GUTs, Neutrinos and Flavor Symmetries

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Grand Unified Theories (GUTs): Elegant and ambitious

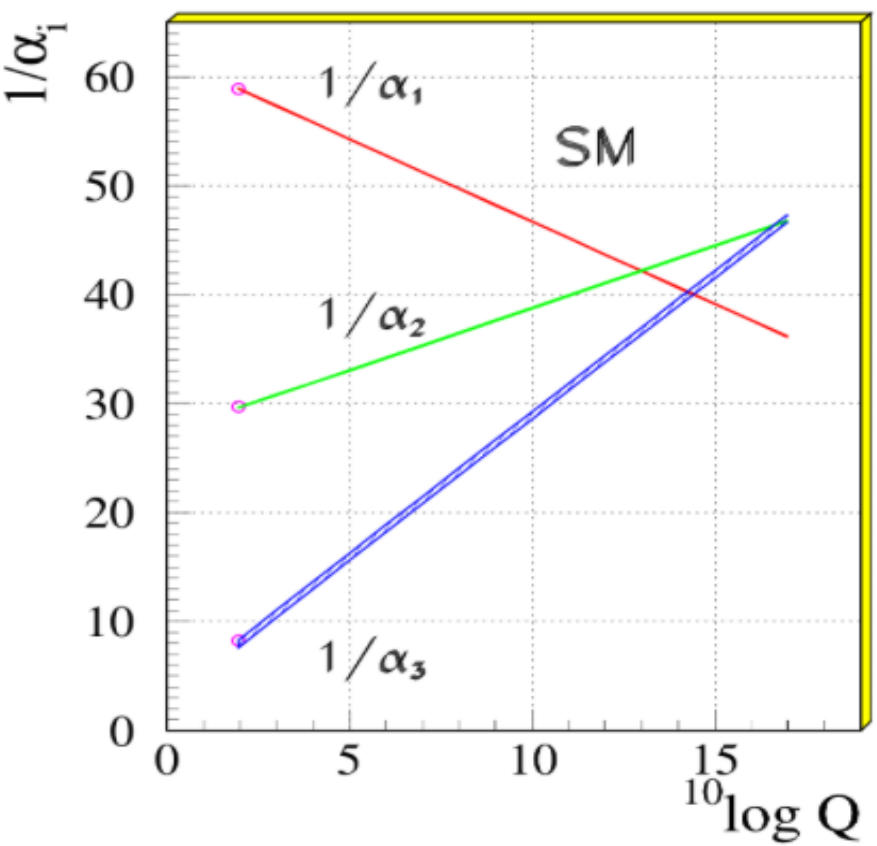
- Unifies all matter and forces
- Makes theory more predictive

  e.g. can predict $\boxed{\sin^2\theta_W}$ + more
- Also quantizes electric charges

(Pati, Salam; Georgi, Glashow'73)

Key idea: coupling unification $g_1=g_2=g_3$

- Prospects in the standard model: g's run towards each other at shorter distances (Georgi, Quinn, Weinberg'74)



→ *But don't quite unify*

(wrong $\sin^2\theta_W$)

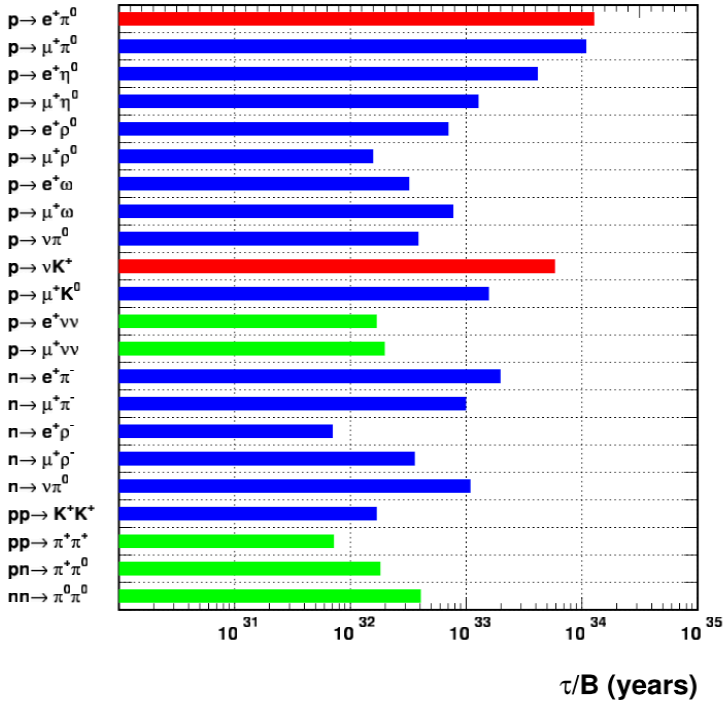
suggesting possibly new physics below GUT scale

