Standard Model, New Physics and Higgs Factory

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People have long asked,

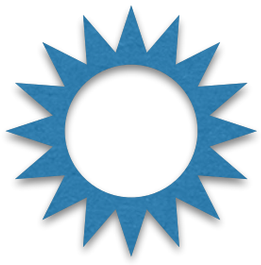
" Of what is the world made ? " and " What holds it together ? "

Elementary Particle Physics
or
High Energy Physics

Studying Fundamental Interactions (Forces) in Nature

Particle Physics:
fundamental constituents of matter and their interactions

Universe



Solar

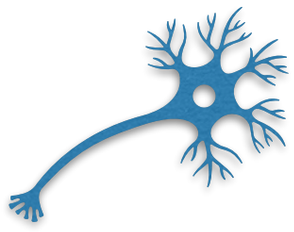
Earth

Human

~100,000,000,000,000,000,000,000,000 Meter

0.000,000,000,000,000,001

Cell



Atom

Proton

Electron

Think big and solve a problem with impossible

Particle Physics: Shorter distance and higher energy

cm:

Flow （flow dynamics）

10^{-5}cm:

Molecule （Molecular dynamics）

10^{-8}cm:

Atom （quantum mechanics）

10^{-13}cm:

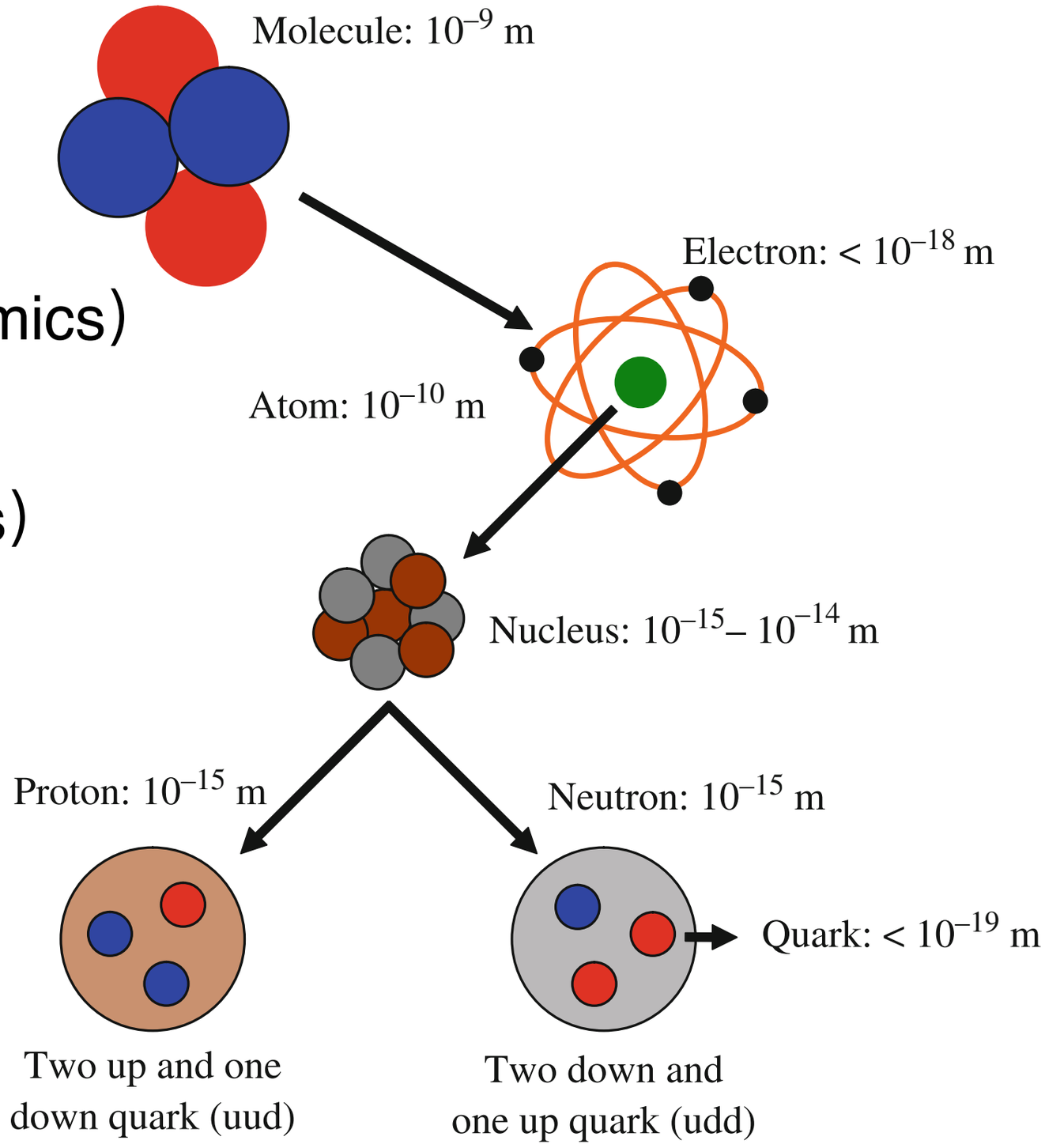
Nucleus （Nuclear physics）

10^{-13}~10^{-18}cm:

Quark （Quantum Chromodynamics）

10^{-33}cm:

String



Physics at different scales never talk to each other

Standard Model of Particle Physics

(1895 - 2012)

