Frontier of Physics/Oct 24th, 2025

History and Progress in Particle Phenomenology

Takumi Kuwahara

Self introduction

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Research: Particle Phenomenology

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

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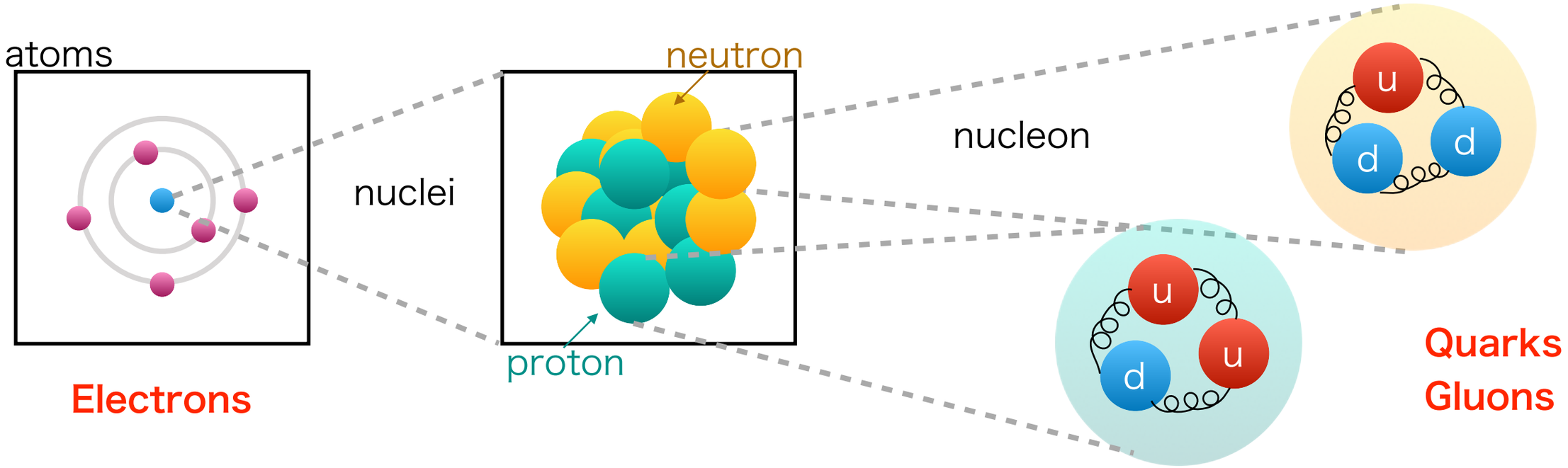
Contents

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)

arXiv New papers everyday

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Physics Search Form Interface Catchup

Physics

- Astrophysics (**astro-ph** new, recent, search) Astrophysics of Galaxies; Cosmology and Nongalactic Astrophysics; Earth and Planetary Astrophysics; High Energy Astrophysical Phenomena; Instrumentation and Methods for Astrophysics; Solar and Stellar Astrophysics
- 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
- General Relativity and Quantum Cosmology (**gr-qc** new, recent, search)
- High Energy Physics - Experiment (**hep-ex** new, recent, search)
- 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

phenomenology

- predictions for elementary particle processes
- modeling unknown dynamics/phenomenology observed at expts. and obs.
- connection between theory and expts.

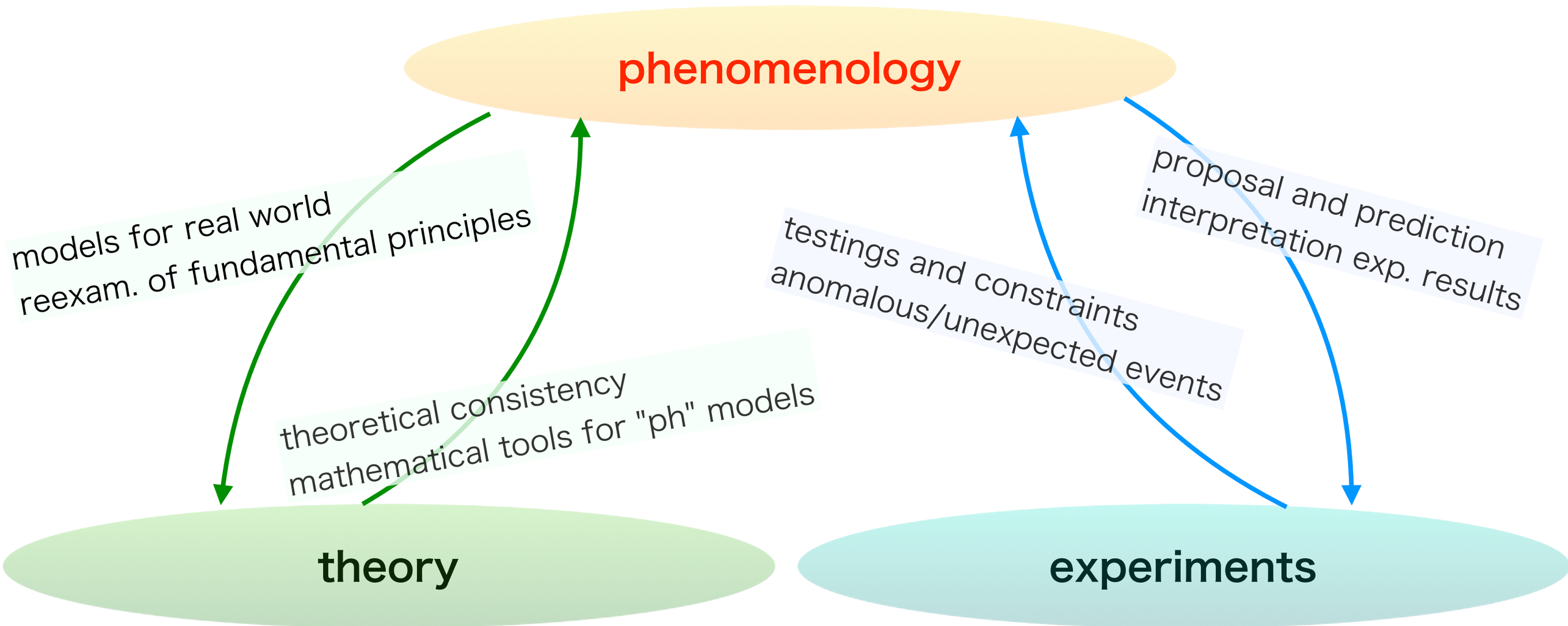
theory

- deepen understanding of structure of physics theories (symmetry, duality...)
- ideal setups and solvable setups
- connection to mathematics (but physics)

experiments

- expt. investigation of particle processes
- produce rare particles by high-energy collision
- observe rare process (of known particles)

Position of High-Energy Phenomenology

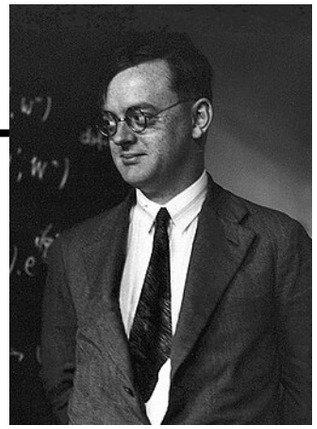


History of Particle Physics and the Standard Model

History of Particle Physics


W.Heisenberg


M.Born

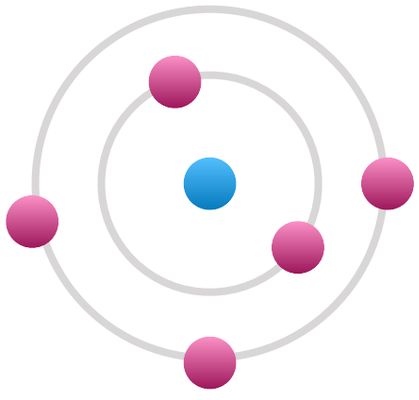

P.Jordan

1900 - early 1920's: old quantum mechanics

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

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


E.Schrödinger



INTERNATIONAL YEAR OF Quantum Science and Technology

100 YEARS OF QUANTUM IS JUST THE BEGINNING

typical size of atoms ~ 10^{-8} cm = 1 Å

To understand Atomic Physics

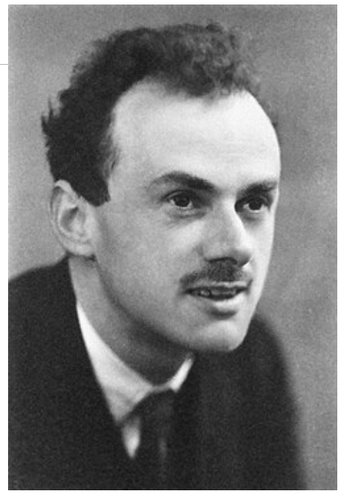
Any entities in the Universe has
particle-like behavior and wave-like behavior

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

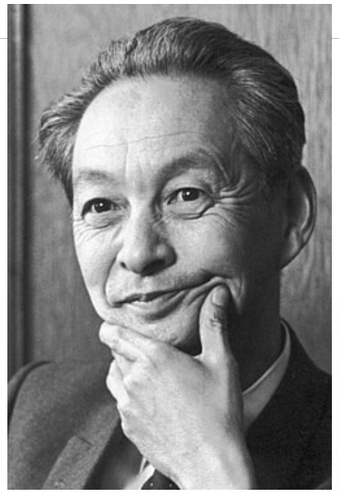
Birth of **Quantum Field Theory** (QFT: 量子场论)

