Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Introduction to Particle Physics

Pedro A. N. Machado

June/2019

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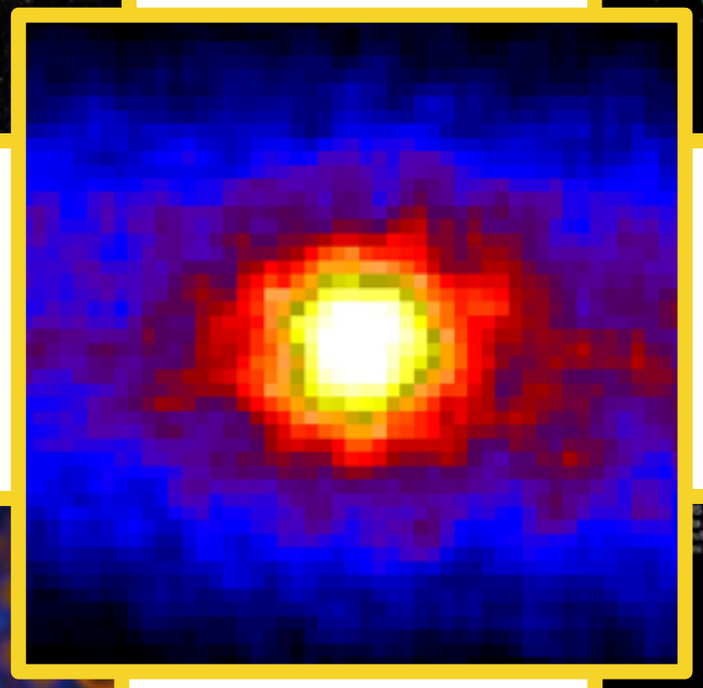
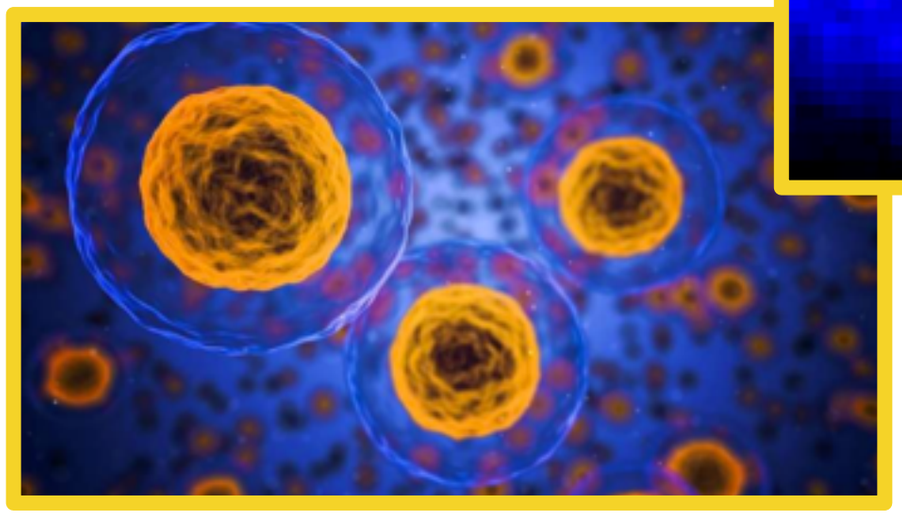
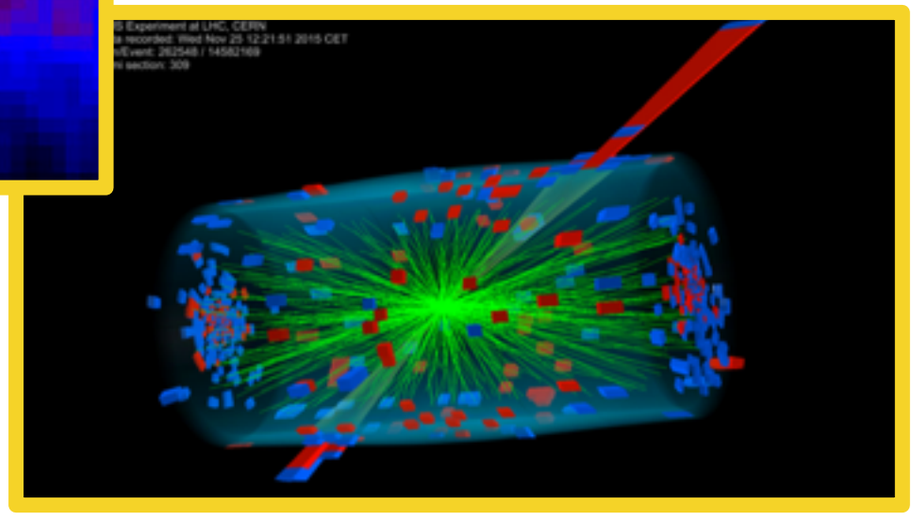
Particle Physics







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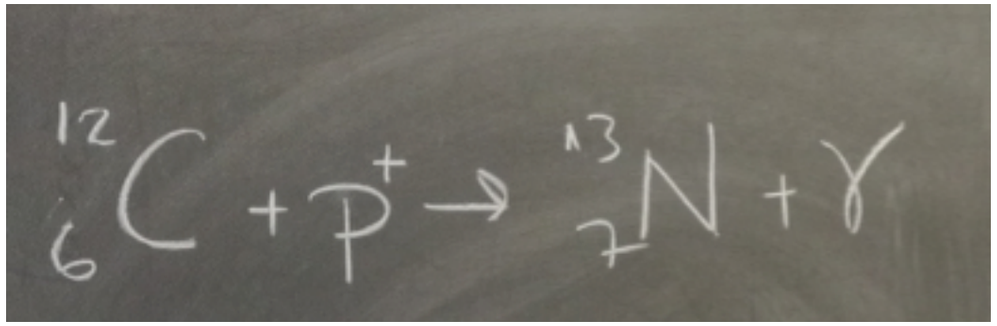

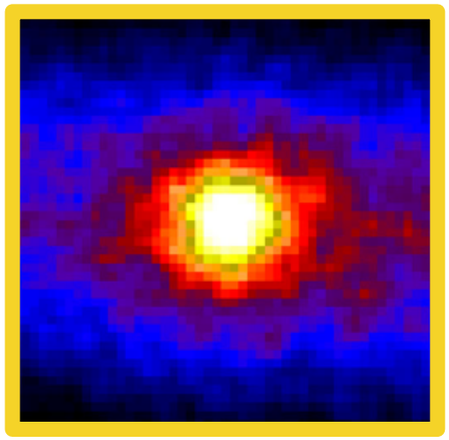

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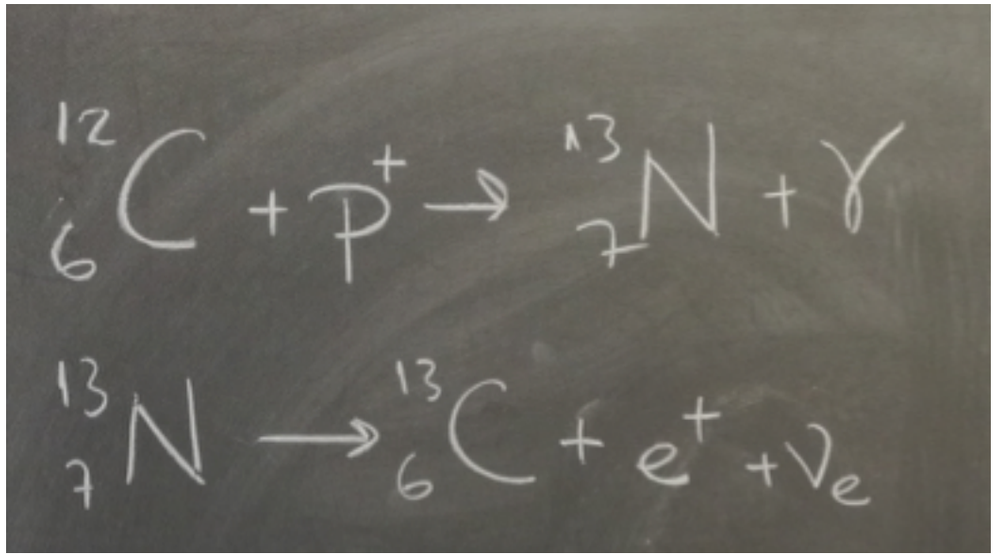

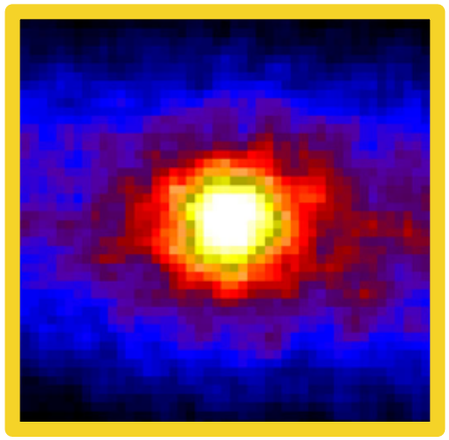

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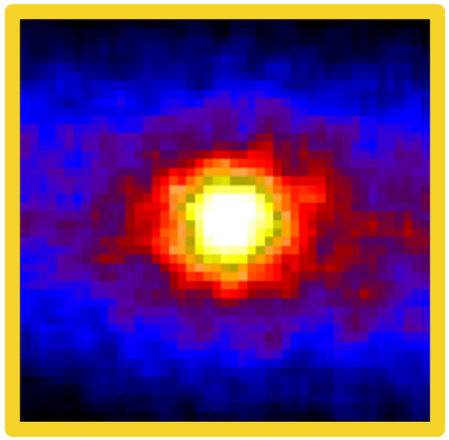

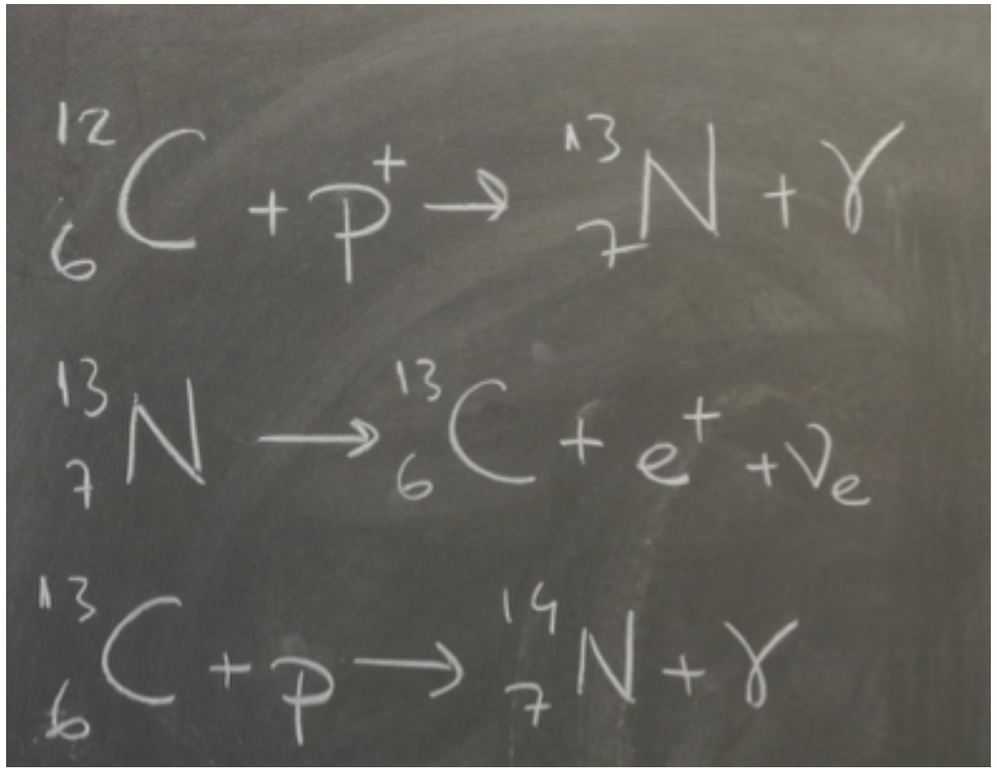

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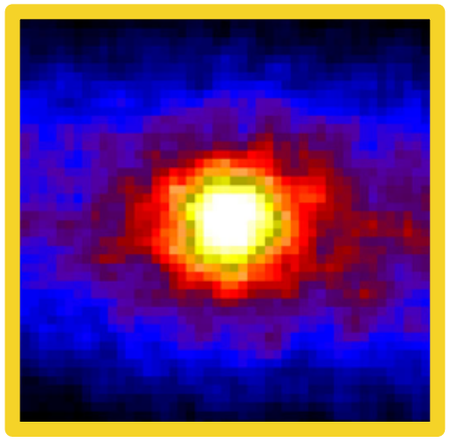

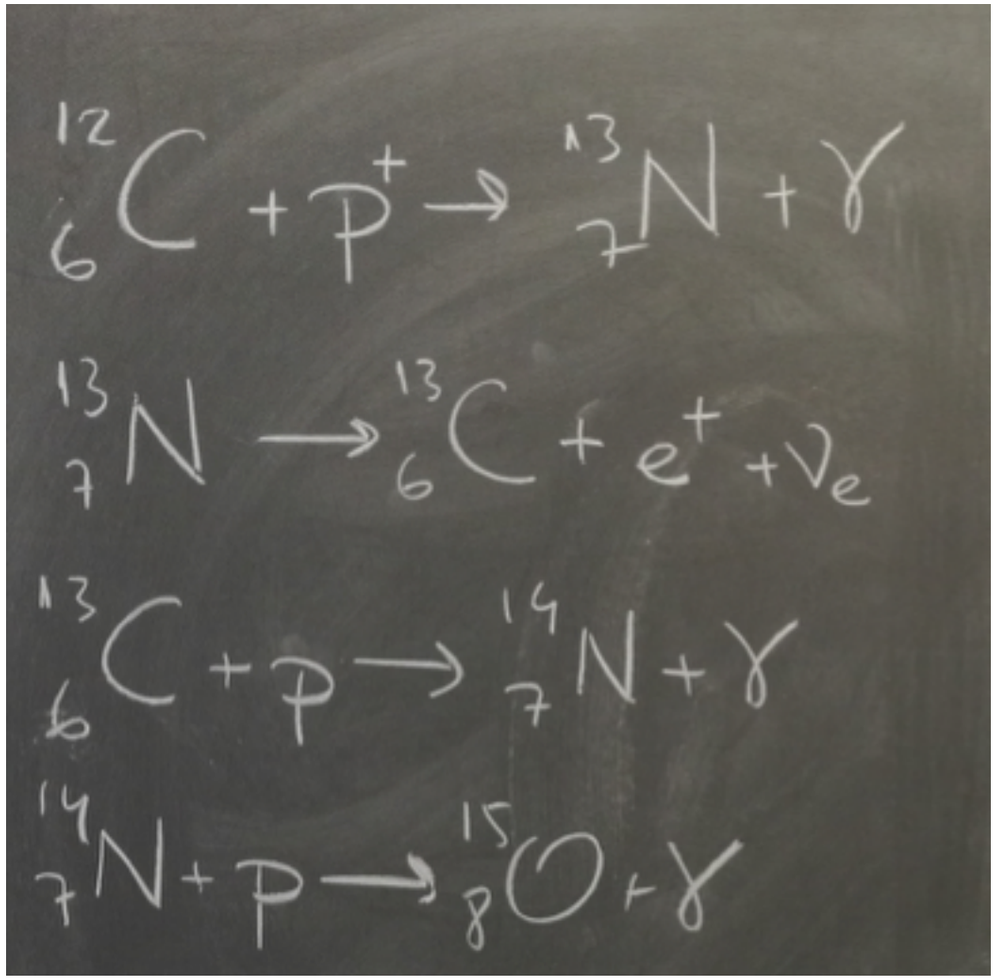

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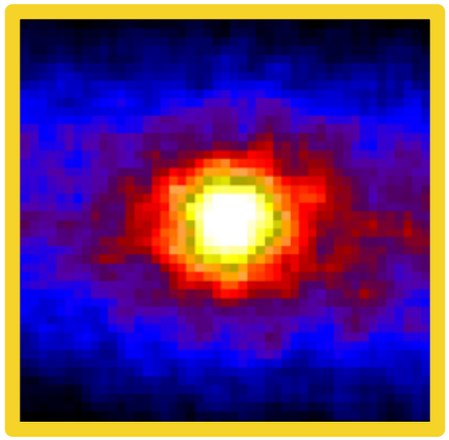

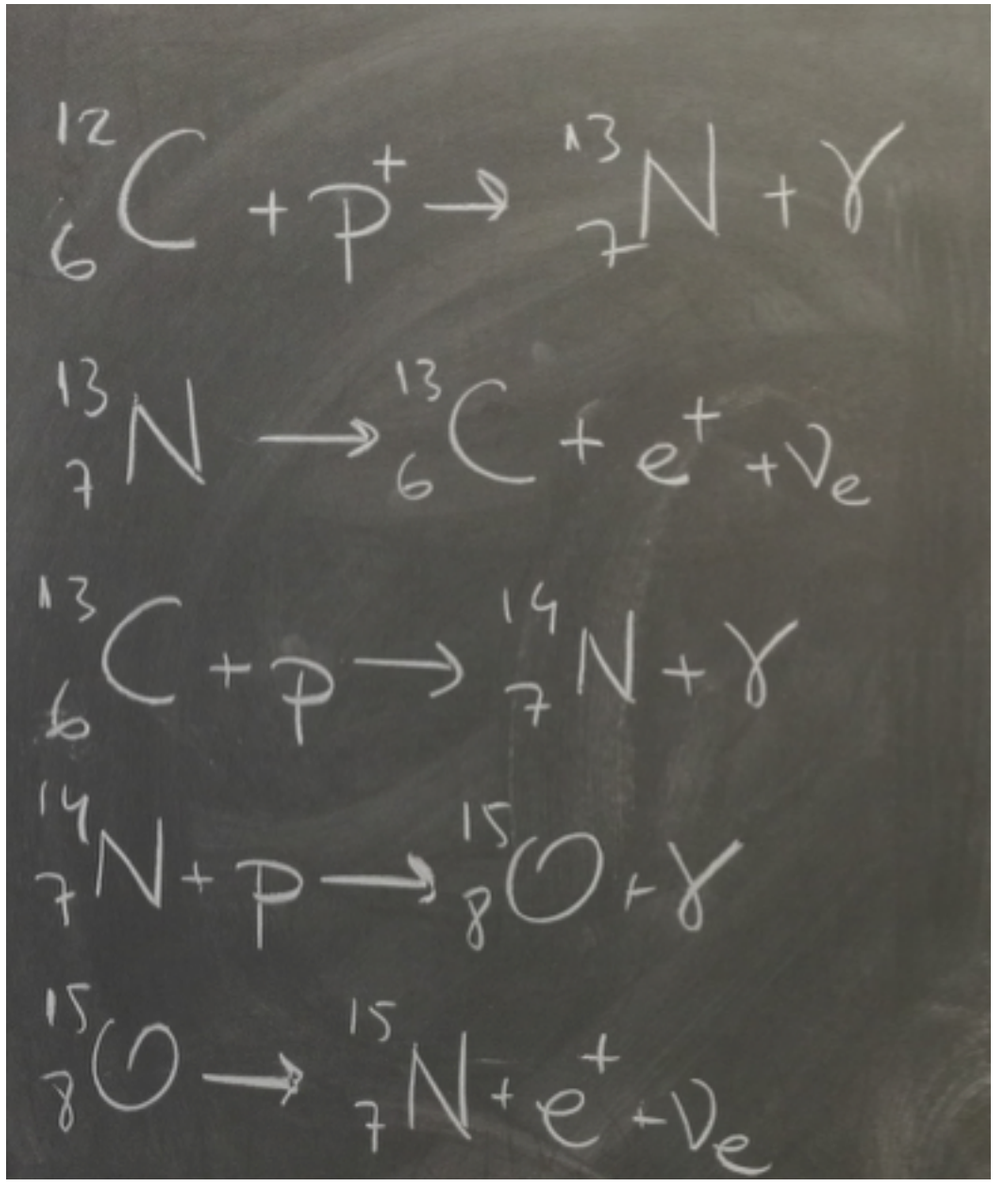

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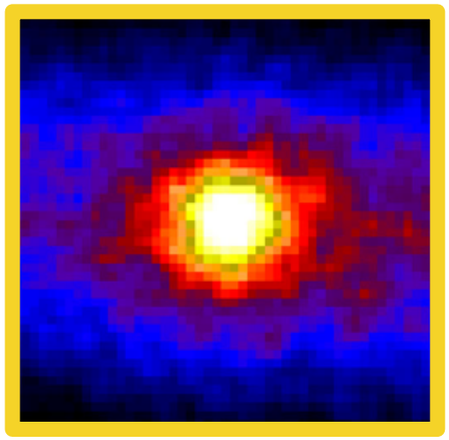

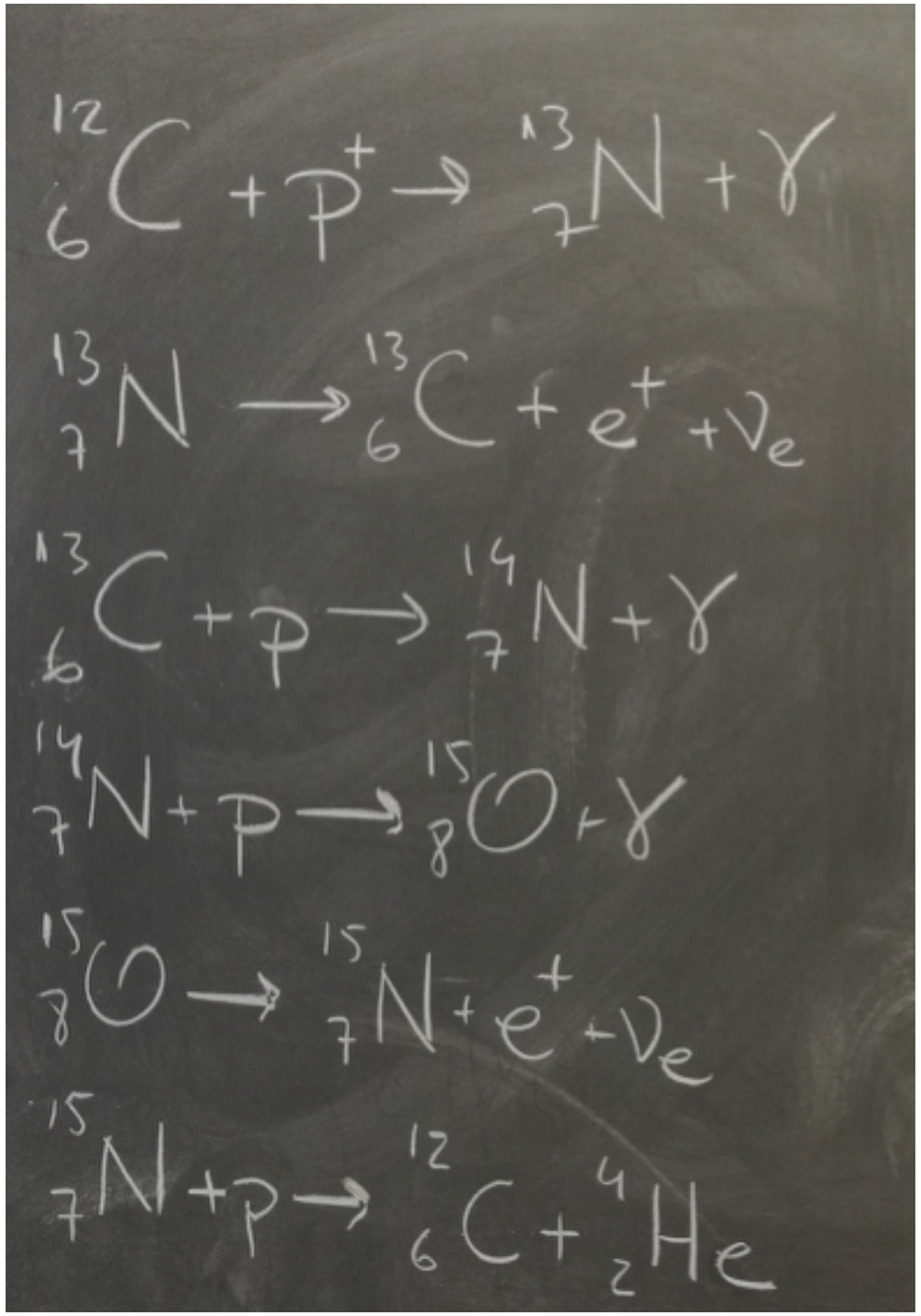

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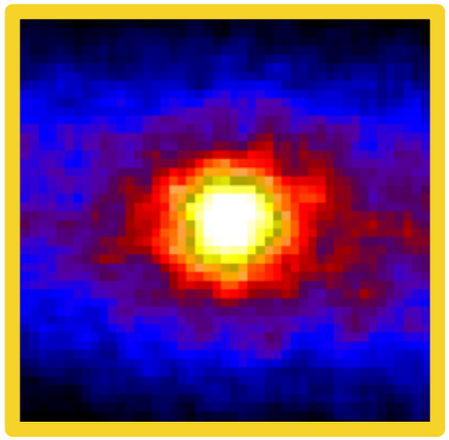

