Beyond the Standard Model: One equation, too many variables

Caruta Sorina, Simina Bilauschi
Coordonator: Diana Bejan

Table of contents

01

Introduction

Standard Model Recap

02

What's the big deal?

Why do we need to go beyond the Standard Model?

03

Limitations of the SM

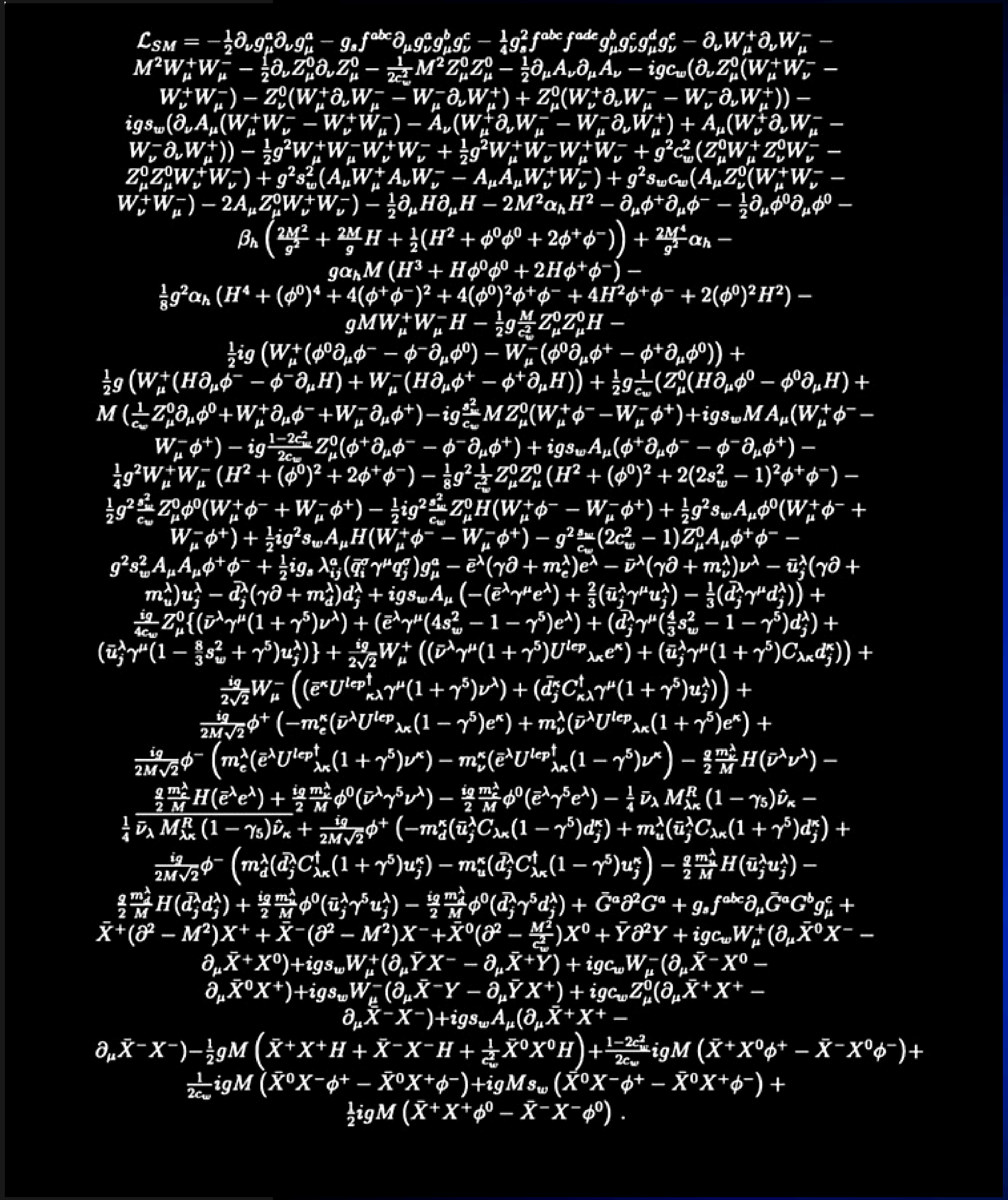
04

What's beyond?

possible theories and extensions

01

Standard Model Recap



We must remember that the Standard Model of particle physics is a remarkably successful physical theory. It has been tested in literally thousands of different and diverse ways. Some of its predictions have been verified to one part in 1010, whereas some of them (particularly the ones involving low energies and the strong interactions) have only been tested at the 10% level.

$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g^2_s f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c^2_w}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s^2_w(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c^2_w}Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s^2_w}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\tfrac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\tfrac{1}{4}g^2 W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c^2_w}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2\phi^+\phi^-\right) - \\
\tfrac{1}{2}g^2\tfrac{s^2_w}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c^2_w - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2 s^2_w A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s^2_w - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s^2_w - 1 - \gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s^2_w + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c^2_w})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \\
\partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \\
\partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM\left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c^2_w}\bar{X}^0 X^0 H\right) + \tfrac{1-2c^2_w}{2c_w}igM\left(\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-\right) + \\
\tfrac{1}{2c_w}igM\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + igMs_w\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + \\
\tfrac{1}{2}igM\left(\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0\right) .
\end{gathered}
$$

How do we know that the Standard Model is incomplete, despite its numerous achievements ?

EXPERIMENTS

Measurements that are inconsistent with the Standard Model predictions

COSMOLOGY

Observations that cannot be explained by the Standard Model

FINE TUNING

Parameters whose values can be explained in the Standard Model only with accidental fine-tuned cancellations among several contributions

CLUES

Various nongeneric features that are just parameterized in the Standard Model, but not explained

02

What is the big deal?

Let’s actually see what we are searching for.

The Standard Model successfully describes a wealth of experimental data,but seems to explain only 5% of the universe

What is the rest of 95% unexplored Universe?

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Dark Matter
Dark Energy

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And some Honorable Mentions to....

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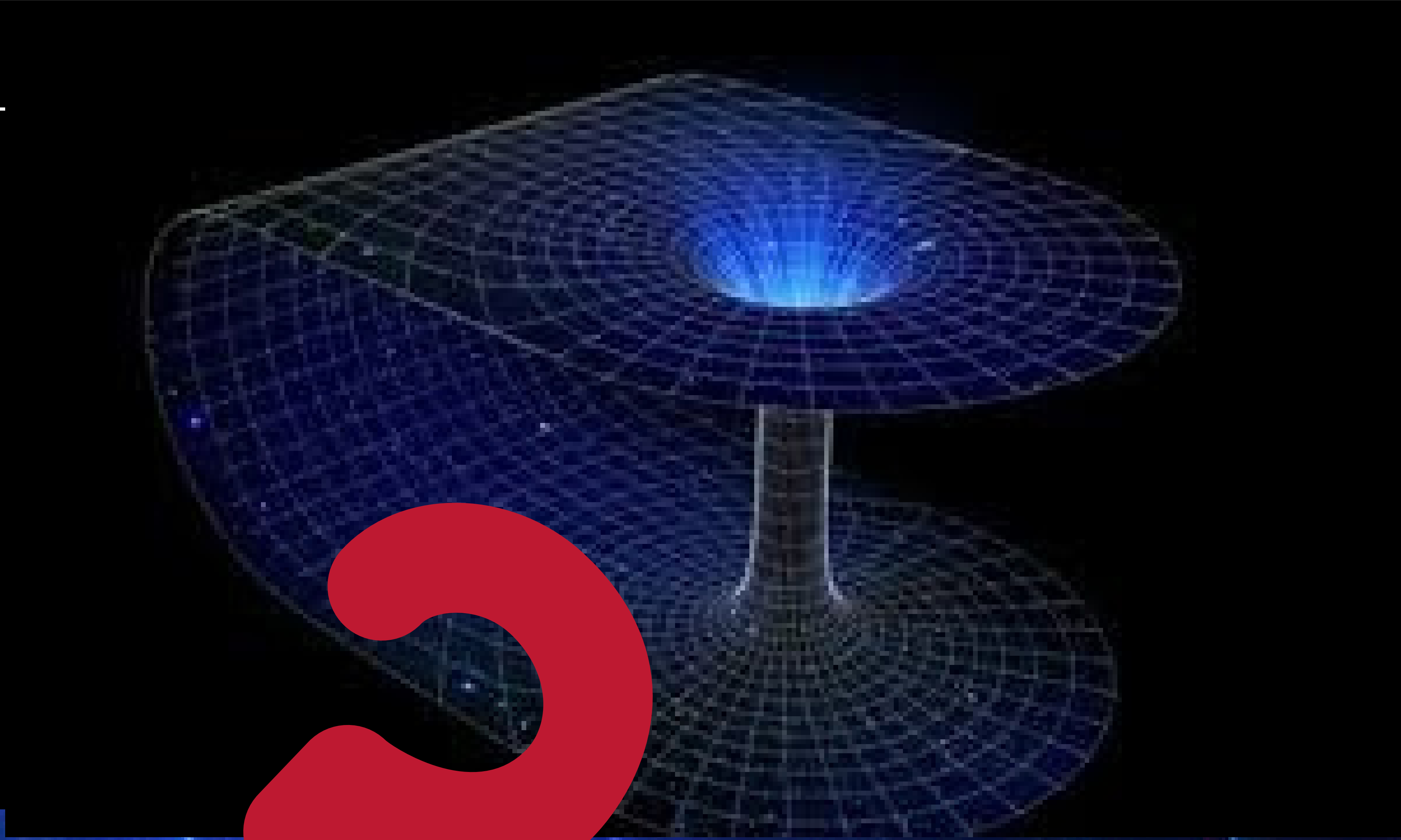

