

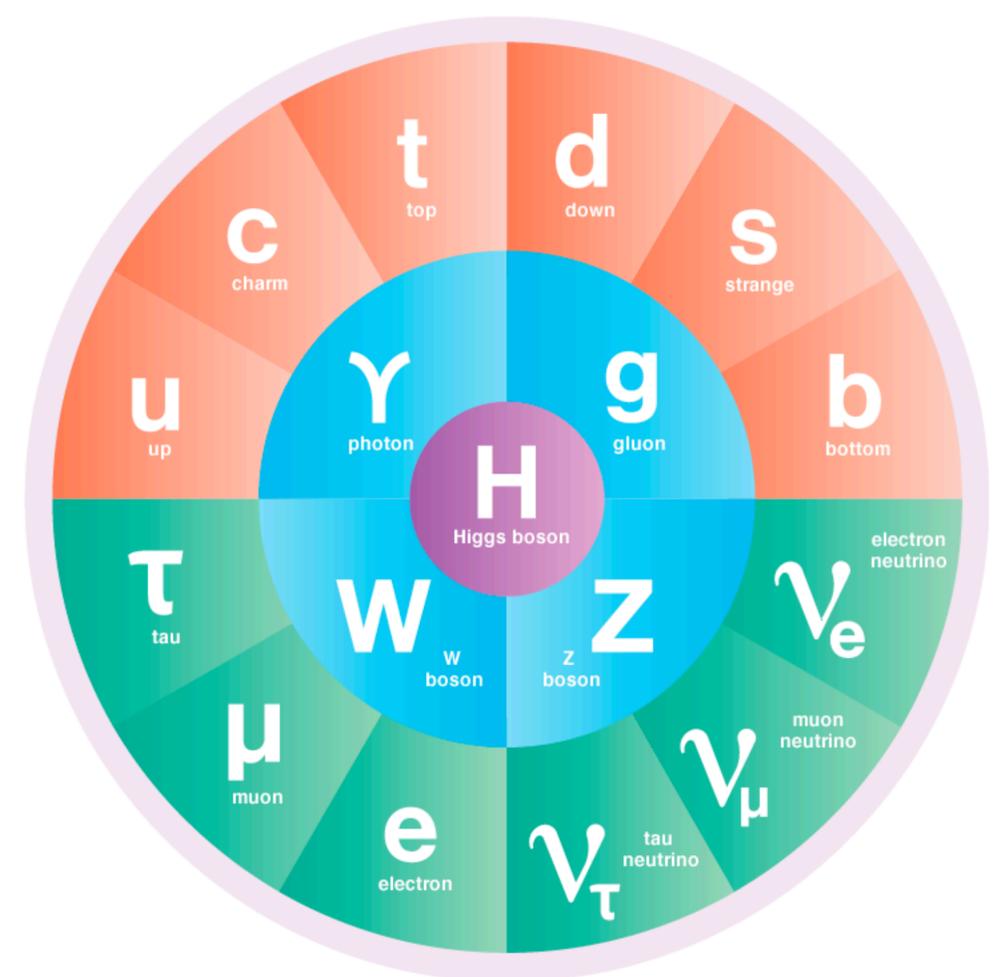
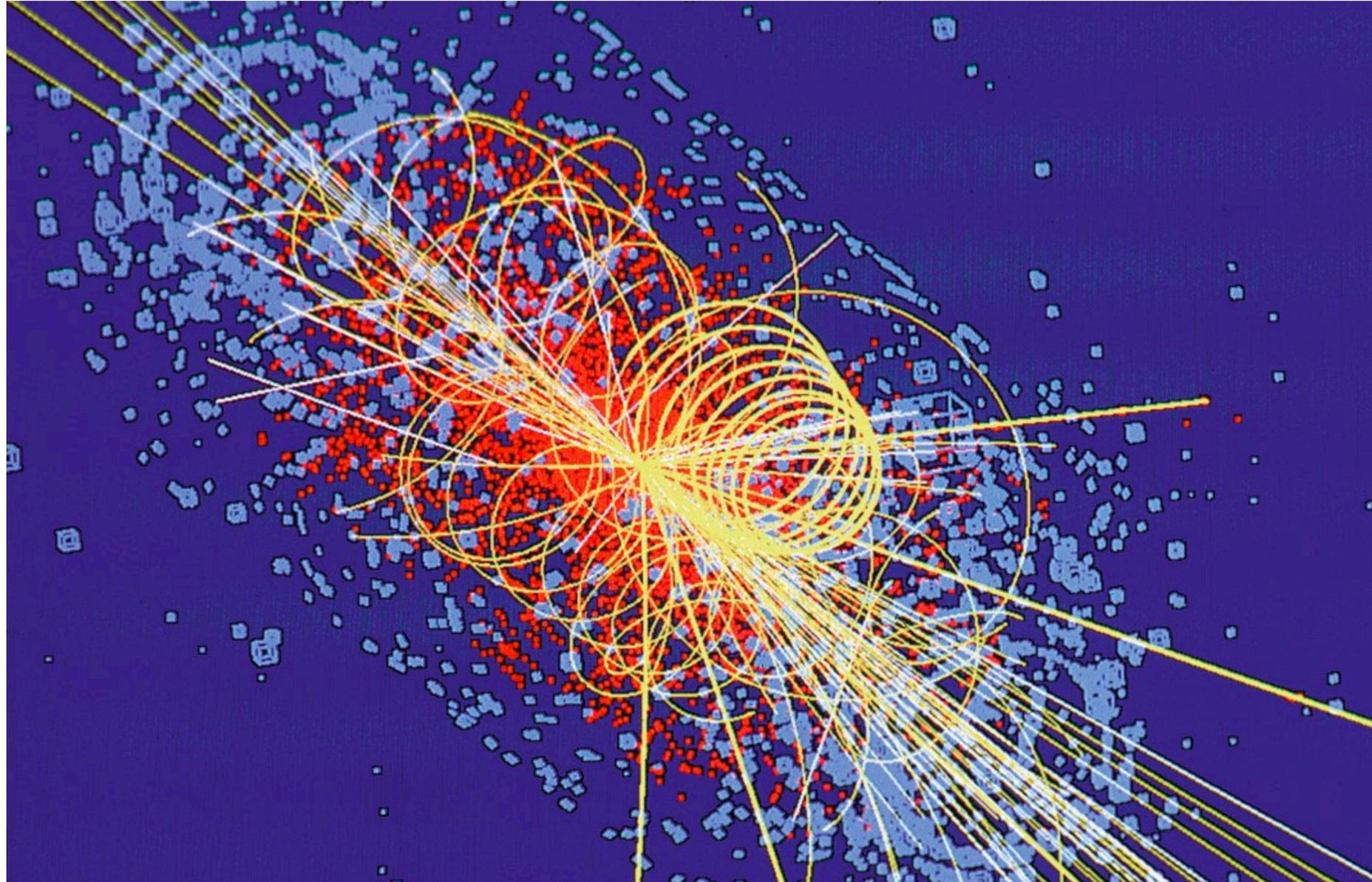


Introduction to Particle Physics

Kevin J. Kelly

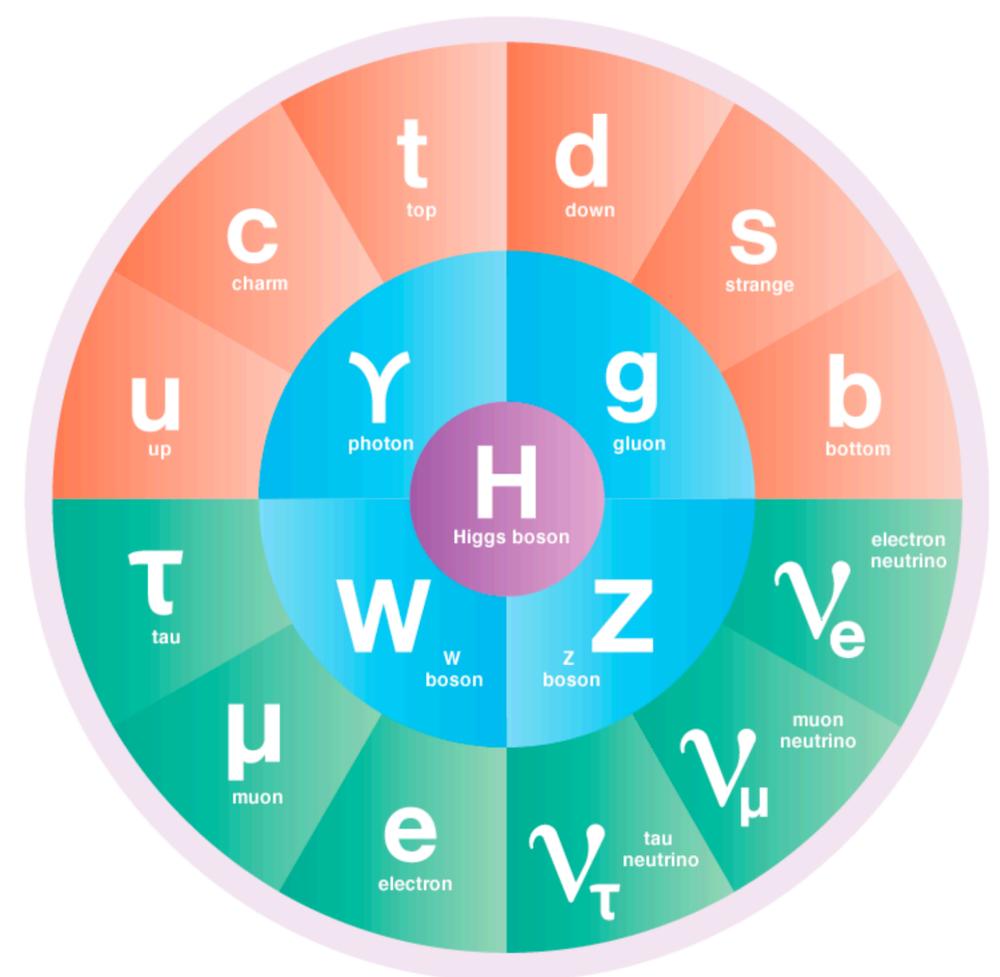
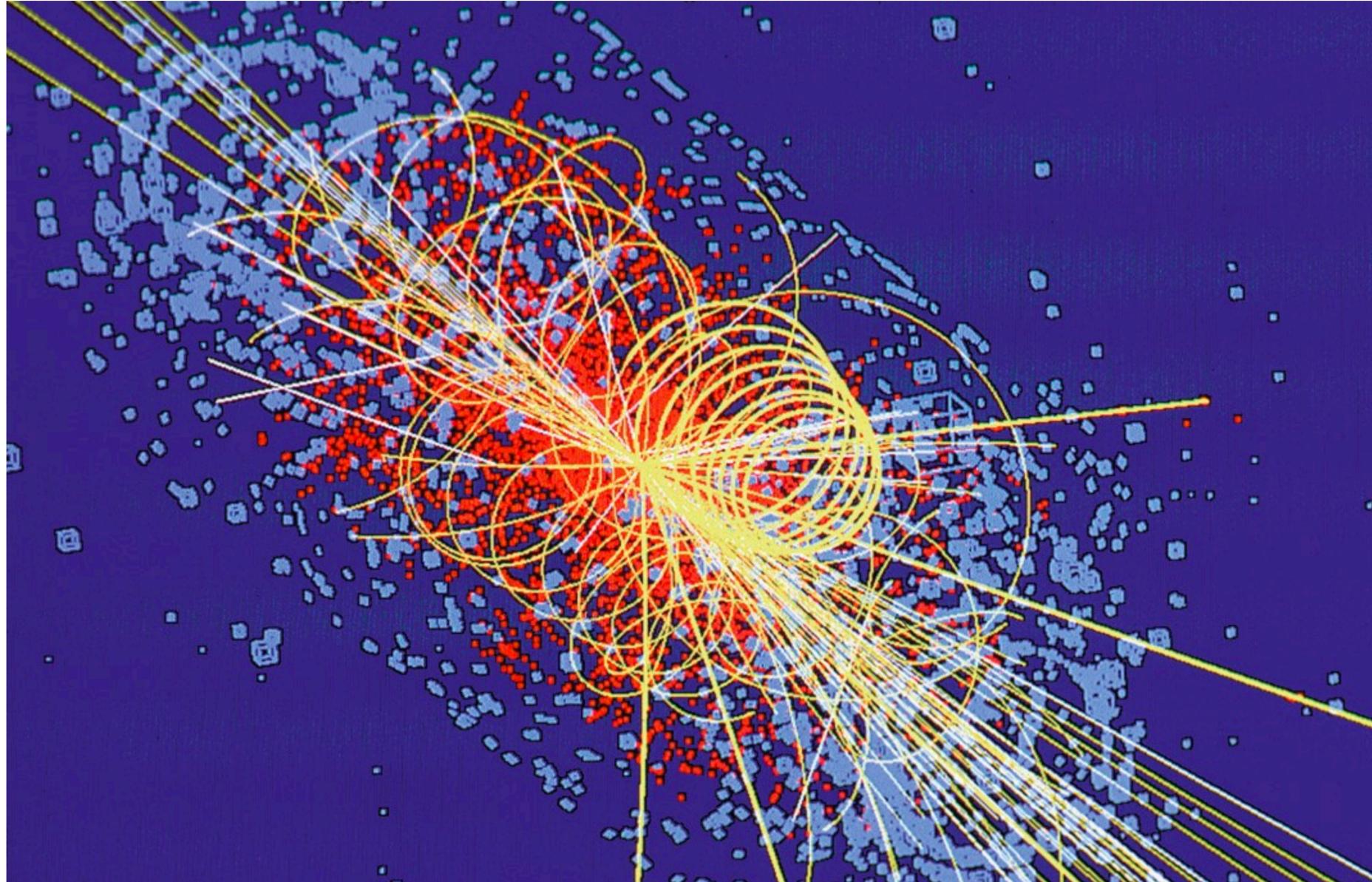
Undergraduate Lecture Series, May 28th, 2020

What is Particle Physics?



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

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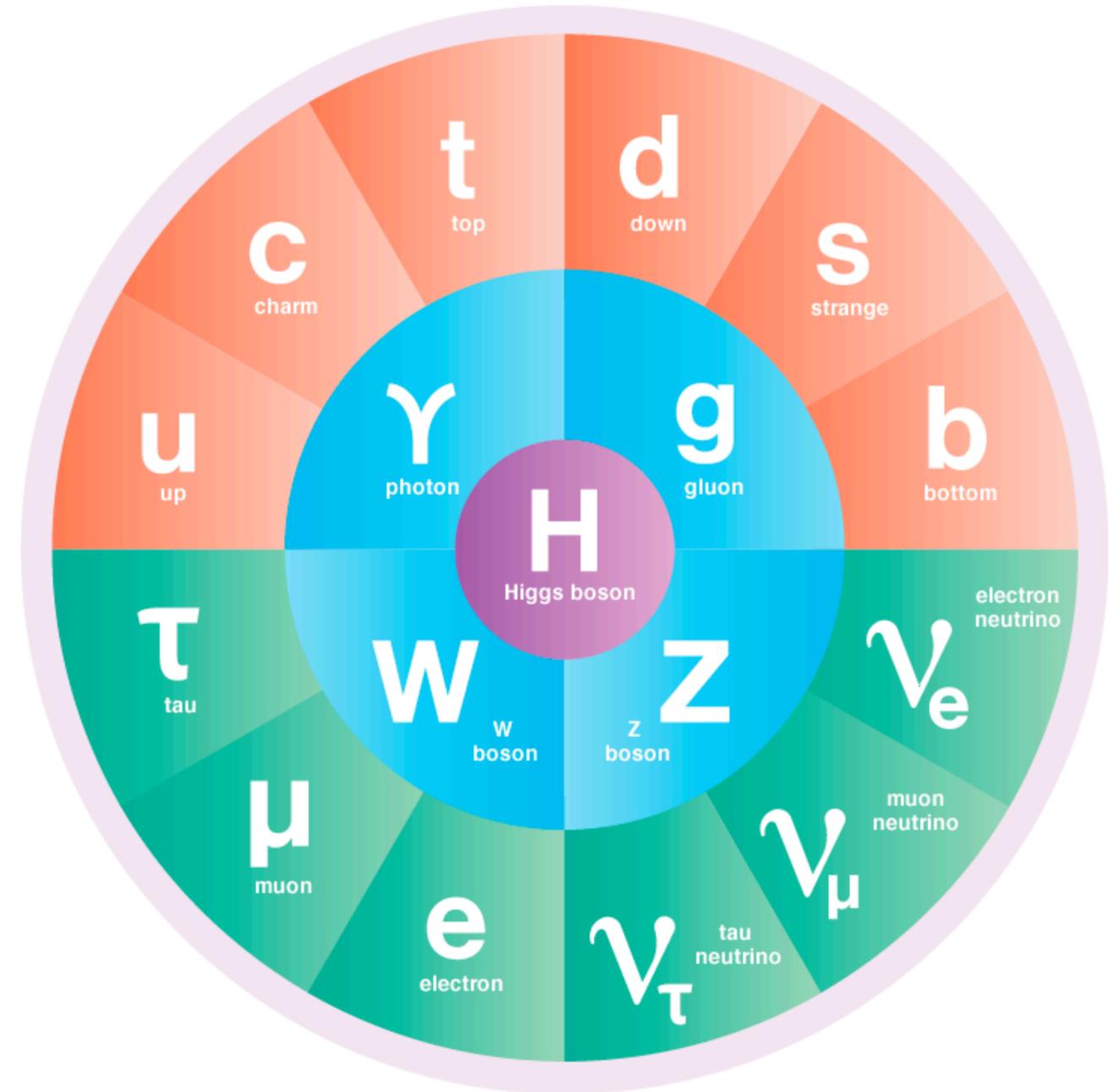


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Broader applications than “just particles” — we’ll get to those later.

A bit of history...

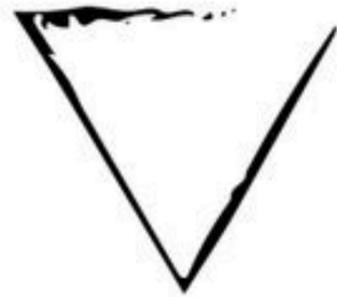
- Physicists today claim to know what “everything” is made up of — the Standard Model. How did we get here?



~2000 years in one slide



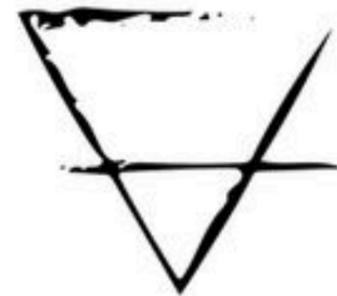
Fire



Water

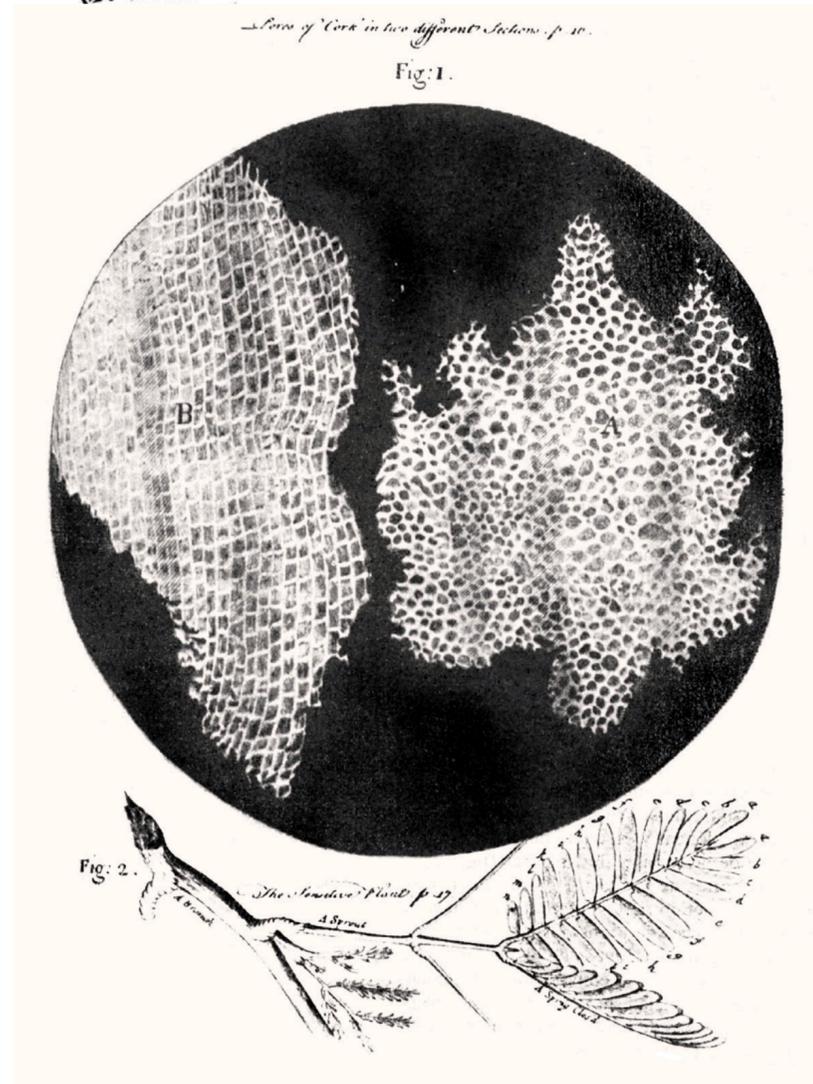
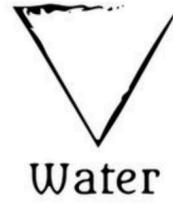


Air



Earth

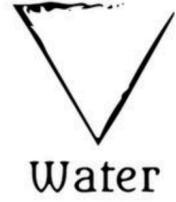
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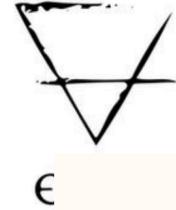
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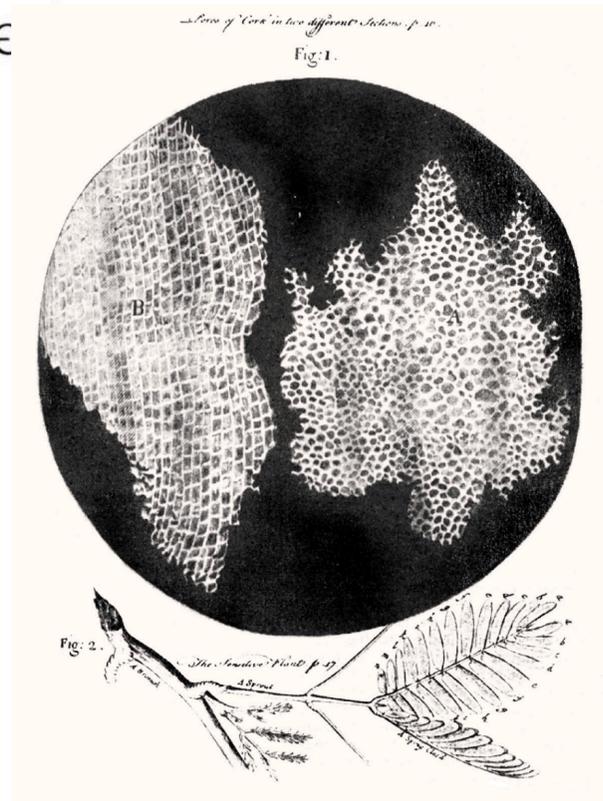
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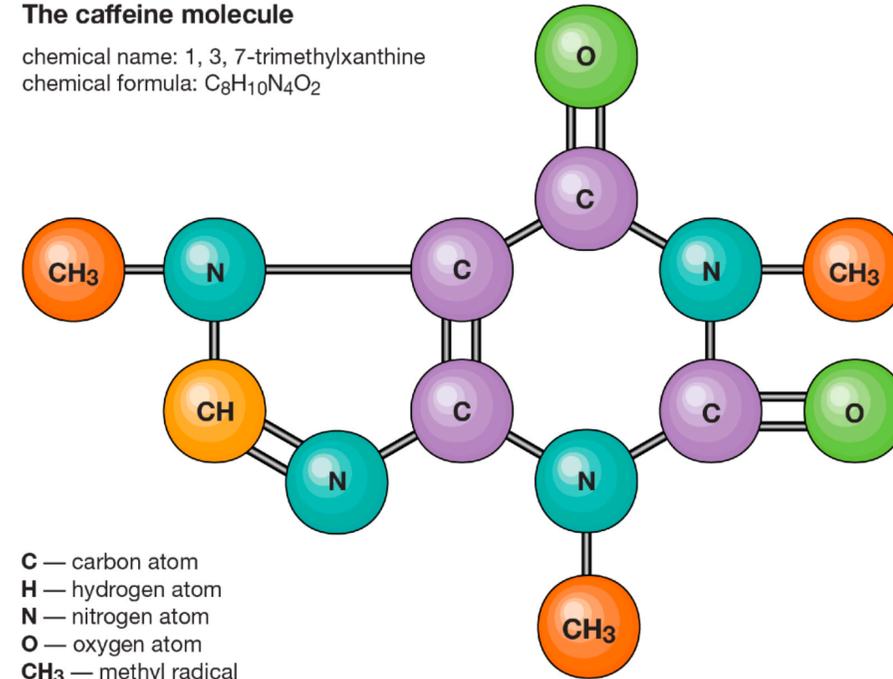


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The caffeine molecule

chemical name: 1, 3, 7-trimethylxanthine
chemical formula: $C_8H_{10}N_4O_2$

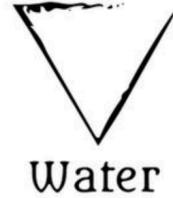


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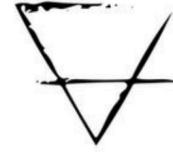
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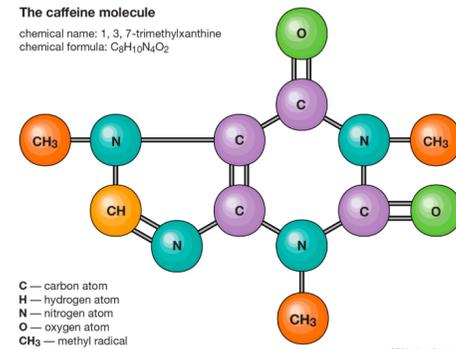
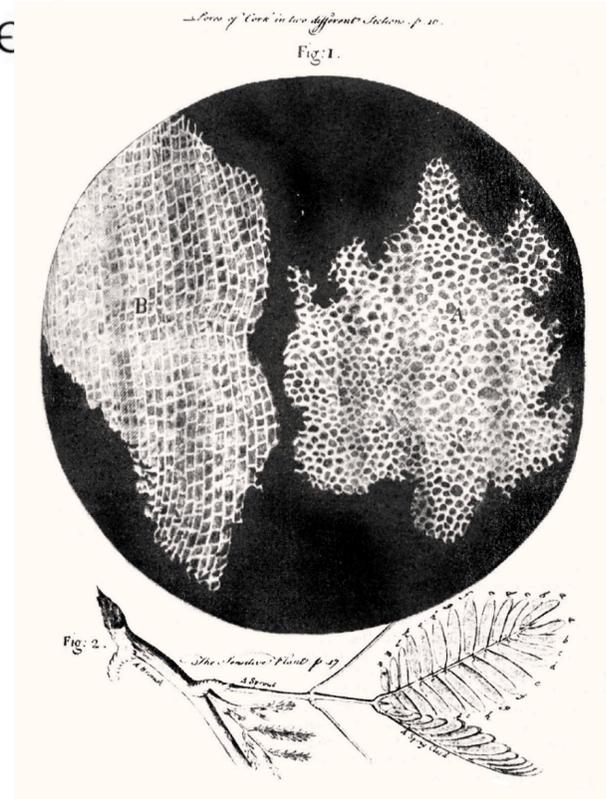
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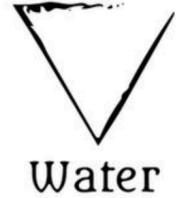


Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period 1	1 H																	2 He
Period 2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
Period 3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
Period 4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
Period 5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
Period 6	55 Cs	56 Ba	57 La *	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
Period 7	87 Fr	88 Ra	89 Ac *	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

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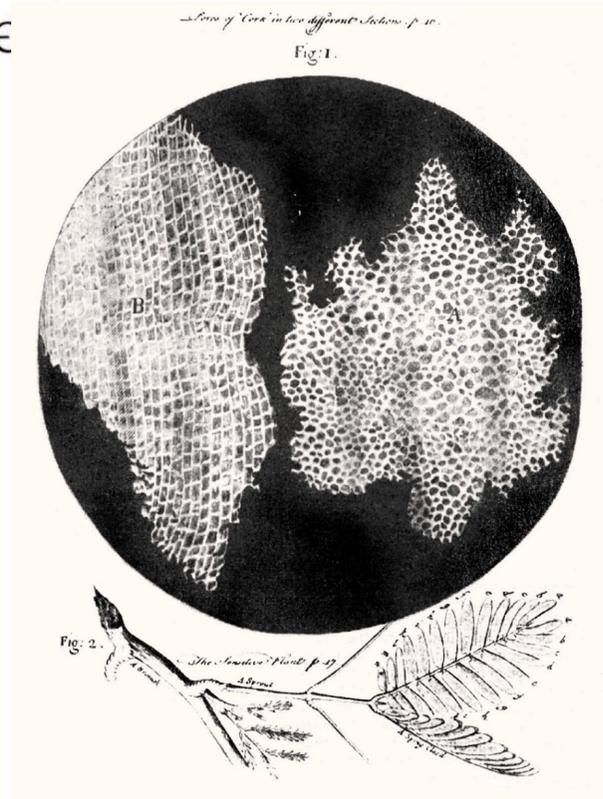
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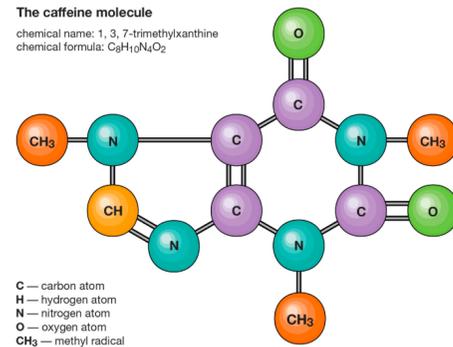


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The caffeine molecule

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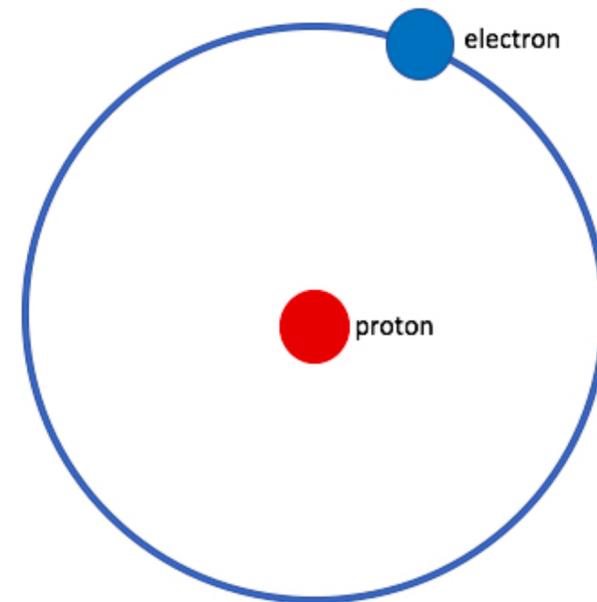


C — carbon atom
H — hydrogen atom
N — nitrogen atom
O — oxygen atom
CH₃ — methyl radical

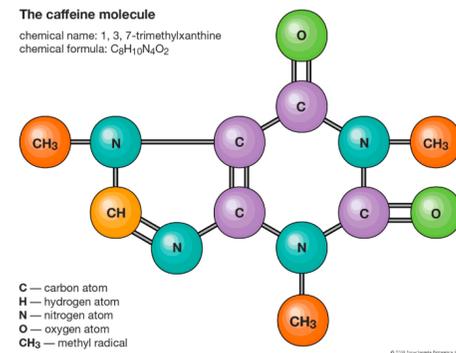
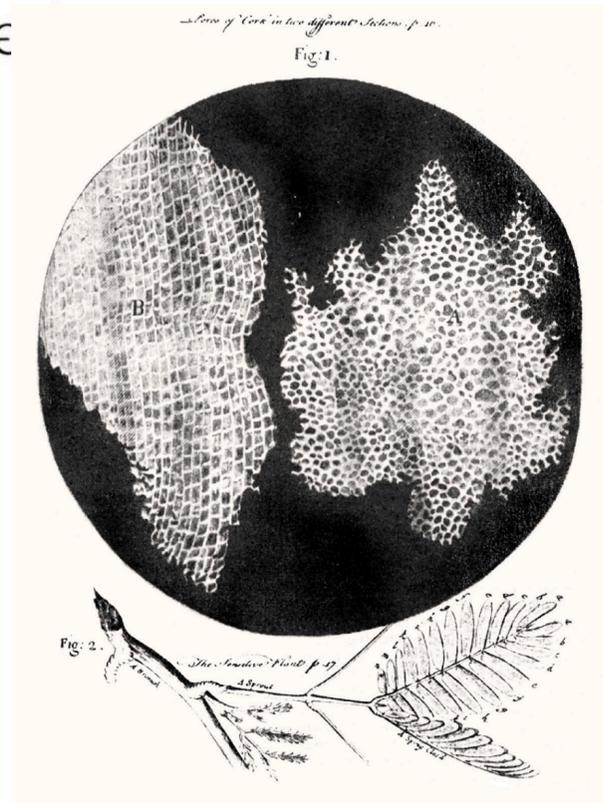
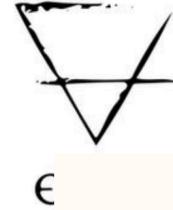
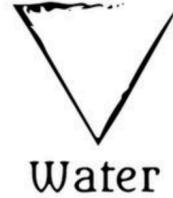
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Hydrogen Atom

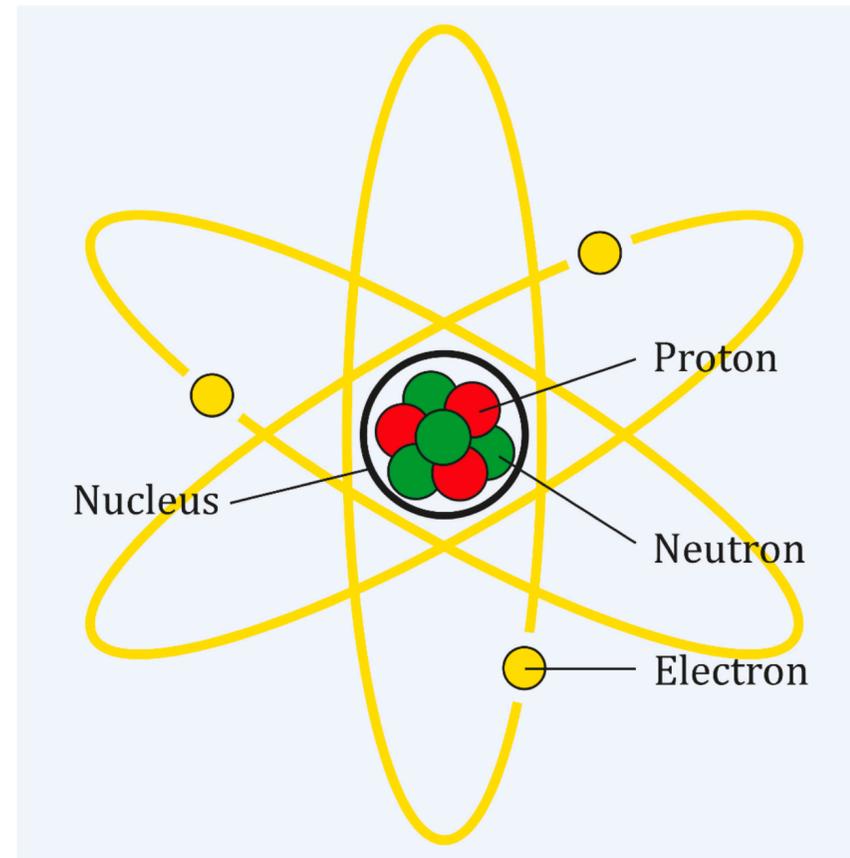
*Not to scale.



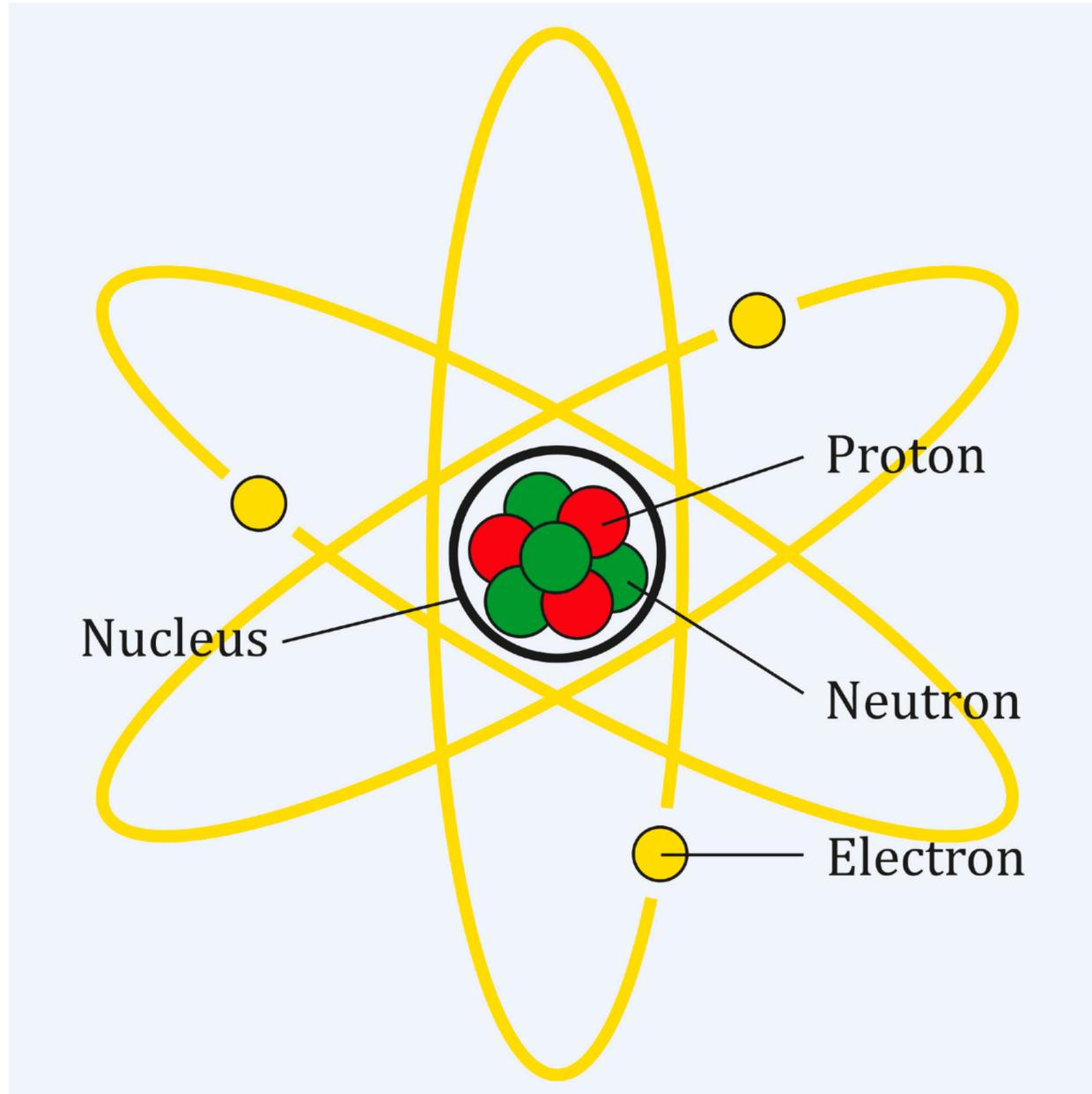
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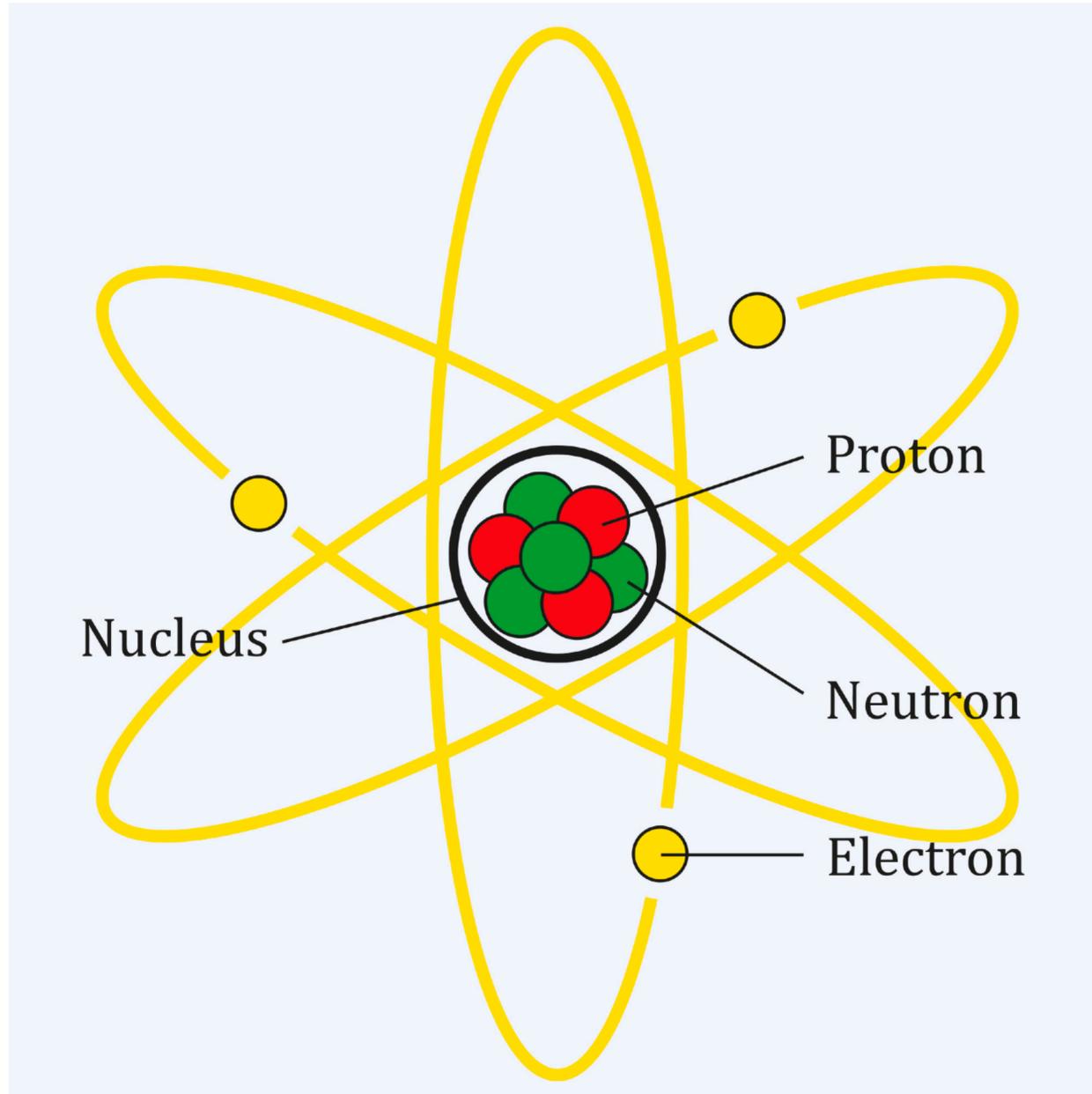
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Early 1900s

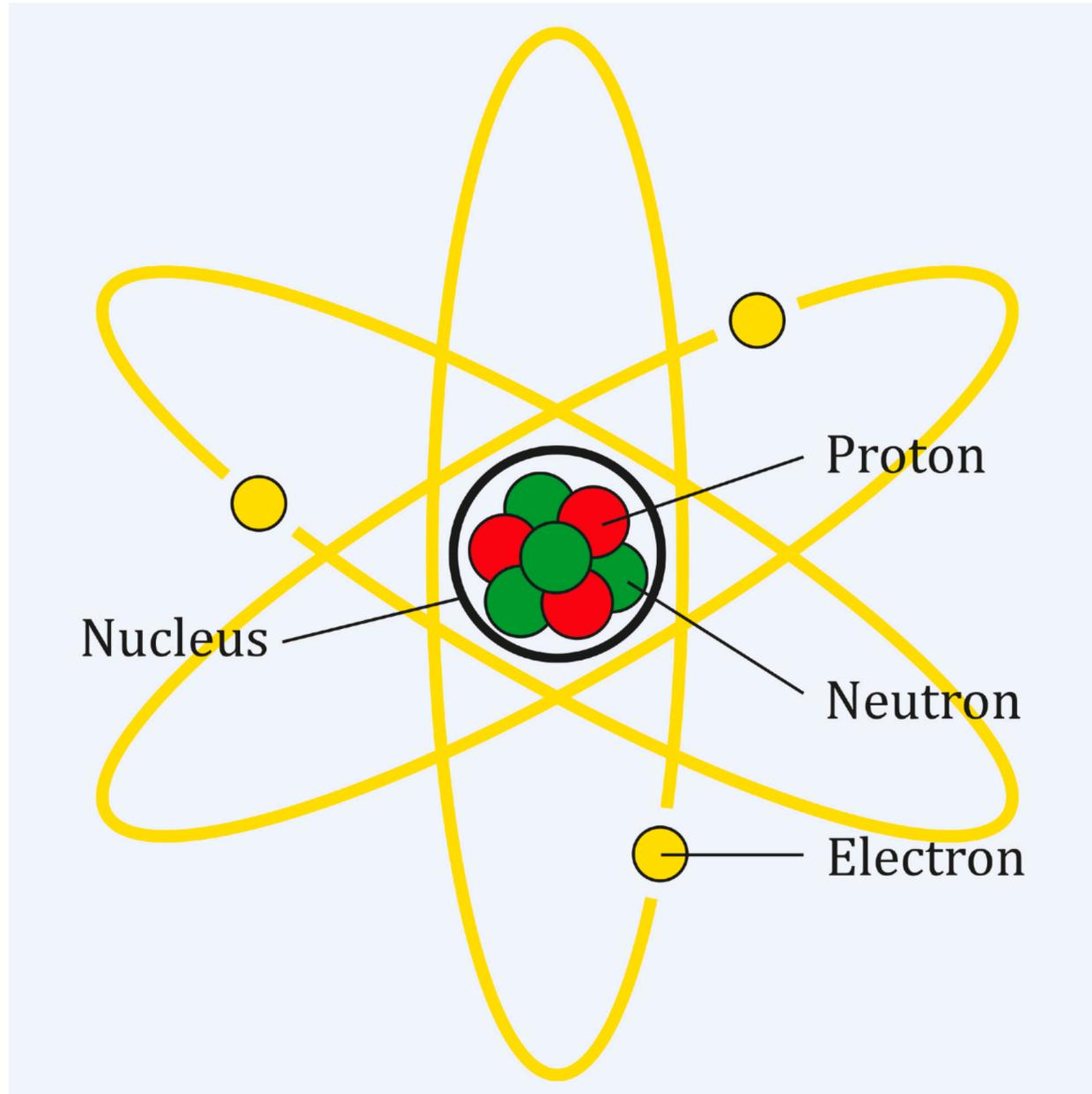


Early 1900s



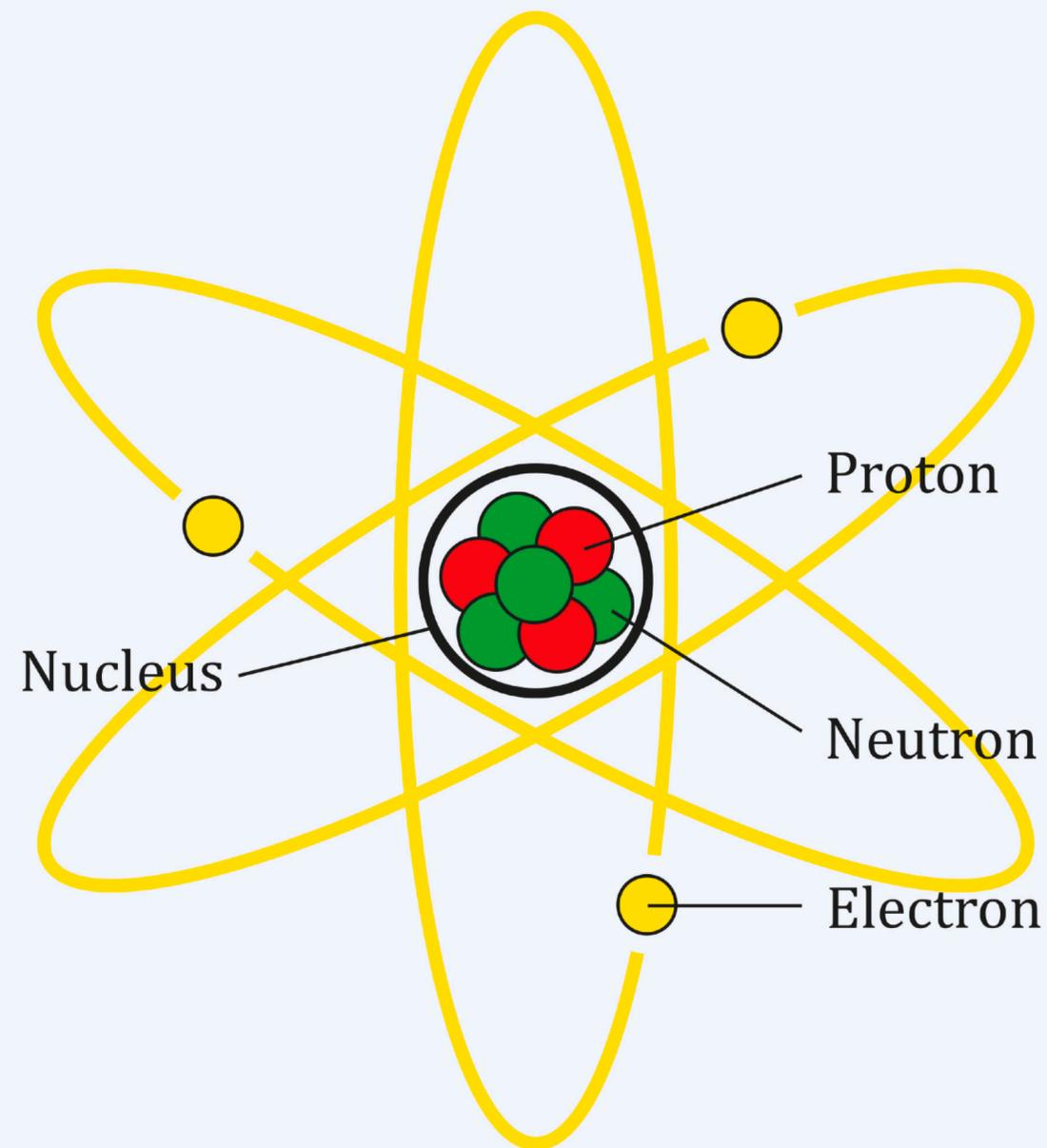
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- Protons and neutrons build up the nuclei of atoms, and electrons occupy orbitals around the nucleus.
- Different models of the atom were explored, leading to the development of quantum mechanics.

