Neutrino physics: present and future

Werner Rodejohann (MPIK)

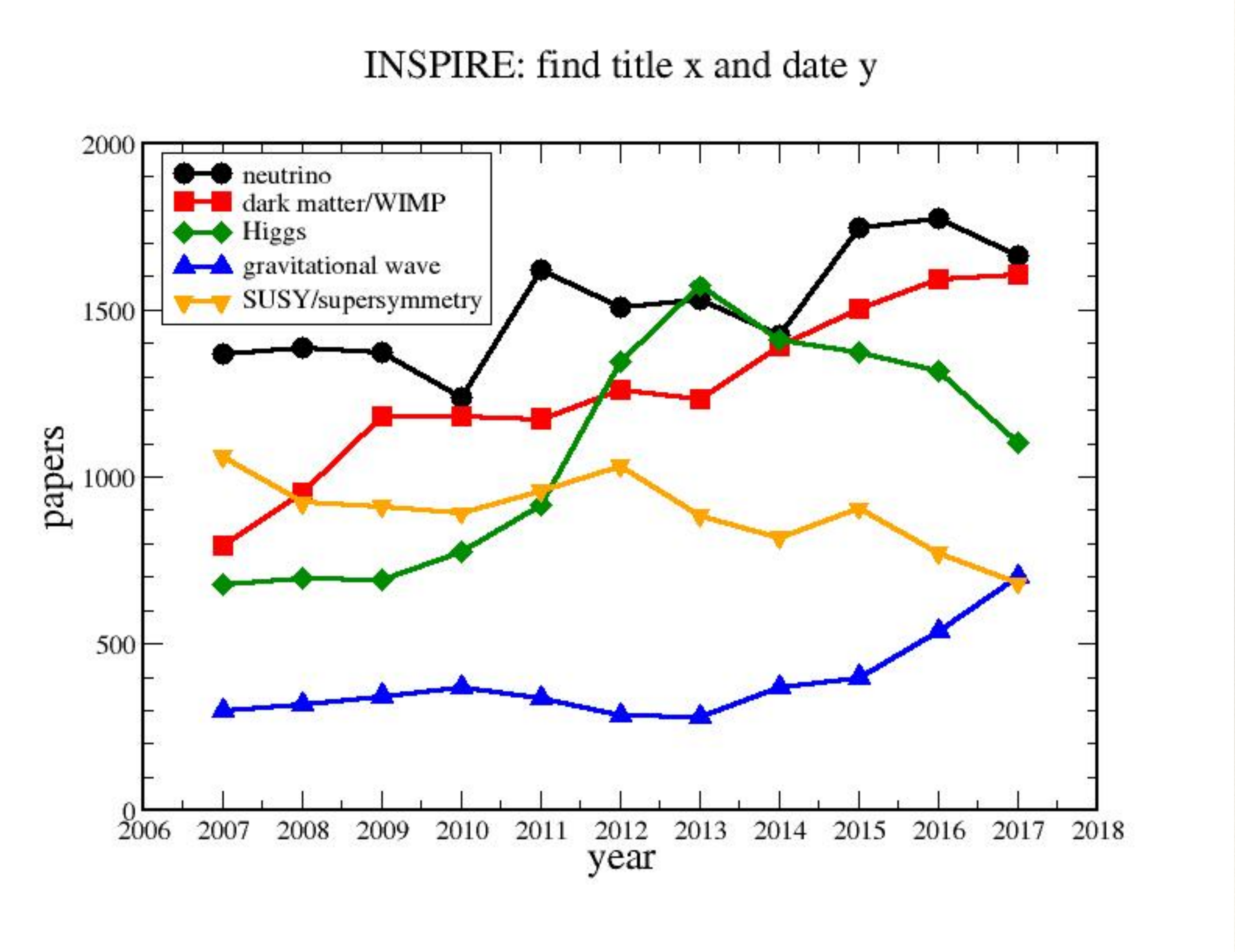
FPCP '18

July 17

Outline

- Neutrino mixing:
  - what have we learned?
  - what remains to be done?
- Neutrino mass:
  - what have we learned?
  - what remains to be done?
- New windows:
  - Coherent elastic neutrino-nucleus scattering

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 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

→

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3 Majorana neutrino paradigm ⇒ needs to be tested!

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3 Majorana neutrino paradigm ⇒ needs to be tested!

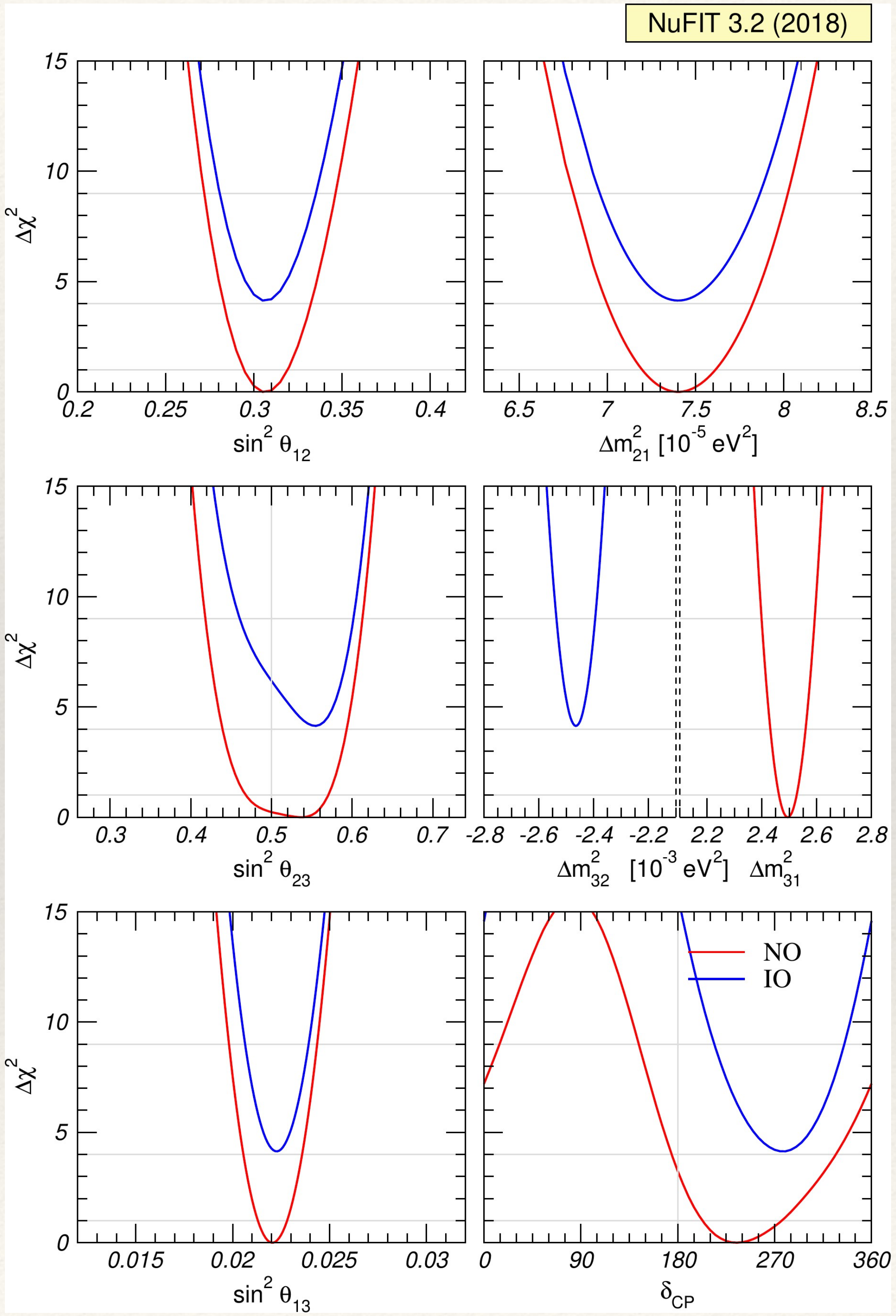
Plus: mechanisms to generate m_ν have new particles, new energy scales, new concepts, new…

Low Energy Paradigm

- 3 Tasks:
  - determine new parameters
  - 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:
  - $\text{sgn}(\Delta m^2_{31})$
  - δ, α, β



Robust fit results by *Valencia (1708.01186), Bari (1804.09678), NuFIT*

See exptl. talks by *Sekiguchi (T2K), Bhatnagar (NOvA), Wu (reactors)*

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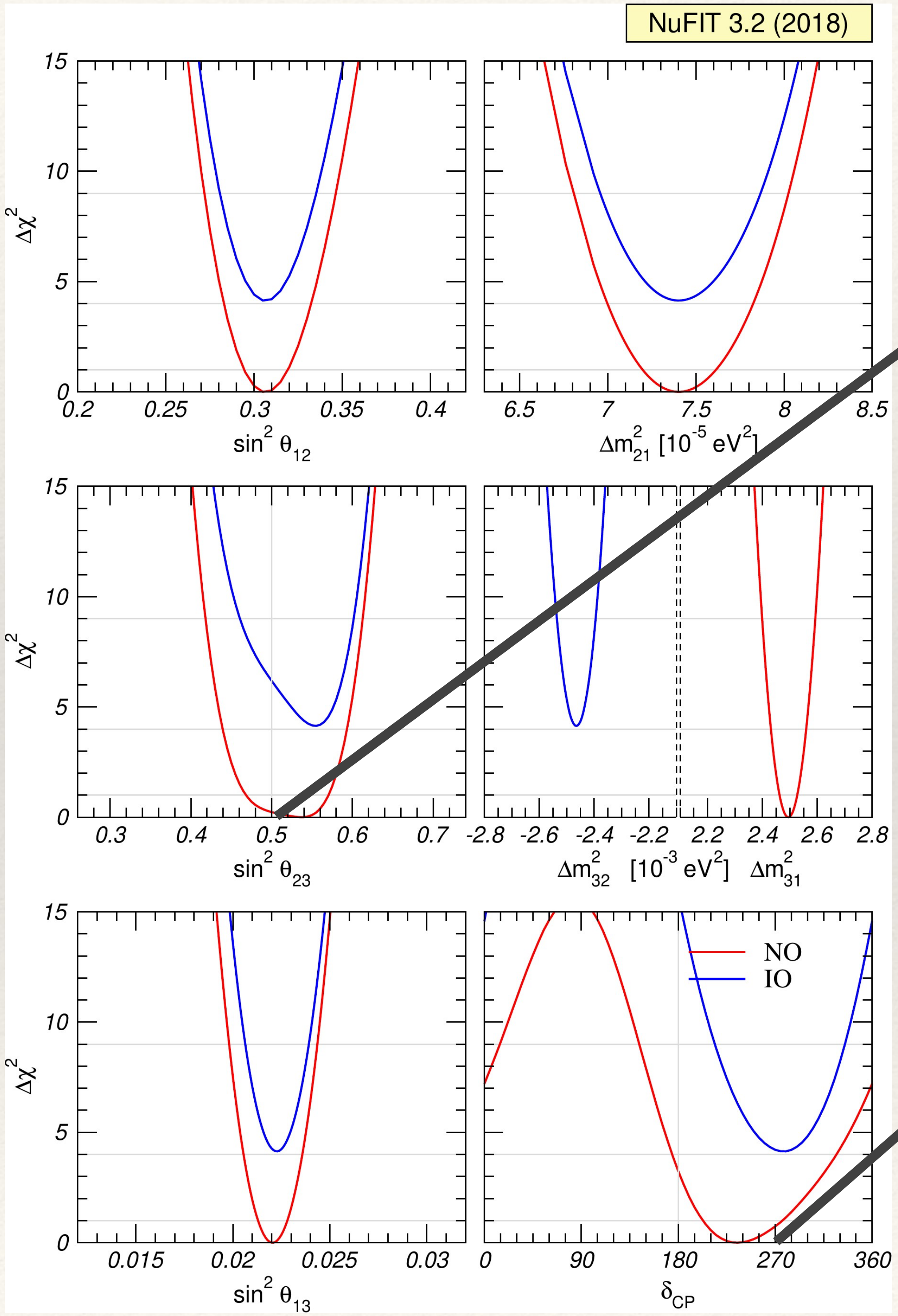

maximal θ_{23} ?

$\delta = 3\pi/2$?

Normal Ordering preferred at ≃ 3σ

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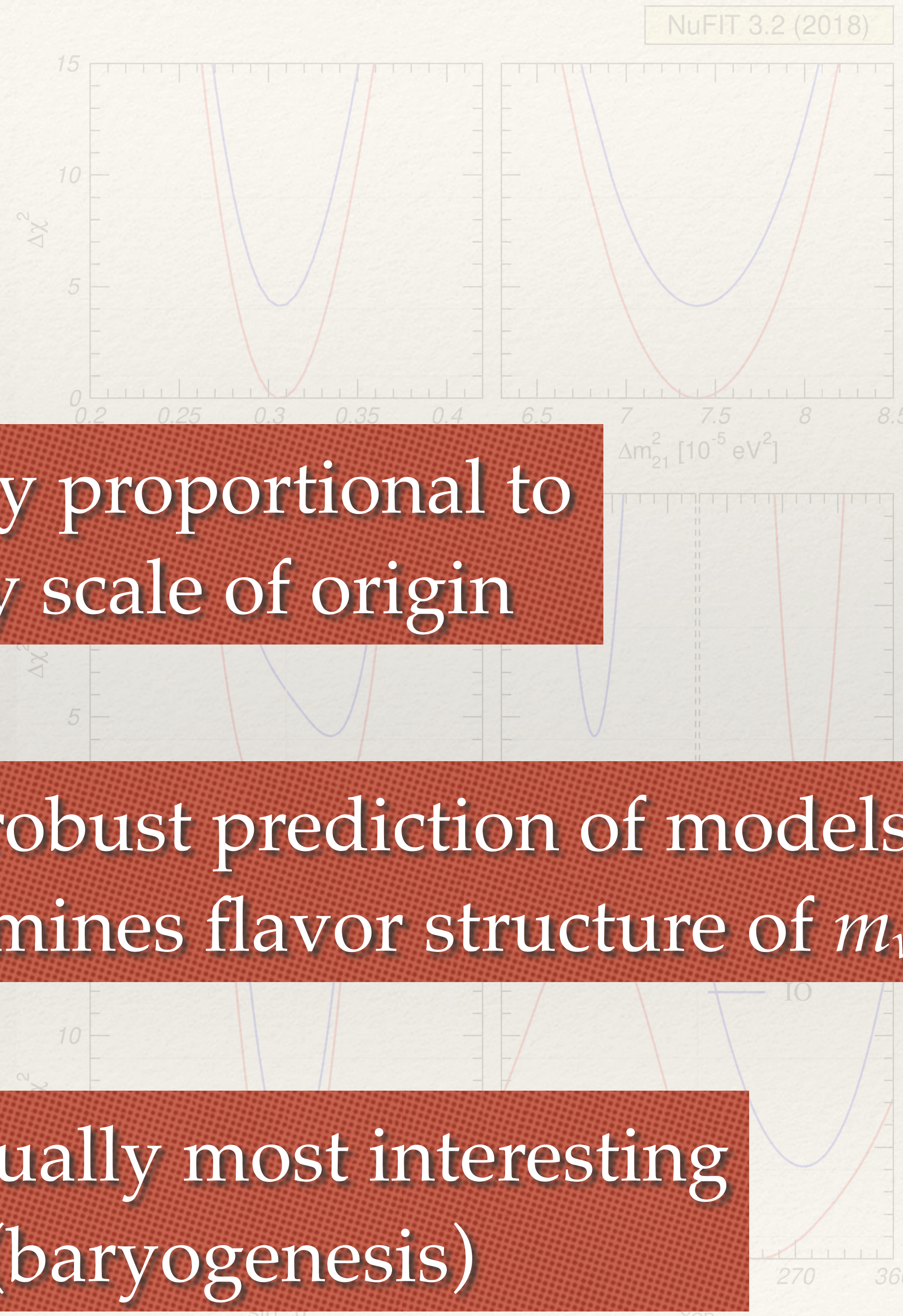

inversely proportional to energy scale of origin

most robust prediction of models; determines flavor structure of m_ν

conceptually most interesting (baryogenesis)

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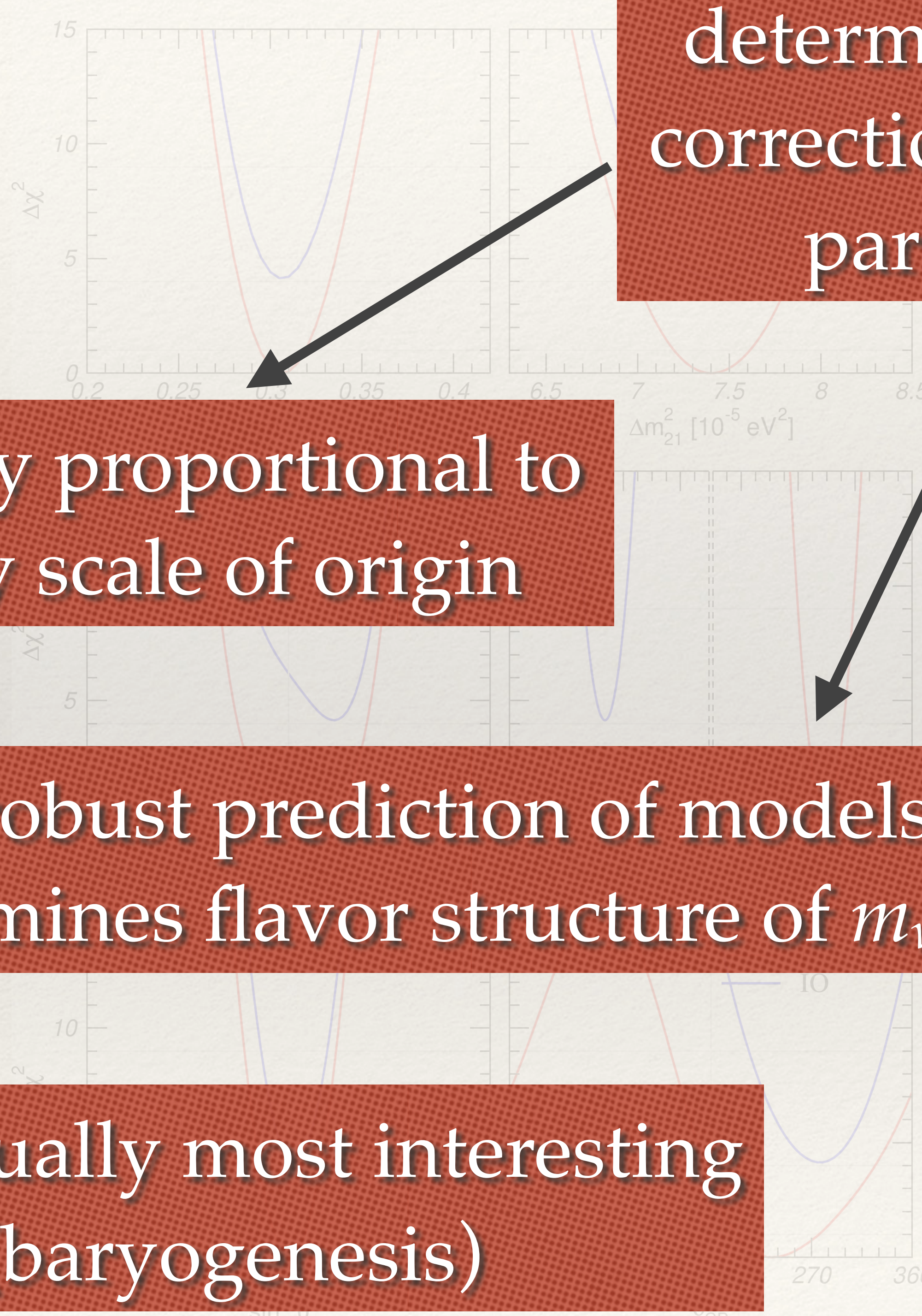

determines size of correction to mixing parameters

inversely proportional to energy scale of origin

most robust prediction of models; determines flavor structure of m_ν

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Oscillation Parameters

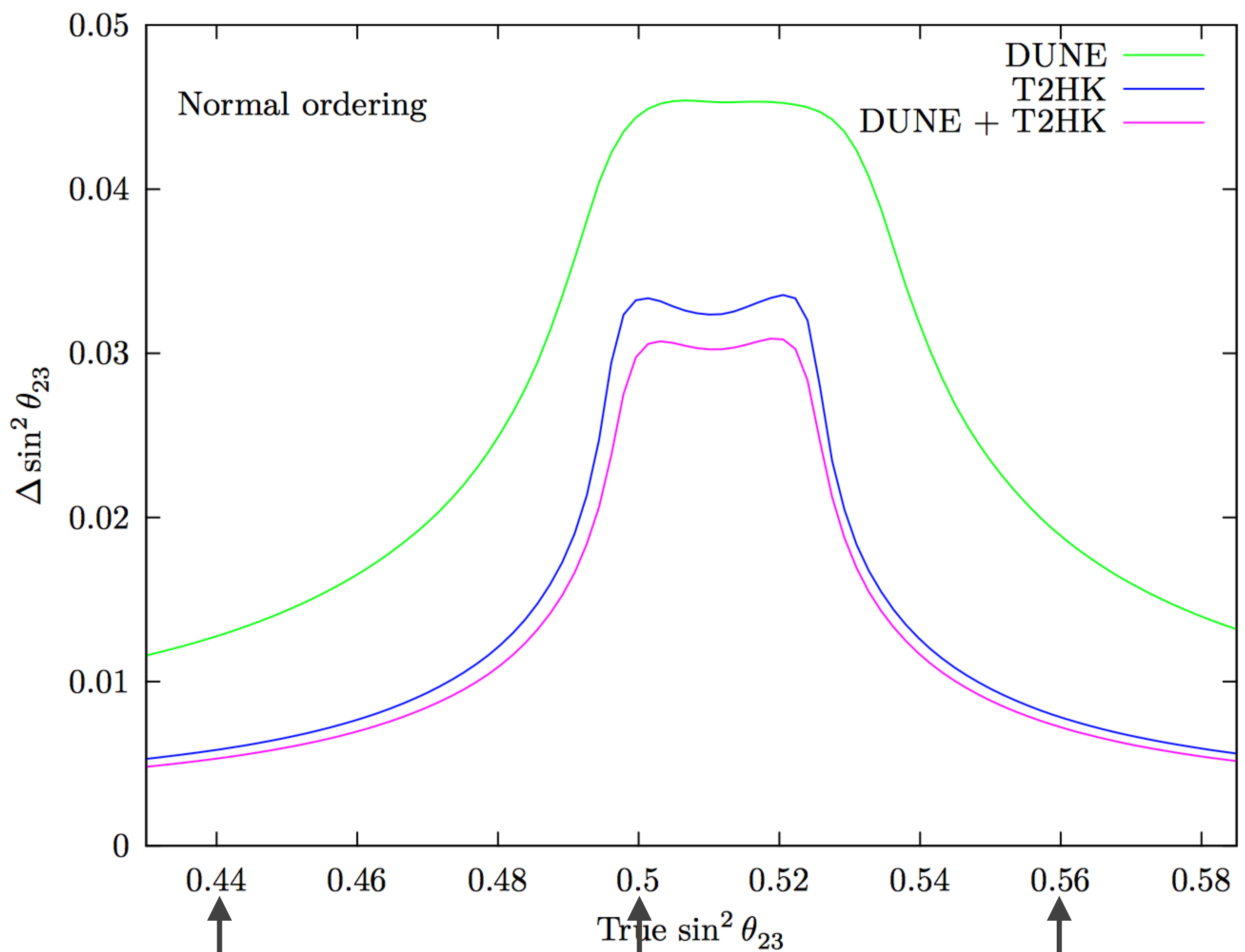
parameter	best fit $\pm$ 1σ	relative 1σ uncertainty
Δm^2_{21} [10^{-5}eV^2]	$7.55^{+0.20}_{-0.16}$	2.4%
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (NO)	2.50 ± 0.03	1.3%
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (IO)	$2.42^{+0.03}_{-0.04}$	
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	5.5%
$\sin^2\theta_{23}/10^{-1}$ (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%

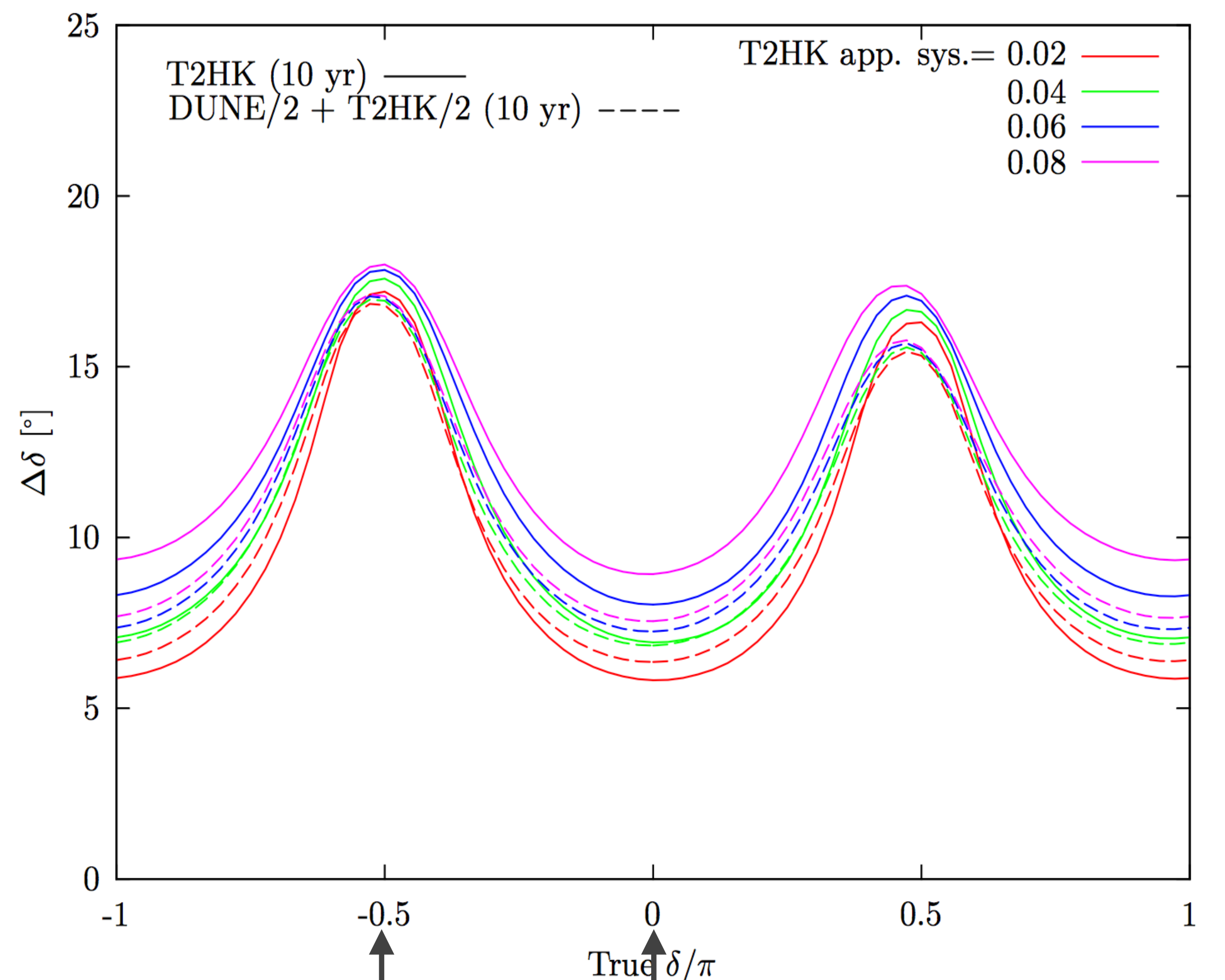
	Current	JUNO
Δm^2_{12}	~3%	~0.6%
Δm^2_{23}	~5%	~0.6%
$\sin^2\theta_{12}$	~6%	~0.7%
$\sin^2\theta_{23}$	~20%	N/A
$\sin^2\theta_{13}$	~14% → ~4%	~ 15%

Tortola, talk at Neutrino2018

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)

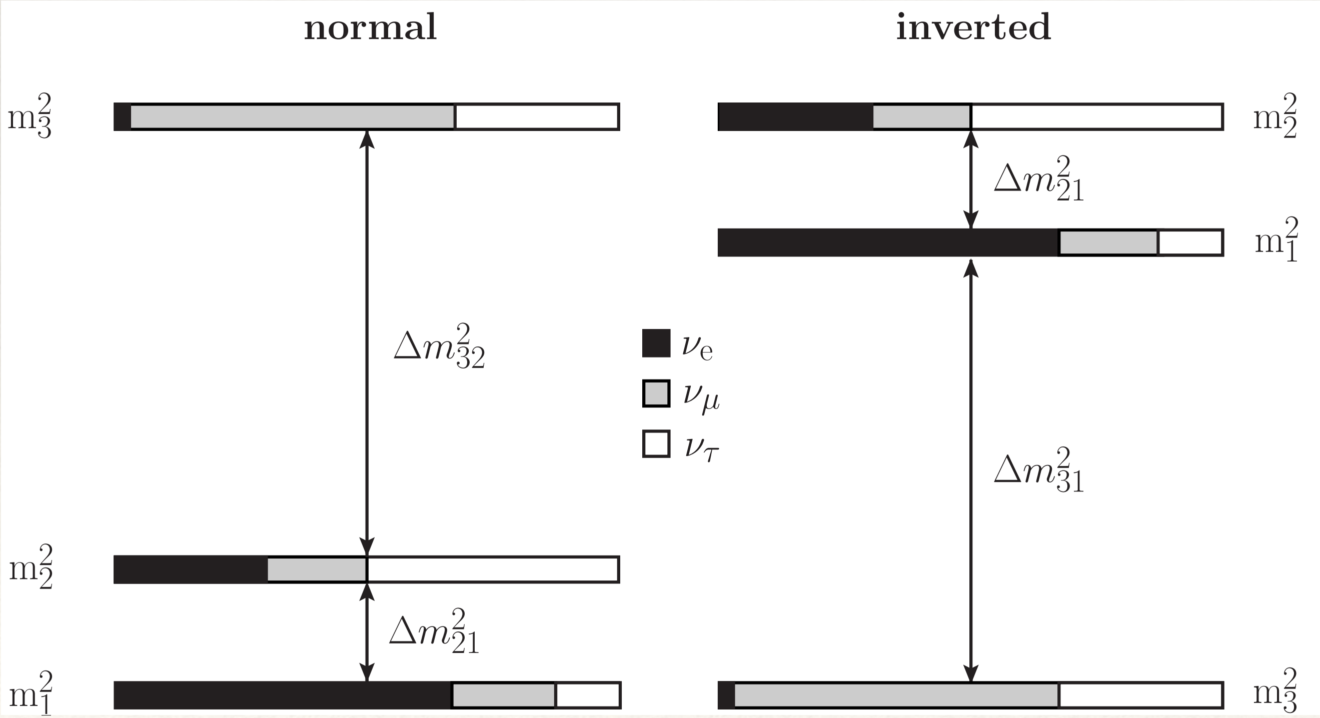
see talks by Tanaka, Indumathi

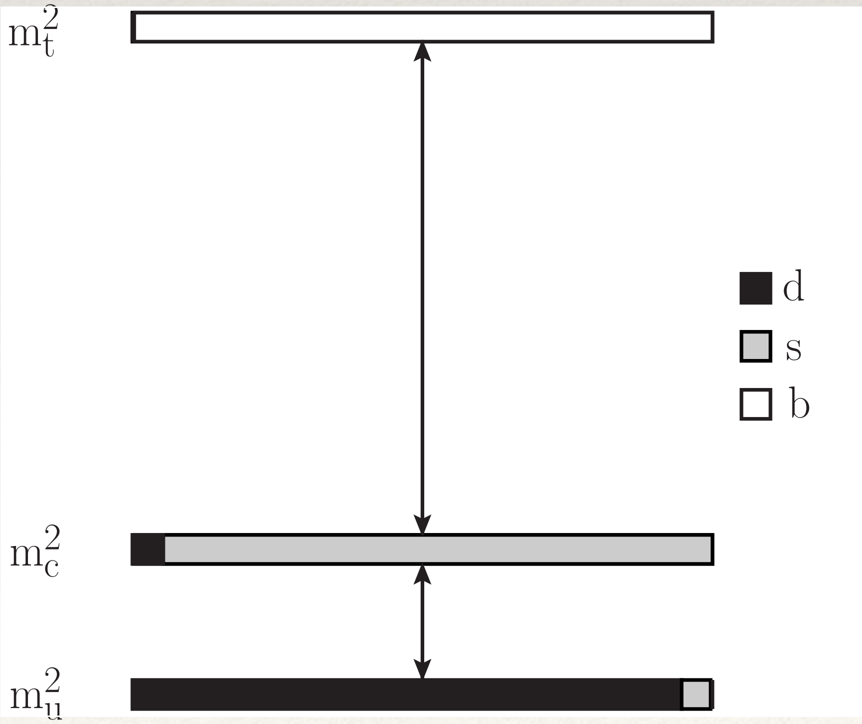
Implications of Lepton Mixing

NuFIT 3.2 (2018)

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

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





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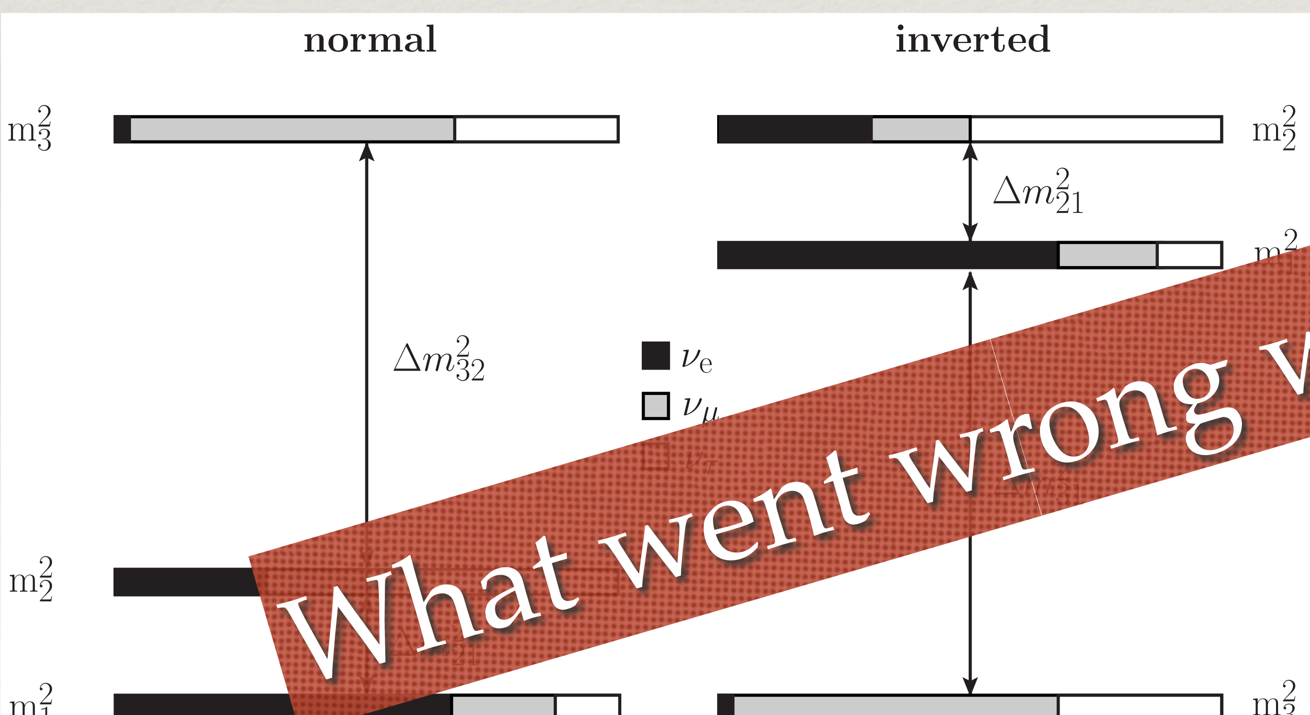
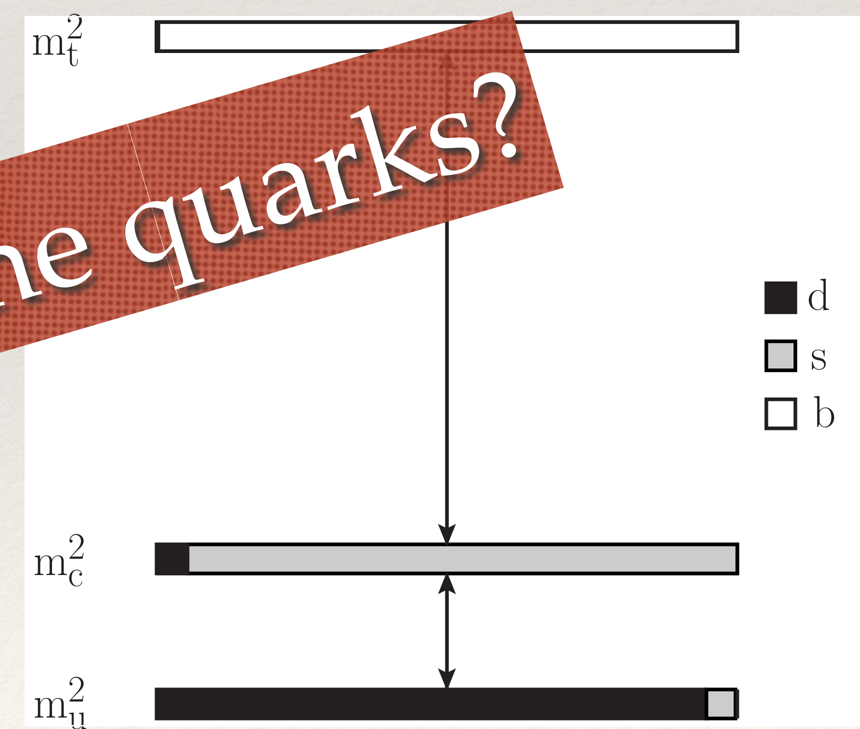




Flavor Symmetries

- Nature seems to prefer 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	$1, 1', \overline{1'}, 3, \overline{3}$	$A^7 = B^3 = 1,\ AB = BA^4$

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				$\cdots$
C2	$\underline{3}$	$\underline{3}$	$\cdots$	$\underline{1}$
C3				$\underline{1}, \underline{3}$
C4				$\underline{1}, \underline{1}', \underline{1}'', \underline{3}$
D1				$\cdots$
D2	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{1}$
D3				$\underline{1}'$
D4				$\underline{1}', \underline{3}$
E	$\underline{3}$	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	$\cdots$
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…

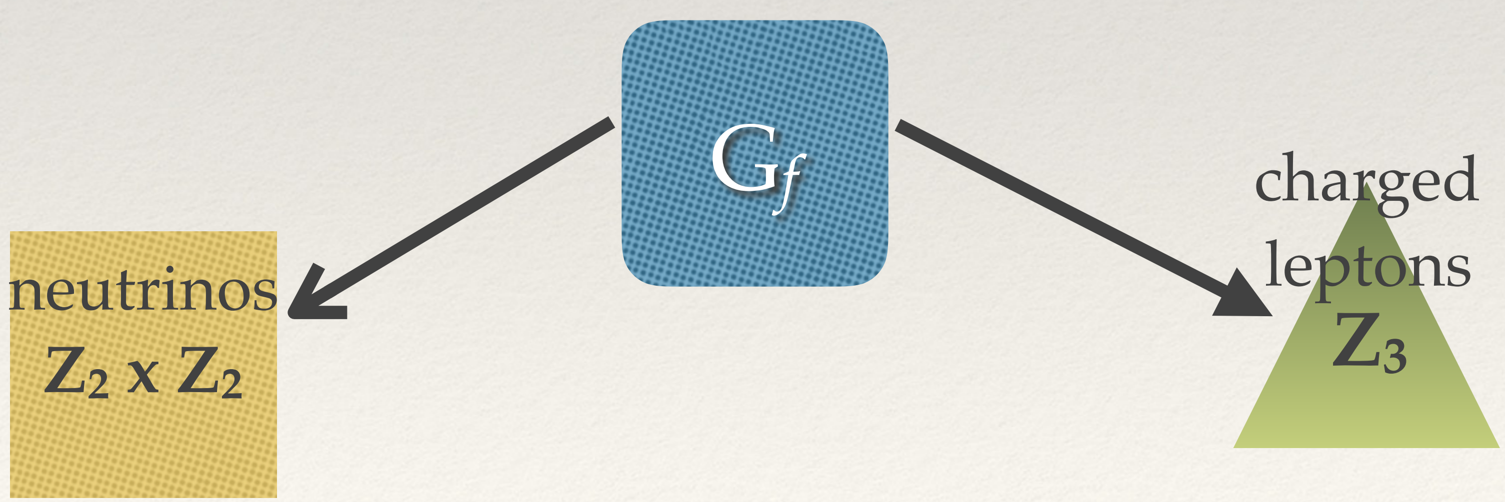
$\Rightarrow$ can distinguish only classes of models

Flavor Symmetries

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

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

Lesson 2: flavor group broken to different subgroups:



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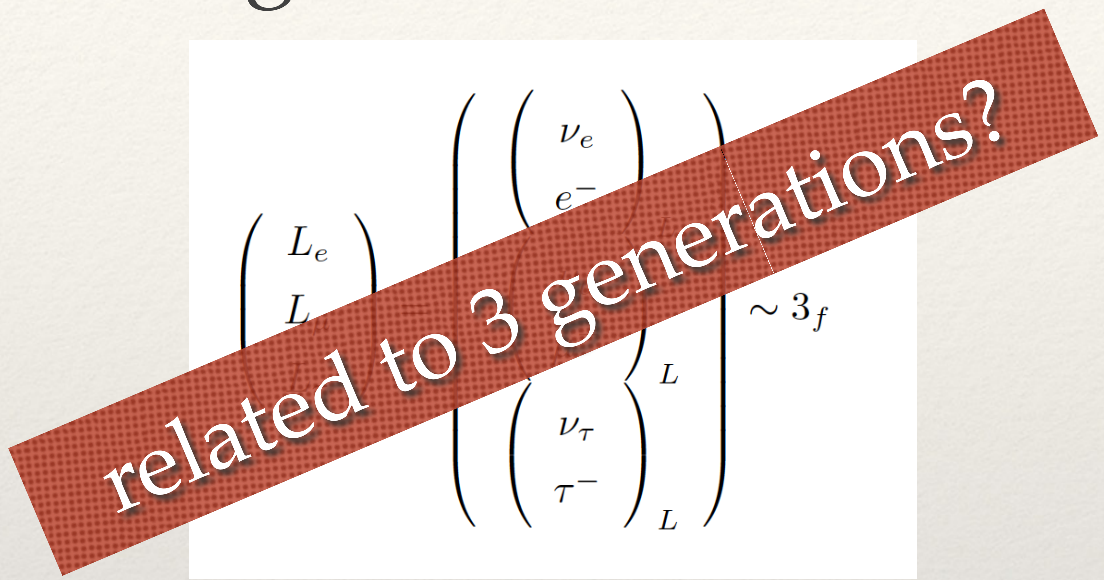