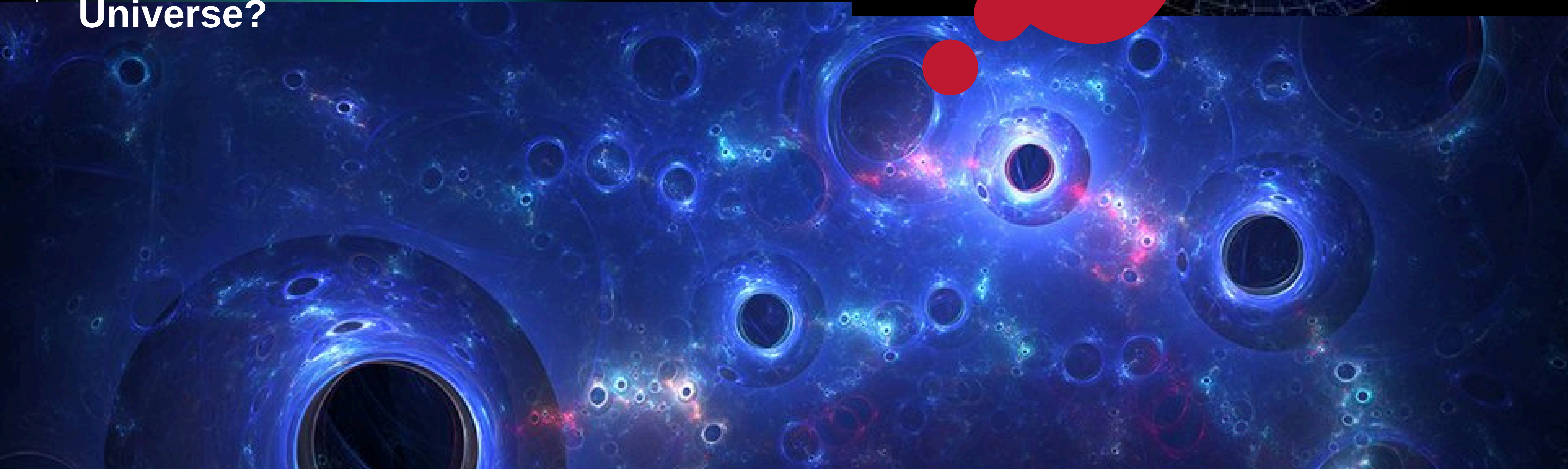

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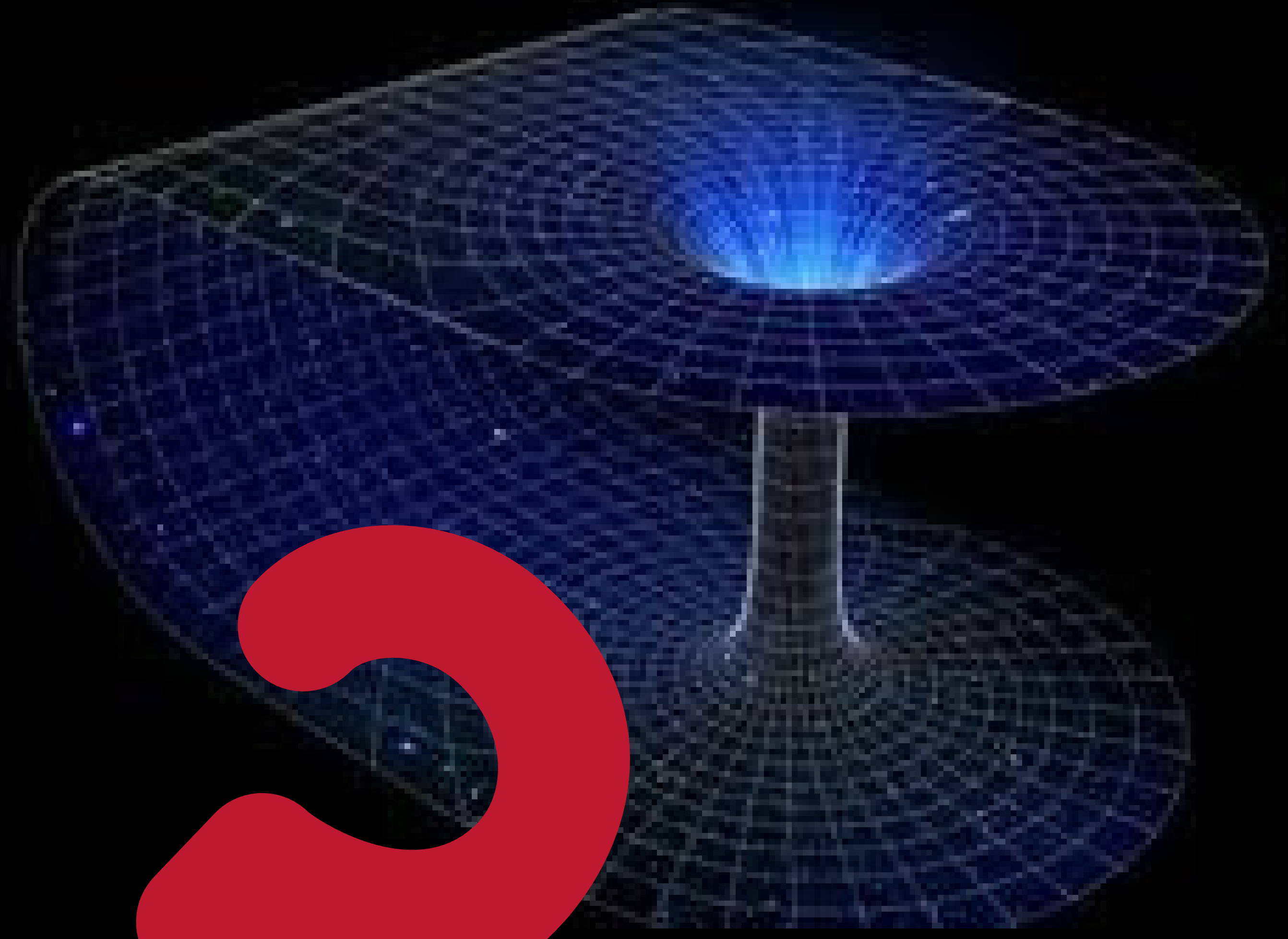

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03 Limitations of SM

The Standard Model is described by a Lagrangian that is the sum of the gauge, matter, Higgs, and Yukawa interactions:

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Matter}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