Key prediction:proton decay

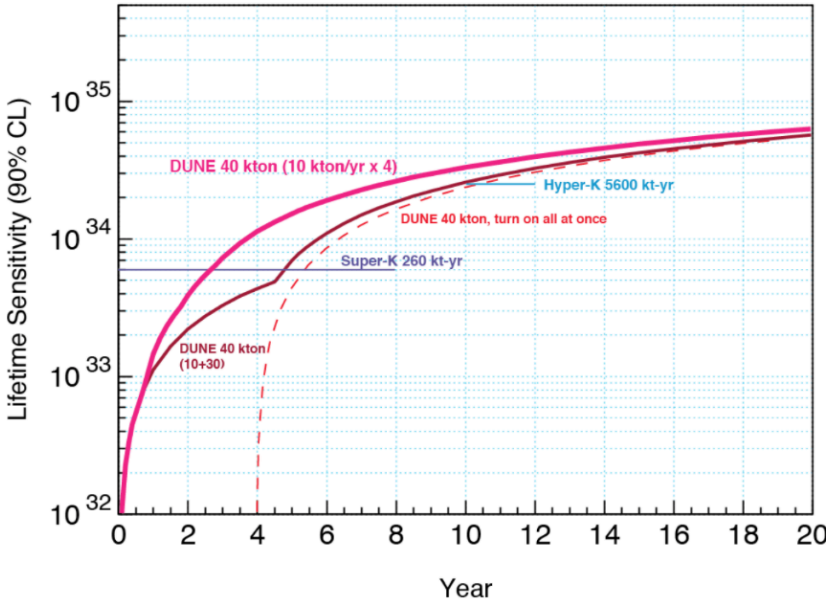
- GUT group→ Q-L unification→proton decay

  e.g. $p \to e^+\pi^0$+...: (Babu's talk)

- **Nucleon Lifetime Limit (90%CL)**

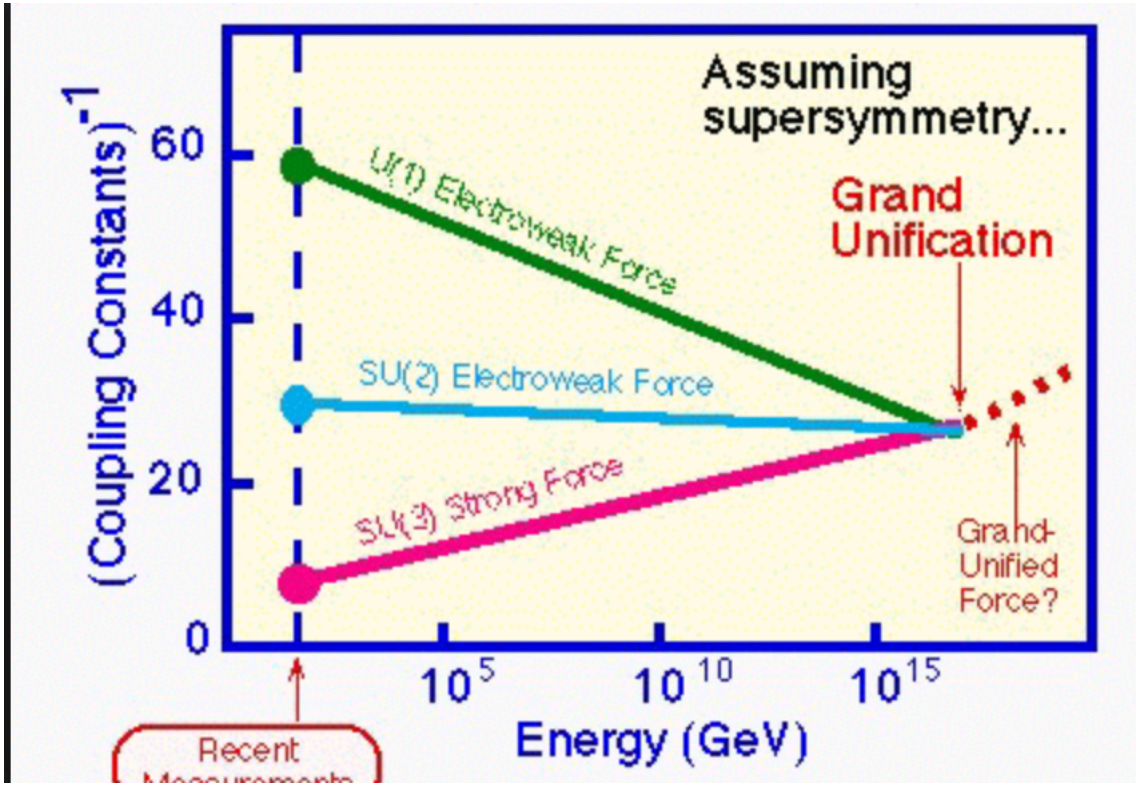


no evidence yet (Miura's tallk)



Simple theories with coupling unif.: SUSY@TeV

- Unification scale $M_U \sim 10^{16}$ GeV; predicts correct $\sin^2\theta_W$ and new *proton decay mode* $p \to \bar{\nu} K^+$



(Dimopoulos, Raby, Wilczek'81)

Also solves gauge hierarchy problem !! (2-step GUT)

Neutrino mass and GUTs

- $m_\nu \neq 0$ needs new physics beyond SM.