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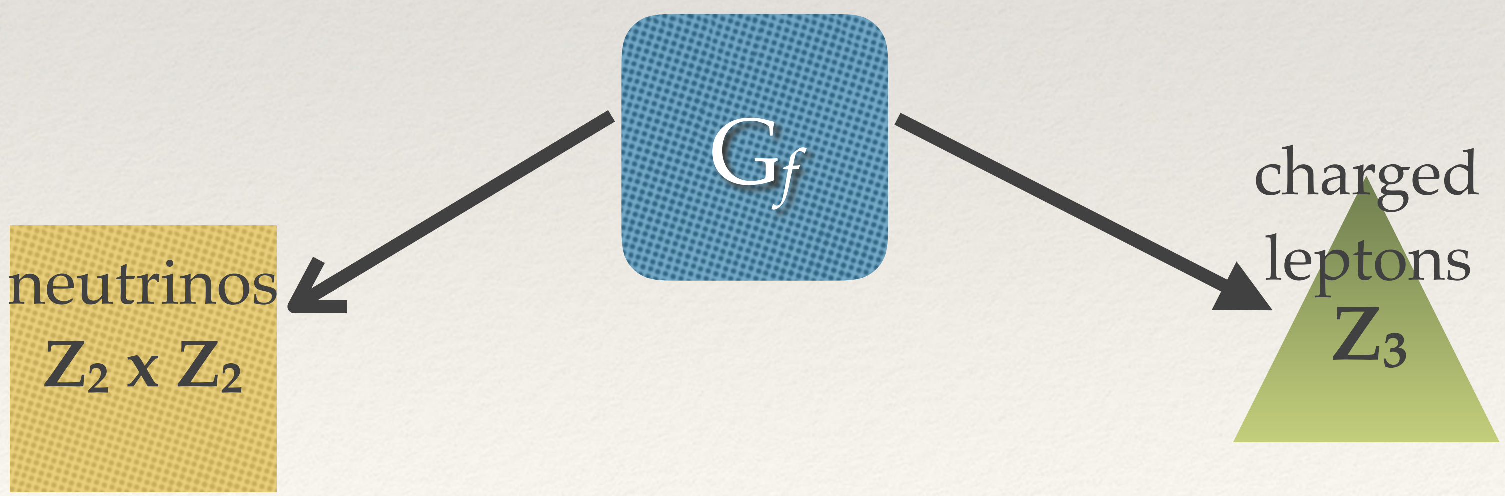

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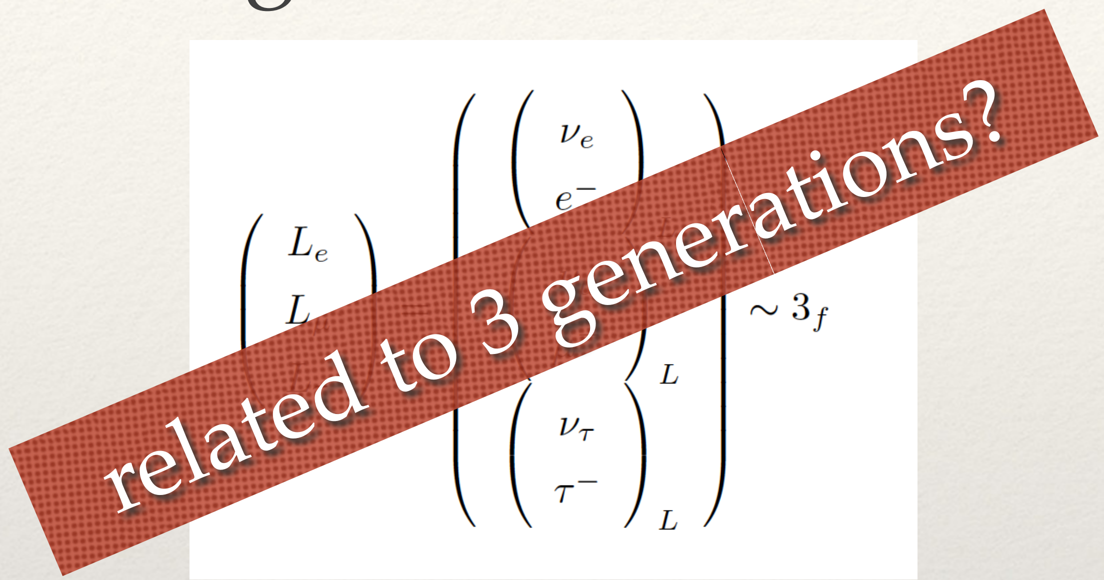


Lesson 2: flavor group broken to different subgroups:

How to predict the CP phase

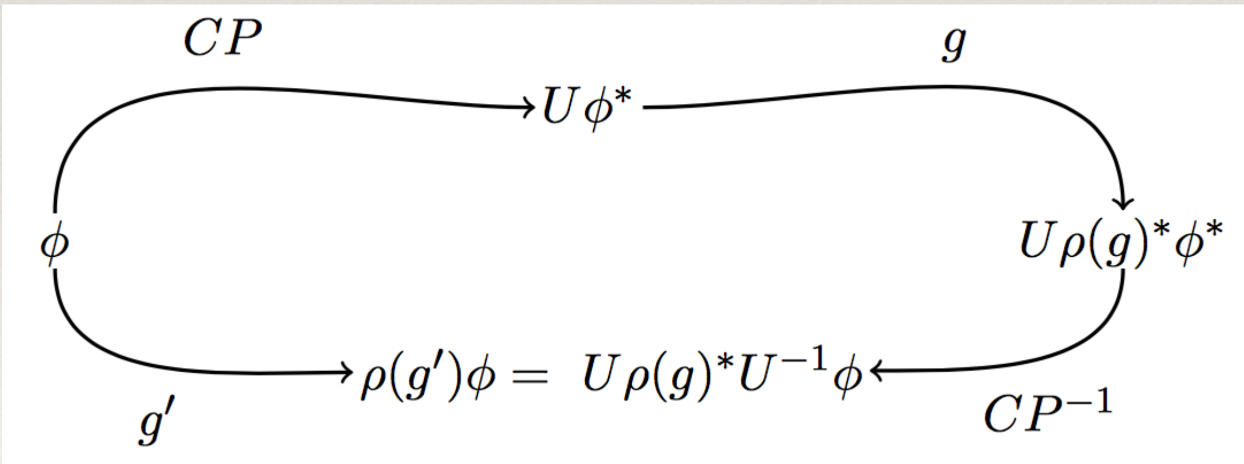
- μ-τ reflection symmetry: $\nu_e \leftrightarrow \nu_e^C$ and $\nu_\mu \leftrightarrow \nu_\tau^C$ *(see talk by Deepthi)*

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

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 a representation of an automorphism of the discrete group)

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

Abelian Flavor Symmetries

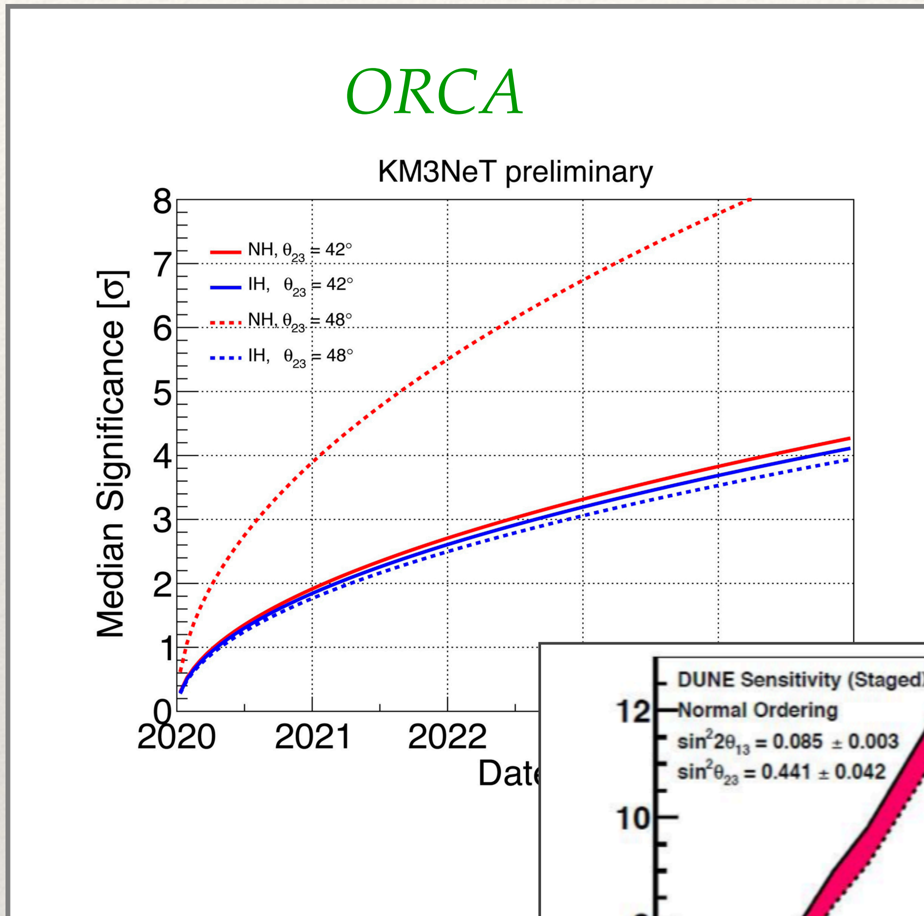
- Less predictive but less complicated: Abelian flavor symmetry, e.g. $L_\mu - L_\tau$
  - anomaly-free, has Z' and can explain $(g-2)_\mu$
  - can be extended to quark sector to explain anomalies in $B \to K^* \mu\mu$ and $\mathrm{BR}(B \to K\mu\mu)/\mathrm{BR}(B \to Kee)$ *[Crivellin, Ambrosio, Heeck,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

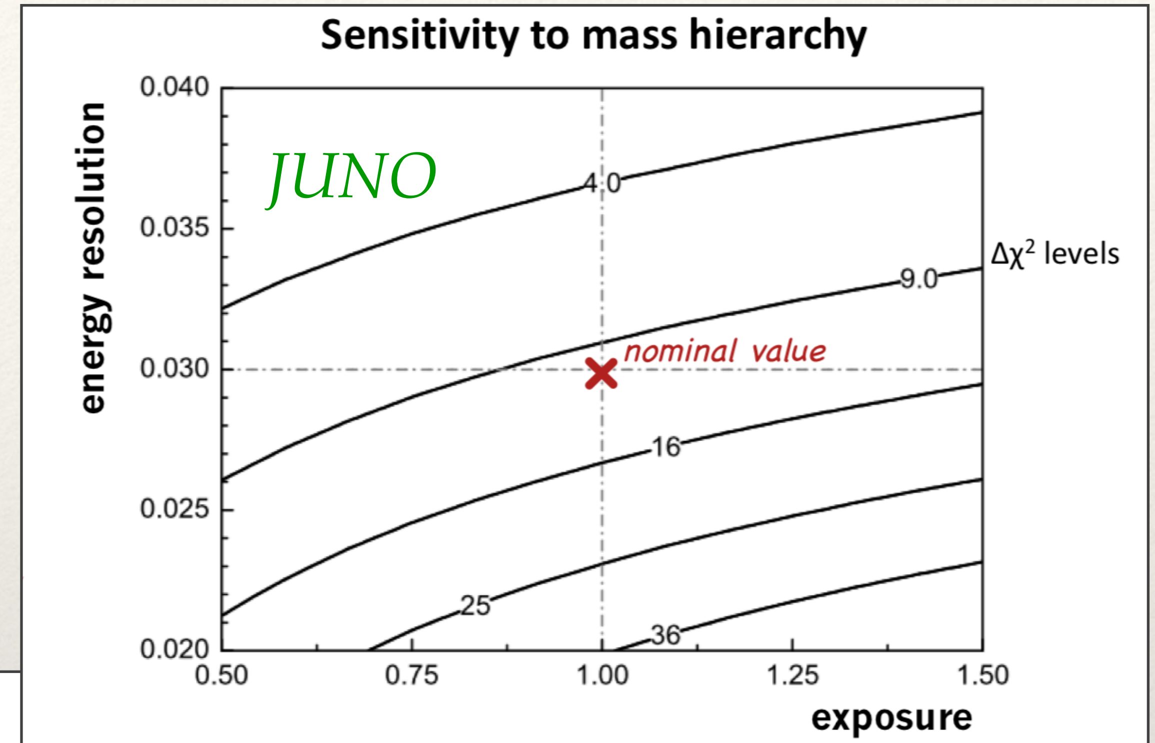
$$(m_\nu)^{L_\mu - L_\tau} = \begin{pmatrix} a & 0 & 0 \\ \cdot & 0 & b \\ \cdot & \cdot & 0 \end{pmatrix}$$

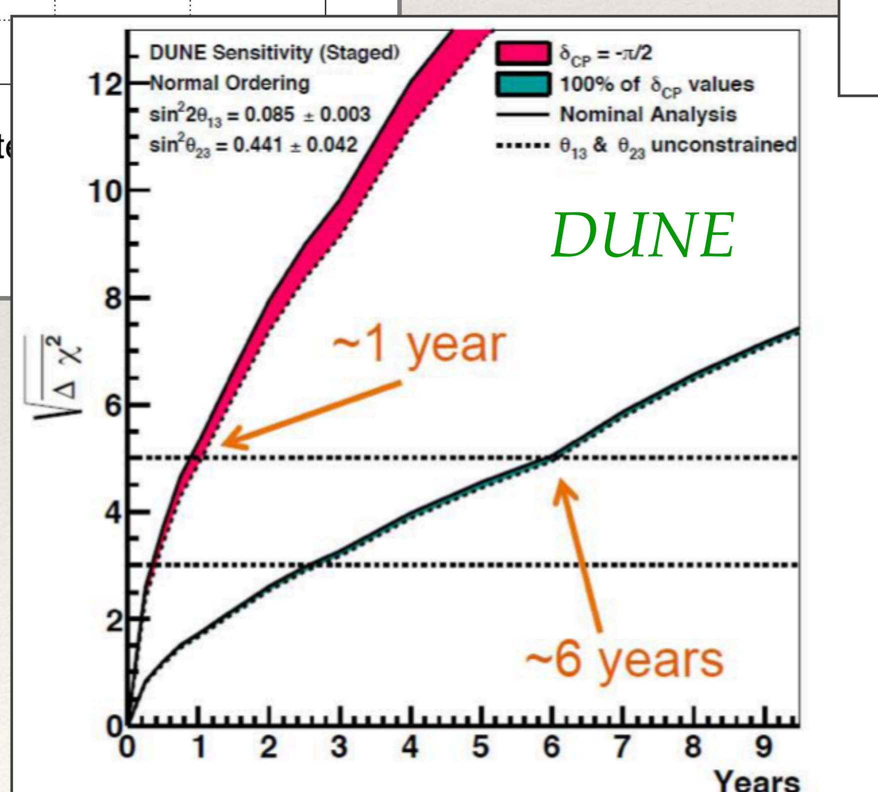
Heeck, WR, 1107.5238

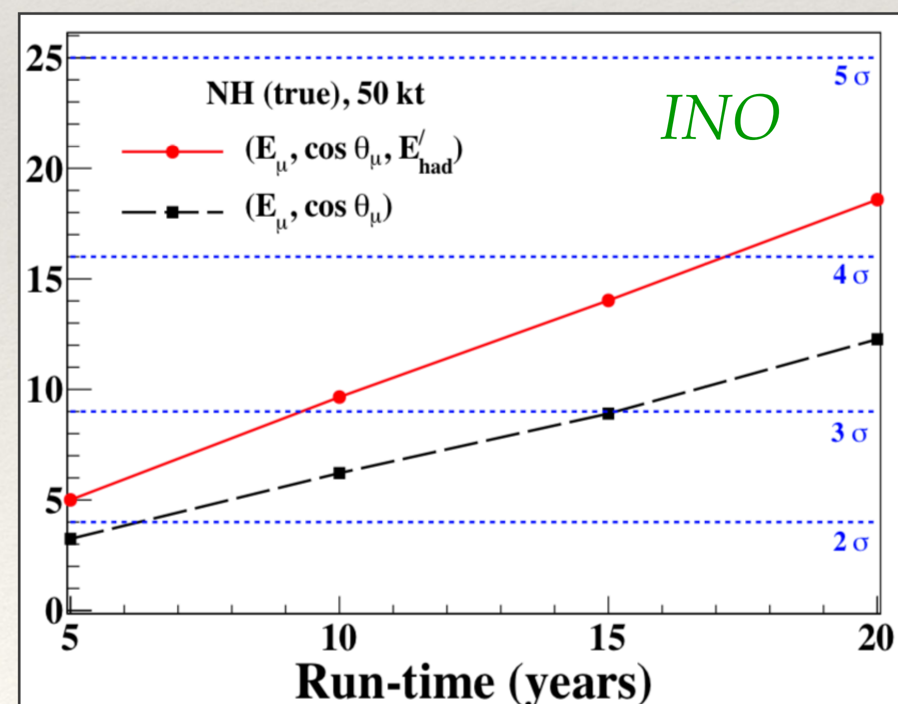
Future of Mass Ordering

see talks by Tanaka, Wu, Indumathi

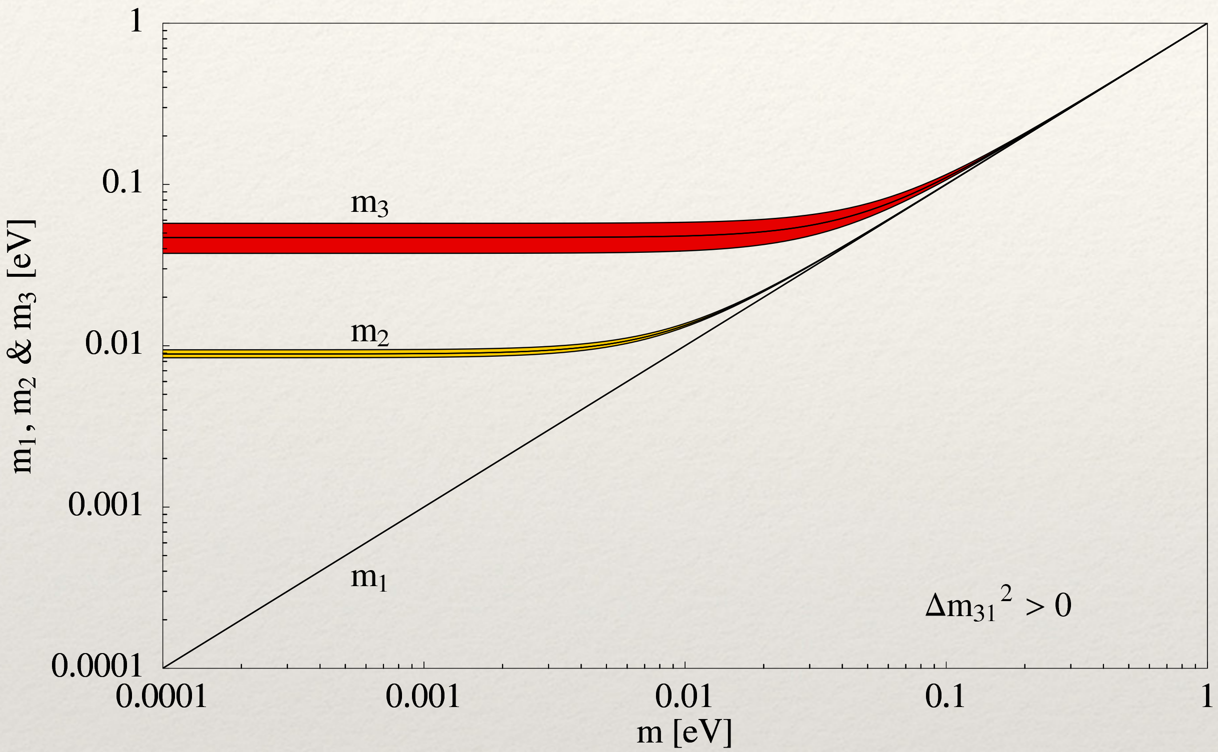


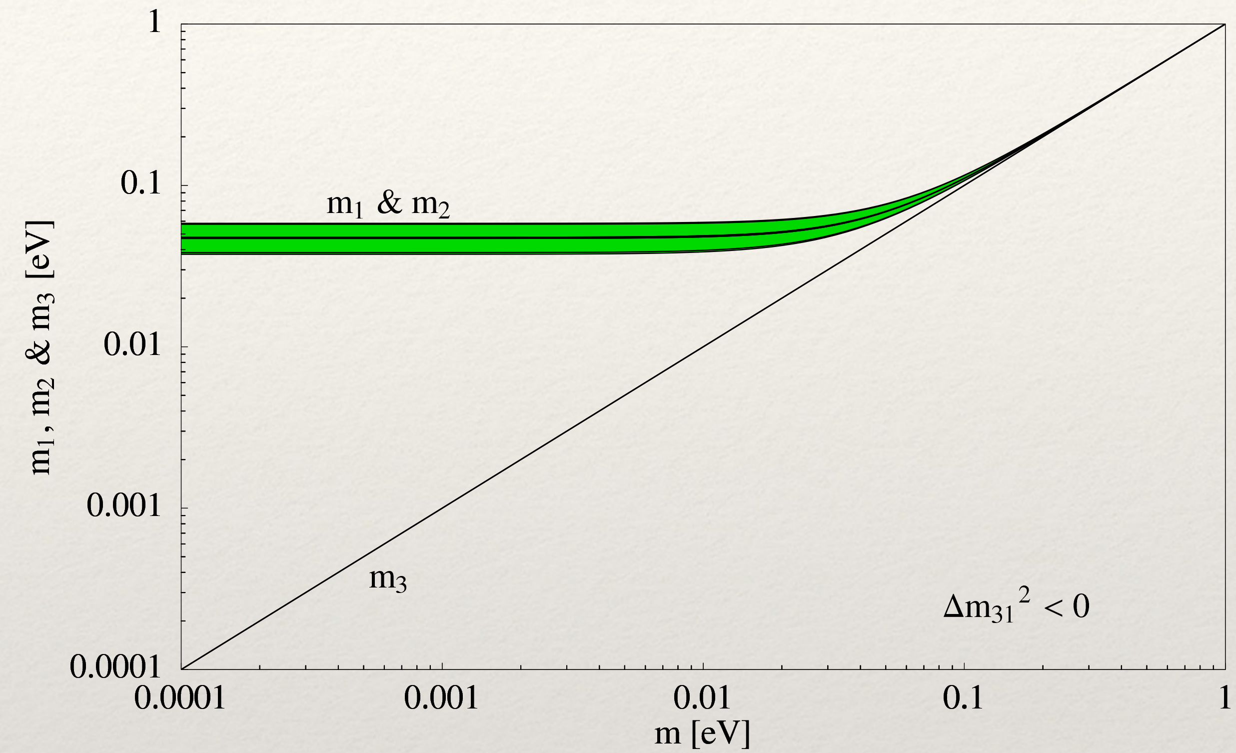






Masses and Ordering





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

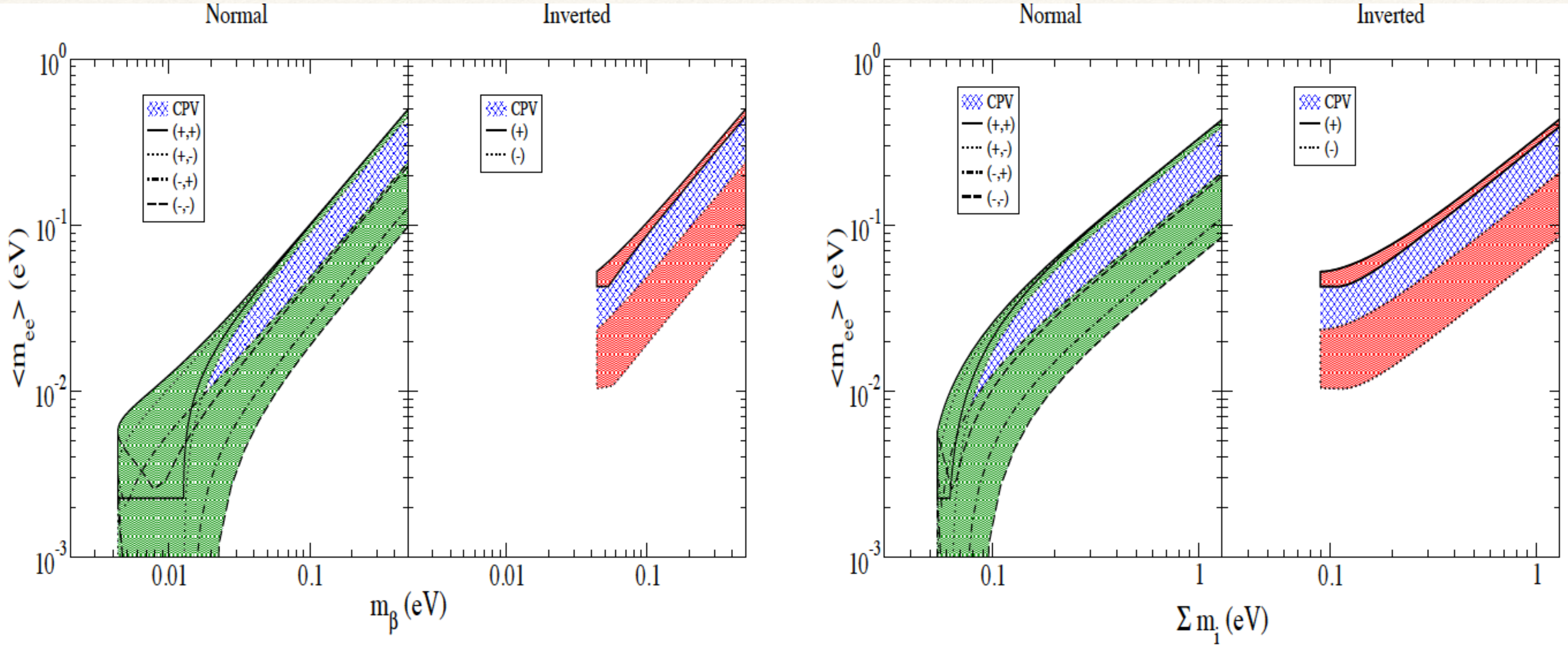
$$(m_\nu)_{\rm IH} \sim \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

plus almost democratic structure of mass matrix

Neutrino Mass Observables

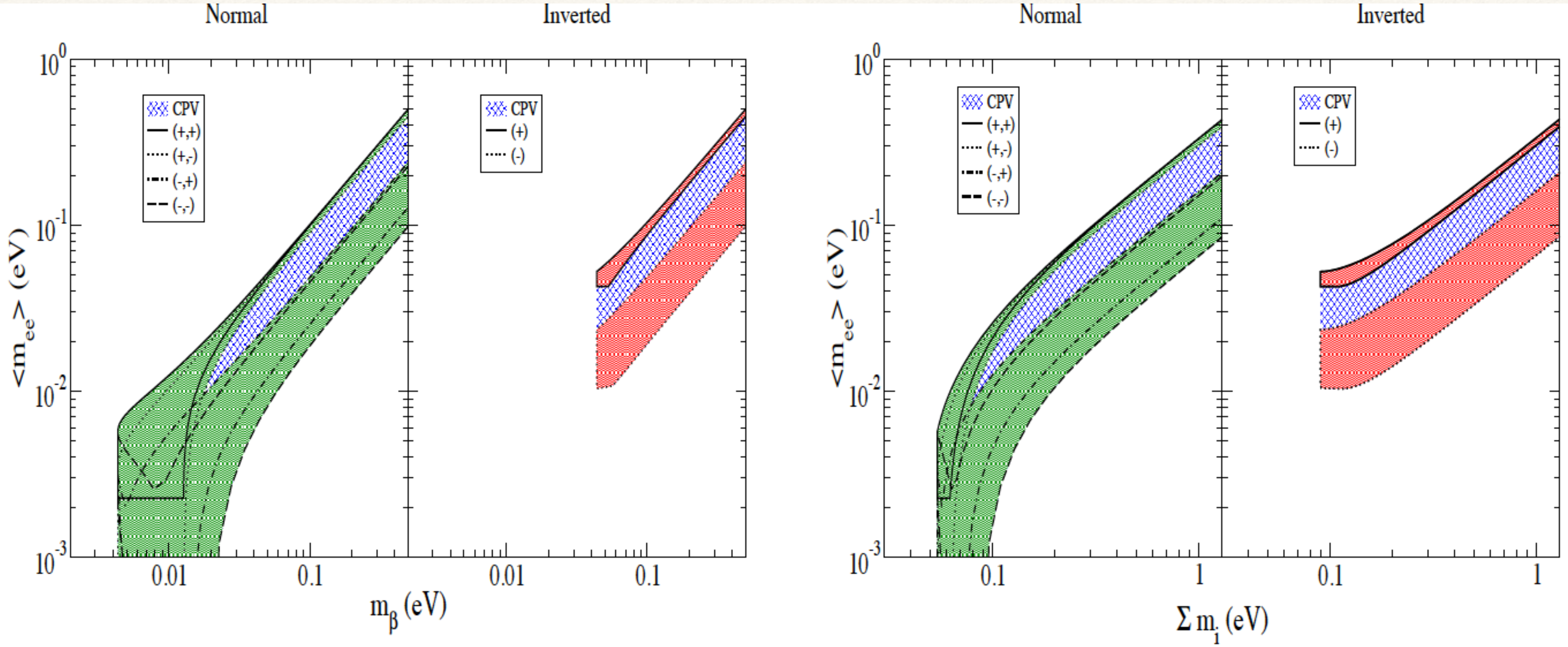
Method	Observable	current	near	far	pro	con
Kurie	$(\sum \lvert U_{ei} \rvert^2 m_i^2)^{1/2}$	2.3 eV	0.3 eV	0.1 eV?	model-indep.; clean	final; weakest
cosmo	$\sum m_i$	0.25 eV	0.1 eV	0.05 eV?	best; NH/IH	model-dep.; systematics
$0\nu\beta\beta$	$\sum U_{ei}^2 m_i$	0.2 eV	0.05 eV	0.01 eV?	fundamental; NH/IH	model-dep.; NMEs

Neutrino Mass Observables



complete complementarity of observables

Neutrino Mass Observables



complete c ... **arity**
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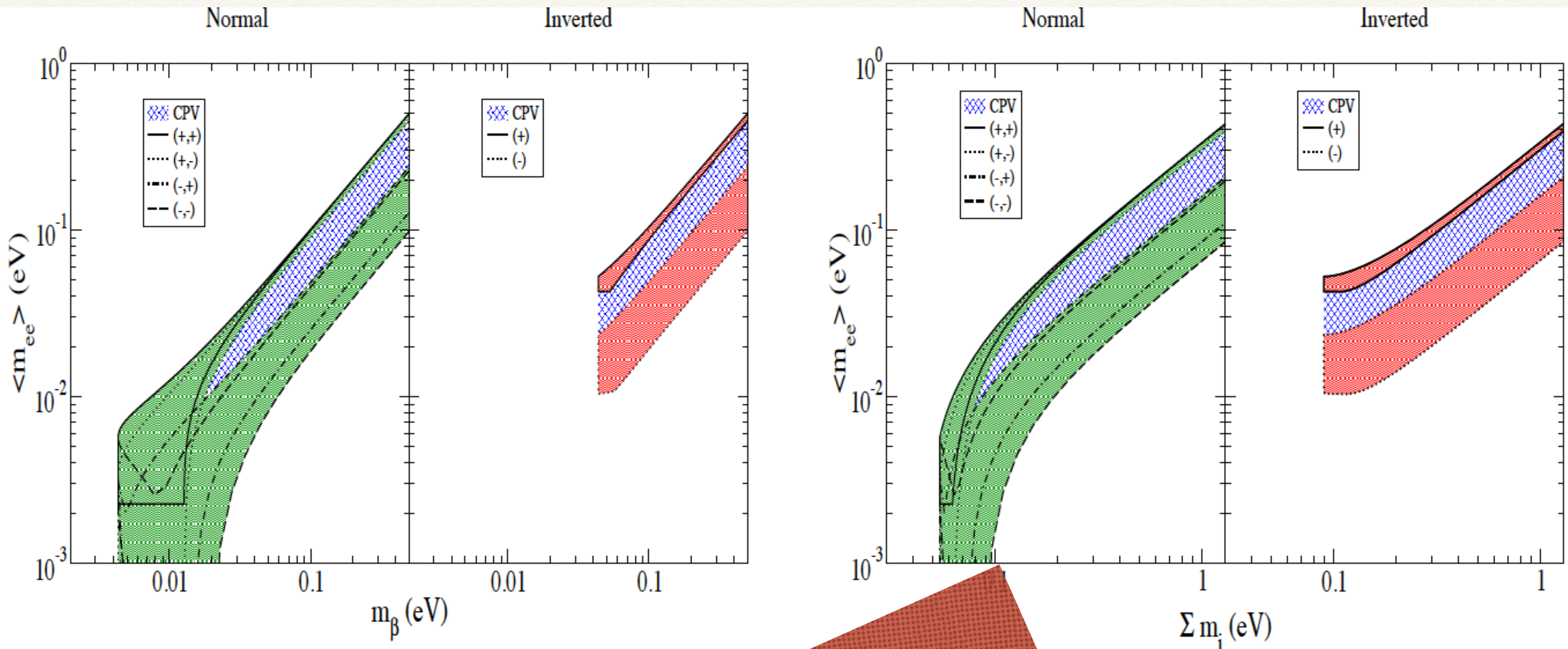
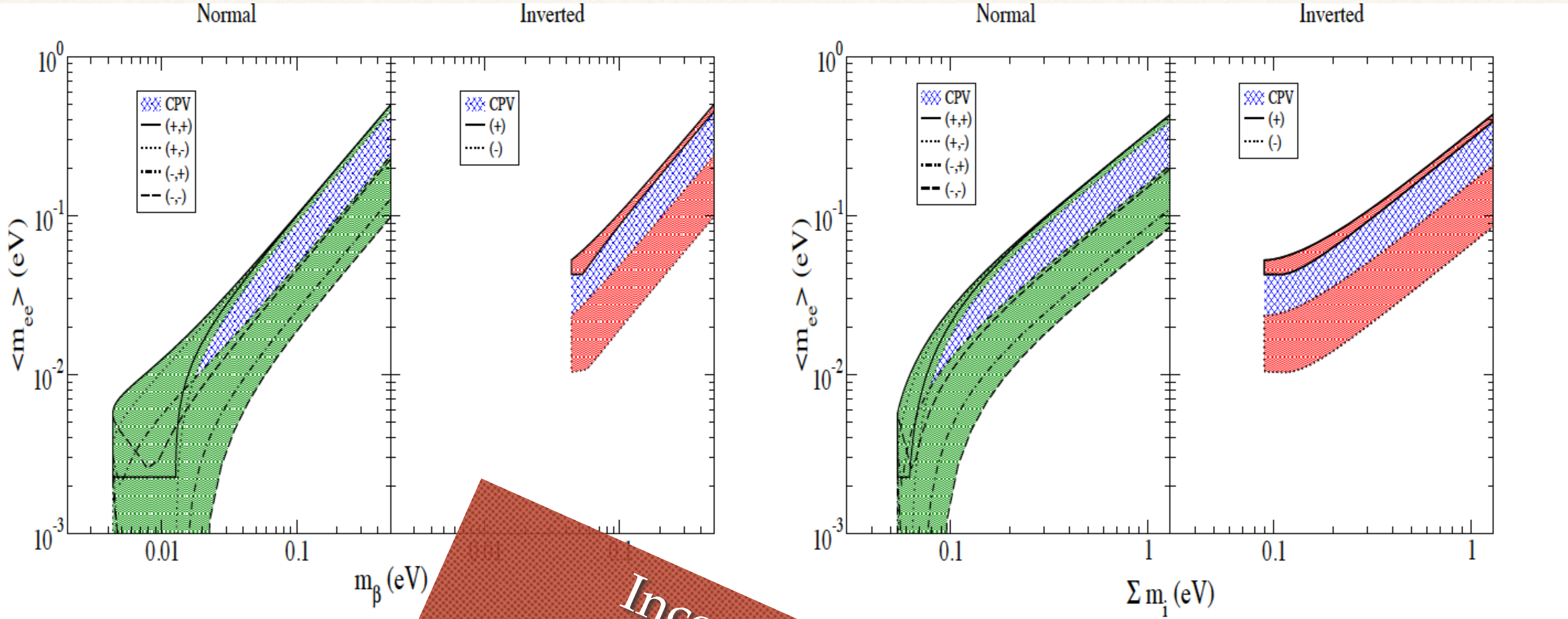
All need to be pursued!

Neutrino Mass Observables



Consistency
would be spectacular
confirmation !

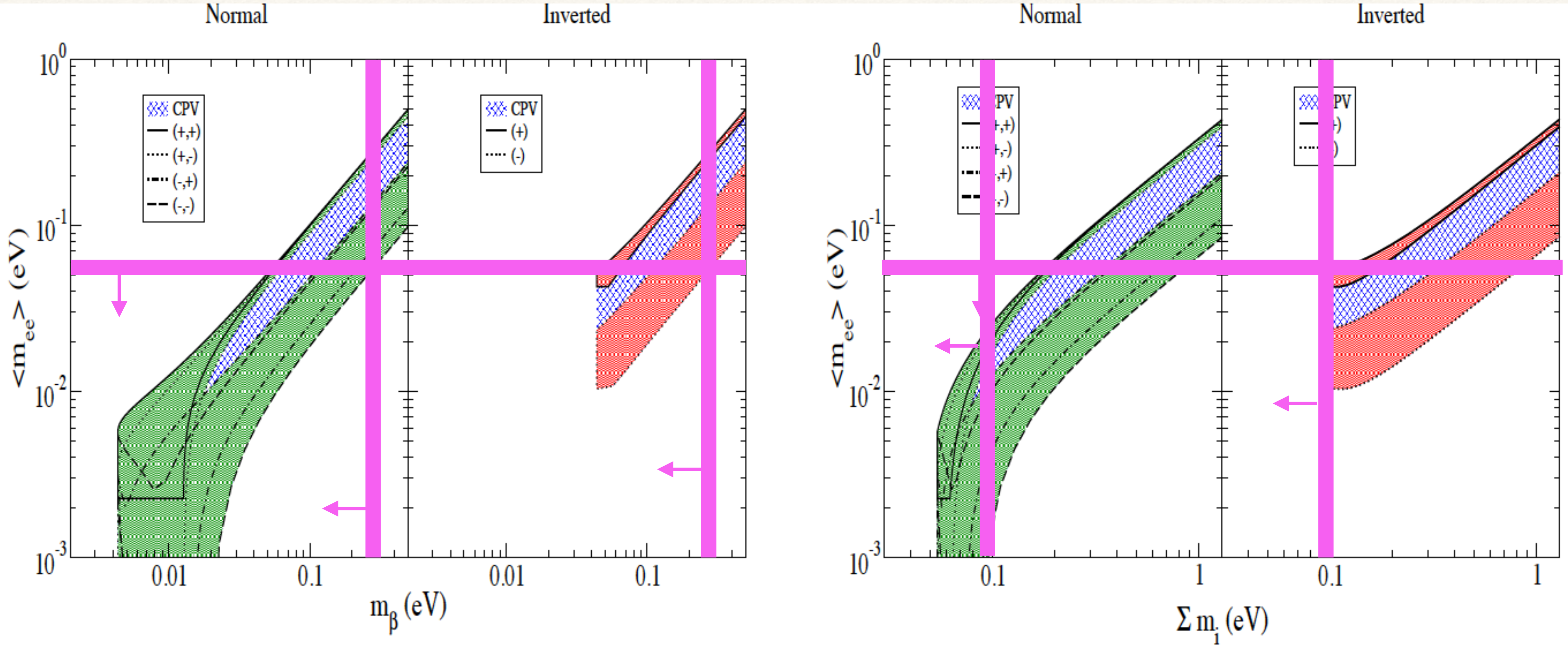
Neutrino Mass Observables



comp
of ob

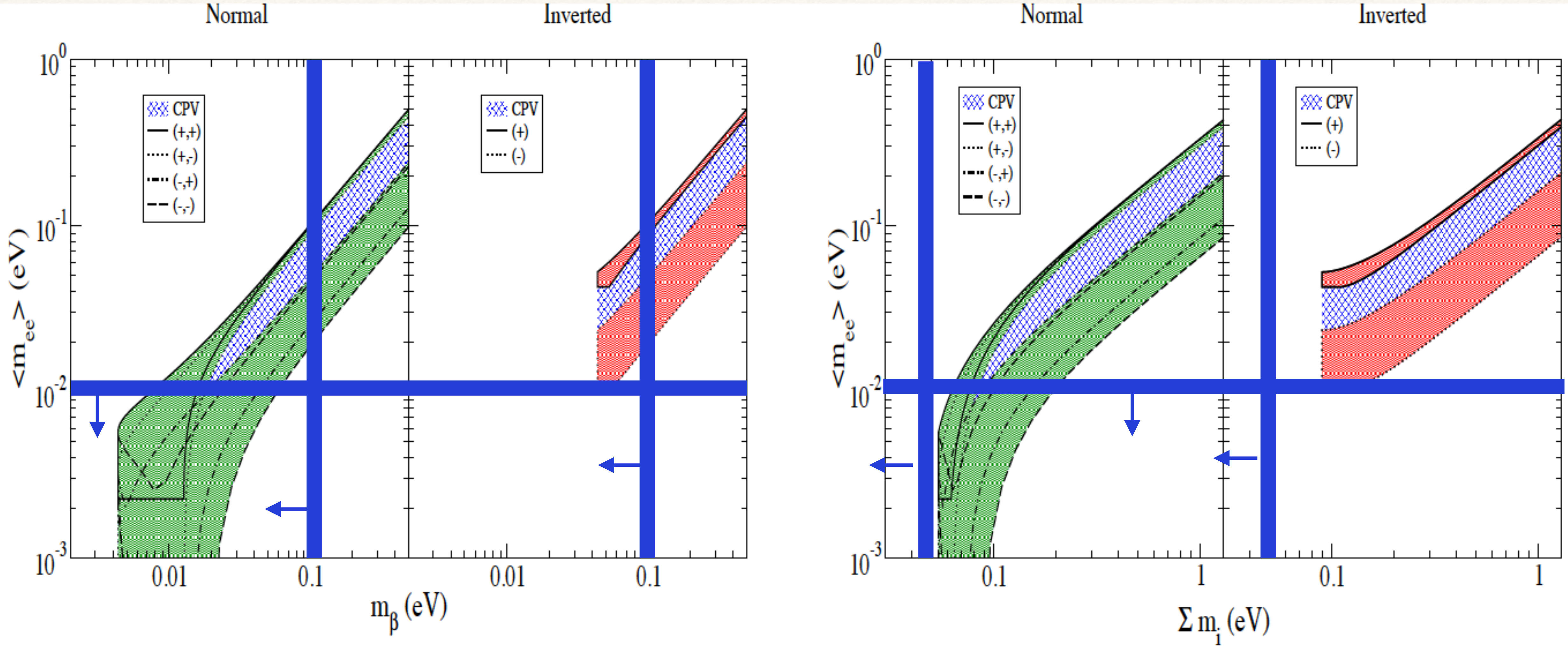
Inconsistencies would be major discovery!

