BEYOND THE STANDARD MODEL OF PARTICLE PHYSICS

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PUC RIO

WANT TO HIGHLIGHT SOME OF THE ISSUES WITH THE STANDARD MODEL AND POINT TO POSSIBLE SOLUTIONS!

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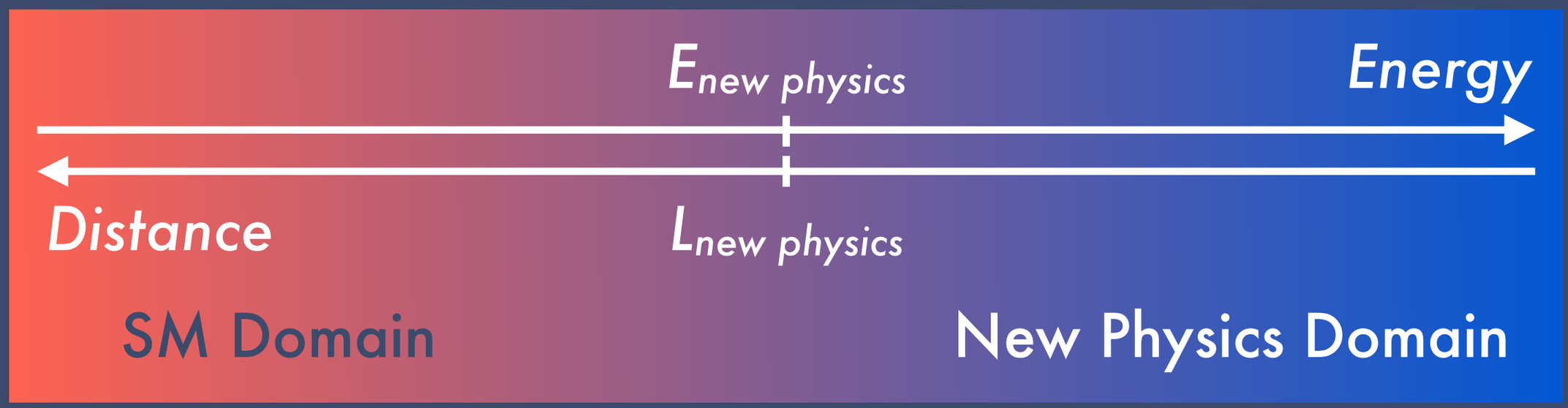
- There are a number of serious issues which lead us to believe that the SM is not the final answer.
- How can the SM be valid and invalid at the same time????
- SM is an effective theory valid only at low energies



Problem #1: Naturalness

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- SM does not include a quantum theory of gravity
- Quantum effects of gravity become important only at extremely high energies: $E_{\mathrm{QG}} \sim M_{\mathrm{Planck}} \sim 10^{19}$ GeV

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- Why are E_{SM} and E_{QG} so vastly different?
- Even worse, the only way to get a small E_{SM} is by cancellations: $E_{SM}^2 = aE_{\mathrm{QG}}^2 - bE_{\mathrm{QG}}^2$

$$\frac{a}{b} = 1{,}000000000000000000000000000001$$

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) Duality

SUPERSYMMETRY

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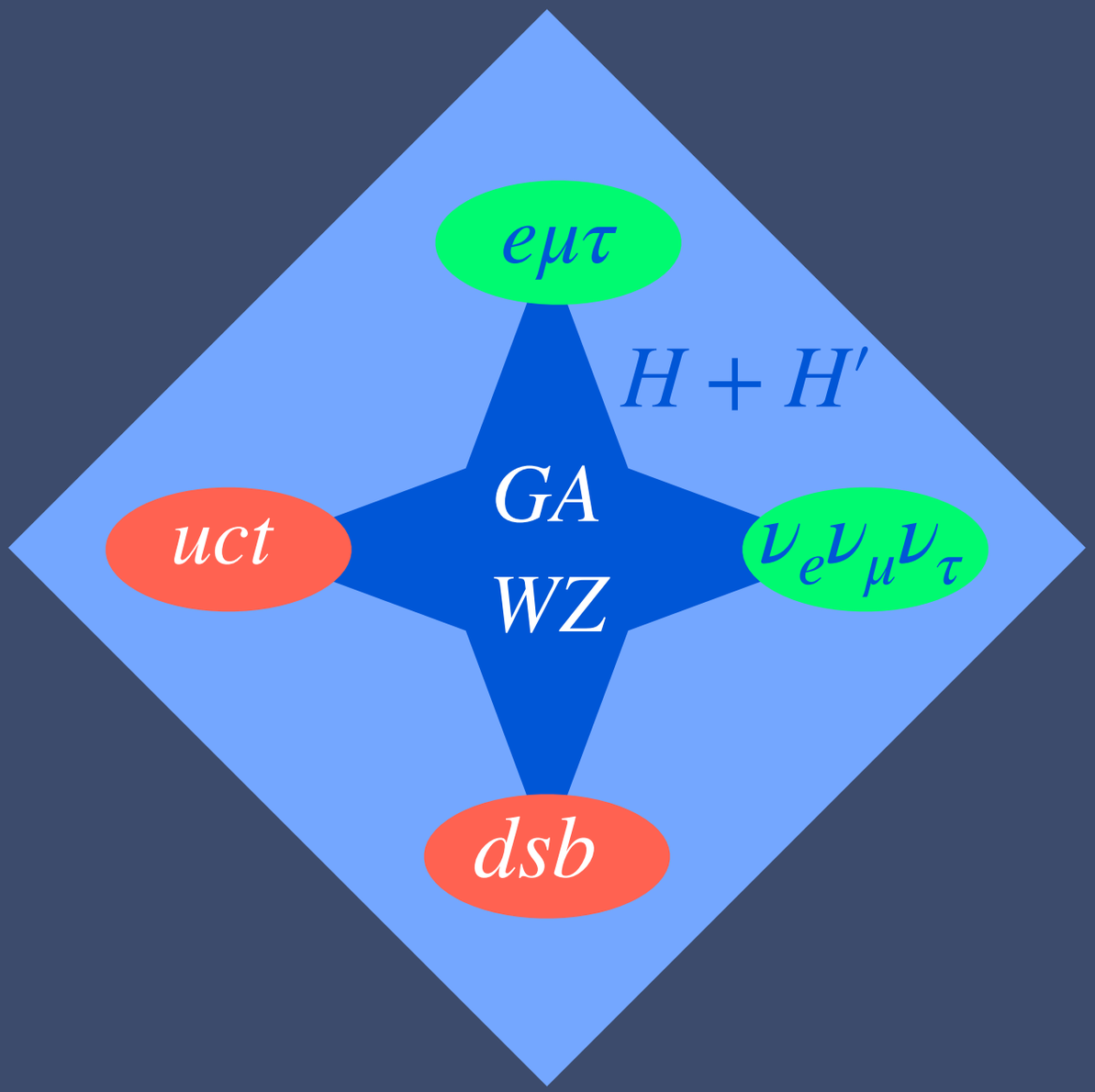

