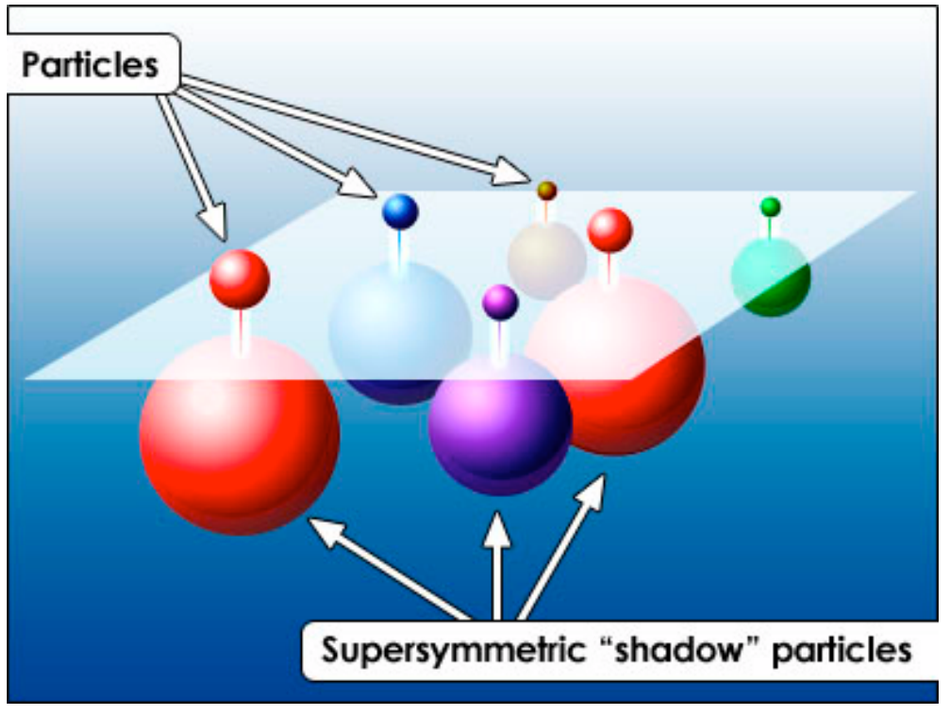
New Physics

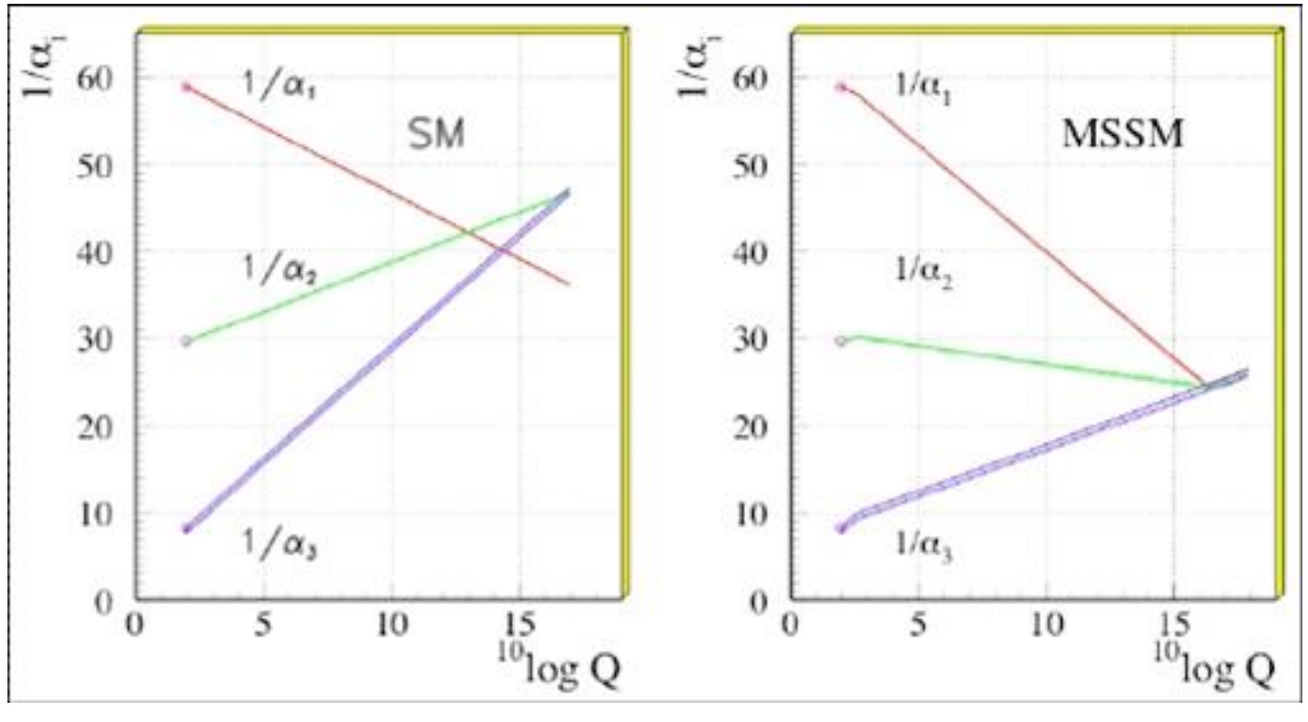
Supersymmetry

Symmetry between fermions and bosons