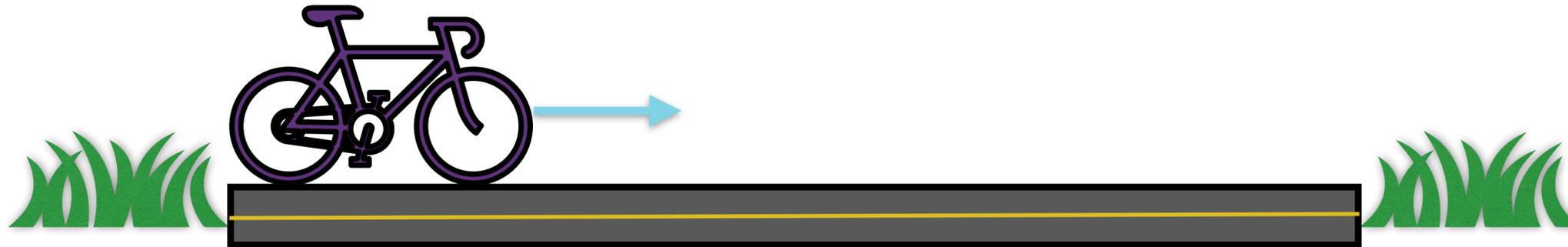
**Let's put a pin in particles
for now.**

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

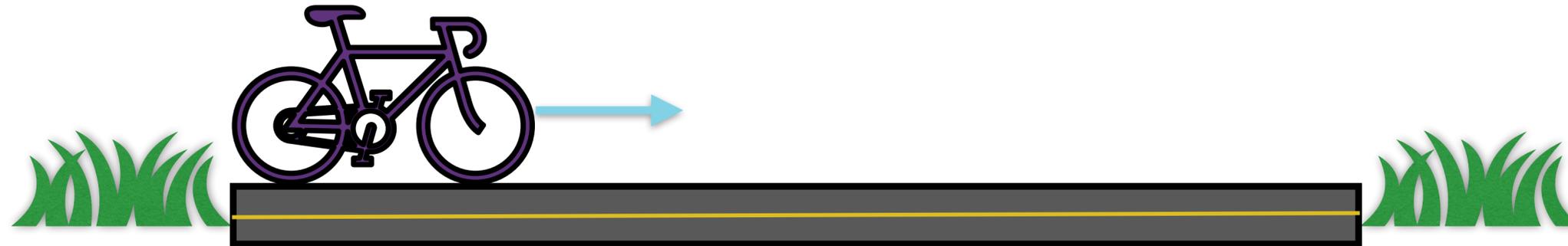
One of the simplest symmetries in nature: *Translational Invariance*

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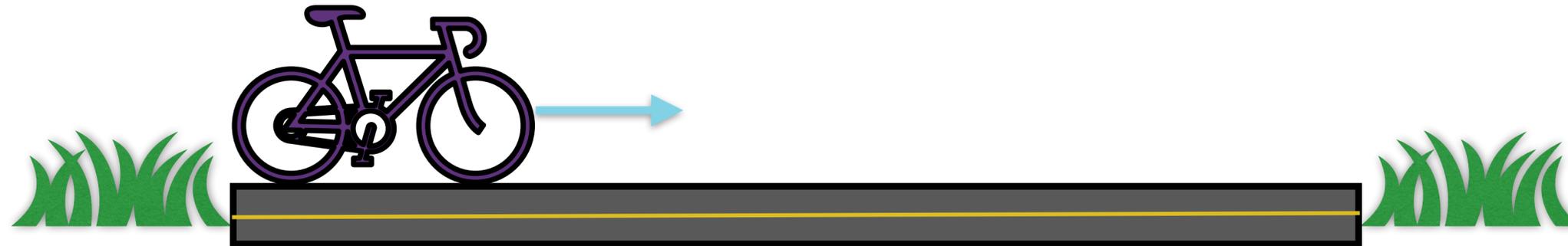


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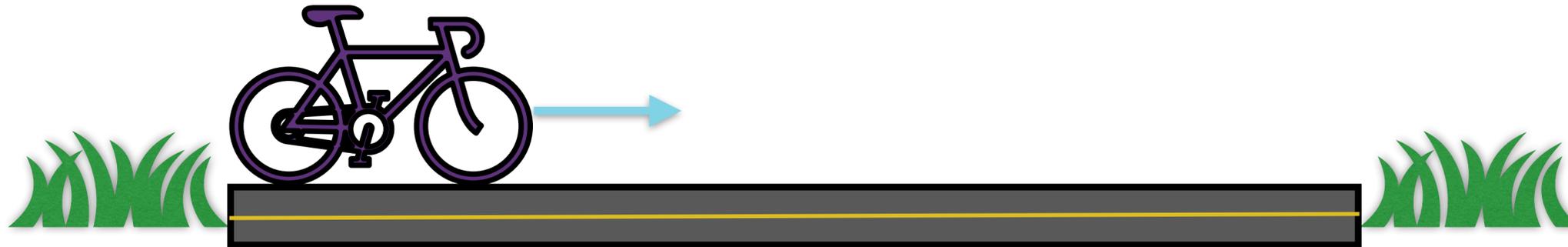


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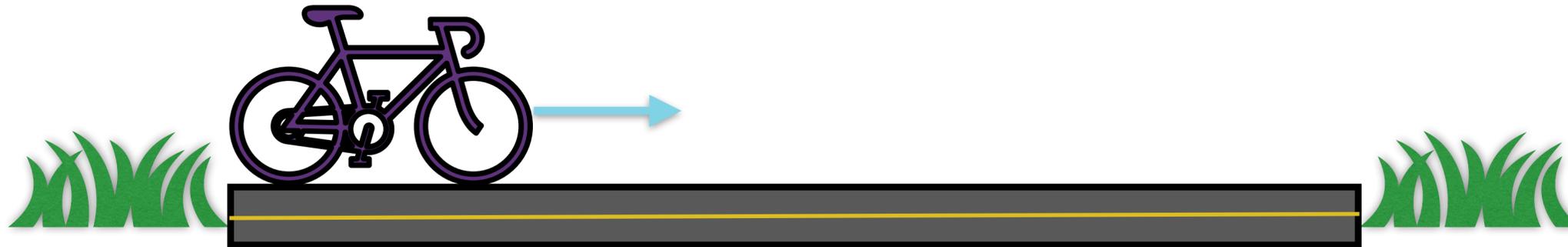


- From the bike's point of view, the surrounding road is unchanged.

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



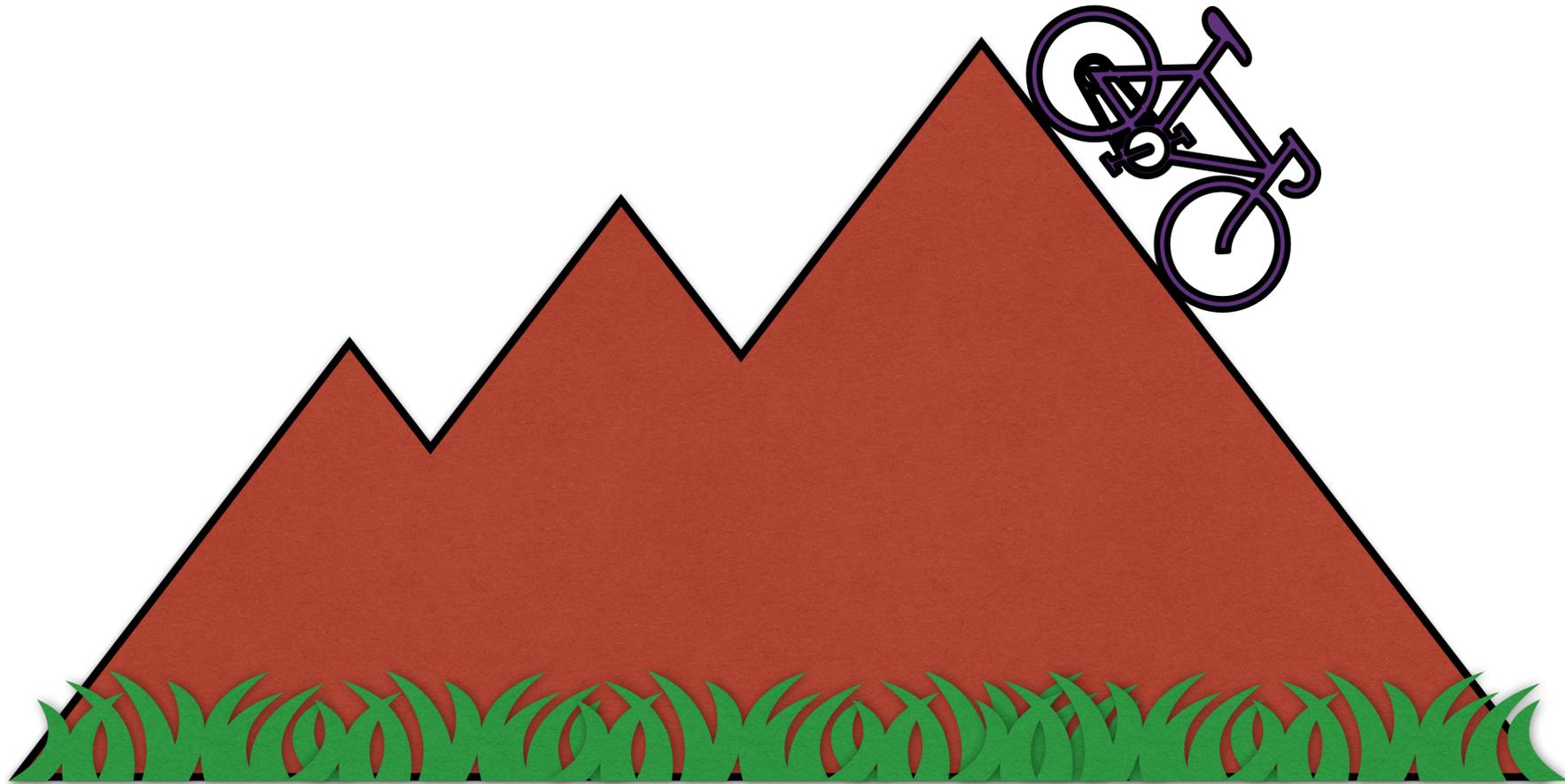
One of the simplest symmetries in nature: *Translational Invariance*



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

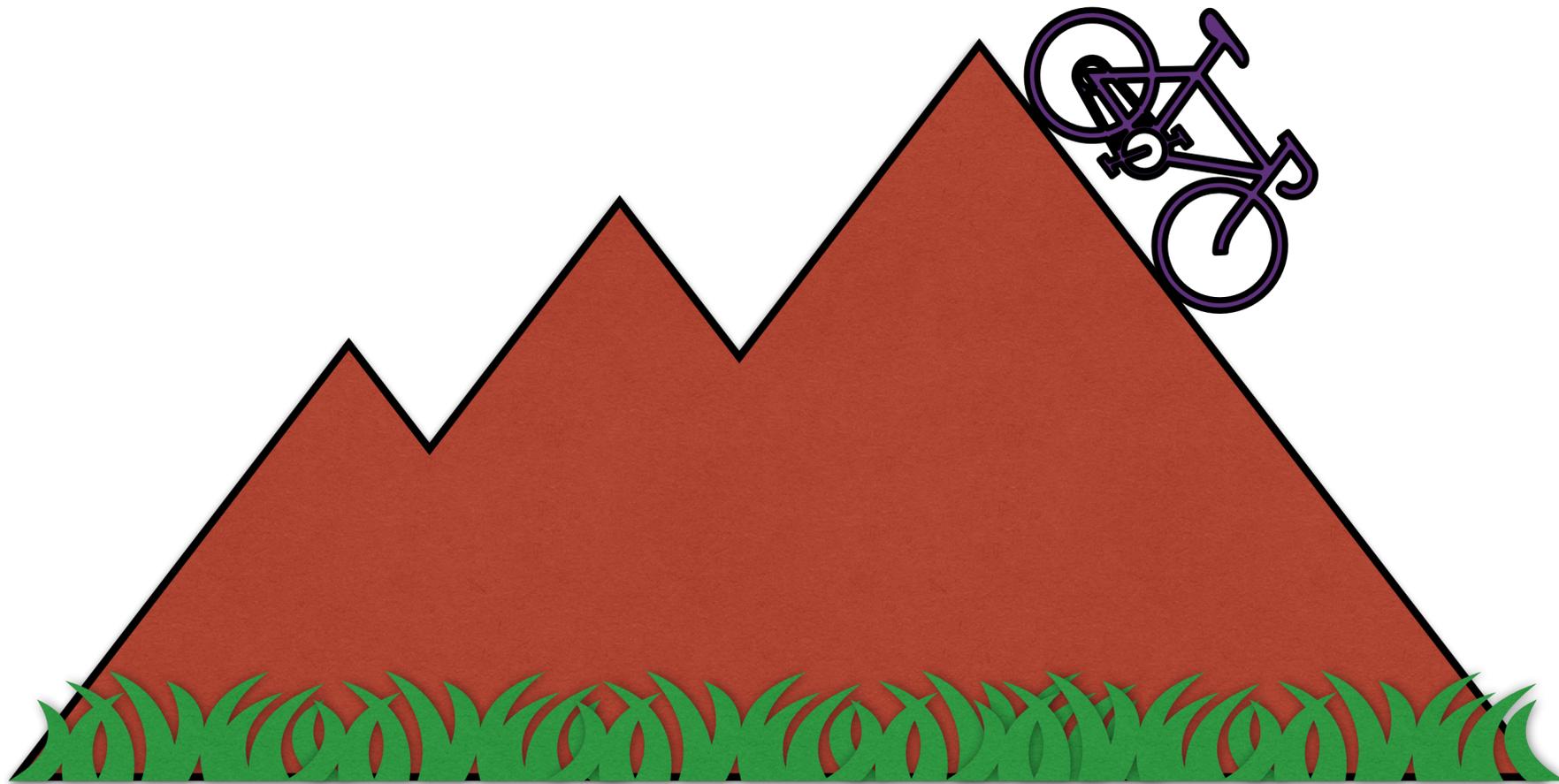
Slightly more complicated: *Time-translation Invariance*

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



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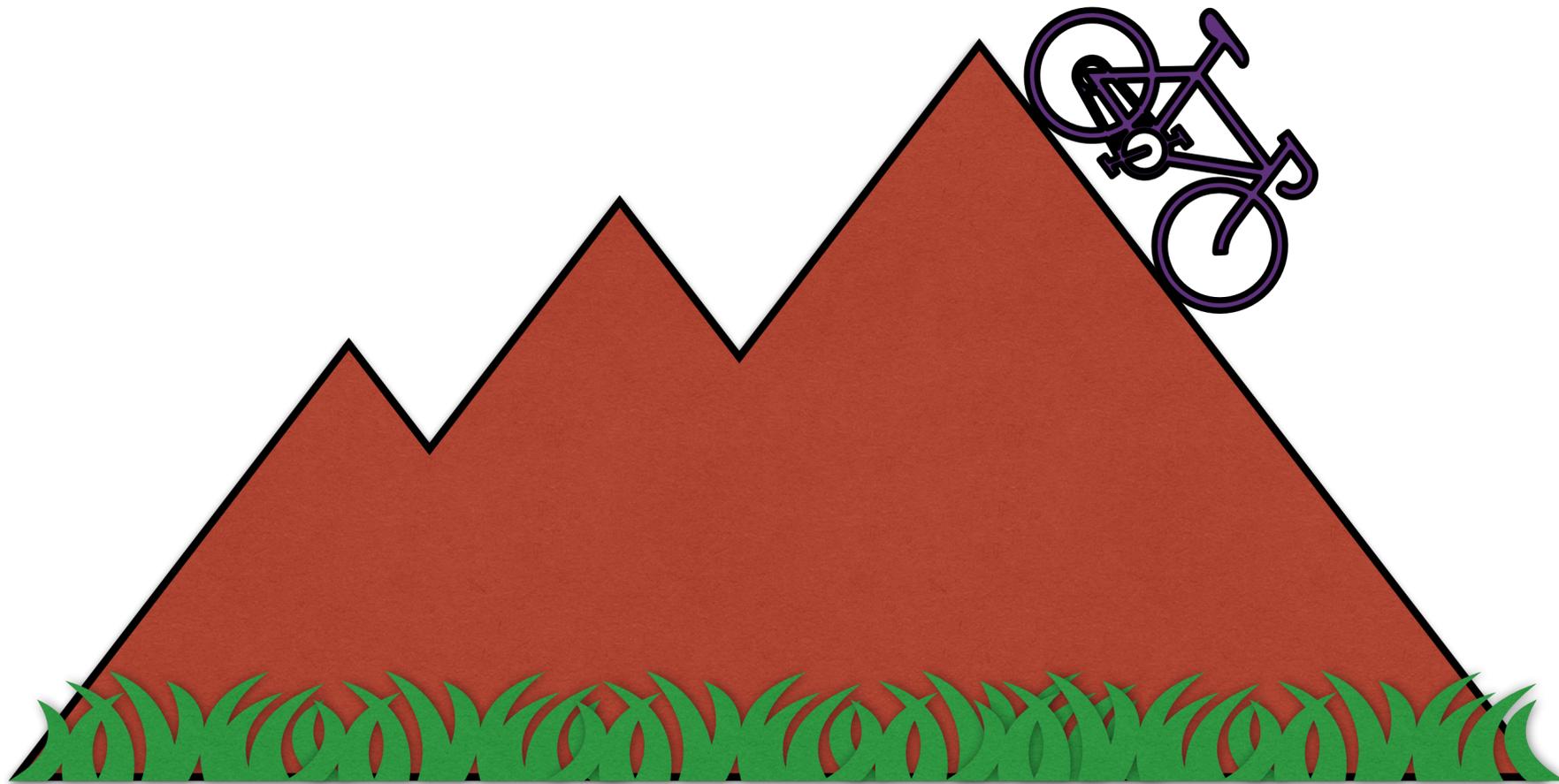
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Slightly more complicated: *Time-translation Invariance*

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

Noether's Theorem



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“To every differential symmetry generated by local actions there corresponds a conserved current.”



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Translational Invariance



Linear Momentum

Noether's Theorem



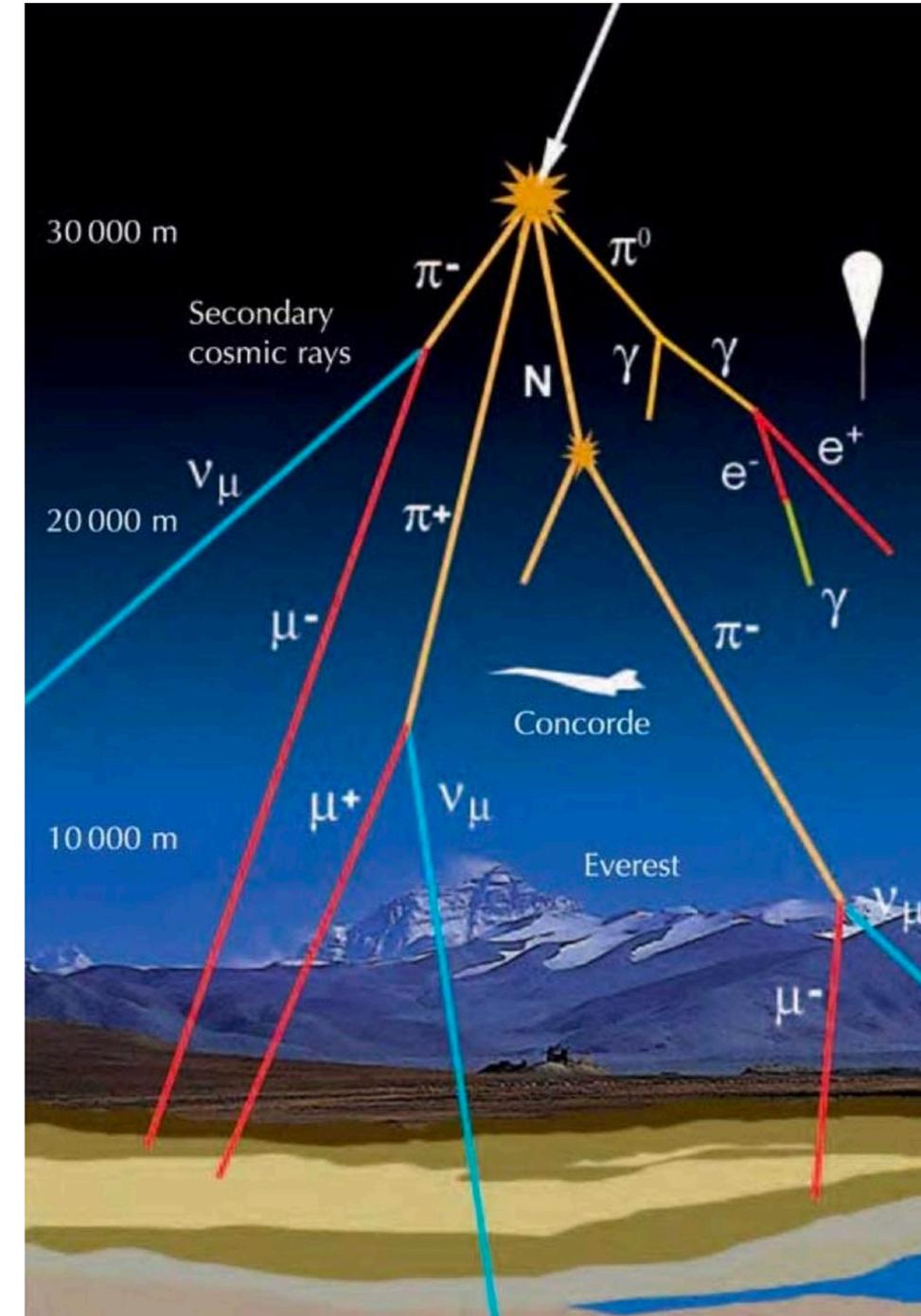
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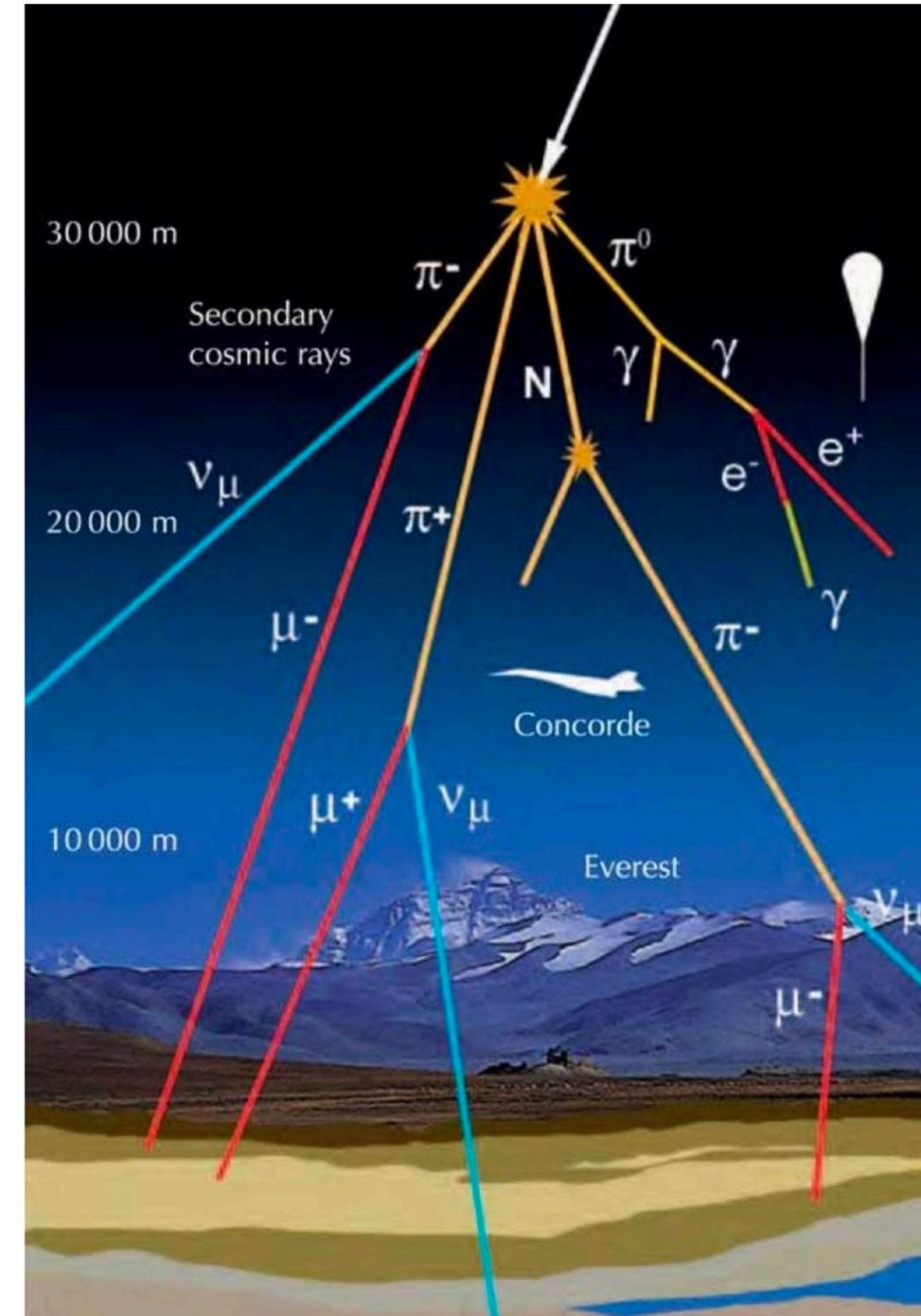


Applying Symmetries to Protons and Neutrons



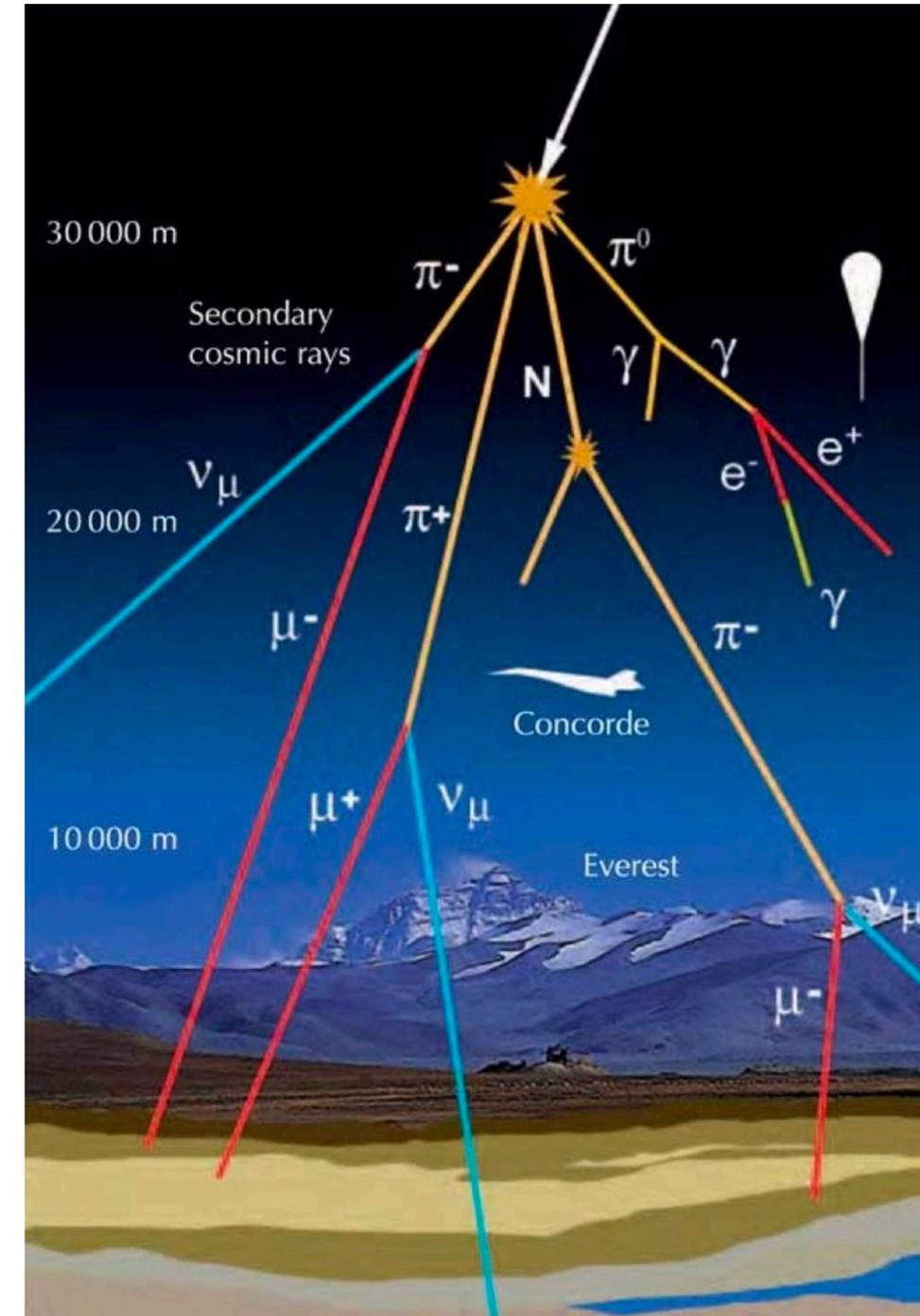
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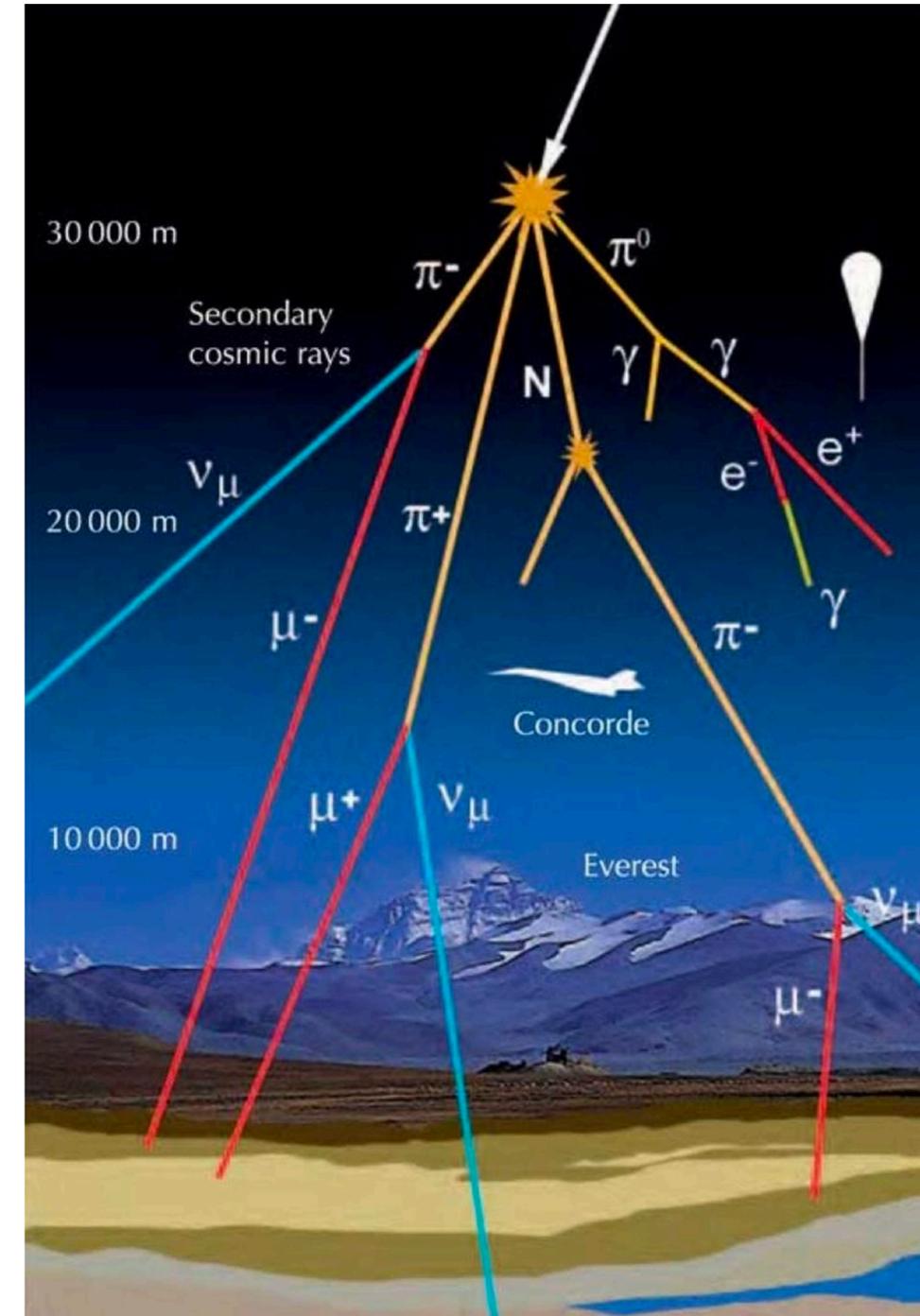
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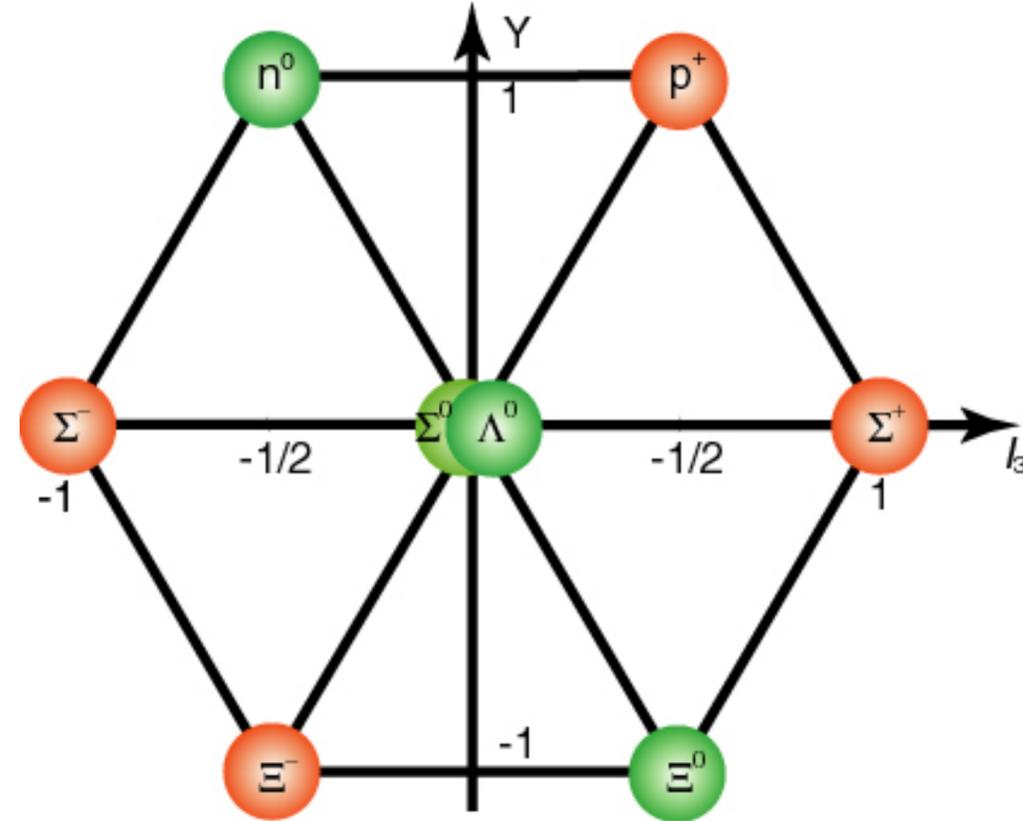


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- Introduce some spin-like symmetry where the proton has “isospin” up, and the neutron has “isospin” down.
- In the meantime, more exotic particles were being discovered in cosmic rays — pions and muons.