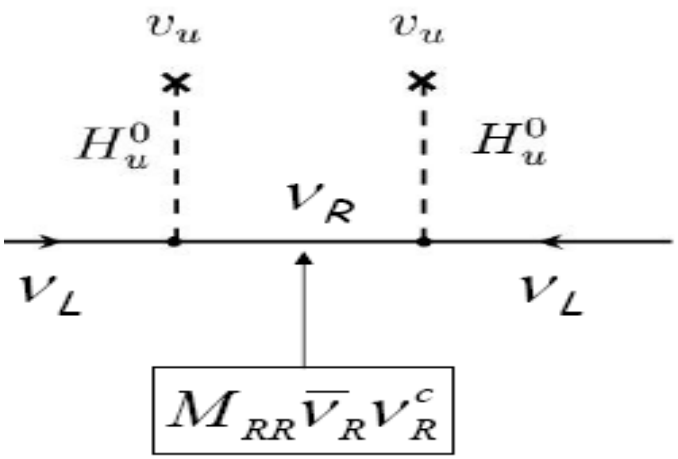
- Two new puzzles from neutrino mass discovery

(i) $m_\nu \ll m_q, m_\ell$

(ii) Lepton mixing patterns different from quarks

Seesaw paradigm for $m_\nu \ll m_q, m_\ell$ and GUTs

- SM+ RH neutrinos ν_R with heavy Majorana mass



→ $m_\nu \simeq -\frac{m_D^2}{M_{\nu_R}}$ (seesaw)

(Minkowski'77; Mohapatra,Senjanovic; Gell-Mann,Ramond, Slansky; Yanagida; Glashow'79)

- Q-L unification→ $m_{D33} \sim m_t$ ➔ $M_{\nu_R} \sim 10^{14}$ GeV
- Fits well into GUT framework since $M_{\nu_R} \sim M_U$

Understanding Flavor: a challenge for GUTs

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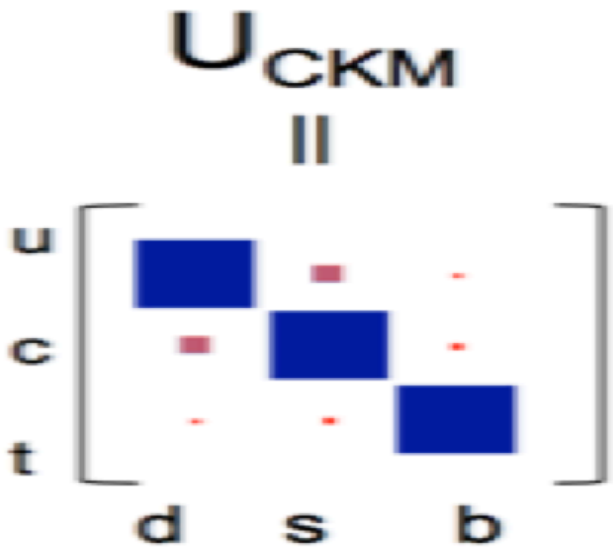
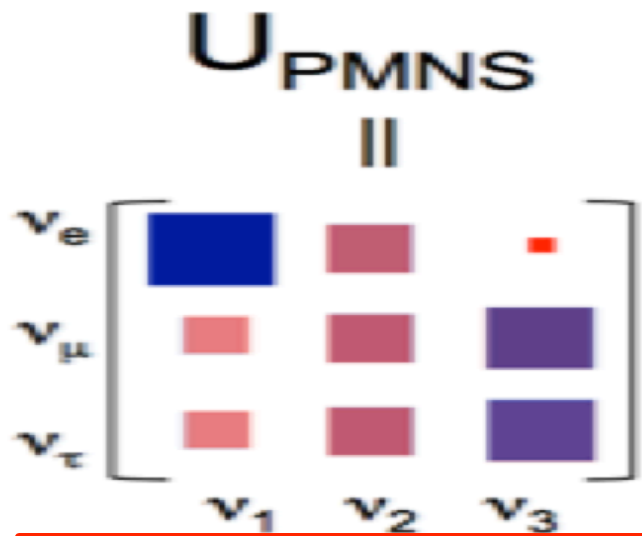




$$V_{CKM} \sim \begin{bmatrix} 0.976 & 0.22 & 0.004 \\ -0.22 & 0.98 & 0.04 \\ 0.007 & -0.04 & 1 \end{bmatrix}$$

$$U_{PMNS} \sim \begin{bmatrix} 0.85 & -0.54 & 0.16 \\ 0.33 & 0.62 & -0.72 \\ -0.40 & -0.59 & -0.70 \end{bmatrix}$$

- *Is this diverse pattern even compatible with quark-lepton unification inherent in GUTs?*

What is the gauge group and how predictive it is?

- SUSY SU(5): minimal version→ disfavored by p-decay, nu mass etc.

- Non-minimal version i.e. SUSY SU(5)+ν_R + extra Higgs: OK but typically too many parameters (with no extra symmetries) to be predictive.

GUT group SO(10): Just right for seesaw

- Two key ingredients of seesaw i.e.

  (a) right handed neutrino

  (b) B-L symmetry

- Both are automatic in SO(10) unification:

(Georgi; Fritzsch, Minkowski'74)

- $\boxed{SO(10) \supset B - L}$
- Fundamental {16}- rep

$$\begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_{L,R}$$

$$\supset \text{SM} \quad \text{fermions} + \nu_R$$

SUSY not essential for coupling unif. in SO(10)

