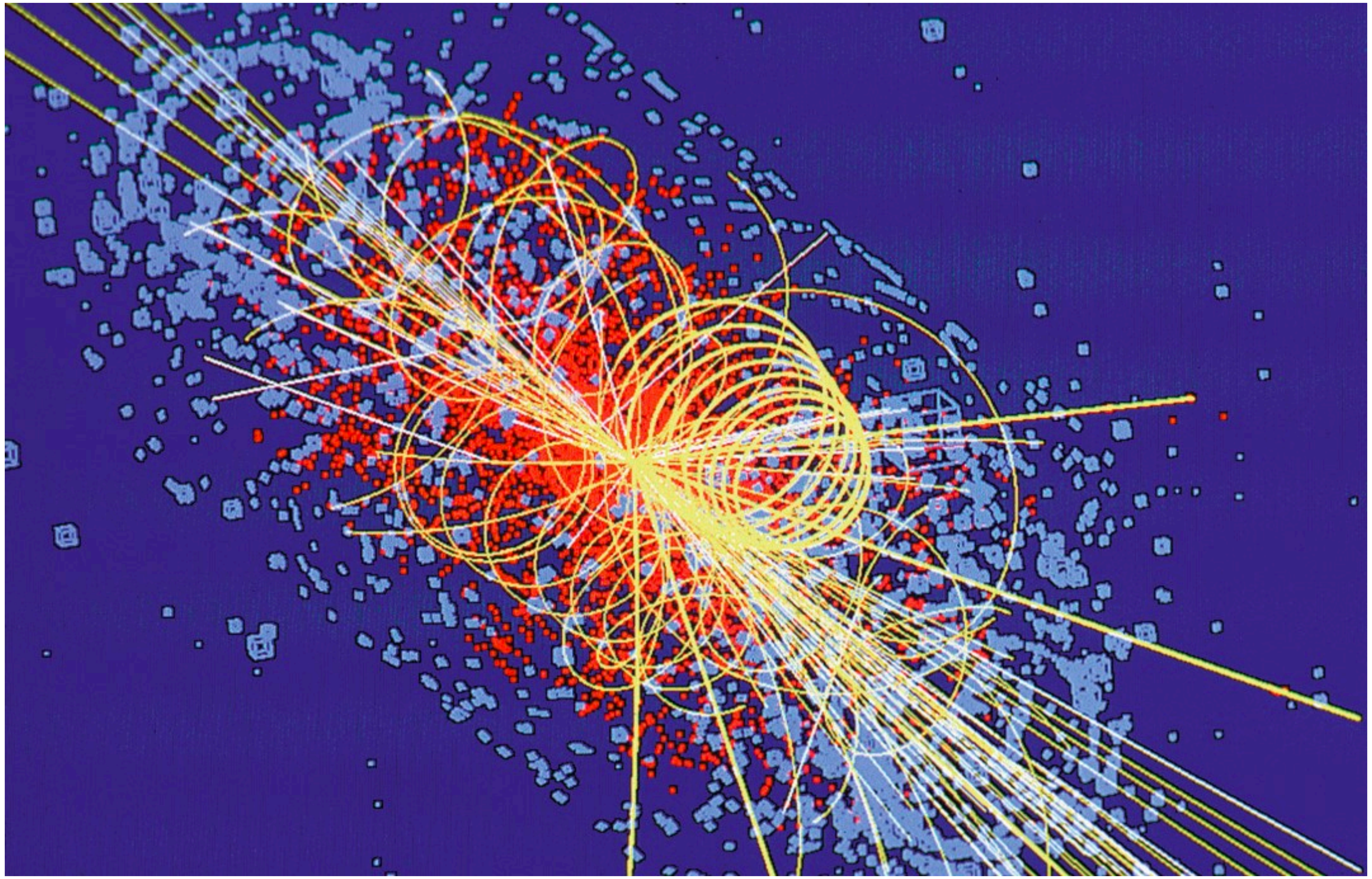
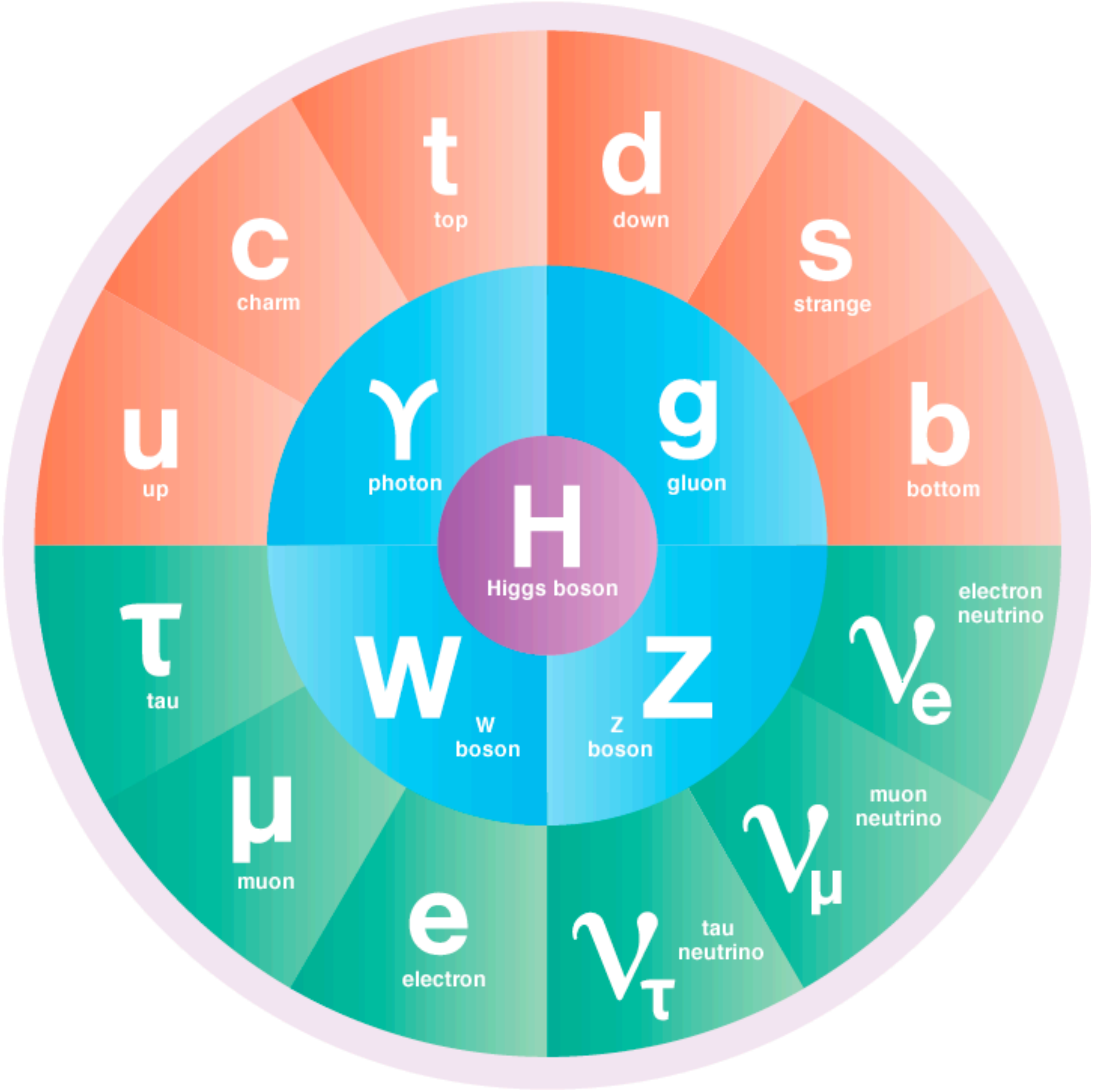
Introduction to Particle Physics

Kevin J. Kelly

Undergraduate Lecture Series, May 28th, 2020

What is Particle Physics?





$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi + h.c. \\
& + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
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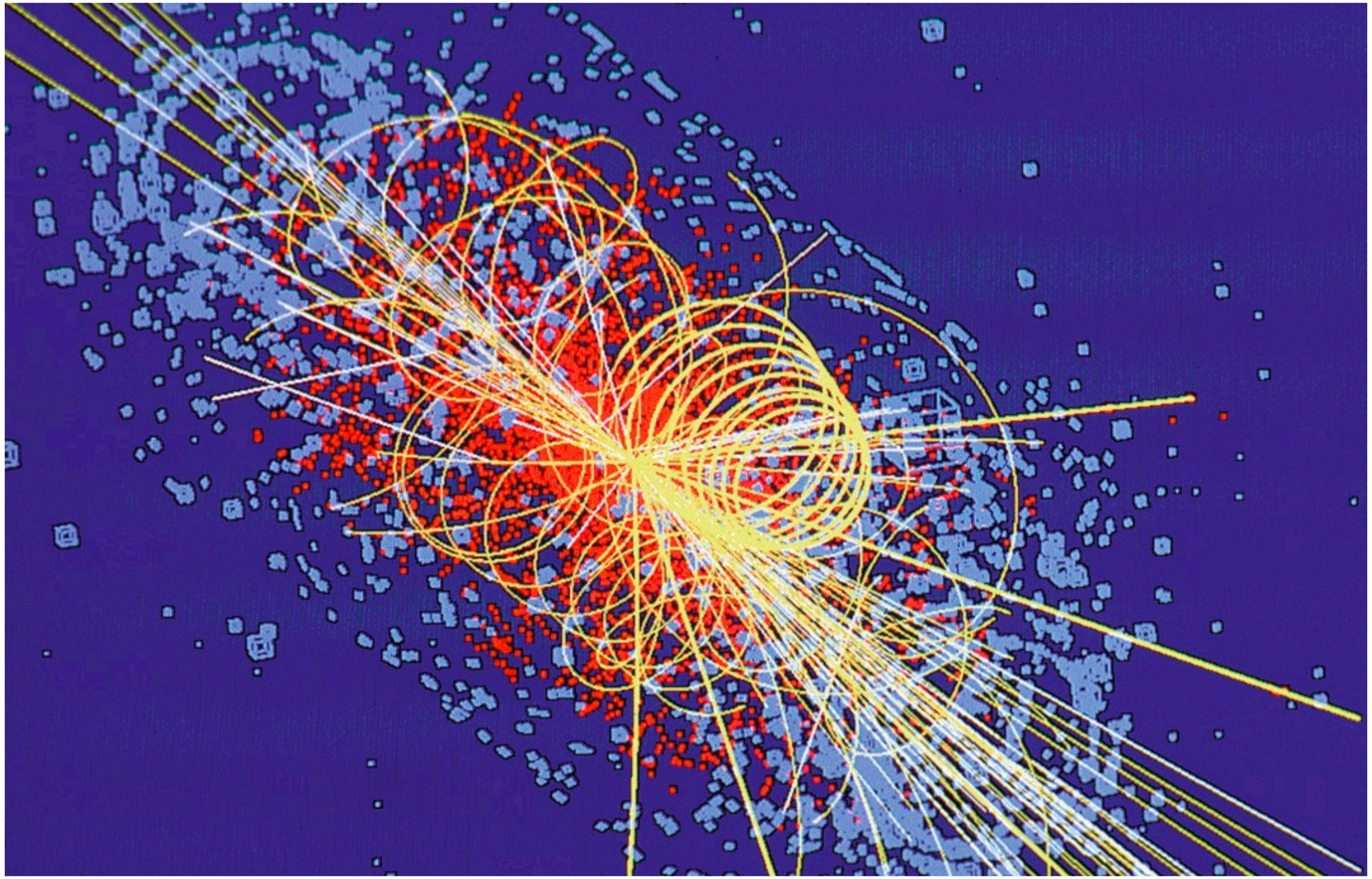
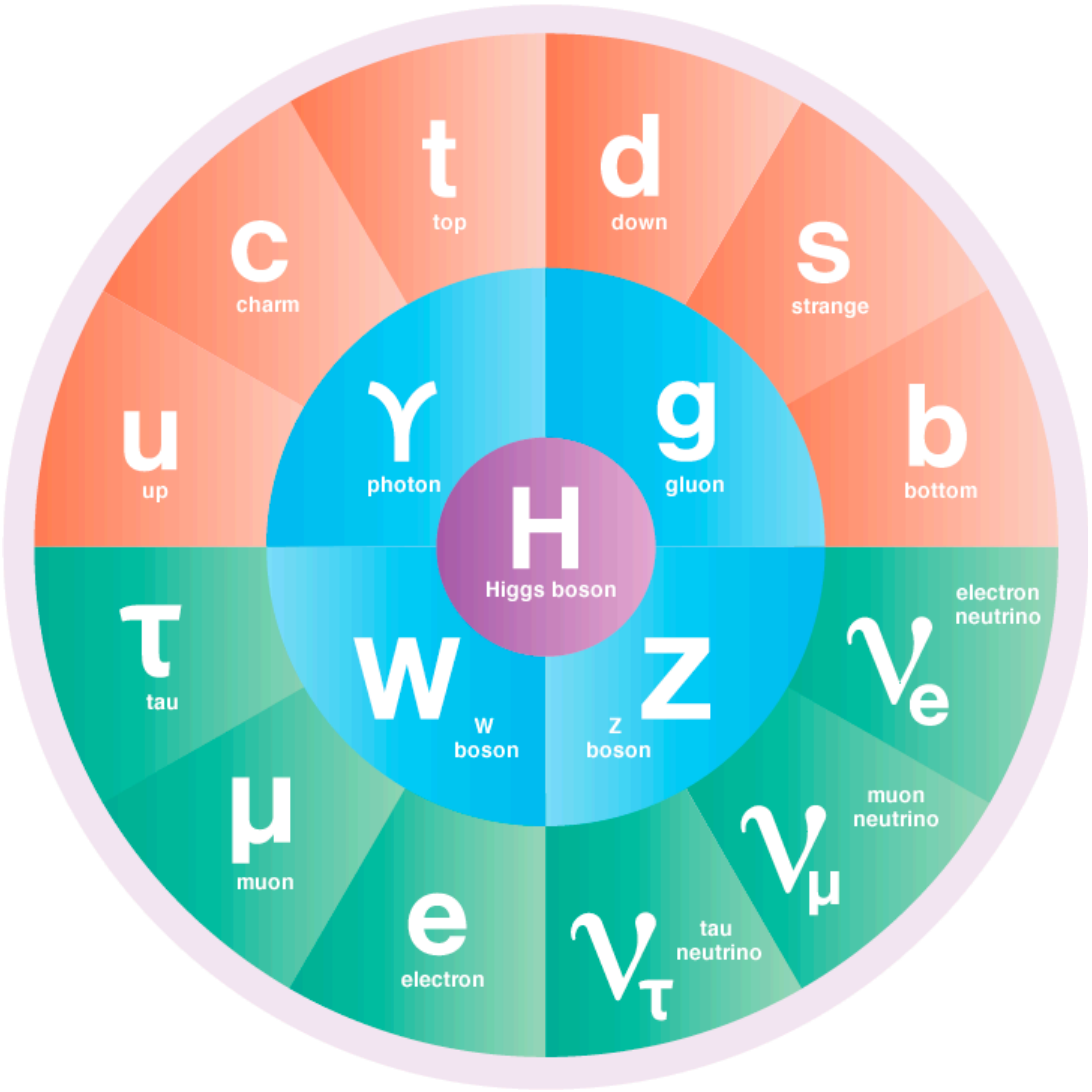


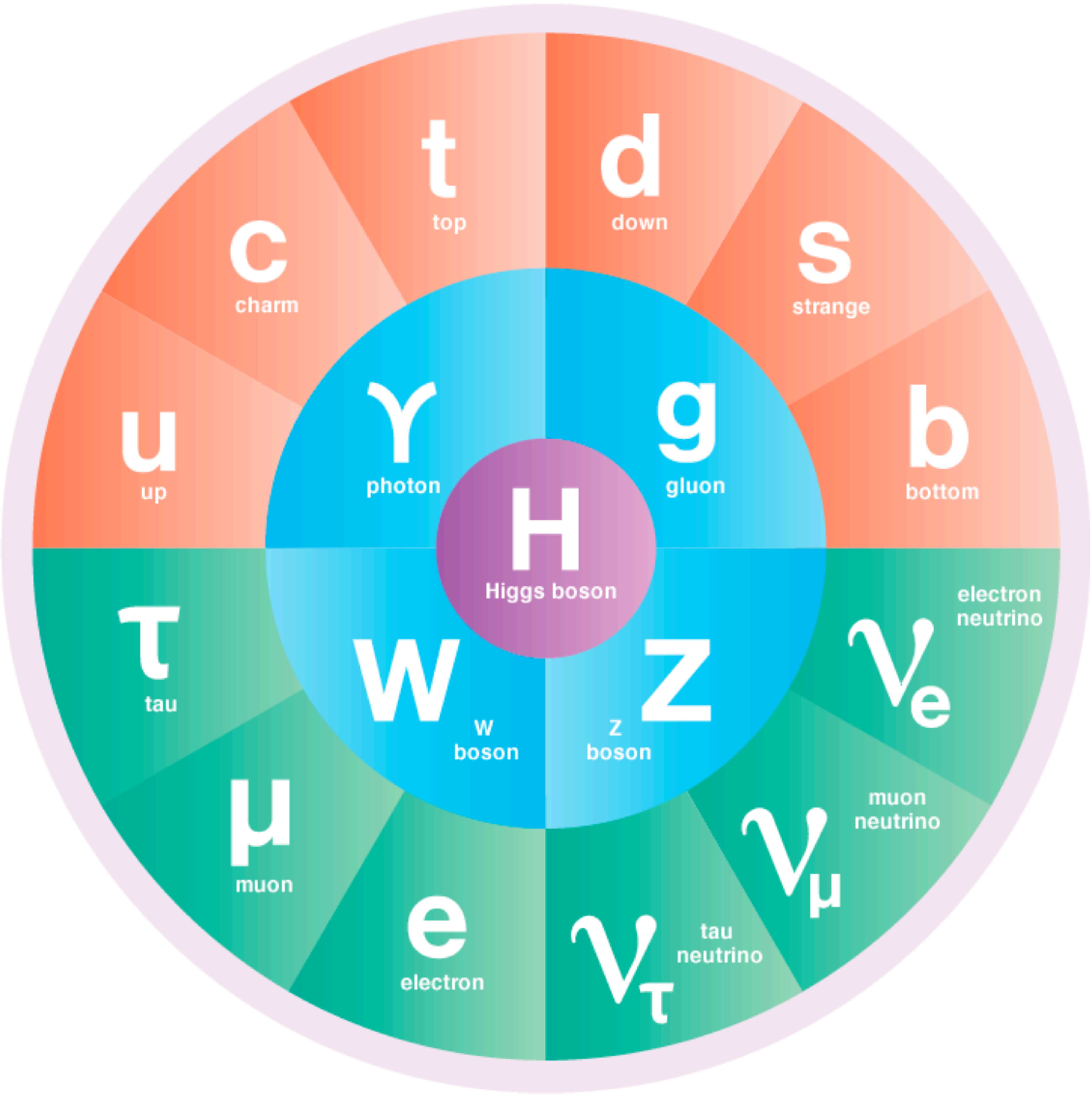


$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

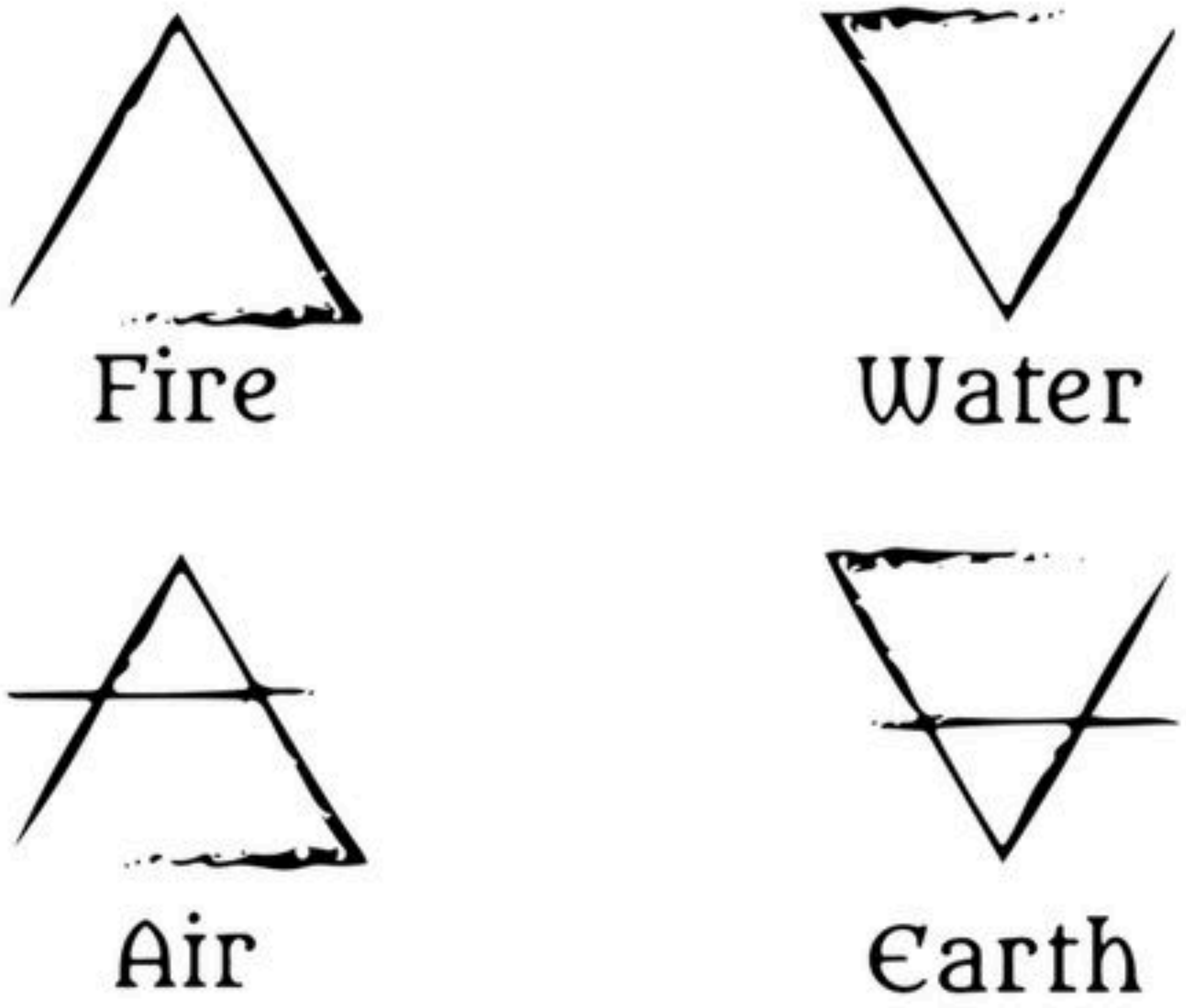
Broader applications than “just particles” — we’ll get to those later.

A bit of history…

- Physicists today claim to know what “everything” is made up of — the Standard Model. How did we get here?



~2000 years in one slide



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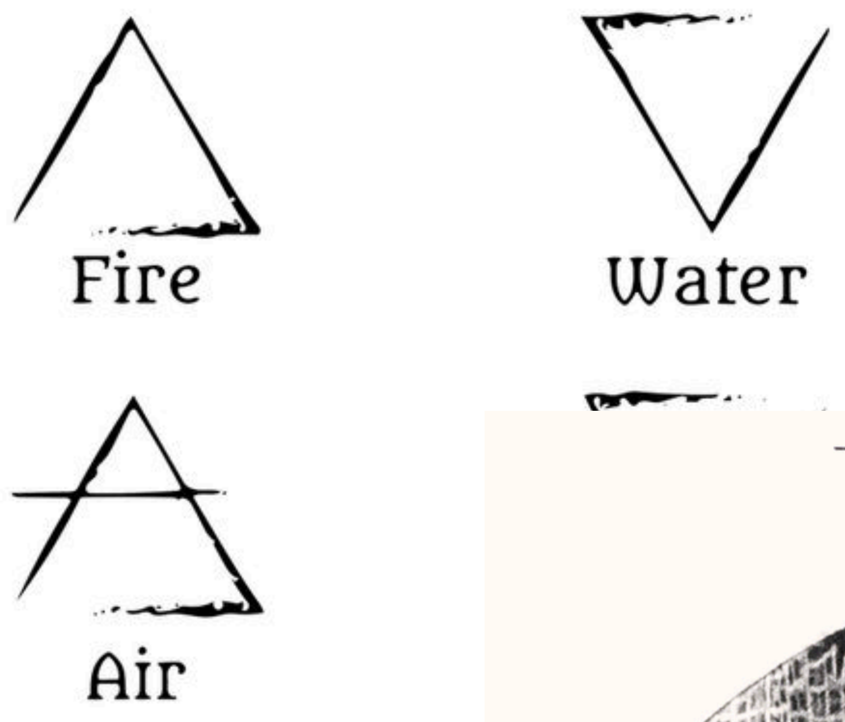

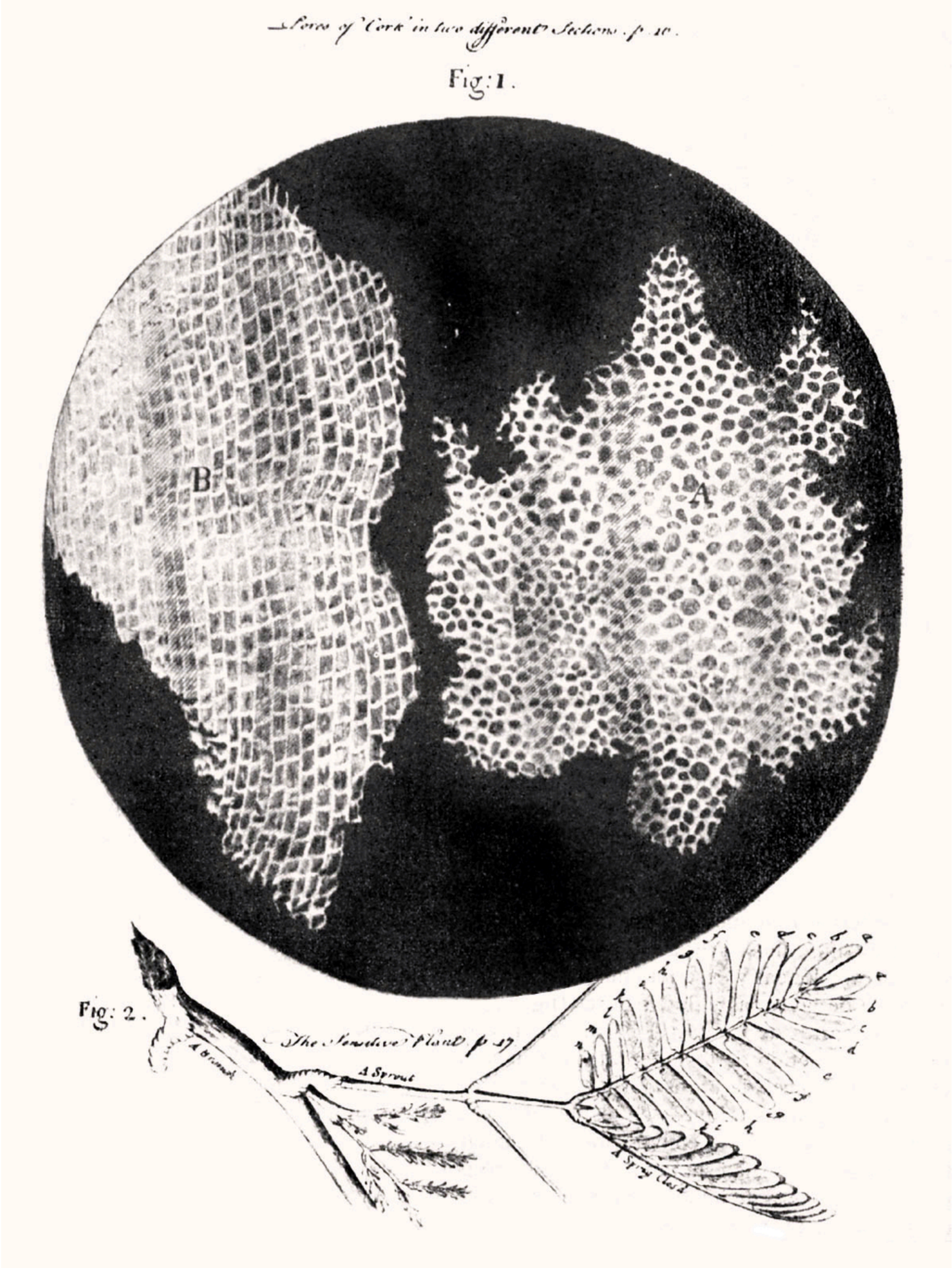

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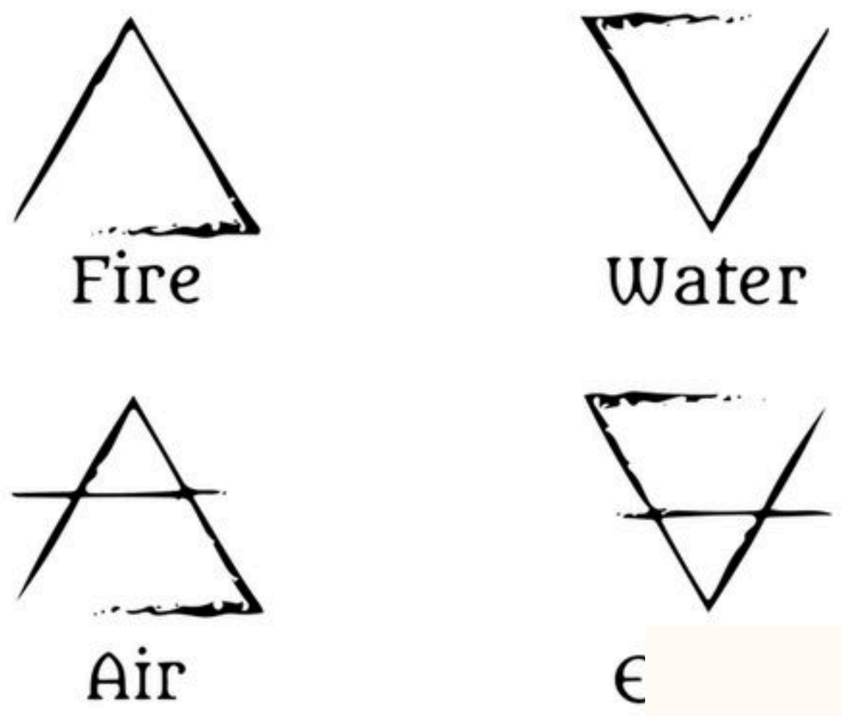

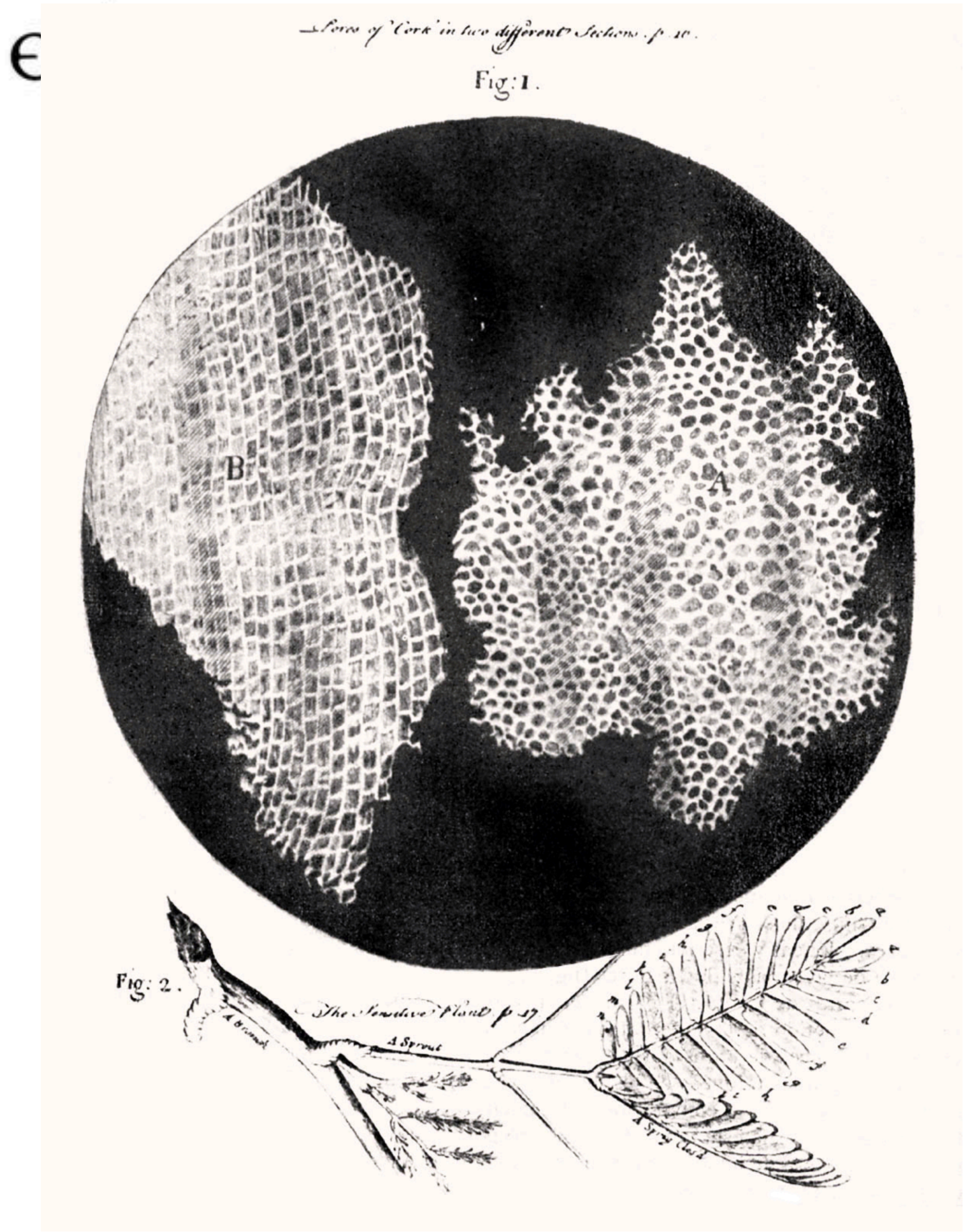

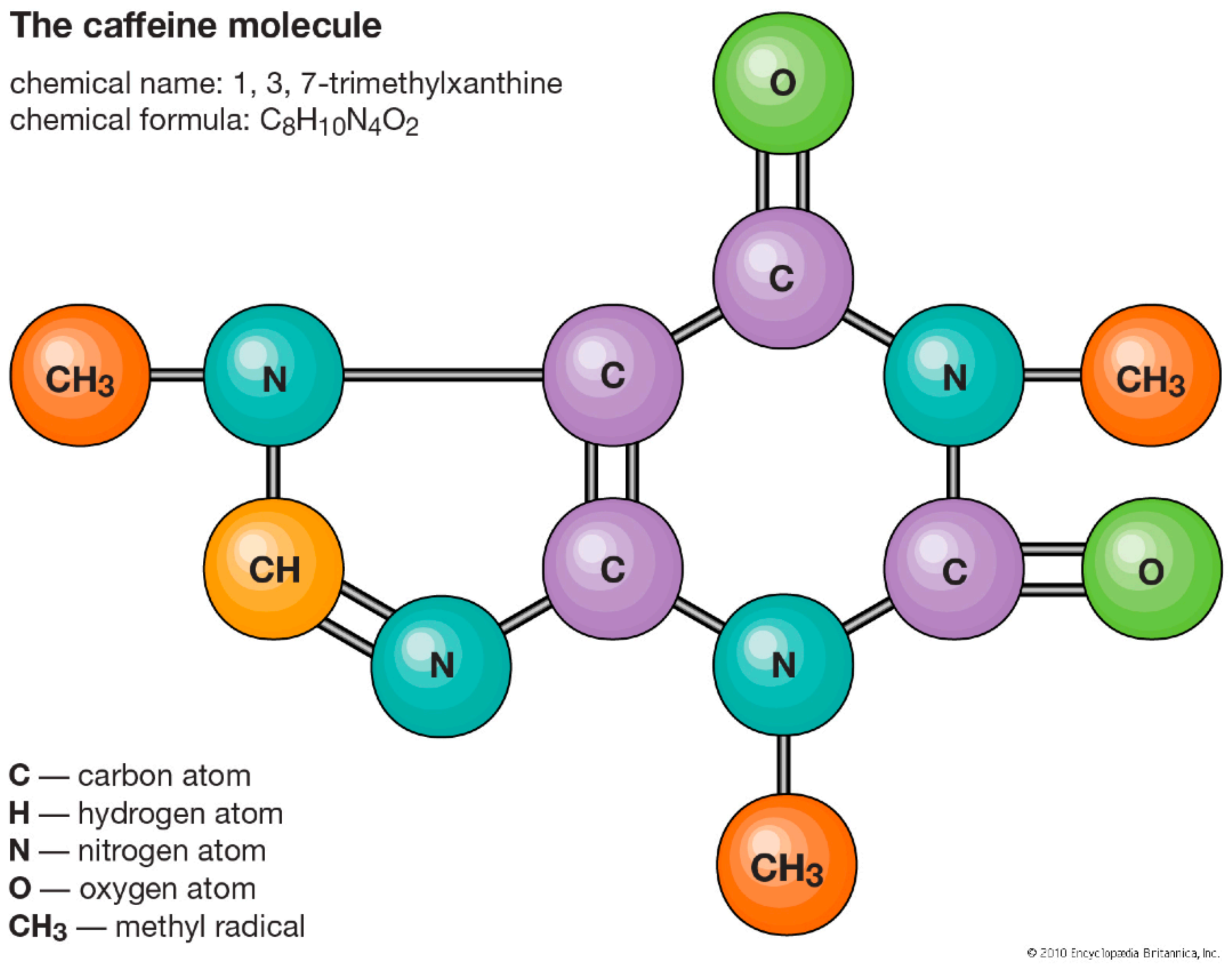

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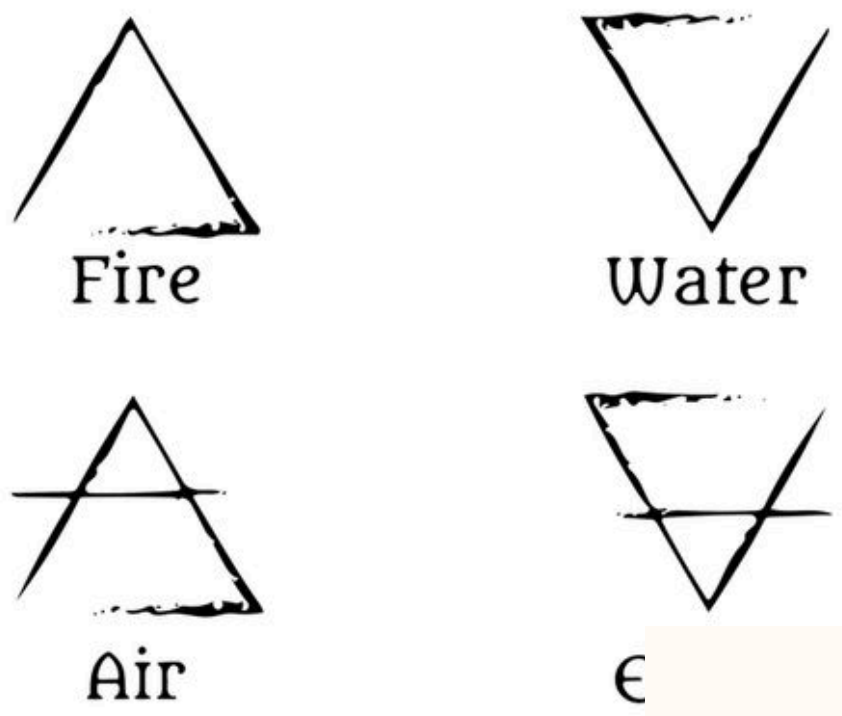

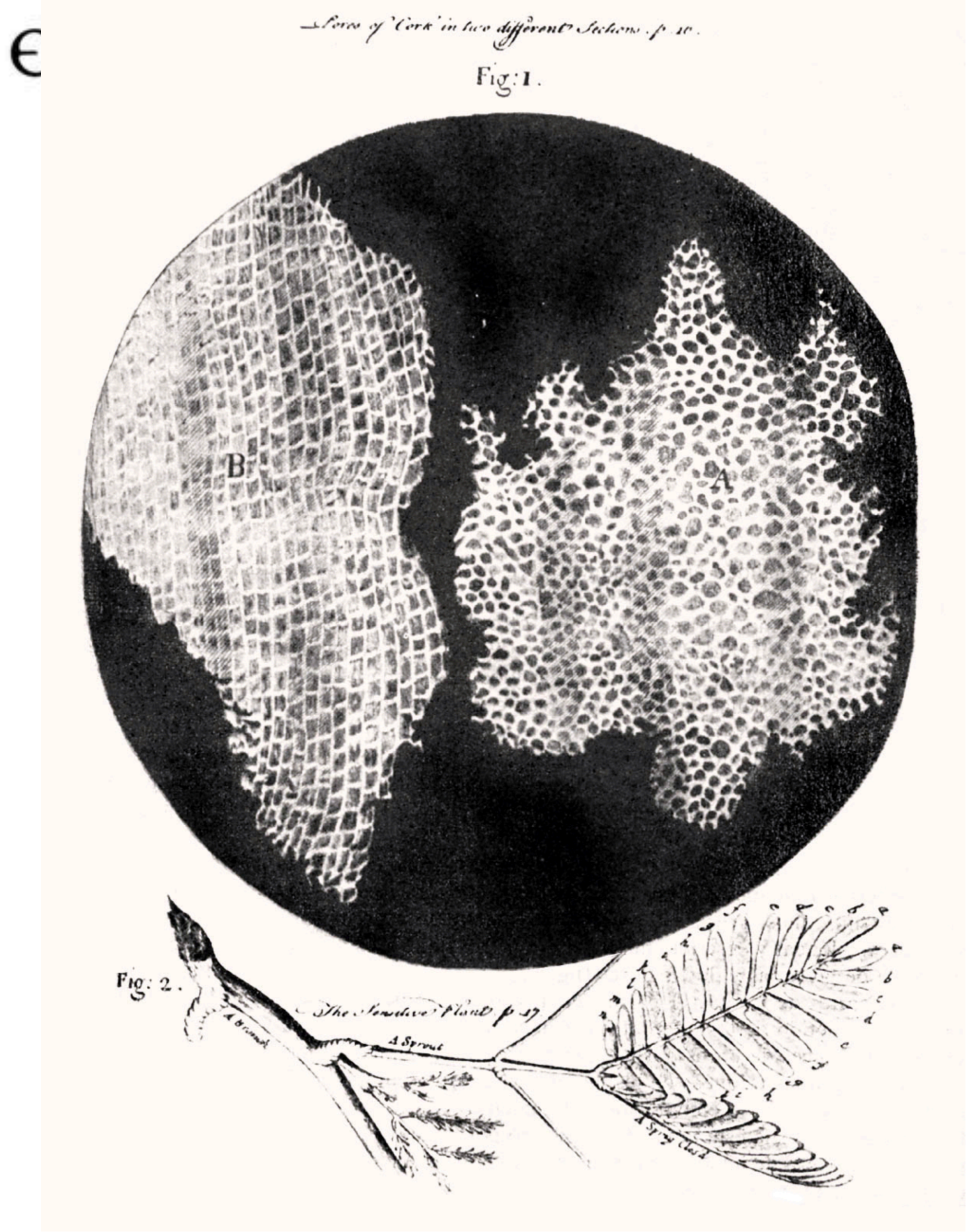

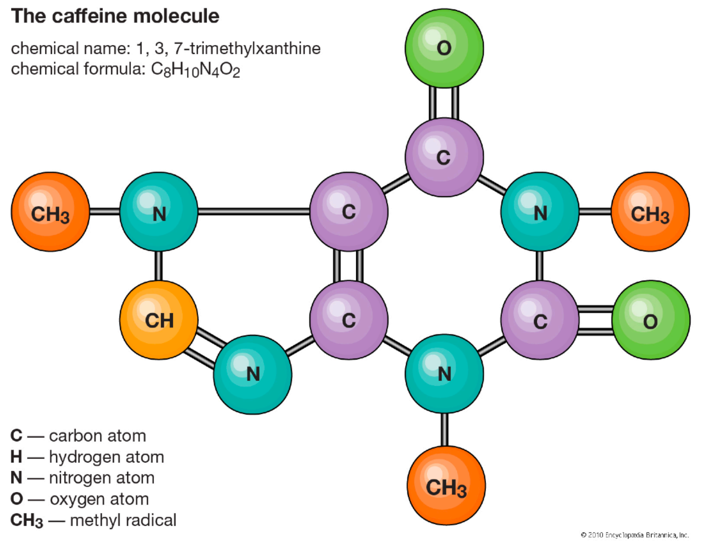

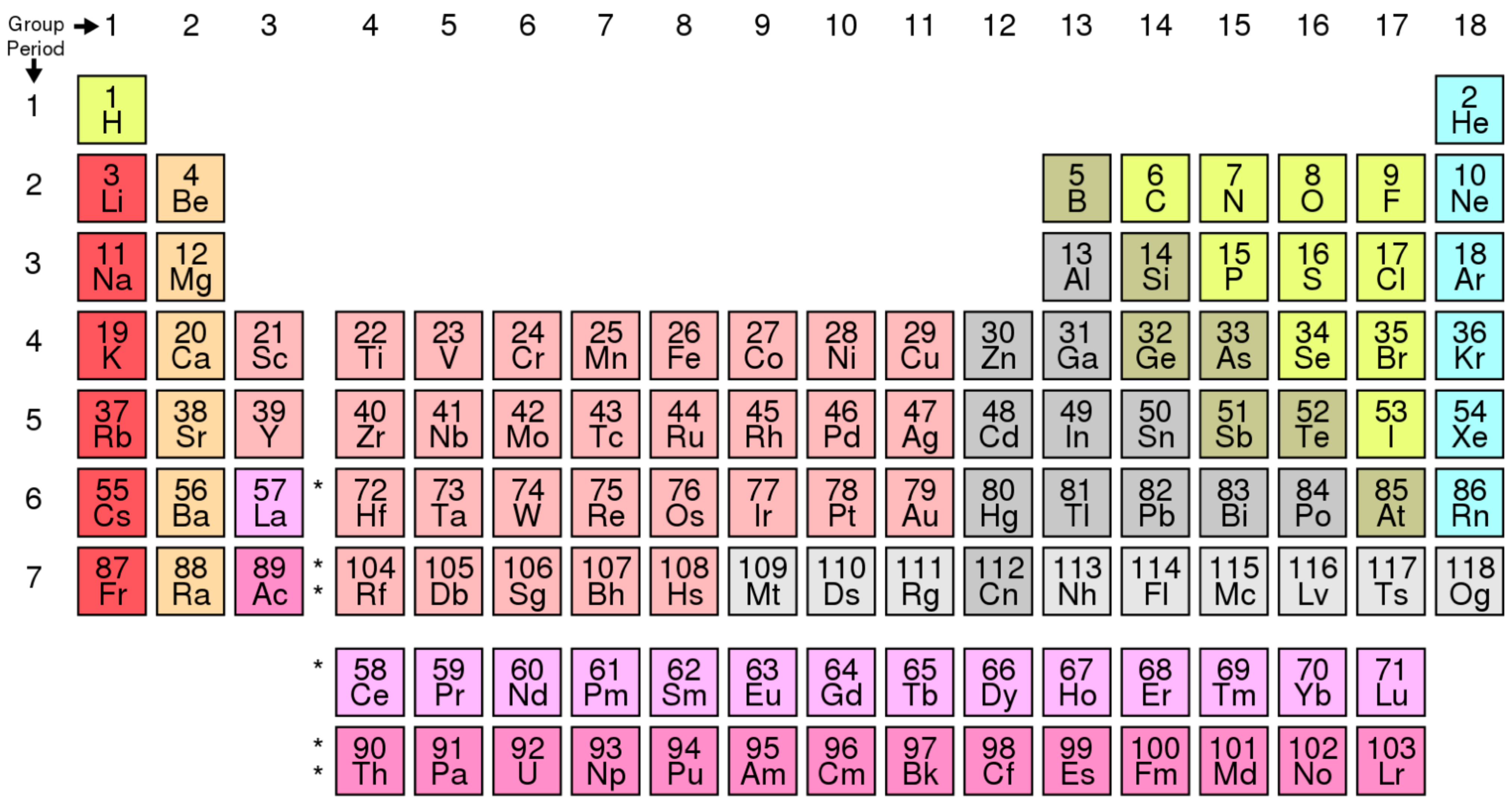

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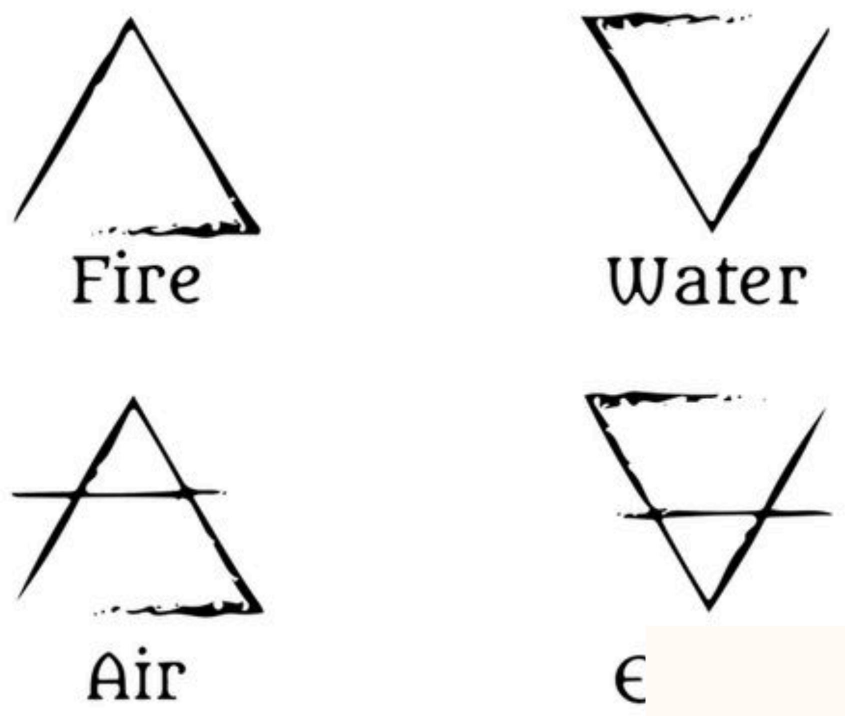

