

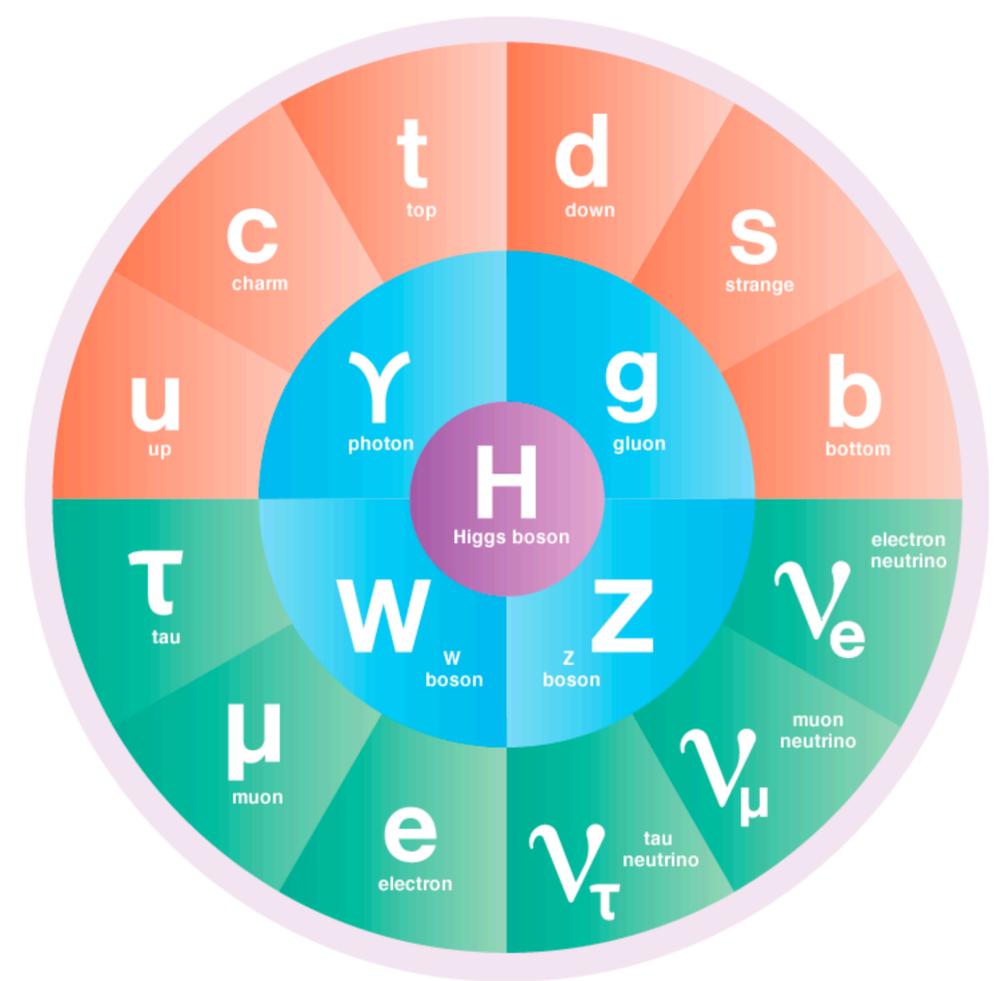
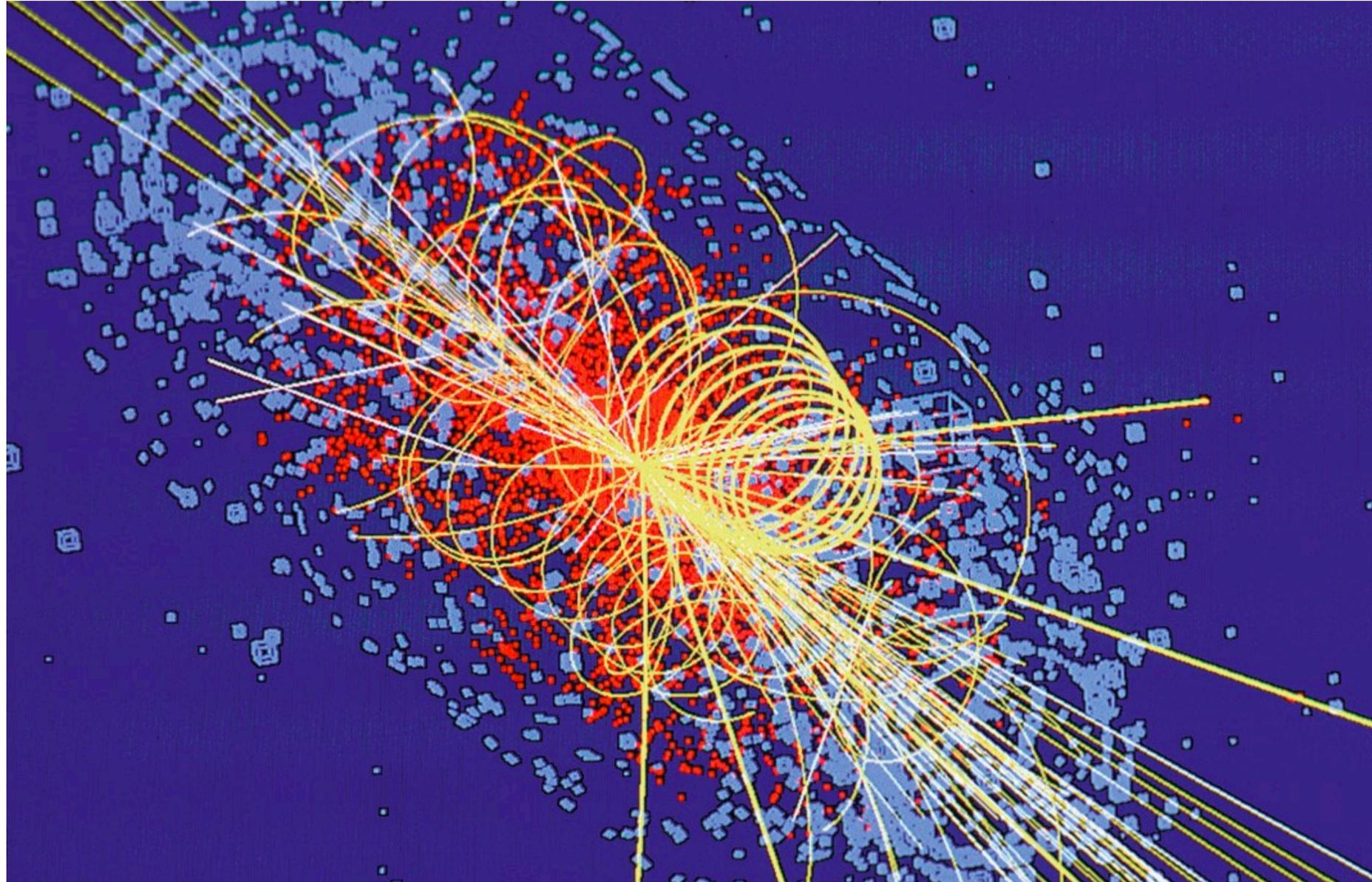


Introduction to Particle Physics

Kevin J. Kelly

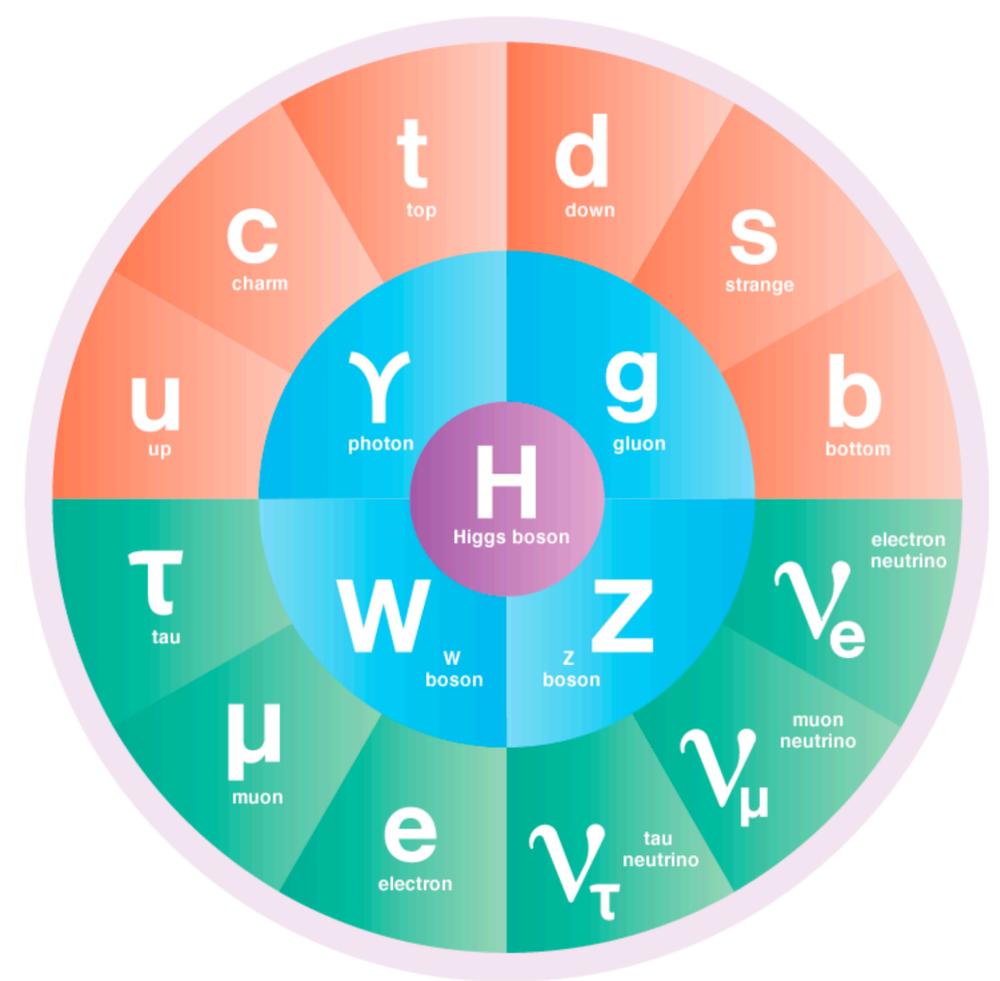
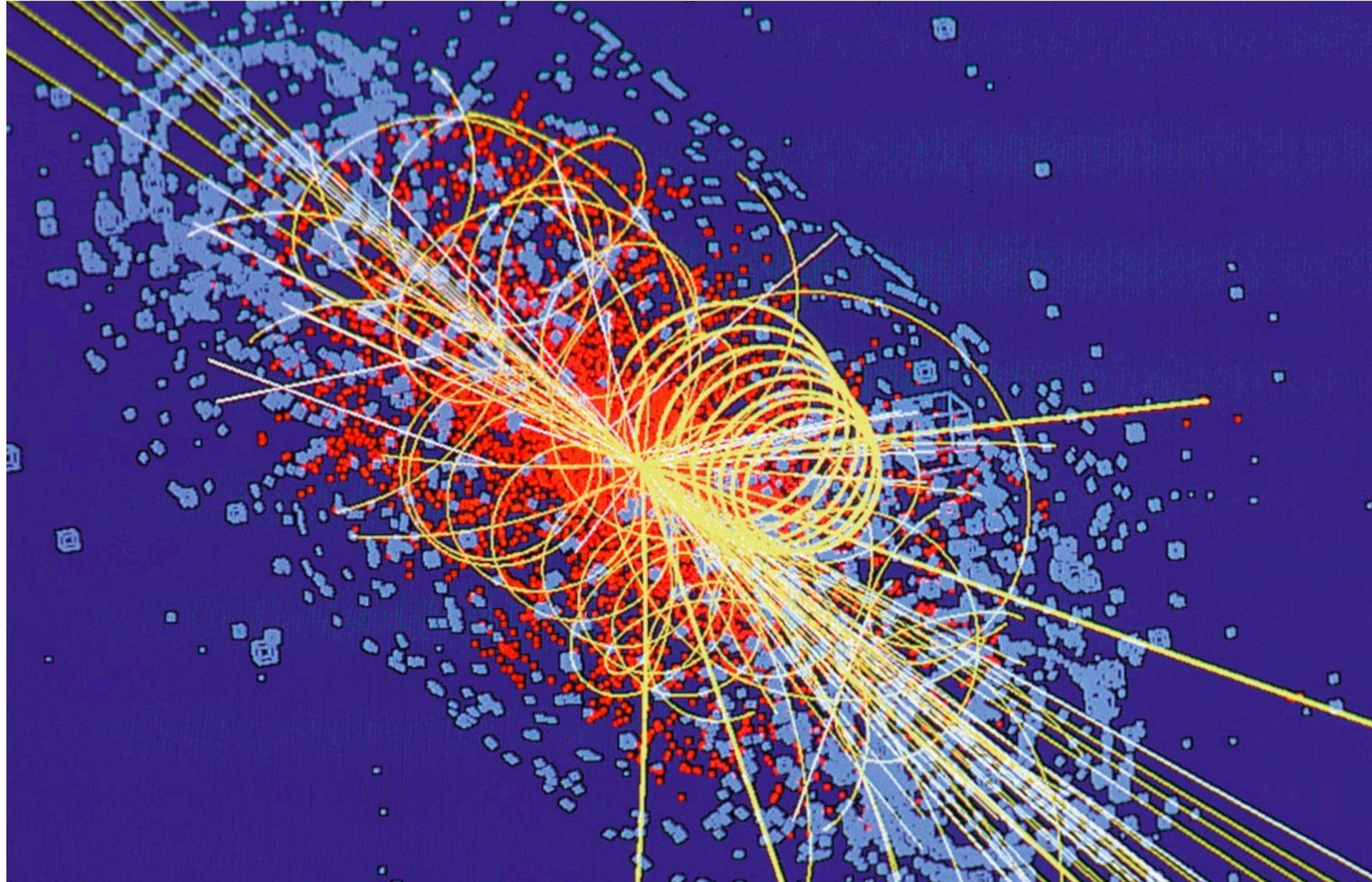
Undergraduate Lecture Series, May 28th, 2020

What is Particle Physics?



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

What is Particle Physics?

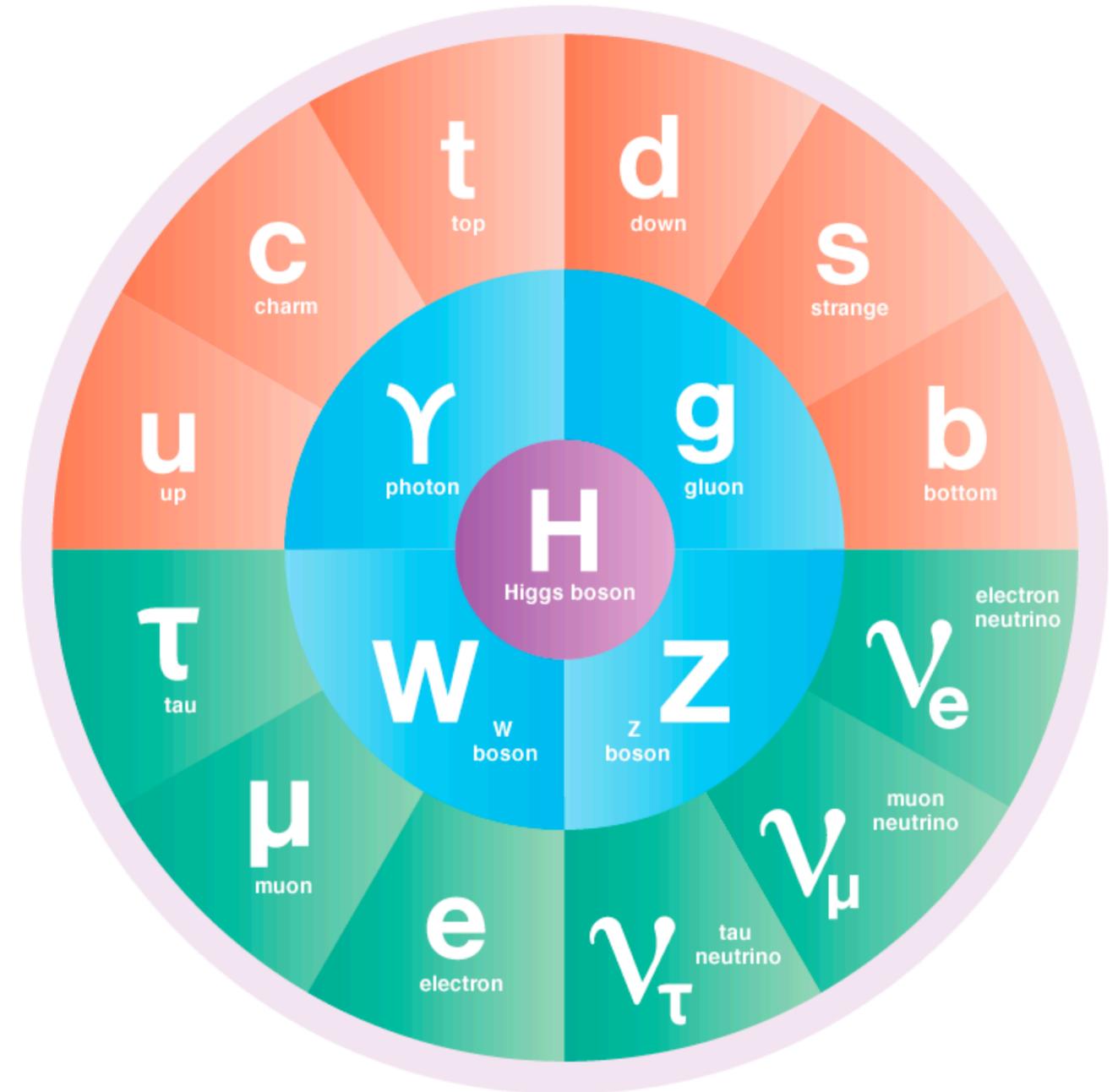


$$\begin{aligned} \mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i \bar{\Psi} \not{D} \Psi + h.c. \\ & + \bar{\Psi}_i \gamma_{ij} \Psi_j \phi + h.c. \\ & + |\mathcal{D}_\mu \phi|^2 - V(\phi) \end{aligned}$$

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

A bit of history...

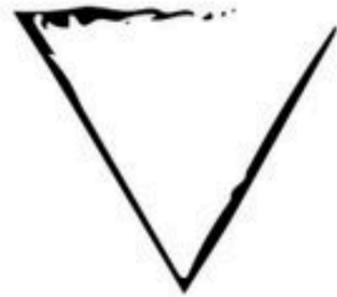
- Physicists today claim to know what “everything” is made up of — the Standard Model. How did we get here?



~2000 years in one slide



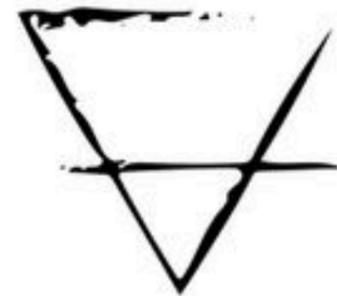
Fire



Water

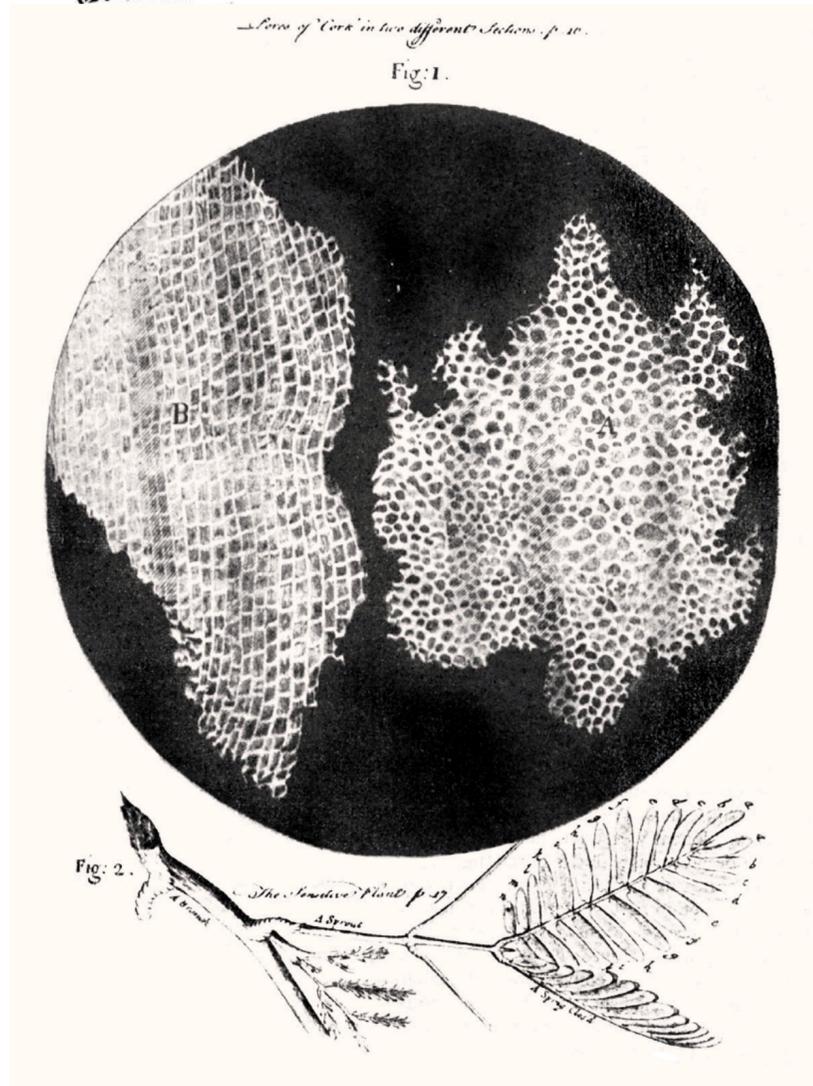
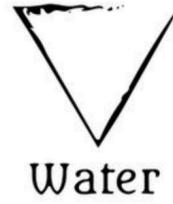


Air



Earth

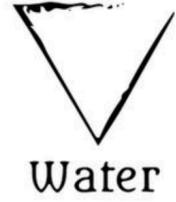
~2000 years in one slide



~2000 years in one slide



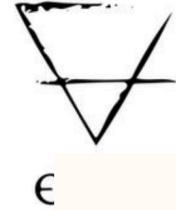
Fire



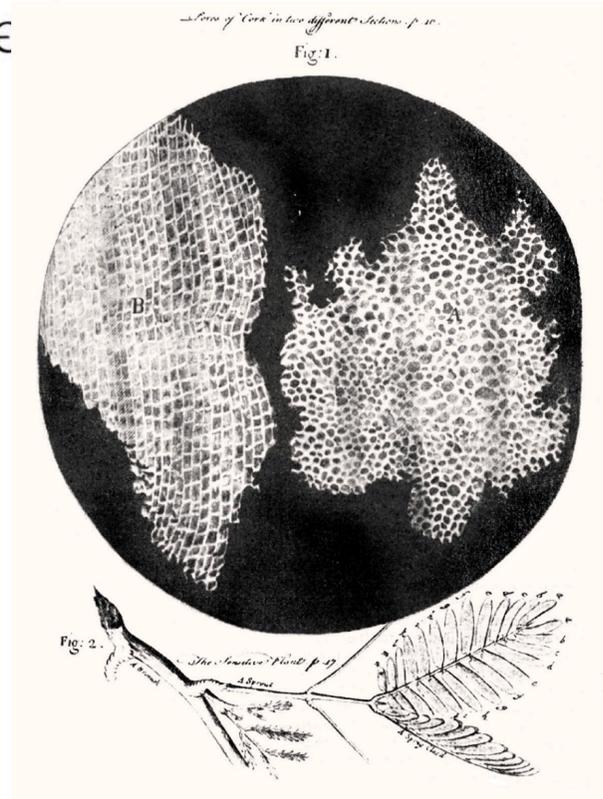
Water



Air

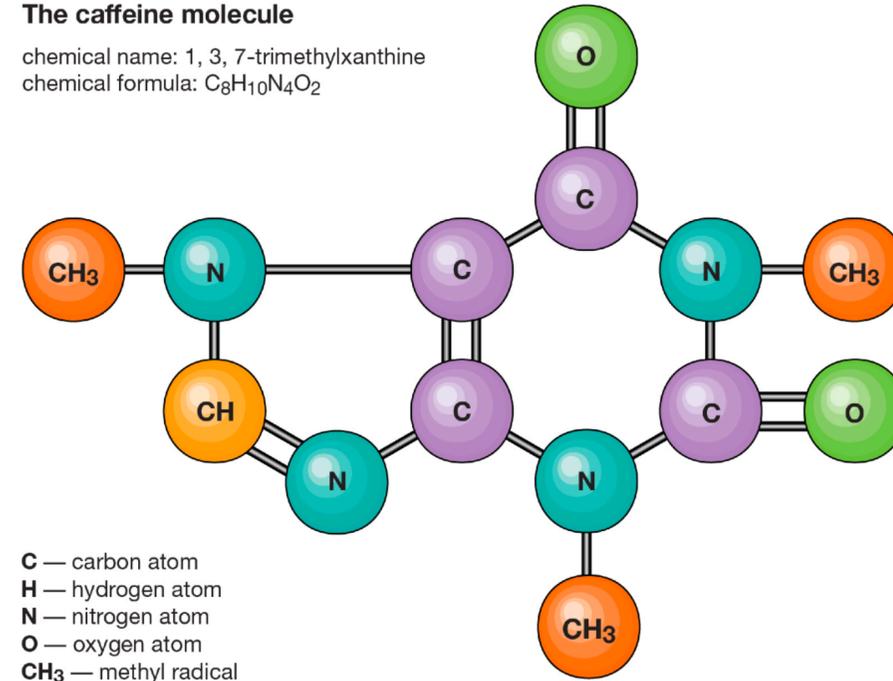


€



The caffeine molecule

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

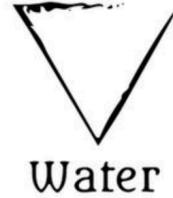


© 2010 Encyclopædia Britannica, Inc.

~2000 years in one slide



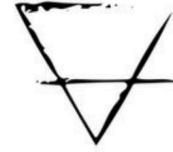
Fire



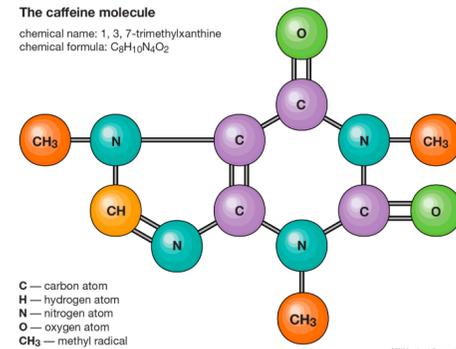
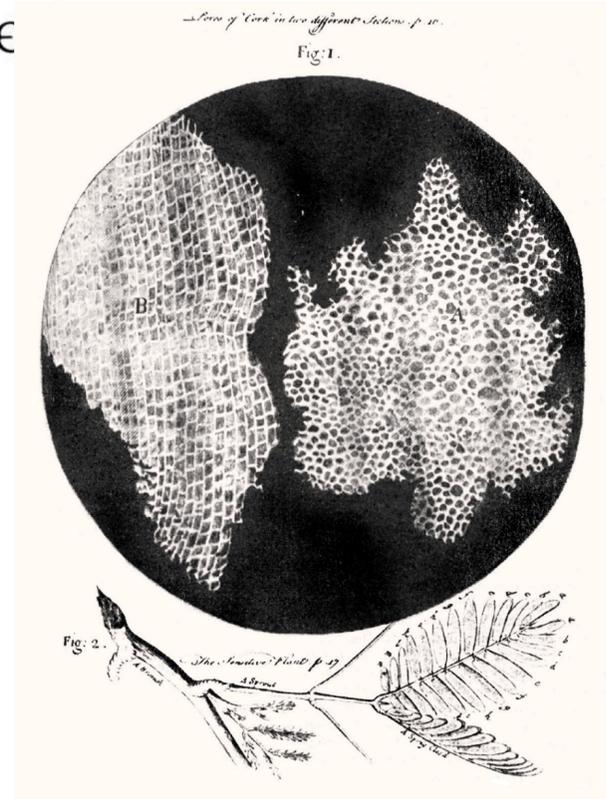
Water



Air

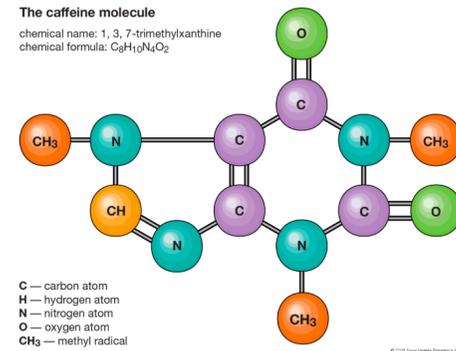
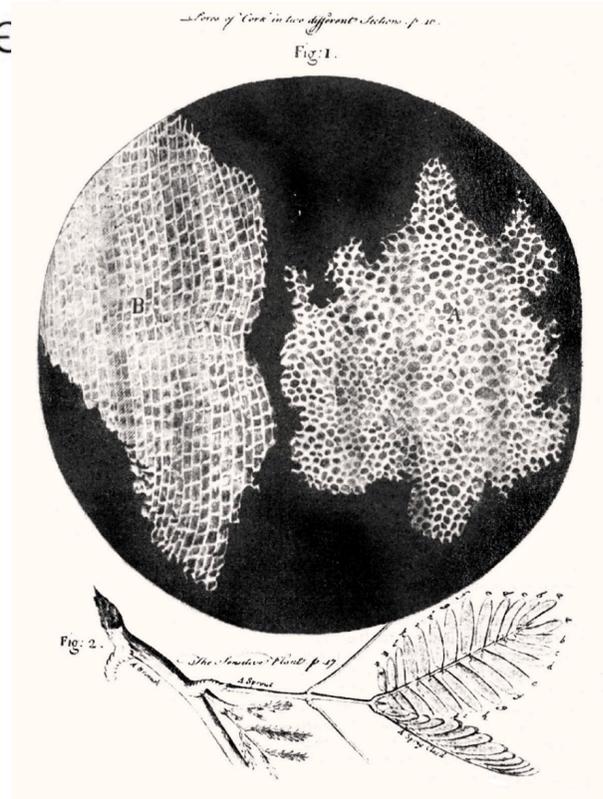
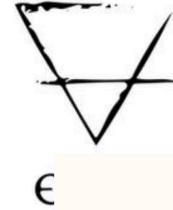


€



Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
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
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
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
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

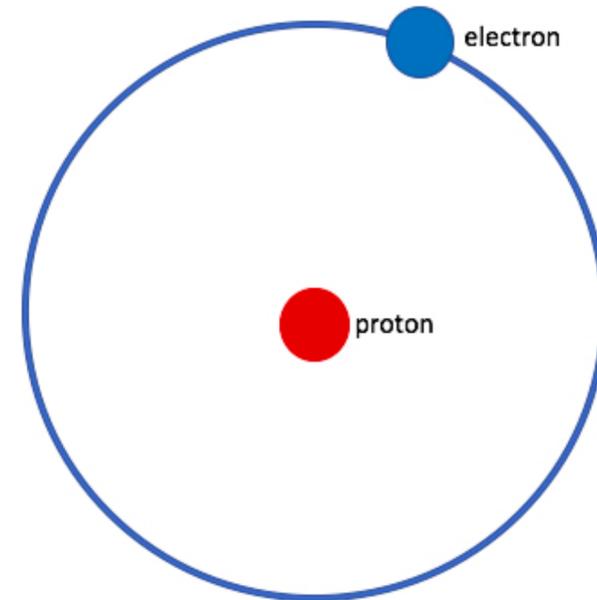
~2000 years in one slide



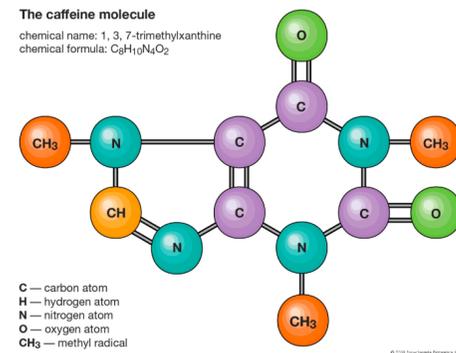
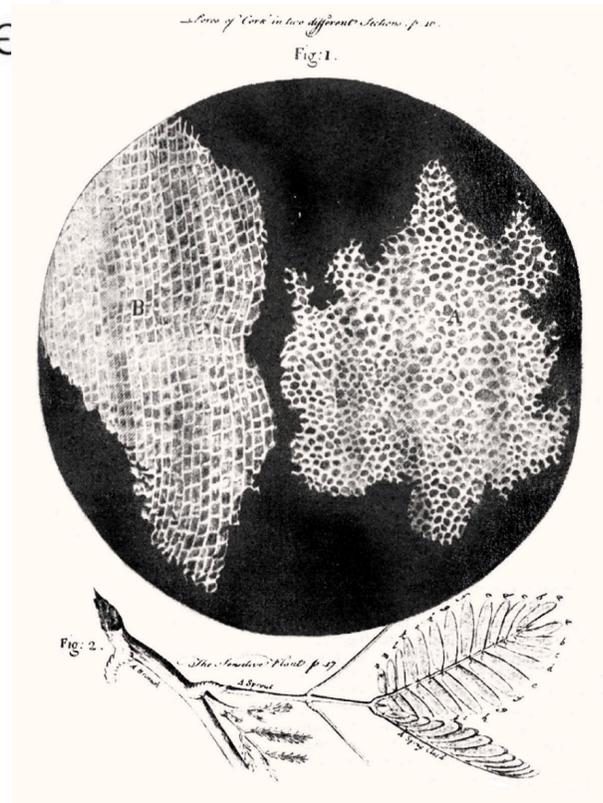
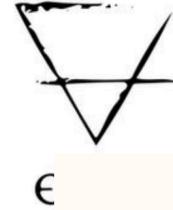
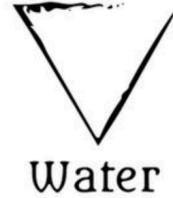
Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period 1	1 H																	2 He
Period 2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
Period 3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
Period 4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	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

Hydrogen Atom

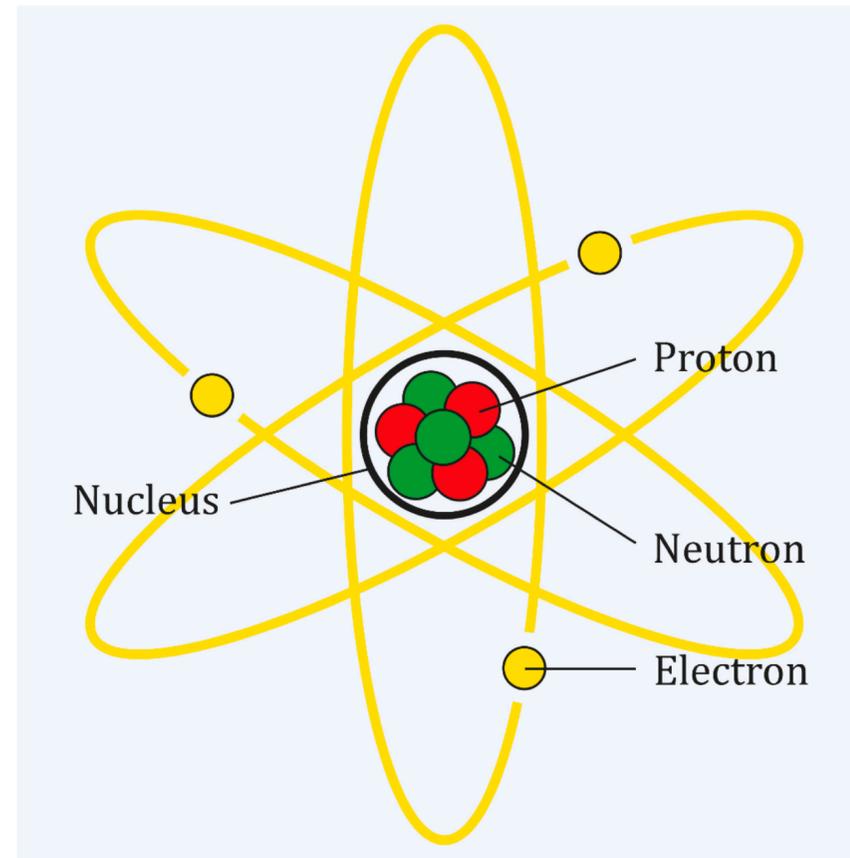
*Not to scale.



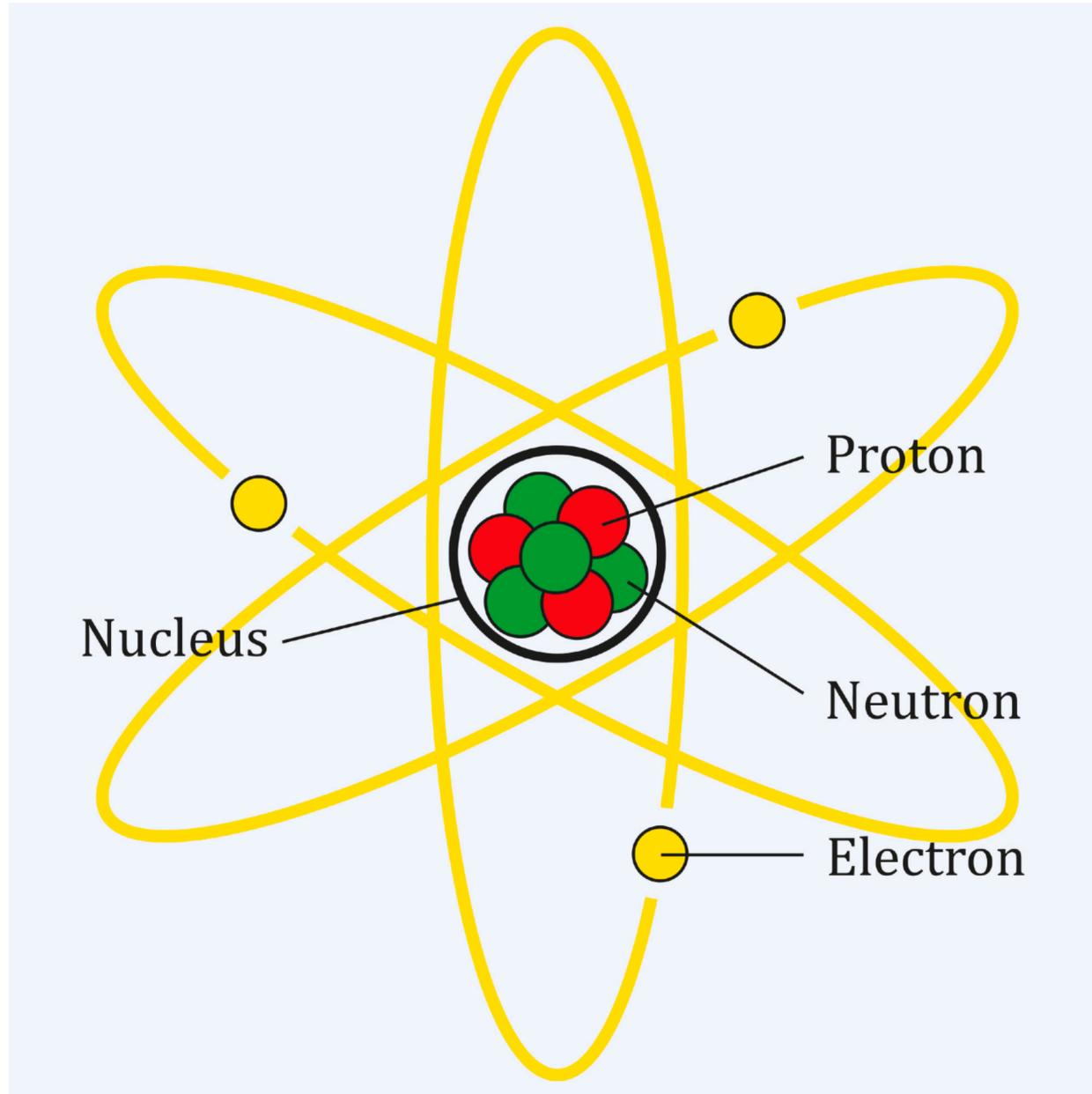
~2000 years in one slide



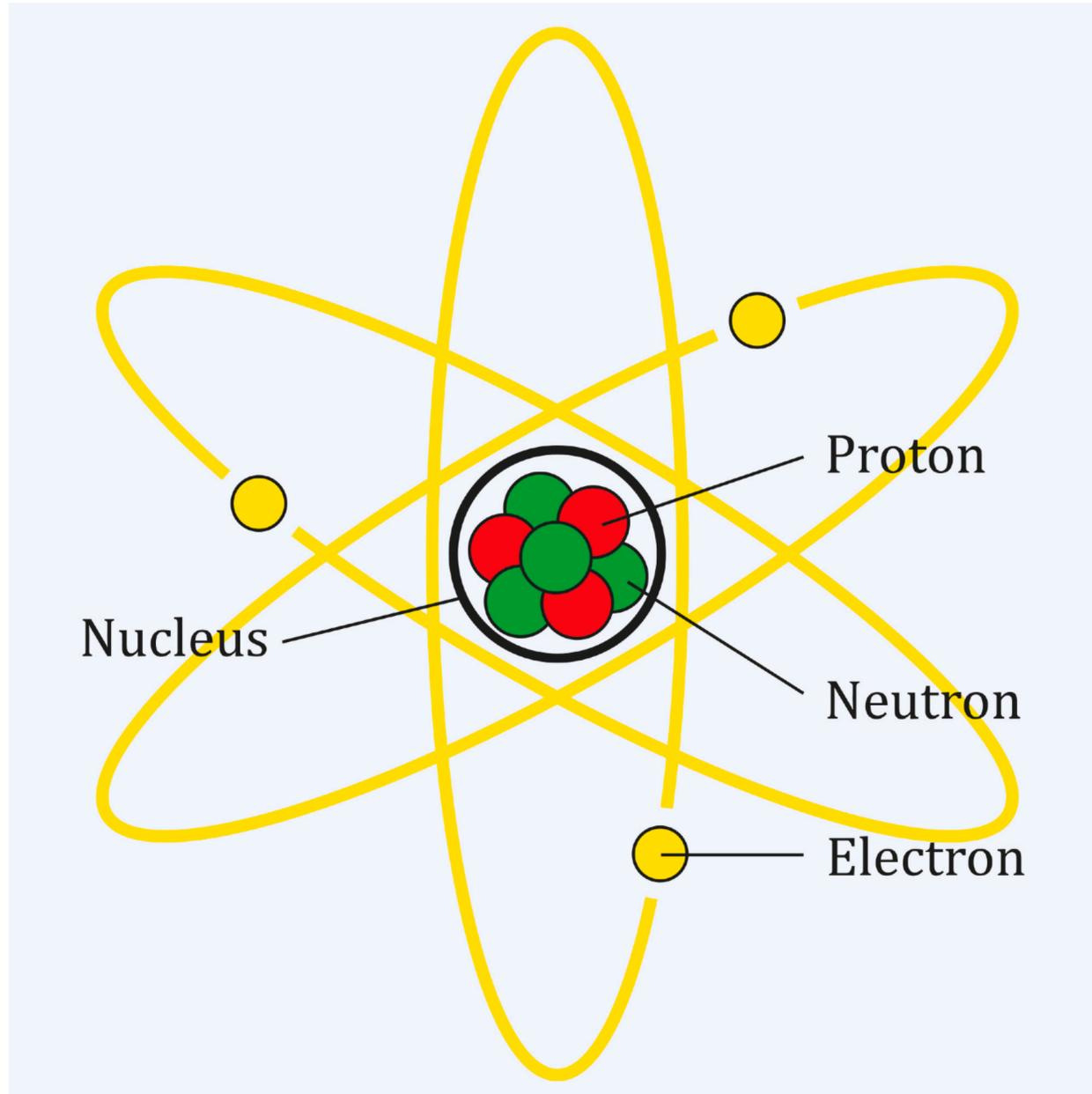
Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period 1	1 H																	2 He
Period 2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
Period 3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
Period 4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	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



