Grand Unified Theories

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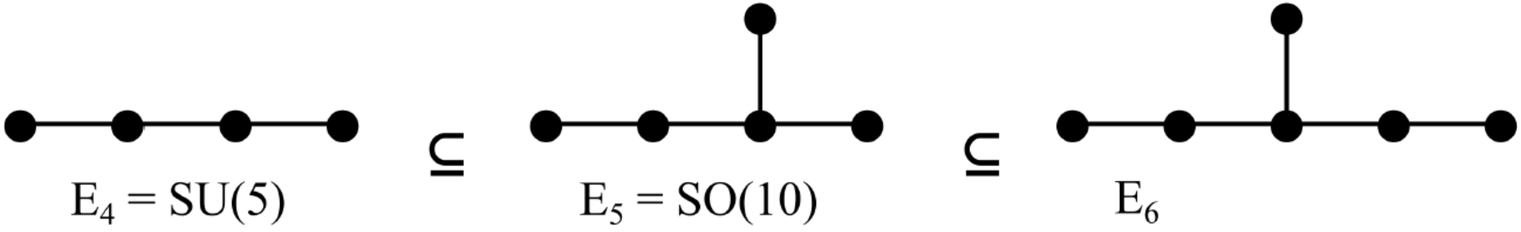
Plan of the Talk

This is a broad-brush overview of GUTs

Much more in 3 dedicated sessions for GUTs

The hallmark of GUTs is proton decay; I will spend some time on this issue

Chiral nature of SM suggests embedding in exceptional Lie groups:



SU(5) is the simplest rank-4 group; SO(10) has ν_R leading to neutrino mass; E_6 has additional vector-like leptons which can be dark matter

See talk on E6 by B. Bajc on Wednesday

Grand Unified Theories: Motivations

- Electric charge quantization
  - ◇ $Q_p = -Q_e$ to better than 1 part in 10^{21}
- Miraculous cancellation of anomalies
- Quantum numbers of quarks and leptons
- Existence of ν_R and thus neutrino mass via seesaw
- Unification of gauge couplings with low energy SUSY
- $b - \tau$ unification and a framework for fermion flavor structure
- Baryon asymmetry of the universe via leptogenesis

Pati, Salam (1973)
Georgi, Glashow (1974)
Georgi, Quinn, Weinberg (1974)

Structure of Matter Multiplets

Standard Model

$$\begin{aligned}
Q &= \begin{pmatrix} u_1 & u_2 & u_3 \\ d_1 & d_2 & d_3 \end{pmatrix} \sim (3, 2, \frac{1}{6}) \\
u^c &= \begin{pmatrix} u^c_1 & u^c_2 & u^c_3 \end{pmatrix} \sim (\bar{3}, 1, -\frac{2}{3}) \\
d^c &= \begin{pmatrix} d^c_1 & d^c_2 & d^c_3 \end{pmatrix} \sim (\bar{3}, 1, \frac{1}{3}) \\
L &= \begin{pmatrix} \nu \\ e^- \end{pmatrix} \sim (1, 2, -\frac{1}{2}) \\
e^c & \qquad \sim (1, 1, +1) \\
\nu^c & \qquad \sim (1, 1, 0)
\end{aligned}$$

SO(10)

$u_r : \{-++\ +-\}$	$d_r : \{-++\ -+\}$	$u^c_r : \{+--\ ++\}$	$d^c_r : \{+--\ --\}$
$u_b : \{+-+\ +-\}$	$d_b : \{+-+\ -+\}$	$u^c_b : \{-+-\ ++\}$	$d^c_b : \{-+-\ --\}$
$u_g : \{++-\ +-\}$	$d_g : \{++-\ -+\}$	$u^c_g : \{--+\ ++\}$	$d^c_g : \{--+\ --\}$
$\nu : \{---\ +-\}$	$e : \{---\ -+\}$	$\nu^c : \{+++\ ++\}$	$e^c : \{+++\ --\}$

Frist 3 spins refer to color, last 2 are weak spins

$$Y = \frac{1}{3}\Sigma(C) - \frac{1}{2}\Sigma(W)$$

Finding Order in Fermion Mass Spectrum

Fermion masses in units of m_t

$$\begin{aligned} m_t &= 1.0 & m_b &= 1.67 \times 10^{-2} \\ m_c &= 3.6 \times 10^{-3} & m_s &= 3.1 \times 10^{-4} \\ m_u &= 1.3 \times 10^{-5} & m_d &= 2.3 \times 10^{-5} \end{aligned}$$

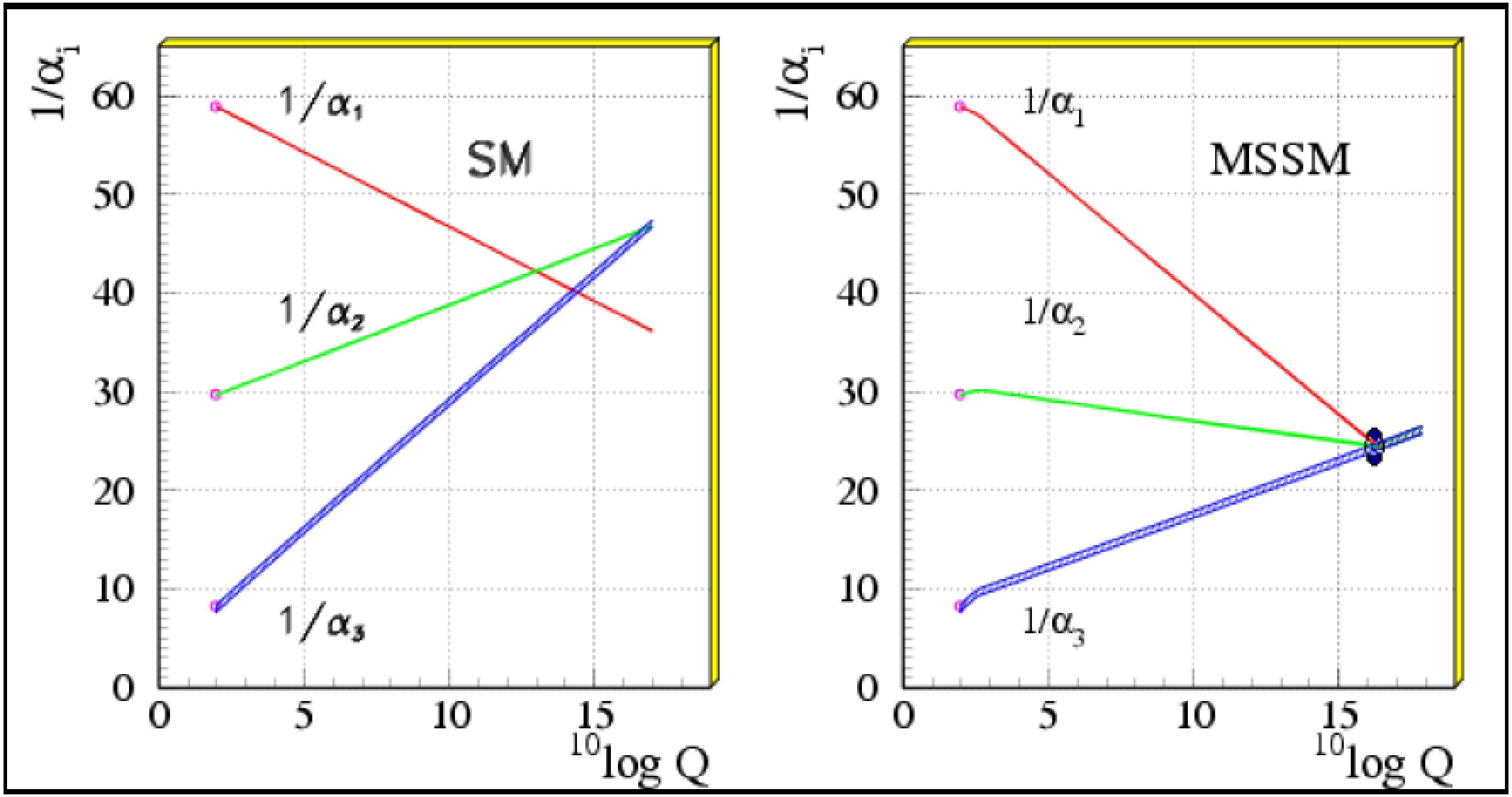
$$\begin{aligned} m_\tau &= 1.0 \times 10^{-2} & m_3 &= 2.9 \times 10^{-13} \\ m_\mu &= 6.2 \times 10^{-4} & m_2 &= 5.2 \times 10^{-14} \\ m_e &= 3.0 \times 10^{-6} & m_1 &= < m_2 \end{aligned}$$