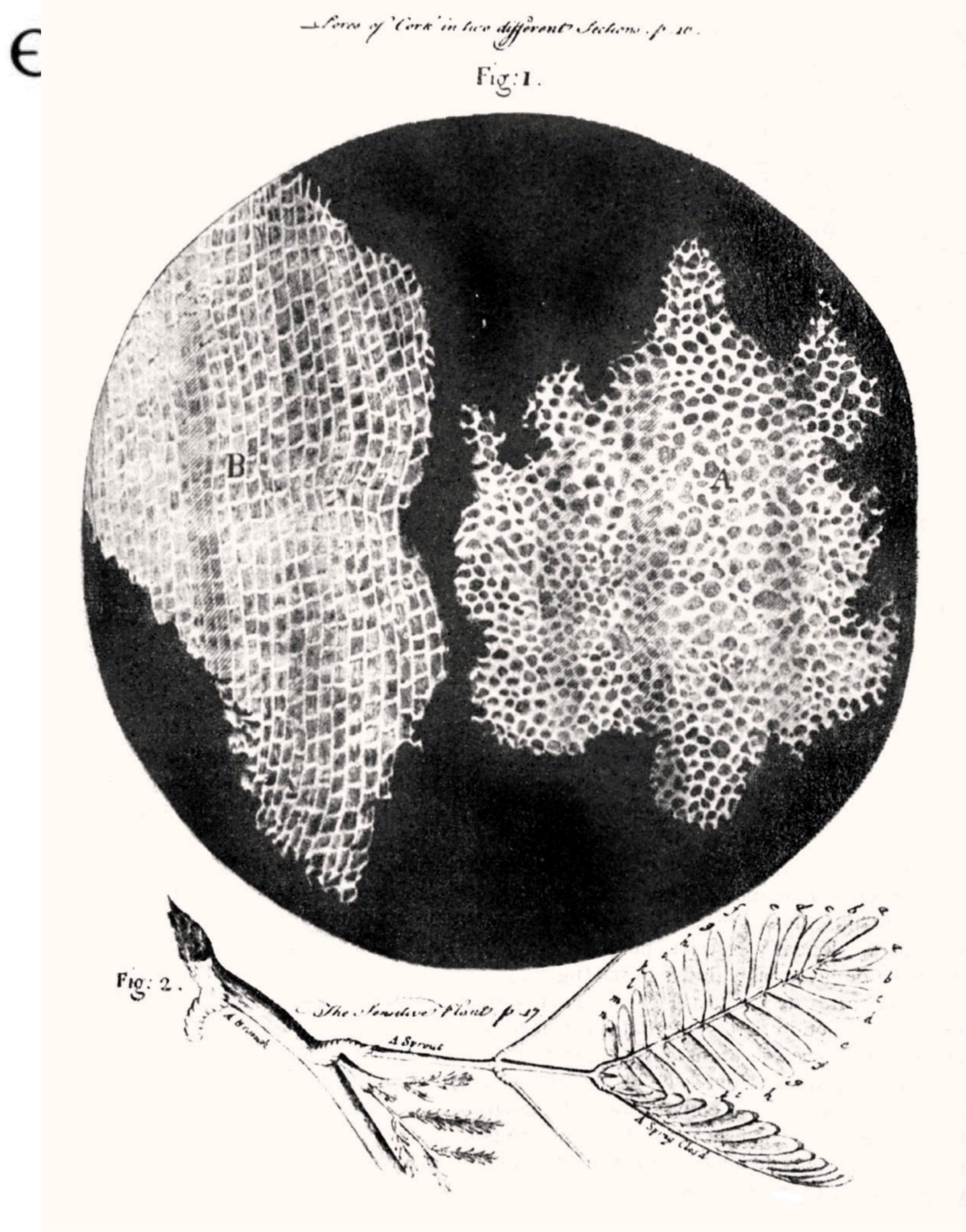

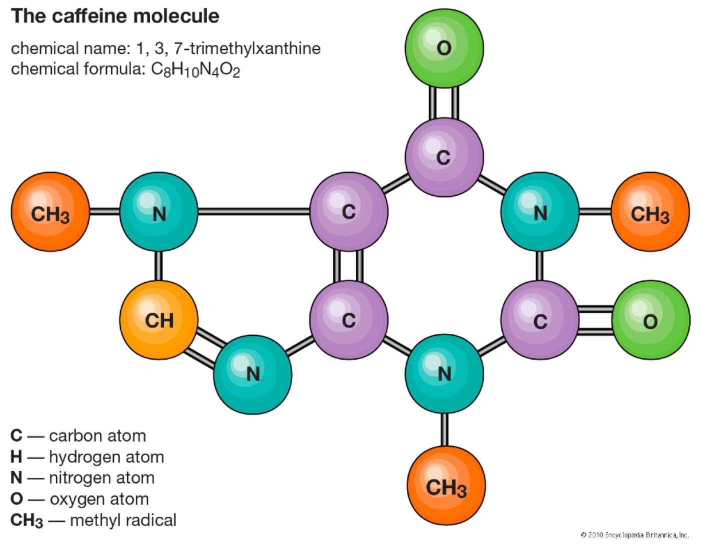

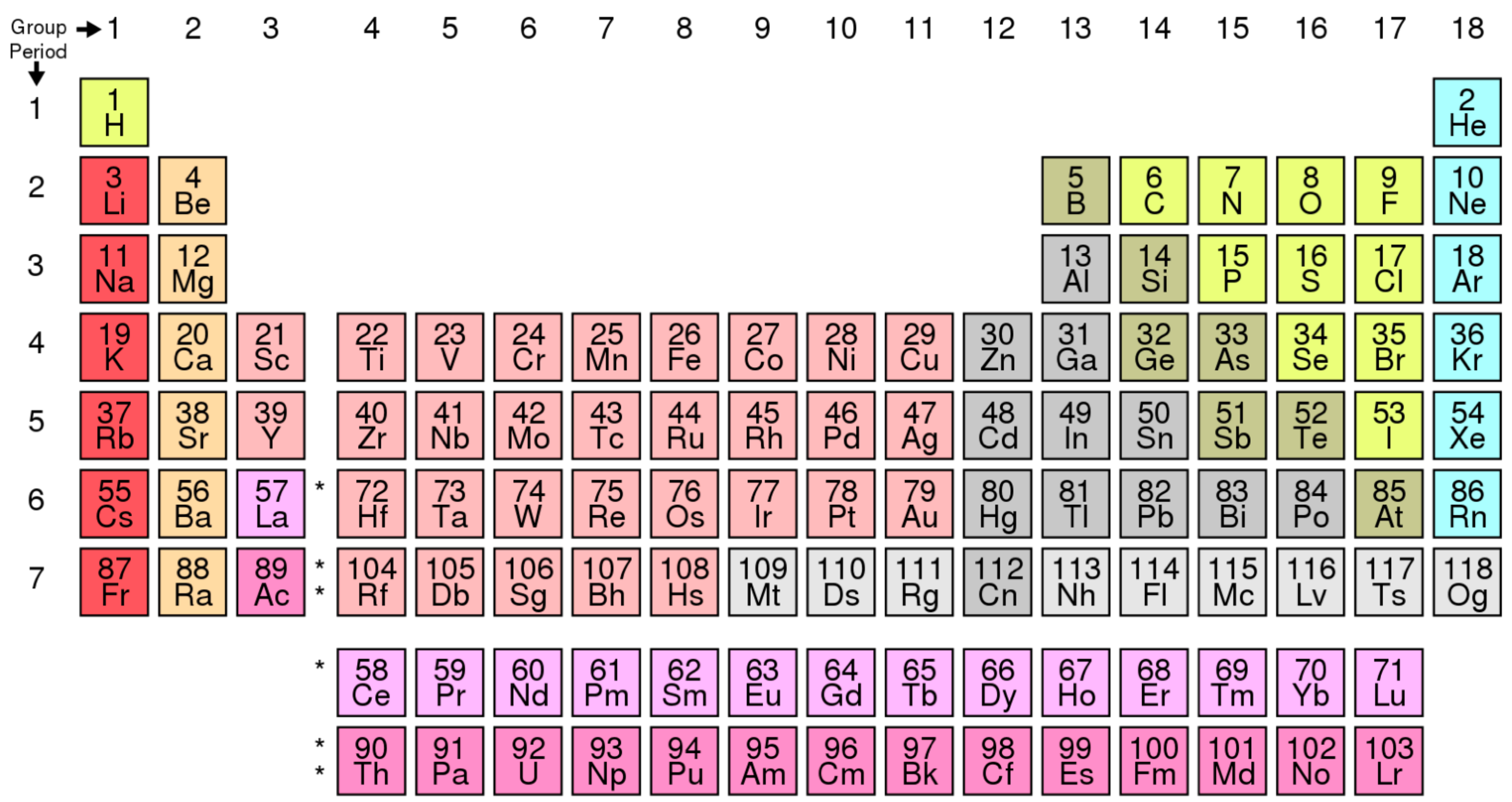

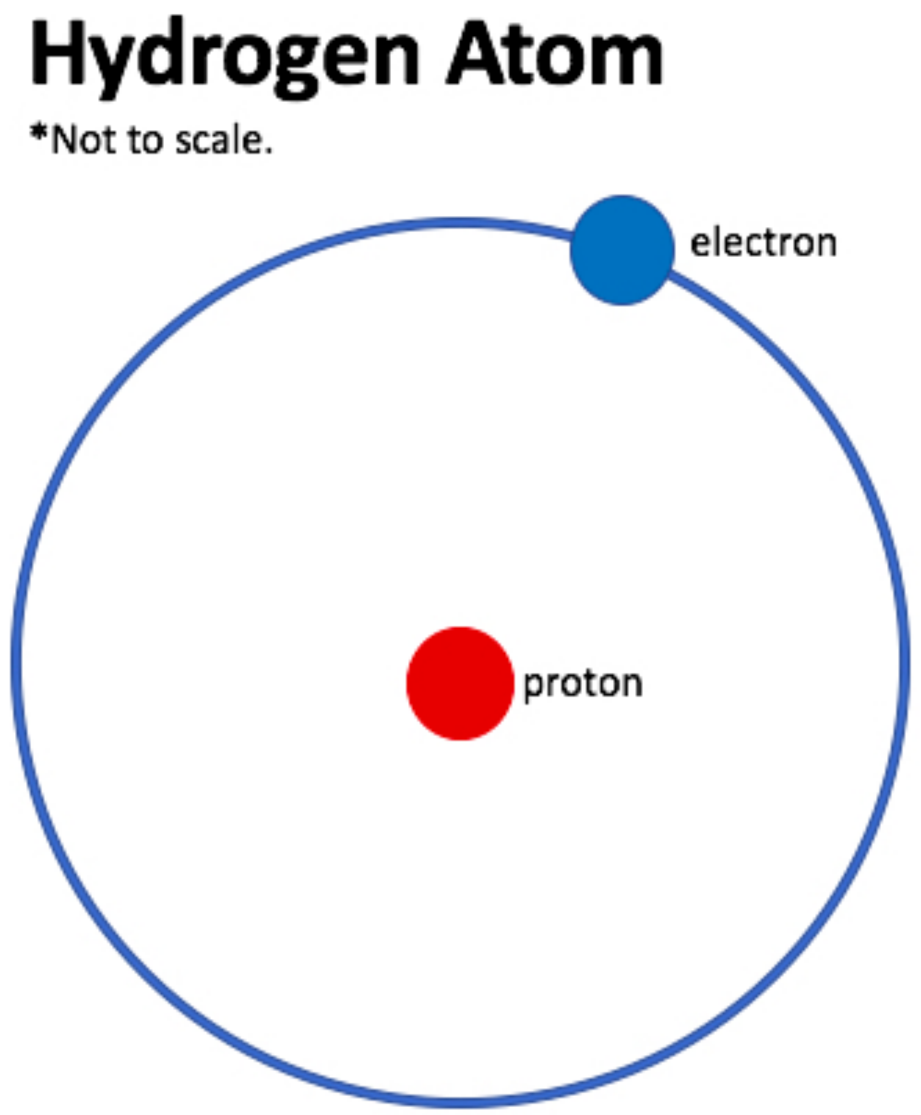

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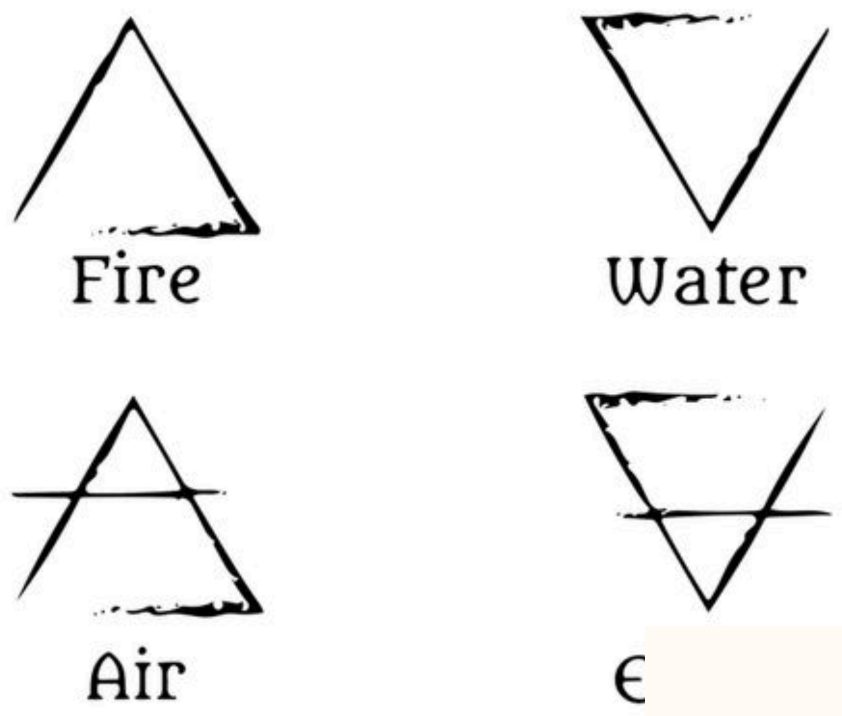
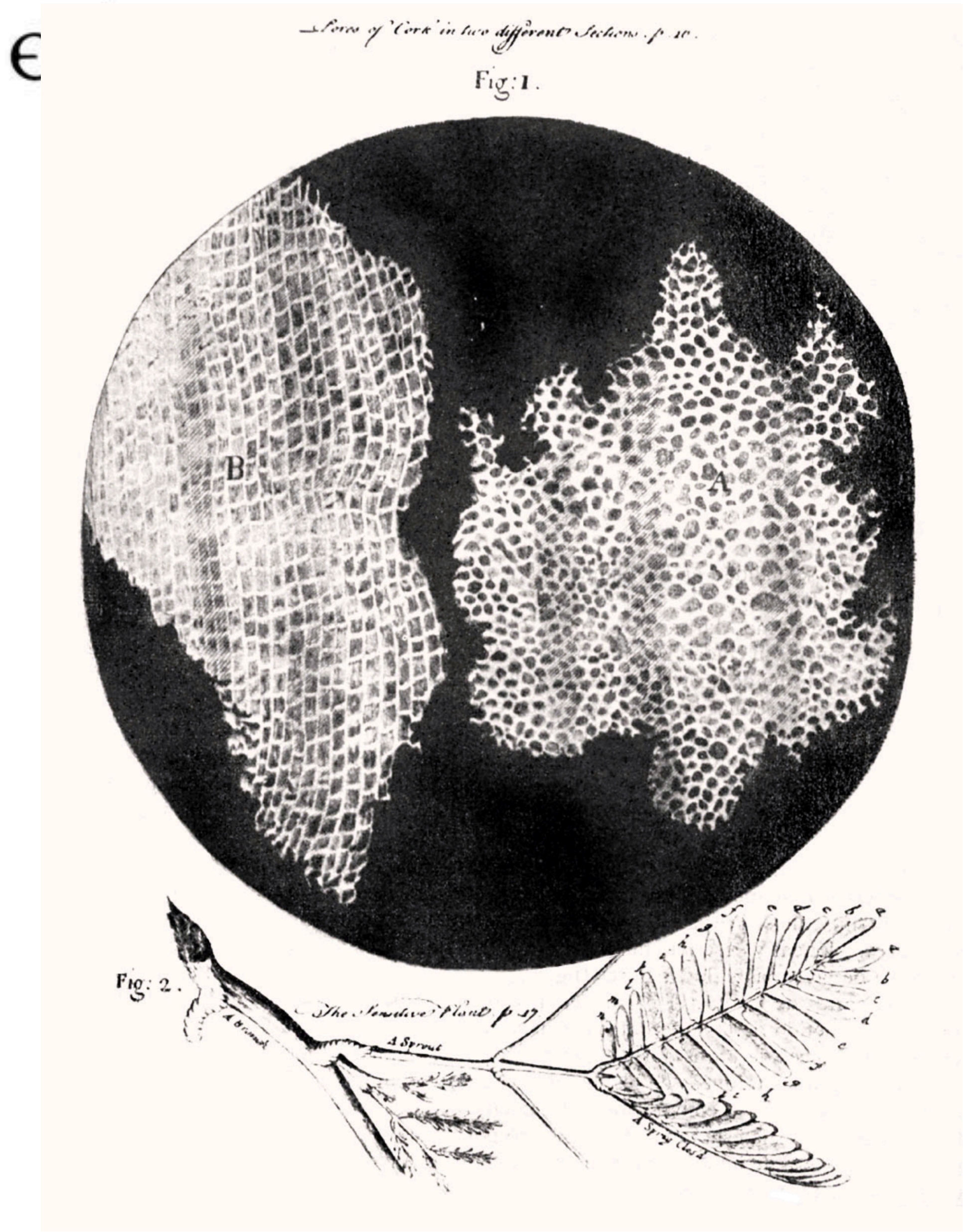
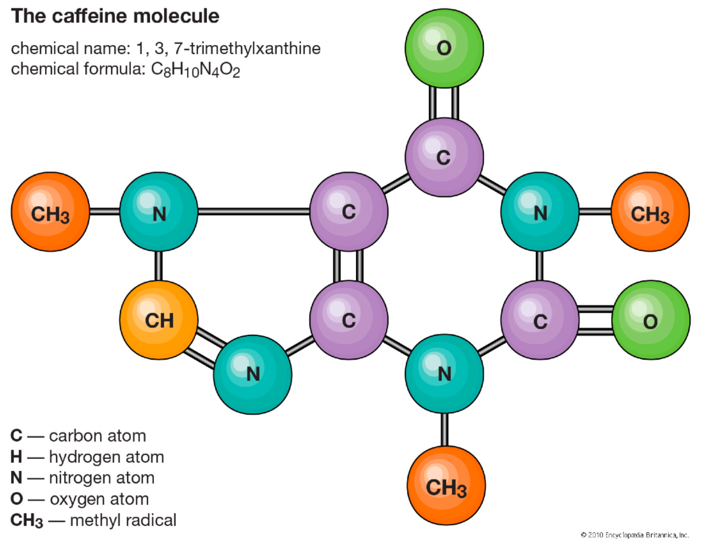
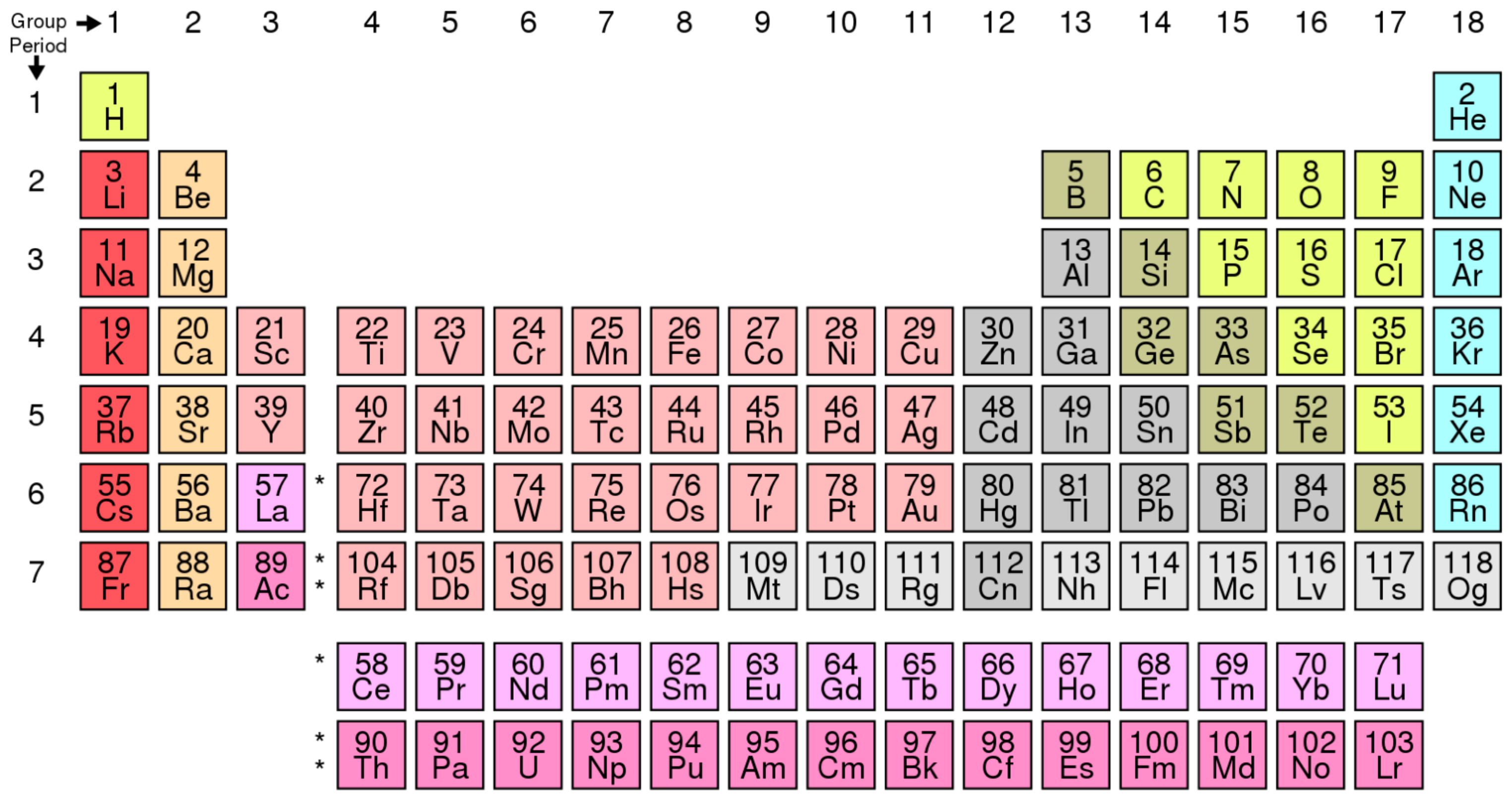
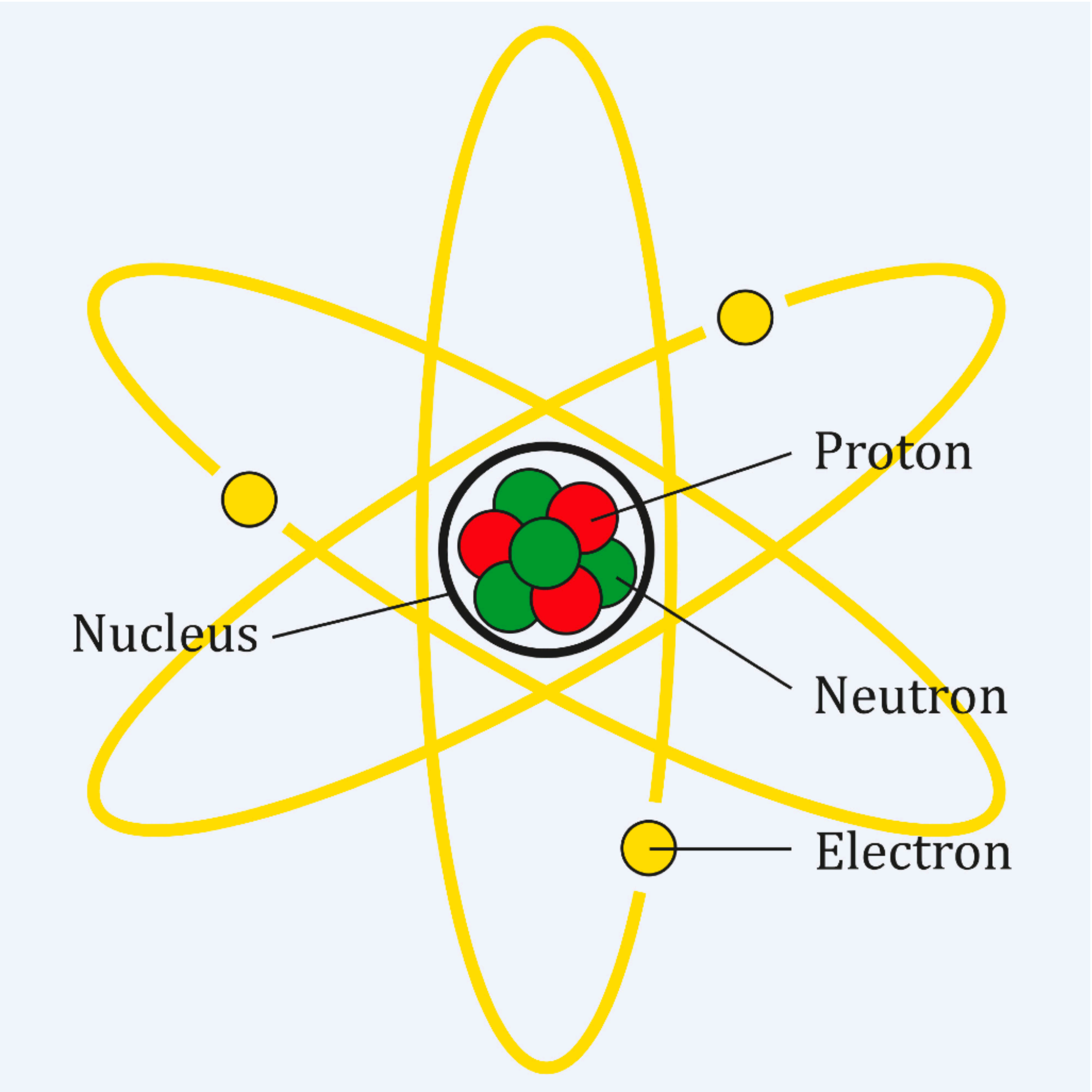


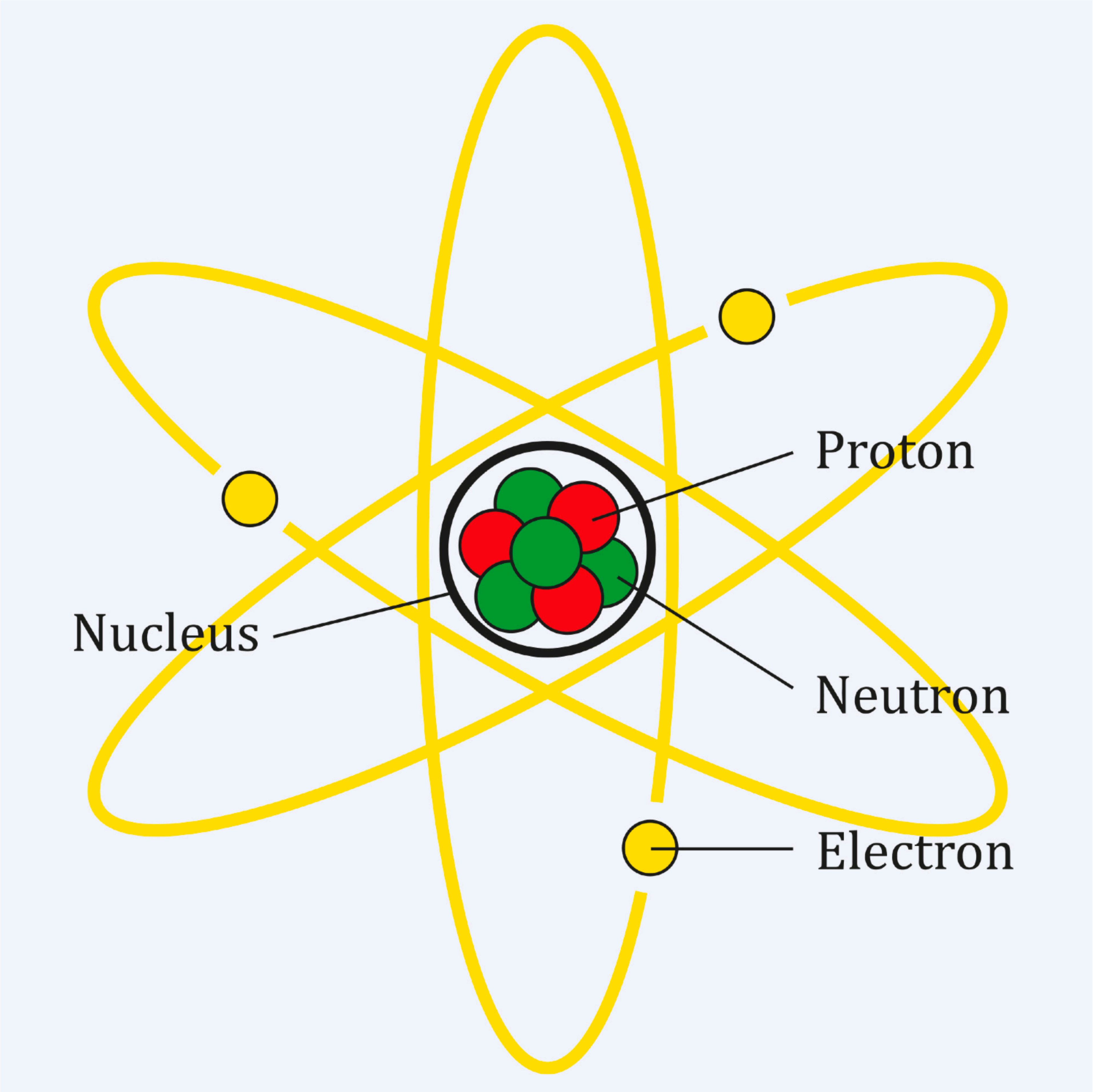








Early 1900s



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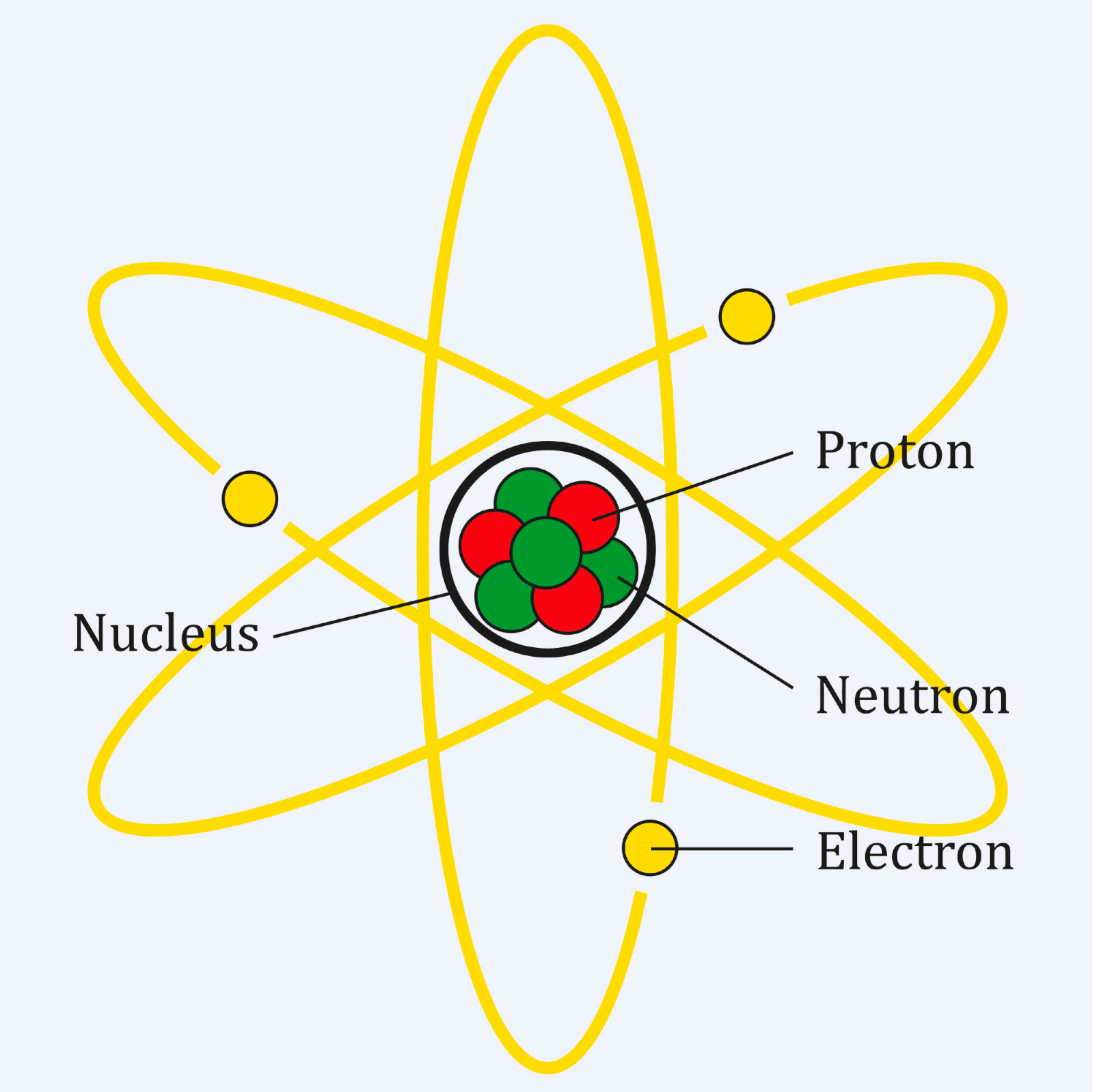

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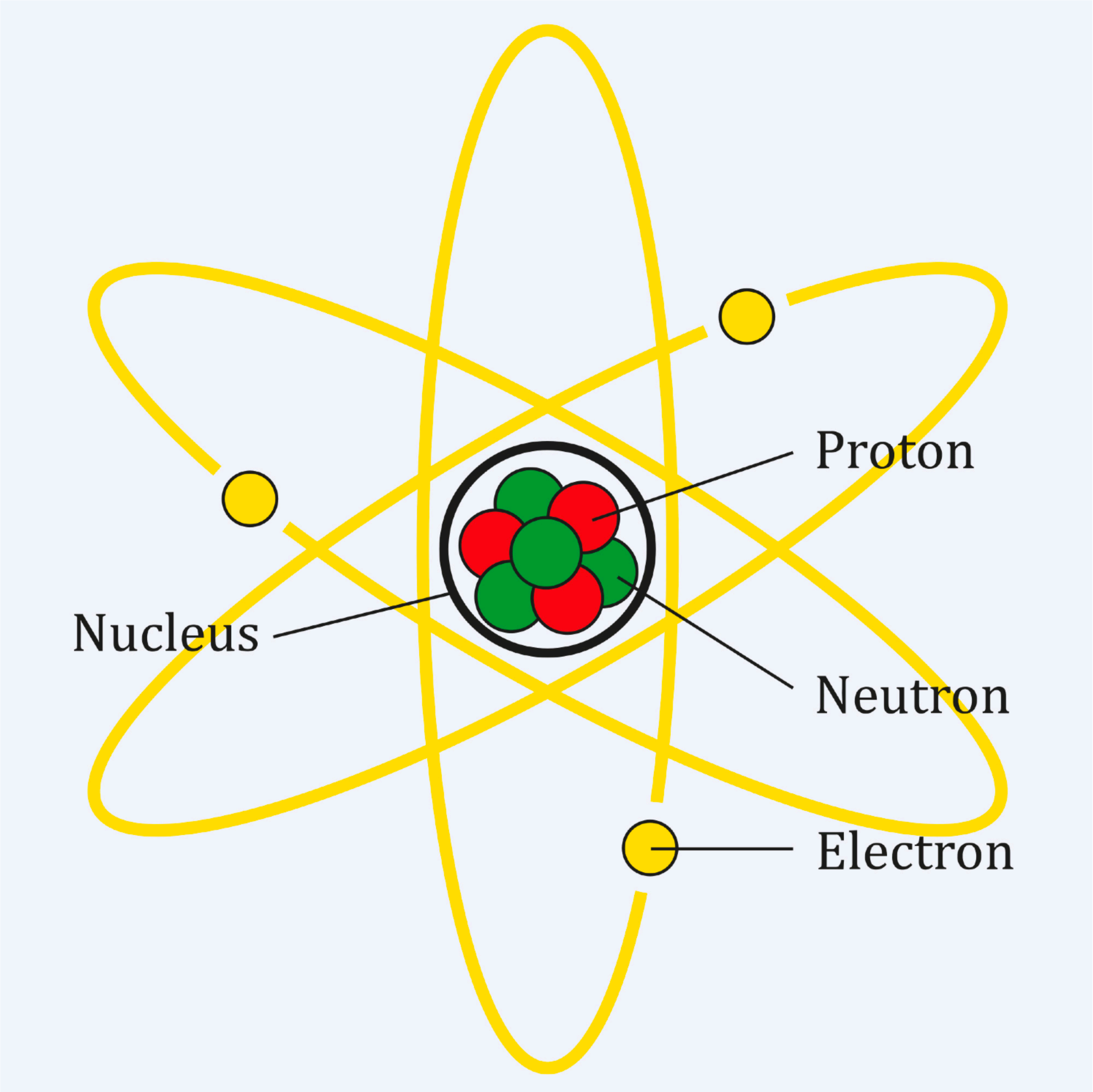

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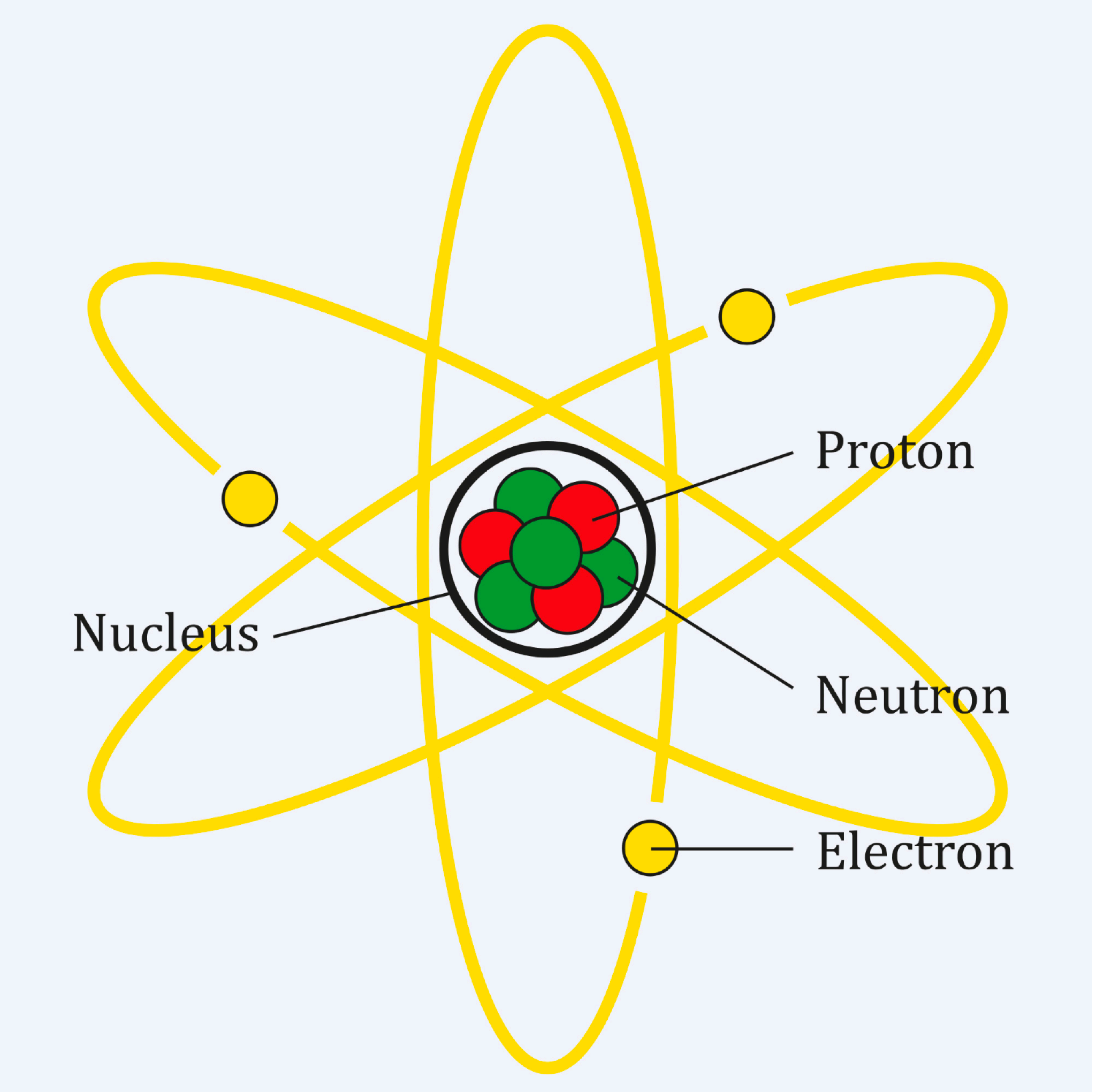

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- Protons and neutrons build up the nuclei of atoms, and electrons occupy orbitals around the nucleus.
- Different models of the atom were explored, leading to the development of quantum mechanics.

Let’s put a pin in particles for now.

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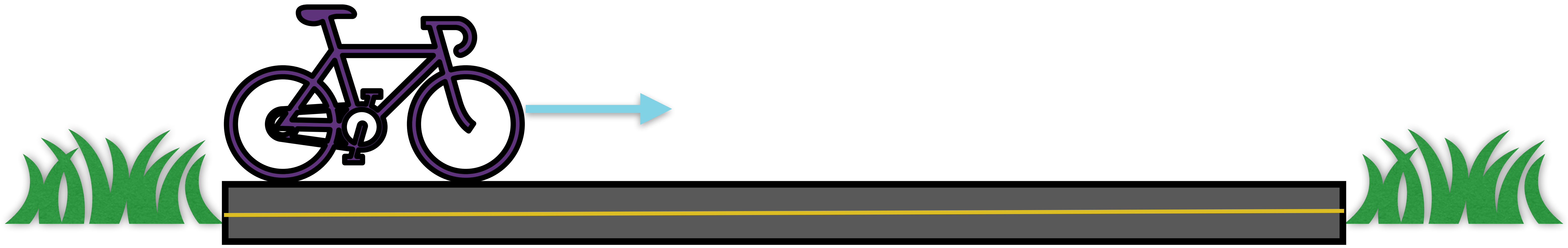
And pivot to every particle physicist's favorite tool: **symmetries**.

One of the simplest symmetries in nature: *Translational Invariance*

- Imagine riding a bike on a flat road…



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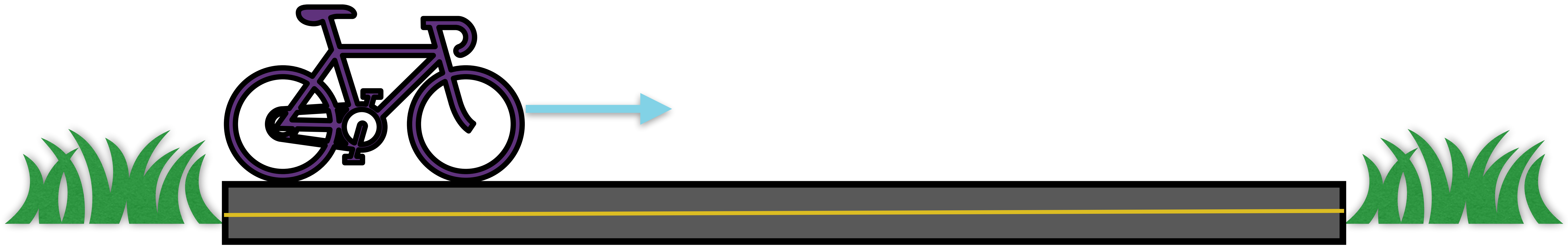
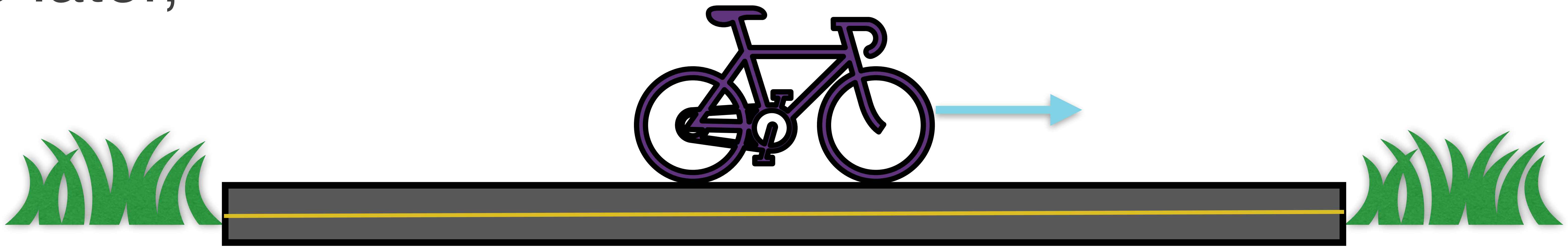


- A short time later,



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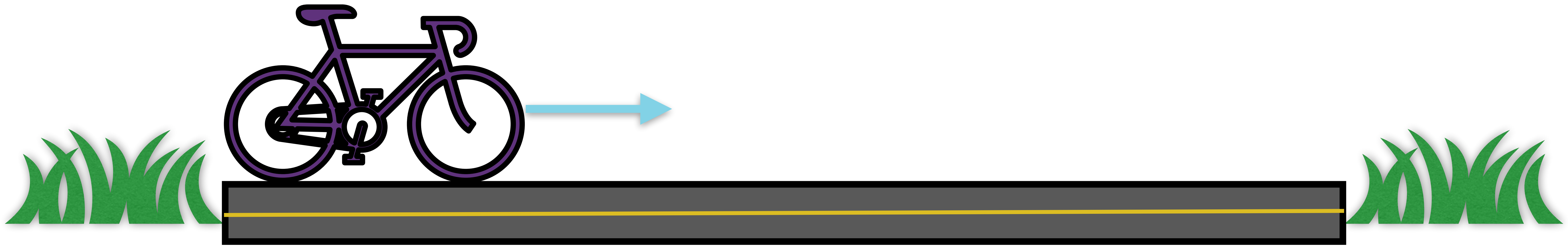

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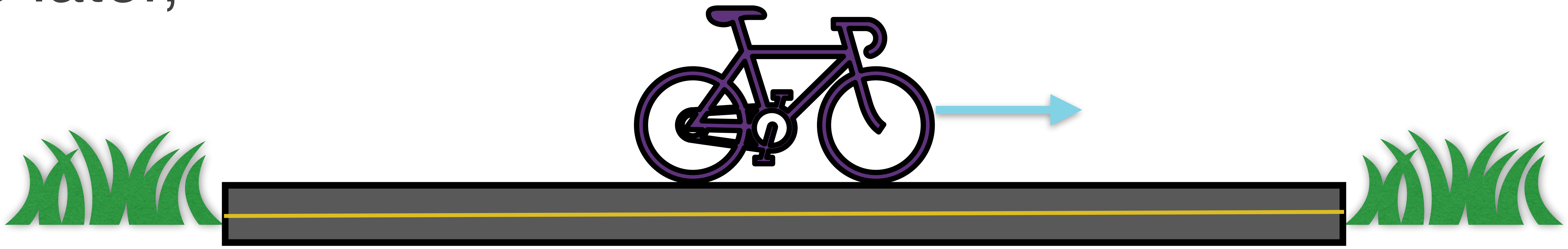

- From the bike's point of view, the surrounding road is unchanged.

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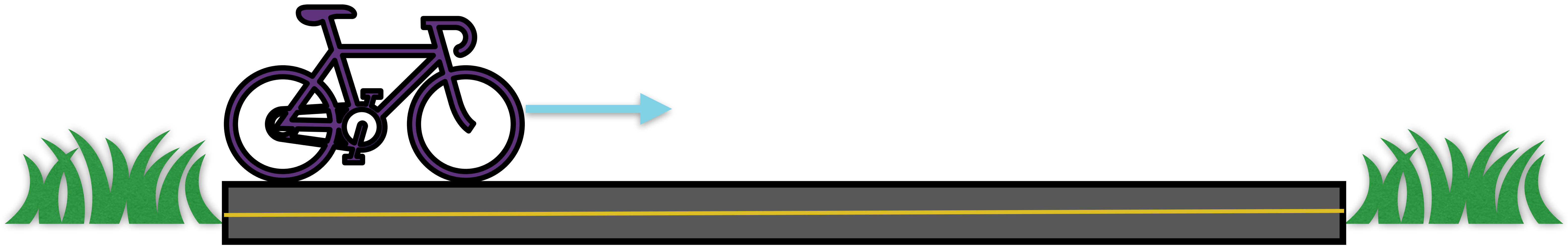

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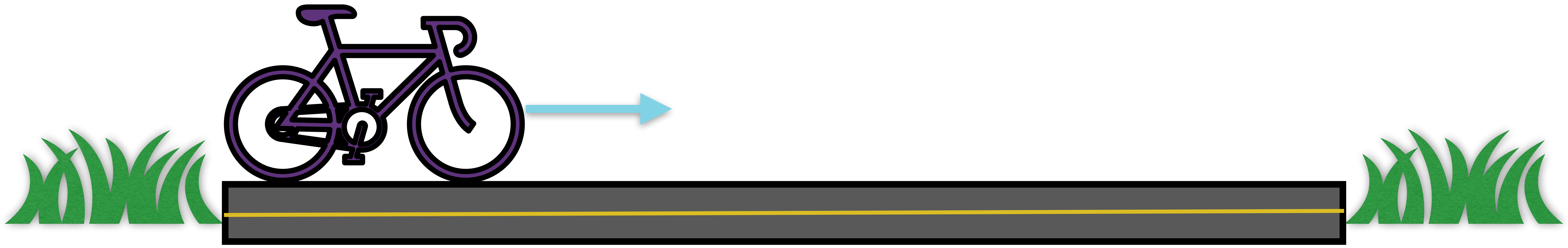
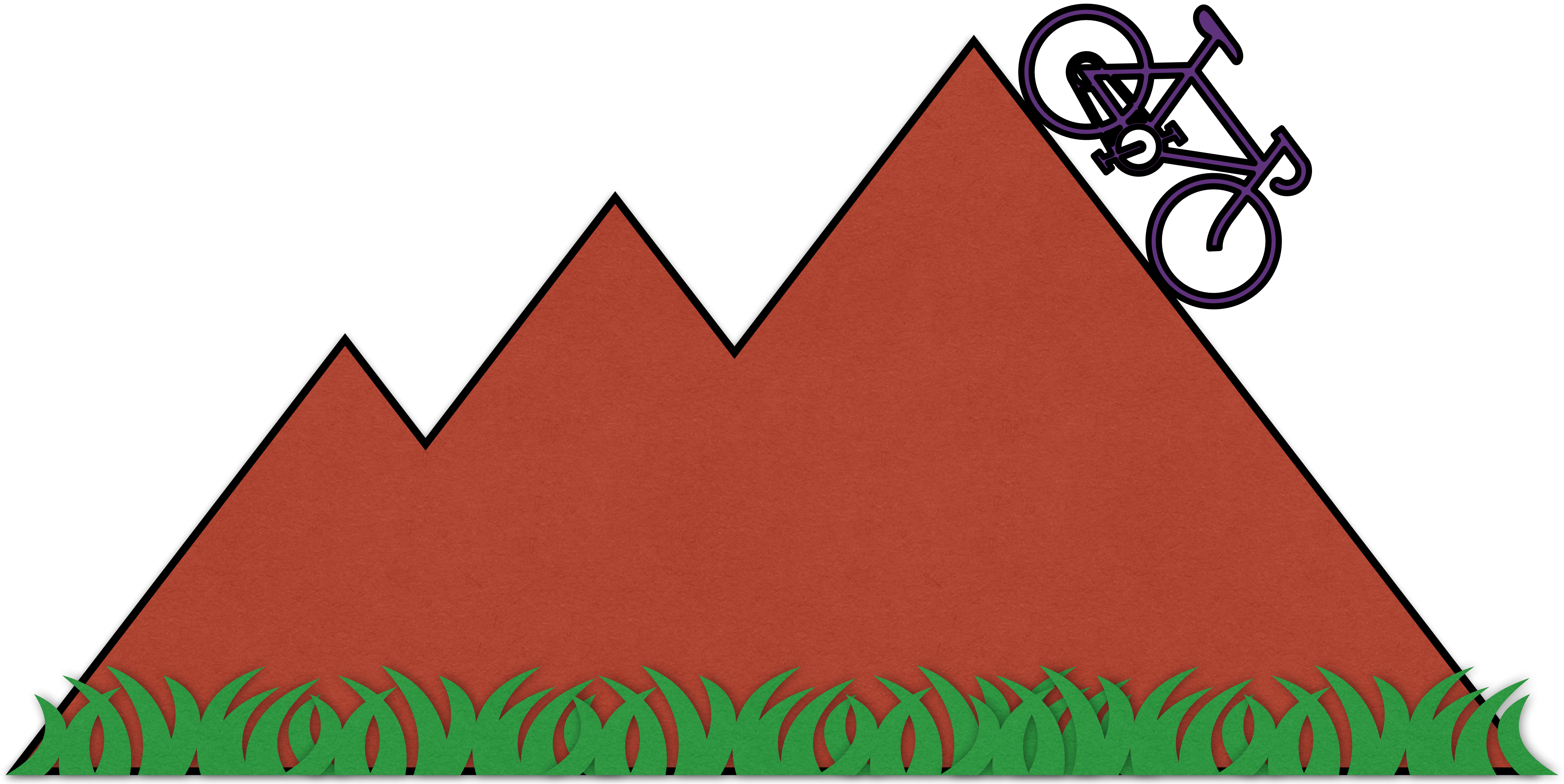


- The flat road exhibits a *translational invariance* symmetry, and, as a result, the bike conserves *linear momentum*.

Slightly more complicated: *Time-translation Invariance*

- (fancy way of saying “constant over time”)



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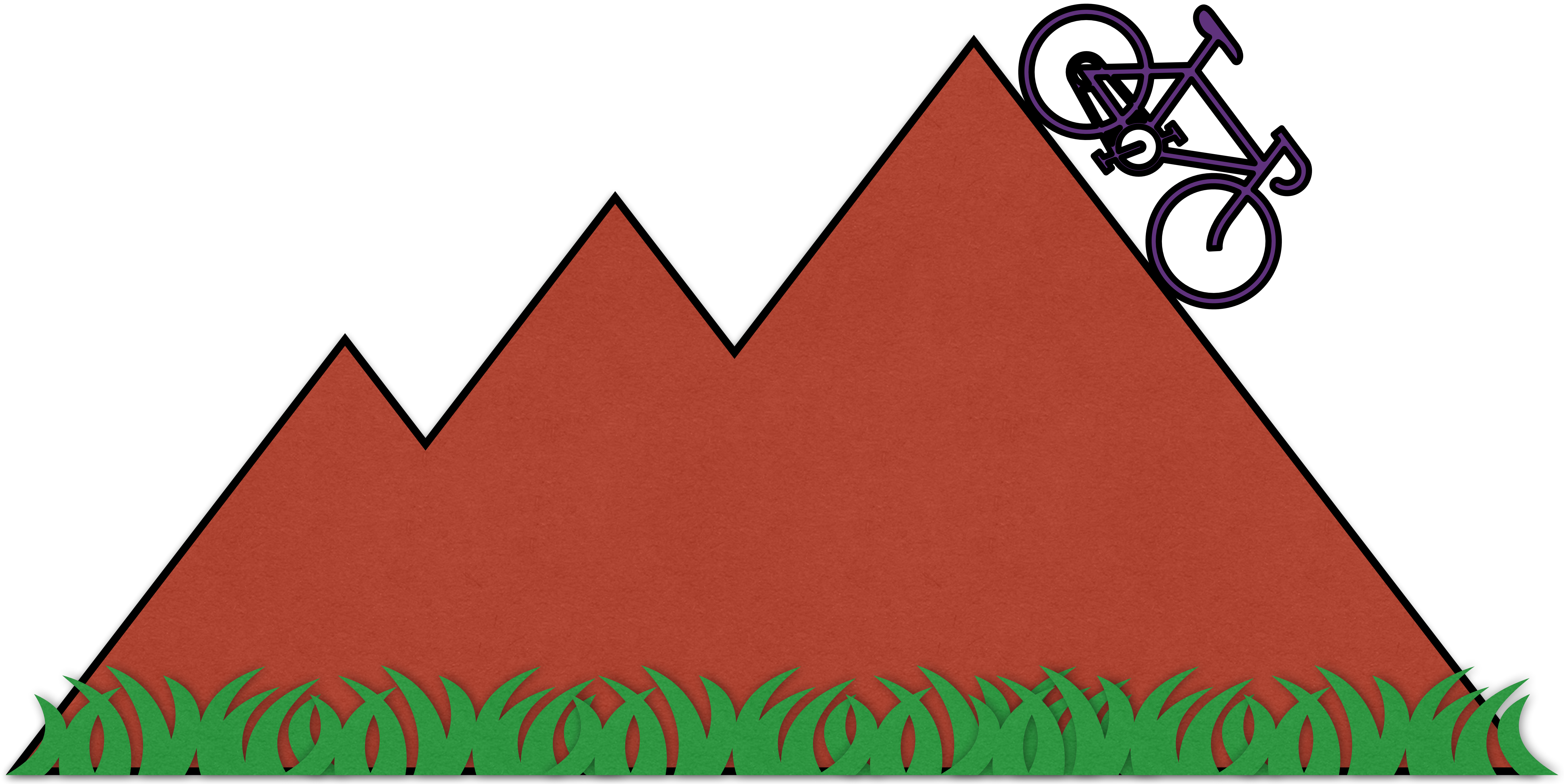

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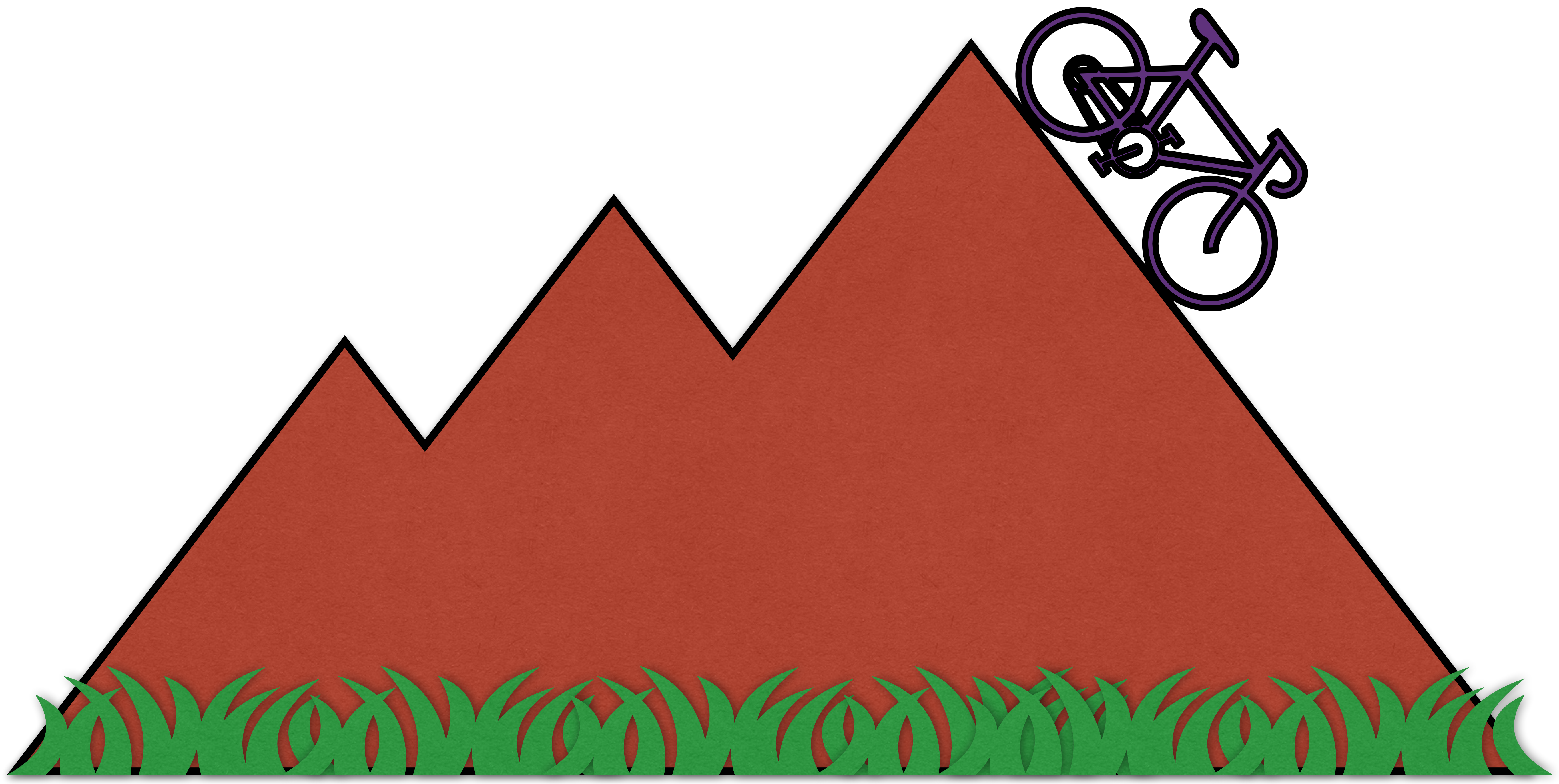

- Now with a bike riding over a hilly terrain — what conservation laws can we apply?
- Conservation of mechanical energy!