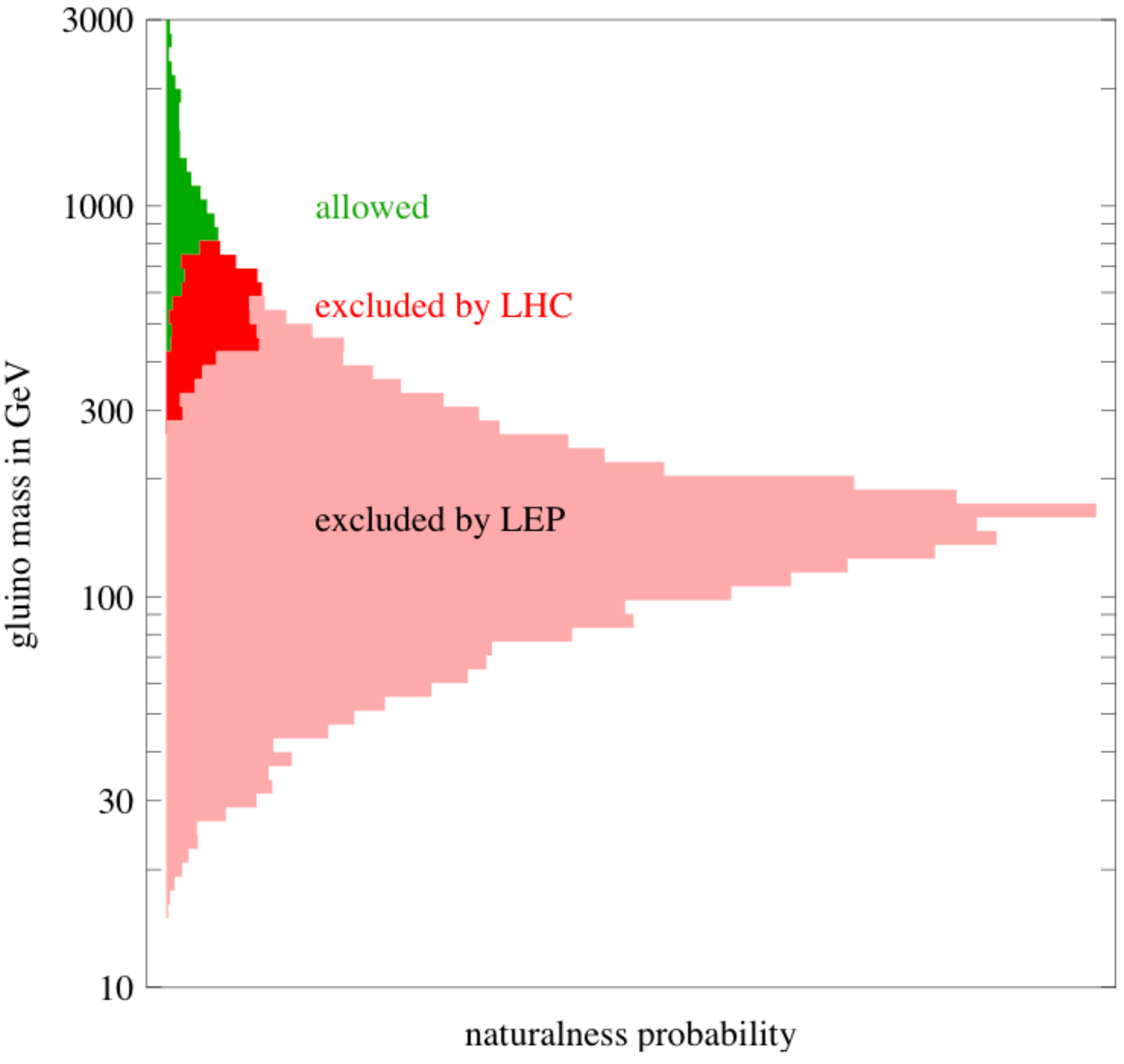
Couplings are unified at the GUT scale

WIMP is predicted to be a dark matter

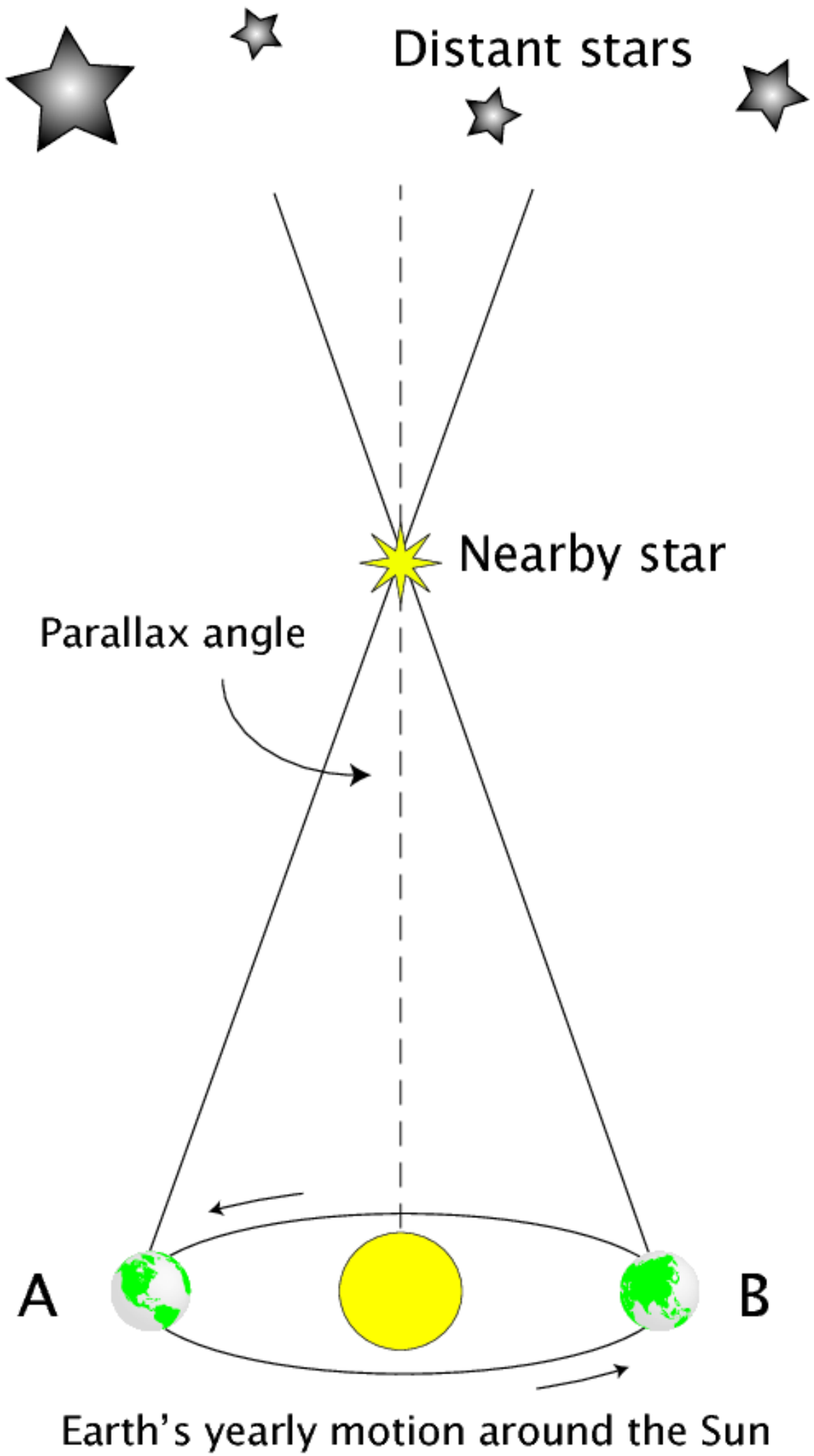




and there were many other theories…


3000
1000
300
100
30
10
gluino mass in GeV
allowed
excluded by LHC
excluded by LEP
naturalness probability