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


J. Schwinger

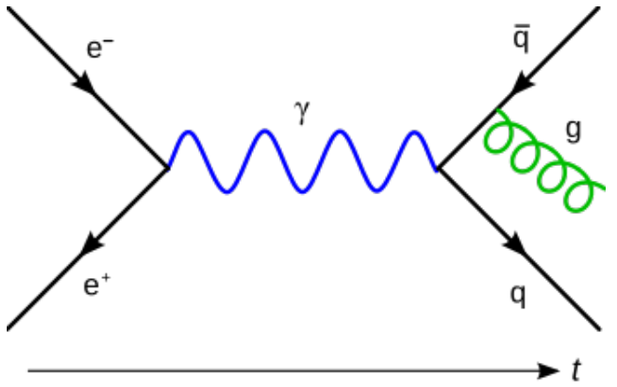

S. Tomonaga

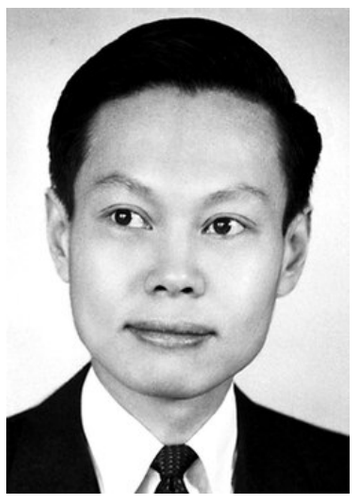

R. Feynman

- **Renormalization** (重整化)
  treatment of infinities in QFT
  J. Schwinger (1948), S. Tomonaga (1948)

- **Feynman Diagram** (1948)
  pictorial representation of mathematical computation

- **Yang-Mills theory**
  basic of fundamental forces
  C. N. Yang and R. Mills (1954)

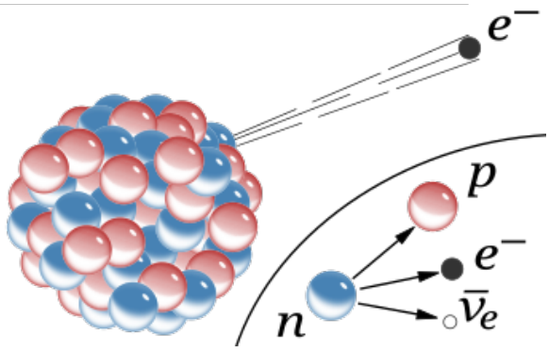



C. N. Yang


R. L. Mills

History of Standard Model

E. Fermi



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")

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)

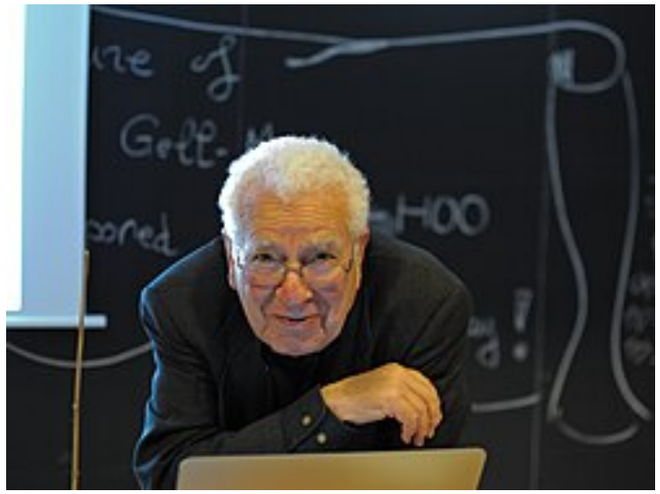
Success of electroweak theory

What about nucleons?

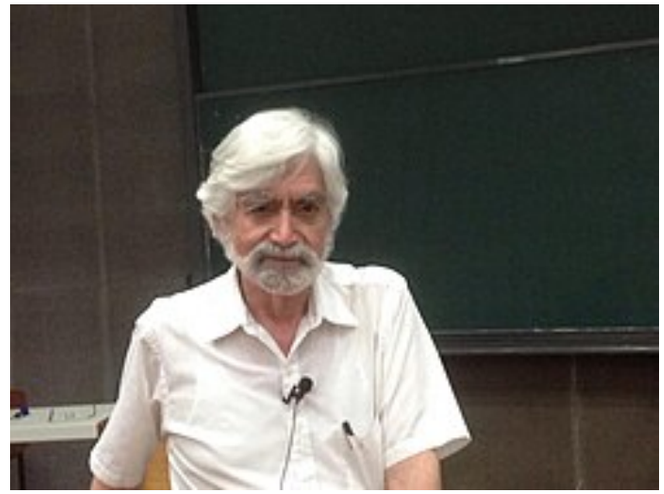
"Particle Zoo" ("subnuclear zoo" by R. Oppenheimer)

many particles (="hadrons")

have been found at accelerators since 1950s



M. Gell-Mann



G. Zweig

Quark Model

M. Gell-Mann, G Zweig (1964)

systematic treatments of

"particle zoo"

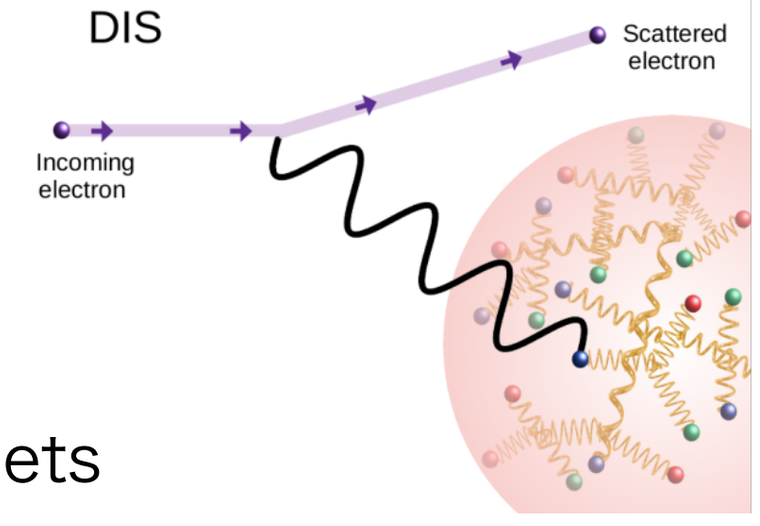
"hadrons" have an inner structure

and consist of "quarks" and "gluons"

Deep inelastic scattering

Stanford Linear Accelerator Center (SLAC)

found the inner structure of proton (1969)



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

How many quarks?

Discovery of an exotic decay process (1964)

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

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

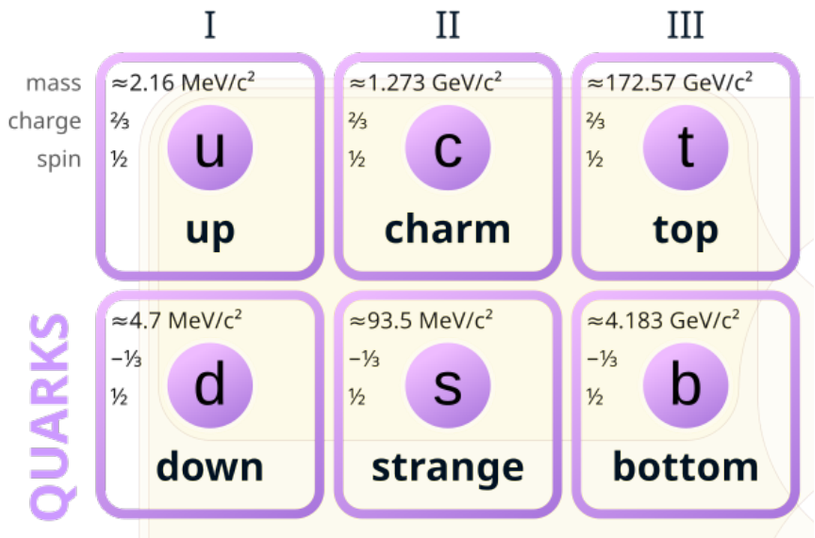
M. Kobayashi

T. Maskawa

M. Kobayashi and T. Maskawa (1973)

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

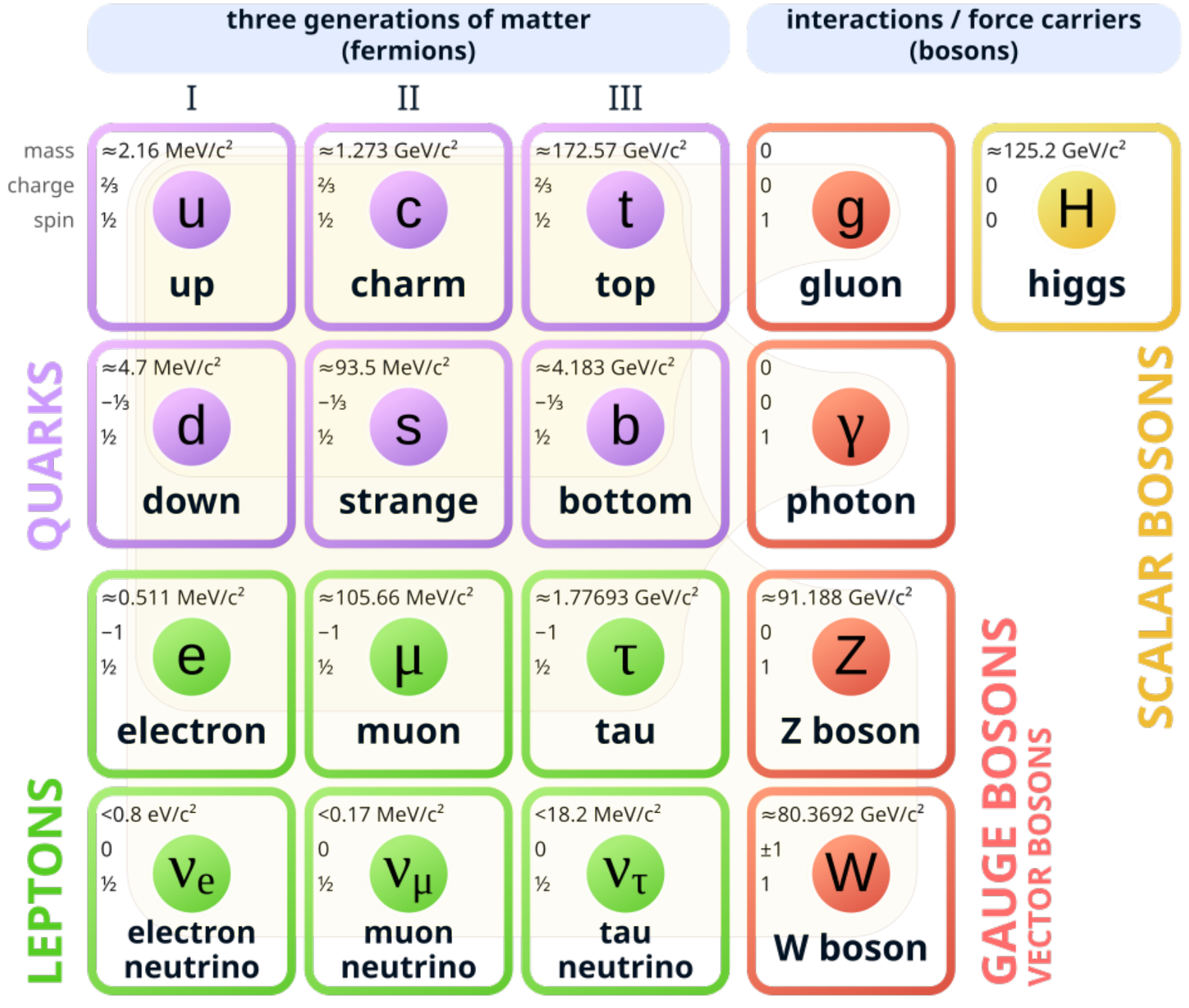
at least **six kinds of quarks** are required in the quark model