Fermilab

Noether's Theorem

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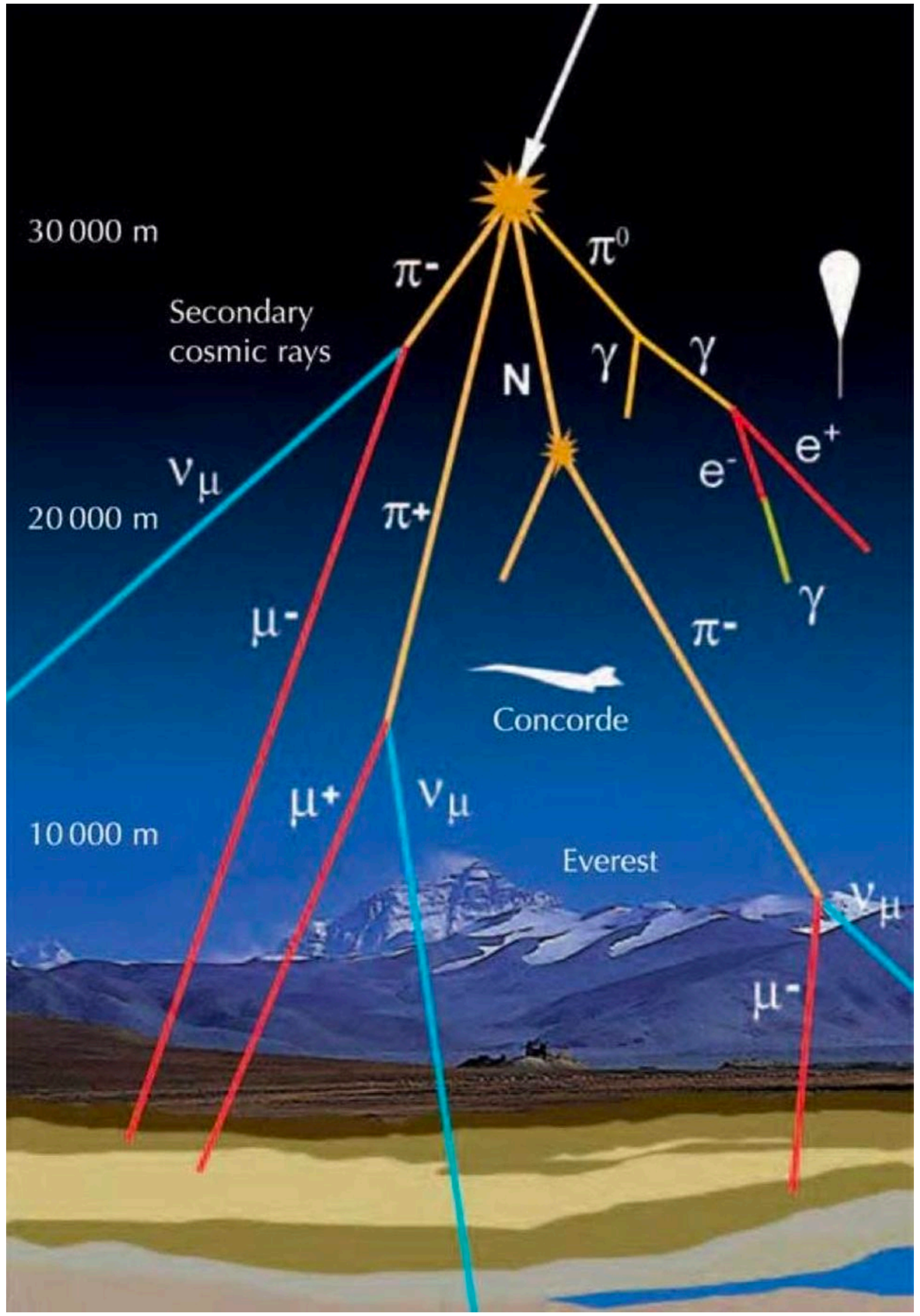
Translational Invariance → Linear Momentum

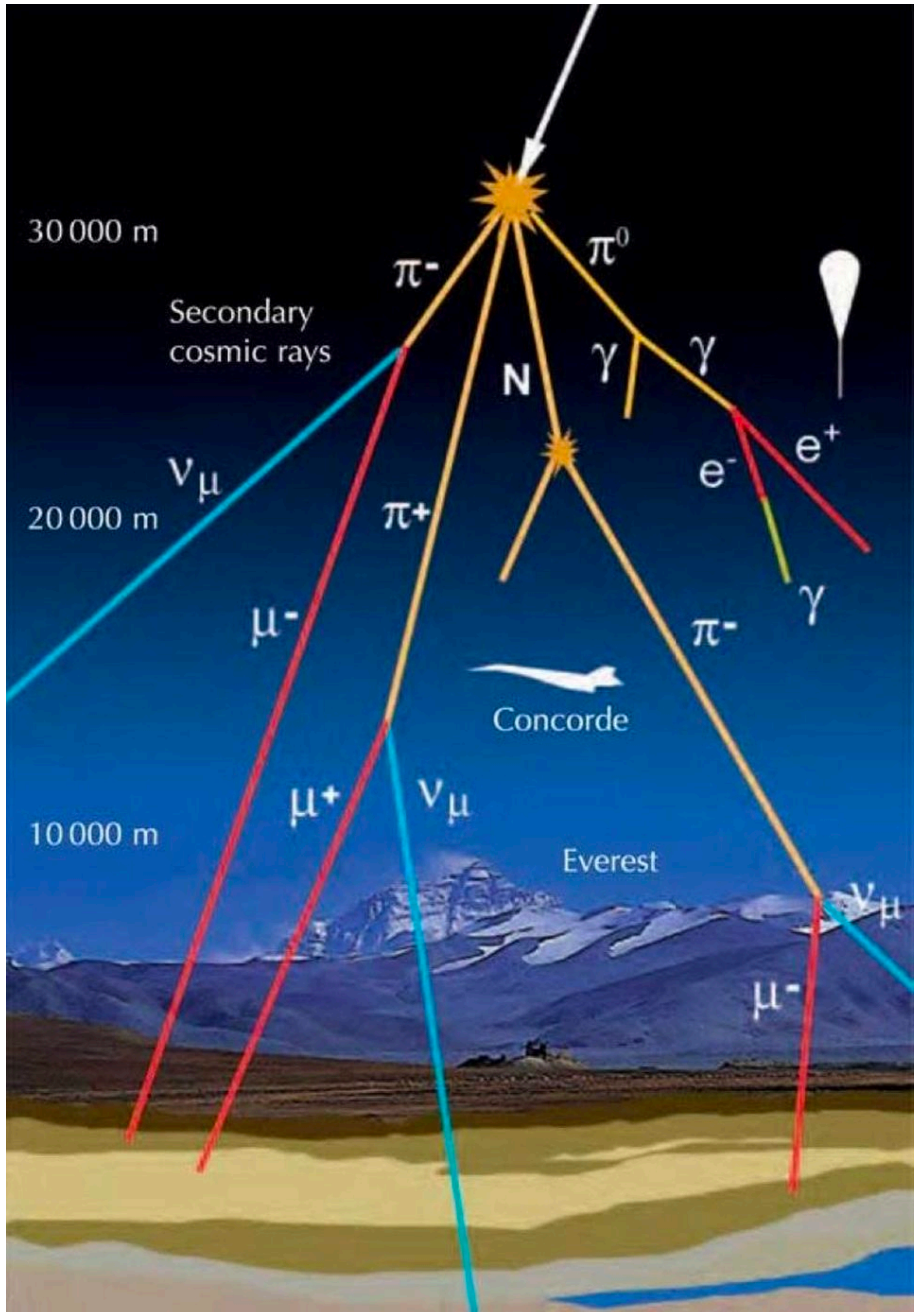
Time-translational Invariance → Mechanical Energy

Applying Symmetries to Protons and Neutrons



Applying Symmetries to Protons and Neutrons

- Mid-1930s: scientists observed that protons and neutrons have very similar masses (both much larger than the electron's), and behave similarly in their interactions.



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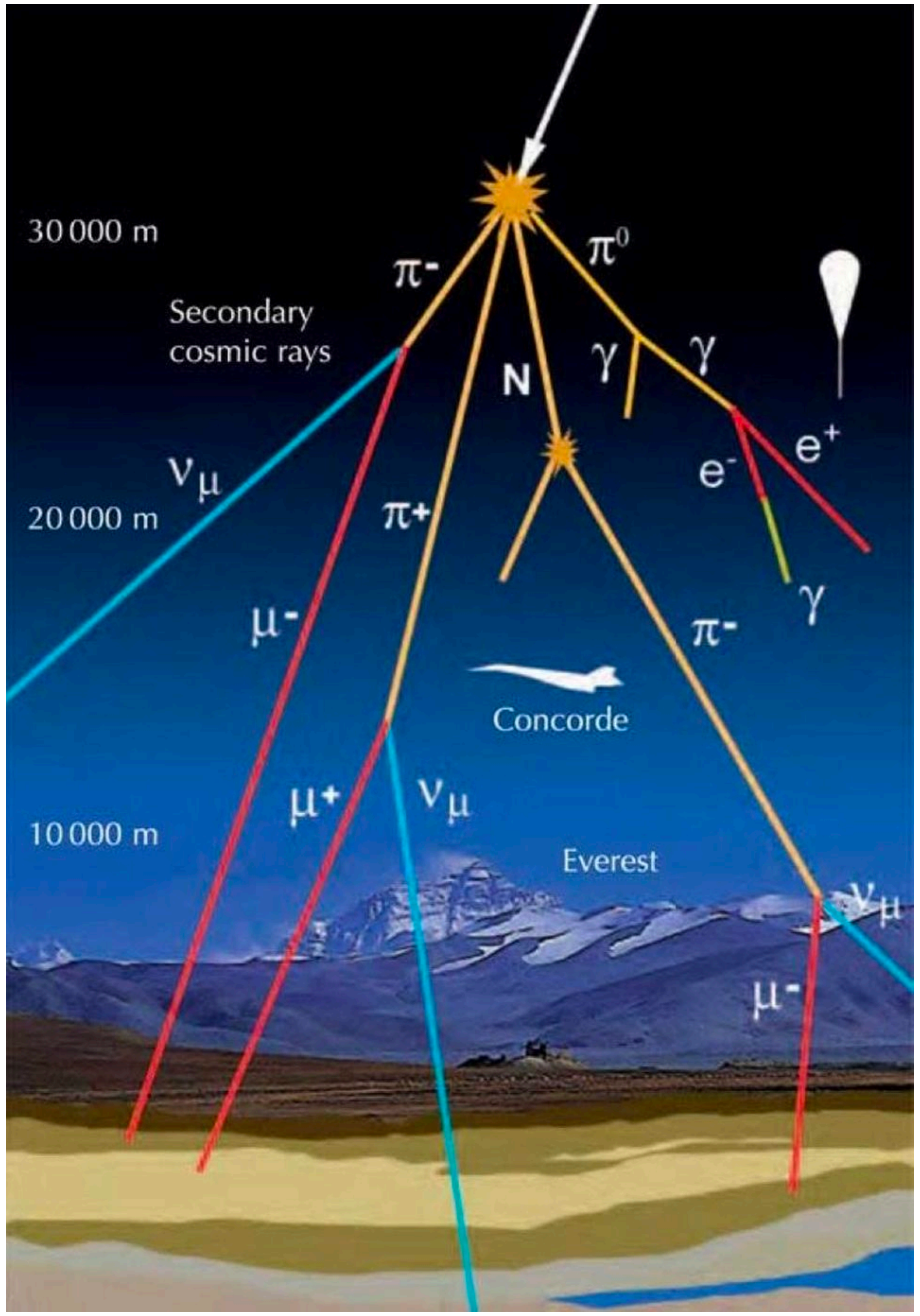

Fermilab

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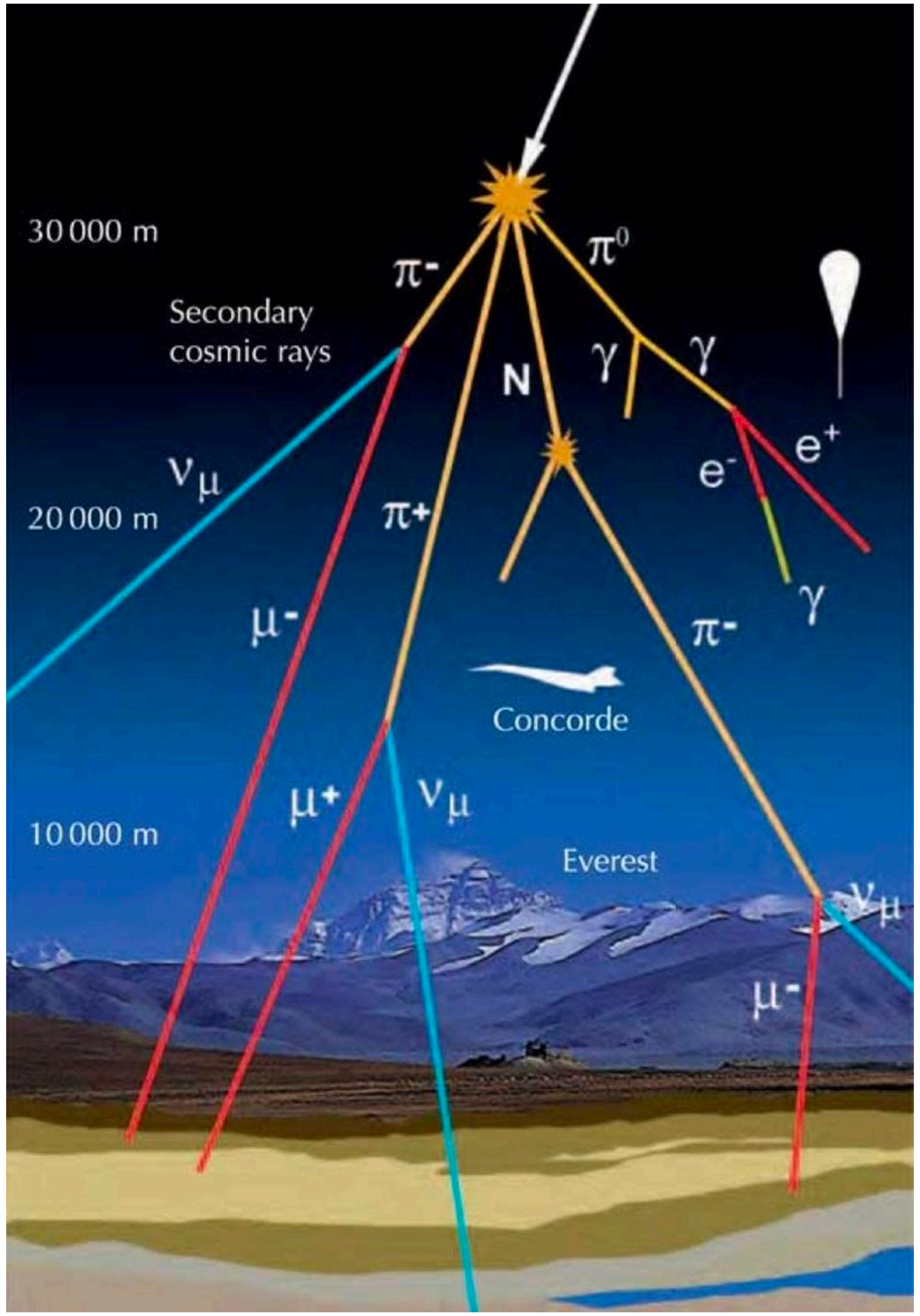
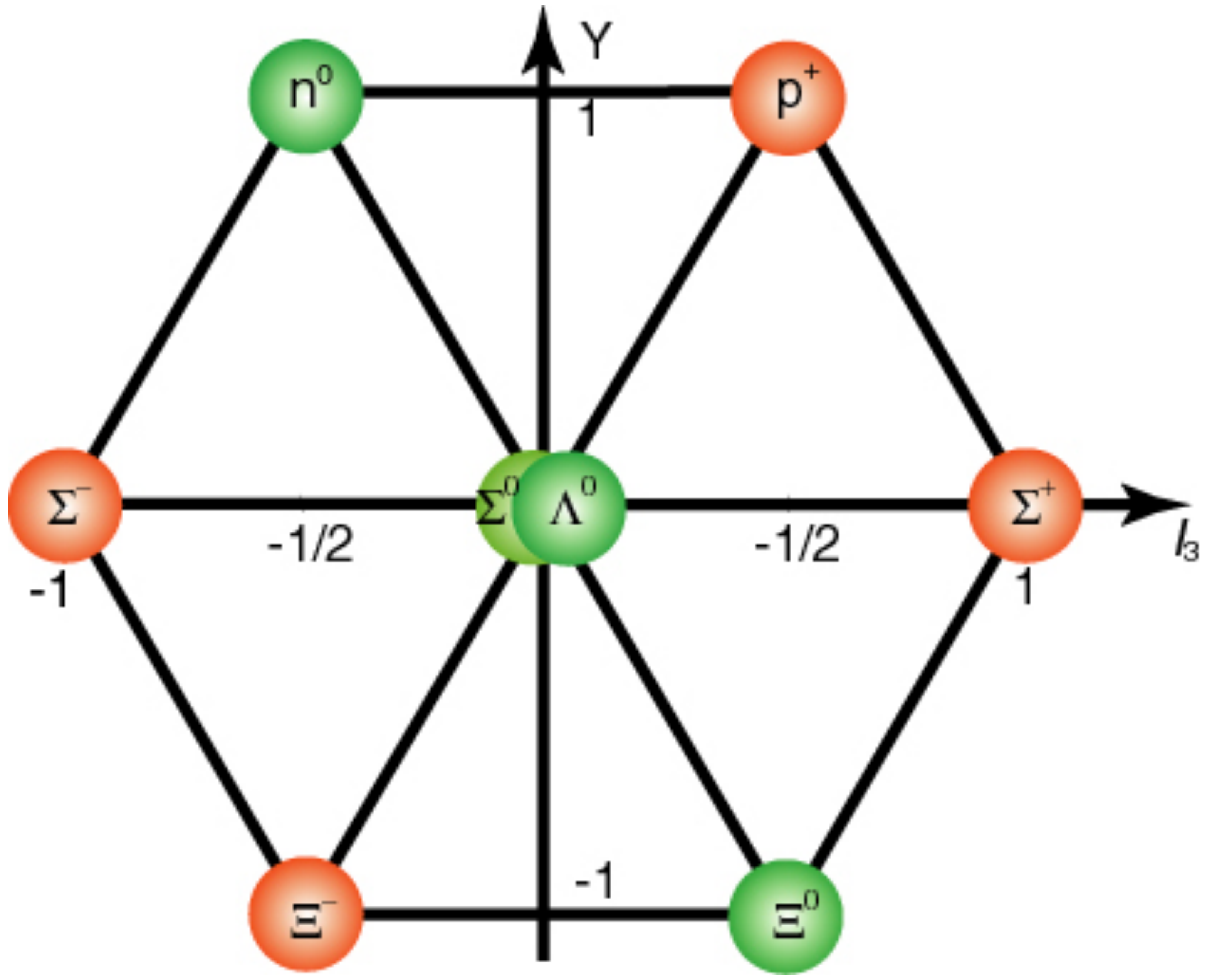
- In the meantime, more exotic particles were being discovered in cosmic rays — pions and muons.

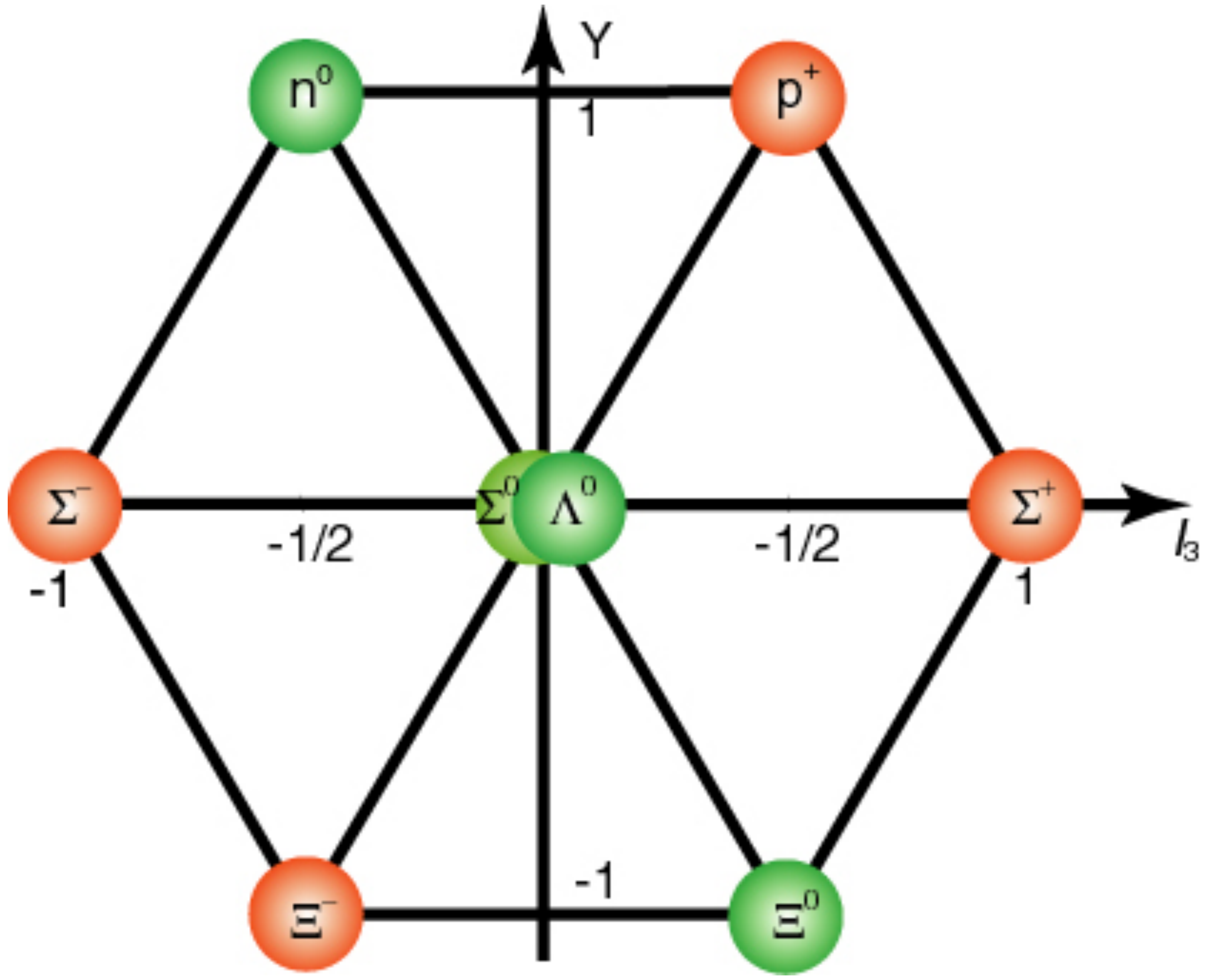


The Eightfold Way



The Eightfold Way

- Mesons, Baryons, and their interactions can be described using isospin and charge.



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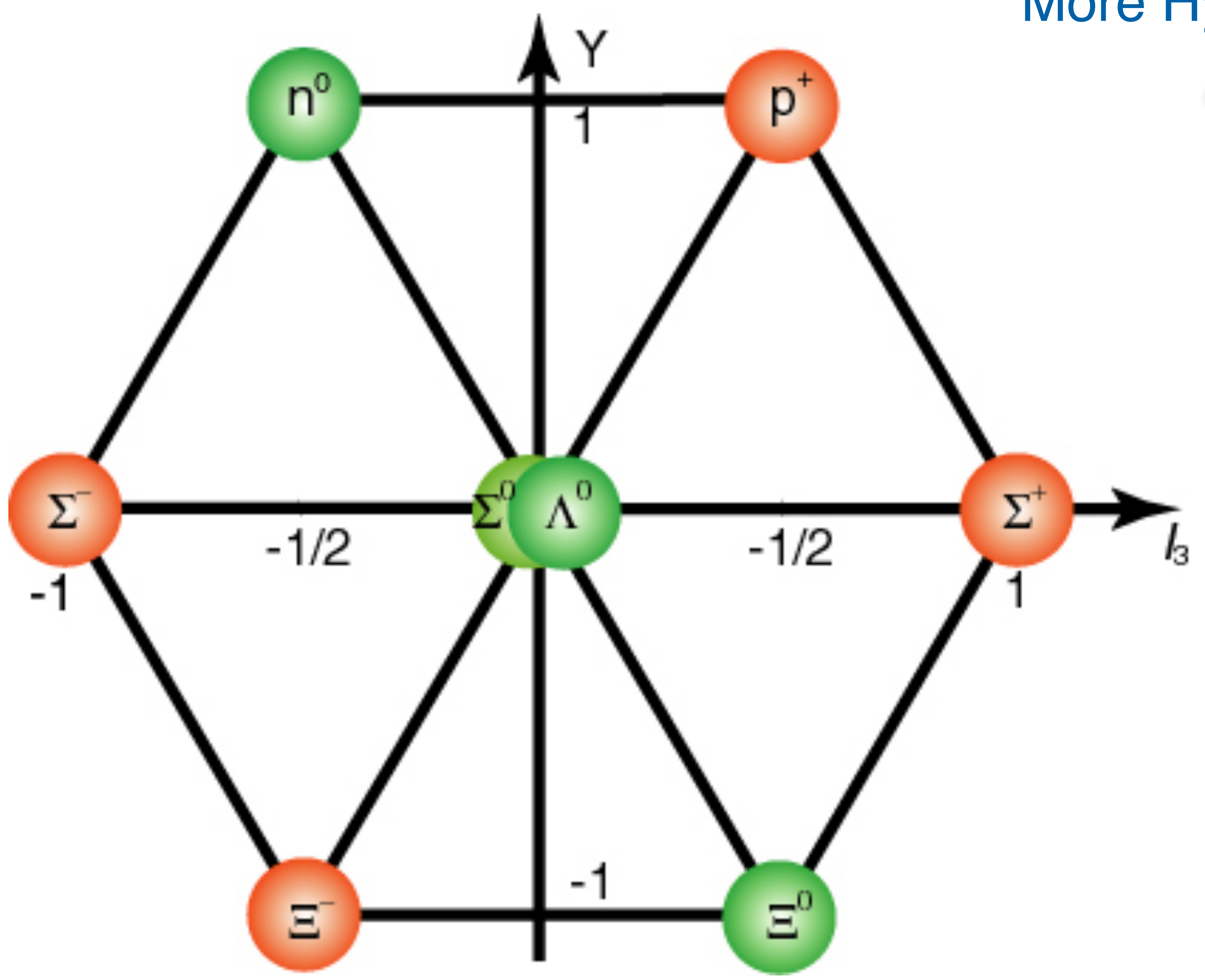

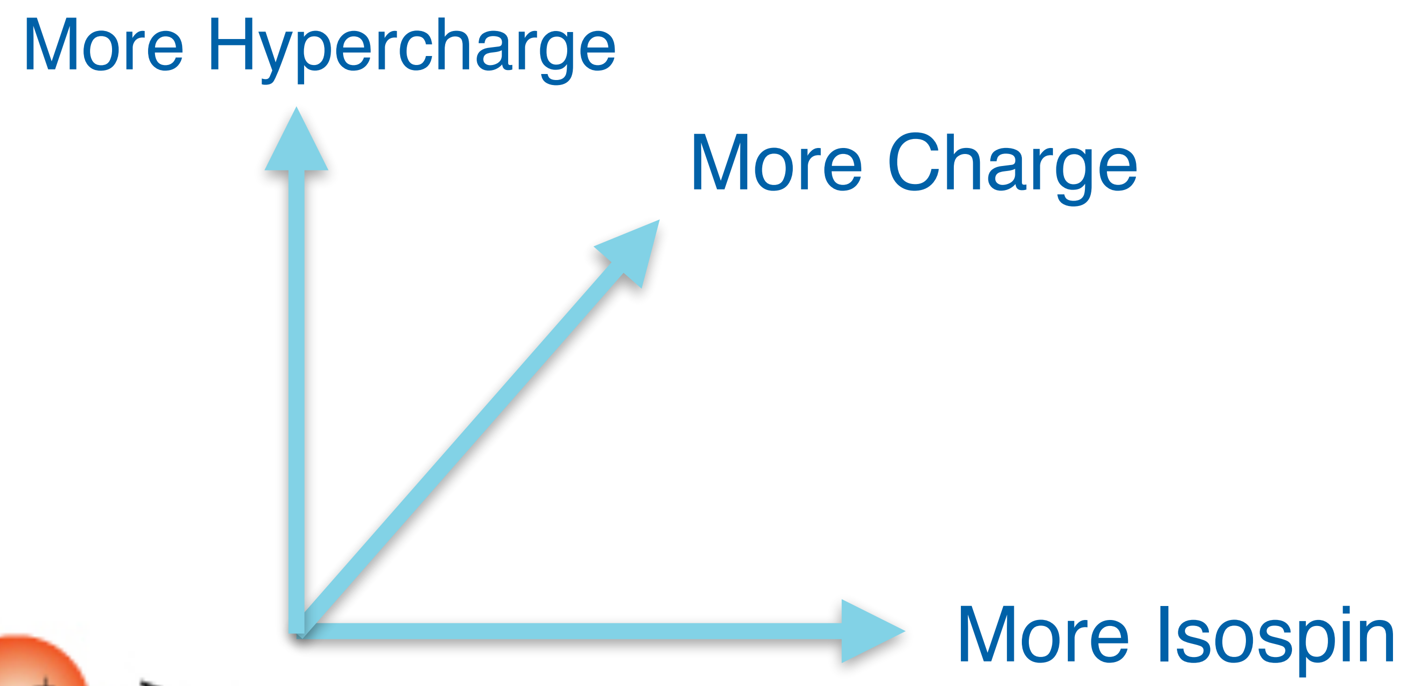

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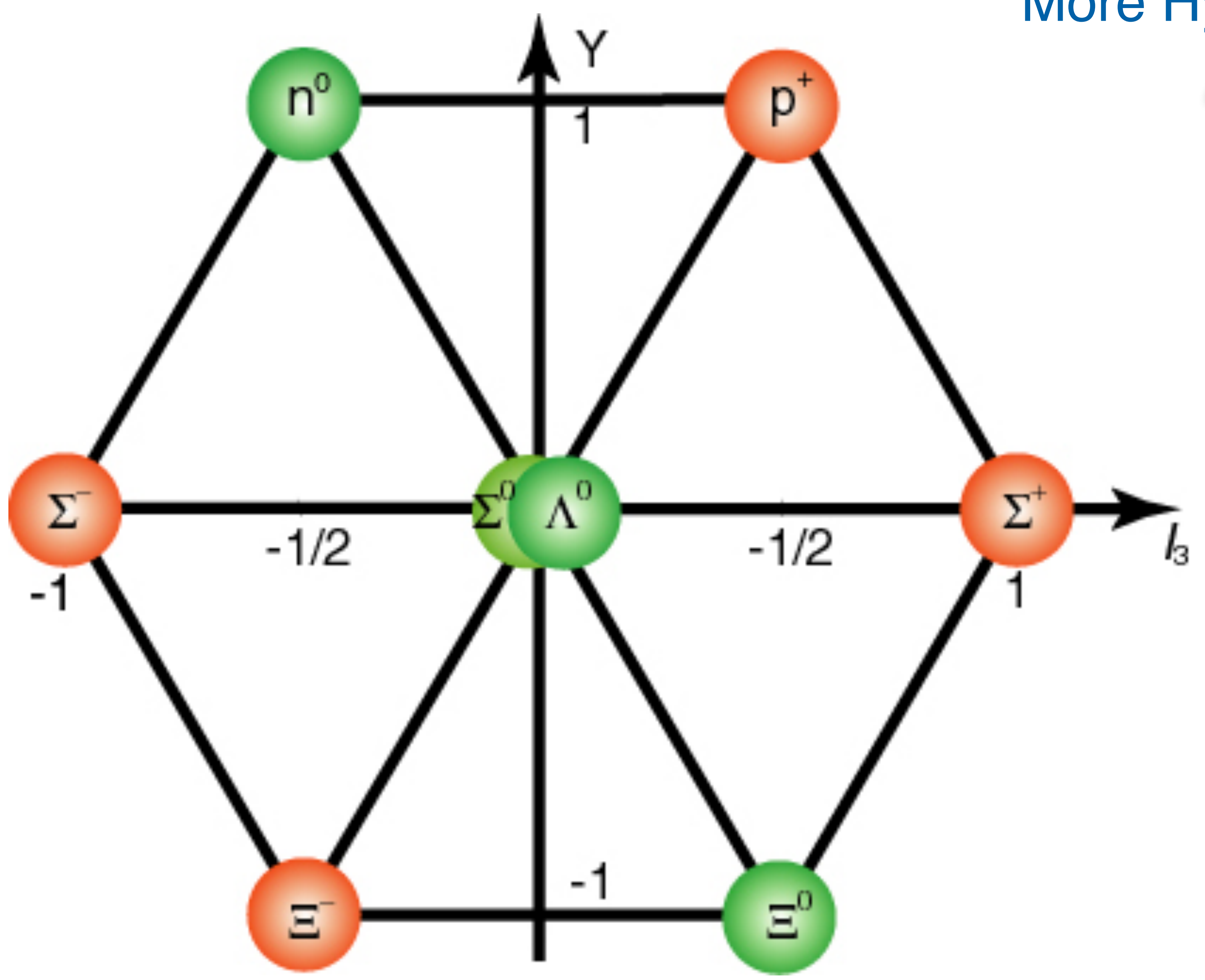
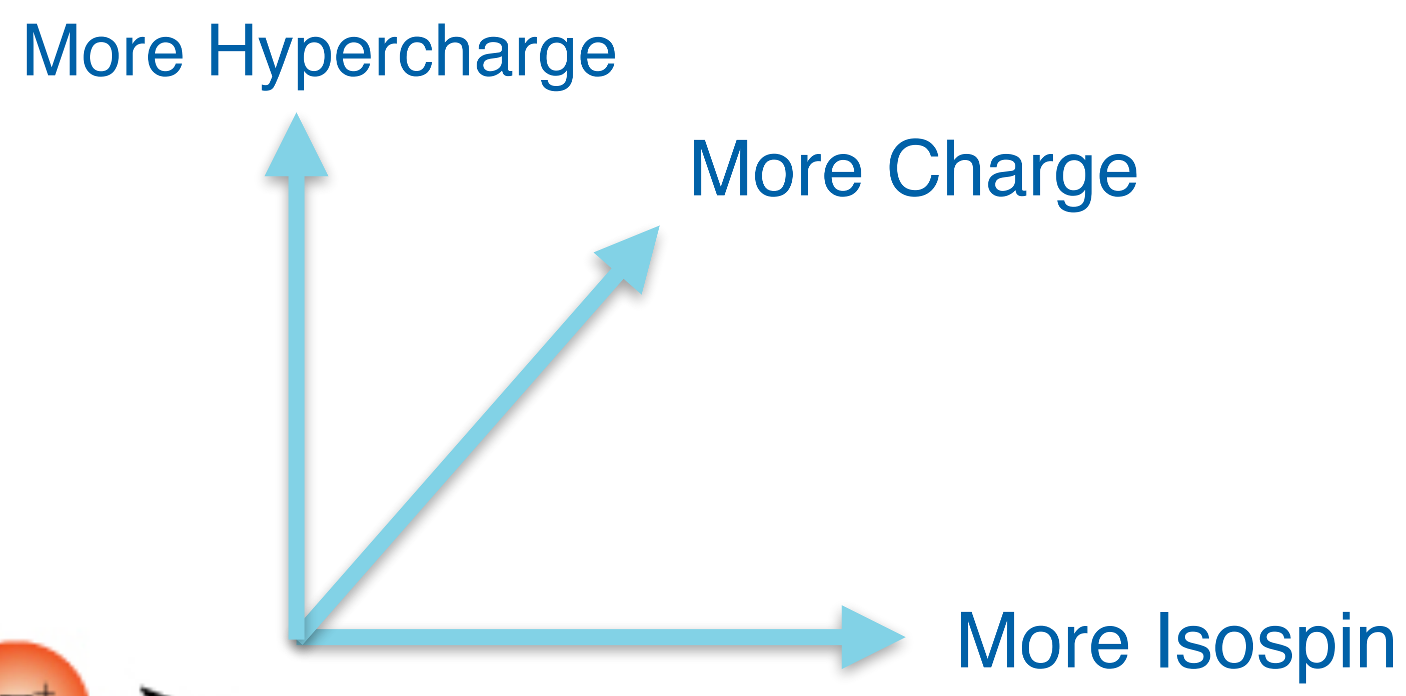


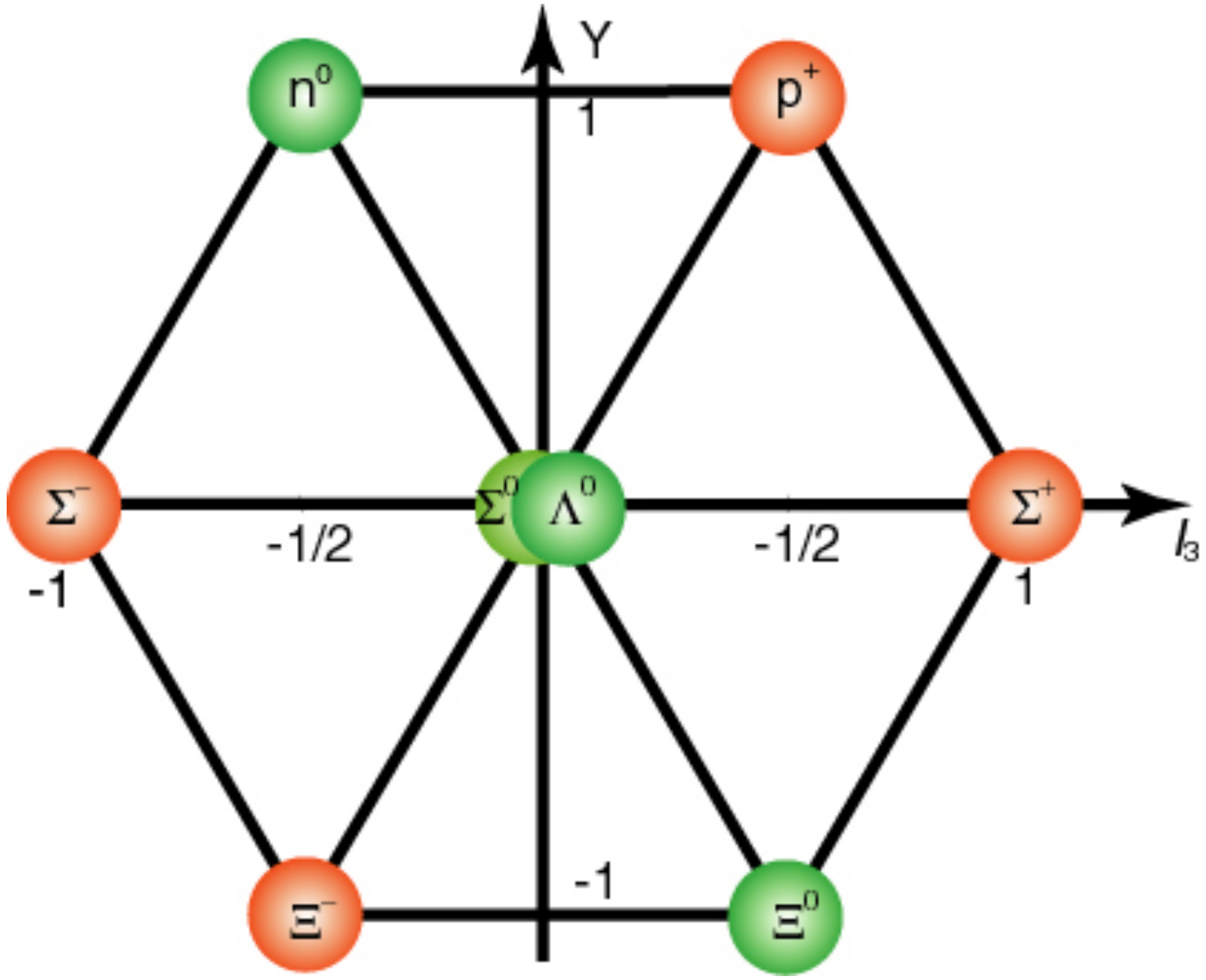


Mesons, like the charged pions, mediate interactions between these hadrons.

Fermilab

Gell-Mann, Zweig, and Quarks

- Proposal: protons/neutrons/etc. are ***not*** fundamental particles, but made up of three different types of quarks: up, down, and strange.



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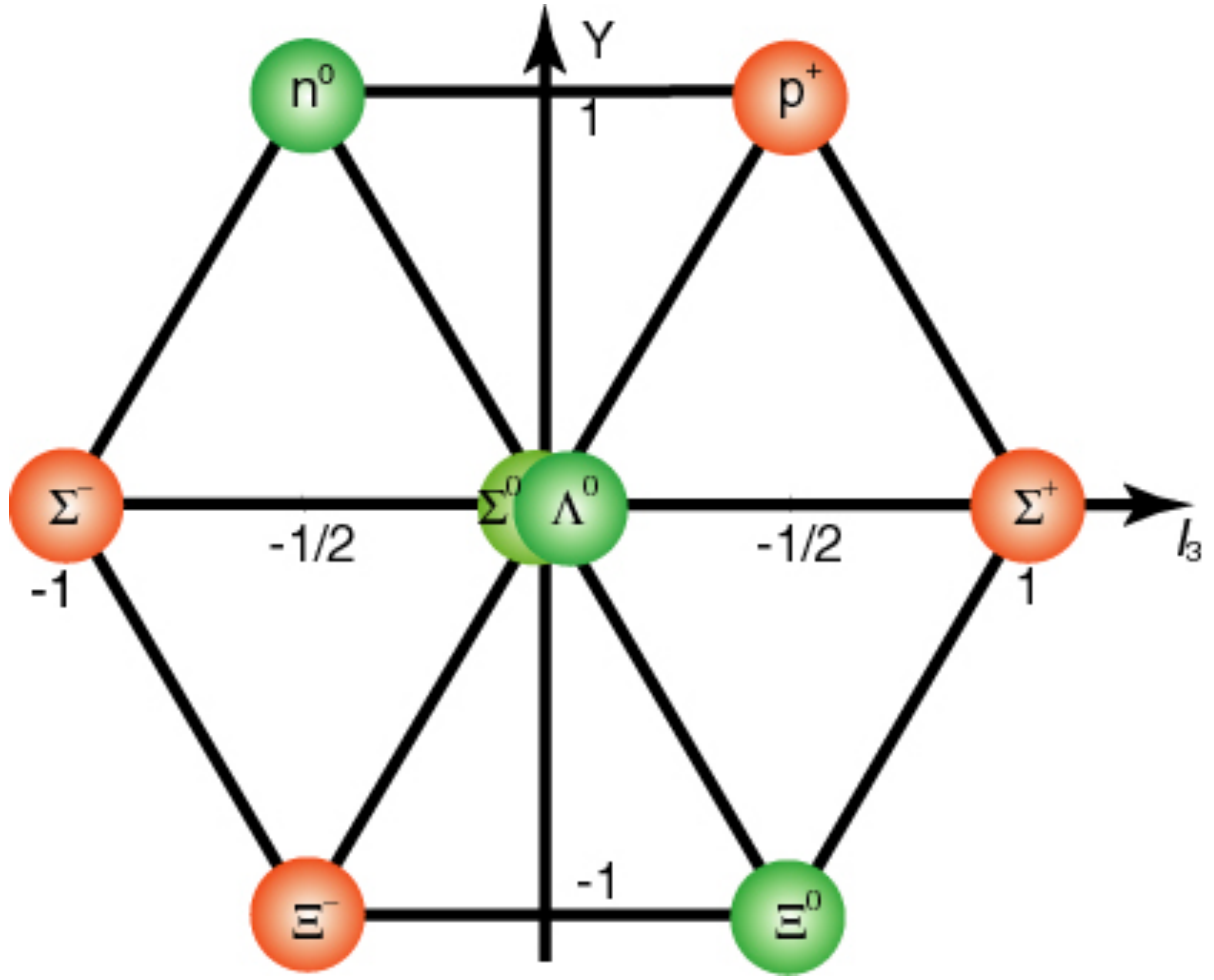

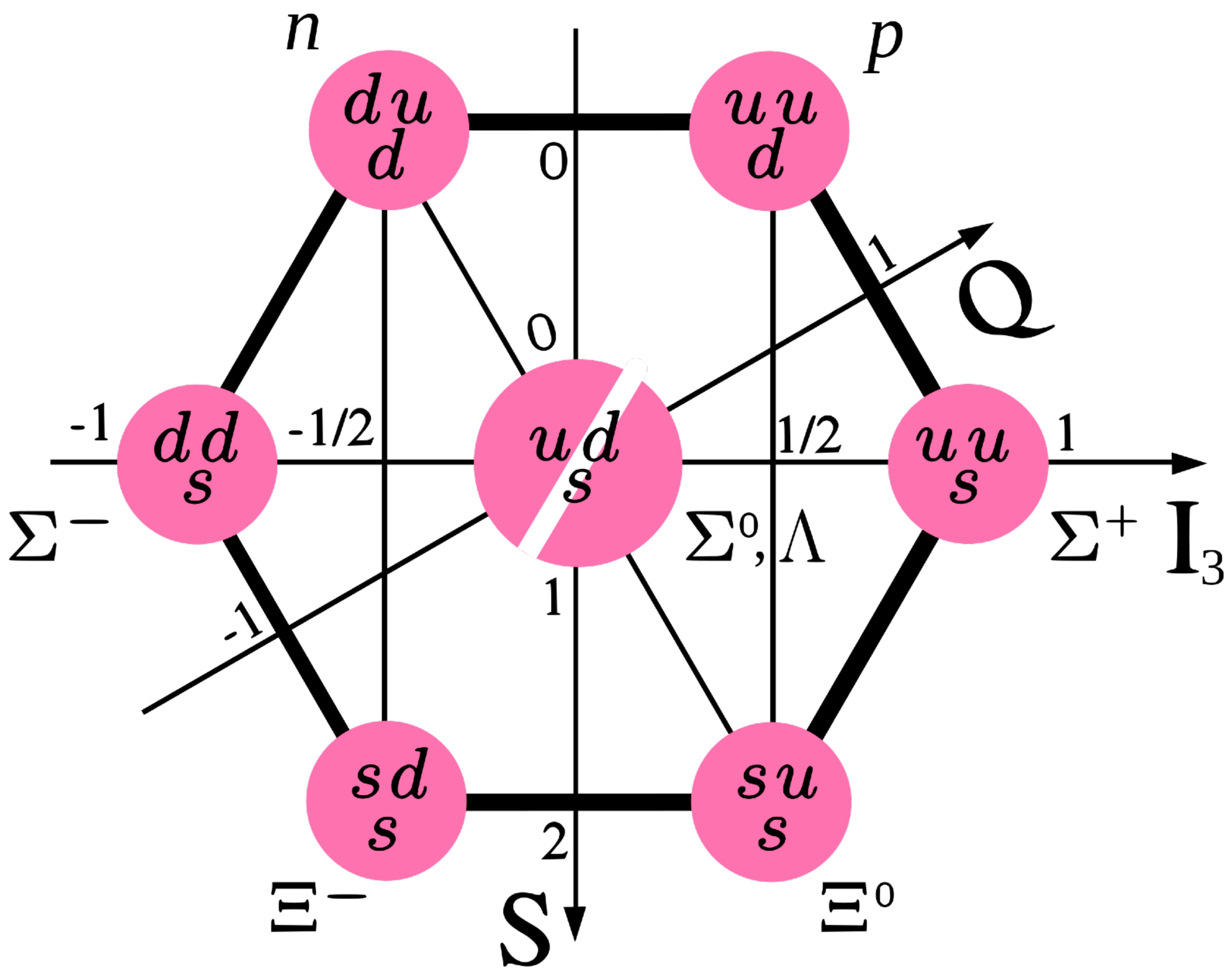

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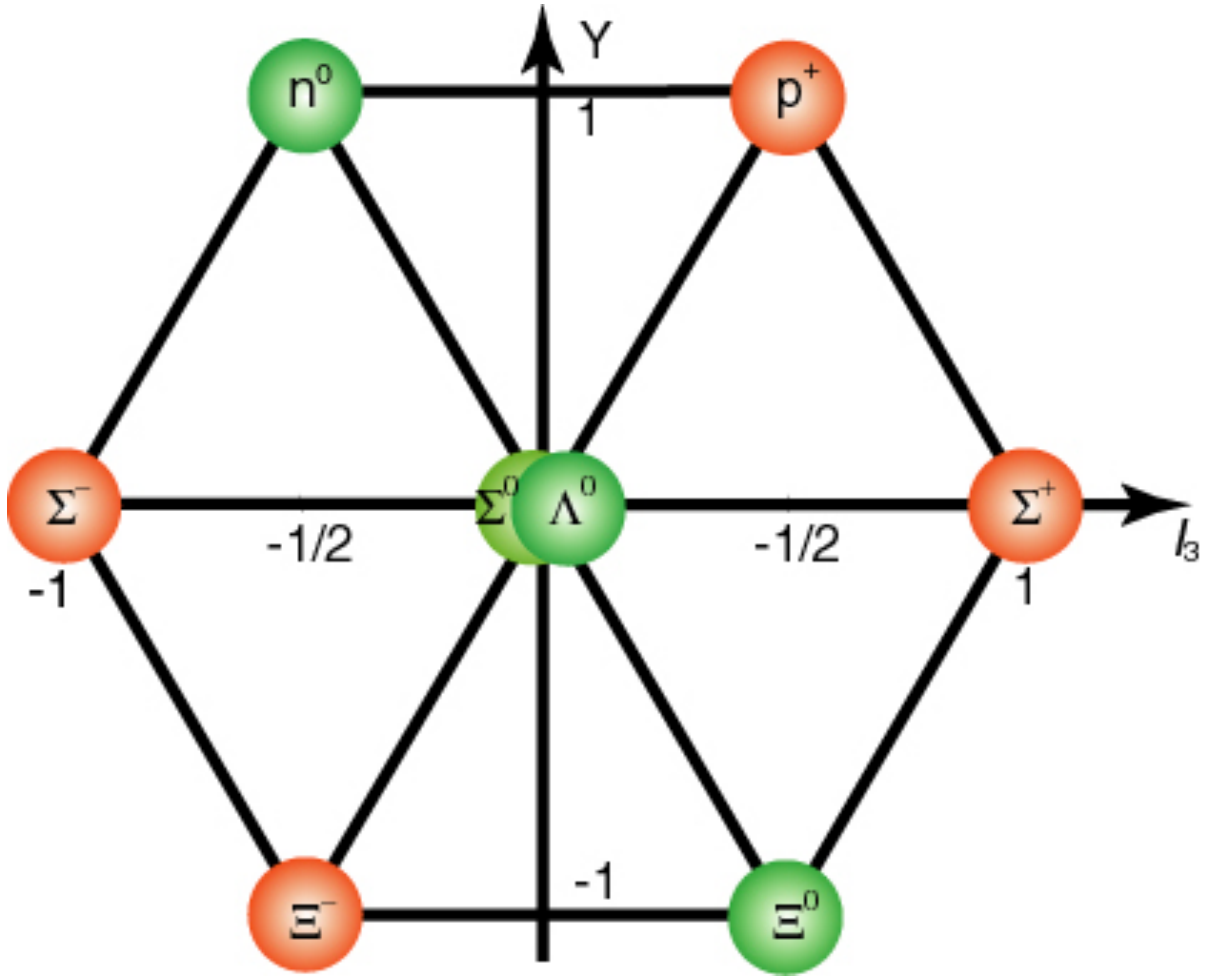

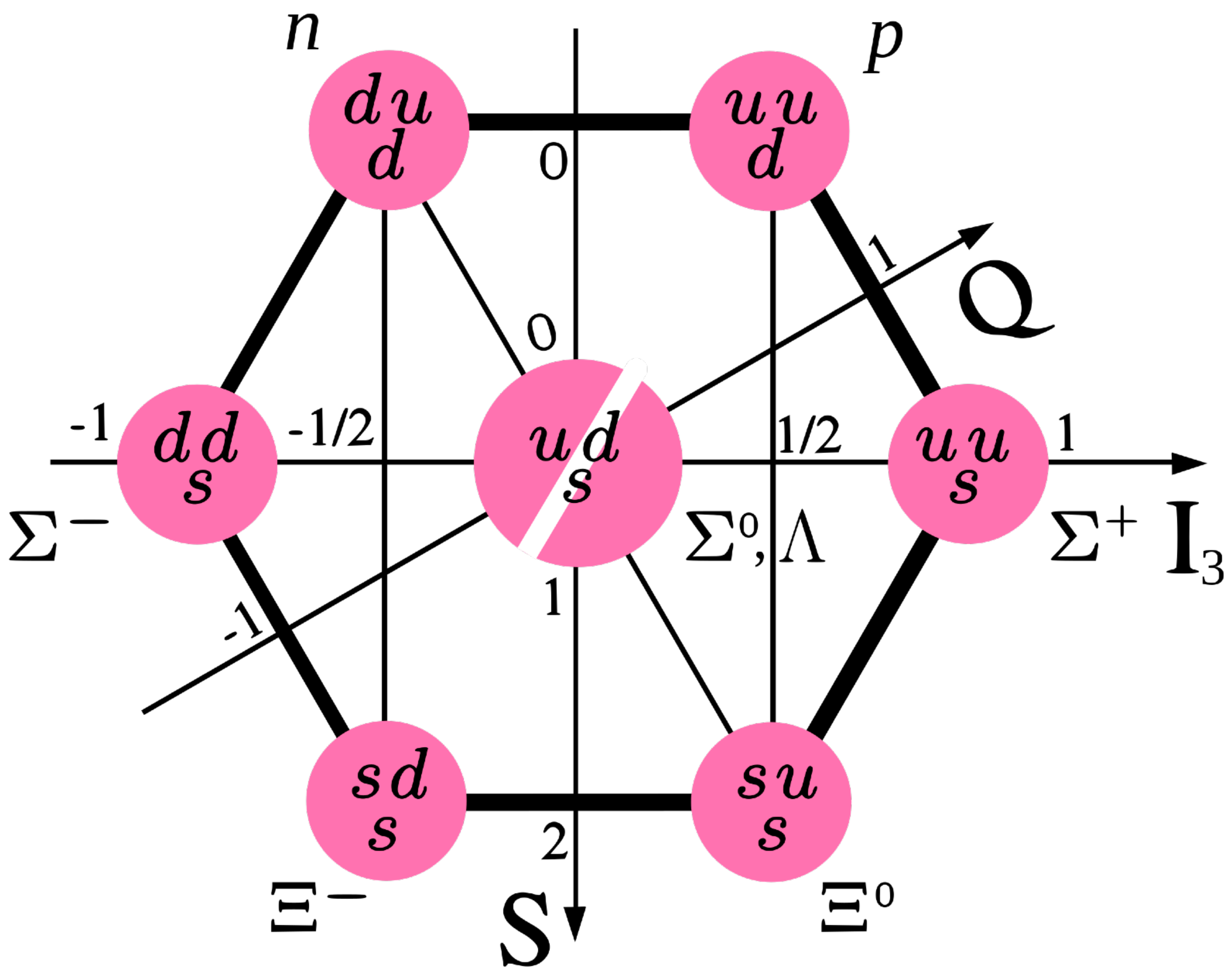

The quarks interact under a symmetry principle called "**SU(3)**", a type of symmetry called a Lie group.

Three quarks to Six quarks

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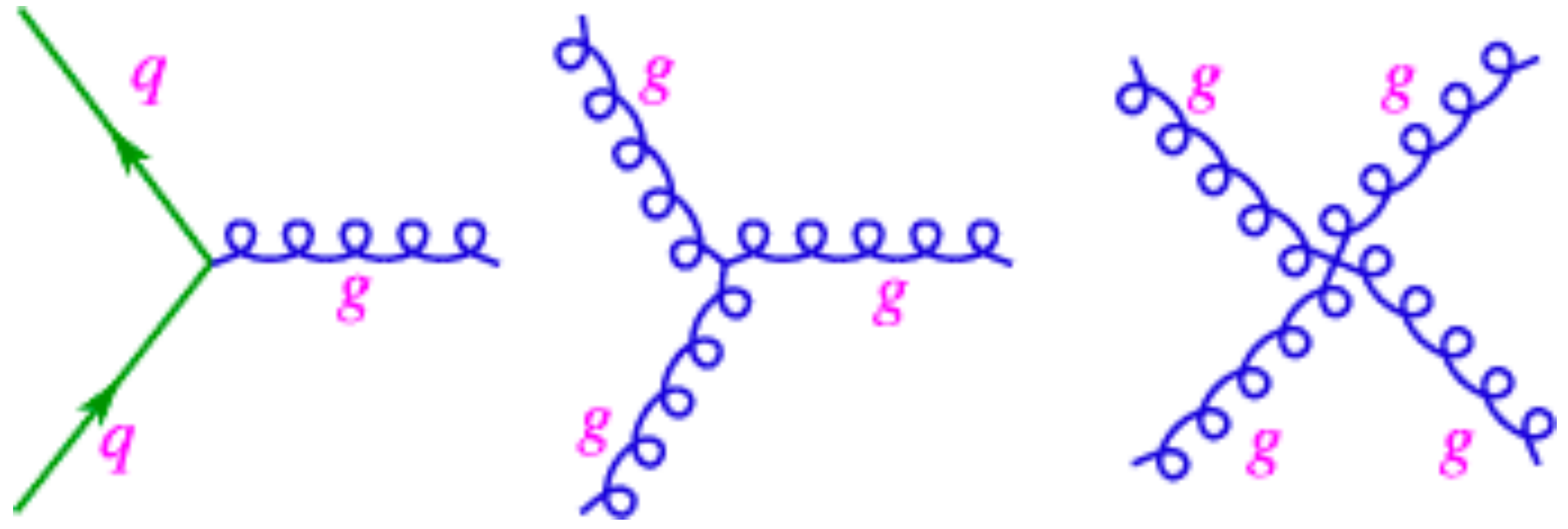
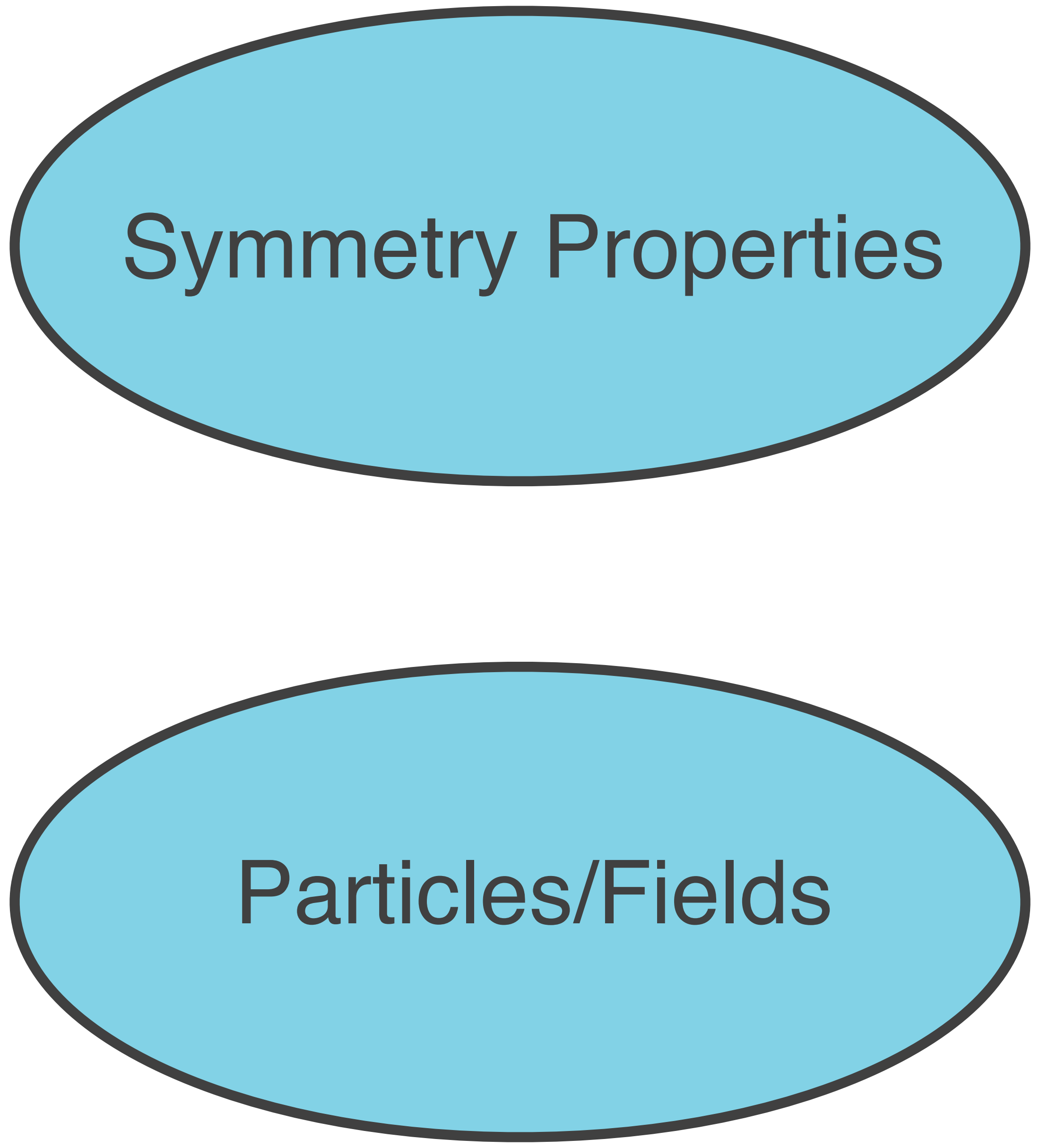
- The **SU(3)** symmetry originally proposed to explain the behavior of the (up, down, strange) quark system had to be modified to accommodate all six quarks.
- This led to the development of Quantum Chromodynamics (QCD), which uses a different **SU(3)** symmetry of “color” to describe all quark interactions.



