Neutrino Theory

Heisenberg-Programm
DFG Deutsche Forschungsgemeinschaft

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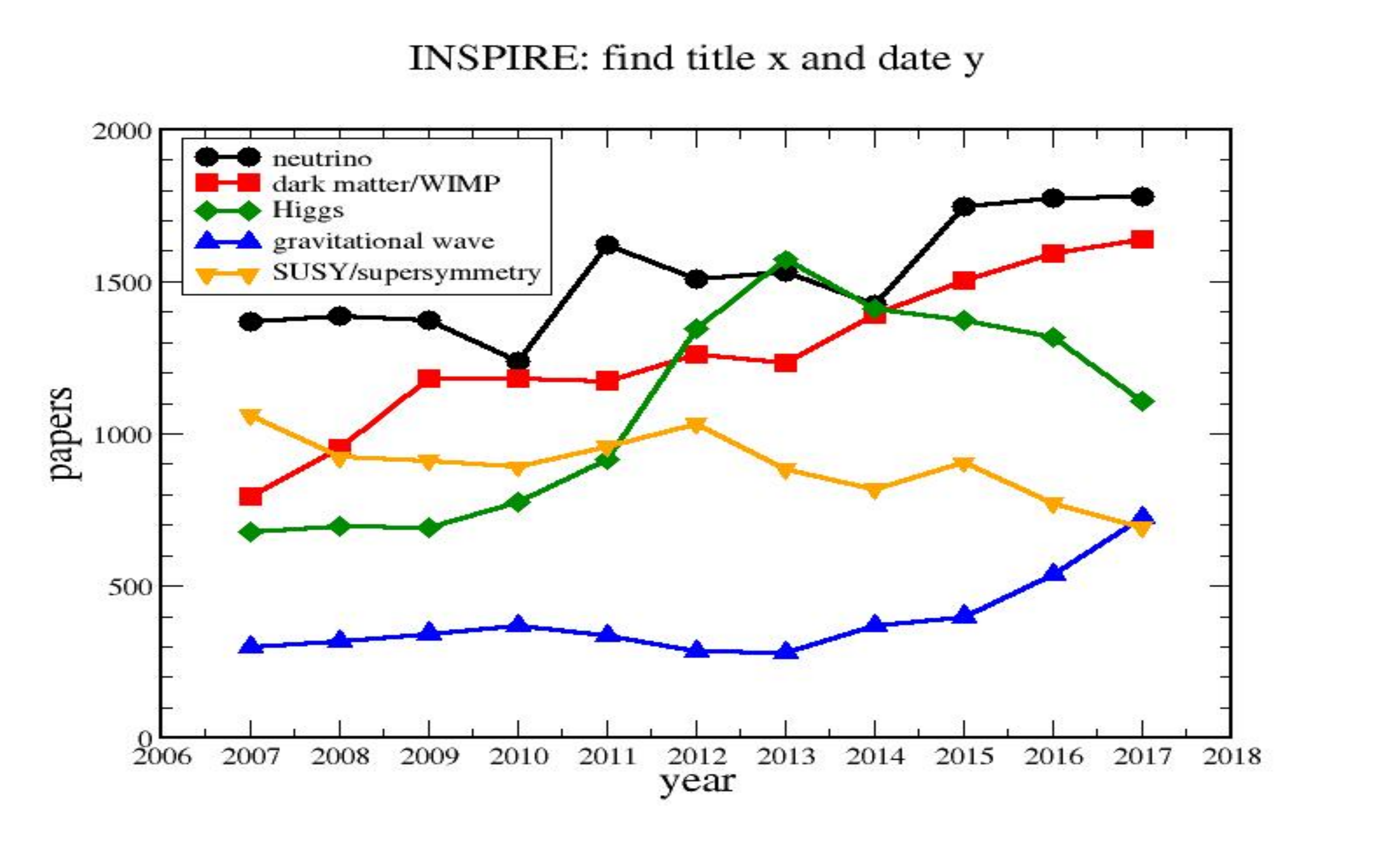
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Outline

- Neutrino mixing:
  - what have we learned?
  - what remains to be done?
  - what's its origin?
  - new physics prospects
- Neutrino mass:
  - what have we learned?
  - what remains to be done?
  - what's its origin?
  - new physics prospects

Neutrinos still a hot topic



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 lepton flavor
  - **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**
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3 Majorana neutrino paradigm ⇒ needs to be tested!

Low Energy Paradigm

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Plus: mechanisms to generate m_ν have new particles, new energy scales, new concepts, new…

Spe…		
Qua…		
Lept…		
Cha…		
Higgs	2	18
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…		…2
…		…5
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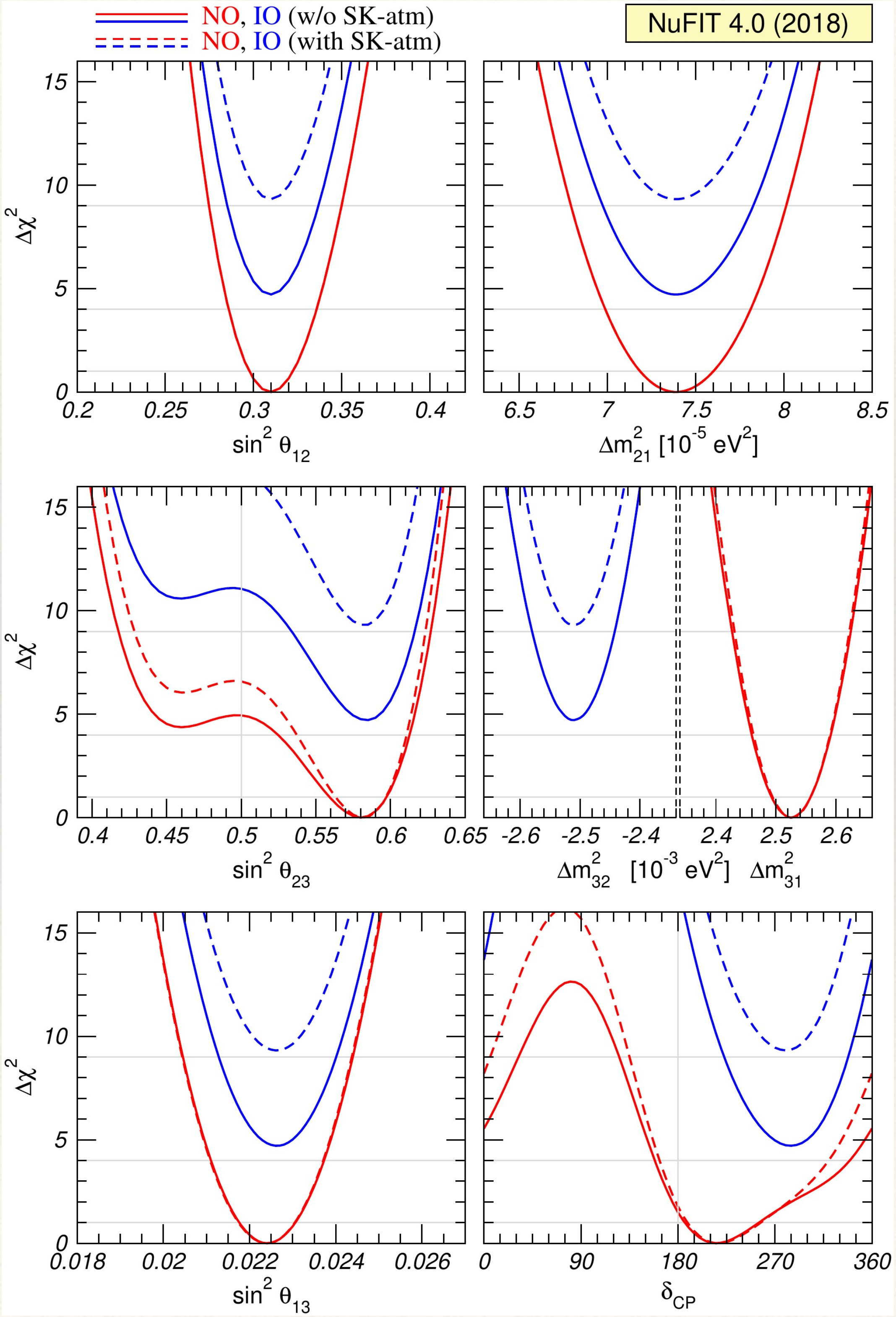
3 Majorana neutrino paradigm ⇒ needs to be tested!

Low Energy Paradigm

- 3 Tasks:
  - determine new parameters *(talk by Seo)*
  - interpret/explain values of new parameters
  - 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:
  - sgn(Δm^2_{31})
  - δ, α, β



consistent fit results by *Valencia, Bari* *NuFIT*

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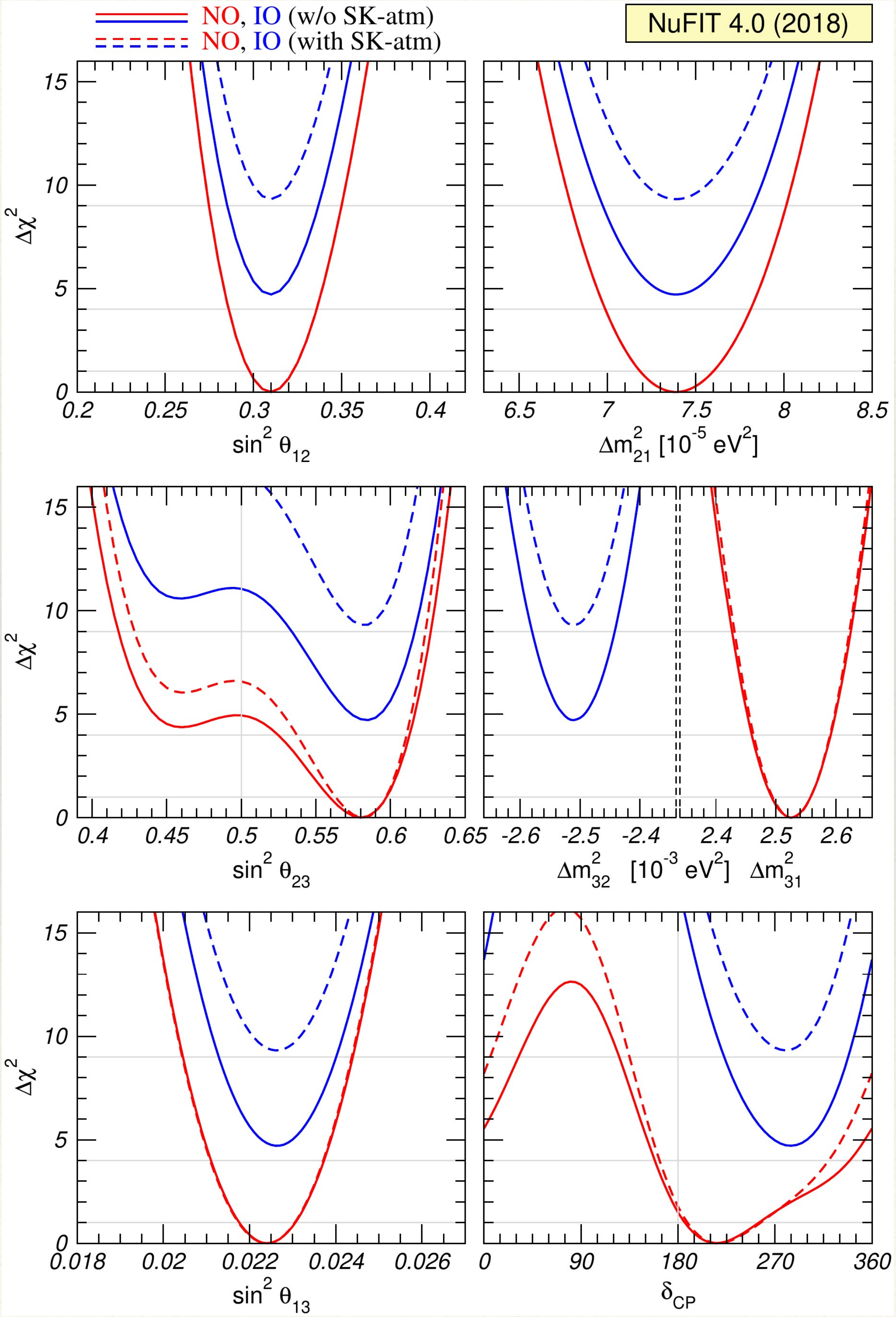

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Complexity increases, experimental collaborations become crucial for realistic fits…

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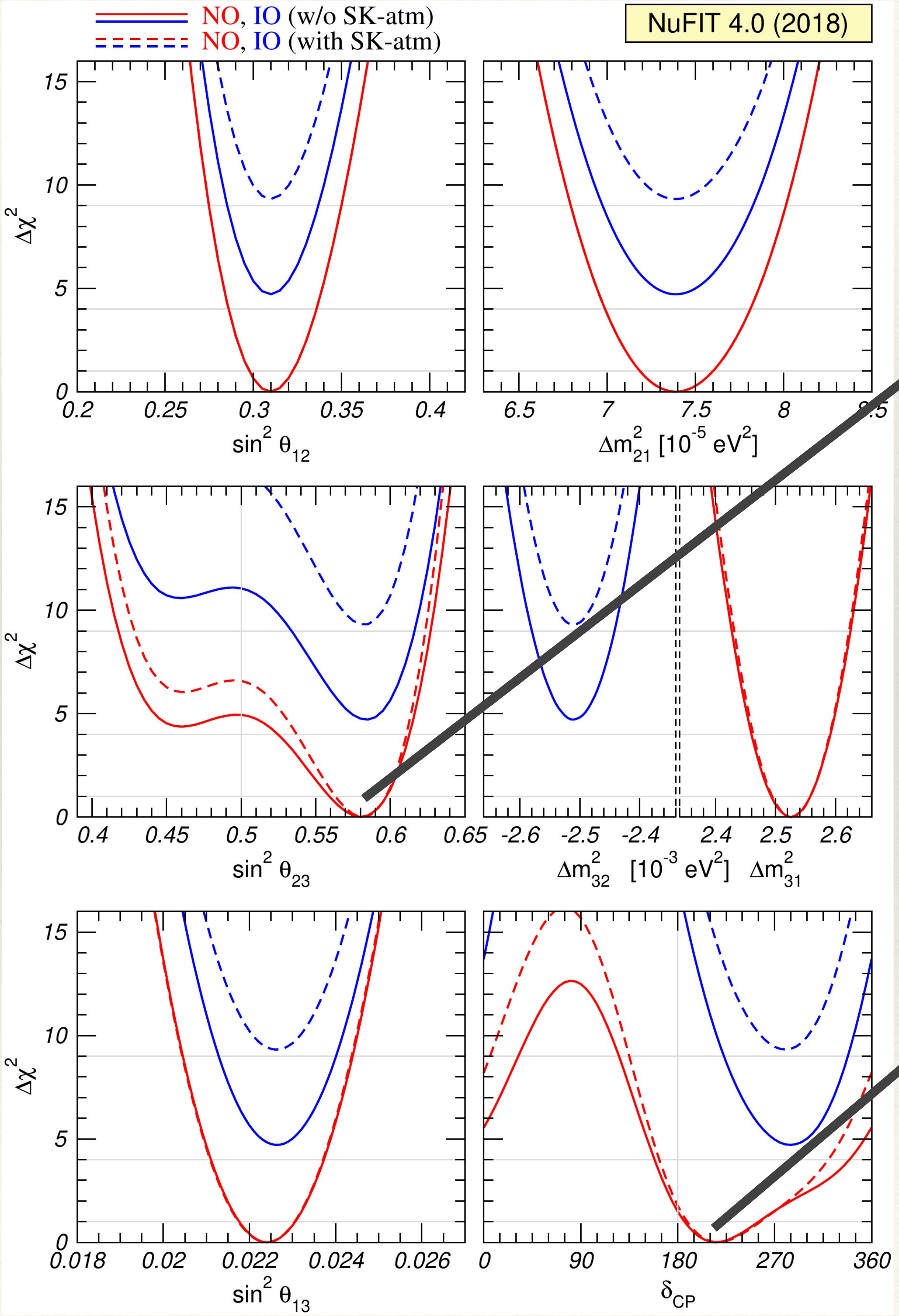

maximal θ_{23} ?

$\delta = 3\pi/2$?

Normal Ordering preferred at ≃ 3σ

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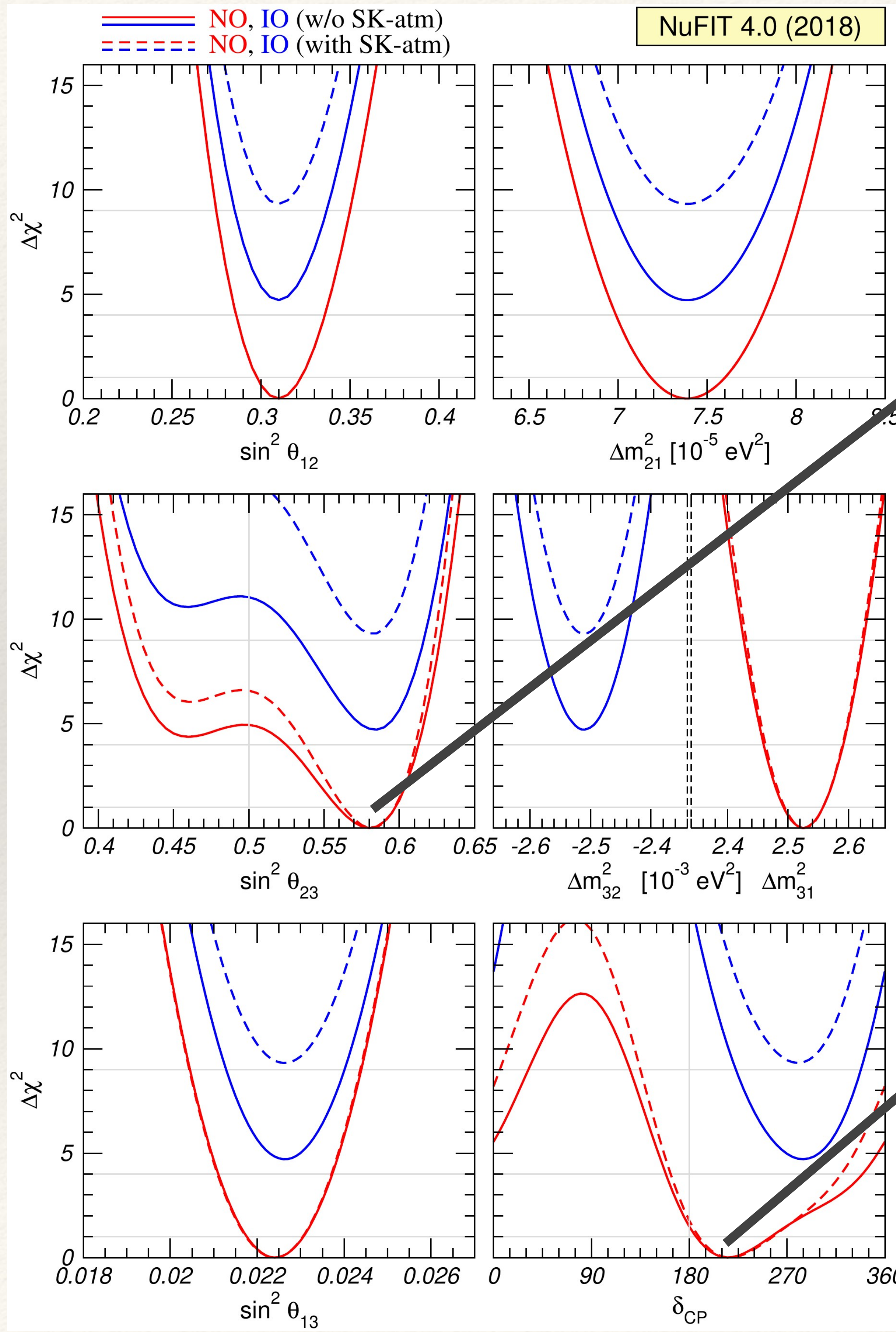


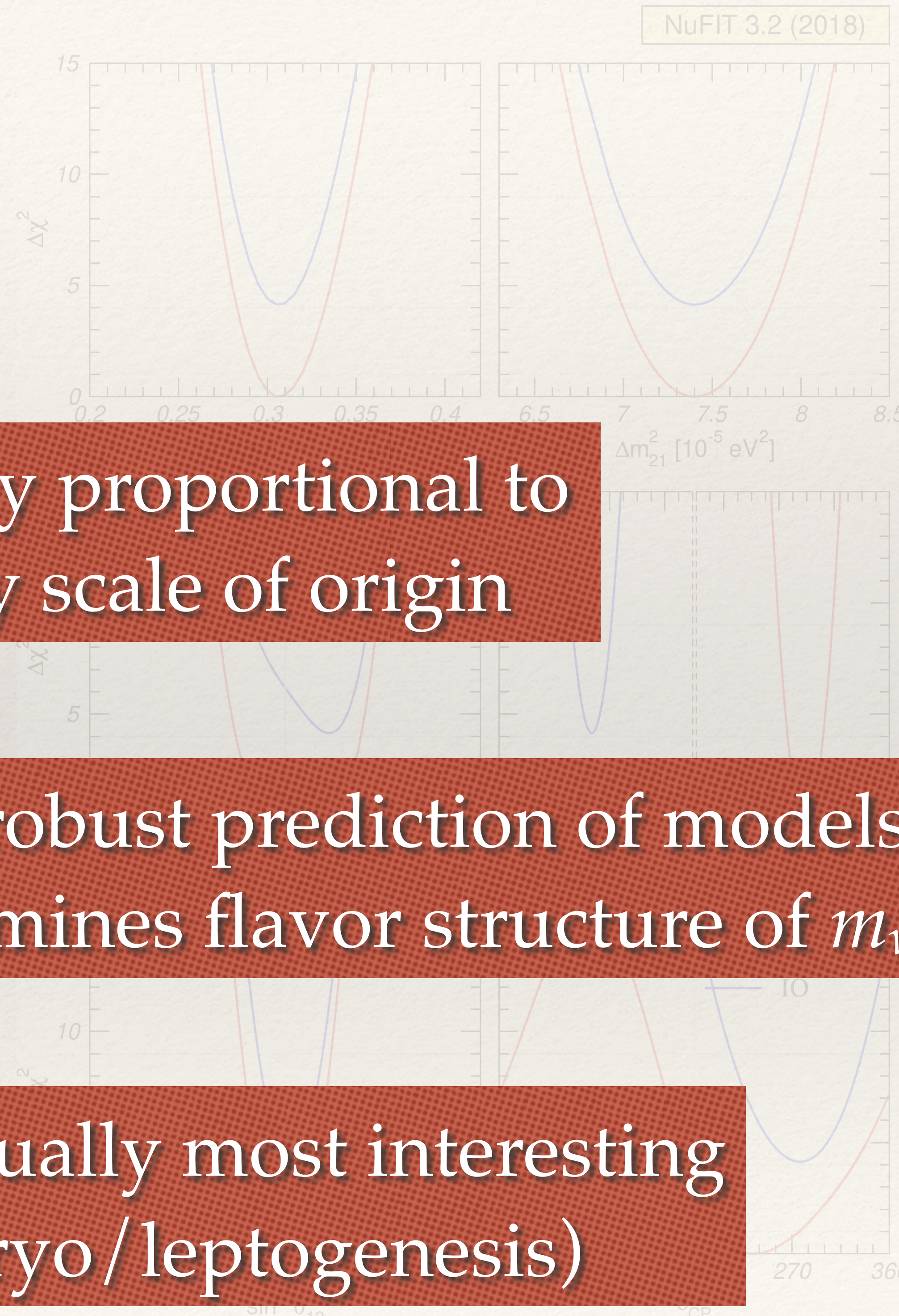
maximal θ_{23} ?

$\delta = 3\pi/2$?

enhanced by tensions?

Normal Ordering preferred at ≃ 3σ

Determine Parameters



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inversely proportional to energy scale of origin

most robust prediction of models; determines flavor structure of m_ν

conceptually most interesting (baryo/leptogenesis)

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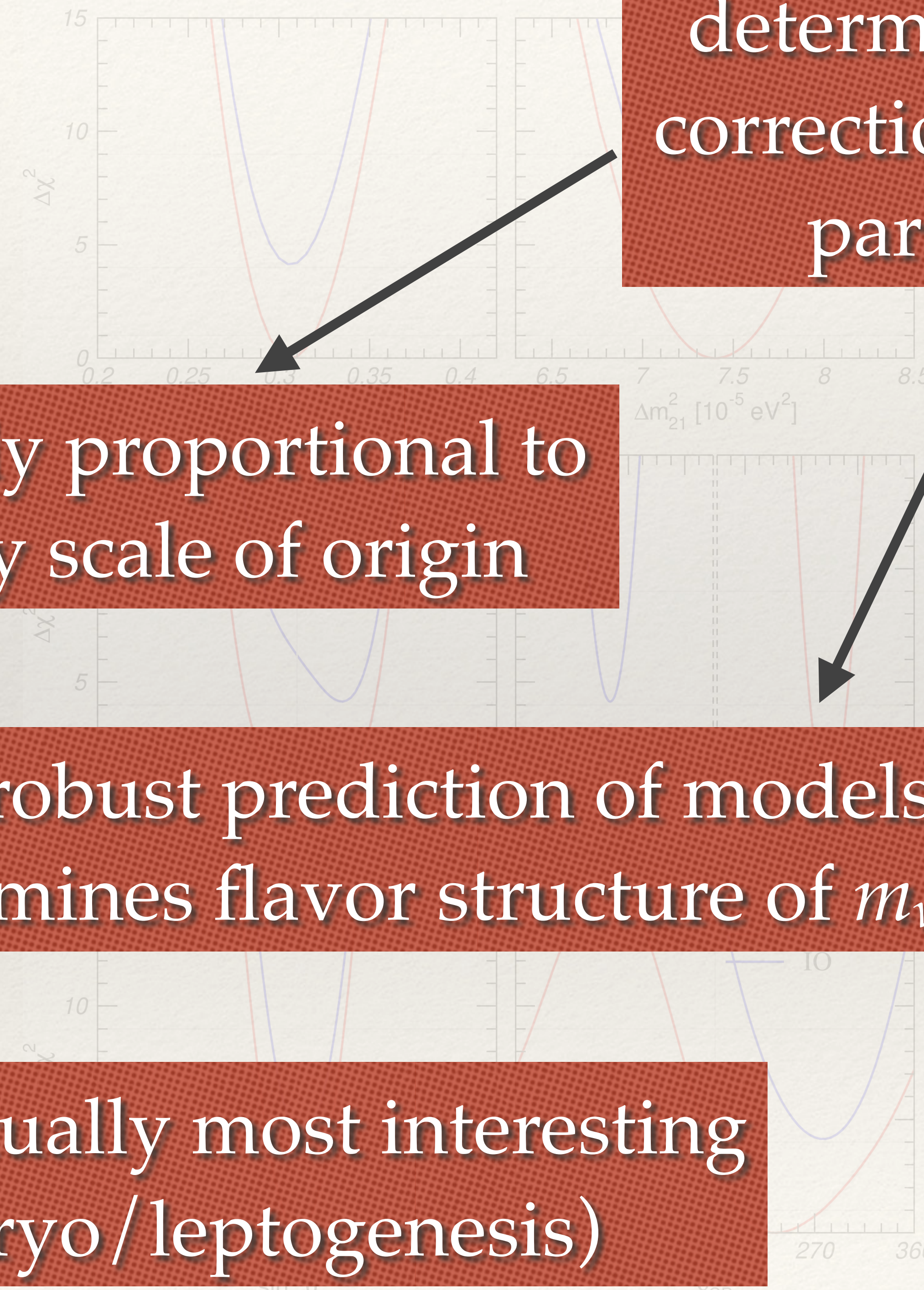


determines size of correction to mixing parameters

inversely proportional to energy scale of origin

most robust prediction of models; determines flavor structure of m_ν

conceptually most interesting (baryo/leptogenesis)

Oscillation Parameters

parameter	best fit ± 1σ	relative 1σ uncertainty
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.55^{+0.20}_{-0.16}$	2.4%
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (NO)	2.50 ± 0.03	1.3%
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	5.5%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.7%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.4%
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	3.5%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	10%
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	9%

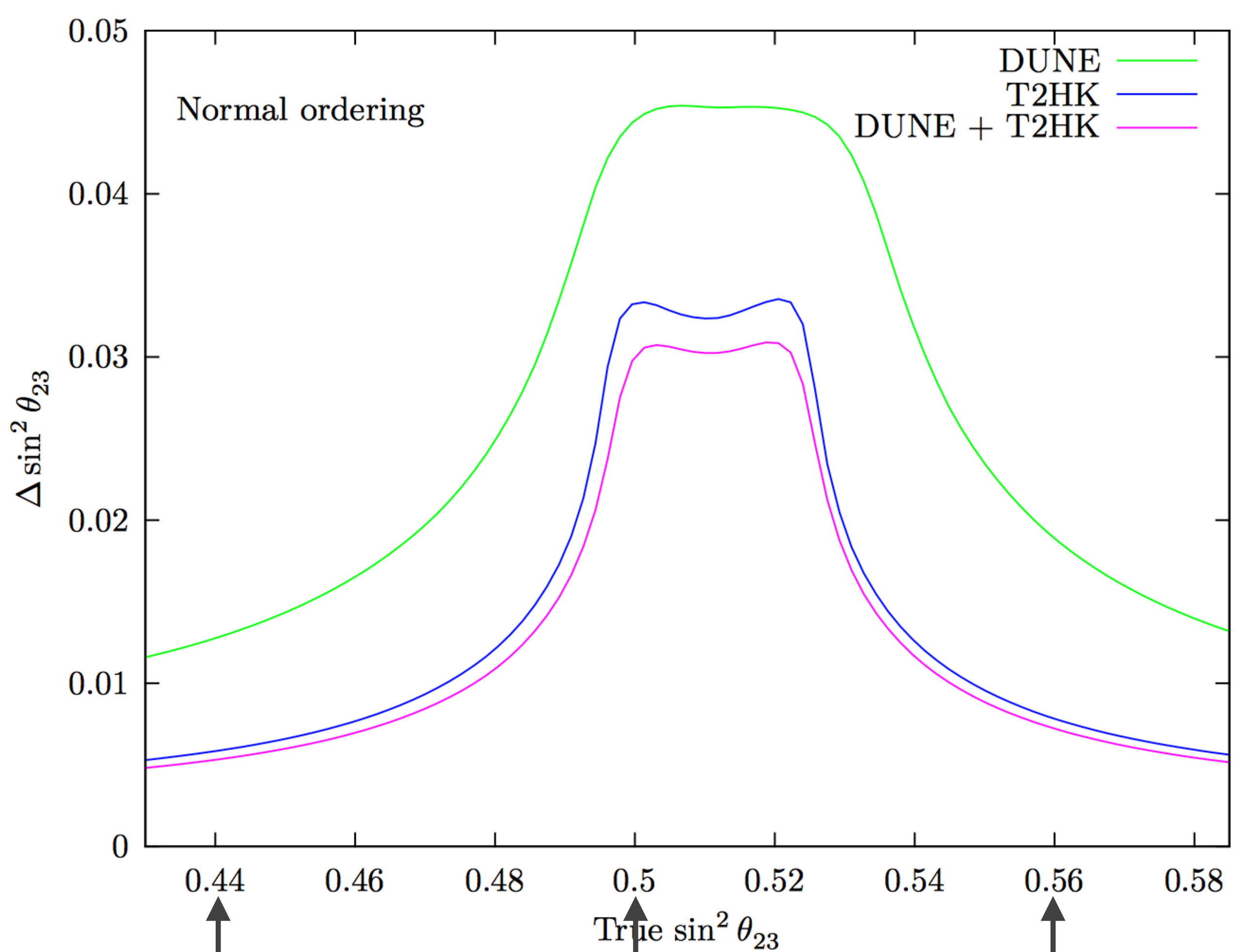
Tortola, talk at Neutrino2018

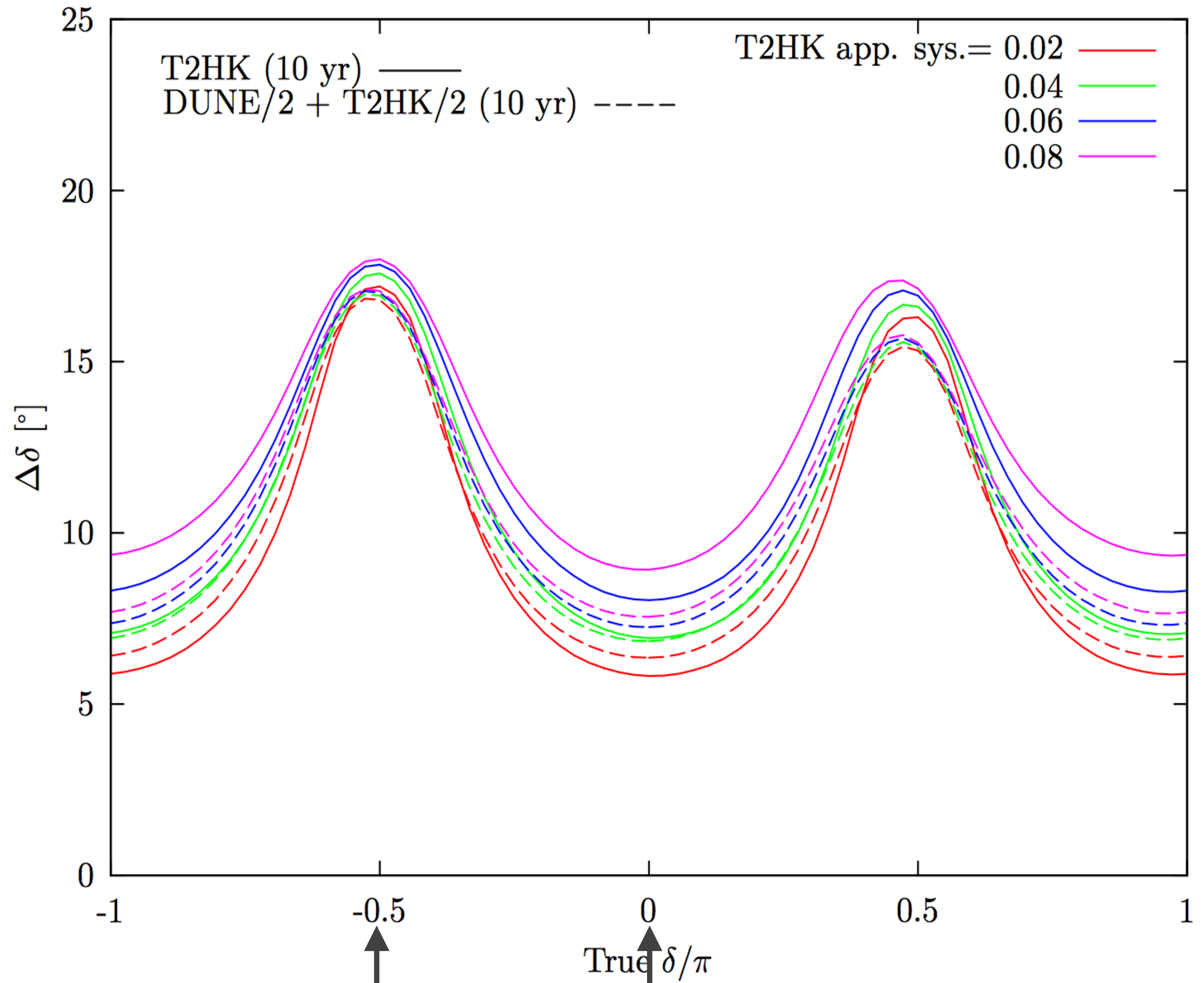
	Current	JUNO
Δm^2_{12}	~3%	~0.6%
Δm^2_{23}	~5%	~0.6%
$\sin^2\theta_{12}$	~6%	~0.7%
$\sin^2\theta_{23}$	~20%	N/A
$\sin^2\theta_{13}$	~14% → ~4%	~ 15%

approaching CKM-like precision!
(not CKM-like redundance…)

Achievable Precision

Ballet et al., 1612.07275

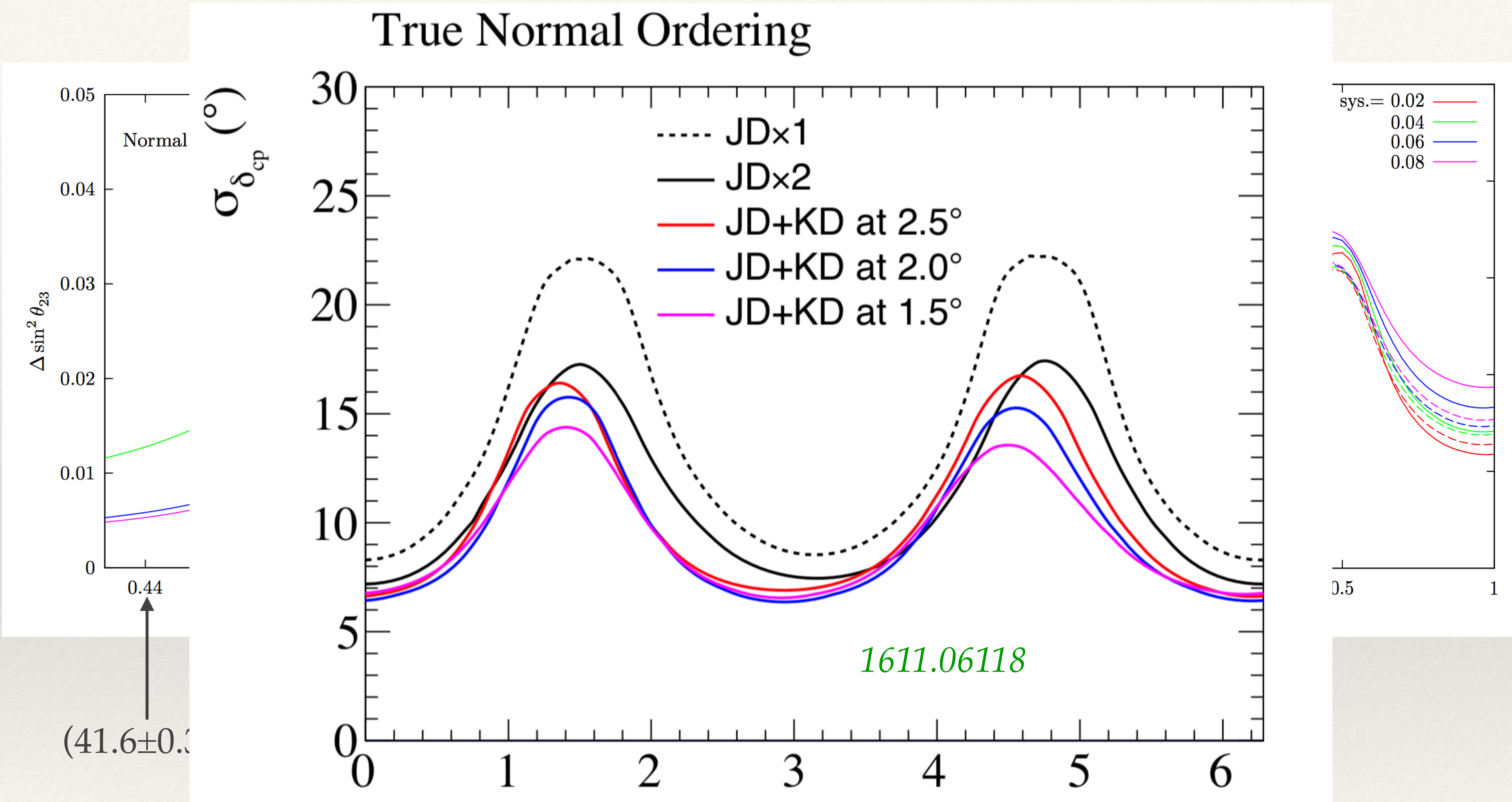




$(41.6\pm0.3)^0$ $(45\pm1.7)^0$ $(48.5\pm0.6)^0$ cos δ: (0 ± 0.29) (1 ± 0.006)

„interesting" values have worst precision…

Achievable Precision

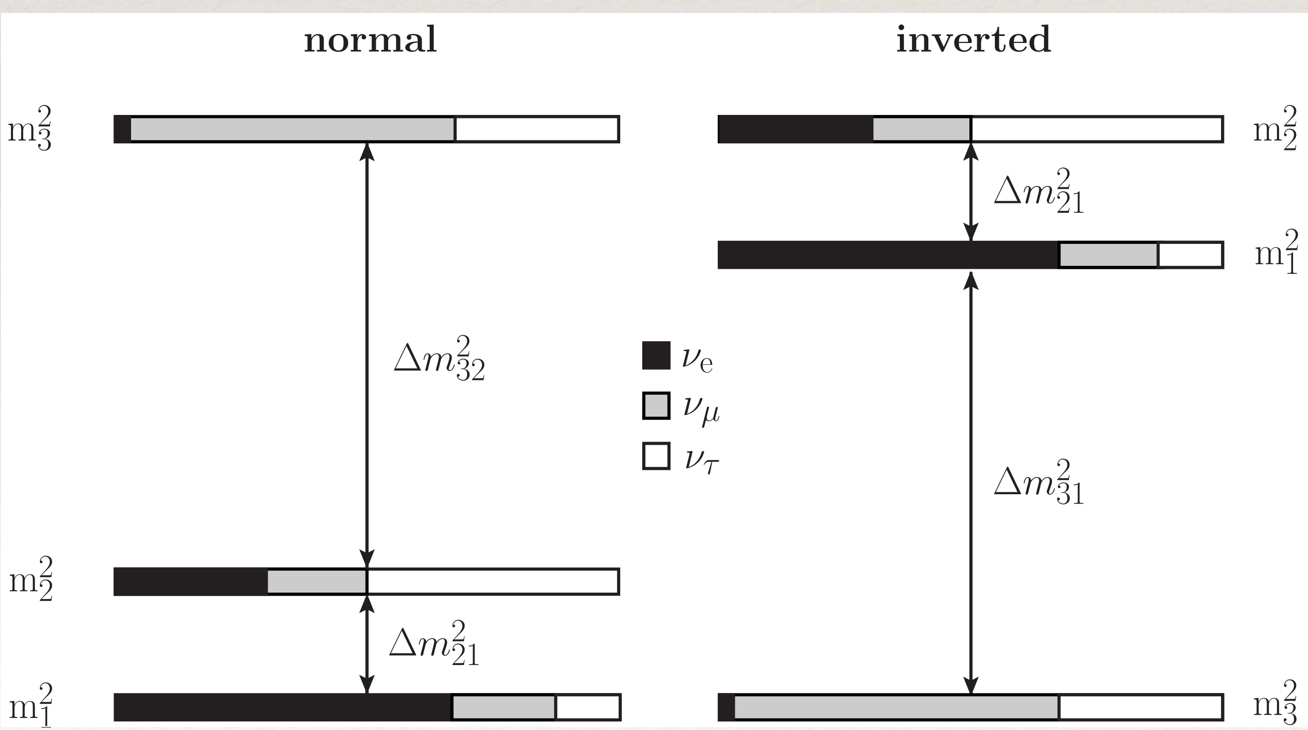


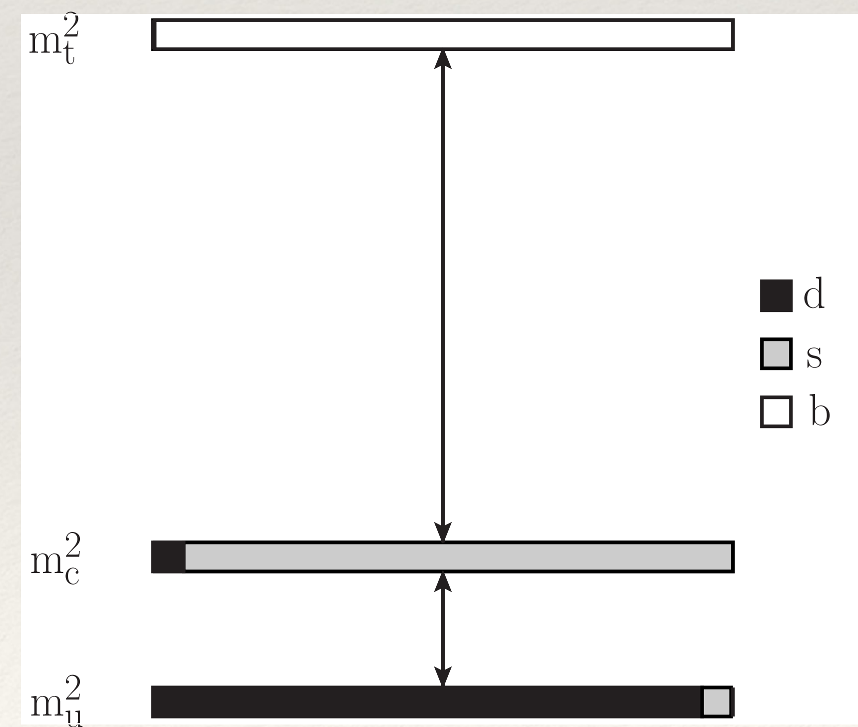
moderate improvement with T2HKK

Implications of Lepton Mixing

$$|U|^{\text{with SK-atm}}_{3\sigma} = \begin{pmatrix} 0.797 \to 0.842 & 0.518 \to 0.585 & 0.143 \to 0.156 \\ 0.235 \to 0.484 & 0.458 \to 0.671 & 0.647 \to 0.781 \\ 0.304 \to 0.531 & 0.497 \to 0.699 & 0.607 \to 0.747 \end{pmatrix}$$

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





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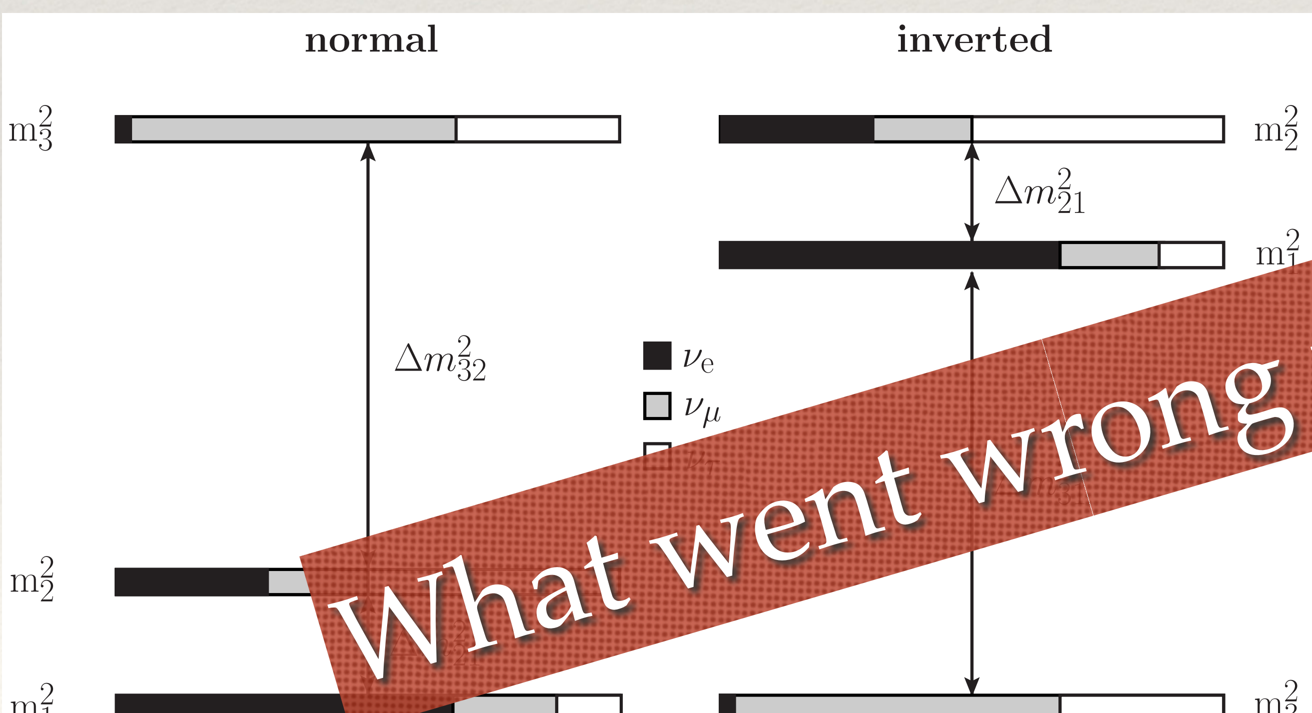
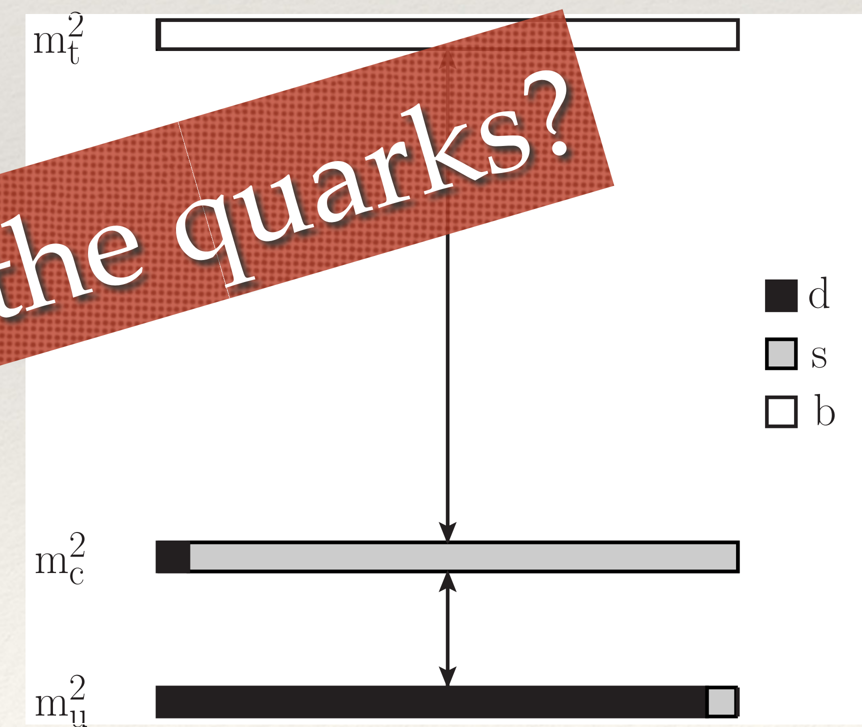




What went wrong with the quarks?

