Theoretical Overview of Neutrino Physics

Heisenberg-Programm
DFG Deutsche Forschungsgemeinschaft

Werner Rodejohann (MPIK)

24/07/17

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

SNOLAB TAUP 2017 UniversitéLaurentienne LaurentianUniversity

Goals/Outline

- implications/motivations/examples of:
  - lepton mixing
  - neutrino mass
  - new physics in the neutrino sector

Neutrinos oscillate and leptons mix

- we know that: $0 \neq \Delta m^2_{21} \neq \Delta m^2_{31}$
  - $\Rightarrow$ all three masses different, at least two are non-zero
  - **hierarchy mild and neutrino mass much much smaller than all other masses**
- we know that: $U_{\rm PMNS} = U_l^\dagger \, U_\nu \neq \mathbb{1}$
  - $\Rightarrow$ charged lepton and neutrino mass matrices diagonalized with different matrices; Nature distinguishes ν_e, ν_μ, ν_τ
  - **mixing completely different from quark mixing**

Low Energy Paradigm

At low energies, neutrino mass matrix m_ν:

$$\mathcal{L} = \frac{1}{2}\,\nu^T\, m_\nu\, \nu \quad \text{with} \quad m_\nu = U\,\mathrm{diag}(m_1, m_2, m_3)\,U^T$$

with PMNS matrix

$$U = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta} \\ -s_{12}\,c_{23} - c_{12}\,s_{23}\,s_{13}\,e^{i\delta} & c_{12}\,c_{23} - s_{12}\,s_{23}\,s_{13}\,e^{i\delta} & s_{23}\,c_{13} \\ s_{12}\,s_{23} - c_{12}\,c_{23}\,s_{13}\,e^{i\delta} & -c_{12}\,s_{23} - s_{12}\,c_{23}\,s_{13}\,e^{i\delta} & c_{23}\,c_{13} \end{pmatrix} P$$

changes number of parameters in **SM′**:

Species	#	Σ
Quarks	10	10
Leptons	3	13
Charge	3	16
Higgs	2	18
strong CP	1	19

→

Species	#	Σ
Quarks	10	10
Leptons	~~3~~ **12**	~~13~~ **22**
Charge	3	~~16~~ **25**
Higgs	2	~~18~~ **27**
strong CP	1	~~19~~ **28**

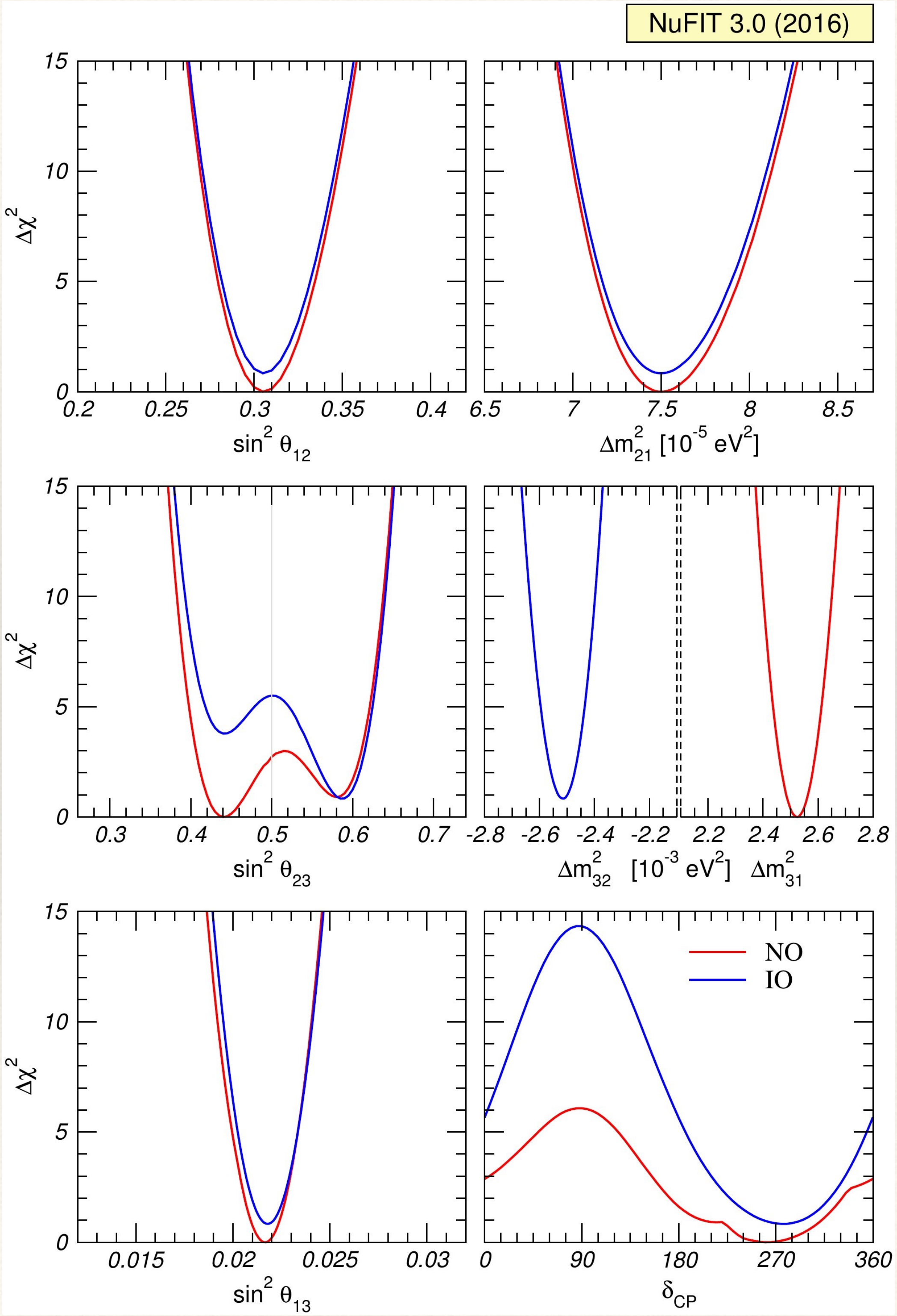
3 Majorana neutrino paradigm ⇒ needs to be tested!

Low Energy Paradigm

- 3 Tasks:
  - determine new parameters
  - interpret/explain values of new parameter
  - check for inconsistencies in standard picture

Determine Parameters

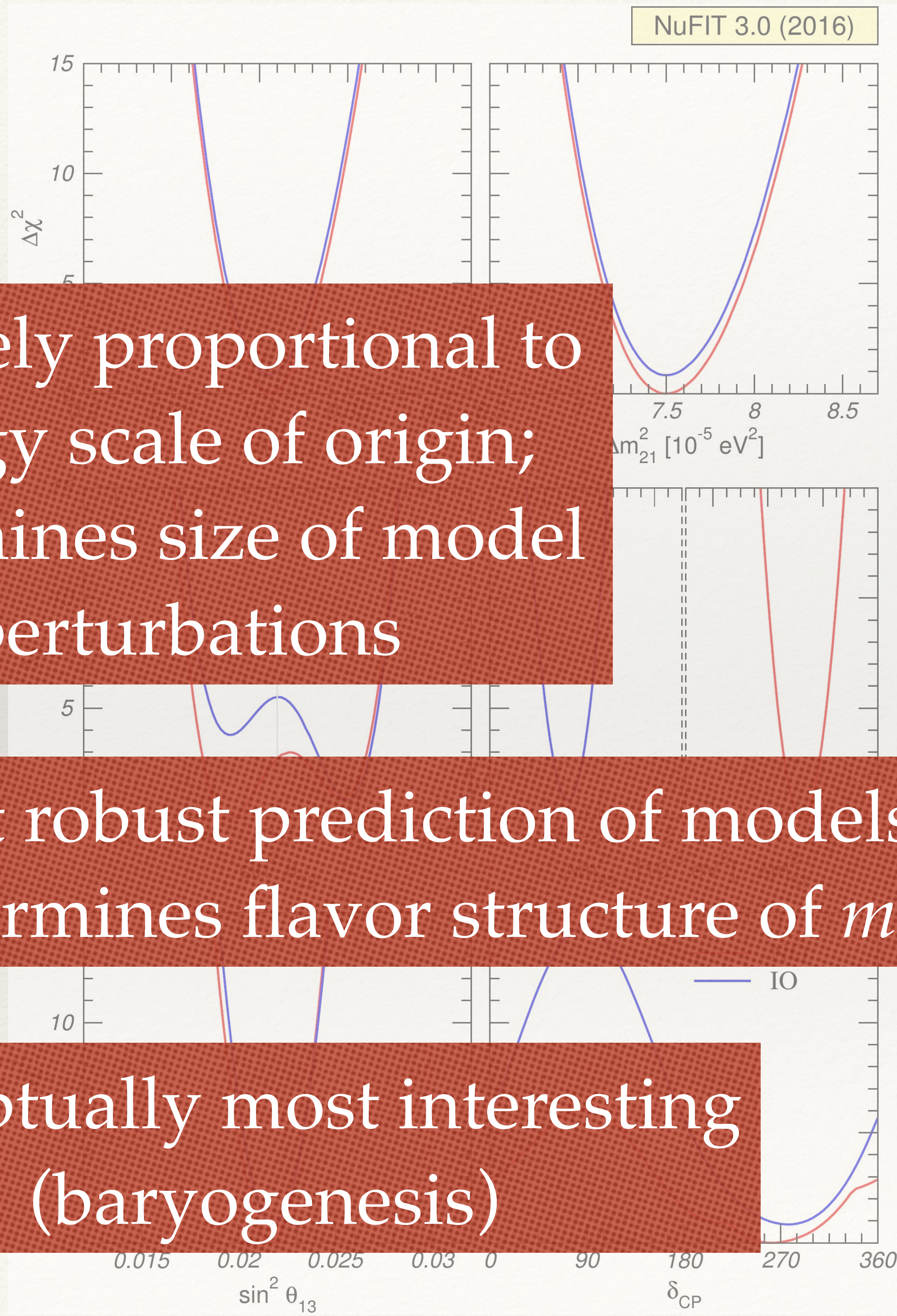
- We know:
  - θ_{12} and Δm^2_{21}
  - θ_{23} and $|\Delta m^2_{31}|$
  - θ_{13}
- We have limits:
  - m_1, m_2, m_3
- We don't know:
  - $\text{sgn}(\Delta m^2_{31})$
  - δ, α, β



Talk by Tórtola

Determine Parameters

- We know:
  - θ_{12} and Δm^2_{21}
  - θ_{23} and $|\Delta m^2_{31}|$
  - θ_{13}
- We have limits:
  - m_1, m_2, m_3
- We don't know:
  - $\text{sgn}(\Delta m^2_{31})$
  - δ, α, β



inversely proportional to energy scale of origin; determines size of model perturbations

most robust prediction of models; determines flavor structure of m_ν

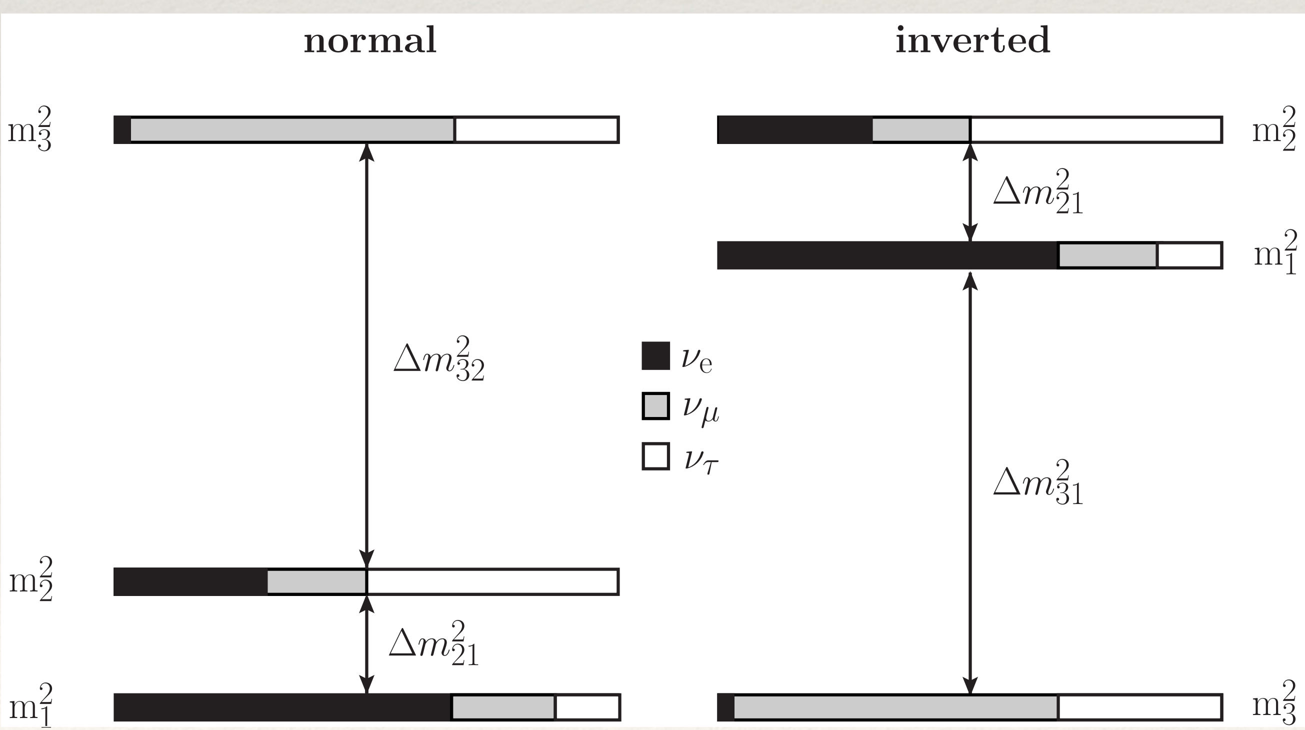
conceptually most interesting (baryogenesis)

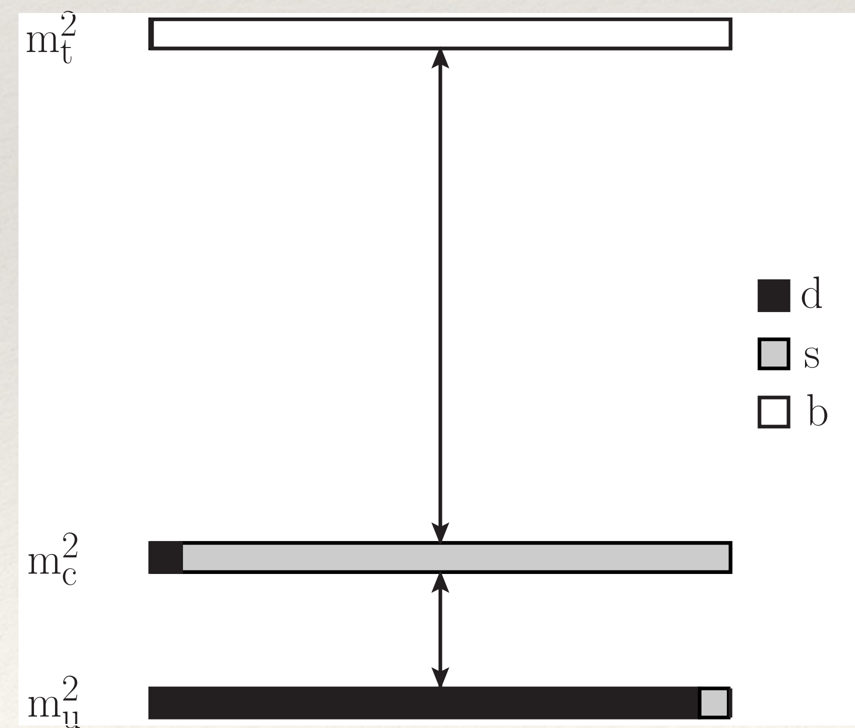
Talk by Tórtola

Implications of Lepton Mixing

$$|U| = \begin{pmatrix} 0.800 \to 0.844 & 0.515 \to 0.581 & 0.139 \to 0.155 \\ 0.229 \to 0.516 & 0.438 \to 0.699 & 0.614 \to 0.790 \\ 0.249 \to 0.528 & 0.462 \to 0.715 & 0.595 \to 0.776 \end{pmatrix}$$

$$V_{\rm CKM} = \begin{pmatrix} 0.97434^{+0.00011}_{-0.00012} & 0.22506 \pm 0.00050 & 0.00357 \pm 0.00015 \\ 0.22492 \pm 0.00050 & 0.97351 \pm 0.00013 & 0.0411 \pm 0.0013 \\ 0.00875^{+0.00032}_{-0.00033} & 0.0403 \pm 0.0013 & 0.99915 \pm 0.00005 \end{pmatrix}$$

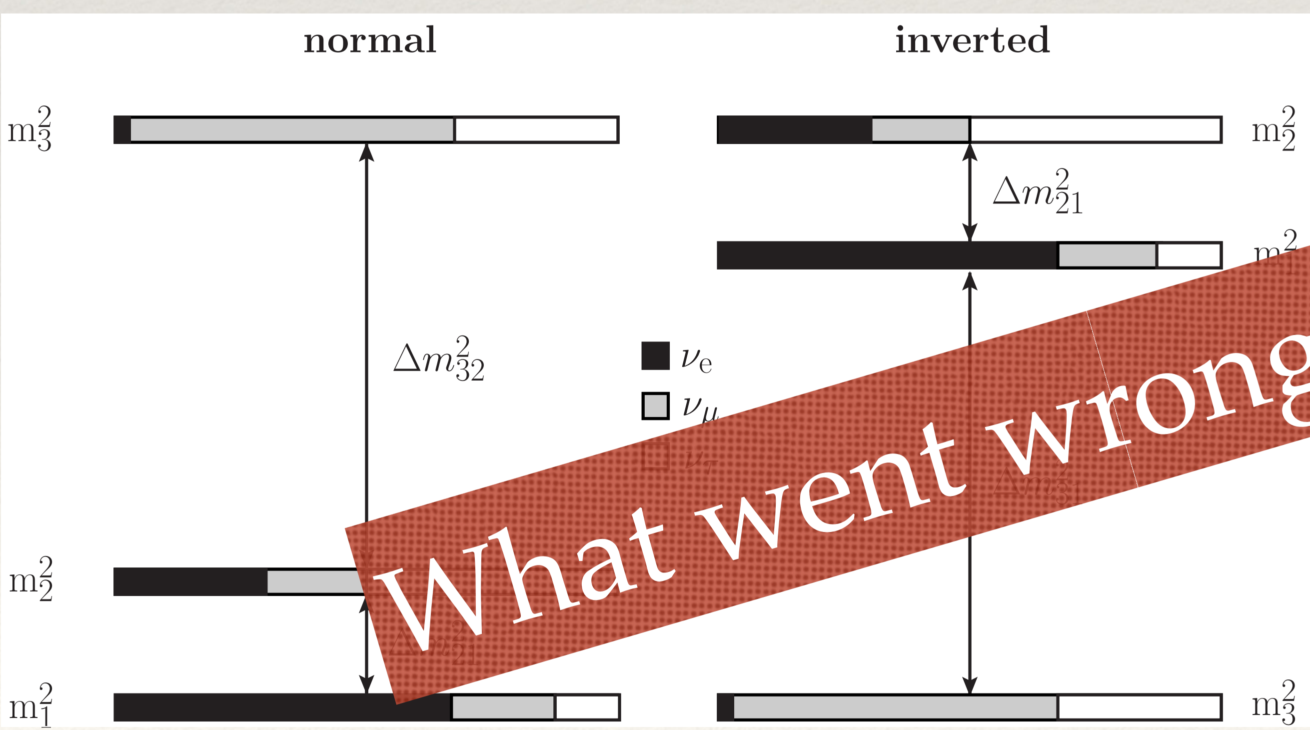


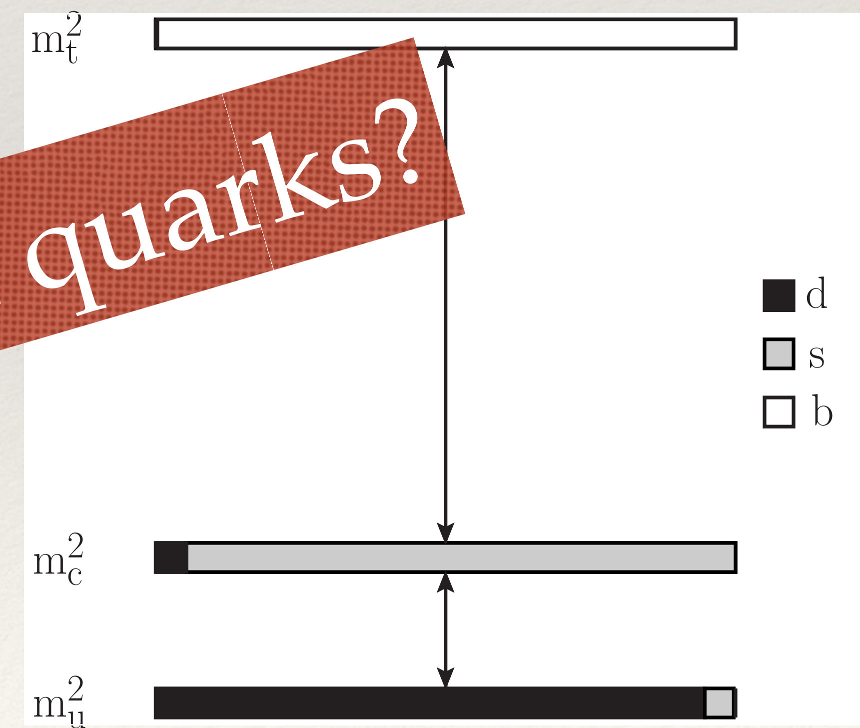


Implications of Lepton Mixing

$$|U| = \begin{pmatrix} 0.800 \to 0.844 & 0.515 \to 0.581 & 0.139 \to 0.155 \\ 0.229 \to 0.516 & 0.438 \to 0.699 & 0.614 \to 0.790 \\ 0.249 \to 0.528 & 0.462 \to 0.715 & 0.595 \to 0.776 \end{pmatrix}$$

$$V_{\rm CKM} = \begin{pmatrix} 0.97434^{+0.00011}_{-0.00012} & 0.22506 \pm 0.00050 & 0.00357 \pm 0.00015 \\ 0.22492 \pm 0.00050 & 0.97351 \pm 0.00013 & 0.0411 \pm 0.0013 \\ 0.00875^{+0.00032}_{-0.00033} & 0.0403 \pm 0.0013 & 0.99915 \pm 0.00005 \end{pmatrix}$$





What went wrong with quarks?

Flavor Symmetries

- Nature seems to prefer large lepton mixing:

$$U_{\rm TBM} = \left(\begin{array}{ccc} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{array} \right)$$

generated by rather special mass matrix

$$(m_\nu)_{\rm TBM} = \left(\begin{array}{ccc} A & B & B \\ \cdot & \frac{1}{2}(A+B+D) & \frac{1}{2}(A+B-D) \\ \cdot & \cdot & \frac{1}{2}(A+B+D) \end{array} \right)$$

mixing angles independent from masses!!

- completely different from quark sector (GST-relation):

$$M = \left(\begin{array}{cc} 0 & a \\ a & b \end{array} \right) \Rightarrow \tan\theta_C \simeq \sqrt{\frac{m_d}{m_s}}$$

Flavor Symmetries

- preferred solution: Discrete Non-Abelian Symmetries

Altarelli, Feruglio, 1002.0211

Group	d	Irr. Repr.'s	Presentation
$D_3 \sim S_3$	6	$1,\ 1',\ 2$	$A^3 = B^2 = (AB)^2 = 1$
D_4	8	$1_1, ...1_4, 2$	$A^4 = B^2 = (AB)^2 = 1$
D_7	14	$1,\ 1',\ 2,\ 2',\ 2''$	$A^7 = B^2 = (AB)^2 = 1$
A_4	12	$1,\ 1',\ 1'',\ 3$	$A^3 = B^2 = (AB)^3 = 1$
$A_5 \sim PSL_2(5)$	60	$1,\ 3,\ 3',\ 4,\ 5$	$A^3 = B^2 = (BA)^5 = 1$
T'	24	$1,\ 1',\ 1'',\ 2,\ 2',\ 2'',\ 3$	$A^3 = (AB)^3 = R^2 = 1,\ \ B^2 = R$
S_4	24	$1,\ 1',\ 2,\ 3,\ 3'$	$BM : A^4 = B^2 = (AB)^3 = 1$ $TB : A^3 = B^4 = (BA^2)^2 = 1$
$\Delta(27) \sim Z_3 \rtimes Z_3$	27	$1_1, ...1_9, 3, \overline{3}$	
$PSL_2(7)$	168	$1, 3, \overline{3}, 6, 7, 8$	$A^3 = B^2 = (BA)^7 = (B^{-1}A^{-1}BA)^4 = 1$
$T_7 \sim Z_7 \rtimes Z_3$	21	$1, 1', \overline{1'}, 3, \overline{3}$	$A^7 = B^3 = 1,\ \ AB = BA^4$

Type	L_i	ℓ_i^c	ν_i^c	Δ
A1	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	$\cdots$	$\cdots$
A2				$\underline{1}, \underline{1}', \underline{1}'', \underline{3}$
B1	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{3}$	$\cdots$
B2				$\underline{1}, \underline{3}$
C1	$\underline{3}$	$\underline{3}$	$\cdots$	$\cdots$
C2				$\underline{1}$
C3				$\underline{1}, \underline{3}$
C4				$\underline{1}, \underline{1}', \underline{1}'', \underline{3}$
D1	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\cdots$
D2				$\underline{1}$
D3				$\underline{1}'$
D4				$\underline{1}', \underline{3}$
E	$\underline{3}$	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	$\cdots$
F	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{3}$	$\underline{3}$	$\underline{1}$ or $\underline{1}'$
G	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{1}, \underline{1}', \underline{1}''$	$\cdots$
H	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\cdots$	$\cdots$
I	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}, \underline{1}, \underline{1}$	$\cdots$
J	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{3}$	$\cdots$

Barry, WR, 1003.2385

Many possible groups, within each group many models…

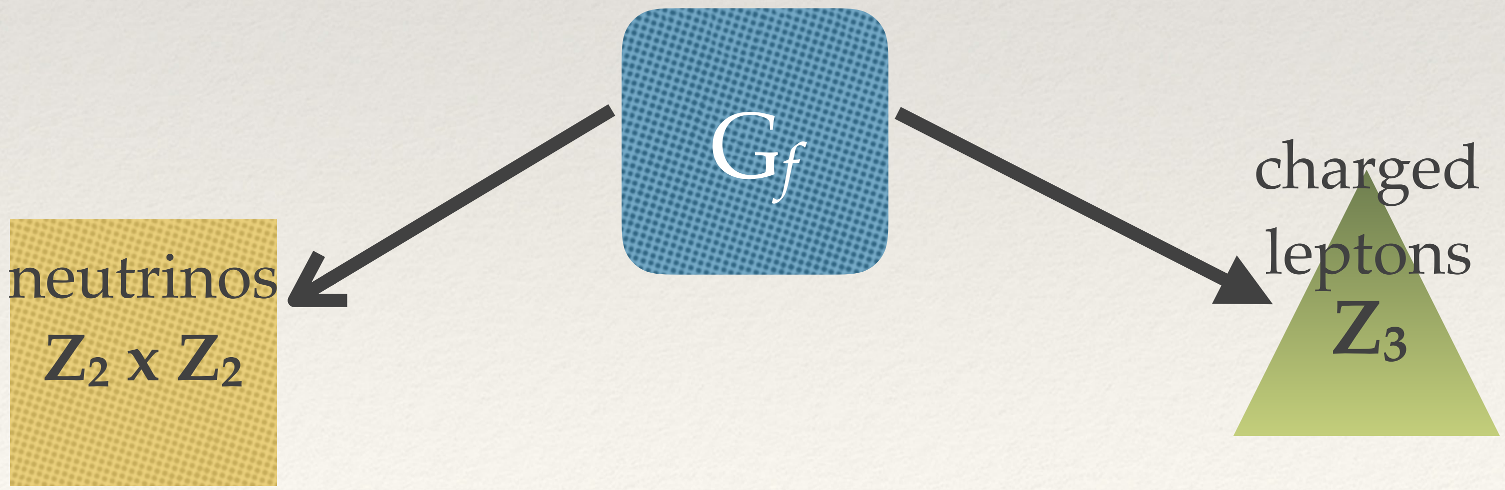
$\Rightarrow$ can distinguish only classes of models

Flavor Symmetries

Lesson 1: put different generations in same irrep of group:

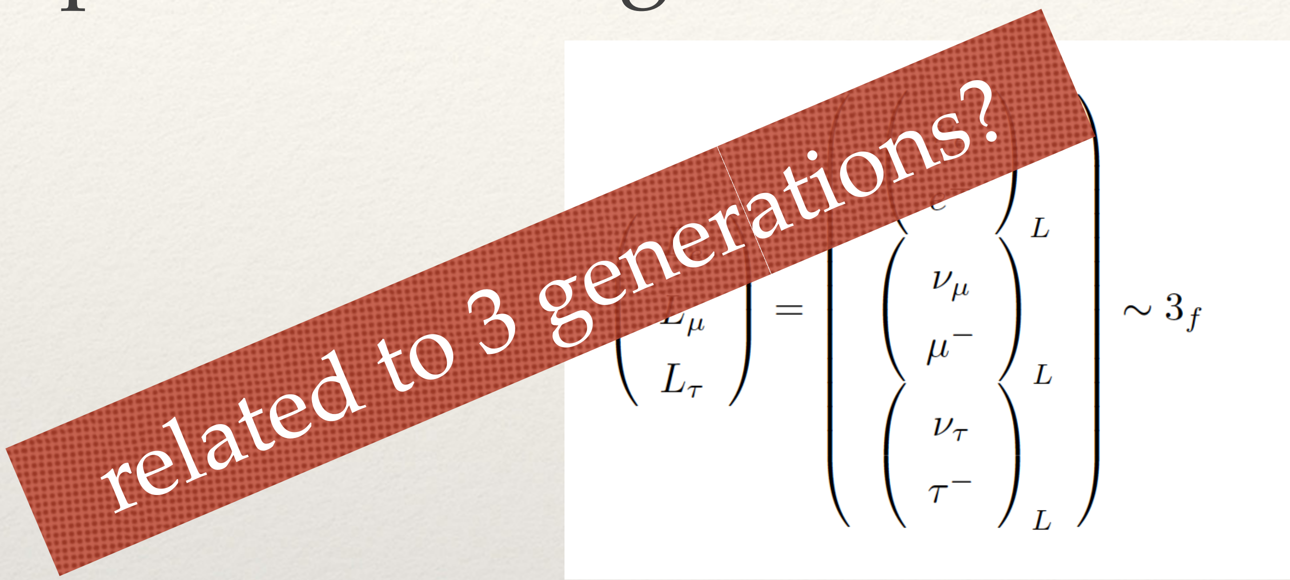
$$\begin{pmatrix} L_e \\ L_\mu \\ L_\tau \end{pmatrix} = \begin{pmatrix} \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \\ \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \\ \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \end{pmatrix} \sim 3_f$$

Lesson 2: flavor group broken to different subgroups:

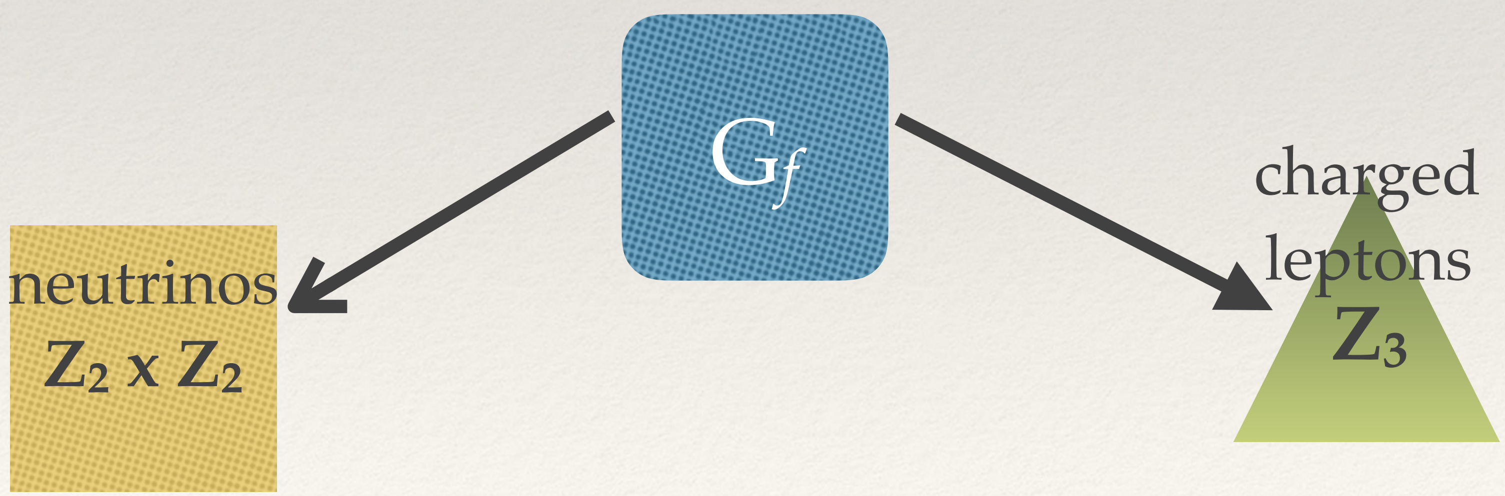


Flavor Symmetries

Lesson 1: put different generations in same irrep of group:

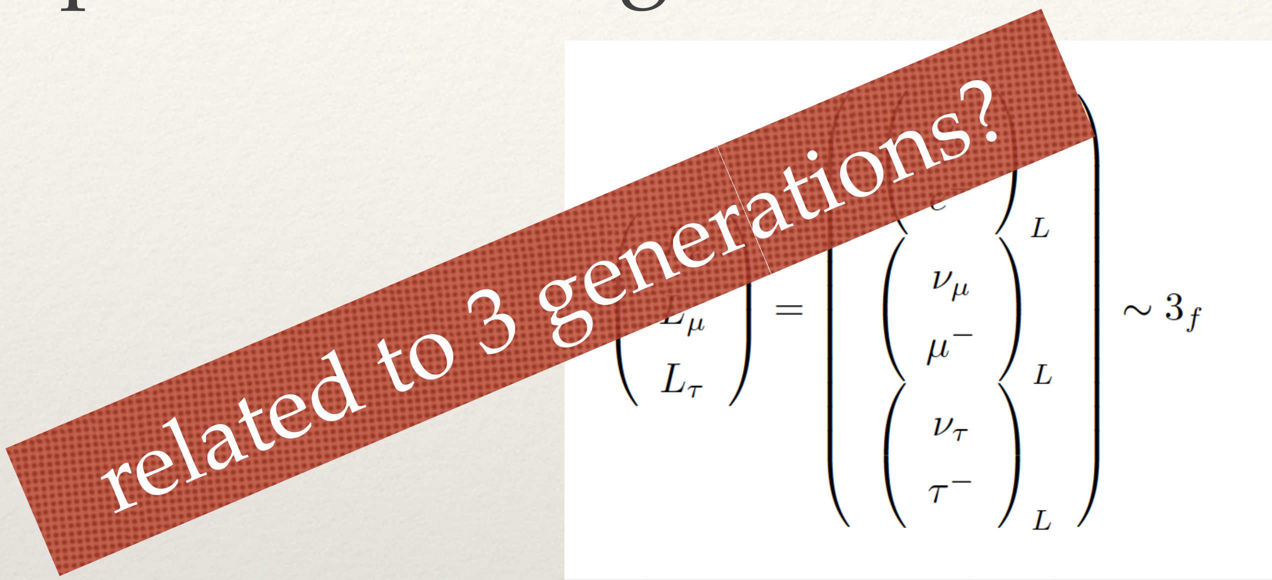


Lesson 2: flavor group broken to different subgroups:

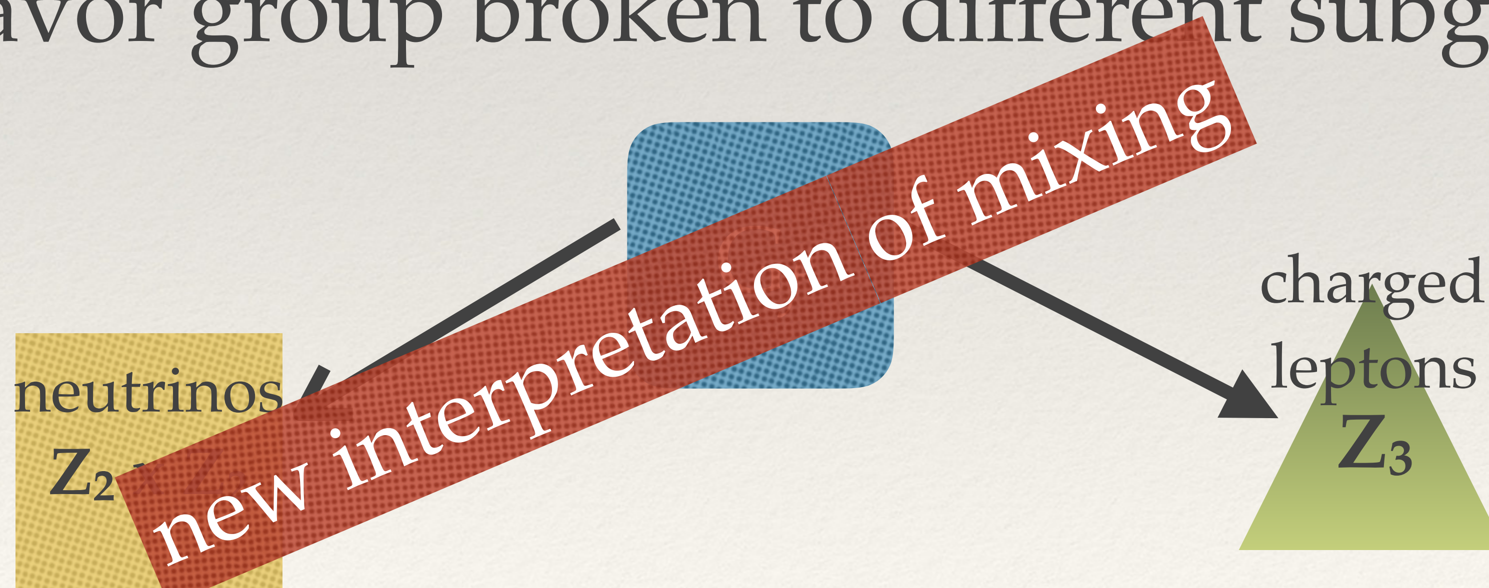


Flavor Symmetries

Lesson 1: put different generations in same irrep of group:

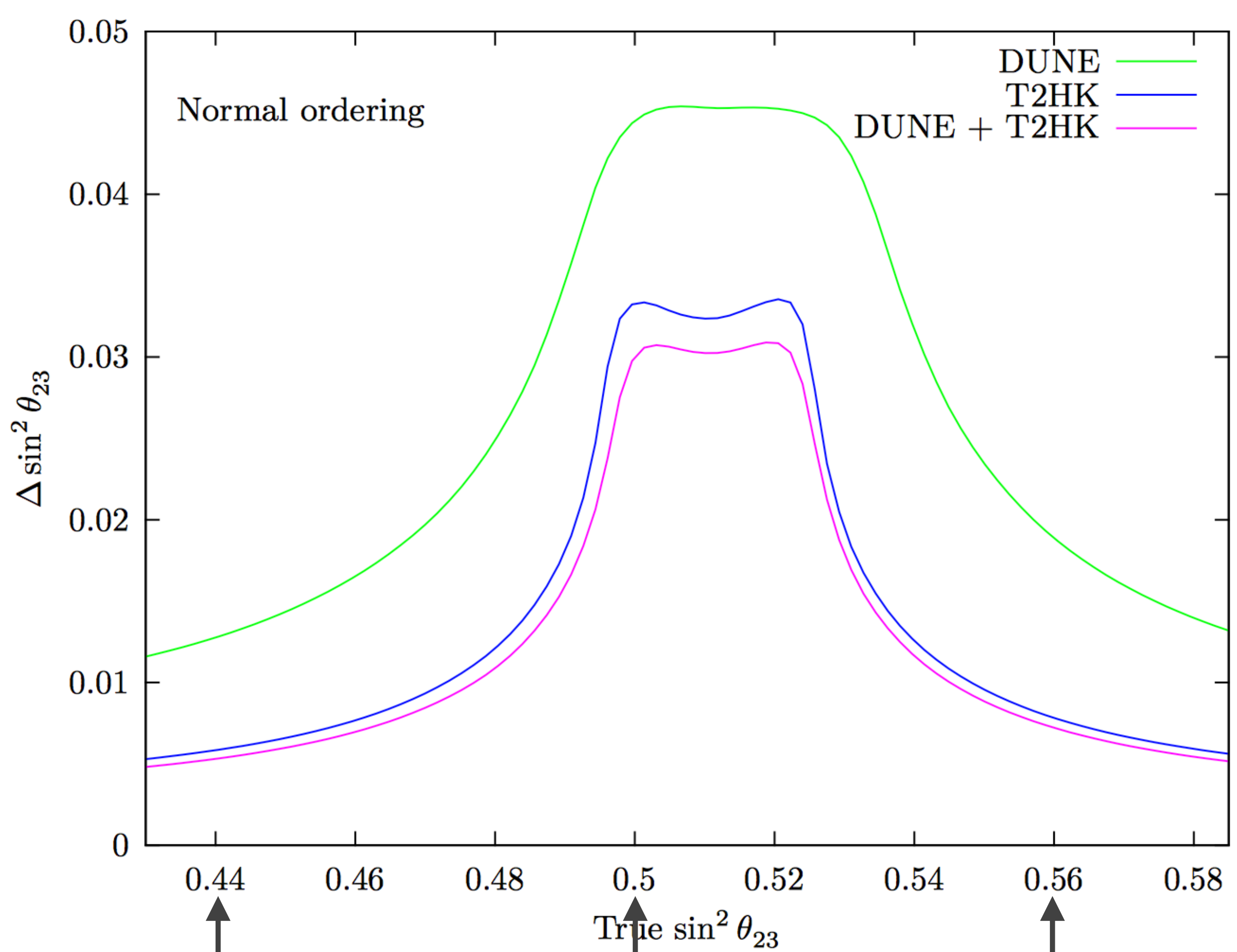


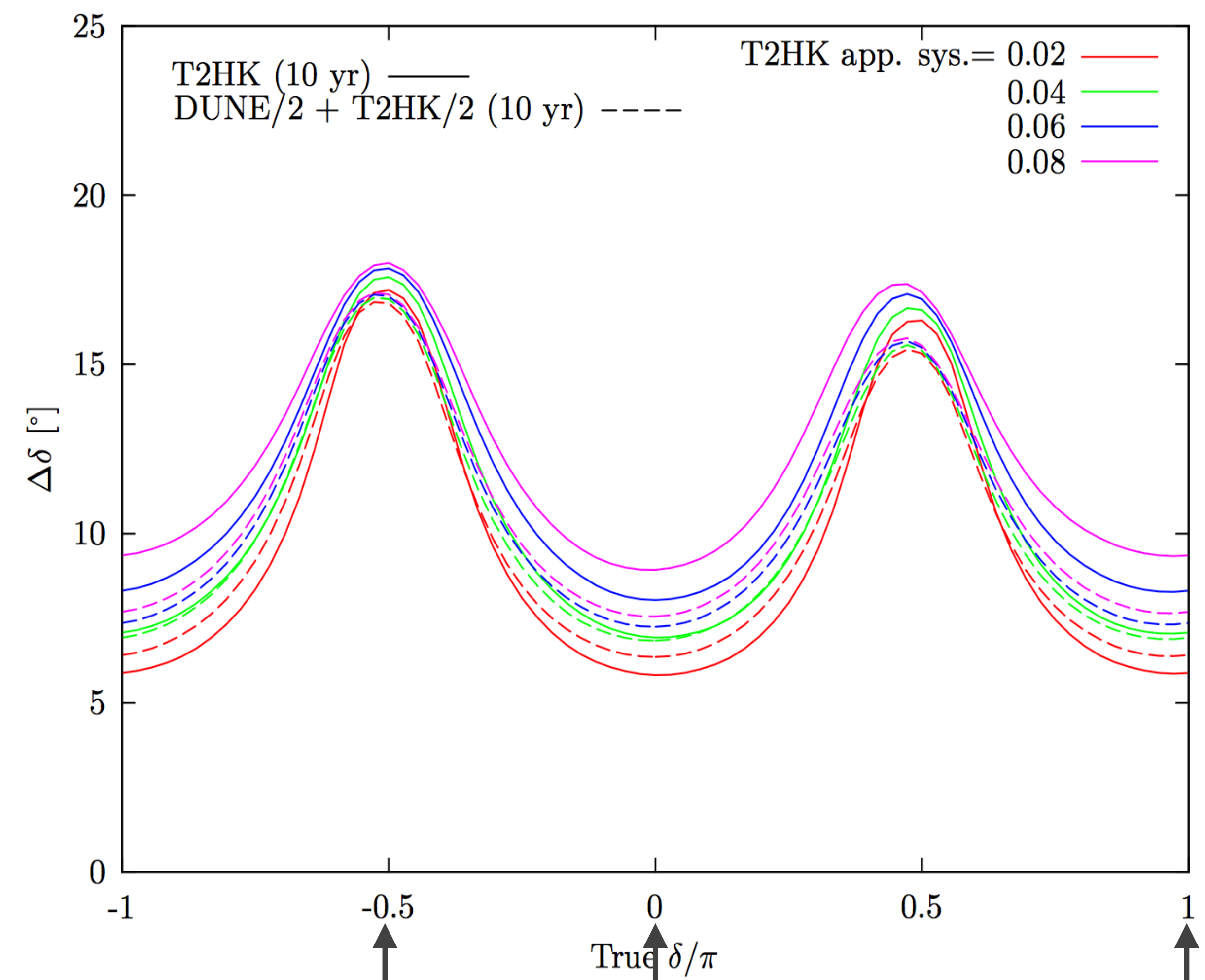
Lesson 2: flavor group broken to different subgroups:



Achievable and necessary precision

Ballet et al., 1612.07275





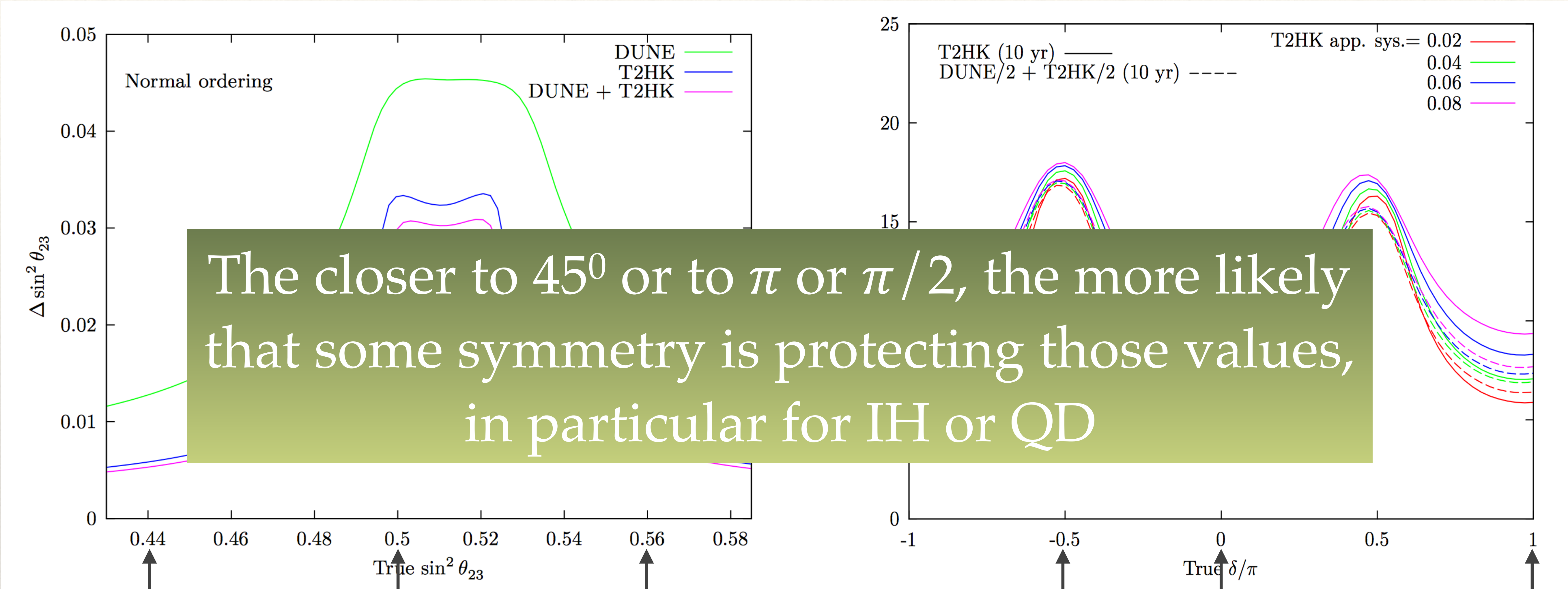
$(41.6 \pm 0.3)^0$ $(45 \pm 1.7)^0$ $(48.5 \pm 0.6)^0$

cos δ: (0 ± 0.29) (1 ± 0.006) (0 ± 0.28)

Interesting values can have larger uncertainties than less interesting ones…

Achievable and necessary precision

Ballet et al., 1612.07275



$(41.6\pm0.3)^0$ $(45\pm1.7)^0$ $(48.5\pm0.6)^0$

cos δ: (0 ± 0.29) (1 ± 0.006) (0 ± 0.28)

The closer to 45^0 or to π or $\pi/2$, the more likely that some symmetry is protecting those values, in particular for IH or QD

Interesting values can have larger uncertainties than less interesting ones…

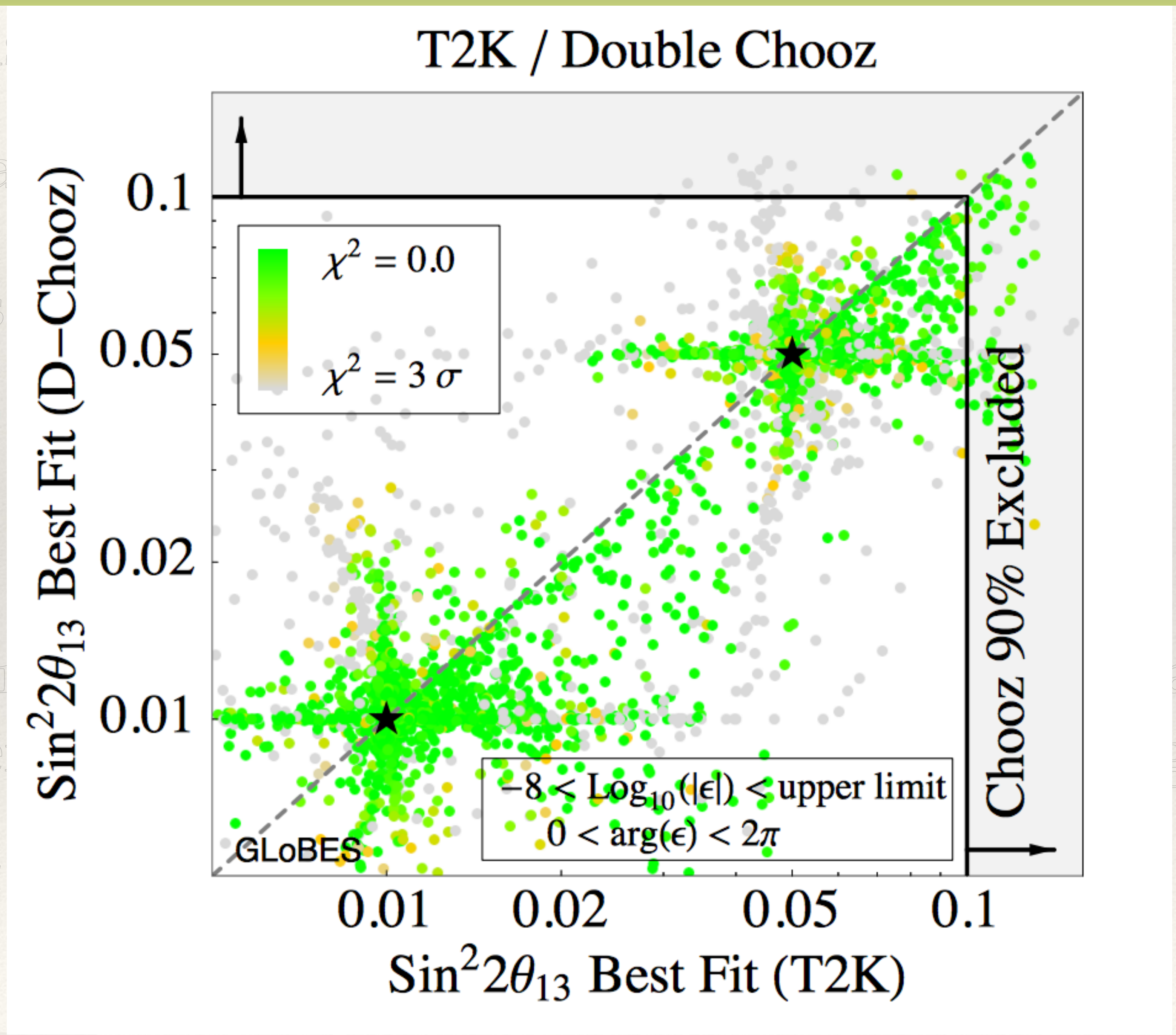
New Physics in Oscillations

- Various good reasons to expect NP:
  - unitarity violation from new fermions
  - NSIs from new physics: $G_F\,\varepsilon = g'^2/M_X^2 \Rightarrow \varepsilon \sim 0.01$ is TeV-scale
  - new interactions (scalar, tensor, etc.)
  - long-range forces
  - Lorentz/CPT violation: effects $\propto \Lambda/M_{Pl}$ with Λ scale of mass generation (seesaw!), in general growing with ν-energy (IC!)
  - light sterile neutrinos…

New Physics in Oscillations

New Physics can mess up oscillation experiments:

Kopp, Lindner, Ota, Sato, 0708.0152



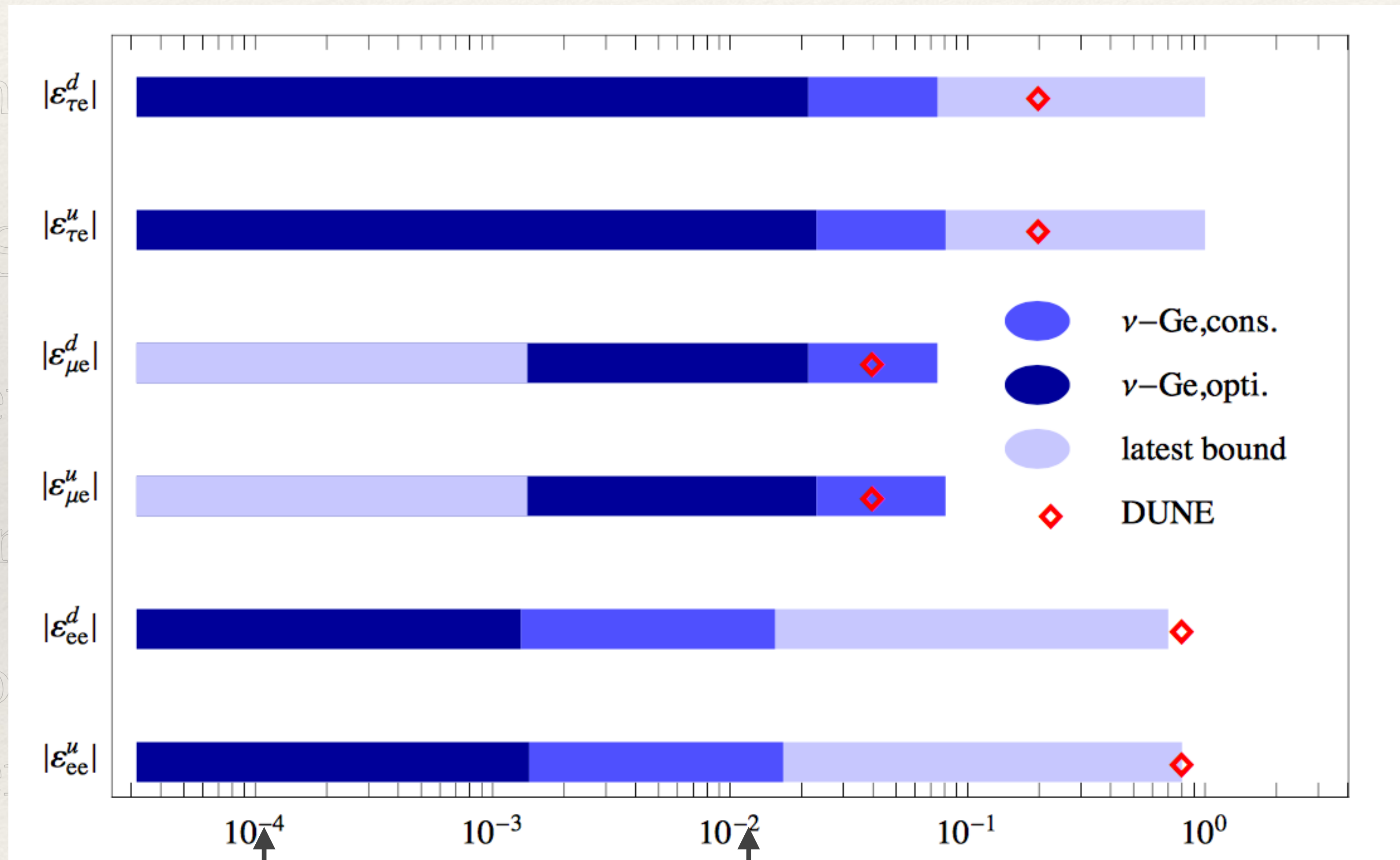
presence of multiple $\varepsilon_{\alpha\beta}$ can make determination of MO, δ and octant of θ_{23} impossible even for DUNE, T2HK and T2HKK

Liao, Marfatia, Whisnant, 1612.01443

New Physics in Oscillations

Next generation coherent scattering experiment (Talk by Hakenmüller):

Lindner, WR, Xu, 1612.04150



10 TeV

TeV

small scale vs. large scale…

- light sterile neutrinos…

Light Sterile Neutrinos

(Thursday parallel)

- not expected / predicted before LSND…
- would be bigger discovery than massive neutrinos
- could be window to new world (new interactions, coupling to DM,…)
- would imply modification of cosmology analyses, possibly non-standard cosmology *(talks by Saviano, Elvin-Poole)*
- experimentally, need
  - to know flux precisely…
  - to know cross section precisely…
  - to see oscillatory pattern…
- ***small scale experiments will tell*** ***(at least the ee-anomalies)***

Origin of Neutrino Mass

- Most straightforward possibility: add N_R and obtain Dirac mass:

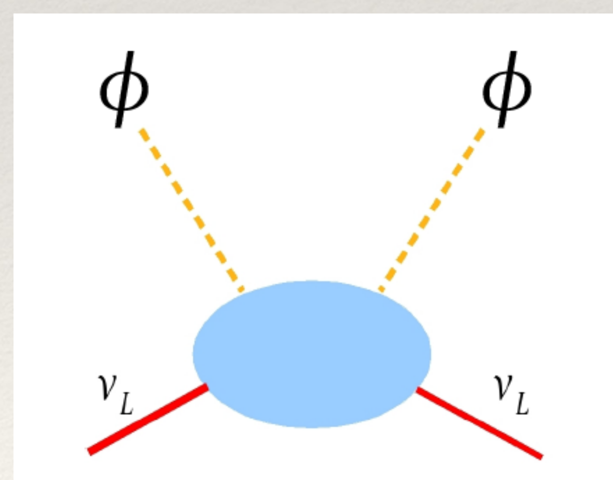
$$L\,\Phi\,N_R \to m_D\,\nu_L\,N_R$$

- <u>Gauge invariance</u> allows Majorana mass:

$$M_R\,N_R\,N_R$$

- in total Majorana mass for SM neutrinos:

$m_\nu\,\nu_L^c\,\nu_L$ with $\boldsymbol{m_\nu = m_D^2/M_R} = m_D\,\varepsilon$ with $\varepsilon = m_D/M_R = m_{SM}/M_R$



m_ν inverse proportional to scale of origin!

Origin of Neutrino Mass

New representation of SM gauge group $N_R \sim (1,0)$

- Most straightforward possibili... mass

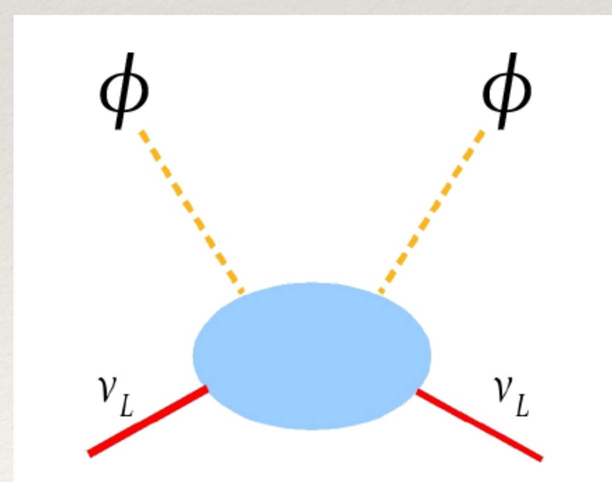
  $$\ldots N_R \to m_D \, \nu_L N_R$$

- Gauge invariance allows Majorana mass

  $$M_R \, N_R \, N_R$$

- in total Majorana mass for SM neutrinos:

  $m_\nu \, \nu_L^c \, \nu_L$ with $\boldsymbol{m_\nu = m_D^2 / M_R} = m_D \, \varepsilon$ with $\varepsilon = m_D / M_R = m_{SM} / M_R$



m_ν inverse proportional to scale of origin!

Origin of Neutrino Mass

- Most straightforward possibili... mass

  New representation of SM gauge group $N_R \sim (1,0)$

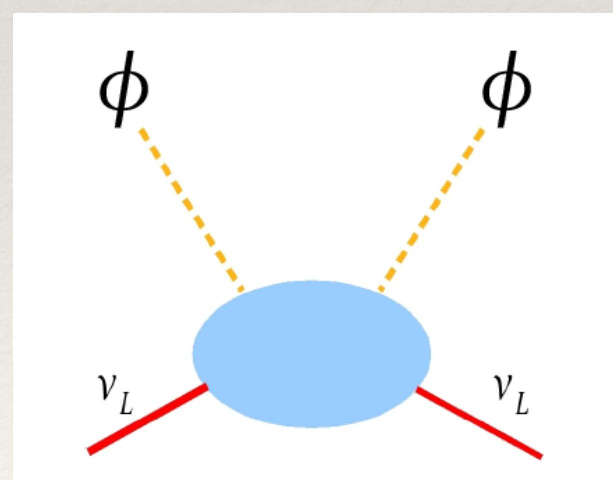
  $\ldots N_R \to m_D\, \nu_L N_R$

- Gauge invariance allows Majorana mass

  New energy scale beyond SM

- in total Majorana mass for SM neutrinos:

  $m_\nu\, \nu_L^c\, \nu_L$ with $\boldsymbol{m_\nu = m_D^2 / M_R} = m_D\, \varepsilon$ with $\varepsilon = m_D/M_R = m_{SM}/M_R$



m_ν inverse proportional to scale of origin!

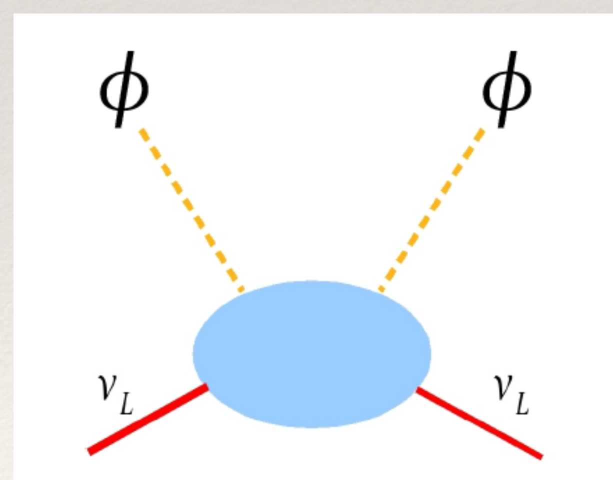
Origin of Neutrino Mass

- Most straightforward possibili… mass
  $N_R \to m_D\, \nu_L N_R$
- Gauge invariance allows Majorana mass
- in total Majorana mass for SM neutrinos:
  $m_\nu\, \nu_L{}^c\, \nu_L$ with … m_{SM}/M_R

New representation of SM gauge group $N_R \sim (1,0)$

New energy scale beyond SM

New concept: lepton number violation

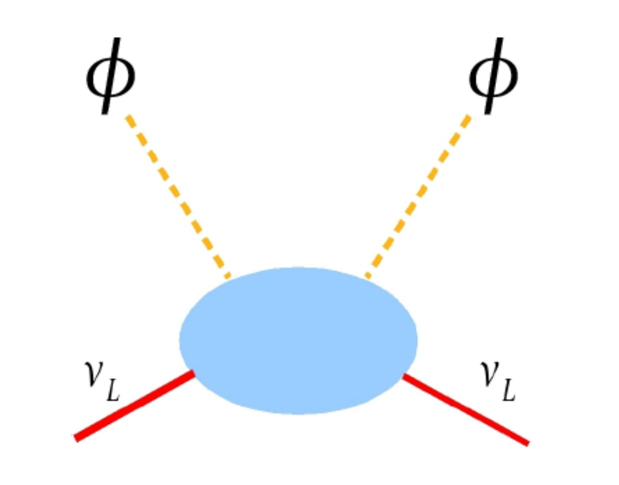


m_ν inverse proportional to scale of origin!

Origin of Neutrino Mass

- Most straightforward possibility: add N_R and obtain Dir...
  $$L\,\Phi\,N_R \to m_D\,\nu_L\,N_R$$
- Gauge invariance allows Majorana mas...
  $$M_R \dots$$
- in total Majorana mas... ...eutrinos:
  $m_\nu\,\nu_L^c\,\nu_L$ with ... $/\boldsymbol{M_R} = m_D\,\varepsilon$ with $\varepsilon = m_D/M_R = m_{SM}/M_R$

plus possible new interactions of N_R (B-L, LR Symmetry, etc.)



m_ν inverse proportional to scale of origin!