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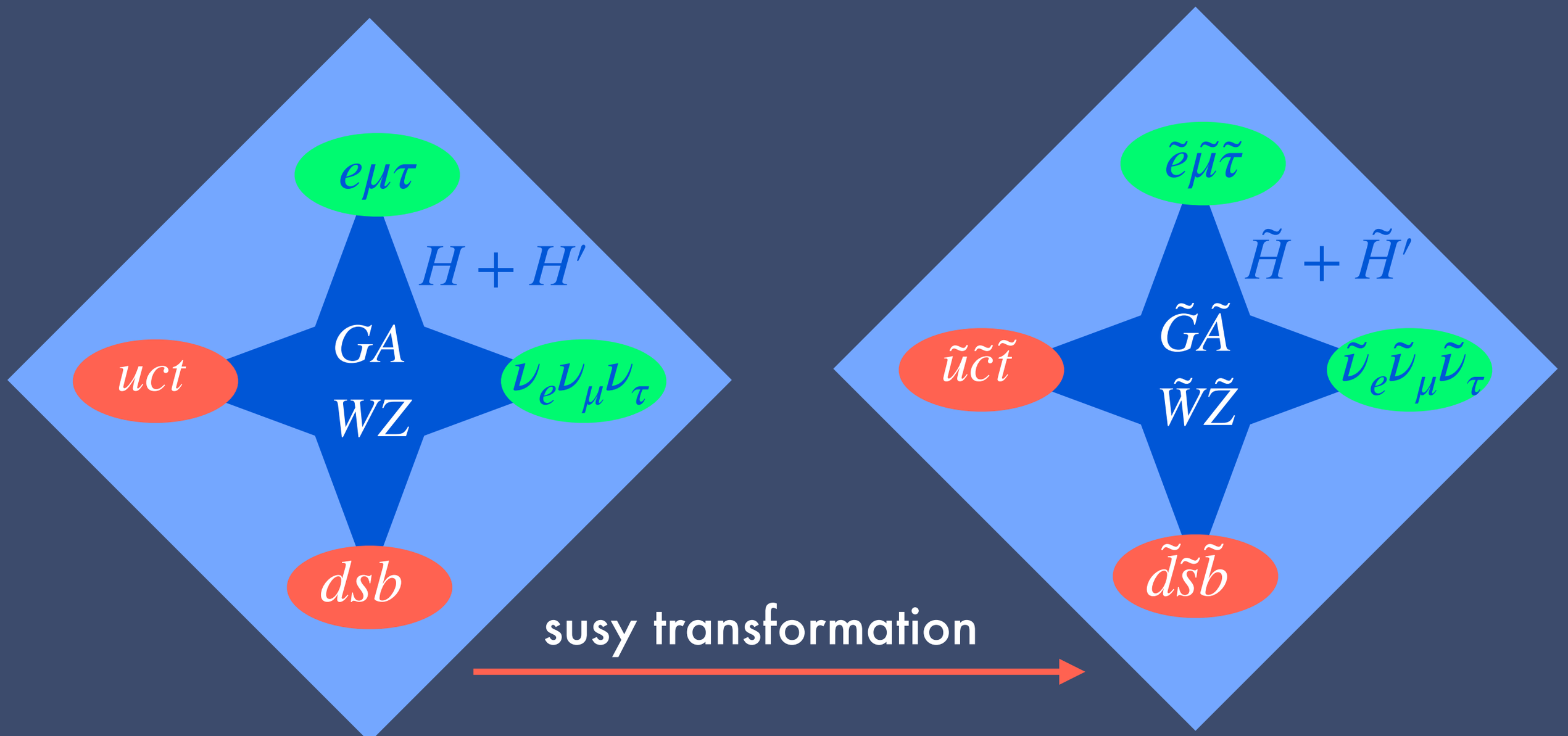

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- The Higgs comes with a spin - $\frac{1}{2}$ partner (Higgsino), whose mass is protected, and only depends logarithmically on E_{QG}.
- SUSY ensures that the mass of the Higgs and the Higgsino are the same
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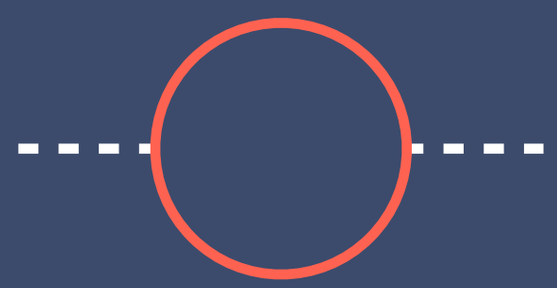

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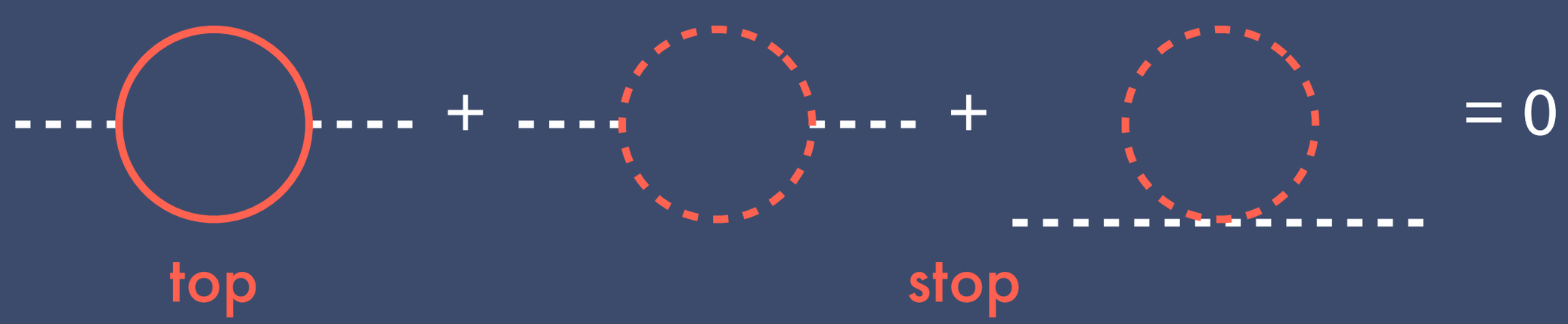

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- Avoided if SUSY is spontaneously broken!
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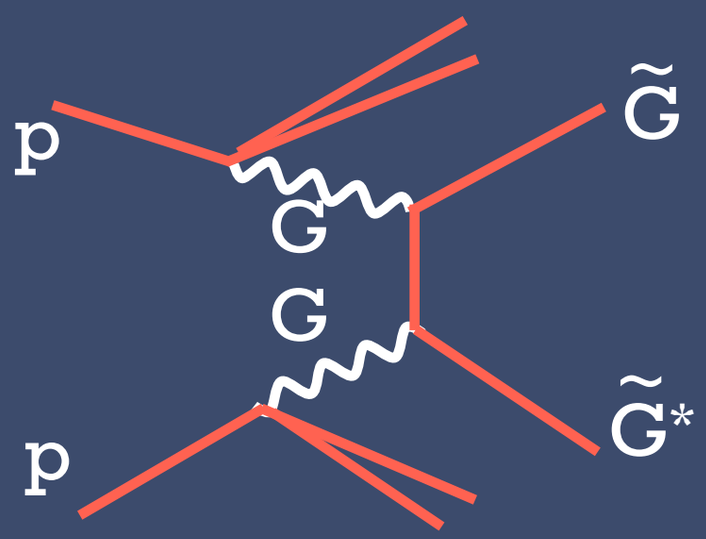

