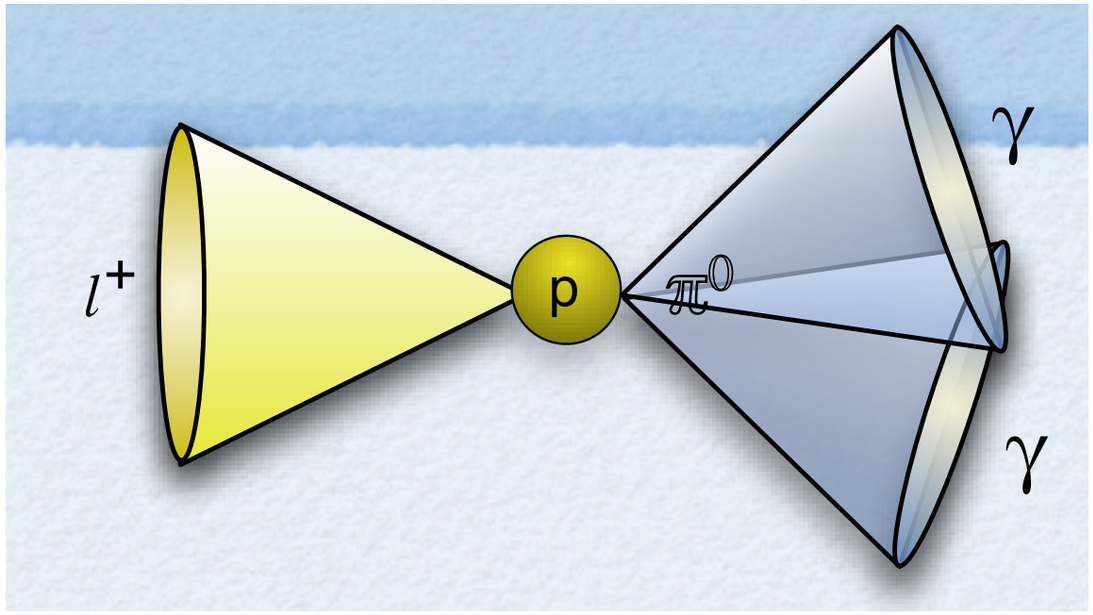
Proton Decay



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Proton Stability

- In the Standard Model, baryon and lepton number is conserved at the perturbative level

- Leptons are the only known fermionic particles lighter than the proton and therefore proton decay would imply violation of both baryon and lepton number (or the existence of new fermions).

- Relevant forces, leading to transitions between quarks and leptons should exist to induce proton decay.

Intriguing relation between quarks and lepton charges : Anomaly cancellation

SM particle	G_{SM}
	$SU(3)_c \times SU(2)_L \times U(1)_Y$
$(\mathrm{S} = 1/2)$	
$Q = (t, b)_L$	(3,2,1/6)
$L = (\nu, l)_L$	(1,2,-1/2)
$U = \left(t^C\right)_L$	($\bar{3}$,1,-2/3)
$D = \left(b^C\right)_L$	($\bar{3}$,1,1/3)
$E = \left(l^C\right)_L$	(1,1,1)
$(\mathrm{S} = 1)$	
B_μ	(1,1,0)
W_μ	(1,3,0)
g_μ	(8,1,0)

$$\sum_{quarks} Y_i = 0; \qquad \sum_{left} Y_i = 0;$$

$$\sum_i Y_i^3 = 0; \qquad \sum_i Y_i = 0$$

Relation between quark and lepton charges suggests an unifying structure

Such a unifying structure exists in GUTs
Minimal SU(5) GUT

Quarks and Leptons belong to the same representations of the group.
For instance, the ordinary quarks and leptons can be accomodated in

$$\{10 + \overline{5} + 1\}$$

$$\mathbf{10} : \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ -u_3^c & 0 & u_1^c & u_2 & d_2 \\ u_2^c & -u_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^c \\ -d_1 & -d_2 & -d_3 & -e^c & 0 \end{pmatrix}$$

$$\bar{\mathbf{5}} : (d_1^c, d_2^c, d_3^c, e, -\nu_e)$$

$$\mathbf{1} : \nu^c$$

GUTs contain Forces which convert Quarks to Leptons !