Flavor Symmetries

- Nature prefers large lepton mixing:

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

generated by rather special mass matrix

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

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	$1_1, ...1_9, 3, \overline{3}$	
$PSL_2(7)$	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	$1, 1', \overline{1'}, 3, \overline{3}$	$A^7 = B^3 = 1,\ AB = BA^4$

Barry, WR, 1003.2385

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	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{3}$	$\cdots$

Many possible groups, within each group many models…

⇒ can distinguish only classes of models

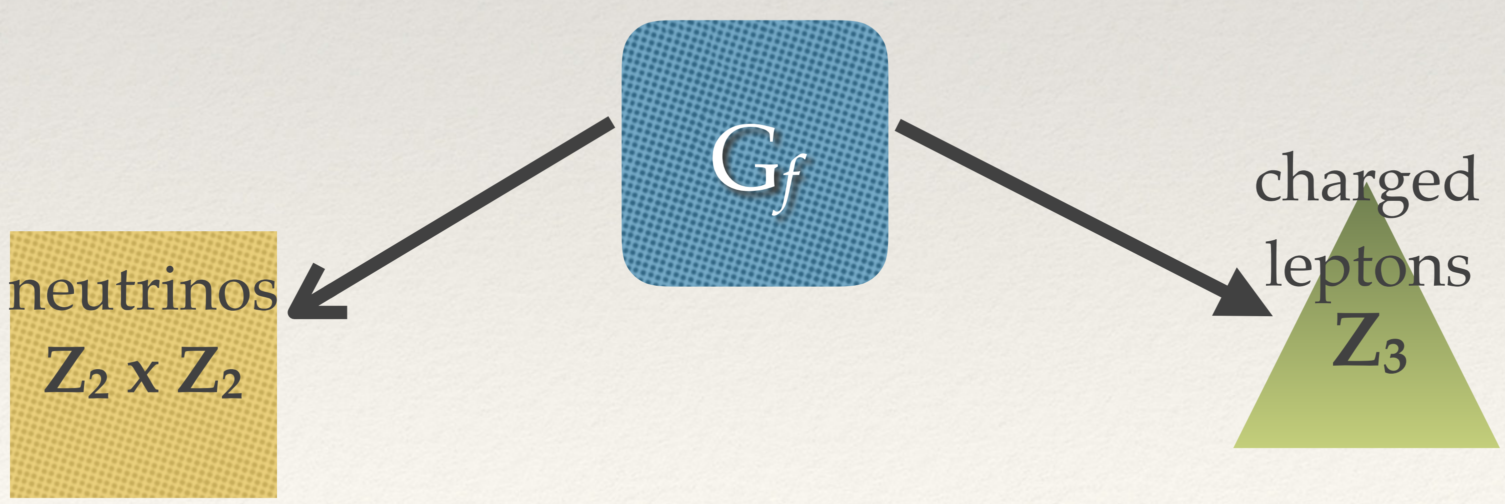
‖-talk by Zhou

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:



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related to 3 generations?

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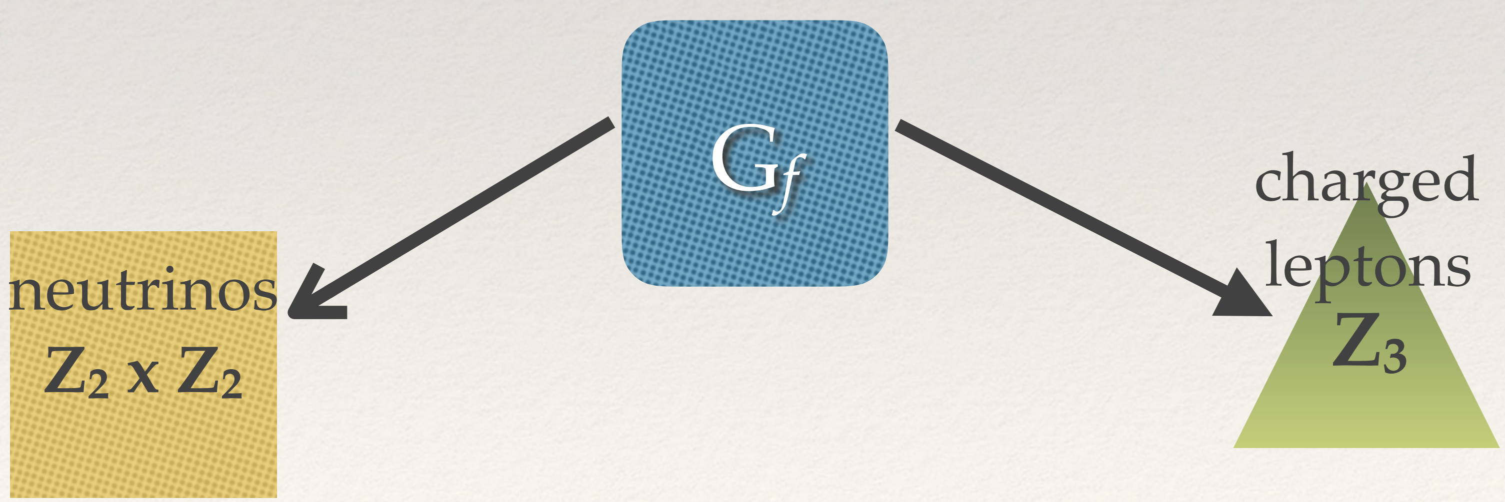

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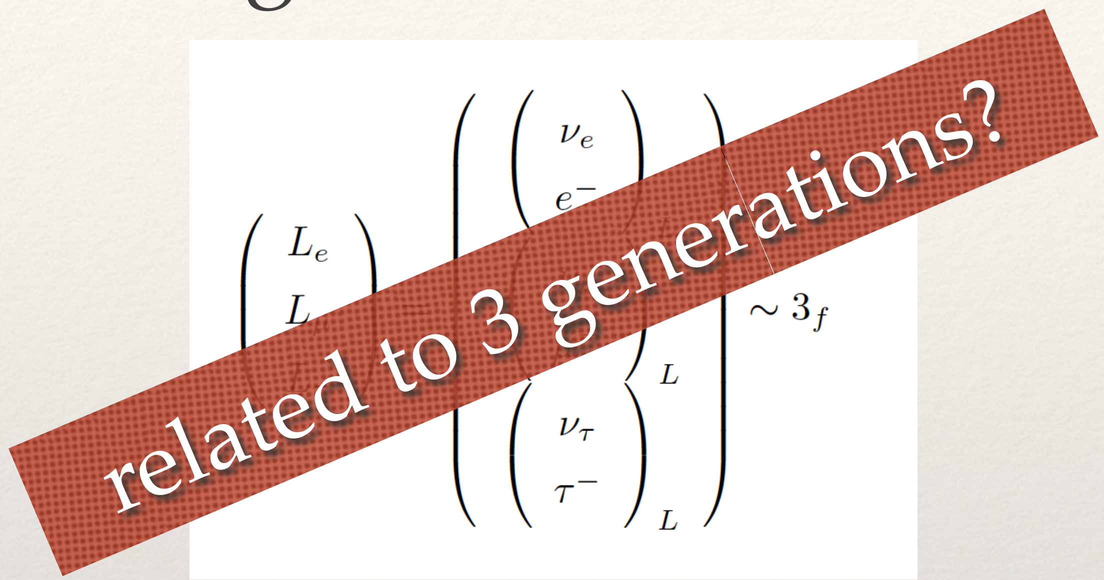


Lesson 2: flavor group broken to different subgroups:

How to predict the CP phase

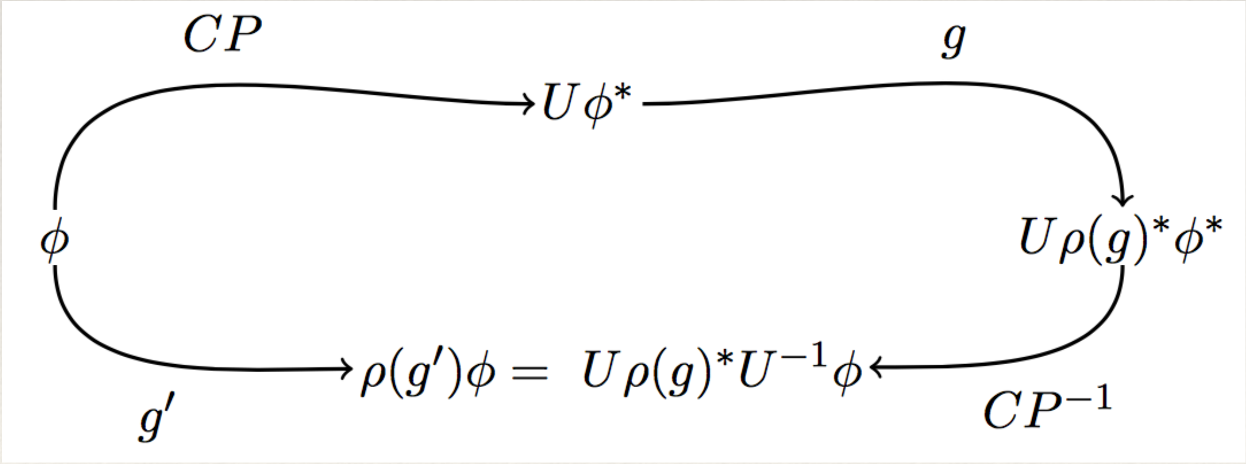
- μ-τ reflection symmetry: $\nu_e \leftrightarrow \nu_e^C$ and $\nu_\mu \leftrightarrow \nu_\tau^C$

$$m_\nu = \begin{pmatrix} x & z_1 & z_1^* \\ \cdot & z_2 & y \\ \cdot & \cdot & z_2^* \end{pmatrix}$$

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

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: generalized CP transformation can be interpreted as representation of outer automorphism of discrete group)

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

„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,…

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

- if $\sin^2\theta = 1/3 = 0.33$ (tri-bimaximal, e.g. A_4, S_4, T')
- if $\sin^2\theta = 1/2 = 0.50$ (bimaximal, e.g. D_4)
- if $\sin^2\theta = 1/4 = 0.25$ (hexagonal, e.g. D_{12})
- if $\tan\theta = 1/\phi$ or $\sin^2\theta = 0.276$ (GRA, e.g. A_5)
- if $\cos\theta = \phi/2$ or $\sin^2\theta = 0.346$ (GRB, e.g. D_{10})

$\Rightarrow$ can distinguish only classes of models

„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,…

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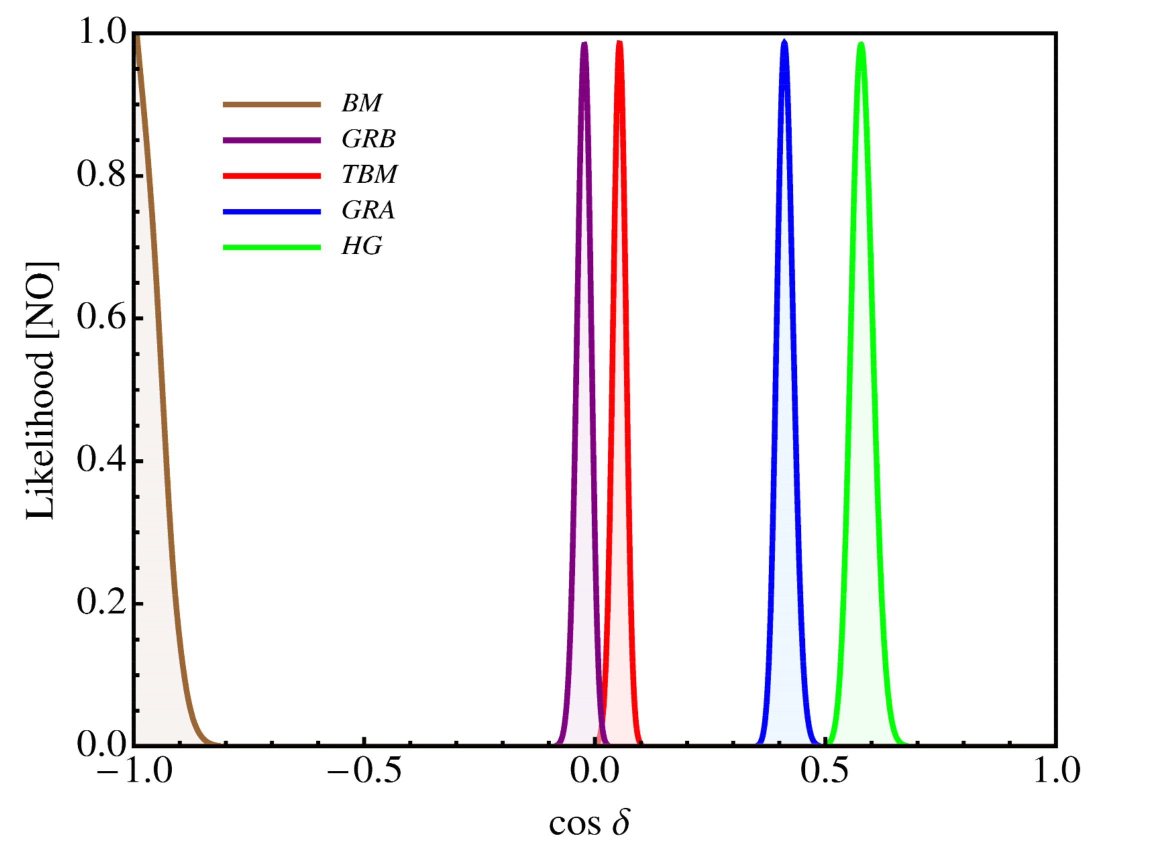
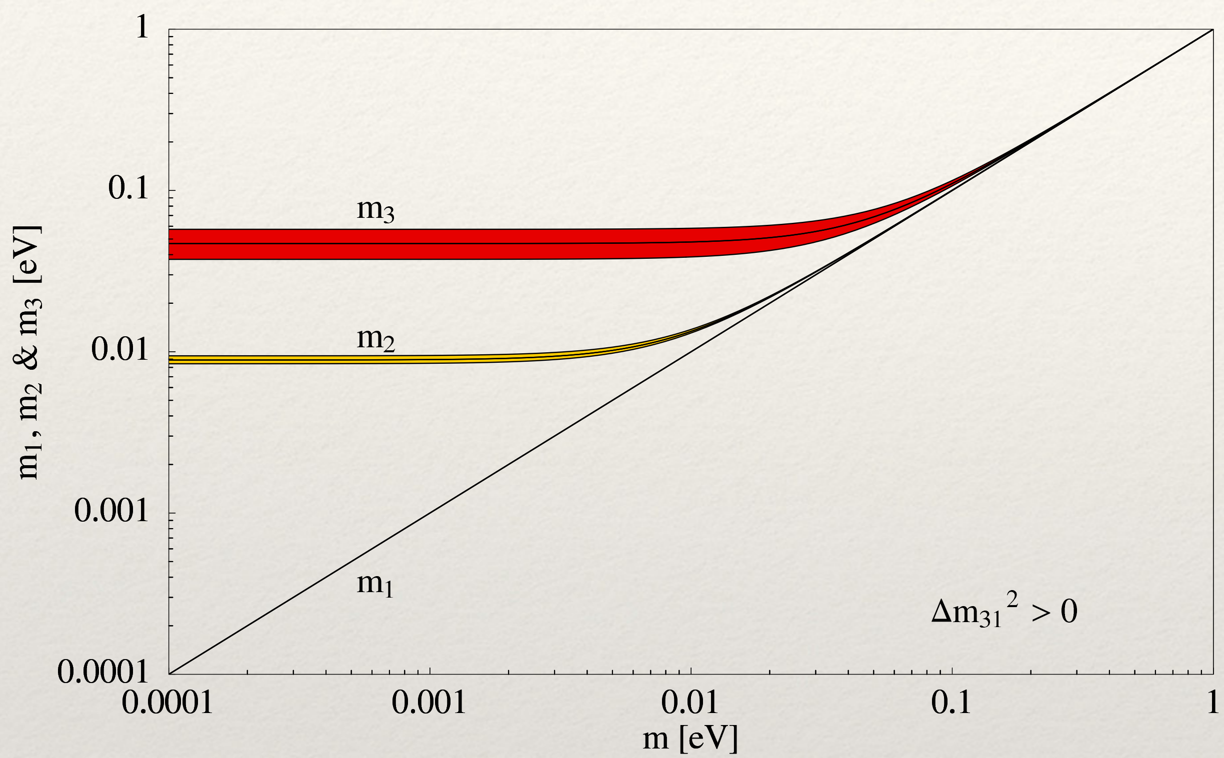
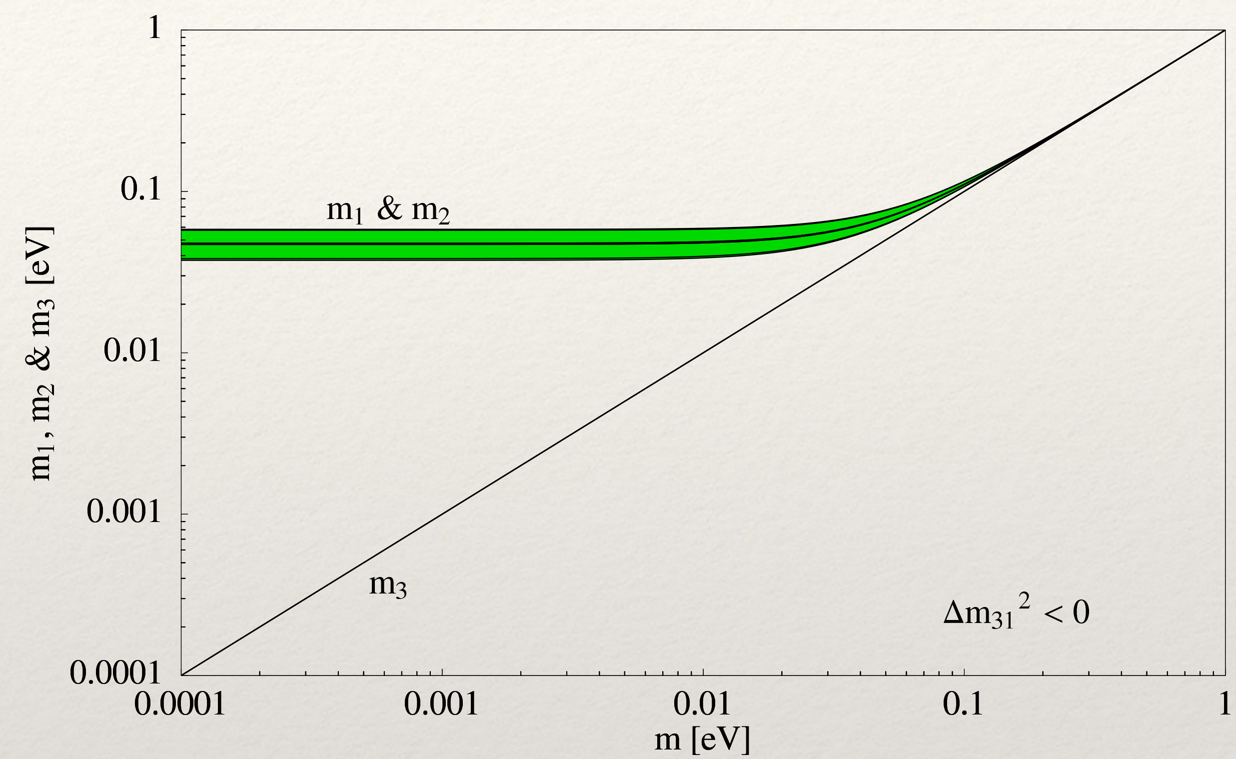
Girardi, Petcov, Titov, 1410.8056



⇒ can distinguish only classes of models

Masses and 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, RG effects
- Frequent feature: $\delta(\theta_{12})$, $\delta(\delta) > \delta(\theta_{13})$, $\delta(\theta_{23})$
- effects larger for IH and QD

large

Example RG corrections:

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

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

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

mass scale and ordering helpful

Example RG corrections:

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

large

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

Many scalar fields…?

	L	e^c	μ^c	τ^c	$\nu^c_{\rm atm}$	$\nu^c_{\rm sol}$	$H_{u,d}$	η_l	ϕ_l	ξ_a	ϕ_a	ξ_s	η_s	χ_s	φ_s	Δ_s	ϕ_s	ψ_s	ξ^0_l	ϕ^0_l	ϕ^0_a	σ^0	ρ^0	η^0	χ^0	φ^0	Δ^0	κ^0
S_4	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1'}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{3'}$	$\mathbf{3'}$	$\mathbf{3'}$	$\mathbf{3'}$	$\mathbf{3'}$	$\mathbf{1}$	$\mathbf{3'}$	$\mathbf{3'}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{3'}$	$\mathbf{3'}$	$\mathbf{3'}$	$\mathbf{1}$
Z_5	ω_5^4	ω_5^3	ω_5^4	1	1	1	1	ω_5	ω_5	1	ω_5	1	ω_5^3	ω_5^2	1	ω_5^3	ω_5	ω_5^4	ω_5^3	ω_5^3	ω_5^3	ω_5^2	ω_5	ω_5^4	1	1	ω_5^2	ω_5^3
Z_8	ω_8^7	ω_8^6	ω_8^7	1	ω_8^5	ω_8	1	ω_8	ω_8	ω_8^6	-1	ω_8^6	1	1	1	1	1	1	ω_8^6	ω_8^6	1	1	1	1	1	1	1	1
Z'_8	ω_8	ω_8^7	ω_8^7	ω_8^7	ω_8^5	1	1	1	1	ω_8^6	ω_8^2	1	ω_8^5	ω_8^5	ω_8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

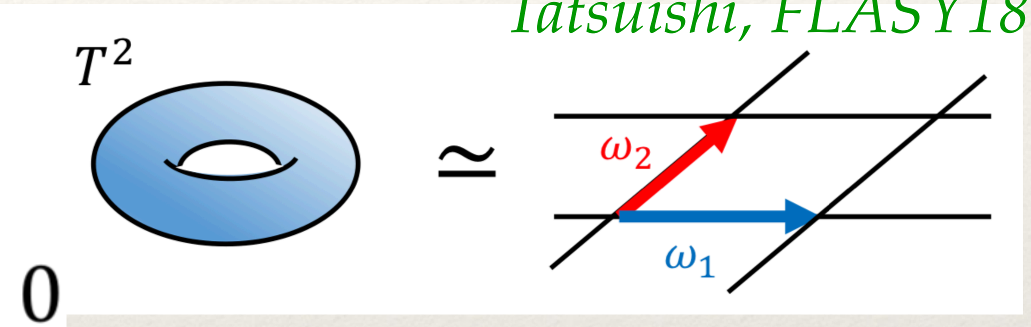
	$G_{\rm SM}$	T'	$U(1)_R$	Z_8	Z_4	Z_4	Z_3	Z_3	Z_2
ϕ	$(\mathbf{1},\mathbf{1},0)$	$\mathbf{3}$	0	2	0	0	1	0	1
$\tilde\phi$	$(\mathbf{1},\mathbf{1},0)$	$\mathbf{3}$	0	2	0	2	0	1	0
$\hat\phi$	$(\mathbf{1},\mathbf{1},0)$	$\mathbf{3}$	0	5	0	3	2	0	0
ξ	$(\mathbf{1},\mathbf{1},0)$	$\mathbf{3}$	0	0	2	2	0	0	0
ψ'	$(\mathbf{1},\mathbf{1},0)$	$\mathbf{2'}$	0	3	2	3	2	0	0
ψ''	$(\mathbf{1},\mathbf{1},0)$	$\mathbf{2''}$	0	7	2	1	2	0	1
$\tilde\psi''$	$(\mathbf{1},\mathbf{1},0)$	$\mathbf{2''}$	0	1	2	3	0	1	1
ζ	$(\mathbf{1},\mathbf{1},0)$	$\mathbf{1}$	0	5	0	1	2	0	1
ζ'	$(\mathbf{1},\mathbf{1},0)$	$\mathbf{1'}$	0	4	0	2	0	0	1
$\tilde\zeta'$	$(\mathbf{1},\mathbf{1},0)$	$\mathbf{1'}$	0	2	0	2	0	1	0
ζ''	$(\mathbf{1},\mathbf{1},0)$	$\mathbf{1''}$	0	2	0	0	1	0	1
$\tilde\zeta''$	$(\mathbf{1},\mathbf{1},0)$	$\mathbf{1''}$	0	0	0	0	0	1	0
ρ	$(\mathbf{1},\mathbf{1},0)$	$\mathbf{1}$	0	0	2	2	0	0	0
$\tilde\rho$	$(\mathbf{1},\mathbf{1},0)$	$\mathbf{1}$	0	0	2	2	0	0	0
ϵ_1	$(\mathbf{1},\mathbf{1},0)$	$\mathbf{1}$	0	4	1	0	0	0	0
ϵ_2	$(\mathbf{1},\mathbf{1},0)$	$\mathbf{1}$	0	4	2	2	0	0	1
ϵ_3	$(\mathbf{1},\mathbf{1},0)$	$\mathbf{1}$	0	4	2	0	0	0	0
ϵ_4	$(\mathbf{1},\mathbf{1},0)$	$\mathbf{1}$	0	0	0	0	1	1	0
ϵ_5	$(\mathbf{1},\mathbf{1},0)$	$\mathbf{1}$	0	0	0	0	2	2	0

Typical flasy model has huuuuuge scalar sector…

number of free parameters exceeds number of predictions by $O(10\ldots100)$

Many scalar fields…?

- can be solved by ***modular invariance*** (*Feruglio*)
- e.g. 10D —> 4D + 3 tori



- $\mathbb{C}$-lattice characterized by $\tau = \frac{\omega_2}{\omega_1}$ $Im(\tau) > 0$
- invariant under modular trafos $\tau \to \gamma\tau \equiv \frac{a\tau + b}{c\tau + d}$
- form discrete group, „quotient groups" act on multiplets φ as:

$$\varphi^{(I)} \to (c\tau + d)^{-k_I} \rho^{(I)}(\gamma) \varphi^{(I)}$$ ($\boldsymbol{\rho}$ is irrep of quotient group)

- model building in its infancy, but very interesting approach (*Feruglio et al., Petcov et al., King et al., Tanimoto et al.,…*)

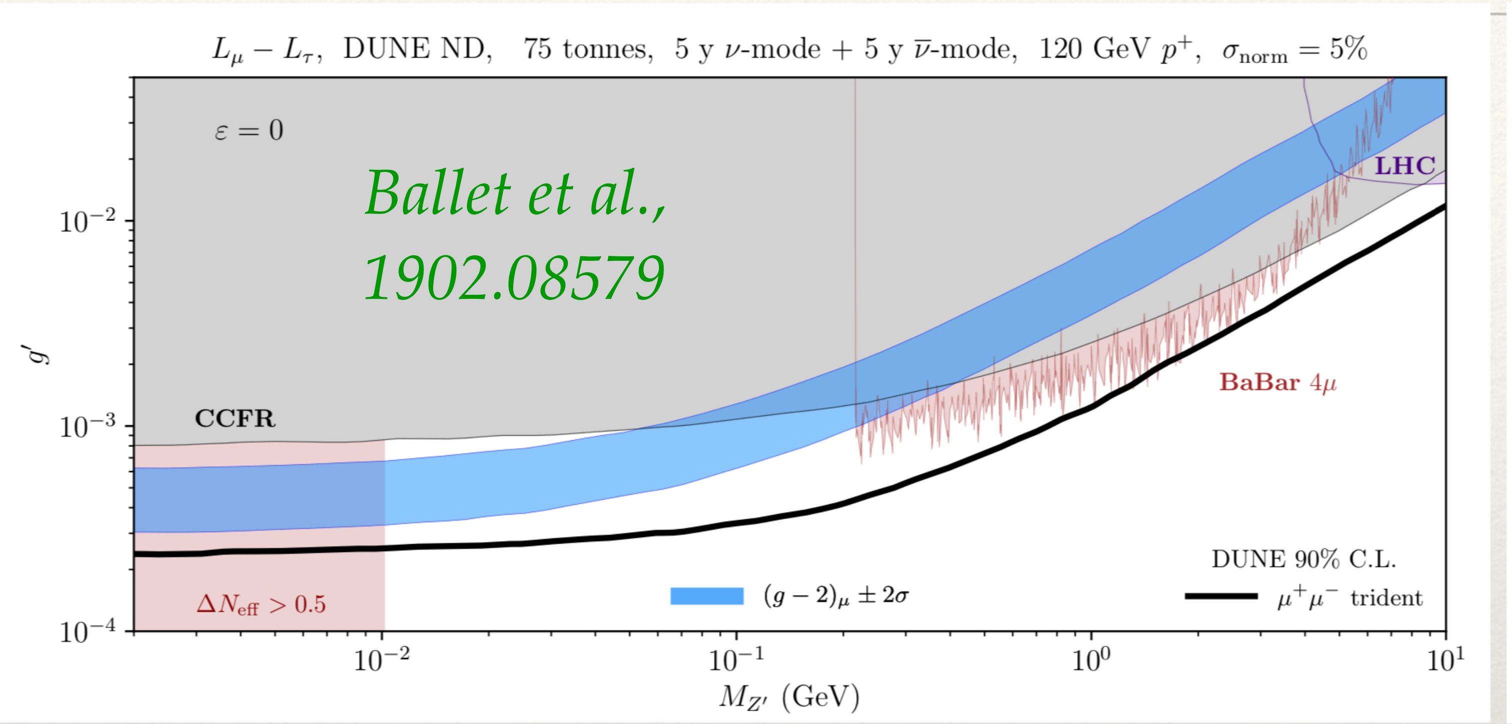
Abelian Flavor Symmetries

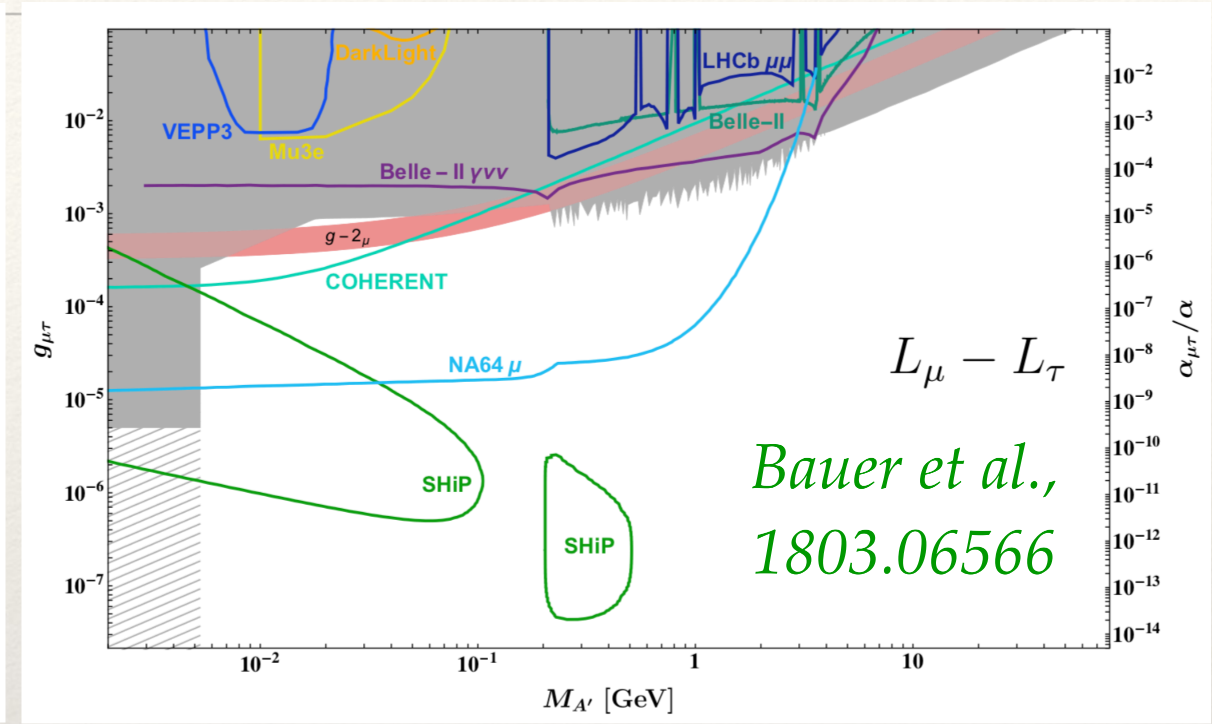
- Less predictive but less complicated: Abelian flavor symmetry, e.g. $L_\mu - L_\tau$
  - anomaly-free, has Z' and can explain $(g-2)_\mu$
  - can be extended to quark sector to explain anomalies in $B \to K^* \mu\mu$ and BR($B \to K\mu\mu$)/BR($B \to Kee$) *[e.g., Crivellin, Ambrosio, Heeck, 1501.00993]* (making predictions for $h \to \mu\tau$, LFV, etc.)
  - masses a and $\pm b$, $\theta_{23} = \pi/4$, $\theta_{13} = 0$

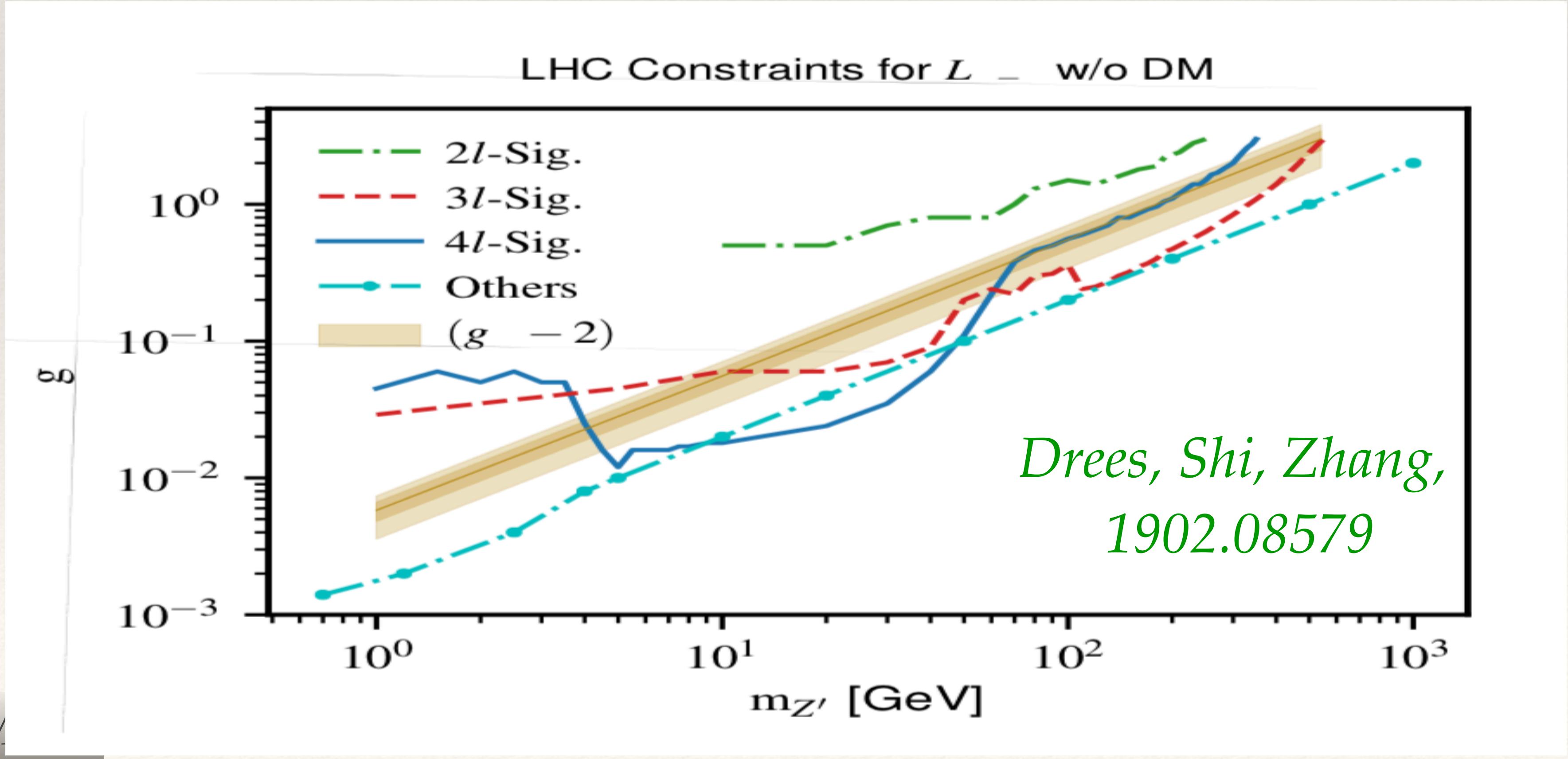
$$(m_\nu)^{L_\mu - L_\tau} = \begin{pmatrix} a & 0 & 0 \\ \cdot & 0 & b \\ \cdot & \cdot & 0 \end{pmatrix}$$

Heeck, WR, 1107.5238

Tests with DUNE, LHC, etc.







New Physics in Oscillations

- Various good reasons to expect NP:
  - unitarity violation from new fermions
  - Non-Standard Interactions (NSI) from new physics
  - General Neutrino Interactions (GNI) (scalar, tensor, etc.)
  - long-range forces
  - decay, Pseudo-Dirac,…
  - Lorentz/CPT violation
  - light sterile neutrinos…

New Physics in Oscillations

- Various good reasons to expect NP:
  - unitarity violation from new fermions

good theory arguments for all those things, except for eV-scale steriles…

  - long-range forces
  - decay, Pseudo-Dirac,…
  - Lorentz/CPT violation
  - light sterile neutrinos…

see ∥-talks by Döring, Farnese, Palazzo, Roca, Ternes

New Physics in Oscillations

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Non-Standard Interactions

$$\delta\mathcal{L}_{\rm NSI} = -2\sqrt{2}\,G_F \sum_{f,P} \epsilon_{\alpha\beta}^{fP} \left(\overline{\nu_\alpha}\gamma^\mu P_L \nu_\beta\right)\left(\bar{f}\gamma_\mu P f\right)$$

modify matter potential in LBL expts: $\varepsilon = \varepsilon^L + \varepsilon^R = \varepsilon^e + 3\varepsilon^u + 3\varepsilon^d$

$$H_{\rm mat} = \sqrt{2}G_F N_e(x) \begin{pmatrix} 1+\epsilon_{ee}(x) & \epsilon_{e\mu}(x) & \epsilon_{e\tau}(x) \\ \epsilon_{e\mu}^*(x) & \epsilon_{\mu\mu}(x) & \epsilon_{\mu\tau}(x) \\ \epsilon_{e\tau}^*(x) & \epsilon_{\mu\tau}^*(x) & \epsilon_{\tau\tau}(x) \end{pmatrix}$$

- $\varepsilon \propto c^2/M_X^2 \;\Rightarrow\; \varepsilon = 0.01$ is TeV-scale physics
- oscillation effect is *t*-channel forward scattering (q^2 very small), hence c can be very small and M_X MeV-ish
- can prevent experiments from determining parameters…

Non-Standard Interactions

	LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$[-0.020, +0.456]$	$\oplus[-1.192, -0.802]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$[-0.005, +0.130]$	$[-0.152, +0.130]$
$\varepsilon^u_{e\mu}$	$[-0.060, +0.049]$	$[-0.060, +0.067]$
$\varepsilon^u_{e\tau}$	$[-0.292, +0.119]$	$[-0.292, +0.336]$
$\varepsilon^u_{\mu\tau}$	$[-0.013, +0.010]$	$[-0.013, +0.014]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$[-0.027, +0.474]$	$\oplus[-1.232, -1.111]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$[-0.005, +0.095]$	$[-0.013, +0.095]$
$\varepsilon^d_{e\mu}$	$[-0.061, +0.049]$	$[-0.061, +0.073]$
$\varepsilon^d_{e\tau}$	$[-0.247, +0.119]$	$[-0.247, +0.119]$
$\varepsilon^d_{\mu\tau}$	$[-0.012, +0.009]$	$[-0.012, +0.009]$
$\varepsilon^p_{ee} - \varepsilon^p_{\mu\mu}$	$[-0.041, +1.312]$	$\oplus[-3.328, -1.958]$
$\varepsilon^p_{\tau\tau} - \varepsilon^p_{\mu\mu}$	$[-0.015, +0.426]$	$[-0.424, +0.426]$
$\varepsilon^p_{e\mu}$	$[-0.178, +0.147]$	$[-0.178, +0.178]$
$\varepsilon^p_{e\tau}$	$[-0.954, +0.356]$	$[-0.954, +0.949]$
$\varepsilon^p_{\mu\tau}$	$[-0.035, +0.027]$	$[-0.035, +0.035]$

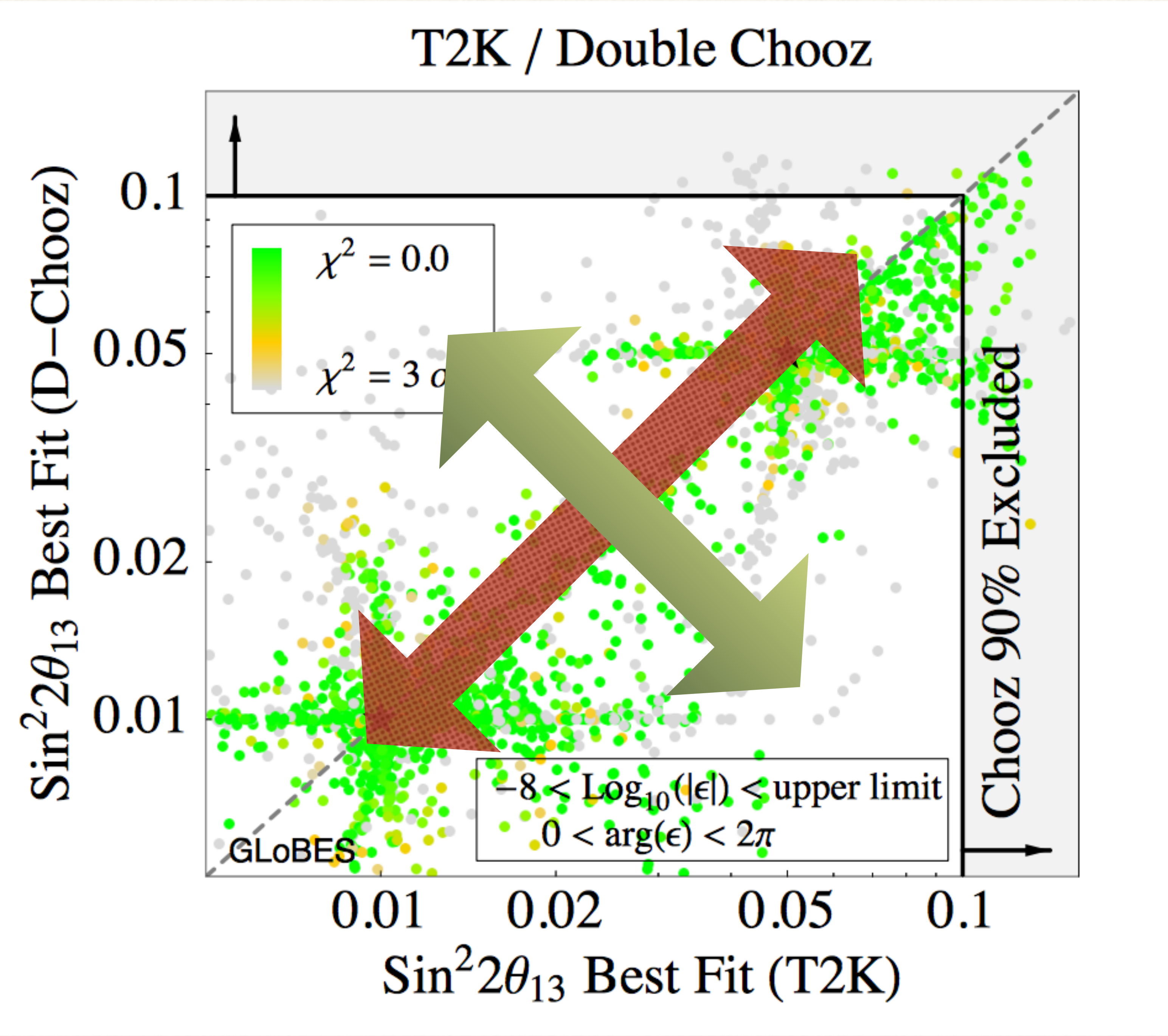
Limits typically EW scale

- $\varepsilon \propto g'^2/M_{Z'}^2$ th…
- oscillation eff… …ng (q^2 very small), hence…
- can prevent e… …arameters…

Esteban et al., 1805.04530

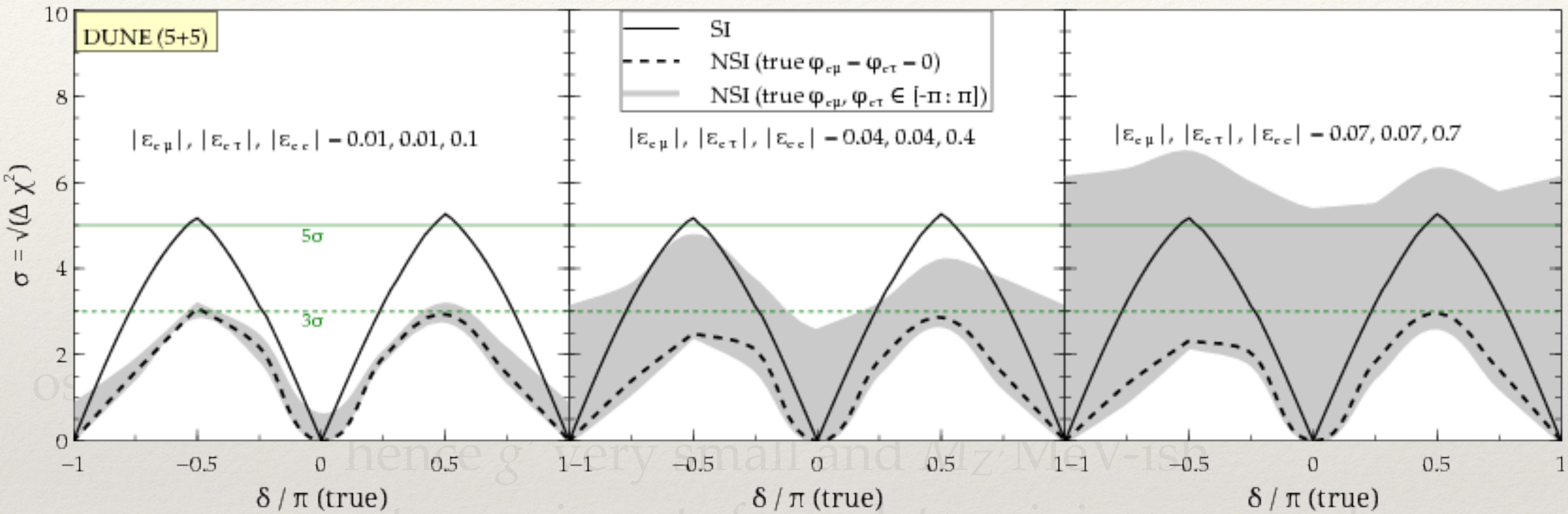
Non-Standard Interactions

- $\varepsilon \propto g'^2/M$...
- oscillatio... q^2 very small), h...
- can prev... meters…



Kopp, Lindner, Ota, Sato, 0708.0152

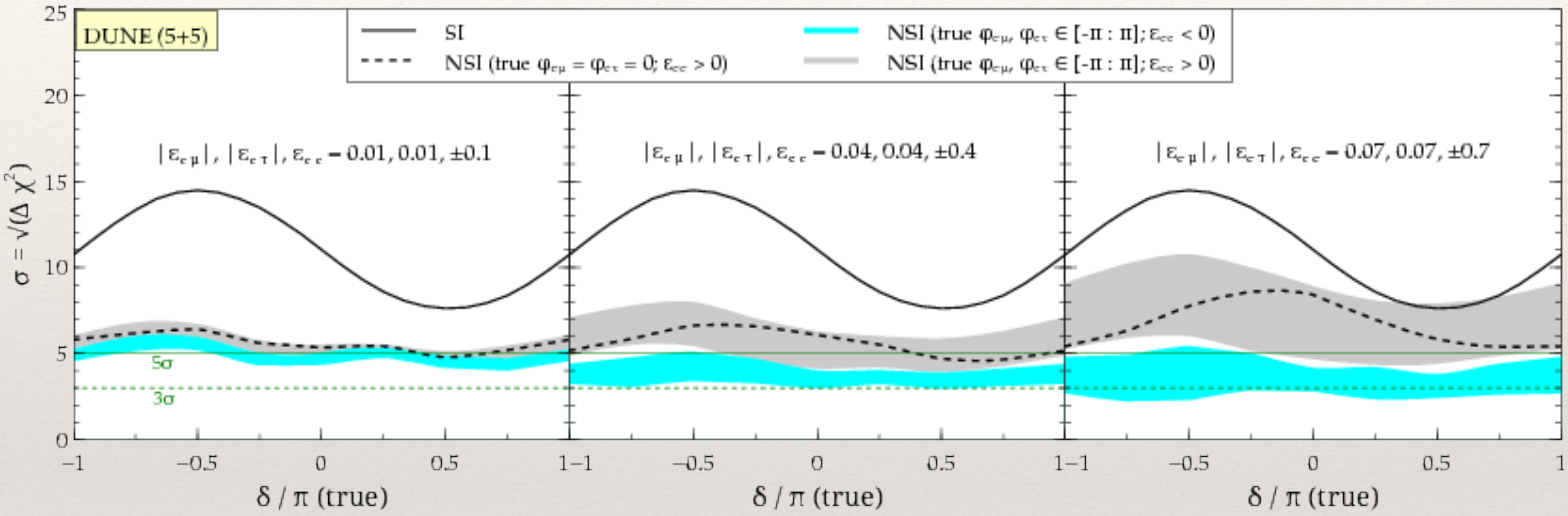
Non-Standard Interactions



NSI can prevent determination of CP violation!