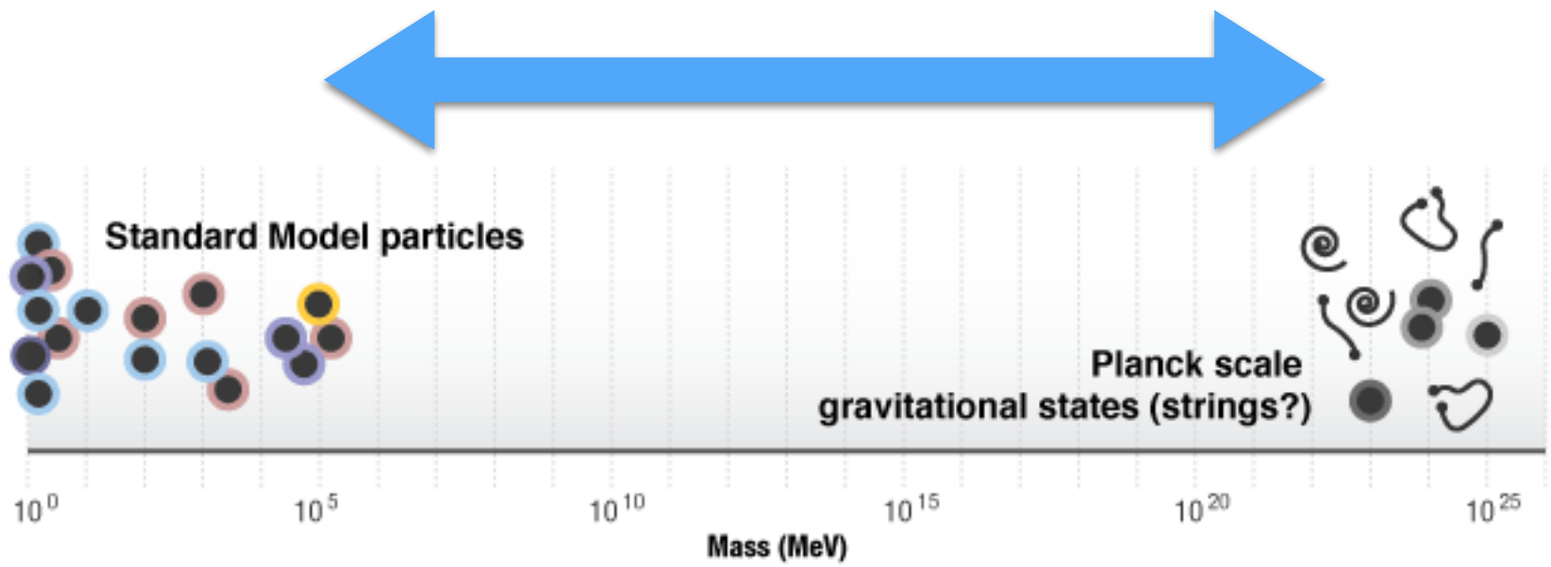
A Strumia

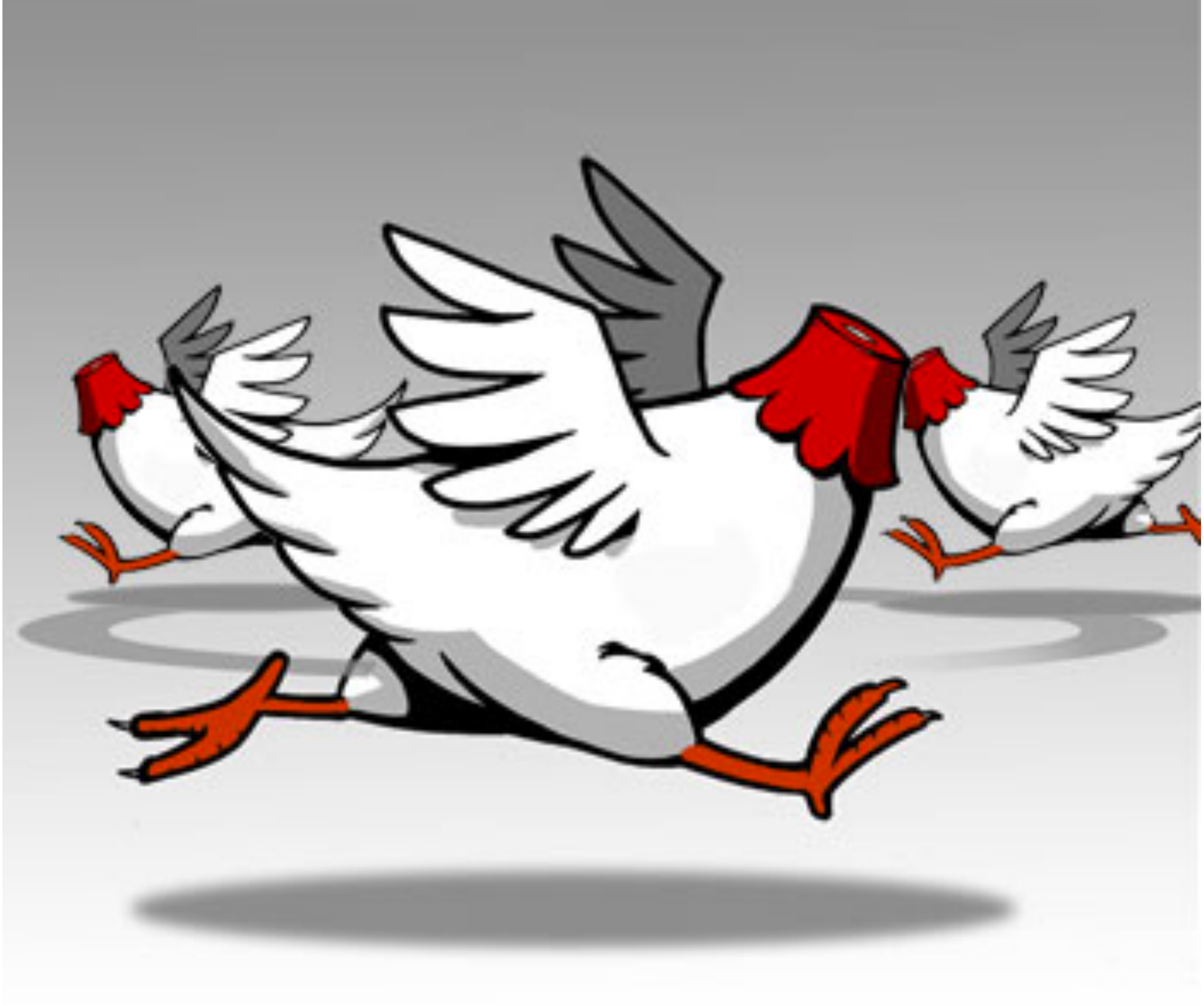


Proxima Centauri
4.22 lyr
20,000 AU

S Dimopoulos

Supersymmetry
Composite Higgs
Technicolor
Extra dimensions





New Ideas

Coleman-Weinberg Higgs :
alternative benchmark for Ginzburg-Landau potential

Chway Dermisek Jung HDK, PRL (2014)

