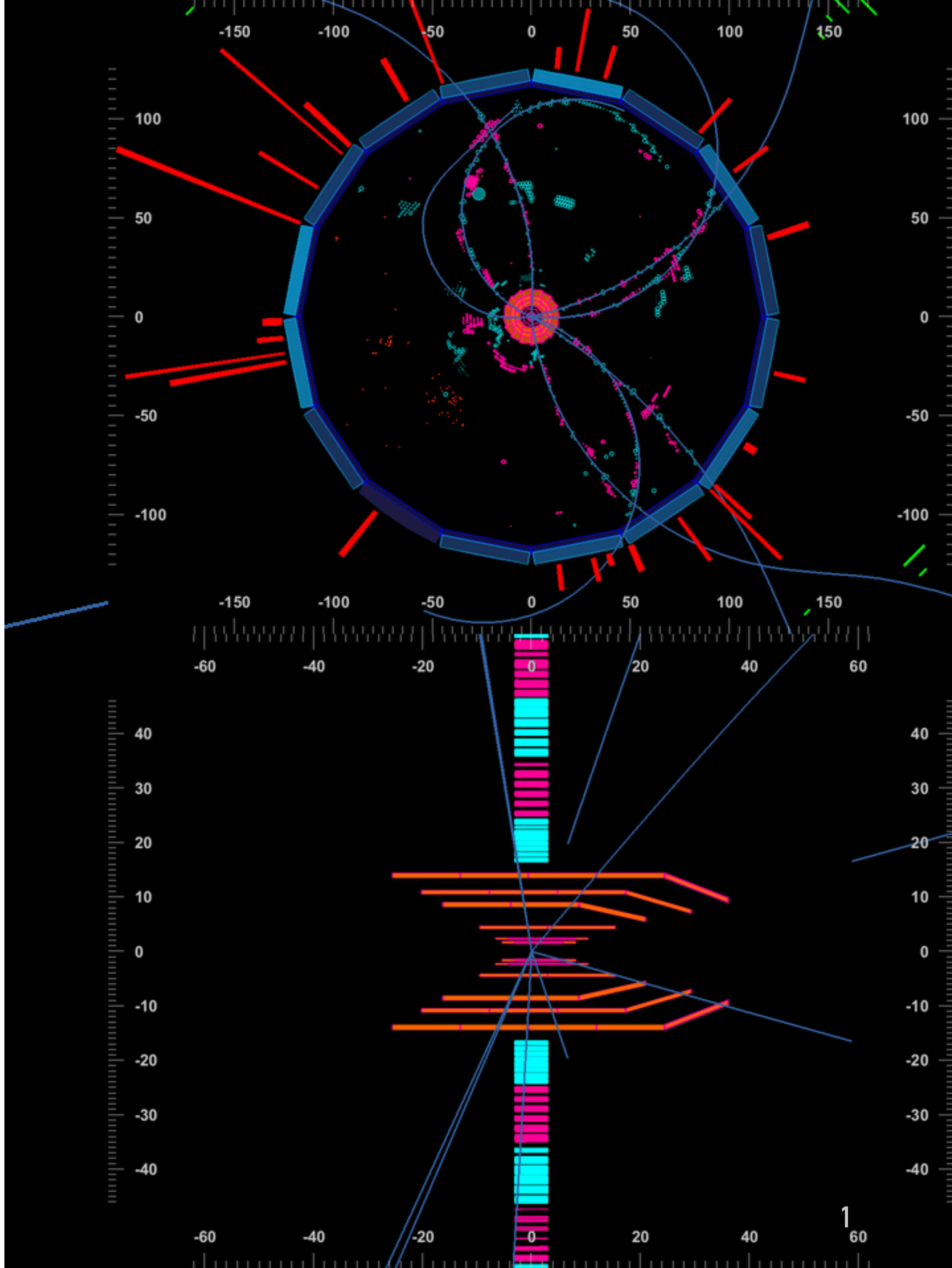
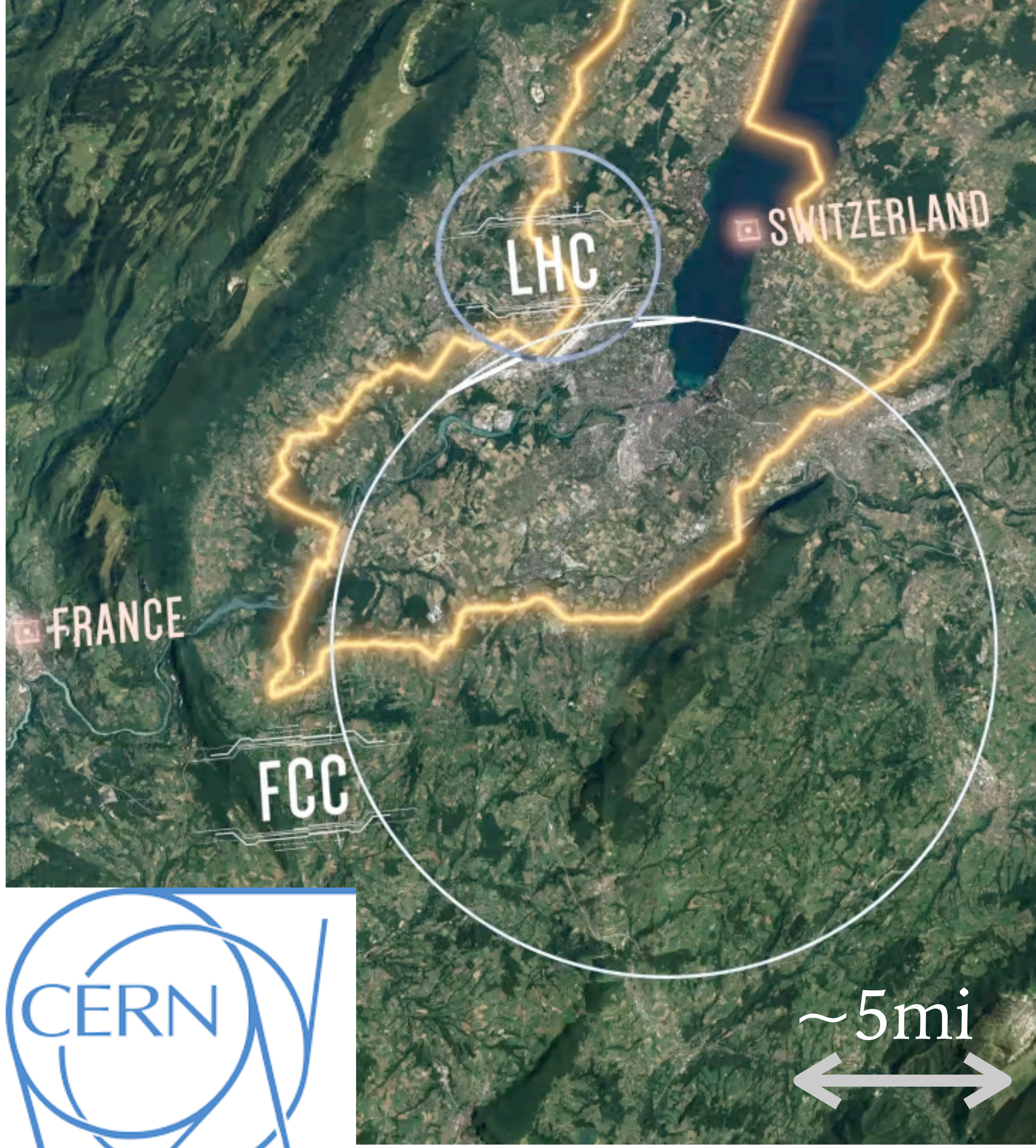
AN EXPLORER'S INTRODUCTION TO PARTICLE PHYSICS

Tommy Lam
2025 June 23



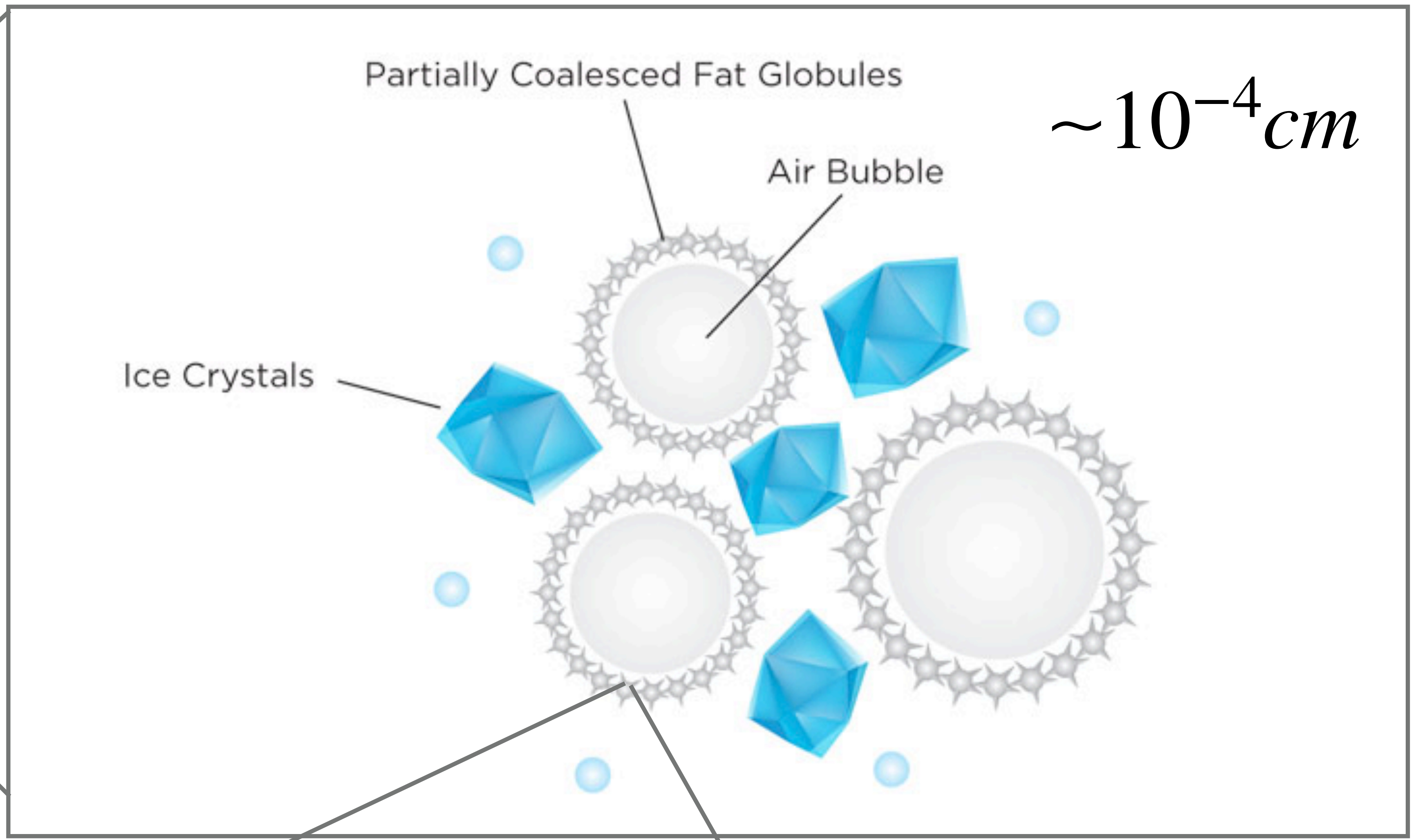
AIMS OF THIS TALK

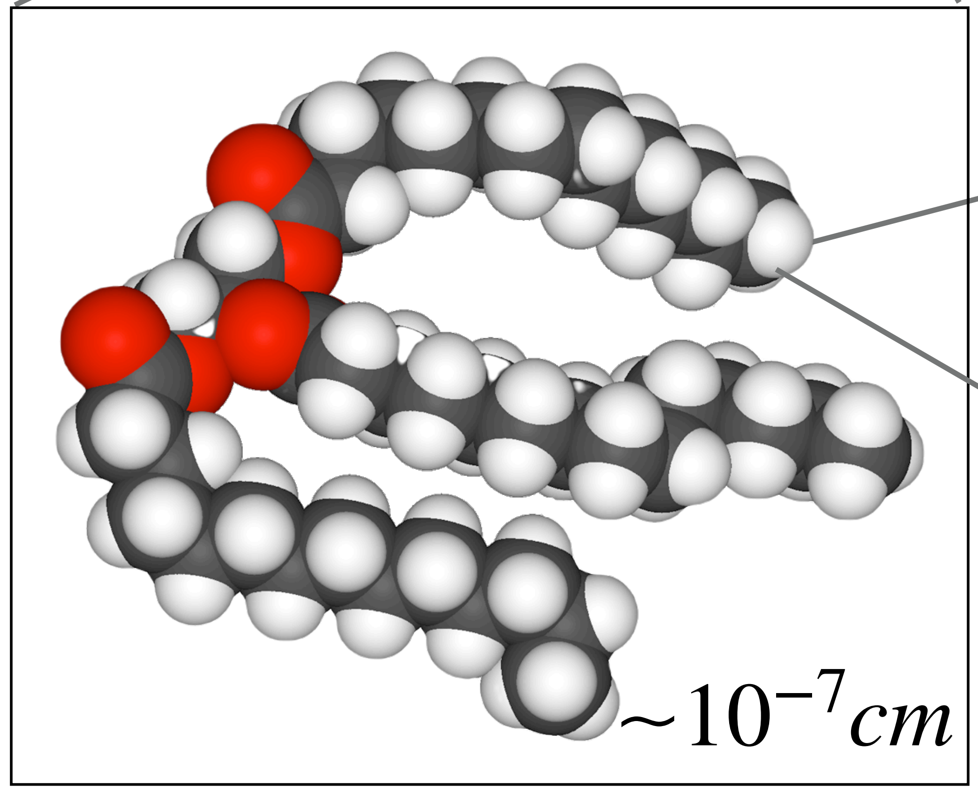
- What are the goals of particle physics?
- What are (elementary) particles?
- What is our best theory of particles so far?

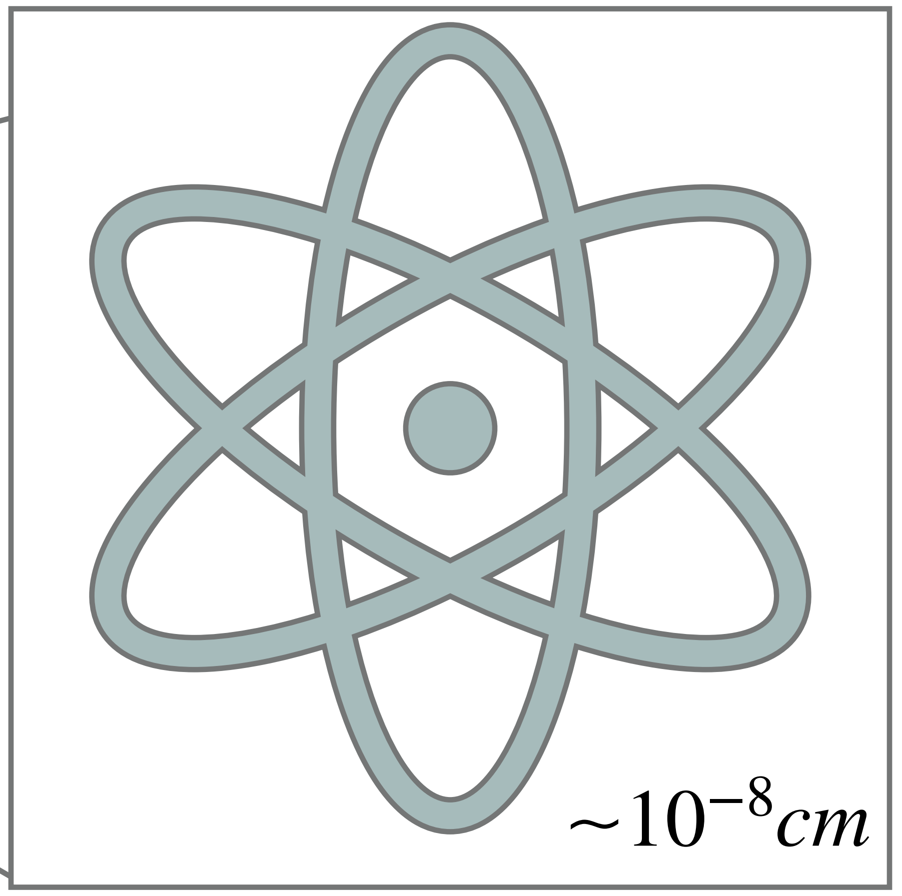


What are the goals of particle physics?

GOAL 1: UNDERSTANDING WHAT MATTER IS MADE OF



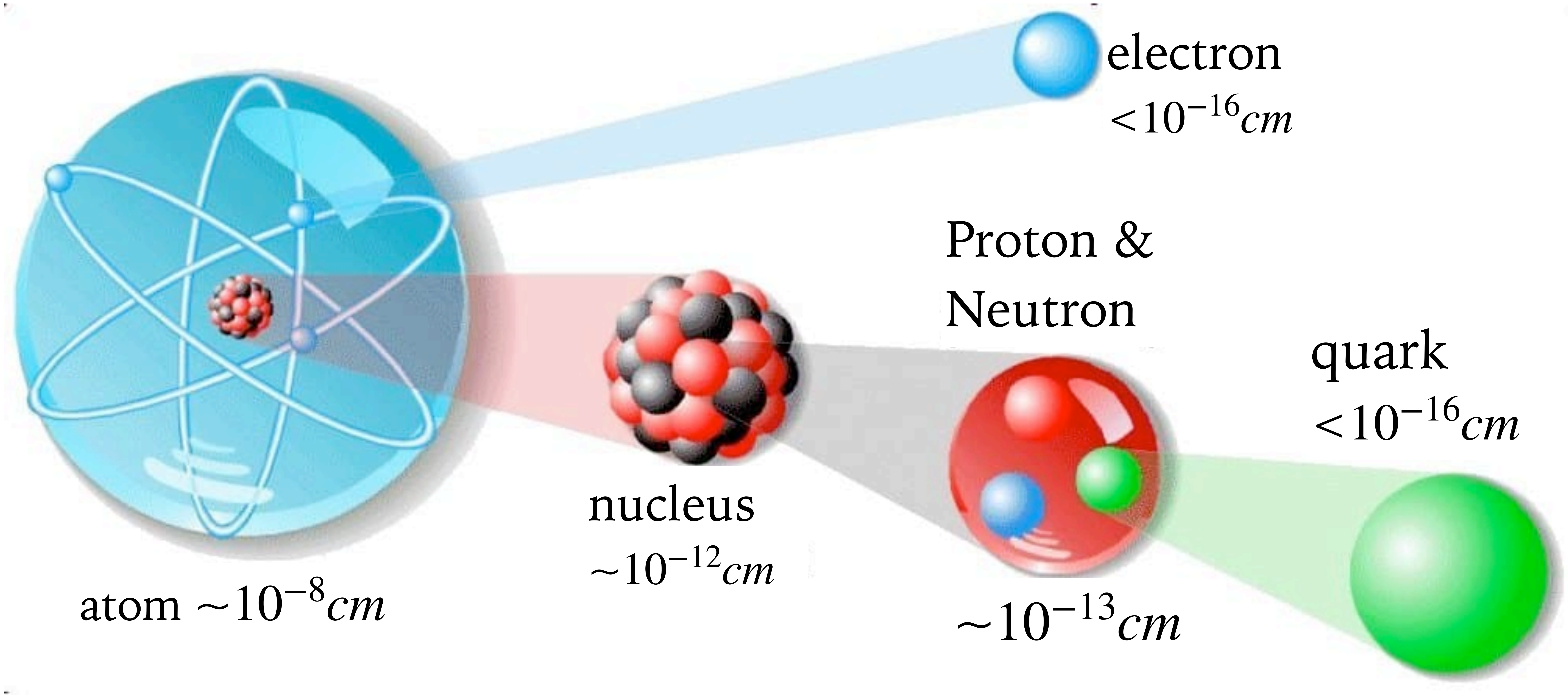




- Long history of understanding what matter is made of
- As technology progressed (ex. microscopes), we were able to delve deeper.