Masud, Mehta, 1603.01380

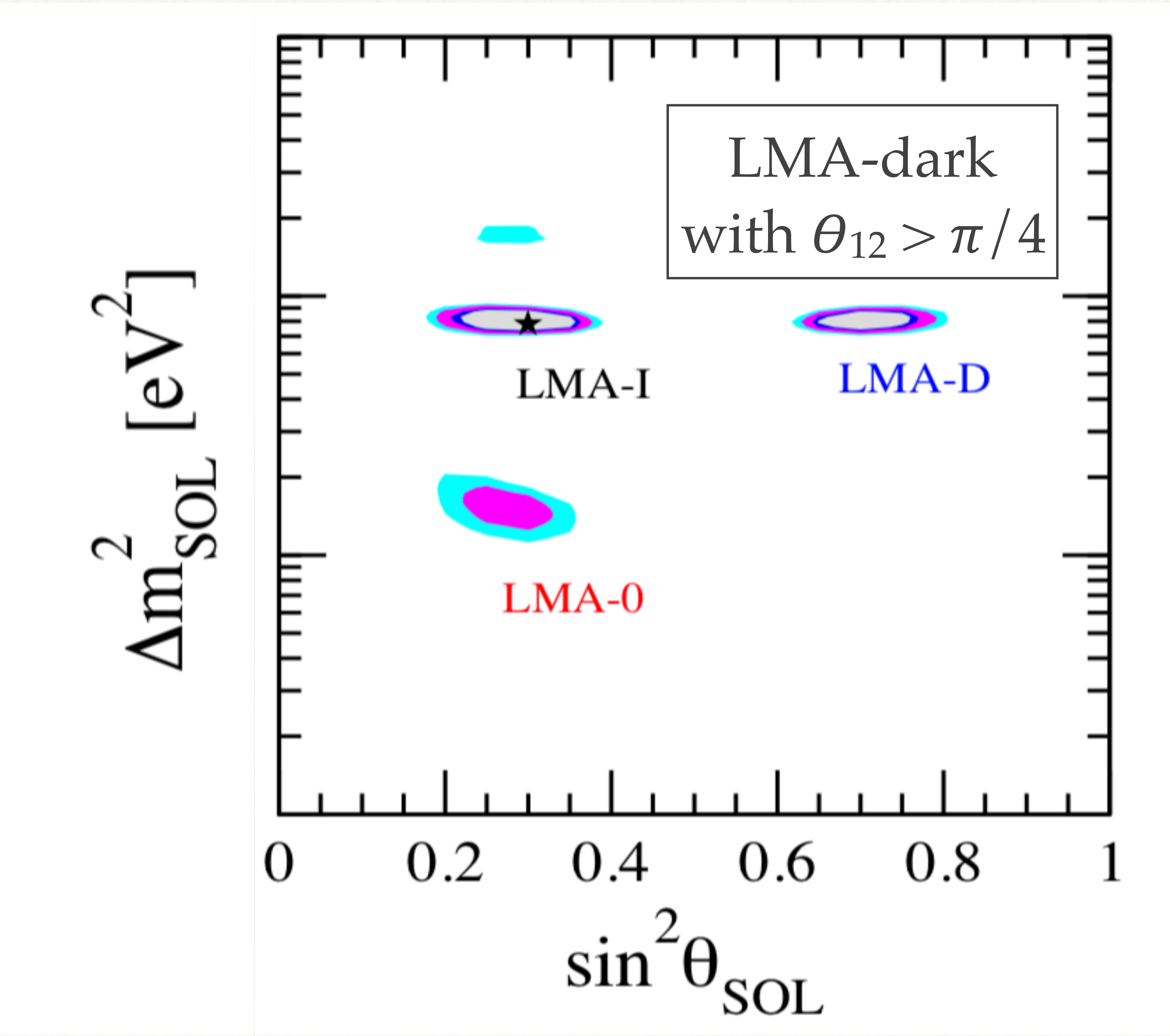
Non-Standard Interactions

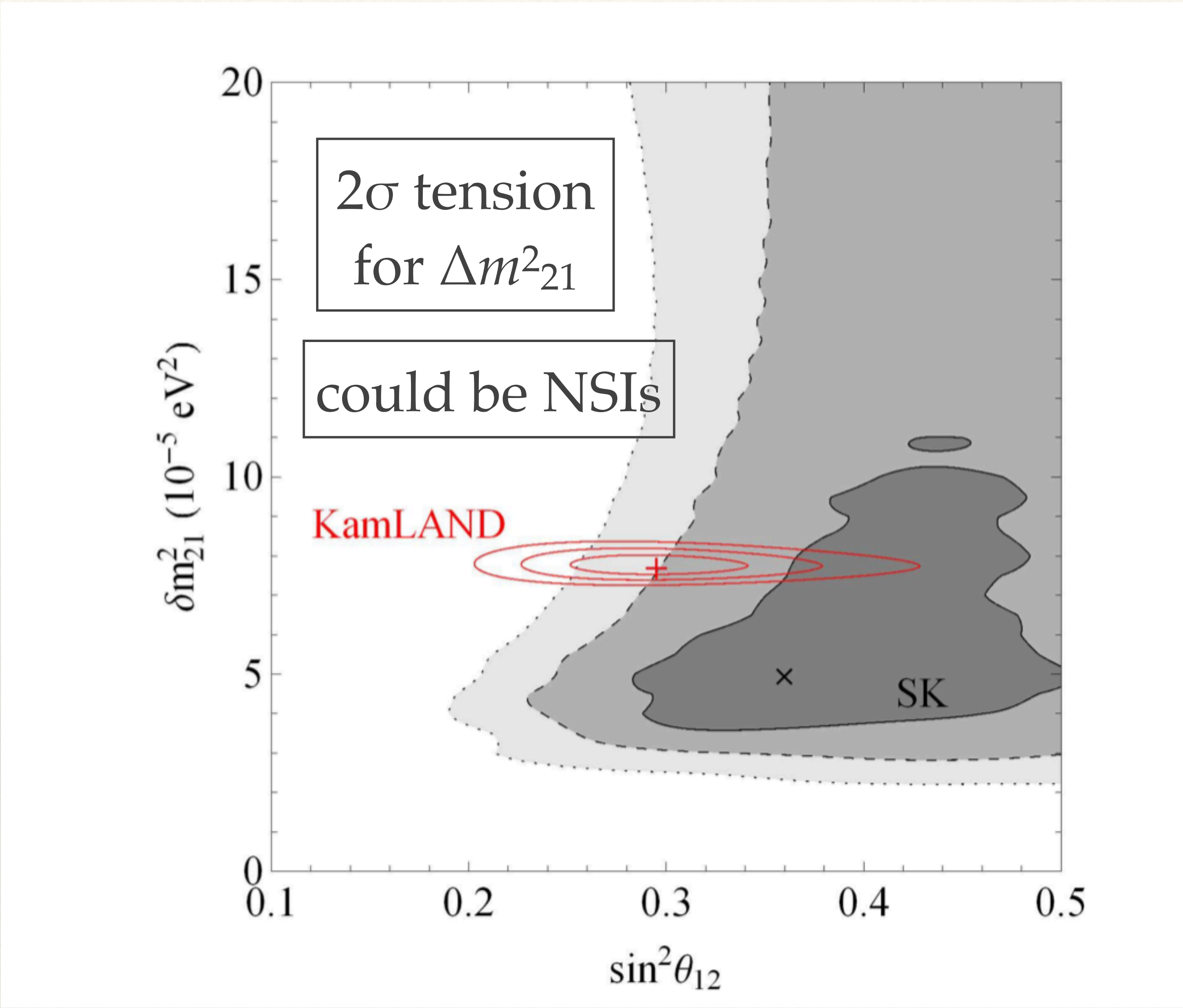


NSI can prevent determination of mass ordering!

Masud, Mehta, 1606.05662

NSIs for solar parameters

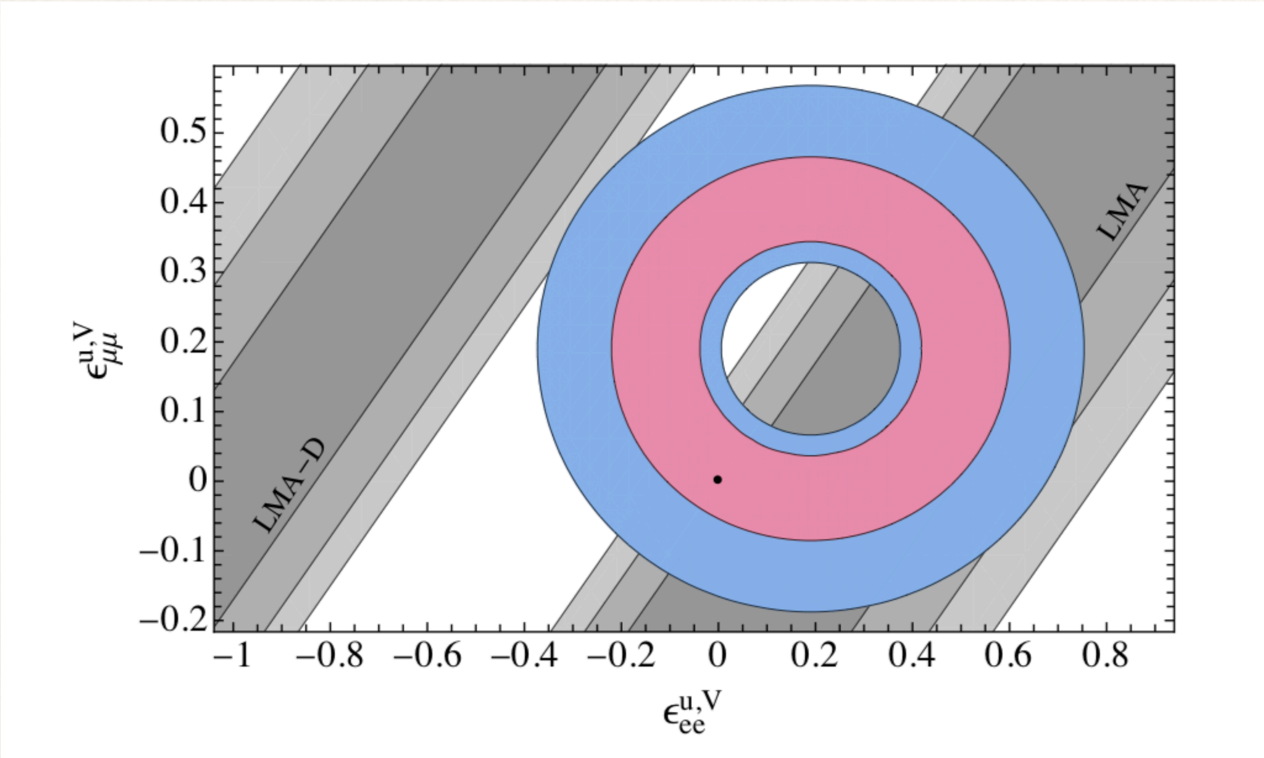




Miranda, Tortola, Valle, hep-ph/0406280

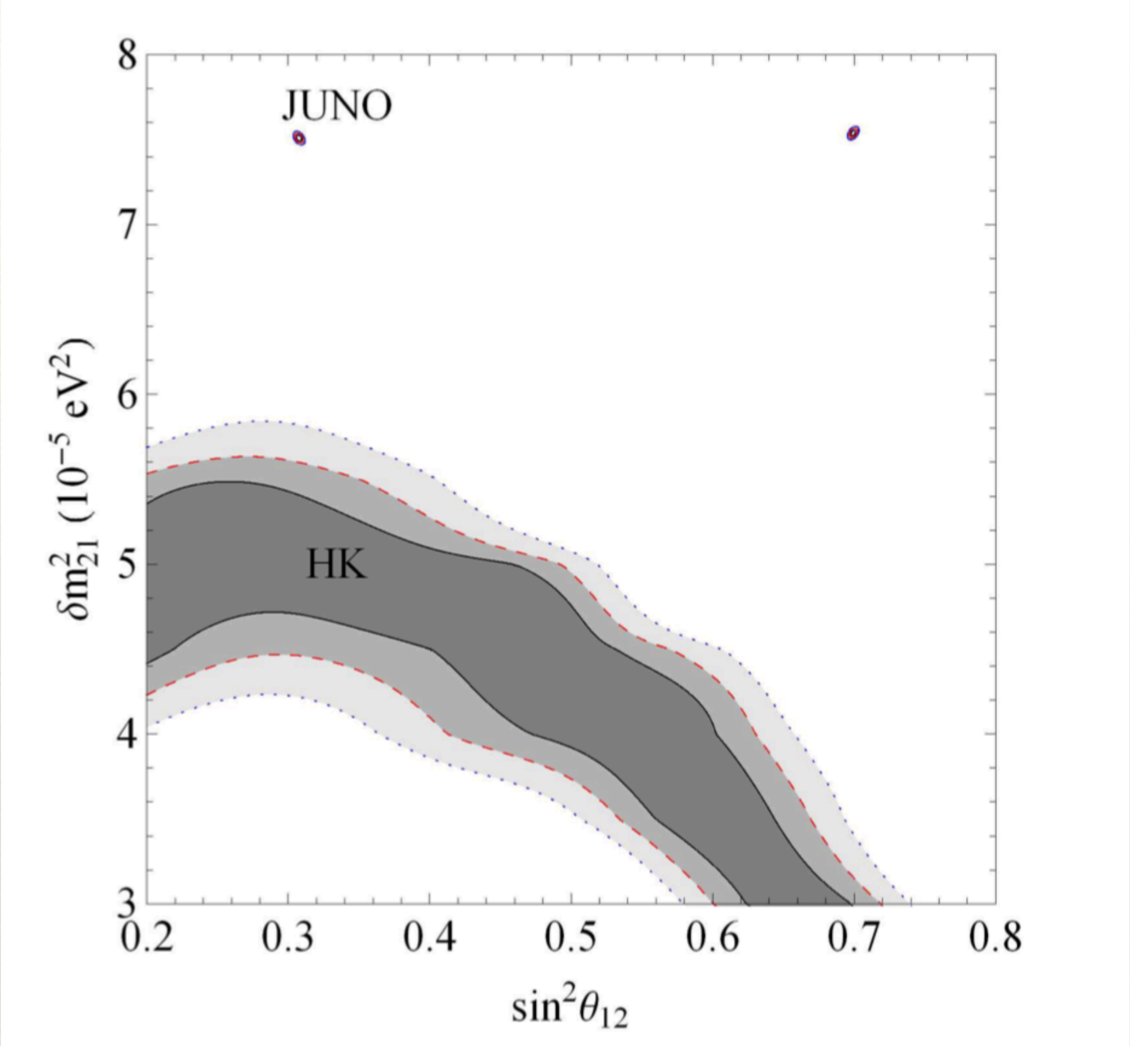
Liao, Marfatia, Whisnant, 1704.04711

NSIs for solar parameters



COHERENT
disfavors LMA-dark
with about 3σ

Coloma et al., 1708.02899



JUNO and HyperK
would reject no NSI-case by 7σ

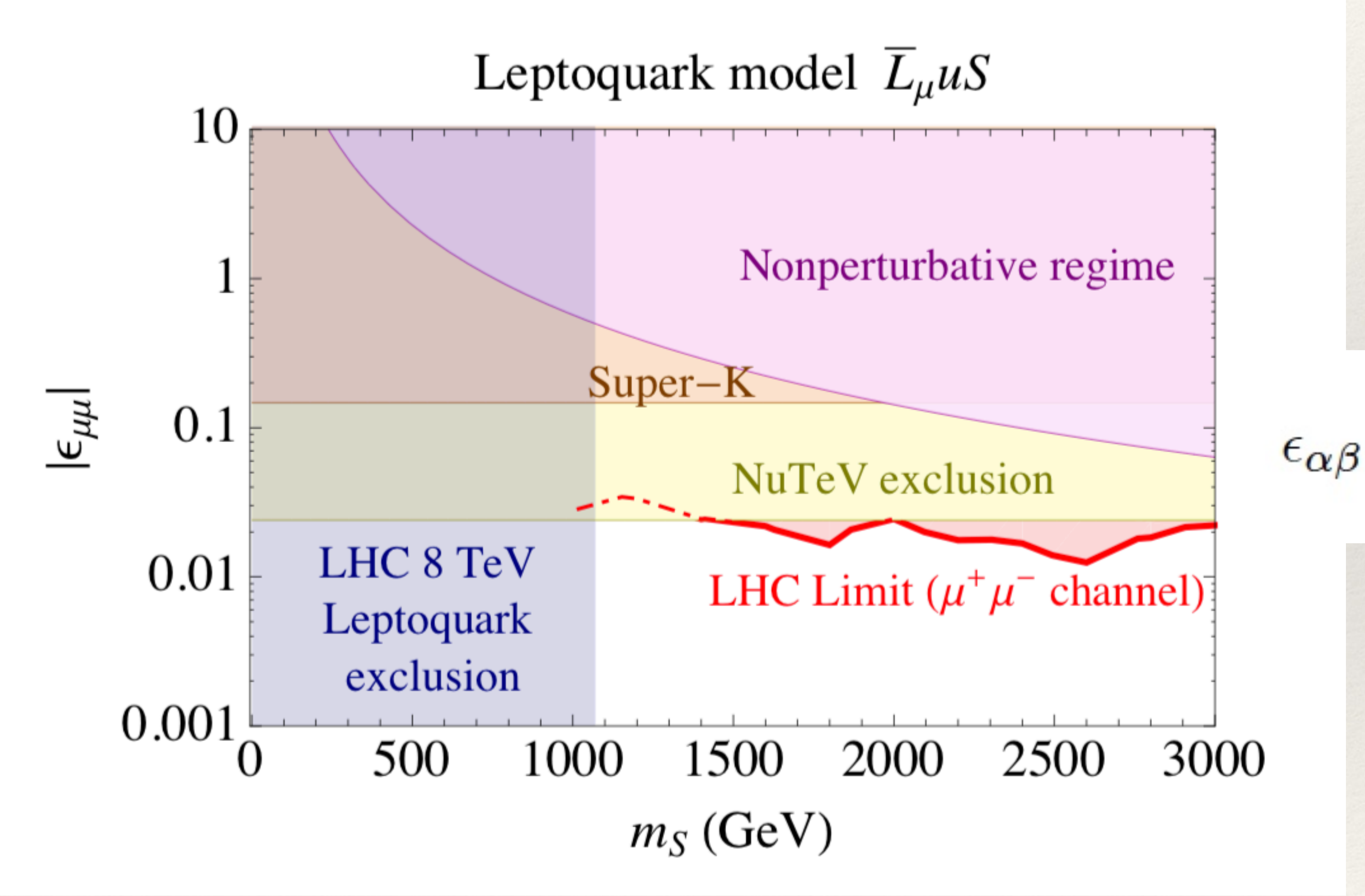
Liao, Marfatia, Whisnant, 1704.04711

Origin of NSIs

- ε from integrating out scalar of type II seesaw: $\varepsilon^e_{\alpha\beta} \propto (m_\nu)_{\alpha\beta}$ *(Malinsky, Ohlsson, Zhang, 0811.3346)*
- if color needed to generate $\varepsilon^q_{\alpha\beta}$: $|\epsilon_{e\mu}|^2 = \epsilon_{ee}\epsilon_{\mu\mu}, \quad |\epsilon_{\mu\tau}|^2 = \epsilon_{\mu\mu}\epsilon_{\tau\tau}, \quad |\epsilon_{e\tau}|^2 = \epsilon_{ee}\epsilon_{\tau\tau}$
- ε from Z' of L_μ - L_τ: $\varepsilon_{\mu\mu} = - \varepsilon_{\tau\tau}$ *(Heeck, WR, 1107.5238)*
- ε from integrating out leptoquarks *(Wise, Zhang, 1404.4663)*
- ε from integrating out charge +1 scalar singlet: $\varepsilon_{\alpha\beta}$ antisymmetric
- ε from loop effects, including secret neutrino interactions *(Bischer, WR, Xu, 1807.08102)*
- ε from higher dimensional operators *(Gavela et al., 0809.3451)*; within flavor symmetry models have information on flavor symmetry *(Wang, Zhou, 1801.05656)*
- ε from integrating out Z' *(Heeck, Lindner, WR, Vogl, 1812.04067)*

Example I: Leptoquark

Colored $SU(2)_L$ doublet with hypercharge -7/3 $\mathcal{L} = \lambda_{ij} \overline{L_i} P_R u_j S$



$$\epsilon_{\alpha\beta} = -\frac{3}{4} \frac{\lambda_{\alpha 1} \lambda^*_{\beta 1}}{\sqrt{2} G_F m_S^2},$$

Wise, Zhang, 1404.4663

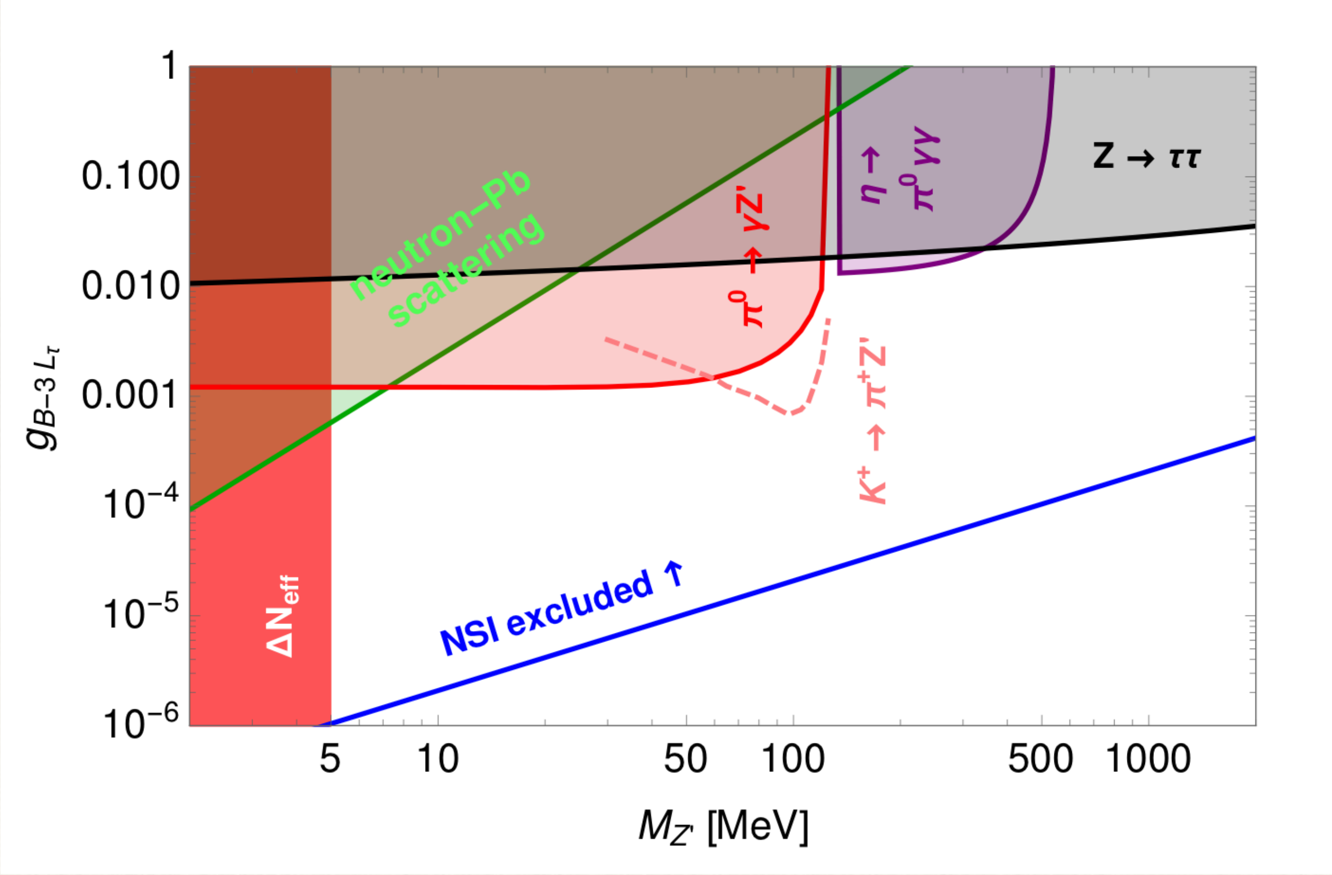
Example II: flavor-dependent Z'

Introducing RH neutrinos: most general anomaly-free $U(1)_X$ given by:

$$X = r_{BL}(B-L) + r_{\mu\tau}(L_\mu - L_\tau) + r_{\mu e}(L_\mu - L_e)$$

Araki, Heeck, Kubo, 1203.4951

for NSI in oscillations and **no** Z-Z' mixing: need r_{BL} or $r_{\mu e}$



Heeck, Lindner, WR, Vogl, 1812.04067

Example II: flavor-dependent *Z'*

now Z' **without** direct coupling to first generation matter $\Rightarrow$ needs Z-Z' mixing:

$$\mathcal{L}_{\rm mix} = -\frac{\sin\chi}{2}\hat{Z}'^{\mu\nu}\hat{B}_{\mu\nu} + \delta\hat{M}^2\hat{Z}'_\mu\hat{Z}^\mu$$

kinetic mixing;
must exist

mass mixing;
needs scalar charged
under SM and $U(1)_X$

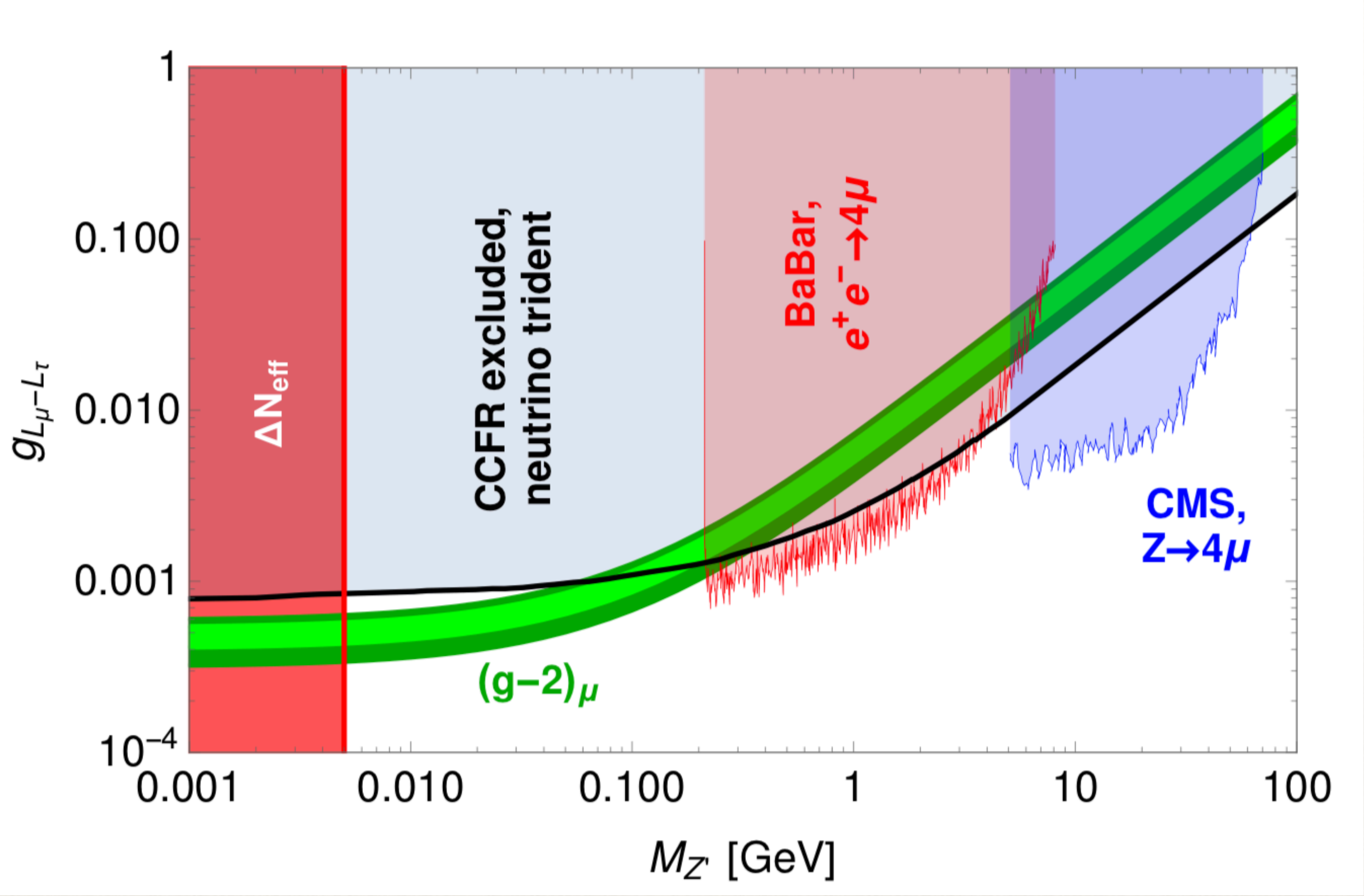
$$\varepsilon \propto \delta M^2$$

- if only kinetic mixing: no NSI in LBL experiments!
- hence, if observed, need scalar charged under SM and $U(1)_X$

$\Rightarrow$ ***non-standard Higgs physics***

Heeck, Lindner, WR, Vogl, 1812.04067

Example II: flavor-dependent *Z'*



$\varepsilon_{\mu\mu} = - \varepsilon_{\tau\tau}$

g-2 region cannot give large NSI

COHERENT weaker than oscillation result

$$\epsilon^n_{\tau\tau} - \epsilon^n_{\mu\mu} = 2(\epsilon^n_{ee} - \epsilon^n_{\mu\mu}) = -2\frac{eg'}{4\sqrt{2}G_F s_W c_W}\frac{\delta\hat{M}^2}{M_Z^2 M_{Z'}^2 c_\chi^2}$$

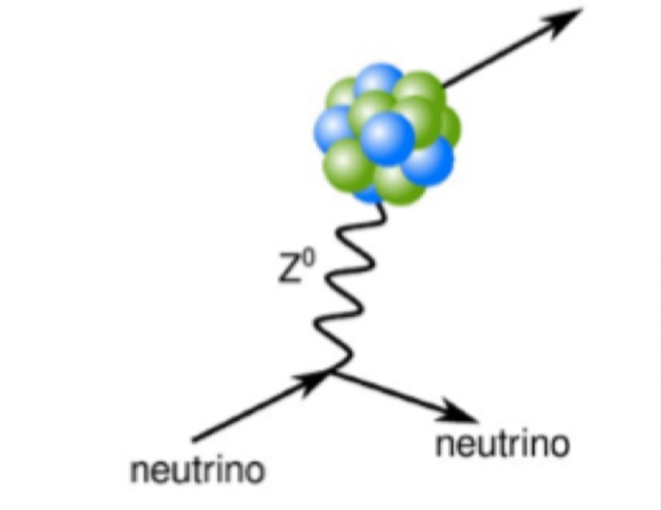
can be % for $M(Z')$= 60…150 GeV

Heeck, Lindner, WR, Vogl, 1812.04067

Coherent Elastic Neutrino-Nucleus Scattering

Freedman, PRD9, 1974

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



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

replace with:

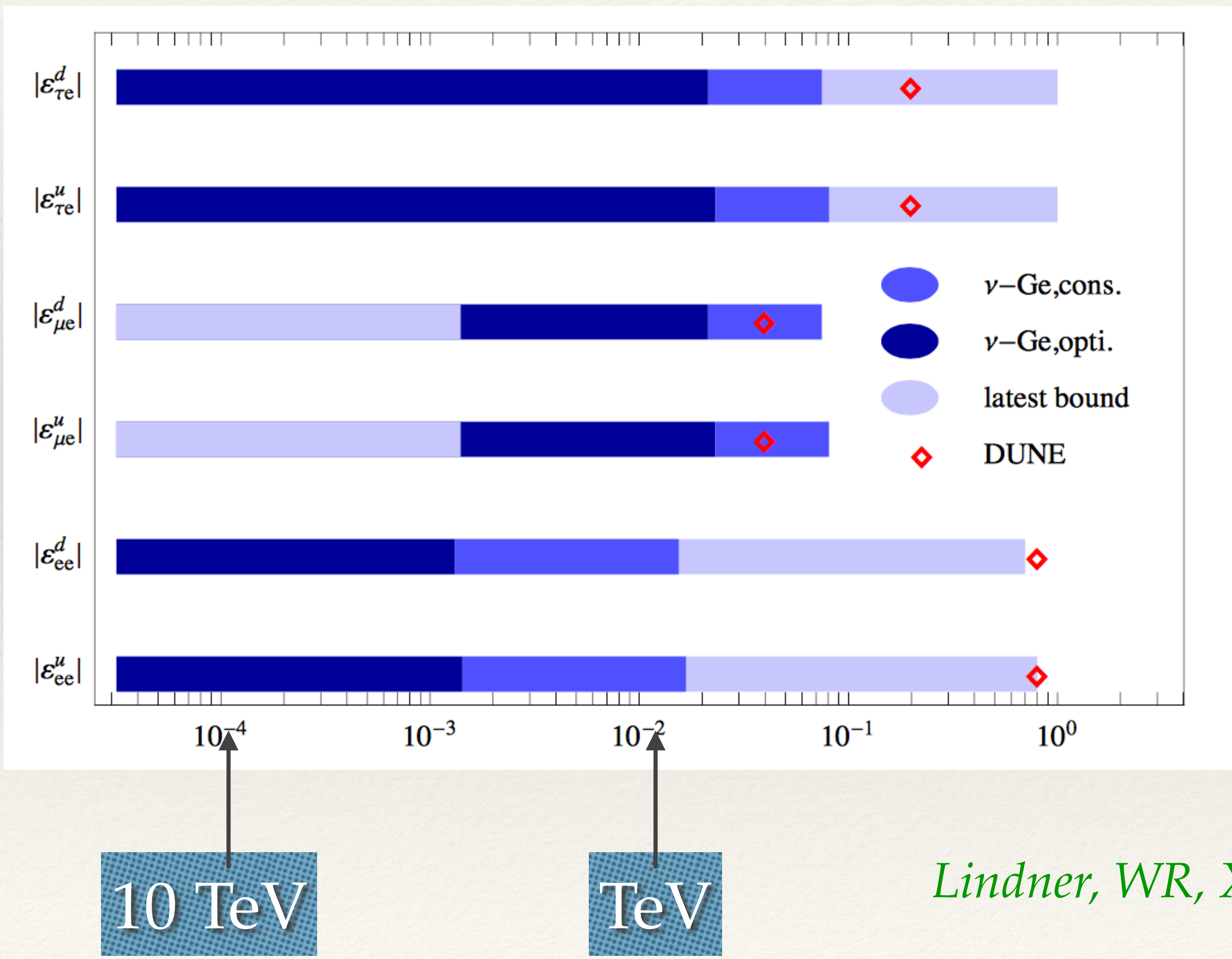
$$Q^2_{\rm NSI} \equiv 4\left[N\left(-\frac{1}{2} + \varepsilon^{uV}_{ee} + 2\varepsilon^{dV}_{ee}\right) + Z\left(\frac{1}{2} - 2s_W^2 + 2\varepsilon^{uV}_{ee} + \varepsilon^{dV}_{ee}\right)\right]^2 + 4\sum_{\alpha=\mu,\tau}\left[N(\varepsilon^{uV}_{\alpha e} + 2\varepsilon^{dV}_{\alpha e}) + Z(2\varepsilon^{uV}_{\alpha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

Complementary to oscillation experiments; sensitive to $\varepsilon \propto \mathbb{1}$

∥-talks by Giunti, Rink

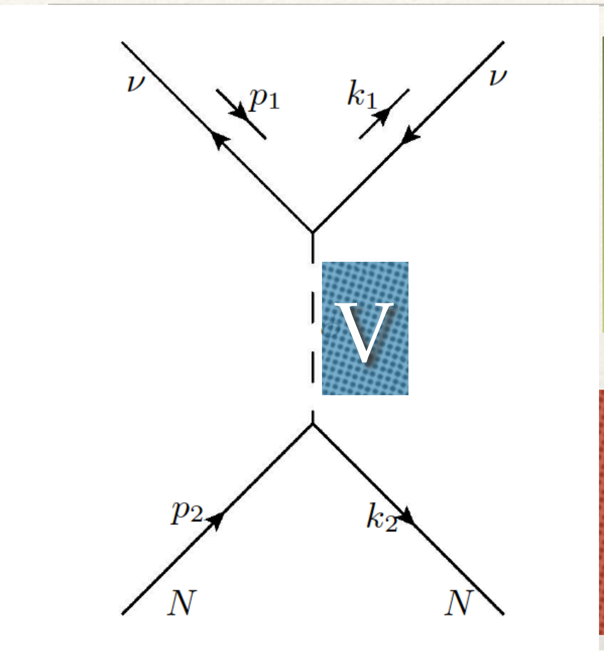
Coherent Elastic Neutrino-Nucleus Scattering

Example: CONUS-100 like, BG 3/day/kg/keV,
exposure: 5 kg yr GW m^{-2}



Lindner, WR, Xu, 1612.04150

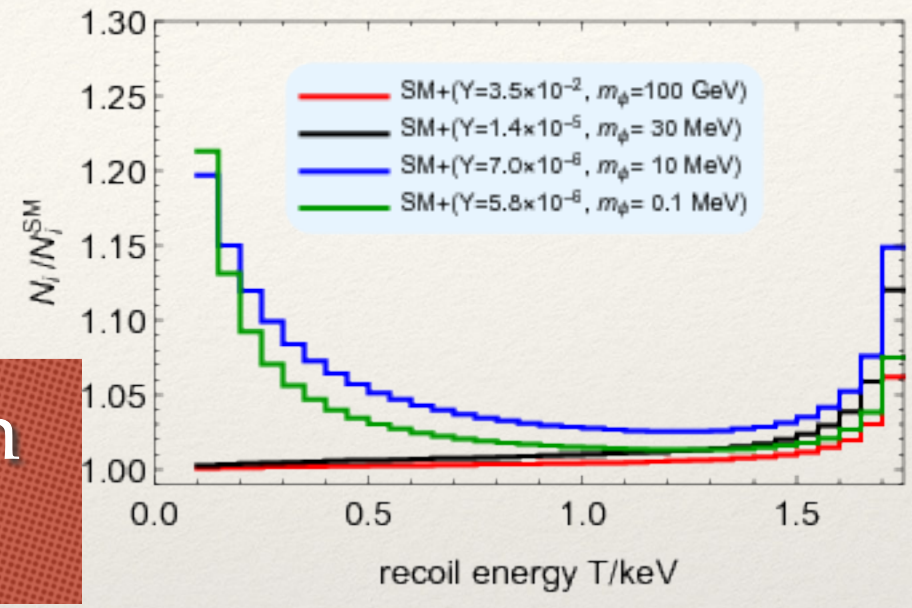
Coherent Elastic Neutrino-Nucleus Scattering

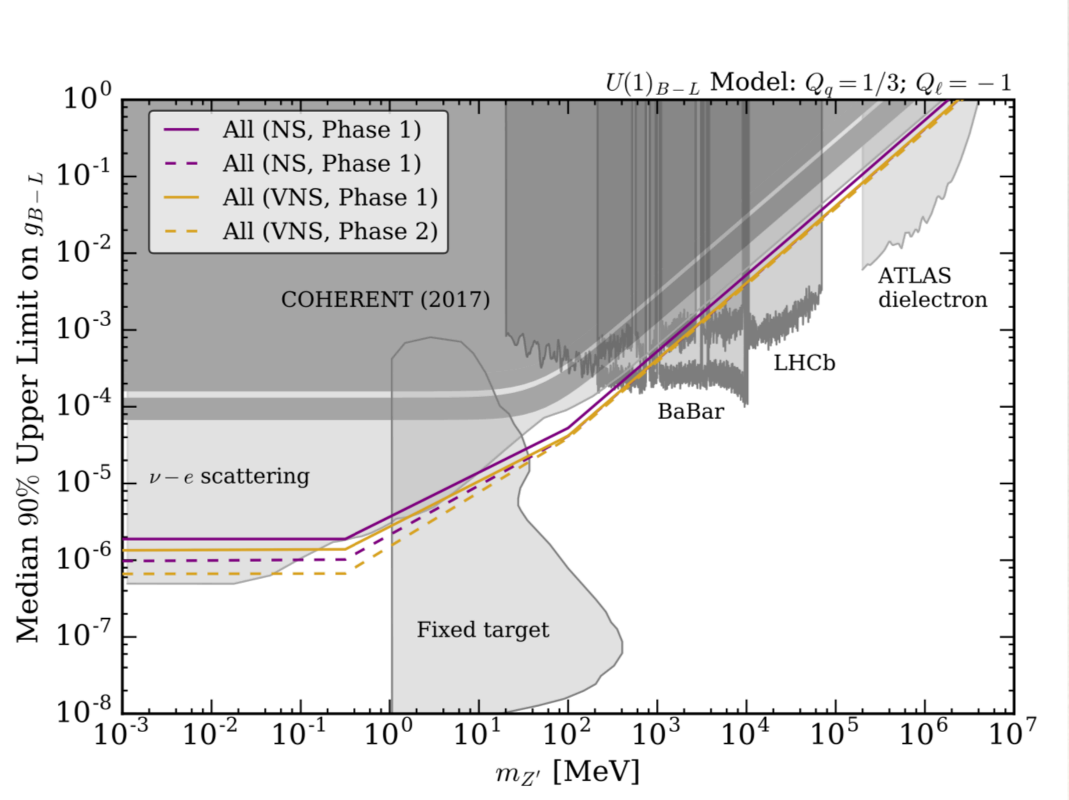


diff. cross section:

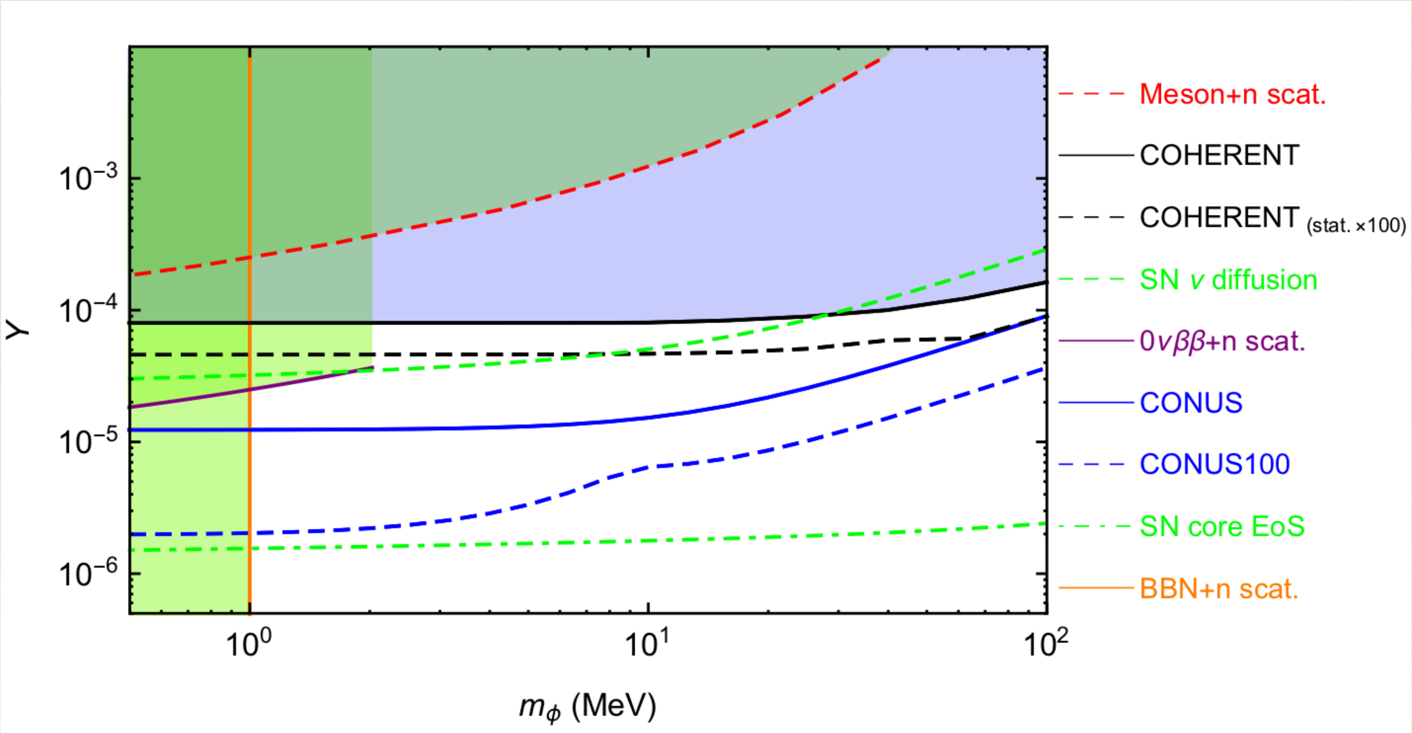
$\propto (2\,M\,T + m^2_V)^{-2}$

heavy and light NSI origin can be distinguished!