So, how do we use symmetries & particles together?



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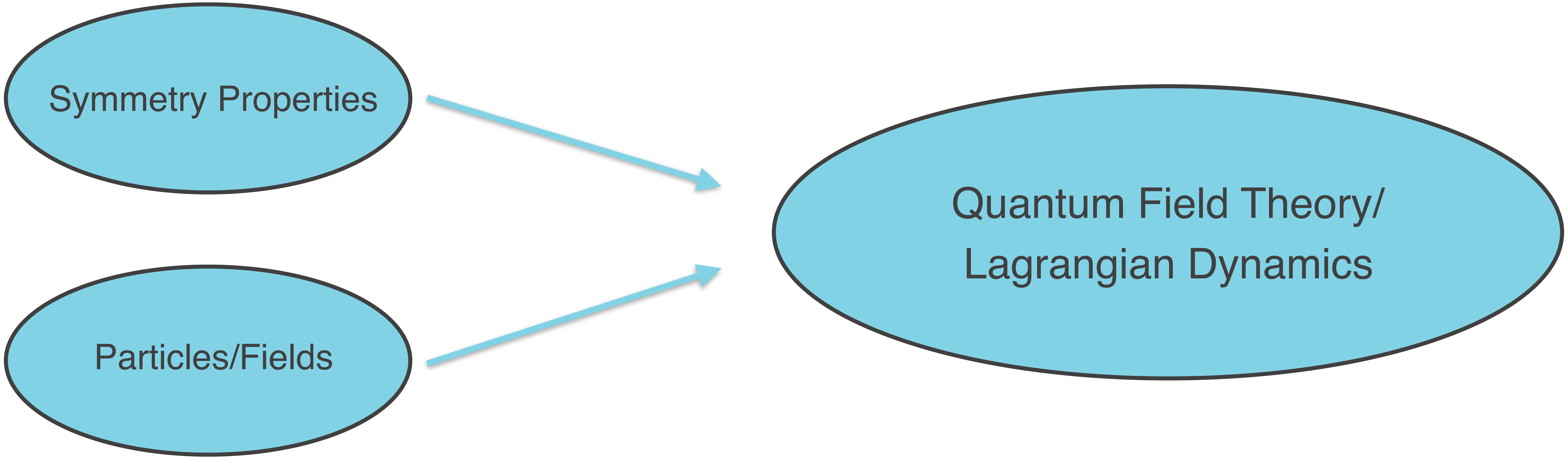

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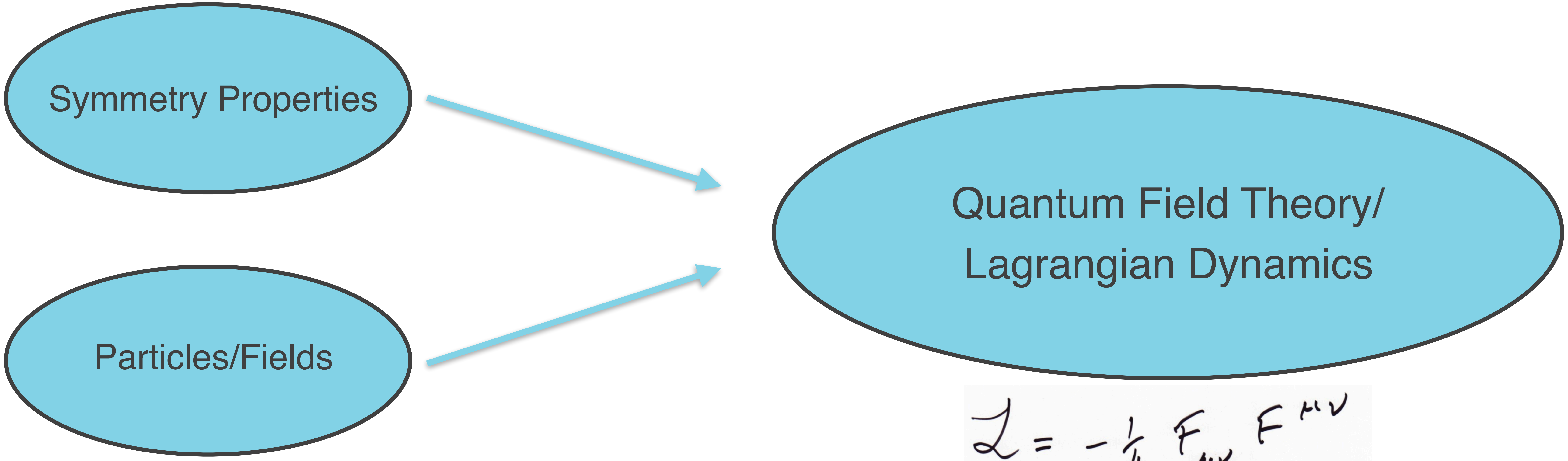

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$$\mathscr{L} = \left(\partial_\mu \phi^*\right)\left(\partial^\mu \phi\right) \qquad \partial_\mu = \frac{d}{dx_\mu}, \quad x_\mu = (t, x, y, z)$$

Fermilab

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$$\text{Particle(s)} + \text{Gauge Symmetry} \longrightarrow \text{Description of Interactions}$$

$$\text{Electrons} + \text{U(1) gauge symmetry} \longrightarrow \text{Quantum Electrodynamics (QED)}$$

Side-note: Gauge Boson Masses

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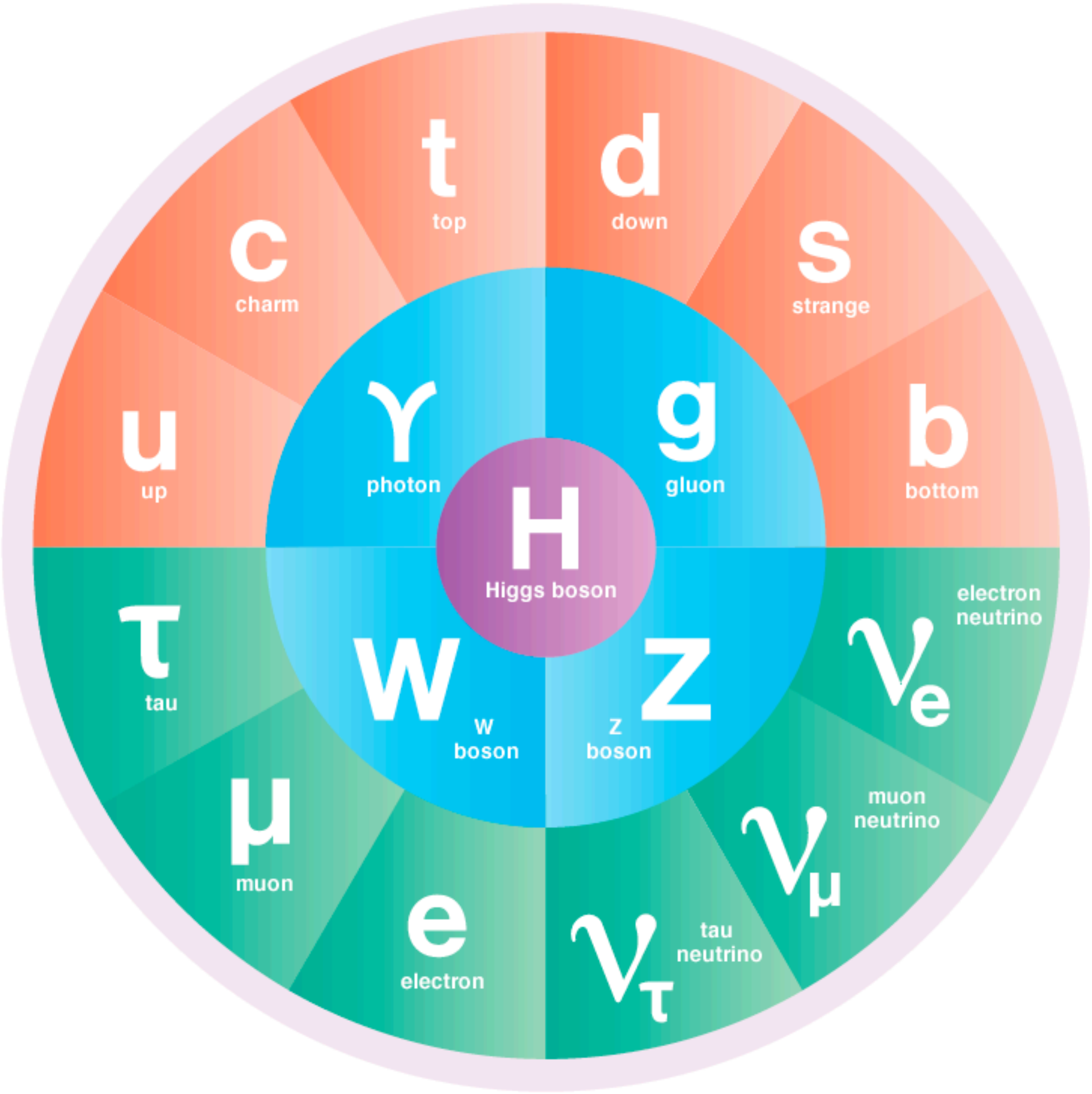
- Under the transformation we introduced for this, though, the Lagrangian is ***not*** invariant — gauge bosons must be massless.

$$A^\mu \to A^\mu - \frac{1}{g}\partial^\mu \theta$$

Let’s check back in on the Standard Model



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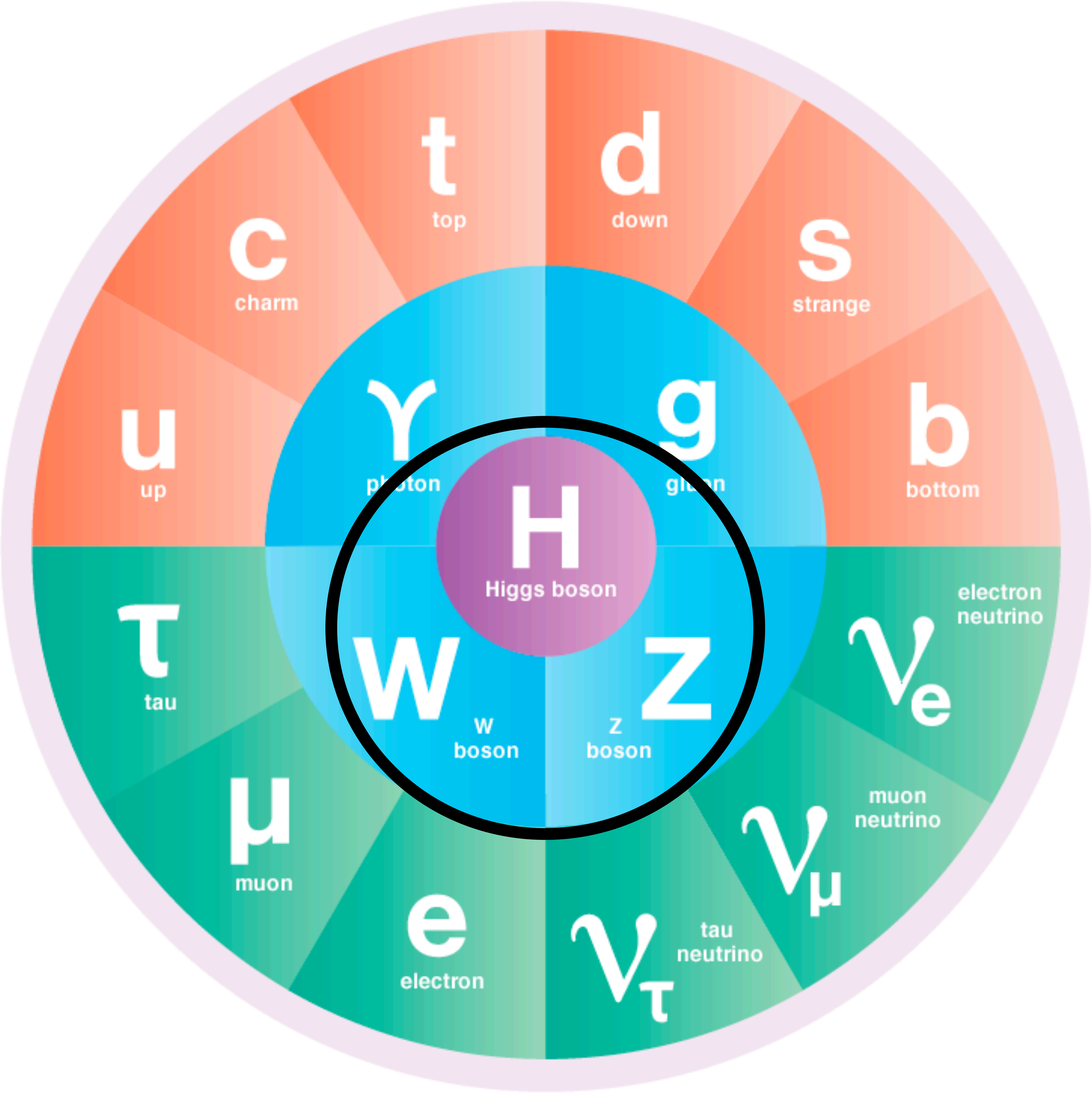

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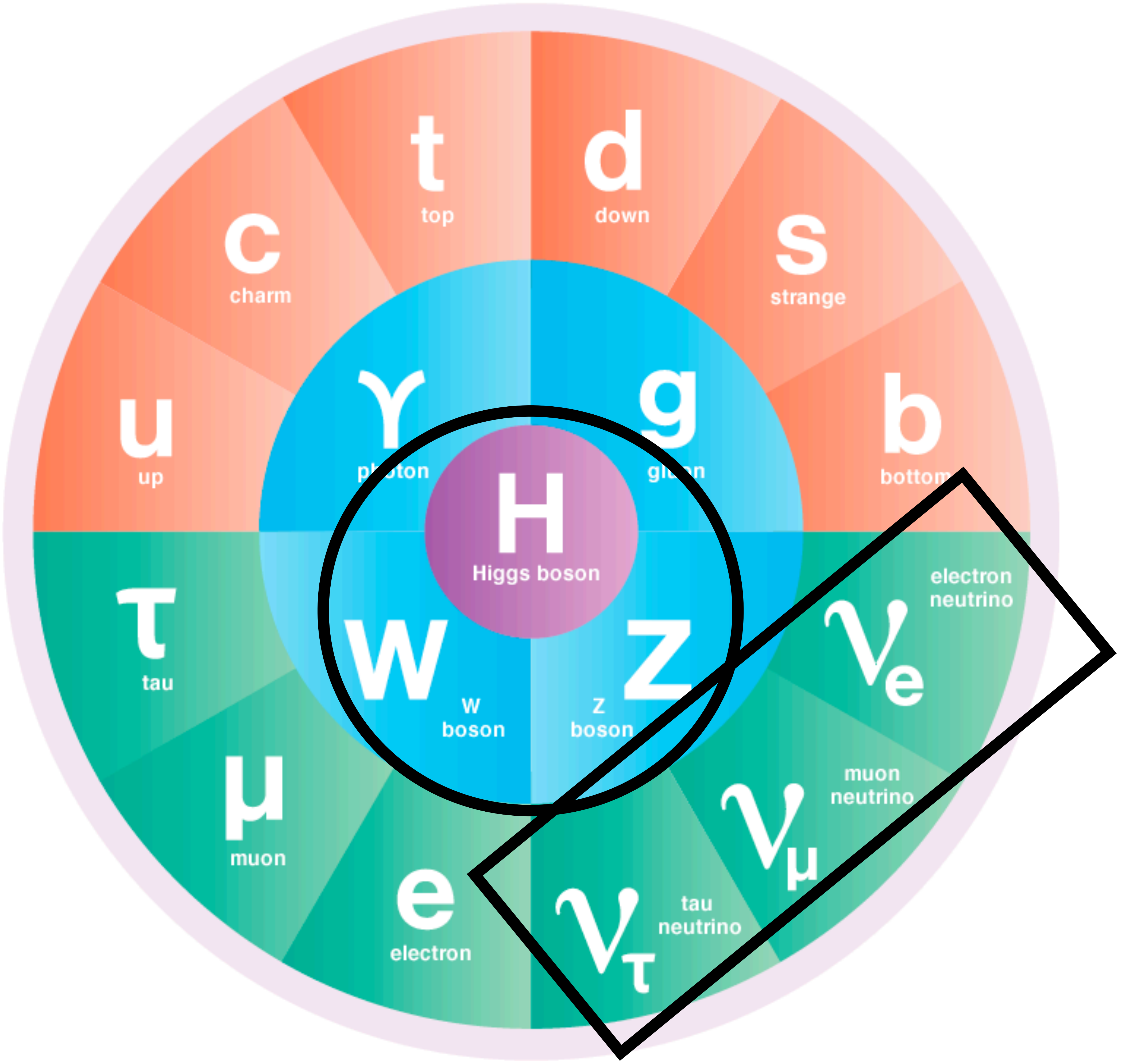
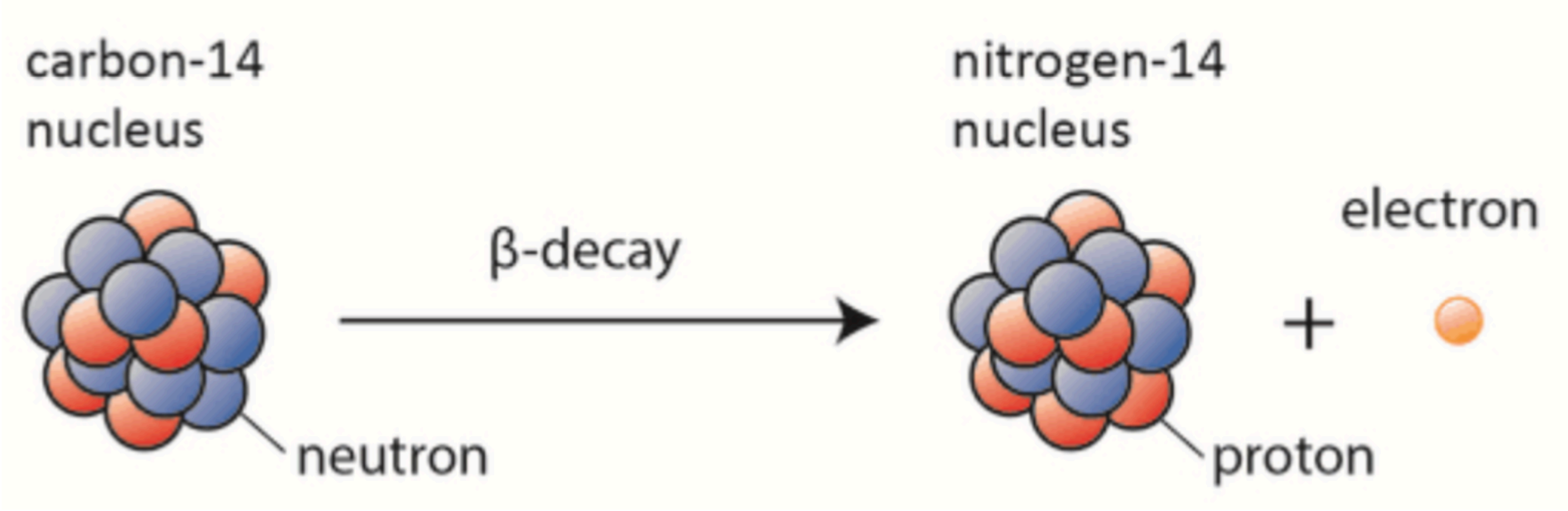


Back to the 1930s: Nuclear Beta Decays



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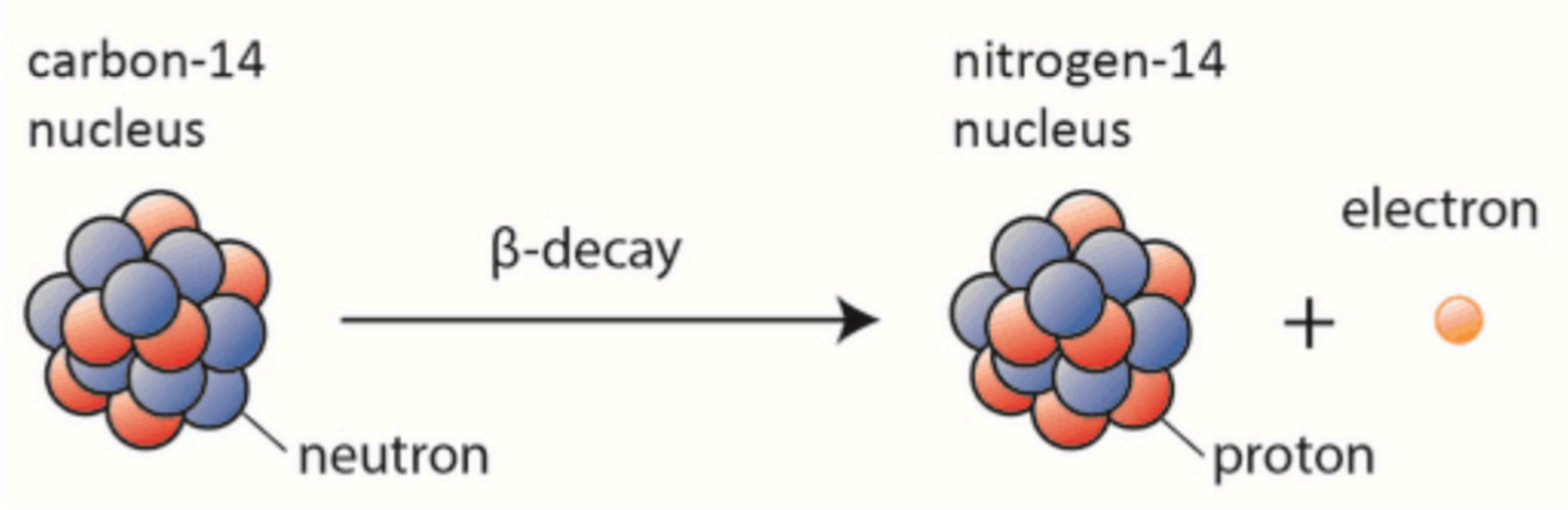

Example beta decay —a neutron inside a Carbon nucleus spontaneously changes to a proton (actually a down quark changing to an up quark), and an electron is emitted to conserve charge.

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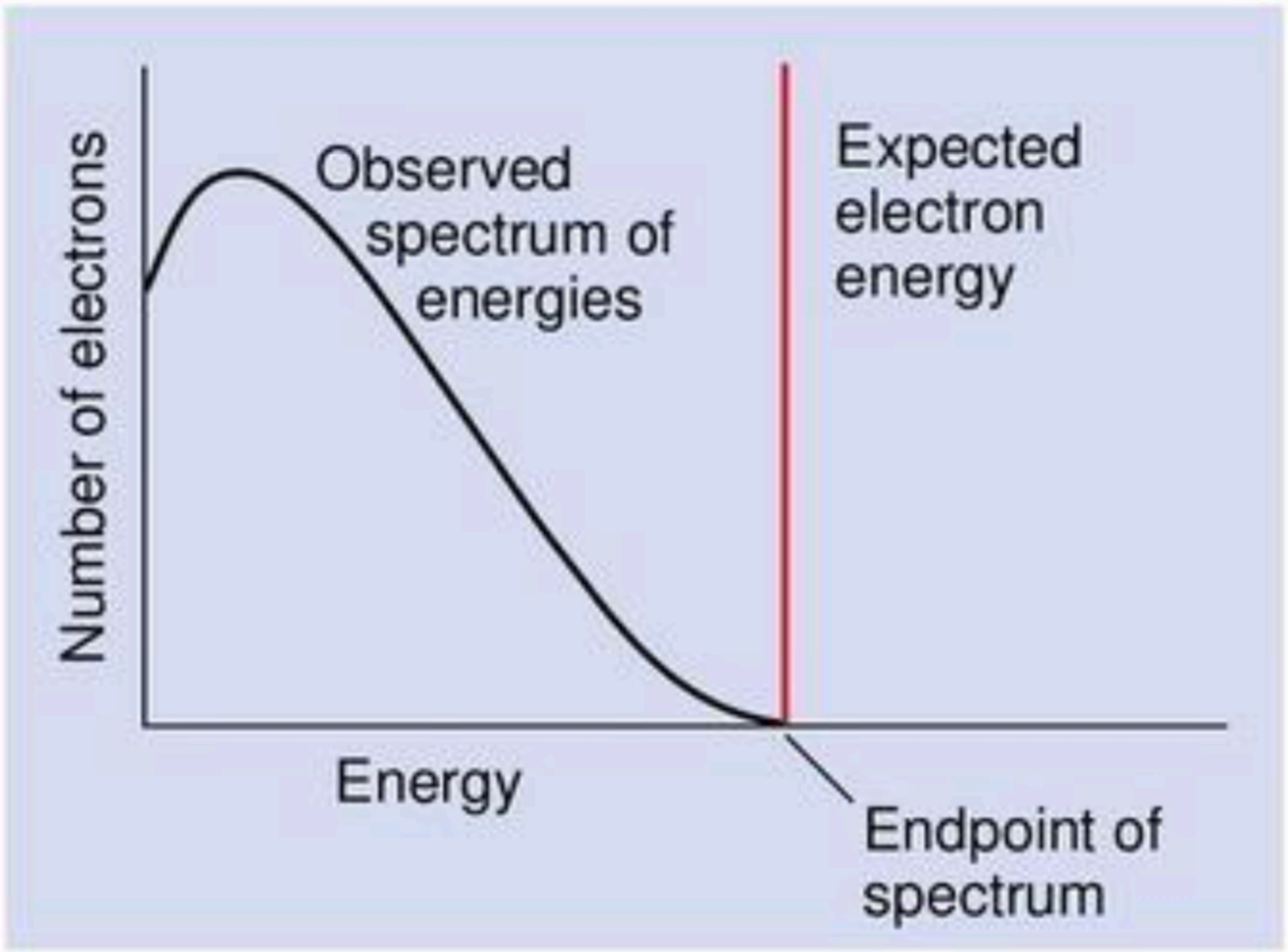

- Measurements of beta decay show that the electron has a spectrum!

Wolfgang Pauli: “Dear Radioactive Ladies and Gentlemen”

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Fermilab

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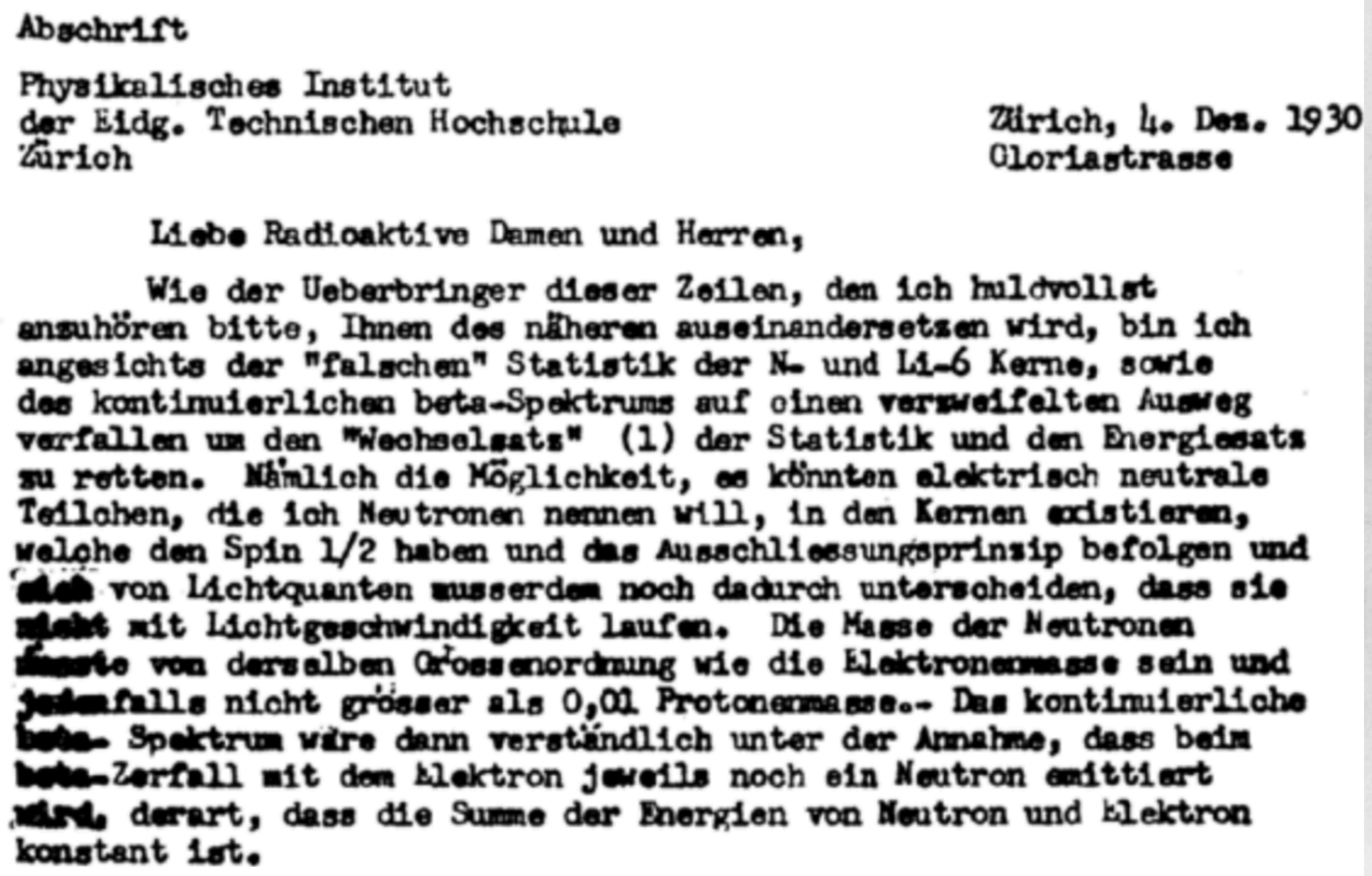

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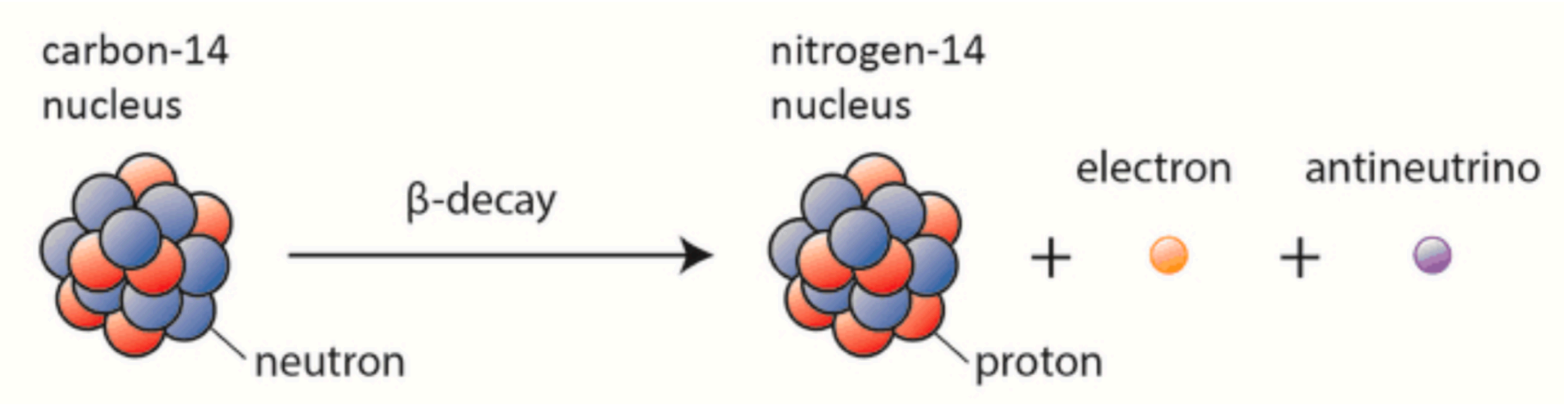

- Pauli’s solution: a new, very weakly interacting “neutrino” comes out of beta decays as well, stealing some of the energy from the outgoing electron and producing a spectrum of electron energies.

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Just how "weak" is "weakly interacting"?

- Enrico Fermi, shortly after Pauli: $\mathscr{L}_{\text{Fermi}} \supset G_F \left(\overline{\psi}_p \Gamma \psi_n\right) \left(\overline{\psi}_e \Gamma' \psi_\nu\right)$

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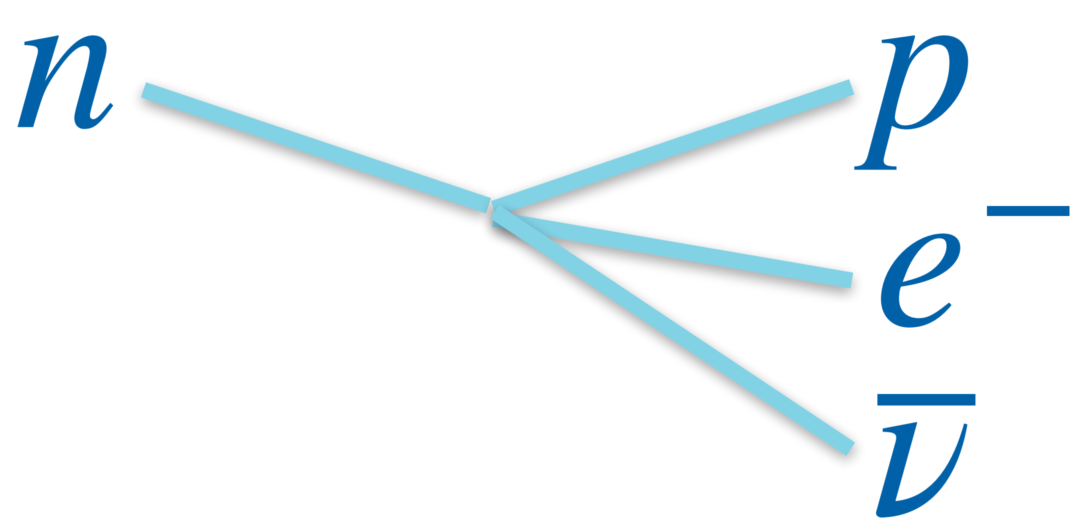

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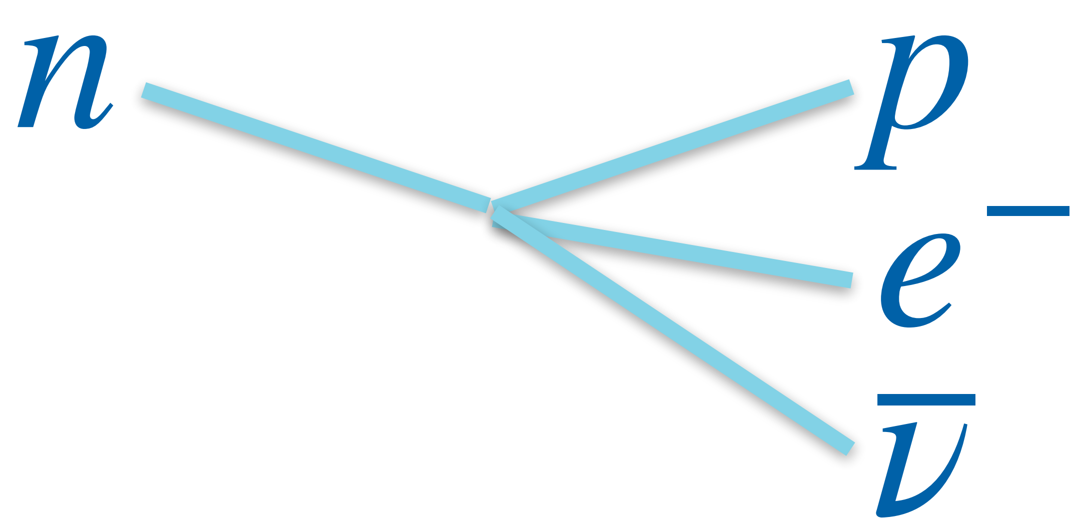
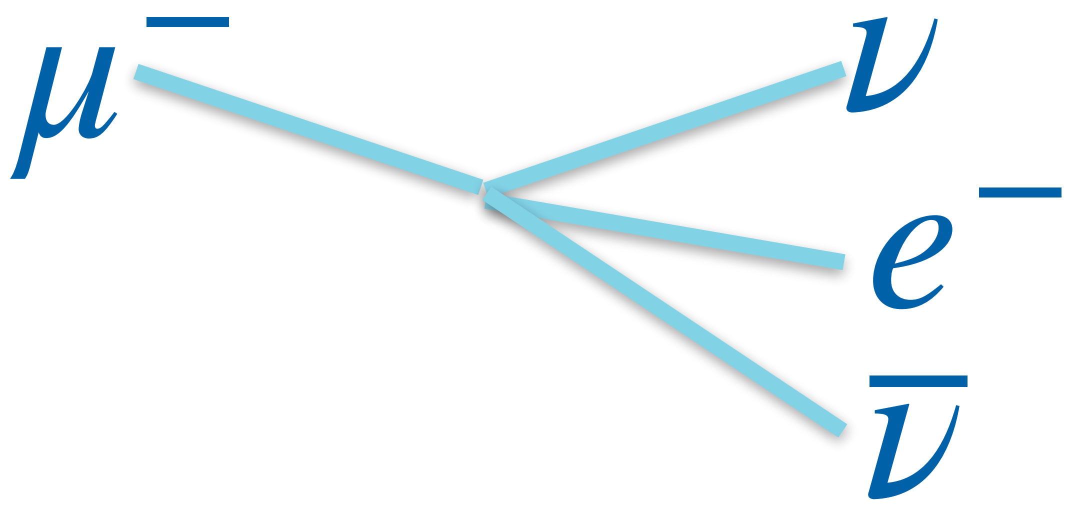


- Also predicts processes like muon decay,



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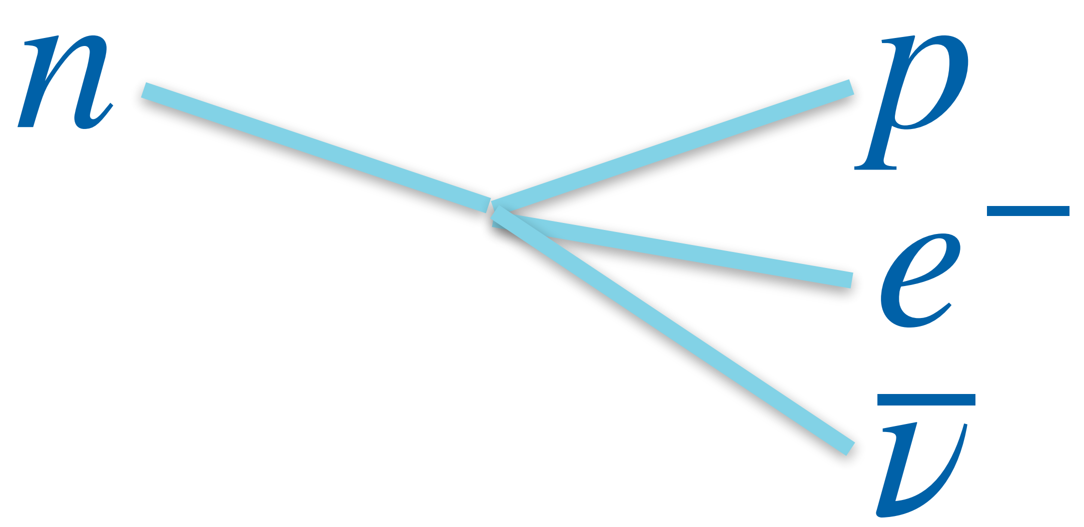

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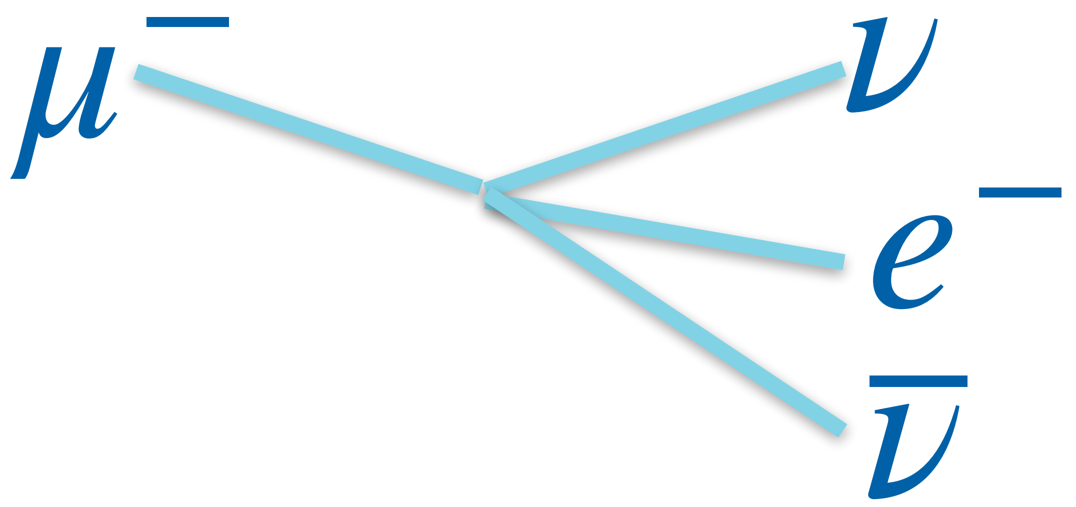

$$G_F \approx \frac{1}{(100\ \text{GeV})^2} \quad \left(m_p \approx 1\ \text{GeV}\right)$$

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- "Weak" **SU(2)** symmetry relating quarks to leptons:

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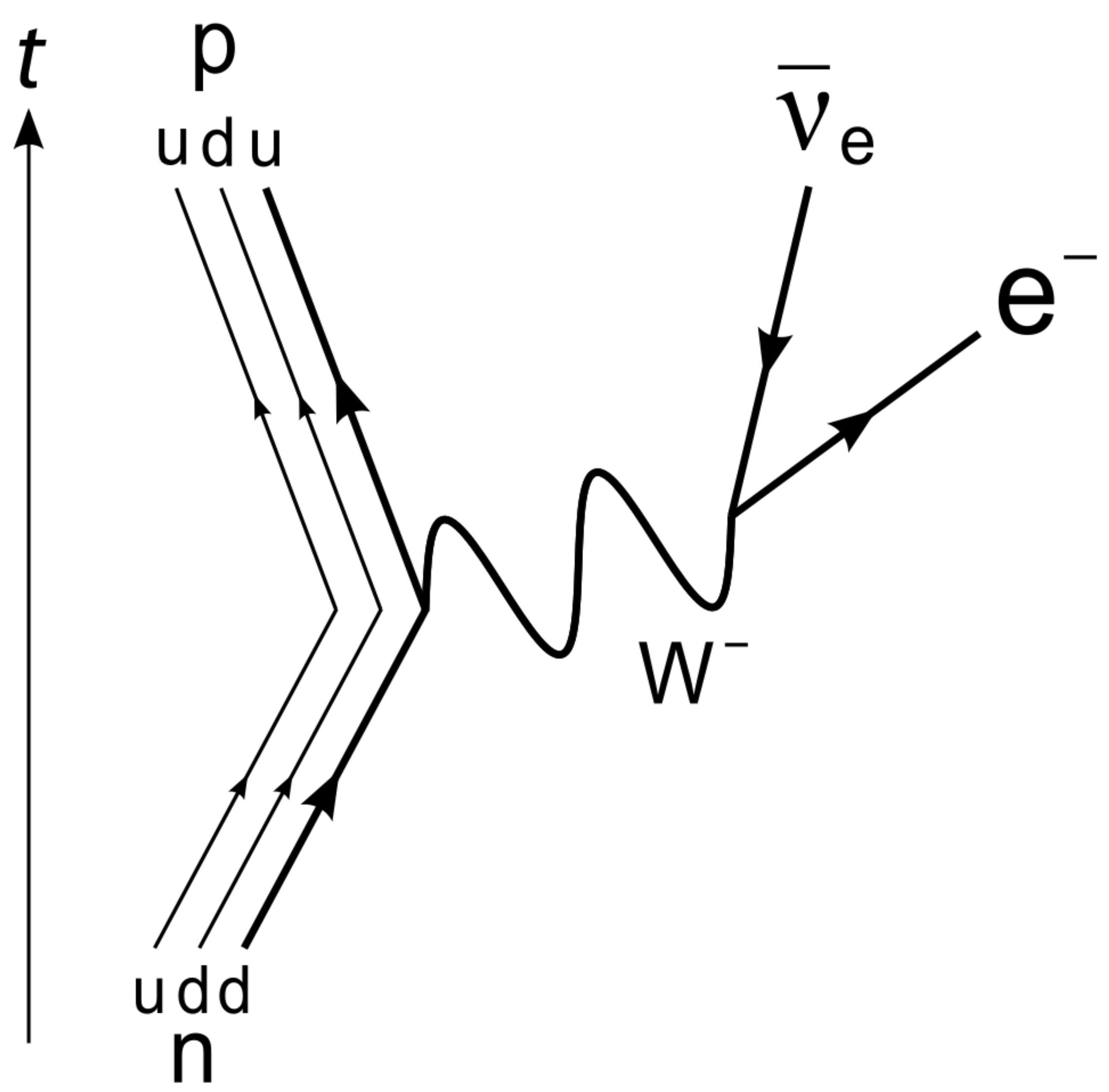

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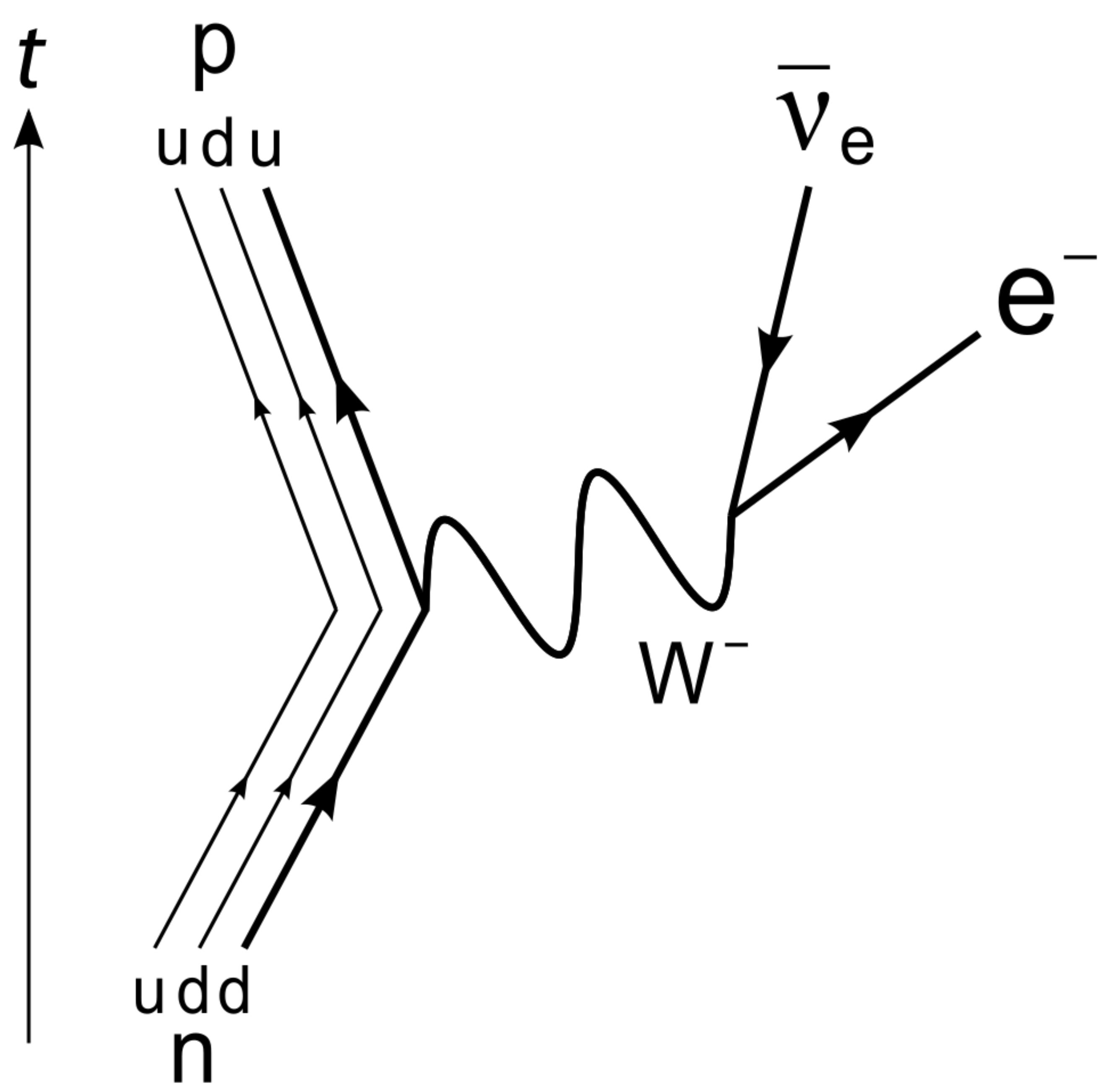

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- Issue: if these are really the gauge bosons of an **SU(2)** theory, they should have zero mass!