Neutrino Mass Observables



near future

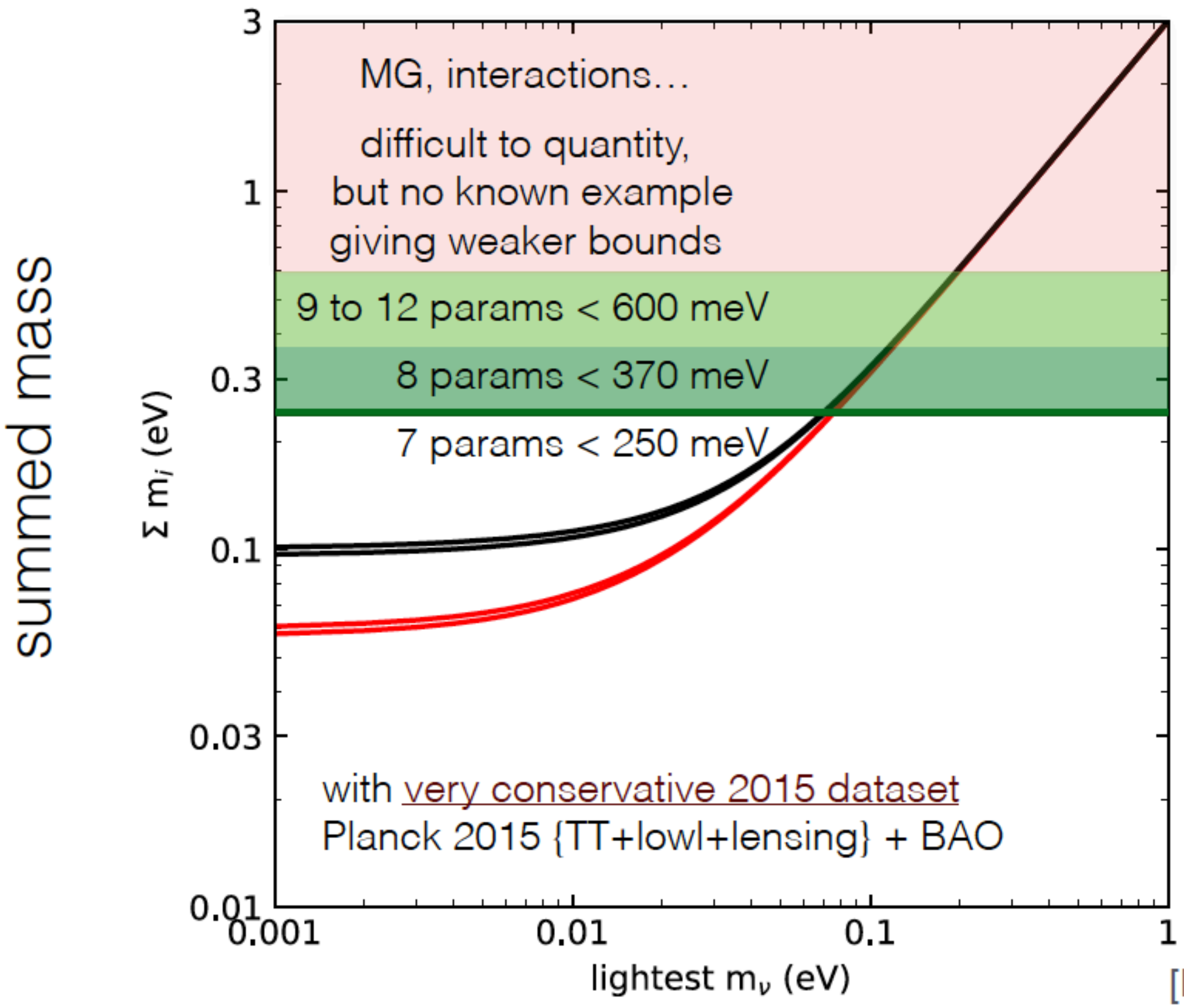
Neutrino Mass Observables



far future

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~~

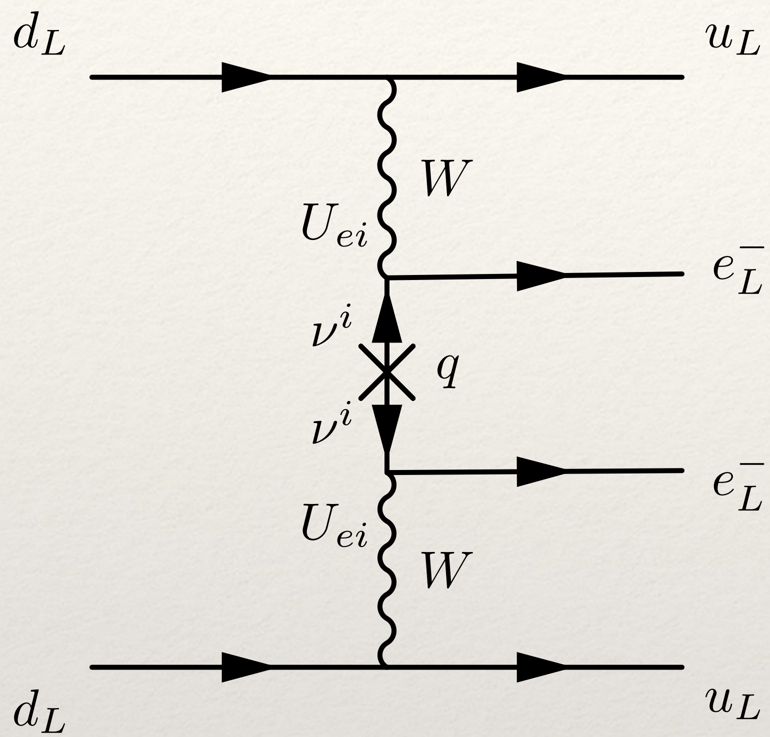
[Planck col.] 1502.01589; Di Valentino et al. 1507.06646

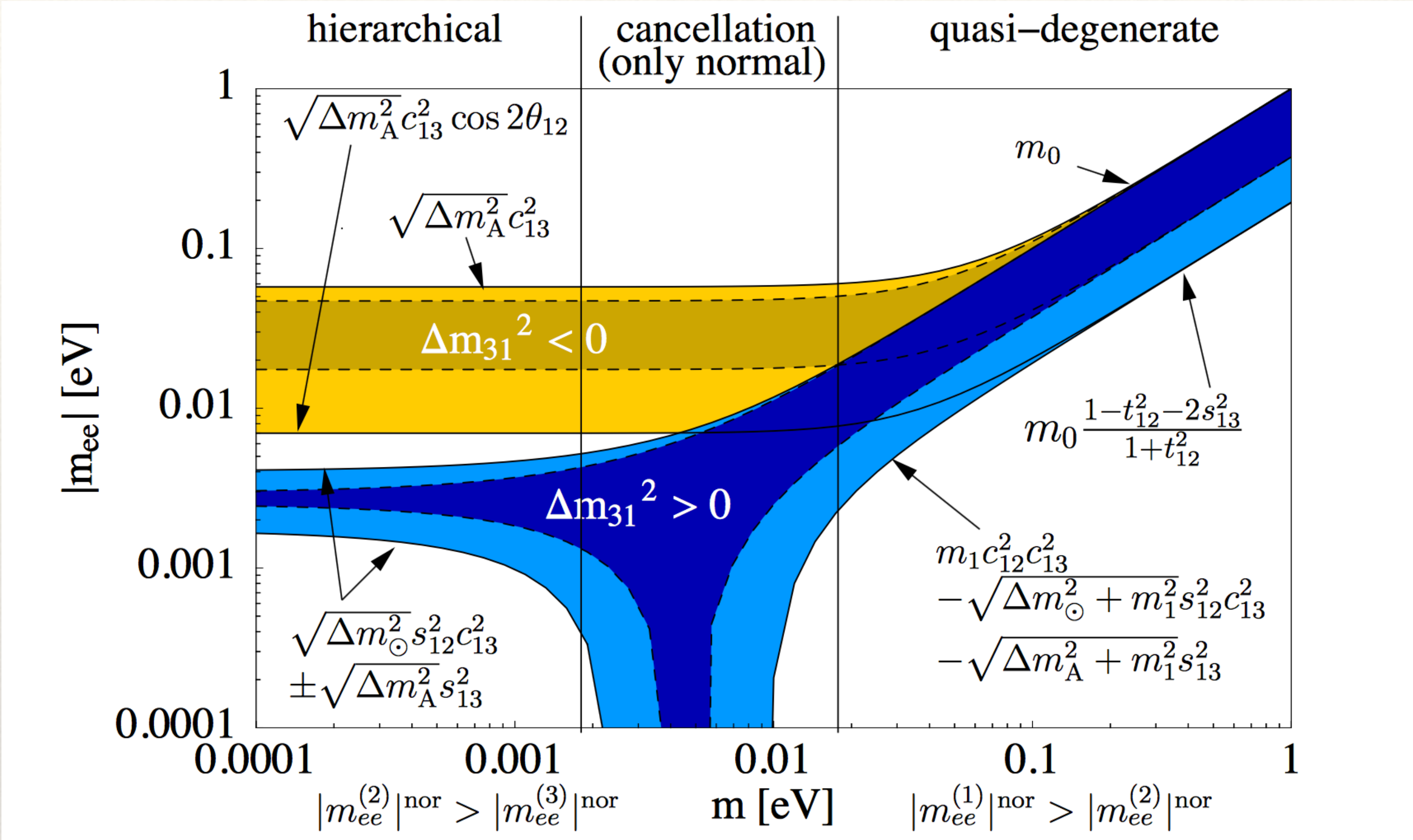
Lesgourgues, talk at Neutrino2018

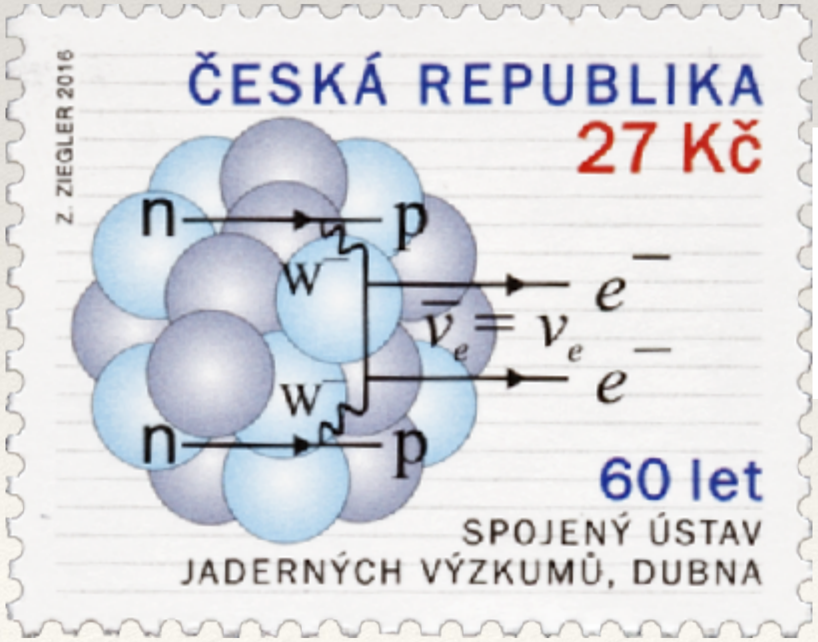
Plus: future observation will have to see neutrino mass even in modest extensions!

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

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 [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]	$\hat{m}_{\beta\beta}$ [meV]	Required Improvement 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

Agostini et al, 1705.02996

Will enter IH regime soon!

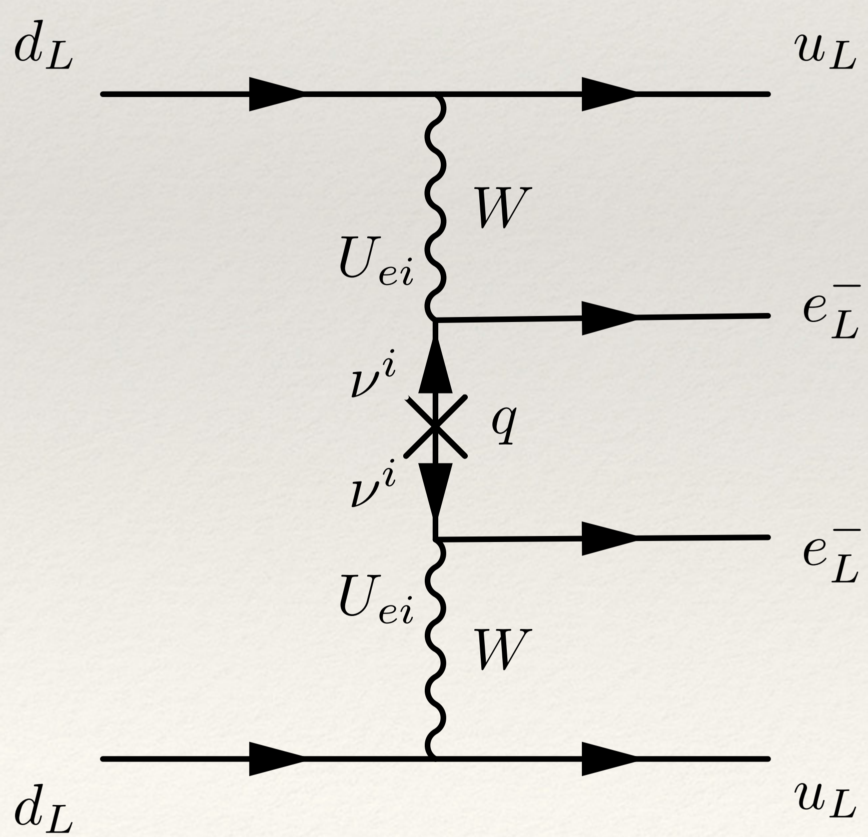
Multi-isotope determination for
mechanism and NMEs!

New Physics in Double Beta Decay

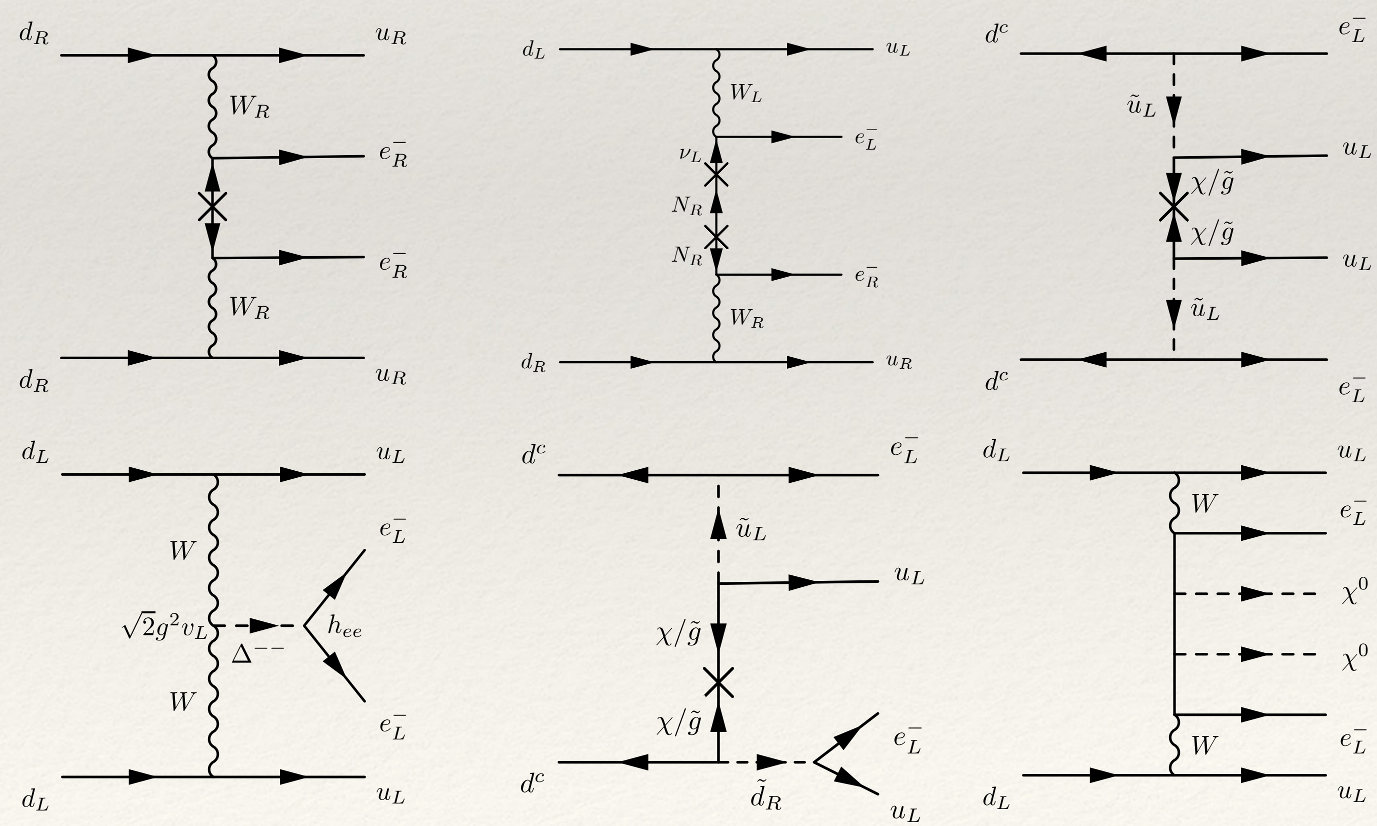
Double Beta Decay is $\Delta L = 2$, not neutrino mass!

Interpretations:

Standard:



Non-Standard:



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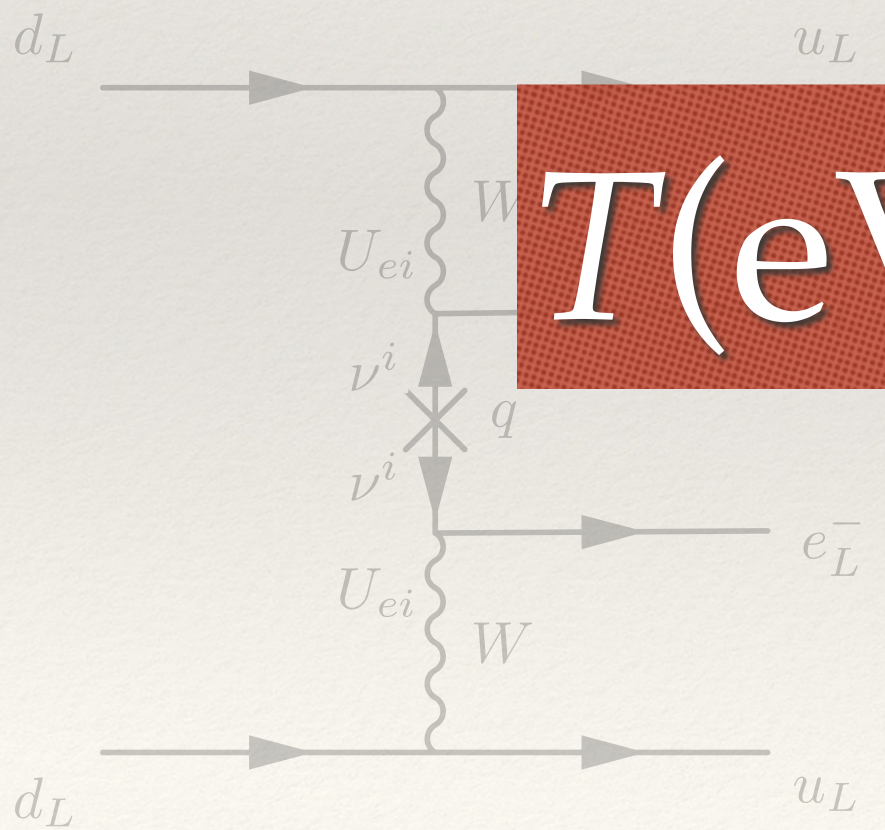

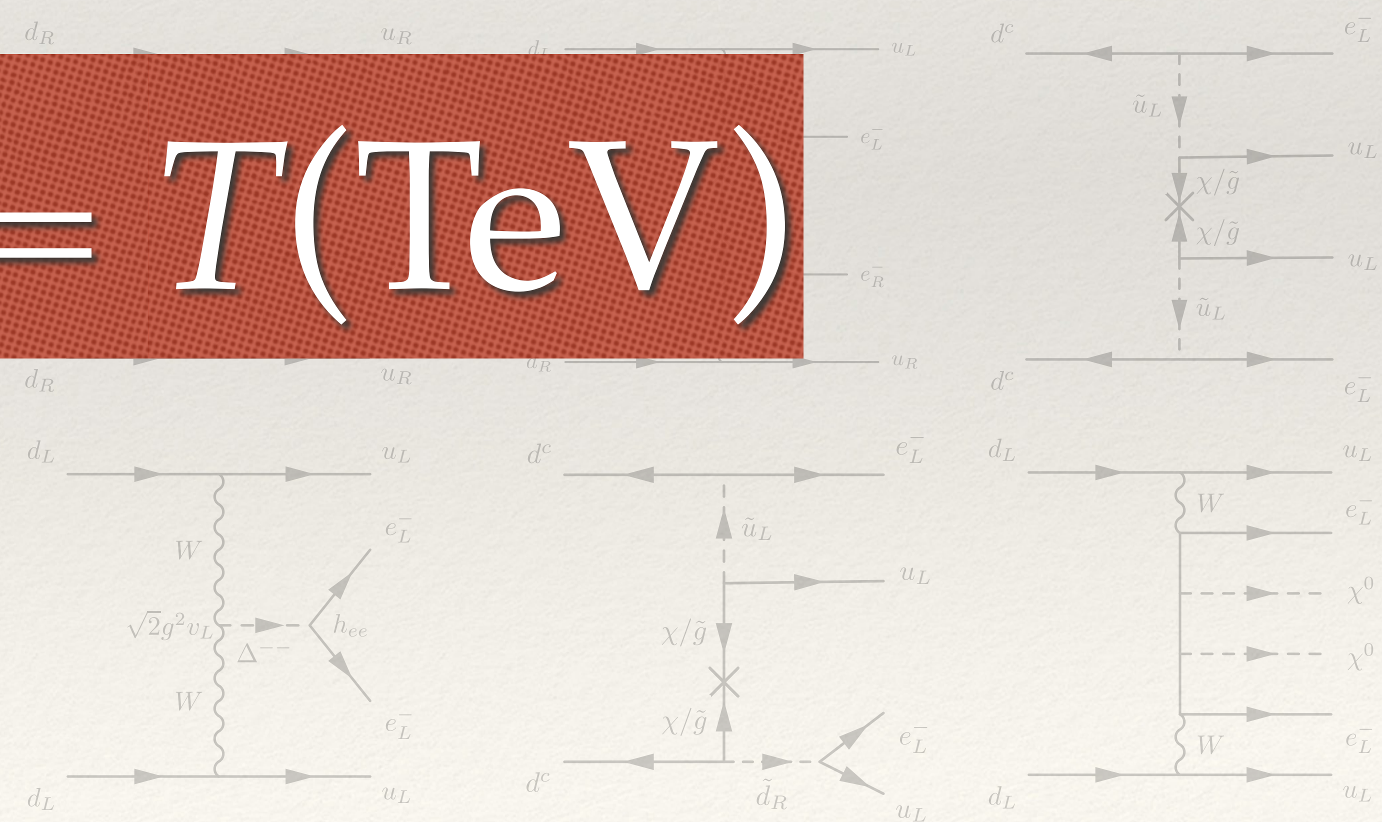

$$T(\text{eV}) = T(\text{TeV})$$

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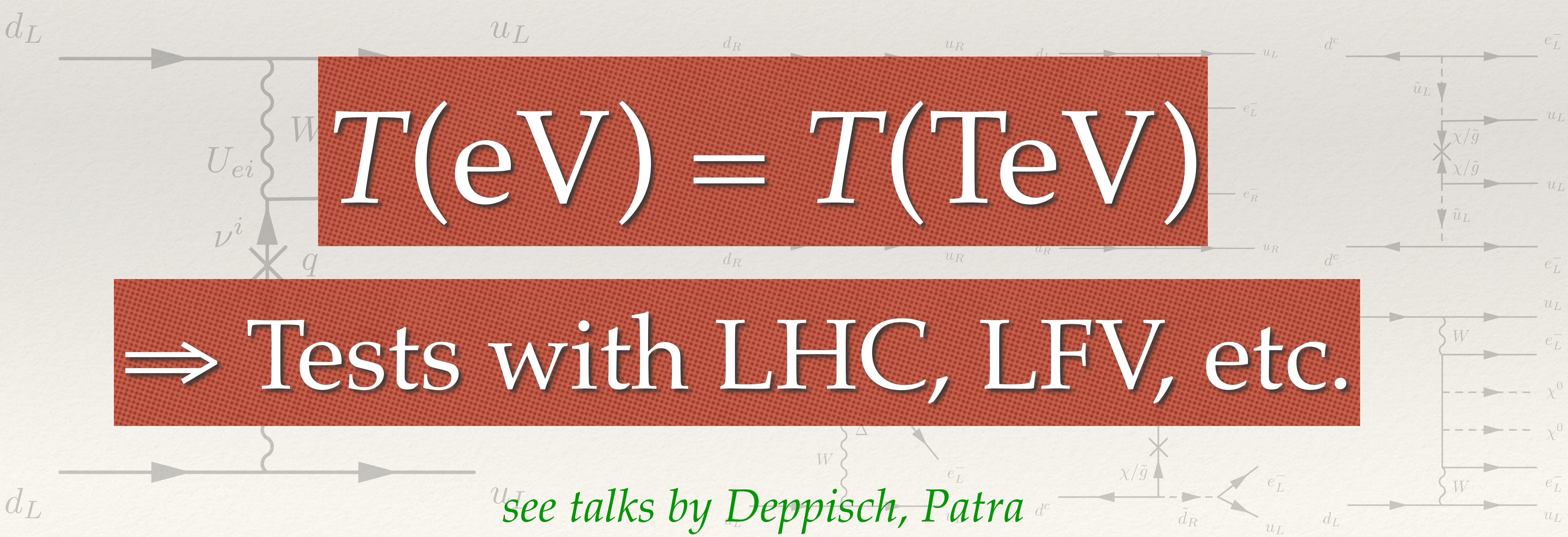


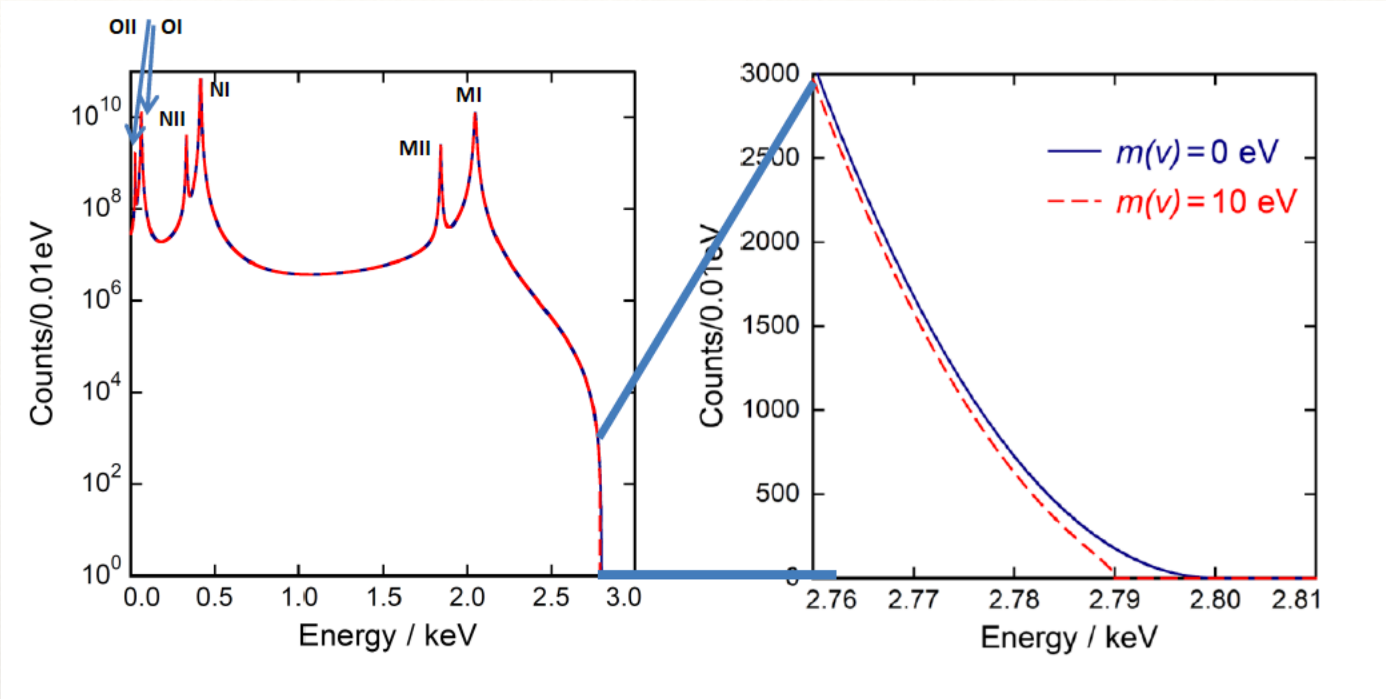
$$T(\mathrm{eV}) = T(\mathrm{TeV})$$

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

see talks by Deppisch, Patra

Direct Neutrino Mass Determination

There are 2 running experiments!!



- Tritium since May 2018, first ν-mass data in early 2019…
- (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…

New Physics in Oscillations

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

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  - light sterile neutrinos…

Non-Standard Interactions

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

- $\varepsilon \propto c^2/M_X^2 \;\Rightarrow\; \varepsilon = 0.01$ 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…

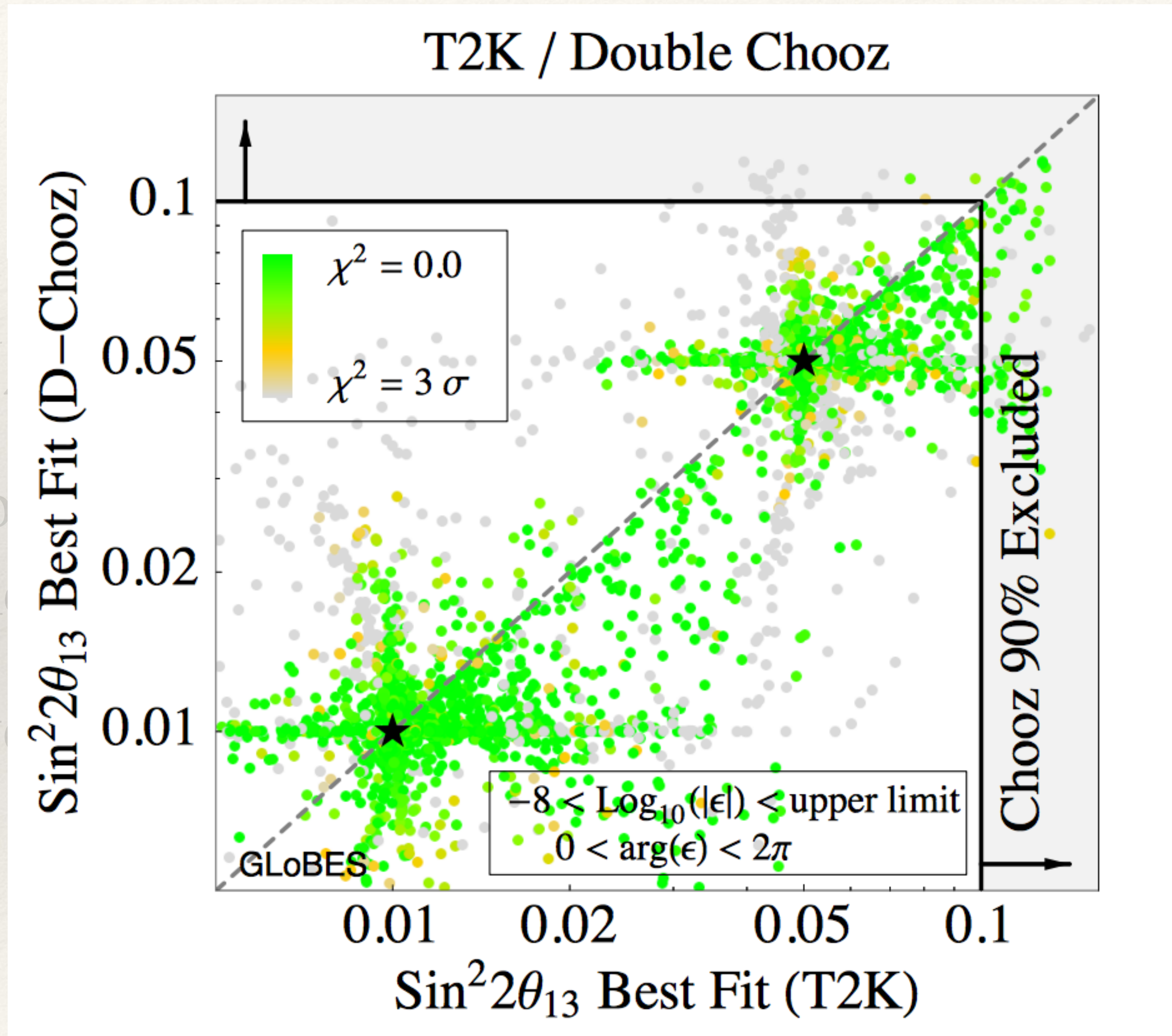
Non-Standard Interactions

	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]

Esteban et al., 1805.04530

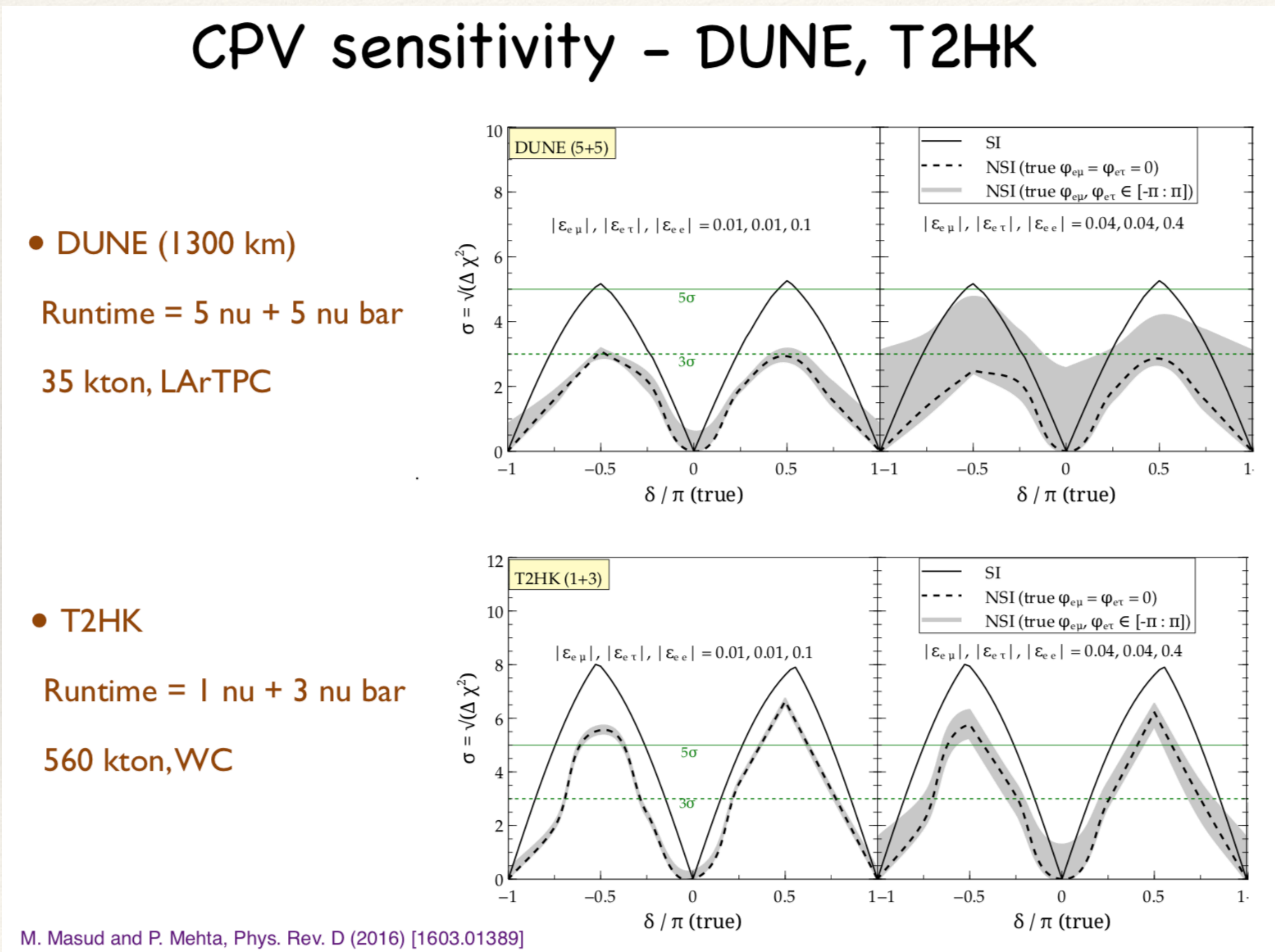
Non-Standard Interactions

- ε∝ g'^2/M...
- oscillatio... q^2 very small), h...
- can prev... meters...