PC: http://www.molecularrecipes.com/ice-cream-class/making-ice-cream-steps/?no_redirect=true, Wikipedia, https://naturphilosophie.co.uk/the-standard-model/

GOAL 1: UNDERSTANDING WHAT MATTER IS MADE OF

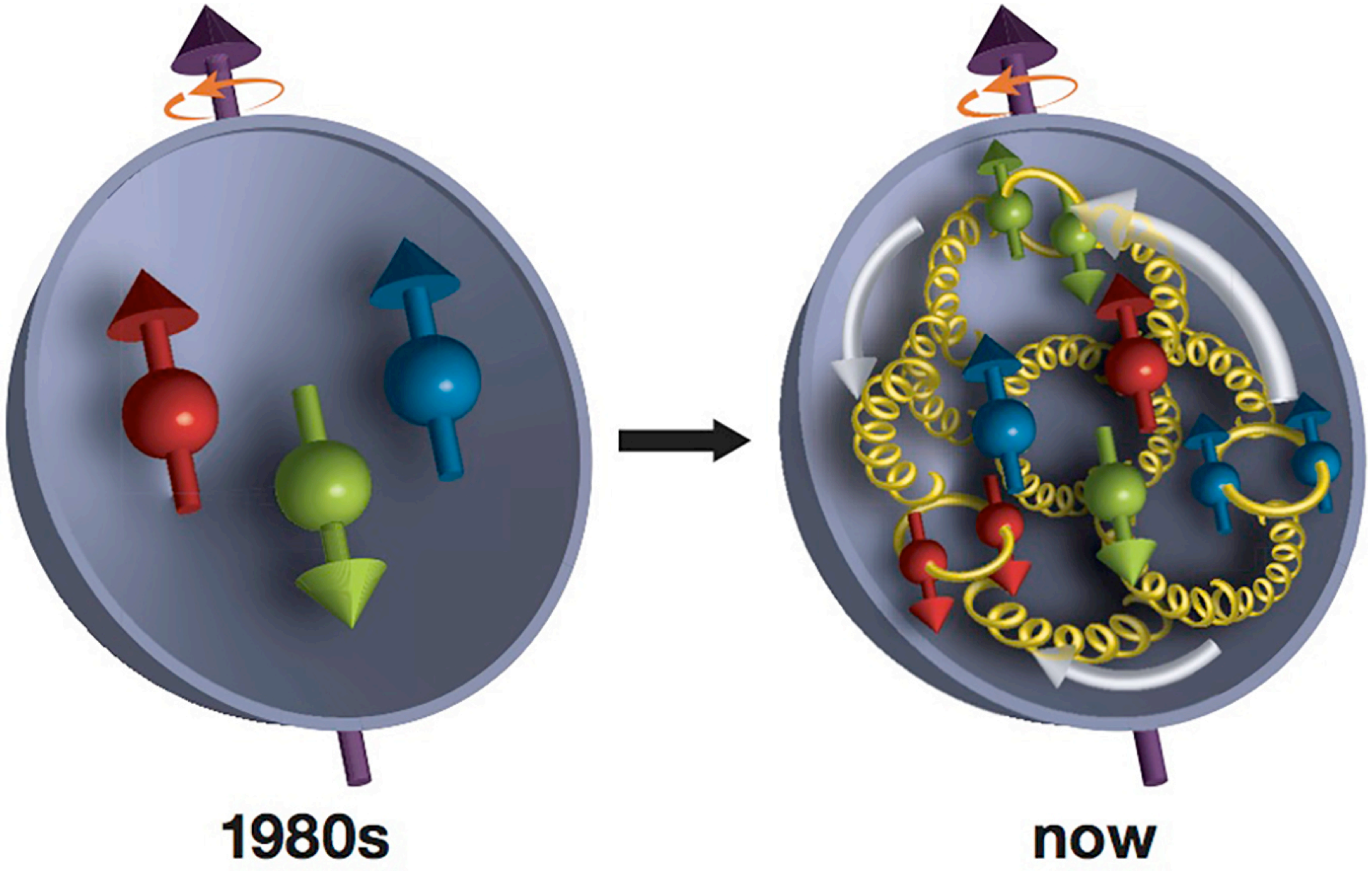


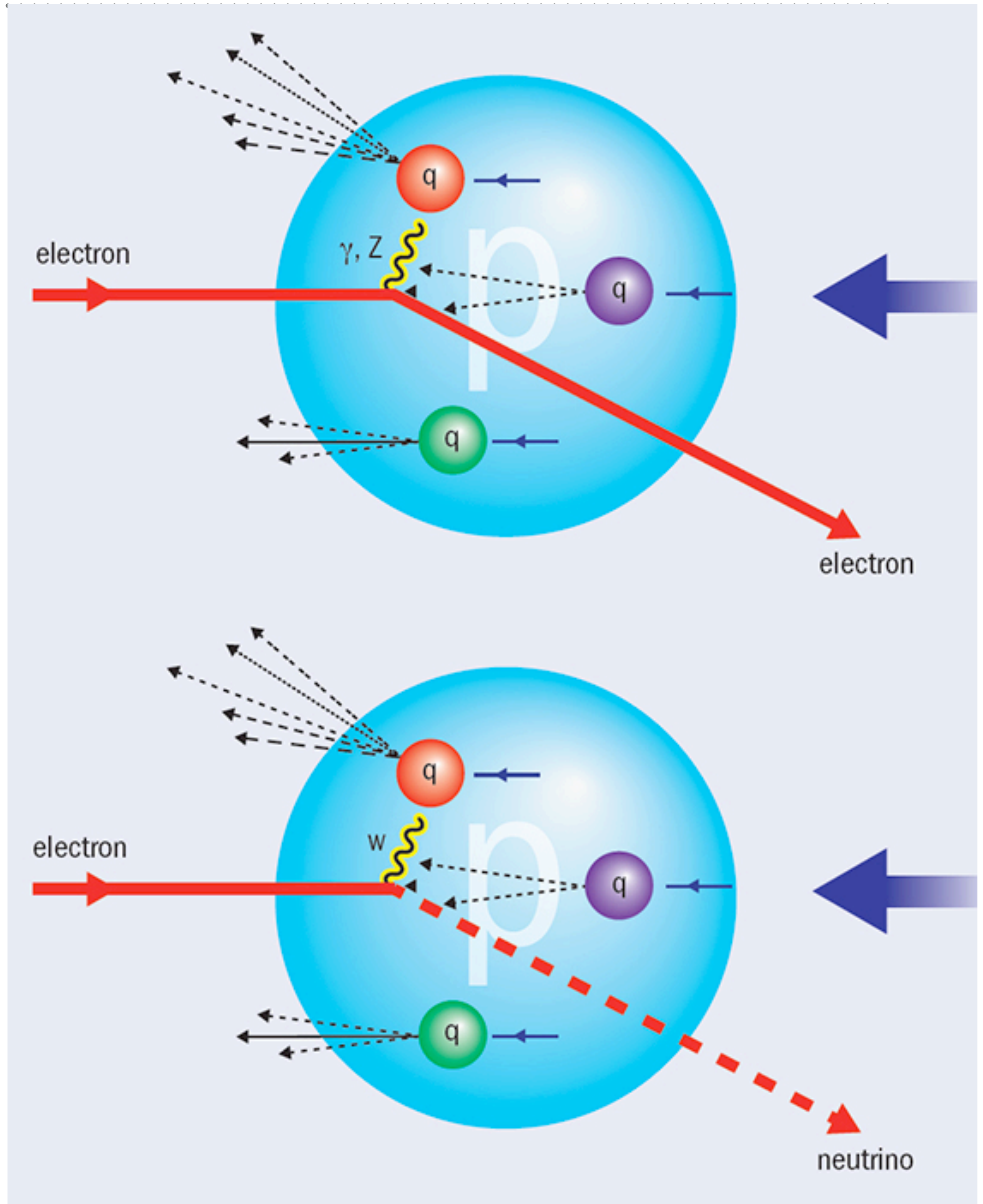
- Good contenders for ‘fundamental particles’: electrons and quarks!

PC: https://naturphilosophie.co.uk/the-standard-model/

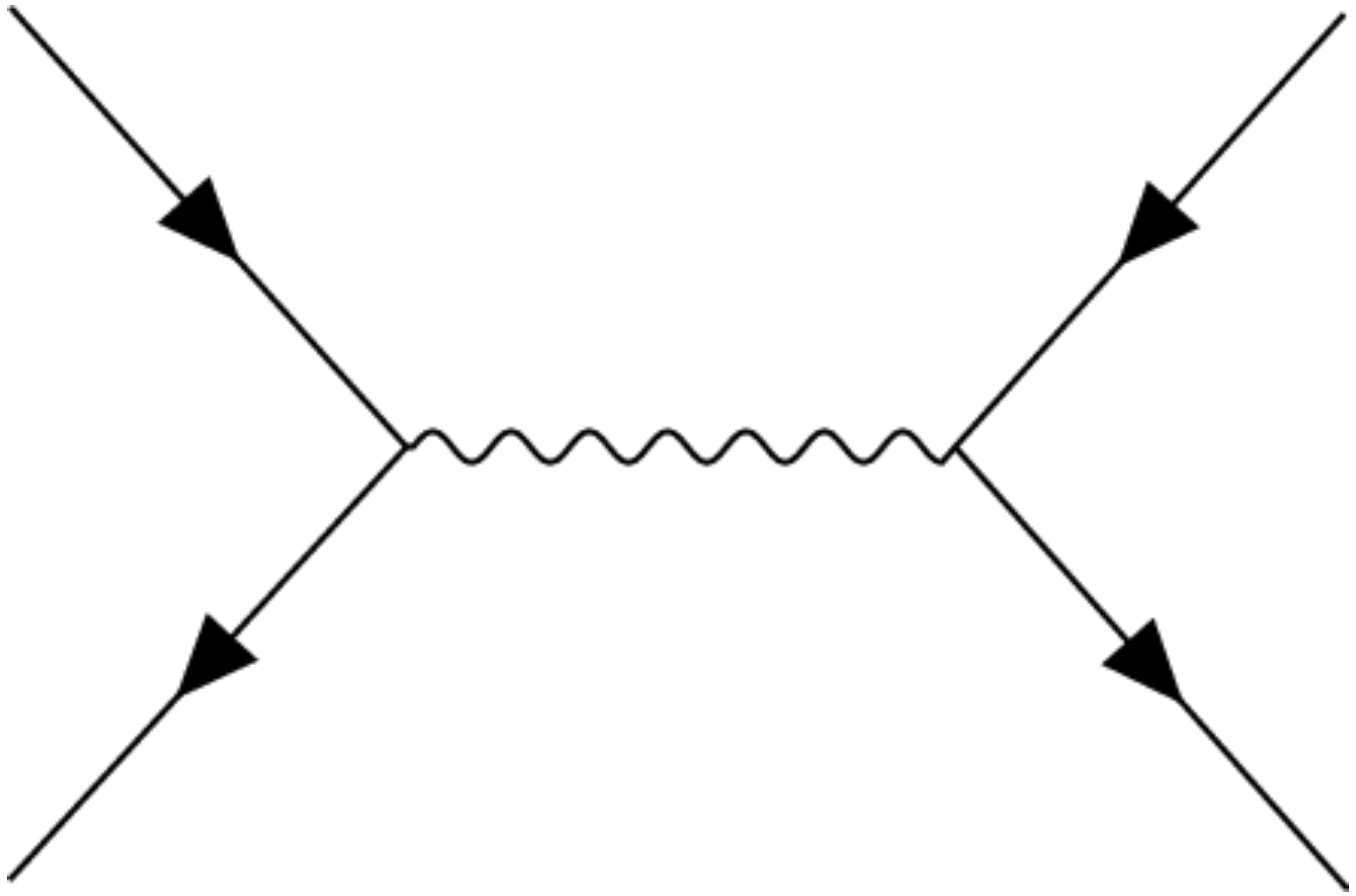
GOAL 2: UNDERSTANDING THEIR PROPERTIES

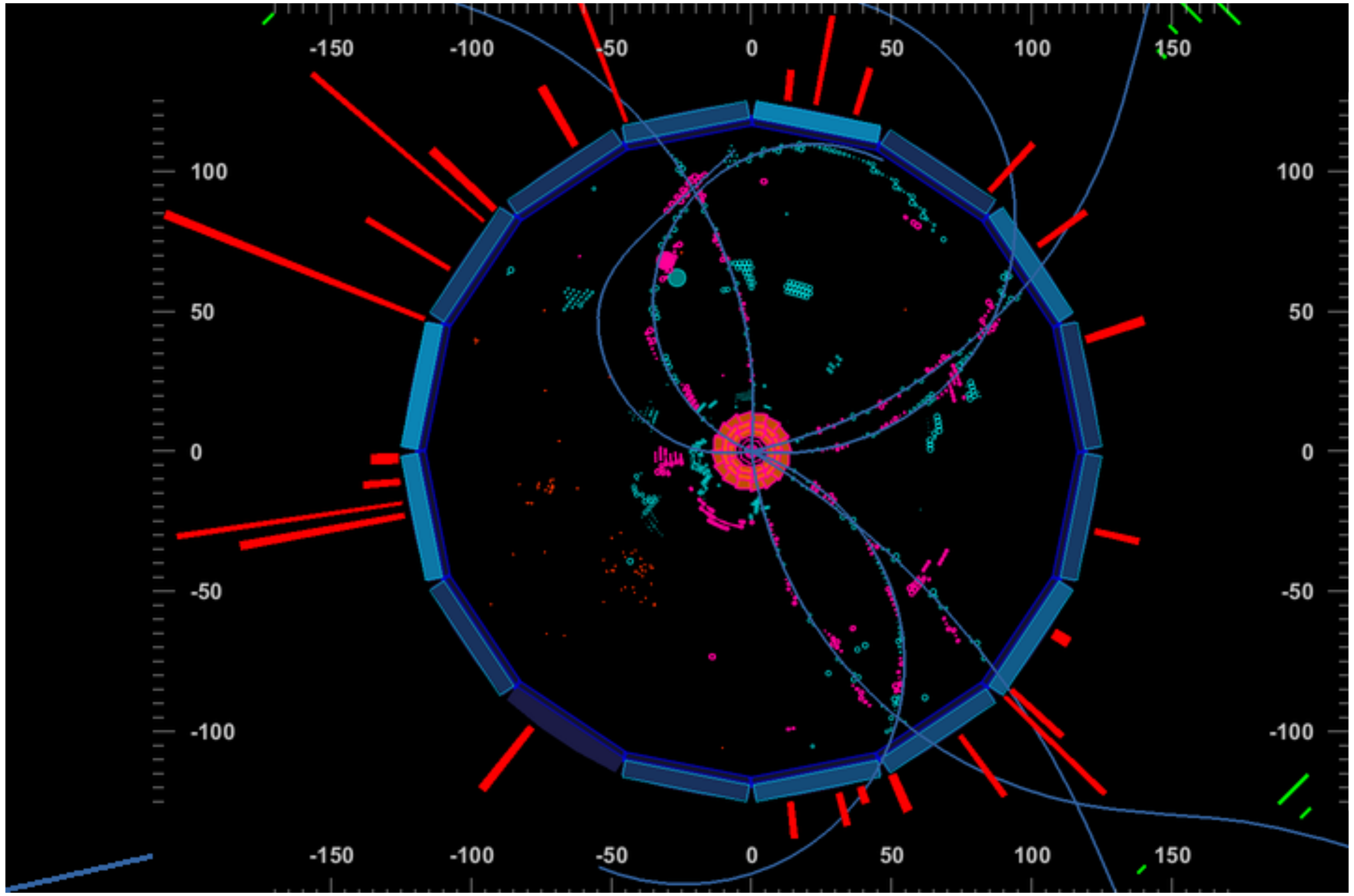
How our understanding of the proton has changed over the years





PC: https://www.forbes.com/sites/startswithabang/2021/03/18/what-rules-the-proton-quarks-or-gluons/ , https://cerncourier.com/a/the-most-precise-picture-of-the-proton/

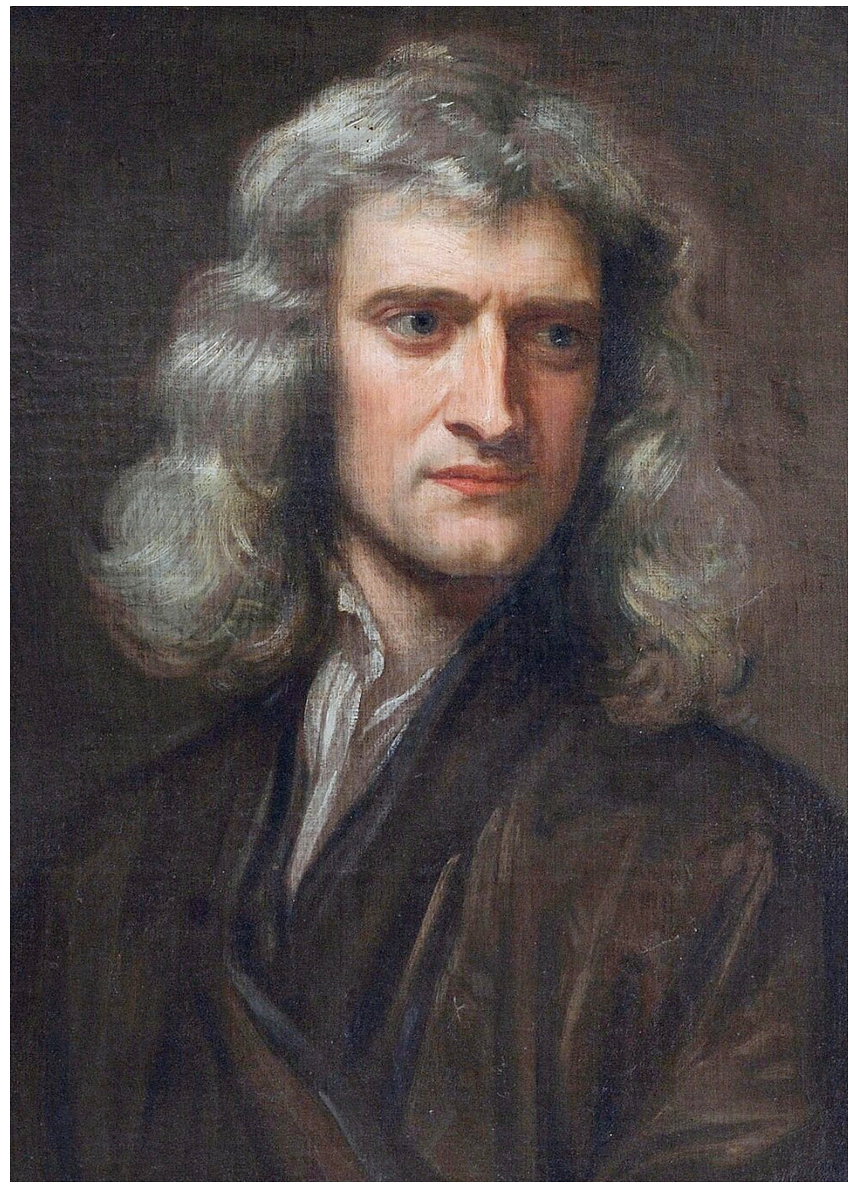




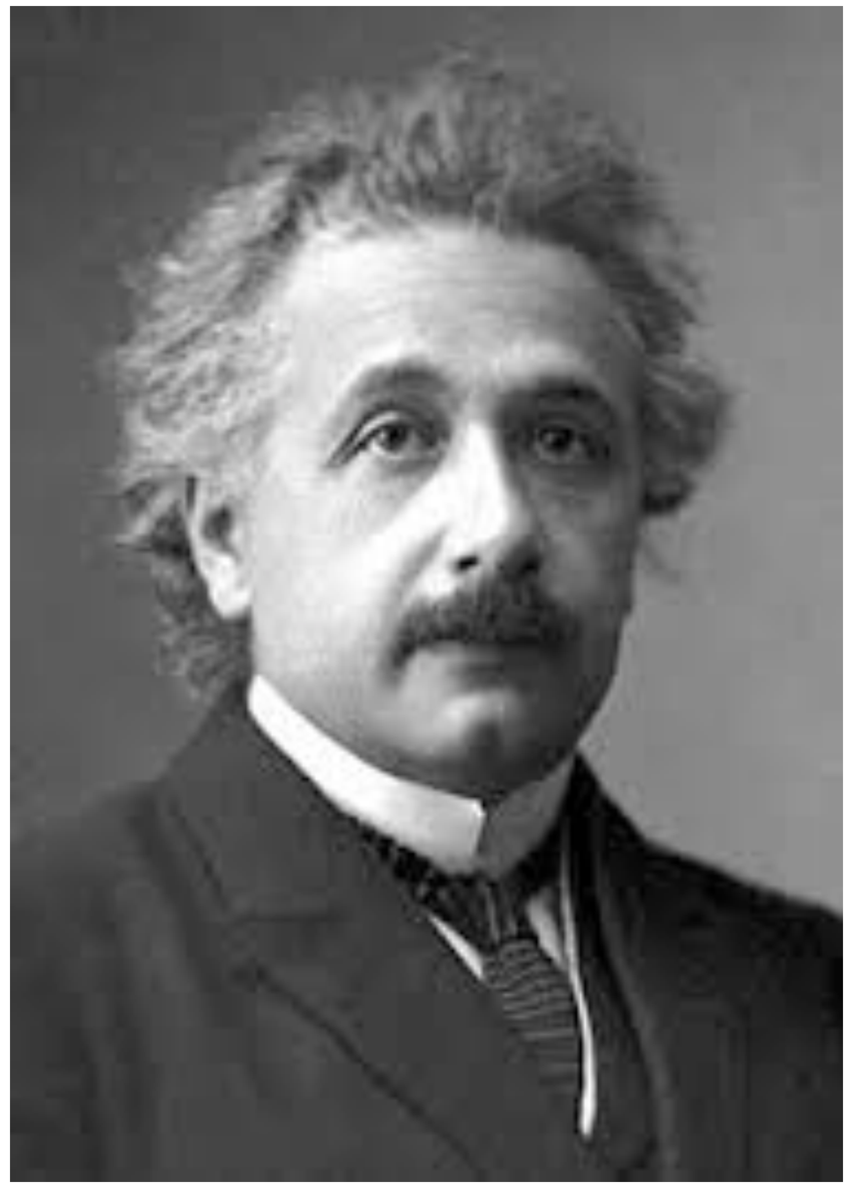
What are particles? What are their properties?

