

Where are we? Where are we heading to?



Werner Rodejohann (MPIK)
29/01/18



NEUTRINO PLATFORM WEEK

29 January 2018 to 2 February 2018

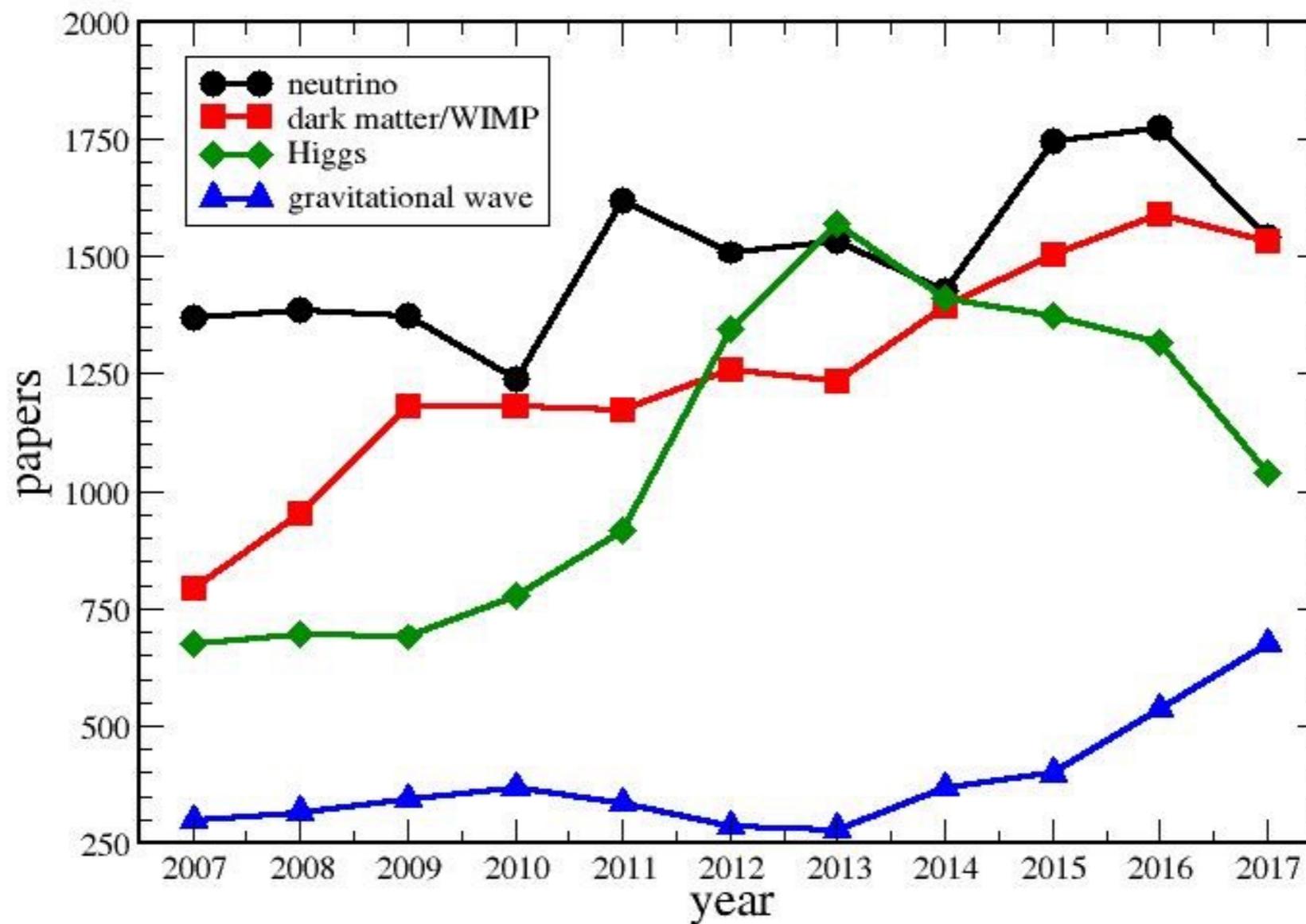
CERN

Europe/Zurich timezone



Neutrinos still hot topic

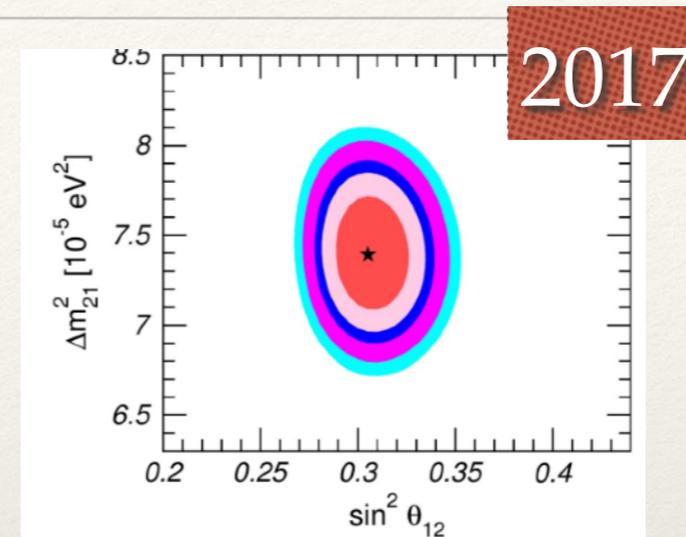
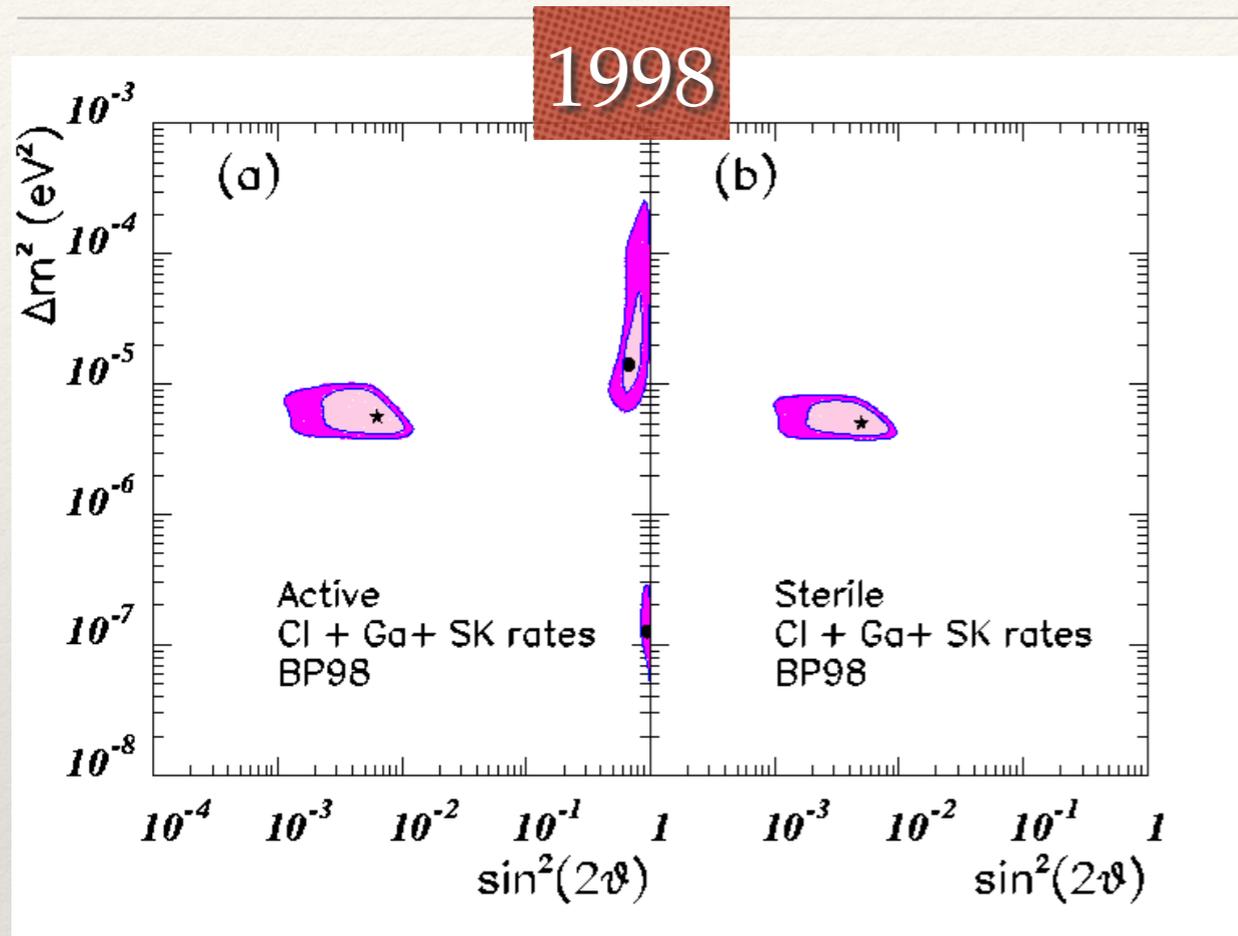
INSPIRE: find title x and date y



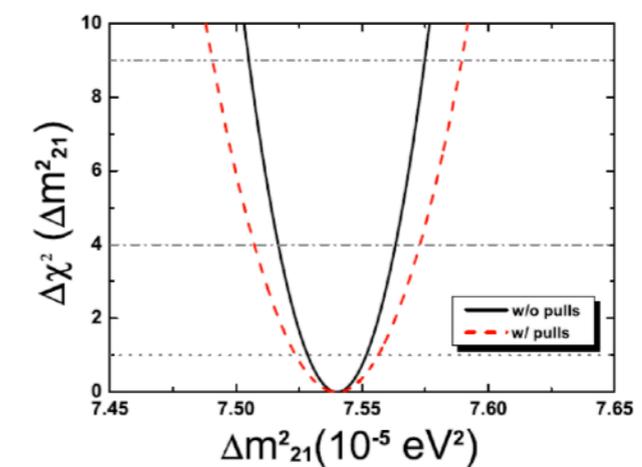
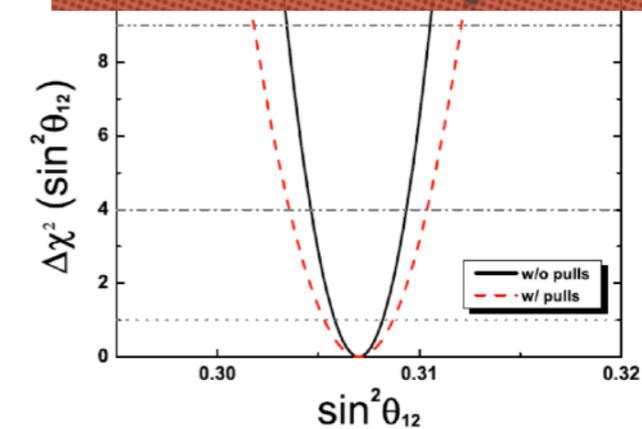
Neutrinos still hot topic

- ❖ ONLY BSM field testable in the lab
- ❖ connected to everything
- ❖ new field, still new windows open:
 - TeV / PeV scale physics with astrophysical ν (\Leftrightarrow multi-messenger options)
 - coherent ν -nucleus scattering
 - full spectrum of β -decay
 - solar physics, geoneutrinos, supernova,...

To answer the question...

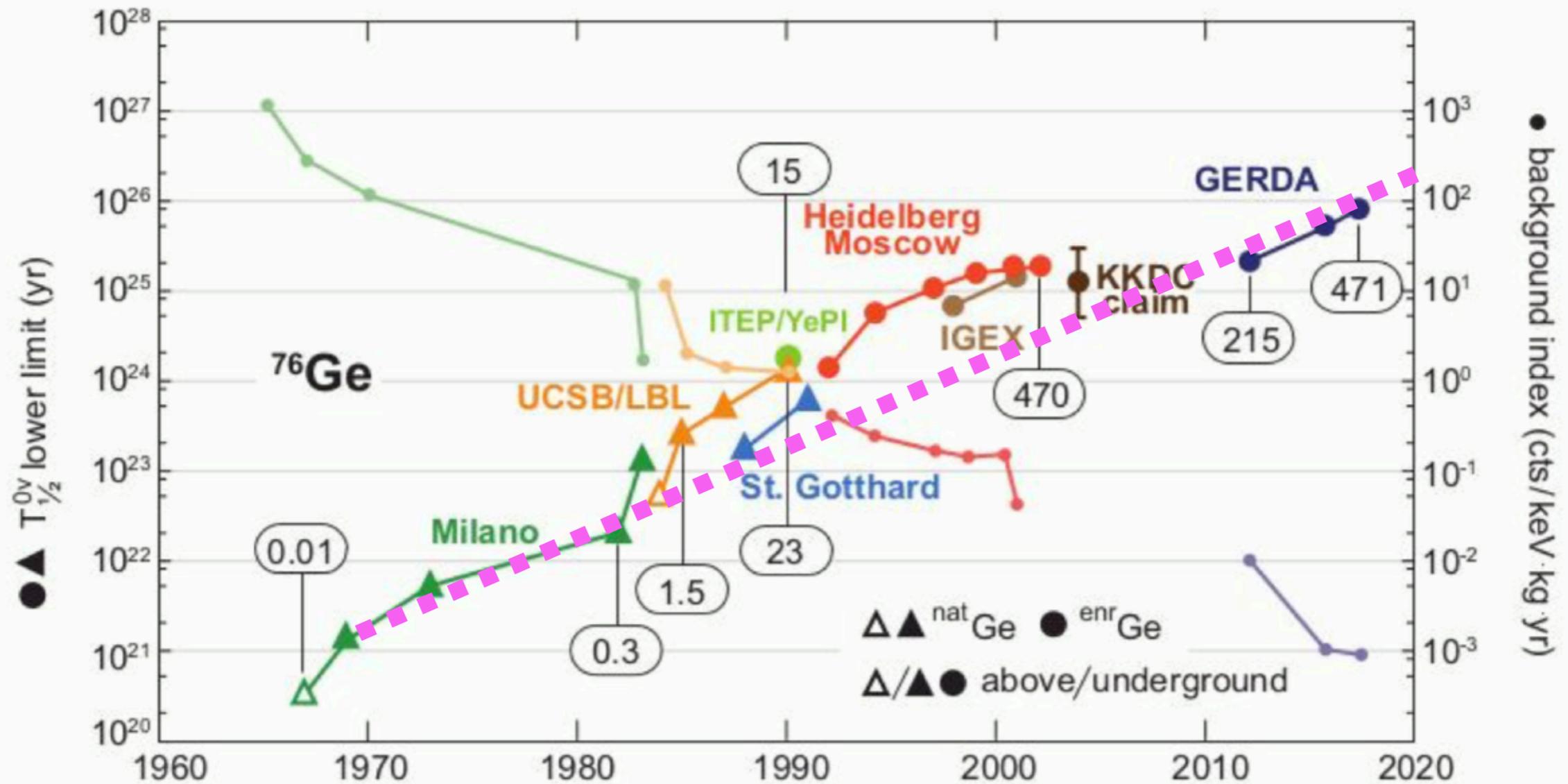


JUNO + 6 years (2026?)



To answer the question...

plot from Knöpfle, 1801.06395



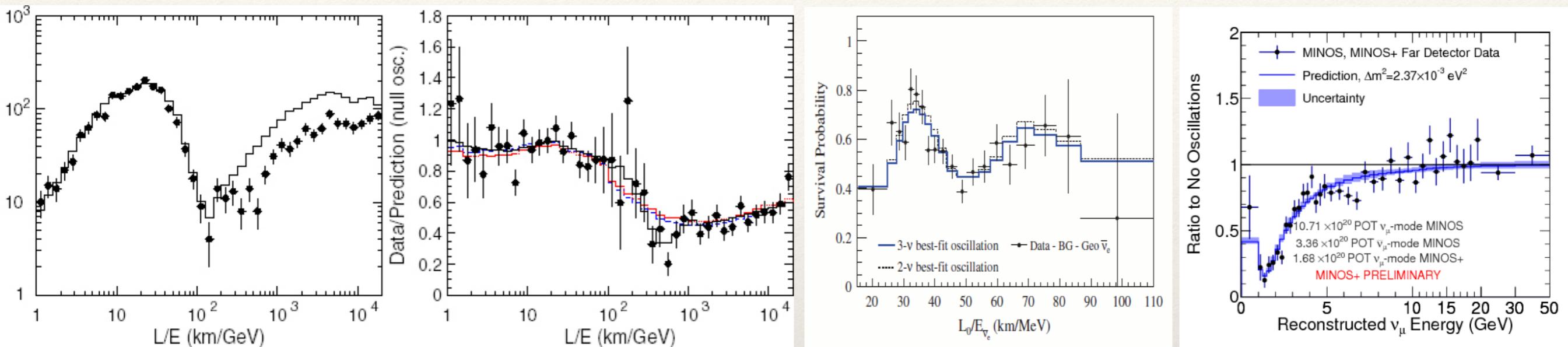
Moore's $0\nu\beta\beta$ law:
doubling of lifetime
limit every 3 years

(nuclear physics calculations here important,
just as for sterile ν hints or ν -N scattering)

Goals/Outline

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

Neutrinos oscillate and leptons mix



observed with various sources and techniques
 \Rightarrow quantum mechanical interference
 on macroscopic distances

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

(plus matter effects)

Talk by Akhmedov

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: $U_{\text{PMNS}} = U_l^\dagger U_\nu \neq \mathbb{1}$
 - \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 :

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

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 \Rightarrow 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:

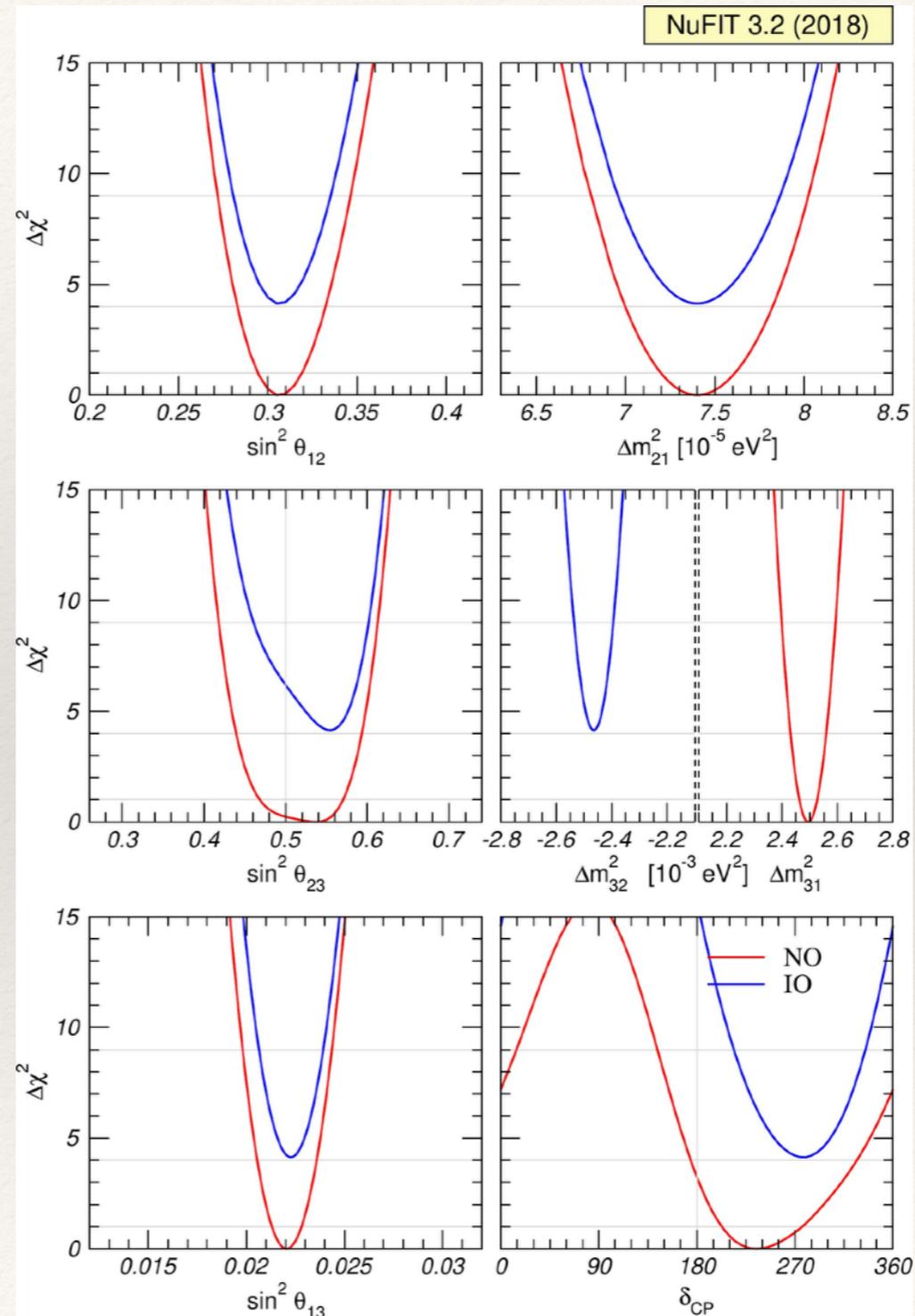
- θ_{12} and Δm_{21}^2
- θ_{23} and $|\Delta m_{31}^2|$
- θ_{13}

❖ We have limits:

- m_1, m_2, m_3

❖ We don't know:

- $\text{sgn}(\Delta m_{31}^2)$
- δ, α, β



Talk by Schwetz

Determine Parameters

❖ We know:

- θ_{12} and Δm^2_{21}
- θ_{23} and $|\Delta m^2_{31}|$
- θ_{13}

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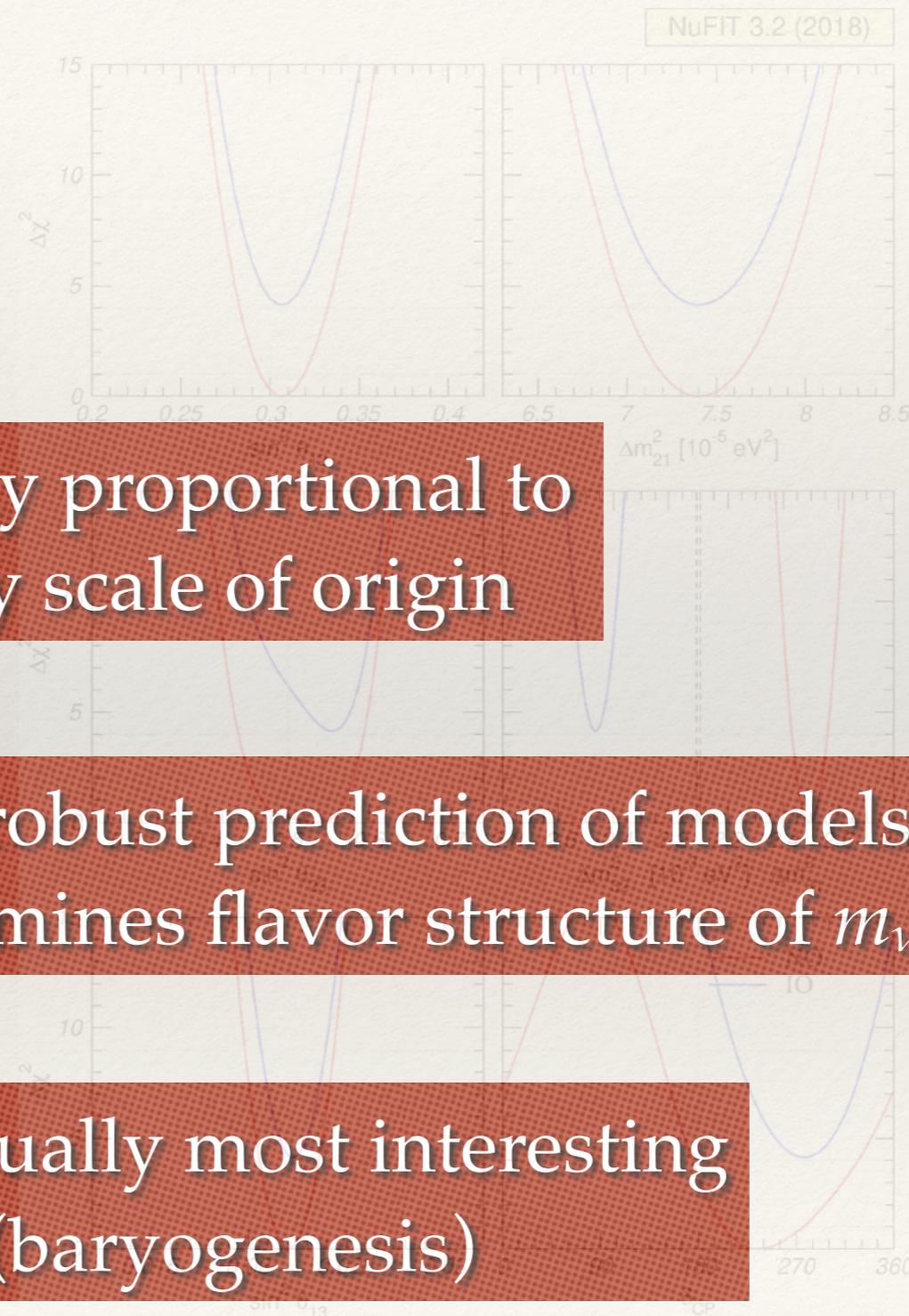
❖ We don't know:

- $\text{sgn}(\Delta m^2_{31})$
- δ, α, β

inversely proportional to
energy scale of origin

most robust prediction of models;
determines flavor structure of m_ν

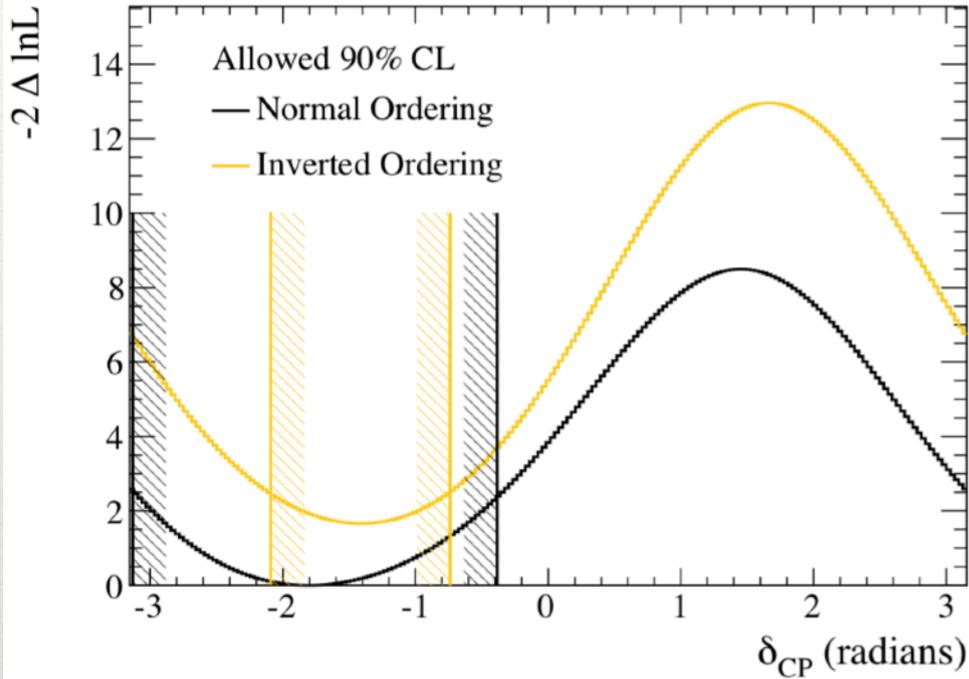
conceptually most interesting
(baryogenesis)



Talk by Schwetz

CP Phase

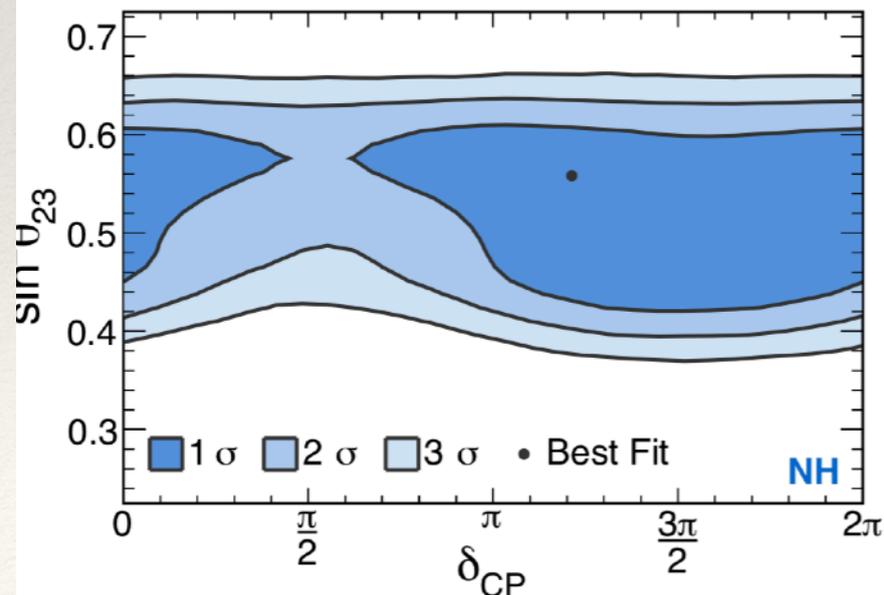
T2K



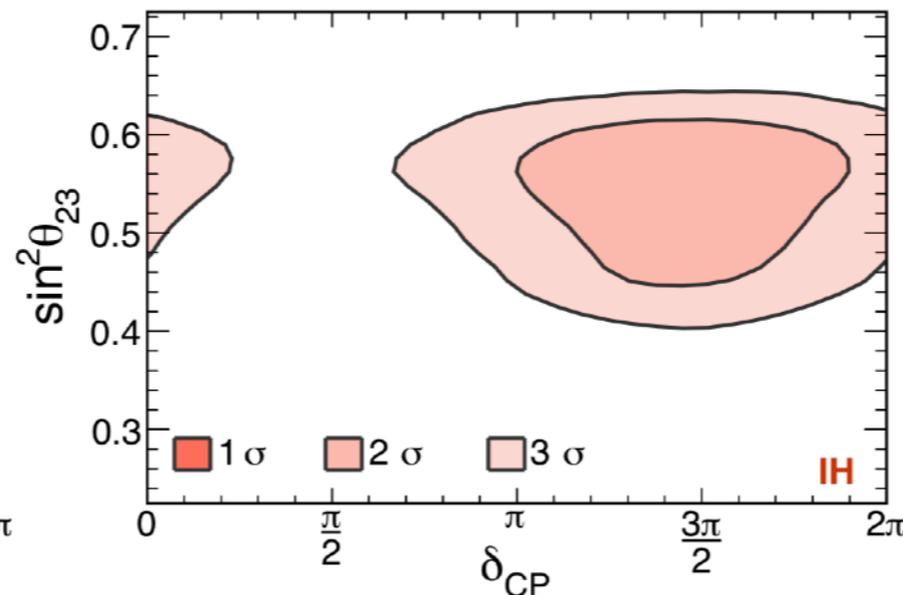
Normal	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\bar{\nu}_e$	6.0	6.9	7.7	6.8	4
Inverted	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν_e	25.4	21.3	17.1	21.3	32
$\bar{\nu}_e$	6.5	7.4	8.4	7.4	4

mostly driven by too many ν_e at T2K

NOvA Preliminary



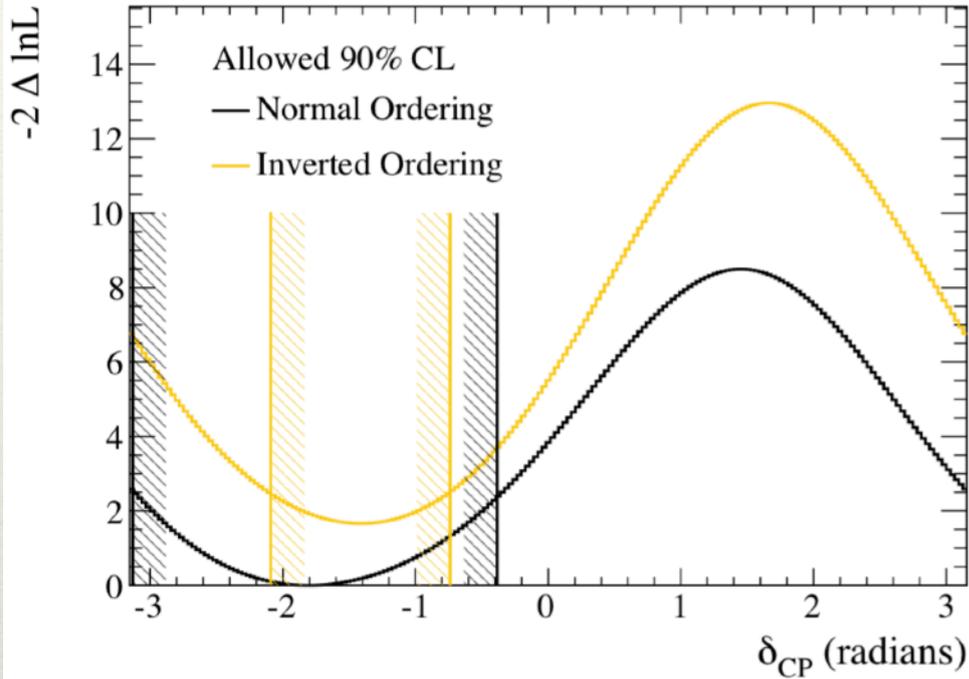
NOvA Preliminary



- $3\pi/2$ highly interesting...
- Symmetry behind it?
- Worth to reconsider ν and anti- ν share?

CP Phase

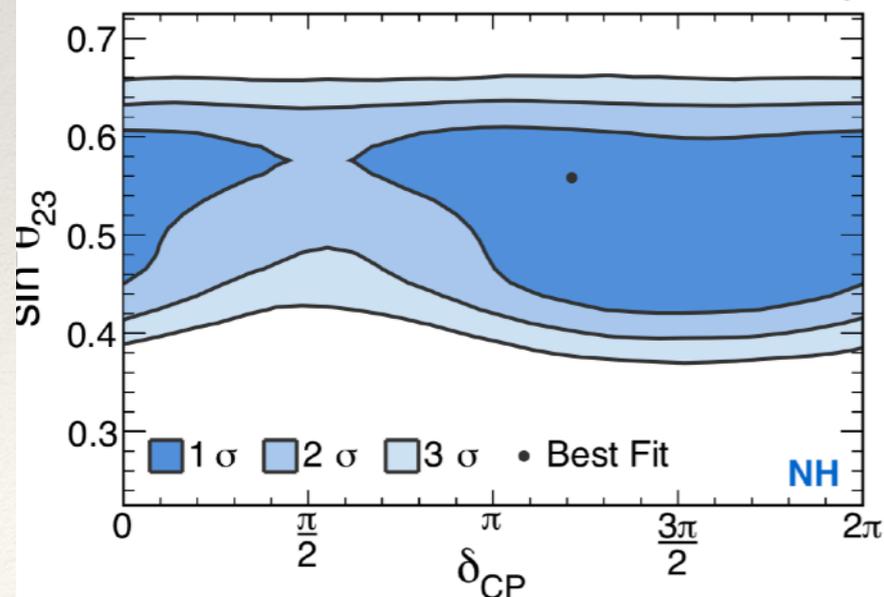
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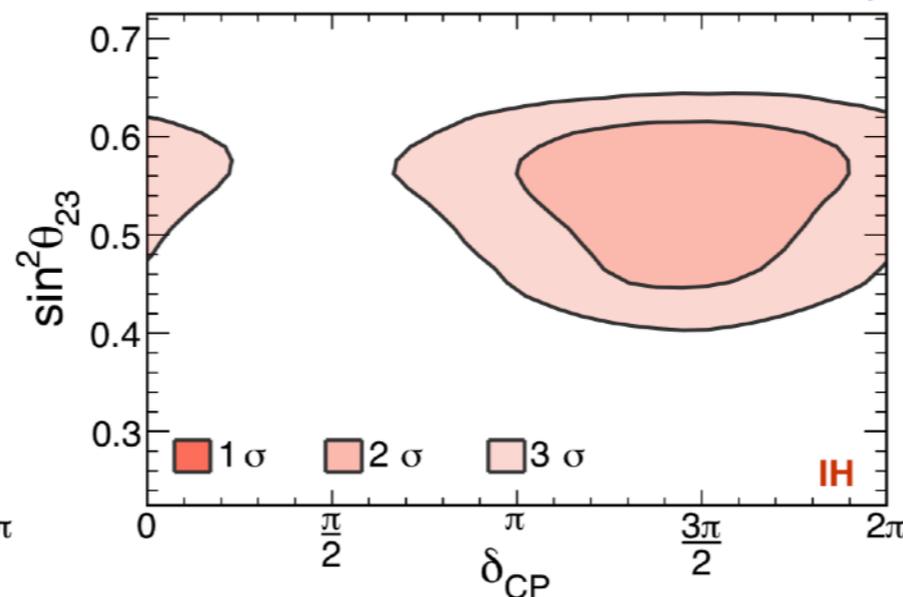
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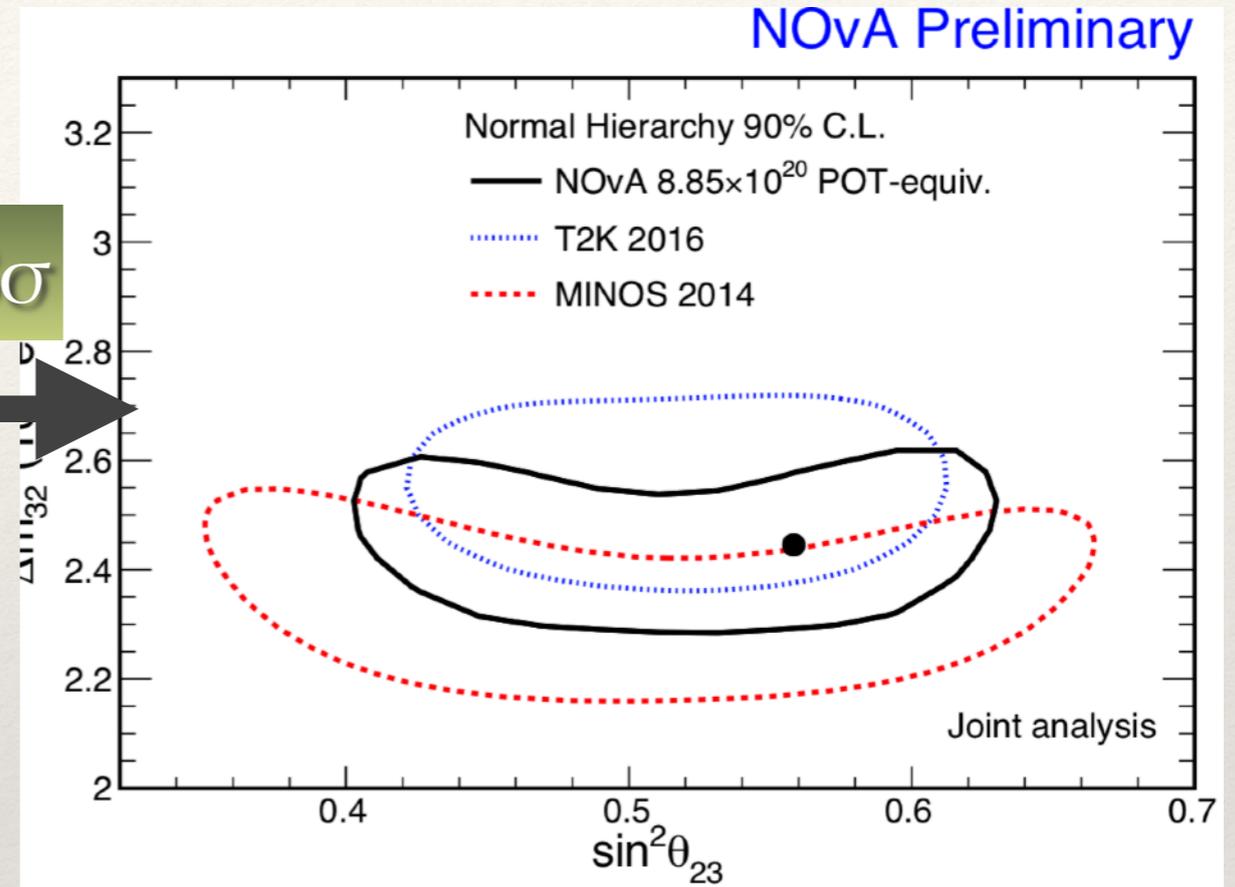
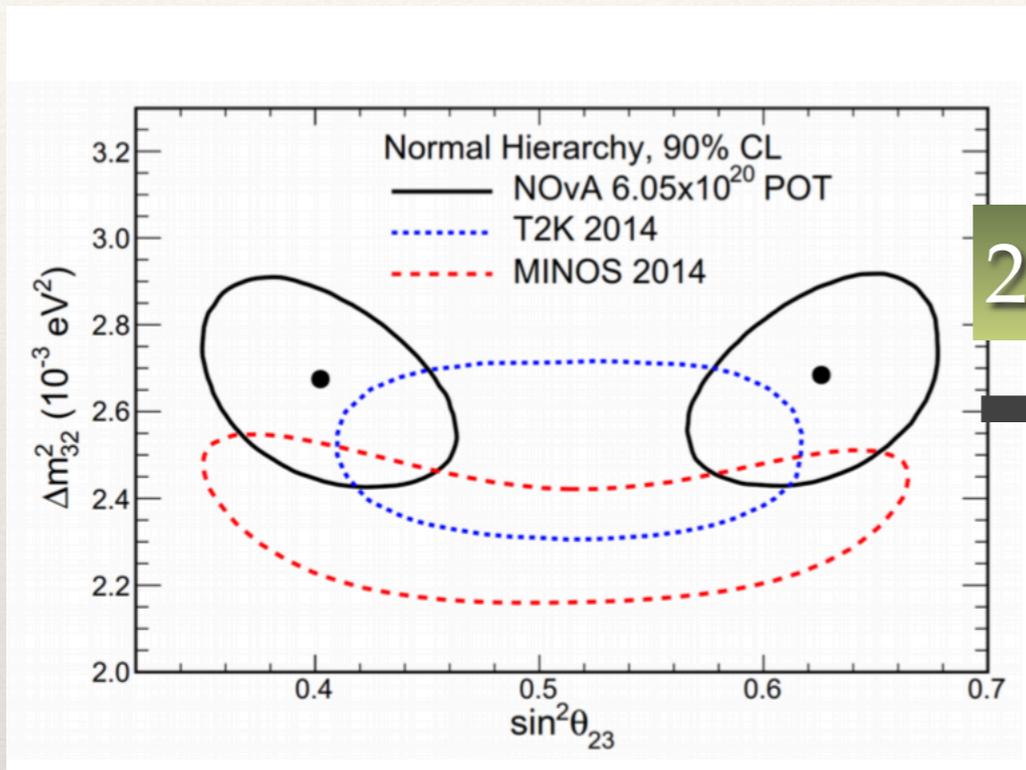


- $3\pi/2$ highly interesting...
- Symmetry behind it?*
- Worth to reconsider ν and anti- ν share?