Kopp, Lindner, Ota, Sato, 0708.0152

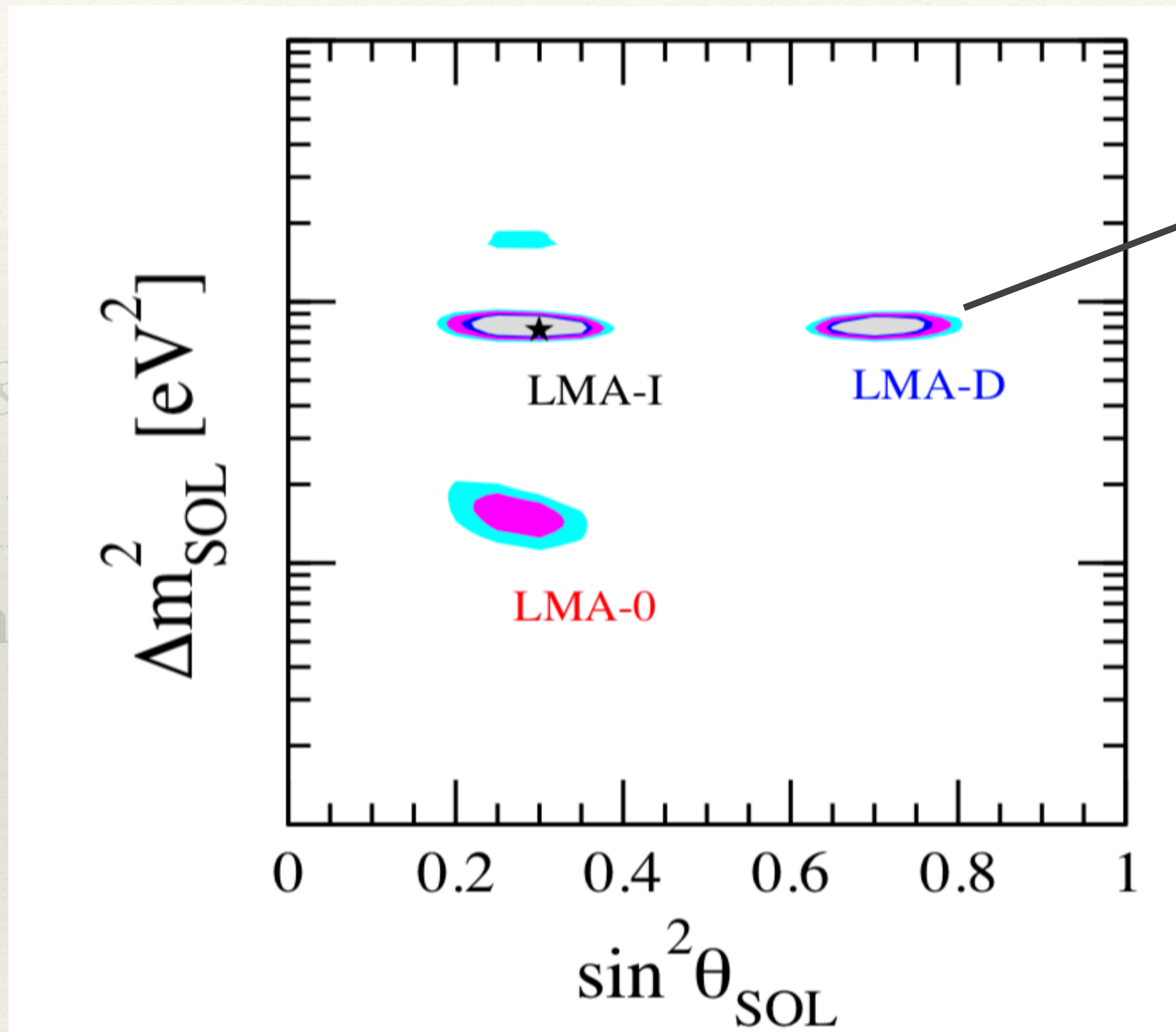
Non-Standard Interactions



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

Liao, Marfatia, Whisnant, 1612.01443

Non-Standard Interactions



LMA-dark
with $\theta_{12} > \pi/4$

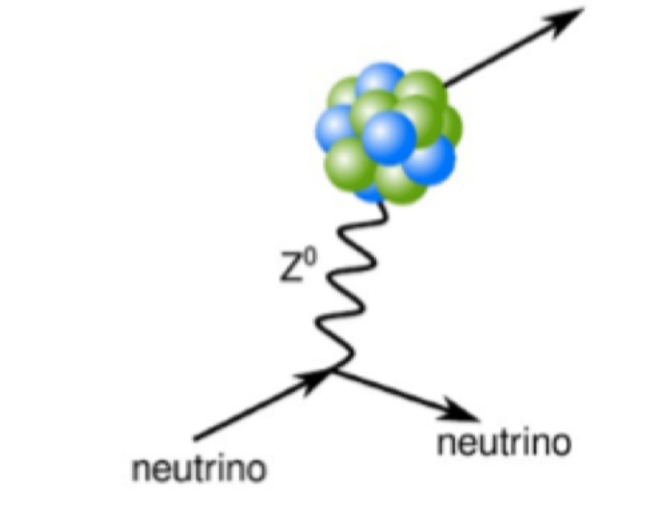
Miranda, Tortola, Valle, hep-ph/0406280

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

Coherent Elastic Neutrino-Nucleus Scattering

Freedmann, PRD9, 1974

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



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

- needs E_ν below 50 MeV
- ⇒ pion decay or reactors as ν-source
- ⇒ low nuclear recoil below few keV
- ⇒ sensitive detectors and smart shielding

Coherent Elastic Neutrino-Nucleus Scattering

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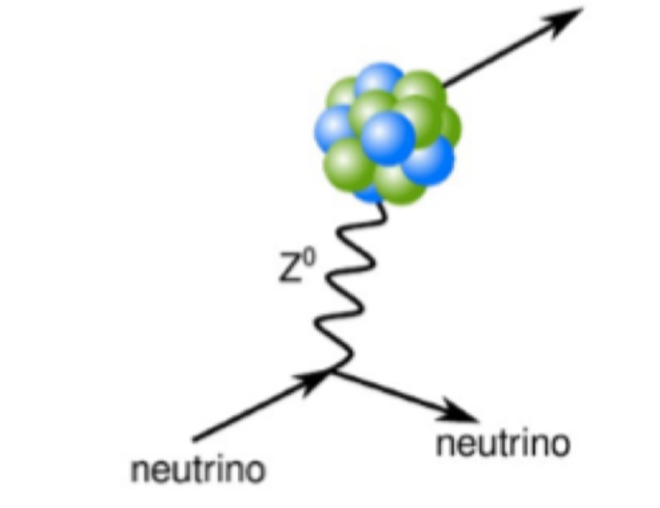

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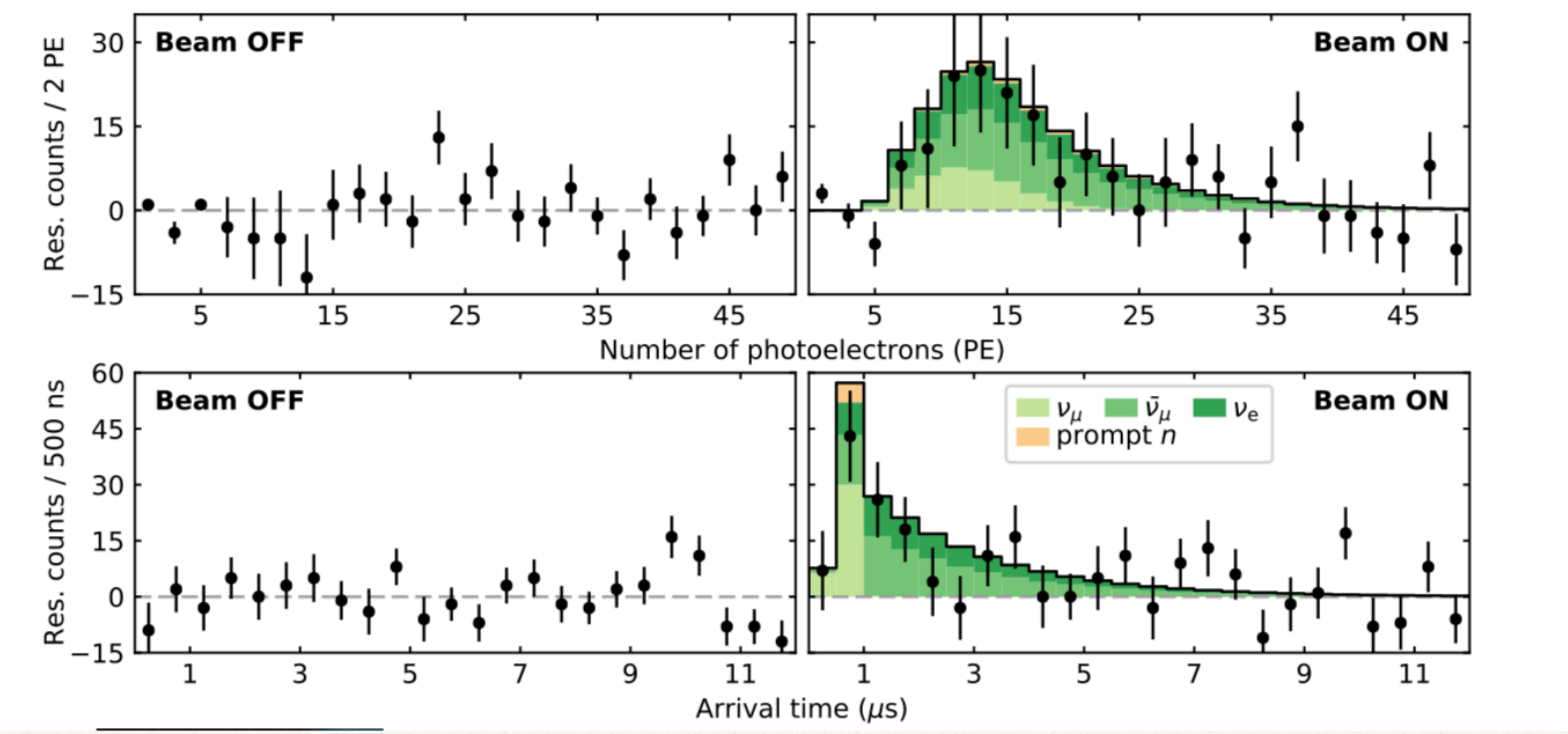


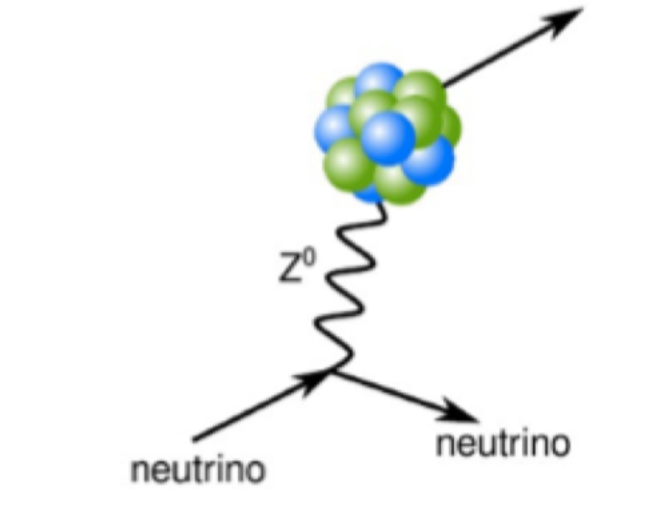
6.7σ detection with pulsed pion source at SNS

COHERENT, Science 357 (2017)

Coherent Elastic Neutrino-Nucleus Scattering

Freedmann, PRD9, 1974

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



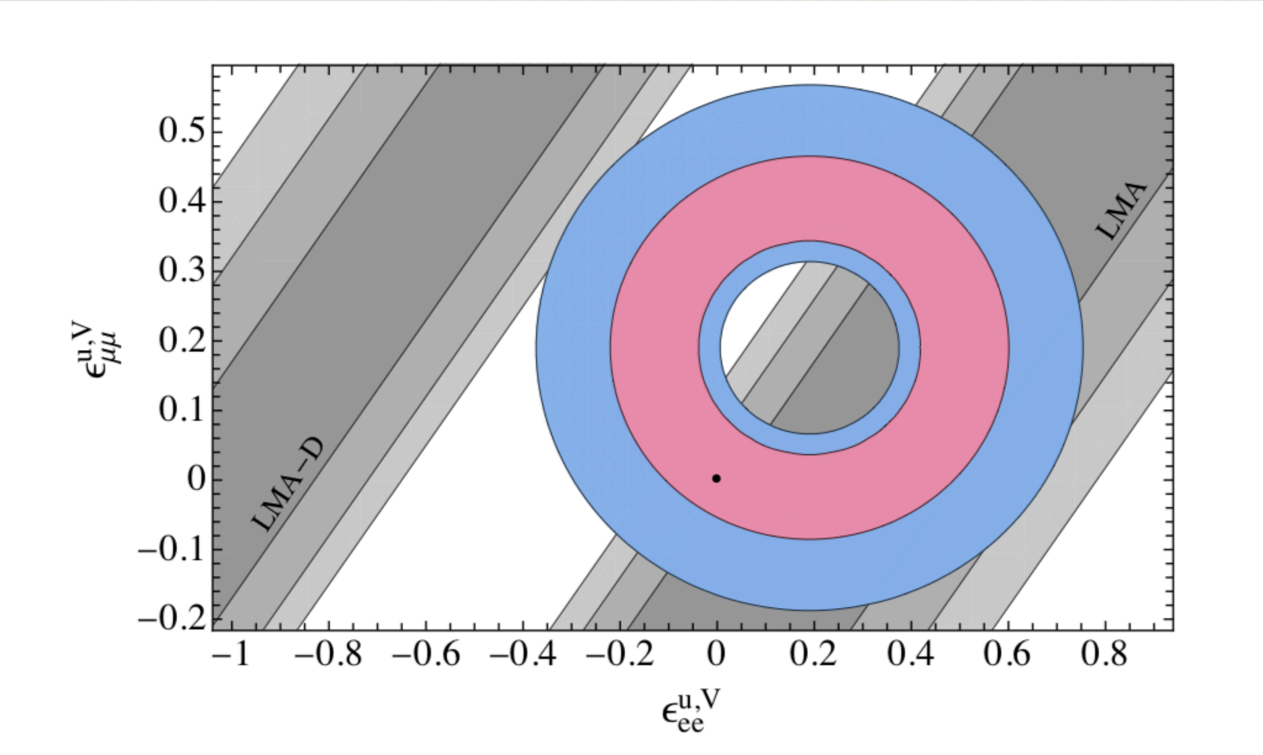
$$\sigma_0^{\rm SM} \equiv \frac{G_F^2\left[N - (1 - 4s_W^2)Z\right]^2 F^2(q^2) M^2}{4\pi}$$

- 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,…

New Physics in Coherent Scattering

if NSIs are present: replace **[*N* - *(1 - 4 s*$_W$*²) Z*]²** with:

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

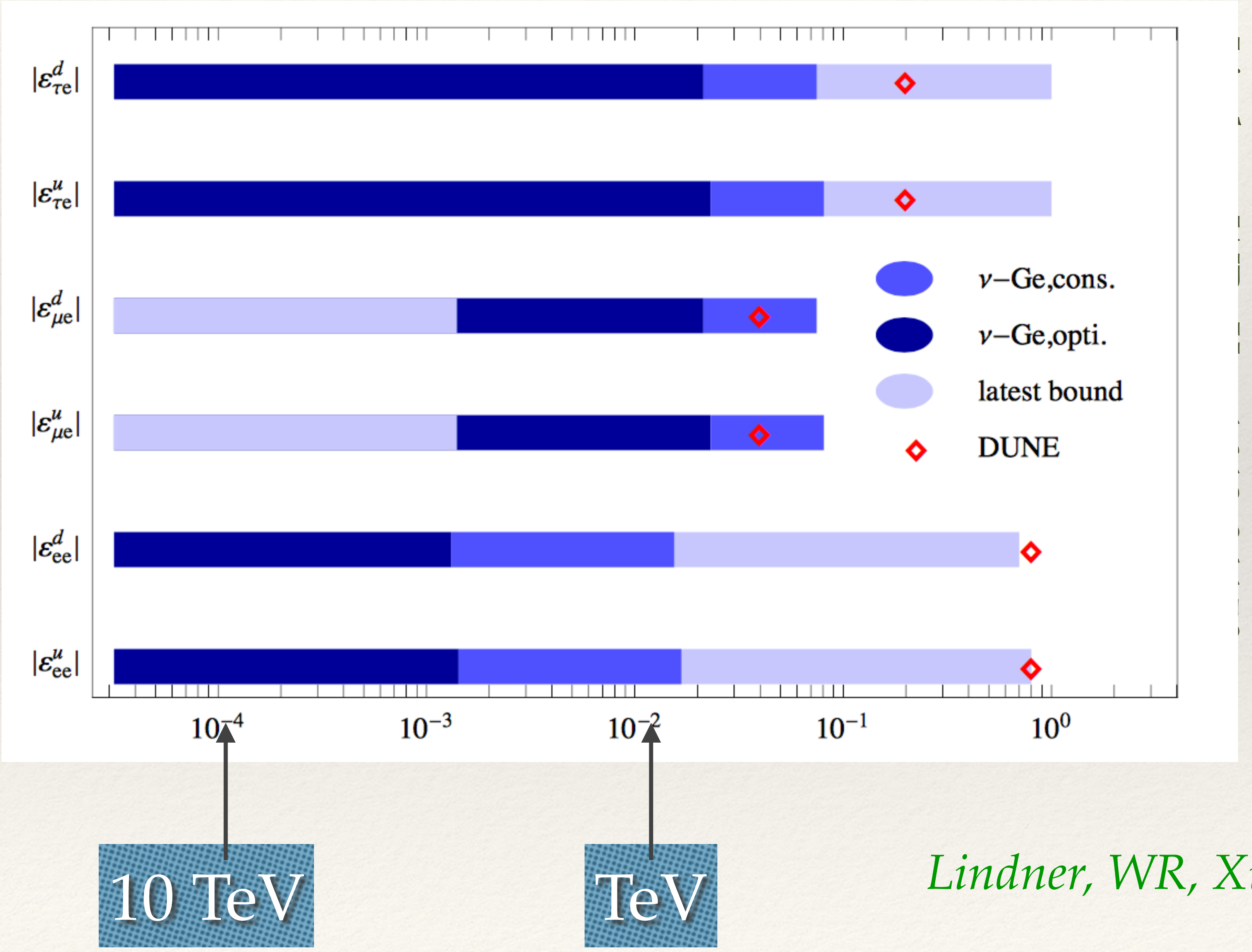


disfavors LMA-dark solution with more than 3σ

Coloma et al., 1708.02899

New Physics in Coherent Scattering

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

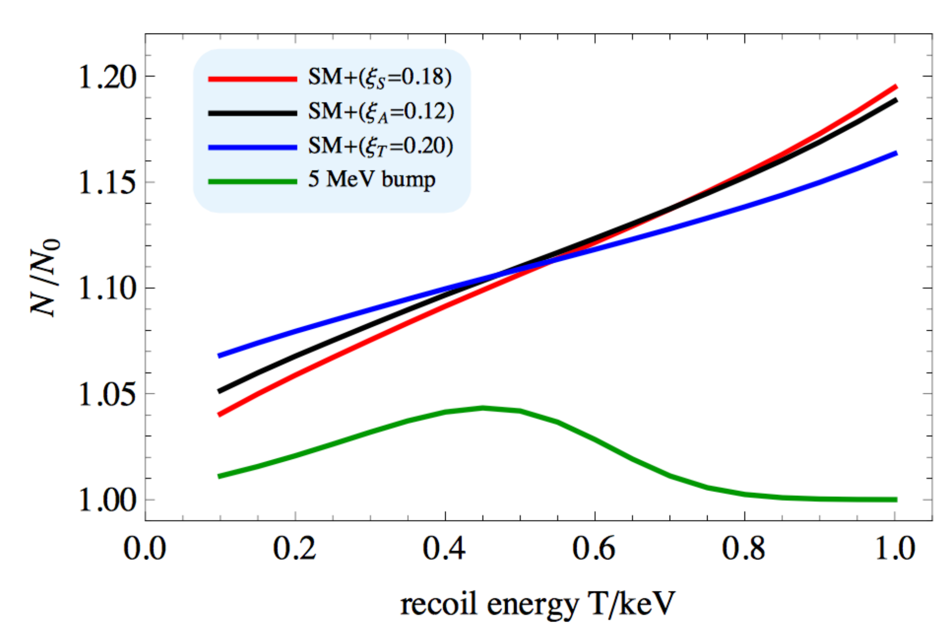


Lindner, WR, Xu, 1612.04150

New Physics in Coherent Scattering

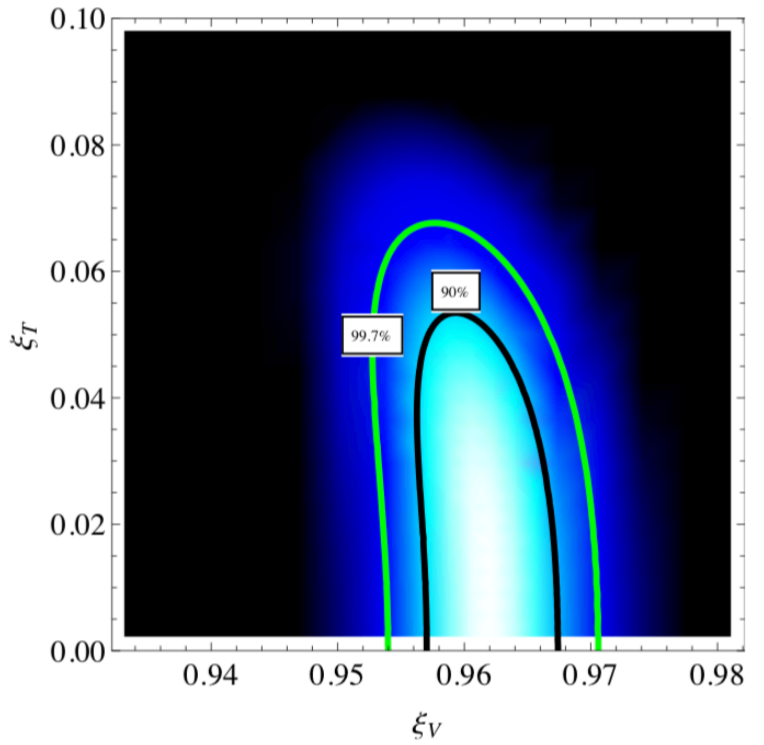
assume exotic neutral currents: $\mathcal{L} \supset \frac{G_F}{\sqrt{2}} \sum_{a=S,P,V,A,T} \overline{\nu}\Gamma^a \nu \left[\overline{\psi_N}\Gamma^a (C_a + \overline{D}_a i\gamma^5)\psi_N\right]$

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



changes *shape of spectrum:*

Lindner, WR, Xu, 1612.04150



Summary

- Neutrinos still only testable BSM physics
- PMNS parameters approach CKM-precision
- first hints on CP, mass ordering
- standard paradigm tested on all fronts
- still new windows open up…

how to „predict“ the CP phase: 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

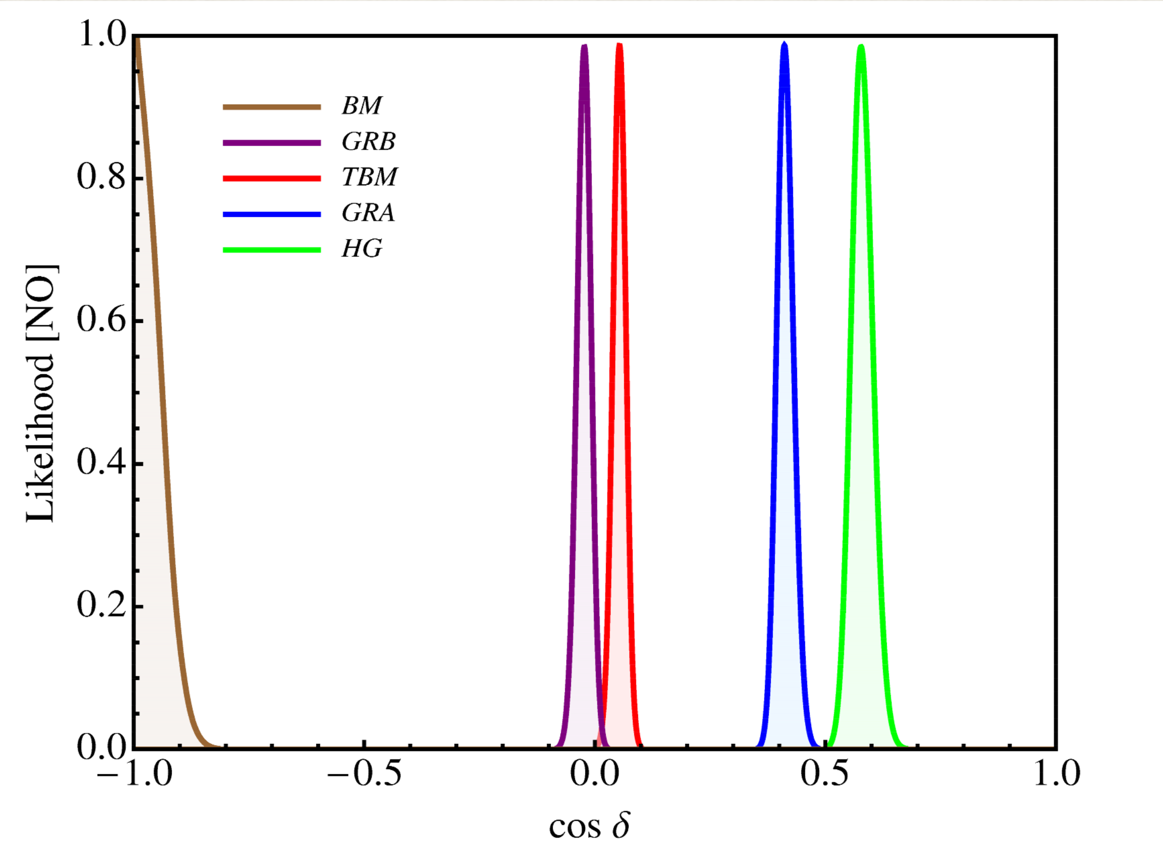
how to „predict“ the CP phase: sum-rules

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

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

King et al.; Frampton, Petcov, WR,…

Girardi, Petcov, Titov, 1410.8056



⇒ can distinguish only classes of models

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), ≃ 2σ effect each, ≃ 3σ total

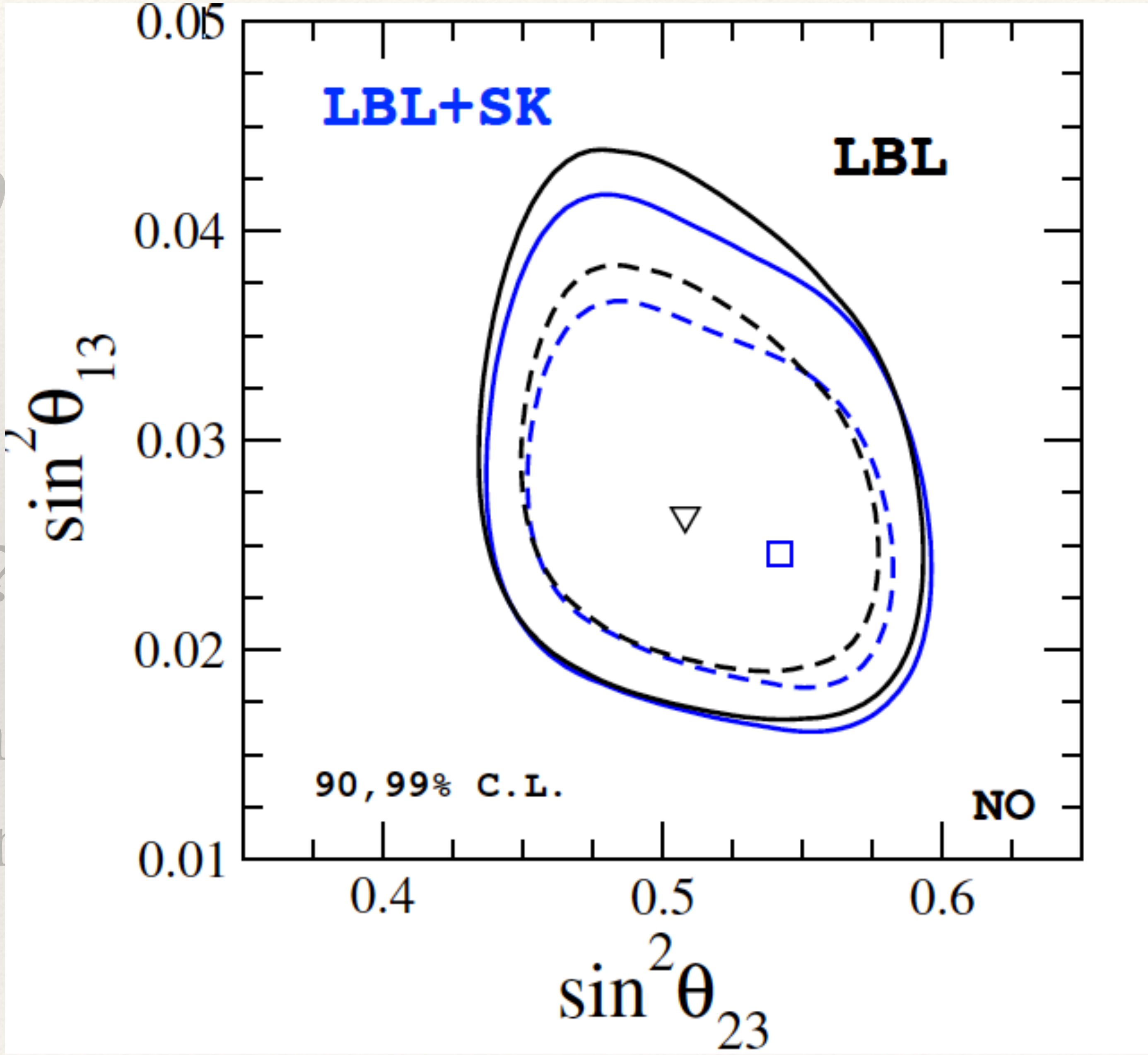
see talks by Sekiguchi, Bhatnagar, Wu, Tanaka

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*)

Oscillation Parameters

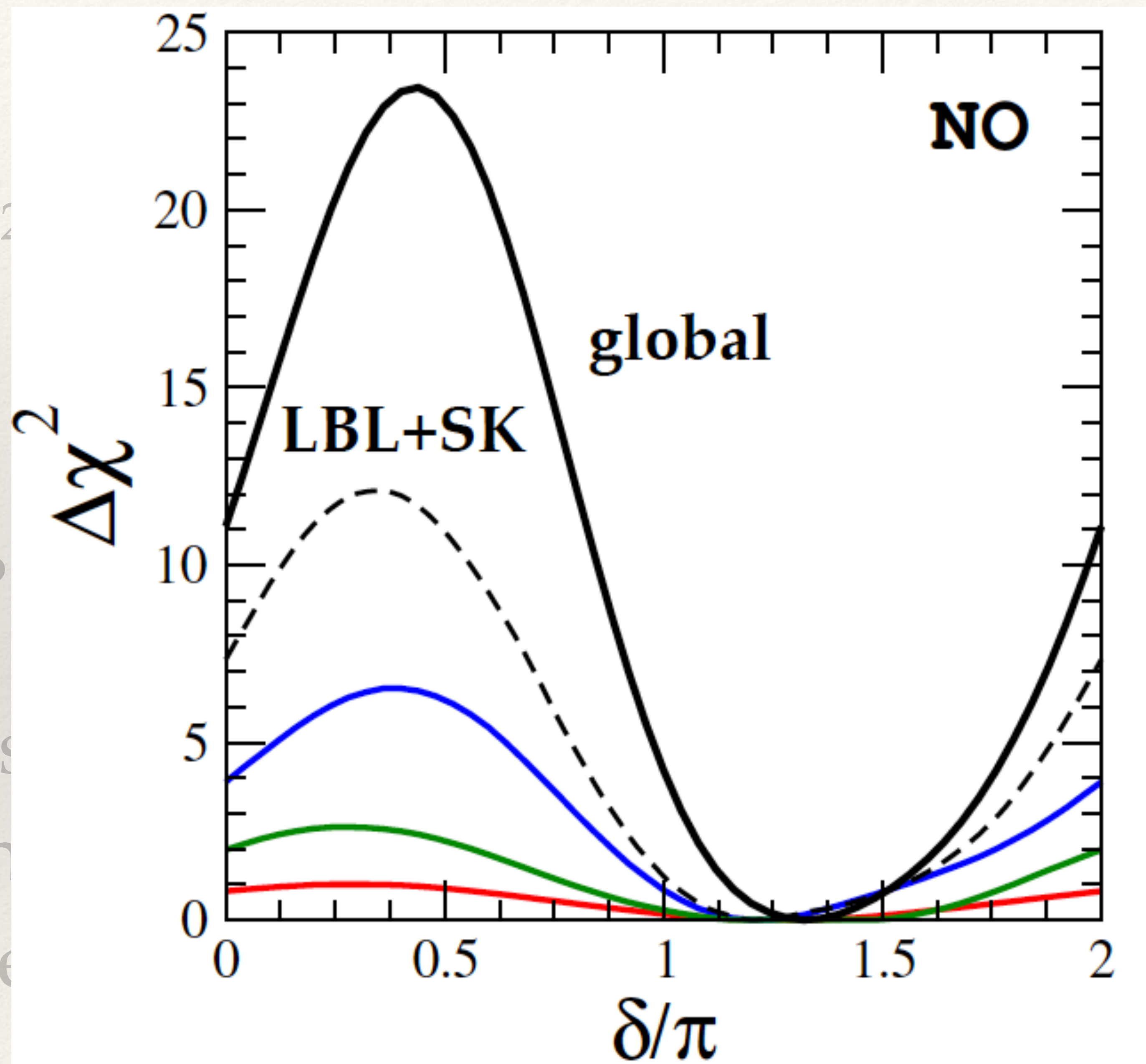
- Maximal θ ... hift to > π/4 by SK
- LBL prefer ... (too many? ... e events
- normal ma ... nsion with reactors) a ... like events), ≃ 2σ effect



deSalas et al, 1708.01186

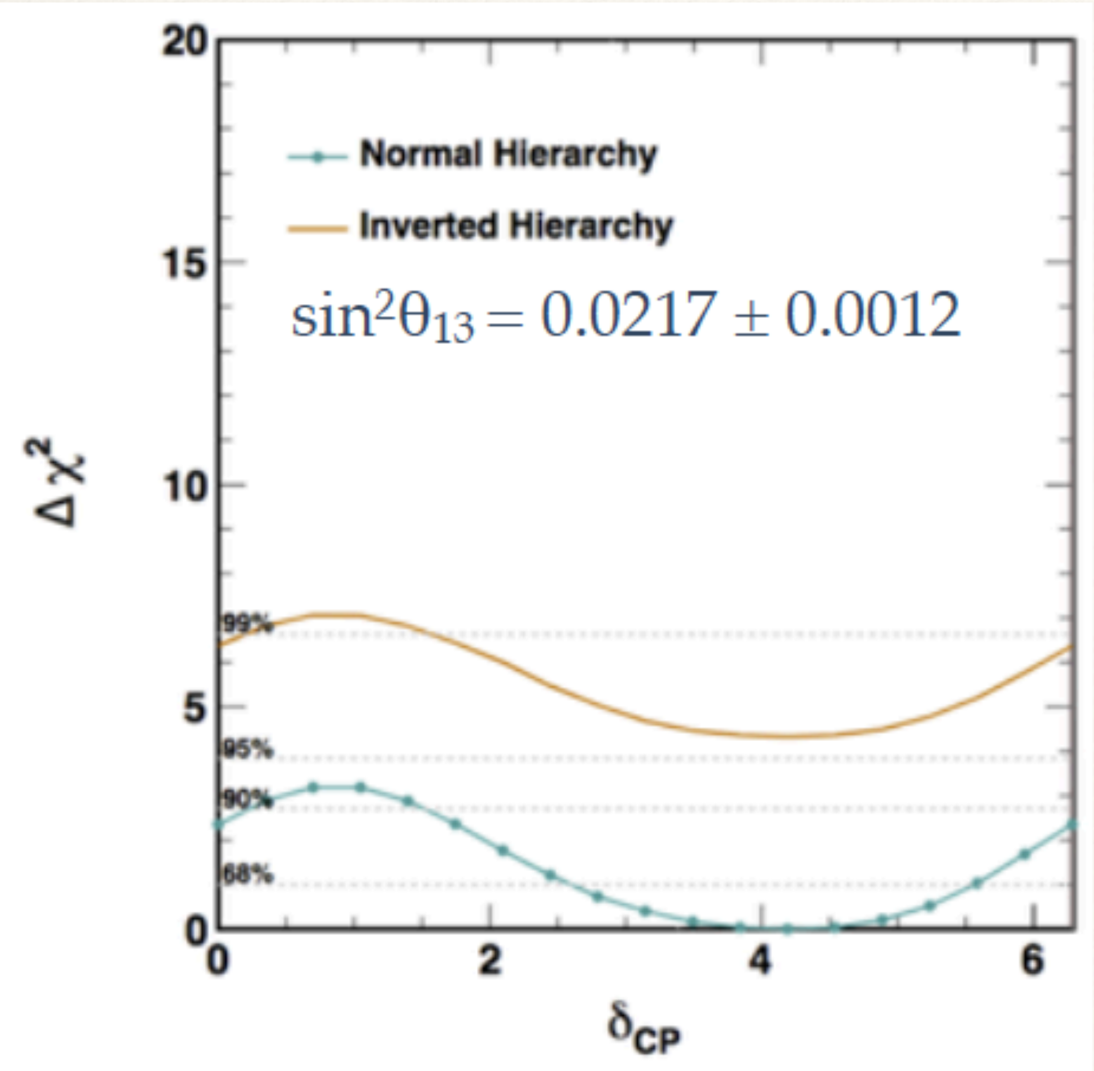
Oscillation Parameters

- Maximal θ_2 … ift to $> \pi/4$ by SK
- LBL prefer … (too many? … e events
- normal mas … sion with reactors) an … like events), $\simeq 2\sigma$ effect e …

