Probing models and New Physics with future neutrino experiments

Heisenberg-Programm

DFG Deutsche Forschungsgemeinschaft

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Astroparticles in Germany

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MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Outline

- DUNE, JUNO *et al.*
  - standard physics program
  - New Physics potential: NSIs
- Coherent elastic neutrino-nucleus scattering
  - New Physics potential
- Theory origin of NSIs

Neutrinos oscillate and leptons mix

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

Low Energy Paradigm

At low energies, neutrino mass matrix m_ν:

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

with PMNS matrix

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

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

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

→

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

3 Majorana neutrino paradigm ⇒ needs to be tested!

Low Energy Paradigm

At low energies, neutrino mass matrix m_ν:

$$\mathcal{L} = \frac{1}{2}\,\nu^T\, m_\nu\, \nu \quad \text{with} \quad m_\nu = \ldots$$

with P[MNS] matrix

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

chan[ges] ... [para]meters in **SM′**:

Species	#	Σ
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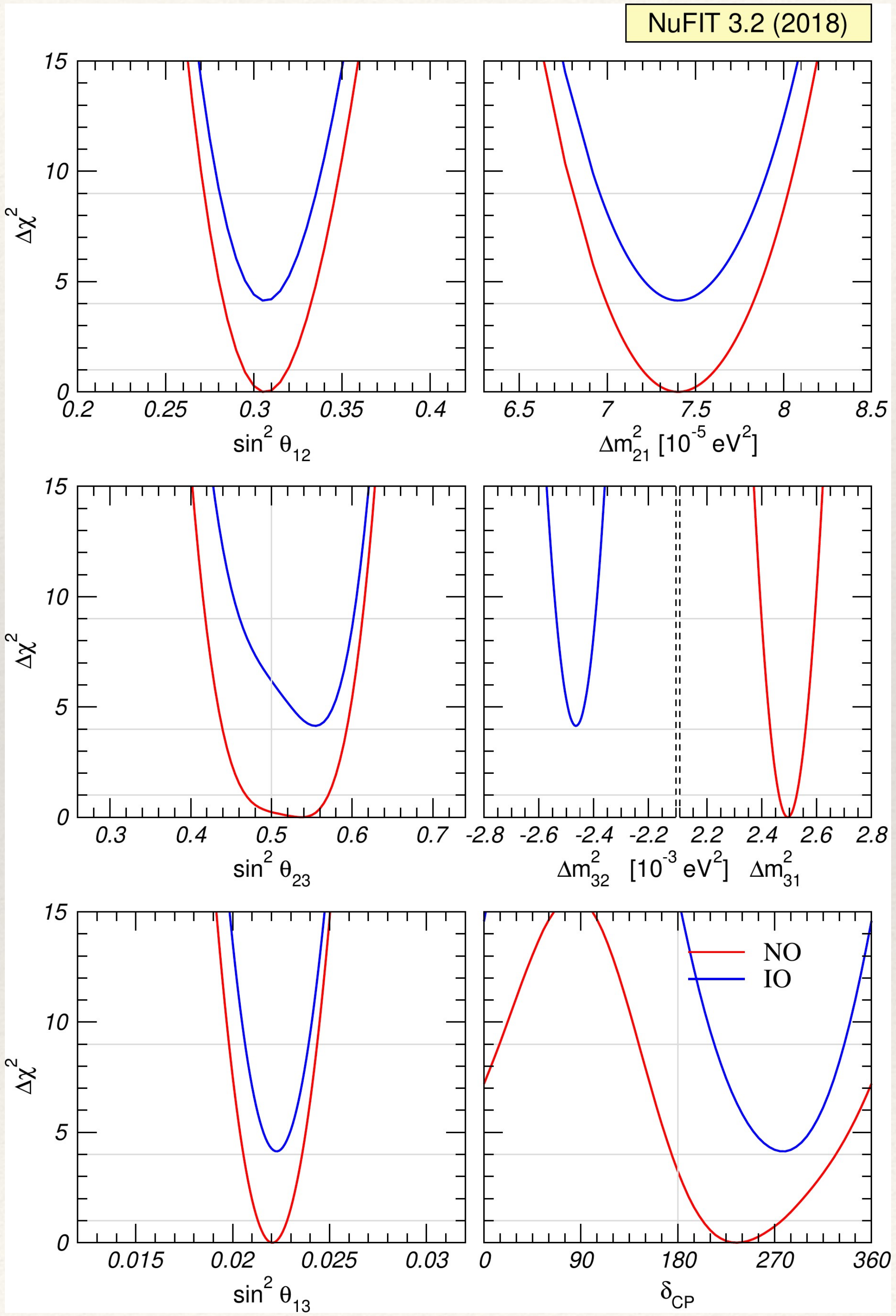
3 ... neutrino paradigm ⇒ needs to be tested!

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

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



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

No post-Neutrino2018 update yet…

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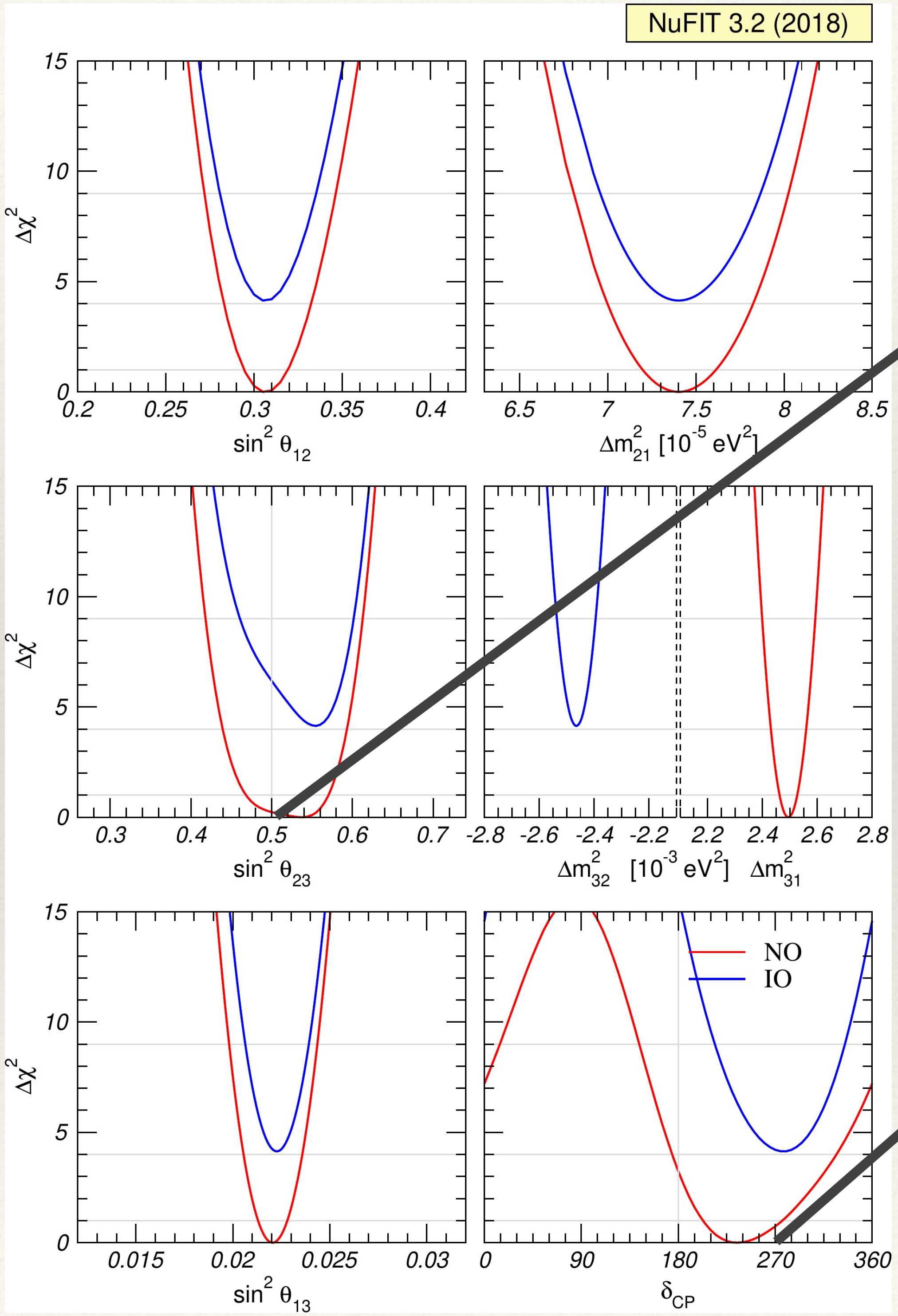

maximal θ_{23} ?

$\delta = 3\pi/2$?

Normal Ordering preferred at ≃ 3σ

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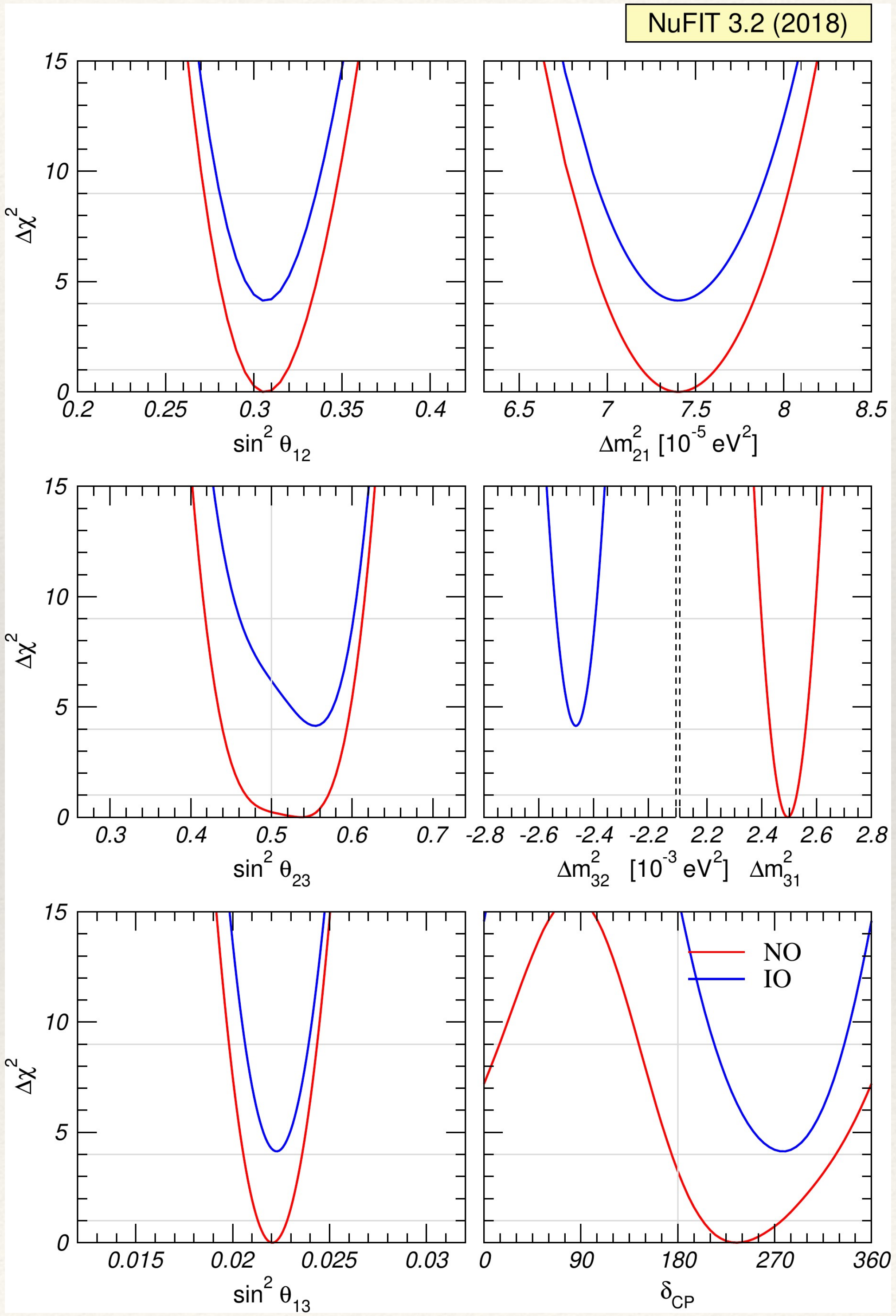

$\delta = 3\pi/2$?

enhanced by tensions…

Normal Ordering preferred at ≃ 3σ

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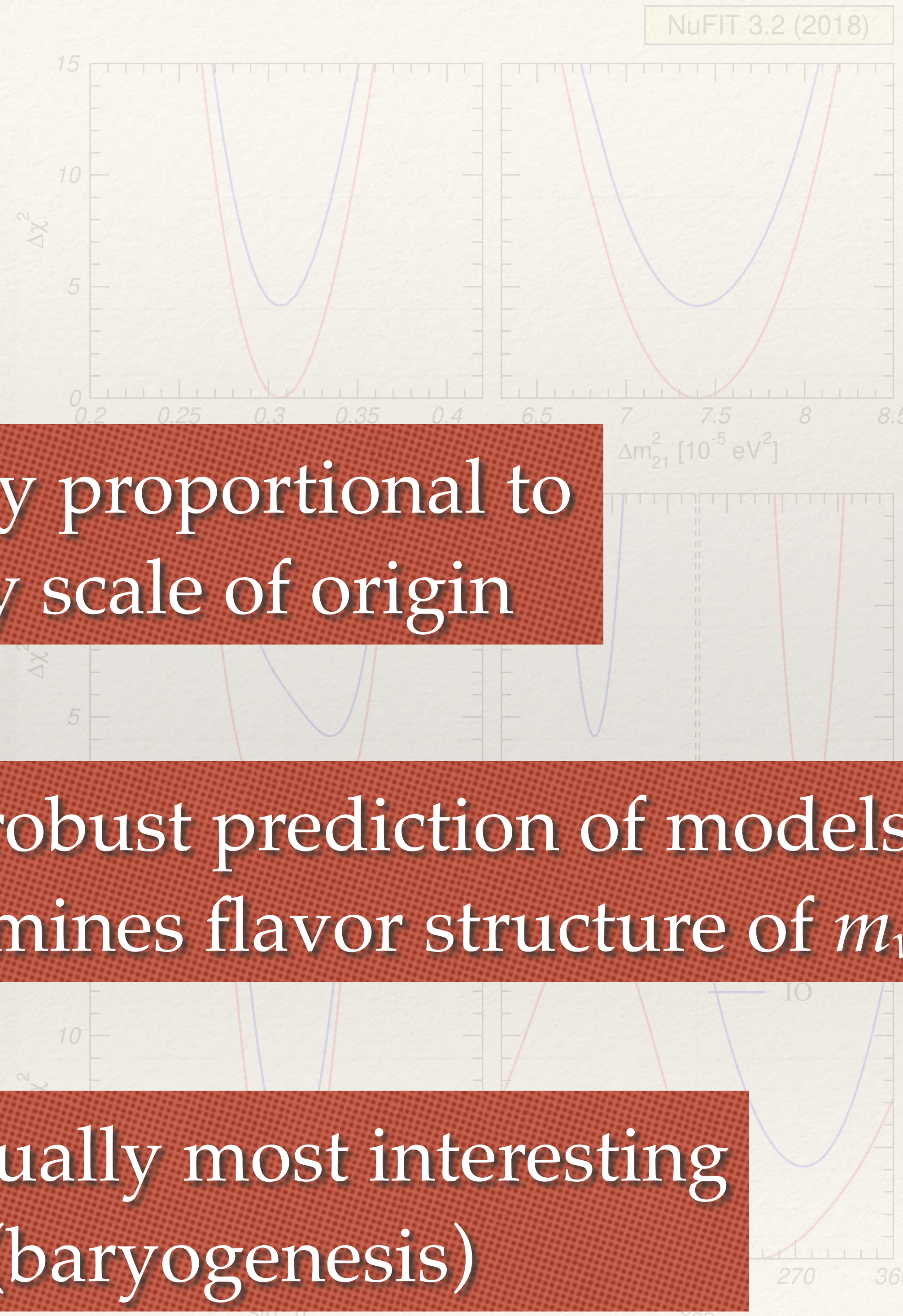

inversely proportional to energy scale of origin

most robust prediction of models; determines flavor structure of m_ν

conceptually most interesting (baryogenesis)

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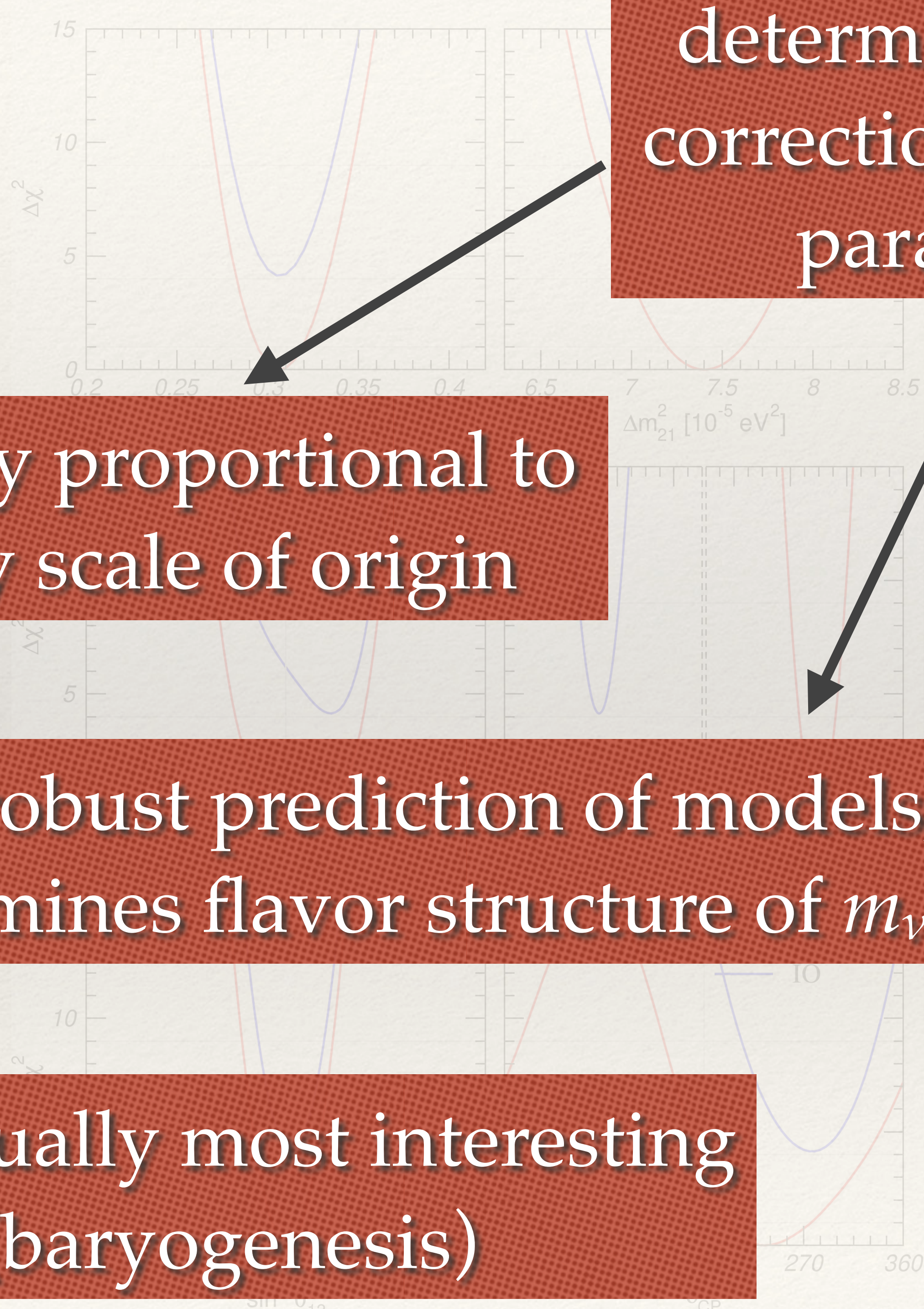


determines size of correction to mixing parameters

inversely proportional to energy scale of origin

most robust prediction of models; determines flavor structure of m_ν

conceptually most interesting (baryogenesis)

Oscillation Parameters

parameter	best fit $\pm$ 1σ	3σ range	
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14	2.4%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NO)	2.50 ± 0.03	2.41–2.60	1.3%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51	
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79	5.5%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99	4.7%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98	4.4%
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41	3.5%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44	

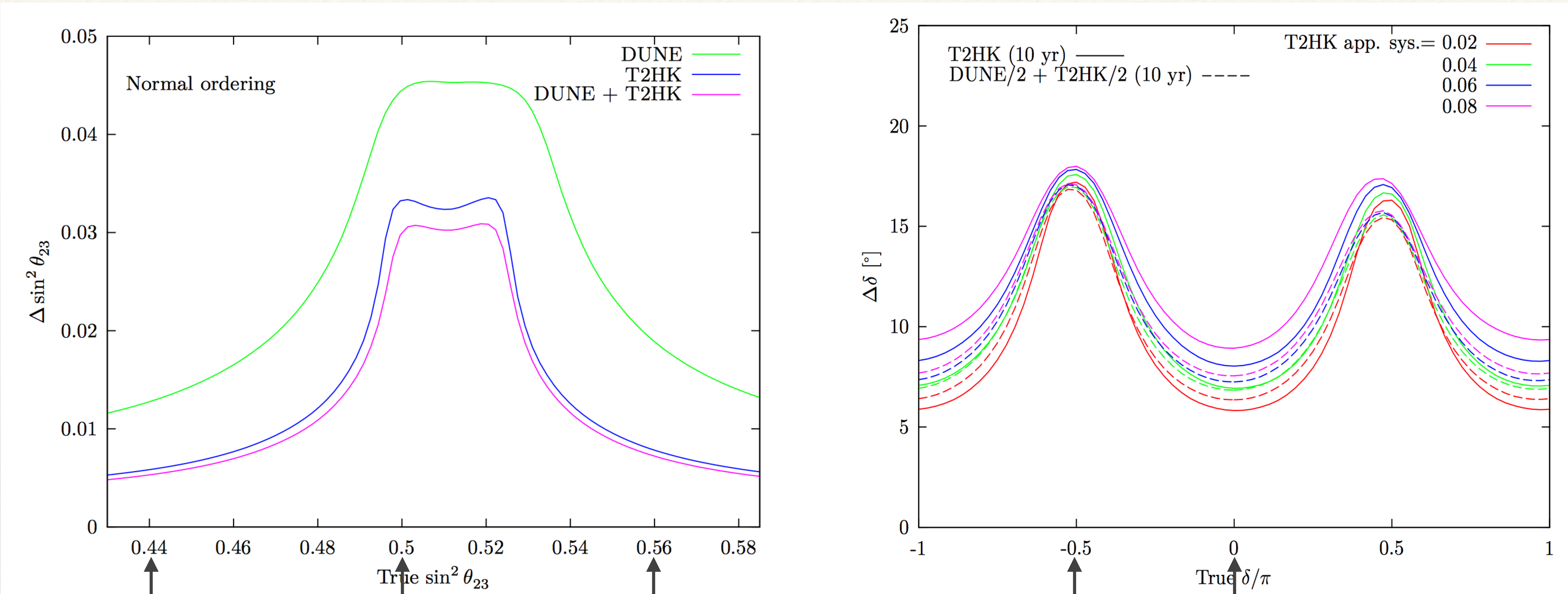
Tortola, talk at Neutrino2018

	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%

Unitarity tests, solar physics, precision for double beta decay

Achievable Precision

Ballet et al., 1612.07275

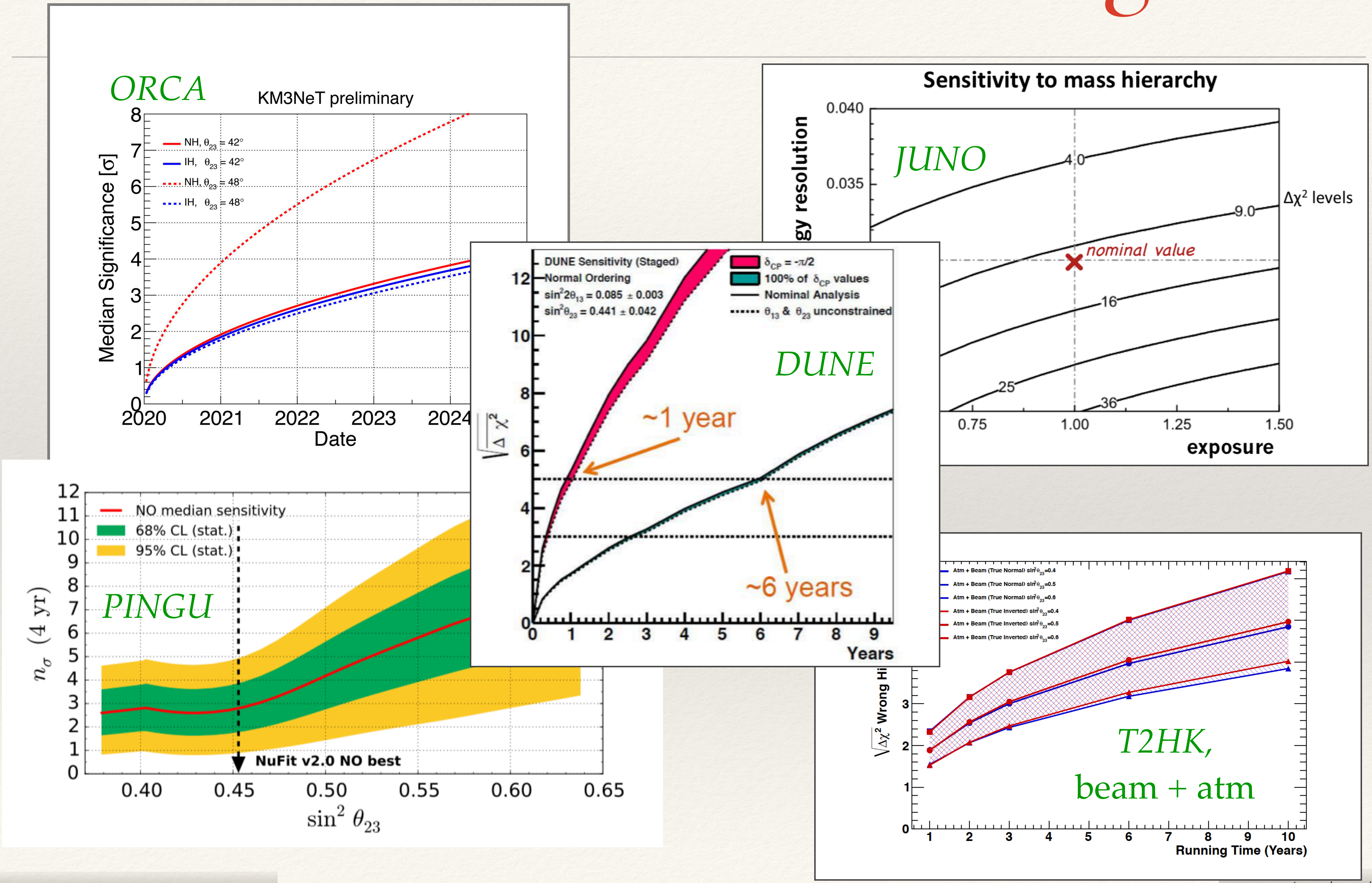


$(41.6\pm0.3)^0$ $(45\pm1.7)^0$ $(48.5\pm0.6)^0$ cos δ: (0 ± 0.29) (1 ± 0.006)