WHAT ARE PARTICLES? - CLASSICAL PICTURE

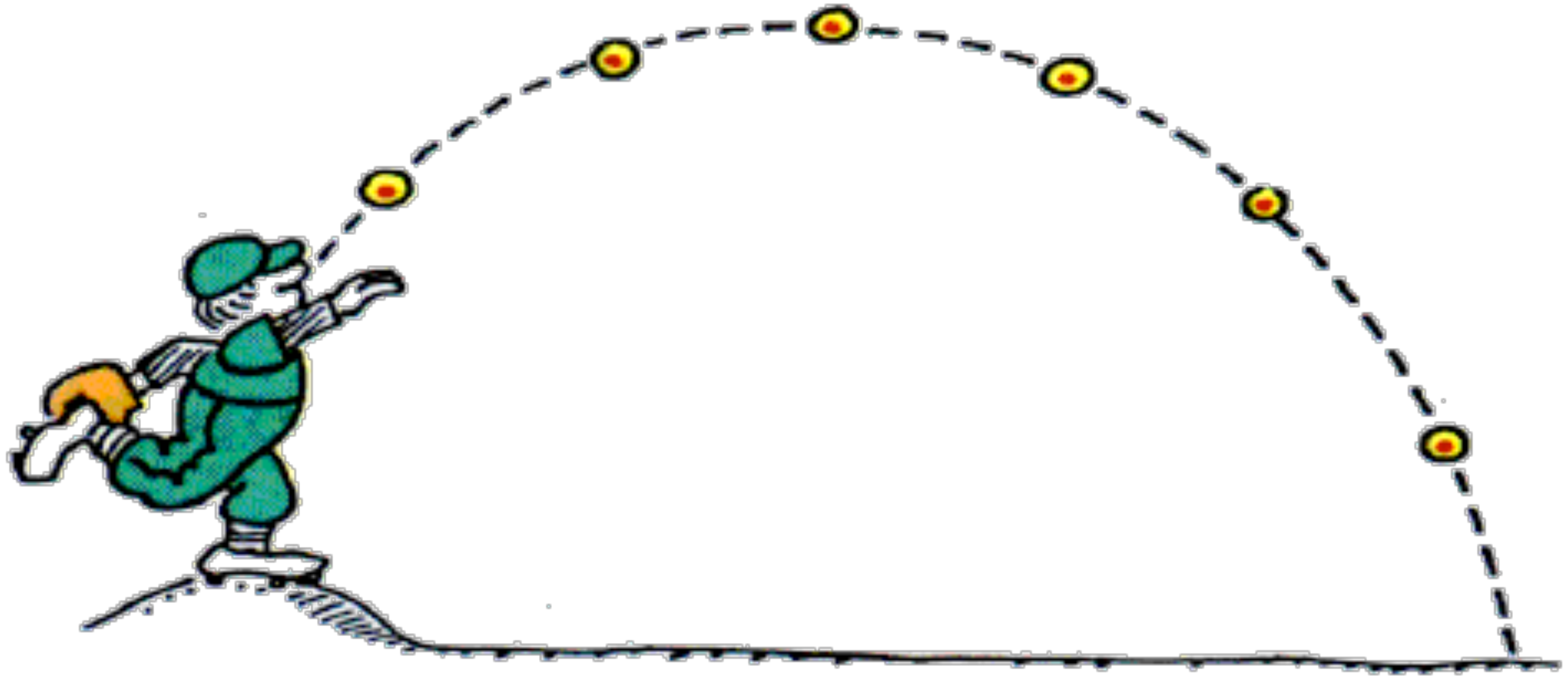
- Matter/energy concentrated into finite space with definite boundaries
- At a fixed location
- Motion described deterministically