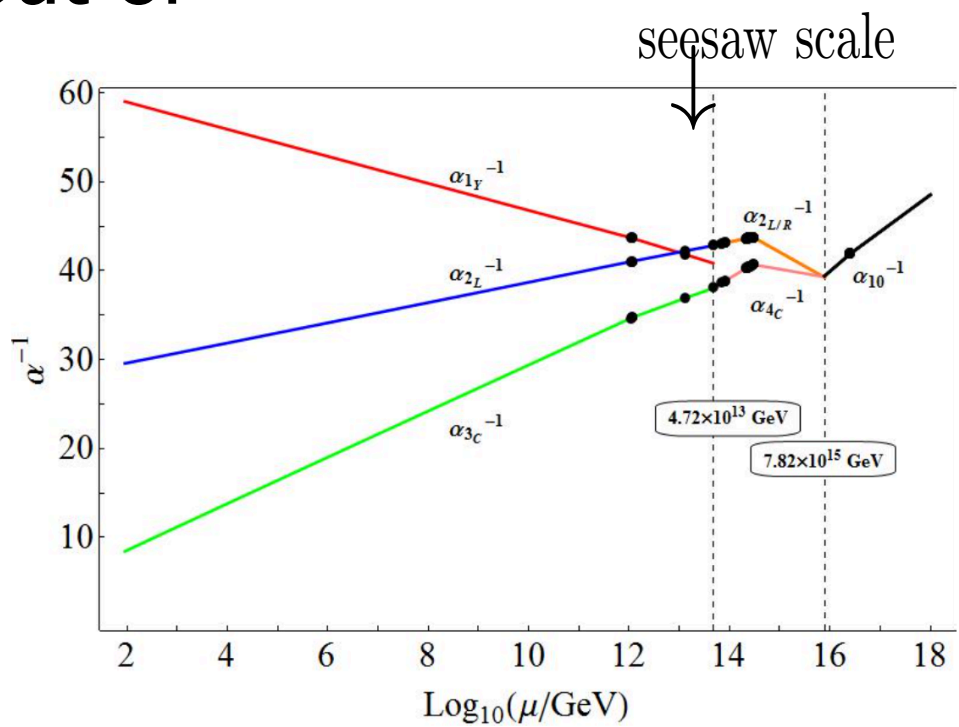
- Non-SUSY SO(10) unification→ correct $\sin^2\theta_W$

(Chang, RNM, parida'83; Chang, RNM,Parida,Gipson,Marshak'85; Deshpande, Keith, Pal'93; RNM, Parida'93; Bertolini, diLuzio, Malinsky'09;Altarelli, Meloni'13)

- Predicts seesaw scale out of 2-step unification
- p-decay signal

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

(Babu, Khan'2015)



Understanding quark-lepton flavor in SO(10)

- Two challenges:
- (i) Fitting challenge due to constraints of quark-lepton unification
- (ii) Deeper understanding of fits (symmetries)

Seesaw helps in the first challenge

- Quark masses out of Higgs vev:

$$m_Q = y_Q v_{wk}$$

- Neutrino mass out of seesaw:

$$m_\nu \simeq m_{\nu^D} M_N^{-1} m_{\nu_D}^T$$

- Unification relates only m_{ν_D} and m_Q whereas M_N flavor structure "independent"; making diverse mixings plausible !!

Two classes of GUT models for diverse flavor patterns

- Minimal SO(10) models without flavor sym. Can meet the first challenge

- Models with flavor symmetries in the hope for a deeper understanding $SO(10) \times G_F$

Minimal SO(10) SUSY GUT without flavor symmetry

- Scenario: SO(10) → MSSM → SM
  or SO(10)x$U(1)_{PQ}$ → SM (no susy)

- Minimal renormalizable models with 10+126-Higgs predictive for nu masses and mixings in terms of quark masses:
- Only two Yukawa matrices+vevs→ 11 real parameters and 7 phases.

(Babu, RNM'93)