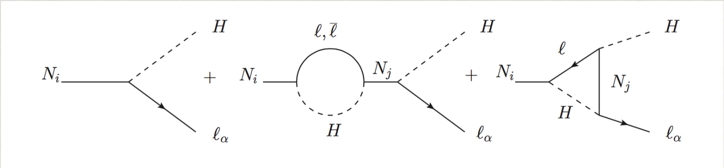
Type I Seesaw $m_\nu = m_D^2 / M_R$

actually, does neither fix m_ν nor m_D nor M_R

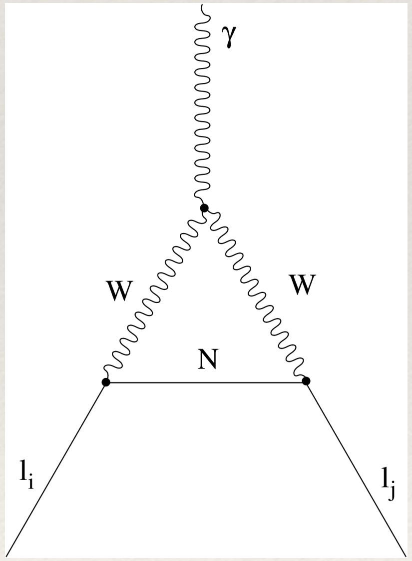
needs to be tested or has phenomenology via *„seesaw portal"*

Lepton-Higgs-Singlet Vertex: $L\, \Phi\, N_R$

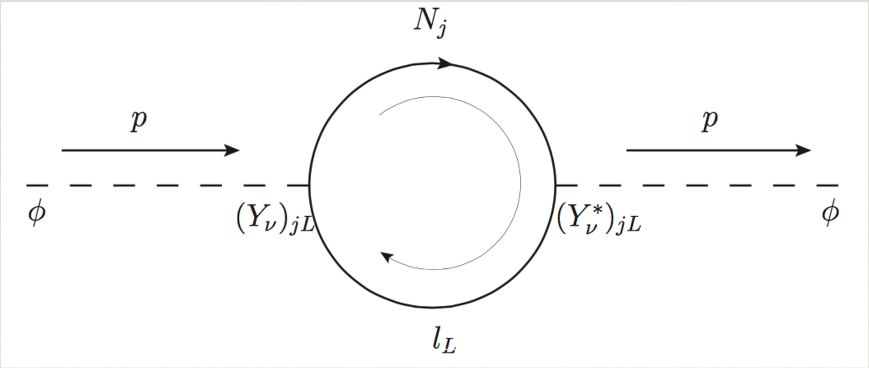
$N_R \to L\, \Phi$ $\quad$ $L_\alpha \to N_R\, \Phi \to L_\beta$ $\quad$ $\Phi \to L\, N_R \to \Phi$



Leptogenesis



Lepton Flavor Violation

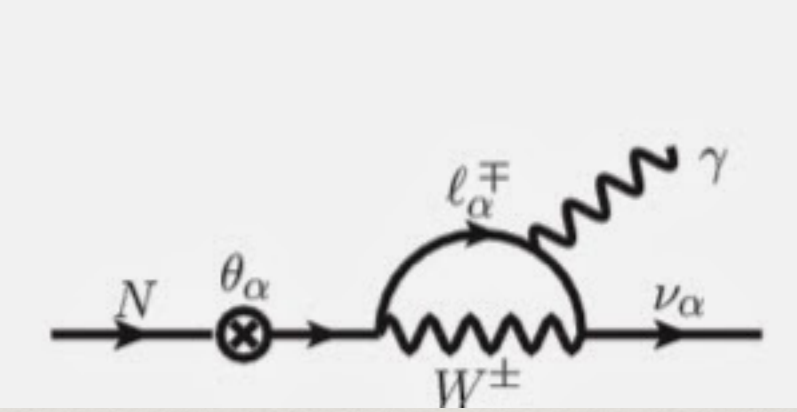


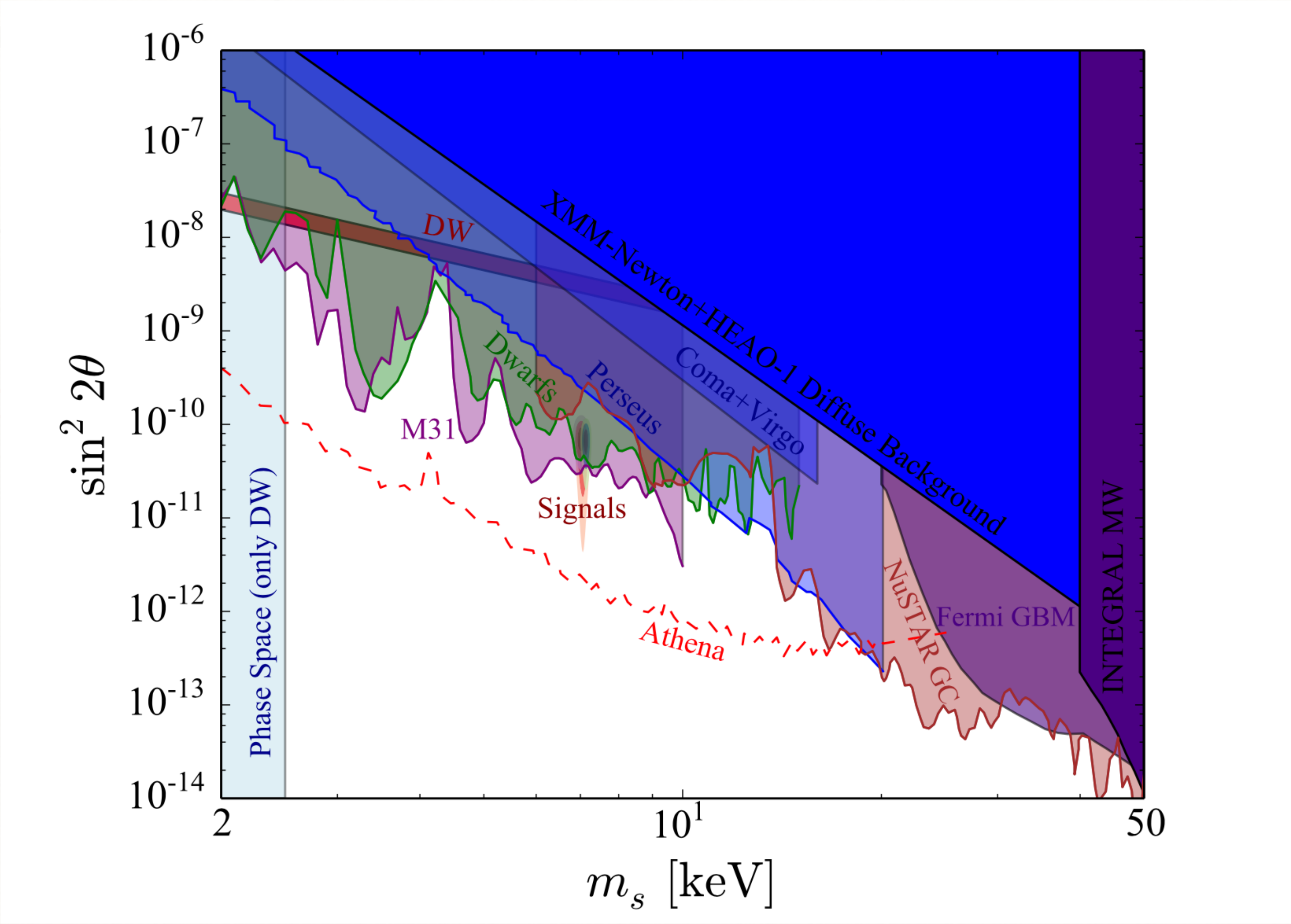
Vacuum stability, naturalness

(plus indirect test with 0νββ)

Type I Seesaw $m_\nu = m_D^2 / M_R$

plus: provides a DM candidate



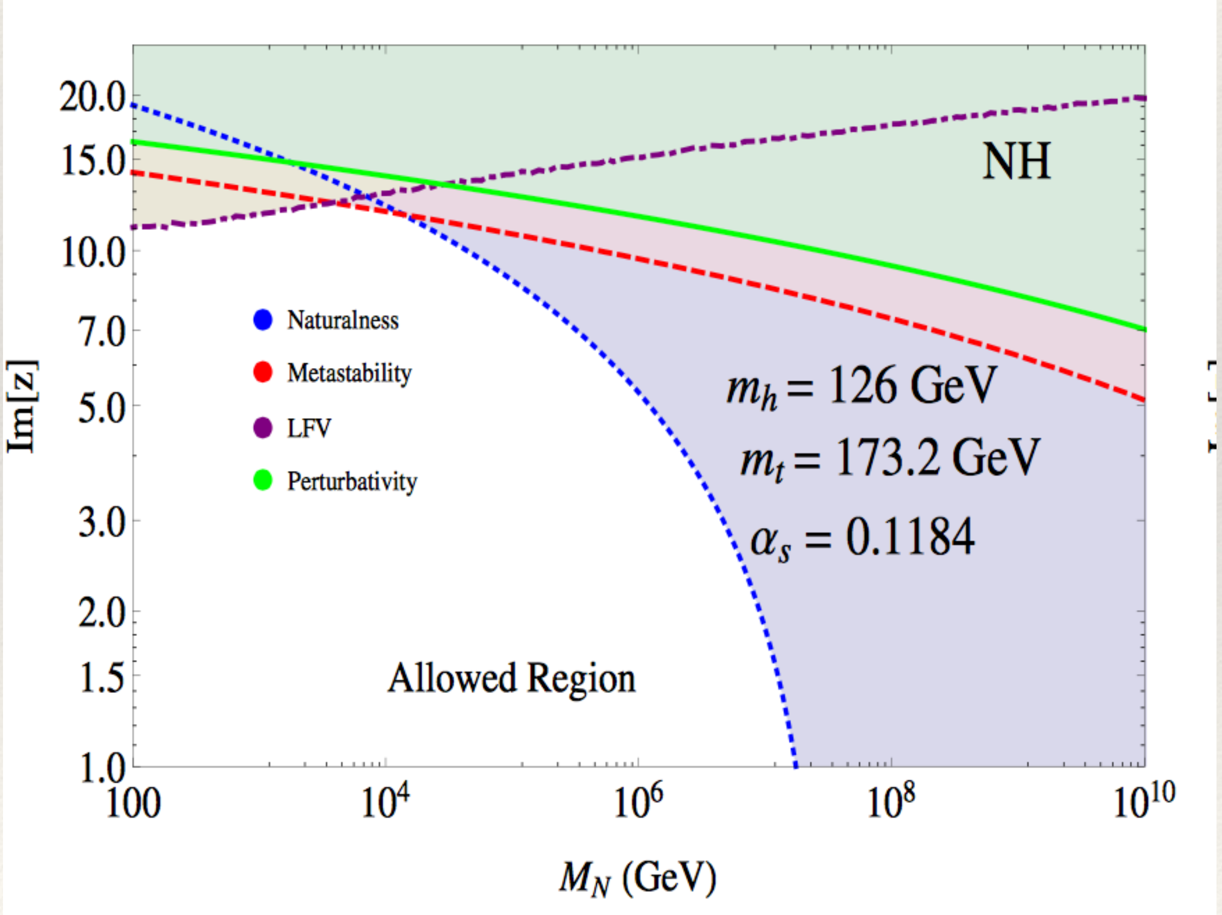


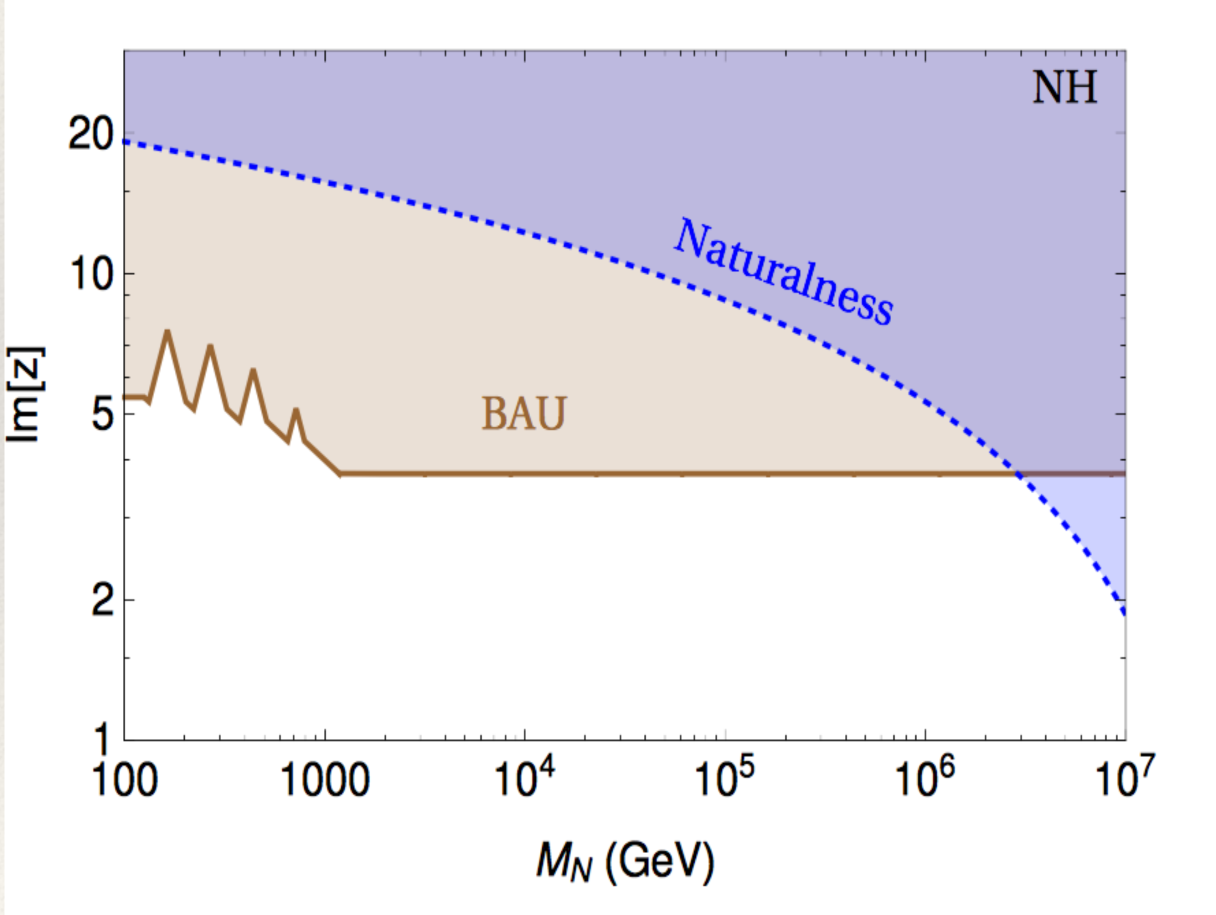
Abazajian, 1705.01837

Type I Seesaw $m_\nu = m_D^2 / M_R$

simplest example, two degenerate RH neutrinos

free parameters: mass M_N and complex parameter z





Bambhaniya et al., 1611.03827

Pathways to Neutrino Mass

similar discussion for all thinkable and unthinkable mass mechanisms

approach	ingredient	quantum number of messenger	$\mathcal{L}$	m_ν	scale
"SM" (Dirac mass)	RH ν	$N_R \sim (1,0)$	$h \overline{N_R} \Phi L$	$h v$	$h = \mathcal{O}(10^{-12})$
"effective" (dim 5 operator)	new scale + LNV	–	$h\, \overline{L^c}\, \Phi\, \Phi\, L$	$\frac{h\, v^2}{\Lambda}$	$\Lambda = 10^{14}$ GeV
"direct" (type II seesaw)	Higgs triplet + LNV	$\Delta \sim (3,-2)$	$h \overline{L^c} \Delta L + \mu \Phi \Phi \Delta$	$h v_T$	$\Lambda = \frac{1}{h\mu} M_\Delta^2$
"indirect 1" (type I seesaw)	RH ν + LNV	$N_R \sim (1,0)$	$h \overline{N_R} \Phi L + \overline{N_R} M_R N_R^c$	$\frac{(hv)^2}{M_R}$	$\Lambda = \frac{1}{h} M_R$
"indirect 2" (type III seesaw)	fermion triplets + LNV	$\Sigma \sim (3,0)$	$h \overline{\Sigma}\, L \Phi + \mathrm{Tr} \overline{\Sigma} M_\Sigma \Sigma$	$\frac{(hv)^2}{M_\Sigma}$	$\Lambda = \frac{1}{h} M_\Sigma$

plus seesaw variants (linear, inverse, double, singular,…)

plus radiative mechanisms

plus higher dimensional operators

plus extra dimensional

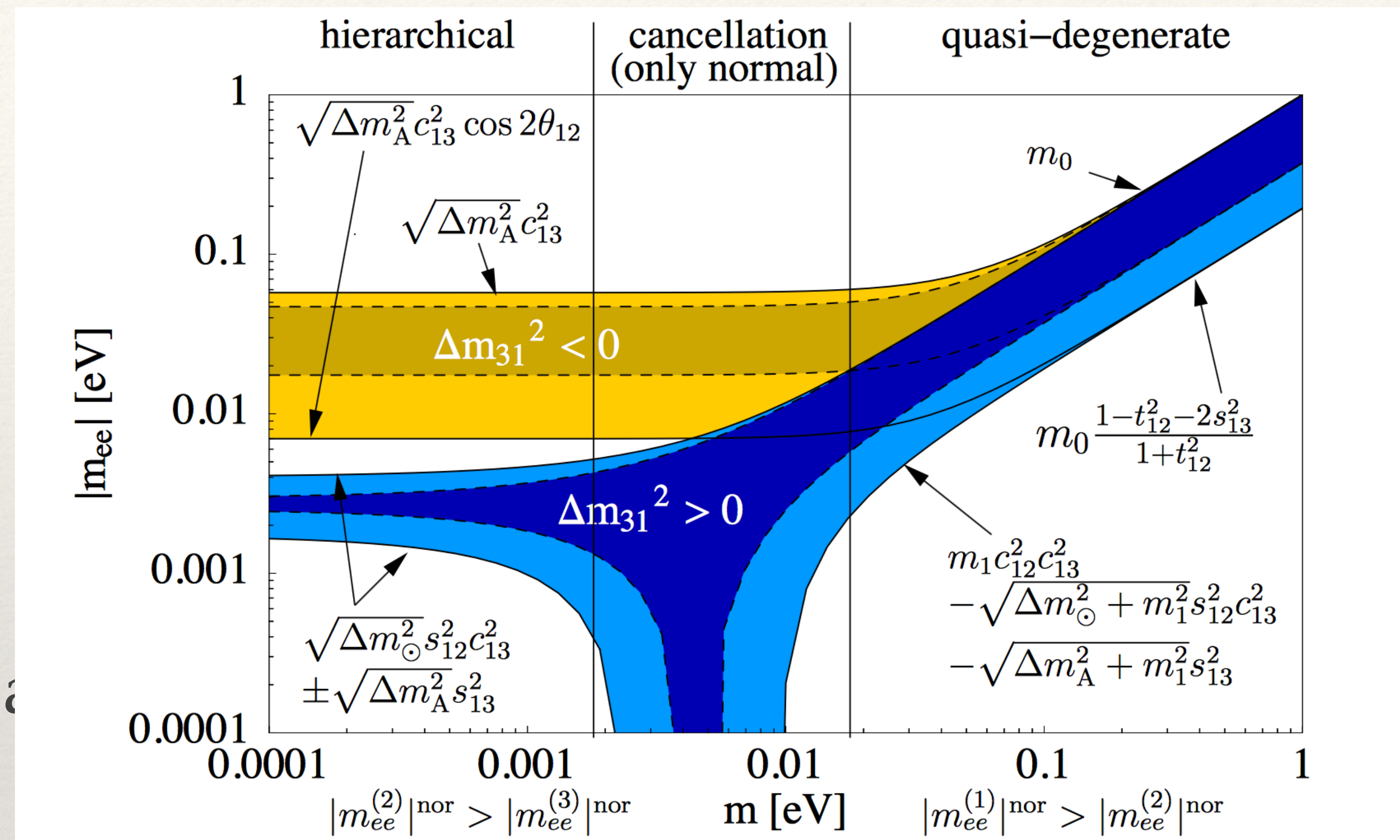
plus plus plus

Common Prediction: Lepton Number Violation

Talk by Schönert

Chi l'ha visto?

Ettore Majorana, ordinario di fisica teorica all' Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Marianecci, Viale Regina Margherita 66 - Roma.

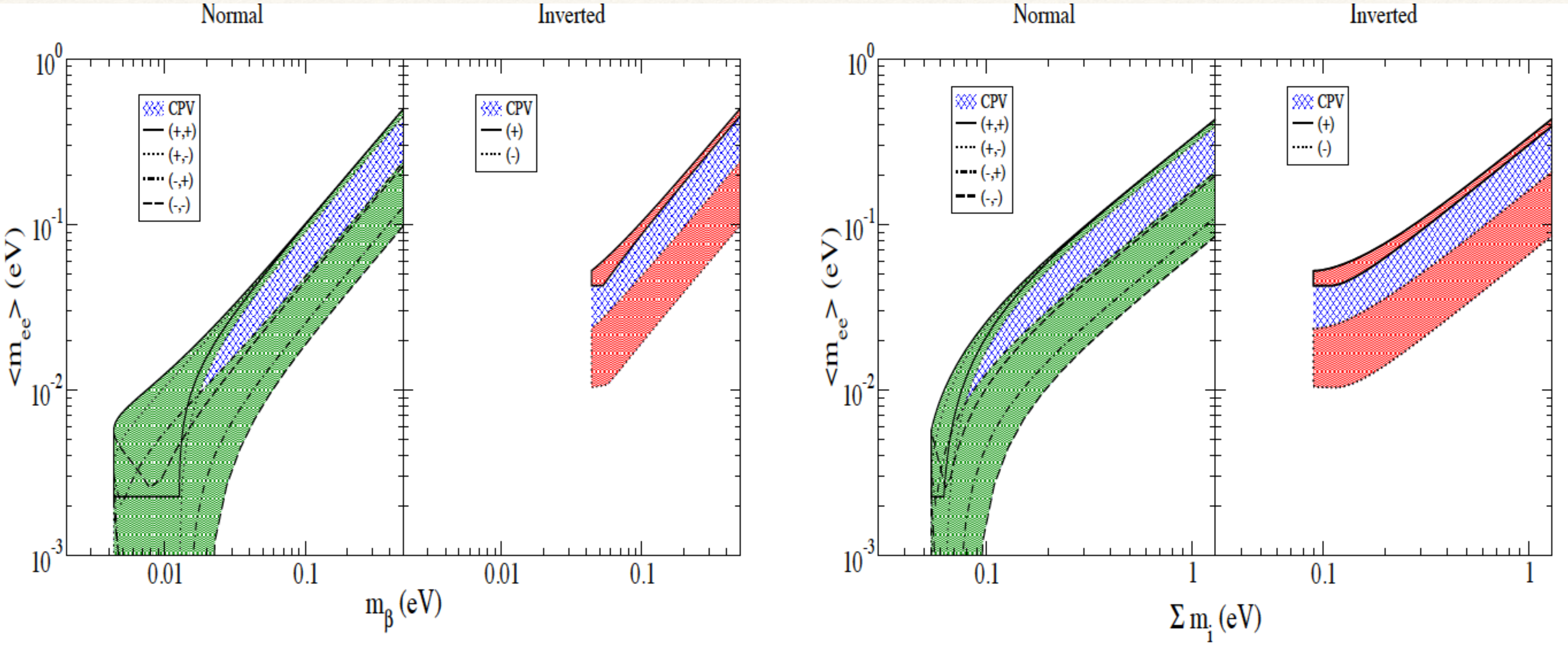


$$|m_{ee}| = \left|\sum U_{ei}^2\, m_i\right| = \left|U_{e1}^2\, m_1 + U_{e2}^2\, m_2 e^{i\alpha} + U_{e3}^2\, m_3 e^{i\beta}\right|$$

$$= f\left(\theta_{12}, |U_{e3}|, m_i, \mathrm{sgn}(\Delta m_A^2), \alpha, \beta\right)$$

known — limits — unknown

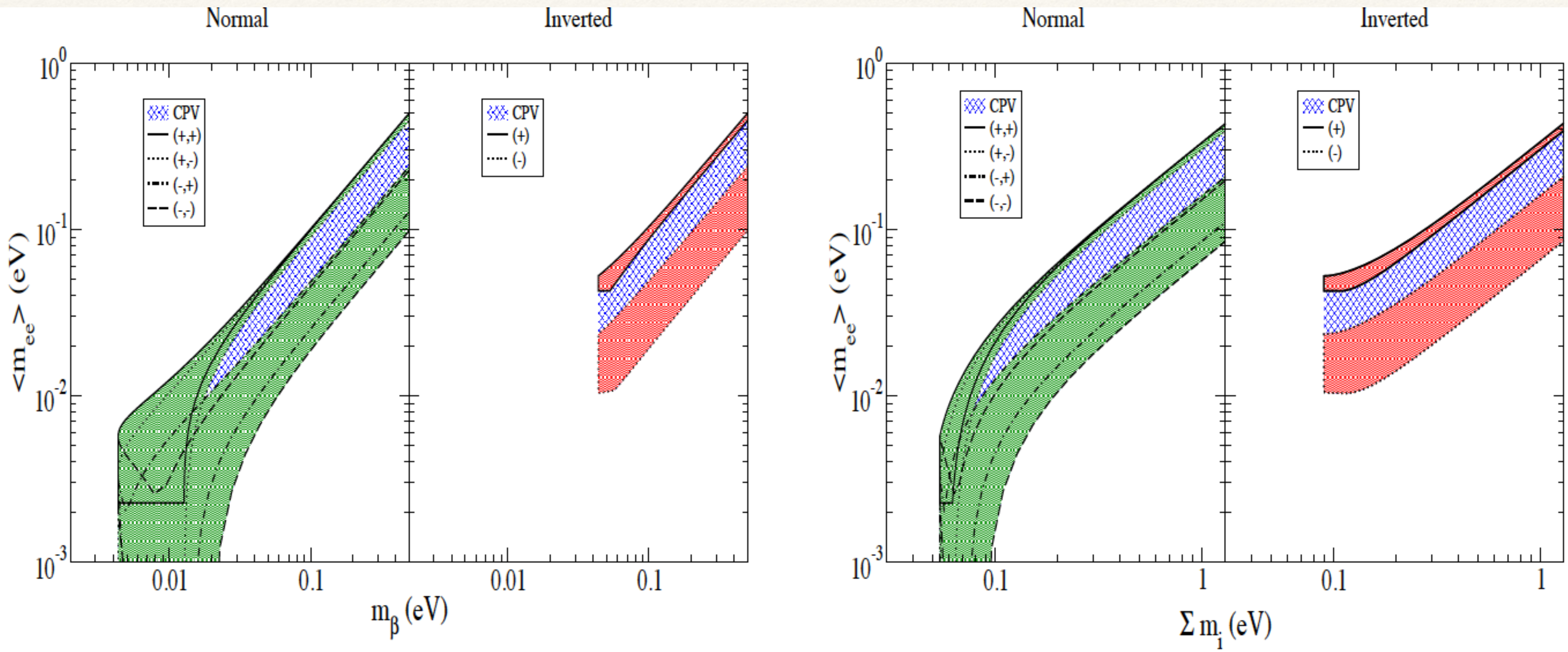
Neutrino Mass Observables



complete complementarity of observables

- $0\nu\beta\beta$ rules out that neutrinos saturate Mainz-limit
- $0\nu\beta\beta$ and cosmology currently roughly the same
- cosmology strongly disfavors a signal in KATRIN

Neutrino Mass Observables

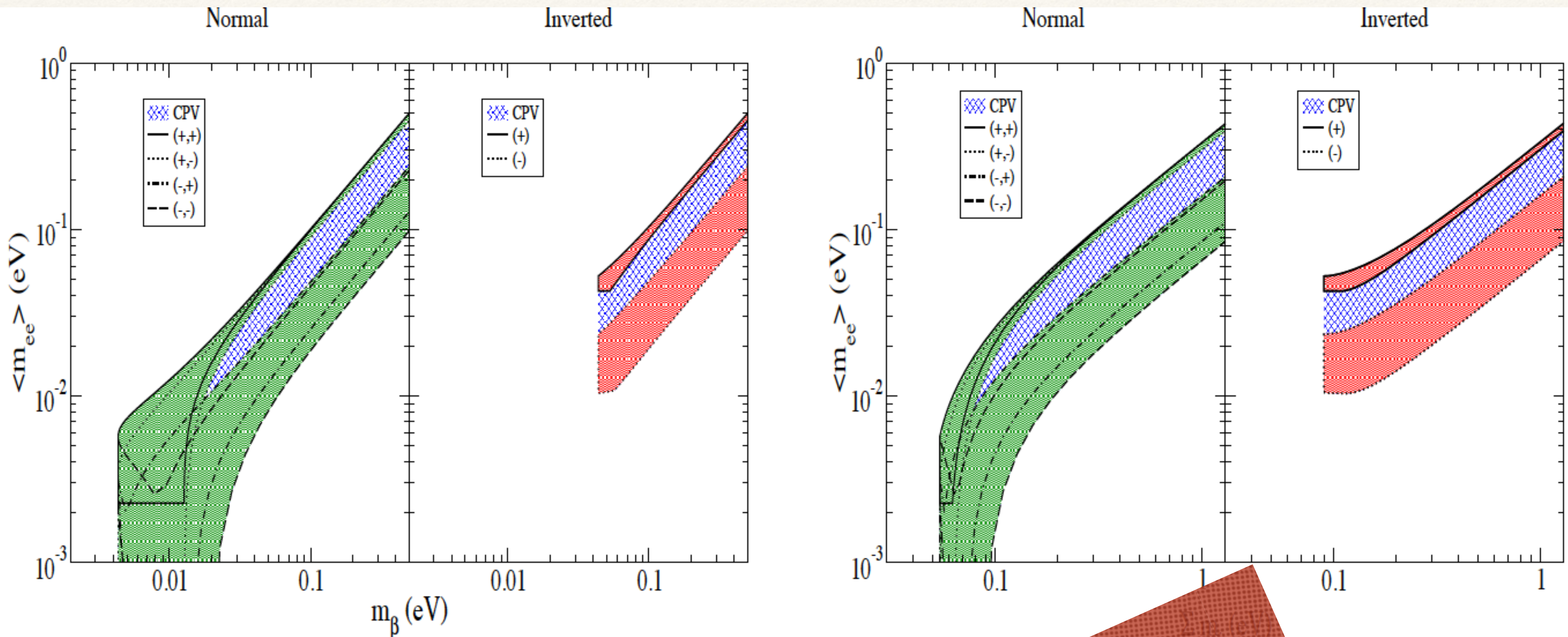


complete complementarity of observables

- 0νββ rules out that neutrin... e Mainz-limit
- 0νββ and cosm... ntly roughly the same
- cosmo... ngly disfavors a signal in KATRIN

All need to be pursued!

Neutrino Mass Observables

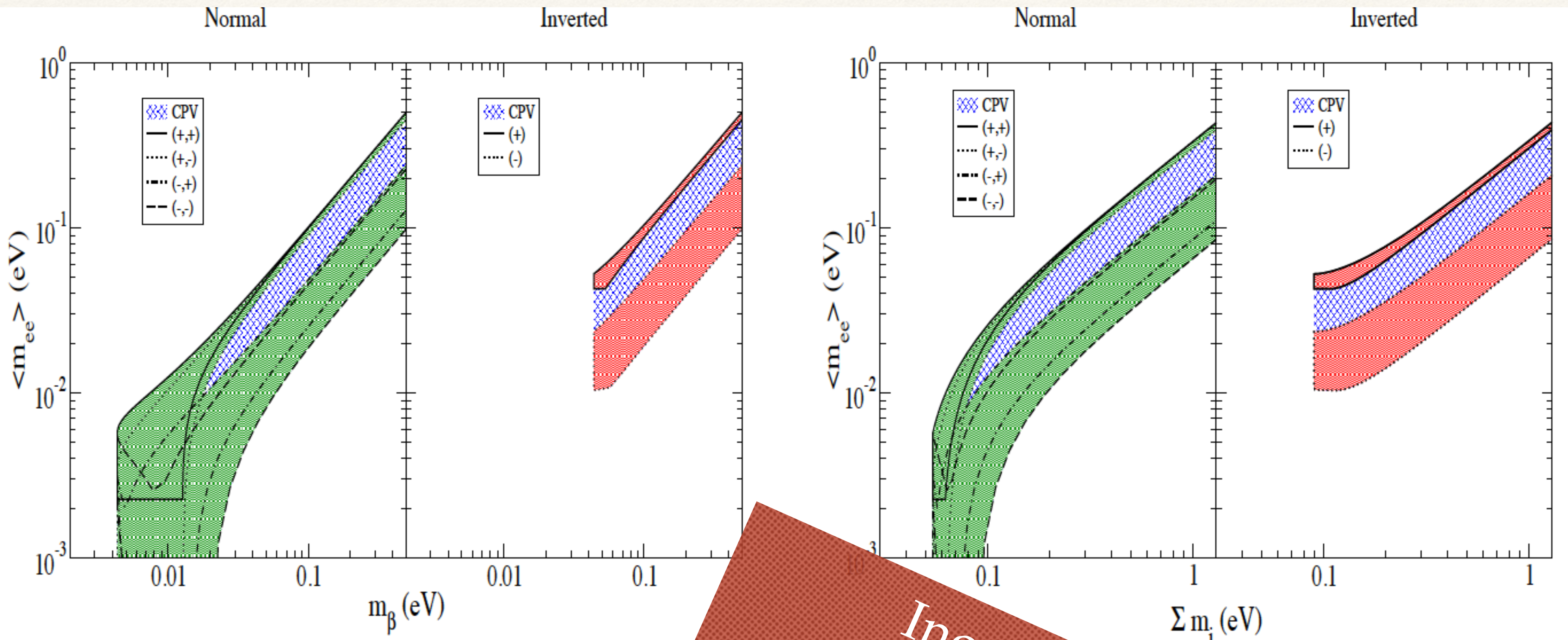


complete complementarity of observables

- 0νββ rules out t[illegible] Mainz-limit
- 0νββ and [illegible]ughly the same
- cosmology [illegible]sfavors a signal in KATRIN

Consistency would be spectacular confirmation !

Neutrino Mass Observables



complete complementarity of observables

- 0νββ rules out that … Mainz-limit
- 0νββ and cosmolog… …ghly the same
- cosmology strongly disfavors a signal in KATRIN

Inconsistencies would be major discovery!

New Physics with m_ν Experiments

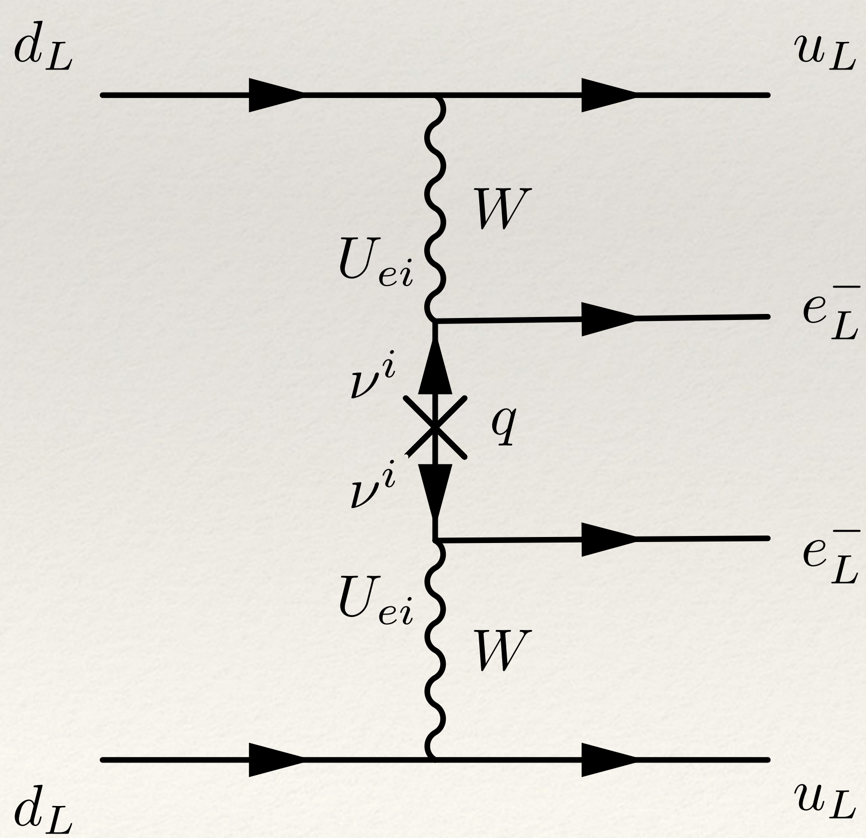
- $0\nu\beta\beta$ constrains many models and could provide most fundamental discovery in the field!
- cosmology limits sensitive to new physics (H_0, ω_{DE}, $N_{\rm eff}$,…)
- KATRIN etc. can do more:
  - eV-scale steriles
  - keV steriles if full spectrum is measured…
  - exotic CC interactions (scalar, tensor, etc.) if full spectrum is measured (TeV-scale physics!)