Early 1900s

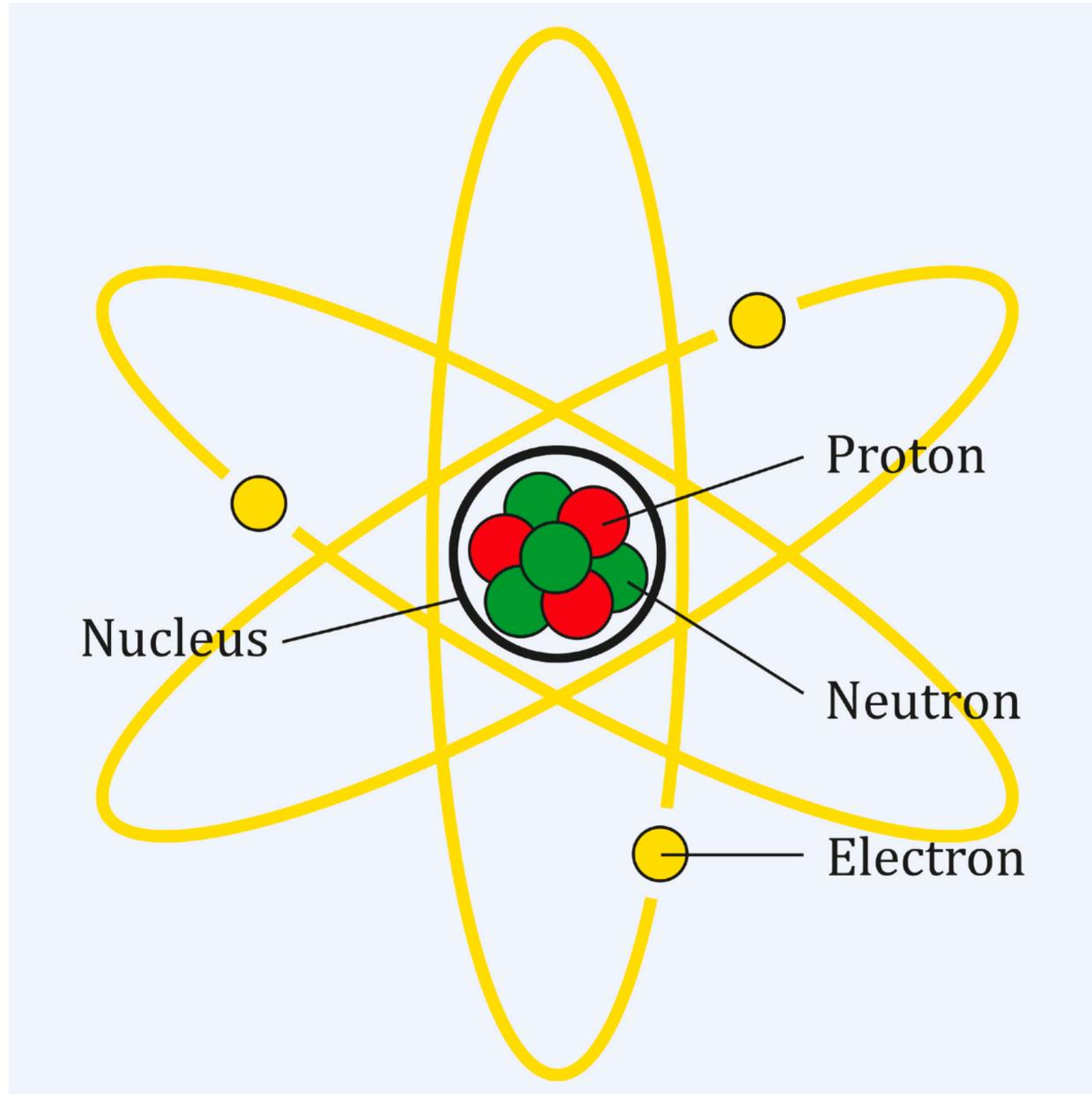


Early 1900s



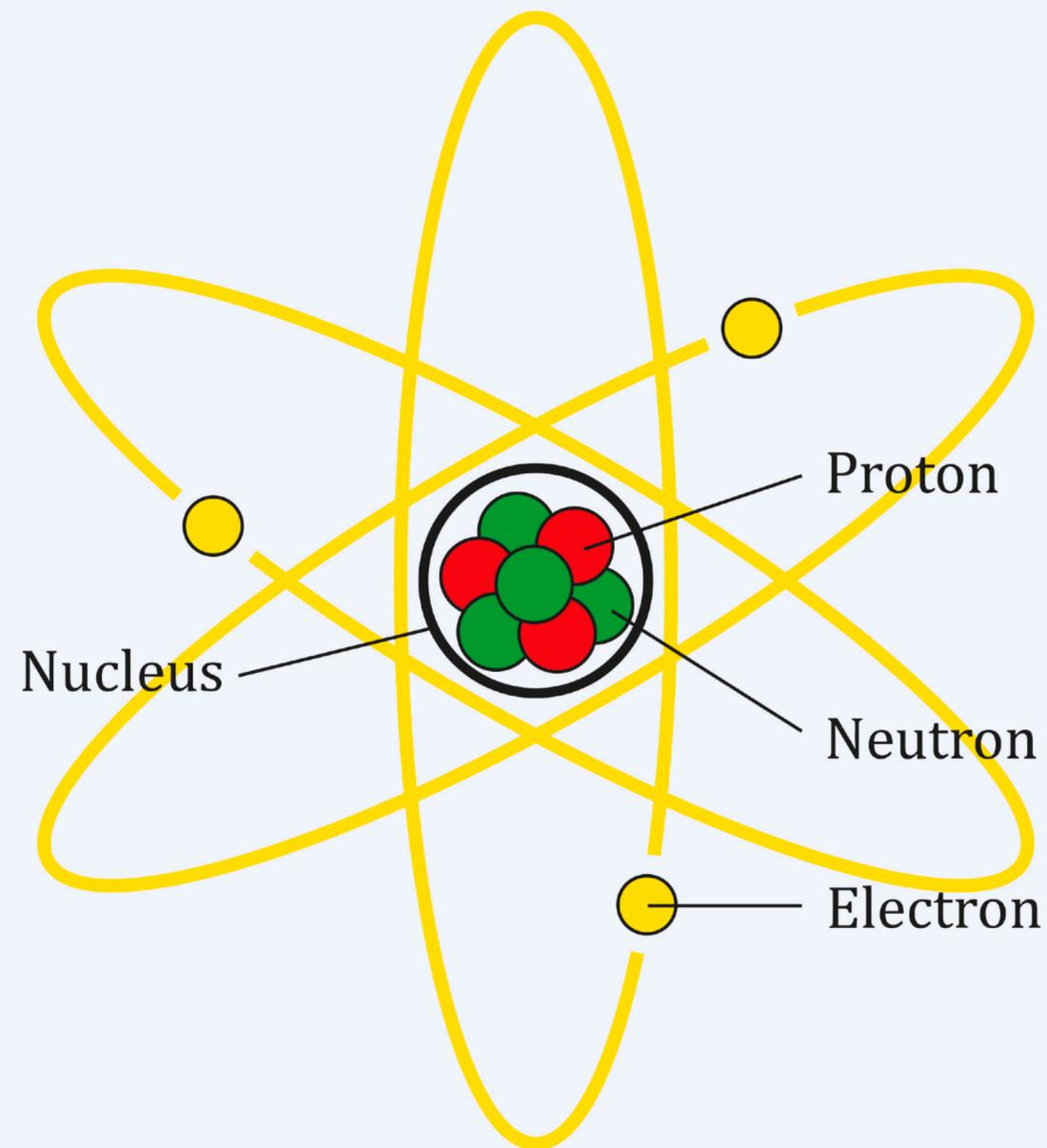
- To the best of our knowledge in the early 1900s, everything that we see can be built out of protons, neutrons, and electrons.

Early 1900s



- To the best of our knowledge in the early 1900s, everything that we see can be built out of protons, neutrons, and electrons.
- Protons and neutrons build up the nuclei of atoms, and electrons occupy orbitals around the nucleus.

Early 1900s



- To the best of our knowledge in the early 1900s, everything that we see can be built out of protons, neutrons, and electrons.
- 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.

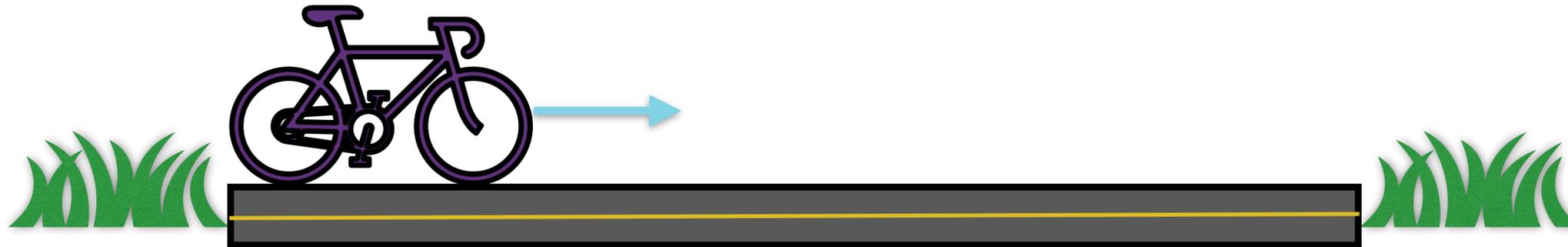
**Let's put a pin in particles
for now.**

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

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

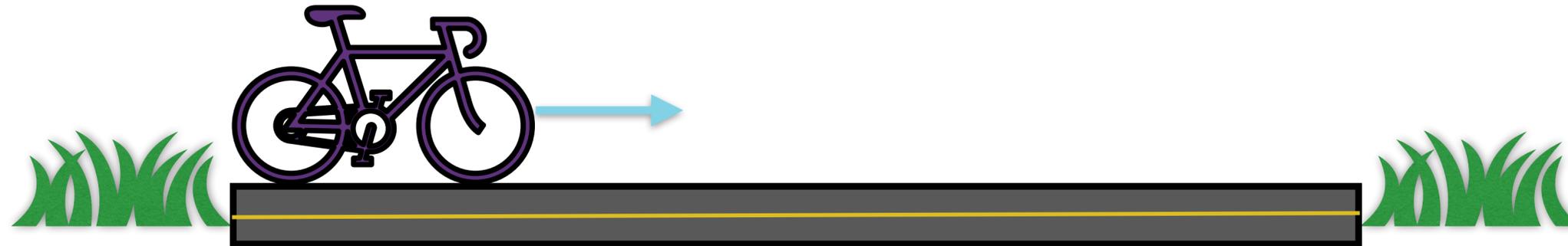
One of the simplest symmetries in nature: *Translational Invariance*

- Imagine riding a bike on a flat road...



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

- Imagine riding a bike on a flat road...

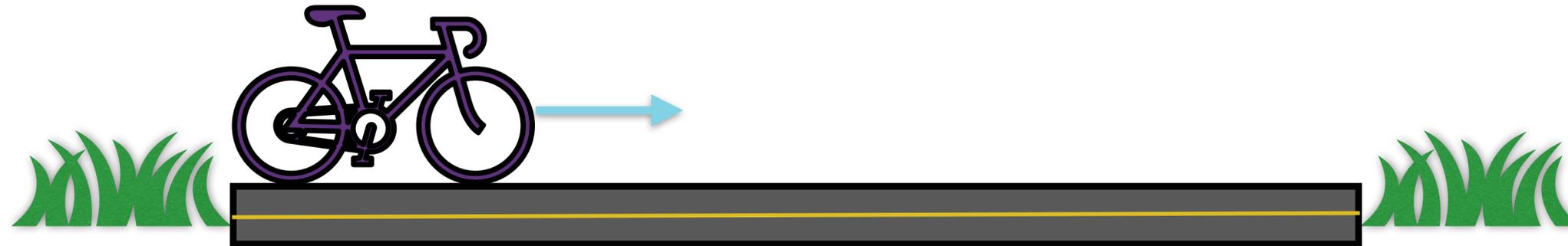


- A short time later,



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

- Imagine riding a bike on a flat road...

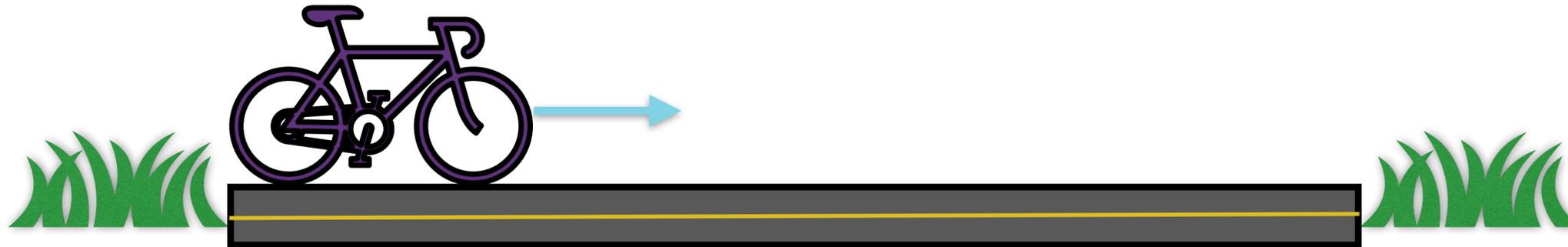


- A short time later,

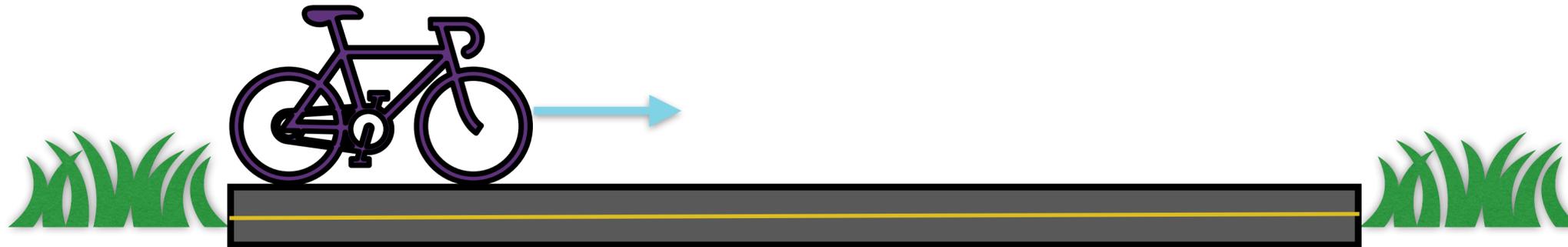


- From the bike's point of view, the surrounding road is unchanged.

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



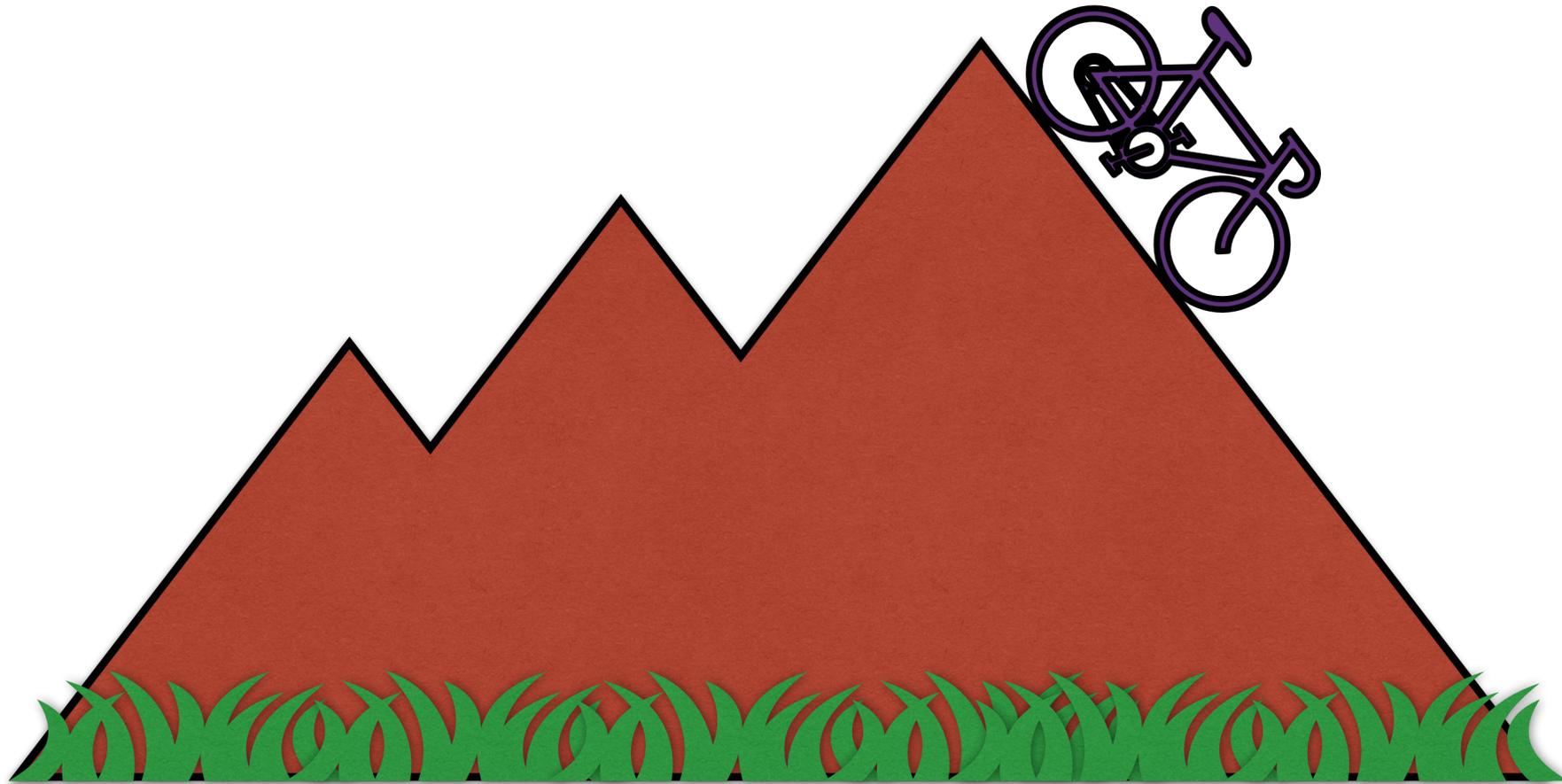
One of the simplest symmetries in nature: *Translational Invariance*



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

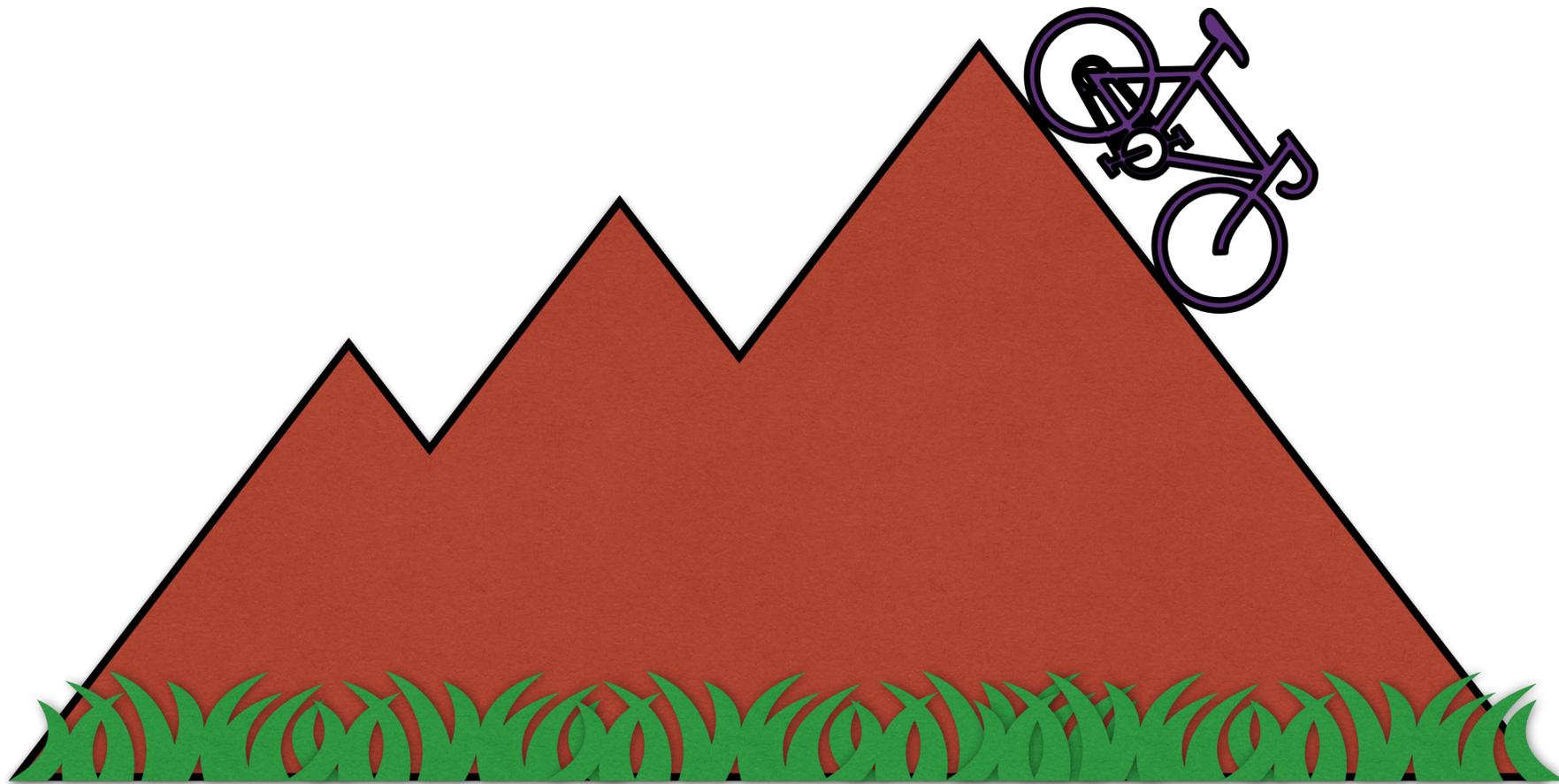
Slightly more complicated: *Time-translation Invariance*

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



Slightly more complicated: *Time-translation Invariance*

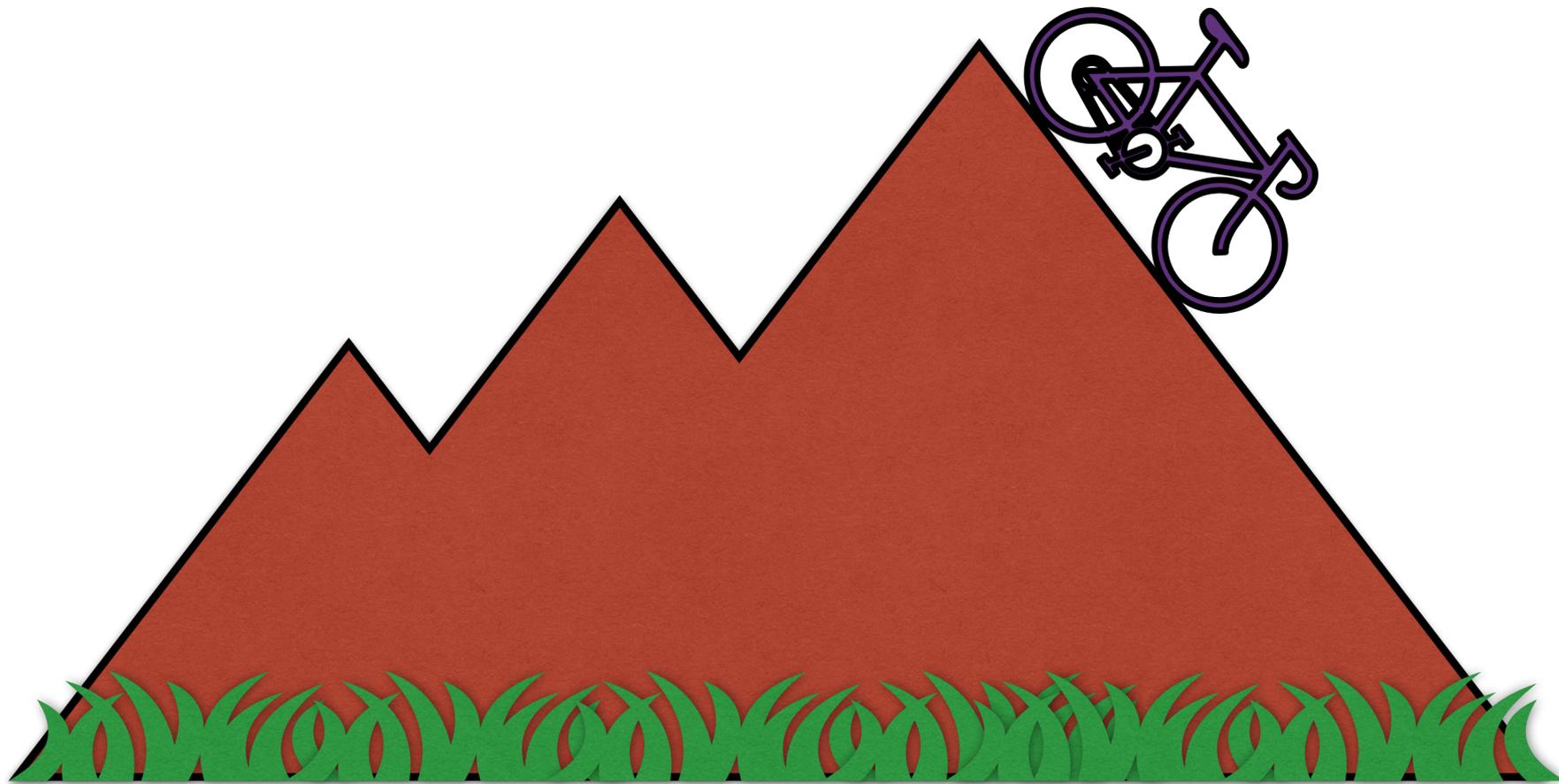
- (fancy way of saying “constant over time”)



- Now with a bike riding over a hilly terrain — what conservation laws can we apply?

Slightly more complicated: *Time-translation Invariance*

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



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

Noether's Theorem



Noether's Theorem

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



Noether's Theorem



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



“For every continuous symmetry that you can identify, there is some conserved quantity in the system”

Noether's Theorem



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



“For every continuous symmetry that you can identify, there is some conserved quantity in the system”

Translational Invariance



Linear Momentum

Noether's Theorem



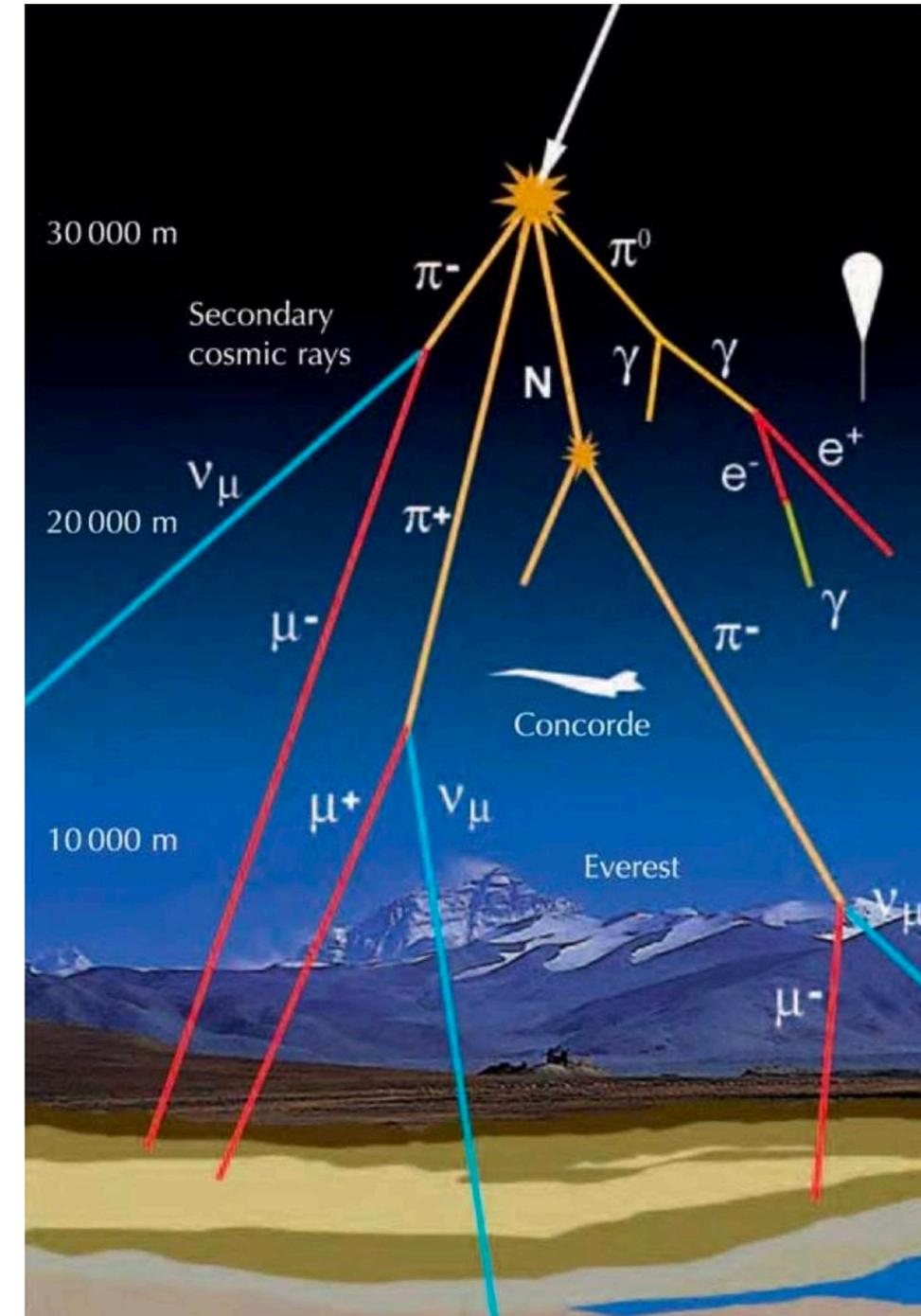
“To every differential symmetry generated by local actions there corresponds a conserved current.”



“For every continuous symmetry that you can identify, there is some conserved quantity in the system”

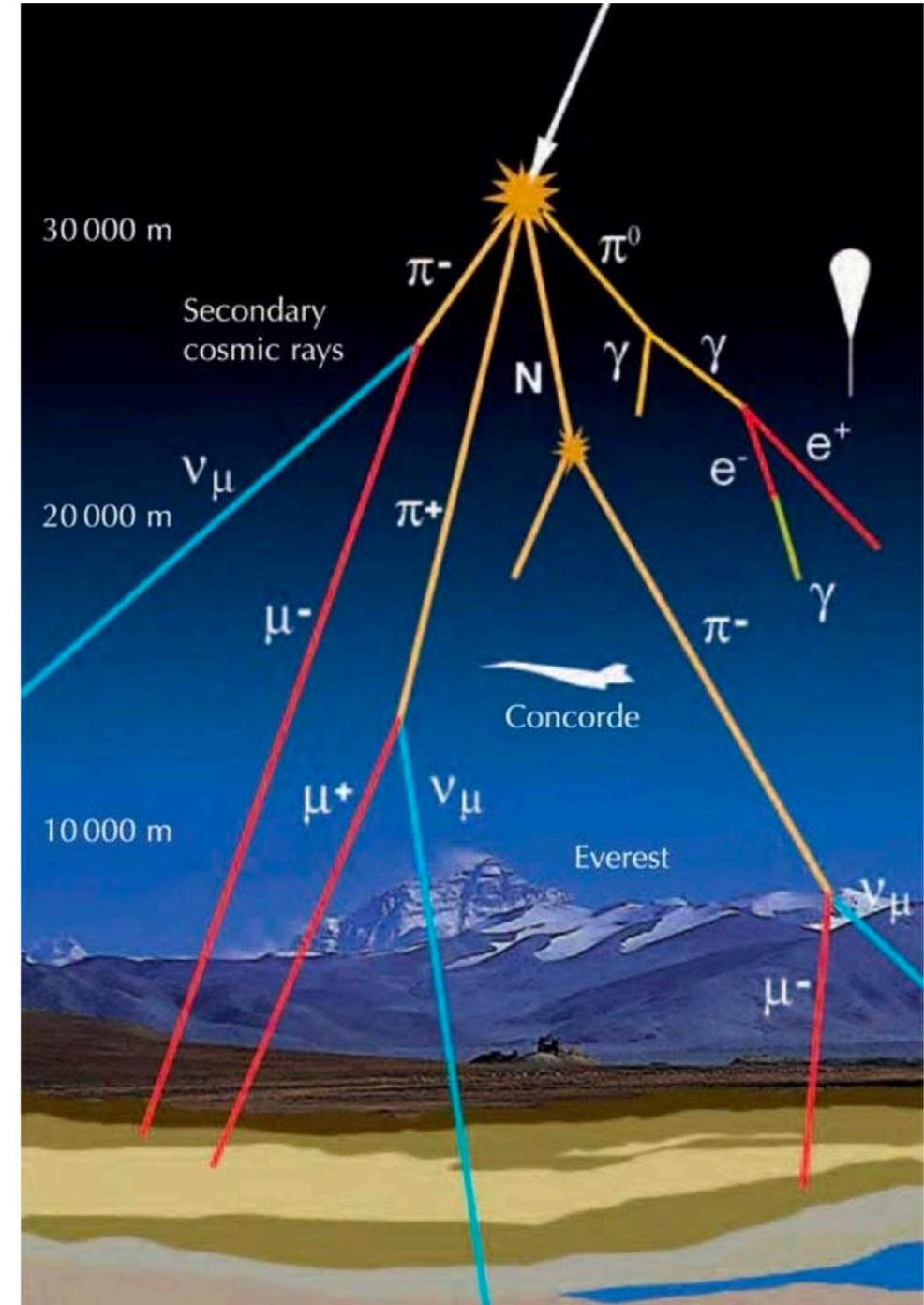


Applying Symmetries to Protons and Neutrons



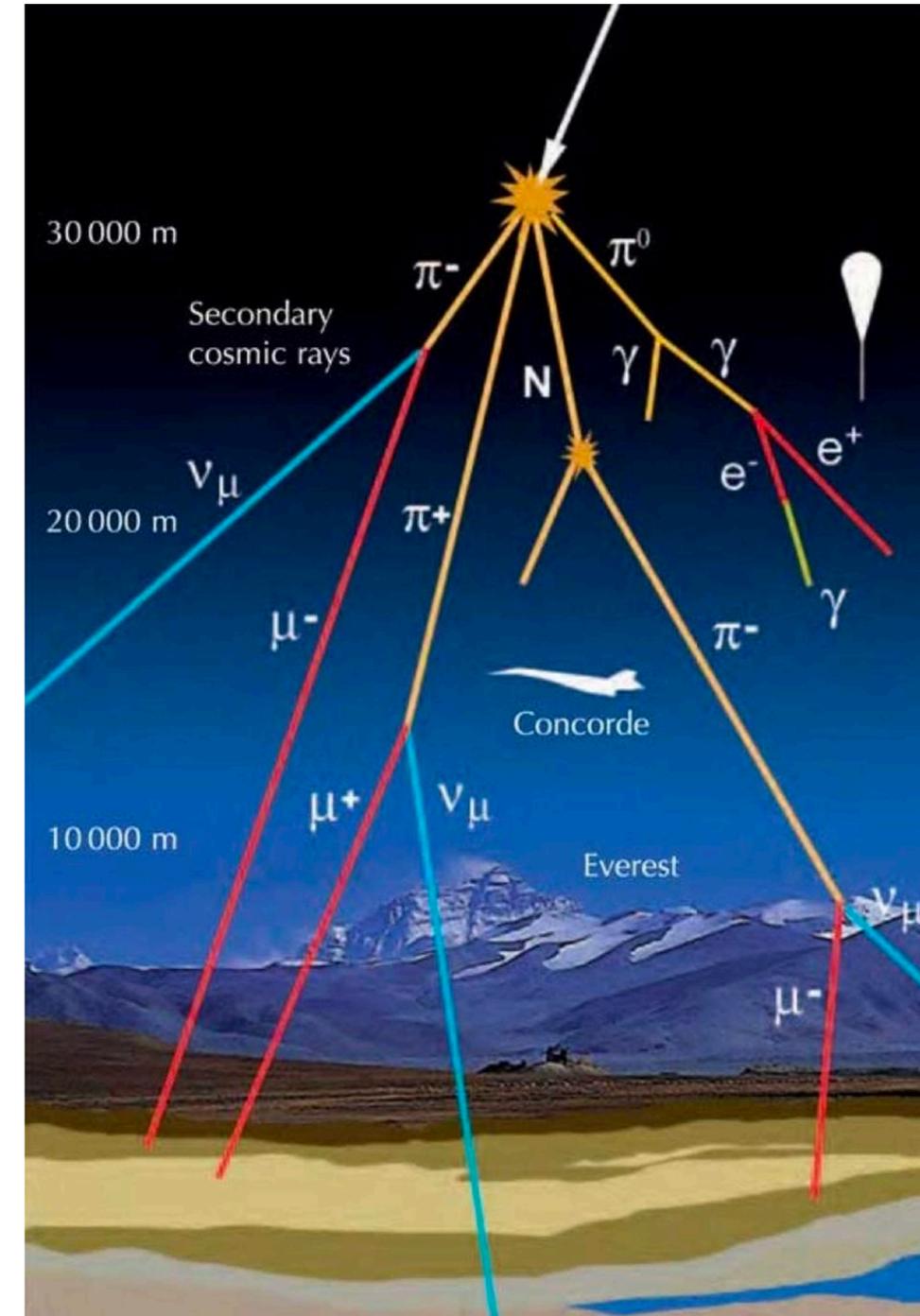
Applying Symmetries to Protons and Neutrons

- 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.



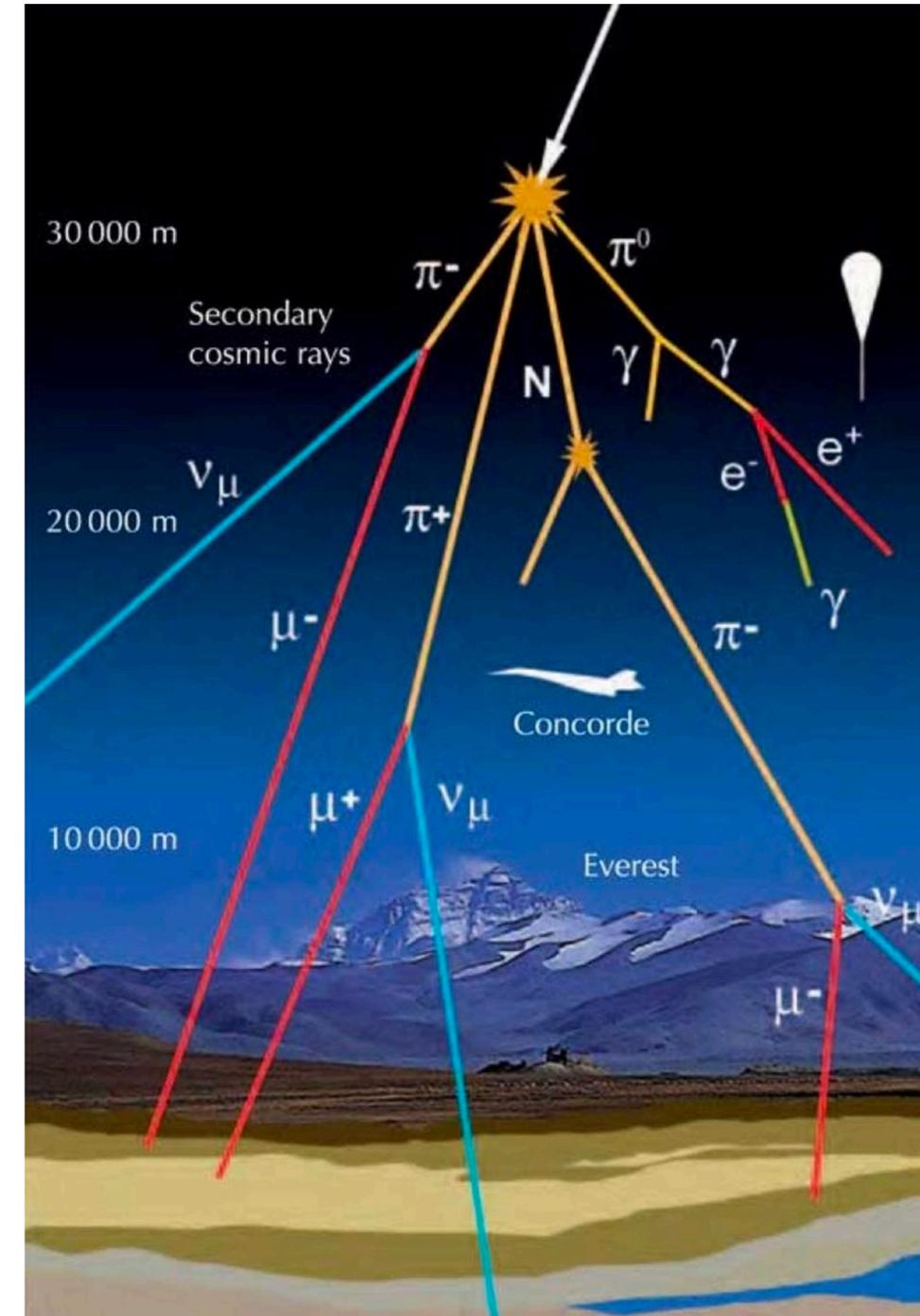
Applying Symmetries to Protons and Neutrons

- 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.
- Introduce some spin-like symmetry where the proton has “isospin” up, and the neutron has “isospin” down.

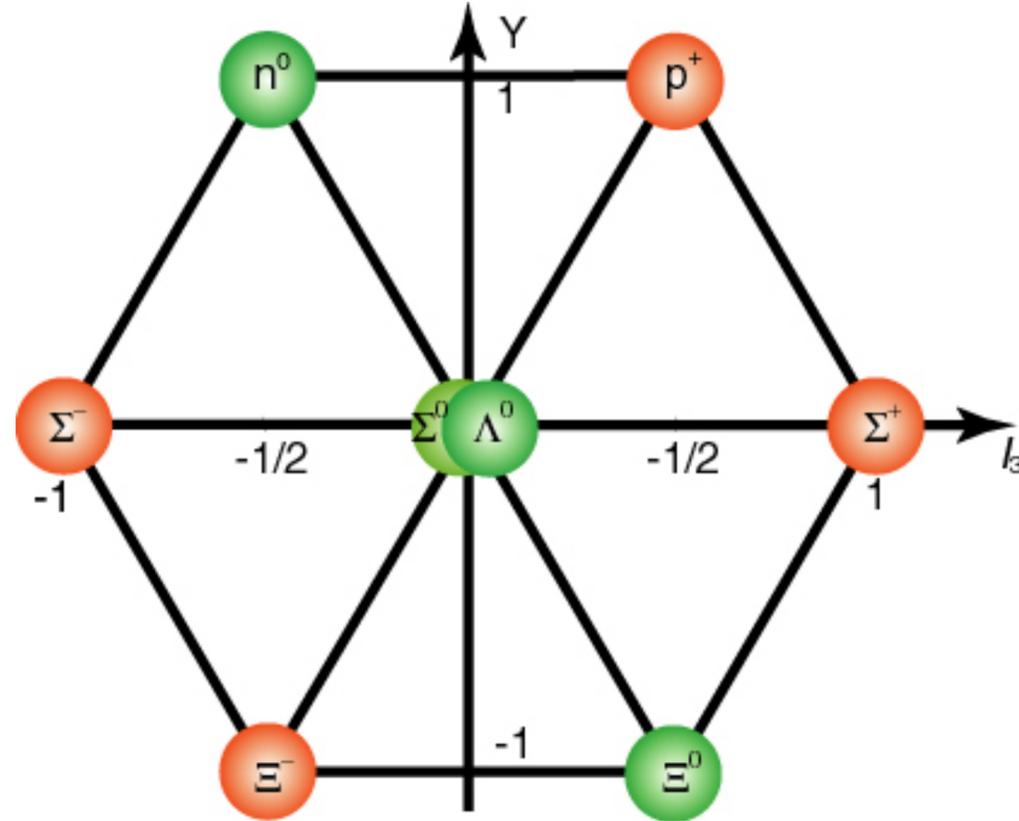


Applying Symmetries to Protons and Neutrons

- 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.
- 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.