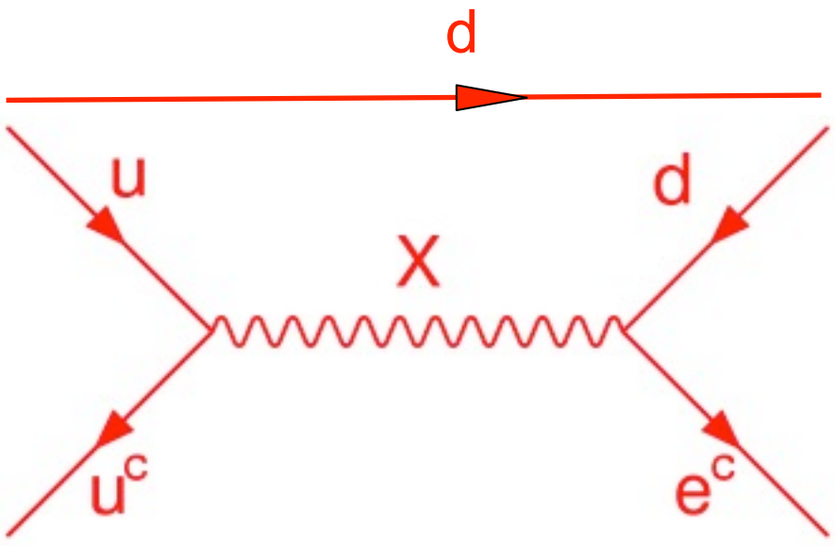
24 gauge bosons of SU(5) contain the 8 gluons, $W^{\pm}$, Z^0, γ, and two new sets of particles, (X, Y)

$(X, Y) \sim (3, 2, -5/6)$ under $SU(3)_c \times SU(2)_L \times U(1)_Y$

(X, Y) have diquark couplings and leptoquark couplings

$\Rightarrow$ proton decay induced by (X, Y)