Discrepancies in experimental results

→ statistical flukes/ experimental errors

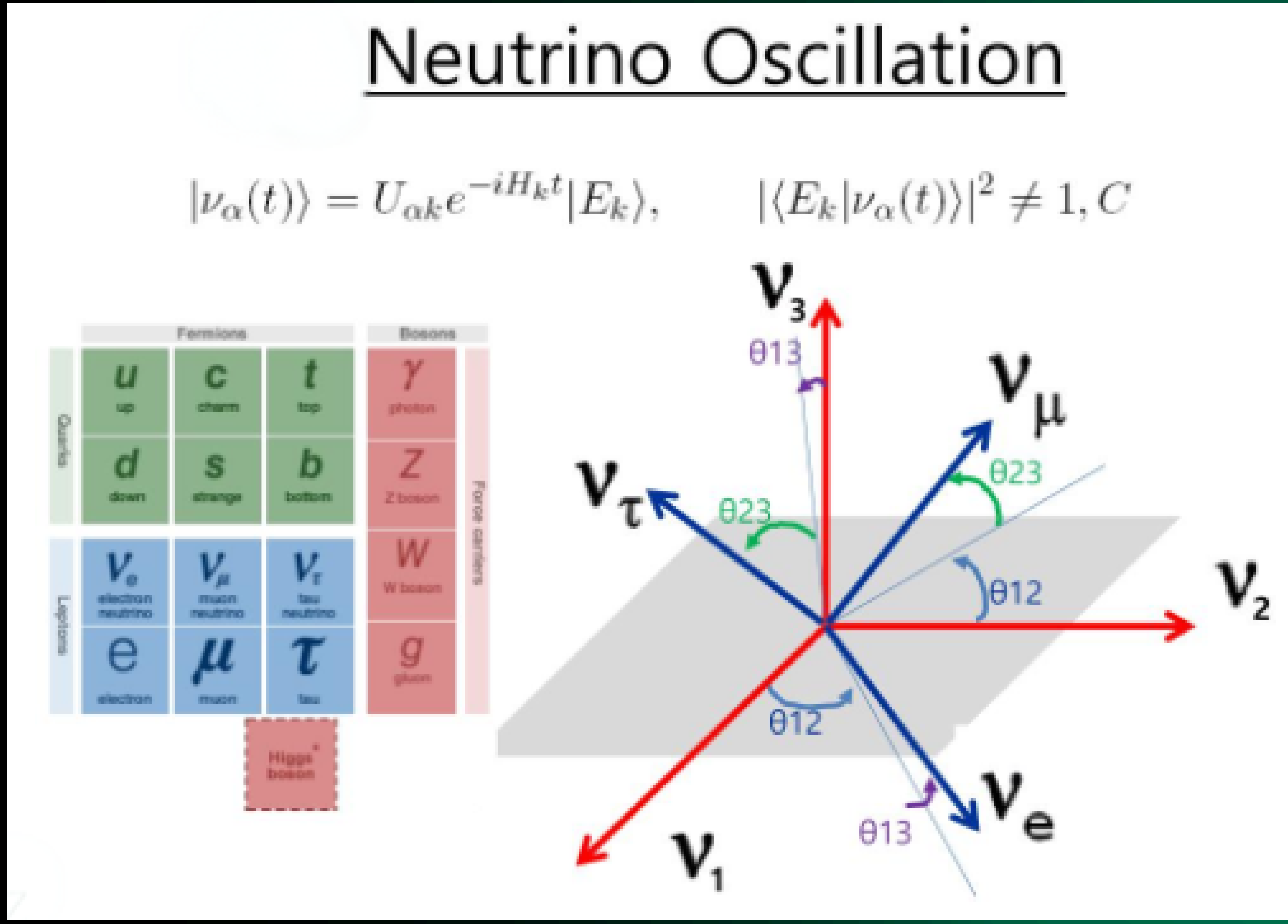
→ Physics Beyond The Standard Model

Gravity and General Relativity

- gravity is not included in the SM
- adding a graviton to the SM fails to replicate phenomena observed experimentally
- SM is considered incompatible with general relativity
- Gravity as described by the GR is a consequence of the curvature of space–time, not mediated by gauge bosons
- a quantum gravity theory, or quantum geometrodynamics (QGD) is yet to be found

Neutrino oscillations

- known also as neutrino mixing
- first pointed to by the observed deficit of electron-neutrinos coming from the Sun, and were directly observed in atmospheric and solar neutrino measurements
- the process of neutrinos spontaneously changing flavour (electron, muon, tau)
- explained by theorising that these particles have mass



Oscillation probability

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta_{23}) \cdot \sin^2\left(\pi \frac{x}{L_{osz}}\right)$$

Survival probability

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23}) \cdot \sin^2\left(\pi \frac{x}{L_{osz}}\right)$$

- **Adding mass to the neutrinos: the seesaw mechanism, is to add right-handed neutrinos and have these couple to left-handed neutrinos with have to be sterile, meaning that they do not participate in any of the standard model interactions.**
- **Because they have no charges, the right-handed neutrinos can act as their own anti-particle**
- **the Majorana mass for the right-handed neutrinos does not arise from the Higgs mechanism, and is therefore expected to be tied to some energy scale of new physics beyond the standard model (e.g. the Planck scale)**
- **Simulations show that neutrinos can explain a few percent of the missing mass in dark matter**
- **heavy, sterile, right-handed neutrinos are a possible candidate for a dark matter WIMP.**

Numerous parameters

- **19 parameter numbers**
- **values are determined experimentally, but their origin is unknown**
- **neutrino ascillations => +9 parameters: three neutrino masses, three real mixing angles, and three CP-violating phases**

- Gauge sector:
  - 3 gauge couplings: g_3, g_2, g'
  - 1 strong CP-violating phase
- Yukawa interactions:
  - 3 charge-lepton masses
  - 6 quark masses
  - 4 CKM angles and phase
- Higgs sector:
  - 2 parameters: μ, λ
- Total: 19 parameters

The Planck Scale

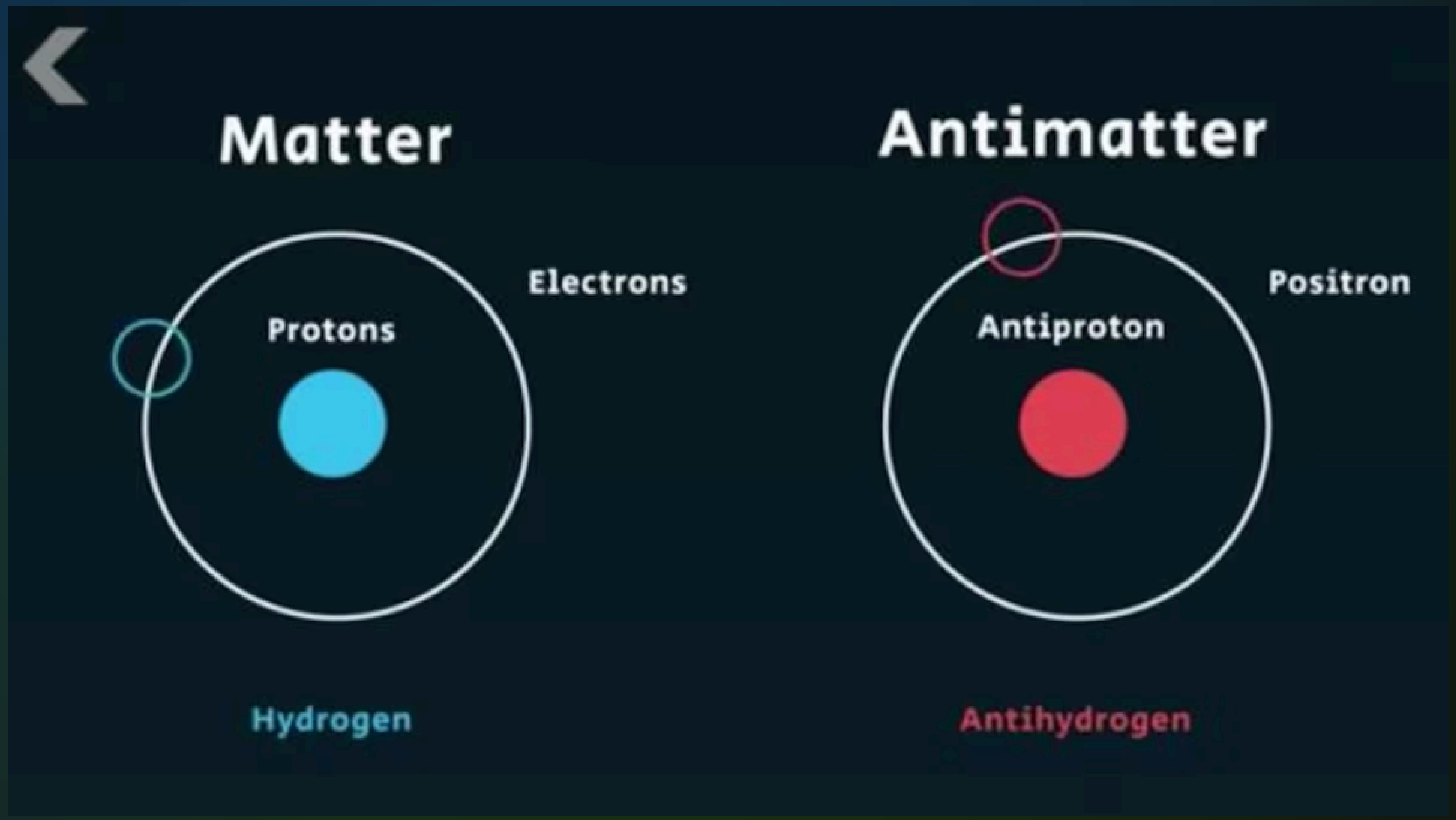
Planck units are a system of units of measurement defined exclusively in terms of four universal physical constants:

- c, the speed of light in vacuum,
- G, the gravitational constant,
- ħ, the reduced Planck constant, and
- kB, the Boltzmann constant.

lace image”

- **refers to quantities of space, time, energy and other units that are similar in magnitude to corresponding Planck units**
- **particle energies of around 1019 GeV or 109 J, time intervals of around 5×10−*44* s and lengths of around 10−35 m**
- **at the Planck scale, the predictions of the Standard Model, quantum field theory and general relativity are not expected to apply, and quantum effects of gravity are expected to dominate.**

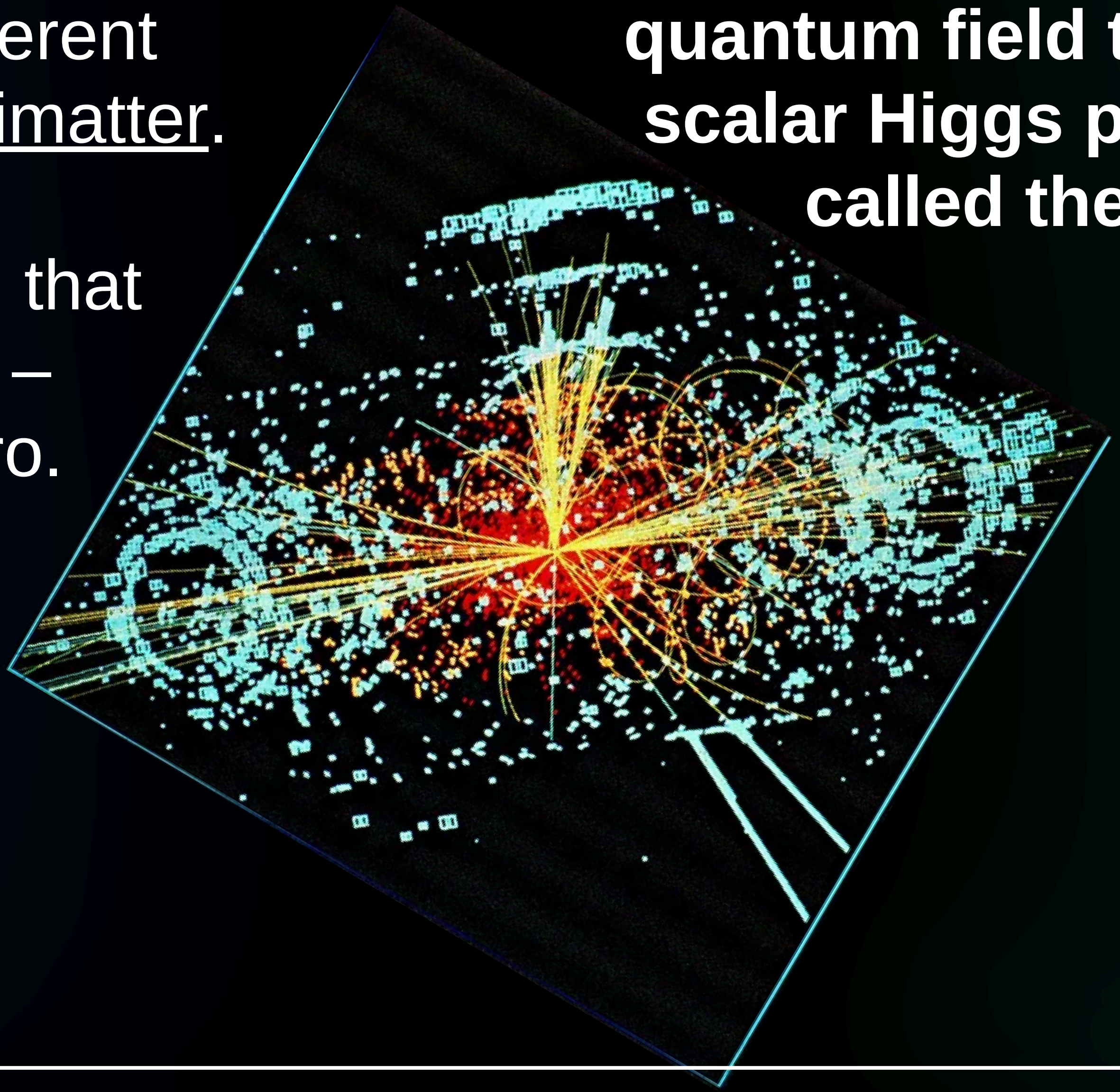
Matter-Antimatter asymmetry



Today, there's nearly no antimatter left in the universe – it appears only in some radioactive decays and in a small fraction of cosmic rays.
The SM predicts equal matter and antimatter production during the Big Bang, yet the observable universe consists mostly of matter. Yet, there is no mechanism in the Standard Model to sufficiently explain this asymmetry.

Strong CP Problem

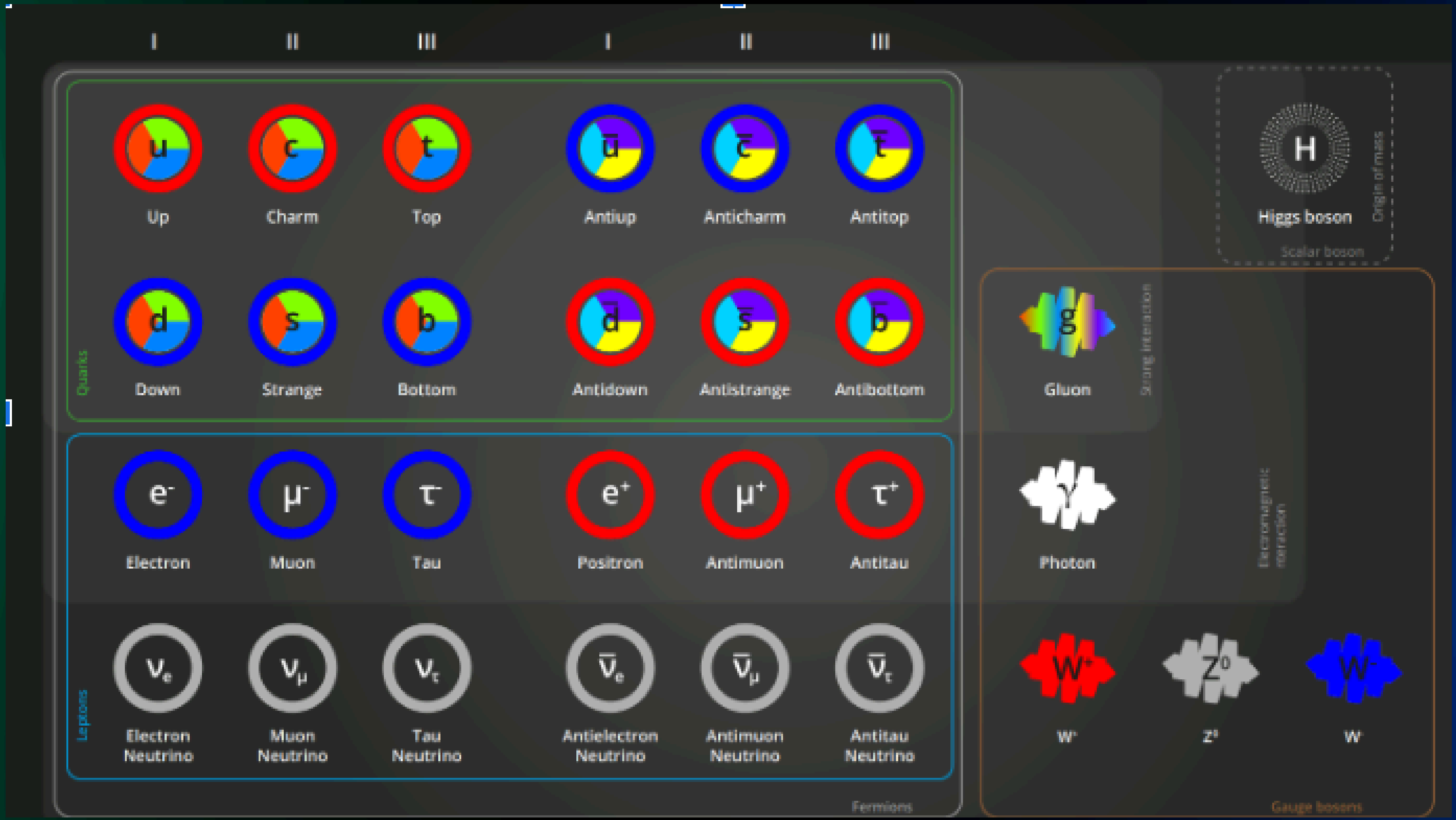
Theoretically, the SM should include a term in the strong interaction breaking CP symmetry. causing slightly different interaction rates for matter vs. antimatter. Experimentally, however, no such violation has been found, implying that the coefficient of this term – if any – would be suspiciously close to zero. ”



Quantum Triviality

Quantum triviality suggests that it may not be possible to create a consistent quantum field theory involving elementary scalar Higgs particles. This is sometimes called the Landau pole problem

- **SM was completed in 2012 through the discovery of the Higgs boson**



Dark Matter

The ,,wanted" particle should be :

-stable or ,at least have lifetimes that are much longer than the age of universe.