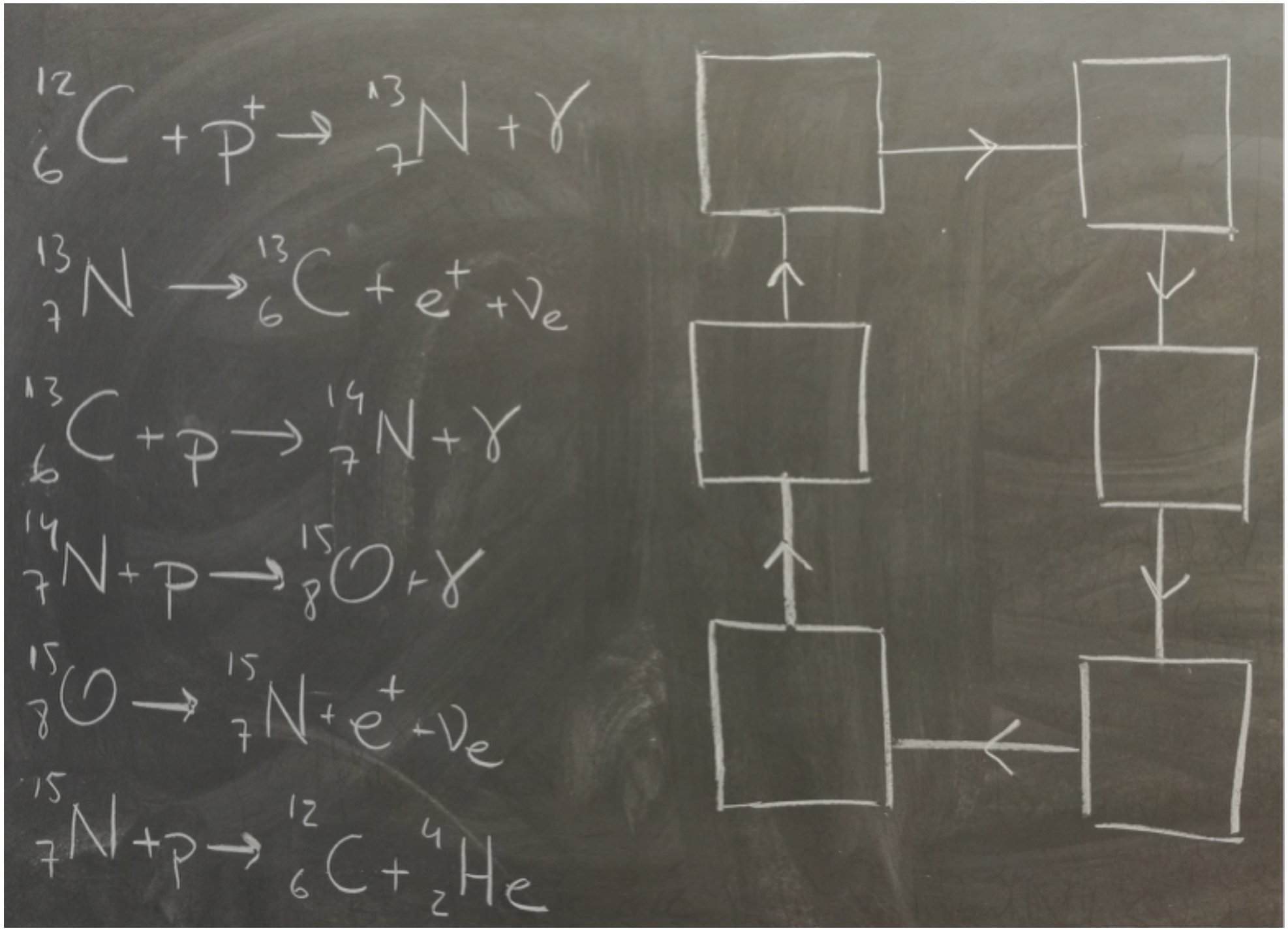

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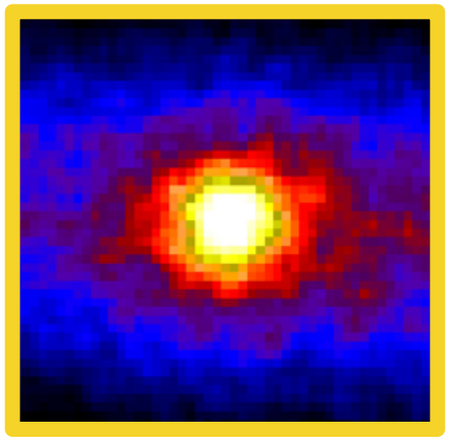

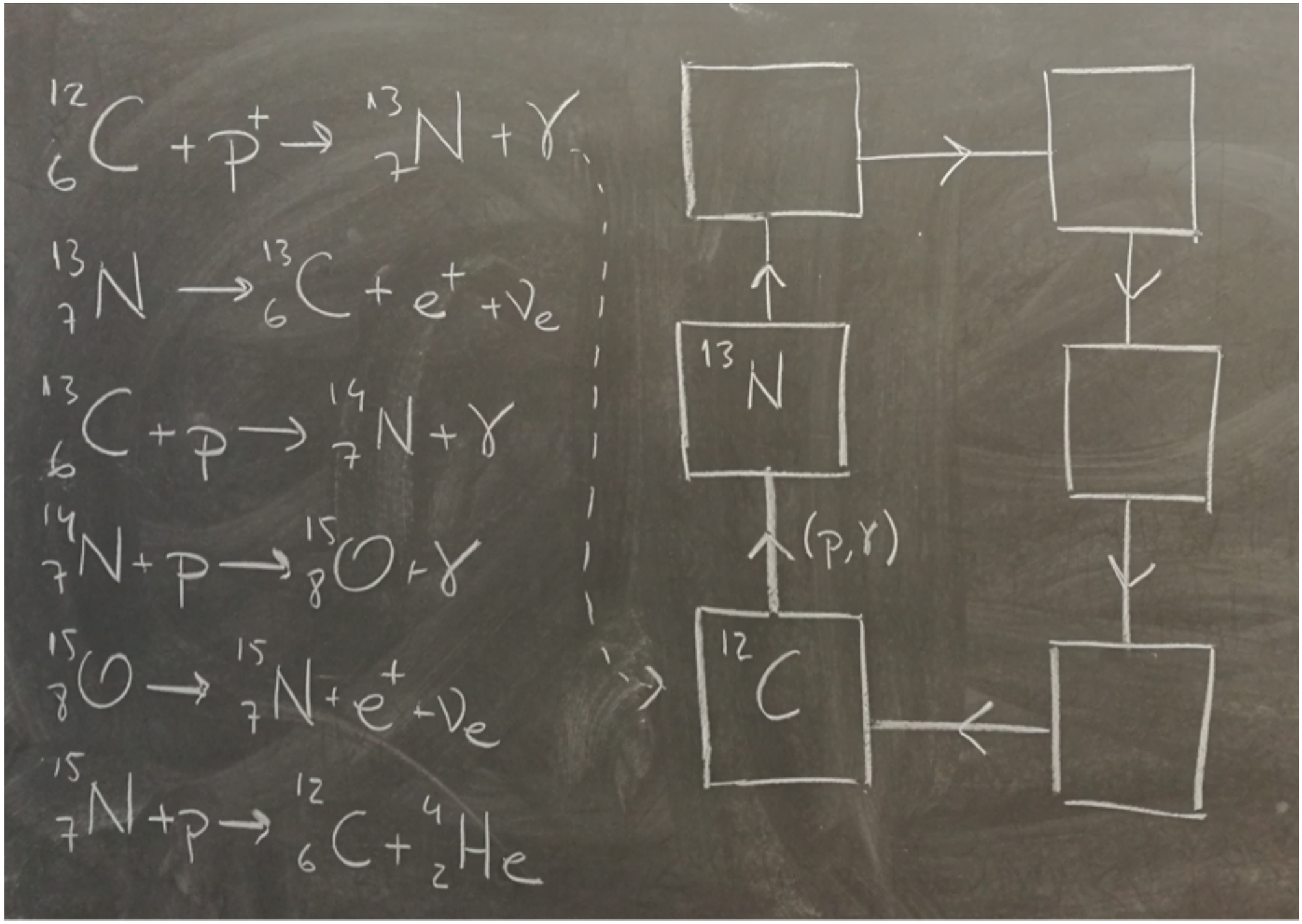

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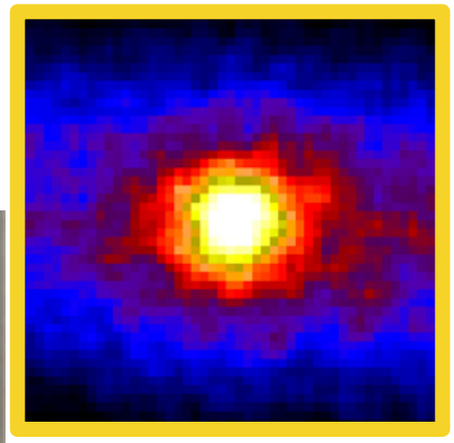

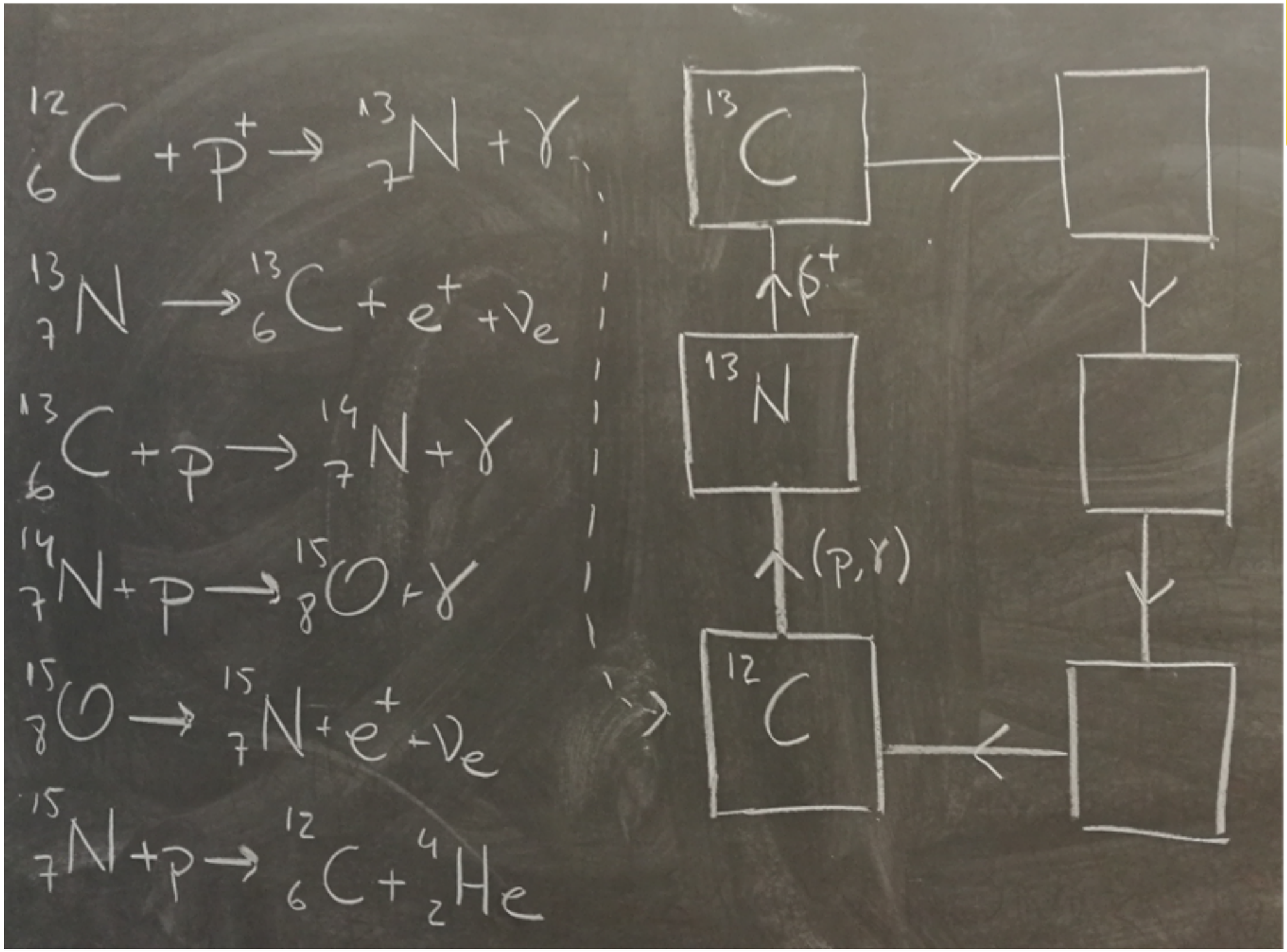

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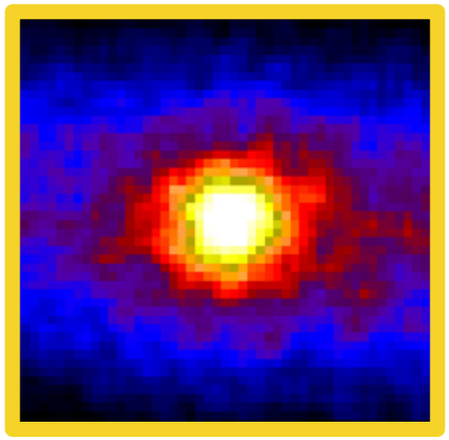

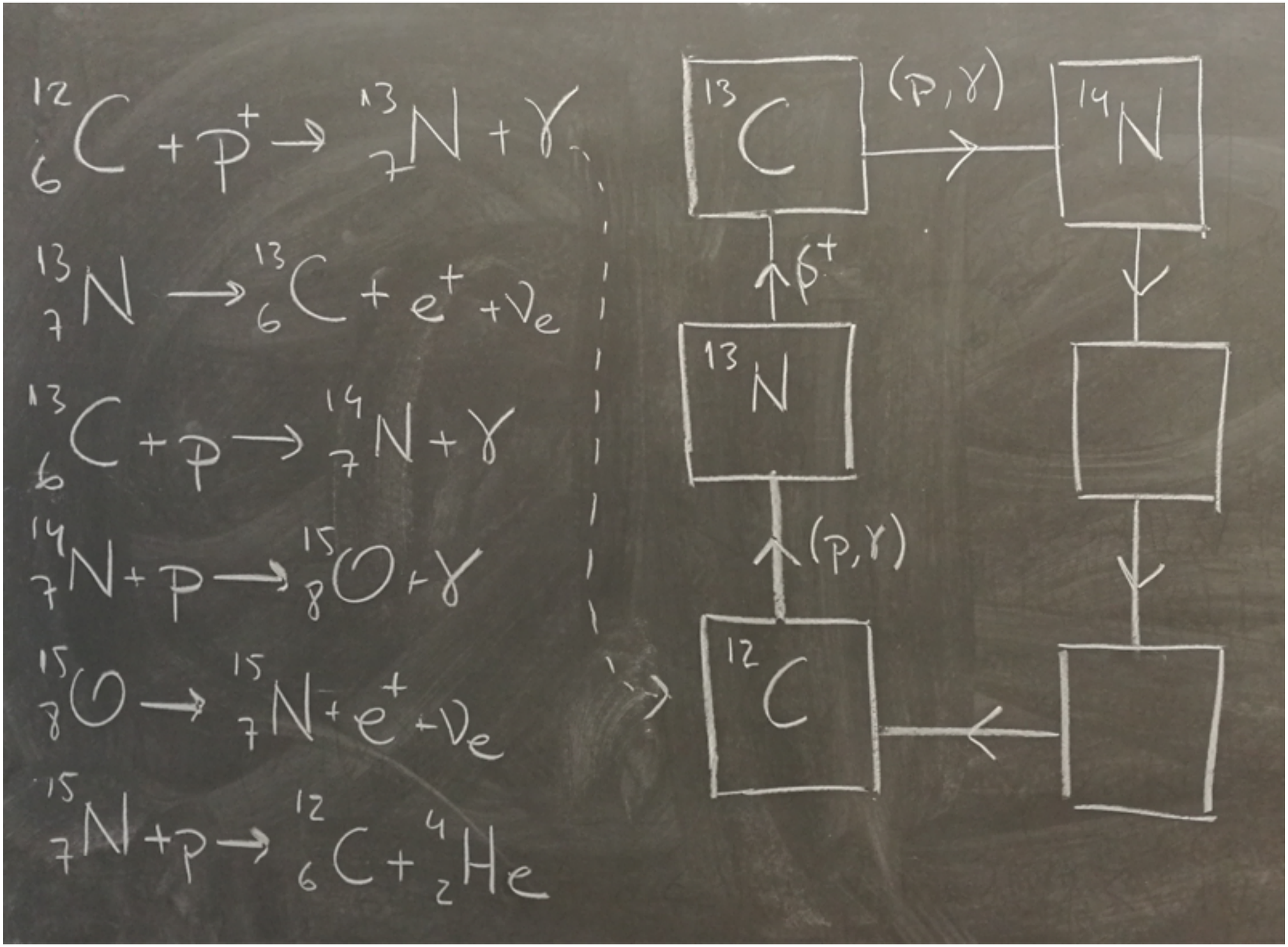

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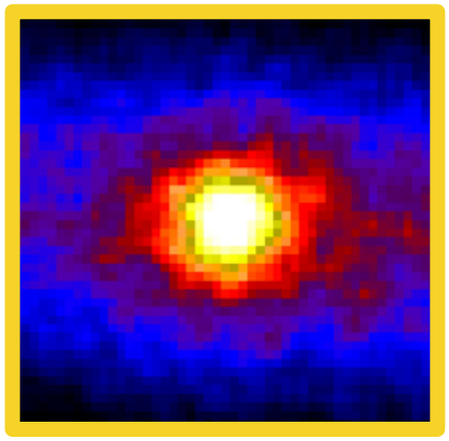

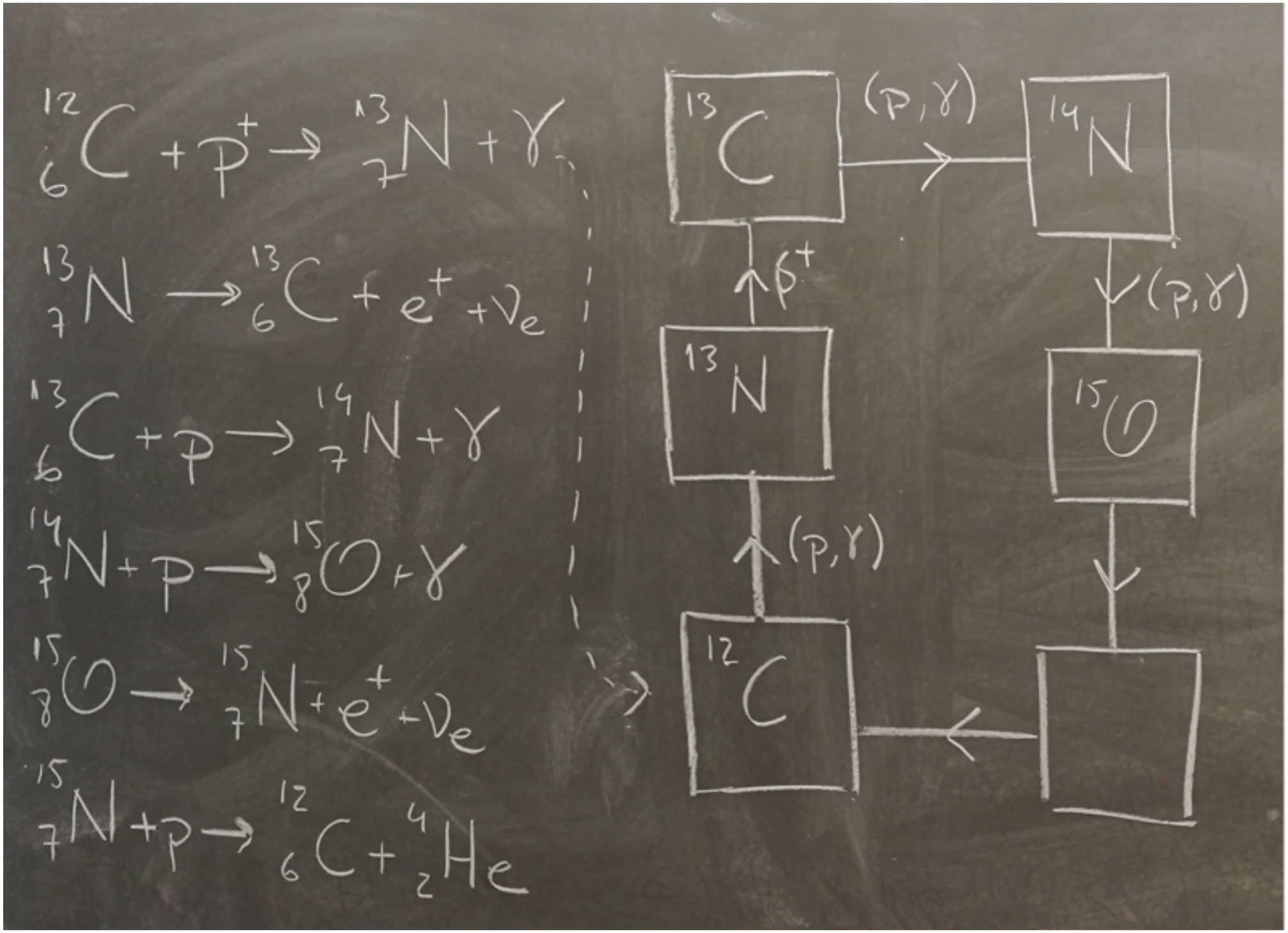

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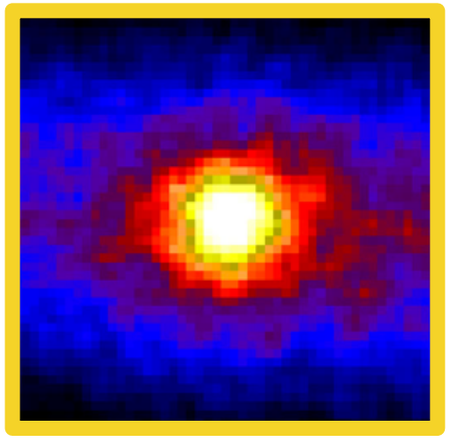

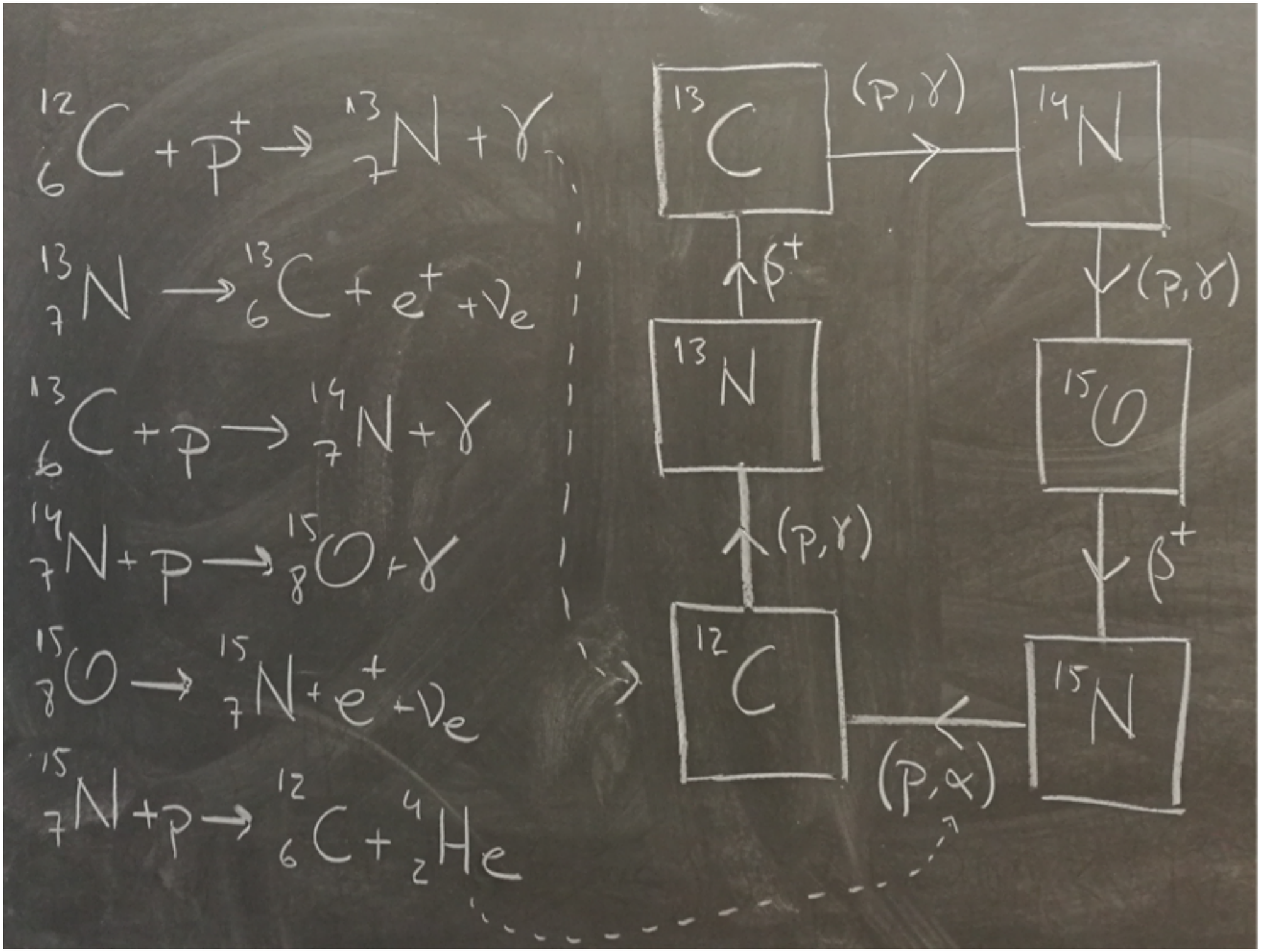

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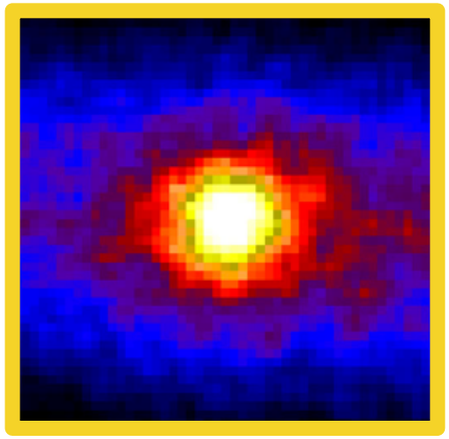

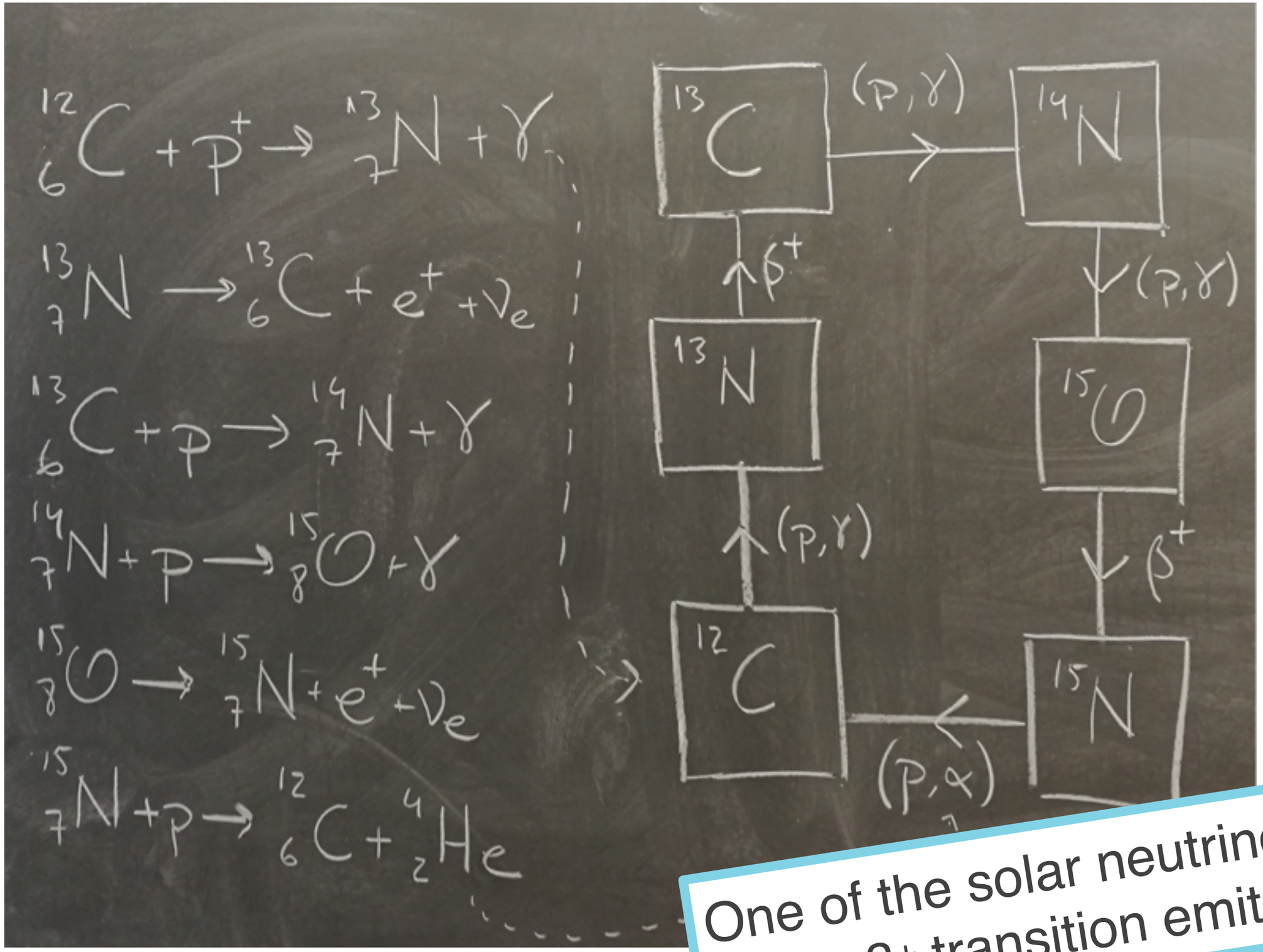

One of the solar neutrino cycles!
Every β^+ transition emits a neutrino!