Solution: The final piece of the Standard Model

- The Higgs boson and the Higgs mechanism:

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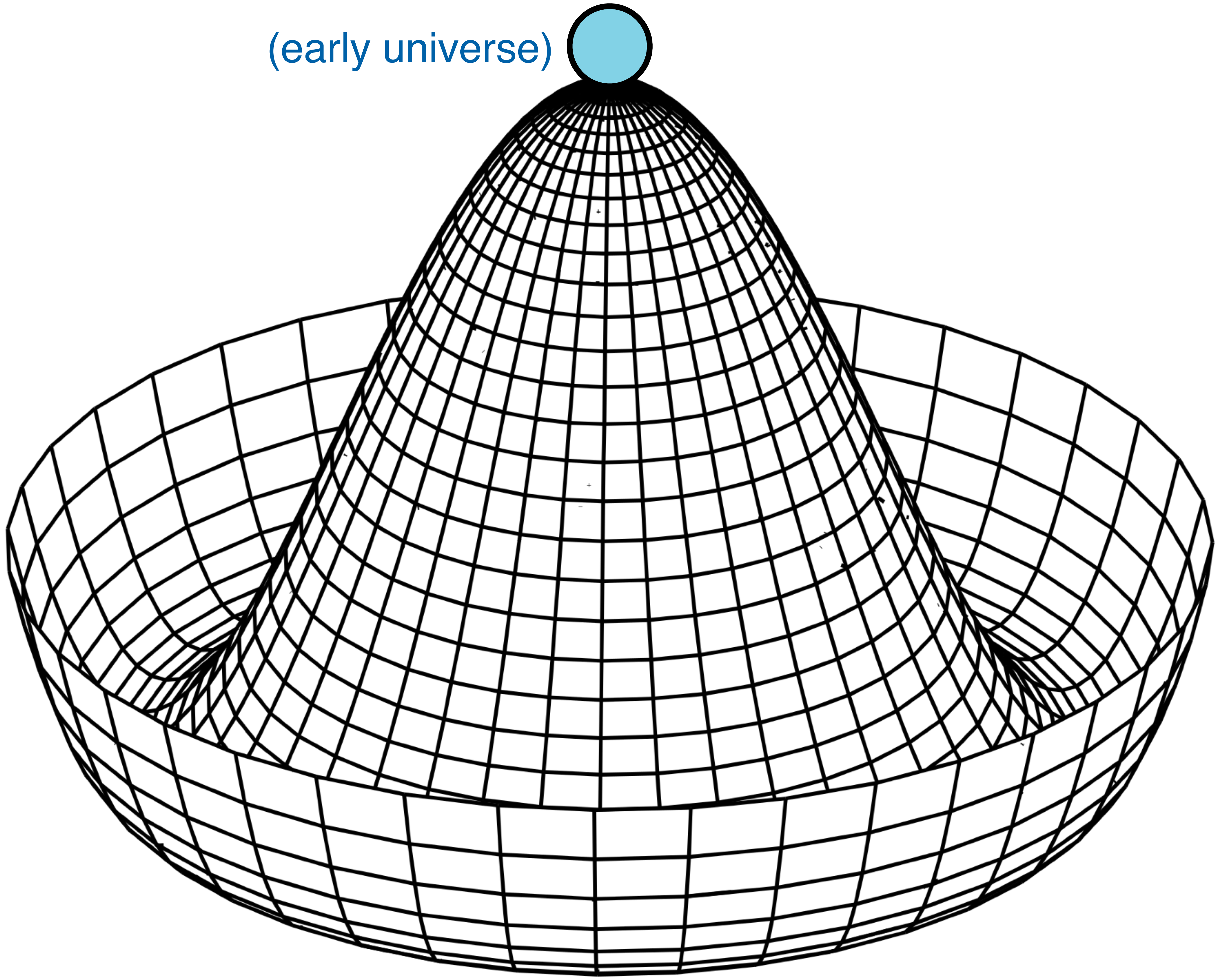

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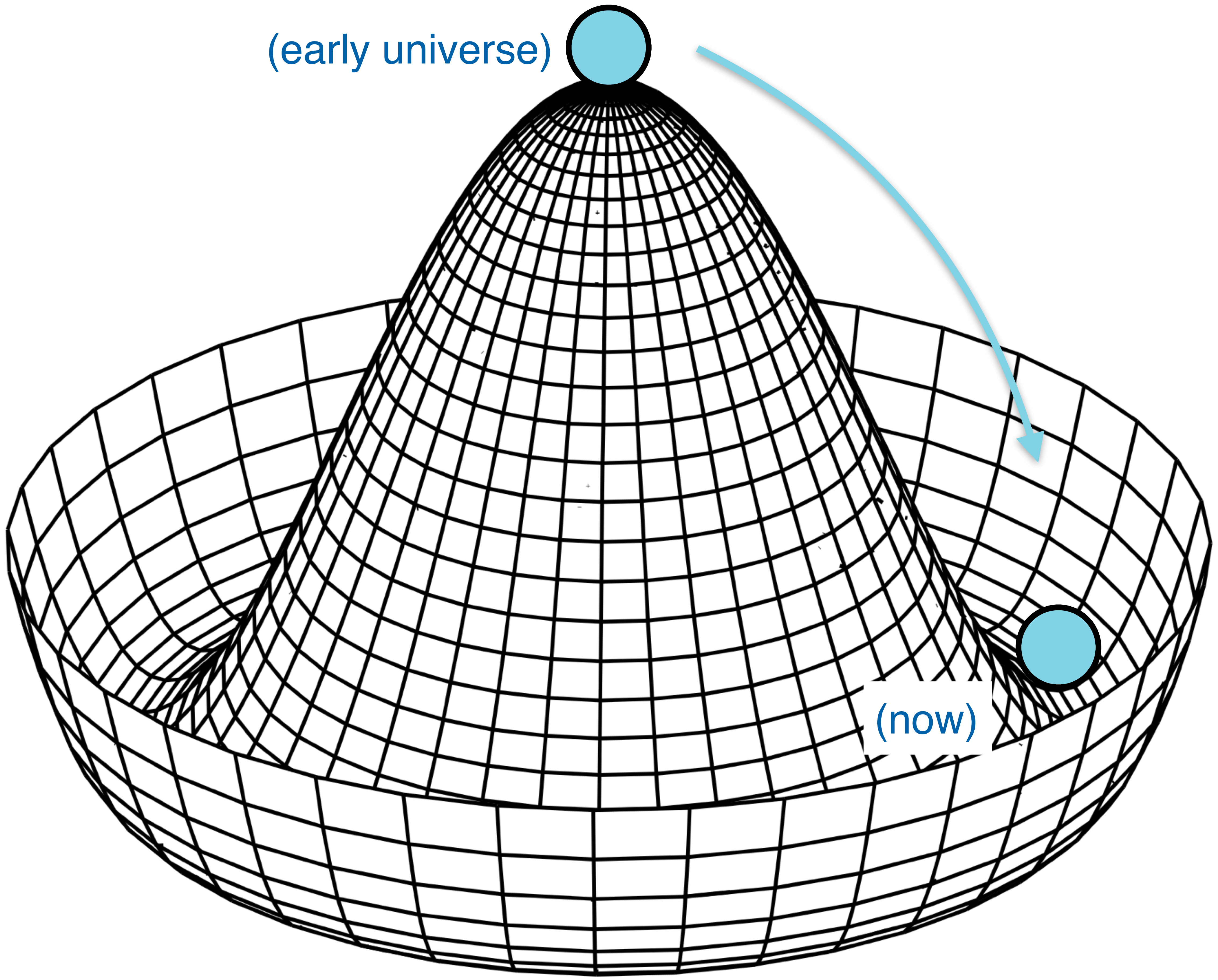

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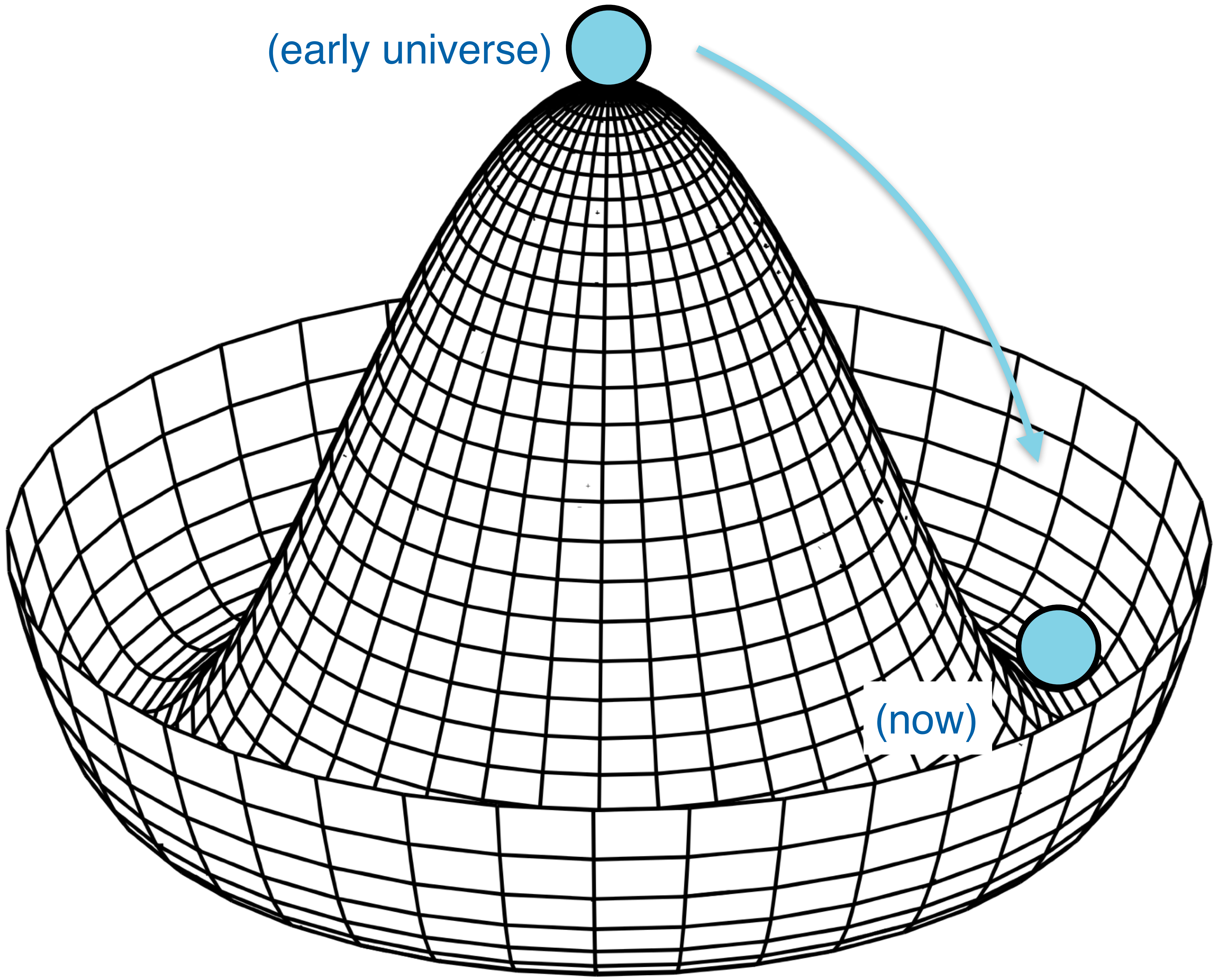

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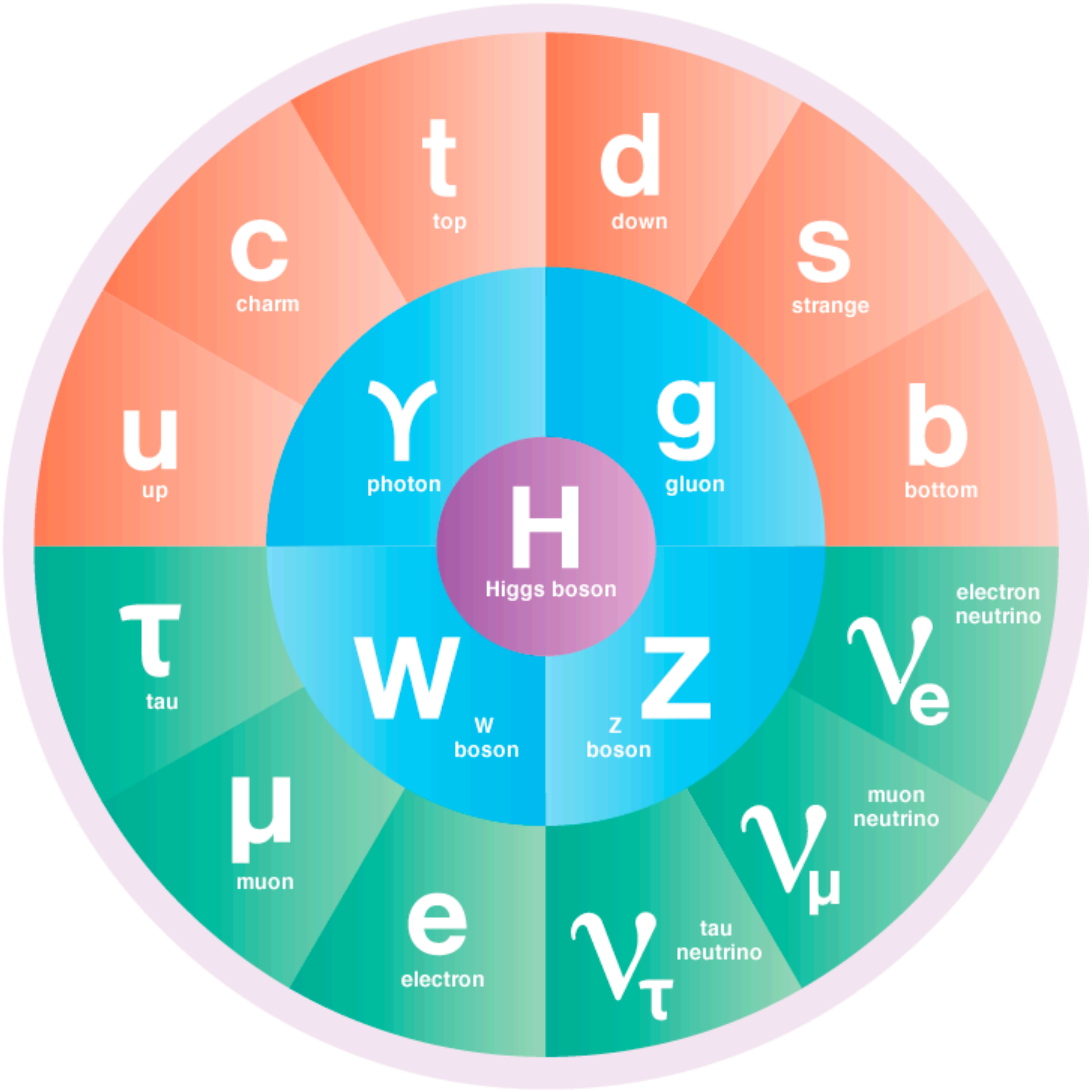
- This new minimum *spontaneously breaks* the **SU(2) x U(1)** symmetry, resulting in things like massive particles, massive gauge bosons, and the resulting “low energy” behavior we see today.

With the Discovery of the Higgs Boson in 2012,

- The "Standard Model" has been completed.



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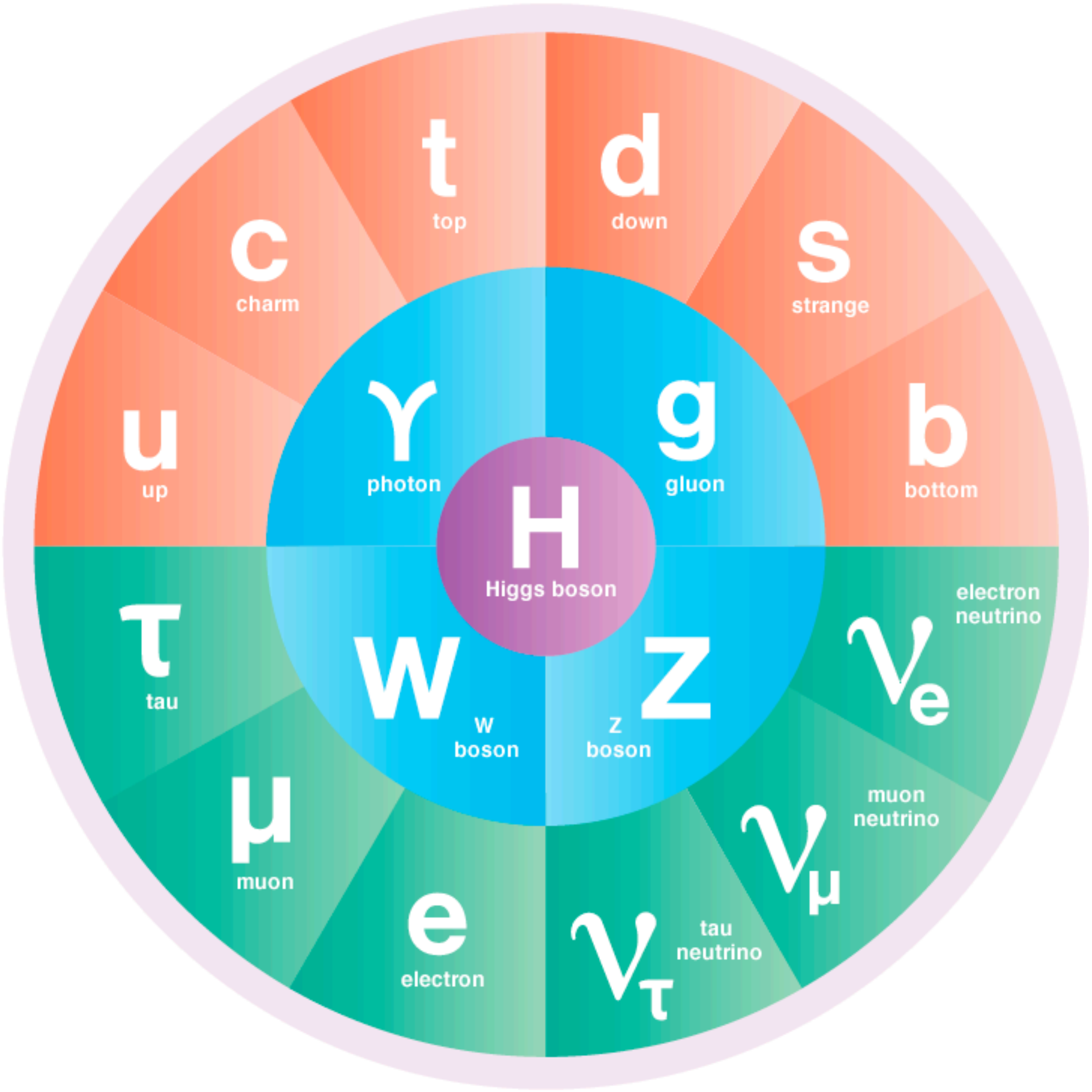

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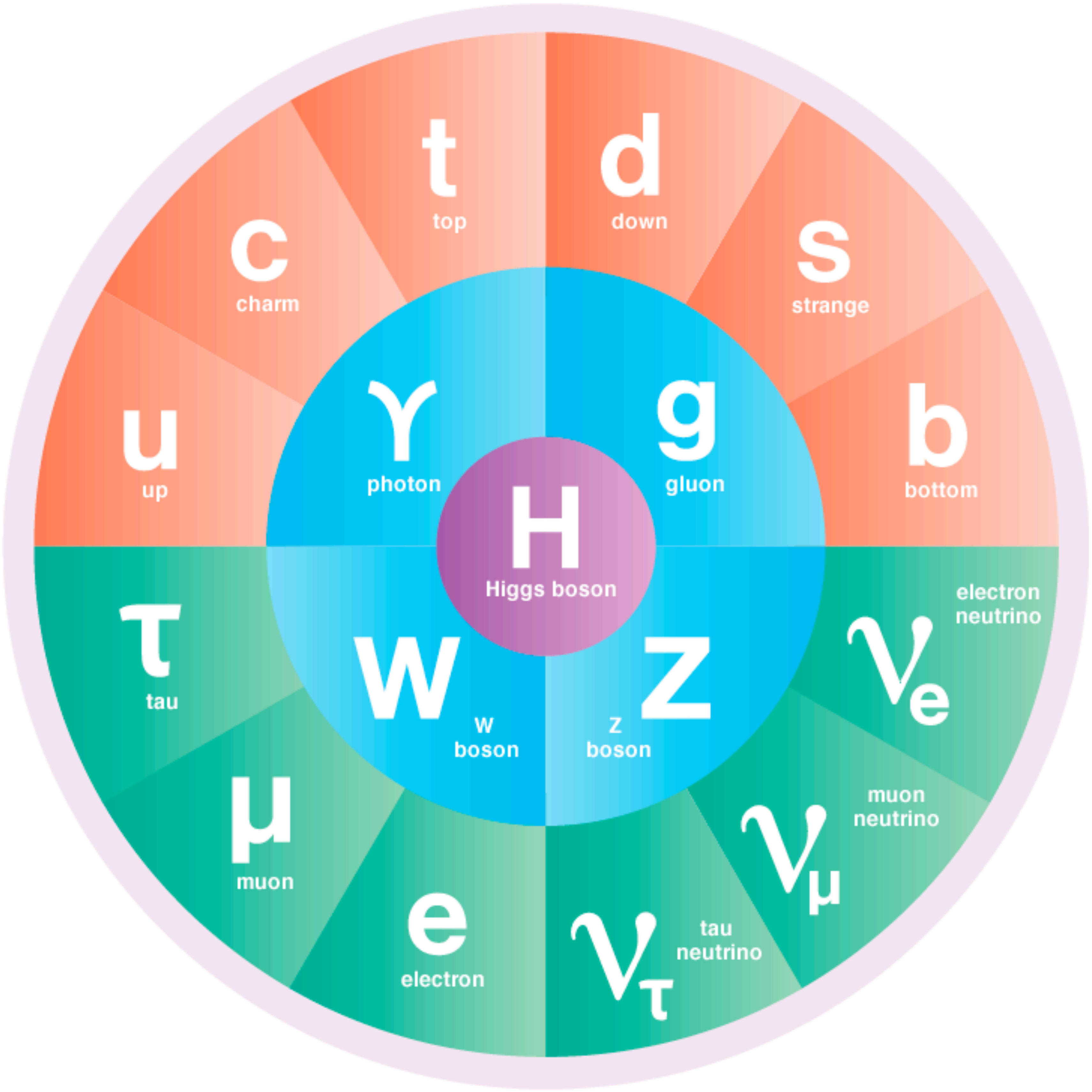

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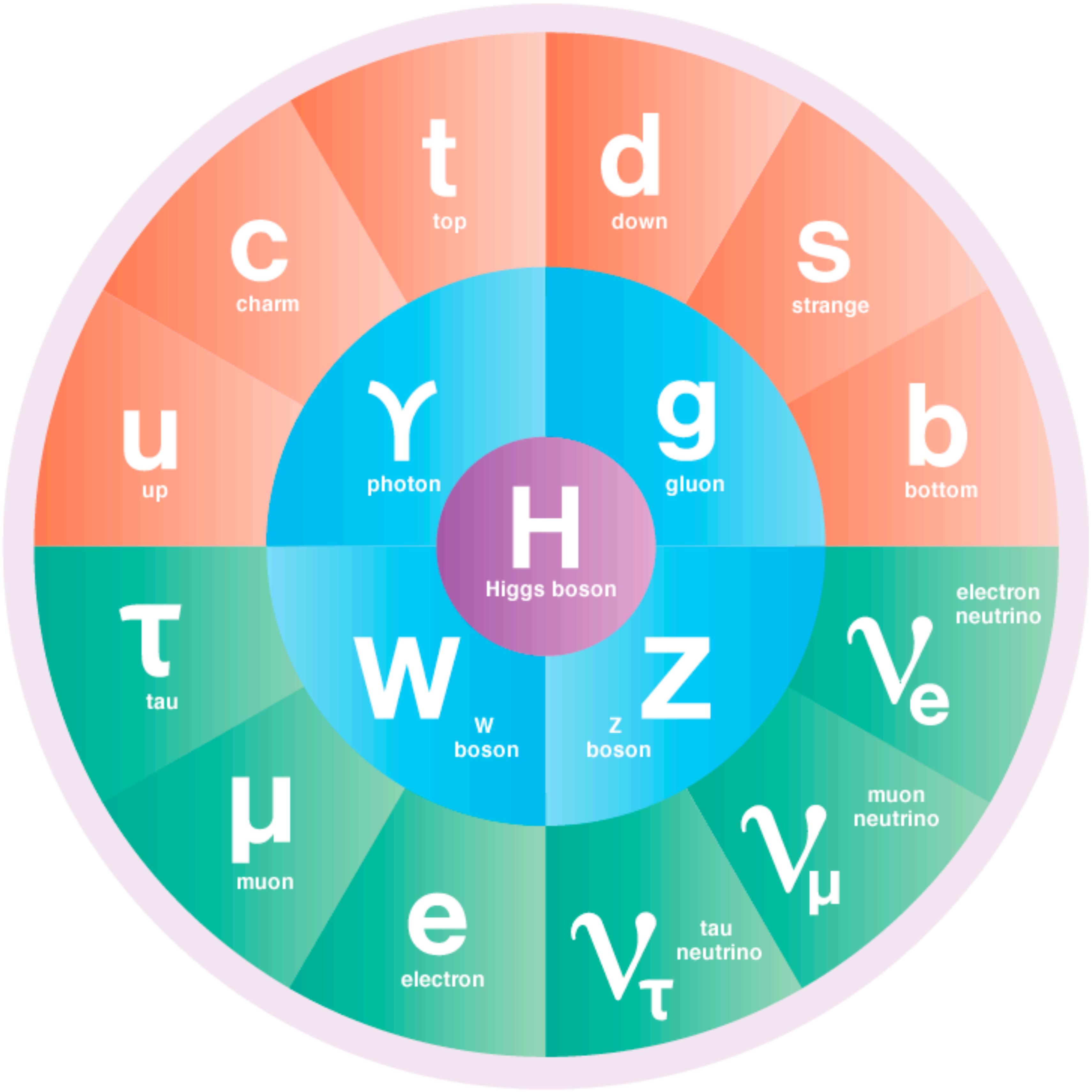

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- Force carriers are the gluons (color, interact with quarks), photons (electromagnetism, interact with charged particles), and weak bosons (weak force, interact with all fermions).

Completing the Standard Model was a HUGE triumph.

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However, there are some problems…

Three Current Challenges (if time allows)

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- Dark Matter & Dark Energy

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- Neutrino Oscillations and Neutrino Masses

- The Higgs Hierarchy Problem

Dark Matter & Dark Energy

Tuesday, 2 June

12:00 PM → 1:00 PM **Cosmology: Dark Matter and Dark Energy** 1h

Speaker: Dan Hooper (Fermilab)

Overwhelming Evidence for Dark Matter over Many Scales

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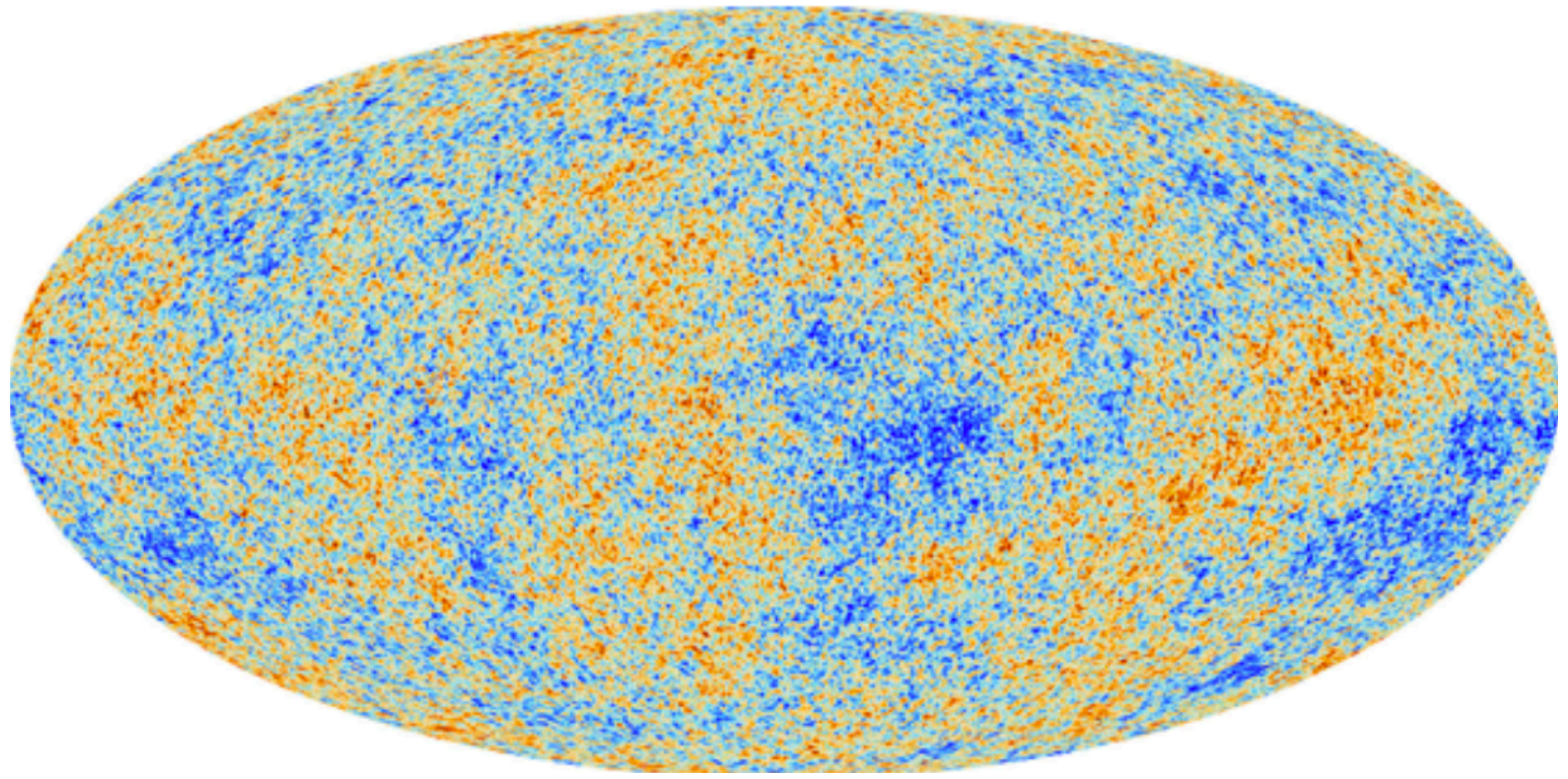

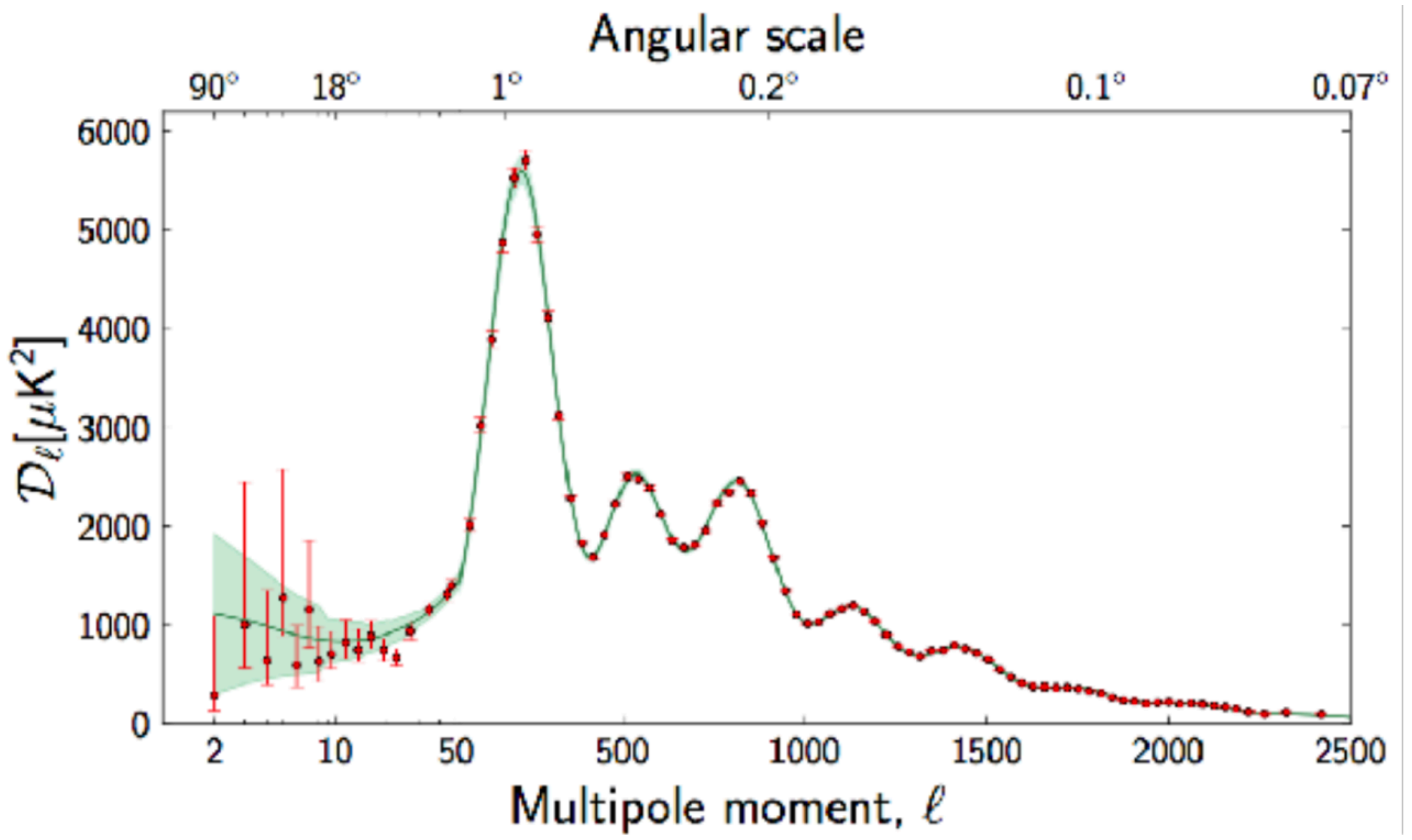

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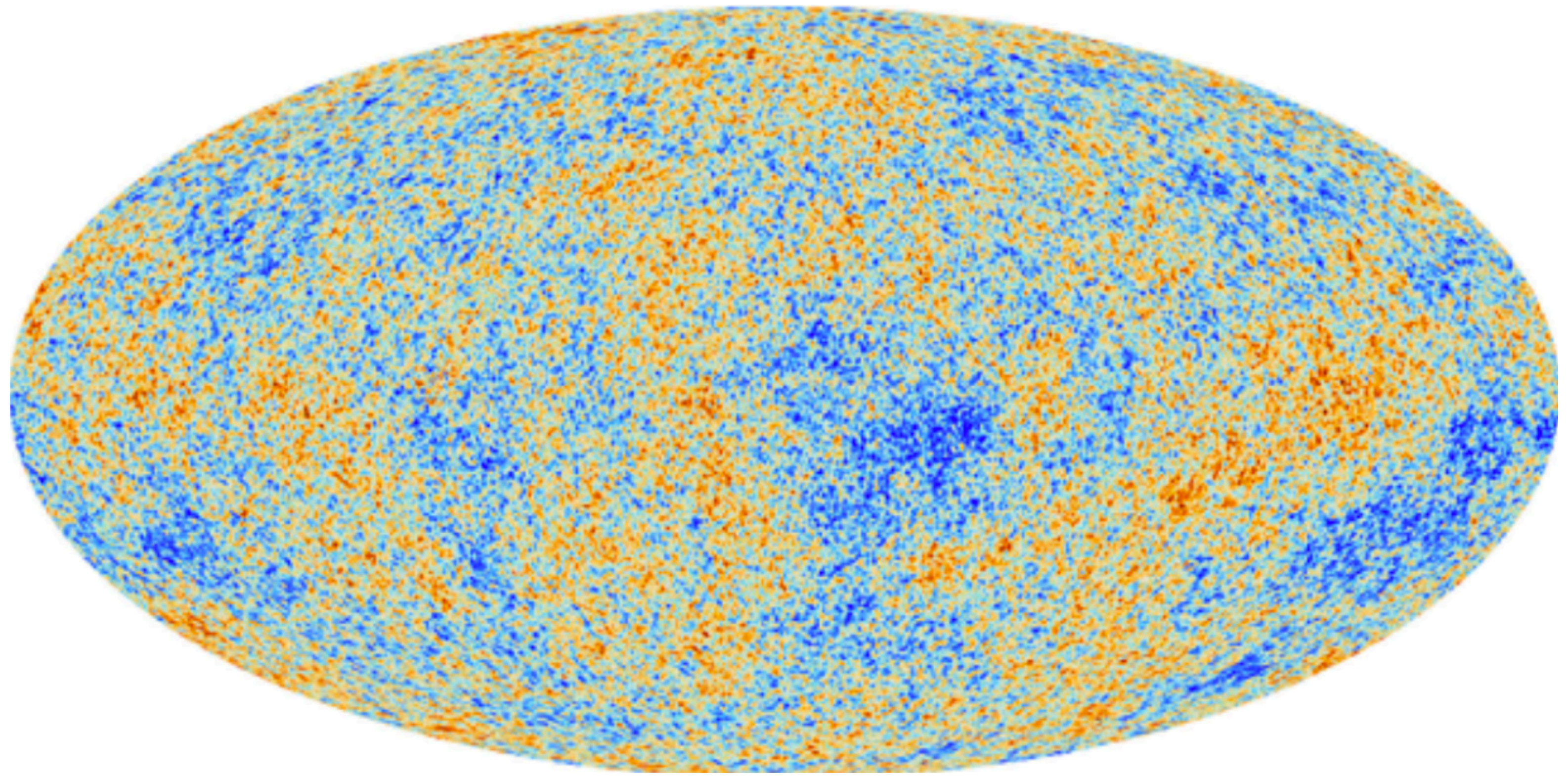

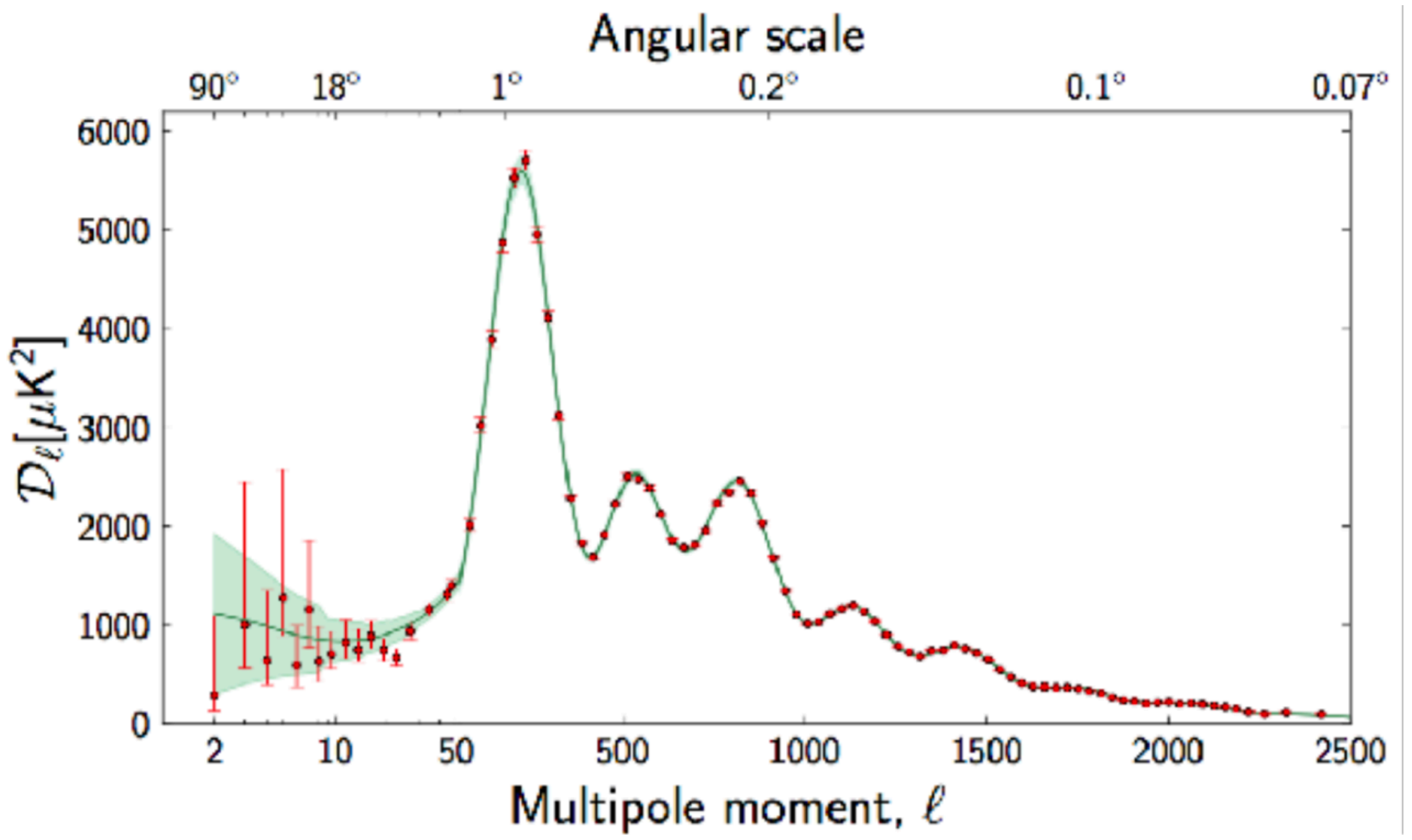

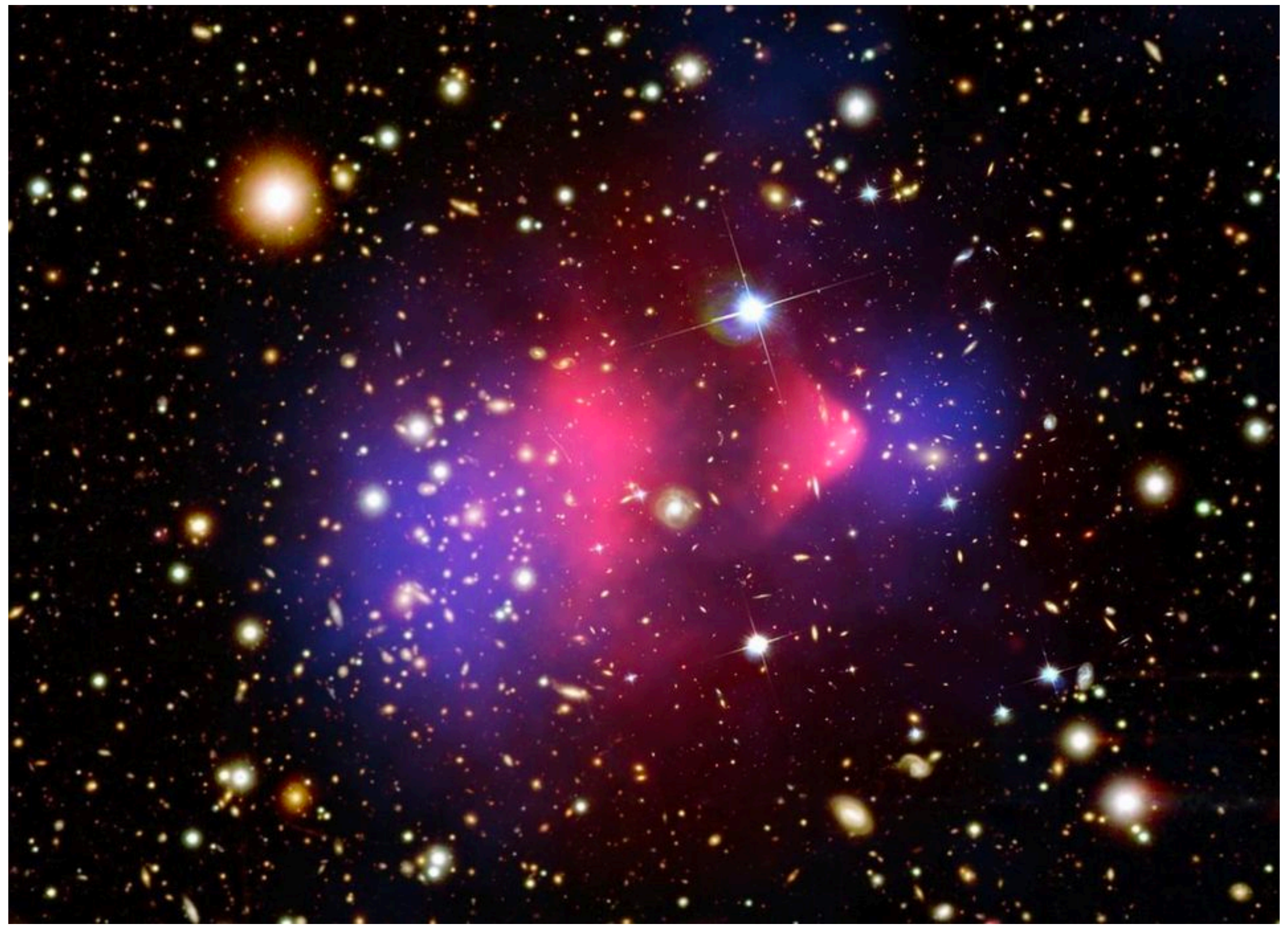

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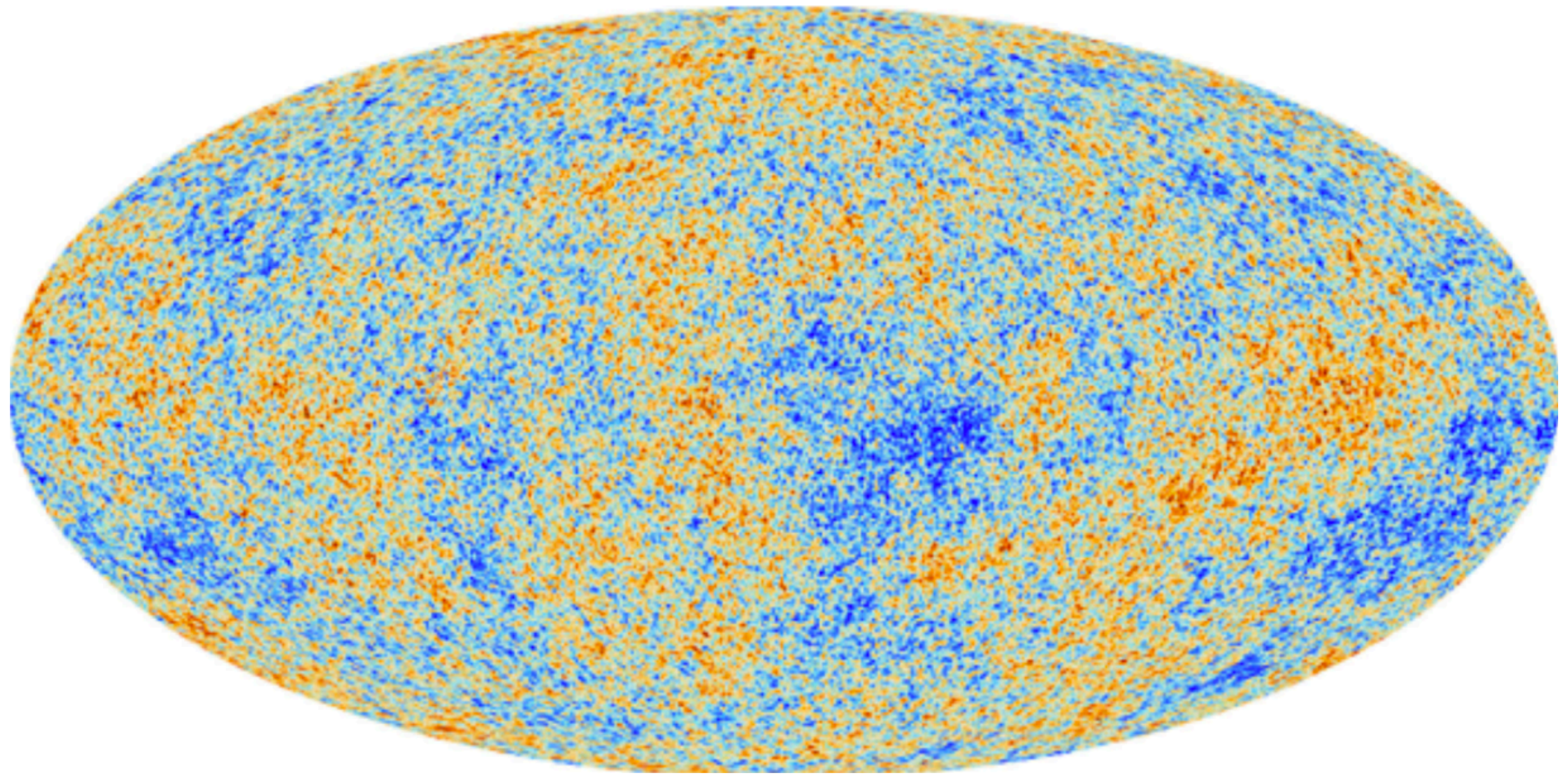

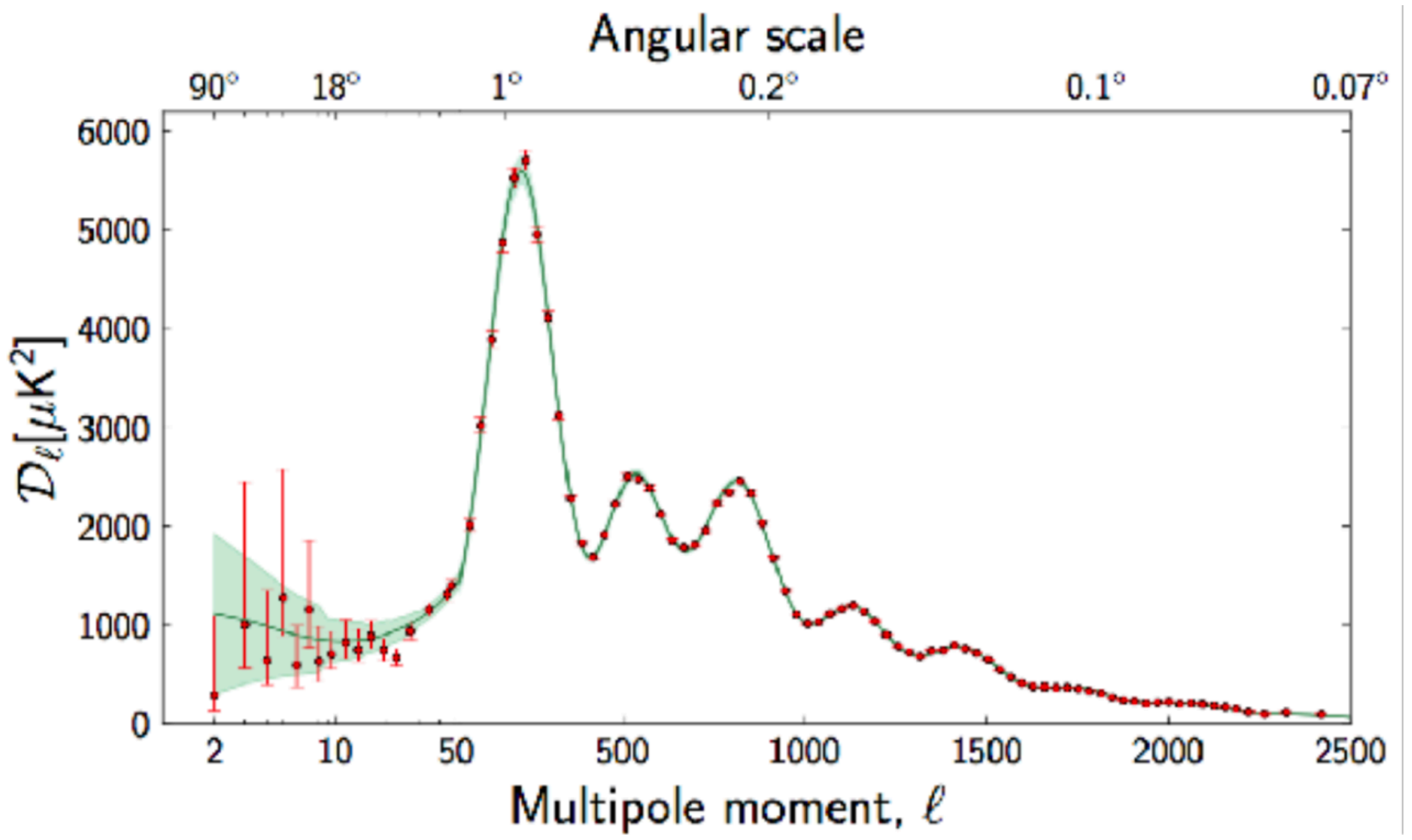

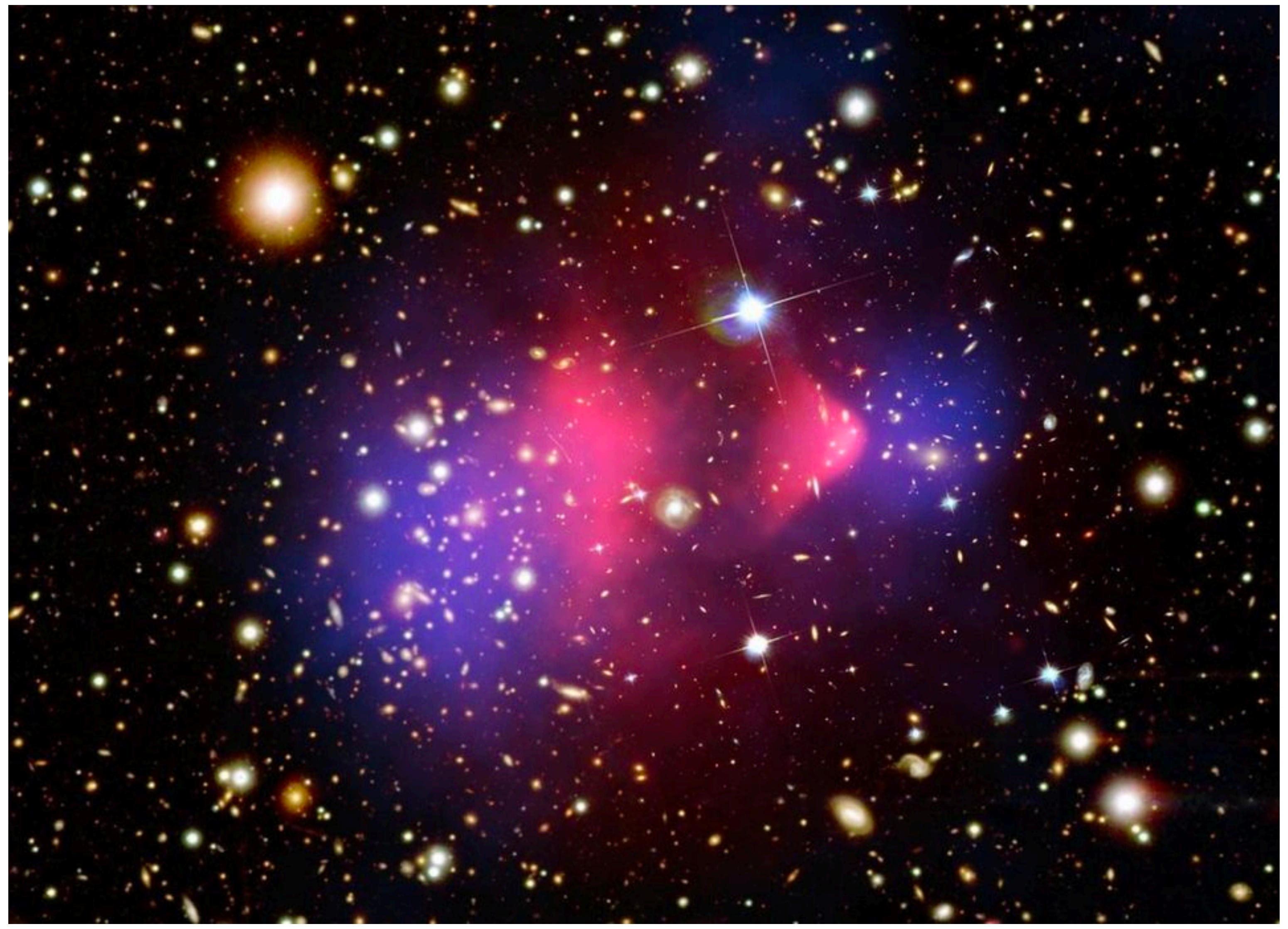

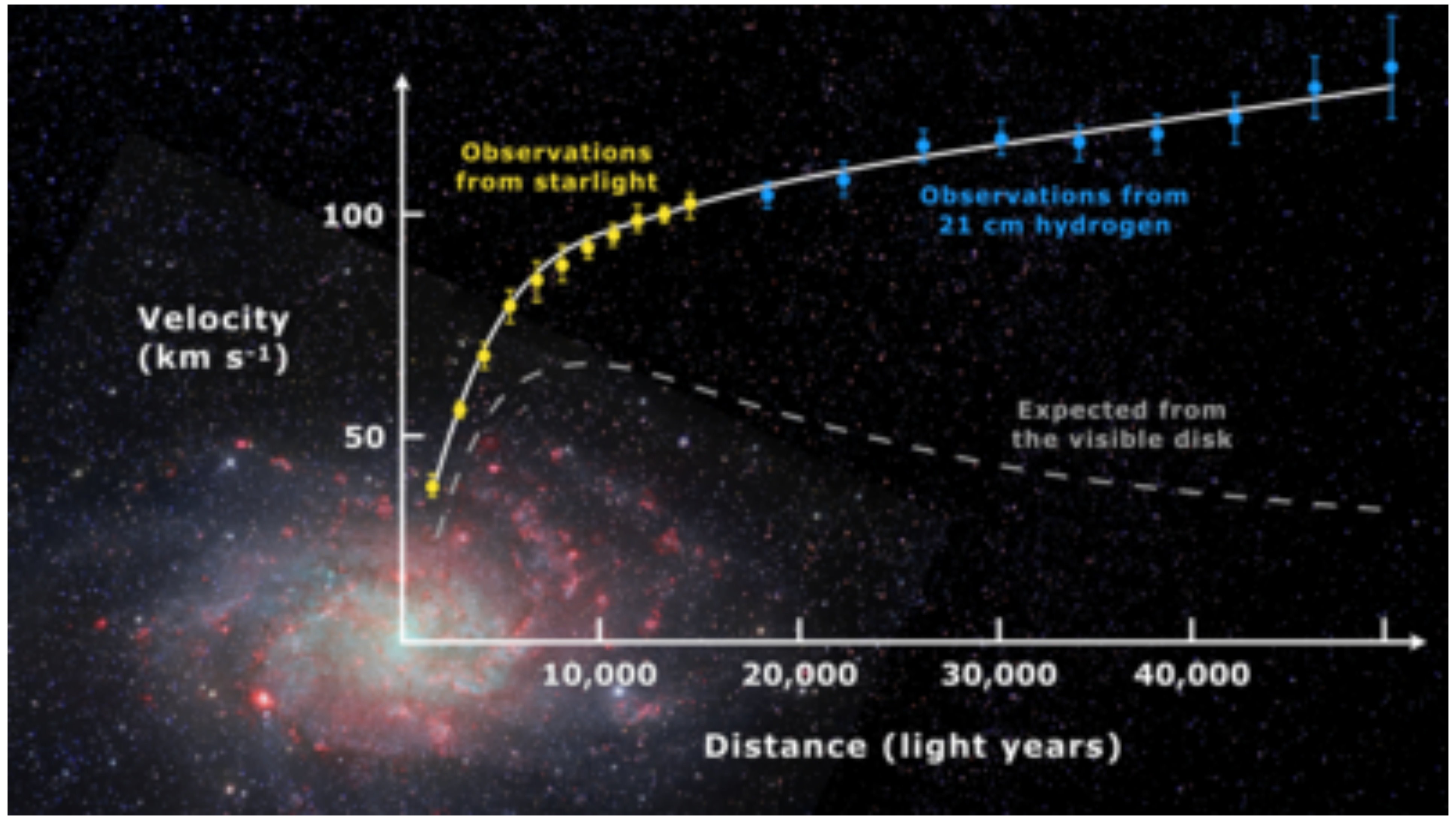

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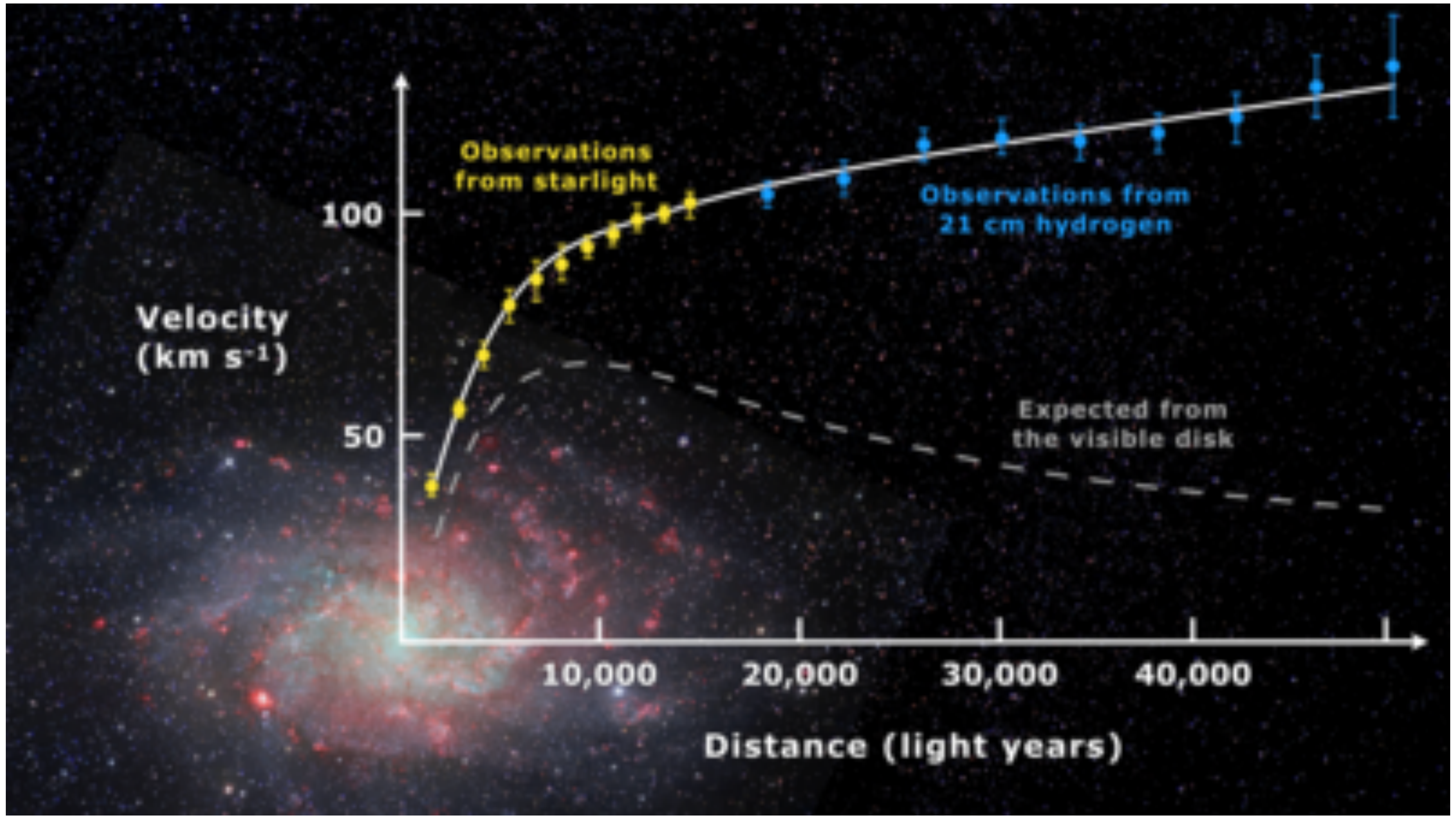

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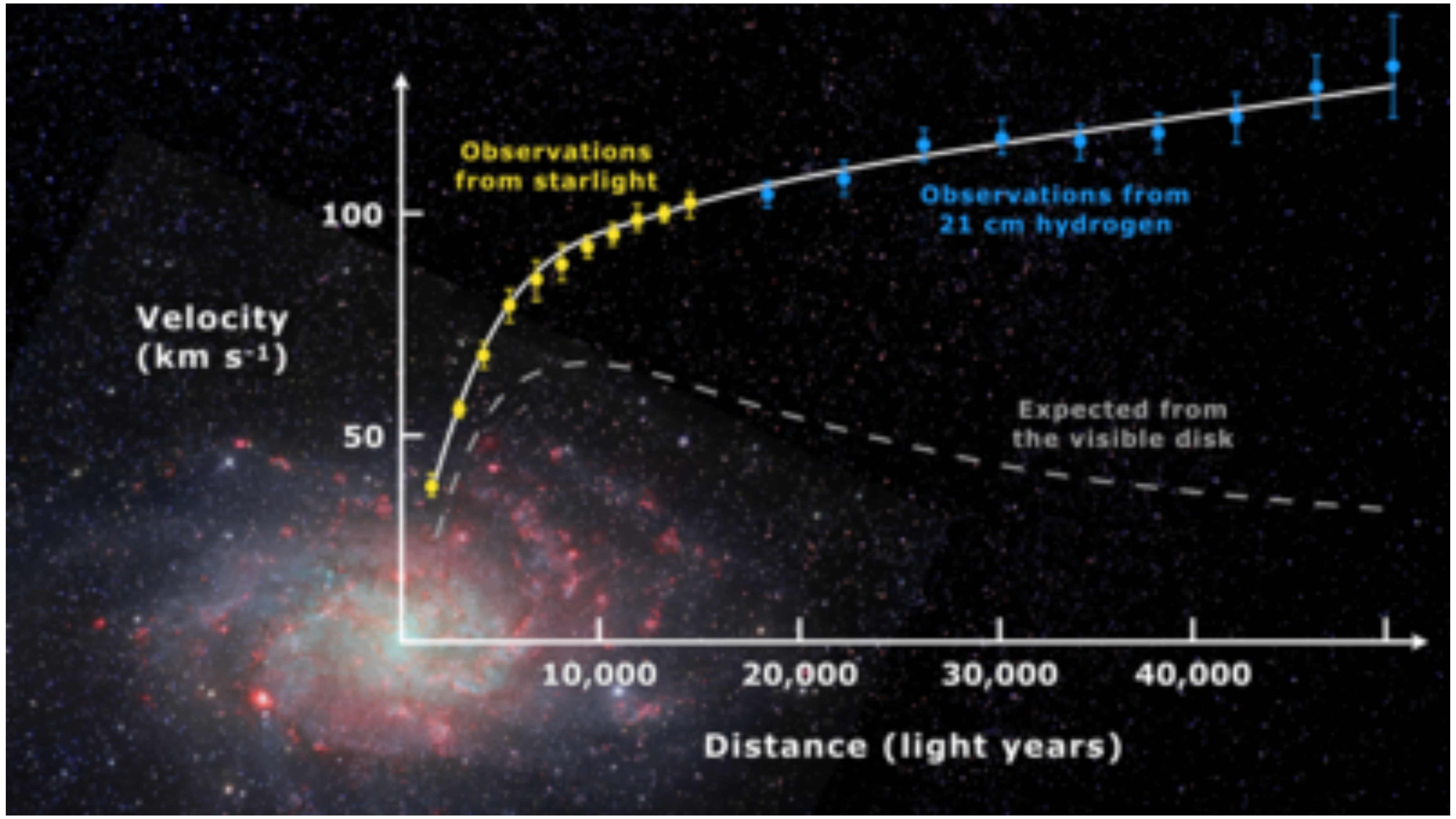

- Galactic rotation curves: one of the first pieces of evidence for dark matter.