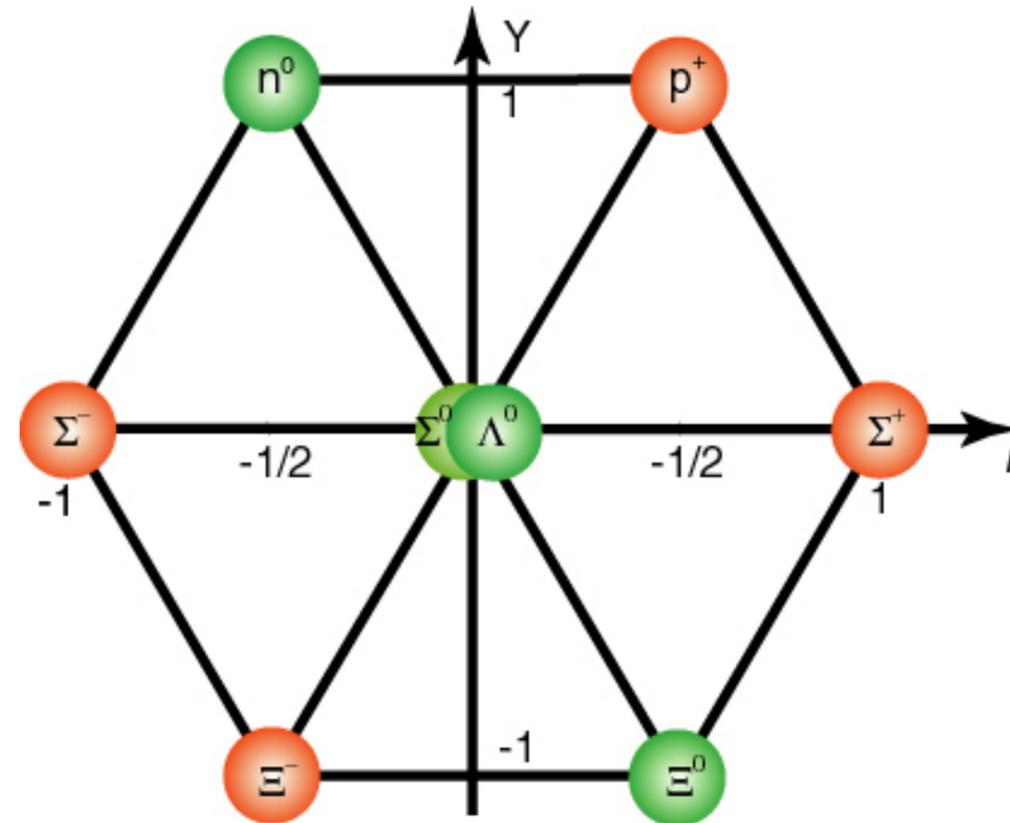


The Eightfold Way



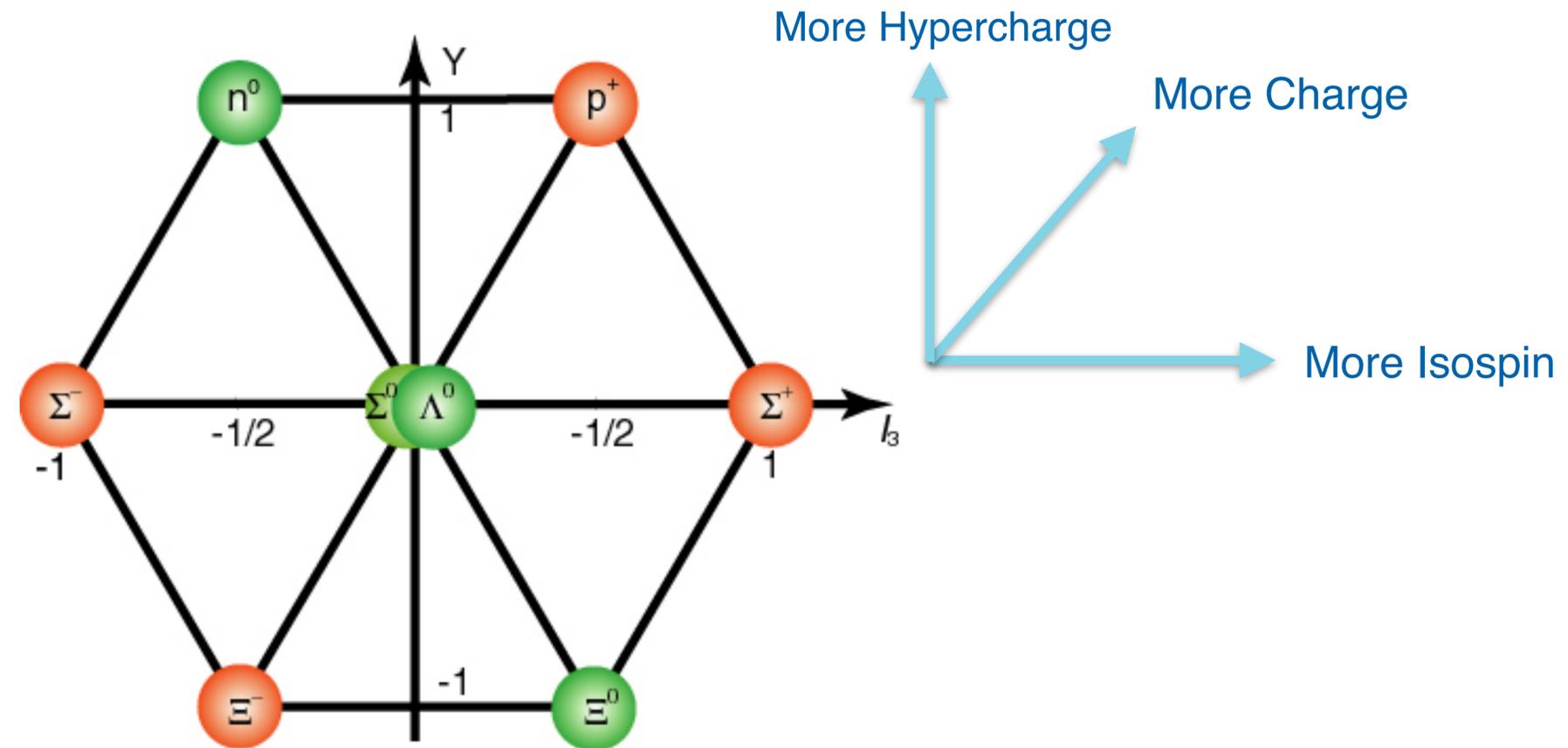
The Eightfold Way

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



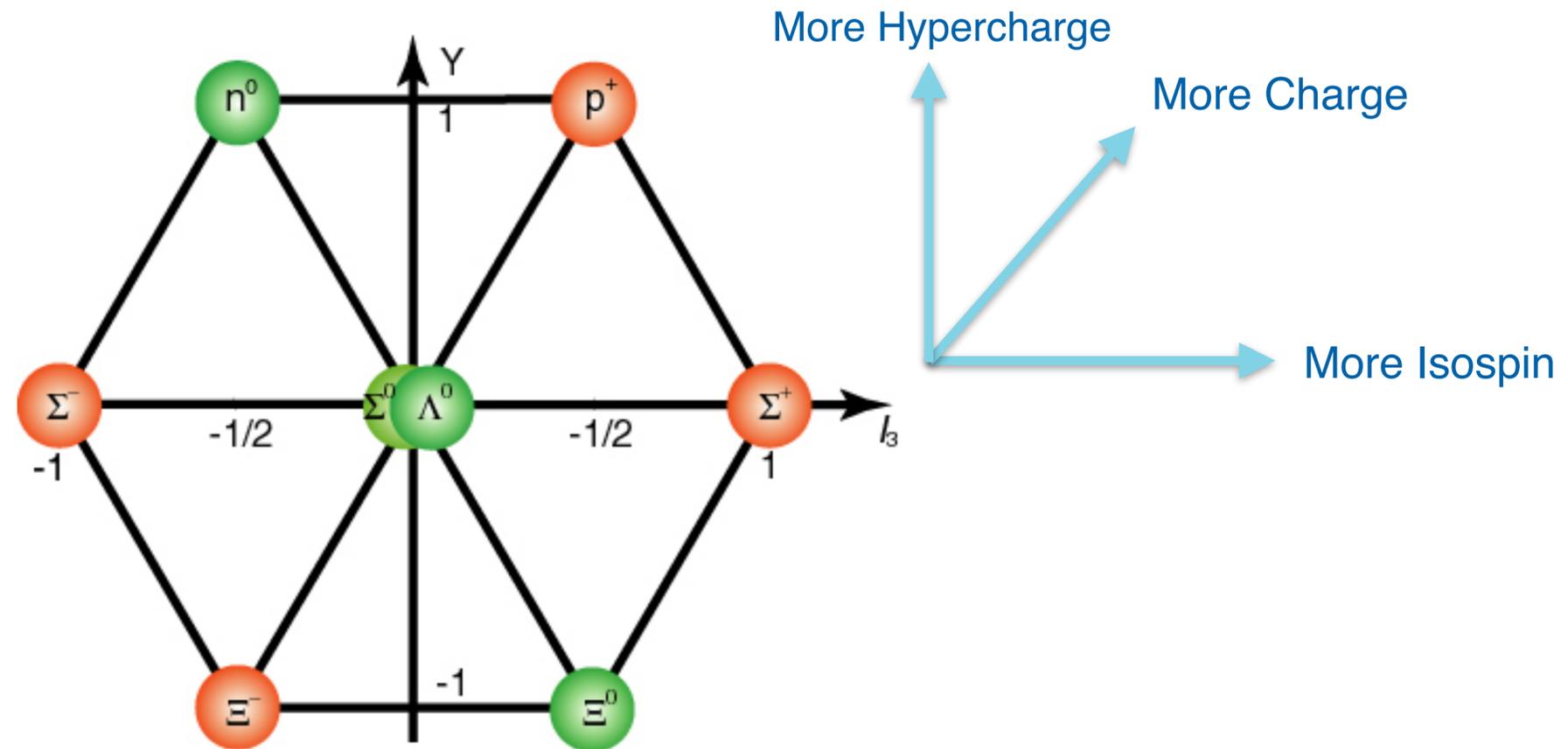
The Eightfold Way

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



The Eightfold Way

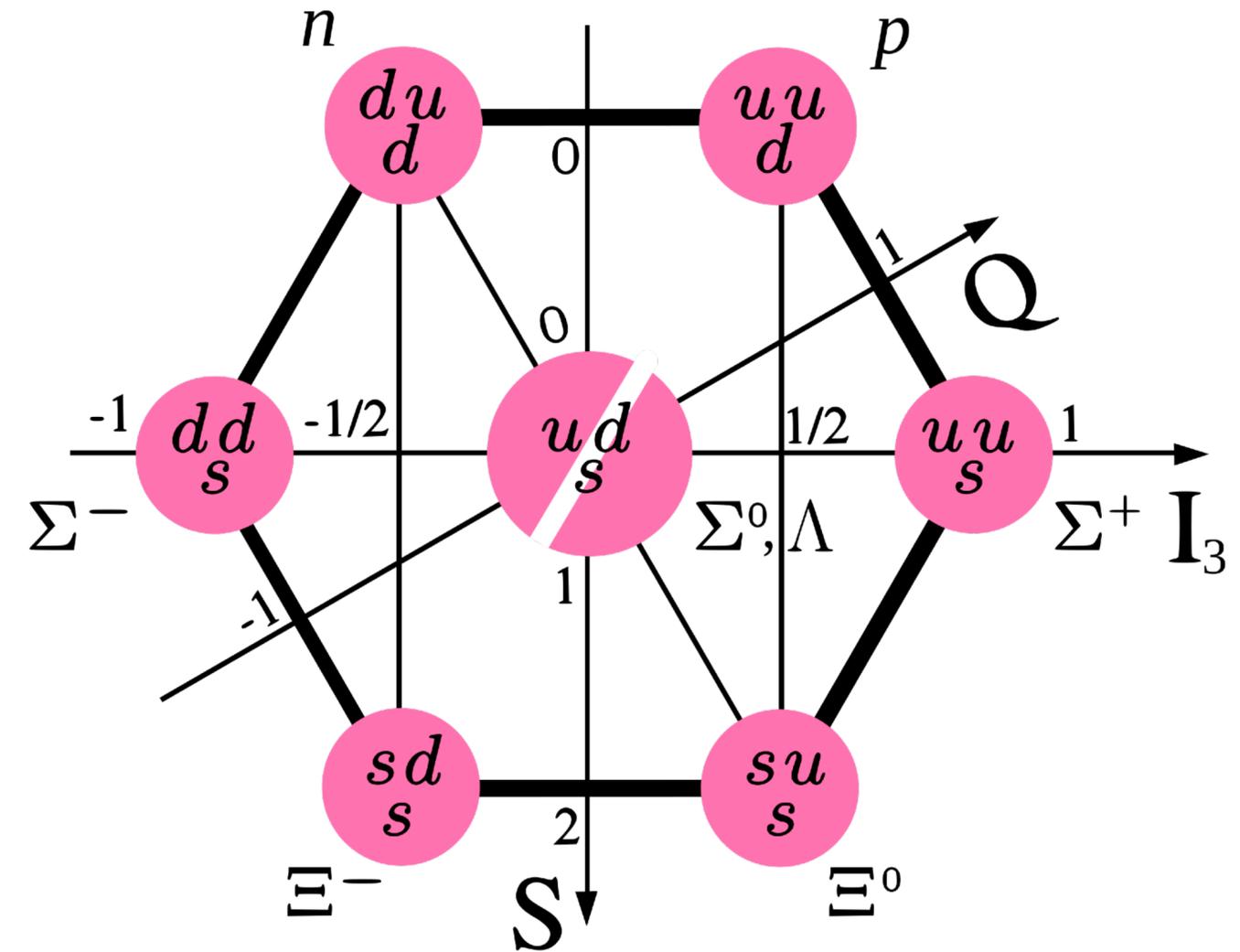
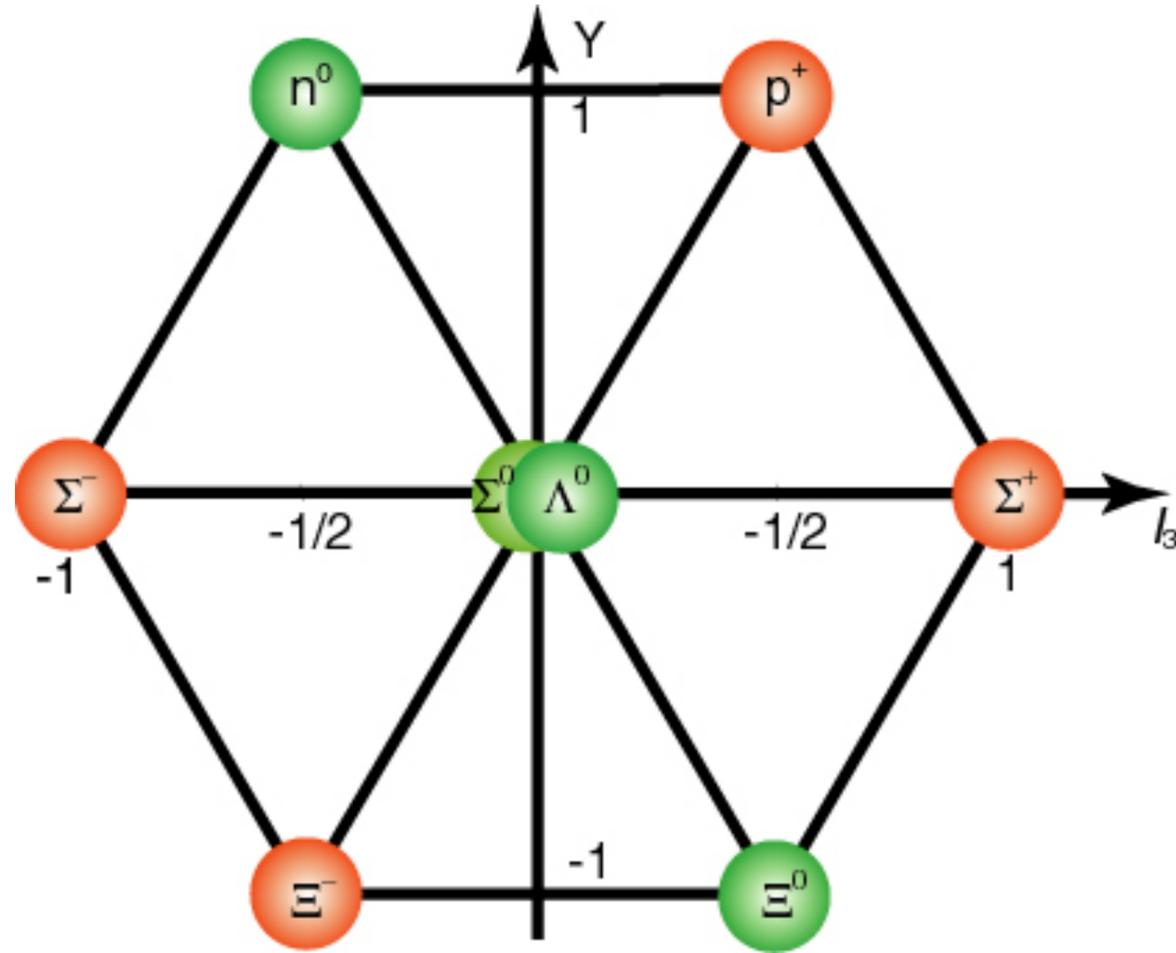
- Mesons, Baryons, and their interactions can be described using isospin and charge.



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

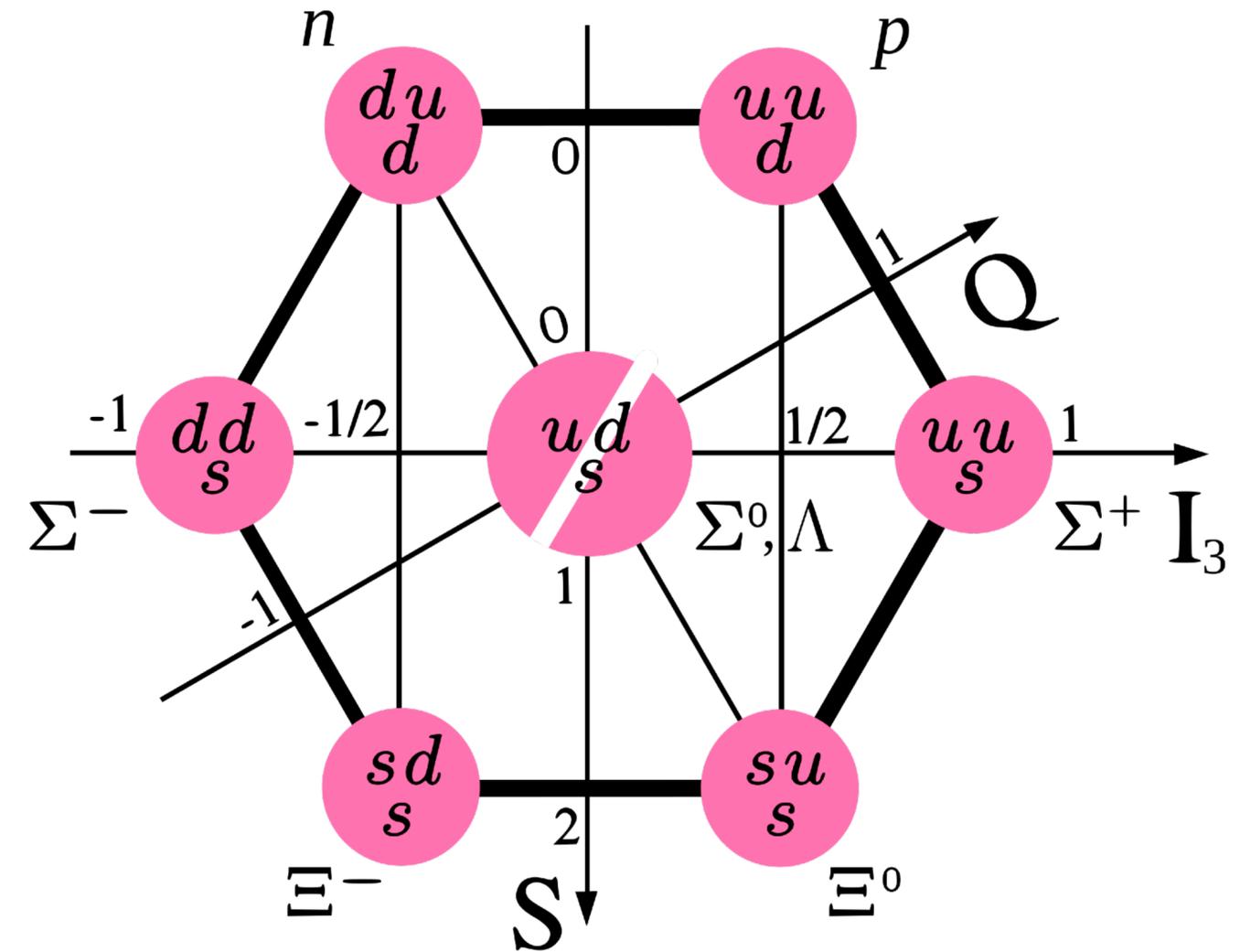
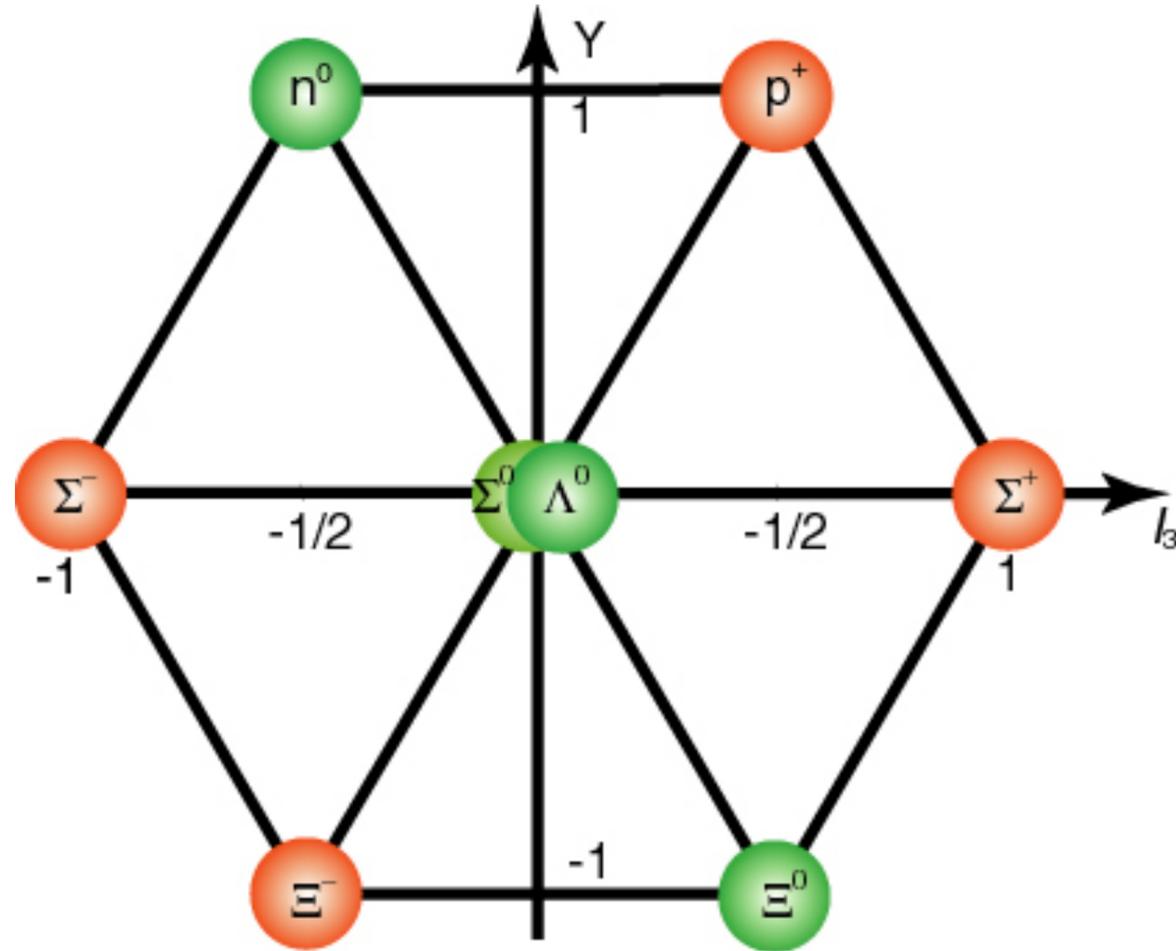
Gell-Mann, Zweig, and Quarks

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



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.



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

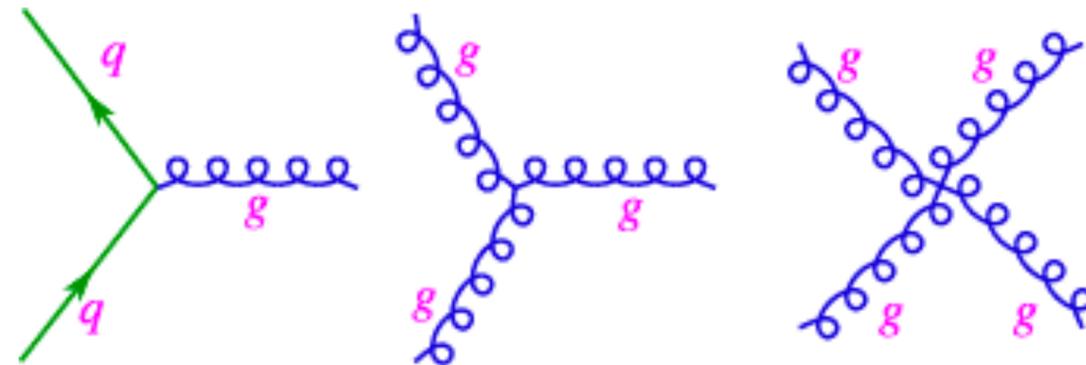
- Over the next several decades, three more quarks (charm, bottom, and top) were discovered.

Three quarks to Six quarks

- 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.

Three quarks to Six quarks

- 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.

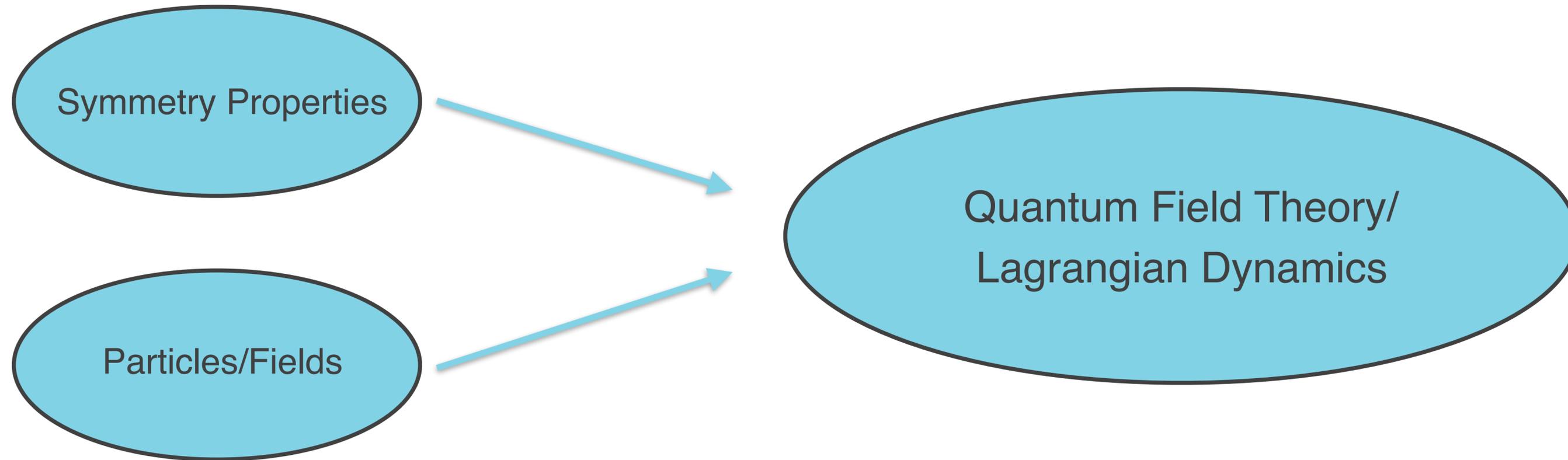


So, how do we use symmetries & particles together?

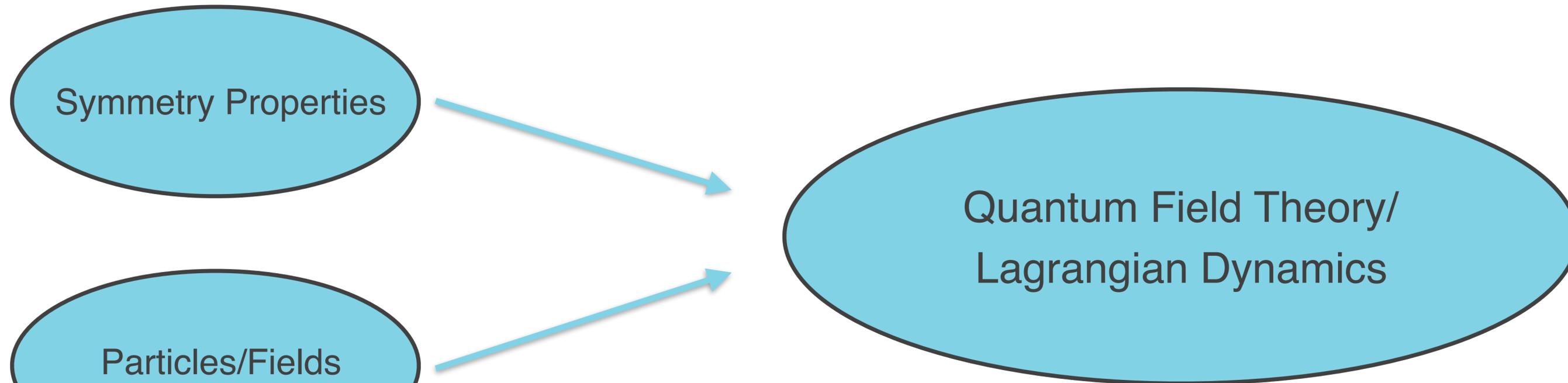
Symmetry Properties

Particles/Fields

So, how do we use symmetries & particles together?



So, how do we use symmetries & particles together?



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

What are these “SU(3)” Lie group symmetries?

- Most common symmetries used in particle physics are called “local transformations”, where we apply some transformation to the Lagrangian but it remains unchanged.

What are these “SU(3)” Lie group symmetries?

- Most common symmetries used in particle physics are called “local transformations”, where we apply some transformation to the Lagrangian but it remains unchanged.

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

What are these “SU(3)” Lie group symmetries?

- Most common symmetries used in particle physics are called “local transformations”, where we apply some transformation to the Lagrangian but it remains unchanged.

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

- Apply some transformation on the particle field ϕ

What are these “SU(3)” Lie group symmetries?

- Most common symmetries used in particle physics are called “local transformations”, where we apply some transformation to the Lagrangian but it remains unchanged.

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

- Apply some transformation on the particle field ϕ
$$\phi \rightarrow \phi' = e^{i\vartheta(x)} \phi$$

What are these “SU(3)” Lie group symmetries?

- Most common symmetries used in particle physics are called “local transformations”, where we apply some transformation to the Lagrangian but it remains unchanged.

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

- Apply some transformation on the particle field ϕ

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

$$\partial_\mu \phi \rightarrow \partial_\mu \phi' = e^{i\vartheta} \left[i \left(\partial_\mu \vartheta \right) \phi + \left(\partial_\mu \phi \right) \right]$$

What are these “SU(3)” Lie group symmetries?

- Most common symmetries used in particle physics are called “local transformations”, where we apply some transformation to the Lagrangian but it remains unchanged.

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

- Apply some transformation on the particle field ϕ

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

$$\partial_\mu \phi \rightarrow \partial_\mu \phi' = e^{i\vartheta} \left[i \left(\partial_\mu \vartheta \right) \phi + \left(\partial_\mu \phi \right) \right]$$

- The Lagrangian will no longer be invariant — need to “promote” the partial derivative to a gauge-covariant derivative,

What are these “SU(3)” Lie group symmetries?

- Most common symmetries used in particle physics are called “local transformations”, where we apply some transformation to the Lagrangian but it remains unchanged.

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

- Apply some transformation on the particle field ϕ

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

$$\partial_\mu \phi \rightarrow \partial_\mu \phi' = e^{i\vartheta} \left[i \left(\partial_\mu \vartheta \right) \phi + \left(\partial_\mu \phi \right) \right]$$

- The Lagrangian will no longer be invariant — need to “promote” the partial derivative to a gauge-covariant derivative,

$$\partial_\mu \rightarrow \partial_\mu - igA_\mu \equiv D_\mu \quad A_\mu \rightarrow \text{Gauge field}$$

Gauge Symmetries introduce new Fields/Particles

$$\partial_\mu \rightarrow \partial_\mu - igA_\mu \equiv D_\mu \quad A_\mu \rightarrow \text{Gauge field}$$

Gauge Symmetries introduce new Fields/Particles

$$\partial_\mu \rightarrow \partial_\mu - igA_\mu \equiv D_\mu \quad A_\mu \rightarrow \text{Gauge field}$$

- The field A_μ being introduced here acts as a “force carrier” between particles, often referred to as a gauge boson.

Gauge Symmetries introduce new Fields/Particles

$$\partial_\mu \rightarrow \partial_\mu - igA_\mu \equiv D_\mu \quad A_\mu \rightarrow \text{Gauge field}$$

- The field A_μ being introduced here acts as a “force carrier” between particles, often referred to as a gauge boson.

Particle(s) + Gauge Symmetry \longrightarrow Description of Interactions

Gauge Symmetries introduce new Fields/Particles

$$\partial_\mu \rightarrow \partial_\mu - igA_\mu \equiv D_\mu \quad A_\mu \rightarrow \text{Gauge field}$$

- The field A_μ being introduced here acts as a “force carrier” between particles, often referred to as a gauge boson.

Particle(s) + Gauge Symmetry \longrightarrow Description of Interactions

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

Side-note: Gauge Boson Masses

- If we wanted the particle A^μ to have a mass, we need a term in the Lagrangian that looks like

$$\mathcal{L} \supset m^2 A_\mu A^\mu$$

Side-note: Gauge Boson Masses

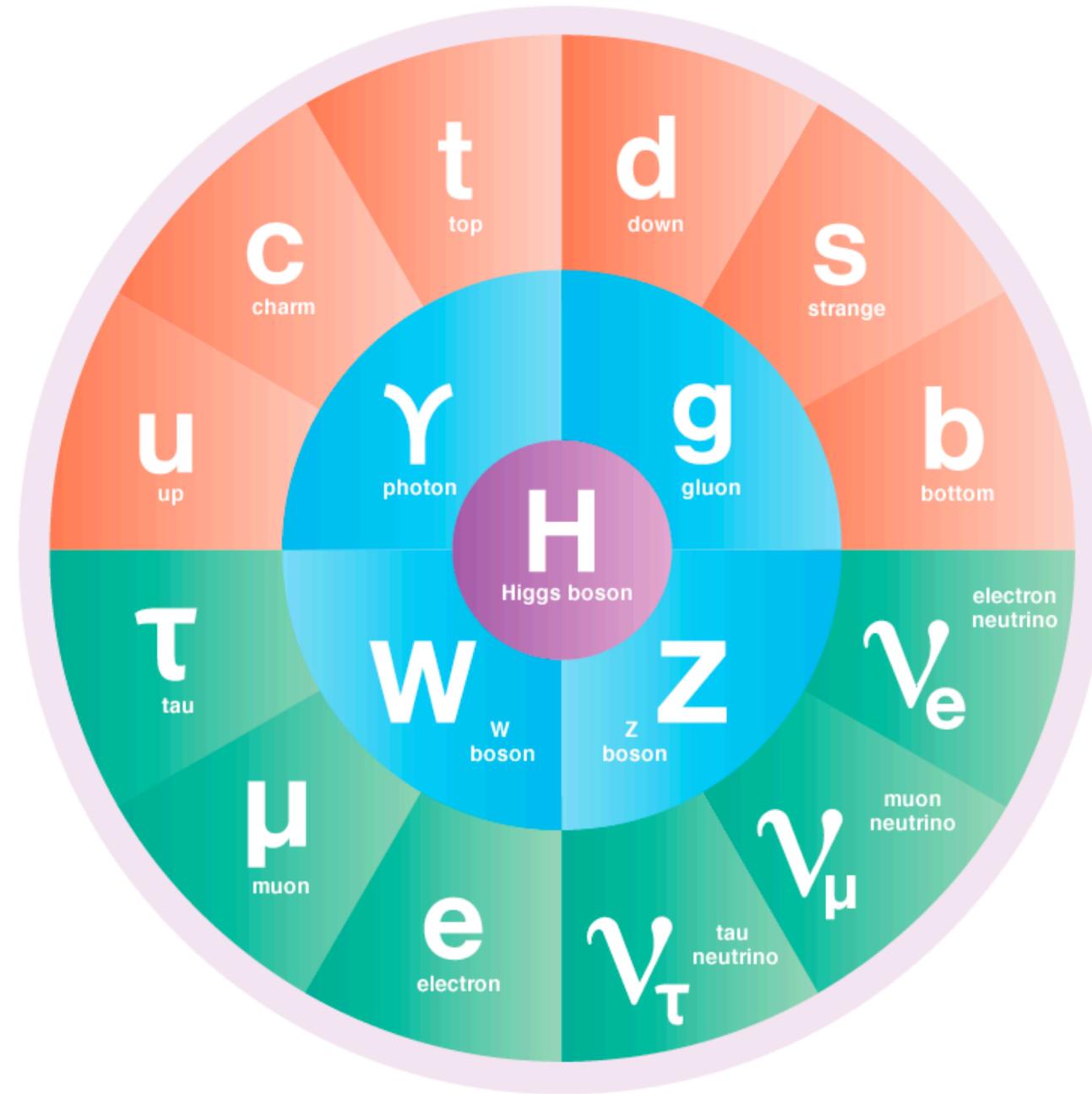
- If we wanted the particle A^μ to have a mass, we need a term in the Lagrangian that looks like

$$\mathcal{L} \supset m^2 A_\mu A^\mu$$

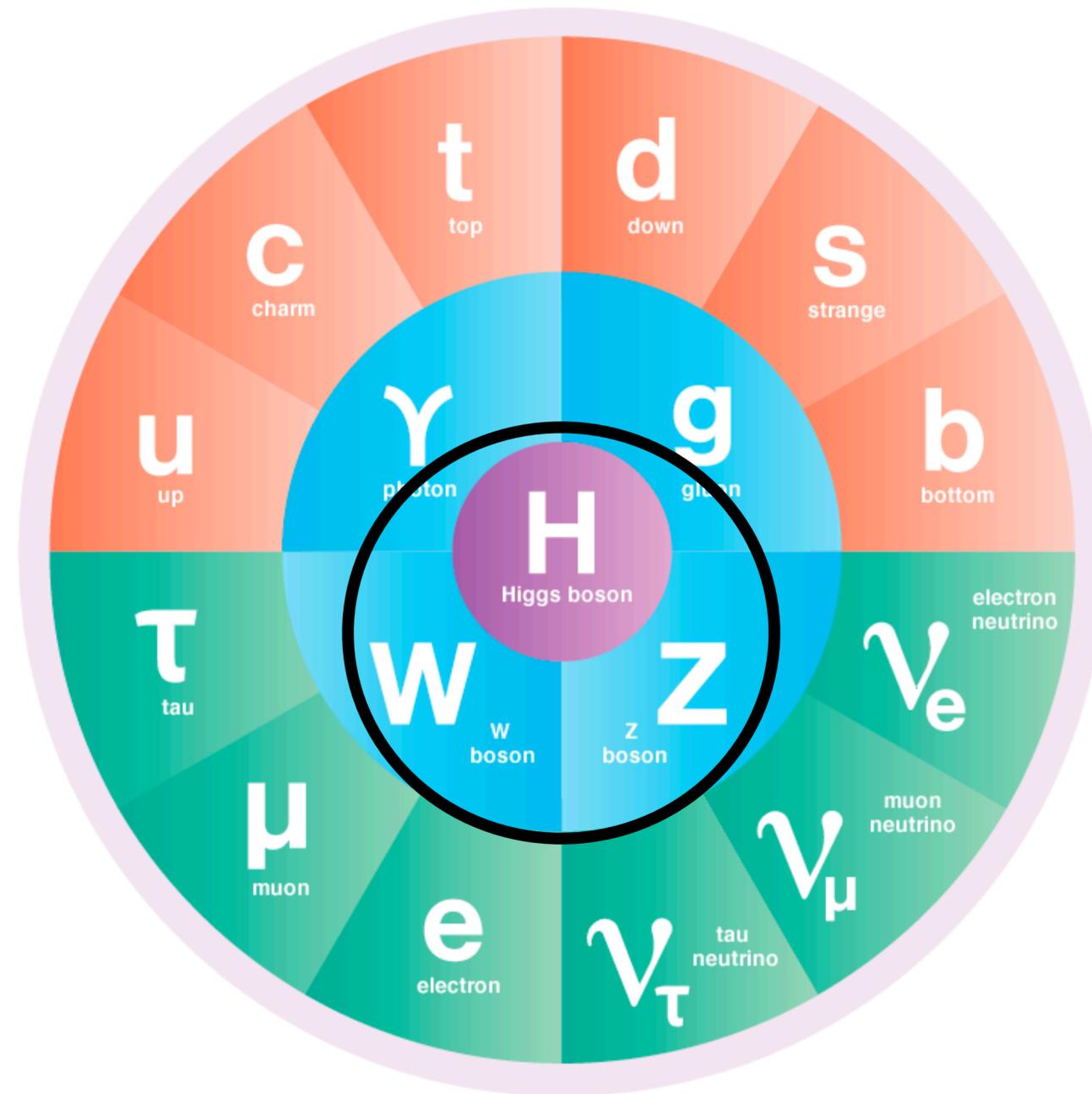
- Under the transformation we introduced for this, though, the Lagrangian is **not** invariant — gauge bosons must be massless.