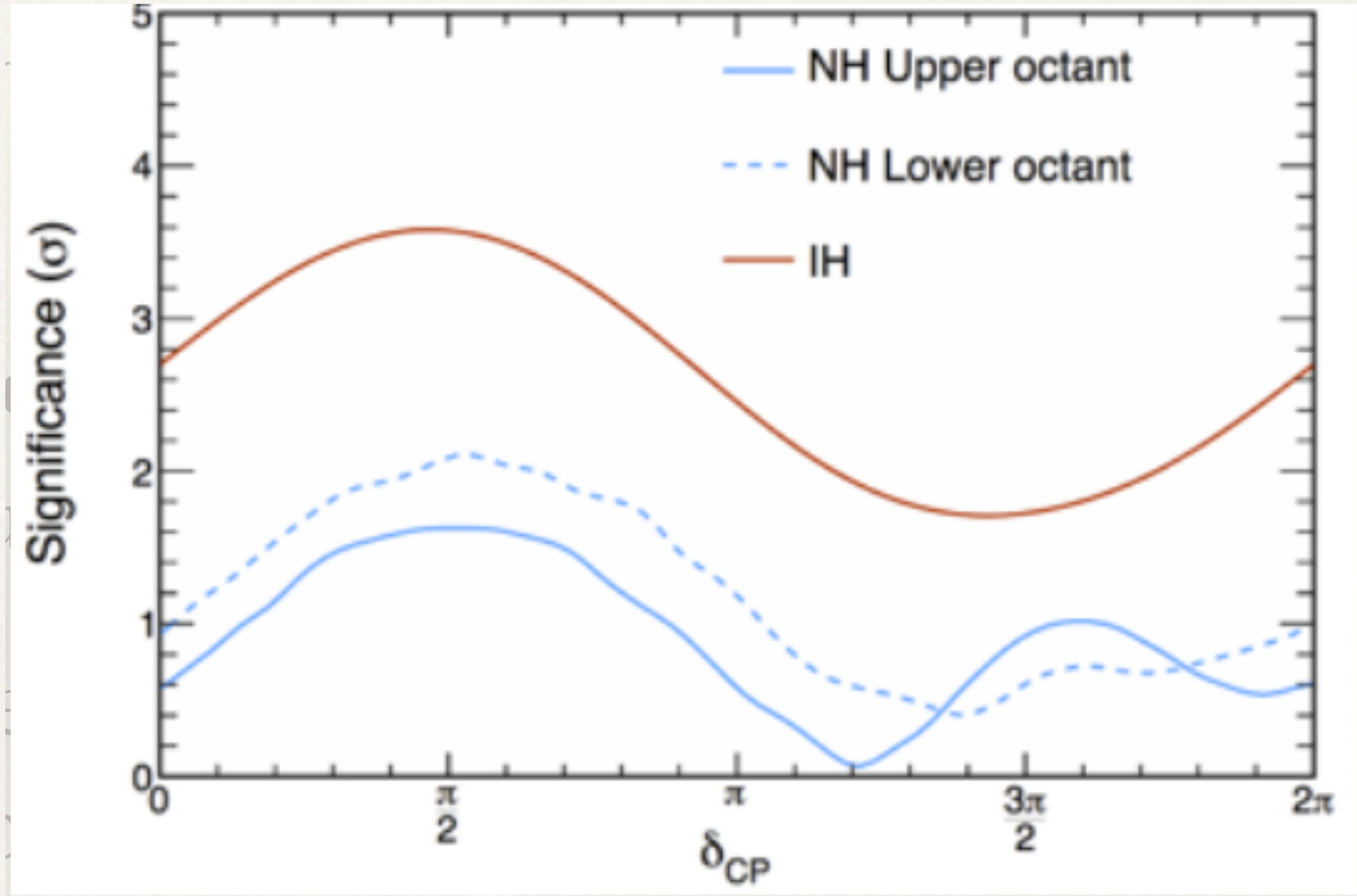


deSalas et al, 1708.01186

Oscillation Parameters



SK, 1710.09126



NOvA, 1806.00096

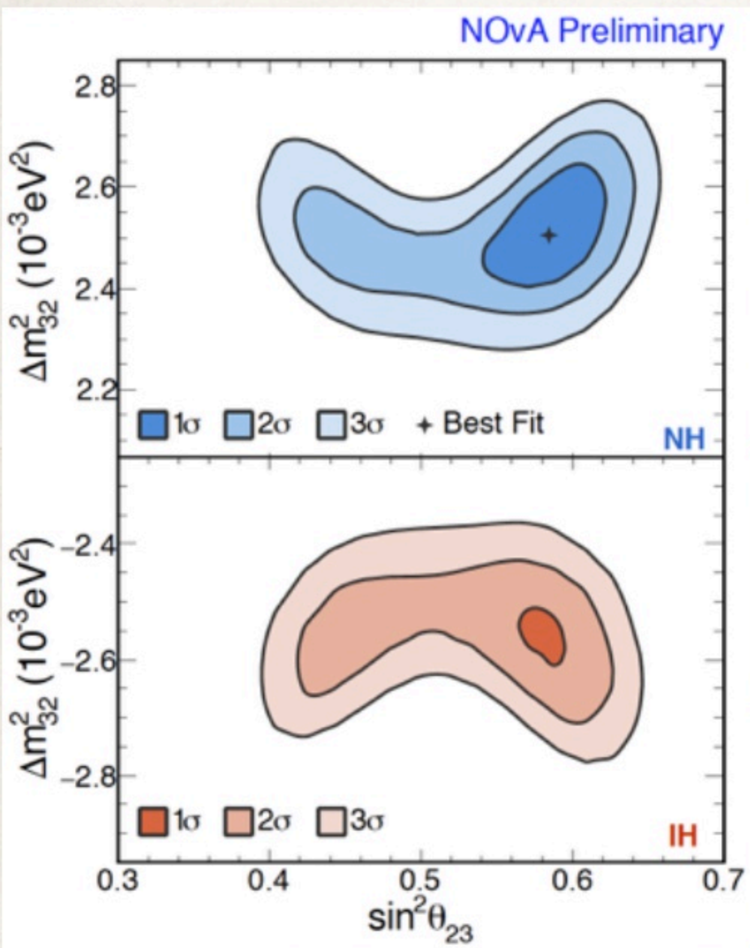
New data presented @Nu2018

see talks by Sekiguchi, Bhatnagar

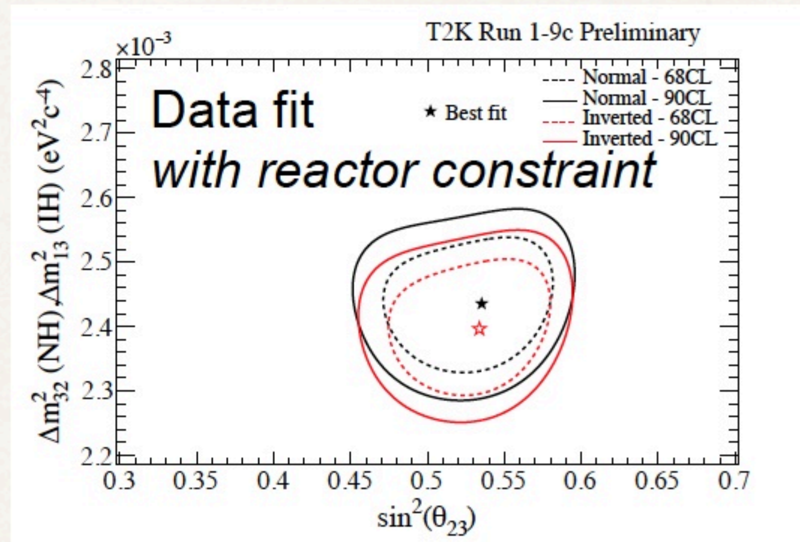
First NOνA antineutrino data

Talk by M. Sánchez

neutrino + antineutrino fit



New T2K antineutrino data

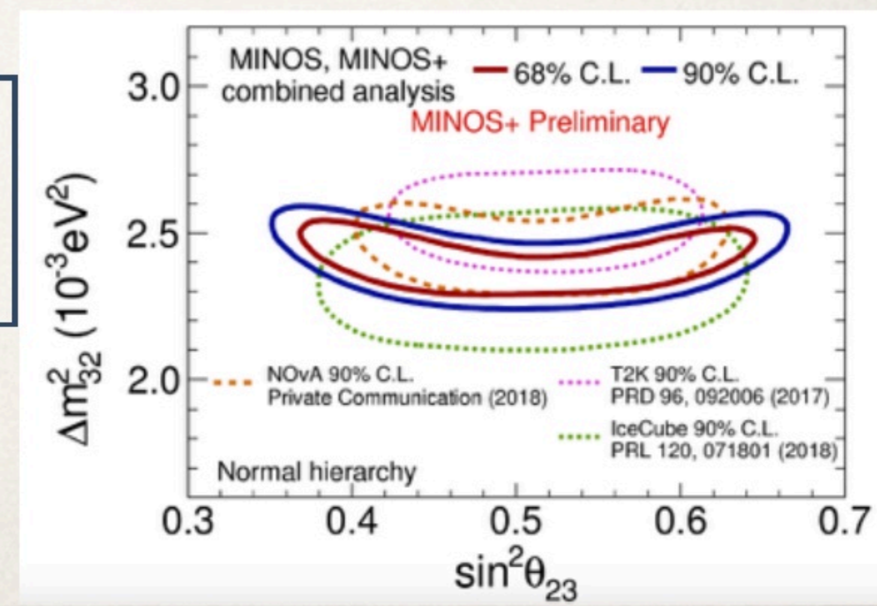


Monday June 4th

Talk by M.Wascko

New combined analysis MINOS/ MINOS+

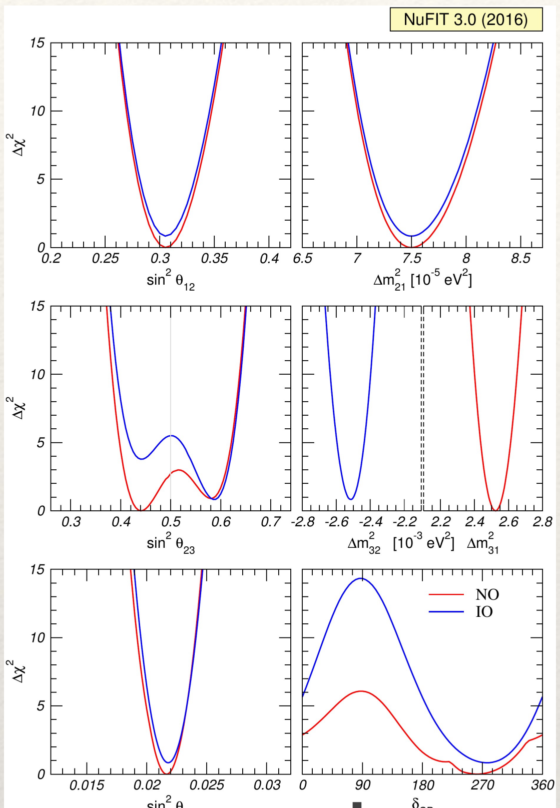
Talk by A. Aurisano



Tortola, talk at Neutrino 2018

…probably adds another σ to each hint…

Expectations of lifetimes

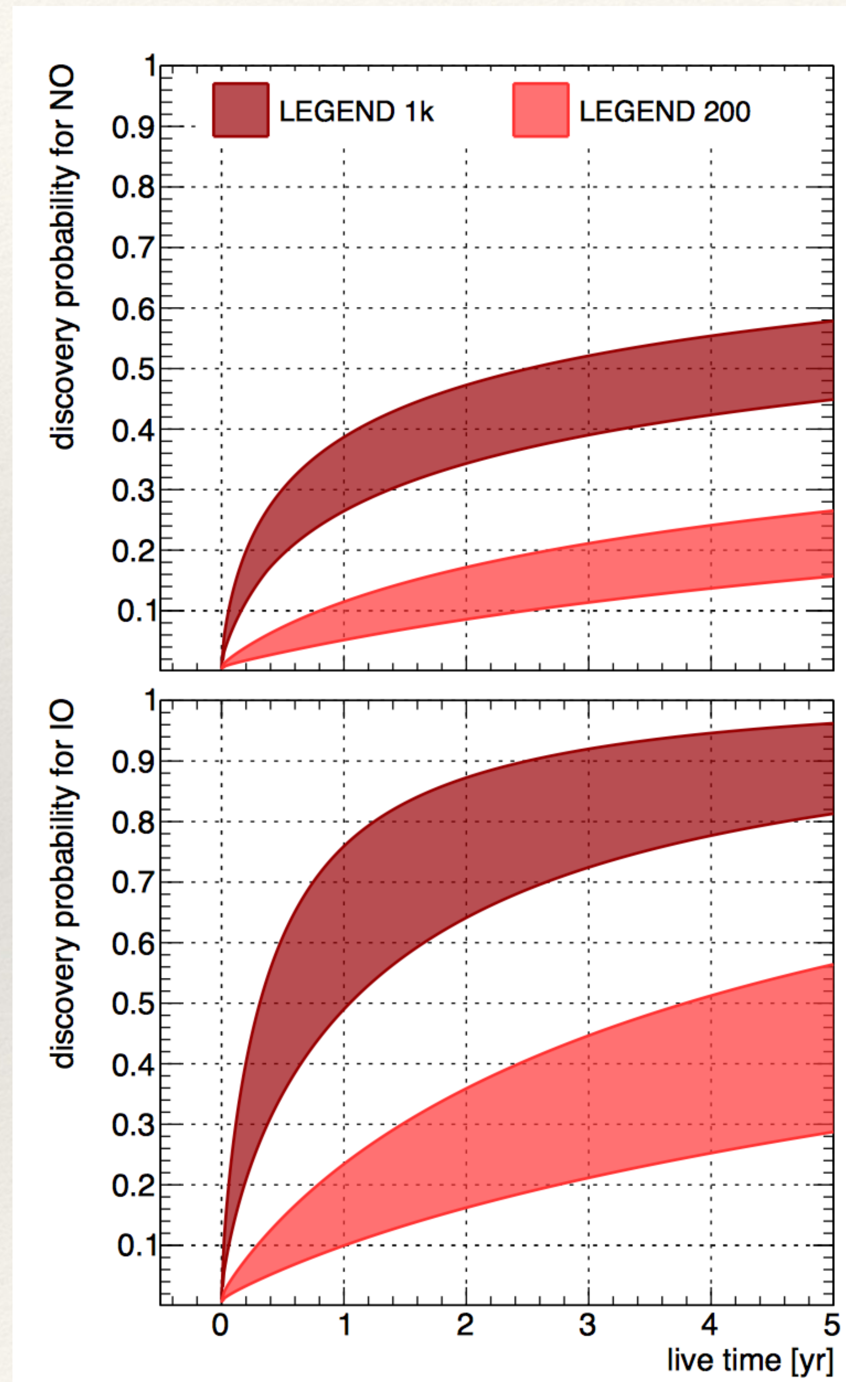


+

oscillation fits

expt. sensitiv.

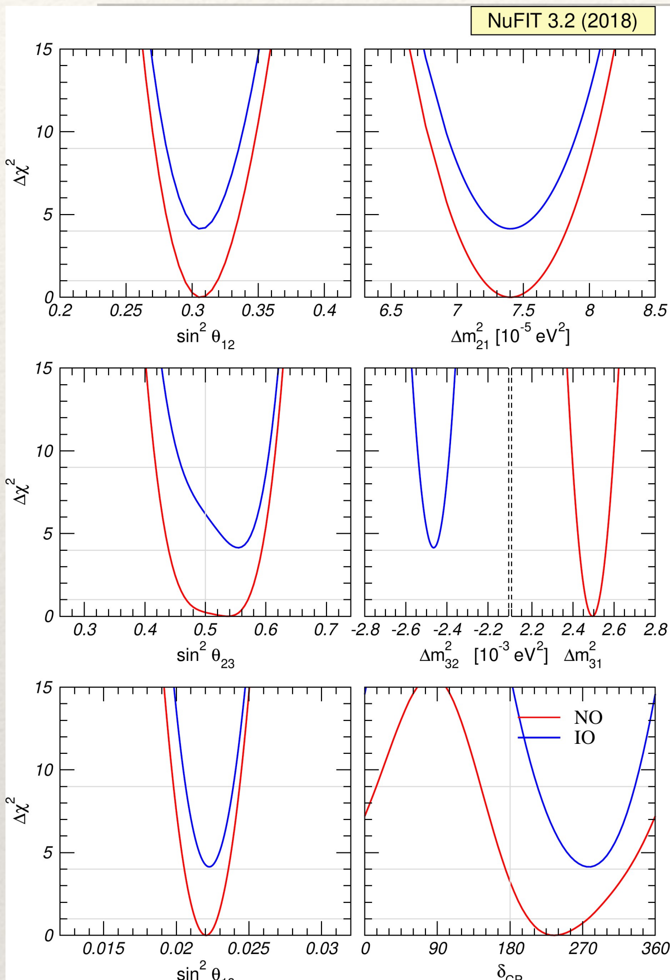
Experiment	Iso.	Iso. Mass [kg_{iso}]	σ [keV]	ROI [σ]	ϵ_{FV} [%]	ϵ_{sig} [%]	$\mathcal{E}$ $\left[\frac{kg_{iso}\,yr}{yr}\right]$	$\mathcal{B}$ $\left[\frac{cts}{kg_{iso}\,ROI\,yr}\right]$	3σ disc. sens. $\hat{T}_{1/2}$ [yr]	3σ disc. sens. $\hat{m}_{\beta\beta}$ [meV]	Required Improvement Bkg	Required Improvement σ	Required Improvement Iso. Mass
LEGEND 200 [61, 62]	^{76}Ge	175	1.3	[-2, 2]	93	77	119	$1.7 \cdot 10^{-3}$	$8.4 \cdot 10^{26}$	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



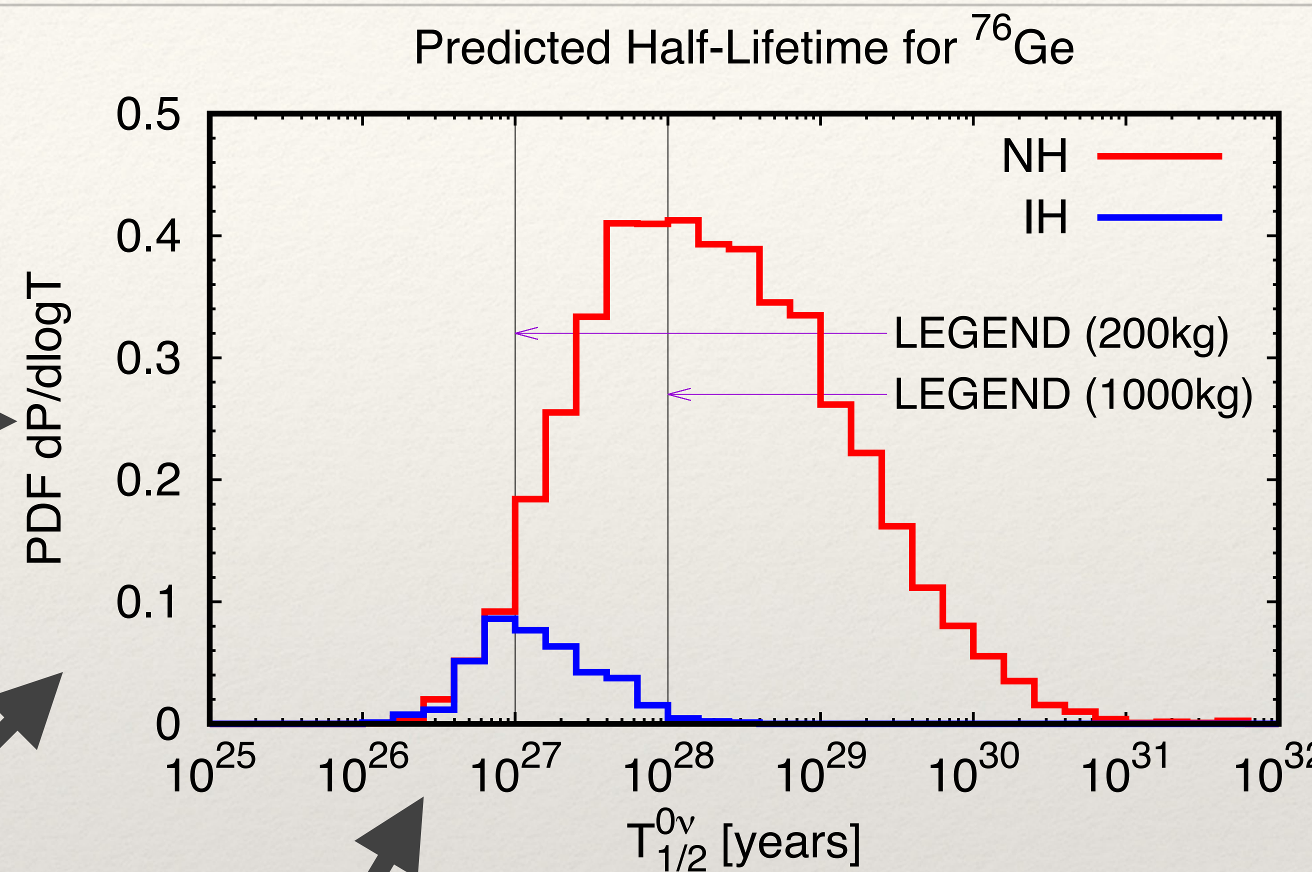
Bayesian discovery probability: discovery sensitivity (value of m_{ee} for which expt. has 50% chance to see it at 3σ) folded with probability distribution of m_{ee}

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

Expectations of lifetimes

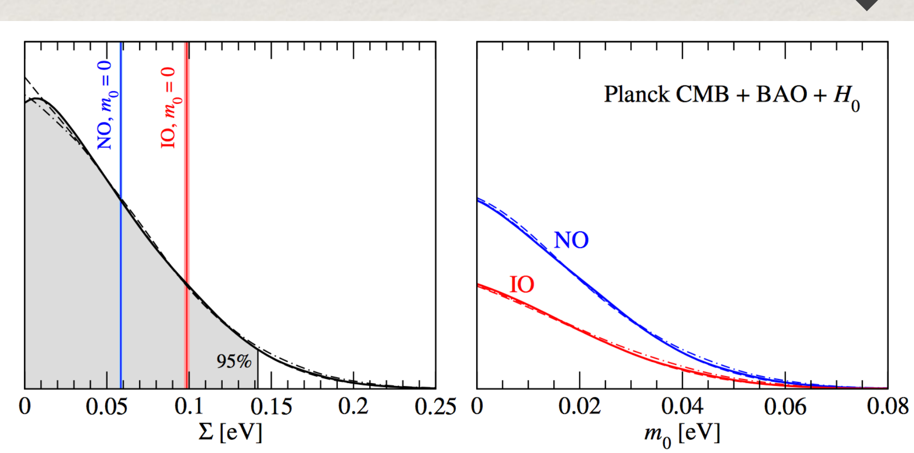


oscillation fits



Ge, WR, Zuber, 1707.07904

cosmology fit



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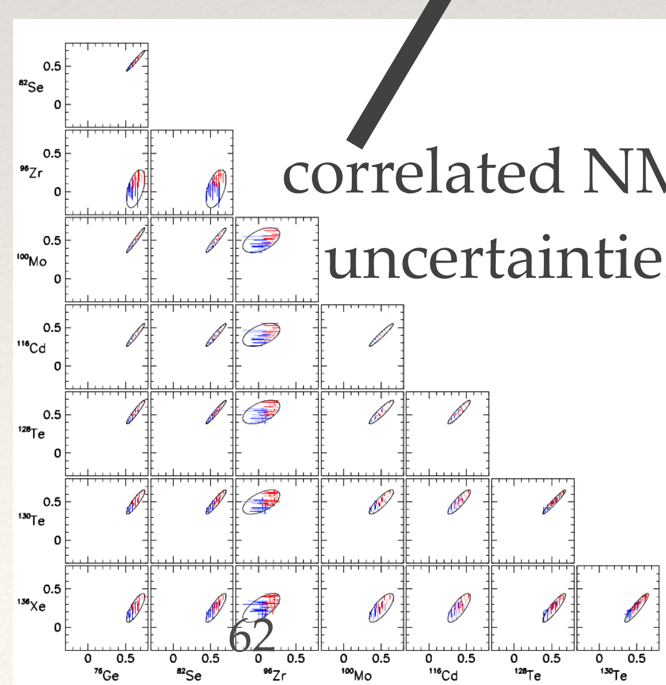
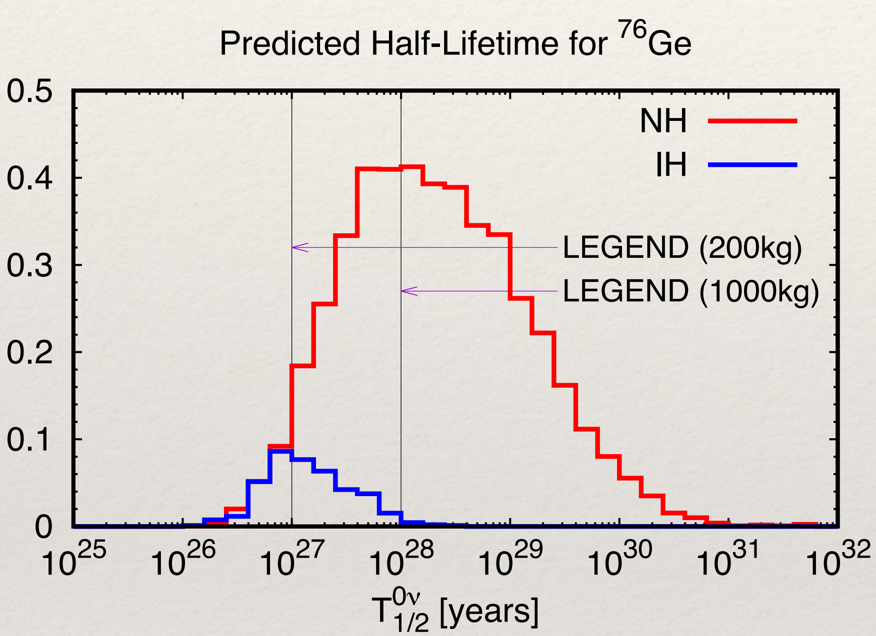


correlated NME uncertainties

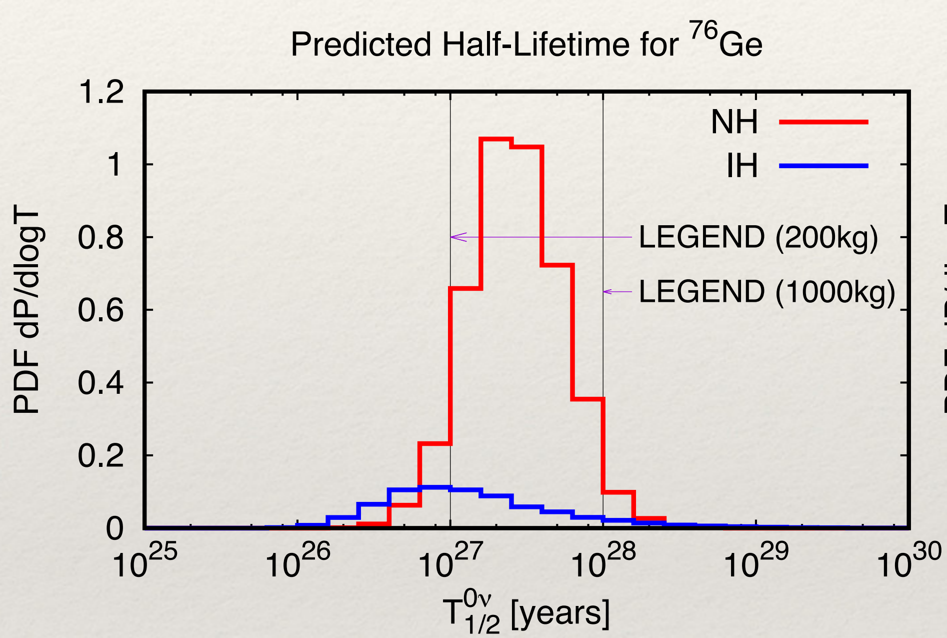
see also Agostini et al, 1705.02996; Caldwell et al., 1705.01945; Zhang, Zhou, 1508.05472; Benato, 1510.01089

Expectations for half-lifes

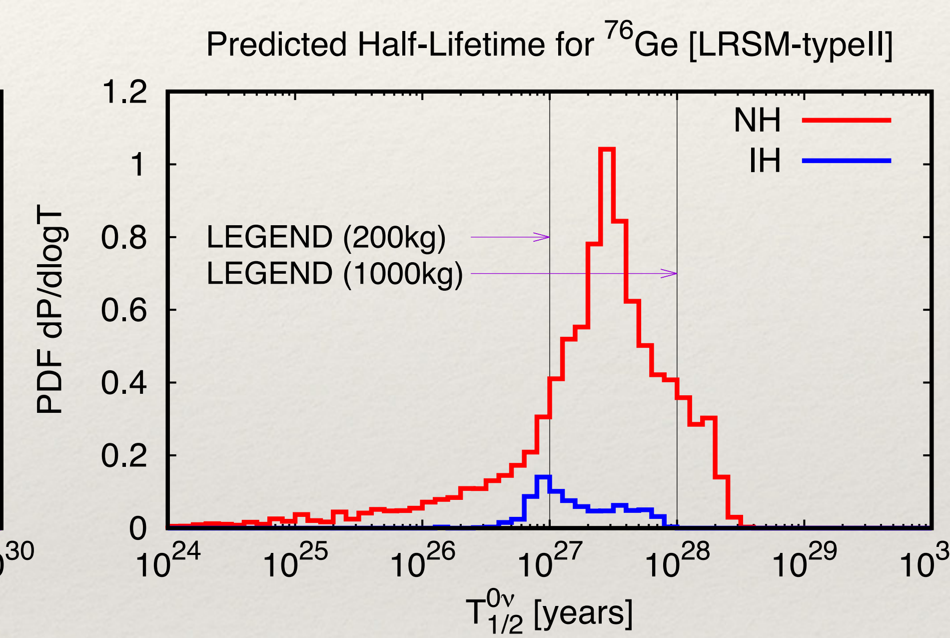
Standard



Sterile



Left-right



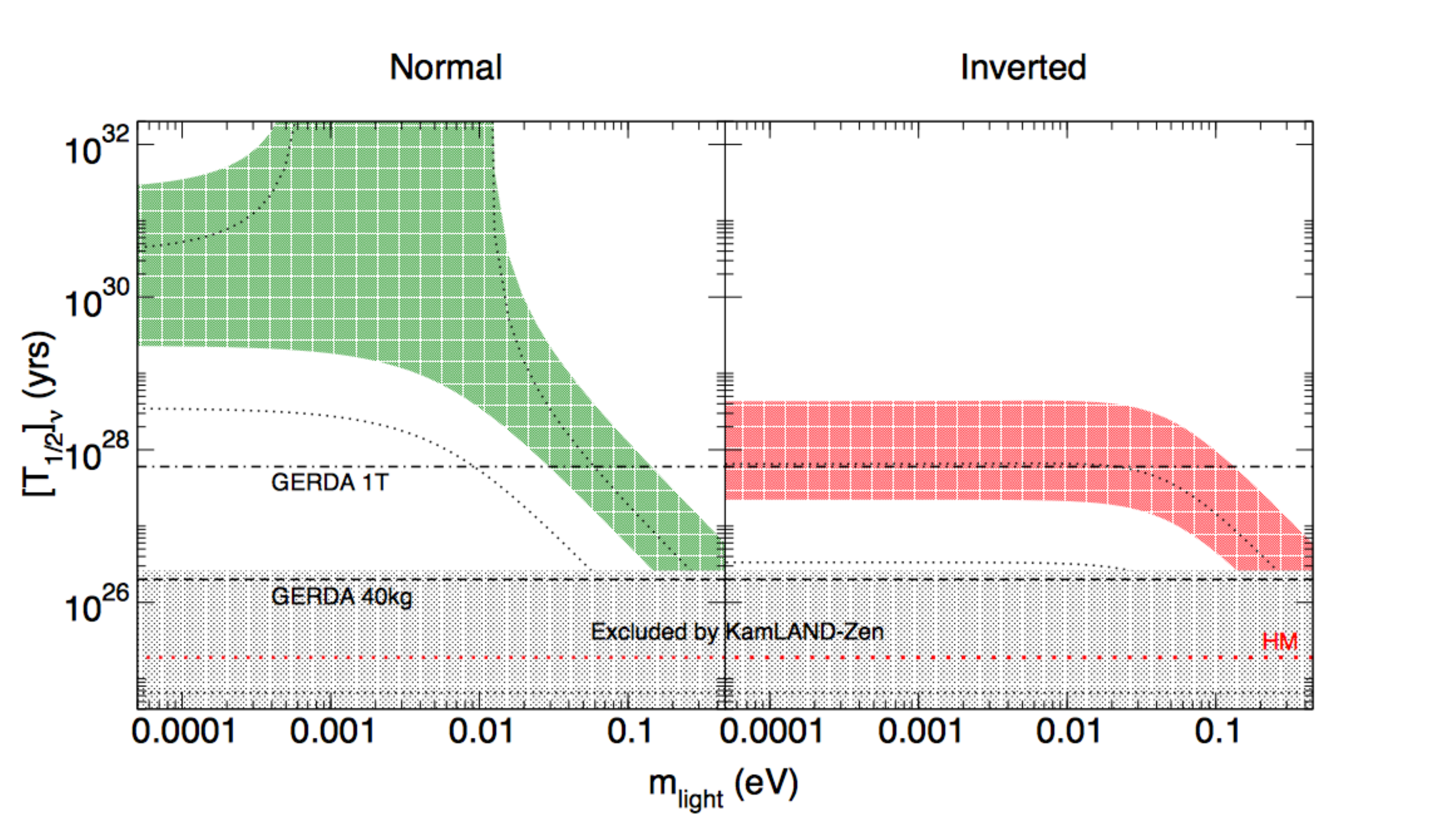
Ge, WR, Zuber, 1707.07904

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

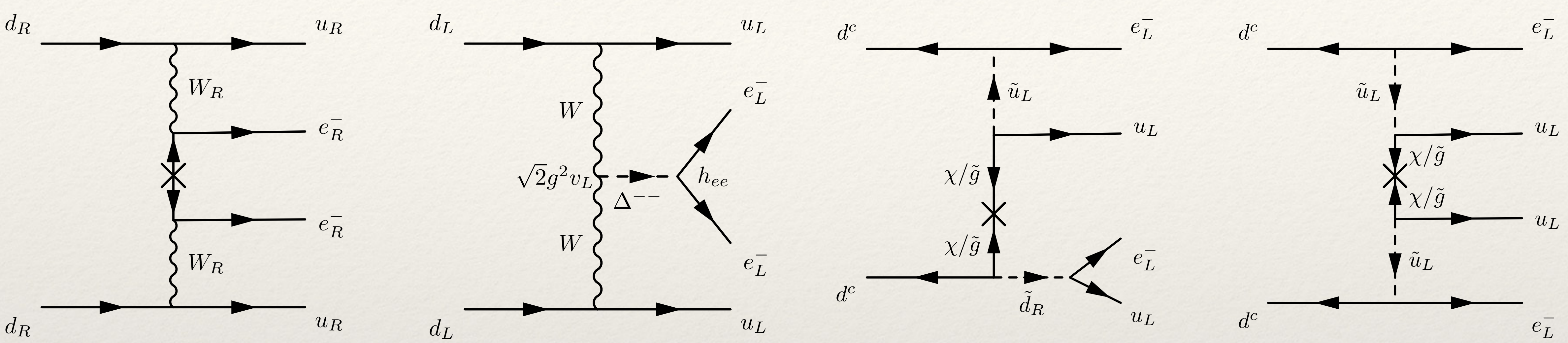
However, most alternative mechanisms unrelated to neutrino parameters…

…thus decoupled from cosmology (and direct experiments)!

The usual plot



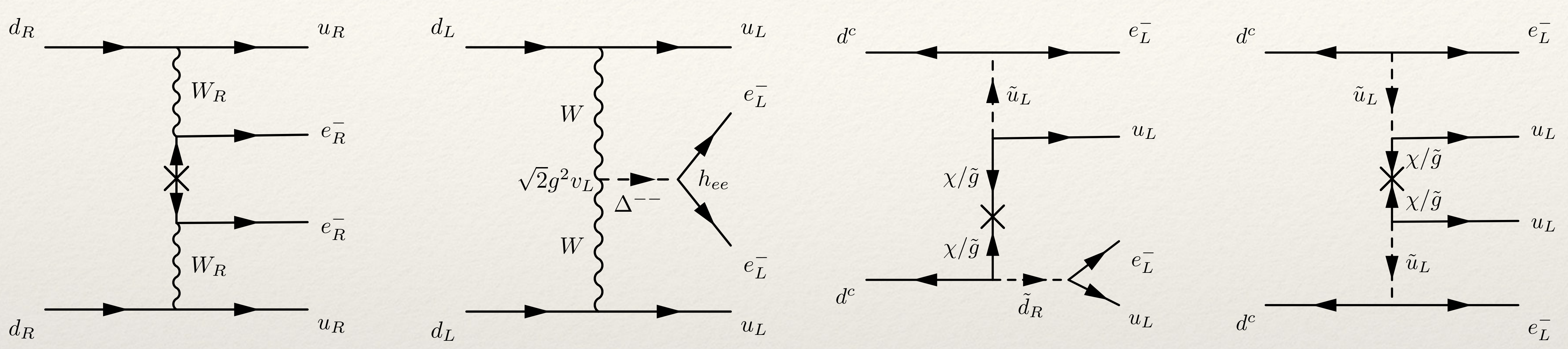
Non-Standard Interpretations



- typically decouples double beta decay from cosmology and KATRIN

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

Non-Standard Interpretations



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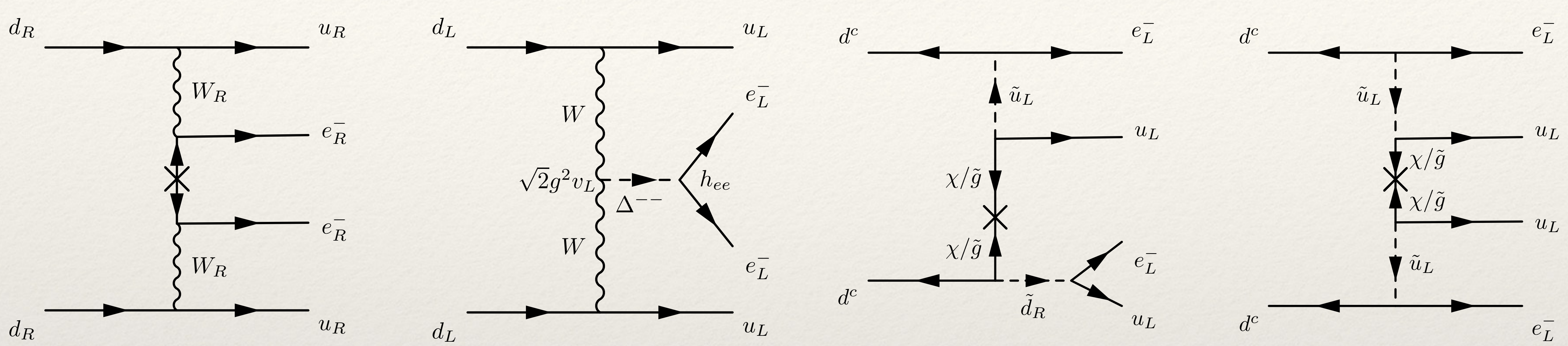
Therefore:
$T(\text{eV}) = T(\text{TeV})$

Non-Standard Interpretations



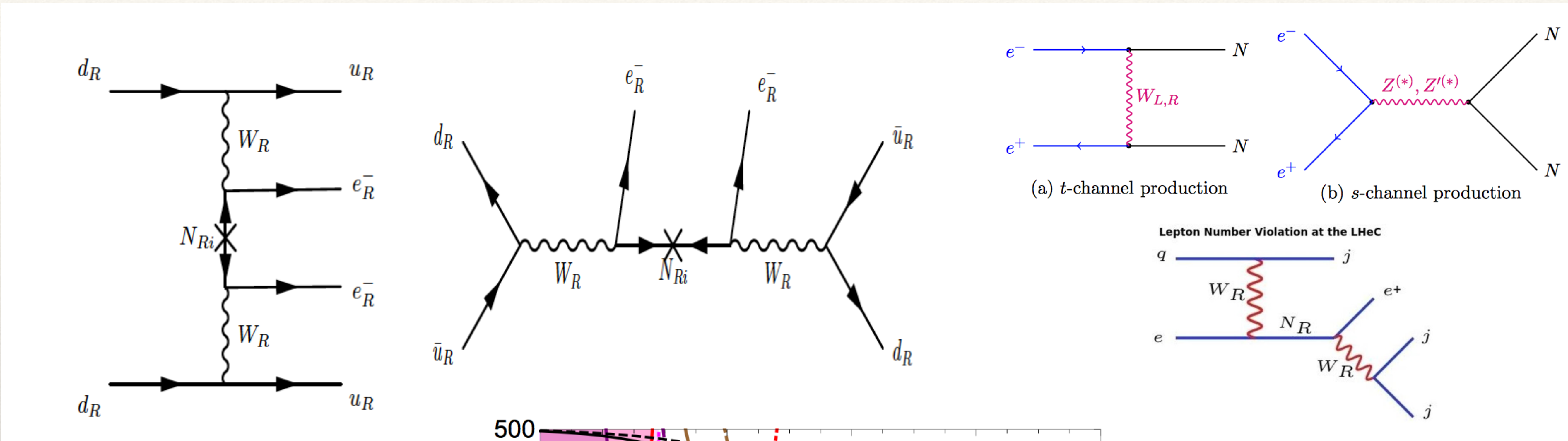
- typically decouples double beta decay from cosmology and KATRIN

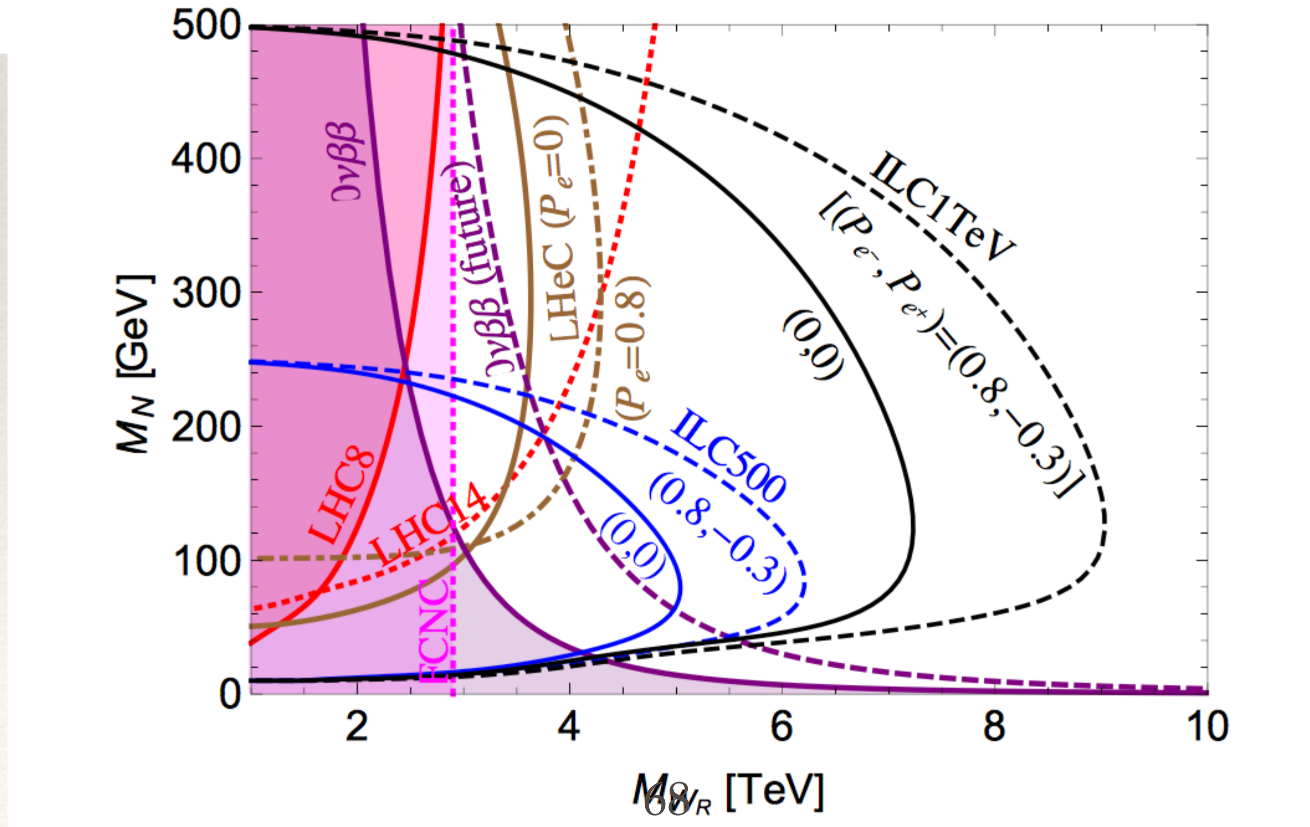
$$\mathcal{A}_{\rm Standard} = G_F^2 \frac{\langle m \rangle}{q^2} \text{ versus } \mathcal{A}_{\rm Non-Standard} = \frac{c}{M_X^5}$$

Therefore:
T(eV) = T(TeV)

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

LHC and Double Beta Decay



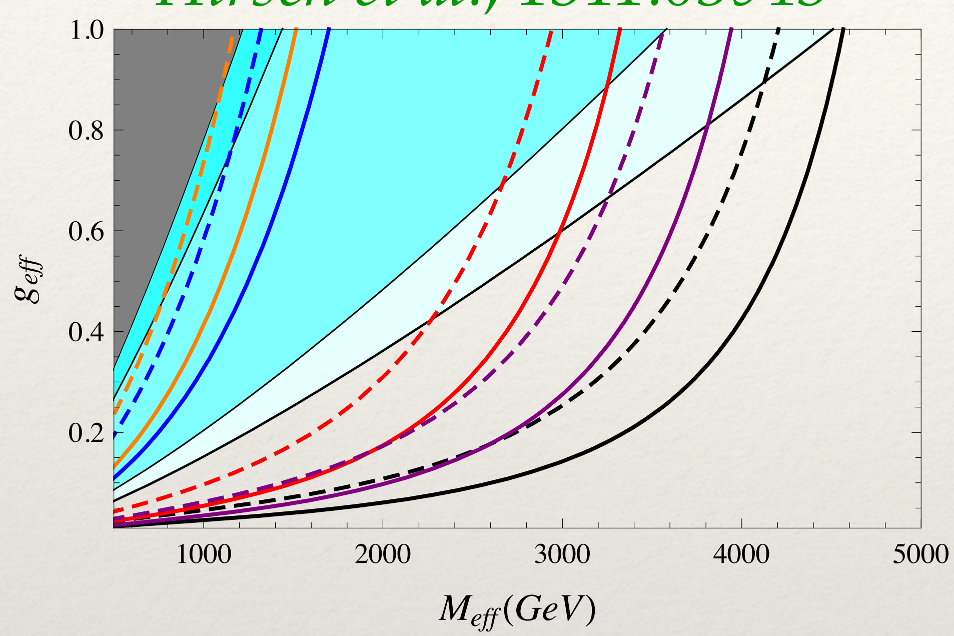


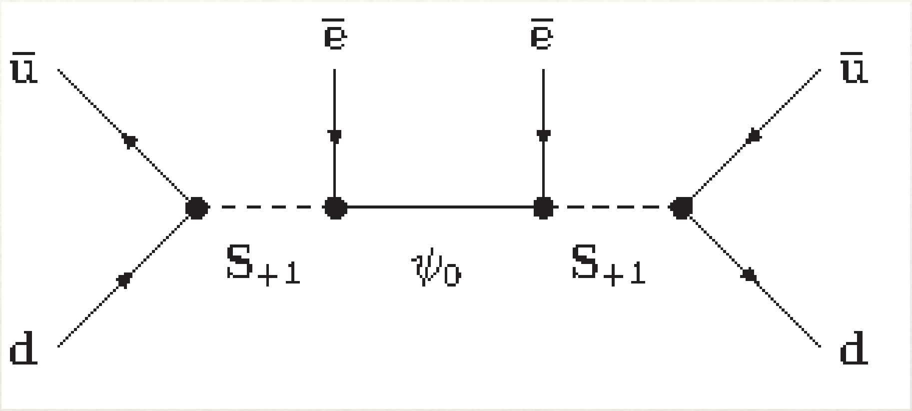
Biwal, Dev, 1701.08751

polarization at LHeC and ILC

Complementarity of LHC and 0νββ

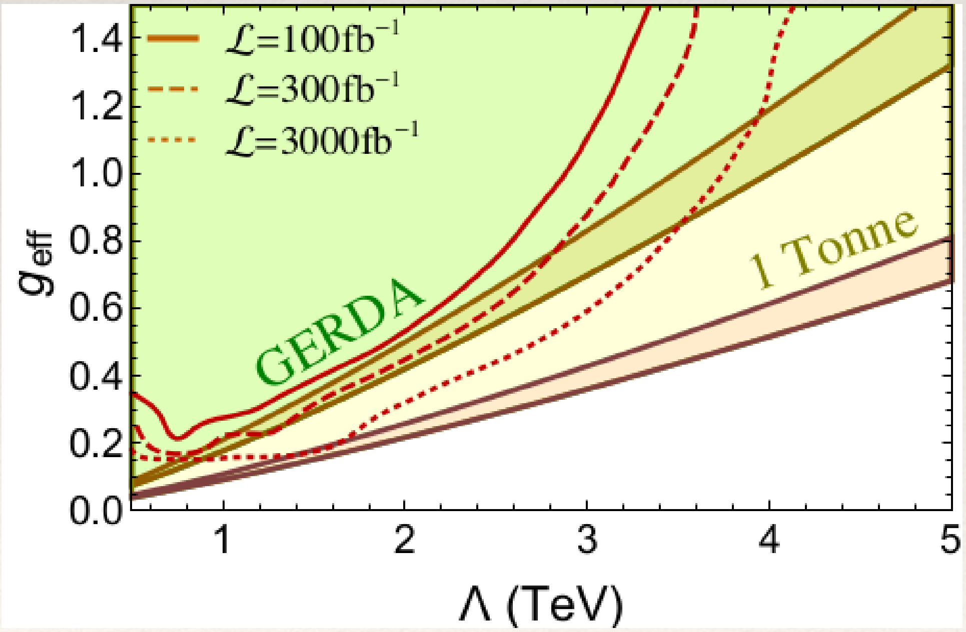
Hirsch et al., 1511.03945





$S \sim (1,2)$

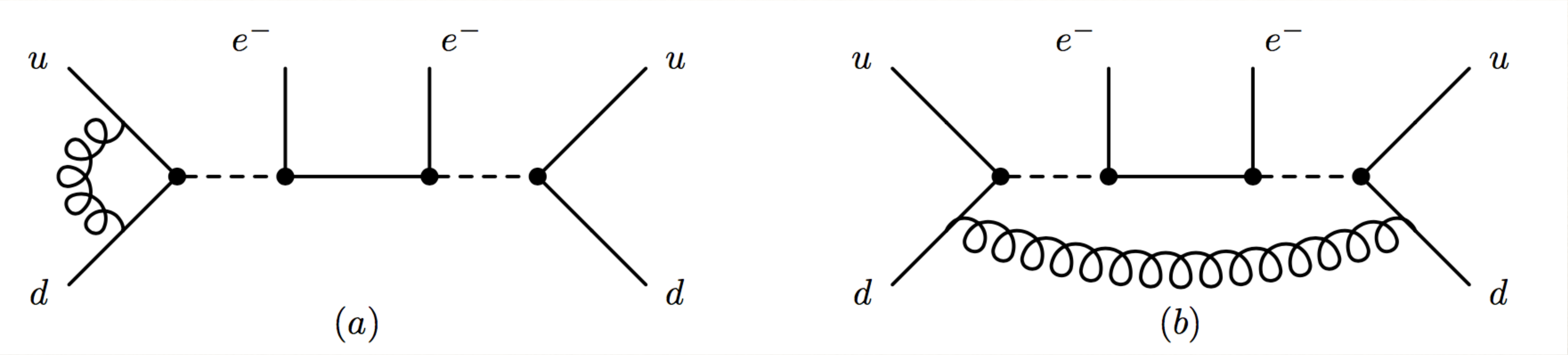
$\psi \sim (1,0)$



Ramsey-Musolf et al., 1508.04444

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

QCD Corrections



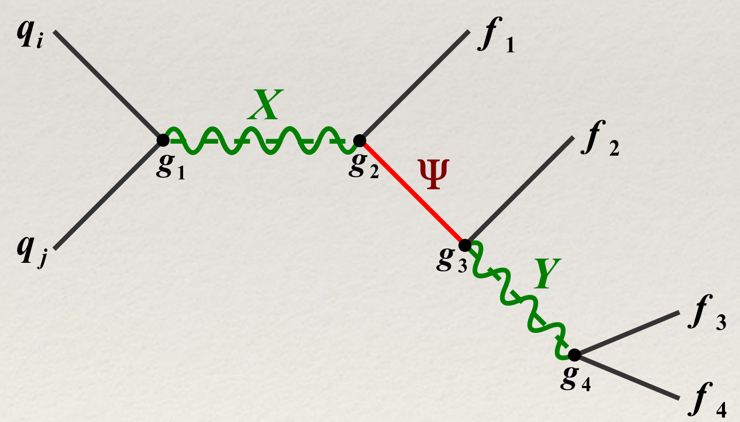
- naive size $(\alpha_s/4\pi) \ln (M_W/100 \text{ MeV})^2 \simeq 10\%$, true for standard diagram
- creates in non (V-A) ⊗ (V-A) short-range mechanisms color non-singlets, Fierzing to singlets gives different operators with vastly different NMEs
- ⇒ can give effect exceeding NME uncertainty…