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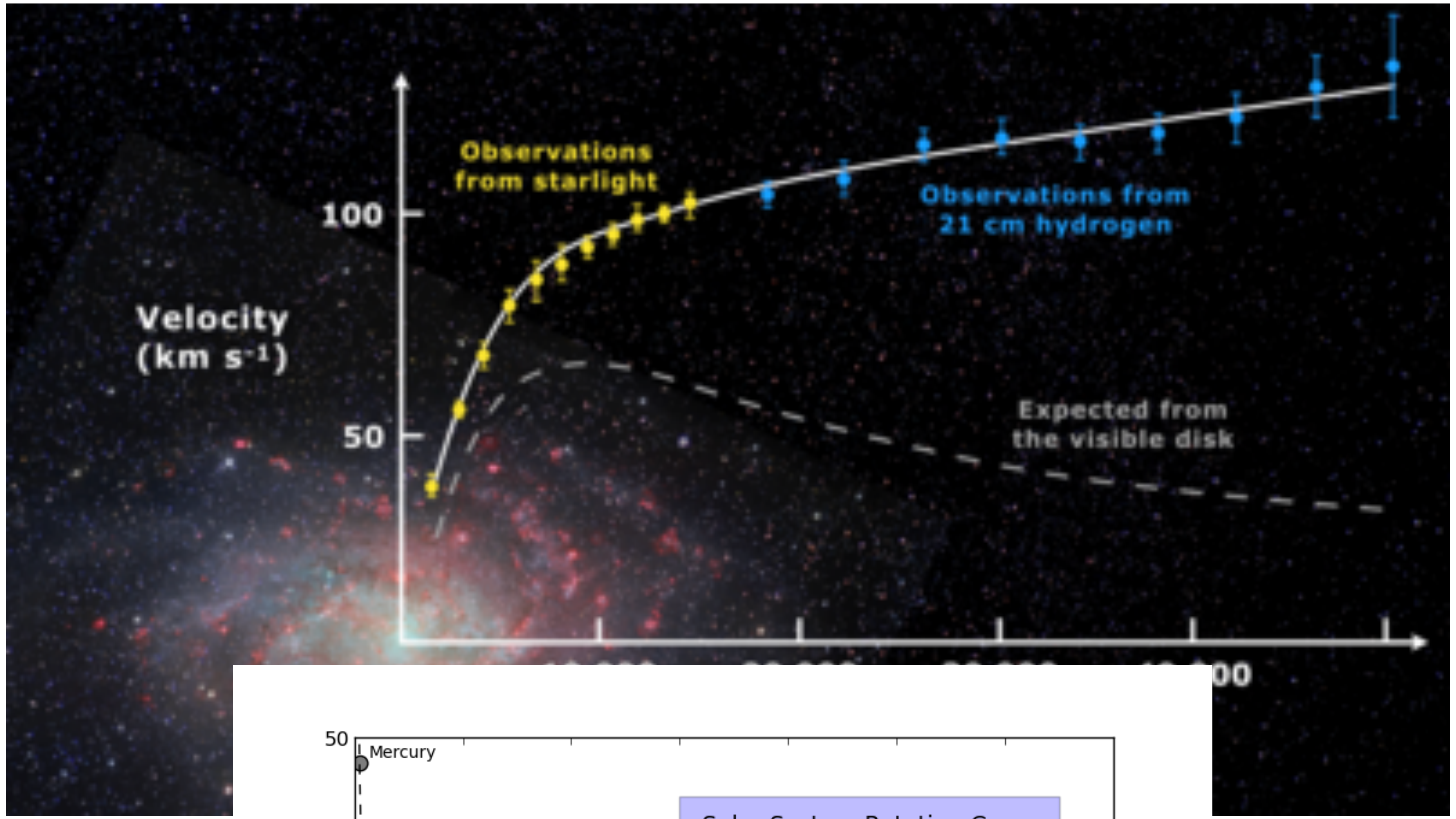

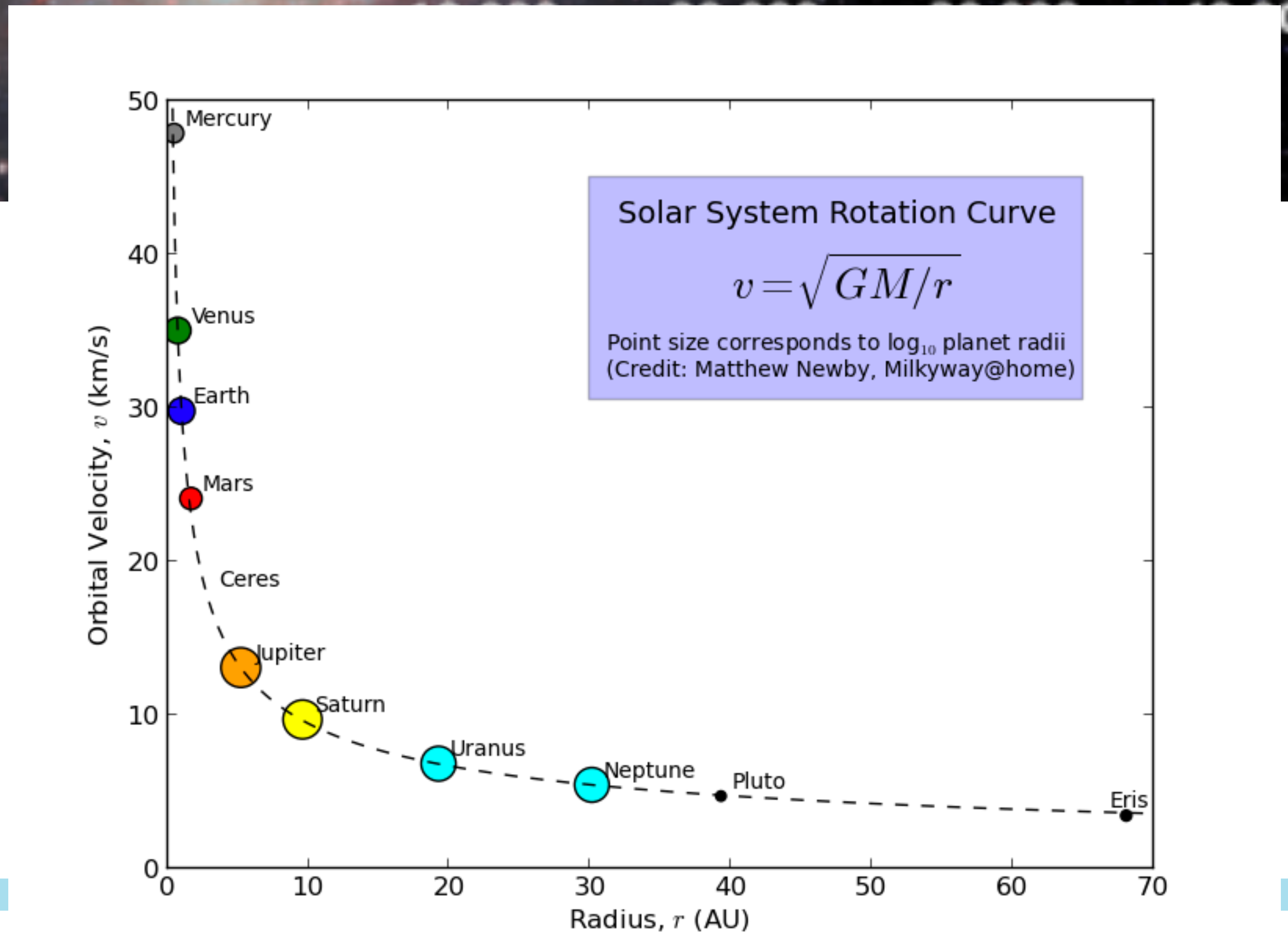

- Galactic rotation curves: one of the first pieces of evidence for dark matter.
- Using Newtonian physics/Kepler's laws, we can calculate what the rotational velocity of a star orbiting the center of its galaxy should be.

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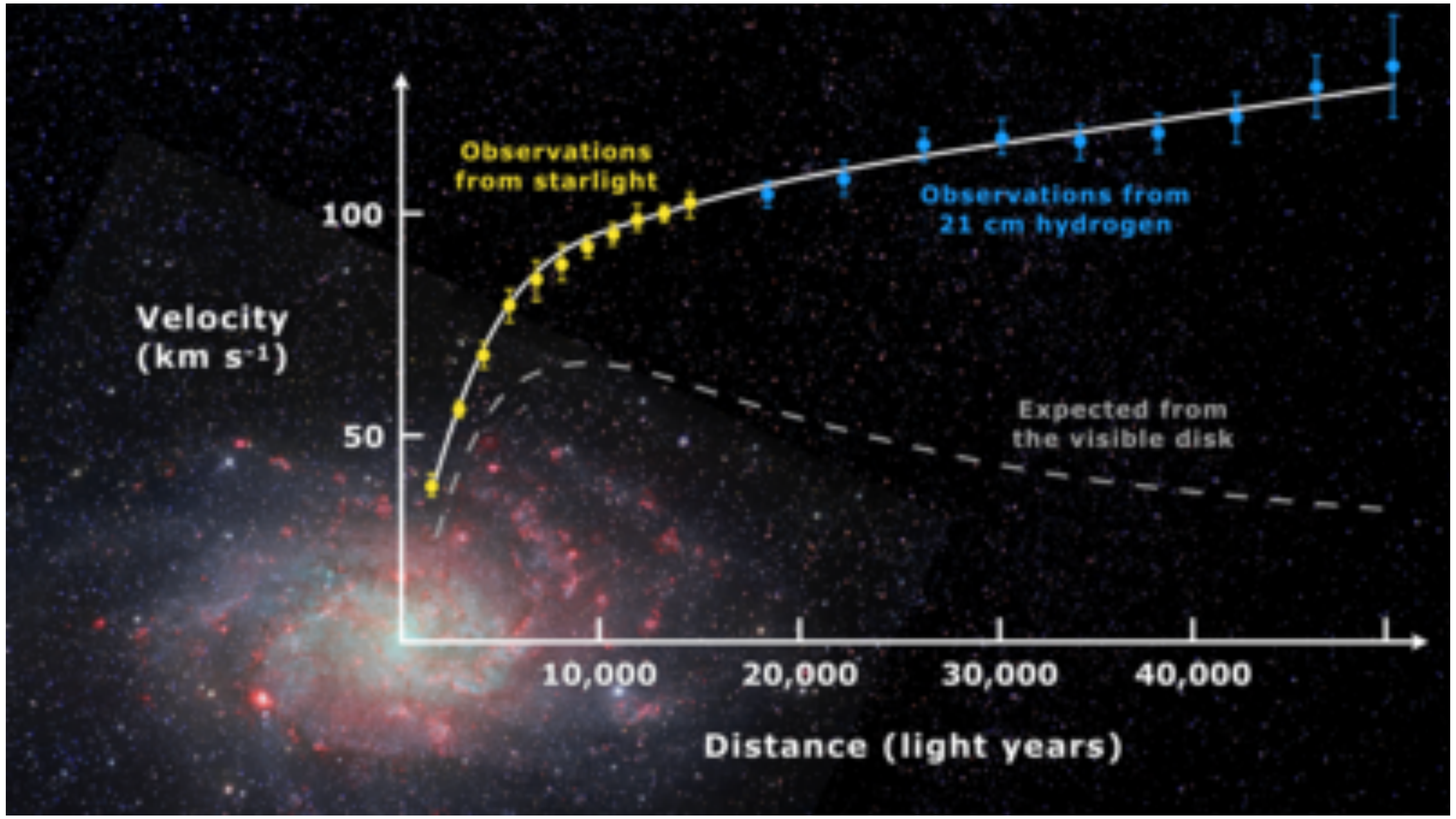
Overwhelming Evidence for Dark Matter over Many Scales



- Galactic rotation curves: one of the first pieces of evidence for dark matter.
- Using Newtonian physics/Kepler's laws, we can calculate what the rotational velocity of a star orbiting the center of its galaxy should be.
- Looking out at distant galaxies and their outermost stars, they seem to be going faster than they should.

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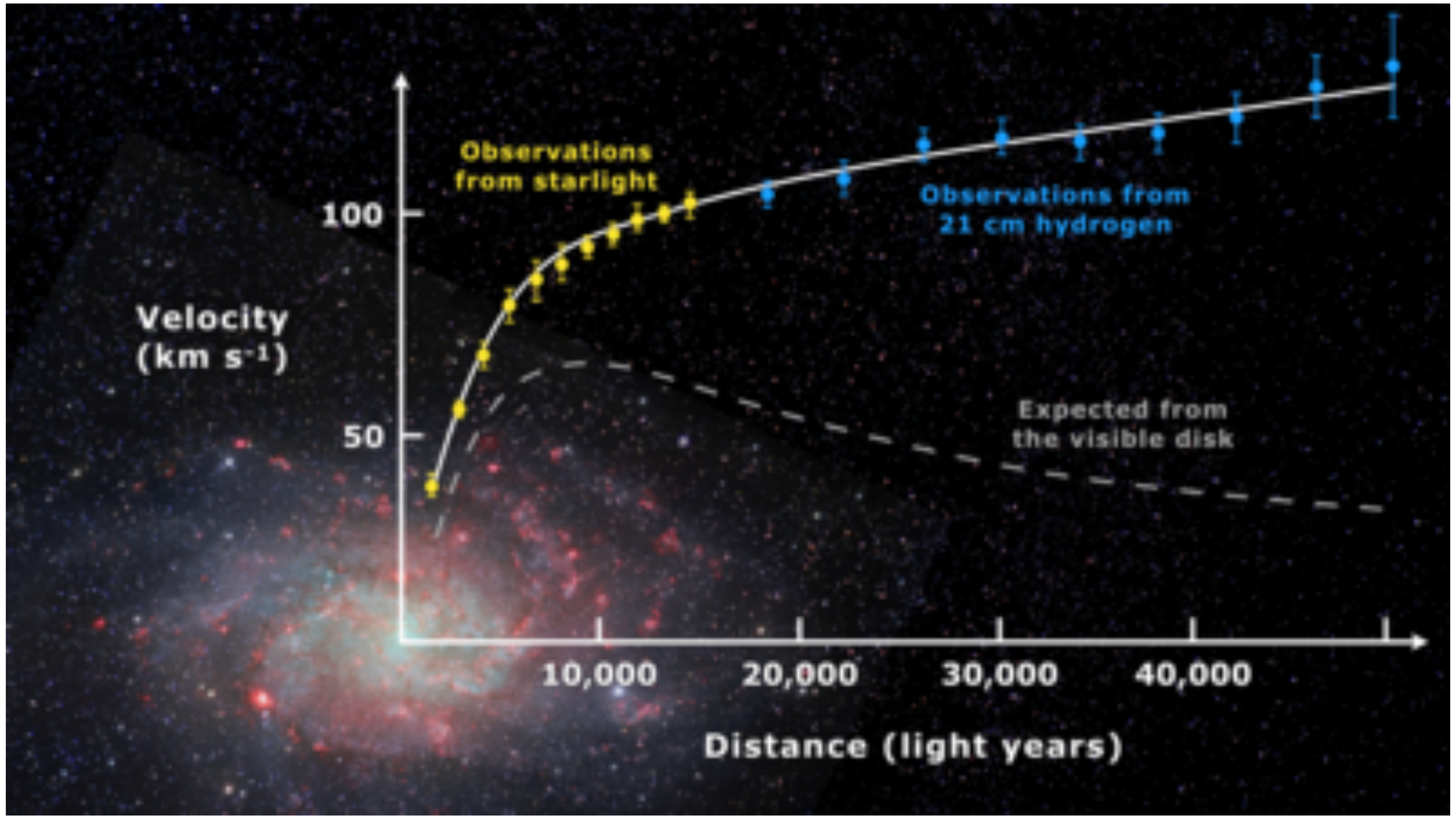

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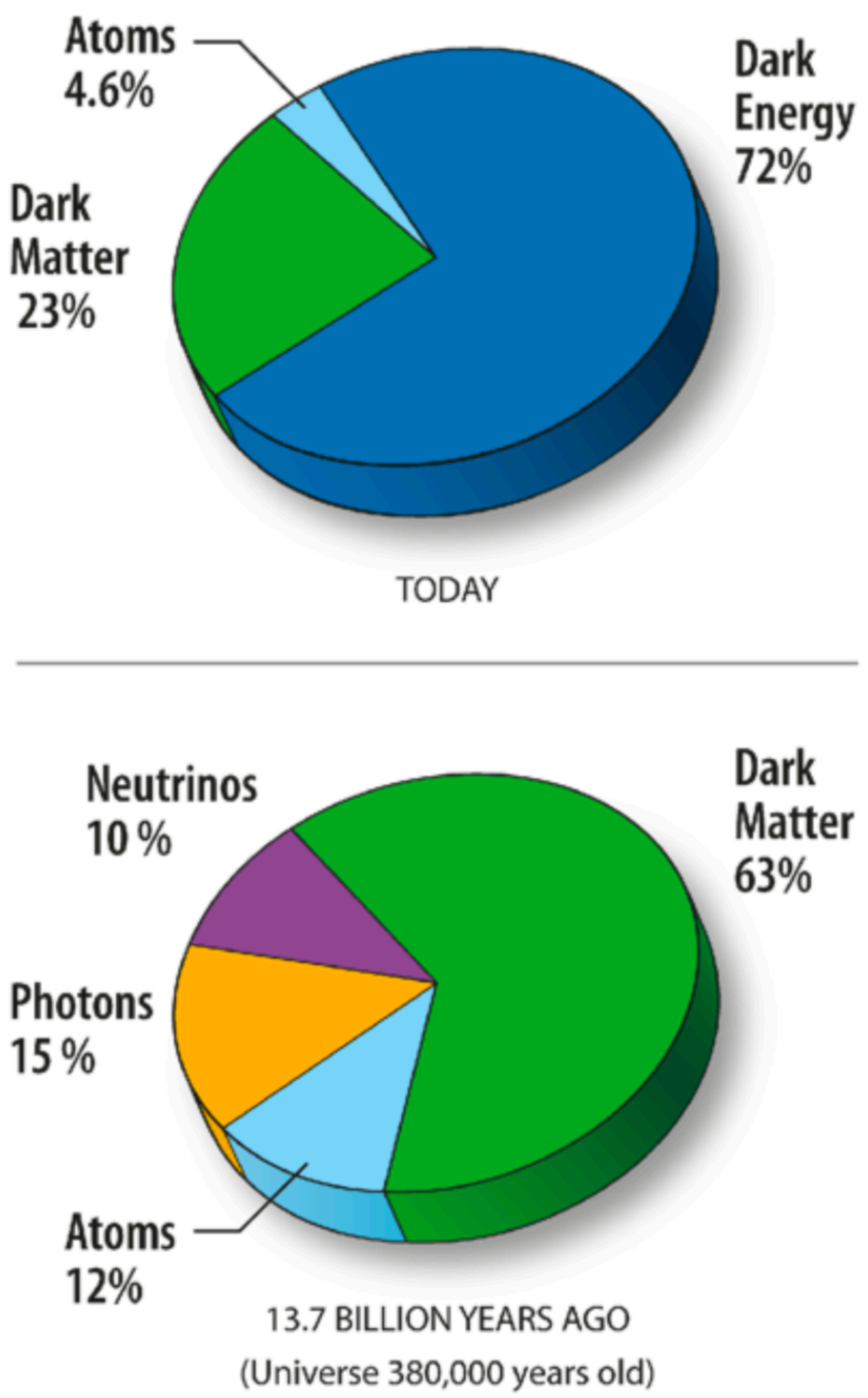
- Using Newtonian physics/Kepler's laws, we can calculate what the rotational velocity of a star orbiting the center of its galaxy should be.
- Looking out at distant galaxies and their outermost stars, they seem to be going faster than they should.
- This implies some sort of "missing" or "dark" matter that's pulling these stars around.

To the best of our knowledge from these observations,



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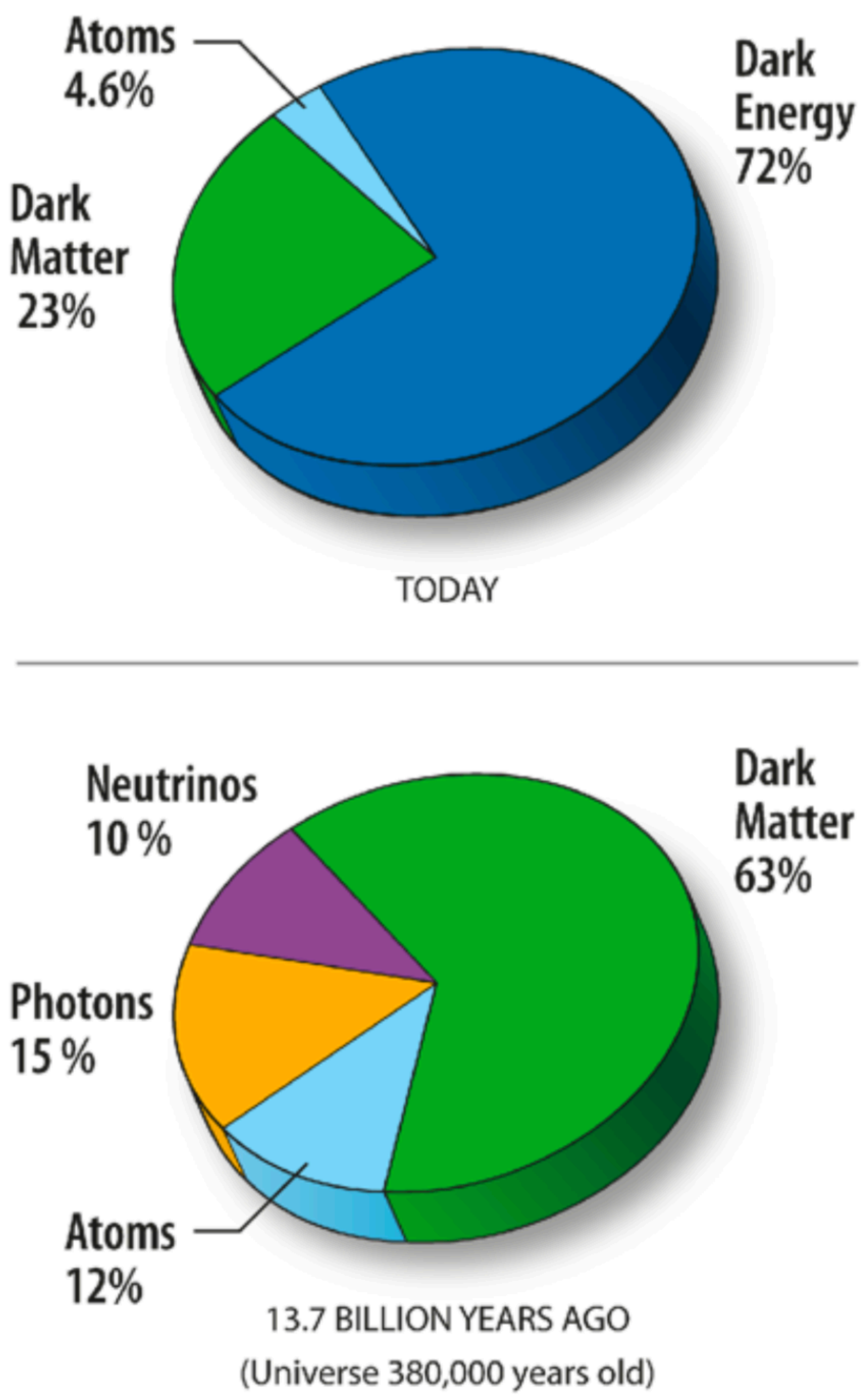

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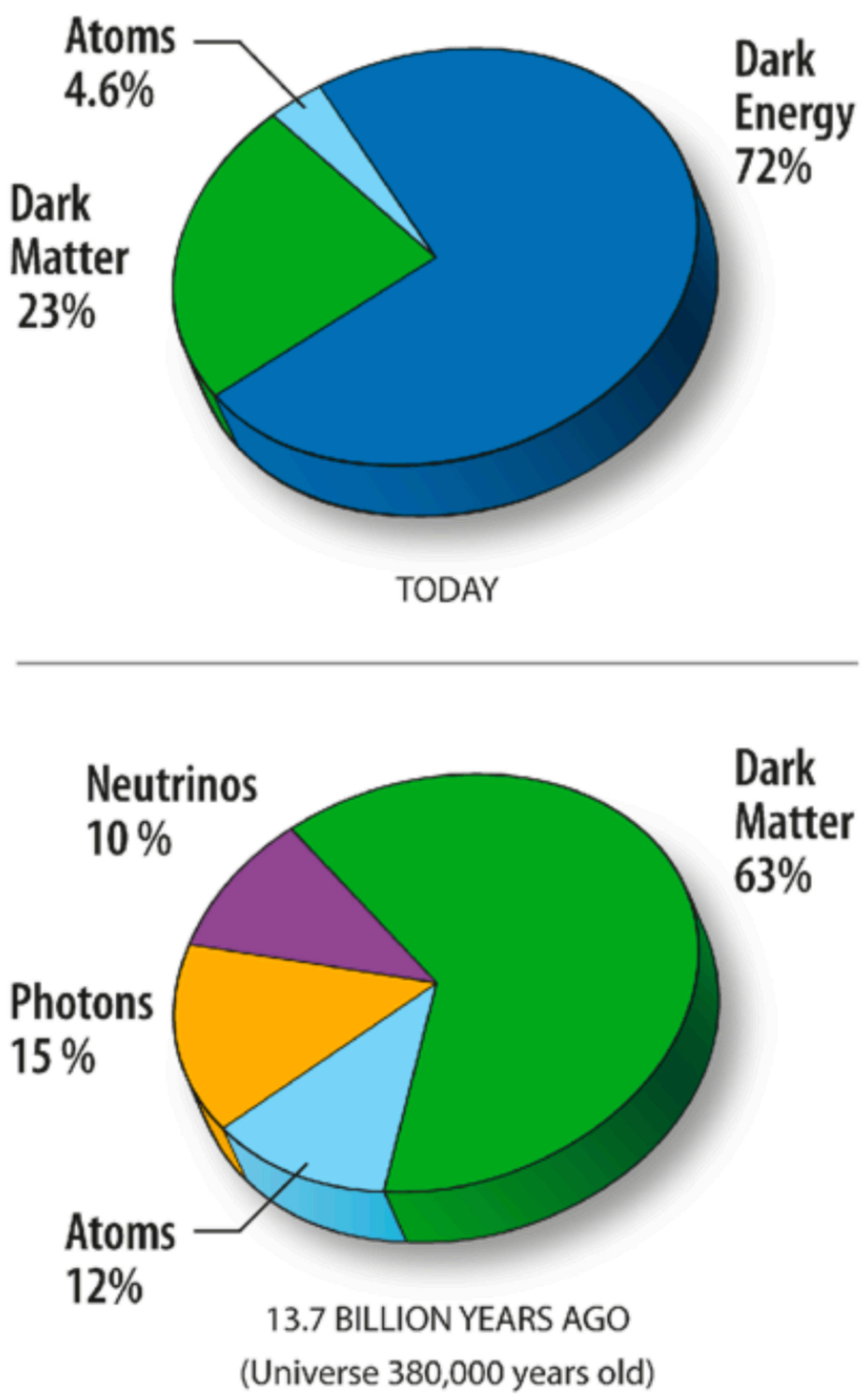

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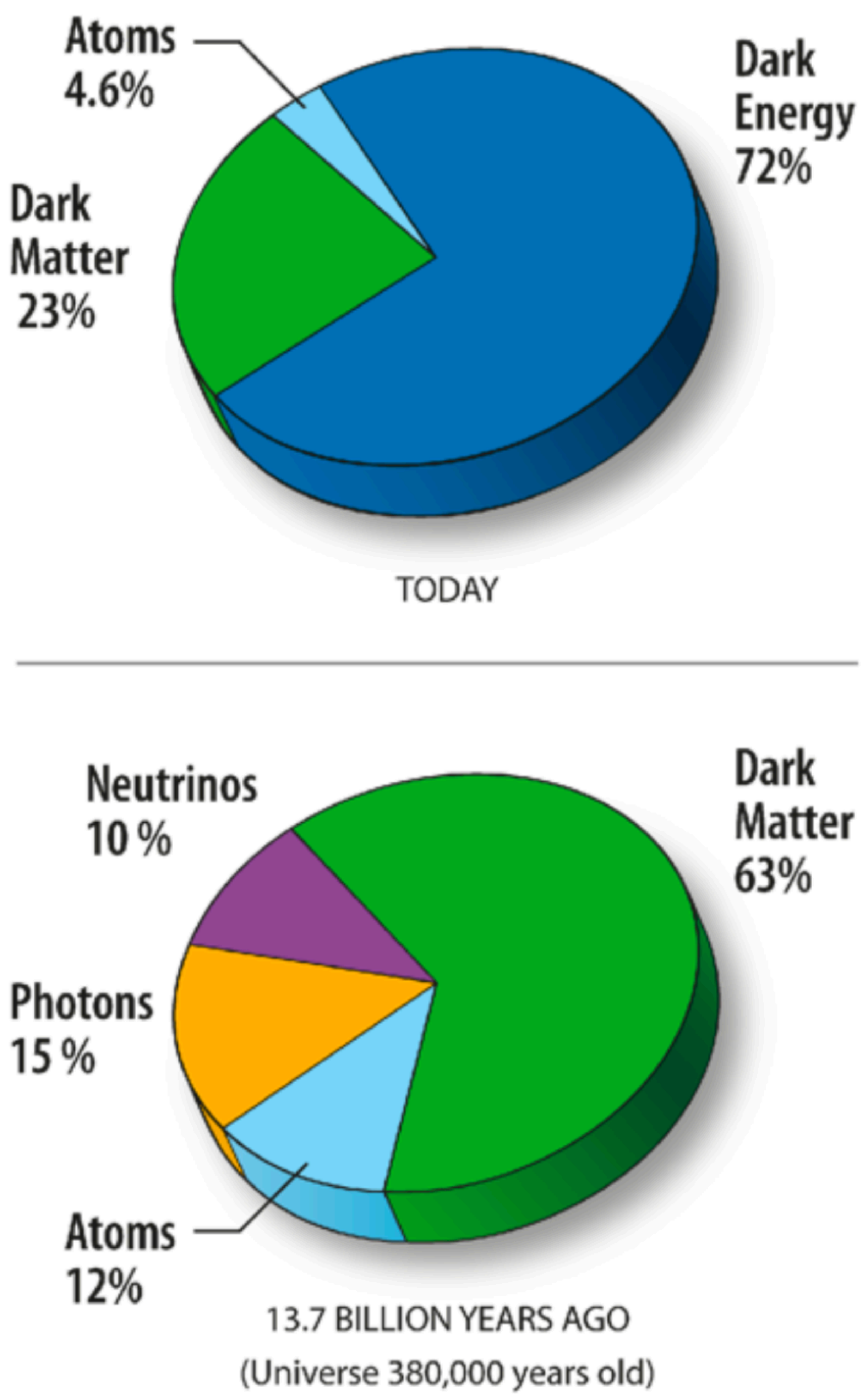

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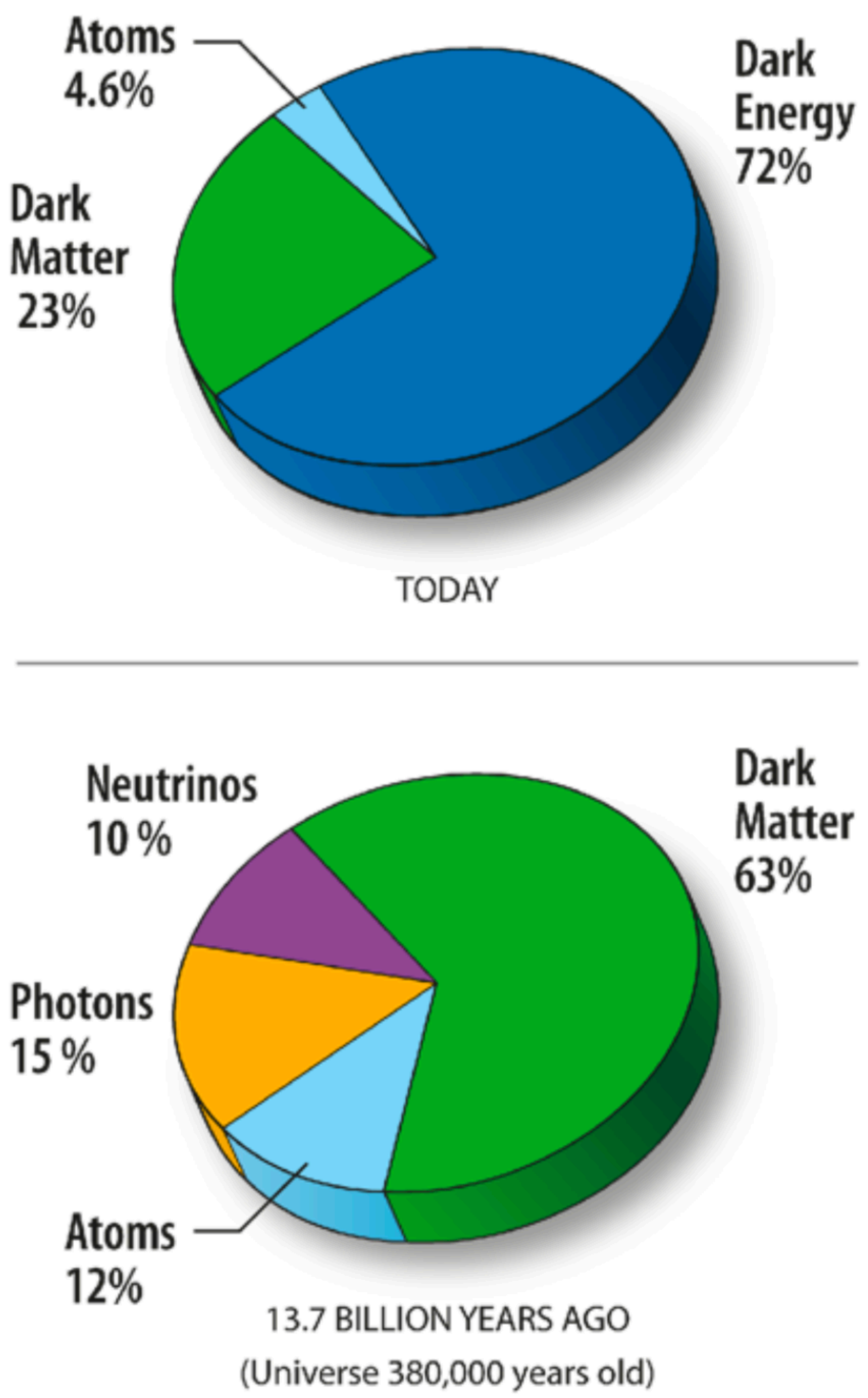

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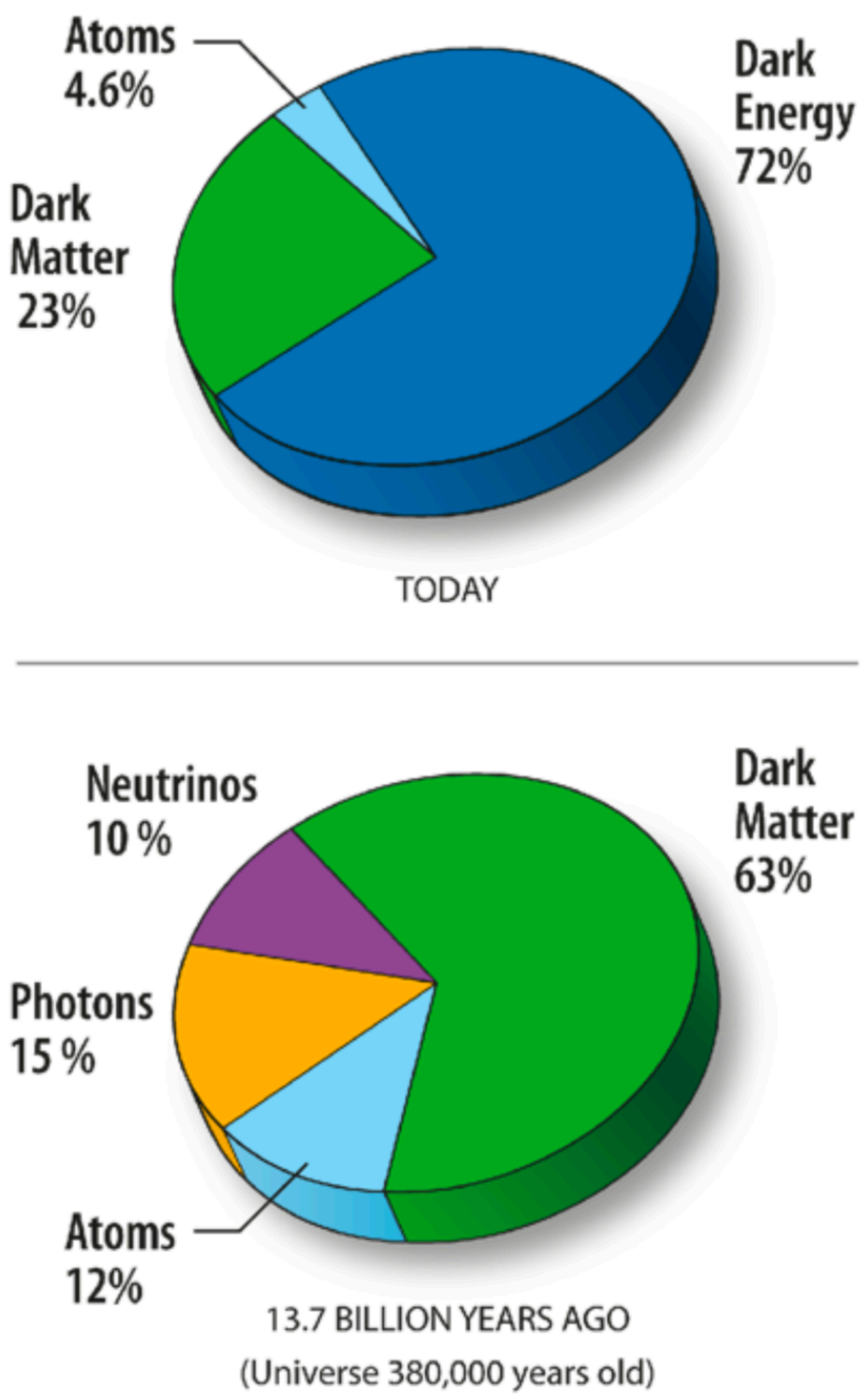

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- Worldwide efforts exist to identify and solve both of these mysteries.

Neutrino Oscillations & Neutrino Masses

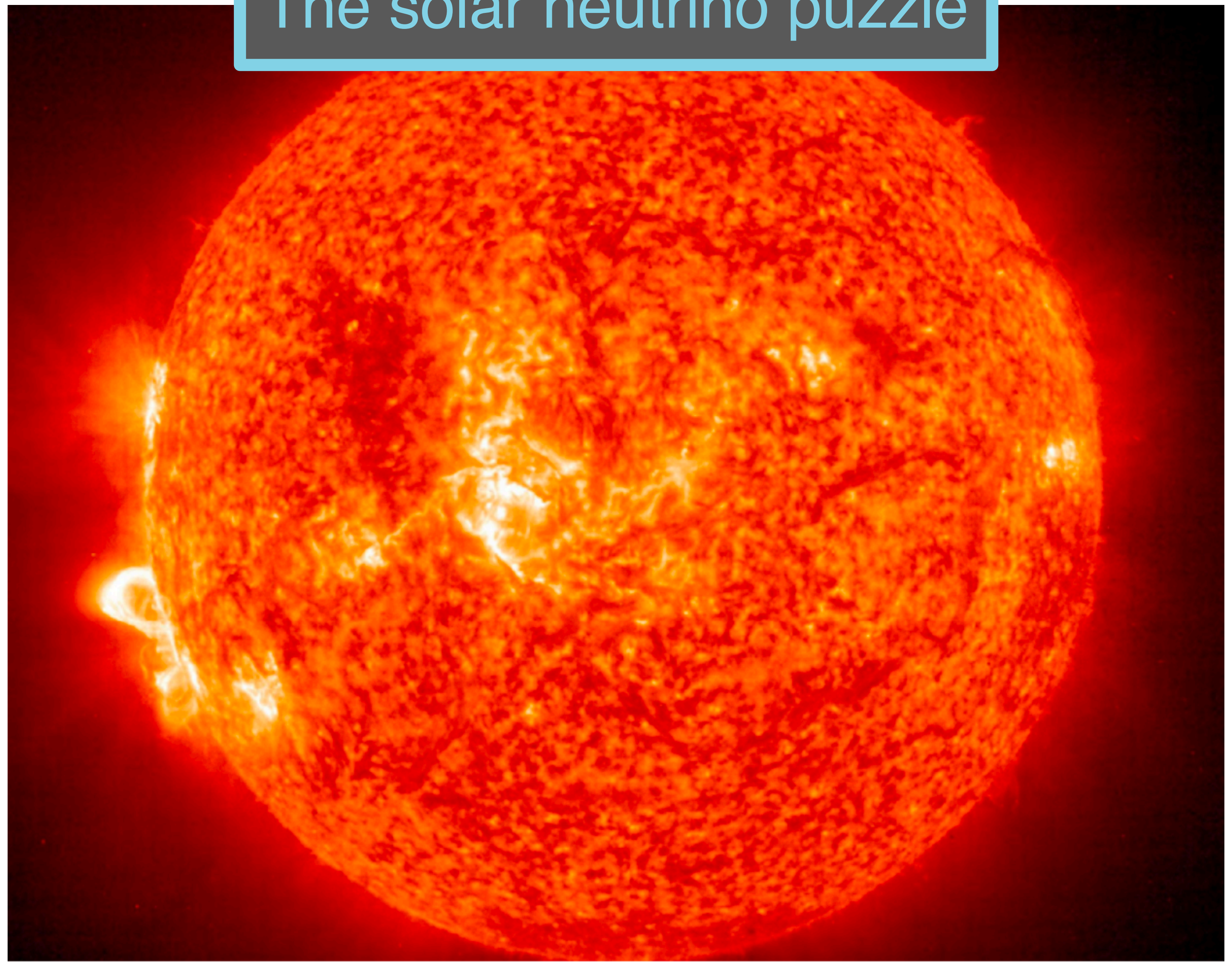
Thursday, 11 June

12:00 PM → 1:00 PM **Neutrino Physics** 1h

Speaker: Kirsty Duffy (Fermilab)

Over several decades, evidence mounted…

The solar neutrino puzzle



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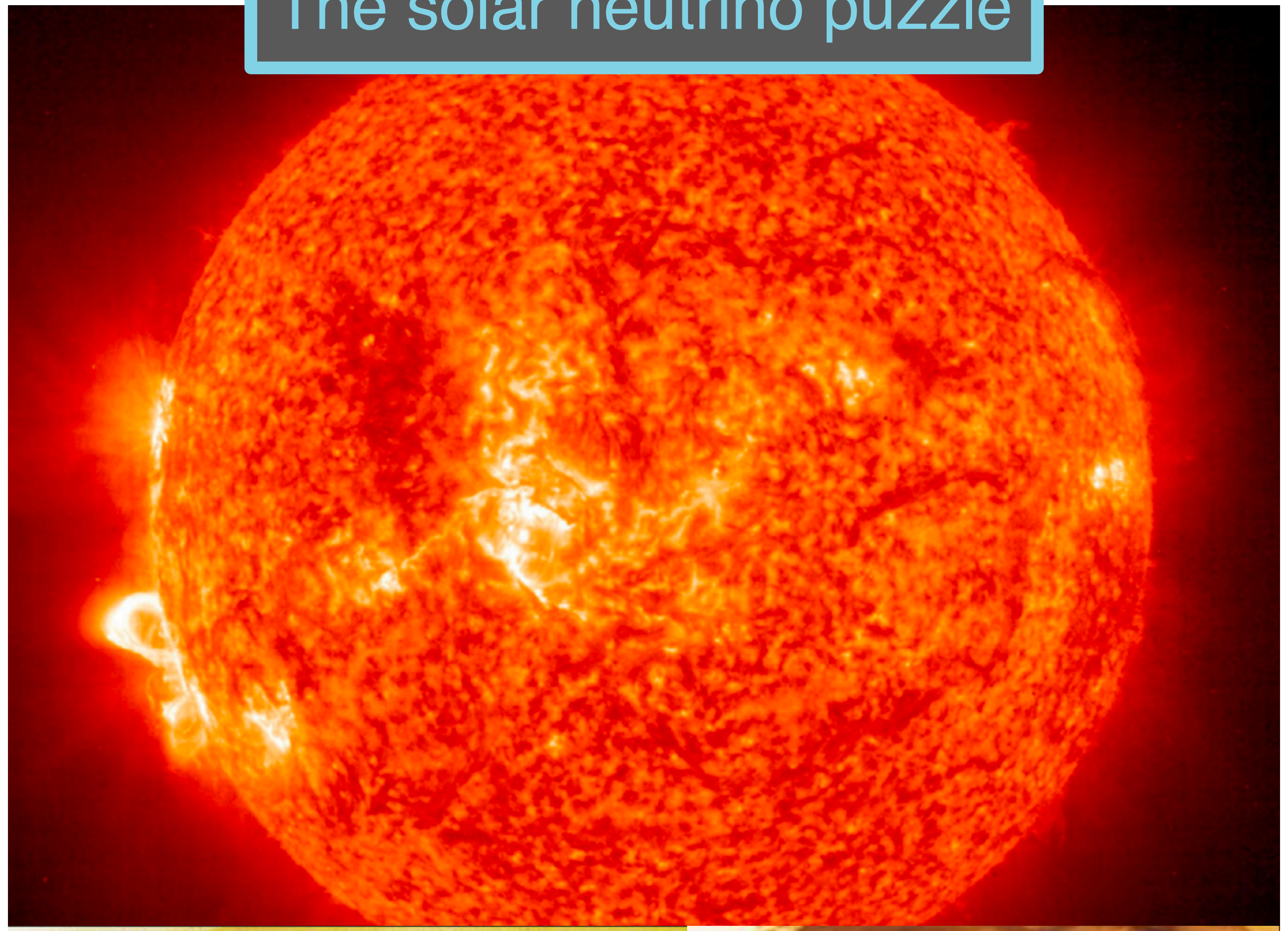

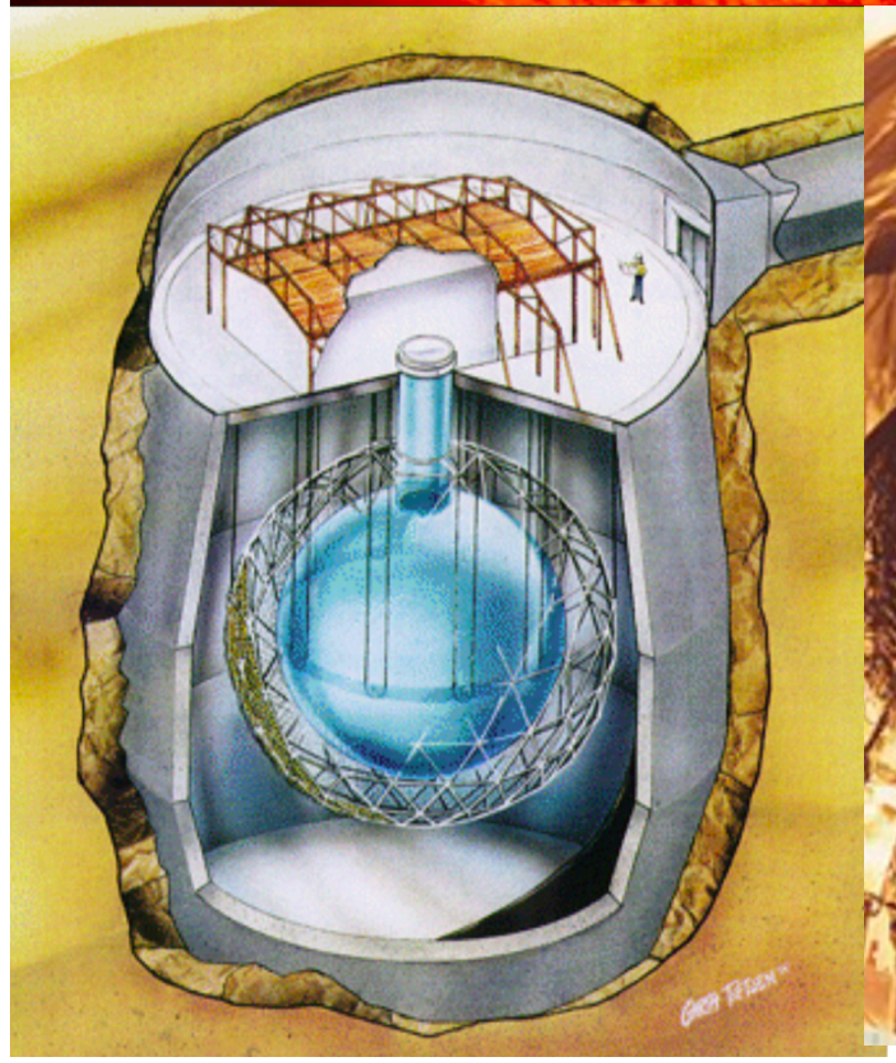

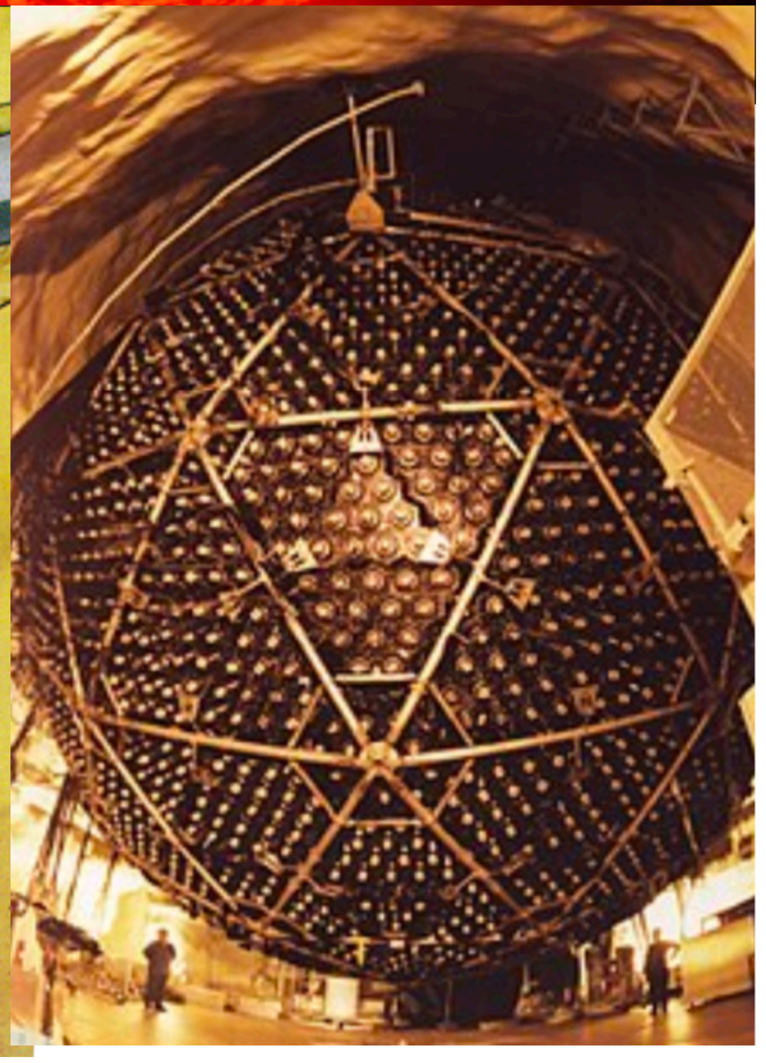

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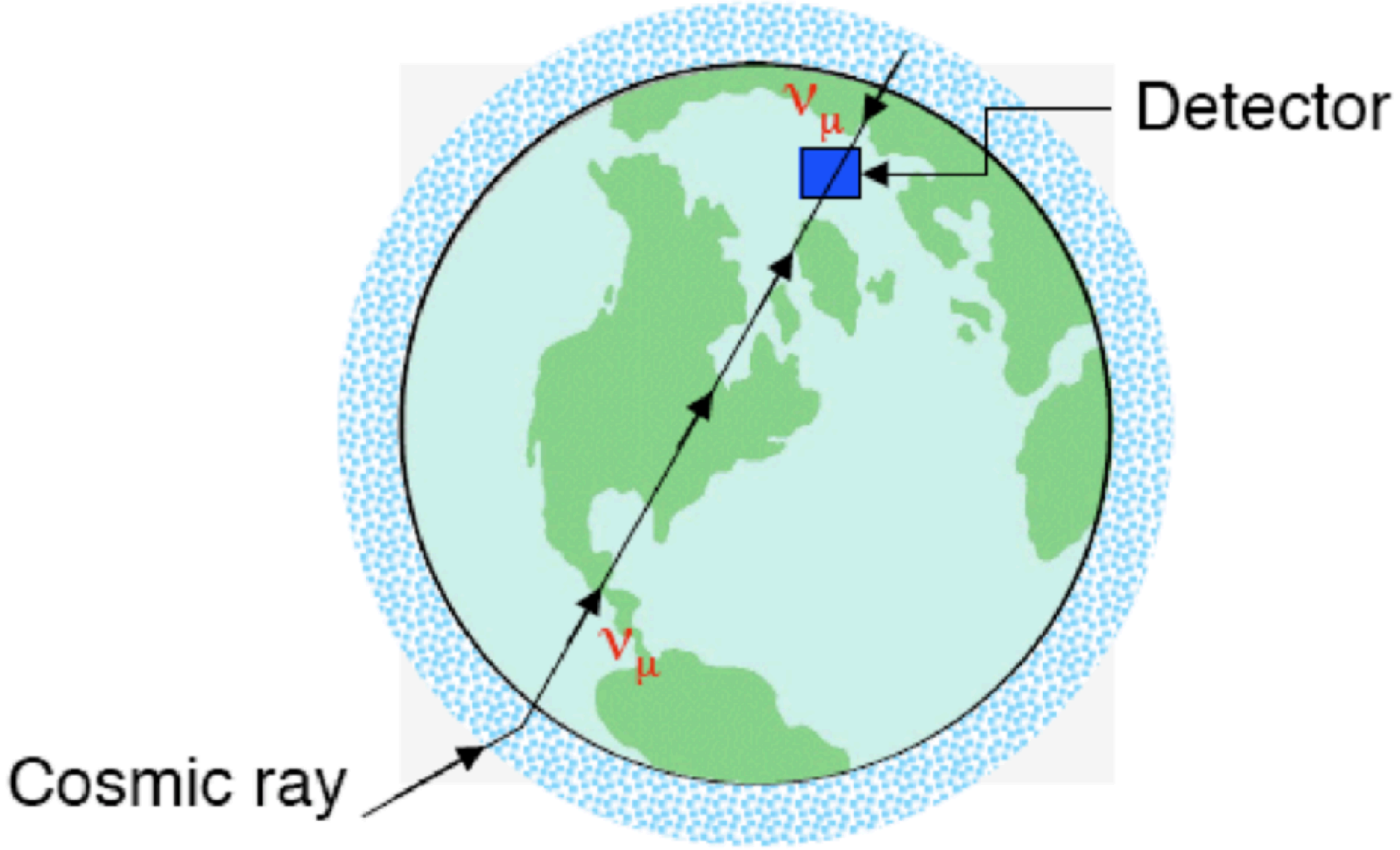