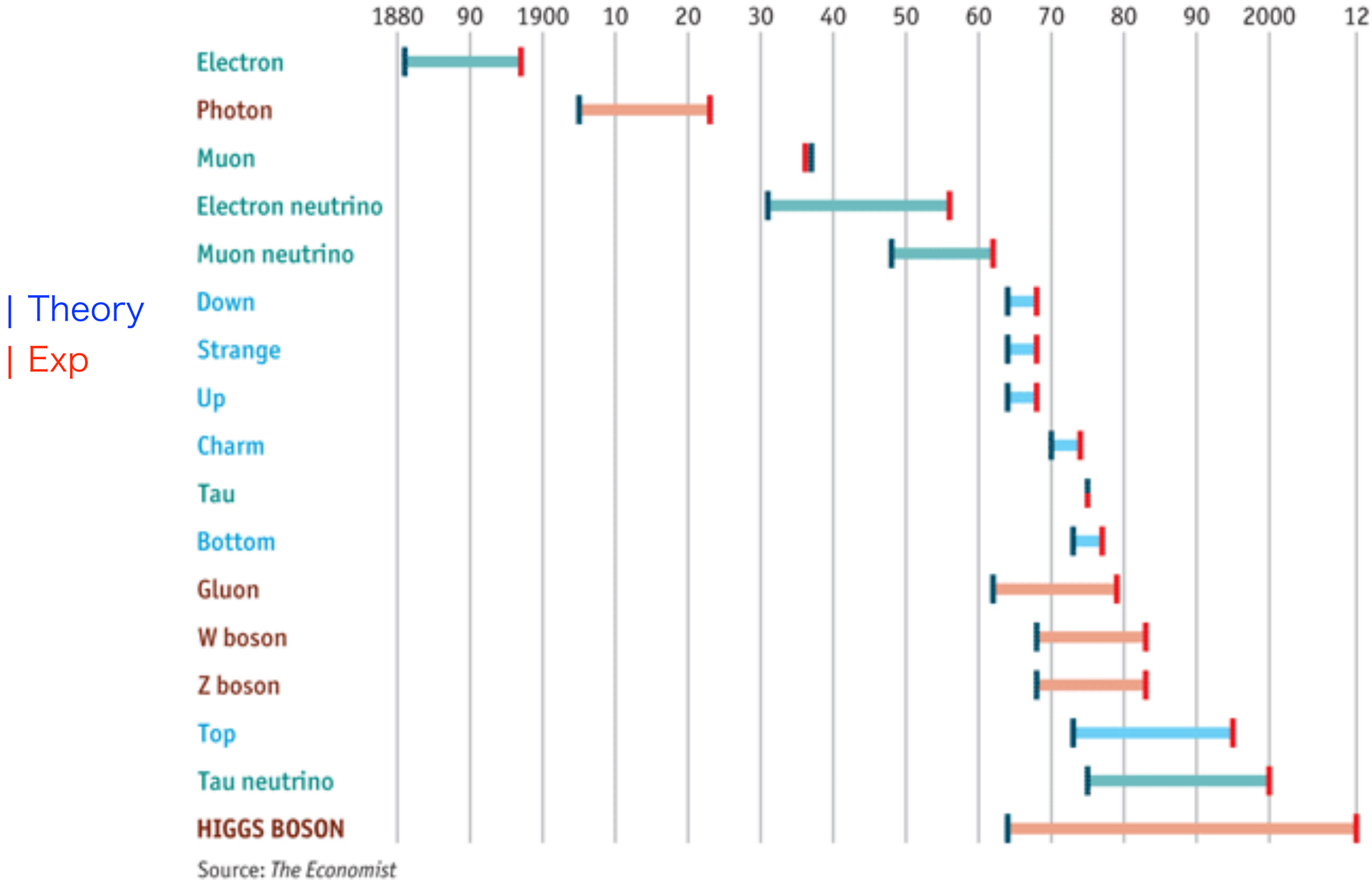
Standard Model

Standard Model (SM)

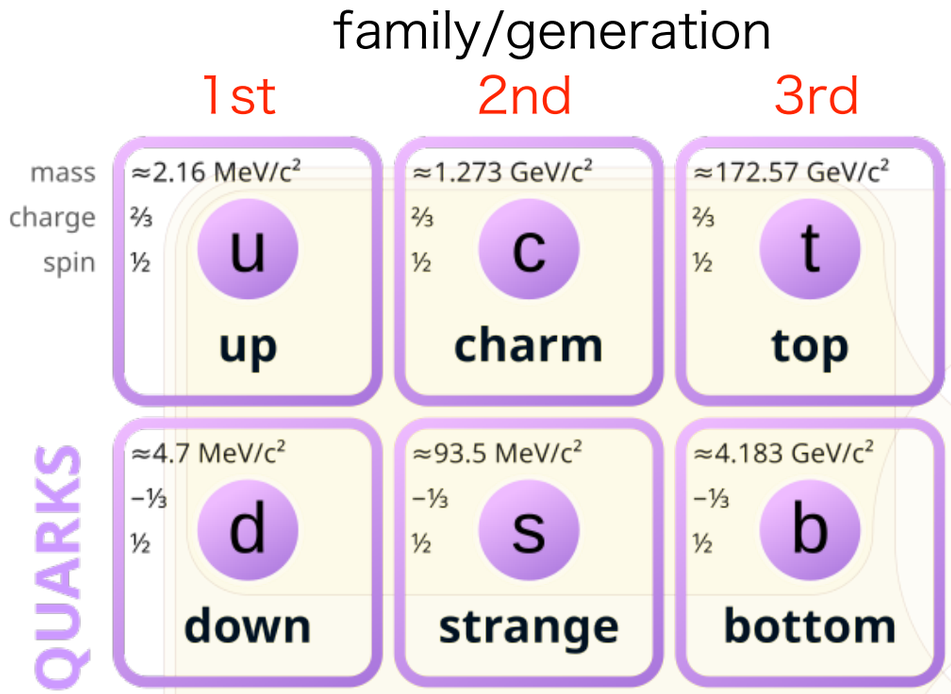
Standard Model of Particle Physics



Time-scale of theoretical prediction/experimental discovery



Quarks



- 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

Special relativity (A. Einstein)

