Theories of Neutrino Masses

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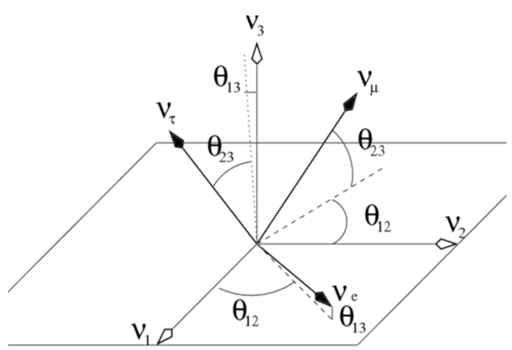
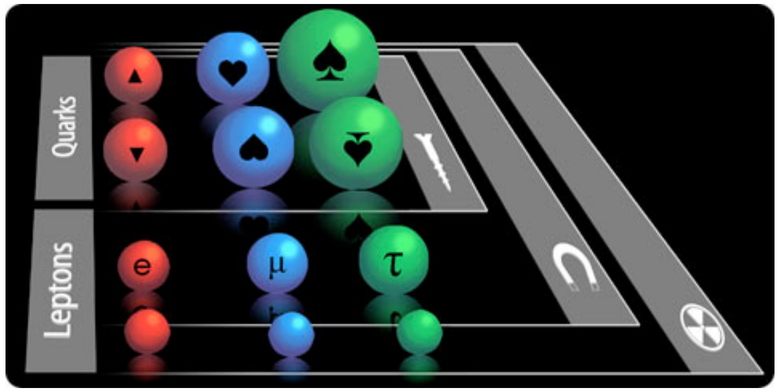
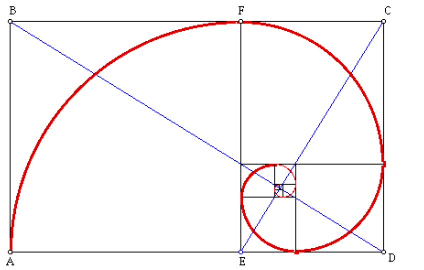
Neutrino 2018: XXVIII International Conference on Neutrino Physics and Astrophysics

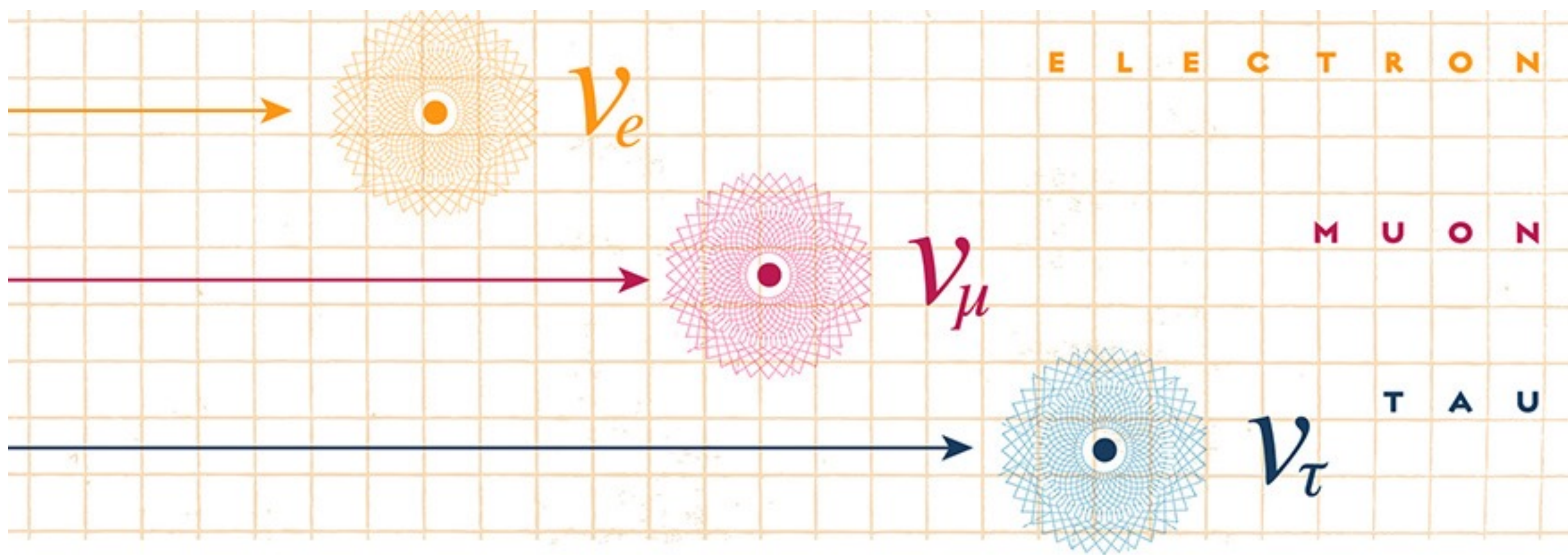




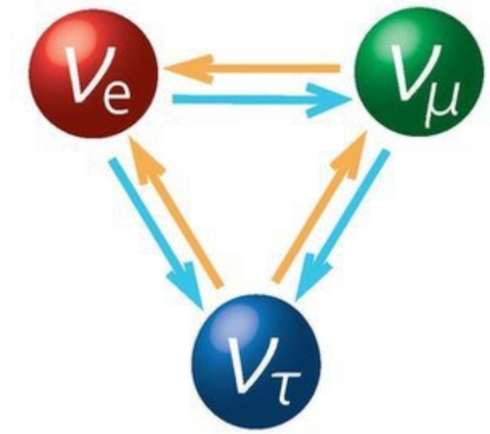


(image credits: Wikipedia, E. Palti)

A wealth of discoveries in neutrino physics since 1998…



(image credit: C. Wiens)



Some highlights:

1998: atmospheric ν_μ disappearance (SK)

2002: solar ν_e disappearance (SK)

2002: solar ν_e appear as ν_μ, ν_τ (SNO)

2004: reactor $\overline{\nu}_e$ oscillations (KamLAND)

2004: accelerator ν_μ disappearance (K2K)

2006: accelerator ν_μ disappearance (MINOS)

2011: accelerator ν_μ appear as ν_e (T2K,MINOS)

2012: reactor $\overline{\nu}_e$ disappear (Daya Bay, RENO)
reactor angle measured!