* μ - τ reflection symmetry? / combining flavor with CP?

Talk by Hagedorn

Atmospheric Mixing Angle



- Maximal mixing?!
- Symmetry behind it?
- Which octant?

Example RG effects:

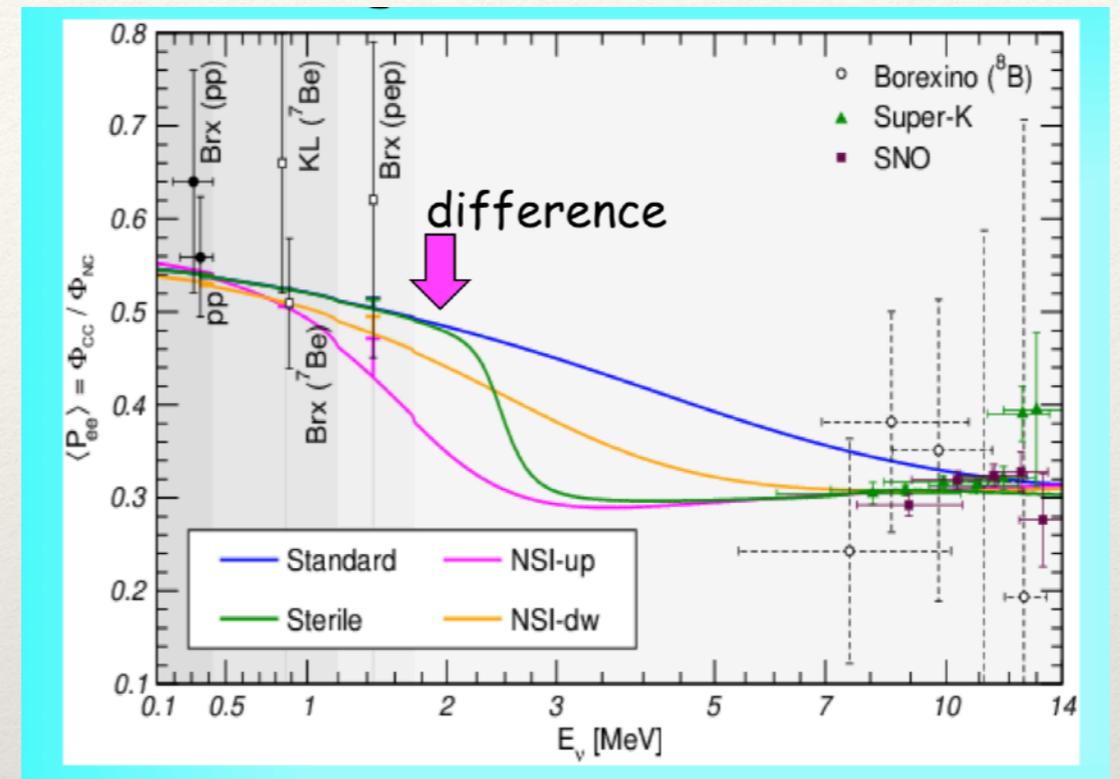
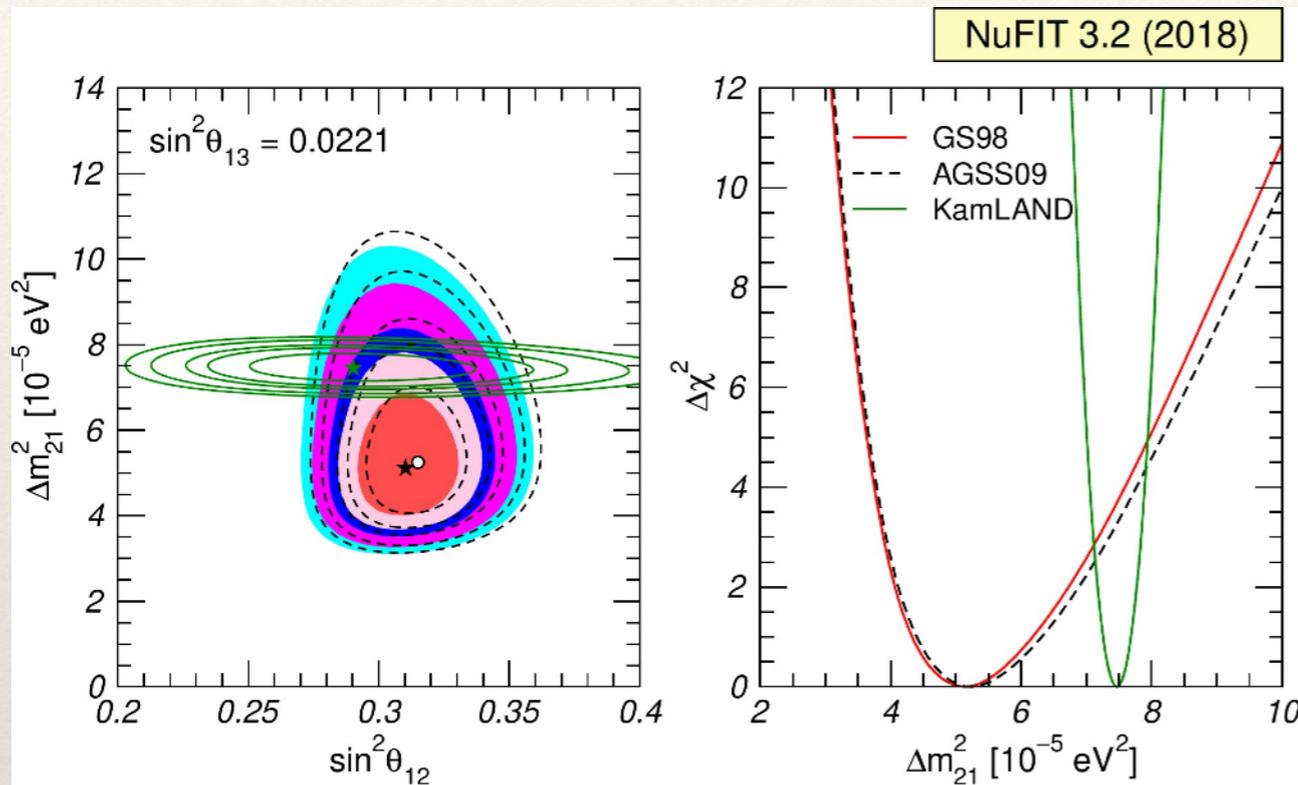
Model	mass ordering	θ_{12}	θ_{23}
SM	$\Delta m_{31}^2 > 0$	↘	↘
	$\Delta m_{31}^2 < 0$	↘	↗
MSSM	$\Delta m_{31}^2 > 0$	↗	↗
	$\Delta m_{31}^2 < 0$	↗	↘

Mass Ordering

- ❖ weak preference for normal ordering
 - tension in the preferred values of θ_{23} in T2K and NOvA, found to be stronger for the case of inverted mass ordering (*Valle et al., 1708.01186*)
 - e -like multi-GeV events in SK? (*Lisi et al., 1703.04471*)
 - supported by strongest cosmological mass bounds
 - ❖ BUT: depends on sampling with logarithmic or linear prior, using m_i or $m_{sm} + \Delta m^2$ (*Gariazzo et al., 1801.04946, Hannestad and Schwetz, 1606.04691*)

Tensions: only in solar sector?

Talks by Beacom, Smirnov



Maltoni, Smirnov, 1507.05287

(plus too large matter effect and too large D/N effect)

Neutrinos oscillate and leptons mix

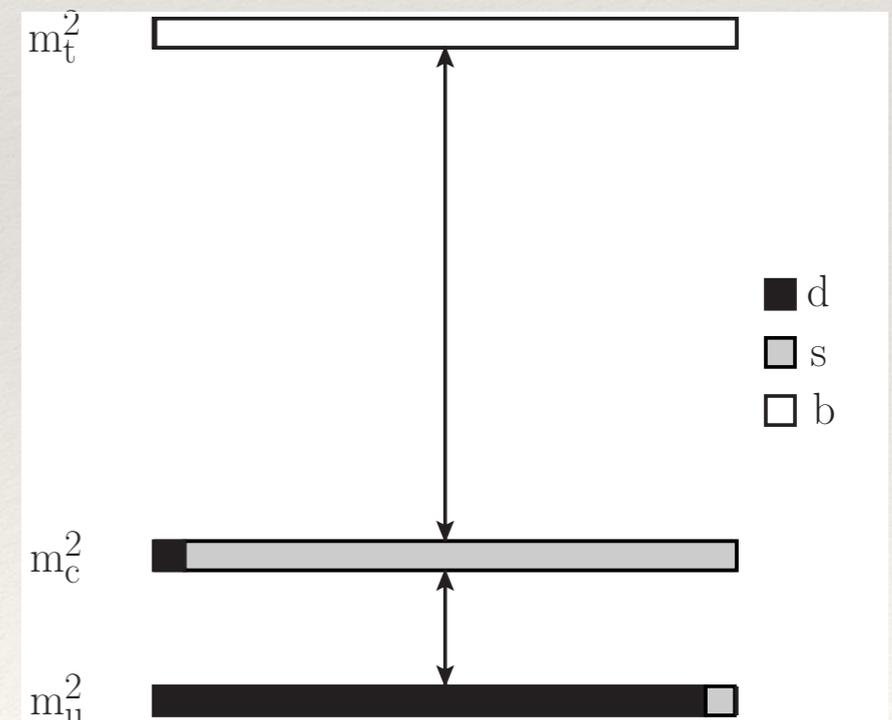
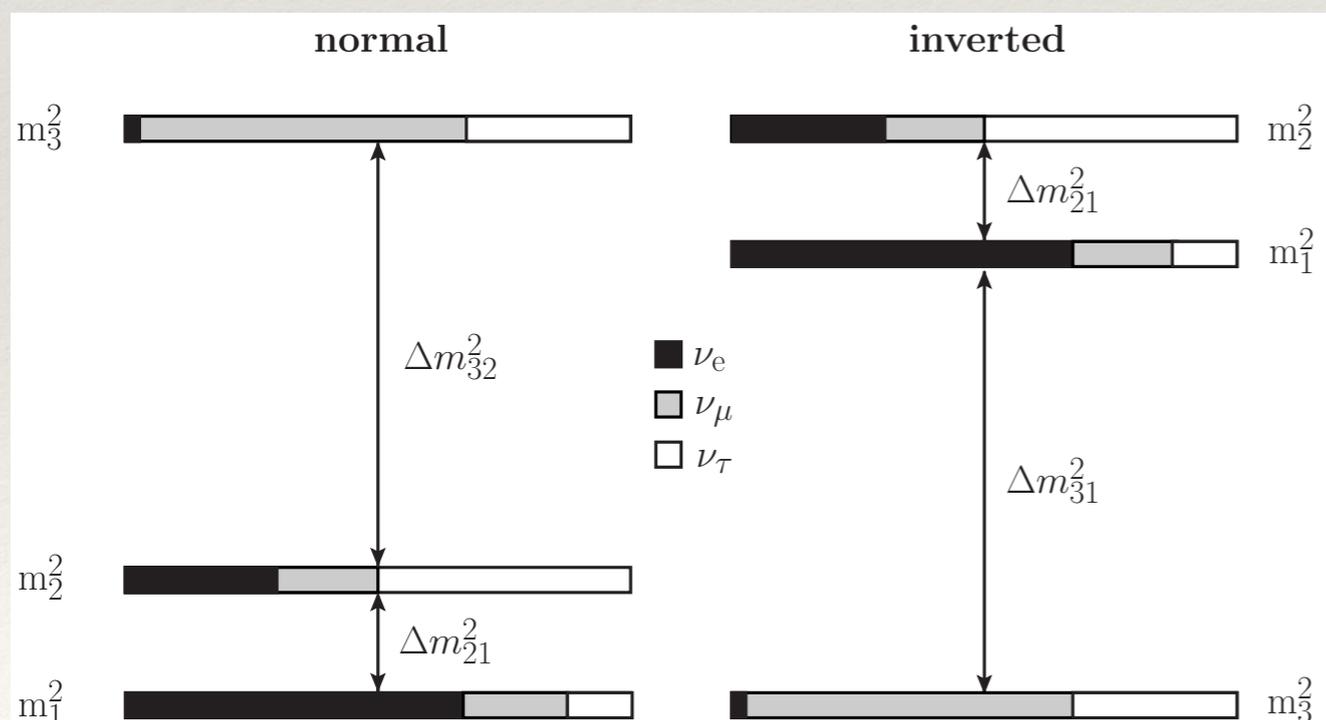
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Implications of Lepton Mixing

NuFIT 3.2 (2018)

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \rightarrow 0.844 & 0.516 \rightarrow 0.582 & 0.141 \rightarrow 0.156 \\ 0.242 \rightarrow 0.494 & 0.467 \rightarrow 0.678 & 0.639 \rightarrow 0.774 \\ 0.284 \rightarrow 0.521 & 0.490 \rightarrow 0.695 & 0.615 \rightarrow 0.754 \end{pmatrix}$$

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

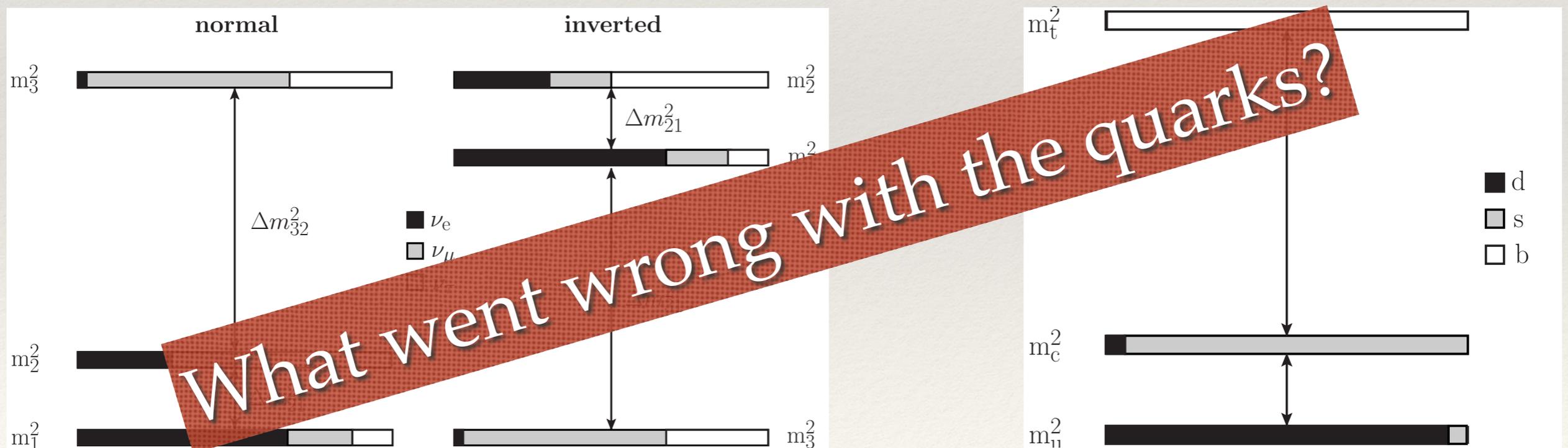


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Flavor Symmetries

- ❖ Nature seems to prefer large lepton mixing:

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

generated by rather special mass matrix

$$(m_\nu)_{\text{TBM}} = \begin{pmatrix} A & B & B \\ \cdot & \frac{1}{2}(A+B+D) & \frac{1}{2}(A+B-D) \\ \cdot & \cdot & \frac{1}{2}(A+B+D) \end{pmatrix}$$

mixing angles
independent from
masses!!

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

$$M = \begin{pmatrix} 0 & a \\ a & b \end{pmatrix} \Rightarrow \tan \theta_C \simeq \sqrt{\frac{m_d}{m_s}}$$

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, $\bar{3}$	
$PSL_2(7)$	168	1, 3, $\bar{3}$, 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', $\bar{1}'$, 3, $\bar{3}$	$A^7 = B^3 = 1, AB = BA^4$

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

Barry, WR, 1003.2385

Many possible groups, within each group many models...

⇒ can distinguish only classes of models

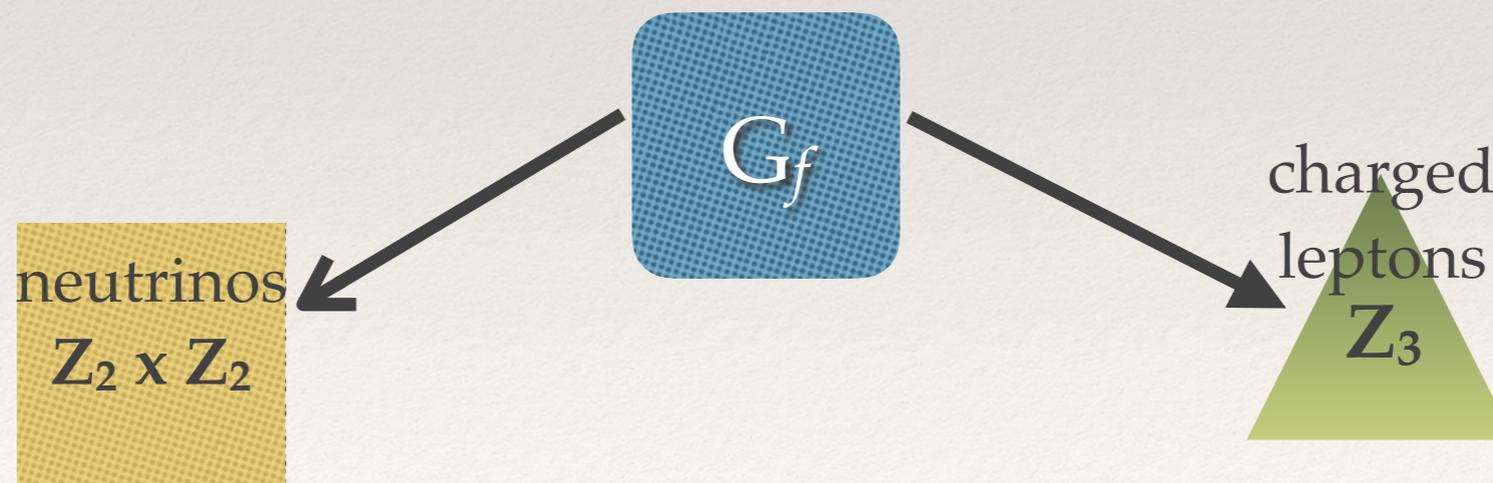
Flavor Symmetries

Talk by Hagedorn

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

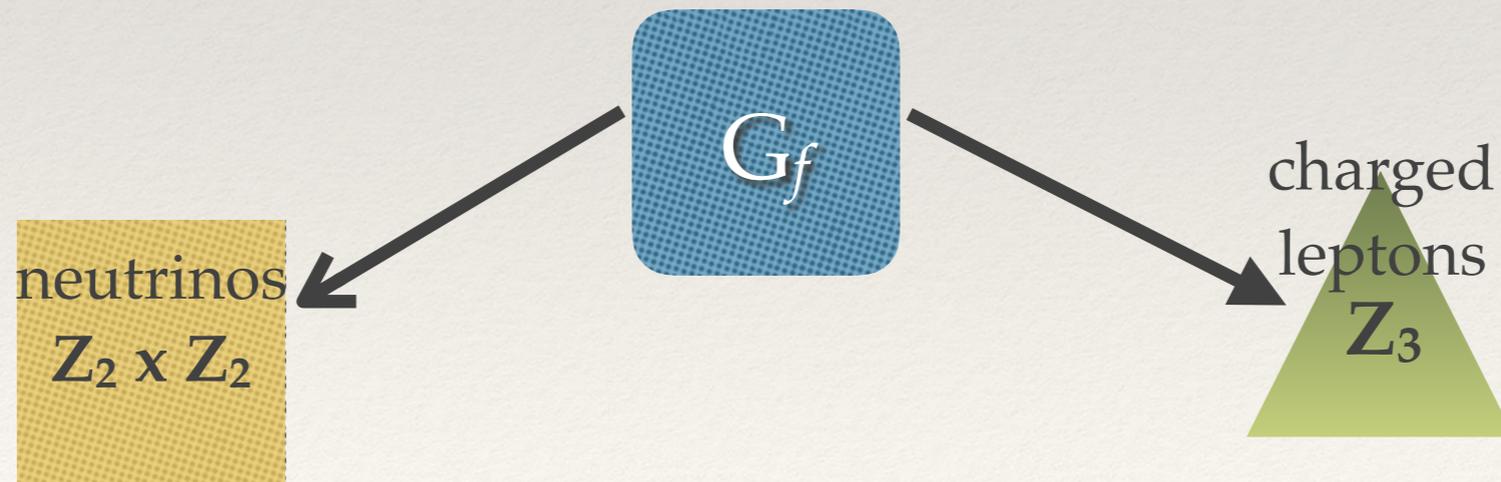
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related to 3 generations?

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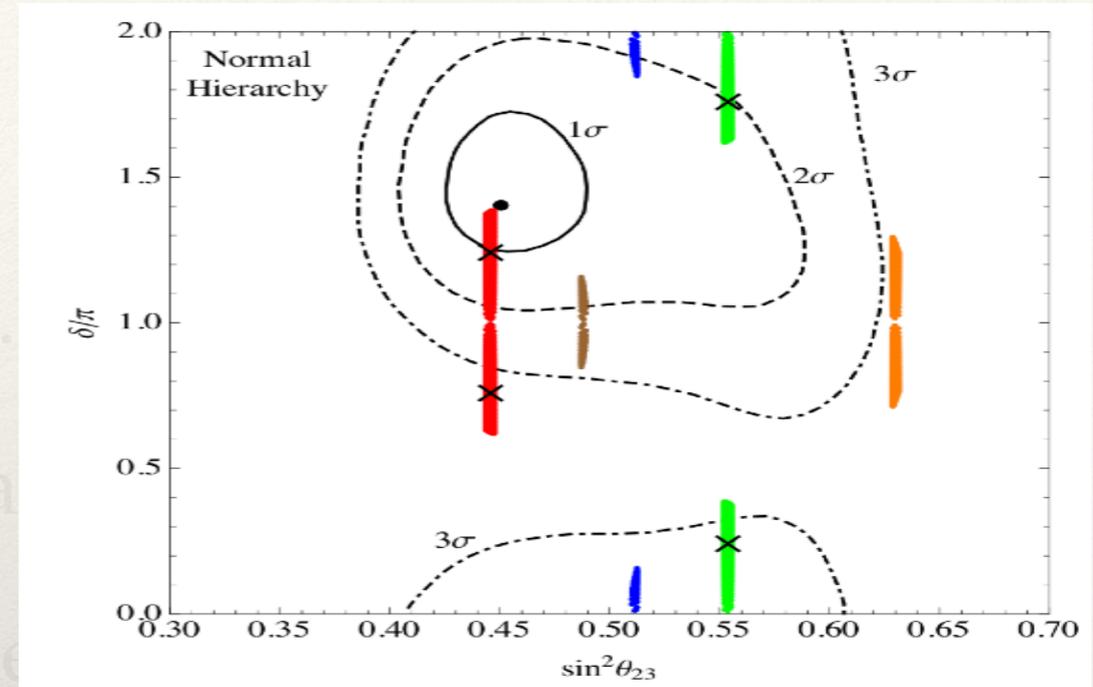
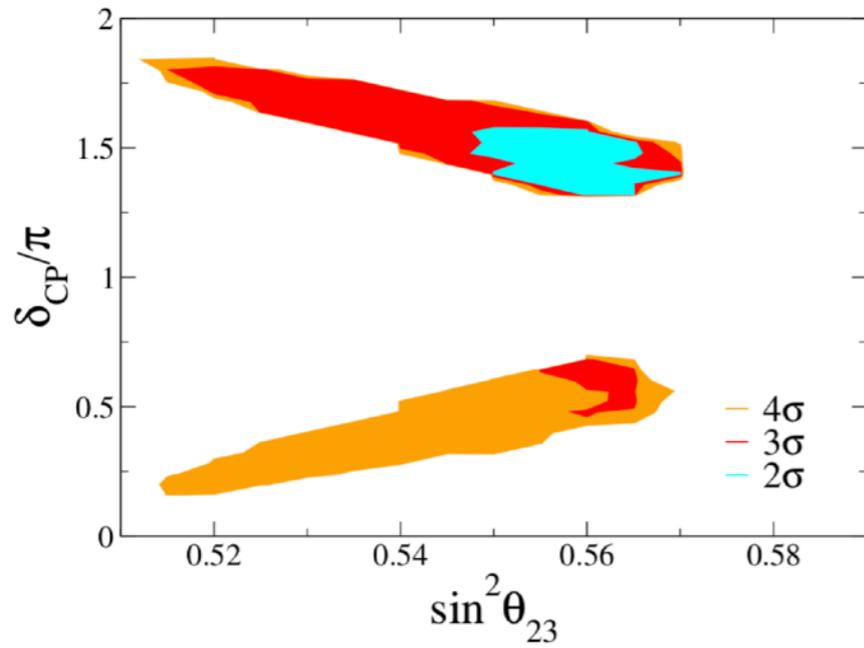


Flavor Symmetries

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

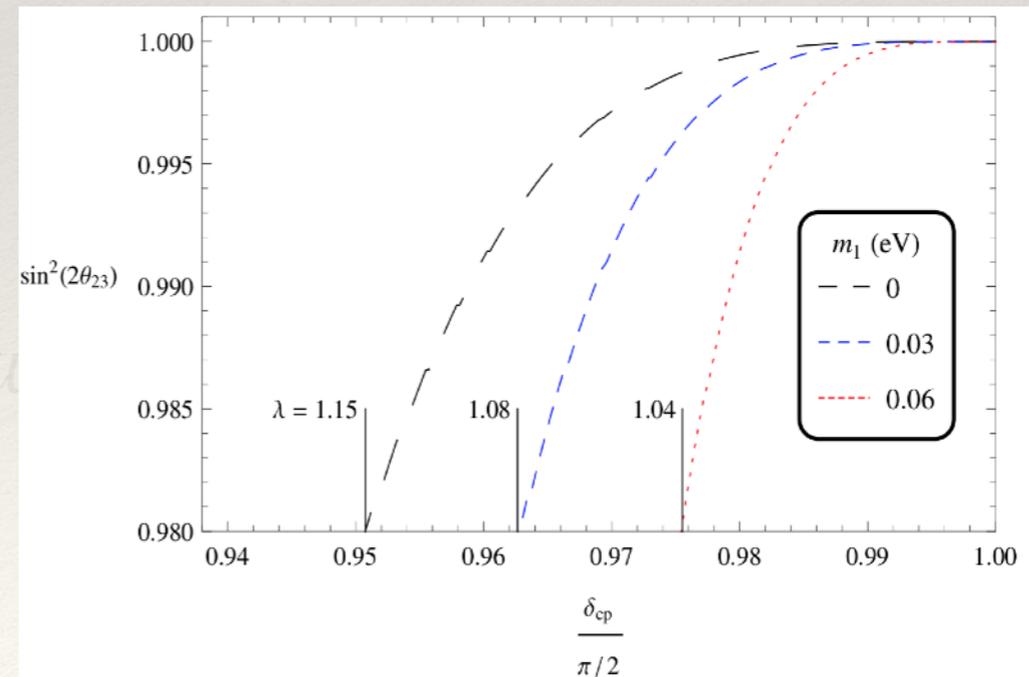
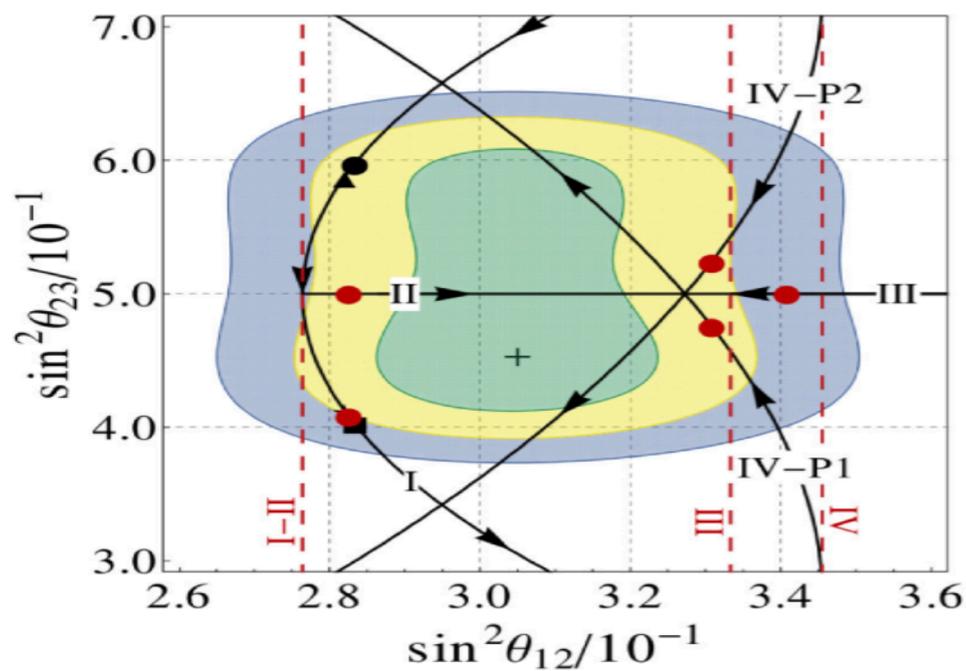
Flavor Symmetries

Valle et al., 1711.10318



Smirnov et al., 1510.00344

Hagedorn et al., 1503.04140

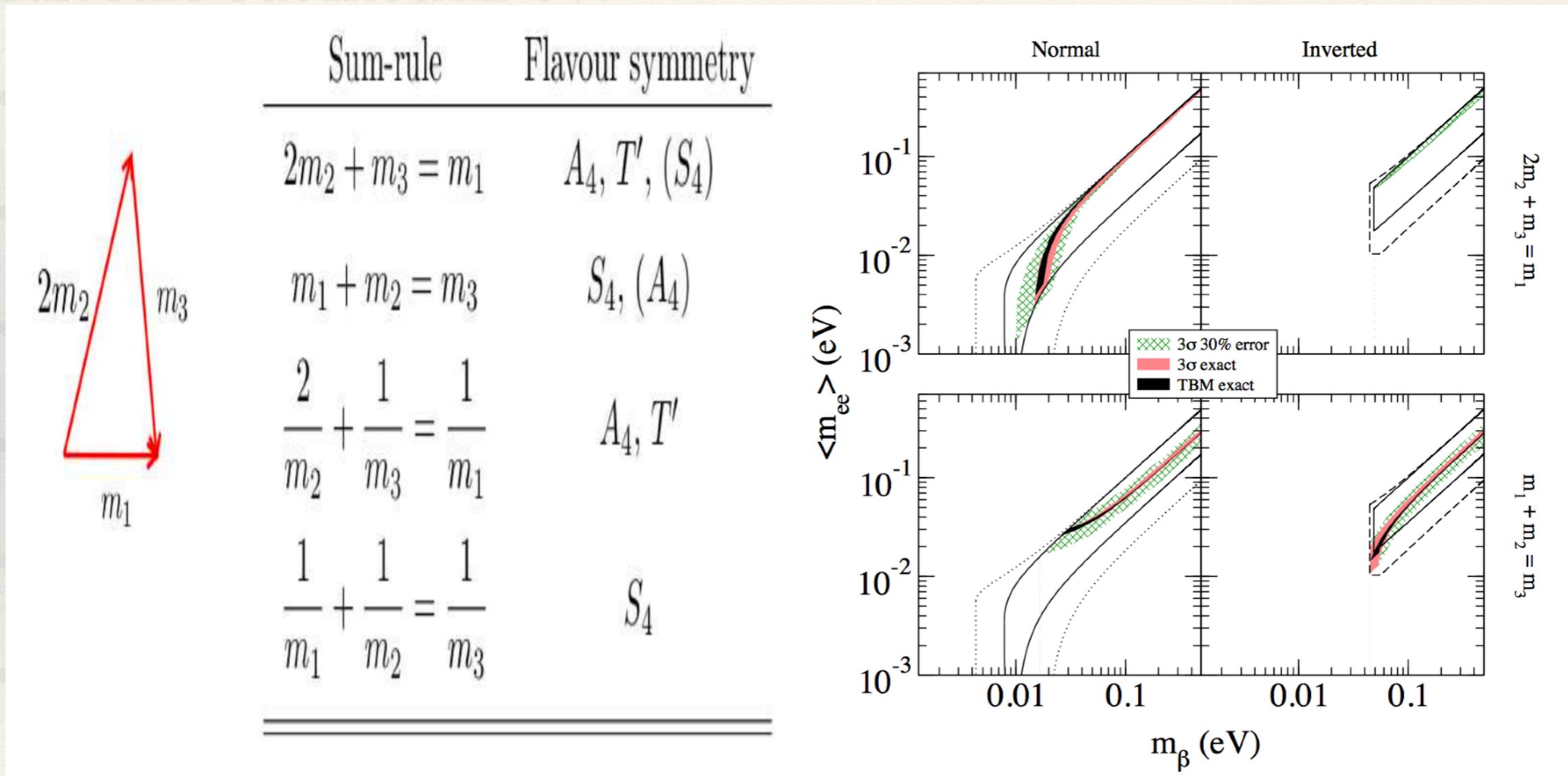


Ma et al., 1508.08023

Flavor Symmetries

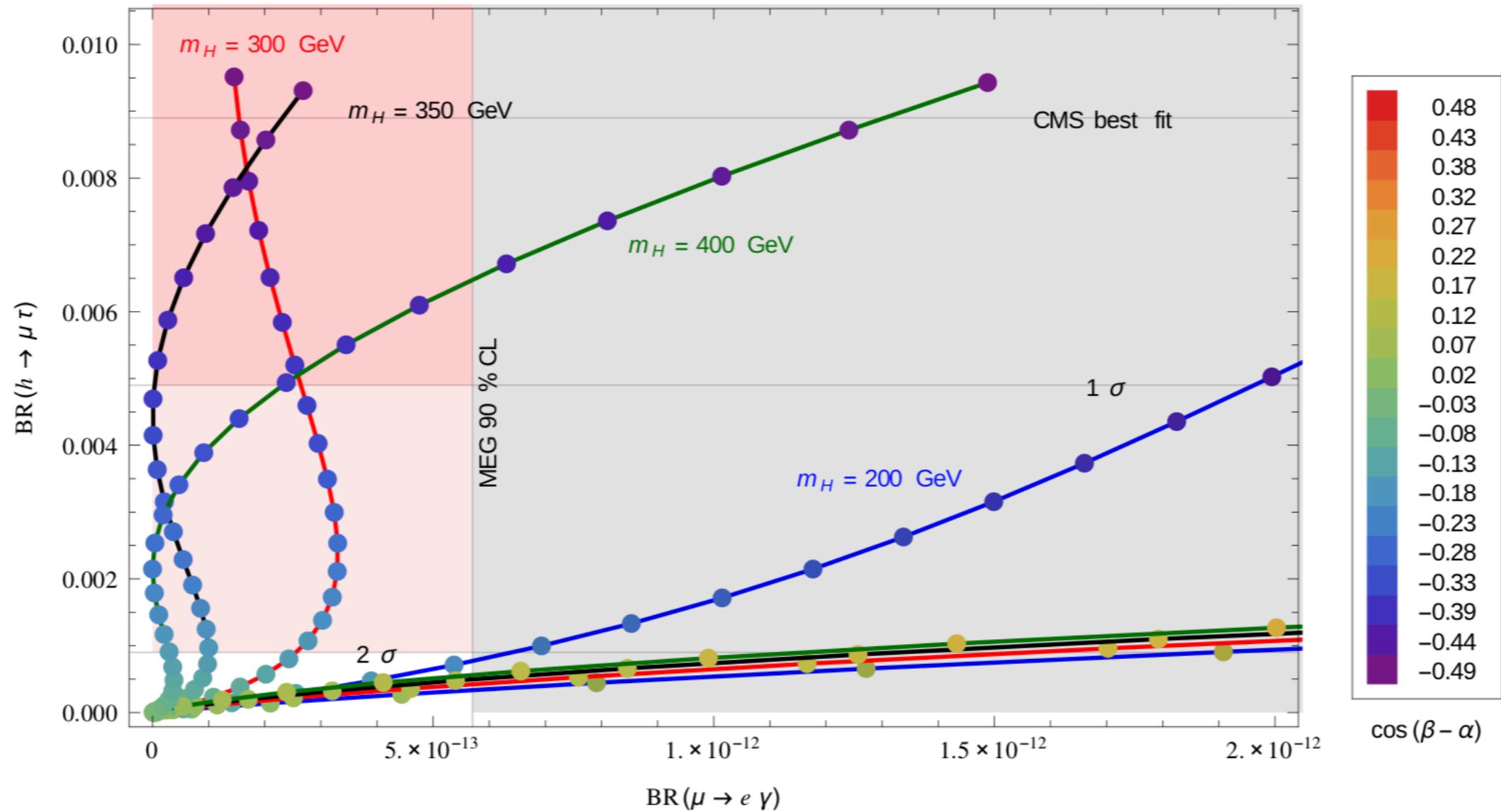
Barry, WR, 1007.5217

Can rule out models by:



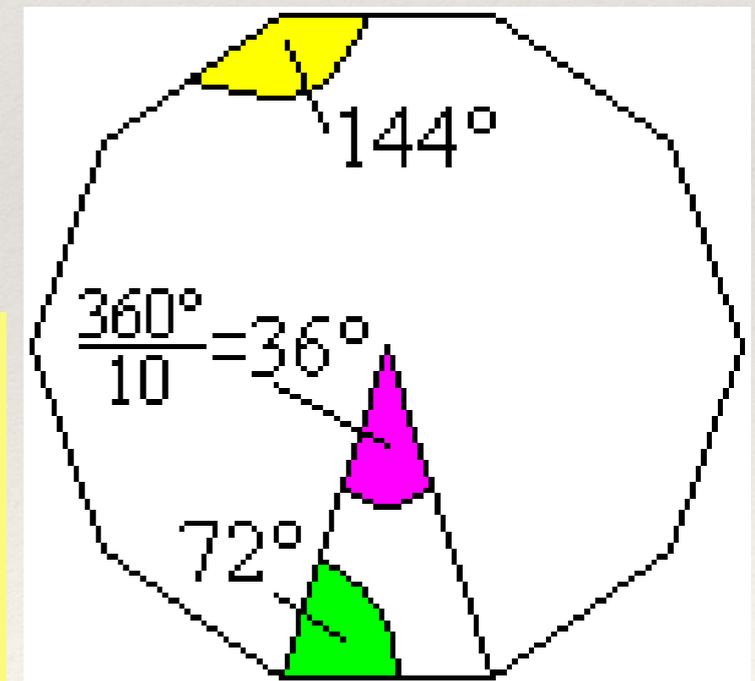
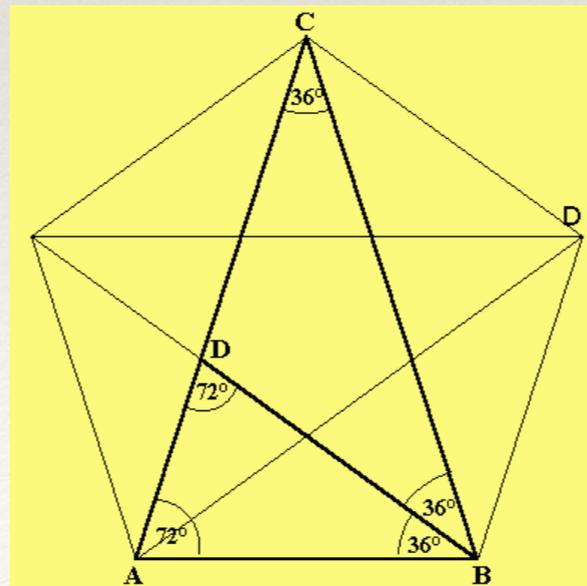
Flavor Symmetries

Heeck et al., 1412.3671



Flavor symmetries and mixing angles

- ❖ look at data
- ❖ look for patterns
- ❖ look for symmetry associated with pattern, e.g. GRB:
 - $\cos \theta_{12} = \phi / 2$ means $\theta_{12} = \pi / 5 = 36^\circ$
 - thus pentagon and thus D_5
 - or decagon and D_{10}



Once you do that...

- ❖ $\theta_{12} = \gamma \Rightarrow \sin^2 \theta_{12} = 0.298$
- ❖ $|U_{e2}| = \gamma \Rightarrow \sin^2 \theta_{12} = 0.34$
- ❖ $\tan 2\theta_{12} = e \Rightarrow \sin^2 \theta_{12} = 0.327$
- ❖ since $\sin \theta_{13} \approx \theta_{13}$, why not $\cos \theta_{23} \approx \theta_{23}$
 $\Rightarrow \sin^2 \theta_{23} = 0.454$ („Dottie's number“)
- ❖ $\theta_{12} + \theta_{13} + \theta_{23} + \delta = 0$
- ❖ ...

On the number of predictions and new parameters...