Sir Isaac Newton



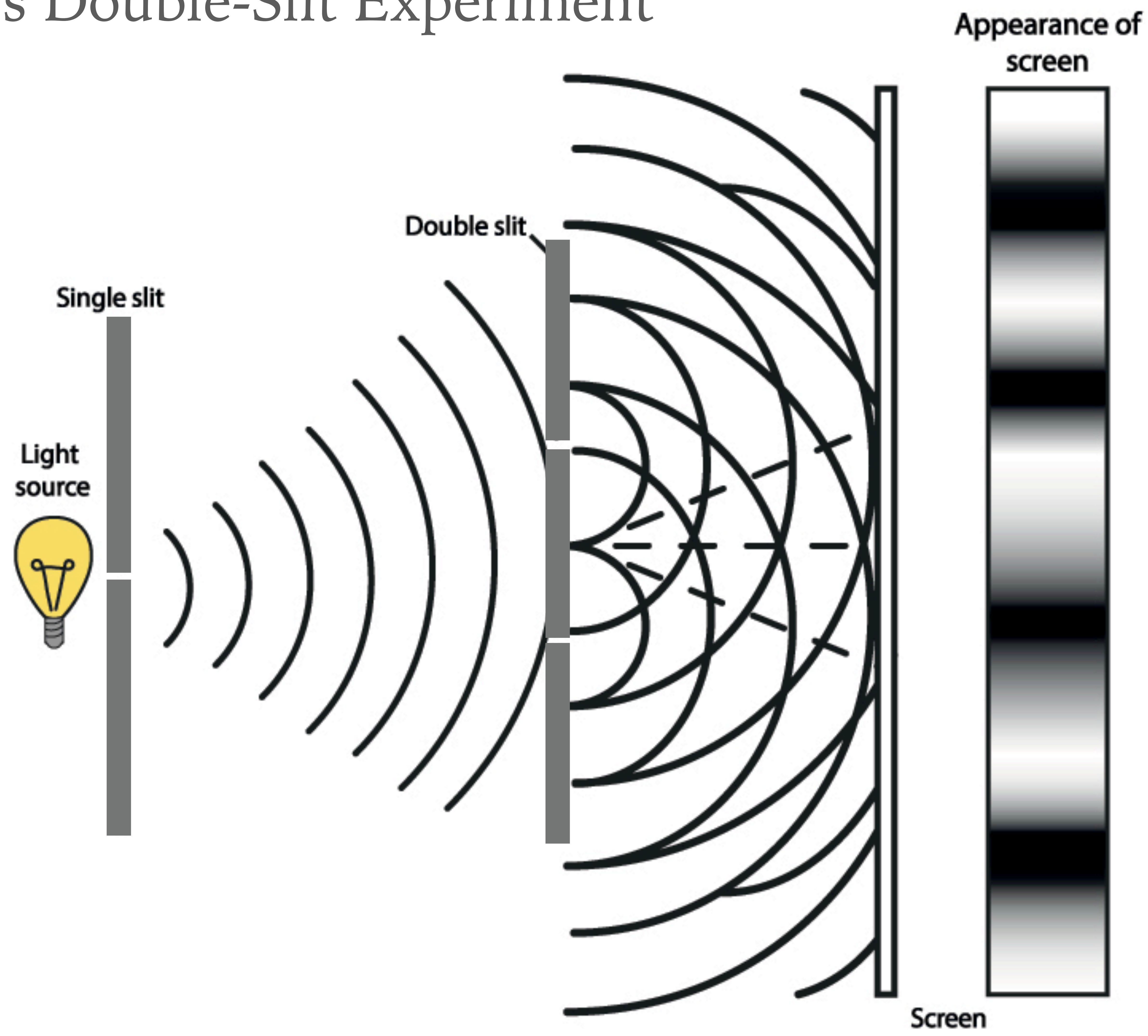
Albert Einstein



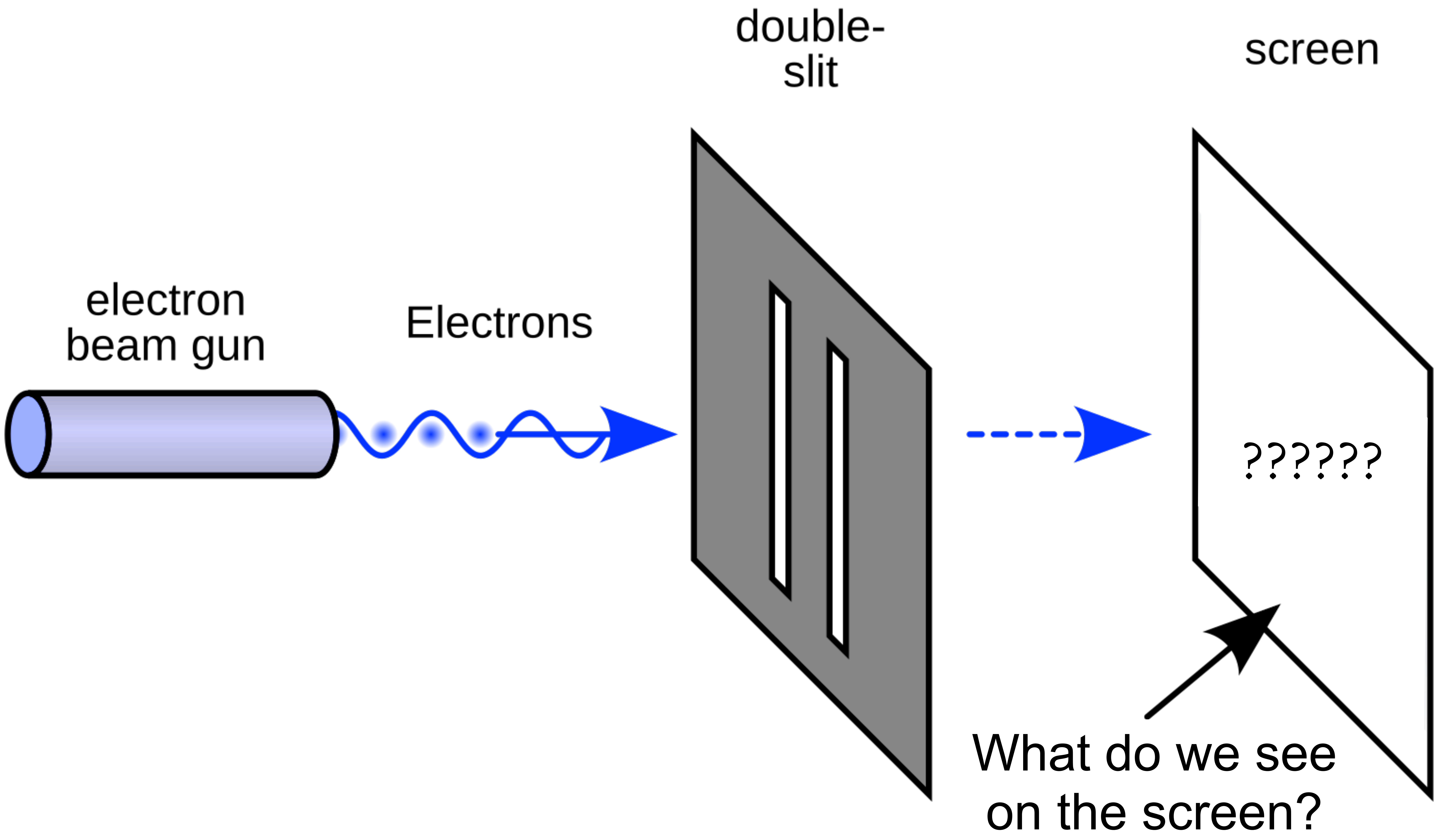
WHAT ARE PARTICLES? – MODERN PICTURE

Gentle Reminder of Young’s Double-Slit Experiment

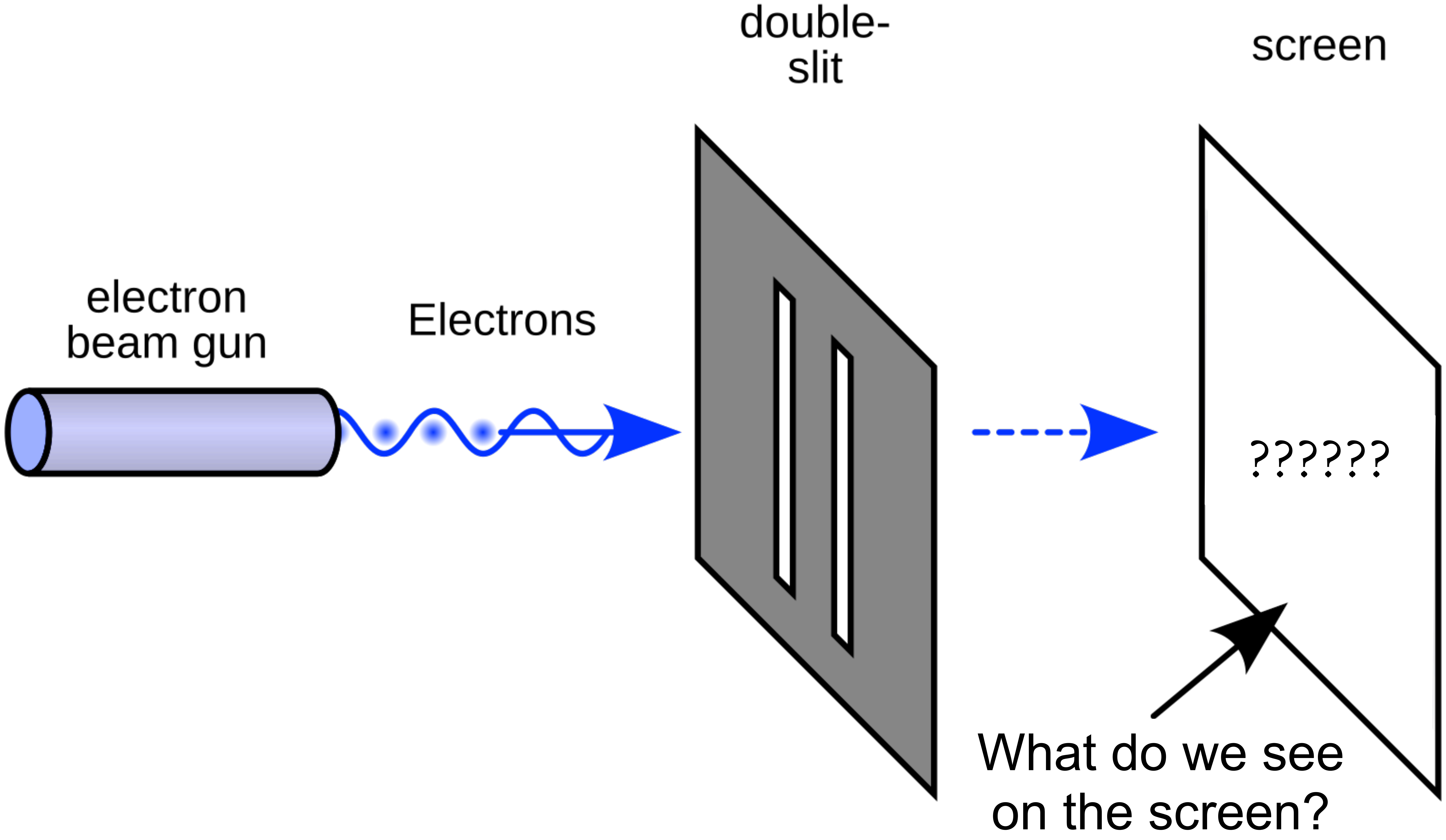
Thomas Young



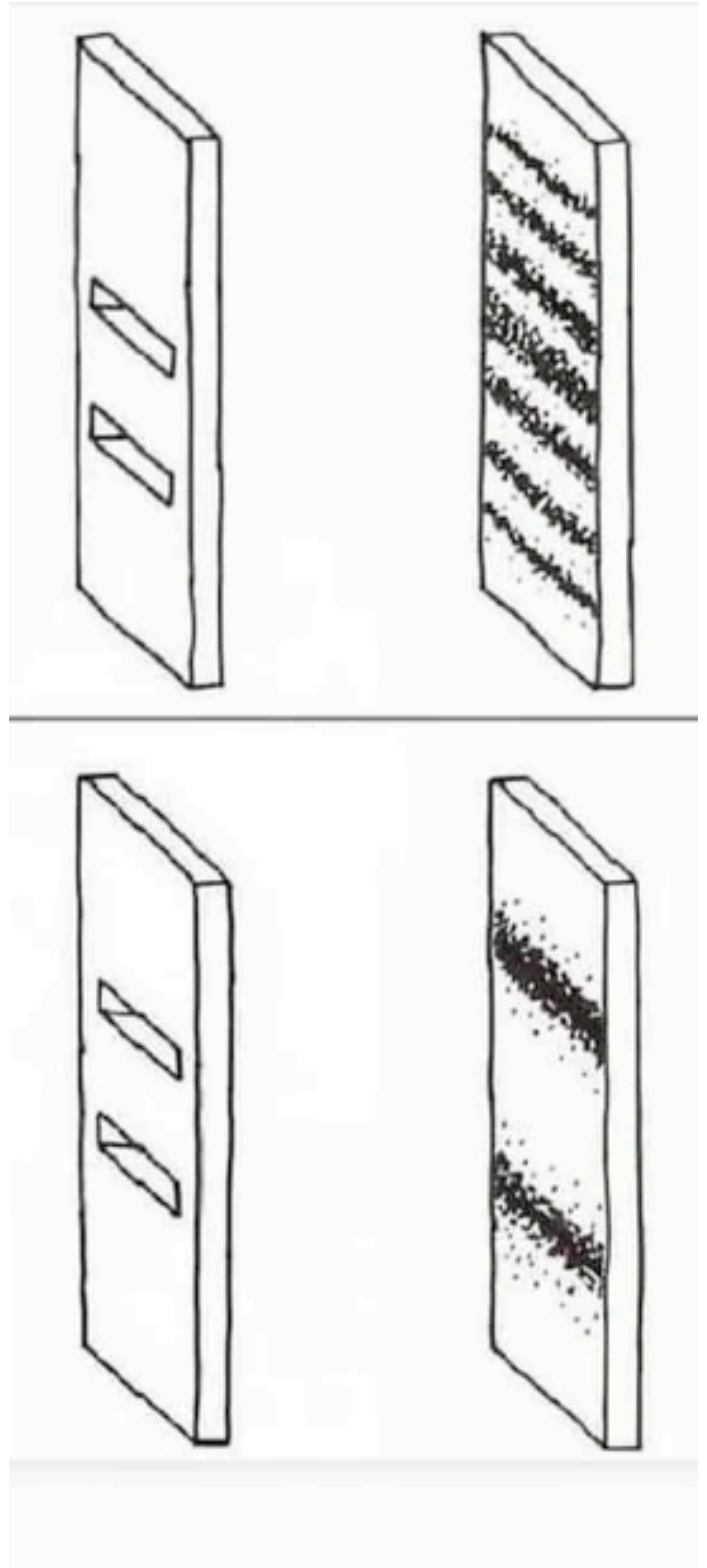
WHAT ARE PARTICLES? – MODERN PICTURE



WHAT ARE PARTICLES? – MODERN PICTURE



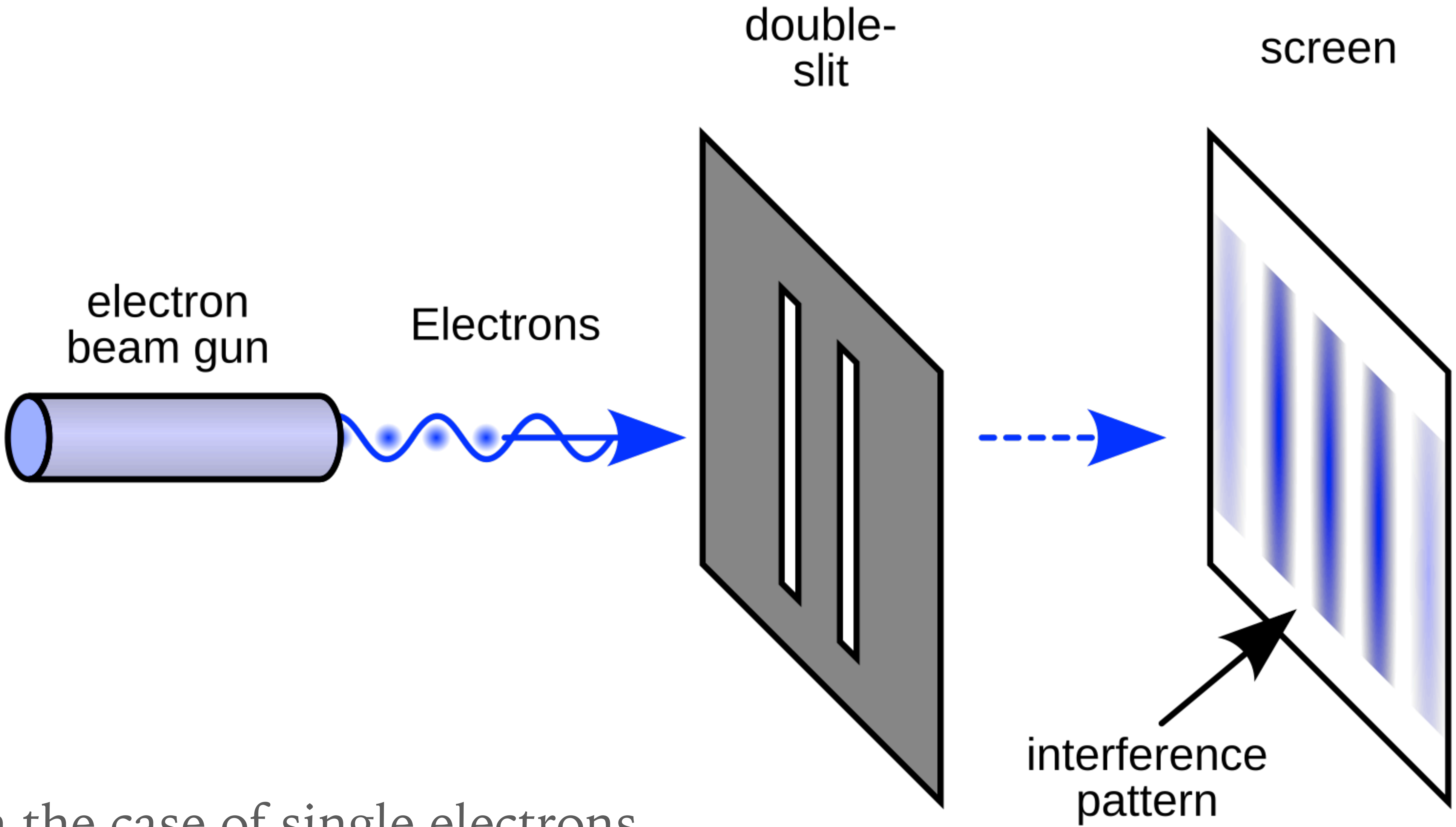
(hint)



WHAT ARE PARTICLES? – MODERN PICTURE

Davisson and Gremer

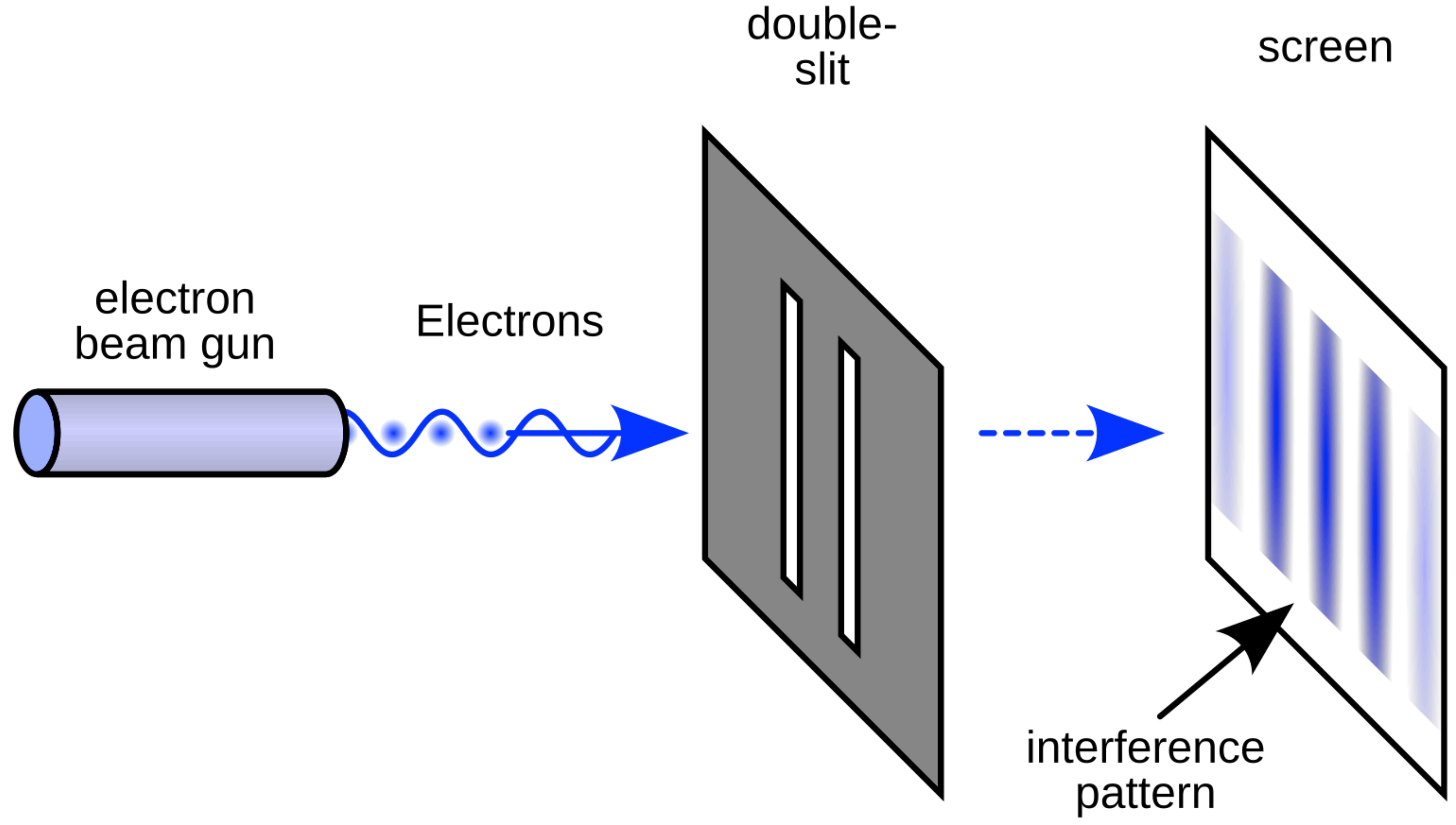
George Paget Thomson



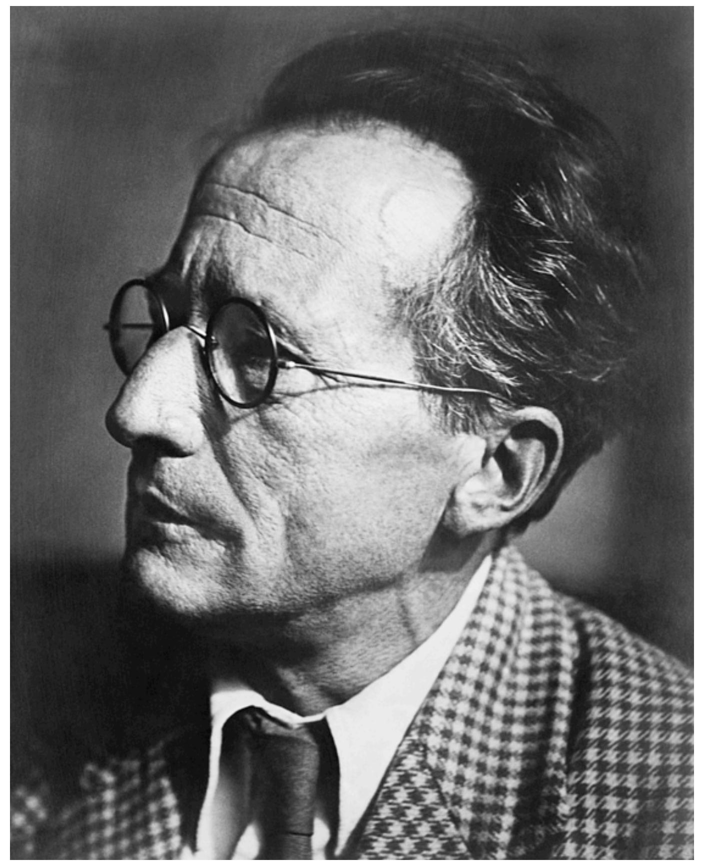
Note: Even in the case of single electrons we still get this pattern!

WHAT ARE PARTICLES? – MODERN PICTURE

- Propagation represented via wave functions (particle-wave duality)
- Not necessarily located at a specific position (Heisenberg uncertainty principle, $\Delta p \Delta x \geq \hbar/2$)
- Discrete (quantum) properties (ex. charge, spin)



Louis de Broglie



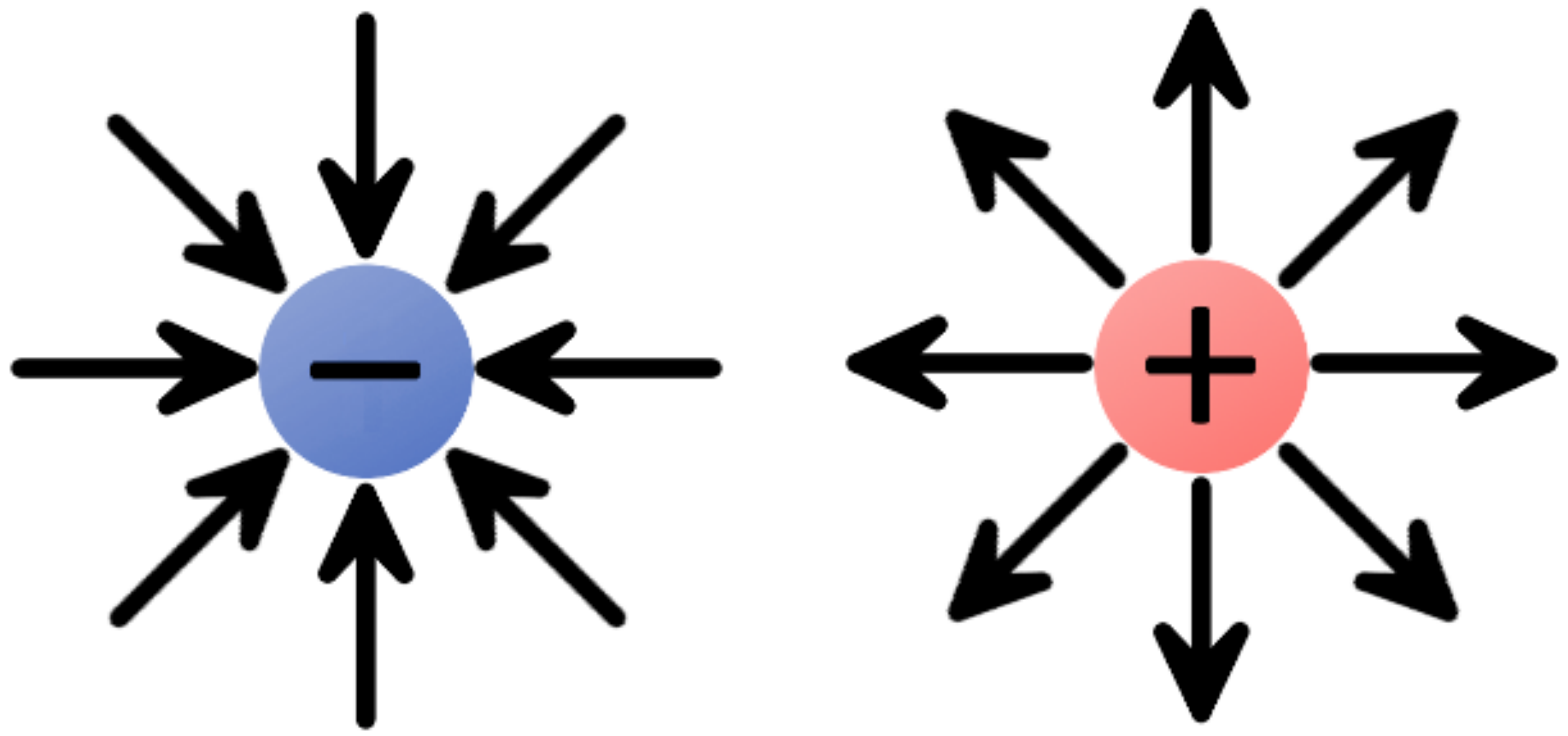
Erwin Schrödinger

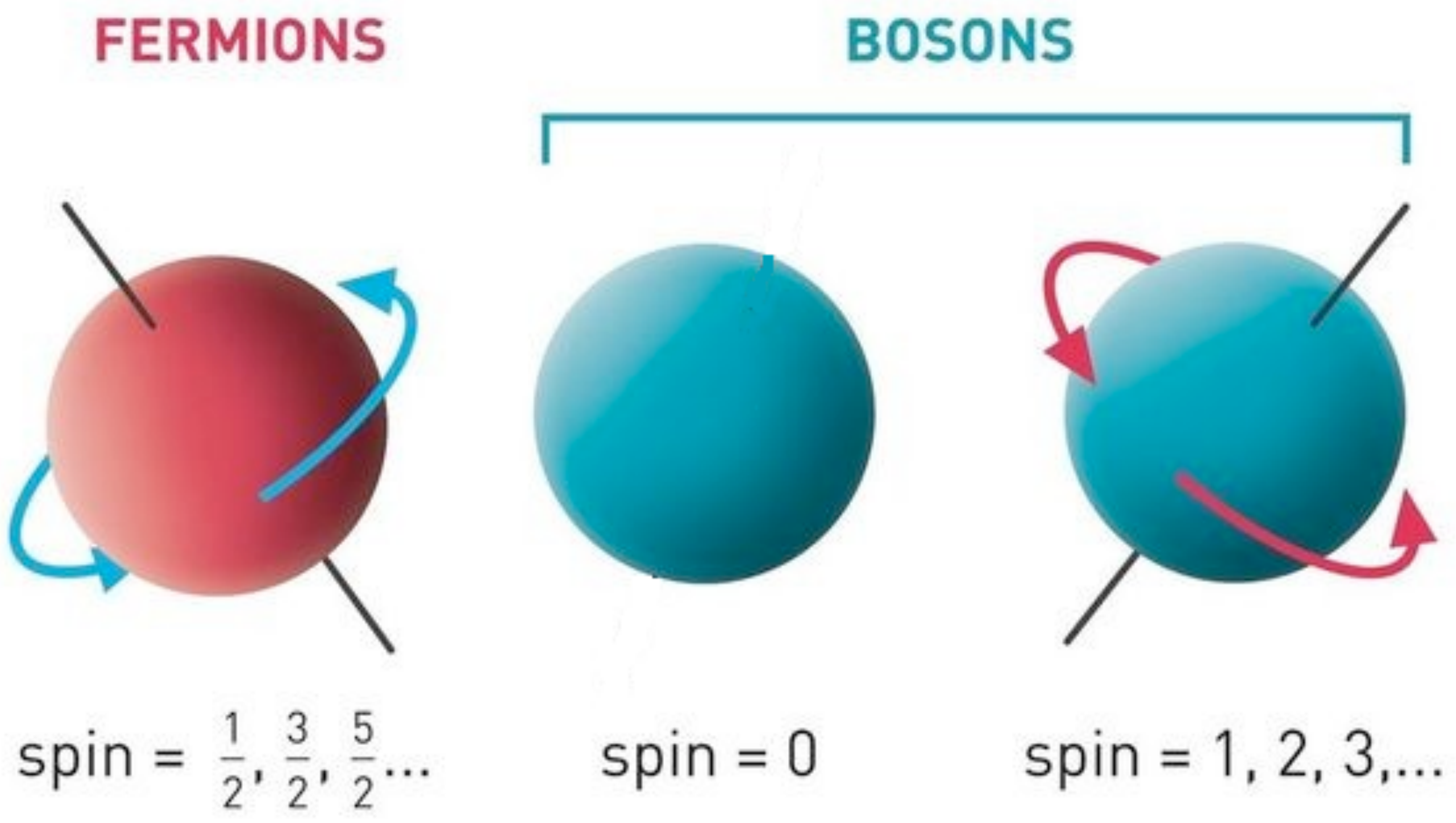
Neils Bohr

Werner Heisenberg

DISCRETE PROPERTIES OF PARTICLES

- Properties that distinguish one particle from another
- Charge: Intrinsic property that informs how it interacts with forces (ex. E&M) or other particles with similar properties
  - $\pm e$ = electrons, protons
  - $\pm e/3$, $\pm 2e/3$: quarks
- Spin: An intrinsic property in the form of angular momentum
  - Fractional Spin (Fermions): electrons, quarks
  - Integer Spin (Bosons): photons, gluons, Higgs

