Neutrino mass and Grand unification

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Grand Unified Theories (GUTs): Elegant and ambitious

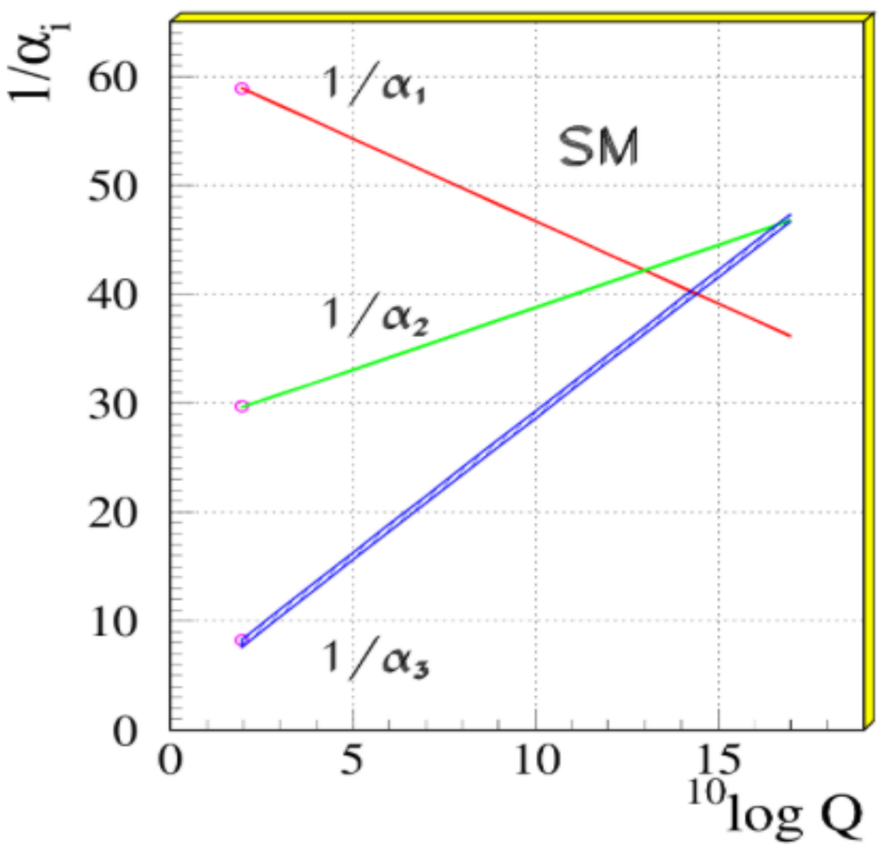
- Unifies all matter and forces
- Makes theory more predictive

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

(Pati, Salam; Georgi, Glashow)

Key ingredient: coupling unification ($g_1=g_2=g_3$)

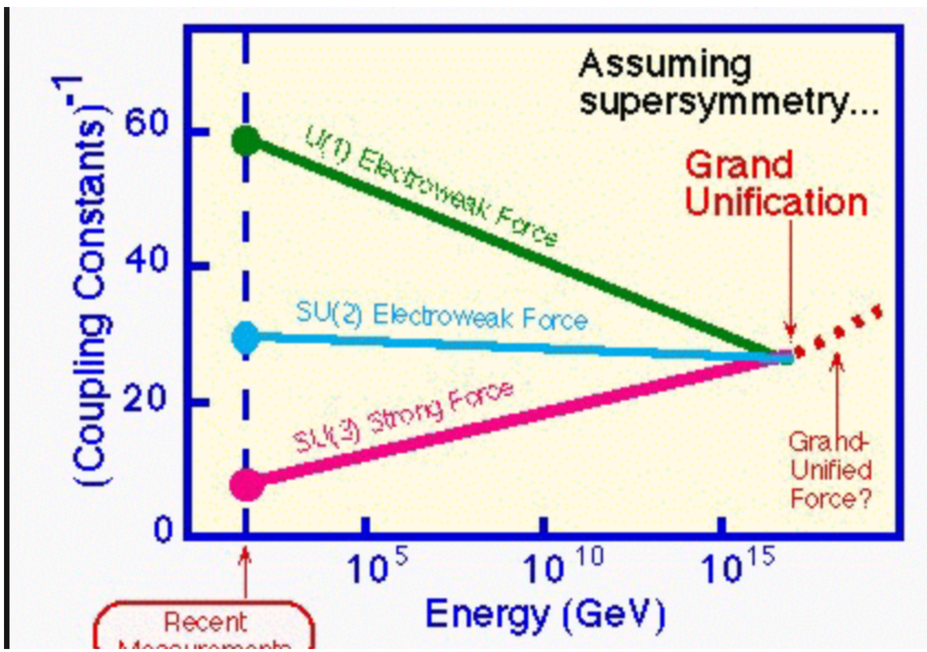
- Prospects in the standard model: g's run towards each other at shorter distances (Georgi, Quinn, Weinberg'74)



→ *But don't quite unify* suggesting possibly new physics below GUT scale

SUSY GUTs

- Couplings unify at scale ~10^{16} GeV with susy breaking at TeV required to solve gauge hierarchy problem

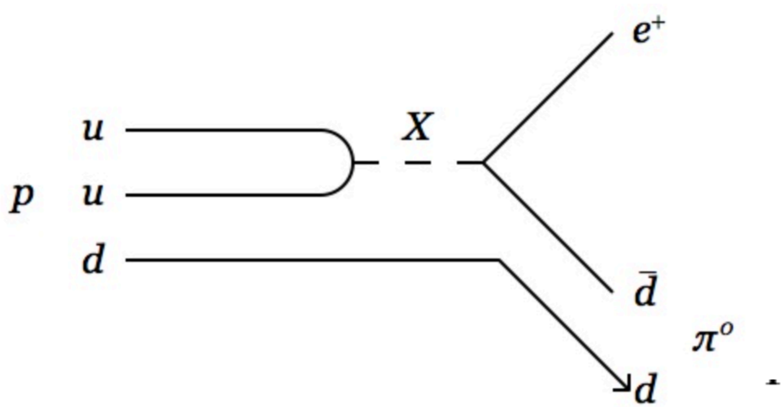


Dimopoulos, Raby, Wilczek’81; Ibanez, Ross’81

Where is SUSY?