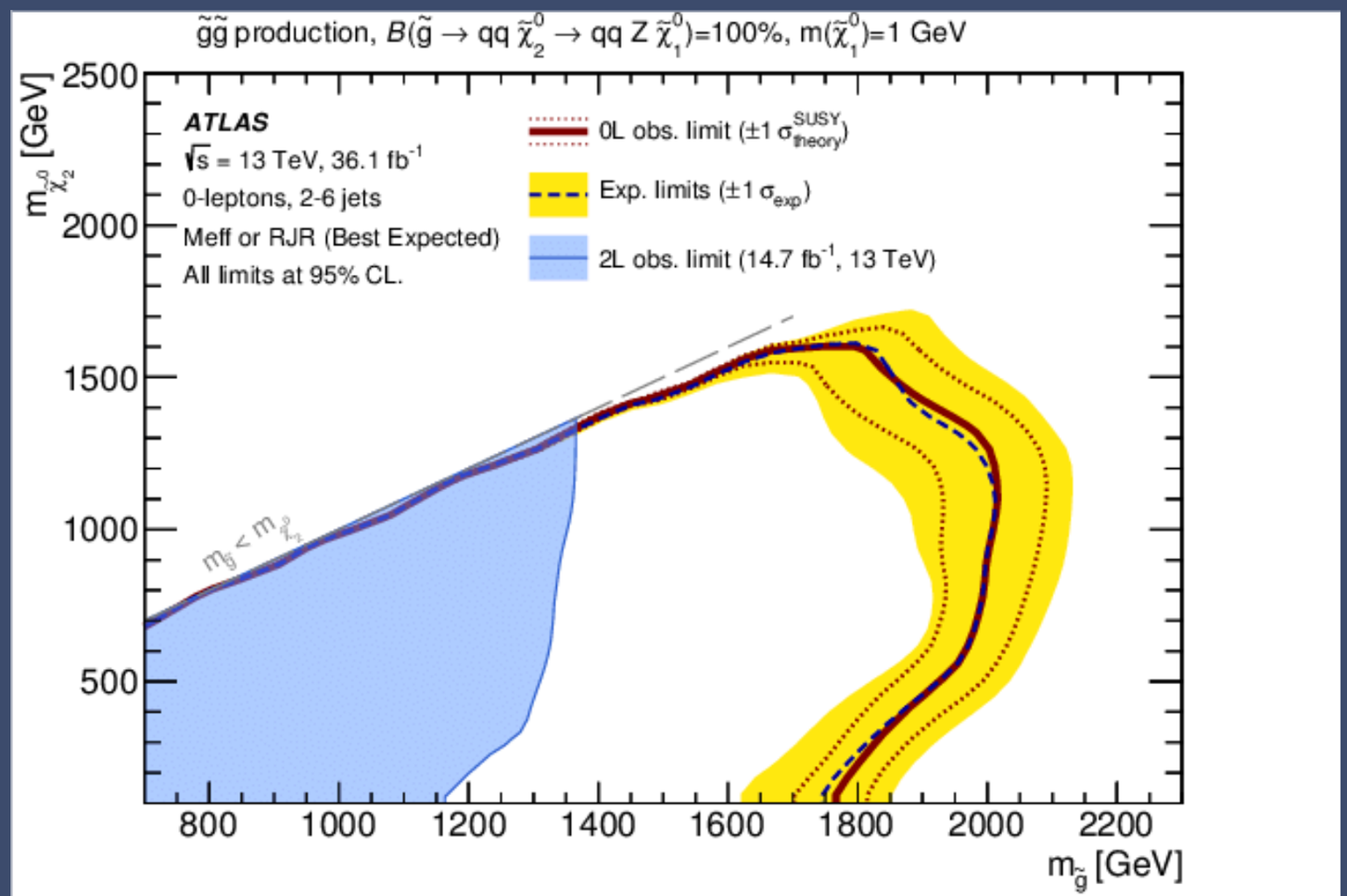

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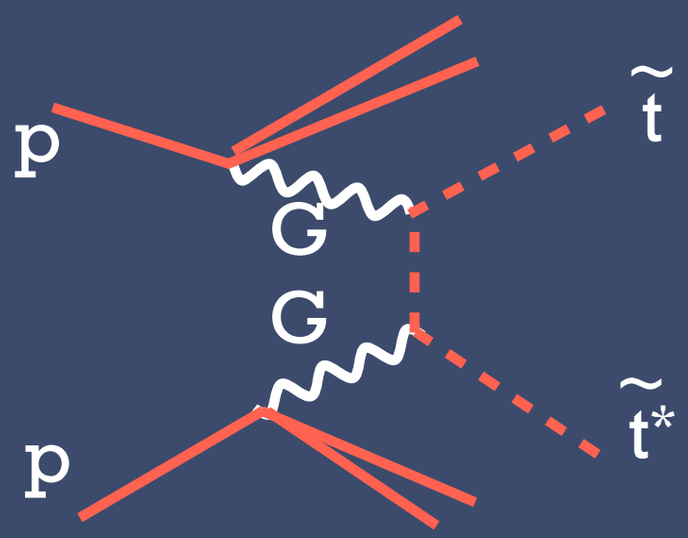
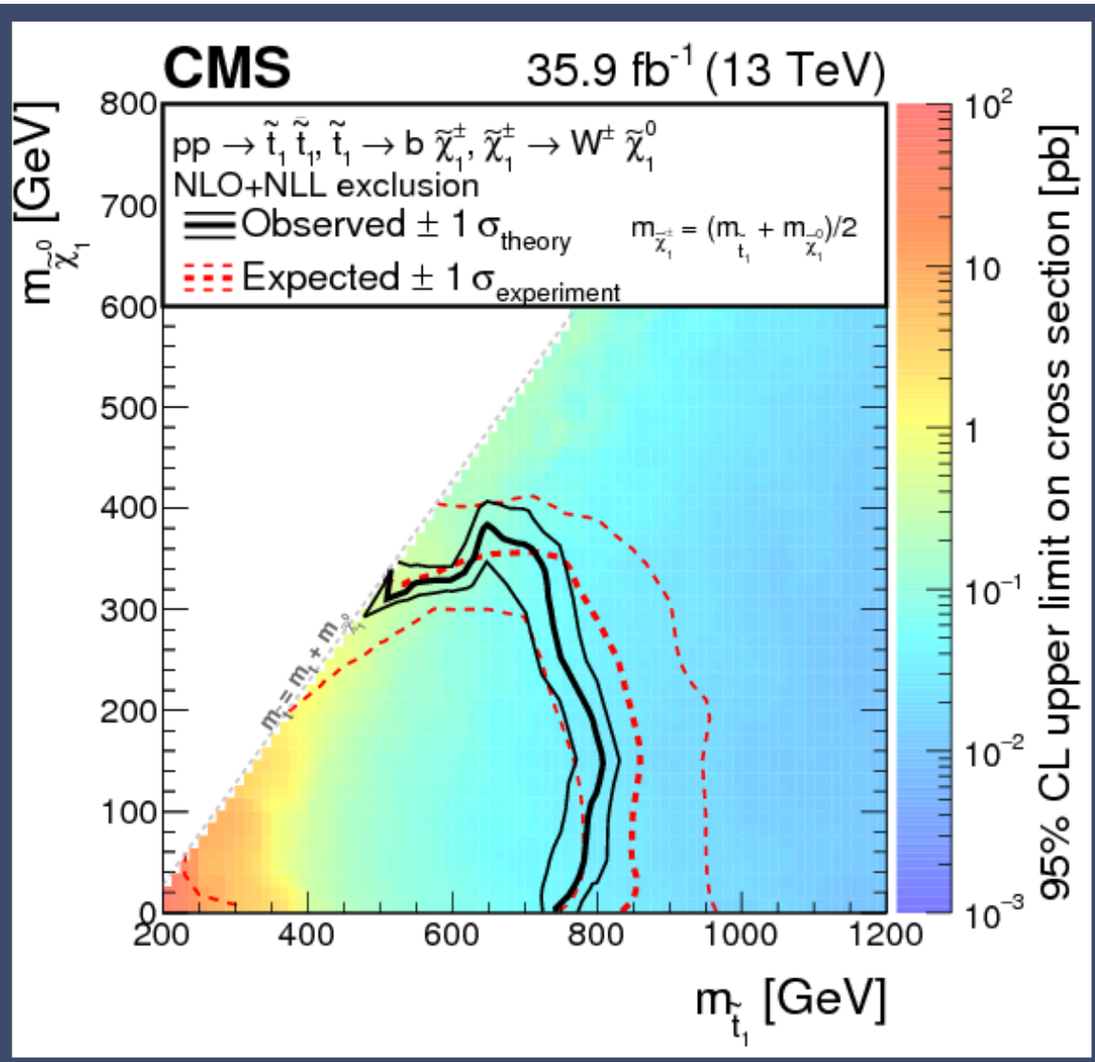
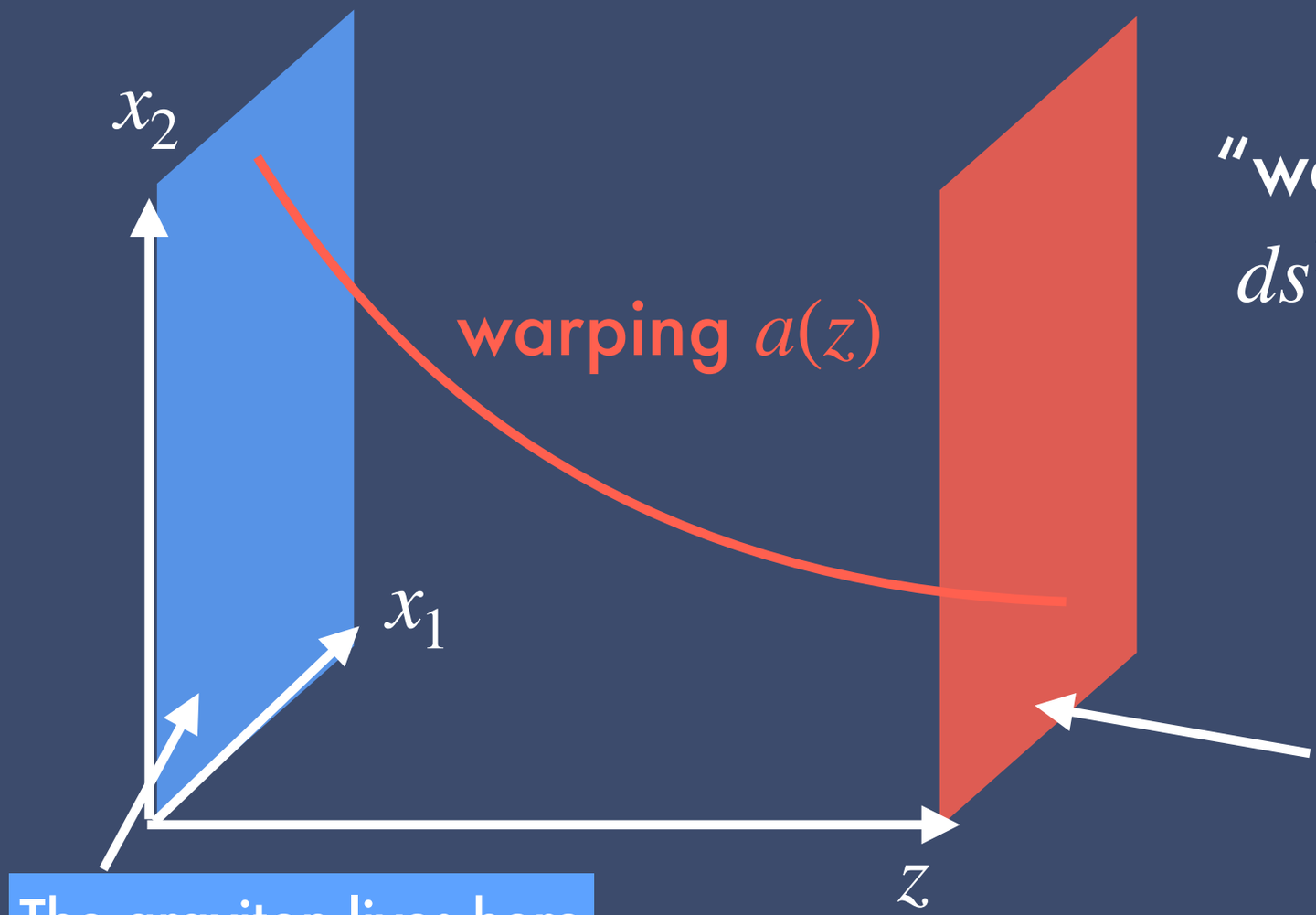