Matter particles

Force particles

Quarks

u up	c charm	t top
d down	s strange	b bottom

Forces

Z Z boson	γ photon
W W boson	g gluon

H Higgs boson

e electron	μ muon	τ tau
ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino

Leptons

Spin $\frac{1}{2}$

Spin 1

Spinless

History of unification

Planets

Apple

Light

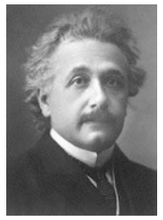
Electrc

Magentic

Atom

Gravity

Mechanics

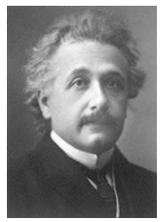


Electromagnetism

Quantum Mechanics

γ-decay

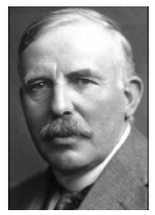
Special Relativity



β-decay

Quantum Electrodynamcis

Weak force



General Relativity

α-decay

Electroweak

Strong

Standard Model

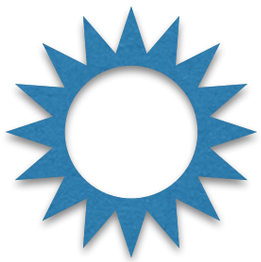
String

Grand Unification

From Hitoshi Murayama's talk

Particle Physics:
fundamental constituents of matter and their interactions

Universe



Solar

Earth

Human

~100,000,000,000,000,000,000,000,000 Meter

0.000,000,000,000,000,001

Cell

Atom

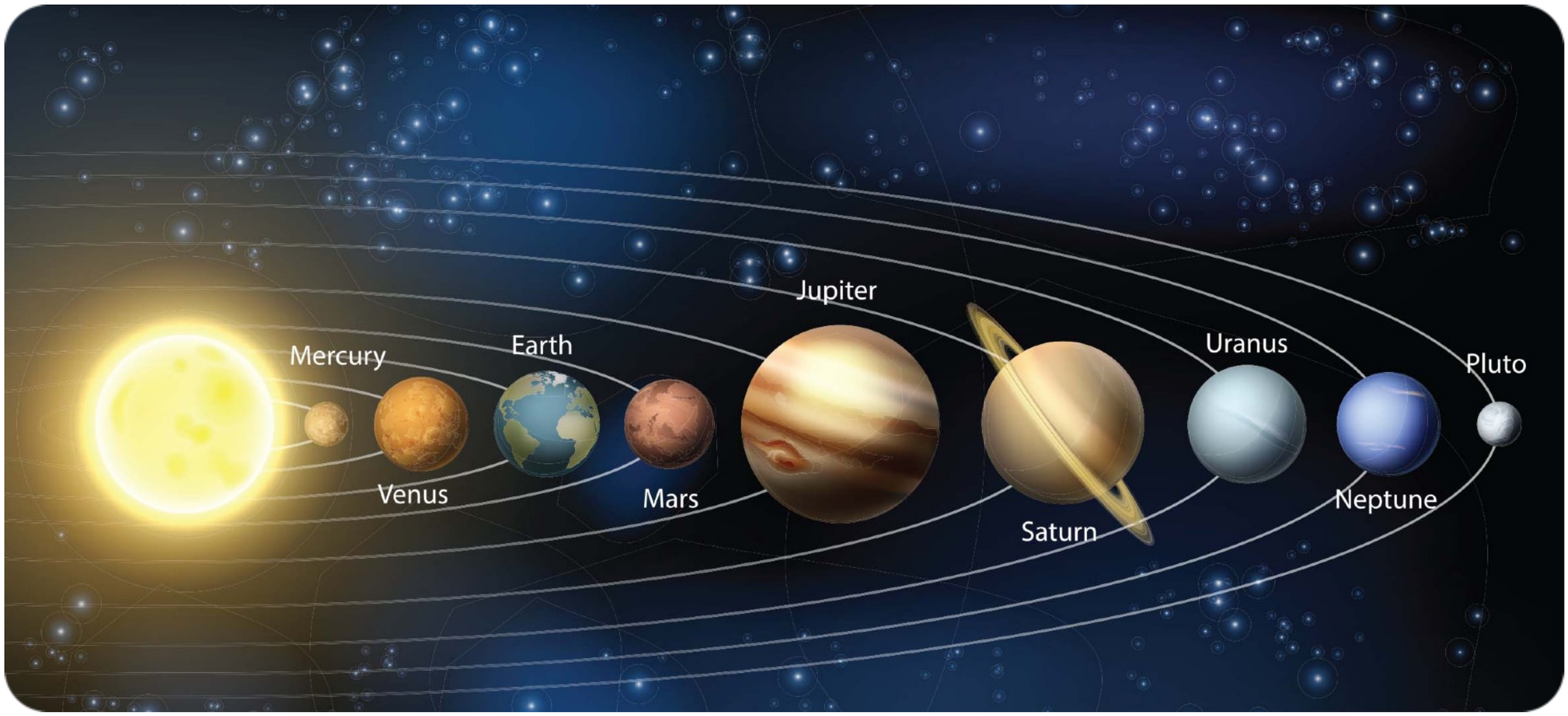
Proton

Electron

Why so?

SM

Why is the solar system so stable ?

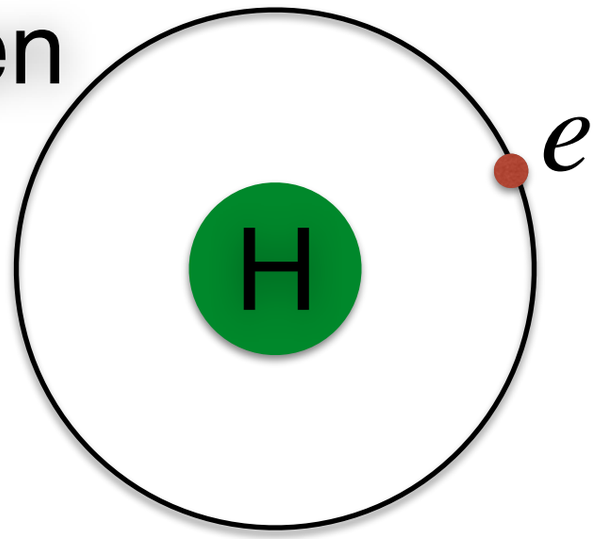


$$F = G_N \frac{Mm}{r^2}$$

The MASS!

Why is the atom stable ?

Hydrogen



Coulomb force

$$F = -K\frac{e^2}{r^2}$$

Schrodinger Equation

$$i\hbar\frac{\partial}{\partial t}\psi = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\psi - \frac{e^2}{r}\psi$$

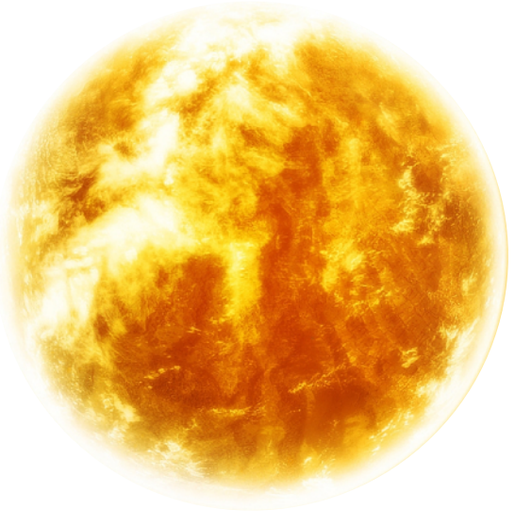
No hydrogen atom exists if electron is massless

The MASS!

Why is the Sun shinning as millions of years ago ?

It looks sooooo stable!

Nothing last for ever!



$$4p \rightarrow {}^{4}\mathrm{He} + 2e^{+} + 2\nu_e + 26.73\ \mathrm{MeV}$$

H. Bethe
1939

The sun is shinning through
the Weak interaction which is weak.