2014: hint for CP violation? (T2K)

2015: hints for normal hierarchy? (SK, T2K, NOvA)

2016: hint for non-maximal atm mixing? (NOvA)

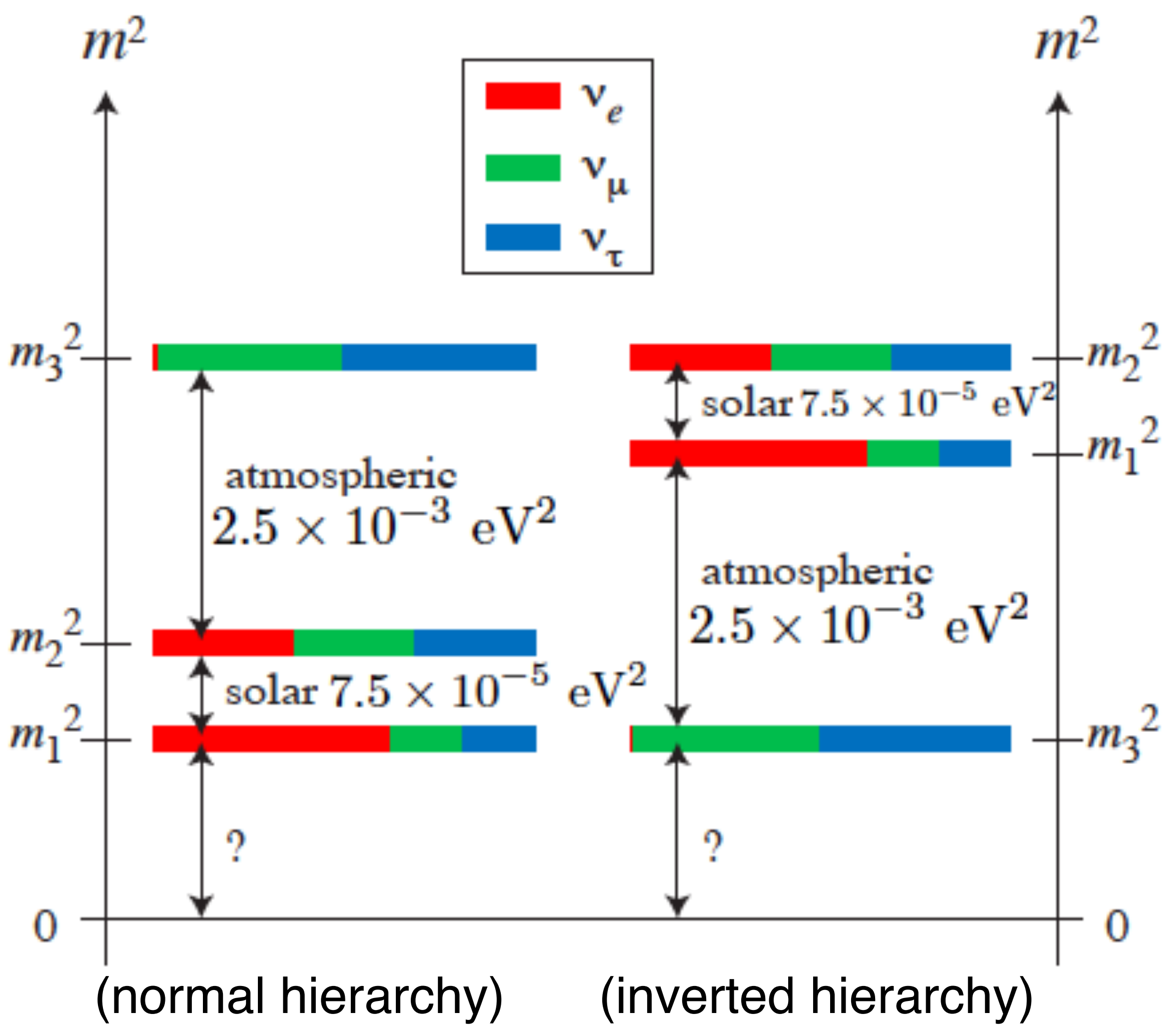
2018: trivial Dirac phase disfavored at 2σ (T2K)

…

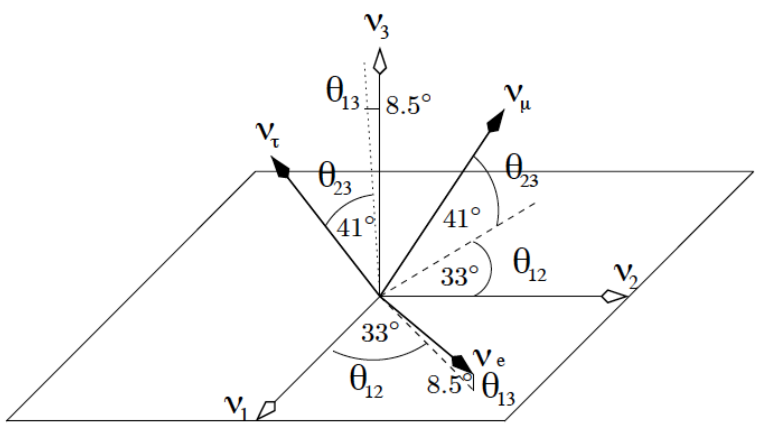
Signals physics beyond the Standard Model (SM)!

The emergent picture…

a (seemingly) robust 3-neutrino mixing scheme



(image credits: King, Luhn)



Global Fits:

Forero et al., '17 Capozzi et al.,'18
Gonzalez-Garcia et al., (www.nu-fit.org)