Key prediction:proton decay

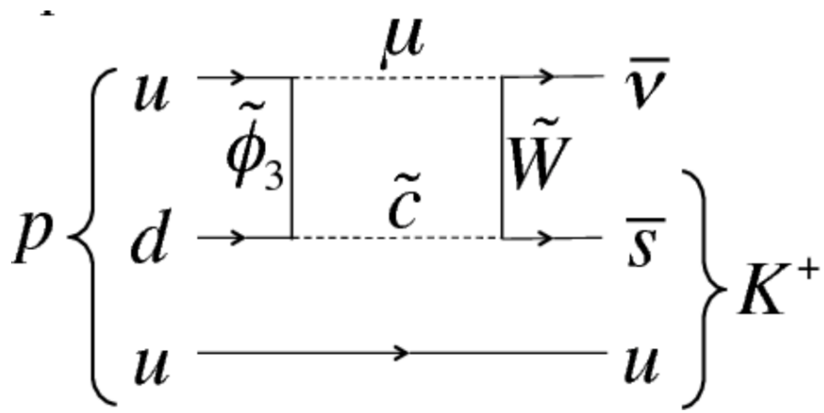
- GUT group→ Q-L unification→proton decay
- Non-SUSY GUTs $p \rightarrow e^+\pi^0$ (Reviews: Nath Perez)



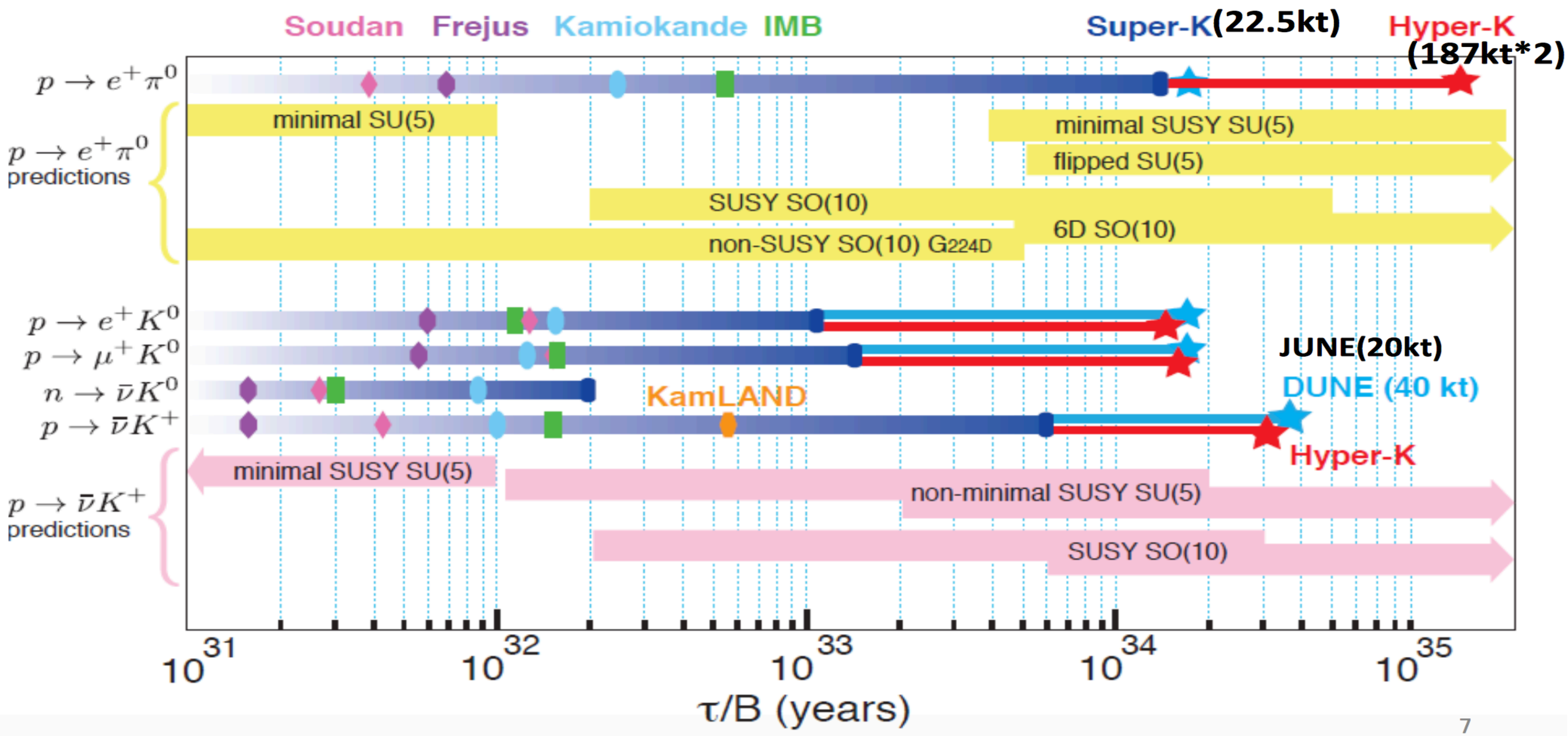
(True test of GUTs)

- SUSY GUTs

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



Current limits on proton life time



No sign of proton decay!

No SUSY, No proton decay; don’t need it to understand electric charge quantization;

Are GUT theories dead?

Neutrino masses may have provided new life to GUTs

Neutrino masses: 20 years ago (<1998)

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Neutrino masses and mixings now

NuFIT 3.2 (2018)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.14$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.272 \to 0.346$
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$	$31.42 \to 36.05$	$33.62^{+0.78}_{-0.76}$	$31.43 \to 36.06$	$31.42 \to 36.05$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.418 \to 0.613$	$0.554^{+0.023}_{-0.033}$	$0.435 \to 0.616$	$0.418 \to 0.613$
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.9}$	$40.3 \to 51.5$	$48.1^{+1.4}_{-1.9}$	$41.3 \to 51.7$	$40.3 \to 51.5$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.01981 \to 0.02436$	$0.02227^{+0.00074}_{-0.00074}$	$0.02006 \to 0.02452$	$0.01981 \to 0.02436$
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	$8.09 \to 8.98$	$8.58^{+0.14}_{-0.14}$	$8.14 \to 9.01$	$8.09 \to 8.98$
$\delta_{CP}/^\circ$	234^{+43}_{-31}	$144 \to 374$	278^{+26}_{-29}	$192 \to 354$	$144 \to 374$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$6.80 \to 8.02$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.494^{+0.033}_{-0.031}$	$+2.399 \to +2.593$	$-2.465^{+0.032}_{-0.031}$	$-2.562 \to -2.369$	$\begin{bmatrix} +2.399 \to +2.593 \\ -2.536 \to -2.395 \end{bmatrix}$