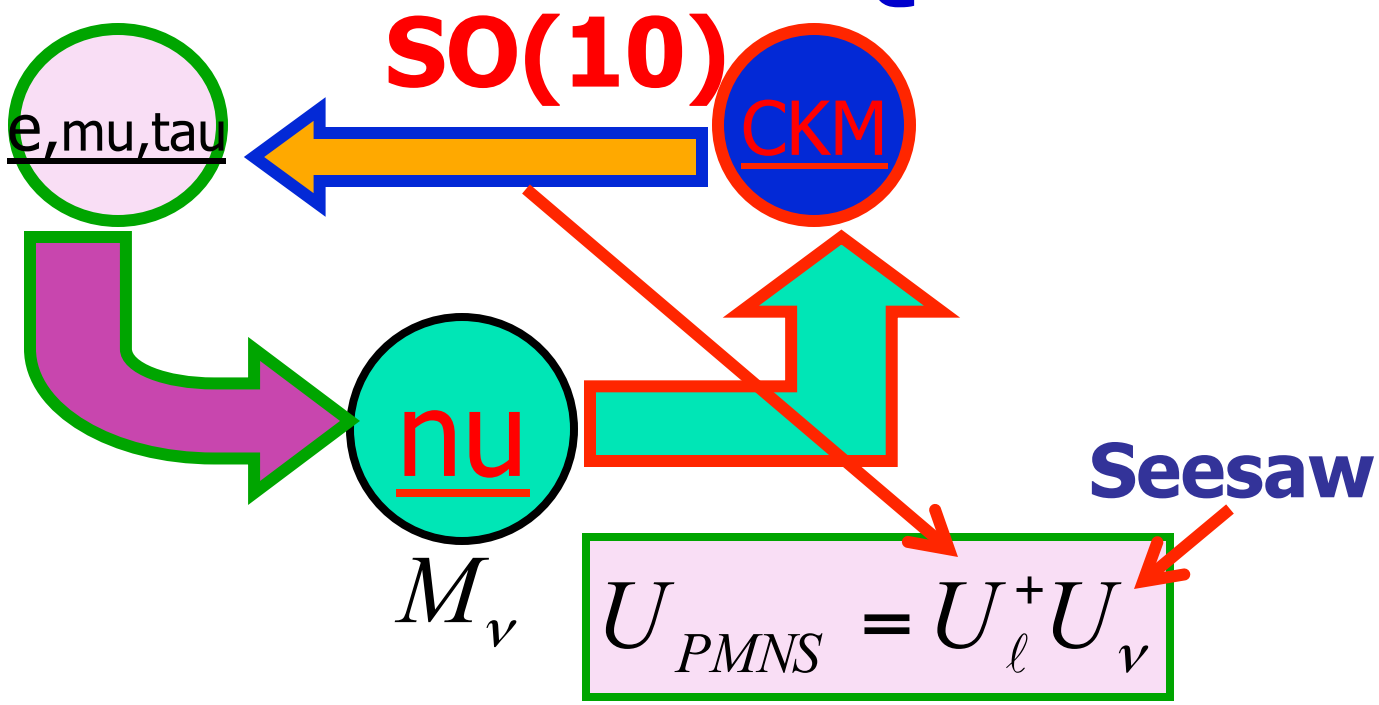
Flavor in minimal SO(10): 10+126

- $$M_u = hv_u + f\kappa_u; \quad M_d = hv_d + f\kappa_d;$$
  $$M_\nu^D = hv_u - 3f\kappa_u; \quad M_l = hv_d - 3f\kappa_d;$$
  $$\boxed{\mathcal{M}_\nu = fv_L - M_\nu^D \frac{1}{fv_R} M_\nu^D} \quad ; \quad f = \frac{1}{4\kappa_d}(M_d - M_\ell)$$
- in GUTs $m_b(M_U) \simeq m_\tau(M_U)$ endows $\mathcal{M}_\nu$ with different flavor structure compared to $M_{u,e,d}$ and leads to maximal θ_{23} . (Bajc, Senjanovic,Vissani'2003)

(Fukuyama, Okada'02; Goh, RNM, Ng'03; Babu, Macesanu'05; Bertolini, Frigerio, Malinsky'04; Bertolini, Malinsky, Schwetz'06; Dutta, Mimura, RNM'07, Grimus, Kubock'07; Aulakh, Garg'05; Joshipura, Patel'11; Dueck, Rodejohann'13; Fukuyama, Ichikawa, Mimura'16; Babu,Bajc,Saad'16)

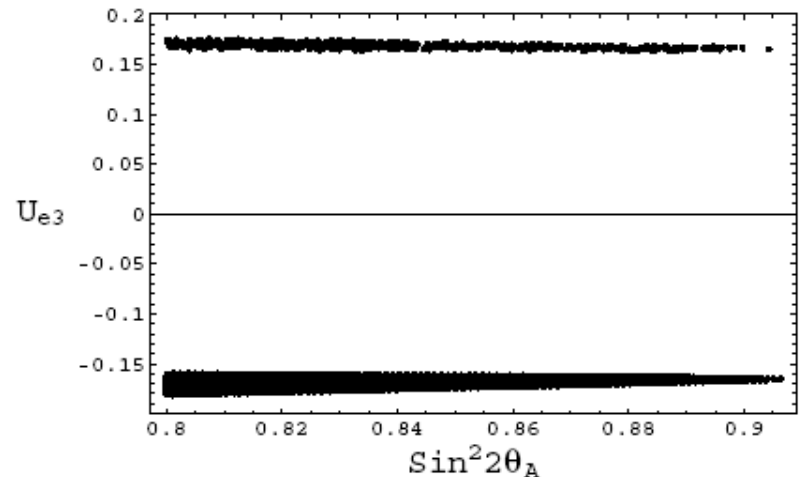
Lepton-quark interplay in renormalizable SO(10)

- **Leptons** **Quarks**



Successes of renormalizable SUSY SO(10)

- Works quantitatively: (10+126)
- *Predicts normal hierarchy*:



- ★ θ_{12}, θ_{23} large
- ★ $\theta_{13} \approx \lambda$ "large" (Goh, RNM, Ng, 03 ; Babu, Macesanu'05)
  - $\theta_{13} \cong 0.15$
- ★ $\dfrac{m_{solar}}{m_{atmos}} \sim \lambda$

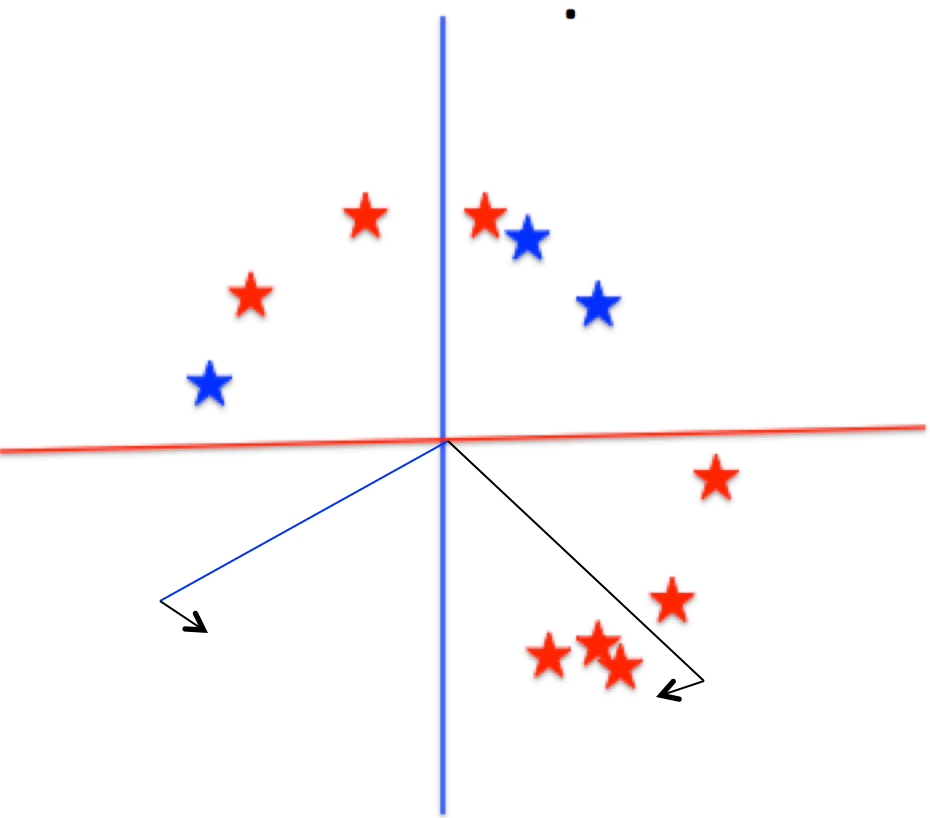
Also predictive and works for non-susy SO(10)+U(1)$_{PQ}$!