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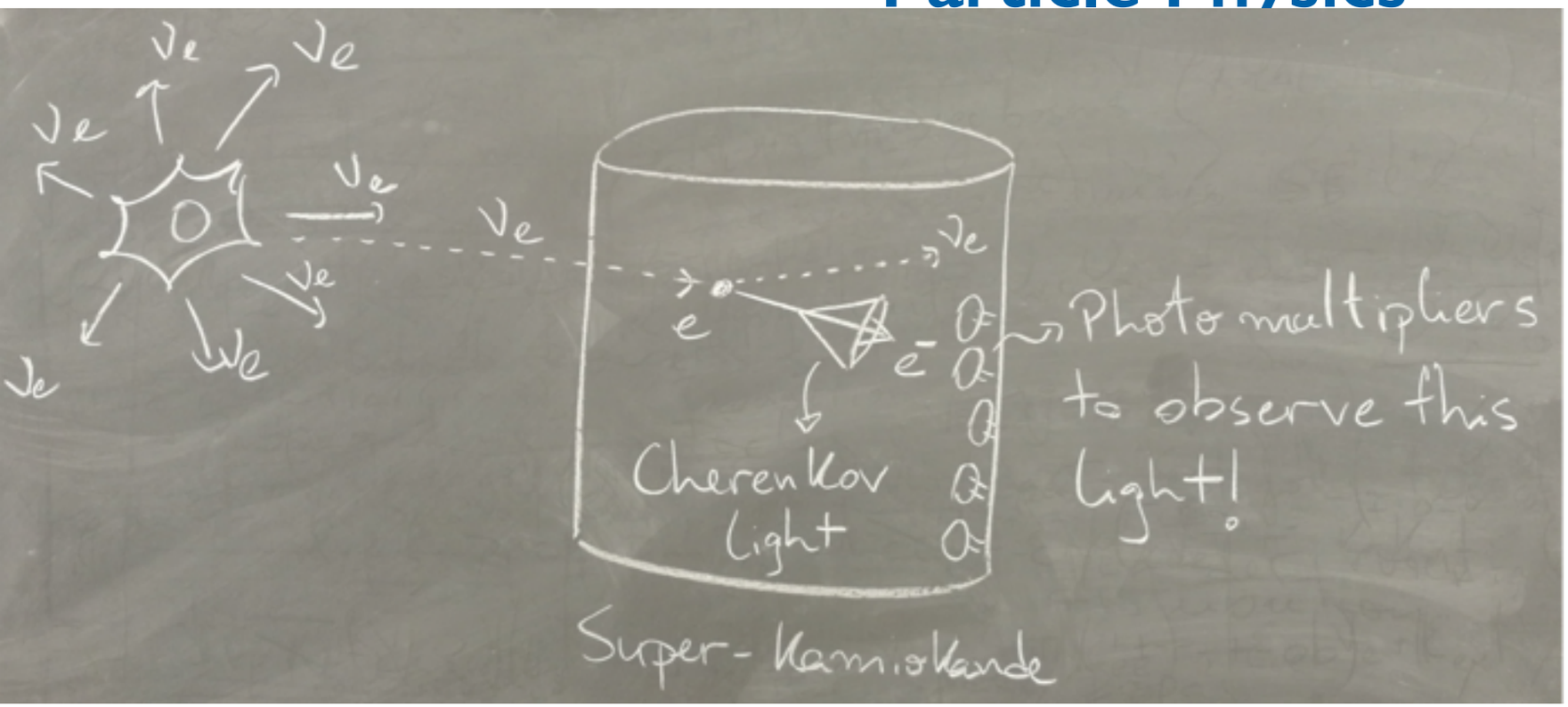

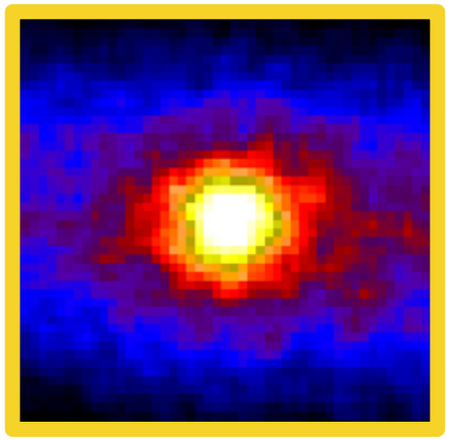

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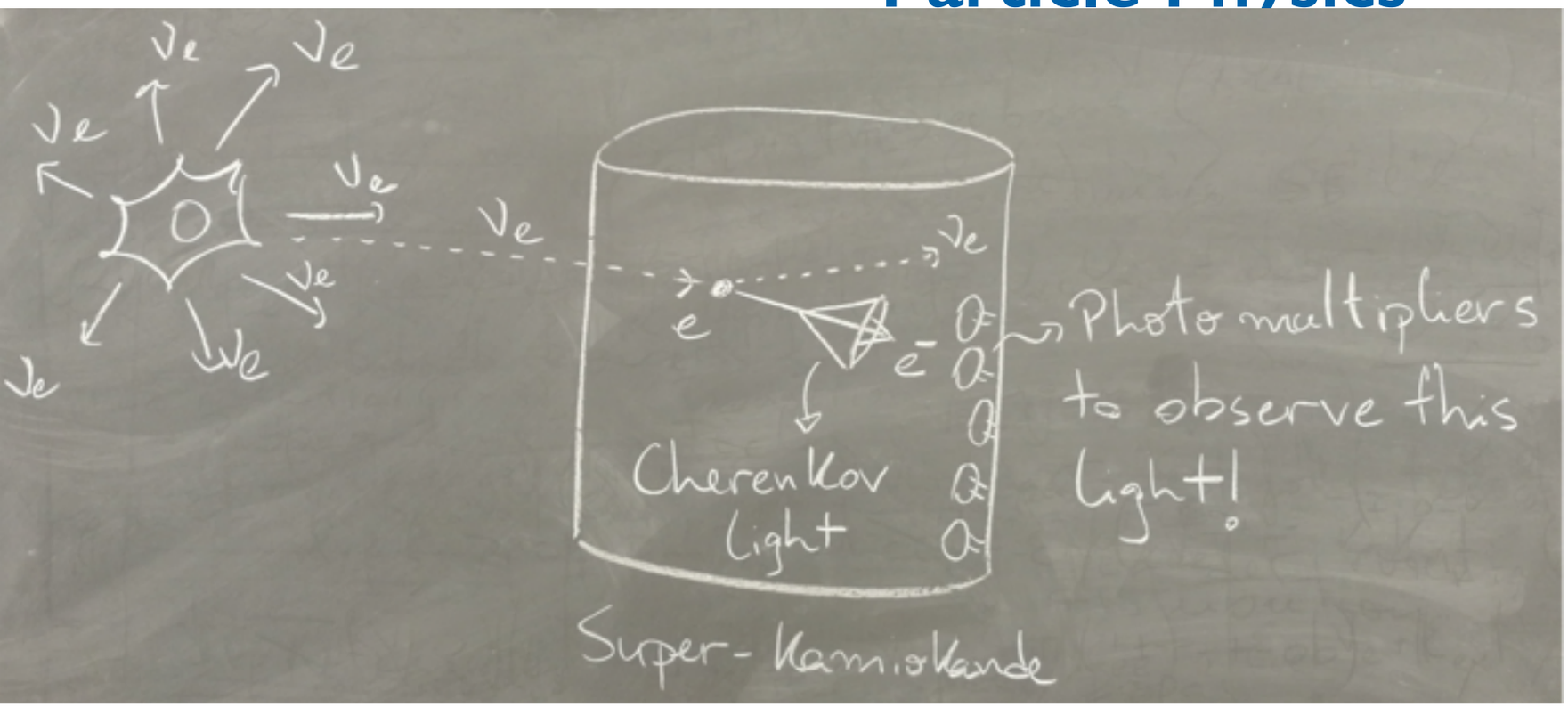

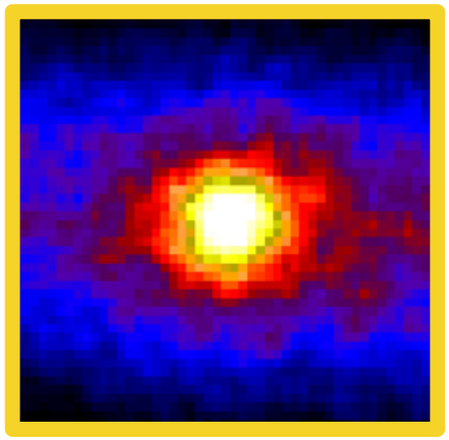

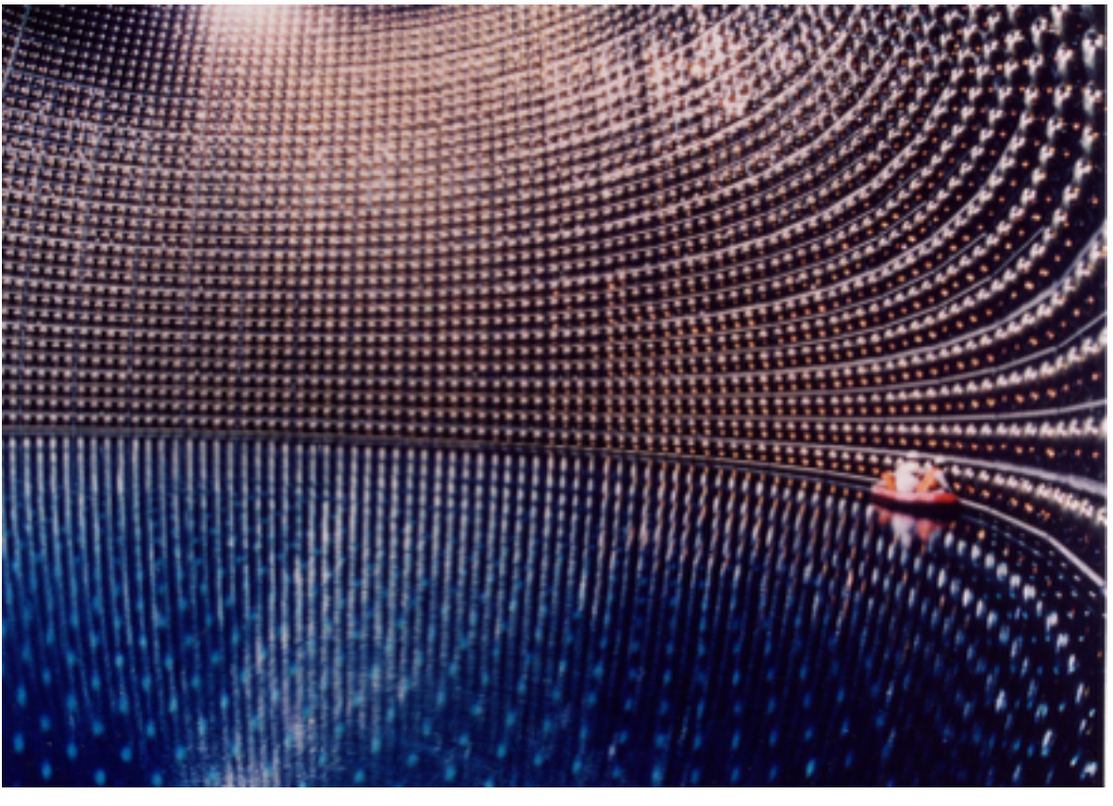

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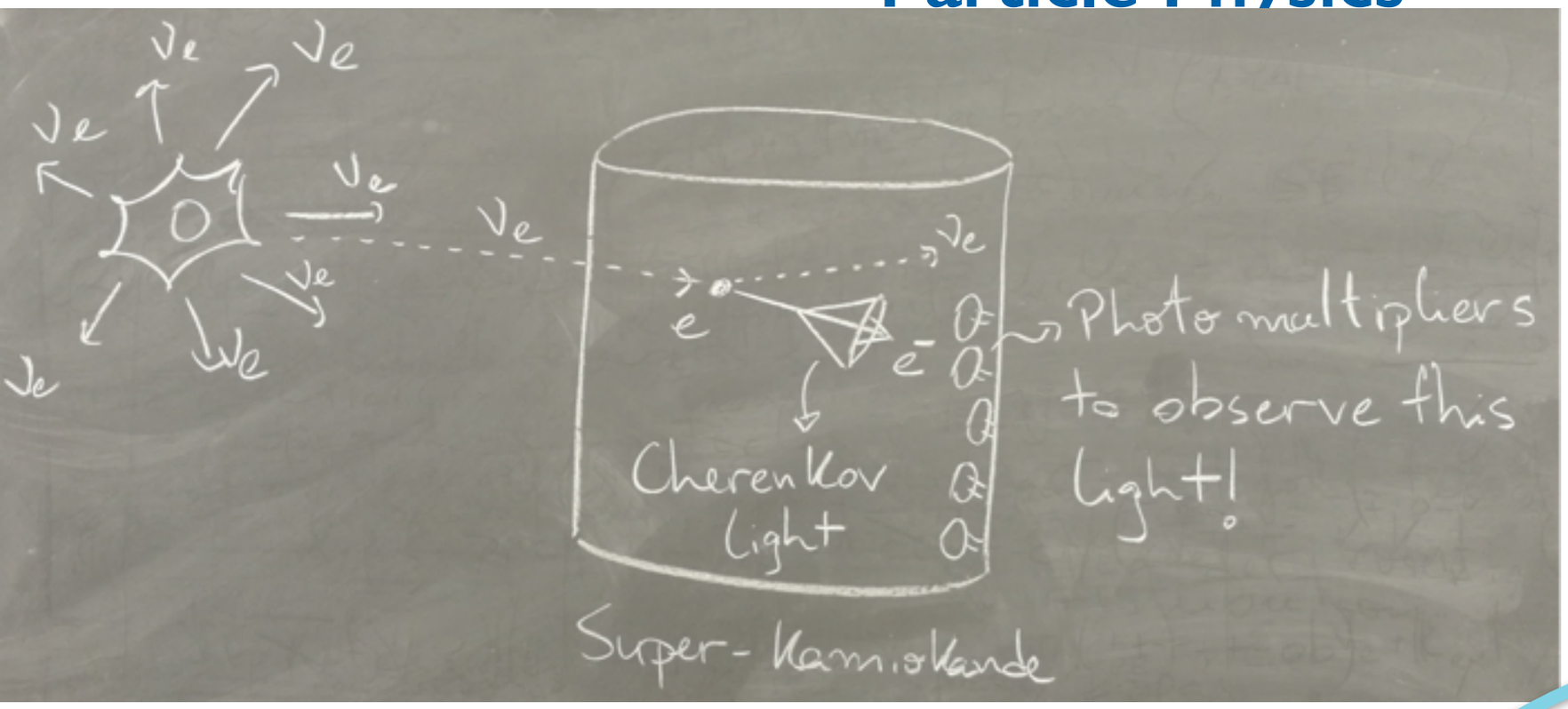