New Physics in Double Beta Decay

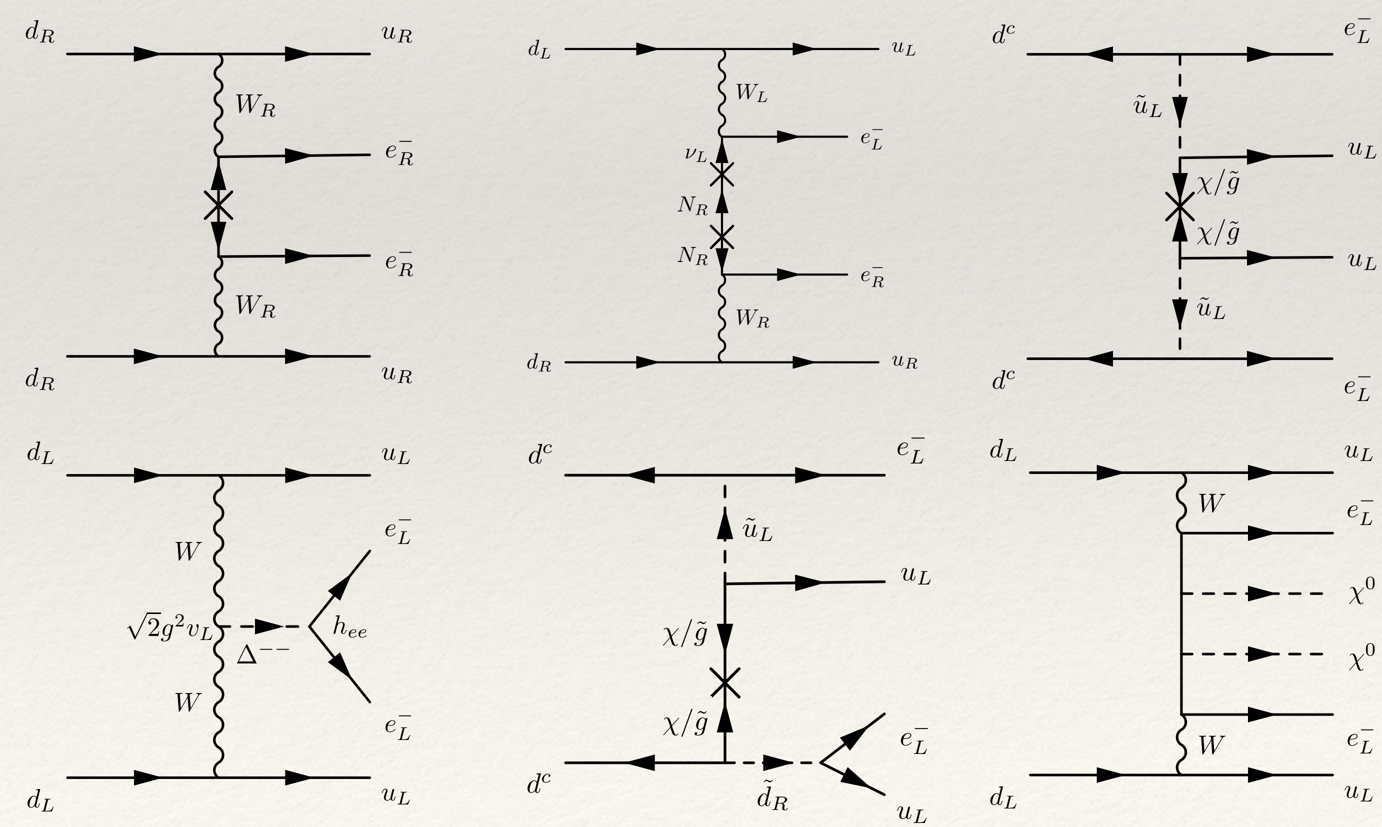
<u>Double Beta Decay is $\Delta L = 2$, not neutrino mass!</u>

Interpretations:

Standard:



Non-Standard:



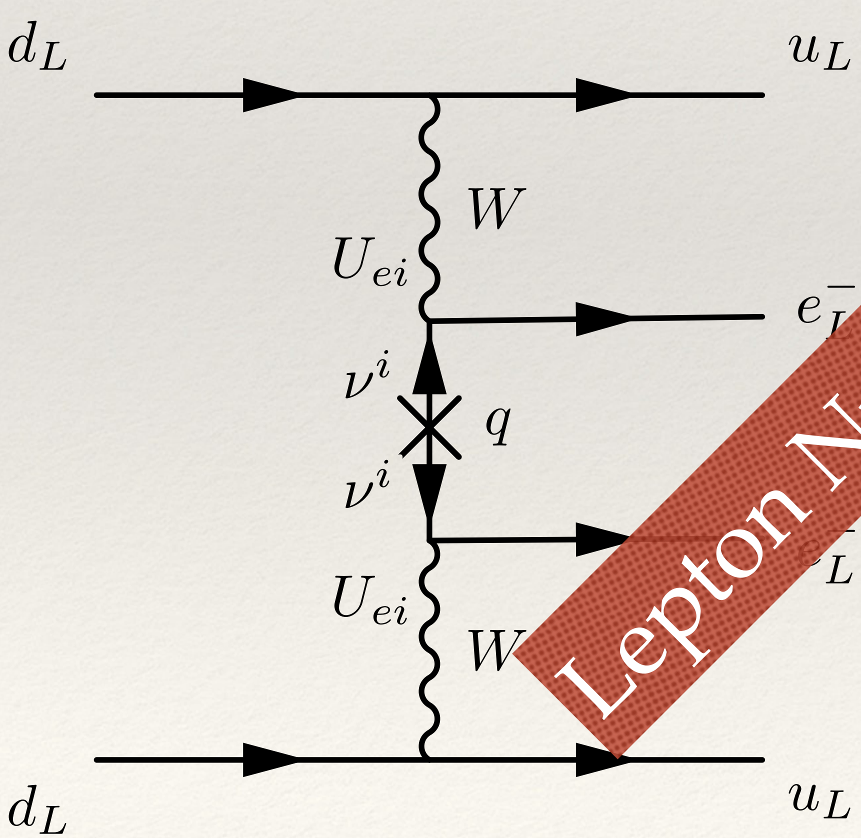
New Physics in Double Beta Decay

Double Beta Decay is $\Delta L = 2$, not neutrino mass!

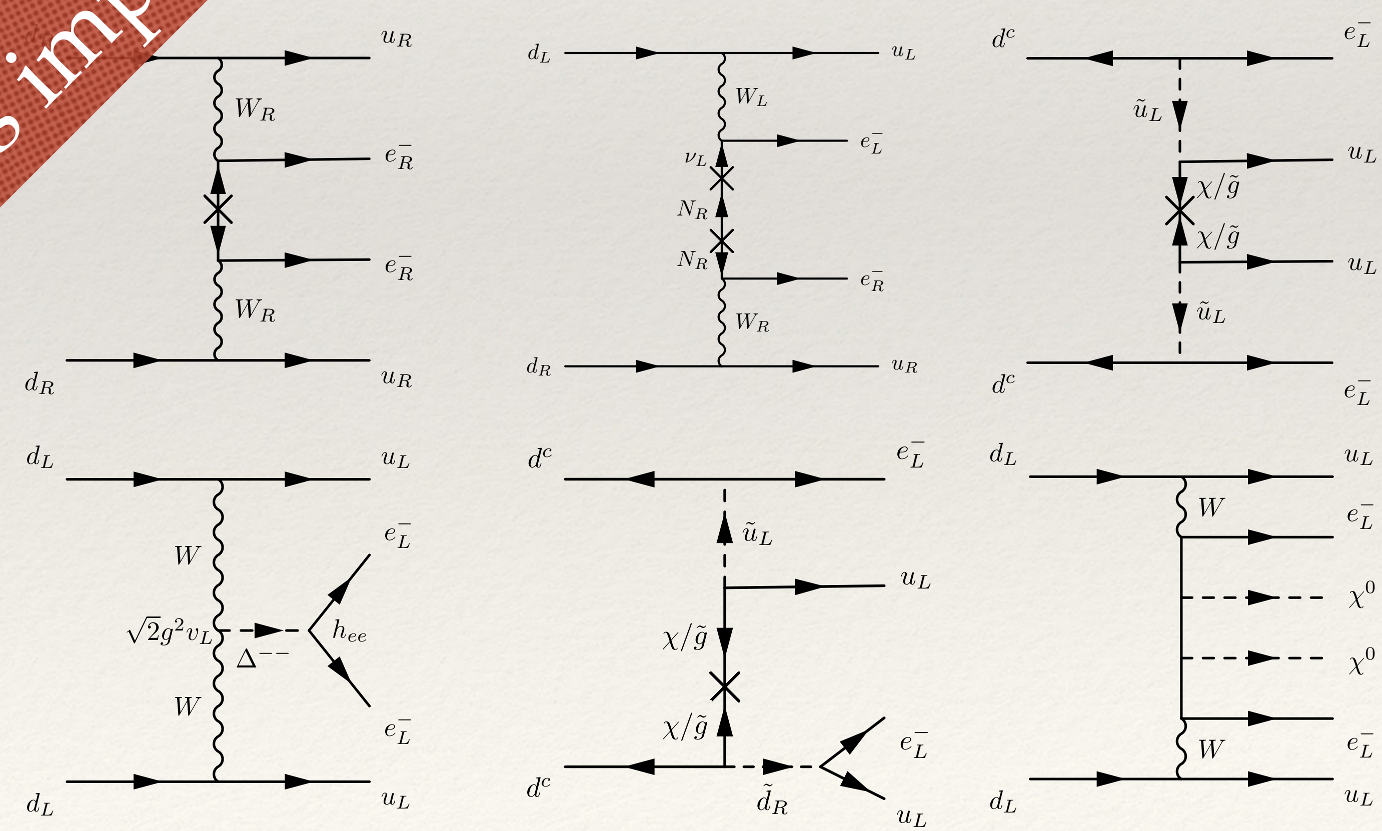
Lepton Number as important as Baryon Number

Interpretations:

Standard:

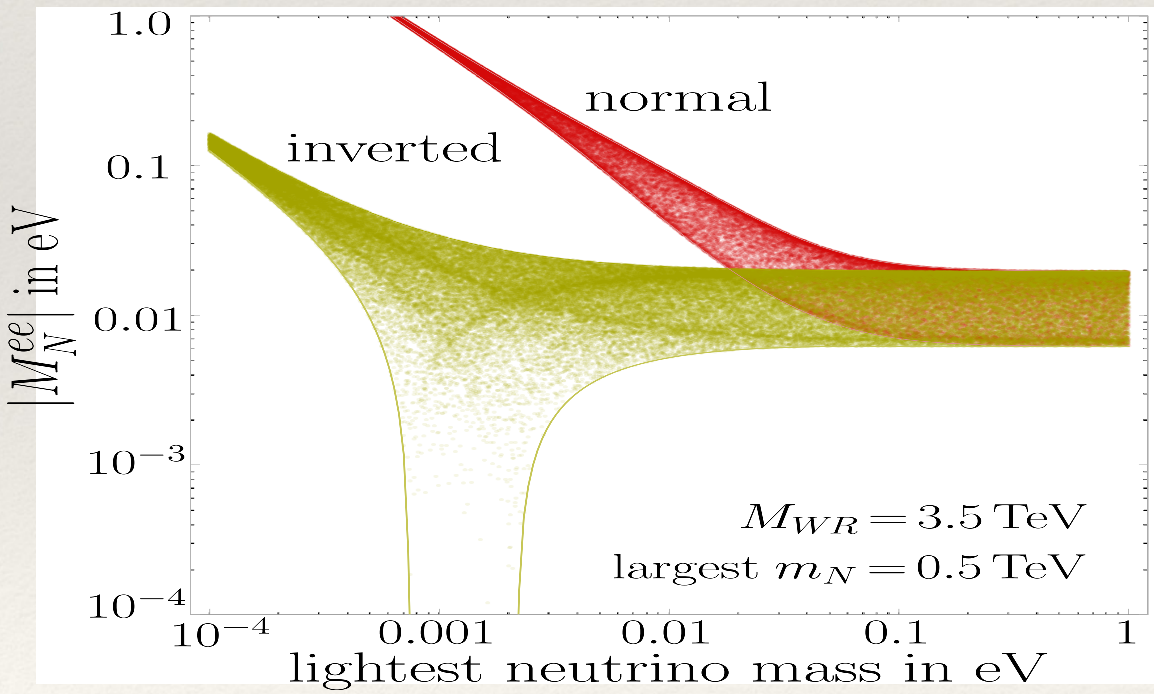


Non-Standard:

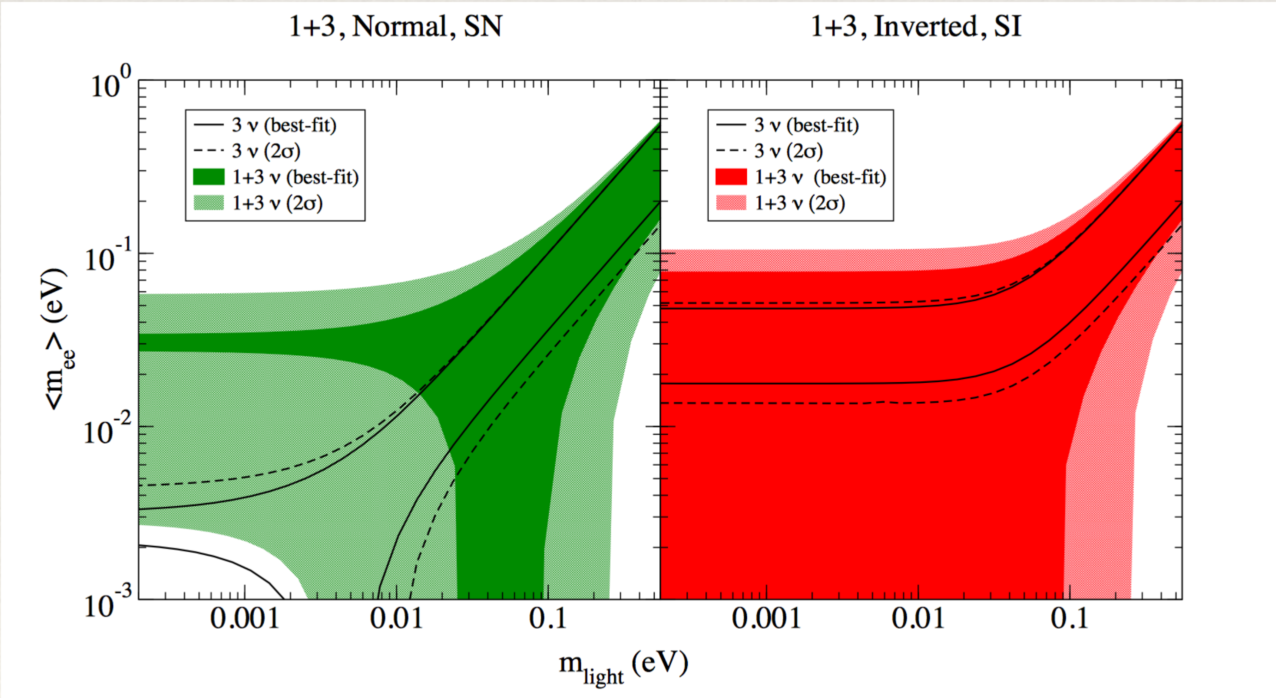


New Physics in Double Beta Decay

- LNV predicted by many BSM theories (Left-Right Symmetry, RPV SUSY, GUTs,…)
- breaks connection between cosmology limits and 0νββ
- spoils usual arguments of mass ordering / neutrino character:



Senjanovic et al., 1011.3522

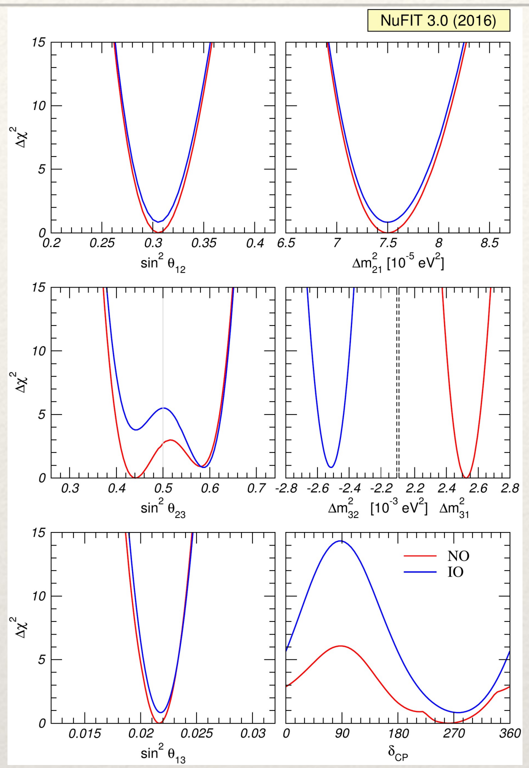


Barry, WR, Zhang, 1105.3911

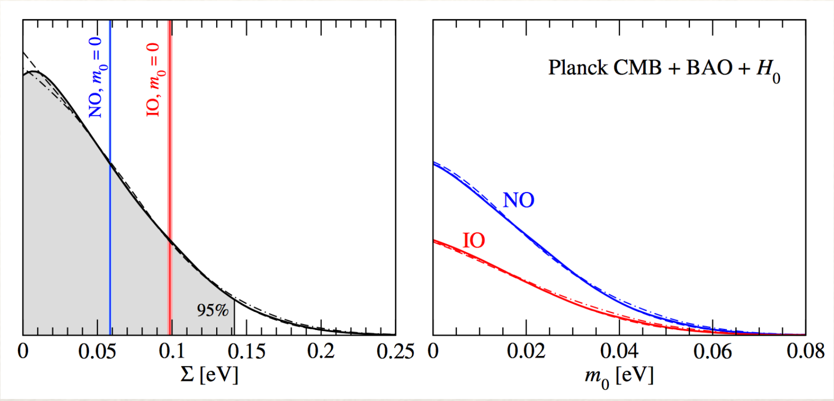
Expectations for half-lifes

Ge, WR, Zuber, to appear, see also 1705.02996; 1705.01945, talk by Benato

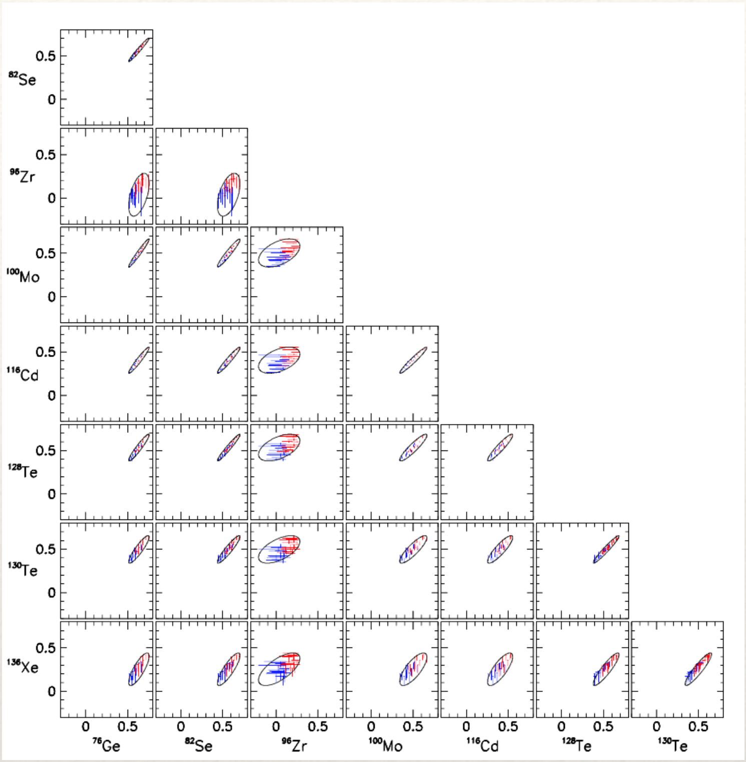
oscillation fits



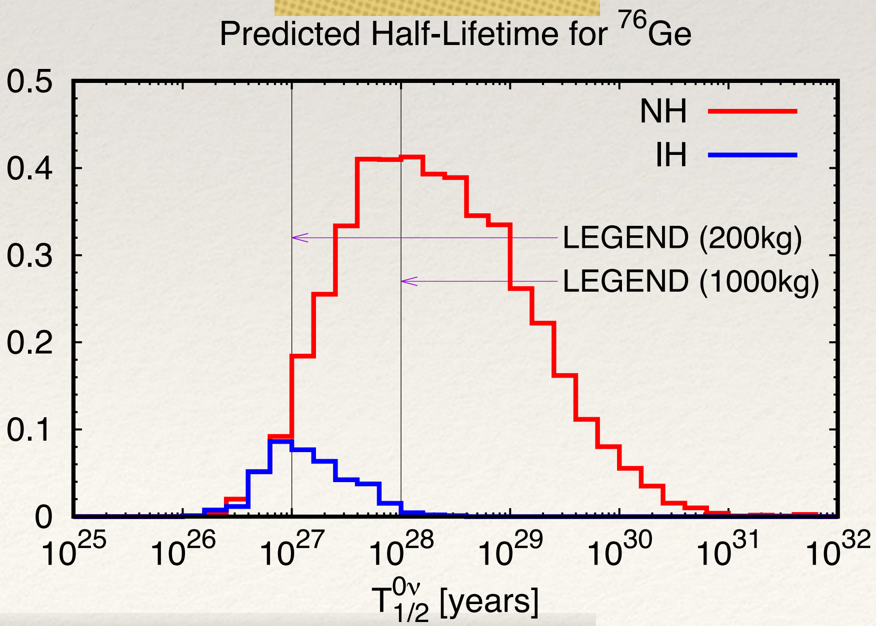
cosmology fits



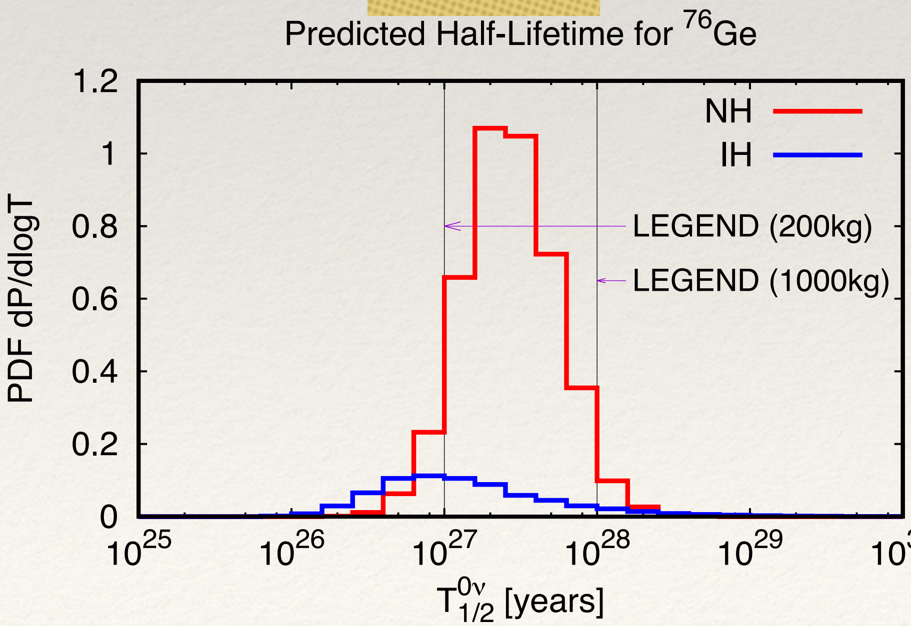
NME errors



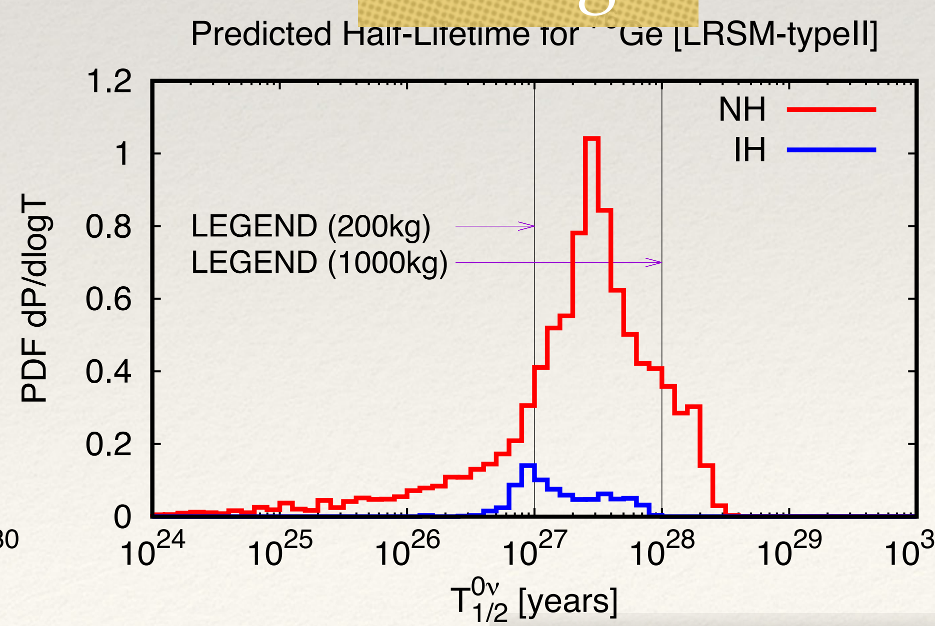
Standard



Sterile



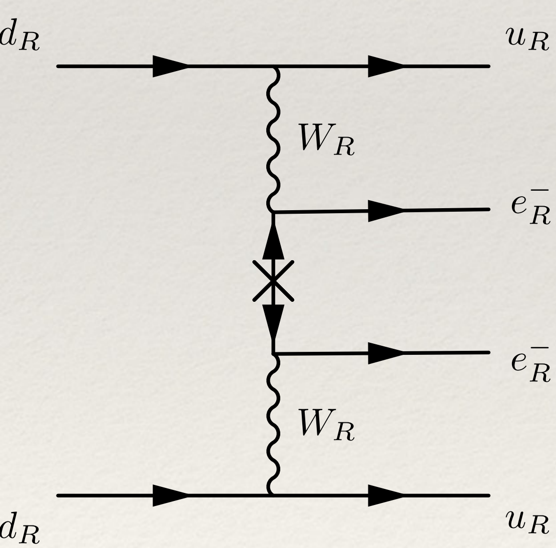
Left-right

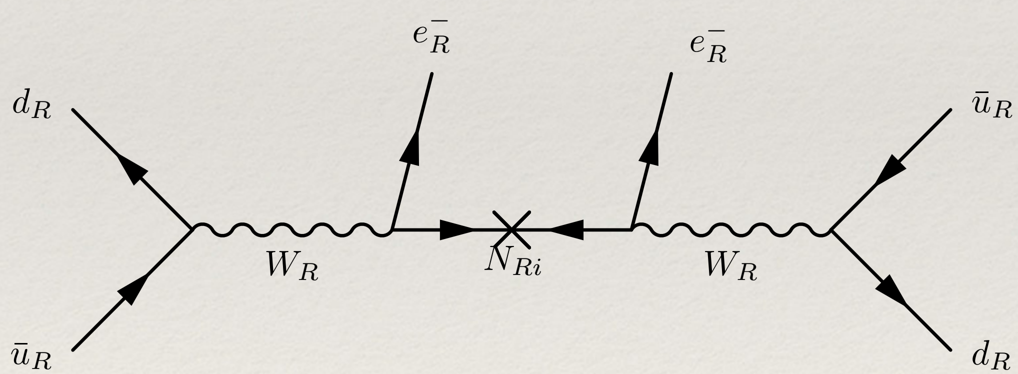


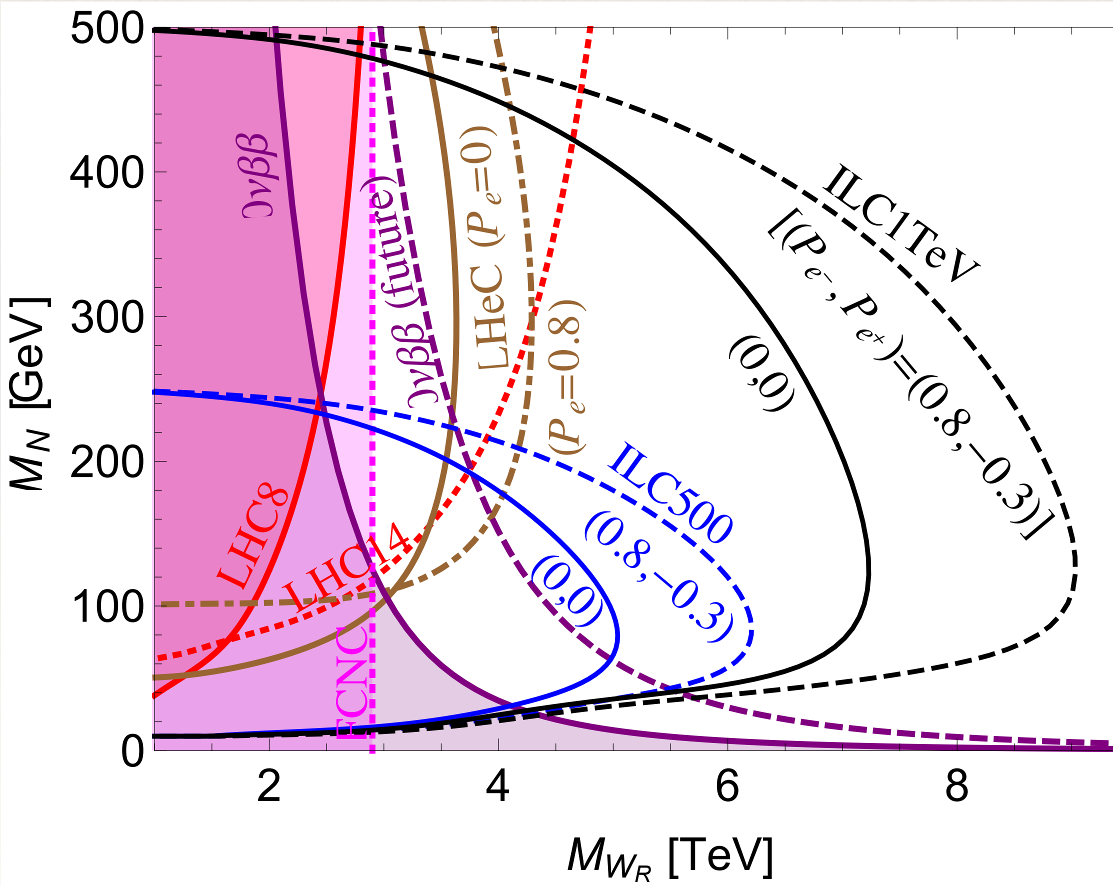
eV = TeV

$$G_F^2 \frac{|m_{ee}|^2}{q^2} = \frac{1}{\Lambda^5} \text{ for } |m_{ee}| \sim \text{eV and } \Lambda \sim \text{TeV}$$

$\Rightarrow$ Constraints from LHC, LFV, etc $\Leftrightarrow$ solve the inverse problem