FULL models including VEV alignment, messenger and driving fields:

Field	φ_T	φ_S	ξ	$\tilde{\xi}$	φ_0^T	φ_0^S	ξ_0	$H_{u,d}$
A_4	3	3	1	1	3	3	1	1
Z_3	1	ω	ω	ω	1	ω	ω	1
$U(1)_R$	0	0	0	0	2	2	2	0

Field	φ_T^0	ζ^0	φ_S^0	$\tilde{\varphi}_S^0$	ξ^0	Δ^0	Ω_1	Ω_1^c	Ω_2	Ω_2^c	Ω_3	Ω_3^c	Σ	Σ^c
S_4	3'	1	3'	3	1	1	2	2	2	2	3	3	3'	3'
Z_4	-1	-1	1	1	1	1	-1	-1	-i	i	1	1	1	1
Z_3	ω	ω	ω^2	ω^2	ω^2	1	1	1	ω	ω^2	ω^2	ω	ω^2	ω
$U(1)_R$	2	2	2	2	2	2	1	1	1	1	1	1	1	1

	$SU(2)$	$U(1)_Y$	T'	$U(1)_R$	Z_8	Z_4	Z_4	Z_3	Z_3	Z_2
$\bar{\Xi}_1, \bar{\Xi}_1$	2, 2	1,1	1, 1	0,2	7,1	0,0	0,0	0,0	1,2	0,0
$\Sigma_1^A, \bar{\Sigma}_1^A$	2, 2	1,1	1, 1	1,1	1,7	3,1	3,1	2,1	1,2	1,1
$\Sigma_1^B, \bar{\Sigma}_1^B$	1, 1	2,2	1, 1	1,1	2,6	1,3	1,3	2,1	0,0	1,1
$\Sigma_{1'}^A, \bar{\Sigma}_{1'}^A$	2, 2	1,1	1', 1''	1,1	7,1	3,1	3,1	0,0	2,1	0,0
$\Sigma_{1'}^B, \bar{\Sigma}_{1'}^B$	1, 1	2,2	1', 1''	1,1	0,0	1,3	1,3	0,0	1,2	0,0
$\Sigma_{1''}^A, \bar{\Sigma}_{1''}^A$	2, 2	1,1	1'', 1'	1,1	1,7	3,1	3,1	2,1	1,2	1,1
$\Sigma_{1''}^B, \bar{\Sigma}_{1''}^B$	2, 2	1,1	1'', 1'	1,1	1,7	3,1	1,3	0,0	0,0	0,0
$\Sigma_{1''}^C, \bar{\Sigma}_{1''}^C$	2, 2	1,1	1'', 1'	1,1	6,2	3,1	0,0	1,2	1,2	0,0
$\Sigma_{2'}^A, \bar{\Sigma}_{2'}^A$	2, 2	1,1	2', 2''	1,1	0,0	1,3	0,0	1,2	1,2	0,0
$\Sigma_{2''}^A, \bar{\Sigma}_{2''}^A$	2, 2	1,1	2'', 2'	1,1	0,0	1,3	0,0	1,2	1,2	0,0
$\Delta_1^A, \bar{\Delta}_1^A$	1, 1	0,0	1, 1	0,2	0,0	2,2	0,0	0,0	0,0	0,0
$\Delta_1^B, \bar{\Delta}_1^B$	1, 1	0,0	1, 1	0,2	0,0	0,0	0,0	2,1	2,1	0,0
$\Delta_{1'}^A, \bar{\Delta}_{1'}^A$	1, 1	0,0	1', 1''	0,2	0,0	0,0	0,0	0,0	2,1	0,0
$\Delta_{2'}^A, \bar{\Delta}_{2'}^A$	1, 1	0,0	2', 2''	0,2	0,0	0,0	3,1	1,2	1,2	1,1
$\Delta_3^A, \bar{\Delta}_3^A$	1, 1	0,0	3, 3	0,2	4,4	0,0	0,0	0,0	0,0	1,1
$\Delta_3^B, \bar{\Delta}_3^B$	1, 1	0,0	3, 3	0,2	6,2	2,2	0,0	1,2	0,0	1,1
$\Delta_3^C, \bar{\Delta}_3^C$	1, 1	0,0	3, 3	0,2	6,2	1,3	2,2	0,0	1,2	0,0
$\Delta_3^D, \bar{\Delta}_3^D$	1, 1	0,0	3, 3	0,2	5,3	0,0	3,1	0,0	1,2	0,0
$\Delta_3^E, \bar{\Delta}_3^E$	1, 1	0,0	3, 3	0,2	2,6	0,0	2,2	2,1	0,0	0,0

O(10-100) scalar fields with masses, couplings, etc.

On the number of predictions and new parameters...

FULL models including VEV alignment, messenger and driving fields:

Field	φ_T	φ_S	ξ	$\tilde{\xi}$	φ_0^T	φ_0^S	ξ_0	$H_{u,d}$
A_4	3	3	1	1	3	3	1	1
Z_3	1	ω	ω	ω	1	ω	ω	1
$U(1)_R$	0	0	0	0	2	2	2	0

Field	φ_T^0	ζ^0	φ_S^0	$\tilde{\varphi}_S^0$	ξ^0	Δ^0	Ω_1	Ω_1^c	Ω_2	Ω_2^c	Ω_3	Ω_3^c	Σ	Σ^c
S_4	3'	1	3'	3	1	1	2	2	2	2	3	3	3'	3'
Z_4	-1	-1	1	1	1	1	-1	-1	-i	i	1	1	1	1
Z_3	ω	ω	ω^2	ω^2	ω^2	1	1	1	ω	ω^2	ω^2	ω	ω^2	ω
$U(1)_R$	2	2	2	2	2	2	1	1	1	1	1	1	1	1

	$SU(2)$	$U(1)_Y$	T'	$U(1)_R$	Z_8	Z_4	Z_4	Z_3	Z_3	Z_2
$\Xi_1, \bar{\Xi}_1$	2, 2	1, 1	1, 1	0, 2	7, 1	0, 0	0, 0	0, 0	1, 2	0, 0
$\Sigma_1^A, \bar{\Sigma}_1^A$	2, 2	1, 1	1, 1	1, 1	1, 7	3, 1	3, 1	2, 1	1, 2	1, 1
$\Sigma_1^B, \bar{\Sigma}_1^B$	1, 1	2, 2	1, 1	1, 1	2, 6	1, 3	1, 3	2, 1	0, 0	1, 1
$\Sigma_{1'}^A, \bar{\Sigma}_{1'}^A$	2, 2	1, 1	1', 1''	1, 1	7, 1	3, 1	3, 1	0, 0	2, 1	0, 0
$\Sigma_{1'}^B, \bar{\Sigma}_{1'}^B$	1, 1	2, 2	1', 1''	1, 1	0, 0	1, 3	1, 3	0, 0	1, 2	0, 0
$\Sigma_{1''}^A, \bar{\Sigma}_{1''}^A$	2, 2	1, 1	1'', 1'	1, 1	1, 7	3, 1	3, 1	2, 1	1, 2	1, 1
$\Sigma_{1''}^B, \bar{\Sigma}_{1''}^B$	2, 2	1, 1	1'', 1'	1, 1	1, 7	3, 1	1, 3	0, 0	0, 0	0, 0
$\Sigma_{1''}^C, \bar{\Sigma}_{1''}^C$	2, 2	1, 1	1'', 1'	1, 1	6, 2	3, 1	0, 0	1, 2	1, 2	0, 0
$\Sigma_{2'}^A, \bar{\Sigma}_{2'}^A$	2, 2	1, 1	2', 2''	1, 1	0, 0	1, 3	0, 0	1, 2	1, 2	0, 0
$\Sigma_{2''}^A, \bar{\Sigma}_{2''}^A$	2, 2	1, 1	2'', 2'	1, 1	0, 0	1, 3	0, 0	1, 2	1, 2	0, 0
$\Delta_1^A, \bar{\Delta}_1^A$	1, 1	0, 0	1, 1	0, 2	0, 0	2, 2	0, 0	0, 0	0, 0	0, 0
$\Delta_1^B, \bar{\Delta}_1^B$	1, 1	0, 0	1, 1	0, 2	0, 0	0, 0	0, 0	2, 1	2, 1	0, 0
$\Delta_{1'}^A, \bar{\Delta}_{1'}^A$	1, 1	0, 0	1', 1''	0, 2	0, 0	0, 0	0, 0	0, 0	2, 1	0, 0
$\Delta_{2'}^A, \bar{\Delta}_{2'}^A$	1, 1	0, 0	2', 2''	0, 2	0, 0	0, 0	3, 1	1, 2	1, 2	1, 1
$\Delta_3^A, \bar{\Delta}_3^A$	1, 1	0, 0	3, 3	0, 2	4, 4	0, 0	0, 0	0, 0	0, 0	1, 1
$\Delta_3^B, \bar{\Delta}_3^B$	1, 1	0, 0	3, 3	0, 2	6, 2	2, 2	0, 0	1, 2	0, 0	1, 1
$\Delta_3^C, \bar{\Delta}_3^C$	1, 1	0, 0	3, 3	0, 2	6, 2	1, 3	2, 2	0, 0	1, 2	0, 0
$\Delta_3^D, \bar{\Delta}_3^D$	1, 1	0, 0	3, 3	0, 2	5, 3	0, 0	3, 1	0, 0	1, 2	0, 0
$\Delta_3^E, \bar{\Delta}_3^E$	1, 1	0, 0	3, 3	0, 2	2, 6	0, 0	2, 2	2, 1	0, 0	0, 0

O(10-100) scalar fields with masses, couplings, etc.



Predictions:
2 to 4 flavor parameters

Abelian Flavor Symmetries

❖ Less predictive but less complicated: Abelian flavor

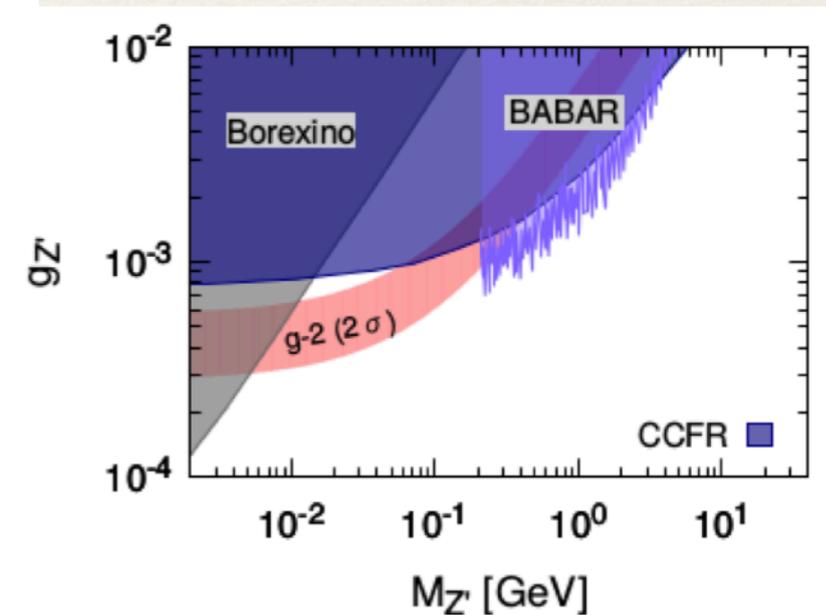
symmetry, e.g. $L_\mu - L_\tau$

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

- anomaly free

- masses a and $\pm b$, $\theta_{23} = \pi/4$, $\theta_{13} = 0$

- has Z' with couplings to μ and τ : $(g - 2)_\mu$



Araki et al., 1702.01497

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

Interpretation/Precision of CP Phase

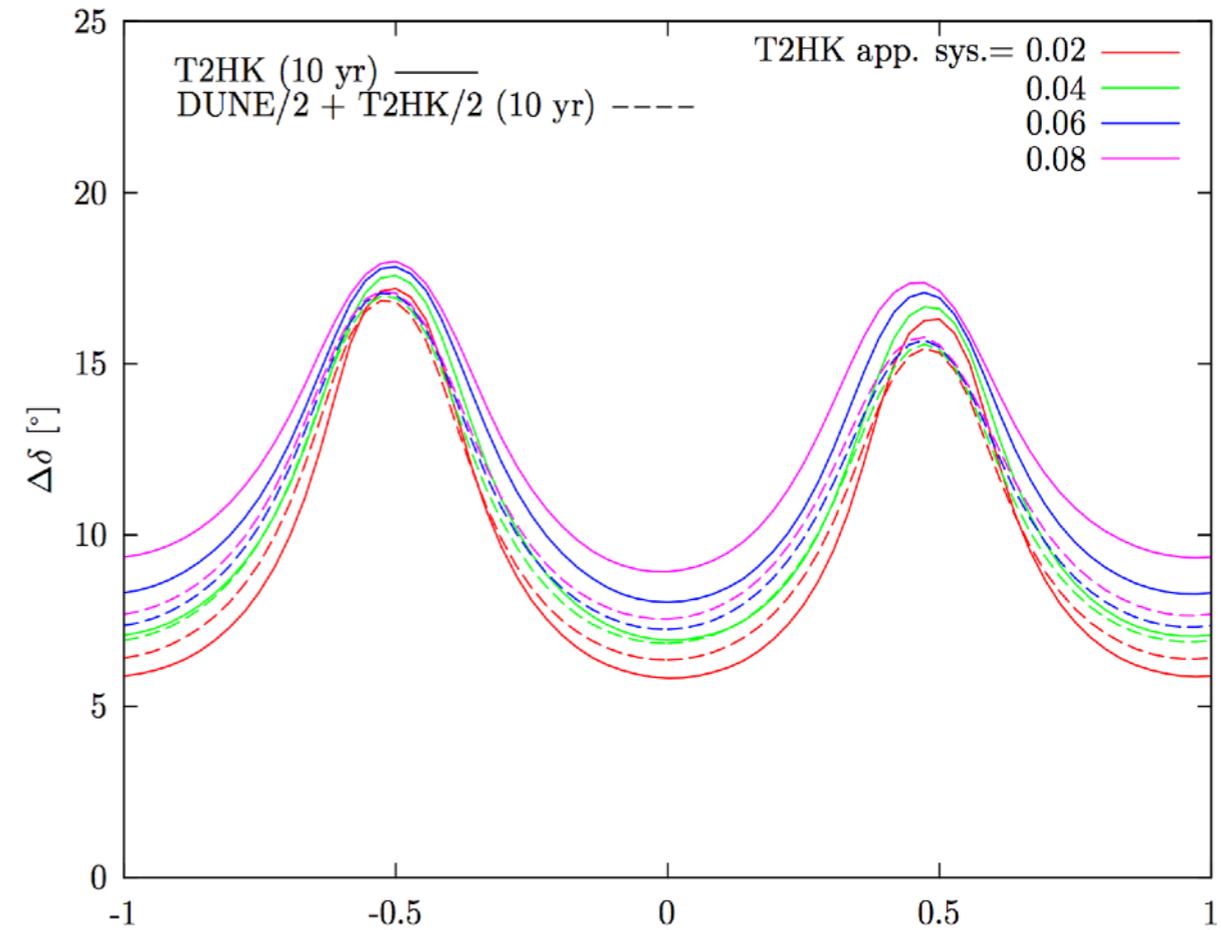
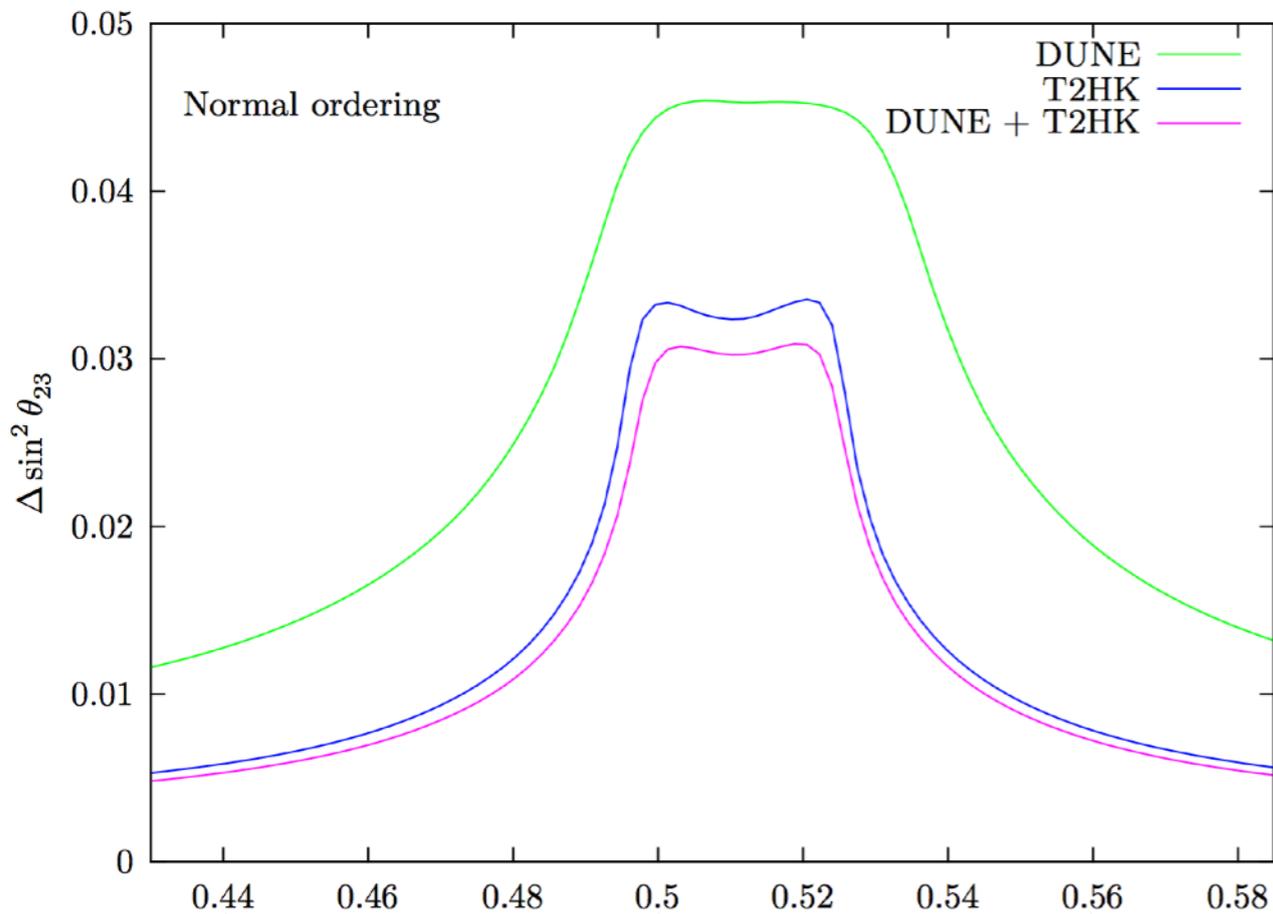
- ❖ if $\delta = 230.7^\circ$: model predicting this value or perturbed model with $270.0^\circ - 39.3^\circ$?
- ❖ BUT: the closer δ to π or $3\pi/2$ the more likely that some symmetry / structure behind it...

Interpretation/Precision of Atmospheric Angle

- ❖ if $\theta_{23} = 41.6^\circ$: model predicting this value or perturbed model with $45.0^\circ - 3.4^\circ$?
 - far away from 45° could be related to $(m_2/m_3)^{1/2}$ similar to GST
- ❖ BUT: the closer θ_{23} to 45° the more likely that some symmetry / structure behind it...

Achievable Precision

Ballet et al., 1612.07275



$(41.6 \pm 0.3)^0$

$(45 \pm 1.7)^0$

$(48.5 \pm 0.6)^0$

$\cos \delta$: (0 ± 0.29)

(1 ± 0.006)

(0 ± 0.28)

Talk by Patterson

Interesting values have largest uncertainties...

Perturbations

- ❖ Various sources:
 - VEV misalignment, NLO terms, RG effects
- ❖ Frequent feature: $\delta(\theta_{12}), \delta(\delta) > \delta(\theta_{13}), \delta(\theta_{23})$
- ❖ effects larger for IH and QD

large

Example RG enhancement:

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

typical size: $\delta(\theta_{ij}) \approx 10^{-5} \tan^2 \beta m_\nu^2 / \Delta m_{ij}^2$

	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

- ❖ Various sources:
 - VEV misalignment, NLO terms, RG effects
- ❖ Frequent feature: $\delta(\theta_{12}), \delta(\delta) > \delta(\theta_{13})$
- ❖ effects larger for IH and QD

mass scale and ordering helpful

large

Example RG enhancement:
(running of phases and θ_{12} can be evaded by cancellations)

typical size: $\delta(\theta_{ij}) \approx 10^{-5} \tan^2 \beta m_\nu^2 / \Delta m_{ij}^2$

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

New Physics in Oscillations

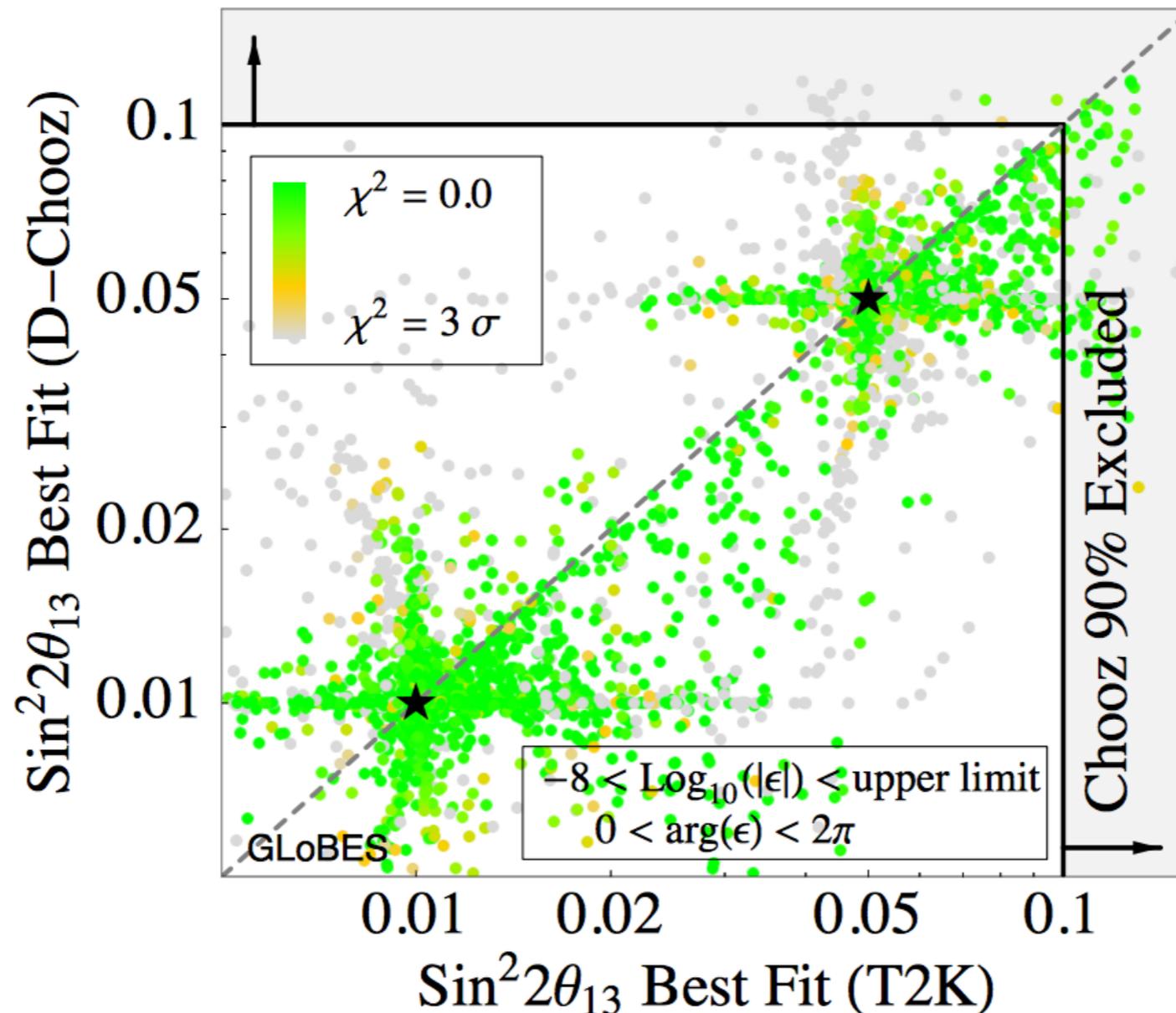
- ❖ Various good reasons to expect NP:
 - unitarity violation from new fermions
 - NSIs from new physics: $G_F \boldsymbol{\epsilon} = g'^2 / M_X^2 \Rightarrow \boldsymbol{\epsilon} \sim 0.01$ is TeV-scale*
 - new interactions (scalar, tensor, etc.)
 - long-range forces
 - decay, Pseudo-Dirac,...
 - 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...

* actually can be small (MeV) scale since q^2 very small

New Physics in Oscillations

New Physics can mess up oscillation experiments:

T2K / Double Chooz



❖ Various

- Unitarity
- NSIs
- new
- long
- Lindner, Ota, Sato, 0708.0152
- Kopp, Lindner, Ota, Sato, 0708.0152
- gne
- light

scale of mass
high ν -energy (IC!)

New Physics in Oscillations

New Physics can mess up oscillation experiments:

❖ Various goals

- unitarity

- NSIs from

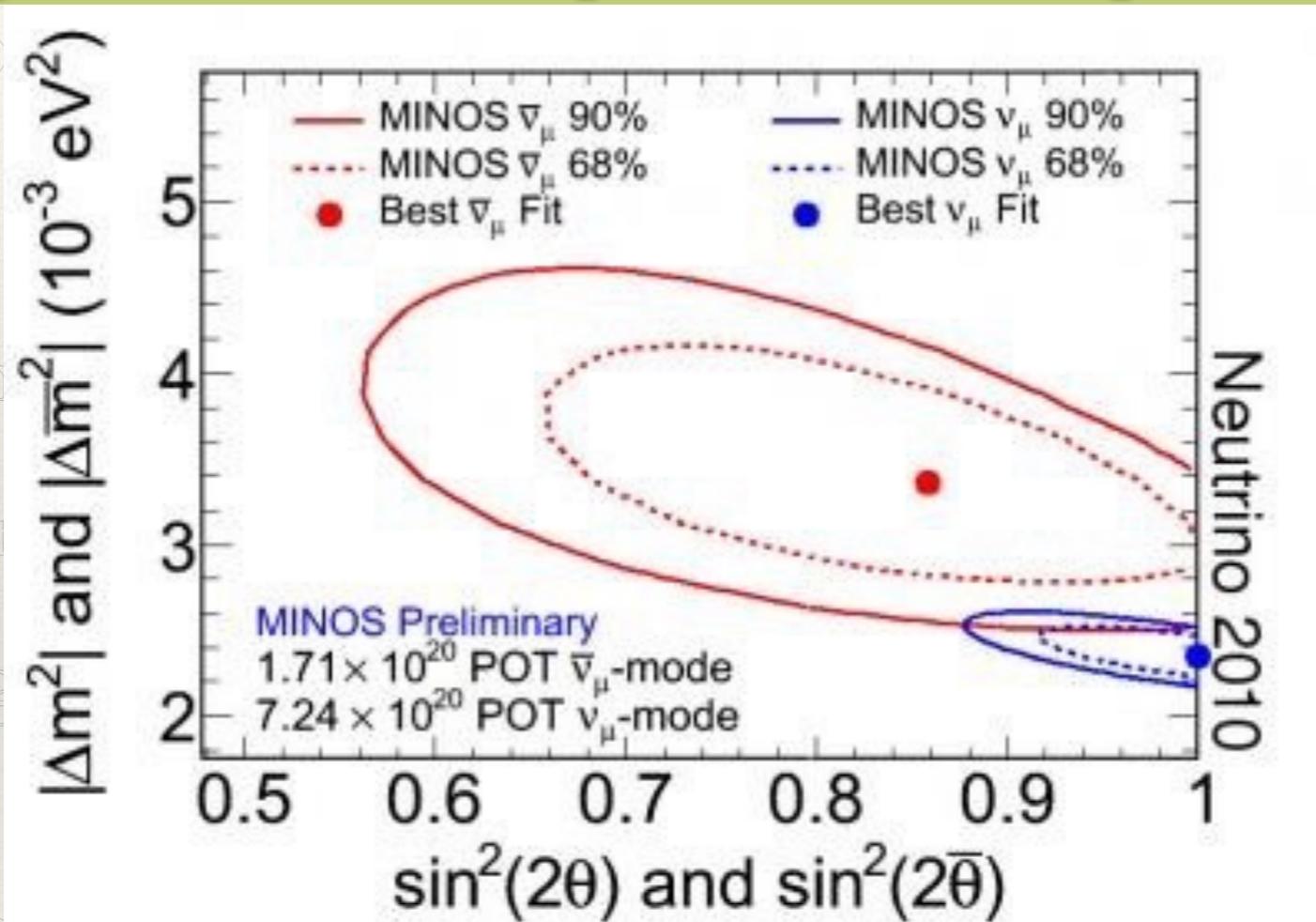
- new interactions

- long range

- Lorentz /

- generation

- light sterile neutrinos...



scale of mass

high ν -energy (IC!)

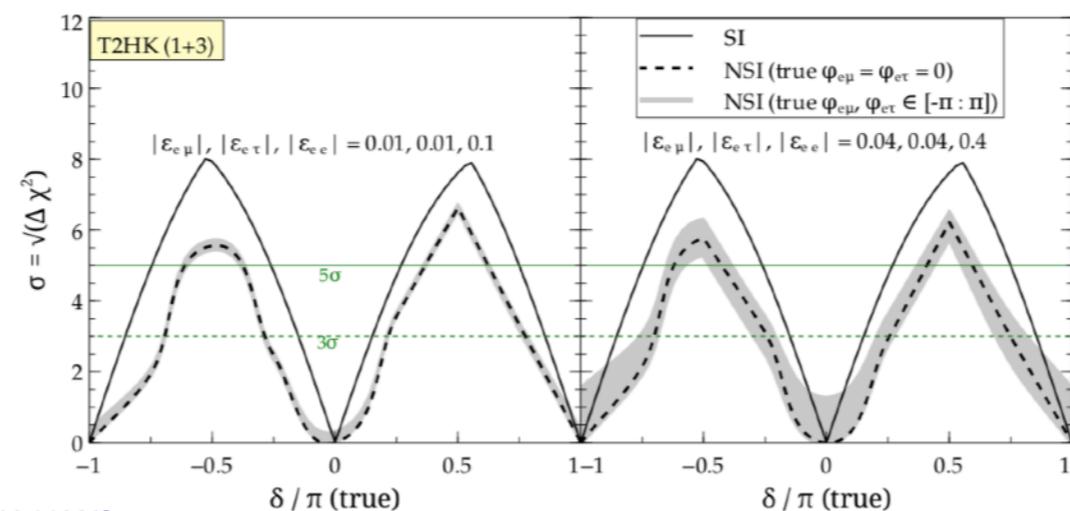
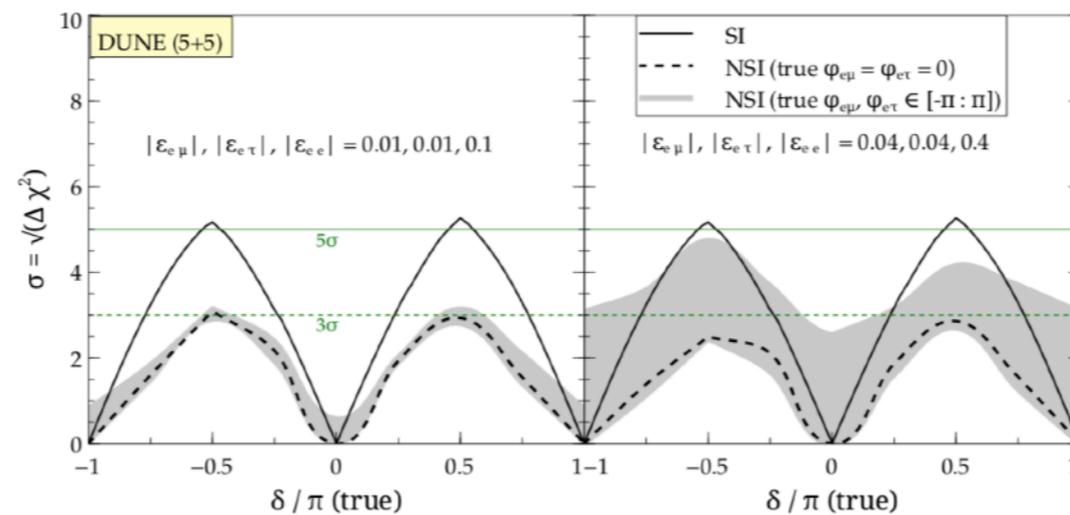
New Physics in Oscillations

New Physics can mess up oscillation experiments:

CPV sensitivity - DUNE, T2HK

- DUNE (1300 km)
Runtime = 5 nu + 5 nu bar
35 kton, LArTPC

- T2HK
Runtime = 1 nu + 3 nu bar
560 kton, WC



M. Masud and P. Mehta, Phys. Rev. D (2016) [1603.01389]

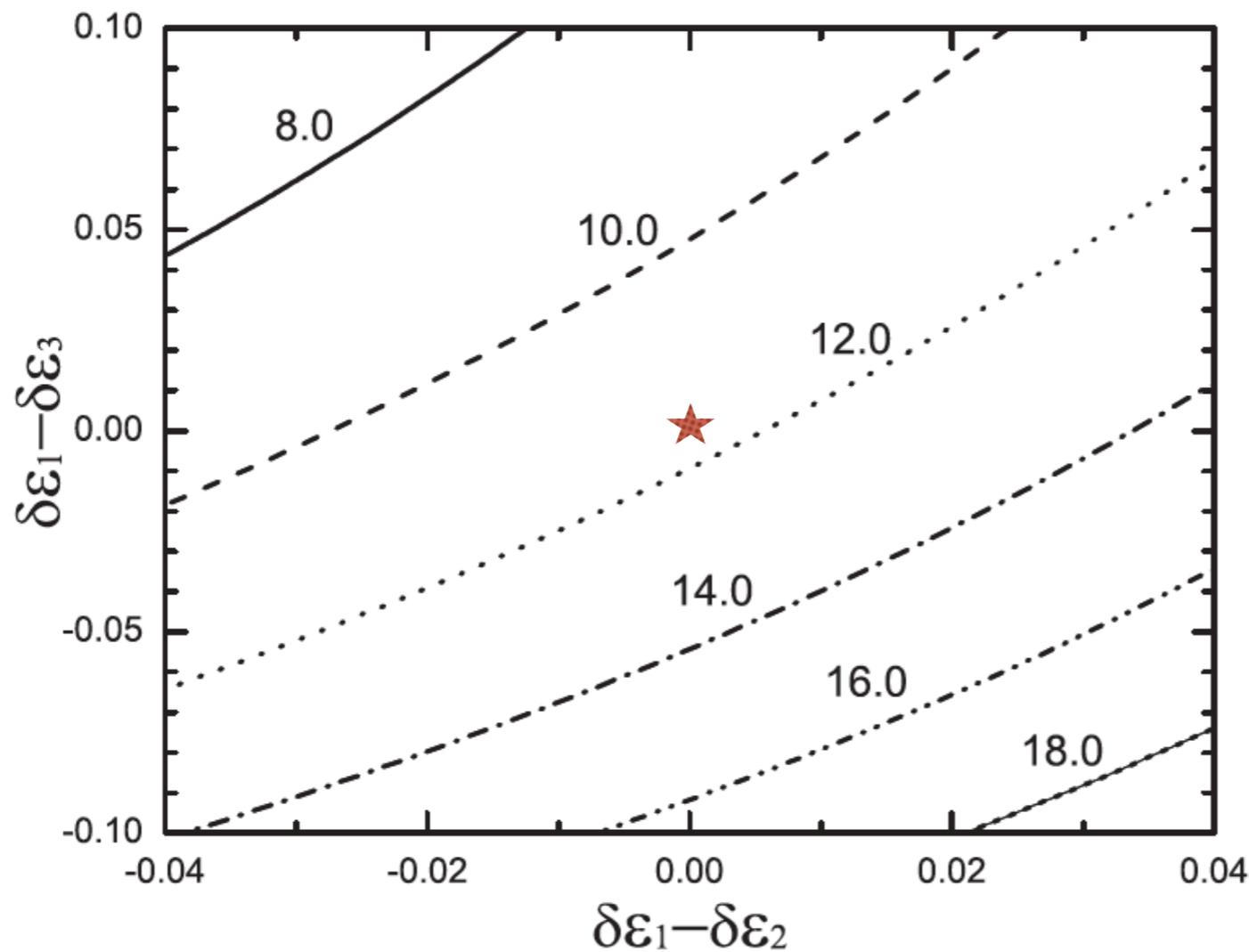
presence of multiple $\epsilon_{\alpha\beta}$ can make determination of MO, δ and octant of θ_{23} impossible even for DUNE, T2HK and T2HKK

scale of mass
high-energy (IC!)

Liao, Marfatia, Whisnant,
1612.01443

New Physics in Oscillations

New Physics can mess up oscillation experiments:



JUNO iso- $\Delta\chi^2$ contours
for mass ordering sensitivity

A scale of mass
in high ν -energy (IC!)

JUNO, 1507.05613

LBL, JUNO, PINGU/ORCA: unlikely that we get fooled in all experiments...?

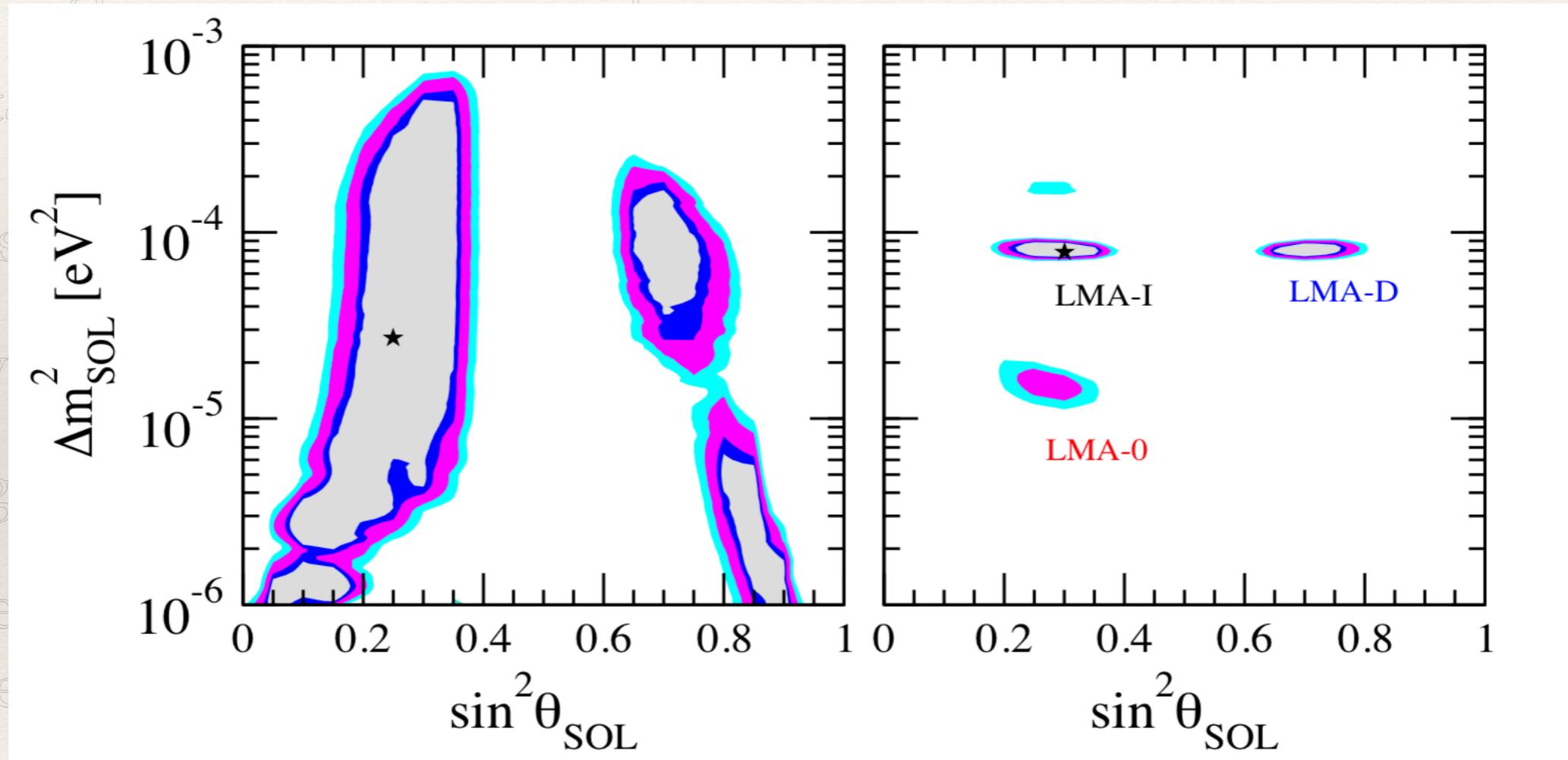
New Physics in Oscillations

New Physics can mess up oscillation experiments:

❖ Various good reasons to expect NP:

- unitarity
- NSIs
- new physics
- long range
- Lorentz violation
- general relativity
- light sterile neutrinos...

Miranda, Tortola, Valle, hep-ph/0406280



C!)

Light Sterile Neutrinos

Talks by Huber, Kopp

- ❖ 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
- ❖ 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)*

Light Sterile Neutrinos

Talks by Huber, Kopp

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❖ experimentally, need

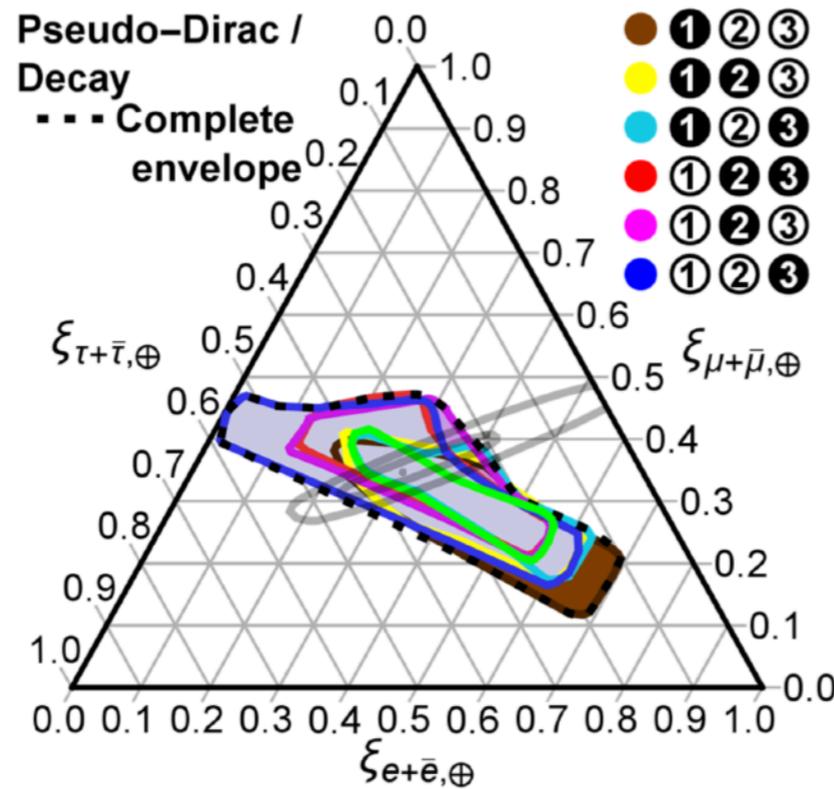
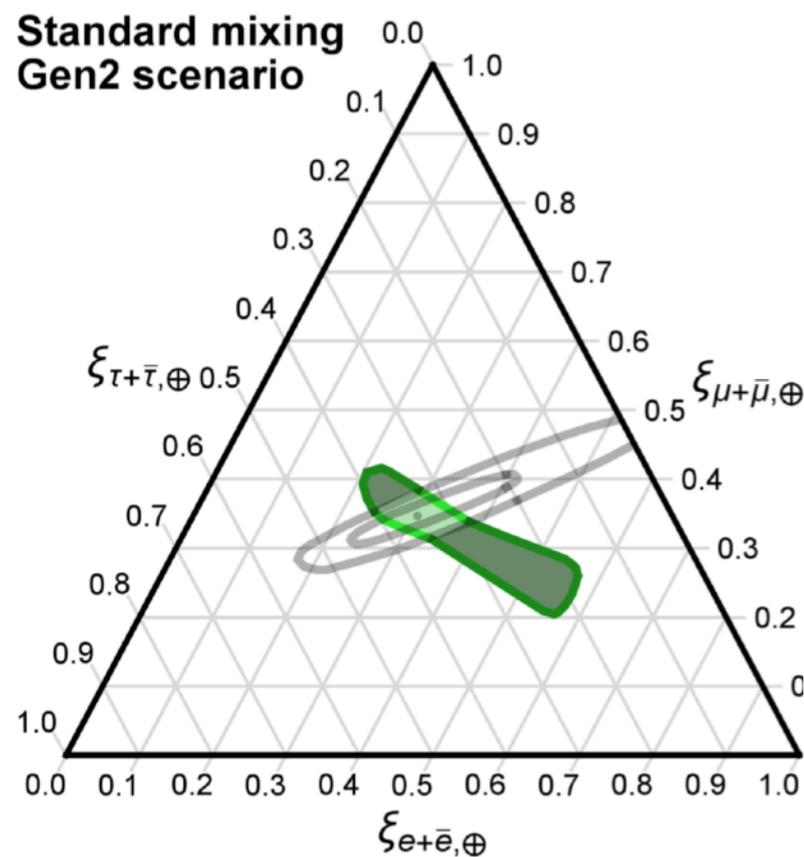
- to know flux precisely...
- to know cross section precisely...
- to see oscillatory pattern...