$$V(\phi) = m^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

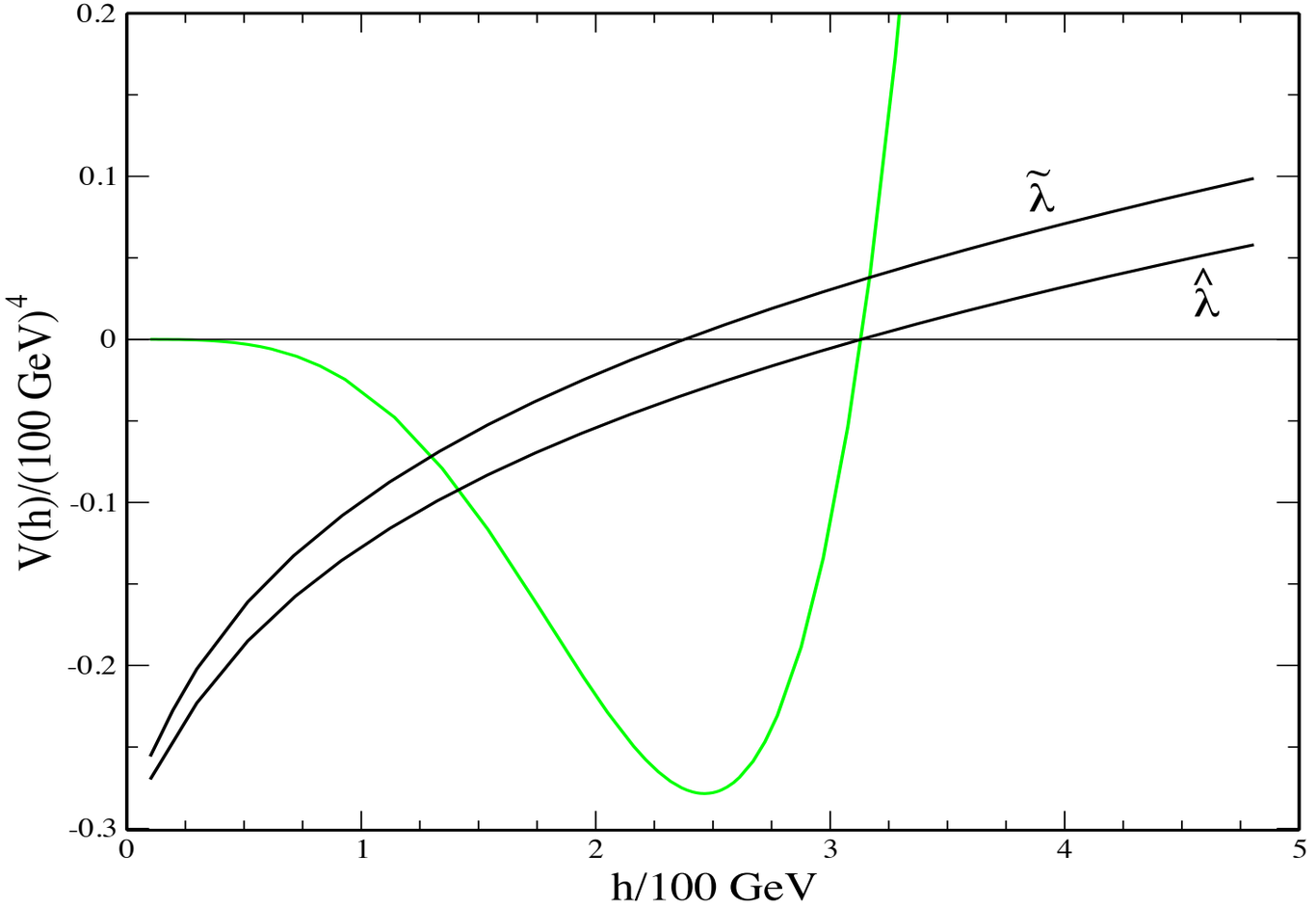
$$m^2 = 0$$

Spontaneous symmetry breaking can occur
by radiative corrections.