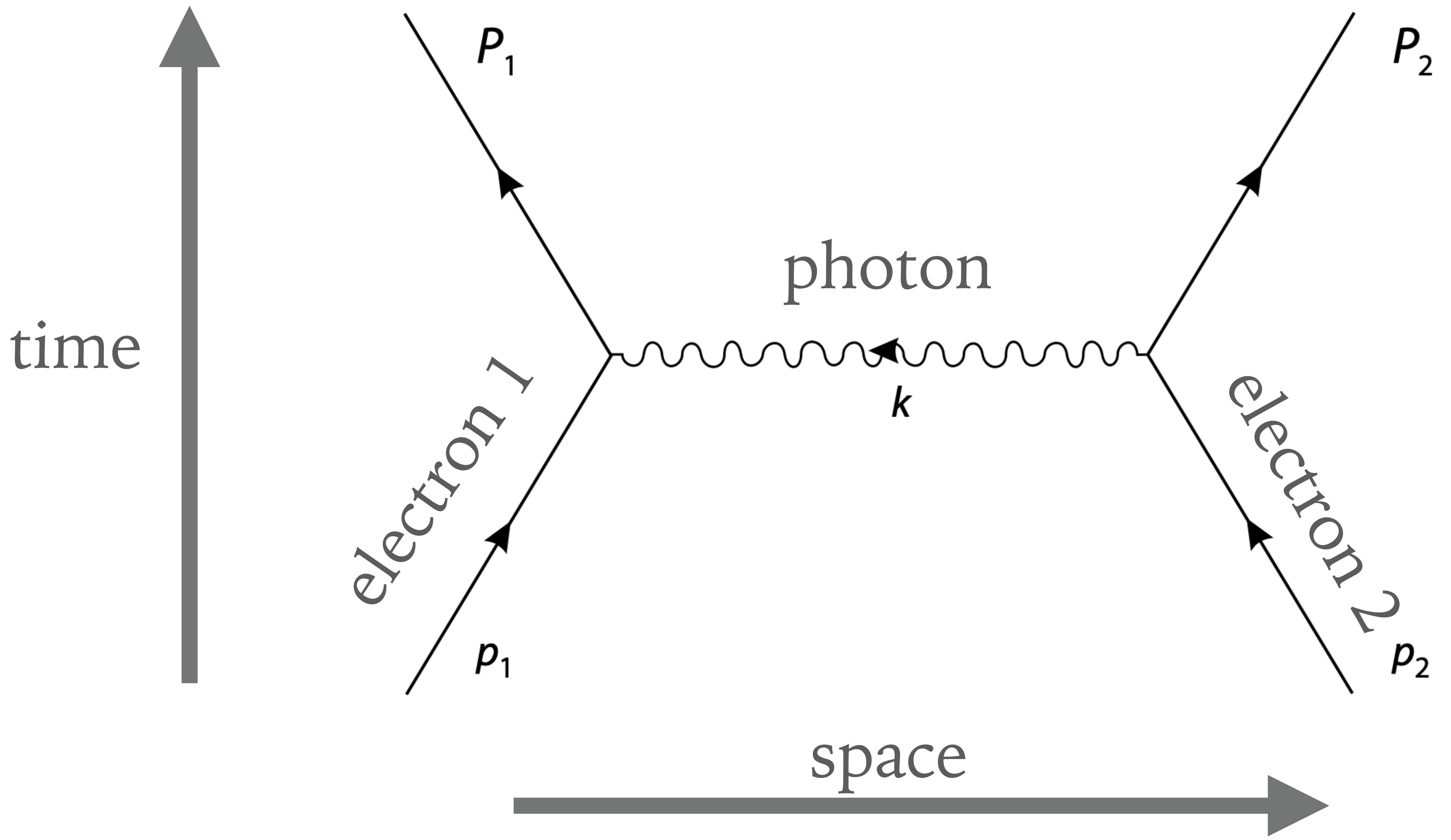


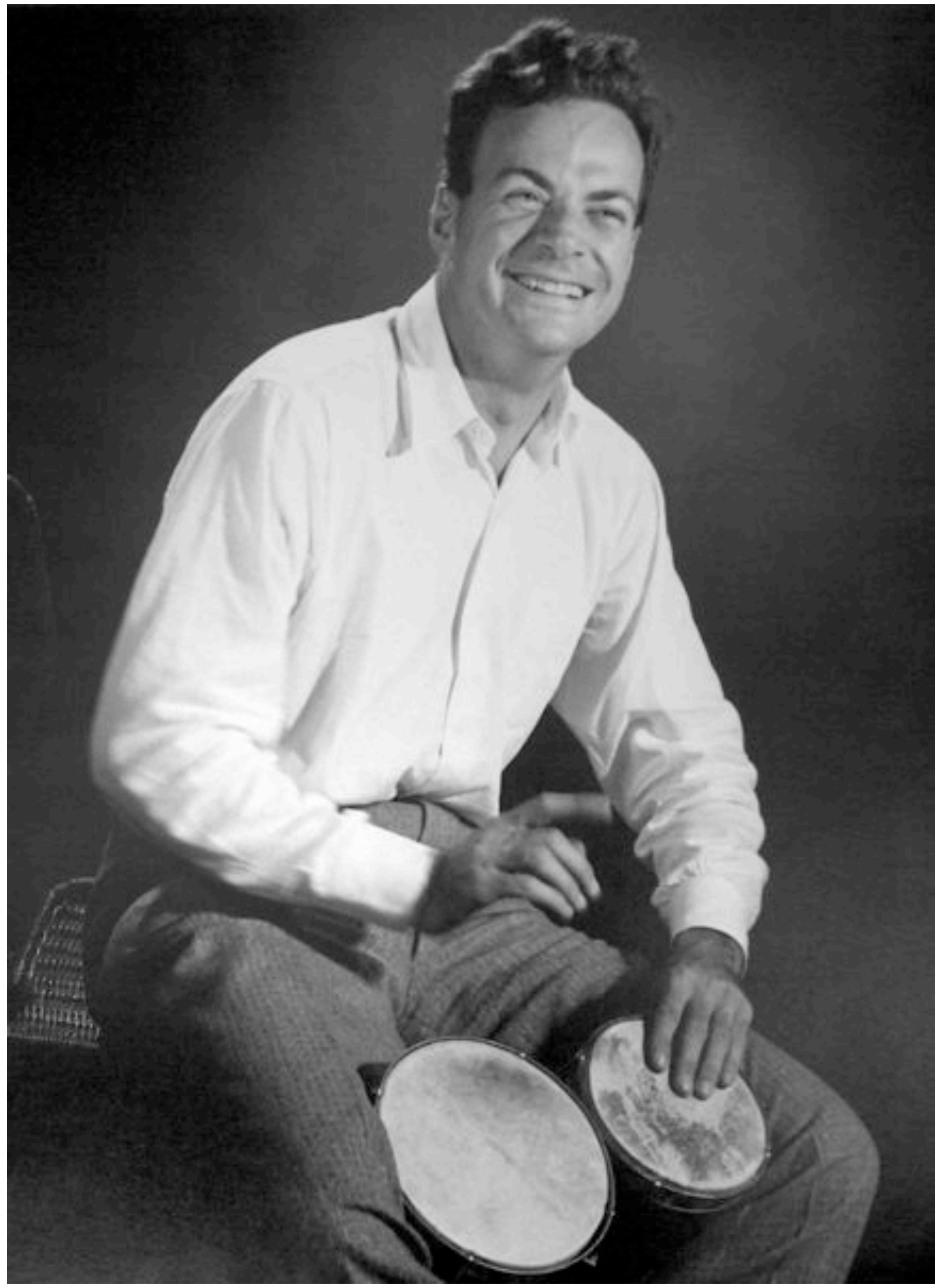


Note: Unfortunately, they're not actually spinning…

DESCRIBING PARTICLE PROPAGATION

- Math of Quantum Field Theory is encoded in Feynman Diagrams
- Ex. To describe electrons interacting with one another…





Richard Feynman

The Standard Model of Particles Physics

FERMIONS

Enrico Fermi

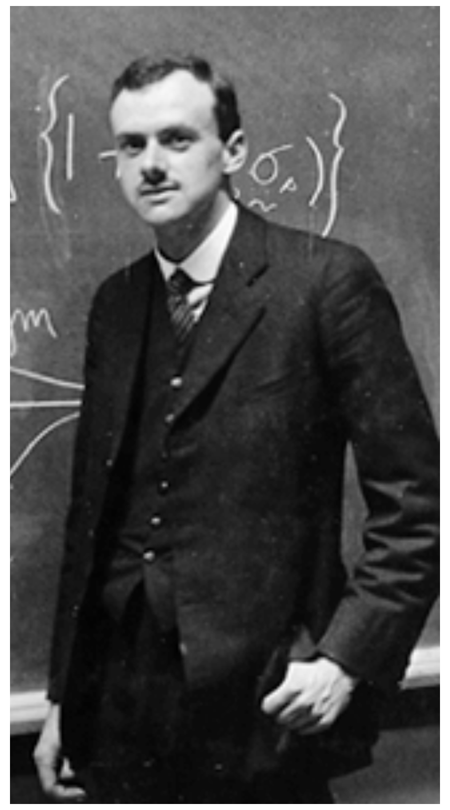
- Quarks:
  - Spin-1/2 with electric charge = $\pm 2e/3$ or $\pm e/3$
  - Contain a 'color' charge which **binds them to composite states** (ex. protons, neutrons)
- Leptons:
  - Spin-1/2 particles with integer charges ($\pm$e, 0)
  - Electron-like fermions (with different masses)
  - Neutrinos: Little neutral versions of the electron-like fermions

Fermions (matter)

Three Generations?

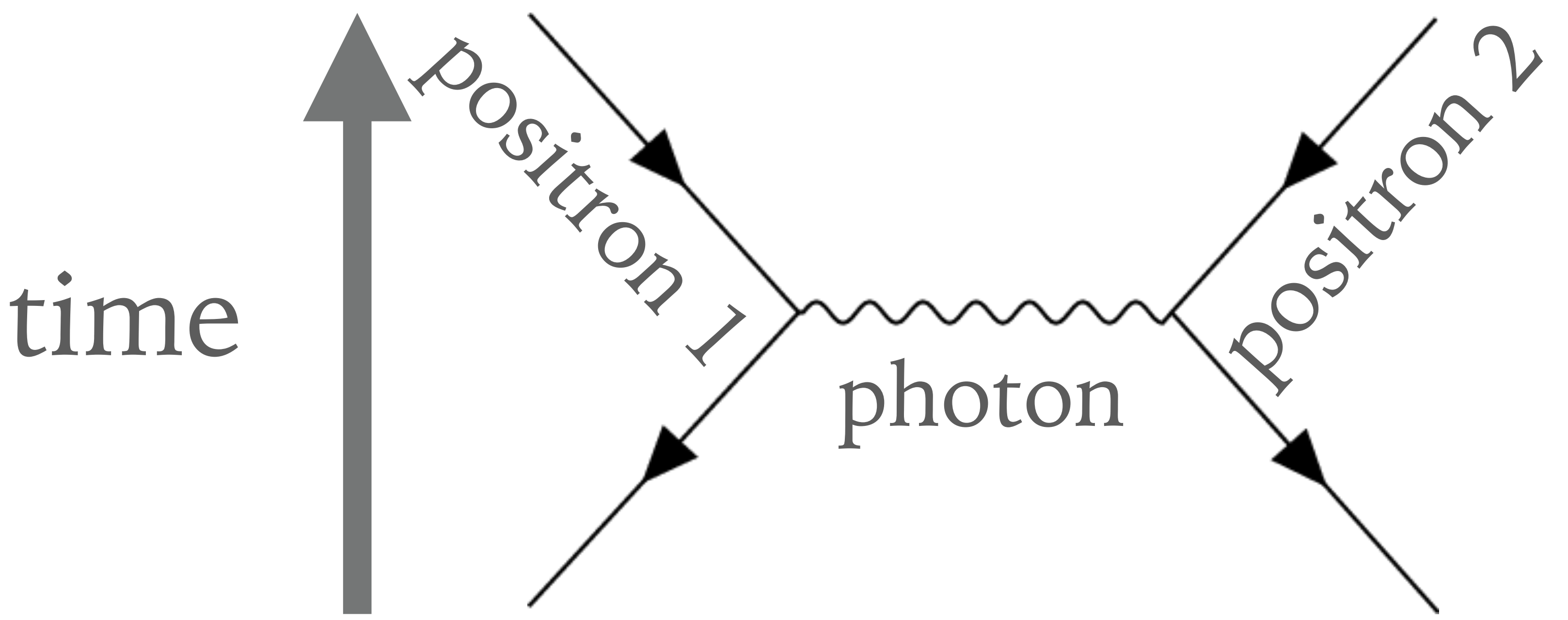
ANTI-FERMIONS?

- Tied with every fermion is an "anti-matter" counterpart with
  - The same mass and spin
  - Opposite electric/color charge
- Where does anti-matter come from?
  - Dirac Equation, part of QFT, predicts anti-matter naturally!
- <u>Summary of the anti-matter history…</u>



Paul Dirac

Anti-fermions (anti-matter)



BOSONS (FORCE CARRIERS & HIGGS)

Satyendra Nath Bose

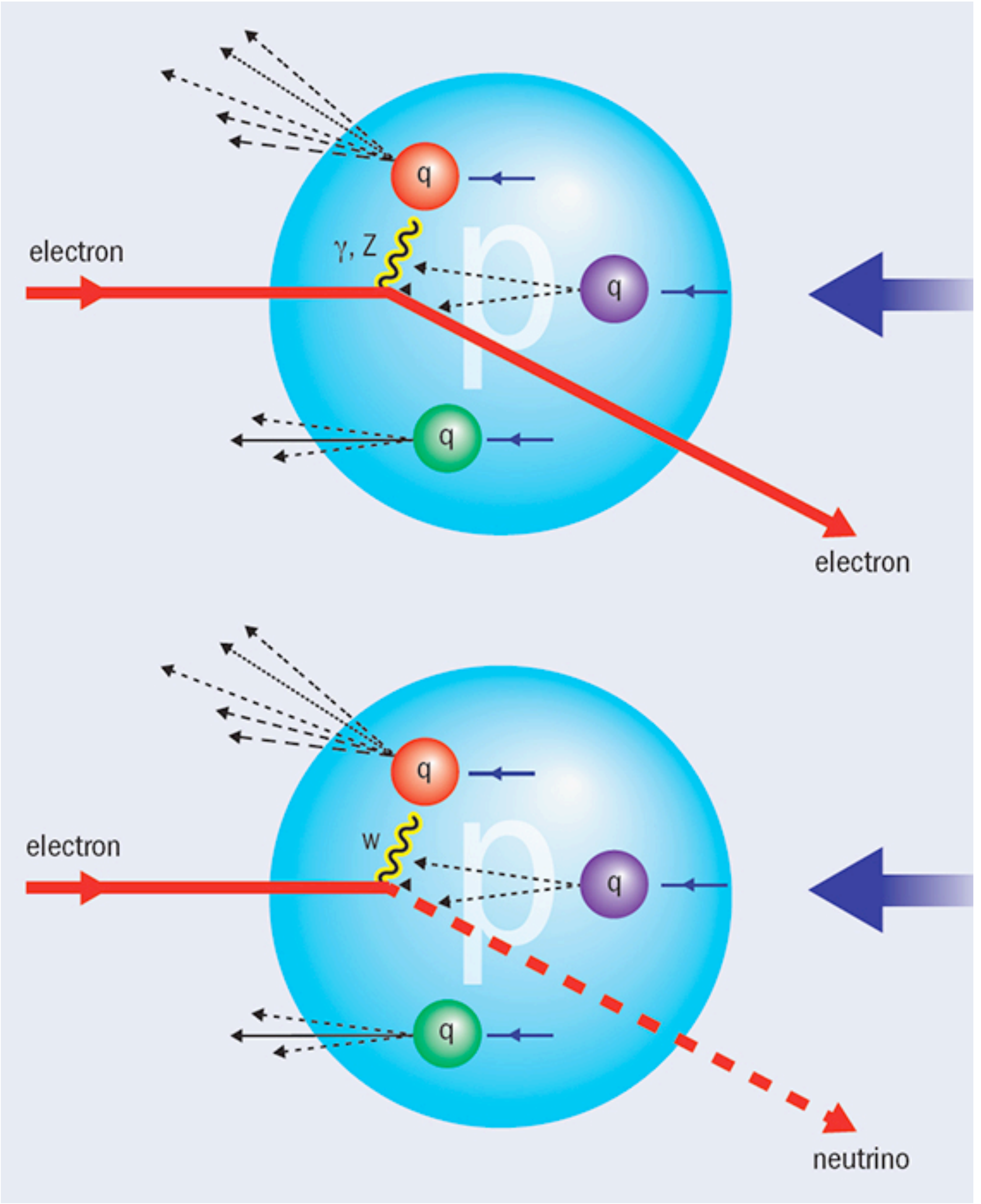
- Photon: Force carrier for the **electromagnetic** force (associated with electric charge)
- Gluons: Force responsible for **binding quarks** together (associated with color charge)
- Weak Force ($W^{\pm}/Z$): Massive bosons responsible for nuclear/radioactive decays and **"flavor changes"**
- Higgs boson: Spin-0 particle associated with the mechanism that imparts mass to other elementary particles
  - Buzz word: Spontaneous Symmetry Breaking

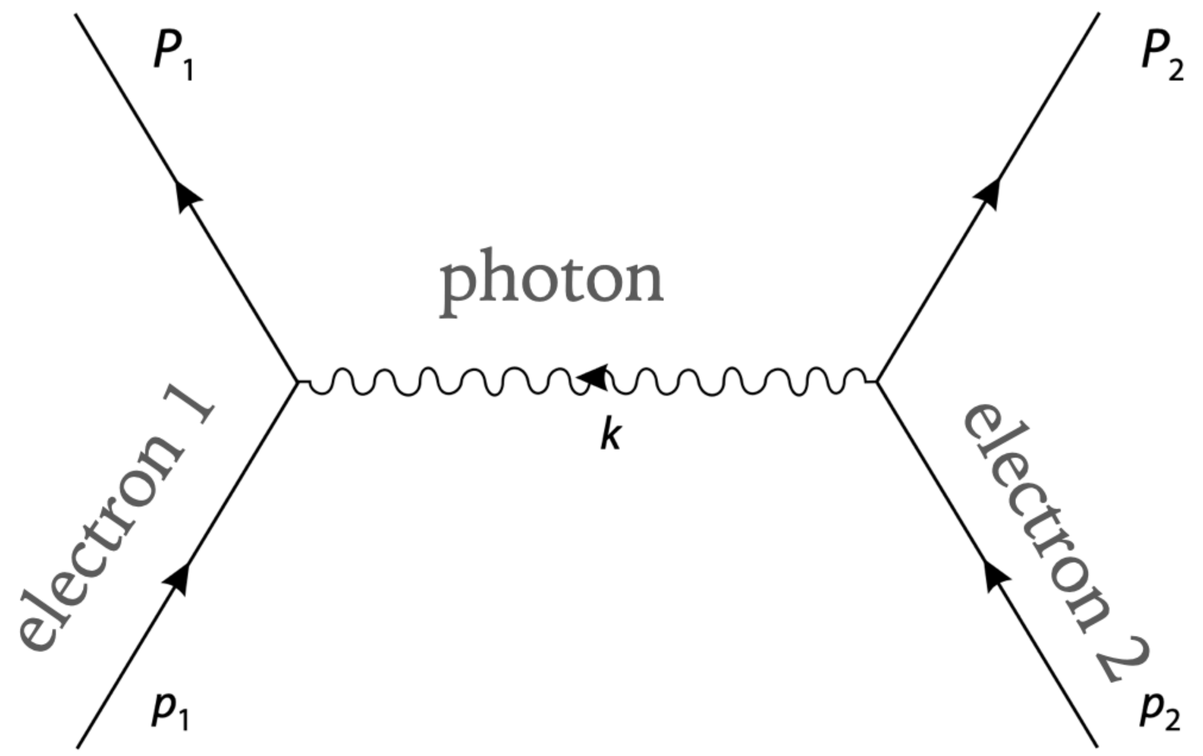
GOING BEYOND THE STANDARD MODEL (SOME UNANSWERED QUESTIONS)

- Why is gravity so much weaker than the other forces? (Hierarchy Problem)
- Why are there three generations of quarks and leptons?
- Why are there three spatial dimensions? (String Theory)
- **What is the neutrino mass and where does it come from? And its ordering?**
- **Why is there so much more matter than anti-matter, when the SM predicts matter and anti-matter should be mostly created in (almost) equal parts?**
  - See Flavor Physics talk for more insight
- **What is dark matter? And, what is dark energy?**
- Why is there no CP violation in the strong sector? (Strong CP problem)
  - Ask a friendly theorist or dark matter expert for more details

SUMMARY

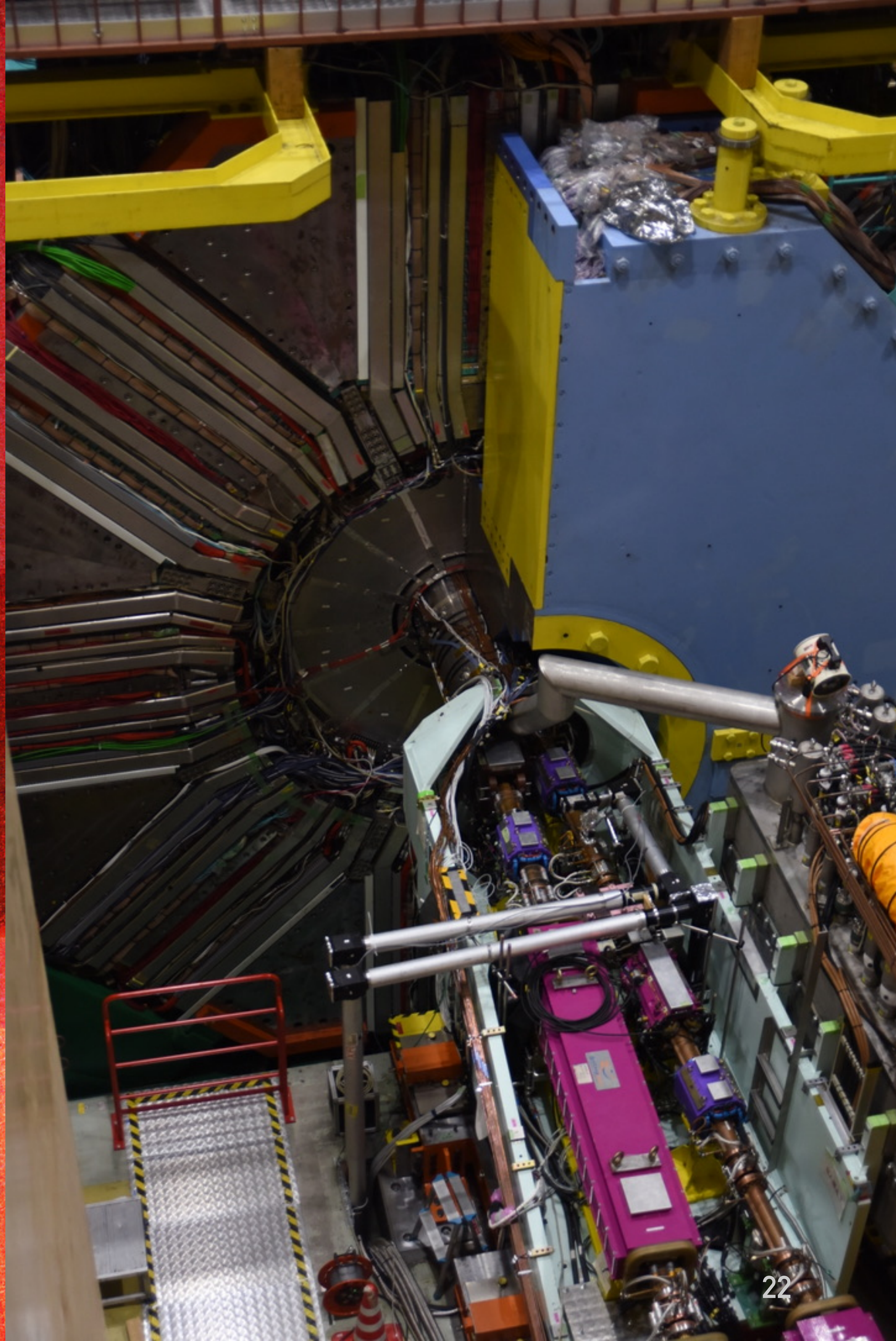
- Particle physics is the study of fundamental matter and its properties
- Particles are point-like bundles of energy that
  - propagate like waves
  - have discrete quantum numbers describing them
- Our best leading theory is the Standard Model (but still many more things to discover)