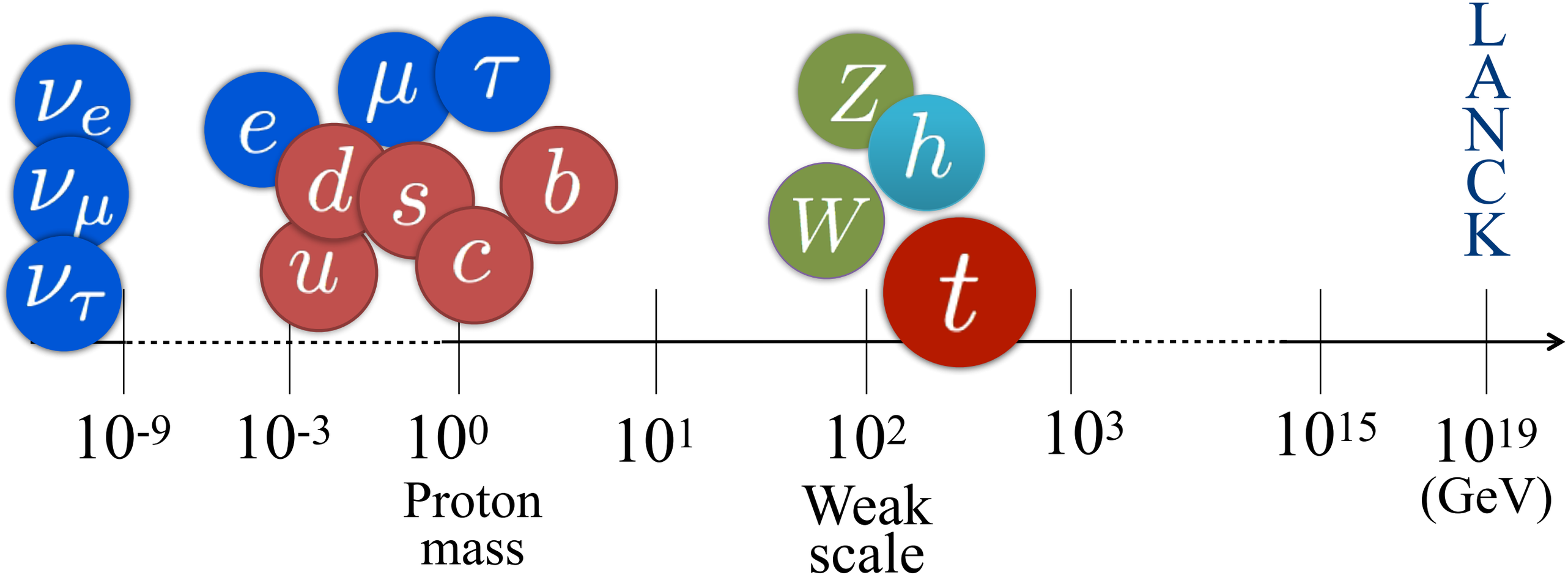
Why so weak?

The weak force carriers are too heavy!

The MASS!

Two outstanding puzzles in Standard Model

Origins of EWSB (*W/Z Mass*) and Flavor breaking (*Fermion Mass*)

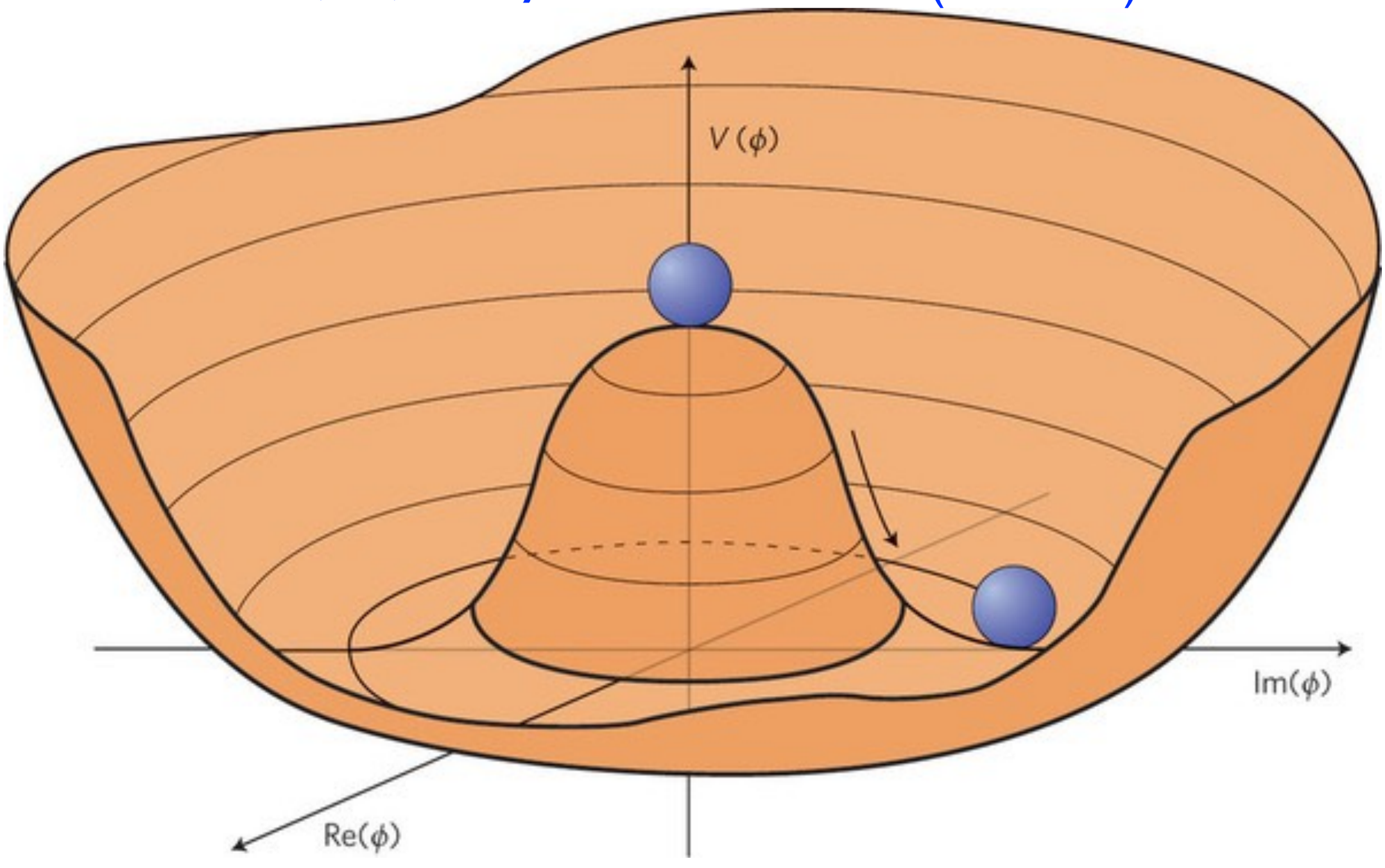


PLANCK

Origin of the weak scale?

Higgs potential and Spontaneously symmetry breaking

$$V(H) = \mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2$$



Higgs Discovery

4th July, 2012

The Particle Data Group has an entry for the Higgs boson after 2012

PDG2014 $J = 0$

Mass $m = 125.7 \pm 0.4$ GeV

H^0 Signal Strengths in Different Channels

Combined Final States $= 1.17 \pm 0.17$ (S = 1.2)
$WW^* = 0.87^{+0.24}_{-0.22}$
$ZZ^* = 1.11^{+0.34}_{-0.28}$ (S = 1.3)
$\gamma\gamma = 1.58^{+0.27}_{-0.23}$
$b\bar{b} = 1.1 \pm 0.5$
$\tau^+\tau^- = 0.4 \pm 0.6$
$Z\gamma < 9.5$, CL = 95%

H^0

PDG2018 $J = 0$

Mass $m = 125.18 \pm 0.16$ GeV
Full width $\Gamma < 0.013$ GeV, CL = 95%

H^0 Signal Strengths in Different Channels

See Listings for the latest unpublished results.