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

TeV-scale LNV and Baryogenesis

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

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



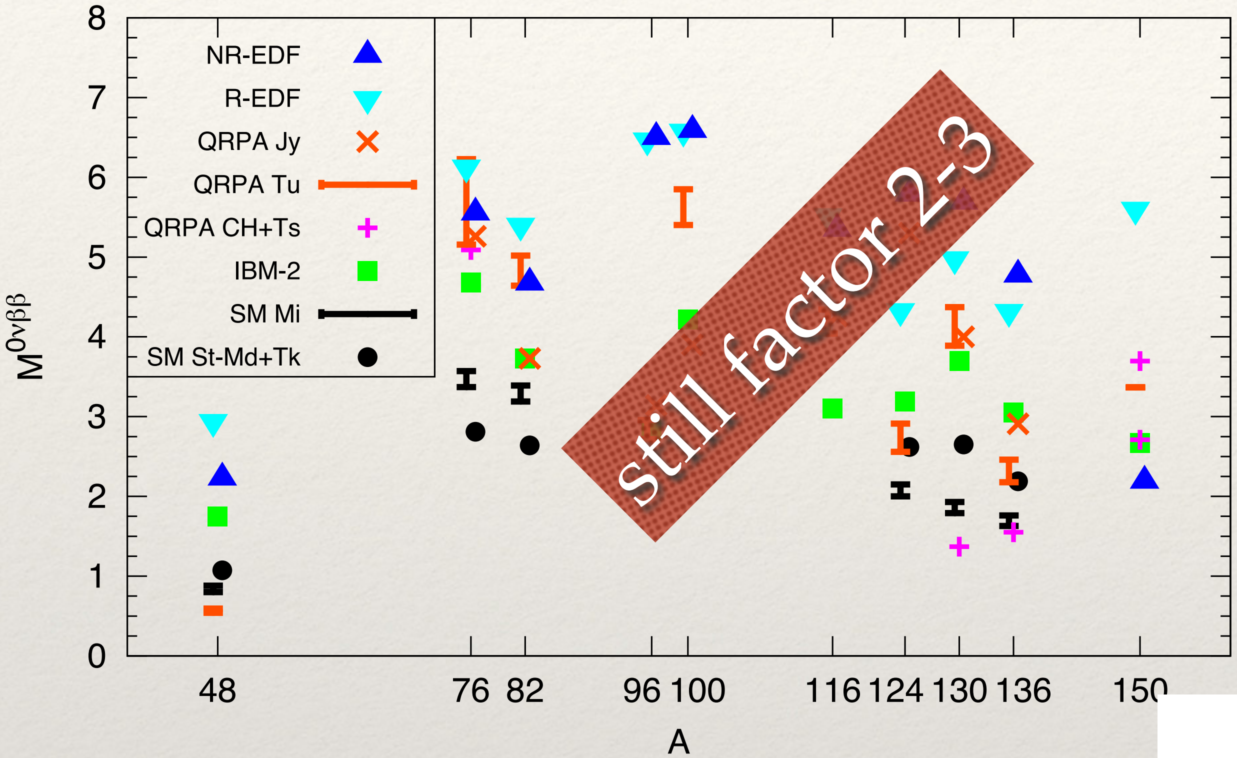
wash-out:

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

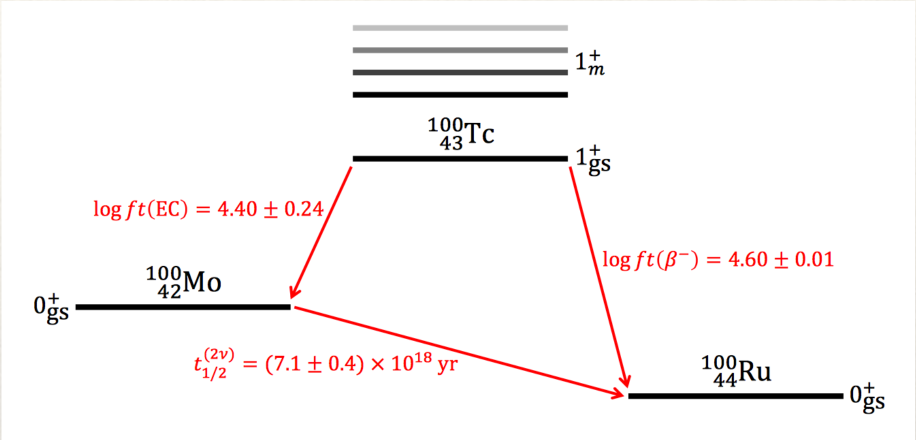
would need electroweak, resonant, ARS, post-sphaleron baryogenesis

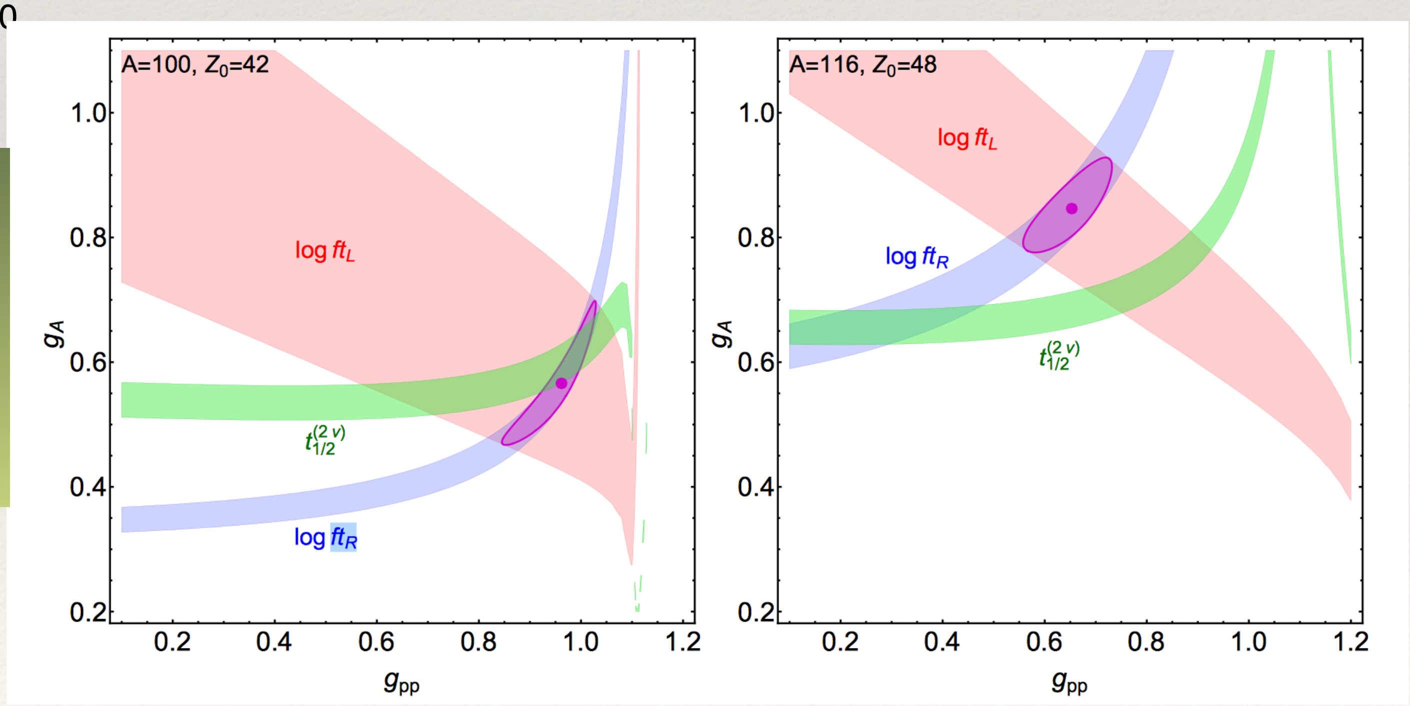
Nuclear Matrix Elements

Engel, Menendez, 1610.06548



How good are the models?
Example isobaric triplets
within QRPA



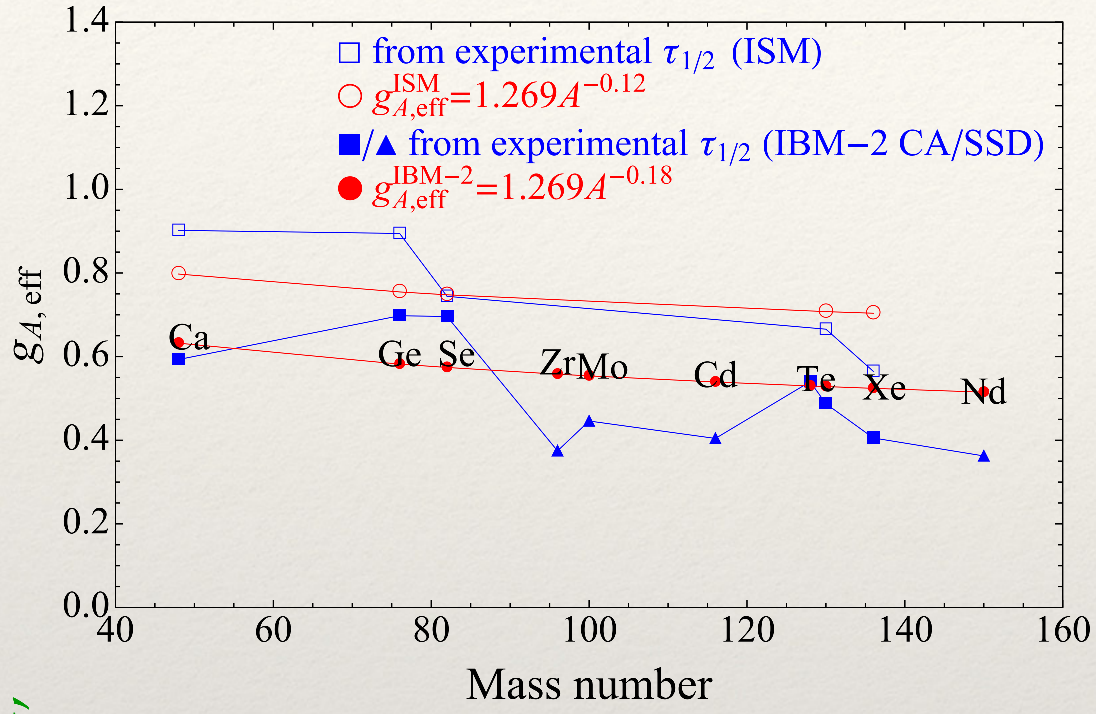


Deppisch, Suhonen, 1606.02908

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

Nuclear Matrix Elements

Iachello et al., 1506.08530

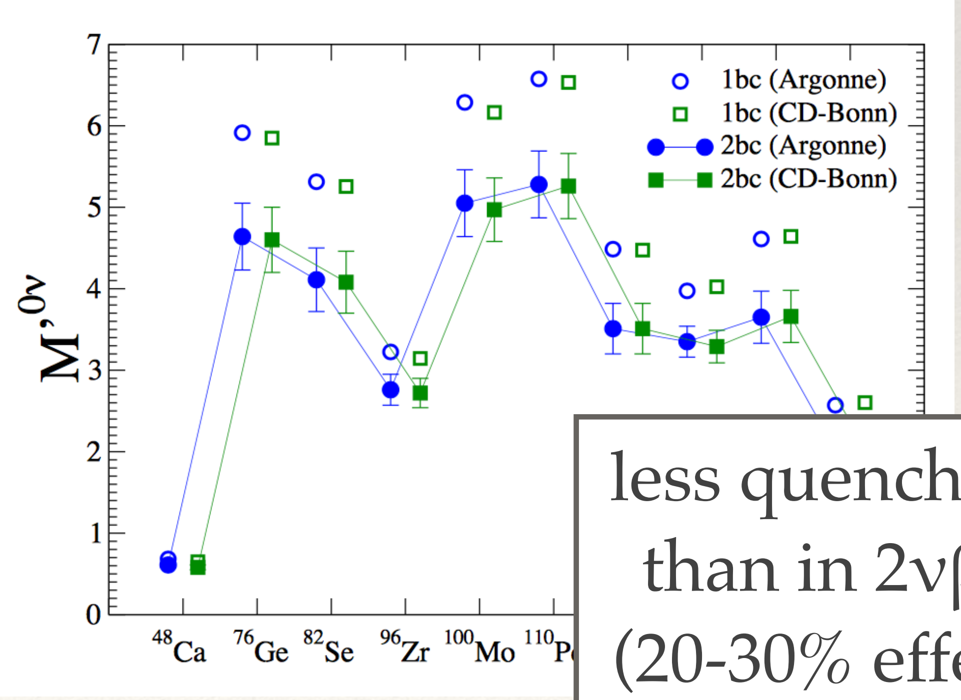


QUENCHING??

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

- fact in β and 2νββ
- truncation of model-space?
- also in 0νββ??
  - q = 10² vs. 10⁰ MeV?
  - higher multipolarities?
  - two-body currents?
  - muon capture?
  - SM vs. QRPA

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



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

Why look for Lepton Number Violation?

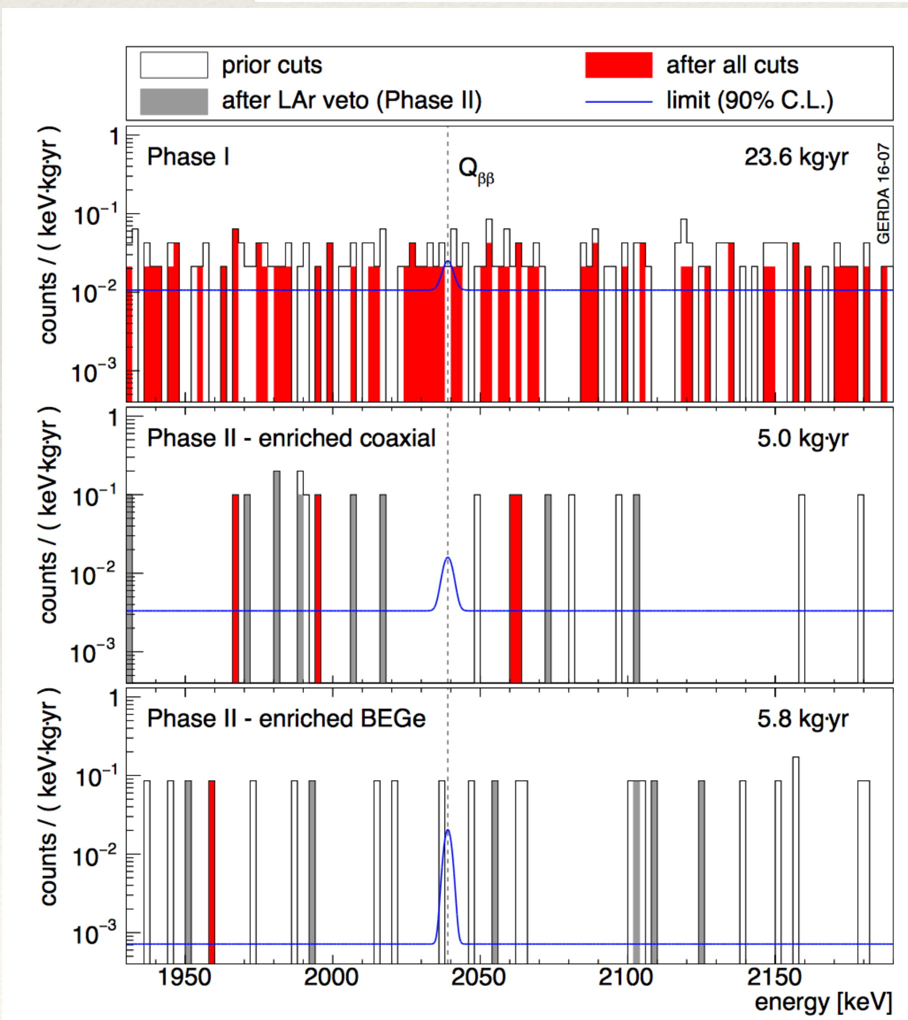
- L and B accidentally conserved in SM
- $\mathcal{L} = \mathcal{L}_{SM} + 1/\Lambda\ \mathcal{L}_5 + 1/\Lambda^2\ \mathcal{L}_6 + \ldots$,with $\mathcal{L}_5 = L^c\phi\ \phi L \to m_\nu\ \nu_L{}^c\ \nu_L$
- Baryogenesis: B is violated
- B, L often connected in GUTs
- GUTs have seesaw and Majoranas
-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

Lepton Number as important as Baryon Number

Neutrinoless Double Beta Decay

$$(T^{0\nu}_{1/2})^{-1} \propto \begin{cases} a\, M\, \varepsilon\, t & \text{without background} \\ a\, \varepsilon \sqrt{\dfrac{M\, t}{B\, \Delta E}} & \text{with background} \end{cases}$$

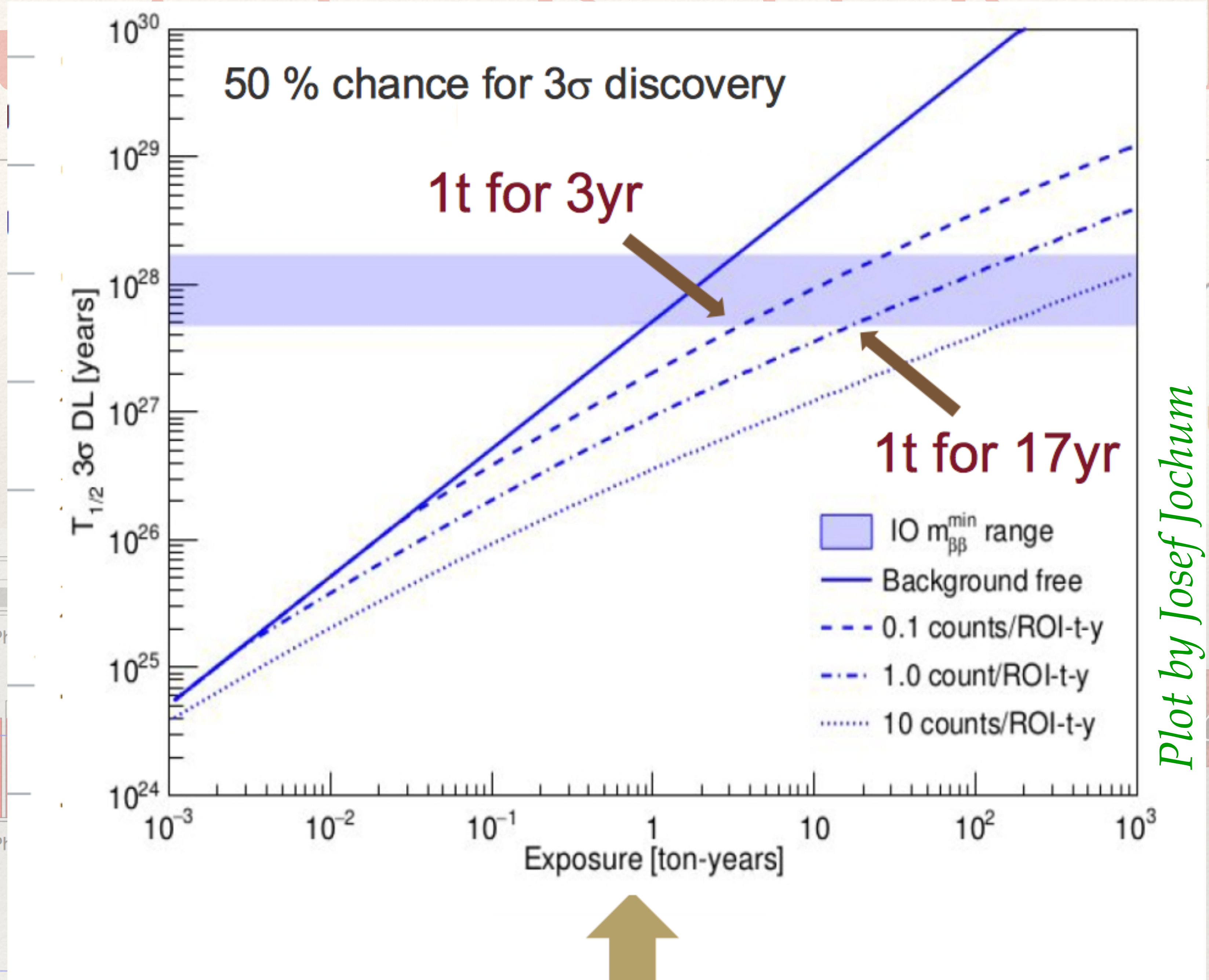
GERDA, 1703.00570, Nature



first background free result

current limits: $T_{1/2} \gtrsim 10^{26}$ years
with exposure of about 100 kg • years

Ne… Decay



Plot by Josef Jochum

low background essential for discovery potential

GERDA, 1703.00570, Nature

…round

…und

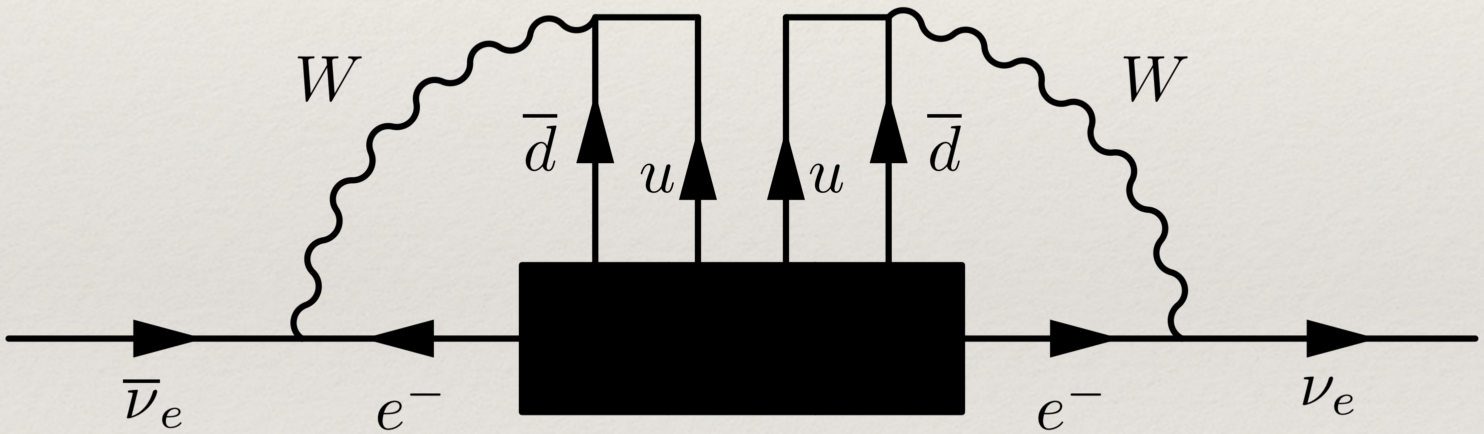
…ree result

… 10^{26} years

with exposure of about 100 kg · years

Black Box Theorem

- Whatever the mechanism, observation of 0νββ implies Majorana neutrinos *(Schechter-Valle, '82)*

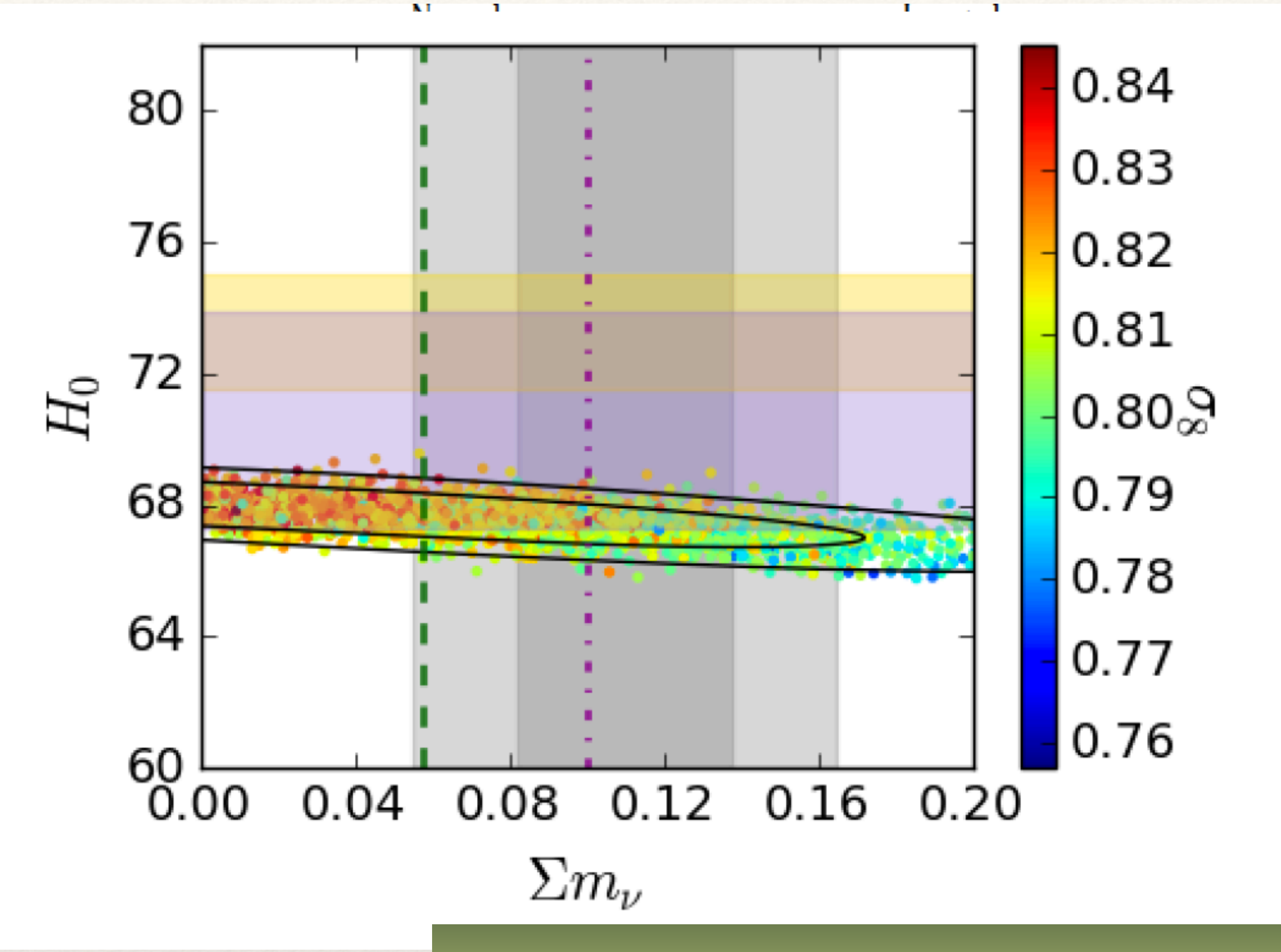


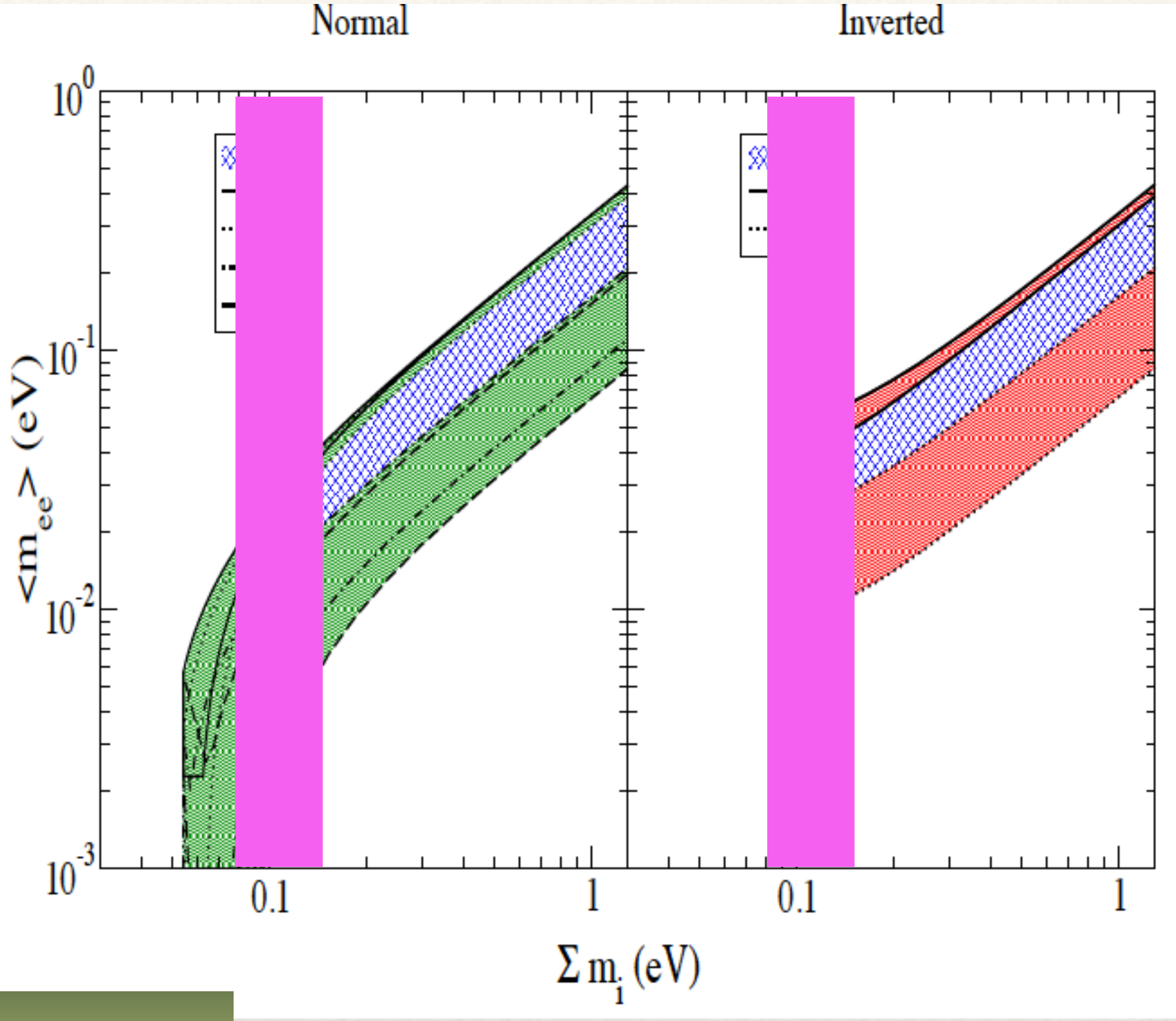
- is 4-loop diagram ⇒ tiny mass *(Dürr, Lindner, Merle, 1105.0901)*

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 $\not{R}$	$\frac{\left\|\lambda'^2_{111}\right\|}{\Lambda^5_{\rm SUSY}}$ $\Lambda_{\rm SUSY} = f(m_{\tilde{g}}, m_{\tilde{u}_L}, m_{\tilde{d}_R}, m_{\chi_i})$	7×10^{-18} GeV^{-5}	collider, flavor
long-range $\not{R}$	$\left\|\sin 2\theta^b\, \lambda'_{131}\, \lambda'_{113} \left(\frac{1}{m^2_{\tilde{b}_1}} - \frac{1}{m^2_{\tilde{b}_2}}\right)\right\|$ $\sim \frac{G_F}{q} m_b \frac{\left\|\lambda'_{131}\, \lambda'_{113}\right\|}{\Lambda^3_{\rm SUSY}}$	2×10^{-13} GeV^{-2} 1×10^{-14} GeV^{-3}	flavor, collider
Majorons	$\left\|\langle g_\chi\rangle\right\|$ or $\left\|\langle g_\chi\rangle\right\|^2$	$10^{-4}\ldots1$	spectrum, cosmology