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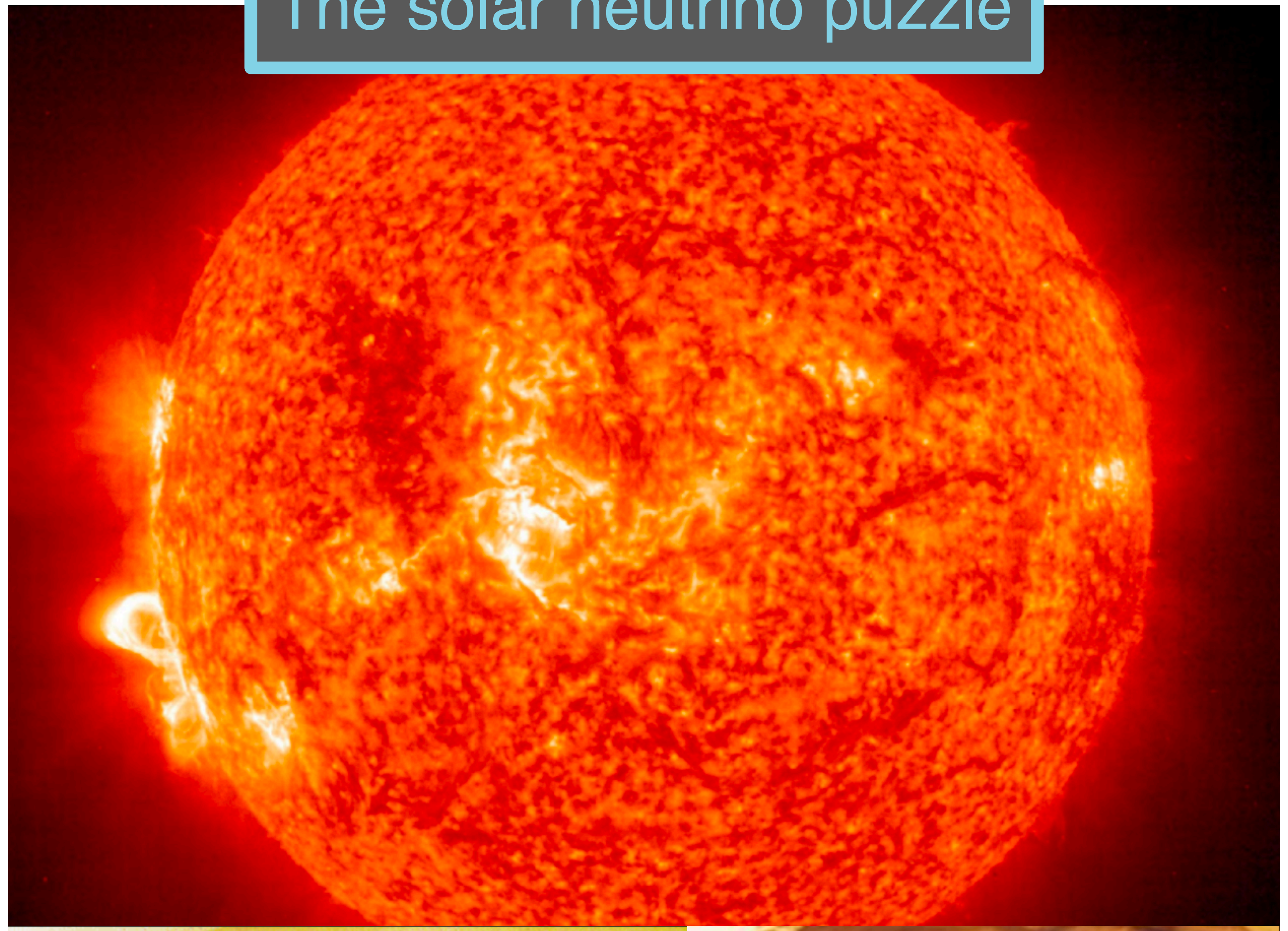

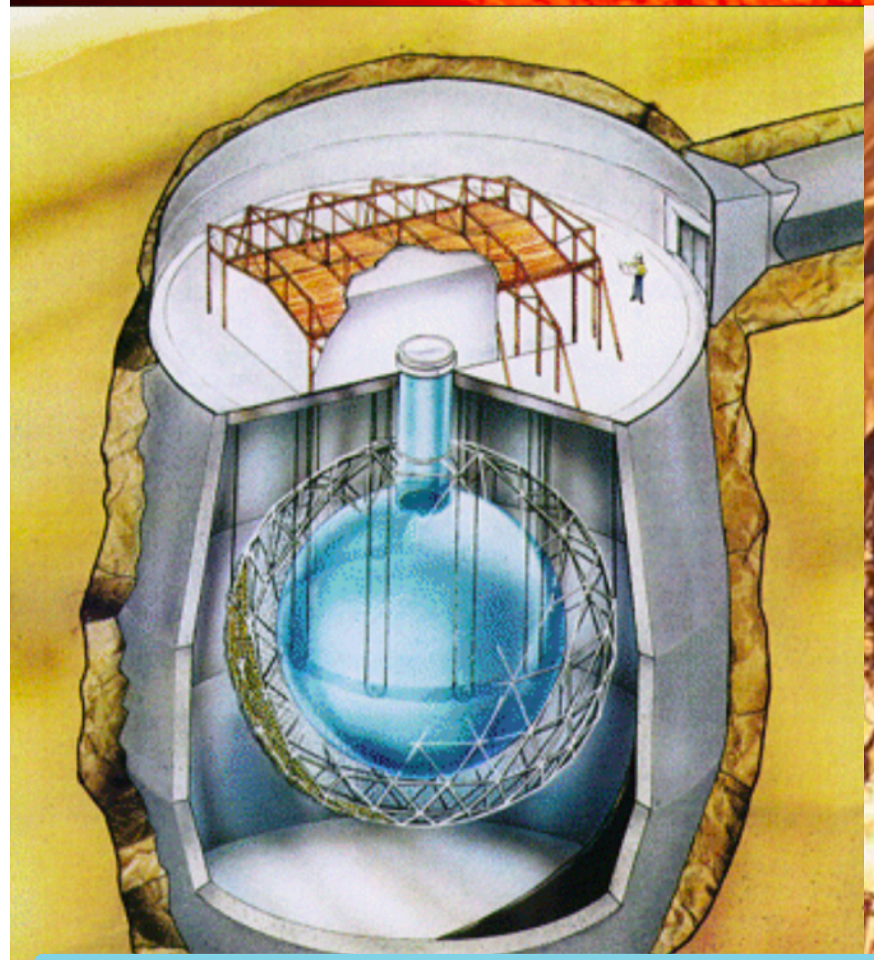

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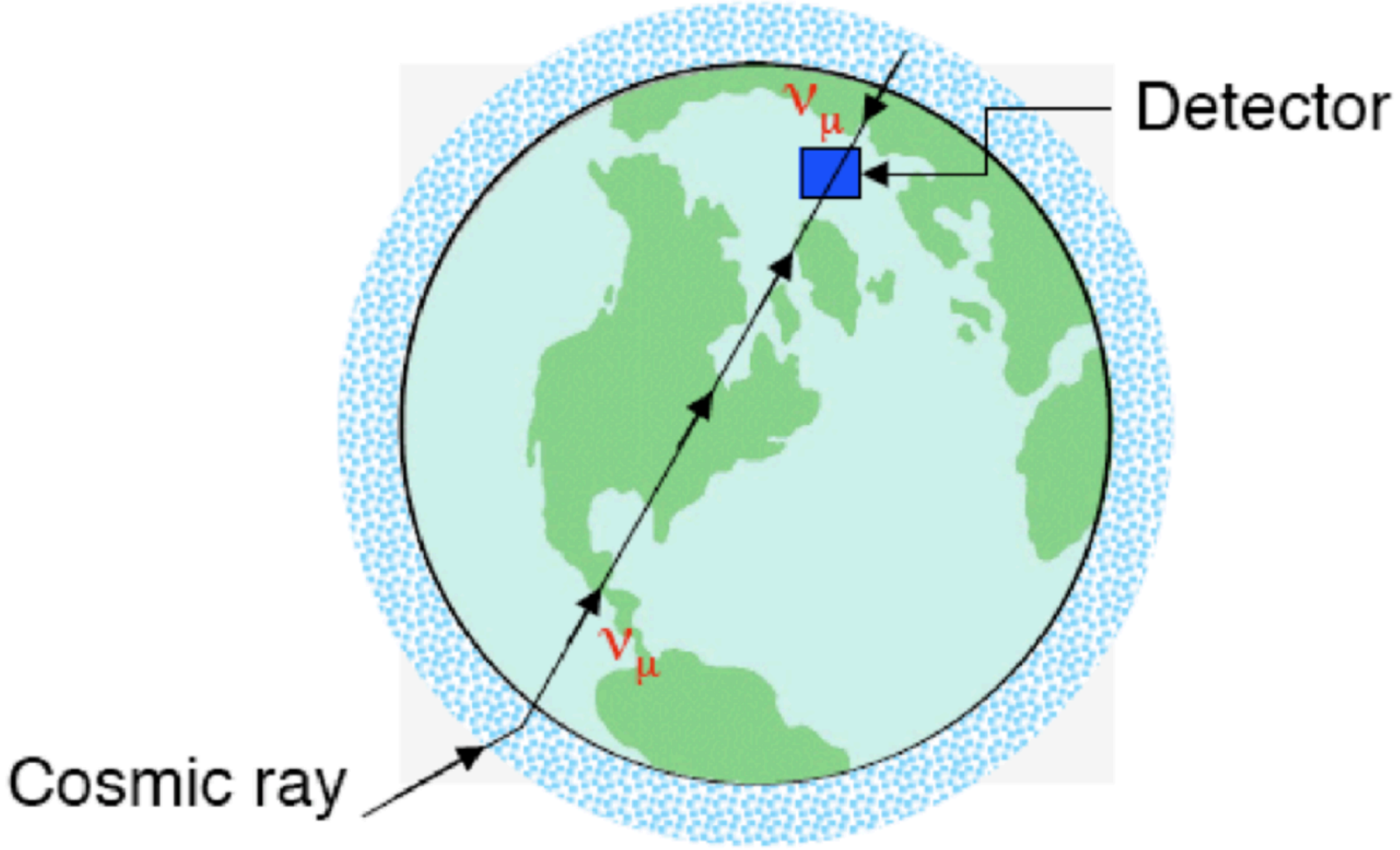

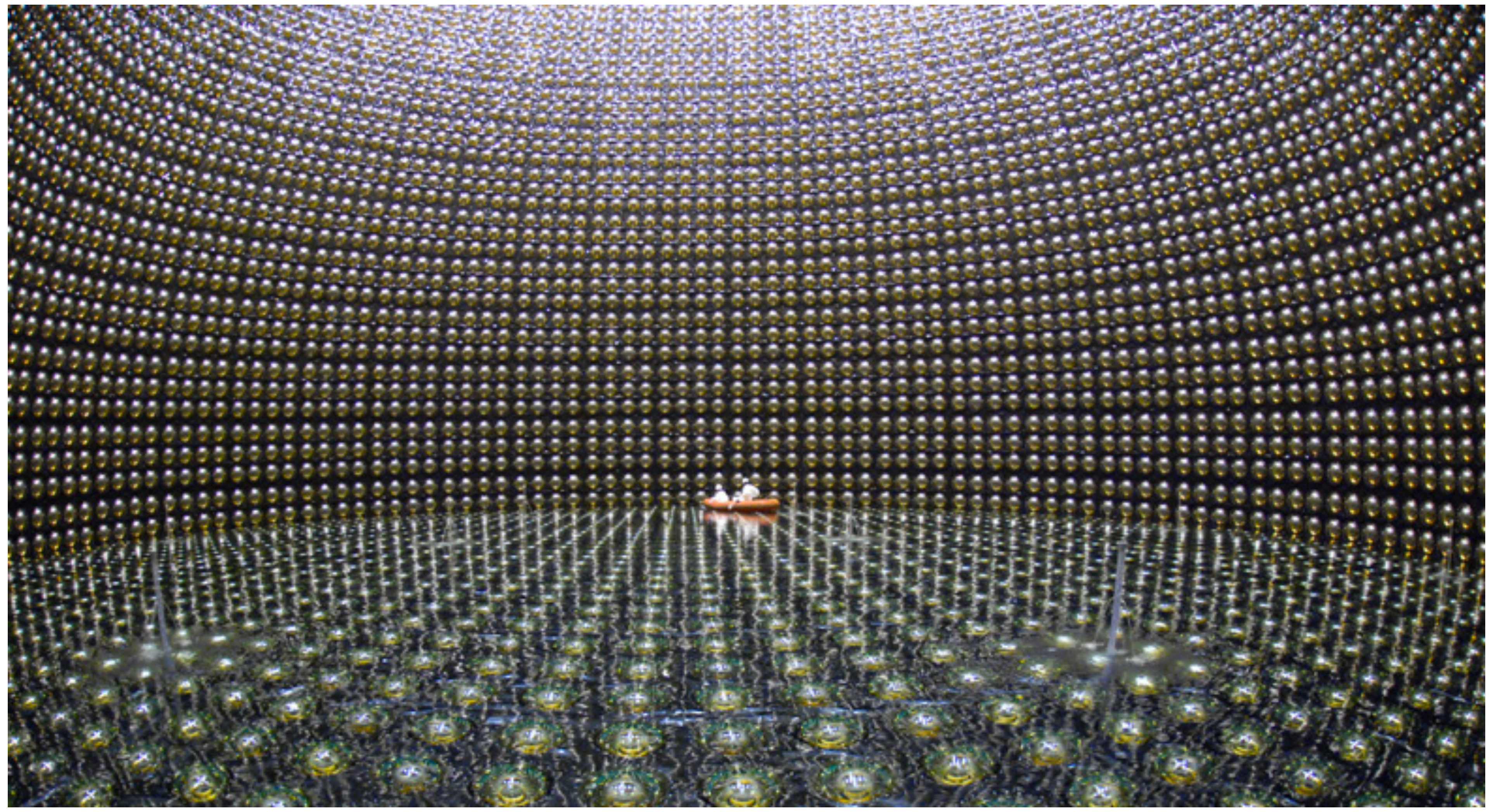

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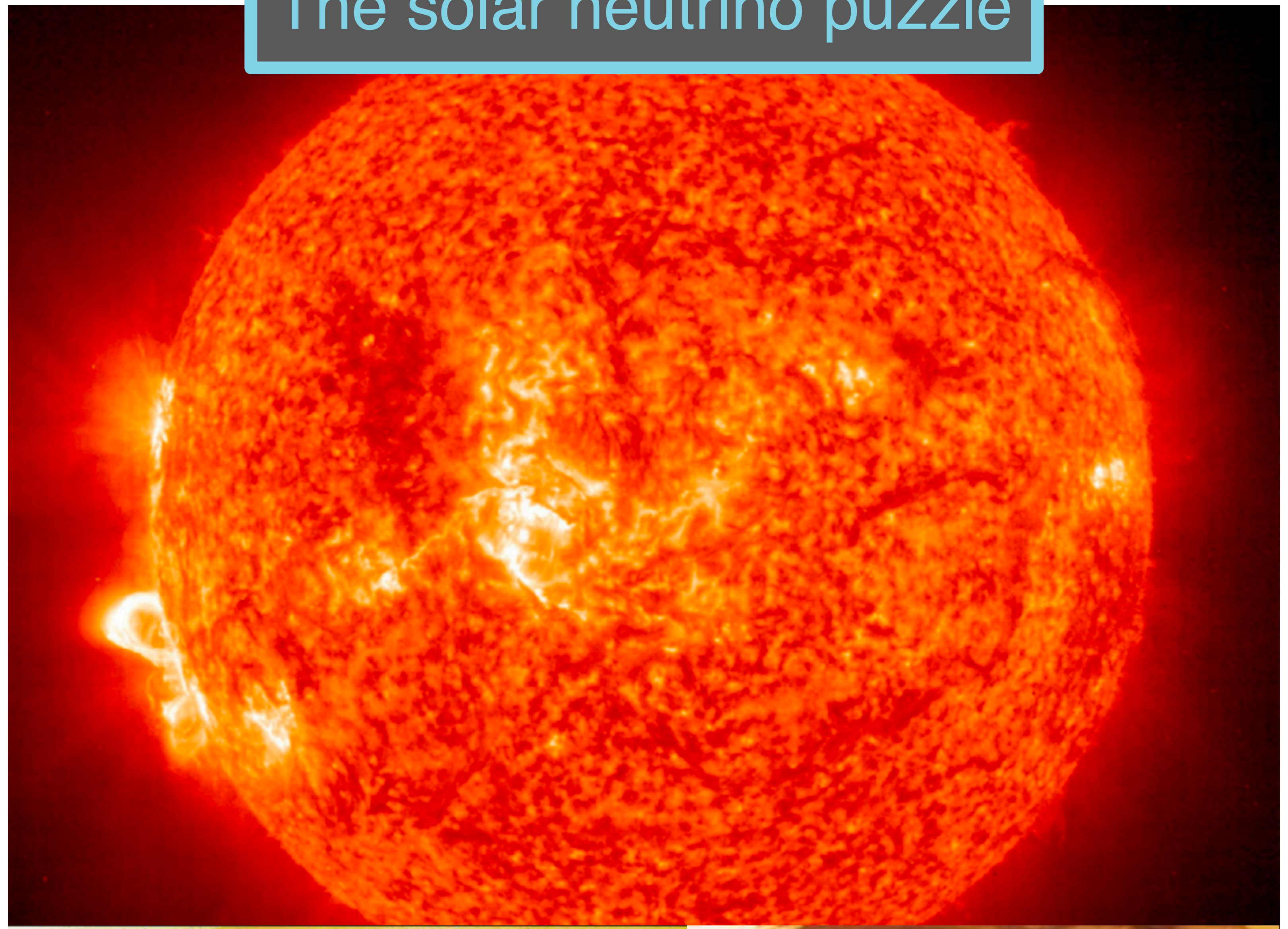

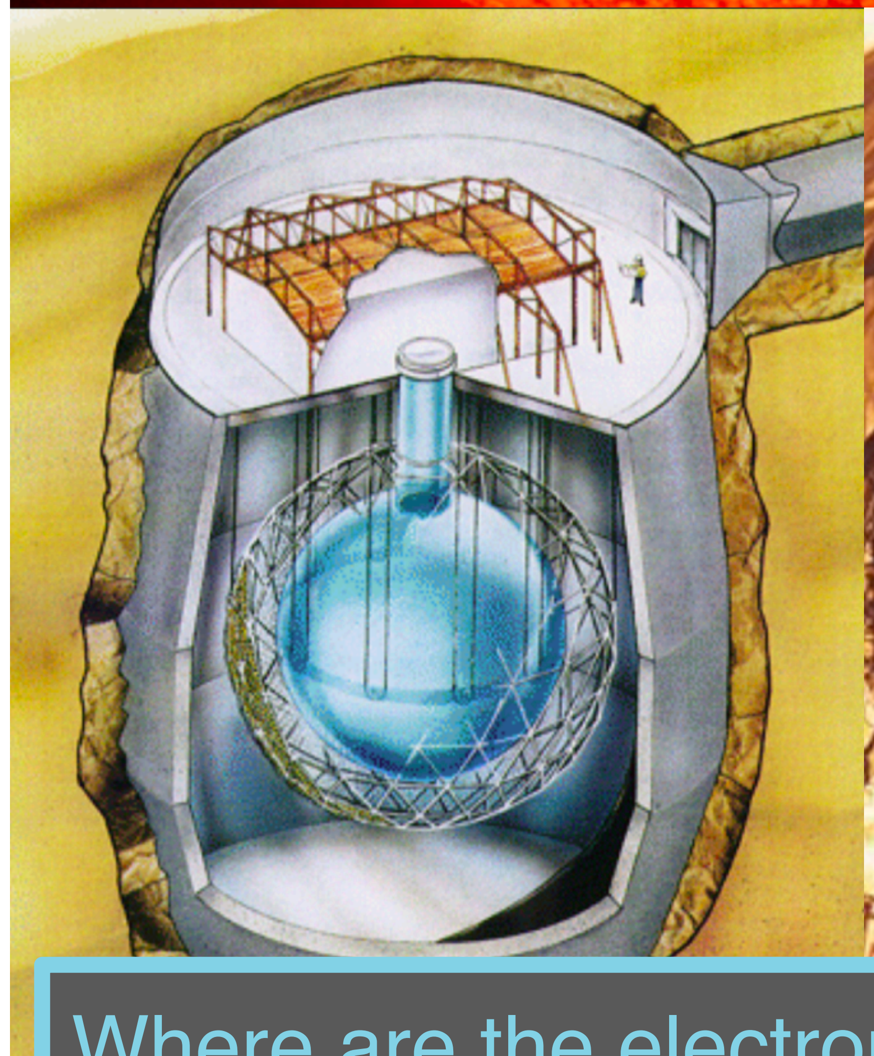

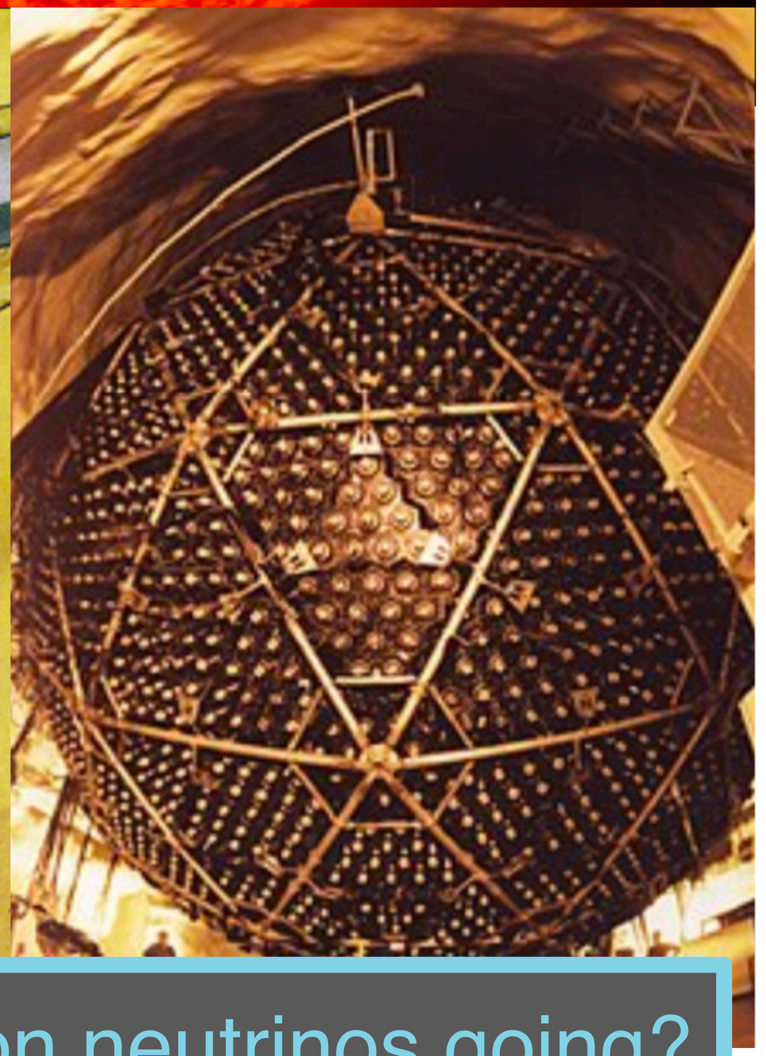

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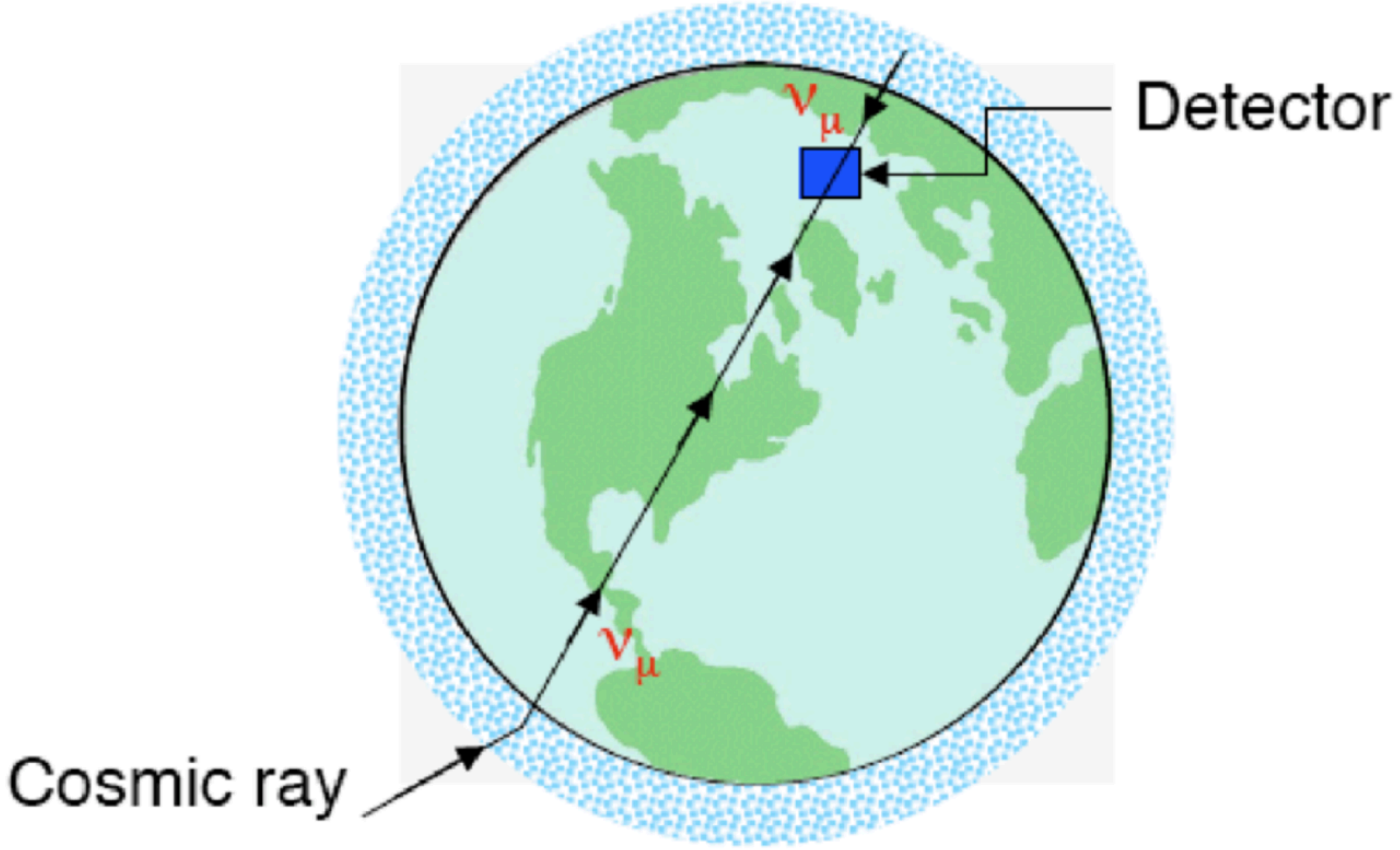

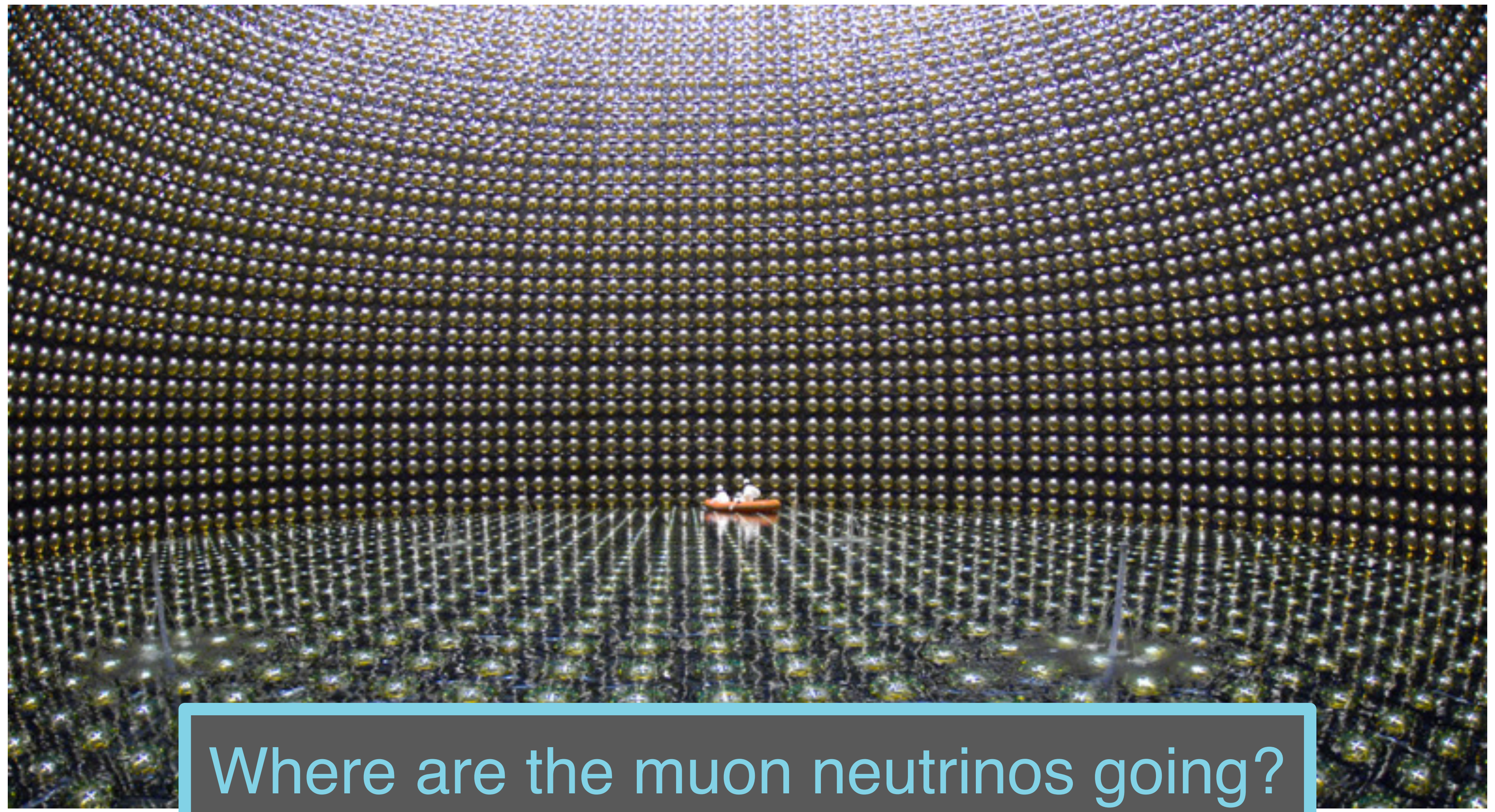

Where are the muon neutrinos going?

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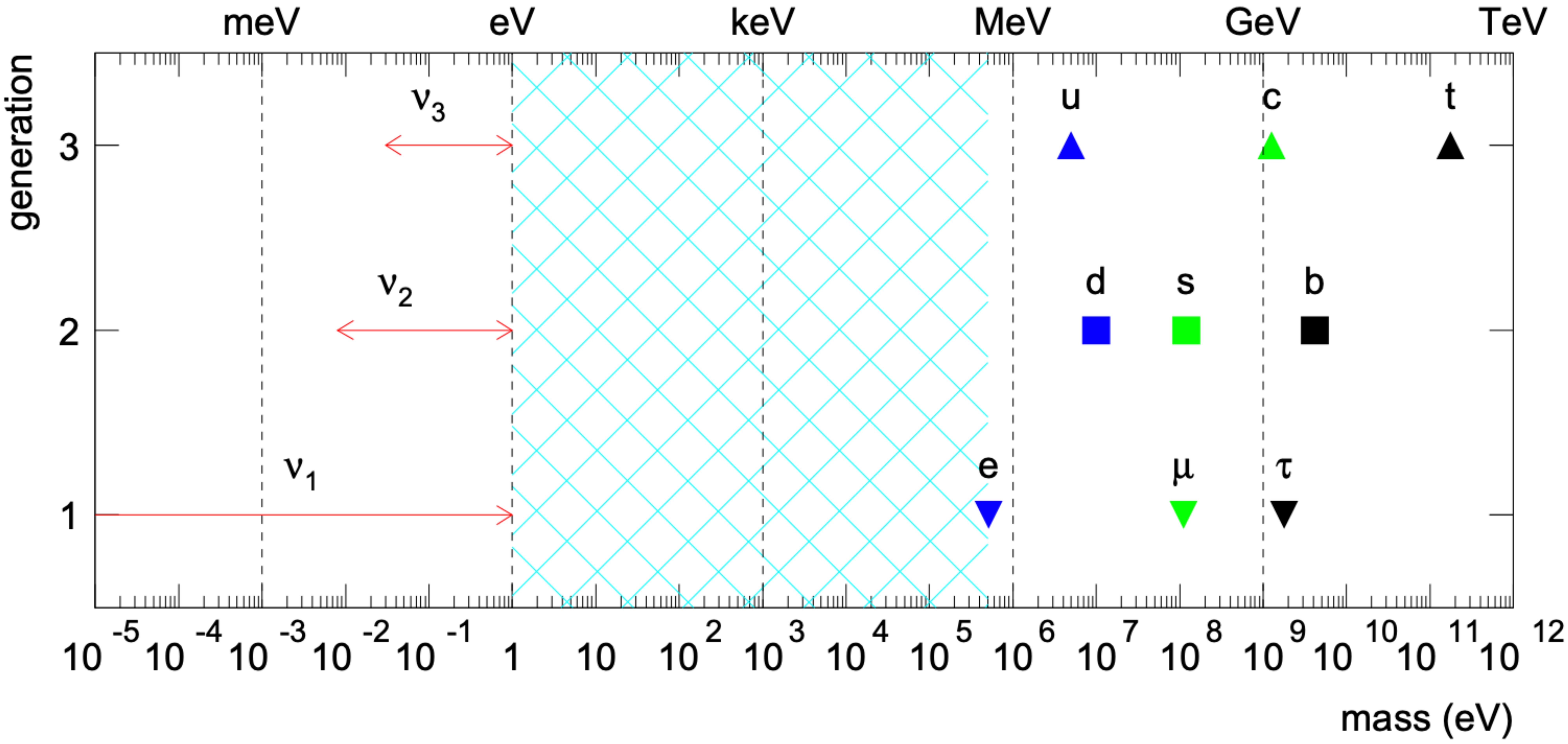
Only consistent explanation of these (and more) observations - Neutrinos have (very small) Masses



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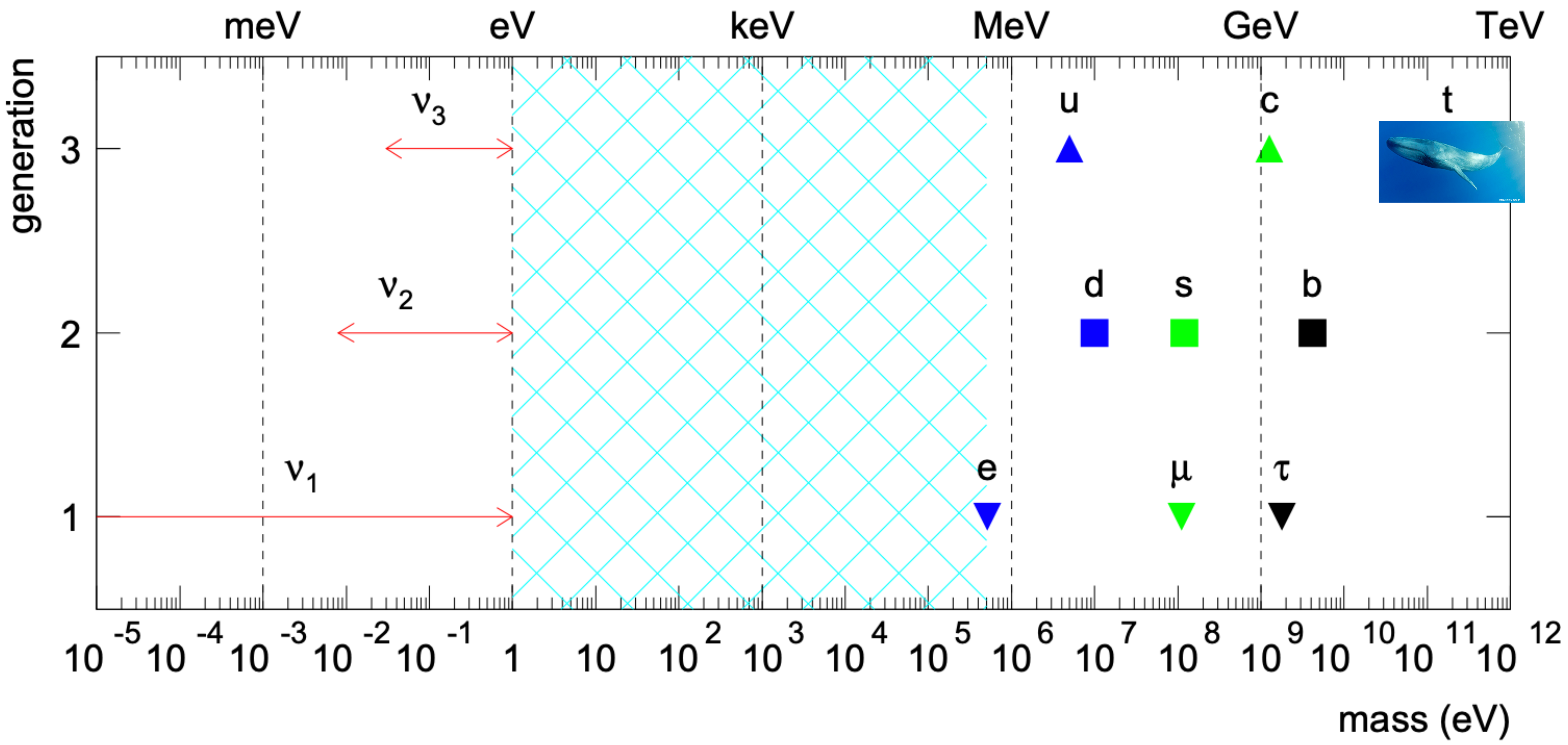

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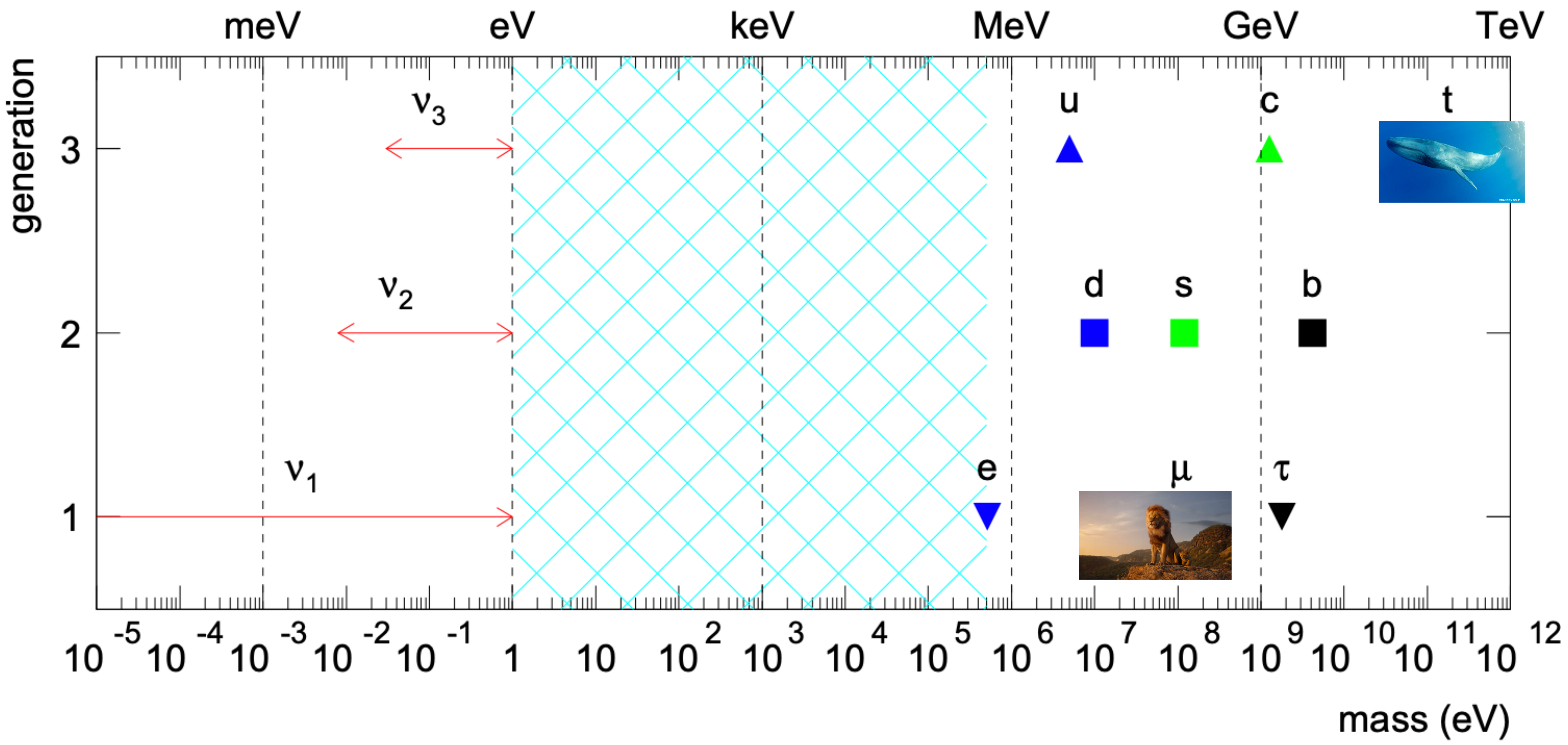

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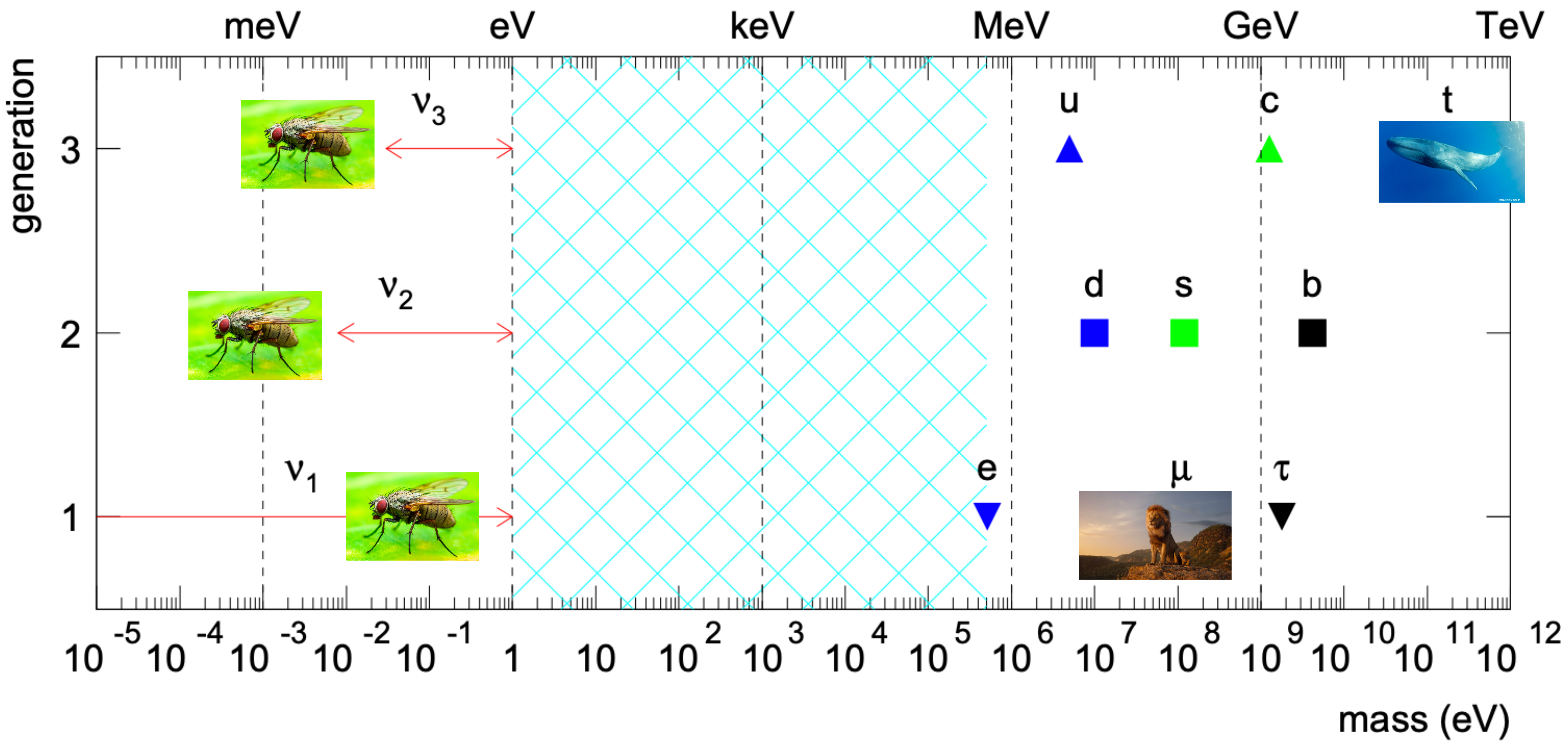

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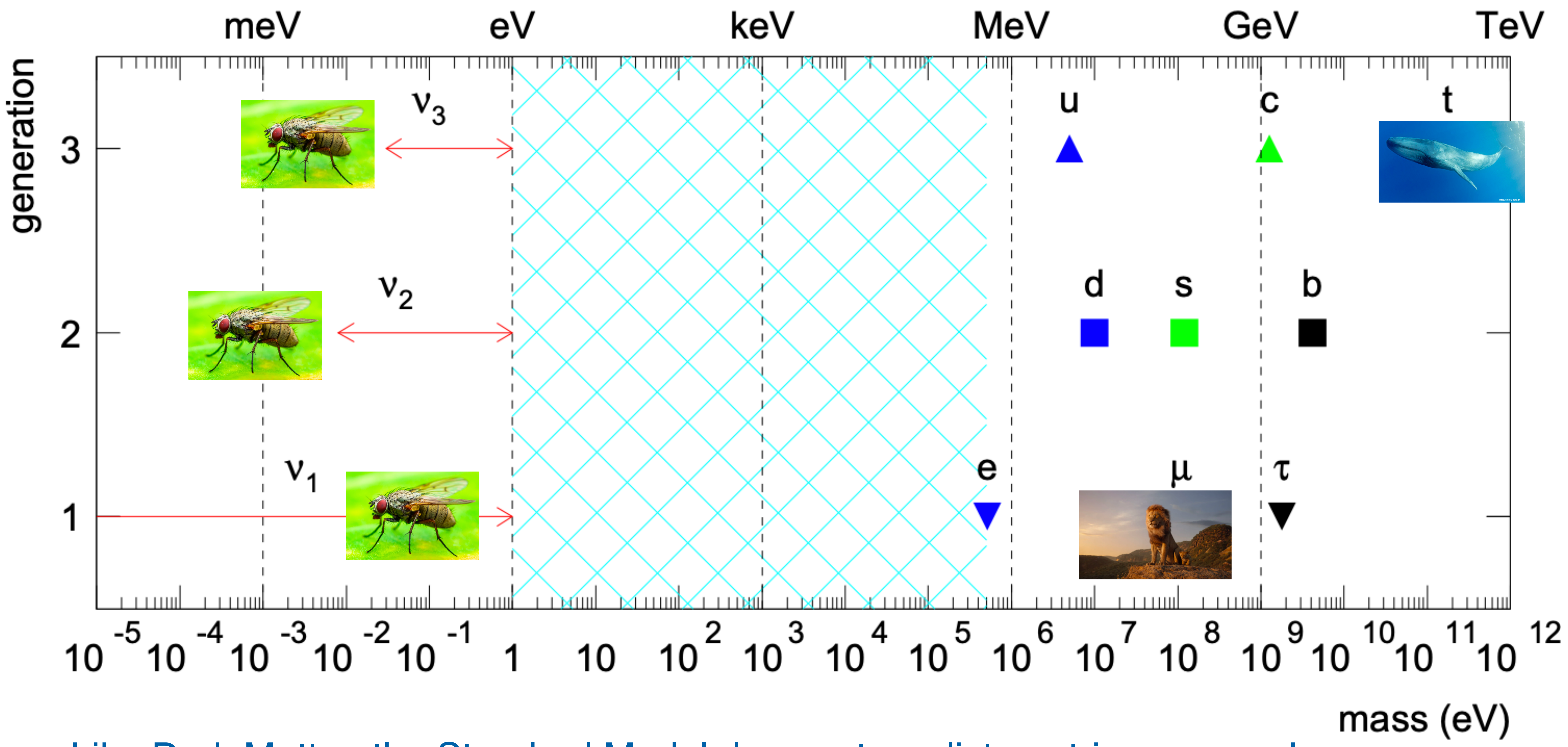
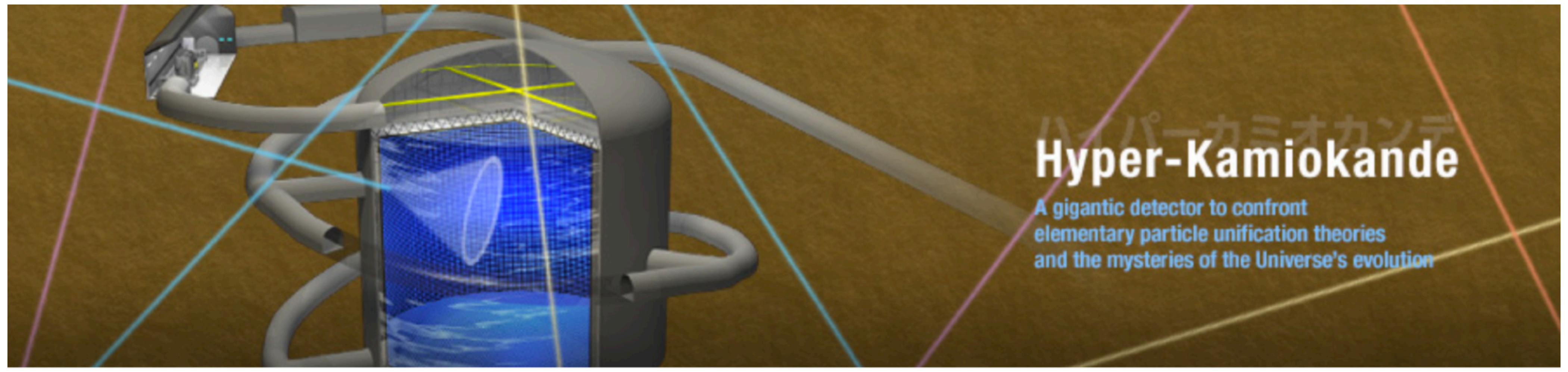


Like Dark Matter, the Standard Model does not predict neutrino masses!