If the quartic changes
sign at low energy,
nontrivial minimum
is developed

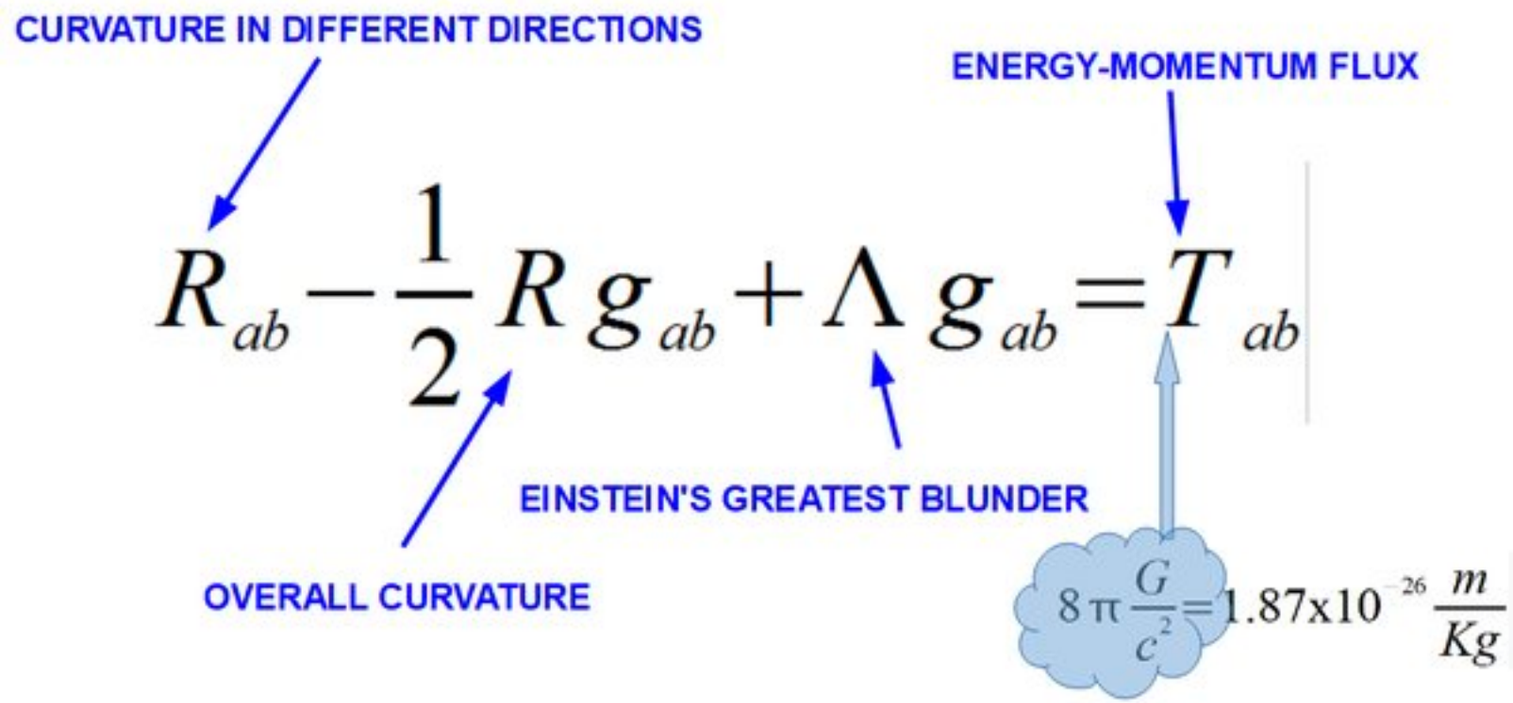
Strong 1st order
electroweak phase
transition is possible

Espinosa and Quiros, PRD (2007)