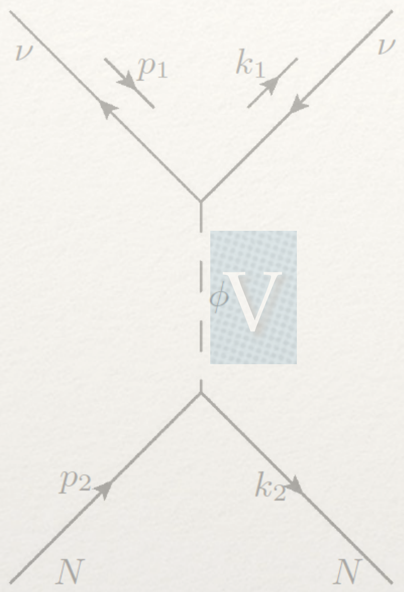


Billard et al., 1805.01798



Farzan et al., 1802.05171

Coherent Elastic Neutrino-Nucleus Scattering



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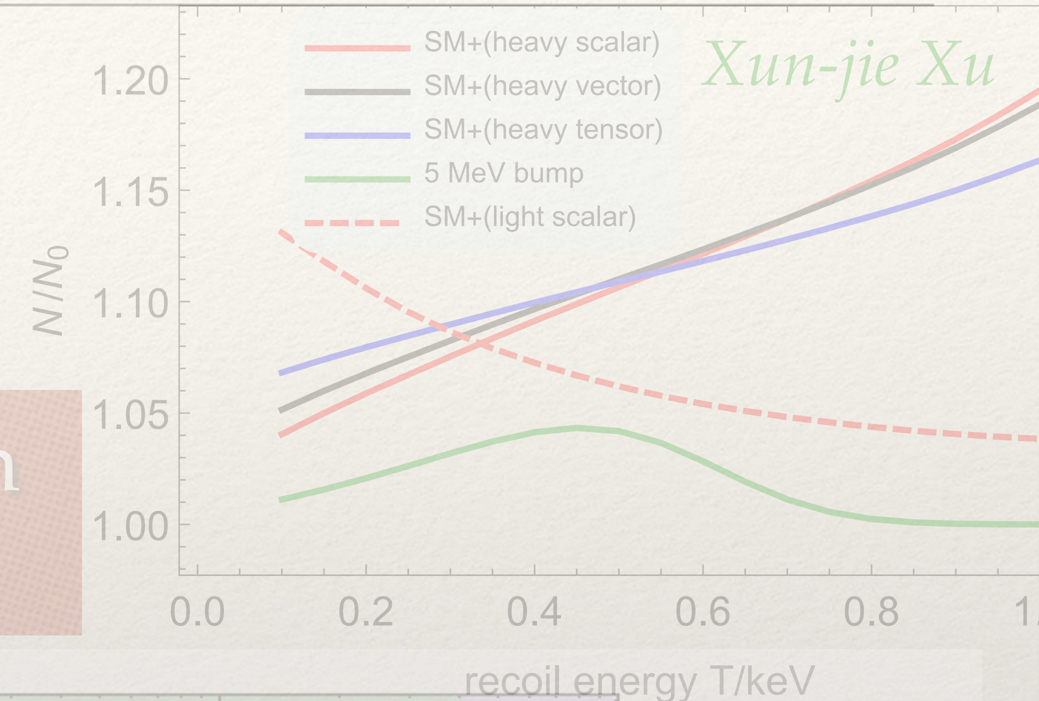
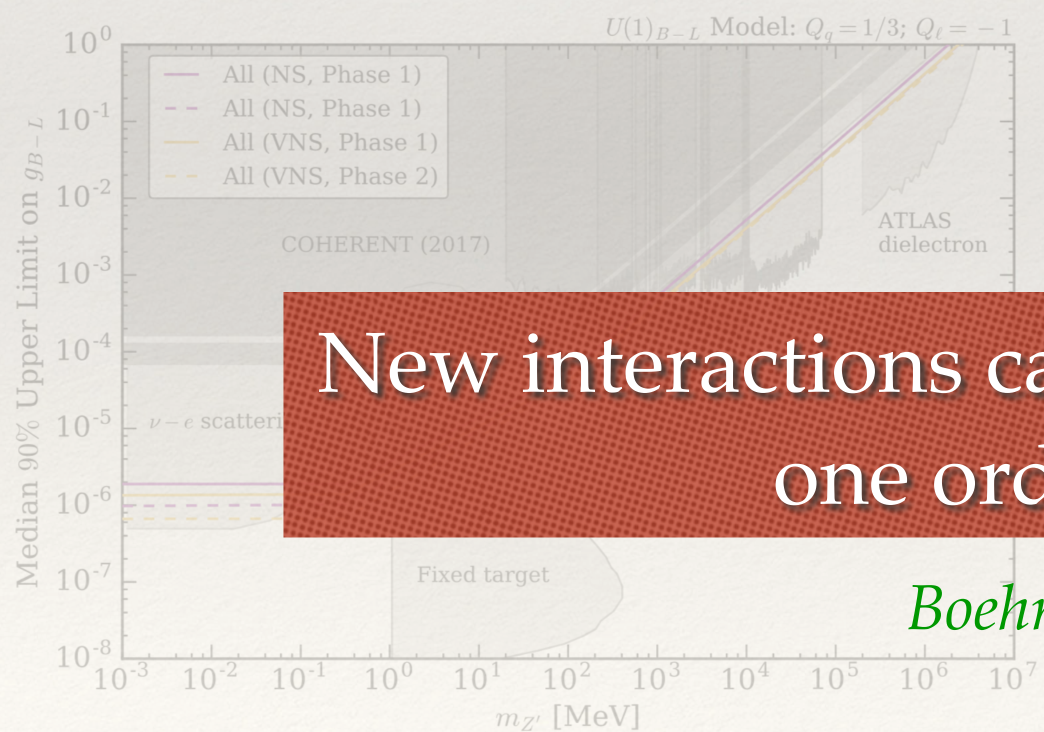
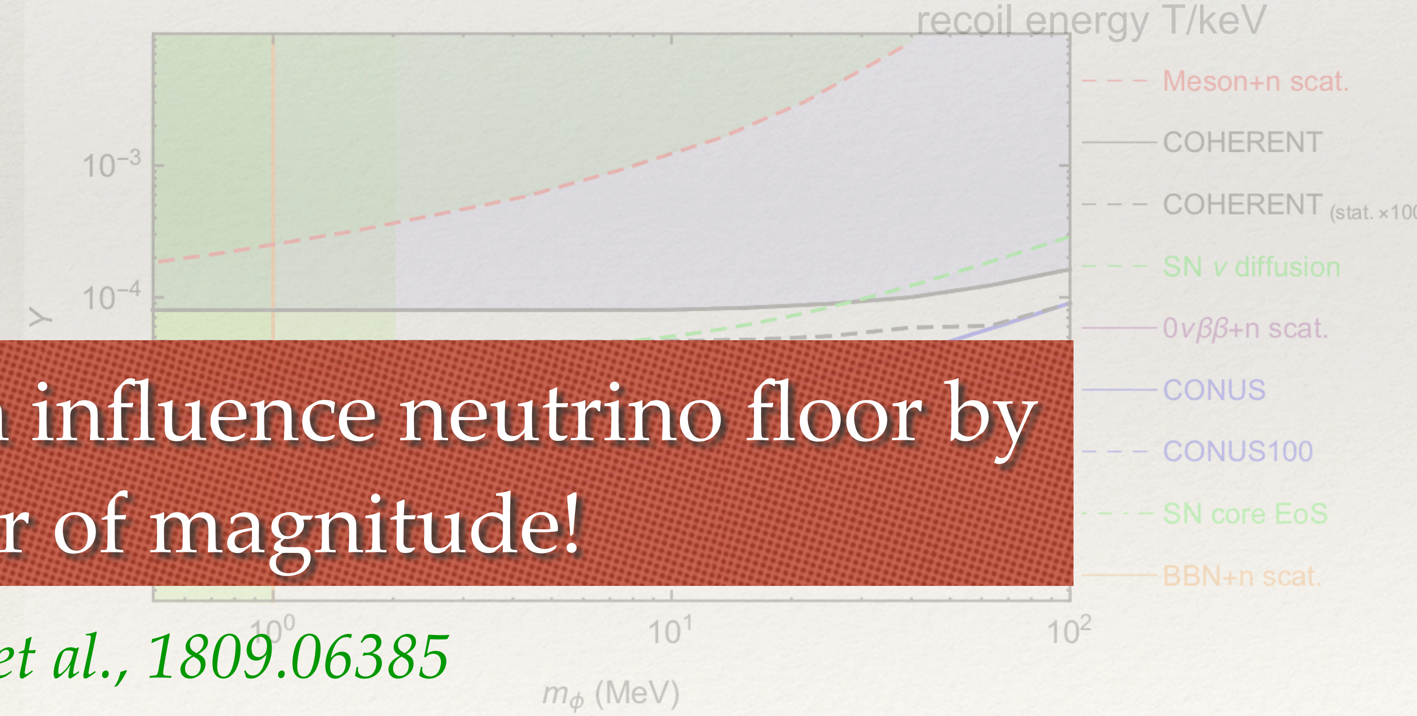






New interactions can influence neutrino floor by one order of magnitude!

Boehm et al., 1809.06385

Billard et al., 1805.01798

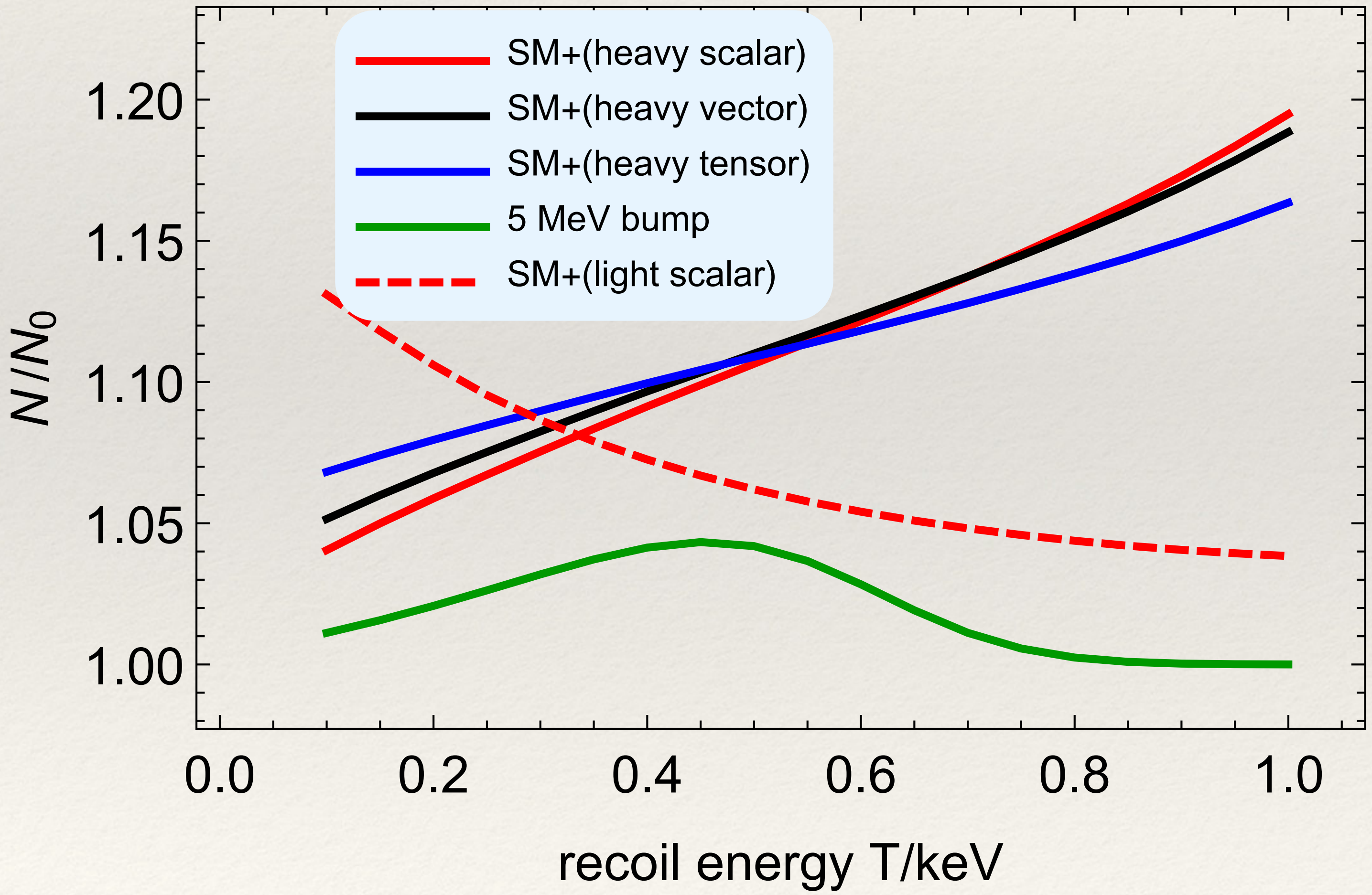
Farzan et al., 1802.05171

Coherent Elastic Neutrino-Nucleus Scattering

General Neutrino Interactions (GNI):
scalar, pseudoscalar, vector, axialvector, tensor

$$\mathcal{L}^{\rm NC} = -\frac{G_F}{\sqrt{2}} \sum_{j=1}^{10} \left(\overset{(\sim)}{\epsilon}_{j,f} \right)^{\alpha\beta\gamma\delta} (\overline{\nu}_\alpha \mathcal{O}_j \nu_\beta)\,(\overline{f}_\gamma \mathcal{O}'_j f_\delta)$$

same for CC (β-decay)



- obtainable from SMEFT with N_R
- then CC and NC correlated
- UV-completion via leptoquarks (*B*-anomalies and radiative neutrino mass)

‖-talk by Bischer

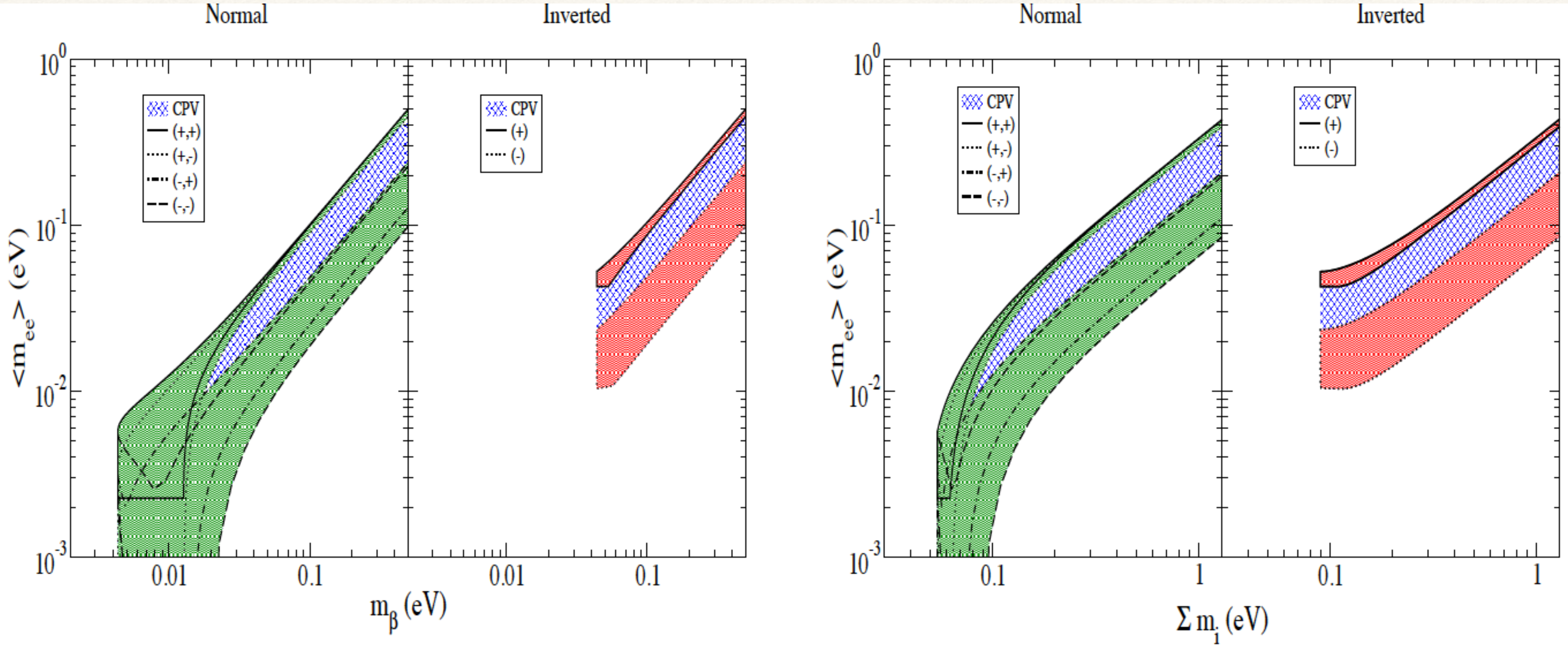
Lindner, WR, Xu, 1612.04150; Sierra et al., 1806.07424

Neutrino Mass Observables

Method	Observable	current	near	far	pro	con
Kurie	$(\sum \lvert U_{ei} \rvert^2 m_i^2)^{1/2}$	2.3 eV	0.3 eV	0.1 eV?	model-indep.; clean	final; weakest
cosmo	$\sum m_i$	0.25 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

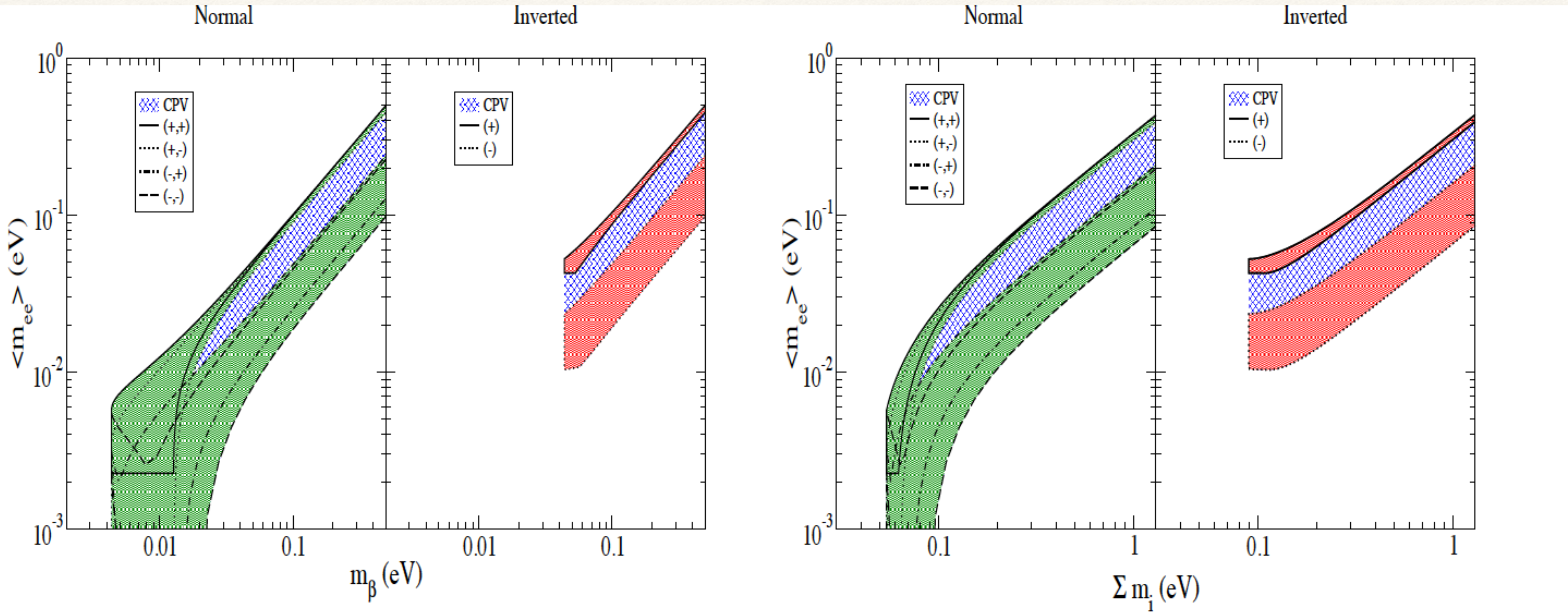
$0\nu\beta\beta$: see talks by Gratta, Vissani, ∥-talks by Singh, Lubashevskiy, Li, Pazos, Chiesa

Neutrino Mass Observables



complete complementarity of observables

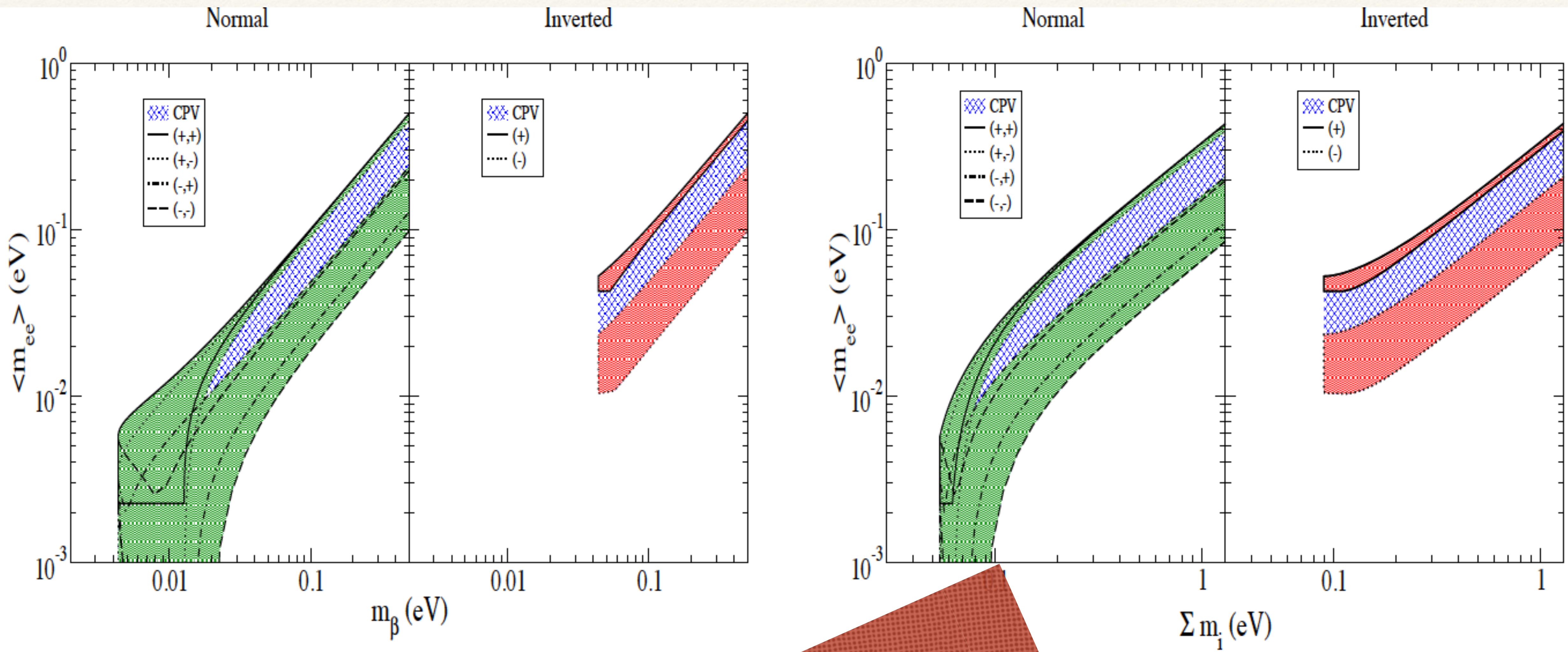
Neutrino Mass Observables



complete c … arity
… vables

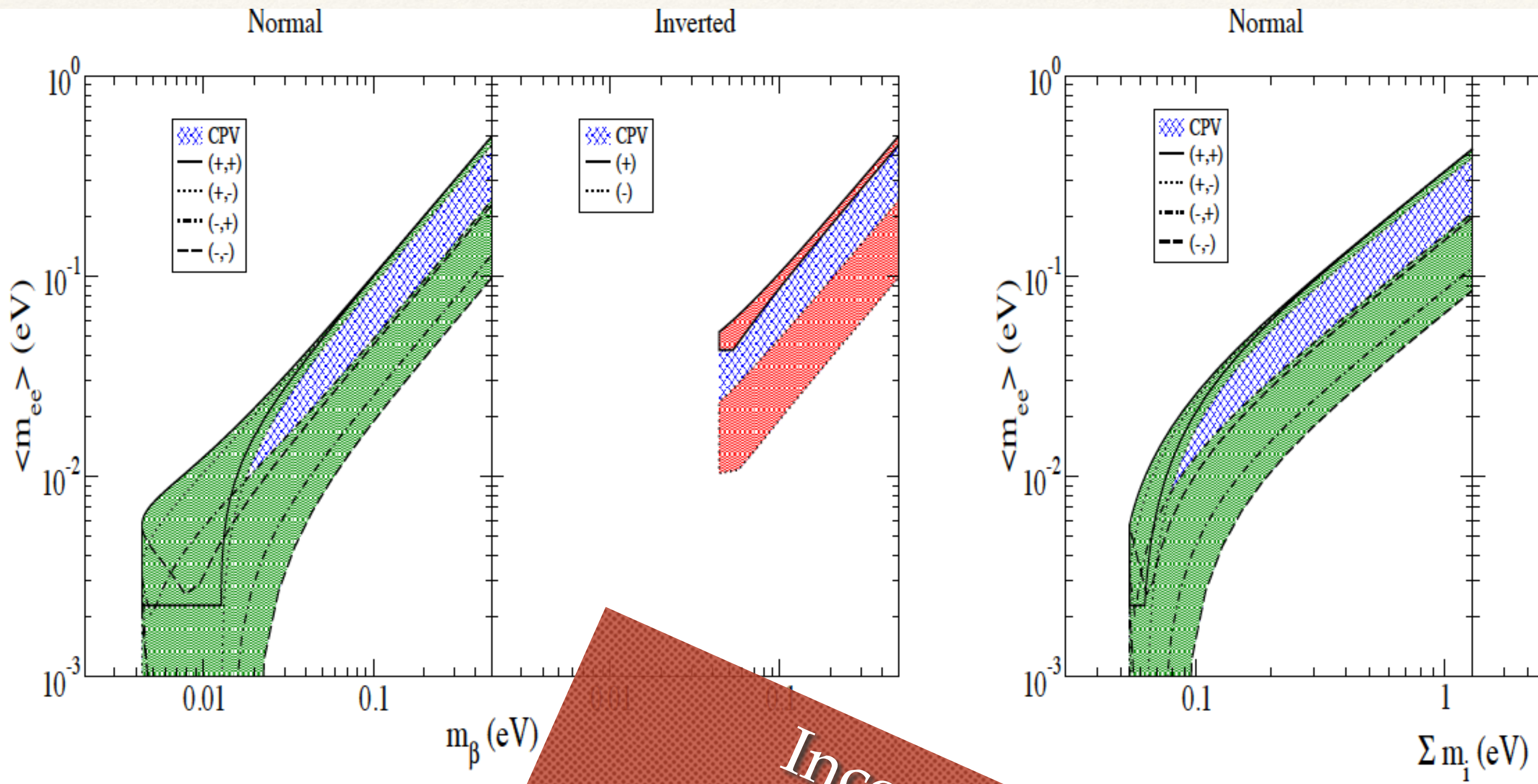
All need to be pursued!

Neutrino Mass Observables



Consistency
would be spectacular
confirmation !

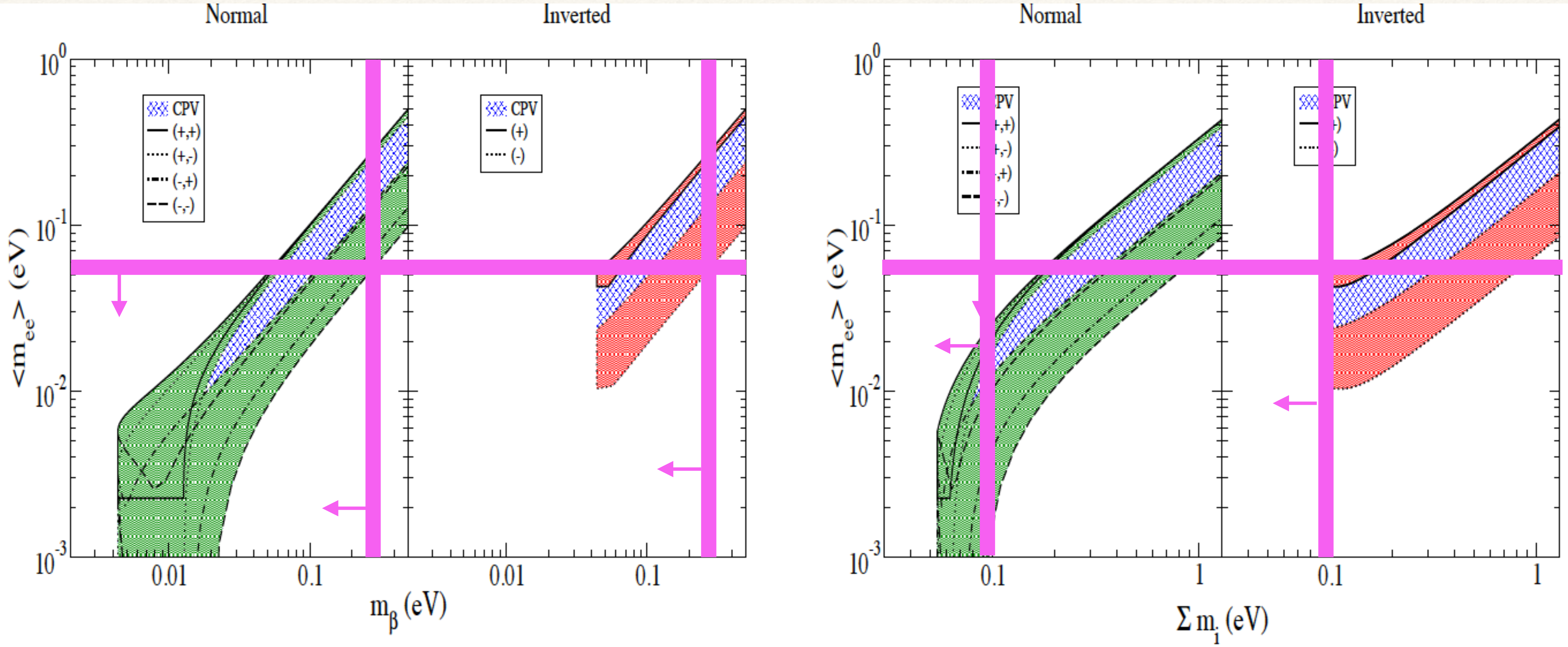
Neutrino Mass Observables



comp
of ob

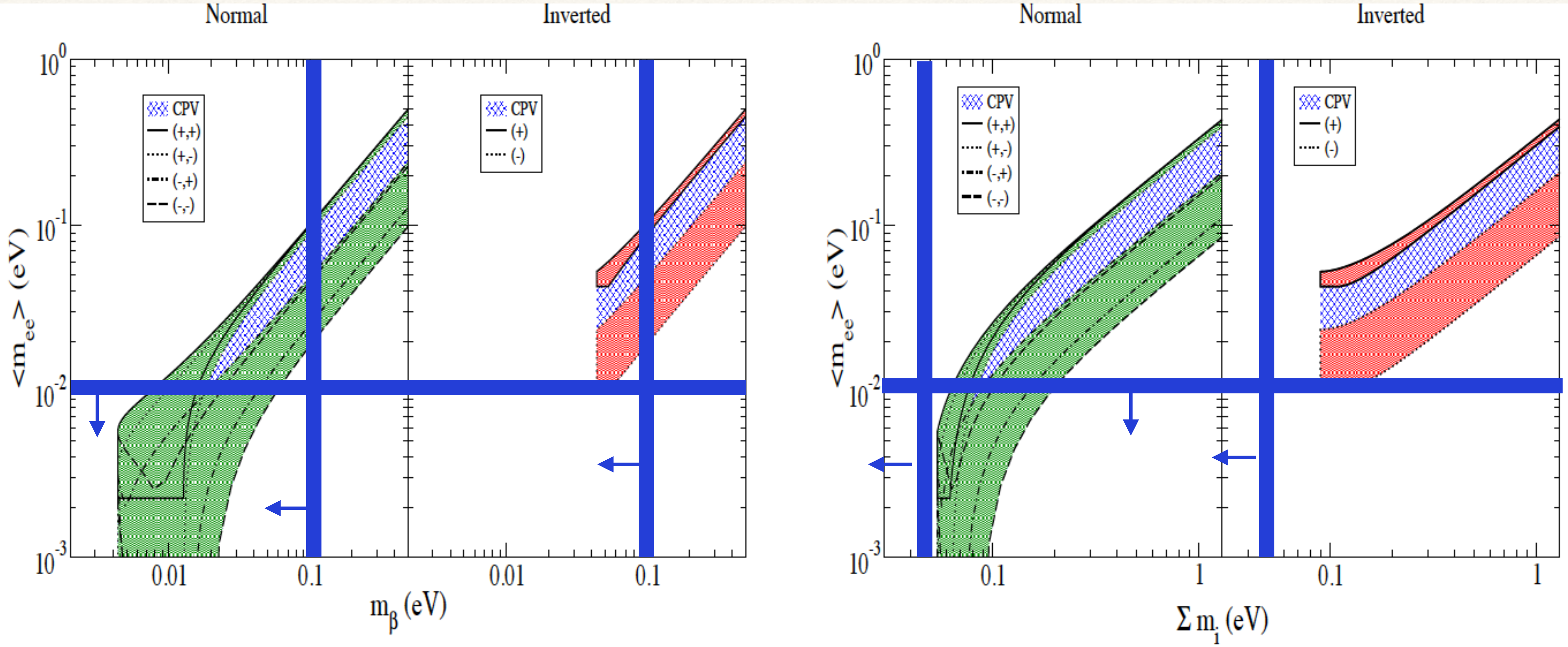
Inconsistencies would be major discovery!

Neutrino Mass Observables



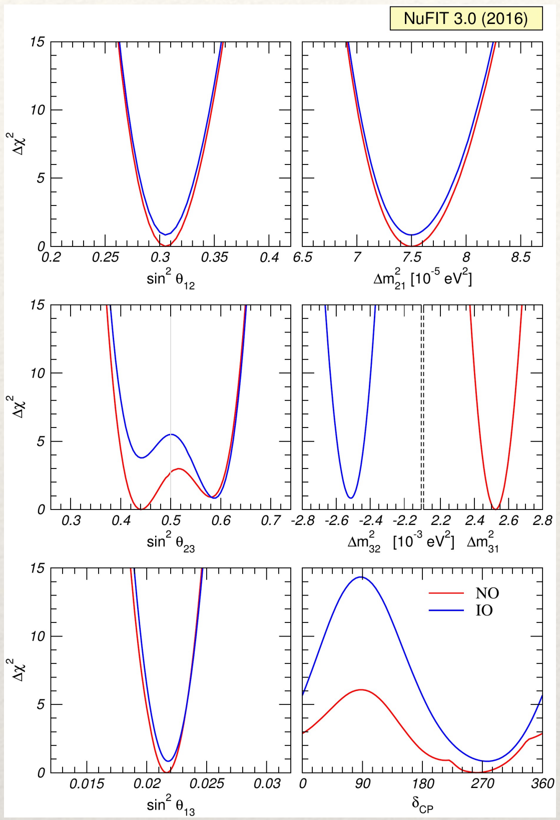
near future

Neutrino Mass Observables



far future

Expectations of lifetimes

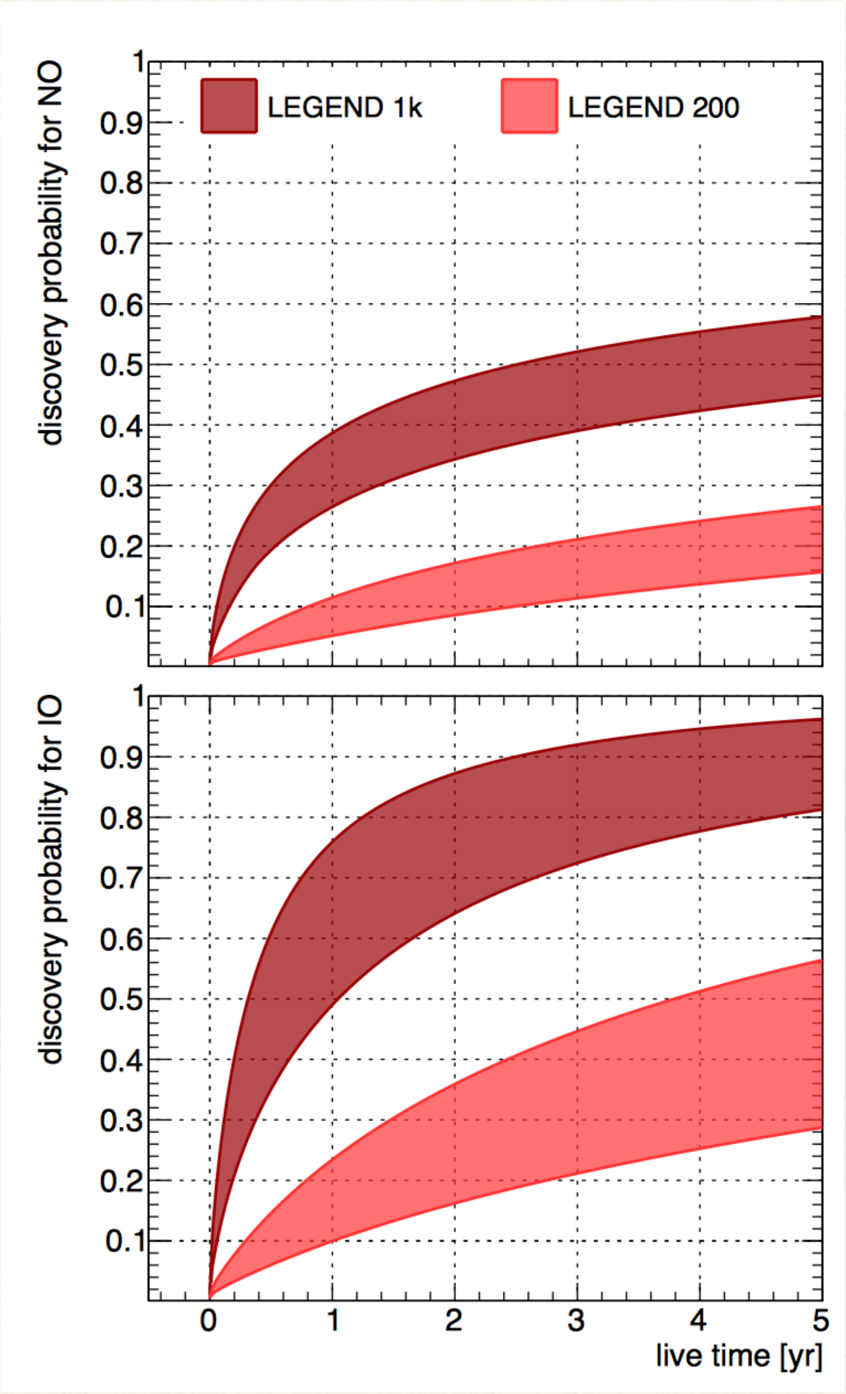


oscillation fits

+

expt. sensitiv.