Combined Final States $= 1.10 \pm 0.11$
$WW^* = 1.08^{+0.18}_{-0.16}$
$ZZ^* = 1.14^{+0.15}_{-0.13}$
$\gamma\gamma = 1.16 \pm 0.18$
$b\bar{b} = 0.95 \pm 0.22$
$\mu^+\mu^- = 0.0 \pm 1.3$
$\tau^+\tau^- = 1.12 \pm 0.23$
$Z\gamma < 6.6$, CL = 95%
$t\bar{t}H^0$ Production $= 2.3^{+0.7}_{-0.6}$

$$\Gamma_H^{\mathrm{SM}} = 4 \text{ MeV}$$

$$\frac{\Gamma_H^{\mathrm{SM}}}{m_H} = 0.000032$$

A common question:

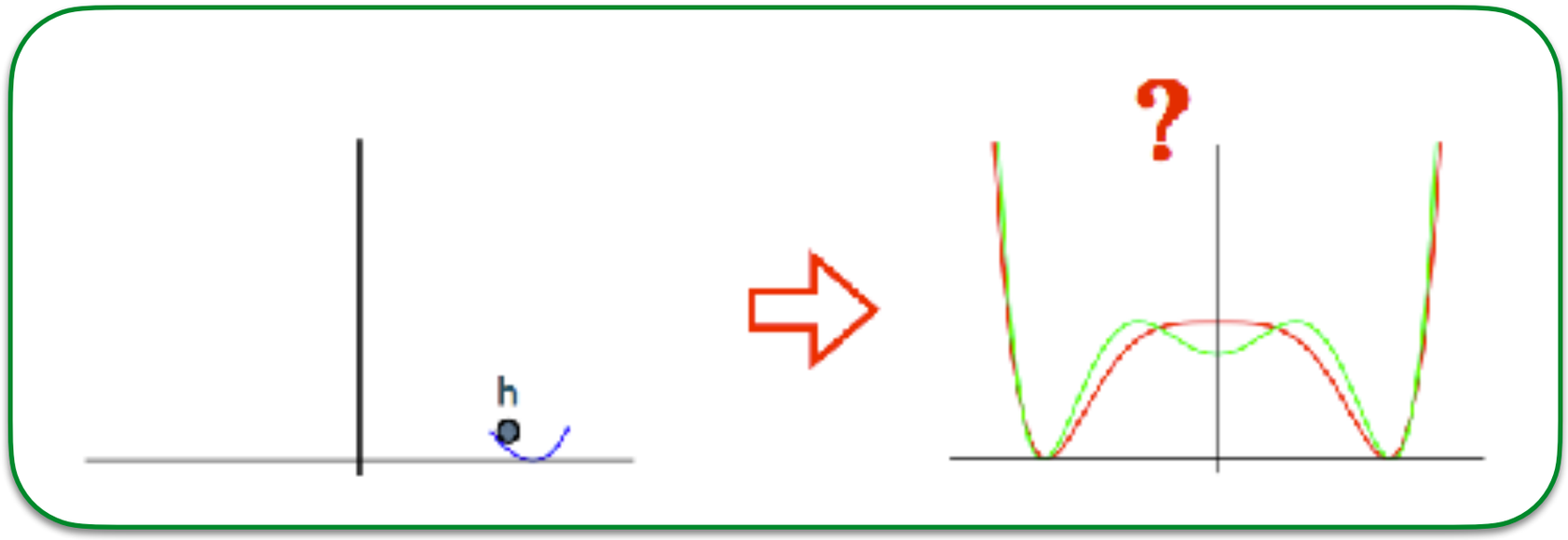
You guys have discovered the Higgs boson, **now what**?

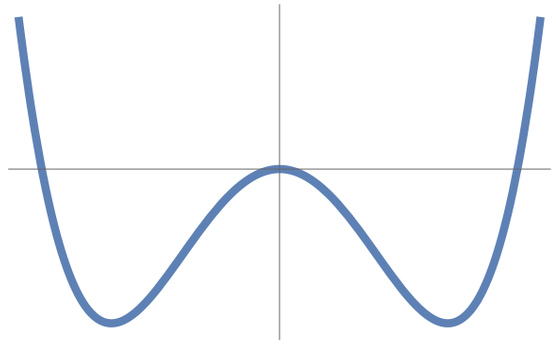
The Higgs boson is important not only for Electroweak symmetry breaking, but also as a WINDOW to NP beyond the Standard Model.

(1) Higgs-boson potential

(probing potential at electroweak scale)

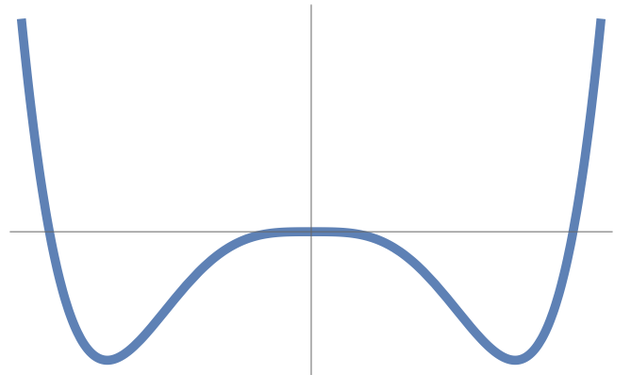
$$V(\phi) = -\mu^2\phi^2 + \lambda(\mu)\phi^4 + \frac{\kappa(\mu)}{\Lambda^2}\phi^6 + \cdots$$





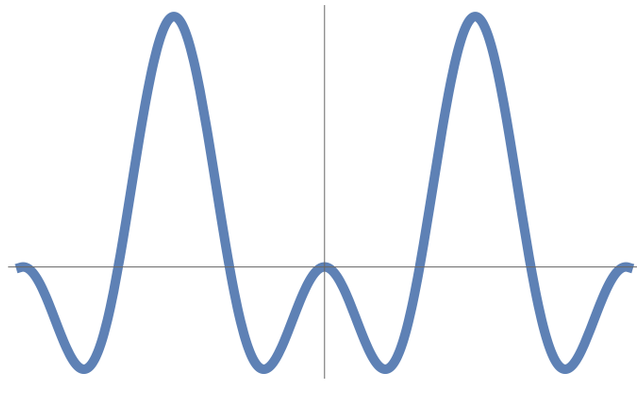
$V(\phi) = -\mu^2\phi^2 + \lambda(\mu)\phi^4$

Fundamental Higgs



$\lambda\left(\phi^\dagger\phi\right)^2 + \epsilon\left(\phi^\dagger\phi\right)^2 \log\frac{\phi^\dagger\phi}{\mu^2}$