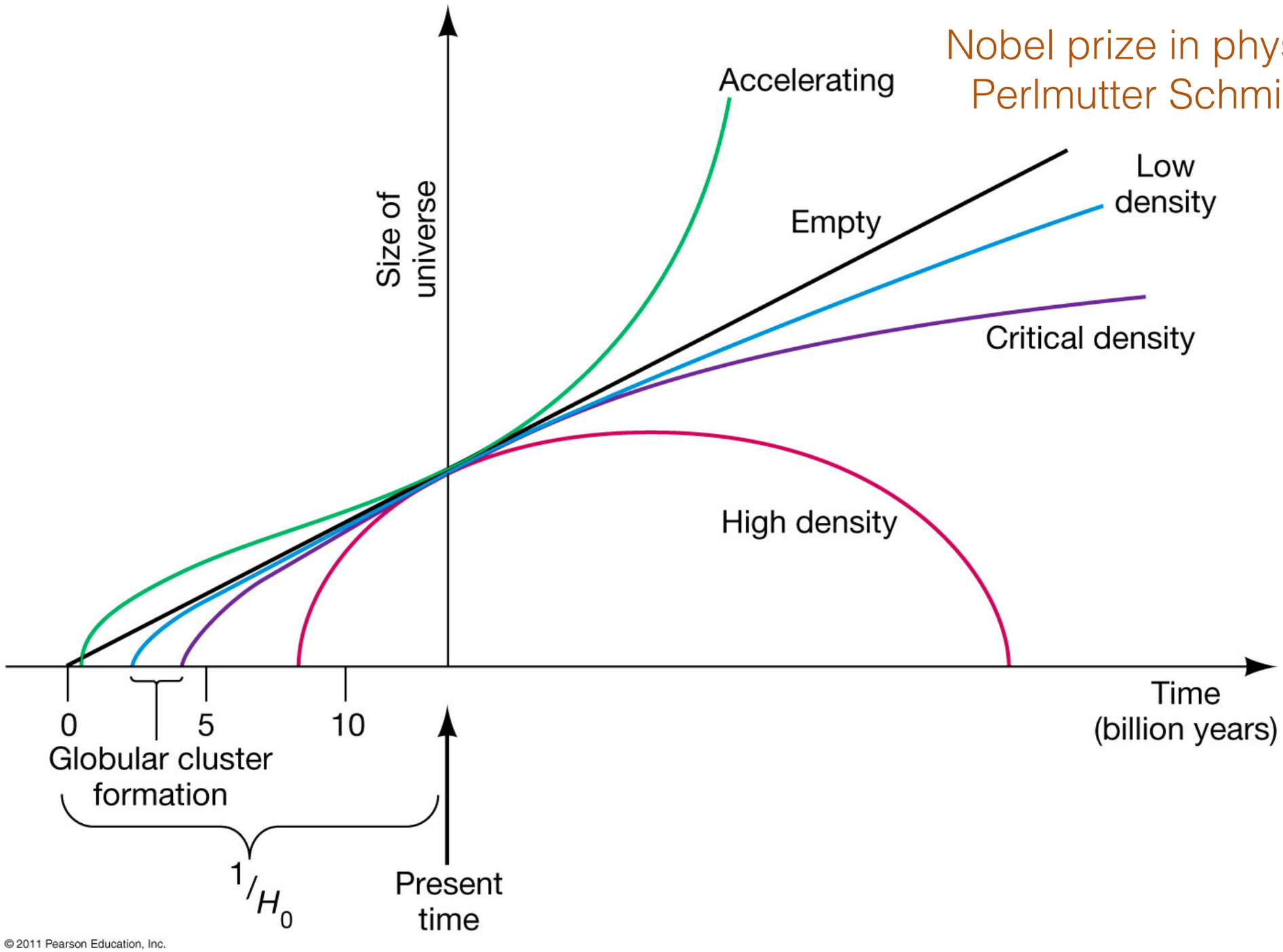
Cosmological Constant

Cosmological Constant

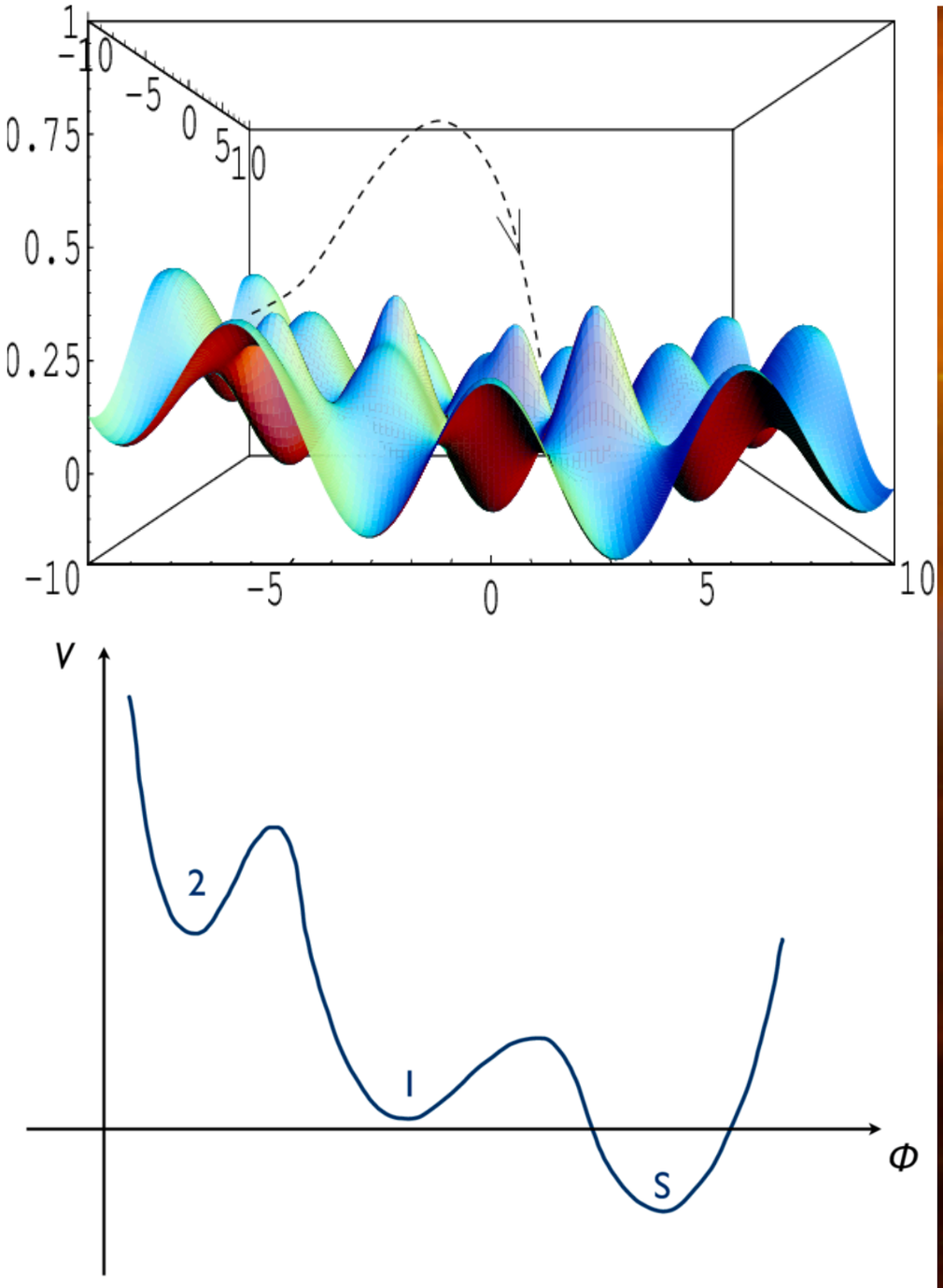


Dark Energy: accelerated expansion of the universe

Nobel prize in physics 2011
Perlmutter Schmidt Riess



Landscape/Multiverse



At the end of the 19th century

There is nothing new to be discovered in physics now.

All that remains is more and more precise measurement.

At the end of the 19th century

It seems probable that most of the grand underlying principles have now been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice…. An eminent physicist has remarked that the future truths of physical science are to be looked for in the sixth place of decimals.

Albert Michelson, 1894

The more important fundamental laws and facts of physical science have all been discovered, and these are so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote…. Instances might be cited, but these will suffice to justify the statement that "our future discoveries must be looked for in the sixth place of decimals".

Albert Michelson, 1903

The most notorious problems in fundamental physics

$$\frac{m_h^2}{M_{\rm Pl}^2} \sim 10^{-32}$$

$$\frac{\Lambda_{\rm cc}}{M_{\rm Pl}^4} \sim 10^{-123}$$

Higgs mass

irrelevant operators!

$$V = m_H^2 |H|^2 + \lambda |H|^4 + \cdots$$

relevant operator! marginal operator!

$\mu \gg m$ $[m_H^2] = 2$ $[\lambda] = 0$

$\mu \sim m$

$\mu \ll m$

cosmological constant

relevant operators are important

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{\rm Pl}^2}{2} R - \Lambda_{\rm cc} \right]$$

relevant operator!

$$[\Lambda_{\rm cc}] = 4$$

Conclusion

- Naturalness has been a long time proven concept and guided physics revolution in the history
- It predicted new physics at the weak scale stabilizing the Higgs mass and miserably failed
- The cosmological constant is incomprehensible
- Is it doomed or dawn to new revolution?