$$V_q = \begin{pmatrix} 0.976 & 0.22 & 0.004 \\ -0.22 & 0.98 & 0.04 \\ 0.007 & -0.04 & 1 \end{pmatrix} \qquad U_\ell = \begin{pmatrix} 0.85 & -0.54 & 0.16 \\ 0.33 & 0.62 & -0.72 \\ -0.40 & -0.59 & -0.70 \end{pmatrix}$$

$$\text{Im}\left(\frac{V_{ub}V_{cs}}{V_{us}V_{cb}}\right) = 0.34$$

GUTs provide a desirable setup to address these issues

Gauge Coupling Unification

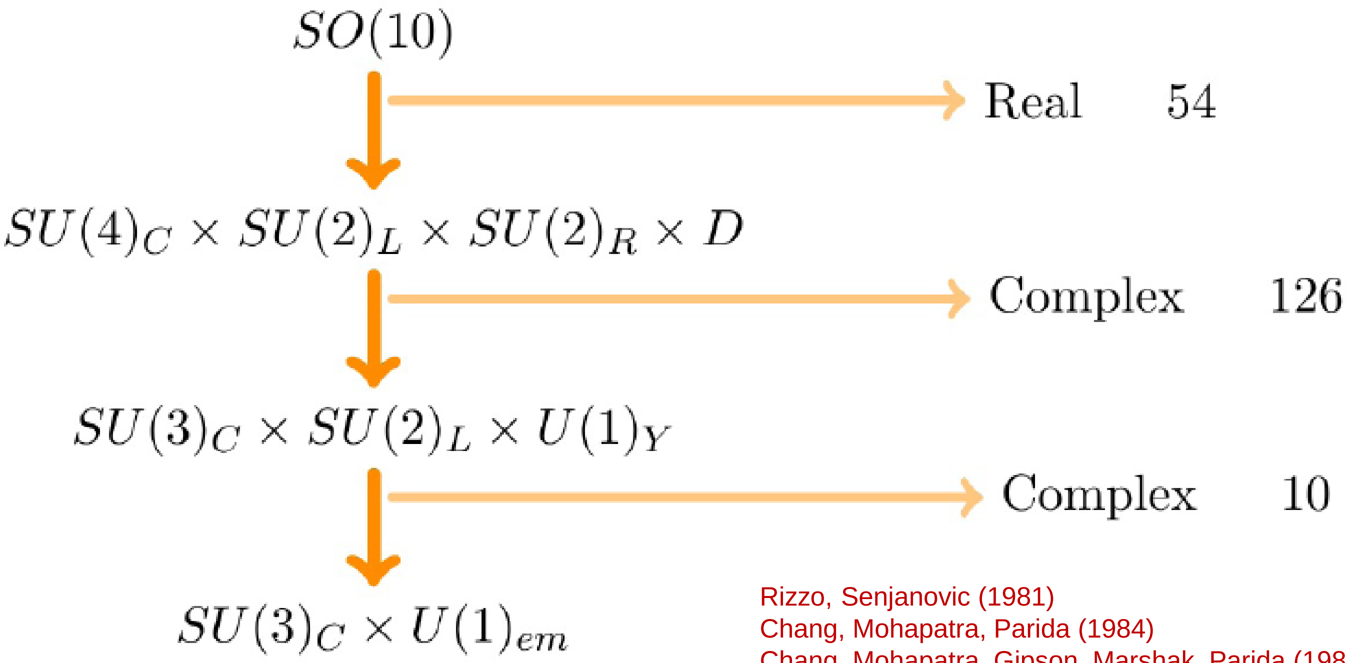


From S. Raby, PDG Review

Gauge Coupling Unification in Non-SUSY SO(10)

$SO(10)$ admits an intermediate Pati-Salam symmetry

Gauge couplings evolve differently above the Pati-Salam scale



$SO(10)$

Real 54

$SU(4)_C \times SU(2)_L \times SU(2)_R \times D$

Complex 126

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

Complex 10

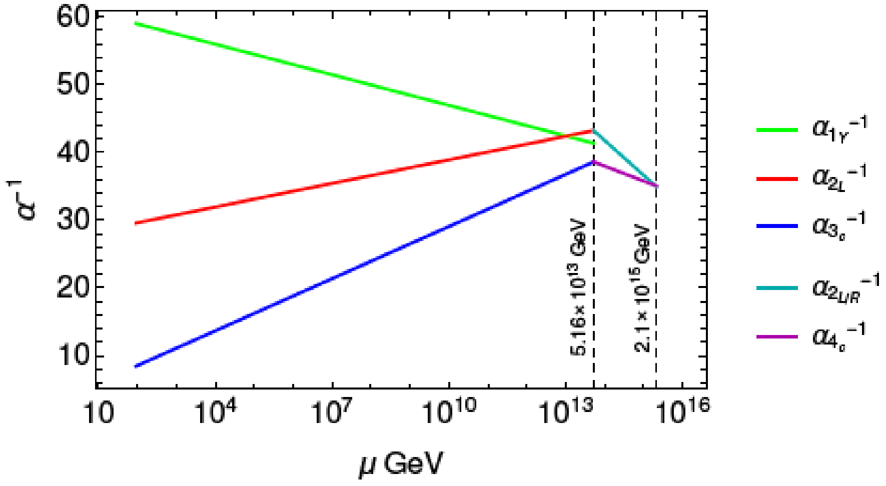
$SU(3)_C \times U(1)_{em}$

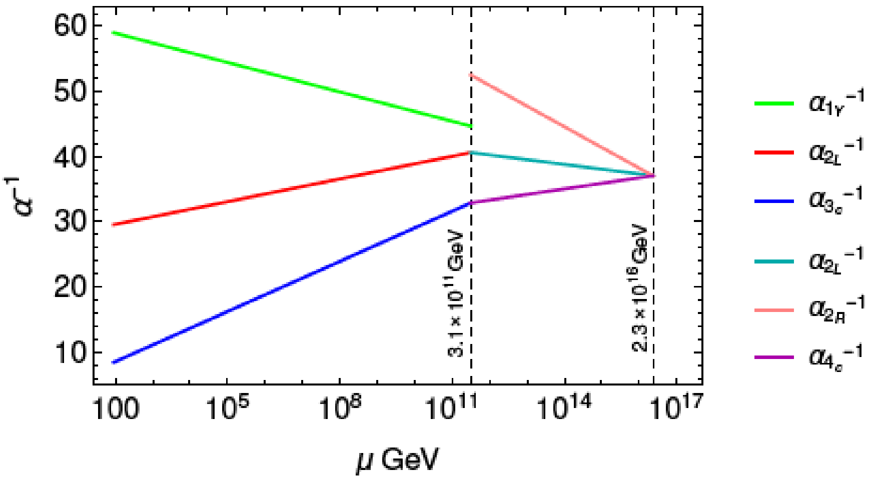
Rizzo, Senjanovic (1981)
Chang, Mohapatra, Parida (1984)
Chang, Mohapatra, Gipson, Marshak, Parida (1985)
Deshpande, Keith, Pal (1993)
Bertolini, Di Luzio, Malinsky (2013)
Babu, Khan (2015)
Graf, Malinsky, Mede, Susic (2016)
Babu, Bajc, Saad (2017)
Babu, Saad (2020)
Ohlsson, Pernow, Sonnerlind (2020)
Meloni, Ohlsson, Pernow (2020)

Unification with Intermediate Scale in SO(10)

Intermediate Pati-Salam symmetry – $SU(4)_c \times SU(2)_L \times SU(2)_R$

With and without left-right Parity





From Babu, Bajc, Saad (2017)

Quark-Lepton Unification

Initial ideas of unification arose from

$$SU(4)_c \times SU(2)_L \times SU(2)_R \times P$$

Pati, Salam (1973)

Quarks and leptons are unified, with lepton number identified as the 4th color

Each family of fermions belong to $\{(4,2,1)_L \oplus (4,1,2)_R\}$

$$\begin{pmatrix} u_1 & u_2 & u_3 & \nu \\ d_1 & d_2 & d_3 & \ell \end{pmatrix}_L \oplus \begin{pmatrix} u_1 & u_2 & u_3 & \nu \\ d_1 & d_2 & d_3 & \ell \end{pmatrix}_R$$

Gauge bosons do not mediate proton decay, but Higgs bosons do

$$p \to e^+ e^- e^+$$

Pati (1984)

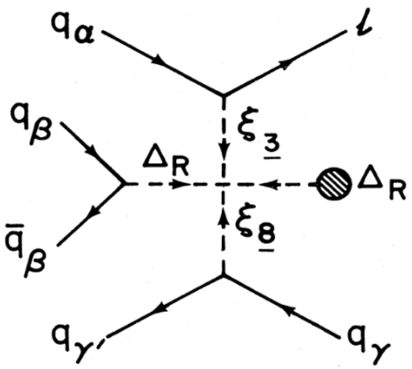


FIG. 1. Mecahnism for $3q \to lq\bar{q}$.