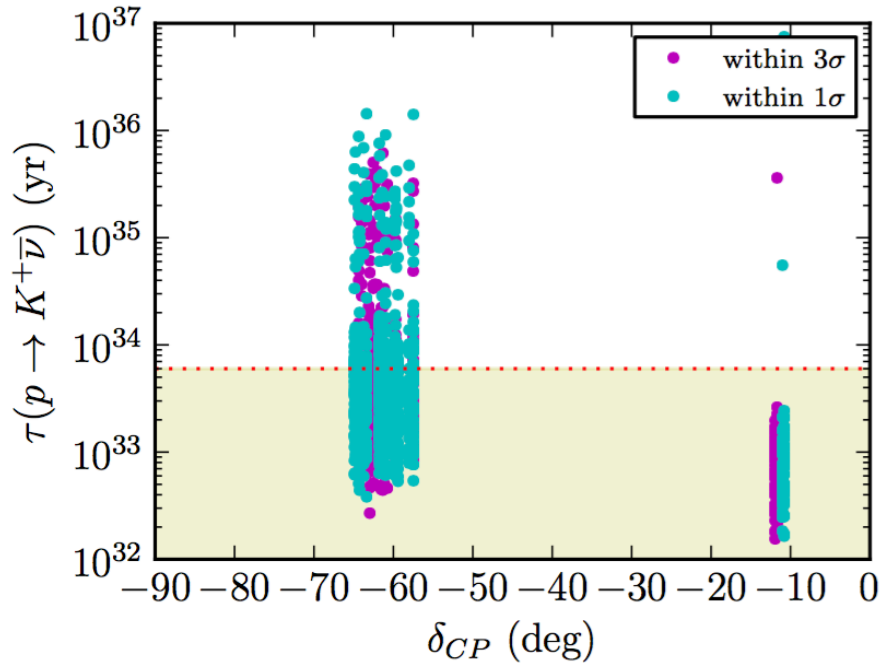
Testing minimal SO(10)

- $\mu \rightarrow e + \gamma$ (tests only susy seesaw)
- <u>Proton decay tests:</u>
- $p \rightarrow e^+ \pi^0$ has B-L=0: does not test seesaw but only GUTs
- In SUSY models, p-decay $p \rightarrow K^+ \bar{\nu}$ connected to neutrino mixings and hence can test seesaw.
- In 10+126 models, p-decay is a challenge
- 10+126+120 works better for p-decay

(Dutta, Mimura, RNM'05; Severson'15)

δ_{CP} in SO(10)





δ_{CP} VS τ_p (10+126+120)

(preliminary) (w/Severson'17)

Ruling out simple 2-step SO(10)

- Inverted mass ordering will "rule out" simple 2-step SO(10);

- Normal mass ordering + evidence for non-zero $\beta\beta_{0\nu}$ at current sensitivity will also rule out two step SO(10): possibly TeV W_R effect→will be profound→neutrino mass, a TeV scale physics !

Beyond minimal GUTs: GUTs+ Flavor symmetries:

- Quark lepton fits in GUTs (and in other models) require certain choice of Yukawa couplings:
- Can we have a deeper understanding of the needed pattern of Yukawas?
- Perhaps symmetries can help! The vacuum alignment in flavor Higgs may explain Yukawas!

Some Tell-tale hints for symmetries

- . $\theta_{23} \sim \pi/4$→ S_2 symmetry between mu- tau
- Tribimaximal mixing (Wolfenstein; Harrison, Perkins,Scott; Xing; He, Zee)

$$U_{\rm TB} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

S_3 S_4, A_4 ?

- But $\theta_{13} \neq 0$ and $\theta_{23} \neq \pi/4$→ TBM ruled out
- Does it mean symmetries not relevant? No.
- TBM could be leading order + symmetry breaking?