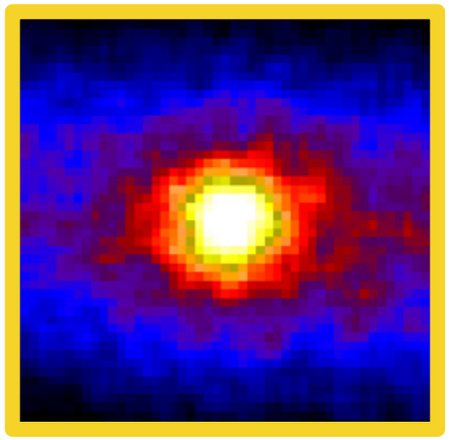

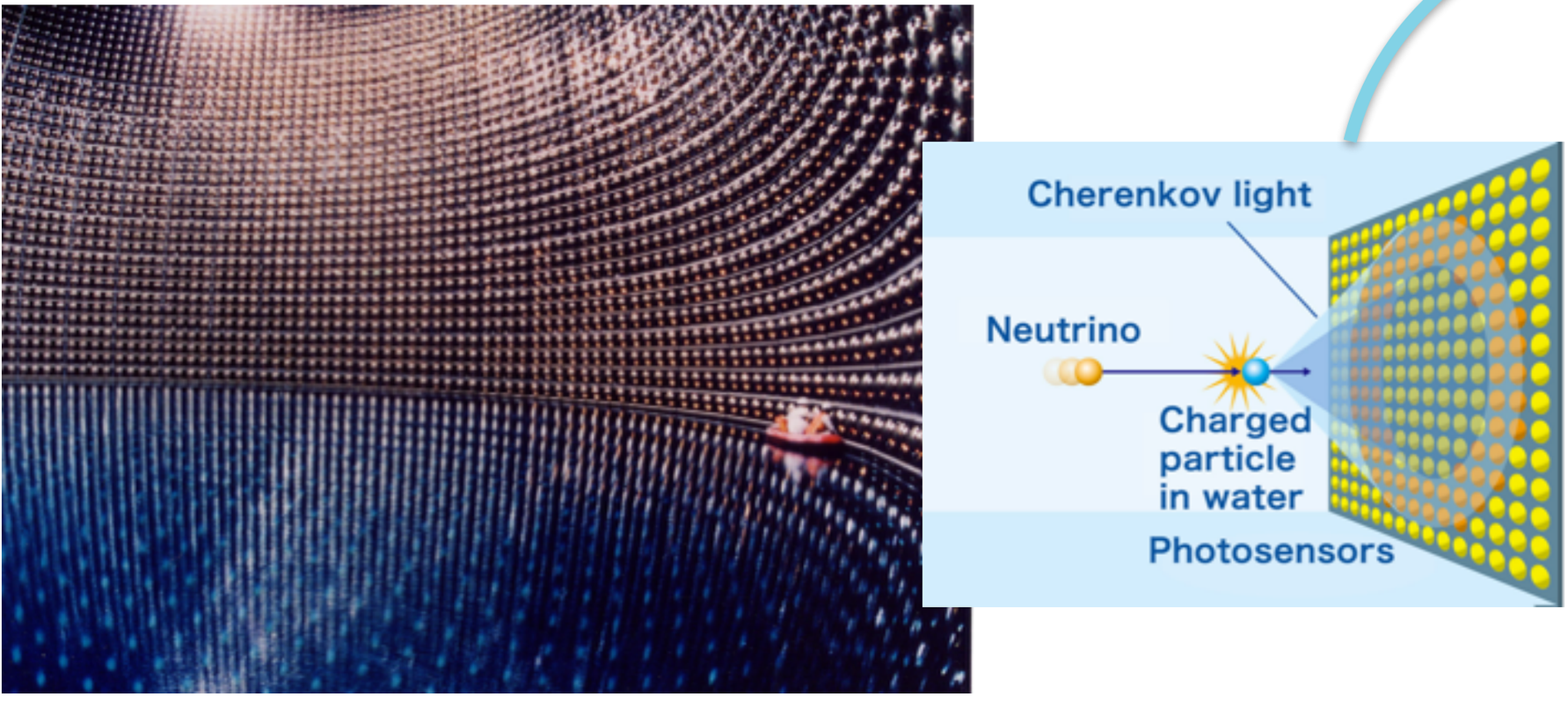

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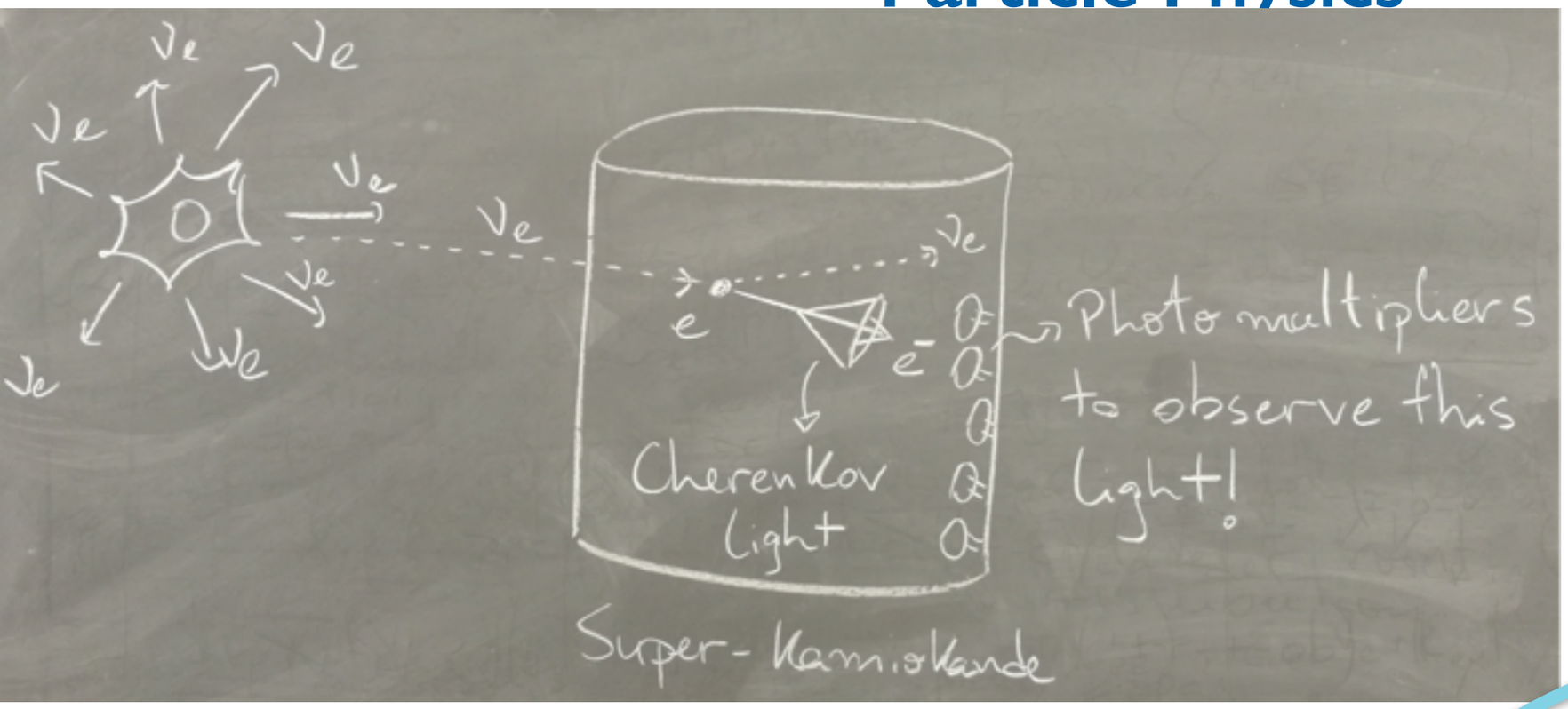
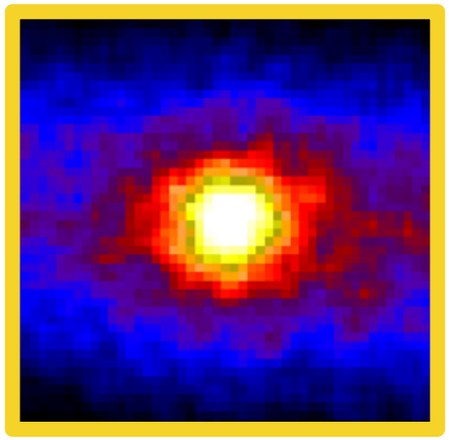
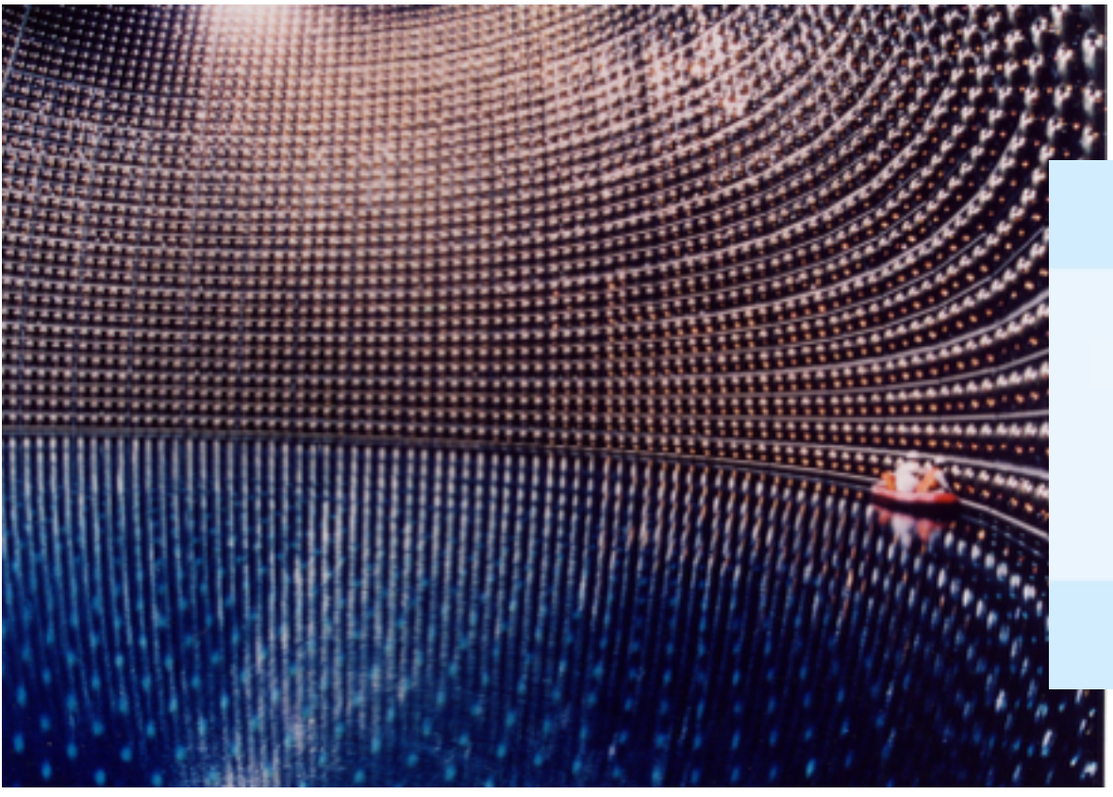
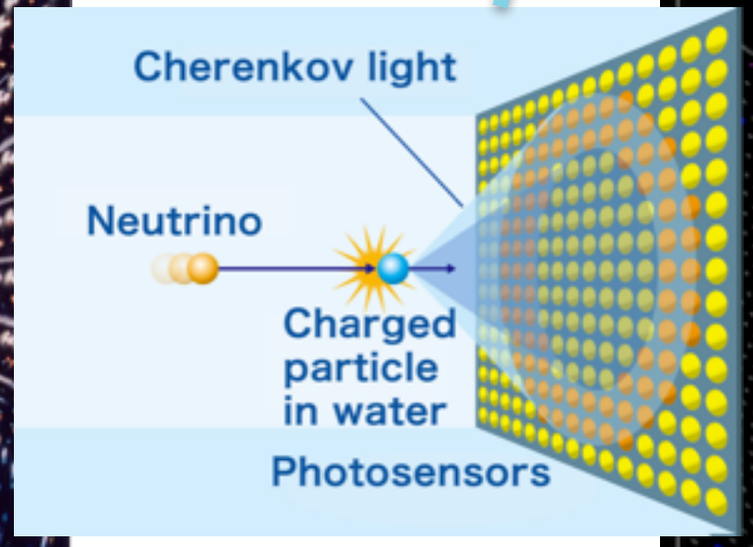
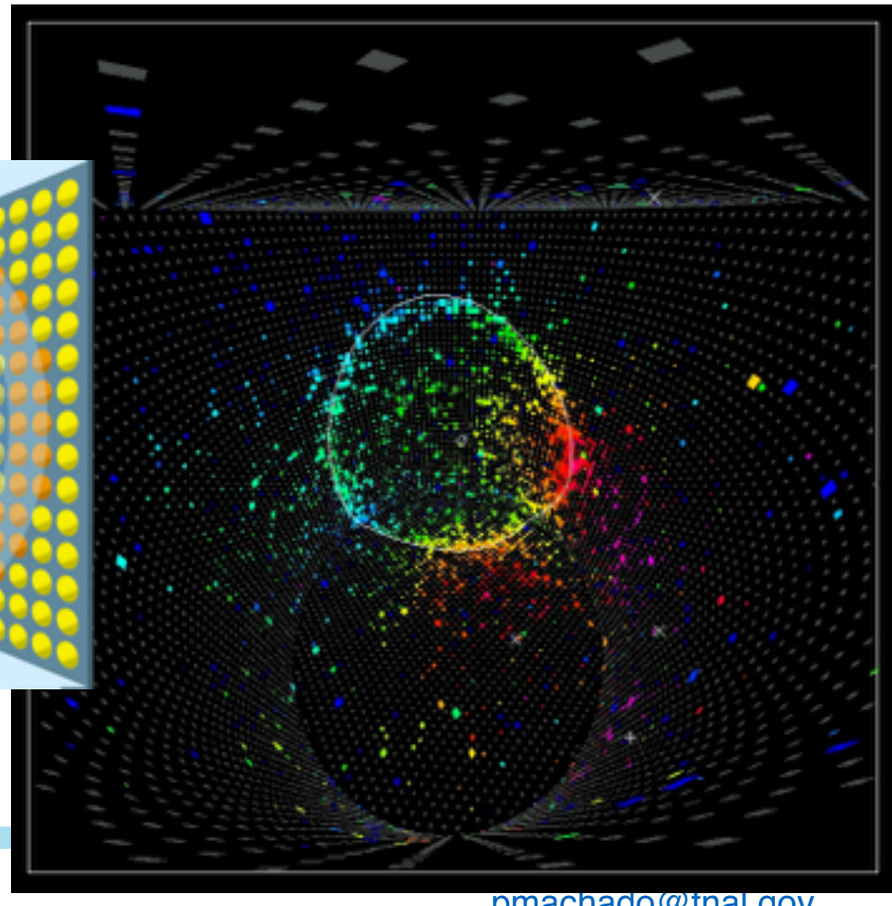
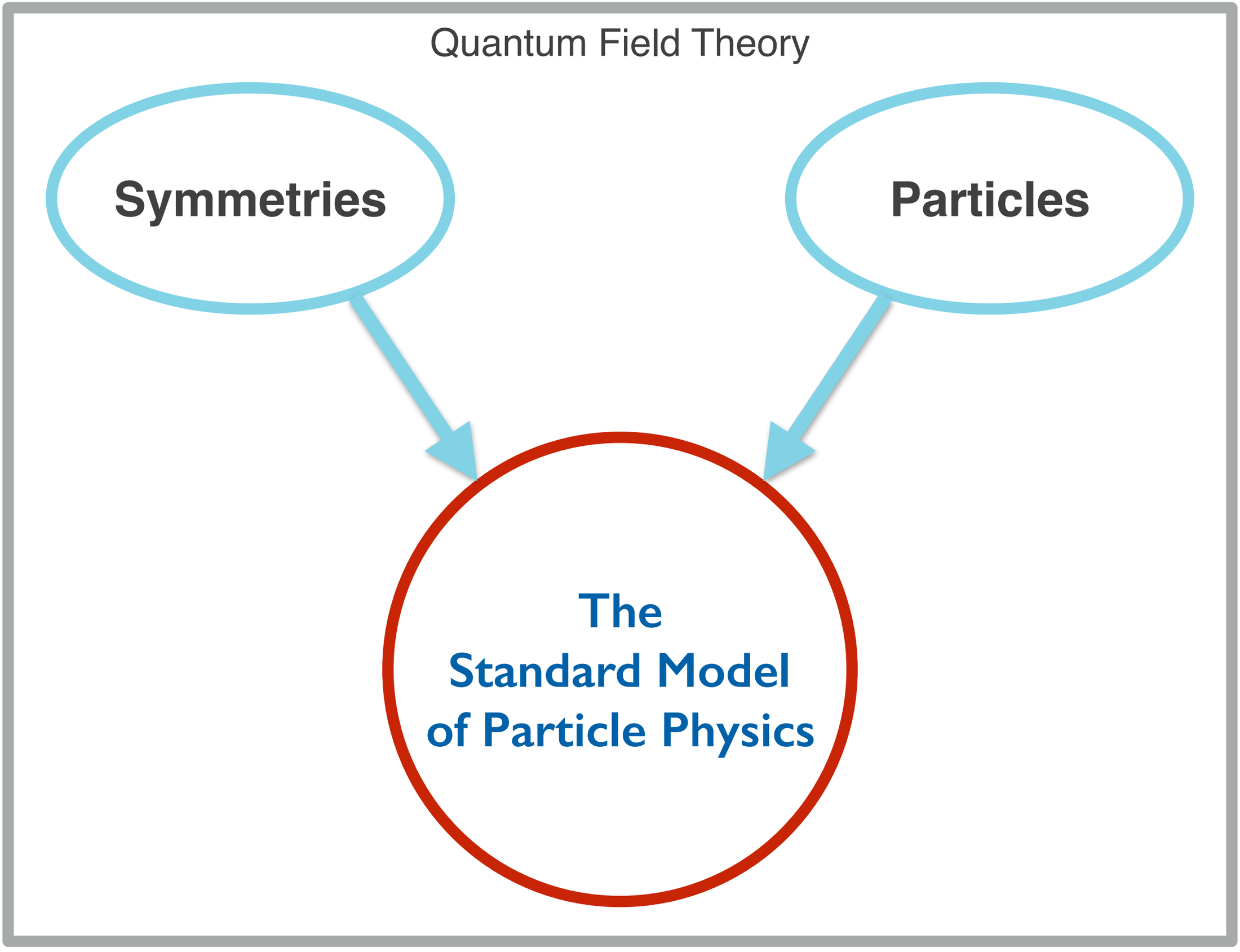











Quantum Field Theory
Symmetries
Particles
The
Standard Model
of Particle Physics

Quantum Field Theory

Consistent framework which incorporates both quantum mechanics and special relativity

Particles are excitations of quantum fields and can be created or annihilated

Symmetries

Emmy Noether

Noether's theorem:

For every differentiable symmetry of the system (action) there exists a corresponding conservation law.

Conservation laws are the backbone of physics: energy, momentum, electric charge, spin, …

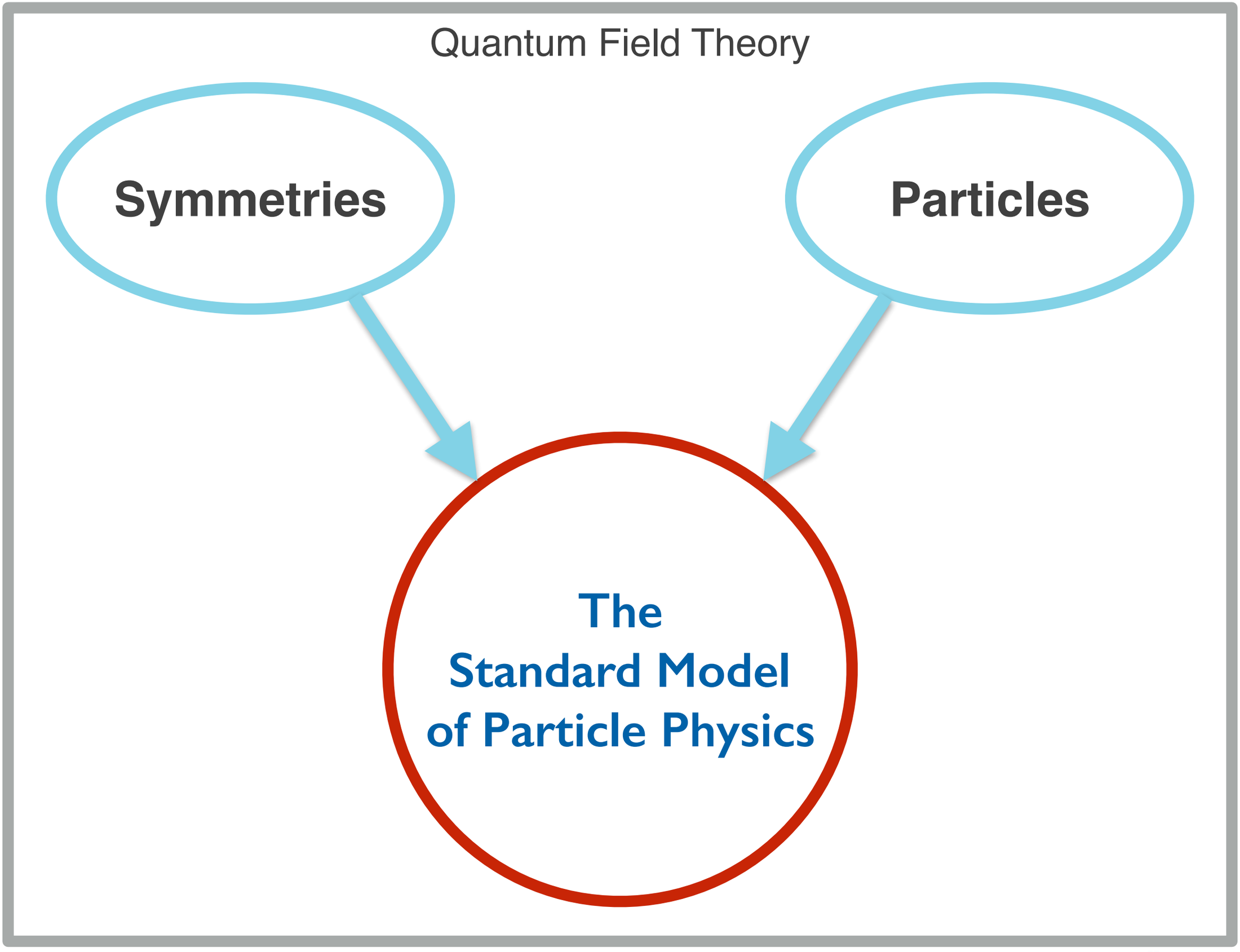
Such symmetries can be described by "Lie groups"

Particles

Symmetries are property of the action which is written in terms of fields (which in turn describe particles).

For every particle discovered, like electrons, muons, and quarks, there is a corresponding field.

QFT predicts antiparticles.


Quantum Field Theory
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What is a symmetry?

A symmetry is a transformation in the fields which leaves the action invariant

$$\psi(x) \to \psi'(x) \Rightarrow \mathcal{L} \to \mathcal{L}$$

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If we forget the electric charge, protons and neutrons are very similar ($m_p \approx m_n \approx 0.938$ GeV)

$$\psi = \begin{pmatrix} p \\ n \end{pmatrix} \rightarrow \psi' = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} p \\ n \end{pmatrix}$$

Or even better (more general)

$$\psi = \begin{pmatrix} p \\ n \end{pmatrix} \rightarrow \psi' = \exp\left(-i\theta_j \tau_j\right) \begin{pmatrix} p \\ n \end{pmatrix}$$

Pauli matrices, the generators of SU(2)

And the Lagrangian remains invariant

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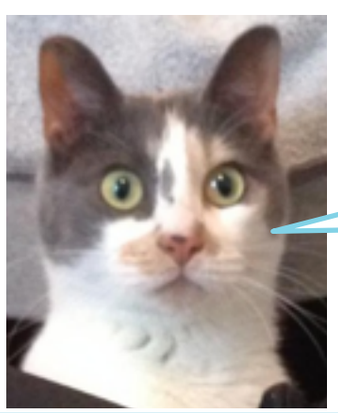

What does that mean???

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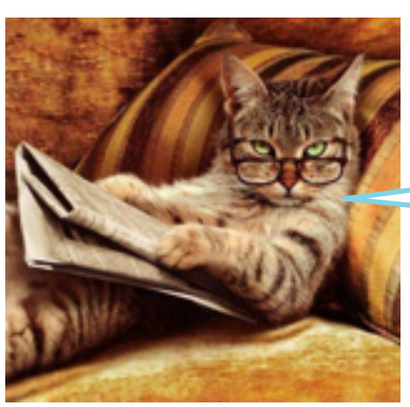

You are free to define proton and neutron, physics should be independent of that.

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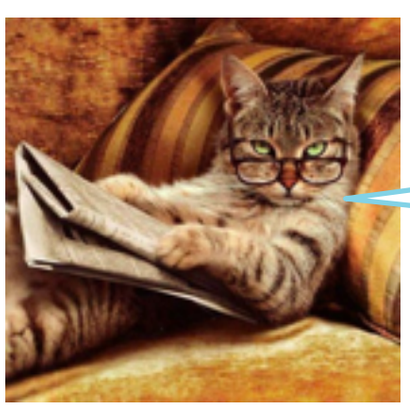

Simpler case: $\psi \rightarrow e^{i\theta}\psi$
Why should it be the same phase everywhere?

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Scalar field and U(1) local transformation

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

$$\phi \to \phi' = e^{i\theta}\phi$$

$\theta = \theta(x)$, don't forget!

Scalar field and U(1) local transformation

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

$$\phi \to \phi' = e^{i\theta}\phi$$

$\theta = \theta(x)$, don't forget!

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

Check: this will make the Lagrangean <u>not</u> invariant!

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Check: this will make the Lagrangean <u>not</u> invariant!

Fix:

$$\partial_\mu \to \partial_\mu - igA_\mu \equiv D_\mu$$

"Gauge field"

"Covariant derivative"

$$D_\mu \phi \to (\partial_\mu - igA'_\mu)\phi'$$

$$A_\mu \to A'_\mu = A_\mu + \delta_\mu$$

Defined to restore invariance

Doing the calculation... $\dashrightarrow$ $A'_\mu = A_\mu - \frac{1}{g}\partial_\mu \theta$

Invariance under local transformations (gauge symmetries), require additional, dynamical fields

These fields are the force carriers, like the photon

fermion + local phase invariance = electromagnetism

electrons U(1) gauge symmetry quantum electrodynamics

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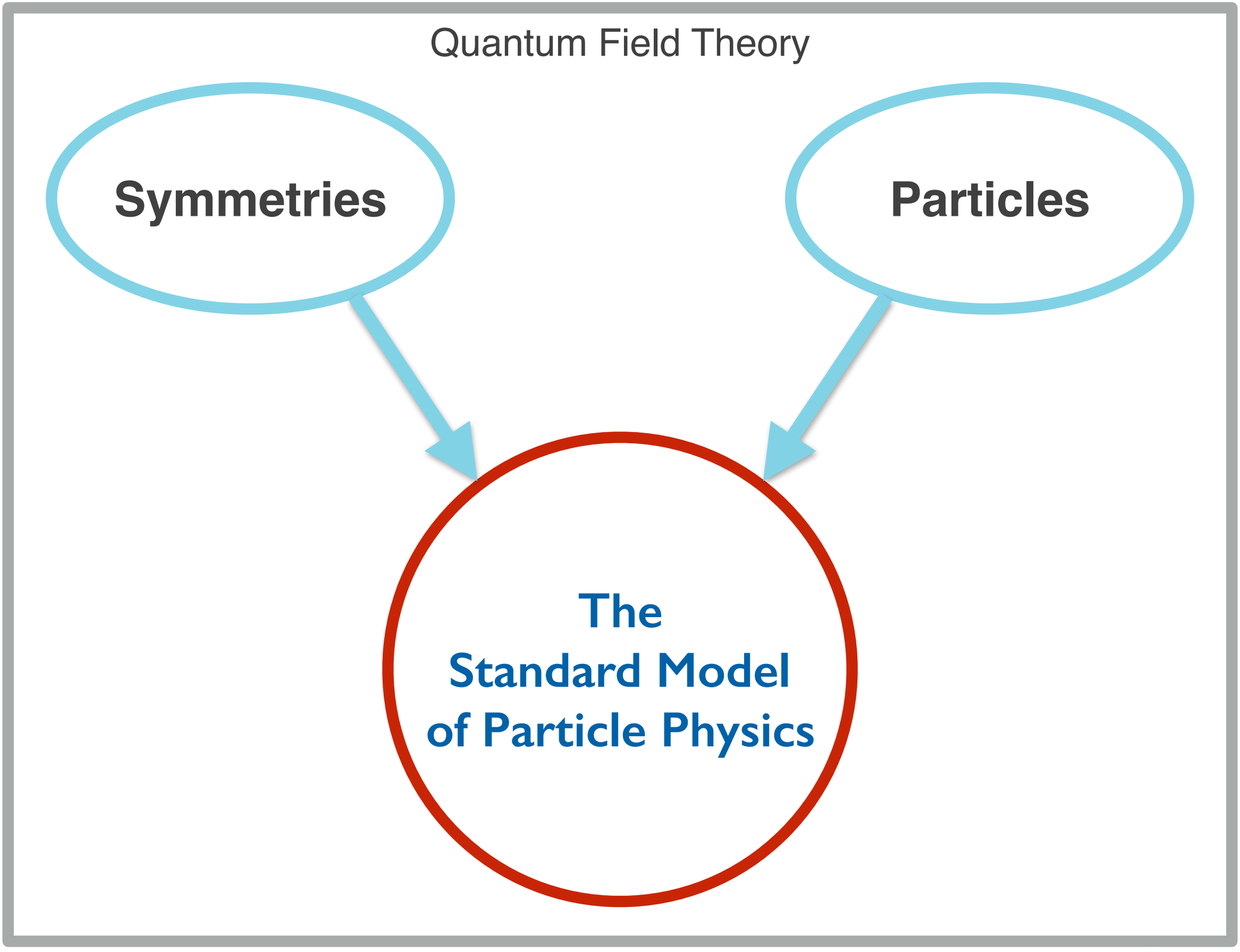
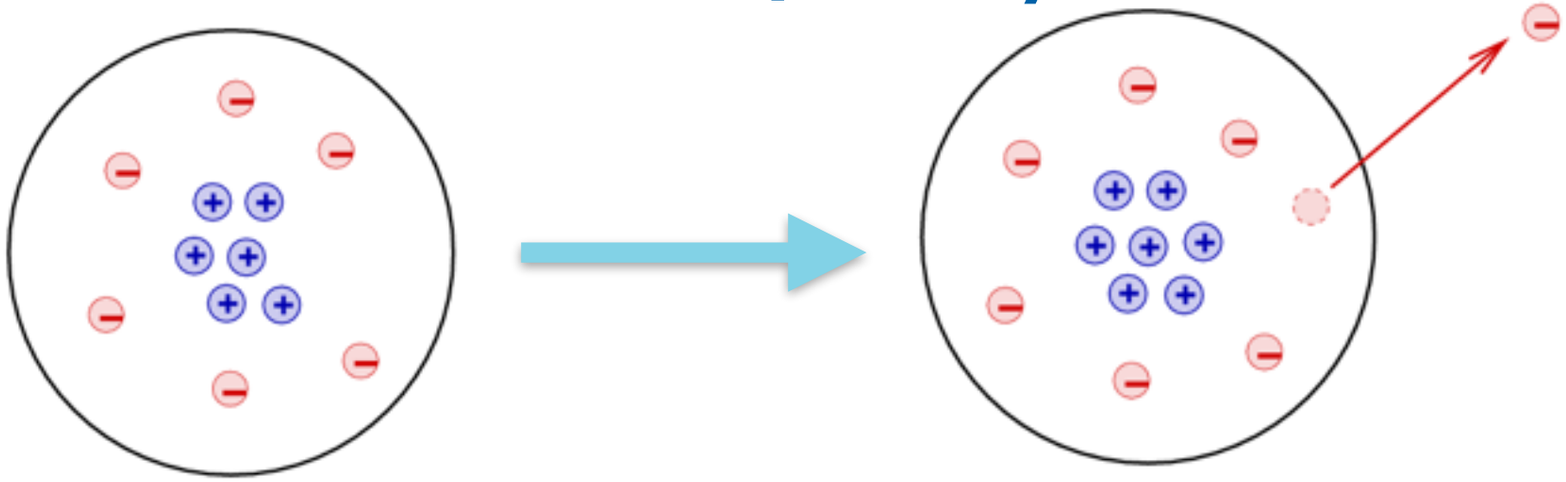
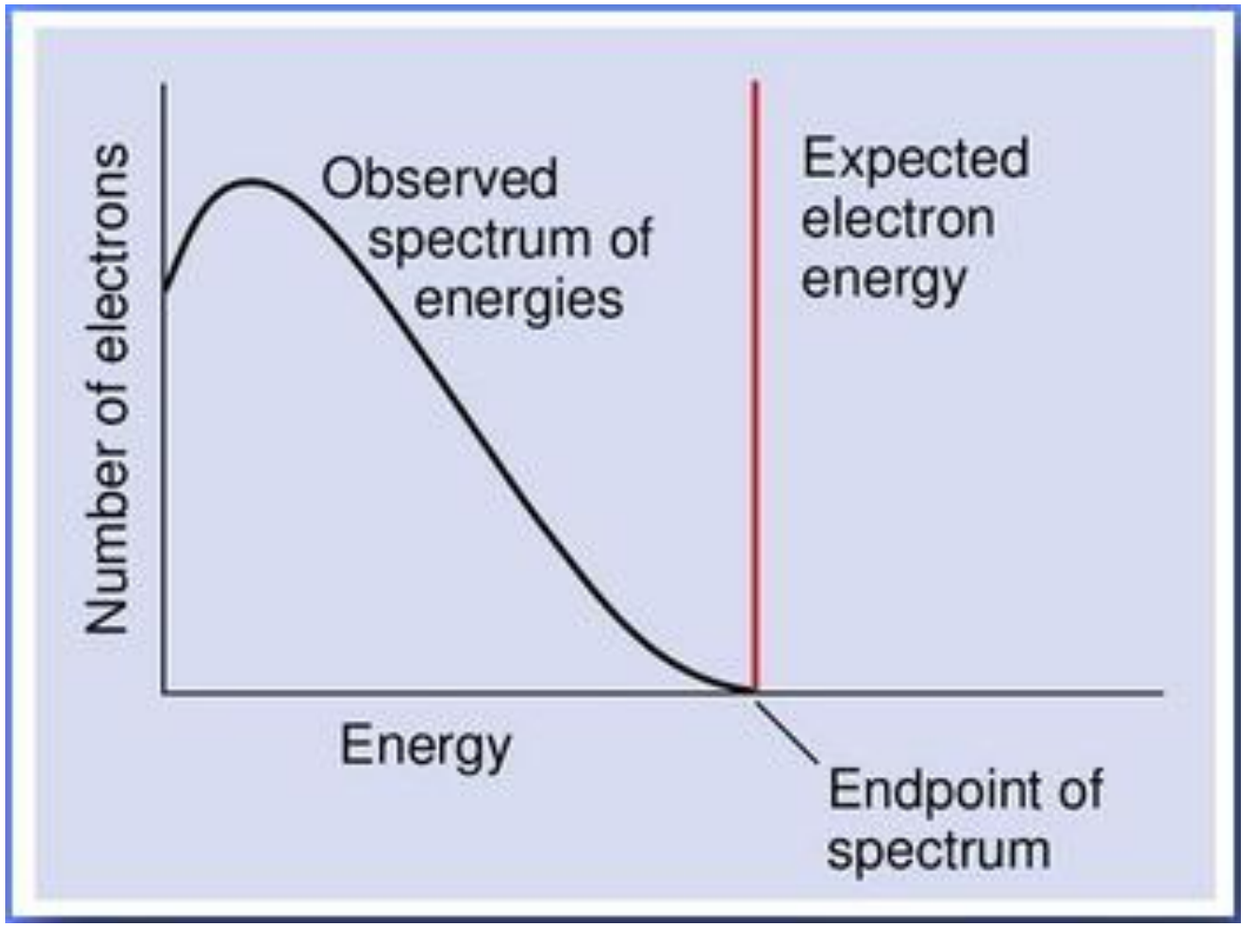