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
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.272 \to 0.346$
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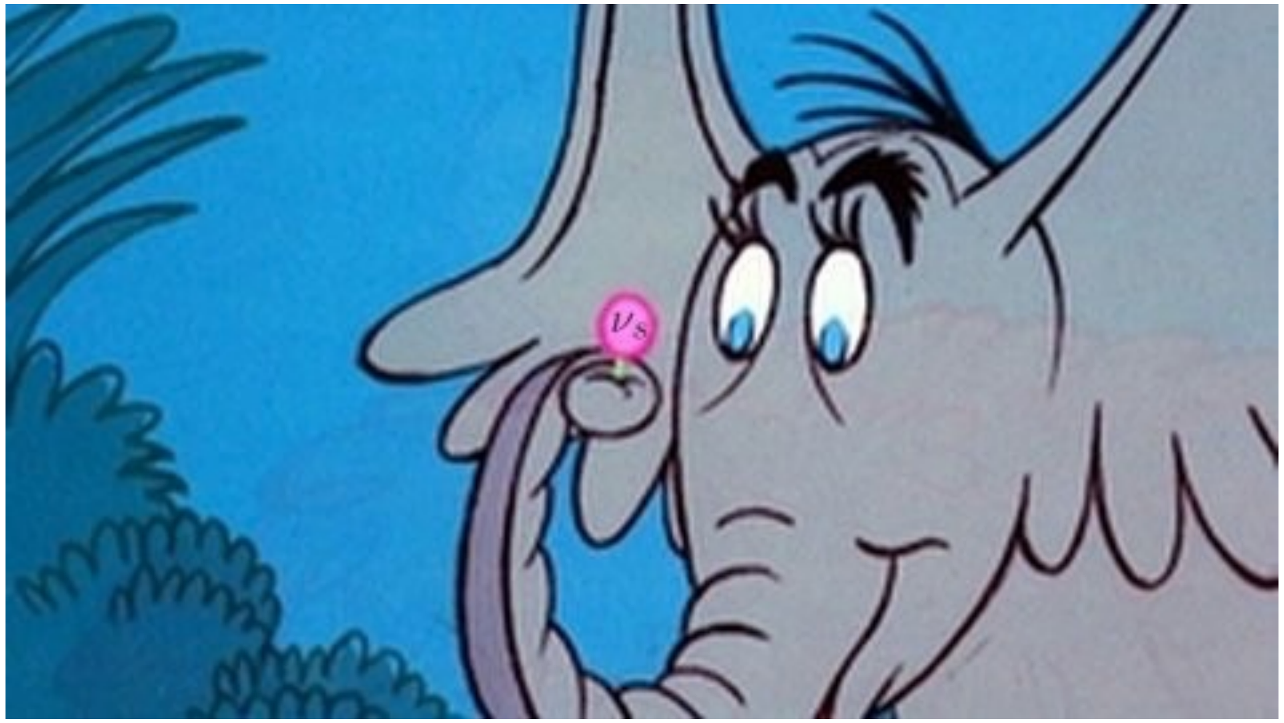
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	$8.09 \to 8.98$	$8.58^{+0.14}_{-0.14}$	$8.14 \to 9.01$	$8.09 \to 8.98$
$\delta_{CP}/^\circ$	234^{+43}_{-31}	$144 \to 374$	278^{+26}_{-29}	$192 \to 354$	$144 \to 374$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$6.80 \to 8.02$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.494^{+0.033}_{-0.031}$	$+2.399 \to +2.593$	$-2.465^{+0.032}_{-0.031}$	$-2.562 \to -2.369$	$\begin{bmatrix} +2.399 \to +2.593 \\ -2.536 \to -2.395 \end{bmatrix}$

Caveat: sterile neutrino(s)?

(image credit: ParticleBites)



Anomalies in the data:

1995: $\overline{\nu}_e$ appearance (LSND)

2007: $\overline{\nu}_e$ appearance (MiniBooNE)

2012: ν_e appearance (MiniBooNE)

1995: ν_e disappearance (Gallium)

2011: ν_e disappearance (Reactor)

[lots of results, investigation in the interim…]

[well-documented tension between appearance and disappearance data]

See IPA 2017 Huber talk for "scorecard"

2018: [some highlights]

global analysis (March 2018) **Dentler et al. '18**

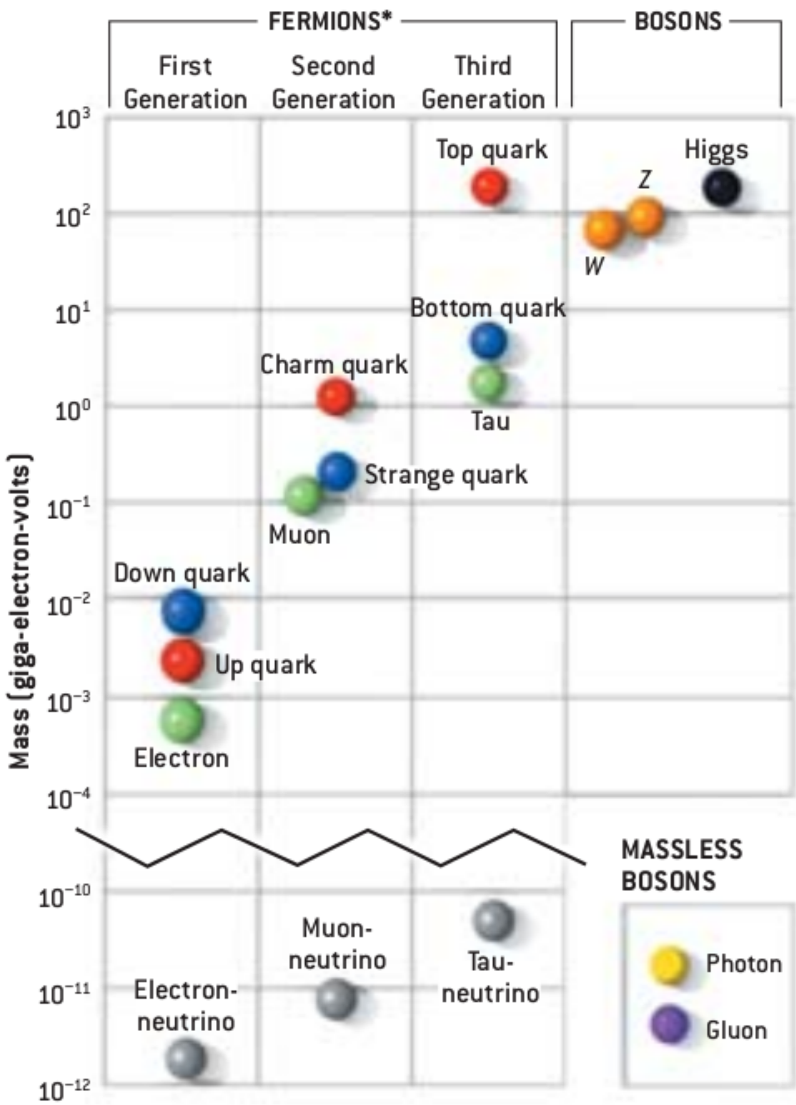
brand new MiniBooNE result (May 2018)

?????

For this talk, focus on 3 active families only…

New questions, excitement for BSM physics!

SM ⟶ ν SM



(image credit: G. Kane, Sci. Am.)

Implications for the SM flavor puzzle:

what is the origin of the quark and lepton masses and mixings?