$E = mc^2$ mass = E/c^2

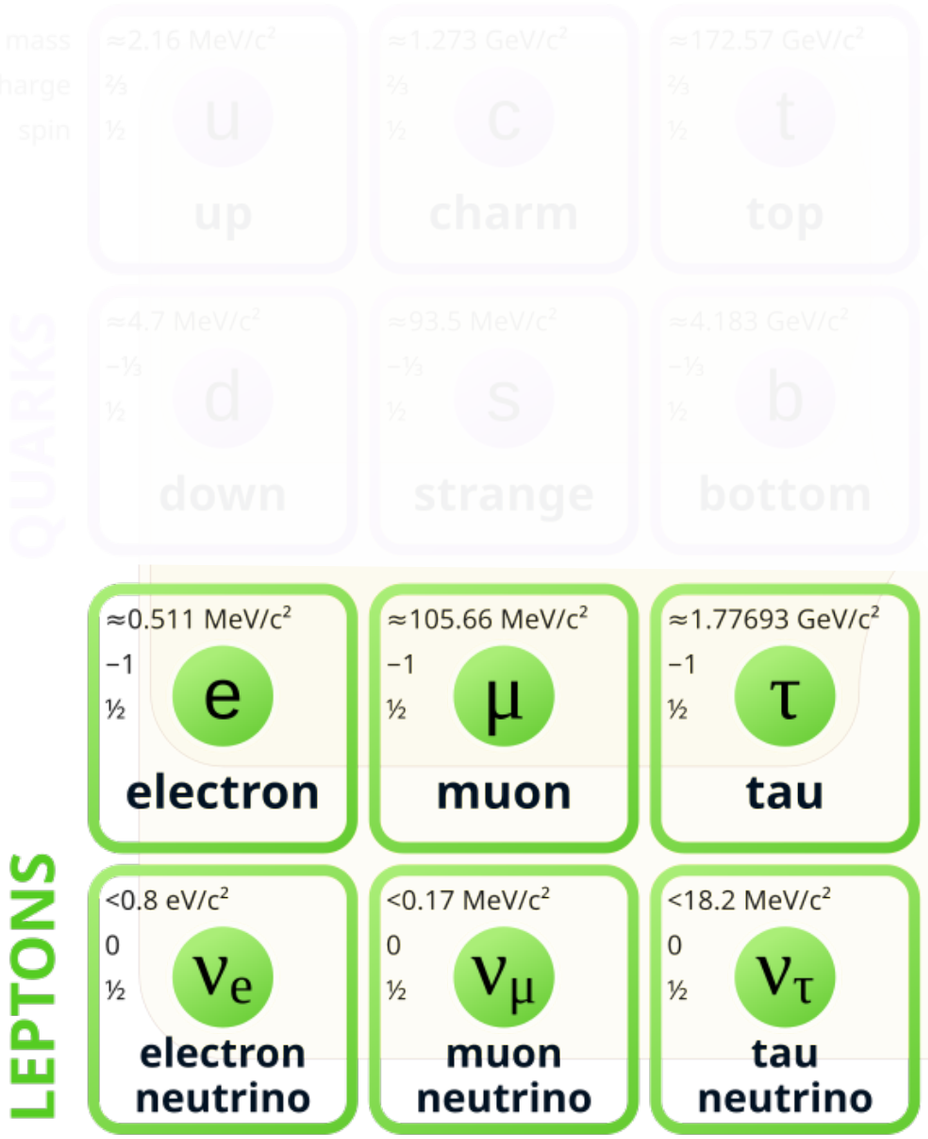
1 eV = 1.602×10^{-19} J

= electron moved through 1V potential

- heavy quarks decay into lighter quarks via "weak interaction"
- have "fractional" electromagnetic charge

  c.f. $q_{proton} = +1$, $q_{neutron} = 0$

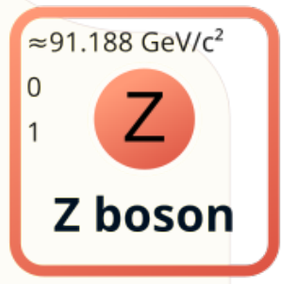
Leptons

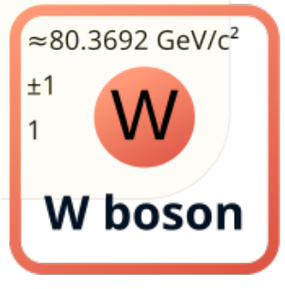


- spin 1/2
- discovered as it is (as elementary particle)
- not feels "strong interaction"
- six leptons discovered, so far
- have "integer" electromagnetic charge
  - ✦ "neutrino" = neutral + very light (-ino)
  - ✦ charged leptons

Gauge bosons (force carriers)

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





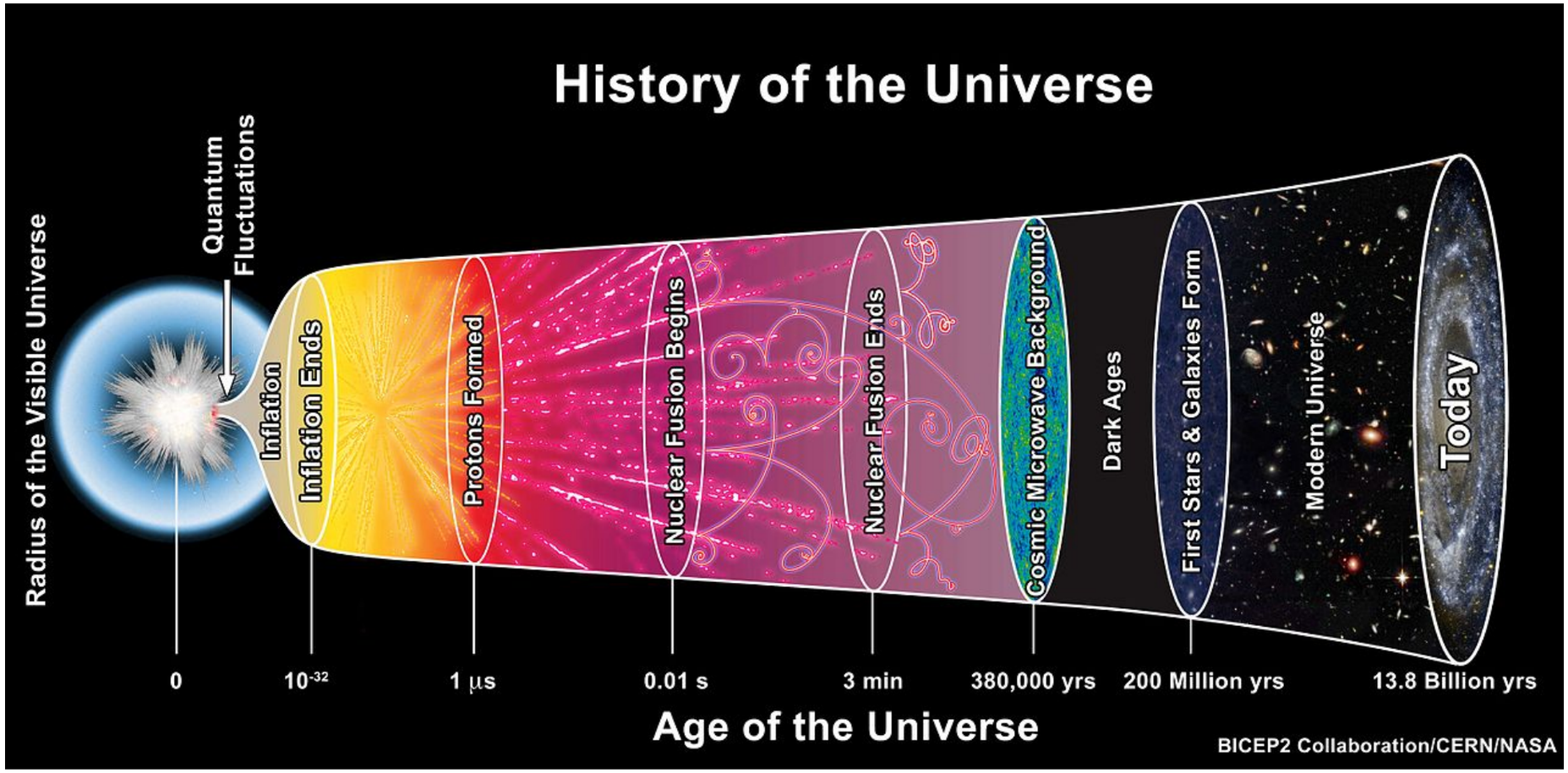
GAUGE BOSONS
VECTOR BOSONS

- 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

- the last piece of the SM discovered in 2012
- gives masses of all elementary particles
  - quark/lepton/weak bosons/Higgs itself
- spin 0, charge neutral

Standard (Big-Bang) Cosmology



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

Beyonds of Standard Model

Short break in 10 mins?

Beyonds

Mysteries 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

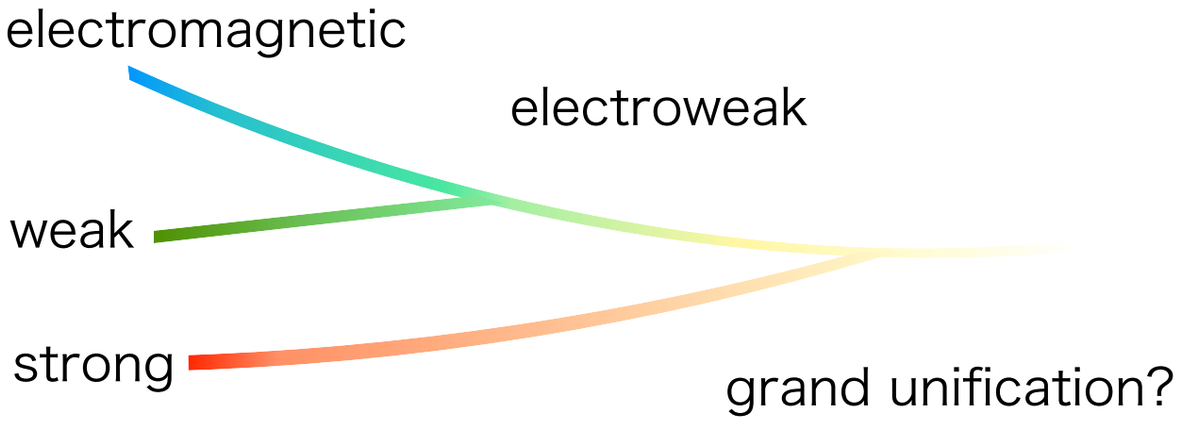
Standard Model "Lagrangian" (a fundamental quantity)

$$\mathscr{L} = \sum_G \left[-\frac{1}{2}\mathrm{tr}(F_G^{\mu\nu} F_{G\,\mu\nu}) - \theta_G \frac{g_G^2}{32\pi^2}\mathrm{tr}(\widetilde{F}_G^{\mu\nu} F_{G\,\mu\nu}) \right]$$

$$+ \sum_f \bar{f} \not{D} f - \sum_{f,f'} (Y_f \phi \bar{f}_L f'_R + \mathrm{h.c.}) + |D_\mu \phi|^2 + \mu^2 |\phi|^2 - \frac{\lambda}{4}|\phi|^4$$ contains 19 parameters

Q: How many parameters are fundamental?