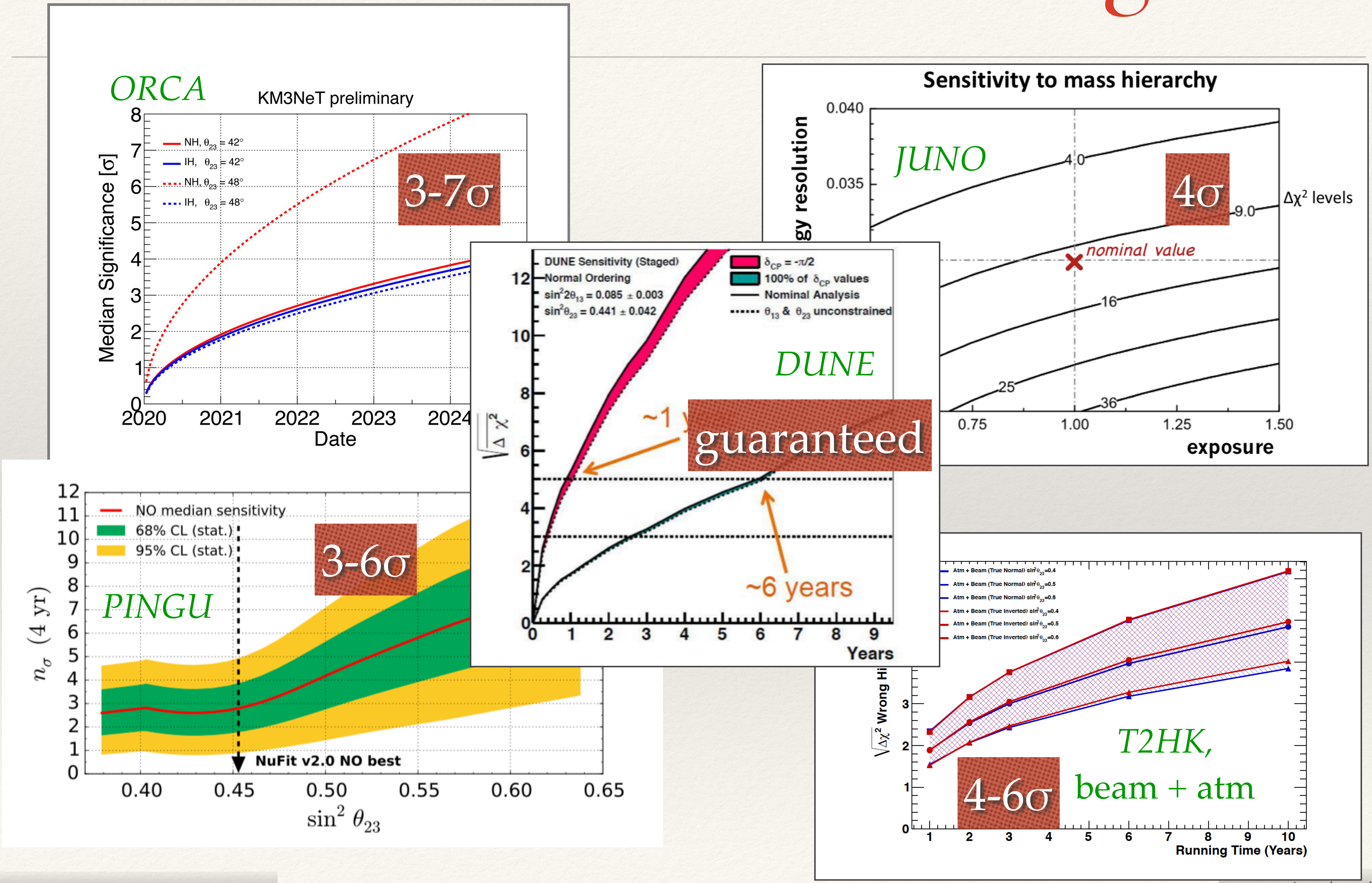
worst precision for most interesting values…

vary neutrino/antineutrino share for better discrimination of δ?

Future of Mass Ordering



Future of Mass Ordering



Flavor Symmetries

- Discrete Non-Abelian Symmetries

Altarelli, Feruglio, 1002.0211

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

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

Barry, WR, 1003.2385

Many possible groups, within each group many models…

$\Rightarrow$ can distinguish only classes of models

Example I: Sumrules

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

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

King et al.; Frampton, Petcov, WR,…

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

$\Rightarrow$ can distinguish only classes of models

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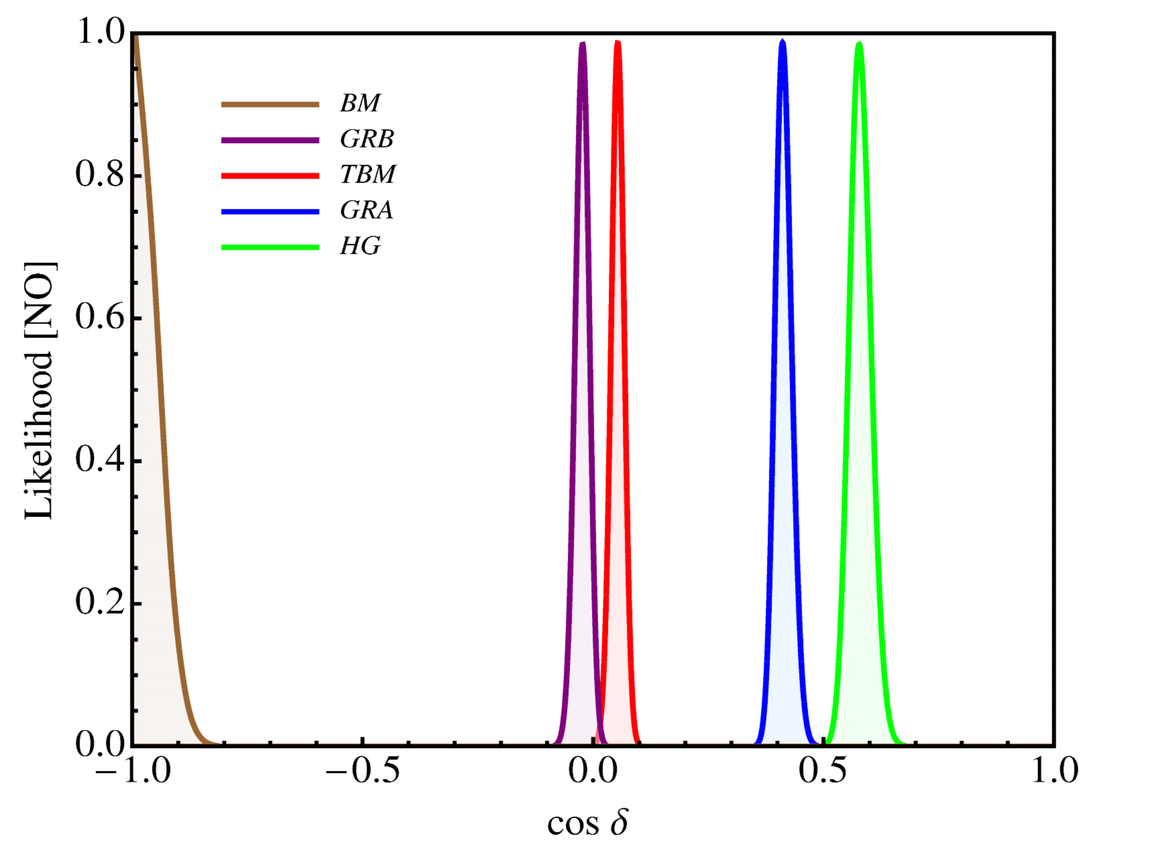
Girardi, Petcov, Titov, 1410.8056



⇒ can distinguish only classes of models

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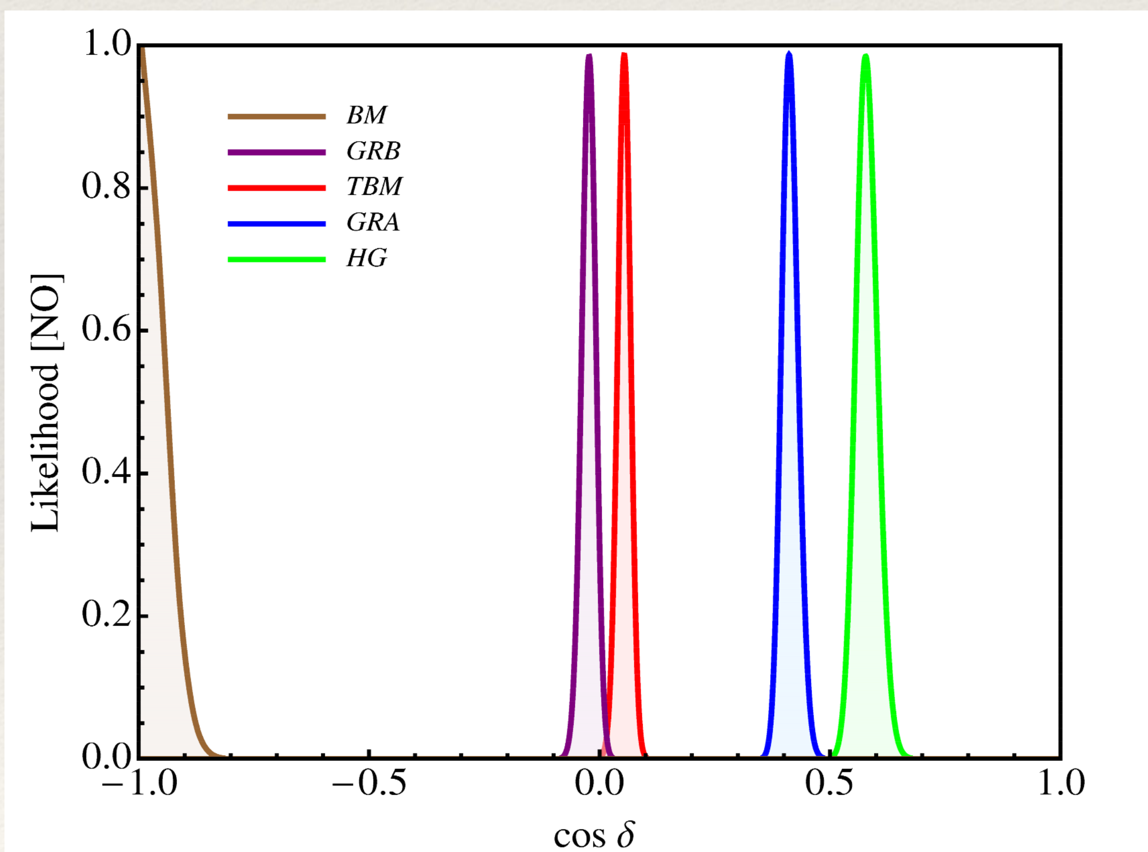
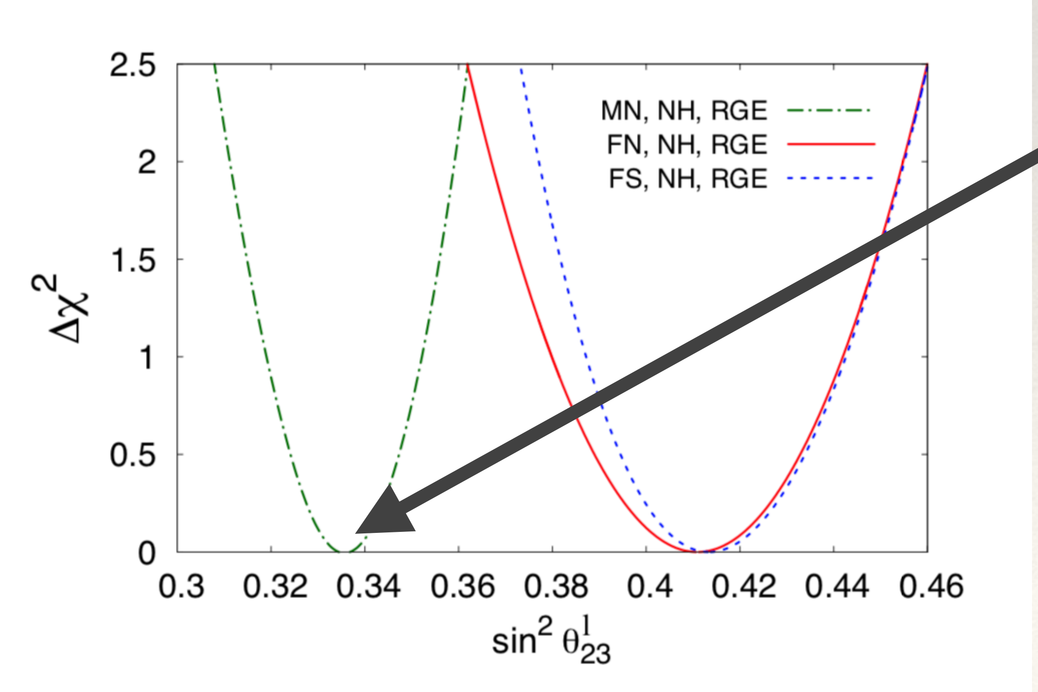


Often additional correlations with double beta decay and neutrino mass

Example II: GUTs

- *SO(10)* can have 10-, 126, and 120-dimensional Higgs-rep
  - 10- and 120-dimensional: no seesaw
  - 120- and 126-dimensional: don't work
  - 10- and 126-dimensional: don't work for IH
  - 10- and 126-dimensional and no SUSY: predict small θ_{23}



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
  - light sterile neutrinos…

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Non-Standard Interactions

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

- $\varepsilon^V \propto c^2/M_X^2 \;\Rightarrow\; \varepsilon^V = 0.01$ is TeV-scale physics
- oscillation effect is MSW-like *t*-channel forward scattering (q^2 very small), hence M_X MeV-ish
- there are also CC-like production and detection NSIs…
- can prevent experiments from determining parameters…

Non-Standard Interactions

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

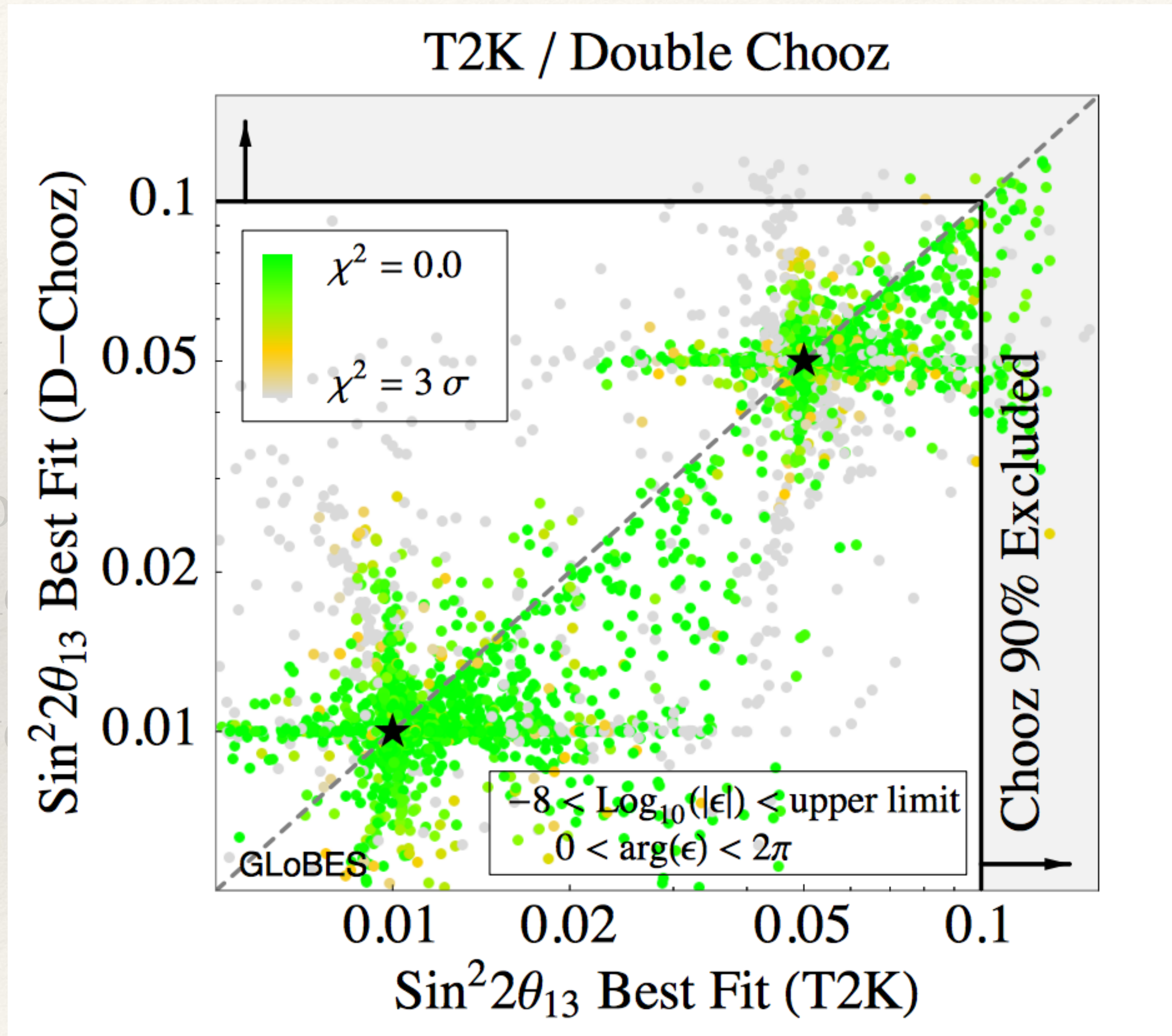
Limits typically EW scale

- $\varepsilon \propto g'^2/M_{Z'}^2$ 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…

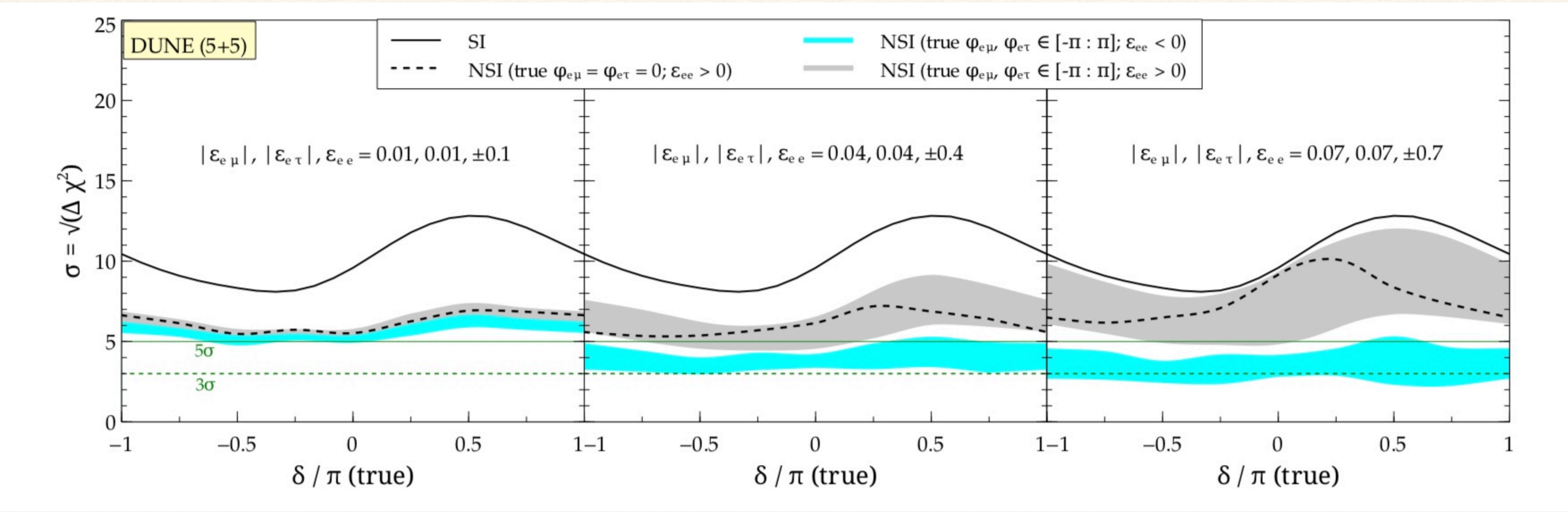


Kopp, Lindner, Ota, Sato, 0708.0152

Non-Standard Interactions

- Degeneracies
  - ε_{ee} - $\varepsilon_{\mu\mu}$ = $O(1)$: **no** oscillation experiment can determine mass ordering
  - individual other $\varepsilon_{\alpha\beta}$ typically resolvable by comparing different $P_{\alpha\beta}$ and different L and E in different extps
  - multiple $\varepsilon_{\alpha\beta}$ can cause problems…

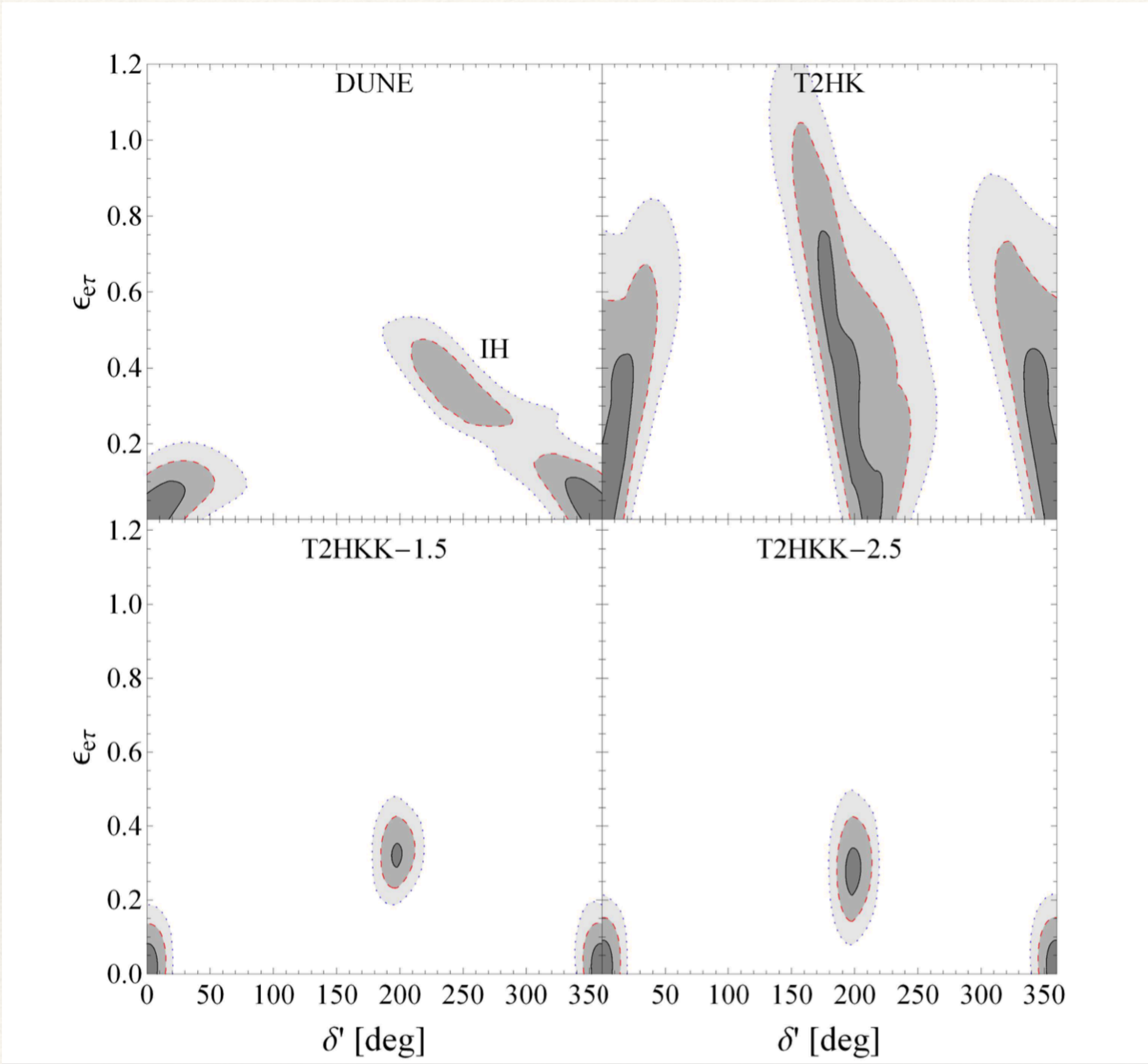
Non-Standard Interactions



NSI can prevent determination of mass ordering!

