

History and Progress in Particle Phenomenology

Takumi Kuwahara

Self introduction

Takumi Kuwahara (桑原 拓巳)

Assistant Professor at Jilin University,
Center for Theoretical Physics (since Sep. 2025)

Research: Particle Phenomenology

Dark Matter (Dark Sector)/Grand Unification/etc.

Contact info. :

e-mail kuwahara@jlu.edu.cn

webpage <https://tkuwaharahep.github.io/>

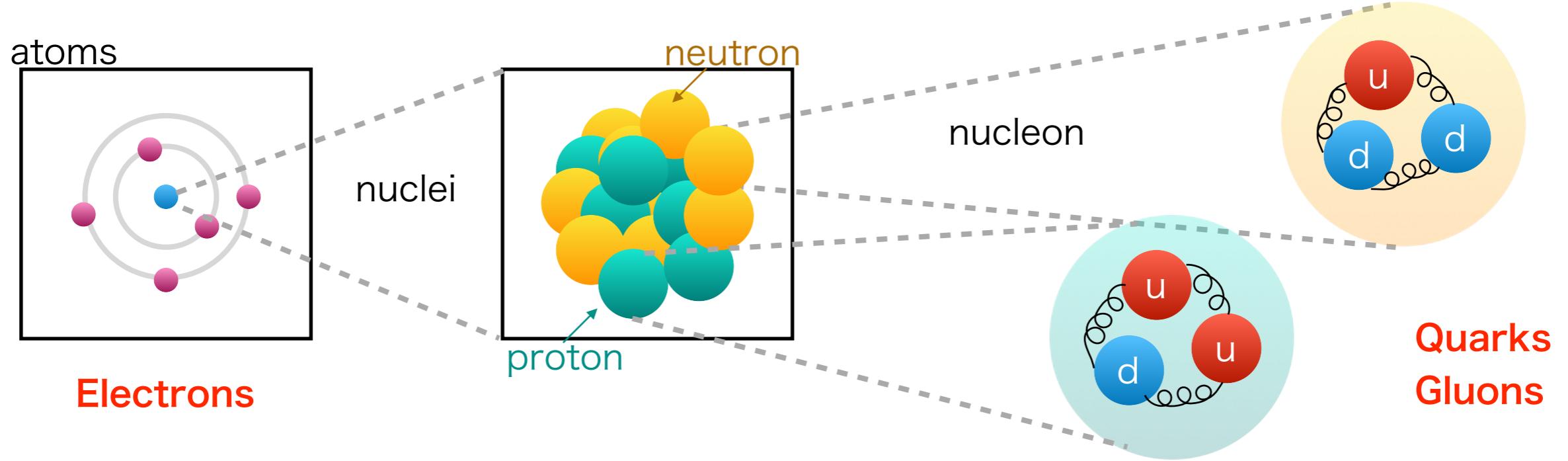


Contents

- ◆ Self Introduction
- ◆ What is Particle Physics?
- ◆ History of Particle Physics
- ◆ The Standard Model
- ◆ Beyonds
- ◆ Take-Home Messages

What is Particle Physics?

Elementary (fundamental) Particles (基本粒子)



Elementary particles are not composed of other particles

electron, neutrino, quark, photon, and gluon ...

High Energy Physics (HEP: 高能物理)

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- [Condensed Matter \(cond-mat new, recent, search\)](#) Disordered Systems and Neural Networks; Materials Science; Mesoscale and Nanoscale Physics; Other Condensed Matter; Quantum Gases; Soft Condensed Matter; Statistical Mechanics; Strongly Correlated Electrons; Superconductivity
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- [High Energy Physics – Lattice \(hep-lat new, recent, search\)](#)
- [High Energy Physics – Phenomenology \(hep-ph new, recent, search\)](#)
- [High Energy Physics – Theory \(hep-th new, recent, search\)](#)
- [Mathematical Physics \(math-ph new, recent, search\)](#)
- [Nonlinear Sciences \(nlin new, recent, search\)](#)
includes: Adaptation and Self-Organizing Systems; Cellular Automata and Lattice Gases; Chaotic Dynamics; Exactly Solvable and Integrable Systems; Pattern Formation and Solitons
- [Nuclear Experiment \(nucl-ex new, recent, search\)](#)
- [Nuclear Theory \(nucl-th new, recent, search\)](#)
- [Physics \(physics new, recent, search\)](#)
includes: Accelerator Physics; Applied Physics; Atmospheric and Oceanic Physics; Atomic and Molecular Clusters; Atomic Physics; Biological Physics; Chemical Physics; Classical Physics; Computational Physics; Data Analysis, Statistics and Probability; Fluid Dynamics; General Physics; Geophysics; History and Philosophy of Physics; Instrumentation and Detectors; Medical Physics; Optics; Physics and Society; Physics Education; Plasma Physics; Popular Physics; Space Physics
- [Quantum Physics \(quant-ph new, recent, search\)](#)

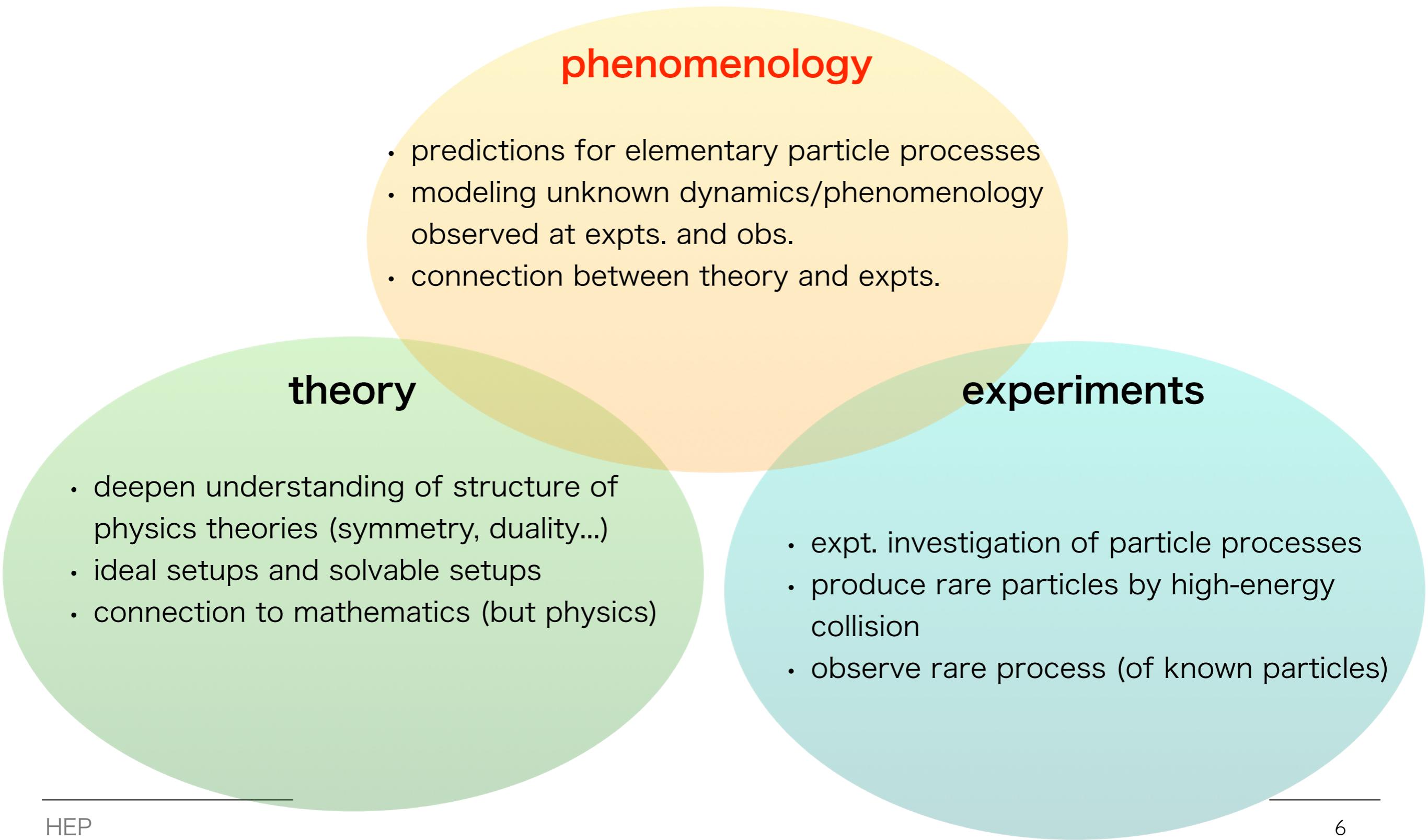
Several categories in HEP community

HEP-theory

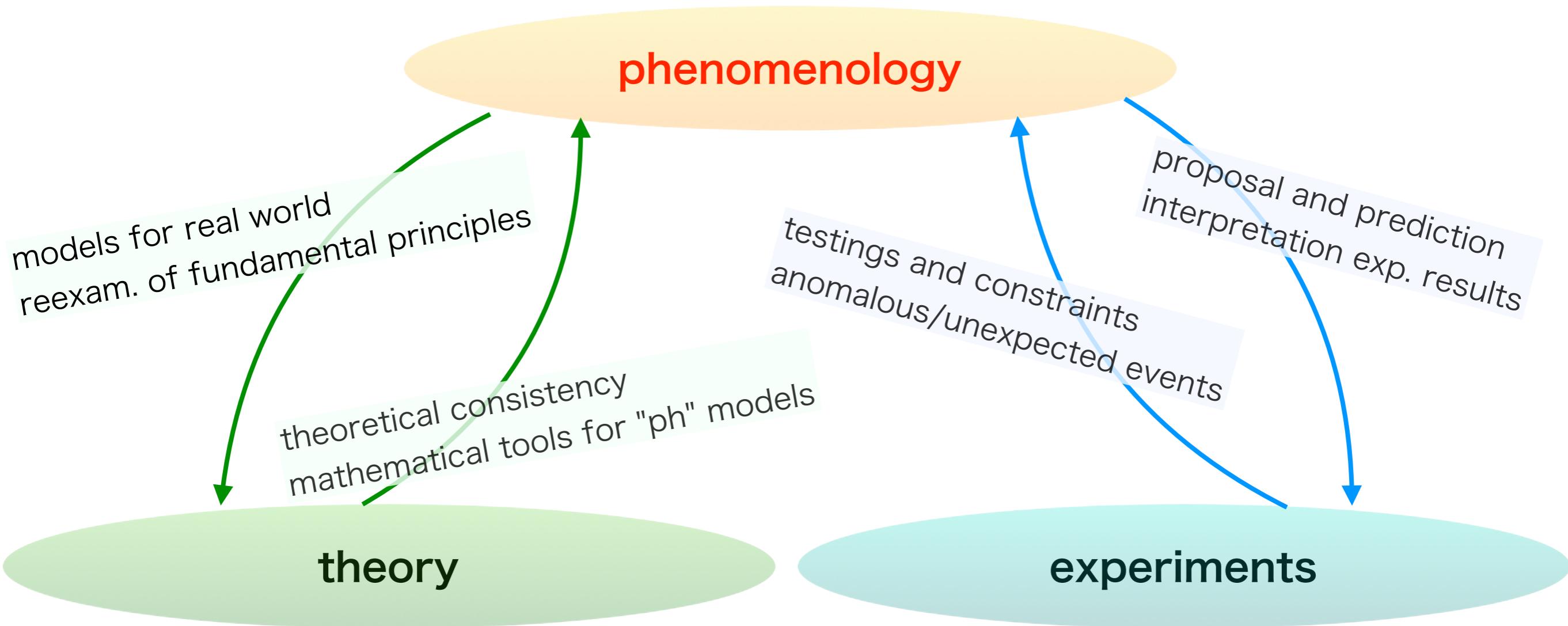
HEP-phenomenology ← today's topic

HEP-experiment

High-Energy Physics



Position of High-Energy Phenomenology



History of Particle Physics and the Standard Model



History of Particle Physics

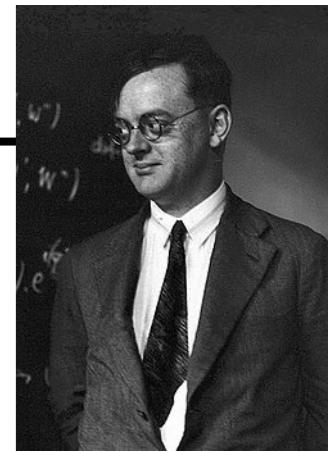
1900 - early 1920's: old quantum mechanics



