Grand Unified Theories

Theory & Experiment

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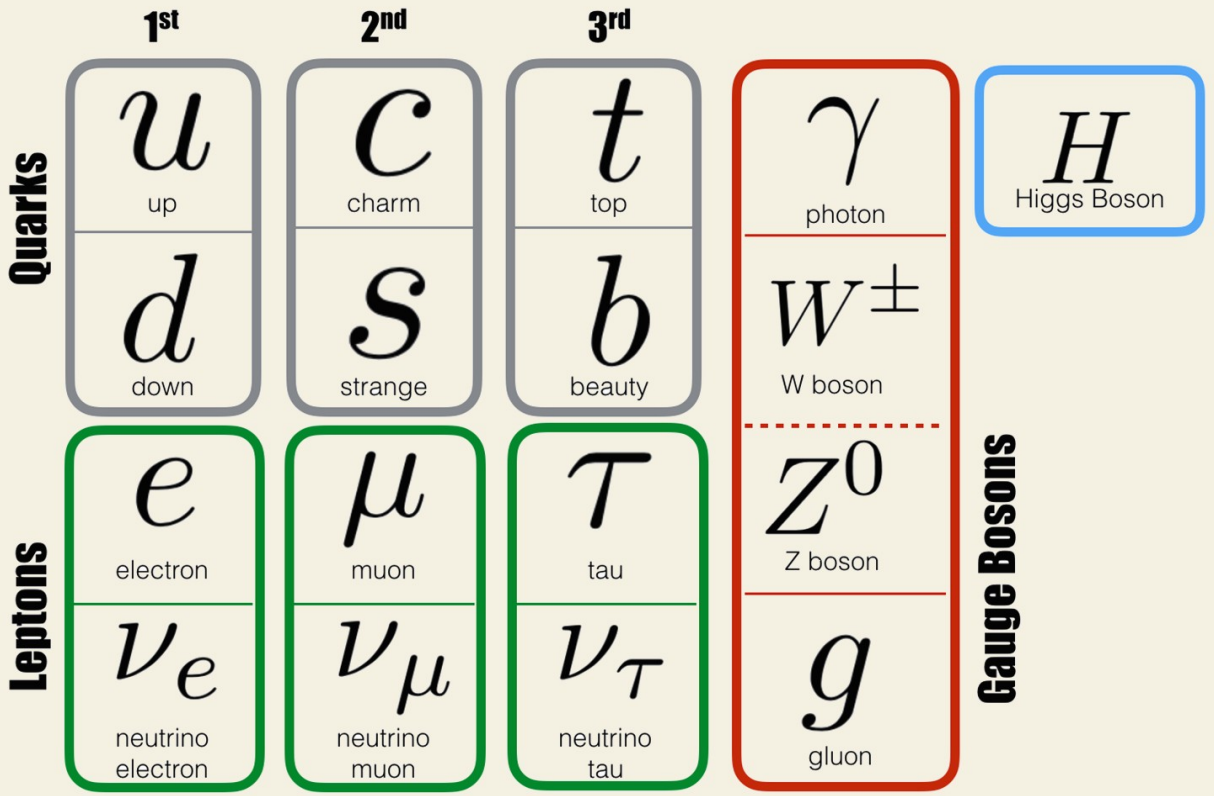
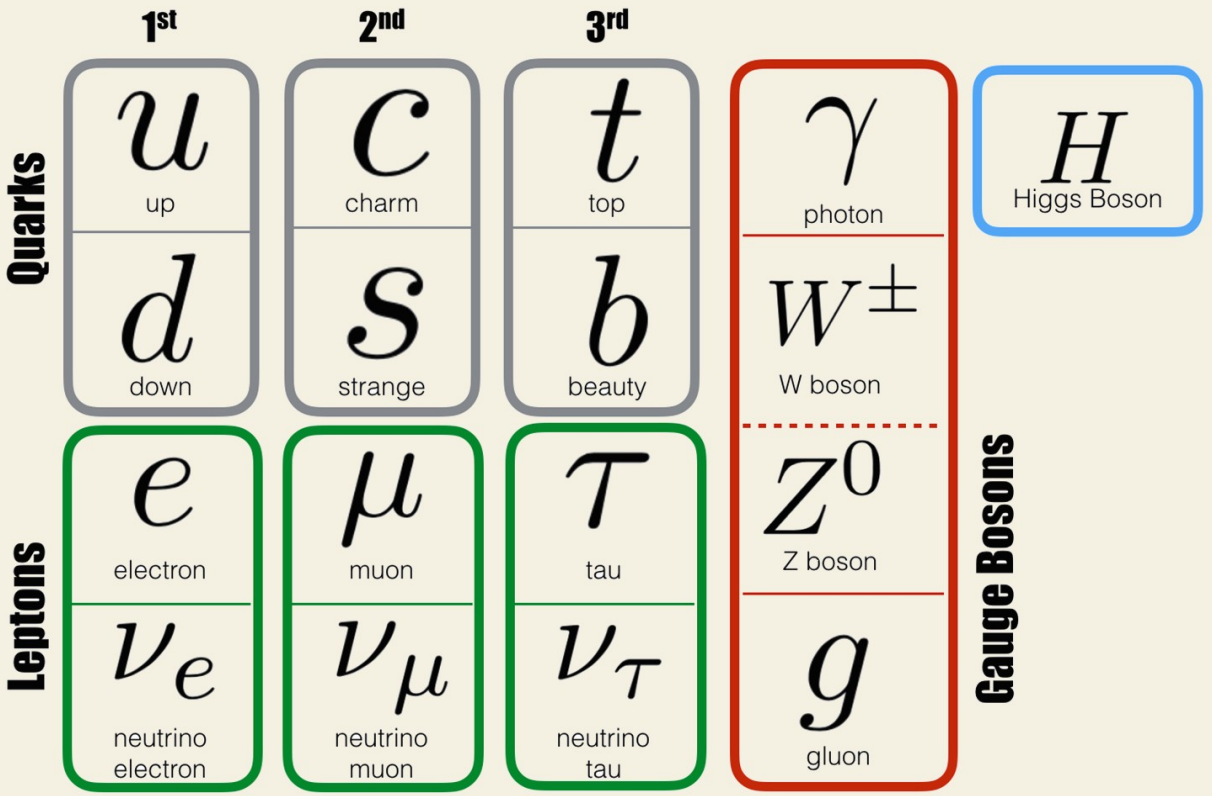
Mala Skala 2019