Goal: a satisfactory and credible theory of flavor *(very difficult!)*

Many questions:

Majorana or Dirac neutrinos? **Nature of neutrino mass suppression?**

Mass hierarchy? **Lepton mixing angle pattern?** **CP violation?**

Implications for BSM paradigms? **Connections to other new physics (NP)?**

Mass Generation

(image credits: Wolfram, Wikipedia)

Quarks, Charged Leptons

"natural" mass scale tied to electroweak scale

Dirac mass terms, parametrized by Yukawa couplings

$$Y_{ij} H \cdot \bar{\psi}_{Li} \psi_{Rj} \longrightarrow \mathcal{M}_u, \mathcal{M}_d, \mathcal{M}_e$$

top quark: O(1) Yukawa coupling

rest: suppression (flavor symmetry)

Neutrinos

Main question: origin of neutrino mass suppression

Options: Dirac

$\Delta L = 0$

Majorana

$\Delta L = 2$

Majorana first: $\Delta L = 2$

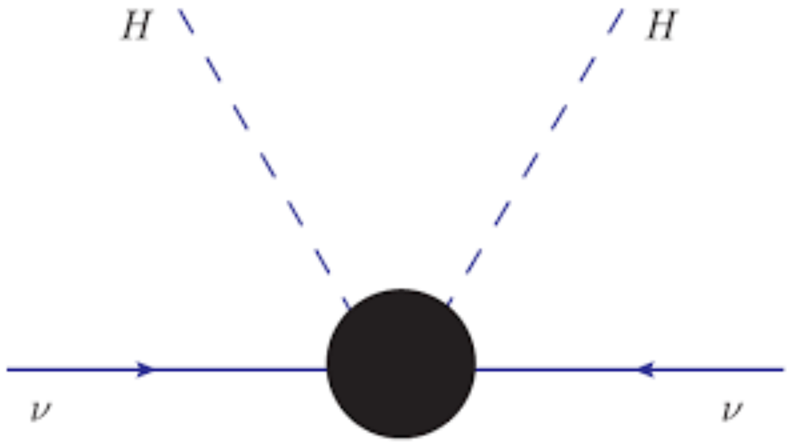
advantages: **naturalness, leptogenesis,** $0\nu\beta\beta$

SM at NR level: Weinberg dimension 5 operator

$$\frac{\lambda_{ij}}{\Lambda} L_i H L_j H$$

if $\lambda \sim O(1)$ $\Lambda \gg m \sim O(100\,\mathrm{GeV})$ (but wide range possible)

Underlying mechanism: 3 tree-level options



(image credit: Dinh et al.)

a. Type I seesaw ν_R (fermion singlet)

b. Type II seesaw Δ (scalar triplet)

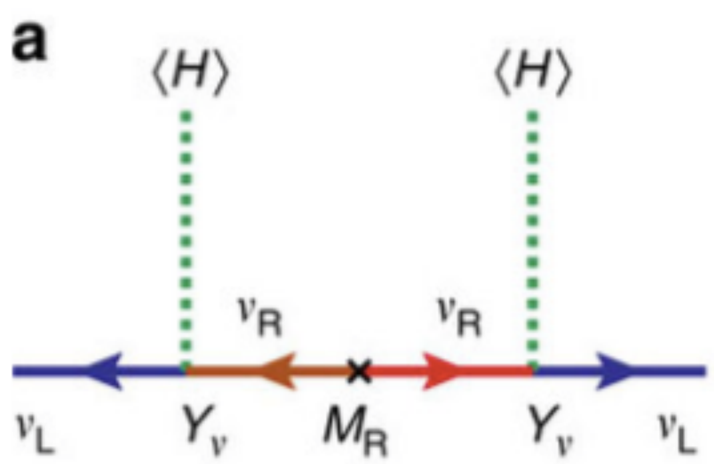
c. Type III seesaw Σ (fermion triplet)

(prediction: superheavy particles)

Prototype: Type I seesaw

Type I: Minkowski;Yanagida; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic;...

right-handed neutrinos:



(image credit: T. Ohlsson et al., Nat. Comm.)

$$Y_{ij} L_i \nu_{Rj} H + M_{R\,ij} \nu_{Ri} \nu^c_{Rj}$$

$$\mathcal{M}_\nu \sim \langle H \rangle^2 Y M_R^{-1} Y^T$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$$

$m \sim \mathcal{O}(100\,\mathrm{GeV})$

$M \gg m$

$$m_1 \sim \frac{m^2}{M} \qquad m_2 \sim M \gg m_1 \qquad \nu_{1,2} \sim \nu_{L,R} + \frac{m}{M} \nu_{R,L}$$

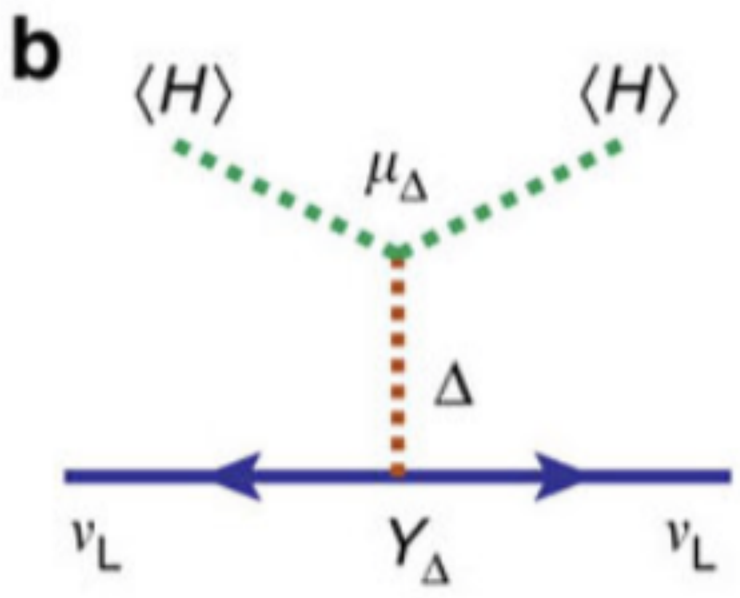
advantages: naturalness, connection to grand unification, leptogenesis,...

disadvantage: testability without model assumptions (even at low scales)

Other tree-level seesaws

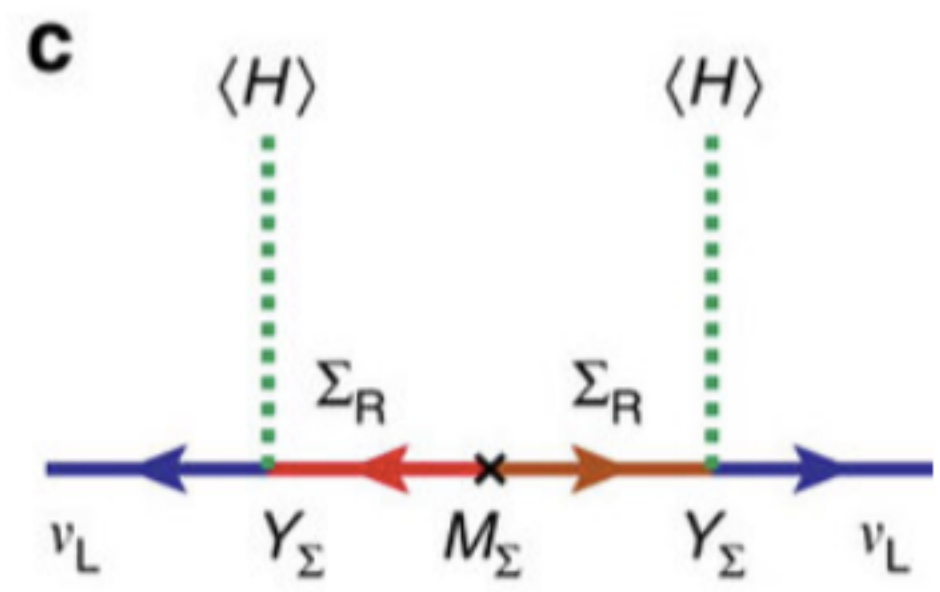
(image credits: T. Ohlsson et al., Nat. Comm.)