None of this happened yet!!!

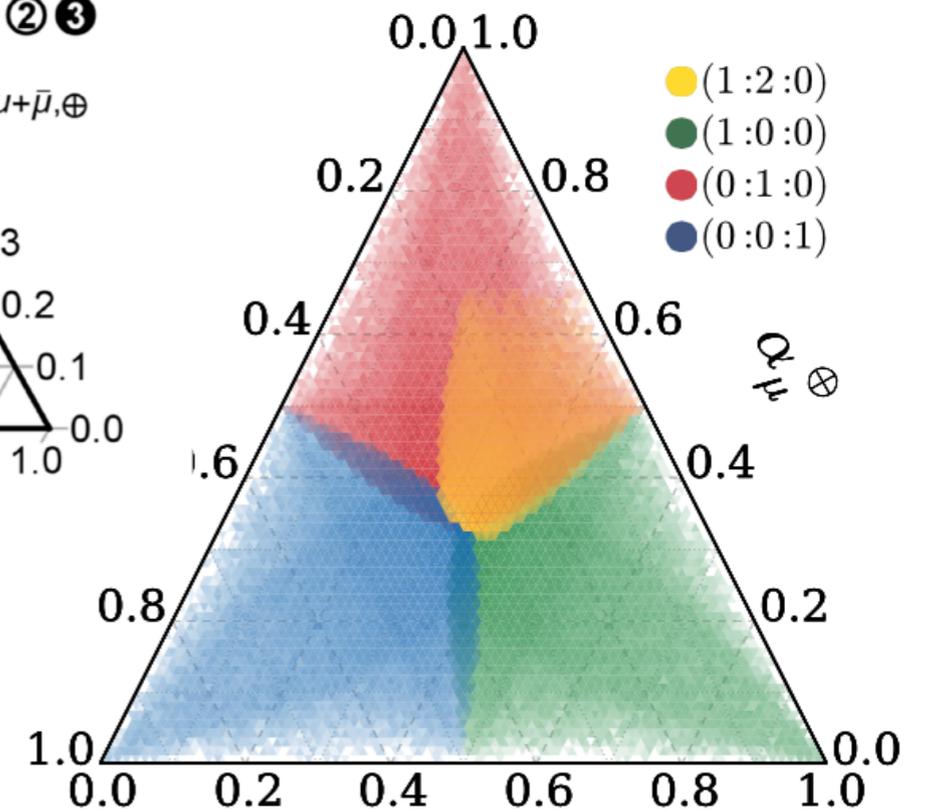
❖ *small scale experiments will tell (at least the ee-anomalies)*

New Physics in Oscillations

Exotic New Physics enhanced by long distance/high energy:



Talk by Salvado



generation (seesaw!), in general growing
Rasmussen et al., 1707.07684

- light sterile neutrinos...

Arguelles et al., 1506.02043

New Physics in Coherent Scattering

$$\frac{d\sigma}{dT} = \frac{\sigma_0^{\text{SM}}}{M} \left(1 - \frac{T}{T_{\text{max}}}\right) \propto 1 - M T/E_\nu^2$$

$$\sigma_0^{\text{SM}} \equiv \frac{G_F^2 [N - (1 - 4s_W^2)Z]^2 F^2(q^2) M^2}{4\pi}$$

Congratulations to COHERENT!

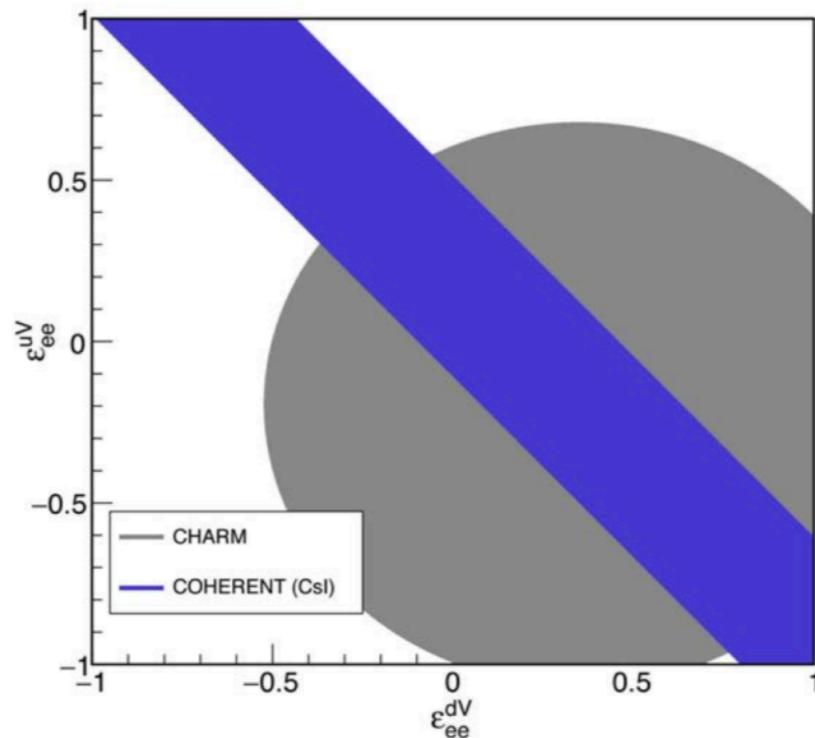
if NSIs are present

$$\mathcal{L} \supset \frac{G_F}{\sqrt{2}} \sum_{q=u,d} \bar{\nu}_\alpha \gamma^\mu (1 - \gamma^5) \nu_\beta \left[\varepsilon_{\alpha\beta}^{qV} \bar{q} \gamma^\mu q + \varepsilon_{\alpha\beta}^{qA} \bar{q} \gamma^\mu \gamma^5 q \right]$$

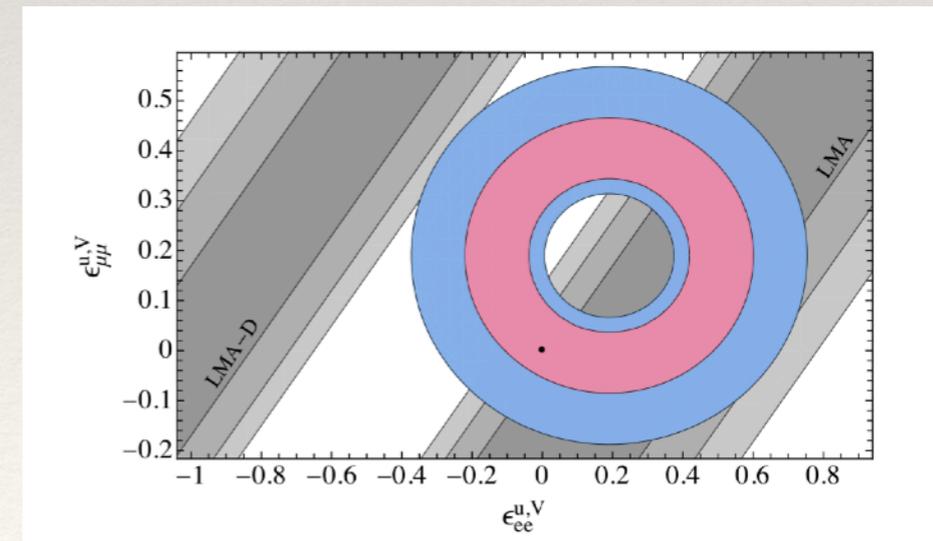
replace $[N - (1 - 4s_W^2)Z]^2$ with:

$$Q_{\text{NSI}}^2 \equiv 4 \left[N \left(-\frac{1}{2} + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV} \right) + Z \left(\frac{1}{2} - 2s_W^2 + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV} \right) \right]^2 + 4 \sum_{\alpha=\mu,\tau} \left[N(\varepsilon_{\alpha e}^{uV} + 2\varepsilon_{\alpha e}^{dV}) + Z(2\varepsilon_{\alpha e}^{uV} + \varepsilon_{\alpha e}^{dV}) \right]^2$$

COHERENT, 1708.01294



disfavors LMA-dark solution



Coloma et al., 1708.02899

New Physics in Coherent Scattering

$$\frac{d\sigma}{dT} = \frac{\sigma_0^{\text{SM}}}{M} \left(1 - \frac{T}{T_{\text{max}}}\right) \propto 1 - M T/E_\nu^2$$

$$\sigma_0^{\text{SM}} \equiv \frac{G_F^2 [N - (1 - 4s_W^2)Z]^2 F^2(q^2) M^2}{4\pi}$$

Congratulations
to COHERENT!

if NSIs are present

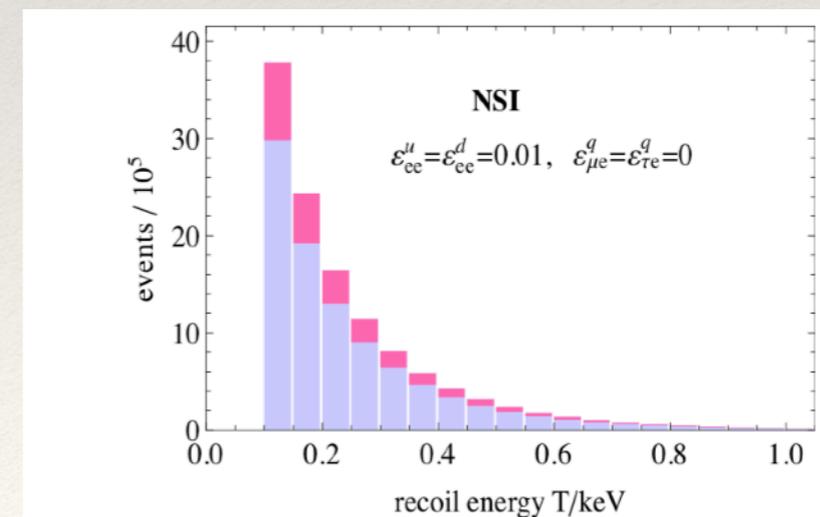
$$\mathcal{L} \supset \frac{G_F}{\sqrt{2}} \sum_{q=u,d} \bar{\nu}_\alpha \gamma^\mu (1 - \gamma^5) \nu_\beta \left[\varepsilon_{\alpha\beta}^{qV} \bar{q} \gamma^\mu q + \varepsilon_{\alpha\beta}^{qA} \bar{q} \gamma^\mu \gamma^5 q \right]$$

replace $[N - (1 - 4s_W^2)Z]^2$ with:

$$Q_{\text{NSI}}^2 \equiv 4 \left[N \left(-\frac{1}{2} + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV} \right) + Z \left(\frac{1}{2} - 2s_W^2 + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV} \right) \right]^2 + 4 \sum_{\alpha=\mu,\tau} \left[N(\varepsilon_{\alpha e}^{uV} + 2\varepsilon_{\alpha e}^{dV}) + Z(2\varepsilon_{\alpha e}^{uV} + \varepsilon_{\alpha e}^{dV}) \right]^2.$$

Example: CONUS-100 like, BG 3/day/kg/keV,
exposure: 5 kg yr GW m⁻², sys/stat/thresh.:

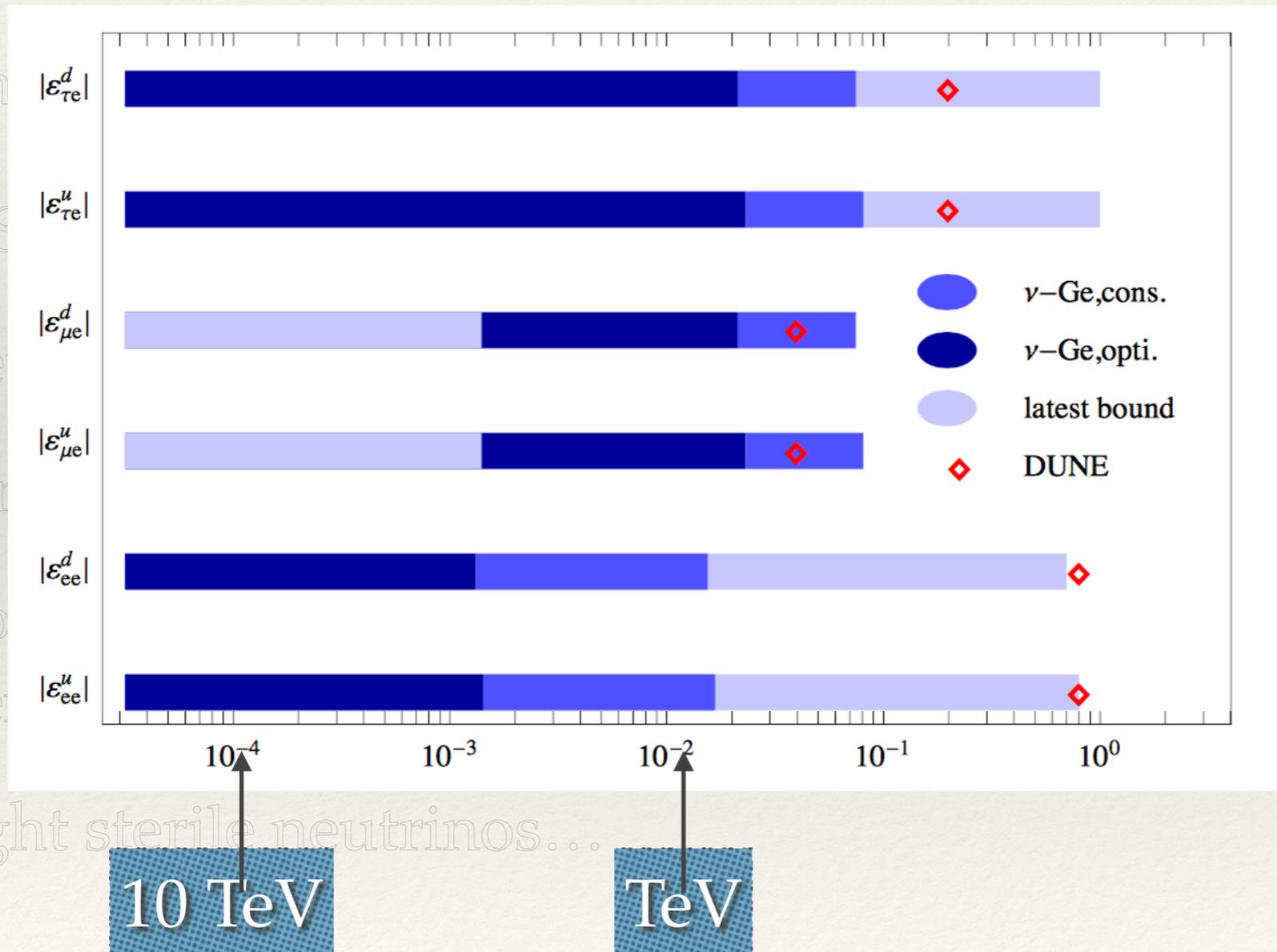
- (i) conservative configuration: $(\sigma_a, \sigma_f, T_{\text{th}}) = (5\%, 3\%, 0.4 \text{ keV})$.
- (ii) intermediate configuration: $(\sigma_a, \sigma_f, T_{\text{th}}) = (2\%, 1\%, 0.2 \text{ keV})$.
- (iii) optimistic configuration: $(\sigma_a, \sigma_f, T_{\text{th}}) = (0.5\%, 0.1\%, 0.1 \text{ keV})$.



New Physics in Oscillations

❖ Various good reasons to expect NP:

- Lindner, WR, Xu, 1612.04150
- scale of mass
- high ν -energy (IC!)
- light sterile neutrinos...



scale of mass
high ν -energy (IC!)

New Physics in Coherent Scattering

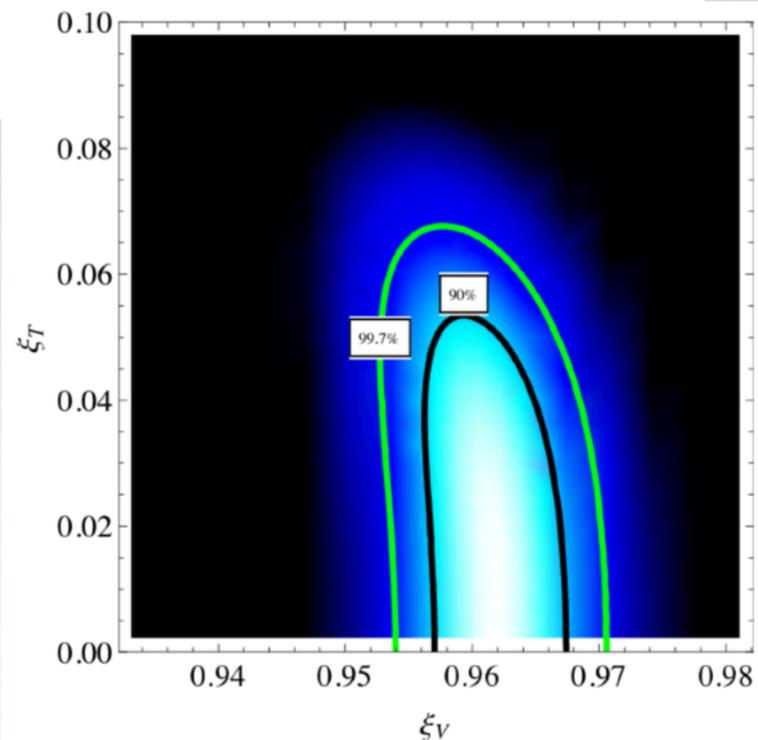
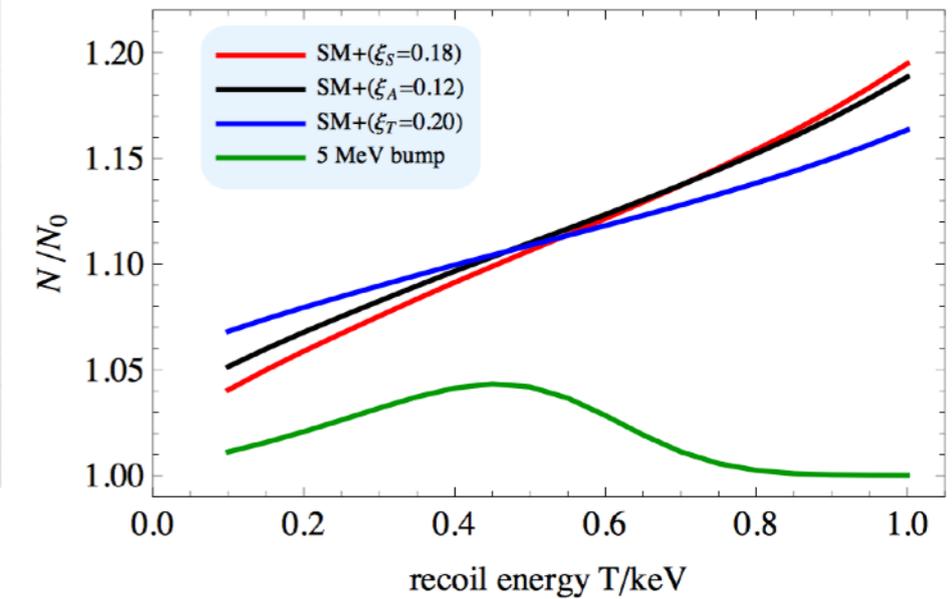
Lindner, WR, Xu, 1612.04150

assume exotic neutral currents:

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

changes *shape of spectrum*:

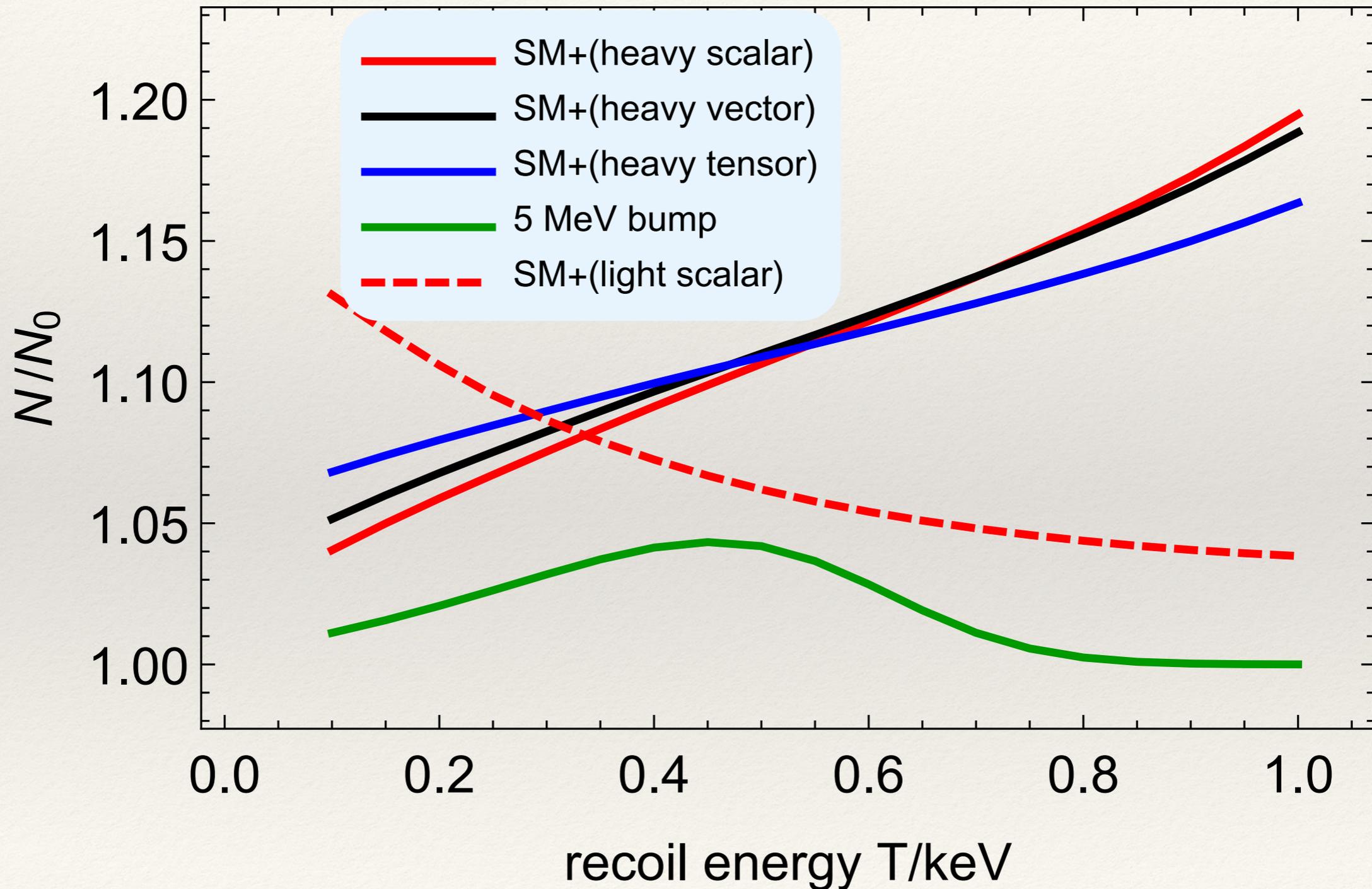
$$\begin{aligned} \frac{d\sigma}{dT} = & \frac{G_F^2 M}{4\pi} N^2 \left[\xi_S^2 \frac{MT}{2E_\nu^2} \right. \\ & + \xi_V^2 \left(1 - \frac{T}{T_{\max}} \right) - 2\xi_V \xi_A \frac{T}{E_\nu} + \xi_A^2 \left(1 - \frac{T}{T_{\max}} + \frac{MT}{E_\nu^2} \right) \\ & + \xi_T^2 \left(1 - \frac{T}{T_{\max}} + \frac{MT}{4E_\nu^2} \right) \\ & \left. - R \frac{T}{E_\nu} + \mathcal{O} \left(\frac{T^2}{E_\nu^2} \right) \right], \end{aligned}$$



limit set:

Papoulias, Kosmas, 1711.09773

New Physics in Coherent Scattering

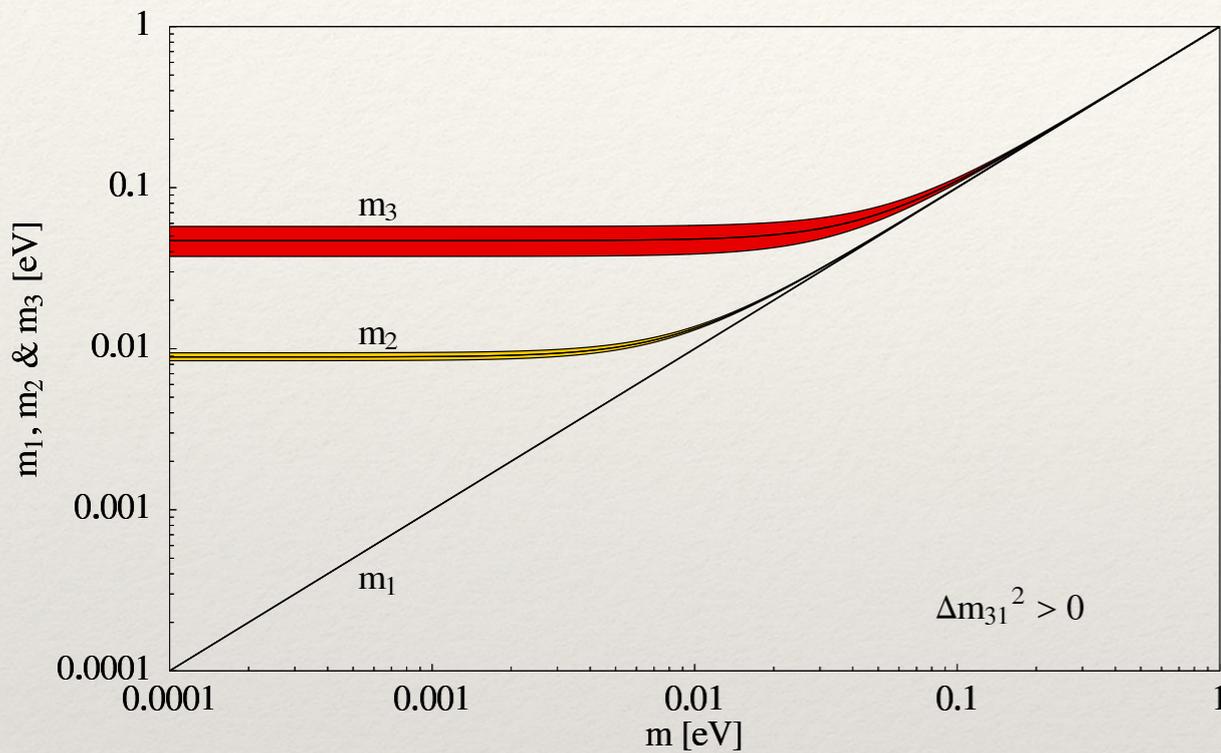


Xun-jie Xu

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: $U_{\text{PMNS}} = U_l^\dagger U_\nu \neq \mathbb{1}$
 - \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**

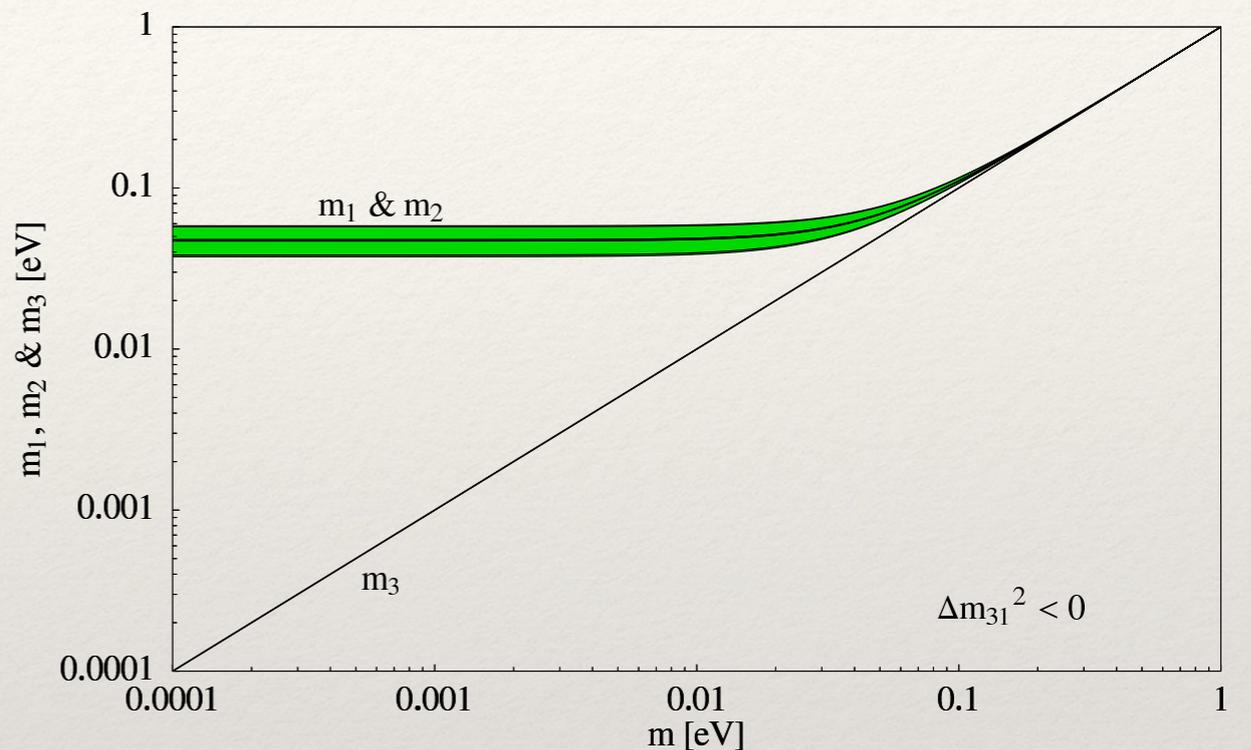
Masses and Ordering



mild hierarchy in normal ordering:

$$m_3 / m_2 \approx (\Delta m_{\text{atm}}^2 / \Delta m_{\text{sol}}^2)^{1/2} \approx 5$$

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



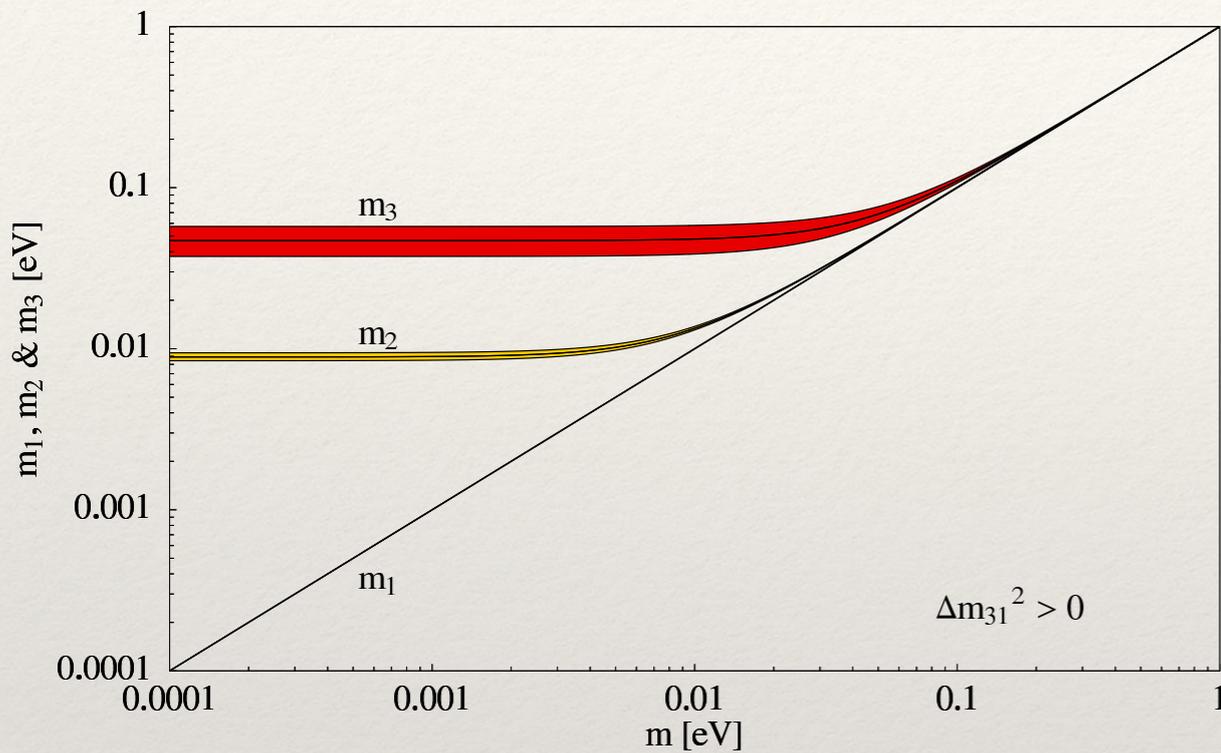
strong tuning in inverted ordering:

$$m_2 / m_1 \approx 1 + \frac{1}{2} \Delta m_{\text{sol}}^2 / \Delta m_{\text{atm}}^2$$

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

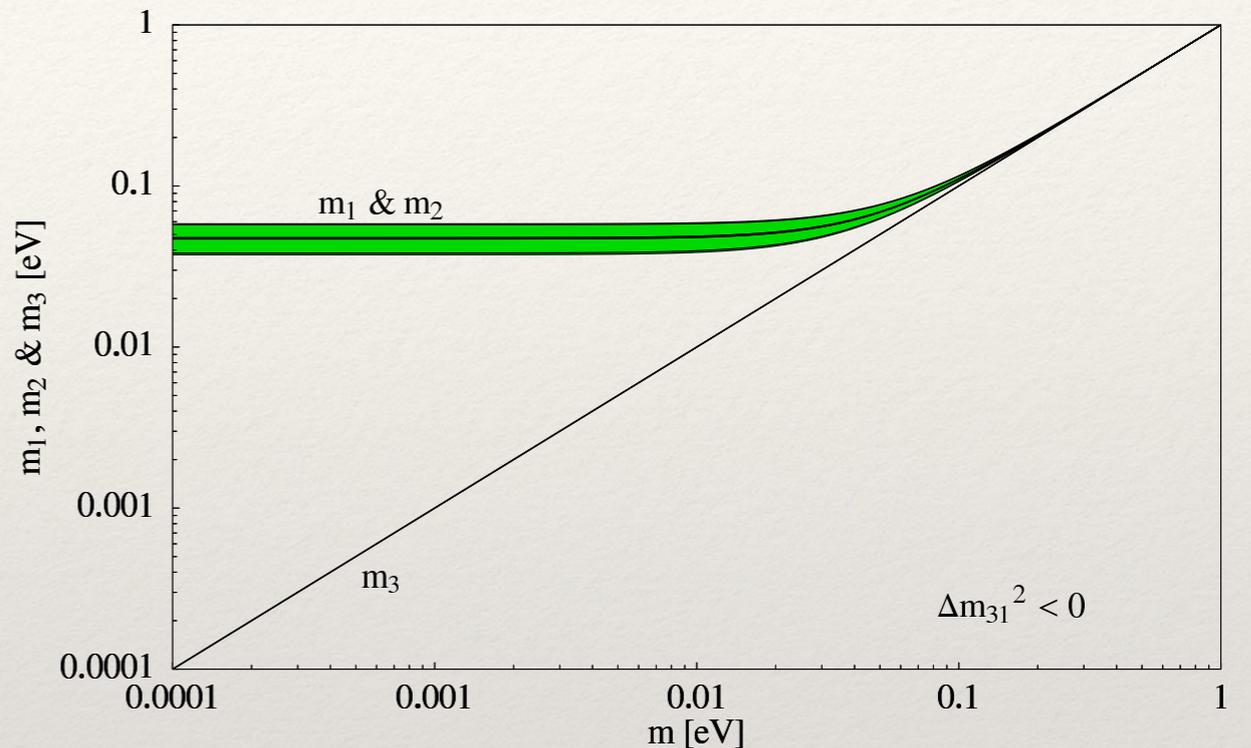
plus almost democratic structure of mass matrix

Masses and Ordering



mild hierarchy in normal ordering:

$$m_3 / m_2 \approx (\Delta m_{\text{atm}}^2 / \Delta m_{\text{sol}}^2)^{1/2} \approx 5$$



strong tuning in inverted ordering:

$$m_2 / m_1 \approx 1 + \frac{1}{2} \Delta m_{\text{sol}}^2 / \Delta m_{\text{atm}}^2$$

(at least the two largest) masses are linearly ordered?!

Origin of Neutrino Mass

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

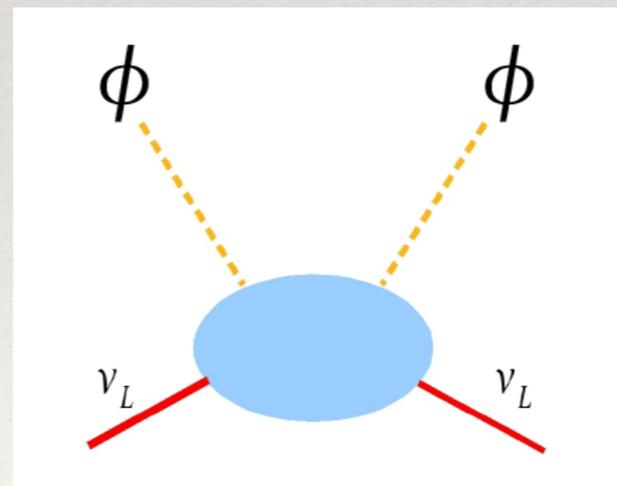
$$L \Phi N_R \rightarrow m_D \nu_L N_R$$

- ❖ Gauge invariance allows Majorana mass:

$$M_R N_R N_R$$

- ❖ in total Majorana mass for SM neutrinos:

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



m_ν inverse
proportional to
scale of origin!

Origin of Neutrino Mass

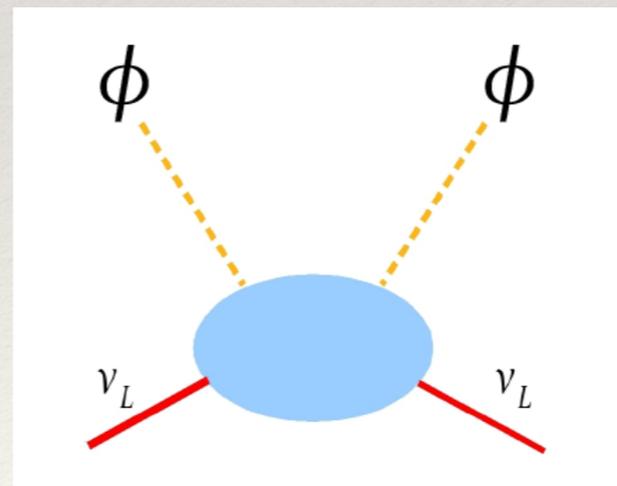
- ❖ Most straightforward possibility: **New representation of SM gauge group $N_R \sim (1,0)$ mass**
 $m_D \nu_L N_R$

- ❖ Gauge invariance allows Majorana mass

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- ❖ in total Majorana mass for SM neutrinos:

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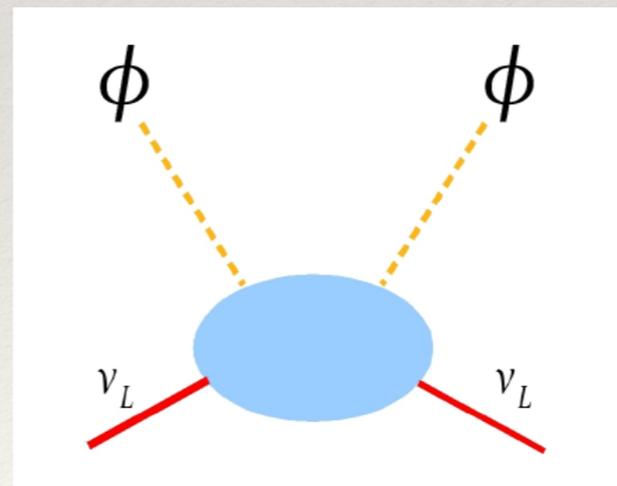
m_ν inverse
proportional to
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Origin of Neutrino Mass

- ❖ Most straightforward possibility:
 New representation of SM gauge group $N_R \sim (1,0)$ mass
 $\phi \rightarrow m_D \nu_L N_R$

- ❖ 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 $m_\nu = m_D^2 / M_R = m_D \epsilon$ with $\epsilon = m_D / M_R = m_{SM} / M_R$



m_ν inverse proportional to scale of origin!

Origin of Neutrino Mass

- ❖ Most straightforward possibility: **New representation of SM gauge group $N_R \sim (1,0)$ mass**

$$m_D \nu_L N_R$$

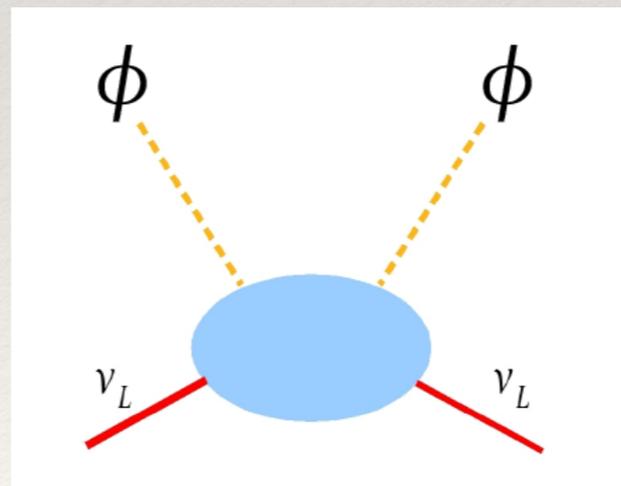
- ❖ Gauge invariance allows Majorana mass

New energy scale beyond SM

- ❖ in total Majorana mass for SM neutrinos:

$$m_\nu \nu_L^c \nu_L \text{ with } m_\nu \sim \frac{m_{SM}}{M_R}$$

New concept: lepton number violation



m_ν inverse proportional to scale of origin!