Standard model



Standard model



$SU(3)_C \times SU(2)_L \times U(1)_Y$

Standard model

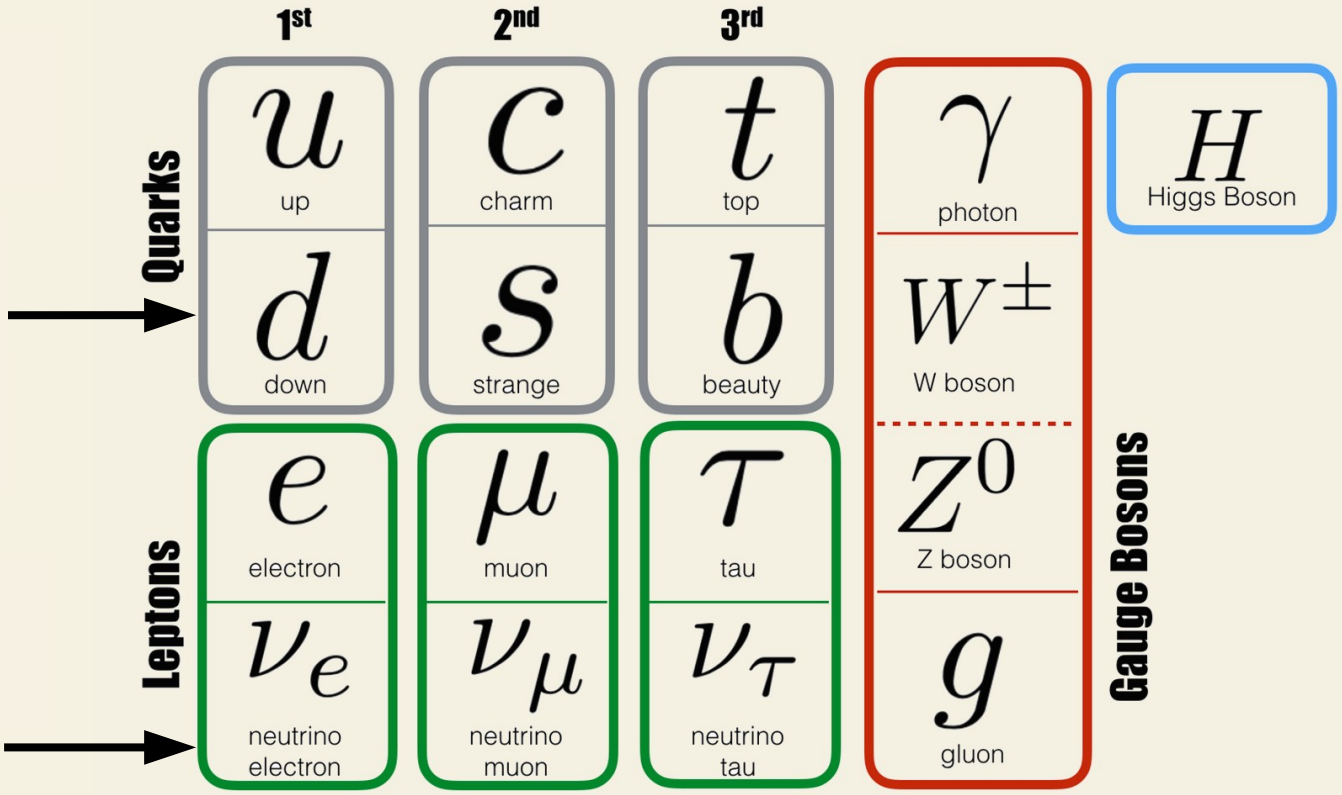
$$\begin{pmatrix} u \\ d \end{pmatrix}_L \in (3, 2, \frac{1}{6})$$

$$(u)_R \in (3, 1, \frac{2}{3})$$

$$(d)_R \in (3, 1, -\frac{1}{3})$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \in (1, 2, -\frac{1}{2})$$

$$(e)_R \in (1, 1, -1)$$



$SU(3)_C \times SU(2)_L \times U(1)_Y$

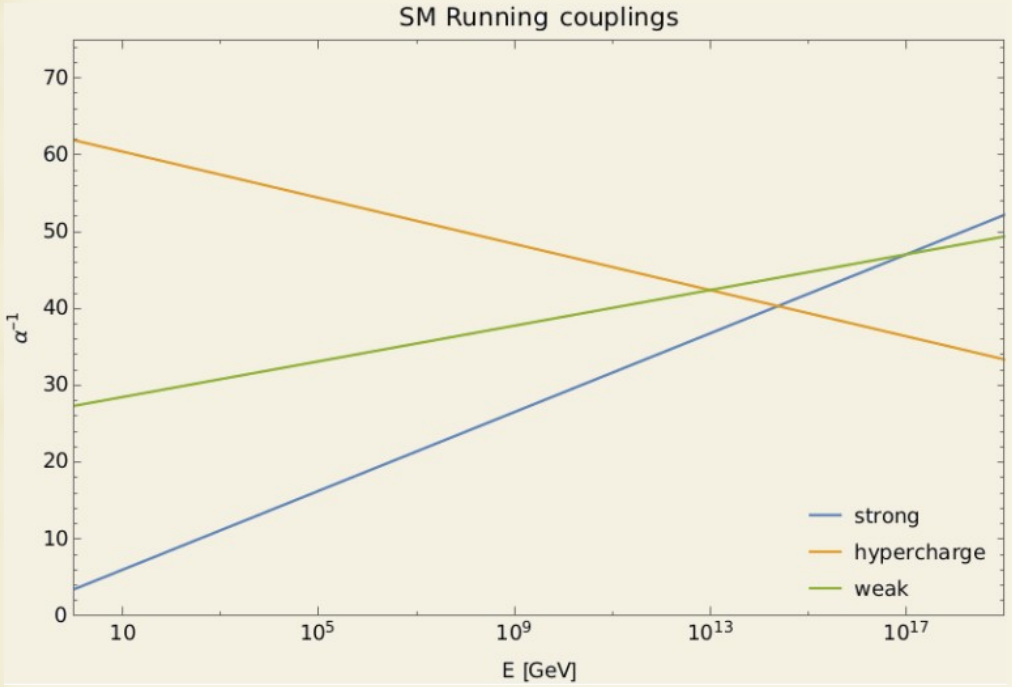
Grand Unified Theory

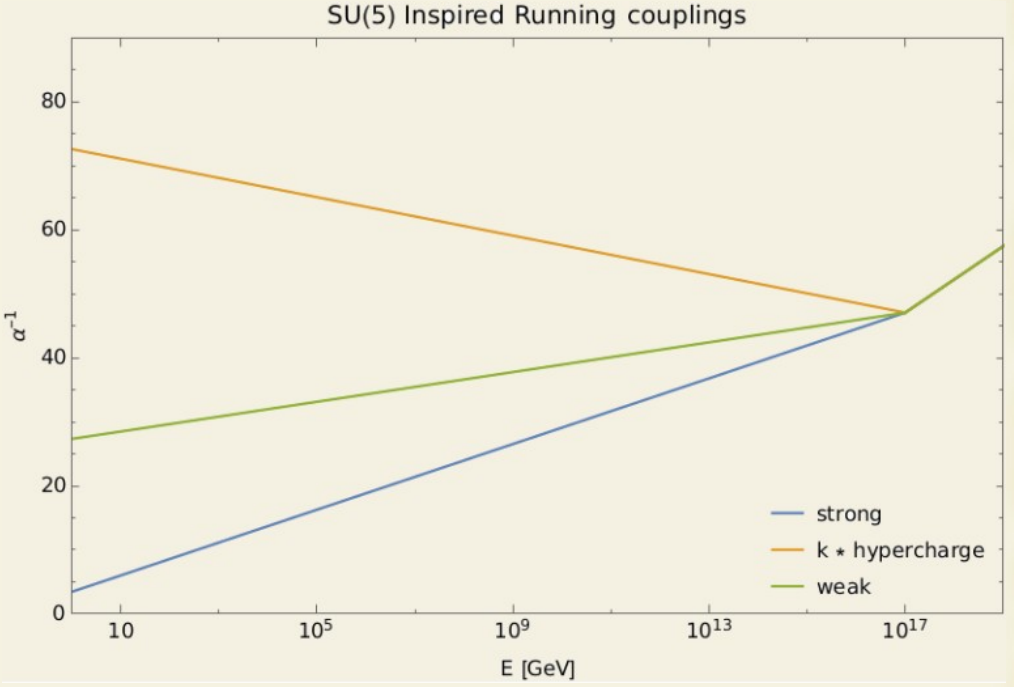
$$SU(3)_C \times SU(2)_L \times U(1)_Y \in G$$

- **Simple**: SU(5), SO(10), E(6), …
- **With discrete symmetry**: SU(3)xSU(3)xSU(3)xD_3, …
- **Not so simple**: SU(5)xU(1), SU(4)x$SU(2)_L$x$SU(2)_R$, …