$p \longrightarrow e^+ \pi^0$



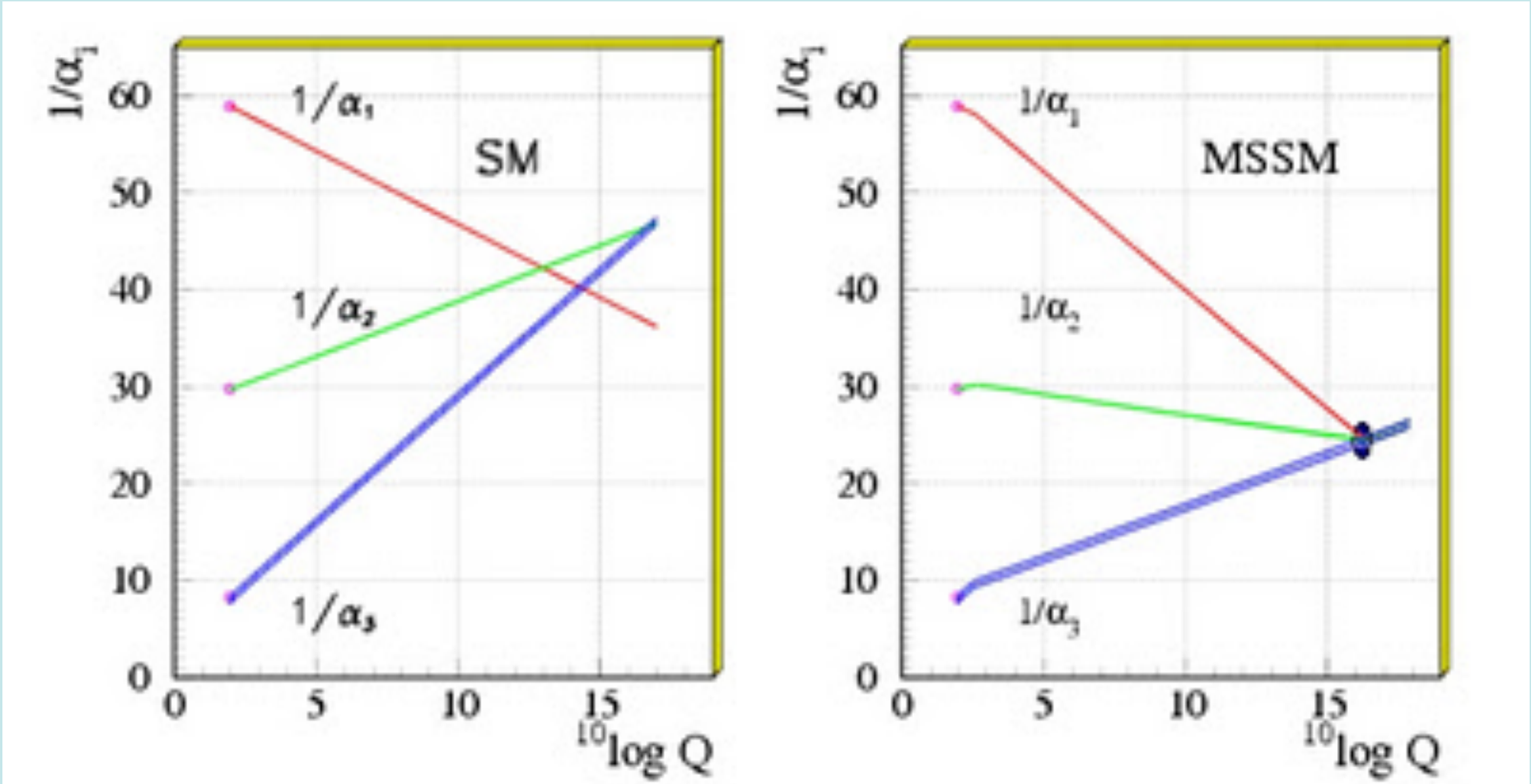
$$\tau_P \propto \frac{M_X^4}{m_P^5}$$

(X, Y) must be super-heavy

SUSY GUT Unification

S. Raby PDG (2010)

Hint of GUT realization :
Unification of Couplings



M_X is of order of the GUT scale
Naturally Superheavy !

Coupling Unification

Current Values: $\alpha_3(m_Z)=0.117(1)$

$\alpha_2(m_Z)=0.0338(1)$

$\alpha_1(m_Z)=0.0170(1)$

Generic SUSY GUT ➔ $m_X \approx (1\text{TeV}/m_{susy})^{2/15} \times \underline{10^{16}\text{GeV}}$

Also depends on other mass splittings (eg. Scalars)

Proton Partial Lifetime:

$\tau(p \rightarrow e^+\pi^0) \approx (1\text{TeV}/m_{susy})^{8/15} \times 10^{35\pm1}\text{yr}$

Larger SUSY masses imply shorter lifetimes !

Uncertainties: Matrix Elements (Lattice), $\alpha_3(m_Z)$, mass splittings, particle content…

Additional hints of GUTs ?

- Neutrino masses and the See-saw mechanism.
- In the presence of heavy right-handed neutrinos, neutrino masses are given by

$$m_\nu \simeq \frac{m_D^2}{M_R}$$

- For Dirac masses of order 100 GeV, the proper neutrino masses are obtained for right handed neutrino masses of order of 10^{14} GeV.
- Such large neutrino masses are naturally obtained in SO(10) GUT scenarios, with unification scales a few orders of magnitude larger than M_R