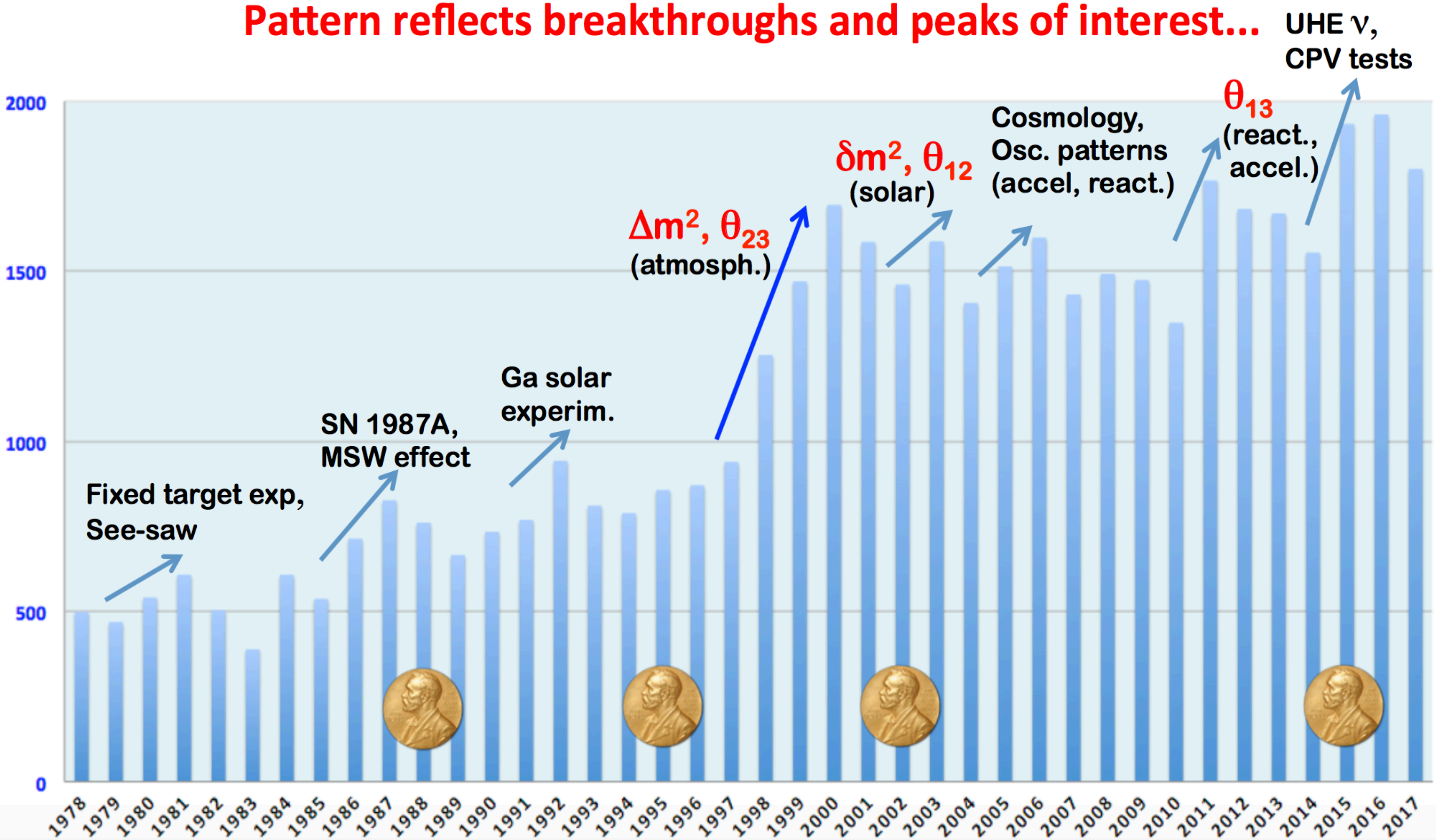
Cosmology $\sum m_\nu[\text{eV}] < 0.3 \quad (\text{EUCLID, LSST}) \to .02\ \text{eV}$

Neutrino activity

N. of #neutrino# preprints per year (1978-2018) from INSPIRE

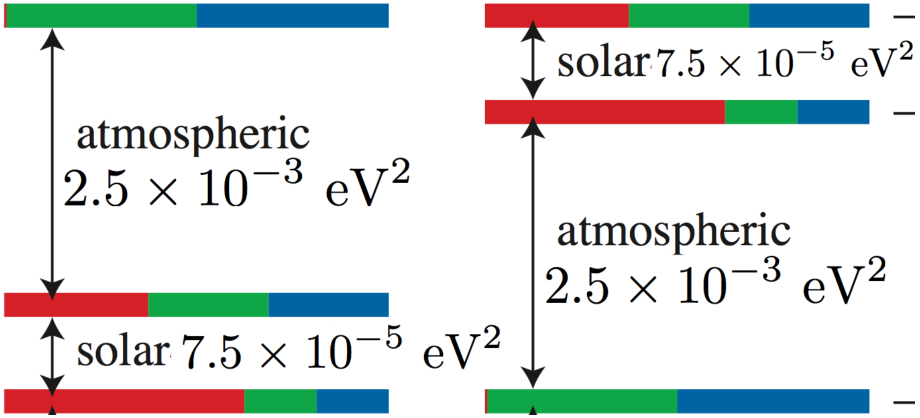
E. Lisi talk, Nu2018.

Pattern reflects breakthroughs and peaks of interest...



Things we do not know

- Mass ordering



- CP phase δ_{CP} (DUNE, T2K,..)
- Are there sterile neutrinos?
- Absolute scale $\sum m_\nu$ (EUCLID, LSST)
- Neutrinos Majorana or Dirac? $\beta\beta_{0\nu}$ Searches

Neutrino mass and revival of GUTs

- Two new puzzles from neutrino mass discovery

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

(ii) Lepton mixings very different from quarks: why?

Where does neutrino mass come from ?