Type II



$$\mathcal{M}_\nu \sim \langle H\rangle^2 Y_\Delta \mu_\Delta / M_\Delta^2$$

Type III



$$\mathcal{M}_\nu \sim \langle H\rangle^2 Y_\Sigma M_\Sigma^{-1} Y_\Sigma^T$$

advantage: testability (when completed)

usually accompanied by new EW charged states — visible at LHC?

disadvantages: naturalness, economy (subjective)

Type II: Konetchsy, Kummer; Cheng, Li; Lazarides, Shafi, Wetterich; Schecter, Valle; Mohapatra et al,; Ma;…

Type III: Foot, He, Joshi; Ma;…

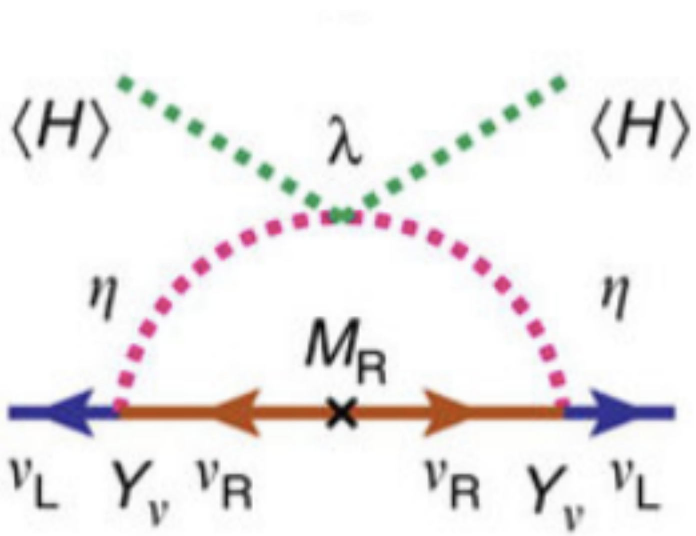
Zee; Babu; Ma; Gustafsson, No, Rivera;…

Radiative neutrino mass generation:

complete Weinberg operator via loops

(loop suppression factor aids in overall mass suppression)

A canonical example: “scotogenic” model



(image credit: T. Ohlsson et al., Nat. Comm.)

introduce new electroweak doublet and right-handed neutrinos

$$\mathcal{M}_\nu \sim \lambda \frac{\langle H \rangle^2}{16\pi^2} Y M_R^{-1} Y^T$$

(new states can be DM candidates)

Generic feature of radiative models:

superheavy states no longer required!

advantage: testability

Radiative neutrino mass generation:

(odd mass dimension d>5)

can have other NR operators in SM with $\Delta L = 2$

Babu and Leung '01
de Gouvea and Jenkins '07

d=7	**d=9**
$LLLe^cH$	$LLLe^cLe^c$ (Zee, Babu)
$LLQd^cH$	$LLQd^cQd^c$
$LL\overline{Q}\overline{u}^cH$	+ many others…
$L\overline{e}^c\overline{u}^cd^cH$	

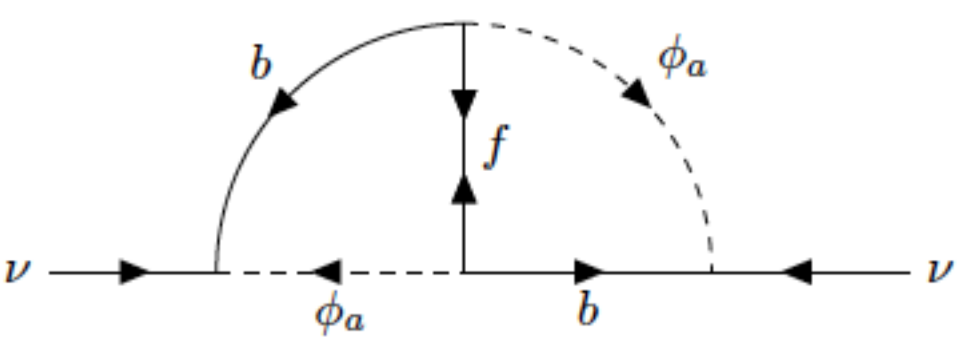
NP scale can be accessible at LHC (subject to LFV bounds)

Connection betweeen loop-induced mass generation and B-physics anomalies…

One way **leptoquarks** can manifest themselves! Päs and Schumacher, '15

A two-loop example:

scalar leptoquark $\phi \sim (\mathbf{3}, \mathbf{1}, -1/3)$
+ octet fermion $f \sim (\mathbf{8}, \mathbf{1}, 0)$



Cai, Gargalones, Schmidt, Volkas '17

→ **see Volkas talk at Neutrino 2018**

Many other ideas for Majorana neutrino masses…

more seesaws (double, inverse,...),
SUSY with R-parity violation, RS models…

lepton number violation → Majorana ν masses

Now for Dirac neutrino masses:

Require strong suppression $Y_\nu \sim 10^{-14}$

Less intuitive, but mechanisms exist…

extra dimensions, new gauge symmetries (non-singlet ν_R),
SUSY breaking effects, string instanton effects,…

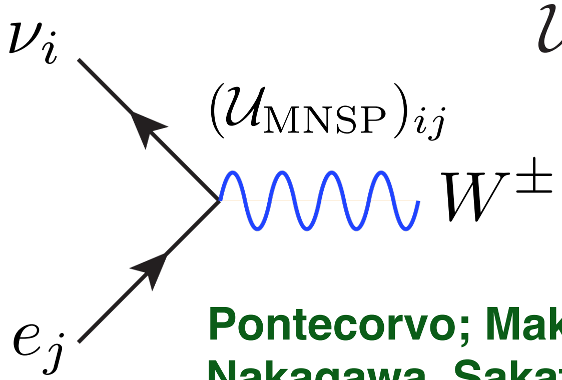
General themes:

Much richer than quark and charged lepton sectors.
Trade-off between naturalness and testability.