Warped Extra Dimensions

Alternative: An extra-dimensional explanation:



"warped" metric:

$$ds^2 = a(z)(\eta_{\mu\nu}dx^\mu dx^\nu + dz^2)$$

The extra dimension is of microscopic size ($\sim E_{\rm QG}^{-1}$)

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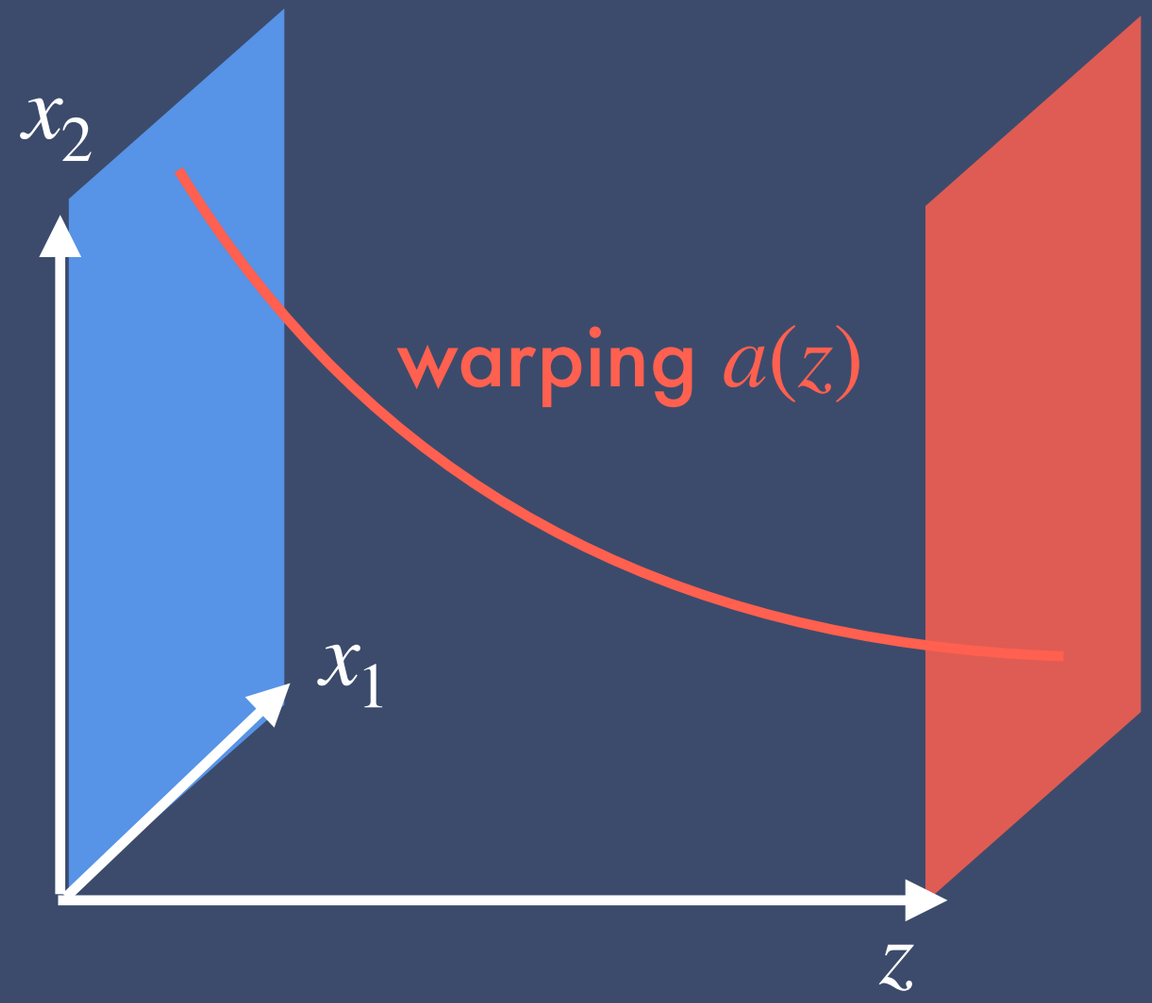
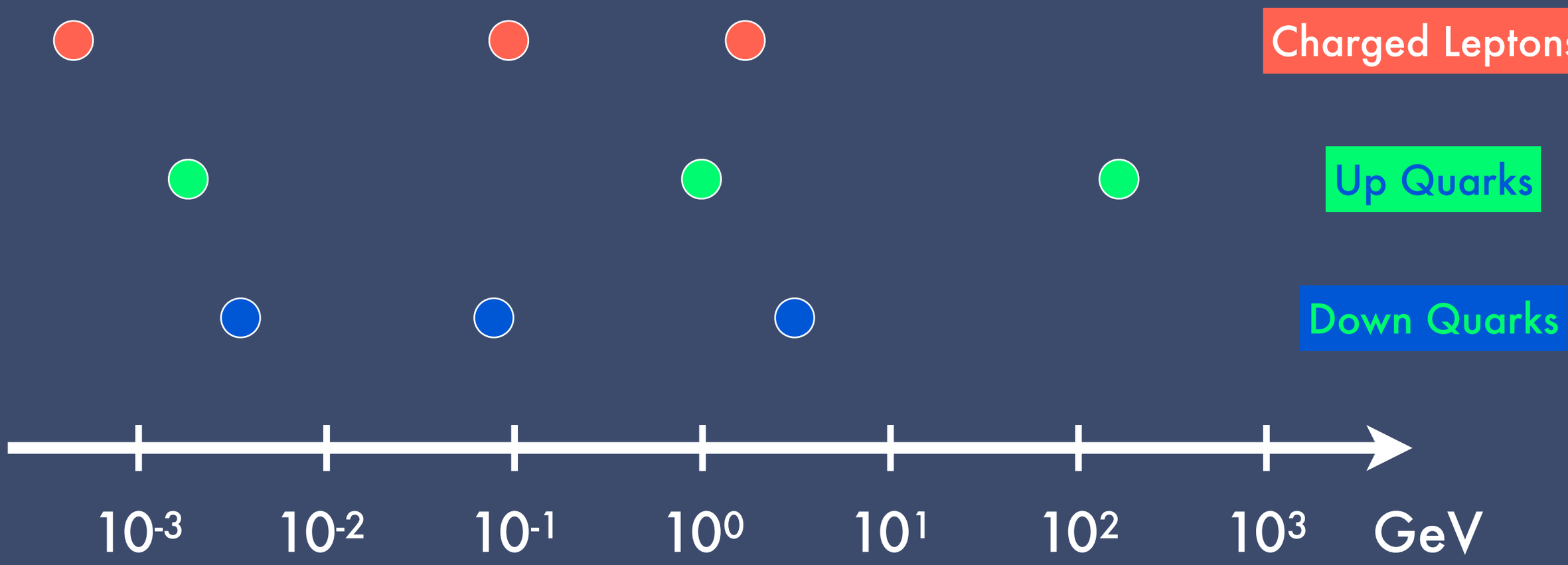


- The theory predicts a tower of new ("Kaluza Klein") particles that can be searched for!
- Their masses are expected at the TeV
- So far, nothing has been found...