New physics (new particles and/or interactions) are necessary)

Upcoming Experiments to better understand Neutrinos

Hyper-Kamiokande



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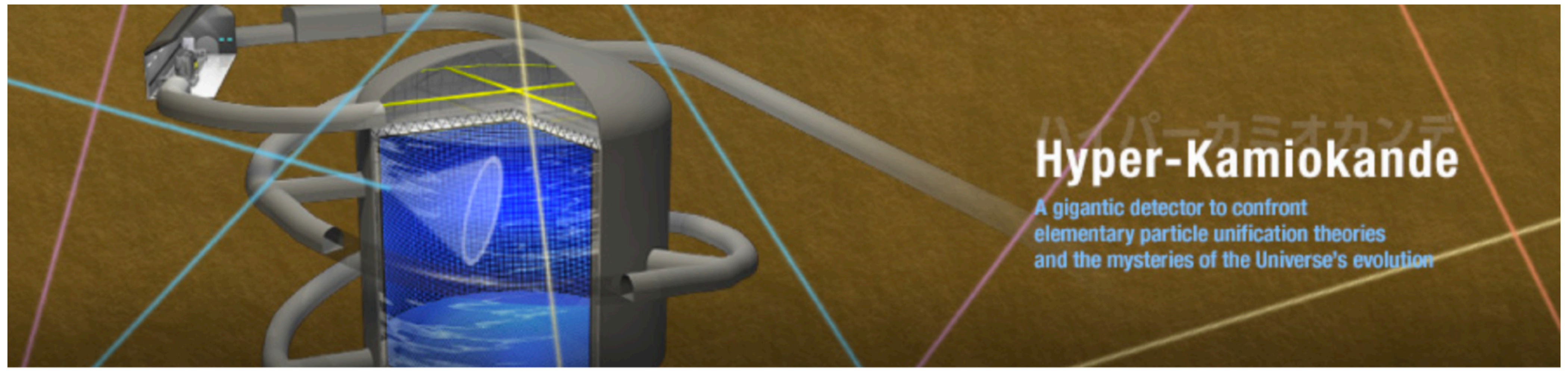

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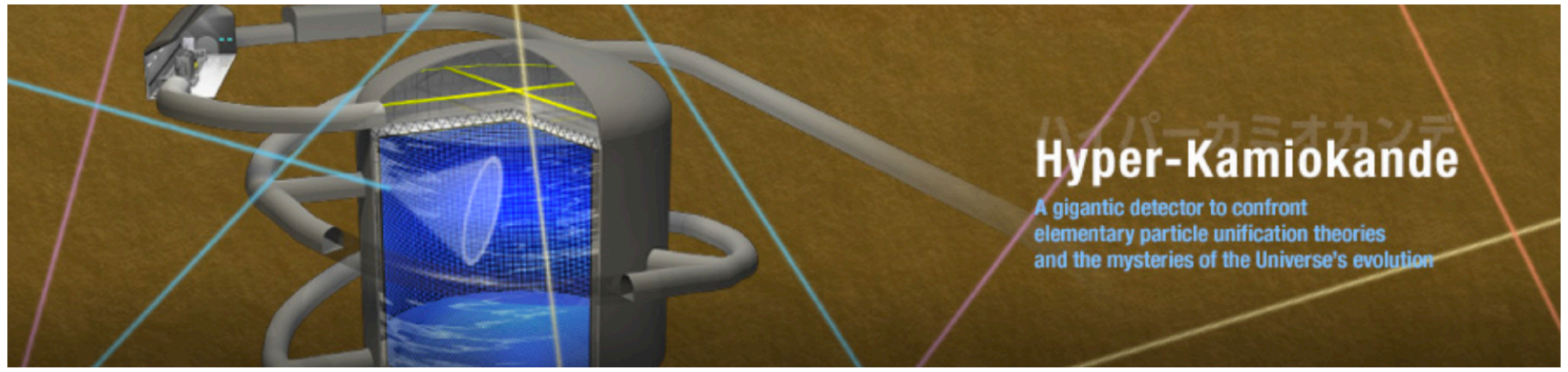

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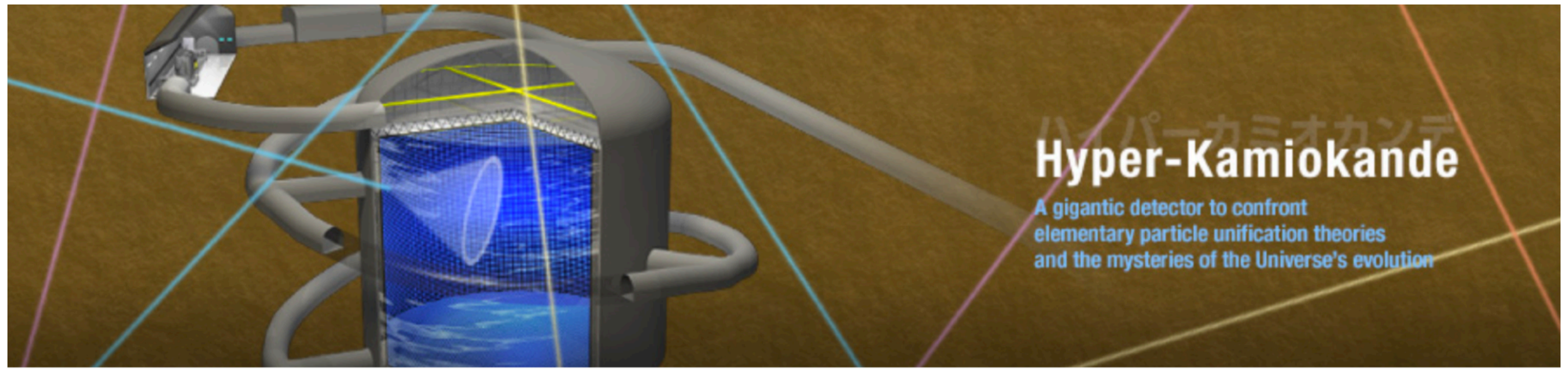

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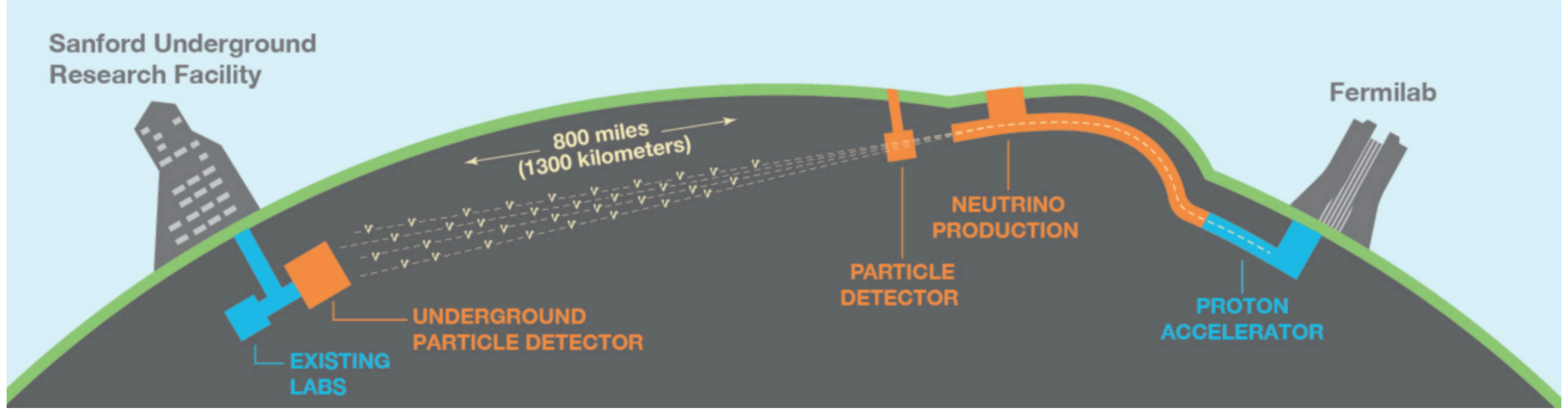

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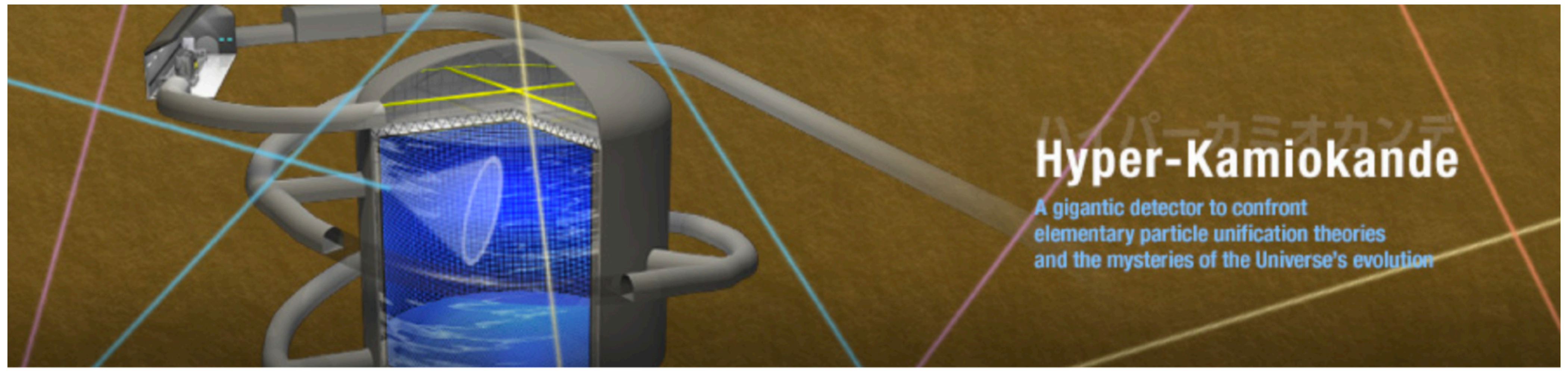

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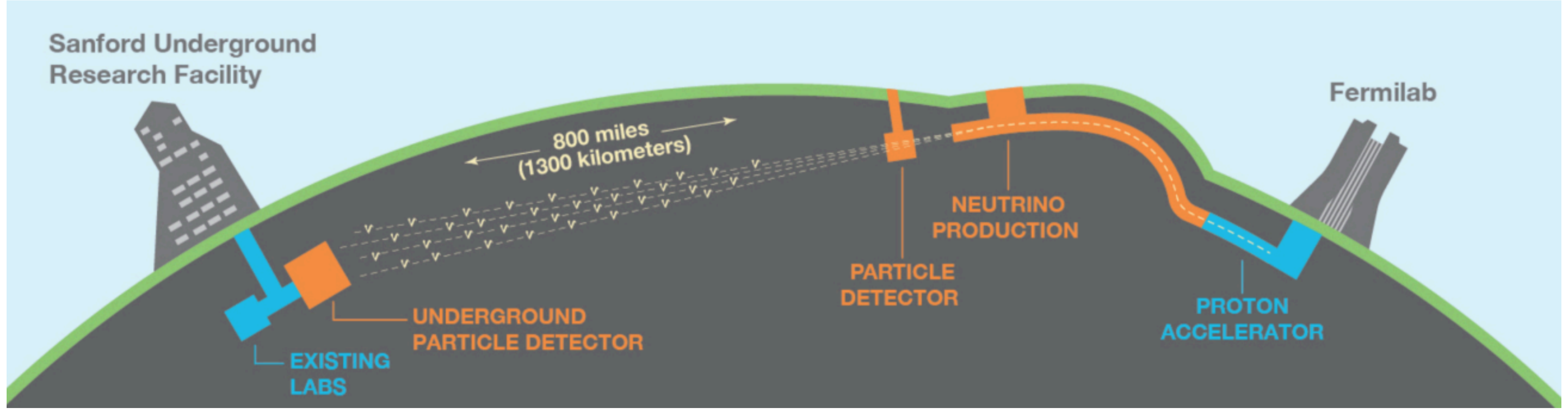
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT



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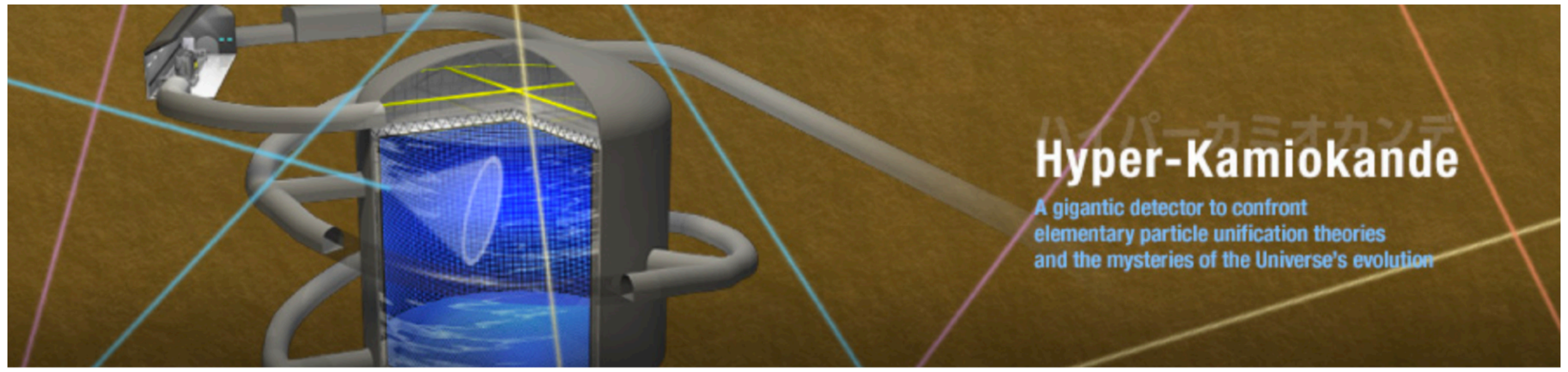

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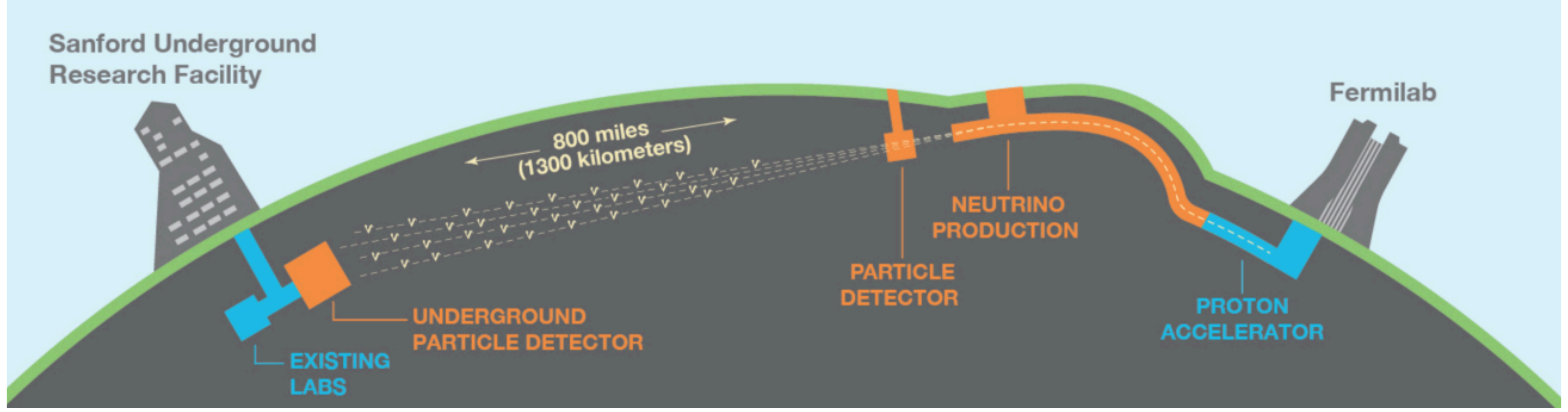

- US-based precision neutrino physics project.
- Built on new, liquid-argon based technology being developed in Fermilab-based “short-baseline” neutrino program.

The Higgs Hierarchy Problem

The Higgs Boson Mass & Quantum Corrections

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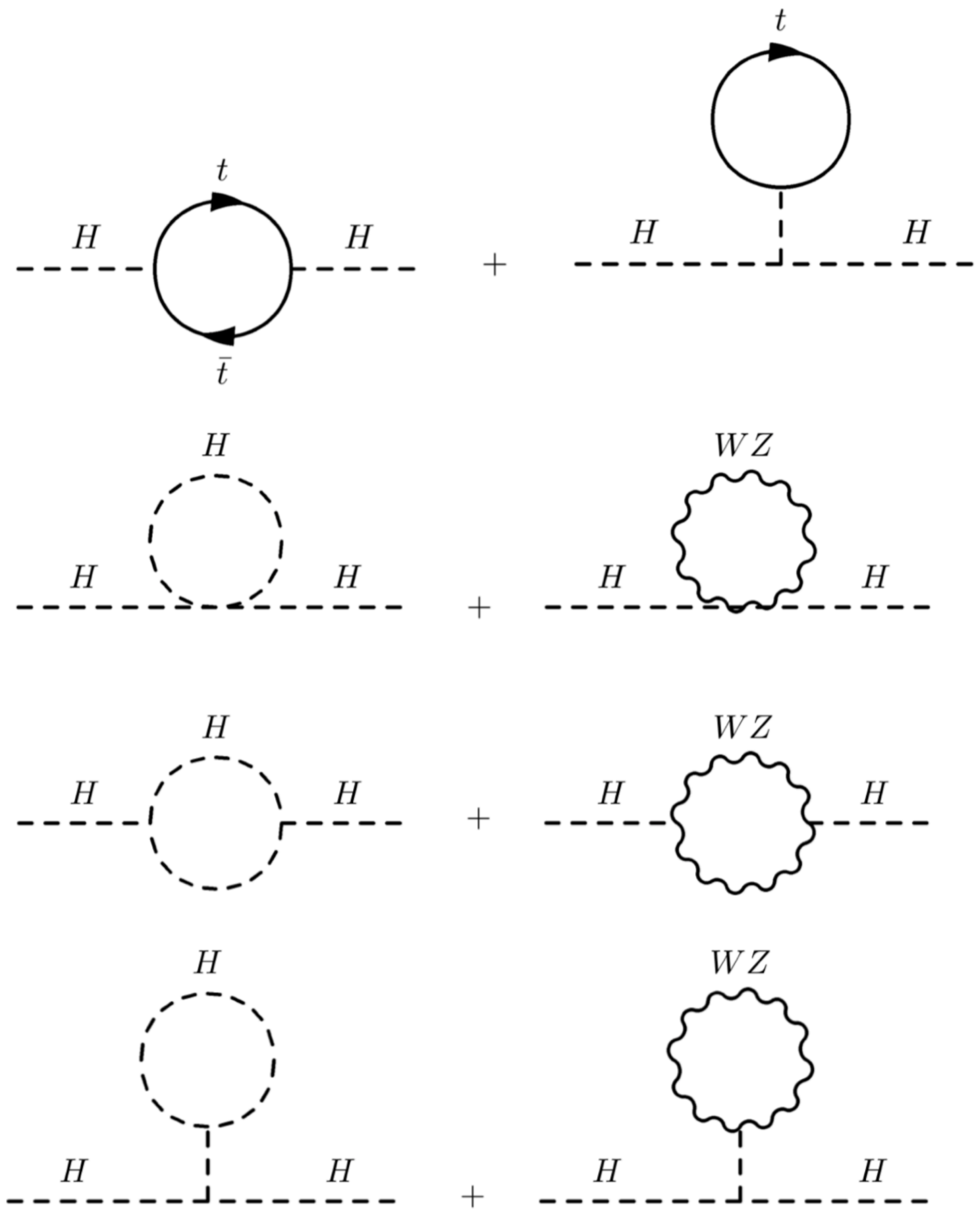

- Quantum field theory predicts that processes like these modify the Higgs boson's mass from its "Lagrangian value".

$$\Delta m_H^2 \approx -\frac{y_t^2}{8\pi^2}\Lambda^2 + \cdots$$

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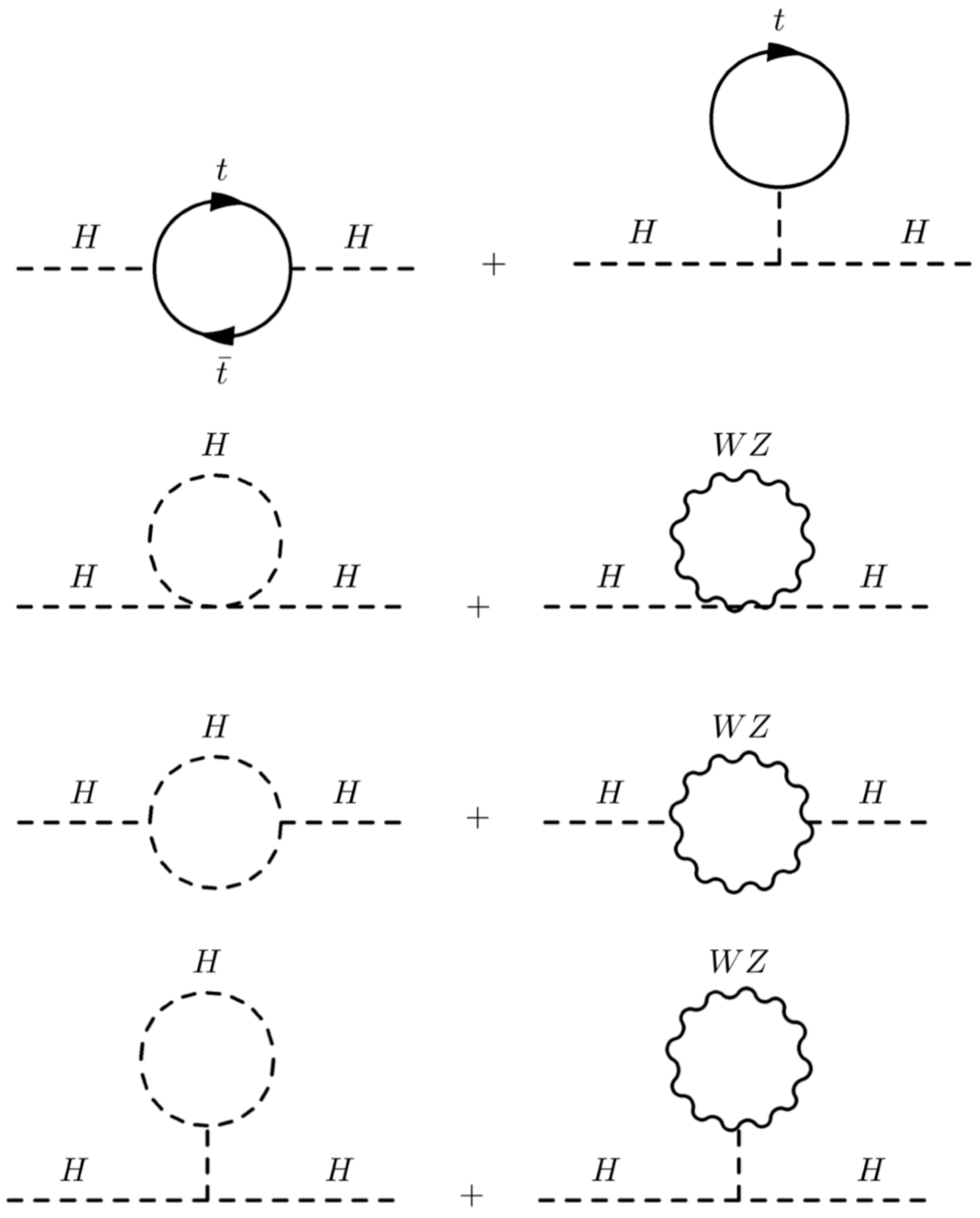

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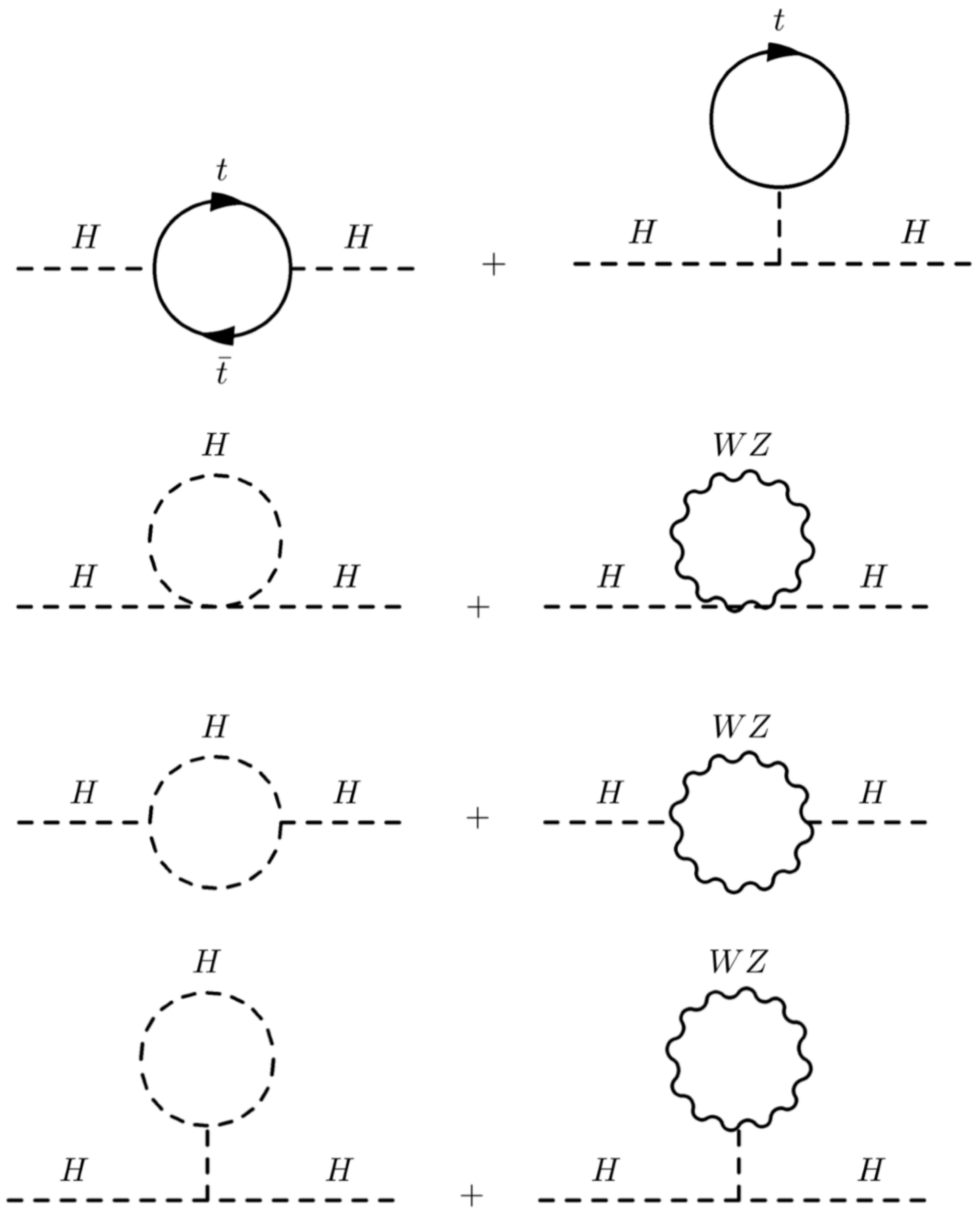

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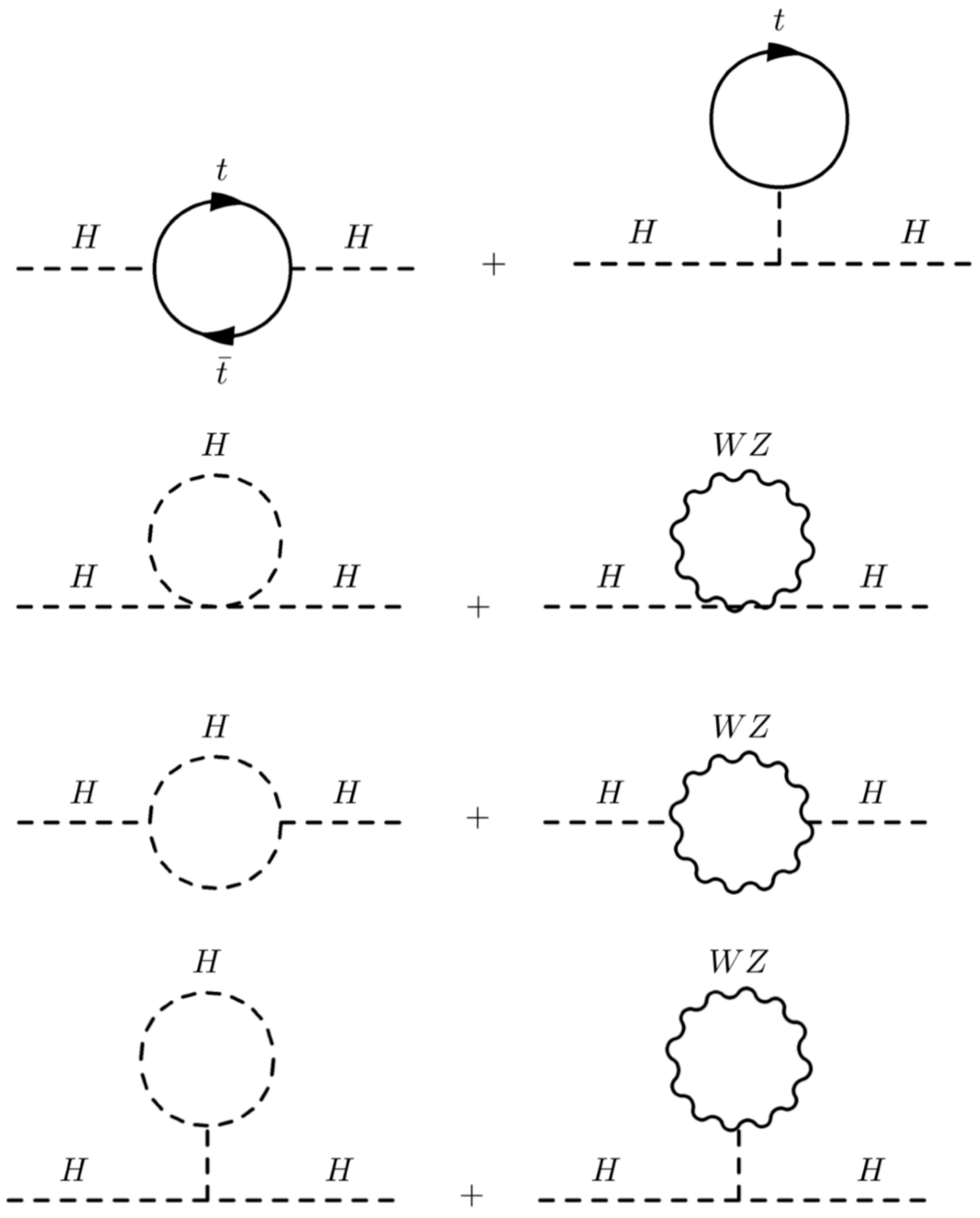

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- Why then, do we see it to be so small?

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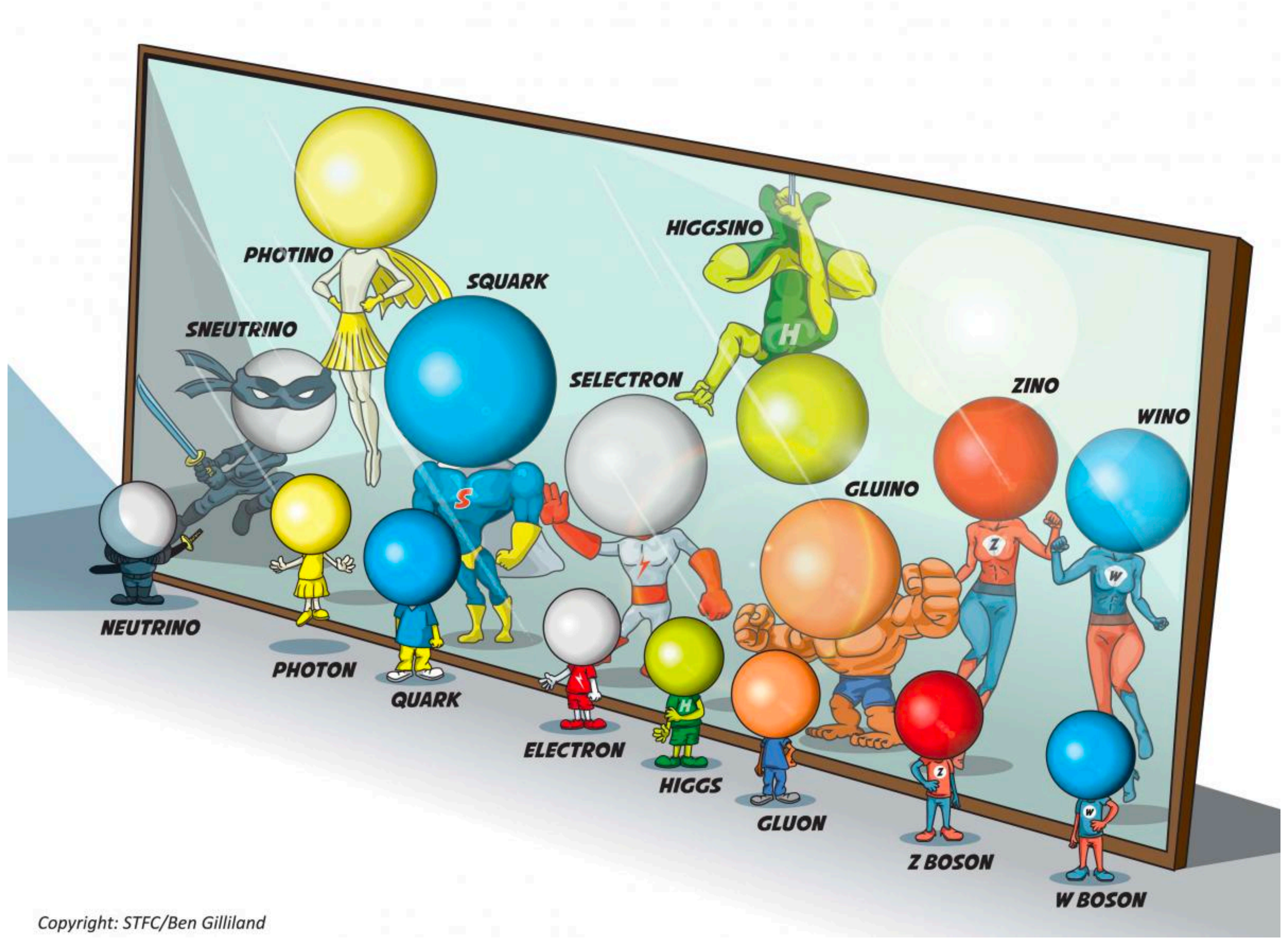

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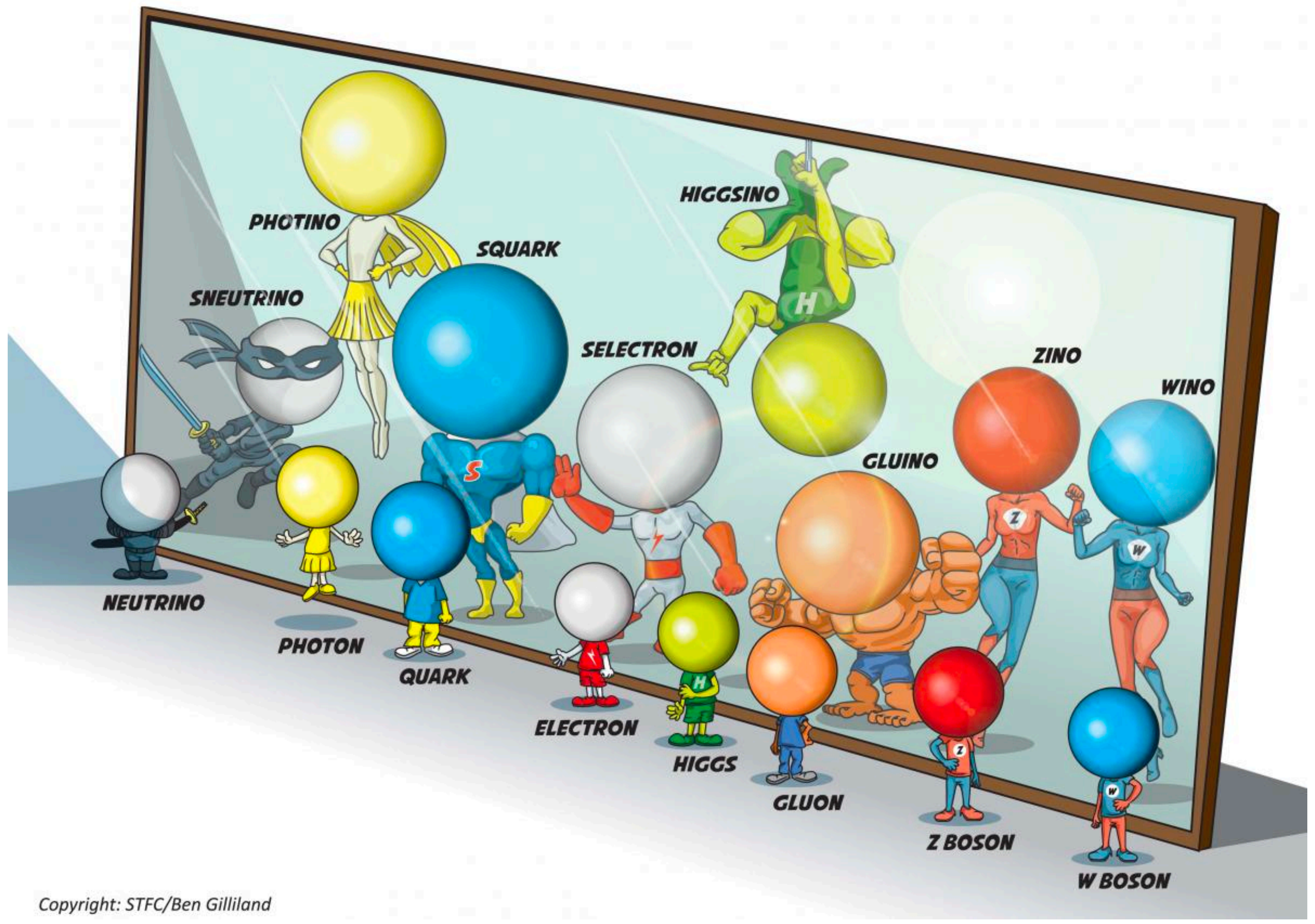

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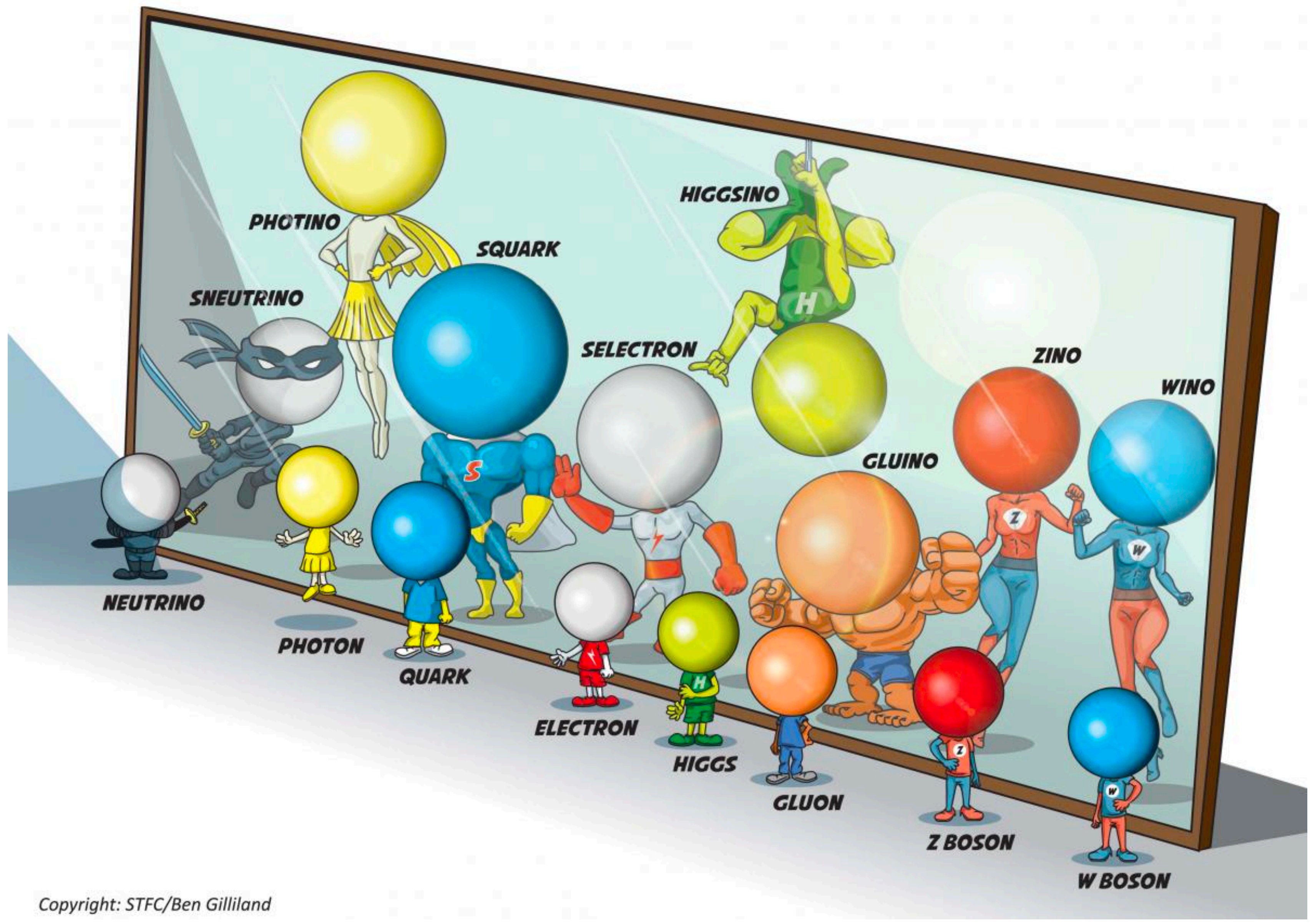
- Supersymmetric theories also may help point to a “theory of everything”, where all of the observed “low-energy” forces are unified into one at high energy.



SUSY Searches at the LHC

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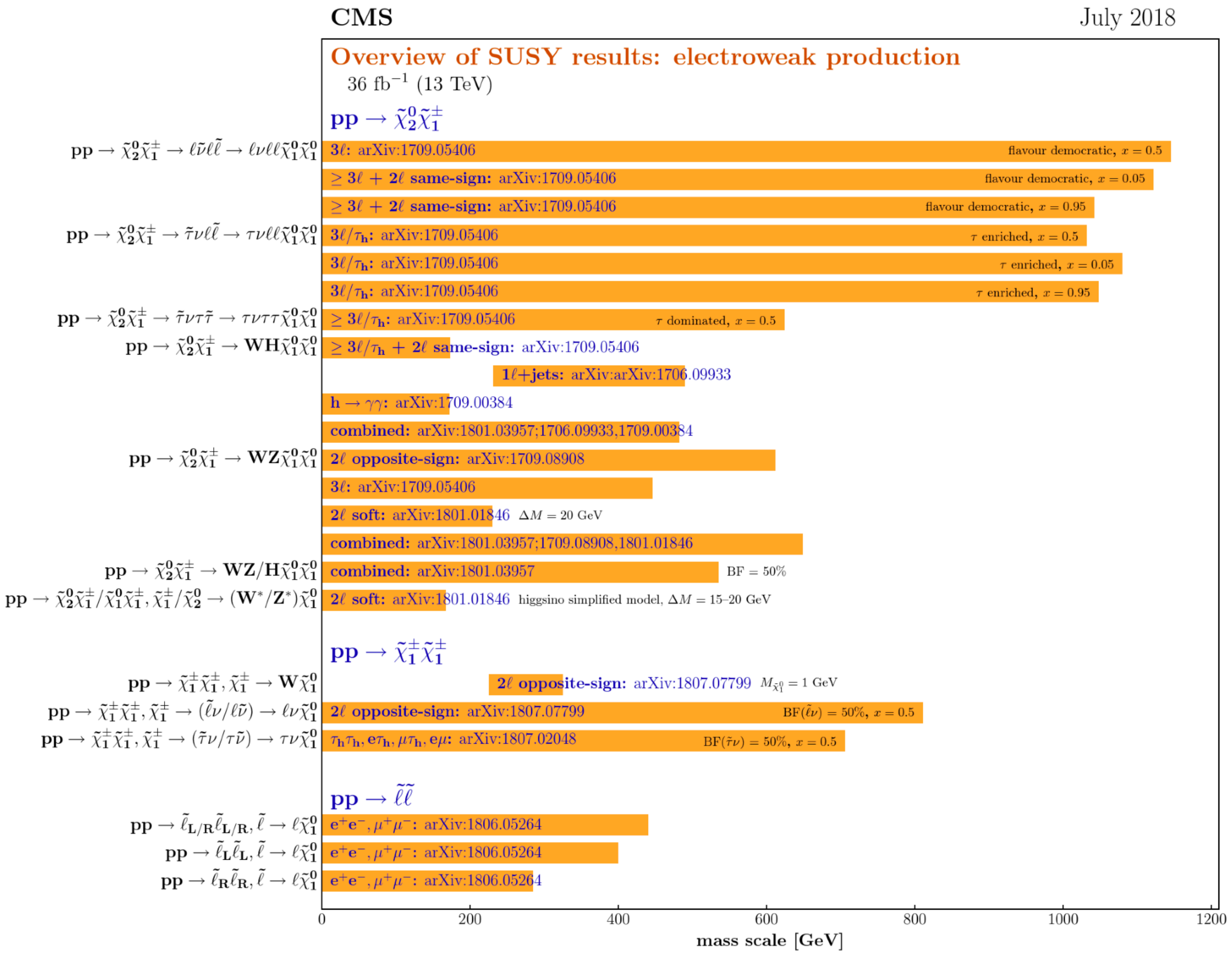

Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe **up to** the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

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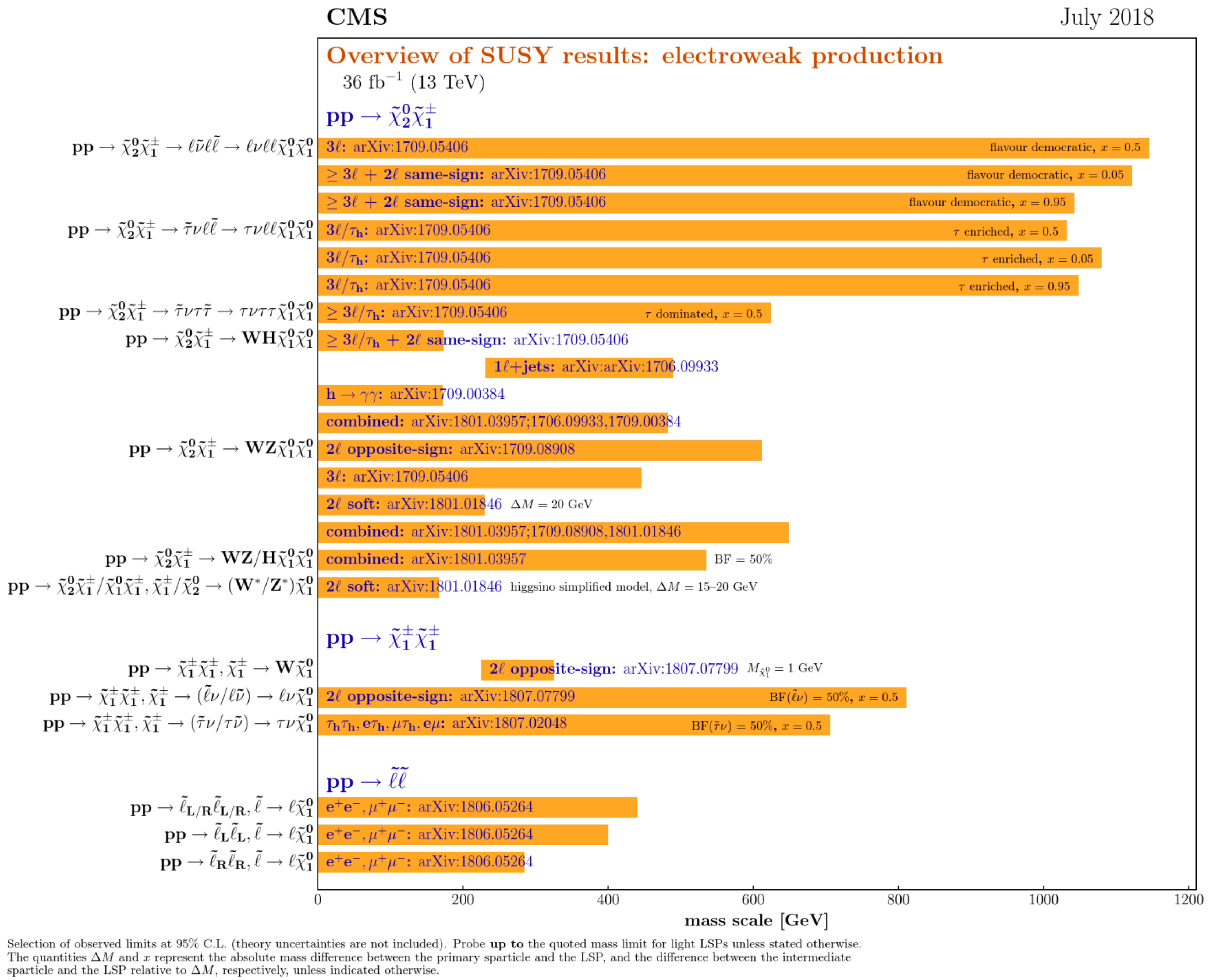

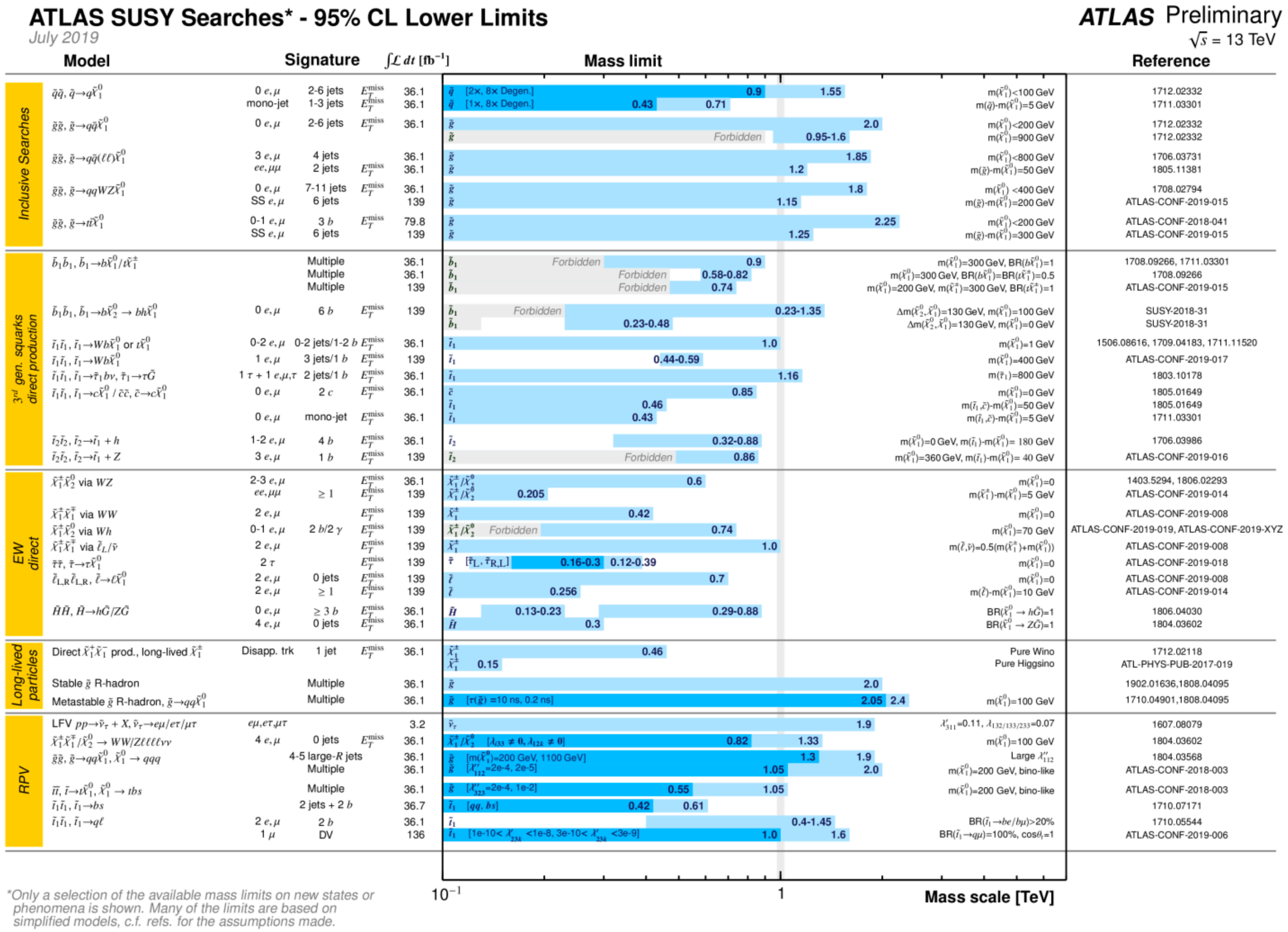

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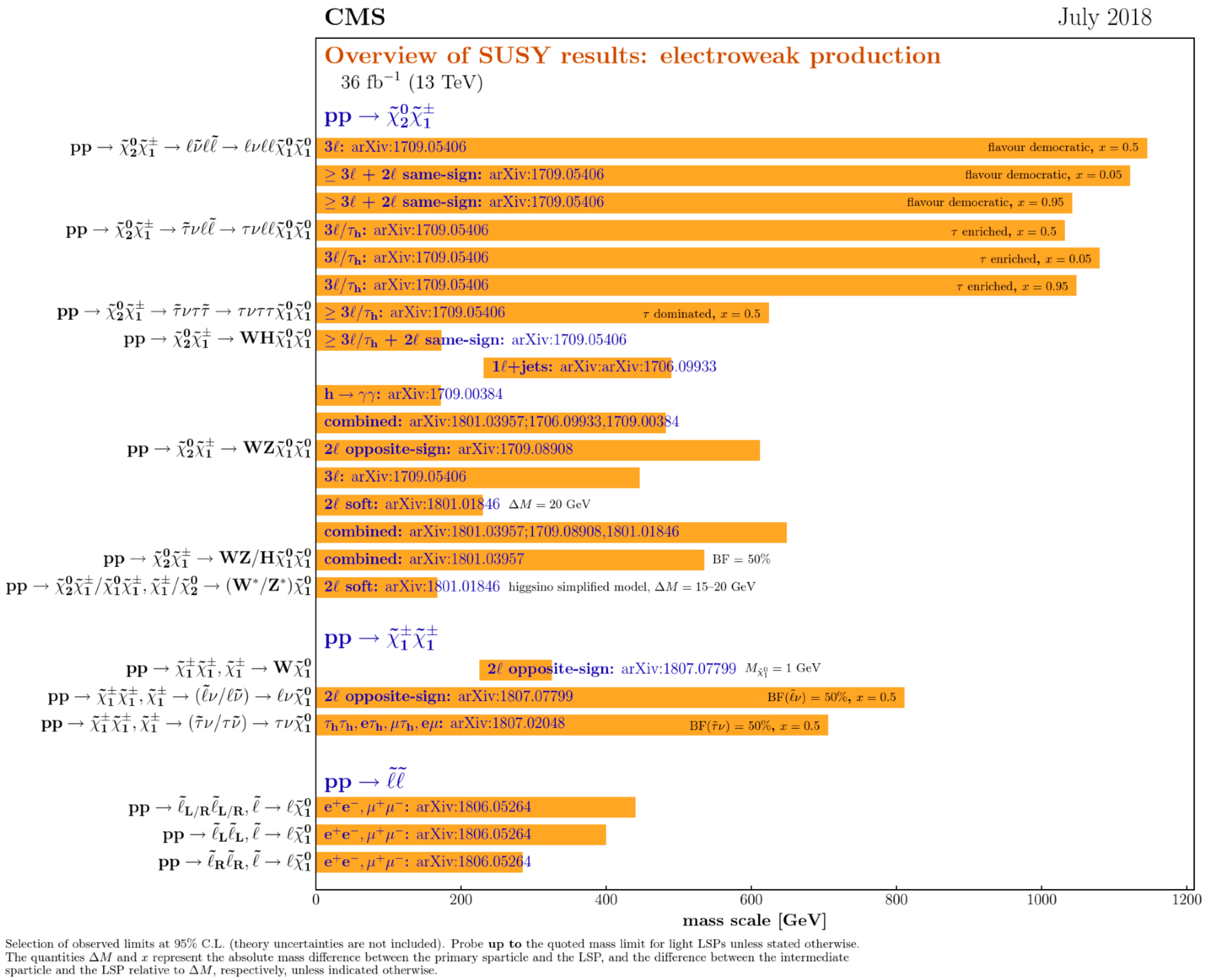

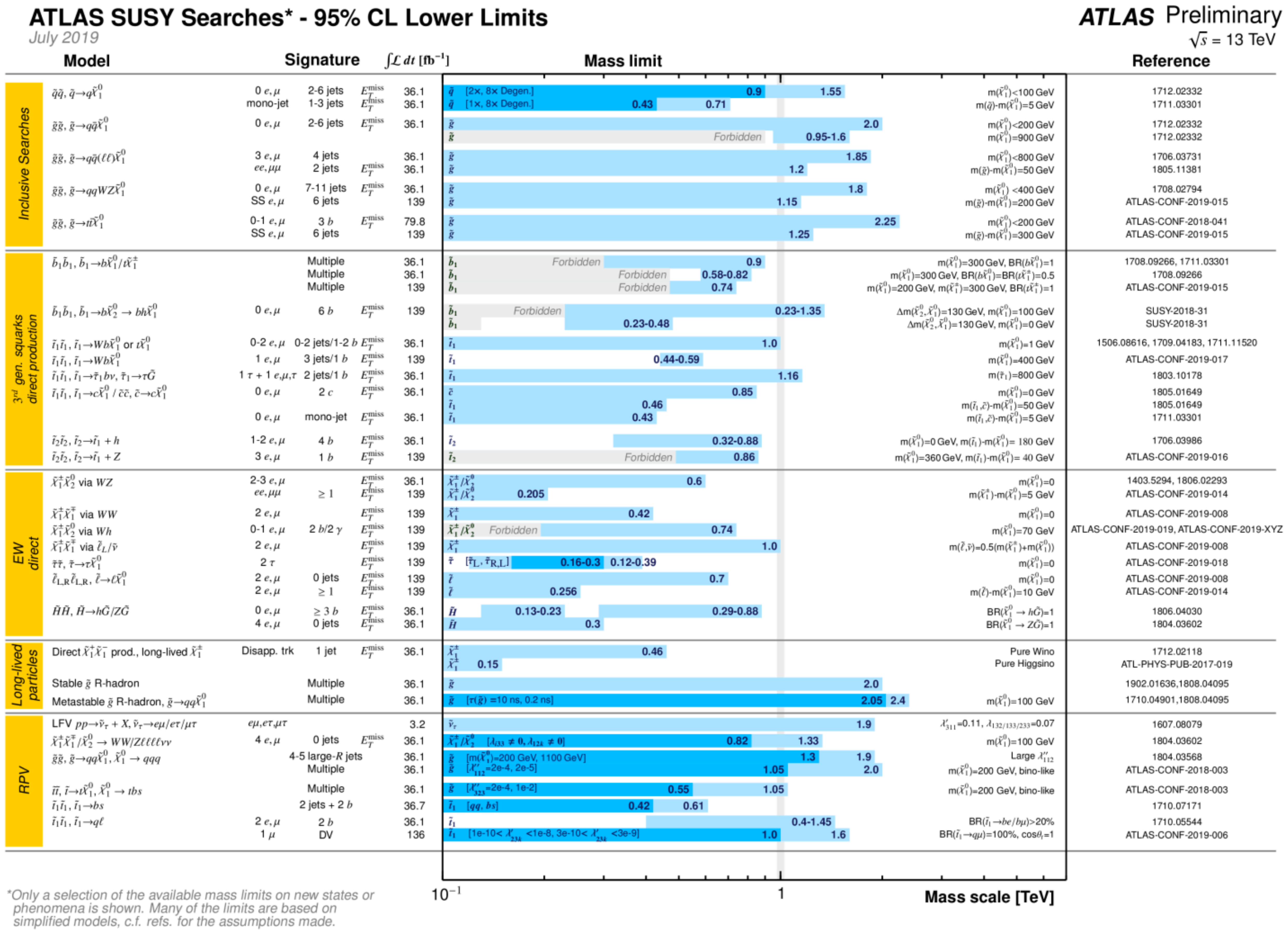

Many, many different ways to search for SUSY at colliders. ATLAS and CMS are the two, powerful, all-purpose detectors at the Large Hadron Collider. To date, no evidence for SUSY has been found.

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  - …

Thank you!