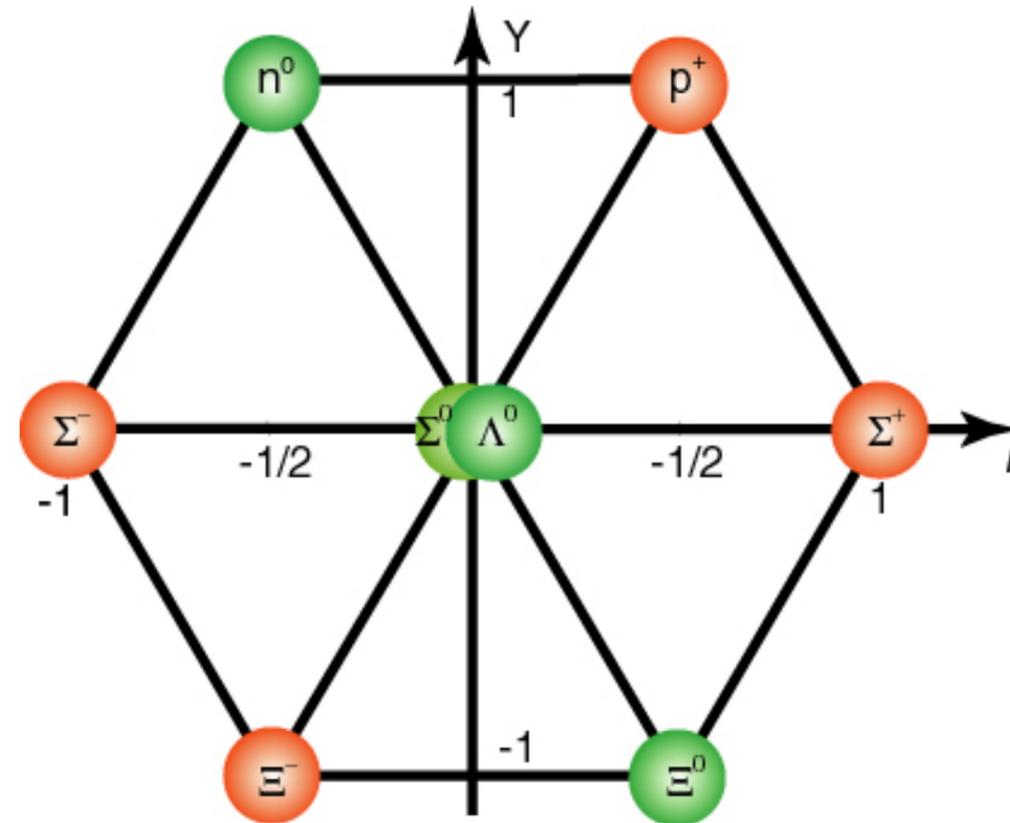


The Eightfold Way



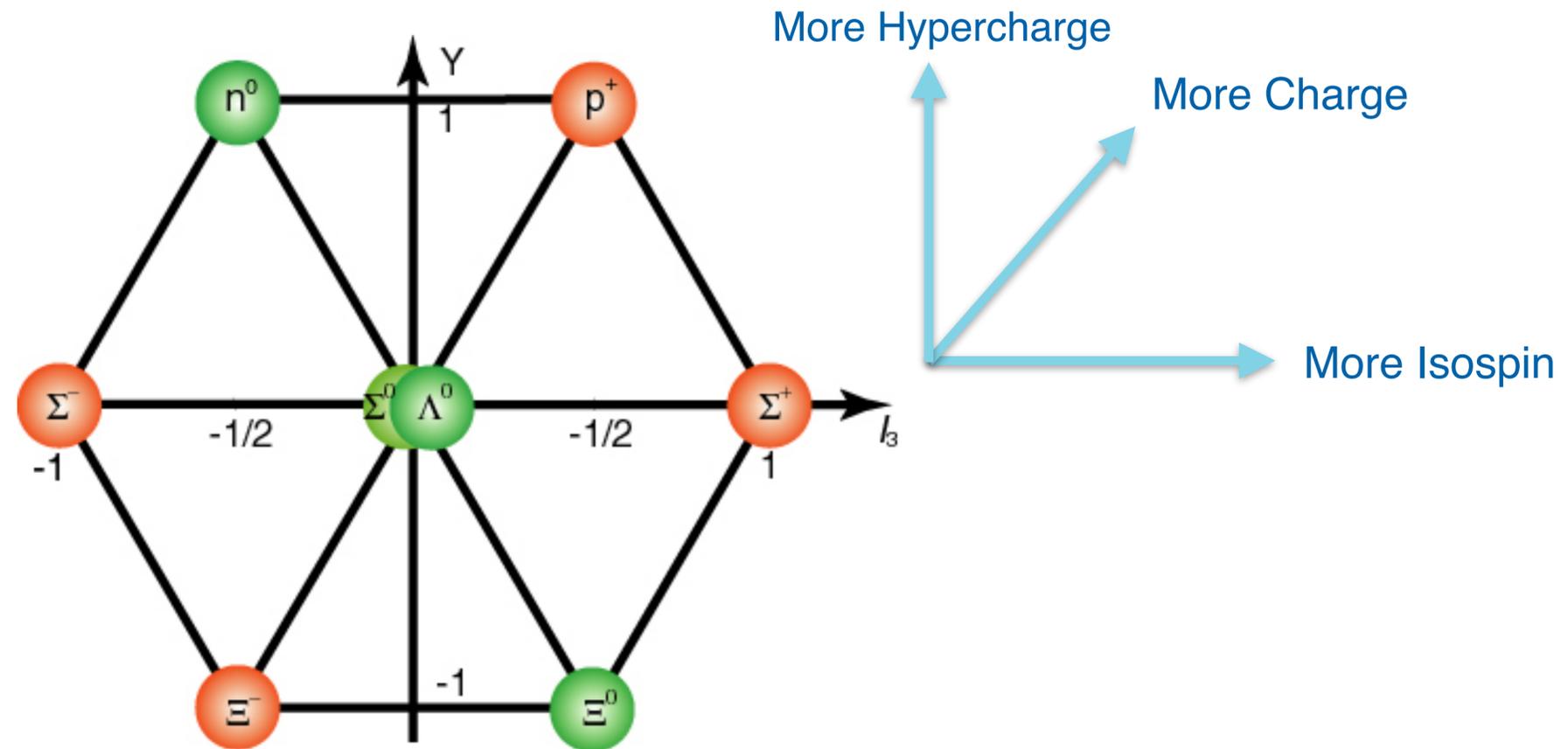
The Eightfold Way

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



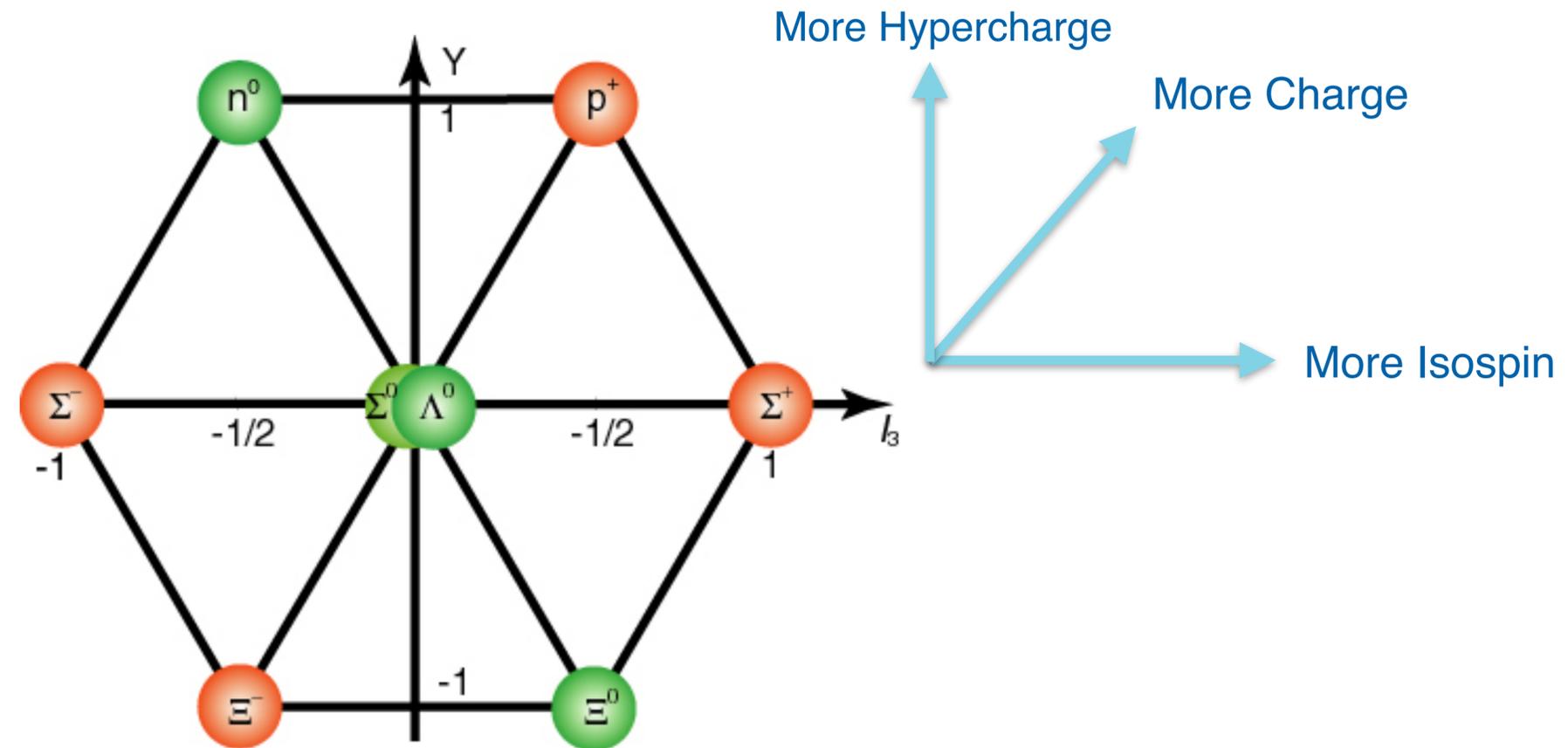
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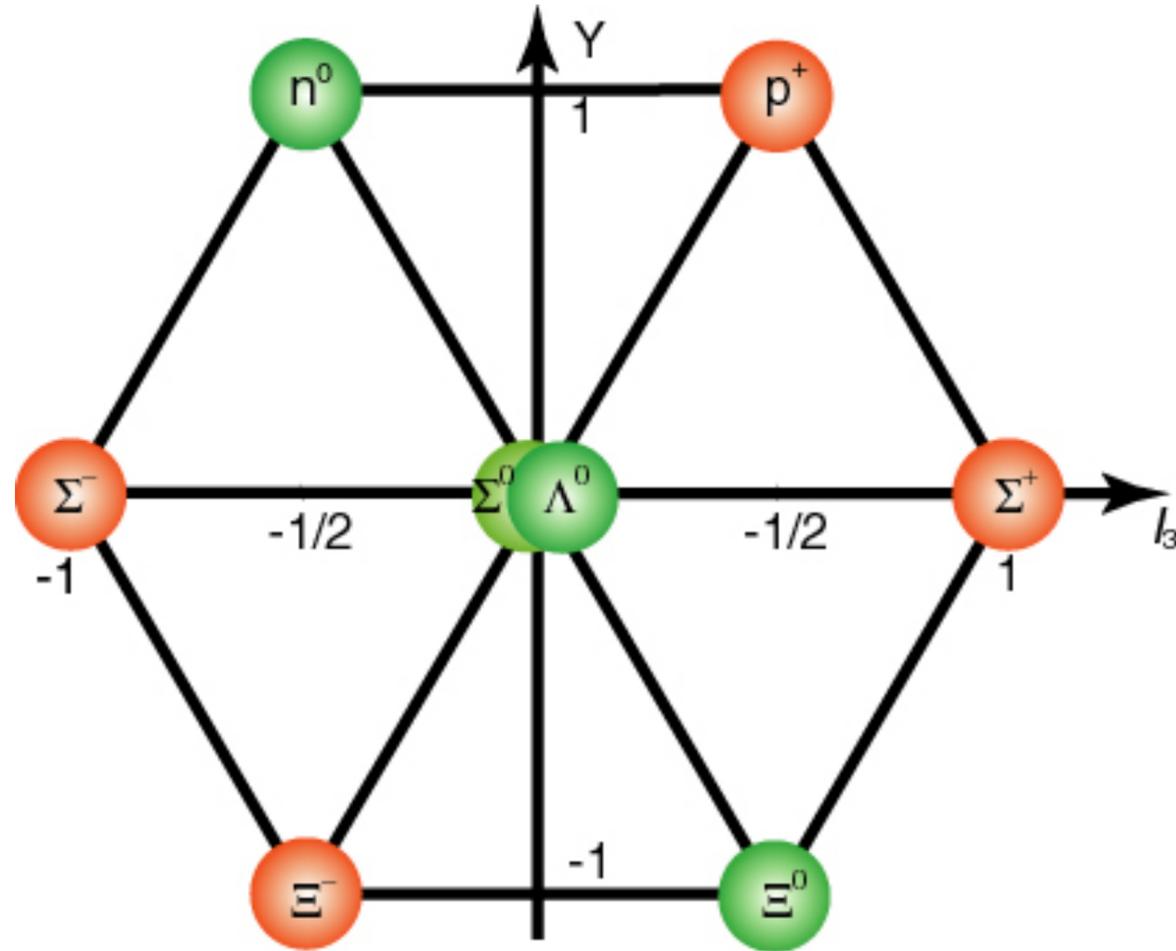
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Mesons, like the charged pions, mediate interactions between these hadrons.

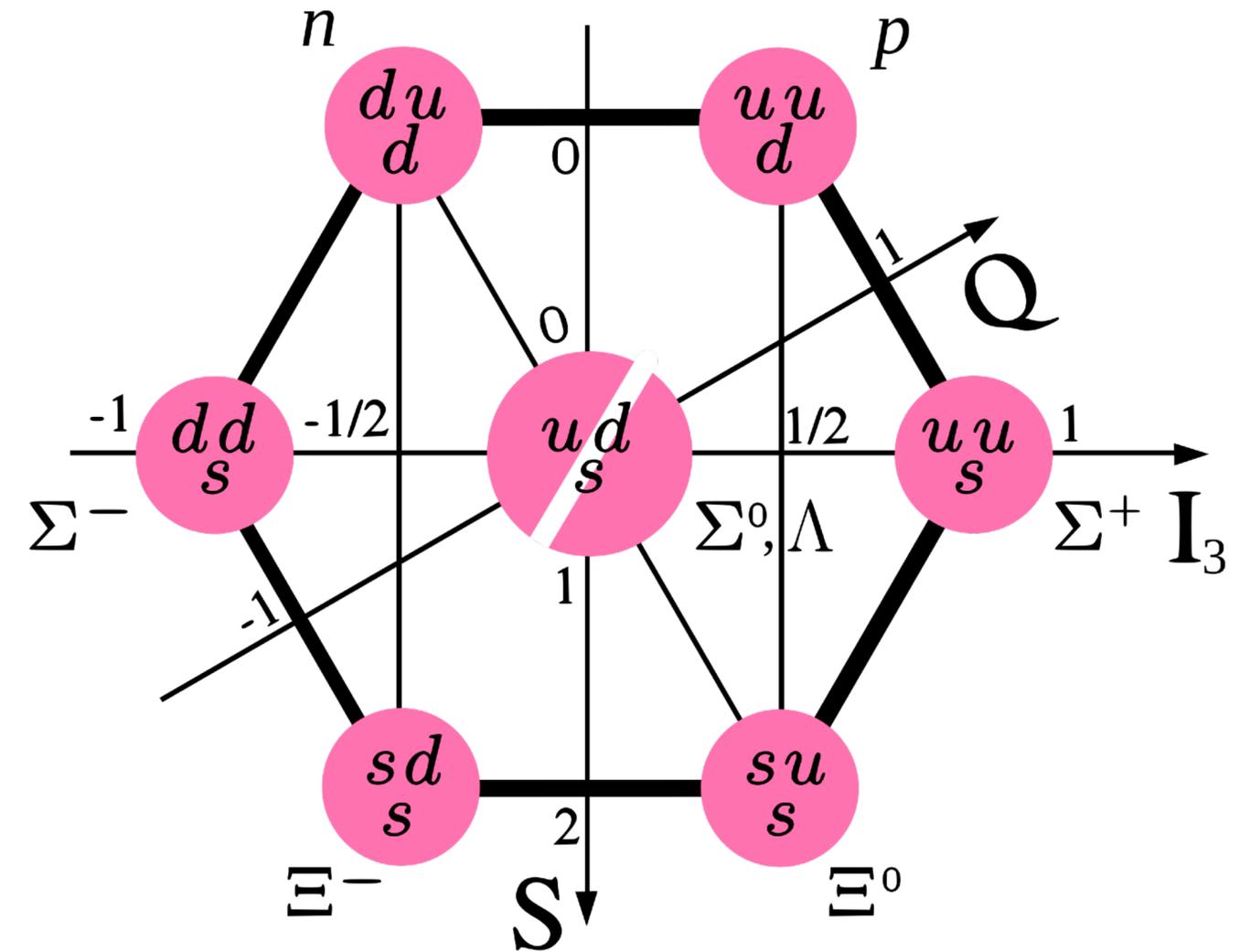
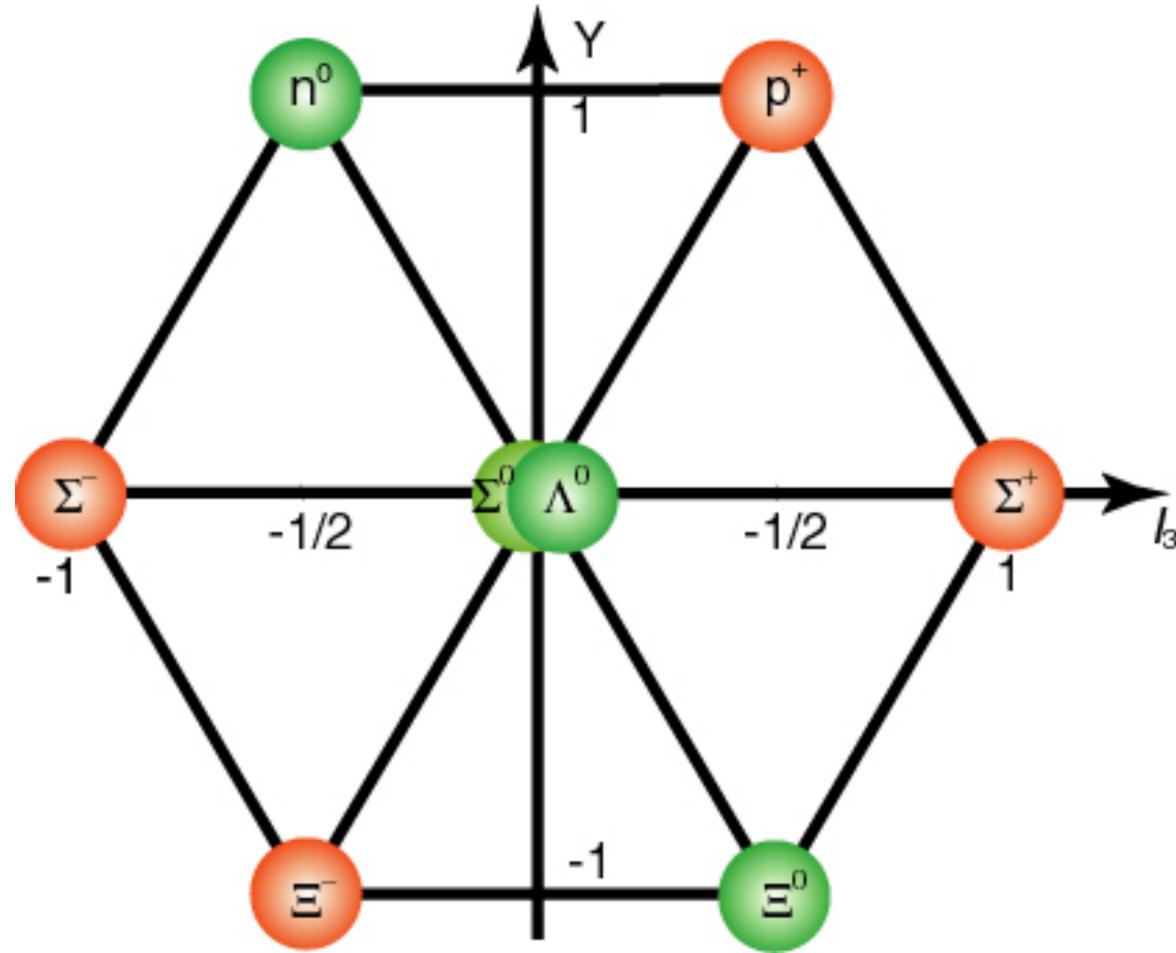
Gell-Mann, Zweig, and Quarks

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



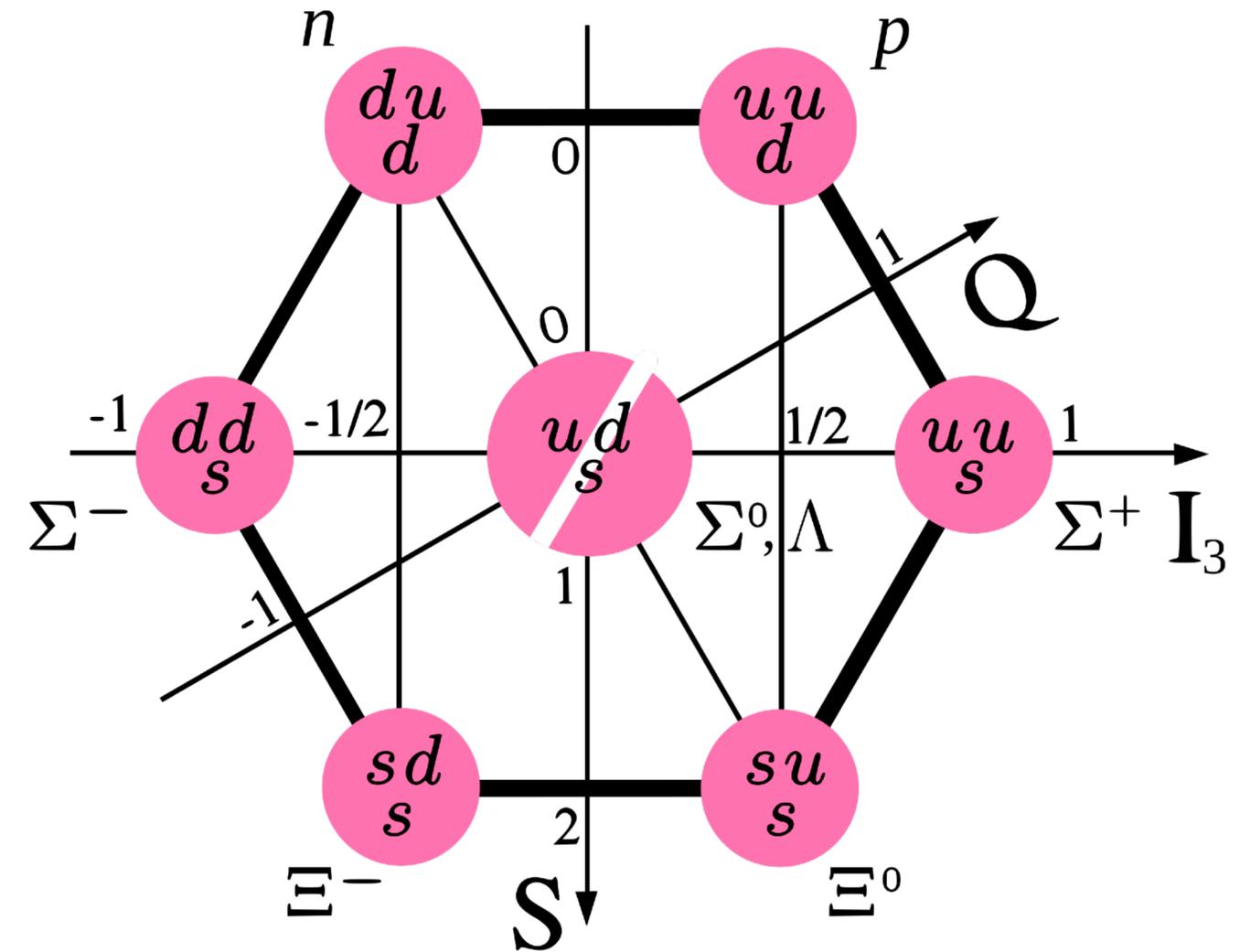
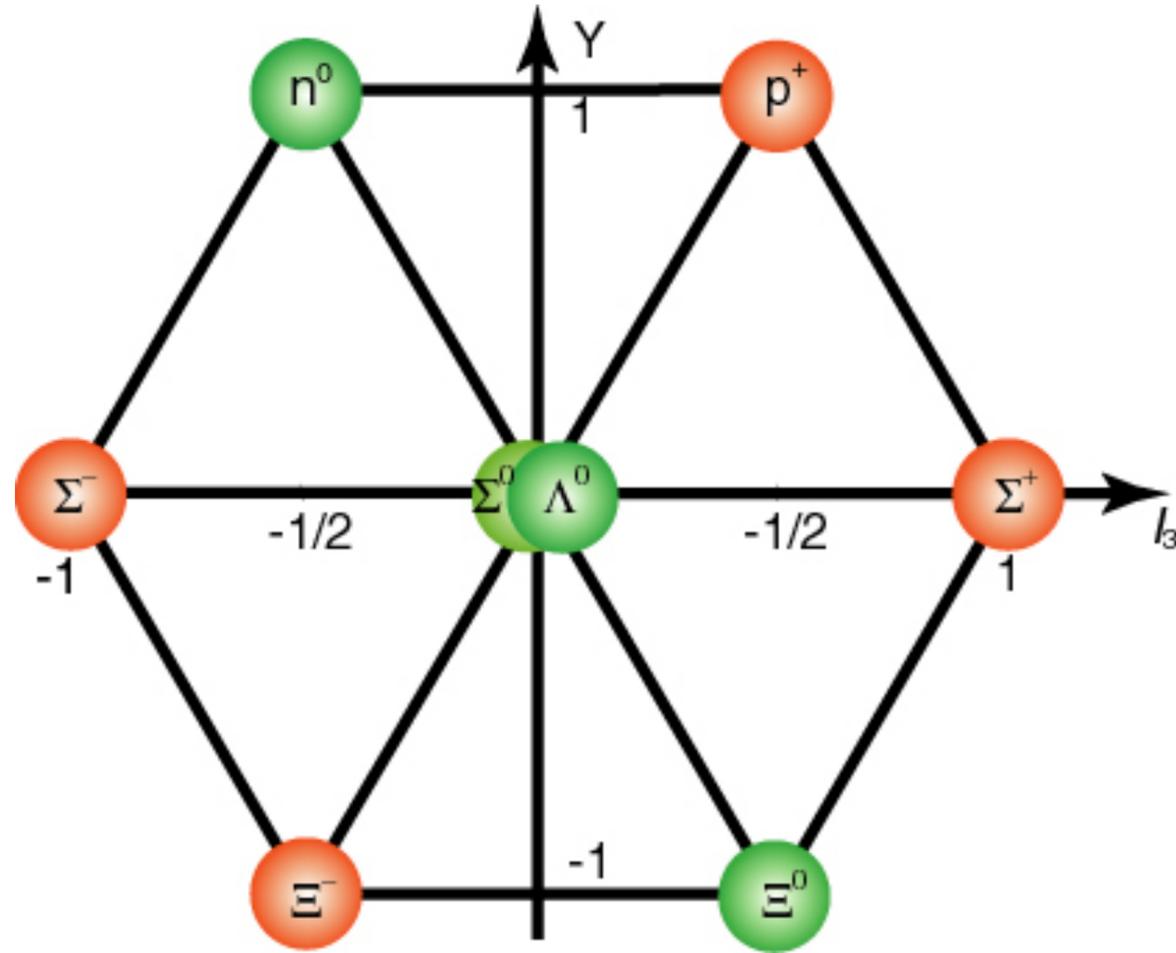
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Gell-Mann, Zweig, and Quarks

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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

Three quarks to Six quarks

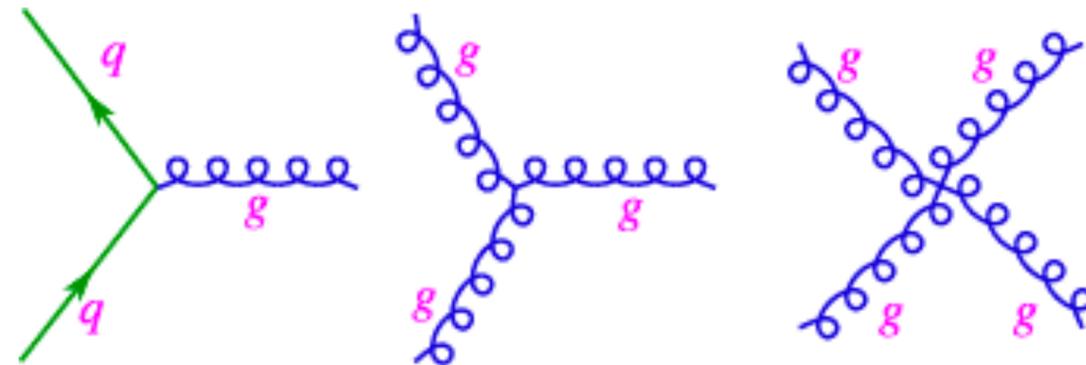
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- Over the next several decades, three more quarks (charm, bottom, and top) were discovered.
- The **SU(3)** symmetry originally proposed to explain the behavior of the (up, down, strange) quark system had to be modified to accommodate all six quarks.
- This led to the development of Quantum Chromodynamics (QCD), which uses a different **SU(3)** symmetry of “color” to describe all quark interactions.

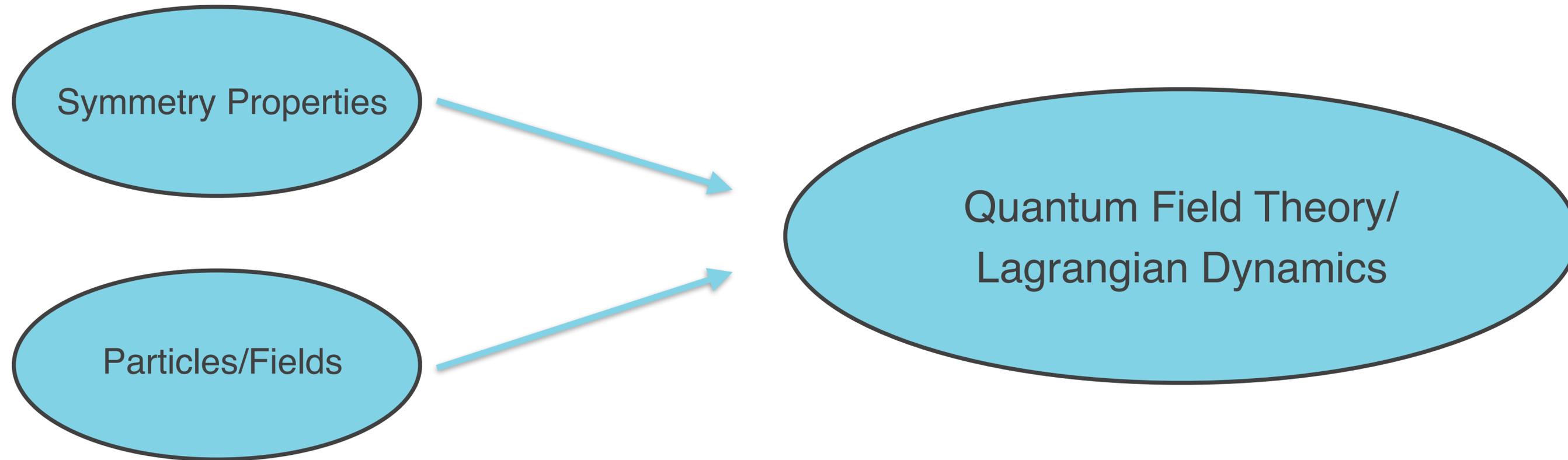


So, how do we use symmetries & particles together?

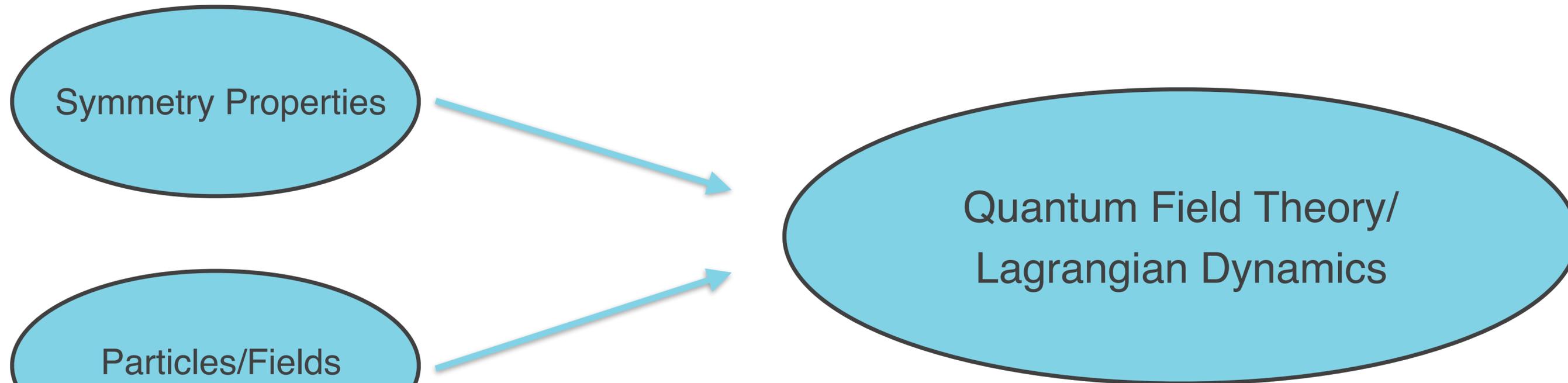
Symmetry Properties

Particles/Fields

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$$\phi \rightarrow \phi' = e^{i\vartheta(x)} \phi$$

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Electrons + U(1) gauge symmetry \longrightarrow Quantum Electrodynamics (QED)

Side-note: Gauge Boson Masses

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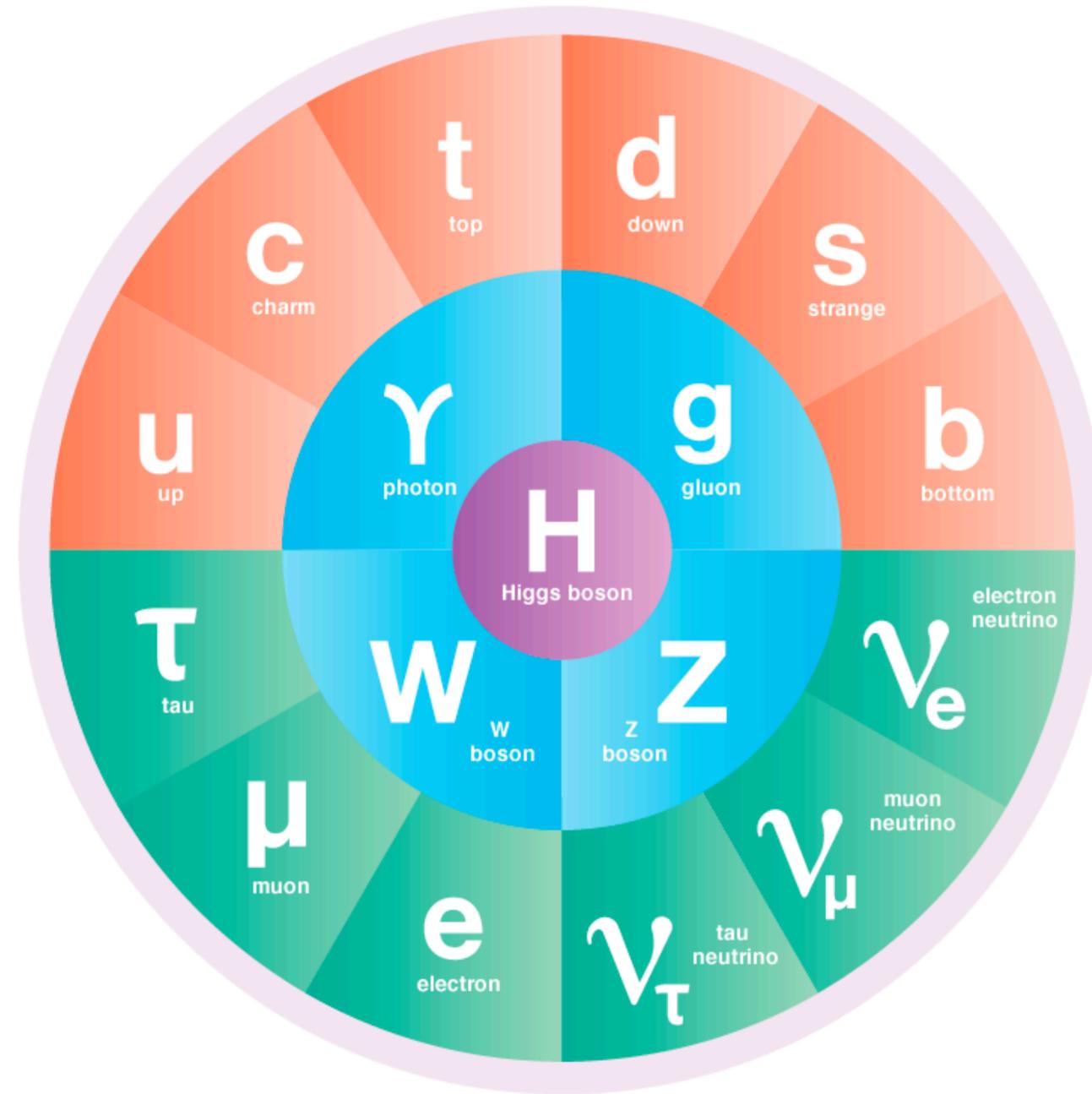
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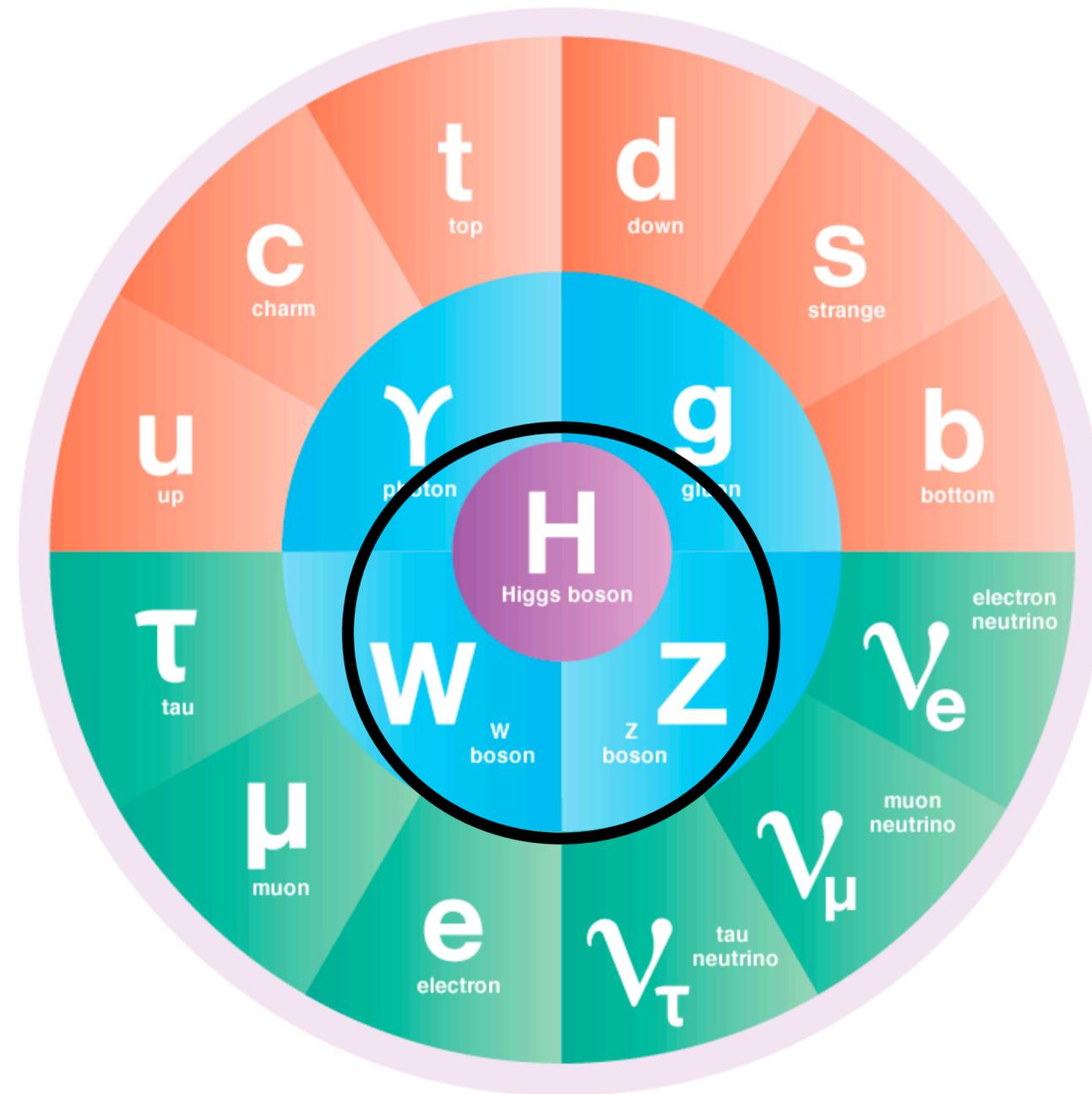
- Under the transformation we introduced for this, though, the Lagrangian is **not** invariant — gauge bosons must be massless.

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

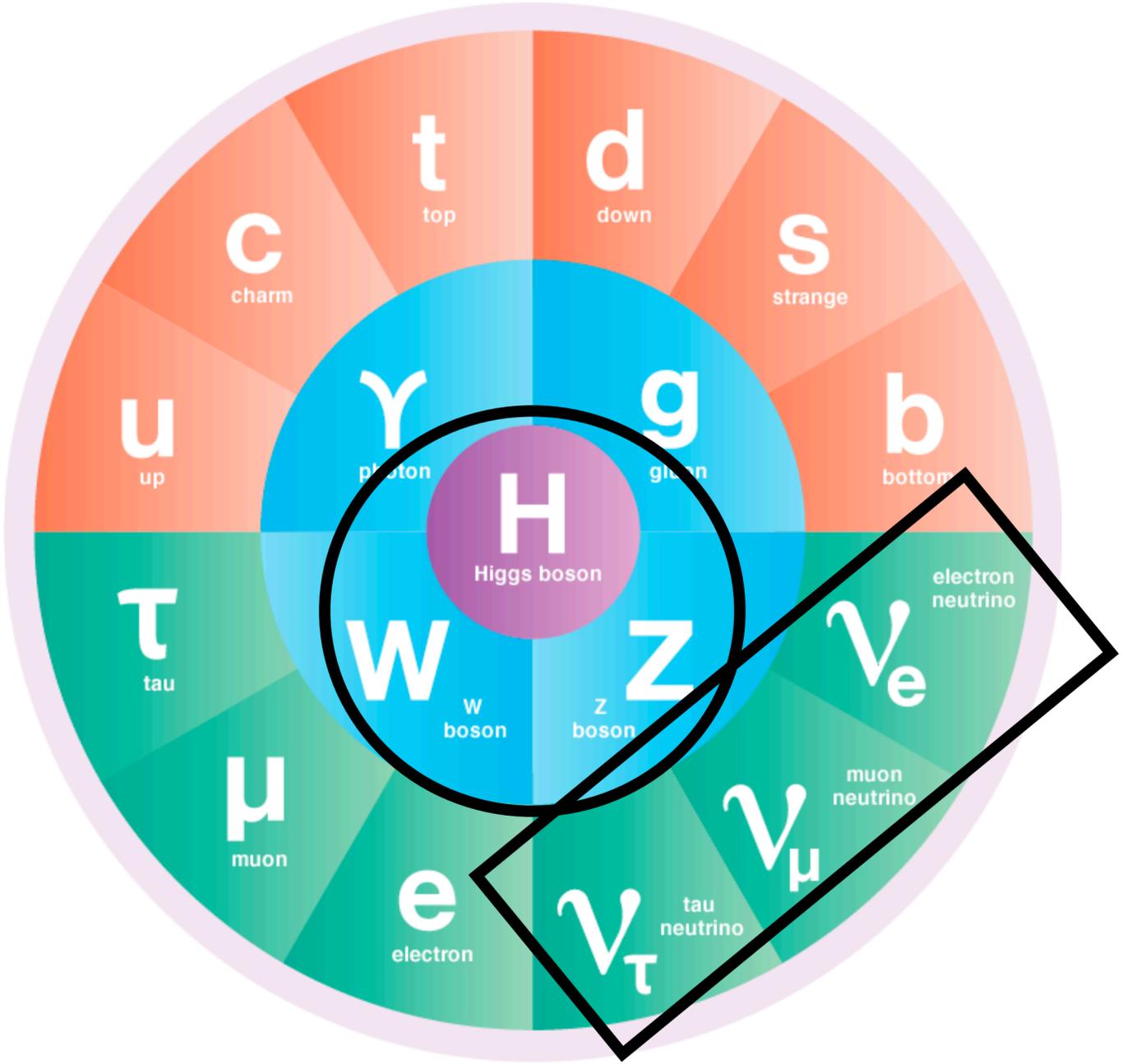
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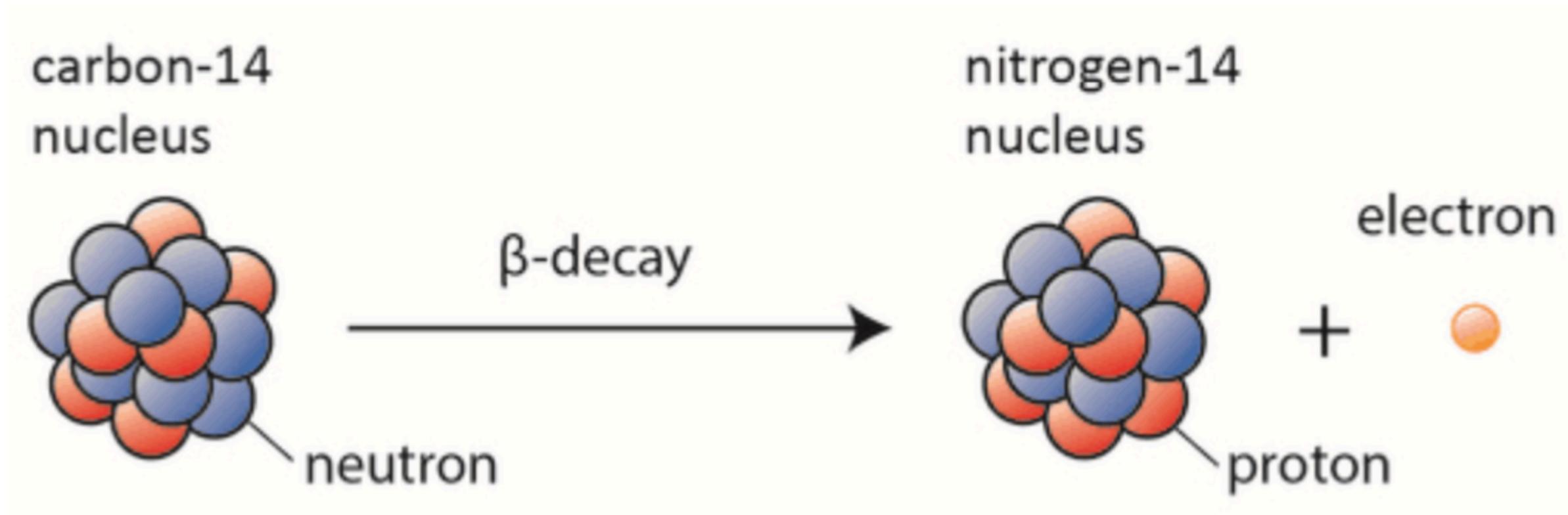
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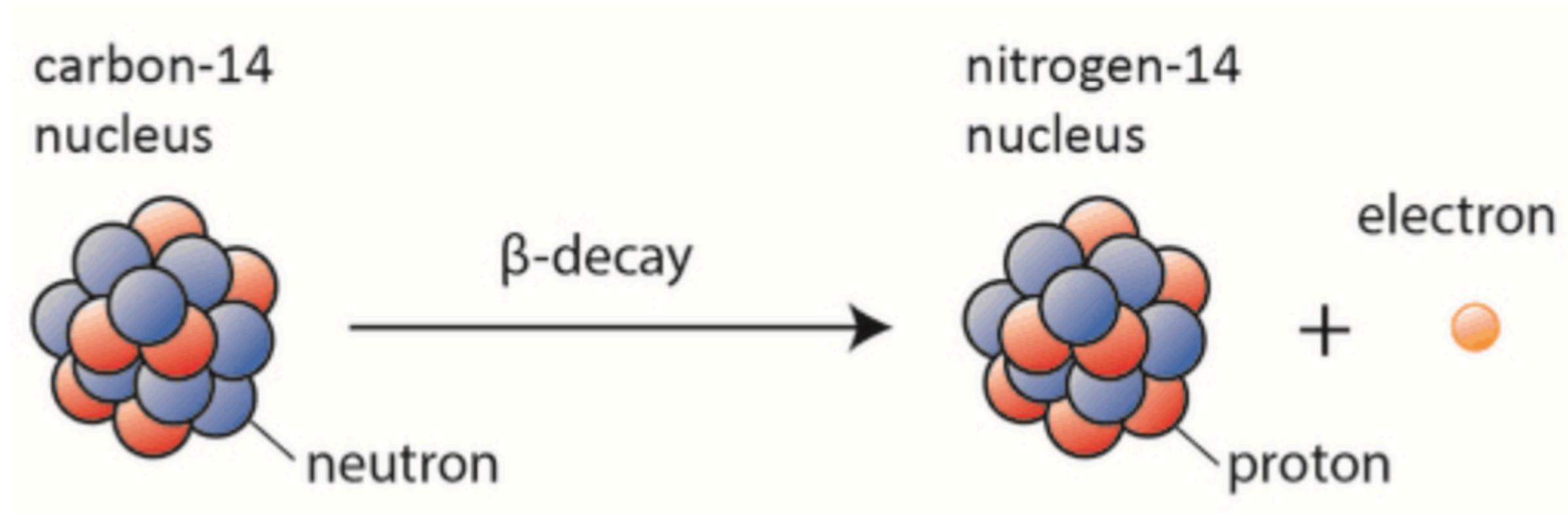
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Back to the 1930s: Nuclear Beta Decays



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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.