Experiment	Iso.	Iso. Mass [kg_{iso}]	σ [keV]	ROI [σ]	ϵ_{FV} [%]	ϵ_{sig} [%]	$\mathcal{E}$ $\left[\frac{kg_{iso}\,yr}{yr}\right]$	$\mathcal{B}$ $\left[\frac{cts}{kg_{iso}\,ROI\,yr}\right]$	3σ disc. sens. $\hat{T}_{1/2}$ [yr]	3σ disc. sens. $\hat{m}_{\beta\beta}$ [meV]	Required Improvement: Bkg	Required Improvement: σ	Required Improvement: Iso. Mass
LEGEND 200 [61, 62]	^{76}Ge	175	1.3	[-2, 2]	93	77	119	$1.7\cdot10^{-3}$	$8.4\cdot10^{26}$	40–73	3	1	5.7
LEGEND 1k [61, 62]	^{76}Ge	873	1.3	[-2, 2]	93	77	593	$2.8\cdot10^{-4}$	$4.5\cdot10^{27}$	17–31	18	1	29
SuperNEMO [68, 69]	^{82}Se	100	51	[-4, 2]	100	16	16.5	$4.9\cdot10^{-2}$	$6.1\cdot10^{25}$	82–138	49	2	14
CUPID [58, 59, 70]	^{82}Se	336	2.1	[-2, 2]	100	69	221	$5.2\cdot10^{-4}$	$1.8\cdot10^{27}$	15–25	n/a	6	n/a
CUORE [52, 53]	^{130}Te	206	2.1	[-1.4, 1.4]	100	81	141	$3.1\cdot10^{-1}$	$5.4\cdot10^{25}$	66–164	6	1	19
CUPID [58, 59, 70]	^{130}Te	543	2.1	[-2, 2]	100	81	422	$3.0\cdot10^{-4}$	$2.1\cdot10^{27}$	11–26	3000	1	50
SNO+ Phase I [66, 71]	^{130}Te	1357	82	[-0.5, 1.5]	20	97	164	$8.2\cdot10^{-2}$	$1.1\cdot10^{26}$	46–115	n/a	n/a	n/a
SNO+ Phase II [67]	^{130}Te	7960	57	[-0.5, 1.5]	28	97	1326	$3.6\cdot10^{-2}$	$4.8\cdot10^{26}$	22–54	n/a	n/a	n/a
KamLAND-Zen 800 [60]	^{136}Xe	750	114	[0, 1.4]	64	97	194	$3.9\cdot10^{-2}$	$1.6\cdot10^{26}$	47–108	1.5	1	2.1
KamLAND2-Zen [60]	^{136}Xe	1000	60	[0, 1.4]	80	97	325	$2.1\cdot10^{-3}$	$8.0\cdot10^{26}$	21–49	15	2	2.9
nEXO [72]	^{136}Xe	4507	25	[-1.2, 1.2]	60	85	1741	$4.4\cdot10^{-4}$	$4.1\cdot10^{27}$	9–22	400	1.2	30
NEXT 100 [64, 73]	^{136}Xe	91	7.8	[-1.3, 2.4]	88	37	26.5	$4.4\cdot10^{-2}$	$5.3\cdot10^{25}$	82–189	n/a	1	20
NEXT 1.5k [74]	^{136}Xe	1367	5.2	[-1.3, 2.4]	88	37	398	$2.9\cdot10^{-3}$	$7.9\cdot10^{26}$	21–49	n/a	1	300
PandaX-III 200 [65]	^{136}Xe	180	31	[-2, 2]	100	35	60.2	$4.2\cdot10^{-2}$	$8.3\cdot10^{25}$	65–150	n/a	n/a	n/a
PandaX-III 1k [65]	^{136}Xe	901	10	[-2, 2]	100	35	301	$1.4\cdot10^{-3}$	$9.0\cdot10^{26}$	20–46	n/a	n/a	n/a

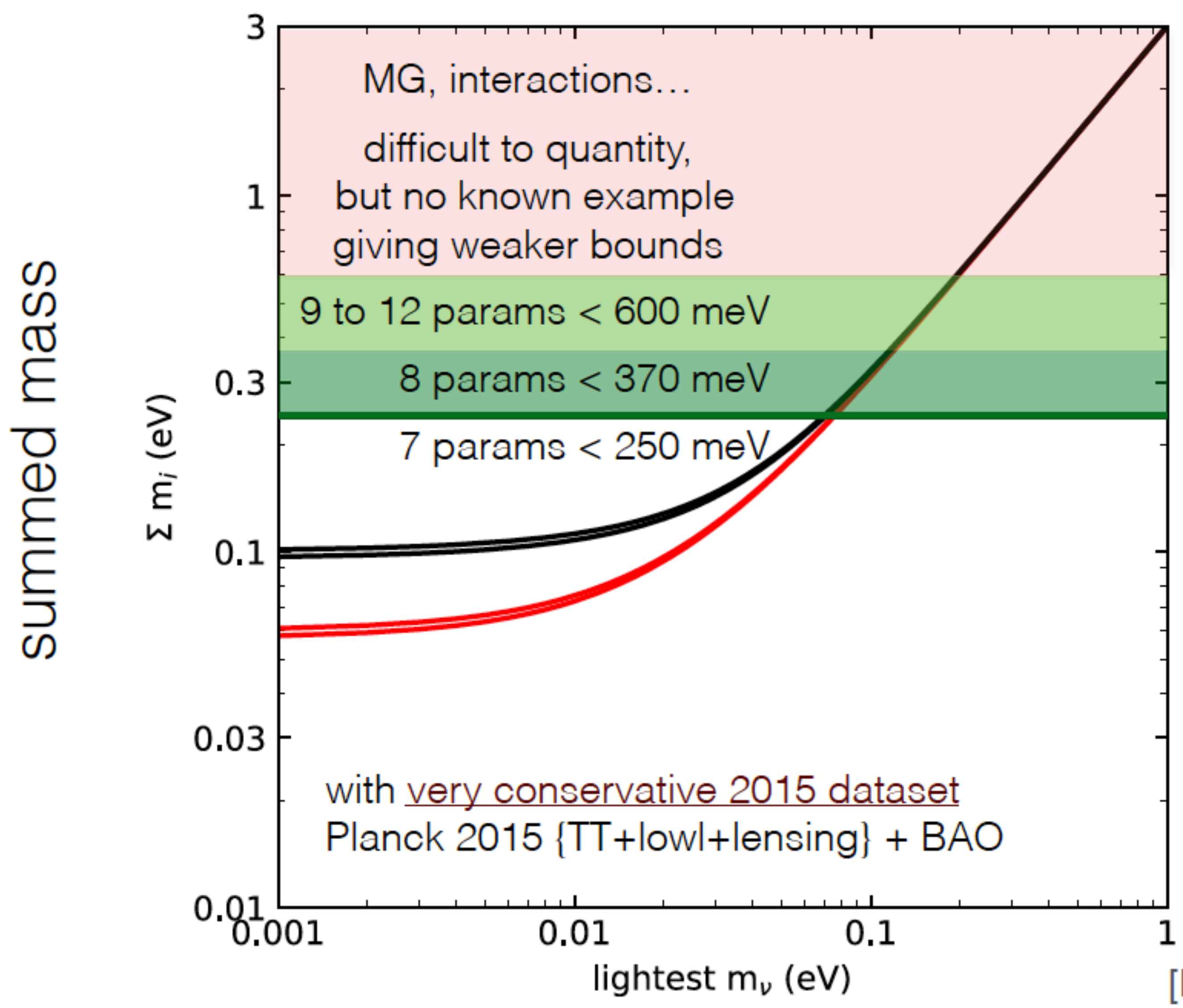


Bayesian discovery probability: discovery sensitivity (value of m_{ee} for which expt. has 50% chance to see it at 3σ) folded with probability distribution of m_{ee}

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

Cosmological Mass Bounds

95%CL upper bounds on $\Sigma_i m_i$ beyond 7 parameters



Usual suspects:

- extra massless relics
- extra light relics
- spatial curvature
- simplest dynamical DE
- primordial GWs
- primordial tilt running

Even more freedom in:

- modified Einstein Gravity
- interactions in DM sector
- ~~primordial perturbations~~

[Planck col.] 1502.01589; Di Valentino et al. 1507.06646

Lesgourgues, talk at Neutrino2018

future observation will have to see neutrino mass even in modest extensions!

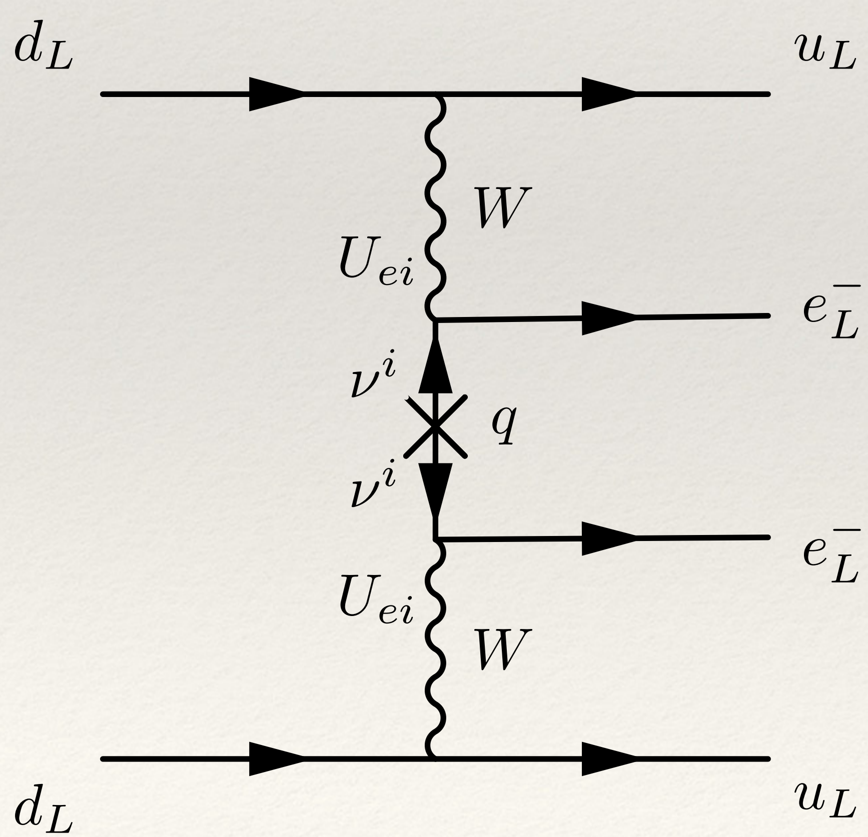
<u>E.g: 5σ detection when Euclid and SKA are combined!</u>

New Physics in Double Beta Decay

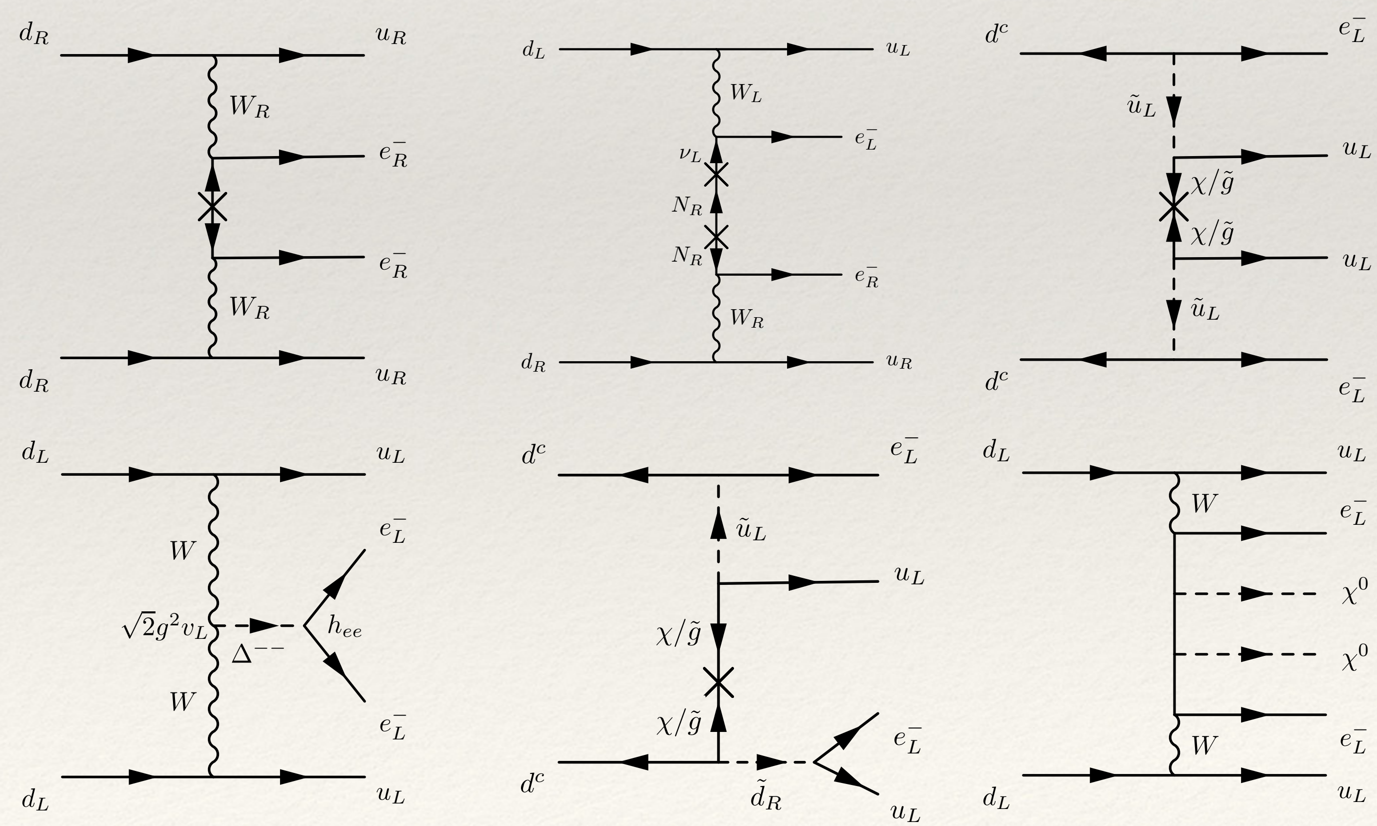
<u>Double Beta Decay is $\Delta L = 2$, not neutrino mass!</u>

Interpretations:

Standard:



Non-Standard:



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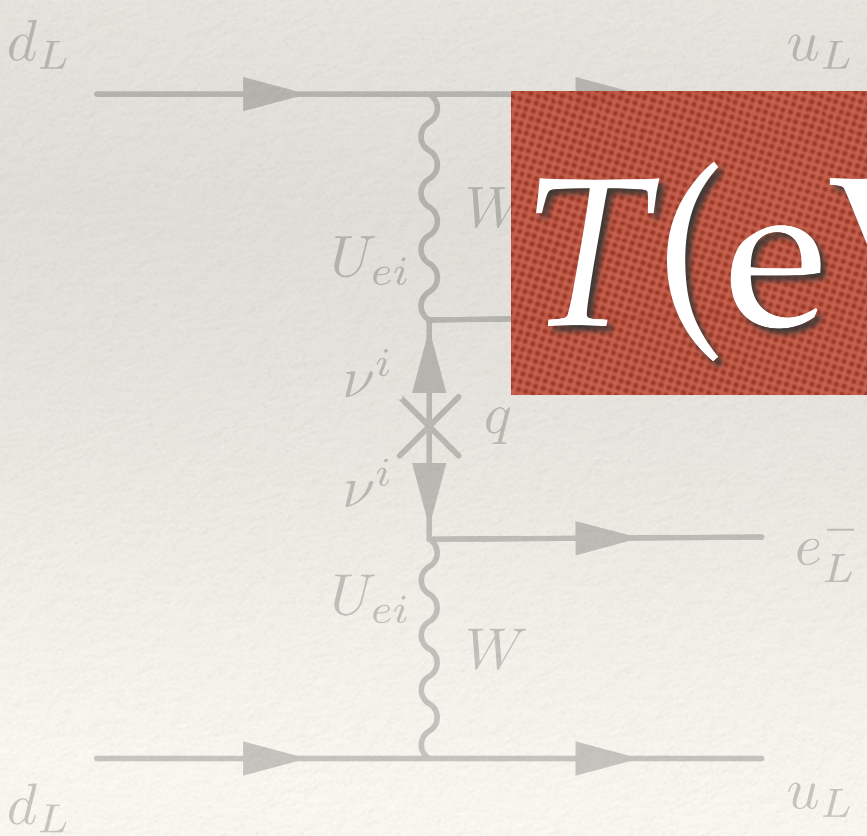

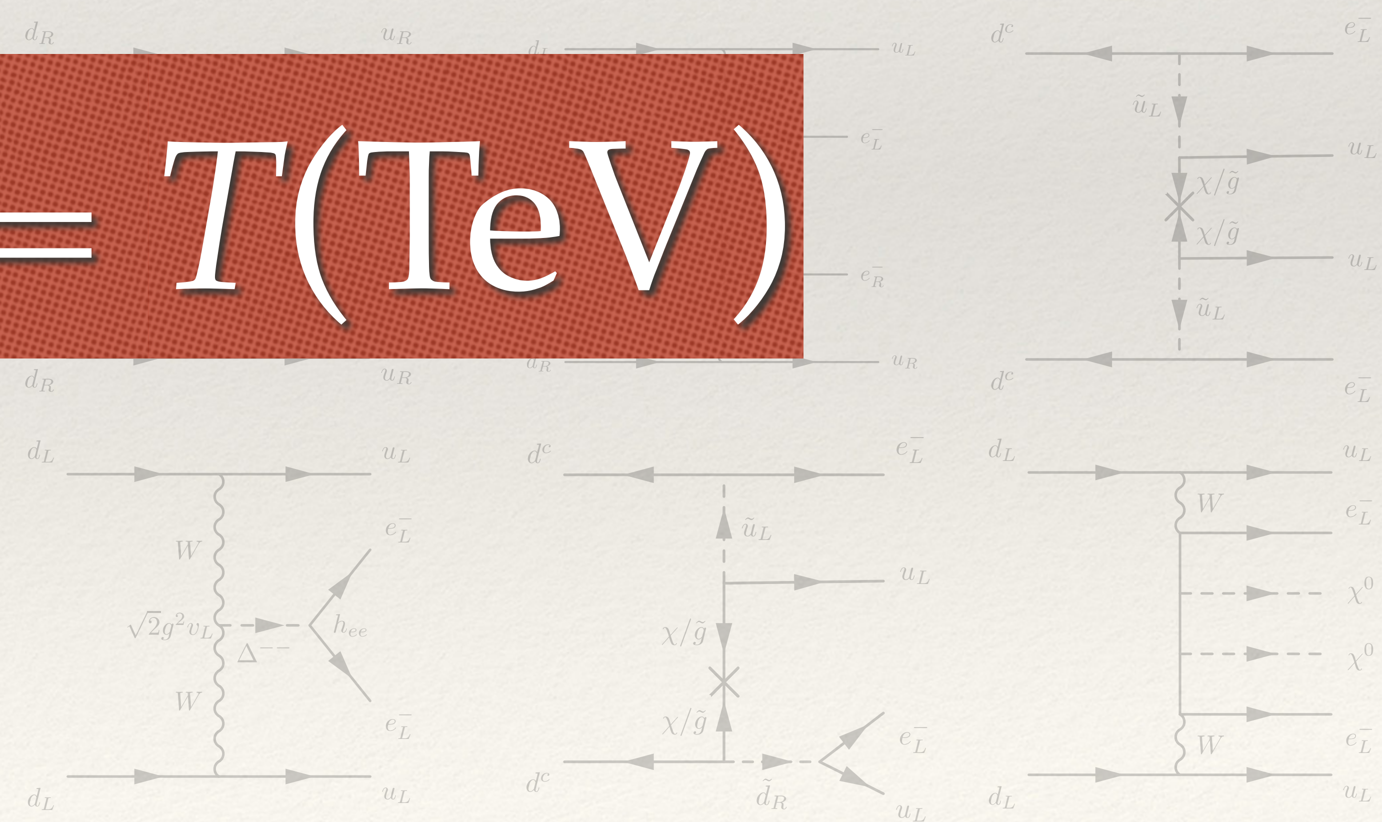

$$T(\mathrm{eV}) = T(\mathrm{TeV})$$

New Physics in Double Beta Decay

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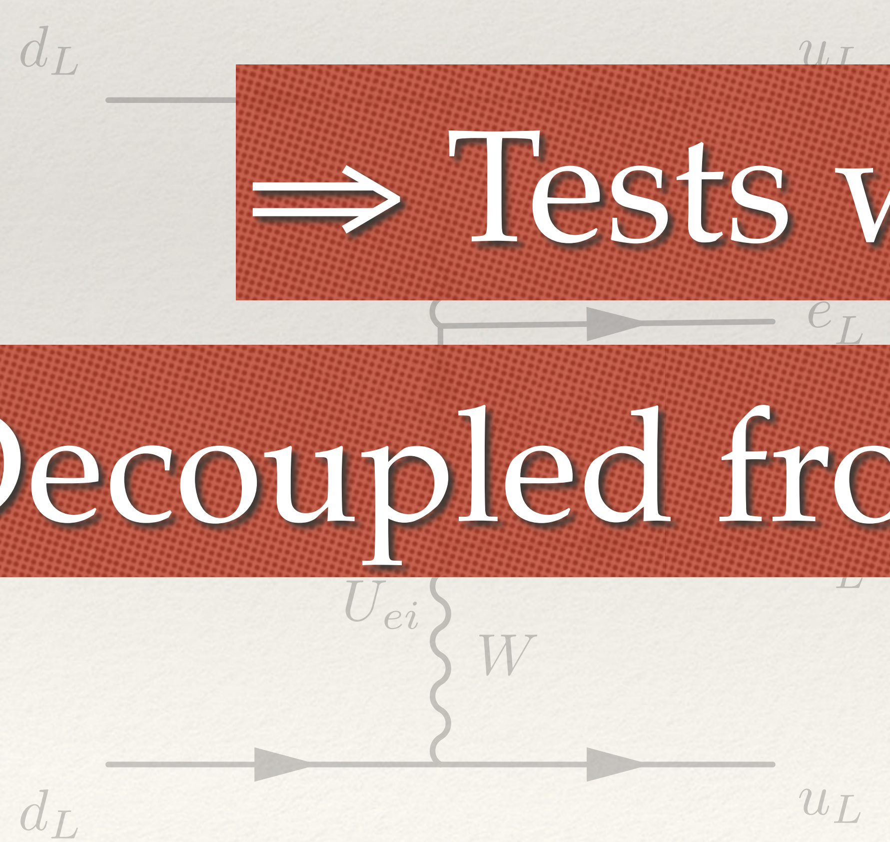


Non-Standard:

$\Rightarrow$ Tests with LHC, LFV, etc.

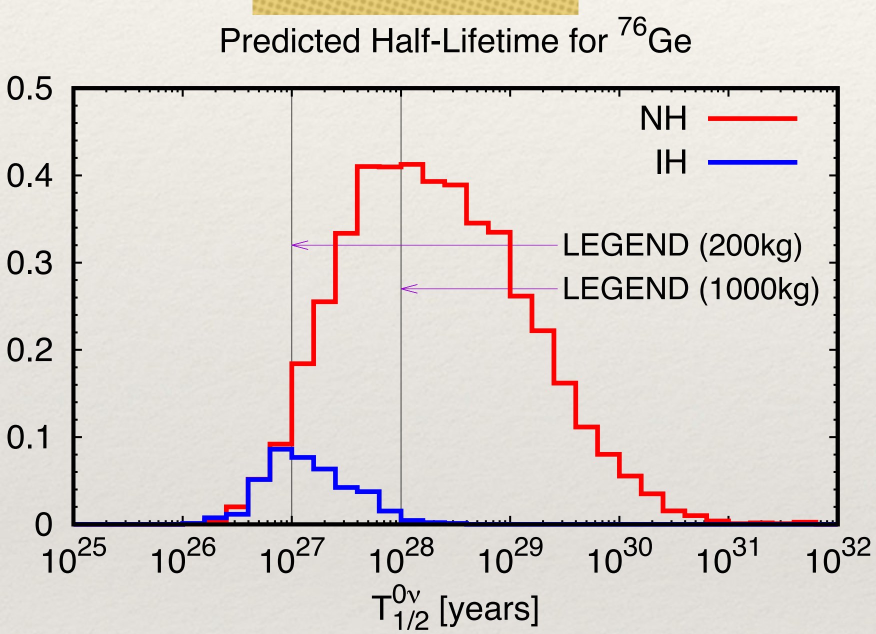
Decoupled from cosmo and KATRIN!

see talk by Vissani

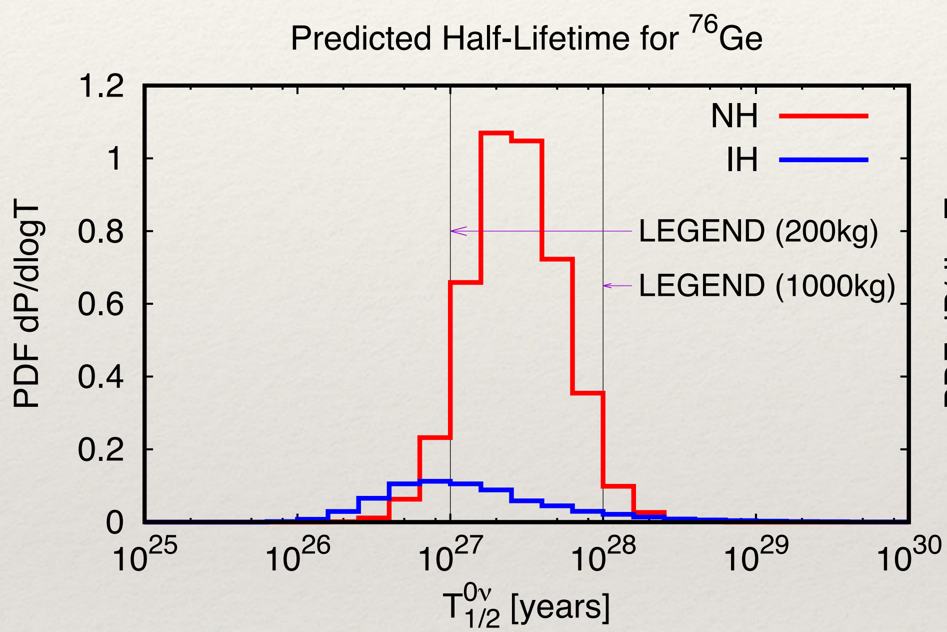
Expectations for half-lifes

probability distributions of half-lives:

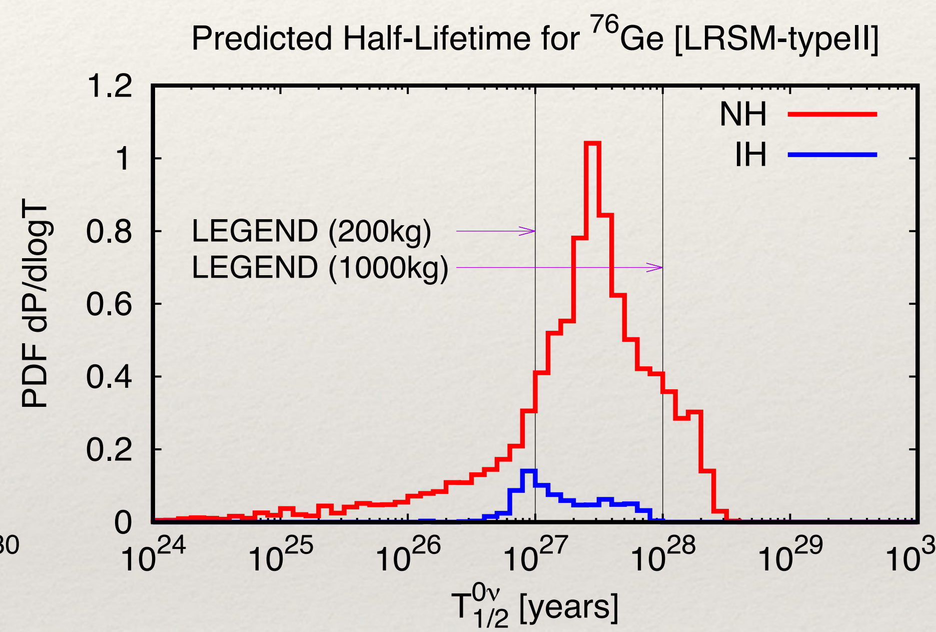
Standard



Sterile



Left-right



Ge, WR, Zuber, 1707.07904

However, most alternative mechanisms unrelated to neutrino parameters…

…thus decoupled from cosmology (and direct experiments)!

very detailed analysis of standard diagram:

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

Origin of Neutrino Mass

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

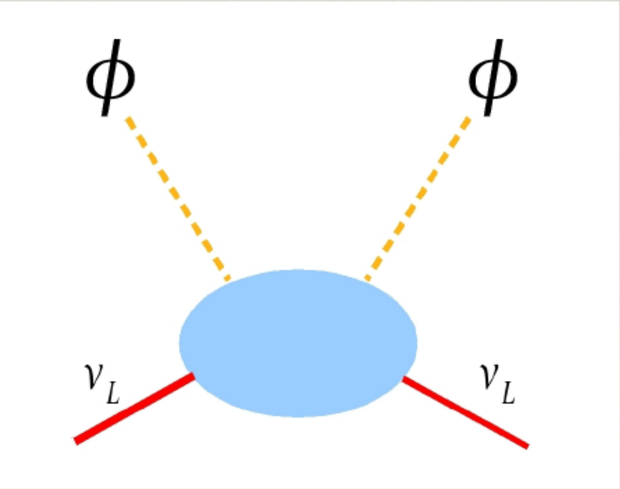
$$L\,\Phi\,N_R \to m_D\,\nu_L\,N_R$$

- 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

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

- Most straightforward possibili... mass
  $$\ldots \Phi\, N_R \to m_D\, \nu_L\, N_R$$
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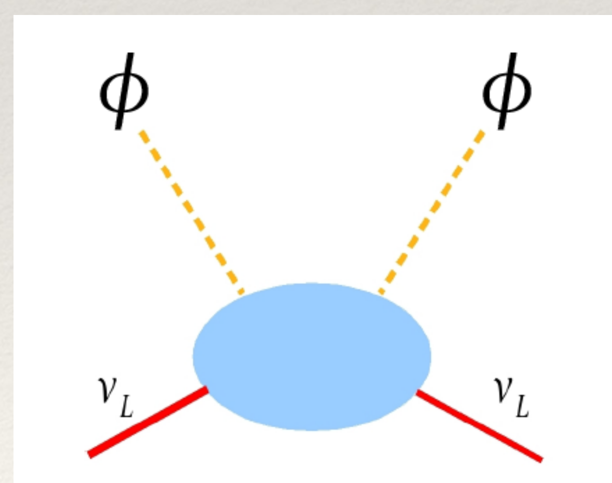


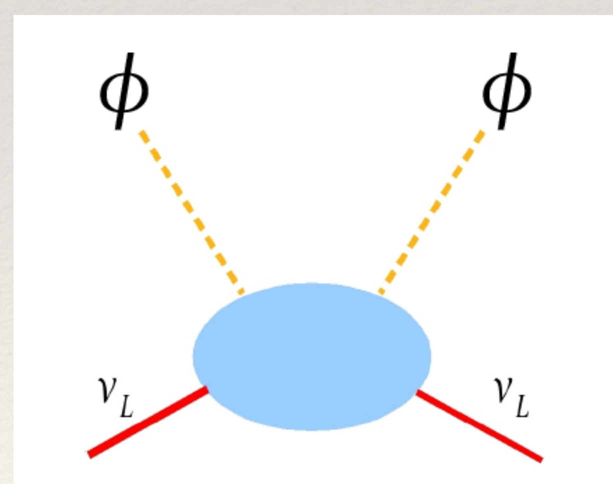
m_ν inverse proportional to scale of origin!

Origin of Neutrino Mass

- Most straightforward … mass
  … $N_R \to m_D\, \nu_L\, N_R$
- Gauge invariance allows Majorana …
- in total Majorana mass for SM neutrinos:
  $m_\nu\, \nu_L^c\, \nu_L$ with $m_\nu = m_D^2 / M_R = m_D\, \varepsilon$ *with* $\varepsilon = m_D / M_R = m_{SM} / M_R$

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

New energy scale beyond SM



m_ν inverse proportional to scale of origin!

Origin of Neutrino Mass

- Most straightforward possibili... mass
  $N_R \to m_D \, \nu_L \, N_R$

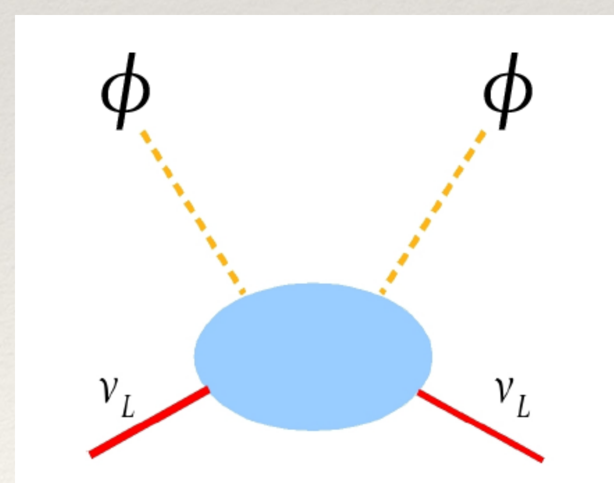
  New representation of SM gauge group $N_R \sim (1,0)$

- 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_{SM}/M_R

  New concept: lepton number violation



m_ν inverse proportional to scale of origin!

Origin of Neutrino Mass

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

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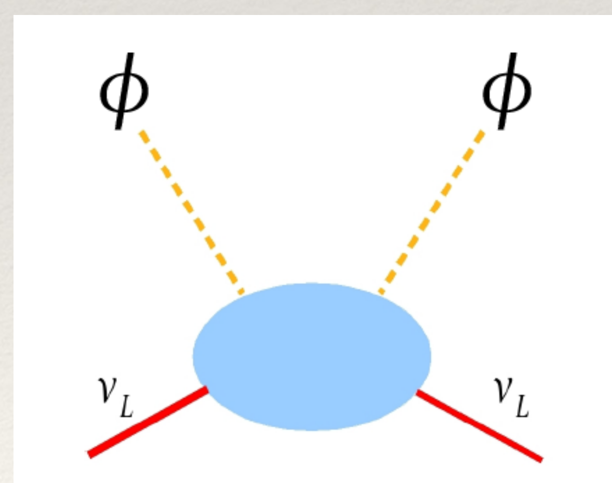
$$M_R\, N_R\, N_R$$

- in total Majorana mass for neutrinos:

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

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



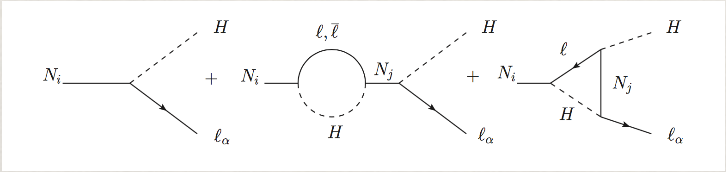
m_ν inverse proportional to scale of origin!

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

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

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

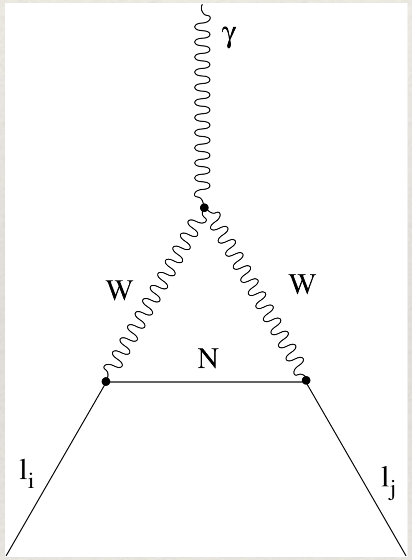
$N_R \to L\, \Phi$ $\quad L_\alpha \to N_R\, \Phi \to L_\beta$ $\quad \Phi \to L\, N_R \to \Phi$



Leptogenesis

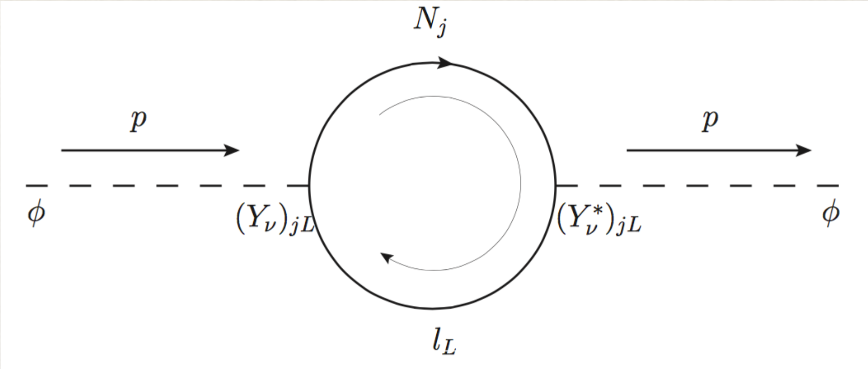
$Y_B \propto Im(y^2)$

⇒-*talk by Rink*



Lepton Flavor Violation

$BR \propto y^4/(M^4_N \text{ or } M^4_{SUSY})$

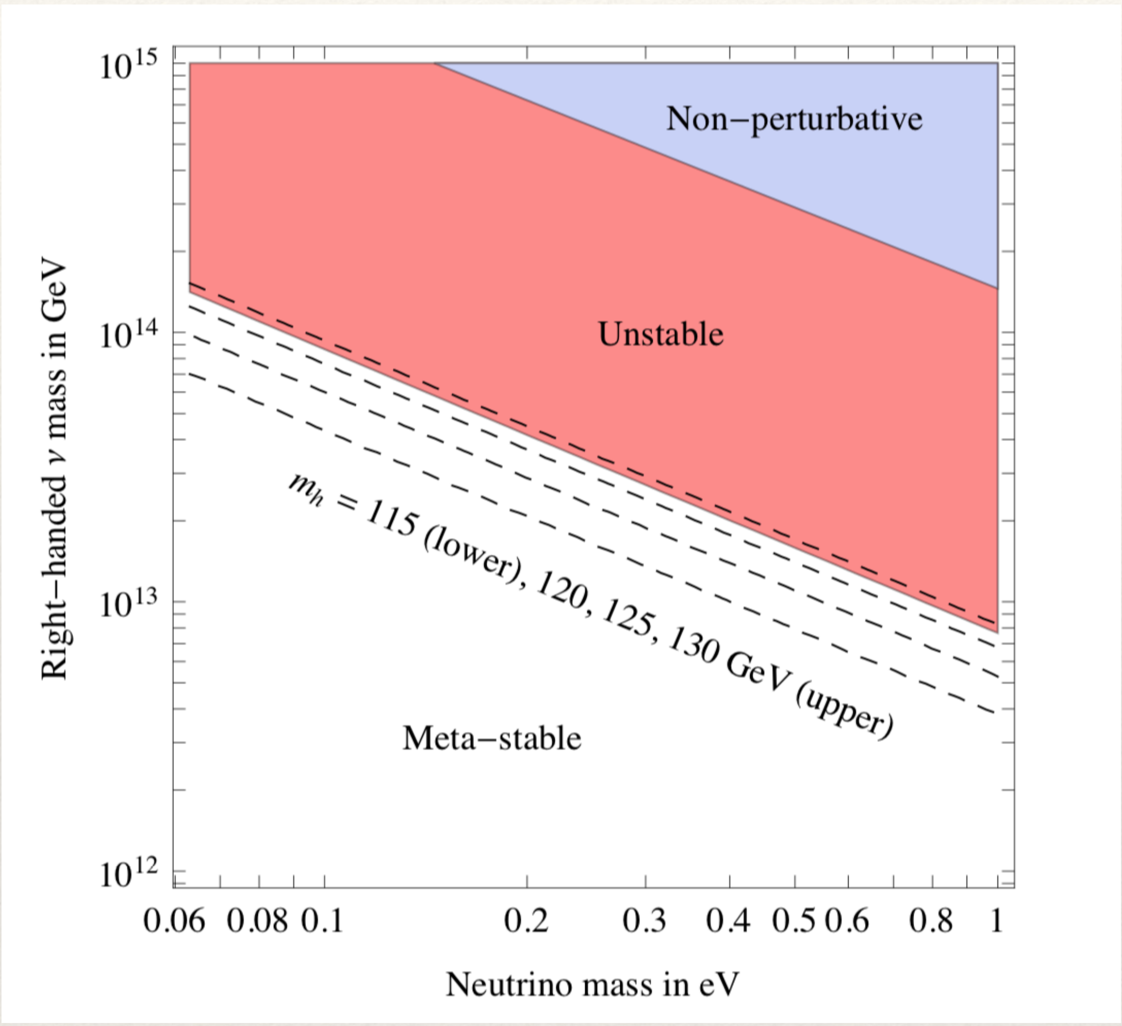


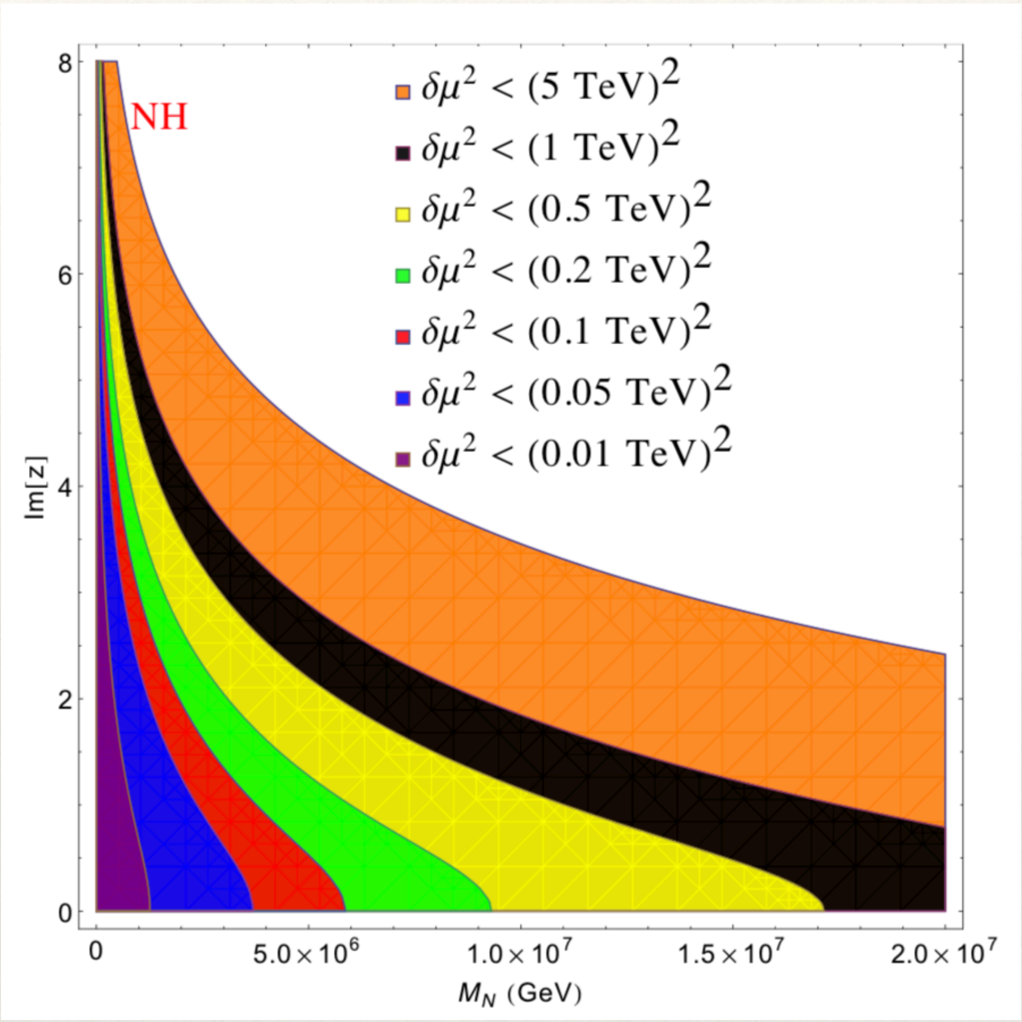
Vacuum stability, naturalness

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

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

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





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

$\delta(m_h^2) \propto y^2 M_N^2 \propto M_N^3 m_\nu$

Elias-Miro et al., 1112.3022

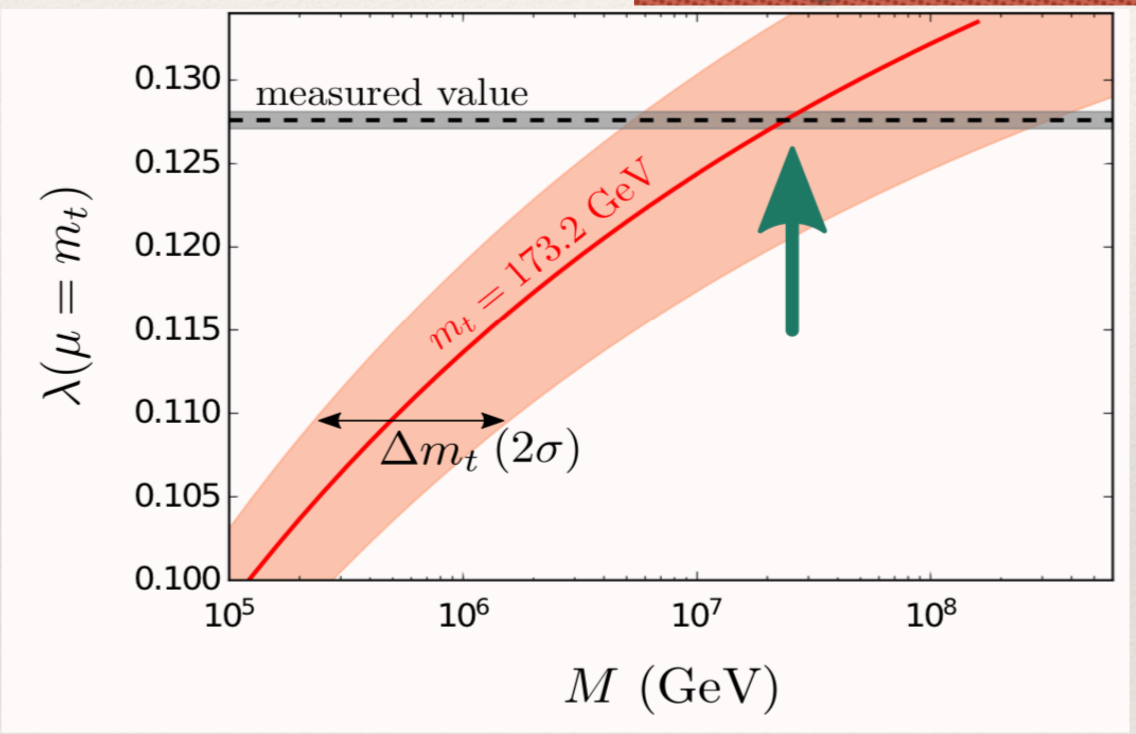
Clarke, Foot, Volkas, 1502.01352; Bambhaniya et al., 1611.03827

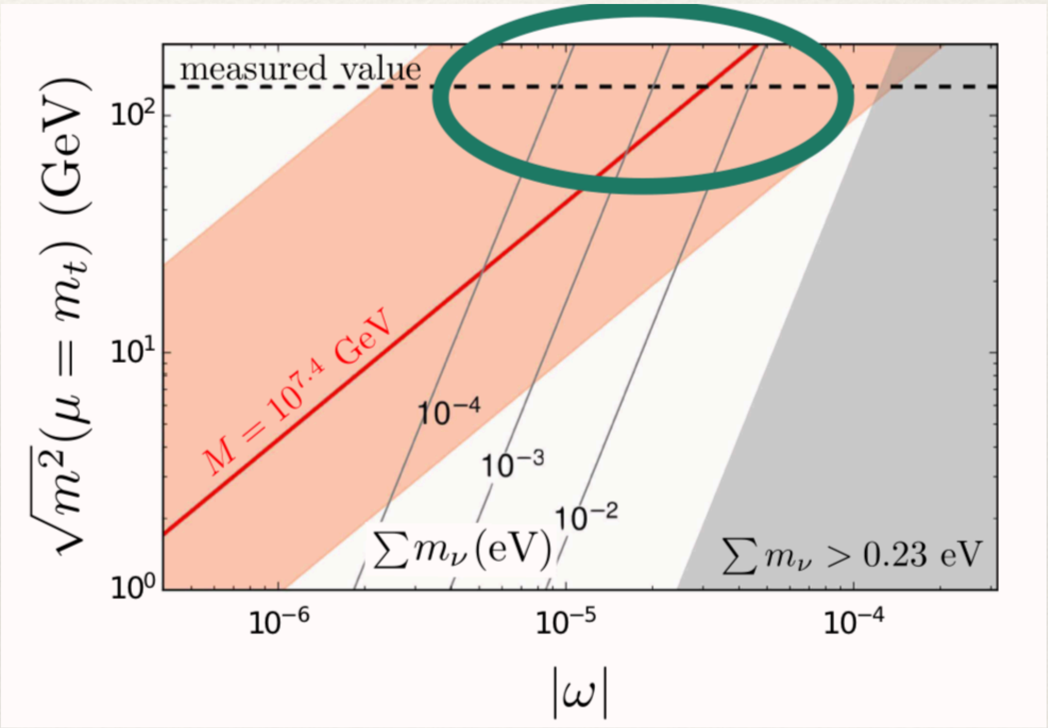
„The neutrino option“

Brivio, Trott, 1703.10924

Seesaw generates μ² term in Higgs potential

compatible with neutrino mass!