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

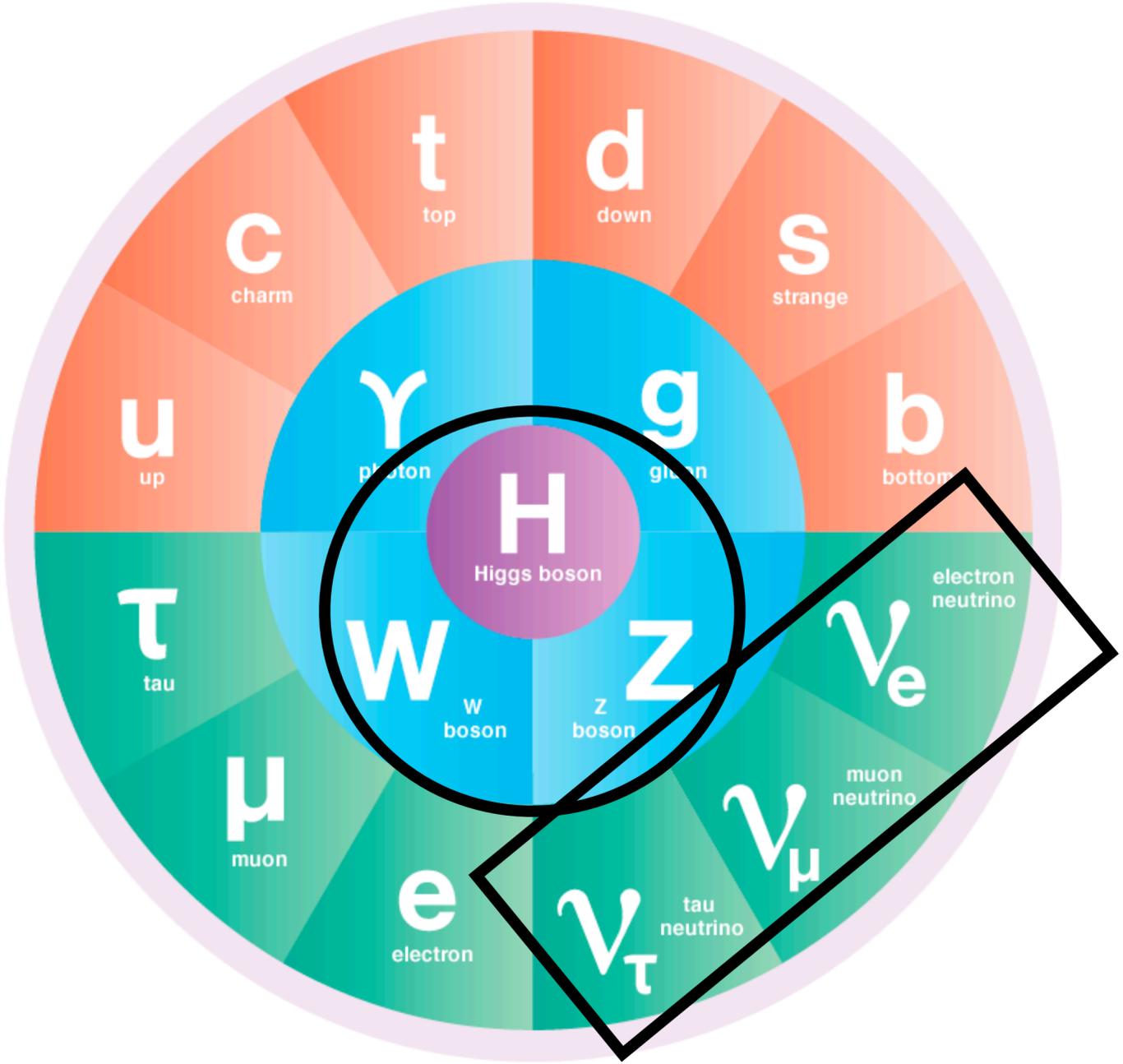
Let's check back in on the Standard Model



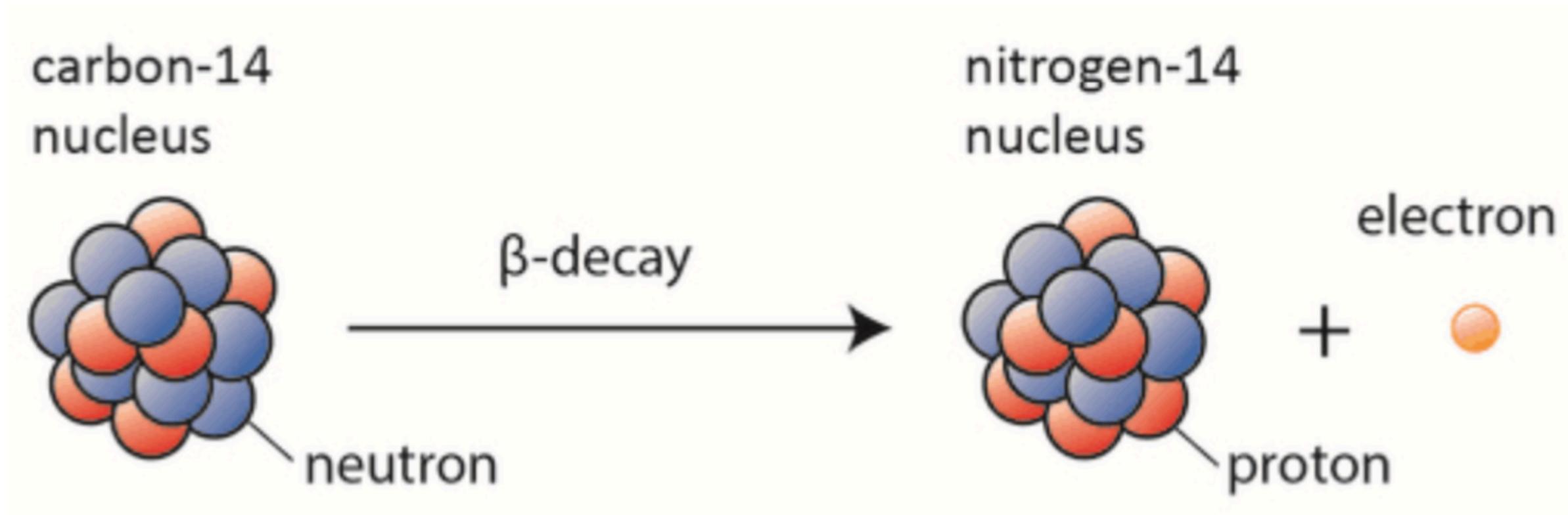
Let's check back in on the Standard Model



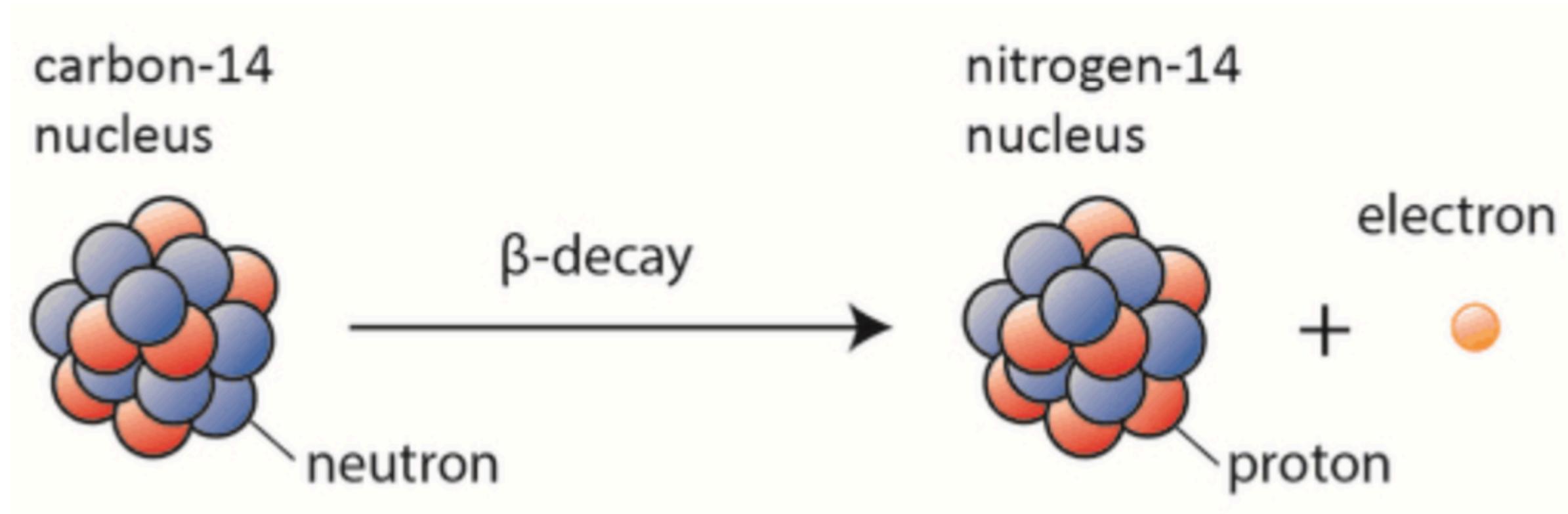
Let's check back in on the Standard Model



Back to the 1930s: Nuclear Beta Decays



Back to the 1930s: Nuclear Beta Decays



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.

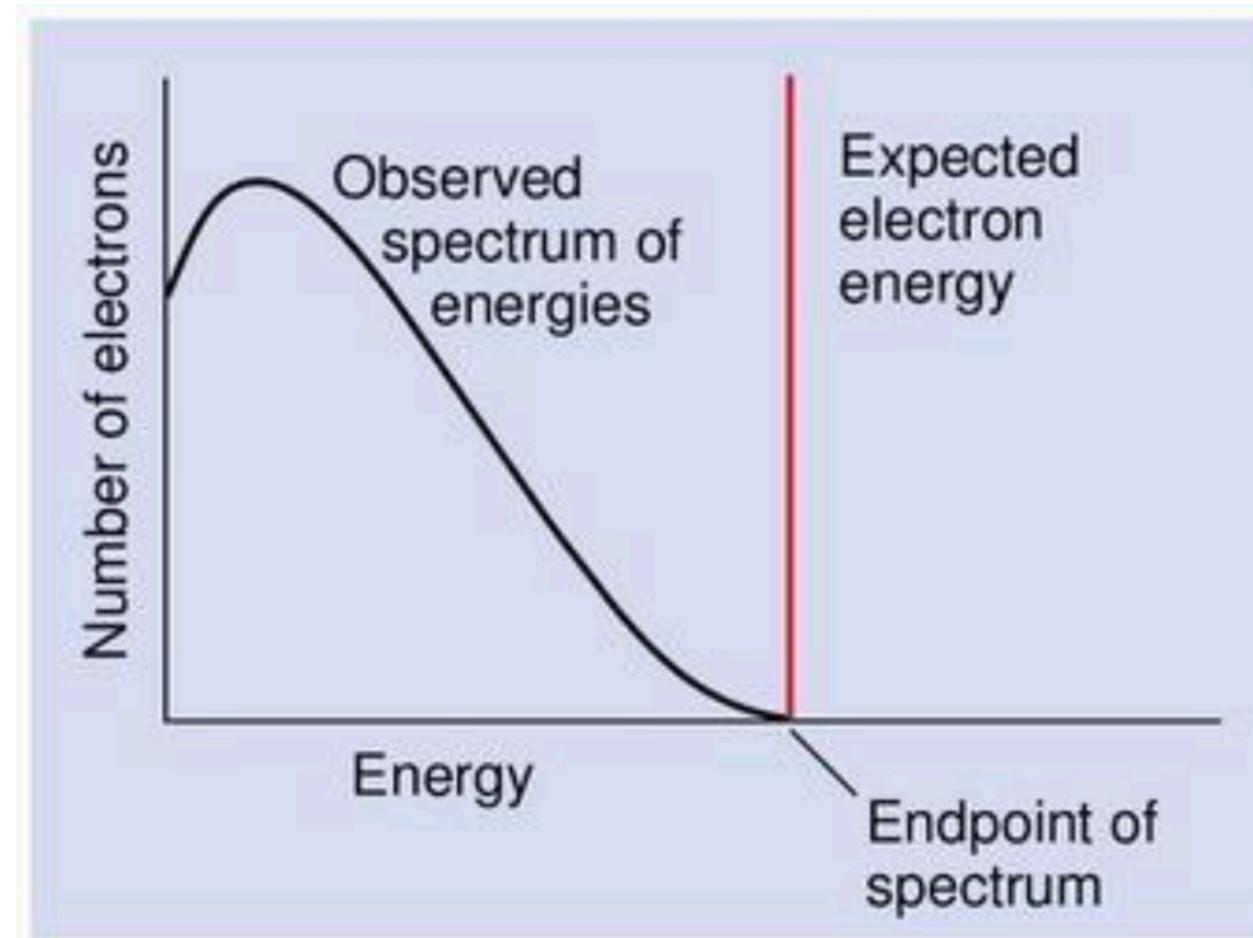
Conservation of Energy in Beta Decays

Conservation of Energy in Beta Decays

- Two-body final state (nitrogen nucleus + electron) — one can show that the electron coming out should be “monoenergetic”

Conservation of Energy in Beta Decays

- Two-body final state (nitrogen nucleus + electron) — one can show that the electron coming out should be “monoenergetic”



- 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
beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert
wird, derart, dass die Summe der Energien von Neutron und Elektron
konstant ist.



Wolfgang Pauli: “Dear Radioactive Ladies and Gentlemen”

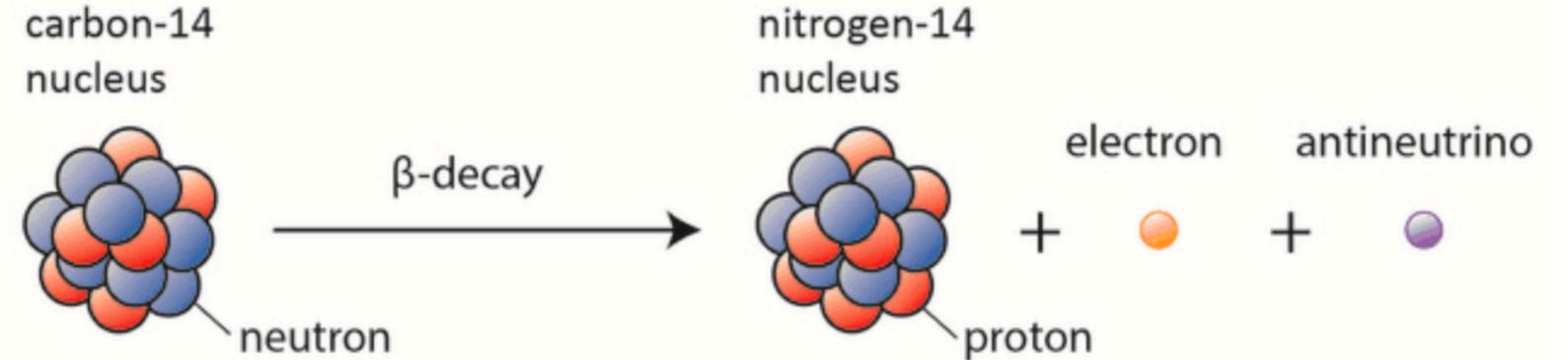
Abschrift

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 anhören 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 beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.



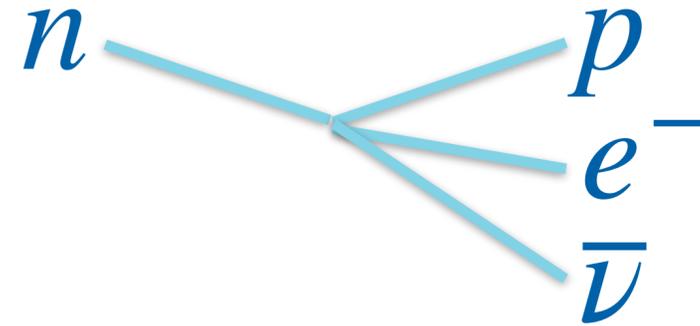
- Pauli’s solution: a new, very weakly interacting “neutrino” comes out of beta decays as well, stealing some of the energy from the outgoing electron and producing a spectrum of electron energies.

Just how “weak” is “weakly interacting”?

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

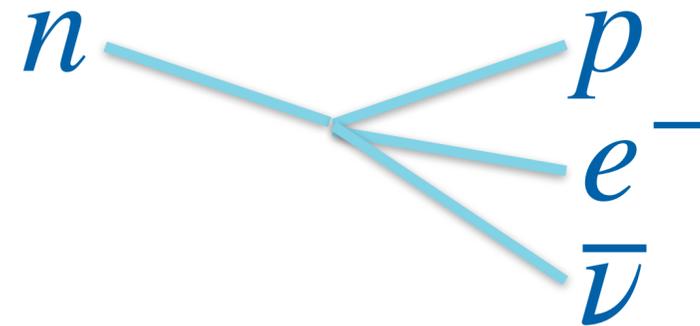
Just how “weak” is “weakly interacting”?

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

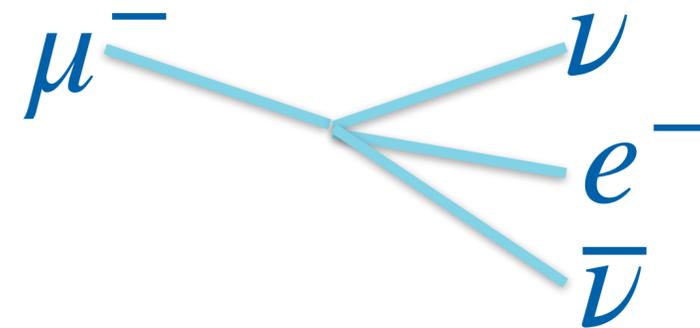


Just how “weak” is “weakly interacting”?

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

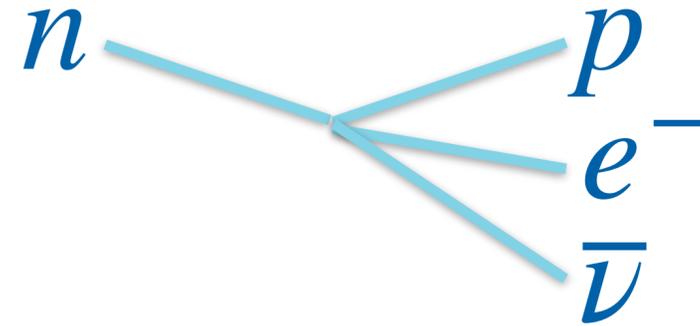


- Also predicts processes like muon decay,

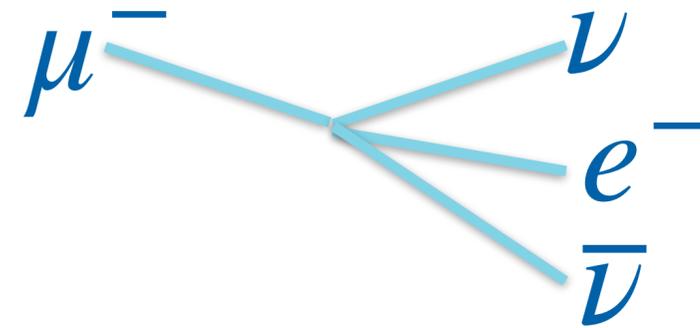


Just how “weak” is “weakly interacting”?

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



- Also predicts processes like muon decay,



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

This theory also unveils new symmetry!

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

$$\begin{pmatrix} n \\ p \end{pmatrix} \longleftrightarrow \begin{pmatrix} \nu \\ e^- \end{pmatrix}$$

$$G_F \approx \frac{1}{(100 \text{ GeV})^2}$$

This theory also unveils new symmetry!

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

$$\begin{pmatrix} d \\ u \end{pmatrix} \longleftrightarrow \begin{pmatrix} \nu \\ e^- \end{pmatrix}$$

$$G_F \approx \frac{1}{(100 \text{ GeV})^2}$$

This theory also unveils new symmetry!

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

$$\begin{pmatrix} d \\ u \end{pmatrix} \longleftrightarrow \begin{pmatrix} \nu \\ e^- \end{pmatrix}$$

$$G_F \approx \frac{1}{(100 \text{ GeV})^2}$$

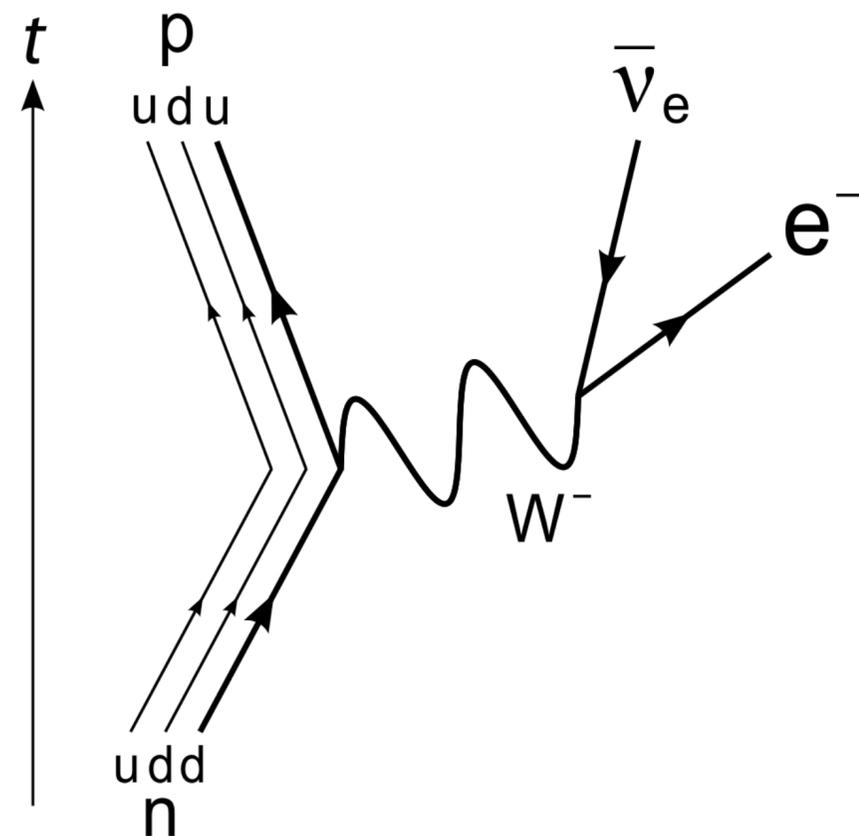
- Force carriers much heavier than the light fermions are mediating these interactions.

This theory also unveils new symmetry!

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

$$\begin{pmatrix} d \\ u \end{pmatrix} \longleftrightarrow \begin{pmatrix} \nu \\ e^- \end{pmatrix}$$

$$G_F \approx \frac{1}{(100 \text{ GeV})^2}$$



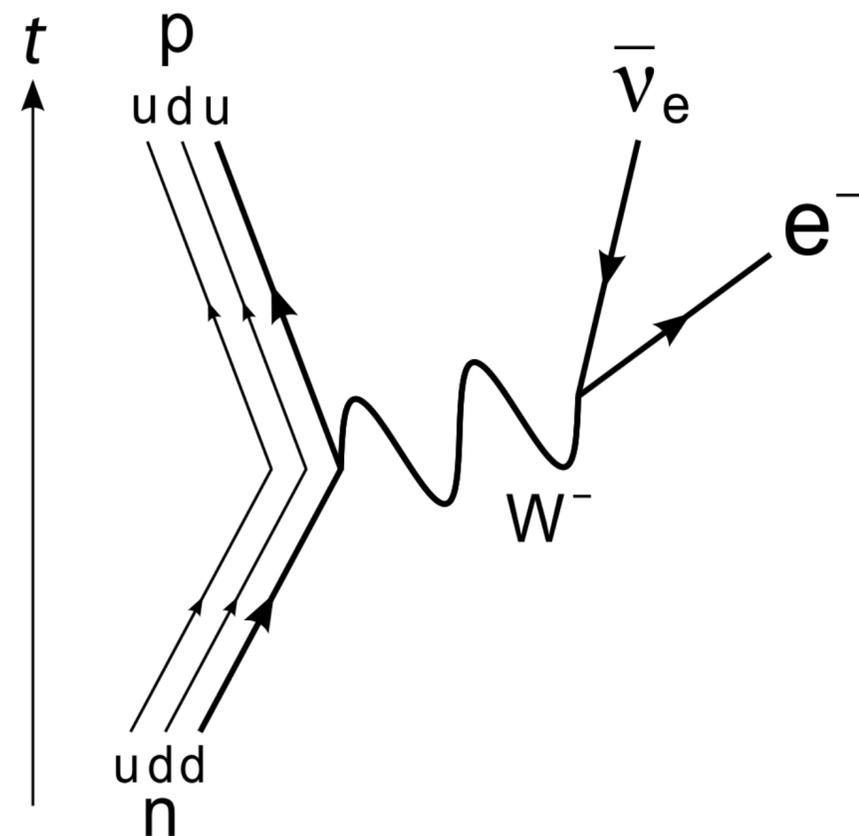
- Force carriers much heavier than the light fermions are mediating these interactions.
- 1983 — the two bosons, W and Z, associated with this interaction, were discovered at CERN.

This theory also unveils new symmetry!

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

$$\begin{pmatrix} d \\ u \end{pmatrix} \longleftrightarrow \begin{pmatrix} \nu \\ e^- \end{pmatrix}$$

$$G_F \approx \frac{1}{(100 \text{ GeV})^2}$$



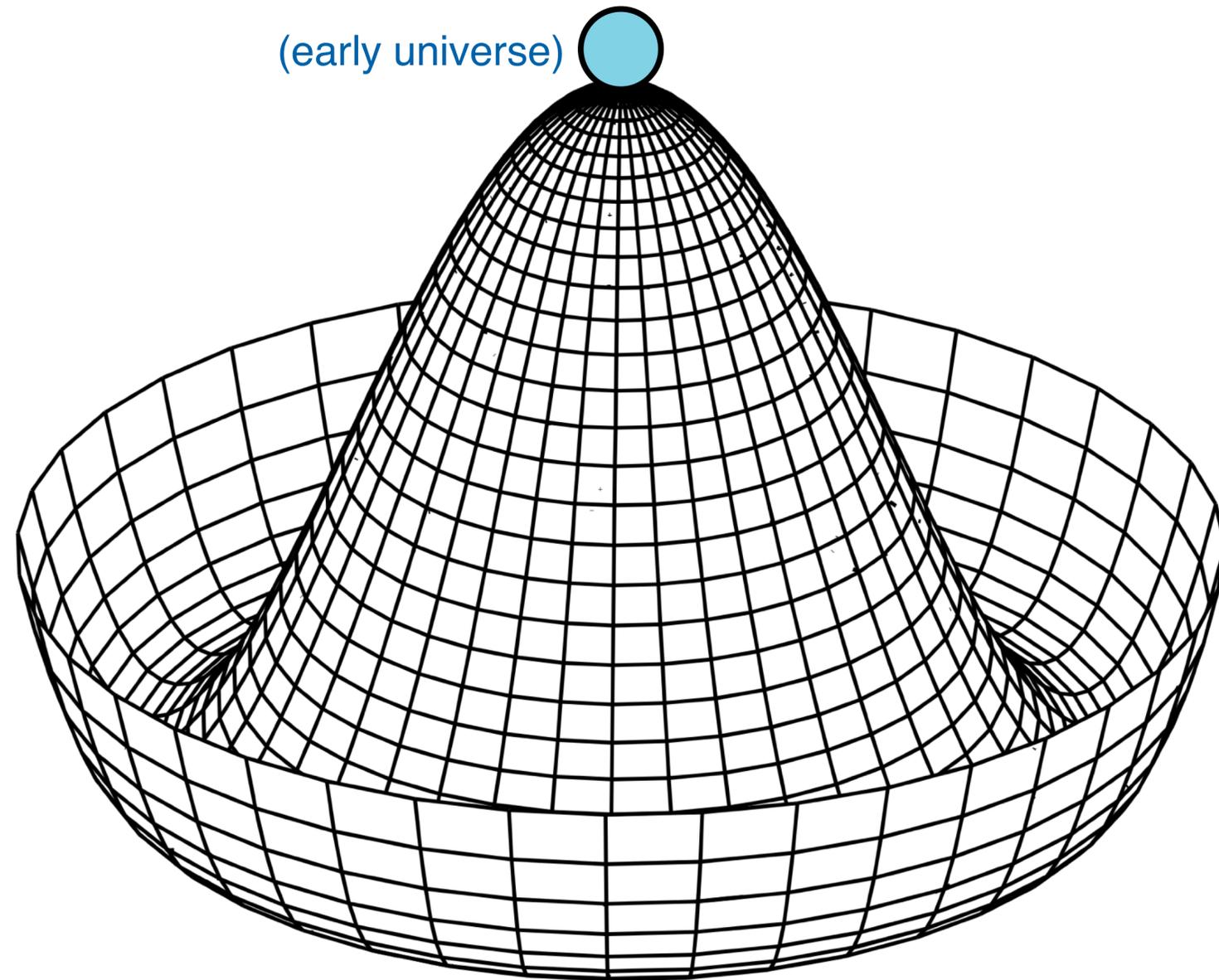
- Force carriers much heavier than the light fermions are mediating these interactions.
- 1983 — the two bosons, W and Z, associated with this interaction, were discovered at CERN.
- Issue: if these are really the gauge bosons of an **SU(2)** theory, they should have zero mass!

Solution: The final piece of the Standard Model

- The Higgs boson and the Higgs mechanism:

Solution: The final piece of the Standard Model

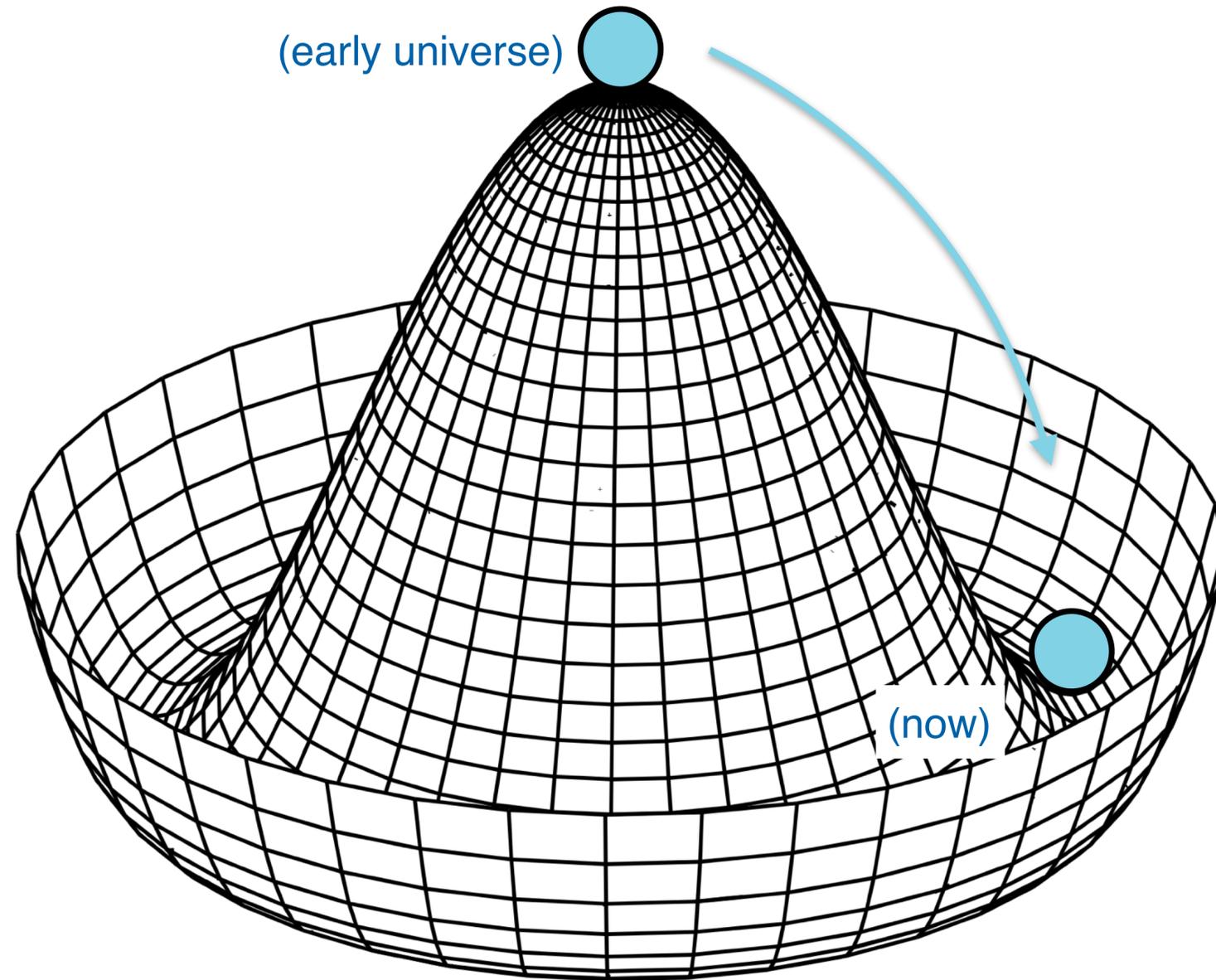
- The Higgs boson and the Higgs mechanism:



- In the early universe, the weak bosons (and the photon) are gauge bosons of a **SU(2) x U(1)** theory.

Solution: The final piece of the Standard Model

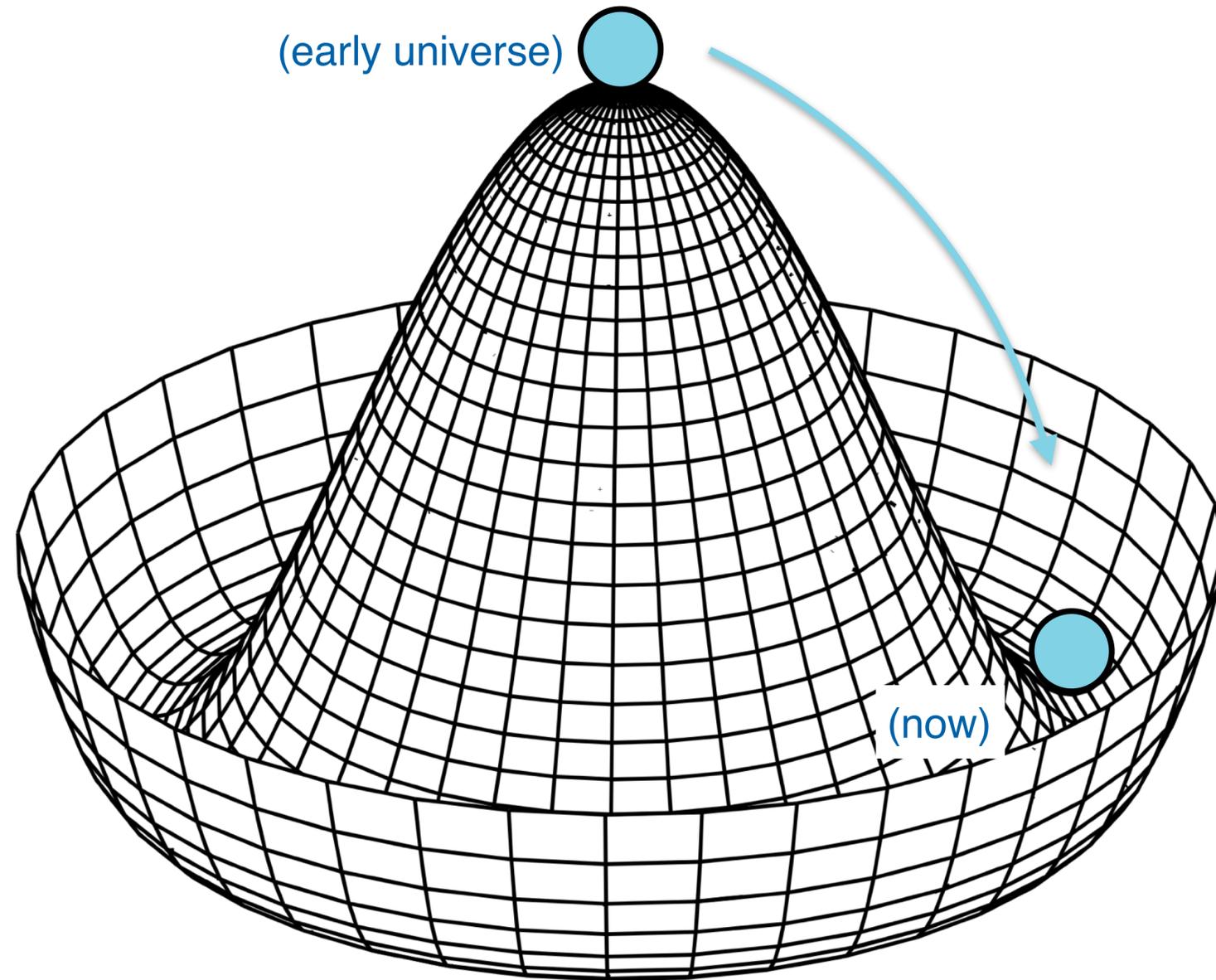
- The Higgs boson and the Higgs mechanism:



- In the early universe, the weak bosons (and the photon) are gauge bosons of a **SU(2) x U(1)** theory.
- As the universe cools, the Higgs boson feels compelled to acquire a “vacuum expectation value” at the bottom of this “Mexican hat” potential.

Solution: The final piece of the Standard Model

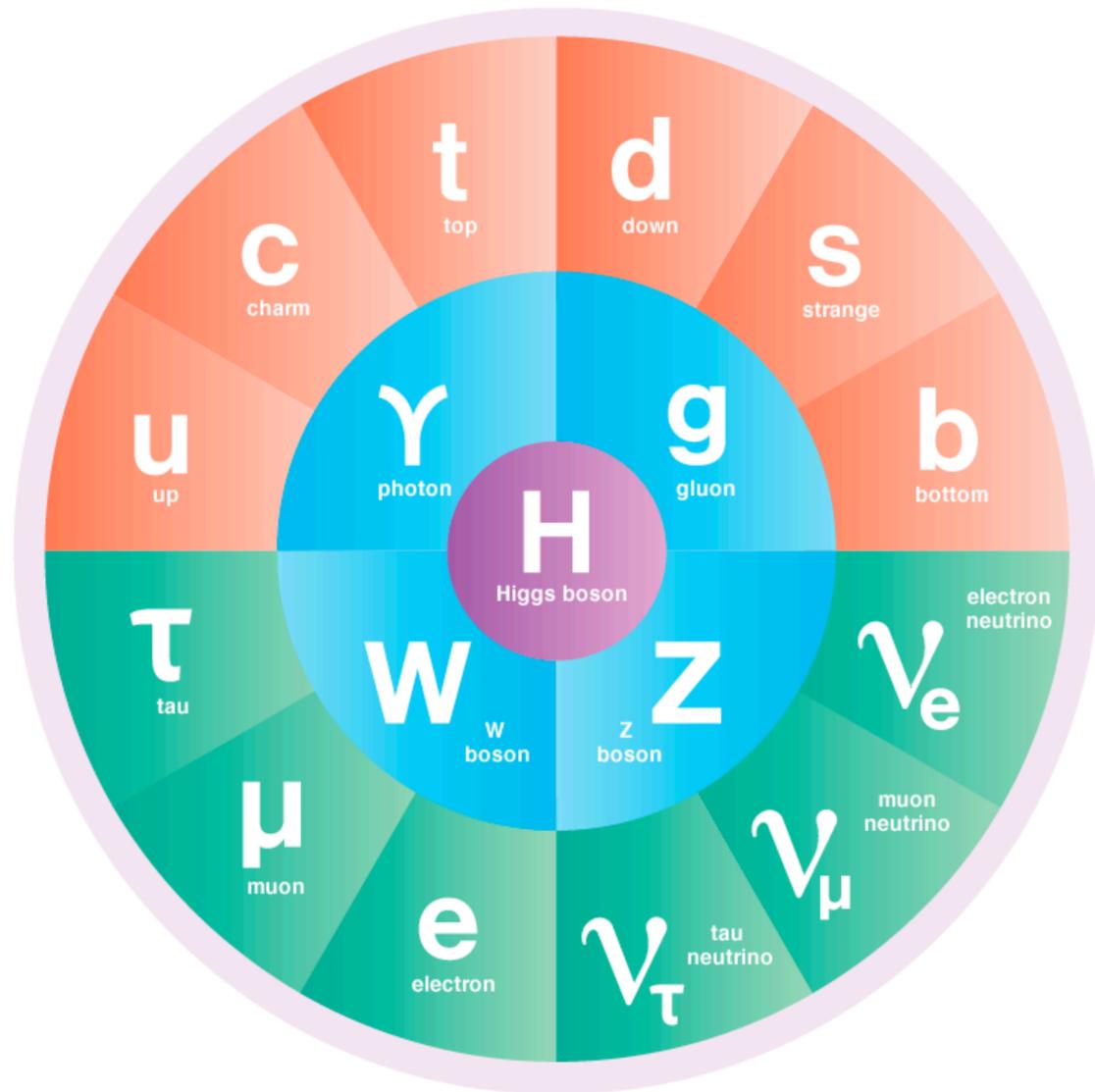
- The Higgs boson and the Higgs mechanism:



- In the early universe, the weak bosons (and the photon) are gauge bosons of a **SU(2) x U(1)** theory.
- 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.

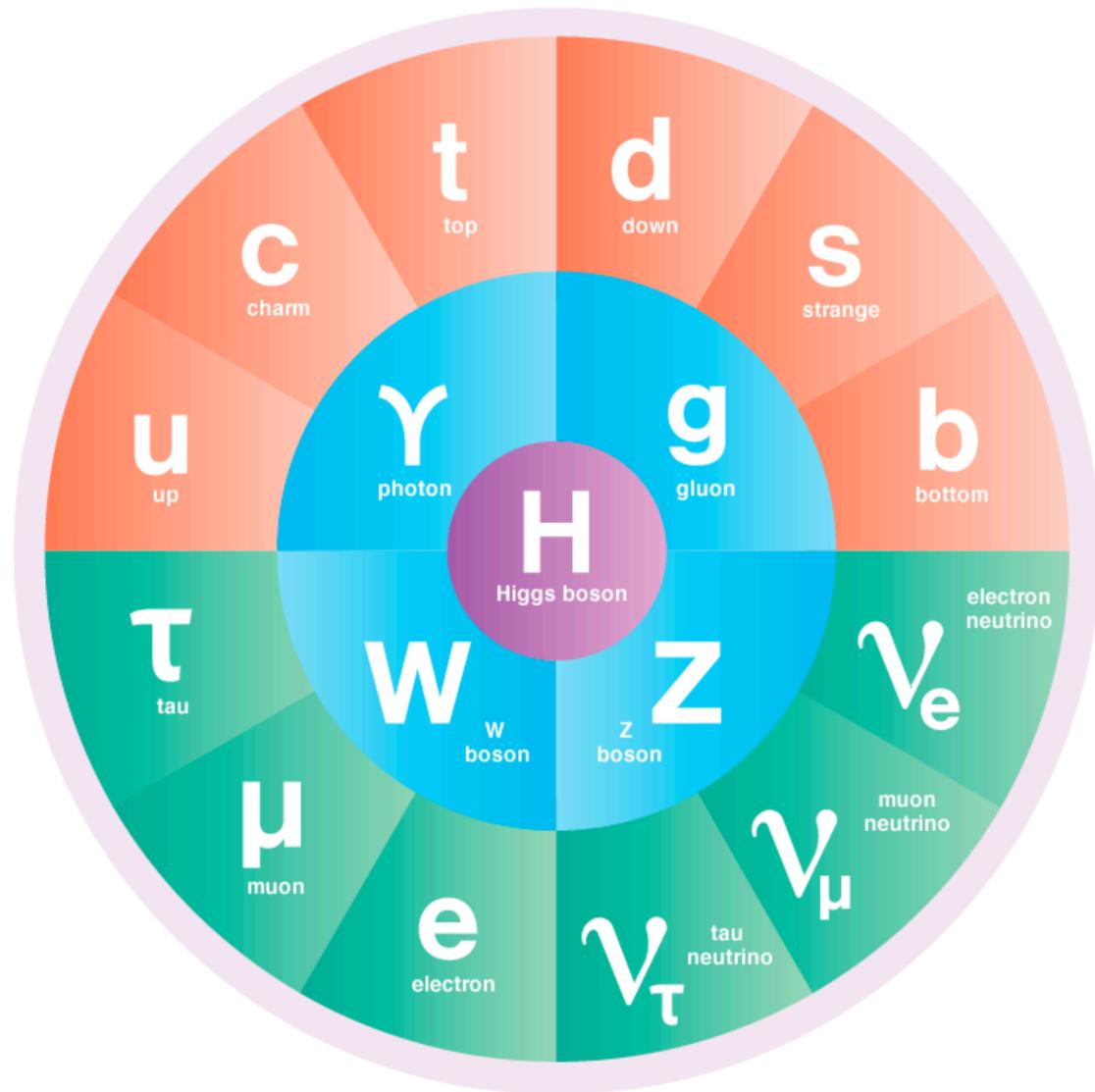
With the Discovery of the Higgs Boson in 2012,

- The “Standard Model” has been completed.



With the Discovery of the Higgs Boson in 2012,

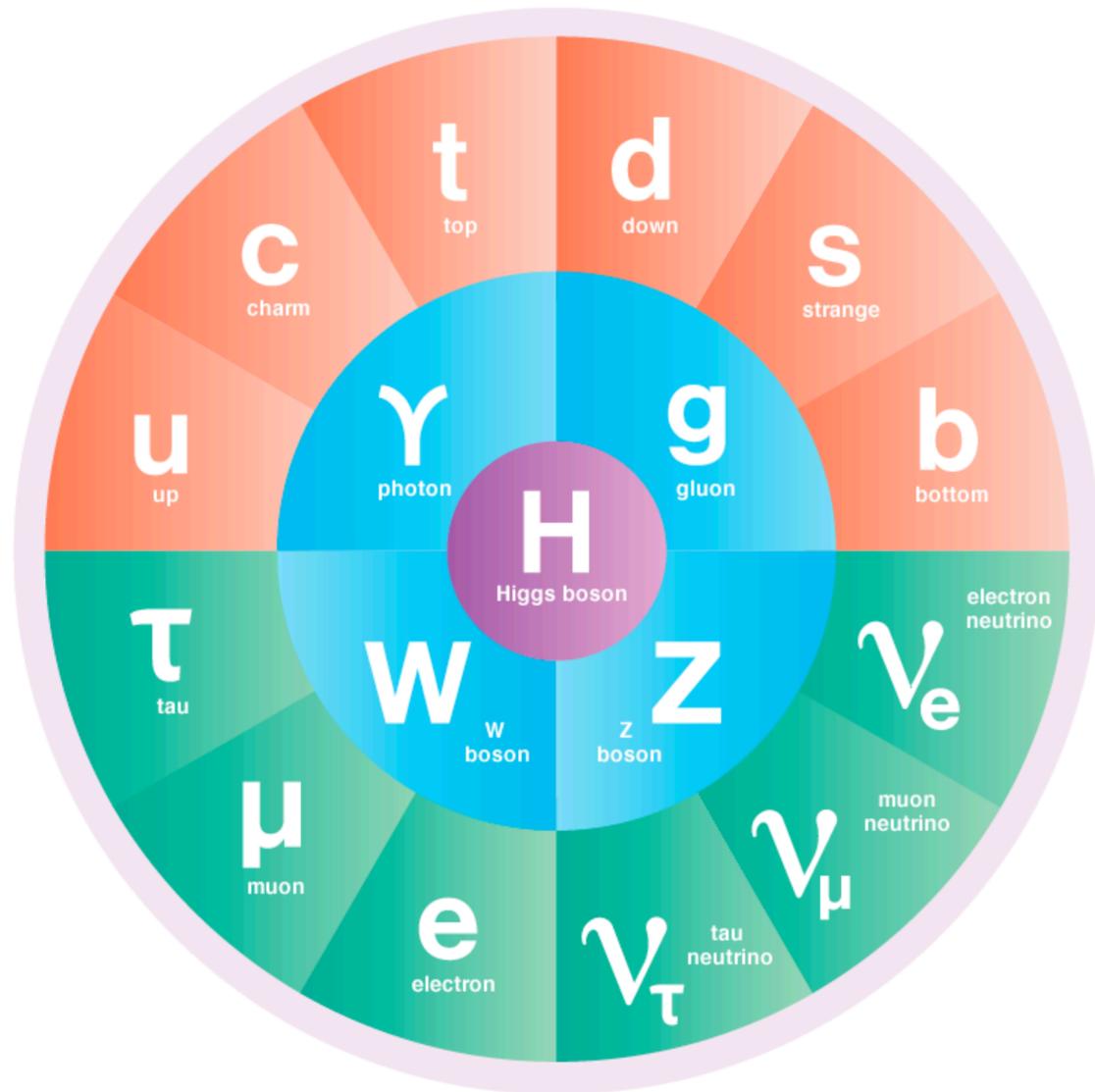
- The “Standard Model” has been completed.