Minimal SU(5) GUT

Matter multiplets: $\{\mathbf{10} + \bar{\mathbf{5}} + \mathbf{1}\}$

Georgi, Glashow (1974)

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

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

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

Higgs: $\mathbf{24}_H, \quad \{\mathbf{5}_H, \quad \bar{\mathbf{5}}_H\}$ ⇒ Contain color triplets $\{H_C, \ \bar{H}_C\}$

Yukawa Couplings $Y_u^{ij} \mathbf{10}_i \mathbf{10}_j \mathbf{5}_H + Y_d^{ij} \mathbf{10}_i \bar{\mathbf{5}}_j \bar{\mathbf{5}}_H$

$$M_\ell = M_d^T \Rightarrow m_b = m_\tau, \quad m_s = m_\mu, \quad m_d = m_e$$

Doublet-Triplet Splitting in SUSY SU(5)

$$W_{D-T} = \bar{\mathbf{5}}_H(\lambda\,\mathbf{24}_H + M)\mathbf{5}_H$$

$$\langle 24_H \rangle = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -3/2 & 0 \\ 0 & 0 & 0 & 0 & -3/2 \end{pmatrix} V$$

FINE-TUNED TO $O(M_W)$

$$M_{H_c} = \lambda V + M \sim O(M_{GUT}) \quad M_H = -\frac{3}{2}\lambda V + M$$

The Good

(1) Predicts unification of couplings

(2) Uses economic Higgs sector

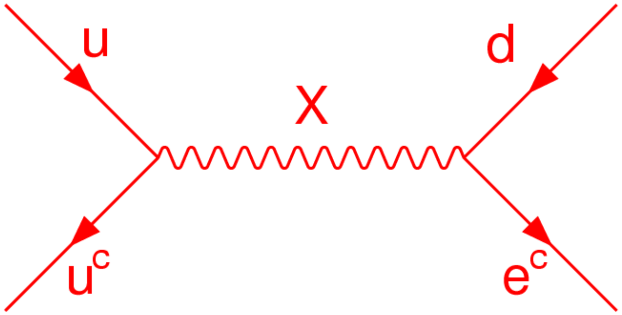
The Not so Good

(1) Unnatural fine tuning

(2) Typically large proton decay rate

Nucleon Decay in SUSY GUTs

Gauge boson exchange



$$\Gamma^{-1}(p \to e^{+}\pi^{0}) = (2.0 \times 10^{35}\ \mathrm{yr}) \times \left(\frac{\alpha_H}{0.01\ \mathrm{GeV}^3}\right)^{-2} \left(\frac{\alpha_G}{1/25}\right)^{-2} \left(\frac{A_R}{2.5}\right)^{-2} \left(\frac{M_X}{10^{16}\ \mathrm{GeV}}\right)^{4}$$

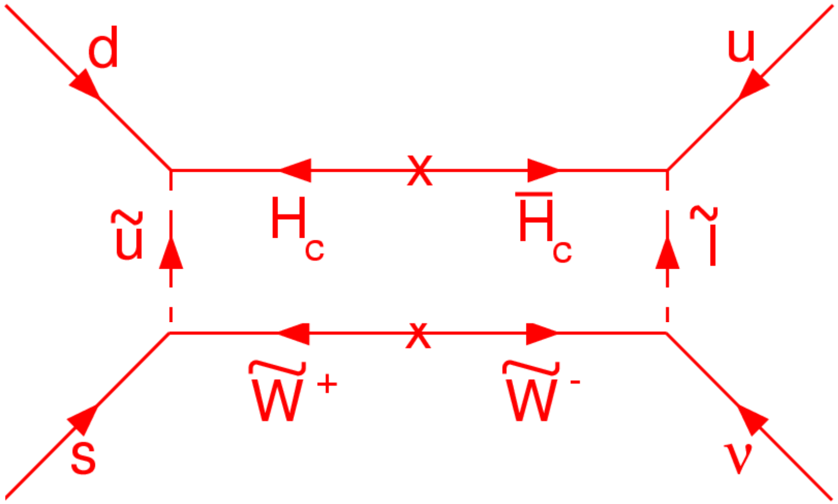
$$(-2\alpha_3^{-1} - 3\alpha_2^{-1} + 3\alpha_Y^{-1})(M_Z) = \frac{1}{2\pi}\left\{36 \ln\left(\frac{M_X}{M_Z}\left(\frac{M_\Sigma}{M_X}\right)^{1/3}\right) + 8 \ln\left(\frac{M_{\mathrm{SUSY}}}{M_Z}\right)\right\}$$

M_Σ: Heavy color octet mass, uncertain: Threshold effect

$\frac{M_\Sigma}{M_X} \leq 1.8$ (perturbation theory)

Hisano, Murayama, Yanagida (1993)
Nath, Perez, Phys. Rept. (2007)
Babu, Kearns, et. al. (2013)

SUSY Proton Decay Modes



Sakai, Yanagida (1982)

Weinberg (1982)

$$\Gamma^{-1}_{d=5}(p \to \bar{\nu} K^{+}) \simeq 1.2\cdot 10^{31}\,\text{yrs} \times \left(\frac{0.012\,\text{GeV}^3}{\beta_H}\right)^2 \left(\frac{7}{\bar{A}_S^{\alpha}}\right)^2 \left(\frac{1.25}{R_L}\right)^2$$

$$\times \left(\frac{M_T}{2\cdot 10^{16}\,\text{GeV}}\right)^2 \left(\frac{m_{\tilde{q}}}{1.5\,\text{TeV}}\right)^4 \left(\frac{190\,\text{GeV}}{M_{\tilde{W}}}\right)^2$$

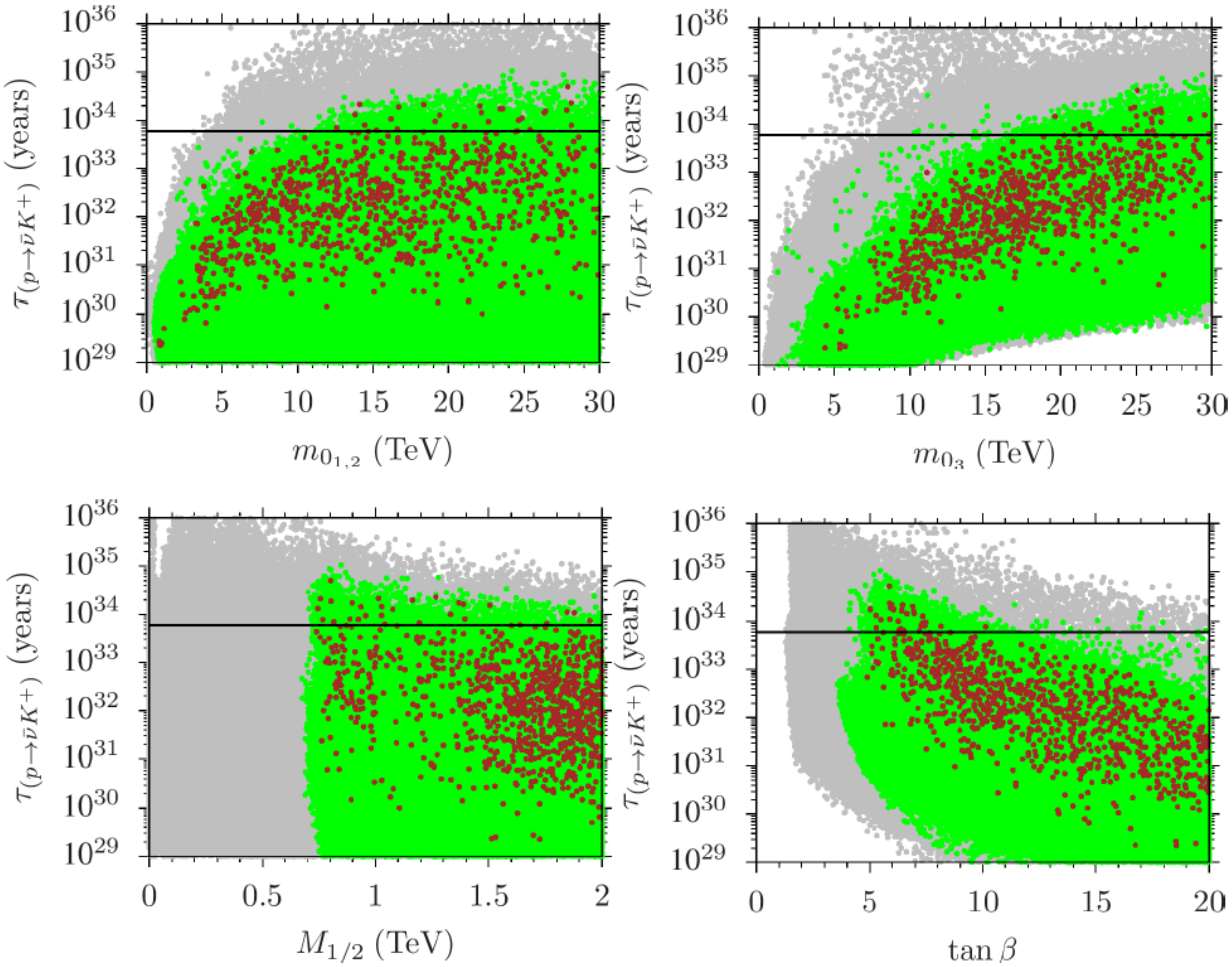
Hisano, Murayama, Yanagida (1993);