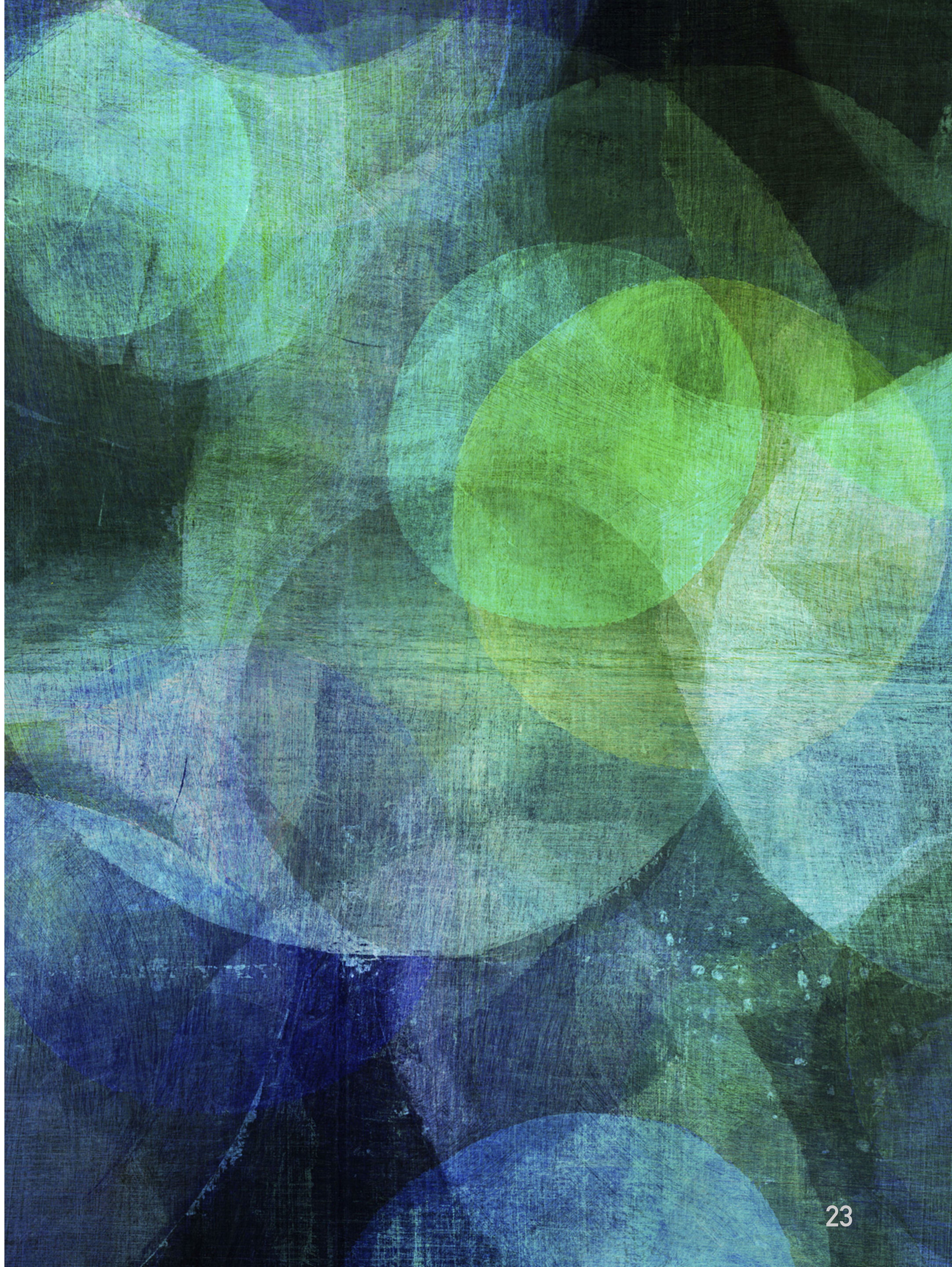


Thank you for your attention!

Questions?

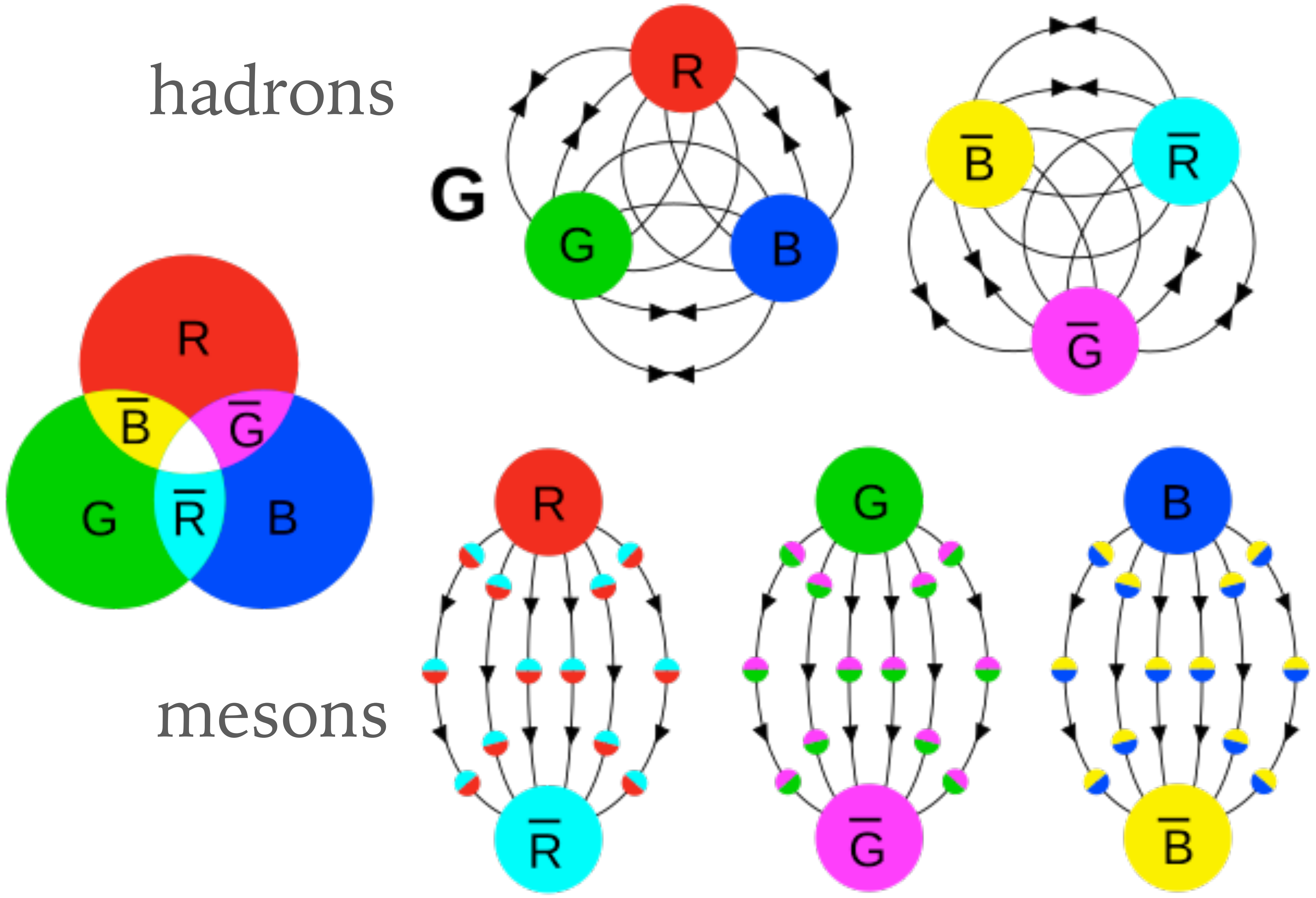


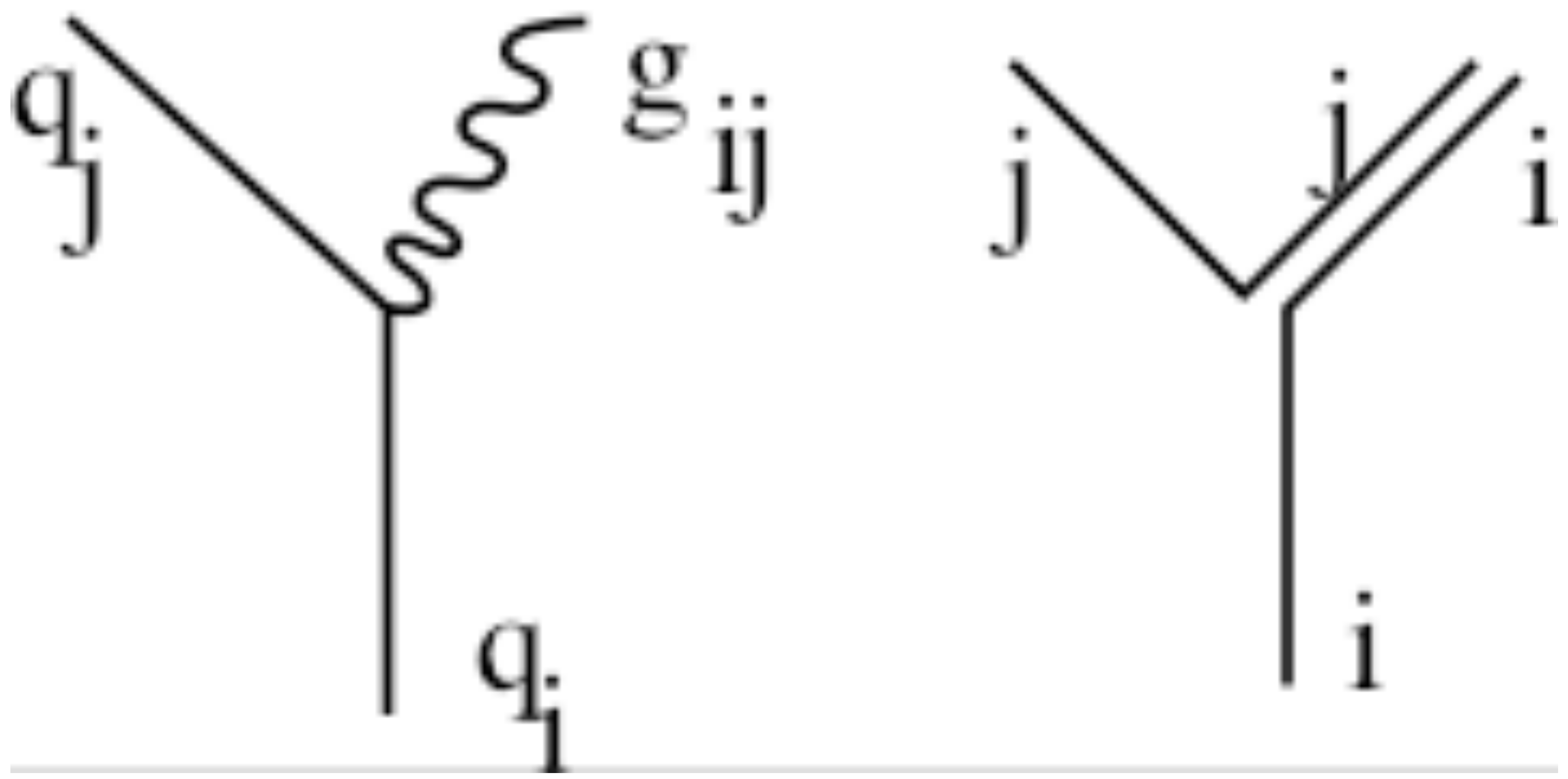
INCASE PEOPLE HAVE QUESTIONS



WHY DO WE CALL IT COLOR CHARGE?

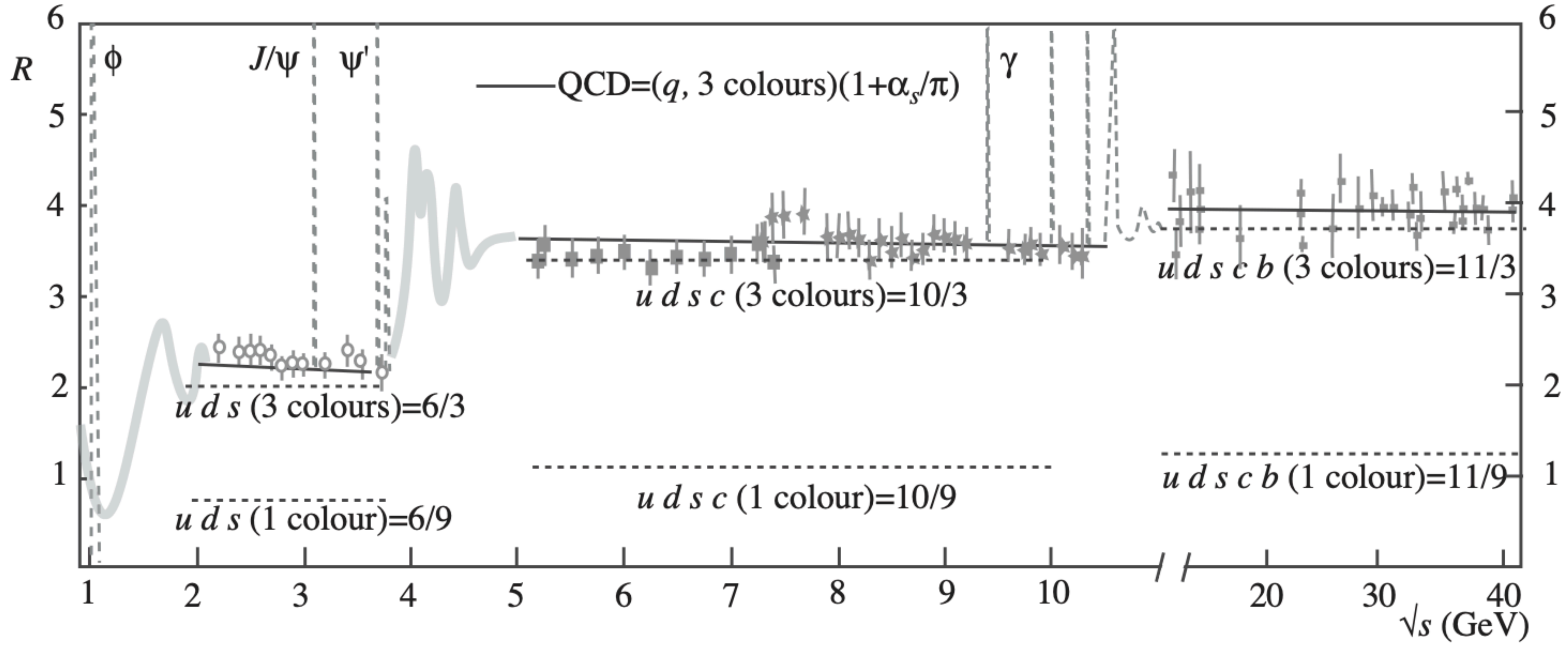
- The ‘algebra’ that describes gluons happens to align with how we think about color
- If you want to see more details, see either “quantum chromodynamics” or SU(3)





HOW DO WE KNOW THAT 'COLOR CHARGE' EXISTS?

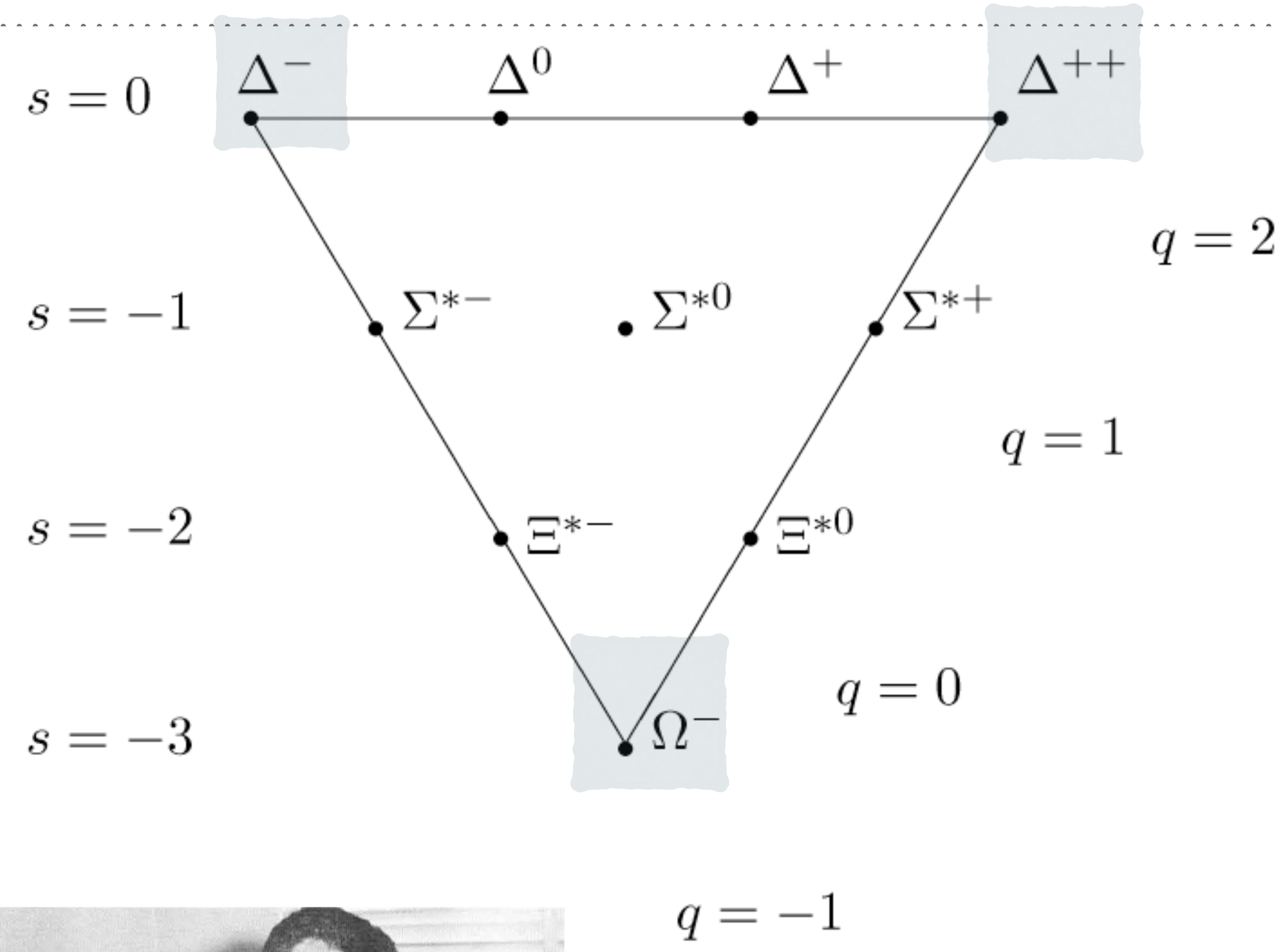
- From models of e^+e^- collisions across a wide range of energies, we notice that:
  - Hadronic cross-sections cannot be understood without an additional charge
  - quarks are observed as hadronic jets with the angular distribution of spin-1/2 particles
  - Gluons are seen as a third jet
  - $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-) = \sum_{flavors} nq_i$, data favors n = 3



Ratio R of hadronic to point-like cross-section in e^+e^- annihilation as a function of $\sqrt{s}$ (Yao *et al.* 2006, by permission of Particle Data Group and the Institute of Physics).

HOW DO WE KNOW THAT 'COLOR CHARGE' EXISTS?

- In addition, there are also some particles whos (valence) quarks are 3 of the same quark species
  - Δ++ = uuu
  - Δ- = ddd
  - Ω- = sss
- Because of the Pauli exclusion principle, there must be something else that distinguishes these particles from one another
  - It cannot be spin and electric charge
  - Answer: 'color' charge!