- Three generations each of “up-type” quarks, “down-type” quarks, charged leptons, and neutral leptons.

With the Discovery of the Higgs Boson in 2012,

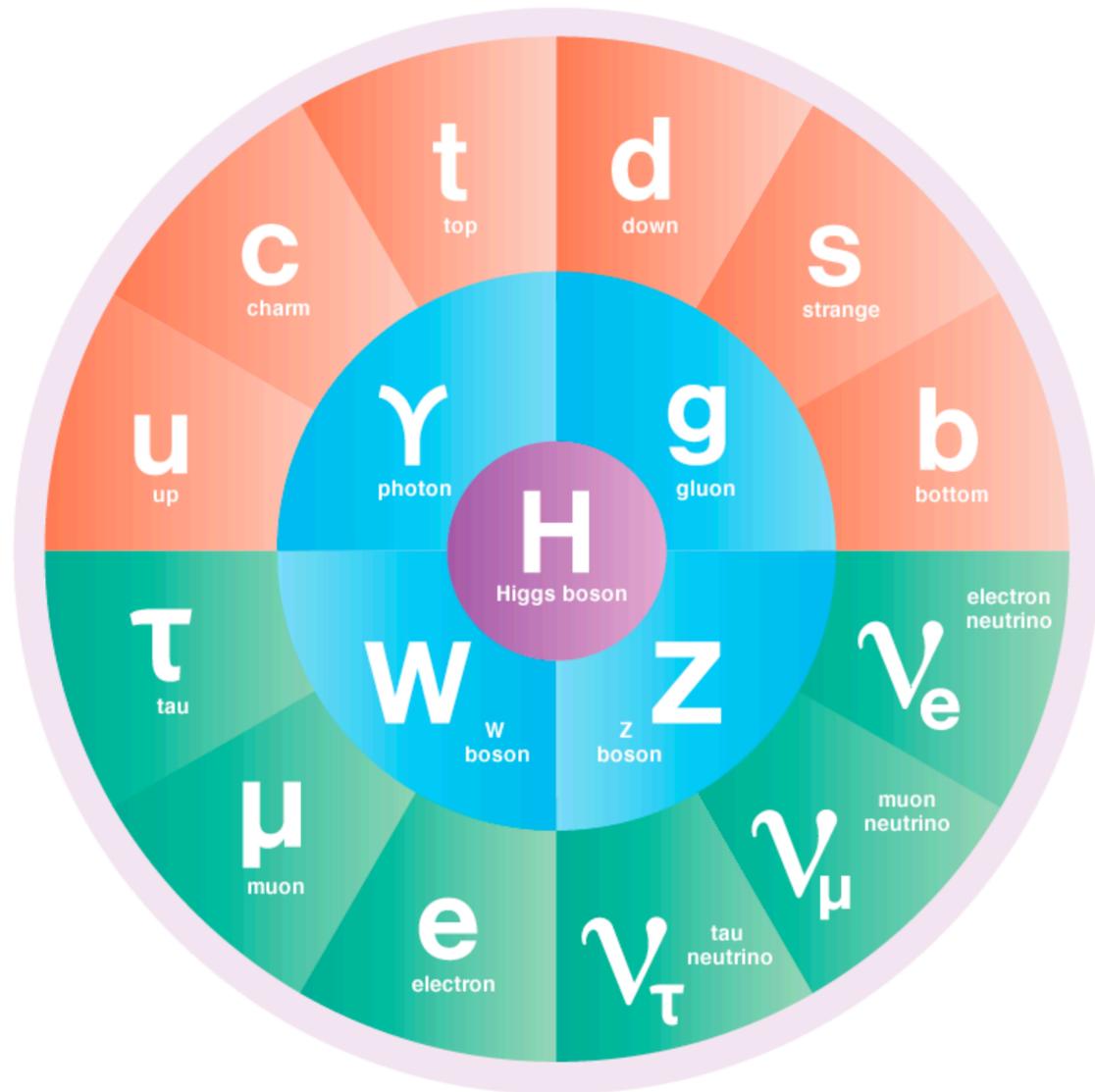
- The “Standard Model” has been completed.



- Three generations each of “up-type” quarks, “down-type” quarks, charged leptons, and neutral leptons.
- Interactions described by gauge theory of $SU(3) \times SU(2) \times U(1)$, where the Higgs boson breaks it to $SU(3) \times U(1)$.

With the Discovery of the Higgs Boson in 2012,

- The “Standard Model” has been completed.



- Three generations each of “up-type” quarks, “down-type” quarks, charged leptons, and neutral leptons.
- Interactions described by gauge theory of $SU(3) \times SU(2) \times U(1)$, where the Higgs boson breaks it to $SU(3) \times U(1)$.
- 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.**

Completing the Standard Model was a HUGE triumph.

However, there are some problems...

Three Current Challenges (if time allows)

Three Current Challenges (if time allows)

- Dark Matter & Dark Energy

Three Current Challenges (if time allows)

- Dark Matter & Dark Energy
- Neutrino Oscillations and Neutrino Masses

Three Current Challenges (if time allows)

- Dark Matter & Dark Energy
- Neutrino Oscillations and Neutrino Masses
- The Higgs Hierarchy Problem

Dark Matter & Dark Energy

TUESDAY, 2 JUNE



12:00 PM

→ 1:00 PM

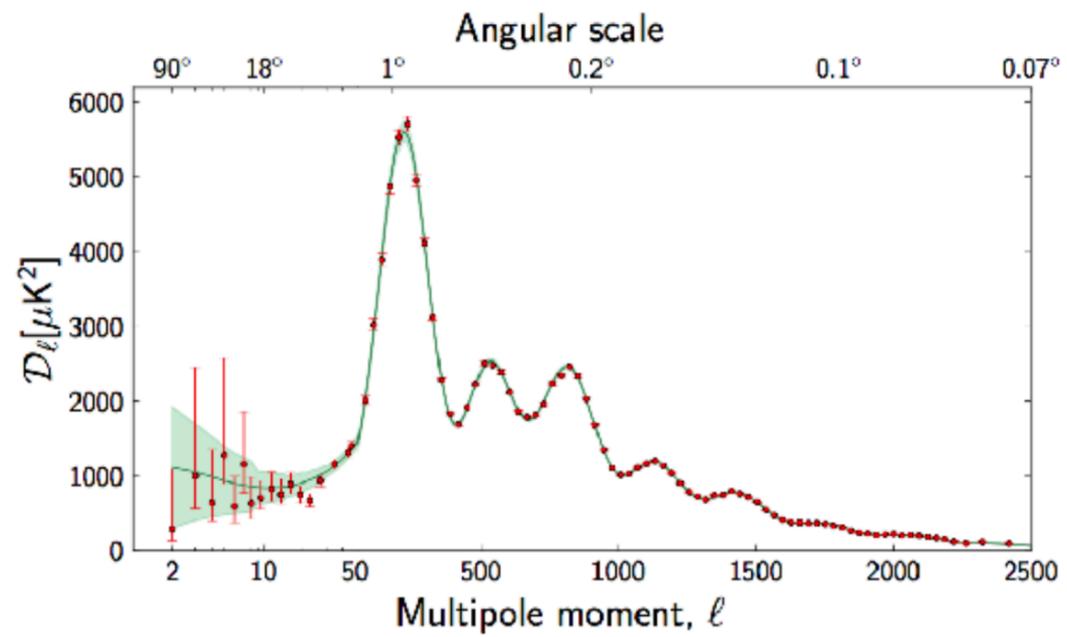
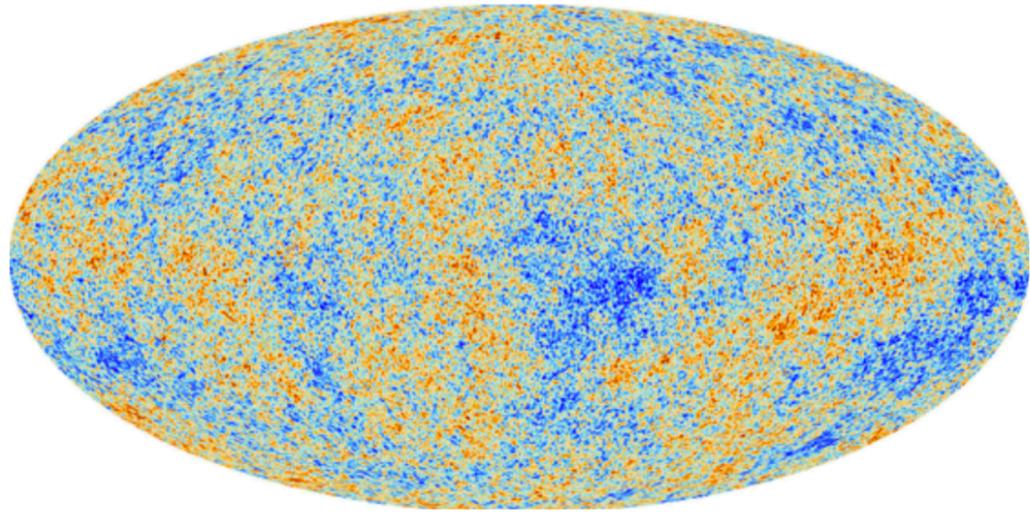
Cosmology: Dark Matter and Dark Energy ↑

🕒 1h

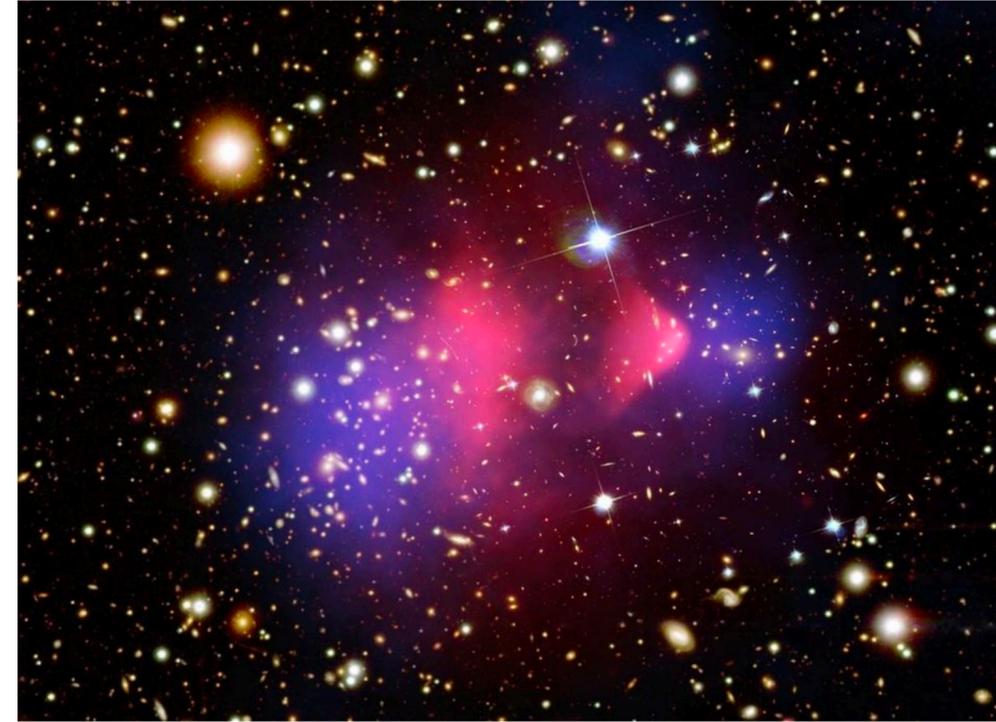
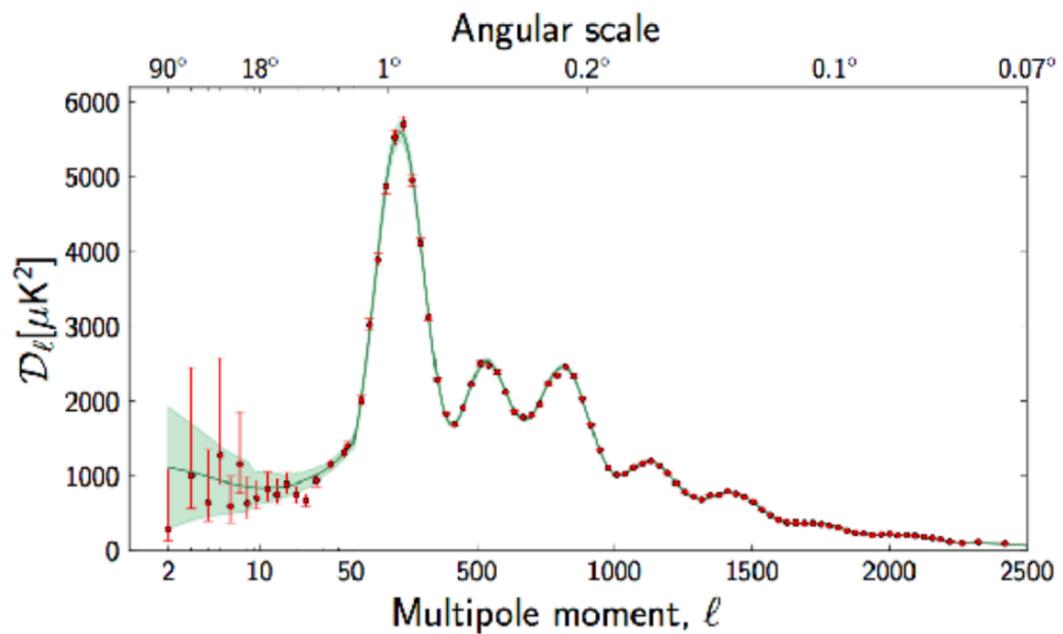
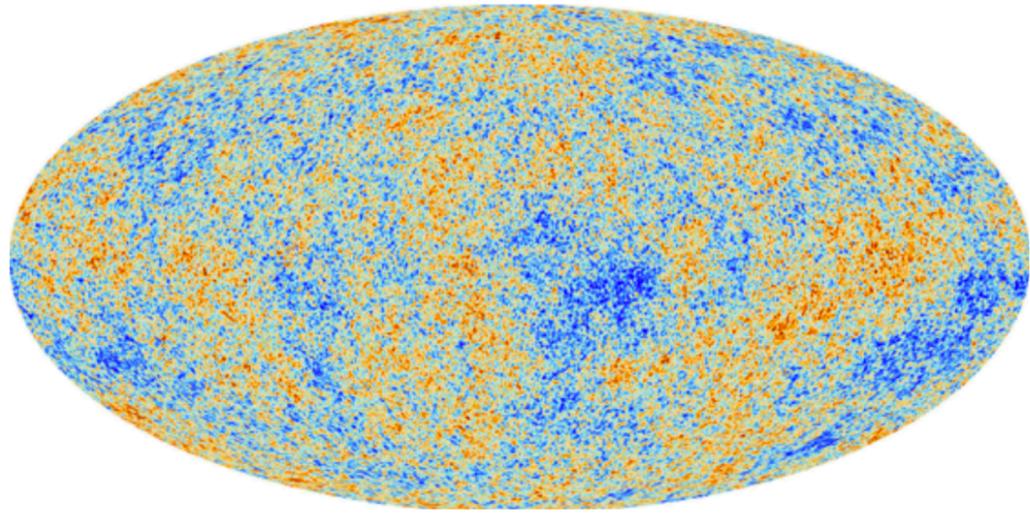
Speaker: Dan Hooper (Fermilab)

Overwhelming Evidence for Dark Matter over Many Scales

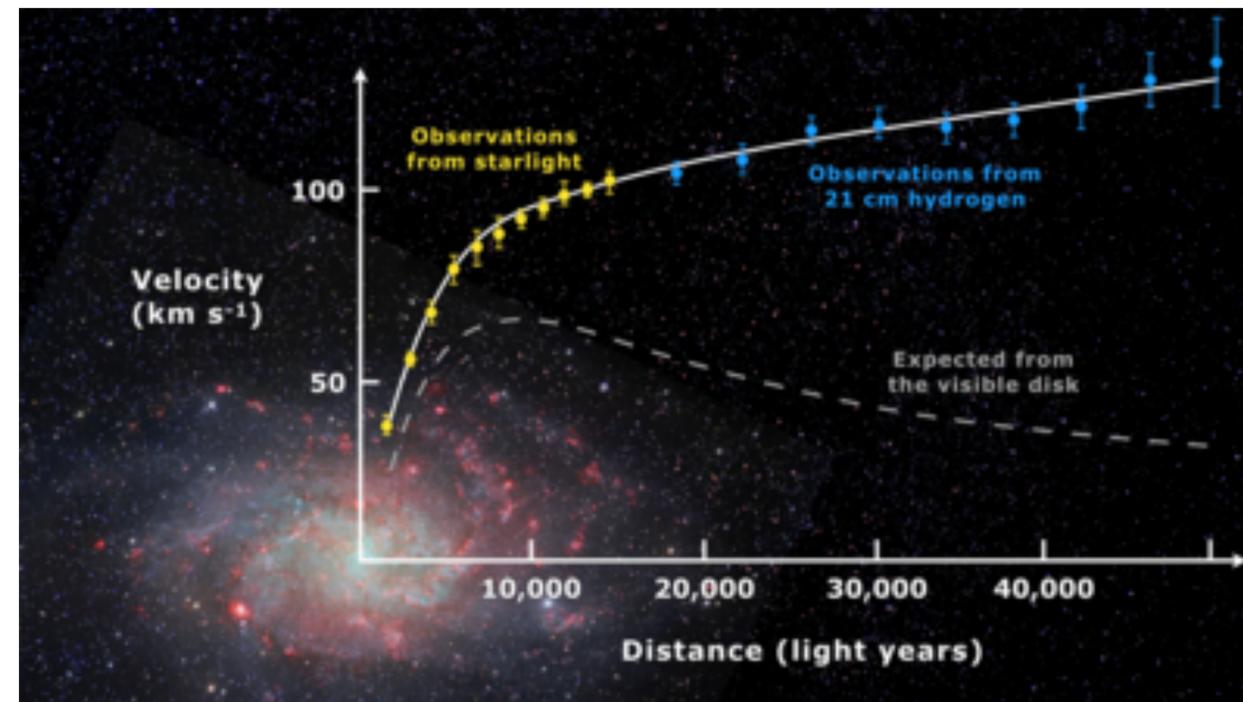
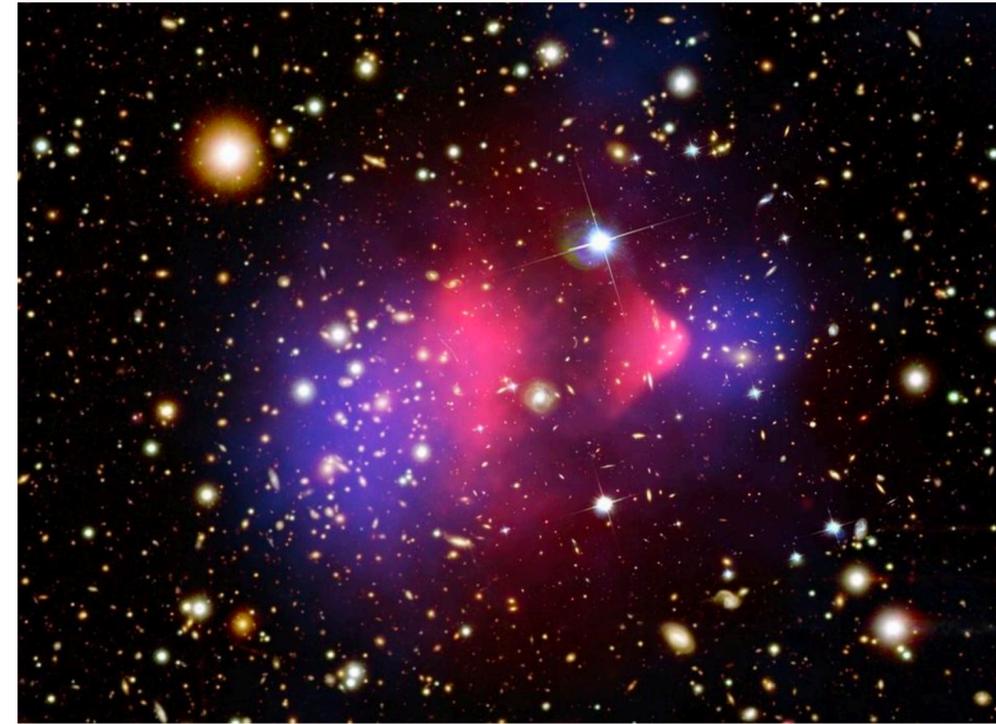
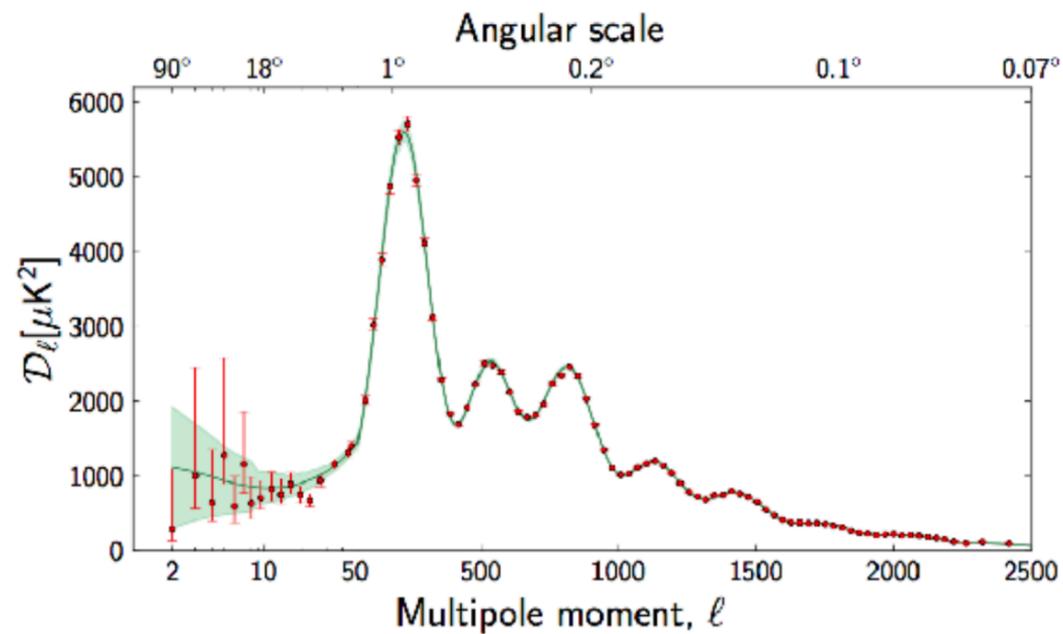
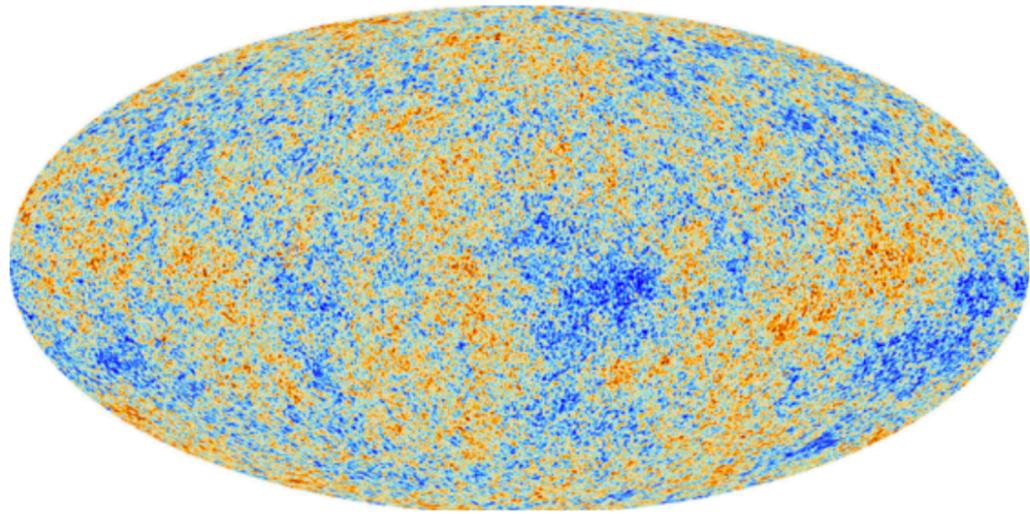
Overwhelming Evidence for Dark Matter over Many Scales



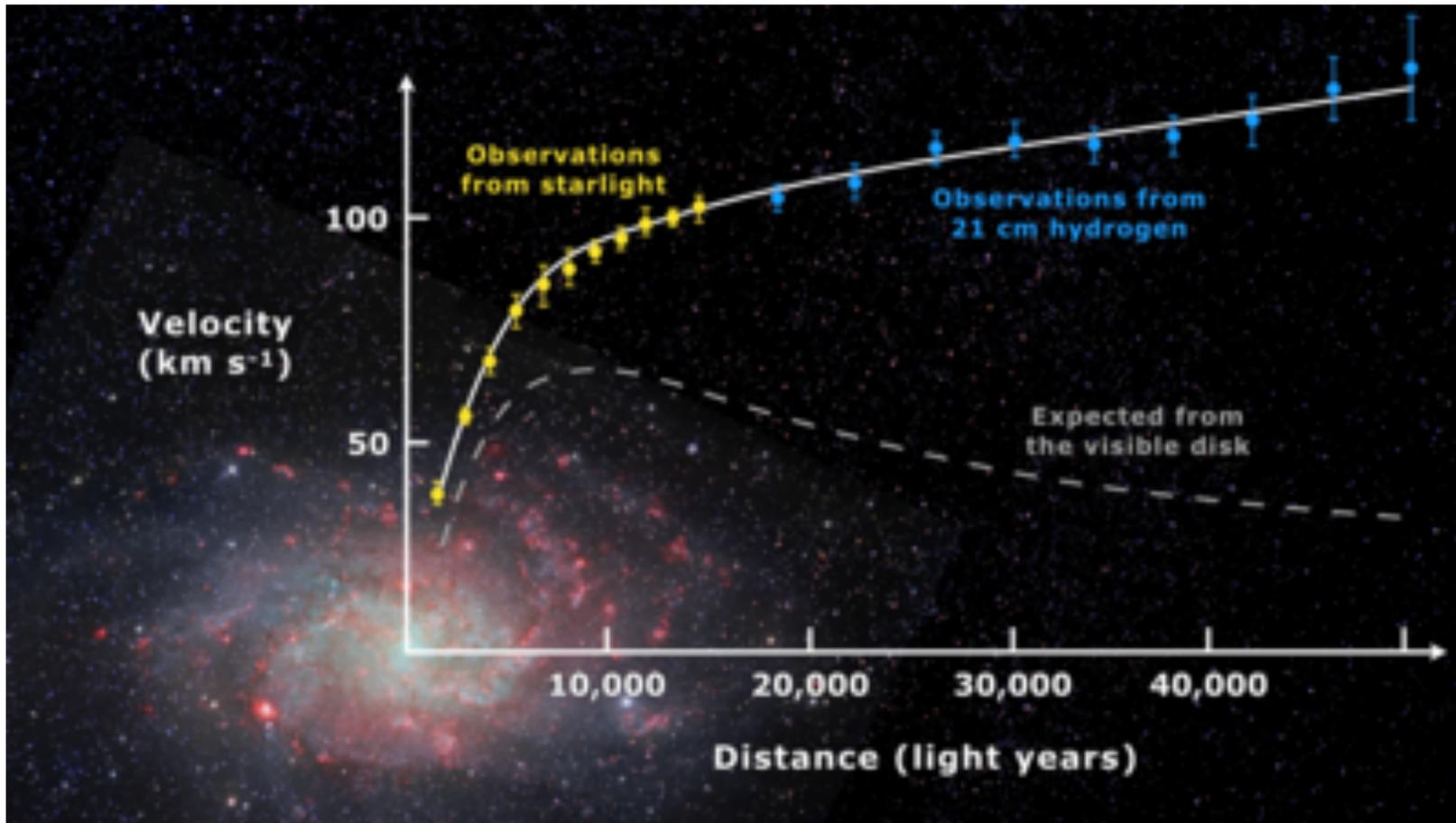
Overwhelming Evidence for Dark Matter over Many Scales



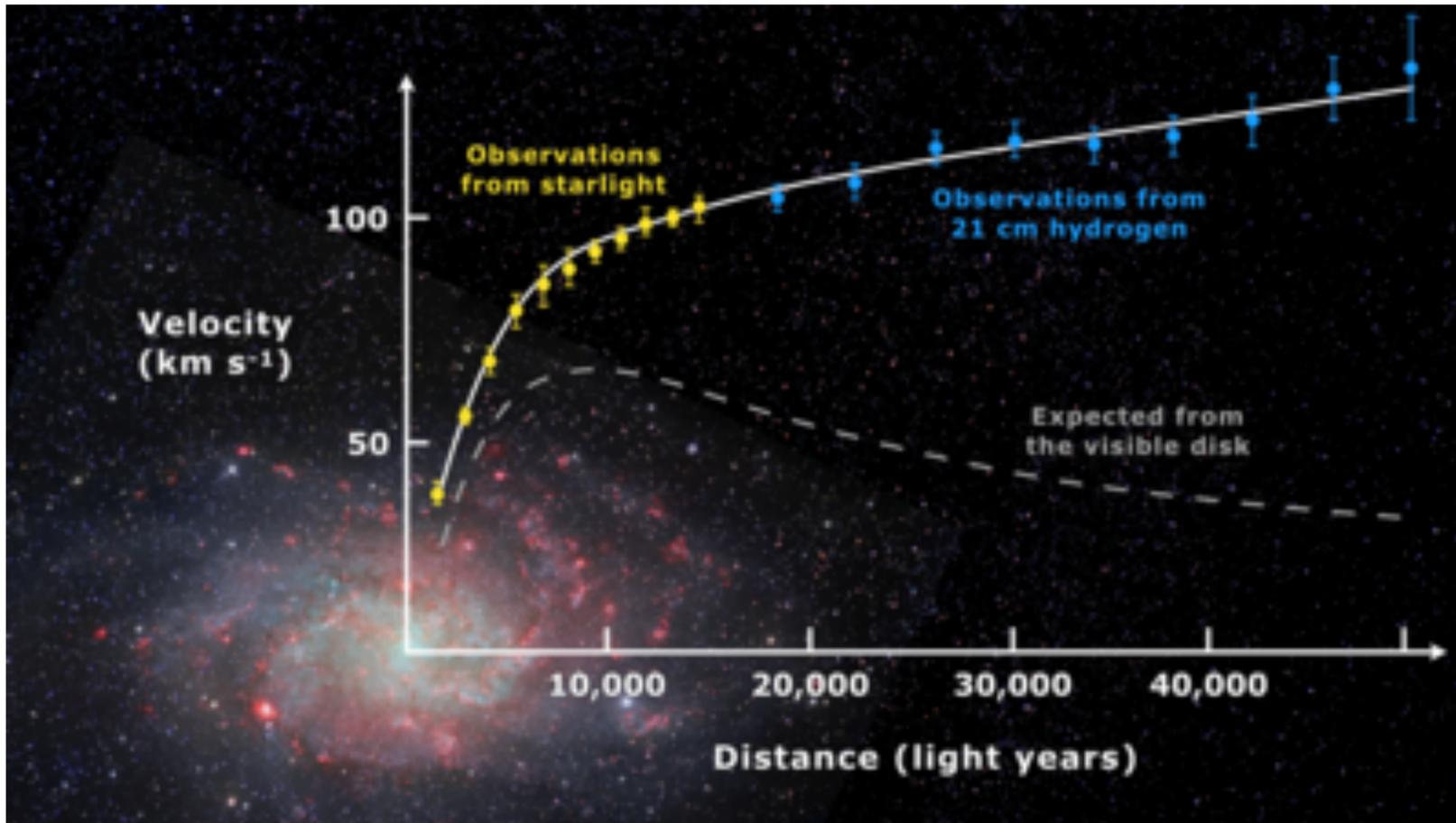
Overwhelming Evidence for Dark Matter over Many Scales



Overwhelming Evidence for Dark Matter over Many Scales



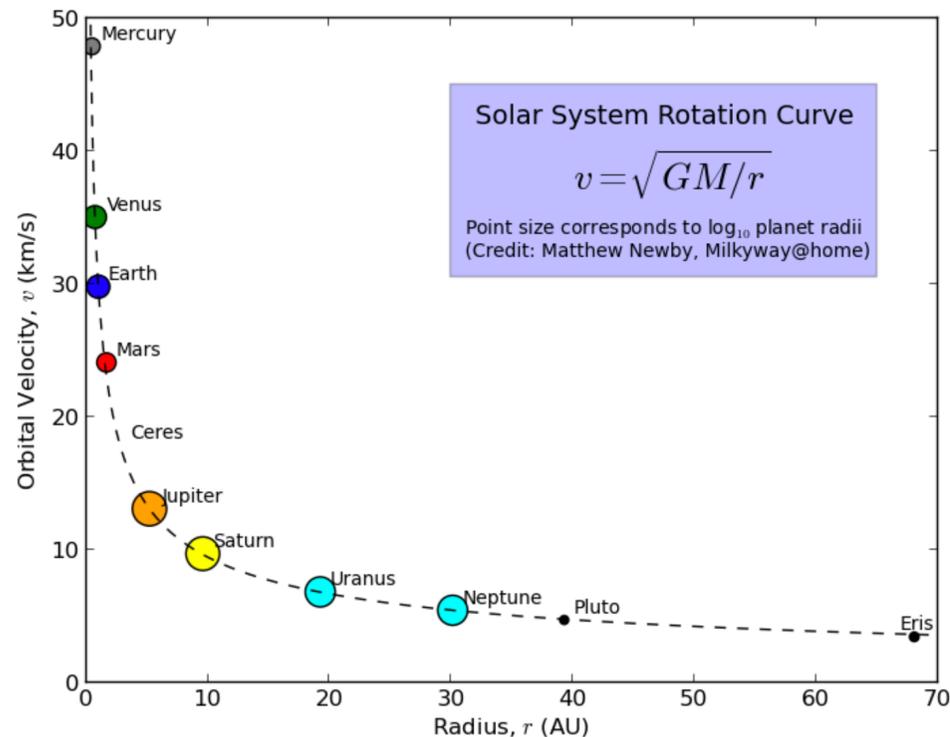
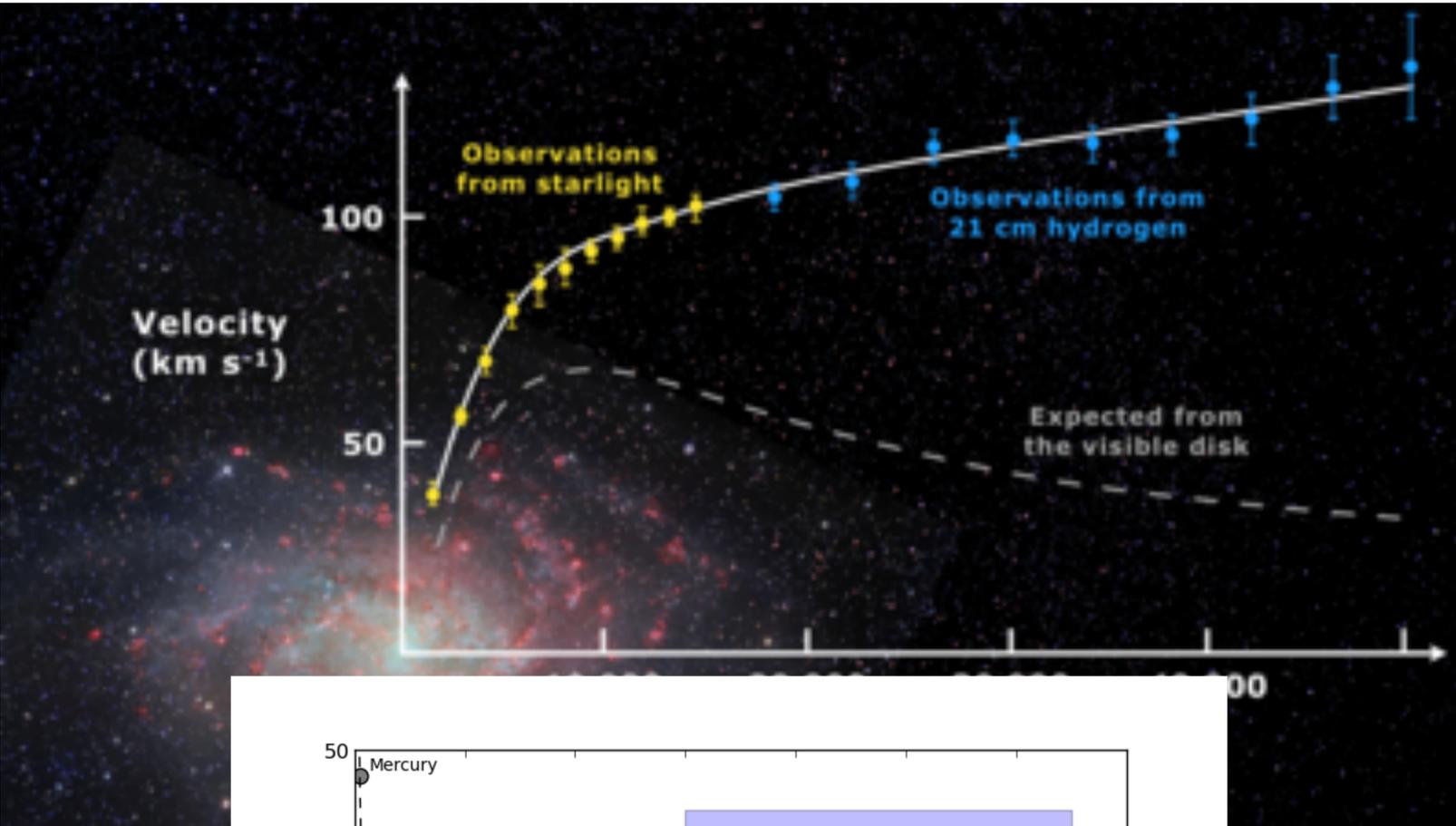
Overwhelming Evidence for Dark Matter over Many Scales



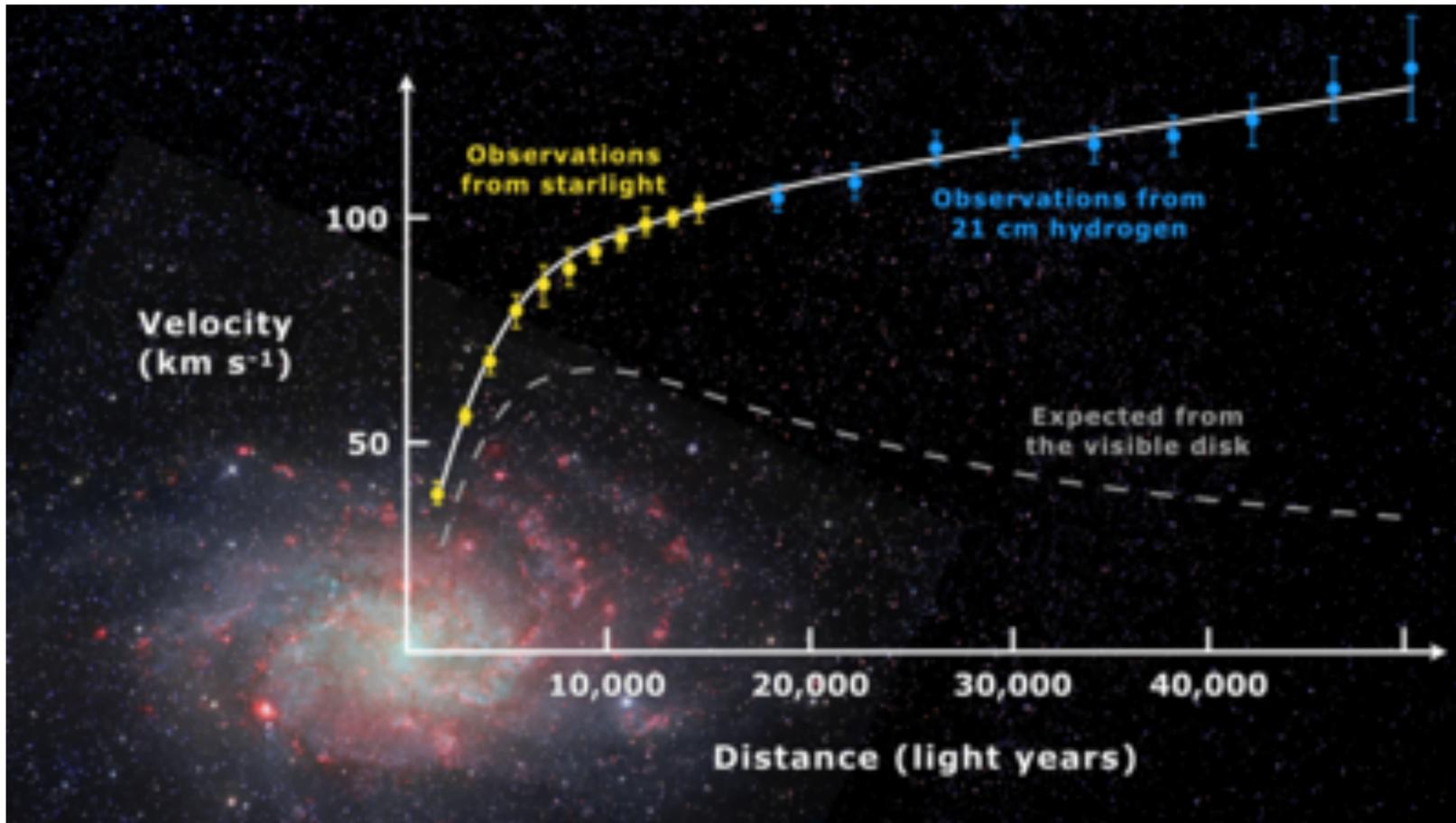
- Galactic rotation curves: one of the first pieces of evidence for dark matter.

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.