Problem #2: masses of fermions

The SM charged fermion masses span several orders of magnitude:



Lots of models to explain this (possibly only at very high scale…)

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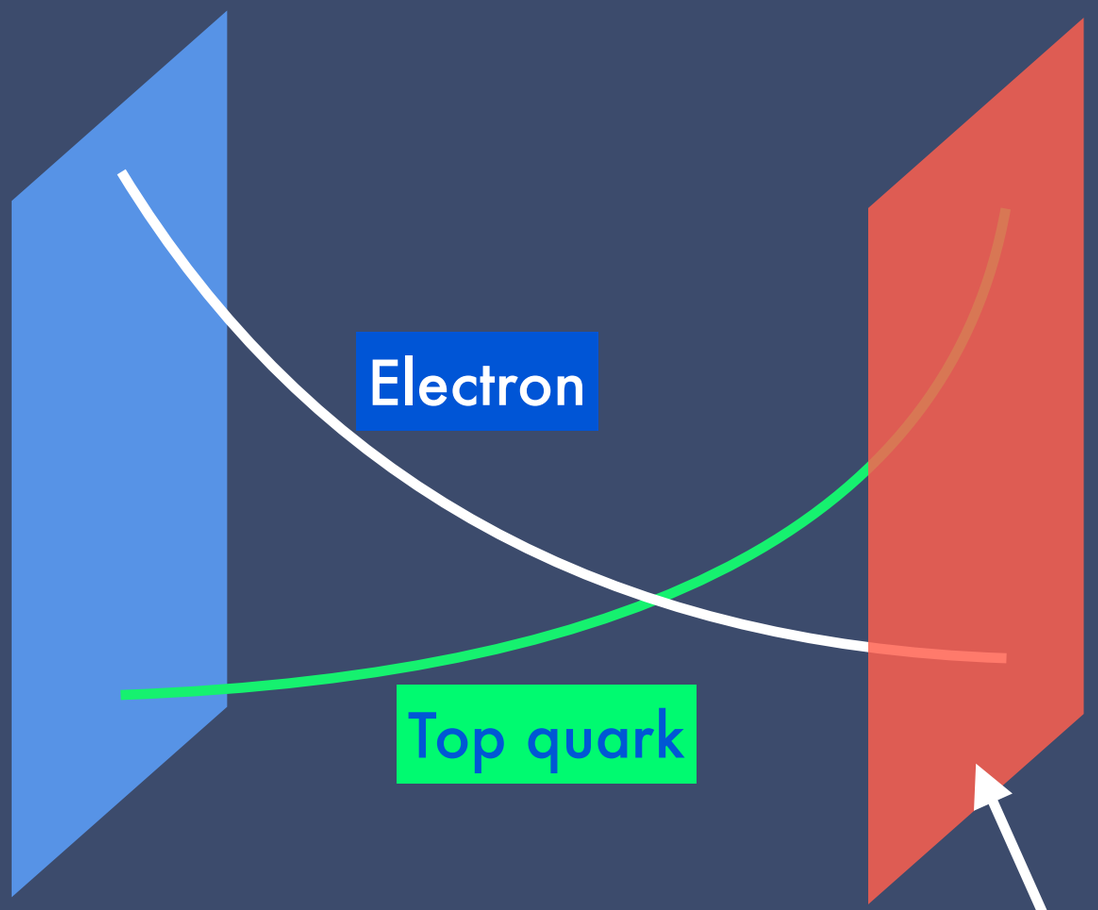
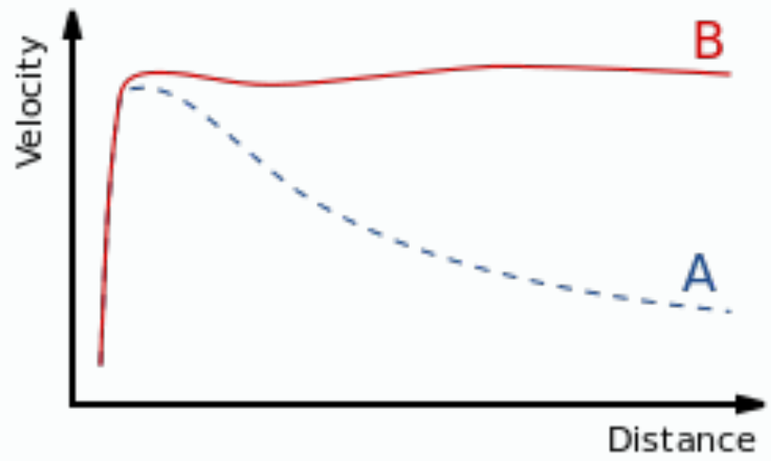
Example: An extra-dimensional explanation



The smaller the "wave function" of the Fermion at the location of the Higgs, the smaller its Yukawa coupling, and the smaller its mass!

Problem #3: Dark Matter

- Purely gravitational observations predict the presence of additional matter in the universe
- This matter does not interact with light, so it is called "dark"



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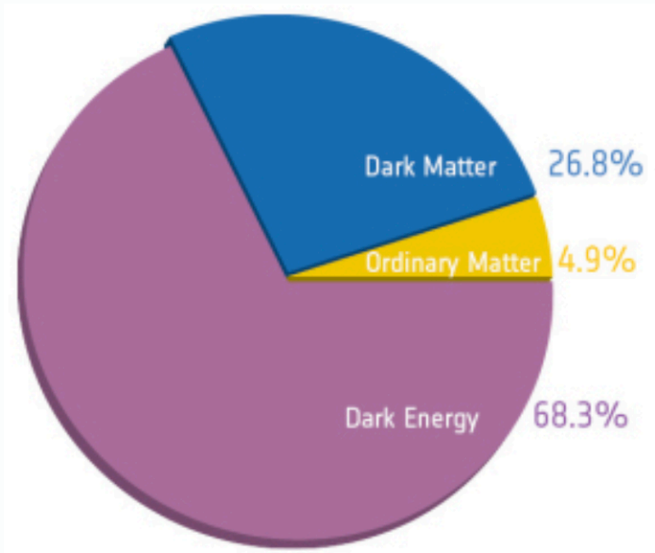

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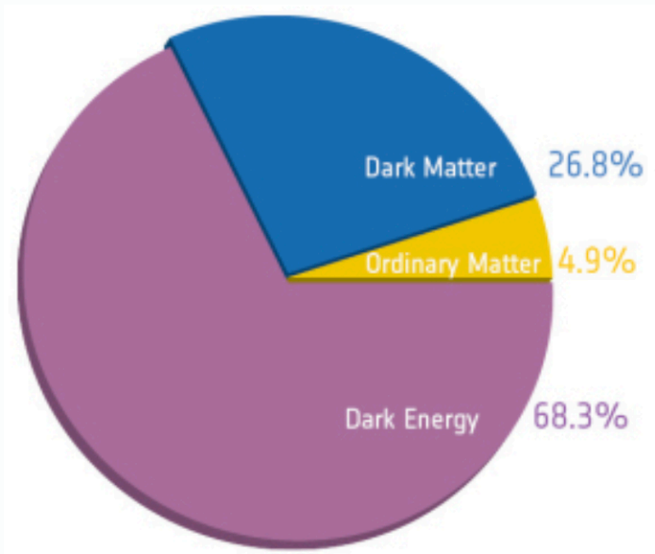