Symmetries at play

- . Flavor symmetries of SM for vanishing Yukawa

$$SU(3)_Q \times SU(3)_u \times SU(3)_d \times SU(3)_\ell \times SU(3)_e \times SU(3)_\nu$$

- Discrete subgroups of SU(3) major ones at play:
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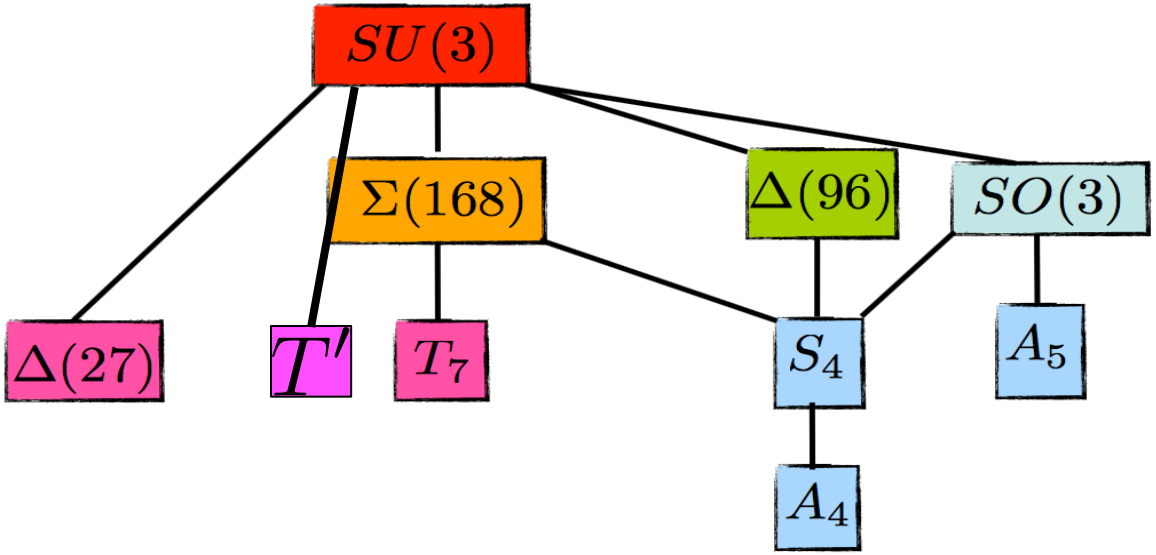


Two approaches: GUT plus symmetries

- SU(5)+ν_R: T′; S_4; A_4 ; A_5

  symmetries make them predictive!!

(Chen, Mahanthappa, Wijanco; King, Dimou, Luhn; King, Bjorkenroth, de Anda,Varzielas; Altarelli, Hagedorn,Feruglio; Gehrlein,Opperman, Schafer,Spinrath; Chen,Fallbacher, Mahanthappa ,Ratz, Trautner; Antusch, Maurer, Gross and Sluka;..)

- SO(10) x (S_4 ; $\Delta(27)$; T_7; ..)

(Dutta, Mimura, RNM, Dev, Severson; King, Luhn; Hagedorn, Smirnov. Schmidt; ….)

- Typically correlate different mixing parameters!

- (Parallel talks: Wegman; Rasmussen, Franklin, Loschner,)

Discrete Flavor Symmetry broken: More ambitious

- G_f (Ma, Rajasekaran; Babu, Ma, Valle; Blum, Hagedorn, Lindner; Lam; King, Luhn, Stuart; Everett, Garon, Stuart; Chen, Ratz, Fallbacher, Ohmura, Staudt. Hernandez,Smirnov.)

$$G_e \qquad\qquad G_\nu = Z_2 \times Z_2$$

$$\Omega_e \qquad\qquad \Omega_\nu$$

- Leptons are 3 of G_f
- $U_{PMNS} = \Omega_e^\dagger \Omega_\nu$ determined only by group th.
- Nontrivial to model. Vacuum must align right?

Flavorized CP and δ_{CP}

$$G_f \rtimes CP$$

$$G_e \rtimes CP \qquad\qquad G_\nu = Z_2 \times Z_2 \rtimes CP$$

$$X^T \mathcal{M}_\nu X = \mathcal{M}_\nu^* \qquad Y^\dagger \mathcal{M}_e \mathcal{M}_e^\dagger Y = (\mathcal{M}_e \mathcal{M}_e^\dagger)^*$$

- Leads to predictions for δ_{CP} (sometimes $\pm\frac{\pi}{2}$)

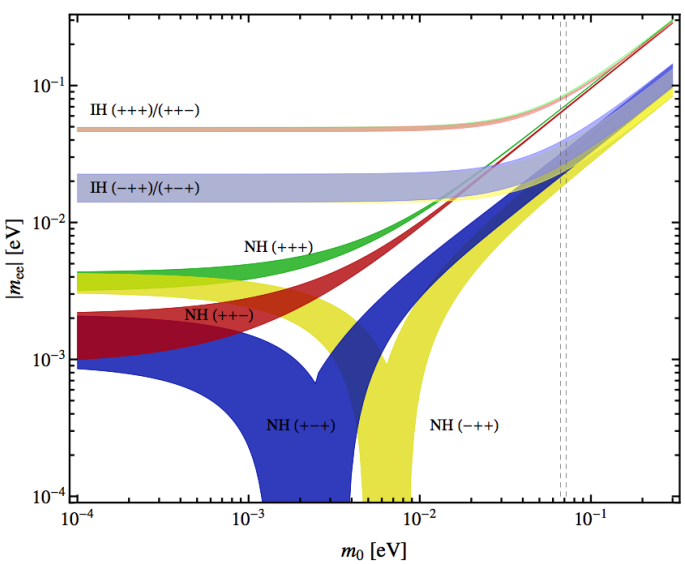
(Grimus, Lavour'03a; RNM, Nishi'12; Holthausen et al; Hagedorn et al; Chen, et al; Everett et al, ...)