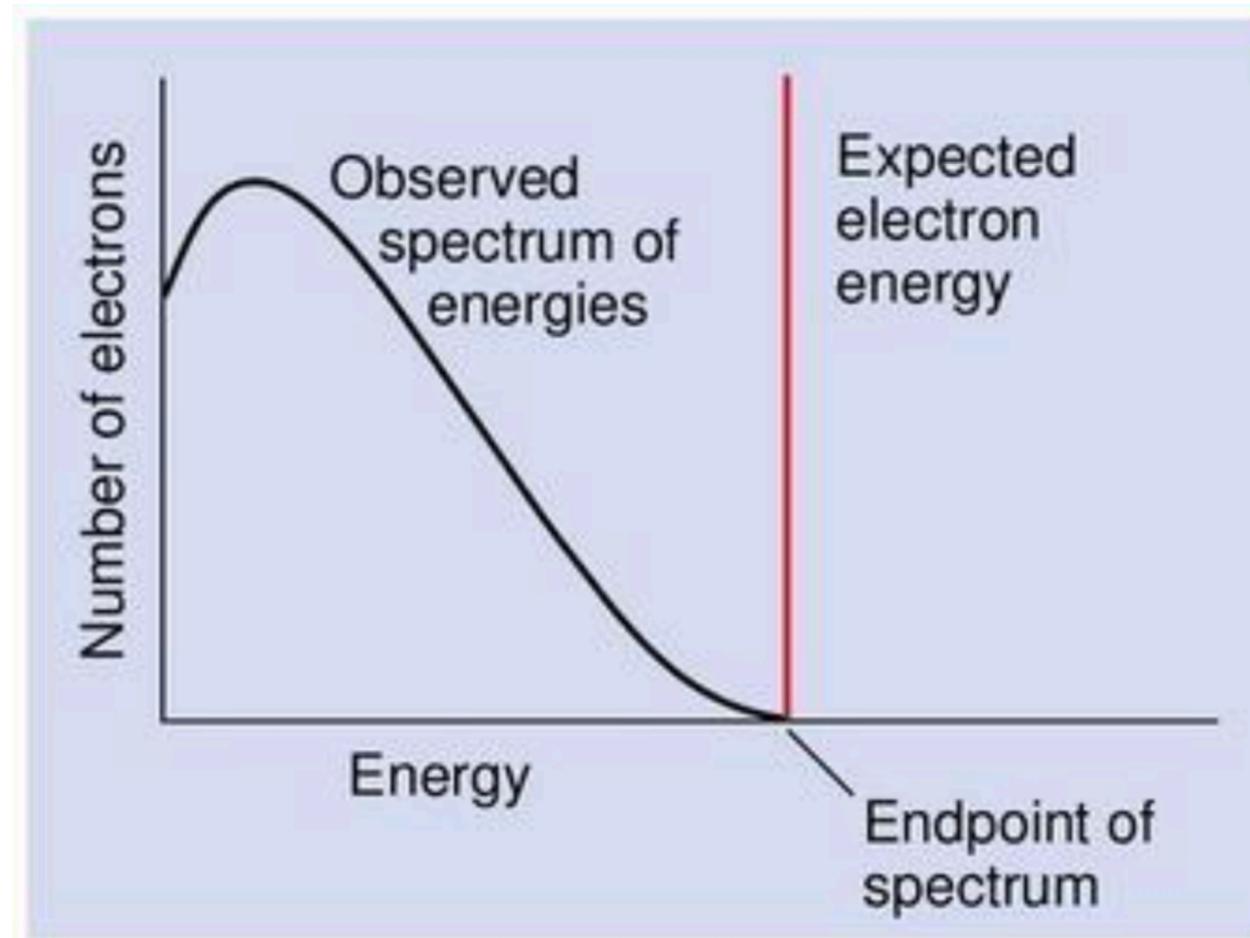
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- Measurements of beta decay show that the electron has a spectrum!

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 halbvollst
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 Grössenordnung wie die Elektronenmasse sein und
jedenfalls nicht grösser als $0,01$ Protonenmasse.- Das kontinuierliche
beta-Spektrum wäre dann verständlich unter der Annahme, dass beim
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wird, derart, dass die Summe der Energien von Neutron und Elektron
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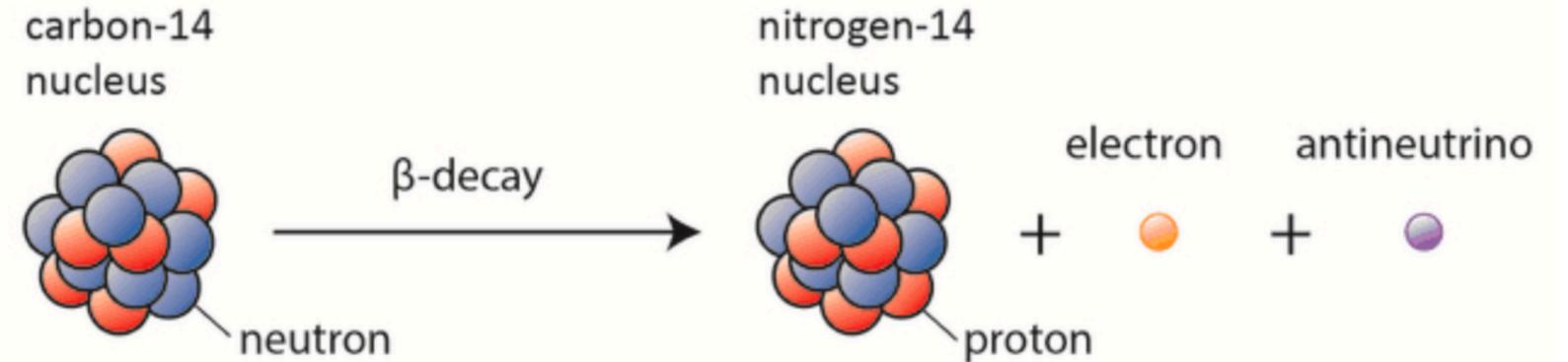
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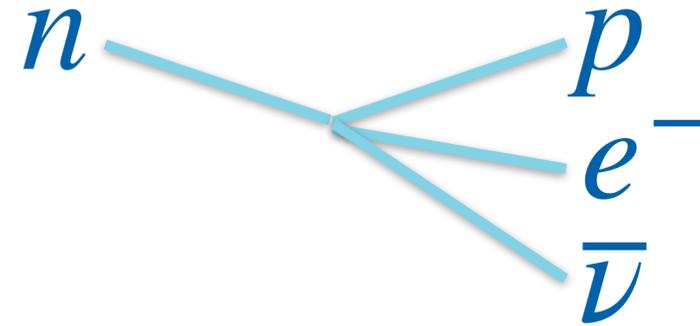
- Pauli’s solution: a new, very weakly interacting “neutrino” comes out of beta decays as well, stealing some of the energy from the outgoing electron and producing a spectrum of electron energies.

Just how “weak” is “weakly interacting”?

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

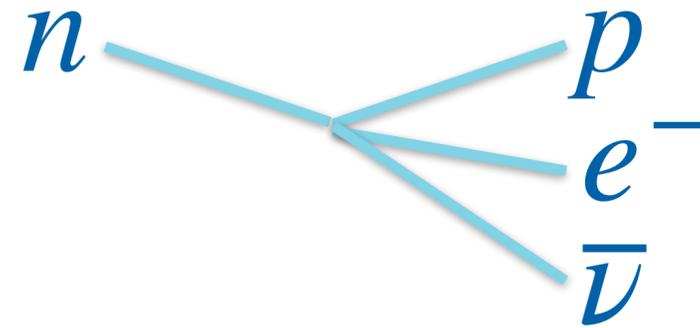
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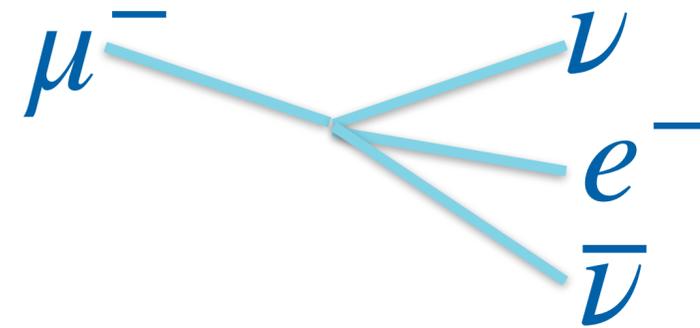


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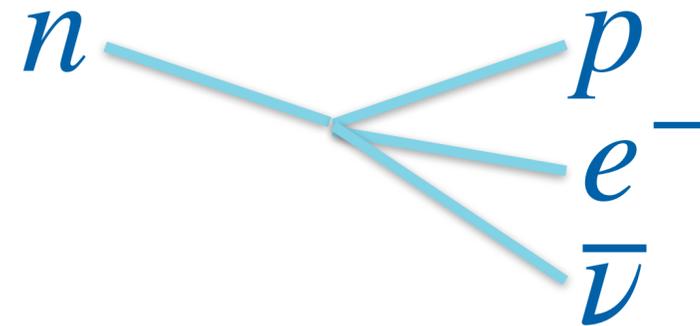


- Also predicts processes like muon decay,

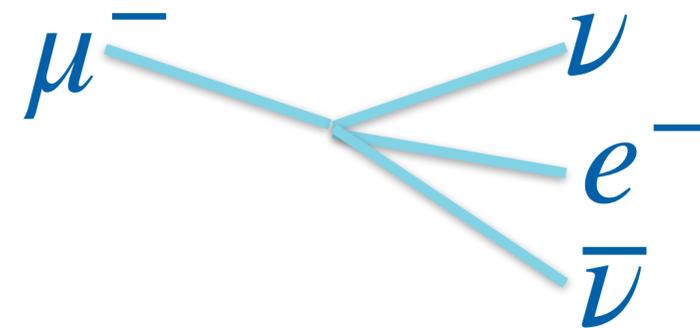


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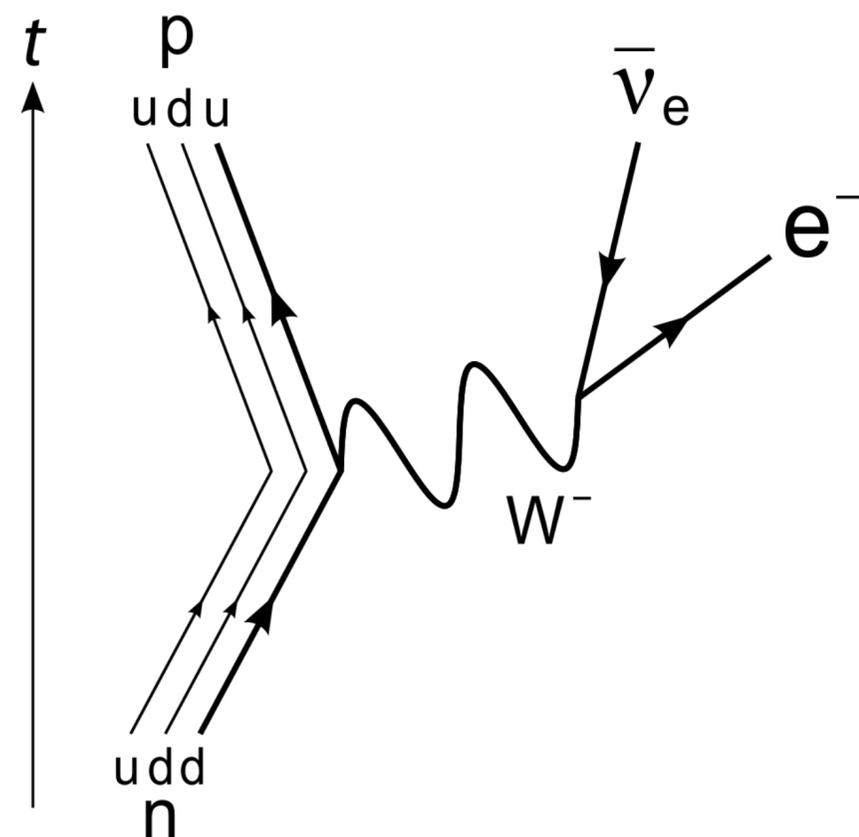
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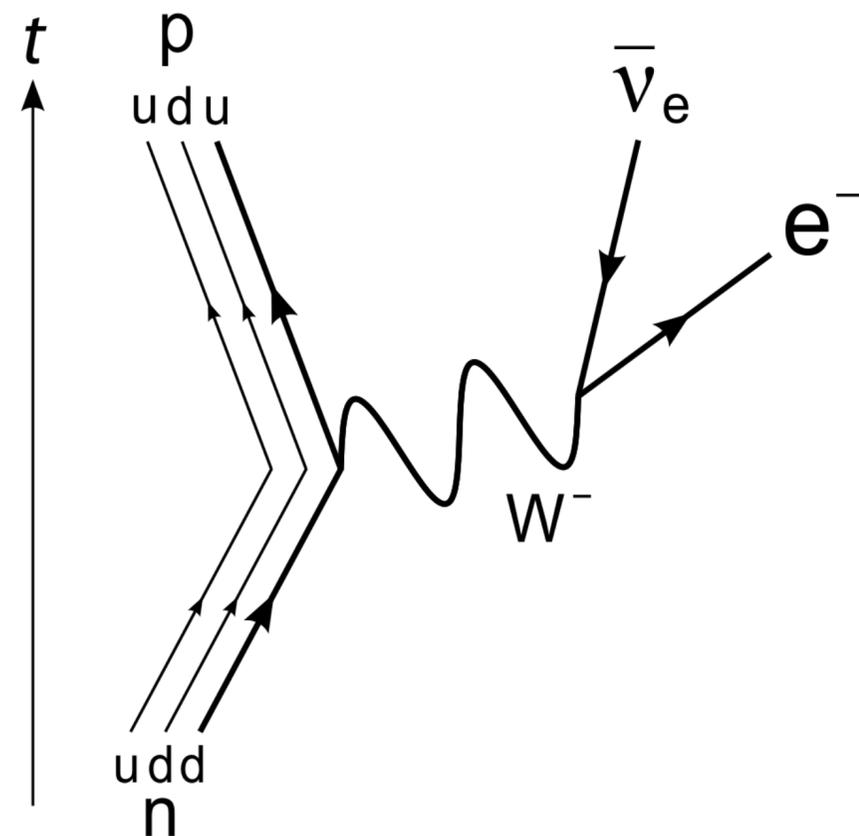
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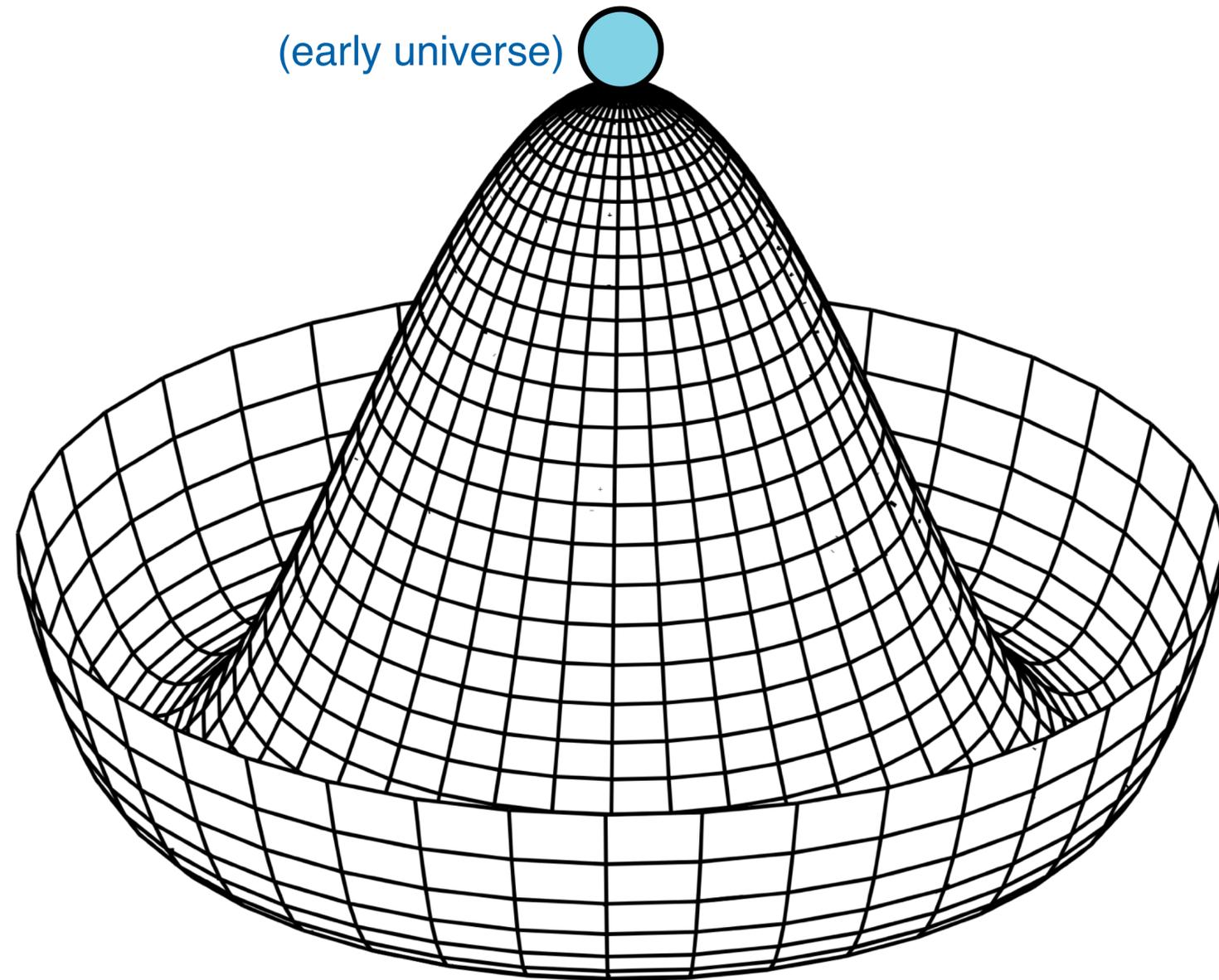
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- Issue: if these are really the gauge bosons of an **SU(2)** theory, they should have zero mass!

Solution: The final piece of the Standard Model

- The Higgs boson and the Higgs mechanism:

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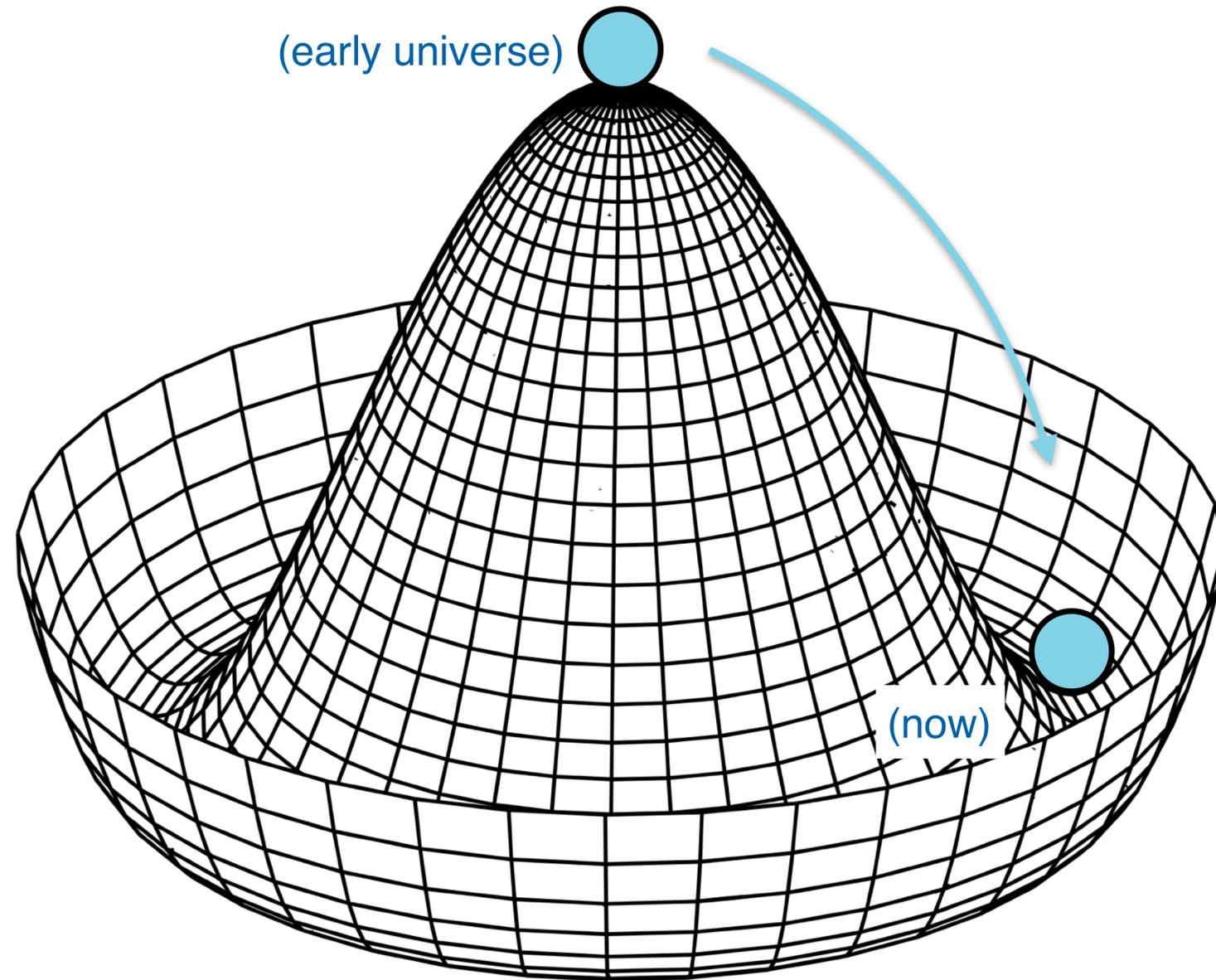
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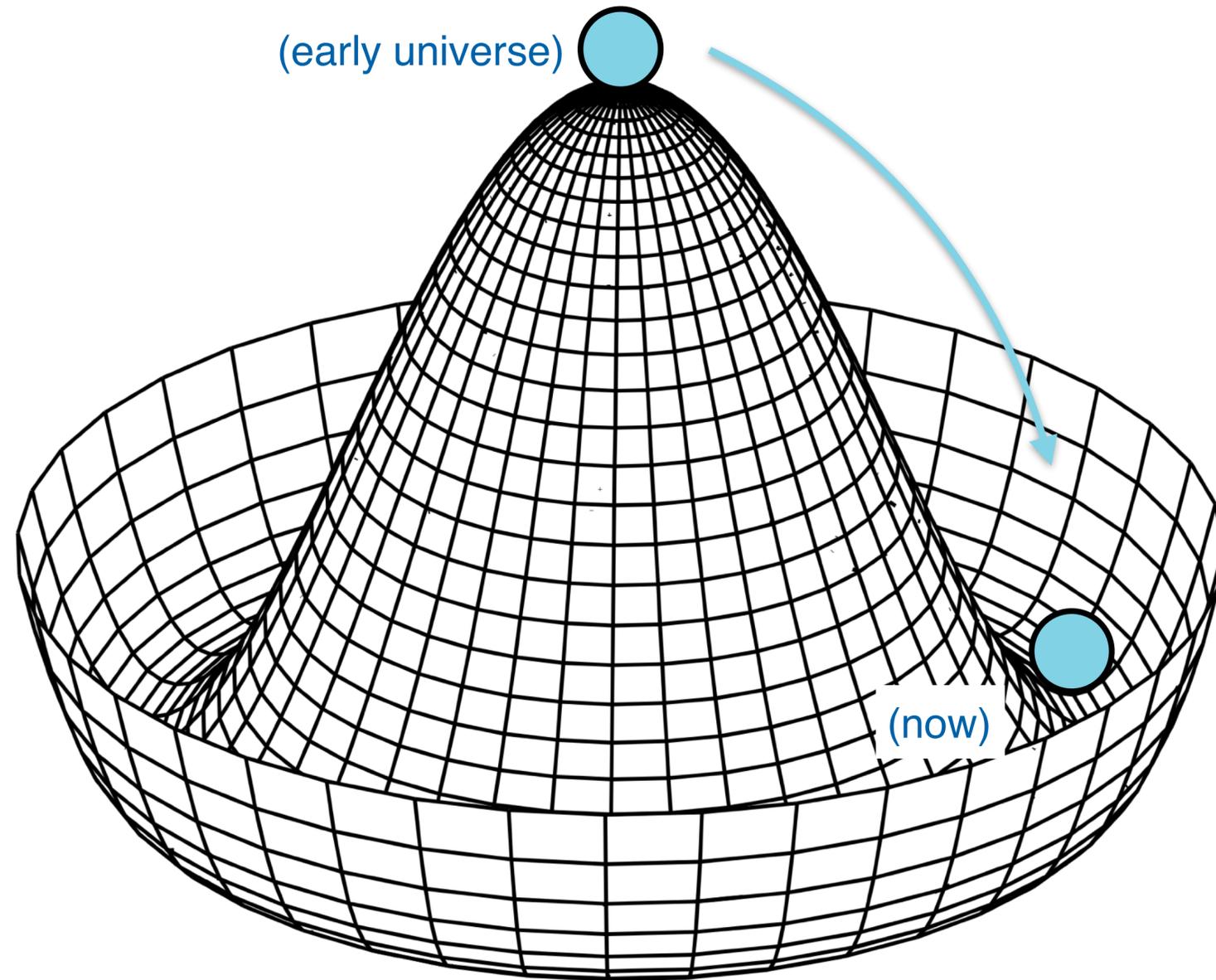
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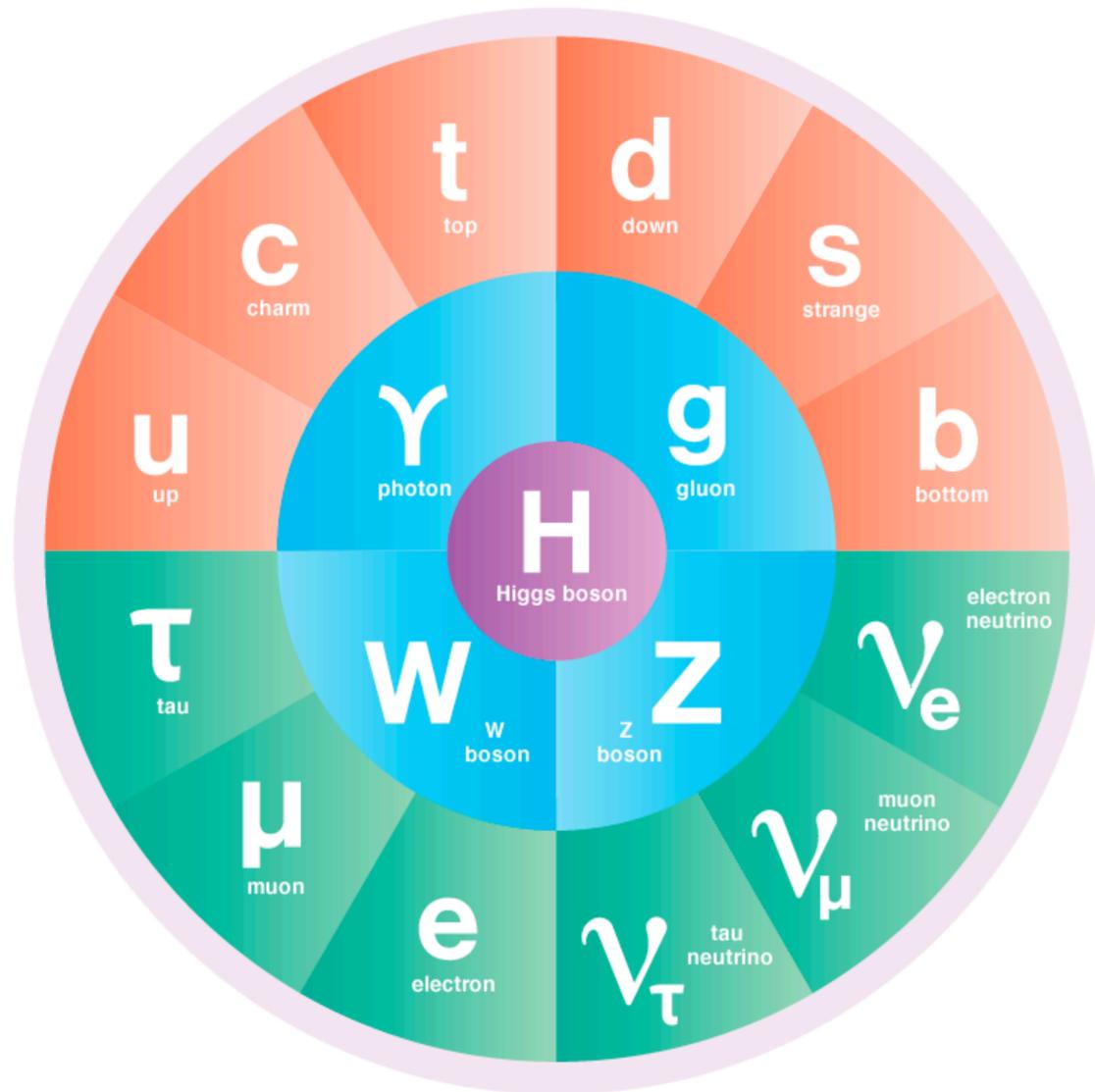
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- As the universe cools, the Higgs boson feels compelled to acquire a “vacuum expectation value” at the bottom of this “Mexican hat” potential.
- This new minimum *spontaneously breaks* the **SU(2) x U(1)** symmetry, resulting in things like massive particles, massive gauge bosons, and the resulting “low energy” behavior we see today.

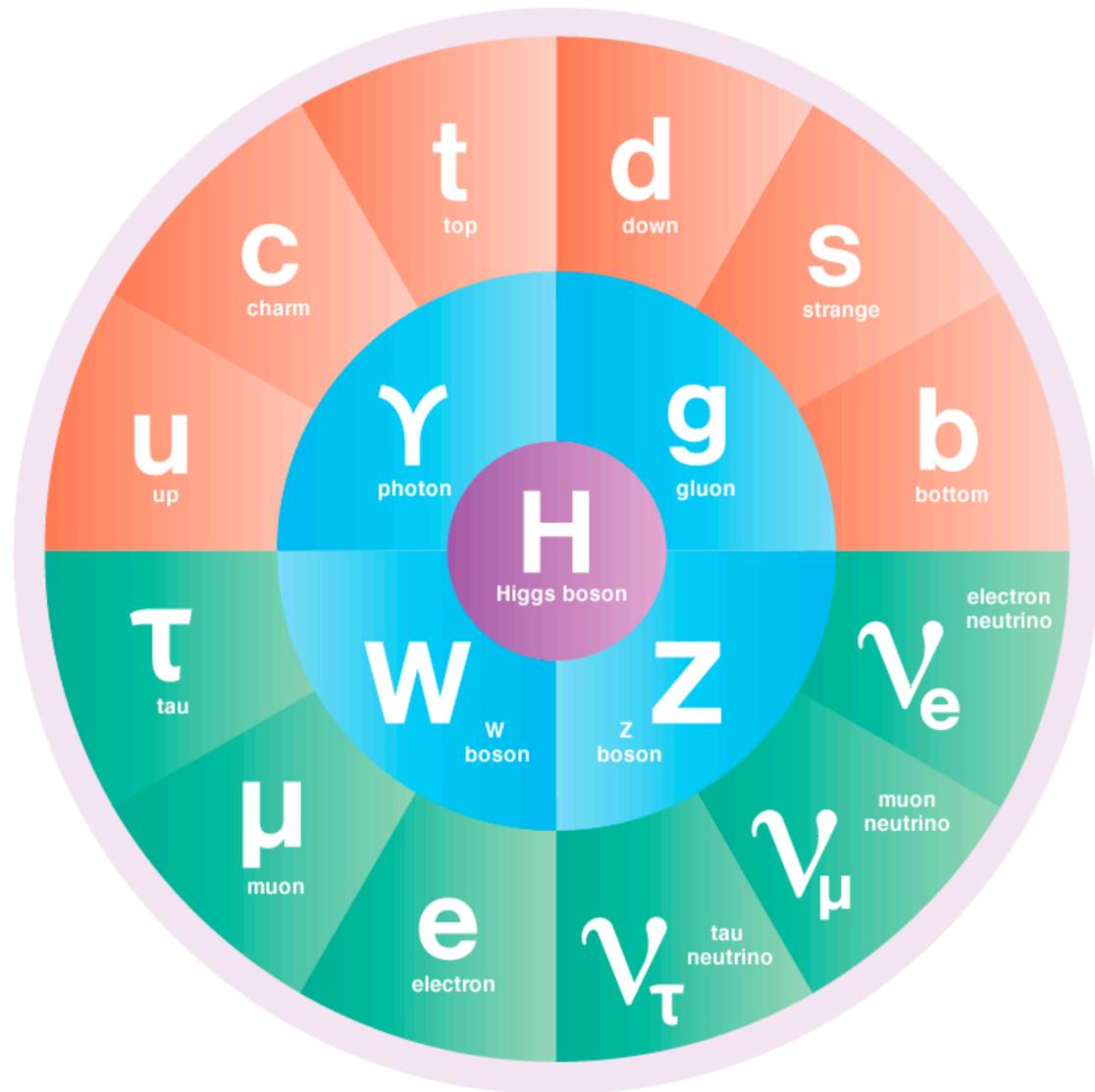
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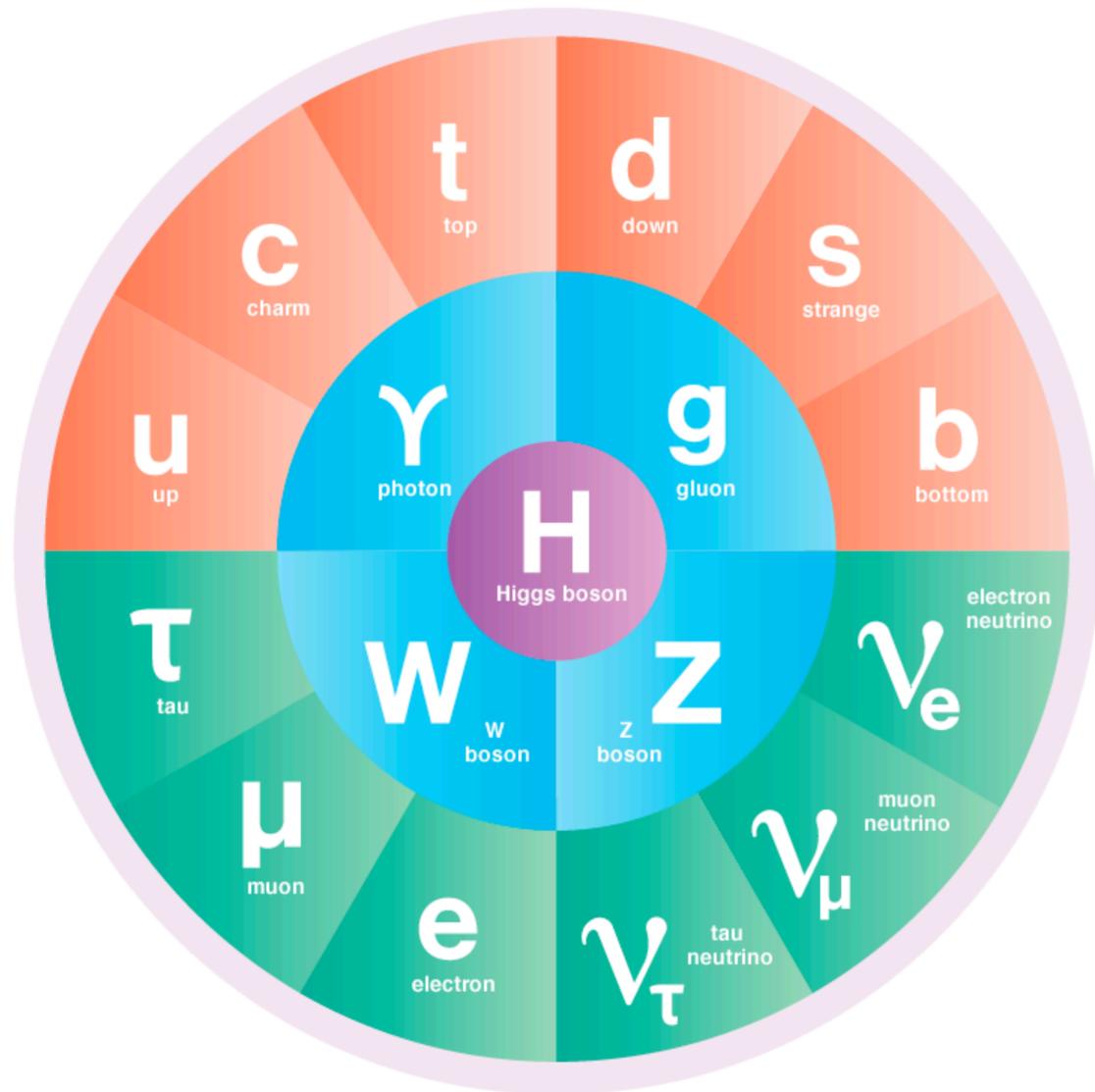
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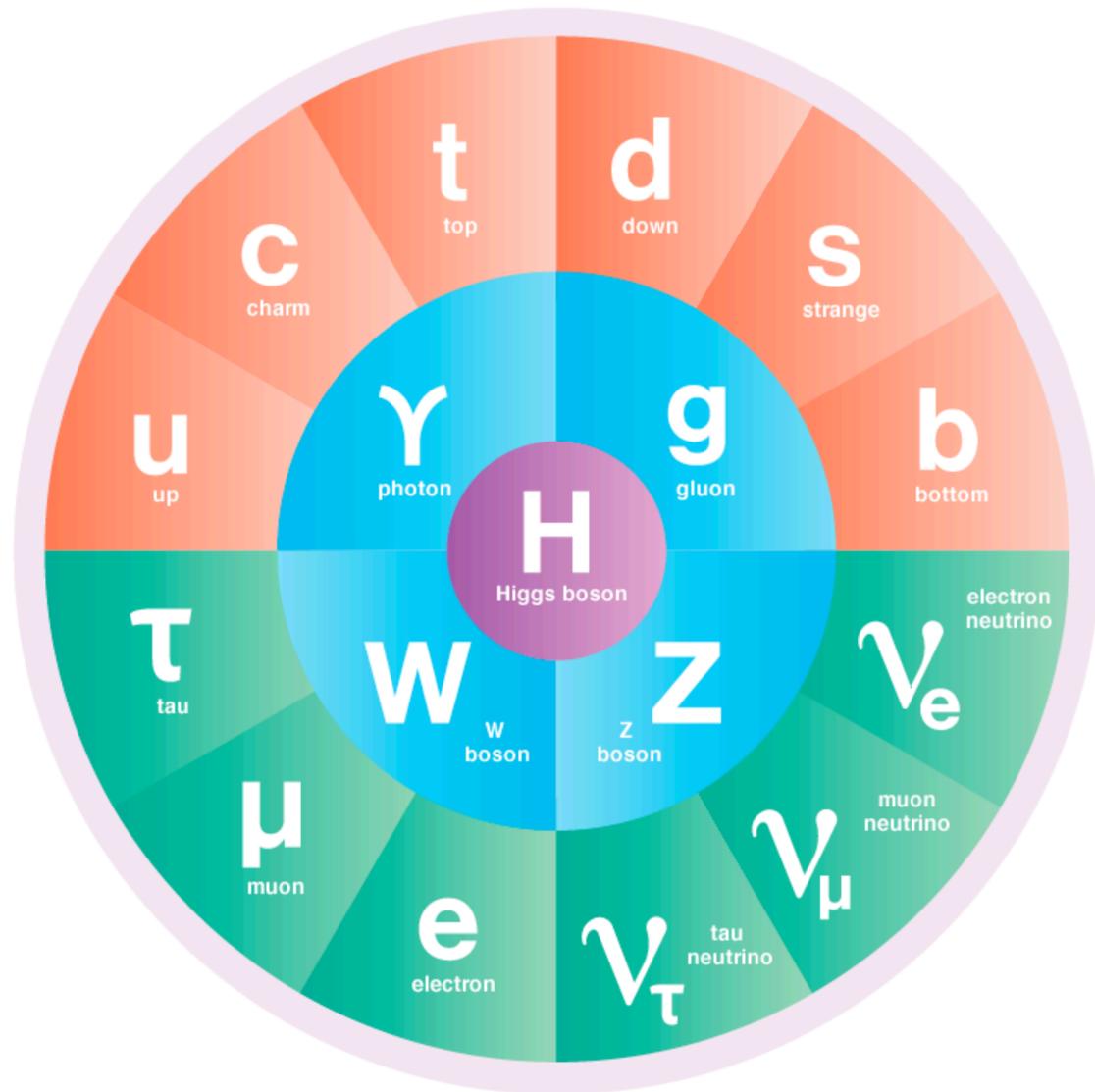
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- Force carriers are the gluons (color, interact with quarks), photons (electromagnetism, interact with charged particles), and weak bosons (weak force, interact with all fermions).

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However, there are some problems...