-interacting weakly,or not at all with the standard model particles.

- carrying neither color nor electromagnetic charge

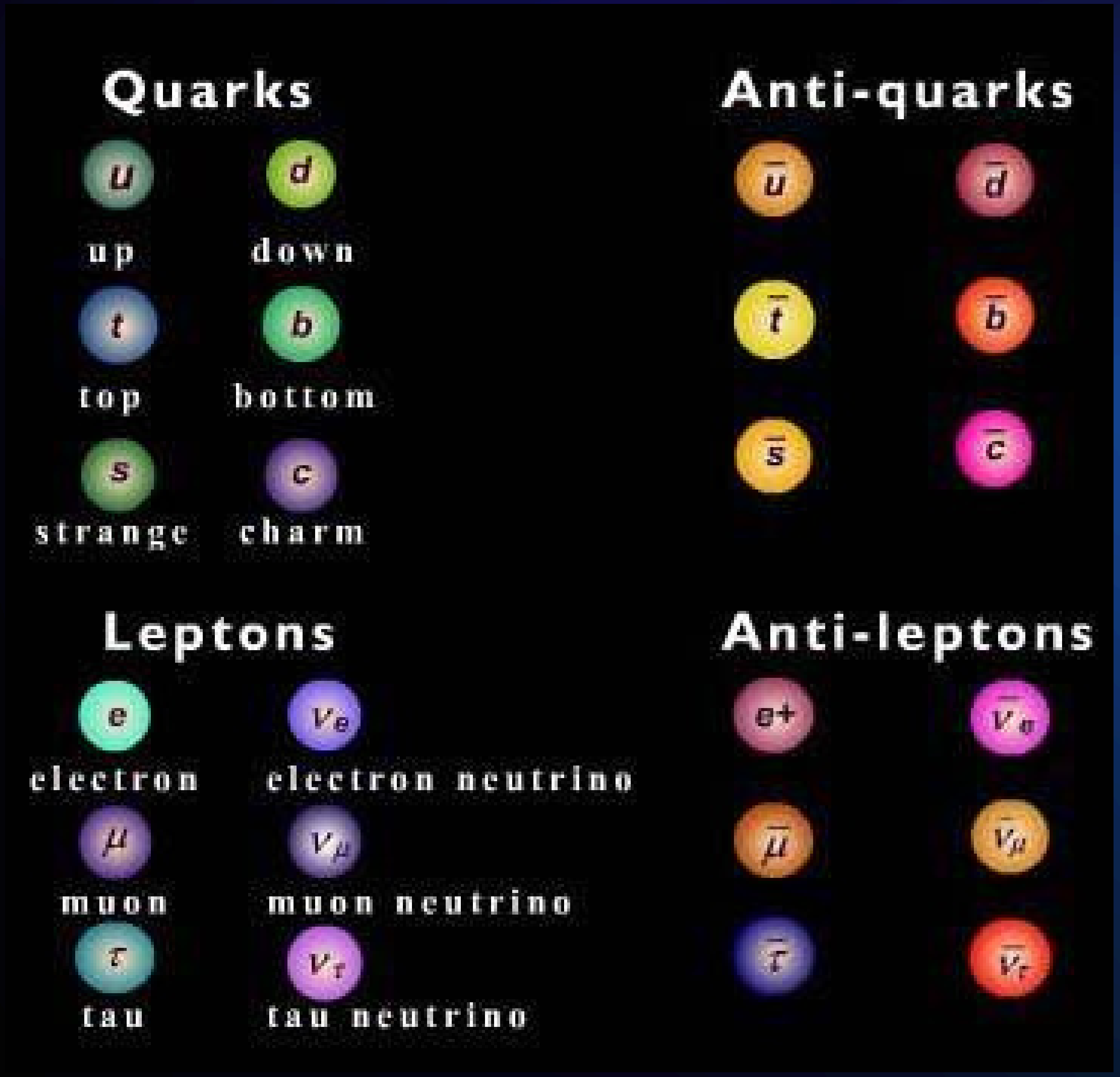
The Standard Model does not supply any fundamental particles that are good dark matter candidates,because none of them has the required characteristics.

→ **Dark Matter calls for new physics**

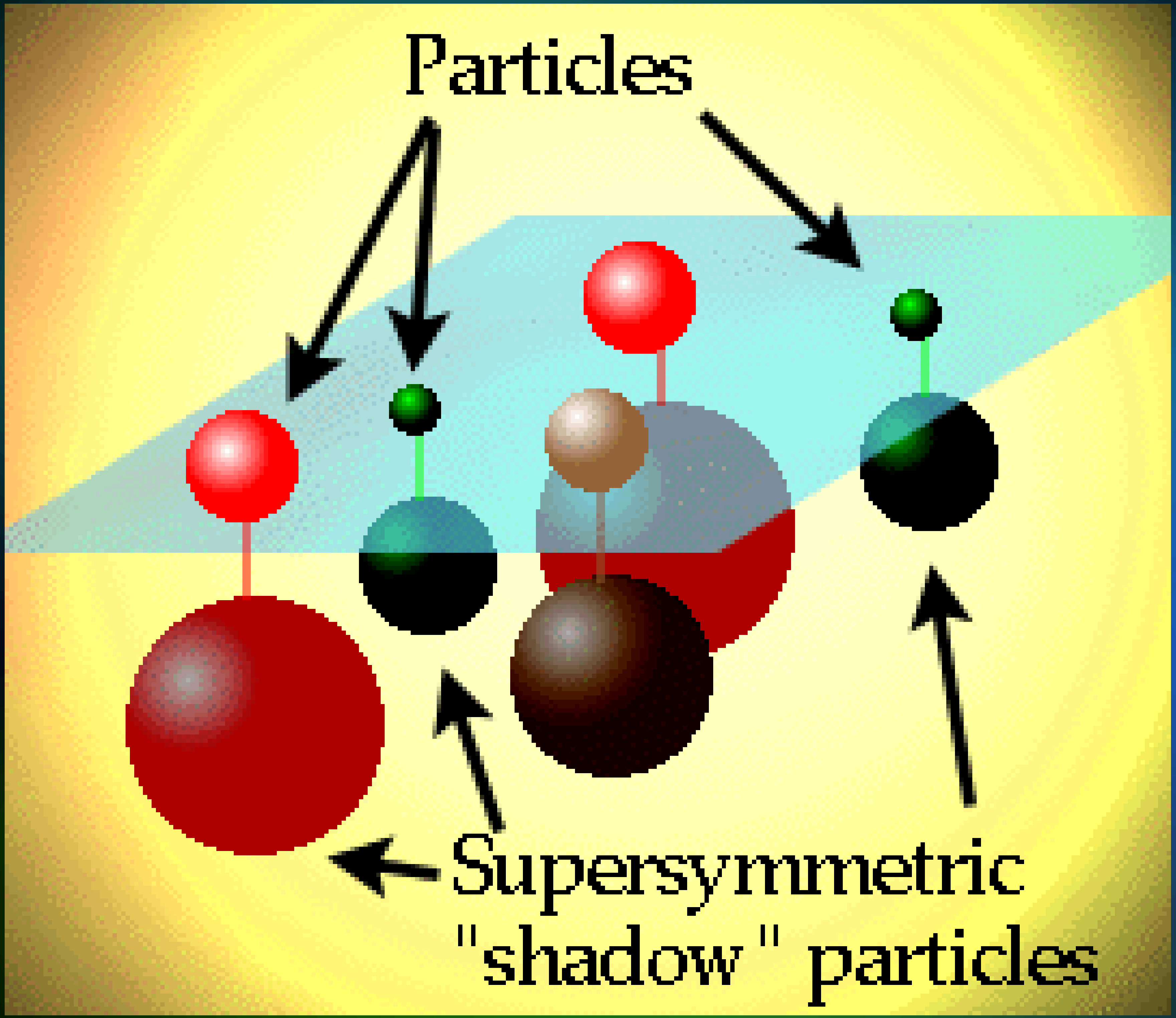
04

Possible Theories

Supersimmetry (SUSY)