Quantum Field Theory
Symmetries
Particles
The
Standard Model
of Particle Physics

Issues with β decays





Observations by Sir J. Chadwick, 1914

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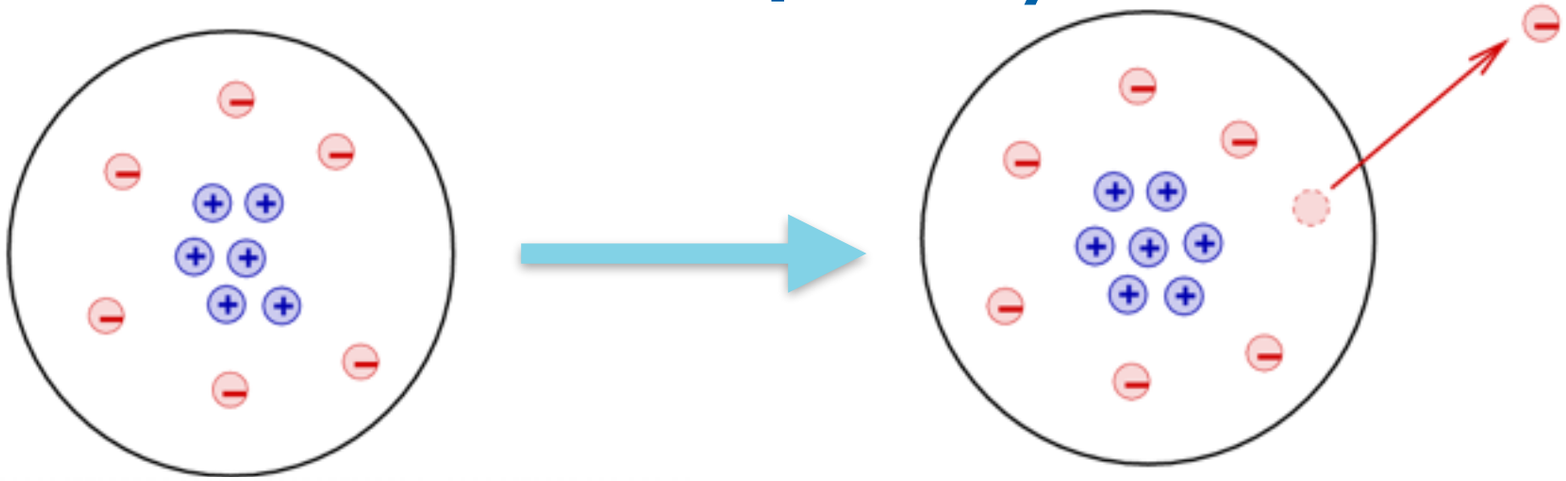
Issues with β decays

Winter of 1930



Original - Photocopie of PLC 0393

Abschrift/15.12.56 FM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

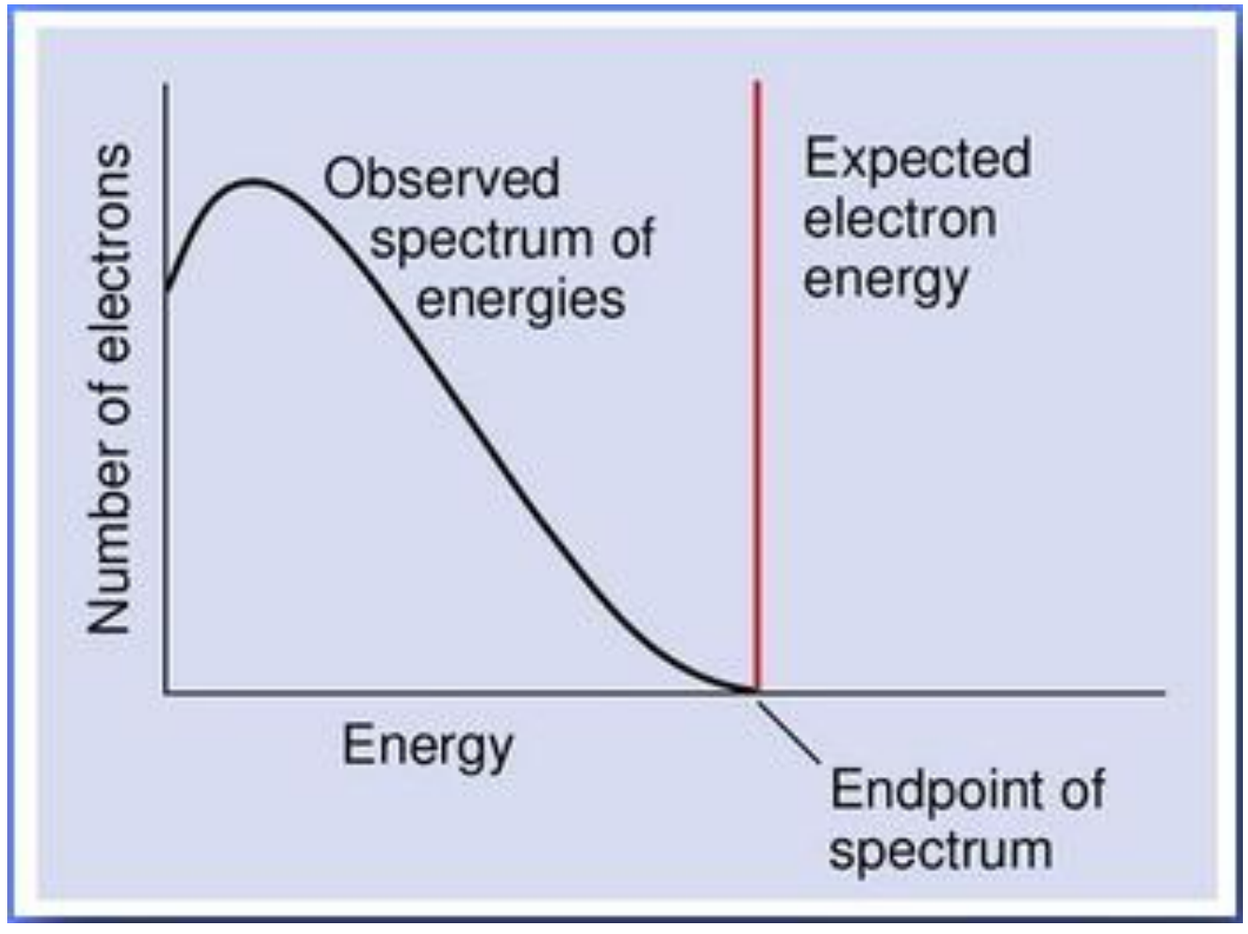
Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

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



Observations by Sir J. Chadwick, 1914

- Gross violation of energy-momentum conservation!
- Postulates an "invisible" particle to avoid catastrophe - the **neutrino**

Theory of β decays

Versuch einer Theorie der β-Strahlen. I[1]).

Von **E. Fermi** in Rom.

Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

Eine quantitative Theorie des β-Zerfalls wird vorgeschlagen, in welcher man die Existenz des Neutrinos annimmt, und die Emission der Elektronen und Neutrinos aus einem Kern beim β-Zerfall mit einer ähnlichen Methode behandelt, wie die Emission eines Lichtquants aus einem angeregten Atom in der Strahlungstheorie. Formeln für die Lebensdauer und für die Form des emittierten kontinuierlichen β-Strahlenspektrums werden abgeleitet und mit der Erfahrung verglichen.

(1) $$Q = \begin{vmatrix} 0 & 1 \\ 0 & 0 \end{vmatrix}; \qquad Q^* = \begin{vmatrix} 0 & 0 \\ 1 & 0 \end{vmatrix}$$

Si riconosce immediatamente che Q determina le transizioni da protone a neutrone, e Q^* le transizioni opposte da neutrone a protone.

$$\psi = \sum_s \psi_s a_s$$ electron

$$\varphi = \sum \varphi_\sigma b_\sigma$$ neutrino

$$\mathcal{H} = g[Q\psi(x)\varphi(x) + Q^*\psi^*(x)^*(x)]$$

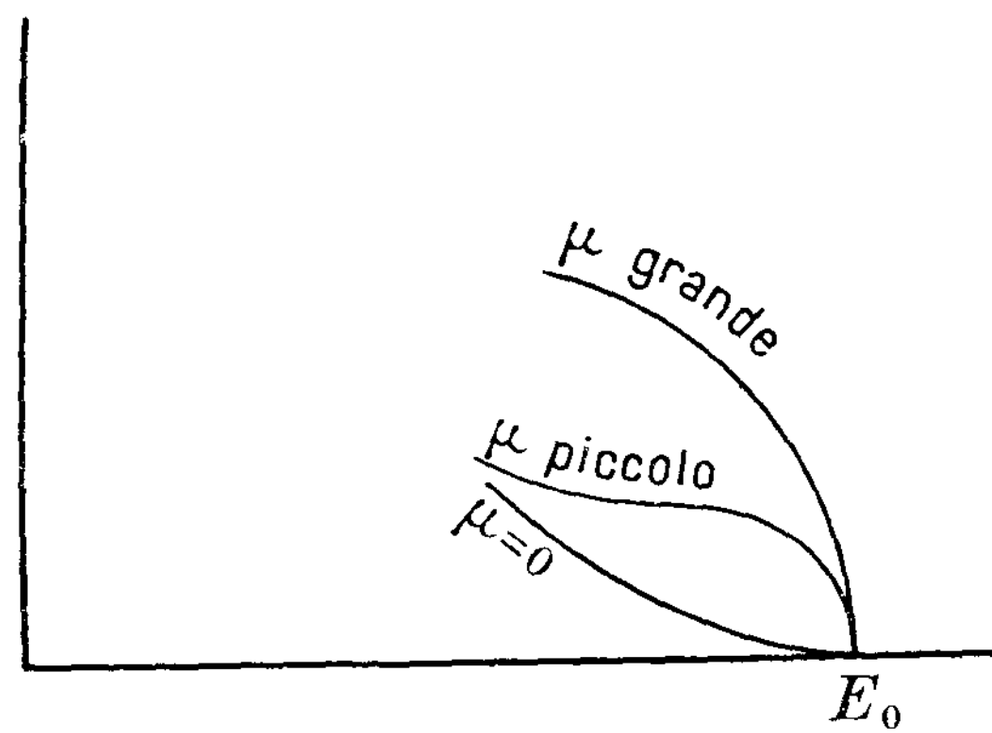


Fig. 1

Theory of β decays

$$H = g\left[Q\psi(x)\phi(x) + Q^*\psi^*(x)\phi^*(x)\right]$$

ψ = electron, ϕ = neutrino

Operator: neutron to proton transition

In modern language: $\mathcal{L}_{\text{Fermi}} \propto G\overline{\psi}_p \Gamma \psi_n \overline{\psi}_e \Gamma' \psi_{\nu_e}$

Predictions: muon and neutron lifetimes!

τ = 2.2 μs: $\mu \to e\nu\nu$

τ = 880 s: $n \to p^+ e^- \nu$

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pmachado@fnal.gov

Making a long story short…

$$\mathcal{L}_{\text{Fermi}} \propto G\overline{\psi}_p \Gamma \psi_n \overline{\psi}_e \Gamma' \psi_{\nu_e}$$

Symmetry!

$$\begin{pmatrix} p \\ n \end{pmatrix} \quad \begin{pmatrix} \nu \\ \ell \end{pmatrix}$$

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Fermi theory originated the theory of weak interactions

SU(2) gauge symmetry

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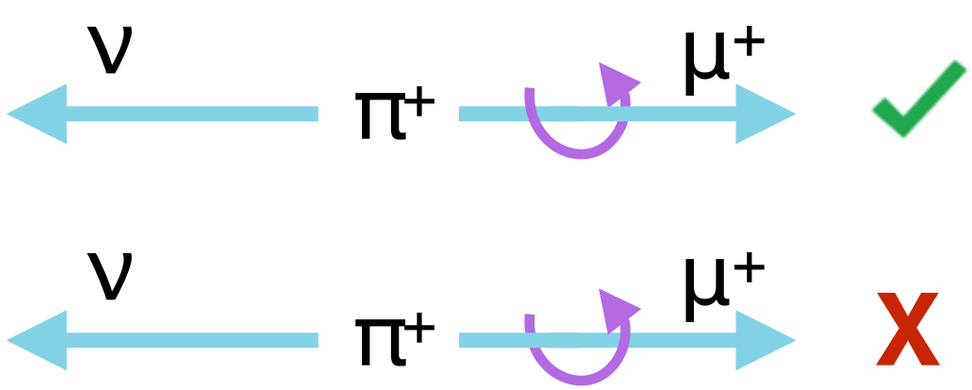
Non-conservation of parity in pion decays

Garwin, Lederman, Weinrich 1957



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SU(2) gauge symmetry

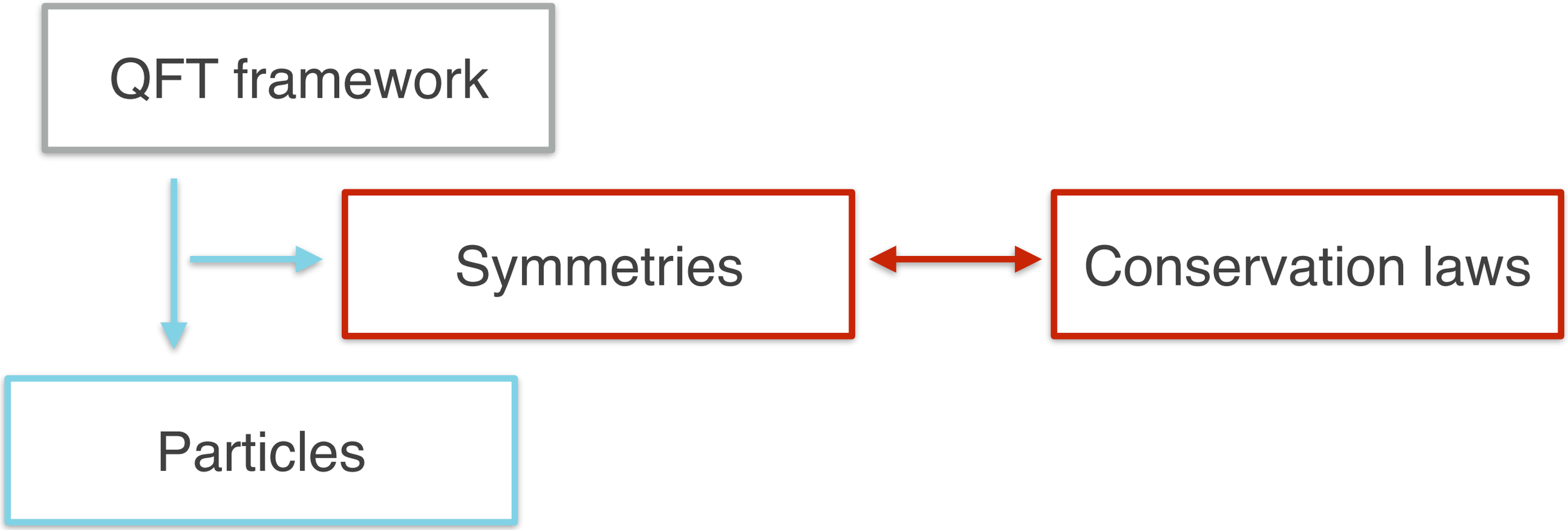
Two problems:

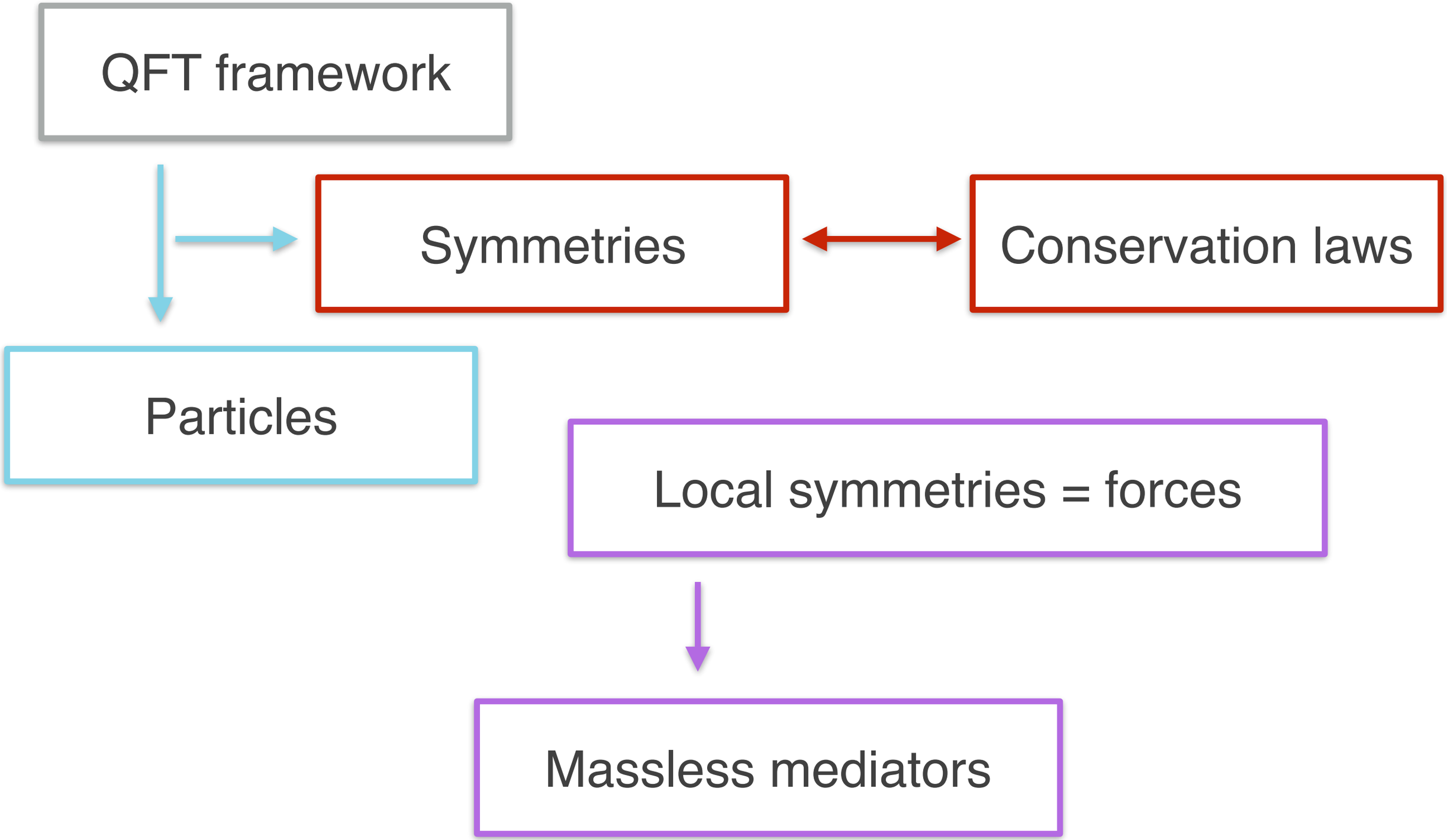
Gauge symmetries do not allow for gauge boson mass term $m^2 A_\mu A^\mu$

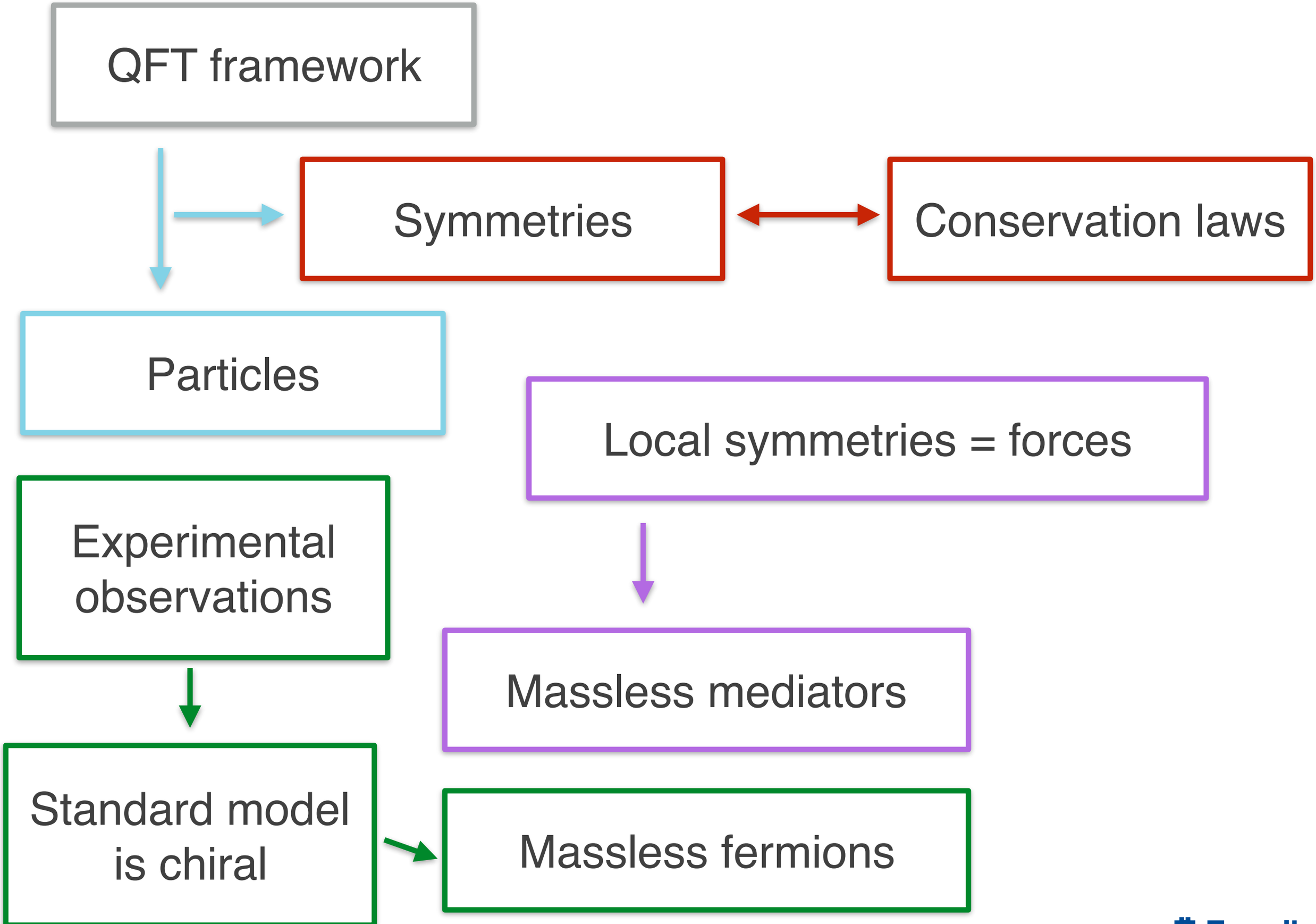
The weak interactions forbid mass terms for the fermions

Solved by the Higgs field!