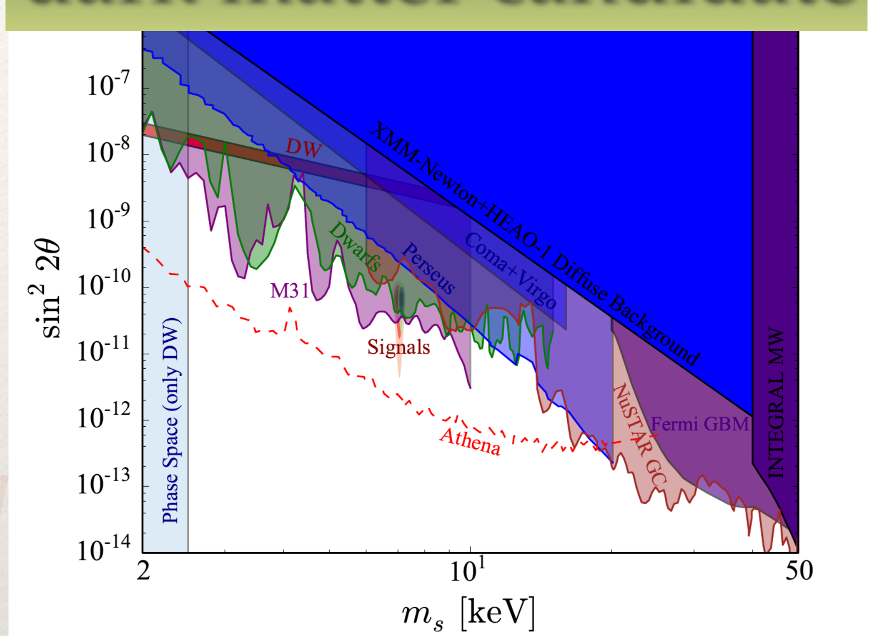


Brivio, talk at NuPhys2018

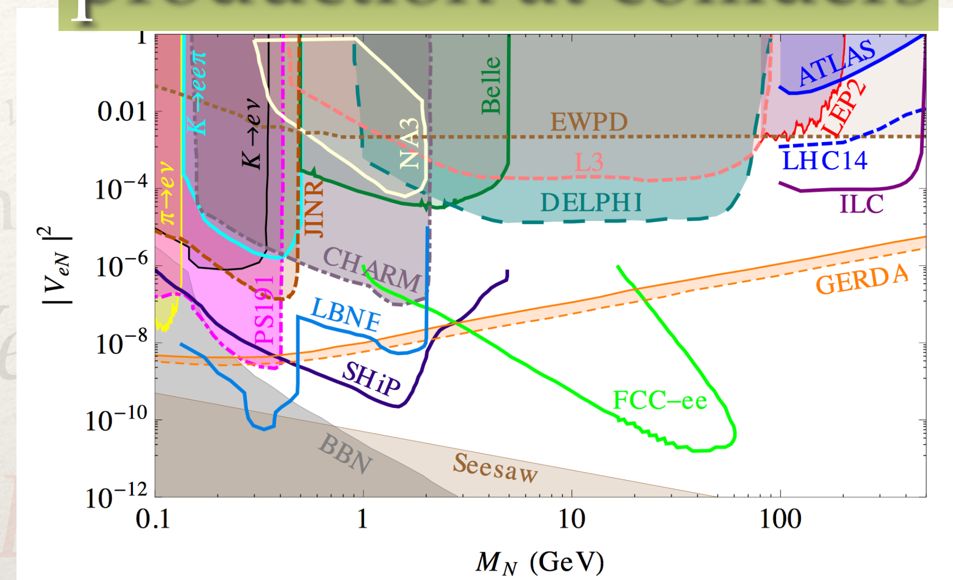
- conformal realization with additional singlets (*Brdar et al., 1807.11490*)
- strong phase transition with GW signals (*Brdar et al., 1810.12306*)
- leptogenesis also possible (*Brdar at al., 1905.12634; Brivio et al., 1905.12642*)

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

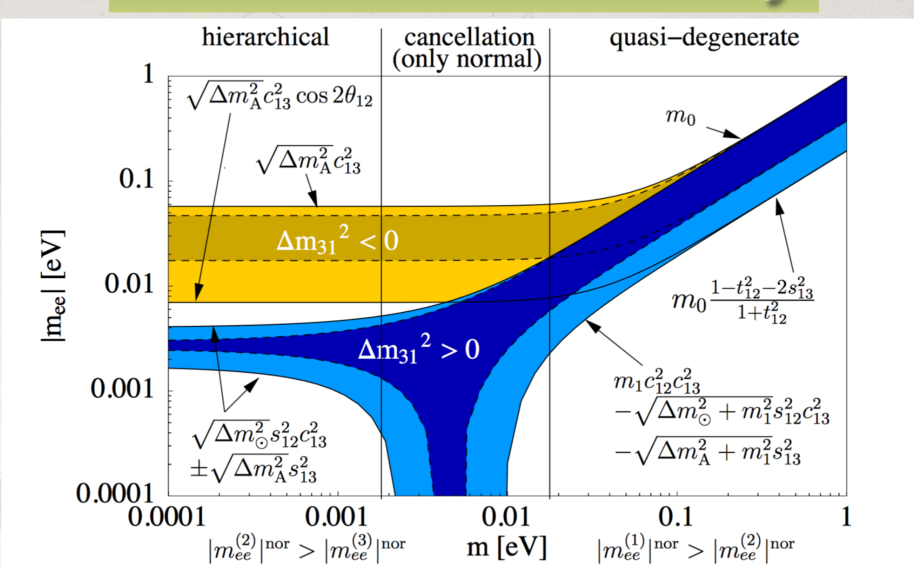
dark matter candidate



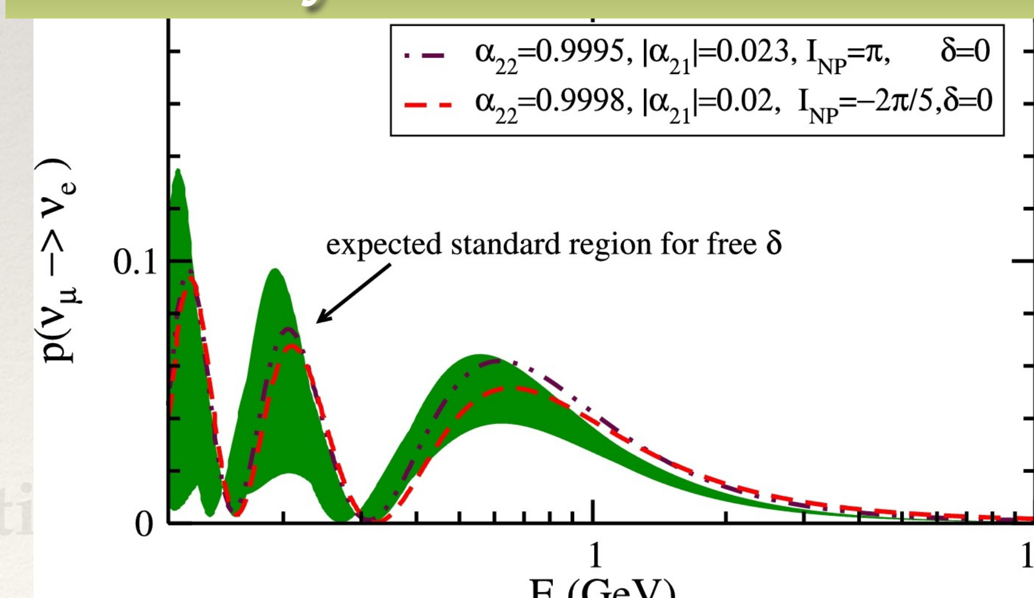
production at colliders



double beta decay



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	$\Sigma \sim (3,0)$	$h \overline{\Sigma} \, L \Phi + \mathrm{Tr} \overline{\Sigma} M_\Sigma \Sigma$	$\frac{(h v)^2}{M_\Sigma}$	$\Lambda = \frac{1}{h} M_\Sigma$

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

plus radiative mechanisms

plus higher dimensional operators *‖-talk by Fonseca*

plus extra dimensional

plus plus plus

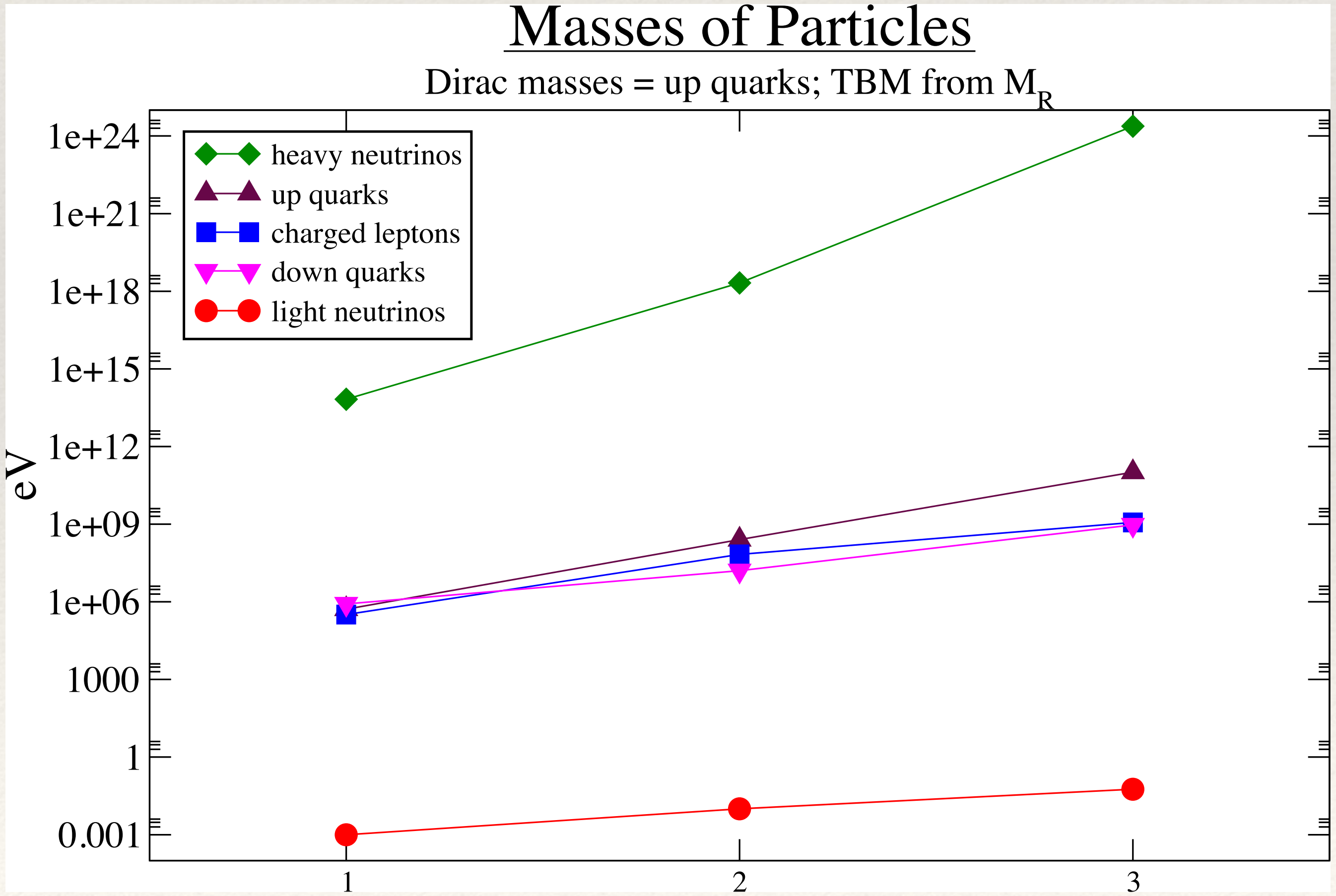
Summary

- Neutrinos still only testable BSM physics
- PMNS parameters approach CKM-precision
- physics behind mass and mixing offers many tests outside of pure neutrino physics
- still new windows open up

Seesaw Mechanism

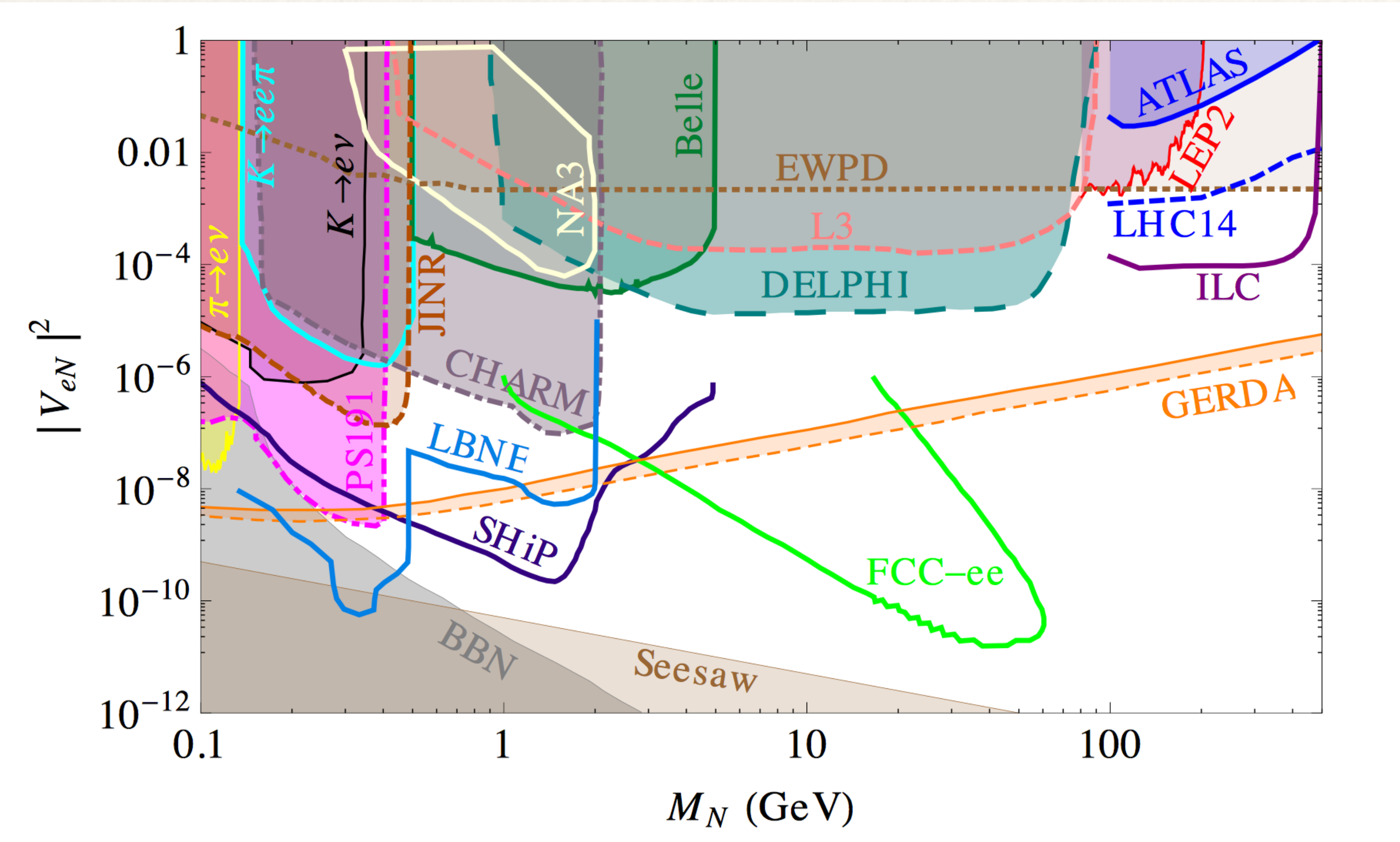
- suppresses neutrino mass *for each generation* ($m_u \simeq m_d$ and $m_b \sim m_t$ vs. $m_{\nu e} \ll m_e$ and $m_{\nu\tau} \ll m_\tau$)
- little hierarchy in m_ν, strong quark-like hierarchy in m_D

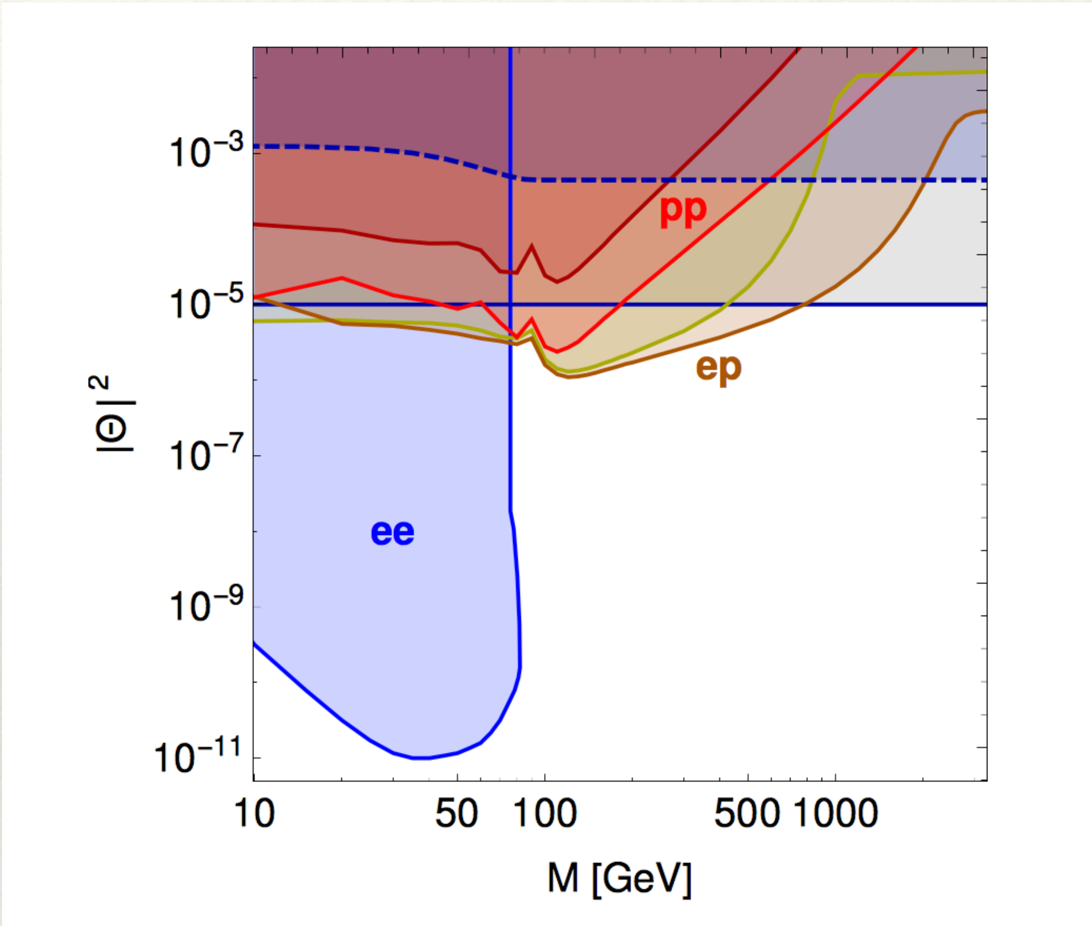
$\Rightarrow$ stronger hierarchy in M_R?



Limits on Heavy Neutrinos

$$M(W_R) \leftrightarrow V_{\alpha N}$$





Deppisch, Dev, Pilaftsis, 1502.06541 *Antusch, Cazzato, Fischer, 1612.02728*

peak searches, kink searches, displaced vertices, LNV decays,…

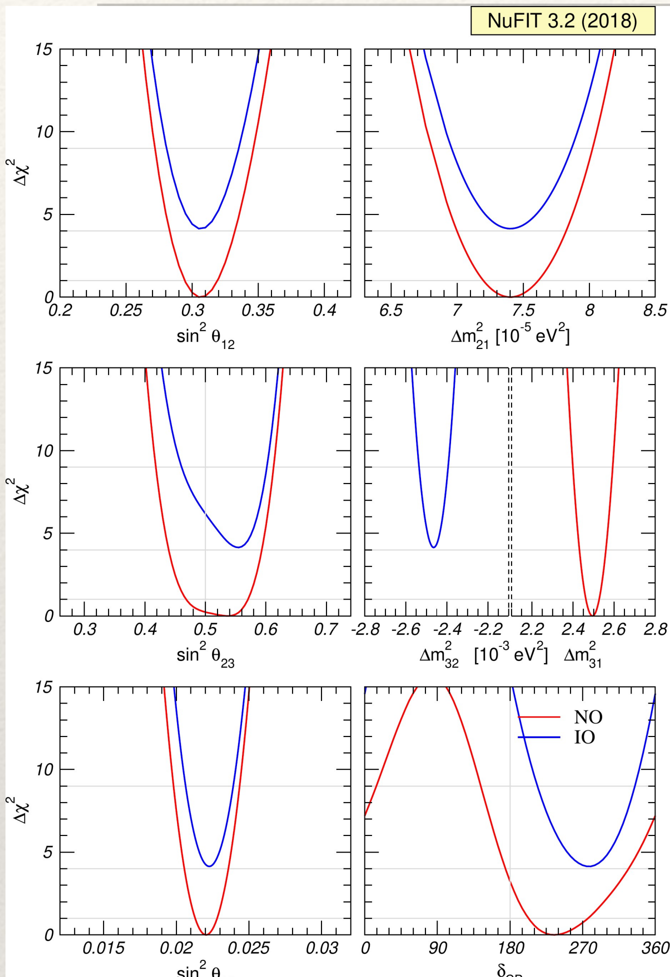
see also Atre et al., 0901.3589

Oscillation Parameters

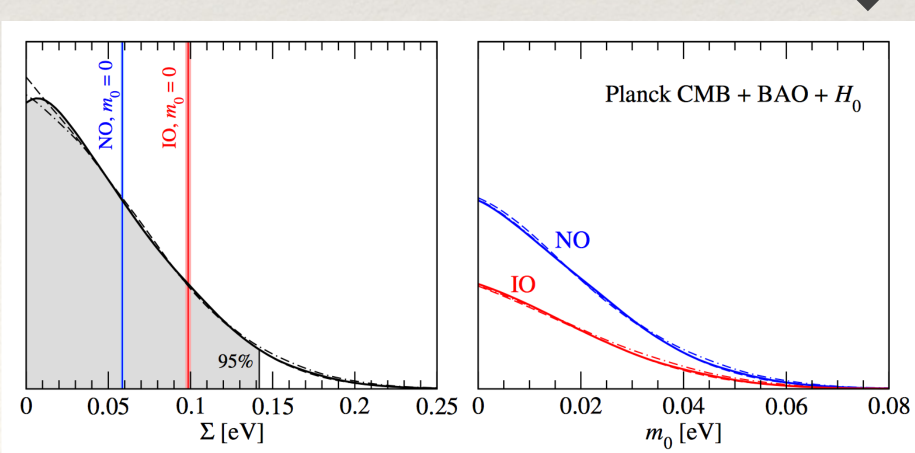
- Maximal θ_{23} preferred by LBL, slight 1-2σ shift to $> \pi/4$ by SK
- LBL prefer $\delta \simeq 3\pi/2$, driven by (too many?) ν_e; also SK due to sub-GeV *e*-like events
- normal mass ordering preferred by LBL (tension with reactors) and SK (excess of upward going *e*-like events), $\simeq 2\sigma$ effect each, $\simeq 3\sigma$ total

see talks by Sekiguchi, Bhatnagar, Wu, Tanaka

Expectations of lifetimes

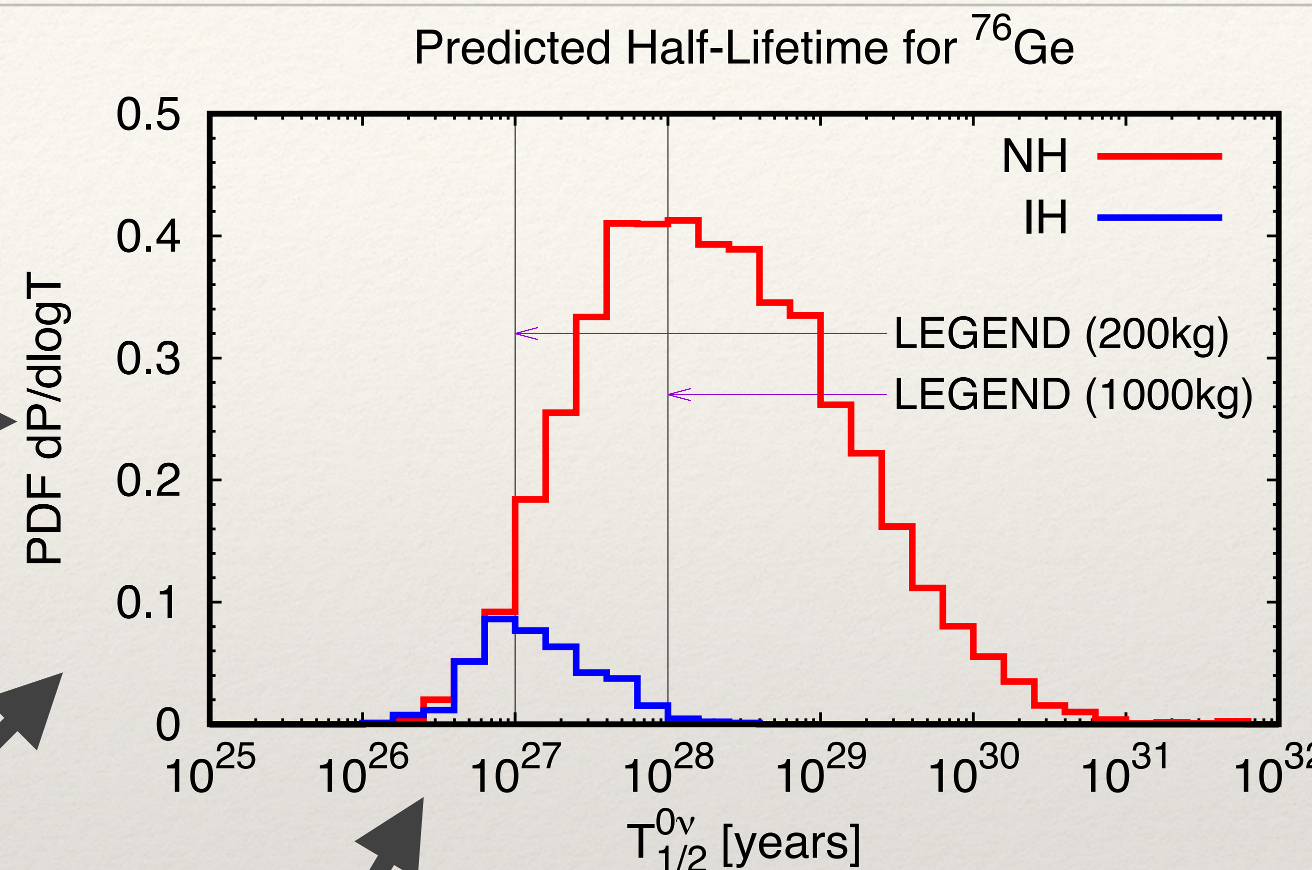


oscillation fits

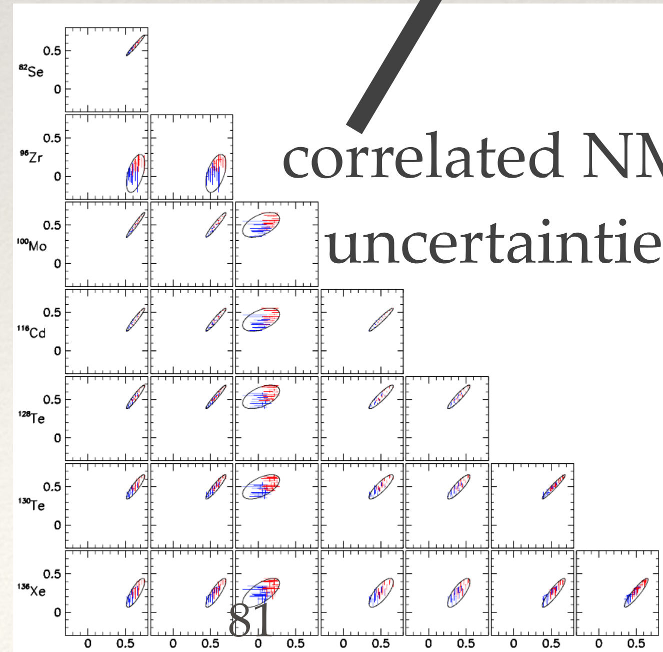


cosmology fit

+



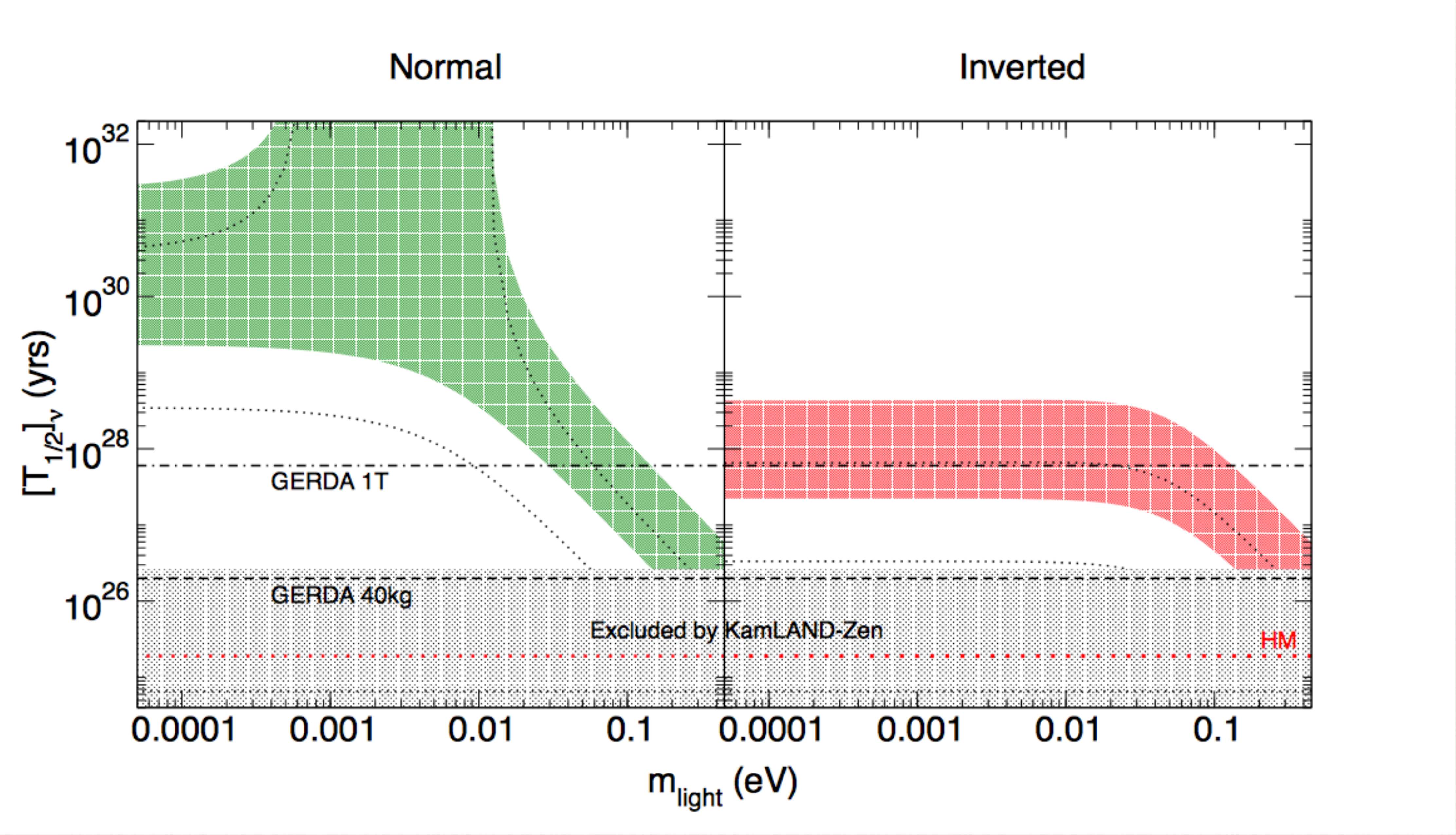
Ge, WR, Zuber, 1707.07904



correlated NME uncertainties

see also Agostini et al, 1705.02996; Caldwell et al., 1705.01945; Zhang, Zhou, 1508.05472; Benato, 1510.01089

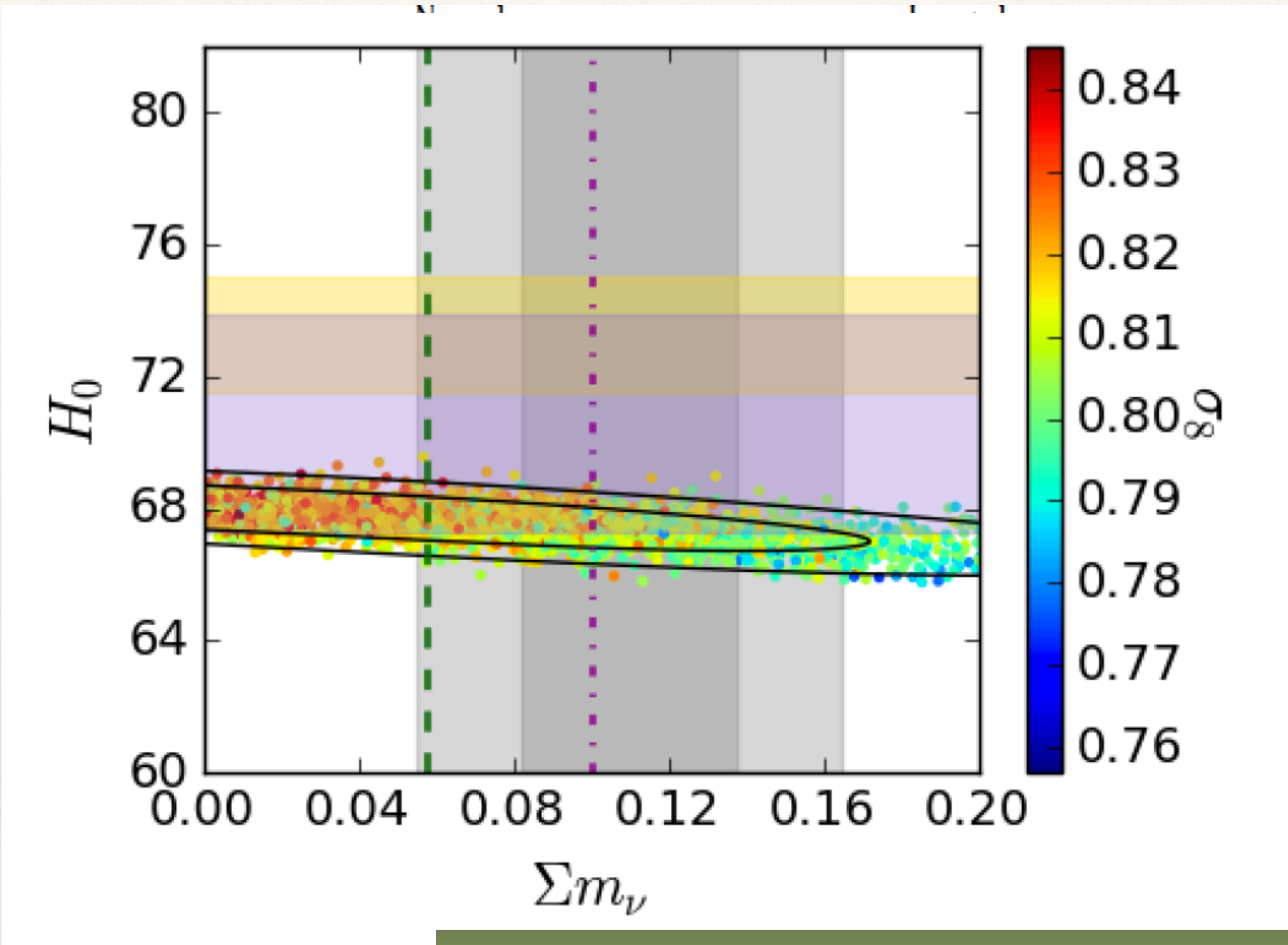
The usual plot

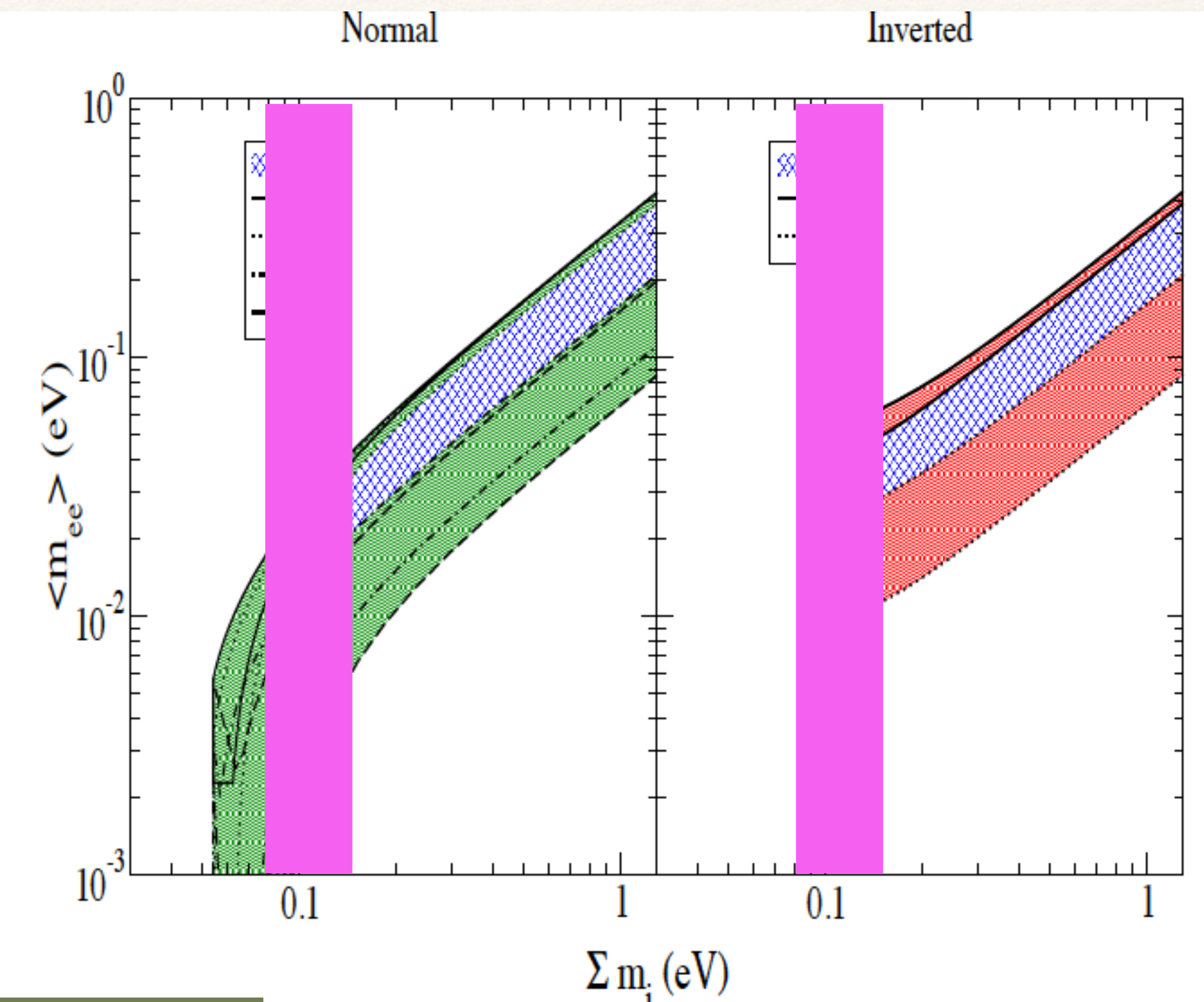


Non-Standard Interpretations

mechanism	physics parameter	current limit	test
light neutrino exchange	$\left\|U_{ei}^2\, m_i\right\|$	0.2 eV	oscillations, cosmology, neutrino mass
heavy neutrino exchange	$\left\|\frac{S_{ei}^2}{M_i}\right\|$	2×10^{-8} GeV^{-1}	LFV, collider
heavy neutrino and RHC	$\left\|\frac{V_{ei}^2}{M_i\, M_{W_R}^4}\right\|$	4×10^{-16} GeV^{-5}	flavor, collider
Higgs triplet and RHC	$\left\|\frac{(M_R)_{ee}}{m_{\Delta_R}^2\, M_{W_R}^4}\right\|$	10^{-15} GeV^{-1}	flavor, collider e^- distribution
λ-mechanism with RHC	$\left\|\frac{U_{ei}\, \tilde{S}_{ei}}{M_{W_R}^2}\right\|$	1.4×10^{-10} GeV^{-2}	flavor, collider, e^- distribution
η-mechanism with RHC	$\tan\zeta\, \left\|U_{ei}\, \tilde{S}_{ei}\right\|$	6×10^{-9}	flavor, collider, e^- distribution
short-range $\not{R}$	$\frac{\|\lambda'^2_{111}\|}{\Lambda^5_{\rm SUSY}}$ $\Lambda_{\rm SUSY} = f(m_{\tilde{g}}, m_{\tilde{u}_L}, m_{\tilde{d}_R}, m_{\chi_i})$	7×10^{-18} GeV^{-5}	collider, flavor
long-range $\not{R}$	$\left\|\sin 2\theta^b\, \lambda'_{131}\, \lambda'_{113} \left(\frac{1}{m^2_{\tilde{b}_1}} - \frac{1}{m^2_{\tilde{b}_2}}\right)\right\|$ $\sim \frac{G_F}{q} m_b \frac{\|\lambda'_{131}\, \lambda'_{113}\|}{\Lambda^3_{\rm SUSY}}$	2×10^{-13} GeV^{-2} 1×10^{-14} GeV^{-3}	flavor, collider
Majorons	$\|\langle g_\chi \rangle\|$ or $\|\langle g_\chi \rangle\|^2$	$10^{-4} \ldots 1$	spectrum, cosmology

Neutrino Mass Observables

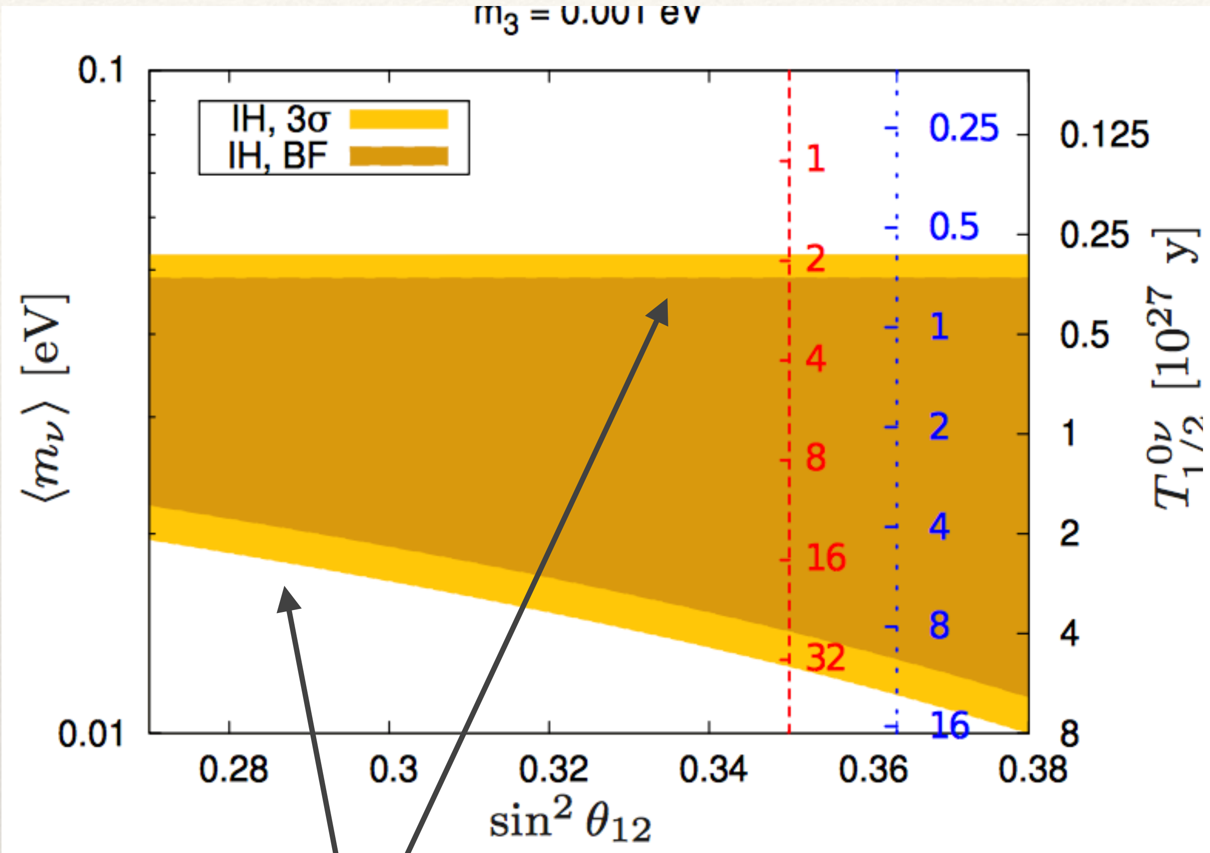


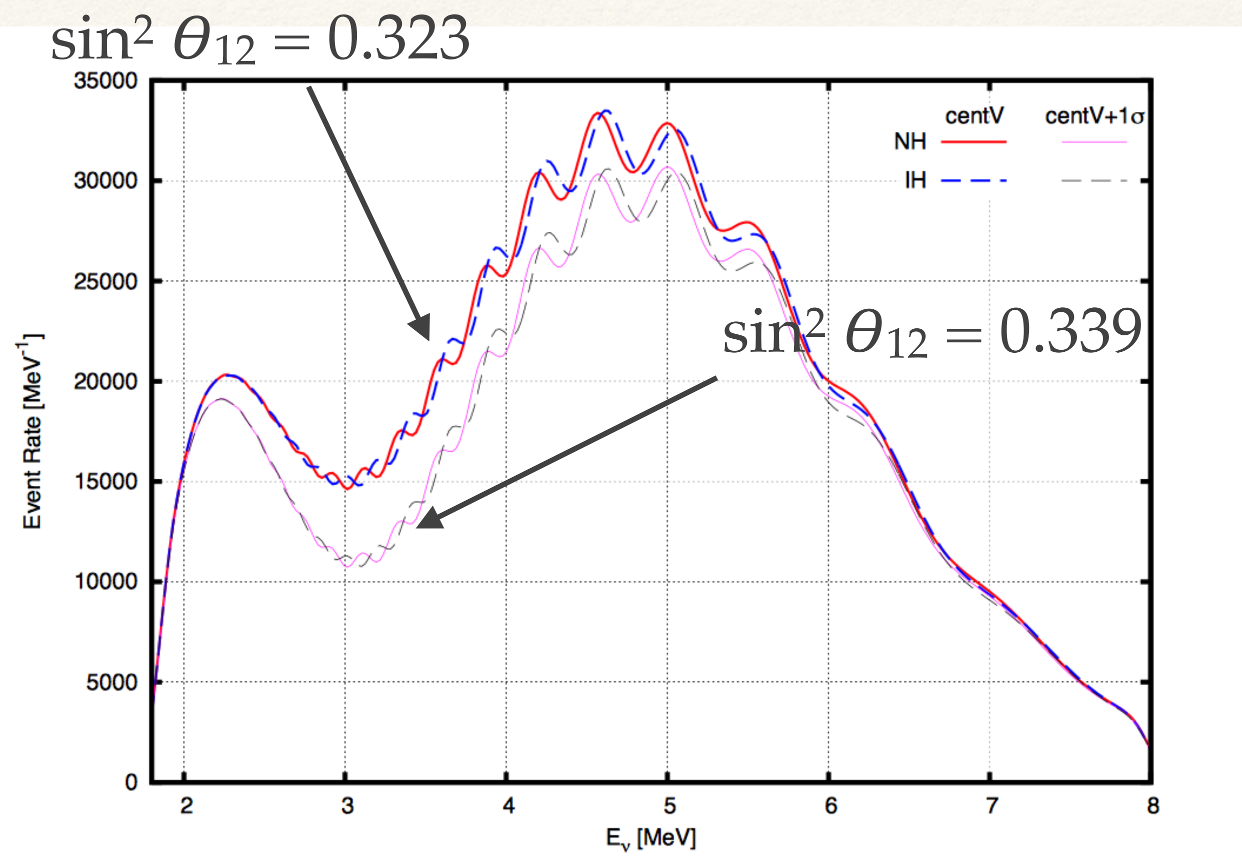


0.11 ± 0.03 eV from 1711.05210

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)