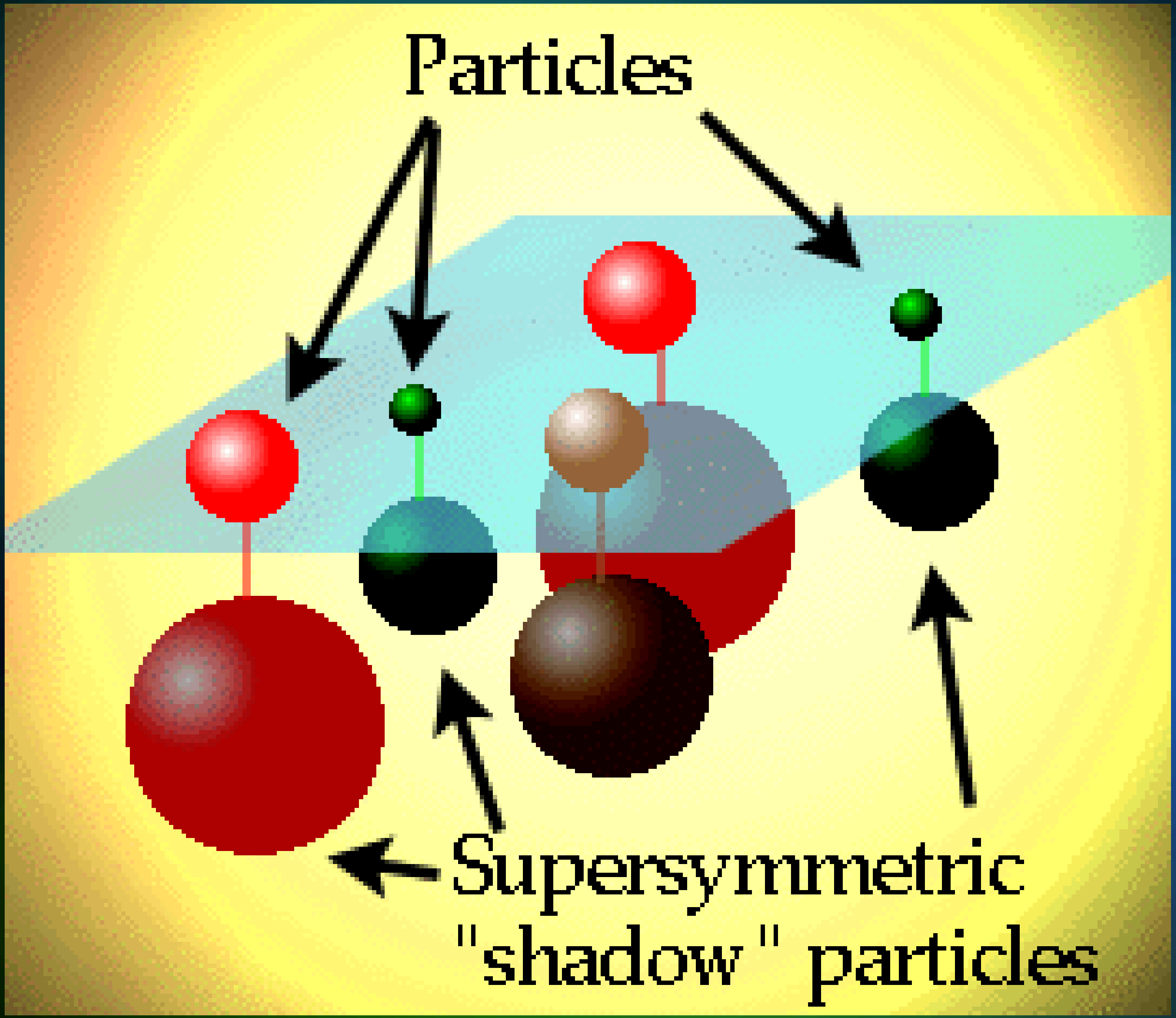


In Supersymmetry (SUSY) each Standard Model particle has a super-partner „sparticle" which differs by half a unit of spin .



Paul Dirac had to introduce the positron, the antiparticle of the electron, which has the same rest mass and the same spin as the electron, but a positive electric charge

Dirac's assumption, however strange, was not only experimentally verified but also became theoretically indispensable.



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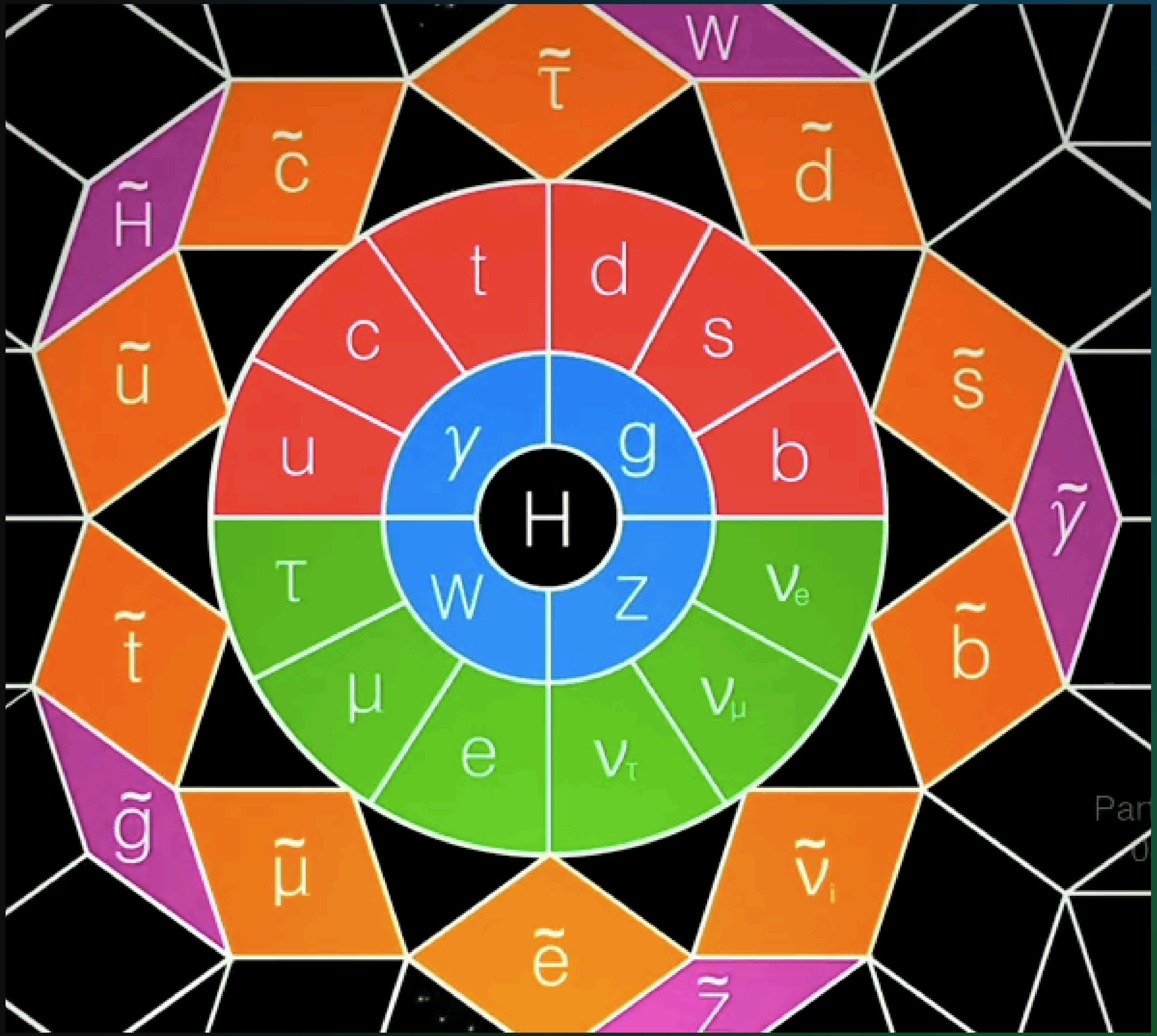
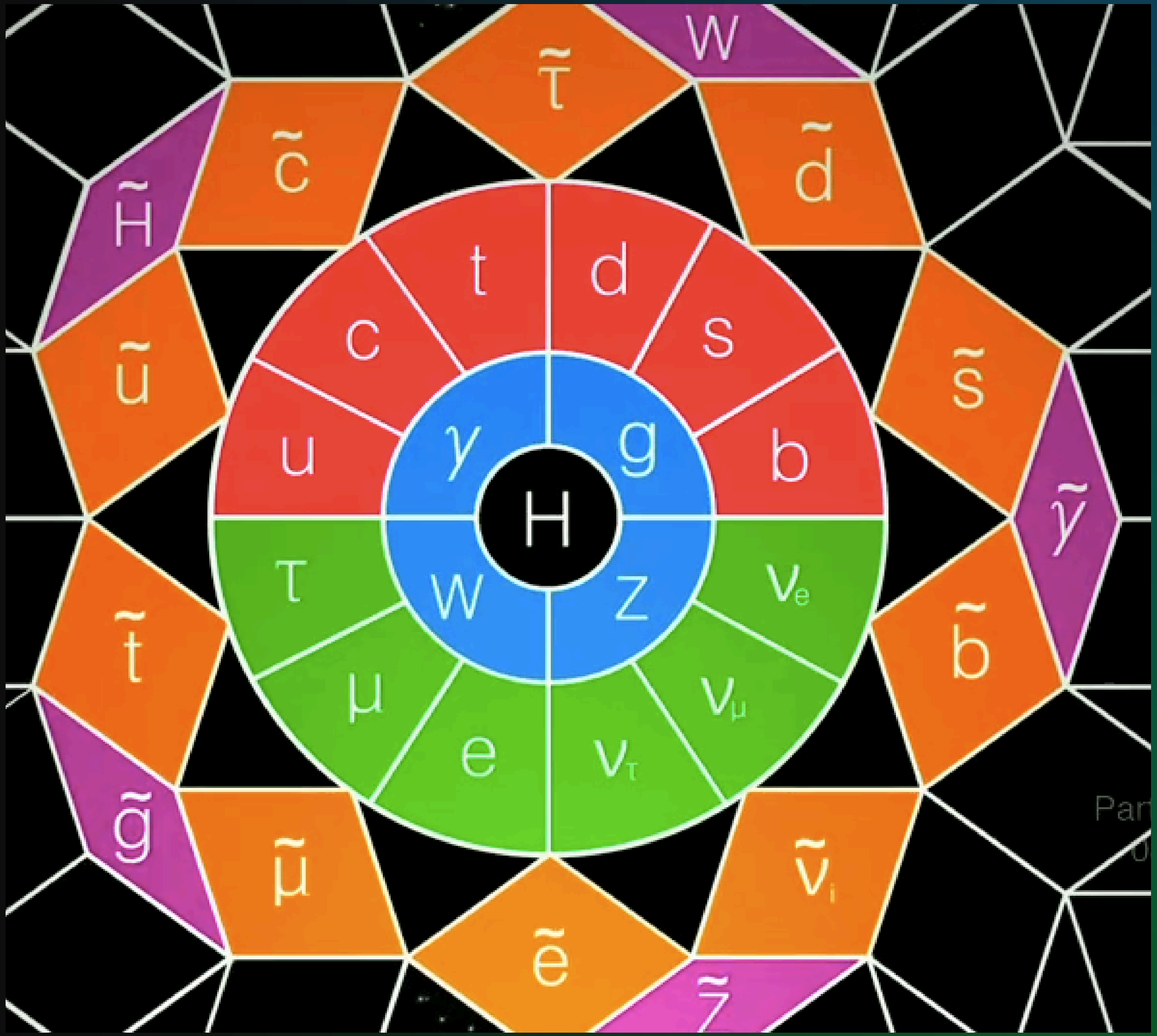
Physicists propose another symmetry