QFT framework


QFT framework
Symmetries
Conservation laws
Particles


QFT framework
Symmetries
Conservation laws
Particles
Local symmetries = forces
Massless mediators



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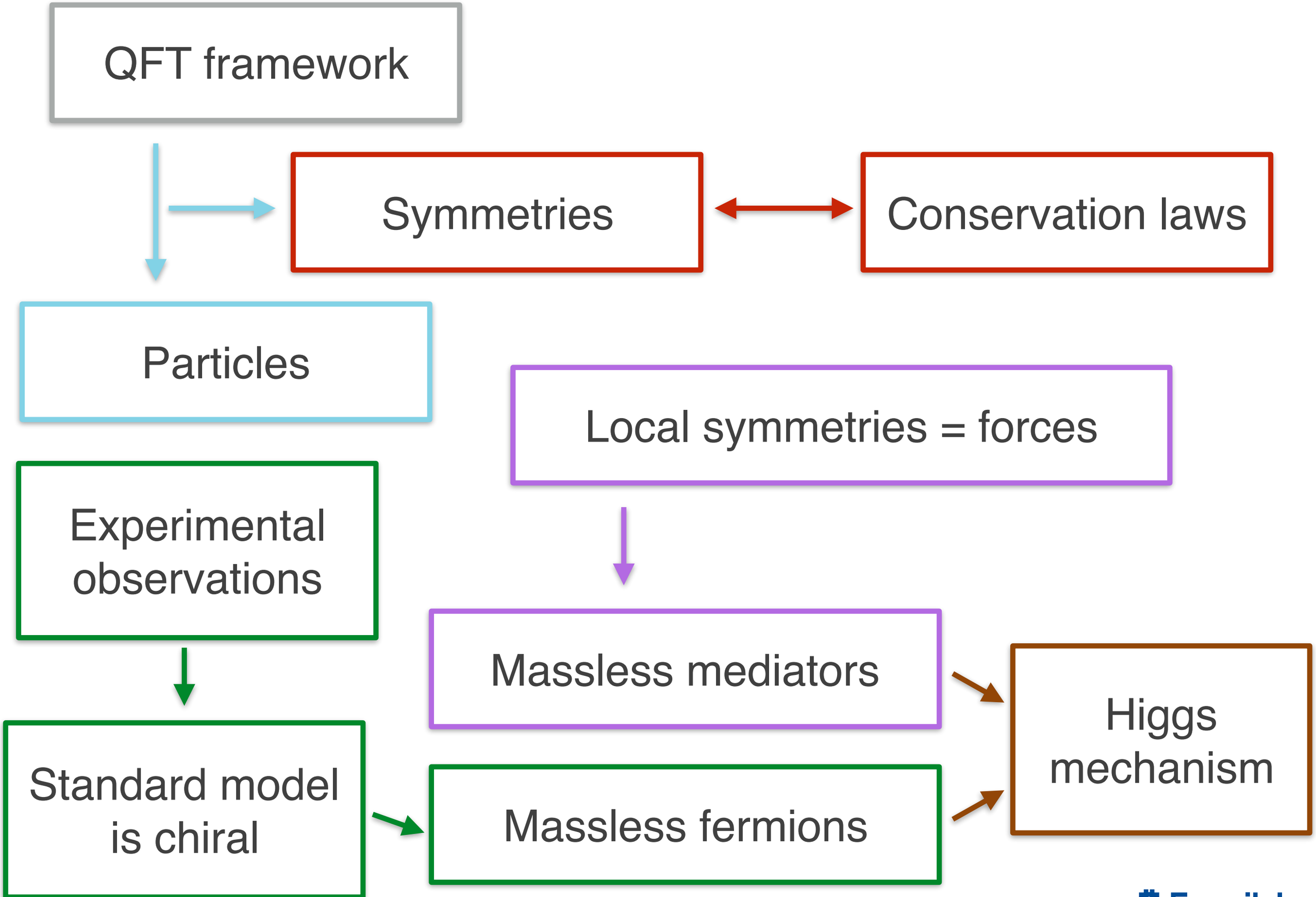

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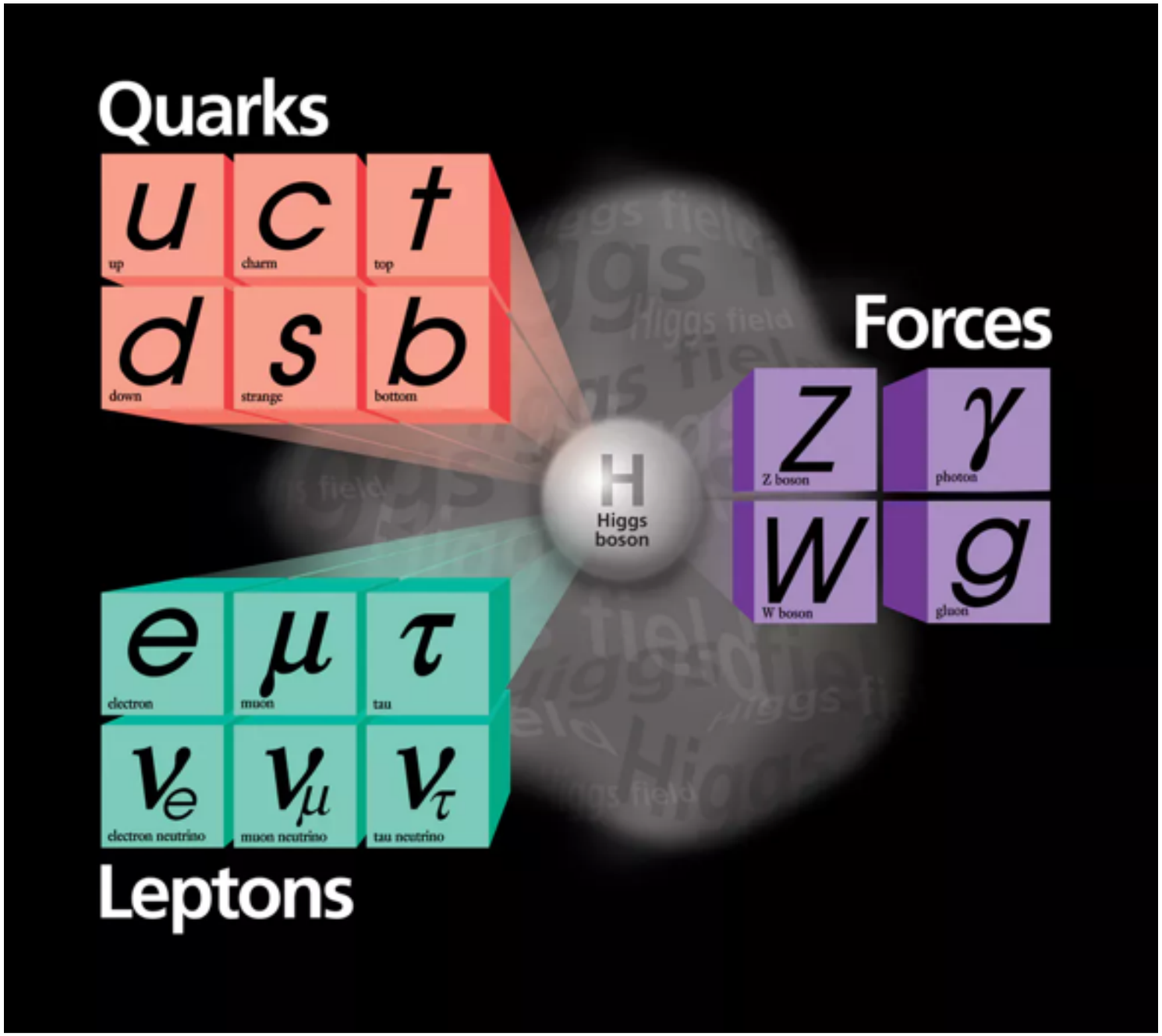
The Standard Model

Building blocks of the universe



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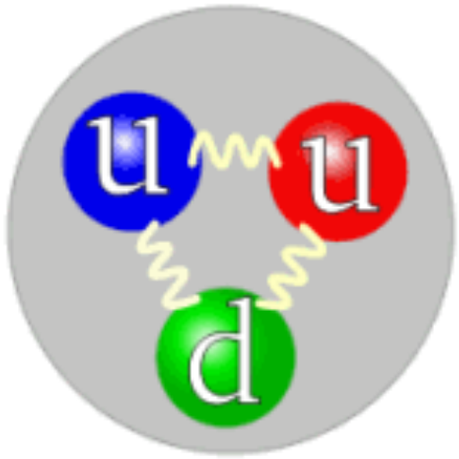
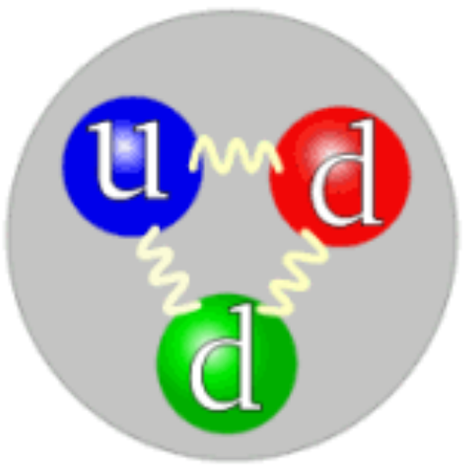
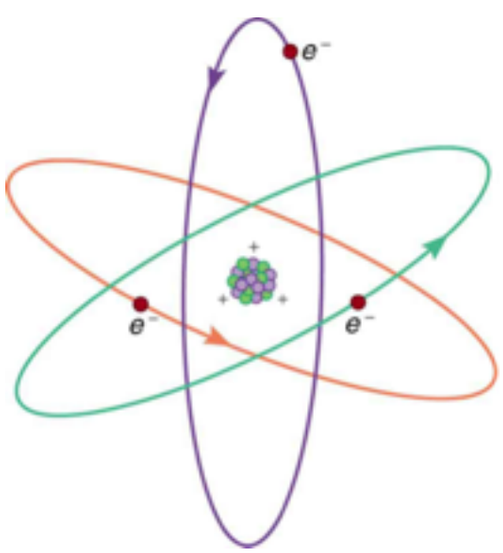


Proton



Neutron



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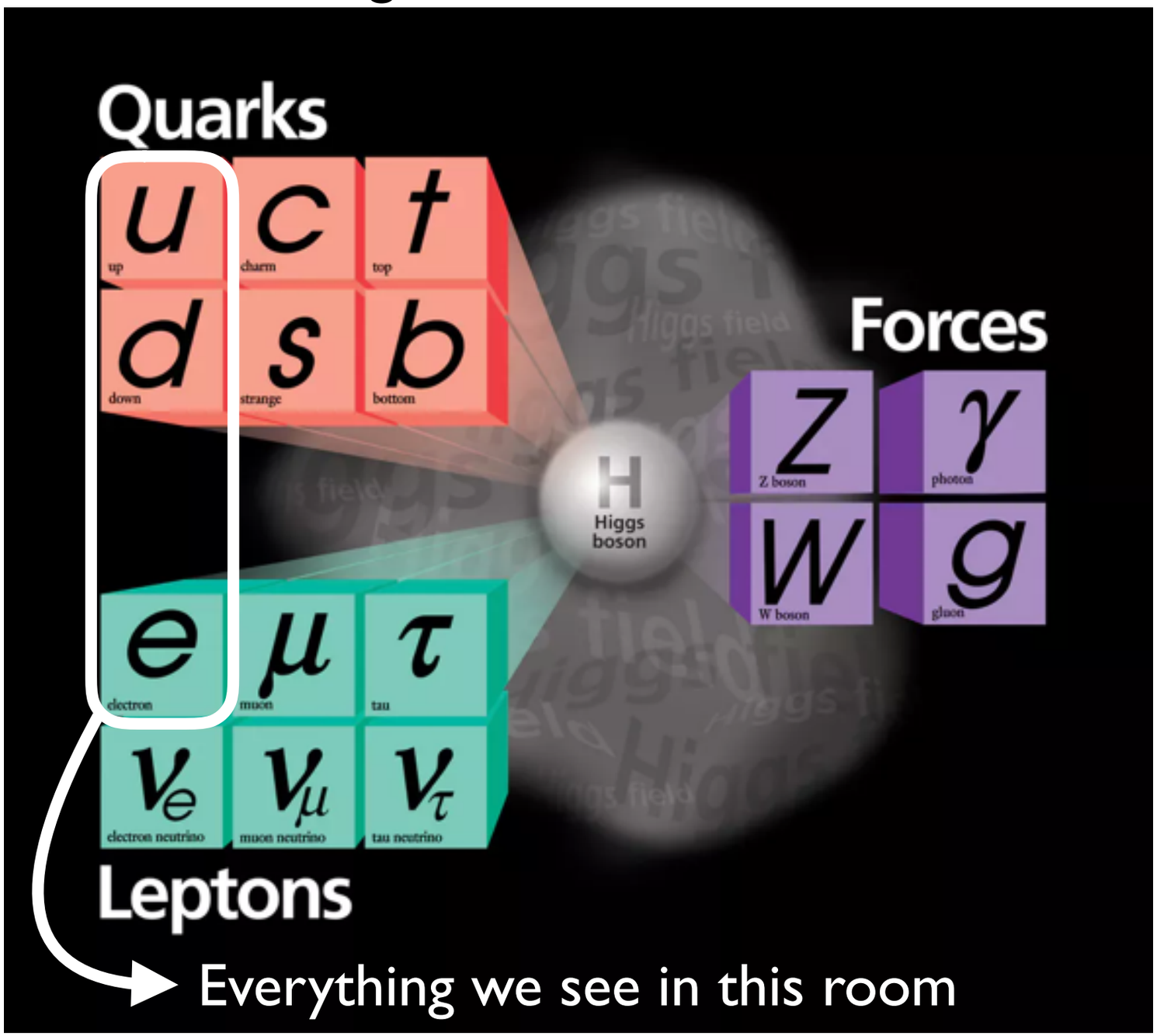

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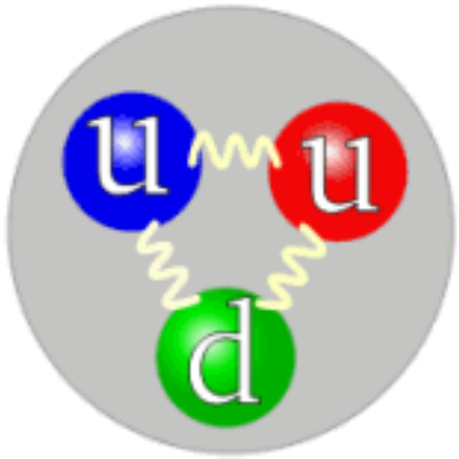

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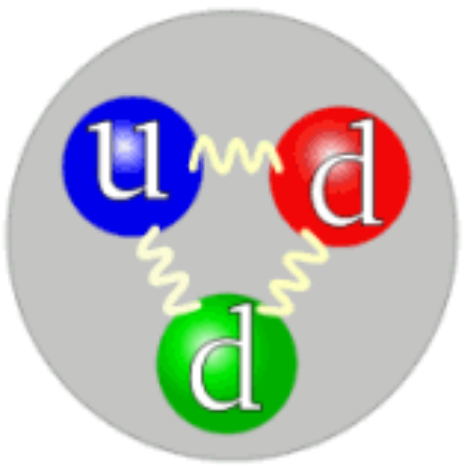

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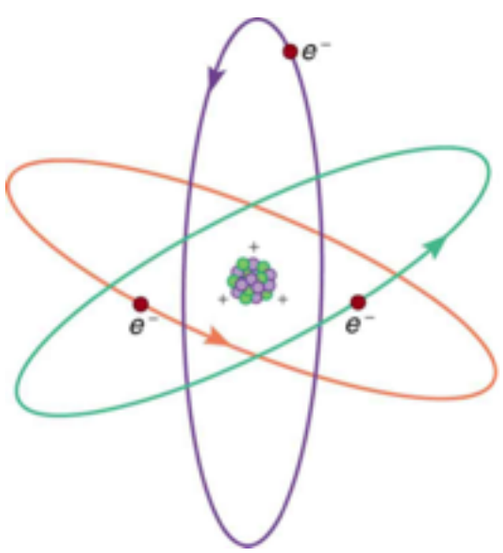

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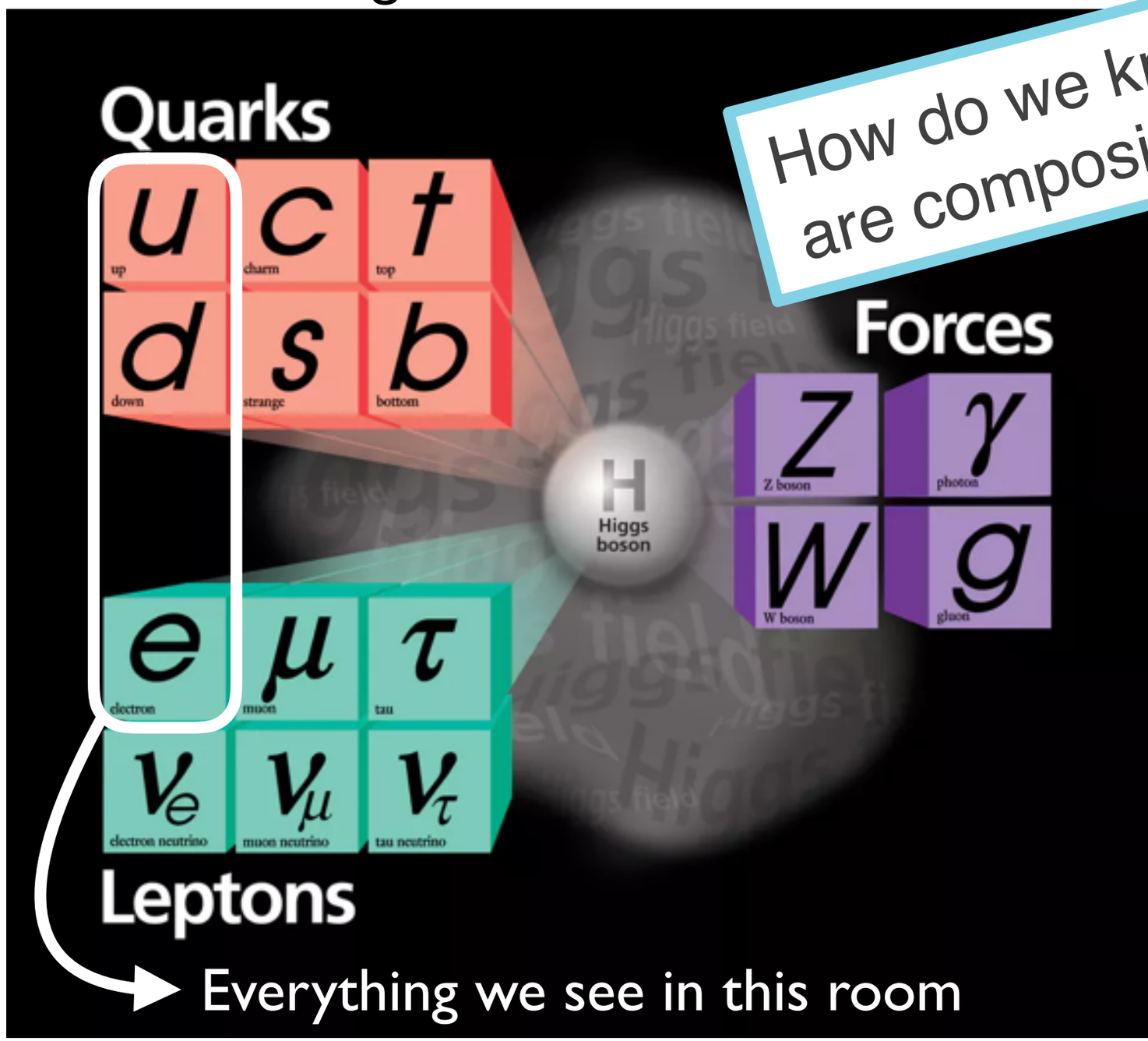
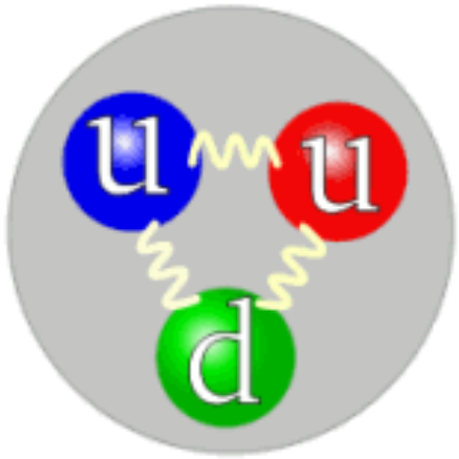


How do we know protons are composite particles?

The Standard Model



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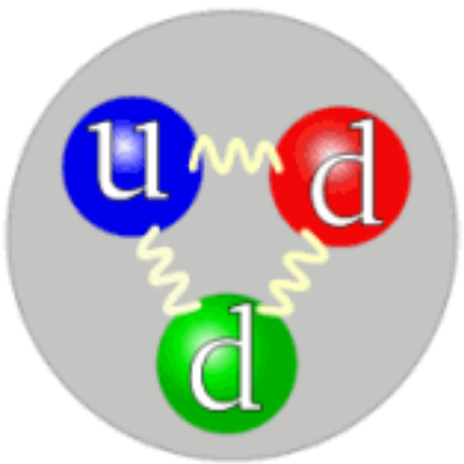

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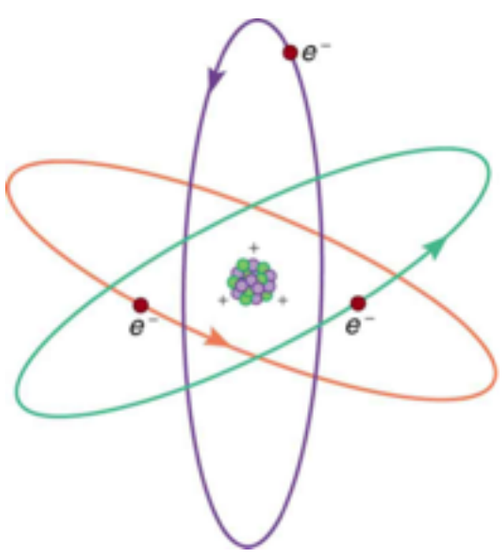

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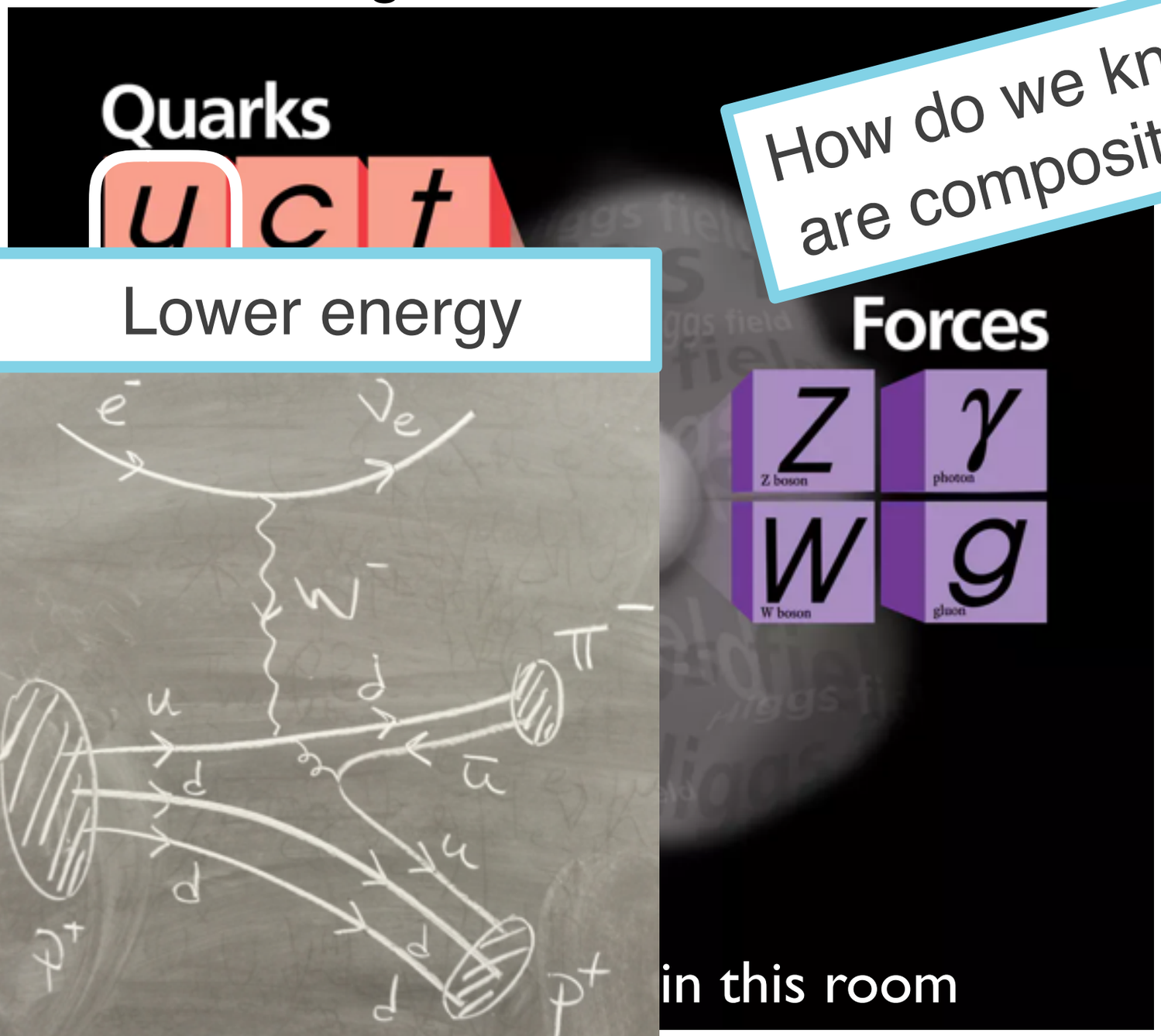

How do we know protons are composite particles?