Connections to future Oscillation Experiments





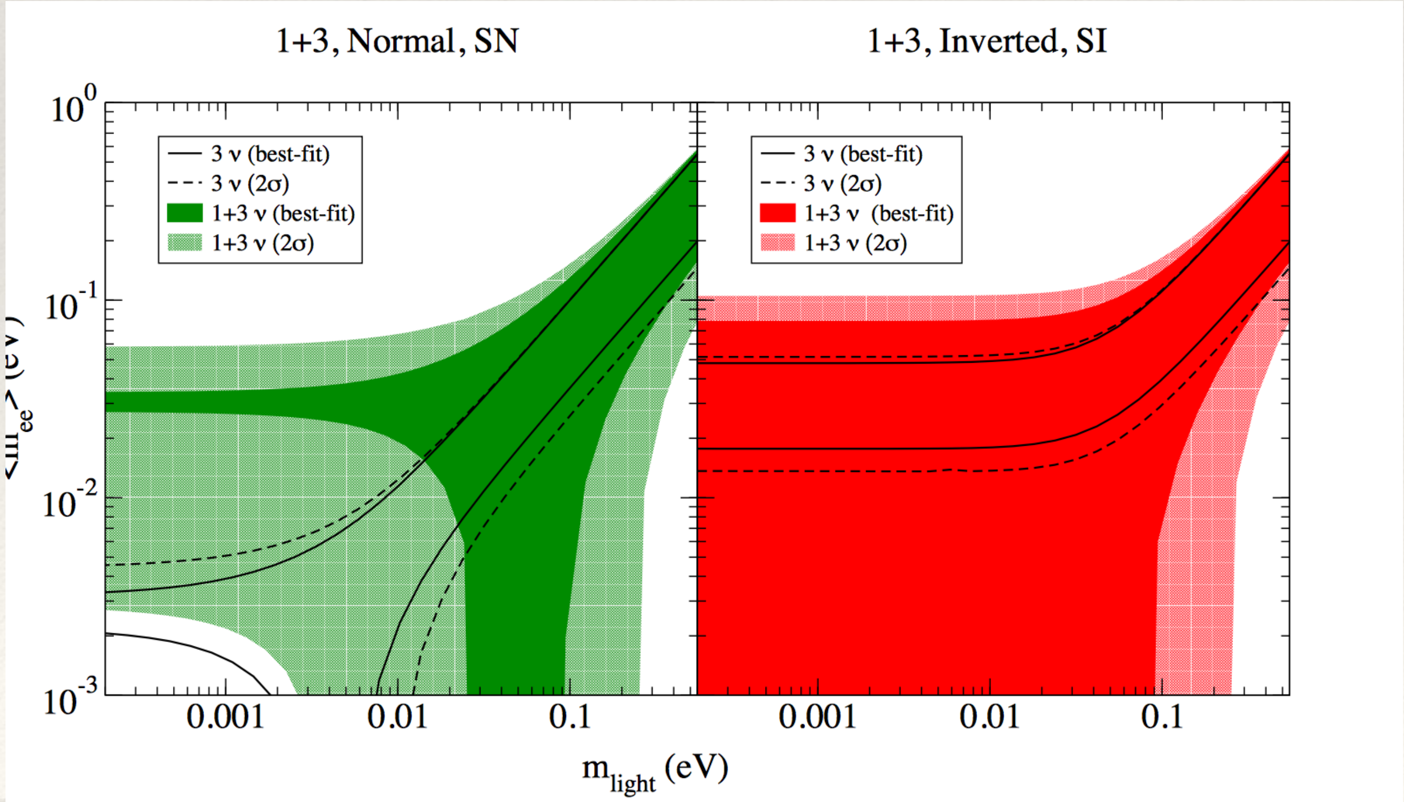
Nature gives us two scales

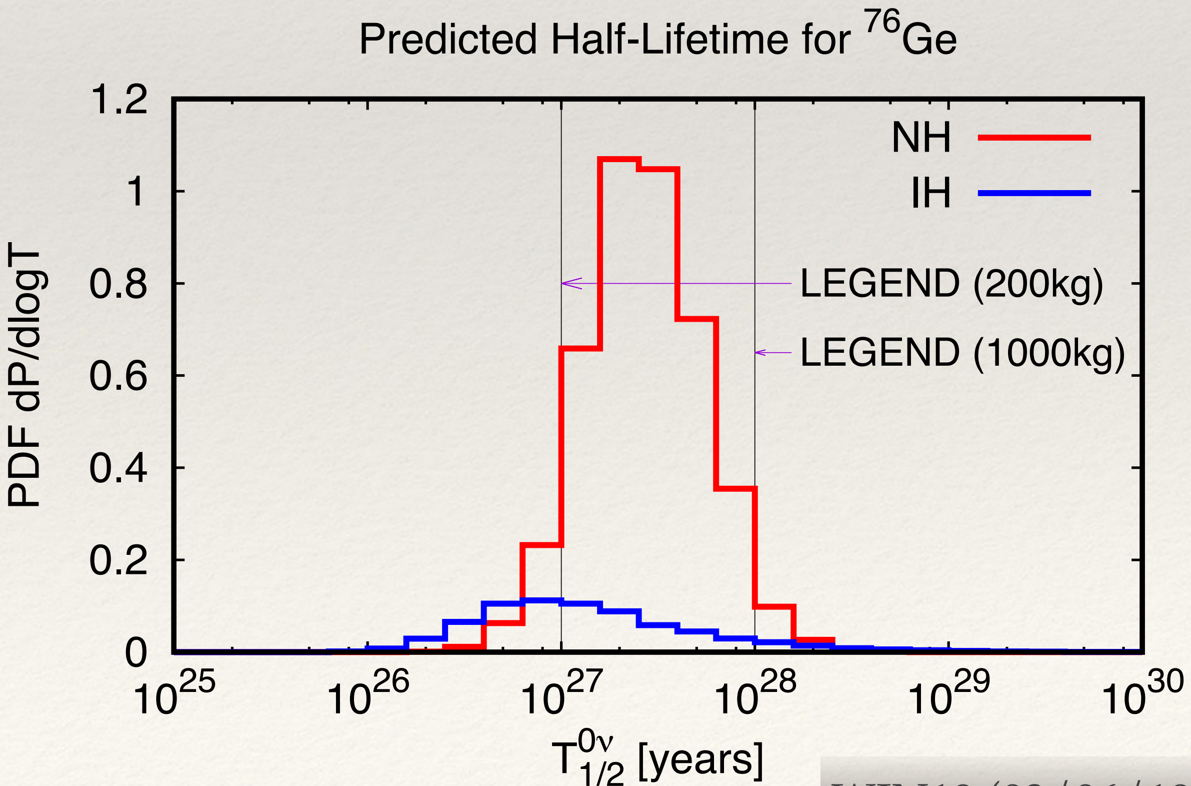
$$\langle m \rangle^{IH}_{min} \propto \cos 2\theta_{12} = 1 - 2\sin^2\theta_{12}$$

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

Sterile Neutrinos

- are there sterile states (LSND/reactor/etc.) with mass $\Delta m^2 \simeq$ eV^2 and mixing $U_{e4} \simeq 0.1$?
- 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!

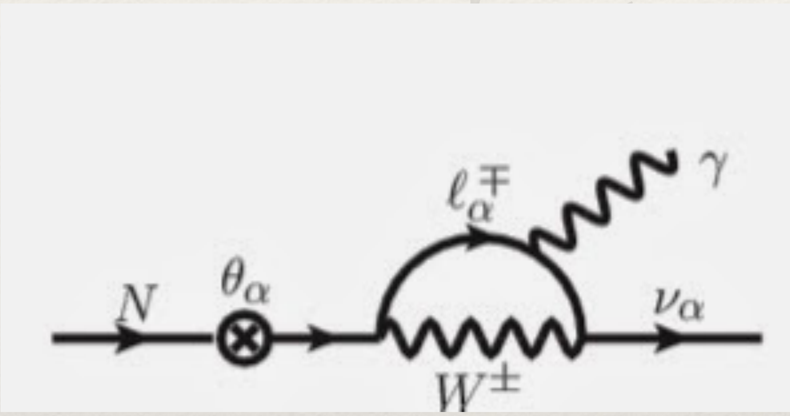


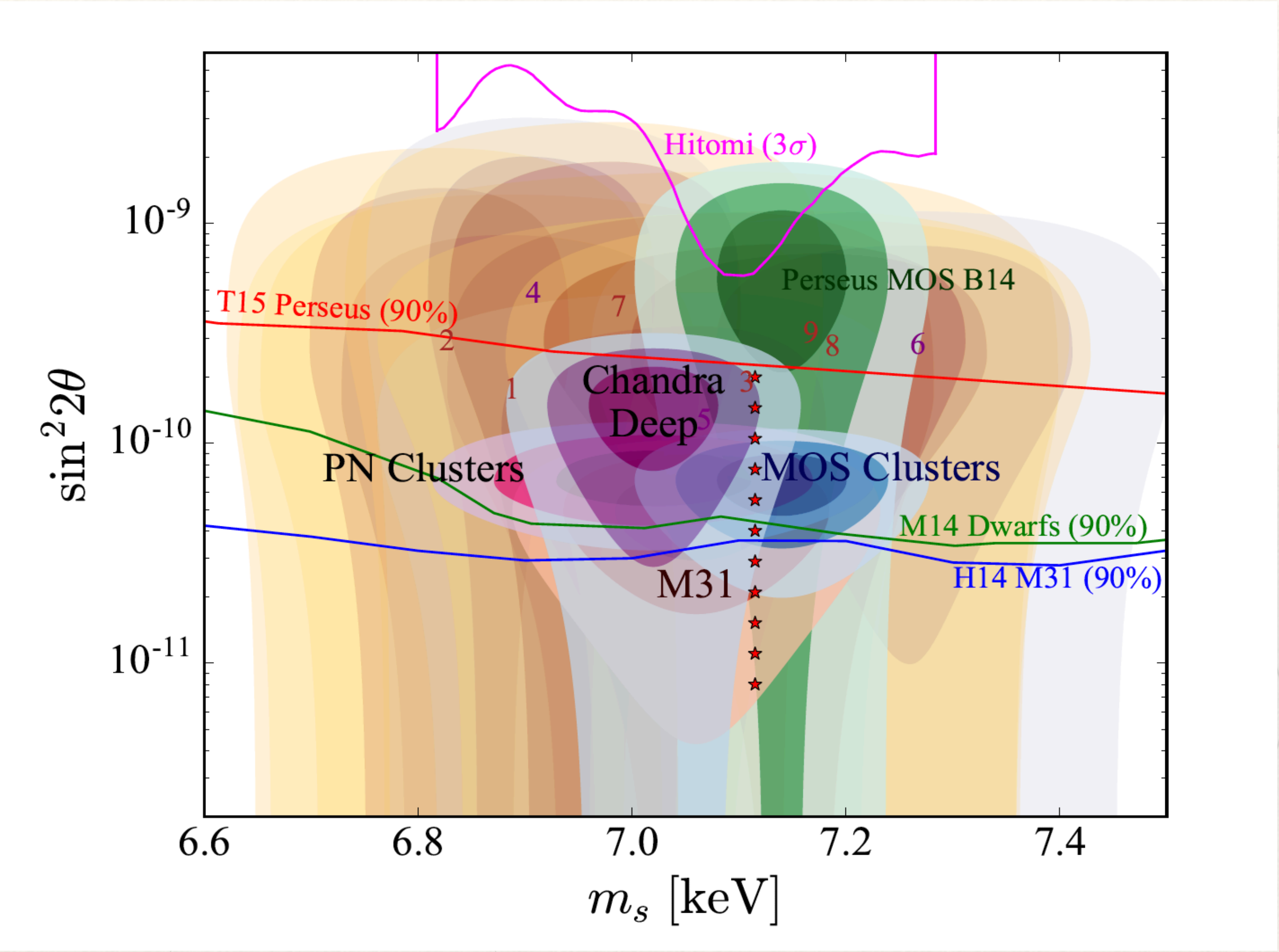


Type I Seesaw $m_\nu = m_D^2 / M_R$

plus: provides a DM candidate

actually, ... needs to be teste...





Abazajian , 1705.01837

Leptogenesis

Lepton Flavor Violation

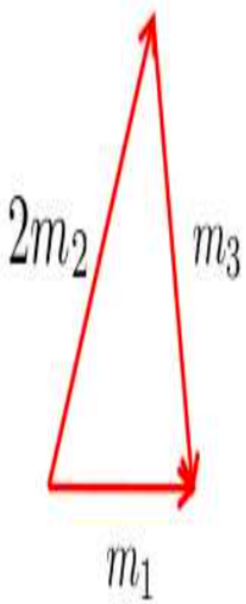
Vacuum stability, naturalness

Flavor Symmetries

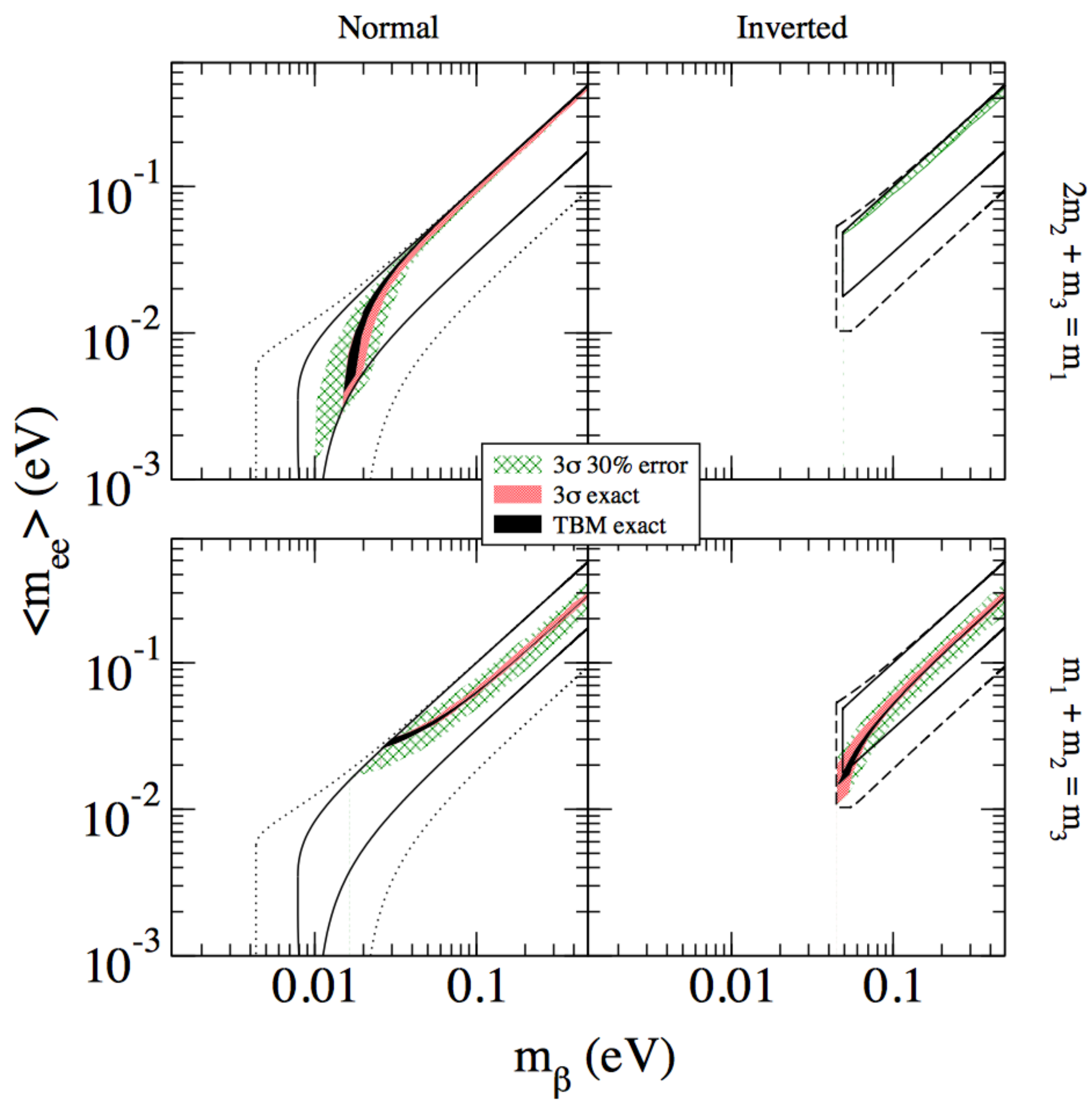
- Can rule out models by:
  - correlations between angles and phases
  - neutrino mass sum-rules, e.g. $m_1 + m_2\, e^{i\alpha} = m_3\, e^{i\beta}$
  - LFV if within SUSY or if broken at low scale
  - *minimality*
  - *robustness*
  - *compatibility with larger frameworks (LR symmetry, Pati-Salam, SU(5),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

Flavor Symmetries

Barry, WR, 1007.5217



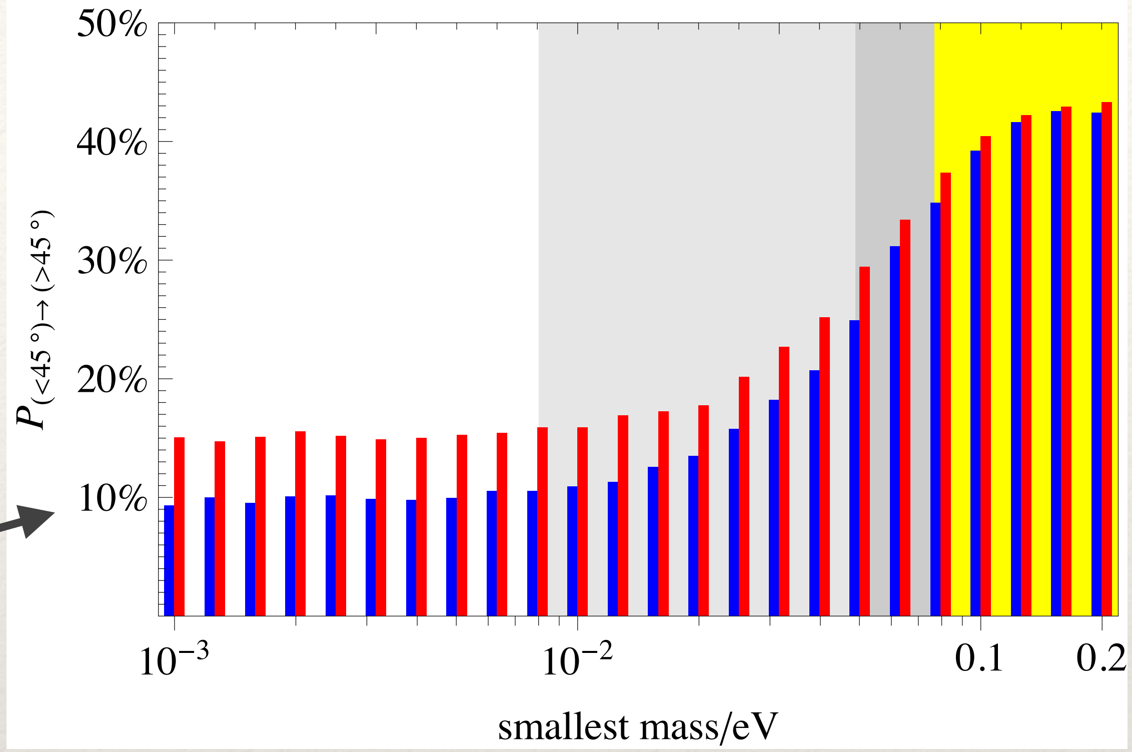
Sum-rule	Flavour symmetry
$2m_2 + m_3 = m_1$	$A_4, T', (S_4)$
$m_1 + m_2 = m_3$	$S_4, (A_4)$
$\frac{2}{m_2} + \frac{1}{m_3} = \frac{1}{m_1}$	A_4, T'
$\frac{1}{m_1} + \frac{1}{m_2} = \frac{1}{m_3}$	S_4



Implications

- Maximal $\theta_{23} = \pi/4$?

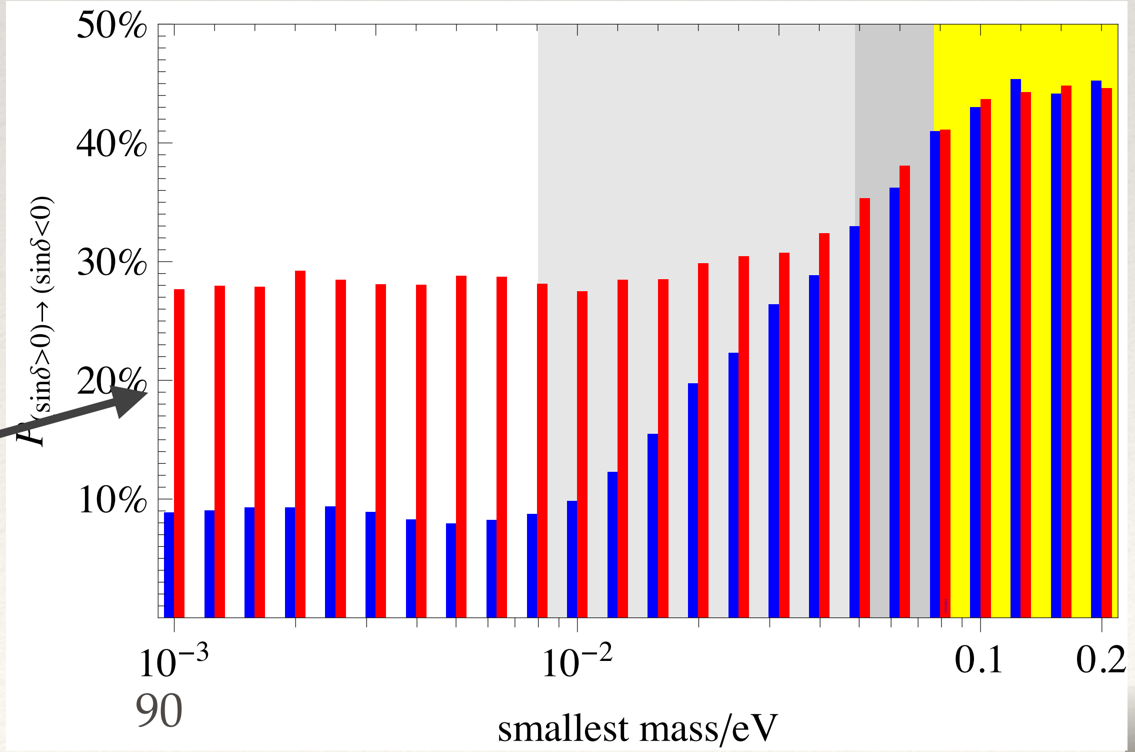
probability to change octant of θ_{23}



(normal / inverted)

- „Maximal“ $\delta = 3\pi/2$?

probability to change sign of sin δ



WR, Xu, 1508.06063

Implications

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

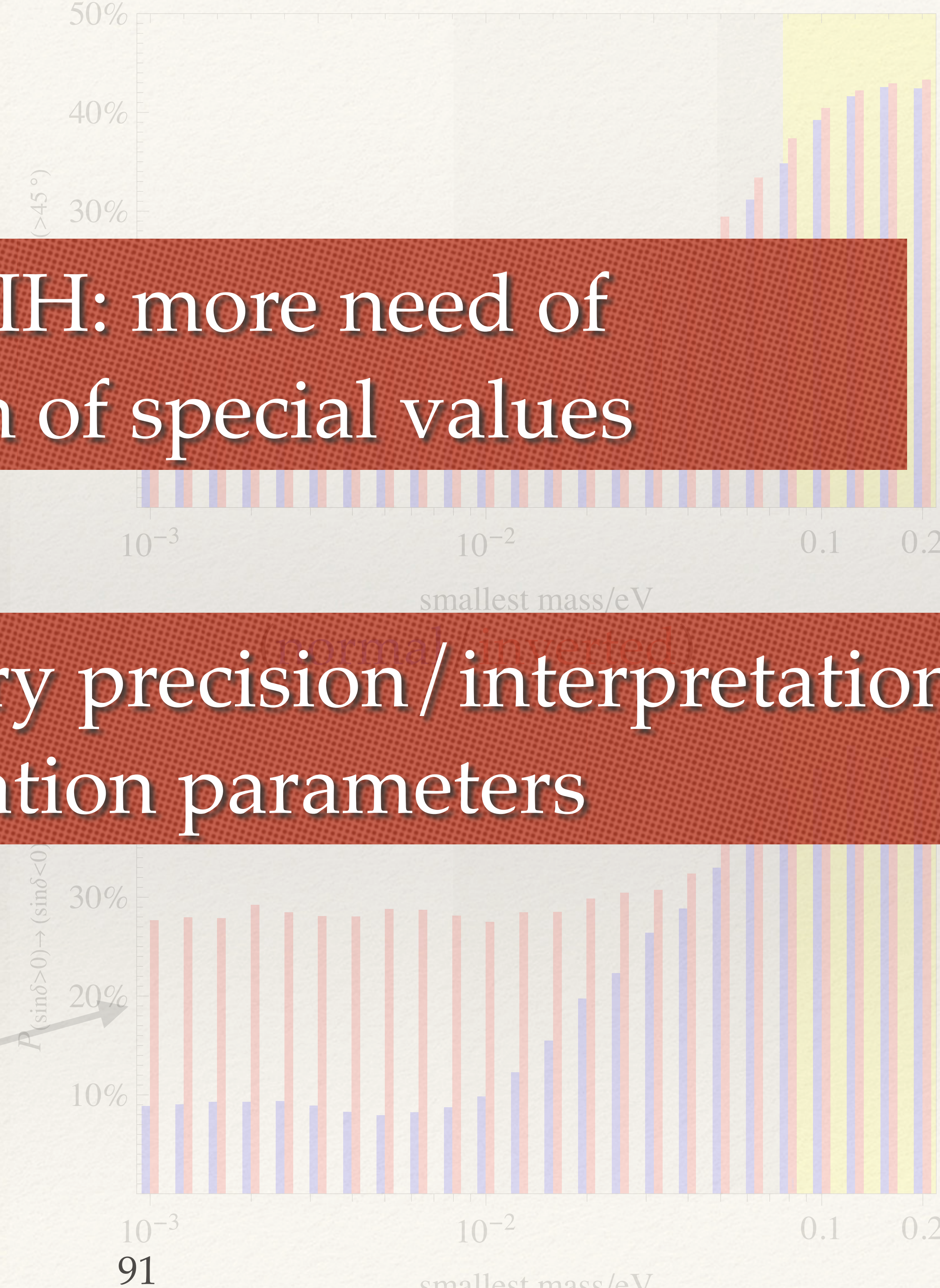
impact on necessary precision/interpretation of oscillation parameters

- Maxi…

pro… octant of θ_{23}

- „Maximal“ $\delta = 3\pi/2$?

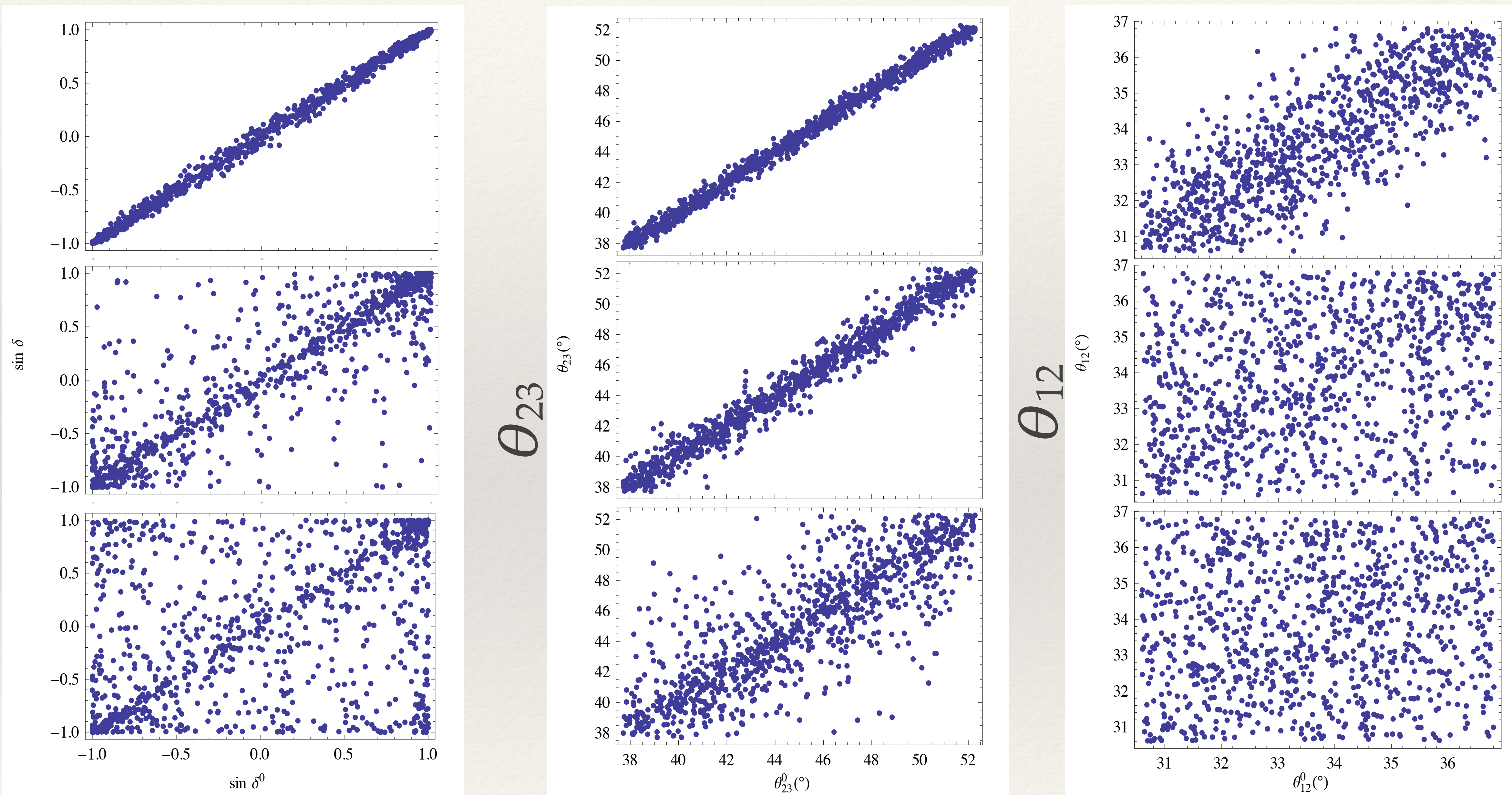
probability to change sign of sin δ



WR, Xu, 1508.06063

Perturbations

smallest mass:



sin δ | θ_{23} | θ_{12}

0.001 eV

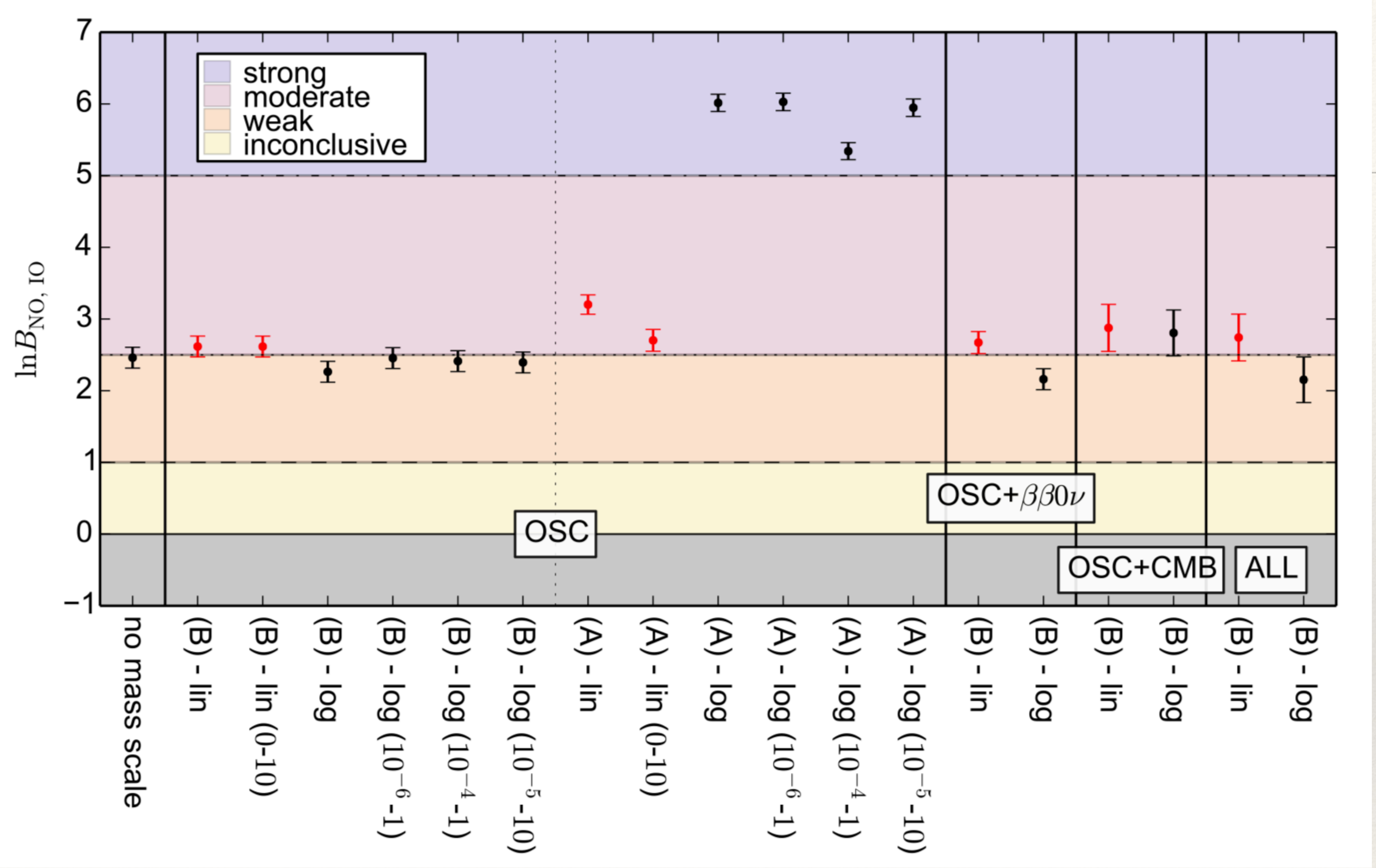
0.04 eV

0.1 eV

sin δ^0 | $\theta_{23}{}^0$ | $\theta_{12}{}^0$

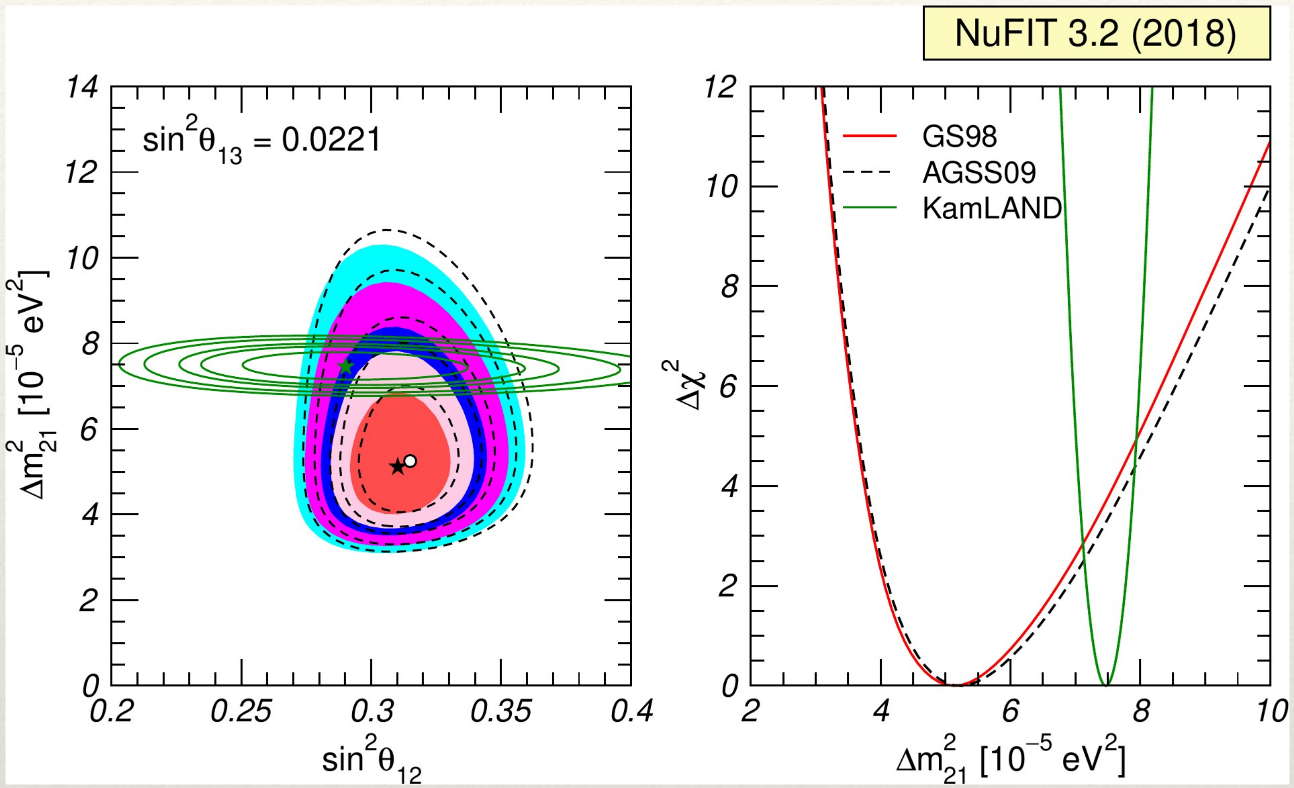
WR, Xu, 1508.06063

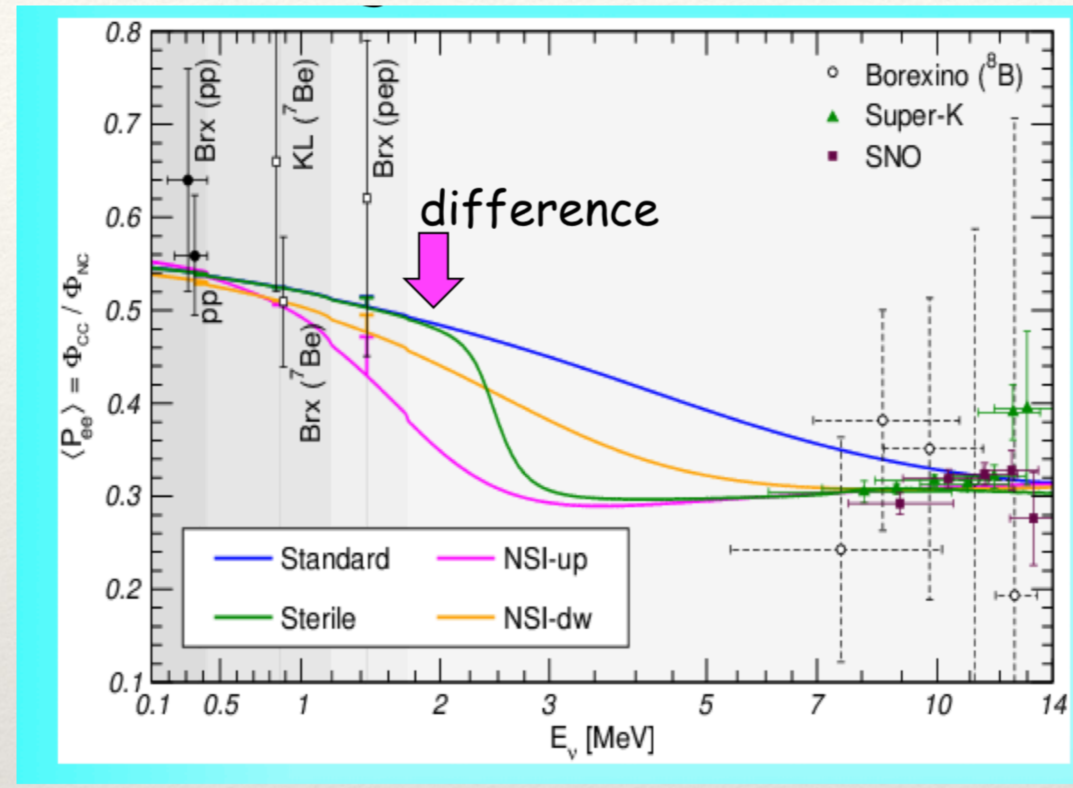
Gariazzo et al., 1801.04946



logarithmic priors on masses give more importance to smaller masses, where NO/IO difference is large

Tensions: only in solar sector?

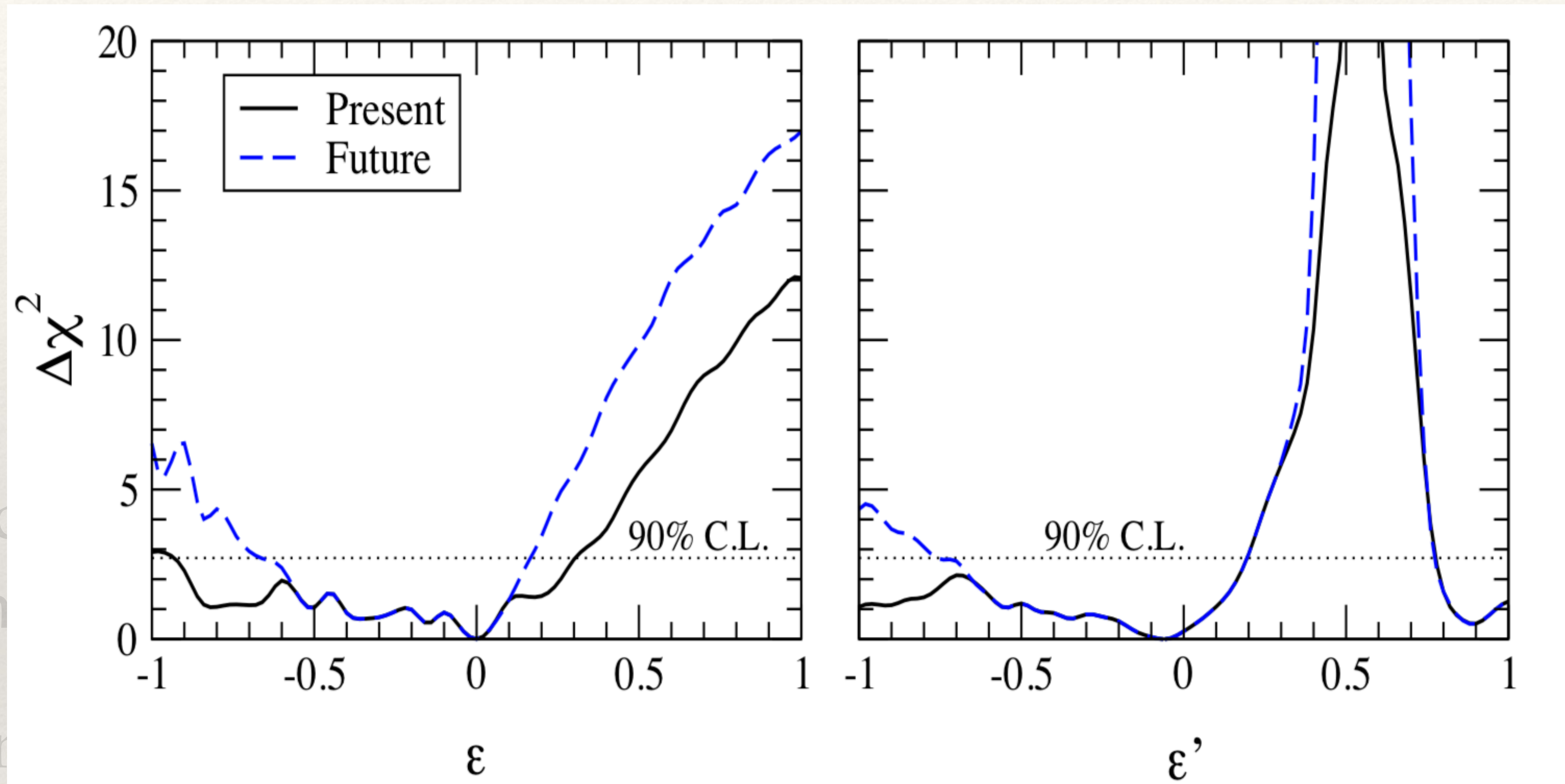




Maltoni, Smirnov, 1507.05287

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

Non-Standard Interactions



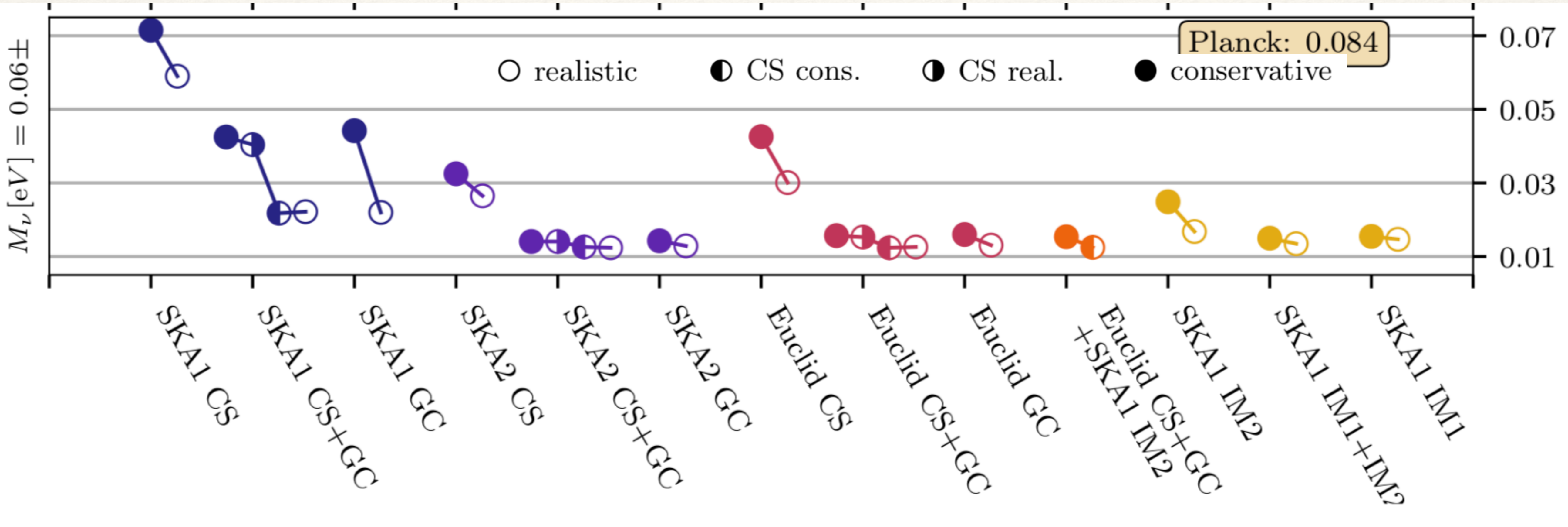
$$\varepsilon = -\sin\theta_{23}\,\varepsilon_{e\tau}^{dV} \qquad \varepsilon' = \sin^2\theta_{23}\,\varepsilon_{\tau\tau}^{dV} - \varepsilon_{ee}^{dV}$$

Miranda, Tortola, Valle, hep-ph/0406280

(can also explain small Δm^2 discrepancy in KamLAND/solar and missing upturn of P_{ee})

Neutrino Mass guaranteed?