Neutrino Mass Observables

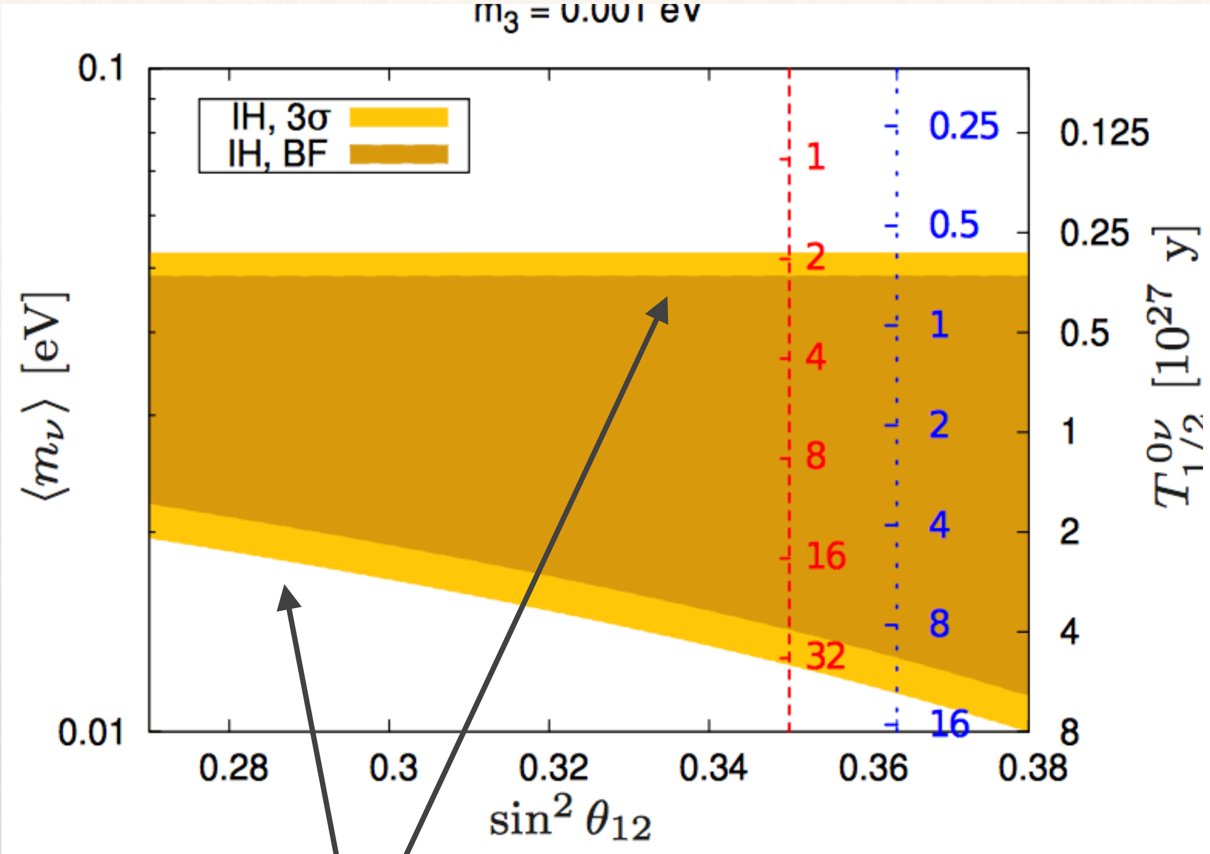


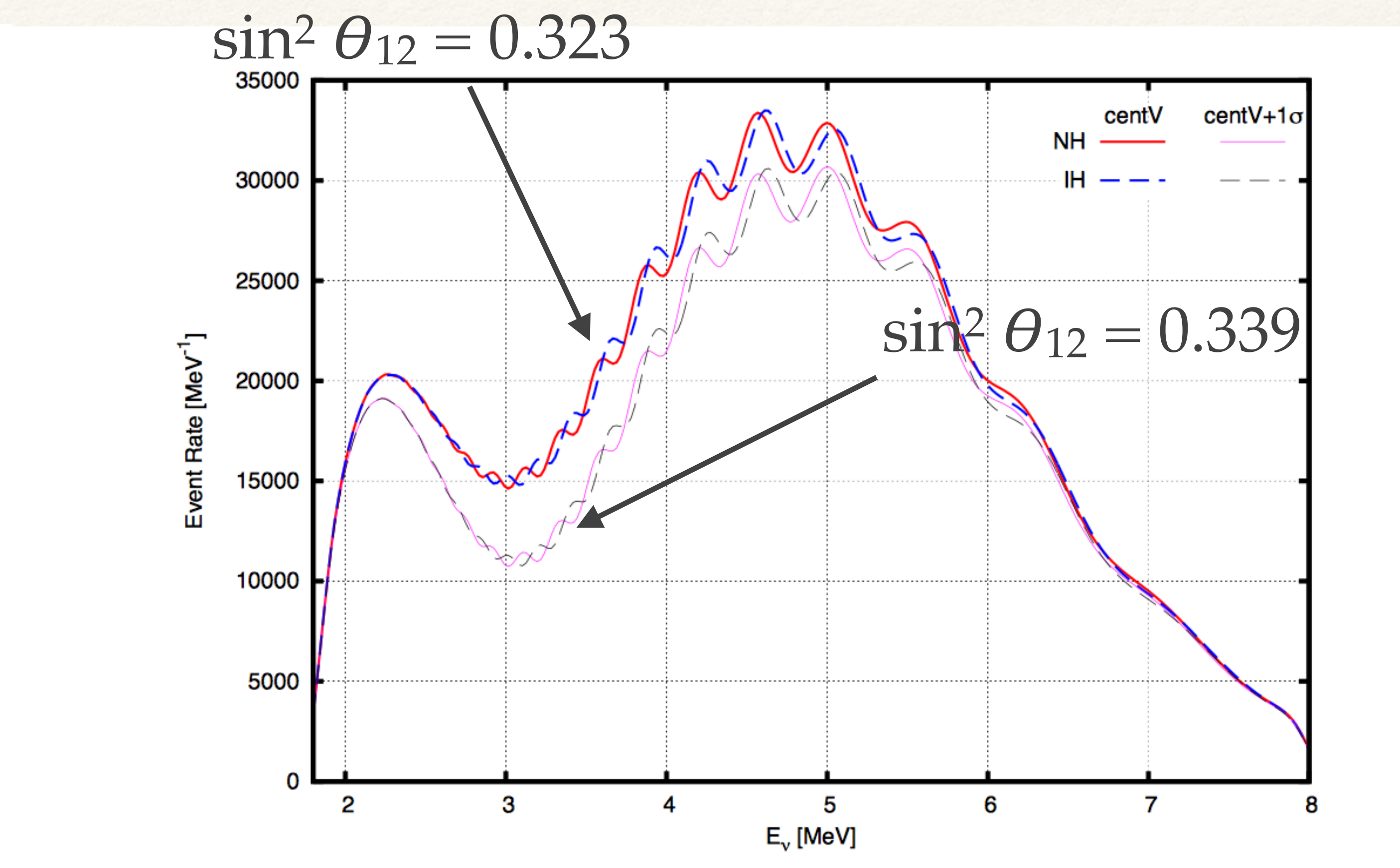


0.11 ± 0.03 eV from 1711.05210

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





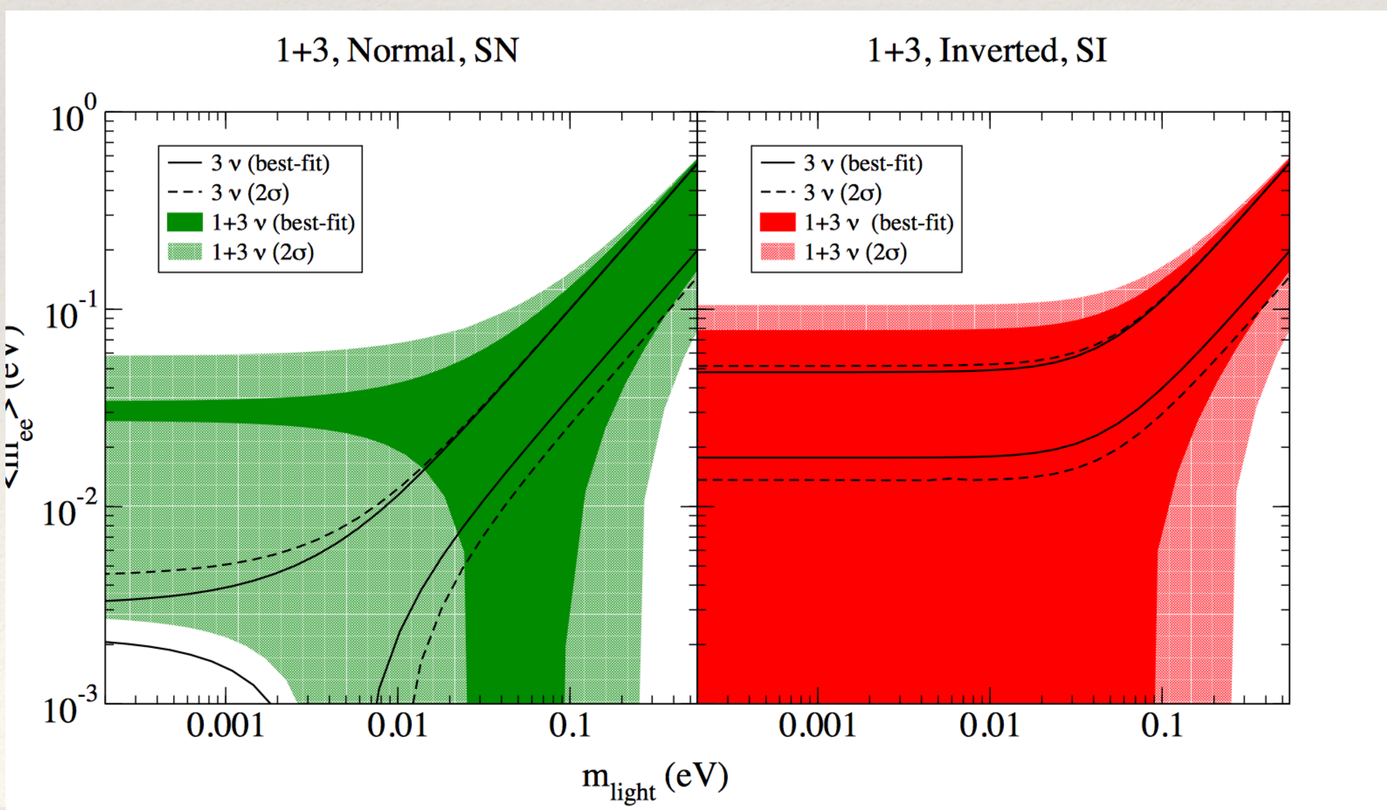
Nature gives us two scales

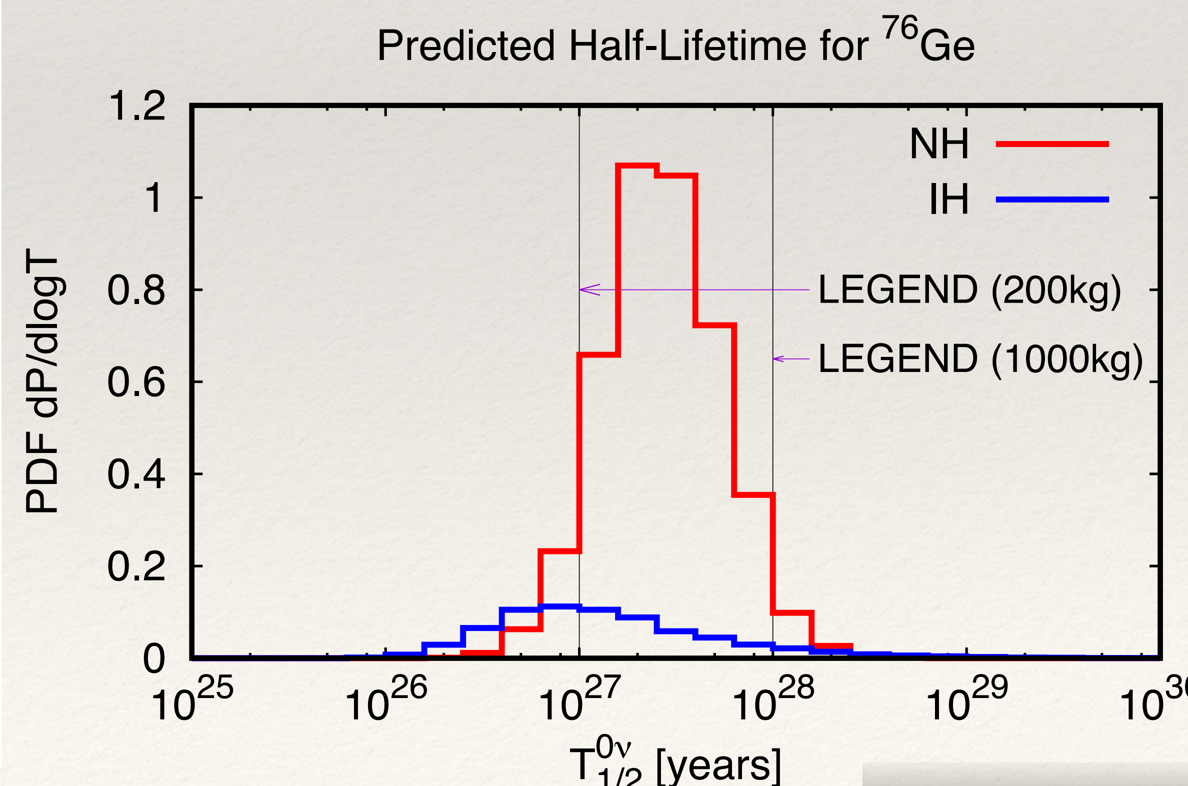
$$\langle m \rangle^{\rm IH}_{\rm min} \propto \cos 2\theta_{12}$$
$$= 1 - 2\sin^2\theta_{12}$$

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 $\Delta m^2 \simeq \text{eV}^2$ 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!





Origin of Neutrino Mass

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

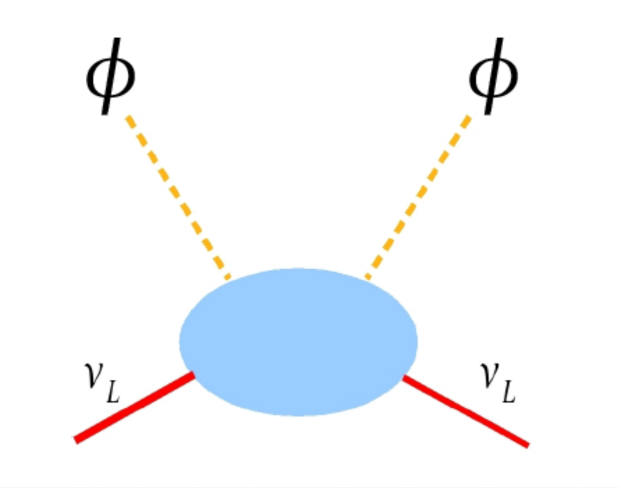
$$L\, \Phi\, N_R \to m_D\, \nu_L\, N_R$$

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

$$M_R\, N_R\, N_R$$

- in total Majorana mass for SM neutrinos:

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



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 … mass

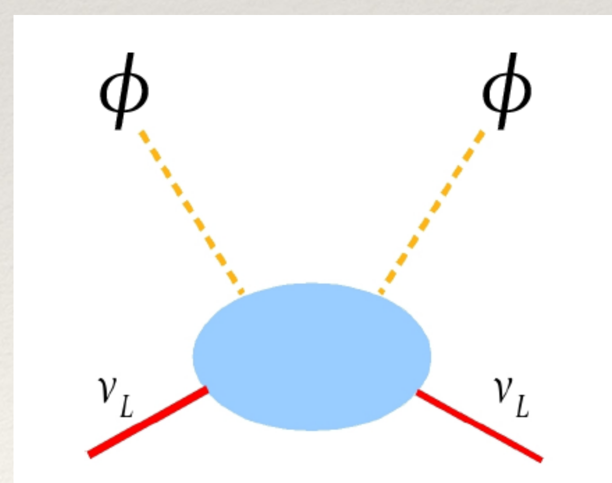
  $$\ldots N_R \to m_D\, \nu_L N_R$$

- Gauge invariance allows Majorana mass

  $$M_R\, N_R\, N_R$$

- in total Majorana mass for SM neutrinos:

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



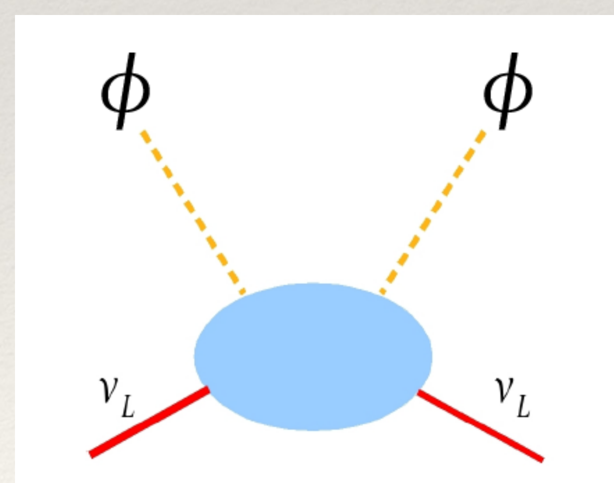
m_ν inverse proportional to scale of origin!

Origin of Neutrino Mass

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

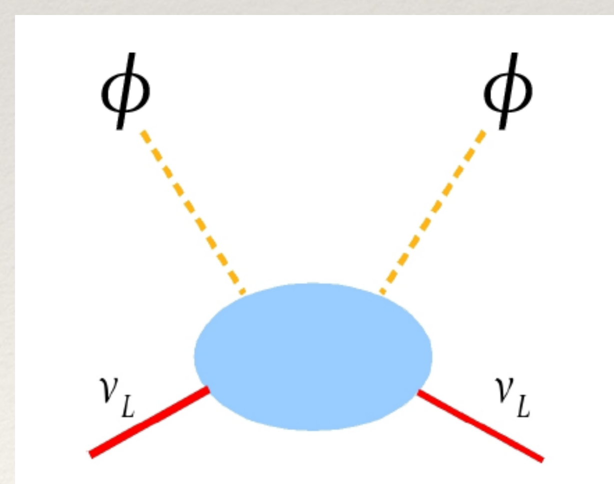
Origin of Neutrino Mass

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

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

New energy scale beyond SM

New concept: lepton number violation



m_ν inverse proportional to scale of origin!

Origin of Neutrino Mass

- Most straightforward possibility: add N_R and obtain Dir...

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

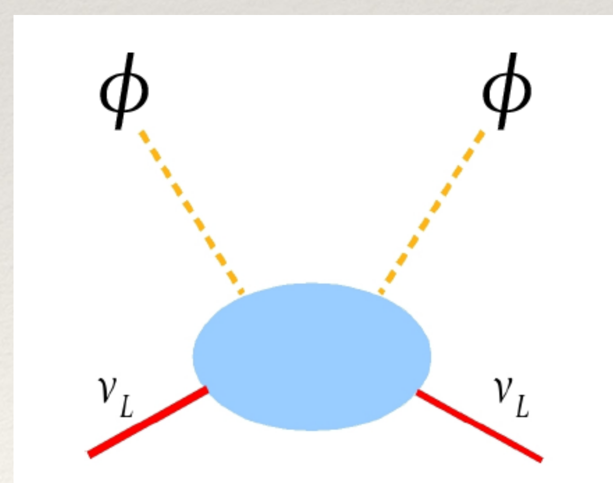
- Gauge invariance allows Majorana mas...

$$M_R\, N_R \ldots$$

- in total Majorana mas... ...utrinos:

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

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



m_ν inverse proportional to scale of origin!

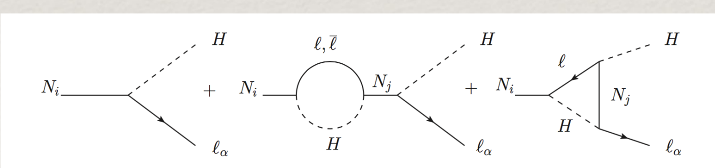
Type I Seesaw $m_\nu = m_D^2/M_N \propto y^2/M_N$

actually, does neither fix m_ν nor m_D nor M_R

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

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

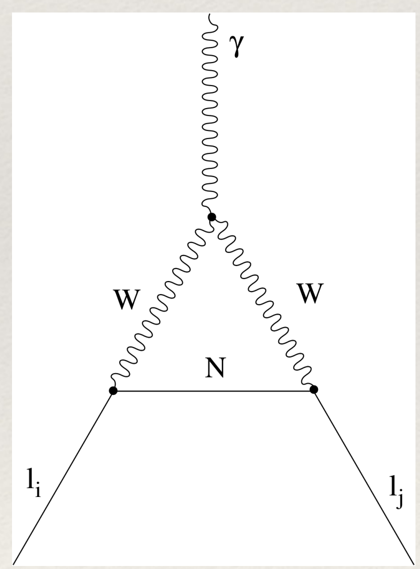
$N_R \to L\, \Phi$ | $L_\alpha \to N_R\, \Phi \to L_\beta$ | $\Phi \to L\, N_R \to \Phi$



Leptogenesis

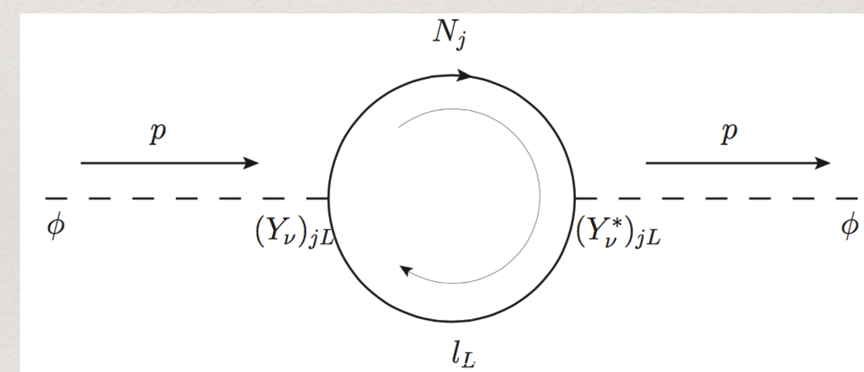
$Y_B \propto Im(y^2)$

Talks by Deppisch, Dev



Lepton Flavor Violation

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

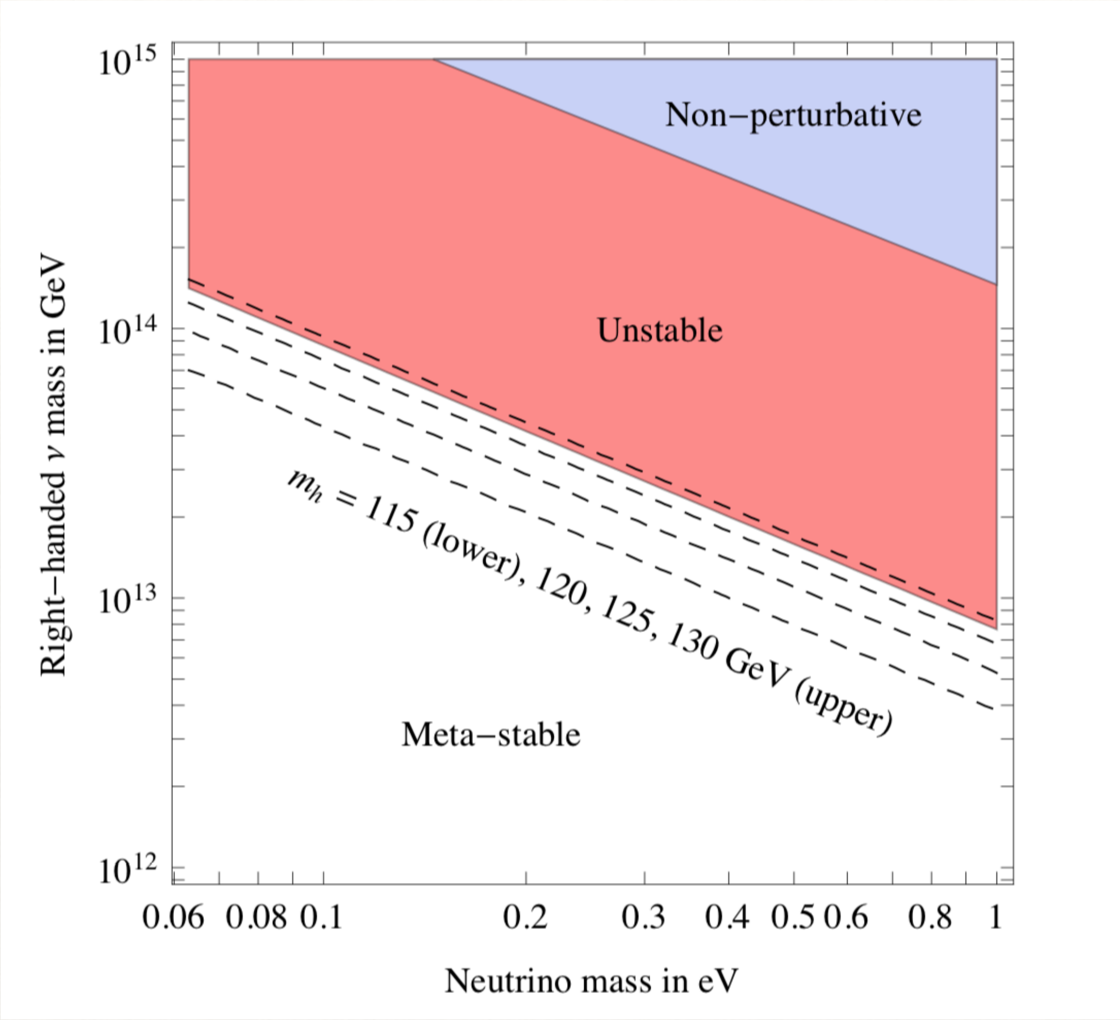


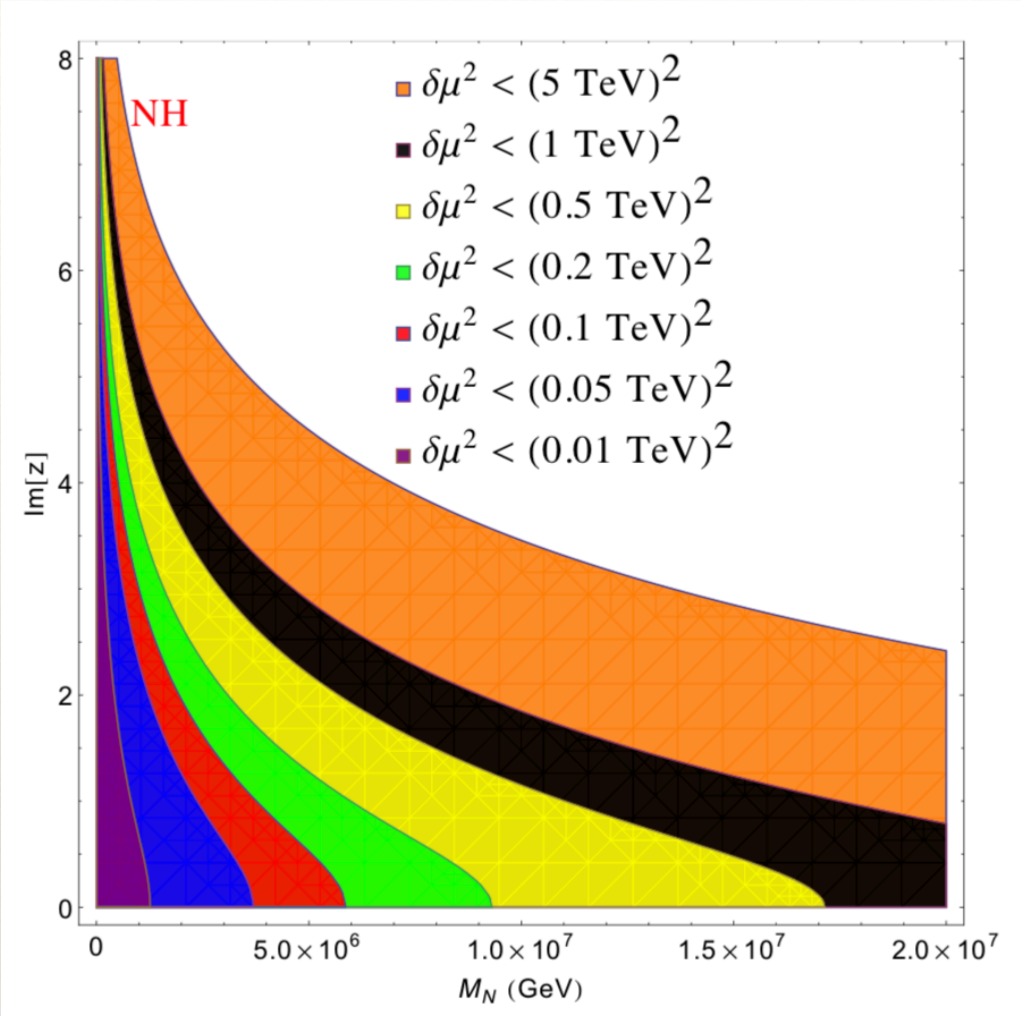
Vacuum stability, naturalness

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

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

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



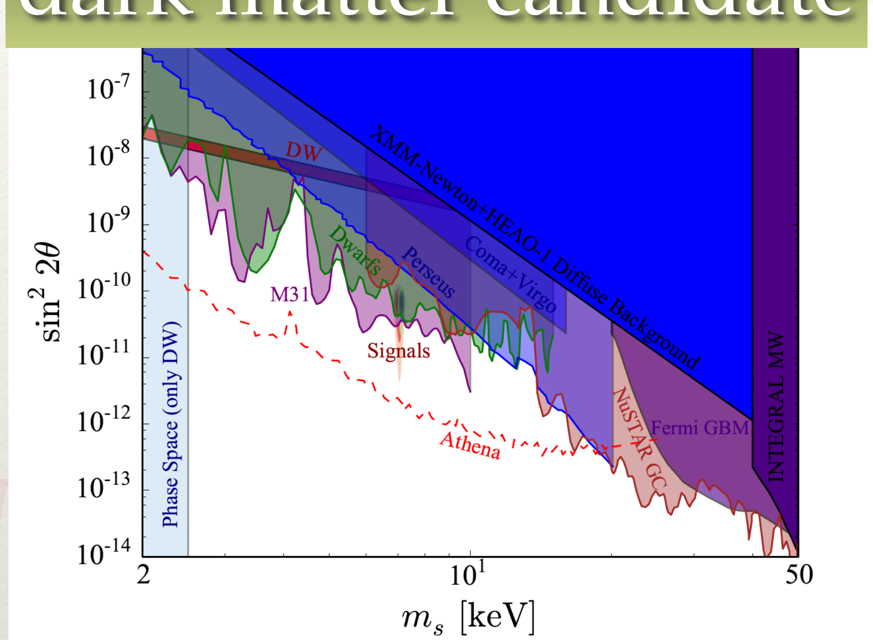


Elias-Miro et al., 1112.3022

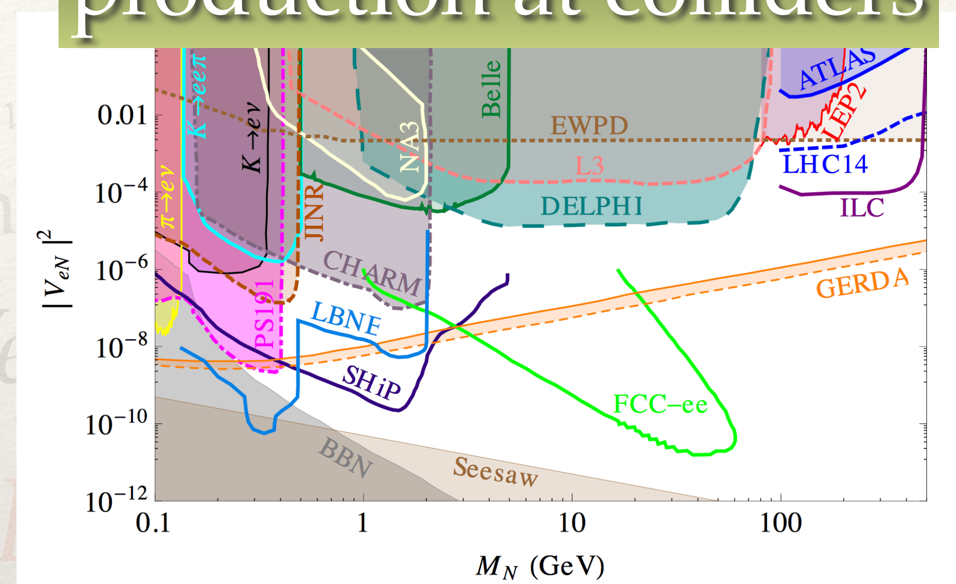
Bambhaniya et al., 1611.03827

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

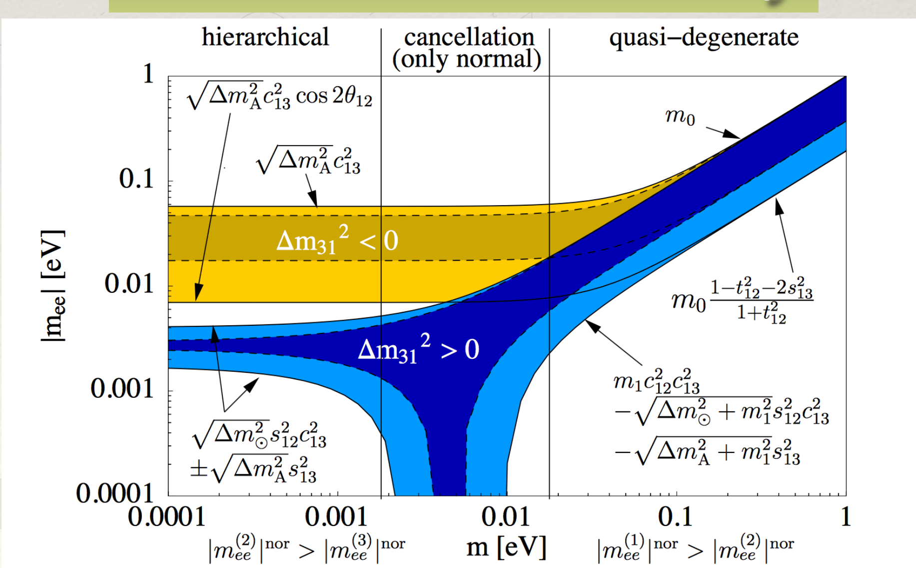
dark matter candidate



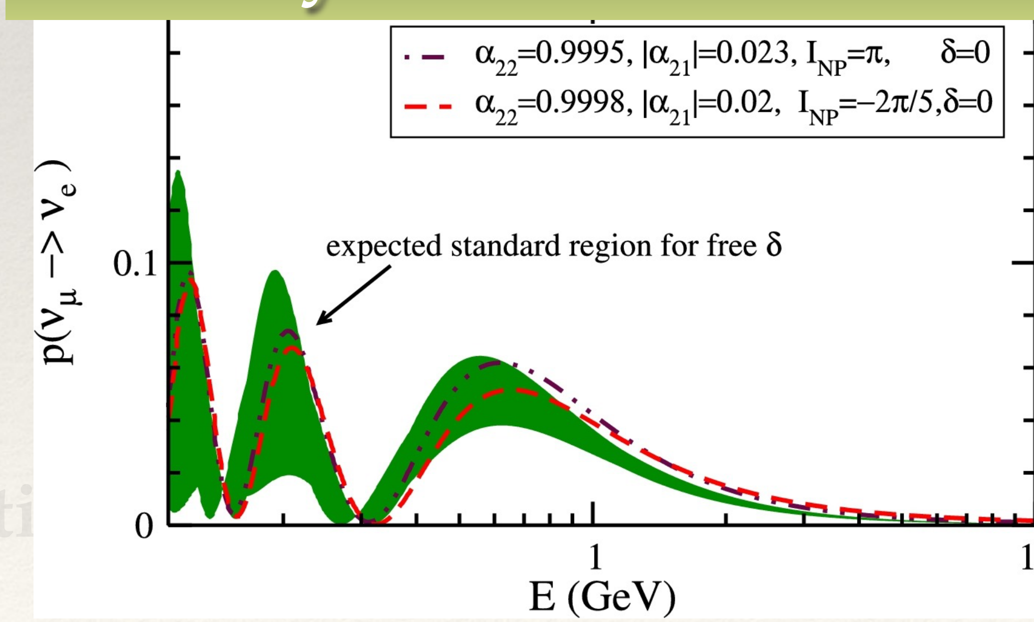
production at colliders



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

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

plus radiative mechanisms

plus higher dimensional operators

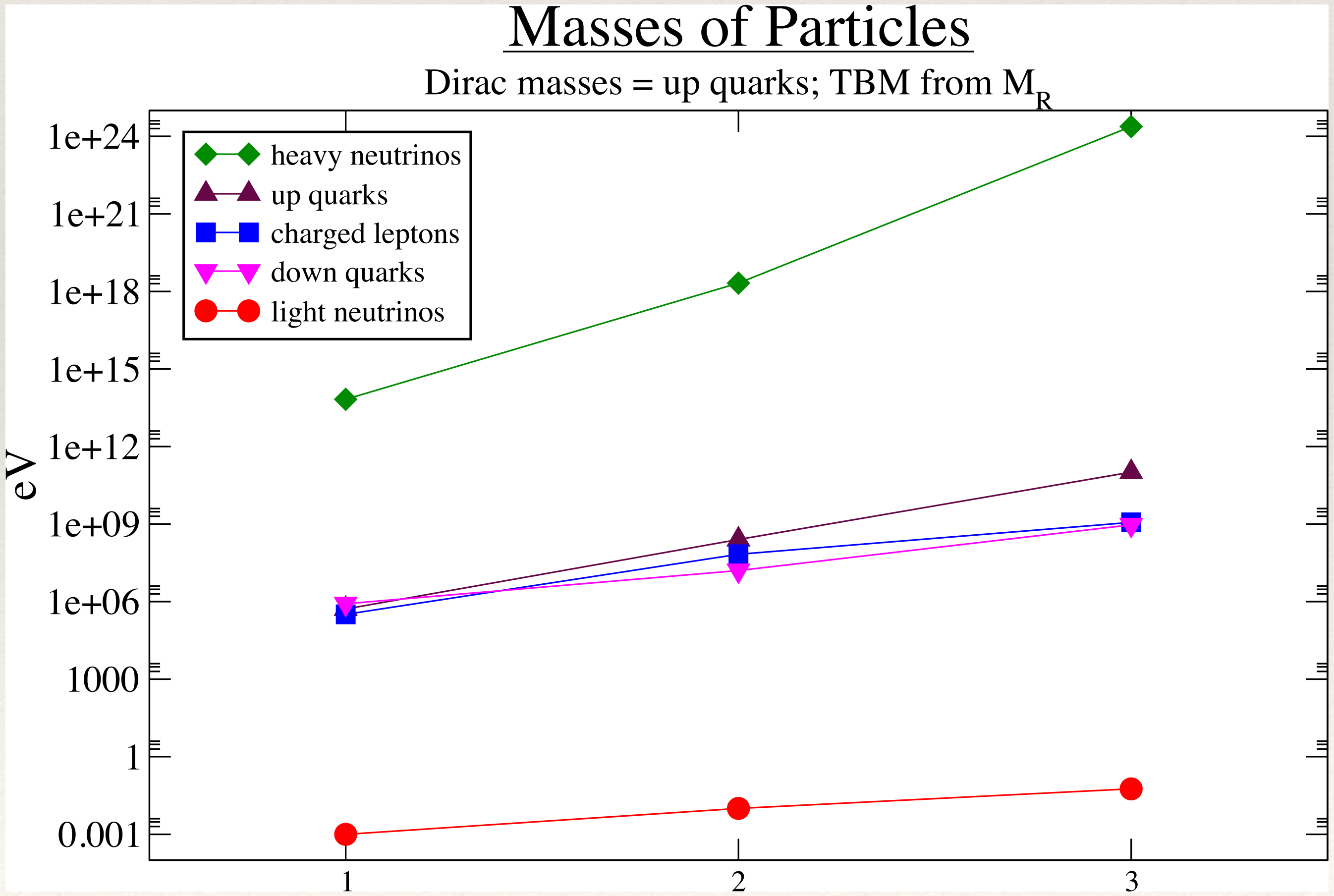
plus extra dimensional

plus plus plus

Seesaw Mechanism

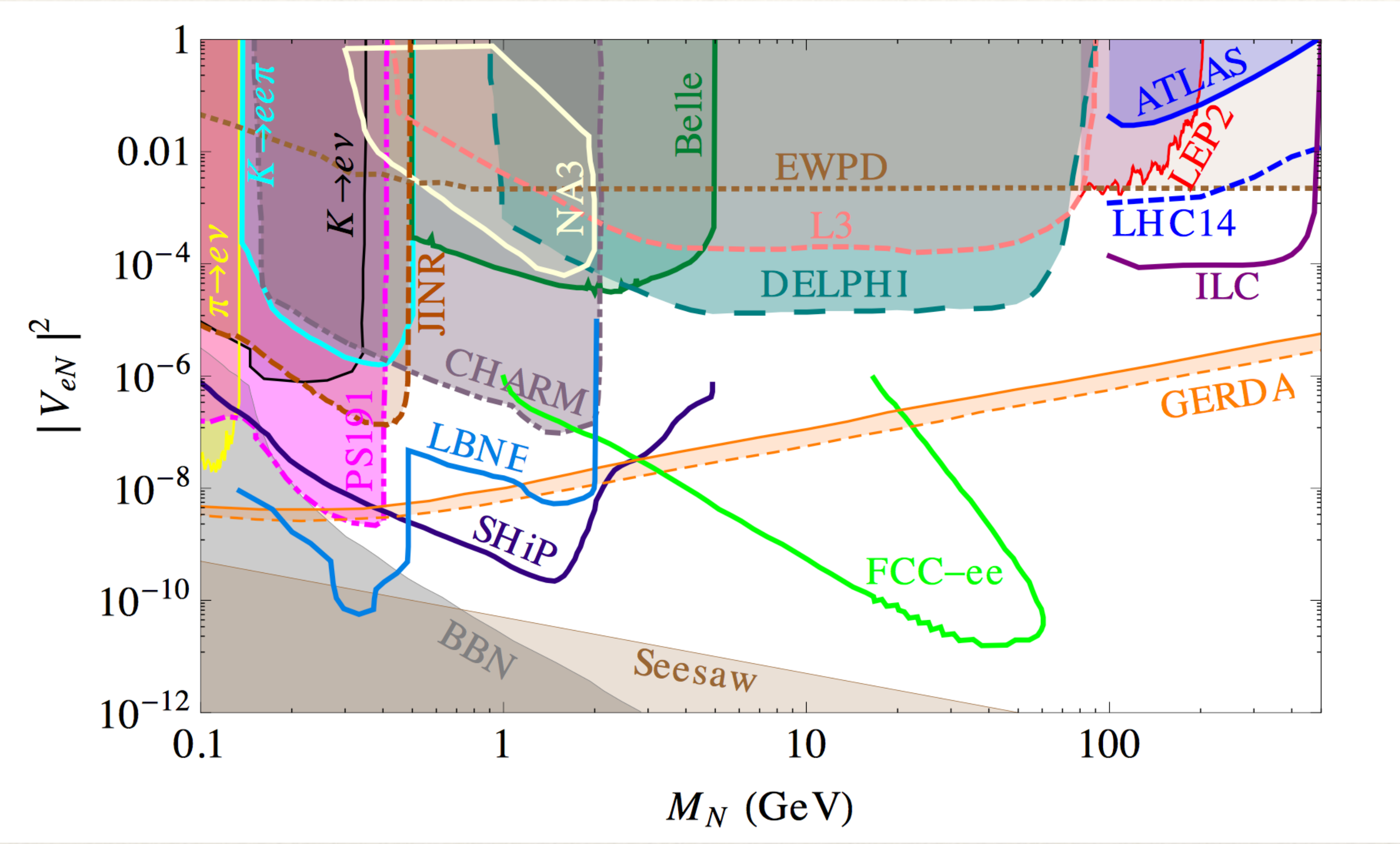
- suppresses neutrino mass *for each generation* ($m_u \simeq m_d$ and $m_b \sim m_t$ vs. $m_{\nu_e} \ll m_e$ and $m_{\nu_\tau} \ll m_\tau$)
- little hierarchy in m_ν, strong quark-like hierarchy in m_D

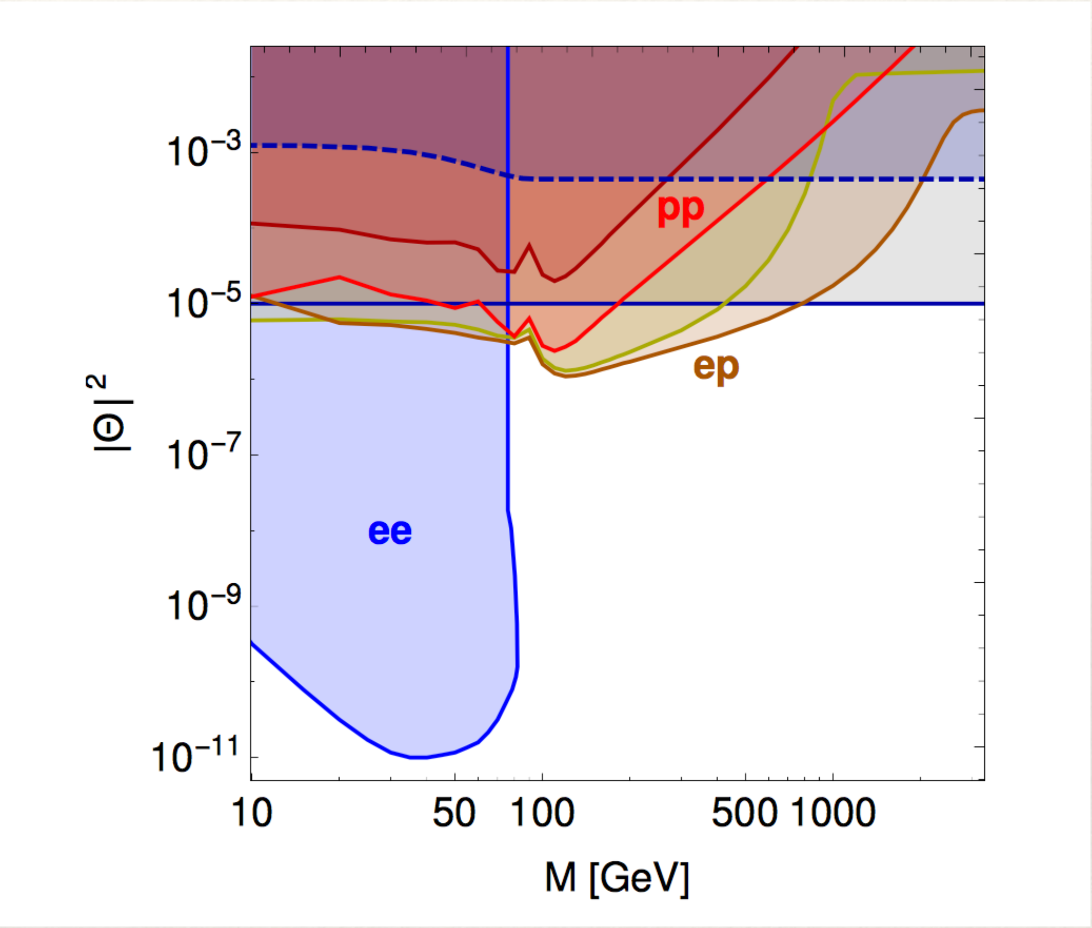
$\Rightarrow$ stronger hierarchy in M_R?