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- Weakly Interacting Massive Particles (WIMPs):
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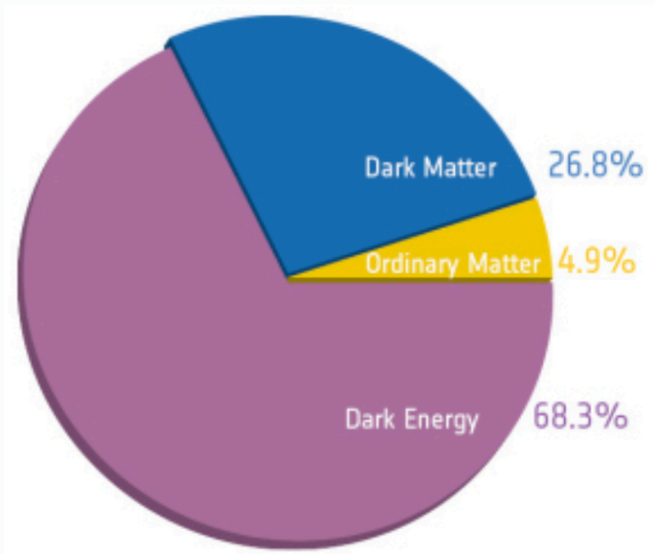

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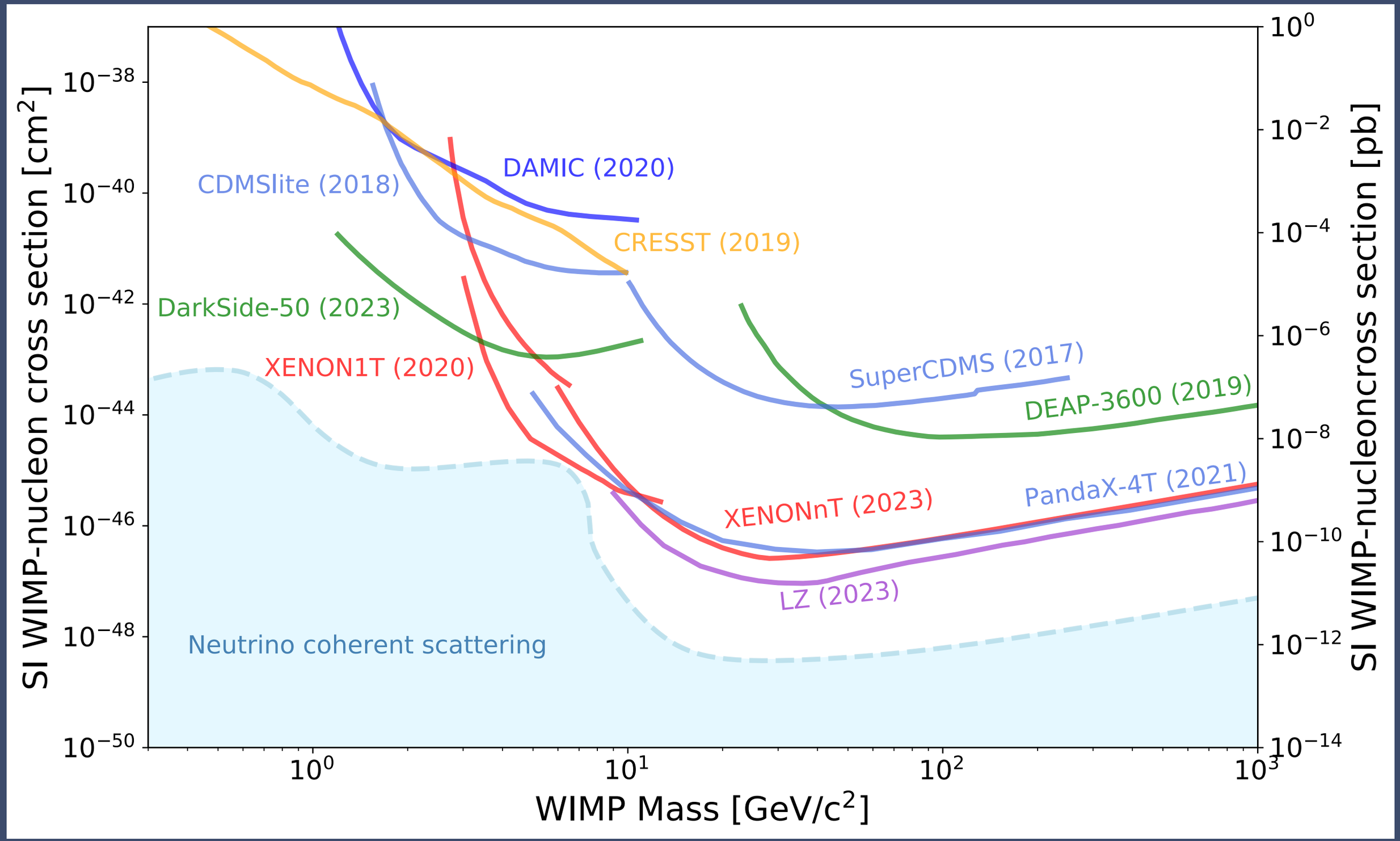

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- Idea: copy quark sector, by introducing right handed neutrinos and writing $\mathscr{L}_{\text{Yukawa}} = g\bar{\ell}_L \tilde{H} \nu_R \rightarrow \frac{gv}{\sqrt{2}} \bar{\nu}_L \nu_R$
- **Very important difference** to quarks: gauge invariance also allows for $\mathscr{L}_{\text{Majorana}} = m_M \nu_R \nu_R$
- Much richer structure!

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$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix} \qquad m_D = \frac{gv}{\sqrt{2}}$$

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- In the limit $m_M \ll m_D$ the eigenvalues are

$$m_{\text{heavy}} \approx m_M \qquad m_{\text{light}} \approx \frac{m_D^2}{m_M} \ll m_D$$

- For $m_D \approx v$ ($g \approx 1$) we get sub-eV neutrino mass for $m_M \sim 10^{15}$ GeV. This is almost the scale of grand unification (see later)

Problem #5: Fermion Quantum numbers

SM:

- 3 gauge groups: SU(3), SU(2), U(1),
  5 "representations"

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad \begin{pmatrix} u_L & d_L \\ u_L & d_L \\ u_L & d_L \end{pmatrix} \quad e_R \quad \begin{pmatrix} u_R \\ u_R \\ u_R \end{pmatrix} \quad \begin{pmatrix} d_R \\ d_R \\ d_R \end{pmatrix}$$

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- Idea: At high energies, we have a GUT group, with a "5" and a "10" representation
- Below a GUT scale, some Higgs mechanism occurs

$$SU(5) \to SU(3) \times SU(2) \times U(1)$$

$$\bar{\mathbf{5}} \to (\bar{\mathbf{3}}, \mathbf{1})_{\frac{1}{3}} + (\mathbf{1}, \mathbf{2})_{-\frac{1}{2}}$$

$$\mathbf{10} \to (\mathbf{3}, \mathbf{2})_{\frac{1}{6}} + (\bar{\mathbf{3}}, \mathbf{1})_{-\frac{2}{3}} + (\mathbf{1}, \mathbf{1})_{1}$$

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- Can even go further $SO(10) \to SU(5)$ with $\mathbf{16} \to \mathbf{10} + \bar{\mathbf{5}} + \mathbf{1}$
- One full SM generation + RH neutrino in a single representation of $SO(10)$

Coupling Unification

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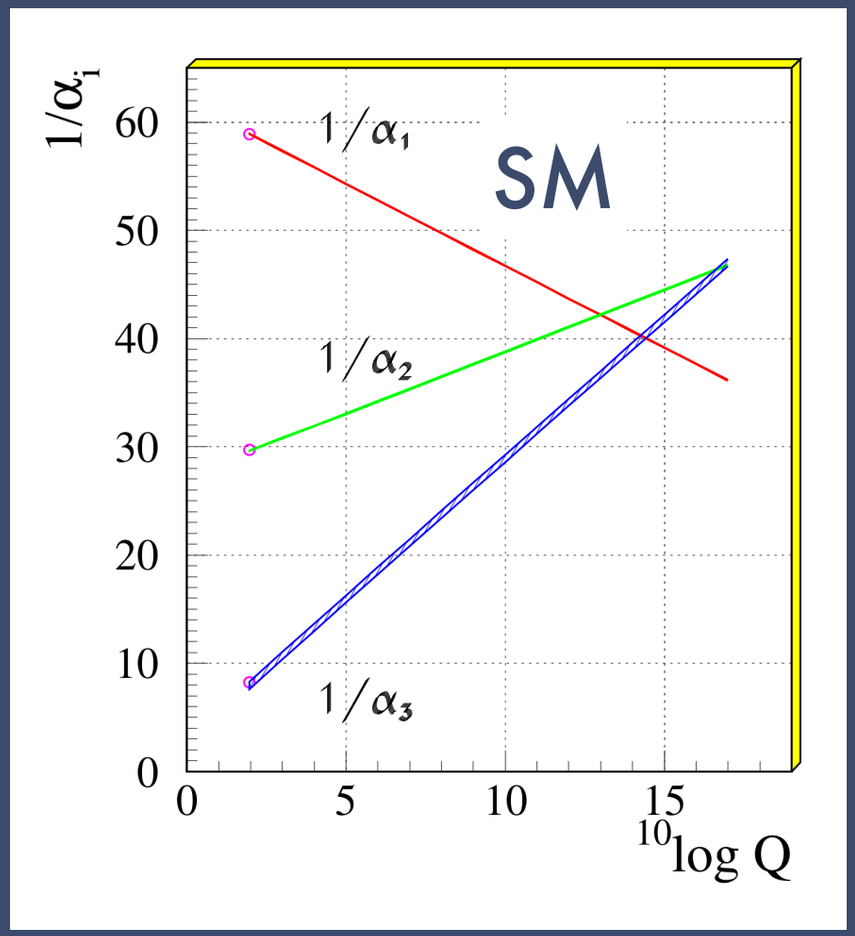