Origin of Neutrino Mass

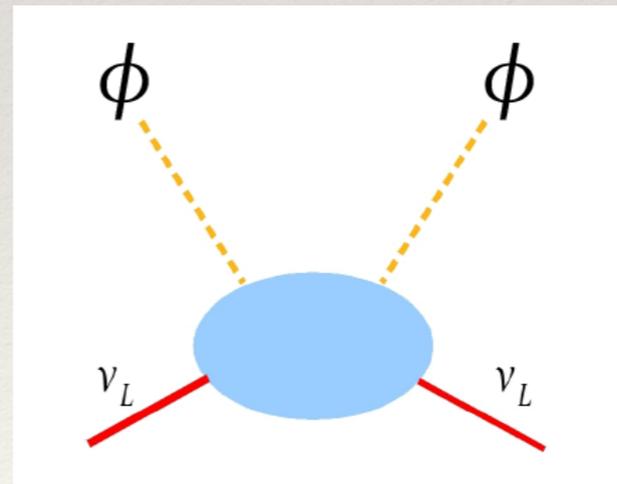
- ❖ Most straightforward possibility: add N_R and obtain Dirac mass

$$L \Phi N_R \rightarrow m_D \nu_L N_R$$
- ❖ Gauge invariance allows Majorana mass

$$N_R N_R \rightarrow M_R N_R N_R$$
- ❖ in total Majorana mass m_ν of neutrinos:

$$m_\nu \nu_L^c \nu_L \text{ with } m_\nu/M_R = m_D \epsilon \text{ with } \epsilon = m_D/M_R = m_{SM}/M_R$$

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



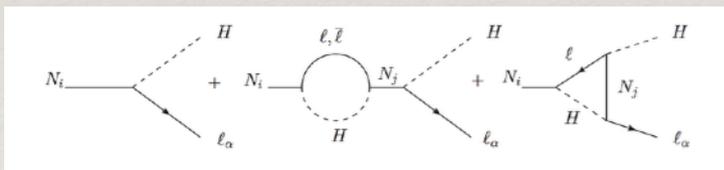
m_ν inverse proportional to scale of origin!

Type I Seesaw $m_\nu = m_D^2 / M_N \propto y^2 / M_N$

actually, does neither fix m_ν nor m_D nor M_N
needs to be tested or has phenomenology via „seesaw portal“:

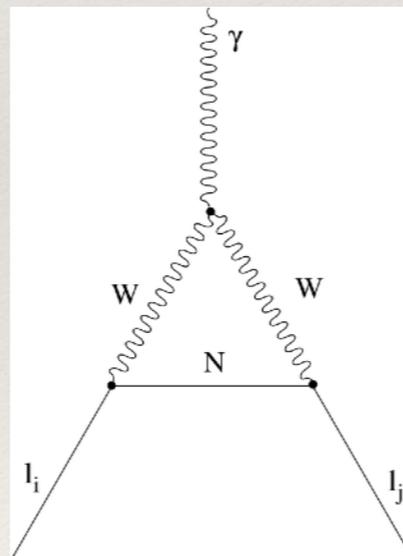
Lepton-Higgs-Singlet Vertex: $y L \Phi N_R$

$$N_R \rightarrow L \Phi \quad L_\alpha \rightarrow N_R \Phi \rightarrow L_\beta \quad \Phi \rightarrow L N_R \rightarrow \Phi$$



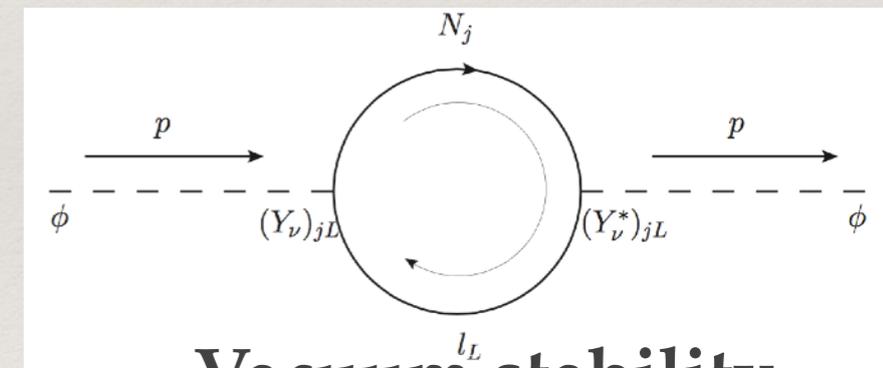
Leptogenesis

$$Y_B \propto \text{Im}(y^2)$$



Lepton Flavor Violation

$$\text{BR} \propto y^4 / (M_N^4 \text{ or } M_{\text{SUSY}}^4)$$

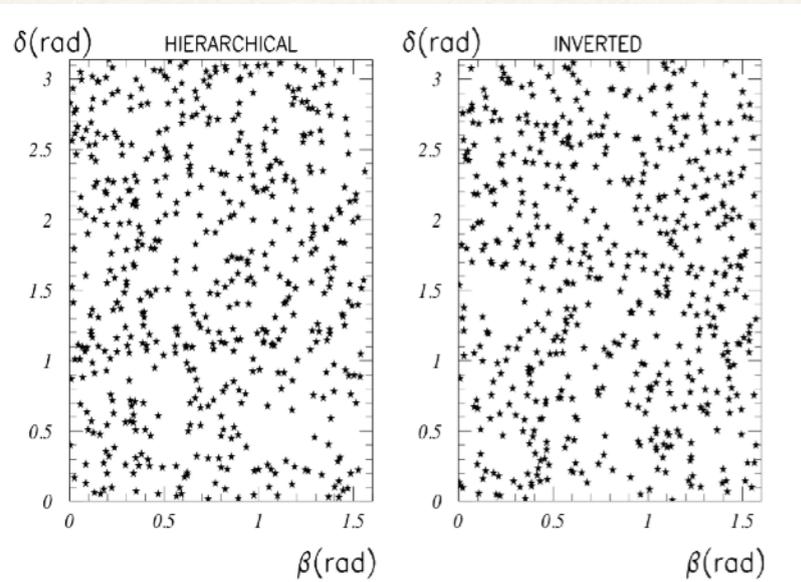


**Vacuum stability,
naturalness**

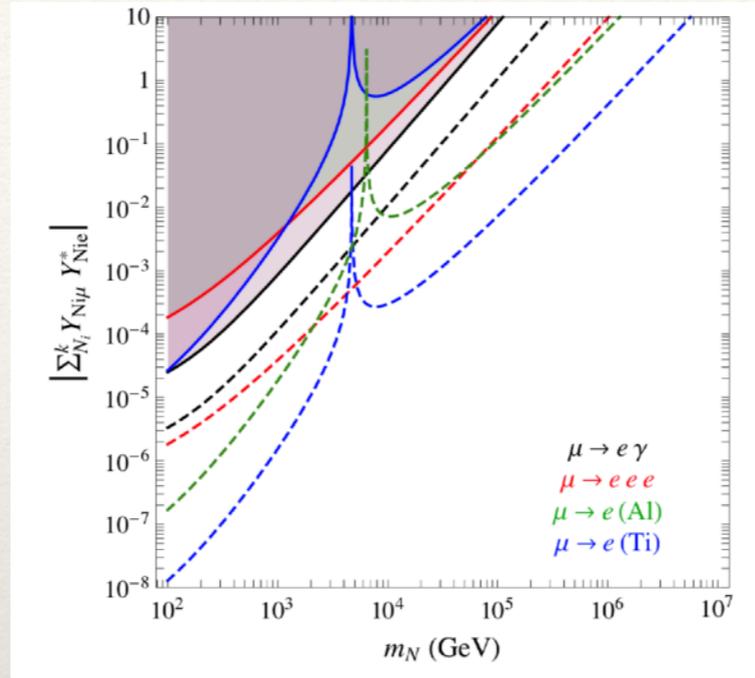
$$d\lambda / dt \propto -y^4$$

$$\delta(m_h^2) \propto y^2 M_N^2$$

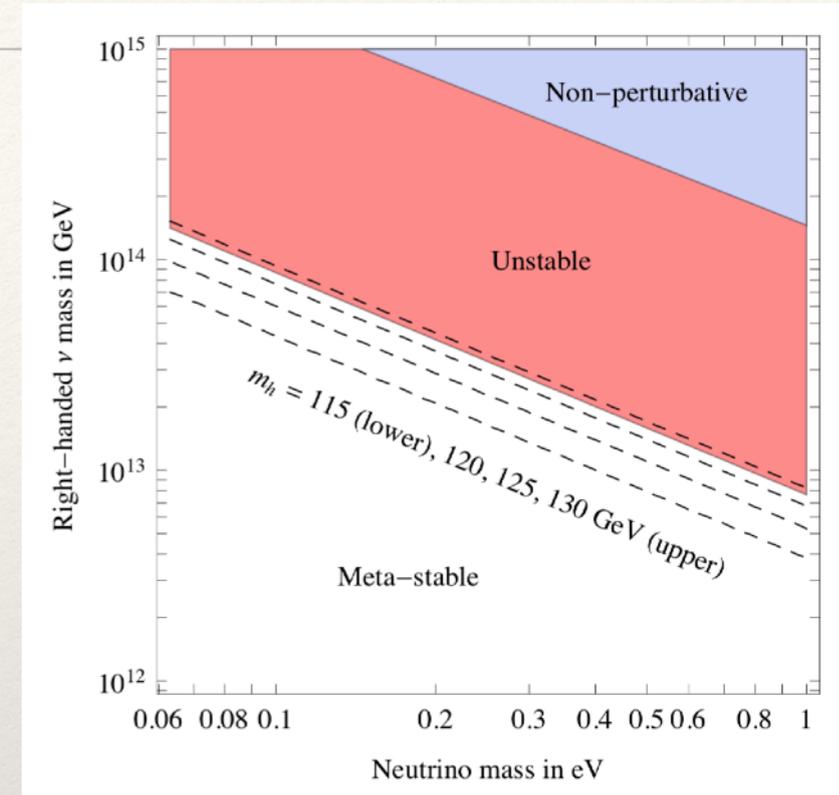
Type I Seesaw $m_\nu = m_D^2 / M_R$



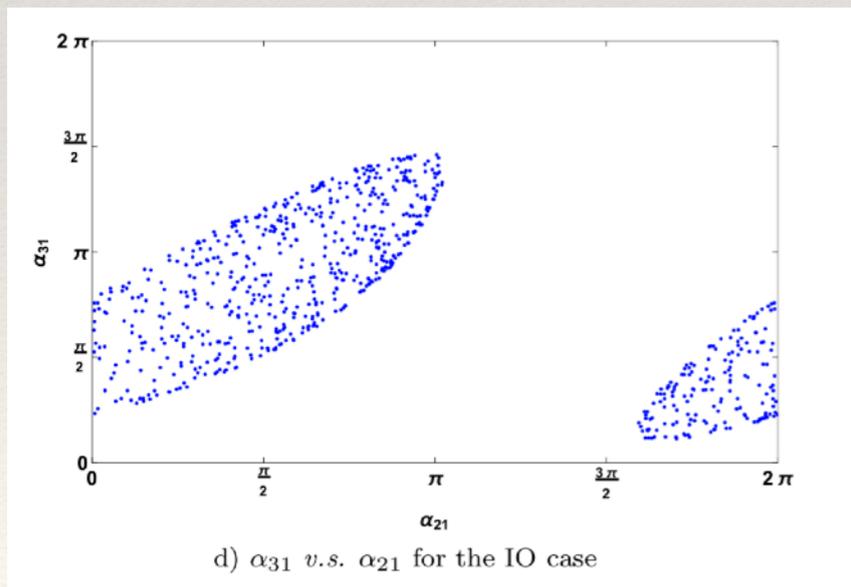
Davidson et al., 0705.1503



Hambye, 1312.5214

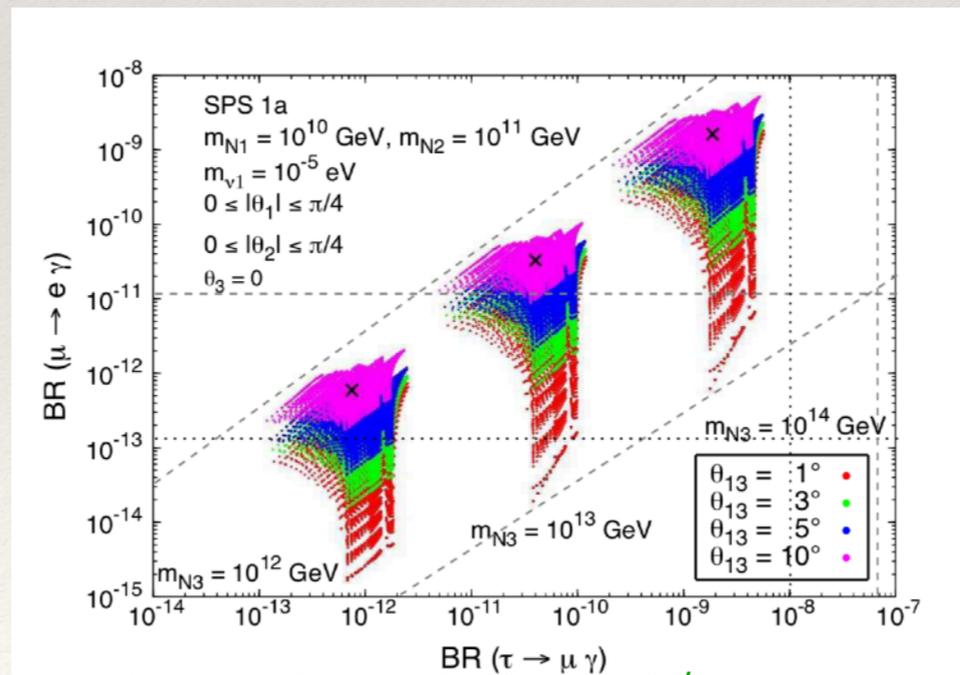


Elias-Miro et al., 1112.3022

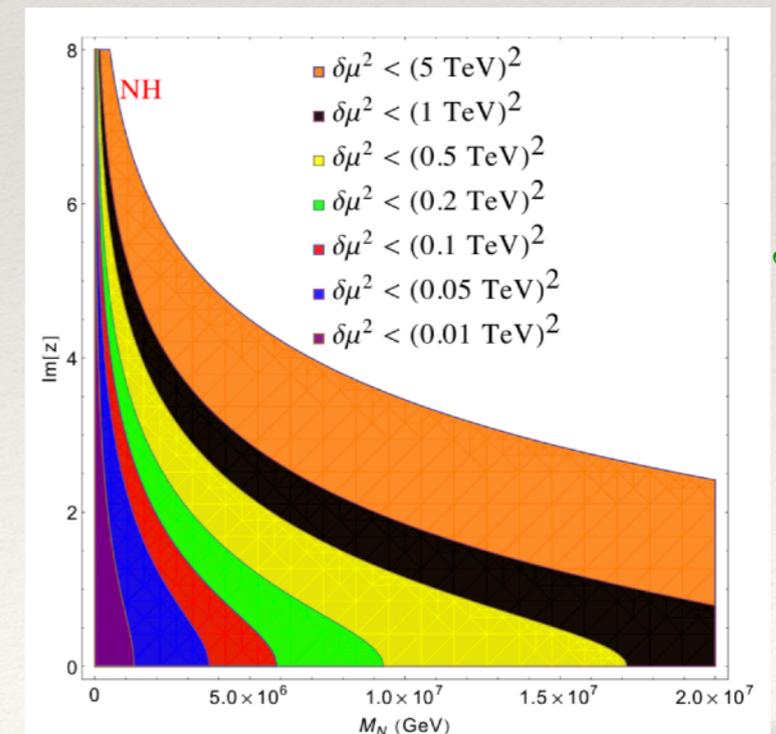


d) α_{31} v.s. α_{21} for the IO case

Merlo, Rosauero-Alcaraz, 1801.03937



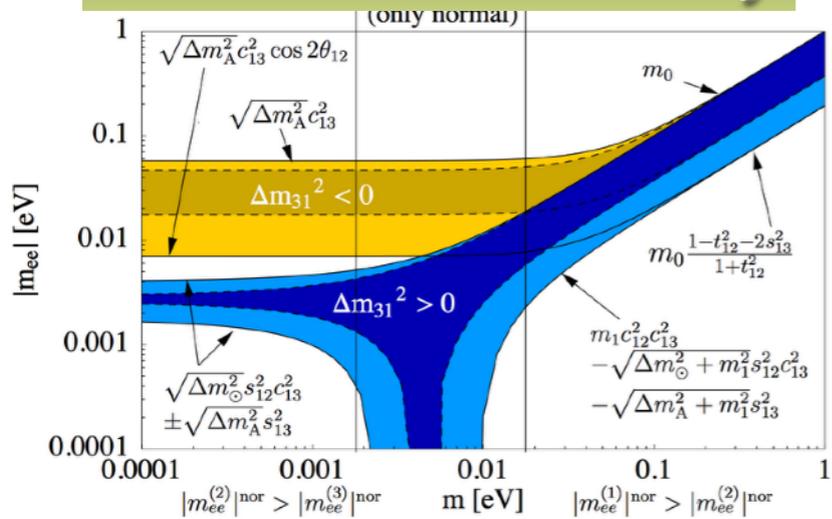
Antusch et al., hep-ph/0607263



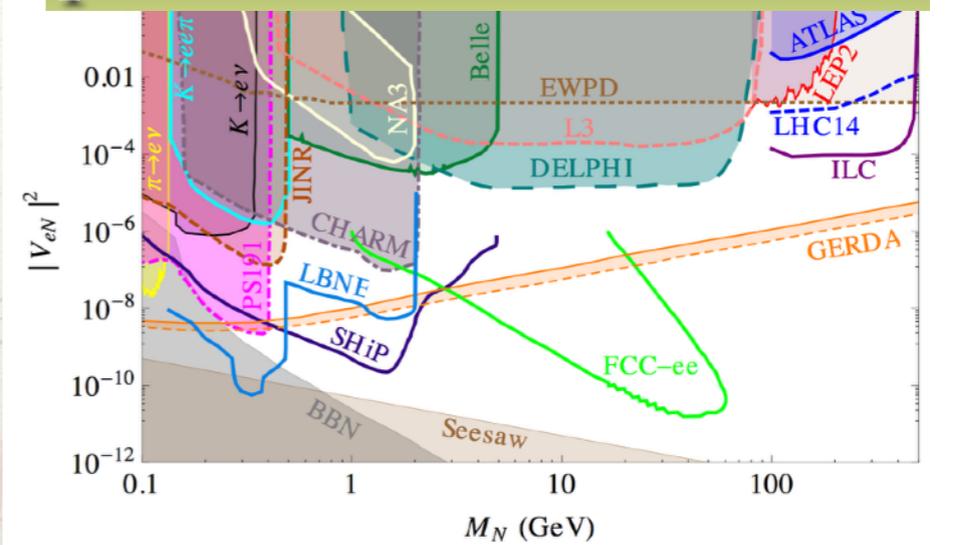
Bambhaniya et al., 1611.03827

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

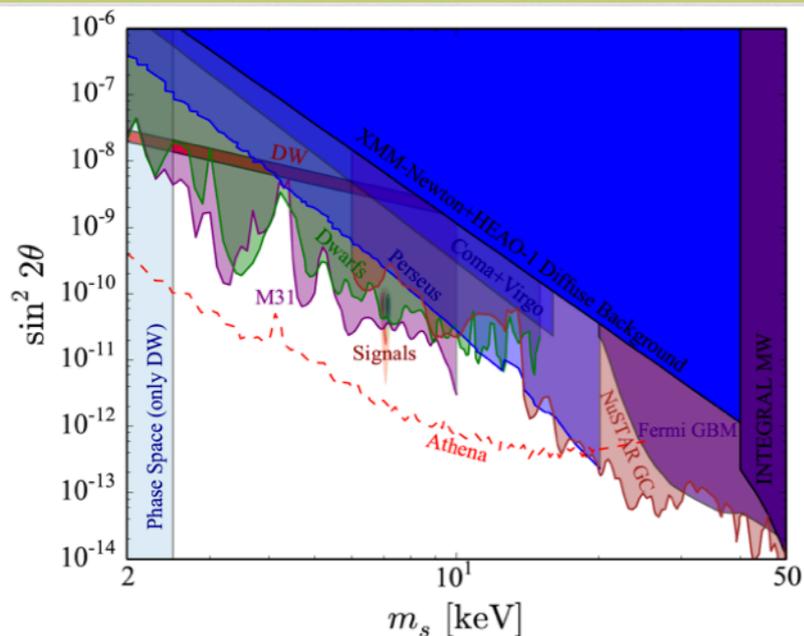
double beta decay



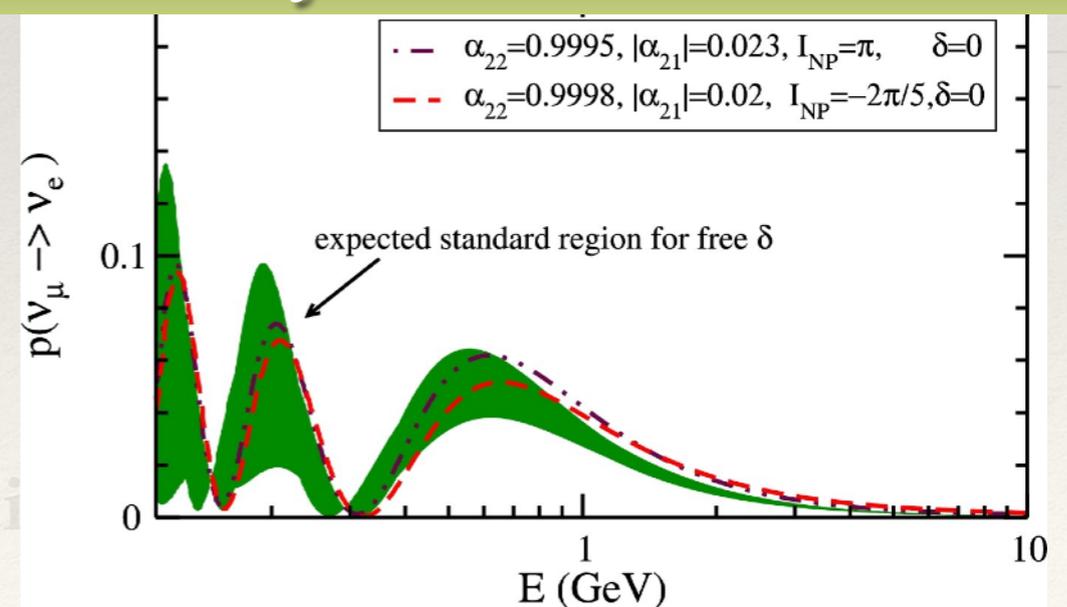
production at colliders



dark matter candidate



unitarity violation of PMNS



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	$N_R \sim (1, 0)$	$h \overline{N}_R \Phi L + \overline{N}_R M_R N_R^c$	$\frac{(h v)^2}{M_R}$	$\Lambda = \frac{1}{h} M_R$
"indirect 2" (type III seesaw)	fermion triplets + LNV	$\Sigma \sim (3, 0)$	$h \overline{\Sigma} L \Phi + \text{Tr} \overline{\Sigma} M_\Sigma \Sigma$	$\frac{(h v)^2}{M_\Sigma}$	$\Lambda = \frac{1}{h} M_\Sigma$

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

plus radiative mechanisms

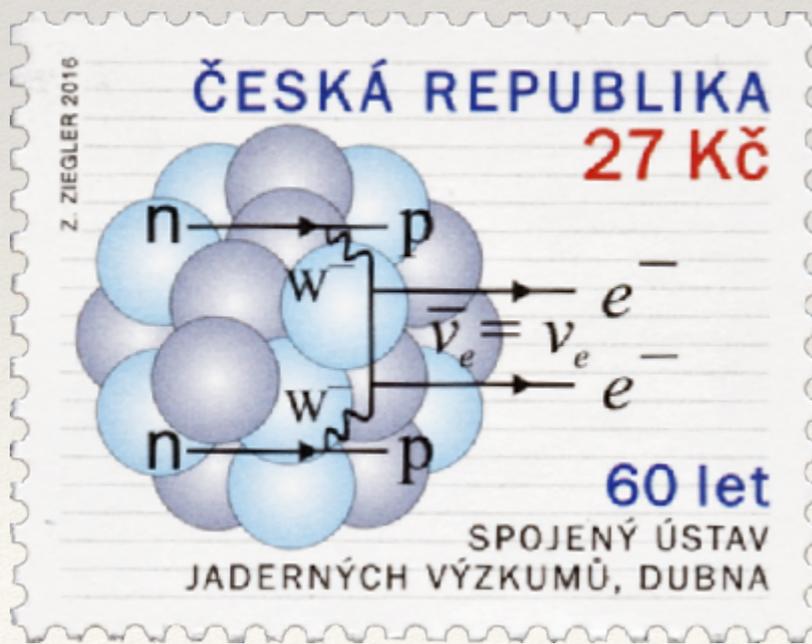
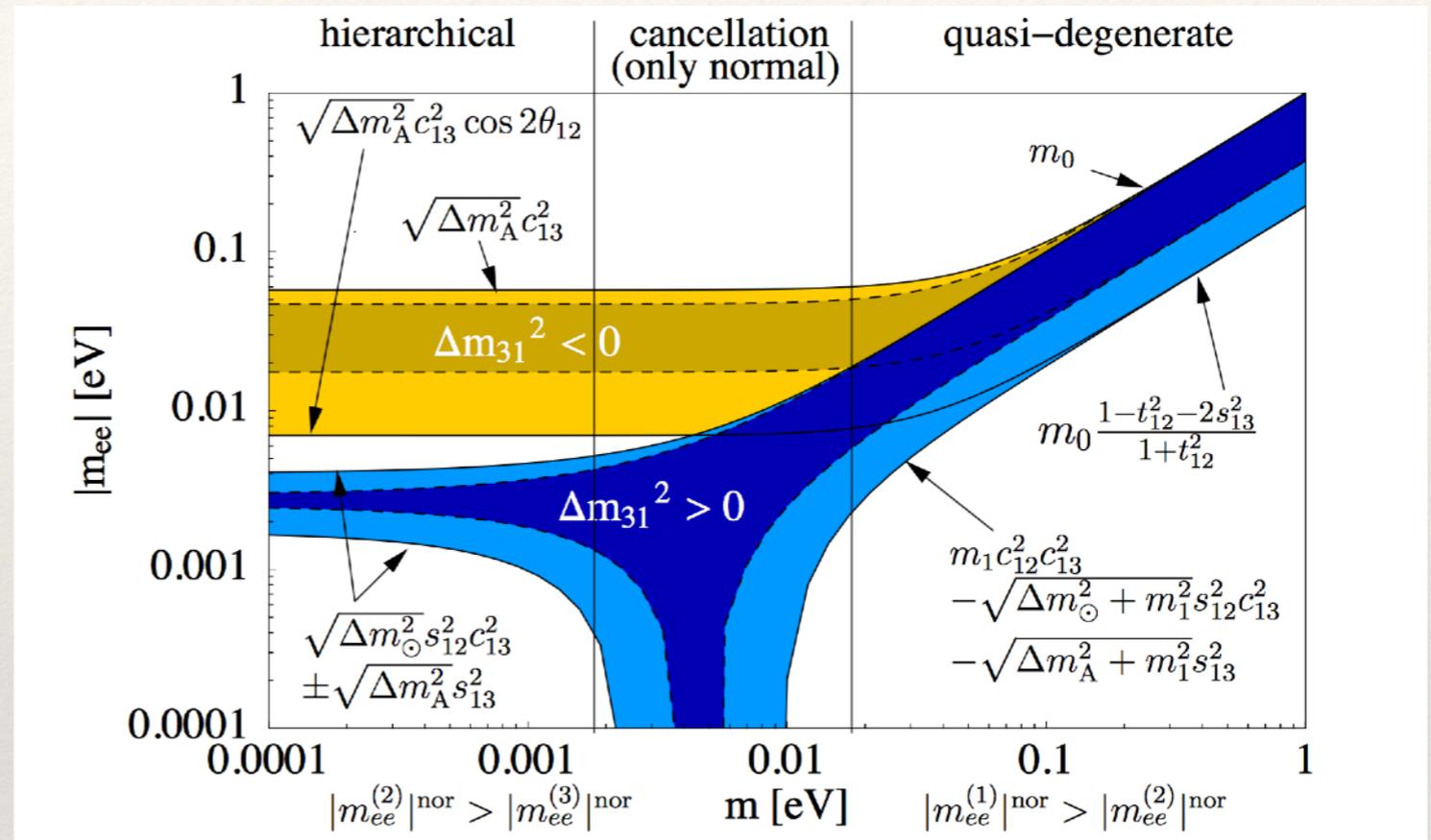
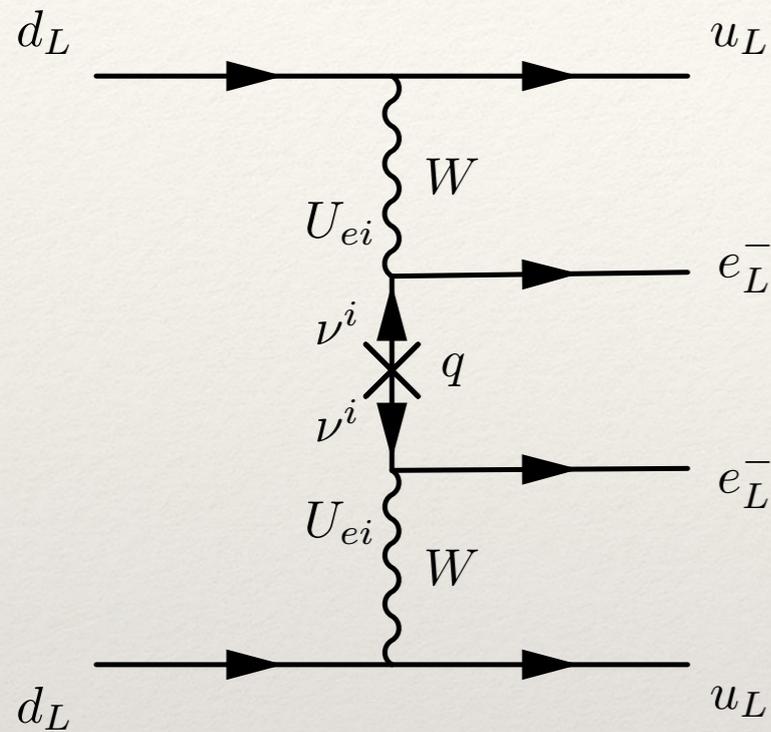
plus higher dimensional operators

plus extra dimensional

plus plus plus

Talks by Volkas, Gavela, Perez, Domcke, Lykken, Senjanovic

Common Prediction: Lepton Number Violation



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

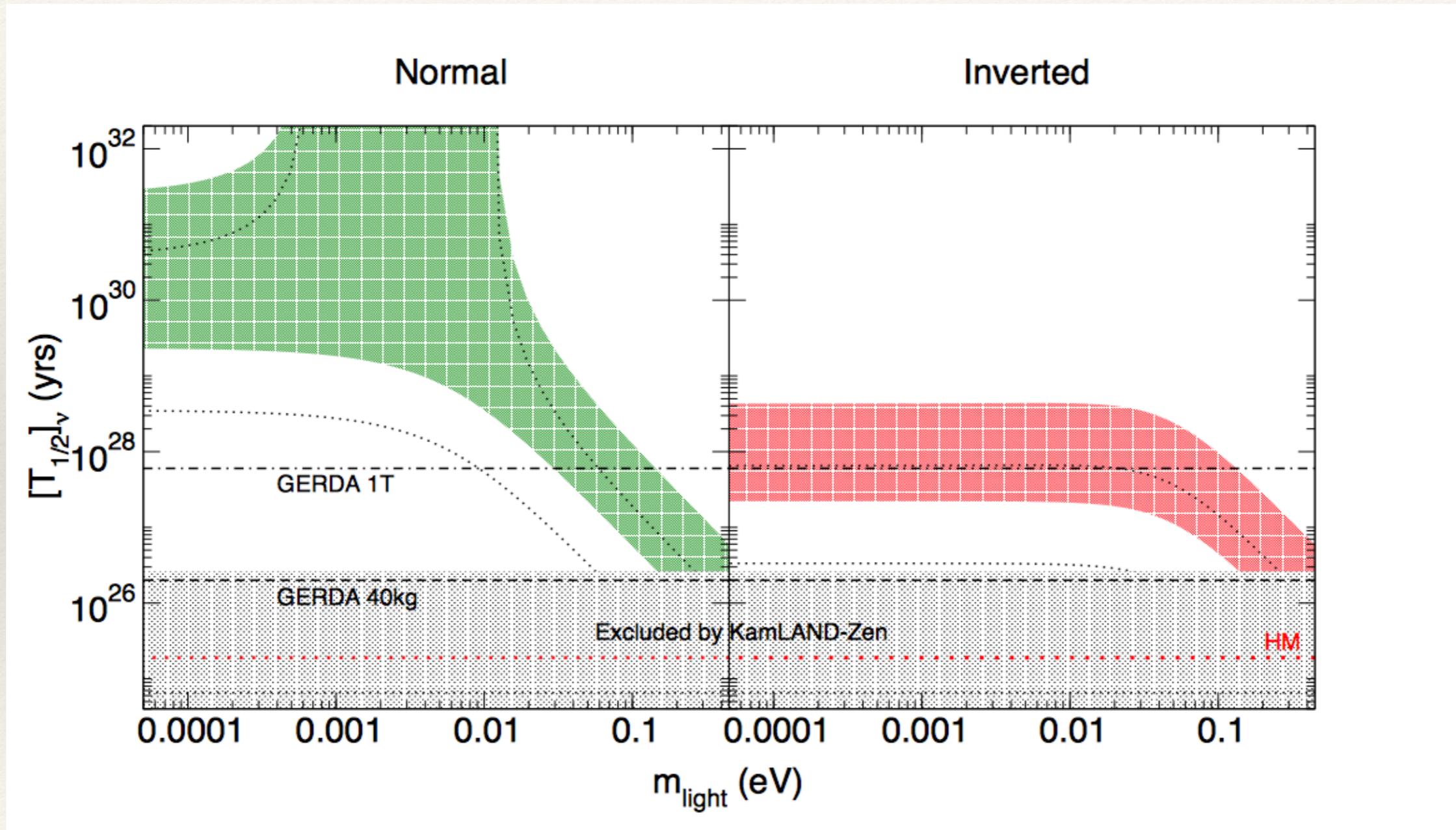
$$= f(\theta_{12}, |U_{e3}|, m_i, \text{sgn}(\Delta m_A^2), \alpha, \beta)$$

known

limits

unknown

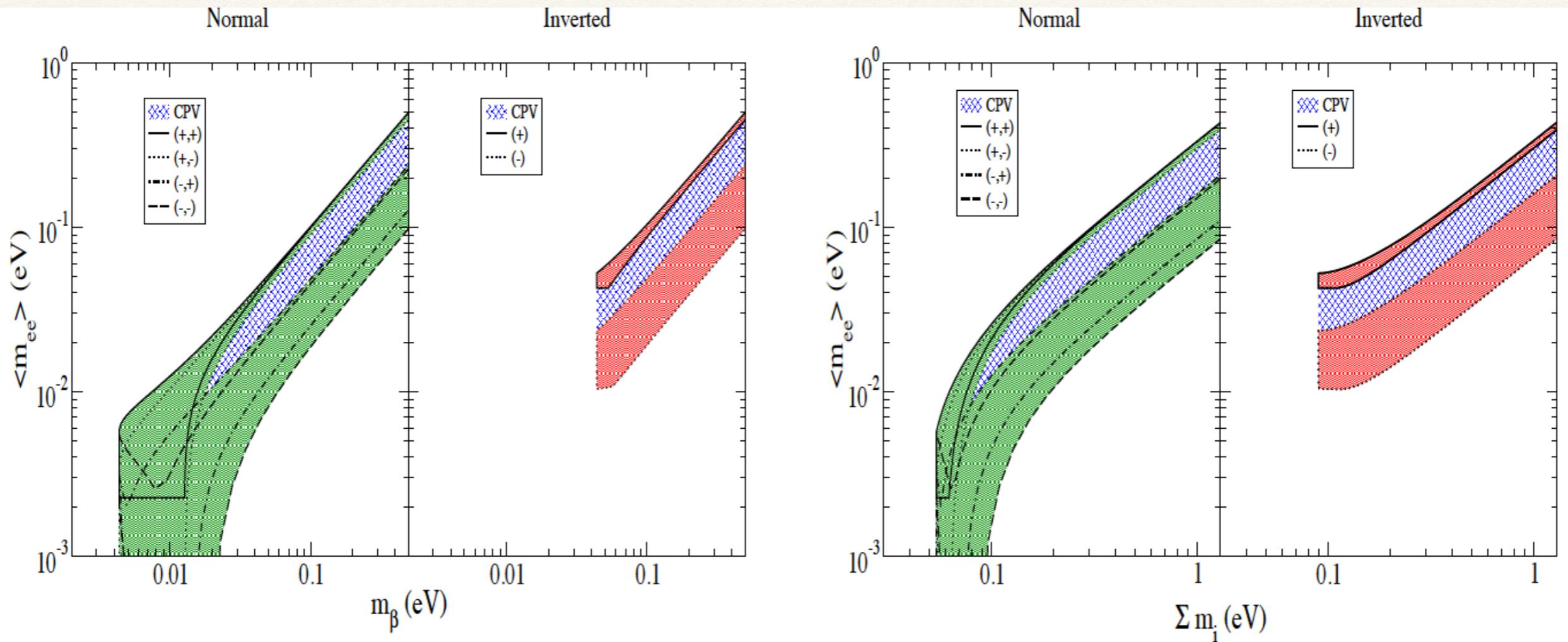
The usual plot



Neutrino Mass Observables

Method	Observable	current	near	far	pro	con
Kurie	$\sum |U_{ei}|^2 m_i$	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

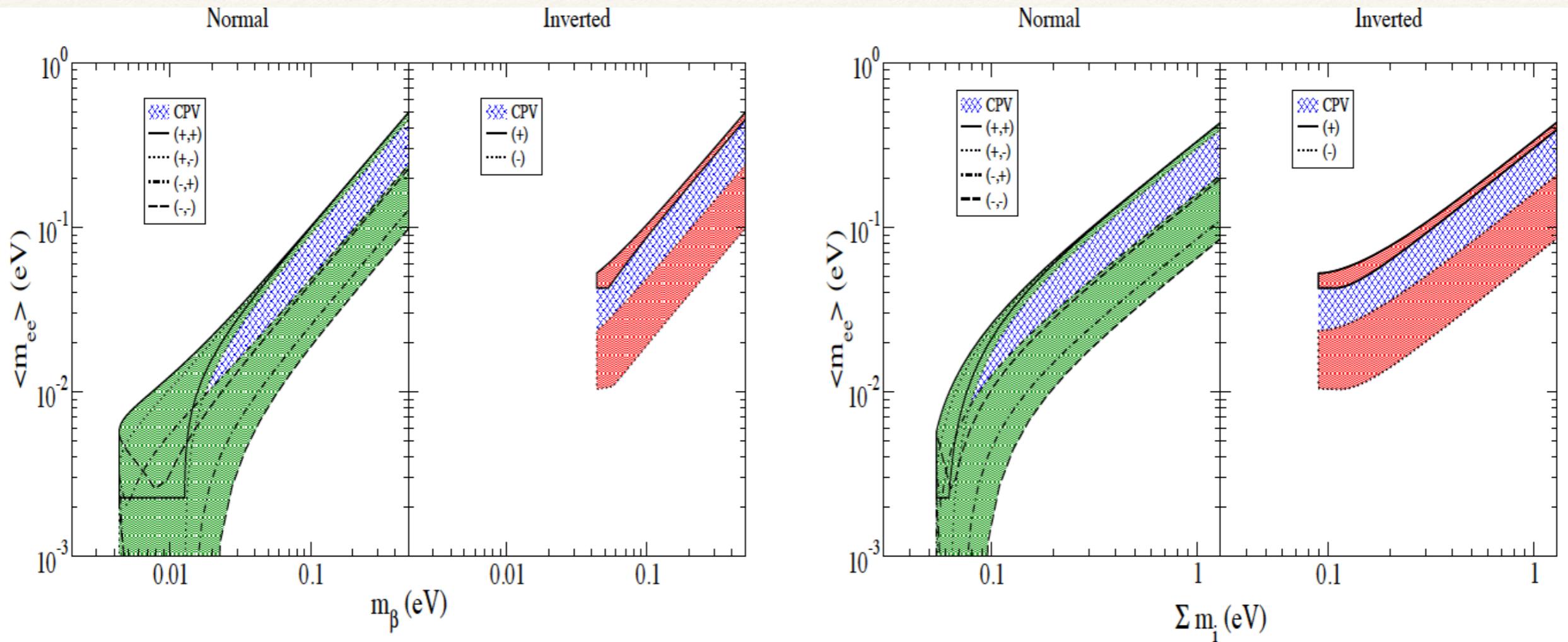
Neutrino Mass Observables



**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

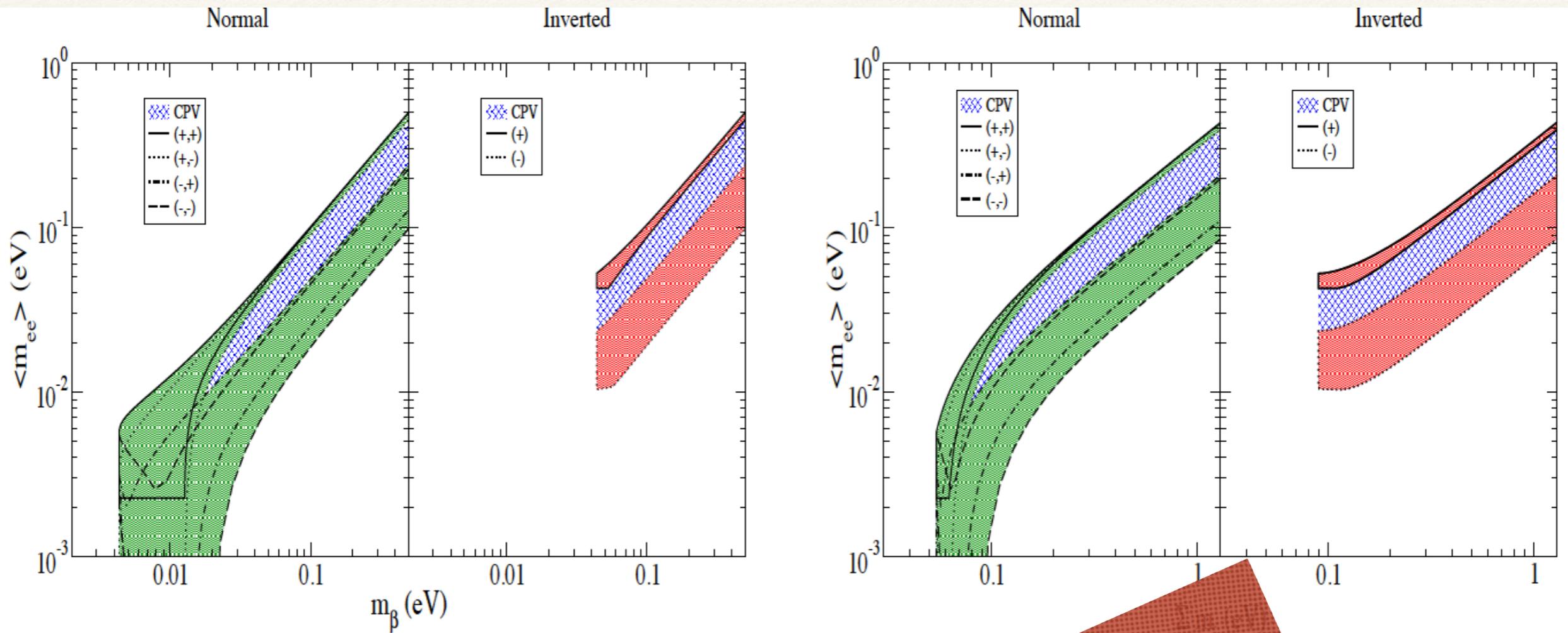


complete complementarity
of observables

- $0\nu\beta\beta$ rules out that neutrino mass is at the Mainz-limit
- $0\nu\beta\beta$ and cosmological Σm_i are consistently roughly the same
- cosmological Σm_i strongly disfavors a signal in KATRIN

All need to be pursued!