W.Heisenberg



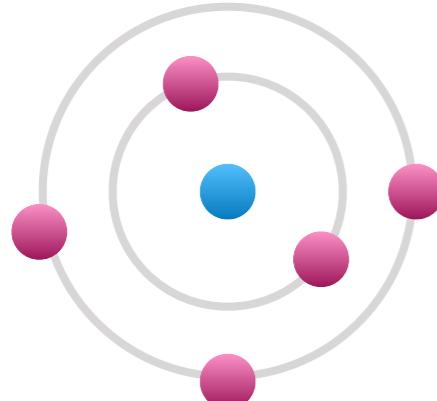
M.Born



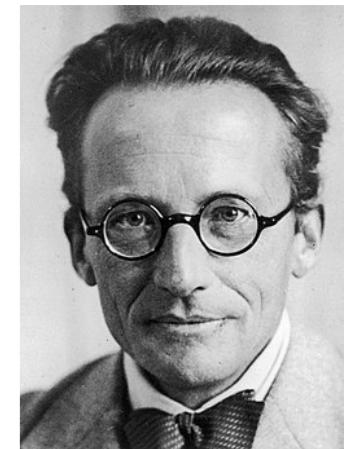
P.Jordan

1925: Birth of Quantum Mechanics (QM: 量子力学)

- Matrix mechanics ([W. Heisenberg, M. Born, P. Jordan](#))
- Schrödinger equation ([E. Schrödinger](#))



**100 YEARS OF QUANTUM
IS JUST THE BEGINNING**



E.Schrödinger

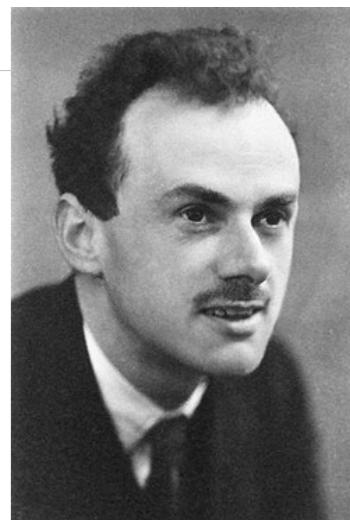
To understand Atomic Physics

typical size of atoms $\sim 10^{-8}$ cm = 1 Å

Any entities in the Universe has
particle-like behavior and wave-like behavior

1927: Relativistic QM

- Dirac equation ([P. Dirac](#))
first attempt to combine
special relativity (狭义相对论) + QM



P. Dirac

- * describes interactions between electrons ("spin-1/2")
and light (photon) ("spin-1")
- * predicts "anti-particle (反粒子)" of electron = positron

Birth of Quantum Field Theory (QFT: 量子场论)

combo of Classical field theory + QM (+ special relativity)

- * deals with many-body processes (e.g. production/decay)
- * found difficulties (e.g. infinities in some calculations)

1950's: Several developments in QFT
important progress in particle physics



- Renormalization (重整化)

treatment of infinities in QFT

J. Schwinger (1948), S. Tomonaga (1948)

J. Schwinger

S. Tomonaga

R. Feynman

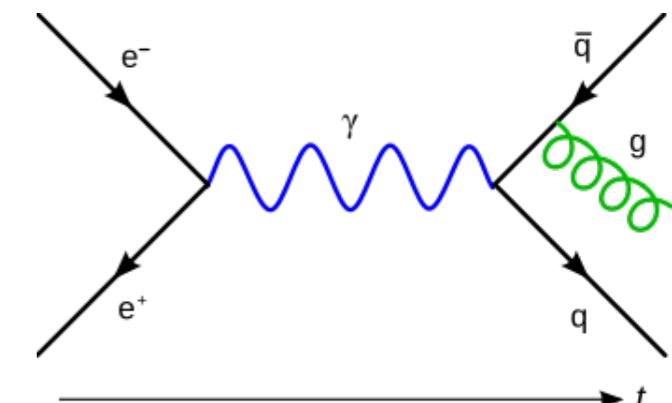
- Feynman Diagram (1948)

pictorial representation of mathematical computation

- Yang-Mills theory

basic of fundamental forces

C. N. Yang and R. Mills (1954)



History of Standard Model

Early in 20th century

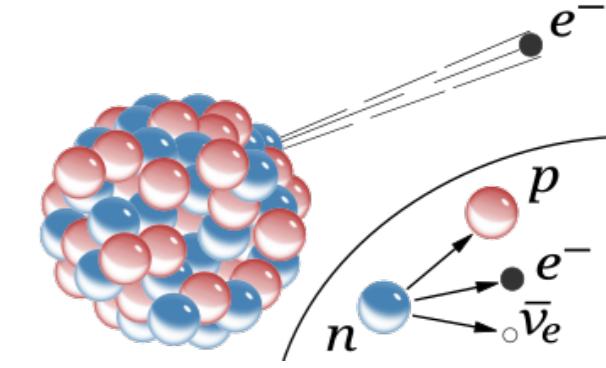
β -decay of nucleus (原子核): weak interaction

violation of energy conservation?

-> 1933: E. Fermi proposed **Fermi theory** (introduced "neutrino")



E. Fermi



force carriers

massless photon (electromagnetic force/long-range)

massive pion (**Yukawa theory**: strong nuclear short-range force)

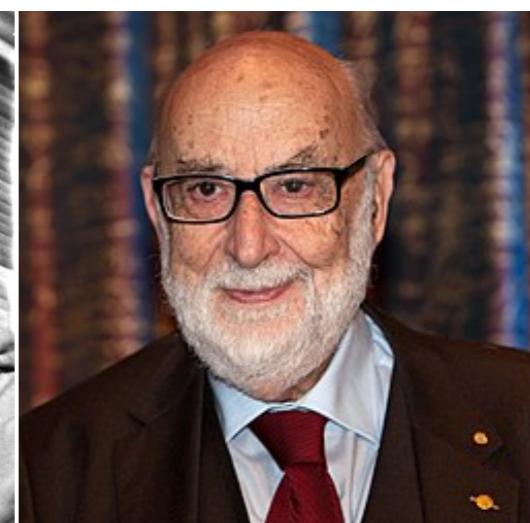
what is for weak? photon-like (spin-1) but short-range

- **Higgs Mechanism** (1964)

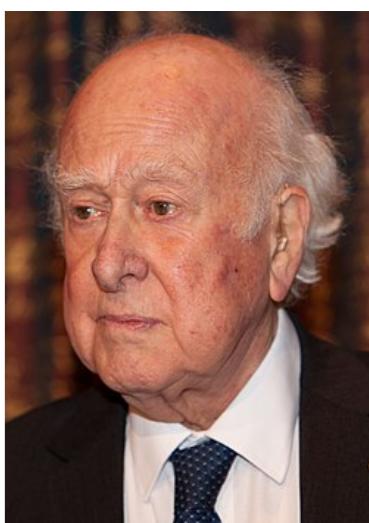
A way to make
photon-like particle massive



R. Brout



F. Englert



P. Higgs

Unification of electroweak theory



S. Glashow



S. Weinberg



A. Salam

electromagnetism + weak theory

[S.Glashow](#) (1961), [S.Weinberg](#) (1967), [A.Salam](#) (1968)

-> discovery of force carrier particles (**W, Z bosons**) at CERN (1983)

-> discovery of **Higgs particle** (origin of mass) at CERN (2012)

Success of electroweak theory

What about nucleons?



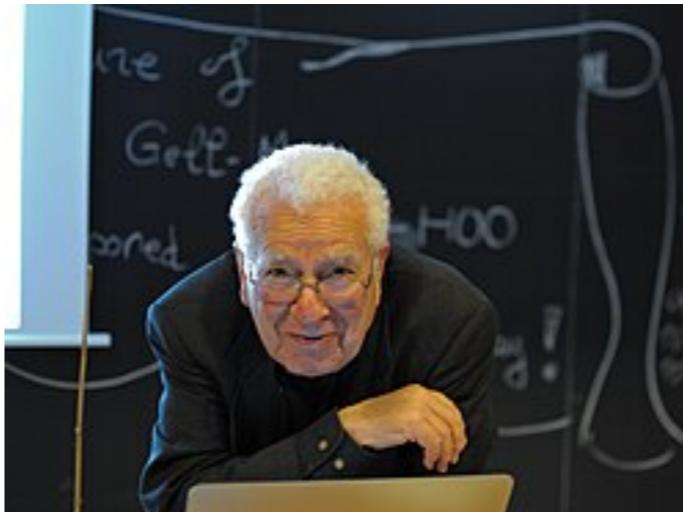
"Particle Zoo" ("subnuclear zoo" by R. Oppenheimer)
many particles (= "hadrons")
have been found at accelerators since 1950s

Quark Model

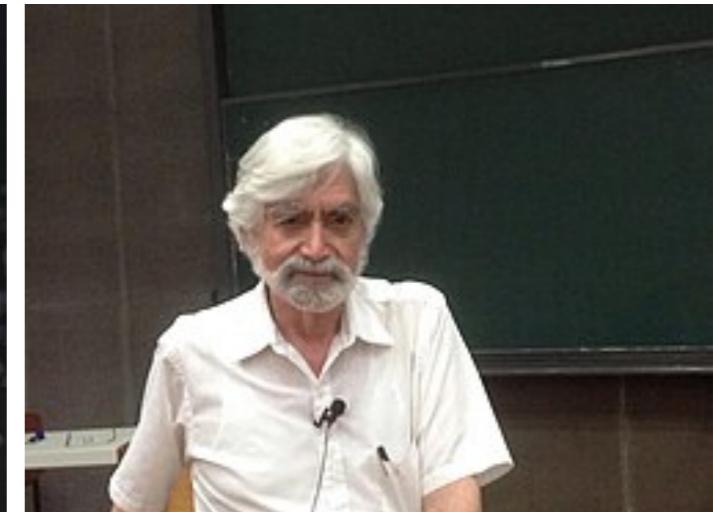
M. Gell-Mann, G Zweig (1964)

systematic treatments of
"particle zoo"

"hadrons" have an inner structure
and consist of "quarks" and "gluons"



M. Gell-Mann

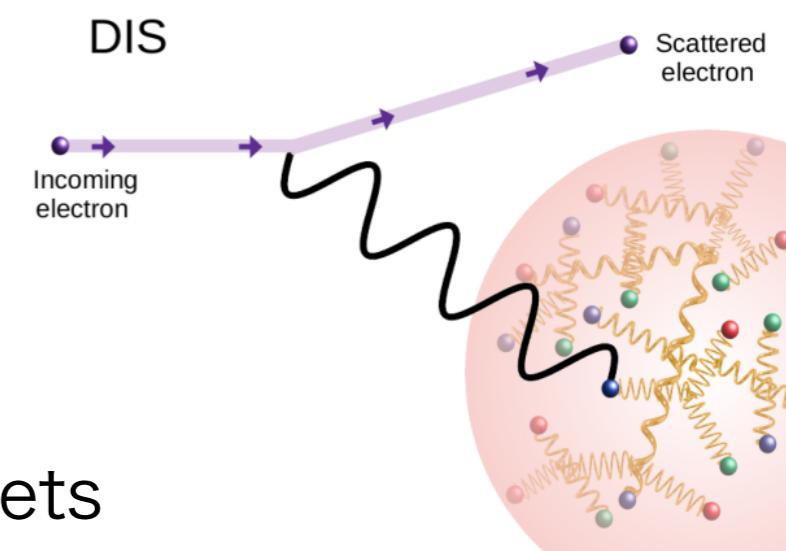


G. Zweig

Deep inelastic scattering

Stanford Linear Accelerator Center (SLAC)
found the inner structure of proton (1969)

"gluon" is found in PETRA (1979): $e^+e^- \rightarrow \bar{q}qg \rightarrow 3 \text{ jets}$



How many quarks?