→ **see Dev talk at Neutrino 2018**

Lepton mixings

diagonal phase matrix (Majorana neutrinos)



Pontecorvo; Maki, Nakagawa, Sakata

$$\mathcal{U}_{\rm MNSP} = \mathcal{R}_1(\theta_{23})\mathcal{R}_2(\theta_{13},\delta)\mathcal{R}_3(\theta_{12})\mathcal{P}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \mathcal{P}$$

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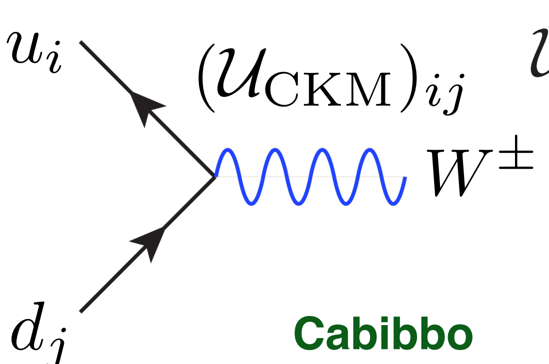
Compare quarks:



Cabibbo
Kobayashi, Maskawa

$$\mathcal{U}_{\rm CKM} = \mathcal{R}_1(\theta_{23}^{\rm CKM})\mathcal{R}_2(\theta_{13}^{\rm CKM},\delta_{\rm CKM})\mathcal{R}_3(\theta_{12}^{\rm CKM})$$

$\theta_{12}^{\rm CKM} = 13.0^\circ \pm 0.1^\circ = \theta_C$ (Cabibbo angle)

$\theta_{23}^{\rm CKM} = 2.4^\circ \pm 0.1^\circ$

$\theta_{13}^{\rm CKM} = 0.2^\circ \pm 0.1^\circ$

$\delta_{\rm CKM} = 60^\circ \pm 14^\circ$

3 “small” angles, 1 *O*(1) phase

Lepton mixings

$$\mathcal{U}_{\rm MNSP} = \mathcal{R}_1(\theta_{23})\mathcal{R}_2(\theta_{13},\delta)\mathcal{R}_3(\theta_{12})\mathcal{P}$$

Certainly **two large mixing angles**: $\theta_{23},\ \theta_{12}$

Dirac phase: too soon to say, but intriguing hints

Majorana phases: unlikely to know anytime soon**

A basic question: is θ_{13} "large" or "small"?

Large reactor angle: vs. **Small reactor angle:**

↓ the case for **anarchy**

↓ the case for **symmetry**

Murayama; Hall; de Gouvea;…

Neutrino anarchy

$\mathcal{U}_\nu$ from a random draw of unbiased distribution of 3x3 unitary matrices

statistical tests: lower bound on $|\mathcal{U}_{e3}|^2$

(character: Watterson)

Post-reactor angle measurement: renewed focus

de Gouvea and Murayama '12 Altarelli et al. '12, Bai and Torroba '12 ,…

Some recent highlights:

RG analysis **Brdar, Konig, Kopp '15**

Model-building + quark sector **Babu et al. '16,…**

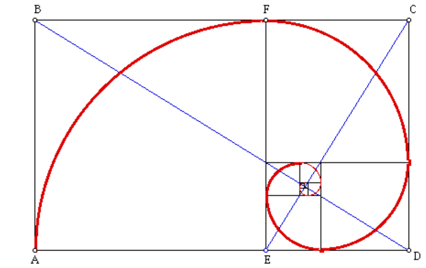
Fortin et al. '17

(anarchy also popular approach for NP flavor violation at scales ~10 TeV)

Baumgart et al. '15,…

Anarchy hypothesis alone does not provide information on Δm^2

Family symmetries (structure)



Very different structure for leptons and quarks!

Quarks:

spontaneously broken family symmetry at scale M

Froggatt, Nielsen

φ = "flavon"

$$Y_{ij} H \cdot \bar{\psi}_{Li} \psi_{Rj} \longrightarrow \left(\frac{\varphi}{M}\right)^{n_{ij}} H \cdot \bar{\psi}_{Li} \psi_{Rj}$$

small mixings and hierarchical masses:

→ continuous family symmetry

both Abelian and non-Abelian: many examples!

$\mathcal{M}_u, \mathcal{M}_d$ approx diagonalized by same unitary transformation

(can choose basis where both close to diagonal)

$$\mathcal{U}_{\rm CKM} = \mathcal{U}_u \mathcal{U}_d^\dagger \sim 1 + \mathcal{O}(\lambda)$$

$$\lambda \sim \frac{\varphi}{M}$$

Wolfenstein parametrization: $\lambda \equiv \sin\theta_c = 0.22$

suggests Cabibbo angle (or some power) as a flavor expansion parameter

Leptons:

For the **charged leptons**: hierarchical masses → similar strategy?

But now, in basis where $\mathcal{M}_e$ is diagonal, $\mathcal{M}_\nu$ is not diagonal:

$\mathcal{M}_\nu$ diagonalization requires 1 small, 2 large mixing angles!

Arguably the **most challenging*** pattern: (* for three families)

3 small angles ⟶ $\sim$ diagonal $\mathcal{M}_\nu$

1 large, 2 small ⟶ $\sim$ $\mathrm{Rank}\mathcal{M}_\nu < 3$

3 large angles ⟶ anarchical $\mathcal{M}_\nu$

} relatively straightforward at leading order

1 **small,** 2 **large** ⟶ **fine-tuning, non-Abelian**

→ **A model-building opportunity!**

Lepton mixings:

No unique theoretical starting point for the flavor expansion!

$$\mathcal{U}_{\rm MNSP} \sim \mathcal{W} + O(\lambda')$$

flavor expansion parameter

mixing angles $(\theta_{12}^\nu, \theta_{23}^\nu, \theta_{13}^\nu)$

(diagonal charged lepton basis)

"Bare" mixing angles generically shift due to $O(\lambda')$ **corrections**

A priori, expansions in quark and lepton sectors unrelated.

Unification paradigm (broad sense): set $\lambda' = \lambda_C$

ideas of **quark-lepton complementarity** and **"Cabibbo haze"**

Raidal '04, Minakata+Smirnov '04, many others...