Neutrino Mass Observables

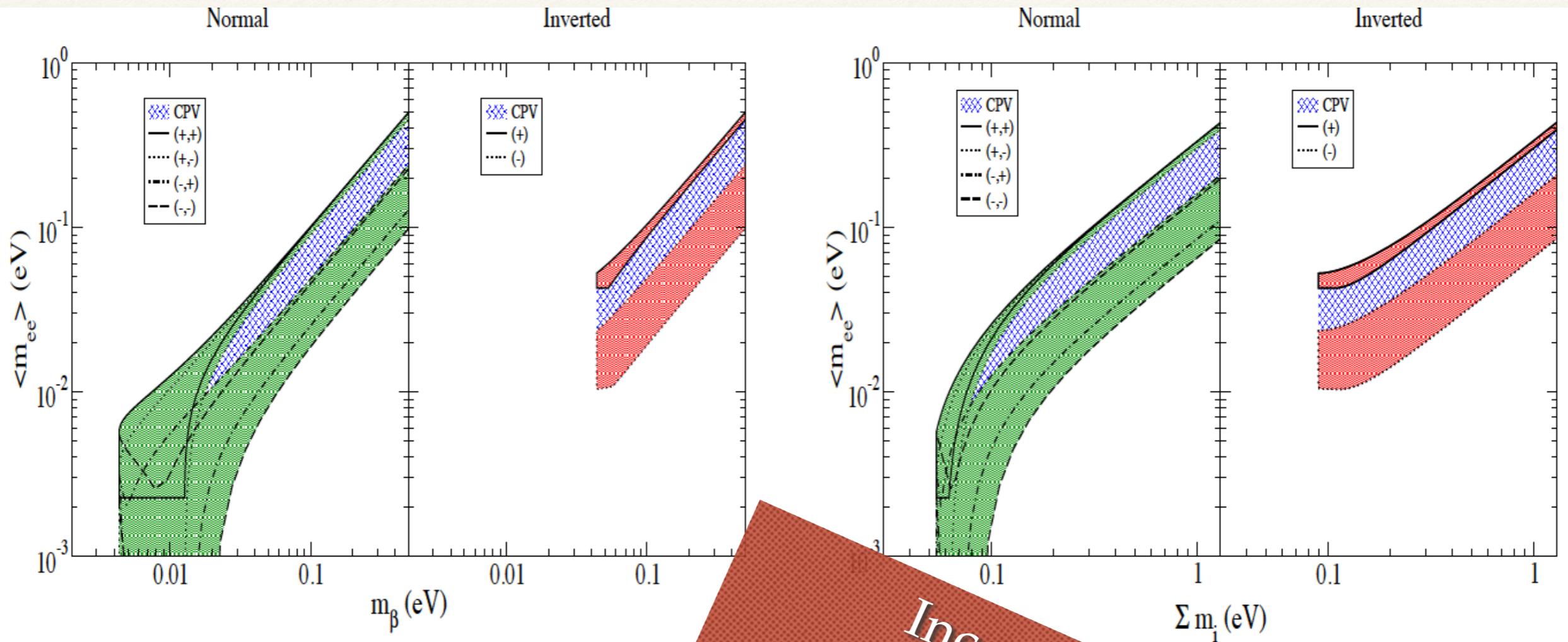


complete complementarity
of observables

- $0\nu\beta\beta$ rules out the Mainz-limit
- $0\nu\beta\beta$ and cosmology are roughly the same
- cosmology favors a signal in KATRIN

Consistency
would be spectacular
confirmation!

Neutrino Mass Observables

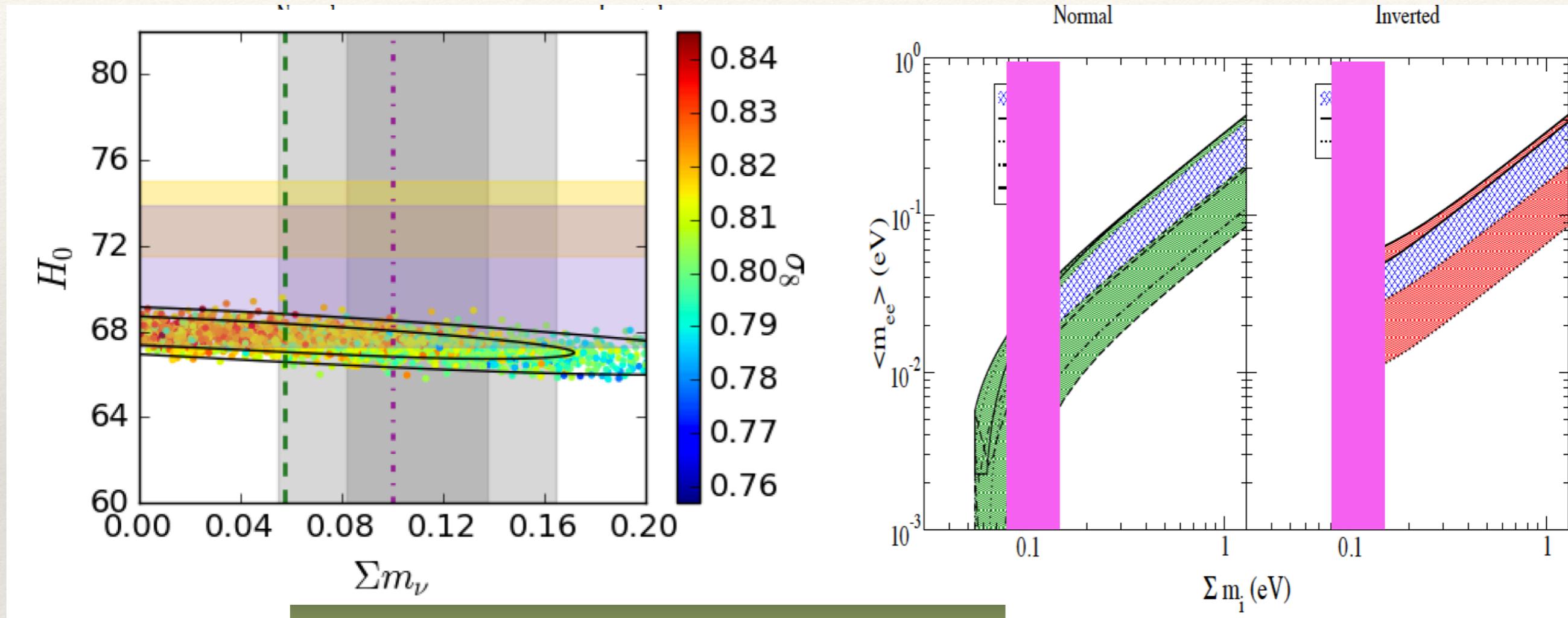


Inconsistencies would be major discovery!

complete complementarity of observables

- $0\nu\beta\beta$ run
- $0\nu\beta\beta$ and cosmology
- cosmology strongly disfavors a Mainz-limit

Neutrino Mass Observables



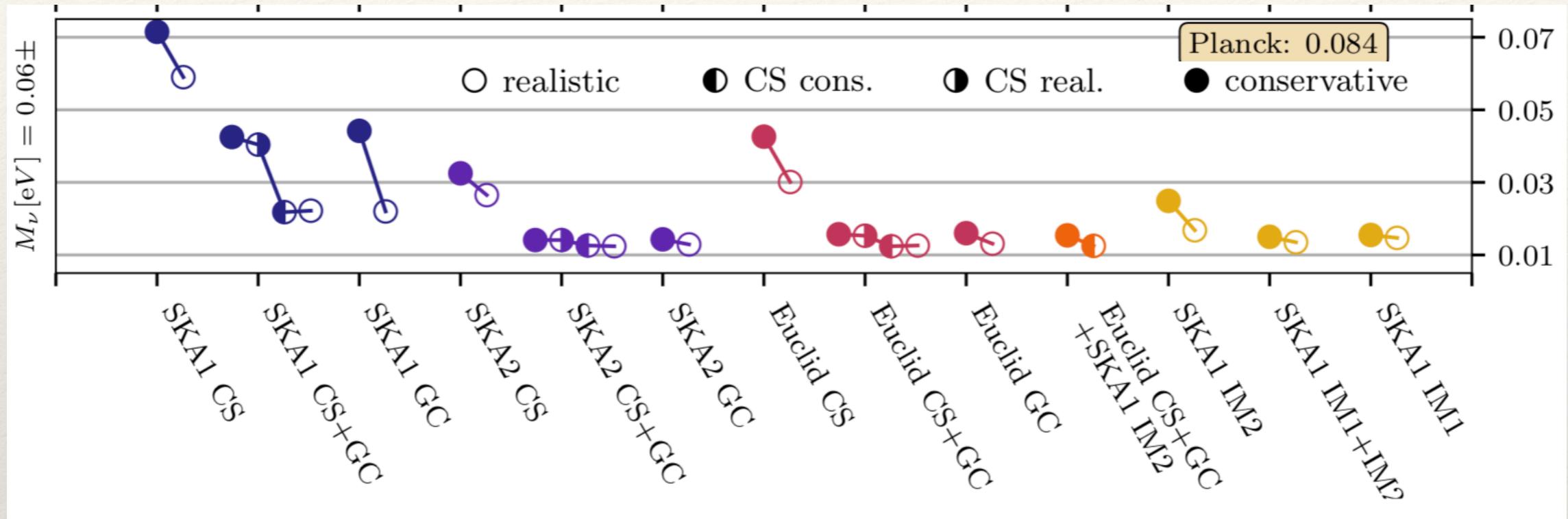
0.11 ± 0.03 eV from 1711.05210

large effect of ν -mass in clustering length of galaxy clusters;
 much larger effect than on power spectrum;
 σ_8 larger locally larger than CMB-value;
 (H_0 still unresolved)

Talk by Wong

Is neutrino mass guaranteed?

Sprenger et al., 1801.08331



- ❖ typically maximal wavenumber assumed, below non-linearities too strong to trust estimates
- ❖ galaxy clustering, cosmic shear, intensity mapping with two bands
- ❖ 5 σ detection when Euclid and SKA are combined!

Experimental Situation

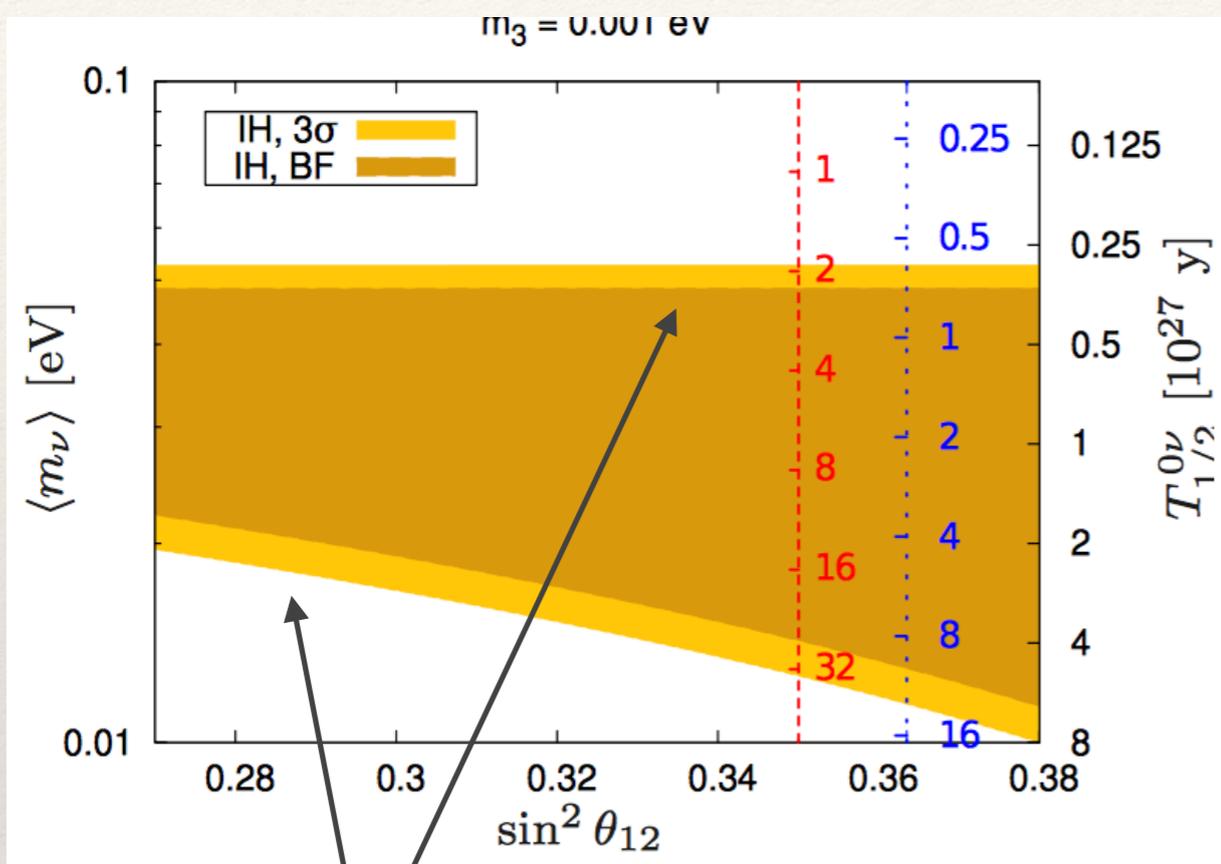
Agostini et al, 1705.02996

Experiment	Iso.	Iso. Mass [kg _{iso}]	σ [keV]	ROI [σ]	ϵ_{FV} [%]	ϵ_{sig} [%]	\mathcal{E} [$\frac{\text{kg}_{iso} \text{ yr}}{\text{yr}}$]	\mathcal{B} [$\frac{\text{cts}}{\text{kg}_{iso} \text{ ROI yr}}$]	3 σ disc. sens.		Required Improvement		
									$\hat{T}_{1/2}$ [yr]	$\hat{m}_{\beta\beta}$ [meV]	Bkg	σ	Iso. Mass
LEGEND 200 [61, 62]	⁷⁶ Ge	175	1.3	[-2, 2]	93	77	119	$1.7 \cdot 10^{-3}$	$8.4 \cdot 10^{26}$	40–73	3	1	5.7
LEGEND 1k [61, 62]	⁷⁶ Ge	873	1.3	[-2, 2]	93	77	593	$2.8 \cdot 10^{-4}$	$4.5 \cdot 10^{27}$	17–31	18	1	29
SuperNEMO [68, 69]	⁸² Se	100	51	[-4, 2]	100	16	16.5	$4.9 \cdot 10^{-2}$	$6.1 \cdot 10^{25}$	82–138	49	2	14
CUPID [58, 59, 70]	⁸² Se	336	2.1	[-2, 2]	100	69	221	$5.2 \cdot 10^{-4}$	$1.8 \cdot 10^{27}$	15–25	n/a	6	n/a
CUORE [52, 53]	¹³⁰ Te	206	2.1	[-1.4, 1.4]	100	81	141	$3.1 \cdot 10^{-1}$	$5.4 \cdot 10^{25}$	66–164	6	1	19
CUPID [58, 59, 70]	¹³⁰ Te	543	2.1	[-2, 2]	100	81	422	$3.0 \cdot 10^{-4}$	$2.1 \cdot 10^{27}$	11–26	3000	1	50
SNO+ Phase I [66, 71]	¹³⁰ Te	1357	82	[-0.5, 1.5]	20	97	164	$8.2 \cdot 10^{-2}$	$1.1 \cdot 10^{26}$	46–115	n/a	n/a	n/a
SNO+ Phase II [67]	¹³⁰ Te	7960	57	[-0.5, 1.5]	28	97	1326	$3.6 \cdot 10^{-2}$	$4.8 \cdot 10^{26}$	22–54	n/a	n/a	n/a
KamLAND-Zen 800 [60]	¹³⁶ Xe	750	114	[0, 1.4]	64	97	194	$3.9 \cdot 10^{-2}$	$1.6 \cdot 10^{26}$	47–108	1.5	1	2.1
KamLAND2-Zen [60]	¹³⁶ Xe	1000	60	[0, 1.4]	80	97	325	$2.1 \cdot 10^{-3}$	$8.0 \cdot 10^{26}$	21–49	15	2	2.9
nEXO [72]	¹³⁶ Xe	4507	25	[-1.2, 1.2]	60	85	1741	$4.4 \cdot 10^{-4}$	$4.1 \cdot 10^{27}$	9–22	400	1.2	30
NEXT 100 [64, 73]	¹³⁶ Xe	91	7.8	[-1.3, 2.4]	88	37	26.5	$4.4 \cdot 10^{-2}$	$5.3 \cdot 10^{25}$	82–189	n/a	1	20
NEXT 1.5k [74]	¹³⁶ Xe	1367	5.2	[-1.3, 2.4]	88	37	398	$2.9 \cdot 10^{-3}$	$7.9 \cdot 10^{26}$	21–49	n/a	1	300
PandaX-III 200 [65]	¹³⁶ Xe	180	31	[-2, 2]	100	35	60.2	$4.2 \cdot 10^{-2}$	$8.3 \cdot 10^{25}$	65–150	n/a	n/a	n/a
PandaX-III 1k [65]	¹³⁶ Xe	901	10	[-2, 2]	100	35	301	$1.4 \cdot 10^{-3}$	$9.0 \cdot 10^{26}$	20–46	n/a	n/a	n/a

Will enter IH regime soon!

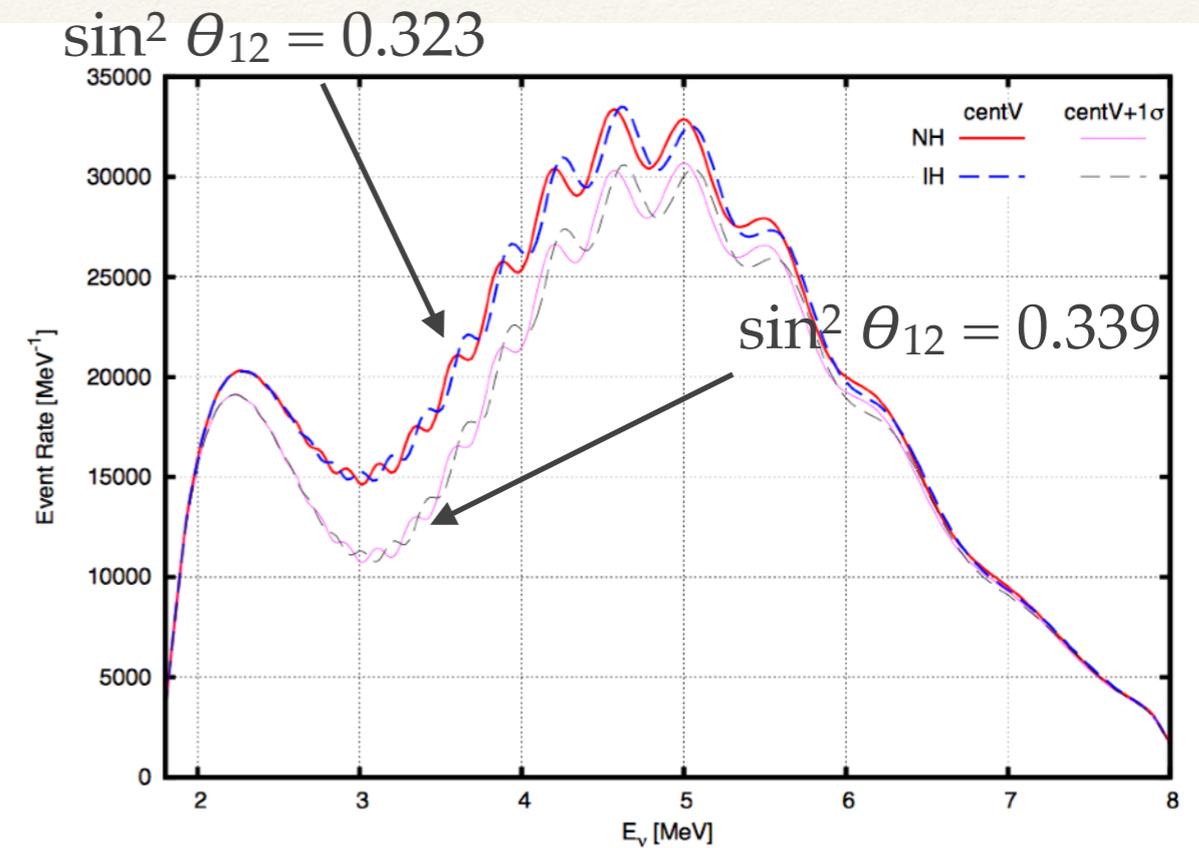
Multi-isotope determination for
mechanism and NMEs!

Connections to future Oscillation Experiments



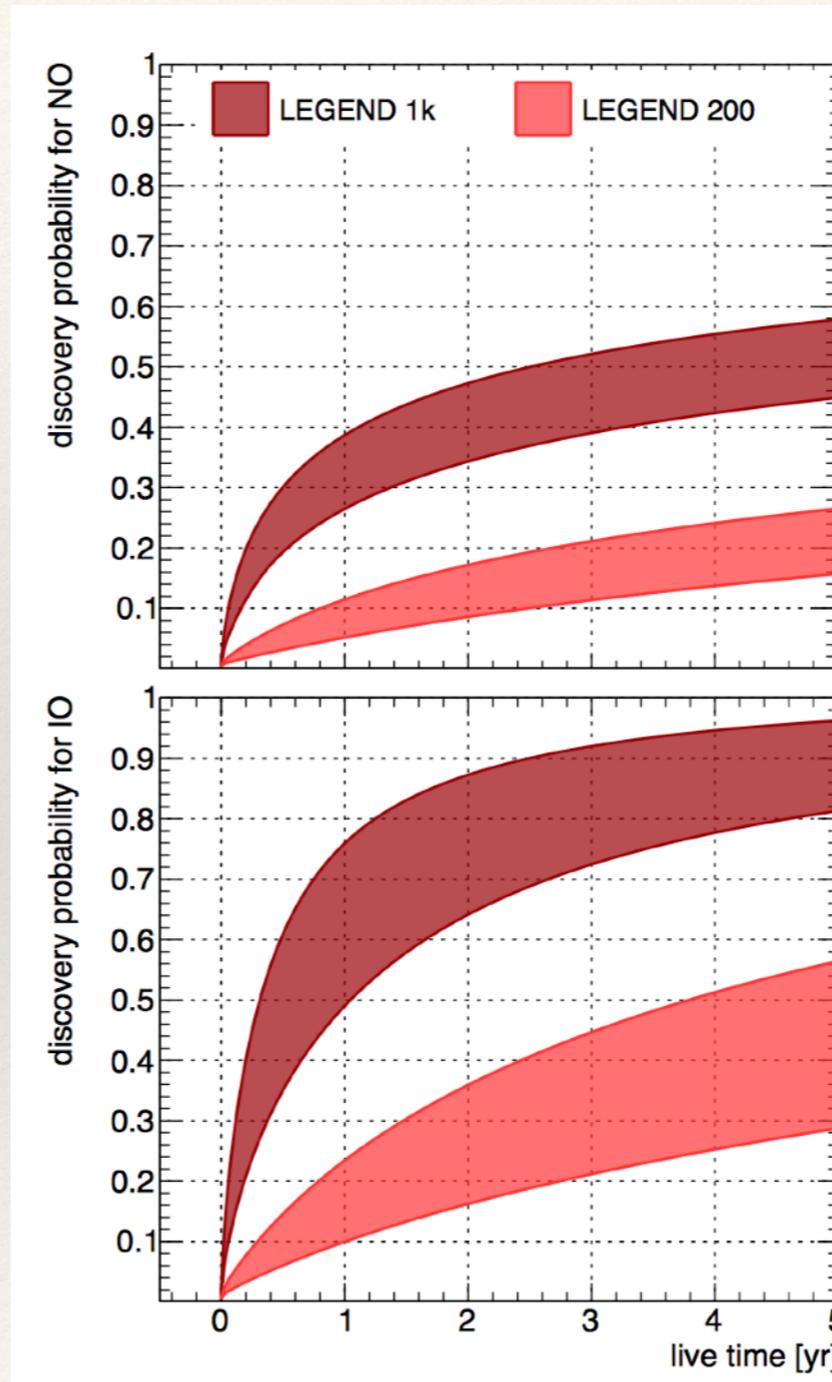
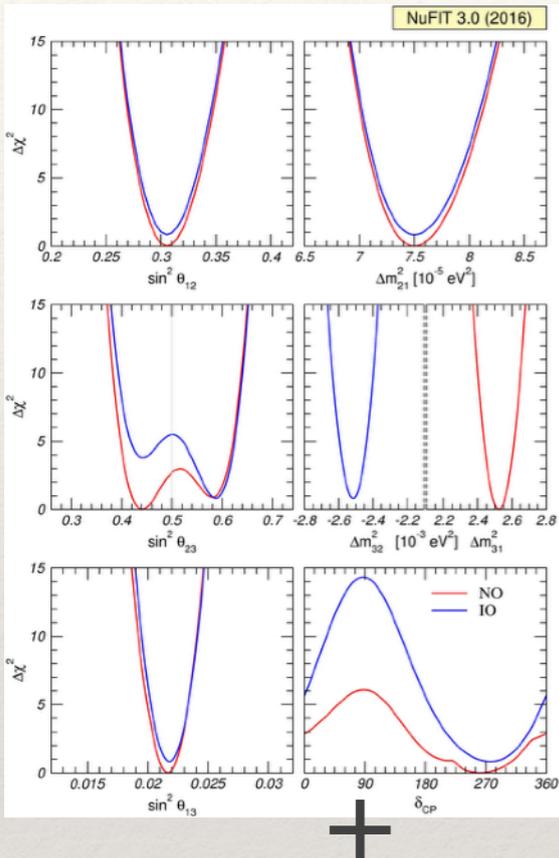
Nature gives us two scales

$$\begin{aligned} \langle m \rangle_{\text{IH}}^{\text{min}} &\propto \cos 2\theta_{12} \\ &= 1 - 2 \sin^2 \theta_{12} \end{aligned}$$



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

Expectations of lifetimes



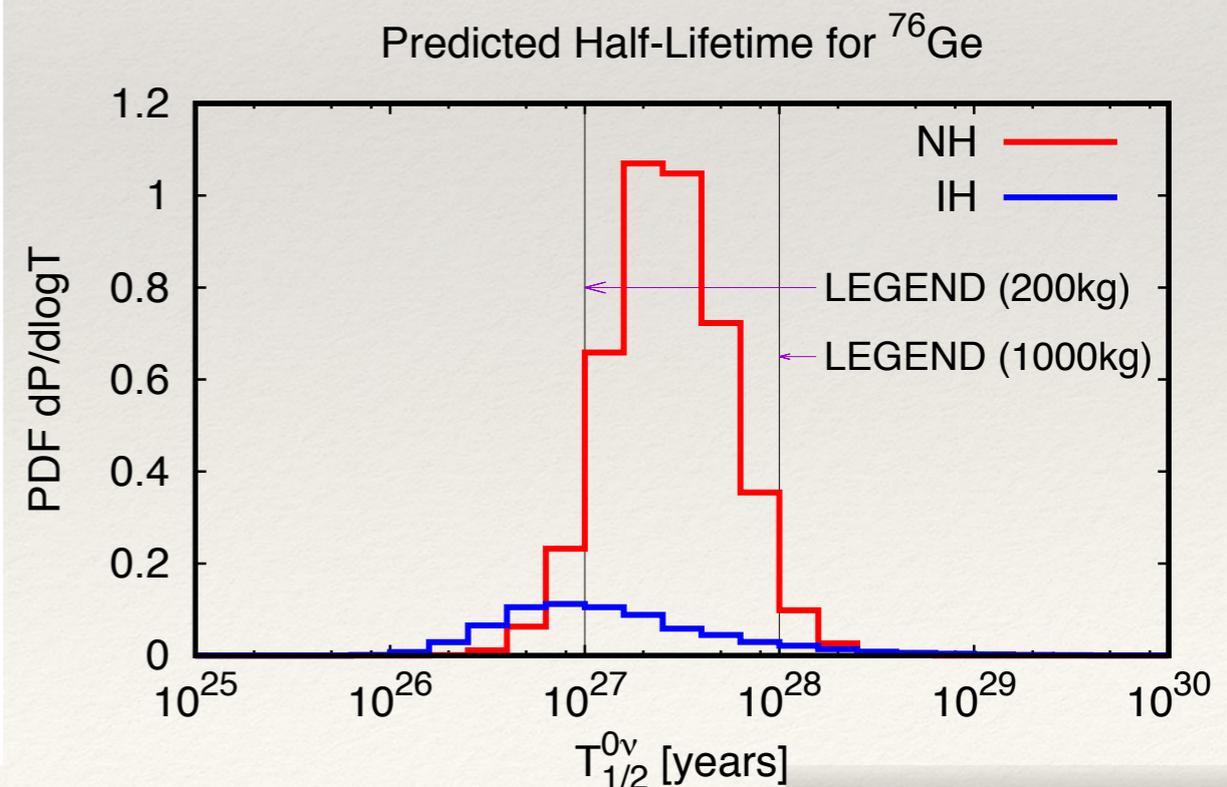
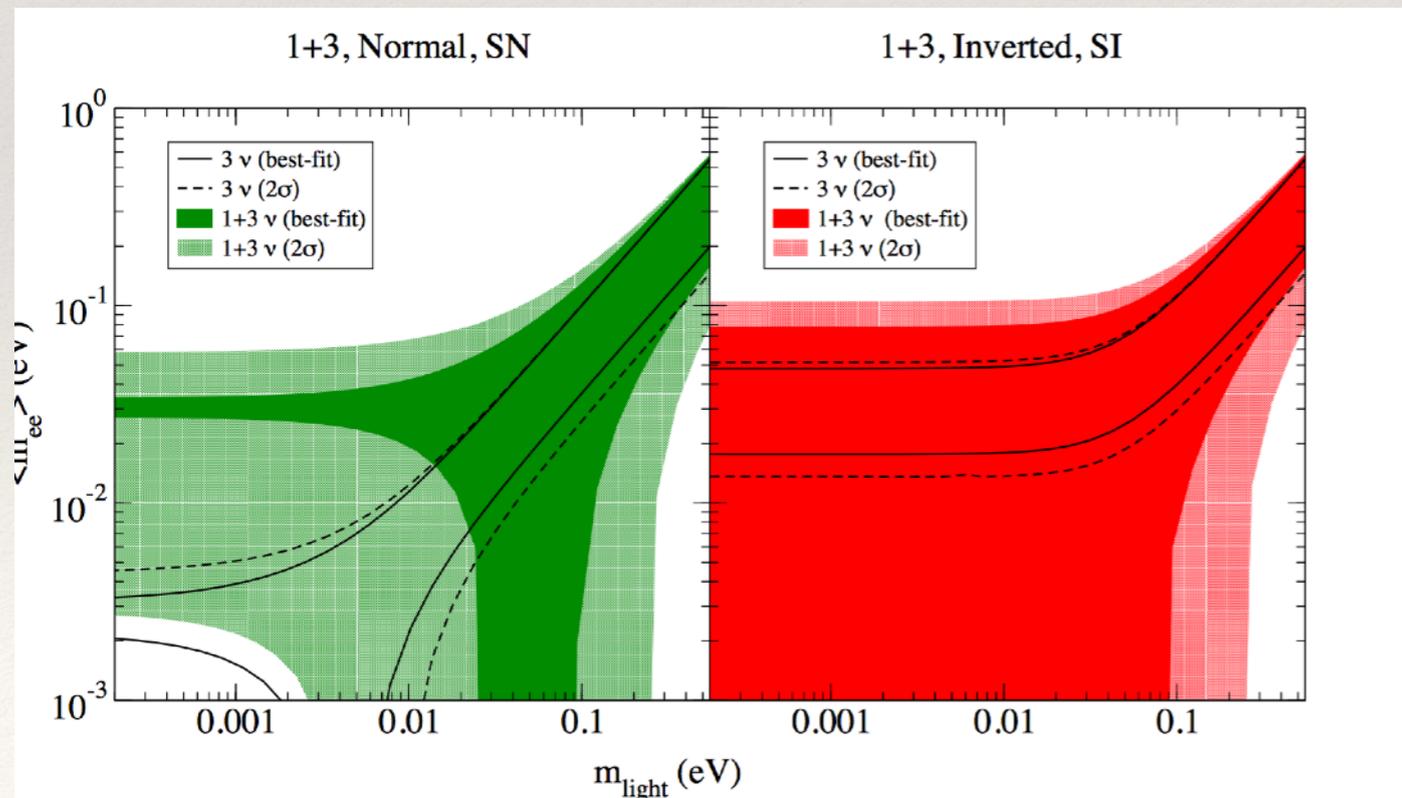
Bayesian discovery probability: discovery sensitivity (value of m_{ee} for which expt. has 50% chance to see it at 3σ) folded with probability distribution of m_{ee}

Agostini et al, 1705.02996; also Caldwell et al., 1705.01945; also Zhang, Zhou, 1508.05472

Experiment	Iso.	Iso. Mass [kg _{iso}]	σ [keV]	ROI [σ]	ϵ_{FV} [%]	ϵ_{sig} [%]	\mathcal{E} [kg _{iso} yr / yr]	\mathcal{B} [cts / kg _{iso} ROI yr]	3σ disc. sens.		Required Improvement		
									$\hat{T}_{1/2}$ [yr]	$\hat{m}_{\beta\beta}$ [meV]	Bkg	σ	Iso. Mass
LEGEND 200 [61, 62]	⁷⁶ Ge	175	1.3	[-2, 2]	93	77	119	$1.7 \cdot 10^{-3}$	$8.4 \cdot 10^{26}$	40-73	3	1	5.7
LEGEND 1k [61, 62]	⁷⁶ Ge	873	1.3	[-2, 2]	93	77	593	$2.8 \cdot 10^{-4}$	$4.5 \cdot 10^{27}$	17-31	18	1	29
SuperNEMO [68, 69]	⁸² Se	100	51	[-4, 2]	100	16	16.5	$4.9 \cdot 10^{-2}$	$6.1 \cdot 10^{25}$	82-138	49	2	14
CUPID [58, 59, 70]	⁸² Se	336	2.1	[-2, 2]	100	69	221	$5.2 \cdot 10^{-4}$	$1.8 \cdot 10^{27}$	15-25	n/a	6	n/a
CUORE [52, 53]	¹³⁰ Te	206	2.1	[-1.4, 1.4]	100	81	141	$3.1 \cdot 10^{-1}$	$5.4 \cdot 10^{25}$	66-164	6	1	19
CUPID [58, 59, 70]	¹³⁰ Te	543	2.1	[-2, 2]	100	81	422	$3.0 \cdot 10^{-4}$	$2.1 \cdot 10^{27}$	11-26	3000	1	50
SNO+ Phase I [66, 71]	¹³⁰ Te	1357	82	[-0.5, 1.5]	20	97	164	$8.2 \cdot 10^{-2}$	$1.1 \cdot 10^{26}$	46-115	n/a	n/a	n/a
SNO+ Phase II [67]	¹³⁰ Te	7960	57	[-0.5, 1.5]	28	97	1326	$3.6 \cdot 10^{-2}$	$4.8 \cdot 10^{26}$	22-54	n/a	n/a	n/a
KamLAND-Zen 800 [60]	¹³⁶ Xe	750	114	[0, 1.4]	64	97	194	$3.9 \cdot 10^{-2}$	$1.6 \cdot 10^{26}$	47-108	1.5	1	2.1
KamLAND2-Zen [60]	¹³⁶ Xe	1000	60	[0, 1.4]	80	97	325	$2.1 \cdot 10^{-3}$	$8.0 \cdot 10^{26}$	21-49	15	2	2.9
nEXO [72]	¹³⁶ Xe	4507	25	[-1.2, 1.2]	60	85	1741	$4.4 \cdot 10^{-4}$	$4.1 \cdot 10^{27}$	9-22	400	1.2	30
NEXT 100 [64, 73]	¹³⁶ Xe	91	7.8	[-1.3, 2.4]	88	37	26.5	$4.4 \cdot 10^{-2}$	$5.3 \cdot 10^{25}$	82-189	n/a	1	20
NEXT 1.5k [74]	¹³⁶ Xe	1367	5.2	[-1.3, 2.4]	88	37	398	$2.9 \cdot 10^{-3}$	$7.9 \cdot 10^{26}$	21-49	n/a	1	300
PandaX-III 200 [65]	¹³⁶ Xe	180	31	[-2, 2]	100	35	60.2	$4.2 \cdot 10^{-2}$	$8.3 \cdot 10^{25}$	65-150	n/a	n/a	n/a
PandaX-III 1k [65]	¹³⁶ Xe	901	10	[-2, 2]	100	35	301	$1.4 \cdot 10^{-3}$	$9.0 \cdot 10^{26}$	20-46	n/a	n/a	n/a

Sterile Neutrinos

- ❖ are there sterile states (LSND / reactor / etc.) with mass $\Delta m^2 \approx eV^2$ and mixing $U_{e4} \approx 0.1$?
- ❖ would make m_{ee} sum of 4 terms with sterile contribution $|U_{e4}|^2 \sqrt{\Delta m^2}$ that can cancel almost completely contribution of IH!
- ❖ usual pheno completely turned around!

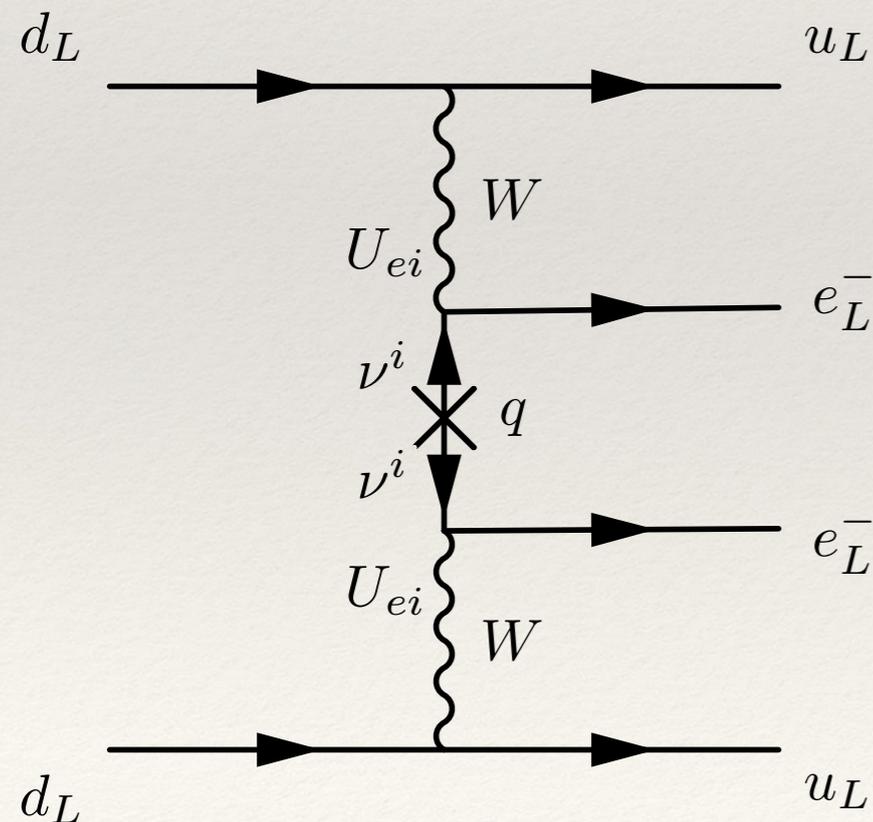


New Physics in Double Beta Decay

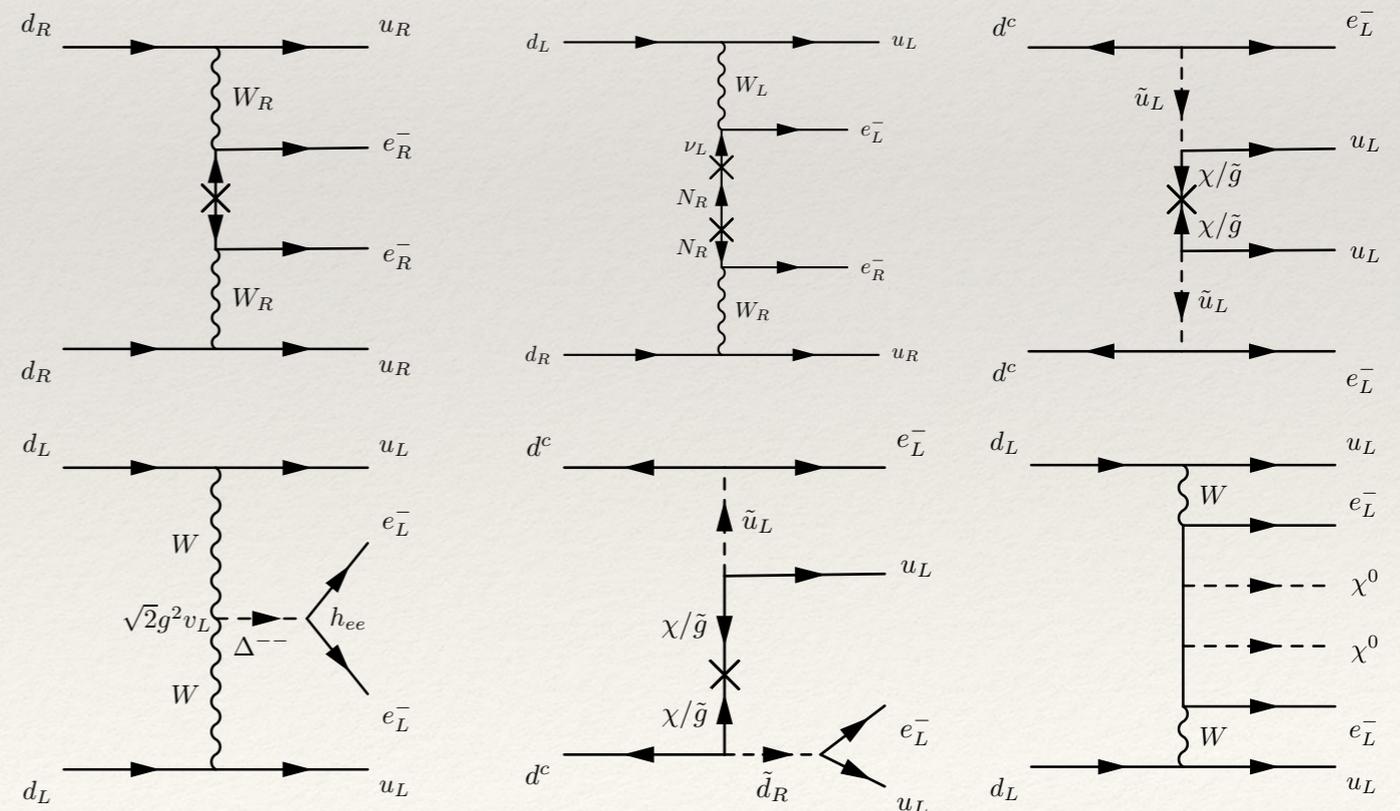
Double Beta Decay is $\Delta L = 2$, not neutrino mass!