Sprenger et al., 1801.08331



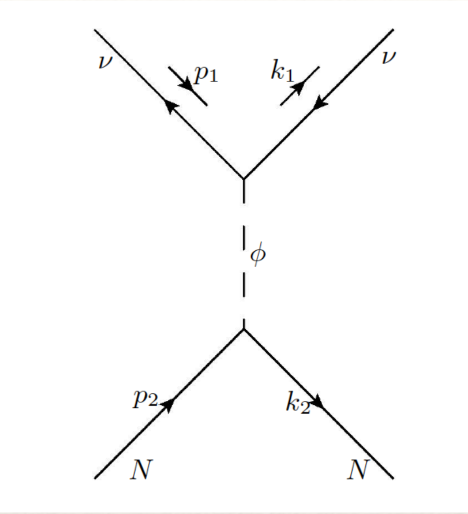
5σ detection when Euclid and SKA are combined!

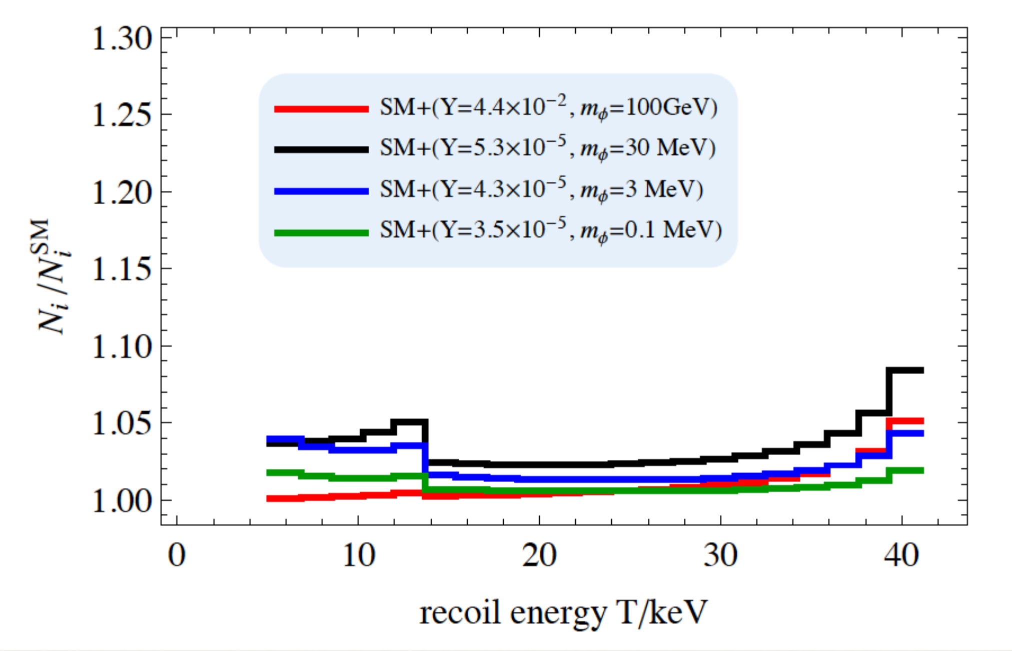
New Physics in Coherent Scattering

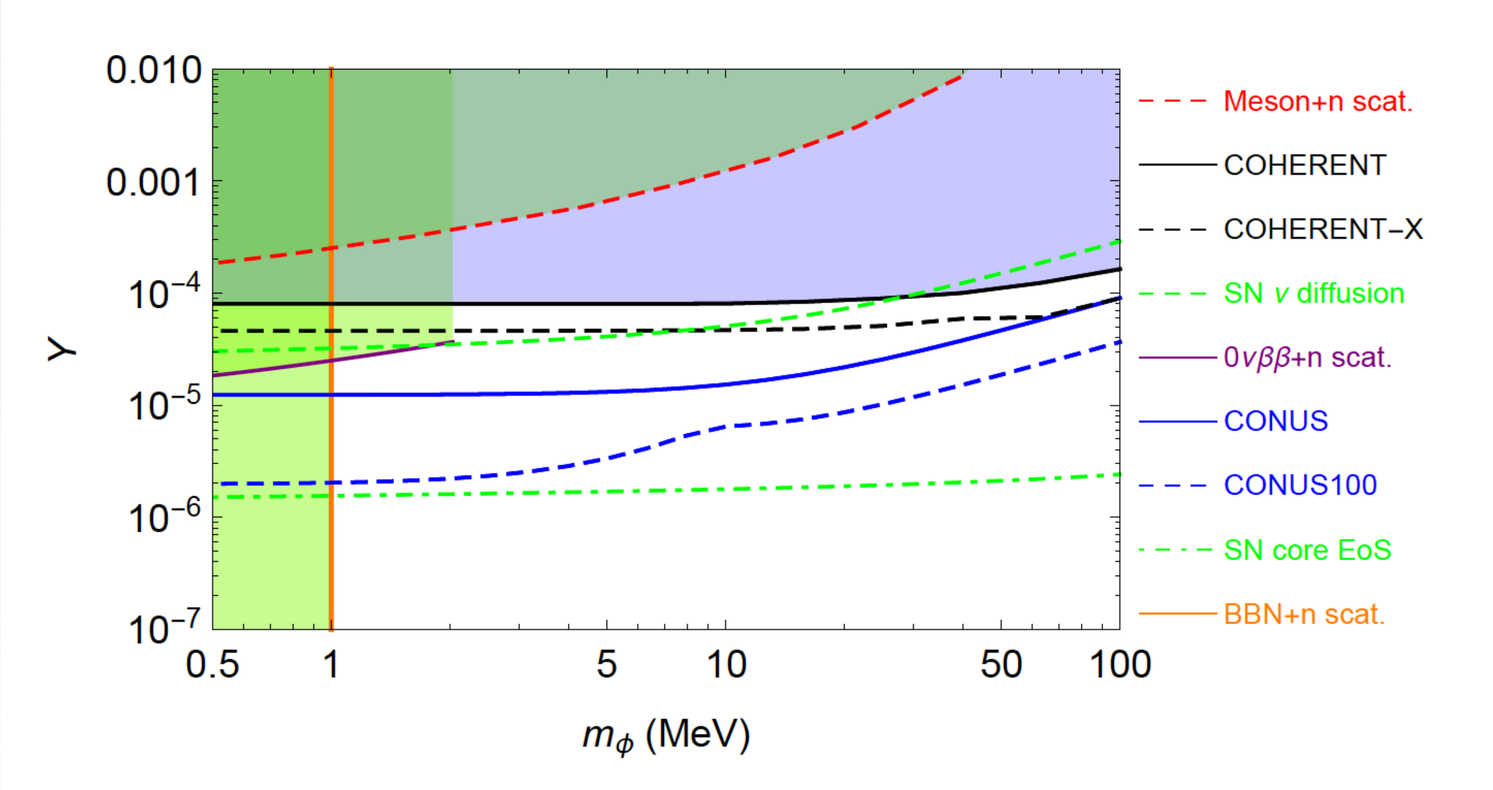
Farzan, Lindner, WR, Xu, 1802.06171

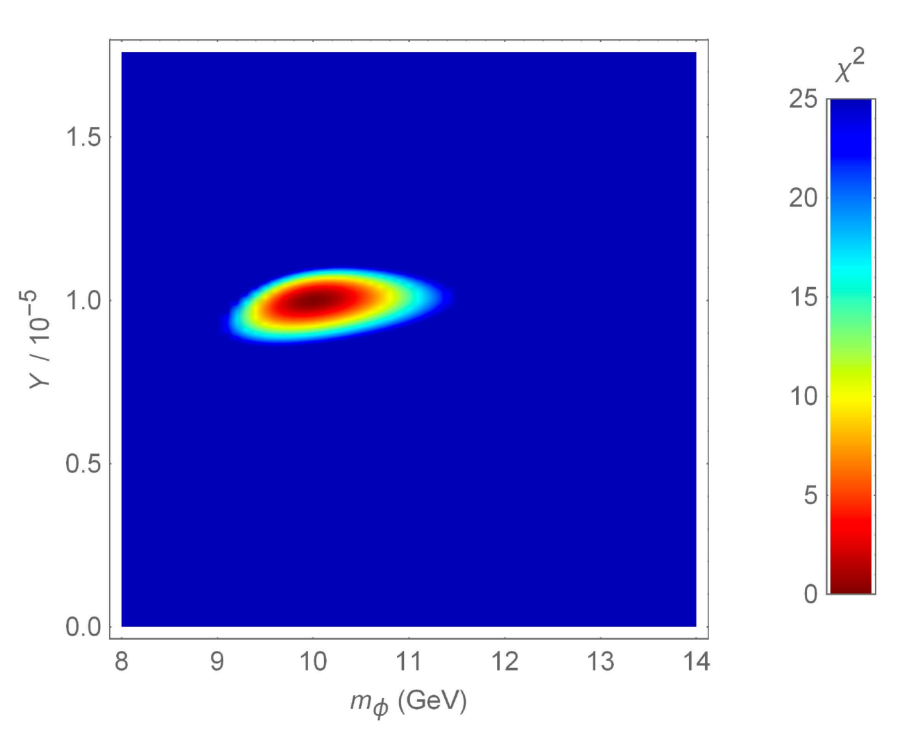
assume light scalar mediator:
(no matter NSI…)

diff. cross section
$\propto T/(2\,M\,T + m^2_\phi)^2\,/E_\nu^2$

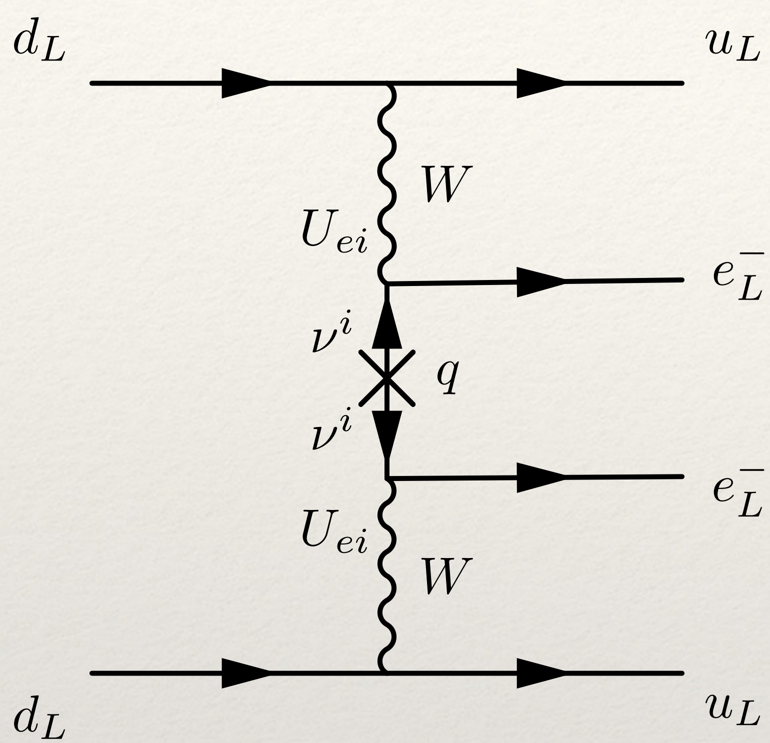


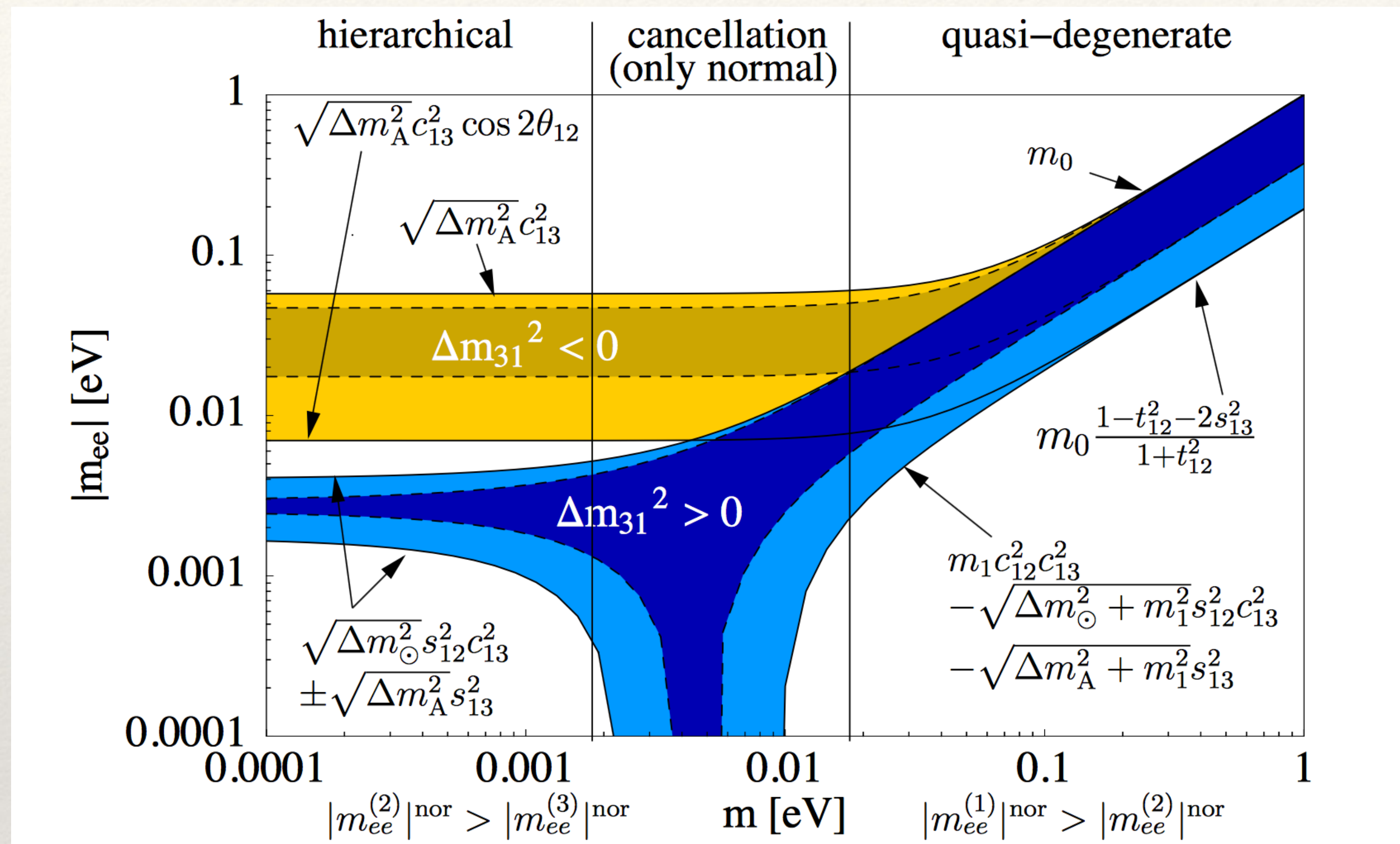






Double Beta Decay





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

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

known — limits — unknown

Experimental Situation

Experiment	Iso.	Iso. Mass $[\text{kg}_{iso}]$	σ [keV]	ROI $[\sigma]$	ϵ_{FV} [%]	ϵ_{sig} [%]	$\mathcal{E}$ $\left[\frac{\text{kg}_{iso}\,\text{yr}}{\text{yr}}\right]$	$\mathcal{B}$ $\left[\frac{\text{cts}}{\text{kg}_{iso}\,\text{ROI yr}}\right]$	3σ disc. sens. $\hat{T}_{1/2}$ [yr]	3σ disc. sens. $\hat{m}_{\beta\beta}$ [meV]	Required Improvement Bkg	Required Improvement σ	Required Improvement 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

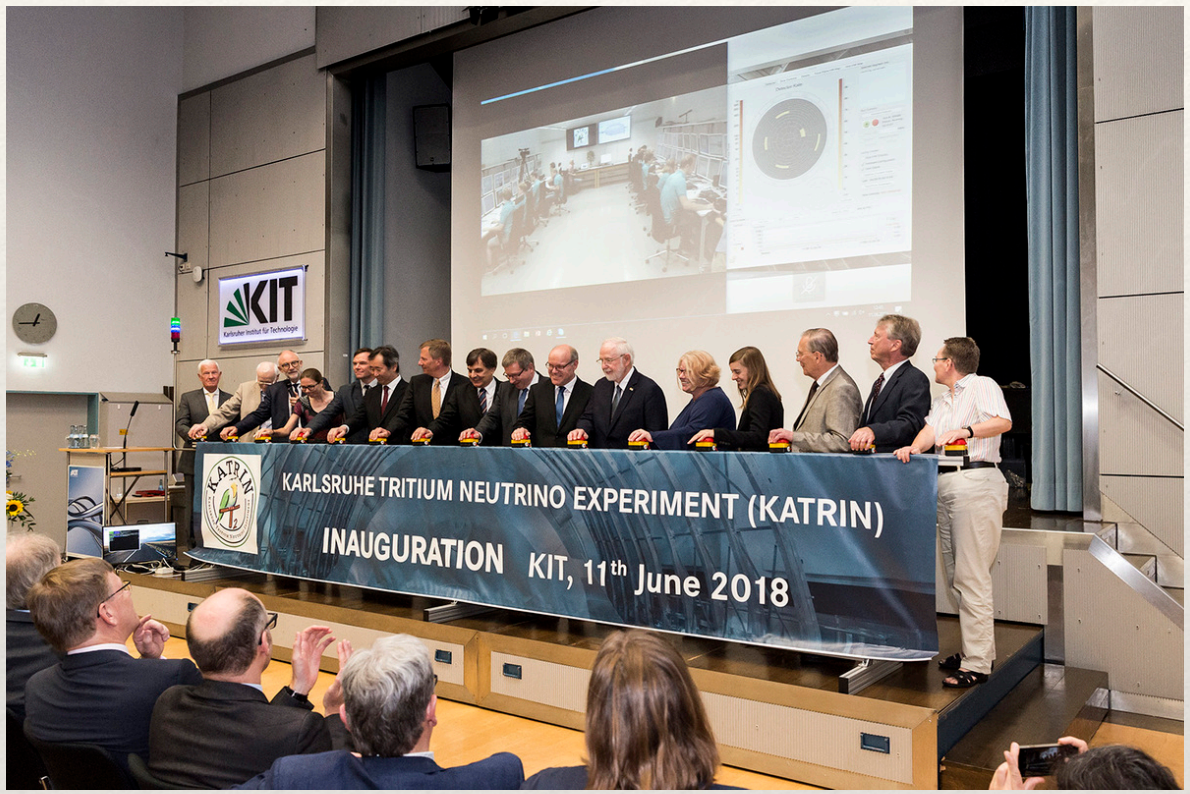
Agostini et al, 1705.02996

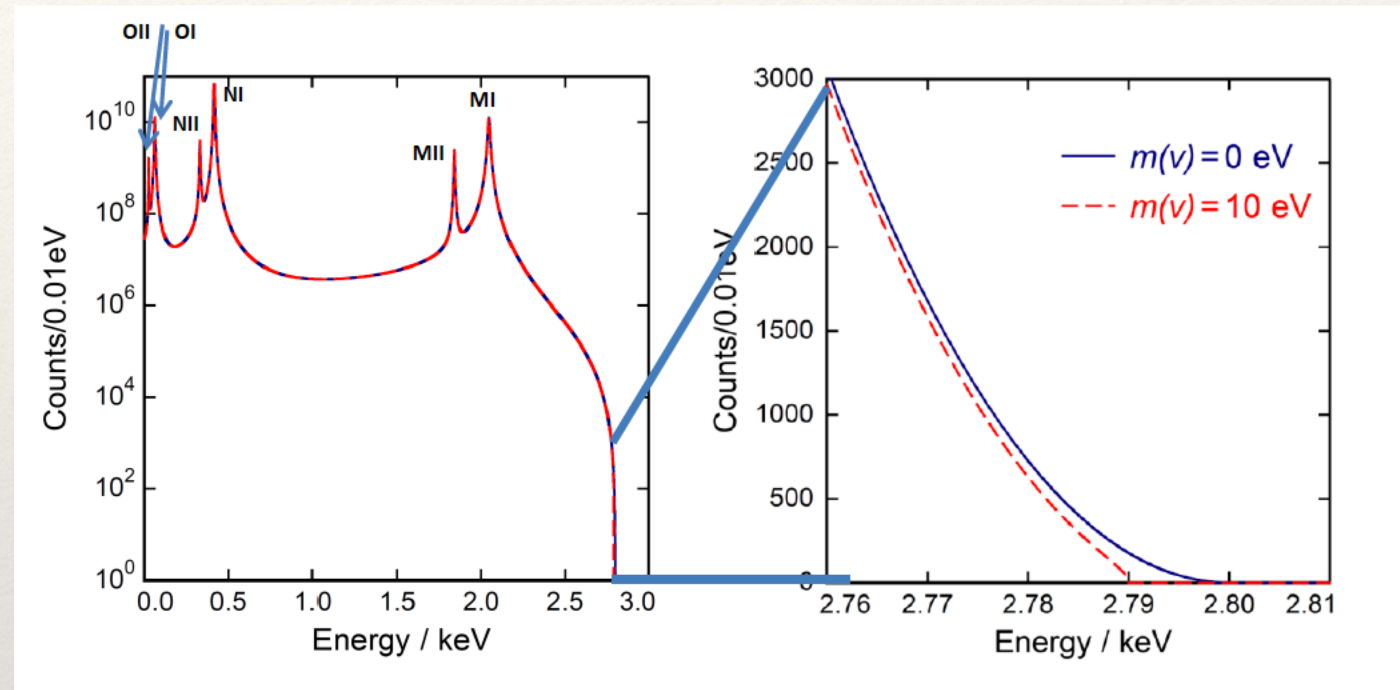
Will enter IH regime soon!

Multi-isotope determination for mechanism and NMEs!

Direct Neutrino Mass Determination

There are 2 running experiments!!





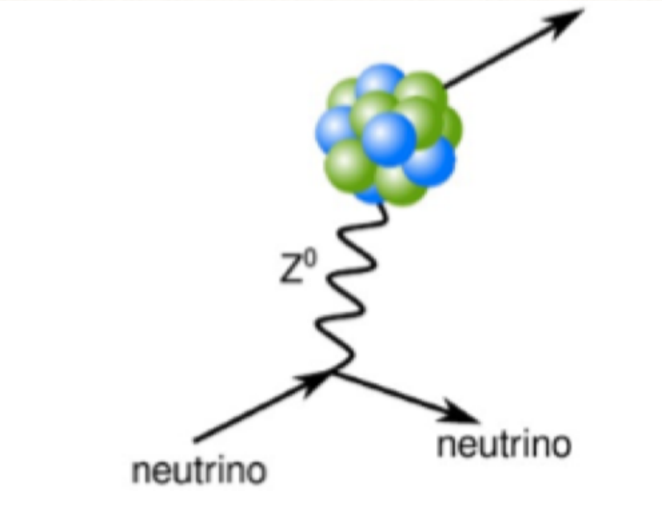
- Tritium since May 2018, first ν-mass data at TAUP…?
- (already plans for future versions, aiming at keV-ν, exotic interactions,…)

- ECHo (EC on ^{163}Ho), spectrum to be measured with low T micro-calorimeters
- first limit coming soon…

Coherent Elastic Neutrino-Nucleus Scattering

Freedmann, PRD9, 1974

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



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

- last missing ν-cross section in SM (largest one…)
- helps SN explode
- neutron charge density ↔ neutron skin ↔ NS eos
- ultimate background for DM direct detection
- measurement of θ_W at low energies
- NSIs, exotic NC, Z', sterile ν,…

Mass Ordering

- weak preference for normal ordering
  - tension in the preferred values of θ_{13} in T2K/NOνA and reactor, found to be stronger for the case of inverted mass ordering
  - tension in the preferred values of Δm^2_{31} in T2K/NOνA and reactor, found to be stronger for the case of inverted mass ordering
  - *e*-like multi-GeV events in SK
  - 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*)

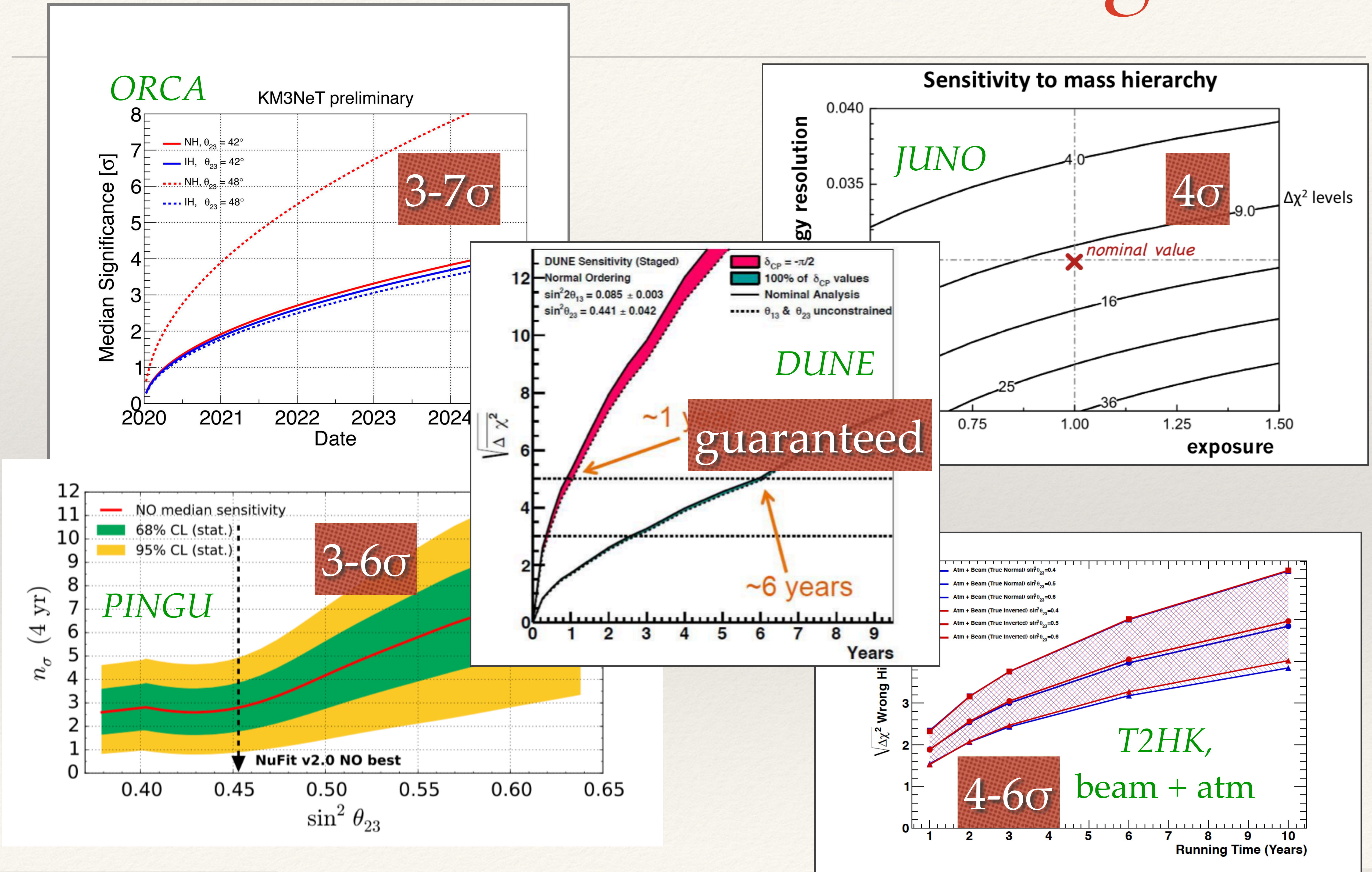
Interpretation/Precision of CP Phase

- 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 $3\pi/2$ the more likely that some symmetry/structure behind it…

Interpretation/Precision of Atmospheric Angle

- 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 to $(m_2/m_3)^{½}$ similar to GST
- BUT: the closer θ_{23} to 45^0 the more likely that some symmetry/structure behind it…

Future of Mass Ordering



CP + Flasy

Combining Flavor and CP Symmetries

Example $G_f = S_4 \times$ CP broken to $G_\nu = S \times$ CP, $G_\ell = T$

$$S^2 = \mathbb{1}\,, \quad T^3 = \mathbb{1}\,, \quad U^2 = \mathbb{1}$$

$$(ST)^3 = \mathbb{1}\,, \quad (SU)^2 = \mathbb{1}\,, \quad (TU)^2 = \mathbb{1}\,, \quad (STU)^4 = \mathbb{1}$$

$\ell \sim \mathbf{3}'$, with $\mathbf{3}'$ irrep:

$$S = \frac{1}{3}\begin{pmatrix} -1 & 2 & 2 \\ 2 & -1 & 2 \\ 2 & 2 & -1 \end{pmatrix}, \quad T = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \omega^2 & 0 \\ 0 & 0 & \omega \end{pmatrix}, \quad U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

$S m_\nu S = m_\nu$ and $X_{3'} m_\nu X_{3'} = m_\nu^*$, consistency is $X_{3'} S^* - S X_{3'} = 0$:

$$X_{\mathbf{3}'} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

gives $\delta = \pm\pi/2$ (Hagedorn, Feruglio, Ziegler, EPJC74)

Mu-tau reflection symmetry

"Constrained Maximal CP Violation"

data seems to want $\delta = -\pi/2$ and $\theta_{23} = \pi/4$, equivalent to

- $J_{\rm CP}$ maximal when first row of PMNS is fixed
- column unitary triangles are isosceles triangles
- **second row of PMNS is (third row)***

"If residual symmetries are real and fully determine the mixing pattern, then $\delta = \pm\pi/2$ and $\theta_{23} = \pi/4$ follows."

He, W.R., Xu, 1507.03541

contains subgroups of $O(3)$, such as A_4, S_4, A_5 (Joshipura, Patel, PLB749)

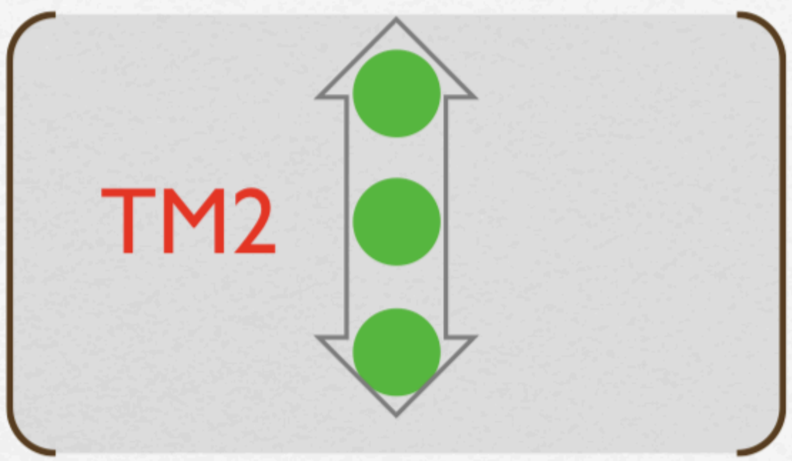
and μ-τ reflection symmetry (Ma; Grimus, Lavoura)

$$\nu_e \to \nu_e^*,\ \nu_\mu \to \nu_\tau^*,\ \nu_\tau \to \nu_\mu^*$$

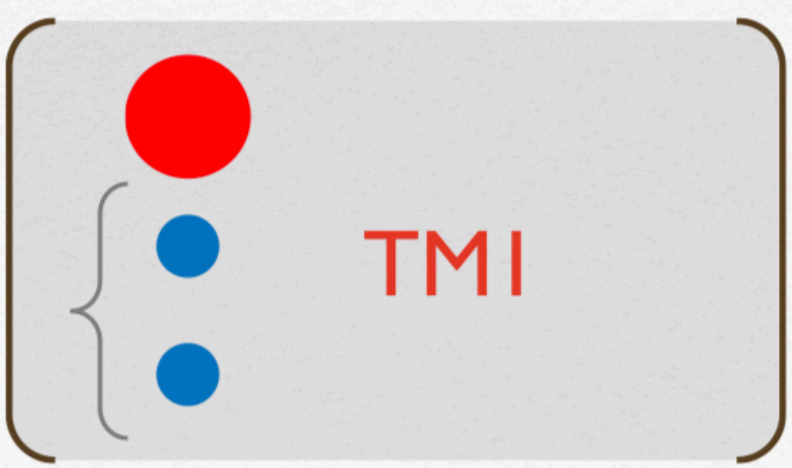
Re-using part of TBM

Tri-maximal Mixing

C.H.Albright and W.Rodejohann, 0812.0436; C.H.Albright, A.Dueck and W.Rodejohann, 1004.2798



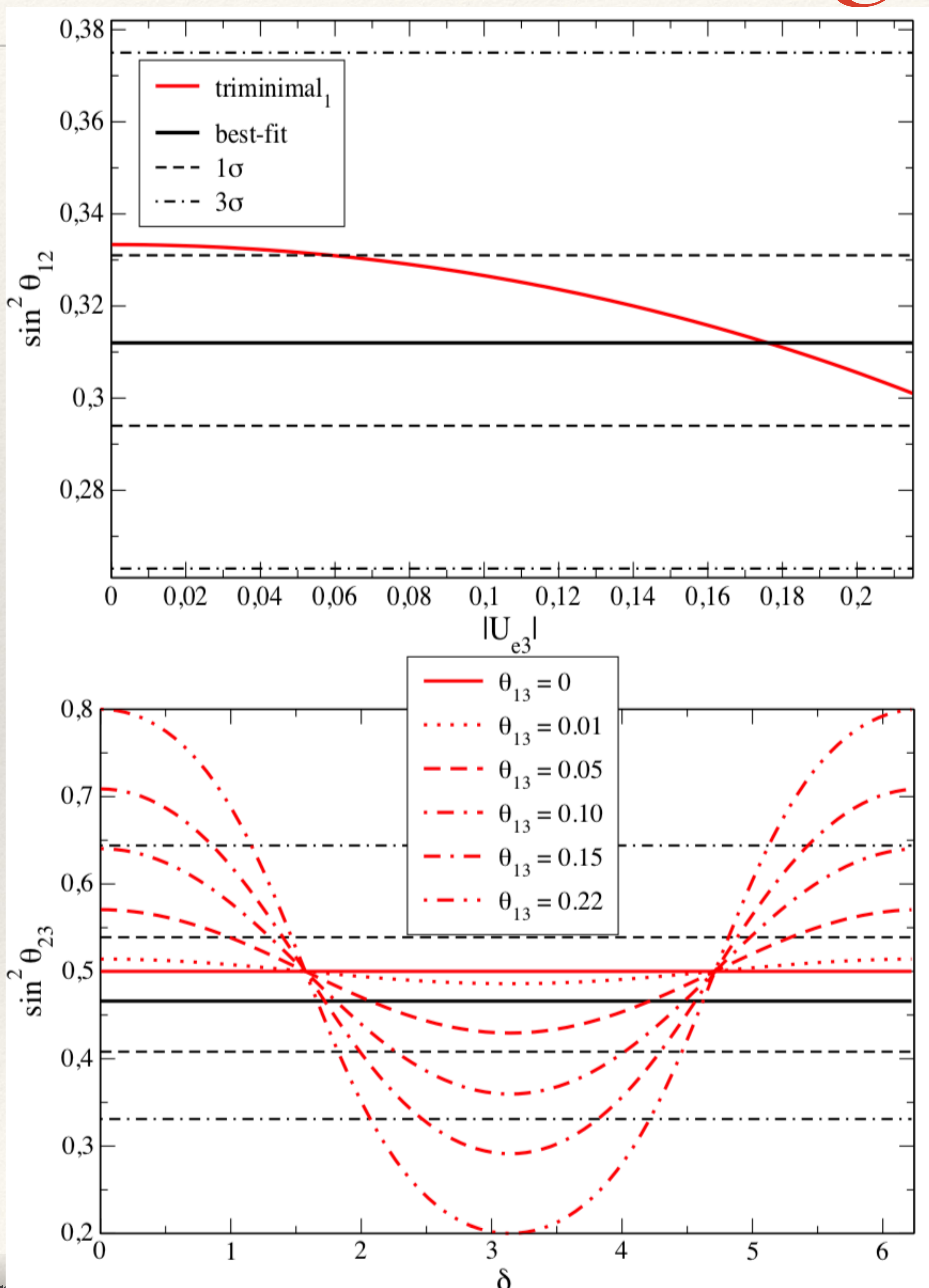
$$U_{\rm TM2} \approx \begin{pmatrix} - & \frac{1}{\sqrt{3}} & - \\ - & \frac{1}{\sqrt{3}} & - \\ - & -\frac{1}{\sqrt{3}} & - \end{pmatrix}$$



$$U_{\rm TM1} \approx \begin{pmatrix} \sqrt{\frac{2}{3}} & - & - \\ -\frac{1}{\sqrt{6}} & - & - \\ \frac{1}{\sqrt{6}} & - & - \end{pmatrix}$$

Slide by Steve King, SUSY19

Re-using part of TBM



$$\sin^2\theta_{12} = \frac{1}{3}\,\frac{1-3\,|U_{e3}|^2}{1-|U_{e3}|^2} \simeq \frac{1}{3}\,\left(1-2\,|U_{e3}|^2\right)$$

less than 1/3

$\sin^2\theta_{12} \sim 1/3 - |U_{e3}|^2$

$$\sin^2\theta_{23} \simeq \frac{1}{2} + \frac{1}{\sqrt{2}}\,|U_{e3}|\left(1+\frac{1}{4}\,|U_{e3}|^2\right)\cos\delta$$

$\delta = 3\pi/2 \leftrightarrow \theta_{23} = \pi/4$

less than maximal for $\cos\delta < 0$

$\sin^2\theta_{23} \sim 1/2 - |U_{e3}|$

General Neutrino Interactions

$$\mathcal{L}^{\rm NC} = -\frac{G_F}{\sqrt{2}} \sum_{j=1}^{10} \left(\overset{(\sim)}{\epsilon}_{j,f} \right)^{\alpha\beta\gamma\delta} (\overline{\nu}_\alpha \mathcal{O}_j \nu_\beta) (\overline{f}_\gamma \mathcal{O}'_j f_\delta) \,,$$

$$\mathcal{L}^{\rm CC} = -\frac{G_F V_{\gamma\delta}}{\sqrt{2}} \sum_{j=1}^{10} \left(\overset{(\sim)}{\epsilon}_{j,ud} \right)^{\alpha\beta\gamma\delta} (\overline{e}_\alpha \mathcal{O}_j \nu_\beta) (\overline{u}_\gamma \mathcal{O}'_j d_\delta) + \text{h.c.}$$

- can come from dim-6 operators incl. SM and N_R
- correlations between ν-scattering and LFV
- correlations between CEνNS and β-decay
- generated e.g. by leptoquarks (⟷ B-anomalies and radiative m_ν)

j	$\overset{(\sim)}{\epsilon}_j$	$\mathcal{O}_j$	$\mathcal{O}'_j$
1	ϵ_L	$\gamma_\mu(\mathbb{1}-\gamma^5)$	$\gamma^\mu(\mathbb{1}-\gamma^5)$
2	$\tilde{\epsilon}_L$	$\gamma_\mu(\mathbb{1}+\gamma^5)$	$\gamma^\mu(\mathbb{1}-\gamma^5)$
3	ϵ_R	$\gamma_\mu(\mathbb{1}-\gamma^5)$	$\gamma^\mu(\mathbb{1}+\gamma^5)$
4	$\tilde{\epsilon}_R$	$\gamma_\mu(\mathbb{1}+\gamma^5)$	$\gamma^\mu(\mathbb{1}+\gamma^5)$
5	ϵ_S	$(\mathbb{1}-\gamma^5)$	$\mathbb{1}$
6	$\tilde{\epsilon}_S$	$(\mathbb{1}+\gamma^5)$	$\mathbb{1}$
7	$-\epsilon_P$	$(\mathbb{1}-\gamma^5)$	γ^5
8	$-\tilde{\epsilon}_P$	$(\mathbb{1}+\gamma^5)$	γ^5
9	ϵ_T	$\sigma_{\mu\nu}(\mathbb{1}-\gamma^5)$	$\sigma^{\mu\nu}(\mathbb{1}-\gamma^5)$
10	$\tilde{\epsilon}_T$	$\sigma_{\mu\nu}(\mathbb{1}+\gamma^5)$	$\sigma^{\mu\nu}(\mathbb{1}+\gamma^5)$

-talk by Bischer

SMEFT Analysis

$\mathcal{O}_{lNqd}$	$(\bar{l}^j_\alpha N_\beta)\epsilon_{jk}(\bar{q}^k_\gamma d_\delta)$
$\mathcal{O}'_{lNqd}$	$(\bar{l}^j_\alpha \sigma_{\mu\nu} N_\beta)\epsilon_{jk}(\bar{q}^k_\gamma \sigma^{\mu\nu} d_\delta)$
$\mathcal{O}_{lNuq}$	$(\bar{l}^j_\alpha N_\beta)(\bar{u}_\gamma q^j_\delta)$

NC:

	e	u	d
$-\epsilon^{\alpha\beta\gamma\delta}_{L,f}$	$C^{\alpha\beta\gamma\delta}_{ll} + C^{\gamma\delta\alpha\beta}_{ll}$	$V_{\gamma\mu}V^\dagger_{\nu\delta}\left(C^{\alpha\beta\mu\nu}_{lq(1)} + C^{\alpha\beta\mu\nu}_{lq(3)}\right)$	$C^{\alpha\beta\gamma\delta}_{lq(1)} - C^{\alpha\beta\gamma\delta}_{lq(3)}$
$-\tilde{\epsilon}^{\alpha\beta\gamma\delta}_{L,f}$	$C^{\alpha\beta\gamma\delta}_{Nl}$	$V_{\gamma\mu}V^\dagger_{\nu\delta}C^{\alpha\beta\mu\nu}_{Nq}$	$C^{\alpha\beta\gamma\delta}_{Nq}$
$-\epsilon^{\alpha\beta\gamma\delta}_{R,f}$	$C^{\alpha\beta\gamma\delta}_{le}$	$C^{\alpha\beta\gamma\delta}_{lu}$	$C^{\alpha\beta\gamma\delta}_{ld}$
$-\tilde{\epsilon}^{\alpha\beta\gamma\delta}_{R,f}$	$C^{\alpha\beta\gamma\delta}_{Ne}$	$C^{\alpha\beta\gamma\delta}_{Nu}$	$C^{\alpha\beta\gamma\delta}_{Nd}$
$-\epsilon^{\alpha\beta\gamma\delta}_{S,f}$	$\frac{1}{2}C^{\alpha\beta\gamma\delta}_{Nlel} + \frac{1}{4}C^{\gamma\beta\alpha\delta}_{Nlel}$	$V_{\gamma\nu}(C^{\beta\alpha\delta\nu}_{lNuq})^*$	$(C^{\beta\alpha\delta\gamma}_{lNqd})^*$
$-\epsilon^{\alpha\beta\gamma\delta}_{P,f}$	$\frac{1}{2}C^{\alpha\beta\gamma\delta}_{Nlel} + \frac{1}{4}C^{\gamma\beta\alpha\delta}_{Nlel}$	$-V_{\gamma\nu}(C^{\beta\alpha\delta\nu}_{lNuq})^*$	$(C^{\beta\alpha\delta\gamma}_{lNqd})^*$
$-\epsilon^{\alpha\beta\gamma\delta}_{T,f}$	$\frac{1}{8}C^{\gamma\beta\alpha\delta}_{Nlel}$	0	$(C'^{\beta\alpha\delta\gamma}_{lNqd})^*$

CC:

$-\epsilon^{\alpha\beta\gamma\delta}_{L,ud}$	$\frac{V_{\gamma\nu}}{V_{\gamma\delta}}2C^{\alpha\beta\nu\delta}_{lq(3)}$	$-\tilde{\epsilon}^{\alpha\beta\gamma\delta}_{L,ud}$	0
$-\epsilon^{\alpha\beta\gamma\delta}_{R,ud}$	0	$-\tilde{\epsilon}^{\alpha\beta\gamma\delta}_{R,ud}$	$\frac{1}{V_{\gamma\delta}}C^{\alpha\beta\gamma\delta}_{eNud}$
$-\epsilon^{\alpha\beta\gamma\delta}_{S,ud}$	$\frac{1}{V_{\gamma\delta}}\left(V_{\gamma\nu}C^{\alpha\beta\nu\delta}_{elqd} + C^{\alpha\beta\gamma\delta}_{eluq}\right)$	$-\tilde{\epsilon}^{\alpha\beta\gamma\delta}_{S,ud}$	$\frac{1}{V_{\gamma\delta}}\left(C^{\alpha\beta\gamma\delta}_{lNuq} - V_{\gamma\nu}C^{\alpha\beta\nu\delta}_{lNqd}\right)$
$-\epsilon^{\alpha\beta\gamma\delta}_{P,ud}$	$\frac{1}{V_{\gamma\delta}}\left(-V_{\gamma\nu}C^{\alpha\beta\nu\delta}_{elqd} + C^{\alpha\beta\gamma\delta}_{eluq}\right)$	$-\tilde{\epsilon}^{\alpha\beta\gamma\delta}_{P,ud}$	$\frac{1}{V_{\gamma\delta}}\left(C^{\alpha\beta\gamma\delta}_{lNuq} + V_{\gamma\nu}C^{\alpha\beta\nu\delta}_{lNqd}\right)$
$-\epsilon^{\alpha\beta\gamma\delta}_{T,ud}$	$\frac{1}{V_{\gamma\delta}}C'^{\alpha\beta\gamma\delta}_{eluq}$	$-\tilde{\epsilon}^{\alpha\beta\gamma\delta}_{T,ud}$	$-\frac{V_{\gamma\nu}}{V_{\gamma\delta}}C'^{\alpha\beta\nu\delta}_{lNqd}$

‖-talk by Bischer