The Fate of the Hydrogen gas

- Hydrogen atom : P + e

- If proton decays into a pion and a positron

$$P \to \Pi^0 + e^+$$

- But then, the positron eventually annihilates with electrons and the pion decays into photons

$$\Pi^0 \to \gamma\gamma\,, \qquad e^+ + e^- \to \gamma\gamma$$

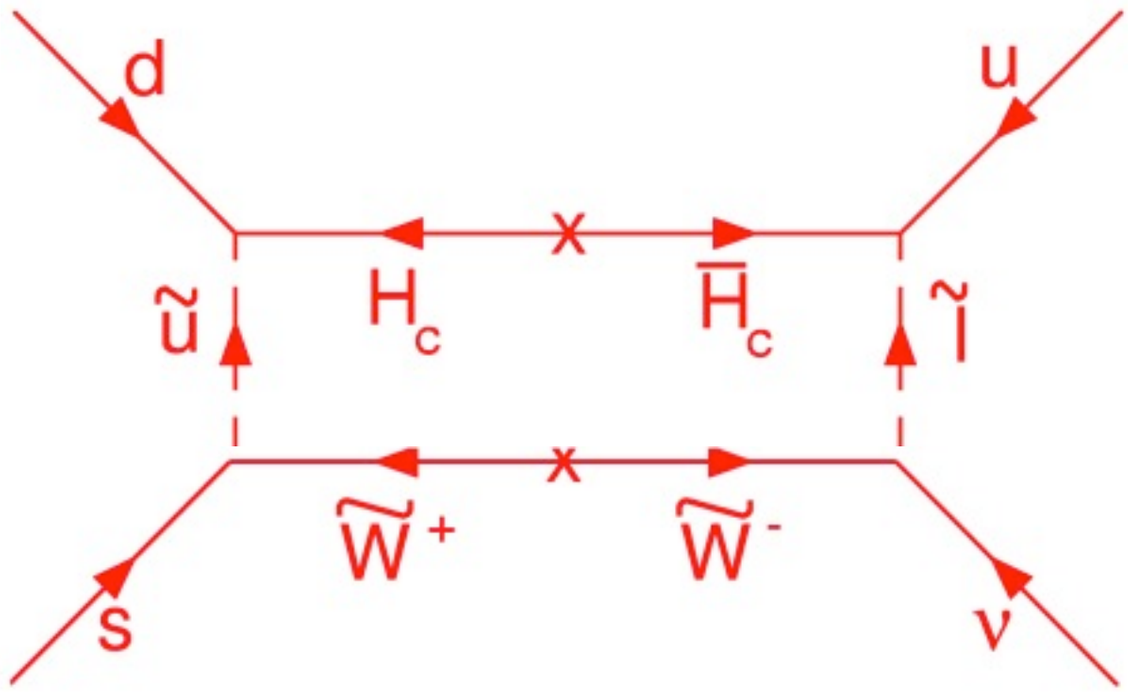
- The whole gas is converted to photons !

- Proton decay implies therefore the instability of ordinary matter transforming into radiation (photons and neutrinos). Fraction converted of order $\frac{\tau_{univ}}{\tau_P}$

Higgsino Exchange:

Sakai, Yanagida (1982)

Weinberg (1982)