Discovery of an exotic decay process (1964)

J.H.Christenson, J.W.Cronin, V.L.Fitch and R.Turle

$K_L \rightarrow \pi^+ \pi^-$ requires a symmetry (charge-parity: CP) violation



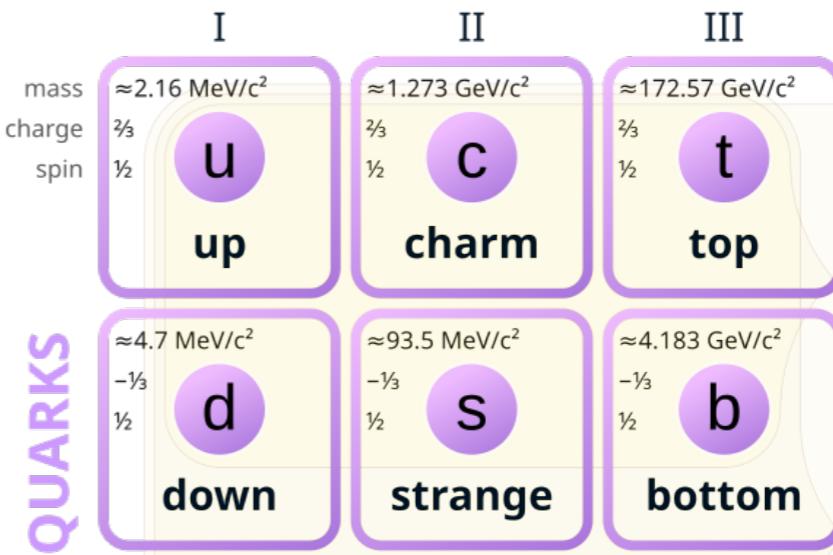
M. Kobayashi and T. Maskawa (1973)

To explain $K_L \rightarrow \pi^+ \pi^-$ decay,

M. Kobayashi

T. Maskawa

at least **six kinds of quarks** are required in the quark model

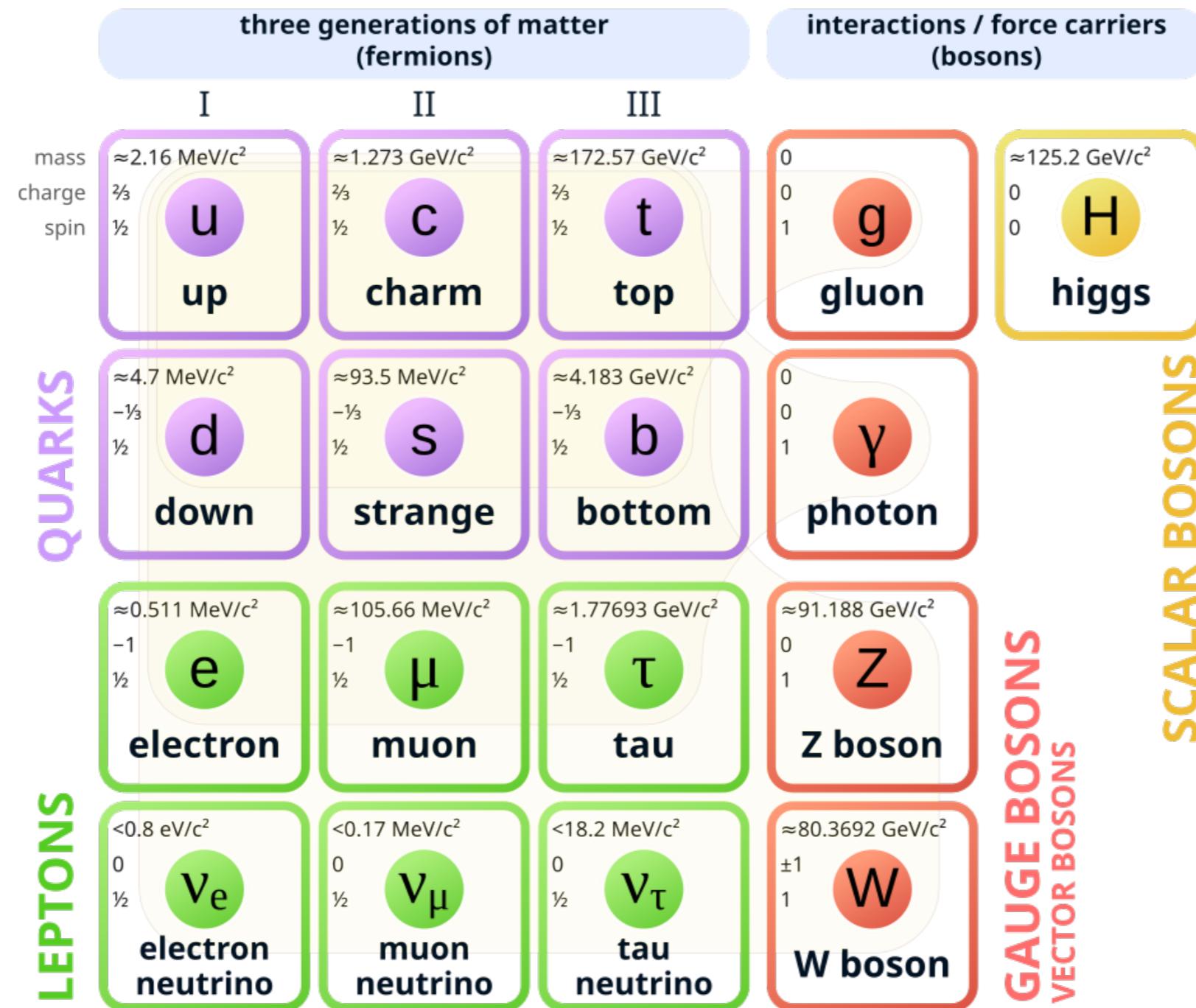


Standard Model

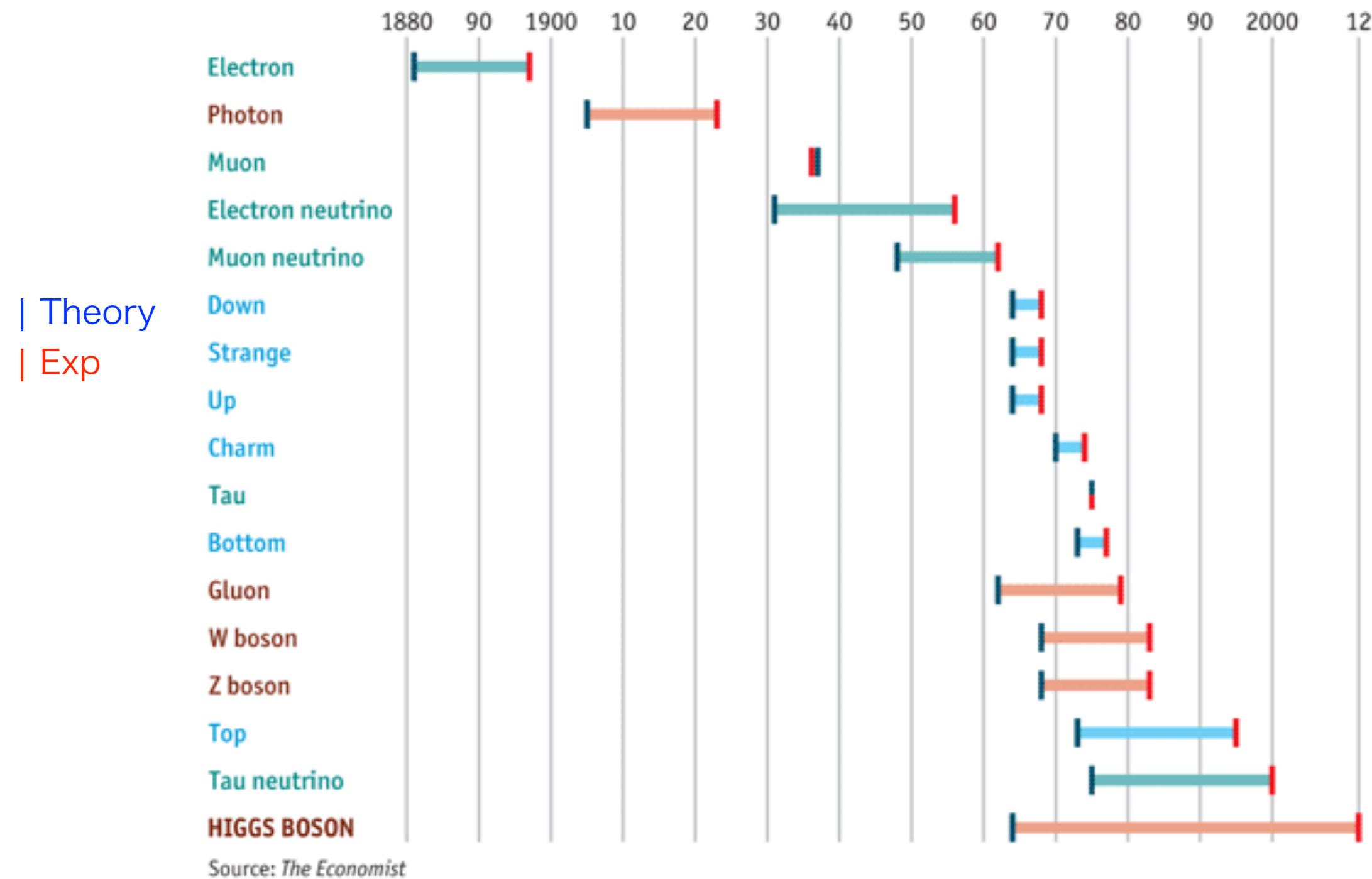


Standard Model (SM)

Standard Model of Particle Physics



Time-scale of theoretical prediction/experimental discovery



Quarks

family/generation			
	1st	2nd	3rd
mass	$\approx 2.16 \text{ MeV}/c^2$	$\approx 1.273 \text{ GeV}/c^2$	$\approx 172.57 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
QUARKS	u up	c charm	t top
	d down	s strange	b bottom

Special relativity (A. Einstein)

$$E = mc^2 \quad \text{mass} = E/c^2$$

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$$

= electron moved through 1V potential

- spin 1/2
- compose of hadrons (nucleons, pion, ..)
 - confined inside hadrons
 - we can't see quarks themselves
- feels "strong interaction" via gluons
- six quarks discovered, so far
- heavy quarks decay into lighter quarks via "weak interaction"
- have "fractional" electromagnetic charge
c.f. $q_{\text{proton}} = +1$, $q_{\text{neutron}} = 0$

Leptons

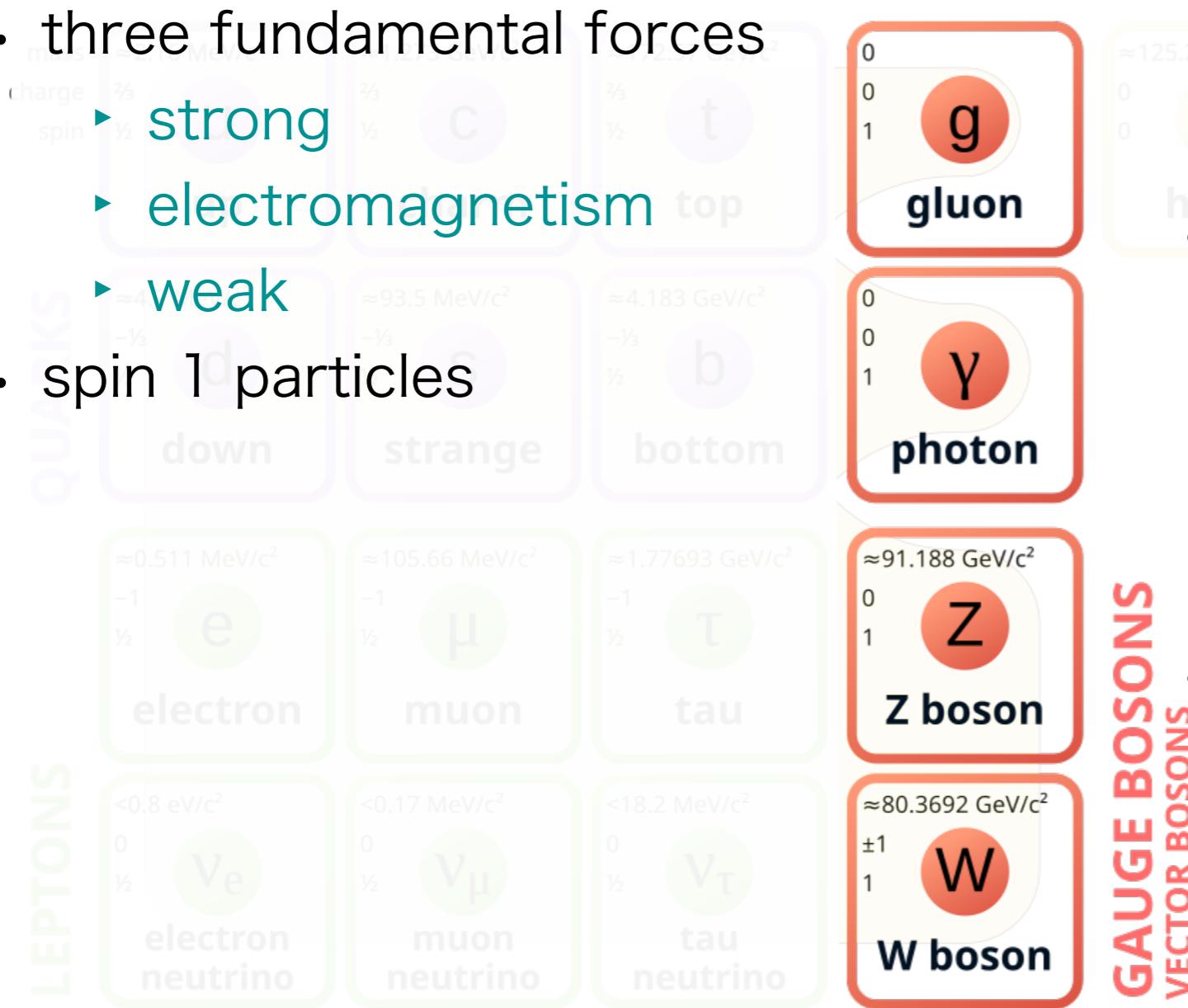
LEPTONS		QUARKS			GAUGE BOSONS		
mass	$\approx 2.16 \text{ MeV}/c^2$	$\approx 1.273 \text{ GeV}/c^2$	$\approx 172.57 \text{ GeV}/c^2$	0	$\approx 125.2 \text{ GeV}/c^2$	0	$\approx 91.188 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0	0	± 1
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	1	1	1
	u up	c charm	t top				
	d down	s strange	b bottom				
	e electron	μ muon	τ tau				
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino				