- Charged fermion masses come from the Higgs vev:

$$m_f = h_f v_{wk} \qquad v_{wk} = < h^0 >$$

★ Discovery of the 125 GeV Higgs h^0 confirms this.

Where does neutrino mass come from ?

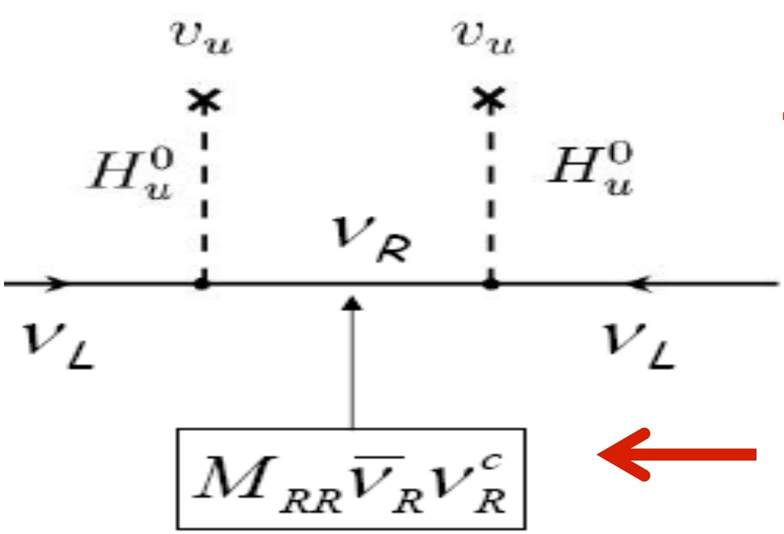
- To get neutrino mass, we can simply add the right handed neutrino ν_R to SM and use the same mechanism as for other fermions to get a Dirac mass.

- However, we get too large mass unless $h_\nu \leq 10^{-12}$

- **We need to go beyond!**

Seesaw paradigm for neutrino mass and GUTs

- SM+ RH neutrinos ν_R but with heavy Majorana mass



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

Breaks B-L

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

- ν_R *and B-L two essential ingredients of seesaw*

A Major plus for seesaw

- It has built in mechanism for explaining the observed matter-anti-matter asymmetry of the universe:

$$\epsilon_\ell = \frac{\Gamma(N \to \ell + H) - \Gamma(N \to \bar{\ell} + \bar{H})}{\Gamma(N \to \ell + H) + \Gamma(N \to \bar{\ell} + \bar{H})}$$

- Lepton asymmetry gets converted to baryons by the SM sphalerons; (Fukugita and Yanagida'86)

What is the seesaw scale?

- Two classes of models where the key ingredients of seesaw i.e. Right handed neutrino and B-L symmetry are automatic.
- (i) Left-right symmetric models: the scale can be anywhere from a few TeV to very high.
- (ii) SO(10)- seesaw scale near GUT scale.
- Leptogenesis works in both cases!!

Seesaw and GUTs

- SO(10) theories generally predicts

$\rightarrow$ $m_{D33} \sim m_t$

+ Seesaw formula $m_\nu \simeq -\frac{m_D^2}{M_{\nu_R}}$ $\rightarrow$ $M_{\nu_R} \sim 10^{14}\ \mathrm{GeV}$

$M_U \sim 10^{16}$ GeV

- Fits naturally into GUT framework : $M_{\nu_R} \sim M_U$

GUT symmetry just right for seesaw: SO(10)

- {16}- spinor of SO(10)

$$\{16\} = \boxed{\begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_{L,R}}$$

$$\boxed{\supset \mathrm{SM\ fermions} + \mathrm{N_R}}$$

- SO(10) contains B-L as a subgroup

Flavor: a challenge for GUTs

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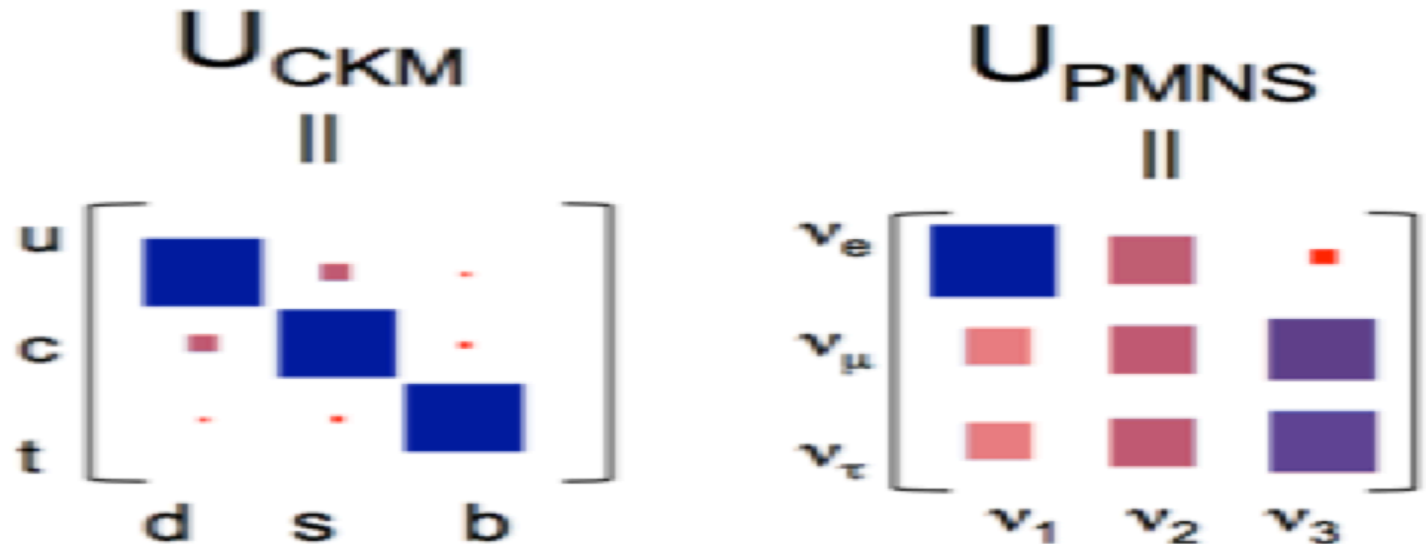


$$V_{CKM} \sim \begin{bmatrix} 0.976 & 0.22 & 0.004 \\ -0.22 & 0.98 & 0.04 \\ 0.007 & -0.04 & 1 \end{bmatrix}$$