Several attempts



Unification of matters/forces

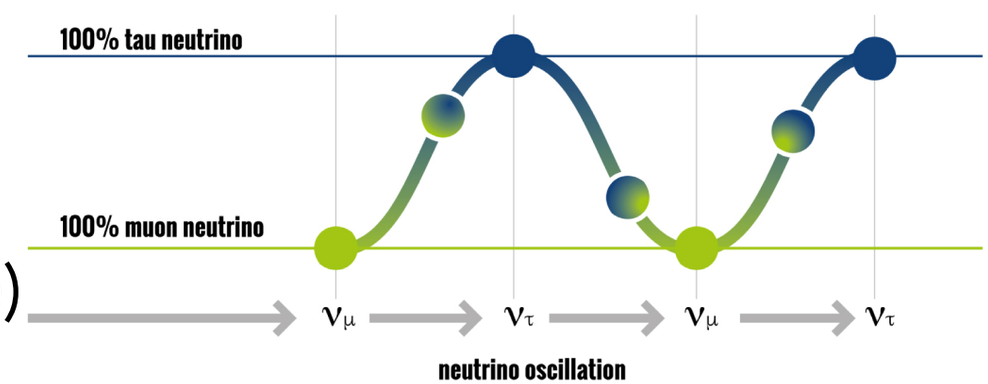
"Grand Unification Theory" (GUT) by H.Georgi and S.Glashow (1974)

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)

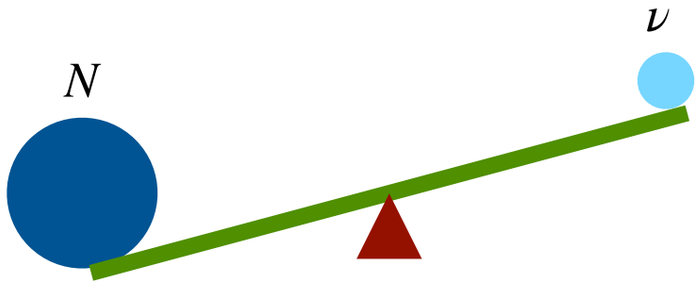


This is the established fact that the SM is not a sufficient model

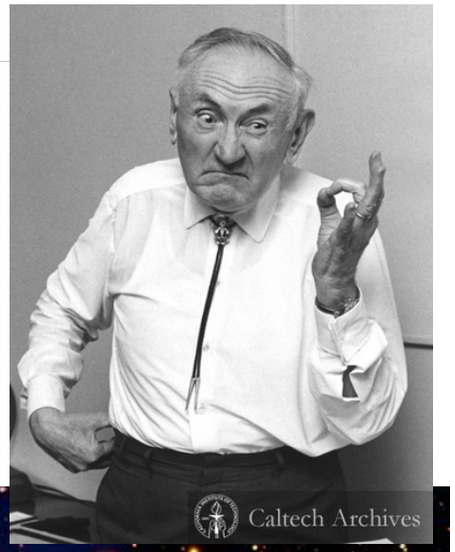
> need to be extended

Many models have been proposed:

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

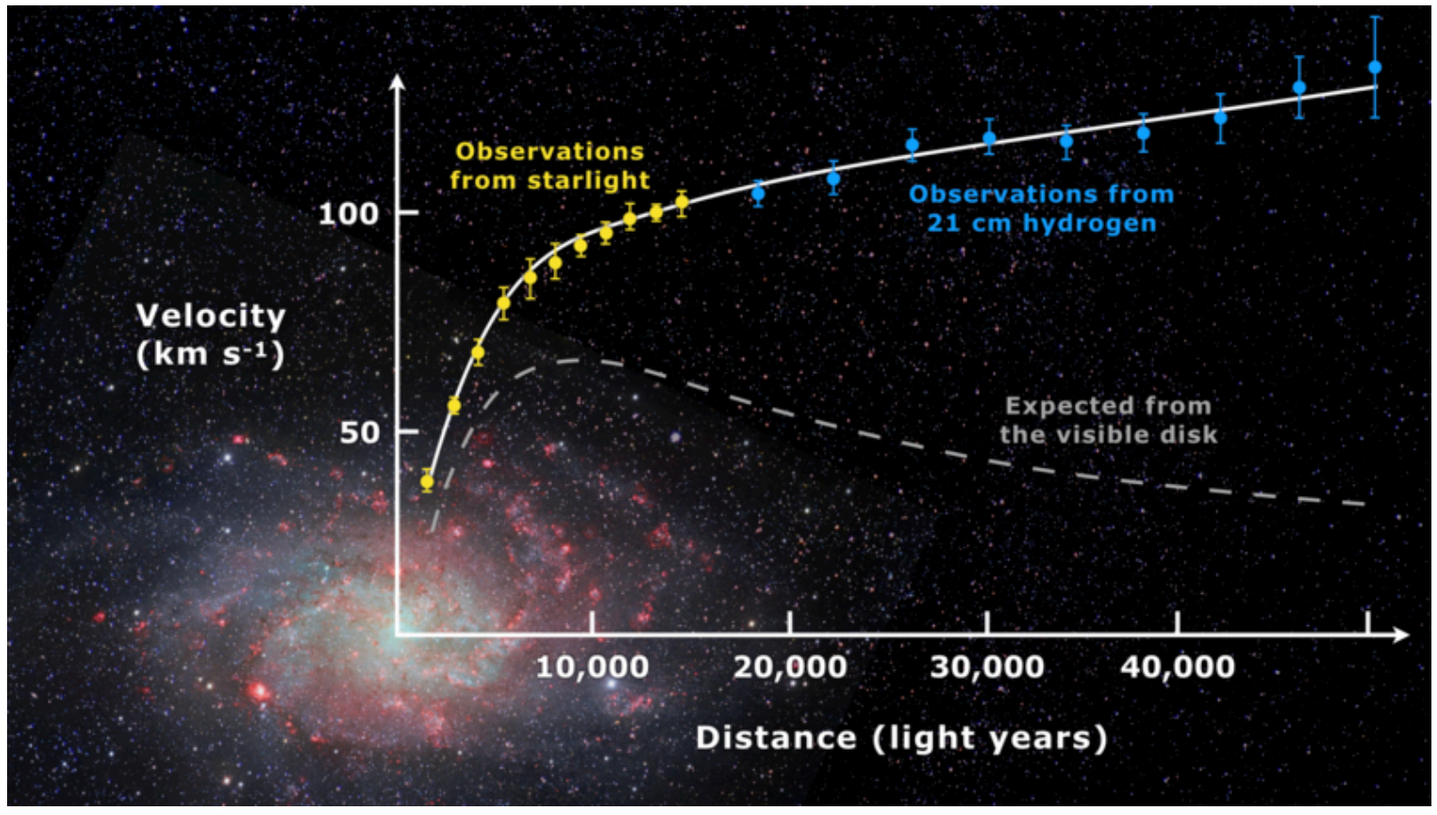


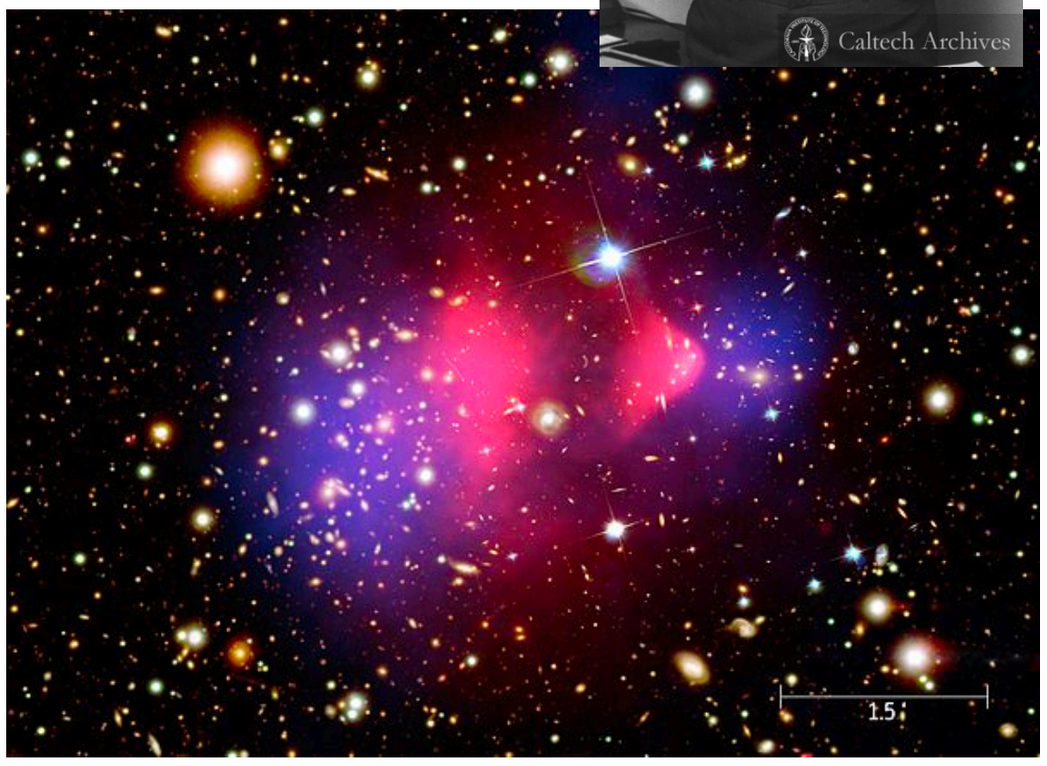
Neutrino gets massive
via mixing with heavy new particles



Dark Matter

Galactic Rotation curve (Newton dynamics) (1933~)