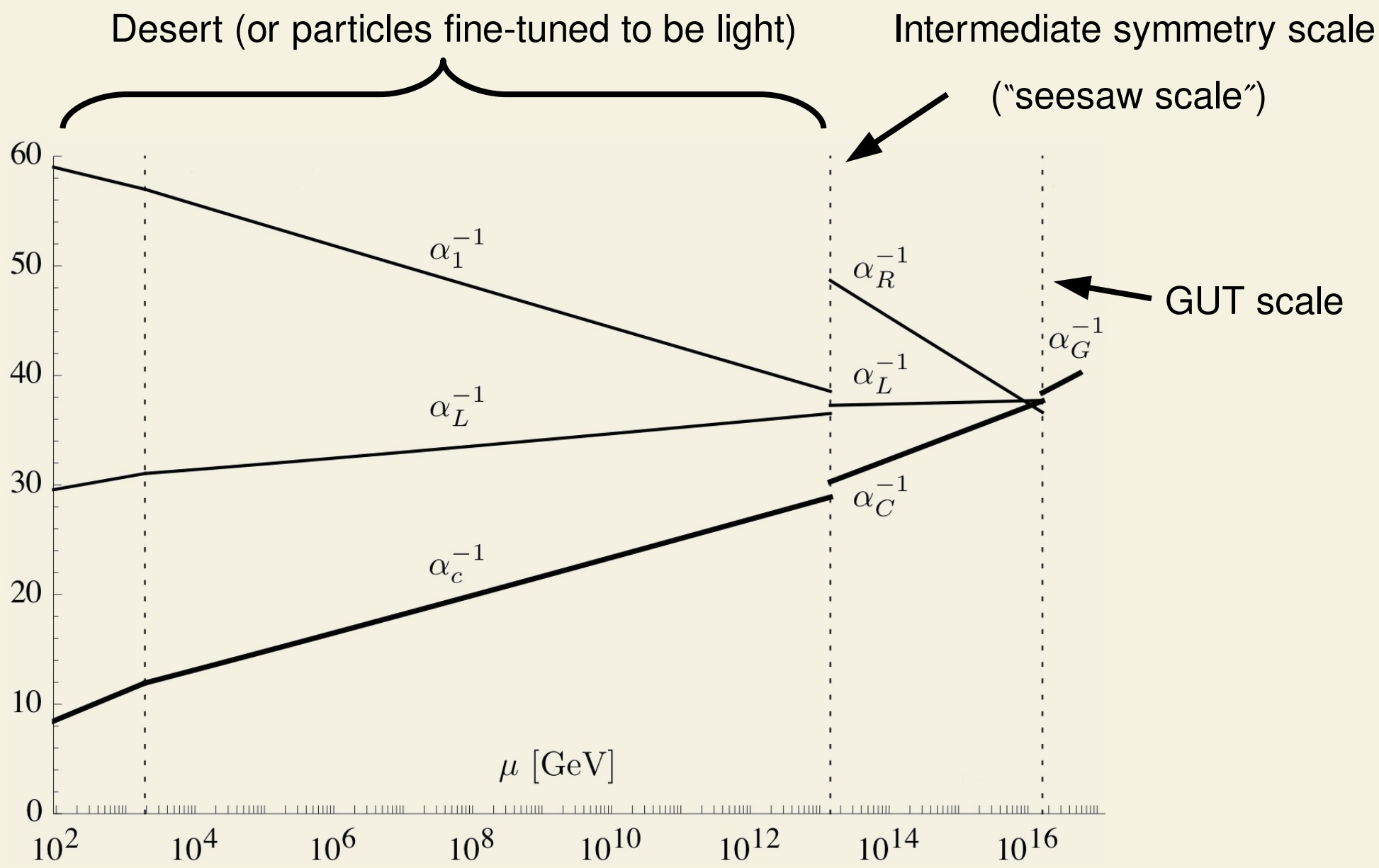
What are general features of GUTs?

Gauge coupling unification





$$g_s(M_{GUT}) = g(M_{GUT}) = g'(M_{GUT})$$


Desert (or particles fine-tuned to be light)
Intermediate symmetry scale
("seesaw scale")
GUT scale
60
50
40
30
20
10
0
α_1^{-1}
α_L^{-1}
α_c^{-1}
α_R^{-1}
α_L^{-1}
α_C^{-1}
α_G^{-1}
μ [GeV]
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}

Fermion "unification"

SU(5): $\begin{pmatrix} \nu_e \\ & \overline{d} \\ e & \end{pmatrix}_L \in \overline{5}$ $\qquad$ $\begin{pmatrix} & u & \\ e^+ & & \overline{u} \\ & d & \end{pmatrix}_L \in 10$

SO(10): $(\overline{\nu}_e)_L \oplus (e^+)_L \oplus \begin{pmatrix} u \\ d \end{pmatrix}_L \oplus (\overline{u})_L \oplus \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \oplus (\overline{d})_L = 16$

- New fermion fields (right-handed neutrinos)
- Quantization of charge
- Sometimes family ("horizontal") symmetries are employed

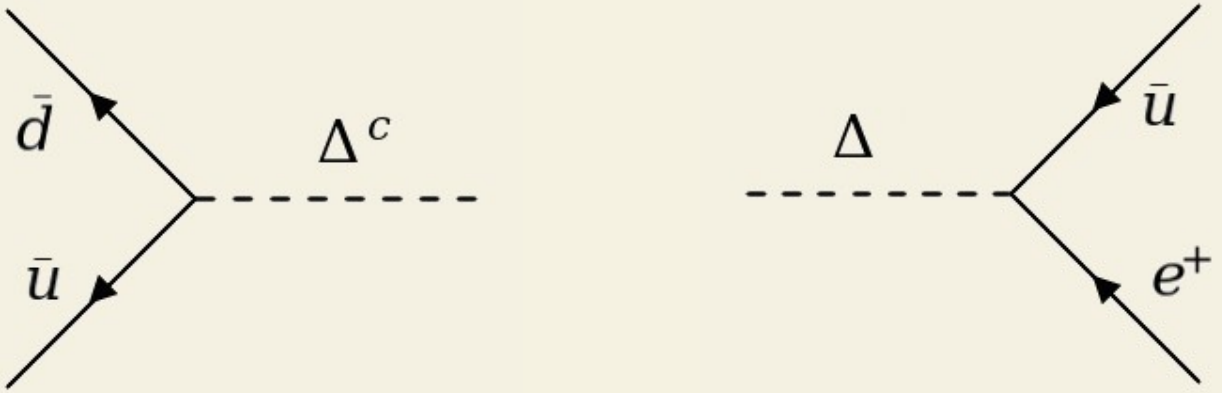
Enlarged scalar sector

- Spontaneous symmetry breaking (intermediate symmetry, SM)

⟷ nonzero Higgs field VEV (GUT scale, intermediate scale)

⟷ gauge, scalar (lepton) masses

- Yukawa interactions with fermions – scalar leptoquarks, diquarks (BNV, LNV)



- Nontrivial relations between fermion masses

SU(5): $m_b = m_\tau$ $\quad m_s = m_\mu$ $\quad m_d = m_e$ at GUT scale

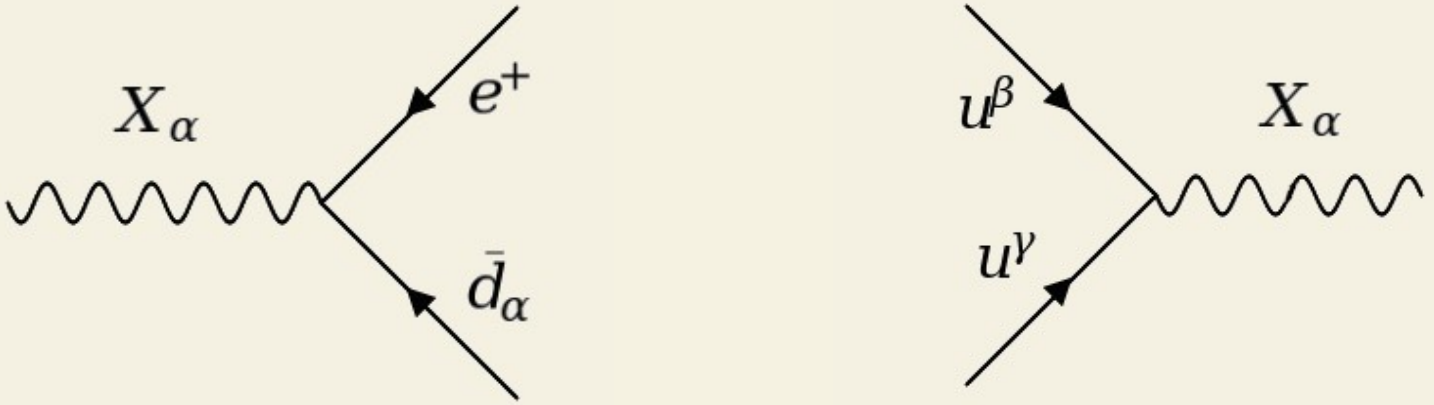
Enlarged gauge sector

- Gauge bosons from G \ SM

  SU(5):

$$G^{\alpha}_{\beta} + W^{\pm}, W^{0} + B^{0} + X_{\alpha}, \overline{X}^{\alpha} + Y_{\alpha}, \overline{Y}^{\alpha} = 24$$