Where is the supersymmetry?

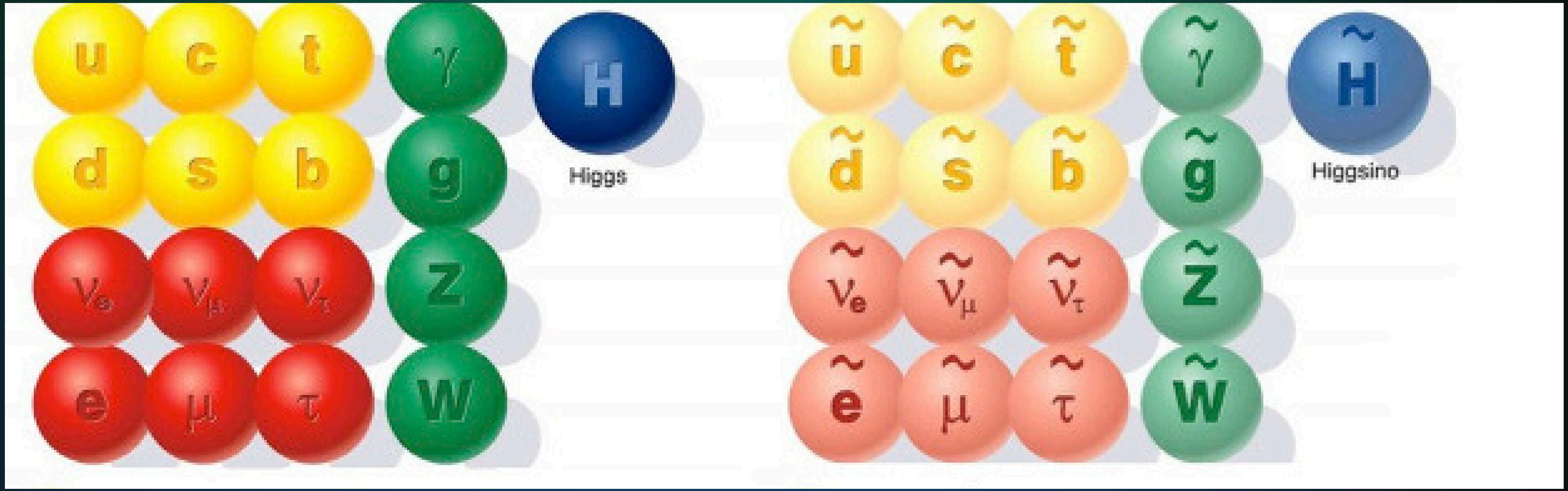


Where is the supersymmetry?

We need more powerful accelerators to detect more massive particles.

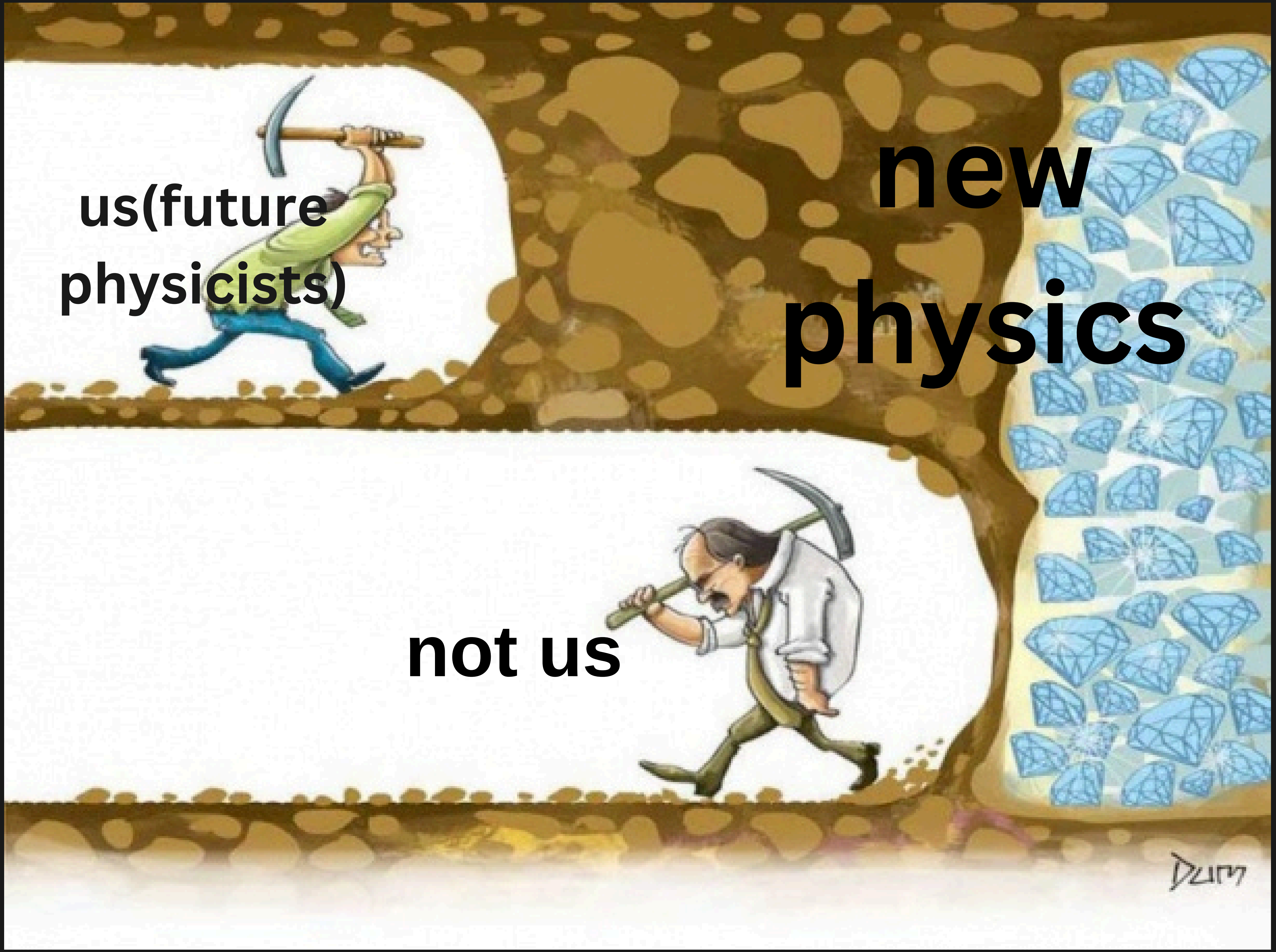
Supersymmetry :Two birds with one stone?