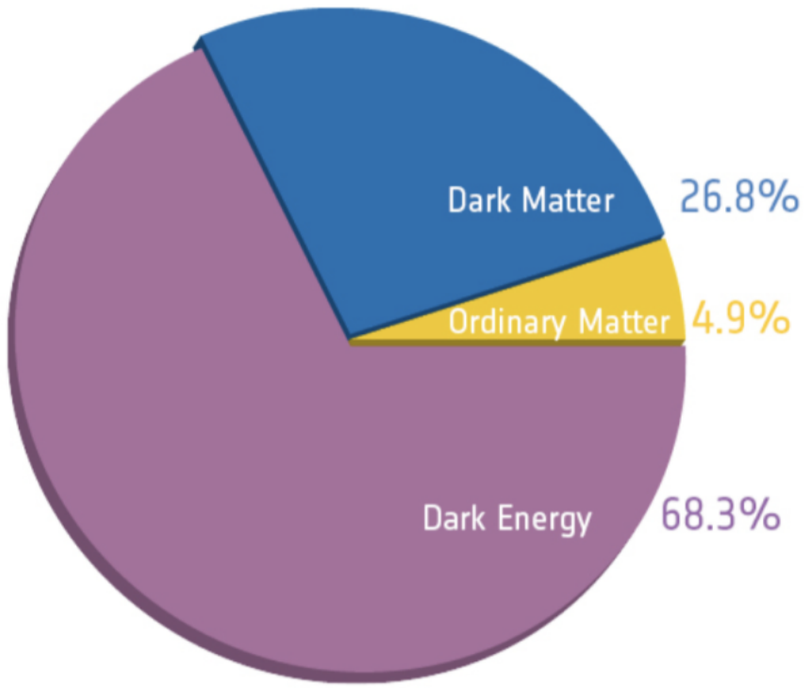




Red: X-ray (Matter)
Blue: Gravitational Source

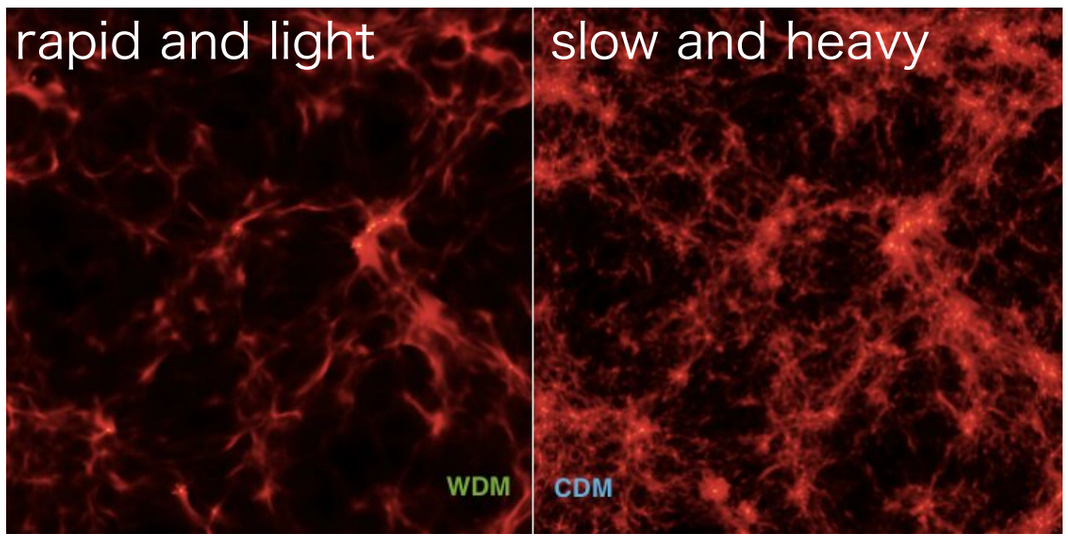
These observations can be explained by "Dark Matter (DM)"

What we know about Dark Matter



Energy density of the Universe

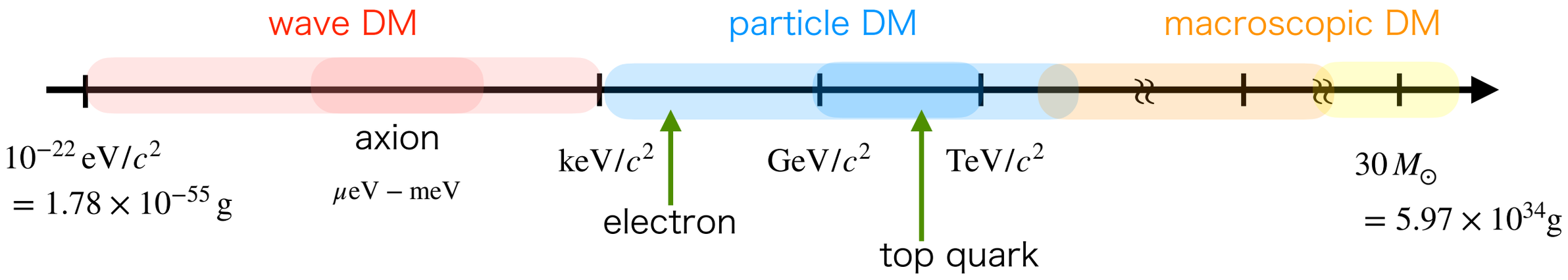
Matter : Dark Matter : Dark Energy
= 5 : 25 : 70



- 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: $\lambda \simeq 1\,\mathrm{kpc}\left(\dfrac{10^{-22}\mathrm{eV}/c^2}{m}\right)$

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

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

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

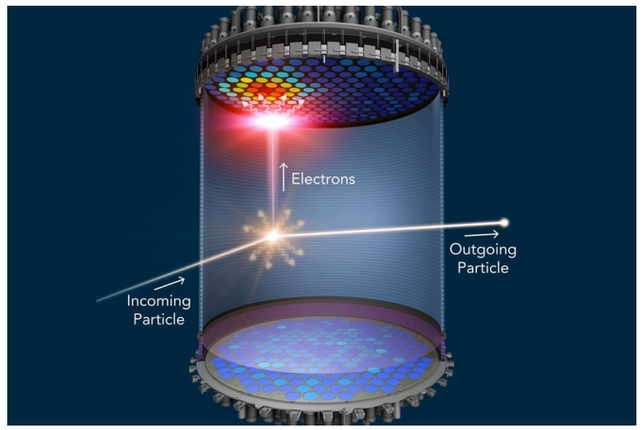
DM is found only through gravitational interaction

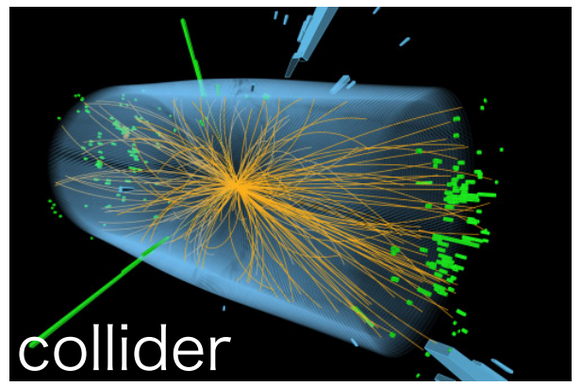
DM production in the Universe (DM-SM interactions?)

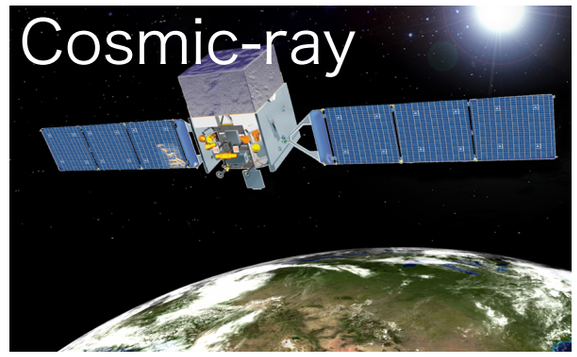
Many scenarios for production proposed
- thermal DM (WIMP, SIMP, ...)
- non-thermal DM (such as decay, ...)
- Asymmetric DM
- so on

have been tested in various ways

DM-nucleus scattering







DM Self-interactions?

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

Dark Energy

observational fact

"**accelerating expansion of the Universe**"

Nobel Prize in Physics 2011

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

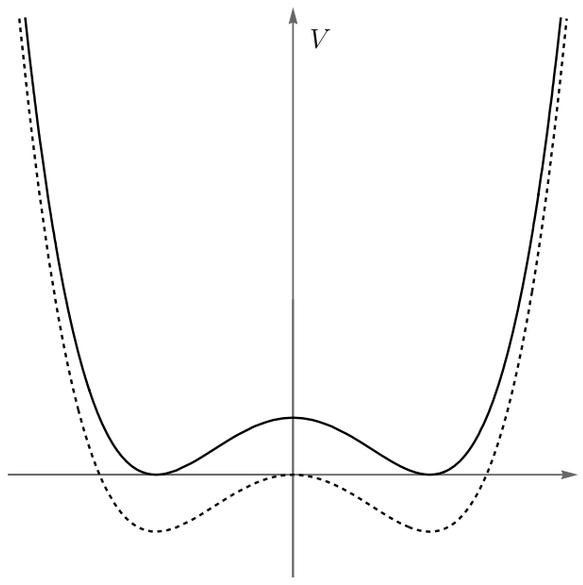
© The Nobel Foundation. Photo: U. Montan
Brian P. Schmidt
Prize share: 1/4

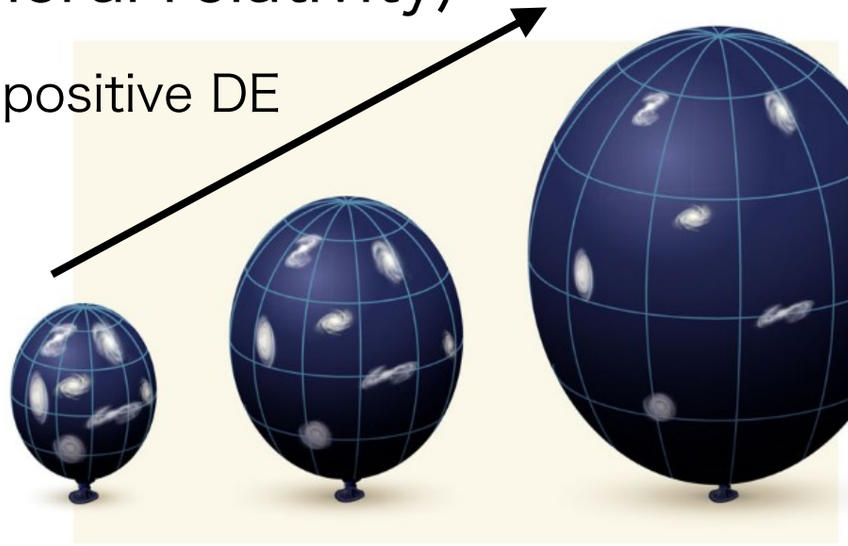
© The Nobel Foundation. Photo: U. Montan
Adam G. Riess
Prize share: 1/4

matter: gravitational collapse
dark energy: anti-gravitational effect (expansion)

vacuum energy behaves as dark energy (general relativity)