- Masses ~ symmetry breaking scale (M_{GUT}, M_{seesaw},...)
- Carry colour and flavour – leptoquarks, diquarks (BNV, LNV)



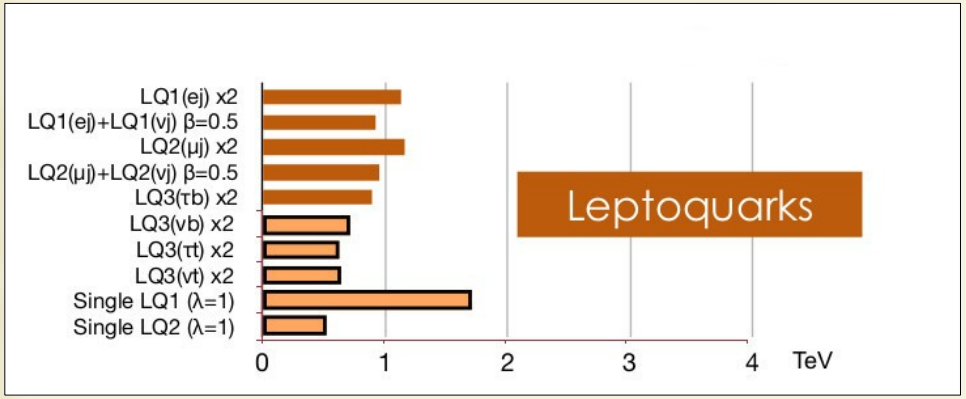
What do GUTs predict?

New particles

One (or more) new scales ⟶ heavy particles (scalar & gauge leptoquarks,…), desert (unless fine-tuned)

Atlas Exotics

LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$
	Scalar LQ 3rd gen	2 τ	2 b	–	36.1	LQ_3^u mass 1.03 TeV	$\mathcal{B}(LQ_3^u \to b\tau) = 1$
	Scalar LQ 3rd gen	0-1 e,μ	2 b	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(LQ_3^d \to t\tau) = 0$
Gauge bosons	SSM $Z' \to \ell\ell$	2 e,μ	–	–	139	Z′ mass 5.1 TeV	
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z′ mass 2.42 TeV	
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z′ mass 2.1 TeV	
	Leptophobic $Z' \to tt$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z′ mass 3.0 TeV	$\Gamma/m = 1\%$
	SSM $W' \to \ell\nu$	1 e,μ	–	Yes	79.8	W′ mass 5.6 TeV	
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W′ mass 3.7 TeV	
	HVT $V' \to WV \to qqqq$ model B	0 e,μ	2 J	–	139	V′ mass 4.4 TeV	$g_V = 3$
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V′ mass 2.93 TeV	$g_V = 3$
	LRSM $W_R' \to tb$	multi-channel			36.1	W′ mass 3.25 TeV	



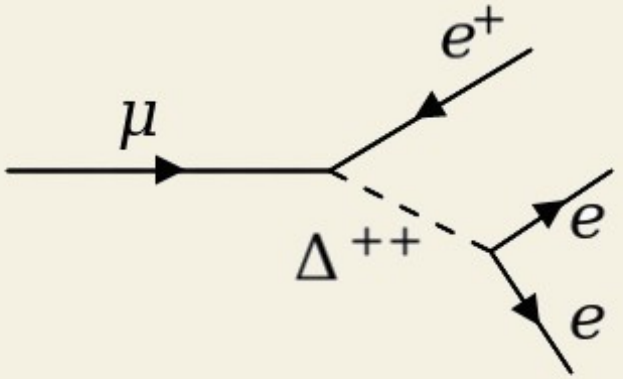
CMS Exotica

Lepton number violation

- **LNV violating processes**:

$$\mu \to 3e$$

(PDG: BR < 10^{-12})

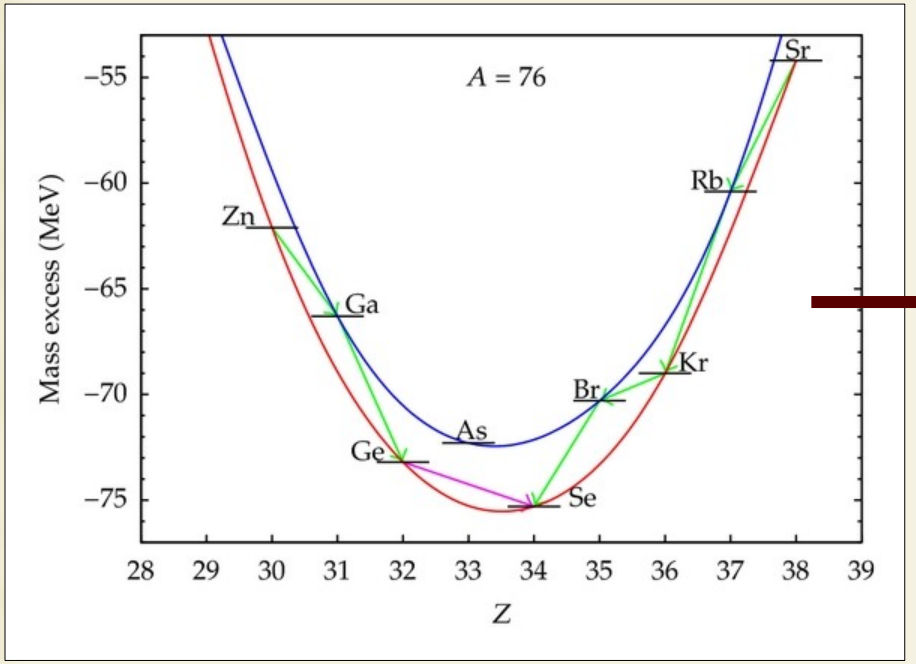


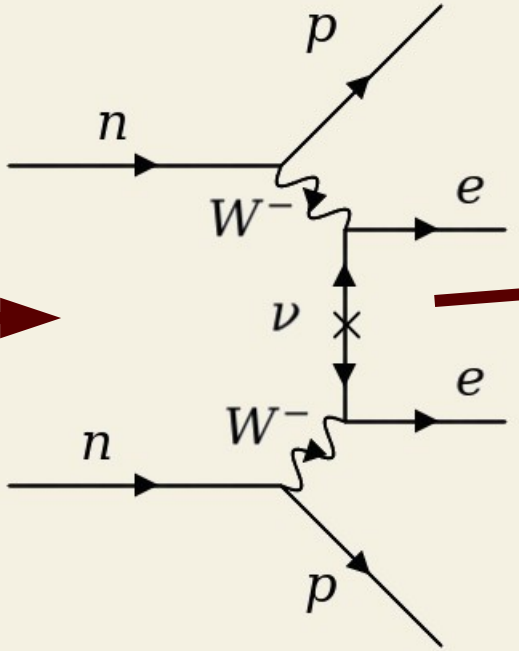
Negligible for M_Δ large

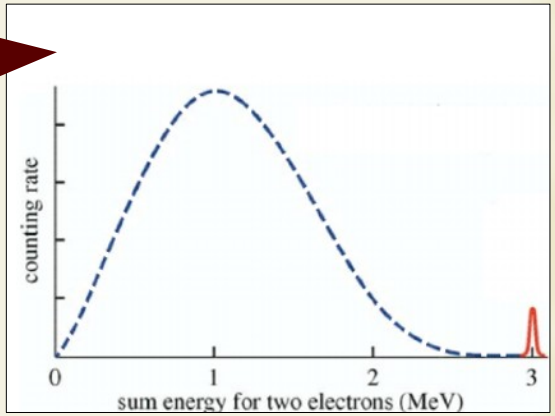
- **Majorana neutrinos**: ΔL = 2, seesaw mechanism $m_\nu \sim \frac{Y_\nu^2}{M_N^2}$