Lower energy

in this room

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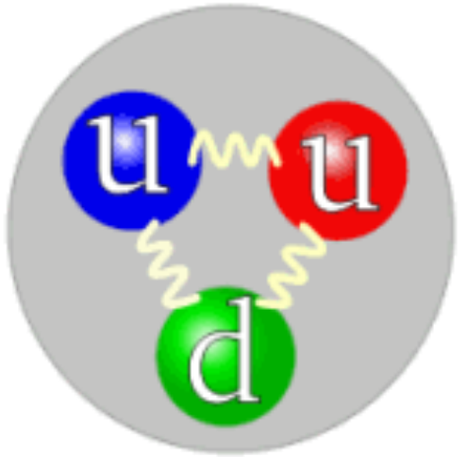
The Standard Model



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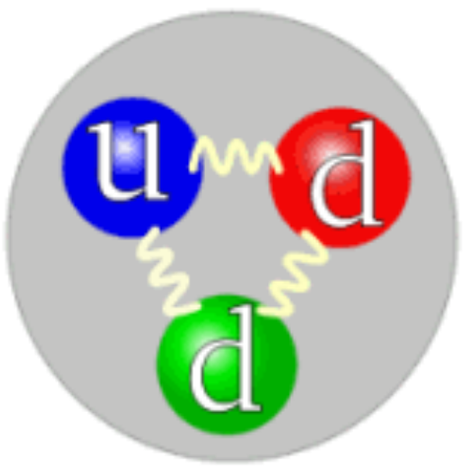

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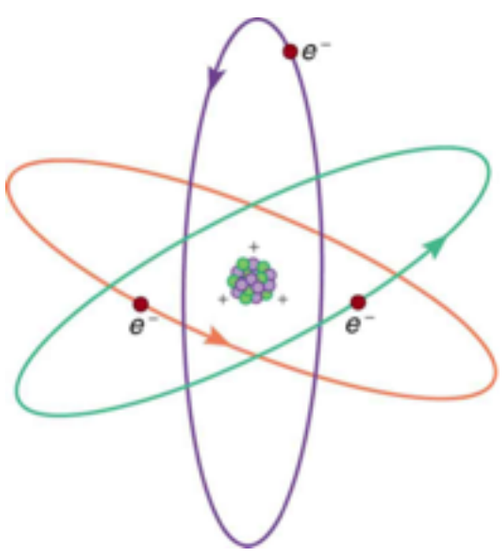

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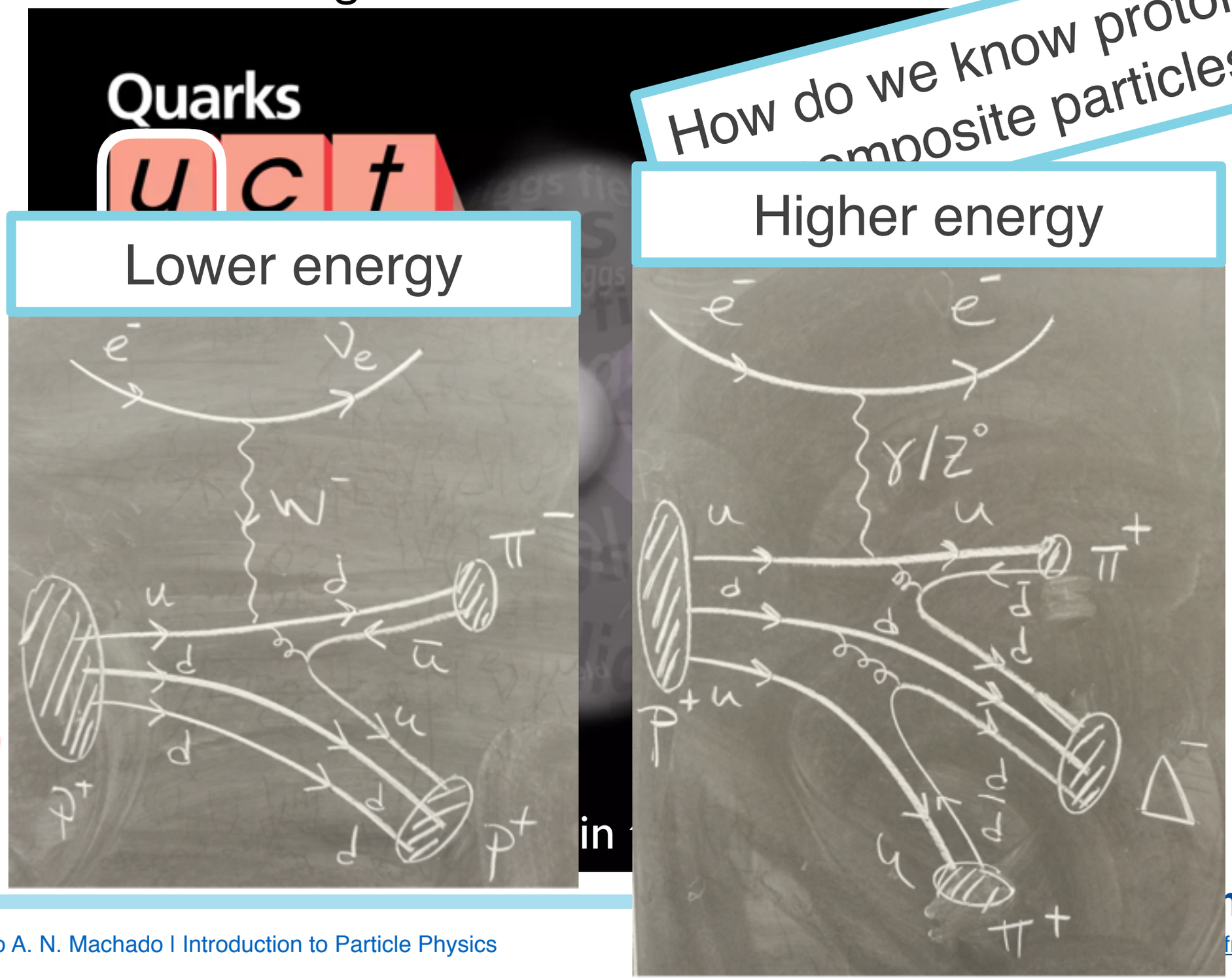

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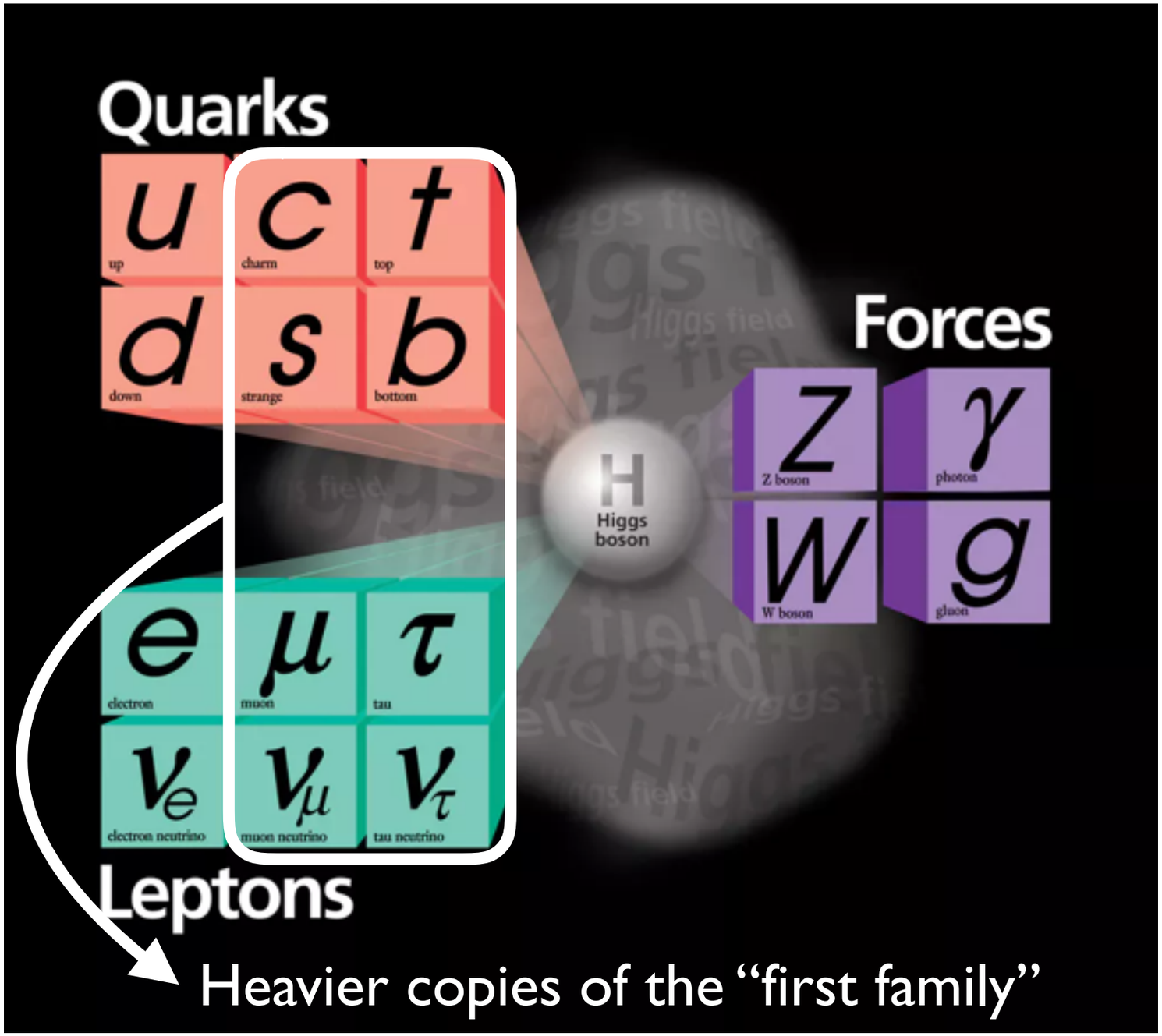

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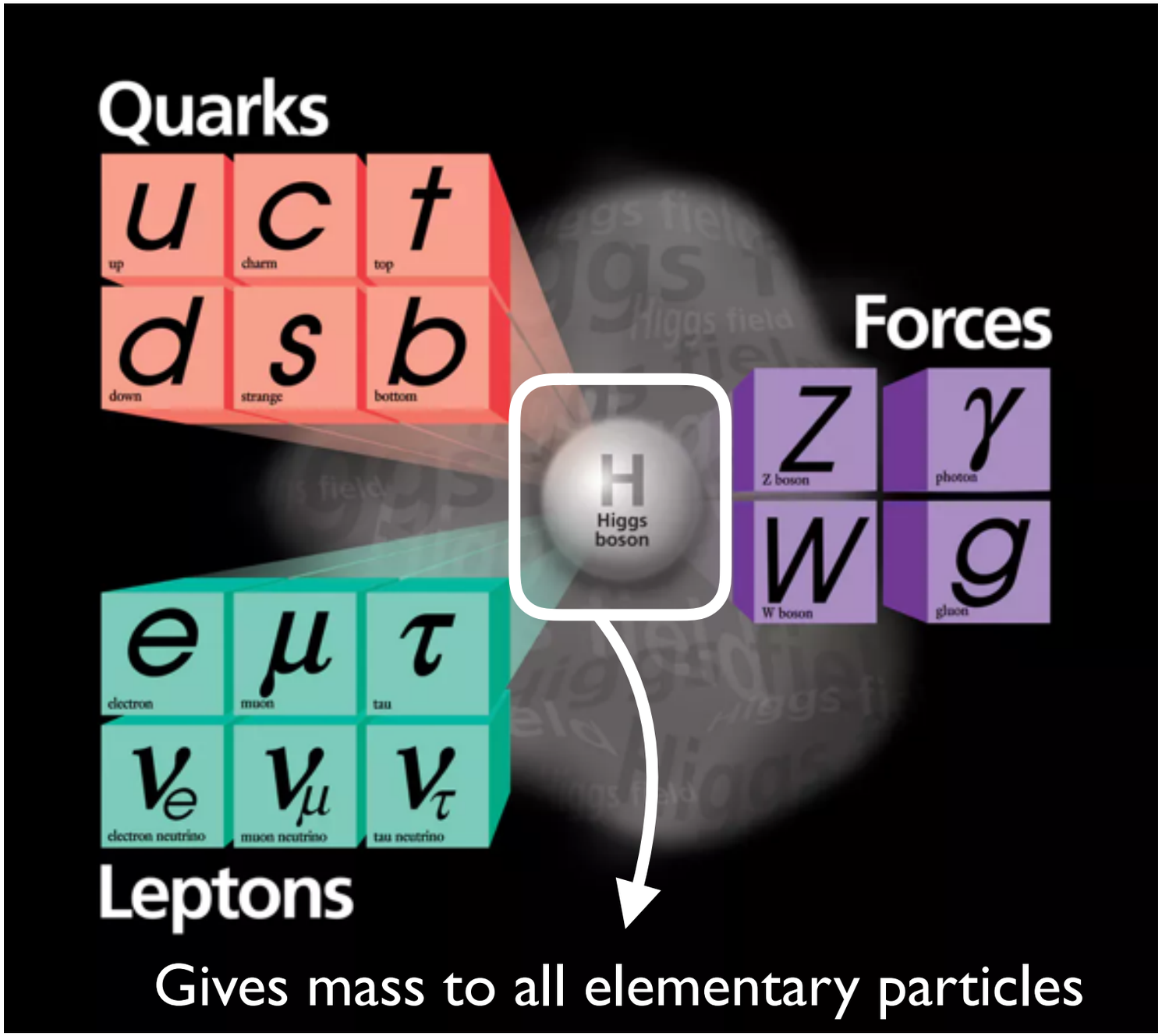

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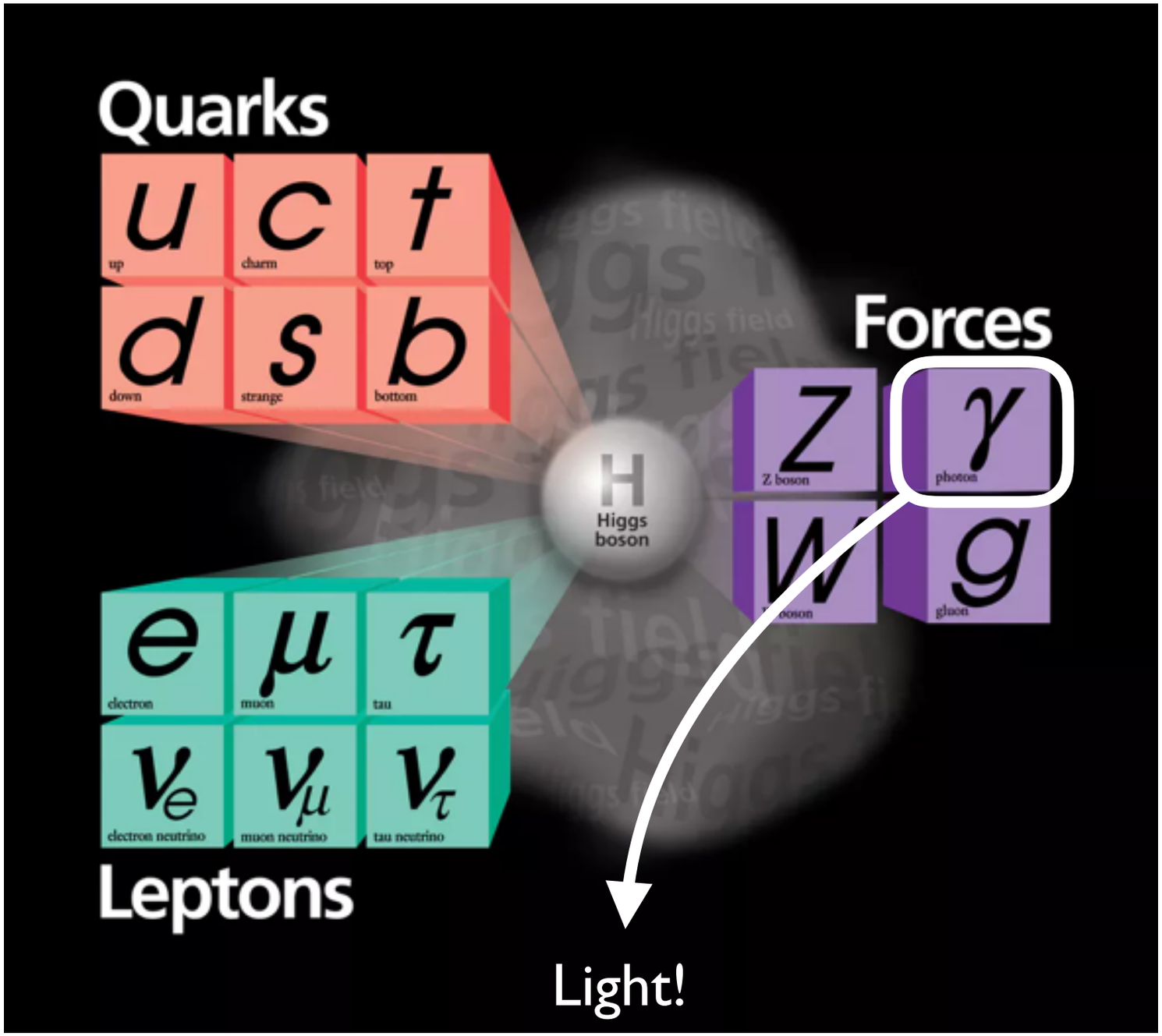
The Standard Model

Building blocks of the universe



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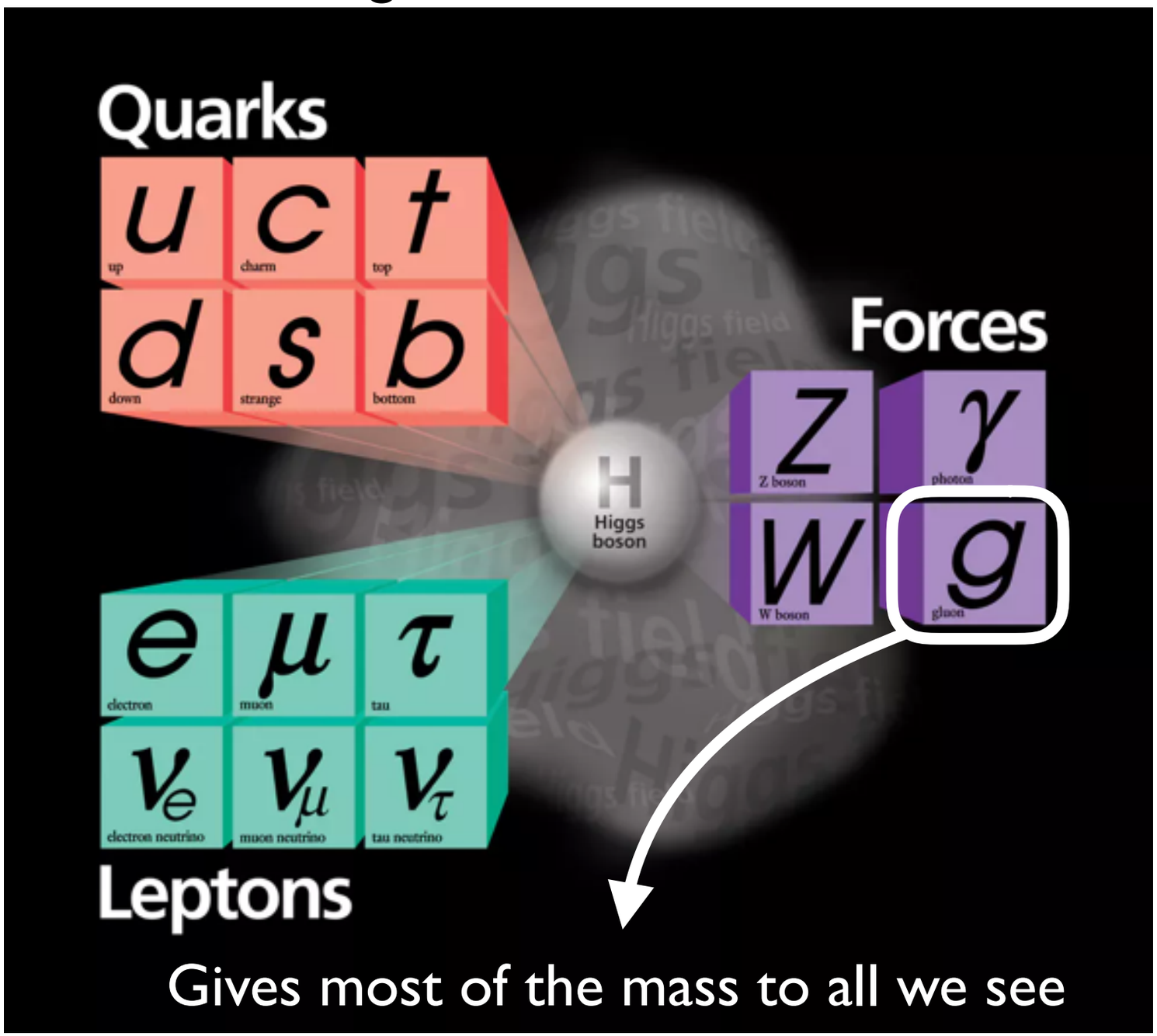

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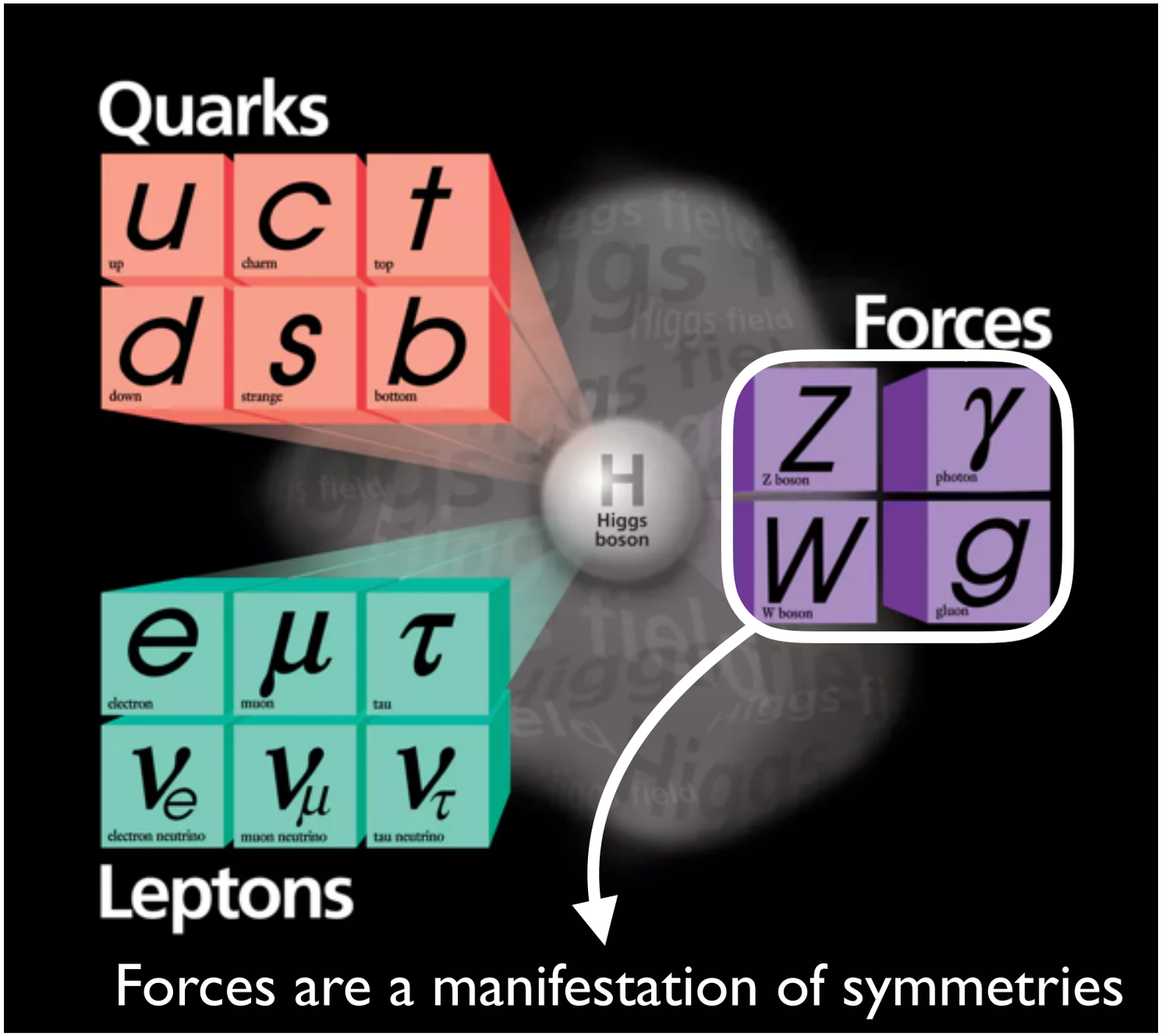
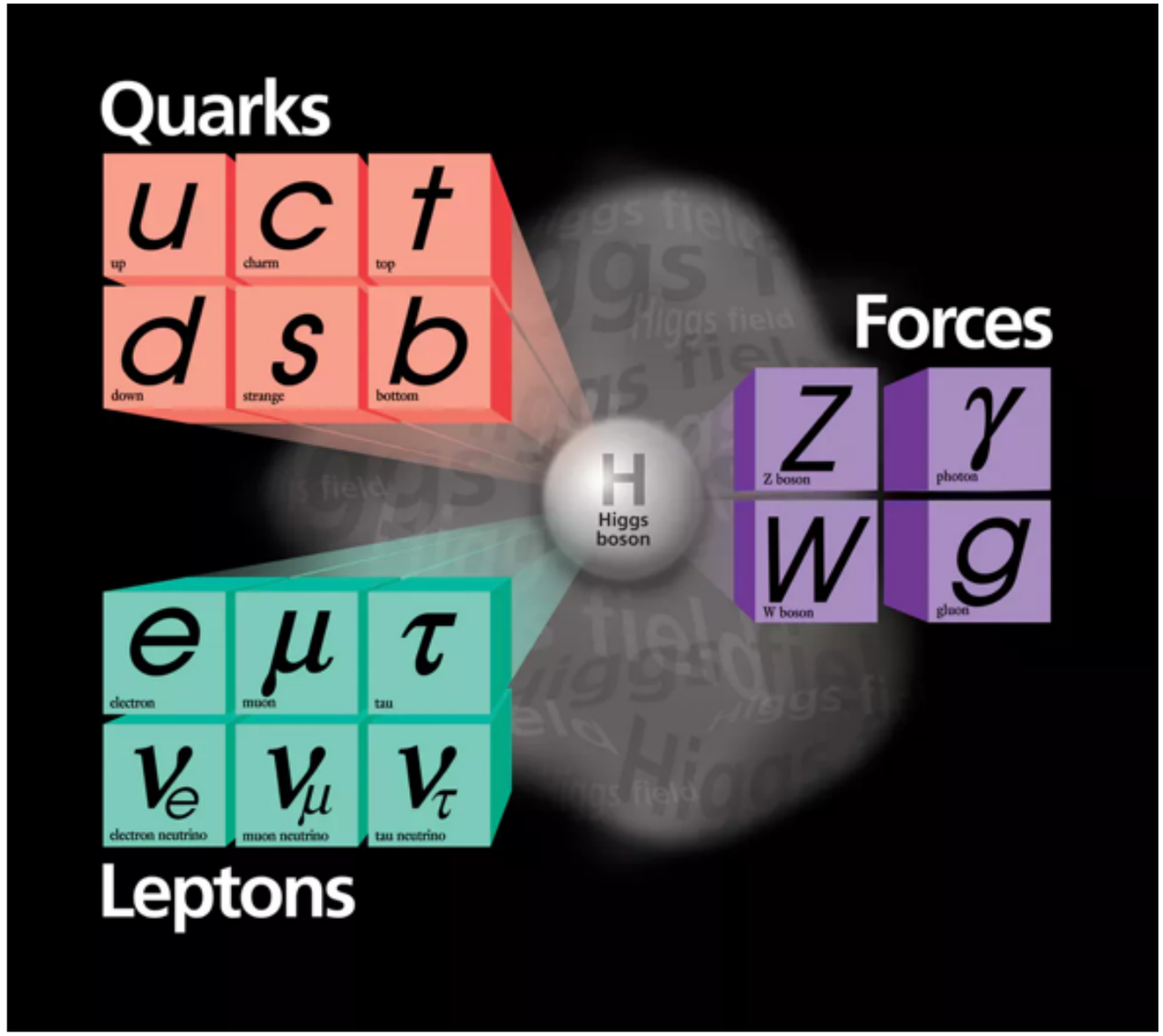


The Standard Model

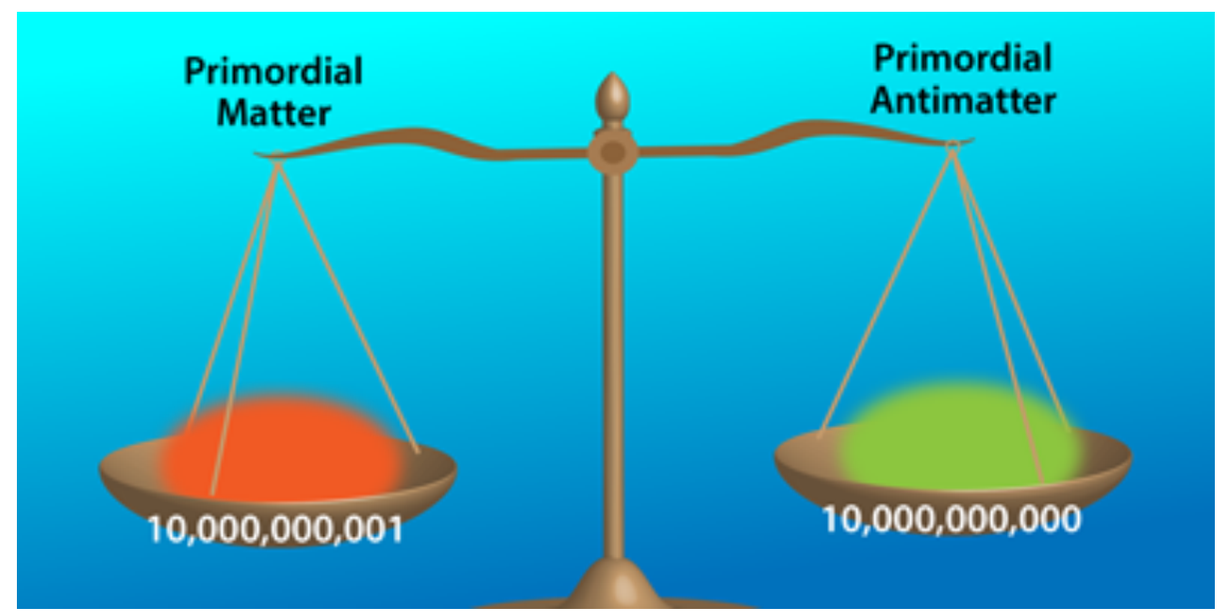
Several observations lead us to believe that

the standard model **is not the final answer**



Open questions:

How did matter (and not antimatter) survived in the big bang?