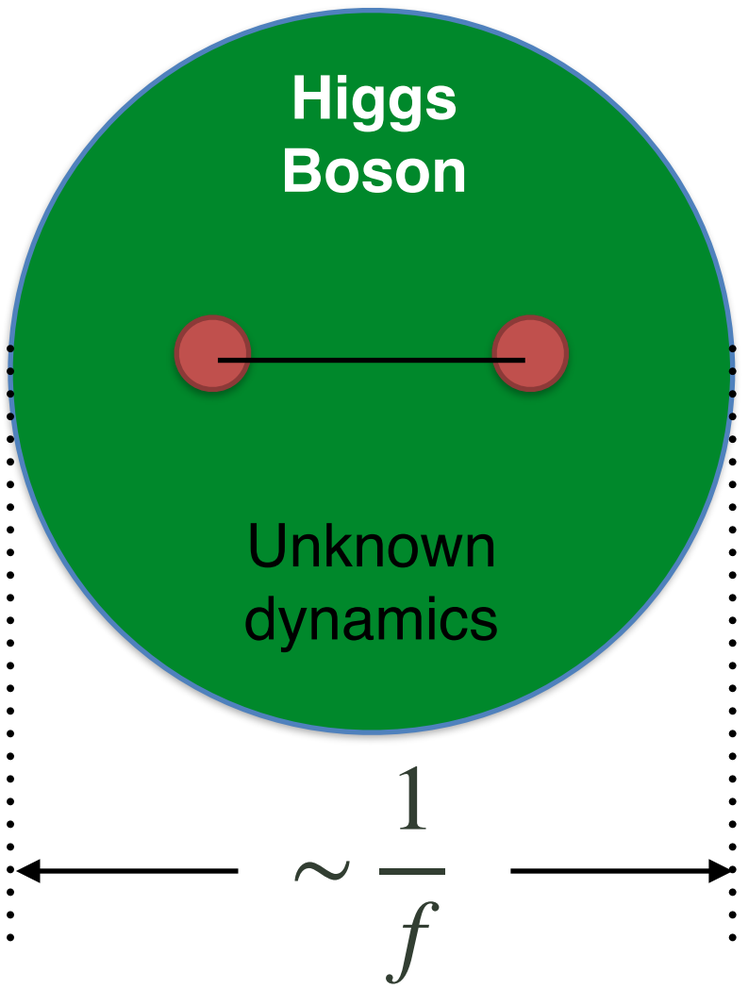
Coleman-Weinberg Higgs



$a\sin^2(\phi/f) + b\sin^4(\phi/f)$

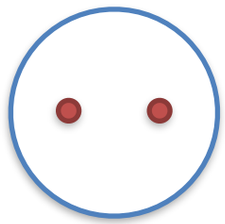
Pseudo-Goldstone Higgs

(2) Higgs boson: Fundamental or Composite



f : composite scale

$$\frac{1}{f} \sim \frac{1}{v}$$

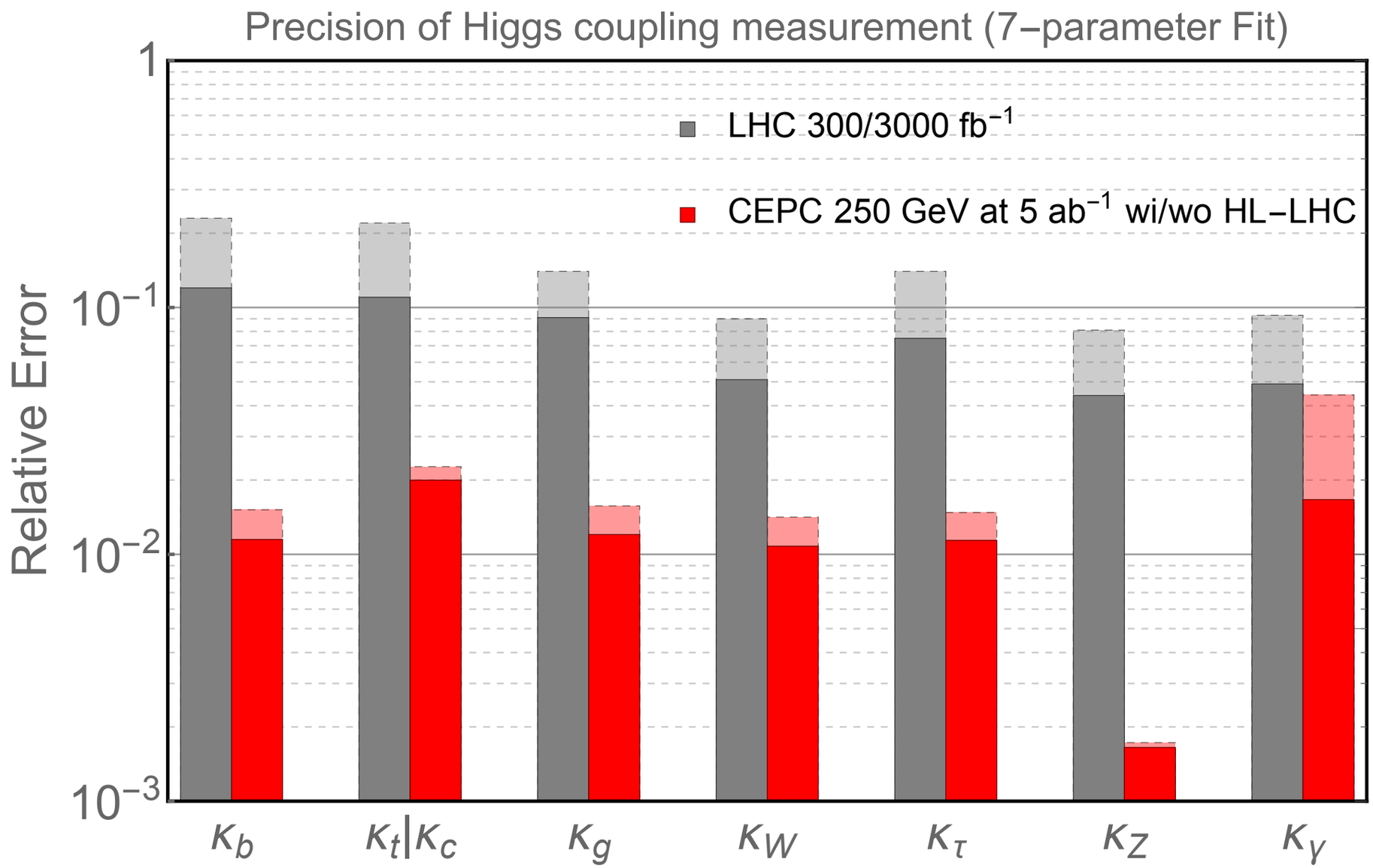


$$\frac{1}{f} < \frac{1}{v}$$

$$\frac{1}{f} \ll \frac{1}{v}$$

How to test?