Limits on Heavy Neutrinos

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





Deppisch, Dev, Pilaftsis, 1502.06541

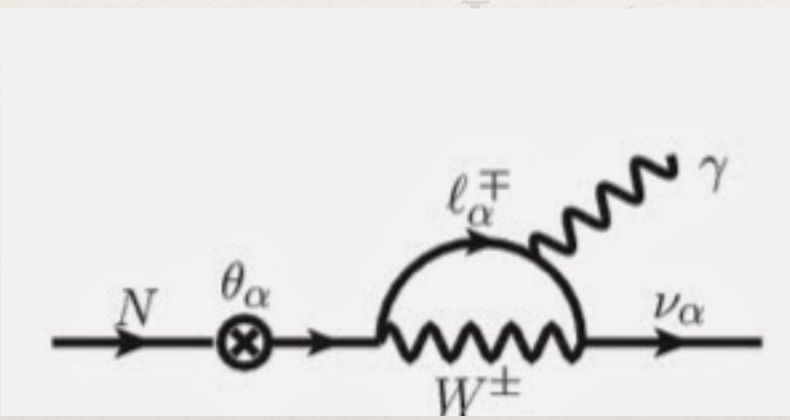
Antusch, Cazzato, Fischer, 1612.02728

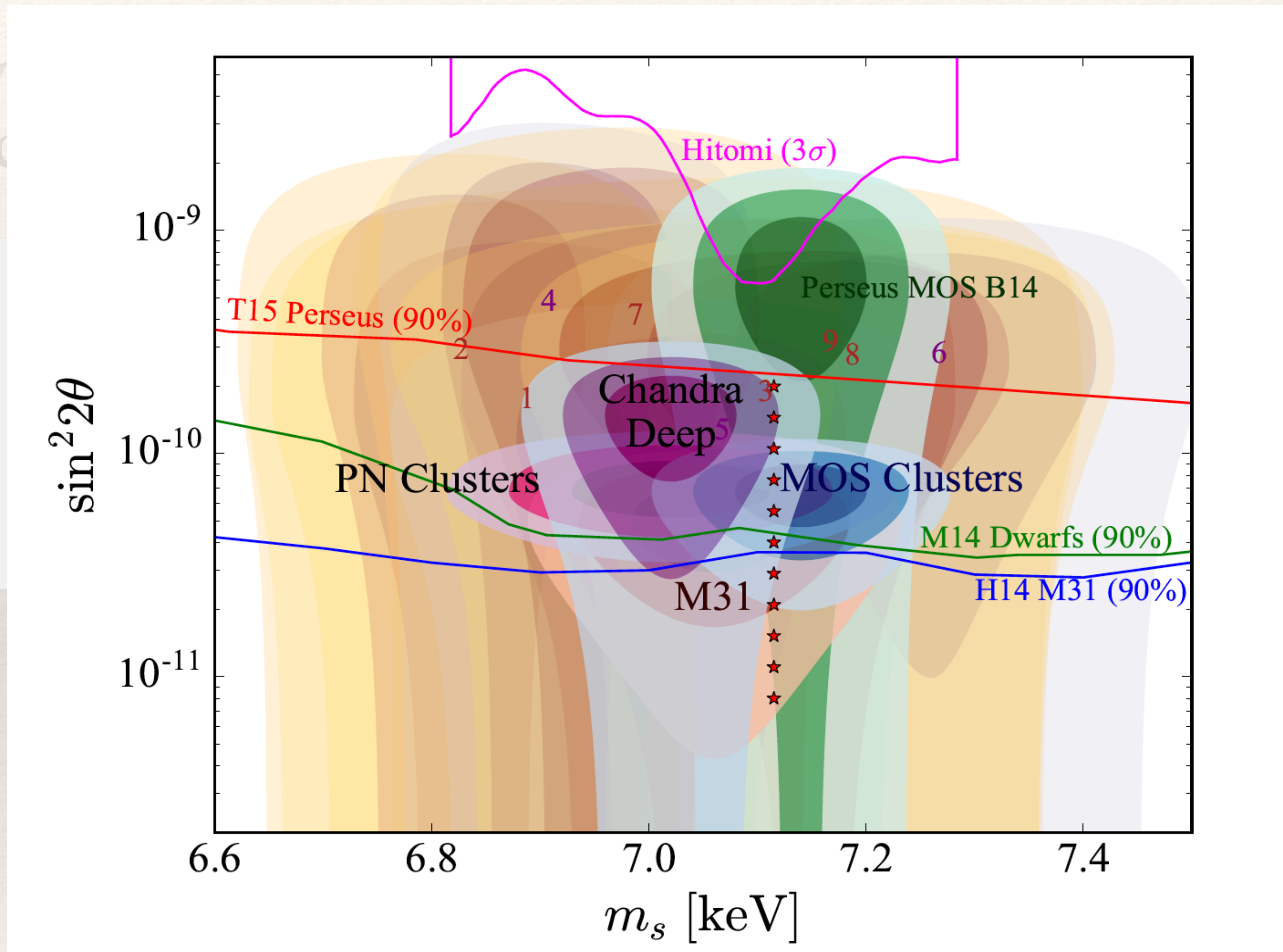
peak searches, kink searches, displaced vertices, LNV decays,…

see also Atre et al., 0901.3589

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

plus: provides a DM candidate





Abazajian , 1705.01837

Leptogenesis

Lepton Flavor Violation

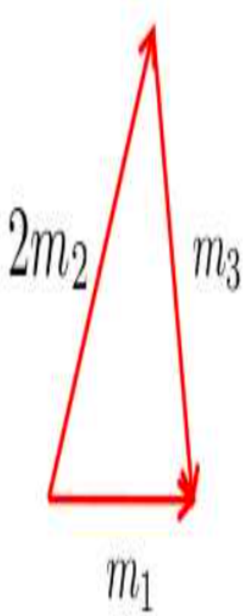
Vacuum stability, naturalness

Flavor Symmetries

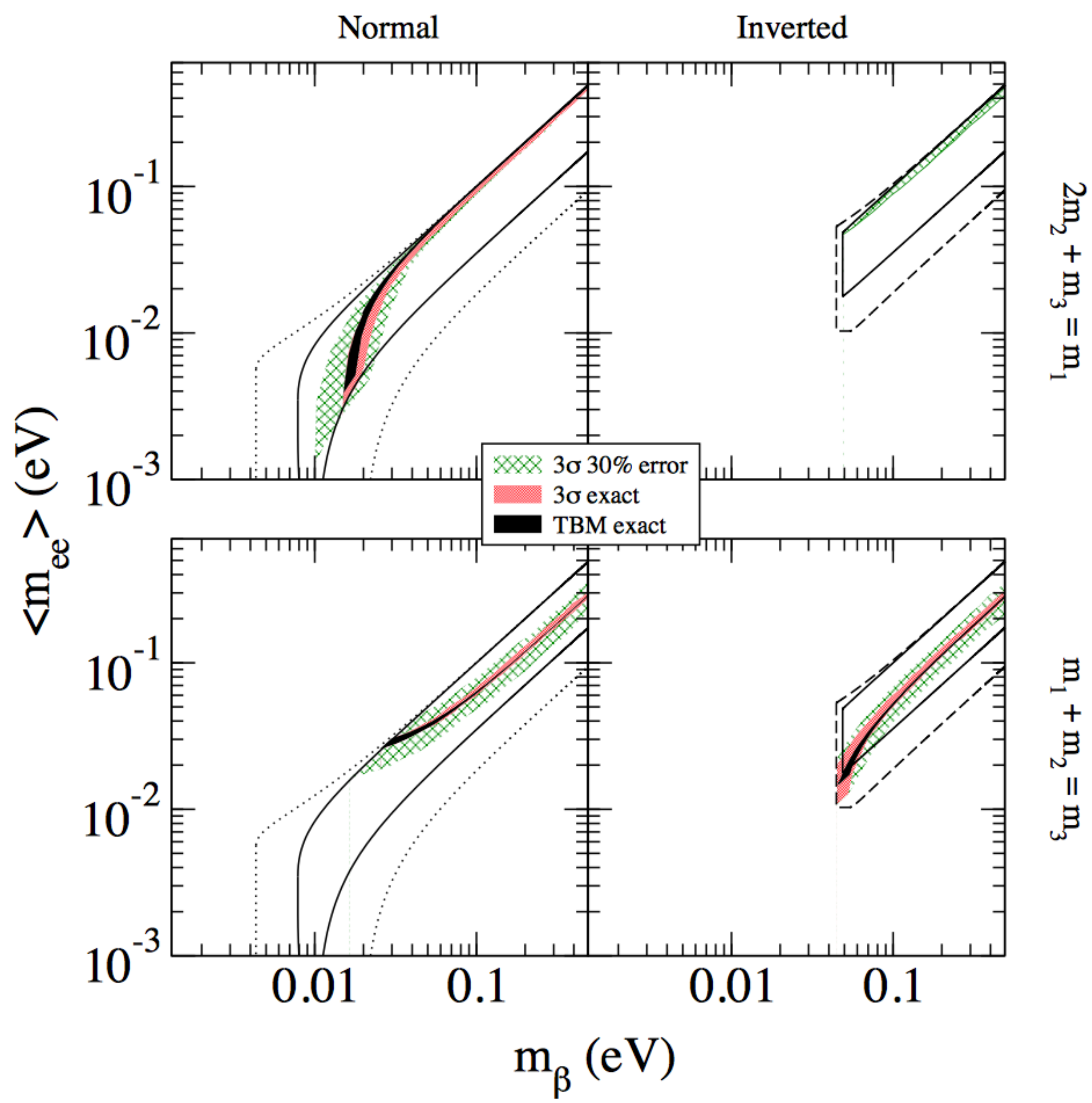
- Can rule out models by:
  - correlations between angles and phases
  - neutrino mass sum-rules, e.g. $m_1 + m_2\, e^{i\alpha} = m_3\, e^{i\beta}$
  - LFV if within SUSY or if broken at low scale
  - *minimality*
  - *robustness*
  - *compatibility with larger frameworks (LR symmetry, Pati-Salam, SU(5),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

Flavor Symmetries

Barry, WR, 1007.5217



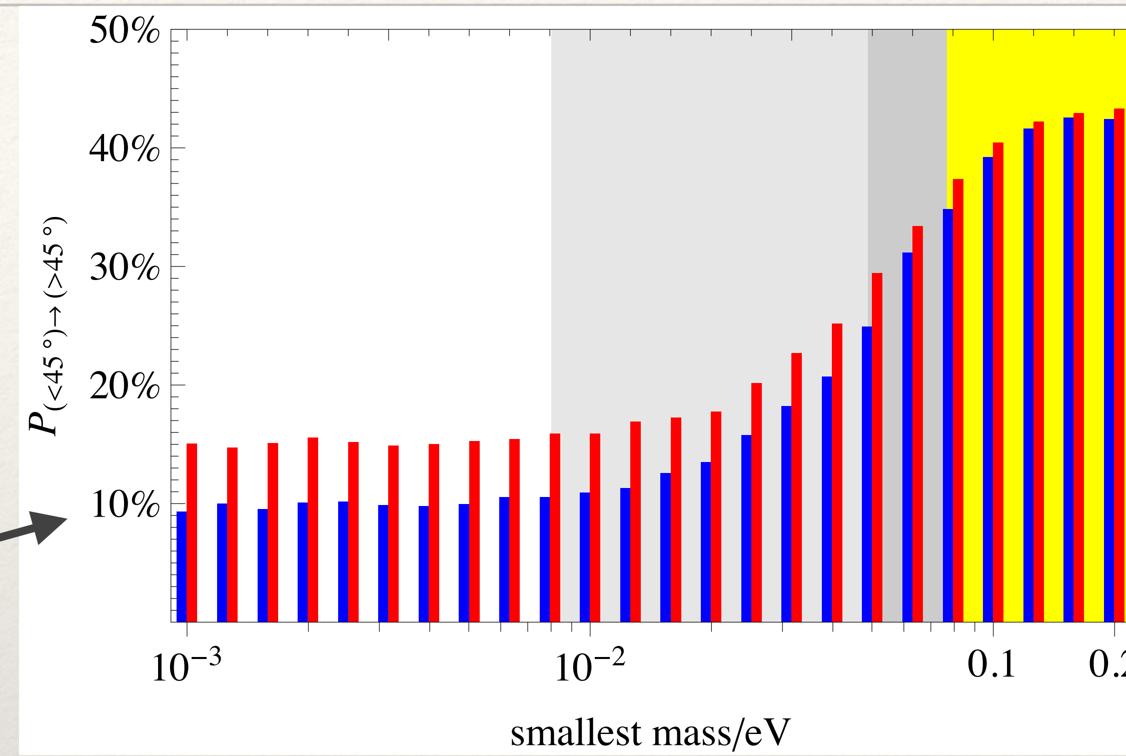
Sum-rule	Flavour symmetry
$2m_2 + m_3 = m_1$	$A_4, T', (S_4)$
$m_1 + m_2 = m_3$	$S_4, (A_4)$
$\frac{2}{m_2} + \frac{1}{m_3} = \frac{1}{m_1}$	A_4, T'
$\frac{1}{m_1} + \frac{1}{m_2} = \frac{1}{m_3}$	S_4



Implications

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

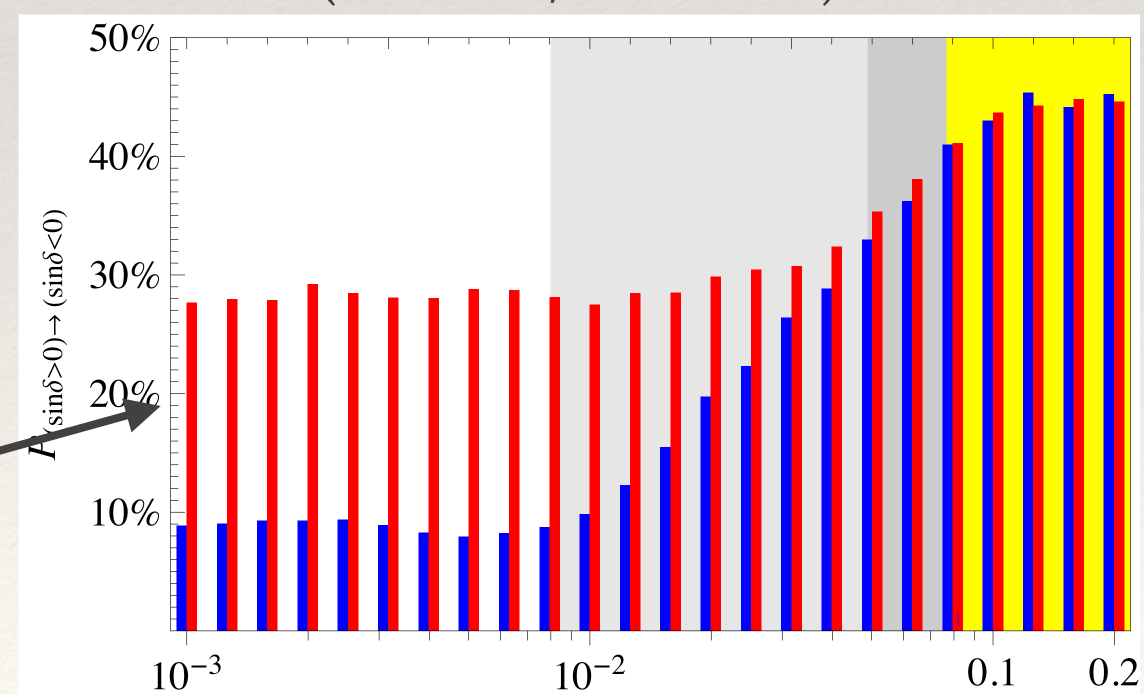
probability to change octant of θ_{23}



(normal/inverted)

- „Maximal" $\delta = 3\pi/2$?

probability to change sign of sin δ



WR, Xu, 1508.06063

Implications

❖ Maxi…

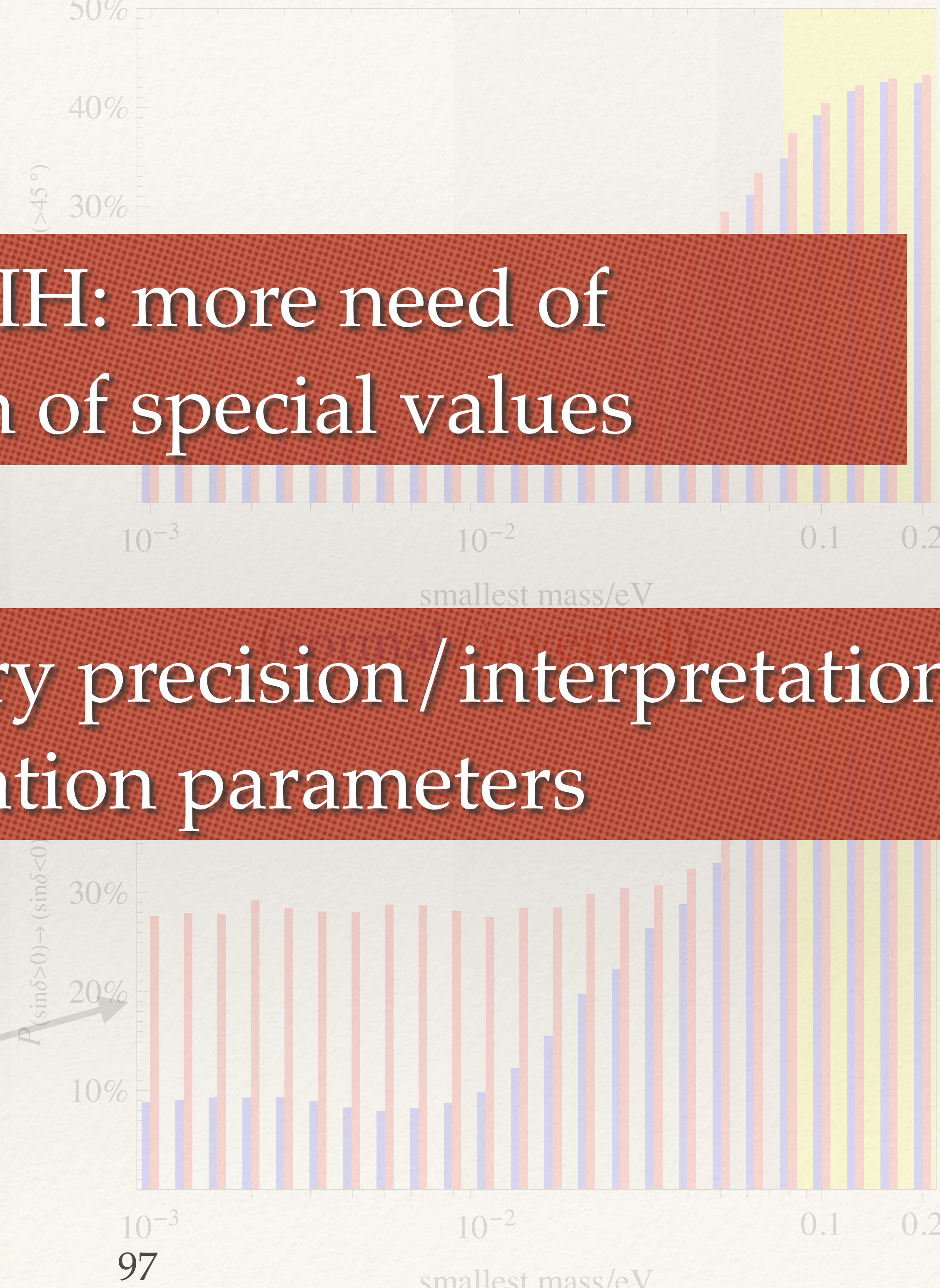
pro…
octant of θ_{23}

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

impact on necessary precision/interpretation of oscillation parameters

❖ „Maximal“ $\delta = 3\pi/2$?

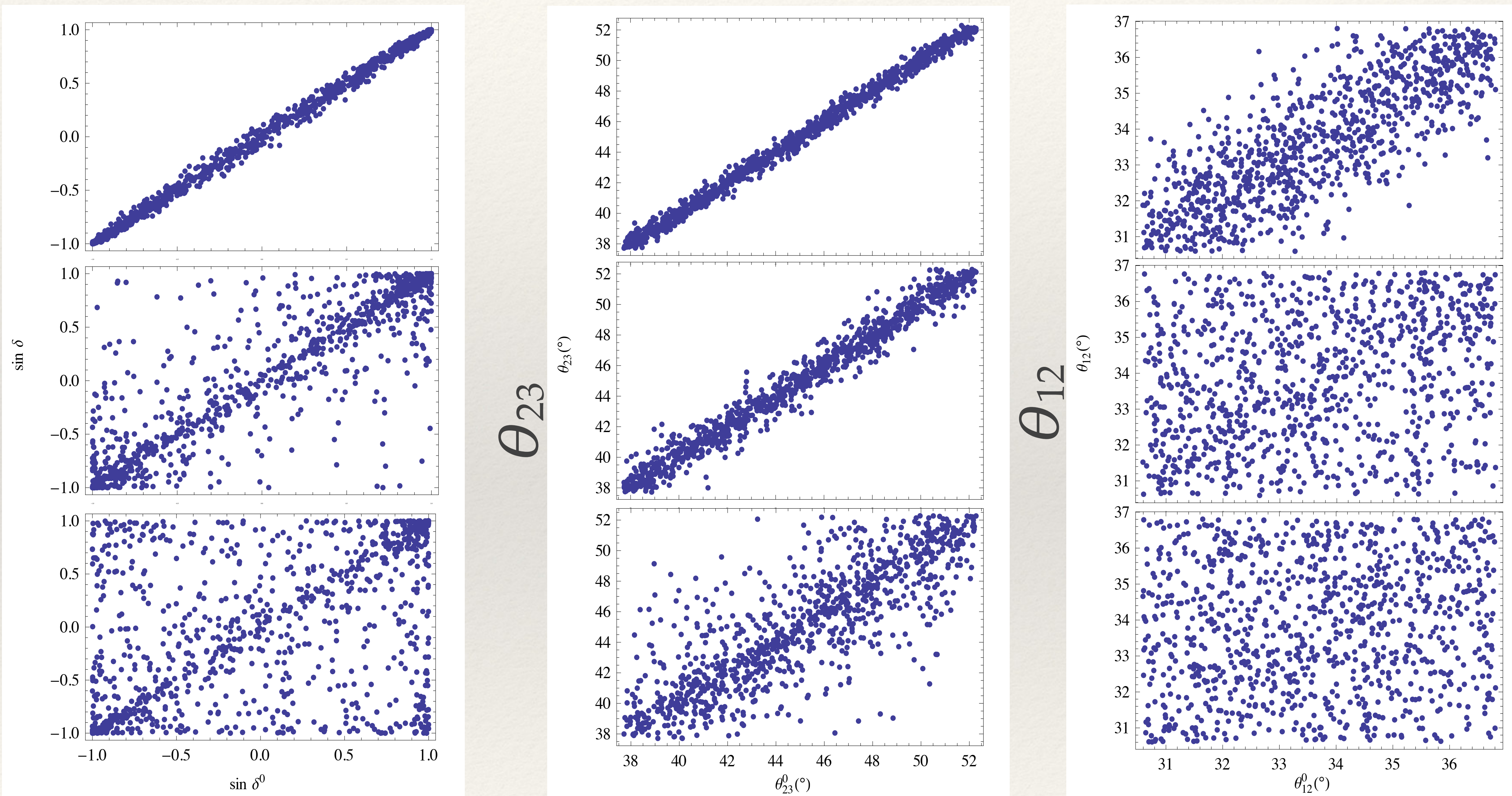
probability to change sign of sin δ



WR, Xu, 1508.06063

Perturbations

smallest mass:



sin δ | θ_{23} | θ_{12}

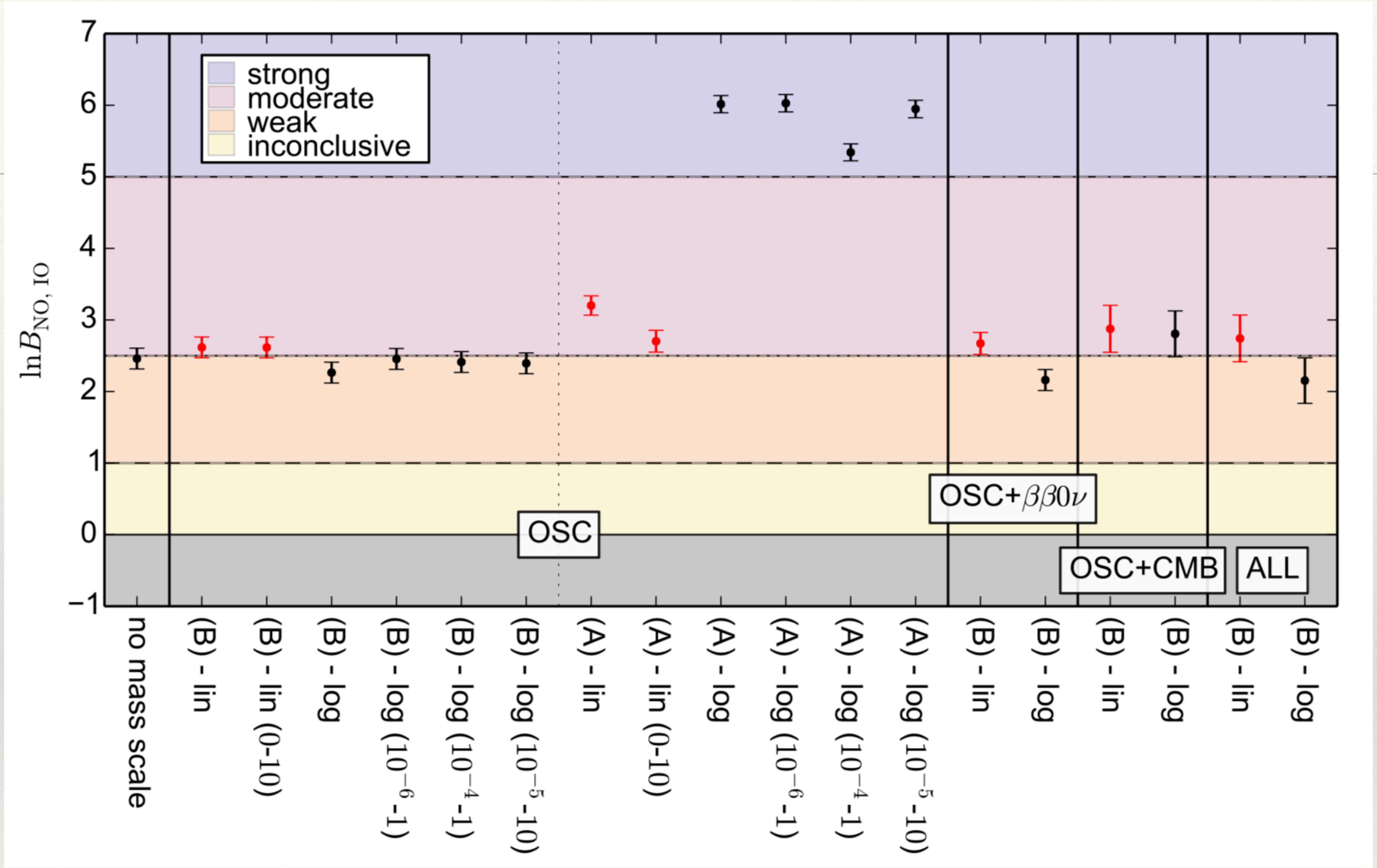
0.001 eV

0.04 eV

0.1 eV

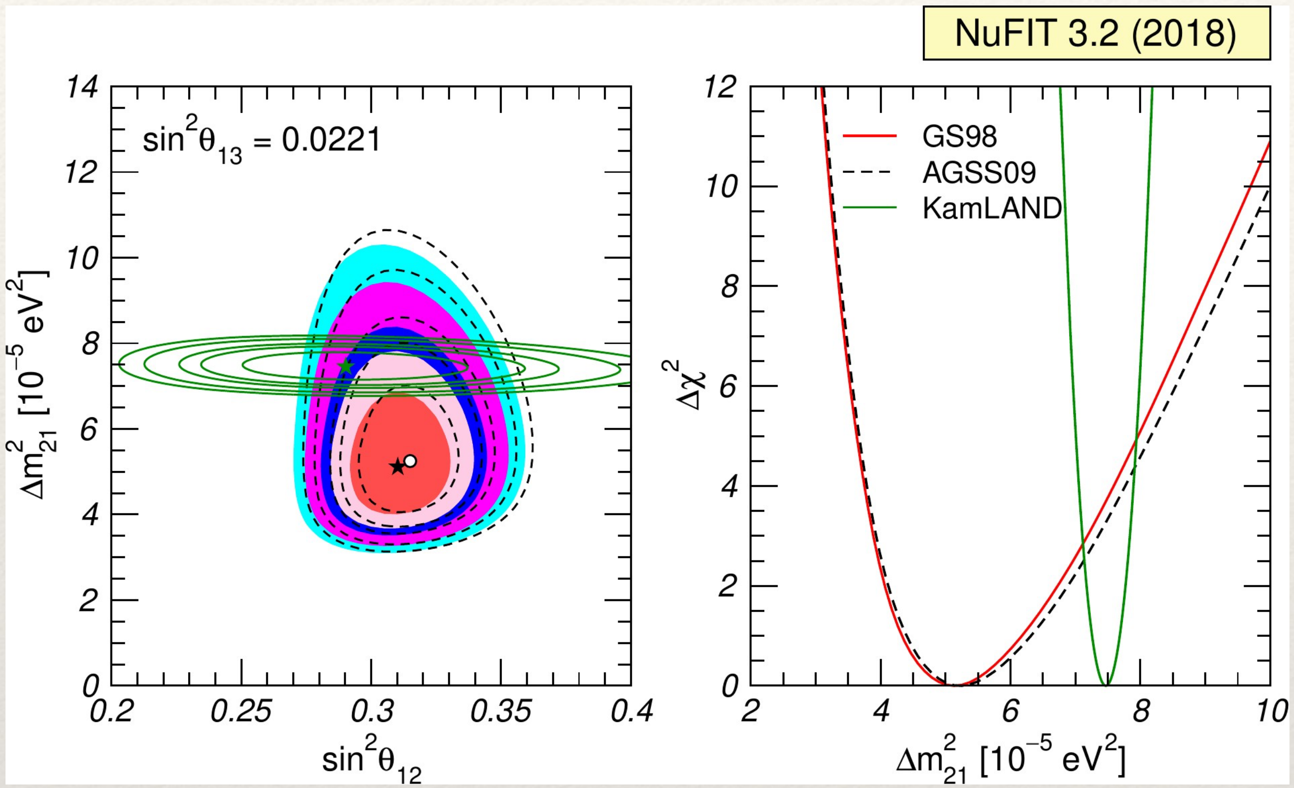
sin δ^0 | $\theta_{23}{}^0$ | $\theta_{12}{}^0$

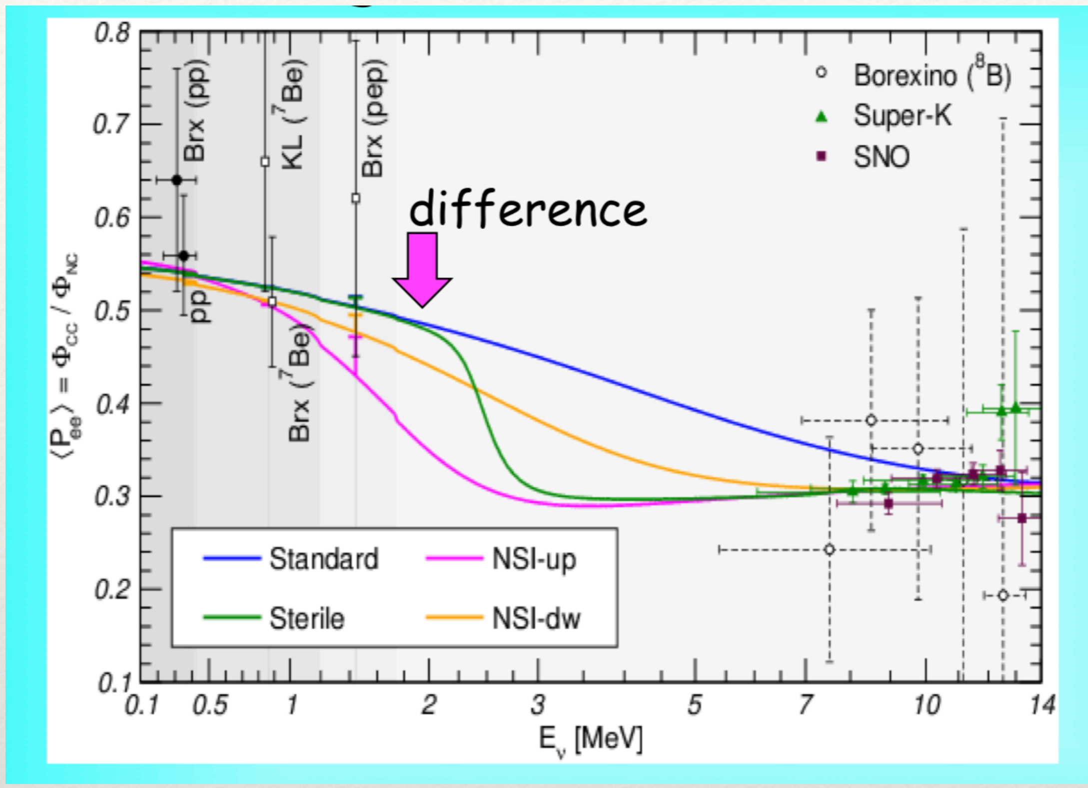
WR, Xu, 1508.06063



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)

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:

[in units of $10^{-5} \tan^2\beta$]

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

mass scale and ordering helpful

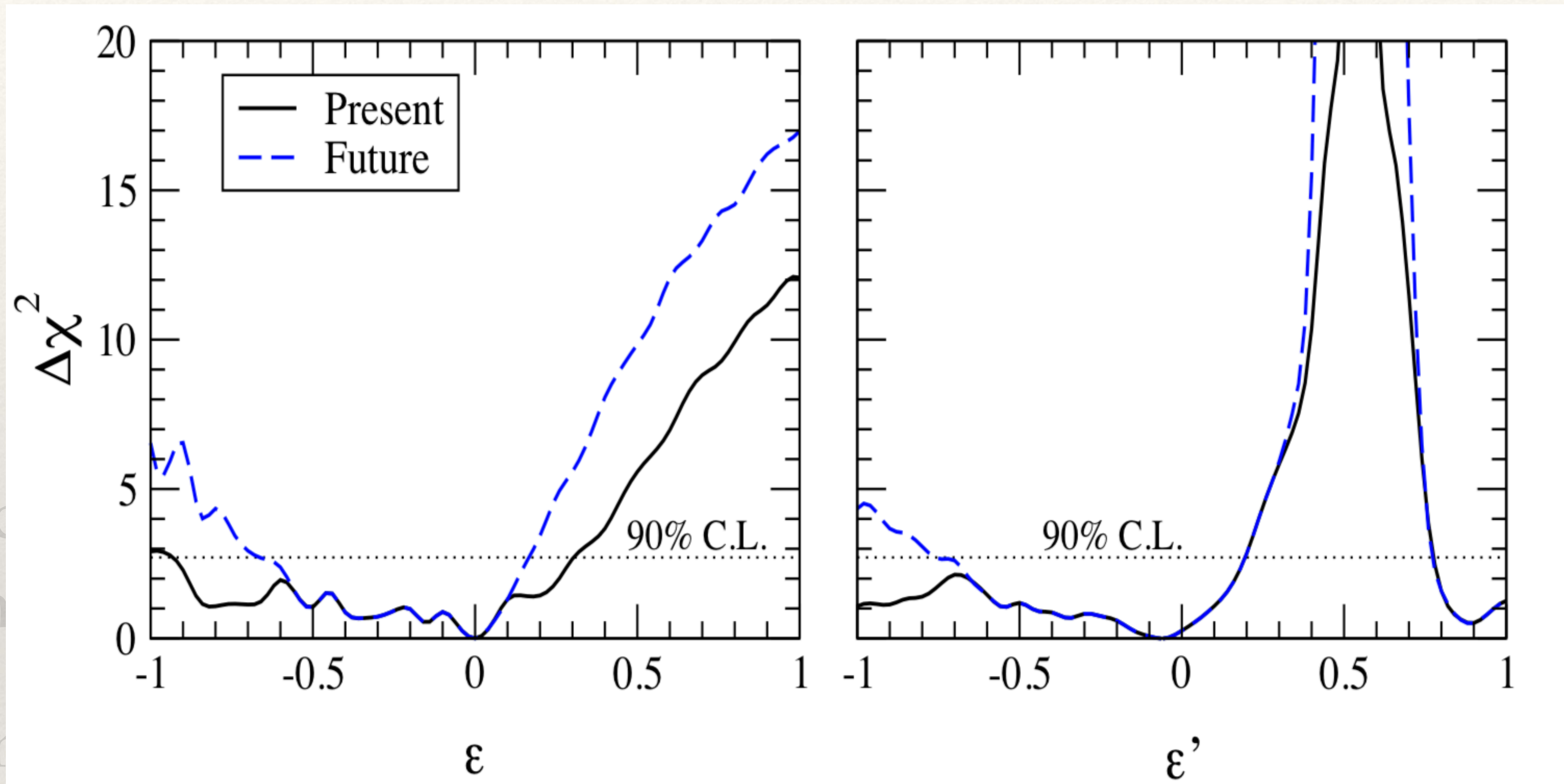
Example RG enhancement:

[in units of $10^{-5} \tan^2\beta$]

large

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

Non-Standard Interactions



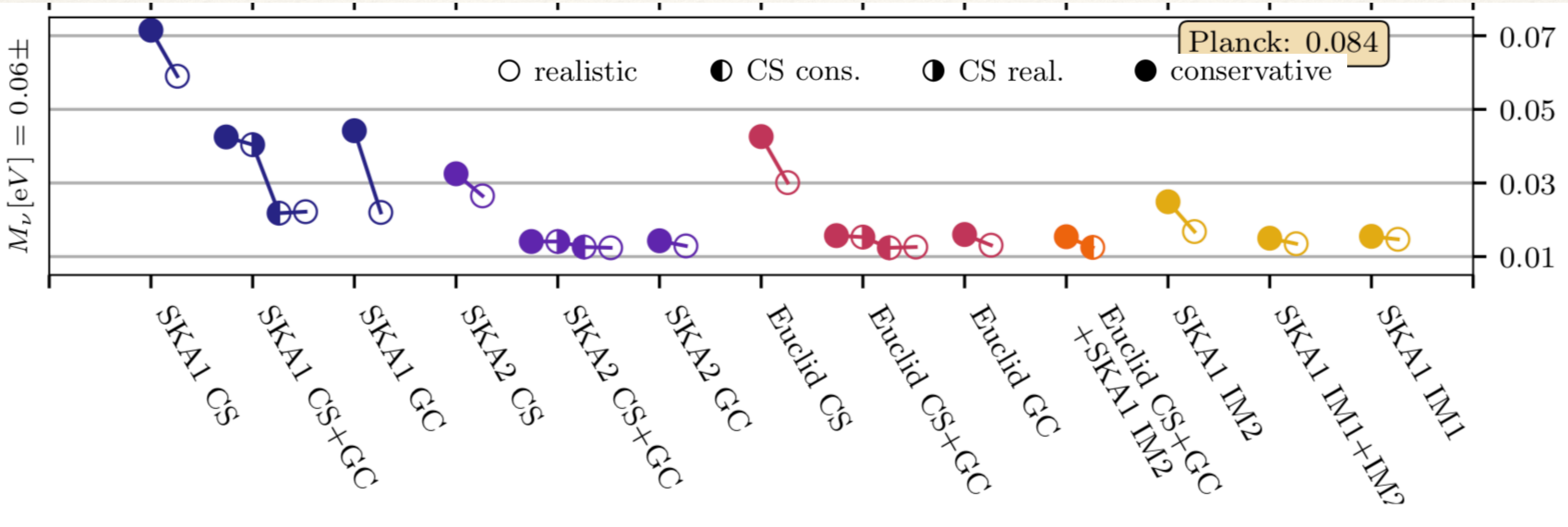
$$\varepsilon = -\sin\theta_{23}\,\varepsilon^{dV}_{e\tau} \qquad \varepsilon' = \sin^2\theta_{23}\,\varepsilon^{dV}_{\tau\tau} - \varepsilon^{dV}_{ee}$$

Miranda, Tortola, Valle, hep-ph/0406280

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

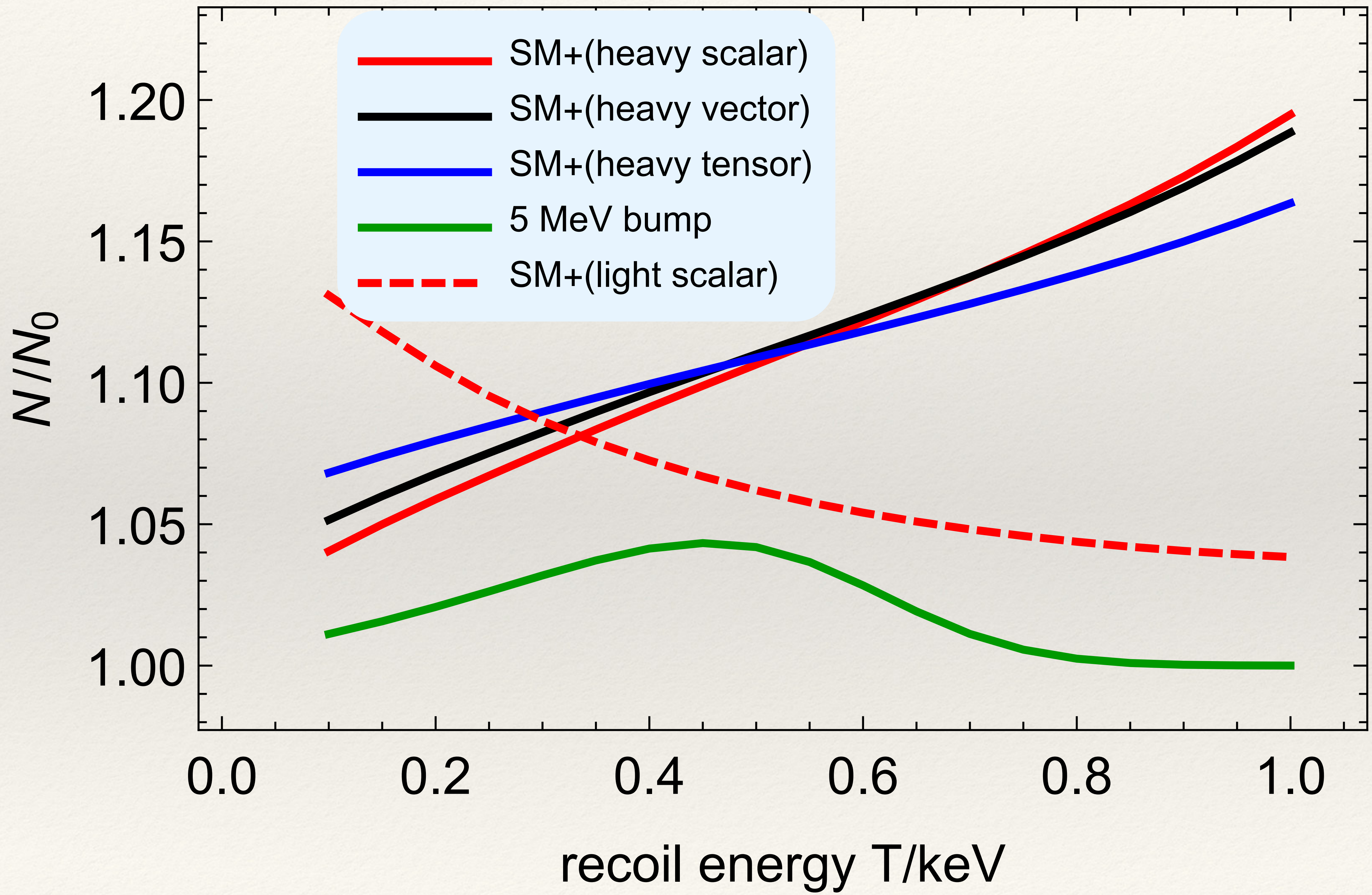
Neutrino Mass guaranteed?

Sprenger et al., 1801.08331



5σ detection when Euclid and SKA are combined!

New Physics in Coherent Scattering



Xun-jie Xu

New Physics in Coherent Scattering

Farzan, Lindner, WR, Xu, 1802.06171

assume light scalar mediator:
(no matter NSI…)

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