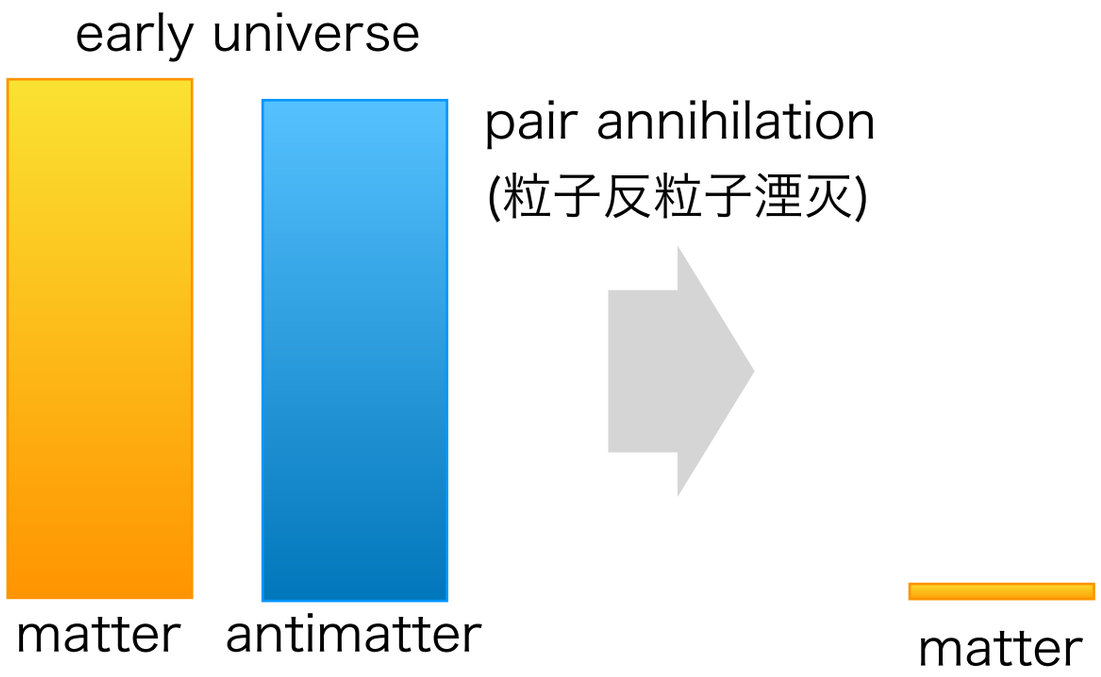
in quantum field theory:
potential hight from vacuum only meaningful
-> beyond QFT?





Baryon Asymmetry of the Universe

no astrophysical objects made of "antimatter" are observed



only matter remains

"matter-antimatter asymmetry"
should be generated in early universe

"Baryogenesis"

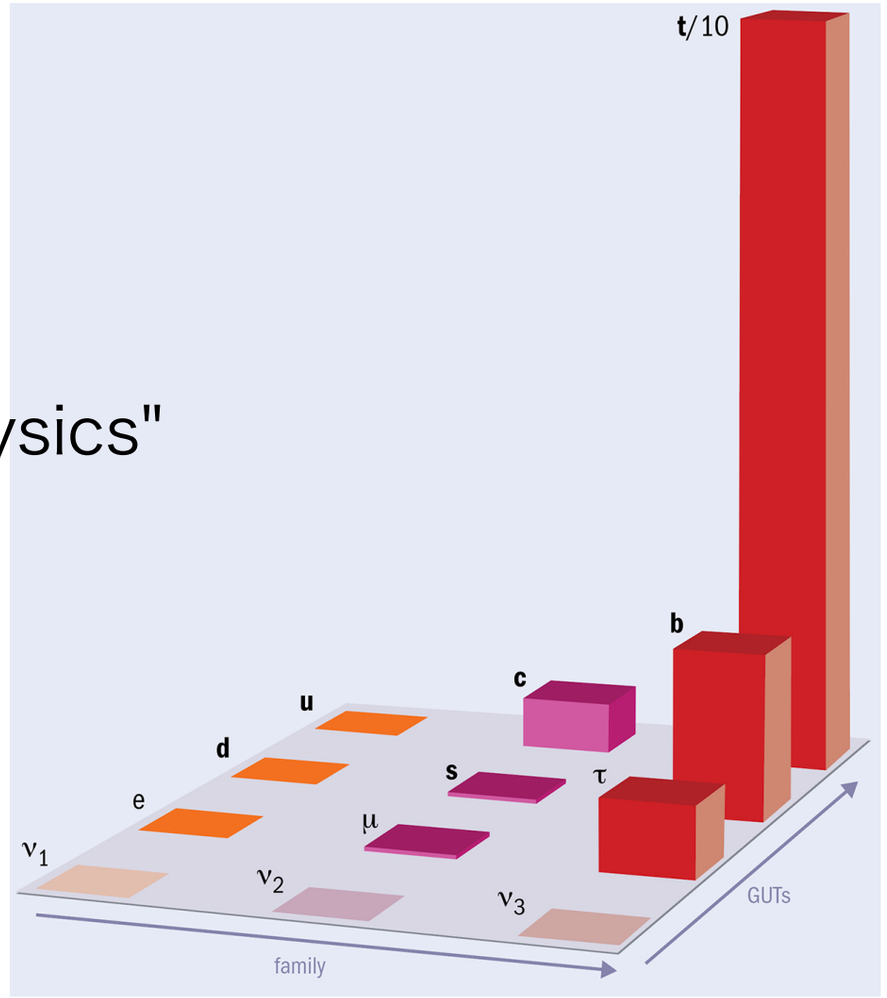
Many models have been proposed:

GUT Baryogenesis	(non-)thermal Leptogenesis
Electroweak Baryogenesis	Resonant Leptogenesis
Spontaneous Baryogenesis	Leptogenesis via neutrino oscillation
Affleck-Dine Baryogenesis	etc...
B-Mesogenesis	

"Flavor" of Matters

"Flavor": species of matter particles

Hints of BSM may be hidden in "flavor physics"



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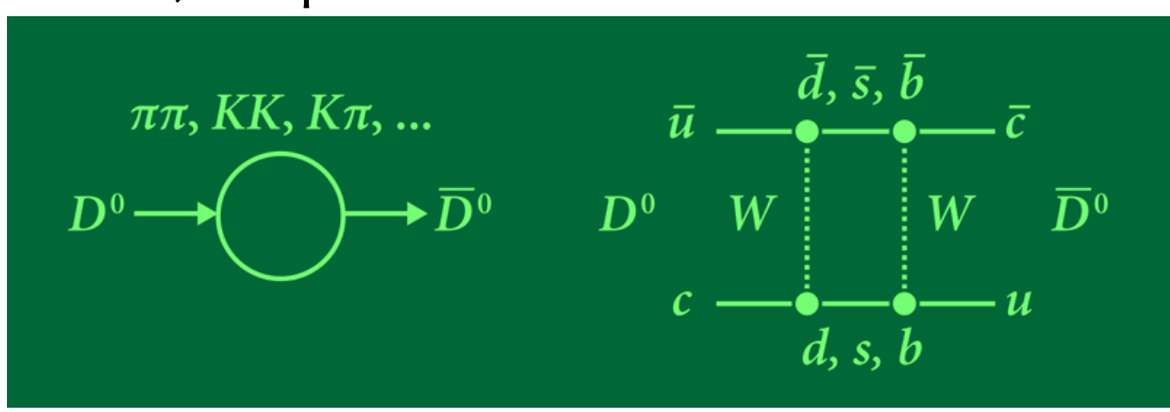
- Why three "families"?
- Mass hierarchy (why is top q too heavy?)
- quark/lepton structures are quite different

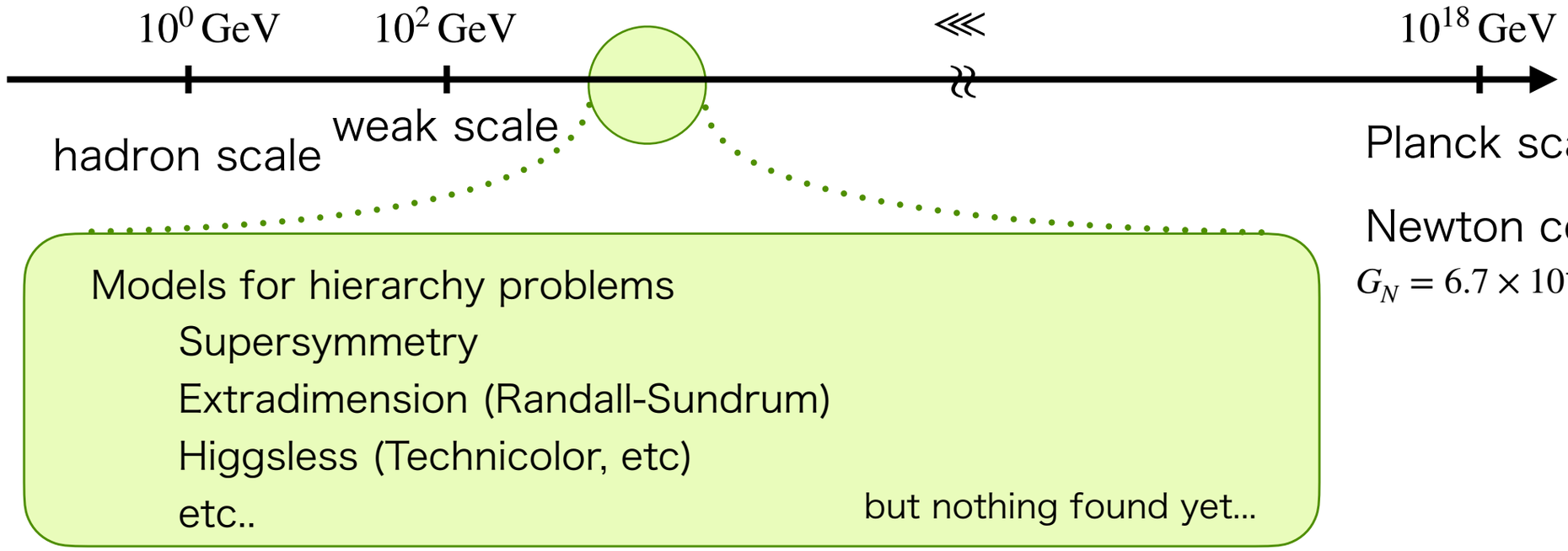
- methodology
  - "quark" picture 👍 -> t quarks
  - "hadron" picture 👍 -> u,d,s quarks
  - dedicated (complicated) analysis -> c, b quarks



Theoretical aspects

- **Hierarchy problem** of Higgs particle

Why is weak scale so smaller than Planck scale?