- spin 1/2

- discovered as it is (as elementary particle)
- not feels "strong interaction"
- six leptons discovered, so far
- have "integer" electromagnetic charge
 - ◆ "neutrino" = neutral + very light (-ino)
 - ◆ charged leptons

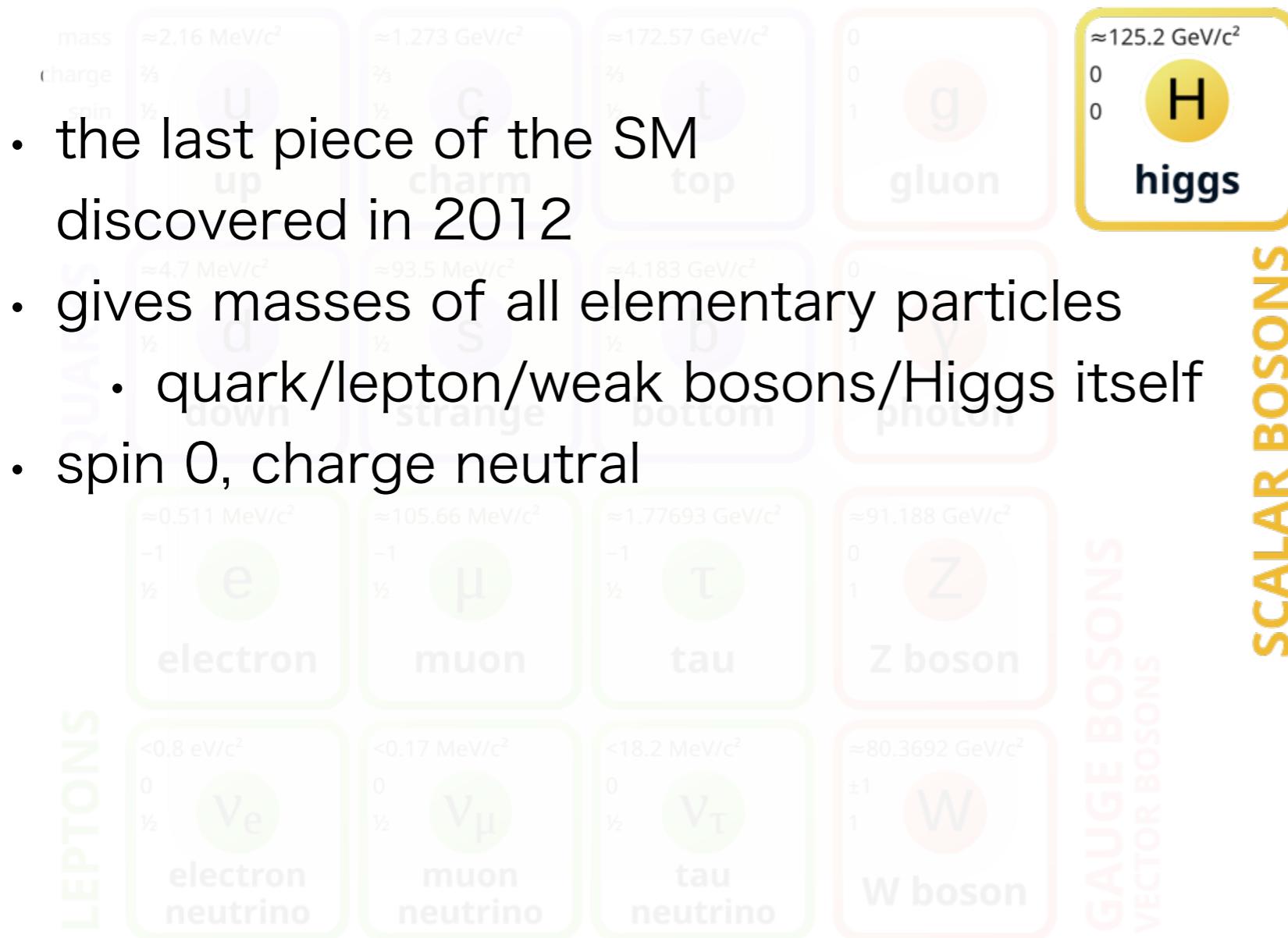
Gauge bosons (force carriers)

- three fundamental forces
 - ▶ **strong**
 - ▶ **electromagnetism**
 - ▶ **weak**
- spin 1 particles

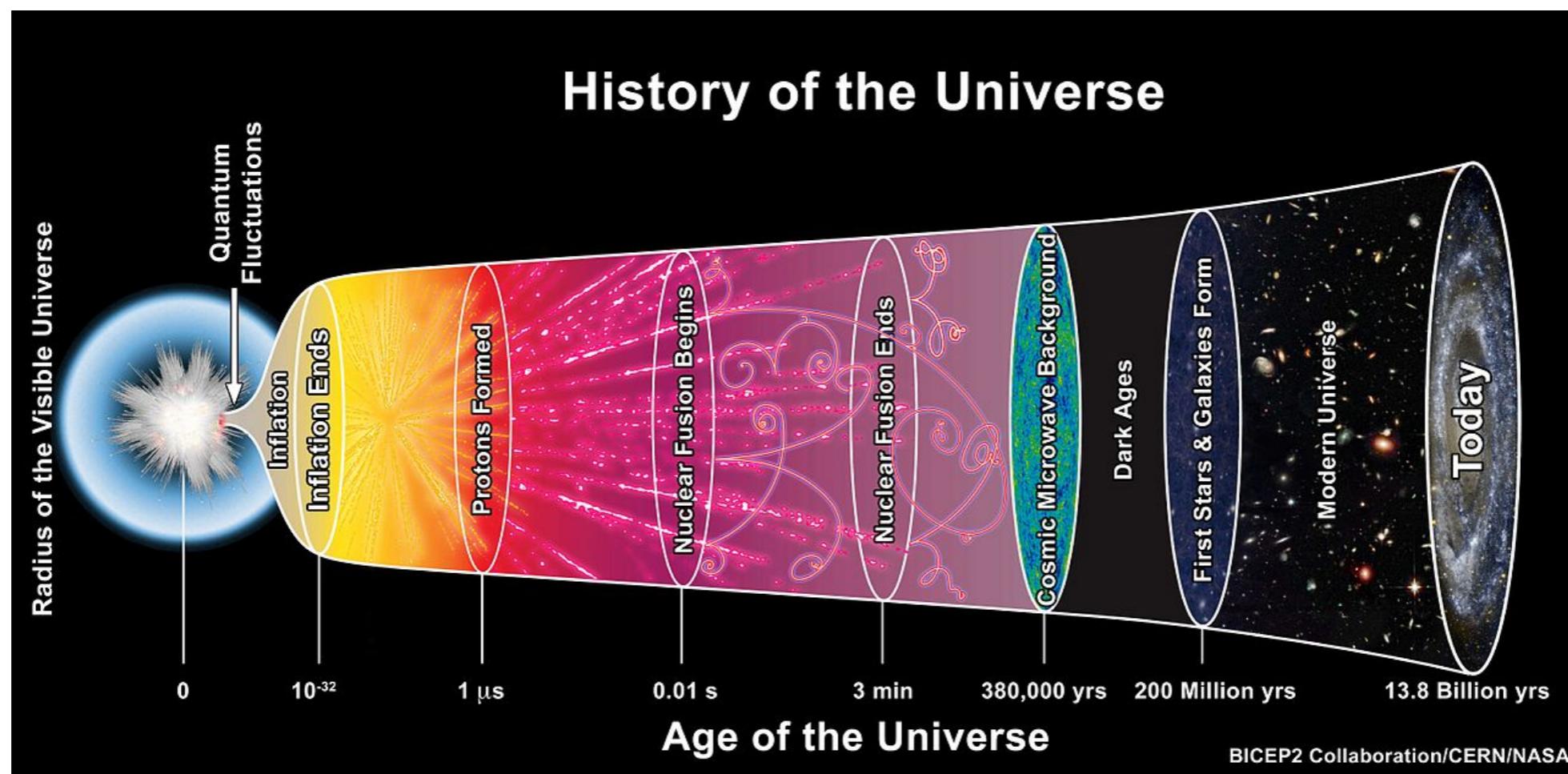


- **gluon (strong)**
 - we can't see isolated gluons as with quarks
- **photon (EM)**
 - known as "light" (X-ray, γ -ray)
 - long-range force
- **weak bosons (weak)**
 - massive particle
 - short-range force
 - charged "W", neutral "Z"

Higgs Particle



Standard (Big-Bang) Cosmology



SM of particle physics + standard cosmology (dark energy + dark matter)
agrees with cosmological observations

Beyonds of Standard Model



Short break in 10 mins?

Beyonds

Misteries in SM

there remain questions/problems in the SM

- Number of parameters (19 in the SM)
- Neutrino is massless particle in the SM (but, neutrino masses are observed)
- No candidate of Dark Matter in the SM / What is dark energy?
- Baryon asymmetry generation
- "Flavor" structure of the SM

- dynamics of quark -> hadron formation
(confinement and mass gap/Millennium puzzle by Clay Mathematics Institute)
- Hierarchy problem from Higgs particle
- Consistent quantum gravity

- etc... Models beyond the SM (BSM) have been pursued

Number of Parameters

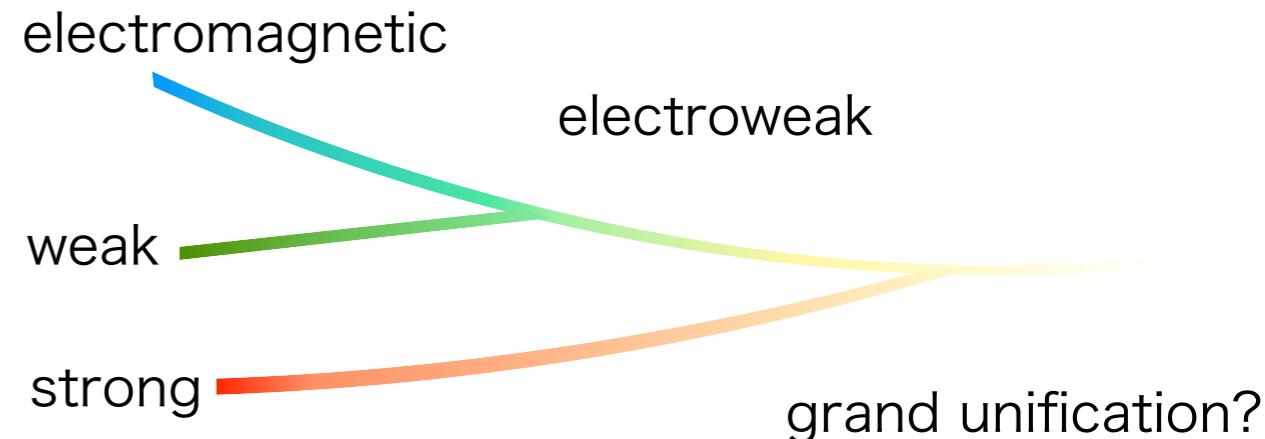
Standard Model "Lagrangian" (a fundamental quantity)

$$\begin{aligned}\mathcal{L} = \sum_G & \left[-\frac{1}{2} \text{tr}(F_G^{\mu\nu} F_{G\mu\nu}) - \theta_G \frac{g_G^2}{32\pi^2} \text{tr}(\widetilde{F}_G^{\mu\nu} F_{G\mu\nu}) \right] \\ & + \sum_f \bar{f} D f - \sum_{f,f'} (Y_f \phi \bar{f}_L f'_R + \text{h.c.}) + |D_\mu \phi|^2 + \mu^2 |\phi|^2 - \frac{\lambda}{4} |\phi|^4\end{aligned}$$

contains 19 parameters

Q: How many parameters are fundamental?