- Current analyses: $\delta_{CP} = (261^{+51}_{-59})^\circ \quad (1\sigma)$ (Esteban et al'16)

Symmetries have consequences (i) $\beta\beta_{0\nu}$ as an example

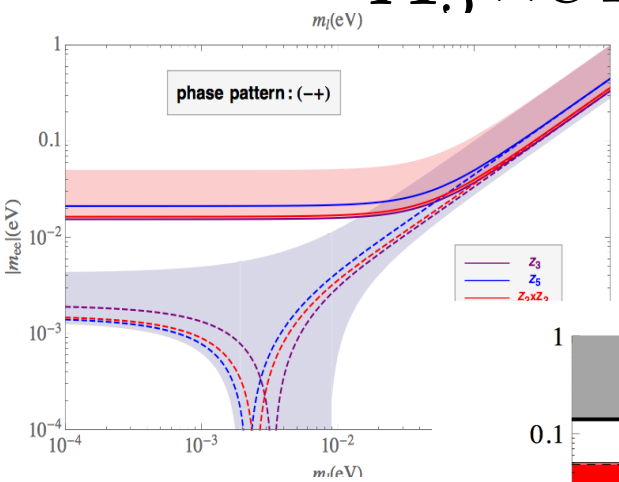
$$m_{\beta\beta} = \left| |m_1| U_{11}^2 + |m_2| U_{12}^2 e^{-i\alpha_2} + |m_3| U_{13}^2 e^{-i\alpha_3} \right|$$

$CP^{\mu\tau}$



(RNM,Nishi)

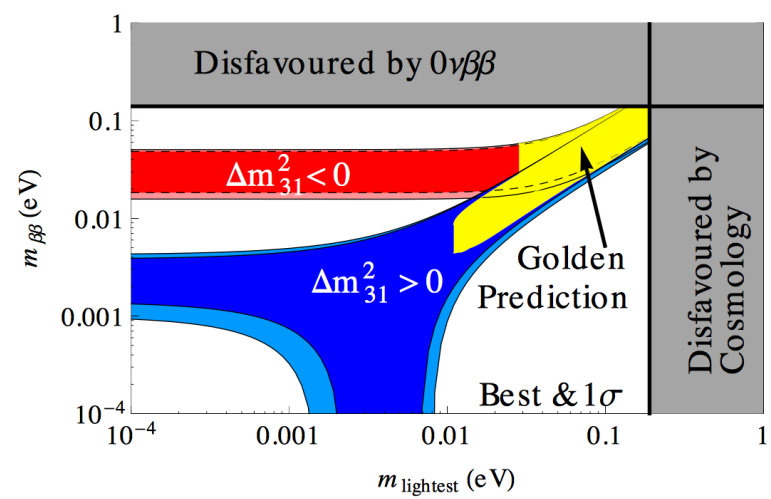
$A_5 \times CP$



(Ballet et al)

(Cooper, King, Stuart)

A_5



(ii) Symmetries affect leptogenesis

- A major selling point of seesaw is leptogenesis; due to ν_R-decay in early universe (Fukugita, Yanagida'86)

$$\Gamma(\nu_R \to L + H) - \Gamma(\nu_R \to \bar{L} + \bar{H}) \propto \epsilon_l$$

- Sphalerons take leptons to baryons (Kuzmin, Rubakov,Shaposnikov)
- Primordial CP asymmetry in leptogenesis models:

$$\epsilon_l \propto \mathrm{Im}\left((m_D^\dagger m_D)^2_{ij}\right)$$

- Flavor symmetries constrain the structure of m_D → hence affect leptogenesis.

Some illustrative examples

- Type I seesaw models: $\epsilon_l \propto (\Delta m_A^2 + b\Delta m_\odot^2)$
- Impose $\mu \leftrightarrow \tau$ sym $\epsilon_l \propto \Delta m_\odot^2$
- Instead impose $\mathrm{CP}^{\mu\tau}$ or $A_4 \rightarrow \epsilon_l = 0$

- How to solve the problem?

(i) Add flavor breaking: $Y_D = y_0\, \mathbb{I} + \delta Y_D + \ldots$

(imposes constraints on mixings)

(ii) Use flavored leptogenesis - specific RHN hierarchy

(Grimus, Lavoura'04; RNM, Nasri, Yu'05; Jenkins, Manohar'08;RNM, Nishi'12; Bertuzzo, diBari,Feruglio,Nardi'09; Chen, Ding,King; Hagedorn, Molinaro, Petcov'16;'17)

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Summary

- Grand unification: an elegant idea for BSM physics with high promise for predictivity!
- Minimal SO(10) models just right and predictive for neutrino seesaw and explain observations.
- Key test is proton decay. SUSY SO(10) relates p-decay to nu mixings and CP phase.
- Understanding flavor a challenge! Symmetries likely to help! Stay tuned ! Some symmetry models testable in $\beta\beta_{0\nu}$ decay and Dirac CPV.

Bottom line for experiments

- Inverted hierarchy will "rule out" GUTs !

- Normal mass ordering + evidence for non-zero $\beta\beta_{0\nu}$ at current sensitivity will rule out two step SO(10); perhaps →TeV W_R

- Eagerly waiting for measurement of δ_{CP} to narrow down the choice of models!

$Thank\ you\ for\ your\ attention\ !$