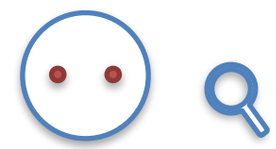
Deciphering Higgs Property through Precision at the CEPC



$f \gg v$

$f > v$

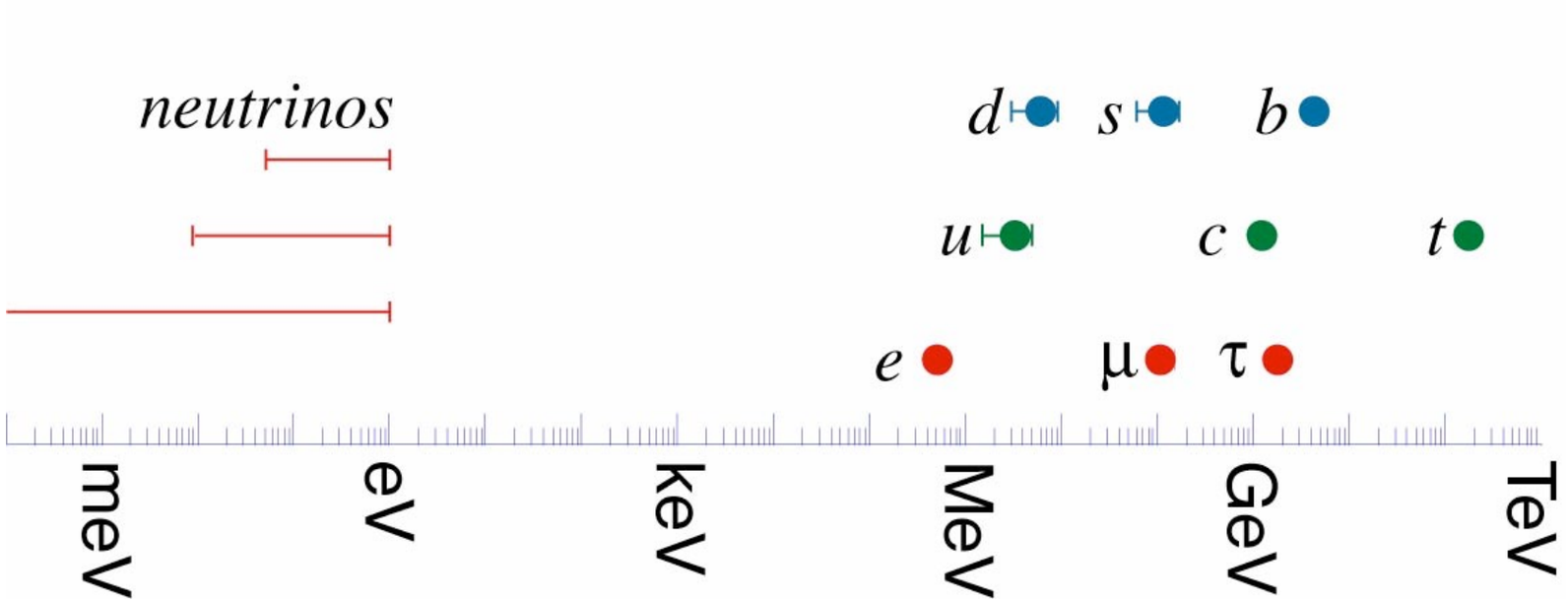
$f \gtrsim v$



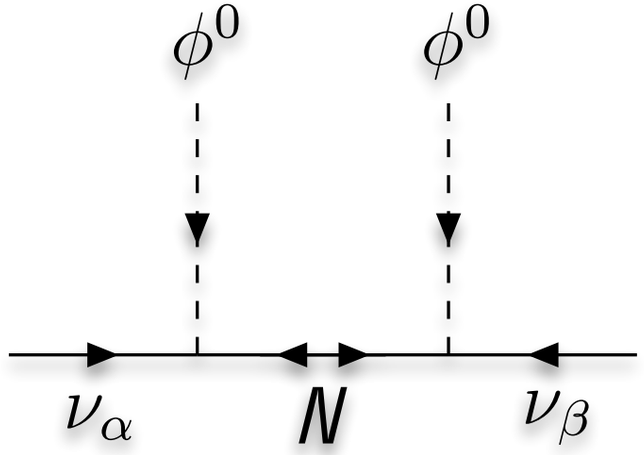
New physics beyond the Standard Model

(three experiment evidences)