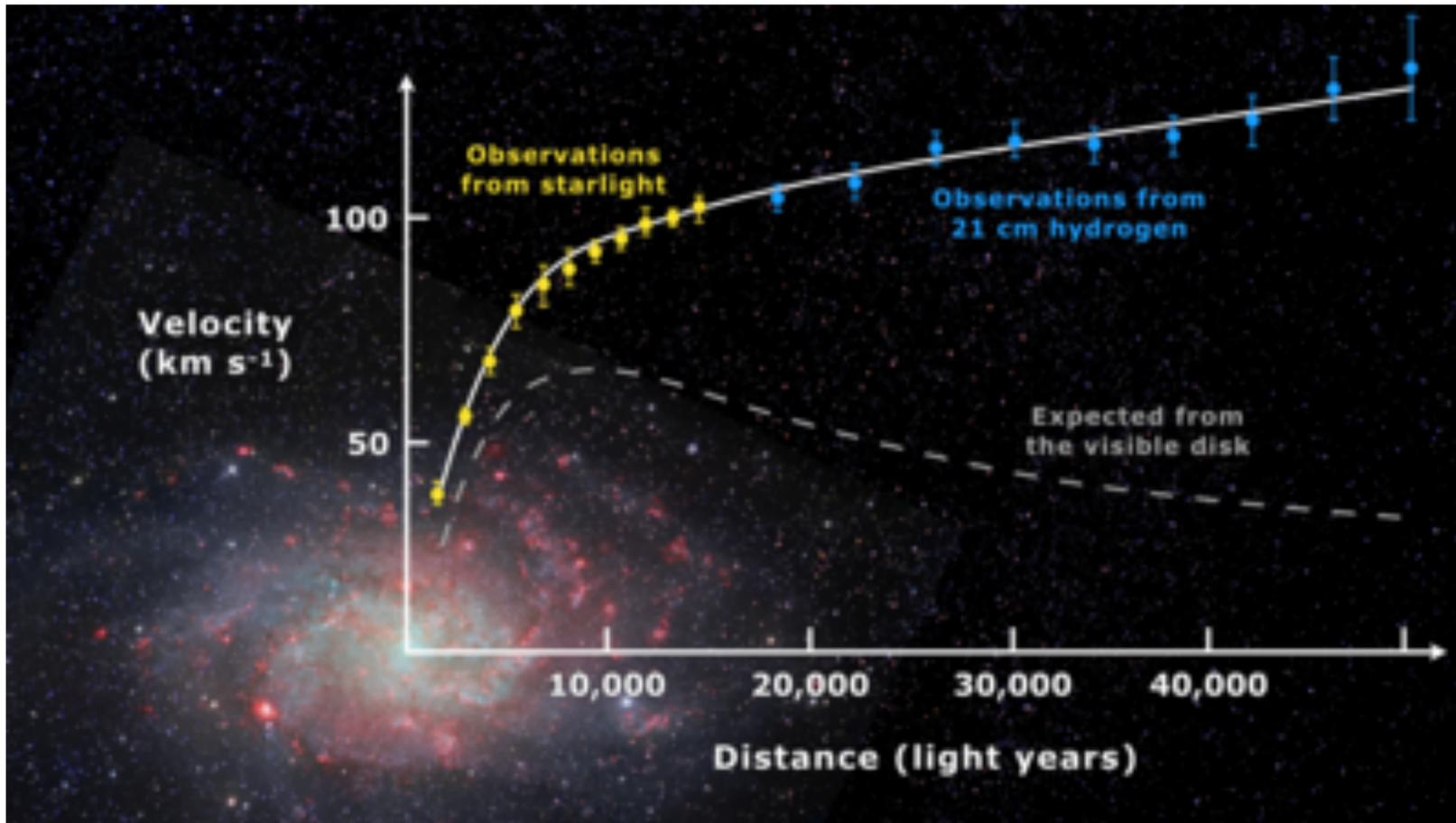


Overwhelming Evidence for Dark Matter over Many Scales



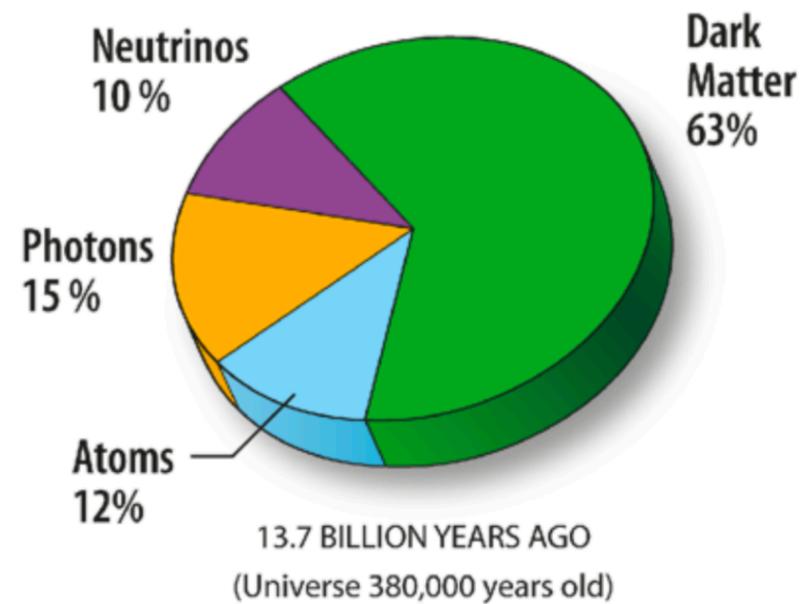
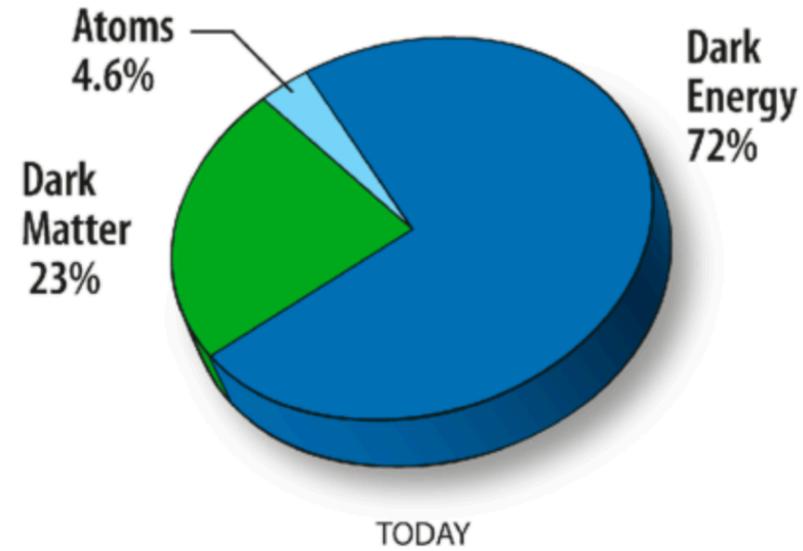
- Galactic rotation curves: one of the first pieces of evidence for dark matter.
- Using Newtonian physics/Kepler's laws, we can calculate what the rotational velocity of a star orbiting the center of its galaxy should be.
- Looking out at distant galaxies and their outermost stars, they seem to be going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

Overwhelming Evidence for Dark Matter over Many Scales



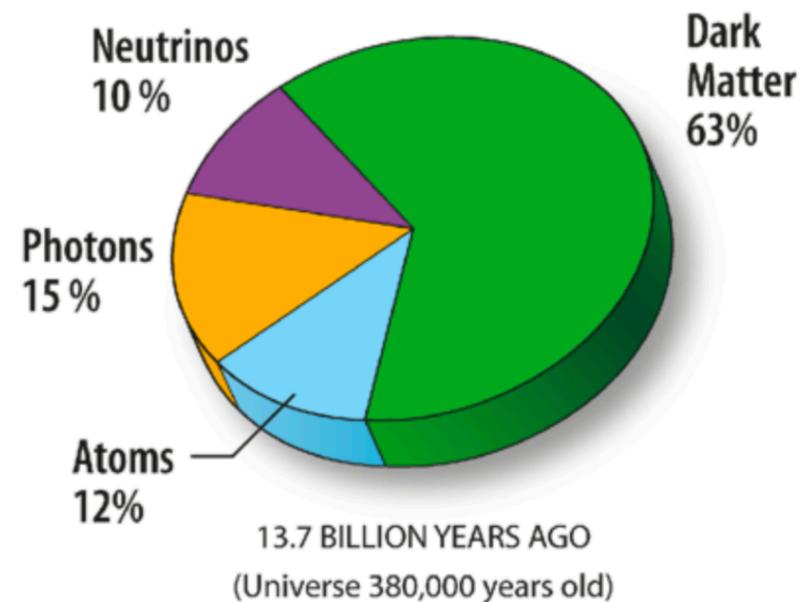
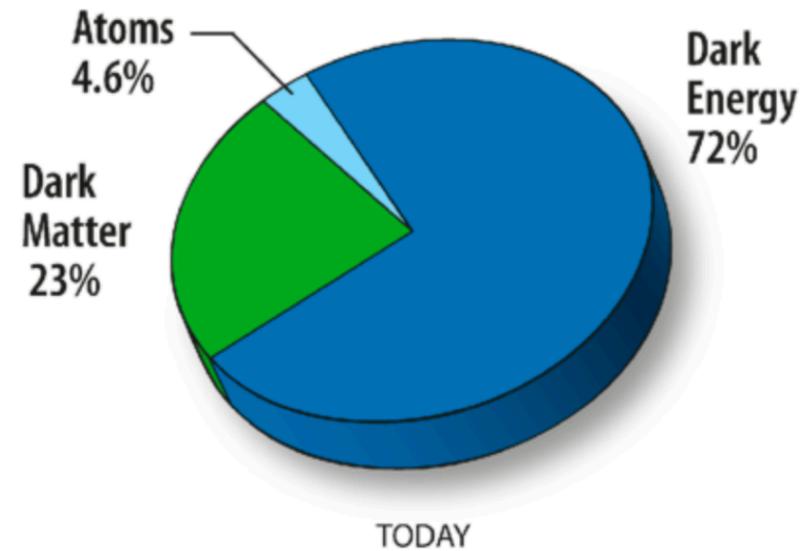
- Galactic rotation curves: one of the first pieces of evidence for dark matter.
- Using Newtonian physics/Kepler's laws, we can calculate what the rotational velocity of a star orbiting the center of its galaxy should be.
- Looking out at distant galaxies and their outermost stars, they seem to be going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

To the best of our knowledge from these observations,



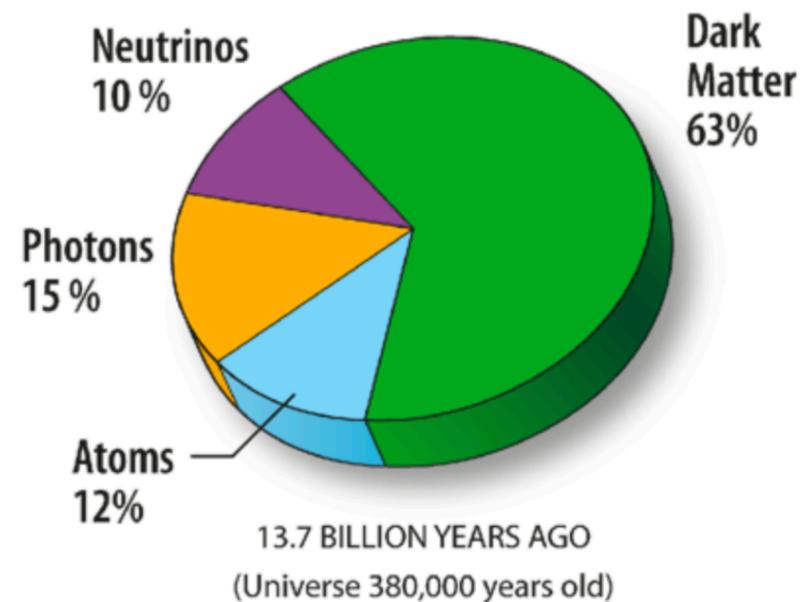
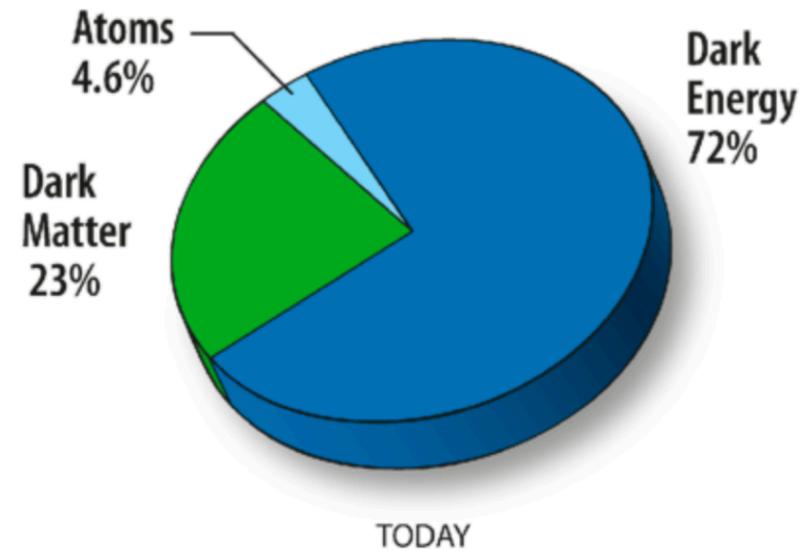
To the best of our knowledge from these observations,

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

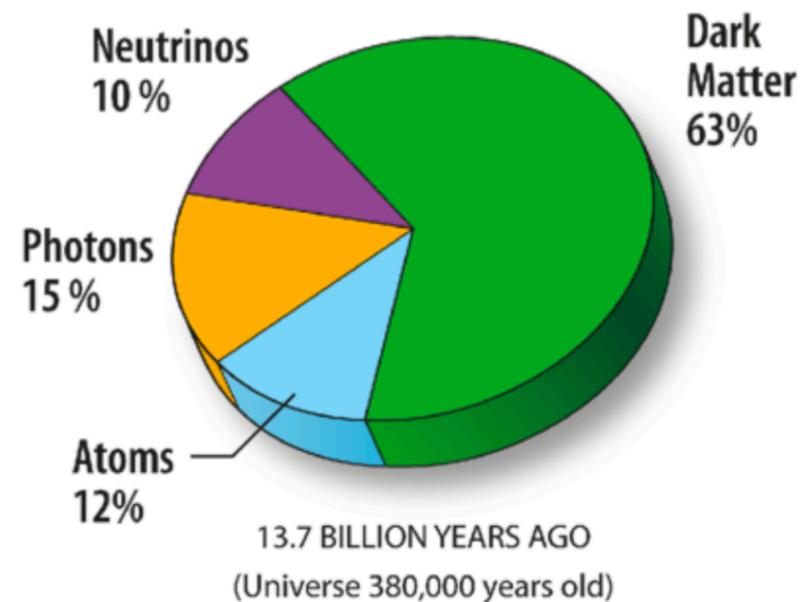
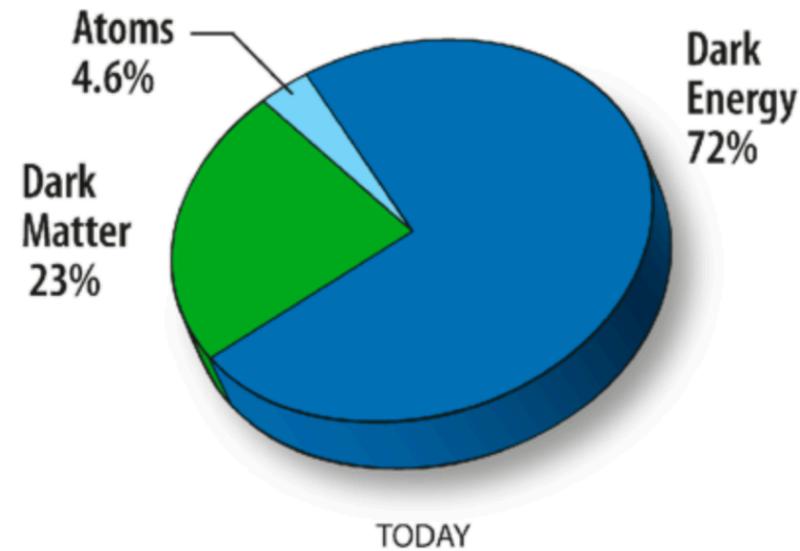


To the best of our knowledge from these observations,

- 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”.

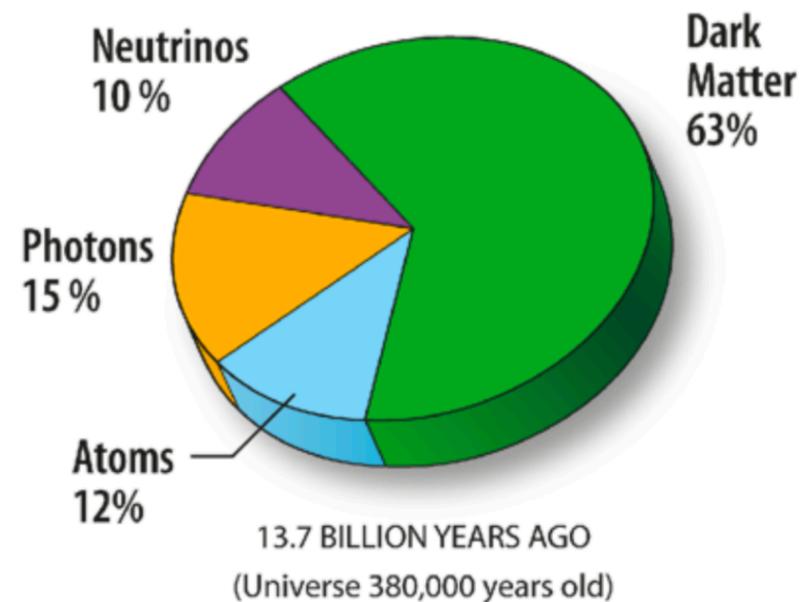
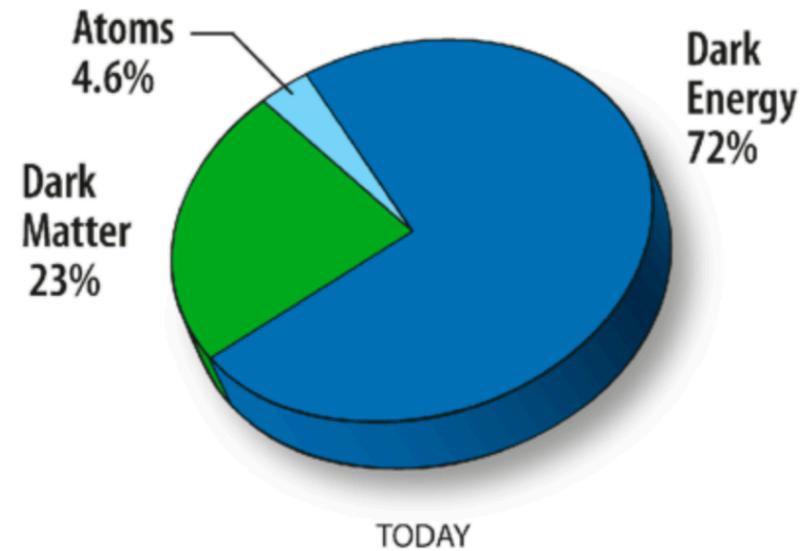


To the best of our knowledge from these observations,



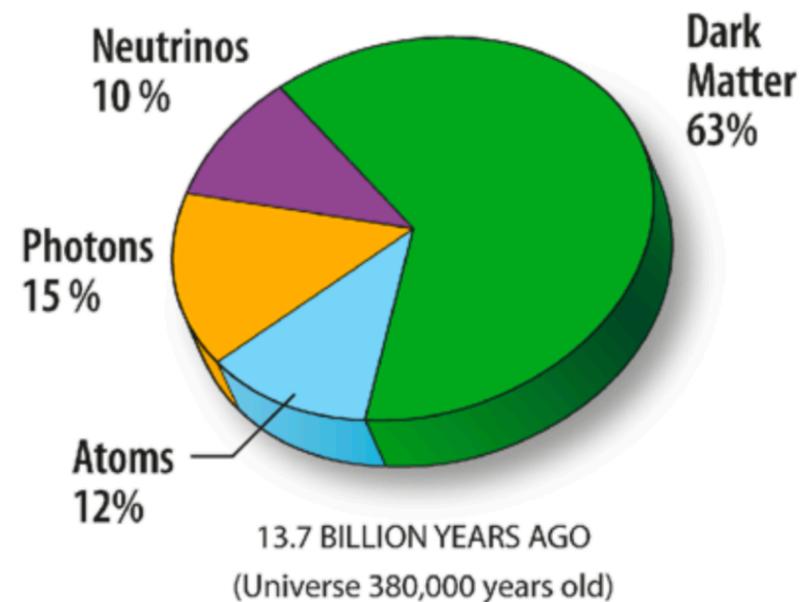
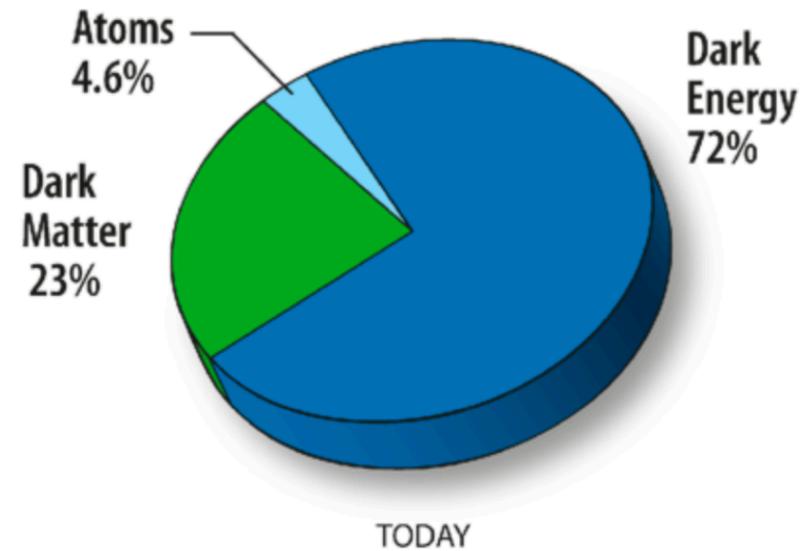
- The particles we have identified in the Standard Model make up a small fraction of all of the observed “energy density” of the universe.
- The majority of this energy density (today) is made up of what we call “dark energy”.
- A component even bigger than SM particles is “dark matter”.

To the best of our knowledge from these observations,



- 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”.
- A component even bigger than SM particles is “dark matter”.
- Many, many ideas exist to explain both of these issues, but the Standard Model, as formulated, has nothing to say on them.

To the best of our knowledge from these observations,



- 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”.
- A component even bigger than SM particles is “dark matter”.
- Many, many ideas exist to explain both of these issues, but the Standard Model, as formulated, has nothing to say on them.
- 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)

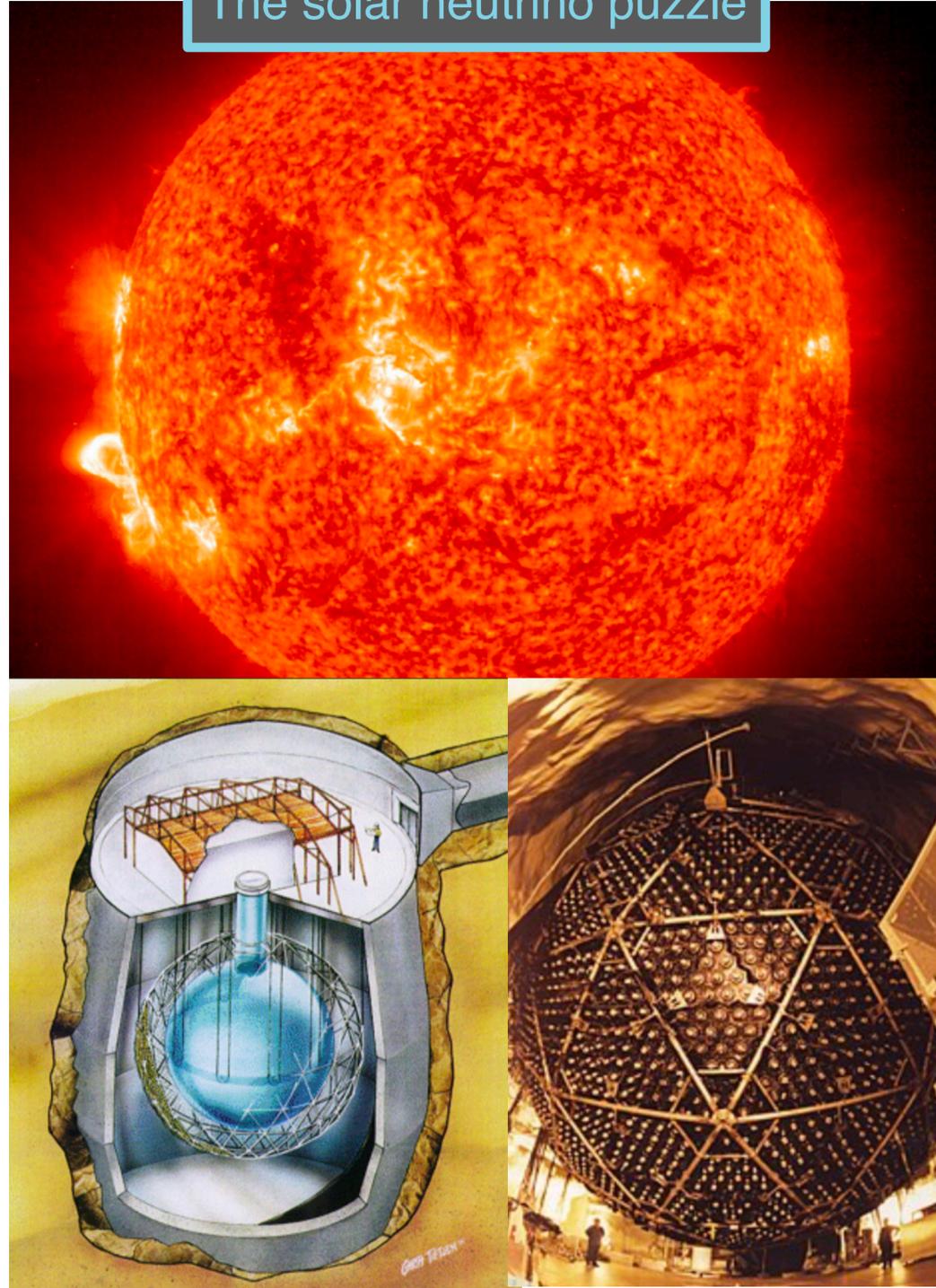
Over several decades, evidence mounted...

The solar neutrino puzzle



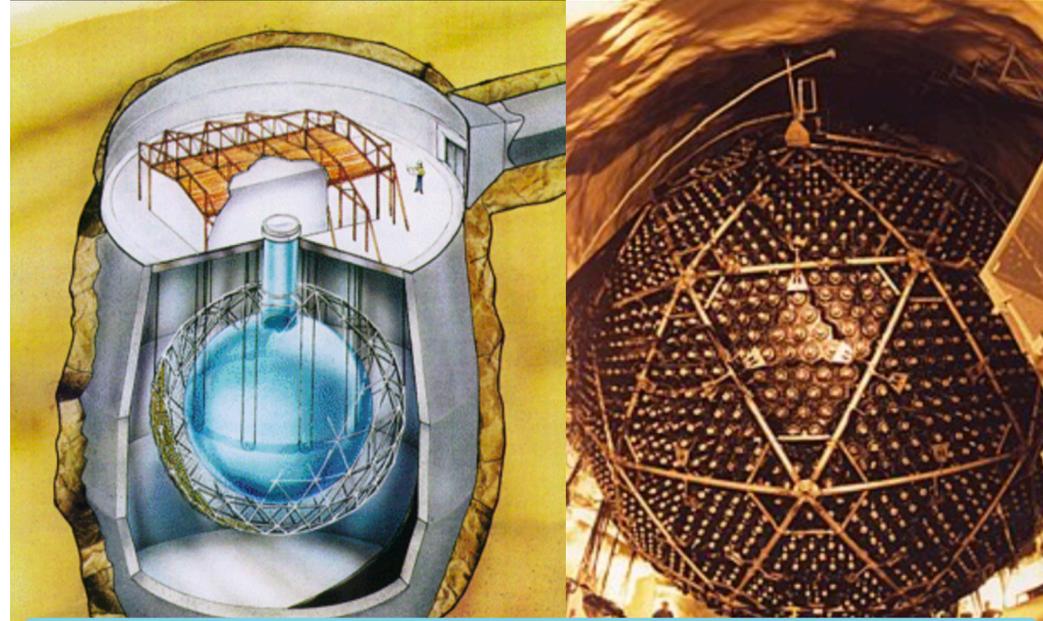
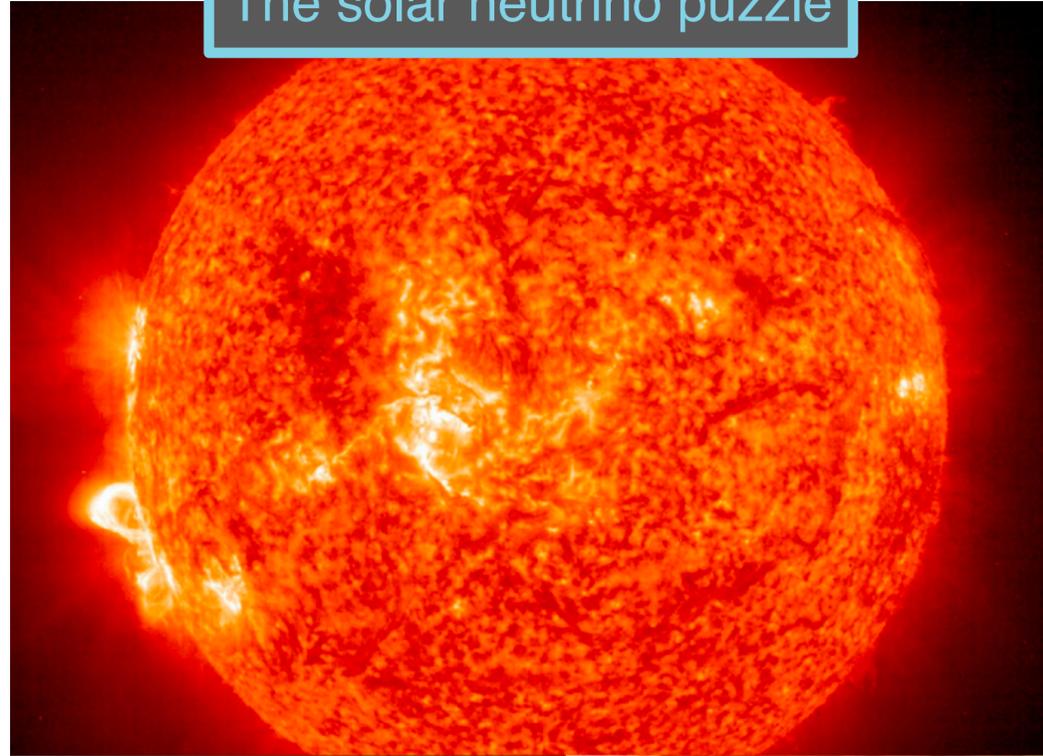
Over several decades, evidence mounted...

The solar neutrino puzzle



Over several decades, evidence mounted...

The solar neutrino puzzle

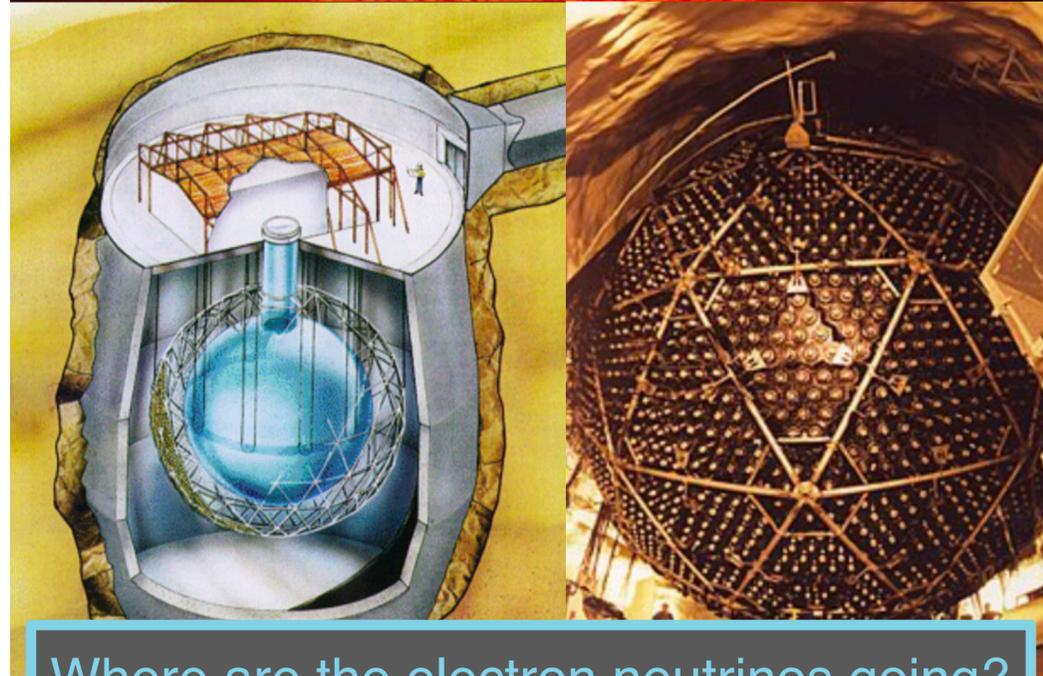
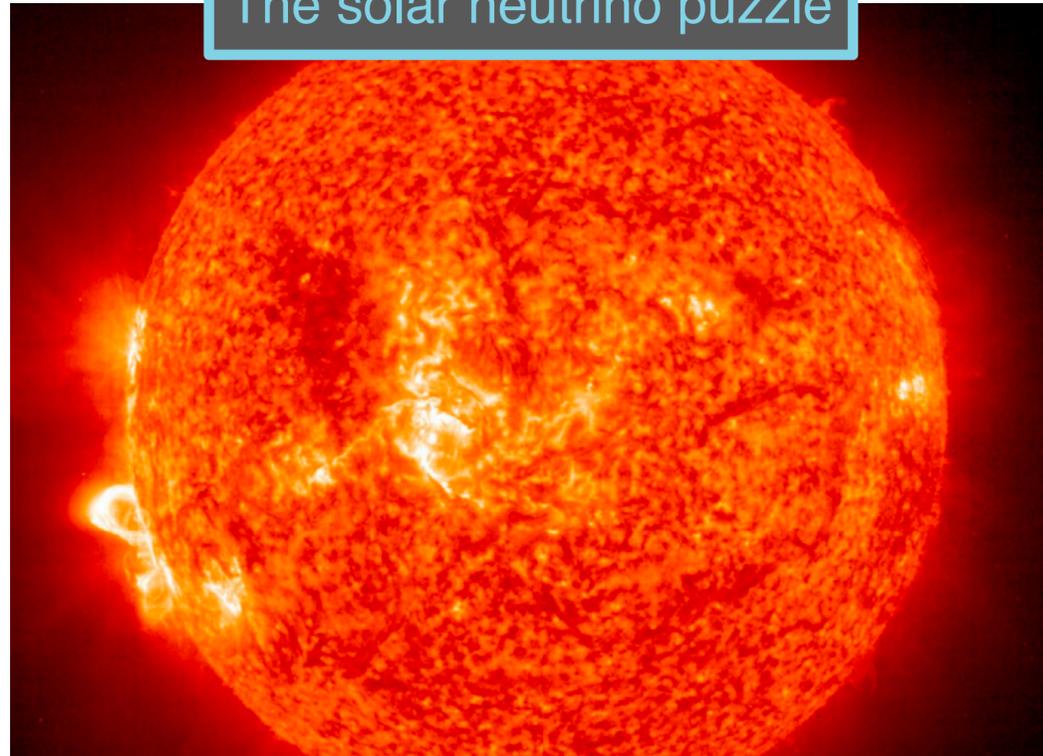


Where are the electron neutrinos going?



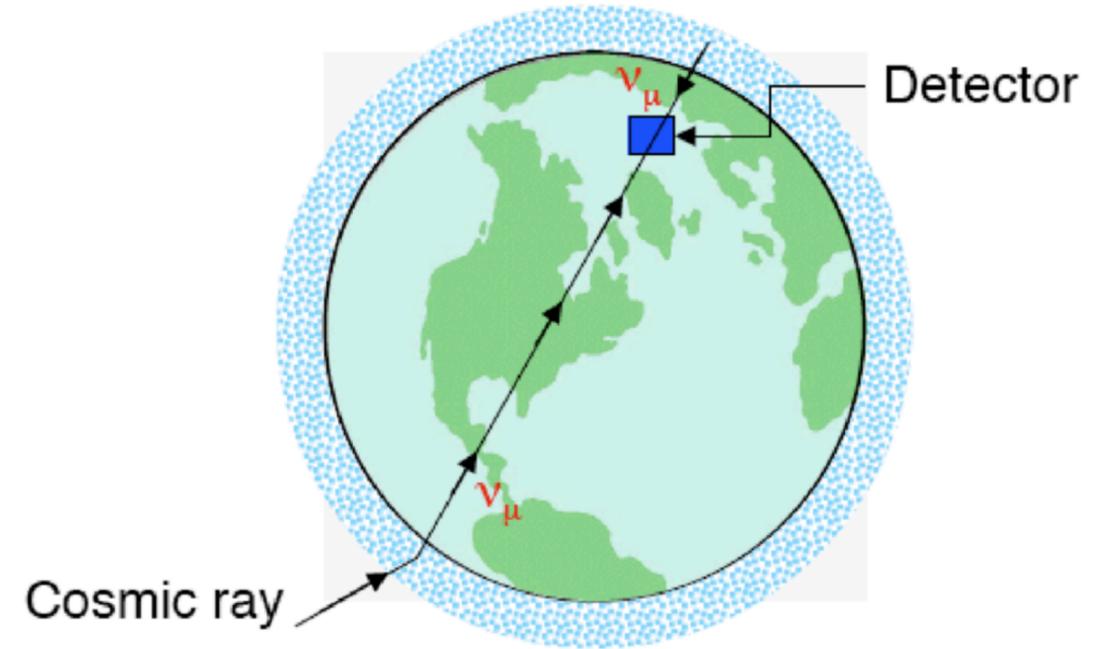
Over several decades, evidence mounted...

The solar neutrino puzzle



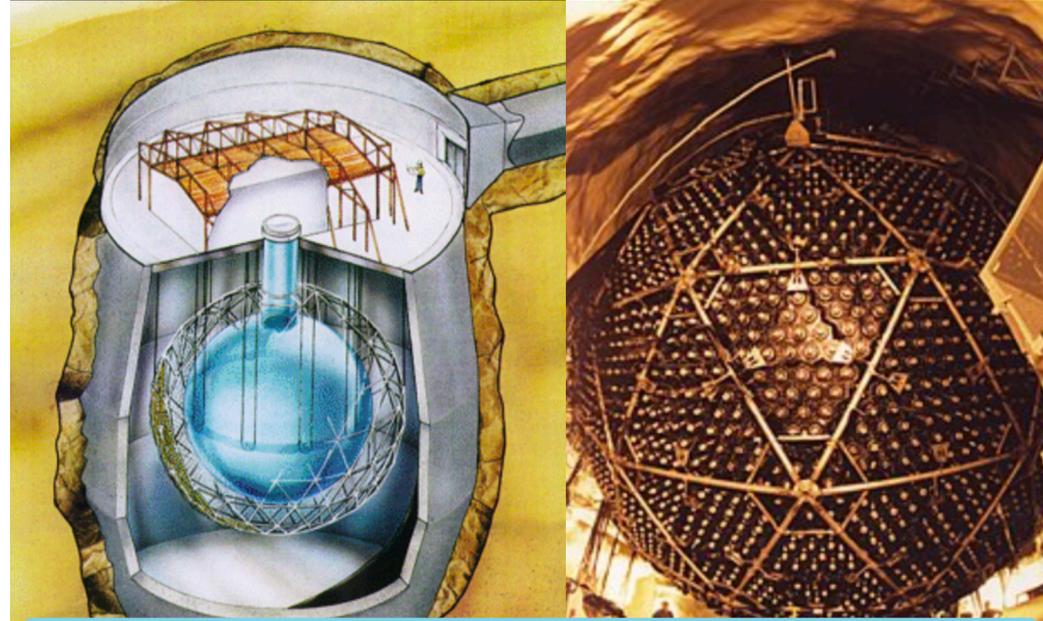
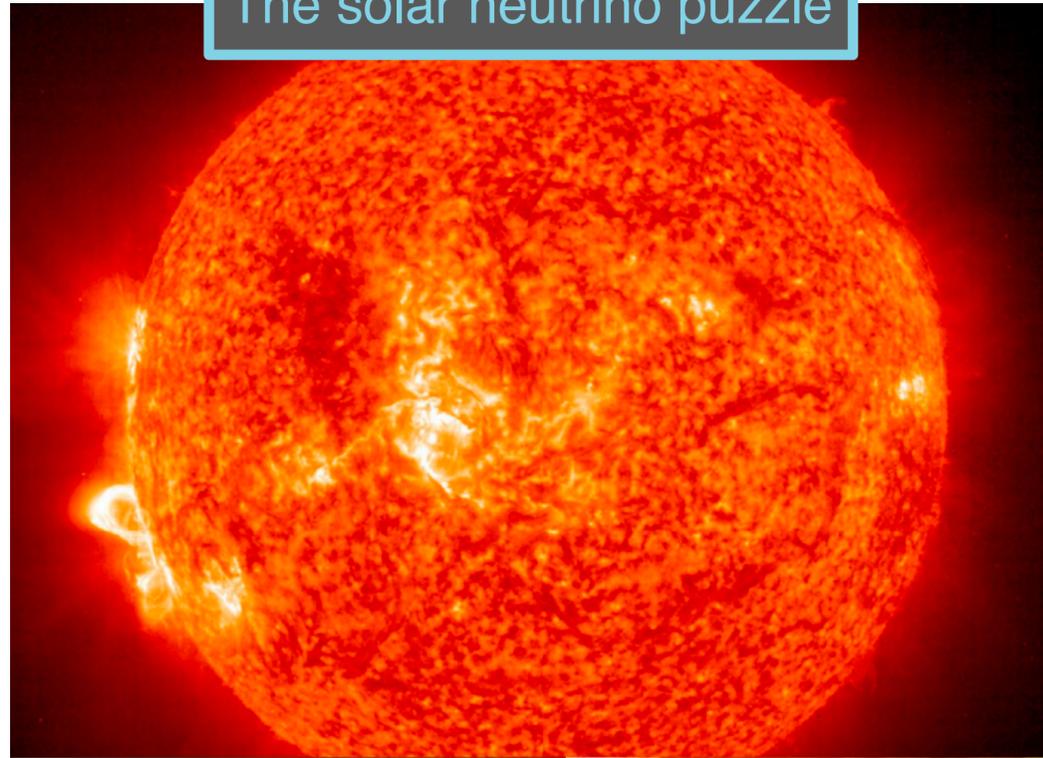
Where are the electron neutrinos going?

The atmospheric neutrino puzzle



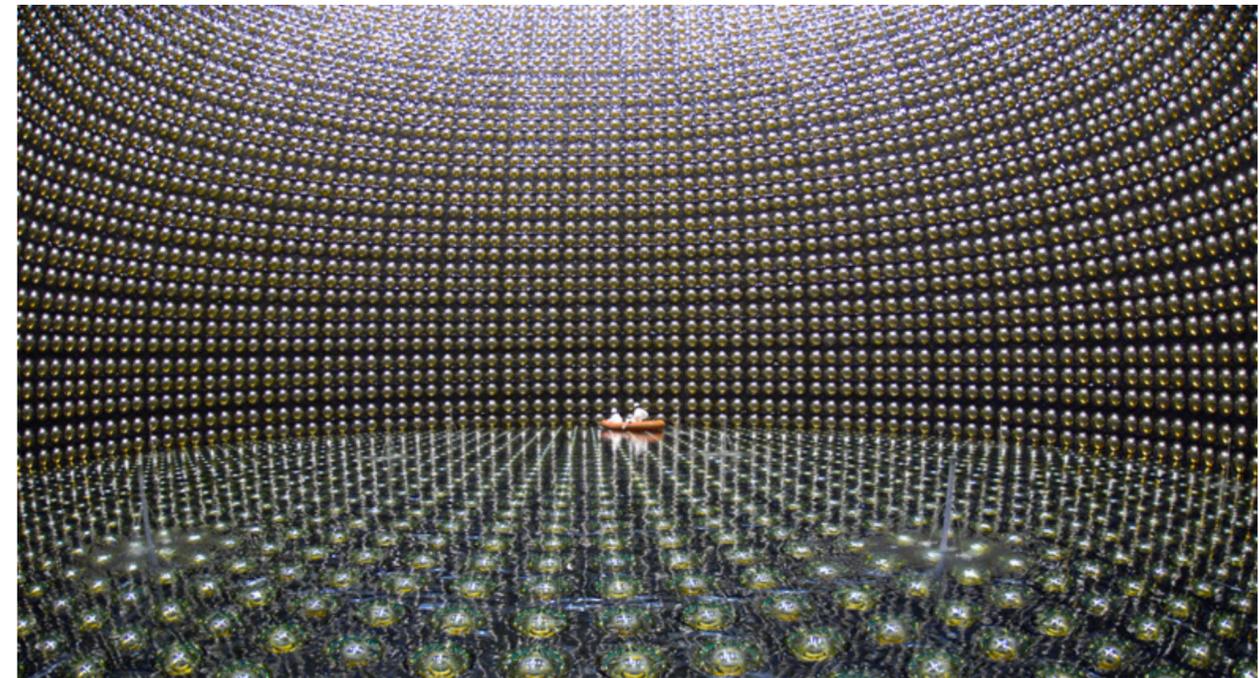
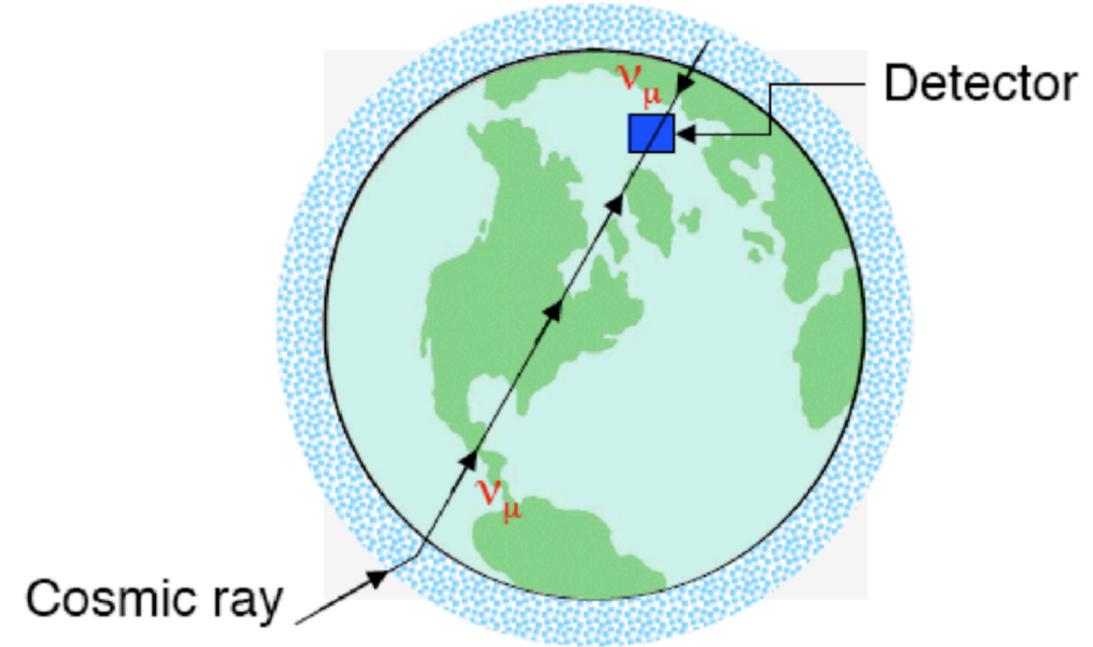
Over several decades, evidence mounted...