Three Current Challenges (if time allows)

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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

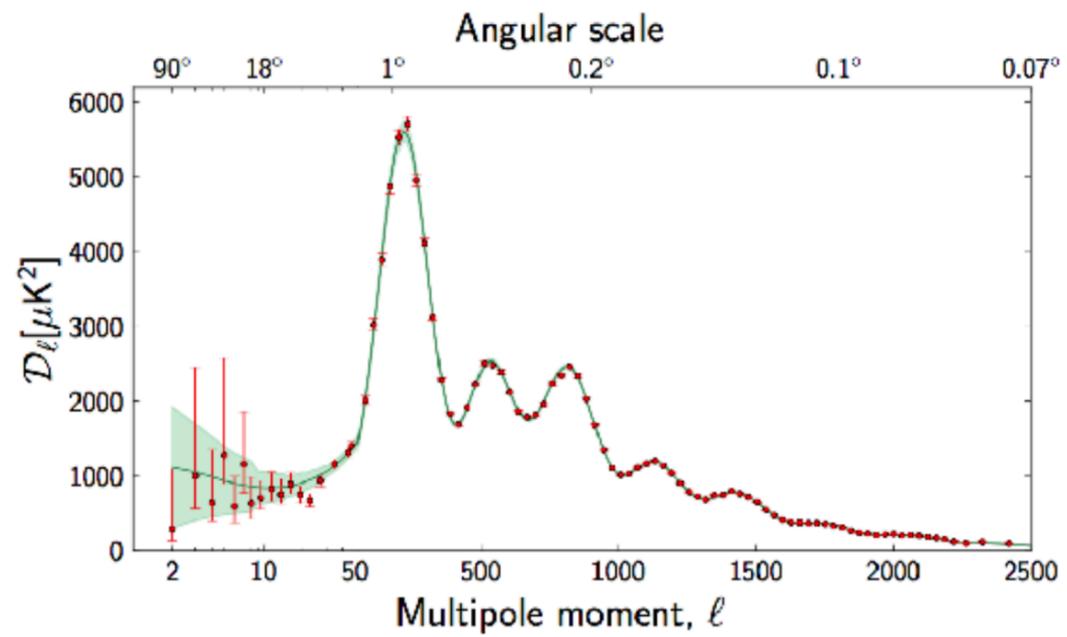
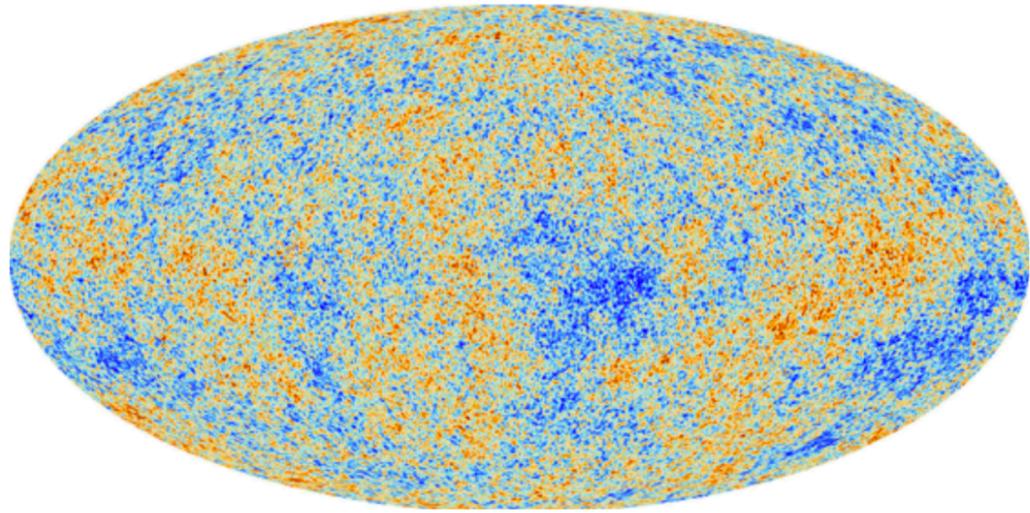
Cosmology: Dark Matter and Dark Energy ↑

🕒 1h

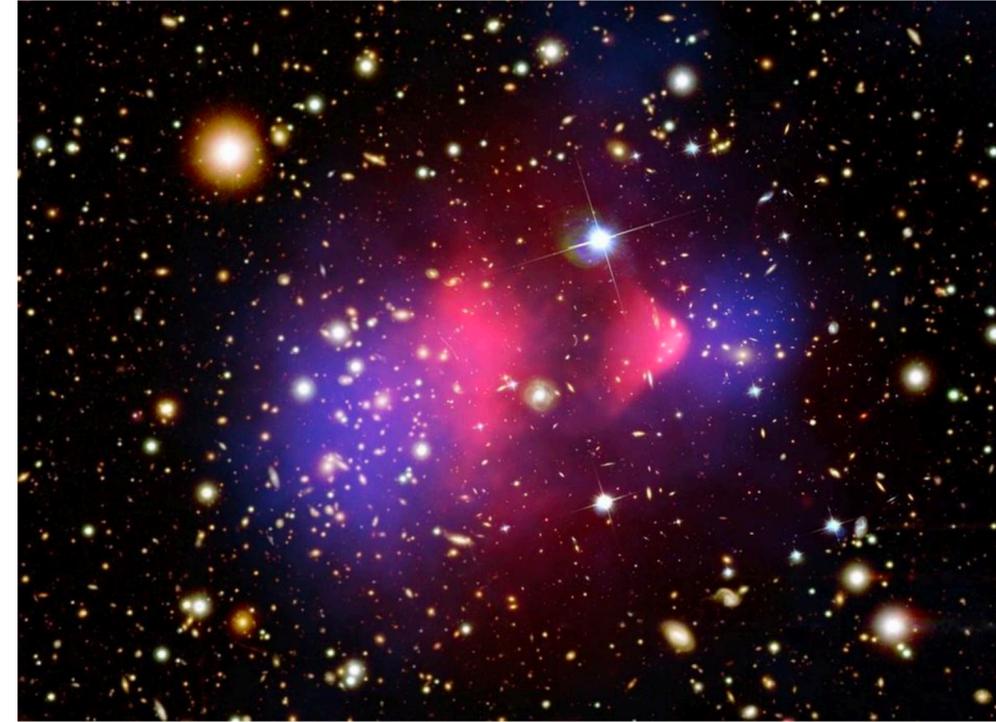
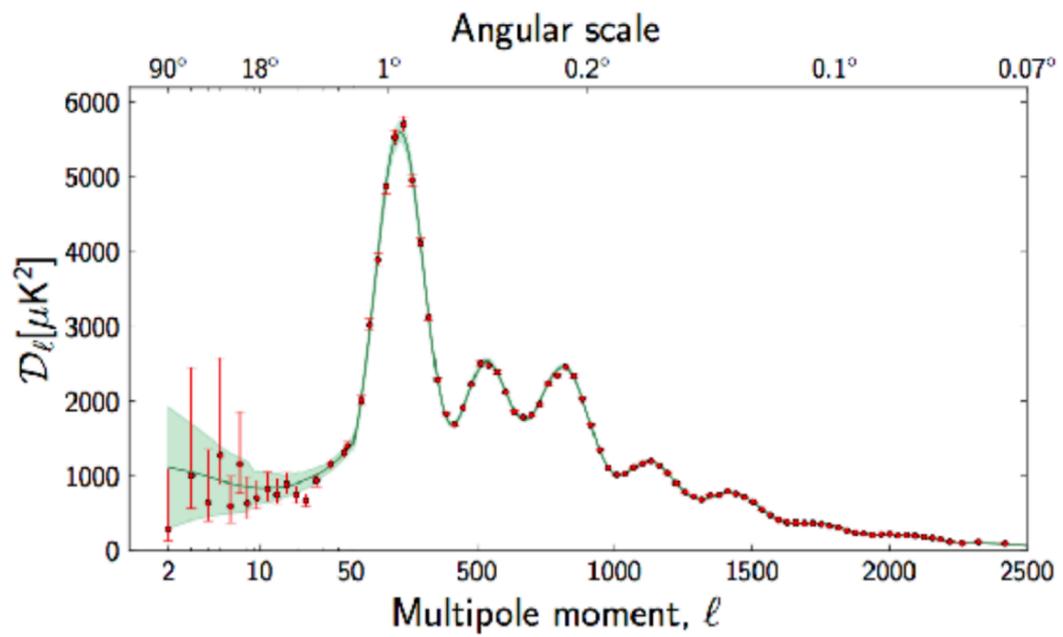
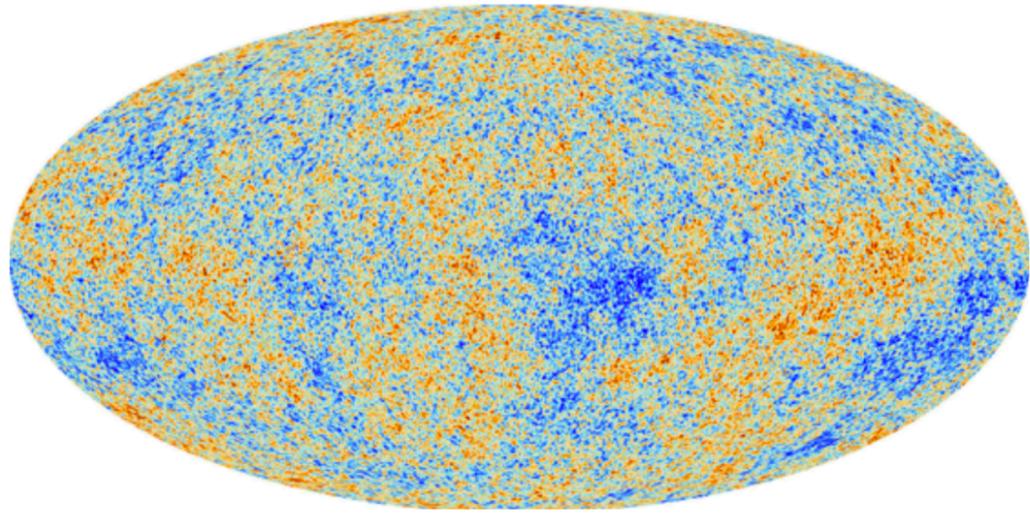
Speaker: Dan Hooper (Fermilab)

Overwhelming Evidence for Dark Matter over Many Scales

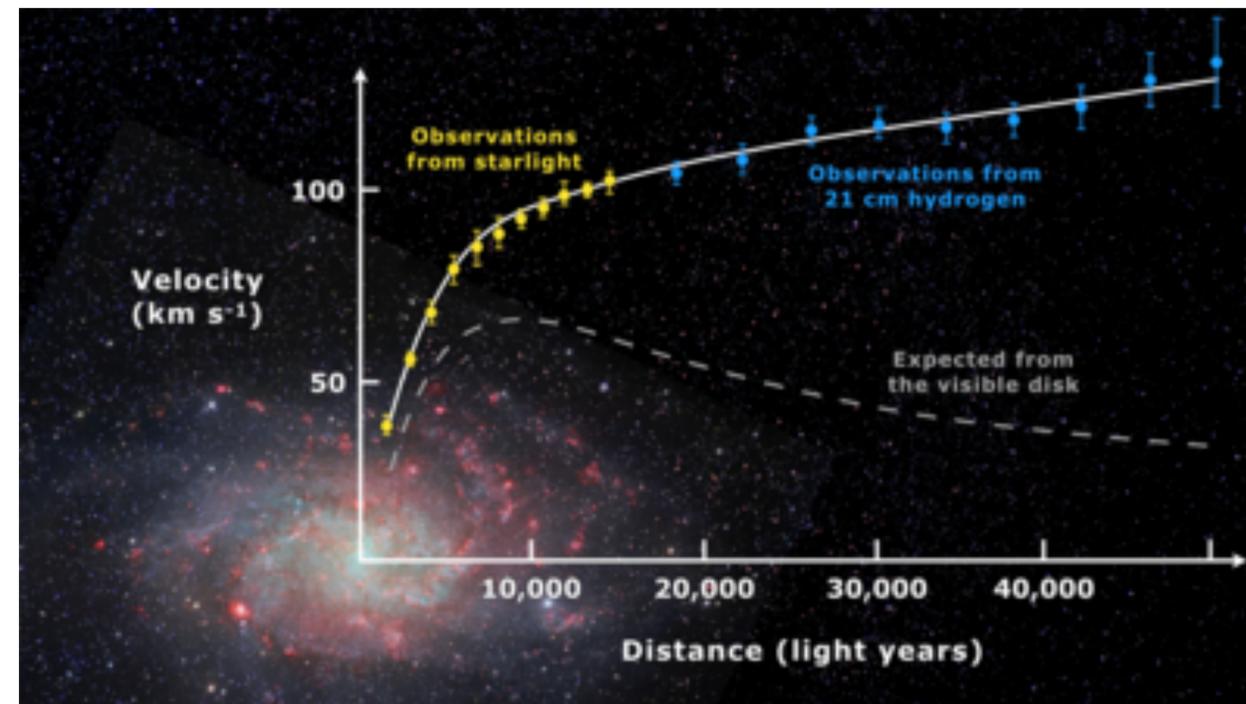
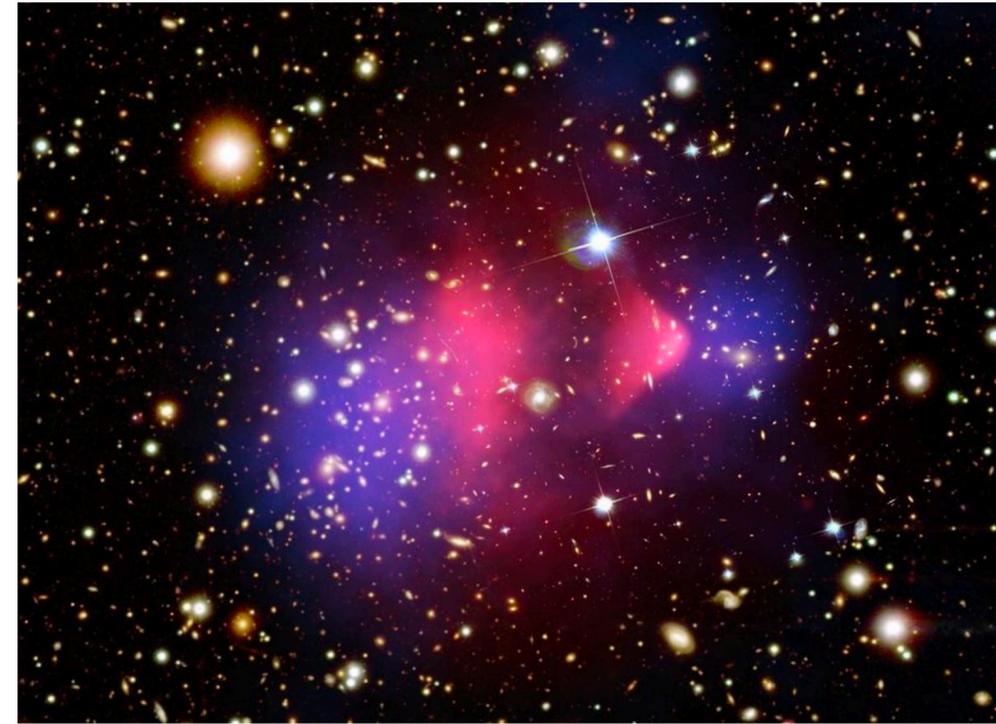
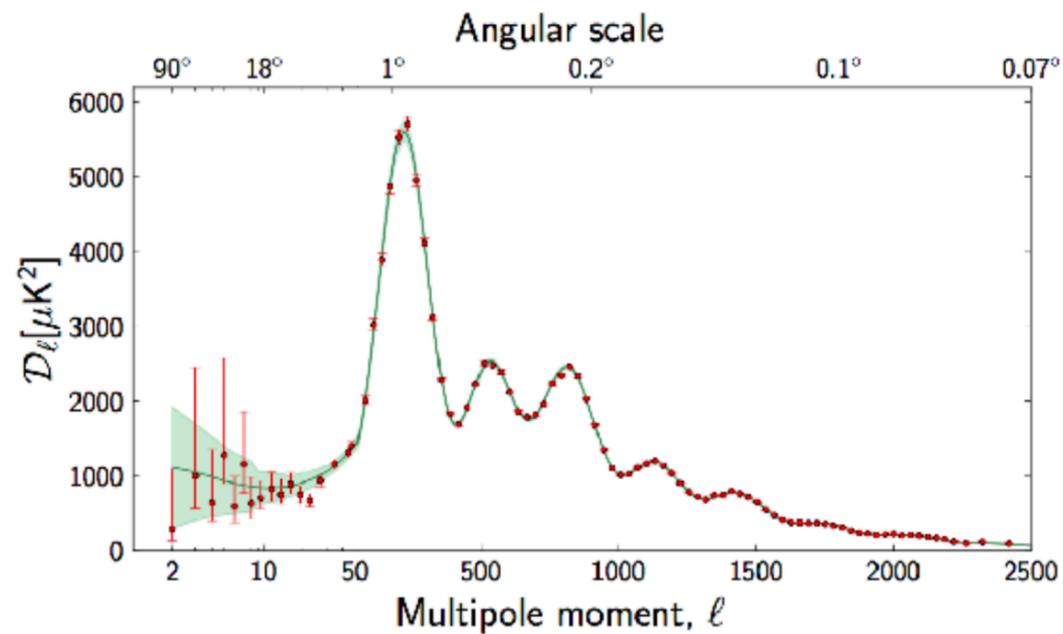
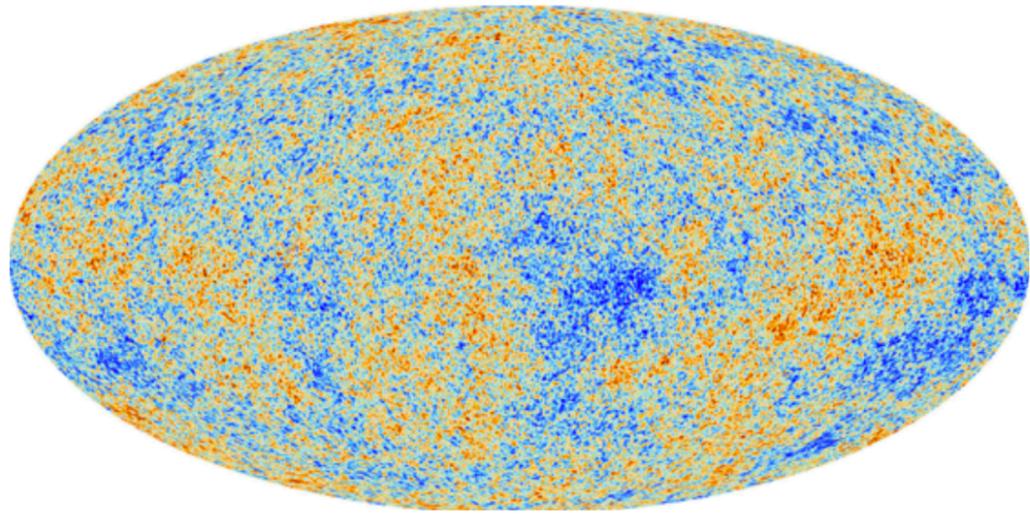
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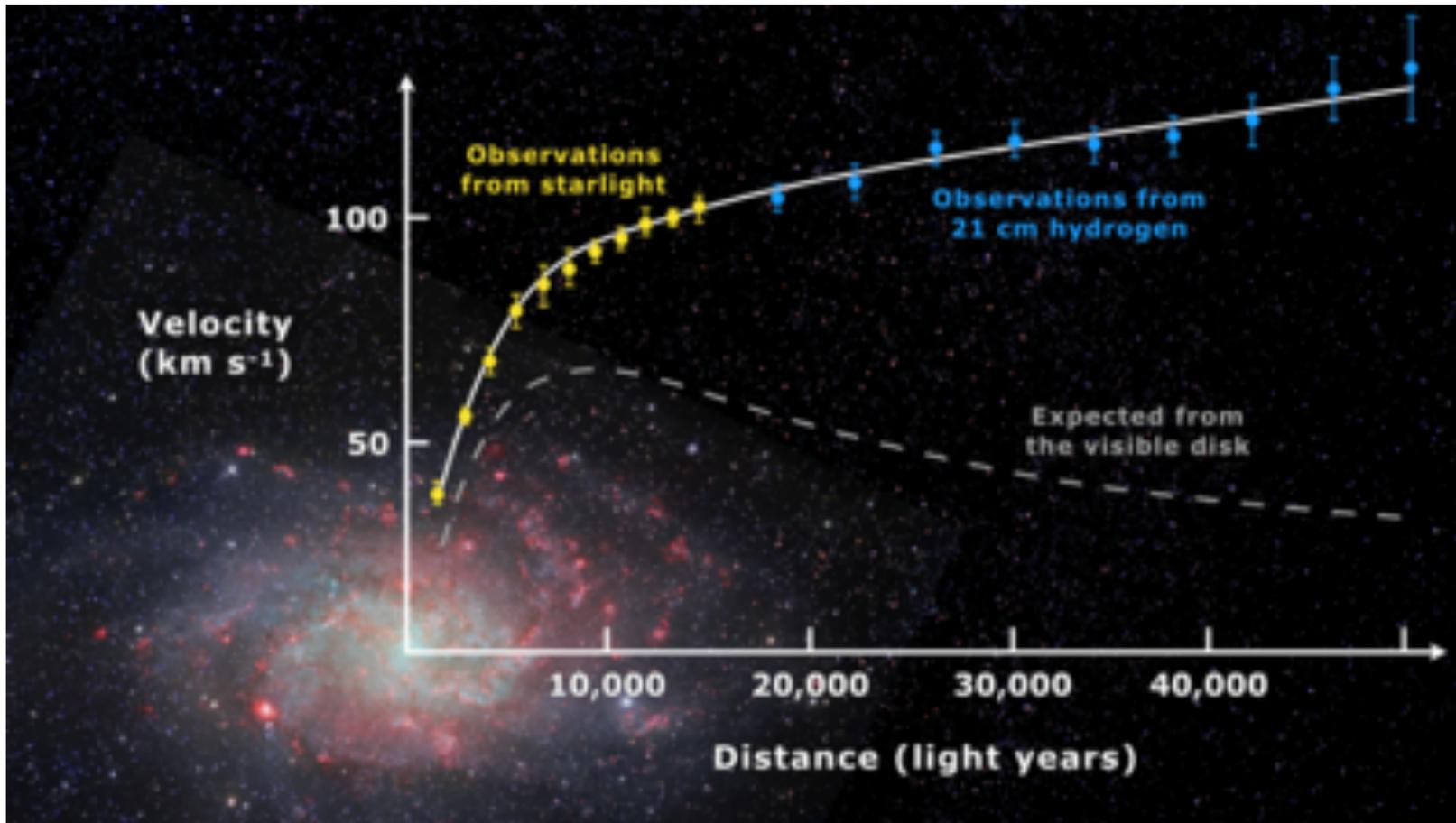
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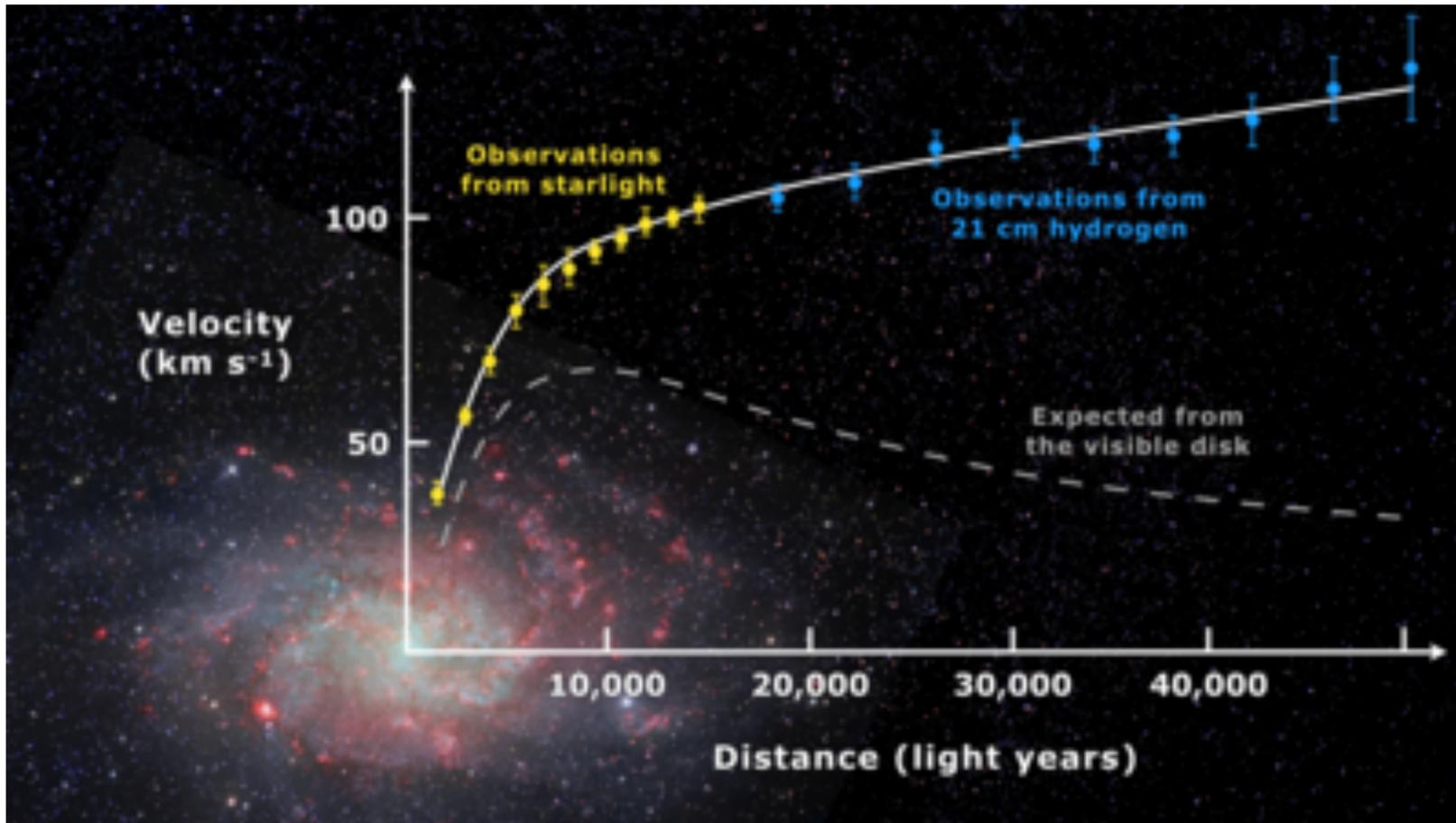
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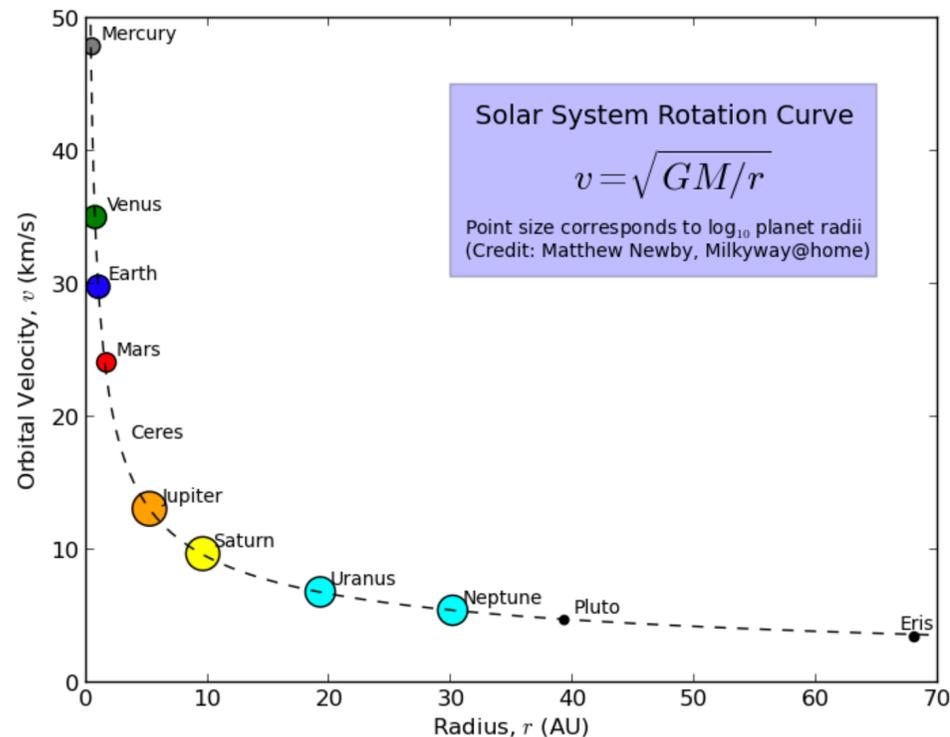
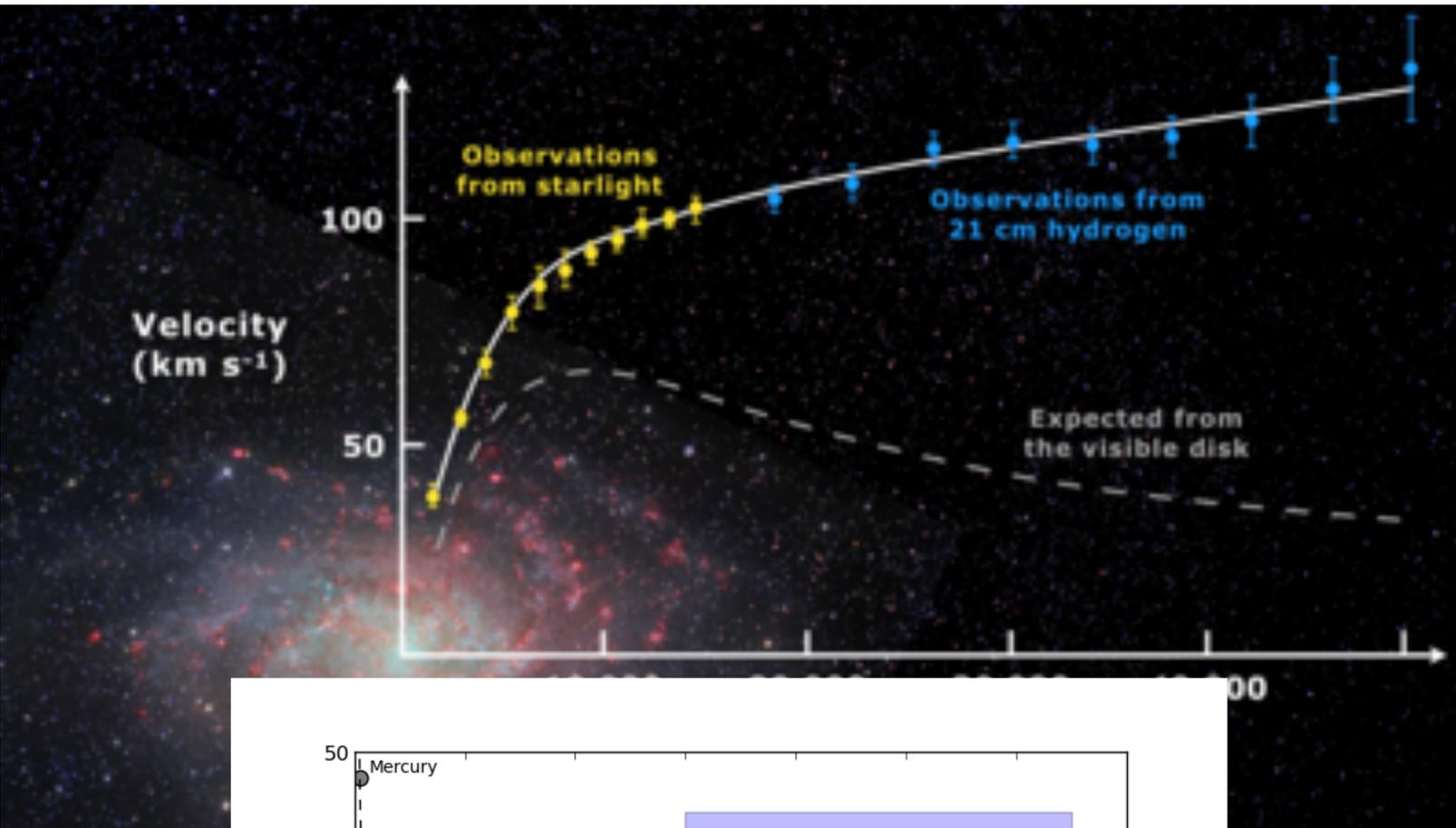
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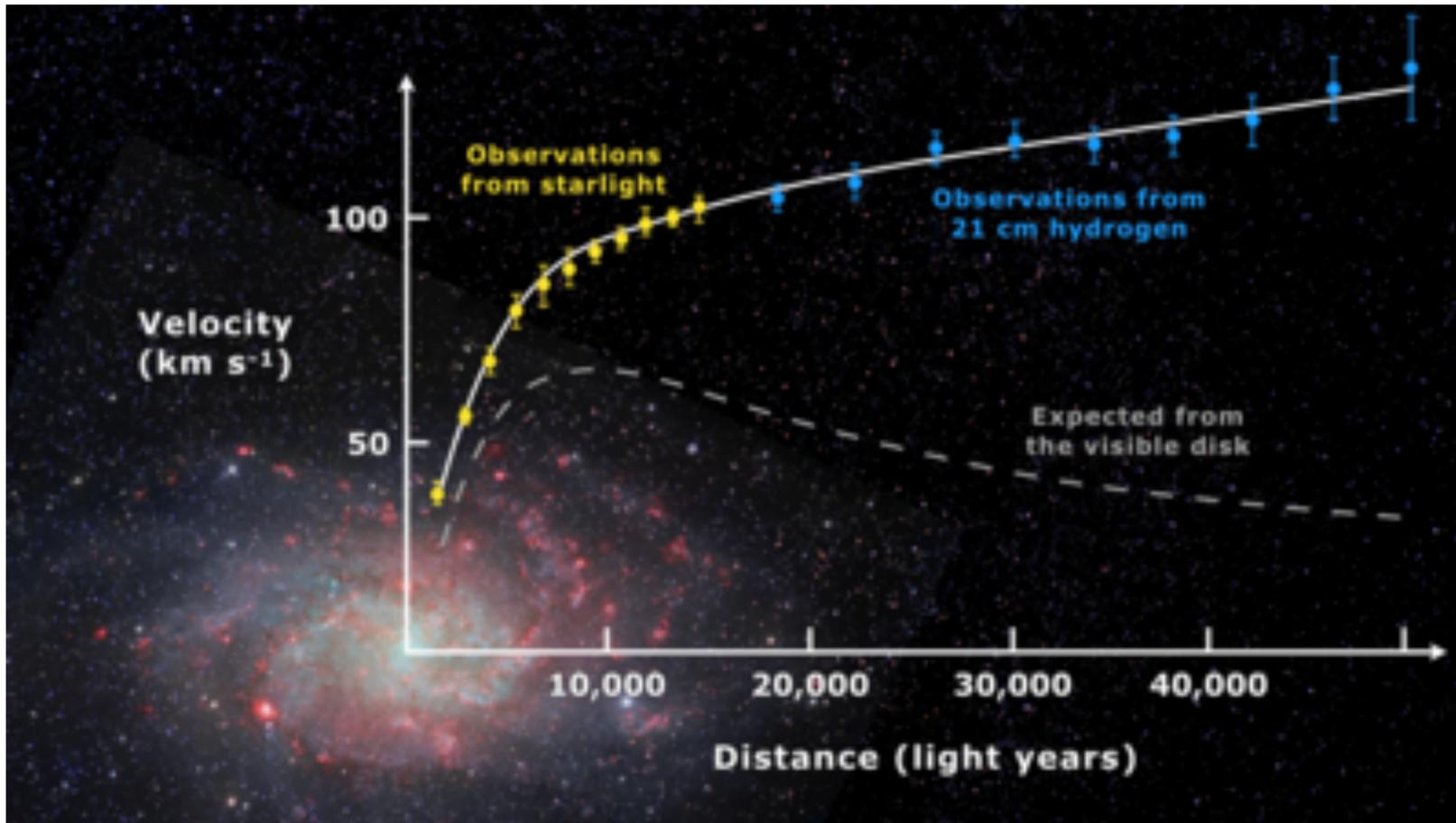
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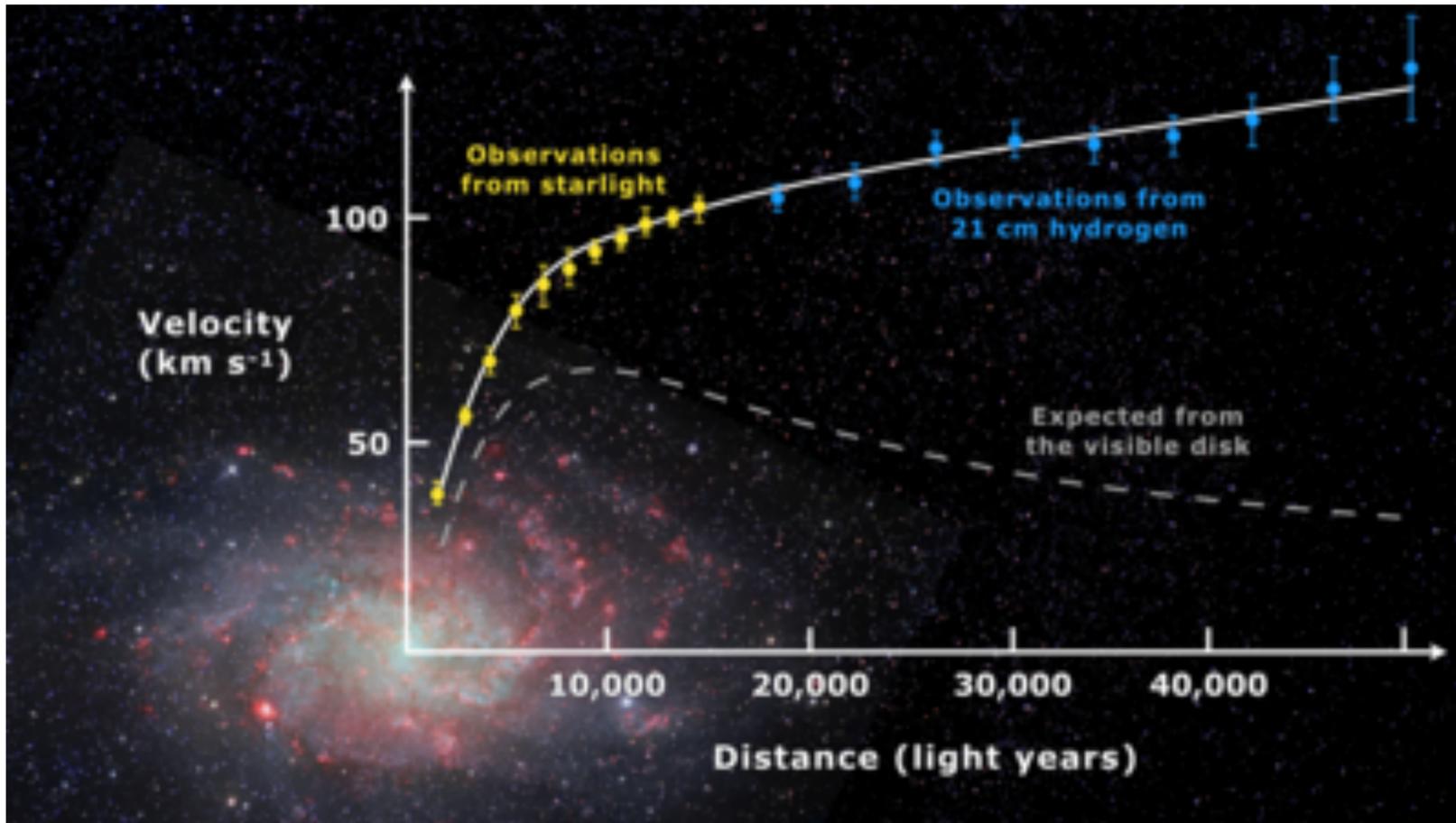


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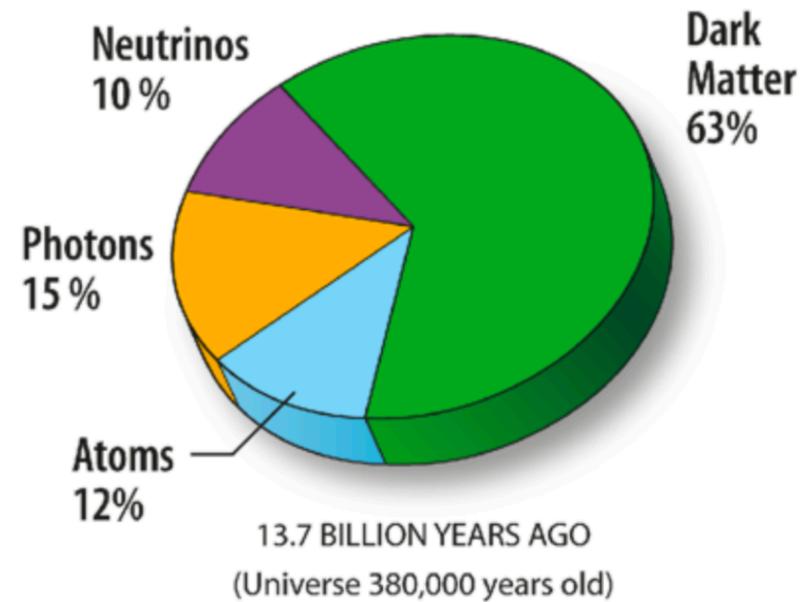
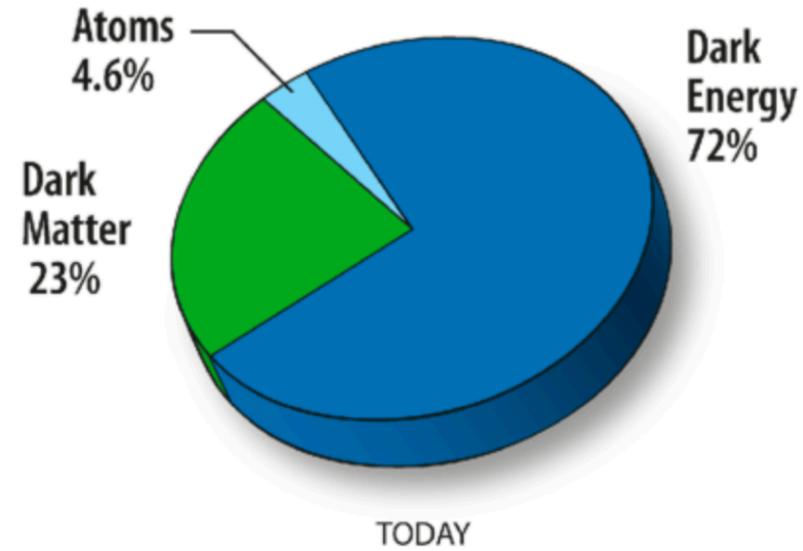
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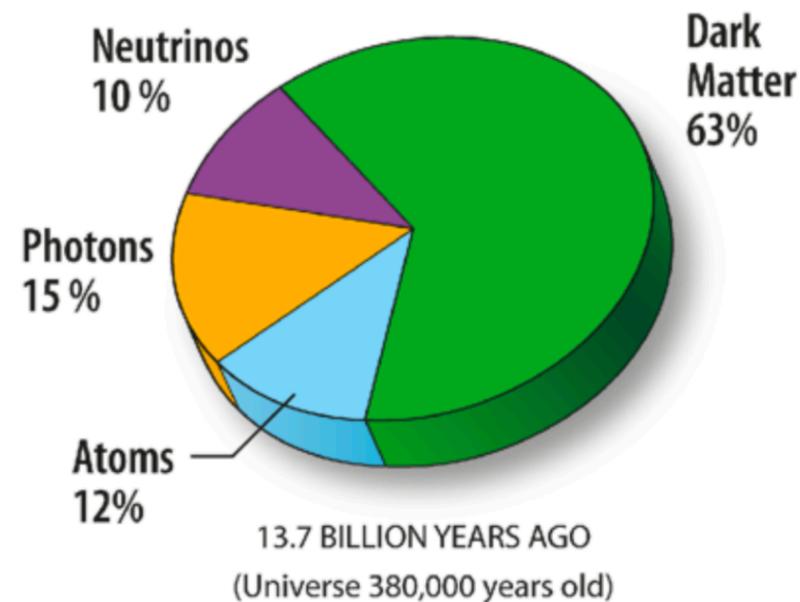
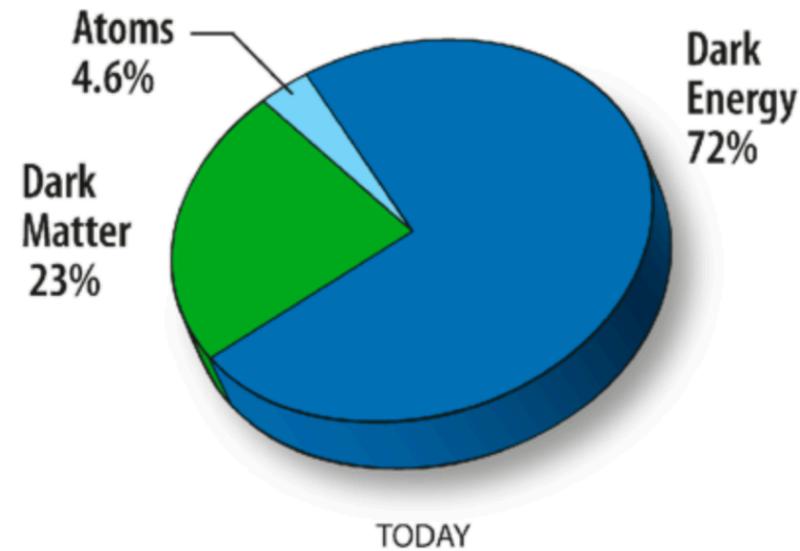
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- This implies some sort of “missing” or “dark” matter that's pulling these stars around.

To the best of our knowledge from these observations,



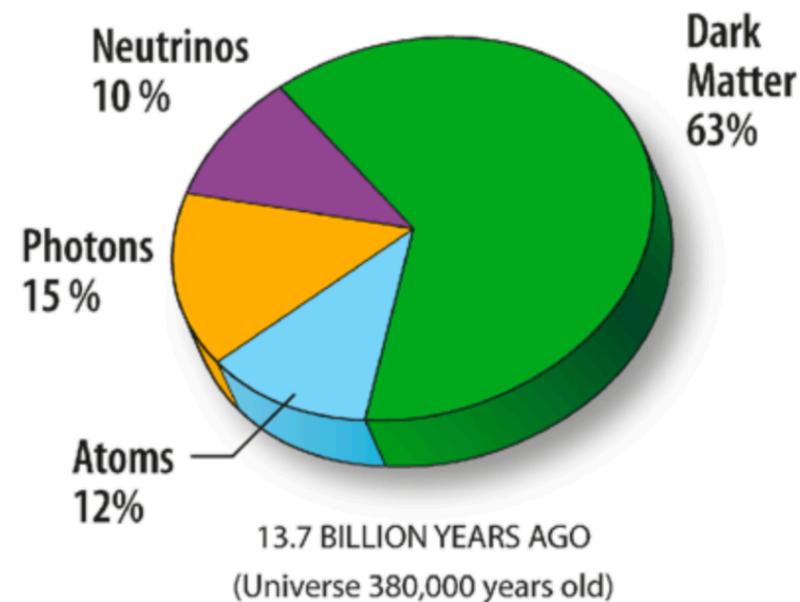
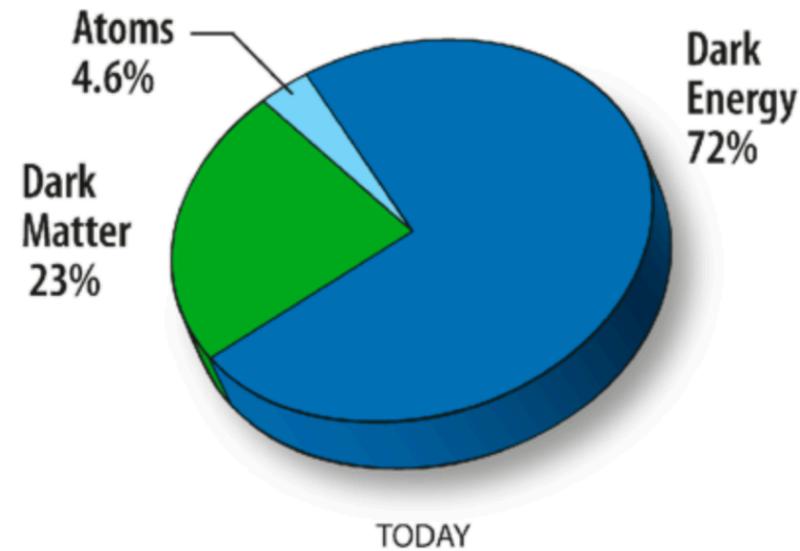
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- The particles we have identified in the Standard Model make up a small fraction of all of the observed “energy density” of the universe.