Interpretations:

Standard:



Non-Standard:

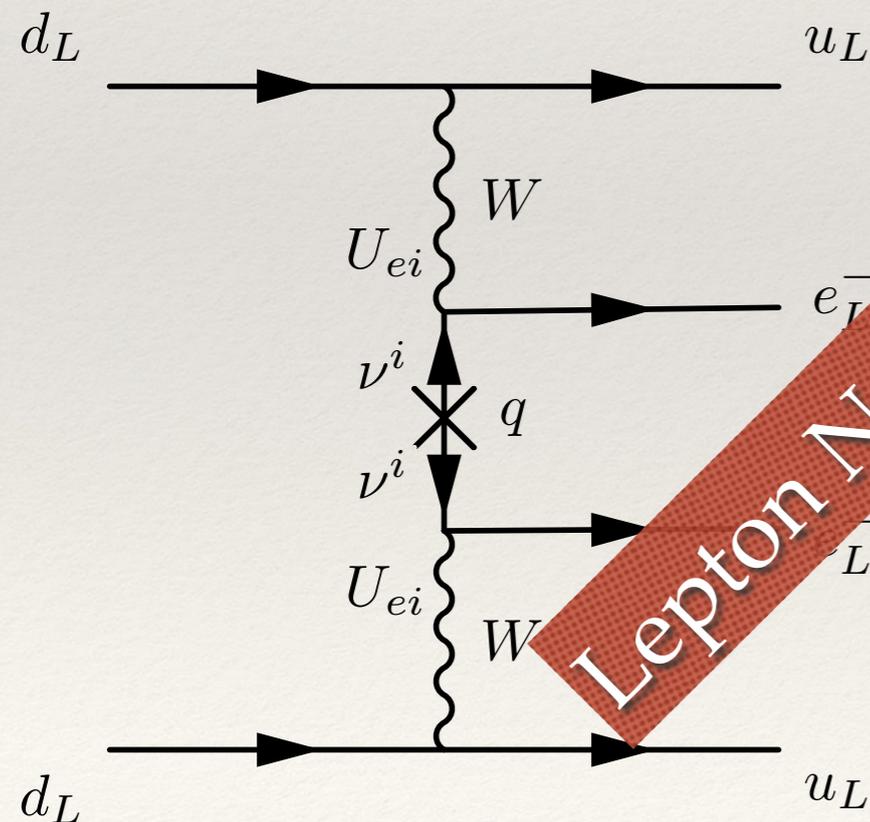


New Physics in Double Beta Decay

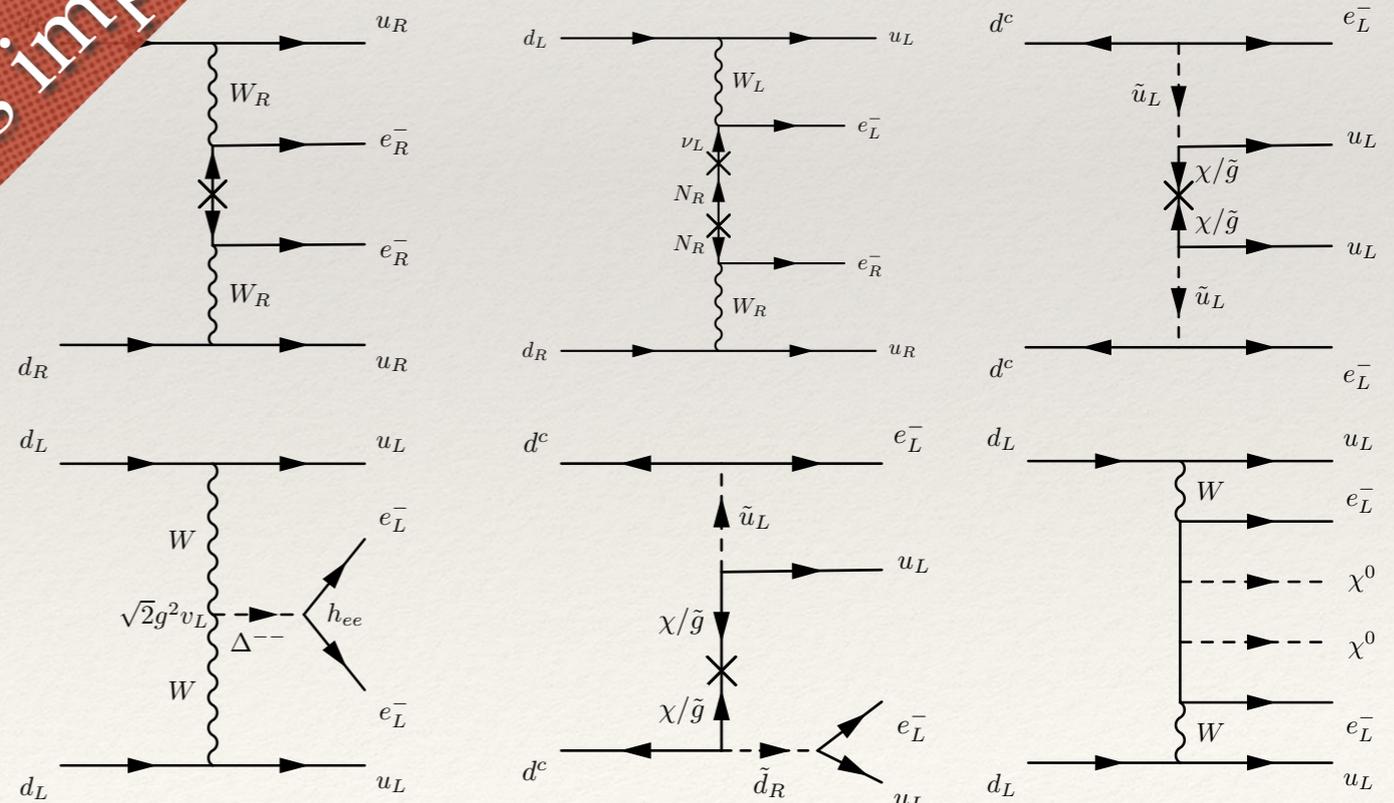
Double Beta Decay is $\Delta L = 2$, not $\Delta B = 2$ or neutrino mass!

Interpretations:

Standard:



Non-Standard:



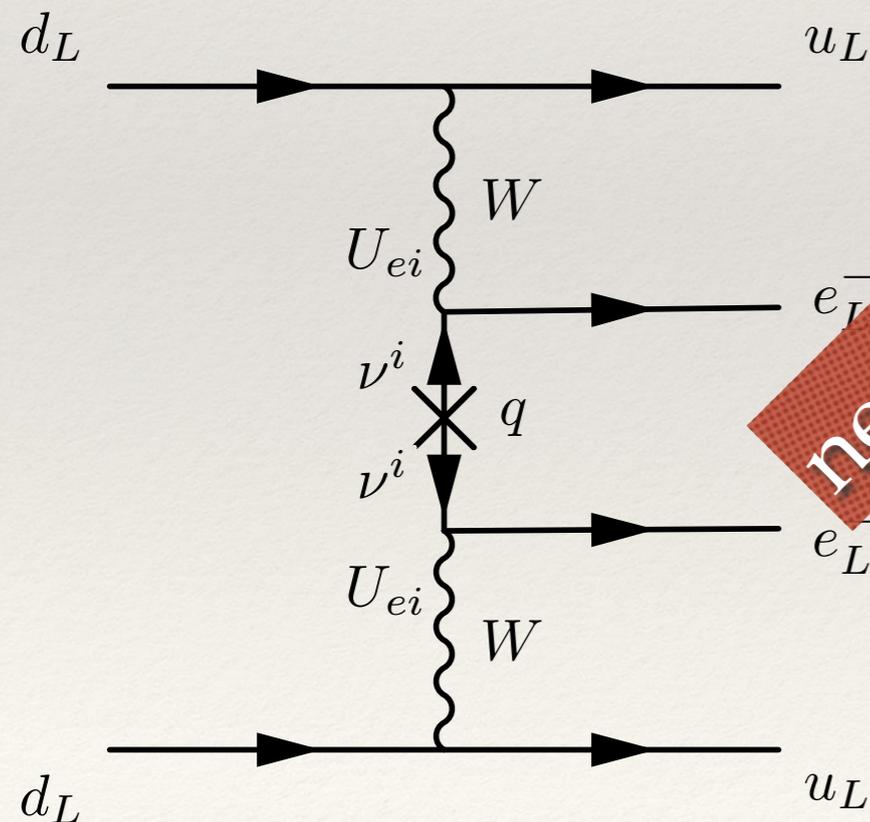
Lepton Number as important as Baryon Number

New Physics in Double Beta Decay

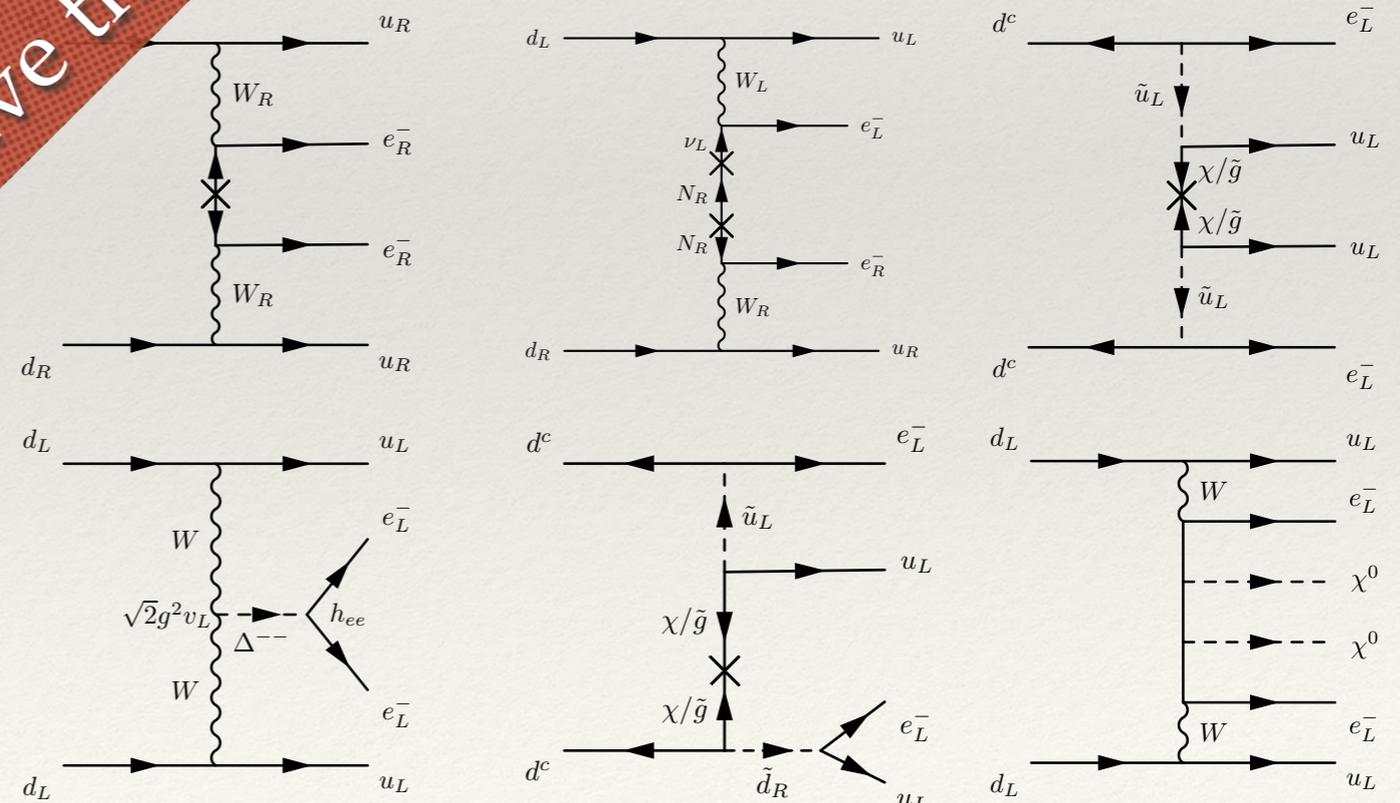
Double Beta Decay is $\Delta L = 2$, not $\Delta L = 1$ due to neutrino mass!

Interpretations:

Standard:

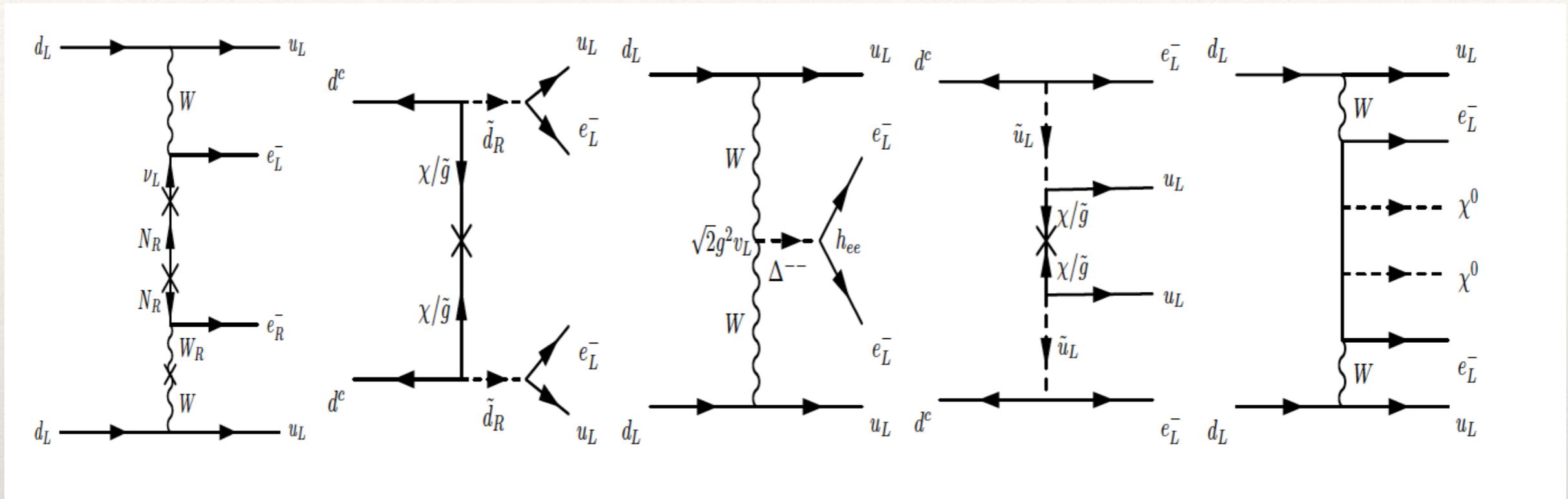


Non-Standard:



need to solve the inverse problem!

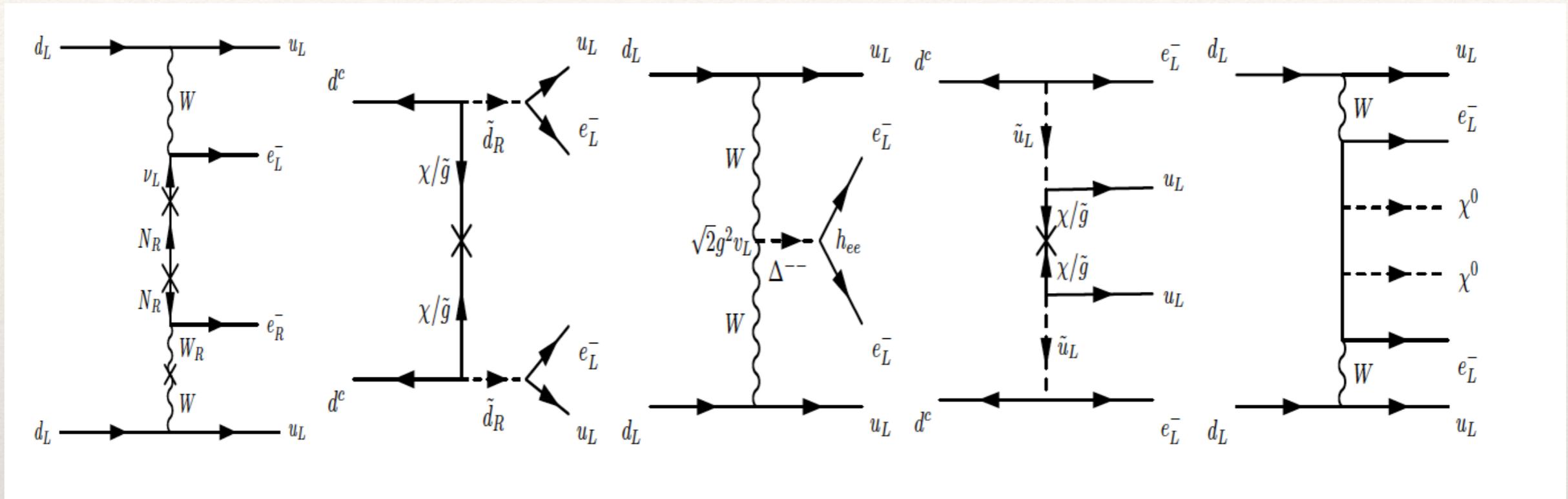
Non-Standard Interpretations



- ❖ decouples double beta decay from cosmology and KATRIN

$$\mathcal{A}_{\text{Standard}} = G_F^2 \frac{\langle m \rangle}{q^2} \quad \text{versus} \quad \mathcal{A}_{\text{Non-Standard}} = \frac{c}{M_X^5}$$

Non-Standard Interpretations

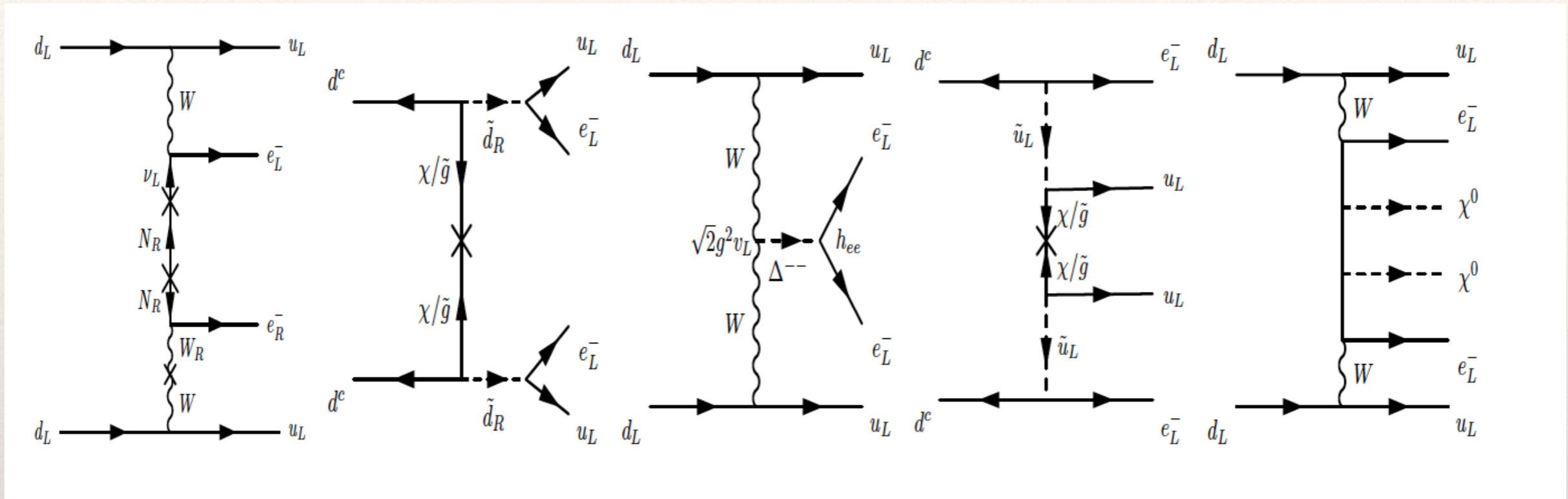


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Therefore:
 $T(\text{eV}) = T(\text{TeV})$

Non-Standard Interpretations



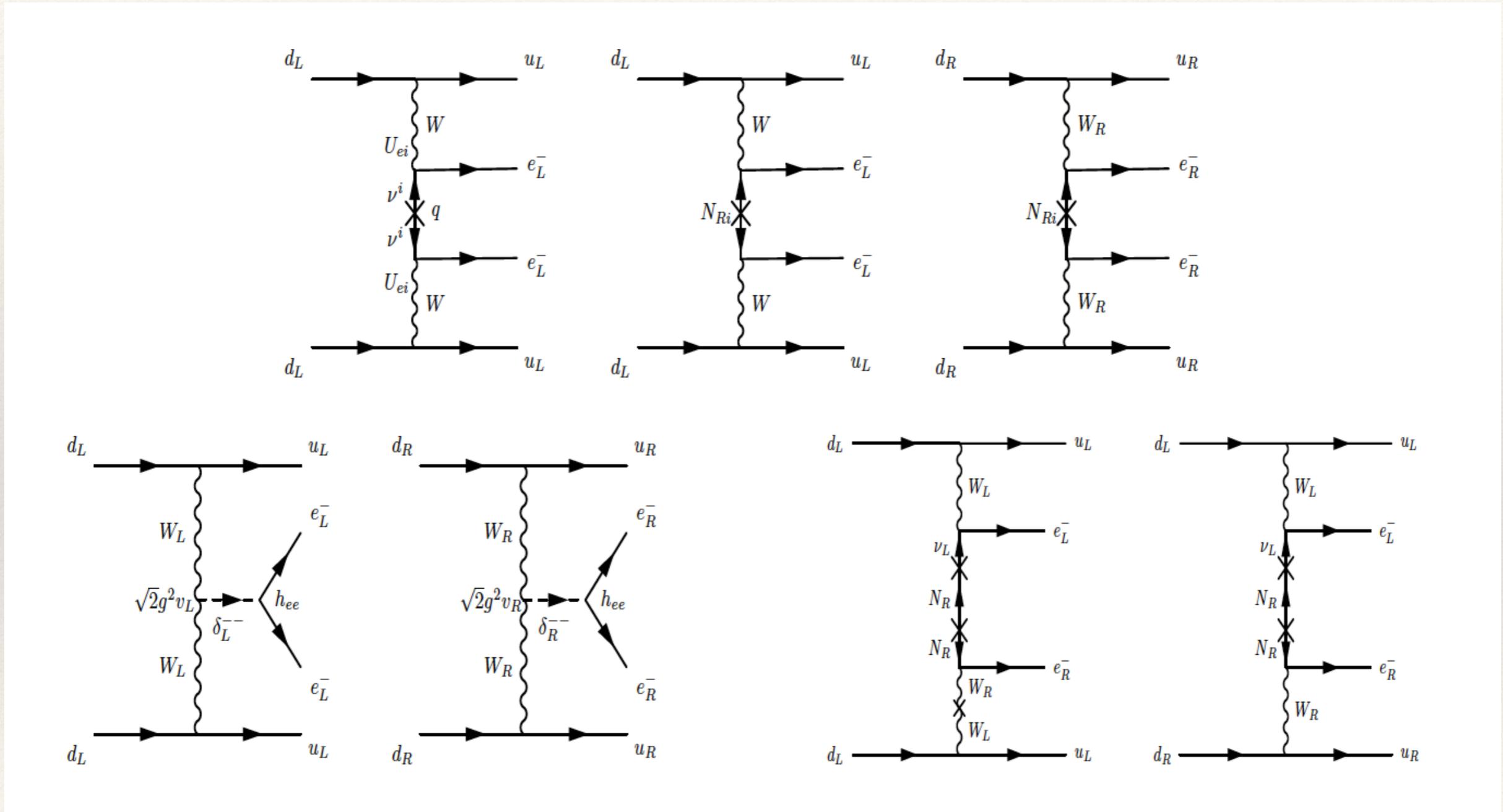
- ❖ decouples double beta decay from cosmology and KATRIN

$$\mathcal{A}_{\text{Standard}} = G_F^2 \frac{\langle m \rangle}{q^2} \quad \text{versus} \quad \mathcal{A}_{\text{Non-Standard}} = \frac{c}{M_X^5}$$

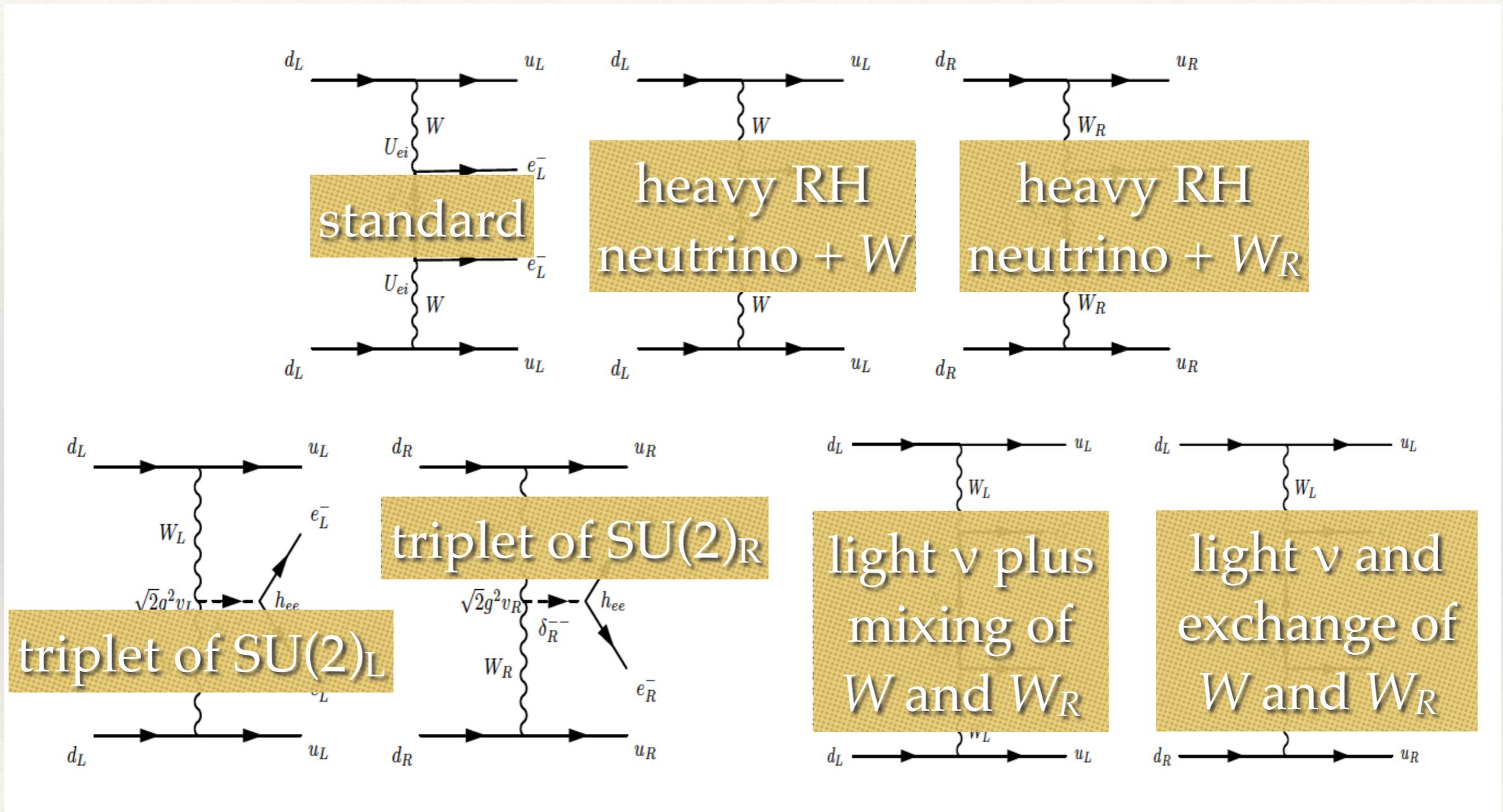
Therefore:
 $T(\text{eV}) = T(\text{TeV})$

⇒ Tests with LHC, LFV, etc.

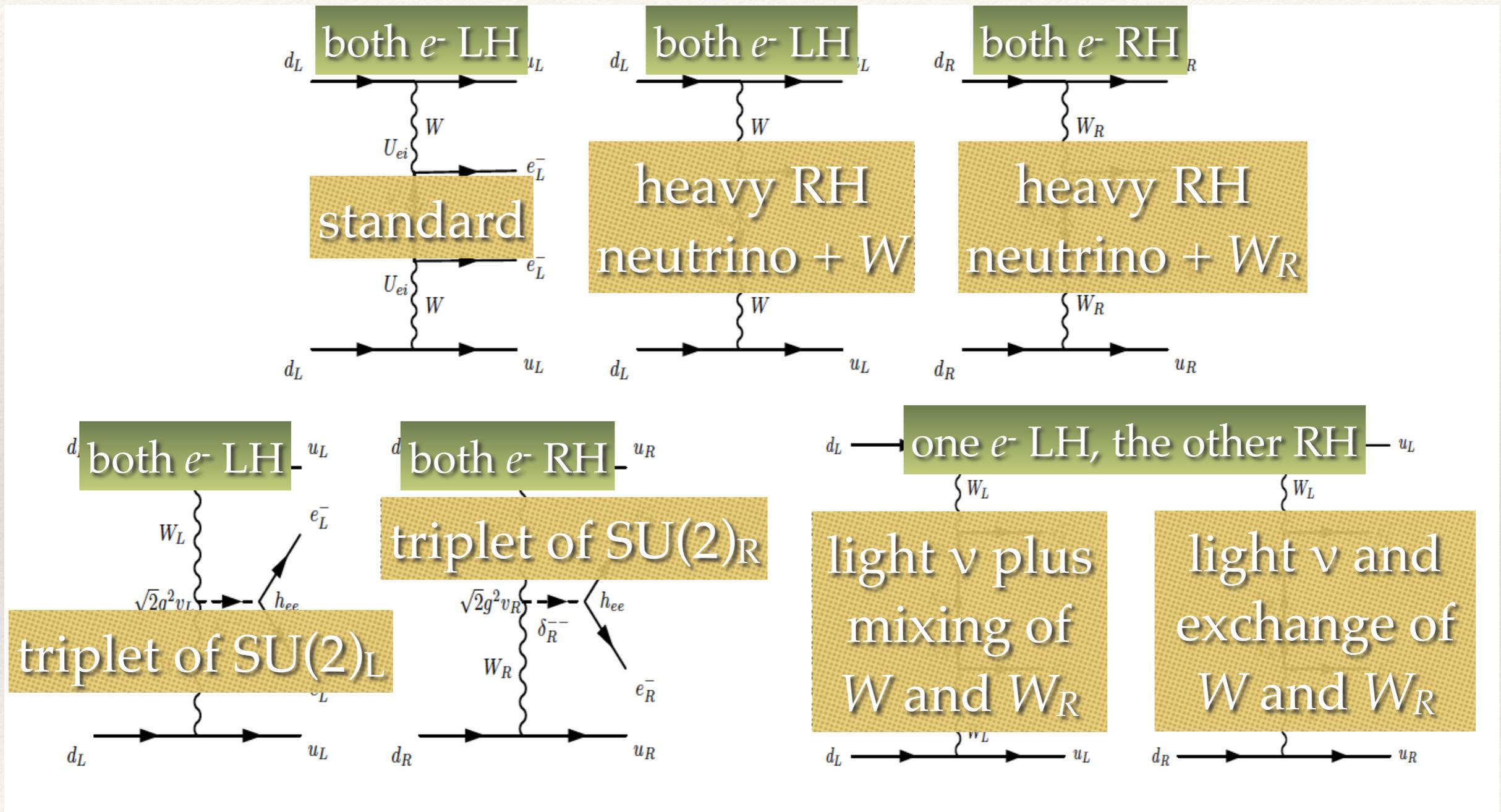
Double Beta Decay and LR-Symmetry



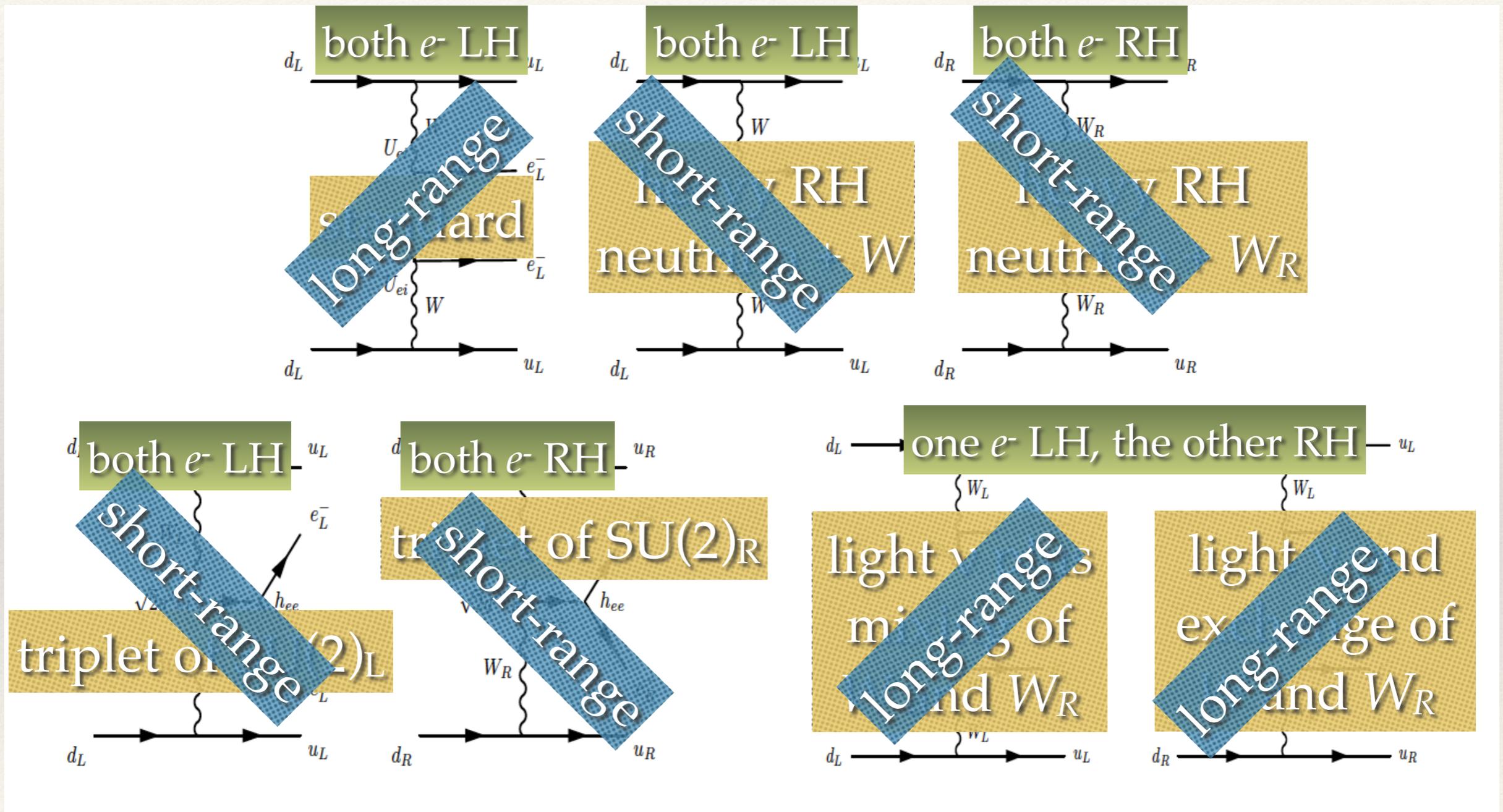
Double Beta Decay and LR-Symmetry



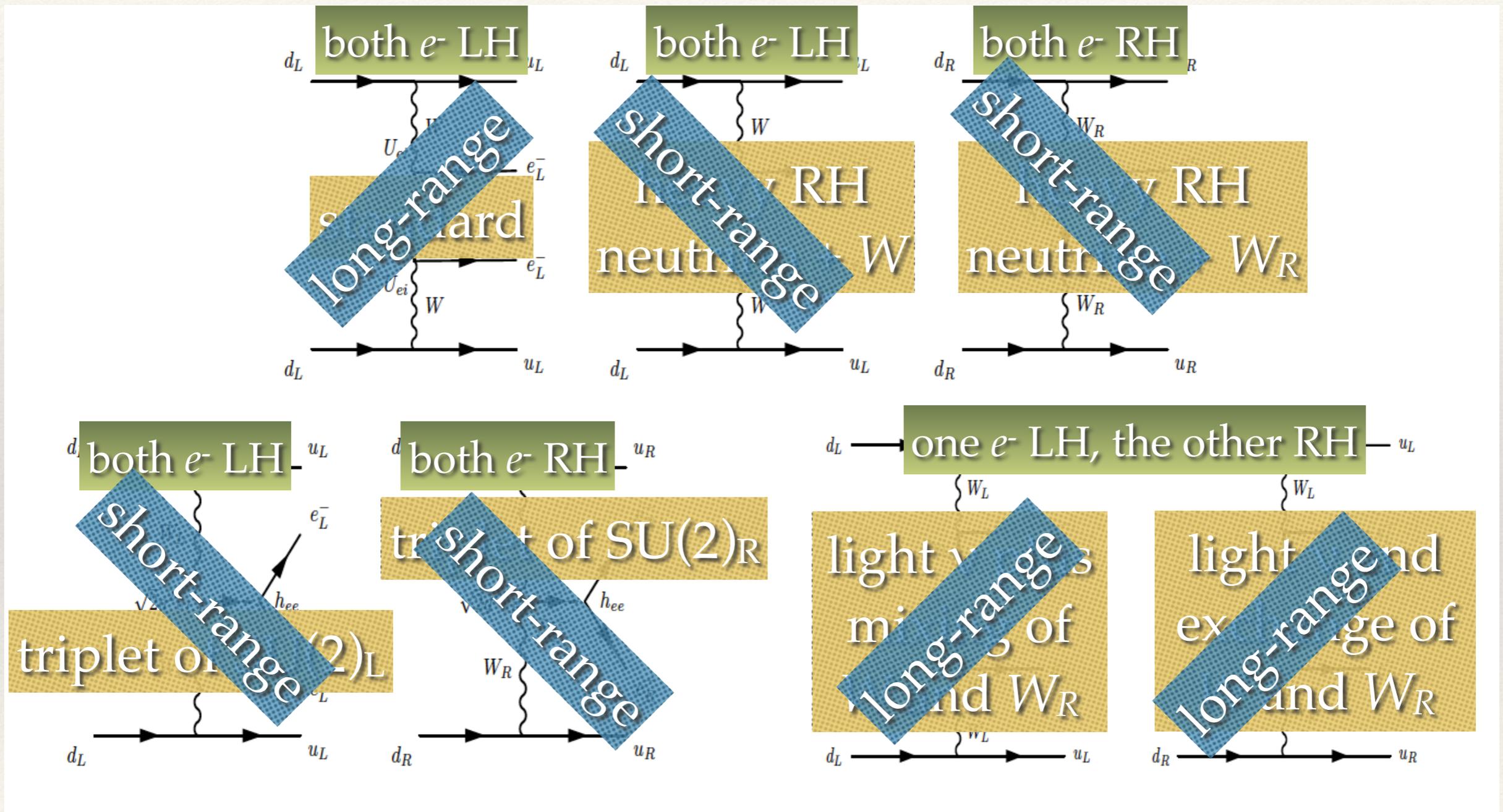
Double Beta Decay and LR-Symmetry



Double Beta Decay and LR-Symmetry



Double Beta Decay and LR-Symmetry

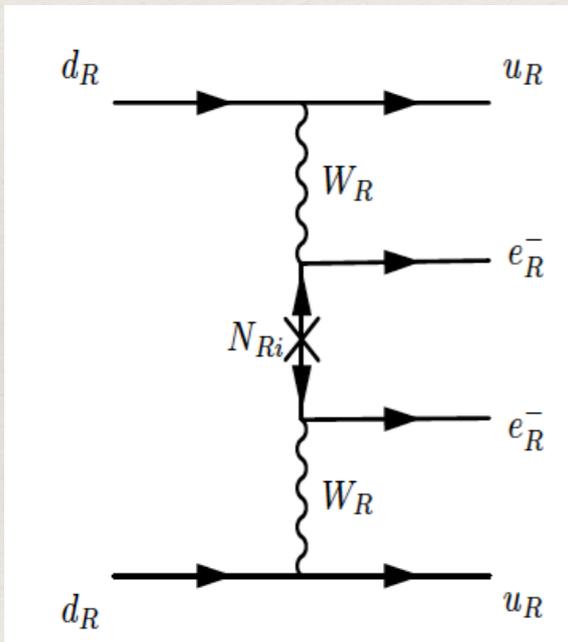


simultaneous presence / interference / ...