The solar neutrino puzzle



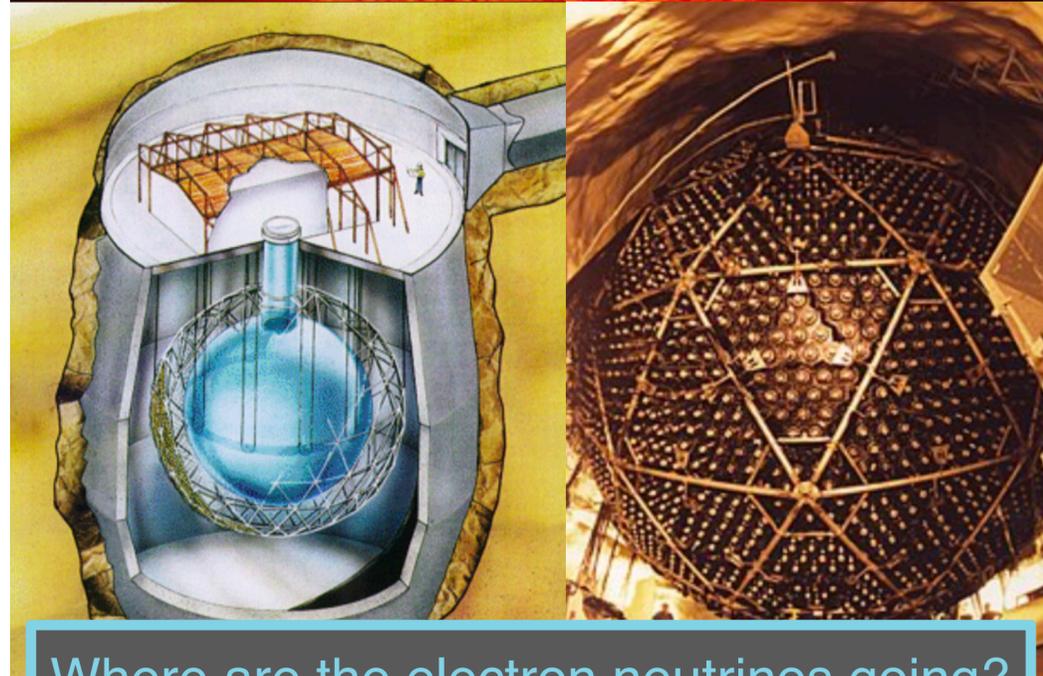
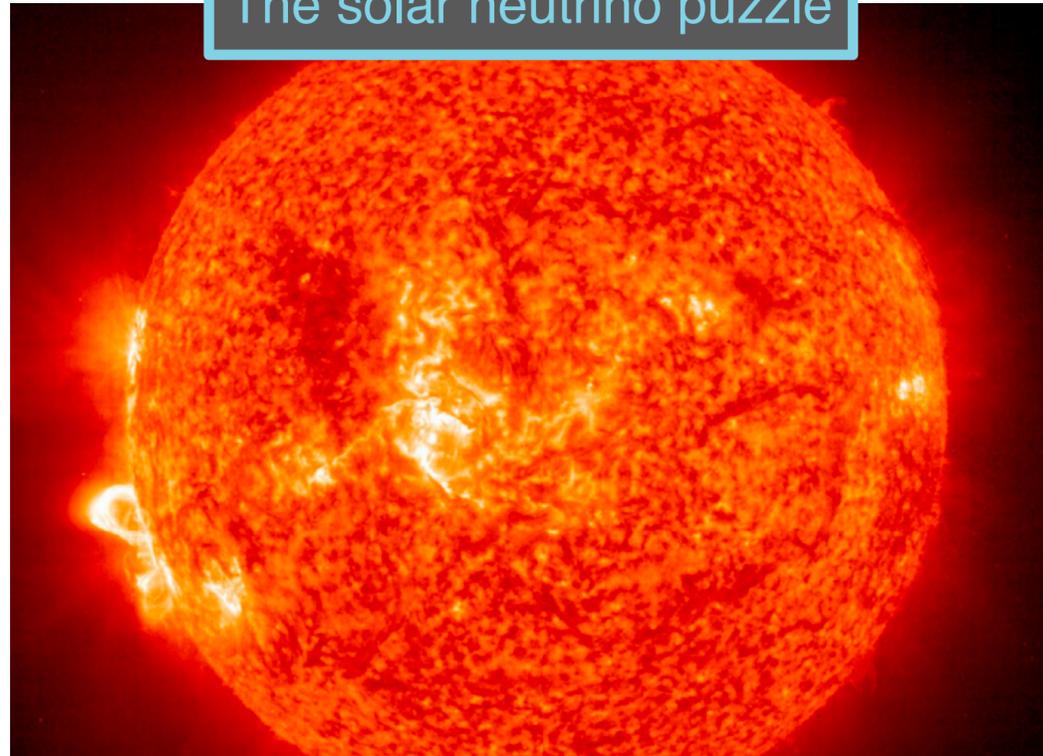
Where are the electron neutrinos going?

The atmospheric neutrino puzzle



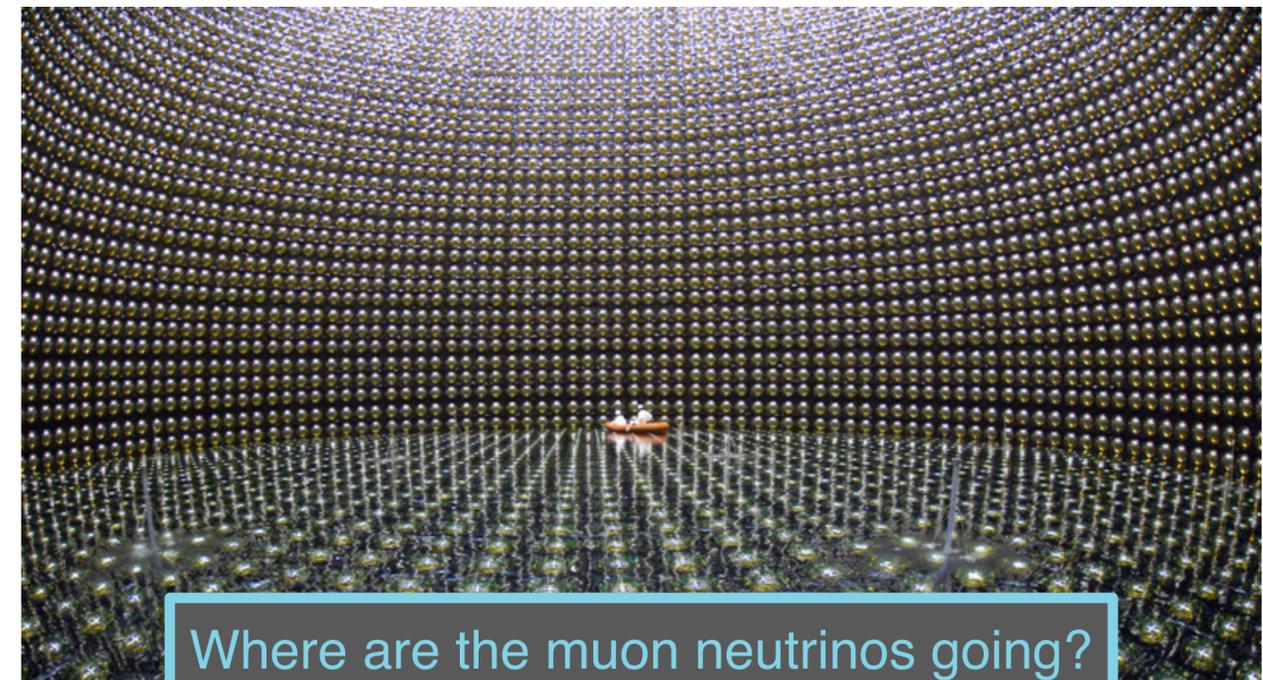
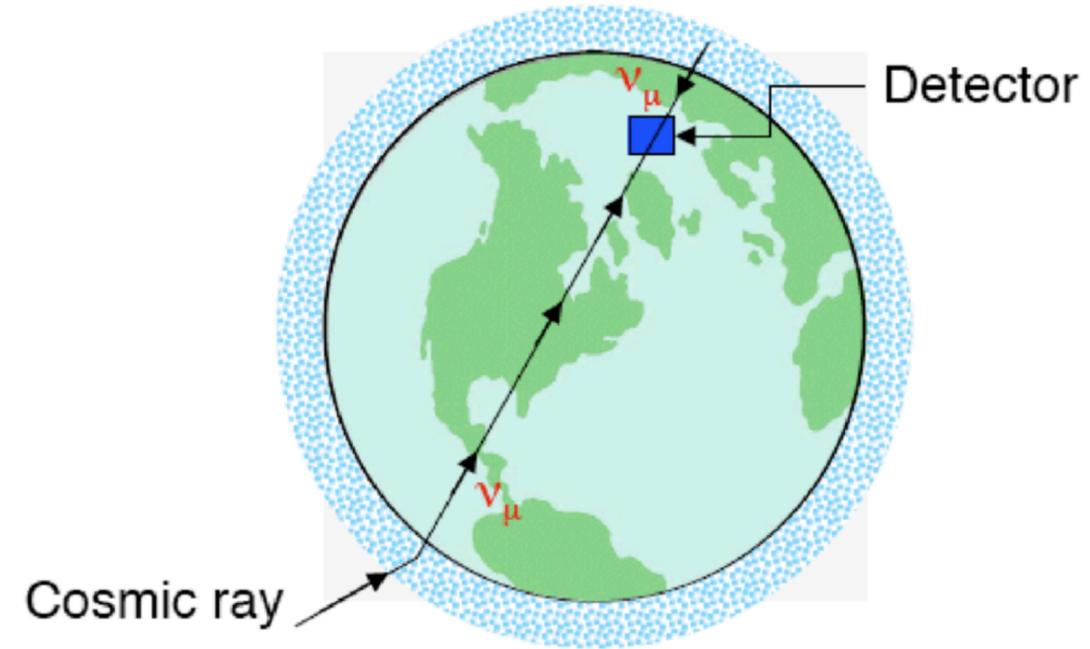
Over several decades, evidence mounted...

The solar neutrino puzzle



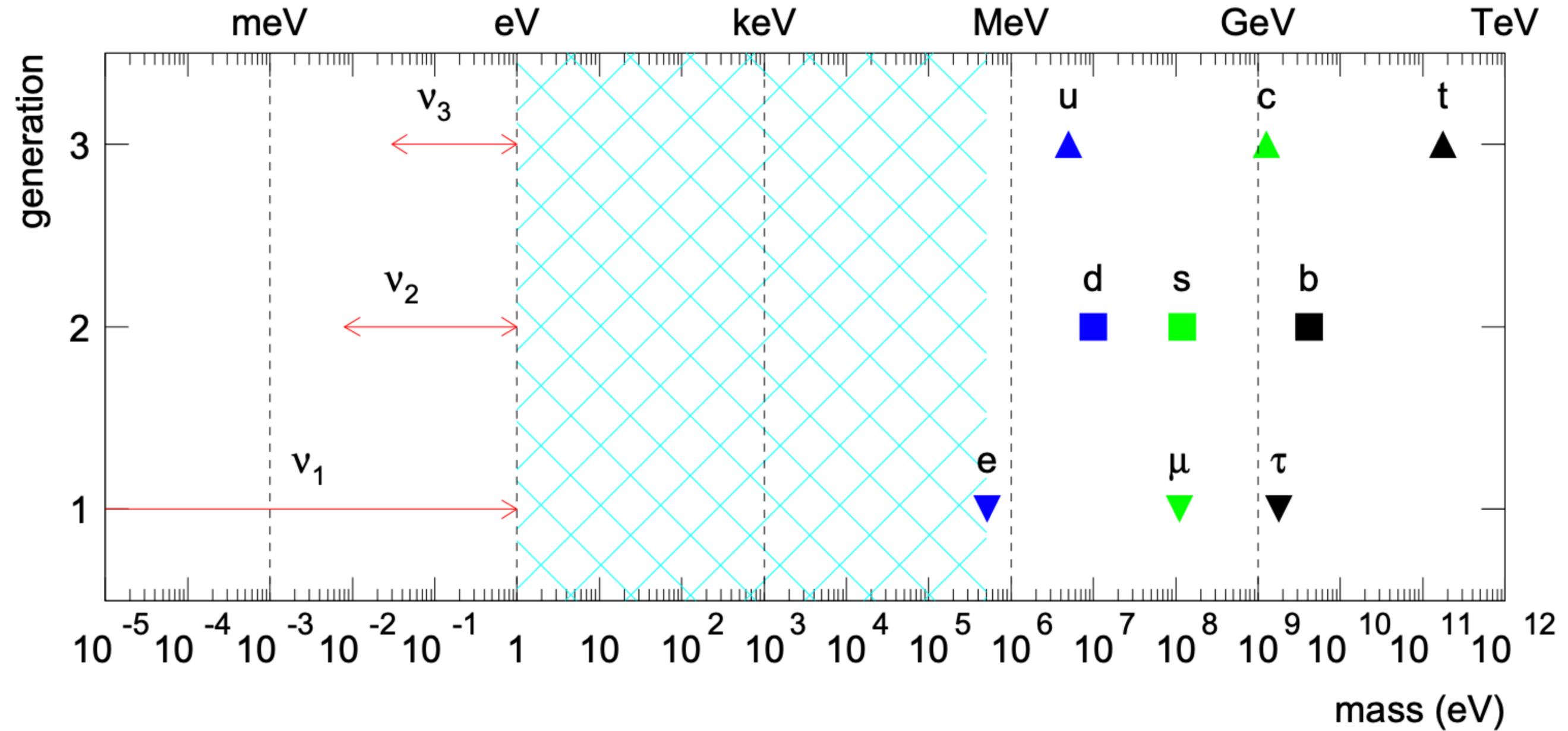
Where are the electron neutrinos going?

The atmospheric neutrino puzzle

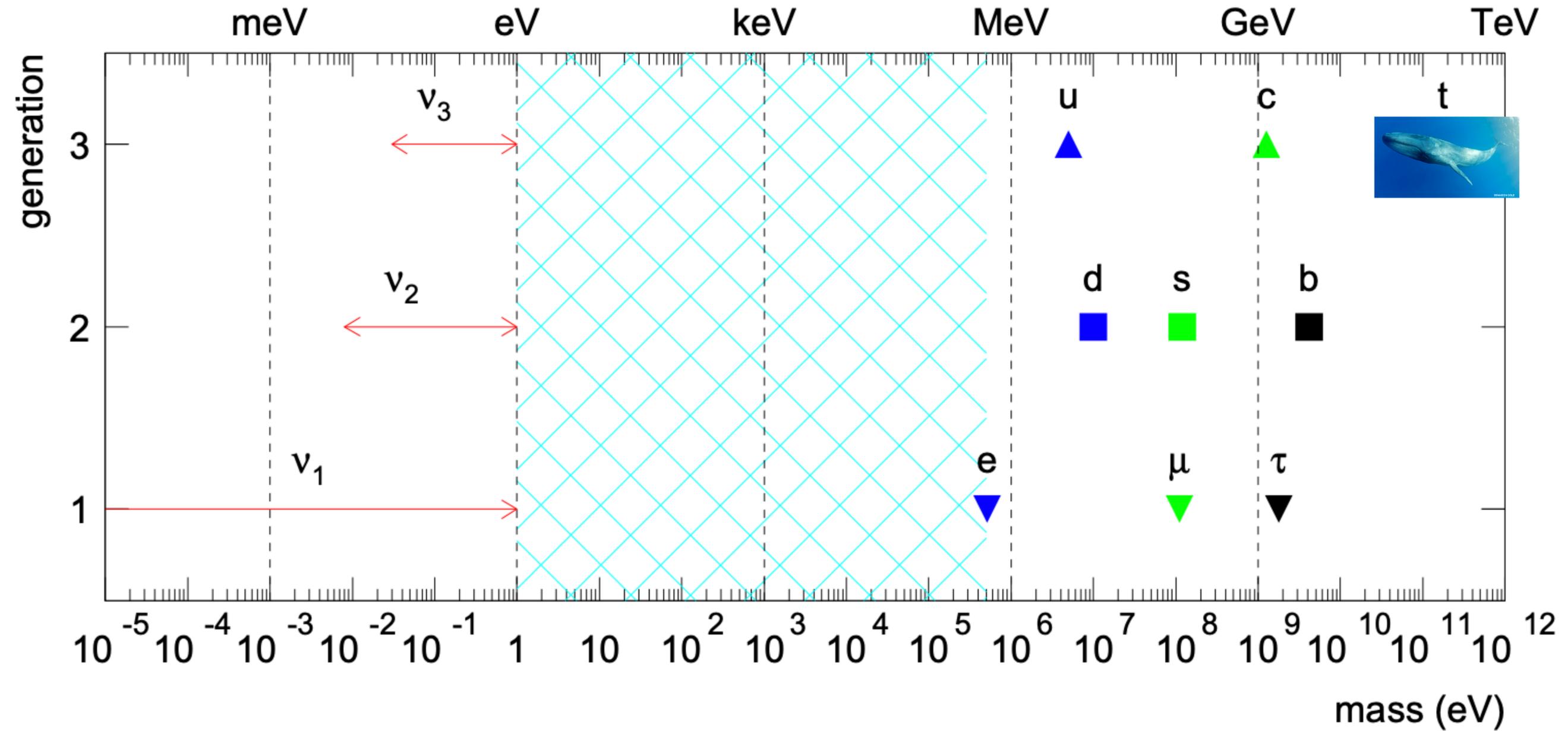


Where are the muon neutrinos going?

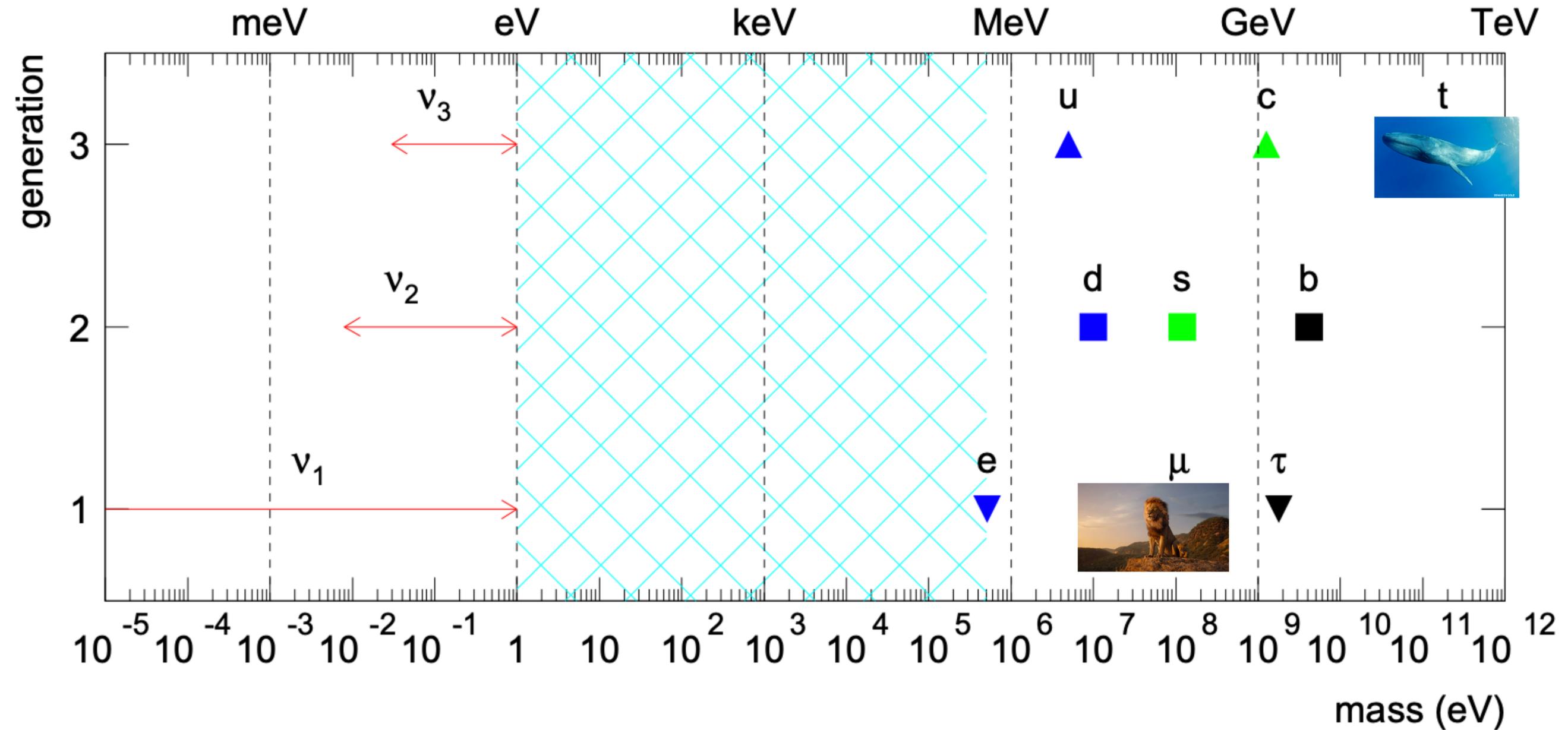
Only consistent explanation of these (and more) observations - Neutrinos have (very small) Masses



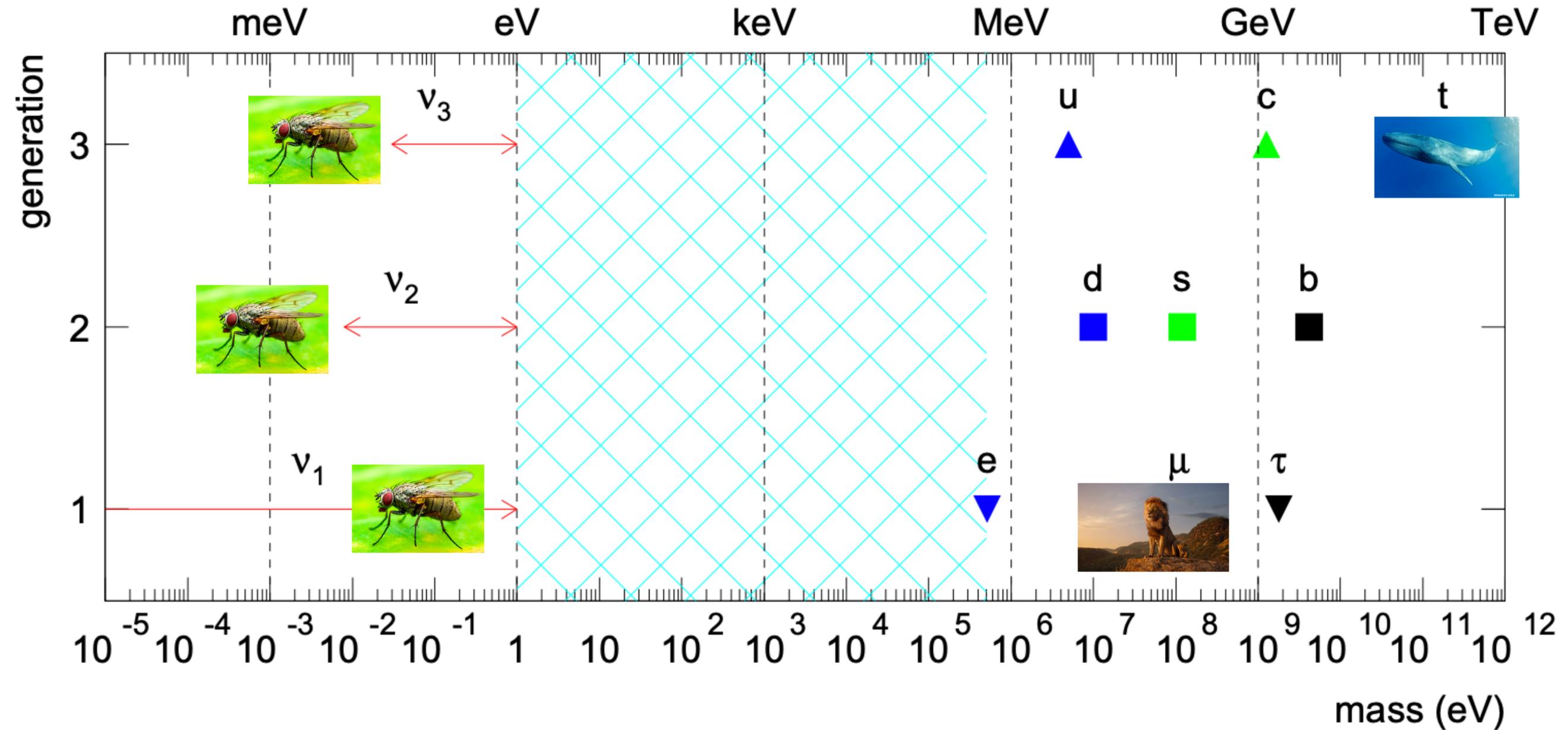
Only consistent explanation of these (and more) observations - Neutrinos have (very small) Masses



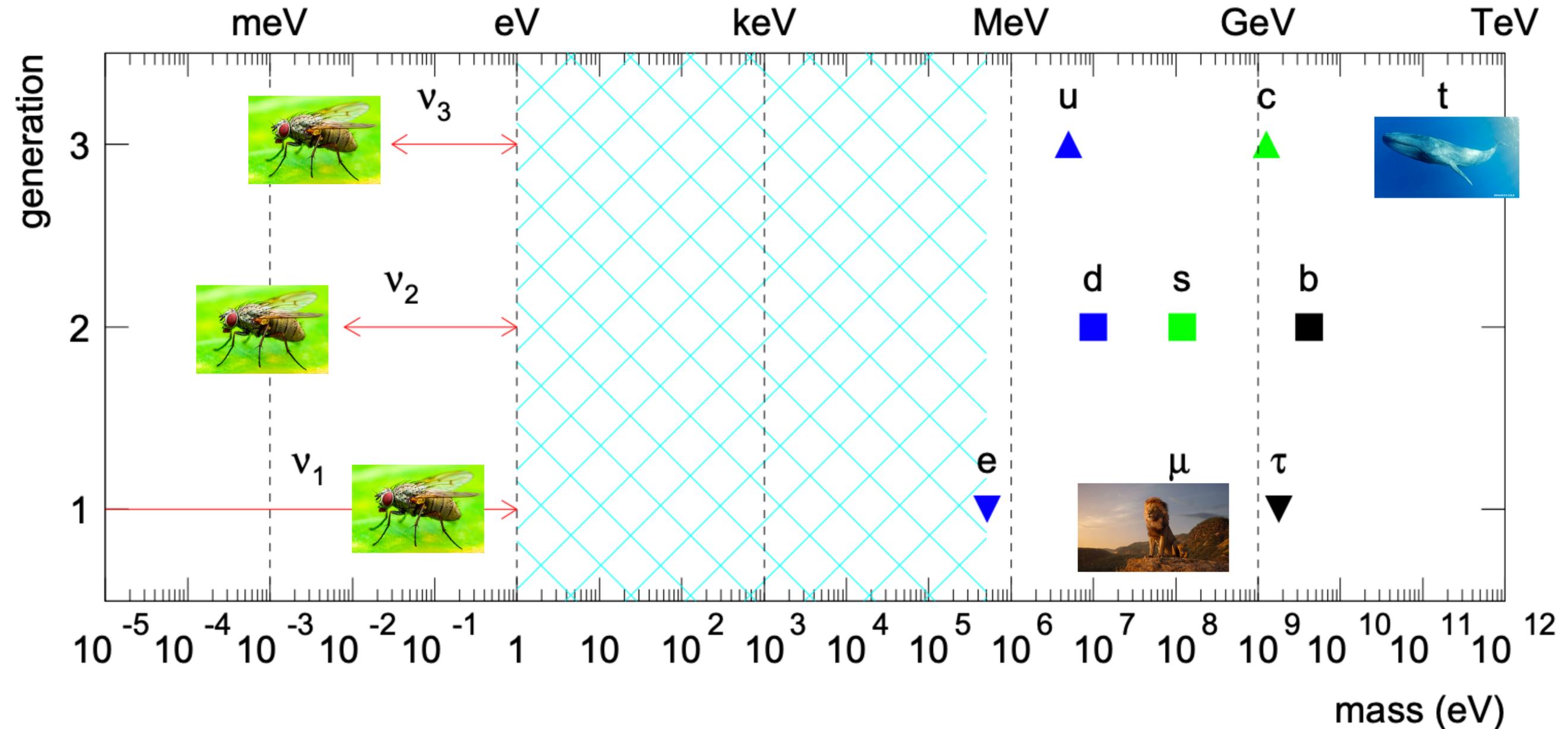
Only consistent explanation of these (and more) observations - Neutrinos have (very small) Masses



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



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



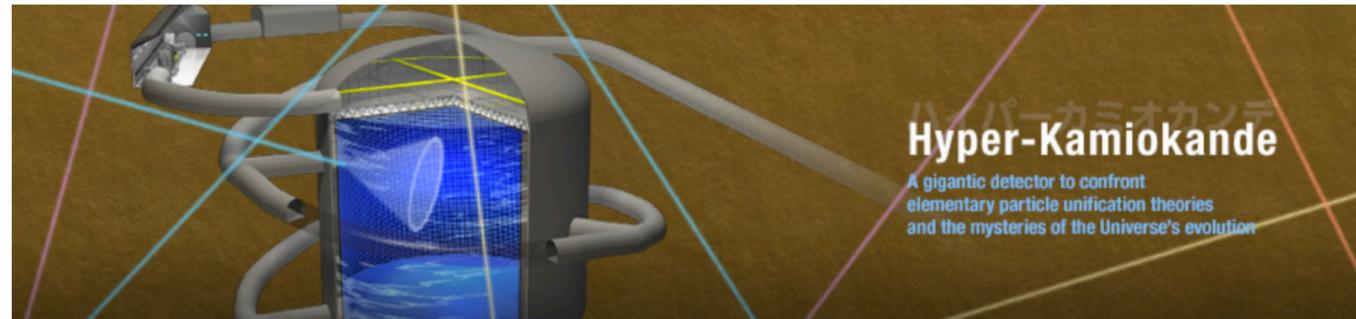
Like Dark Matter, the Standard Model does not predict neutrino masses!

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

Upcoming Experiments to better understand Neutrinos



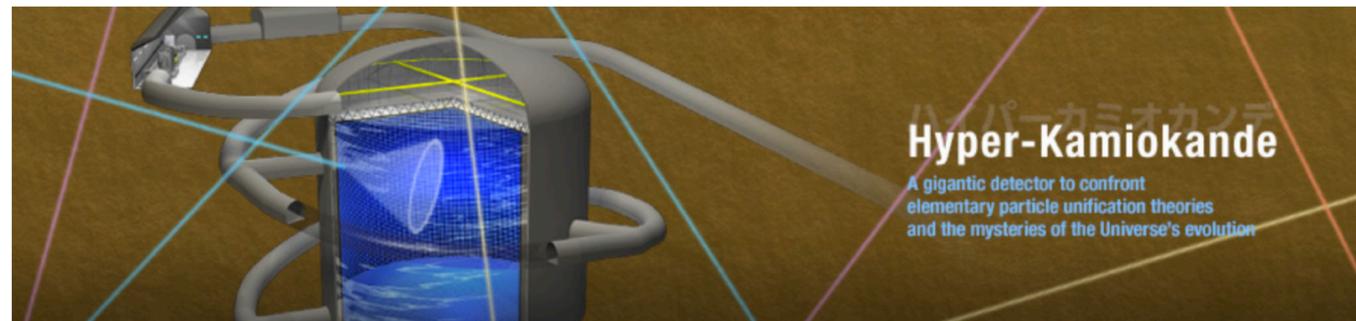
Hyper-Kamiokande



Upcoming Experiments to better understand Neutrinos



Hyper-Kamiokande

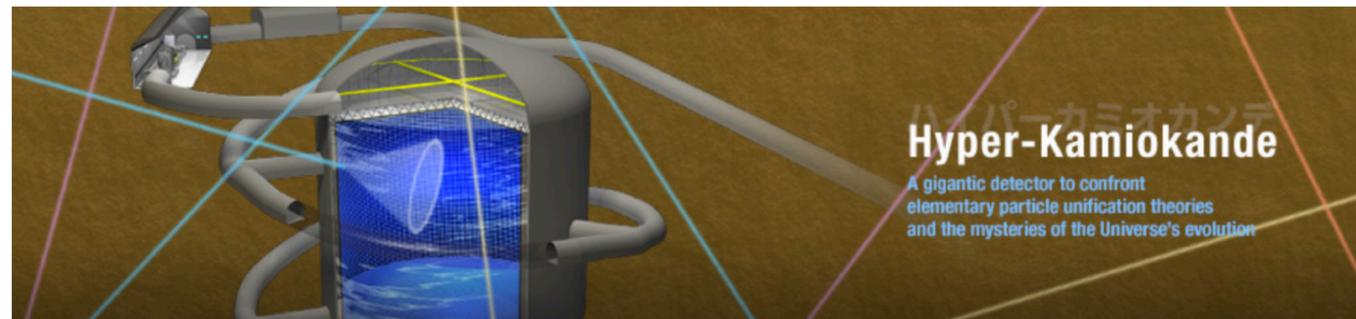


- Successor to the wildly successful Super-Kamiokande Experiment in Japan.

Upcoming Experiments to better understand Neutrinos



Hyper-Kamiokande

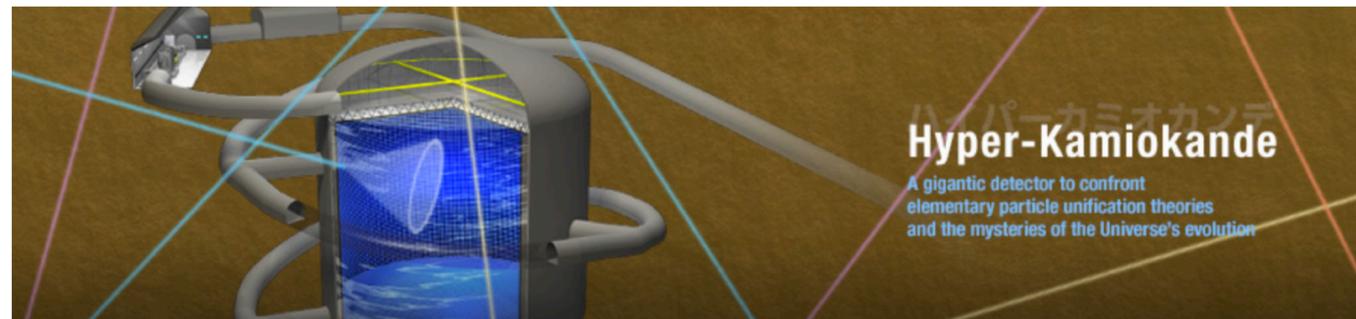


- Successor to the wildly successful Super-Kamiokande Experiment in Japan.
- Uses the technique of Water Cerenkov neutrino detection to identify neutrino scattering.

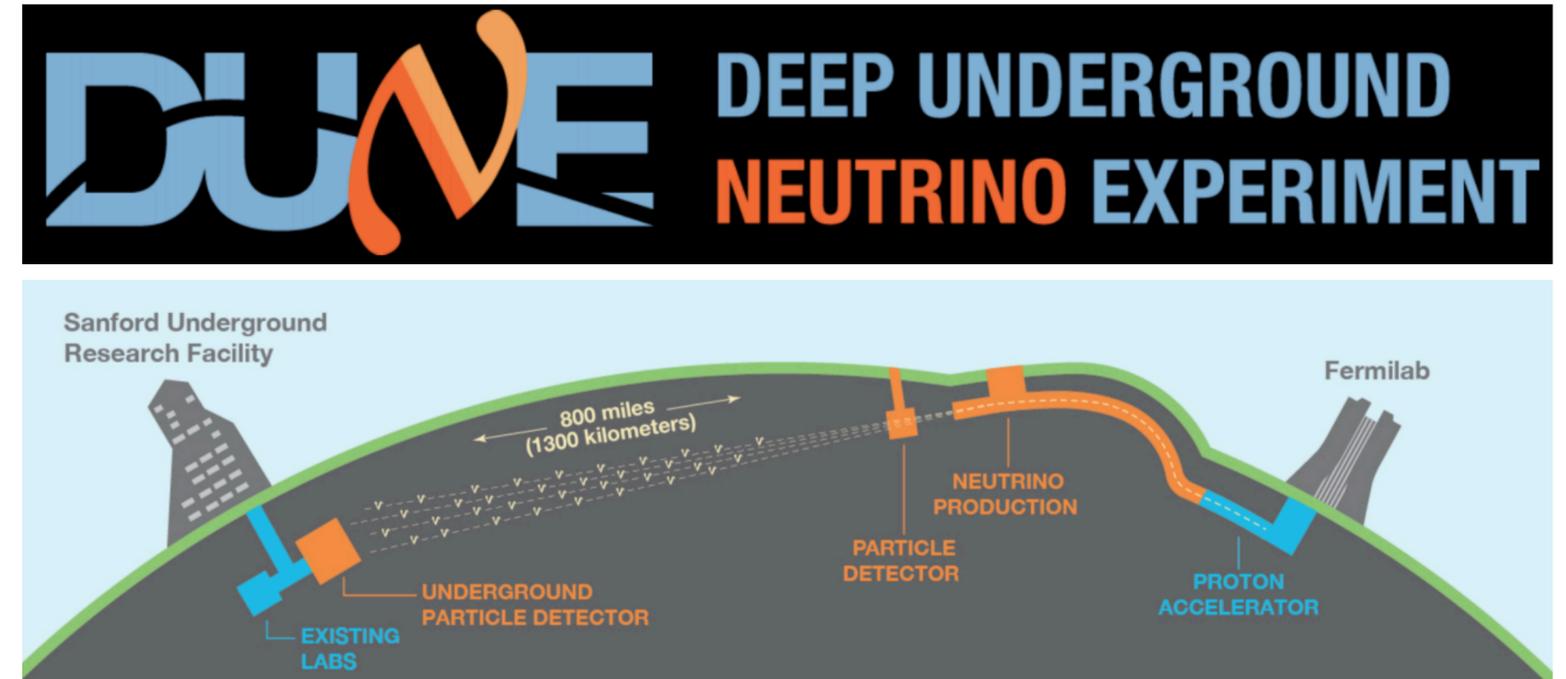
Upcoming Experiments to better understand Neutrinos



Hyper-Kamiokande



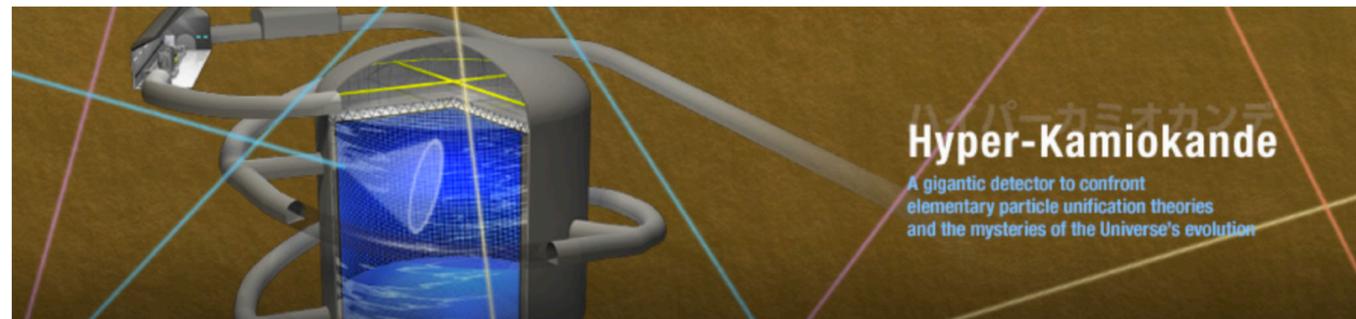
- Successor to the wildly successful Super-Kamiokande Experiment in Japan.
- Uses the technique of Water Cerenkov neutrino detection to identify neutrino scattering.



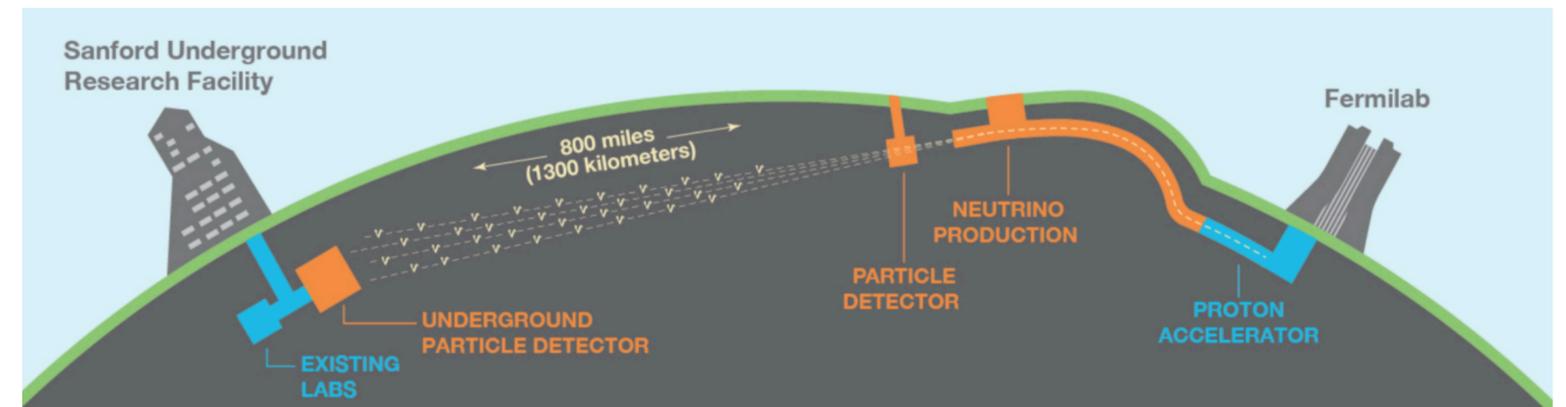
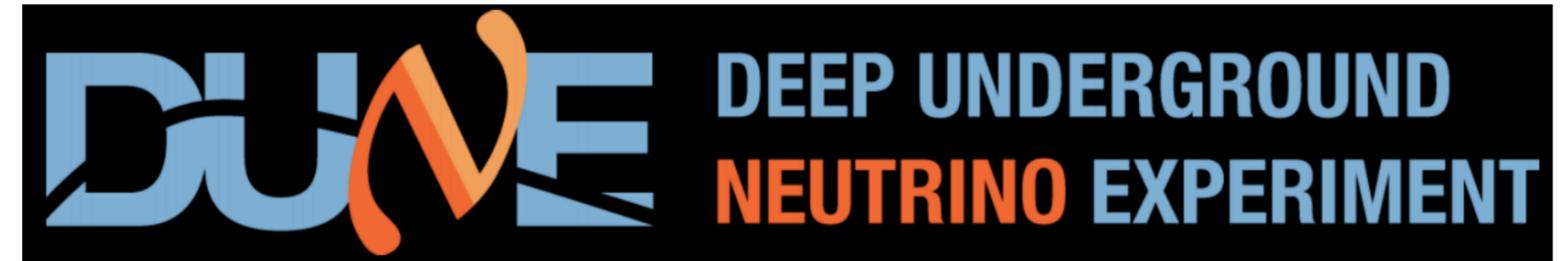
Upcoming Experiments to better understand Neutrinos



Hyper-Kamiokande



- Successor to the wildly successful Super-Kamiokande Experiment in Japan.
- Uses the technique of Water Cerenkov neutrino detection to identify neutrino scattering.