Several attempts



Unification of matters/forces

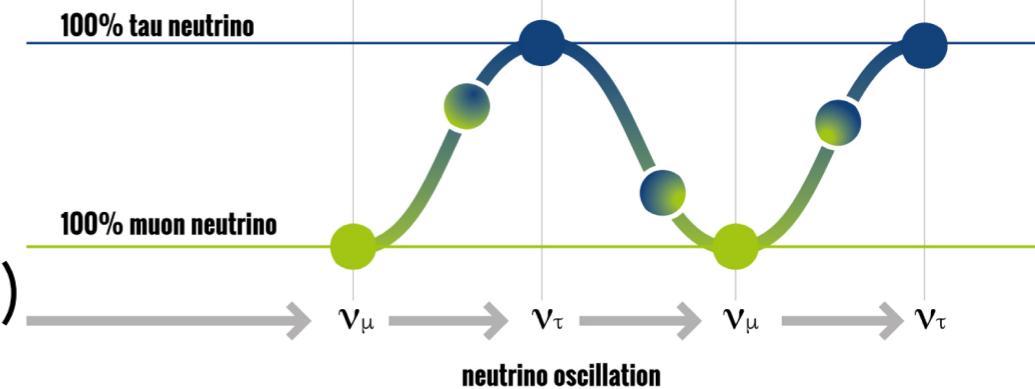
"Grand Unification Theory" (GUT) by H.Georgi and S.Glashow (1974)

proton is no longer stable: simple models are excluded by (Super-)Kamiokande

Neutrino Masses

Neutrinos are massless particles in the SM

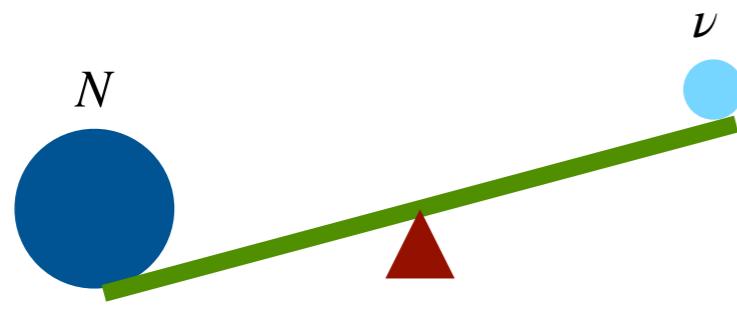
neutrino oscillation during flight (if massive)



This is the established fact that the SM is not a sufficient model
> need to be extended

Many models have been proposed:

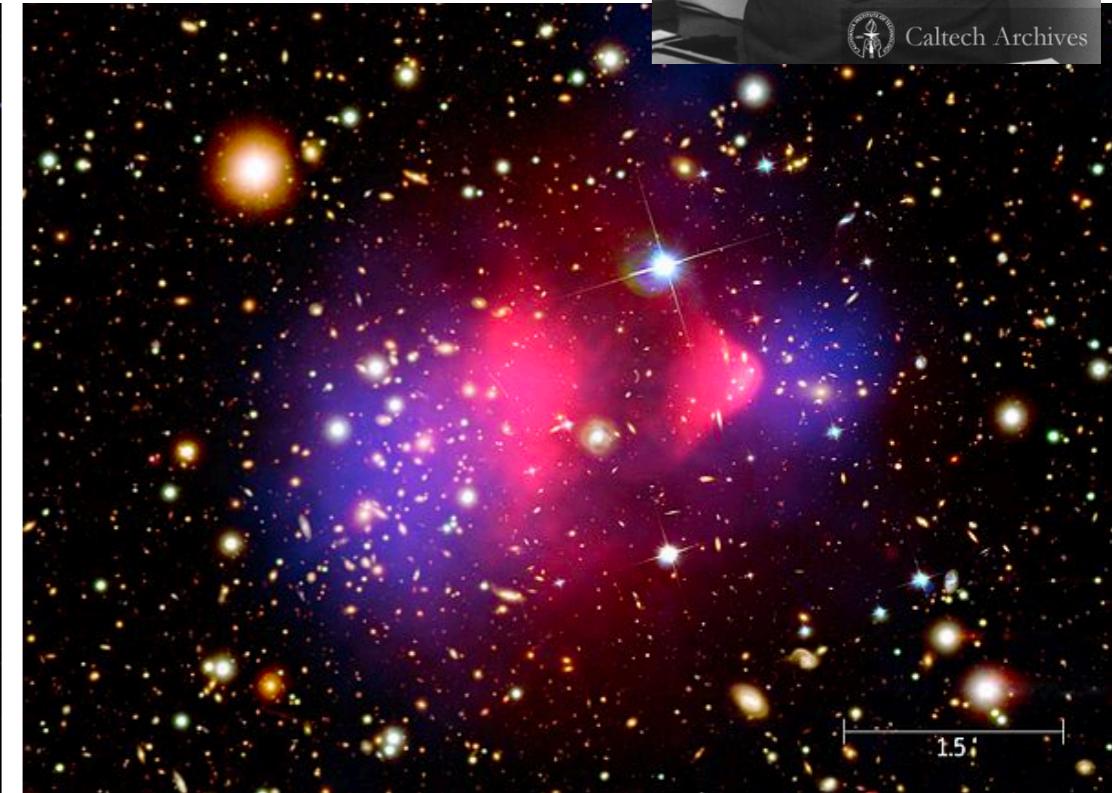
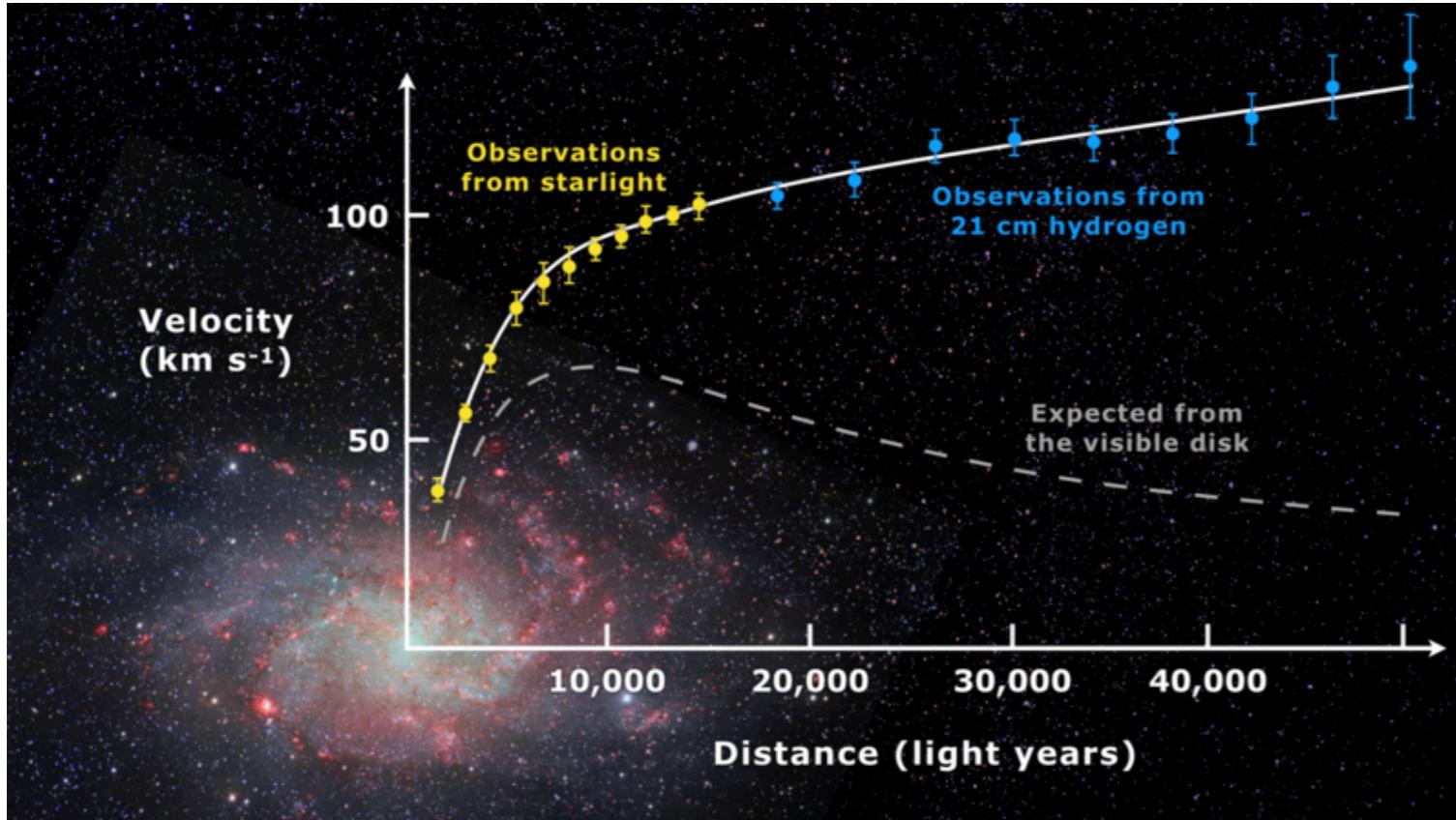
basic idea "seesaw mechanism" by T.Yanagida (1979)



Neutrino gets massive
via mixing with heavy new particles

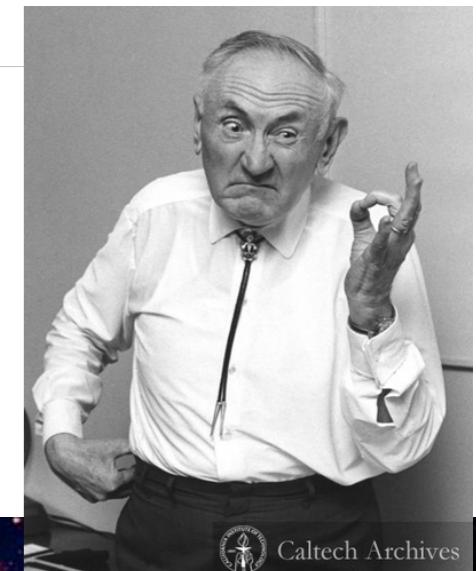
Dark Matter

Galactic Rotation curve (Newton dynamics) (1933~)