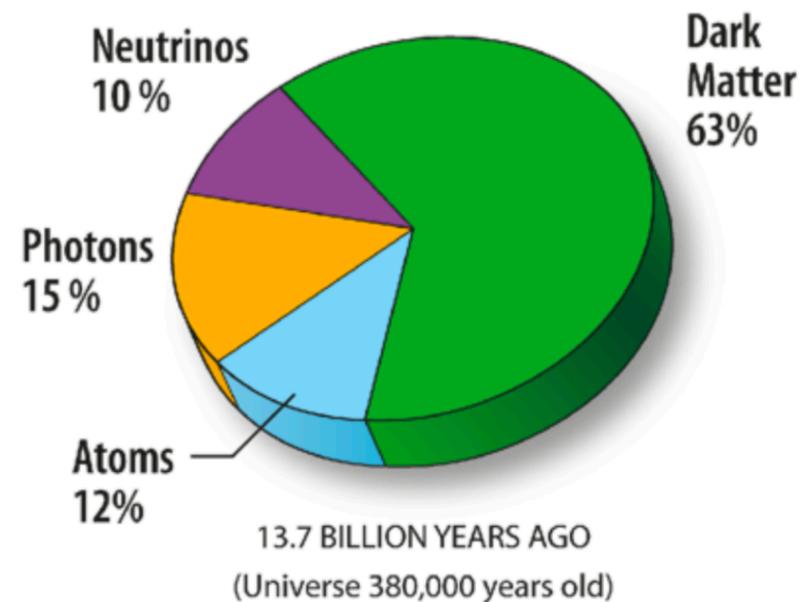
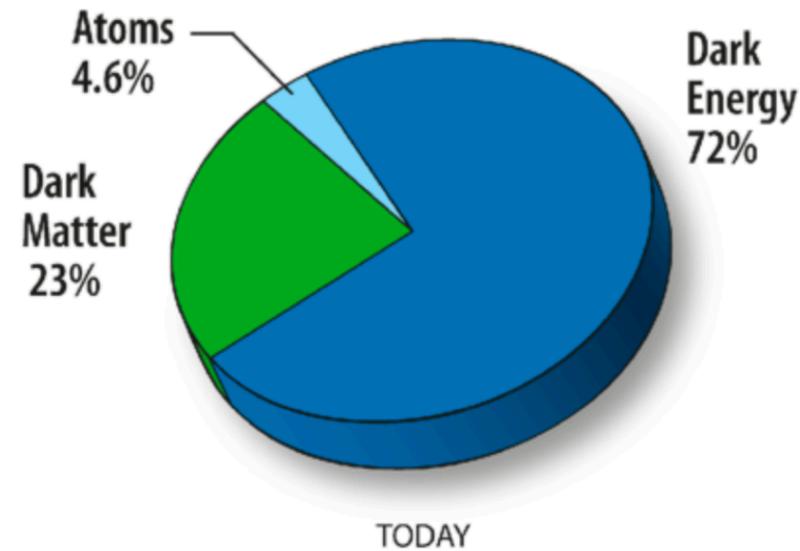


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- The particles we have identified in the Standard Model make up a small fraction of all of the observed “energy density” of the universe.
- The majority of this energy density (today) is made up of what we call “dark energy”.

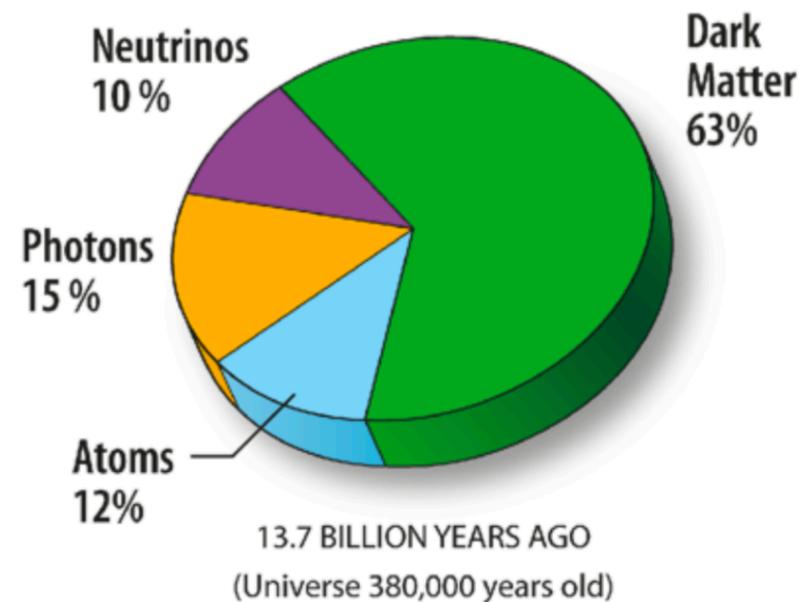
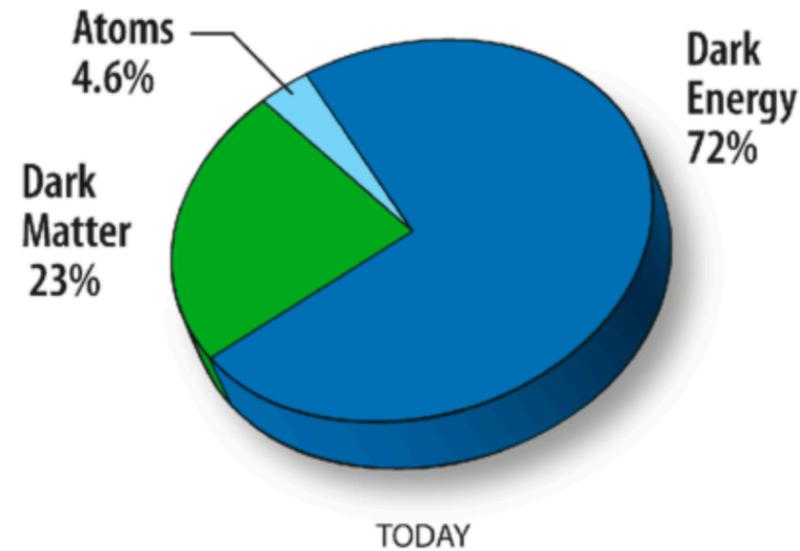


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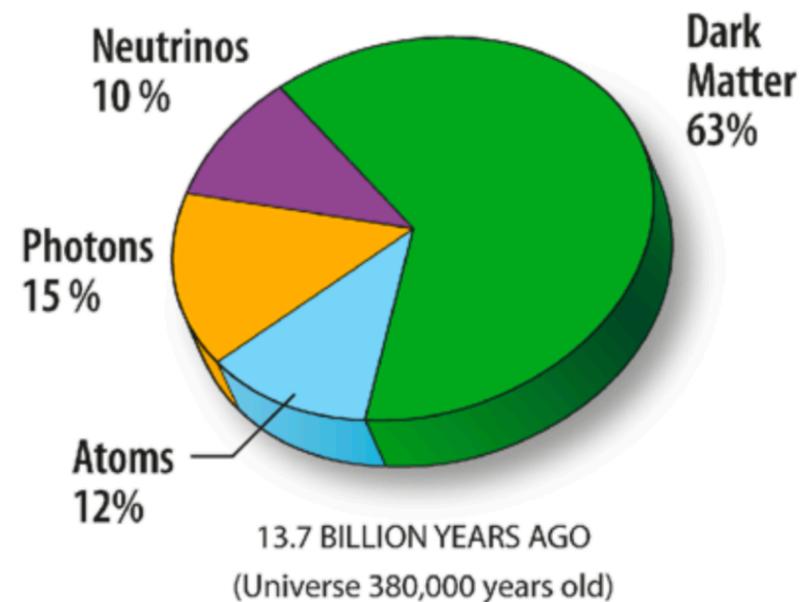
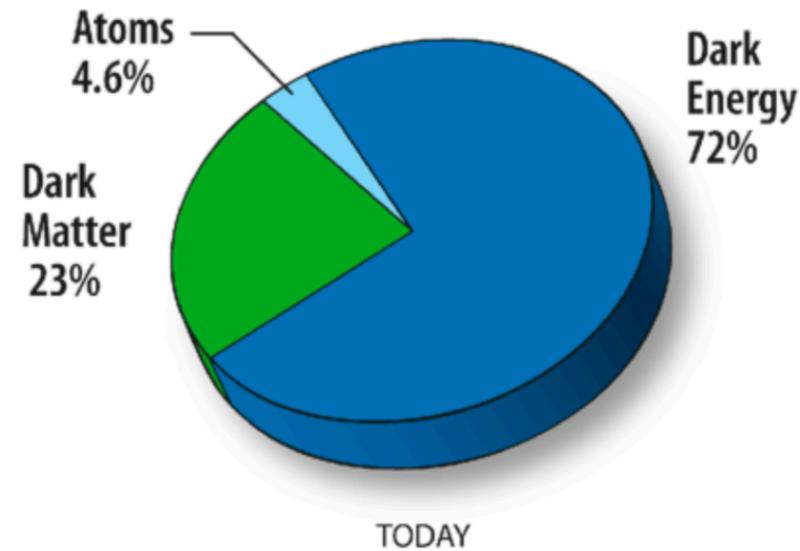
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- Worldwide efforts exist to identify and solve both of these mysteries.

Neutrino Oscillations & Neutrino Masses

THURSDAY, 11 JUNE



12:00 PM

→ 1:00 PM

Neutrino Physics

🕒 1h

Speaker: Kirsty Duffy (Fermilab)

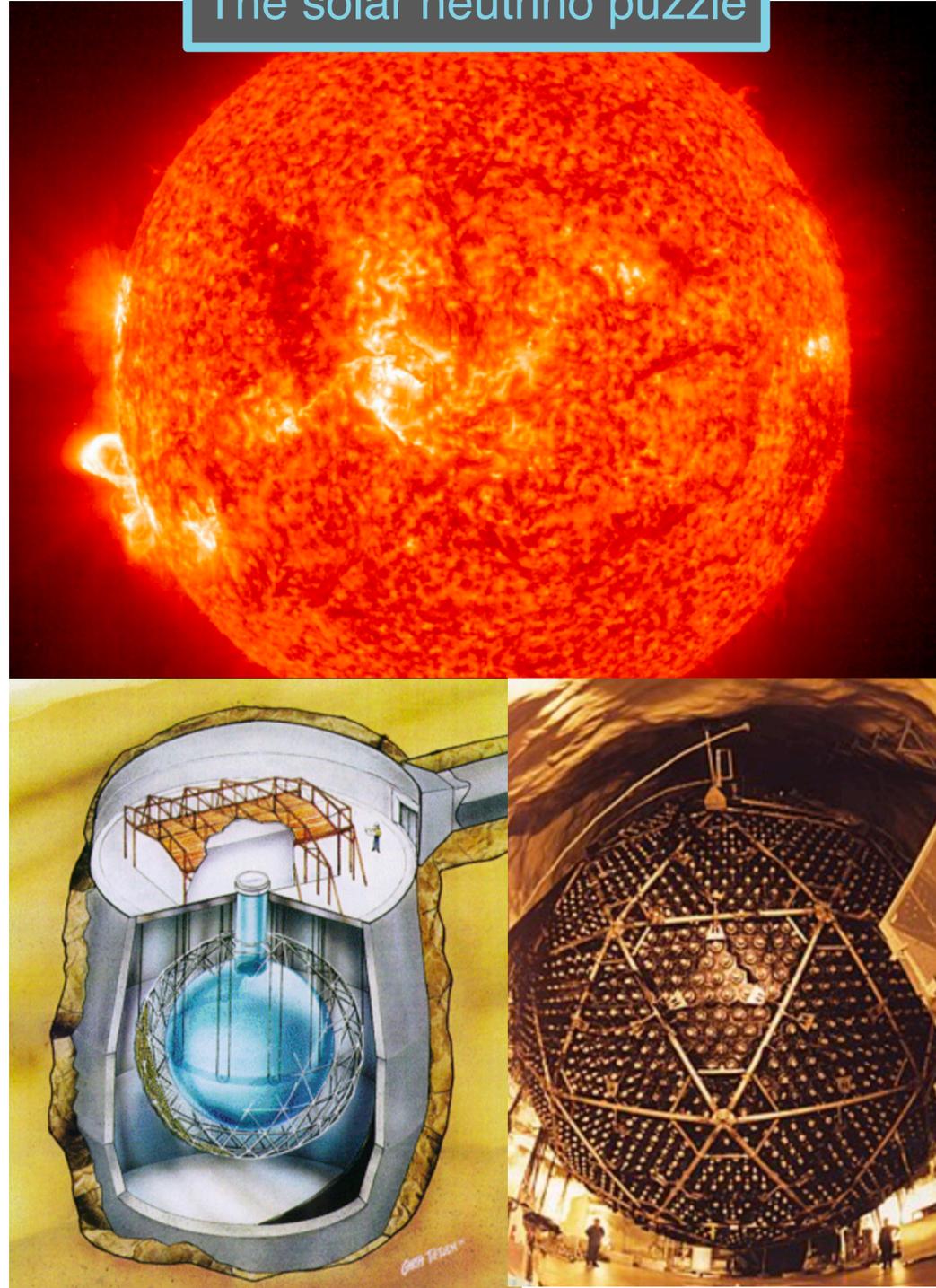
Over several decades, evidence mounted...

The solar neutrino puzzle



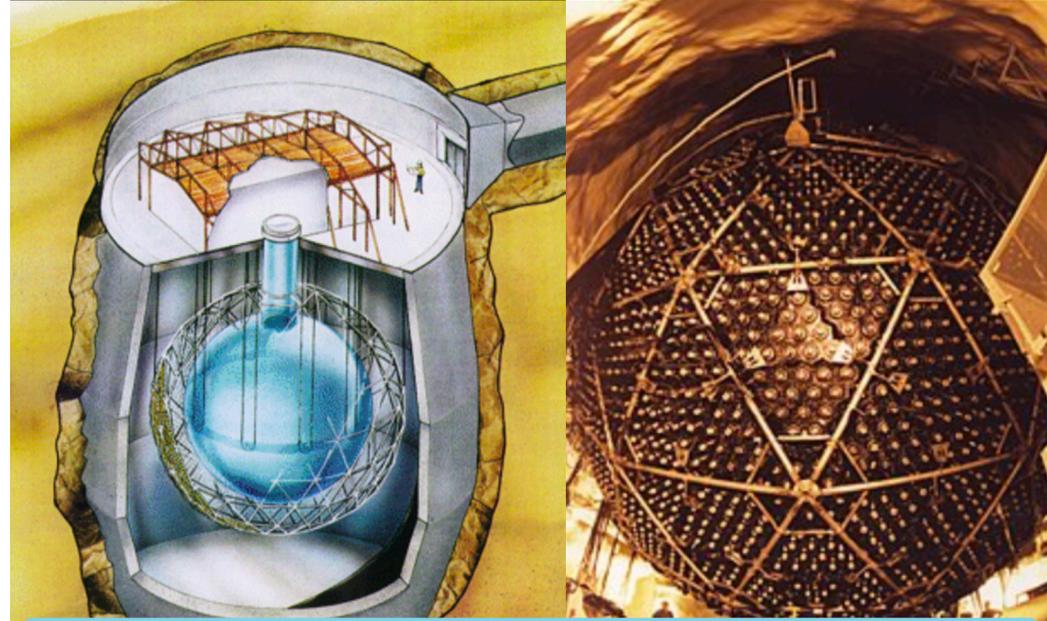
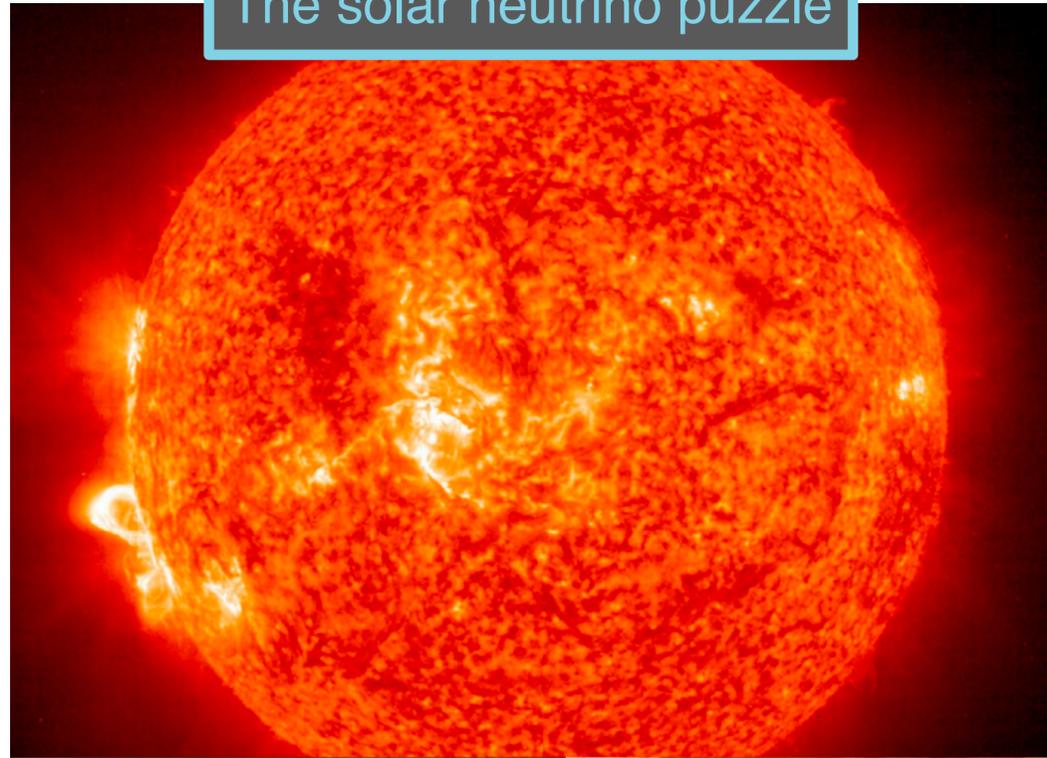
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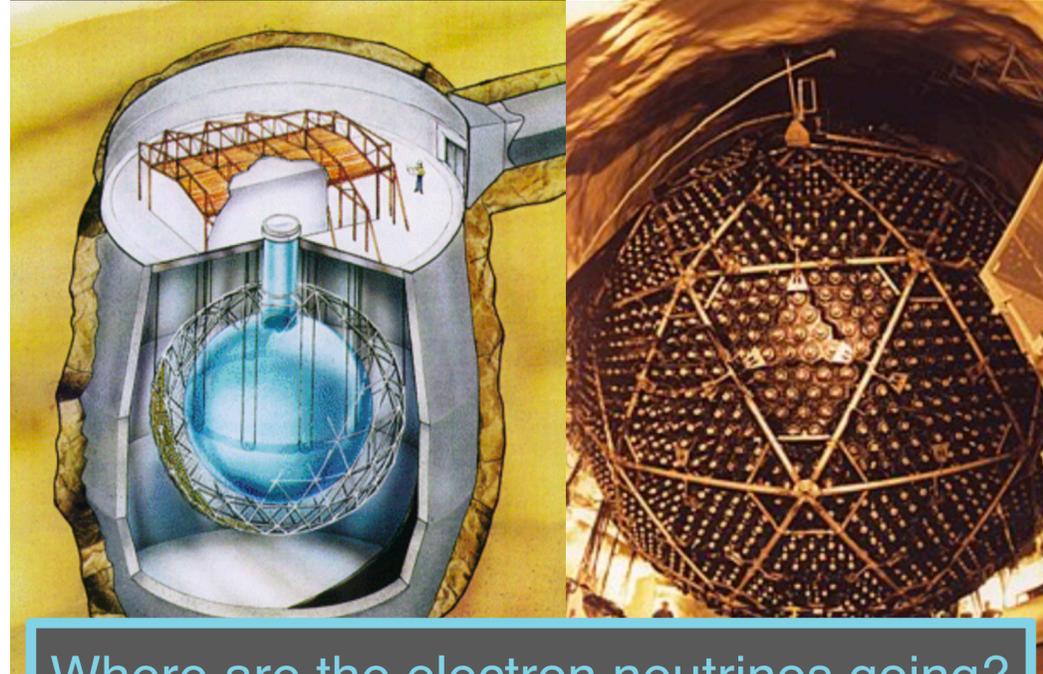
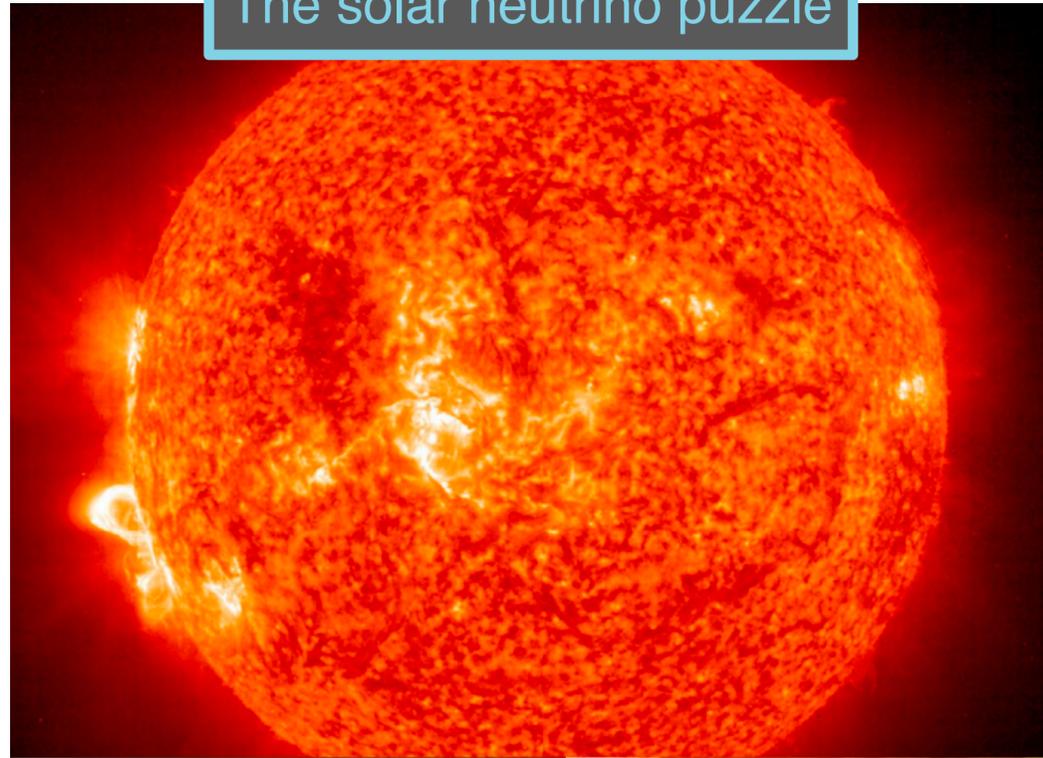


Where are the electron neutrinos going?



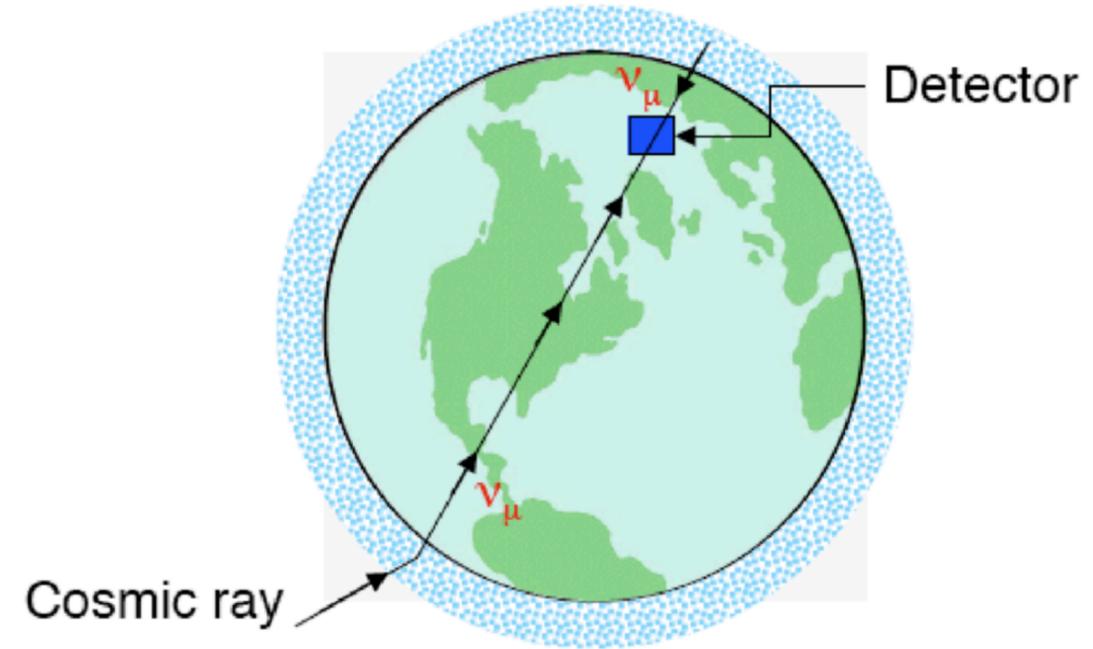
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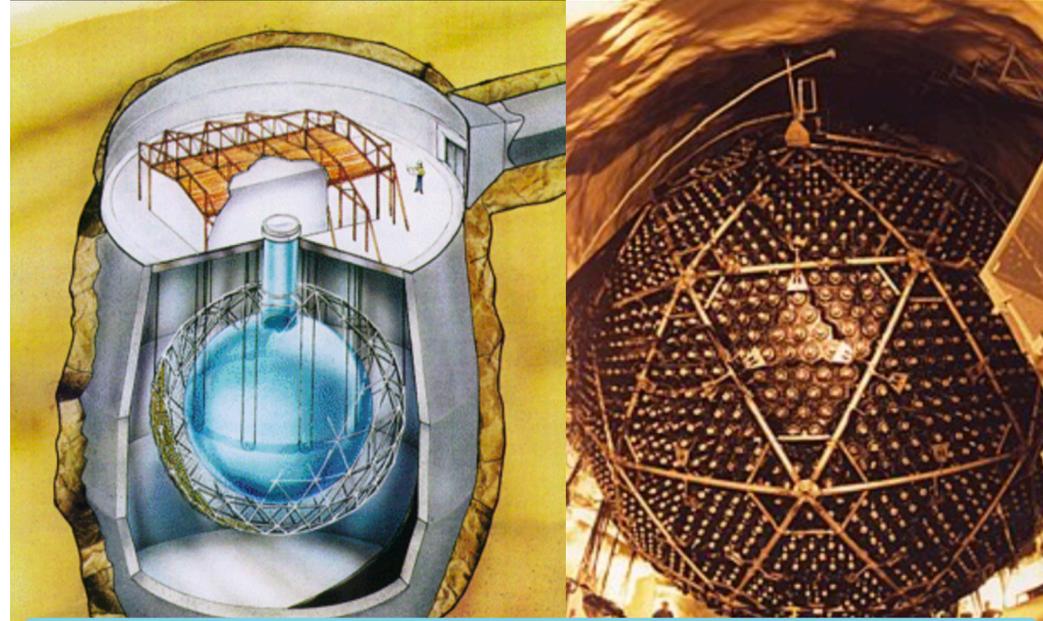
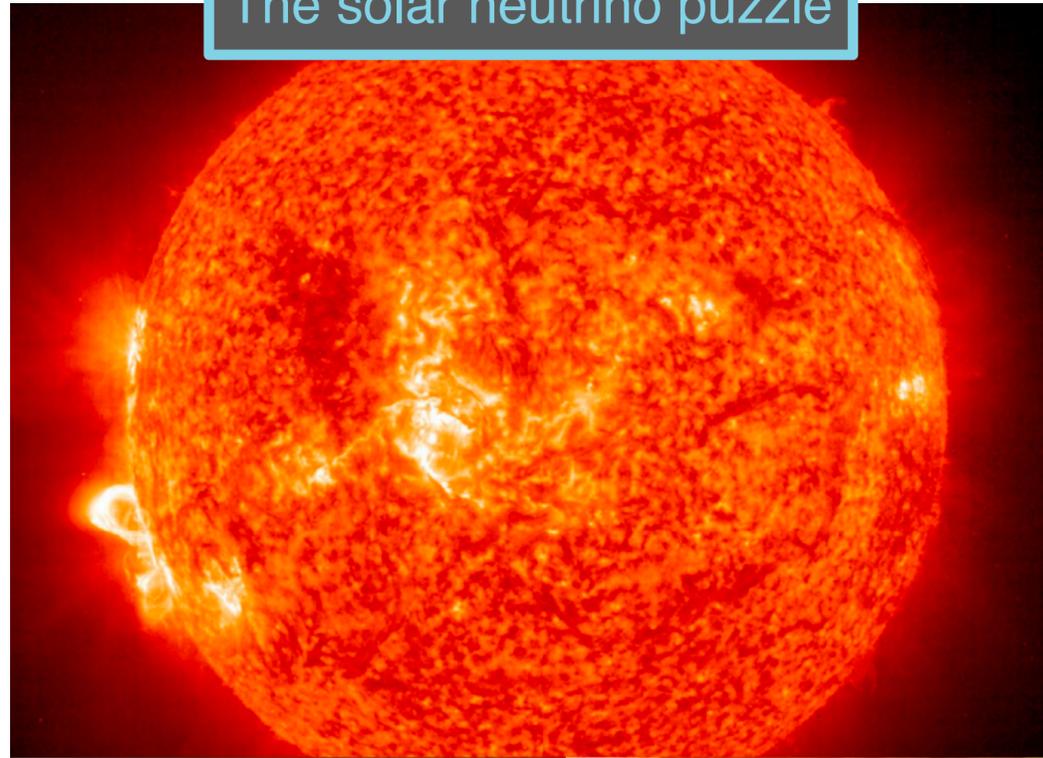
Where are the electron neutrinos going?

The atmospheric neutrino puzzle



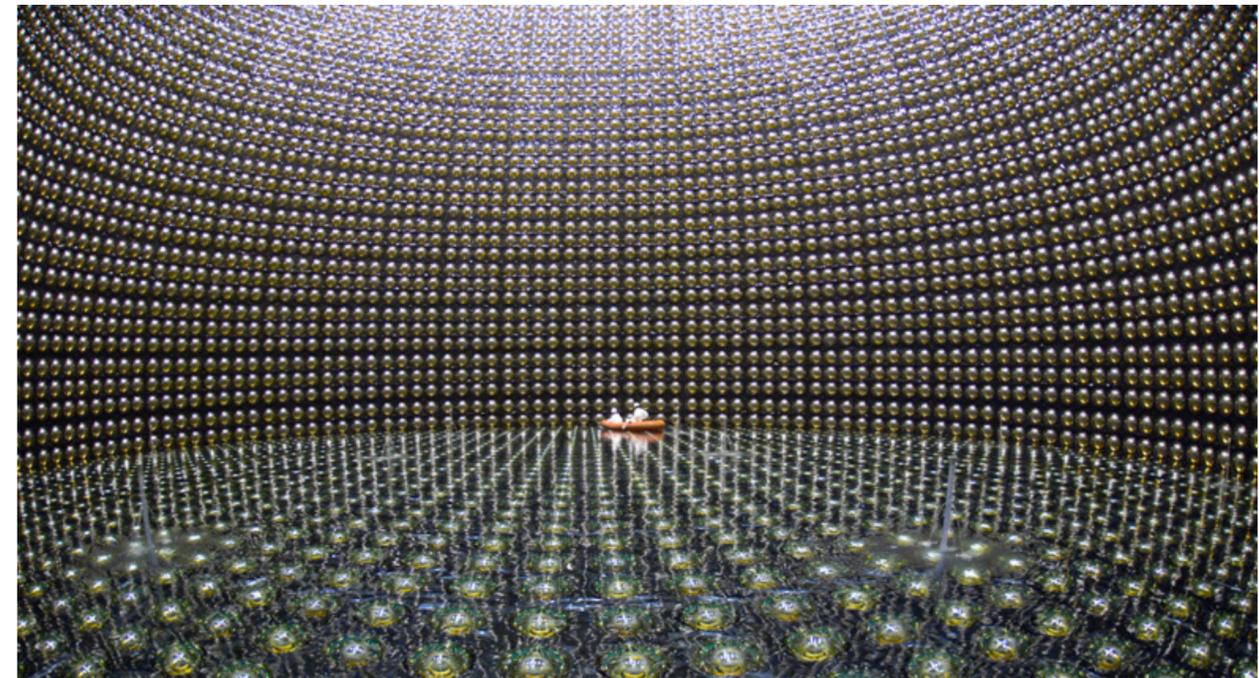
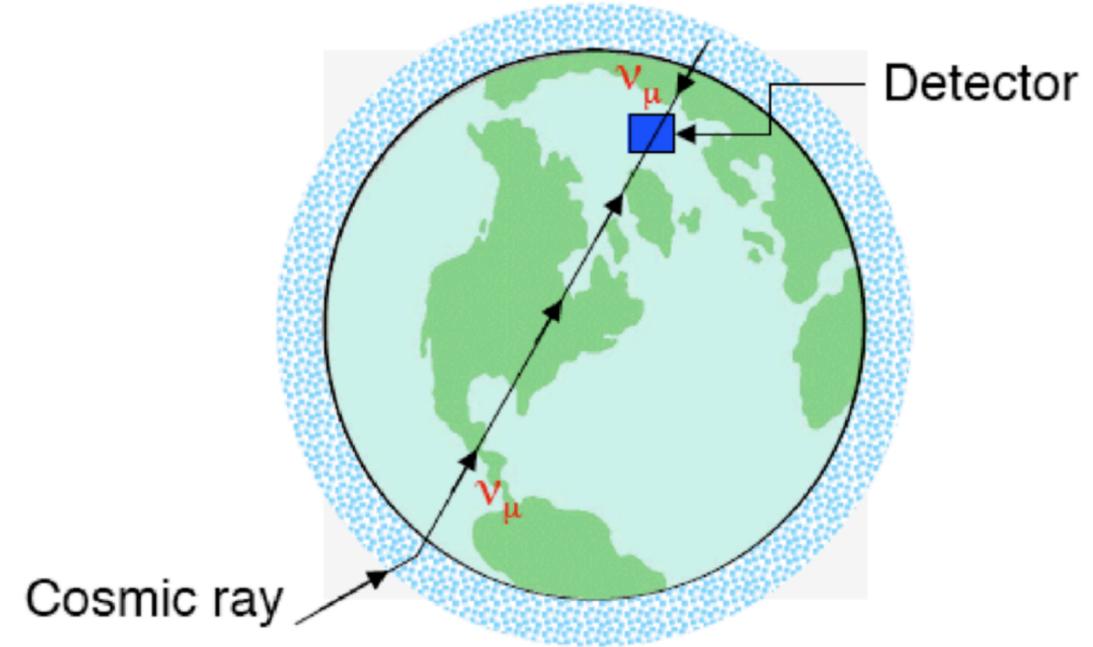
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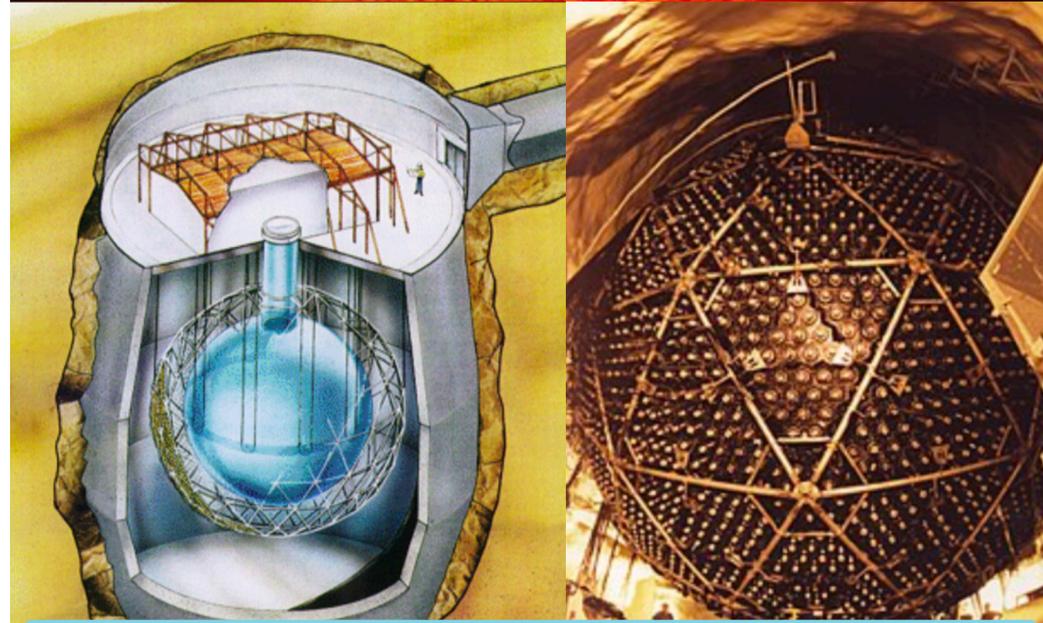
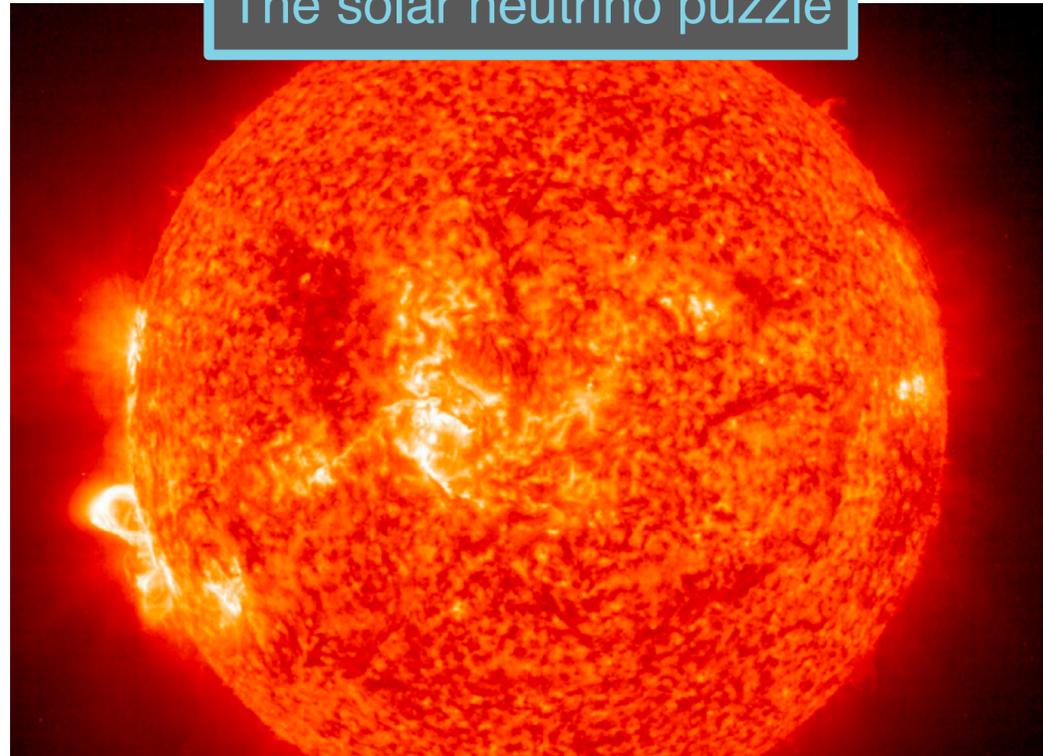
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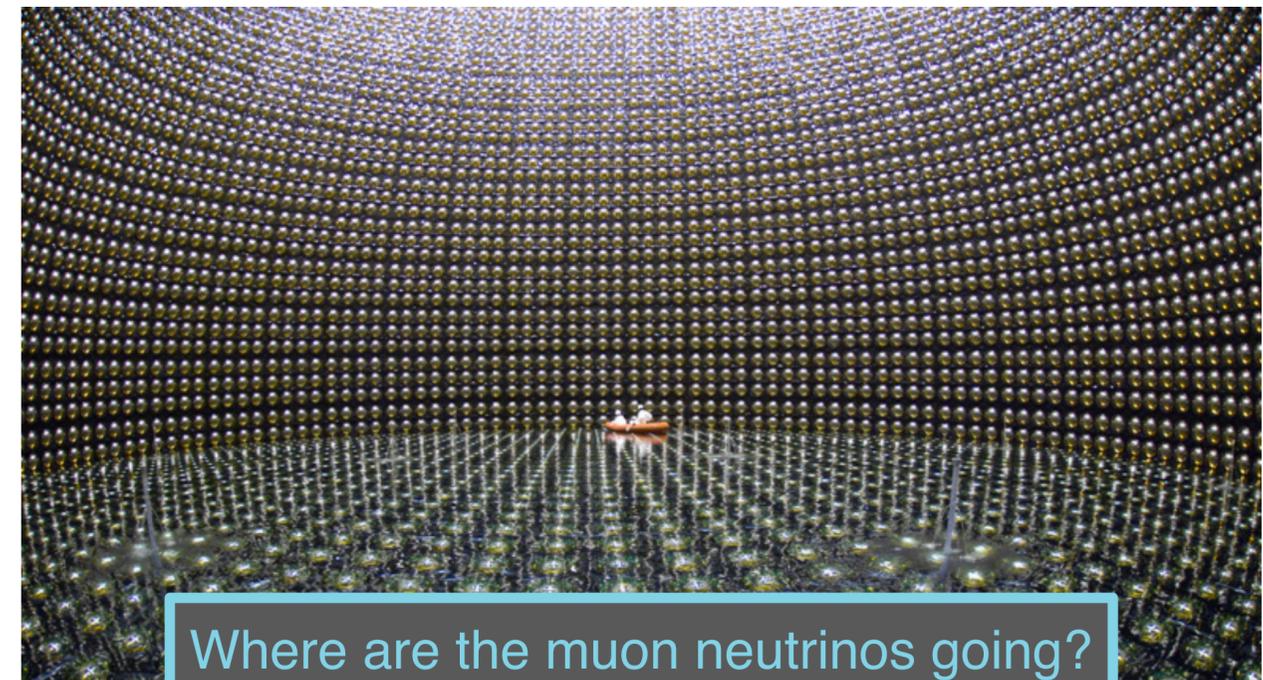
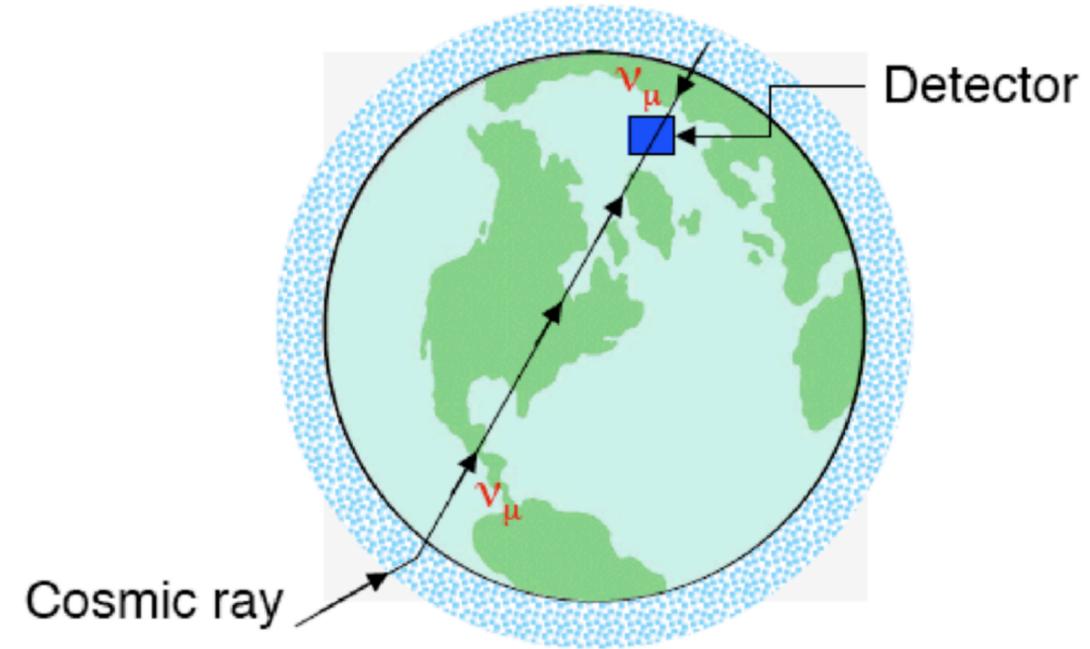
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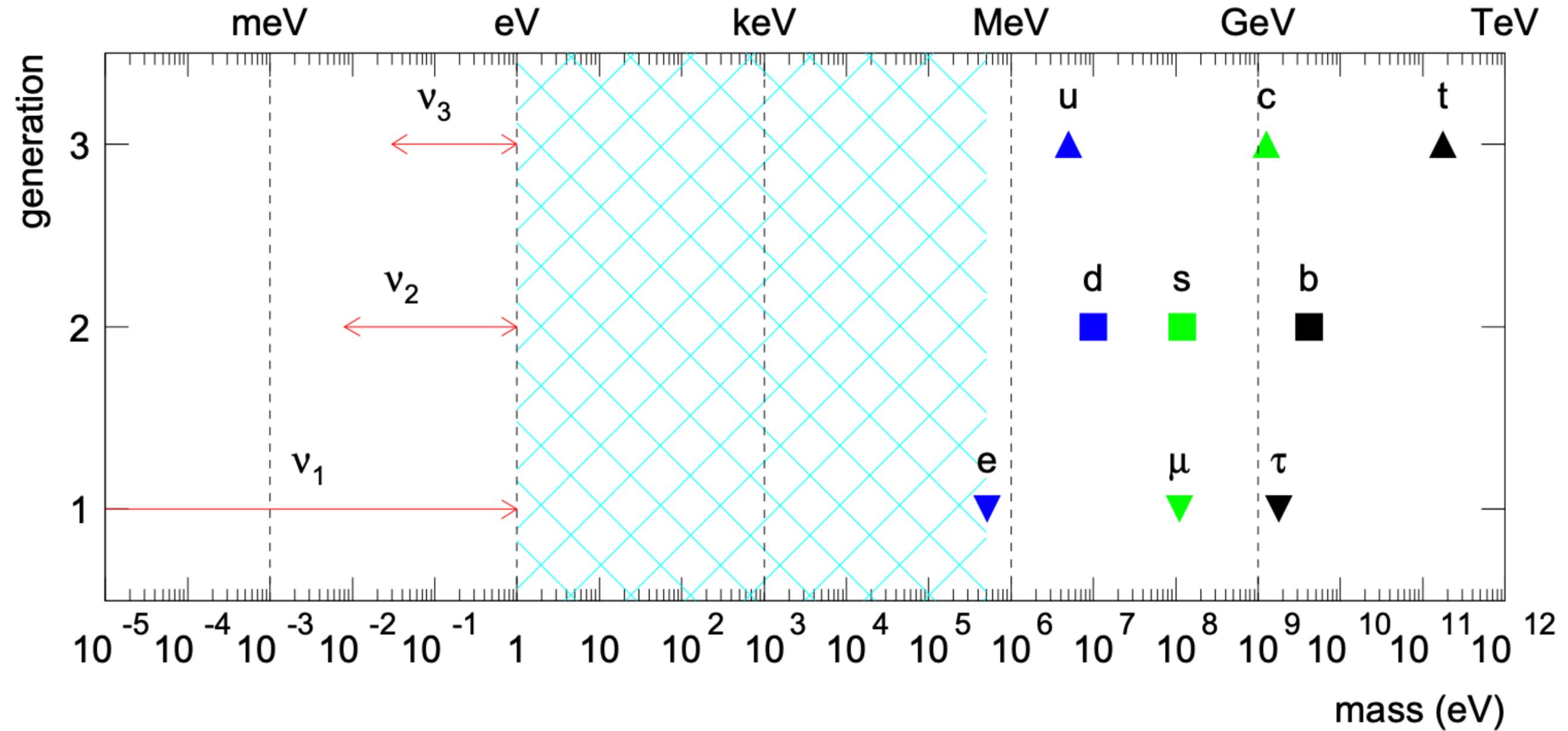
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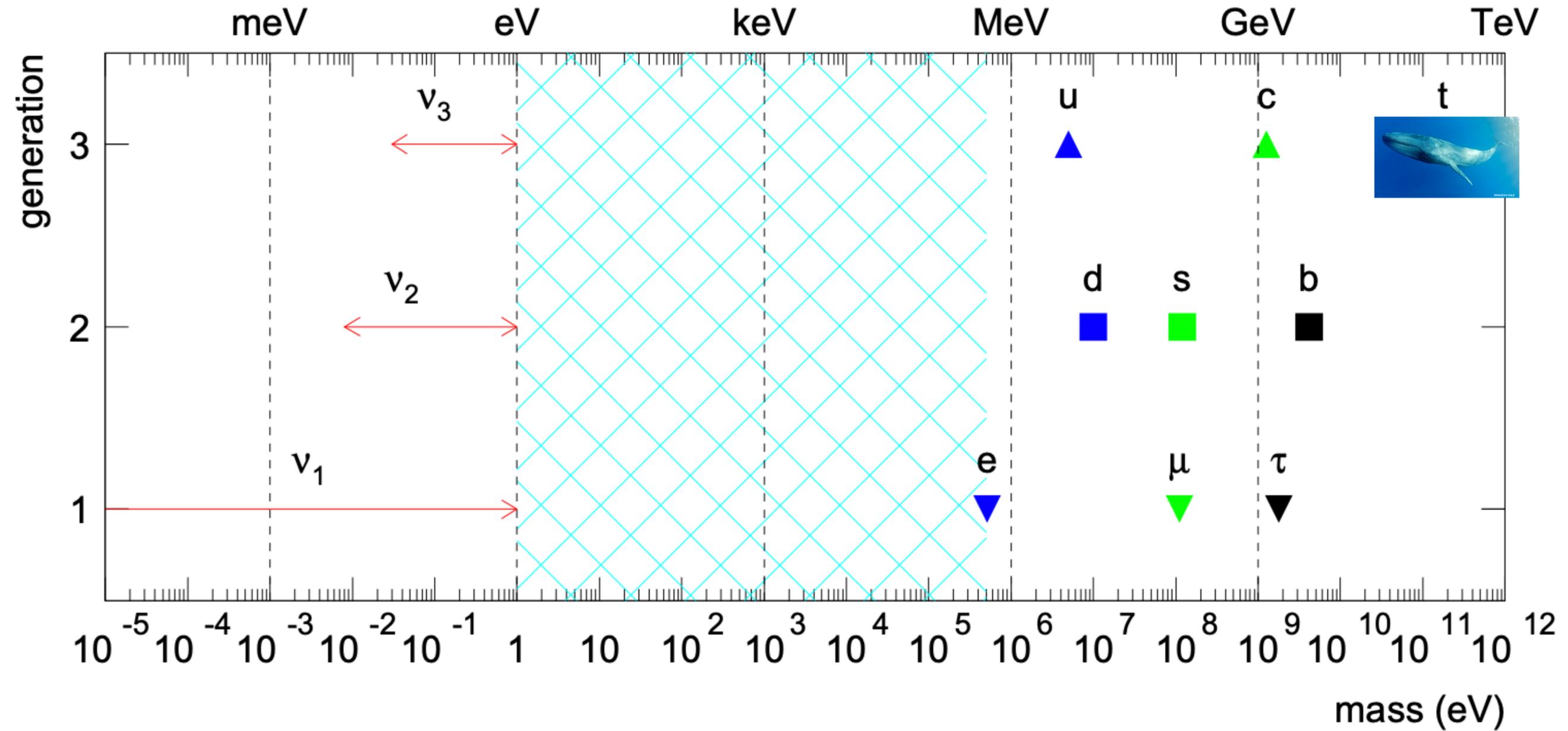


Where are the muon neutrinos going?