Masud, Mehta, 1606.05662

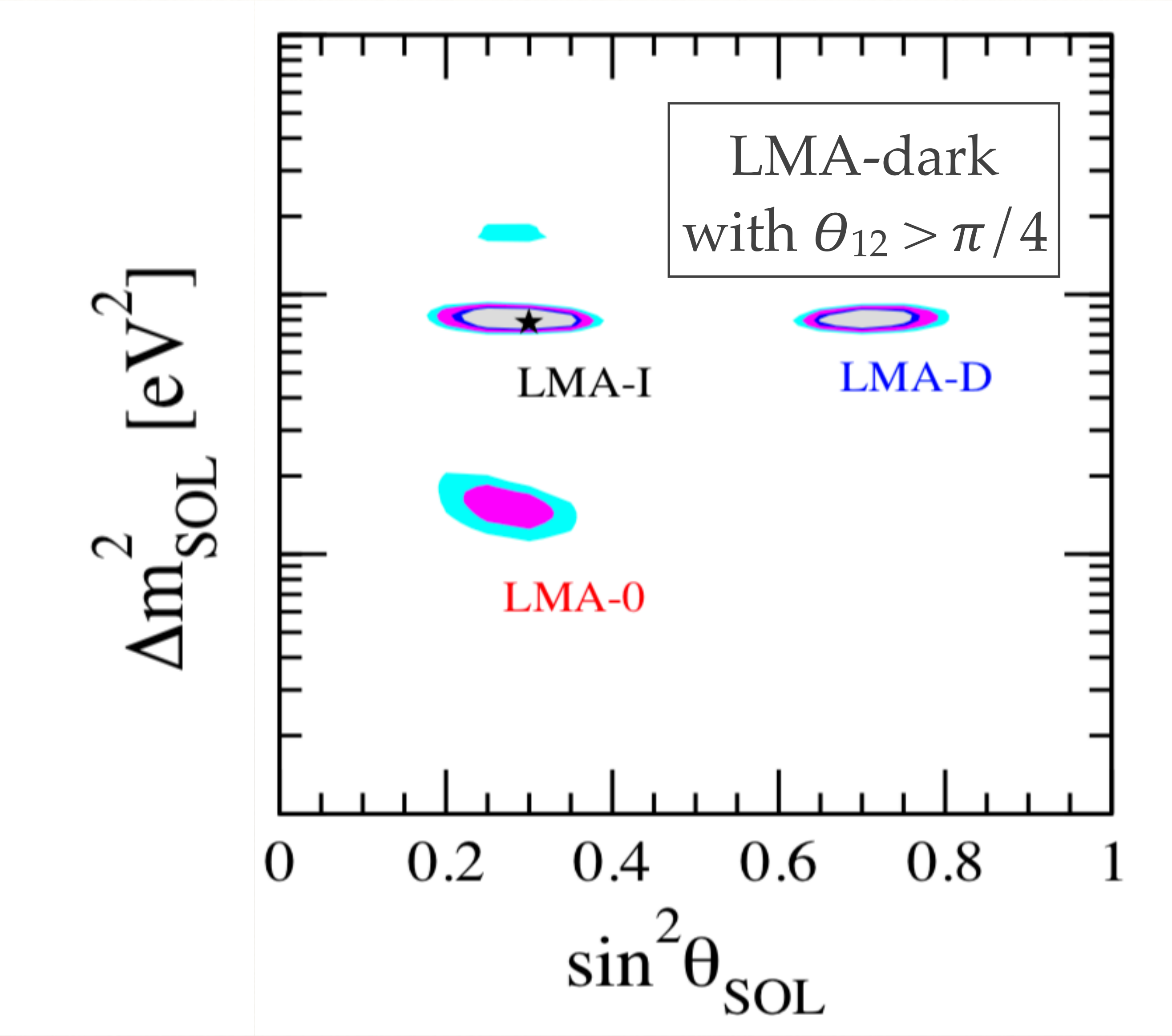
Non-Standard Interactions

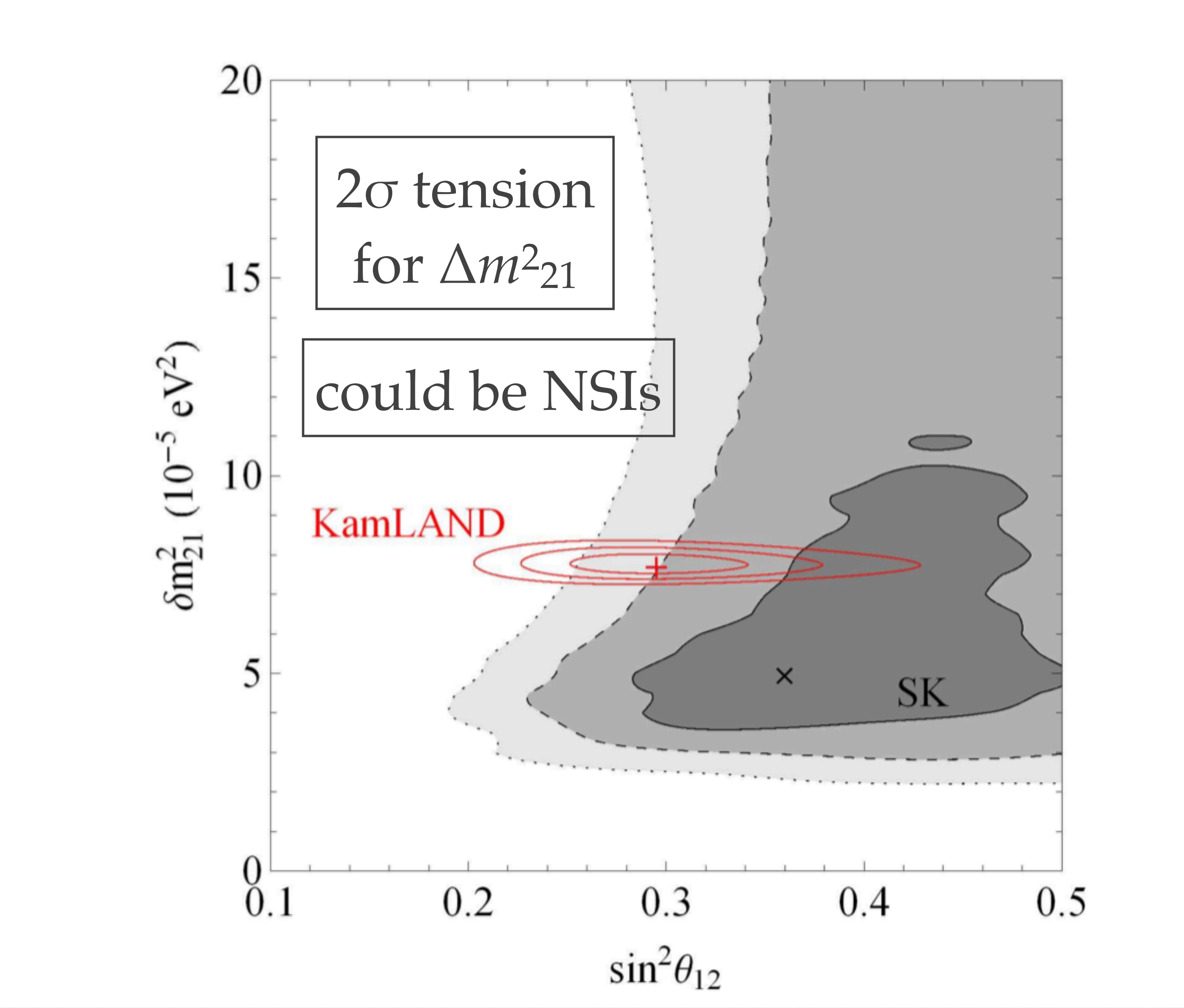


DUNE has better NSI sensitivity than T2HK

Liao, Marfatia, Whisnant, 1612.01443

NSIs for solar parameters

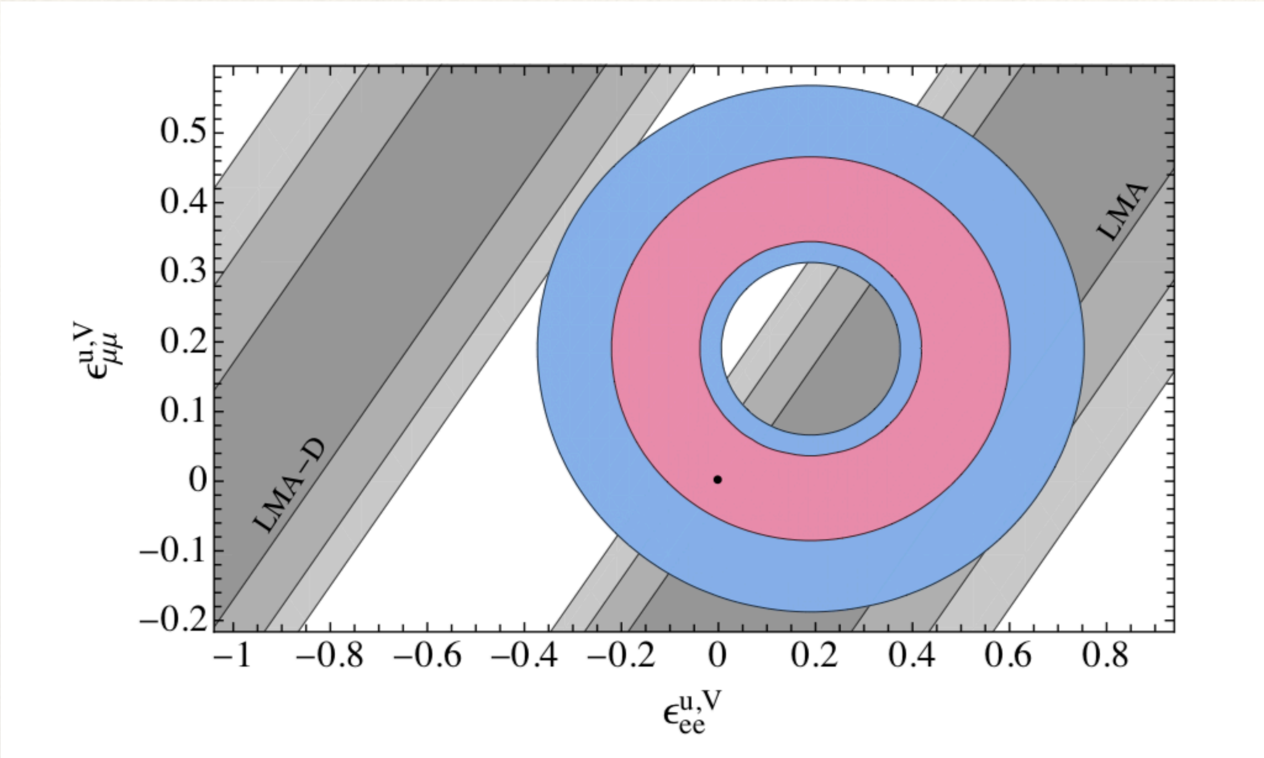




Miranda, Tortola, Valle, hep-ph/0406280

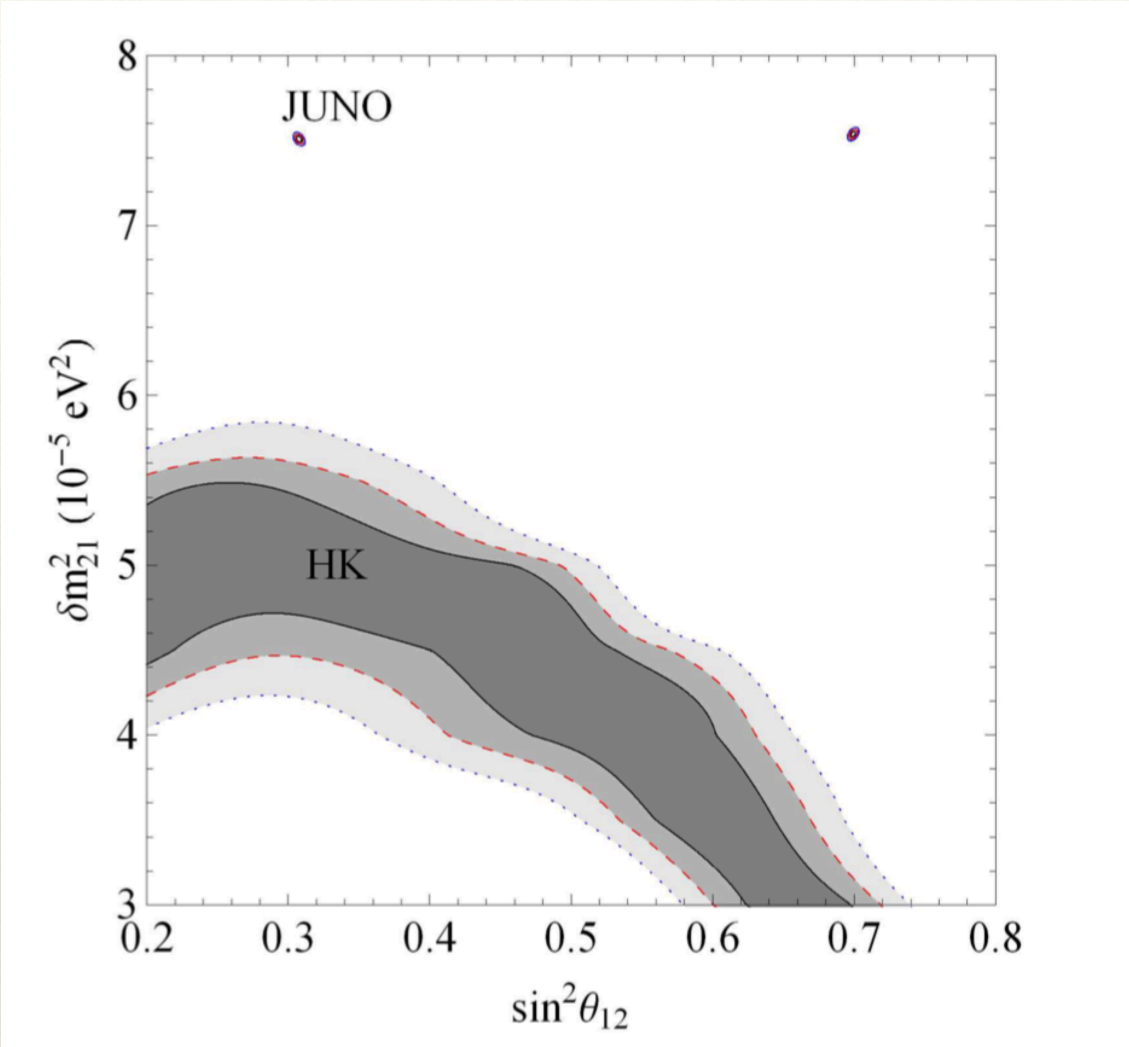
Liao, Marfatia, Whisnant, 1704.04711

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

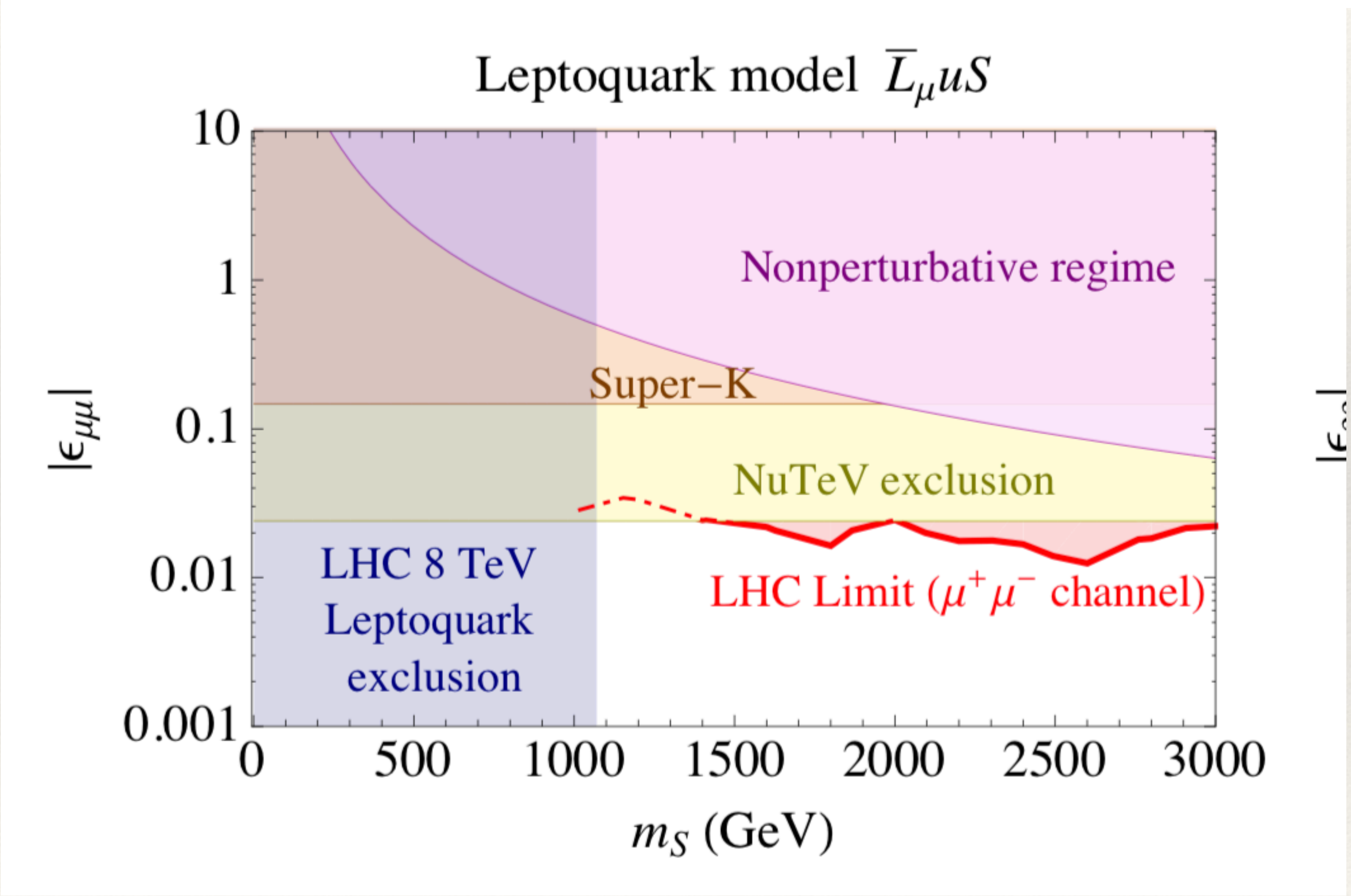
Liao, Marfatia, Whisnant, 1704.04711

Origin of NSIs

- ε from integrating out scalar of type II seesaw: $\varepsilon^e_{\alpha\beta} \propto (m_\nu)_{\alpha\beta}$ *(Malinsky, Olsson, Zhang, 0811.3346)*
- scalar needs color to generate $\varepsilon^q_{\alpha\beta}$, often have $|\epsilon_{e\mu}|^2 = \epsilon_{ee}\epsilon_{\mu\mu}, \quad |\epsilon_{\mu\tau}|^2 = \epsilon_{\mu\mu}\epsilon_{\tau\tau}, \quad |\epsilon_{e\tau}|^2 = \epsilon_{ee}\epsilon_{\tau\tau}$
- ε from Z' of L_μ - L_τ: $\varepsilon_{\mu\mu} = -\,\varepsilon_{\tau\tau}$ *(Heeck, WR, 1107.5238)*
- ε from integrating out doublet 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':
  - if only kinetic Z-Z' mixing: no NSI effect in LBL: $\varepsilon^e + 3\,\varepsilon^u + 3\,\varepsilon^d = 0$
  - if there is non-zero NSI in DUNE: needs mass mixing $\delta M^2\, Z\, Z'$, i.e. scalar with charges under SM and $U(1)'$ $\Rightarrow$ Higgs pheno! *(Heeck, Lindner, WR, Vogl, to appear)*

Example I: Leptoquark

SU(2)$_L$ doublet with hypercharge -7/3 $\mathcal{L} = \lambda_{ij} \overline{L_i} P_R u_j S$ gives: $\epsilon_{\alpha\beta} = -\frac{3}{4} \frac{\lambda_{\alpha 1} \lambda^*_{\beta 1}}{\sqrt{2} G_F m_S^2}$,



in matter:

$\varepsilon^e + 3\varepsilon^u + 3\varepsilon^d$

Wise, Zhang, 1404.4663

Example II: flavor-dependent *Z'*

$$\mathcal{L}_{Z'} = -\frac{1}{4}\hat{Z}'_{\mu\nu}\hat{Z}'^{\mu\nu} + \frac{1}{2}\hat{M}'^2_Z\hat{Z}'_\mu\hat{Z}'^\mu - \hat{g}' j'^\mu \hat{Z}'_\mu \,,$$

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

kinetic mixing; must exist

mass mixing; needs scalar charged under SM and *U(1)'*

- if only kinetic mixing: no NSI in LBL experiments!

$$\varepsilon^e + 3\,\varepsilon^u + 3\,\varepsilon^d = 0$$

- hence, if observed, need scalar charged under SM and *U(1)'*

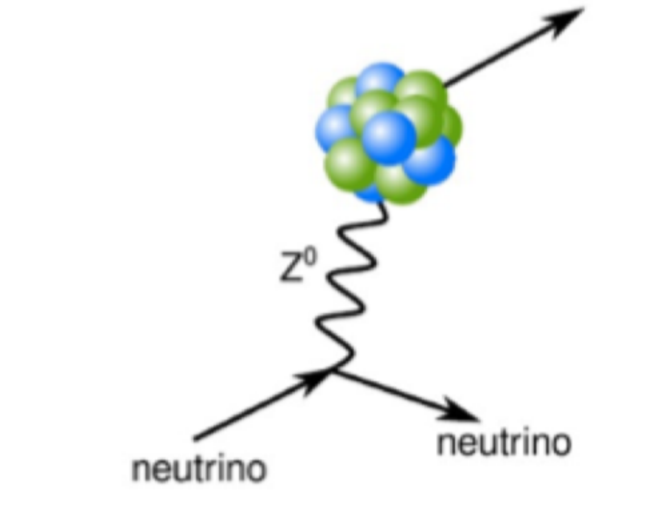
$\Rightarrow$ ***non-standard Higgs physics***

Heeck, Lindner, WR, Vogl, to appear

Coherent Elastic Neutrino-Nucleus Scattering

Freedmann, PRD9, 1974

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



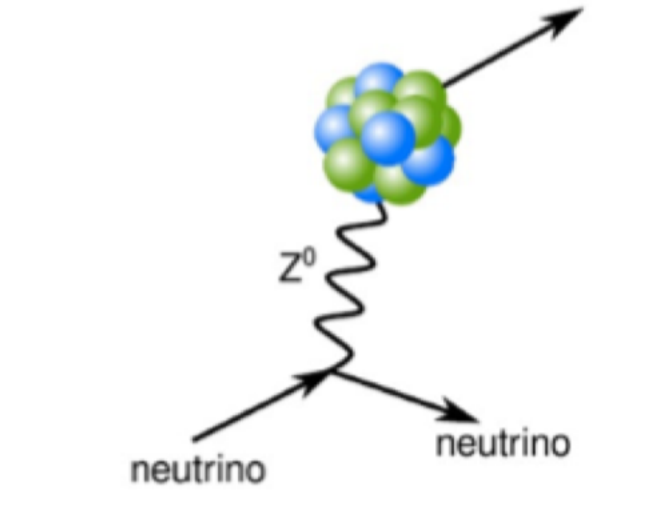
$$\sigma_0^{\rm SM} \equiv \frac{G_F^2\left[N - (1-4s_W^2)Z\right]^2 F^2(q^2)M^2}{4\pi}$$

- 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,…

Coherent Elastic Neutrino-Nucleus Scattering

Freedmann, PRD9, 1974

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



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

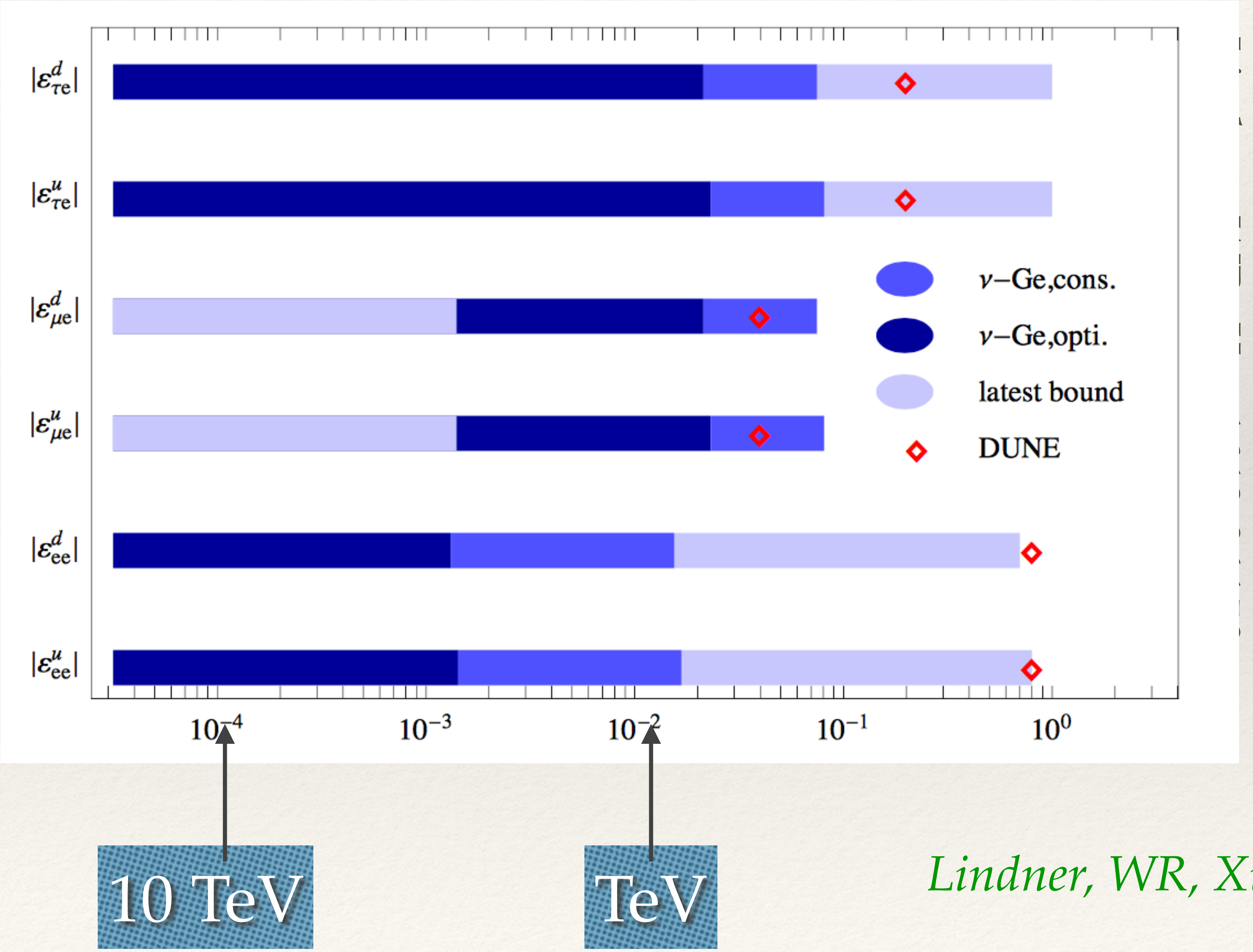
replace with:

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

Complementary to oscillation experiments!!