Double Beta Decay and LR-Symmetry

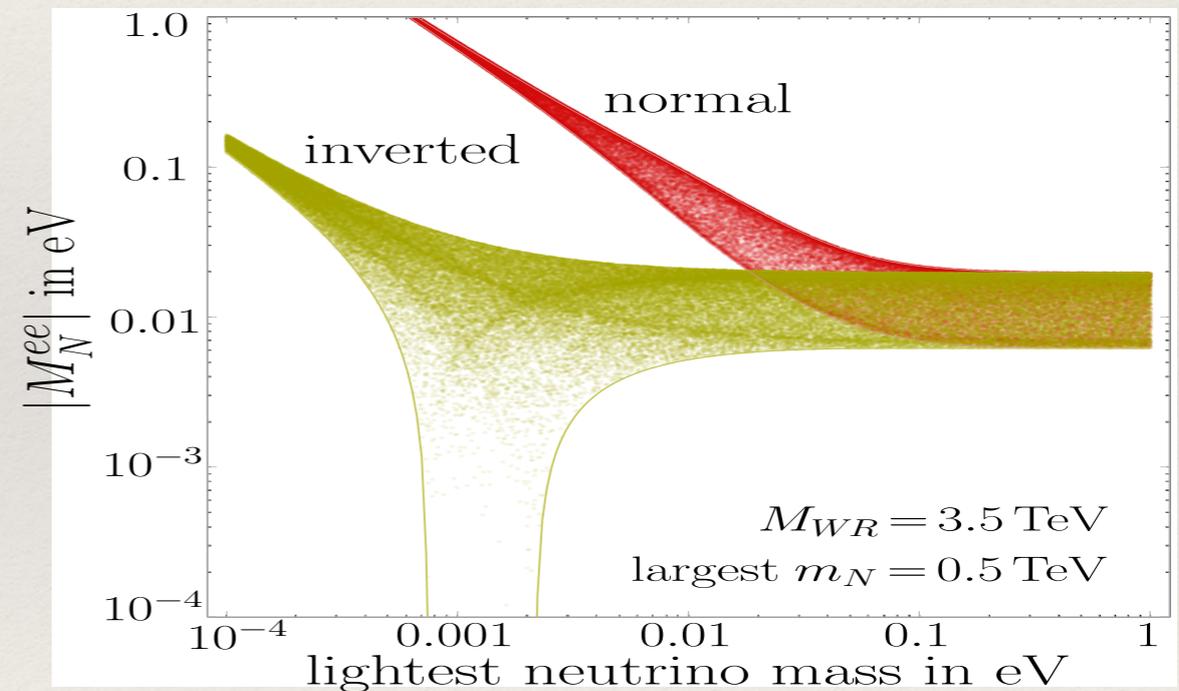
Type II dominance: $m_\nu = m_L - M_D^2/M_R \rightarrow m_L$ with $m_L \propto M_R$

\Rightarrow right-handed neutrinos diagonalized by PMNS matrix!



$$\mathcal{A} \propto \frac{V_{ei}^2}{M_i} \propto \frac{U_{ei}^2}{m_i}$$

amplitude determined by PMNS, but $\propto 1/m_\nu$

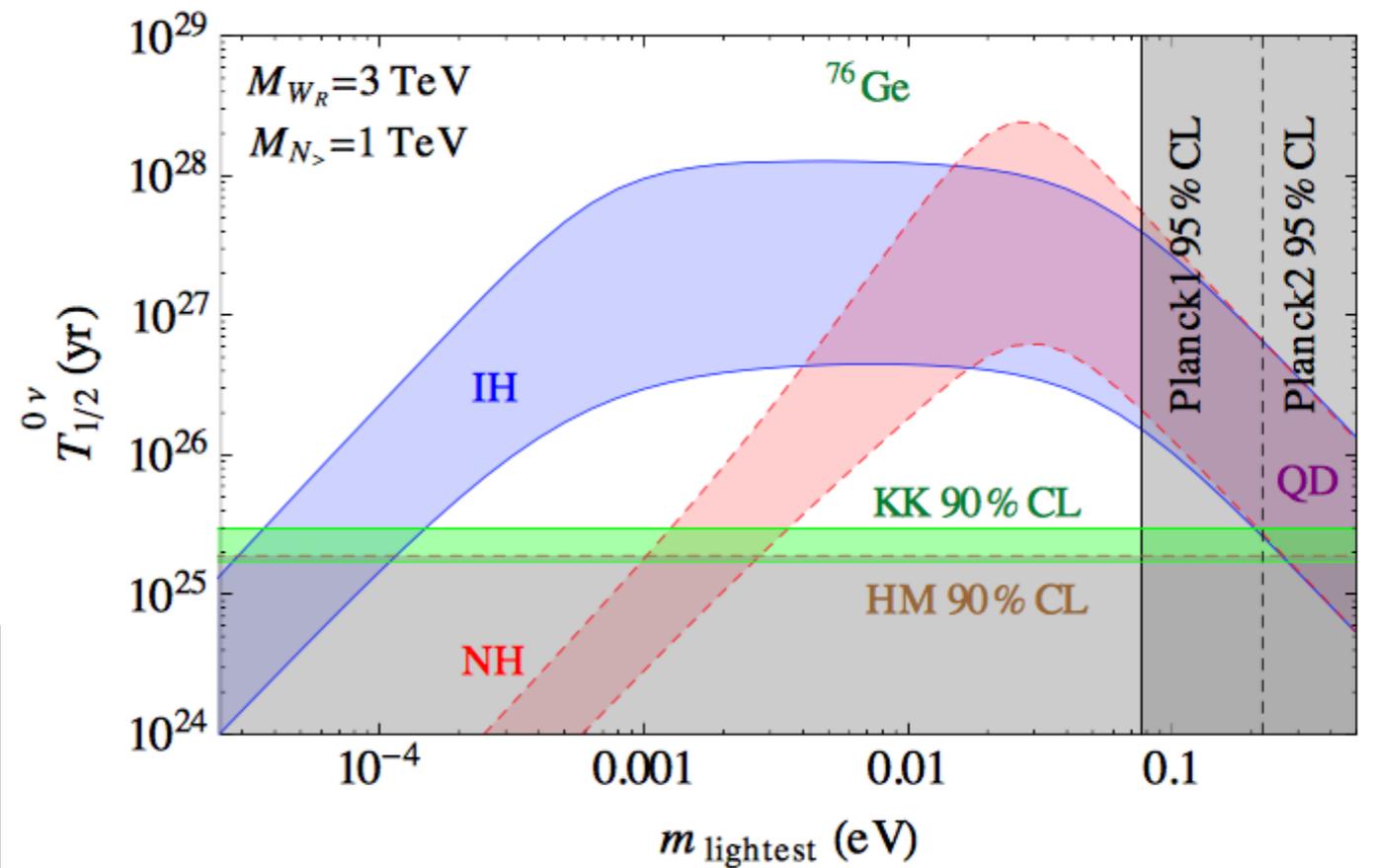


again, NH/IH turned around...

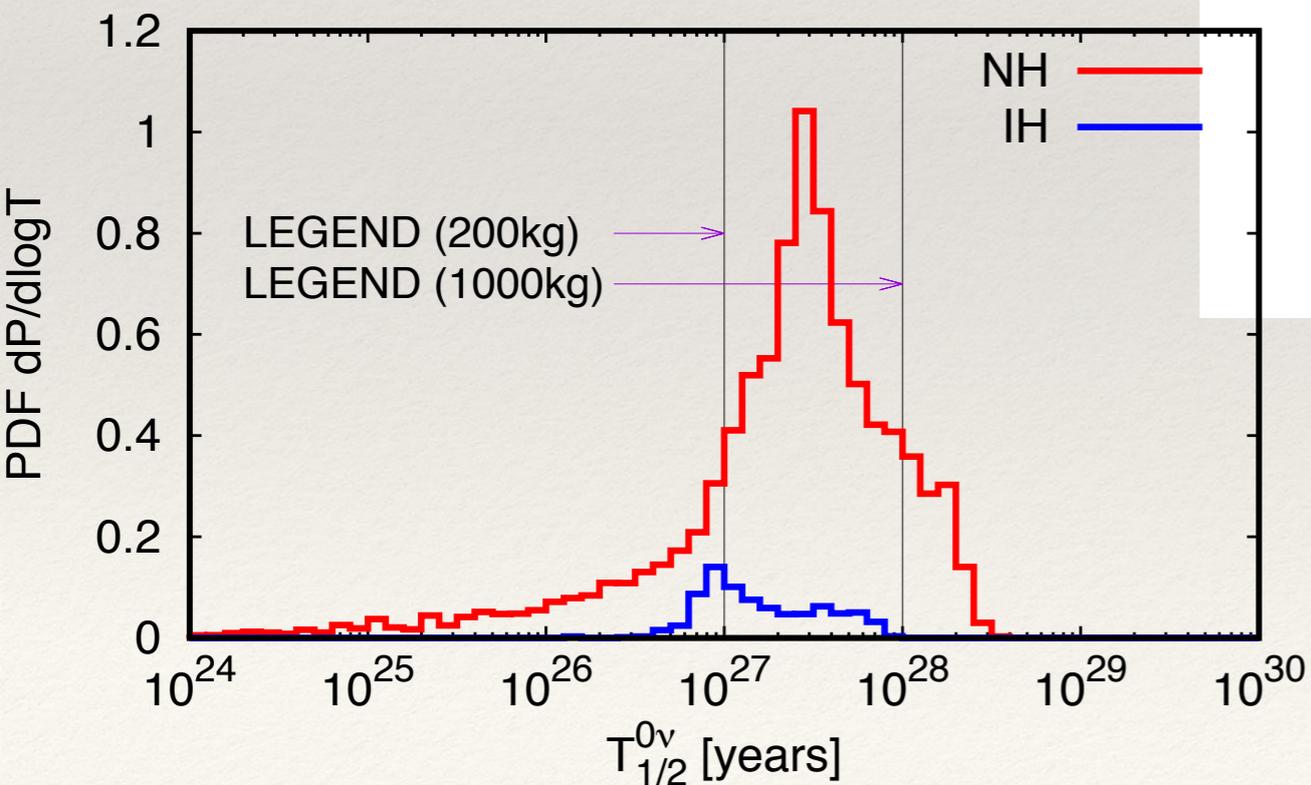
Senjanovic et al., 1011.3522

Double Beta Decay and LR-Symmetry

- ❖ add Standard and LR-diagram
- ❖ $T_{St} \propto 1/m_\nu^2$ and $T_{LR} \propto m_\nu^2$
- ❖ gives lower limit on m_ν



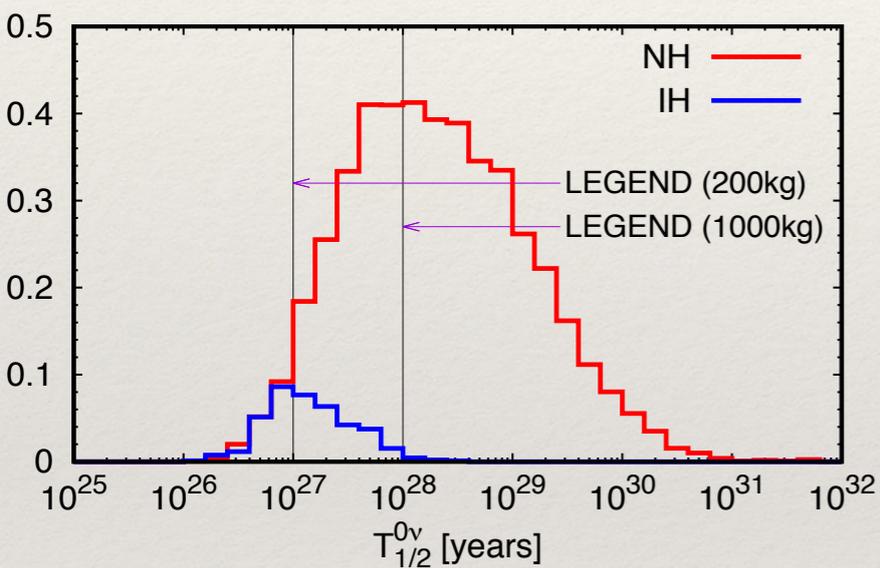
Predicted Half-Lifetime for ^{76}Ge [LRSM-typeII]



Expectations for half-lives

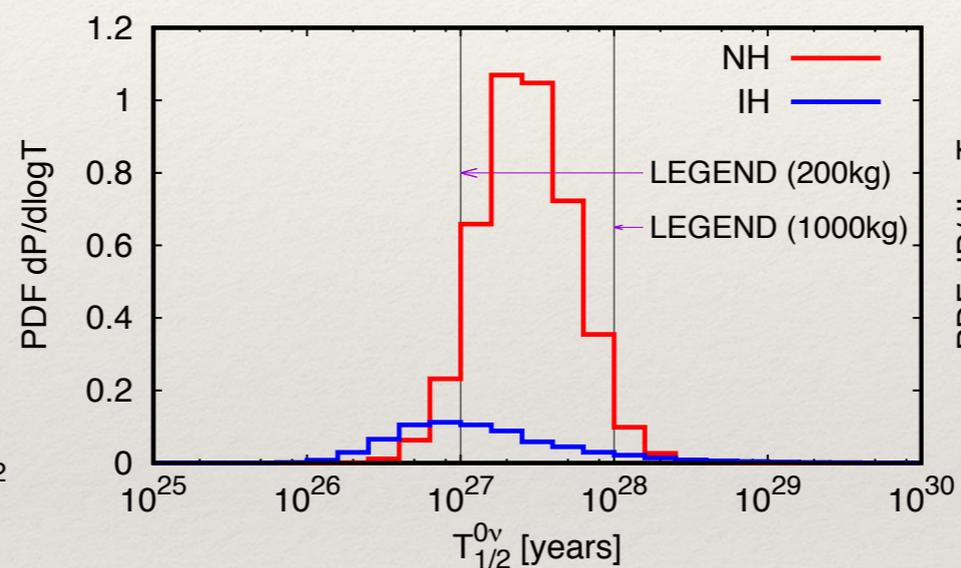
Standard

Predicted Half-Lifetime for ^{76}Ge



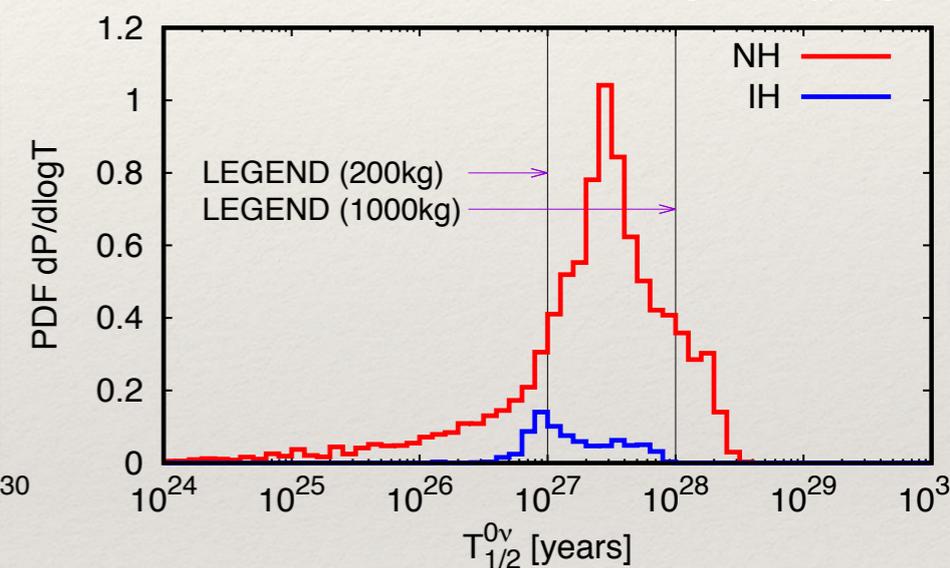
Sterile

Predicted Half-Lifetime for ^{76}Ge



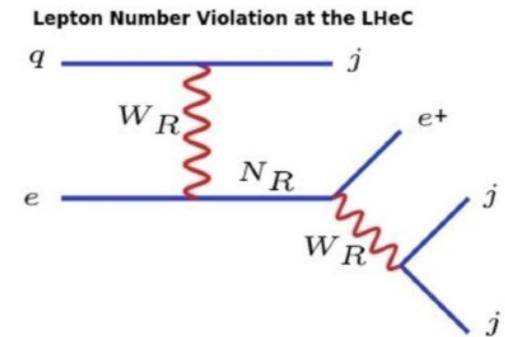
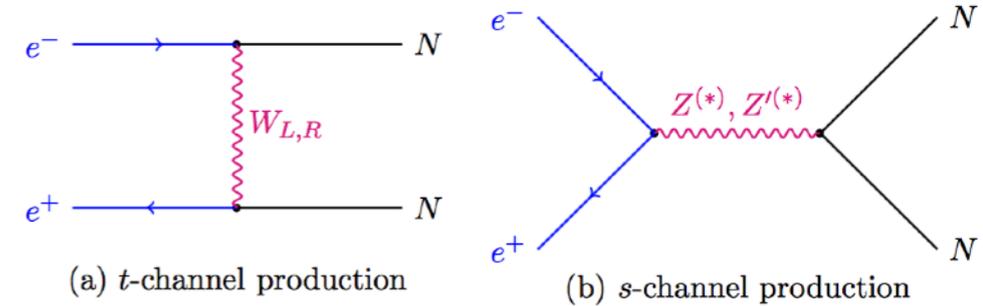
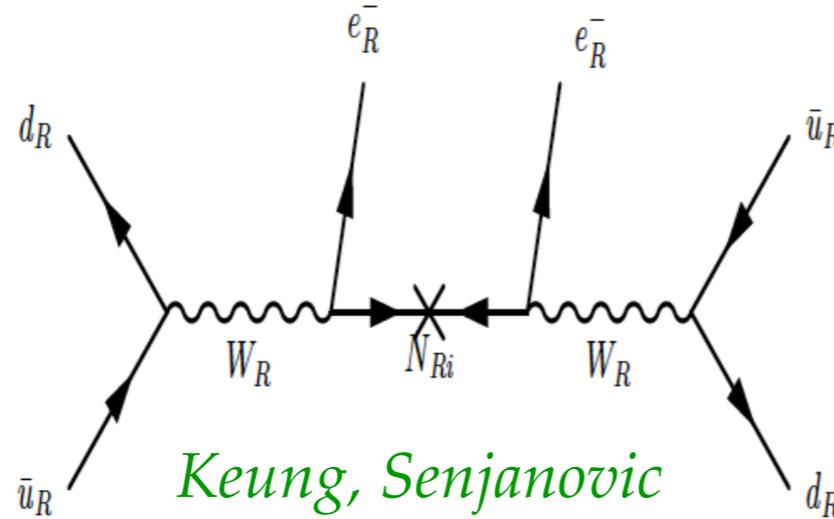
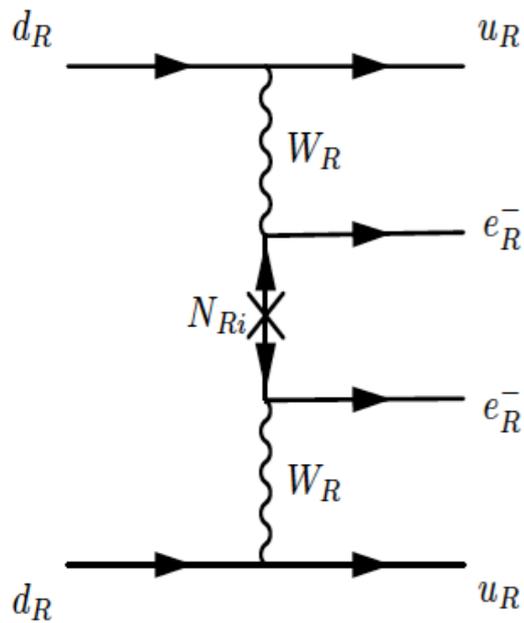
Left-right

Predicted Half-Lifetime for ^{76}Ge [LRSM-typeII]

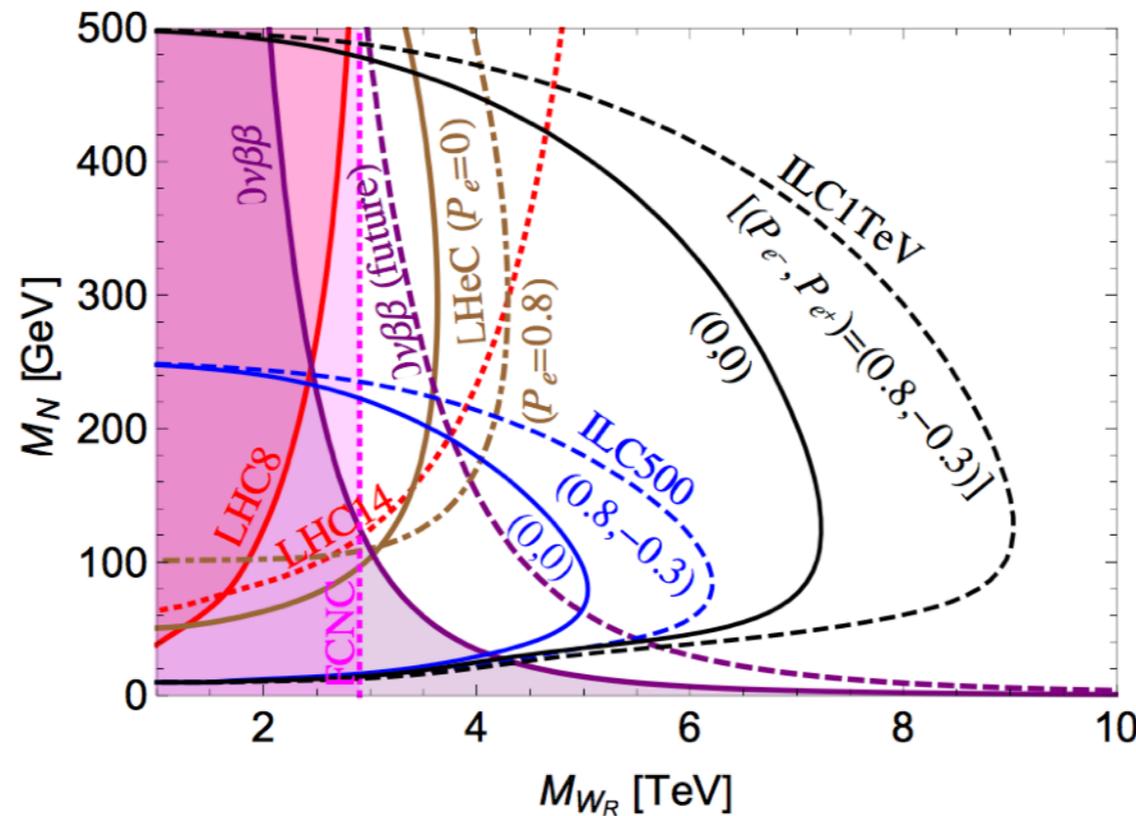


Ge, WR, Zuber, 1707.07904

LHC and Double Beta Decay



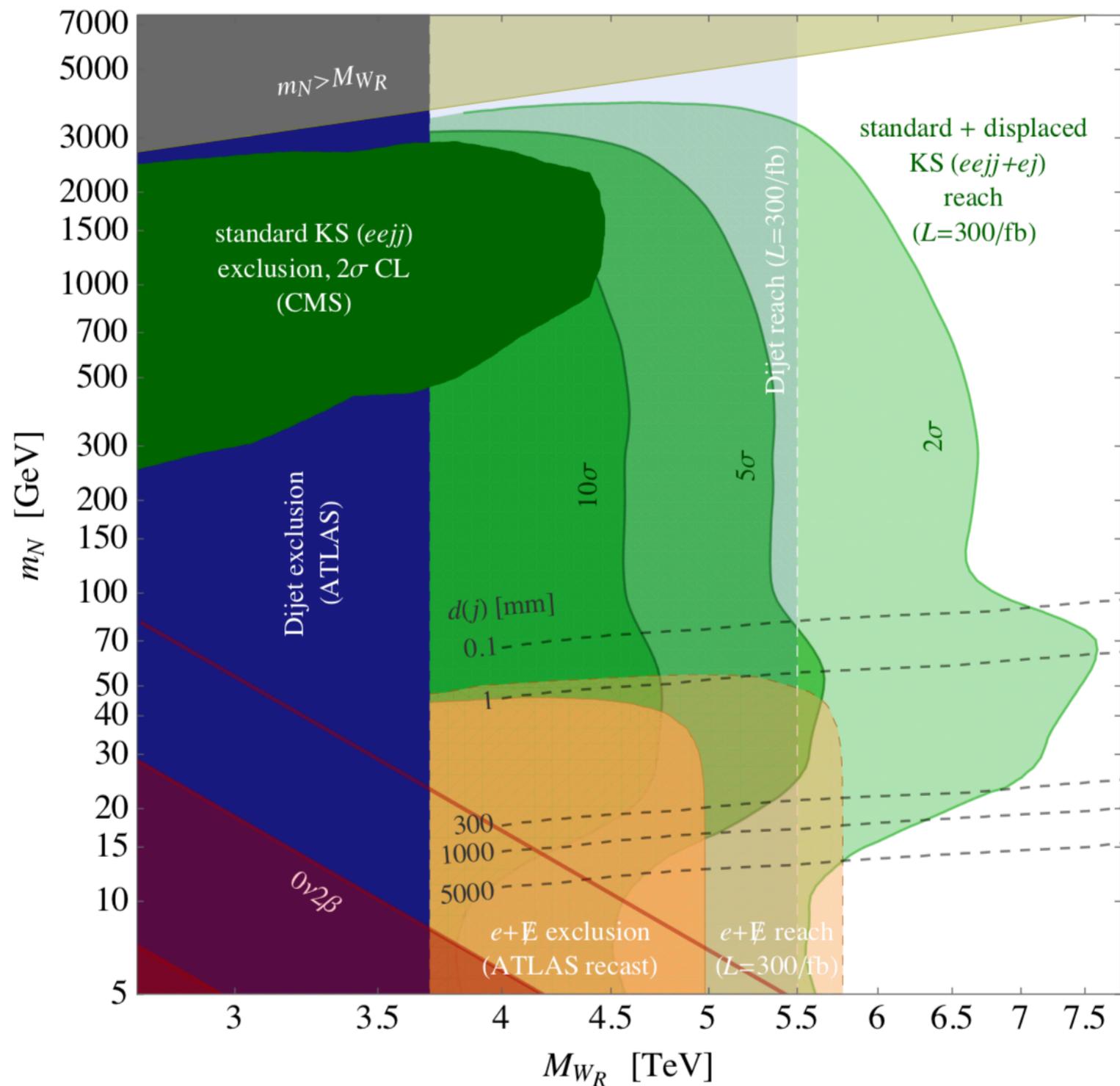
Biwal, Dev, 1701.08751



polarization at
LHeC and ILC

LHC and Double Beta Decay

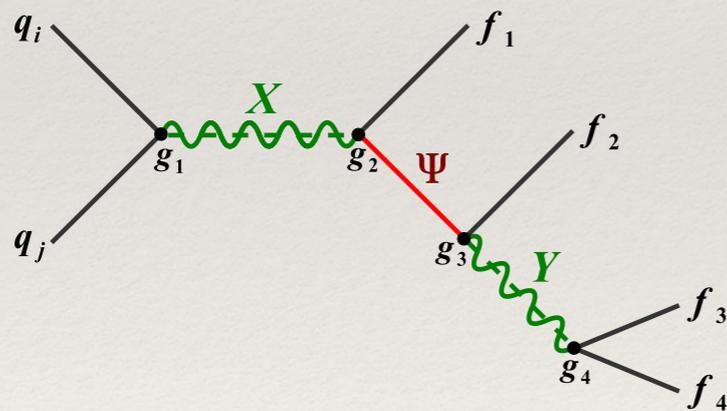
Nemevsek, Nesti, Popara, 1801.05813



low mass N with displaced vertices or vertices outside detector

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:

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

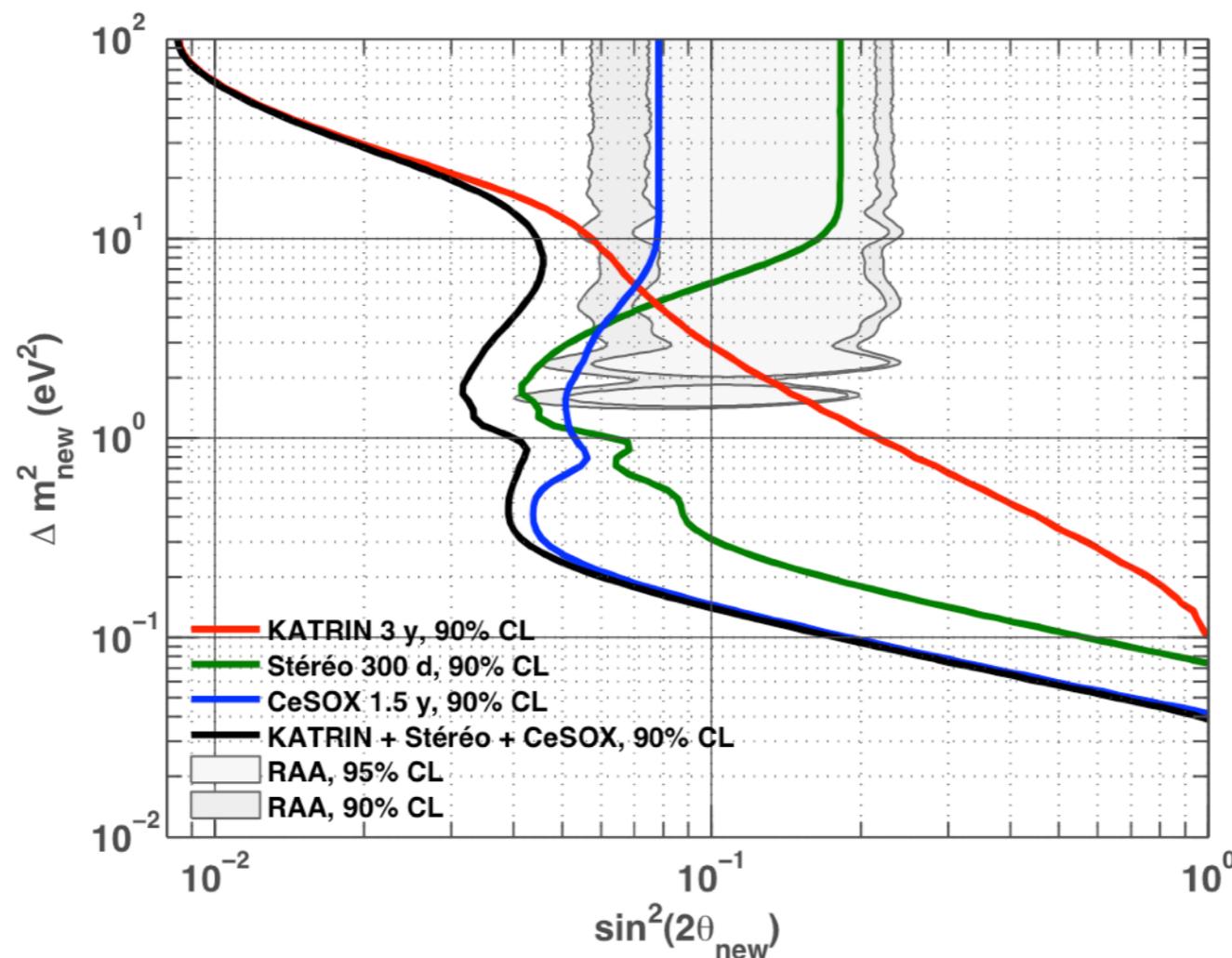
would need electroweak, resonant, ARS, post-sphaleron baryogenesis

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
- ❖ 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 with m_ν Experiments

eV-scale neutrinos and KATRIN

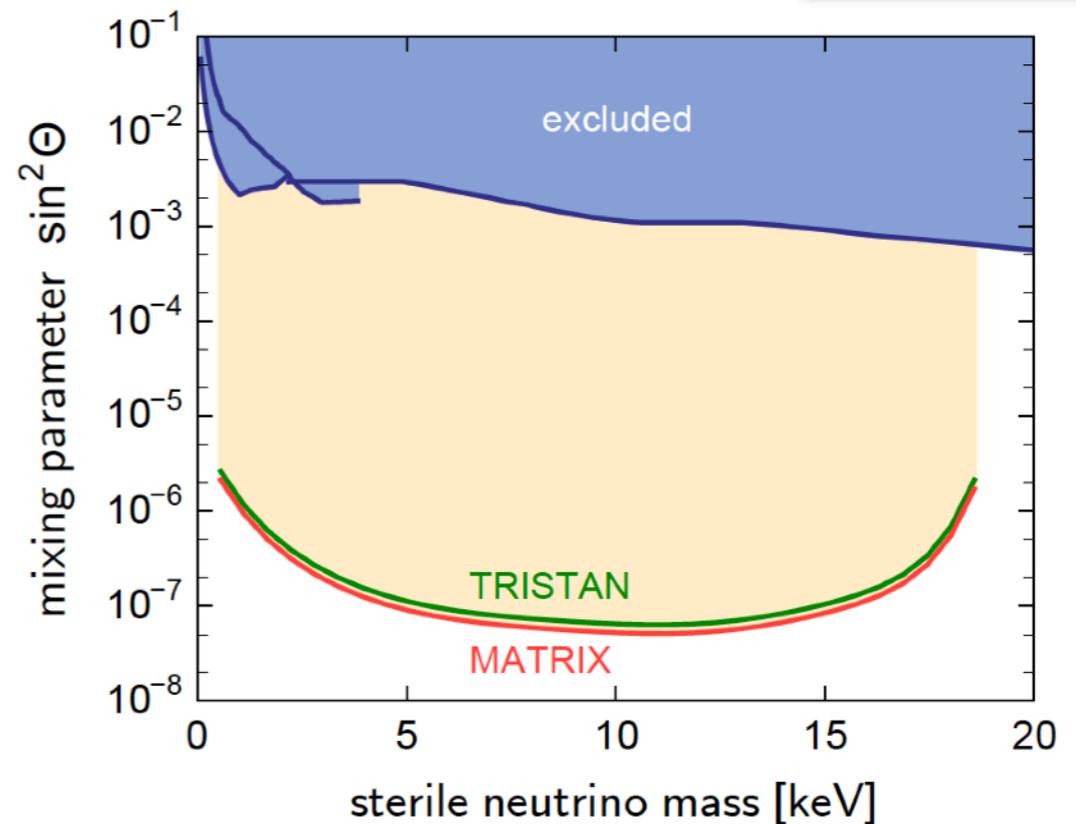
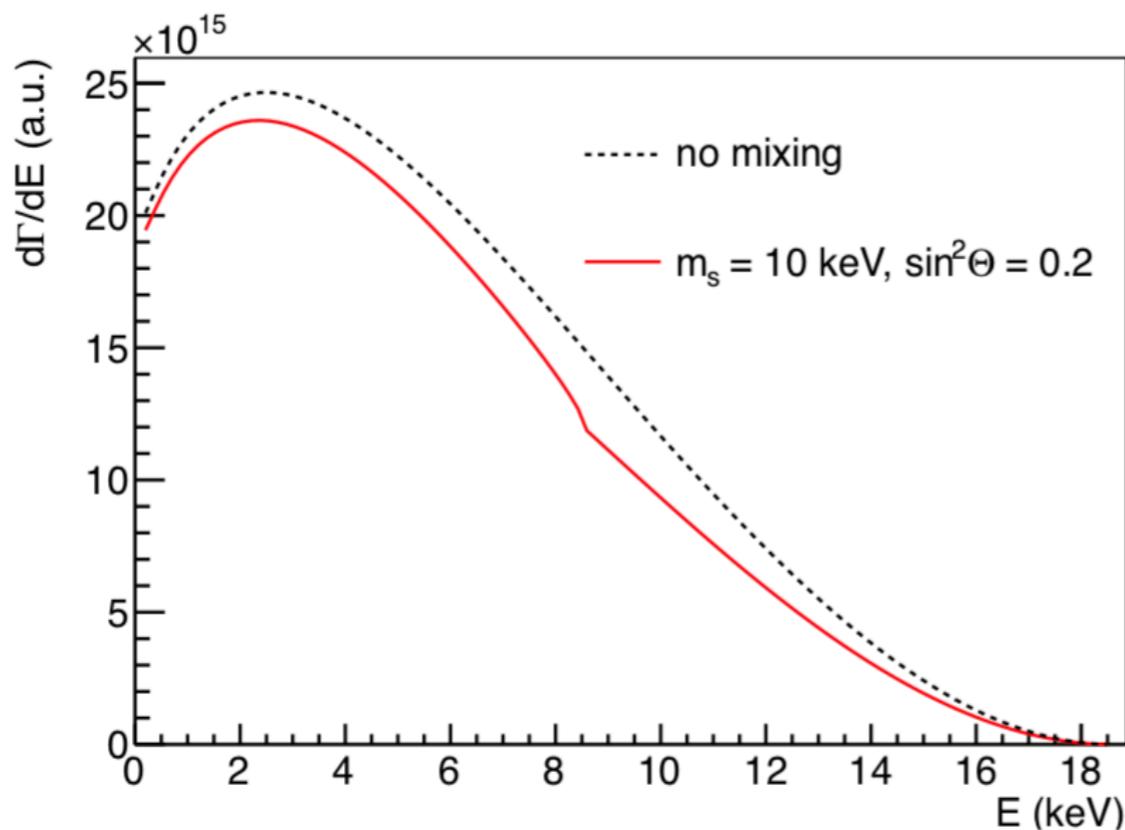


Lasserre

New Physics with m_ν Experiments

keV-scale neutrinos and modified KATRIN

❖ $0\nu\beta\beta$ decay of ^{136}Xe is the most fundamental discovery in the field!



e.g. Mertens et al., 1409.0920

measured (TeV-scale physics!)

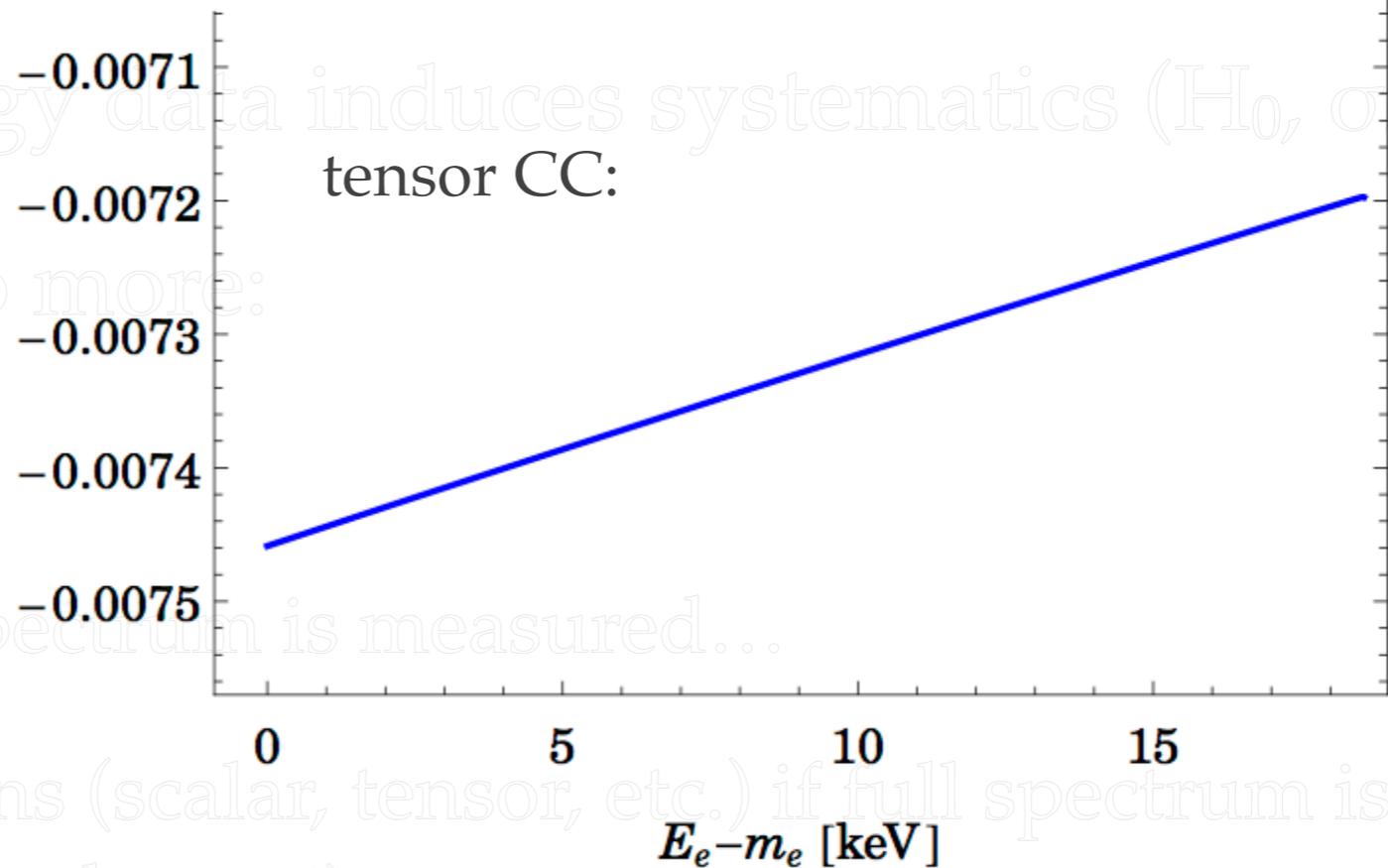
New Physics with m_ν Experiments

exotic charged currents and modified KATRIN

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

exotic charged currents

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



Ludl, WR, 1603.08690

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

Summary

- ❖ More models than one can distinguish with oscillation data...
 - δ close to $3\pi/2$ and/or θ_{23} very close to $\pi/4$ would be huge: something protects these special values, in particular for IH and QD
 - \Rightarrow can at least distinguish main classes of models
 - \Rightarrow should focus also on New Physics in experiments, often complementarily to LHC
- ❖ Neutrino mass and ordering important for many reasons
- ❖ $0\nu\beta\beta$ well motivated for NP, almost no model is secondary
- ❖ KATRIN also sensitive to interesting new physics
- ❖ can do interesting physics with large and small scale experiments

NEUTRINO 2018

XXVIII INTERNATIONAL CONFERENCE ON NEUTRINO PHYSICS AND ASTROPHYSICS

4-9 June
Heidelberg

TOPICS

Neutrino Oscillations and Mass Measurements
Accelerator Neutrinos
Reactor Neutrinos
Solar Neutrinos
Atmospheric Neutrinos
Neutrinoless Double Beta Decay
Leptonic CP-violation
Coherent Scattering
Neutrino Interactions
Sterile Neutrinos
Connections to Dark Matter and BSM Physics
Theory of Masses and Mixings
Astrophysical Neutrinos
Neutrino Cosmology
Supernova Neutrinos
Geoneutrinos
Future Projects

International Advisory Committee

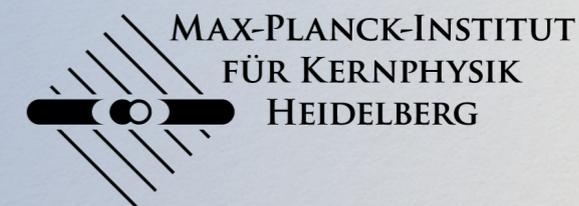
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P. Coyle (Marseille)	Y. Kuno (Osaka)	Y. Wang (IHEP)
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A.D. Dolgov (Novosibirsk)	M.C. Sanchez (ISU)	Y.Y.Y. Wong (UNSW)
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Scan to discover!



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