Murayama, Pierce (2002);………

Ellis, Evans, Nagata, Olive, Valesco-Sevilla (2019);

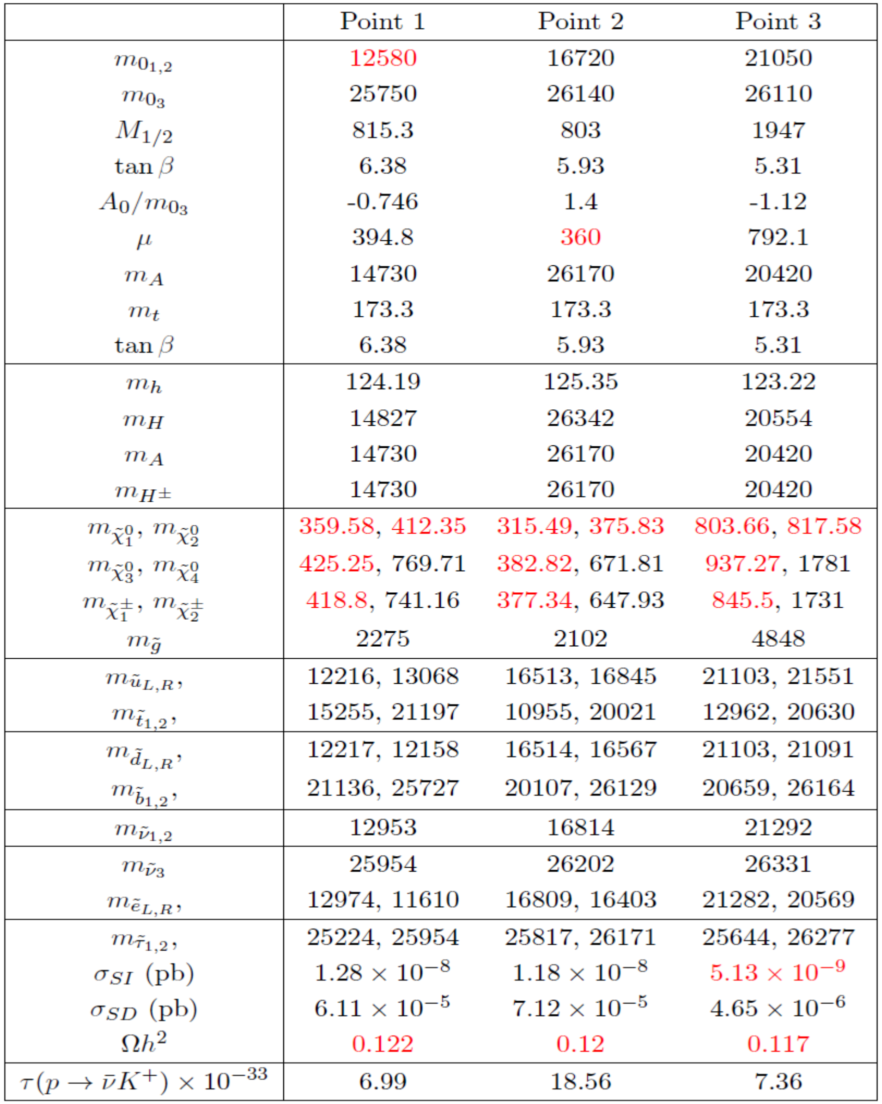
Babu, Gogoladze, Un (2020)

Proton Decay in SUSY SU(5)



Babu, Gogoladze, Un (2020)

SUSY SU(5) Benchmark Points



	Point 1	Point 2	Point 3
$m_{0_{1,2}}$	12580	16720	21050
m_{0_3}	25750	26140	26110
$M_{1/2}$	815.3	803	1947
$\tan\beta$	6.38	5.93	5.31
A_0/m_{0_3}	-0.746	1.4	-1.12
μ	394.8	360	792.1
m_A	14730	26170	20420
m_t	173.3	173.3	173.3
$\tan\beta$	6.38	5.93	5.31
m_h	124.19	125.35	123.22
m_H	14827	26342	20554
m_A	14730	26170	20420
$m_{H^\pm}$	14730	26170	20420
$m_{\tilde\chi_1^0}$, $m_{\tilde\chi_2^0}$	359.58, 412.35	315.49, 375.83	803.66, 817.58
$m_{\tilde\chi_3^0}$, $m_{\tilde\chi_4^0}$	425.25, 769.71	382.82, 671.81	937.27, 1781
$m_{\tilde\chi_1^\pm}$, $m_{\tilde\chi_2^\pm}$	418.8, 741.16	377.34, 647.93	845.5, 1731
$m_{\tilde g}$	2275	2102	4848
$m_{\tilde u_{L,R}}$,	12216, 13068	16513, 16845	21103, 21551
$m_{\tilde t_{1,2}}$,	15255, 21197	10955, 20021	12962, 20630
$m_{\tilde d_{L,R}}$,	12217, 12158	16514, 16567	21103, 21091
$m_{\tilde b_{1,2}}$,	21136, 25727	20107, 26129	20659, 26164
$m_{\tilde\nu_{1,2}}$	12953	16814	21292
$m_{\tilde\nu_3}$	25954	26202	26331
$m_{\tilde e_{L,R}}$,	12974, 11610	16809, 16403	21282, 20569
$m_{\tilde\tau_{1,2}}$,	25224, 25954	25817, 26171	25644, 26277
σ_{SI} (pb)	1.28×10^{-8}	1.18×10^{-8}	5.13×10^{-9}
σ_{SD} (pb)	6.11×10^{-5}	7.12×10^{-5}	4.65×10^{-6}
Ωh^2	0.122	0.12	0.117
$\tau(p \to \bar\nu K^+) \times 10^{-33}$	6.99	18.56	7.36

Babu, Gogoladze, Un (2020)

SUSY SO(10) Models

Fermions of each family unified in $\{16\}_i$ $(i = 1 - 3)$

Generally three types of Higgs are needed:

- $SO(10)$ breaking to rank 5 subgroup $(45_H$ or $210_H)$
- Rank reduction $(16_H$ or $126_H)$
- Electroweak symmetry breaking (10_H)

(1) $\{45_H + 16_H + 10_H\}$ models perturbative upto Planck scale

(2) $\{210_H + 126_H + 10_H\}$ models have direct couplings, automatic R parity, and are very predictive

SUSY SO(10) with Natural Doublet-Triplet Splitting

Higgs sector: $\{45_H + 10_H + 16_H + \overline{16}_H + 16'_H + \overline{16}'_H\}$

$$W_{D-T} = \lambda(\mathbf{10}_H \mathbf{45}_H \mathbf{10}'_H) + M' \mathbf{10}'_H \mathbf{10}'_H$$

$$\langle 45_H \rangle = \begin{pmatrix} a & 0 & 0 & 0 & 0 \\ 0 & a & 0 & 0 & 0 \\ 0 & 0 & a & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \otimes i\tau_2 \quad \propto B-L$$