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

- *If quarks and leptons are similar, how to explain this diversity?*

A Simple SO(10) set-up to address the flavor issue

$$16_f \times 16_f = 10_H + 126_H + 120_H$$

- Minimal models 10+126-Higgs (Babu, RNM'92)

$$W = h\psi\psi H + f\psi\psi\bar{\Delta}$$

- Slightly generalized:

  10+126+120+CP (# param=17)

  (Dutta, Mimura, RNM'05; Bertolini,Frigerio,Malinsky'05)

$$W = h\psi\psi H + f\psi\psi\bar{\Delta} + g\psi\psi\Sigma$$

- Lead naturally to DM without extra assumptions

Explaining lepton-quark Flavor diversity:10+126

- . $$\mathcal{M}_\nu = f v_L - M_d \frac{1}{f v_R} M_d$$

- $$; \quad f = \frac{1}{4\kappa_d}(M_d - M_\ell)$$

- 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 provides a way to understand diverse quark-leptons flavor patterns: (Bajc, Senjanovic,Vissani'2003)

How does it work?

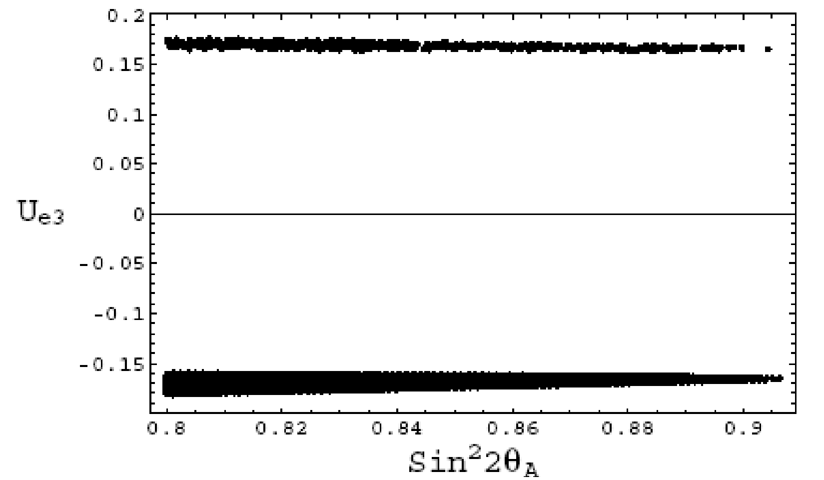
- 2 gen; if f- dominates $\mathcal{M}_\nu = c(M_d - M_\ell)$

$$M_d = m_b \begin{pmatrix} \sim\lambda^2 & \sim\lambda^2 \\ \sim\lambda^2 & 1 \end{pmatrix} \quad M_\ell = m_\tau \begin{pmatrix} a_1\lambda^2 & a_2\lambda^2 \\ a_2\lambda^2 & 1 \end{pmatrix}$$

- At GUT scale $m_b \simeq m_\tau(1+\lambda^2)$
- Then $\mathcal{M})_\nu = \begin{pmatrix} a'\lambda^2 & b'\lambda^2 \\ b'\lambda^2 & \lambda^2 \end{pmatrix}$
- $a_1, a_2, a', b' \sim 1$→ large θ_{23}natural; easily extends to 3 generation case

Three gen. extension

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



- ★ θ_{12}, θ_{23} large
- ★ $\theta_{13} \approx \lambda$ "large" (Goh, RNM, Ng, 03 ; Babu, Macesanu'05)

★ $\frac{m_{solar}}{m_{atmos}} \sim \lambda$

- $\theta_{13} \cong 0.15$

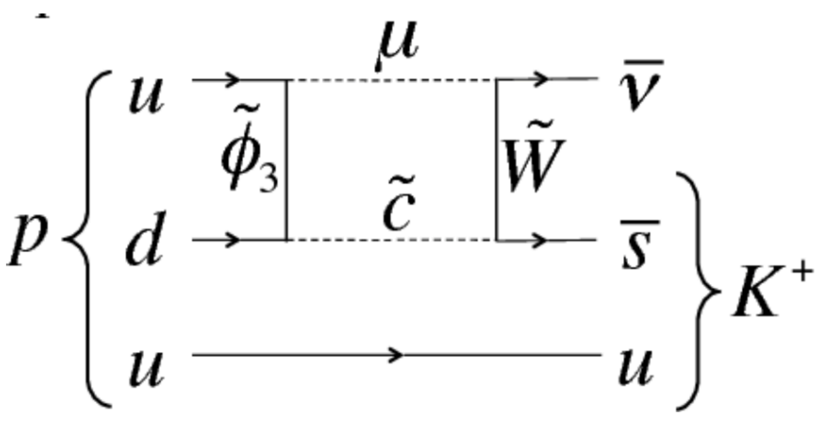
$$\mathrm{Expt} : \theta_{13} = 0.14 - 0.156$$

(Fukuyama, Okada; Babu, Macesanu; Bertolini, Malinsky, Schwetz'; Dutta, Mimura, RNM', Grimus, Kubock'; Aulakh, Garg; Joshipura, patell; Dueck, Rodejohann; Fukuyama, Ichikawa, Mimura; Babu,Bajc,Saad)

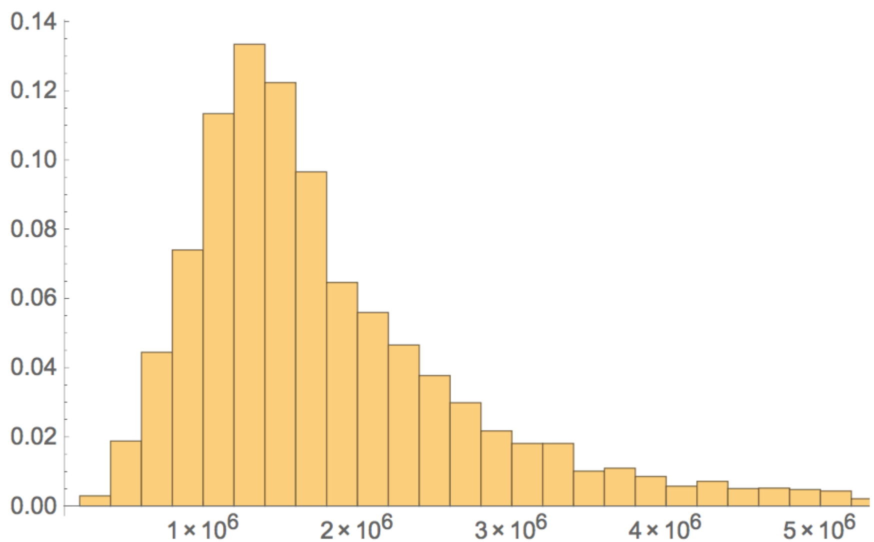
Proton decay in SUSY GUTs

- In Non-SUSY models, $p \to e^+\pi^0$ dominates – does not test seesaw but a key test of GUTs

- In SUSY models, p-decay $p \to K^+\bar{\nu}$ connected to neutrino mixings and hence can test seesaw



What does proton decay say about these models?