New Physics in Coherent Scattering

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

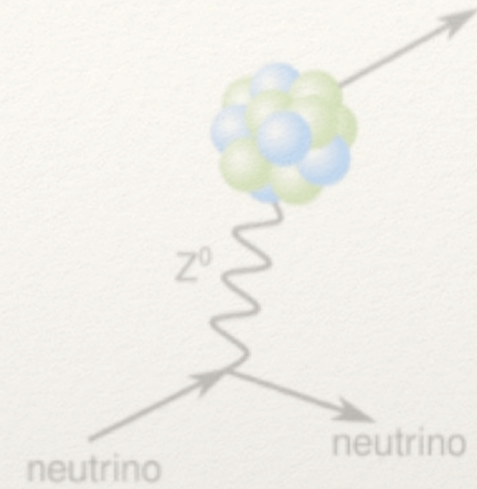


Lindner, WR, Xu, 1612.04150

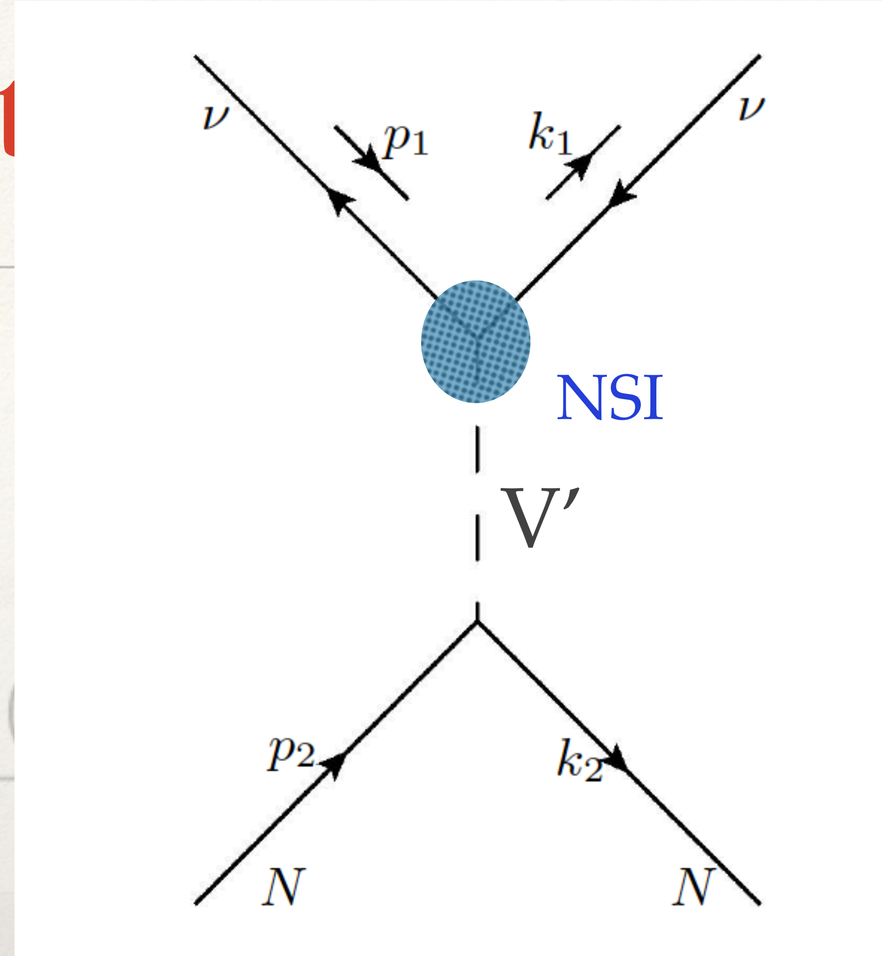
Coherent Elast… …leus Scattering

Freedmann, PRD9, 1974

N^2



$$\sigma_0^{SM} = \frac{G_F^2 \left[N - (\ldots \right]^2}{\ldots}$$



if NSIs are preser…

diff. cross section:

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

$$Q^2_{\rm NSI} = 4\left[N \left(\ldots + \varepsilon \ldots + 2\varepsilon \ldots \right) + Z \left(\ldots - 2 s_W \ldots + 2\varepsilon^{uV} \ldots + \varepsilon^{dV}_{ee} \right) \right]^2$$

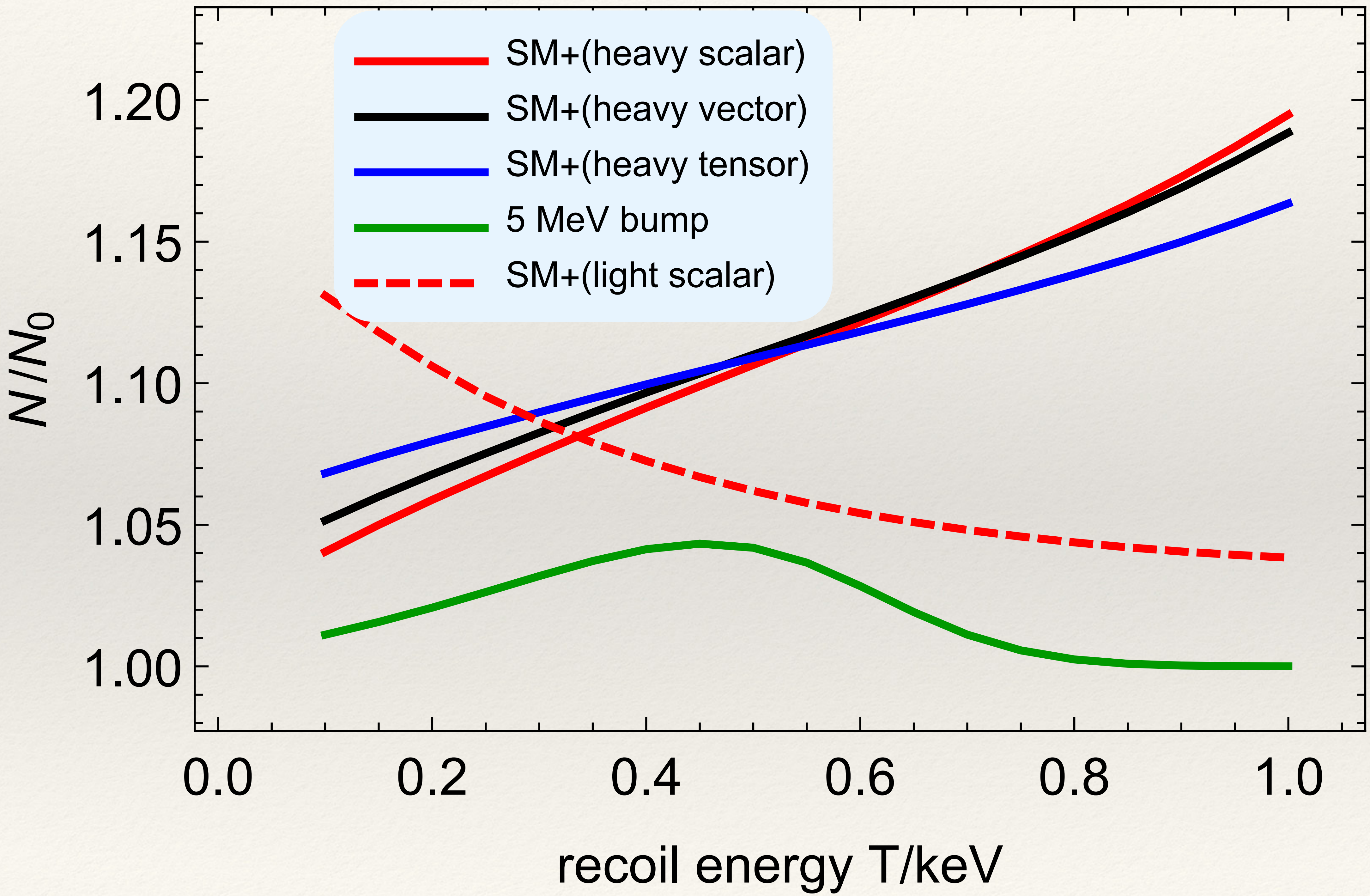
$\alpha = \mu, \tau$

heavy and light NSI origin can be distinguished!

(if scalar, pseudoscalar, tensor, axialvector interactions: no effect in oscillations!)

New Physics in Coherent Scattering

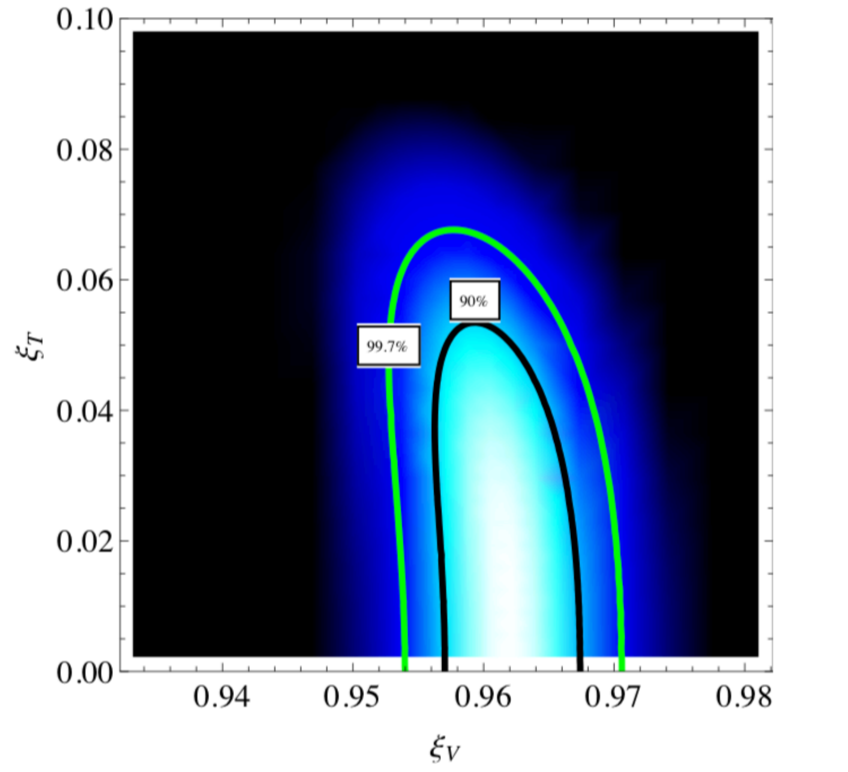
Xun-jie Xu



New Physics in Coherent Scattering

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

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

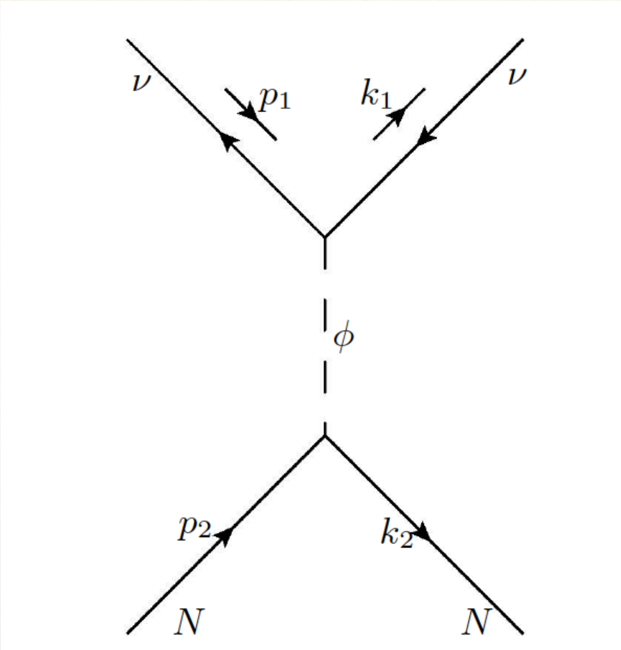


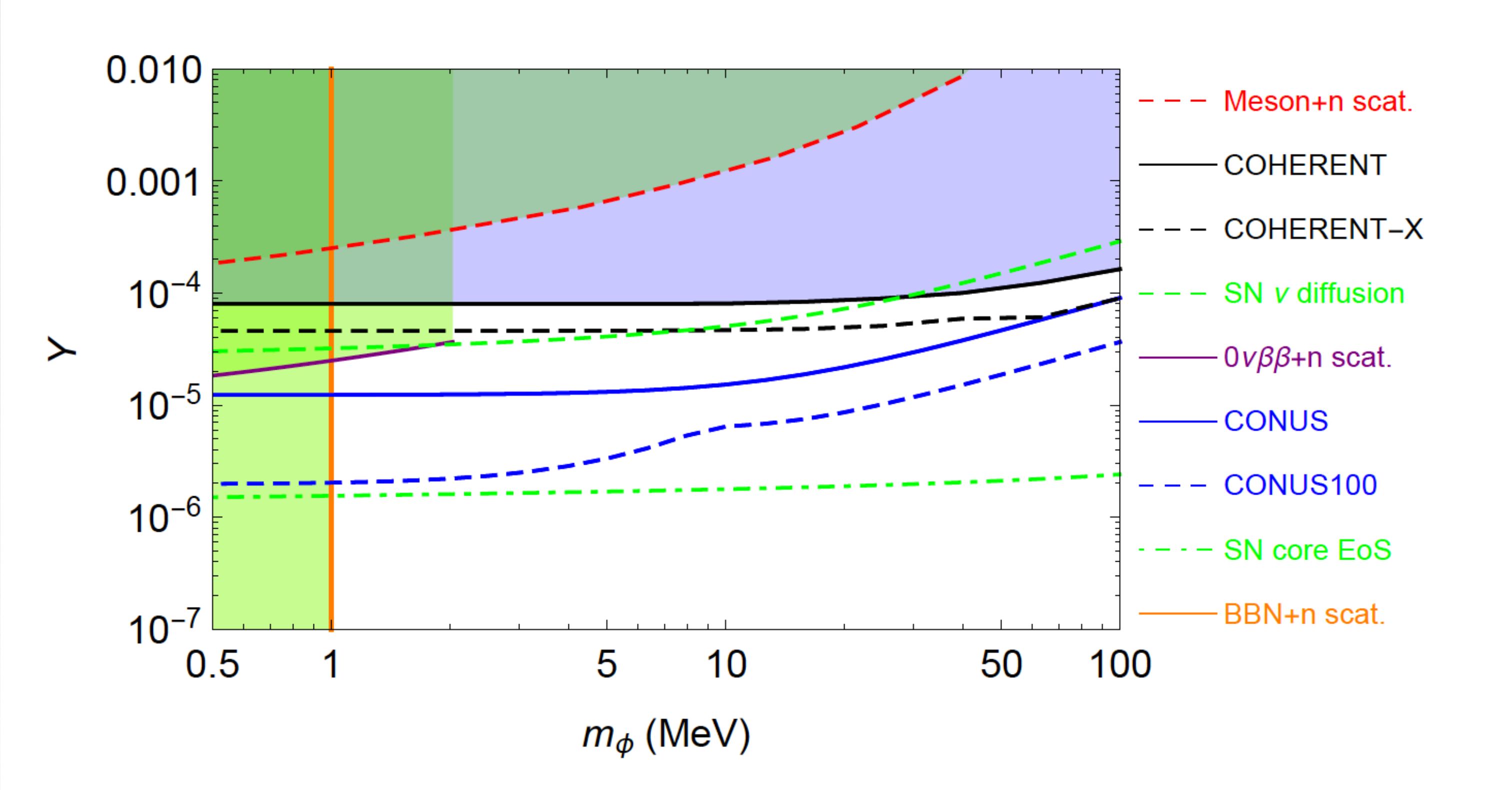
Lindner, WR, Xu, 1612.04150; Sierra et al., 1806.07424

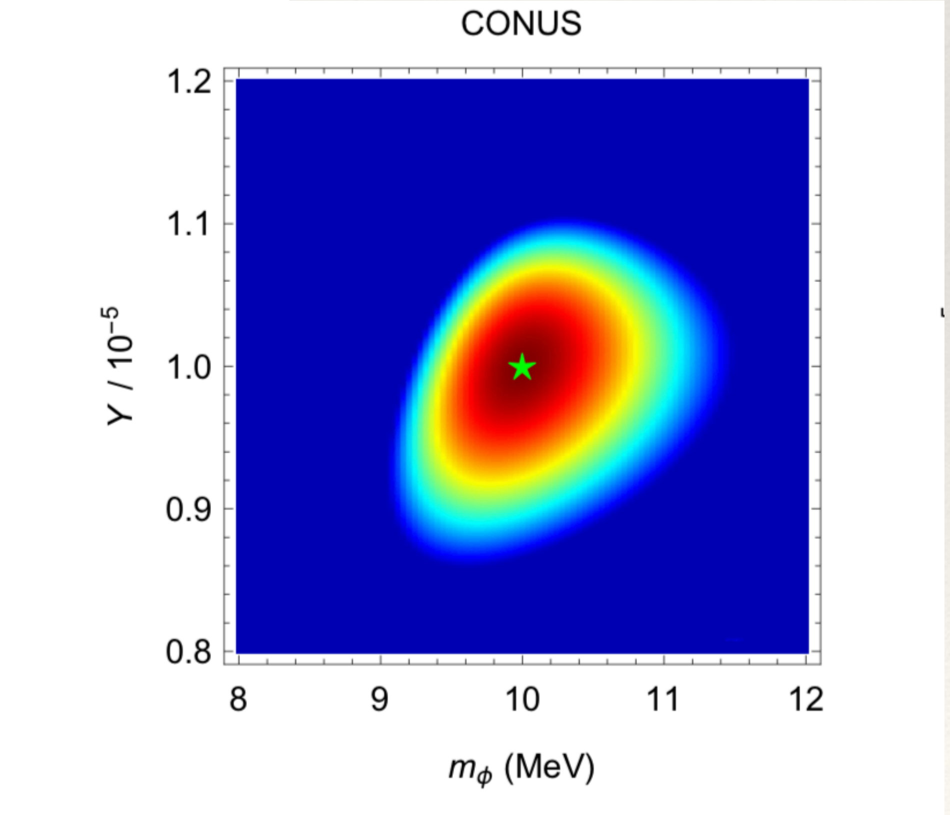
Light Physics in Coherent Scattering

Farzan, Lindner, WR, Xu, 1802.06171

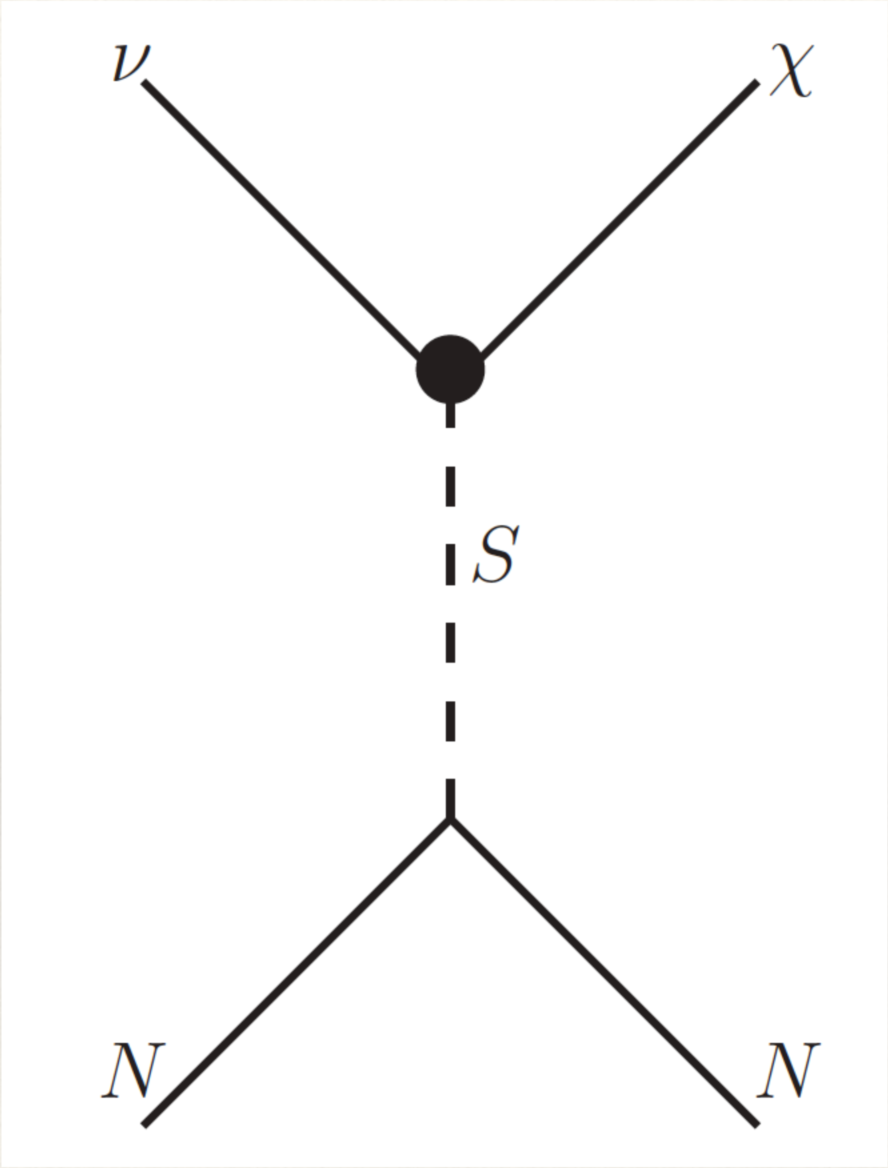
diff. cross section:
$\propto 1/(2\,M\,T + m^2{}_\phi)^2$



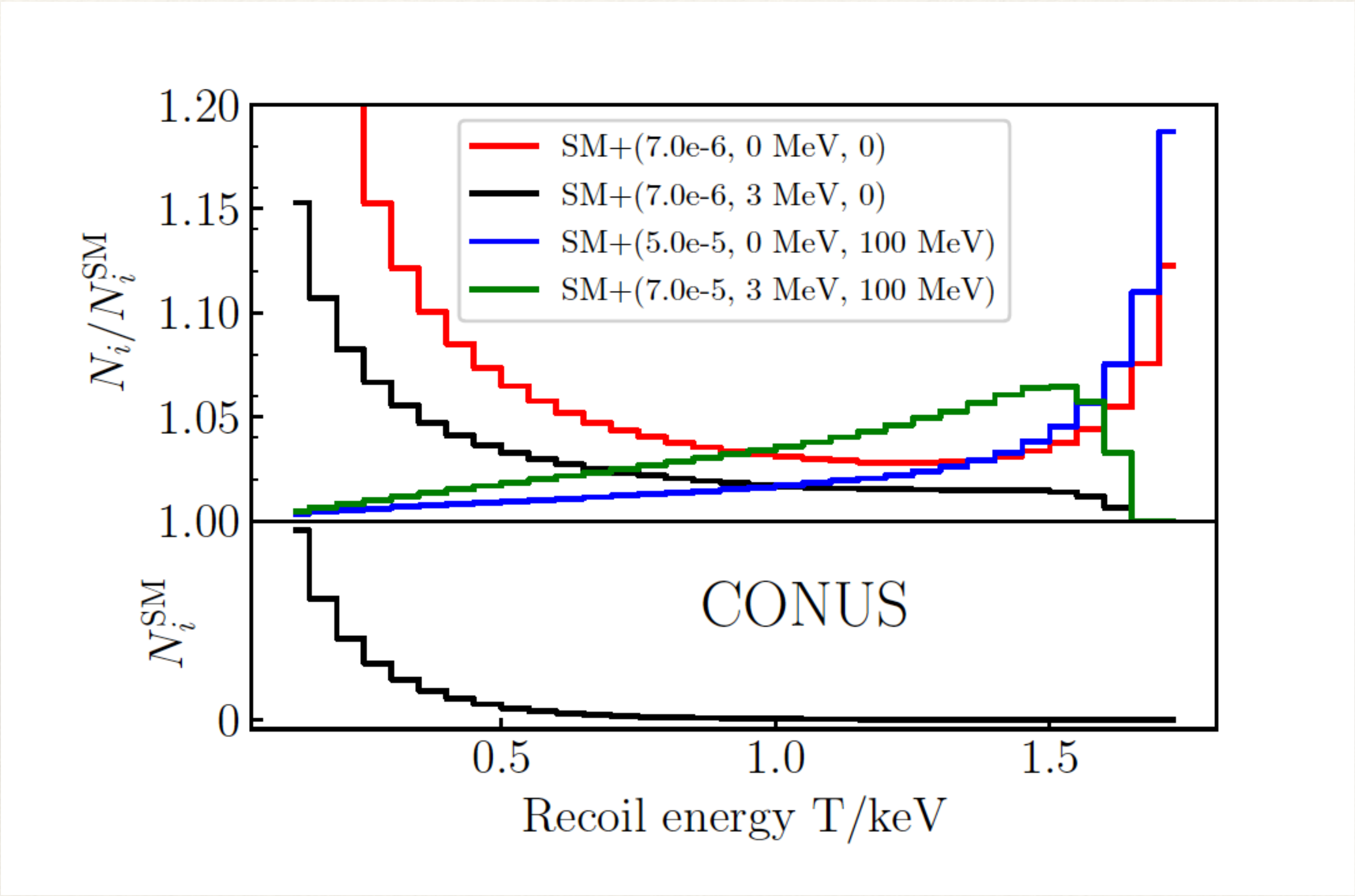




New Physics in Coherent Scattering



can also produce new particle (could be DM and related to neutrino mass)