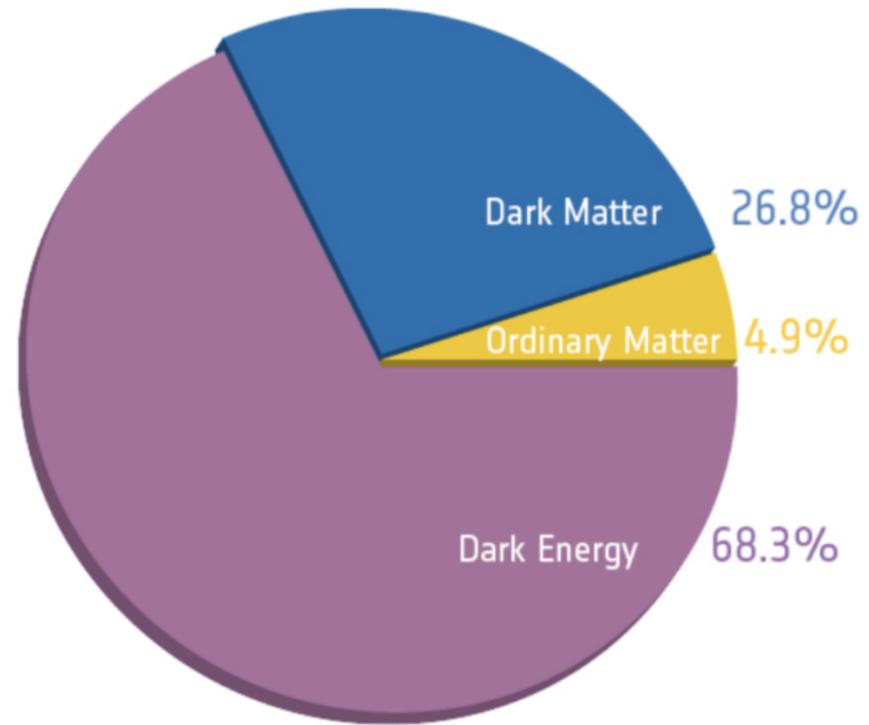


Red: X-ray (Matter)
Blue: Gravitational Source

These observations can be explained by "Dark Matter (DM)"

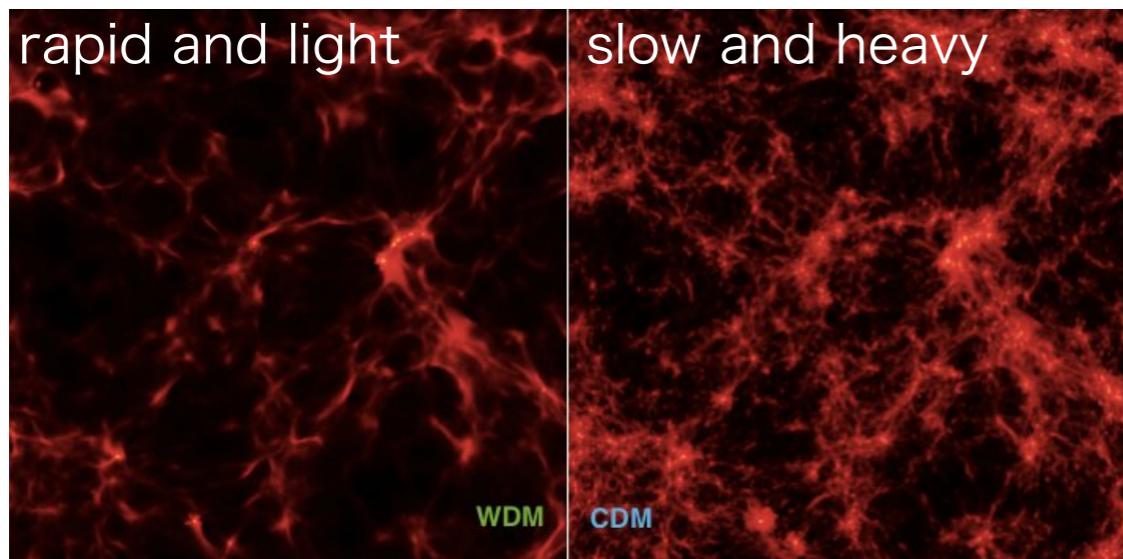


What we know about Dark Matter



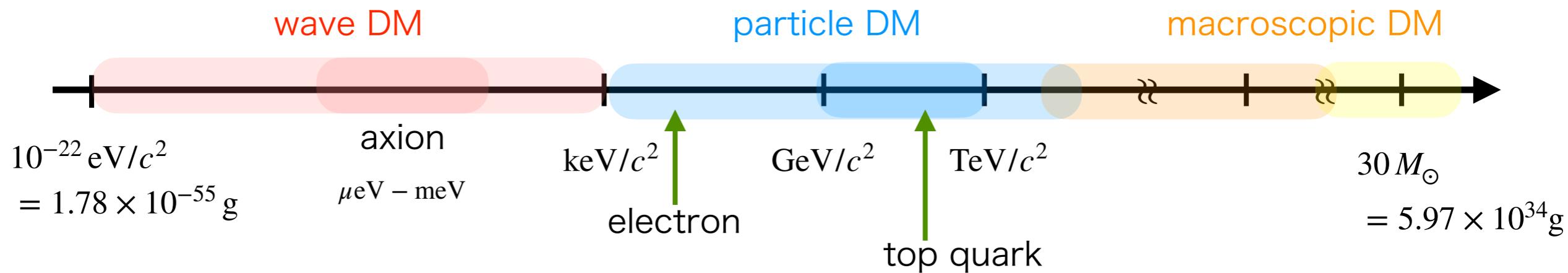
Energy density of the University
Matter : Dark Matter : Dark Energy
 $= 5 : 25 : 70$

- Stable
- Invisible/less interactive with others
(Electromagnetic Neutral)
- As a Gravitational Source
(= very slow and seed of galaxies)
- No candidate in SM
(= definite evidence for BSM)



Dark Matter Candidates

DM mass range is very broad



wave dark matter: de Broglie wavelength $\lambda = h/mv$ is large

"quantum" wave behaves as dark matter: $\lambda \simeq 1 \text{ kpc} \left(\frac{10^{-22} \text{ eV}/c^2}{m} \right)$

particle dark matter: destroys the structure of the Universe if too light ($mc^2 \gtrsim 1 \text{ keV}$)

not produced in the Universe if too heavy (also unitarity bound $mc^2 \lesssim 10^2 \text{ TeV}$)

macroscopic dark matter: compact objects/astronomical objects

- non-trivial objects in QFT, such as Q-ball and Quark Nuggets
- primordial black holes, massive compact halo objects (MACHOs)

Interactions of Dark Matter

DM is found only through gravitational interaction

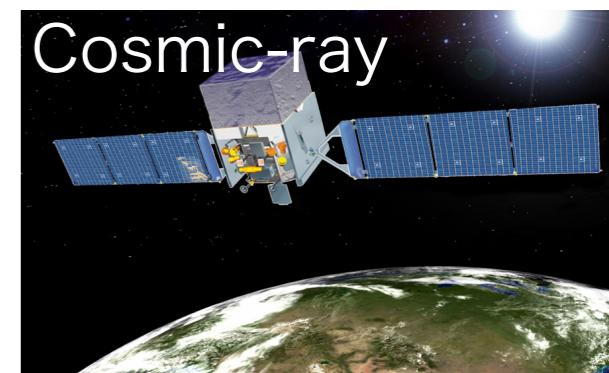
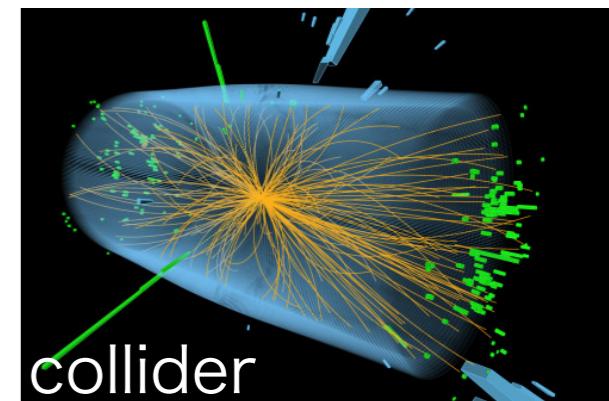
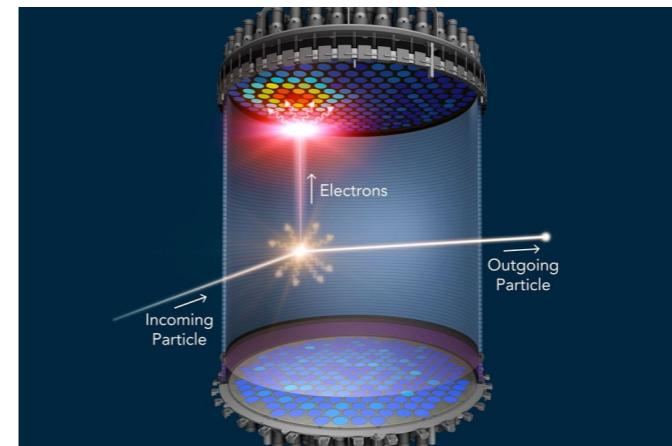
DM production in the Universe (DM-SM interactions?)

Many scenarios for production proposed
thermal DM (WIMP, SIMP, ...)
non-thermal DM (such as decay, ...)
Asymmetric DM
so on

have been tested in various ways

DM Self-interactions?

DM-nucleus scattering



- 👍 Large-scale structure (galaxy scale larger than $1 \text{ Mpc} = 3 \times 10^{22} \text{ m}$): gravity
- 🤔 Small-scale structure (under debates) -> Hints for DM self-interaction

Dark Energy

observational fact

"accelerating expansion of the Universe"



© The Nobel Foundation. Photo:
U. Montan
Saul Perlmutter
Prize share: 1/2



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matter: gravitational collapse

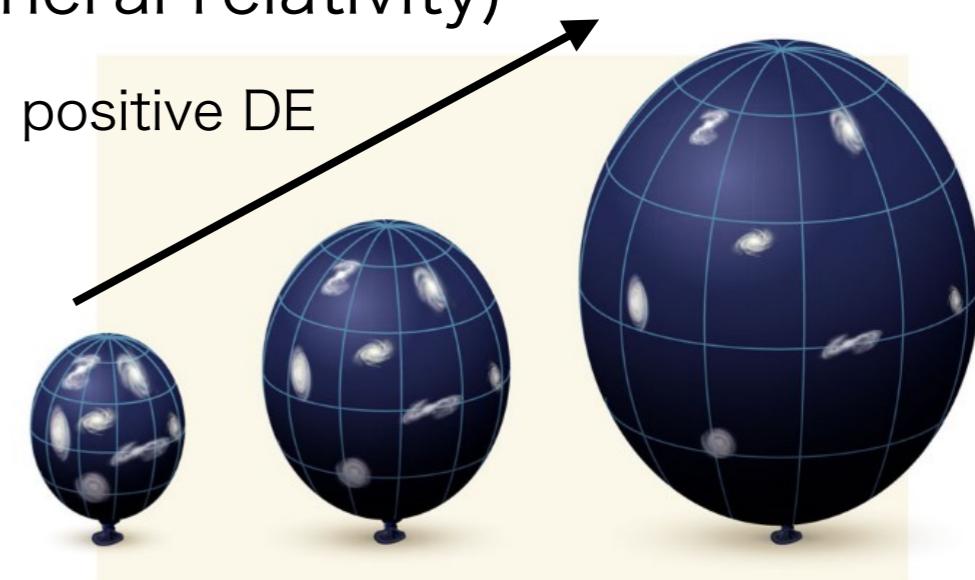
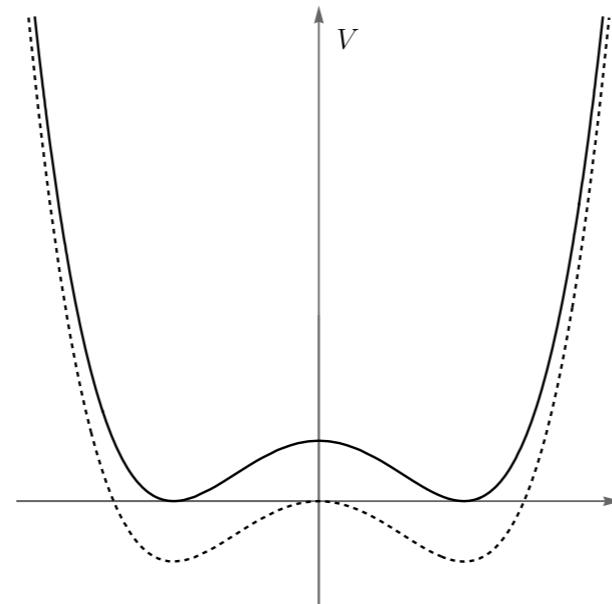
dark energy: anti-gravitational effect (expansion)

vacuum energy behaves as dark energy (general relativity)

in quantum field theory:

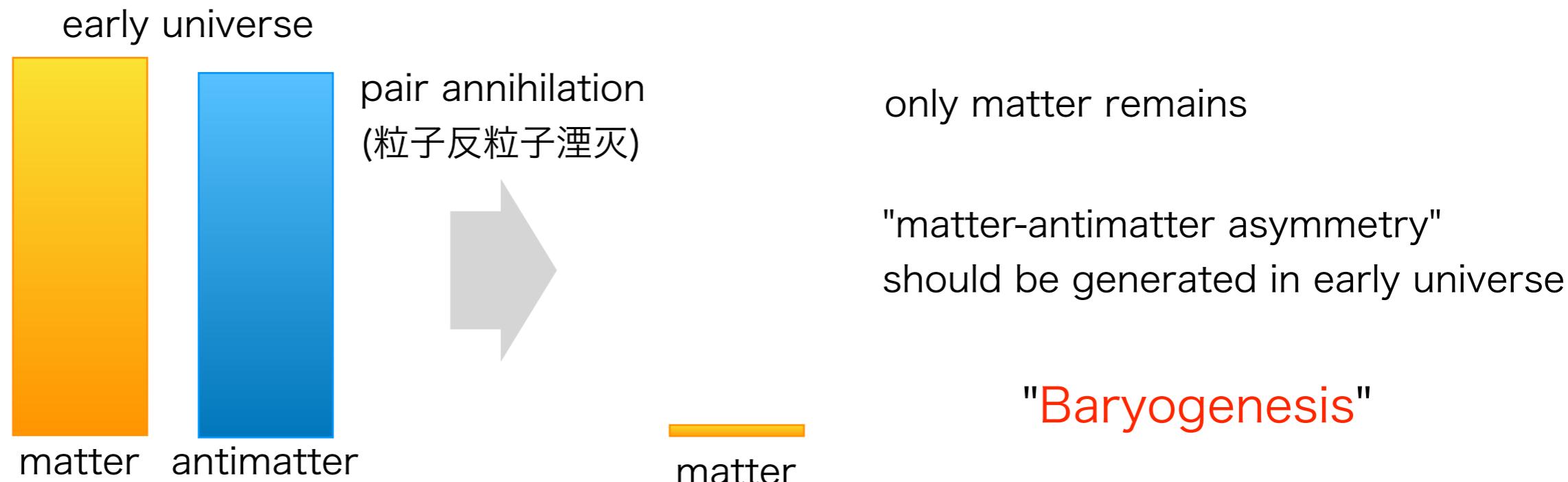
potential hight from vacuum only meaningful

-> beyond QFT?



Baryon Asymmetry of the Universe

no astrophysical objects made of "antimatter" are observed



Many models have been proposed:

- GUT Baryogenesis
- Electroweak Baryogenesis
- Spontaneous Baryogenesis
- Affleck-Dine Baryogenesis
- B-Mesogenesis

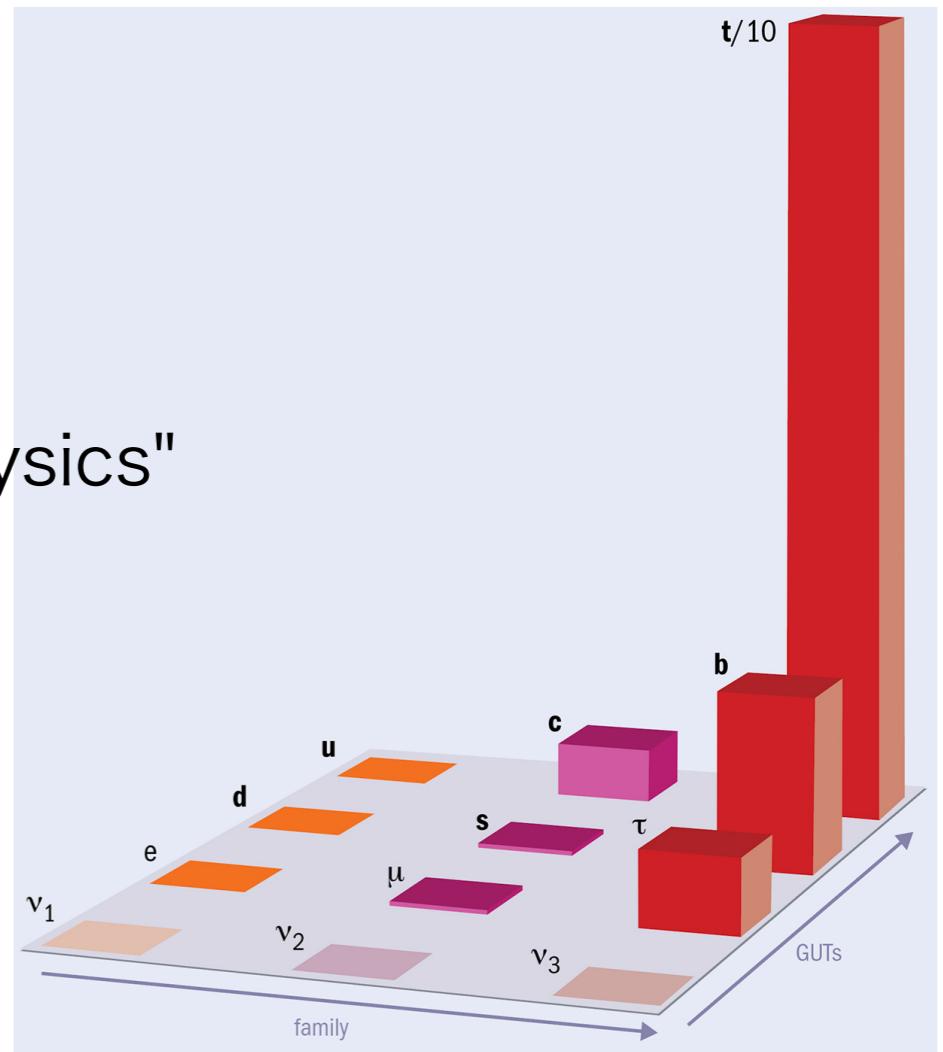
- (non-)thermal Leptogenesis
- Resonant Leptogenesis
- Leptogenesis via neutrino oscillation
- etc...

"Flavor" of Matters

"Flavor": species of matter particles

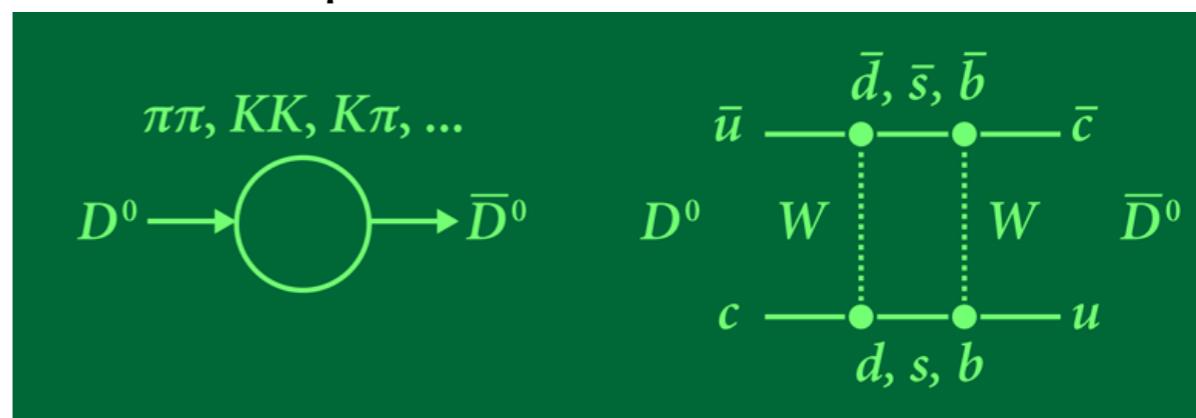
Hints of BSM may be hidden in "flavor physics"

- Why three "families"?
- Mass hierarchy (why is top q too heavy?)
- quark-lepton structures are quite different
- methodology
 - "quark" picture  -> t quarks
 - "hadron" picture  -> u,d,s quarks
 - dedicated (complicated) analysis -> c, b quarks



©CERN

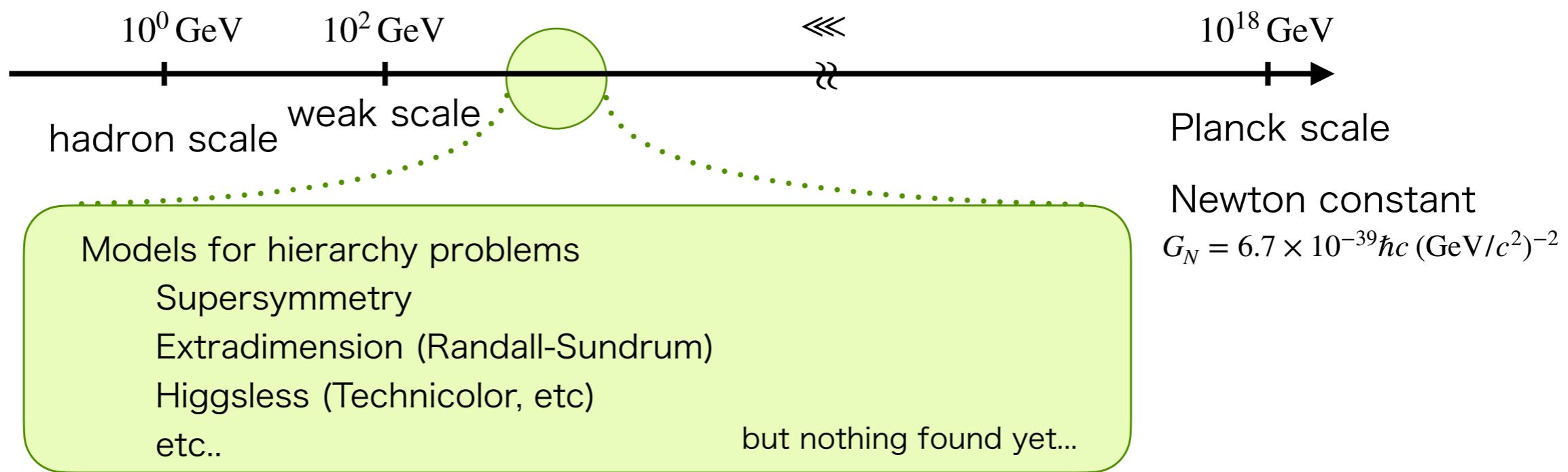
Flavor



Theoretical aspects

- **Hierarchy problem** of Higgs particle

Why is weak scale so smaller than Planck scale?



- Only gravity is not quantized in the SM

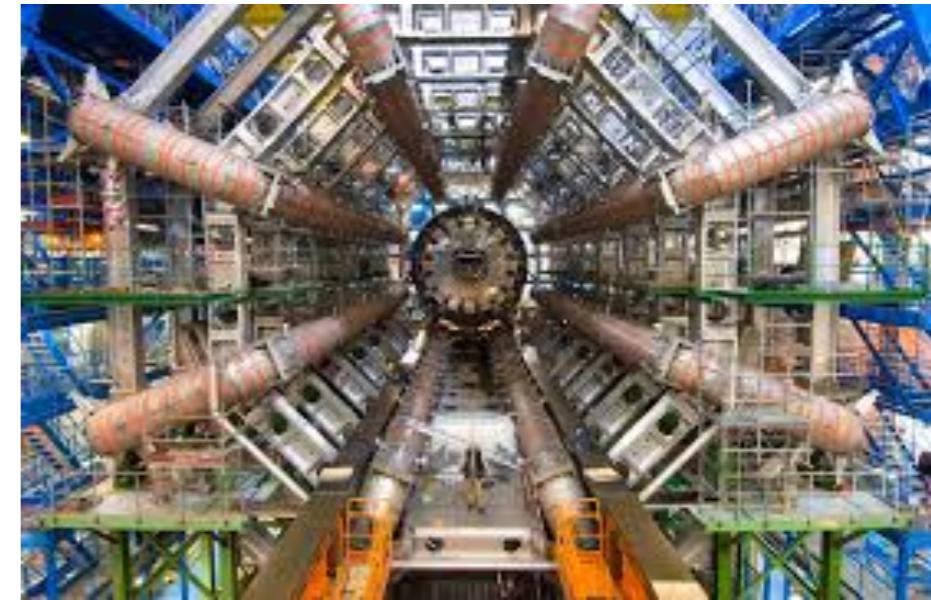
consistent quantum gravity (beyond Planck scale): string theory?

Recent Days

Despite great efforts of expts....