Newton constant

$G_N = 6.7 \times 10^{-39} \hbar c\,(\mathrm{GeV}/c^2)^{-2}$

- 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

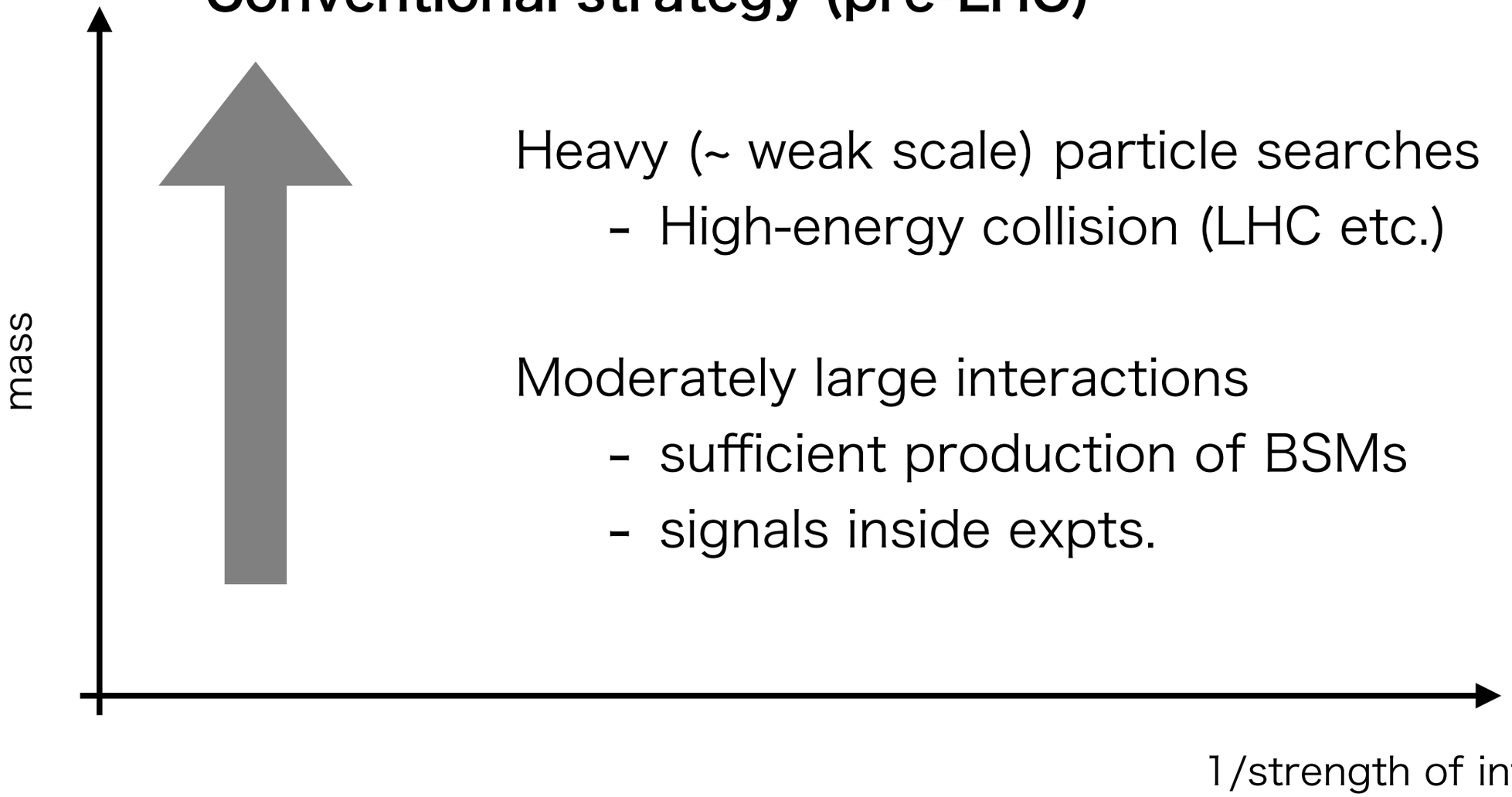
But, we also know the missing pieces of SM

Large Hadron Collider (LHC) @ CERN

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

Alternative Particle Model "Dark Sector"

Conventional strategy (pre-LHC)

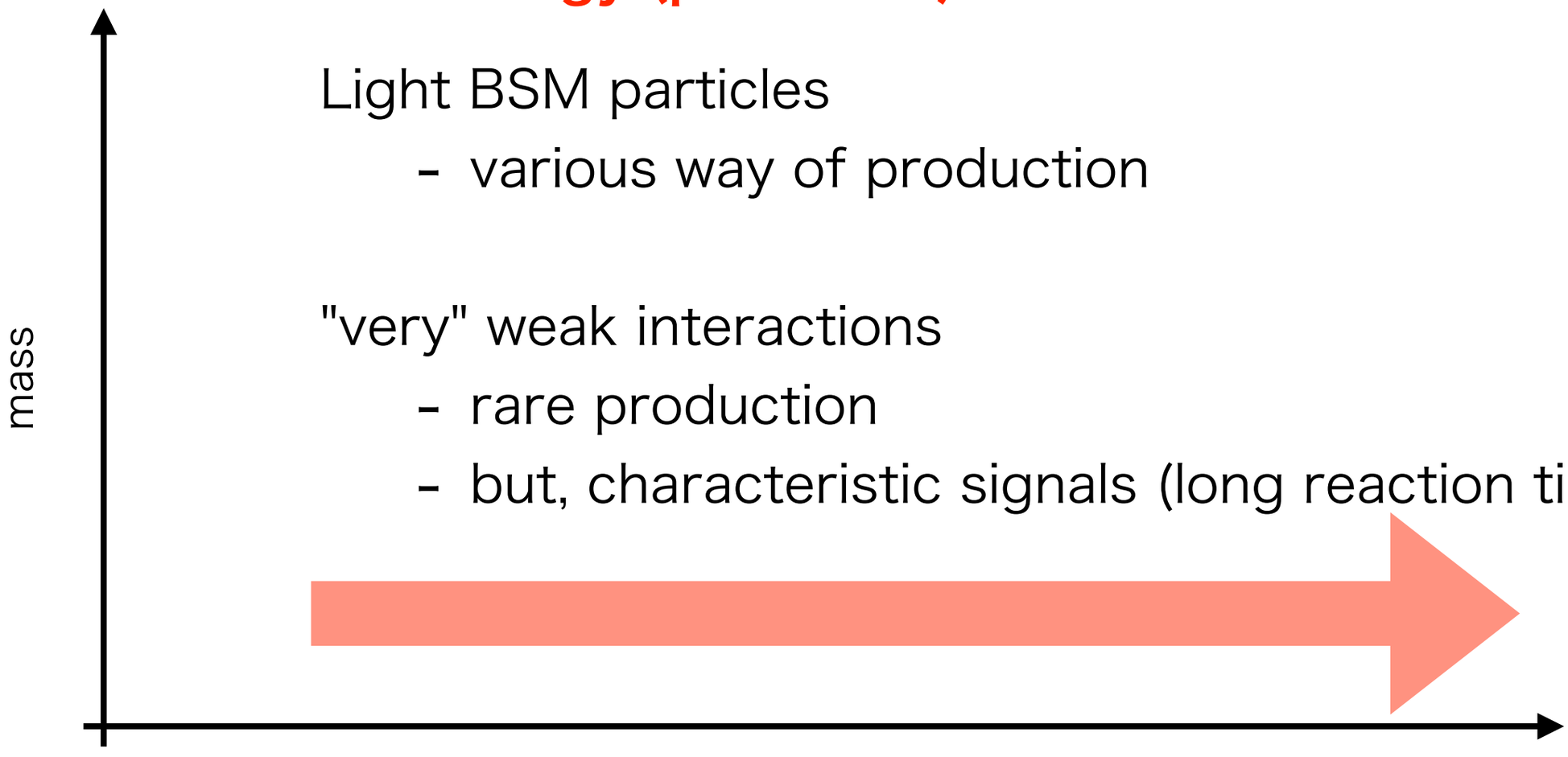


Heavy (~ weak scale) particle searches
- High-energy collision (LHC etc.)

Moderately large interactions
- sufficient production of BSMs
- signals inside expts.

Alternative Particle Model "Dark Sector"

A new strategy (post-LHC)



Light BSM particles

- various way of production

"very" weak interactions

- rare production
- but, characteristic signals (long reaction time)

Various way to investigate:

- long-lived particles (far-detector experiments/cosmology)
- impacts on "atomic physics"

Alternative Particle Model "Dark Sector"

Future Circular Colliders?

Muon Colliders?

CERN

China

LHC

mass

cosmology/astrophysics

Japan

CERN

China

US

1/strength of interaction

Flavor Facilities

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