- 10+126 model has tension with p-decay – specially RRRR operators troublesome:
  $p \to K^+ + \bar{\nu}_\tau$ rate $\propto (\tan\beta)^2$
- 

  $M_{susy} > 232$ TeV

  (Babu, Bajc, Saad'18)
- What if susy is discovered at lower scale?

SO(10) model with 10+126+120 works better

- In 10+126 models all Yukawas fixed by fermion mass fits, which leads to p-decay tension.
- On the other hand in models with 120, one can choose textures to suppress proton decay: e.g.

$$\tilde{h} = \begin{pmatrix} 0 & & \\ & 0 & \\ & & M \end{pmatrix}, \qquad \tilde{f} = \begin{pmatrix} \sim 0 & \sim 0 & f_{13} \\ \sim 0 & f_{22} & f_{23} \\ f_{13} & f_{23} & f_{33} \end{pmatrix}, \quad \tilde{g} = i \begin{pmatrix} 0 & g_{12} & g_{13} \\ -g_{12} & 0 & g_{23} \\ -g_{13} & -g_{23} & 0 \end{pmatrix}.$$

- P-decay bound OK with 3 TeV susy breaking!

(Dutta, Mimura, RNM'05)

Fermion mass fit and predictions

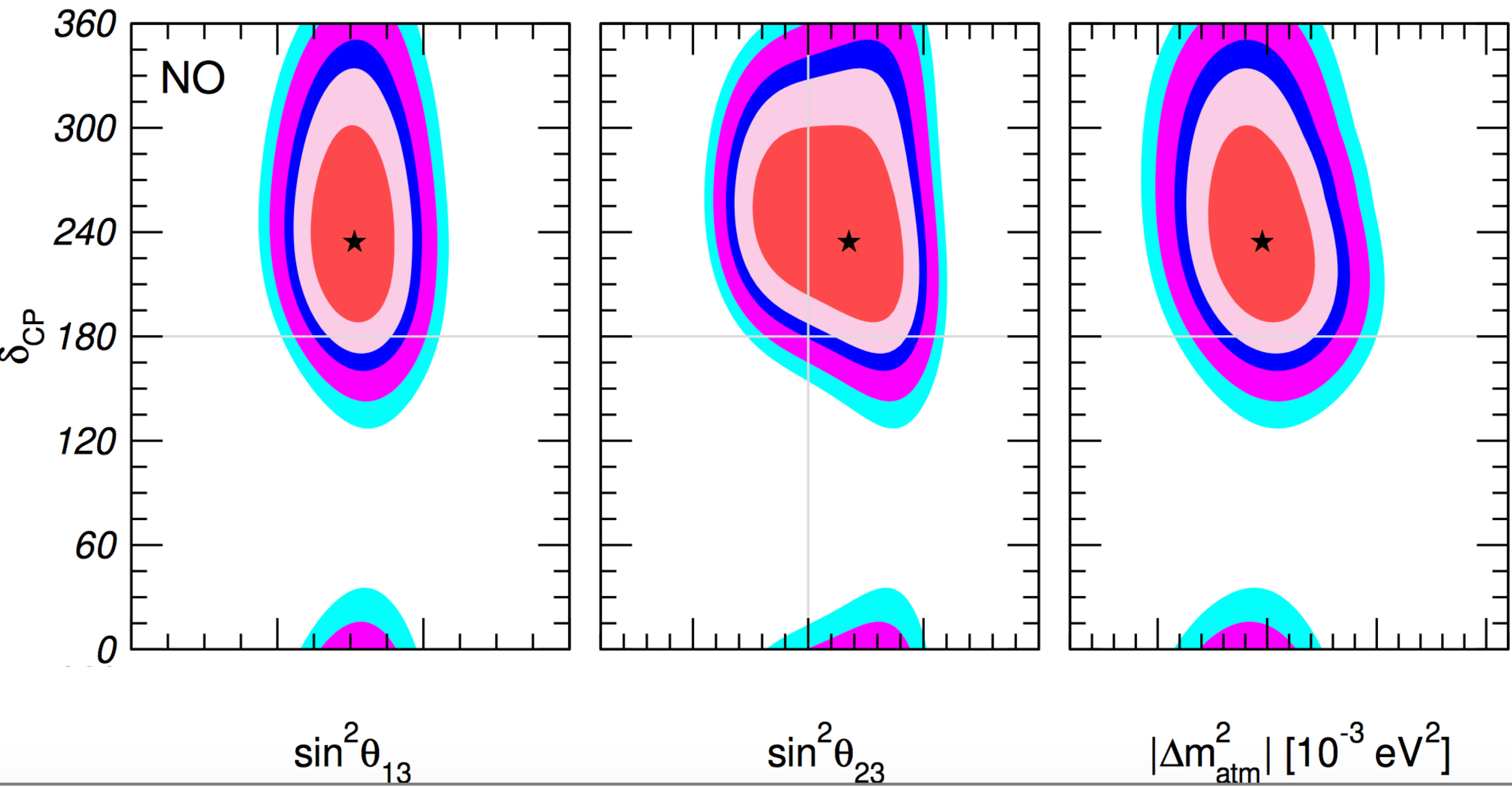
- Best fit values for neutrinos with large CP phase