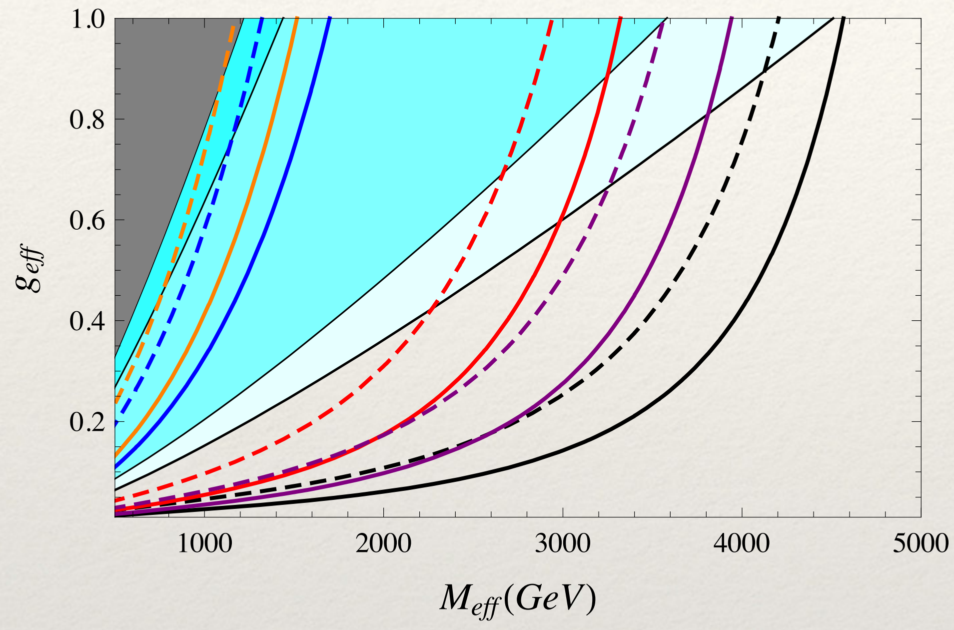




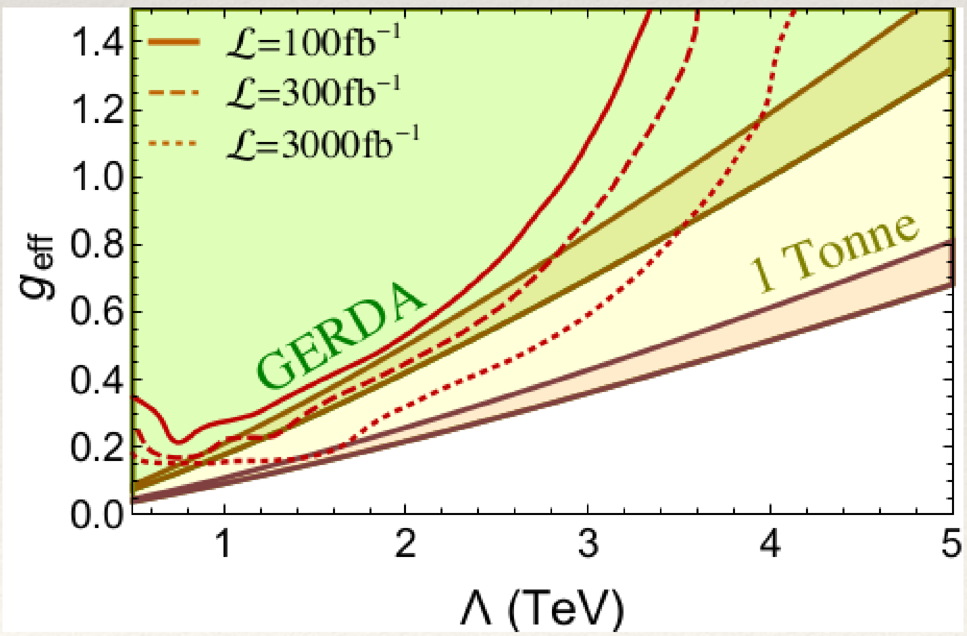
Biswal, Dev, 1701.08751

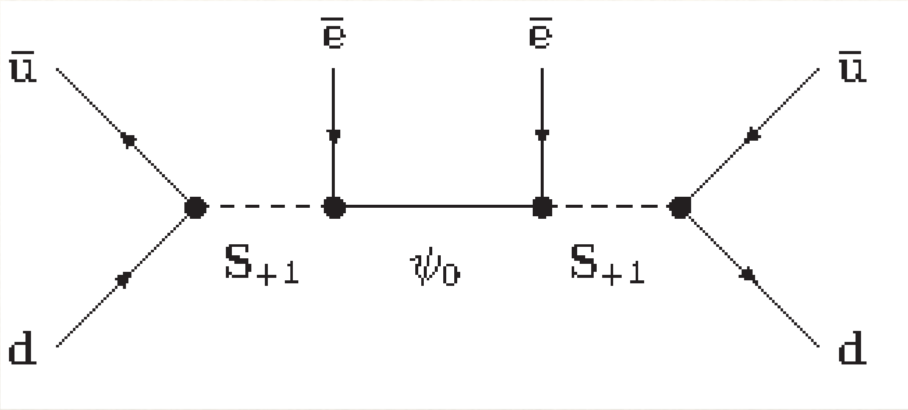
Complementarity of LHC and 0νββ

Hirsch et al., 1511.03945



Ramsey-Musolf et al., 1508.04444





$S \sim (1,2)$

$\psi \sim (1,0)$

- LHC needs $M_S > M_\psi$
- LHC has low sensitivity for small M_ψ
- include jet-fake rate, charge mis-ID, QCD corrections in 0νββ, etc.
- ⇒ complementary

Summary

- Learned a lot already!
- Unknown parameters very important!
- New Physics may lurk in all experiments

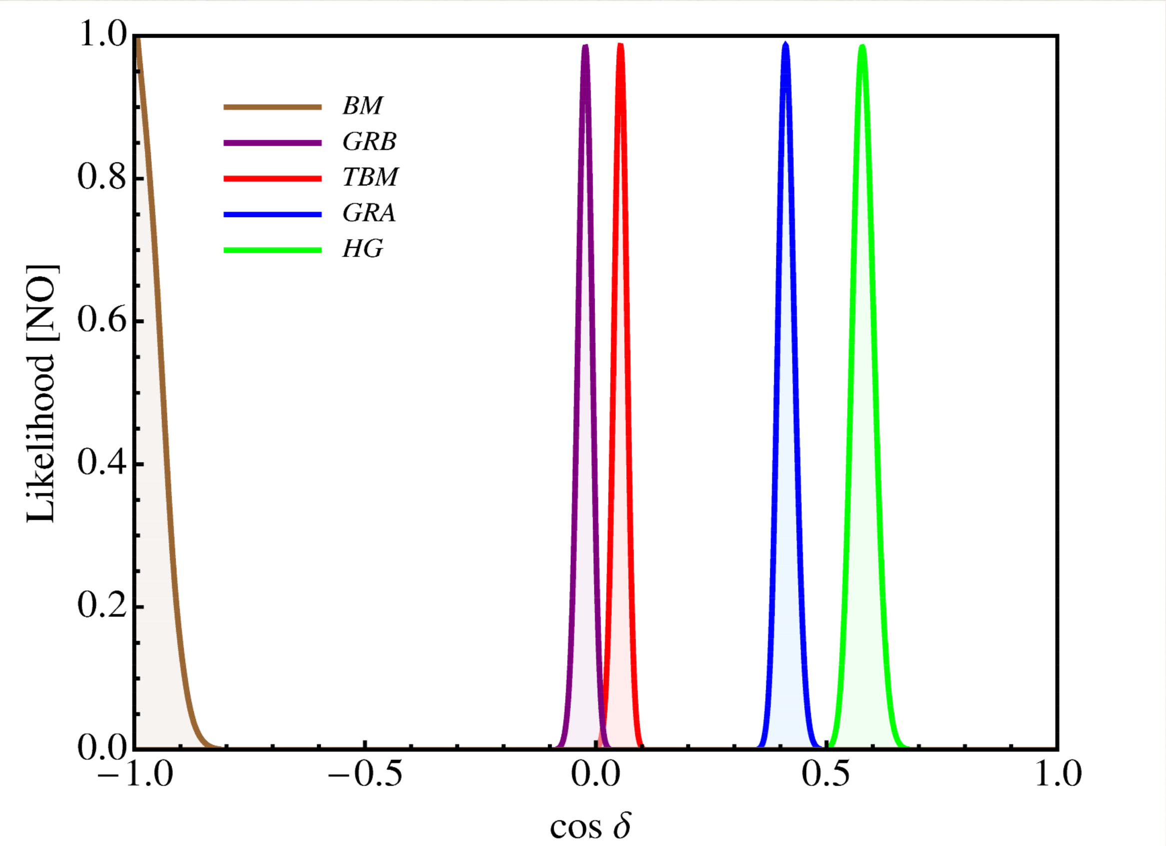
Example I: Sum-rules

$$U_\nu = \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta/\sqrt{2} & \cos\theta/\sqrt{2} & \sqrt{\frac{1}{2}} \\ \sin\theta/\sqrt{2} & \cos\theta/\sqrt{2} & \sqrt{\frac{1}{2}} \end{pmatrix} \text{ and } U_\ell \sim \text{CKM}$$

King et al.; Frampton, Petcov, WR,…

$$\Rightarrow \sin^2\theta_{12} \simeq \sin^2\theta - |U_{e3}| \sin 2\theta \cos\delta$$

Girardi, Petcov, Titov, 1410.8056



⇒ can distinguish only classes of models

Example II: CP phase

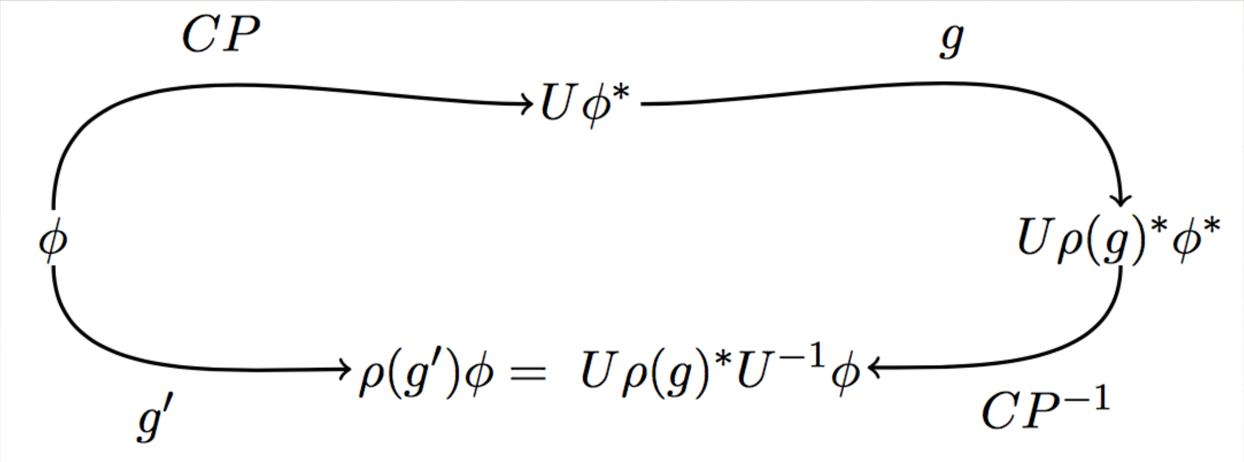
- μ-τ reflection symmetry: $\nu_e \leftrightarrow \nu_e^*$ and $\nu_\mu \leftrightarrow \nu_\tau^*$

  gives $\delta = \pm\pi/2$ and $\theta_{23} = \pi/4$

  - can happen if mass matrices are invariant under real subgroups of O(3)

    Ma; Grimus, Lavoura; Joshipura, Patel; He, WR, Xu

- combine *CP* and flavor symmetry, typically gives $\delta = \pm\pi/2, \pm\pi, 0$



(implies consistency relation)

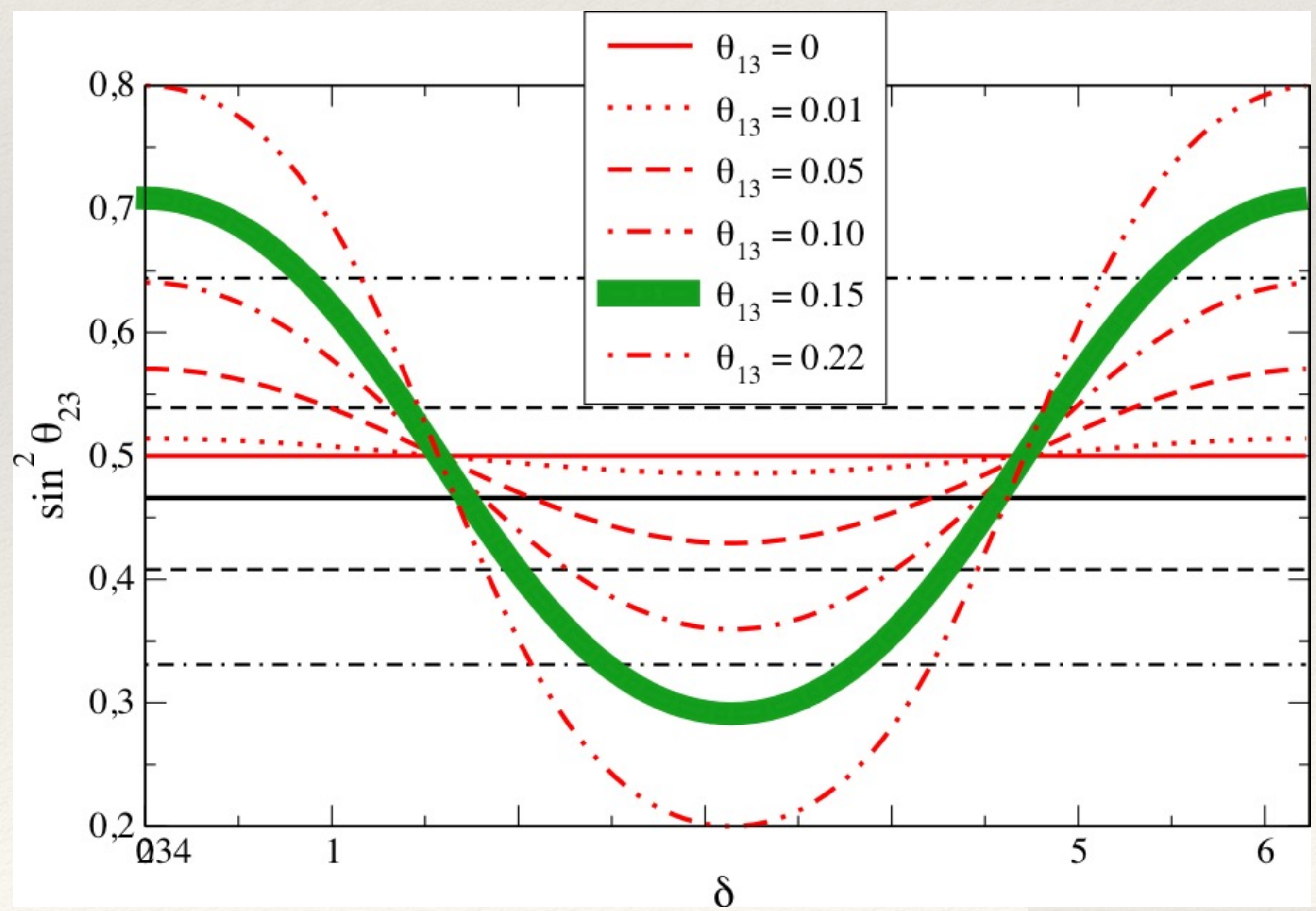
Grimus; Chen; Feruglio, Hagedorn, Ziegler; Holthausen, Schmidt, Lindner; Ding, King, Stuart; Meroni, Petcov; Branco, King, Varzielas,…

Example III: Trimaximal

frequent outcome of realistic models: trimaximal mixing

$\sin^2 \theta_{12} \simeq ⅓ (1 - 2 \, |U_{e3}|^2)$ and $\delta = 3\pi/2$ gives $\theta_{23} < \pi/4$

$$U = \begin{pmatrix} \sqrt{\frac{2}{3}} & \# & \# \\ \sqrt{\frac{1}{6}} & \# & \# \\ \sqrt{\frac{1}{6}} & \# & \# \end{pmatrix}$$

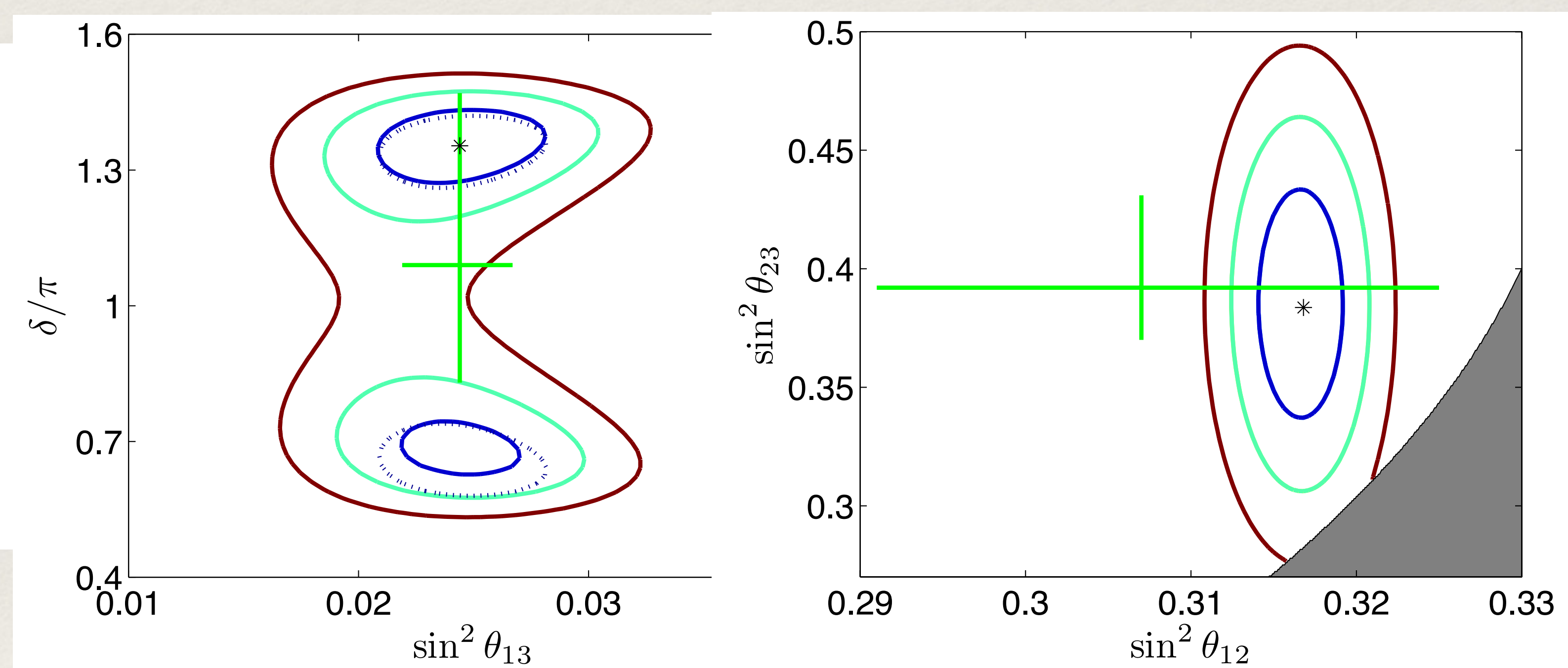


Example III: Trimaximal

frequent outcome of realistic models: trimaximal mixing

$\sin^2\theta_{12} \simeq \frac{1}{3}\,(1 - 2\,|U_{e3}|^2)$ and $\delta = 3\pi/2$ gives $\theta_{23} < \pi/4$

$$U = \begin{pmatrix} \sqrt{\frac{2}{3}} & \# & \# \\ \sqrt{\frac{1}{6}} & \# & \# \\ \sqrt{\frac{1}{6}} & \# & \# \end{pmatrix}$$



New Physics with m_ν Experiments

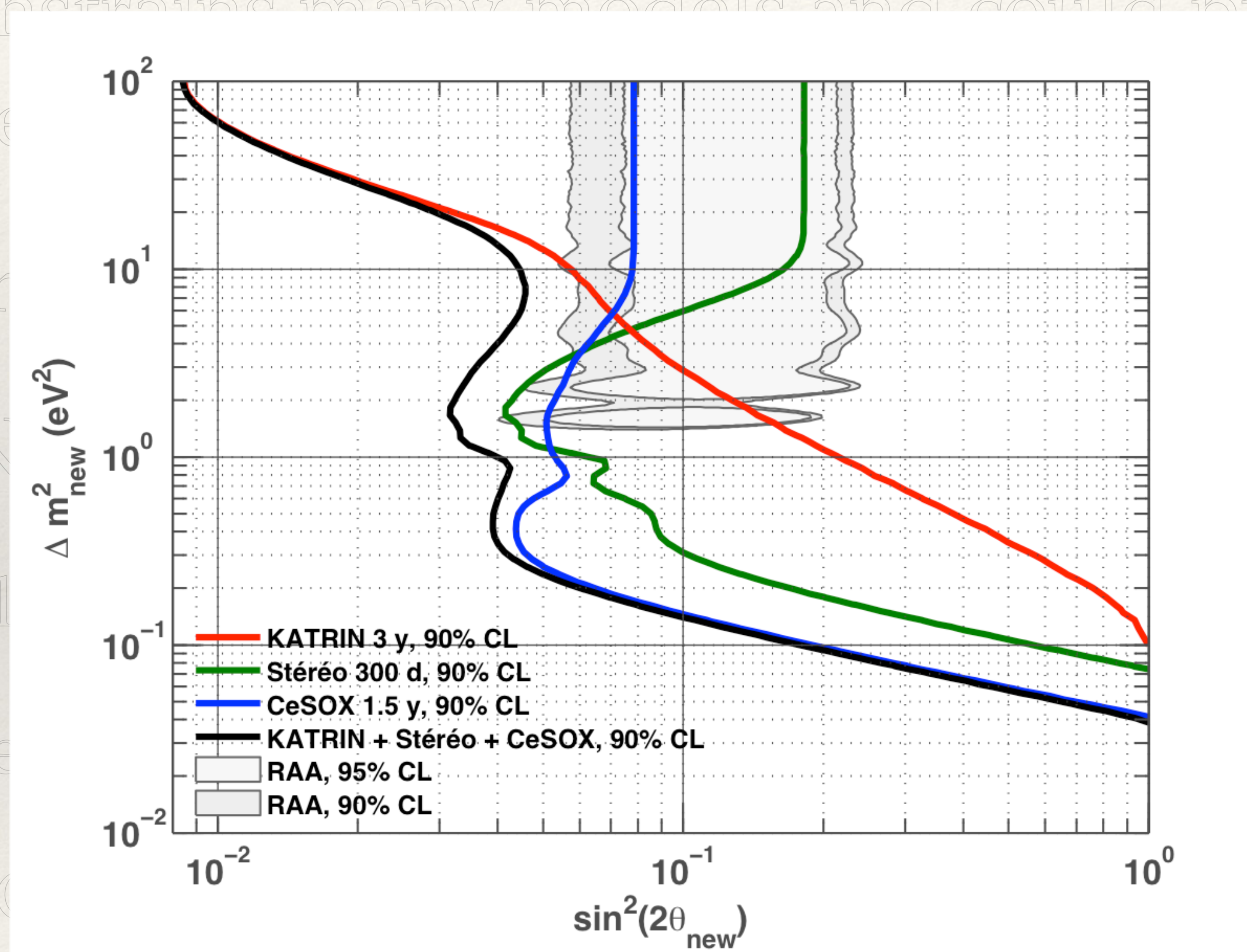
eV-scale neutrinos and KATRIN

❖ $0\nu\beta\beta$ con… …ovide most fundame…

❖ increasi… …tics (H_0, σ_8,…)

❖ KATRI…

- eV-scal…
- keV ste…
- exotic … …spectrum is measured (TeV-scale physics!)

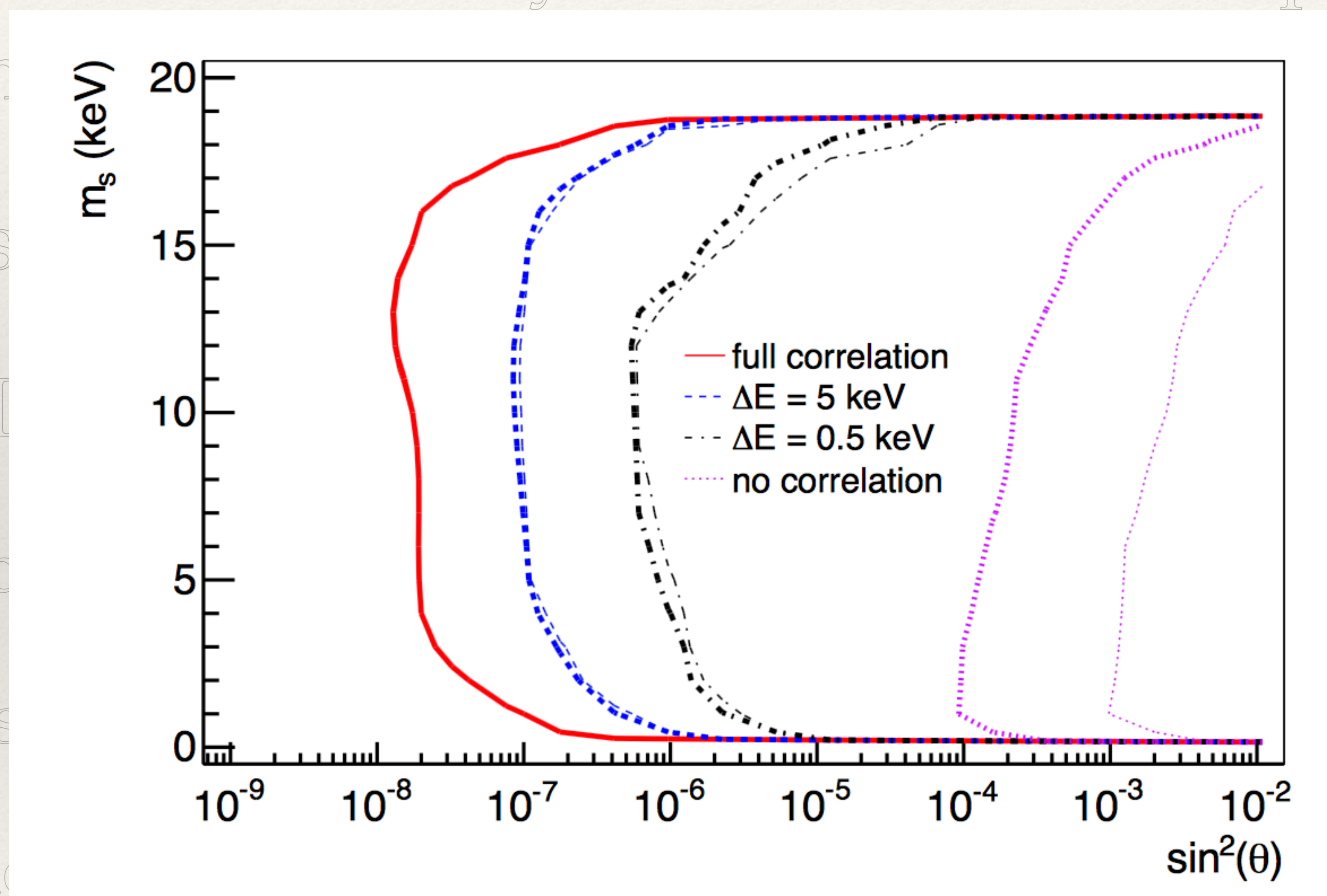


Lasserre

New Physics with m_ν Experiments

keV-scale neutrinos and modified KATRIN

- $0\nu\beta\beta$ constrains many models and could provide most fundan
- increas ... atics (H_0, σ_8, …)
- KATRI
  - eV-sc
  - keV s
  - exoti ... spectrum is measured (TeV-scale physics!)



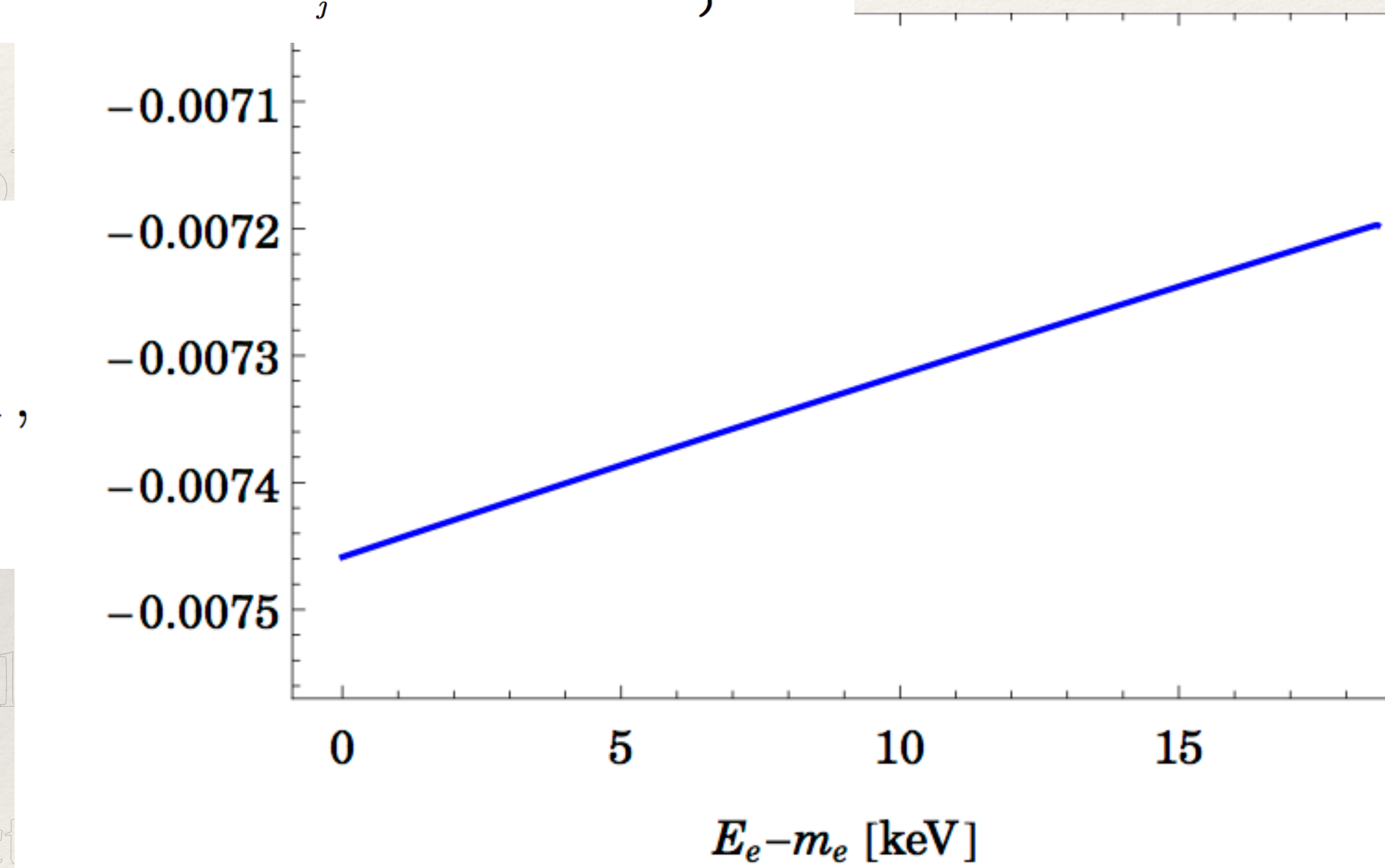
Mertens et al., 1409.0920

New Physics with m_ν Experiments

exotic charged currents and modified KATRIN

$$\mathcal{L}_{\rm CC} = -\frac{G_F V_{ud}}{\sqrt{2}} \left\{ (1+\delta_\beta)(\bar{e} L_\mu \nu_e)(\bar{u} L^\mu d) + \sum_j \overset{(\sim)}{\epsilon_j} \, (\bar{e}\, \mathcal{O}_j\, \nu_e)(\bar{u}\, \mathcal{O}'_j\, d) \right\} + \text{H.c.}$$

$$\Delta_B(\overset{(\sim)}{\epsilon_\alpha}) \equiv \frac{\left(\frac{d\Gamma}{dE_e}\right)^{\text{NP}(\overset{(\sim)}{\epsilon_\alpha})}_{m_\beta=0.5\,\text{eV}}}{\left(\frac{d\Gamma}{dE_e}\right)^{\text{no NP}}_{m_\beta=0.5\,\text{eV}}} - 1\,,$$

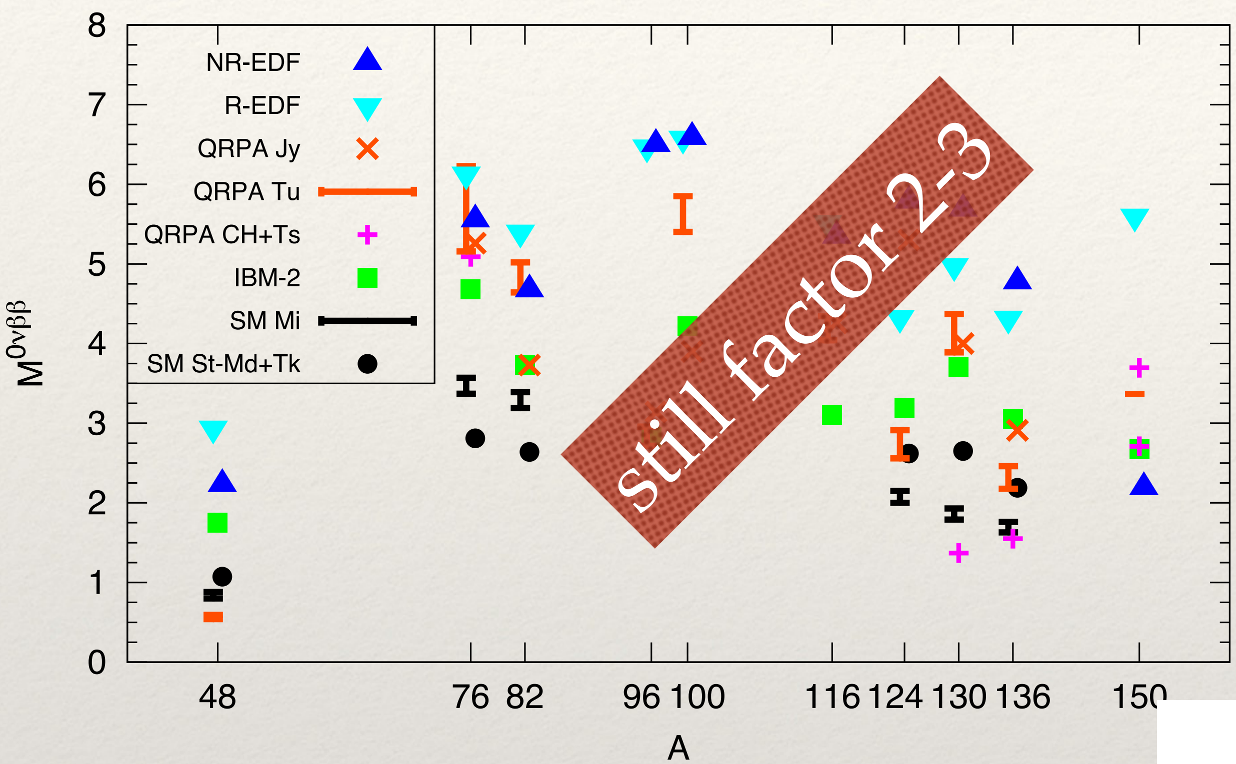


Ludl, WR, 1603.08690

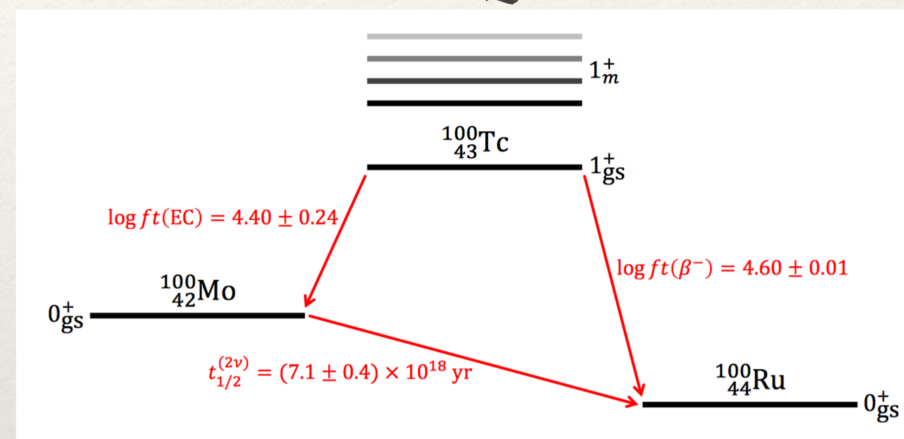
$\varepsilon = 10^{-3} \Rightarrow$ multi-TeV-scale physics