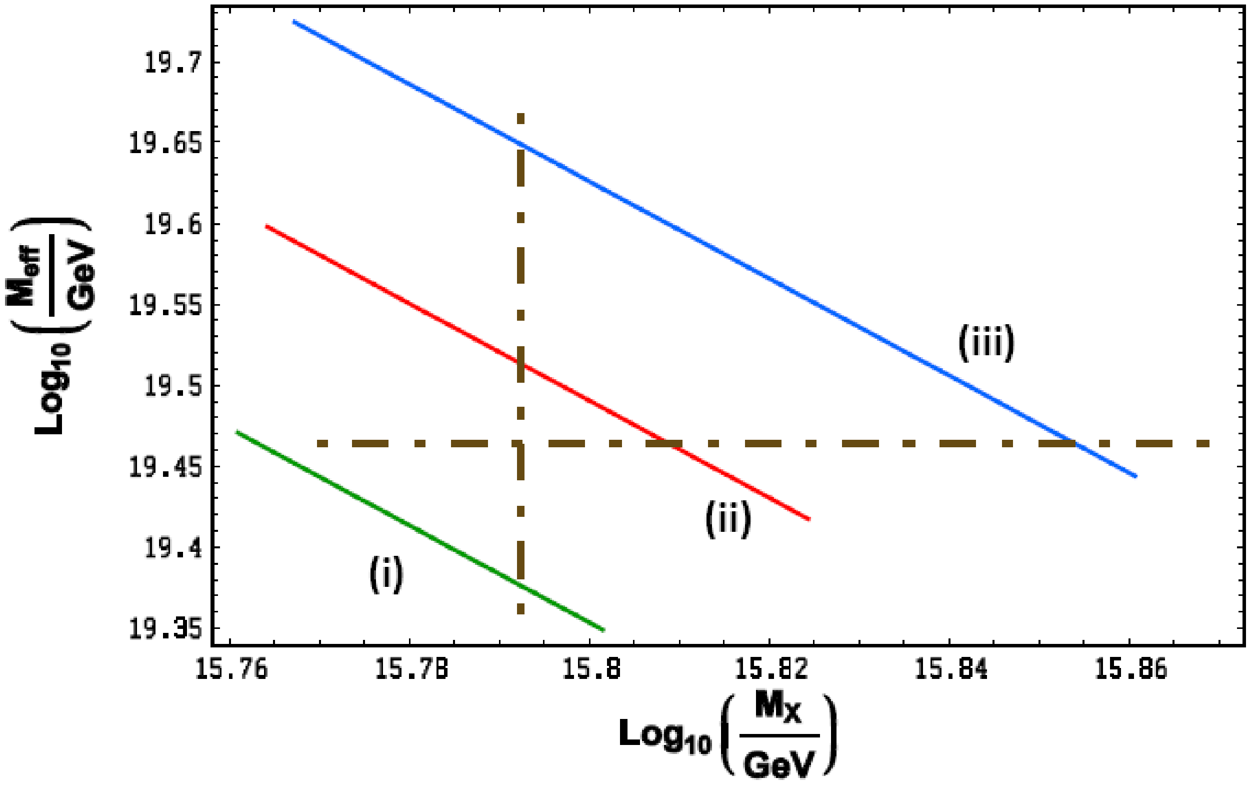
Dimopoulos, Wilczek (1981)
Babu, Barr (1993)
Barr, Raby (2000)

Adjoint VEV along $B-L$ gives mass only to color triplets and not to doublets

Superpotential:

$$\begin{aligned} W(A) &= M_A \mathrm{tr} A^2 + \frac{\lambda_A}{M_*}\left(\mathrm{tr} A^2\right)^2 + \frac{\lambda'_A}{M_*}\mathrm{tr} A^4 \\ W(A,C,C') &= C\left(\frac{a_1}{M_*}ZA + \frac{b_1}{M_*}C\bar{C} + c_1 S\right)\bar{C}' + C'\left(\frac{a_2}{M_*}ZA + \frac{b_2}{M_*}C\bar{C} + c_2 S\right)\bar{C} \\ W(DT) &= \lambda_1 HAH' + \lambda_{H'}\frac{S^k}{M_*^{k-1}}(H')^2 + \lambda_2 H\bar{C}\bar{C} \end{aligned}$$

Babu, Pati, Tavartkiladze (2010)



Correlation for spectrum with $tan\beta = 7$ and r=1/1200.

(i): $\alpha_3 = 0.1177$. (ii): $\alpha_3 = 0.1184$. (iii): $\alpha_3 = 0.1191$.

See also: Dermisek, Mafi, Raby (2000)
Babu, Pati, Wilczek (2000)
Altarelli, Feruglio (2001)
Bajc, Perez, Senjanovic (2002)
Li, Nanopoulos, Walker (2010)
Babu, Bajc, Tavartkiladze (2012)
Chen, Zhang (2014)

Minimal SO(10) Yukawa Theory

$$\mathcal{L}_{\text{Yukawa}} = \mathbf{16}\left(Y_{10}\,\mathbf{10}_H + Y_{126}\,\overline{\mathbf{126}}_H\right)\mathbf{16}$$

Two Yukawa matrices determine all fermion masses and mixings, including the neutrinos

$$\begin{aligned} M_u &= \kappa_u Y_{10} + \kappa_u' Y_{126} \\ M_d &= \kappa_d Y_{10} + \kappa_d' Y_{126} \\ M_\nu^D &= \kappa_u Y_{10} - 3\kappa_u' Y_{126} \\ M_l &= \kappa_d Y_{10} - 3\kappa_d' Y_{126} \end{aligned}$$

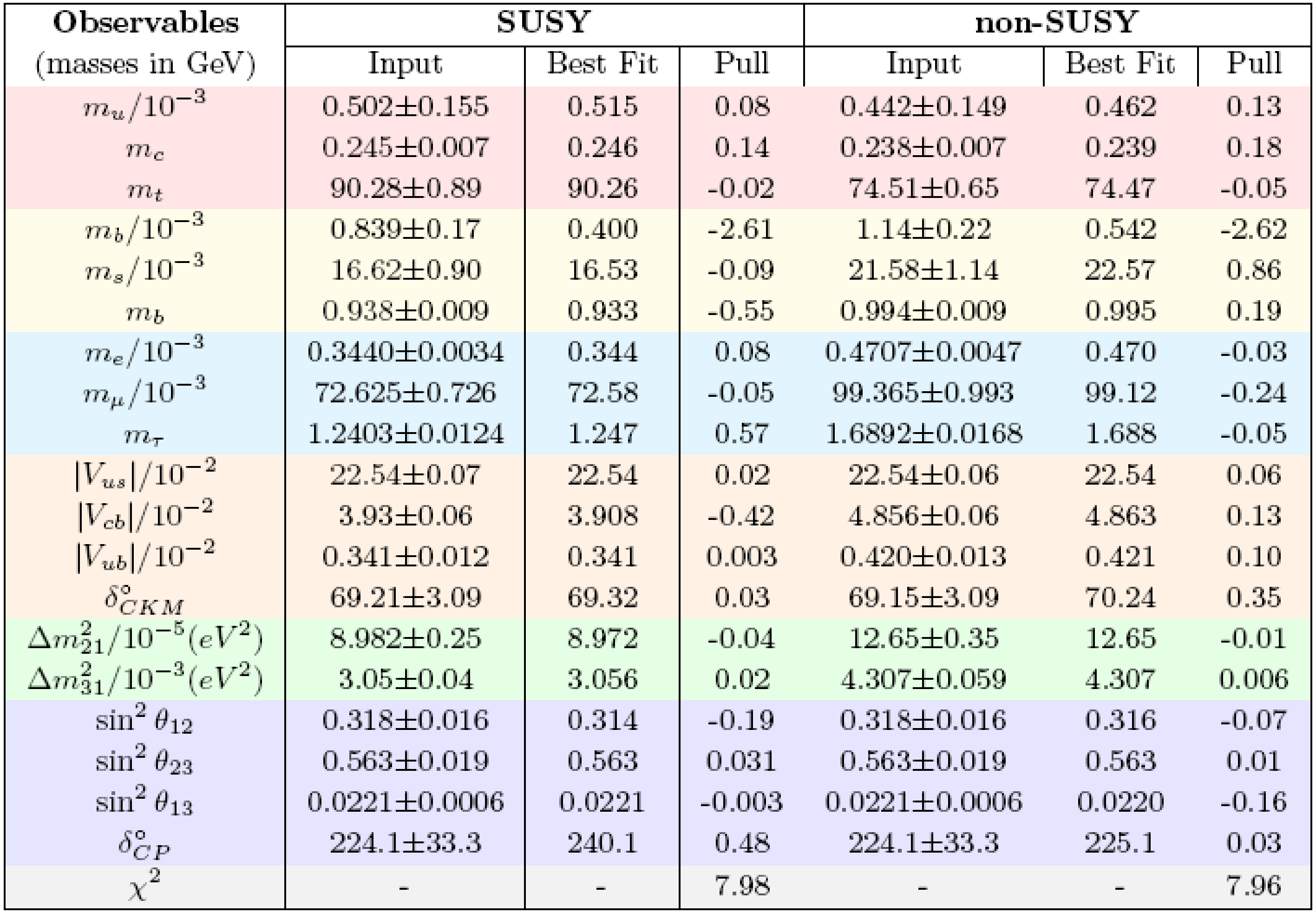
$$\begin{aligned} M_{\nu R} &= \langle \Delta_R \rangle Y_{126} \\ M_{\nu L} &= \langle \Delta_L \rangle Y_{126} \end{aligned}$$