("haze" terminology from Datta, L.E., Ramond '05)

Pre-measurement, speculation that **reactor angle is a Cabibbo effect**

Vissiani '98, '01

Ramond '04

$$\theta_{13}^\nu = 0 \qquad \theta_{13} \sim \frac{\lambda_C}{\sqrt{2}}$$

Possible starting points:

Most studied: maximal atmospheric, zero reactor $\theta_{23}^{\nu} = \frac{\pi}{4}$ $\theta_{13}^{\nu} = 0$

→ **classify scenarios by bare solar angle**

tri-bimaximal mixing: $\sin^2\theta_{12}^{\nu} = 1/3$ — Harrison, Perkins, Scott '02; Xing '02; He, Zee '02; Ma '03…

bimaximal mixing: $\sin^2\theta_{12}^{\nu} = 1/2$ — Vissiani '97; Barger et al. '98; Baltz, A. Goldhaber, M. Goldhaber '98;…

golden ratio (A) mixing: $\sin^2\theta_{12}^{\nu} = 1/(2+r) \sim 0.276$ — Datta, Ling, Ramond '03; Kajiyama, Raidal, Strumia '08;…

$r = (1+\sqrt{5})/2$

golden ratio (B) mixing: $\sin^2\theta_{12}^{\nu} = (3-r)/4 \sim 0.345$ — Rodejohann '09,…

hexagonal mixing: $\sin^2\theta_{12}^{\nu} = 1/4$ — Albright, Duecht, Rodejohann '10, Kimand, Seo '11,…

Also can study scenarios without $\theta_{13}^{\nu} = 0$ — Lam '13; Holthausen et al. '12; Hagendorn…

many others…

All can be obtained via discrete non-Abelian family symmetries

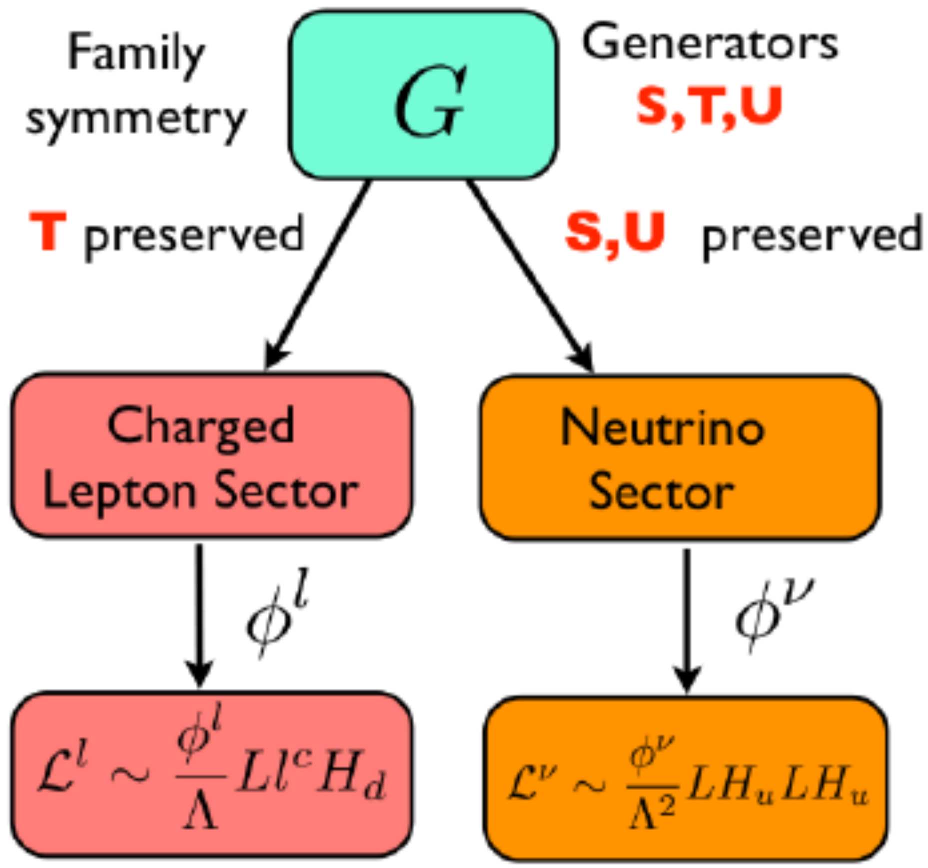
Model-building approach

Choose a discrete non-Abelian group for family symmetry

Options: $SU(3),\ SO(3)$ subgroups:

$$\mathcal{A}_4 \quad \mathcal{S}_4 \quad \mathcal{A}_5 \quad \Delta(3n^2) \quad \Delta(6n^2) \quad \mathcal{D}_n \quad \mathcal{T}' \quad \mathcal{I}' \quad \ldots$$

(image credit: King, Luhn)



see e.g. reviews by King, Luhn '13, King '17

Example (Majorana ν):

Flavons:

$$\phi^l, \phi^\nu$$

Residual symmetries:

$$T\langle\phi^l\rangle \approx \langle\phi^l\rangle$$
$$S, U\langle\phi^\nu\rangle \approx \langle\phi^\nu\rangle$$

(or broken further, e.g. only *S* or *U* unbroken)

corrections in flavor expansion: (i) NLO in flavons, (ii) "charged lepton"/kinetic/RG…

Many papers! Some authors (not comprehensive):

King, Ma, Ding, Feruglio, Lam, Rodejohann, Chen, Hagedorn, Luhn, Stuart, LE…

Example: tri-bimaximal mixing (TBM/HPS)

(Majorana neutrinos, Type I seesaw)

$$\mathcal{U}_{\rm MNSP}^{\rm (HPS)} = \begin{pmatrix} \sqrt{\frac{2}{3}} & -\frac{1}{\sqrt{3}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

(~Clebsch-Gordan coeffs!)

Meshkov, Zee…

Many models pre-dated reactor angle measurements

see e.g. Albright et al. '10

→ current data requires Cabibbo-sized corrections

Prototypical scenarios: $\mathcal{A}_4$ $\mathcal{S}_4$ $\mathcal{T}'$ (typically SUSY/SUSY-GUT)

Many, many authors!!

Ma et al.; Altarelli, Feruglio; Carone et al.; Chen et al.; King et al.; Ding; Lam…

↑

"minimal" flavor group
(contains *S*, *T*, *U* generators)

Lam; Ding et al;…

Residual symmetries: $\mathcal{Z}_3$ ~*T* $\mathcal{Z}_2 \times \mathcal{Z}_2$ ~*S*,*U*,*SU* (Klein symmetry)

Can further break down Klein symmetry:

1 column only of HPS matrix preserved: TM1, TM2 + corrections

see e.g. King '17 for review

Example: tri-bimaximal mixing (TBM/HPS)

Bottom-up approach: get needed corrections through "Cabibbo Haze"

Interesting (very) recent example:

asymmetric charged lepton corrections to TBM/HPS (with a dash of grand unification) — **Rahat, Ramond, Xu '18**

SU(5), SO(10) GUT-inspired relations:

<u>symmetric</u> Yukawas → insufficient corrections to θ_{13}

Kile, Perez, Ramond, Zhang '14

<u>asymmetric</u> Yukawas → possible for specific $O(\lambda_C)$ corrections to Y_e (via $Y_{\bar{5}}$)

Notable feature:

phase required in $\mathcal{U}_\nu \sim \mathcal{U}^{(\mathrm{HPS})}$ for consistency with mixing angle data

numerical example: $\delta \simeq \pm 1.3\pi, \quad J \simeq \mp 0.03$

good agreement!