⟶ Neutrinoless double beta decay

Neutrinoless double beta decay





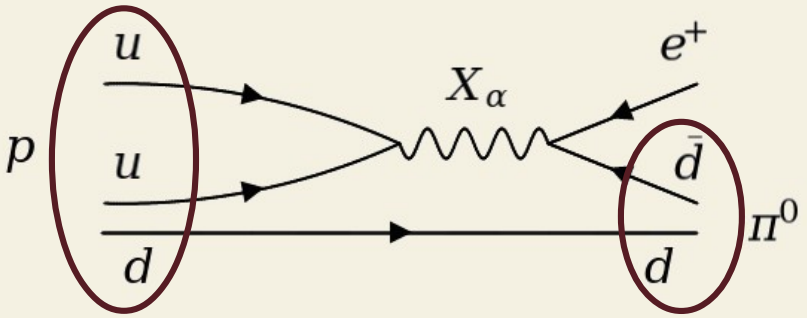


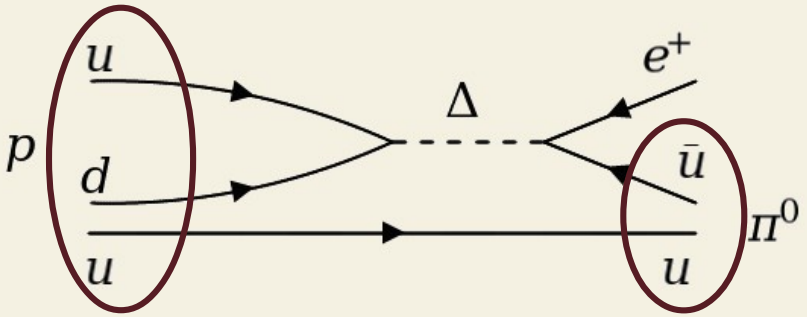
experiment	isotope	M_i [kg]	NME	sensitivity $T^{0\nu}_{1/2}$ [10^{25} yr]	sensitivity $m_{\beta\beta}$ [eV]	limit $T^{0\nu}_{1/2}$ [10^{25} yr]	limit $m_{\beta\beta}$ [eV]
GERDA	^{76}Ge	31	2.8-6.1	5.8	0.14–0.30	8.0	0.12–0.26
MAJORANA	^{76}Ge	26	2.8-6.1	2.1	0.23–0.51	1.9	0.24–0.53
KamLAND-Zen	^{136}Xe	343	1.6-4.8	5.6	0.07–0.22	10.7	0.05–0.16
EXO	^{136}Xe	161	1.6-4.8	1.9	0.13–0.37	1.1	0.17–0.49
CUORE	^{130}Te	206	1.4-6.4	0.7	0.16–0.73	1.5	0.11–0.50

arXiv:1803.11100v1

Proton decay

Proton stable in SM, unstable in GUTs (gauge & scalar leptoquarks)



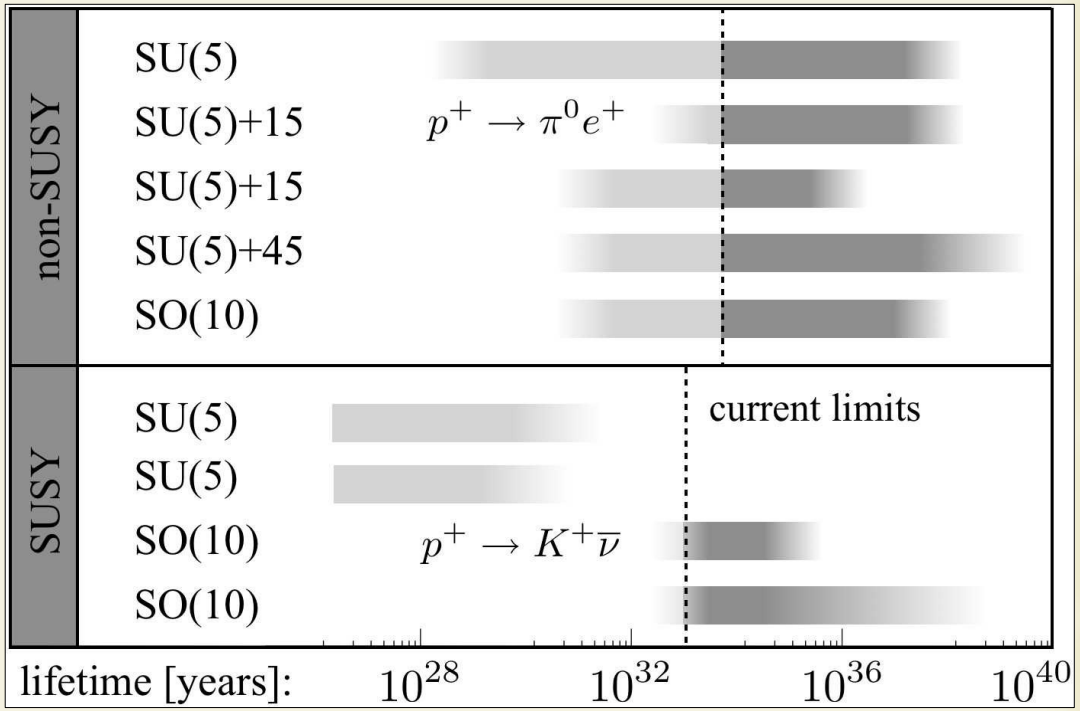


- Partial decay widths are model-dependent:

  Golden channel: $p \to \pi^0 e^+$

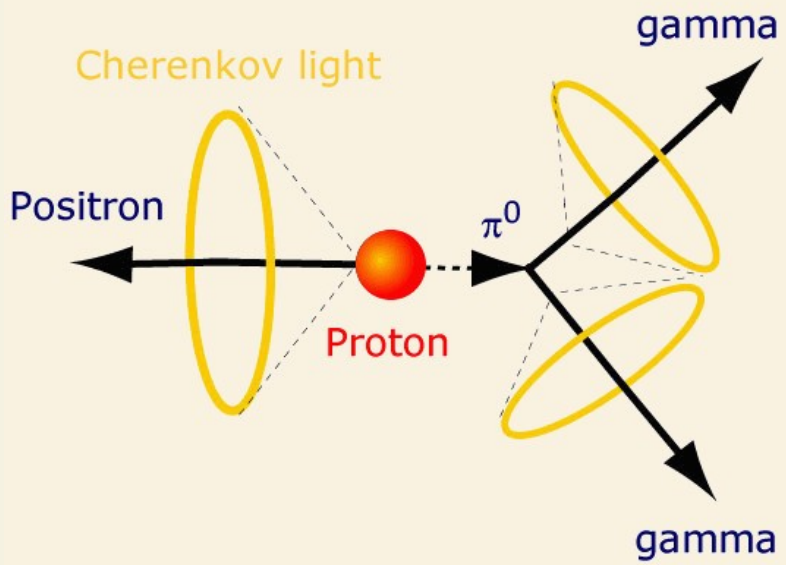
  Silver channel: $p \to \pi^+ \nu$

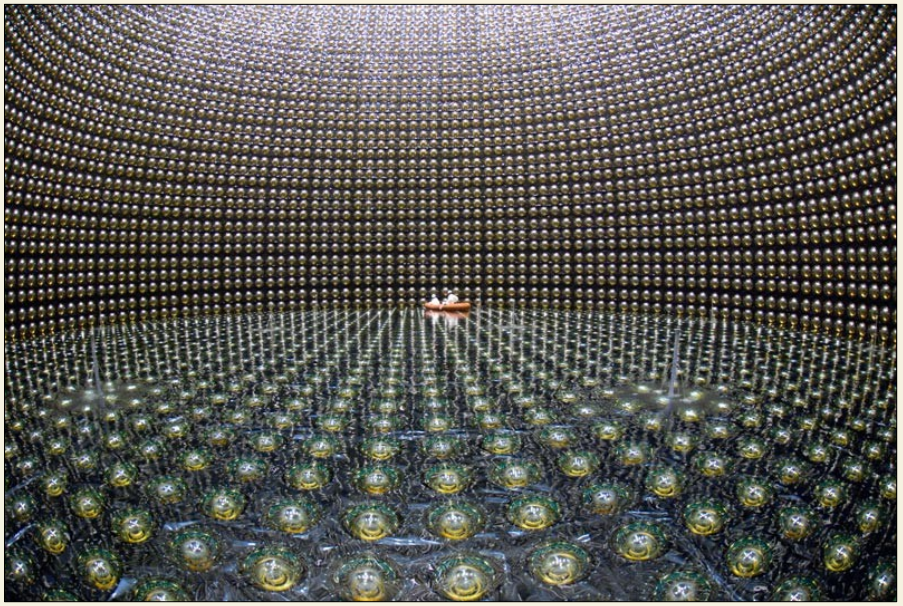
- Usually large theoretical uncertainties