	best fit	exp value		best fit	exp value
m_u (MeV)	0.7246	$0.72^{+0.12}_{-0.15}$	V_{us}	0.22427	0.2243 ± 0.0016
m_c (MeV)	208.6	$210.5^{+15.1}_{-21.2}$	V_{ub}	0.0030	0.0032 ± 0.0005
m_t (GeV)	80.113	$80.45^{+2.9}_{-2.6}{}^*$	V_{cb}	0.03497	0.0351 ± 0.0013
m_d (MeV)	1.515	$0.930 \pm 0.38^*$	$J \times 10^{-5}$	2.29	2.2 ± 0.6
m_s (MeV)	24.47	$17.6^{+4.9}_{-4.7}{}^*$	$\Delta m^2_{21}/\Delta m^2_{32}$	0.0308	0.0309 ± 0.0015
m_b (GeV)	1.311	$1.24 \pm 0.06^*$	θ_{13} (°)	9.397	8.88 ± 0.385
m_e (MeV)	0.3565	$0.3565^{+0.0002}_{-0.001}$	θ_{12} (°)	33.62	33.5 ± 0.8
m_μ (MeV)	75.297	$75.29^{+0.05}_{-0.19}$	θ_{23} (°)	43.79	44.1 ± 3.06
m_τ (GeV)	1.61	$1.63^{+0.04}_{-0.03}$	$\boldsymbol{\delta_{\mathrm{CP}}}$ (°)	**-67**	
			$\sum \chi^2$	3.16	

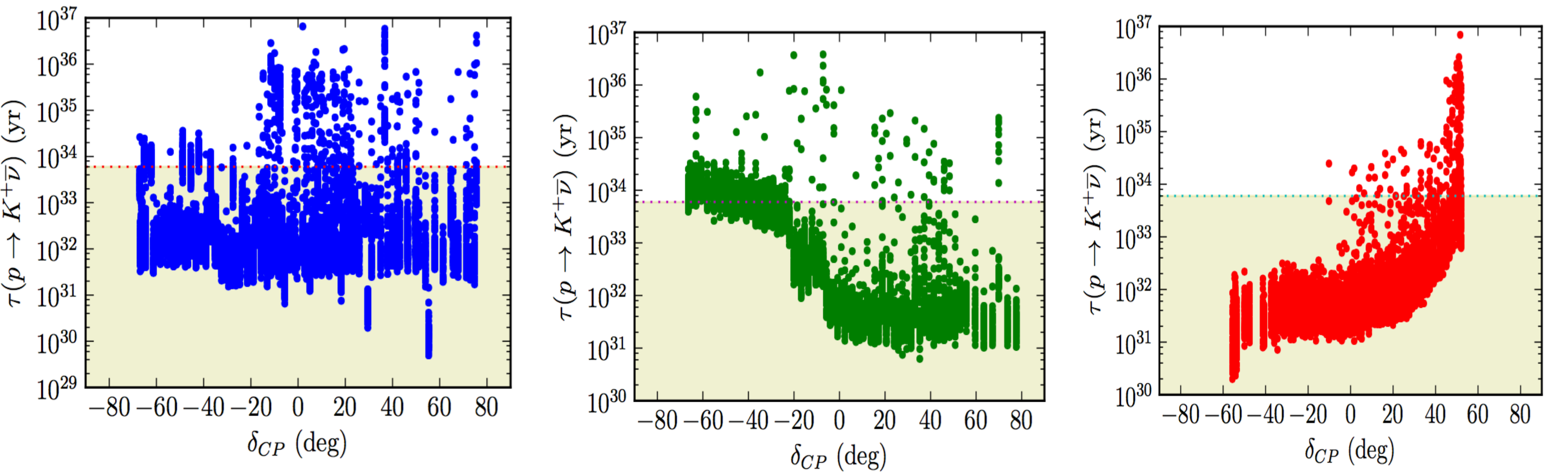
$$\sum m_\nu = .074 \text{ eV}$$

RNM and Severson'18

Nu-Fit 3.2 result for CP phase



proton life time and δ_{CP} correlation in SO(10)



δ_{CP} vs τ_p $\quad M_{SUSY} = 5$ TeV

- Can help to test these models (RNM,Severson'18)

SO(10) with 120 solves strong CP without axion

- Note that in 10+126+120 models $M_q = M_q^\dagger$
- → in the effective theory, $\theta = \mathrm{Arg\ Det\ M_q} = 0$
- Potential to solve the strong CP problem without the axion.
- Structure natural even in the presence of higher dimensional terms!!

Beyond Minimal SO(10)

- Add discrete symmetries to understand the Yukawa pattern.
- Embed in orbifold models in 5, 6 D to solve problems of GUTs e.g. doublet triplet splitting, less threshold effect etc
- Possibly eventually embed into string theories?

Broad message

- Grand unified theories are elegant.
- However, with no evidence for SUSY and proton decay, neutrino masses provide compelling theoretical reason for them.
- Important to search for seesaw scale (e.g. N_R, W_R etc) in colliders to test TeV vs GUT seesaw.
- Discovery of evidence for TeV scale seesaw will change thinking about GUTs.