Model has only 11 real parameters plus 7 phases

Babu, Mohapatra (1993)
Bajc, Melfo, Senjanovic, Vissani (2002)
Fukuyama, Okada (2002)
Bajc, Melfo, Senjanovic, Vissani (2004)
Fukuyama, Ilakovac, Kikuchi, Meljanac, Okada (2004)
Aulakh et al (2004)
Bertolini, Frigerio, Malinsky (2004)
Babu, Macesanu (2005)
Bertolini, Malinsky, Schwetz (2016)
Dutta, Mimura, Mohapatra (2007), (2009)
Bajc, Dorsner, Nemevsek (2009)
Joshipura, Patel (2011)
Dueck, Rodejohann (2013)
Fukuyama, Mimura (2015)
Babu, Bajc, Saad (2018)
Babu, Fukuyama, Khan, Saad (2018)
Babu, Saad (2020)

Recent Global Fit Including CP Phase

$$\mathcal{L}_{\text{Yukawa}} = \mathbf{16}\left(Y_{10}\,\mathbf{10}_H + Y_{126}\,\overline{\mathbf{126}}_H\right)\mathbf{16}$$

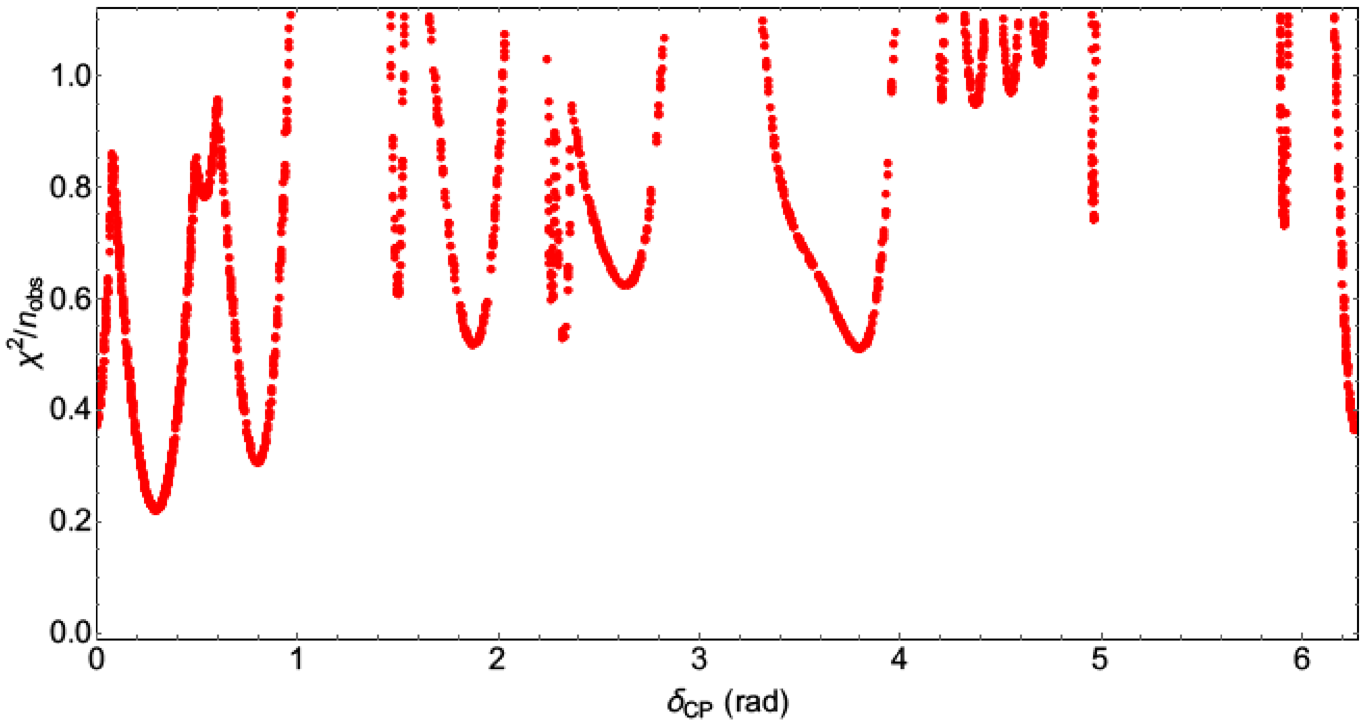


Observables	SUSY			non-SUSY		
(masses in GeV)	Input	Best Fit	Pull	Input	Best Fit	Pull
$m_u/10^{-3}$	0.502±0.155	0.515	0.08	0.442±0.149	0.462	0.13
m_c	0.245±0.007	0.246	0.14	0.238±0.007	0.239	0.18
m_t	90.28±0.89	90.26	-0.02	74.51±0.65	74.47	-0.05
$m_b/10^{-3}$	0.839±0.17	0.400	-2.61	1.14±0.22	0.542	-2.62
$m_s/10^{-3}$	16.62±0.90	16.53	-0.09	21.58±1.14	22.57	0.86
m_b	0.938±0.009	0.933	-0.55	0.994±0.009	0.995	0.19
$m_e/10^{-3}$	0.3440±0.0034	0.344	0.08	0.4707±0.0047	0.470	-0.03
$m_\mu/10^{-3}$	72.625±0.726	72.58	-0.05	99.365±0.993	99.12	-0.24
m_τ	1.2403±0.0124	1.247	0.57	1.6892±0.0168	1.688	-0.05
$\lvert V_{us}\rvert/10^{-2}$	22.54±0.07	22.54	0.02	22.54±0.06	22.54	0.06
$\lvert V_{cb}\rvert/10^{-2}$	3.93±0.06	3.908	-0.42	4.856±0.06	4.863	0.13
$\lvert V_{ub}\rvert/10^{-2}$	0.341±0.012	0.341	0.003	0.420±0.013	0.421	0.10
δ°_{CKM}	69.21±3.09	69.32	0.03	69.15±3.09	70.24	0.35
$\Delta m^2_{21}/10^{-5}(eV^2)$	8.982±0.25	8.972	-0.04	12.65±0.35	12.65	-0.01
$\Delta m^2_{31}/10^{-3}(eV^2)$	3.05±0.04	3.056	0.02	4.307±0.059	4.307	0.006
$\sin^2\theta_{12}$	0.318±0.016	0.314	-0.19	0.318±0.016	0.316	-0.07
$\sin^2\theta_{23}$	0.563±0.019	0.563	0.031	0.563±0.019	0.563	0.01
$\sin^2\theta_{13}$	0.0221±0.0006	0.0221	-0.003	0.0221±0.0006	0.0220	-0.16
δ°_{CP}	224.1±33.3	240.1	0.48	224.1±33.3	225.1	0.03
χ^2	-	-	7.98	-	-	7.96

Babu, Saad (2020)

Pinning Down the CP Phase?

When other parameters are marginalized, CP phase is found to have multiple minima in χ^2



Babu, Bajc, Saad (2018)

Fermion Mass Hierarchy From Clockwork

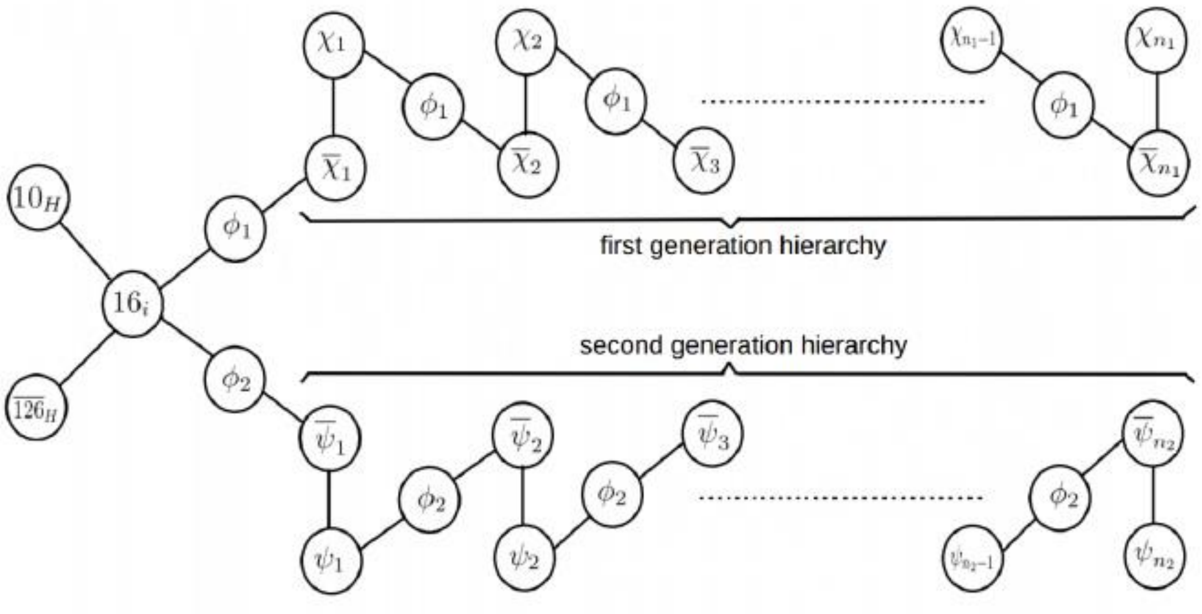
- GUTs alone cannot explain fermions mass hierarchy
- A “clockwork mechanism” can explain hierarchy
  Analogous to Froggatt-Nielsen mechanism
- SM Fermions mix with a chain of vector-like fermions
  Vector fermions have nearest neighbor interactions
  SM fermions are zero modes in this chain
- Small numbers arise naturally
  Recently applied to minimal SO(10)

Choi, Im (2016); Kaplan, Rattazzi (2016); Giudice, Mccullough (2016)

Von Gersdroff (2017); Patel (2017); Alonso et al (2018); Sanino et al (2019),…

Clockwork SO(10)

Three fermion families mix with two clockwork chains



$$\begin{pmatrix} -q_1 & 1 & 0 & \cdots & 0 \\ 0 & -q_1 & 1 & \cdots & 0 \\ 0 & 0 & -q_1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots -q_1 & 1 \end{pmatrix}_{n_1 \times (n_1+1)}$$

Babu, Saad (2020)

Clockwork SO(10) (cont.)