Supersymmetry solves the Hierarchy problem and the new particles are possible canditates for Dark Matter



Conclusion

There are many ideas that address the problems listed above, and that require some kind of "new physics" at higher energy scales. Whatever the answer, these ideas will be around for the foreseeable future,waiting to be discovered, and will continue to be explored at the LHC and other experiments.



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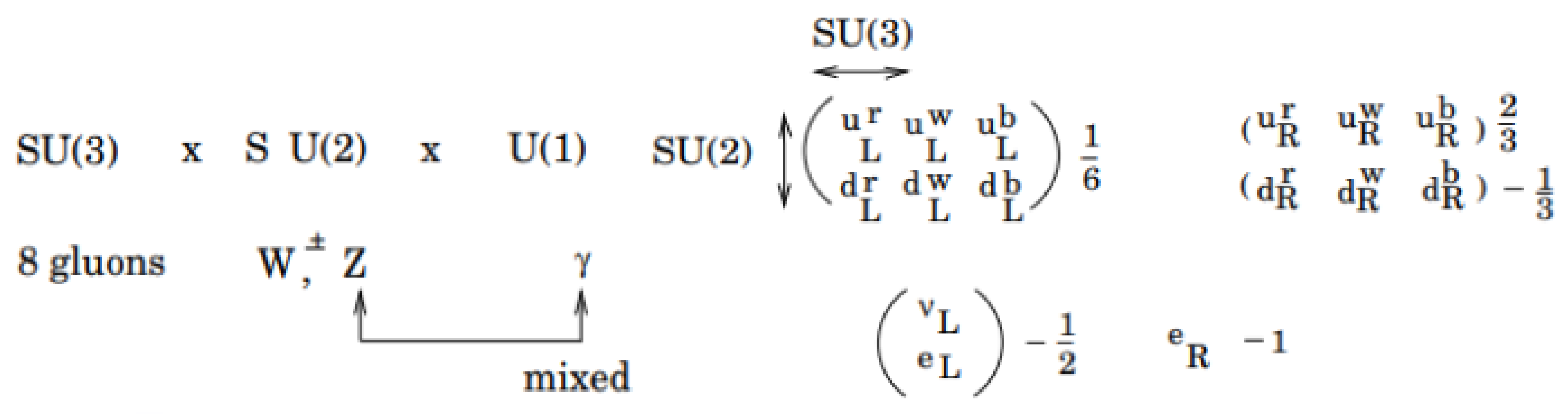
Interesting relations within the Standard Model

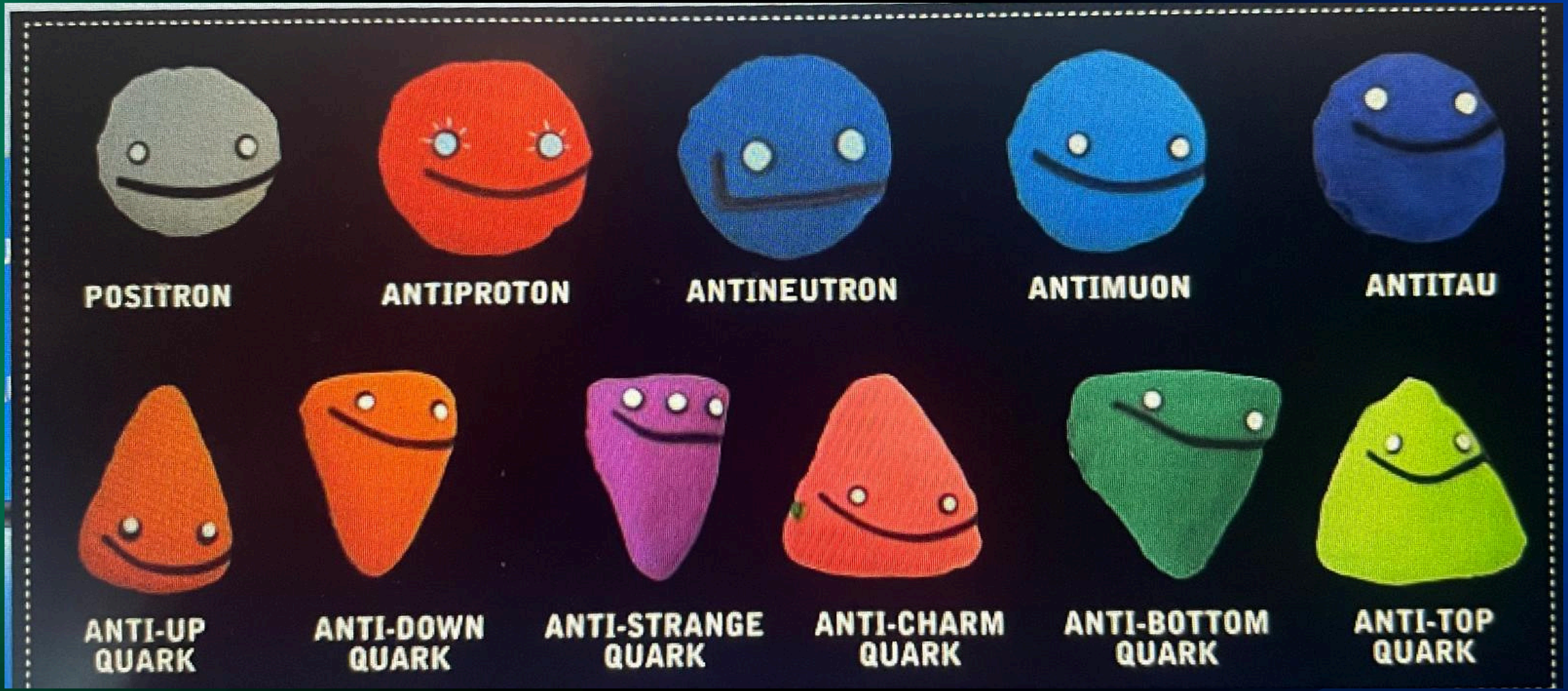
- The value of the Koide formula is equal to 2/3 within experimental errors of the measured lepton masses suggests the existence of a theory which is able to predict lepton masses
- The sum of squares of the Yukawa couplings of all Standard Model fermions is approximately 0.984, which is very close to 1. To put it another way, the sum of squares of fermion masses is very close to half of squared Higgs vacuum expectation value.
- The sum of squares of boson masses (that is, W, Z, and Higgs bosons) is also very close to half of squared Higgs vacuum expectation value, the ratio is approximately 1.004.

- Consequently, the sum of squared masses of all Standard Model particles is very close to the squared Higgs vacuum expectation value, the ratio is approximately 0.994



The core of the Standard Model: the gauge groups and the quantum numbers of quarks and leptons

Thanks for watching!



Resources

Beyond the Standard Model - CERN Document Server
https://arxiv.org/pdf/hep-ph/9802400
Five mysteries the Standard Model can't explain | symmetry magazine
https://design-guidelines.web.cern.ch/sites/default/files/2022-01/Quantum-particles-design-basis-2021.pdf
Physics beyond the Standard Model - Wikipedia
Microsoft PowerPoint - 20240606_RoumanianStudent [Compatibility Mode] (cern.ch)
12. Beyond the Standard Model - Particle and Nuclear Physics (cam.ac.uk)
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