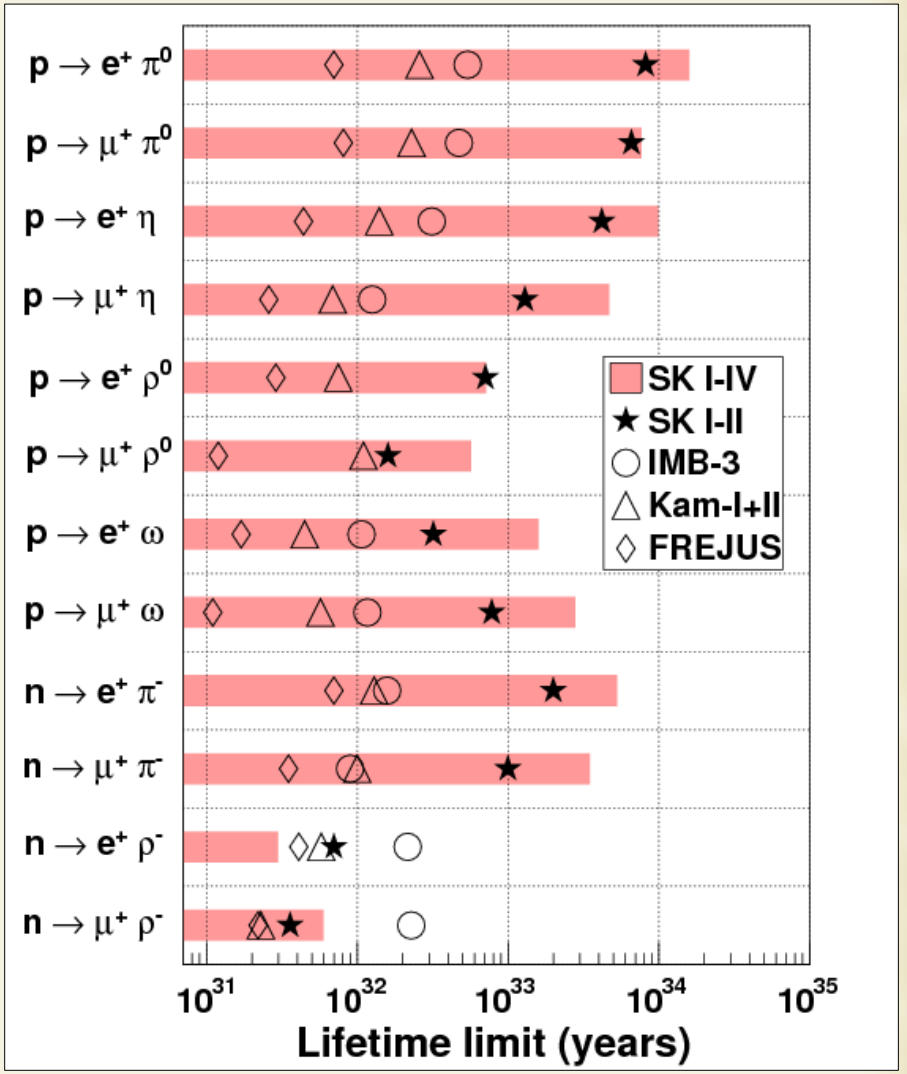


Experimental searches

Super-Kamiokande:

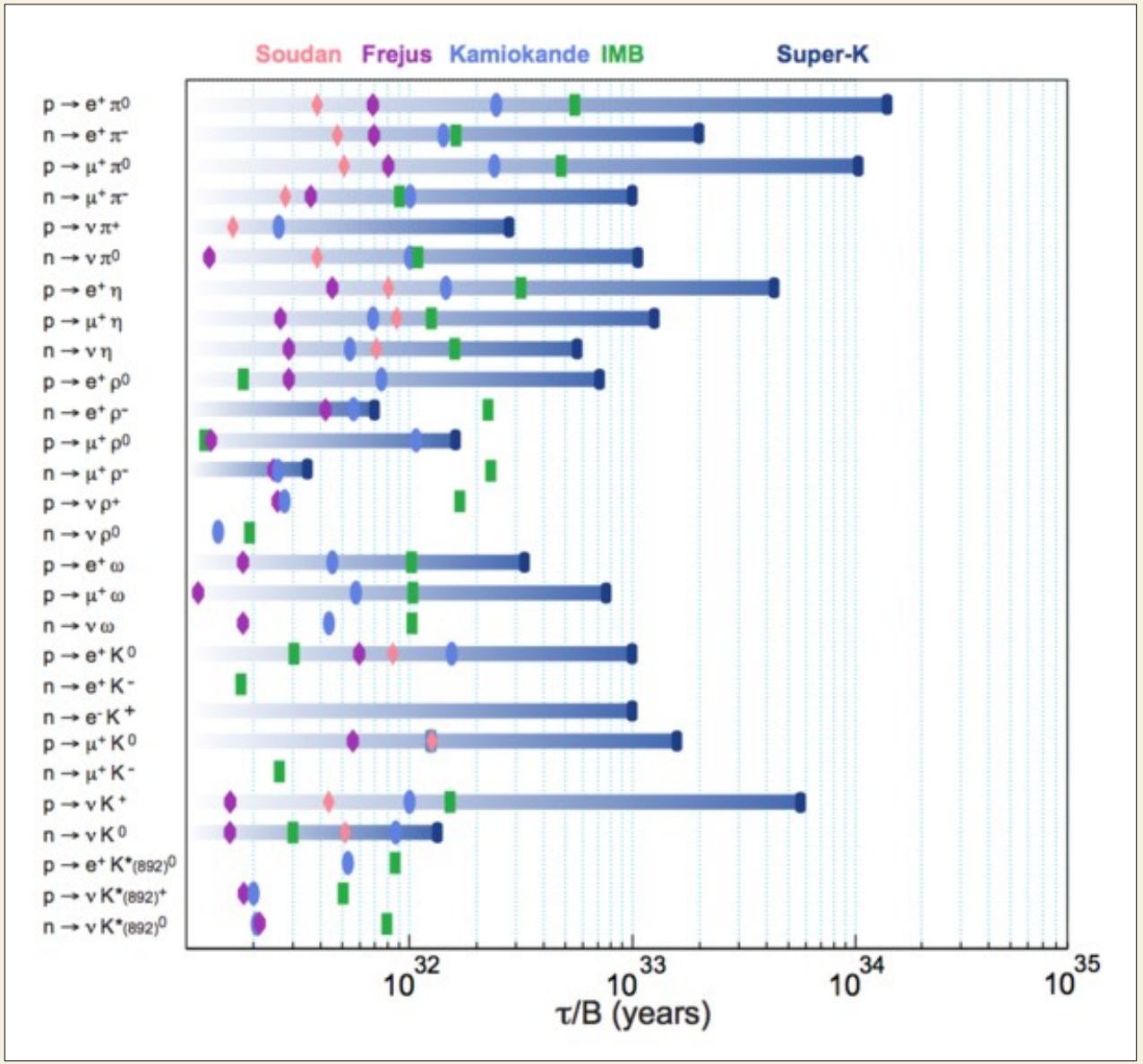






arXiv:1705.07221v1

Experimental searches



arXiv:1501.01886v2

Magnetic monopoles

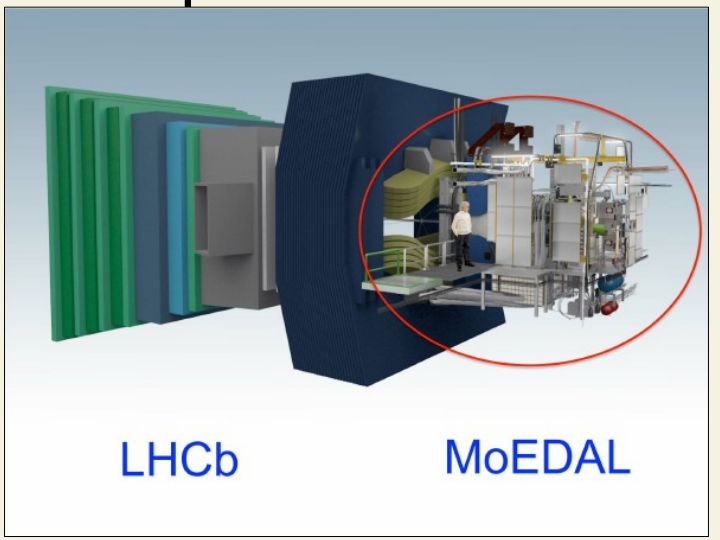
= topologically stable classical configuration of the gauge and Higgs field