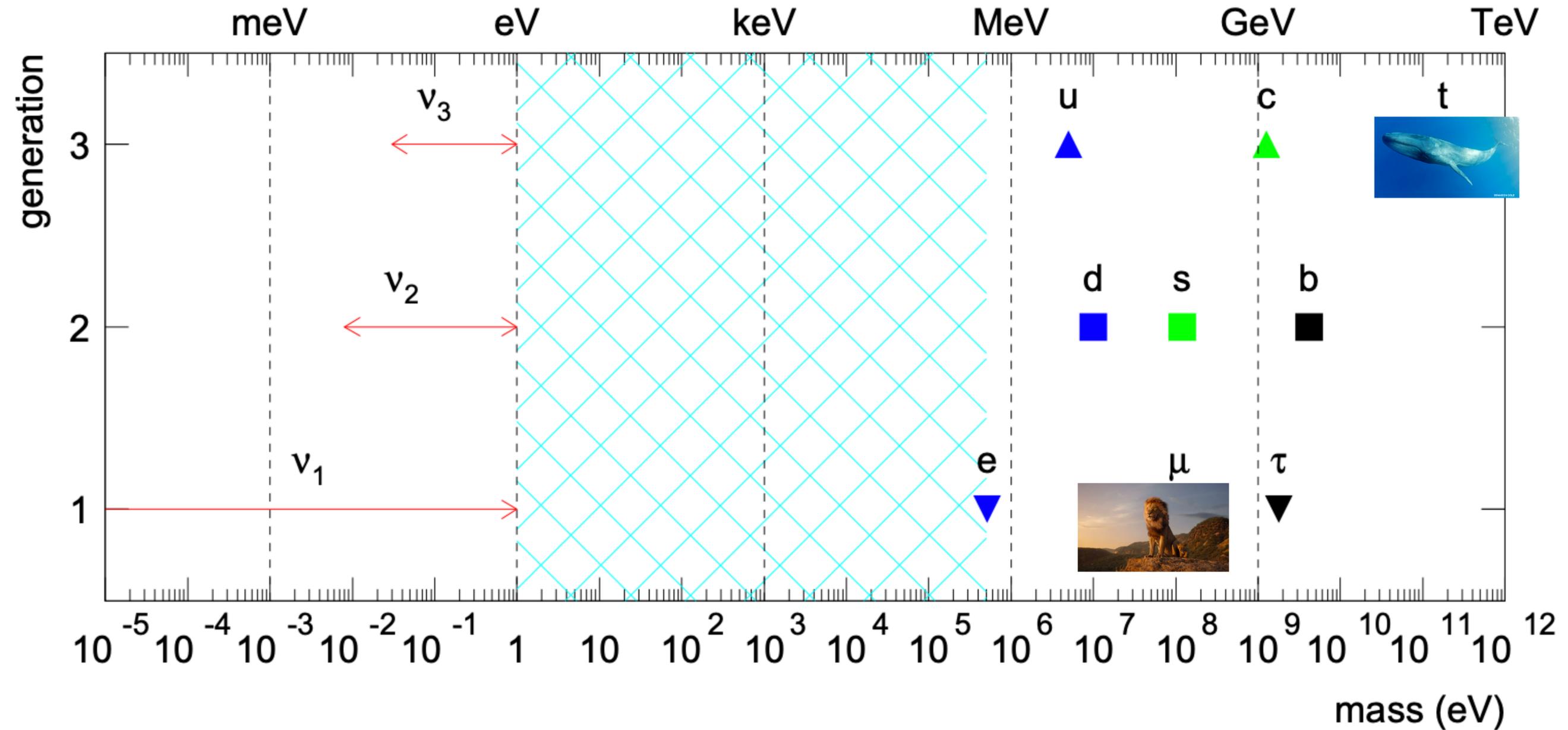
Only consistent explanation of these (and more) observations - Neutrinos have (very small) Masses



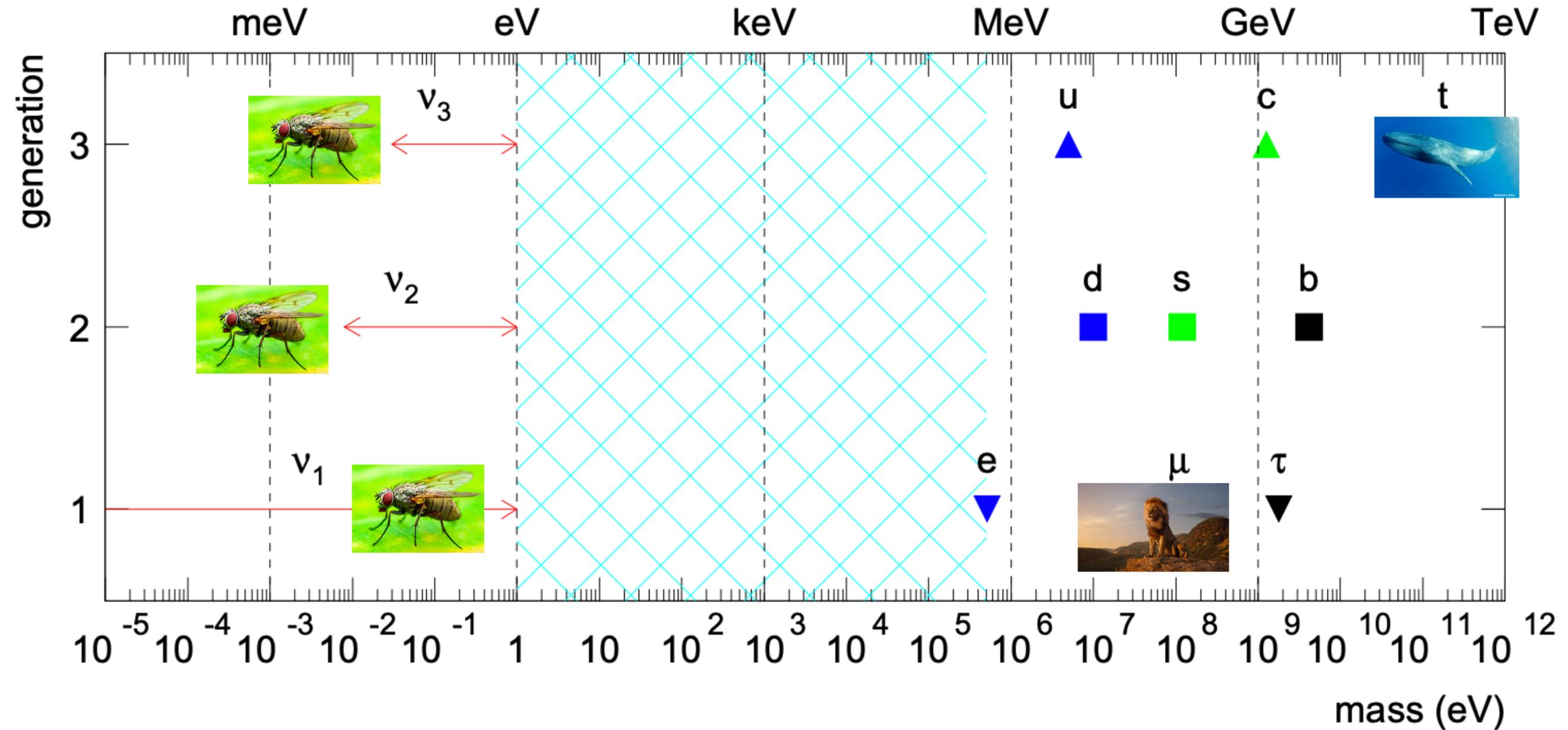
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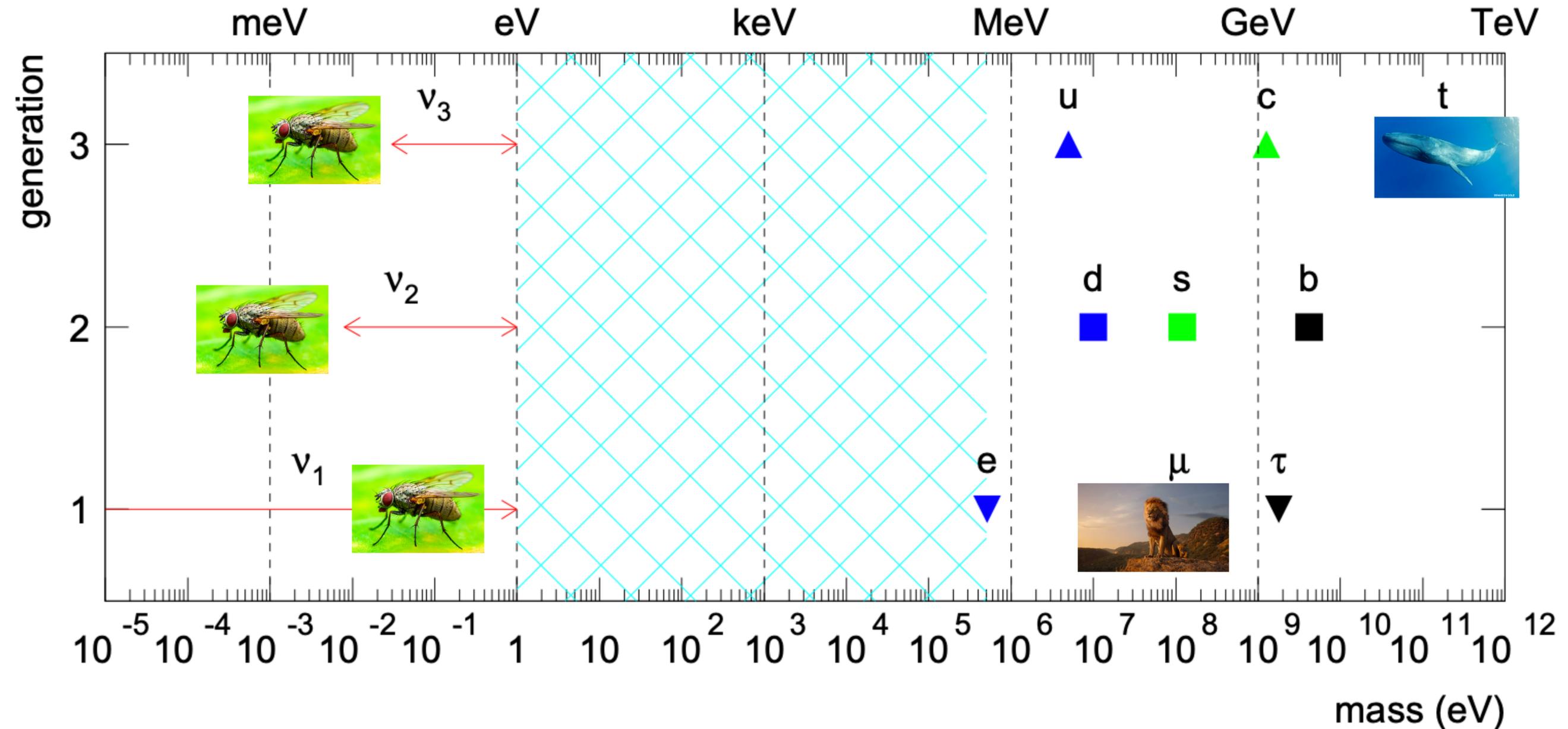
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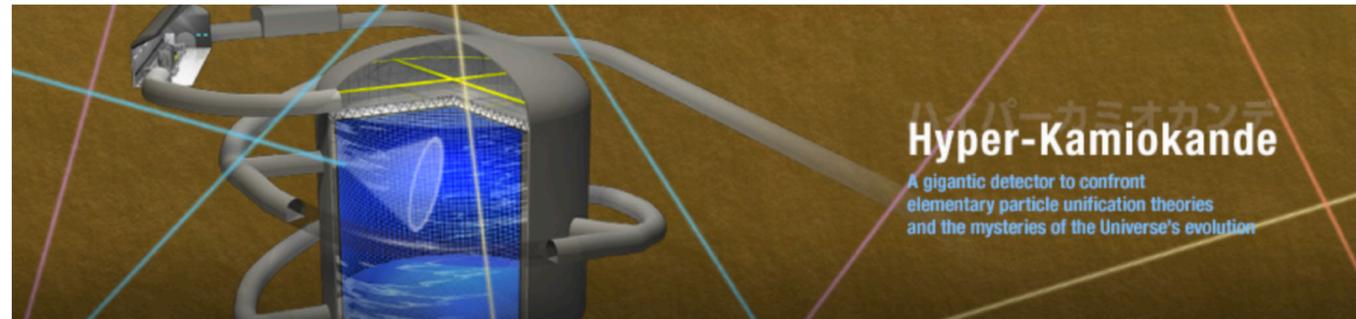
Like Dark Matter, the Standard Model does not predict neutrino masses!

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

Upcoming Experiments to better understand Neutrinos



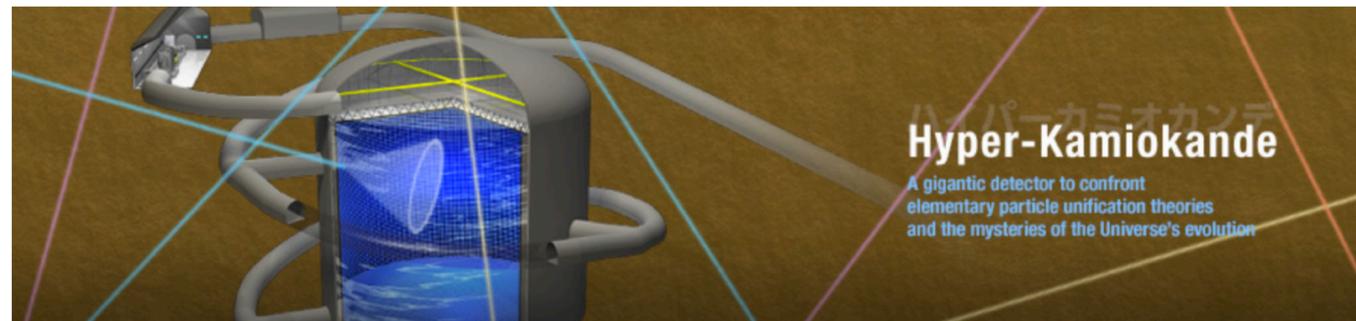
Hyper-Kamiokande



Upcoming Experiments to better understand Neutrinos



Hyper-Kamiokande

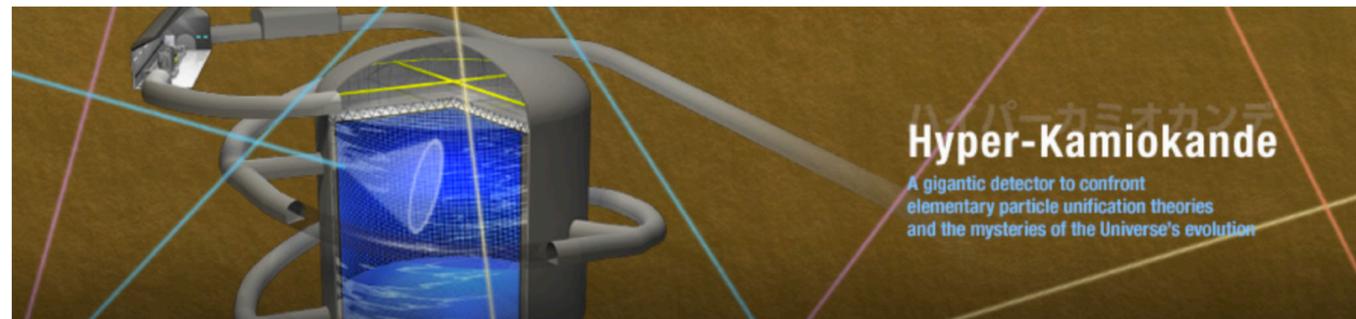


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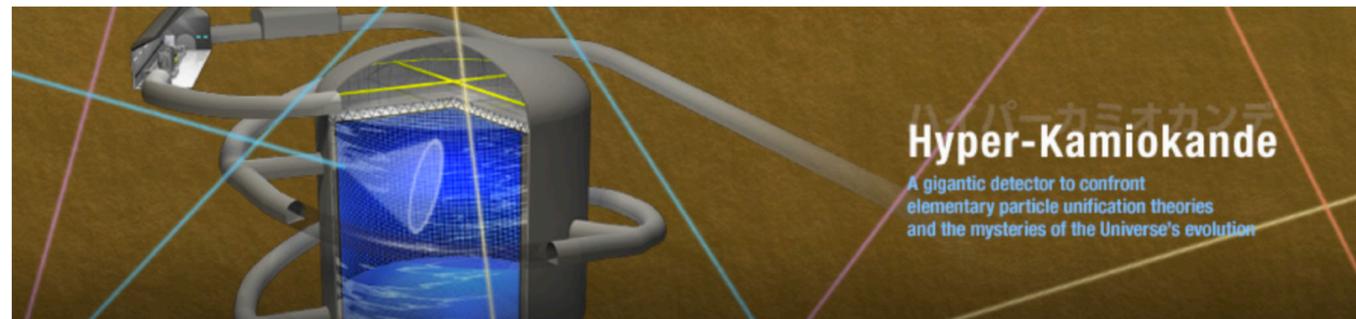


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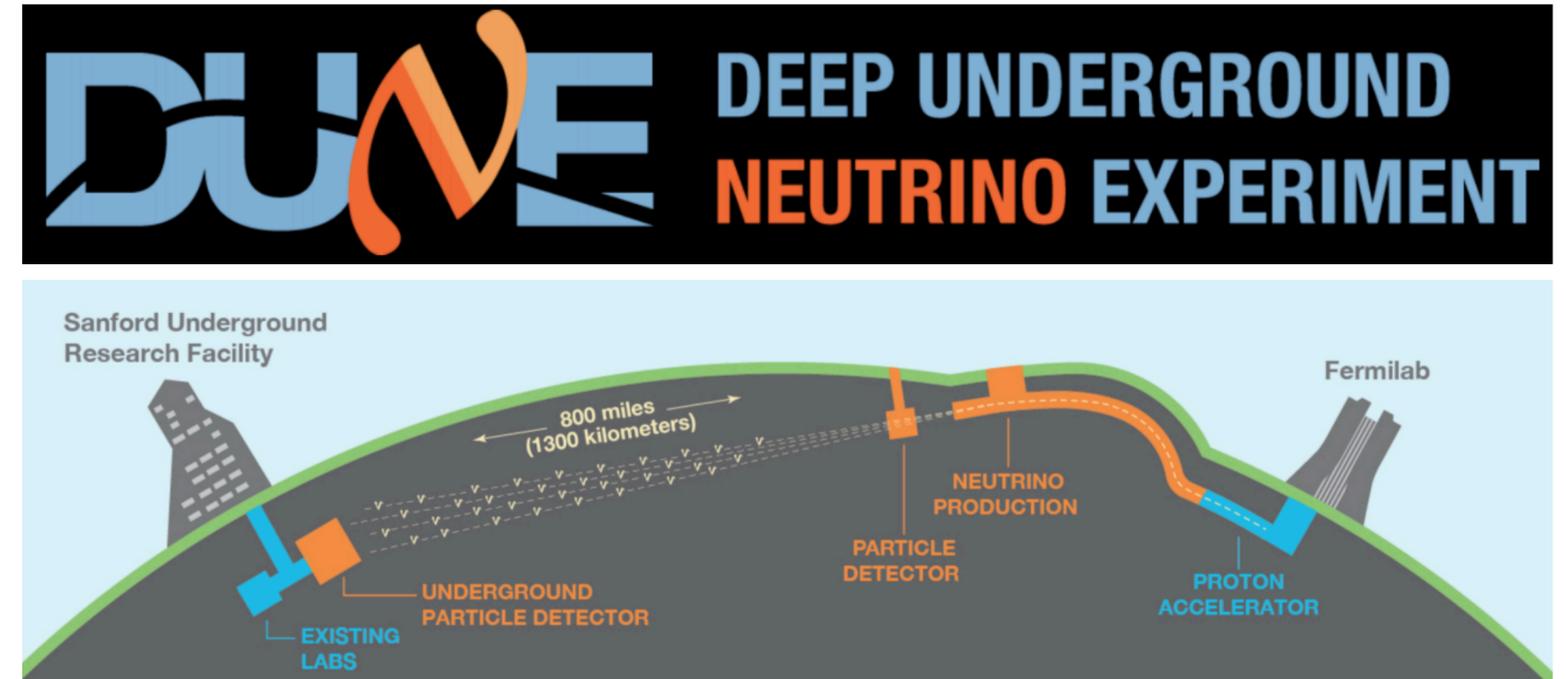
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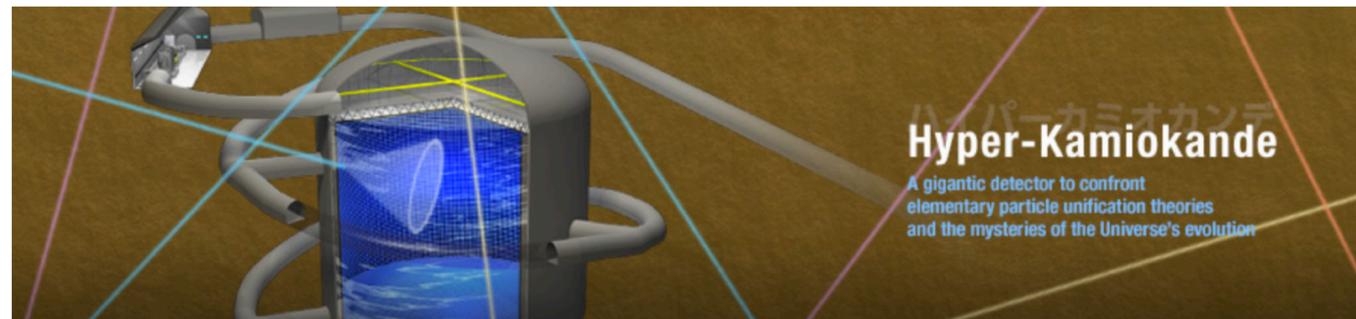
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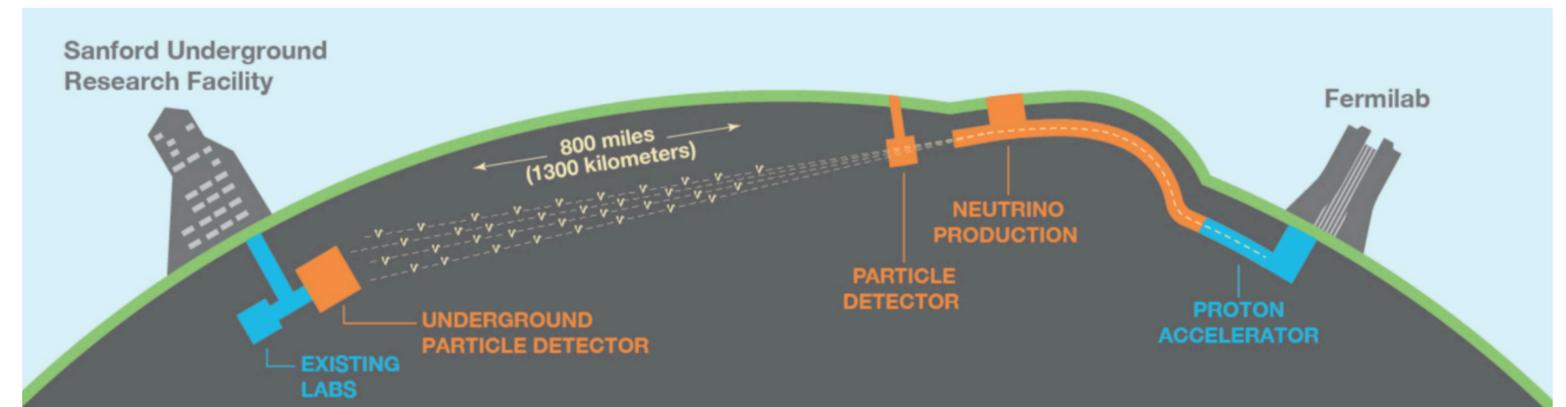
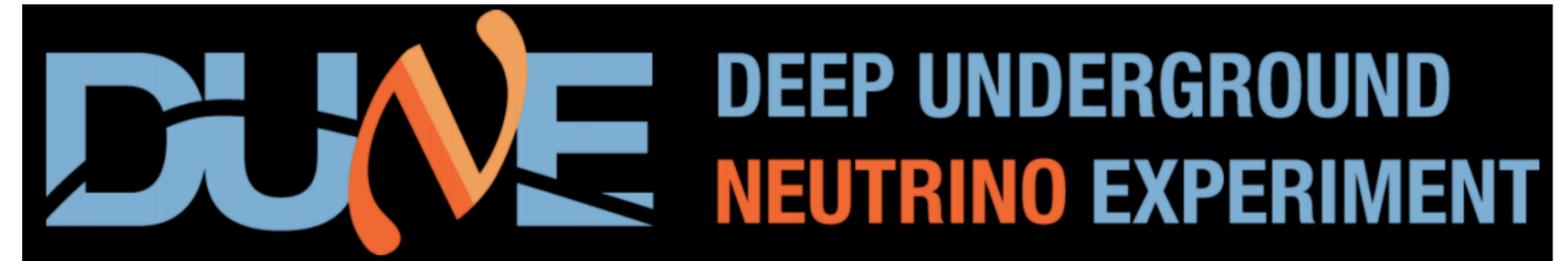
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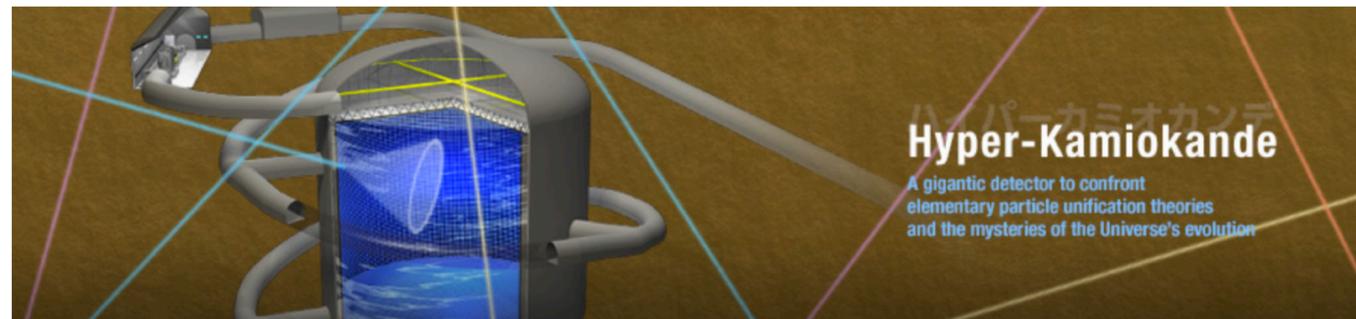


- US-based precision neutrino physics project.

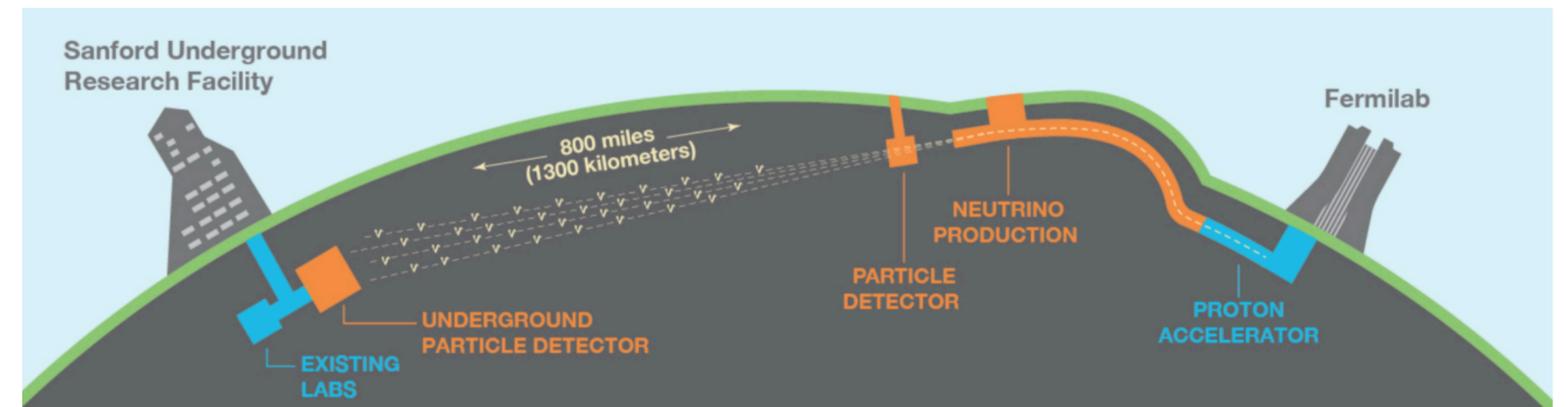
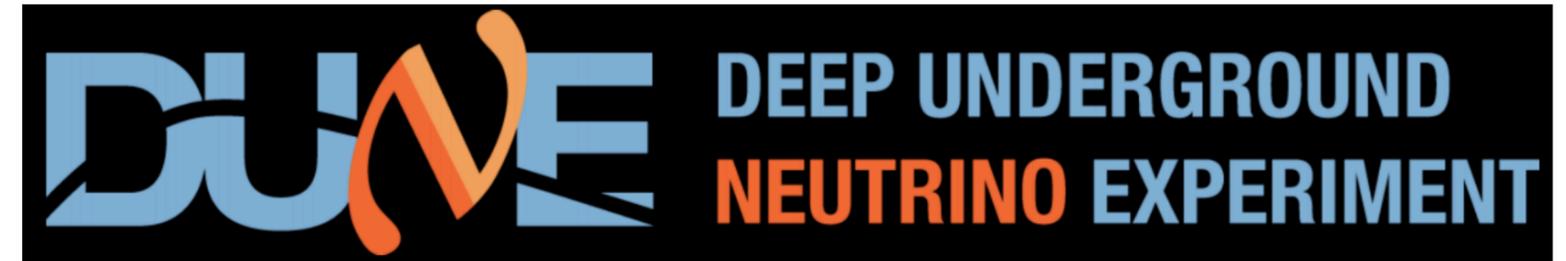
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- US-based precision neutrino physics project.
- Built on new, liquid-argon based technology being developed in Fermilab-based “short-baseline” neutrino program.

The Higgs Hierarchy Problem

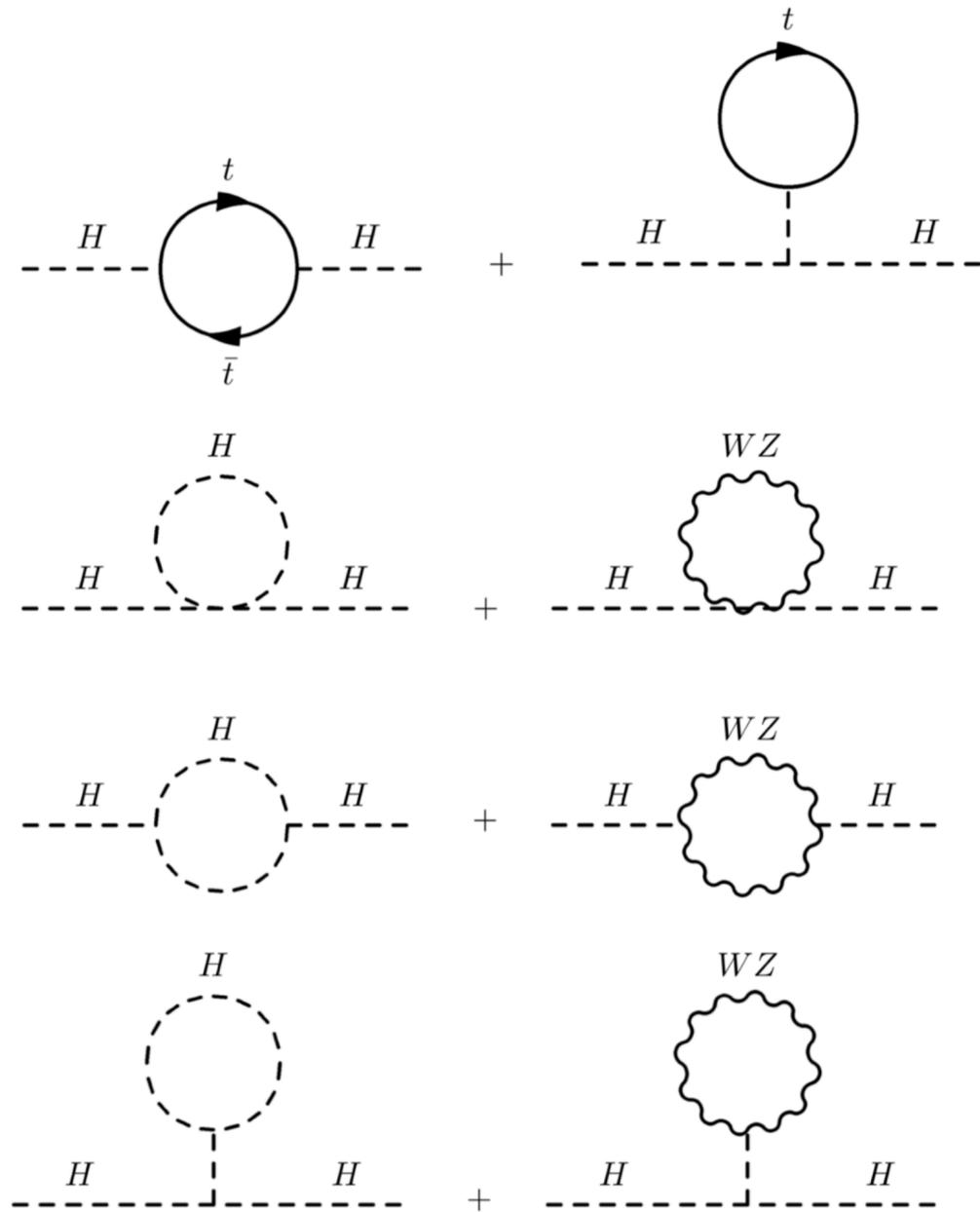
THURSDAY, 18 JUNE 

12:00 PM → 1:00 PM **Particle Physics at CMS**  1h

Speaker: Karri DiPetrillo (Harvard University)

The Higgs Boson Mass & Quantum Corrections

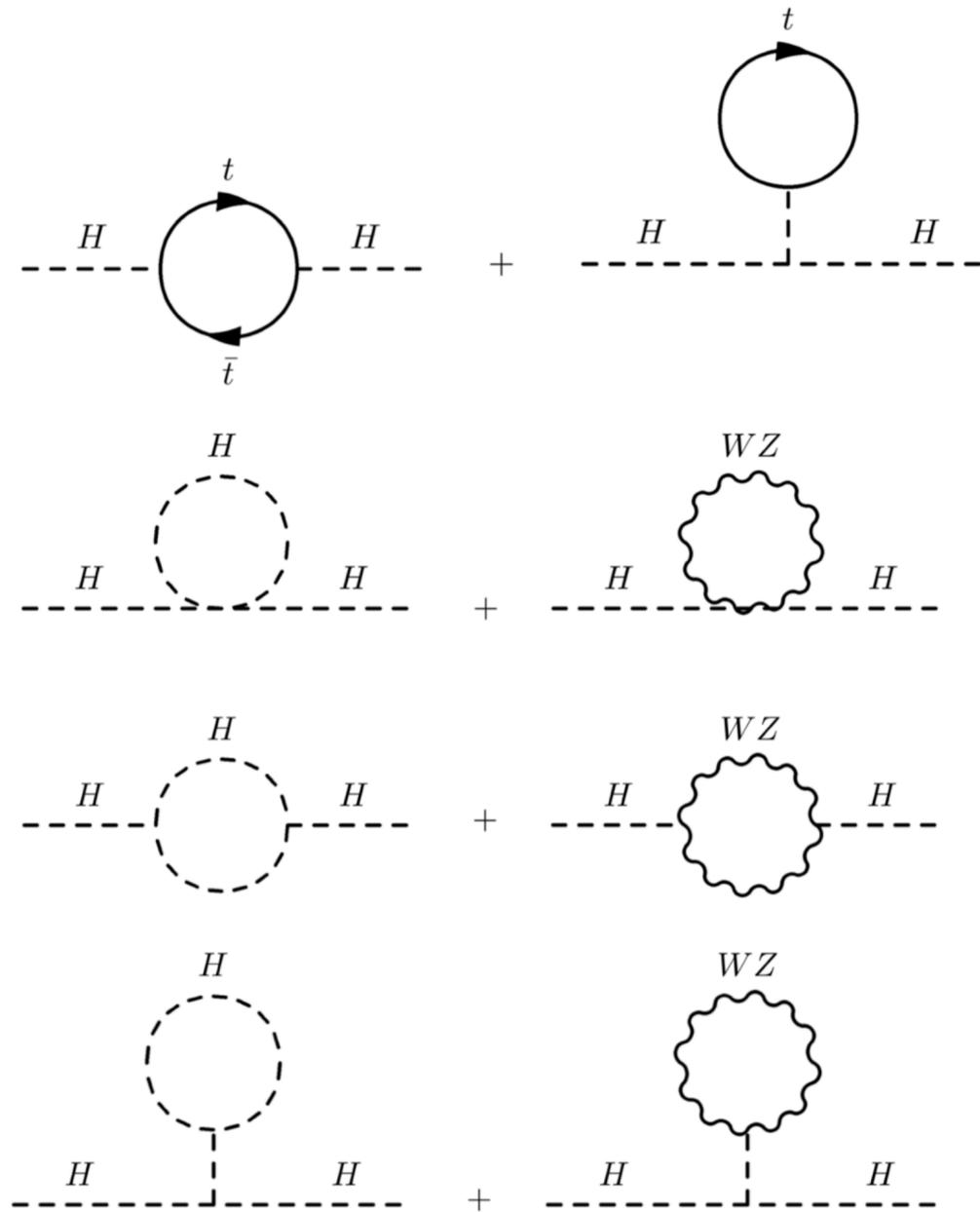
The Higgs Boson Mass & Quantum Corrections



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

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

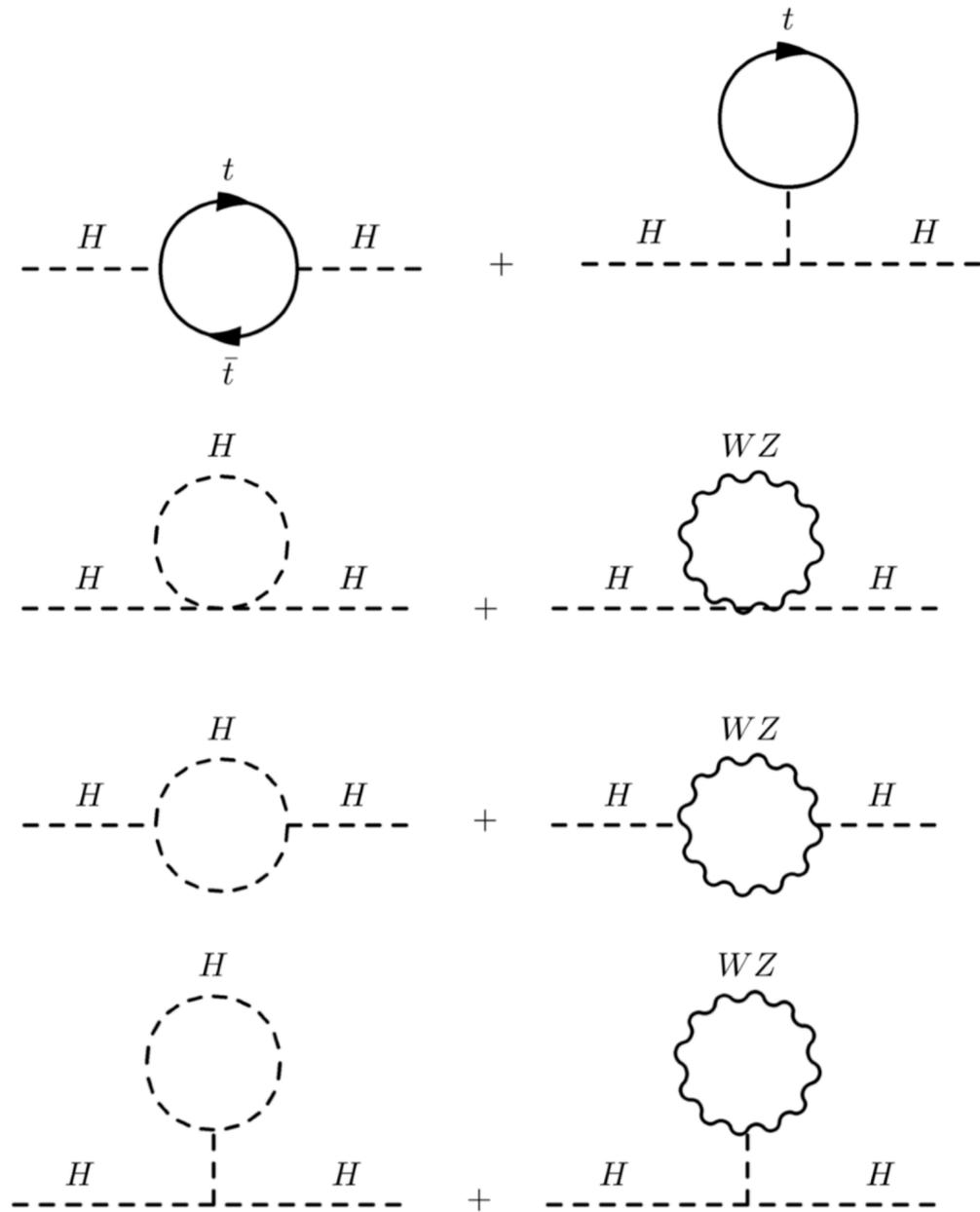
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- Quantum field theory predicts that processes like these modify the Higgs boson's mass from its “Lagrangian value”.
- We observe the Higgs mass to be near the other weak-scale particles, about 125 GeV.