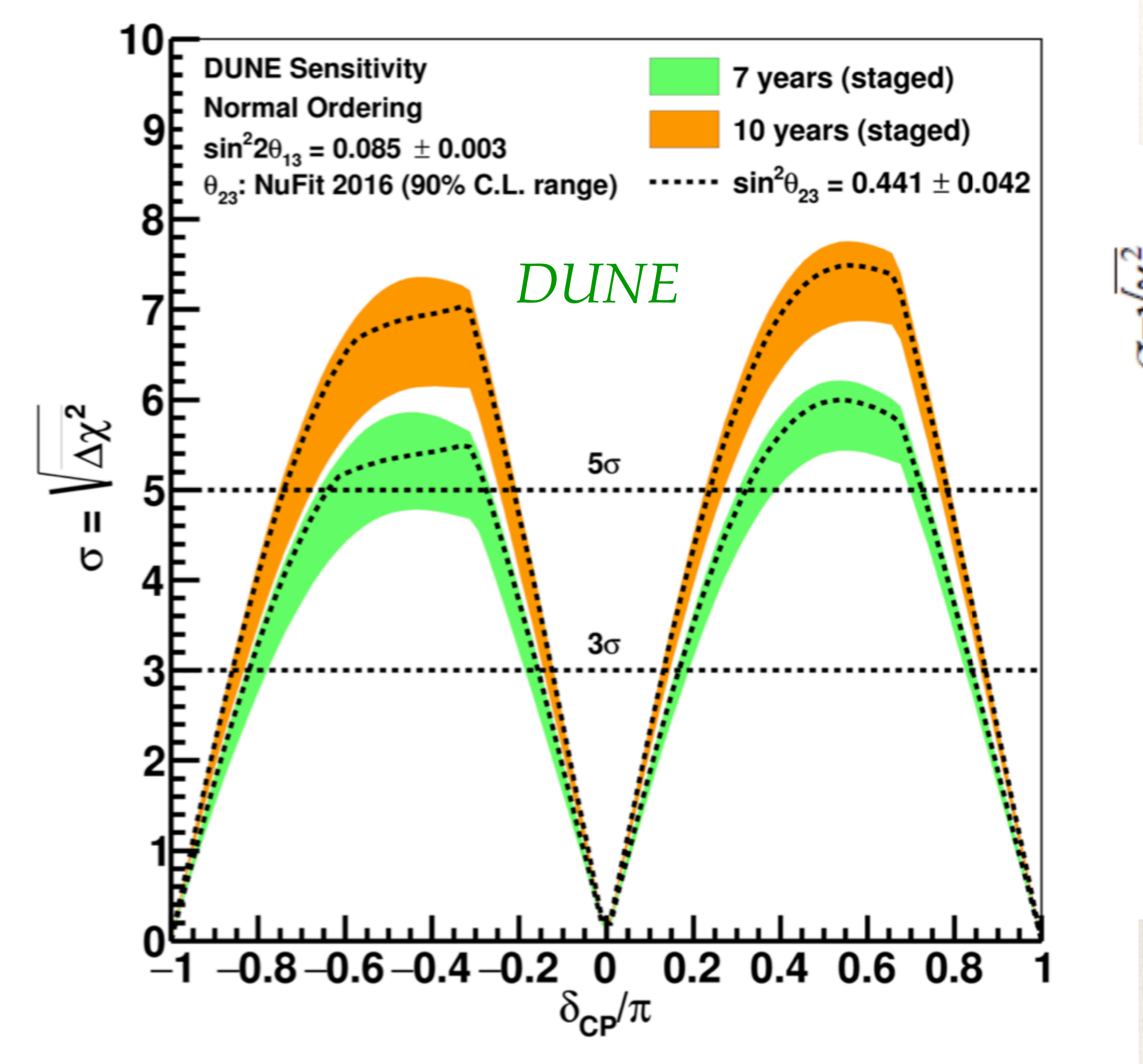


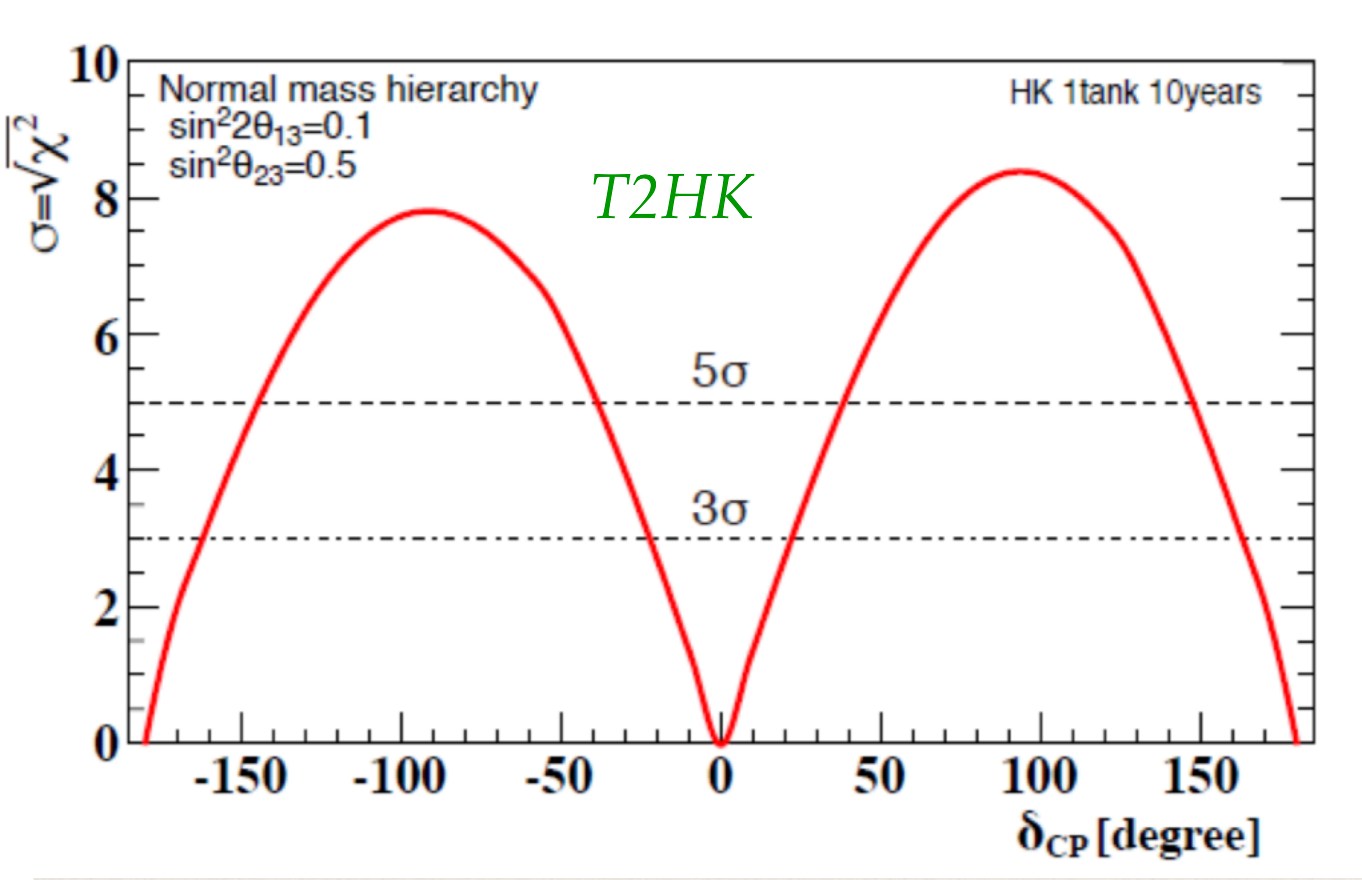
Brdar, WR, Xu, in preparation

Summary

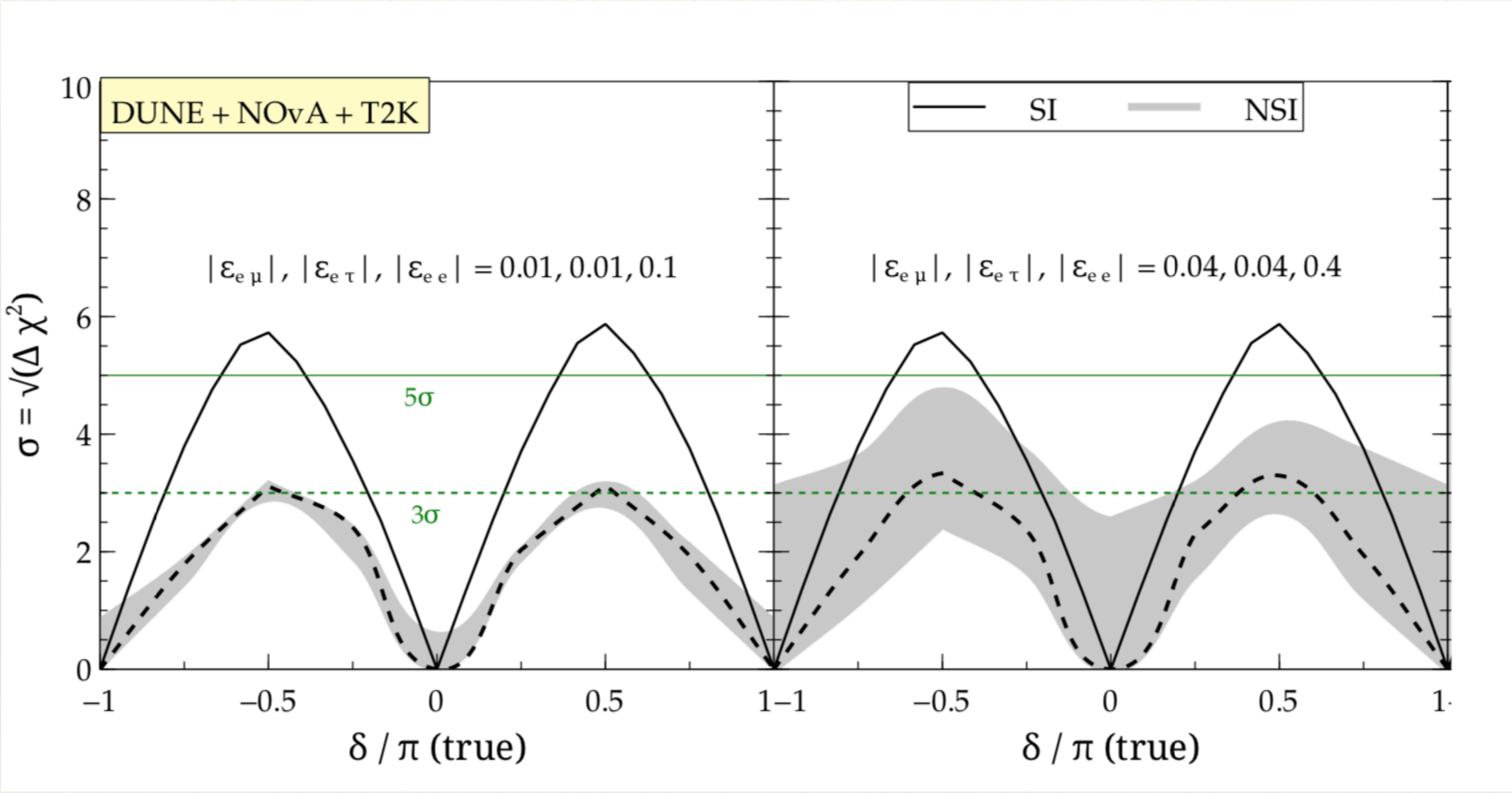
- Situation for unknown neutrino mixing parameters promising!
- Various reasons to believe neutrinos come with NP
- can generate interesting phenomenology
- both low and high masses possible!!
- can mess up our determination of parameters
- connected to various fields including colliders

Future of CP Phase





Non-Standard Interactions



Masud, Mehta, 1603.01389

東京大学
THE UNIVERSITY OF TOKYO

The University of Tokyo

Hongo, Bunkyo-ku, Tokyo 113-8654, Japan

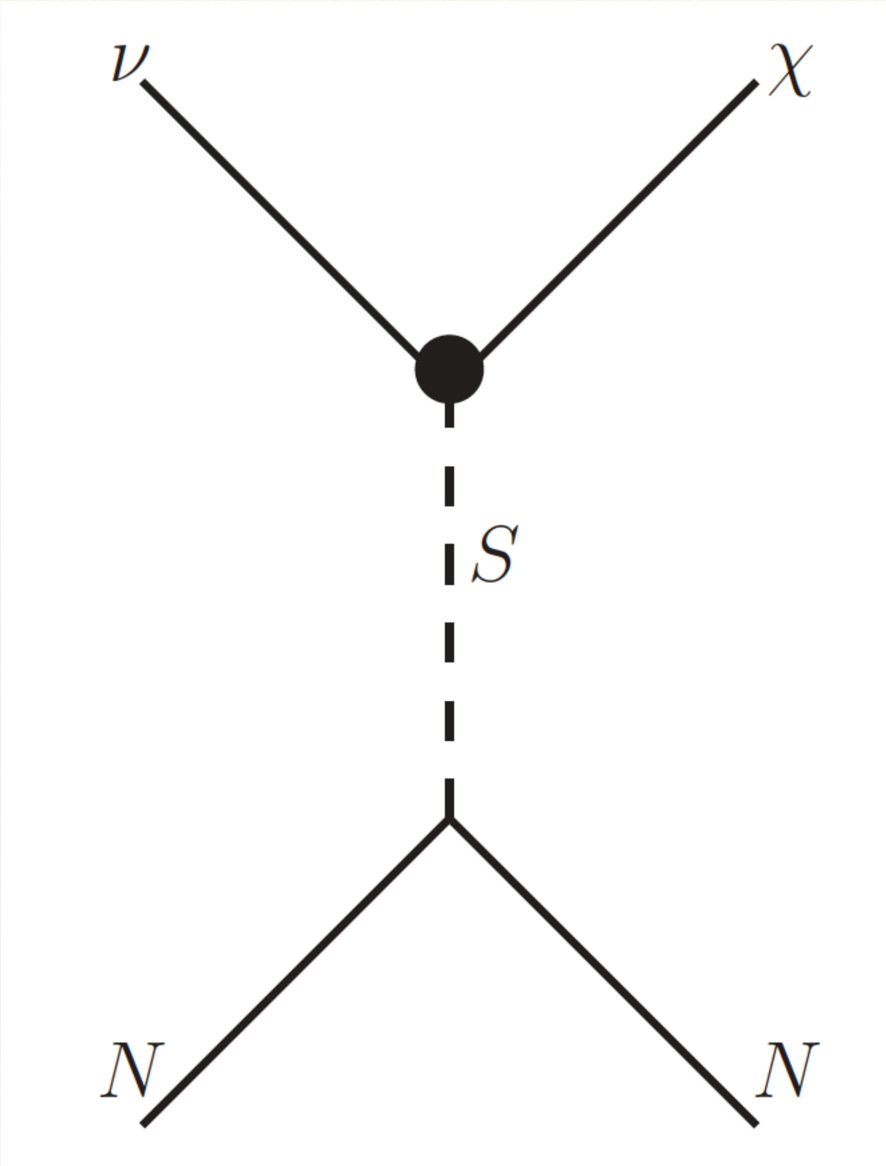
September 12th, 2018

Concerning the Start of Hyper-Kamiokande

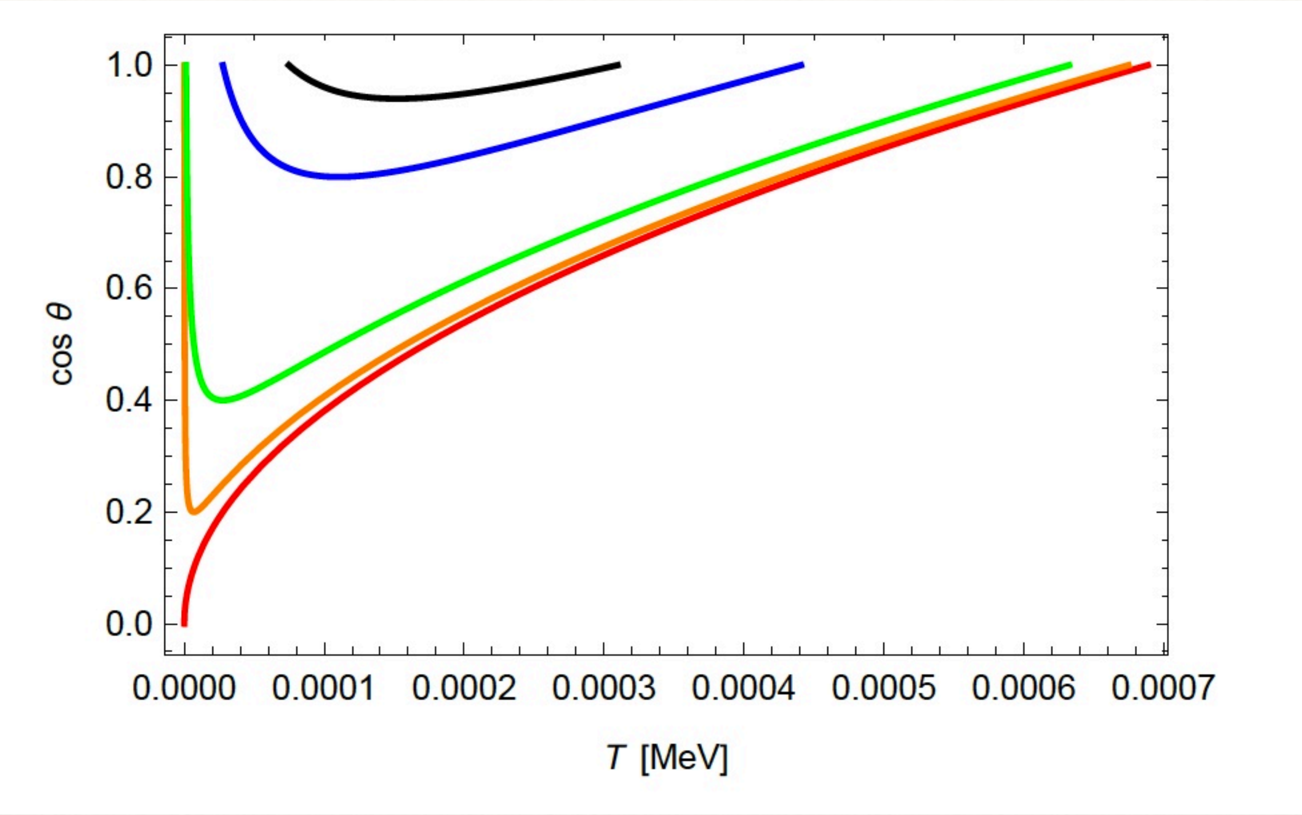
Seed funding towards the construction of the next-generation water Cherenkov detector Hyper-Kamiokande has been allocated by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) within its budget request for the 2019 fiscal year. Seed fundings in the past projects usually lead to full funding in the following year, as it was the case for the Super-Kamiokande project.

The University of Tokyo pledges to ensure construction of the Hyper-Kamiokande detector commences as scheduled in April 2020. The University of Tokyo has made

New Physics in Coherent Scattering

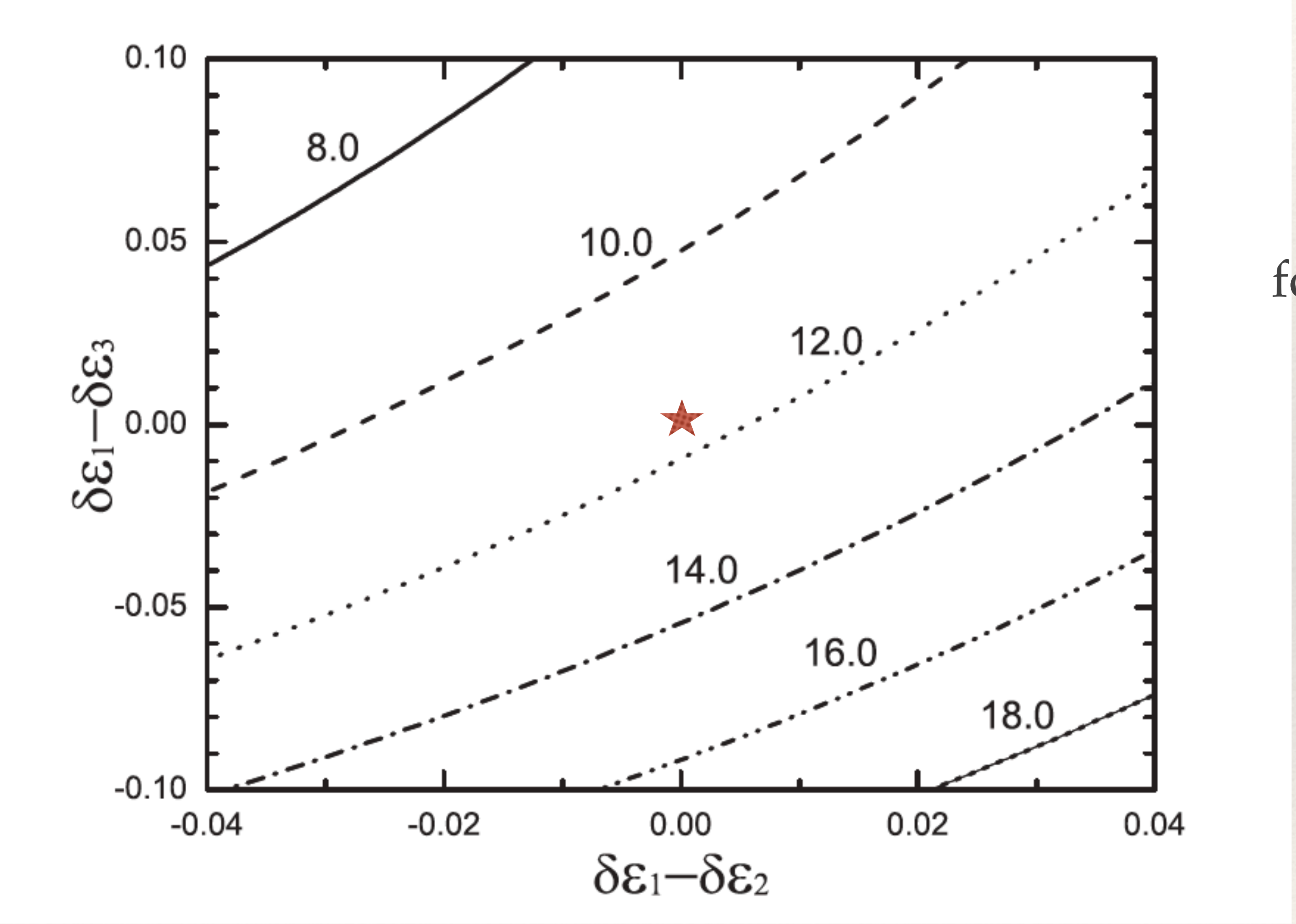


can also produce new particle (could be DM and related to neutrino mass)



Brdar, WR, Xu, in preparation

Non-Standard Interactions

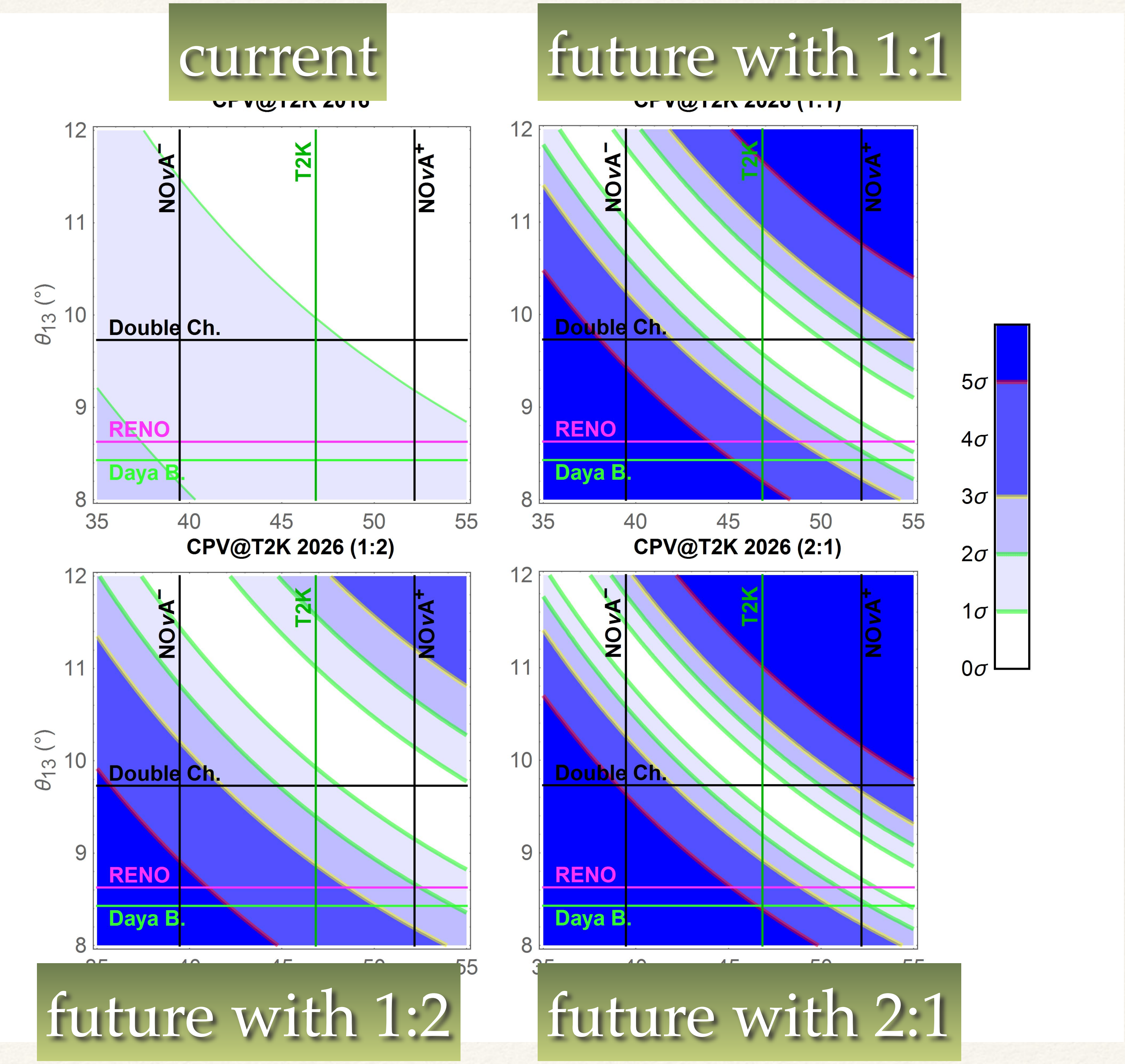


JUNO, 1507.05613

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

Note: production
and detection NSIs….