CP Violation

Consider case of spontaneous CP violation — calculable phases.

Idea of generalized CP: $X^T \mathcal{M}_\nu X = \mathcal{M}_\nu^*$ $\quad Y^\dagger \mathcal{M}_e \mathcal{M}_e^\dagger Y = (\mathcal{M}_e \mathcal{M}_e^\dagger)^*$

"ordinary" CP has $X = Y = 1$

Branco, Lavoura, Rebelo '86…

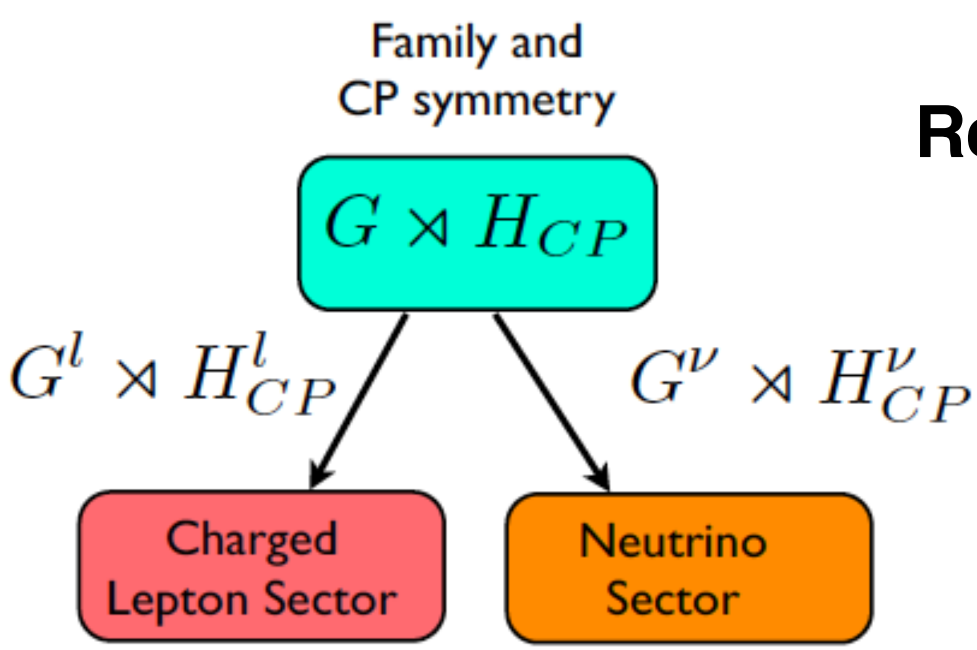
Grimus, Rebelo '95

automorphisms of discrete family symmetry:

Holthausen et al. '12; Feruglio et al. '12; Chen et al. '14; Ding et al. '14; Branco et al. '15; …

$X\rho(g)^* X^{-1} = \rho(g')$ **(consistency condition)**

family symmetry



many recent papers! see King '17 for review

Residual/generalized CP symmetries

existence of "CP basis"

group classification

Holthausen, Lindner, Schmidt '12

Chen et al. '14

Lots of interesting recent work along these lines!

Residual/CP symmetries (model-independent approach)

LE, Garon, Stuart '15; LE and Stuart '16

Assumptions: Majorana neutrinos, full Klein symmetry preserved

$U_\nu^T \mathcal{M}_\nu U_\nu = \mathcal{M}_\nu^{\rm diag}$ invariant if $U_\nu \to U_\nu Q_\nu$ $\quad Q_\nu = {\rm Diag}(\pm 1, \pm 1, \pm 1)$, ${\rm Det}\, Q_\nu = 1$

From these, obtain diagonal Klein generators $G^{\rm diag}_{i=0,1,2,3}$

$$(G_i^{\rm diag})^T \mathcal{M}_\nu^{\rm diag} G_i^{\rm diag} = \mathcal{M}_\nu^{\rm diag}$$

Then obtain **Klein generators:** $G_i = U_\nu G_i^{\rm diag} U_\nu^\dagger$ $\qquad G_i^T \mathcal{M}_\nu G_i = \mathcal{M}_\nu$

(reconstruct from MNSP for diagonal charged leptons)

For generalized CP operators in neutrino sector:

from above and $X_\nu G_i^* - G_i X_\nu = 0$ Feruglio et al. '12, Holthausen et al. '12

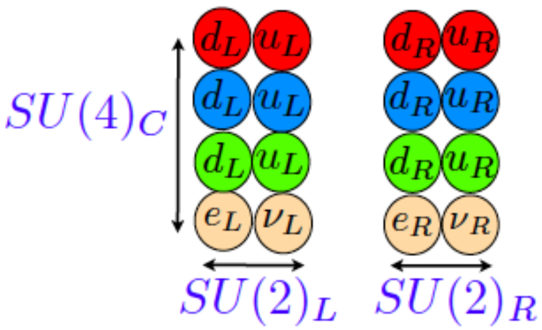
$\longrightarrow$ $X_i X_i^* = G_0 \quad X_0 X_i^* = G_i \quad X_i X_j^* = G_k$

Similar approach for **charged lepton** generalized CP:

but need to be careful of phase redefinition degrees of freedom

SUSY GUTs and String Models: Top-Down

SUSY GUTs: explicit realizations of these scenarios (+ quark sector)



recent example: **SUSY Pati-Salam** Poh, Raby, Wang '17

$$SU(4)_C \times SU(2)_L \times SU(2)_R \quad \mathcal{D}_3 \times U(1) \times \mathcal{Z}_2 \times \mathcal{Z}_3$$

can achieve consistency with LHC, neutrino data

(26-parameter fit)

String Models:

variety of possibilities, not necessarily just minimal Type I seesaw

→ ν_R **candidates often not pure gauge singlets**

explorations of Type I seesaw in heterotic orbifolds Giedt et al.; Buchmuller et al.;…

braneworlds: exponentially suppressed Yukawas

see e.g. Langacker for reviews

"Mixed" scenarios with seesaw and R-parity violation

e.g. G2 models Acharya et al. '16;…

Conclusions

Neutrino data has led to a renaissance for SM flavor puzzle

Model-building starting point question: Dirac or Majorana?

Many ways known to suppress neutrino mass scale

often a tradeoff between minimality/naturalness and testability

For 3 active neutrinos only:

mixings: anarchy or symmetry

symmetry approach: paradigm shift to discrete non-Abelian groups

many examples (top-down and bottom-up)

but still seeking **compelling, complete, testable** theories

More data (atmospheric angle, Dirac CP phase,…) will help enormously!

If sterile neutrinos confirmed: paradigm shifts again!

Stay tuned!