Nuclear Matrix Elements

Engel, Menendez, 1610.06548

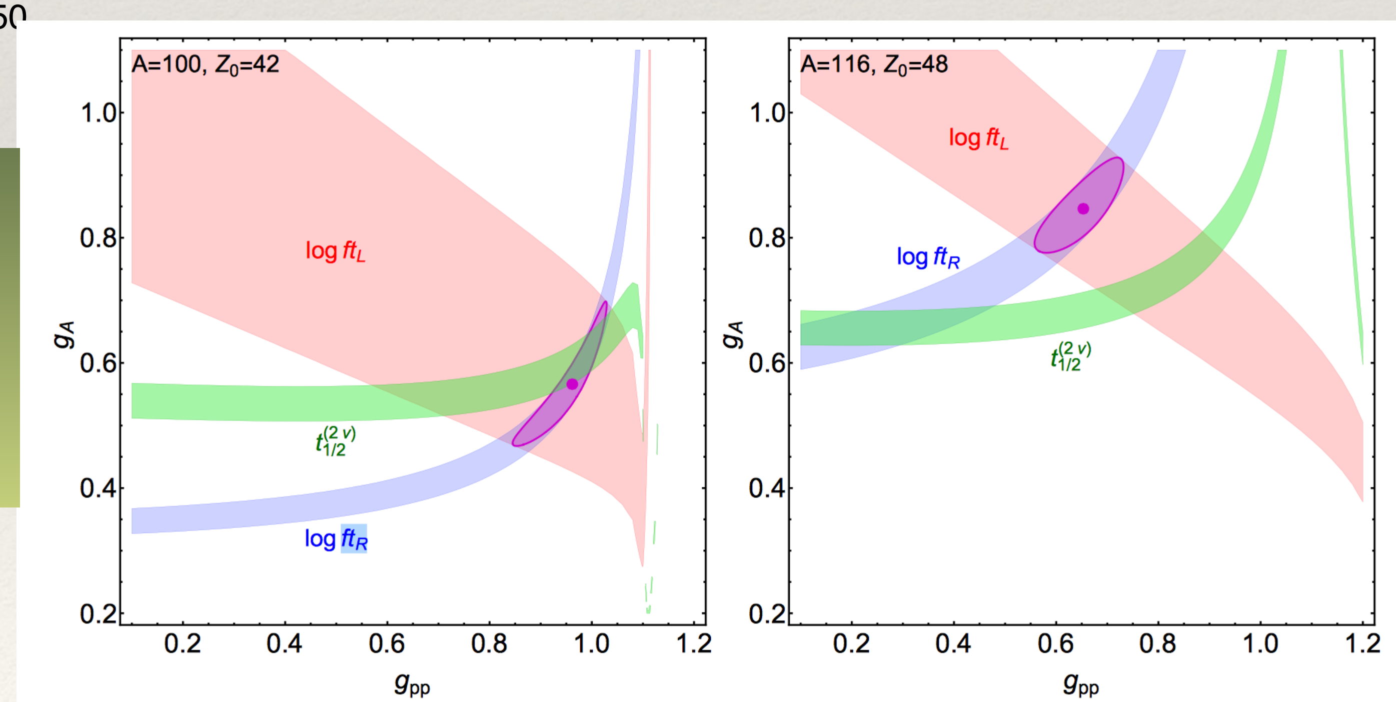


How good are the models?
Example isobaric triplets
within QRPA



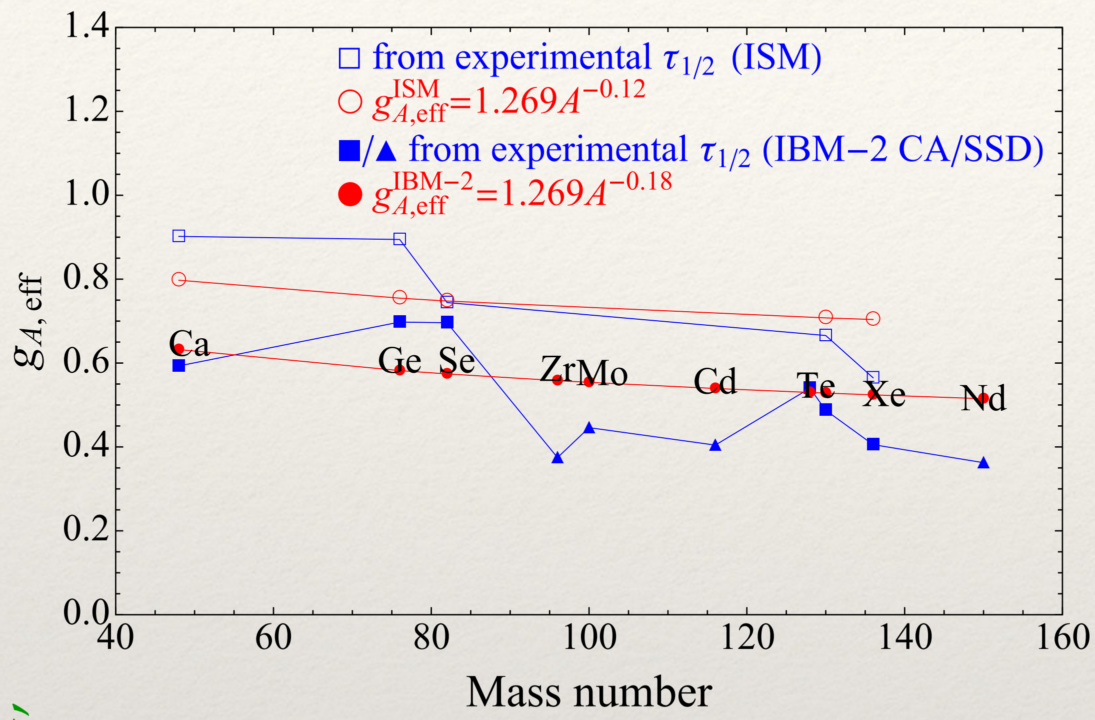
Deppisch, Suhonen, 1606.02908

⇒ Need as much experimental input (e.g. charge exchange) as possible…

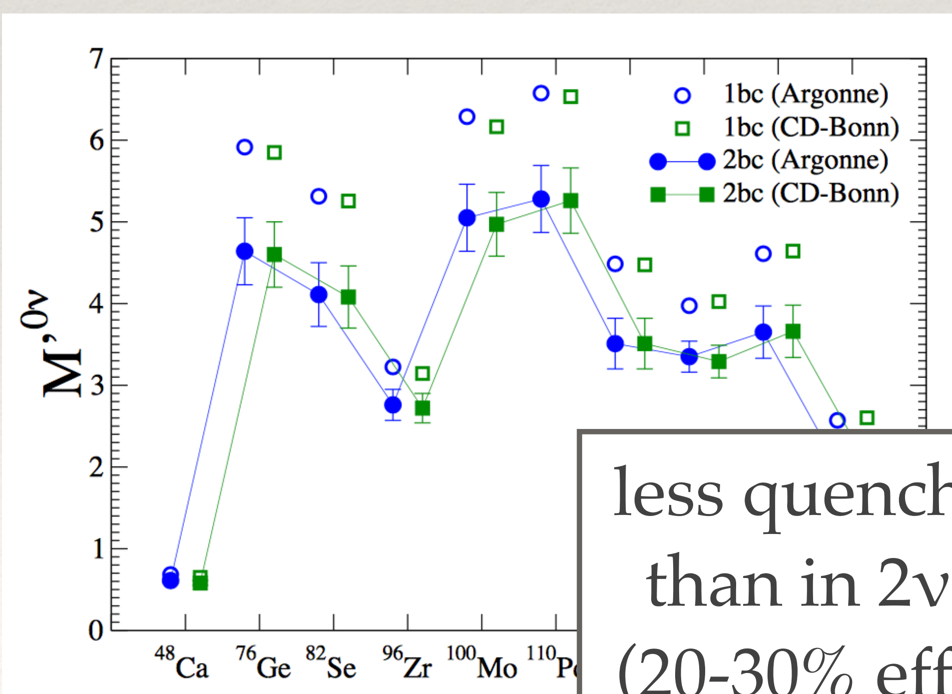


Nuclear Matrix Elements

Iachello et al., 1506.08530



Menendez, Gazit, Schwenk, 1103.3622; Engel, Simkovic, Vogel, 1403.7860



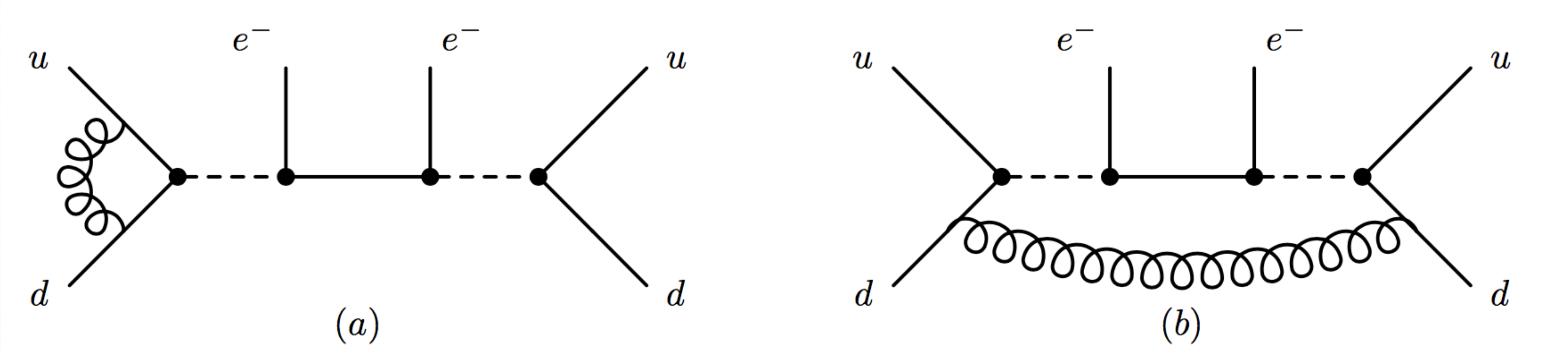
less quenching than in 2νββ (20-30% effect)

QUENCHING??

$$T^{0\nu}_{\frac{1}{2}} \propto g_A^{-4}$$

- fact in β and 2νββ
- truncation of model-space?
- also in 0νββ??
  - $q = 10^2$ vs. 10^0 MeV?
  - higher multipolarities?
  - two-body currents?
  - muon capture?
  - SM vs. QRPA

QCD Corrections



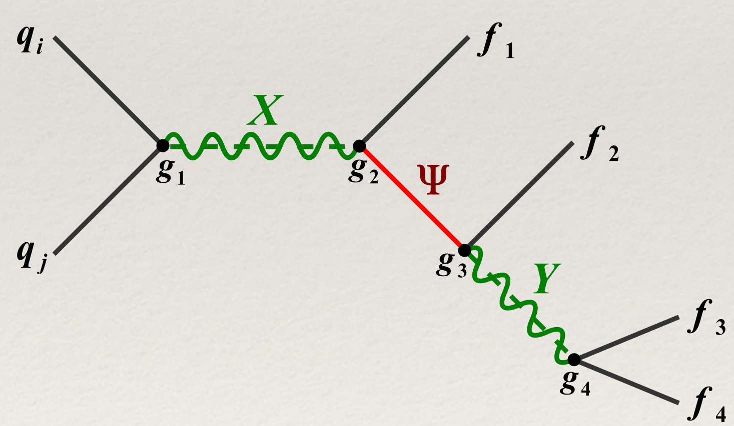
- naive size $(\alpha_s/4\pi)\ln(M_W/100\text{ MeV})^2 \simeq 10\%$, true for standard diagram
- creates in non (V-A) ⊗ (V-A) short-range mechanisms color non-singlets, Fierzing to singlets gives different operators with vastly different NMEs
- ⇒ can give effect exceeding NME uncertainty…

Mahajan, PRL 112; Gonzalez, Kovalenko, Hirsch, PRD 93; Peng, Ramsey-Musolf, Winslow, PRD 93

TeV-scale LNV and Baryogenesis

- Example TeV-scale W_R: leads to washout in early Universe via $e_R\, e_R \leftrightarrow W_R\, W_R$ and $e_R\, W_R \leftrightarrow W_R\, e_R$; processes stay long in equilibrium *(Frere, Hambye, Vertongen; Bhupal Dev, Mohapatra; Sarkar et al.)*

- more model-independent *(Deppisch, Harz, Hirsch)*:



wash-out:

$$\log_{10} \frac{\Gamma_W(qq \to \ell^+ \ell^+ qq)}{H} \gtrsim 6.9 + 0.6 \left(\frac{M_X}{\mathrm{TeV}} - 1 \right) + \log_{10} \frac{\sigma_{\mathrm{LHC}}}{\mathrm{fb}}$$

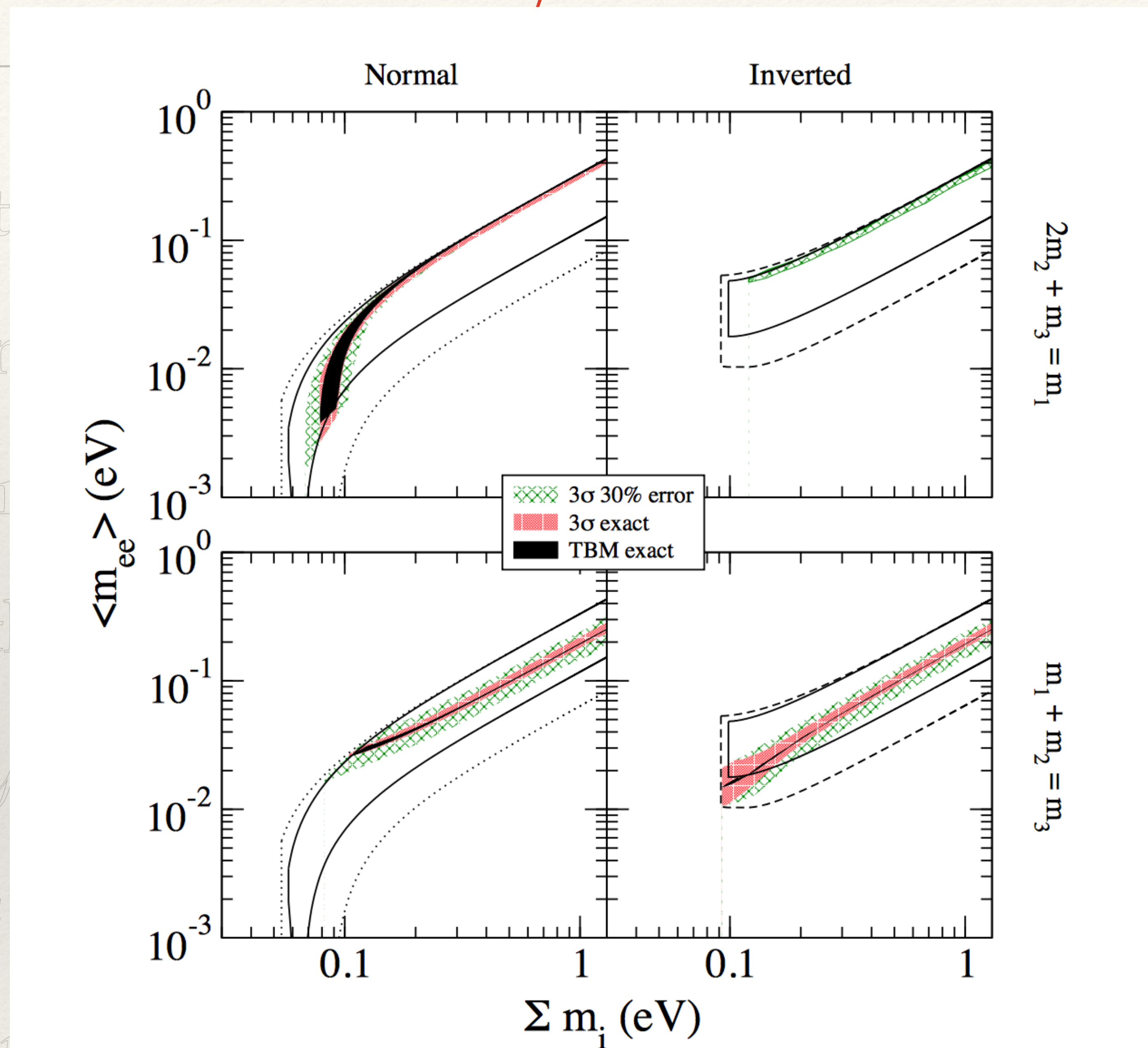
would need electroweak, resonant, ARS, post-sphaleron baryogenesis

Flavor Symmetries

- Can rule out models by:
  - neutrino mass sum-rules, e.g. $m_1 + m_2\, e^{i\alpha} = m_3\, e^{i\beta}$
  - correlations between angles and phases
  - LFV if within SUSY or if broken at low scale
  - *minimality*
  - *robustness*
  - *compatibility with larger frameworks (LR symmetry, Pati-Salam, SU(5), SO(10),…)*

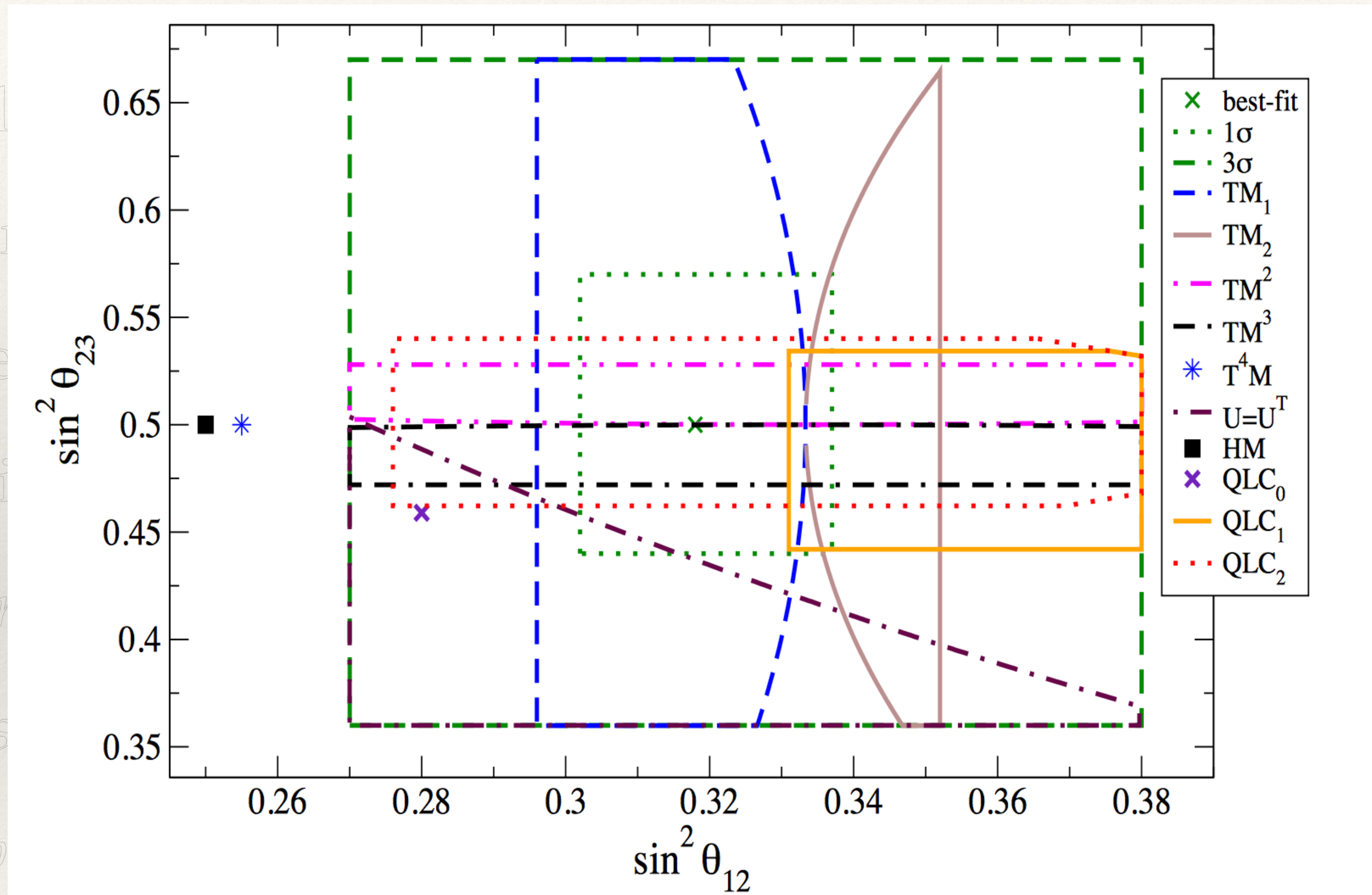
Flavor Symmetries

- Can rule out
  - neutrino m
  - correlation
  - LFV if wit
  - *minimality*
  - *robustness*
  - *compatibility with larger frameworks (LR symmetry, Pati-Salam, SU(5), SO(10),...)*



Flavor Symmetries

- Can rul
  - neutr
  - corre
  - LFV i
  - *minir*
  - *robus*
  - *comp* ... *alam, SU(5), SO(10),...)*



Seesaw Variants

extend $(\nu_L^c,\, N_R)$ to $(\nu_L^c,\, N_R,\, S)$

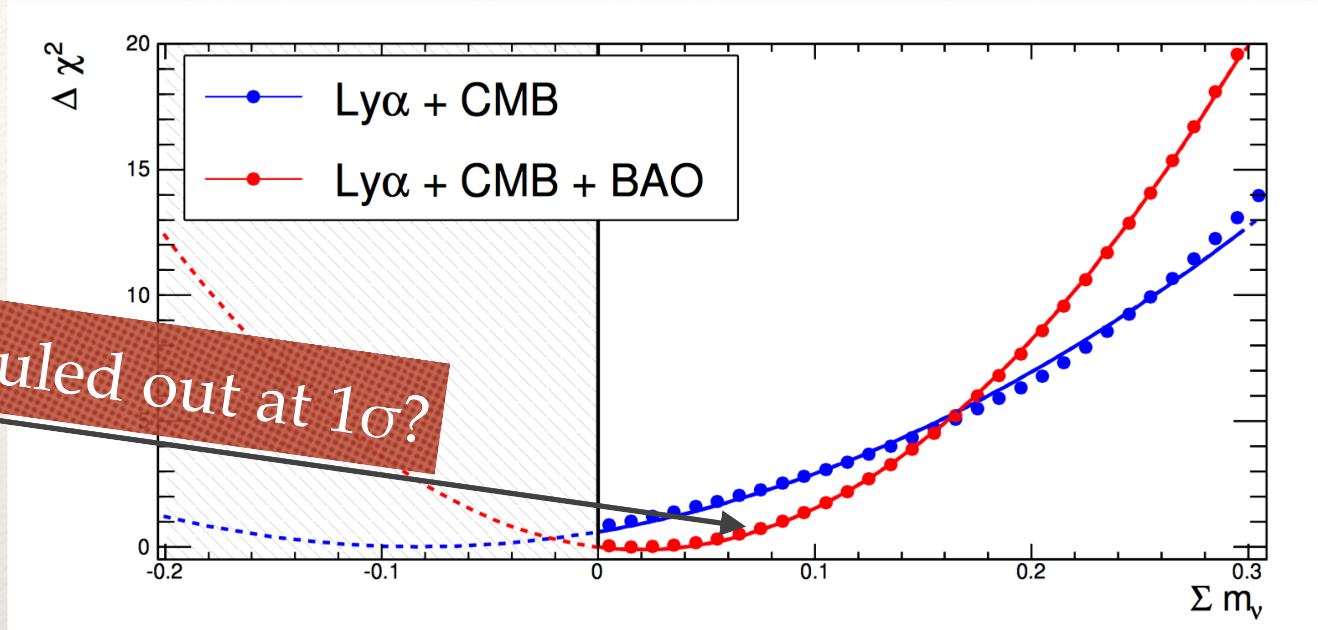
$$\mathcal{M} = \begin{pmatrix} 0 & m_D^T & m_{DS}^T \\ m_D & M_R & m_{RS}^T \\ m_{DS} & m_{RS} & M_S \end{pmatrix}$$

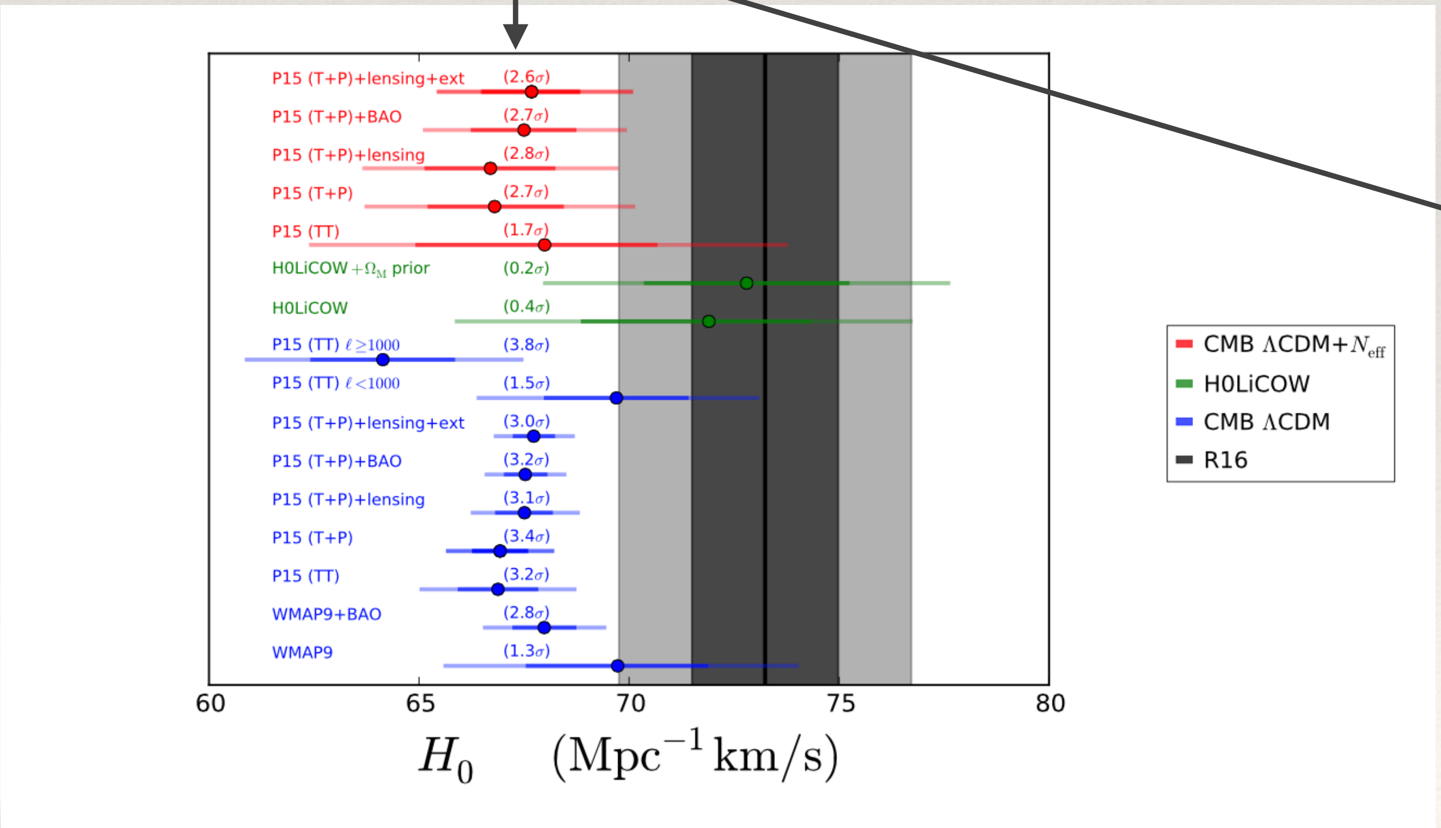
name	entries	m_ν
double	$m_D, m_{RS} \ll M_S$ $m_D \ll m_{RS}^2/M_S$	$\left(\frac{m_D}{10^2\,\text{GeV}}\right)^2 \left(\frac{10^{16}\,\text{GeV}}{m_{RS}}\right)^2 \left(\frac{M_S}{10^{19}\,\text{GeV}}\right)$ eV
inverse	$M_S \ll m_D \ll m_{RS}$	$\left(\frac{m_D}{10^2\,\text{GeV}}\right)^2 \left(\frac{\text{TeV}}{m_{RS}}\right)^2 \left(\frac{M_S}{0.1\,\text{keV}}\right)$ eV
linear	$m_{RS} \gg m_D \sim m_S$	$\left(\frac{m_D}{10^2\,\text{GeV}}\right) \left(\frac{m_{DS}}{10^2\,\text{GeV}}\right) \left(\frac{10^{13}\,\text{GeV}}{m_{RS}}\right)$ eV

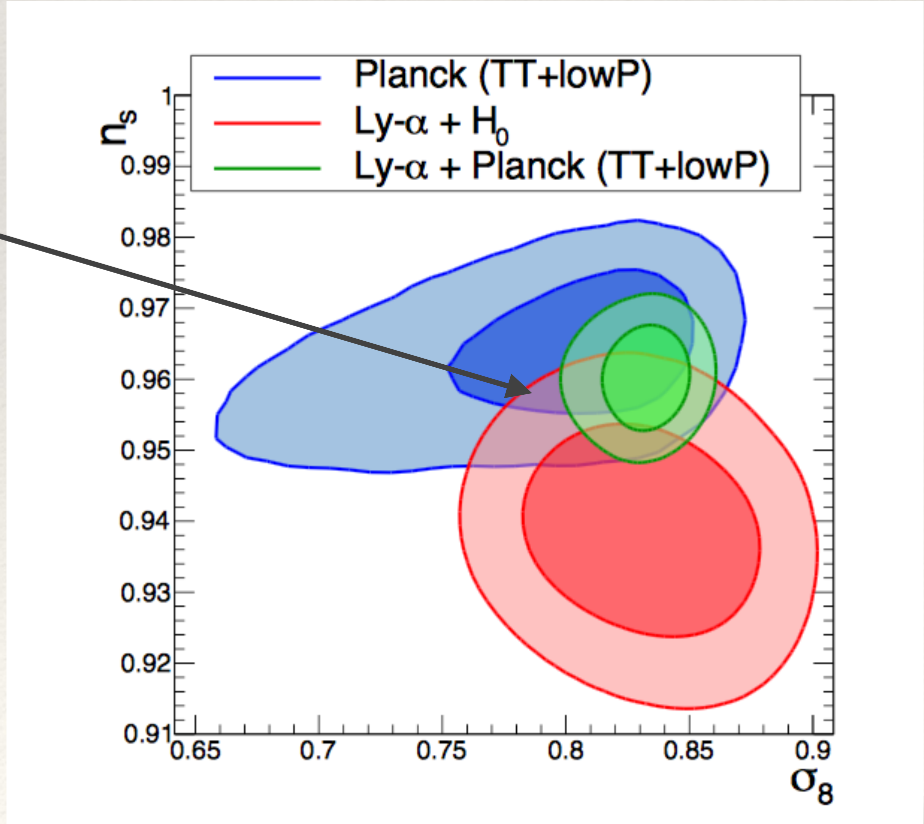
Cosmological Mass Limits

- adding more and more data sets: breaks degeneracies and improves limits
- BUT: can introduce systematics?

IH ruled out at 1σ?