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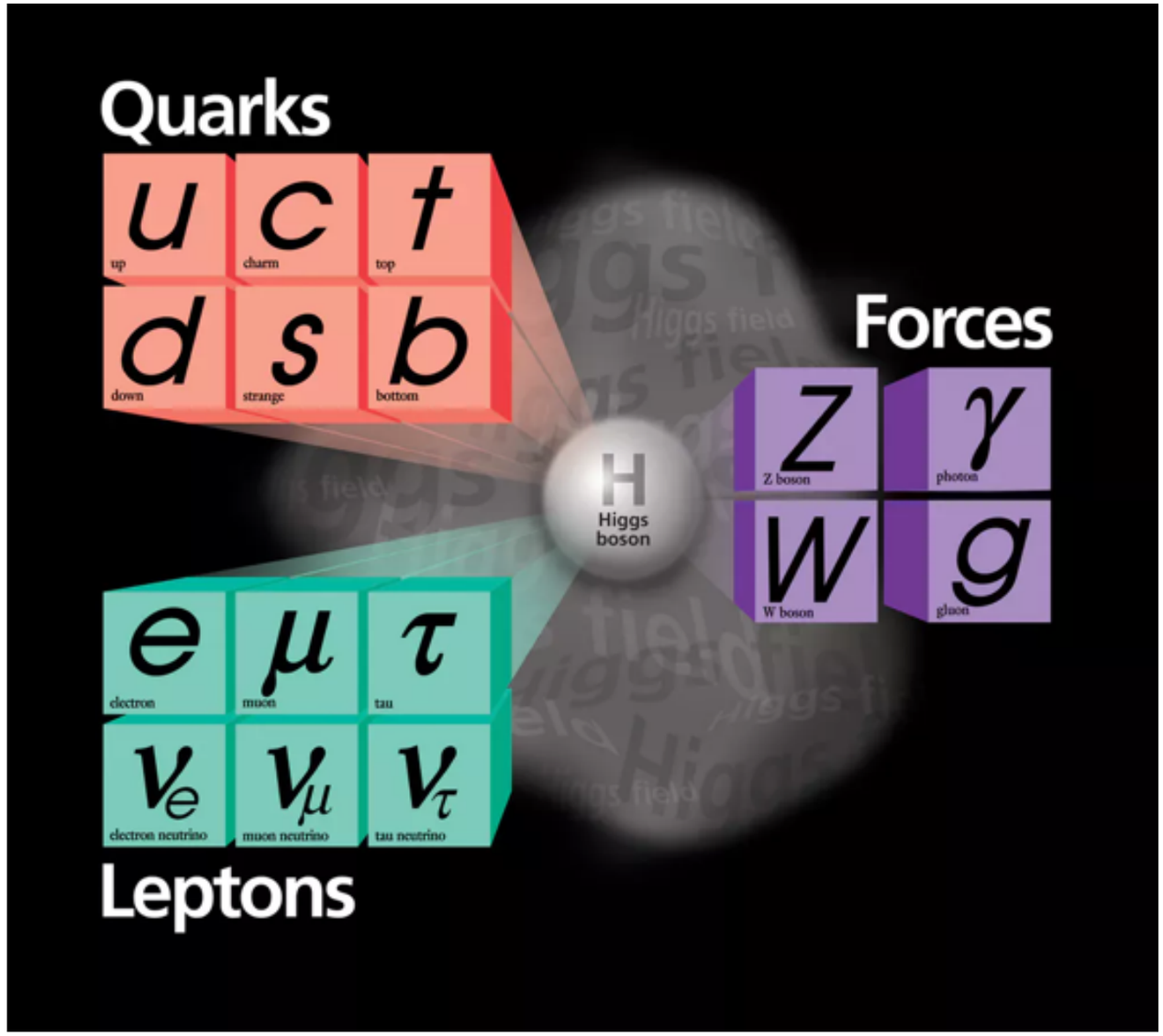

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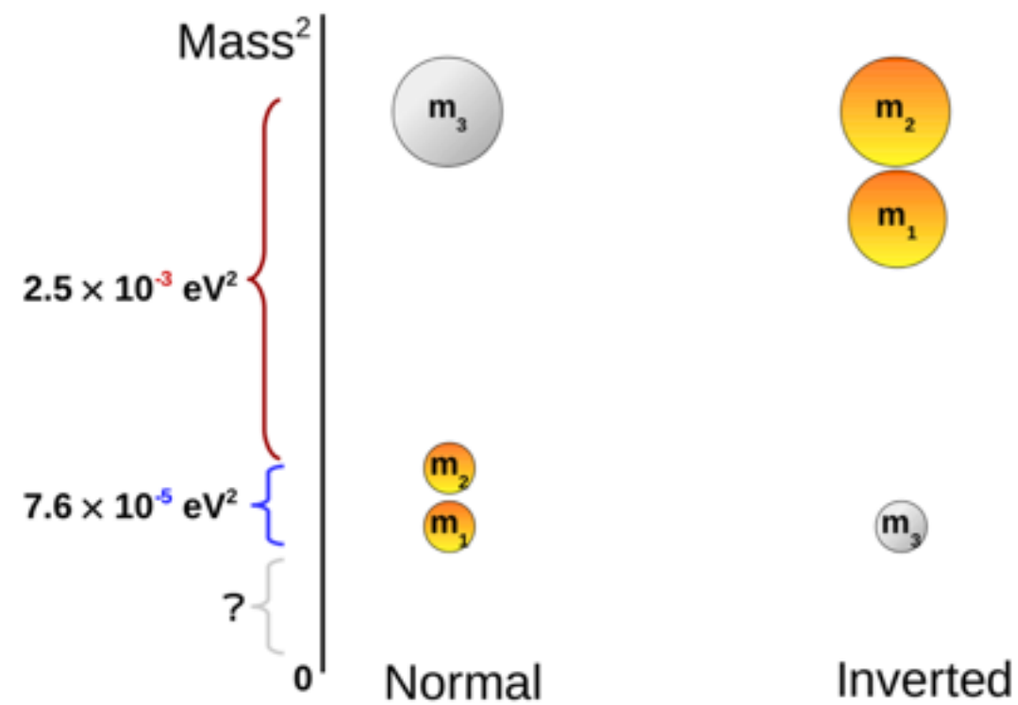

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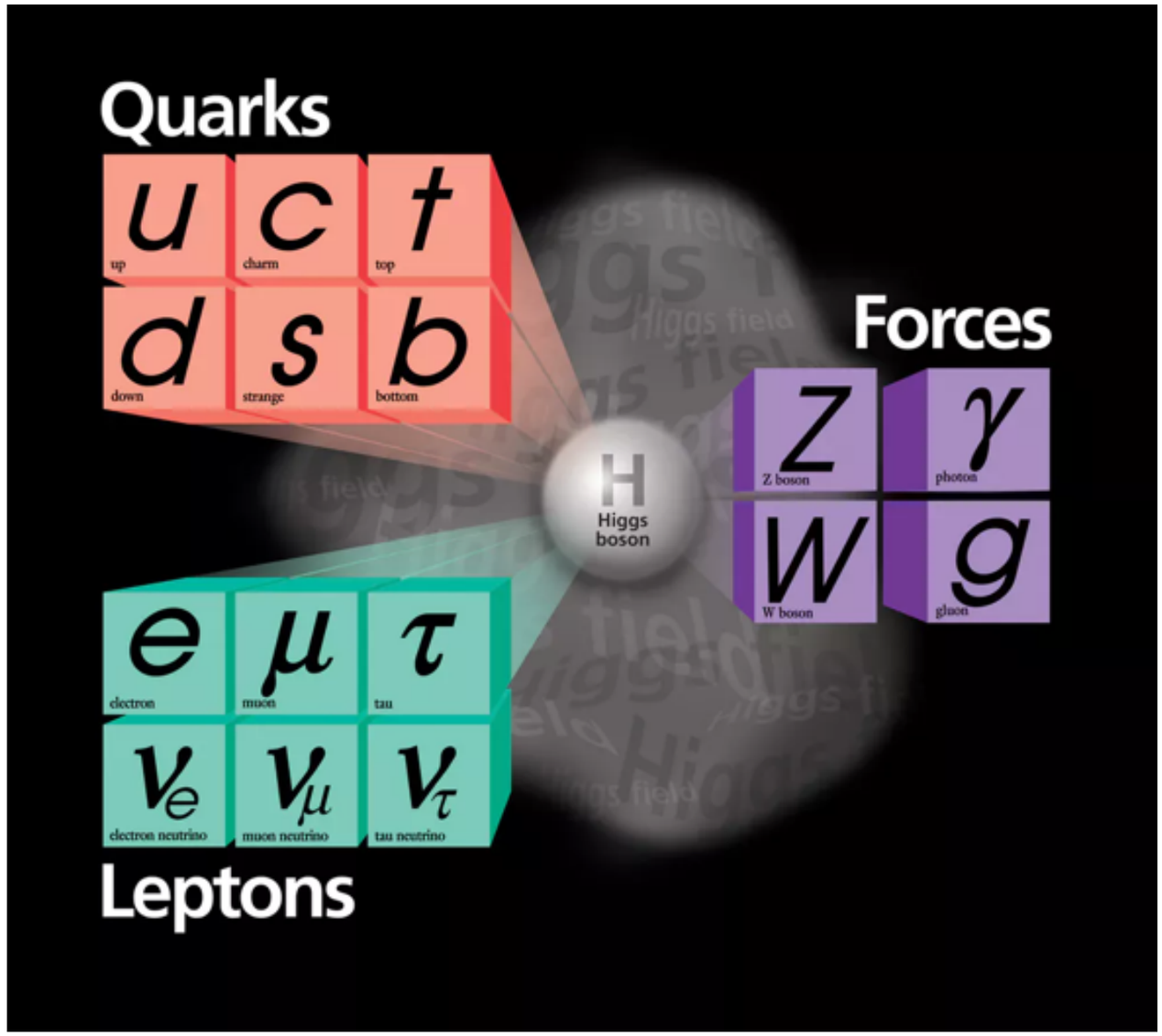

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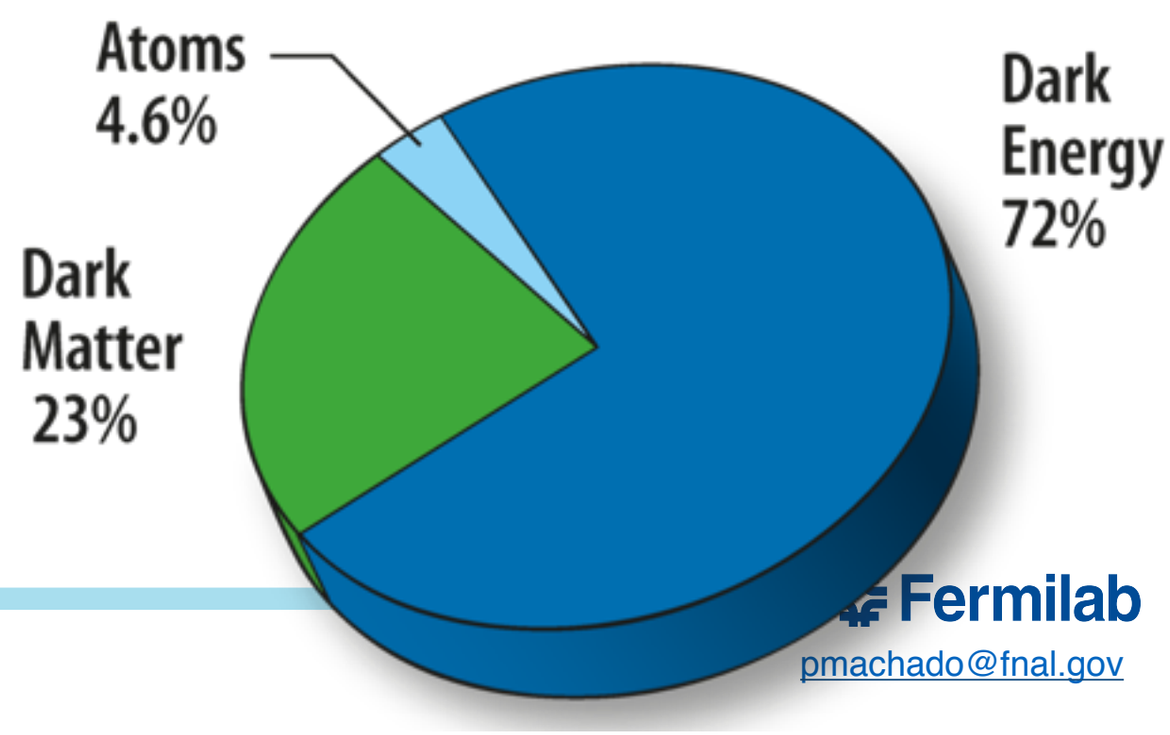
What is the mass of the neutrinos?

What is dark matter and dark energy?



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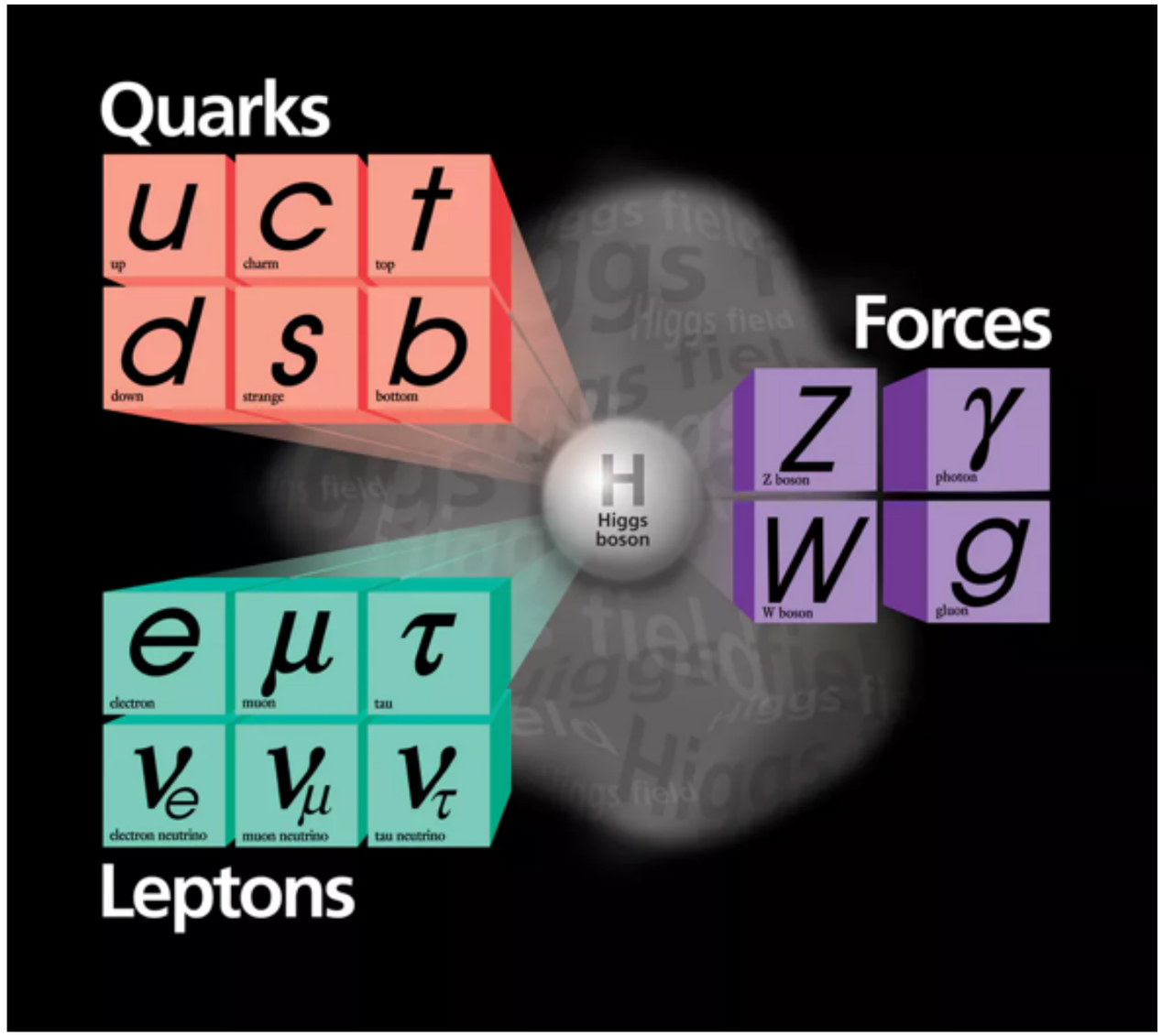
The Standard Model

Several observations lead us to believe that the standard model **is not the final answer**



Open questions:

How did matter (and not antimatter) survived in the big bang?

What is the mass of the neutrinos?

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Why is the universe expanding?

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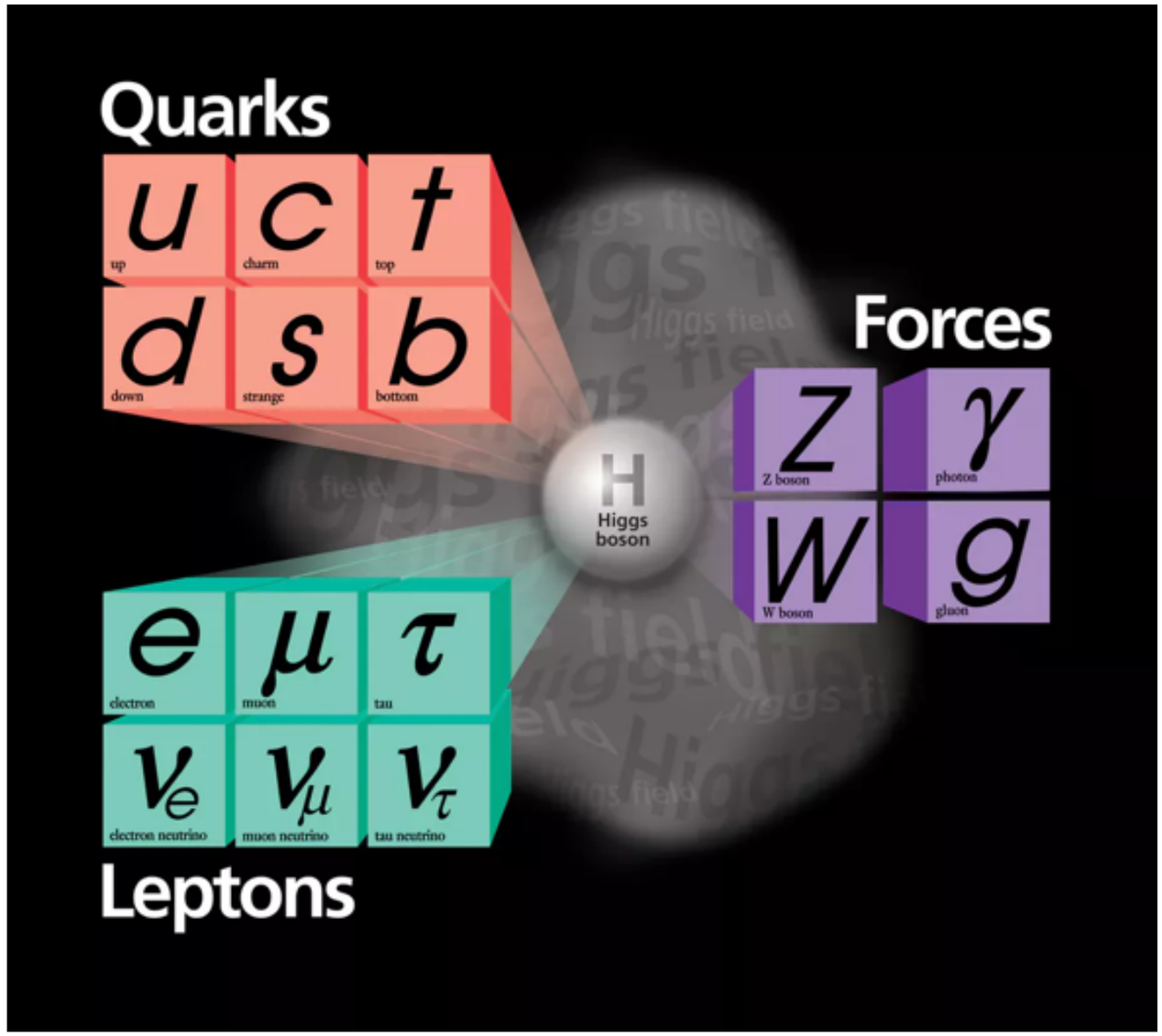

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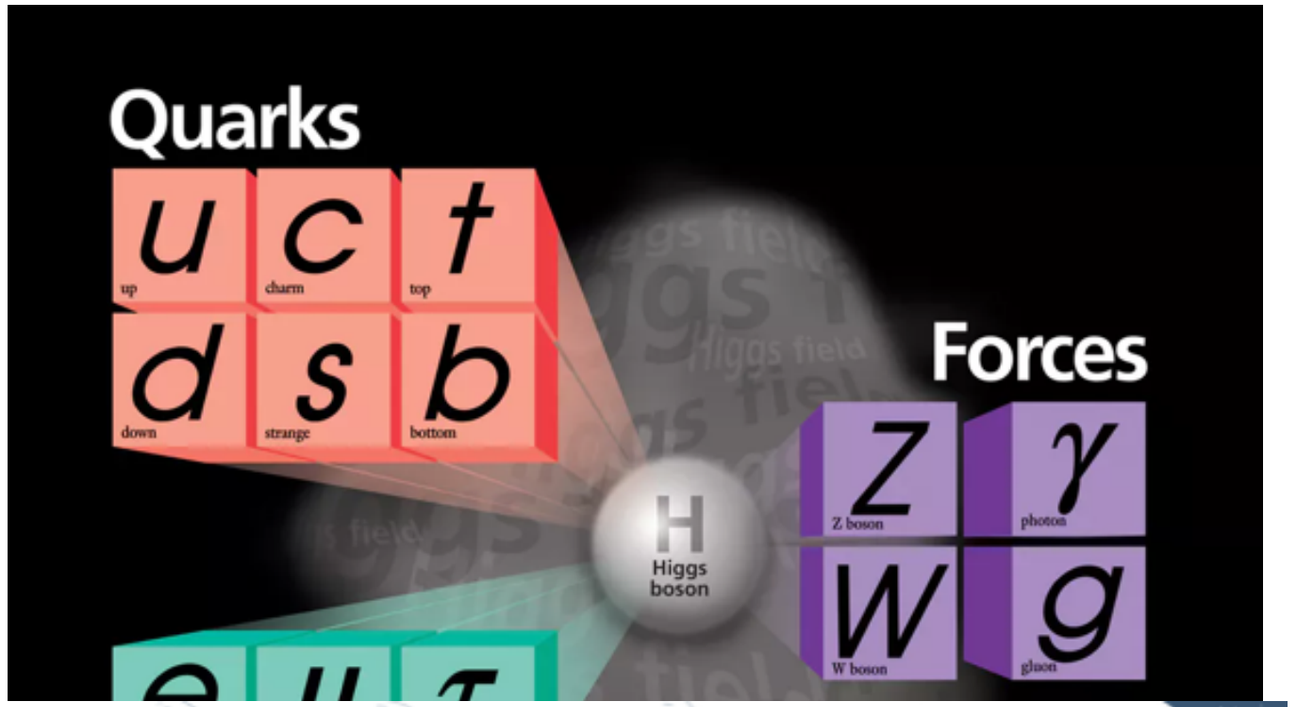

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What is the mechanism of neutrino masses?

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Conclusions

The standard model of particle physics elegantly explains mostly of what we observe

The SM is just symmetries and particles in QFT

But the SM is not satisfactory:
Unexplained puzzles (theory argument)
Unexplained experimental observations

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