- Particle-like object: massive, energy density localized, stable
- "Heavy bound state of the gauge boson and Higgs fields"
- Non-perturbative object
- Symmetry unbroken in the core

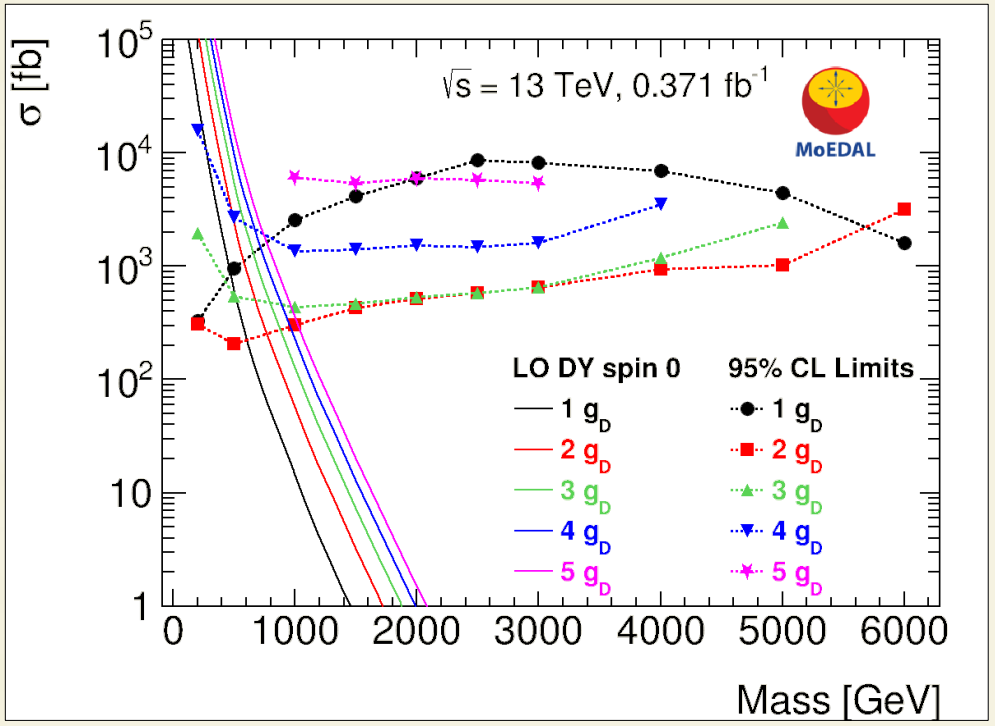
$$M \sim \frac{v}{g}$$

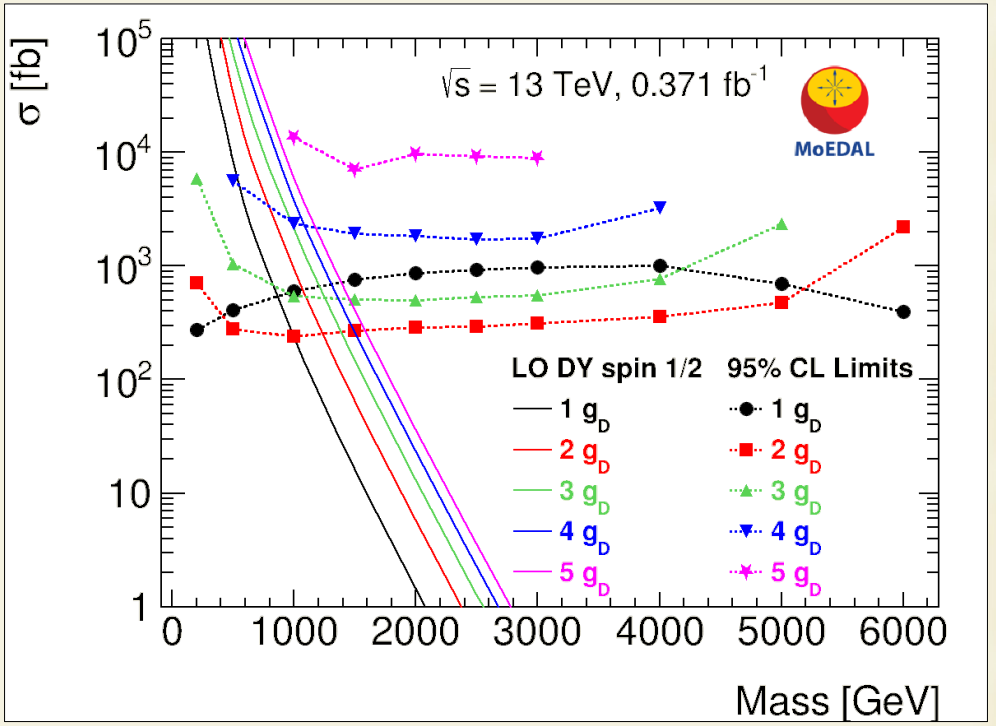
Experimental searches fo monopoles

- **Collider searches**: MoEDAL at CERN



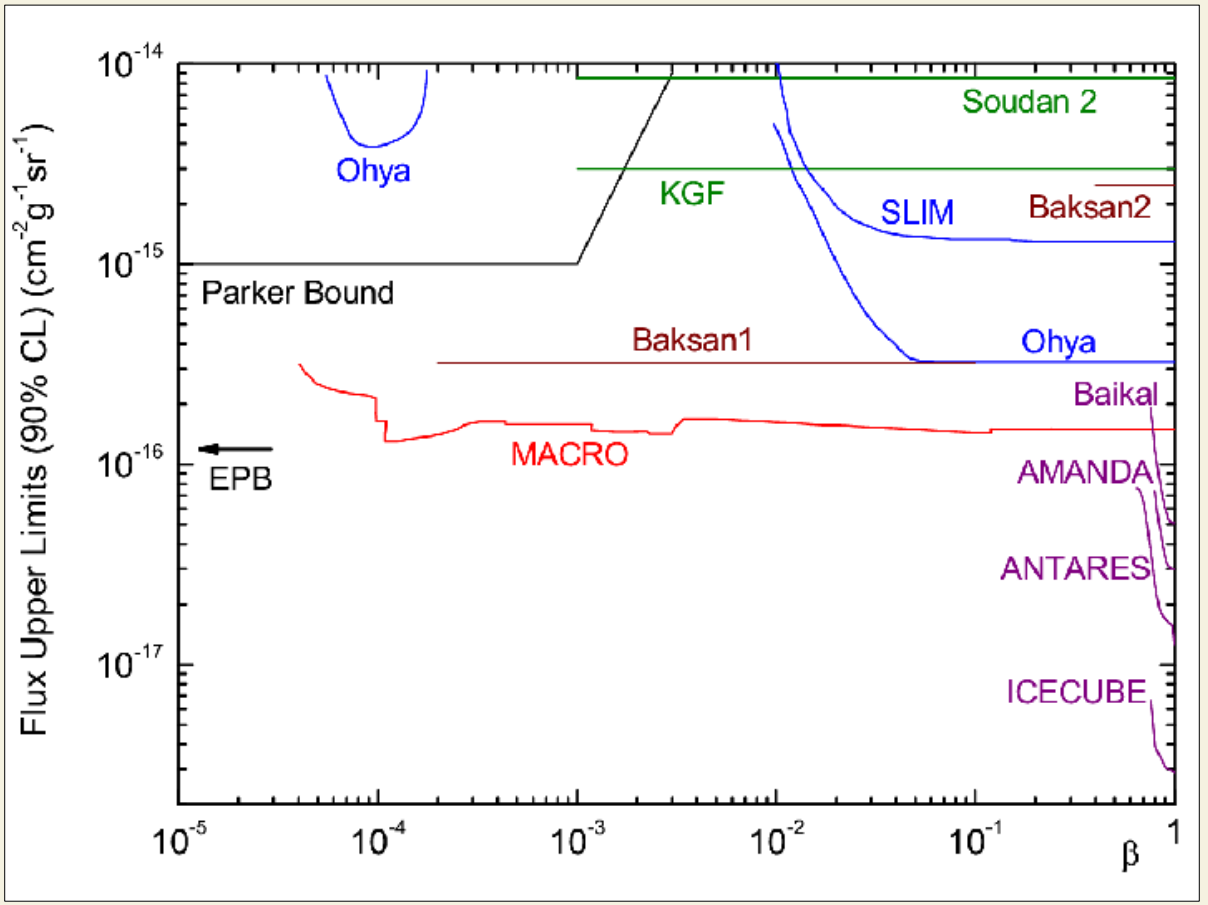
arXiv:1611.06817





Experimental searches for monopoles

- **Direct searches in the Cosmic Radiation**:

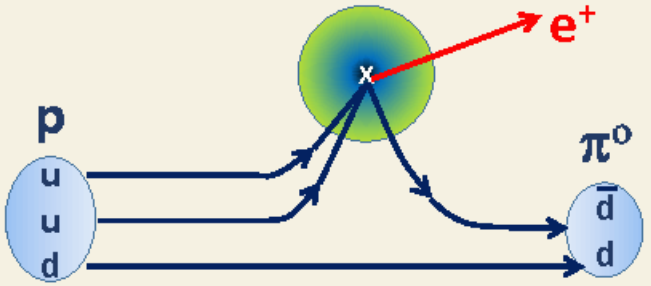


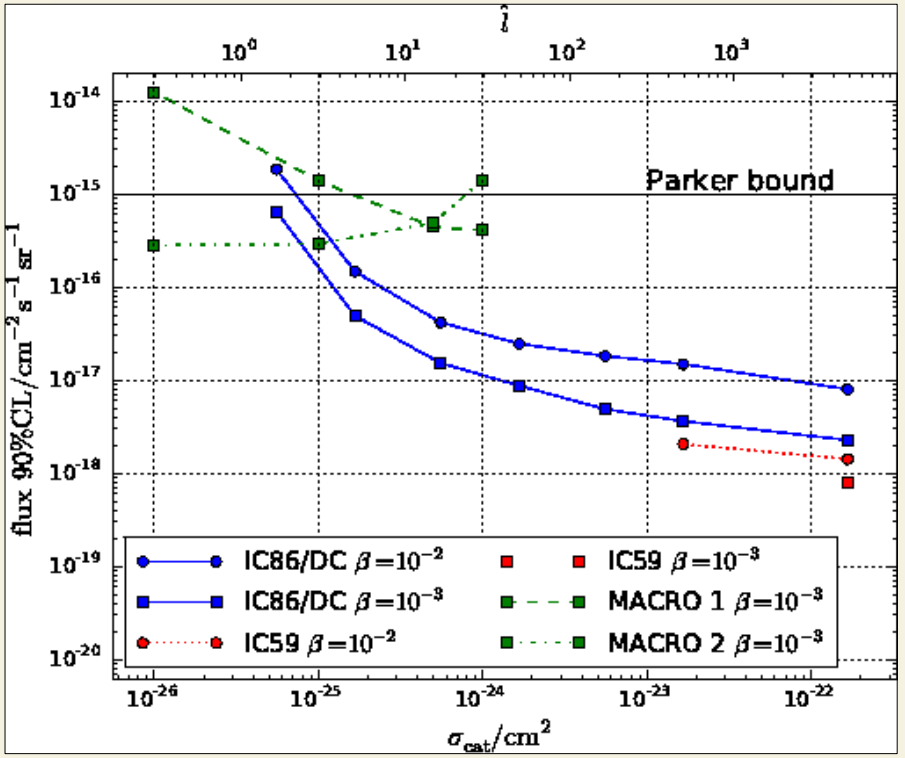
arXiv:1510.07125v1, MACRO: arXiv:hep-ex/0207020