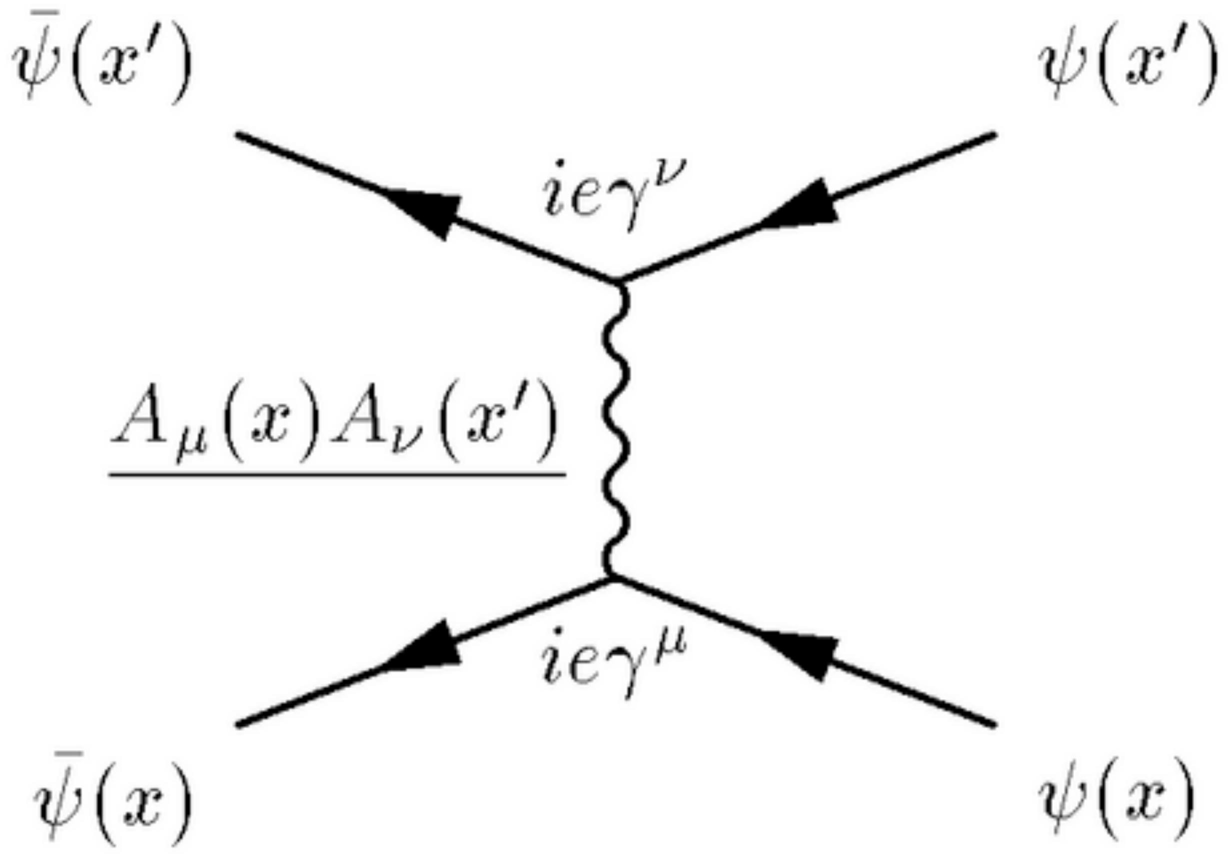
Murray Gell-Man

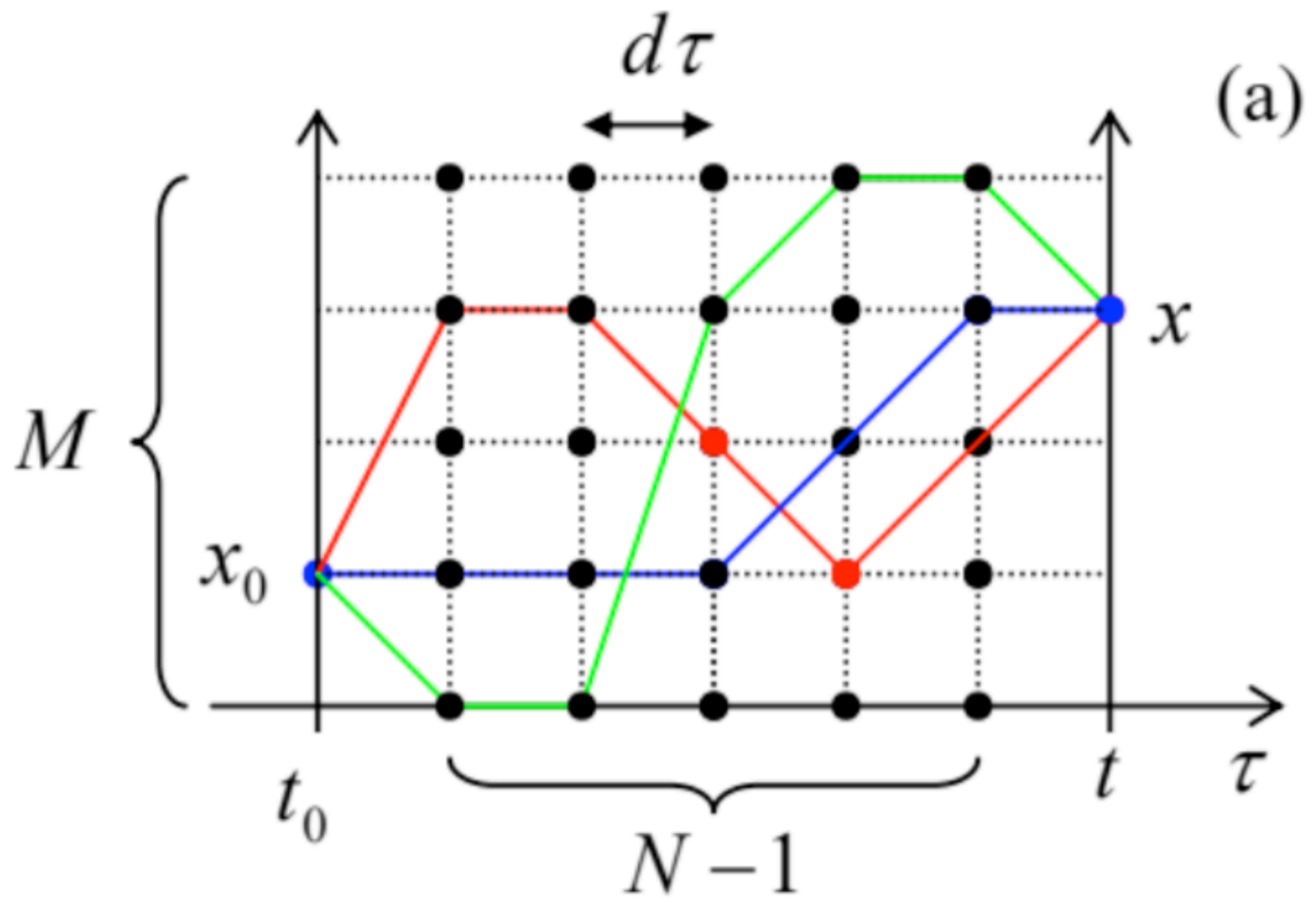
QUANTUM FIELD THEORY

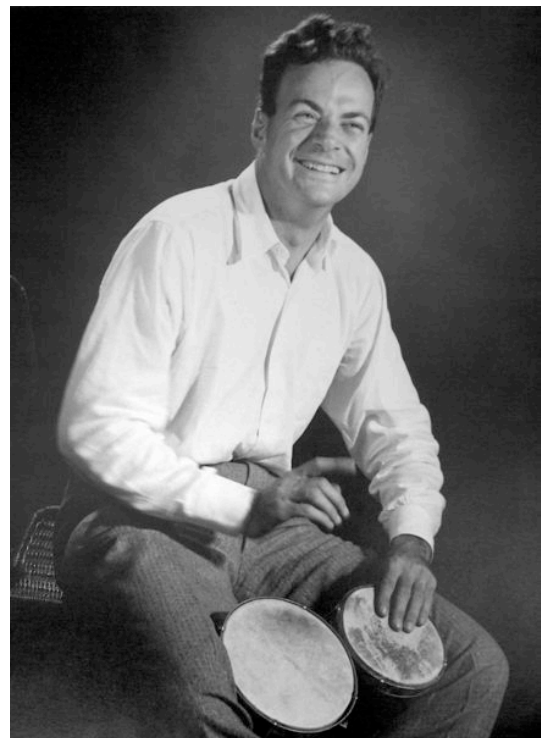
- Our best tool to describe the propagation of elementary particles
- Simplest Examples:
  - Klein-Gordon Equation: $\left(\partial^2 - m^2c^2/\hbar^2\right)\phi = 0 \quad \rightarrow E^2 - \vec{p}^2 - m^2 = 0$
  - Dirac Equation: $(i\partial\!\!\!/ - mc)\psi = 0 \quad \rightarrow E \mp (\overrightarrow{\alpha} \cdot \vec{p} + \beta m) = 0$
  - Photons and Matter : $-(1/4)F^{\mu\nu}F_{\mu\nu} + \bar{\psi}(iD\!\!\!/ - mc)\psi$ $\rightarrow$ Maxwell's Equation
- For comparison, Schrödinger Equation: $\left(\frac{-\hbar^2}{2m}\vec{\partial}^2 + V\right)\psi = E\psi \ \rightarrow KE + PE = E$

THE RELATION BETWEEN FEYNMAN DIAGRAMS AND QFT

- Starting point: Equations as shown in [math slide] are terms in a Lagrangian density $\mathscr{L}$
  - These diagrams come from relating initial state $|i\rangle$ with final state $|f\rangle$ via some evolution operator S via $\langle f|S|i\rangle$. These S's roughly come from interaction terms (ex. $\mathscr{L}_{QED} \ni -e\bar{\psi}\gamma^\mu A_\mu \psi$)
  - By summing over all paths a particle can take $\left(\exp\left(\frac{i}{\hbar}\int \mathscr{L} dt\right)\right)$ and terms in this summation correspond to S



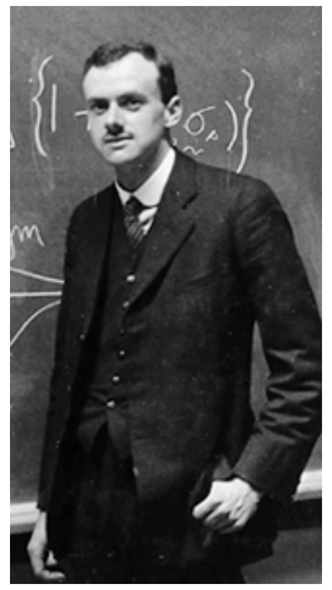




STATISTICS

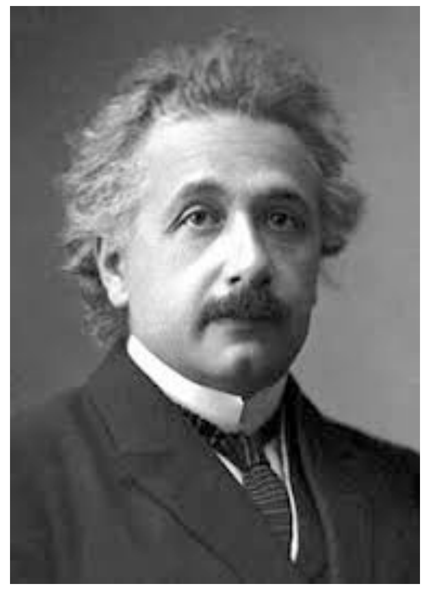
- For many body systems, two types of statistics for non-interacting quantum systems:
  - Fermi-Dirac For identical particles, they must obey the Pauli-exclusion principle
  - Bose-Einstein: Allows for identical particles to occupy the same state
- Spin-Statstics Theorem
  - Properties of spin are directly related to their many-body statistics
  - Fermi-Dirac —> Fermions (fractional spins)
  - Bose-Einstein —> Bosons (integer spins)

Enrico Fermi



Paul Dirac

Satyendra Nath Bose



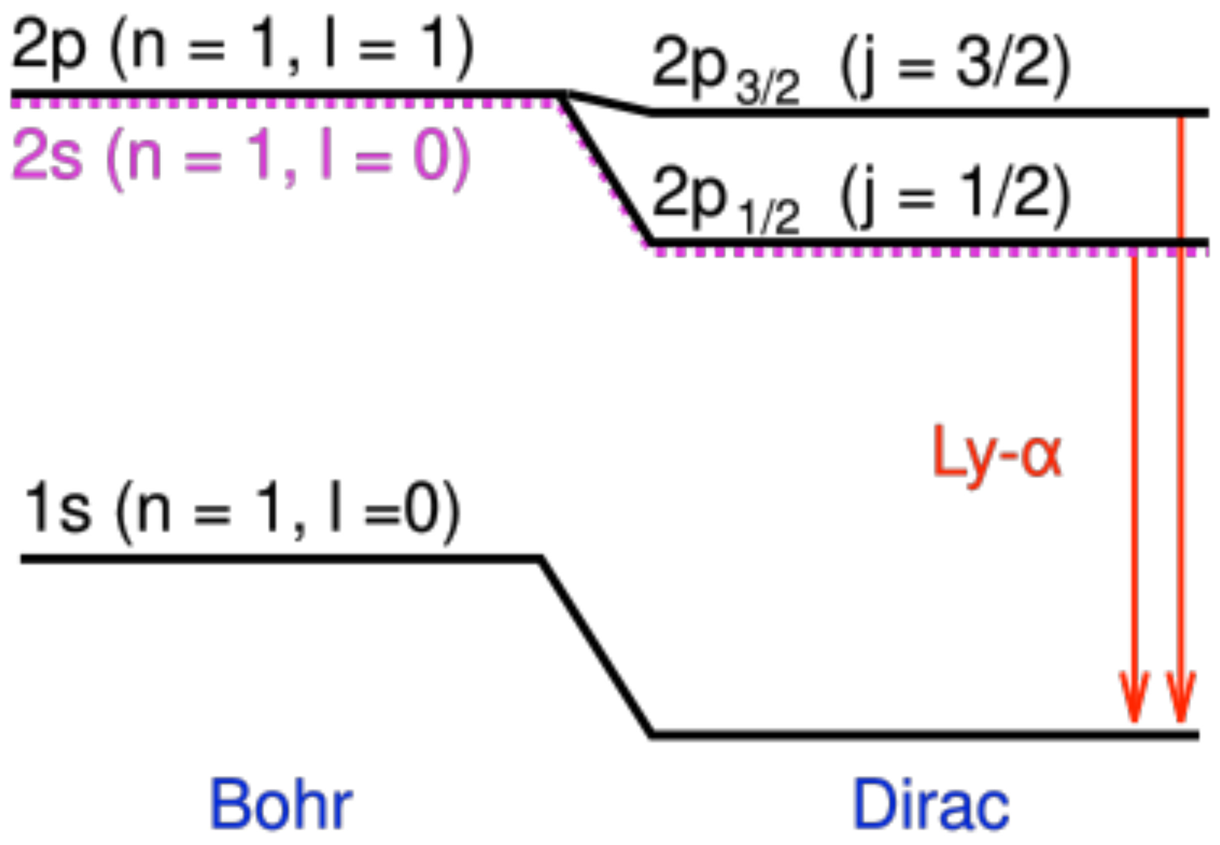
Albert Einstein

WHAT IS SPONTANEOUS SYMMETRY BREAKING

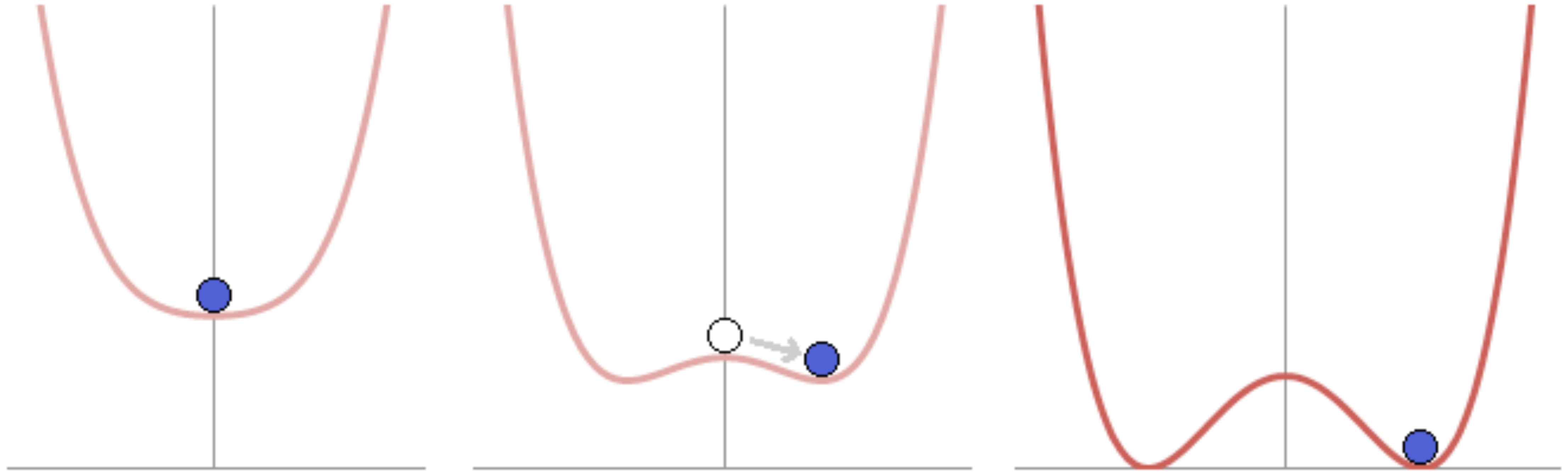
Yoichiro Nambu,
Jeffery Goldstone,
Peter Higgs

- Symmetry Breaking: When our system has an intrinsic symmetry and 'breaks' it
  - Explicit: When something external perturbs a system to break some symmetry
  - Spontaneous: When a (vacuum) state of a symmetric system becomes not symmetric
    - In SM, Higgs acts to modify the vacuum state of Ws/Zs and the result states mass

explicit



spontaneous



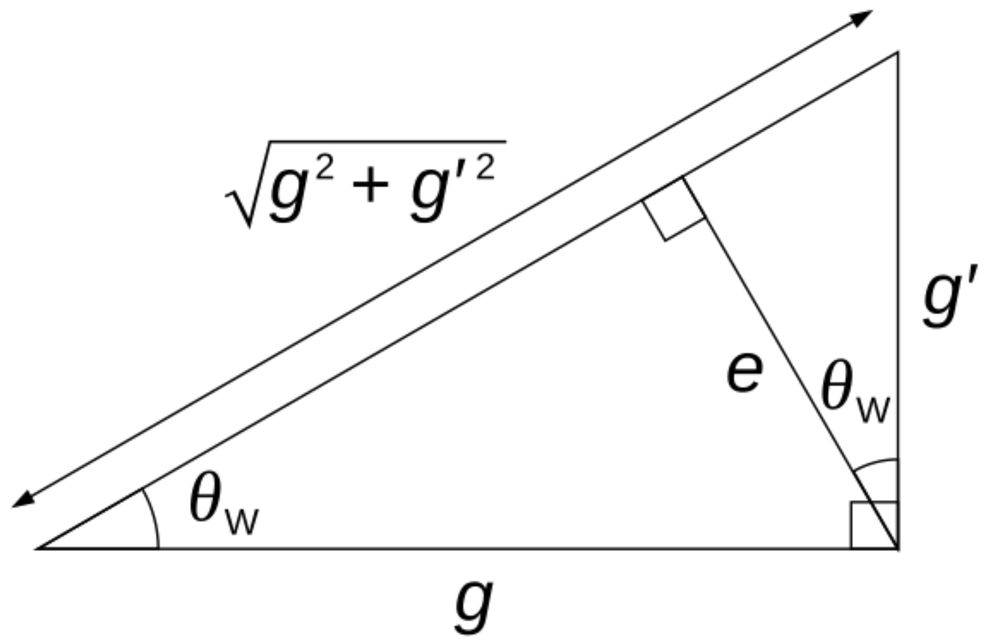
ELECTRO-WEAK?

Steven Weinberg,
Abdus Salam,
Sheldon Glashow

- In the SM, we typically think about the electromagnetic and weak force as the same 'electroweak' force.