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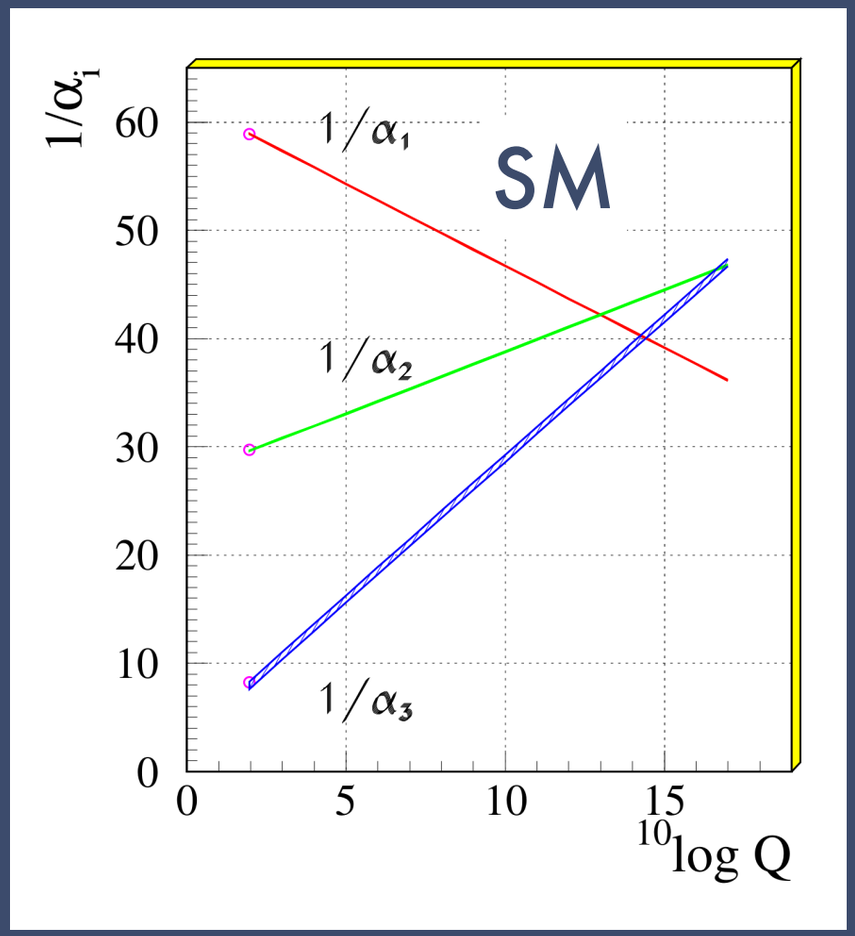