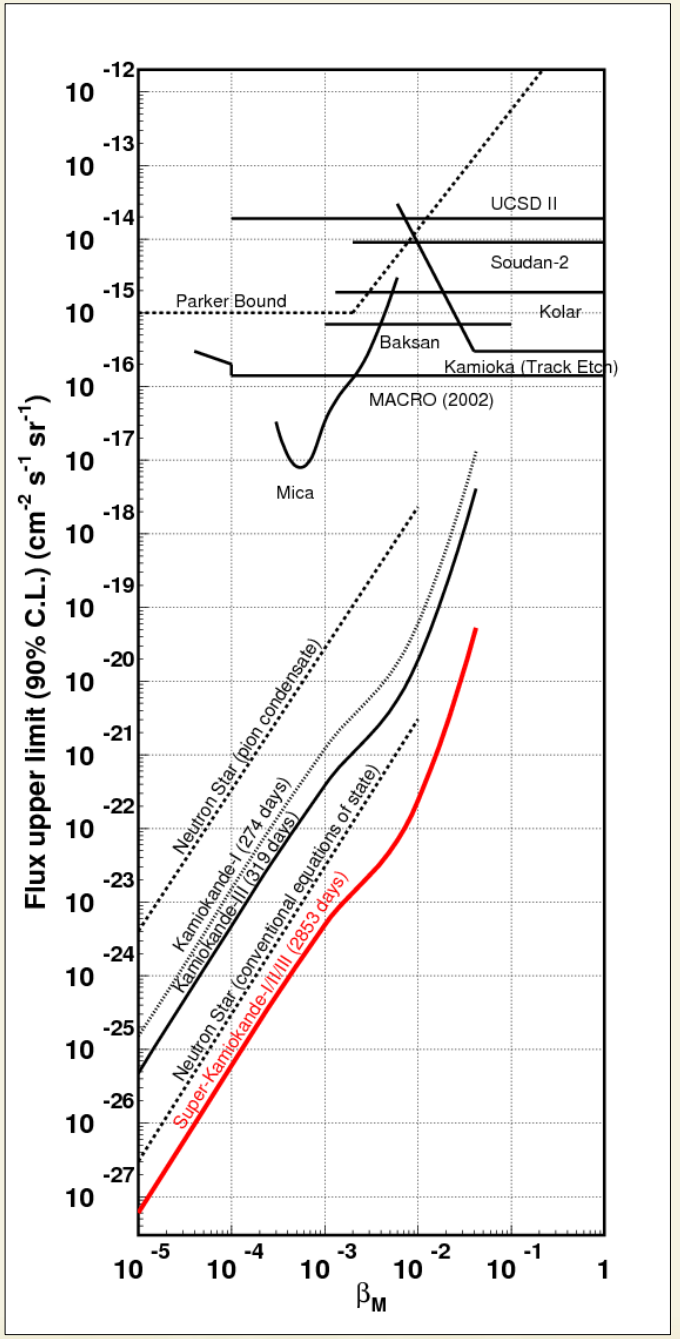
- **Monopoles bound in matter**: upper limit 9.8×10^{-5} monopoles per gram (90% confidence, arXiv:1301.6530v2)

Experimental searches for monopoles

- **Searches using induced nucleon decay**:







SK: arXiv:1203.0940v1, IceCube: arXiv:1402.3460v2

Summary

GUTs are theories where $SU(3)_C \times SU(2)_L \times U(1)_Y \in G$ **:**

- Gauge coupling unification
- Fermion "unification"
- Enlarged scalar & gauge sector

GUTs predict:

- New particles, desert
- Lepton number violation
  - → Majorana neutrinos
  - → Neutrinoless double beta decay
- Baryon number violation
  - → Proton decay
- Magnetic monopoles