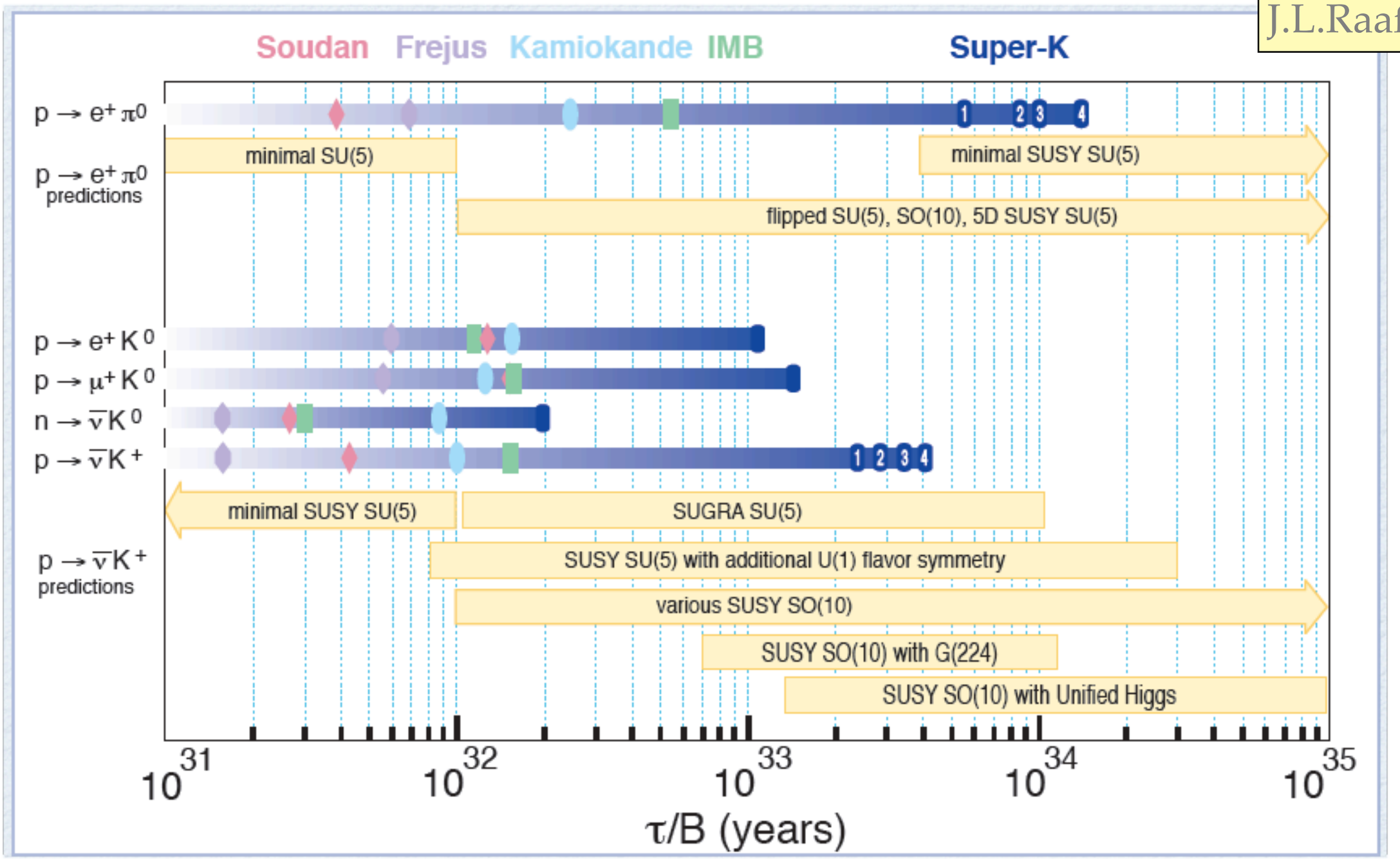
$p \to \bar{\nu} K^+$

Strongly constrained
Grows rapidly with MSUSY and depends on the Fermion Yukawa structure (Higgsino couplings)

$$\tau_p^{-1} \approx [\frac{f^2}{M_{H_c} M_{SUSY}}]^2 (\frac{\alpha}{4\pi})^2 m_p^5 \approx [10^{28} - 10^{33} yr]^{-1}$$

EXPERIMENTS & PREDICTION

J.L.Raaf



What would non-observation of proton decay imply ?

- Simplest, well motivated GUT models, which lead to accordance with fermion masses, tend to predict rate from the ones probed at SuperK to an order of magnitude above present bounds

- These models would be severely constrained by next generation experiments, like deep underground LBNE ones.

- Idea of GUT will survive, since there are mechanism to suppress the rate, in more sophisticated models.

What would observation of proton decay imply ?

- Important Physical and arguably Philosophical Implications
- Consistency with predictions of simple GUT models will provide evidence, together with gauge coupling unification and arguably neutrino masses, of their realization
- Instability of matter, affecting the structure of the Universe at long times
- Landmark Discovery for Mankind
- Possibility of Testing Proton Decay should be considered in future experiment planning.