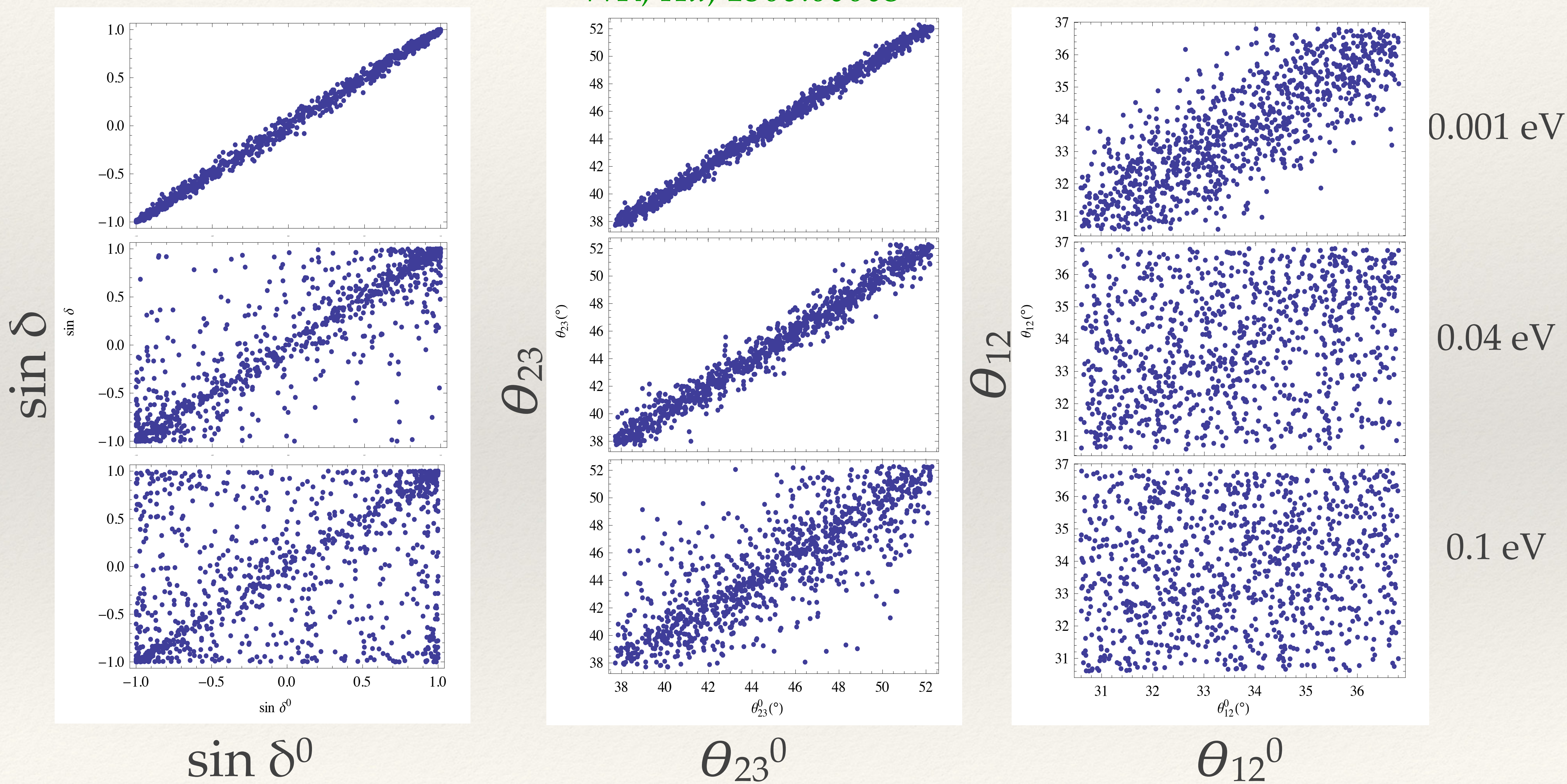


Bernal, Verde, Riess, 1607.05617

Palanque-Delabrouille et al., 1410.7244 + 1506.05976

Perturbations

WR, Xu, 1508.06063

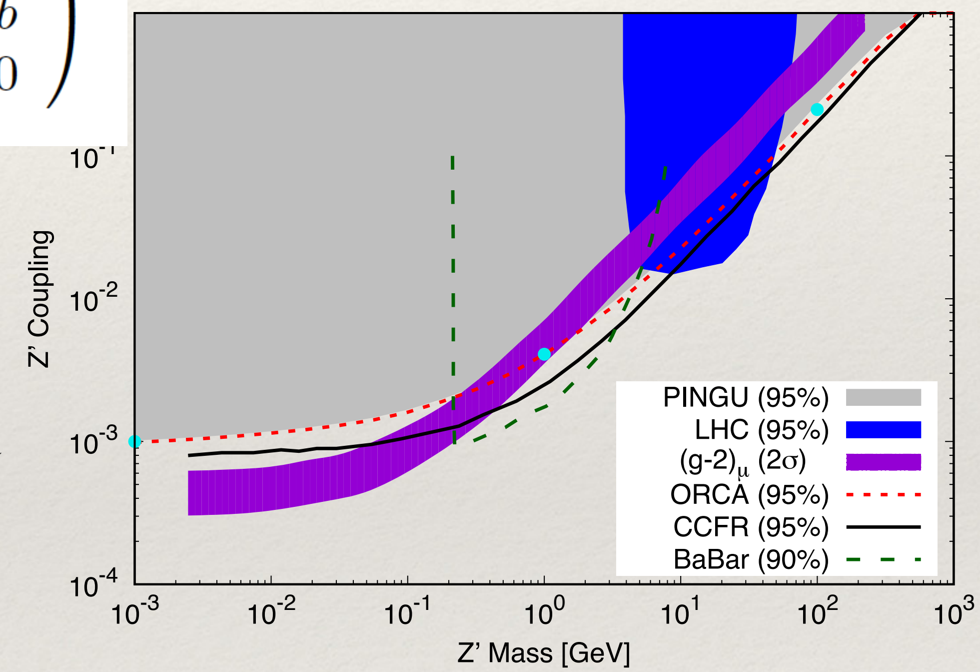


Flavor Symmetries

- Less predictive but less complicated: Abelian flavor symmetry, e.g. L_μ - L_τ

$$(m_\nu)^{L_\mu - L_\tau} = \begin{pmatrix} a & 0 & 0 \\ \cdot & 0 & b \\ \cdot & \cdot & 0 \end{pmatrix}$$

  - anomaly free
  - masses a and $\pm b$, $\theta_{23} = \pi/4$, $\theta_{13} = 0$
  - has Z' with couplings to μ and τ: $(g - 2)_\mu$

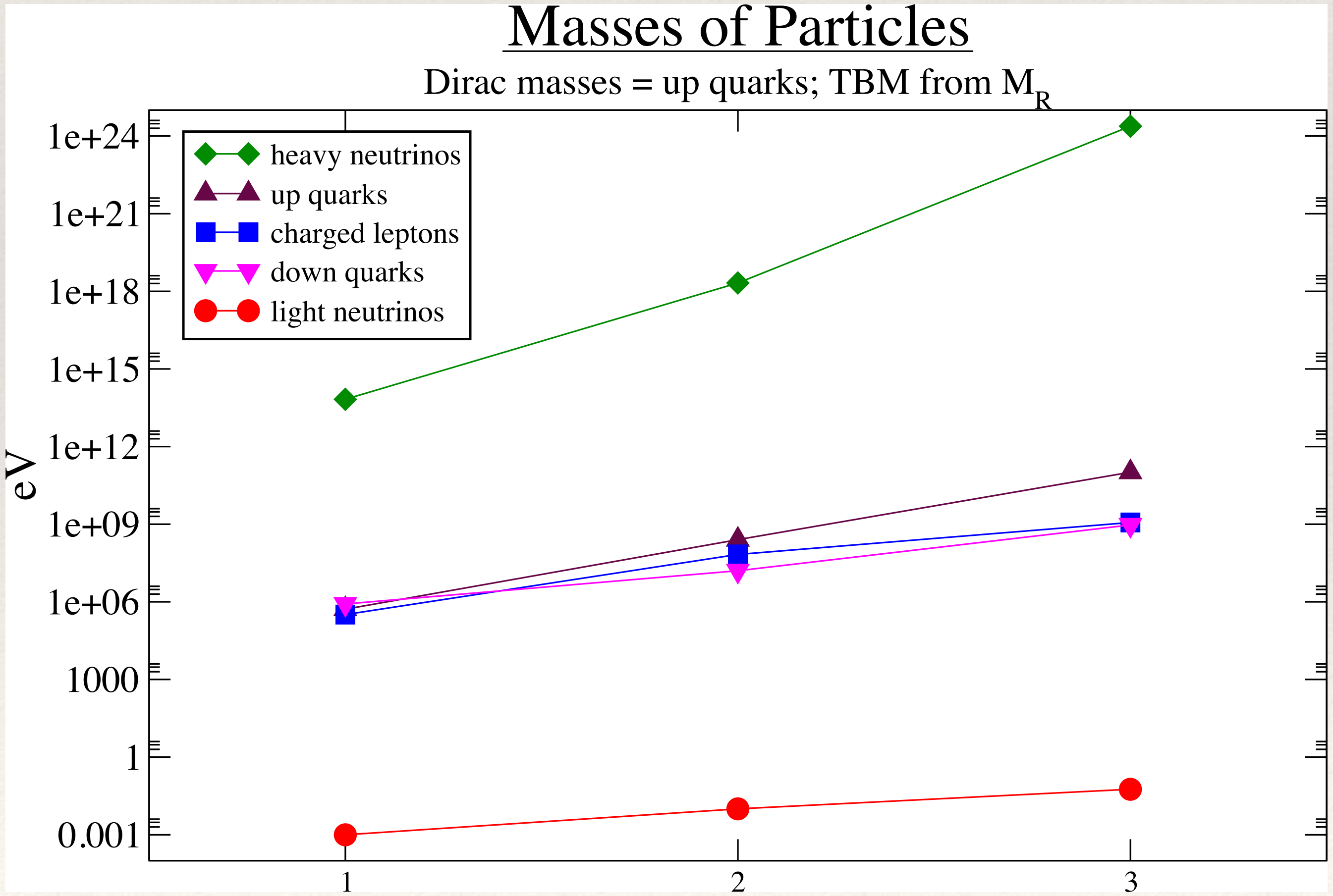


  - can be extended to quark sector to explain anomalies in $B \to K^*$ $\mu\mu$ and BR($B \to K\mu\mu$)/BR($B \to Kee$) *[Crivellin, Ambrosio, Heeck, 1501.00993]* (making predictions for $h \to \mu\tau$, LFV, etc.)

Seesaw Mechanism

- suppresses neutrino mass *for each generation* ($m_u \simeq m_d$ and $m_b \sim m_t$ vs. $m_{\nu e} \ll m_e$ and $m_{\nu\tau} \ll m_\tau$)
- little hierarchy in m_ν, strong quark-like hierarchy in m_D

$\Rightarrow$ stronger hierarchy in M_R?



Why look for Lepton Number Violation?

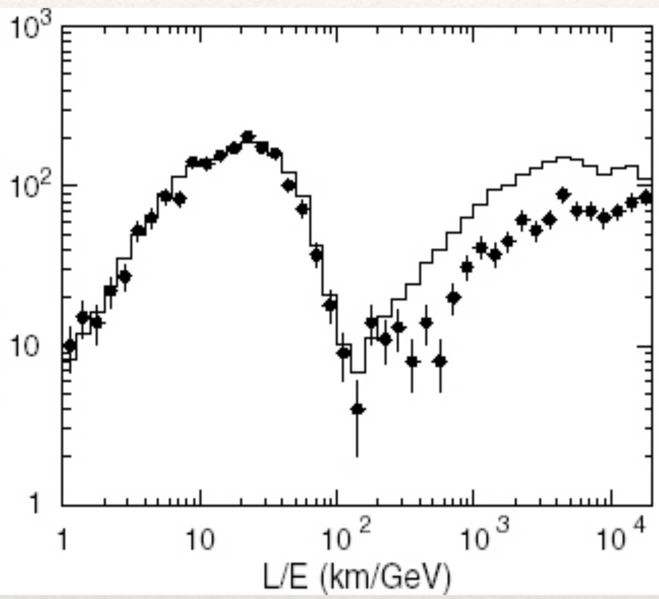
- L and B accidentally conserved in SM
- $\mathcal{L} = \mathcal{L}_{\rm SM} + 1/\Lambda\ \mathcal{L}_5 + 1/\Lambda^2\ \mathcal{L}_6 + \ldots$,with $\mathcal{L}_5 = L^c\phi\ \phi L \to m_\nu\, \nu_L{}^c\, \nu_L$
- Baryogenesis: B is violated
- B, L often connected in GUTs
- GUTs have seesaw and Majoranas
- (B and L non-perturbatively violated by 3 units in SM…)

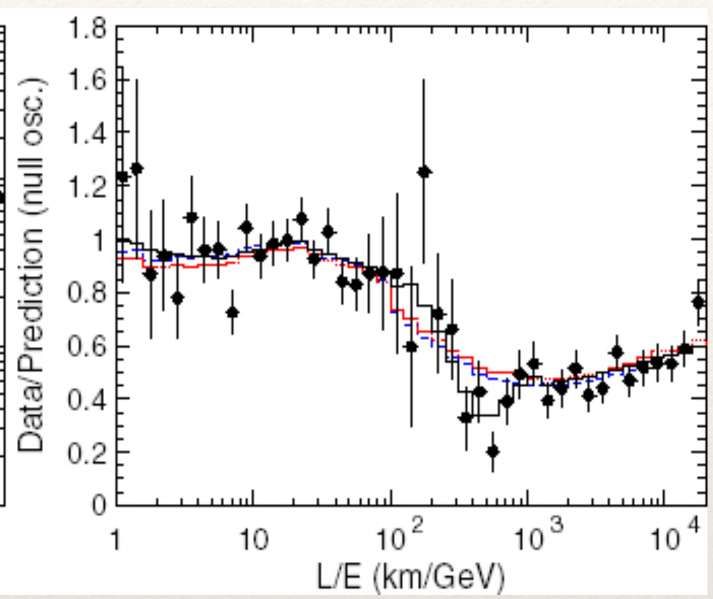
Lepton Number as important as Baryon Number

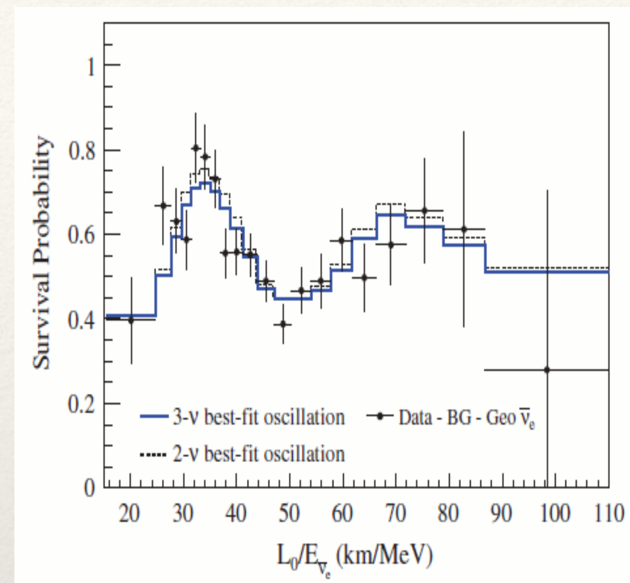
Neutrino Mass Observables

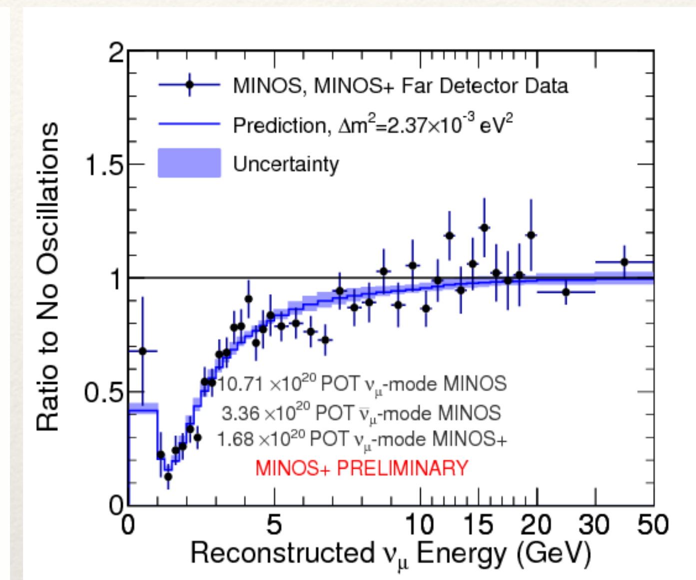
Method	Observable	current	near	far	pro	con
Kurie	$\sum \vert U_{ei} \vert^2 m_i$	2.3 eV	0.3 eV	0.1 eV?	model-indep.; clean	final; weakest
cosmo	$\sum m_i$	0.5 eV	0.1 eV	0.05 eV?	best; NH/IH	model-dep.; systematics
$0\nu\beta\beta$	$\sum U_{ei}^2 m_i$	0.2 eV	0.05 eV	0.01 eV?	fundamental; NH/IH	model-dep.; NMEs

Neutrinos oscillate and Leptons mix







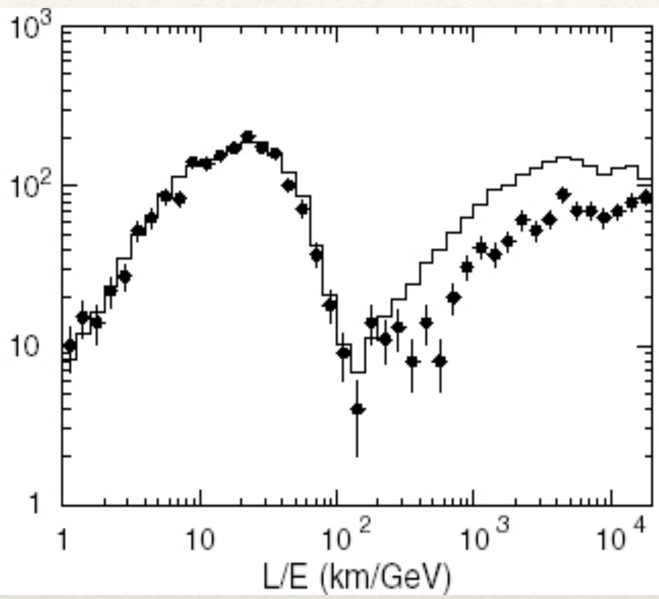


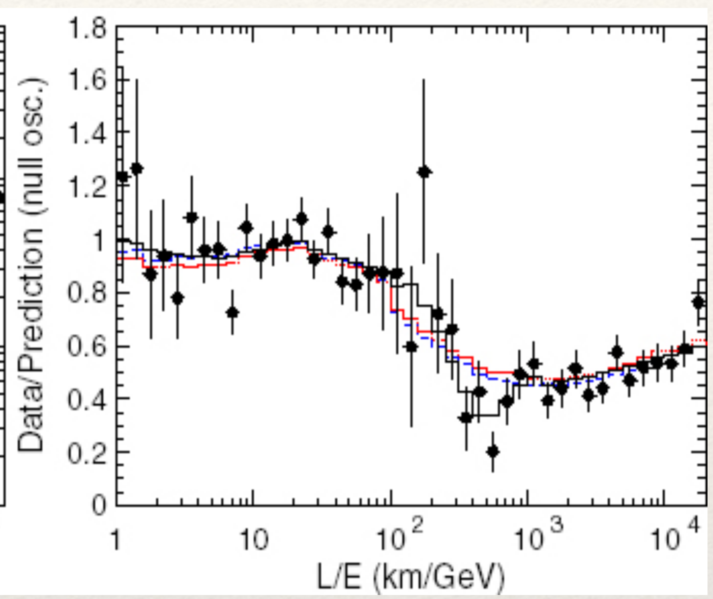
observed with various sources and techniques
=> quantum mechanical interference
on macroscopic distances

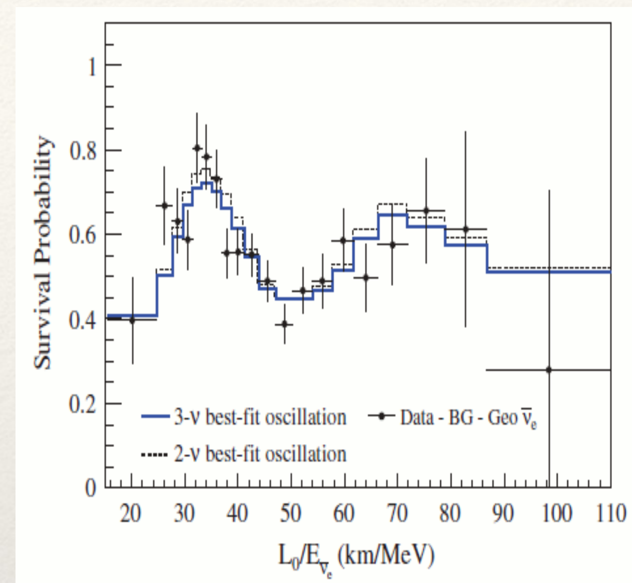
$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*)\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right) + 2\sum_{i>j}\mathrm{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*)\sin\left(\frac{\Delta m_{ij}^2 L}{2E}\right),$$

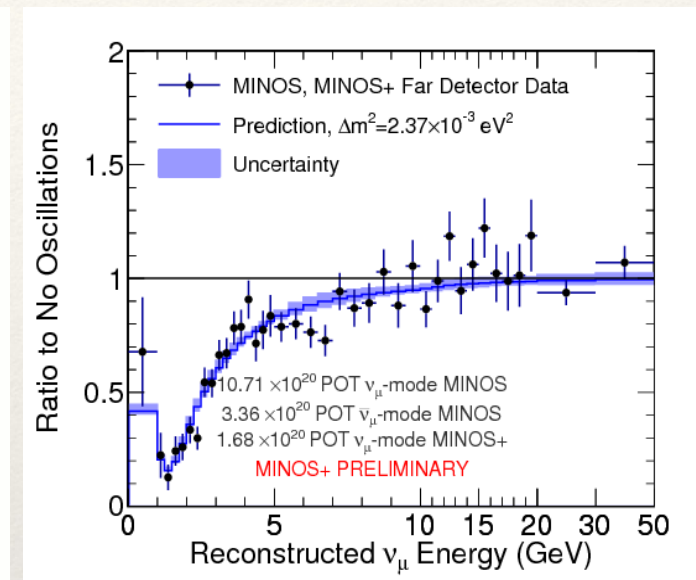
(plus matter effects)

Neutrinos oscillate and leptons mix





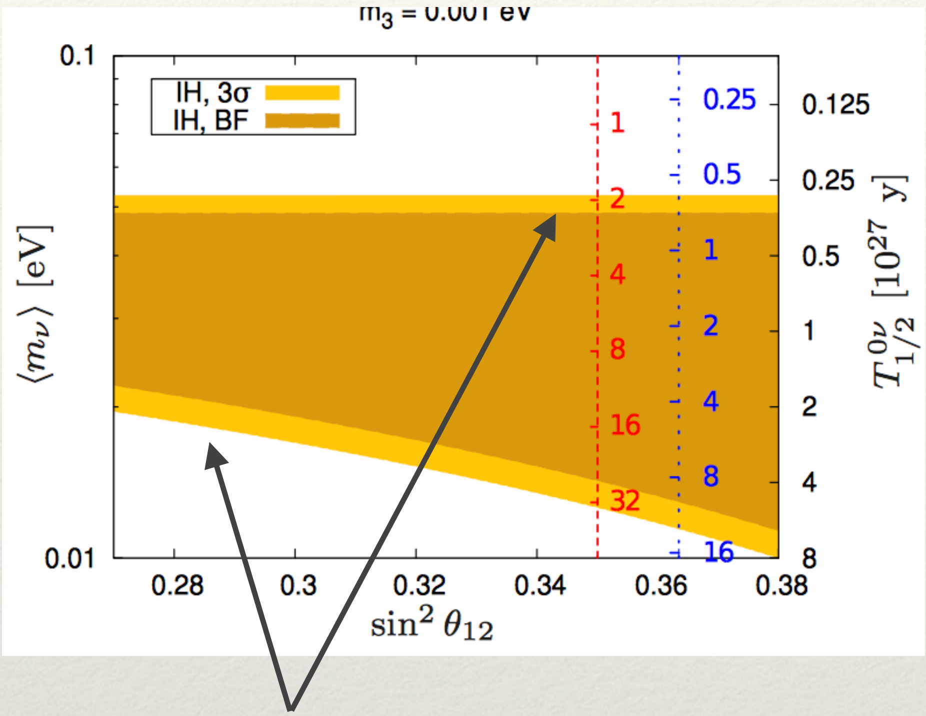




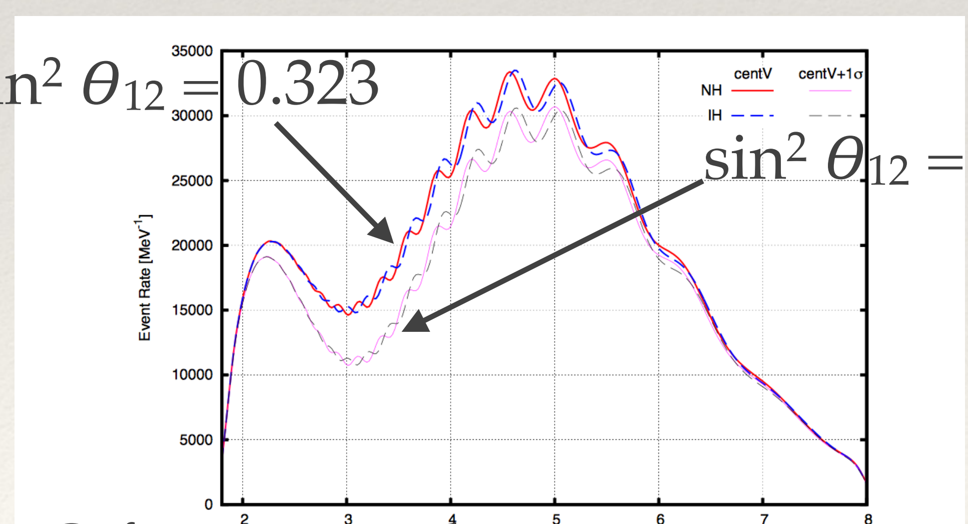
observed with various sources and techniques
=> quantum mechanical interference
on macroscopic distances

$$P_{\nu_\alpha \to \nu_\beta}(\vec{L}) \propto \sum_{j,k} U_{\alpha j}^* U_{\beta j} U_{\alpha k} U_{\beta k}^* \exp\left\{ -i \left[(\tilde{E}_j - \tilde{E}_k) \frac{\vec{v}_j + \vec{v}_k}{v_j^2 + v_k^2} - (\tilde{\vec{p}}_j - \tilde{\vec{p}}_k) \right] \cdot \vec{L} \right\}$$
$$\times \exp\left\{ -\frac{L^2}{2\sigma_x^2} + \frac{(\vec{v}_j \cdot \vec{L})^2 + (\vec{v}_k \cdot \vec{L})^2}{2\sigma_x^2 (v_j^2 + v_k^2)} - \frac{\left[(\vec{v}_j - \vec{v}_k) \cdot \vec{L} \right]^2}{4\sigma_x^2 (v_j^2 + v_k^2)} - \frac{(\tilde{E}_j - \tilde{E}_k)^2}{4\sigma_p^2 (v_j^2 + v_k^2)} \right\}.$$

Double Beta Decay:
Connections to Oscillation Experiments



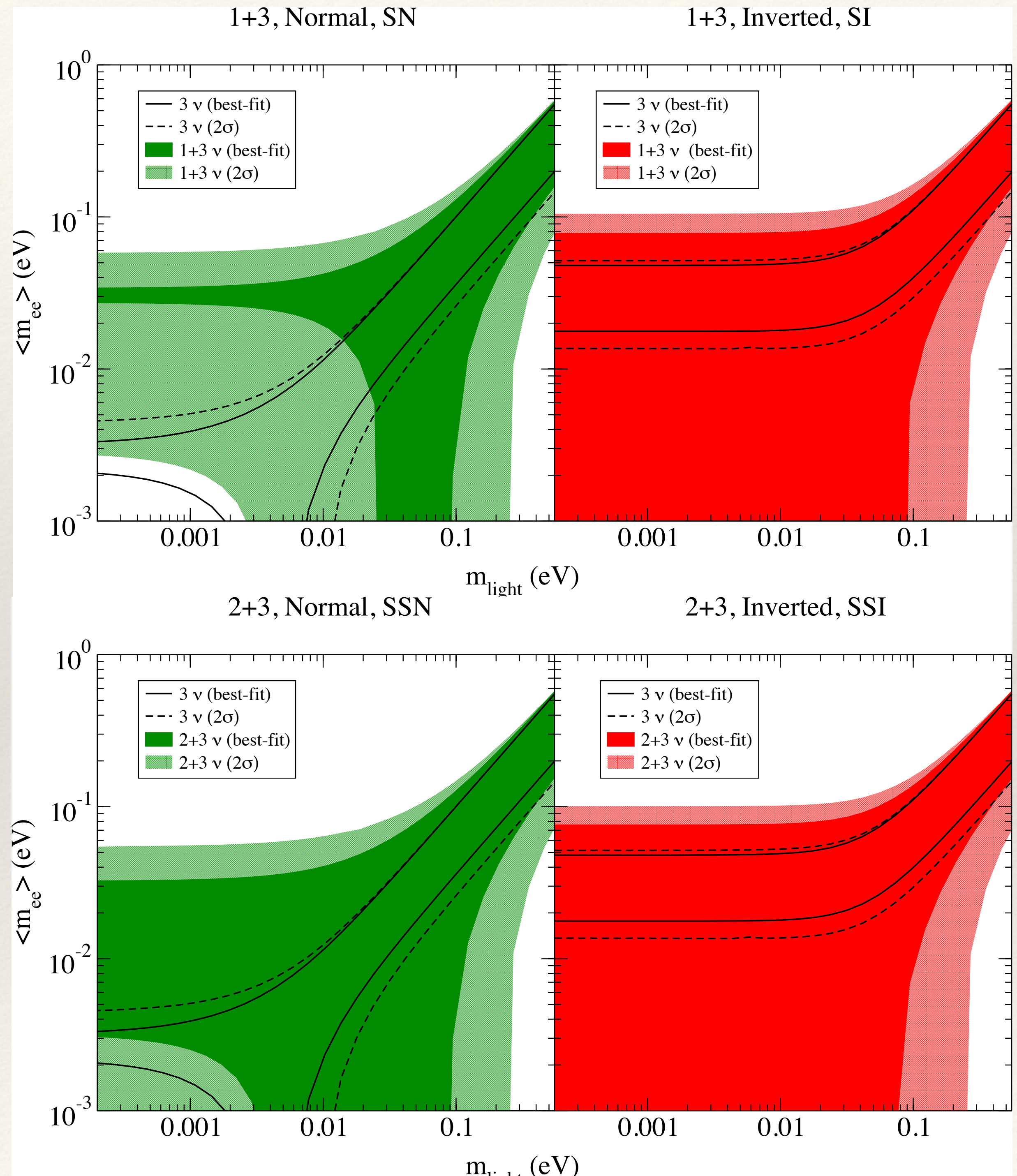
Nature gives us two scales



$\sin^2\theta_{12} = 0.323$

$\sin^2\theta_{12} = 0.339$

JUNO fixes θ_{12} and removes uncertainty in value of minimal m_{ee} in IH



sterile neutrinos turn pheno around

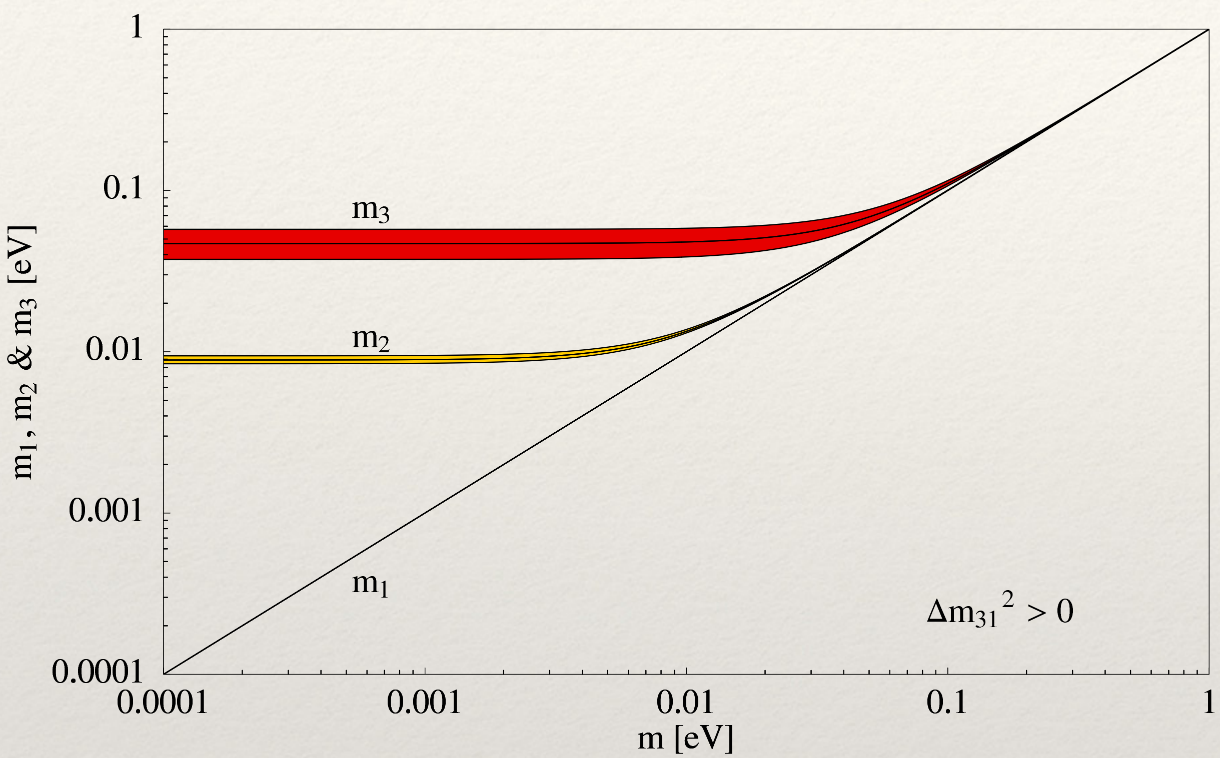
Flavor Symmetries

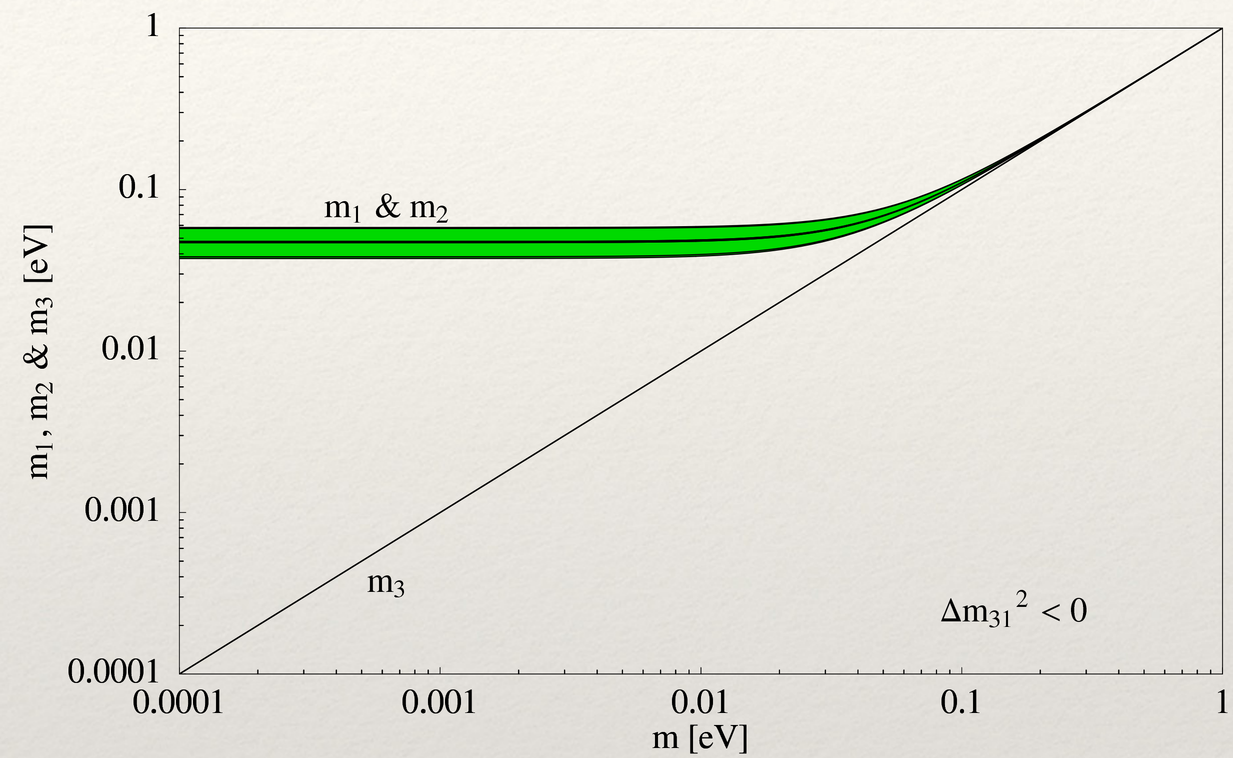
- if $\theta_{23} = 41.6^0$: model predicting this value or perturbed model with $45.0^0 - 3.4^0$?
- far away from 45^0 could be related $(m_2/m_3)^{½}$ similar to GST
- BUT: the closer θ_{23} to 45^0 the more likely that some symmetry / structure behind it…
- in larger frameworks (LR Symmetry, Pati-Salam, SU(5), SO(10),…):
  - model building becomes more difficult:
    $M_{\rm up} = 10_{\rm H} + \underline{126}_{\rm H} + 120_{\rm H}$ versus $M_D = 10_{\rm H} - 3\ \underline{126}_{\rm H} + c\ 120_{\rm H}$
  - mixing angles become less „extreme“ *[Hagedorn, Lindner, Mohapatra; Bajc, Smirnov]*