Each chain generates a small parameter ϵ

$$M_d = 0.80166 e^{2.18422i} \begin{pmatrix} 1.27815\ \epsilon_1^2\ e^{-3.0004i} & 1.26174\ \epsilon_1\epsilon_2\ e^{-2.71759i} & 1.11777\ \epsilon_1\ e^{1.63891i} \\ 1.26174\ \epsilon_1\epsilon_2\ e^{-2.71759i} & 1.61178\ \epsilon_2^2\ e^{-2.31606i} & 1.20224\ \epsilon_2\ e^{2.02843i} \\ 1.11777\ \epsilon_1\ e^{1.63891i} & 1.20224\ \epsilon_2\ e^{2.02843i} & 1 \end{pmatrix} \mathrm{GeV}$$

$$M_u = 79.1467 e^{2.27241i} \begin{pmatrix} 1.09514\ \epsilon_1^2\ e^{3.10025i} & 1.17556\ \epsilon_1\epsilon_2\ e^{-2.80578i} & 1.04143\ \epsilon_1\ e^{1.55072i} \\ 1.17556\ \epsilon_1\epsilon_2\ e^{-2.80578i} & 1.24674\ \epsilon_2^2\ e^{-2.42765i} & 1.12012\ \epsilon_2\ e^{1.94025i} \\ 1.04143\ \epsilon_1\ e^{1.55072i} & 1.12012\ \epsilon_2\ e^{1.94025i} & 1 \end{pmatrix} \mathrm{GeV}$$

$\epsilon_1 \simeq 0.06$, $\epsilon_2 \simeq 0.33$ arise from length of chains

Neutrino masses and mixings fixed in terms of these

The main test of these models is in proton decay

Proton Decay in non-SUSY SO(10)

$$\tau_P \approx \frac{\pi}{4} R_L^2 (1+F+D)\frac{|\alpha|^2}{f_\pi^2} m_p \alpha_G^2 \left[A_{SR}^2\left(\frac{1}{M_{(X,Y)}^2}+\frac{1}{M_{(X',Y')}^2}\right)^2+\frac{4A_{SL}^2}{M_{(X,Y)}^4}\right]^{-1}$$

Here,

$$A_{SL(R)} = \prod_{i=1}^{n}\prod_{sc}^{Mz\leq m_{sc}<M_G}\left[\frac{\alpha_i(m_{sc+1})}{\alpha_i(m_{sc})}\right]^{\frac{\gamma_{L(R)i(sc)}}{b_i(m_{sc+1}-m_{sc})}}$$

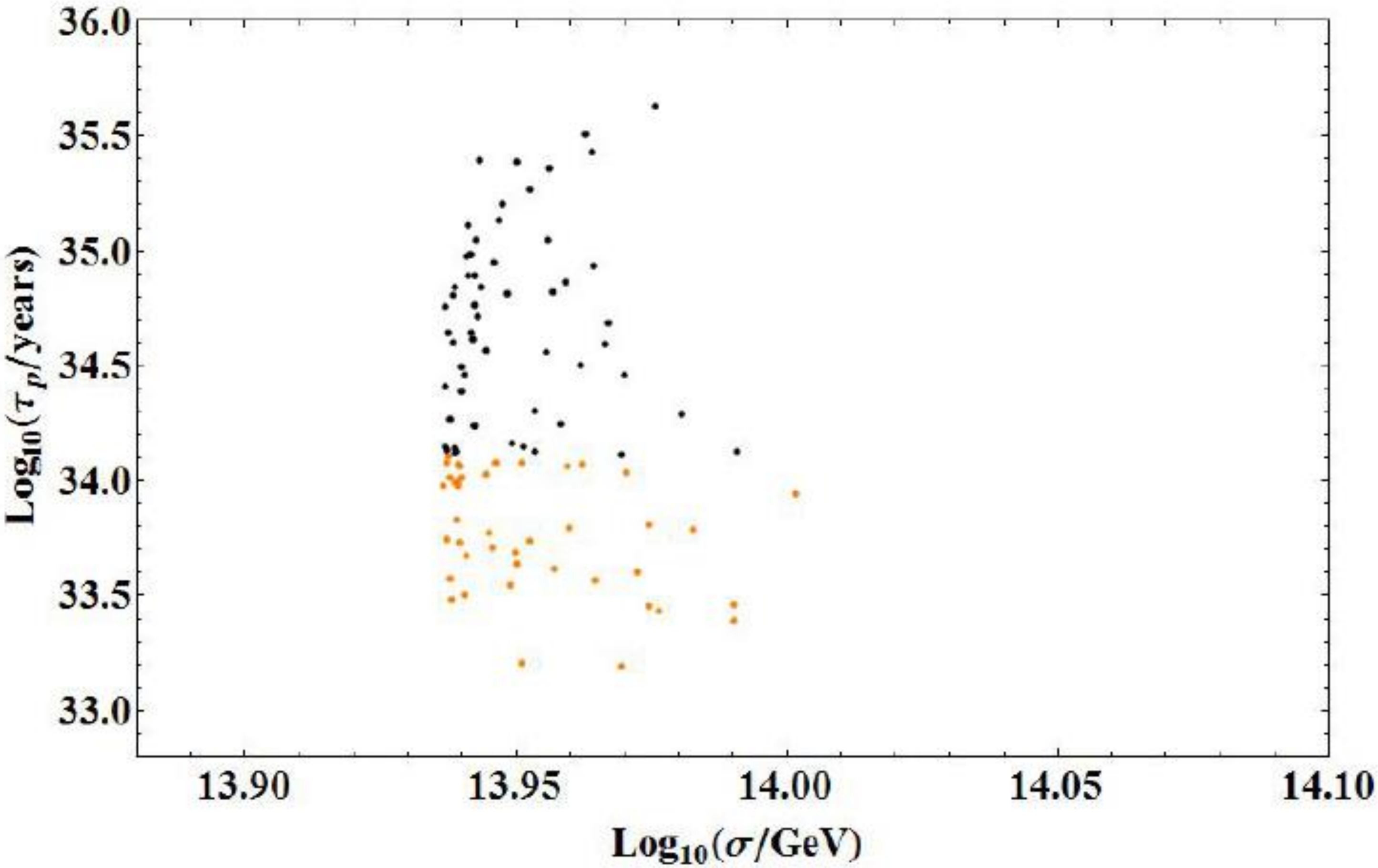
where,

$$\gamma_{L(sm)} = \left\{\frac{23}{20},\frac{9}{4},2\right\}; \quad \gamma_{R(sm)} = \left\{\frac{11}{20},\frac{9}{4},2\right\}; \quad \gamma_{L/R(ps)} = \left\{\frac{15}{4},\frac{9}{4},\frac{9}{4}\right\}$$

Proton Life Time

$$\begin{aligned}\Gamma^{-1}(p\to e^+\pi^0) &\approx (8.2\times 10^{34} yr)\\ &\times \left(\frac{\alpha_H}{0.0122\,GeV^3}\right)^{-2}\left(\frac{\alpha_G}{1/34.7}\right)^{-2}\left(\frac{A_R}{3.35}\right)^{-2}\left(\frac{M_X}{10^{16}\,GeV}\right)^{4}\end{aligned}$$

Prediction for Proton Lifetime



Non-SUSY $SO(10)$

Babu, Khan (2015)