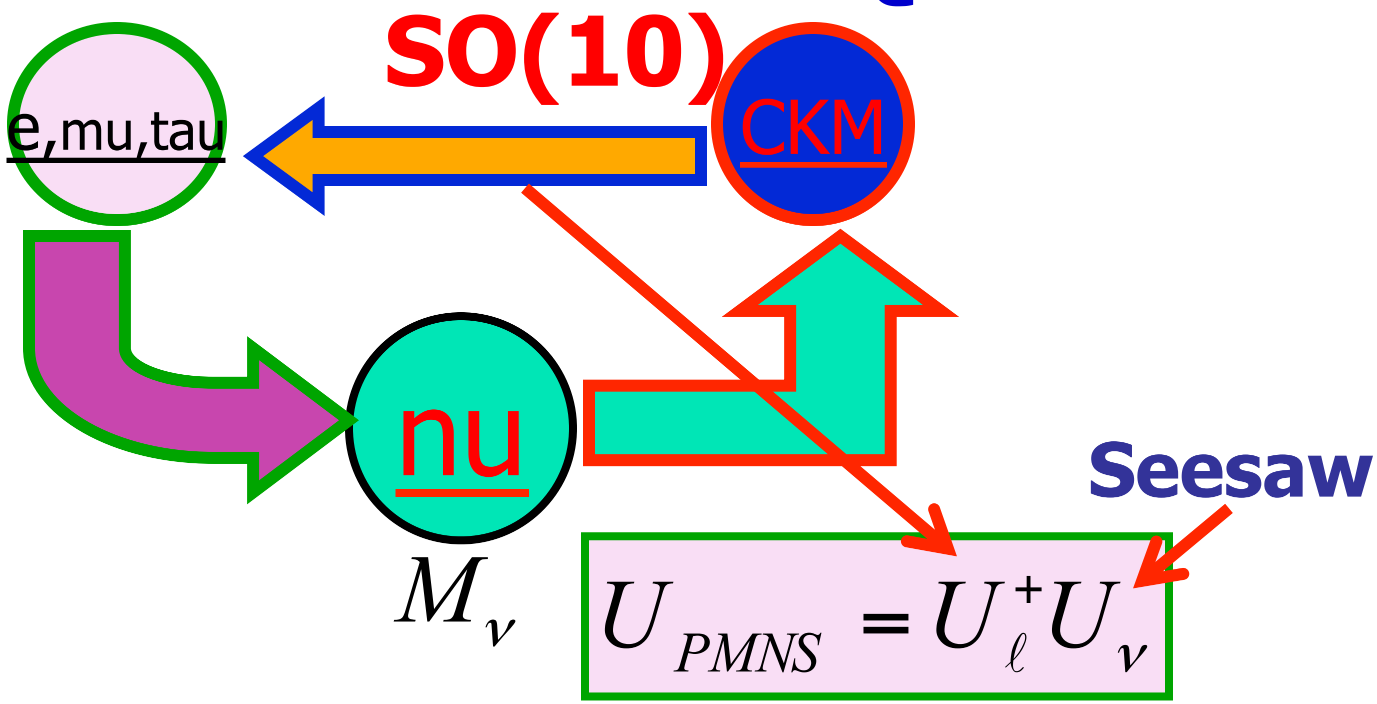
Broad message

- GUT theories have the advantage of being very predictive and therefore testable!
- Renormalizable SO(10) theory with a number of interesting properties, a serious candidate;
- They predicted correct θ_{13} prior to discovery;
- Explain matter-anti-matter asymmetry; dark matter of the universe; solve strong CP problem!
- Testable via link of proton decay to neutrino mixings and CP phase (~-30^0 to -70^0)

Thank you !

Lepton-quark interplay in SO(10)

- **Leptons** **Quarks**



Moving on to 3 generations

- M_d and M_l typical:

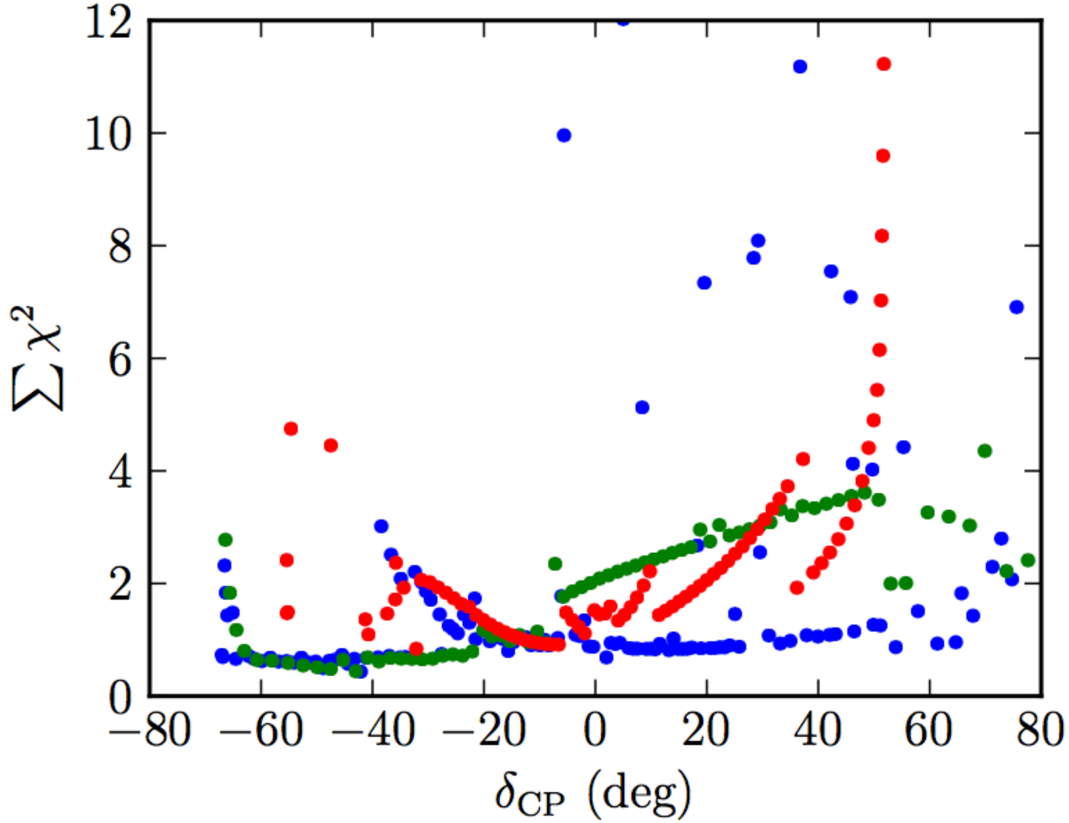
$$M_{d,\ell} \approx m_{b,\tau} \begin{pmatrix} \sim\lambda^4 & \sim\lambda^5 & \sim\lambda^3 \\ \sim\lambda^5 & \sim\lambda^2 & \sim\lambda^2 \\ \sim\lambda^3 & \sim\lambda^2 & 1 \end{pmatrix}$$

- b-tau unif at GUT scale→

$$M_\nu \;=\; c(M_d - M_\ell) \approx \; m_0 \begin{pmatrix} \lambda^4 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^2 & \lambda^2 \\ \lambda^3 & \lambda^2 & \lambda^2 \end{pmatrix}$$

- Atmospheric, solar, theta13, all large: (Goh, RNM, Ng'03)

CP phase prediction



$$\delta_{CP} = -67^0 \rightarrow +45^0$$

SO(10) to SM: Scale set up

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$$
\begin{array}{c}
SO(10) \\
\Big\downarrow {\scriptstyle M_U} \\
MSSM \\
\Big\downarrow {\scriptstyle TeV} \\
SM
\end{array}
$$