(1) Neutrino mass



1 10^{12}

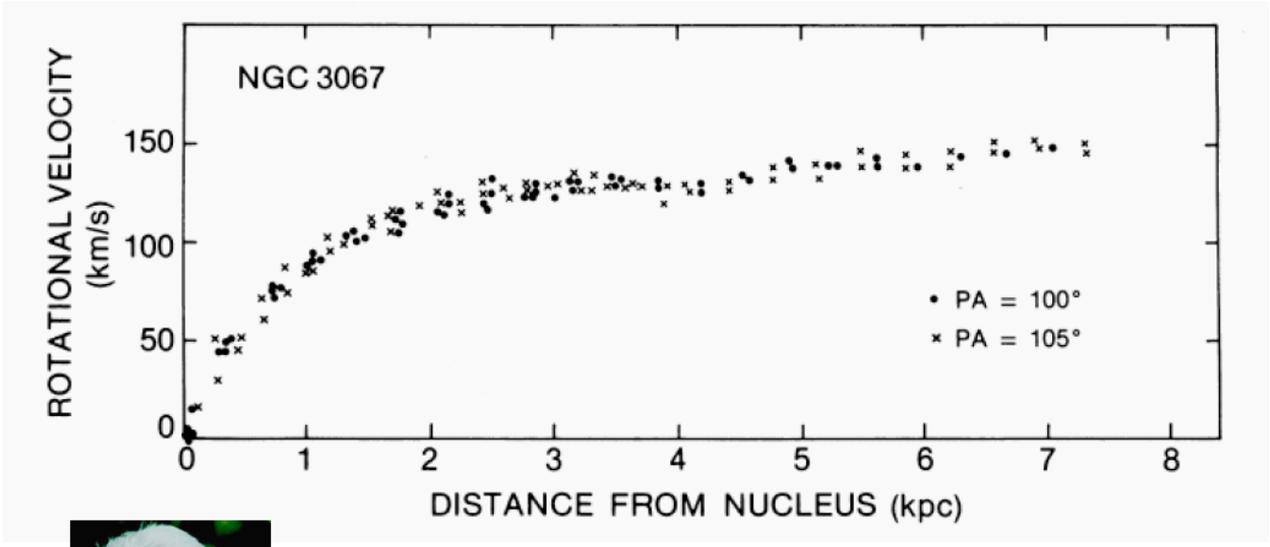


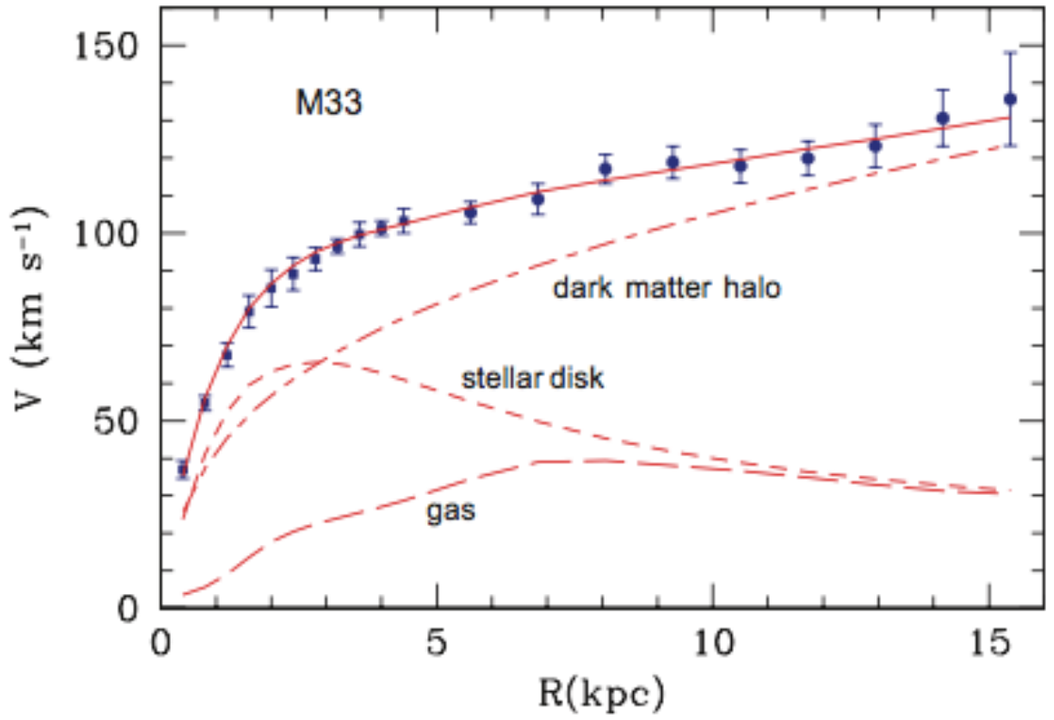
$$m_\nu \propto \frac{v^2}{M_N}$$

See-saw mechanism

Questions: 1. Mass ordering 2. CP phase 3. Majorana or Dirac

(2) Dark matter

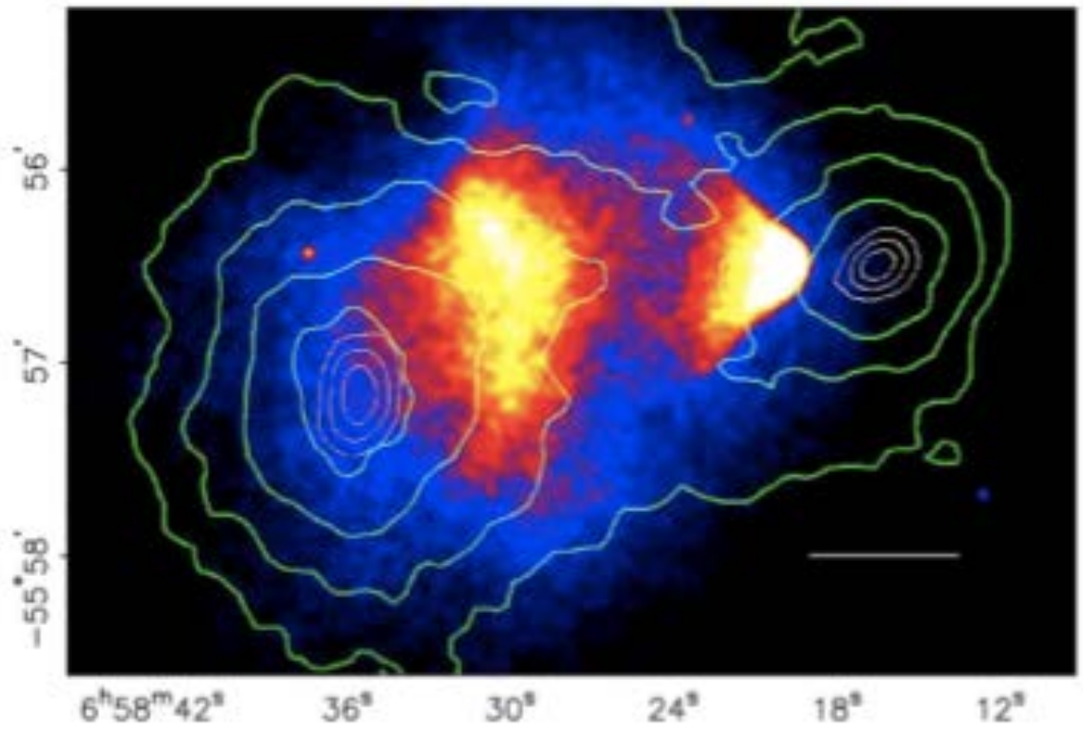


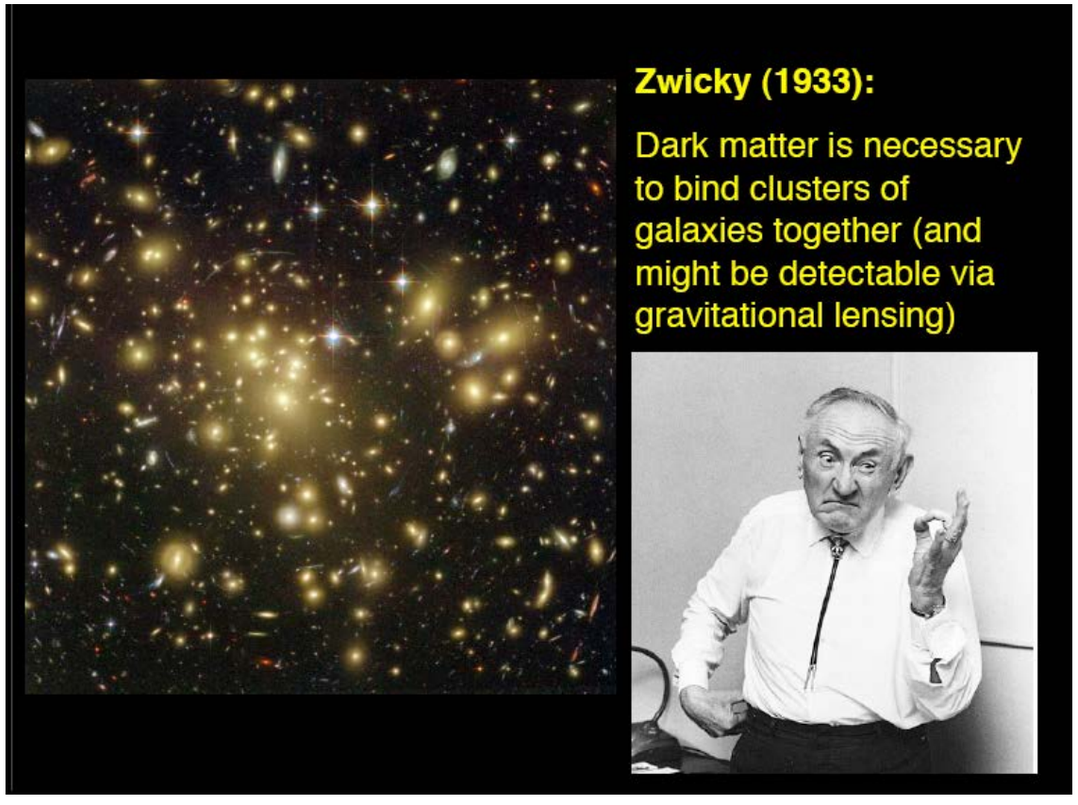


Vera Rubin

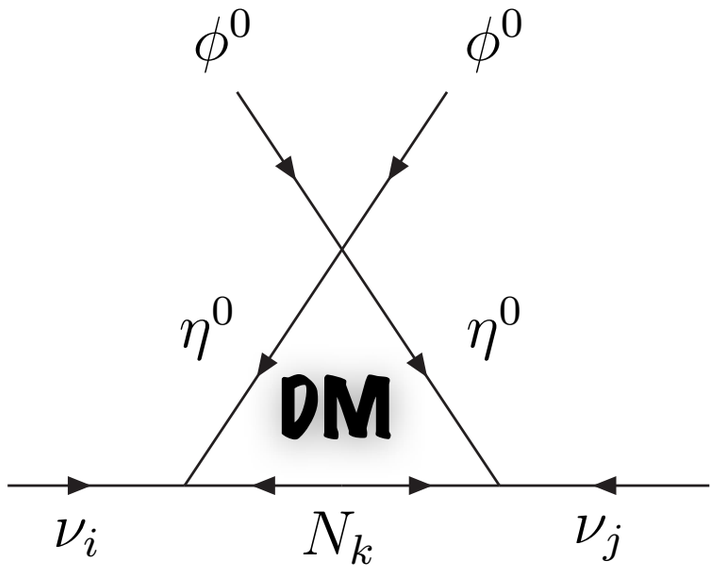
Rubin, Thonnard, Ford

"Such a velocity implies that 94% of the mass is located beyond the optical image; this mass has a ratio M/L greater than 100."