CP Phase



Significance of CP Violation

$$\chi^2_{\rm CPV}(\theta_{23},\theta_{13}) = \min_{\delta_{CP}=0 \text{ or } \pi}\left[\chi^2_{\nu_e+\overline{\nu}_e}(\theta_{23},\theta_{13},\delta_{CP})\right] - \min_{\delta_{CP}\in[-\pi,\pi]}\left[\chi^2_{\nu_e+\overline{\nu}_e}(\theta_{23},\theta_{13},\delta_{CP})\right]$$

can gain up to 1σ,
having more neutrinos
seems to be better…
but depends on θ_{13} and θ_{23}
Lindner, WR, Xu, 1709.10252

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?) $\nu_{e;}$ 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

Mass Ordering

- 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*)

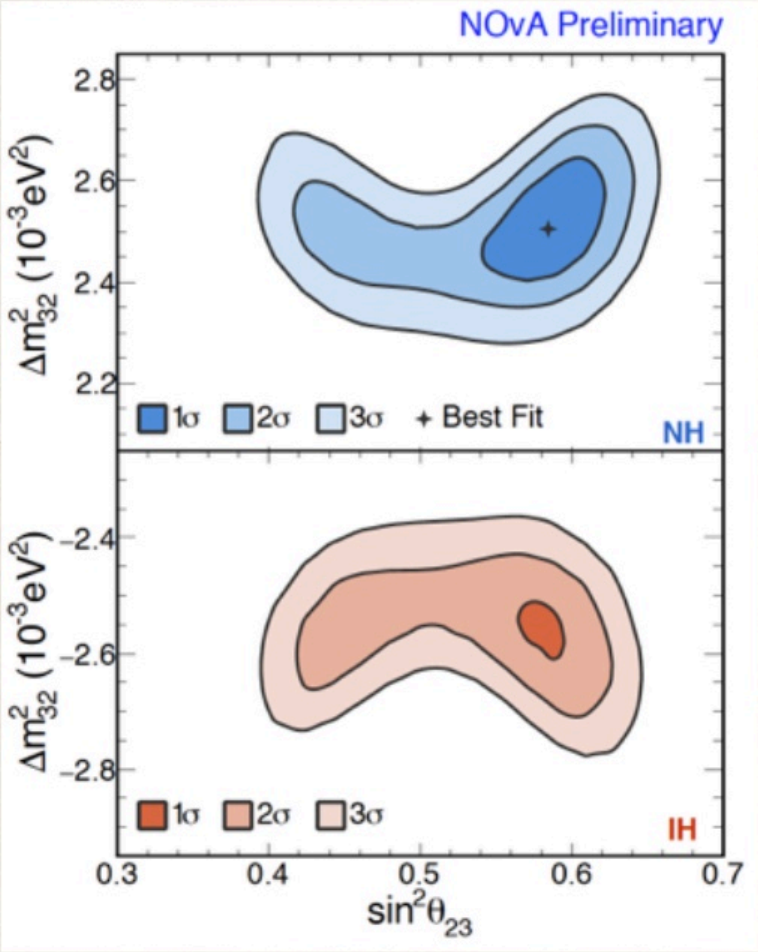
New data presented @Nu2018

see talks by Sekiguchi, Bhatnagar

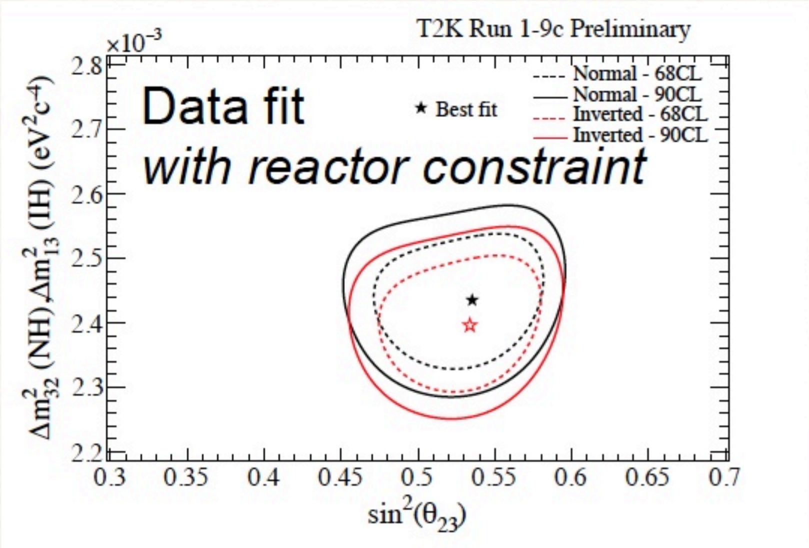
First NOνA antineutrino data

Talk by M. Sánchez

neutrino + antineutrino fit



New T2K antineutrino data

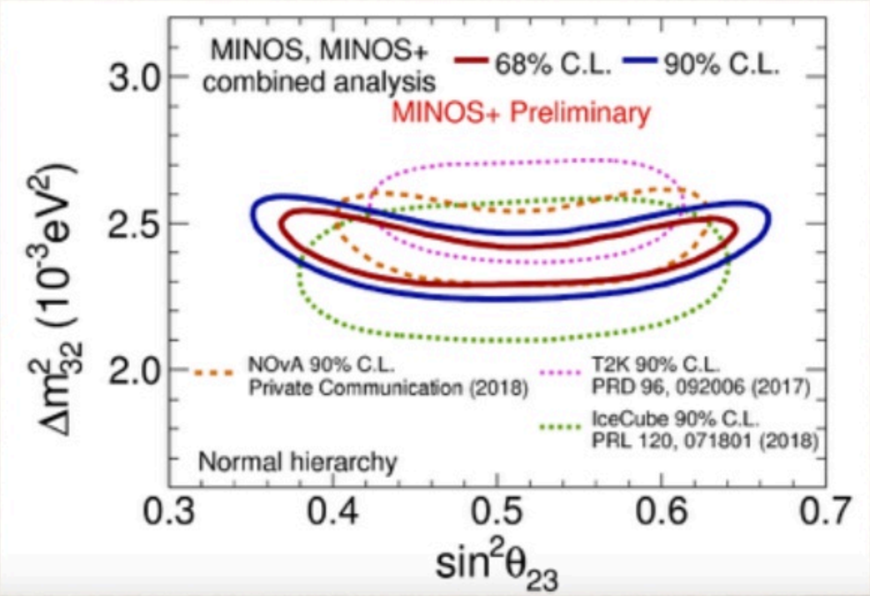


Monday June 4th

Talk by M.Wascko

New combined analysis MINOS/ MINOS+

Talk by A. Aurisano

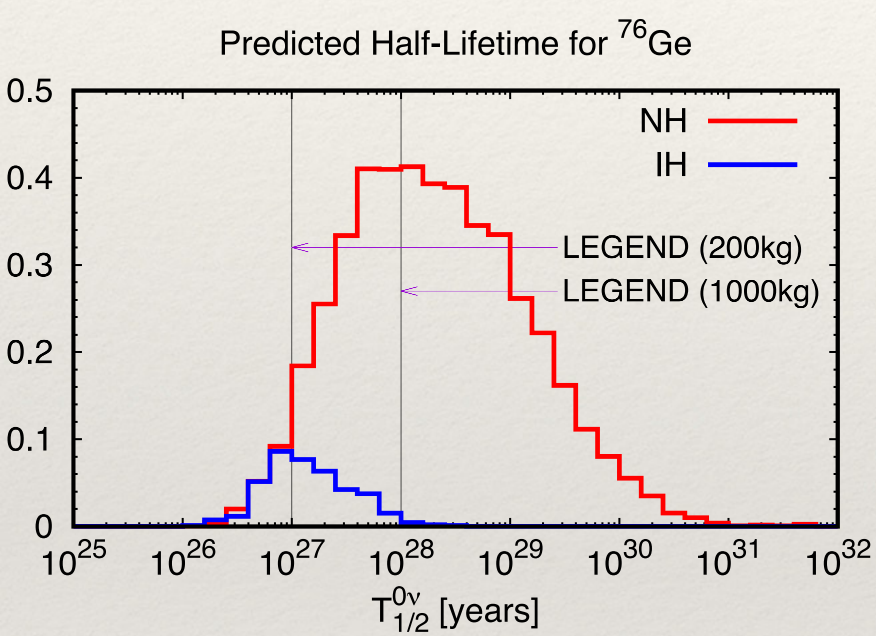


Tortola, talk at Neutrino 2018

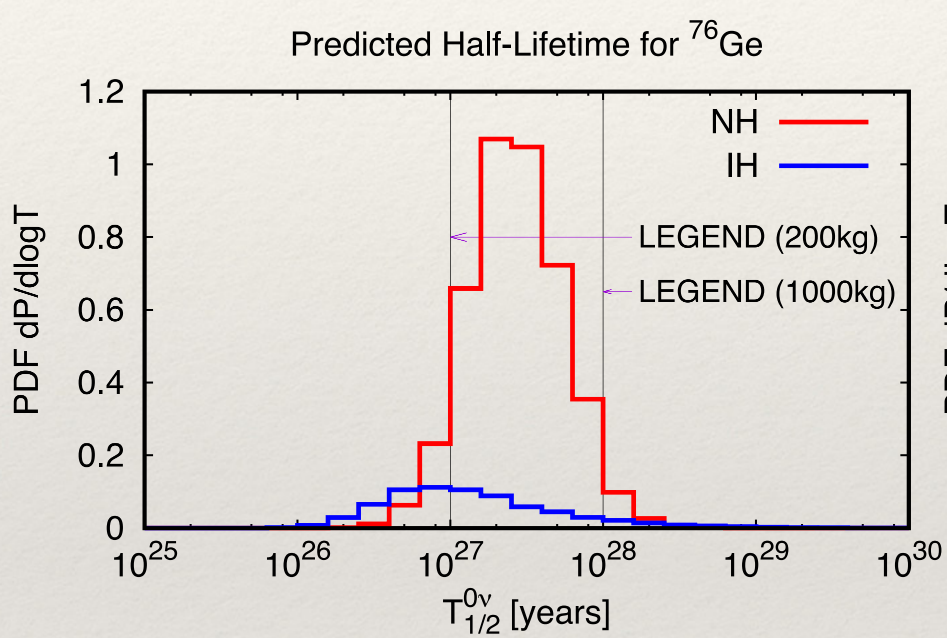
…probably adds another σ to each hint…

Expectations for half-lifes

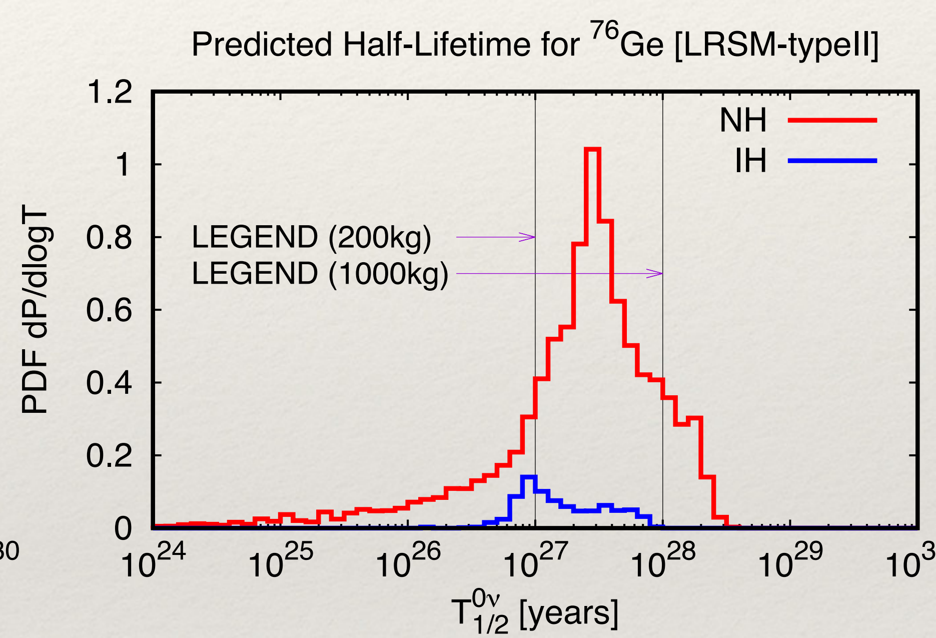
Standard



Sterile



Left-right



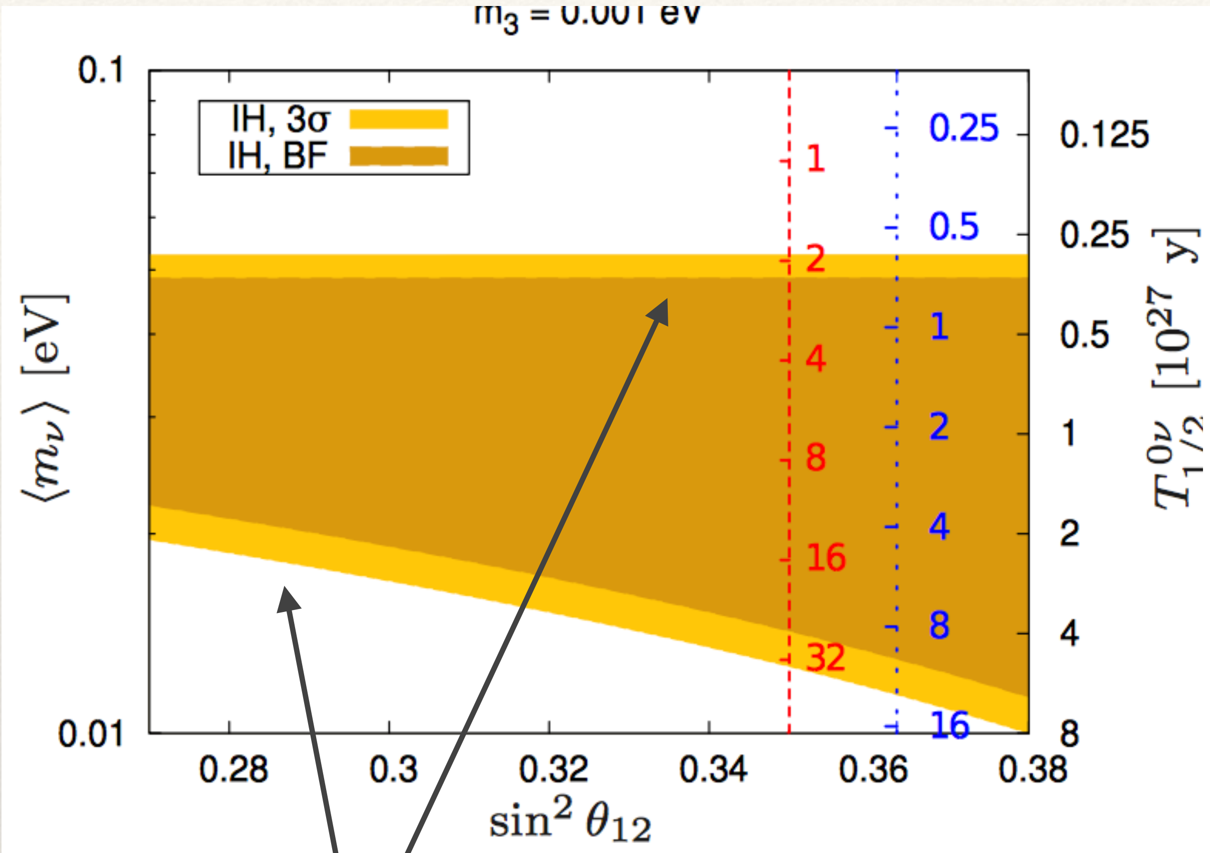
Ge, WR, Zuber, 1707.07904

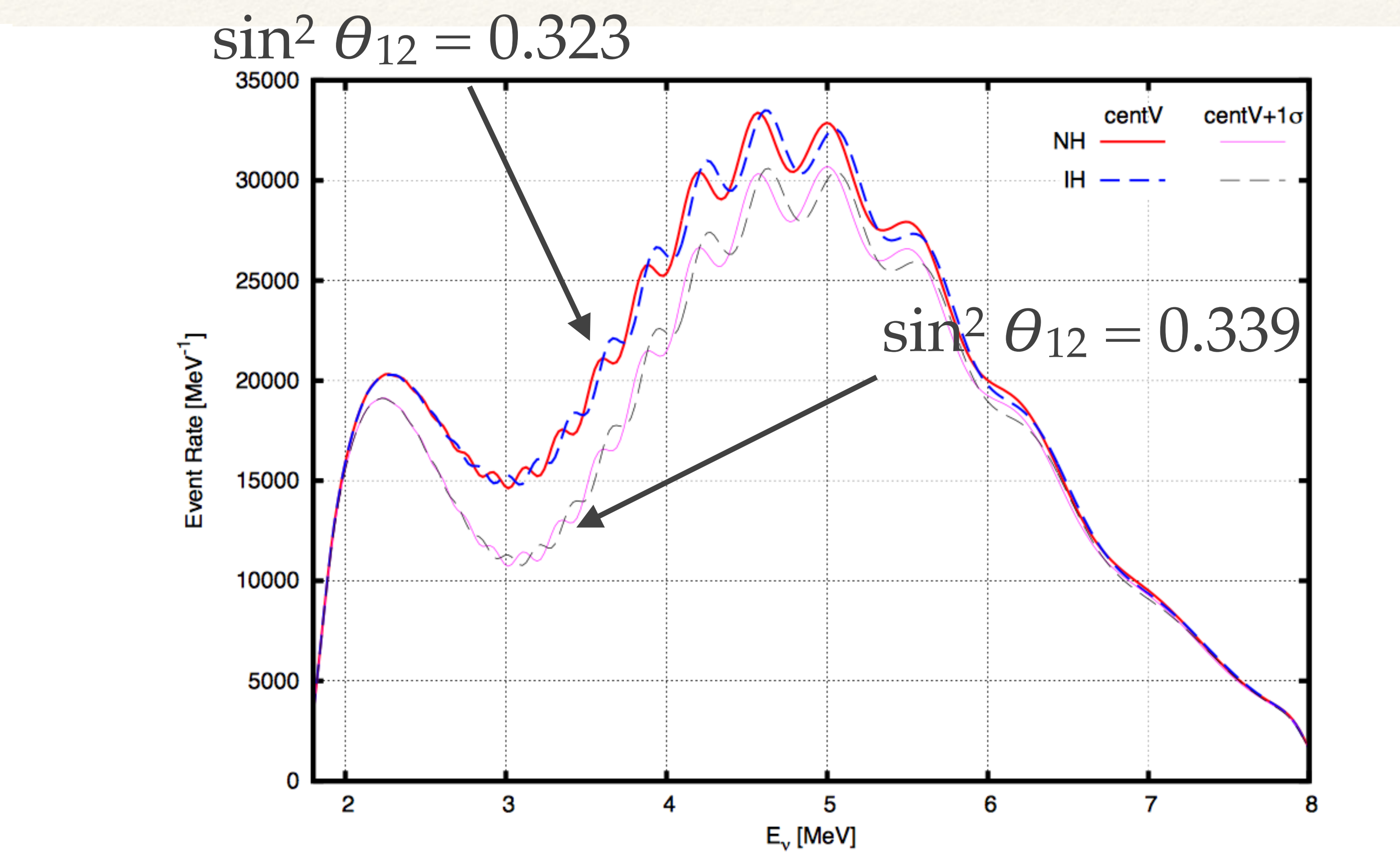
For standard scenario, see also Agostini et al, 1705.02996; Caldwell et al., 1705.01945; Zhang, Zhou, 1508.05472; Benato, 1510.01089

However, most alternative mechanisms unrelated to neutrino parameters…

…thus decoupled from cosmology (and direct experiments)!

Connections to future Oscillation Experiments





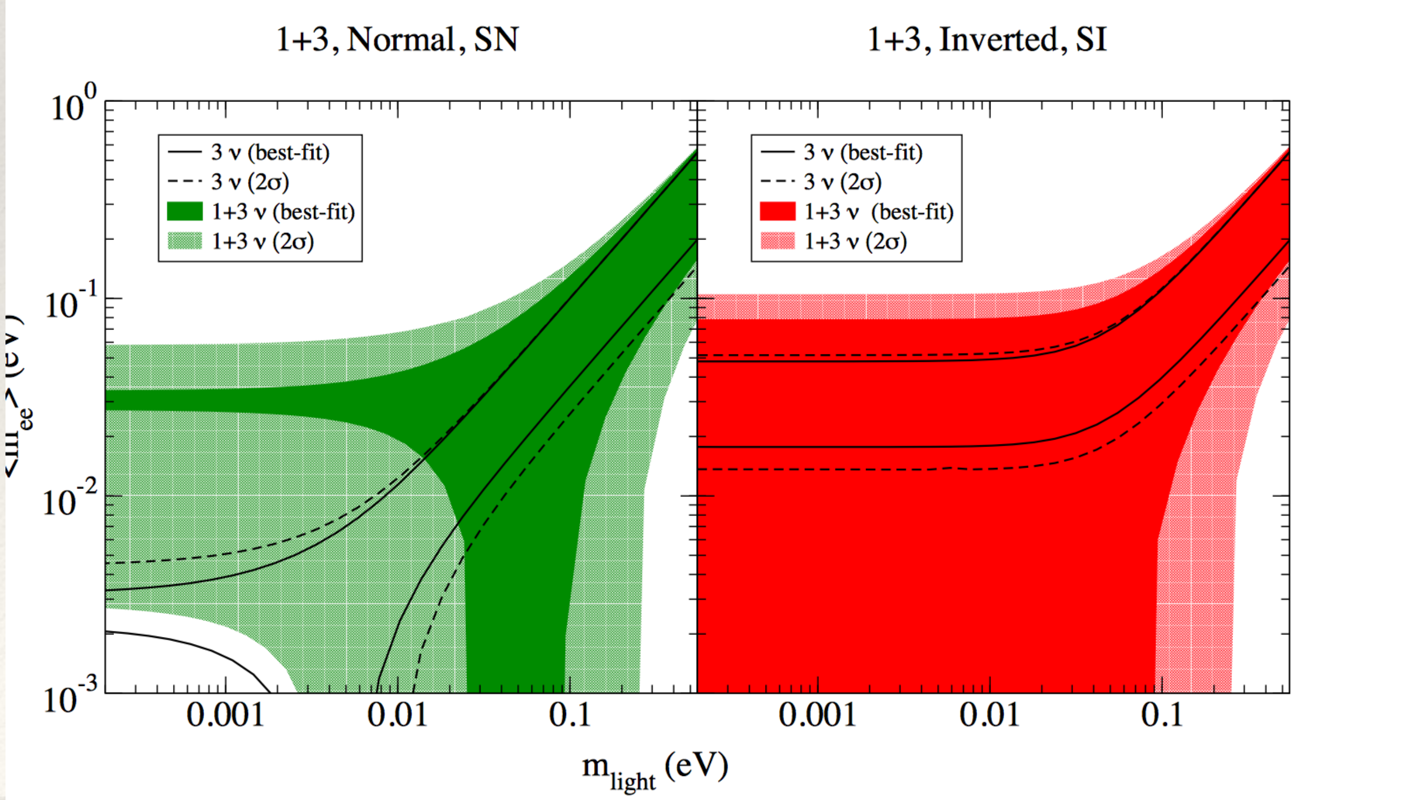
Nature gives us two scales

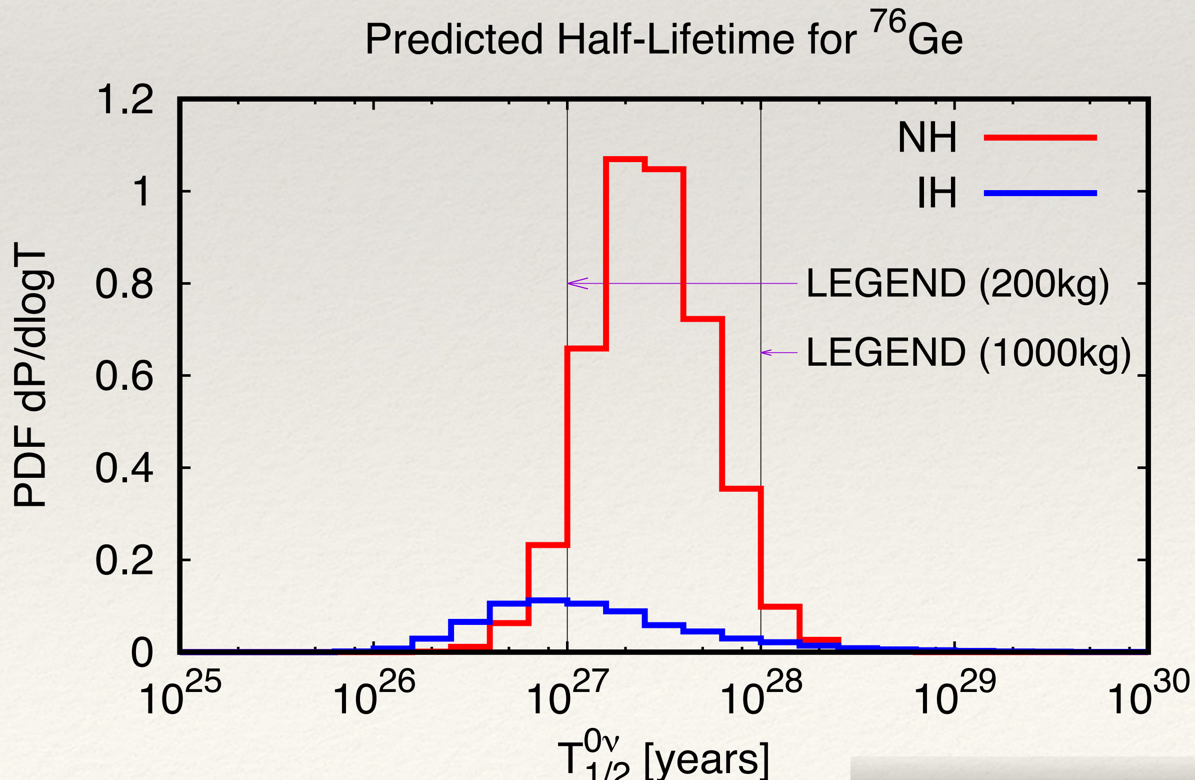
JUNO fixes θ_{12} and removes uncertainty in value of minimal m_{ee} in IH

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

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!