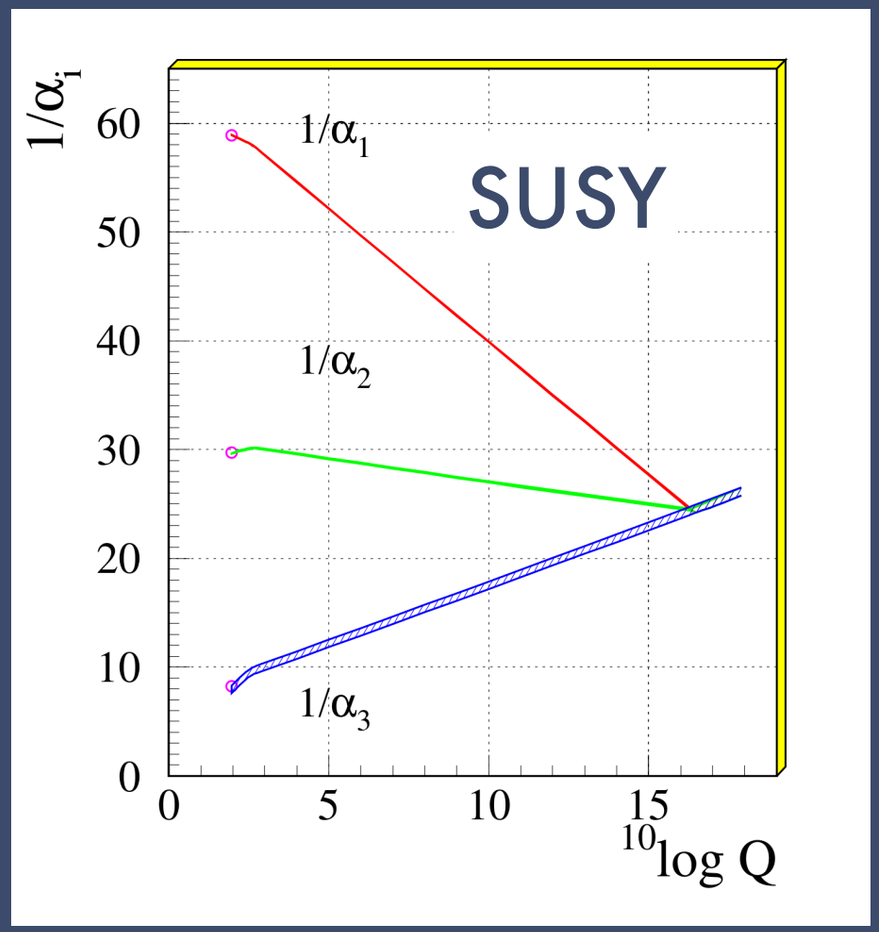

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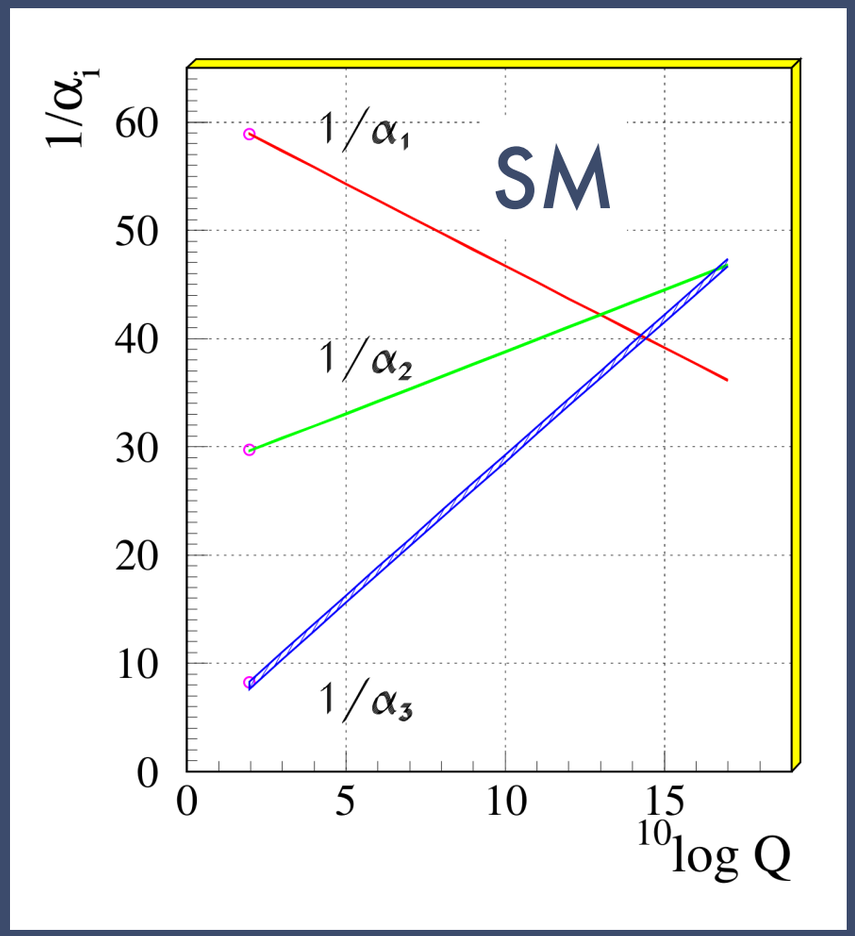
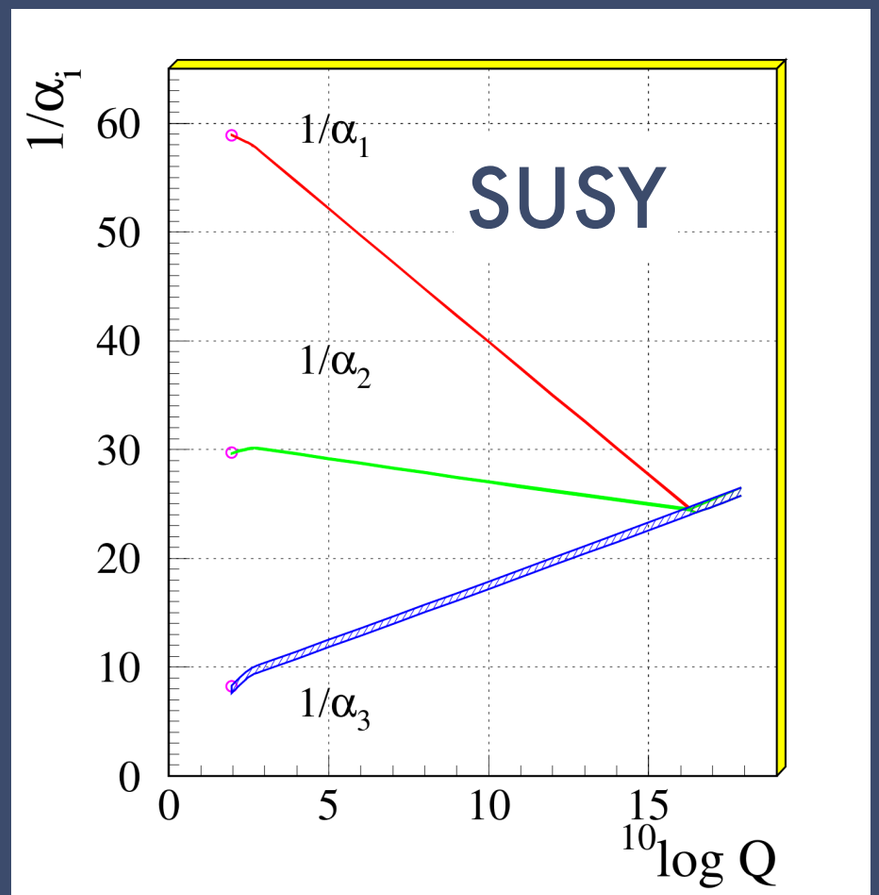


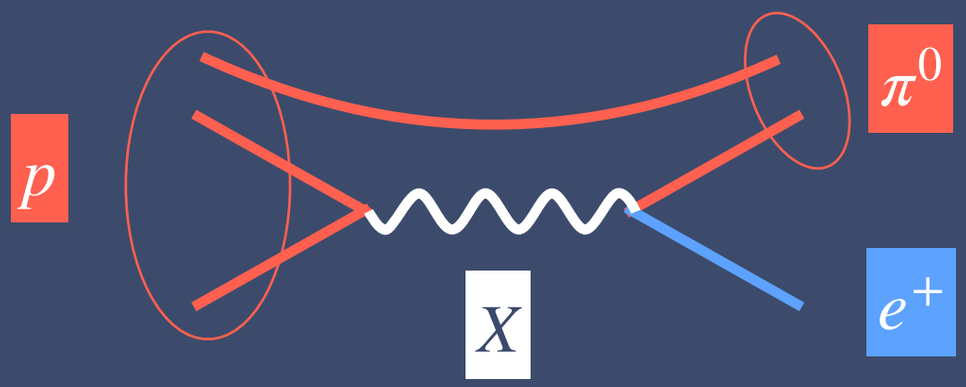


E_{SM} E_{susy} E_{GUT} E_{QG}

Can GUTs be tested?

- The GUT scale is HUGE ($\sim 10^{16}$ GeV)
- Far beyond reach of current colliders

- GUT theories (SUSY or not) violate Baryon Number
- Proton is no longer stable!



$$\Gamma(p \to \pi^0 e^+) \sim \frac{m_p^5}{m_X^4} \sim \frac{1}{10^{34}\ \text{years}}$$

- Close to exp. bound
- Some GUTs are excluded!

The Big 5 of Particle Physics

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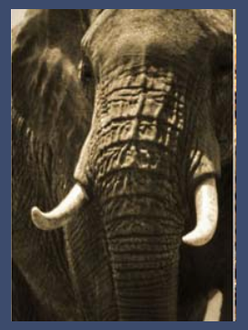

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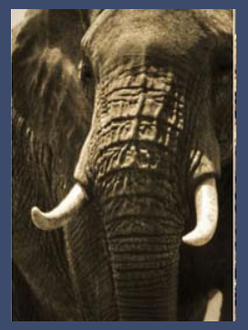

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What mechanism explains the curious pattern of fermion masses and mixings, and how can it be tested ?

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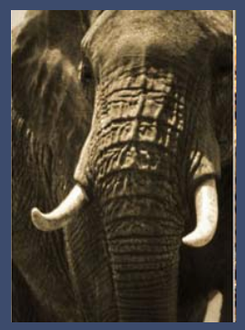

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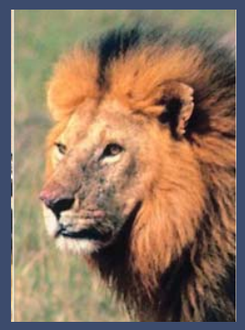

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What is the nature of Dark Matter ?

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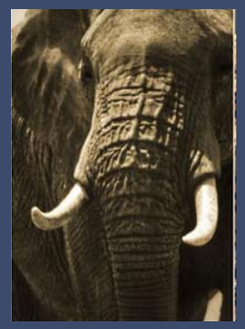

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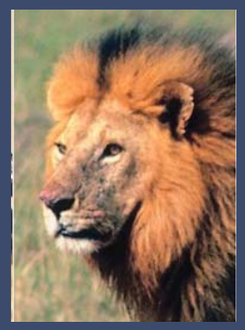

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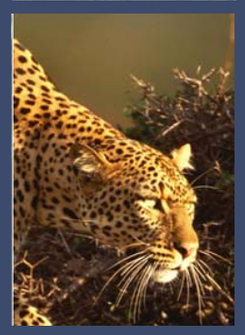
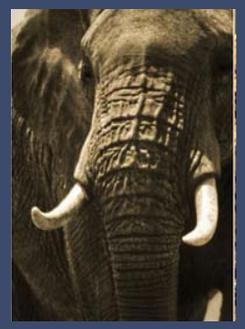
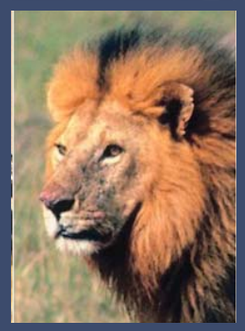


What are the masses of Neutrinos, and are they Majorana or Dirac particles ?

The Big 5 of Particle Physics

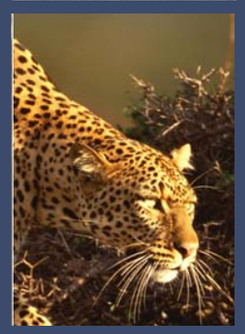


What Physics is responsible for Electroweak Symmetry Breaking, and is it natural (not fine-tuned) ?



What mechanism explains the curious pattern of fermion masses and mixings, and how can it be tested ?

What is the nature of Dark Matter ?



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What causes the matter-antimatter asymmetry of the universe?