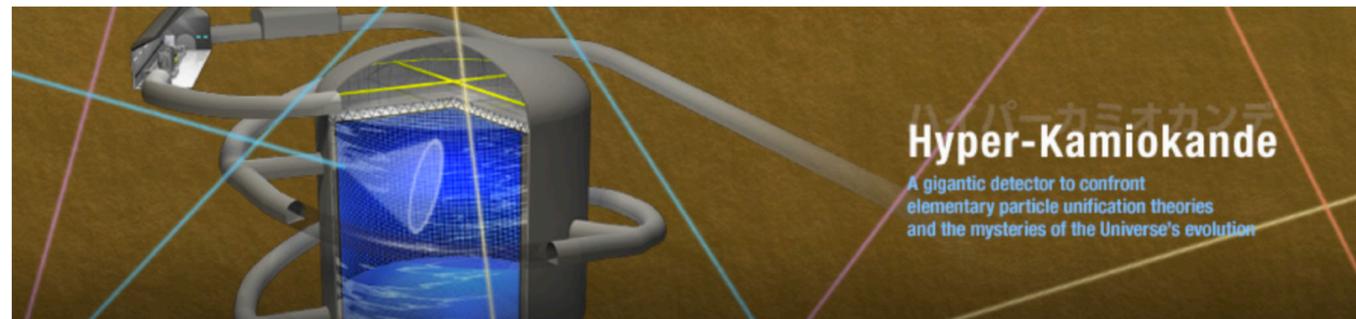


- US-based precision neutrino physics project.

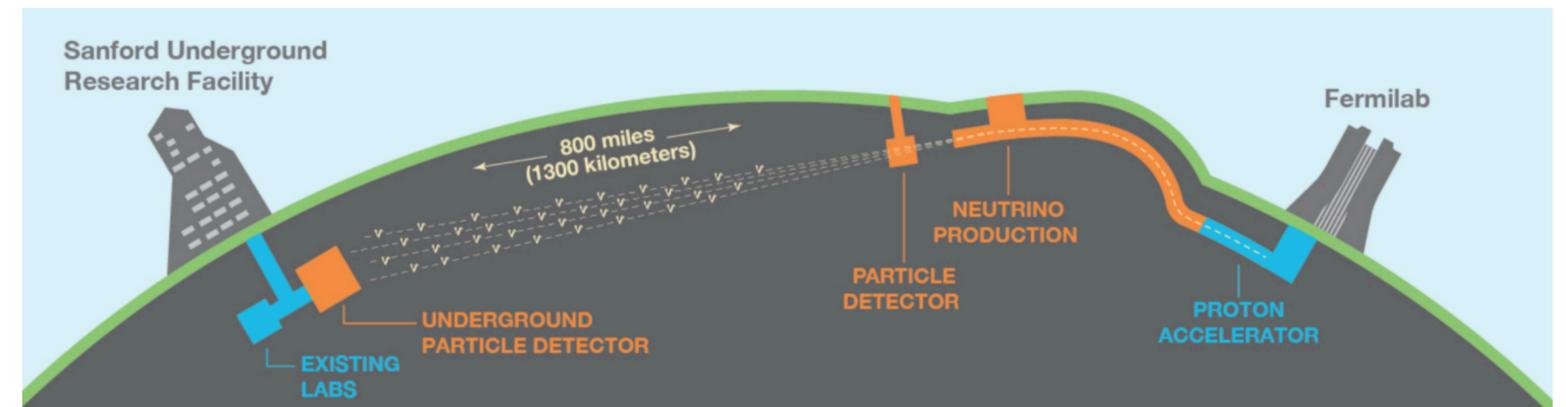
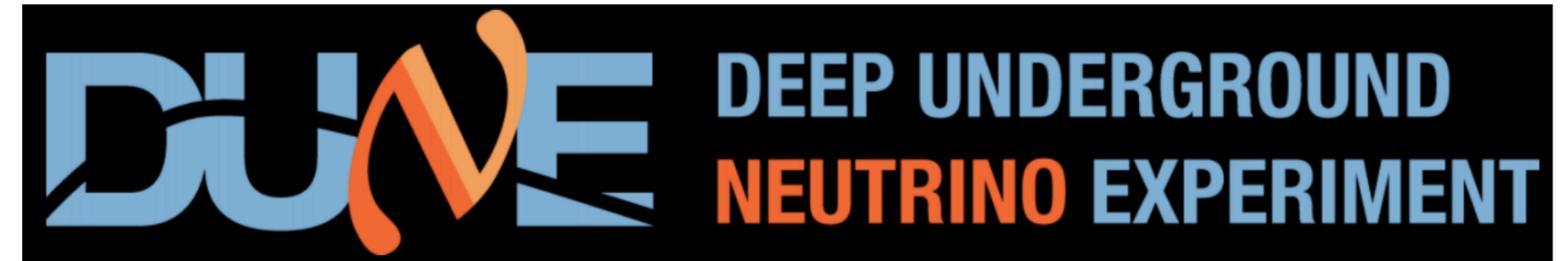
Upcoming Experiments to better understand Neutrinos



Hyper-Kamiokande



- Successor to the wildly successful Super-Kamiokande Experiment in Japan.
- Uses the technique of Water Cerenkov neutrino detection to identify neutrino scattering.



- 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

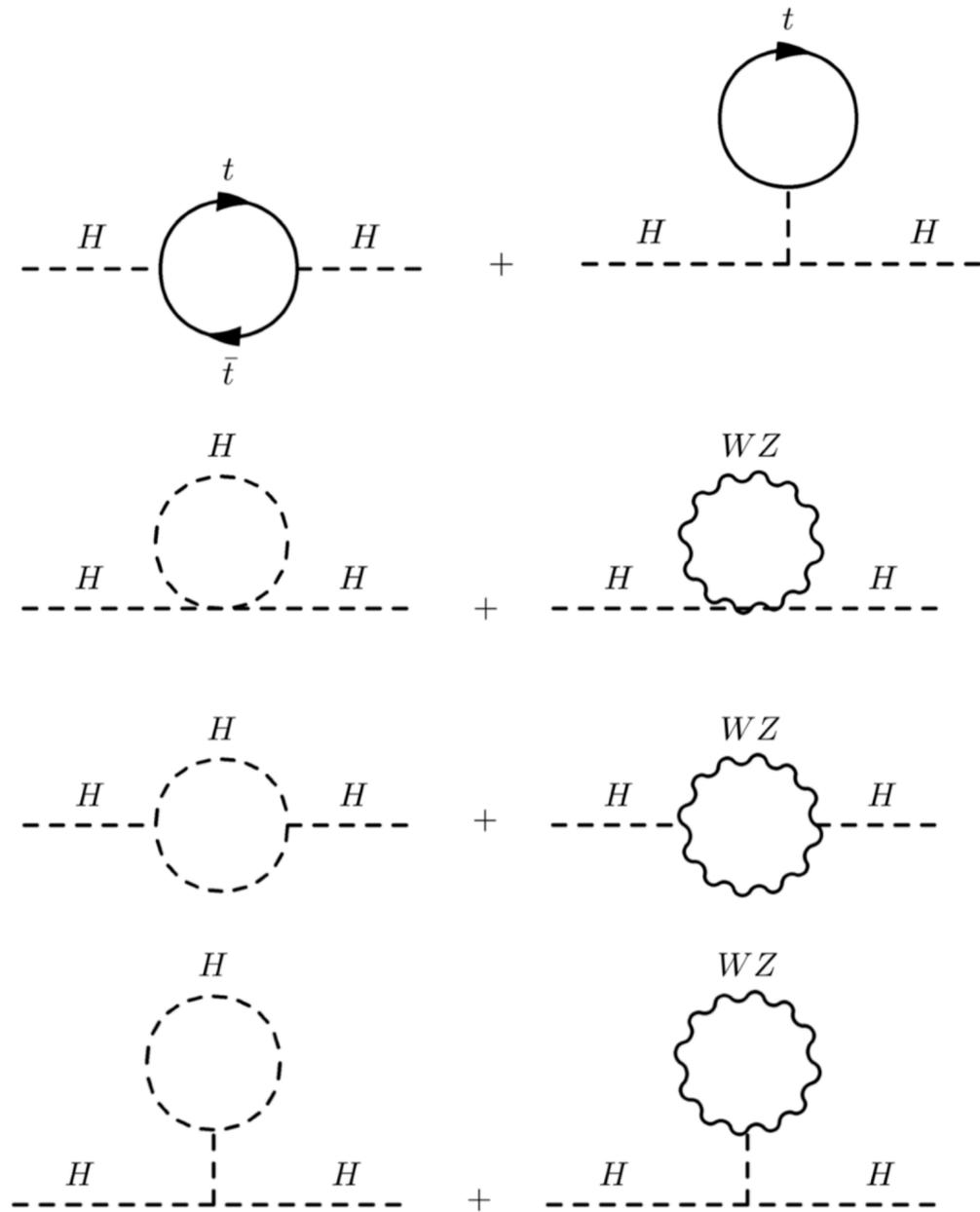
THURSDAY, 18 JUNE 

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

Speaker: Karri DiPetrillo (Harvard University)

The Higgs Boson Mass & Quantum Corrections

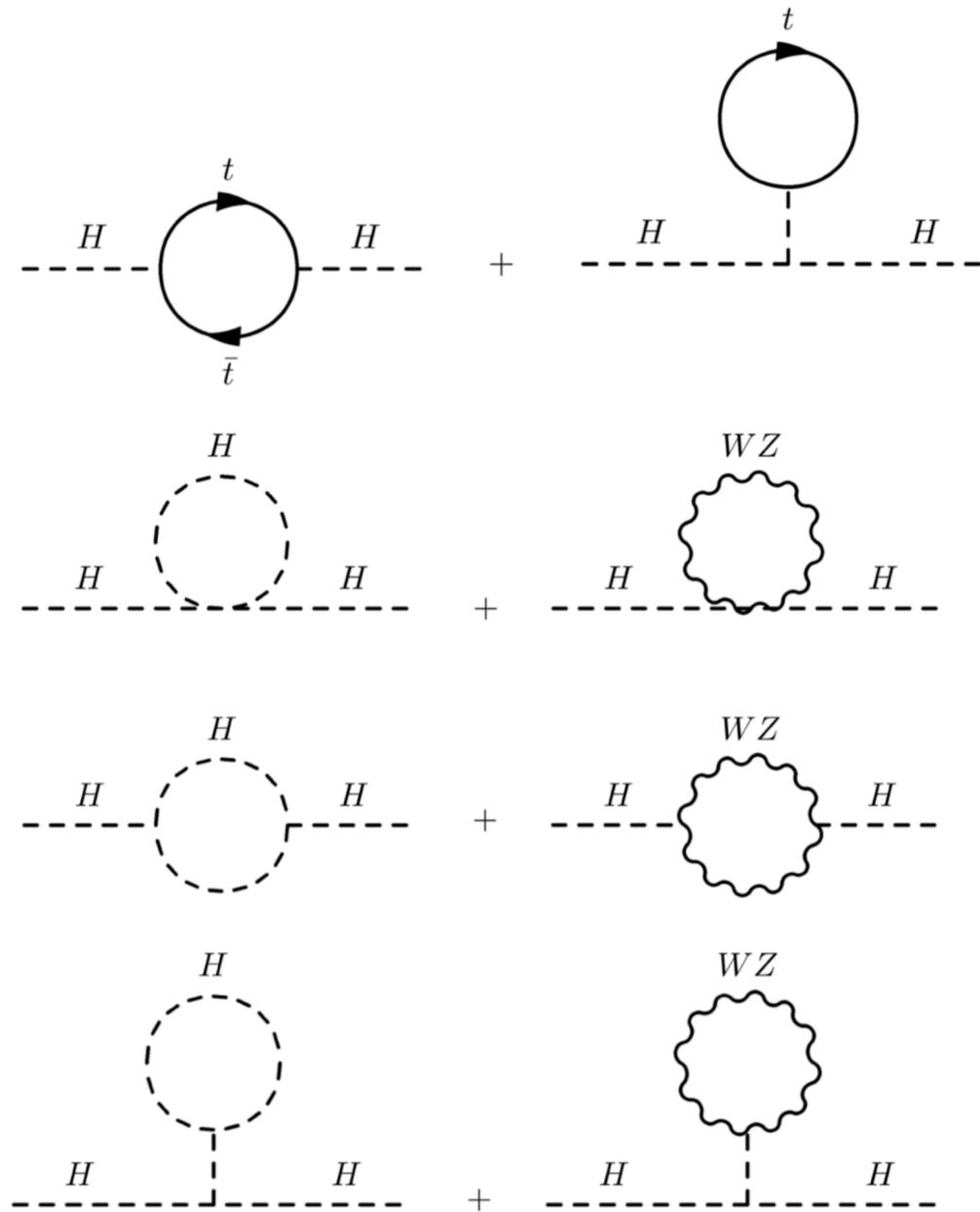
The Higgs Boson Mass & Quantum Corrections



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

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

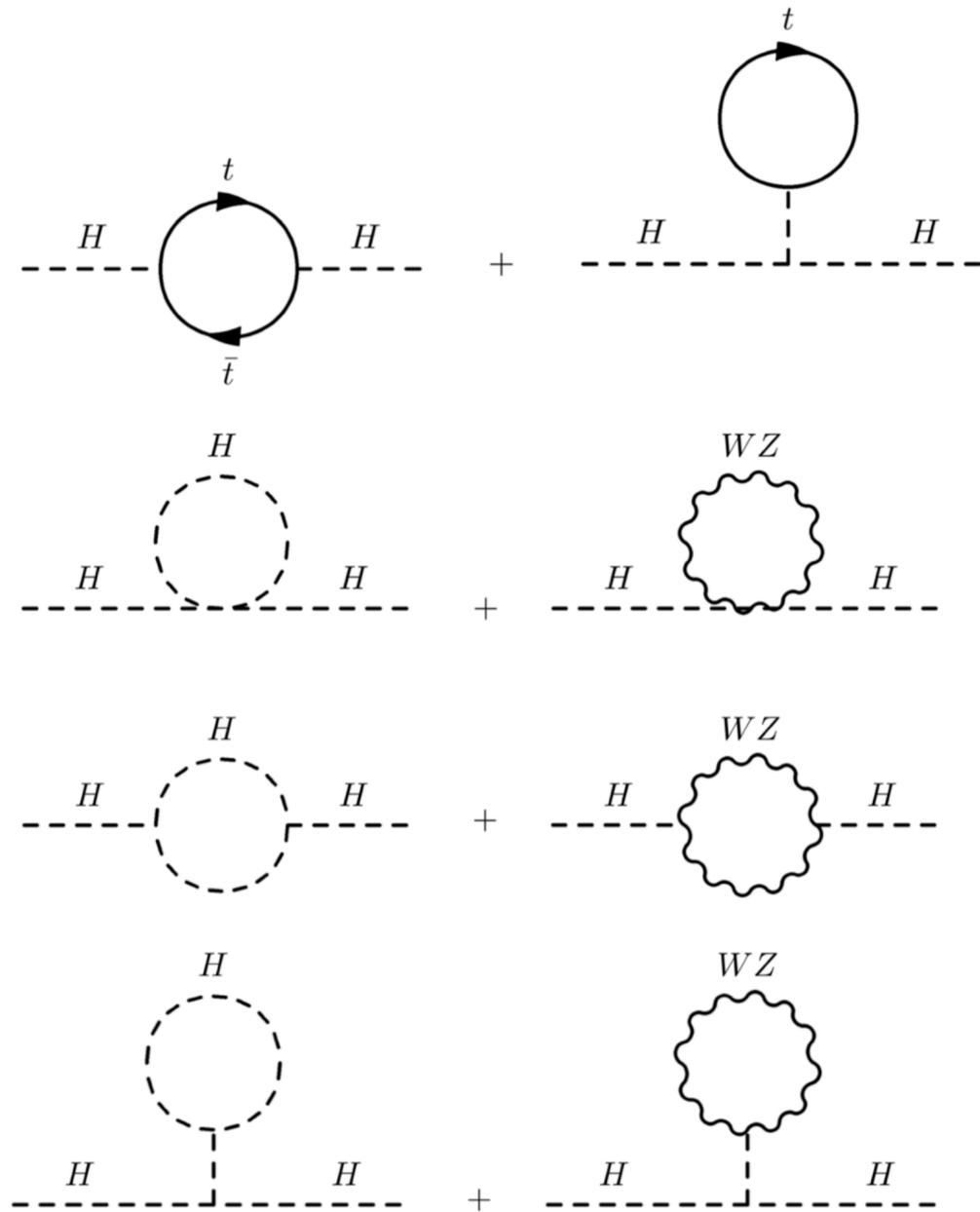
The Higgs Boson Mass & Quantum Corrections



- 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.

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

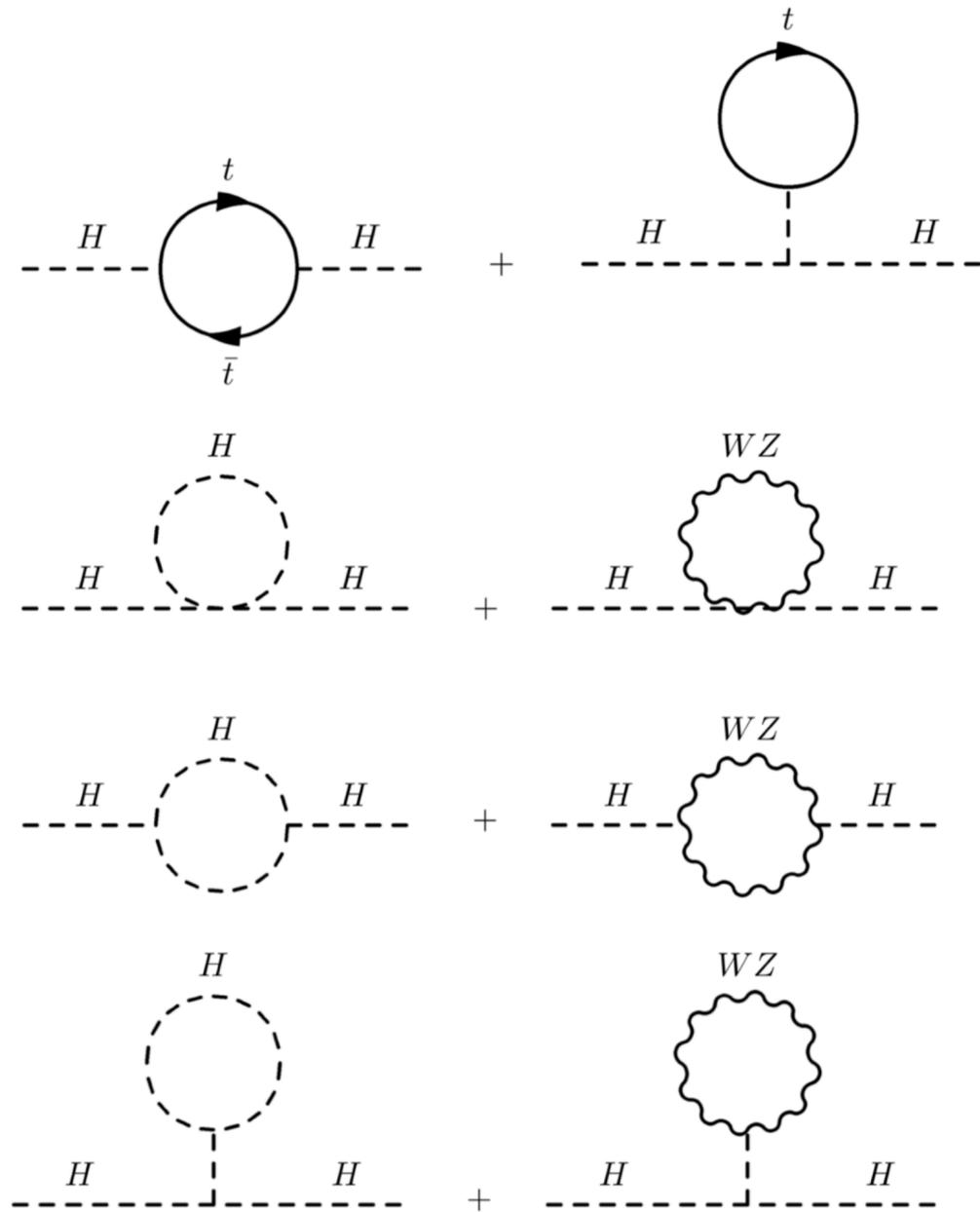
The Higgs Boson Mass & Quantum Corrections



- 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.
- 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.

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

The Higgs Boson Mass & Quantum Corrections



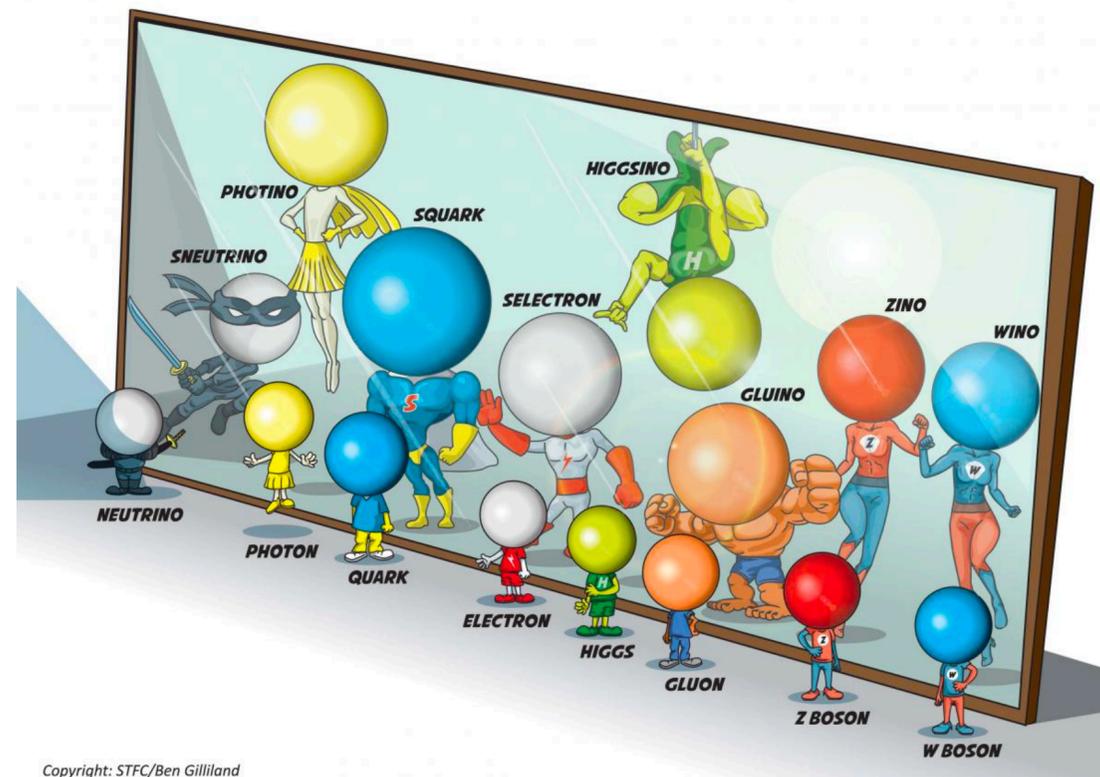
- Quantum field theory predicts that processes like these modify the Higgs boson's mass from its “Lagrangian value”.
- We observe the Higgs mass to be near the other weak-scale particles, about 125 GeV.
- Due to the nature of these diagrams though, any new mass scale above the weak scale should pull 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

Solution: Supersymmetry

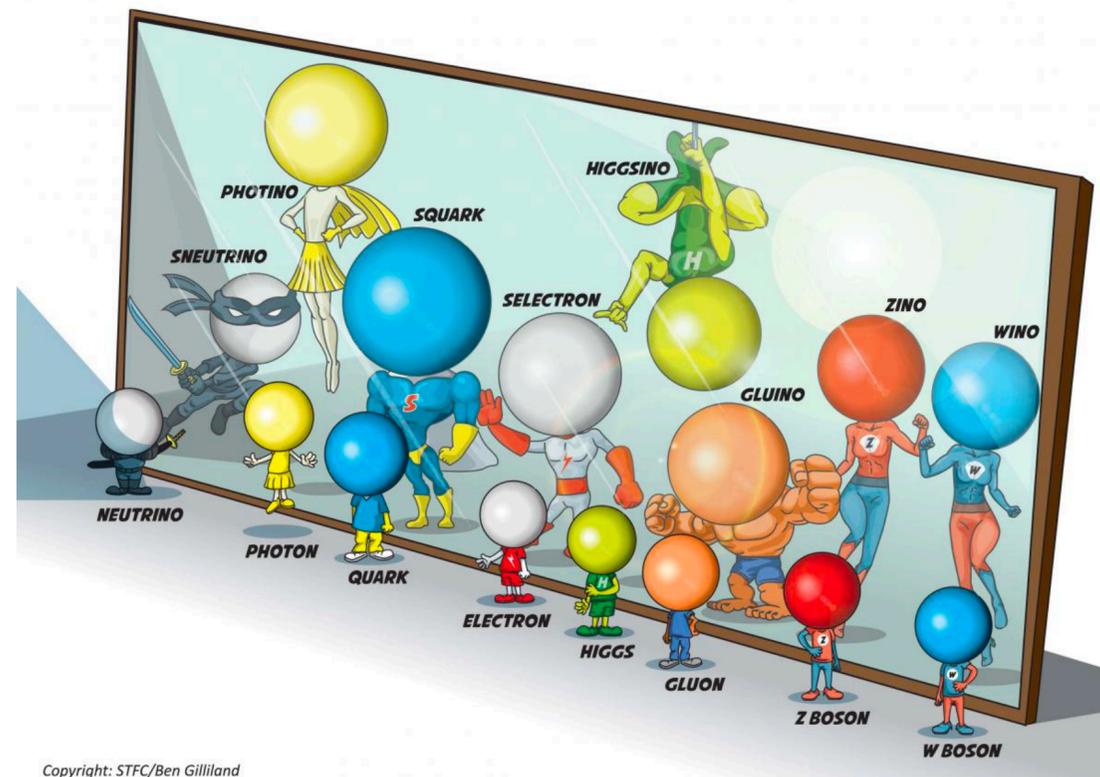
- Every standard model particle has a super-symmetric partner. These superparticles perfectly cancel out all of these quantum corrections to the Higgs mass.



Copyright: STFC/Ben Gilliland

Solution: Supersymmetry

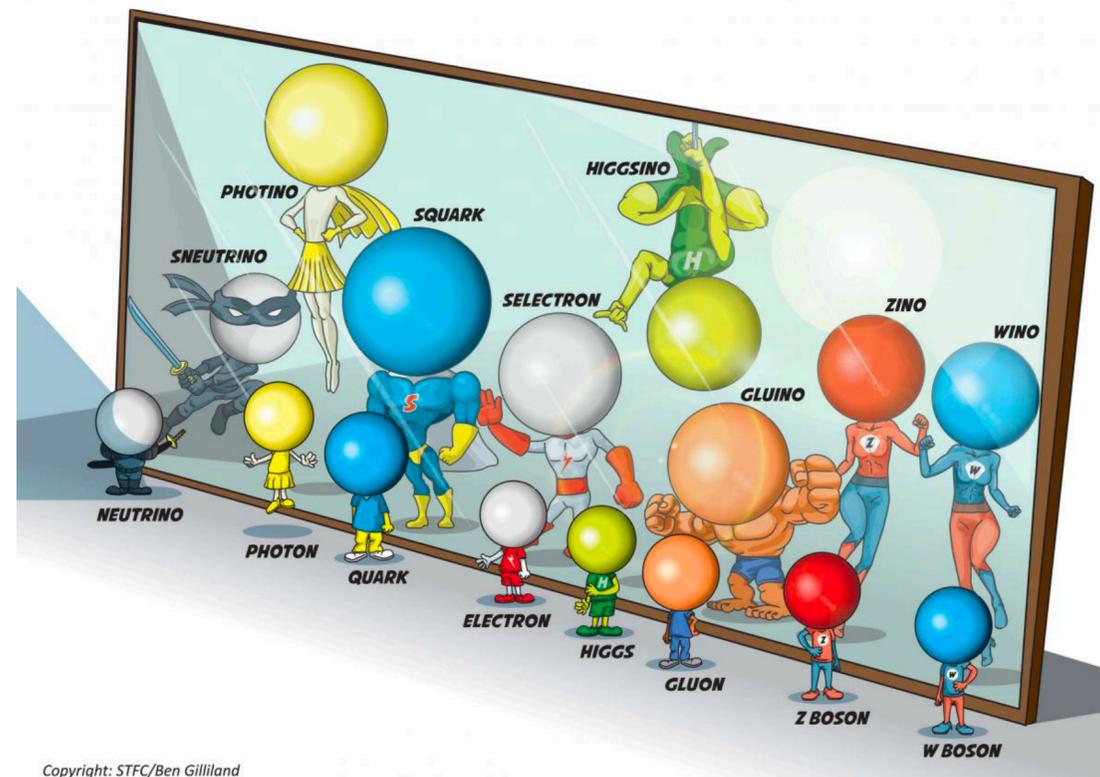
- Every standard model particle has a super-symmetric partner. These superparticles perfectly cancel out all of these quantum corrections to the Higgs mass.
- Many theories of supersymmetry also include a stable particle that can explain the observed Dark Matter in the universe.



Copyright: STFC/Ben Gilliland

Solution: Supersymmetry

- 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.

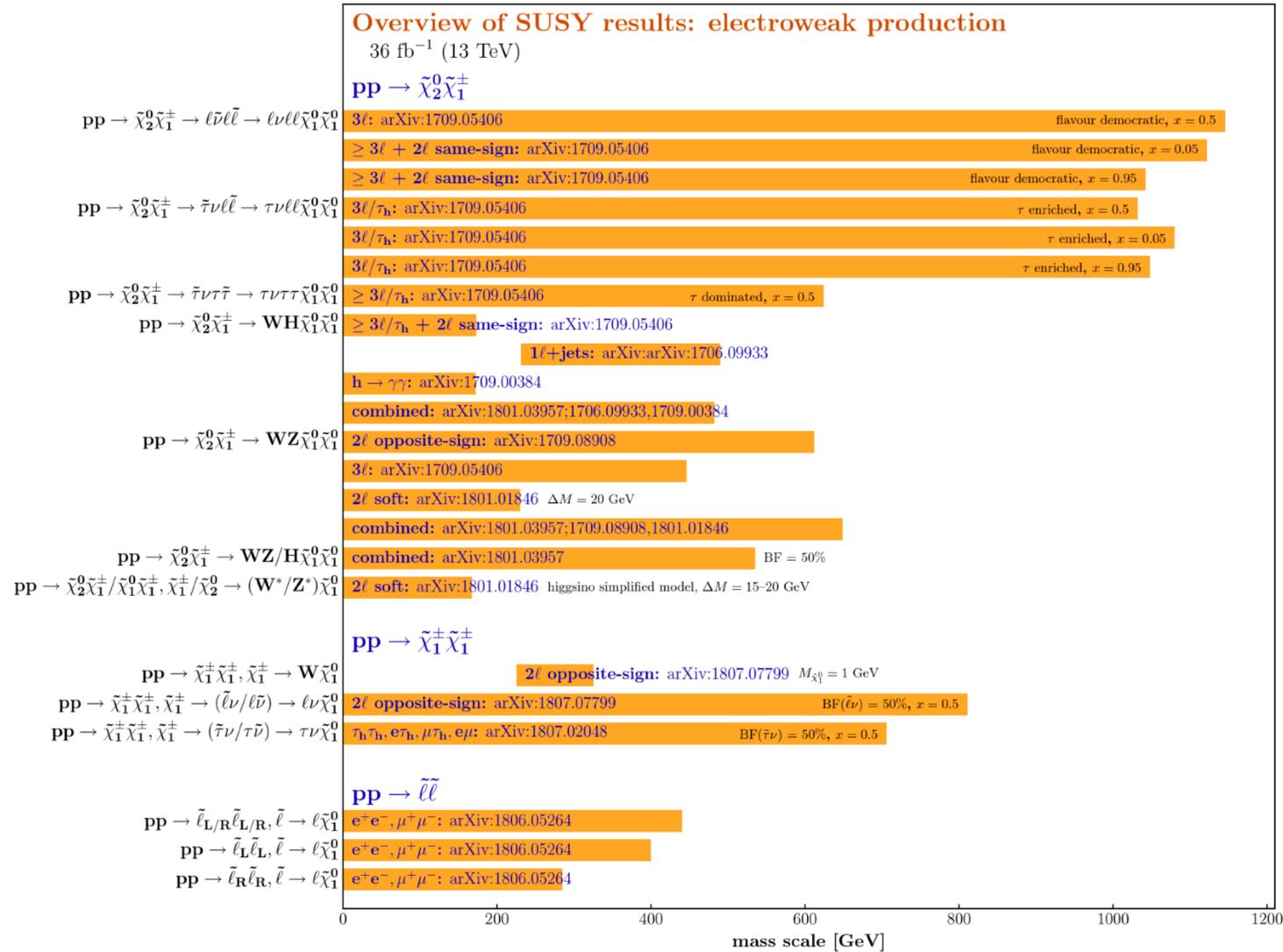


SUSY Searches at the LHC

SUSY Searches at the LHC

CMS

July 2018

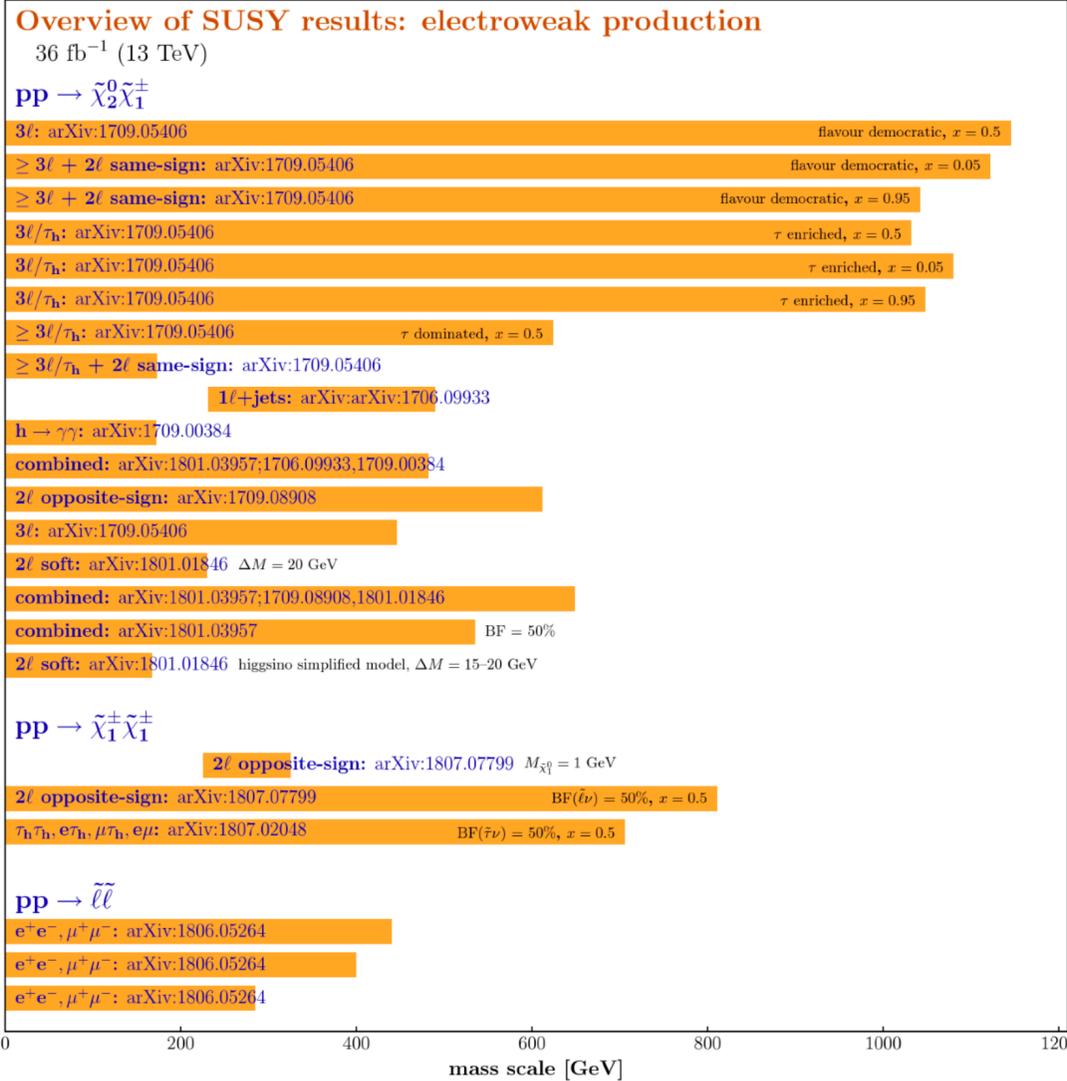


Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe up to the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate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

SUSY Searches at the LHC

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.

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

ATLAS Preliminary
 $\sqrt{s} = 13$ TeV

Model	Signature	$\int \mathcal{L} dt$ [fb ⁻¹]	Mass limit	Reference						
Inclusive Searches	$q\bar{q}, q \rightarrow q\tilde{\chi}_1^0$	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
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	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
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$	3 e, μ $ee, \mu\mu$	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
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	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
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	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	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0/\tilde{t}\tilde{\chi}_1^0$	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
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0 \rightarrow b\tilde{b}\tilde{\chi}_1^0$		0 e, μ	6 b	E_T^{miss}	139	\tilde{b}_1	Forbidden	0.23-0.48	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)=130$ 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 $\tilde{t}\tilde{\chi}_1^0$		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
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}b\nu, \tilde{\tau}_1 \rightarrow \tau\tilde{G}$		1 $\tau + 1 e, \mu, \tau$	2 jets/1 b	E_T^{miss}	139	\tilde{t}_1	Forbidden	1.16	$m(\tilde{\chi}_1^0)=800$ GeV	1803.10178
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0/\tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$		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	$m(\tilde{\chi}_1^0)=0$ 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	0.86		
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	2-3 e, μ $ee, \mu\mu$	≥ 1	E_T^{miss} E_T^{miss}	36.1 139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	Forbidden	0.6 0.205	$m(\tilde{\chi}_1^0)=0$ $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_2^0)=5$ GeV	1403.5294, 1806.02293 ATLAS-CONF-2019-014
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via WW	2 e, μ		E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$	Forbidden	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 $b/2 \gamma$	E_T^{miss}	139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	Forbidden	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		E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$	Forbidden	1.0	$m(\tilde{\chi}_1^0)=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2019-008
Long-lived particles	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	2 τ		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 0 jets 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
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, μ 4 e, μ	$\geq 3 b$ 0 jets	E_T^{miss} E_T^{miss}	36.1 36.1	\tilde{H}	Forbidden	0.256 0.13-0.23 0.3	$m(\tilde{\chi}_1^0)=10$ GeV BR($\tilde{H}\tilde{H} \rightarrow h\tilde{G}$)=1 BR($\tilde{H}\tilde{H} \rightarrow Z\tilde{G}$)=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	$\tilde{\chi}_1^{\pm}$	Forbidden	0.46	Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019
	Stable \tilde{g} R-hadron	Multiple			36.1	\tilde{g}	Forbidden	2.0		1902.01636, 1808.04095
	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	Multiple			36.1	\tilde{g}	Forbidden	2.05 2.4	$m(\tilde{\chi}_1^0)=100$ GeV	1710.04901, 1808.04095
RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu$	$e\mu, e\tau, \mu\tau$			3.2	$\tilde{\nu}_\tau$	Forbidden	1.9	$A'_{311}=0.11, A'_{32/33/233}=0.07$	1607.08079
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell/\nu\nu$	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
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}\tilde{\chi}_1^0$	4-5 large-R jets			36.1	\tilde{g}	Forbidden	1.3 1.9	Large A'_{12}	1804.03568
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}\tilde{\chi}_1^0$	Multiple			36.1	\tilde{g}	Forbidden	1.05 2.0	$m(\tilde{\chi}_1^0)=200$ GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{u}_L, \tilde{t} \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow t\tilde{b}s$	Multiple			36.1	\tilde{u}_L	Forbidden	0.55	$m(\tilde{\chi}_1^0)=200$ GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	2 jets + 2 b			36.7	\tilde{t}_1	Forbidden	0.42 0.61		1710.07171
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\tilde{\ell}$	2 e, μ 1 μ	2 b DV		36.1 136	\tilde{t}_1	Forbidden	1.0 1.6	BR($\tilde{t}_1 \rightarrow b\tilde{\ell}$)/BR($\tilde{t}_1 \rightarrow q\tilde{\ell}$)>20% BR($\tilde{t}_1 \rightarrow q\tilde{\mu}$)=100%, $\cos\theta_{\tilde{t}_1}=1$	1710.05544 ATLAS-CONF-2019-006	

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

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.

Conclusions

Conclusions

- Decades of discoveries and explorations led to the development of the Standard Model of Particle Physics.

Conclusions

- Decades of discoveries and explorations led to the development of the Standard Model of Particle Physics.
- We can understand how these particles interact using Quantum Field Theory and careful applications of Symmetry.

Conclusions

- Decades of discoveries and explorations led to the development of the Standard Model of Particle Physics.
- We can understand how these particles interact using Quantum Field Theory and careful applications of Symmetry.
- The Standard Model has a few gaps that fuel our interest today

Conclusions

- Decades of discoveries and explorations led to the development of the Standard Model of Particle Physics.
- We can understand how these particles interact using Quantum Field Theory and careful applications of Symmetry.
- The Standard Model has a few gaps that fuel our interest today
 - What is dark matter?

Conclusions

- Decades of discoveries and explorations led to the development of the Standard Model of Particle Physics.
- We can understand how these particles interact using Quantum Field Theory and careful applications of Symmetry.
- The Standard Model has a few gaps that fuel our interest today
 - What is dark matter?
 - Why are neutrinos so light, and why do they have mass at all?

Conclusions

- Decades of discoveries and explorations led to the development of the Standard Model of Particle Physics.
- We can understand how these particles interact using Quantum Field Theory and careful applications of Symmetry.
- The Standard Model has a few gaps that fuel our interest today
 - What is dark matter?
 - Why are neutrinos so light, and why do they have mass at all?
 - Are there only three families of particles? Why three?

Conclusions

- Decades of discoveries and explorations led to the development of the Standard Model of Particle Physics.
- We can understand how these particles interact using Quantum Field Theory and careful applications of Symmetry.
- The Standard Model has a few gaps that fuel our interest today
 - What is dark matter?
 - Why are neutrinos so light, and why do they have mass at all?
 - Are there only three families of particles? Why three?
 - Why is the universe expanding?

Conclusions

- Decades of discoveries and explorations led to the development of the Standard Model of Particle Physics.
- We can understand how these particles interact using Quantum Field Theory and careful applications of Symmetry.
- The Standard Model has a few gaps that fuel our interest today
 - What is dark matter?
 - Why are neutrinos so light, and why do they have mass at all?
 - Are there only three families of particles? Why three?
 - Why is the universe expanding?
 - Why are we made of matter and not antimatter? How did matter survive after the big bang?

Conclusions

- Decades of discoveries and explorations led to the development of the Standard Model of Particle Physics.
- We can understand how these particles interact using Quantum Field Theory and careful applications of Symmetry.
- The Standard Model has a few gaps that fuel our interest today
 - What is dark matter?
 - Why are neutrinos so light, and why do they have mass at all?
 - Are there only three families of particles? Why three?
 - Why is the universe expanding?
 - Why are we made of matter and not antimatter? How did matter survive after the big bang?
 - ...

Thank you!