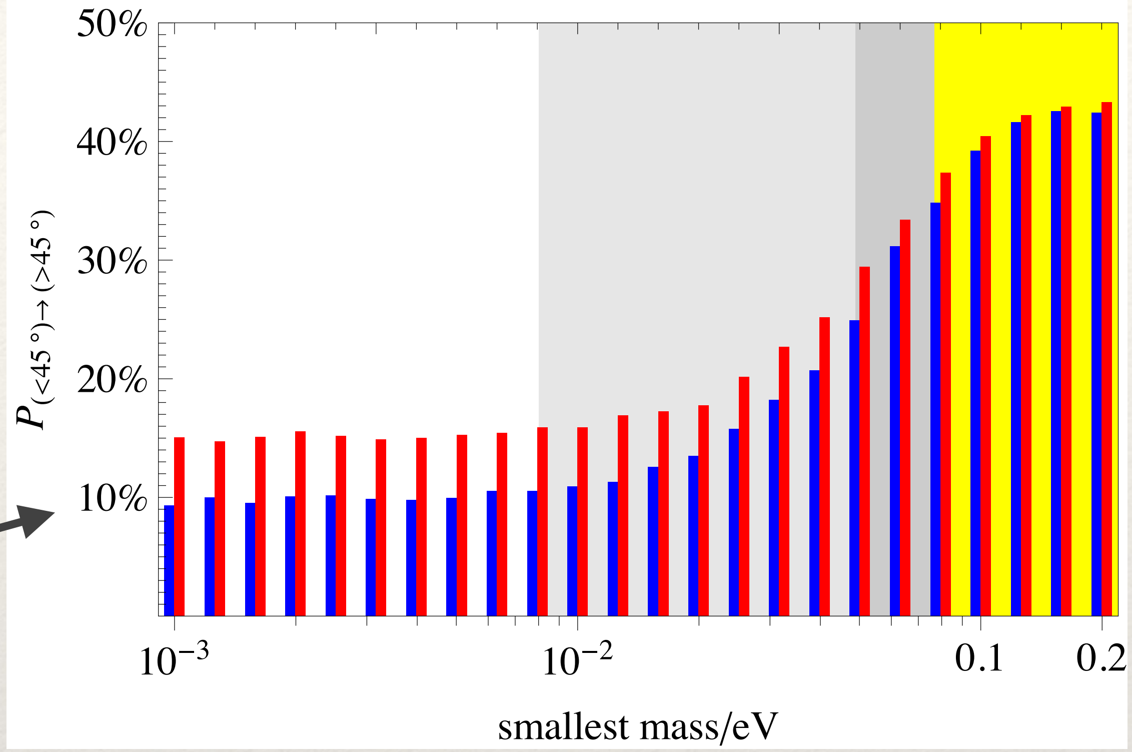




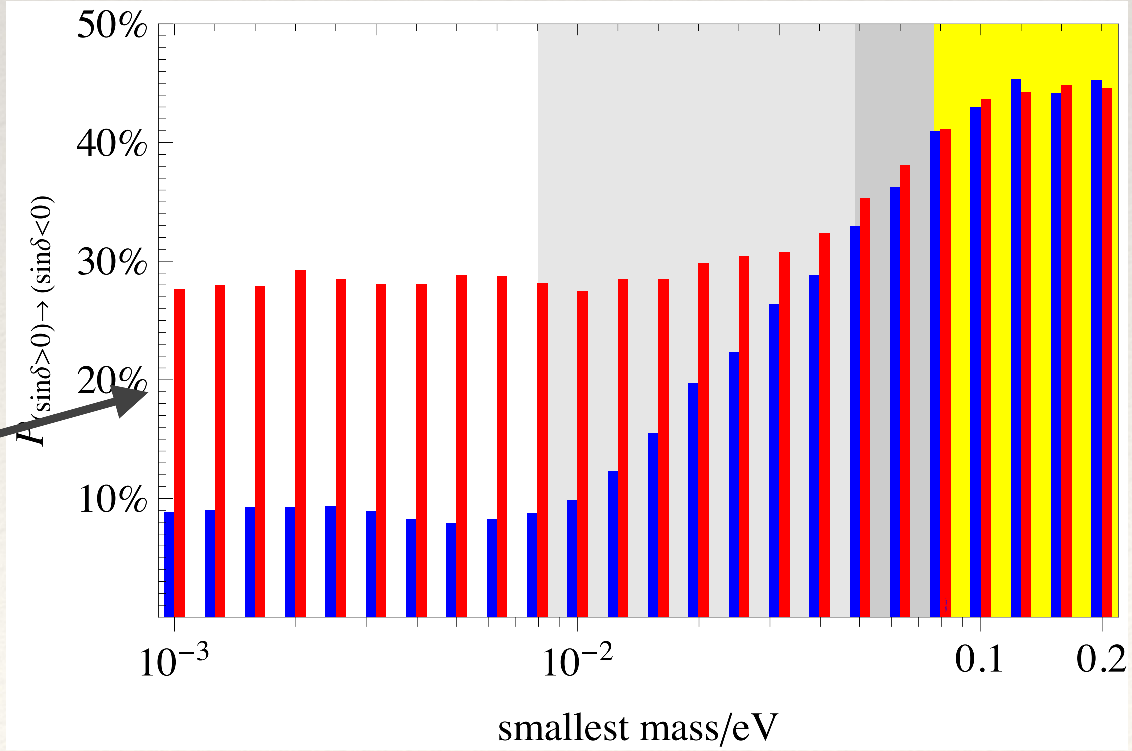
Implications

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

probability to change octant of θ_{23}



(normal/inverted)



WR, Xu, 1508.06063

- „Maximal" $\delta = 3\pi/2$?

probability to change sign of $\sin\delta$

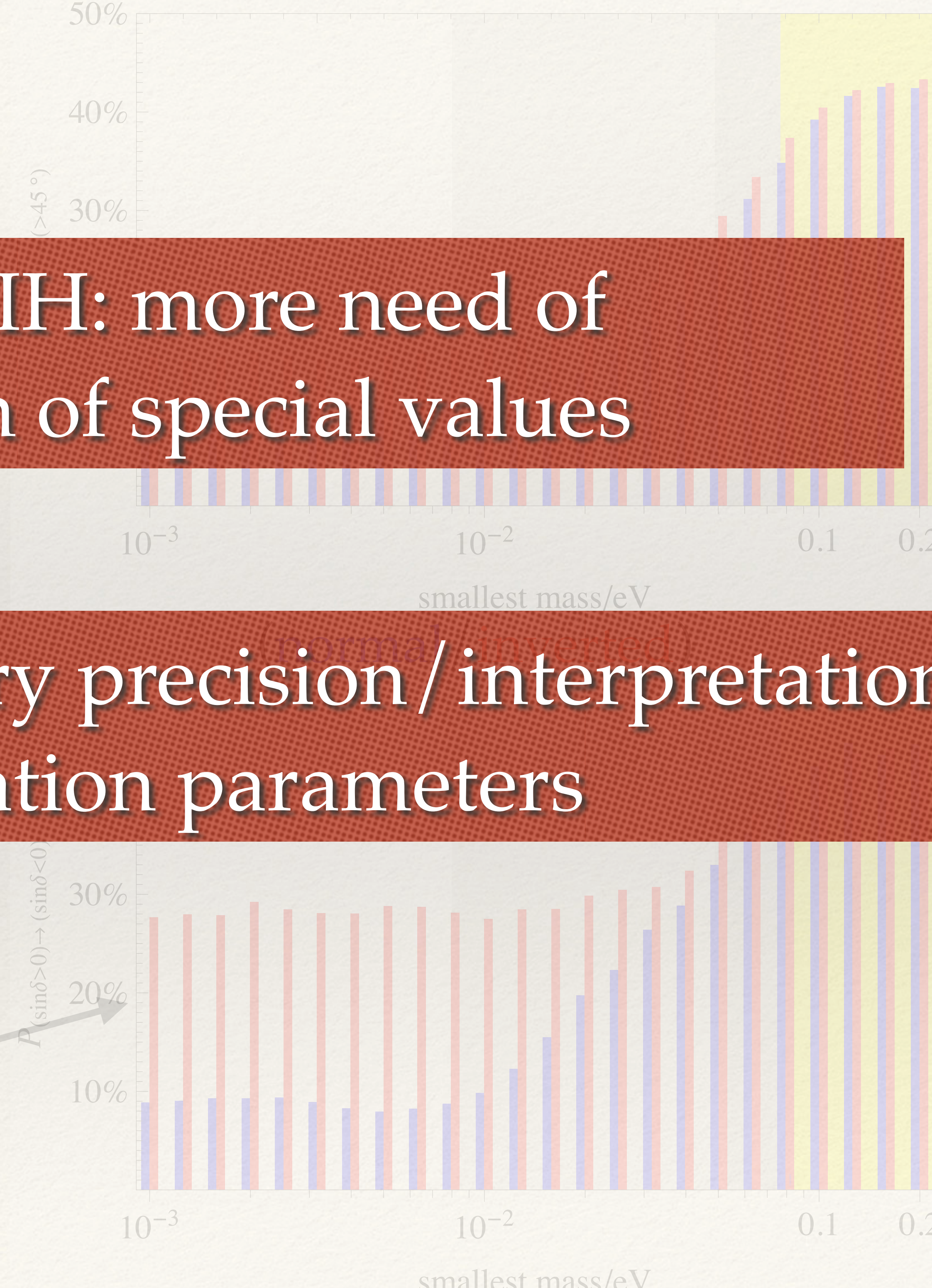
Implications

- Maxi…

pro… octant of θ_{23}

- „Maximal“ $\delta = 3\pi/2$?

probability to change sign of sin δ



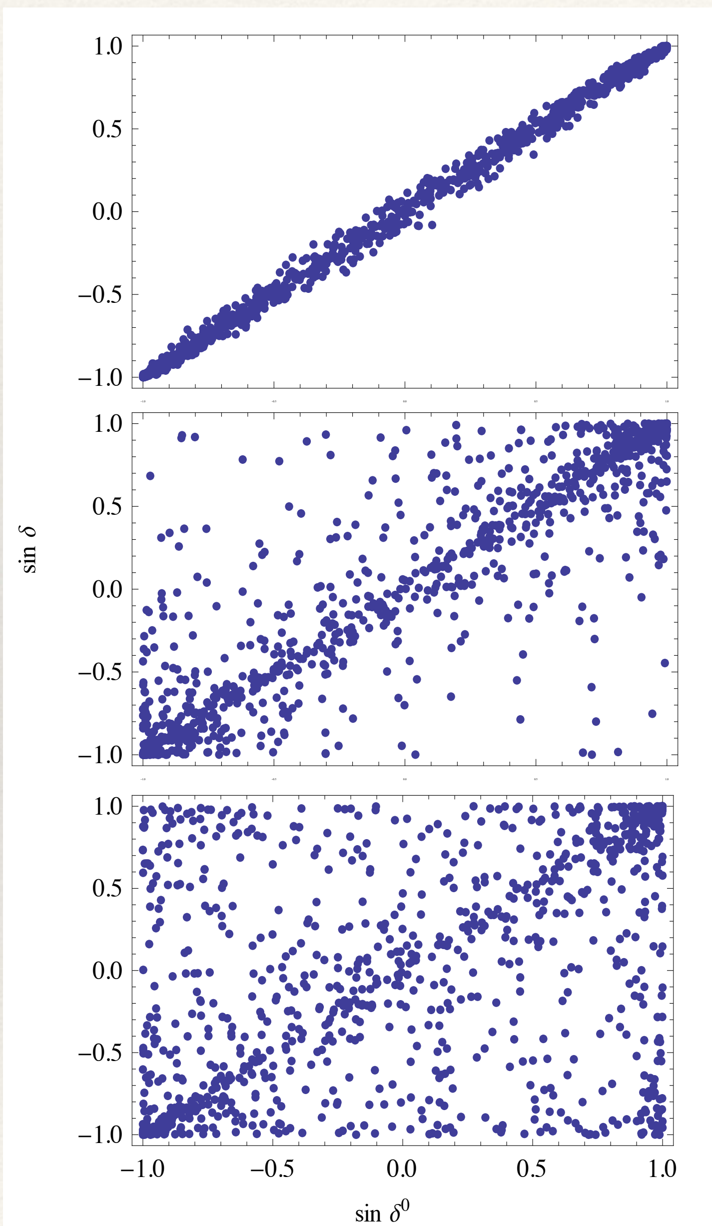
If QD or IH: more need of protection of special values

impact on necessary precision/interpretation of oscillation parameters

Perturbations

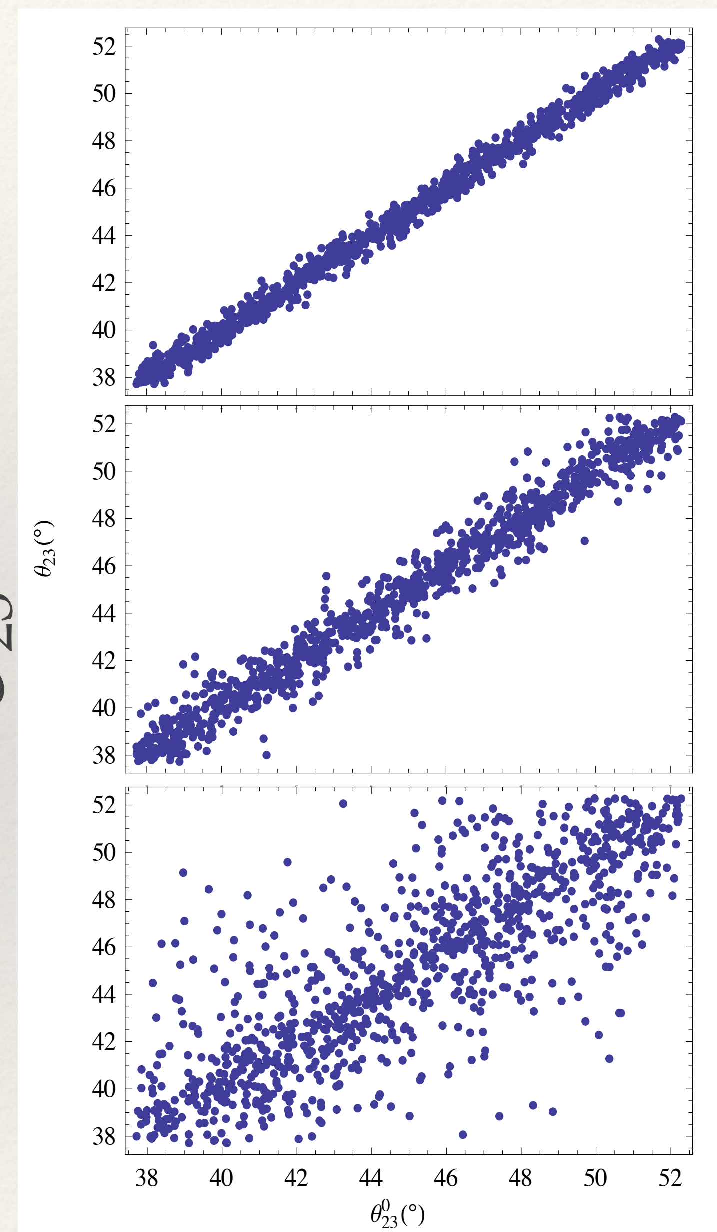
smallest mass:

$\sin\delta$



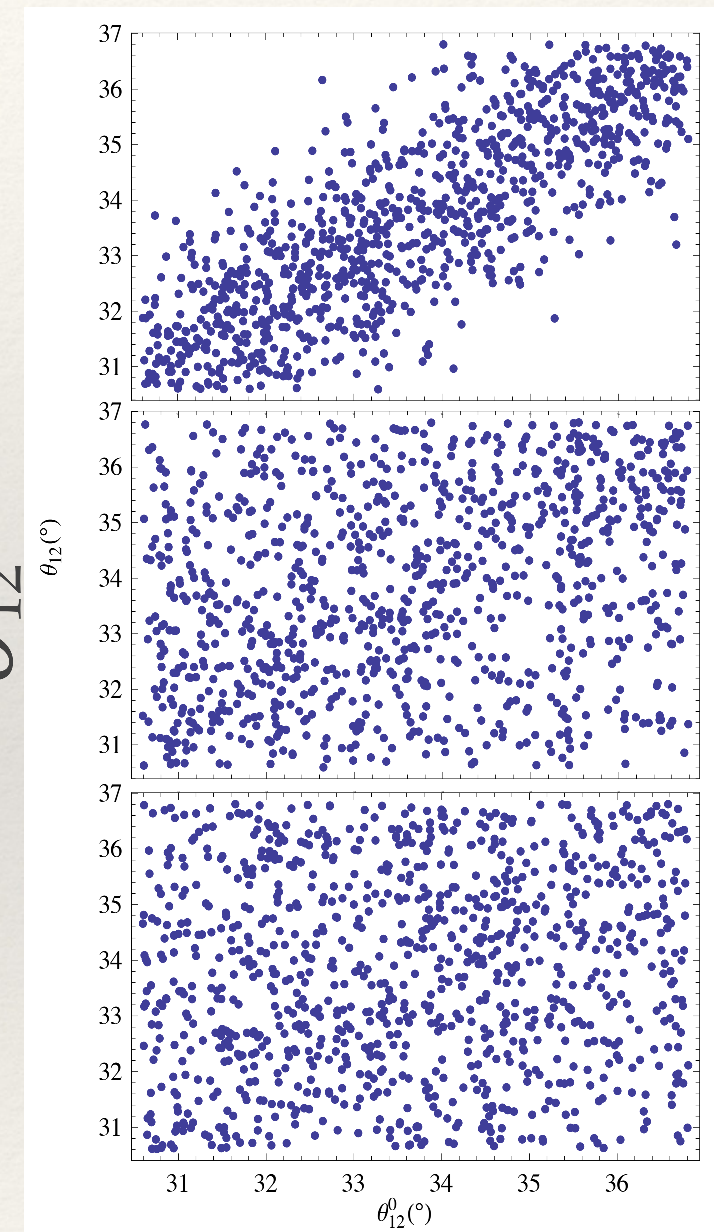
$\sin\delta^0$

θ_{23}



$\theta_{23}{}^0$

θ_{12}



$\theta_{12}{}^0$

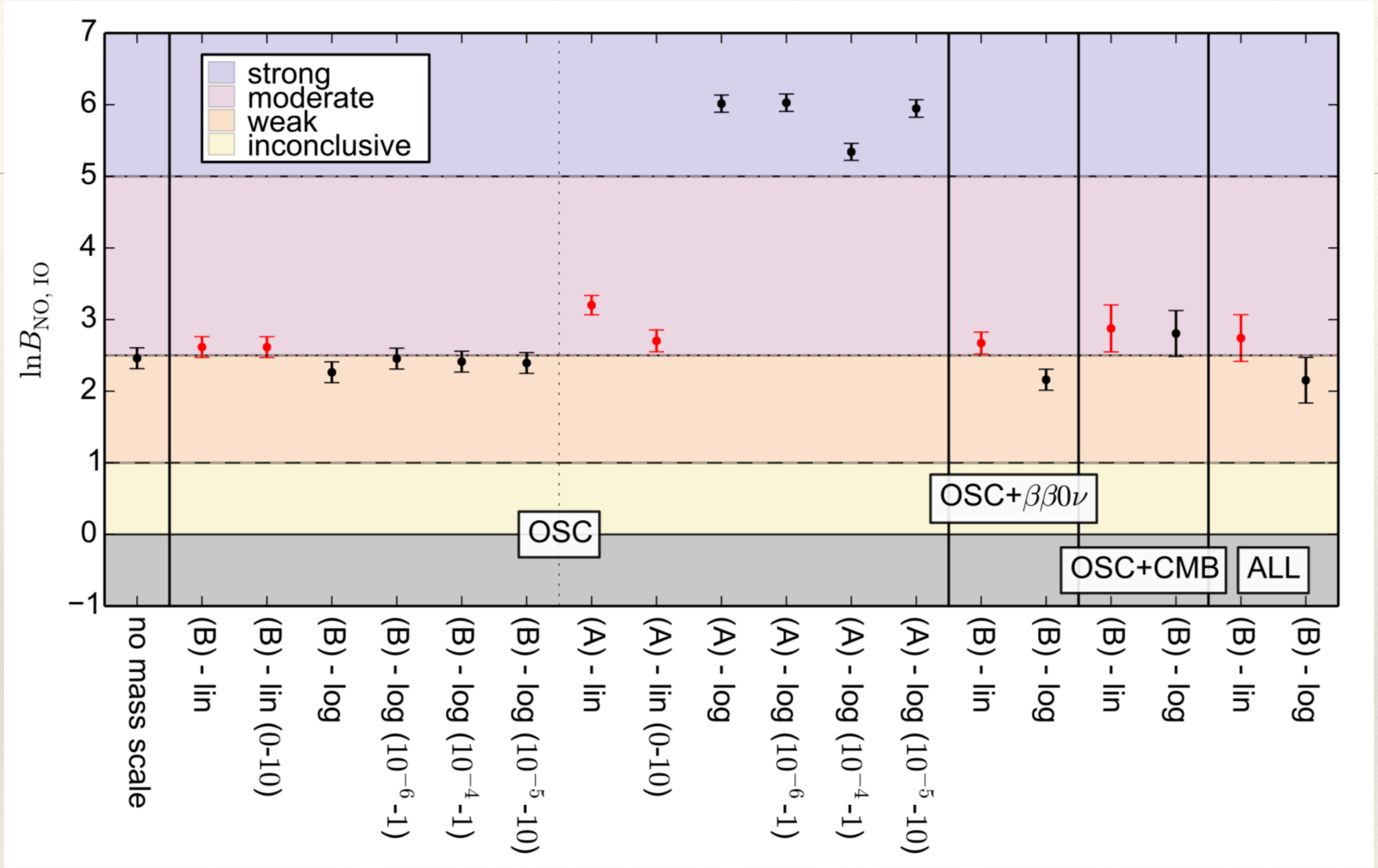
0.001 eV

0.04 eV

0.1 eV

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

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

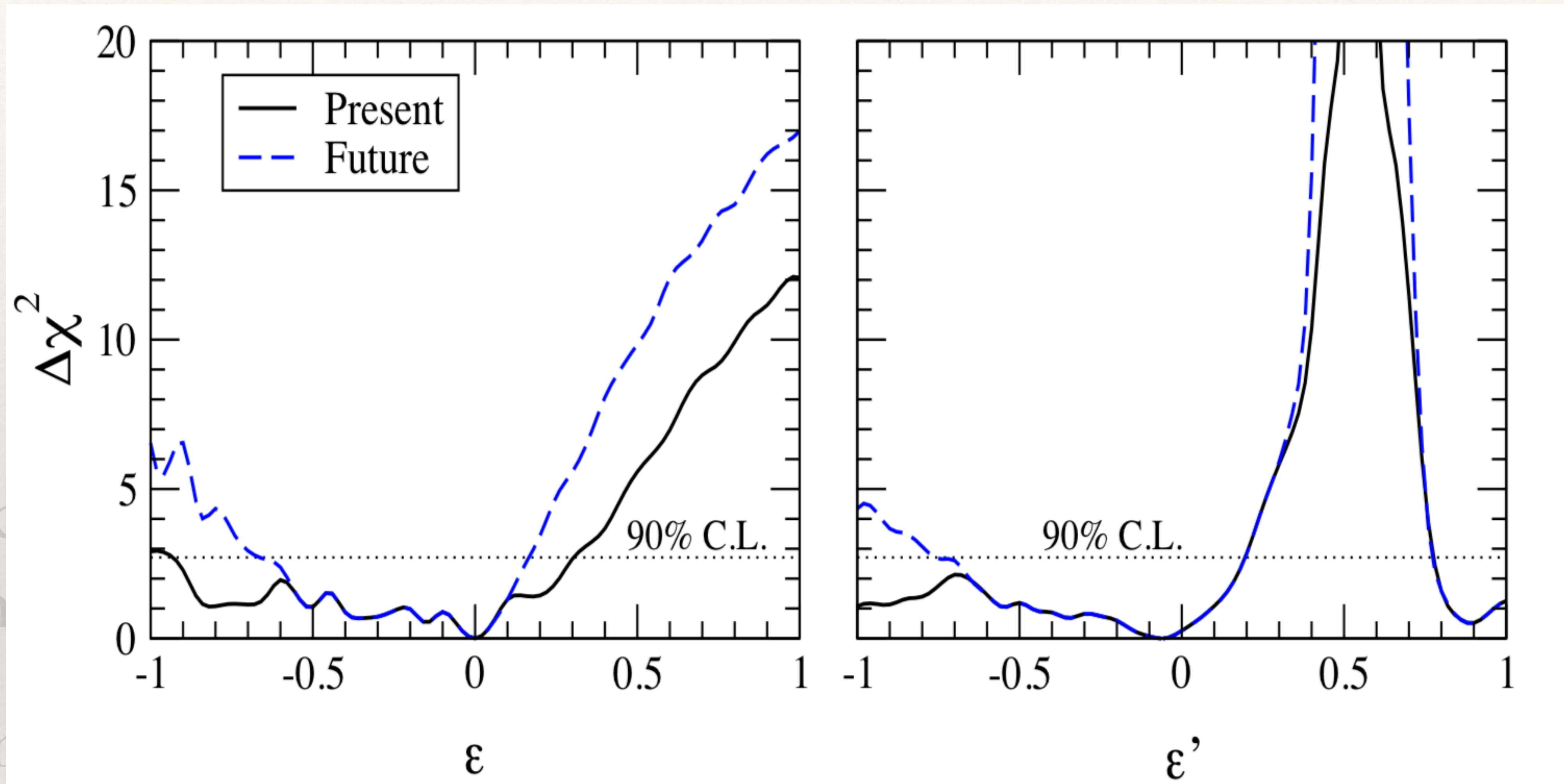
large

Example RG enhancement:

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

	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



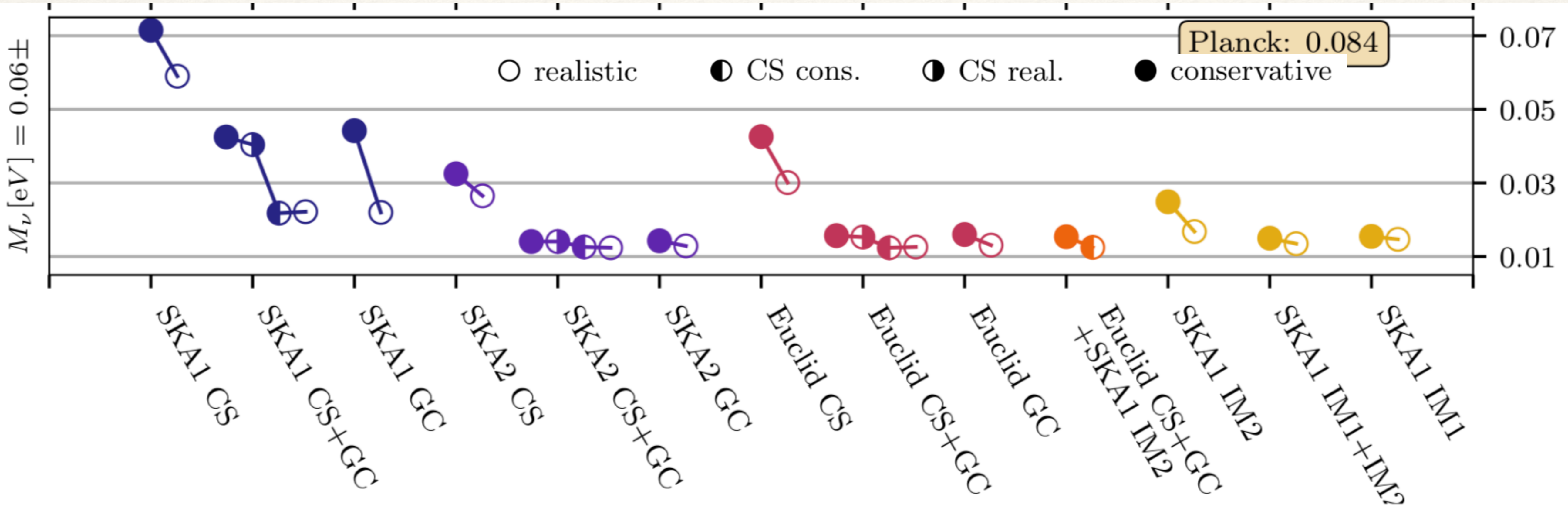
$$\varepsilon = -\sin\theta_{23}\,\varepsilon^{dV}_{e\tau} \qquad \varepsilon' = \sin^2\theta_{23}\,\varepsilon^{dV}_{\tau\tau} - \varepsilon^{dV}_{ee}$$

Miranda, Tortola, Valle, hep-ph/0406280

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

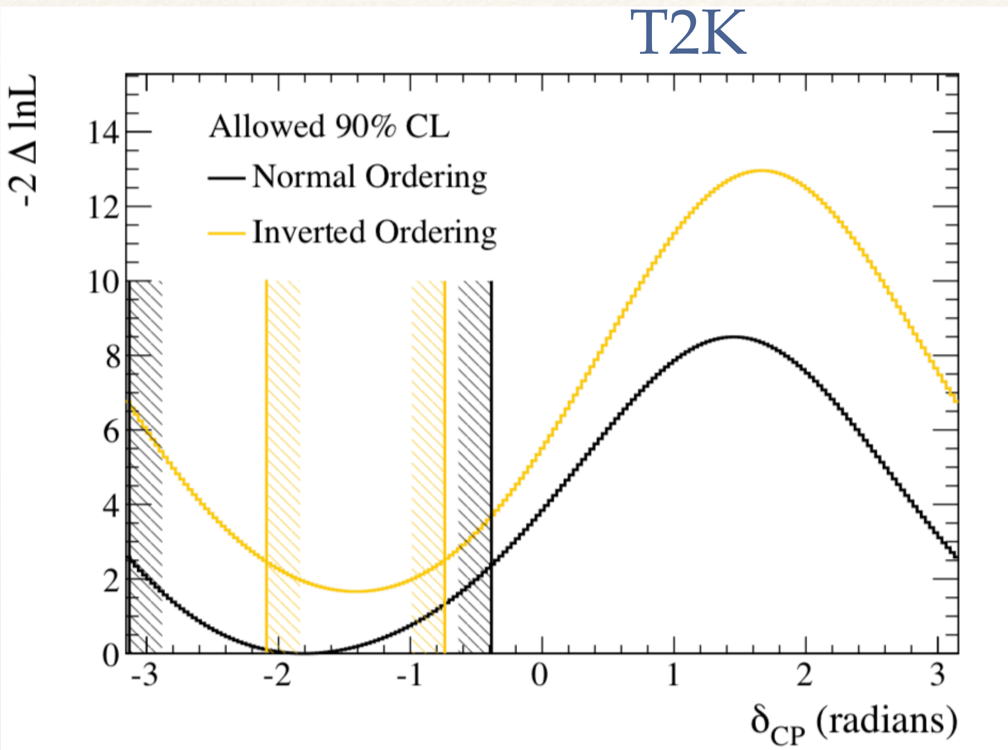
Neutrino Mass guaranteed?