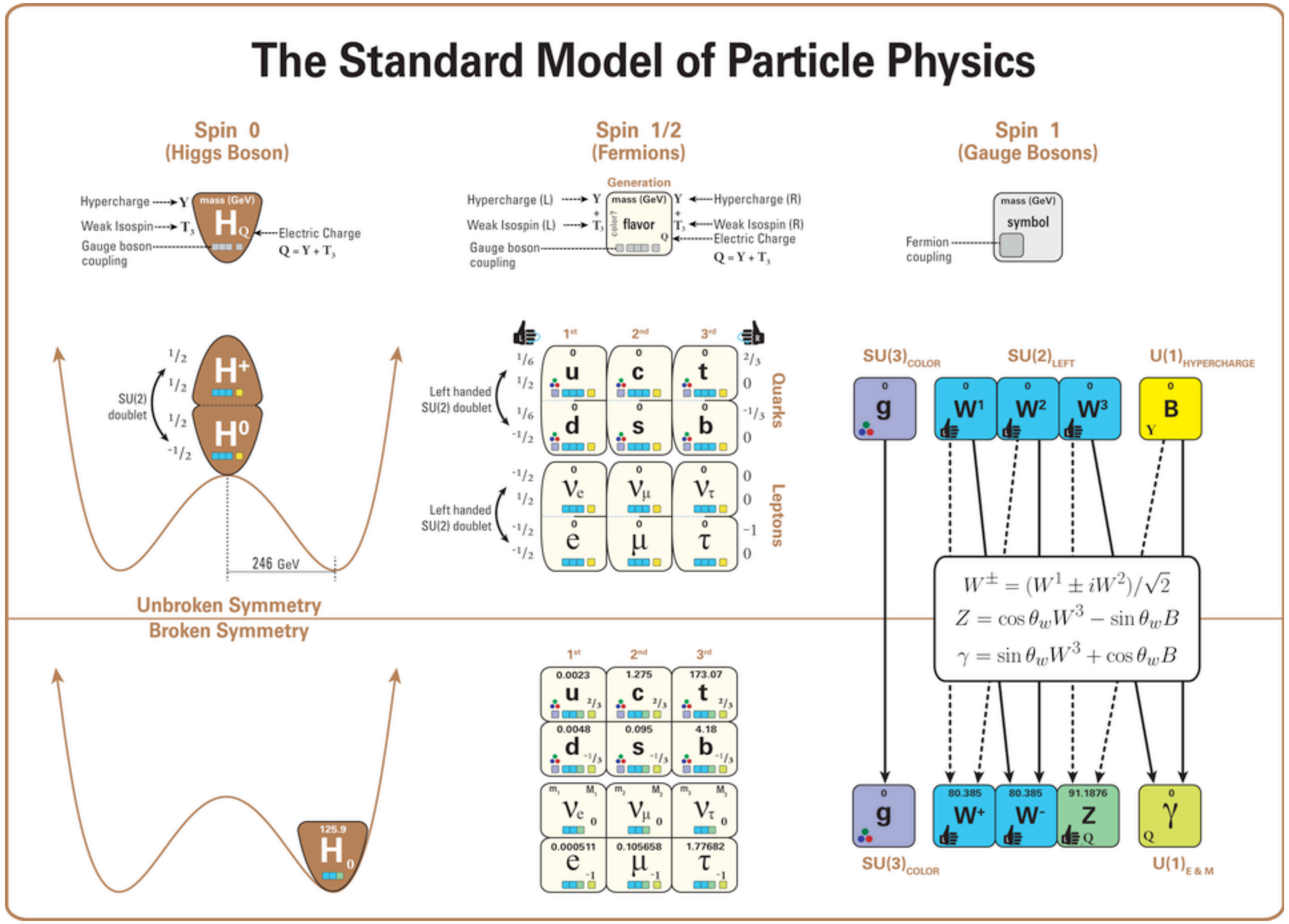
$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B \\ W_3 \end{pmatrix},$$

  - Why? — Symmetry Breaking!
    - At high energies, $\mathscr{L}_{EW} \ni$ W and B boson terms. At low energies, these terms separate into the $W^\pm/Z$ and γ, which are the weak and photon forces.
  - We can relate the "weak isospin" (charge related to W) and "weak hypercharge" (related to Z) to E&M charge via:
    - electric charge = weak isospin + 1/2 x weak hypercharge

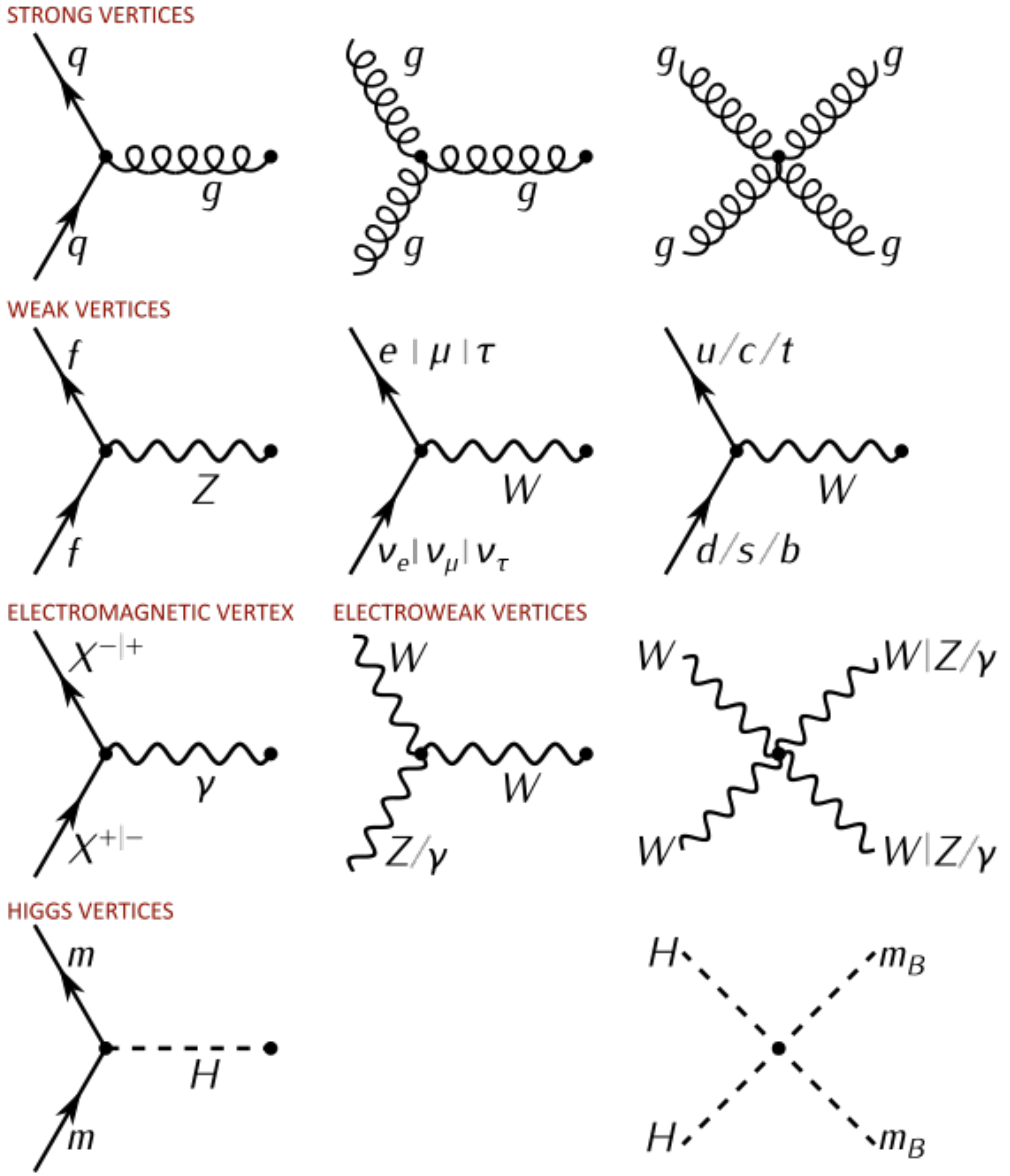


    - Technical Jargon: Coming from SU(2) x U(1), hypercharge comes from the U(1) generator, SU(2) generator comes in as weak isospin

STANDARD MODEL LAGRANGIAN

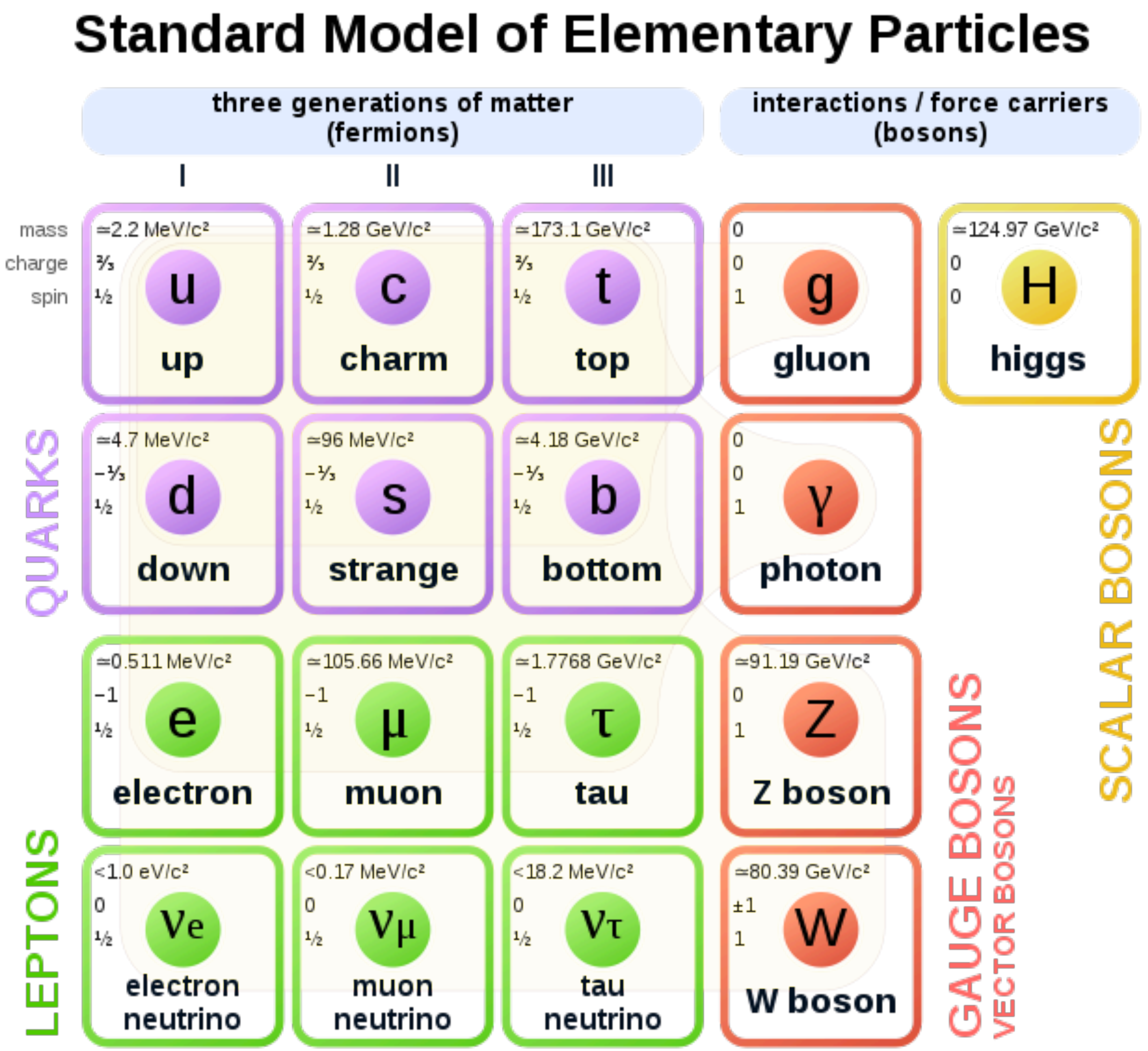


“The deconstructed Standard Model equation”

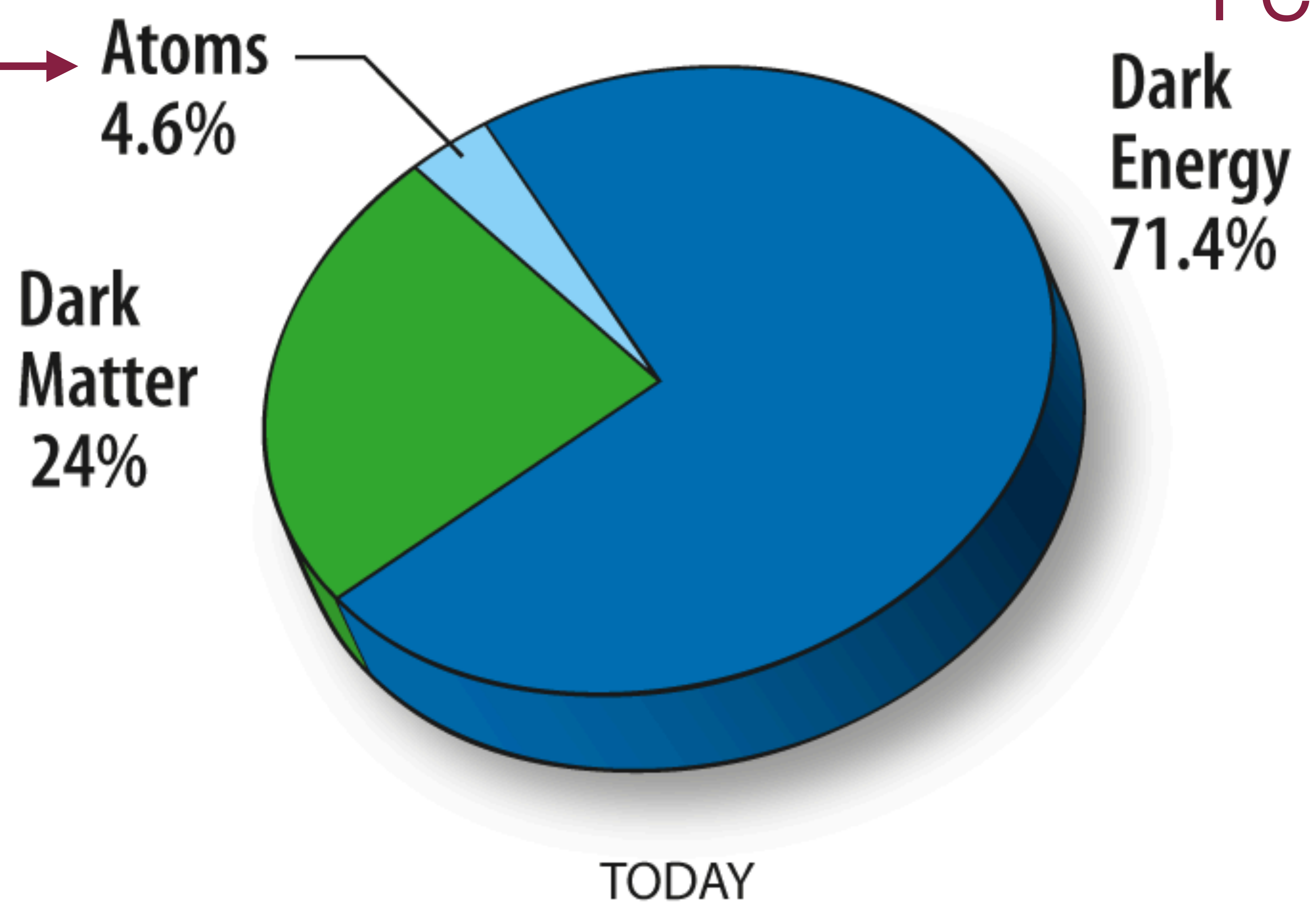


MATTER CONTENT OF THE UNIVERSE

PC: [1]



PC: [2]



[1]: Wikipedia Commons. "File:Standard Model of Elementary Particles.svg-Wikimedia Commons, the free media repository" (2020) - out of date?
[2]: https://wmap.gsfc.nasa.gov/universe/uni_matter.html

STRONG CP PROBLEM

- In the SM lagrangian, there is nothing stopping (massive) quarks from having complex phases and flavor violation via the strong force
  - CKM mechanism is described in the weak sector

CP Violating phase

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \theta\frac{g^2}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi.$$

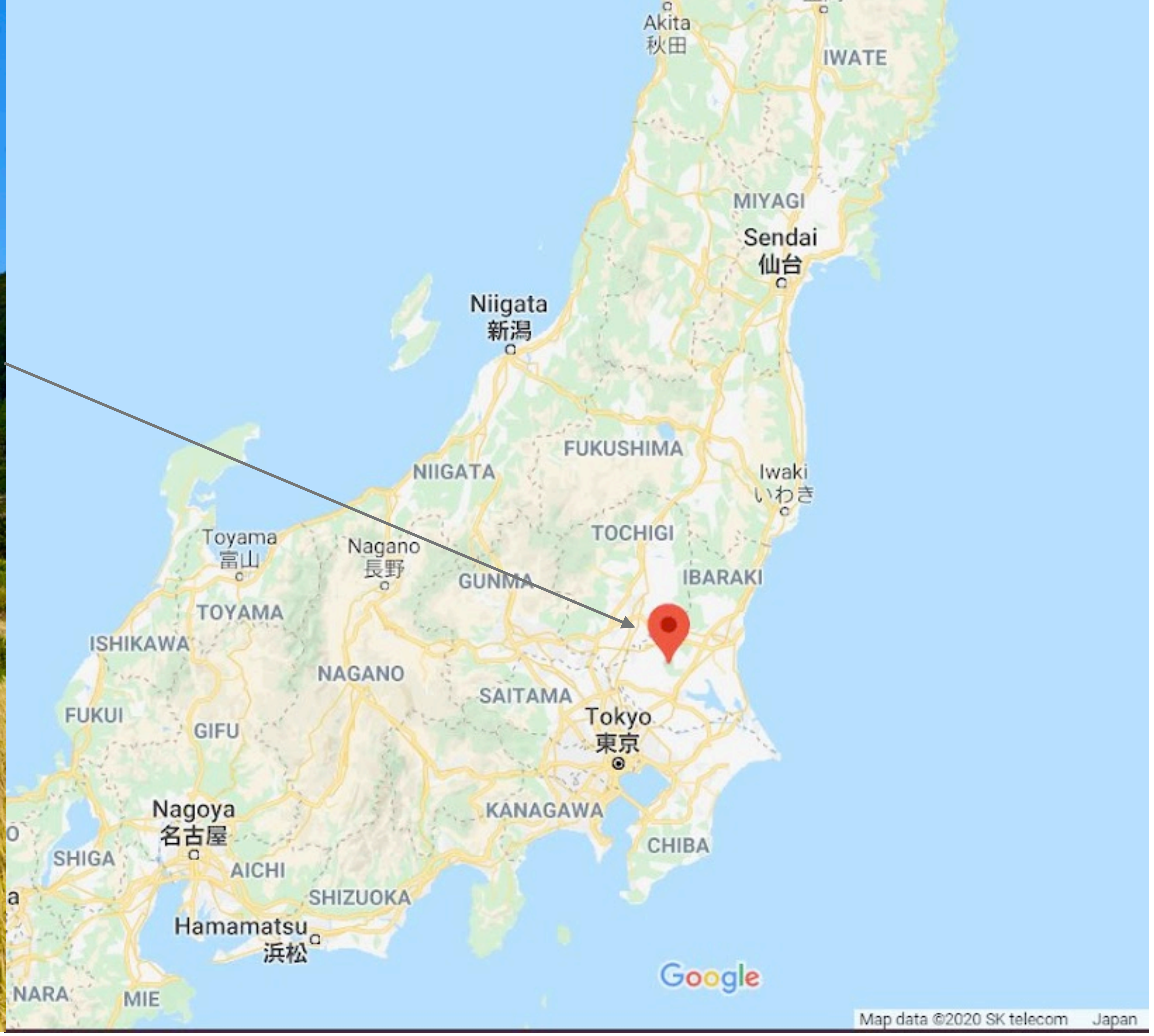
CP Violating term

Chiral Transformation

$$\psi' = e^{i\alpha\gamma_5/2}\psi, \qquad \bar{\psi}' = \bar{\psi}e^{i\alpha\gamma_5/2},$$

- In order to solve this, theorist have tried to introduce a pseudo-Goldstone mode that breaks the CP symmetry (new particle called axion)
  - An attractive dark matter candidate due to its relevance to the Standard Model


Tsukuba-san
(筑波山)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秋田
IWATE
MIYAGI
Sendai
仙台
Niigata
新潟
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Iwaki
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TOCHIGI
IBARAKI
Toyama
富山
Nagano
長野
GUNMA
TOYAMA
ISHIKAWA
NAGANO
SAITAMA
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Nagoya
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