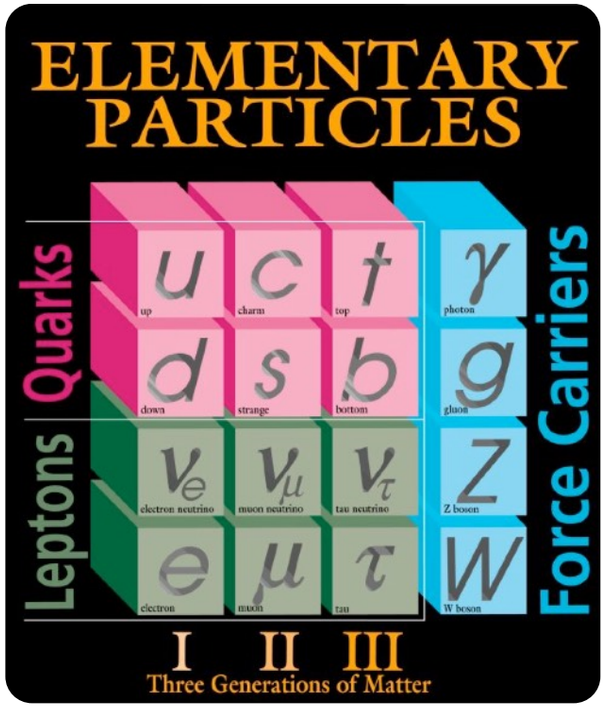
My favorite new physics model



Neutrino

Dark Matter

Neutrino mass is generated by dark matter quantum effects.

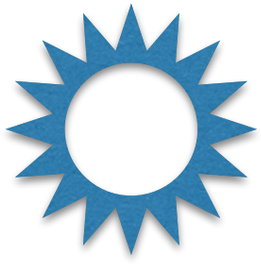


Rich signals at the CEPC

3. Matter and Antimatter asymmetry

Astrophysics looks at matter in its largest dimensions.

Universe



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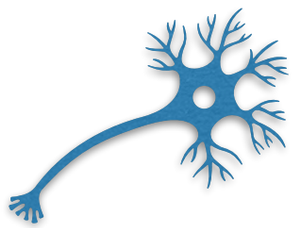


Atom

Proton

Electron

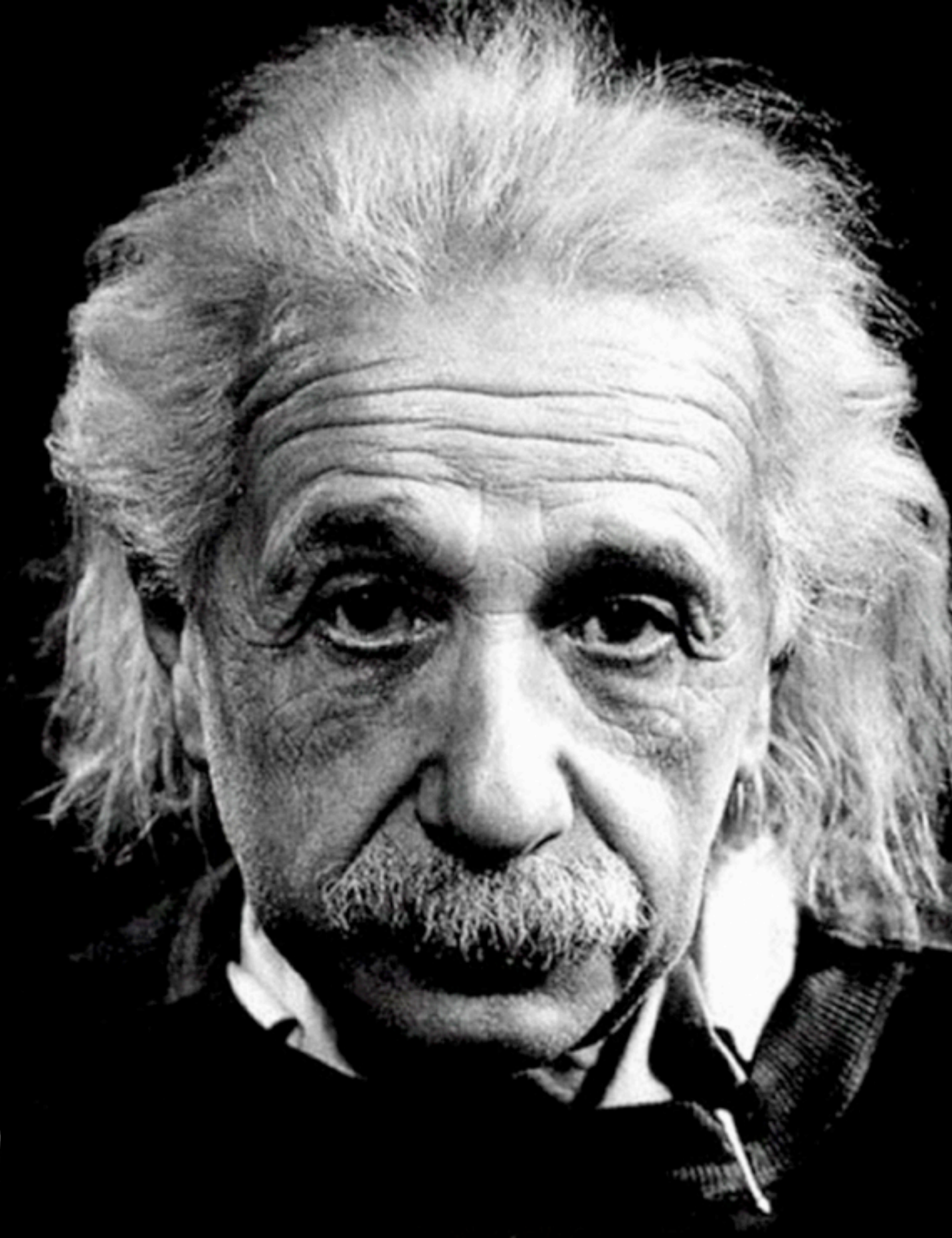
Particle physics looks at matter in its smallest dimensions.

They are related!

Two things are
infinite. The Universe
and human stupidity.

…

…
and I'm not sure
about the Universe.



Thank You!