Prediction of branching ratios

$$\Gamma(p \to \pi^0 e^+) \to 47\%$$

$$\Gamma(p \to \pi^0 \mu^+) \to 1\%$$

$$\Gamma(p \to \eta^0 e^+) \to 0.20\%$$

$$\Gamma(p \to \eta^0 \mu^+) \to 0.00\%$$

$$\Gamma(p \to K^0 e^+) \to 0.16\%$$

$$\Gamma(p \to K^0 \mu^+) \to 3.62\%$$

$$\Gamma(p \to \pi^+ \overline{\nu}) \to 48\%$$

$$\Gamma(p \to K^+ \overline{\nu}) \to 0.22\%$$

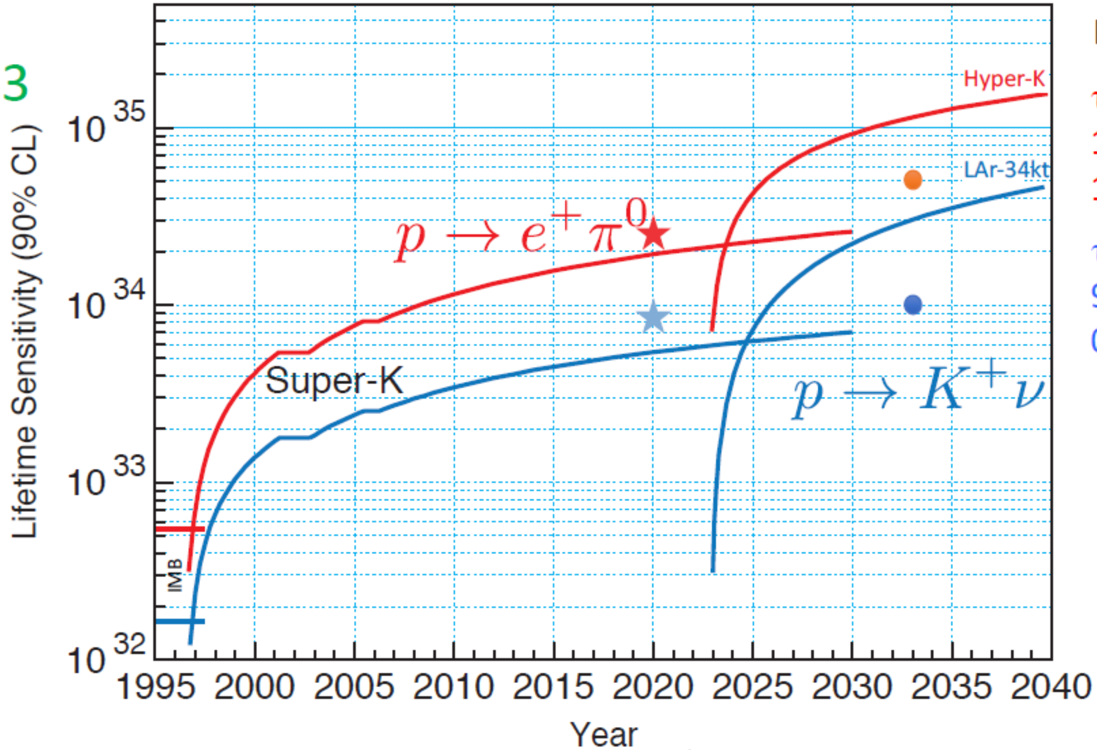
See also: Meloni, Ohlsson, Pernow (2019)
Perez, Murugui, Plascencia (2019)
GUT session talks by Malinksy, Susic, and others

Experimental Probes of Proton Decay

Particle Physics at the Intensity Frontier
Intensity Frontier Workshop
25-27 April 2013 *Argonne National Laboratory*

Retrospective:
Snowmass 2013

★ = prelim. SK (2020)



10 year
sample
points ● ●

τ/B = 5e35
17 evts
1 BG

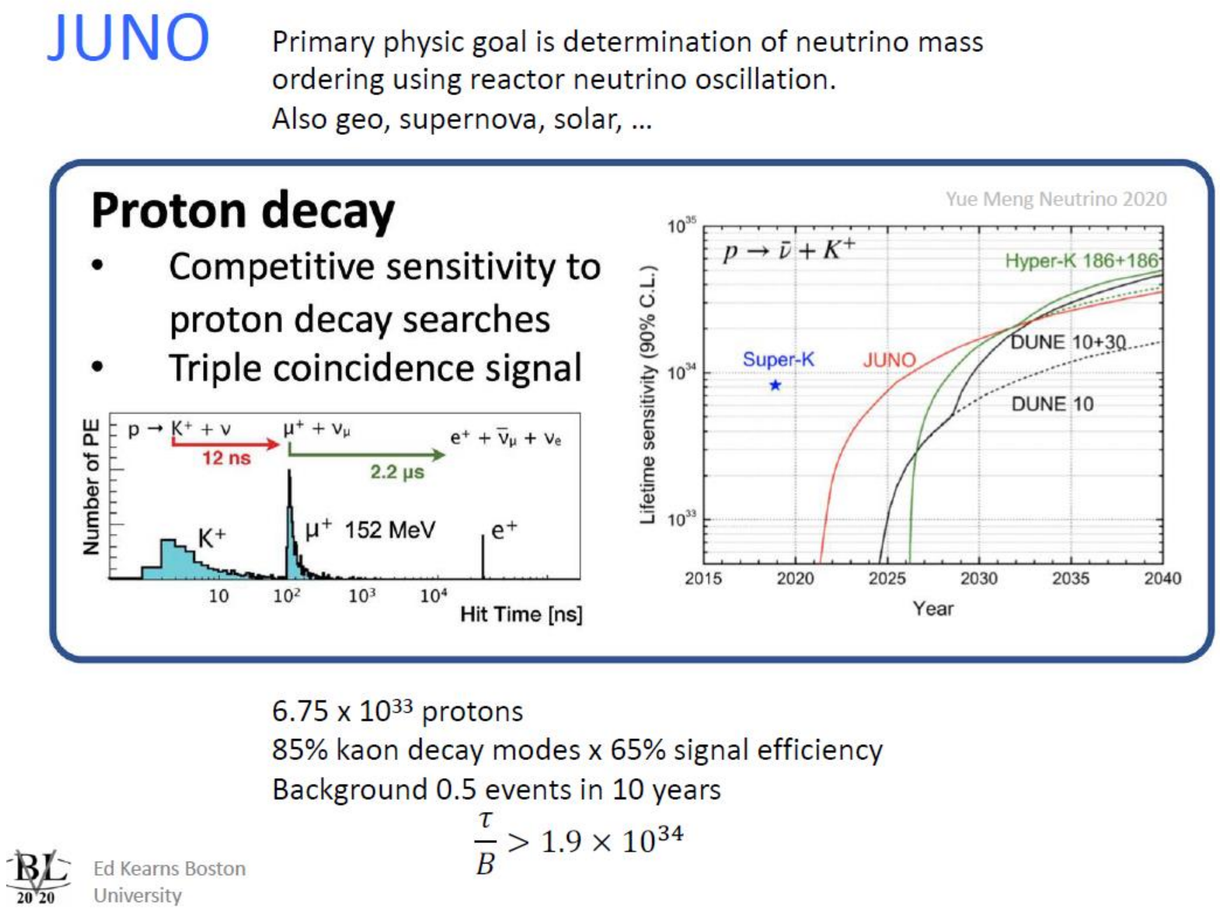
τ/B = 1e34
9 evts
0.3 BG

~ 0.5 Mt yr exposure
by Super-K before next
generation experiments

⟷
Starting time? Guess 1 decade from now.
Adjust starting time as you wish.

From Ed Kearns, BNV circa 2020

Experimental Probes of Proton Decay



JUNO

Primary physic goal is determination of neutrino mass ordering using reactor neutrino oscillation.
Also geo, supernova, solar, …

Proton decay

- Competitive sensitivity to proton decay searches
- Triple coincidence signal

6.75×10^{33} protons
85% kaon decay modes x 65% signal efficiency
Background 0.5 events in 10 years

$$\frac{\tau}{B} > 1.9 \times 10^{34}$$

Ed Kearns Boston University

Should enter new territory before DUNE/HK turn on

From Ed Kearns, BNV circa 2020

Proton Decay and Long-term Fate of the Universe

Last stage of stellar evolution controlled by proton decay

At large time scale, evolution of white dwarfs and neutron stars driven by proton decay

$$p \rightarrow e^{+}\pi^{0}$$

π^0 decays to two photons, and e^+ annihilates with e^-

$$p + e^{-} \rightarrow \gamma + \gamma + \gamma + \gamma$$

White dwarf powered by proton decay generates 400 Watts of power

Proton decay becomes dominant power source at

$$t \approx 30 \times \tau_p \approx 10^{36} \text{ yrs.}$$

F. Adams, G. Laughlin (1997)

Conclusions

- SUSY GUTs are well motivated BSM candidates
- Proton decay is their hallmark prediction
- SUSY GUTs are under stress from proton decay limits
- Both $p \to \overline{\nu} K^+$ and $p \to e^+ \pi^0$ should be within reach of HyperK, DUNE and JUNO experiments
- Light gauginos and heavy scalars preferred for LHC