CP Phase

- in general, leptogenesis ***independent*** of δ, *α*, β
- if $\delta = 230.7^0$: model predicting this value or perturbed model with $270.0^0 - 39.3^0$?
- BUT: the closer δ to *π* or 3*π*/2 the more likely that some symmetry/structure behind it…
  - combine CP and flavor symmetry *[Holthausen et al., Hagedorn et al., King et al.,…]*
  - μ-*τ* reflection symmetry $\nu_\mu \leftrightarrow \nu_\tau^*$ *[Ma; Grimus, Lavoura; Joshipura, Patel; WR, Xu]*
  - certain mixing sum-rules *[King et al., Frampton, Petcov, WR;…]*

Mass Ordering





mild hierarchy in normal ordering:

$m_3/m_2 \lesssim (\Delta m^2_{\rm atm}/\Delta m^2_{\rm sol})^{1/2} \simeq 5$

$$(m_\nu)_{\rm NH} \sim \begin{pmatrix} \epsilon^2 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix}$$

strong tuning in inverted ordering:

$m_2/m_1 \lesssim 1 + \frac{1}{2}\, \Delta m^2_{\rm sol}/\Delta m^2_{\rm atm}$

$$(m_\nu)_{\rm IH} \sim \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

plus almost democratic structure of mass matrix

Perturbations

- Various sources:
  - VEV misalignment, NLO terms: follow model structure, hard to predict size
  - RG effects
- Frequent feature: δ(θ_{12}), δ(δ) > δ(θ_{13}), δ(θ_{23}):

Example RG enhancement:

(running of phases and θ_{12} can be evaded by cancellations)

large

	NH	IH	QD
$\delta(\theta_{12})$	1	$\Delta m^2_{\rm A}/\Delta m^2_\odot$	$m_0^2/\Delta m^2_\odot$
$\delta(\theta_{13})$	$\sqrt{\Delta m^2_\odot/\Delta m^2_{\rm A}}$	1	$m_0^2/\Delta m^2_{\rm A}$
$\delta(\theta_{23})$	1	1	$m_0^2/\Delta m^2_{\rm A}$
$\delta(\delta)$	$\sqrt{\Delta m^2_\odot/\Delta m^2_{\rm A}}$	$\Delta m^2_{\rm A}/\Delta m^2_\odot$	$m_0^2/\Delta m^2_{\rm A}$
$\delta(\alpha,\beta)$	$\sqrt{\Delta m^2_\odot/\Delta m^2_{\rm A}}$	$\Delta m^2_{\rm A}/\Delta m^2_\odot$	$m_0^2/\Delta m^2_{\rm A}$

Perturbations

- Various sources:
  - VEV misalignment, NLO terms: follow model structure, hard to predict size
  - RG effects
- Frequent feature: $\delta(\theta_{12}), \delta(\delta) \gg \delta(\theta_{13}), \delta(\theta_{23})$:

mass scale and ordering helpful

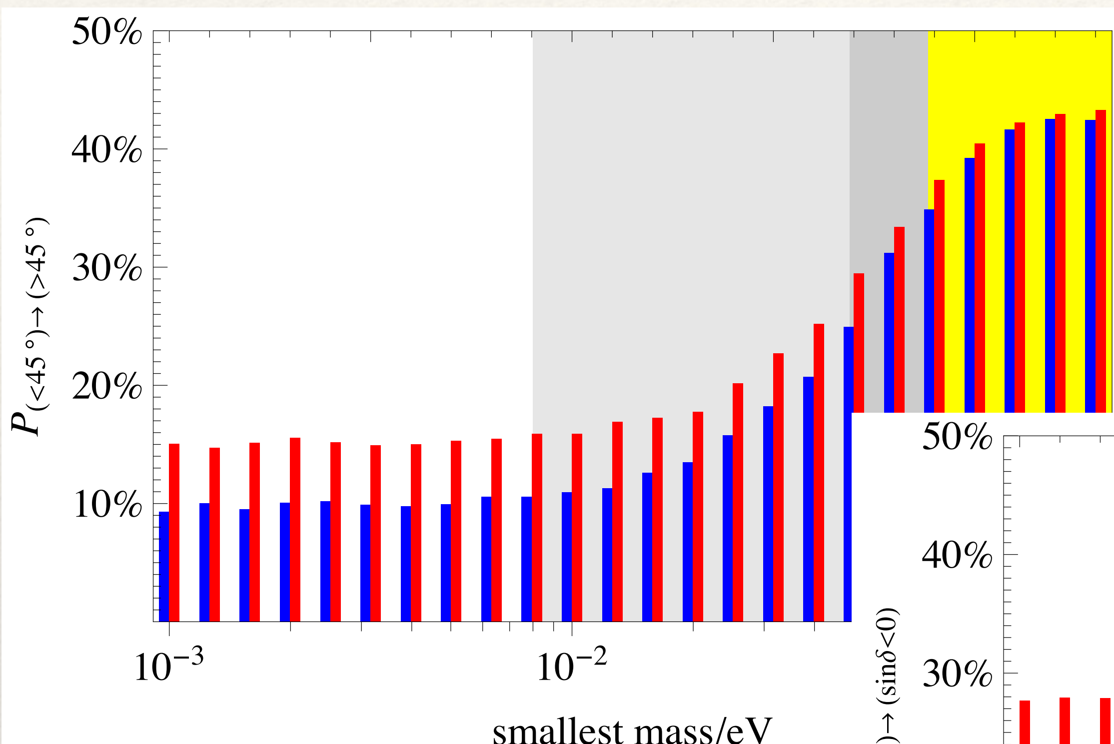
large

Example RG enhancement:

(running of phases and θ_{12} can be evaded by cancellations)

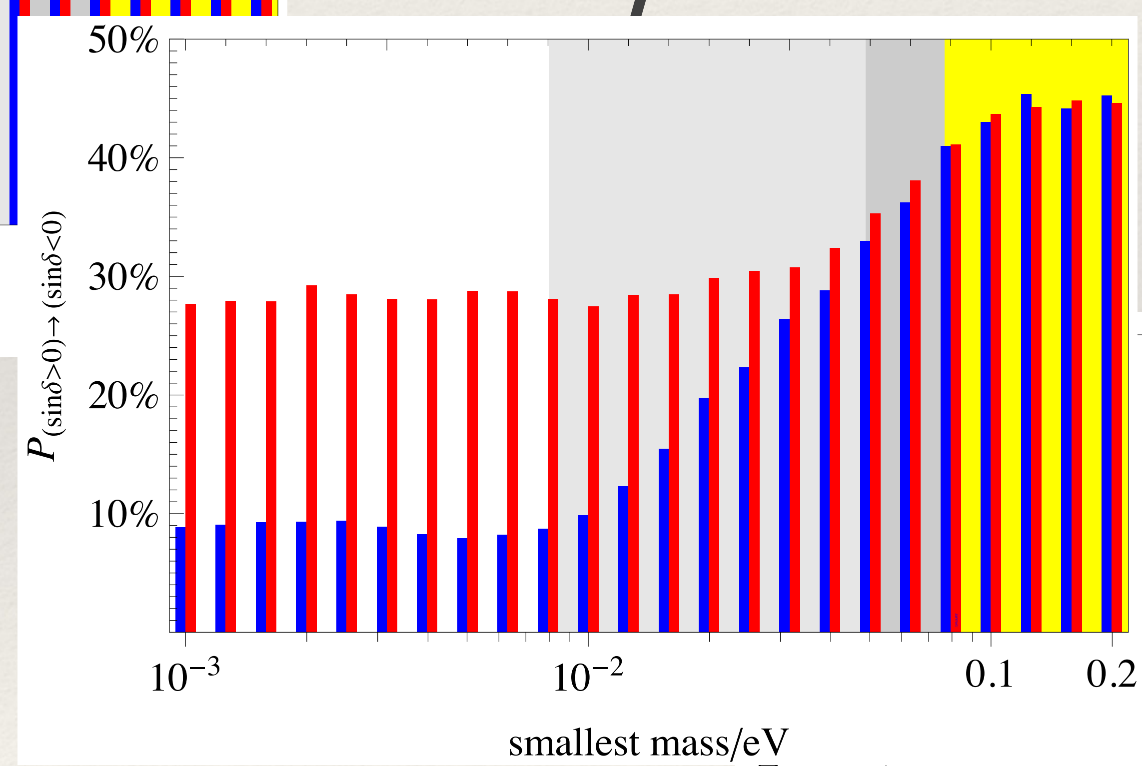
	NH	IH	QD
$\delta(\theta_{12})$	1	$\Delta m_A^2/\Delta m_\odot^2$	$m_0^2/\Delta m_\odot^2$
$\delta(\theta_{13})$	$\sqrt{\Delta m_\odot^2/\Delta m_A^2}$	1	$m_0^2/\Delta m_A^2$
$\delta(\theta_{23})$	1	1	$m_0^2/\Delta m_A^2$
$\delta(\delta)$	$\sqrt{\Delta m_\odot^2/\Delta m_A^2}$	$\Delta m_A^2/\Delta m_\odot^2$	$m_0^2/\Delta m_A^2$
$\delta(\alpha,\beta)$	$\sqrt{\Delta m_\odot^2/\Delta m_A^2}$	$\Delta m_A^2/\Delta m_\odot^2$	$m_0^2/\Delta m_A^2$

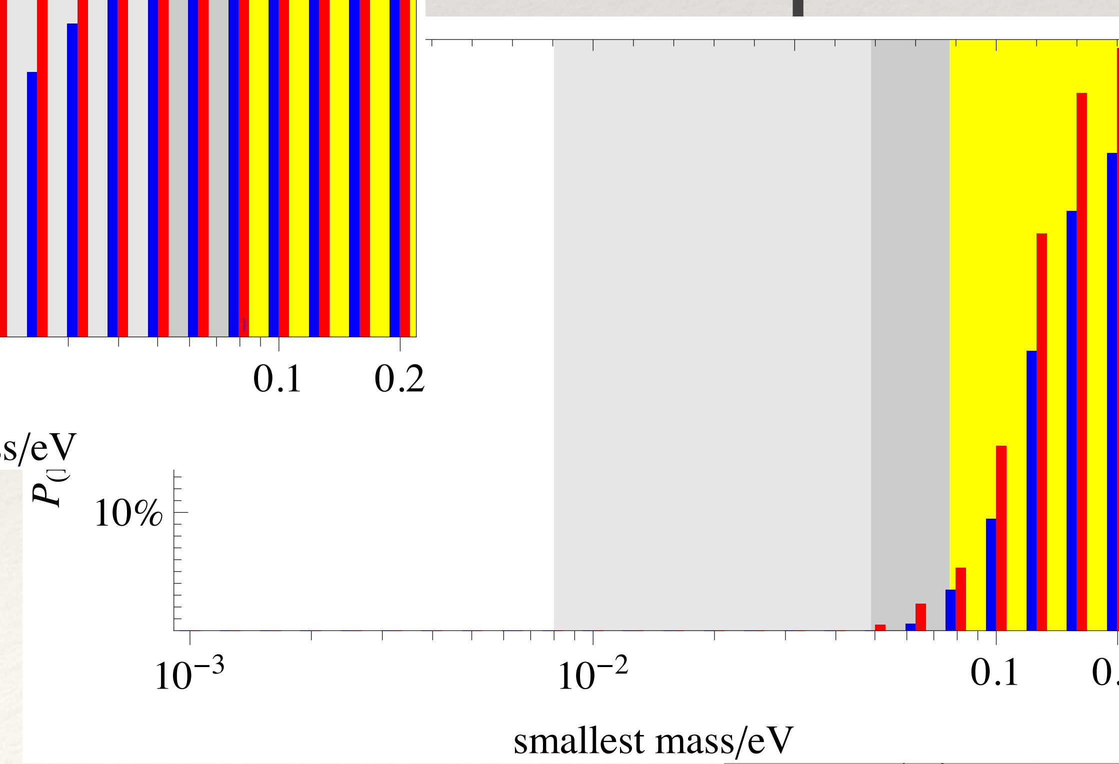
Perturbations



probability to change sign of sin δ

probability to change mass ordering

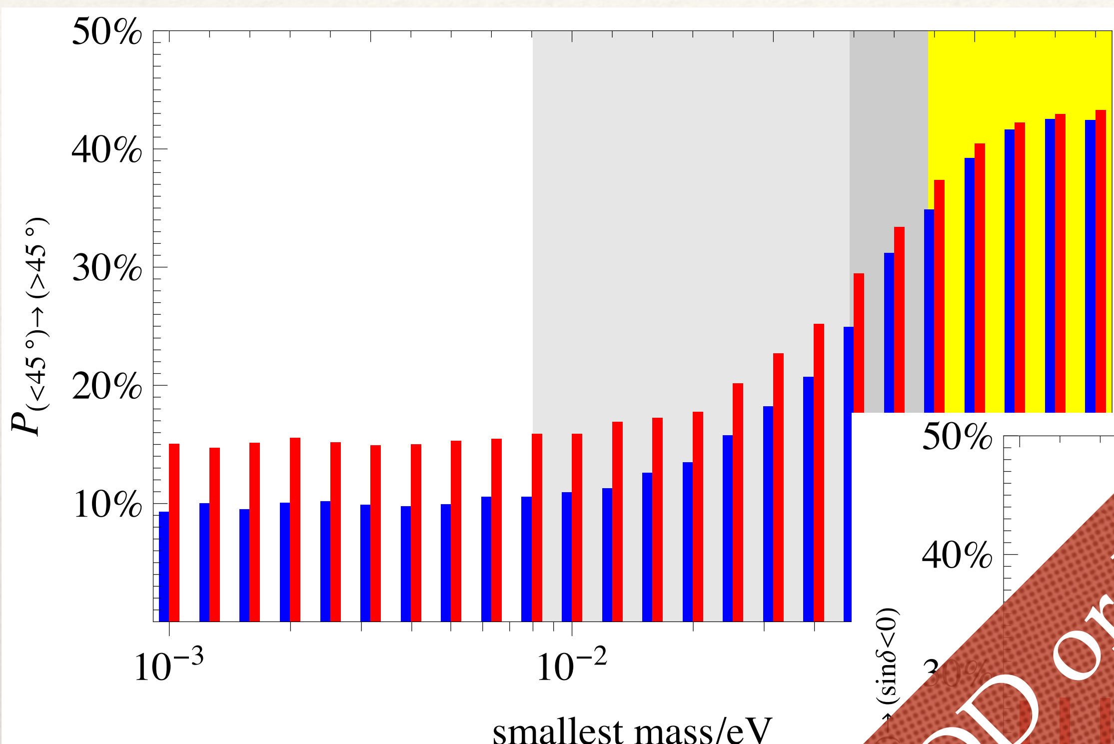




probability to change octant of θ_{23}

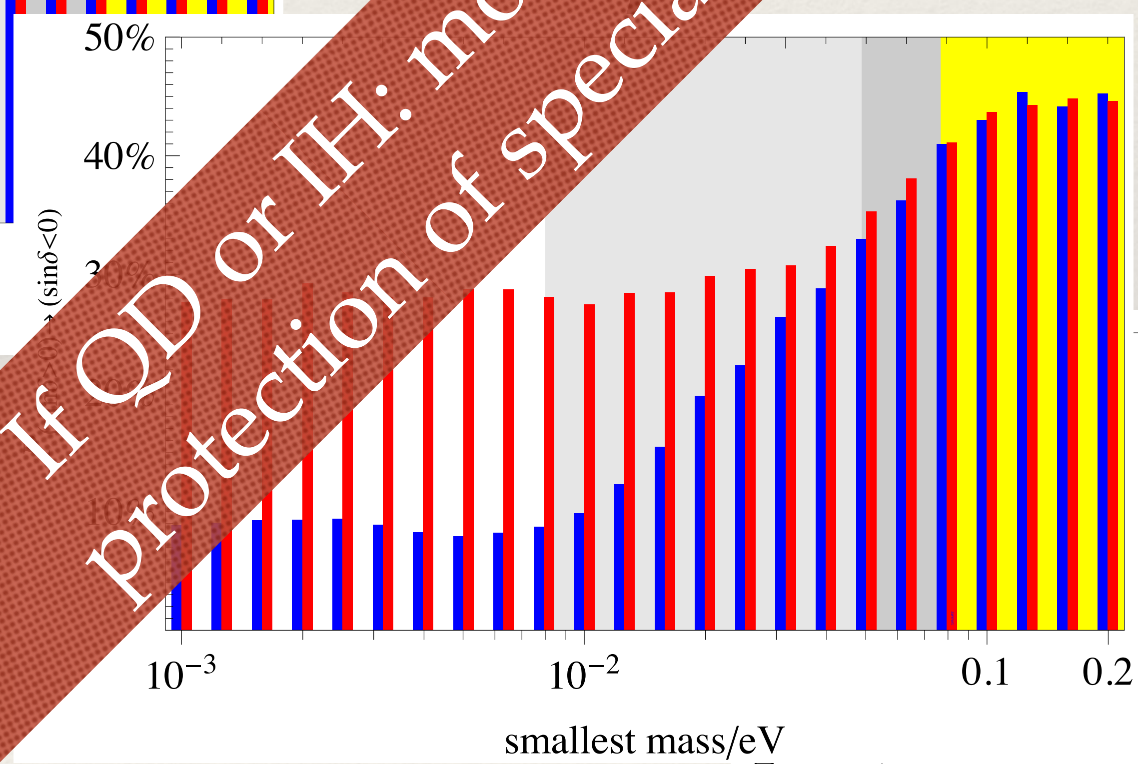
WR, Xu, 1508.06063

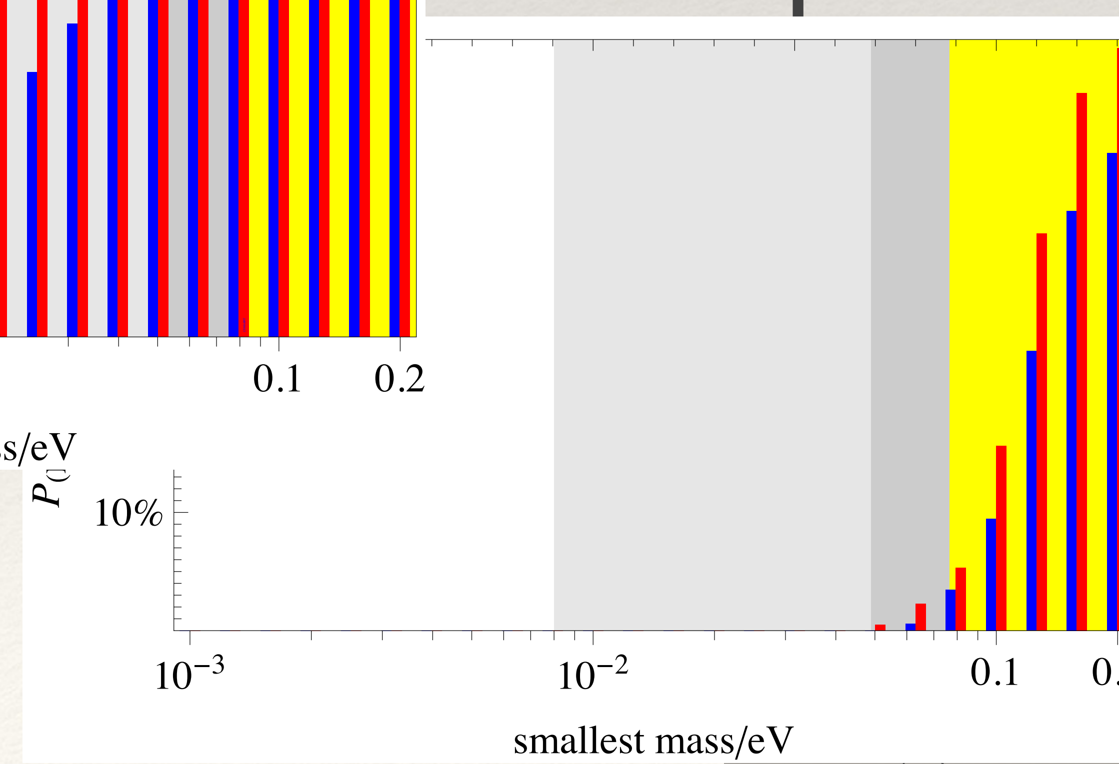
Perturbations



probability to change sign of sin δ

probability to change mass ordering





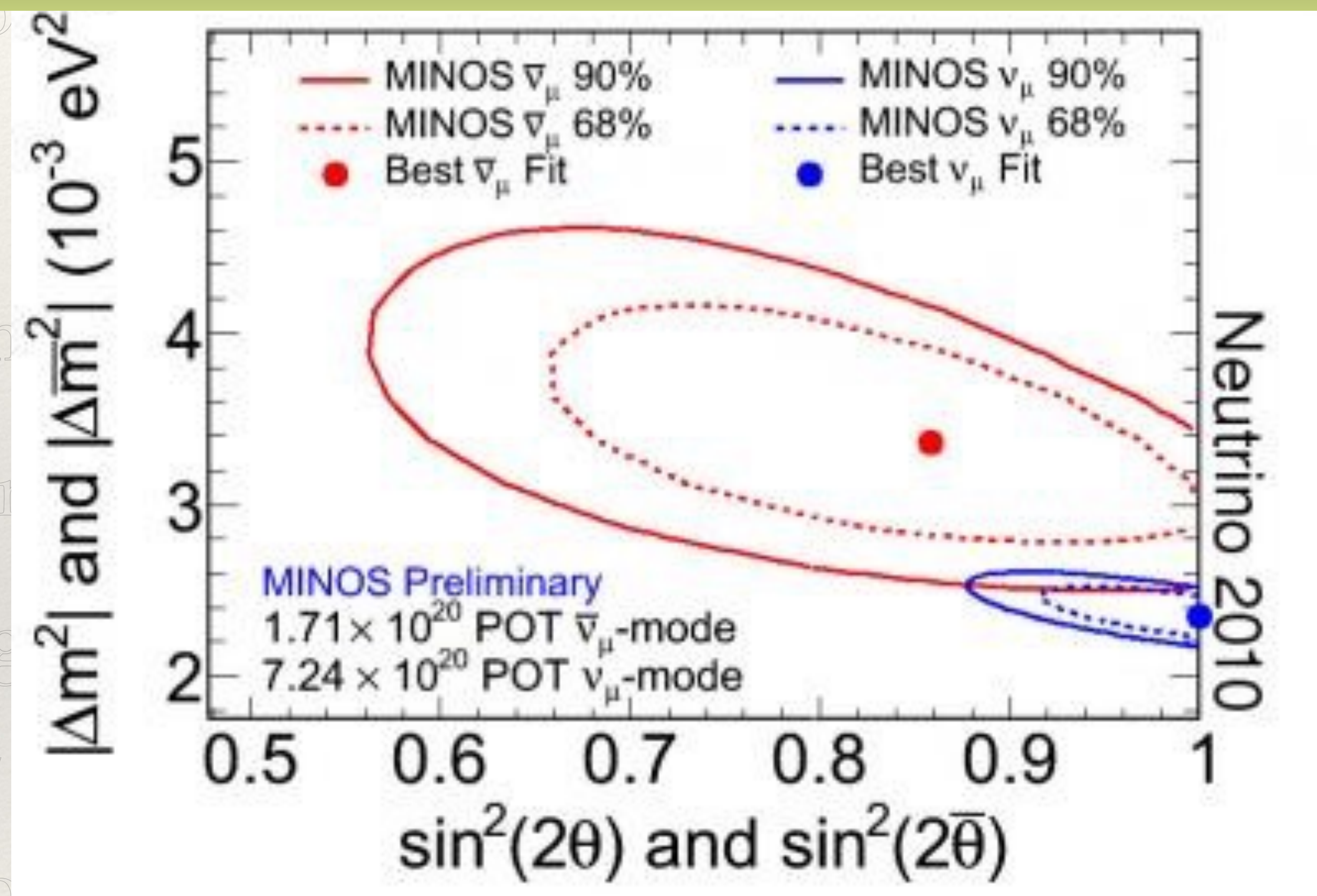
If QD or IH: more need of protection of special values

probability to change octant of θ_{23}

WR, Xu, 1508.06063

New Physics in Oscillations

New Physics can mess up oscillation experiments:



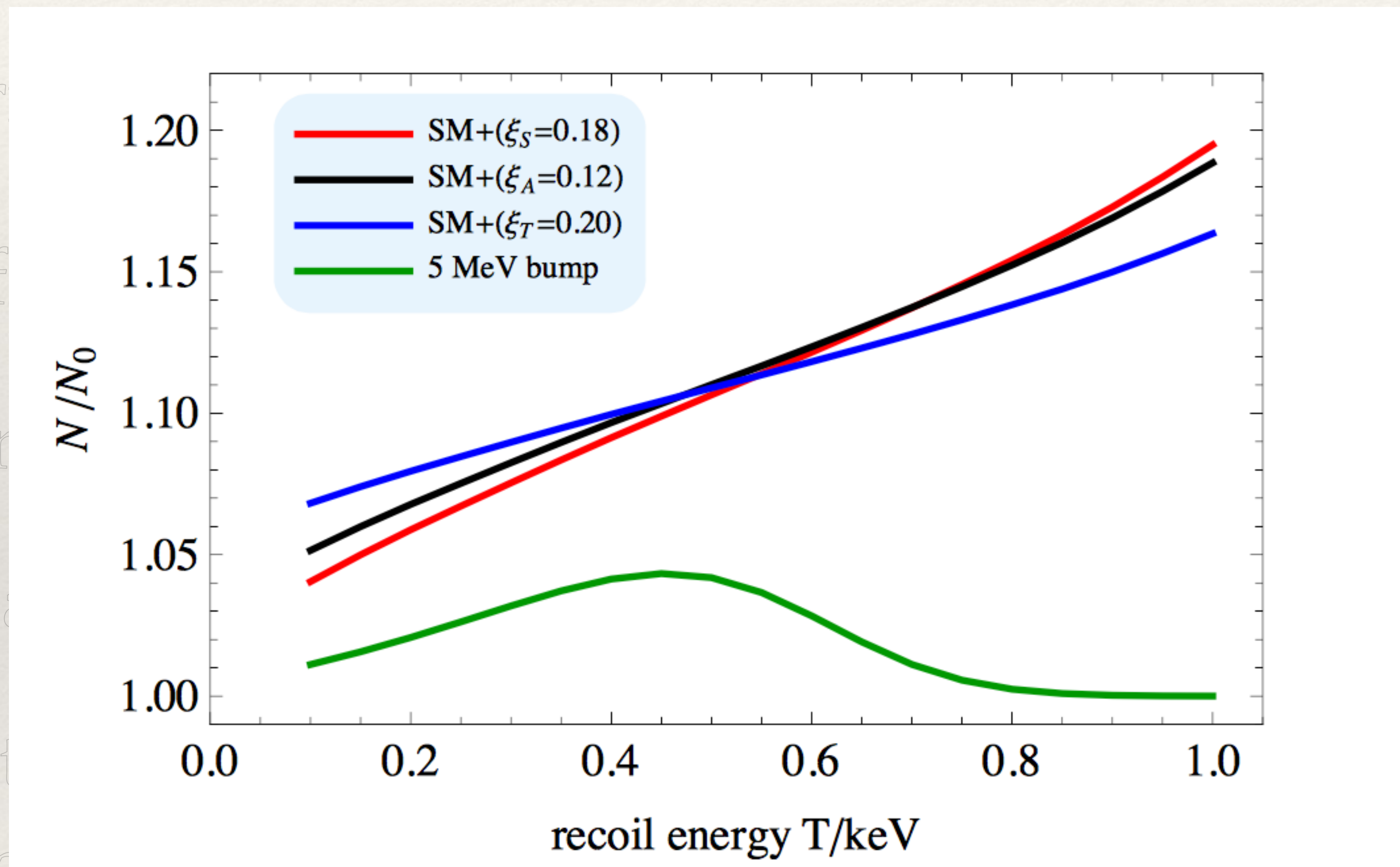
- Various go…
  - unitarity
  - NSIs fro…
  - new inter…
  - long rang…
  - Lorentz / … ale of mass generatio… in general growing with high ν-energy (IC!)
  - light sterile neutrinos…

New Physics in Oscillations

Next generation coherent scattering experiment (Talk by Hakenmüller):

- unitar
- NSIs f
- new in
- long r
- Lorent ... scale of mass generation (seesaw)), in general growing with high ν-energy (IC!)
- light ste

Lindner, WR, Xu, 1612.04150



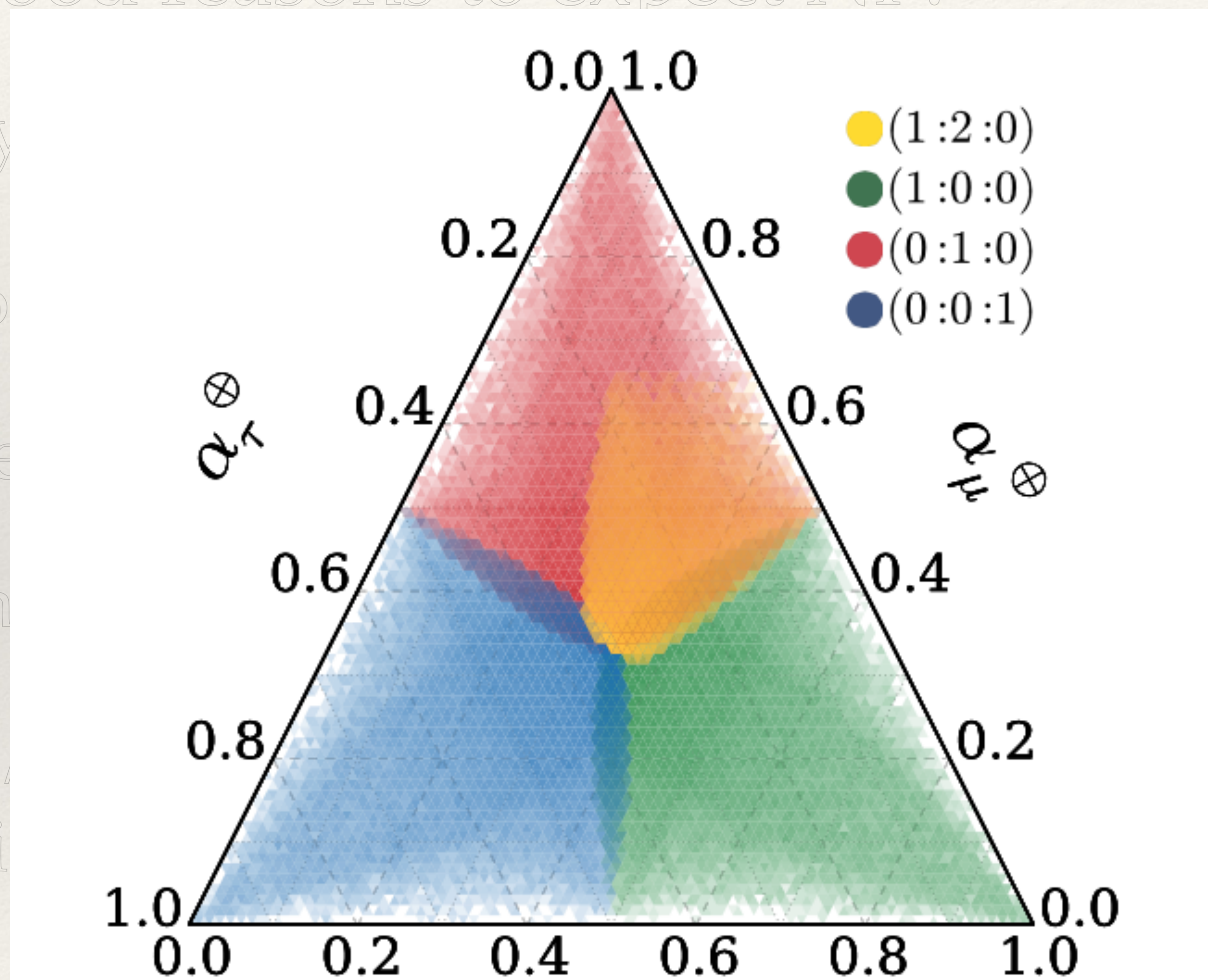
$$\mathcal{L} \supset \frac{G_F}{\sqrt{2}} \sum_{a=S,P,V,A,T} \overline{\nu} \Gamma^a \nu \left[\overline{q} \Gamma^a (C_a^{(q)} + \overline{D}_a^{(q)} i\gamma^5) q\right]$$

New Physics in Oscillations

Exotic New Physics enhanced by long distance / high energy:

❖ Various good reasons to expect NP:

- unitarity
- NSIs fro
- new inte
- long ran
- Lorentz ... scale of mass generati... high ν-energy (IC!)
- light sterile neutrinos...



Arguelles et al., 1506.02043