New signature not found so far

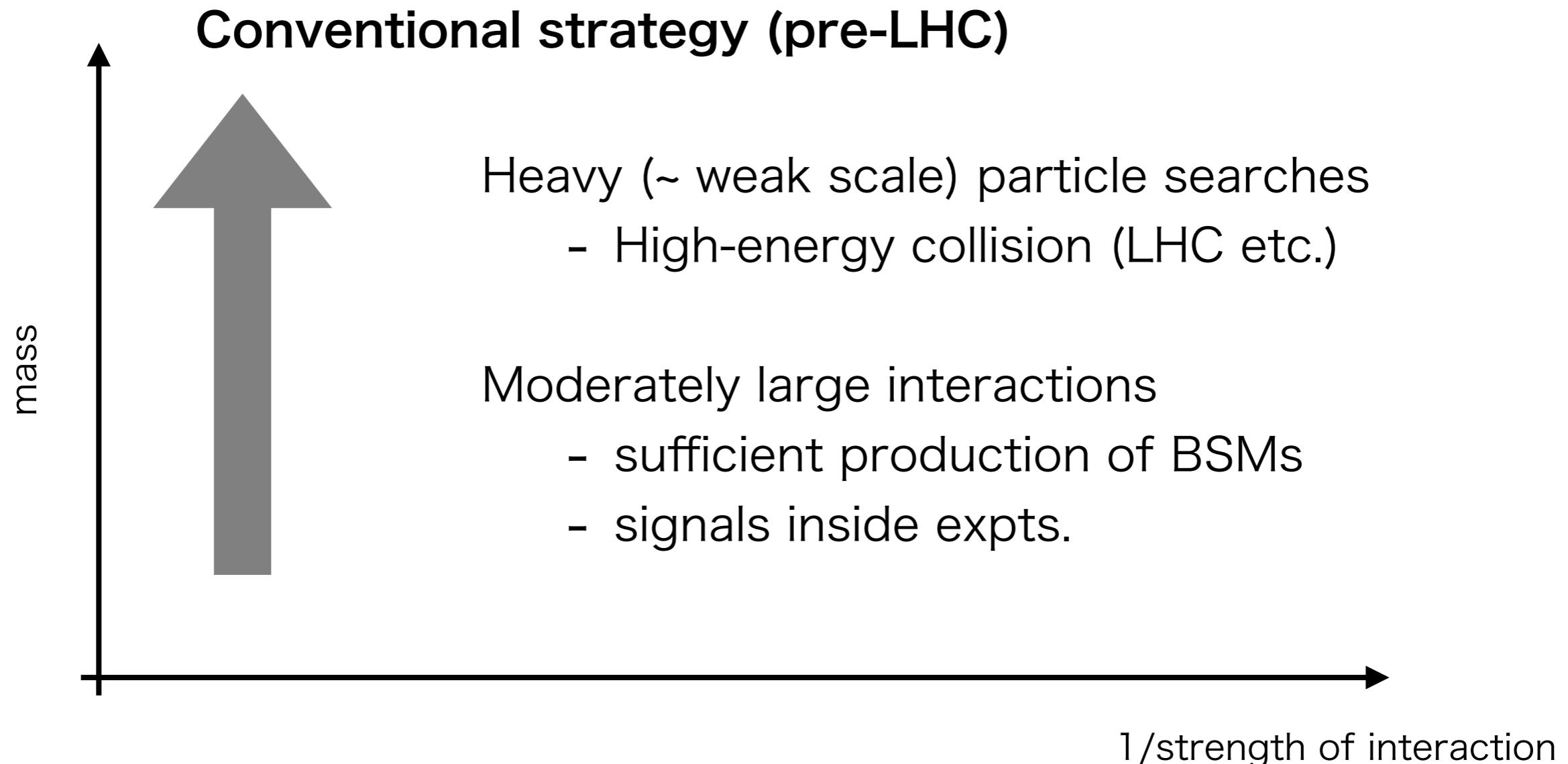
But, we also know the missing pieces of SM



Large Hadron Collider (LHC) @ CERN

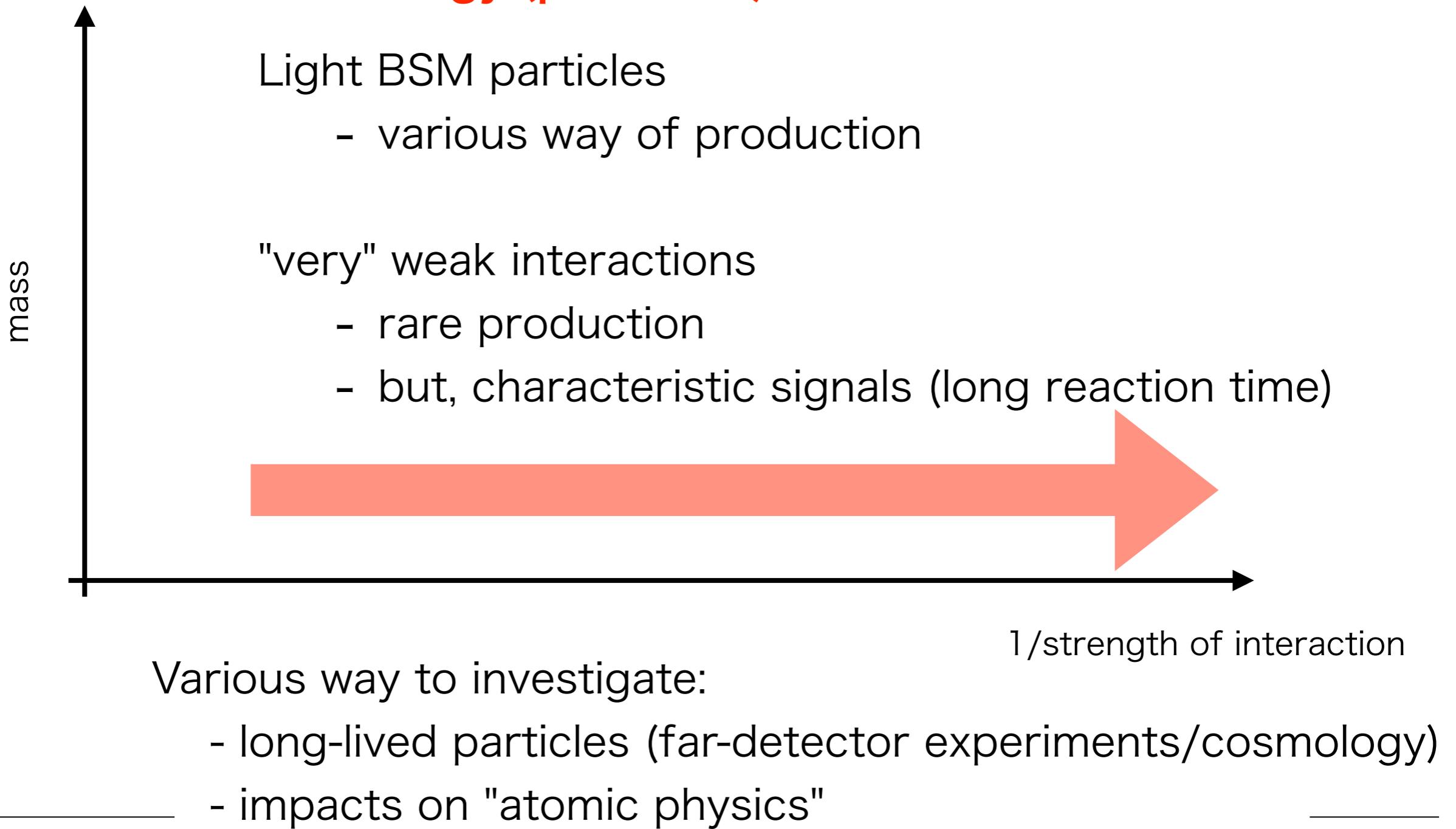
- Misunderstanding of mysteries in the SM?
- Wrong search strategies?
- any other else?

Alternative Particle Model "Dark Sector"

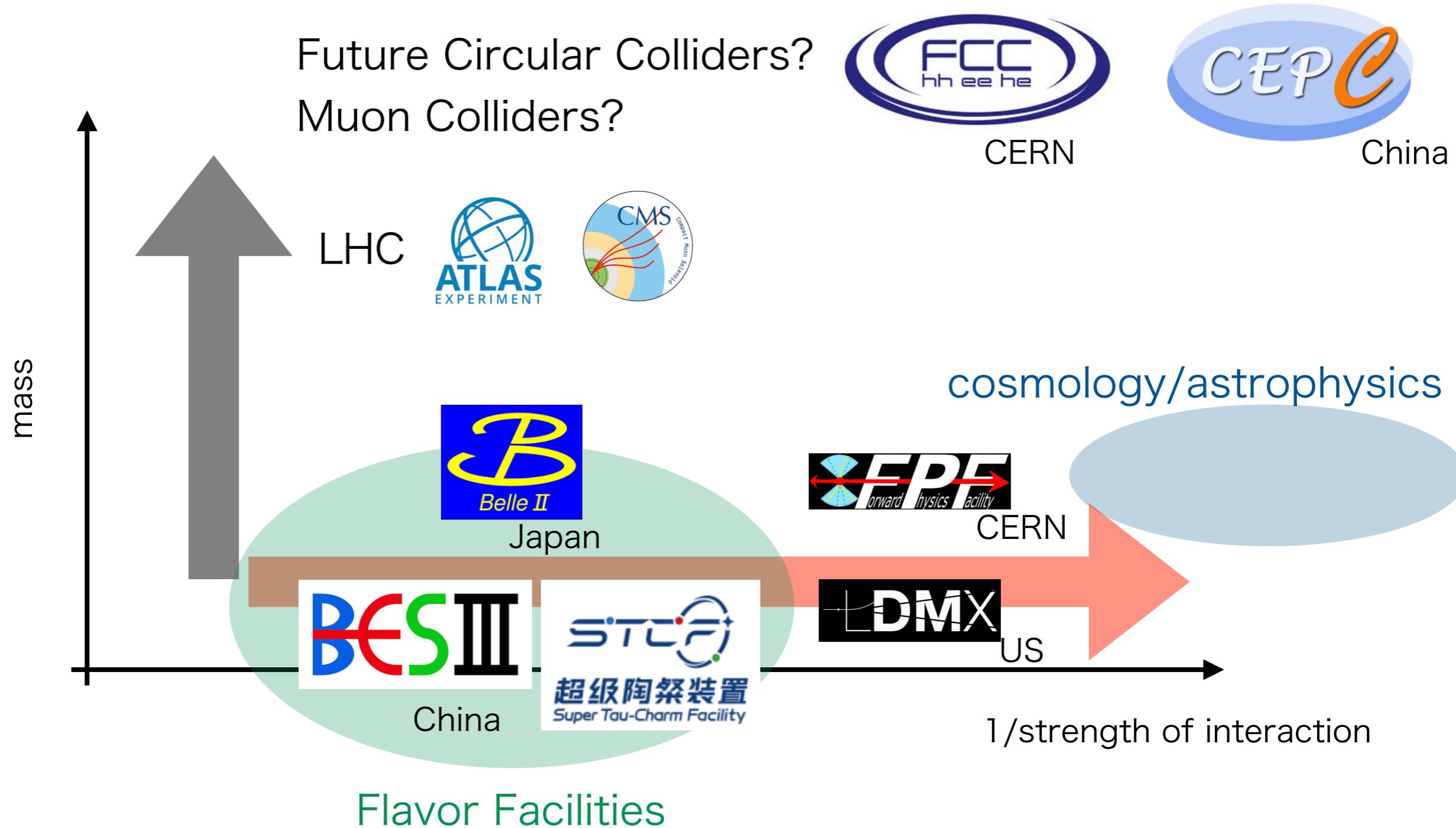


Alternative Particle Model "Dark Sector"

A new strategy (post-LHC)



Alternative Particle Model "Dark Sector"



Take-home Messages

- Particle Phenomenology:
 - investigates nature of elementary particles based on experimental data
 - understanding "theory" and "experiment" is important
- There are many unsolved problems
 - Dark Matter, Dark Energy, Neutrino Mass, Baryon Asymmetry of the Universe
- We must have something beyond the Standard Model, but not found yet.

Our Group

Phenomenology Group in Center for Theoretical Physics

Shinya Matsuzaki:

QCD, QCD-like BSM (cosmology), etc



Hiroyuki Umeeda:

Heavy Flavor Physics (b, c quark)



Me:

Dark Matter (Dark Sector), BSM Model Building