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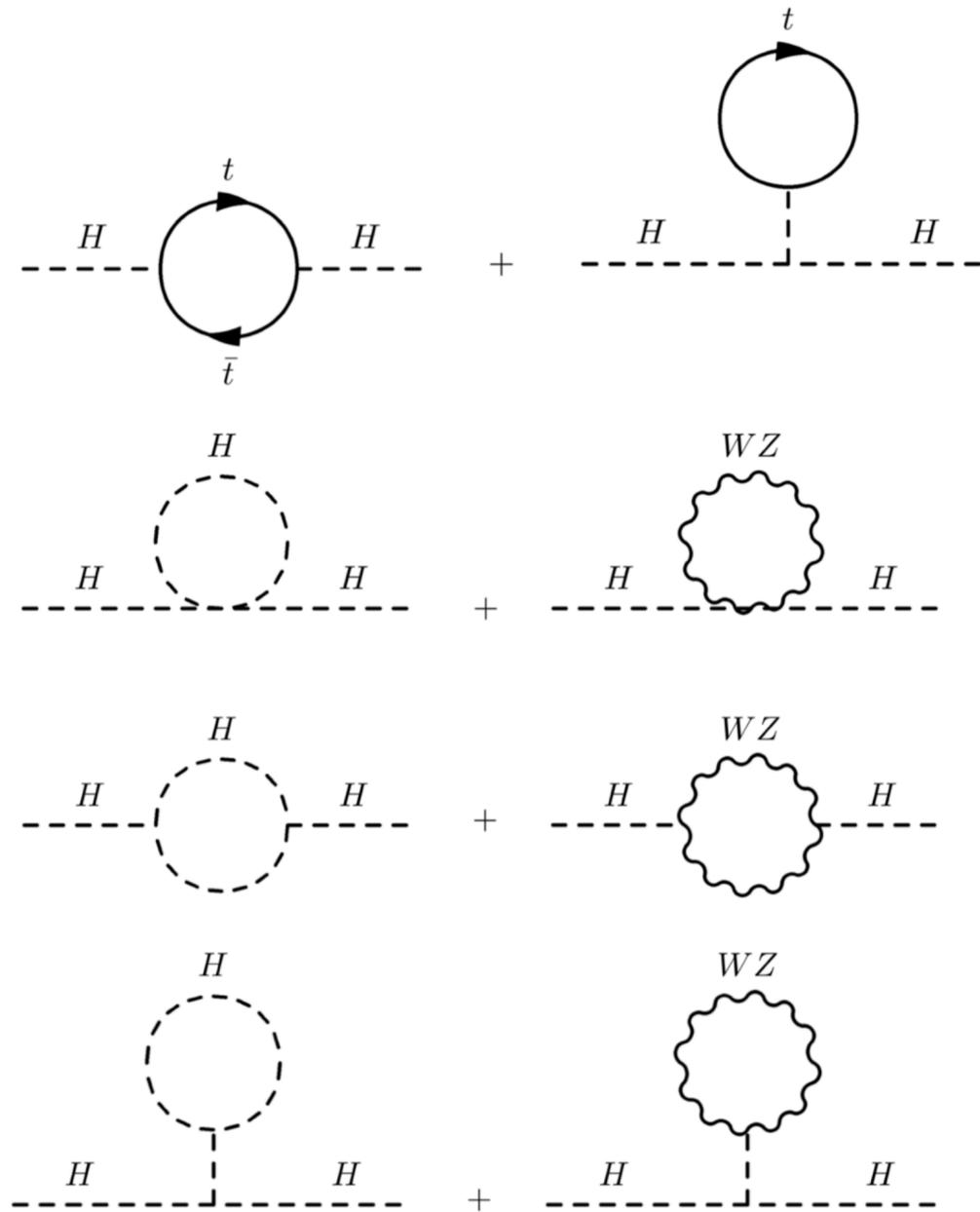
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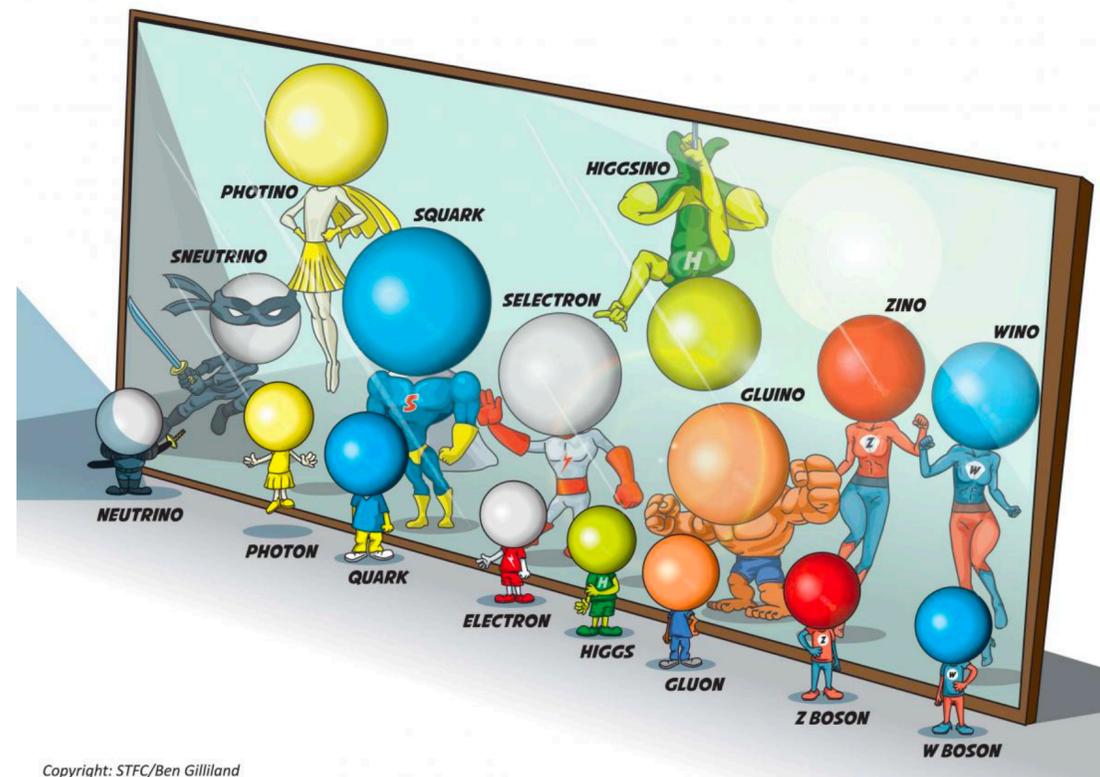
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- We observe the Higgs mass to be near the other weak-scale particles, about 125 GeV.
- Due to the nature of these diagrams though, any new mass scale above the weak scale should pull the Higgs boson mass to be very, very large.
- Why then, do we see it to be so small?

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

Solution: Supersymmetry

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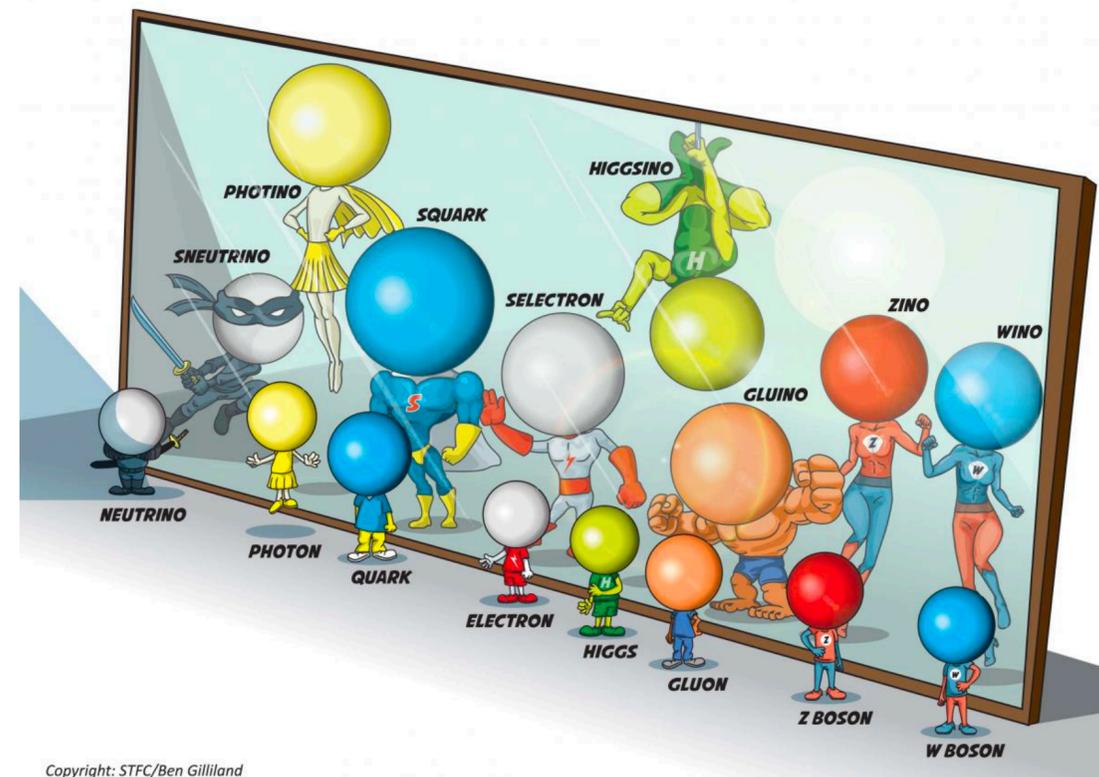
- Every standard model particle has a super-symmetric partner. These superparticles perfectly cancel out all of these quantum corrections to the Higgs mass.



Copyright: STFC/Ben Gilliland

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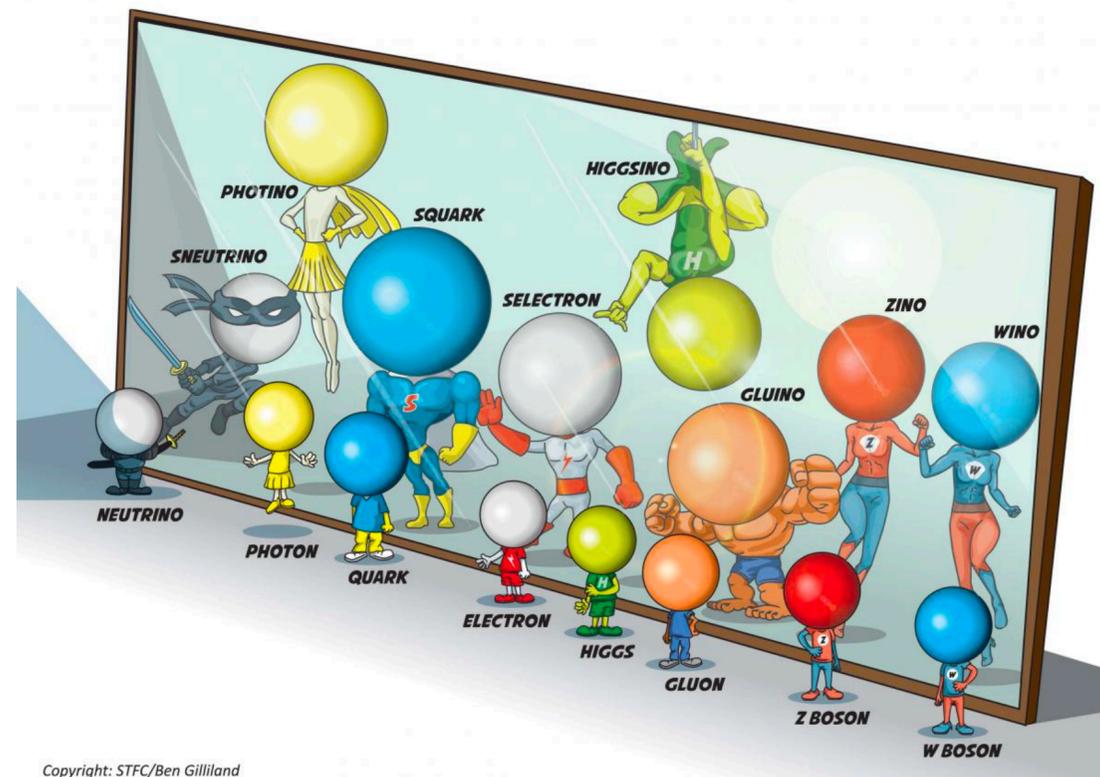
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- Many theories of supersymmetry also include a stable particle that can explain the observed Dark Matter in the universe.



Copyright: STFC/Ben Gilliland

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- Every standard model particle has a super-symmetric partner. These superparticles perfectly cancel out all of these quantum corrections to the Higgs mass.
- Many theories of supersymmetry also include a stable particle that can explain the observed Dark Matter in the universe.
- 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.



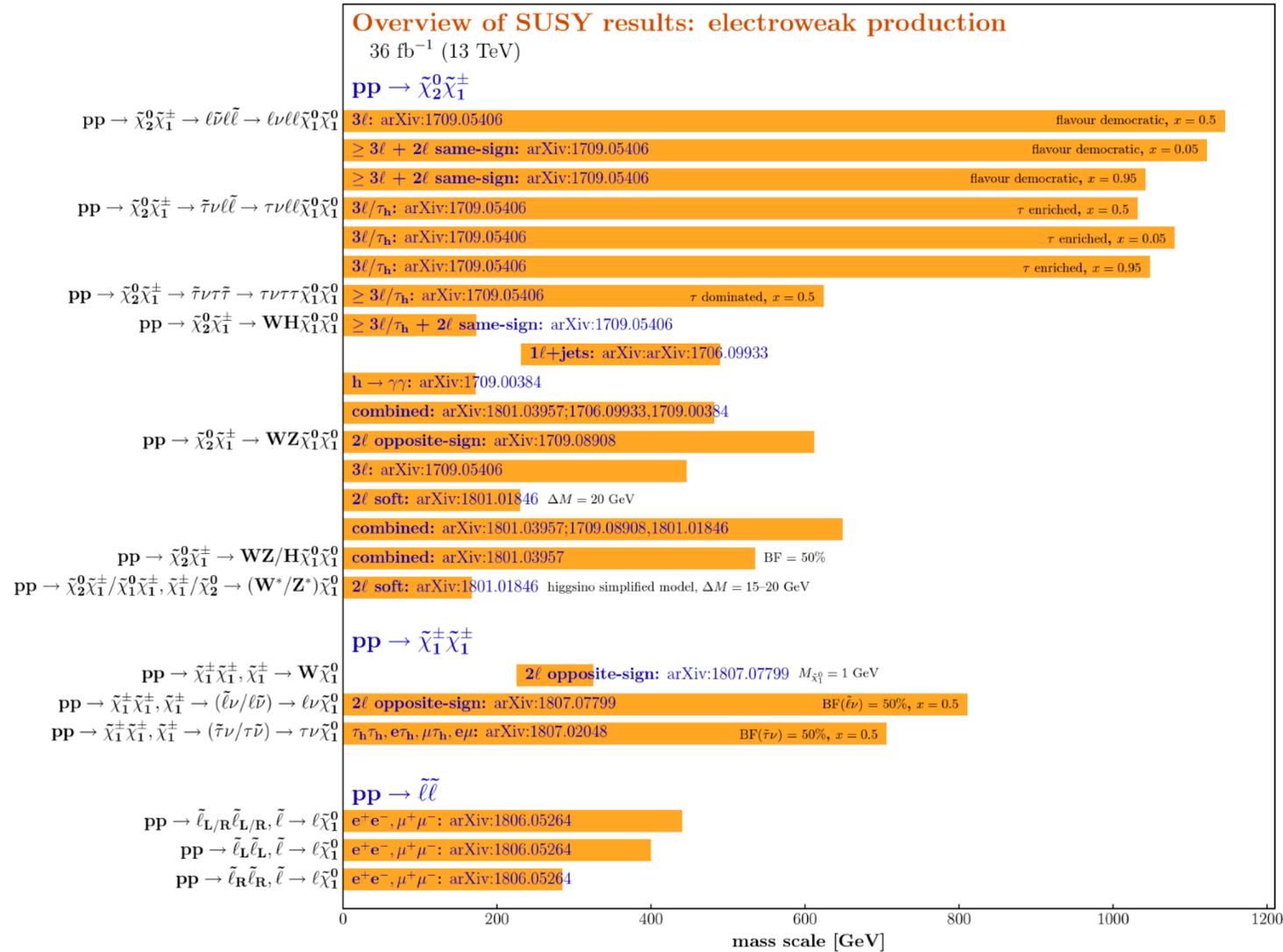
Copyright: STFC/Ben Gilliland

SUSY Searches at the LHC

SUSY Searches at the LHC

CMS

July 2018

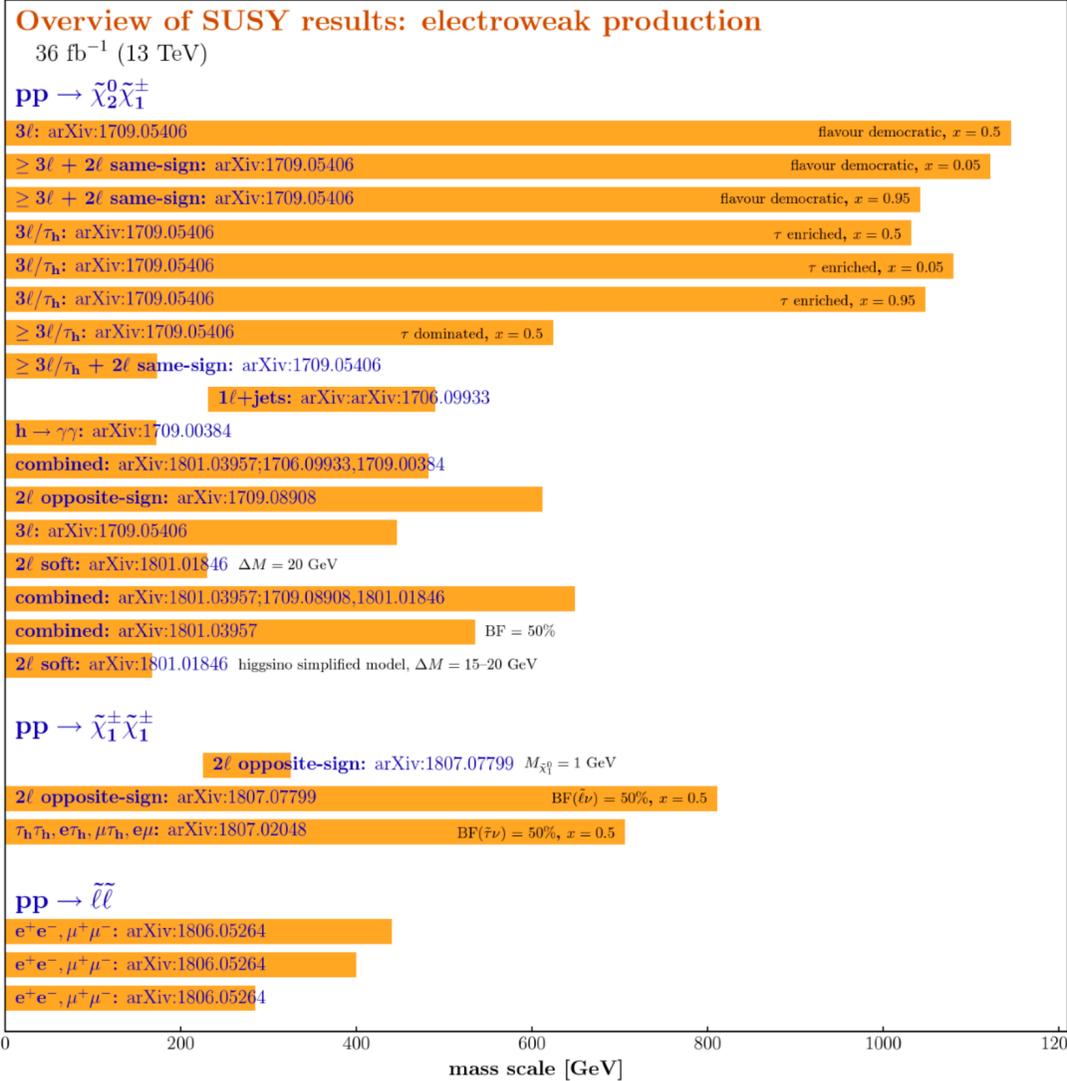


Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe up to the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate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

SUSY Searches at the LHC

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ATLAS SUSY Searches* - 95% CL Lower Limits

July 2019

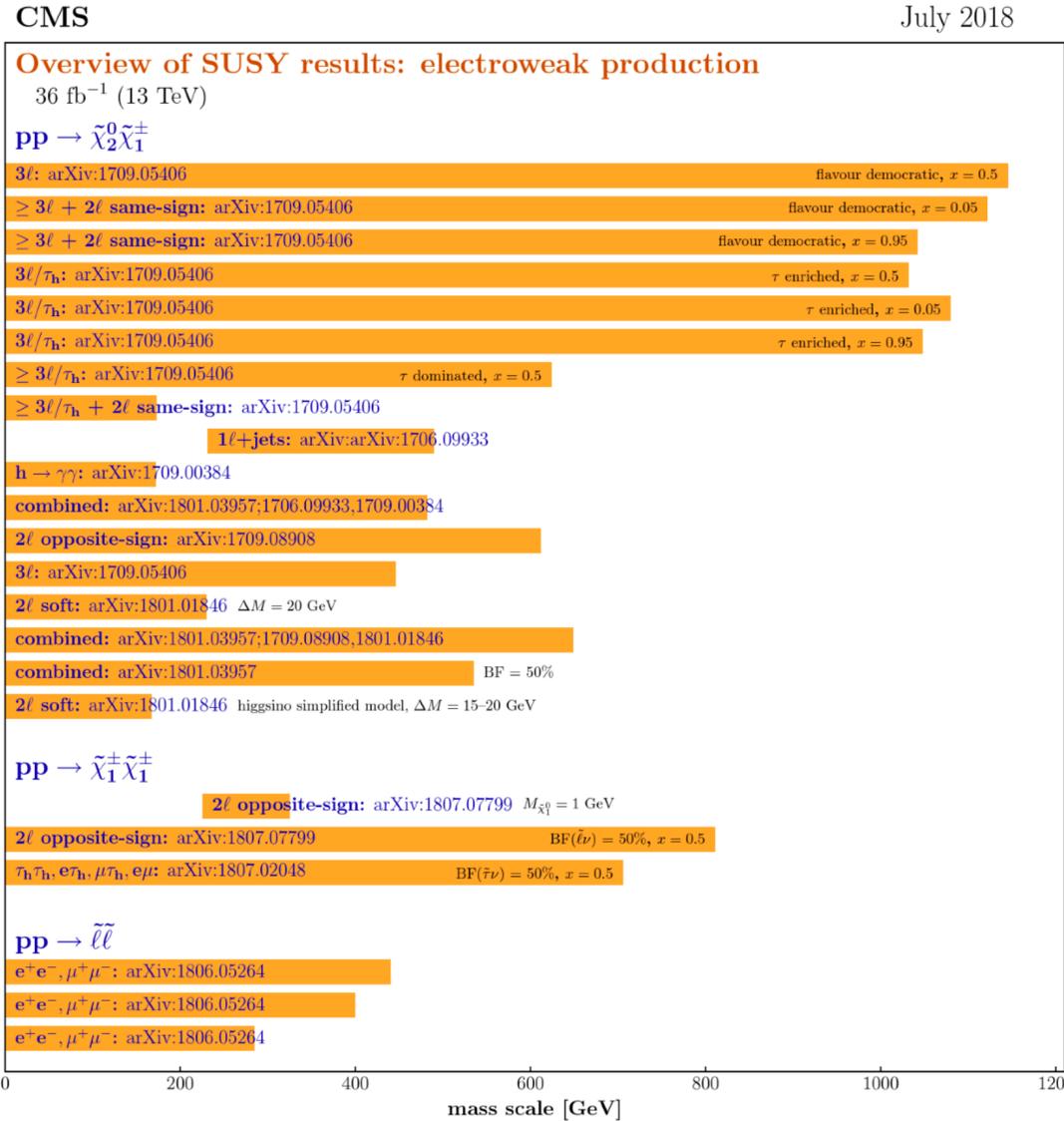
ATLAS Preliminary

√s = 13 TeV

Model	Signature	$\int \mathcal{L} dt$ [fb ⁻¹]	Mass limit	Reference			
Inclusive Searches	$q\bar{q}, \bar{q} \rightarrow q\bar{\chi}_1^0$	0 e, μ mono-jet	2-6 jets 1-3 jets	E_T^{miss} 36.1	0.9, 1.55	$m(\tilde{\chi}_1^0) < 100$ GeV $m(\tilde{q})-m(\tilde{\chi}_1^0)=5$ GeV	1712.02332 1711.03301
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 e, μ	2-6 jets	E_T^{miss} 36.1	0.43, 0.71, 2.0	$m(\tilde{\chi}_1^0) < 200$ GeV $m(\tilde{\chi}_1^0)=900$ GeV	1712.02332 1712.02332
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e, μ ee, μμ	4 jets 2 jets	E_T^{miss} 36.1	1.2, 1.85	$m(\tilde{\chi}_1^0) < 800$ GeV $m(\tilde{g})-m(\tilde{\chi}_1^0)=50$ GeV	1706.03731 1805.11381
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	0 e, μ SS e, μ	7-11 jets 6 jets	E_T^{miss} 36.1 139	1.15, 1.8	$m(\tilde{\chi}_1^0) < 400$ GeV $m(\tilde{g})-m(\tilde{\chi}_1^0)=200$ GeV	1708.02794 ATLAS-CONF-2019-015
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ SS e, μ	3 b 6 jets	E_T^{miss} 79.8 139	1.25, 2.25	$m(\tilde{\chi}_1^0) < 200$ GeV $m(\tilde{g})-m(\tilde{\chi}_1^0)=300$ GeV	ATLAS-CONF-2018-041 ATLAS-CONF-2019-015
	3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\bar{\chi}_1^0/\bar{b}\tilde{\chi}_1^0$	Multiple Multiple Multiple	Multiple Multiple Multiple	E_T^{miss} 36.1 36.1 139	0.9, 0.58-0.82, 0.74	$m(\tilde{\chi}_1^0)=300$ GeV, BR($h\tilde{\chi}_1^0$)=1 $m(\tilde{\chi}_1^0)=300$ GeV, BR($h\tilde{\chi}_1^0$)=0.5 $m(\tilde{\chi}_1^0)=200$ GeV, $m(\tilde{\chi}_1^0)=300$ GeV, BR($h\tilde{\chi}_1^0$)=1
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\bar{\chi}_2^0 \rightarrow b\bar{h}\tilde{\chi}_1^0$		0 e, μ	6 b	E_T^{miss} 139	0.23-0.48, 0.23-1.35	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)=130$ GeV, $m(\tilde{\chi}_1^0)=100$ GeV $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)=130$ GeV, $m(\tilde{\chi}_1^0)=0$ GeV	SUSY-2018-31 SUSY-2018-31
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $\tilde{t}_1\tilde{\chi}_1^0$		0-2 e, μ	0-2 jets/1-2 b	E_T^{miss} 36.1	1.0	$m(\tilde{\chi}_1^0)=1$ GeV	1506.08616, 1709.04183, 1711.11520
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$		1 e, μ	3 jets/1 b	E_T^{miss} 139	0.44-0.59	$m(\tilde{\chi}_1^0)=400$ GeV	ATLAS-CONF-2019-017
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \bar{\tau}b\nu, \tau_1 \rightarrow \tau\tilde{G}$		1 τ + 1 e, μ, τ	2 jets/1 b	E_T^{miss} 36.1	1.16	$m(\tilde{\chi}_1^0)=800$ GeV	1803.10178
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\bar{\chi}_1^0/\bar{c}\tilde{\chi}_1^0$		0 e, μ	2 c	E_T^{miss} 36.1	0.46, 0.85	$m(\tilde{\chi}_1^0)=0$ GeV $m(\tilde{t}_1, \tilde{t}_2)-m(\tilde{\chi}_1^0)=50$ GeV $m(\tilde{t}_1, \tilde{t}_2)-m(\tilde{\chi}_1^0)=5$ GeV	1805.01649 1805.01649 1711.03301
EW direct	$\tilde{\tau}_2\tilde{\tau}_2, \tilde{\tau}_2 \rightarrow \tilde{\tau}_1 + h$	0 e, μ mono-jet	E_T^{miss} 36.1	0.43, 0.32-0.88, 0.86	$m(\tilde{\chi}_1^0)=0$ GeV, $m(\tilde{\tau}_1)-m(\tilde{\chi}_1^0)=180$ GeV $m(\tilde{\chi}_1^0)=360$ GeV, $m(\tilde{\tau}_1)-m(\tilde{\chi}_1^0)=40$ GeV	1706.03986 ATLAS-CONF-2019-016	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	2-3 e, μ ee, μμ	≥ 1	E_T^{miss} 139	0.6, 0.205	$m(\tilde{\chi}_1^0)=0$ $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)=5$ GeV	1403.5294, 1806.02293 ATLAS-CONF-2019-014
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via WW	2 e, μ	≥ 1	E_T^{miss} 139	0.42	$m(\tilde{\chi}_1^0)=0$	ATLAS-CONF-2019-008
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh	0-1 e, μ	2 b/2 γ	E_T^{miss} 139	0.74	$m(\tilde{\chi}_1^0)=70$ GeV	ATLAS-CONF-2019-019, ATLAS-CONF-2019-XYZ
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e, μ	≥ 1	E_T^{miss} 139	1.0	$m(\tilde{\chi}_1^0)=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2019-008
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via $\tilde{\ell}_R/\tilde{\nu}$	2 τ	≥ 1	E_T^{miss} 139	0.16-0.3, 0.12-0.39	$m(\tilde{\chi}_1^0)=0$	ATLAS-CONF-2019-018
Long-lived particles	$\tilde{\tau}, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	2 e, μ 2 e, μ	0 jets ≥ 1	E_T^{miss} 139 139	0.7, 0.256	$m(\tilde{\chi}_1^0)=0$ $m(\tilde{\tau})-m(\tilde{\chi}_1^0)=10$ GeV	ATLAS-CONF-2019-008 ATLAS-CONF-2019-014
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, μ 4 e, μ	≥ 3 b 0 jets	E_T^{miss} 36.1 36.1	0.13-0.23, 0.3, 0.29-0.88	BR($\tilde{\chi}_1^0 \rightarrow h\tilde{G}$)=1 BR($\tilde{\chi}_1^0 \rightarrow Z\tilde{G}$)=1	1806.04030 1804.03602
	Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	E_T^{miss} 36.1	0.46	Pure Wino Pure Higgsino	1712.02118 ATL-Phys-PUB-2017-019
	Stable \tilde{g} R-hadron	Multiple	Multiple	36.1	2.0		1902.01636, 1808.04095
	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	Multiple	Multiple	36.1	2.05, 2.4	$m(\tilde{\chi}_1^0)=100$ GeV	1710.04901, 1808.04095
	RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu/\mu\tau$	eμ, eτ, μτ	3.2		1.9	$A'_{311}=0.11, A'_{32/33/233}=0.07$
$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\nu\nu$		4 e, μ	0 jets	E_T^{miss} 36.1	0.82, 1.33	$m(\tilde{\chi}_1^0)=100$ GeV	1804.03602
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq$		4-5 large-R jets	Multiple	36.1	1.3, 1.9, 2.0	Large A'_{12} $m(\tilde{\chi}_1^0)=200$ GeV, bino-like	1804.03568 ATLAS-CONF-2018-003
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq$		Multiple	Multiple	36.1	1.05, 2.0	$m(\tilde{\chi}_1^0)=200$ GeV, bino-like	ATLAS-CONF-2018-003
$\tilde{u}_L, \tilde{u}_L \rightarrow t\bar{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$		Multiple	Multiple	36.1	0.55, 1.05	$m(\tilde{\chi}_1^0)=200$ GeV, bino-like	ATLAS-CONF-2018-003
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$		2 jets + 2 b	Multiple	36.7	0.42, 0.61		1710.07171
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\bar{q}$	2 e, μ 1 μ	2 b DV	36.1 136	0.4-1.45, 1.6	BR($\tilde{t}_1 \rightarrow b\bar{q}/b\mu$)>20% BR($\tilde{t}_1 \rightarrow q\bar{q}$)=100%, $\cos\theta_{\tilde{t}_1}=1$	1710.05544 ATLAS-CONF-2019-006	

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SUSY Searches at the LHC



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.

ATLAS SUSY Searches* - 95% CL Lower Limits
 July 2019

Model	Signature	$\int \mathcal{L} dt$ [fb ⁻¹]	Mass limit	Reference							
Inclusive Searches	$q\bar{q}, q \rightarrow q\bar{\chi}_1^0$	0 e, μ mono-jet	2-6 jets 1-3 jets	E_T^{miss} E_T^{miss}	36.1 36.1	\tilde{q} [2x, 8x Degen] \tilde{q} [1x, 8x Degen]	0.43 0.71	0.9 1.55	$m(\tilde{\chi}_1^0) < 100$ GeV $m(\tilde{q})-m(\tilde{\chi}_1^0)=5$ GeV	1712.02332 1711.03301	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 e, μ	2-6 jets	E_T^{miss}	36.1	\tilde{g}	Forbidden	2.0	$m(\tilde{\chi}_1^0) < 200$ GeV $m(\tilde{g})=900$ GeV	1712.02332 1712.02332	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e, μ ee, μμ	4 jets 2 jets	E_T^{miss} E_T^{miss}	36.1 36.1	\tilde{g}	Forbidden	1.2	$m(\tilde{\chi}_1^0) < 800$ GeV $m(\tilde{g})-m(\tilde{\chi}_1^0)=50$ GeV	1706.03731 1805.11381	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}WZ\tilde{\chi}_1^0$	0 e, μ SS e, μ	7-11 jets 6 jets	E_T^{miss}	36.1 139	\tilde{g}	Forbidden	1.8	$m(\tilde{\chi}_1^0) < 400$ GeV $m(\tilde{g})-m(\tilde{\chi}_1^0)=200$ GeV	1708.02794 ATLAS-CONF-2019-015	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ SS e, μ	3 b 6 jets	E_T^{miss} E_T^{miss}	79.8 139	\tilde{g}	Forbidden	2.25	$m(\tilde{\chi}_1^0) < 200$ GeV $m(\tilde{g})-m(\tilde{\chi}_1^0)=300$ GeV	ATLAS-CONF-2018-041 ATLAS-CONF-2019-015	
	3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\bar{b}\tilde{\chi}_1^0/\tilde{t}\tilde{\chi}_1^0$	Multiple Multiple Multiple	Multiple Multiple Multiple	E_T^{miss} E_T^{miss} E_T^{miss}	36.1 36.1 139	\tilde{b}_1 \tilde{b}_1 \tilde{b}_1	Forbidden Forbidden Forbidden	0.9 0.58-0.82 0.74	$m(\tilde{\chi}_1^0)=300$ GeV, BR($h\tilde{\chi}_1^0$)=1 $m(\tilde{\chi}_1^0)=300$ GeV, BR($h\tilde{\chi}_1^0$)=0.5 $m(\tilde{\chi}_1^0)=200$ GeV, $m(\tilde{\chi}_1^0)=300$ GeV, BR($h\tilde{\chi}_1^0$)=1	1708.09266, 1711.03301 1708.09266 ATLAS-CONF-2019-015
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\bar{b}\tilde{\chi}_1^0 \rightarrow b\bar{b}\tilde{\chi}_1^0$		0 e, μ	6 b	E_T^{miss}	139	\tilde{b}_1	Forbidden	0.23-0.48	0.23-1.35	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)=130$ GeV, $m(\tilde{\chi}_1^0)=100$ GeV $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)=130$ GeV, $m(\tilde{\chi}_1^0)=0$ GeV	SUSY-2018-31 SUSY-2018-31
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $\tilde{t}\tilde{t}_1^0$		0-2 e, μ	0-2 jets/1-2 b	E_T^{miss}	36.1	\tilde{t}_1	Forbidden	1.0	$m(\tilde{\chi}_1^0)=1$ GeV	1506.08616, 1709.04183, 1711.11520	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$		1 e, μ	3 jets/1 b	E_T^{miss}	139	\tilde{t}_1	Forbidden	0.44-0.59	$m(\tilde{\chi}_1^0)=400$ GeV	ATLAS-CONF-2019-017	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}b\nu, \tilde{t}_1 \rightarrow \tau\tilde{G}$		1 τ + 1 e, μ, τ	2 jets/1 b	E_T^{miss}	139	\tilde{t}_1	Forbidden	1.16	$m(\tilde{\tau})=800$ GeV	1803.10178	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\bar{c}\tilde{\chi}_1^0/\tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$		0 e, μ	2 c	E_T^{miss}	36.1	\tilde{t}_1	Forbidden	0.46 0.85	$m(\tilde{\chi}_1^0)=0$ GeV $m(\tilde{t}, \tilde{c})-m(\tilde{\chi}_1^0)=50$ GeV $m(\tilde{t}, \tilde{c})-m(\tilde{\chi}_1^0)=5$ GeV	1805.01649 1805.01649 1711.03301	
EW direct	$\tilde{\tau}_2\tilde{\tau}_2, \tilde{\tau}_2 \rightarrow \tilde{\tau}_1 + h$	0 e, μ mono-jet	E_T^{miss}	36.1	$\tilde{\tau}_2$	Forbidden	0.32-0.88	0.86	$m(\tilde{\chi}_1^0)=0$ GeV, $m(\tilde{\tau}_1)-m(\tilde{\chi}_1^0)=180$ GeV $m(\tilde{\chi}_1^0)=360$ GeV, $m(\tilde{\tau}_1)-m(\tilde{\chi}_1^0)=40$ GeV	1706.03986 ATLAS-CONF-2019-016	
	$\tilde{\tau}_2\tilde{\tau}_2, \tilde{\tau}_2 \rightarrow \tilde{\tau}_1 + Z$	1-2 e, μ 3 e, μ	4 b 1 b	E_T^{miss} E_T^{miss}	36.1 139	$\tilde{\tau}_2$	Forbidden	0.6	$m(\tilde{\chi}_1^0)=0$ $m(\tilde{\tau}_1)-m(\tilde{\chi}_1^0)=5$ GeV	1403.5294, 1806.02293 ATLAS-CONF-2019-014	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	2-3 e, μ ee, μμ	≥ 1	E_T^{miss} E_T^{miss}	139 139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	Forbidden	0.205	0.42	$m(\tilde{\chi}_1^0)=0$ $m(\tilde{\chi}_1^0)=70$ GeV	ATLAS-CONF-2019-008 ATLAS-CONF-2019-019, ATLAS-CONF-2019-XYZ
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WW	2 e, μ	2 b/2 γ	E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$	Forbidden	0.74	1.0	$m(\tilde{\chi}_1^0)=0$ $m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{\chi}_2^0))$	ATLAS-CONF-2019-008 ATLAS-CONF-2019-018
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh	0-1 e, μ	2 jets	E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$	Forbidden	0.7	$m(\tilde{\chi}_1^0)=0$	ATLAS-CONF-2019-008 ATLAS-CONF-2019-014	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm}$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e, μ	≥ 1	E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$	Forbidden	0.256	0.29-0.88	$m(\tilde{\tau})-m(\tilde{\chi}_1^0)=10$ GeV	1806.04030 1804.03602
Long-lived particles	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	2 τ	0 jets	E_T^{miss}	139	$\tilde{\tau}$	Forbidden	0.16-0.3	0.12-0.39	$m(\tilde{\chi}_1^0)=0$	ATLAS-CONF-2019-018
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 e, μ 2 e, μ	0 jets ≥ 1	E_T^{miss} E_T^{miss}	139 139	$\tilde{\ell}$	Forbidden	0.7	$m(\tilde{\chi}_1^0)=0$	ATLAS-CONF-2019-008 ATLAS-CONF-2019-014	
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, μ 4 e, μ	≥ 3 b 0 jets	E_T^{miss} E_T^{miss}	36.1 36.1	\tilde{H}	Forbidden	0.13-0.23	0.3	$m(\tilde{H}) \rightarrow h\tilde{G}=1$ $BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G})=1$	1806.04030 1804.03602
	Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm}$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	E_T^{miss}	36.1	$\tilde{\chi}_1^{\pm}$	Forbidden	0.46	0.15	Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019
	Stable \tilde{g} R-hadron	Multiple	Multiple	E_T^{miss}	36.1	\tilde{g}	Forbidden	2.0	2.05	$m(\tilde{\chi}_1^0)=100$ GeV	1902.01636, 1808.04095 1710.04901, 1808.04095
	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	Multiple	Multiple	E_T^{miss}	36.1	\tilde{g}	Forbidden	2.05	2.4	$m(\tilde{\chi}_1^0)=100$ GeV	1710.04901, 1808.04095
RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu$	eμ, eτ, μτ	0 jets	E_T^{miss}	3.2	$\tilde{\nu}_\tau$	Forbidden	1.9	$A'_{311}=0.11, A'_{32/33/233}=0.07$	1607.08079	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\nu\nu$	4 e, μ	0 jets	E_T^{miss}	36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	Forbidden	0.82	1.33	$m(\tilde{\chi}_1^0)=100$ GeV	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\bar{q}$	4-5 large-R jets	Multiple	E_T^{miss}	36.1	\tilde{g}	Forbidden	1.3	1.9	Large A'_{12} $m(\tilde{\chi}_1^0)=200$ GeV, bino-like	1804.03568 ATLAS-CONF-2018-003
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\bar{q}$	Multiple	Multiple	E_T^{miss}	36.1	\tilde{g}	Forbidden	1.05	2.0	$m(\tilde{\chi}_1^0)=200$ GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{u}_L, \tilde{t} \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow t\tilde{b}$	Multiple	Multiple	E_T^{miss}	36.1	\tilde{u}_L	Forbidden	0.55	1.05	$m(\tilde{\chi}_1^0)=200$ GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$	2 jets + 2 b	Multiple	E_T^{miss}	36.7	\tilde{t}_1	Forbidden	0.42	0.61	$m(\tilde{\chi}_1^0)=200$ GeV, bino-like	1710.07171
RPV	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\bar{q}$	2 e, μ	2 b	E_T^{miss}	36.1	\tilde{t}_1	Forbidden	0.4-1.45	BR($\tilde{t}_1 \rightarrow b\tilde{q}/b\tilde{q}$) > 20%	1710.05544	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\bar{q}$	1 μ	DV	E_T^{miss}	136	\tilde{t}_1	Forbidden	1.0	1.6	BR($\tilde{t}_1 \rightarrow q\mu$) = 100%, $\cos\theta_{\tilde{t}_1} = 1$	ATLAS-CONF-2019-006

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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!