Sprenger et al., 1801.08331



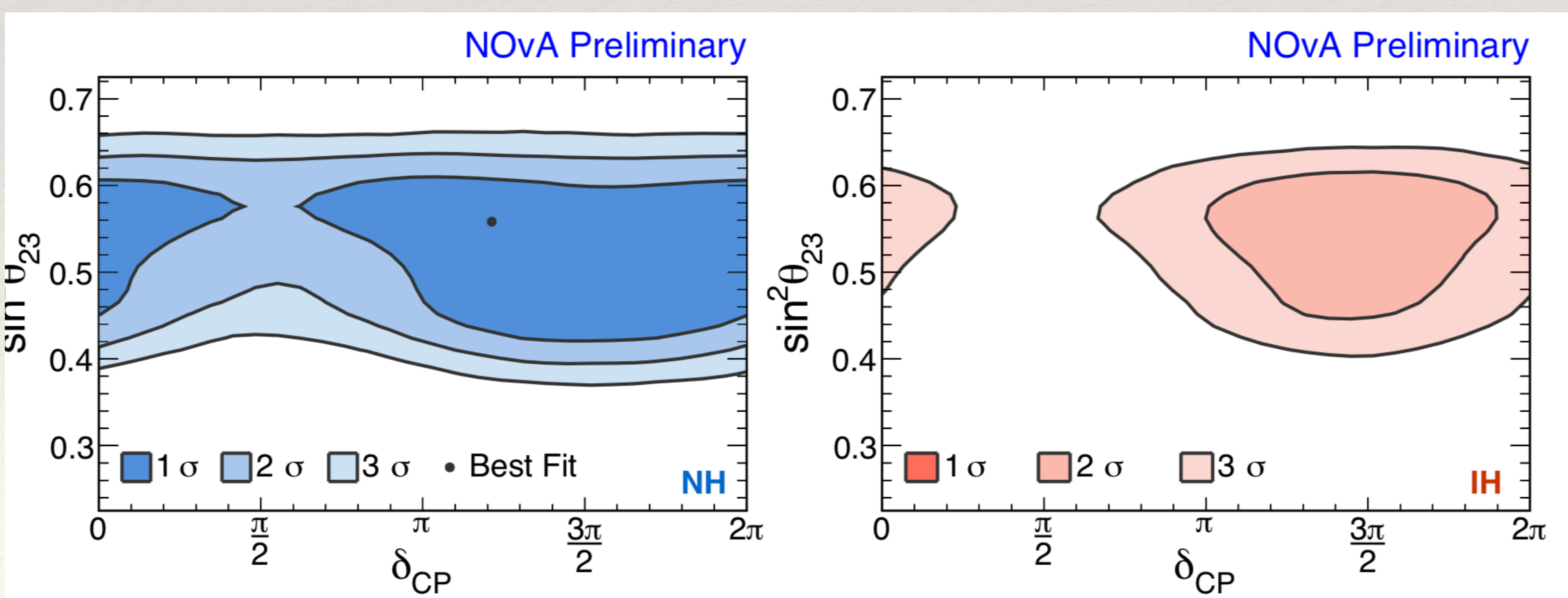
5σ detection when Euclid and SKA are combined!

CP Phase



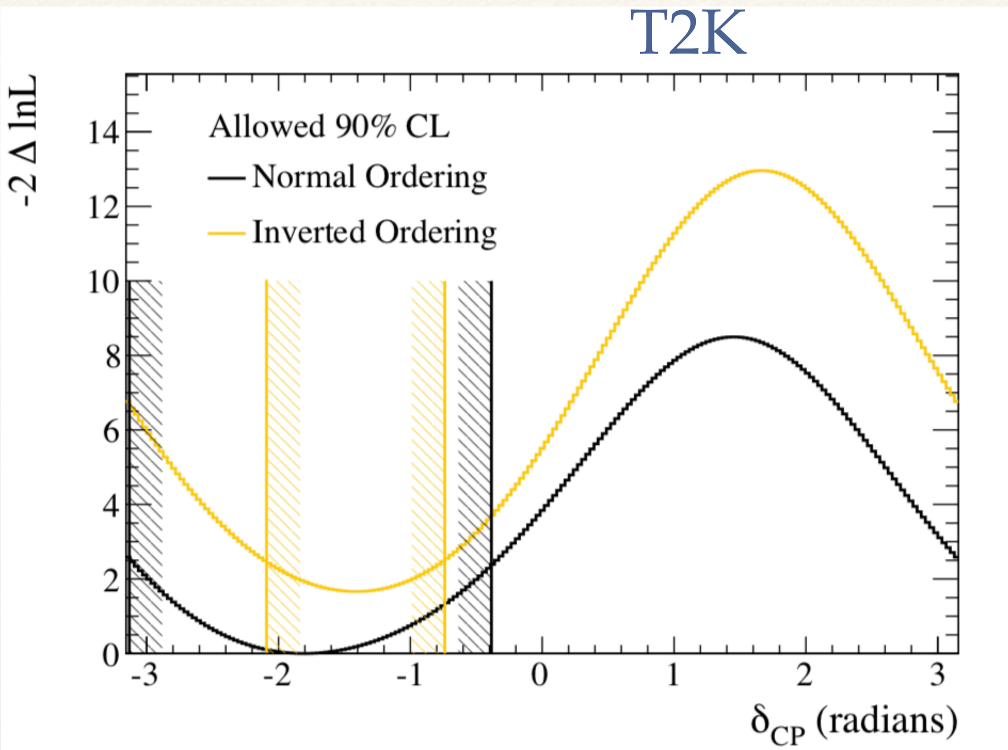
Normal	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\overline{\nu}_e$	6.0	6.9	7.7	6.8	4
Inverted	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν_e	25.4	21.3	17.1	21.3	32
$\overline{\nu}_e$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

mostly driven by too many ν_e at T2K



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

CP Phase



Normal	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν_e	28.7	24.2	19.6	24.1	32
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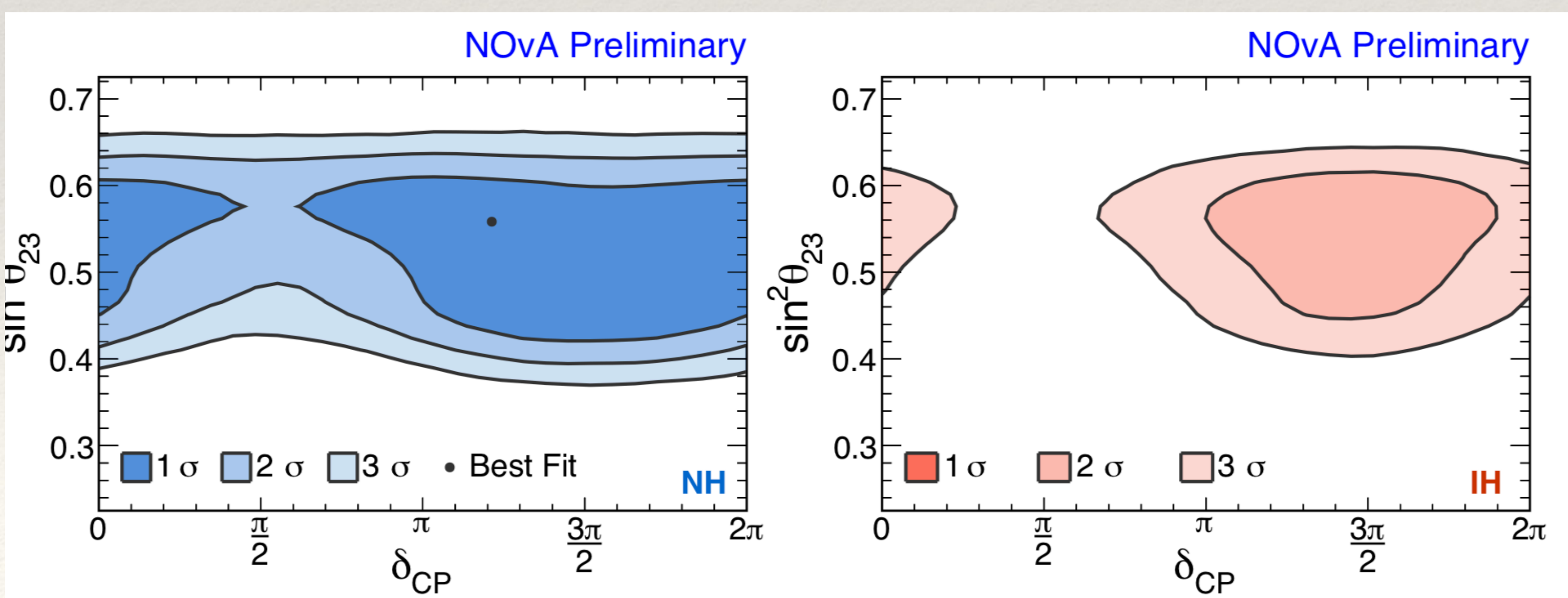
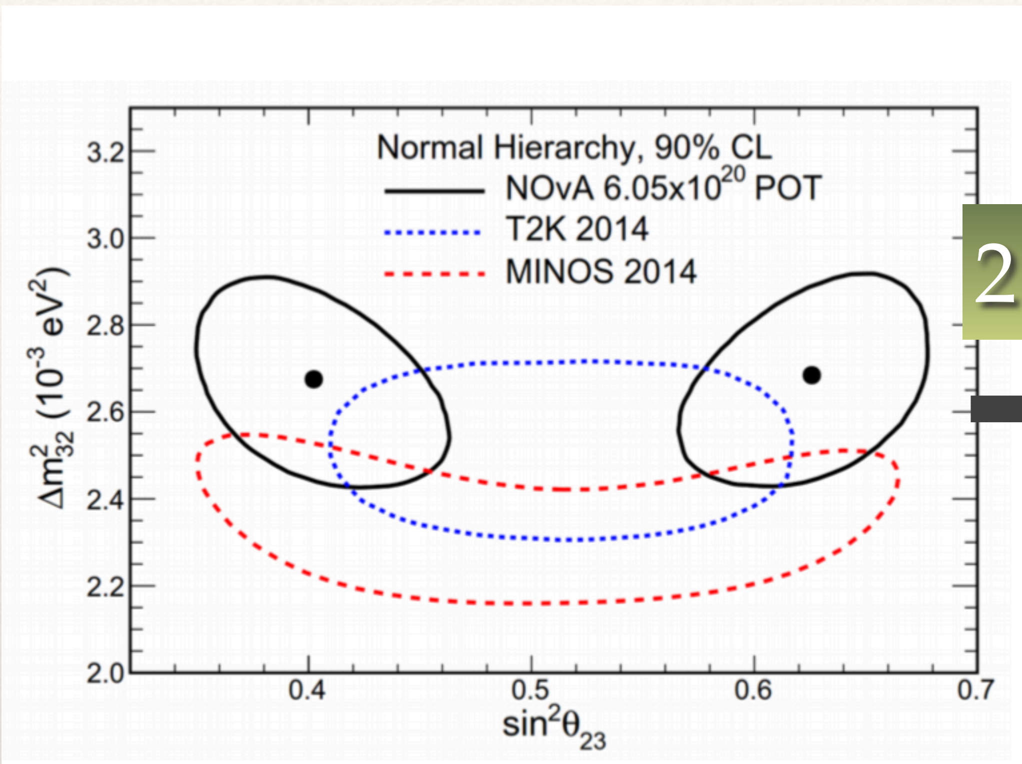


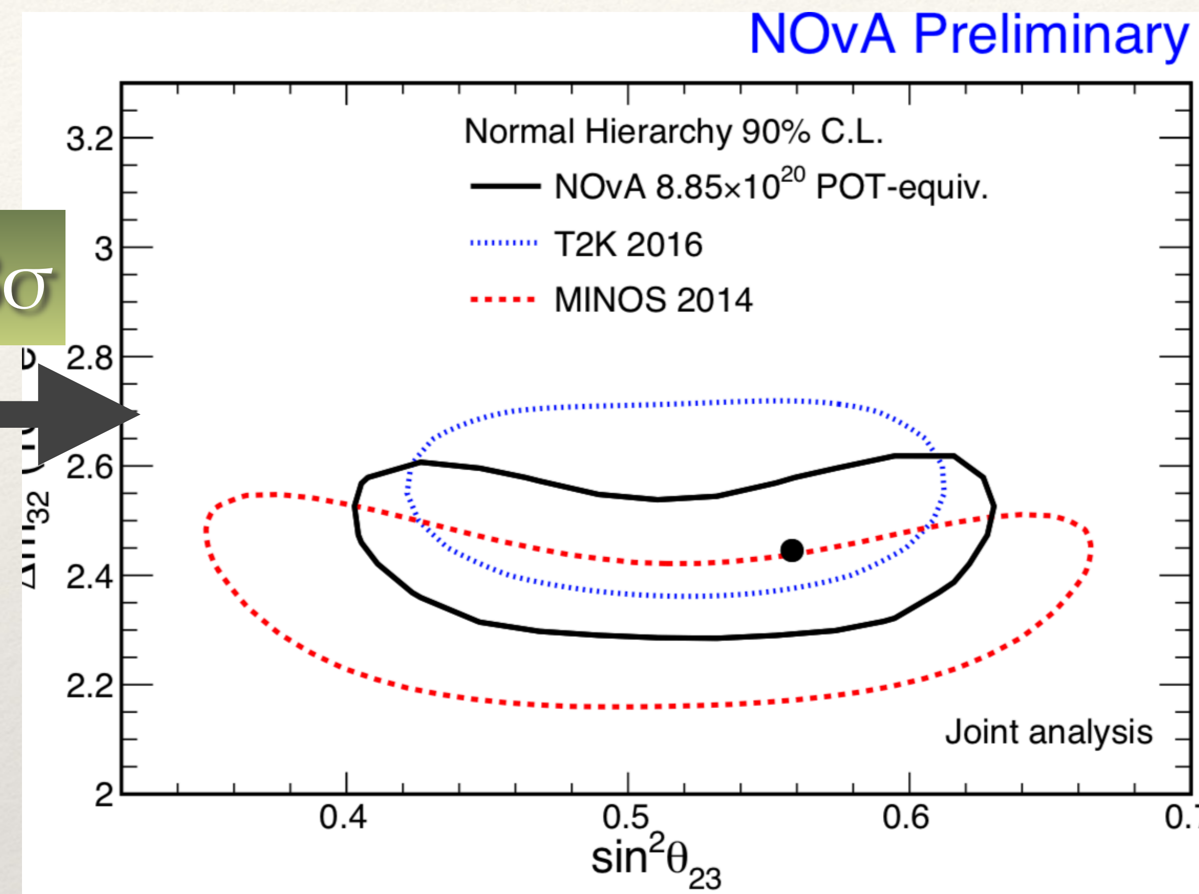
- $3\pi/2$ highly interesting…
- Symmetry behind it?*
- Worth to reconsider ν and anti-ν share?

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

Atmospheric Mixing Angle



2.6σ → 0.8σ

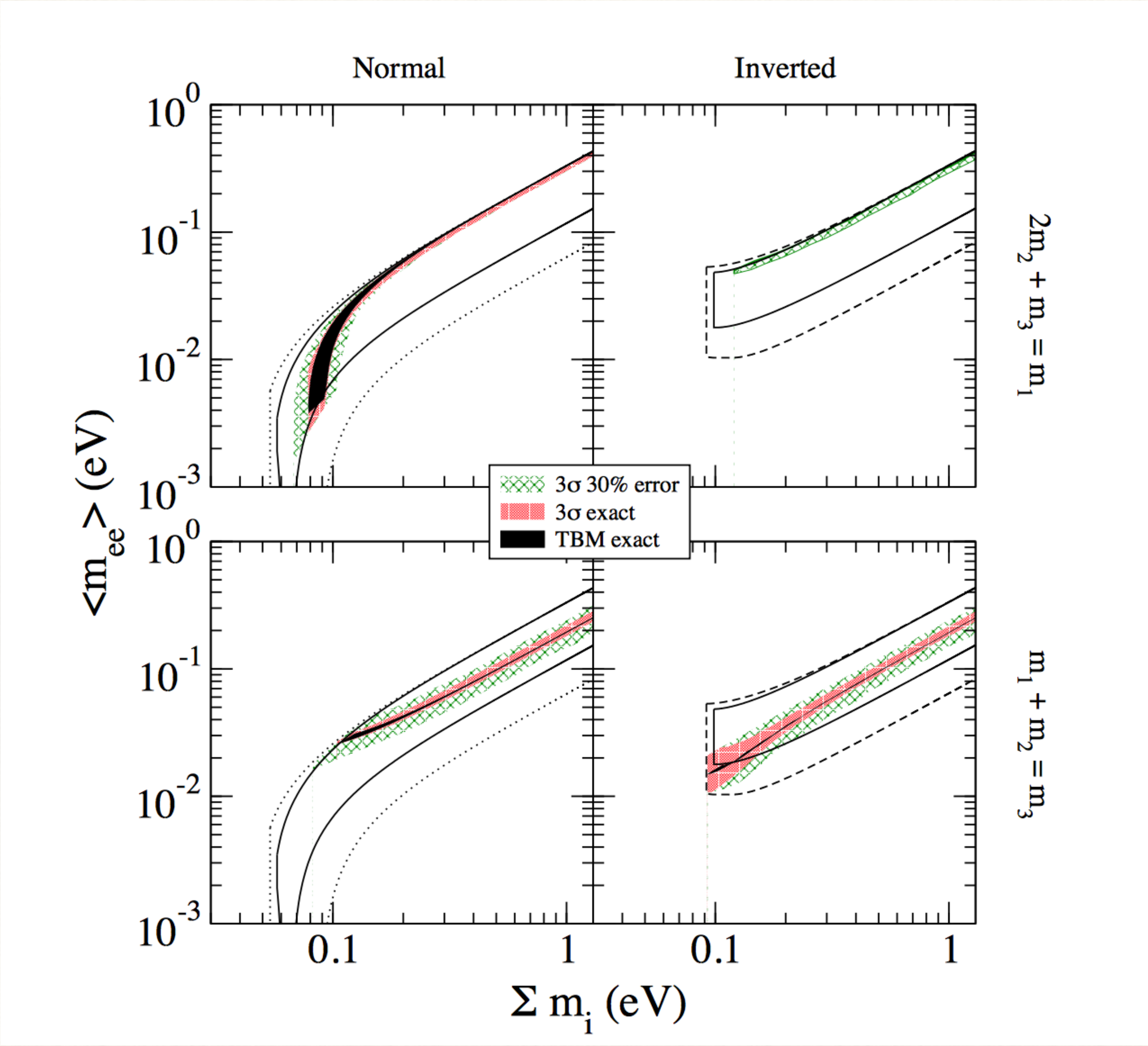


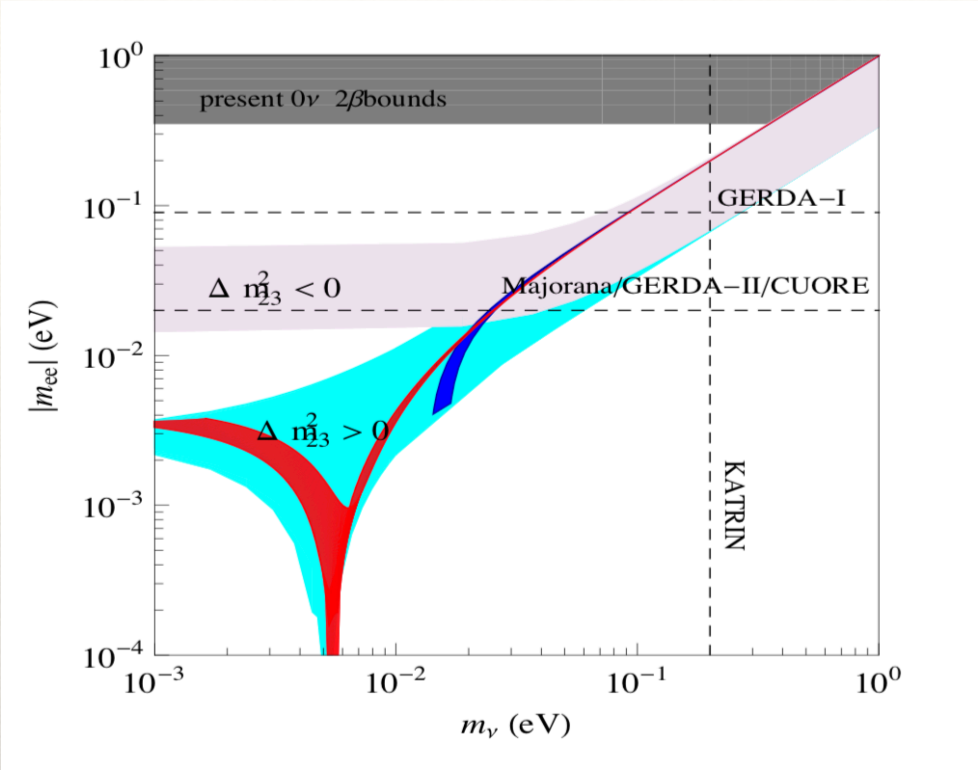
- Maximal mixing?!
- Symmetry behind it?
- Which octant?

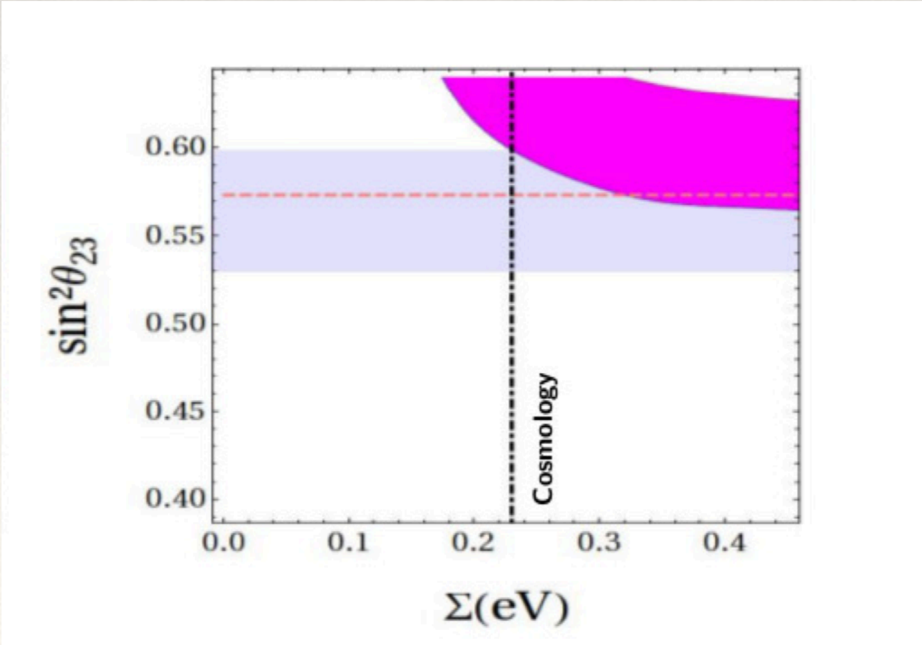
Example RG effects:

Model	mass ordering	θ_{12}	θ_{23}
SM	$\Delta m^2_{31} > 0$	$\searrow$	$\searrow$
	$\Delta m^2_{31} < 0$	$\searrow$	$\nearrow$
MSSM	$\Delta m^2_{31} > 0$	$\nearrow$	$\nearrow$
	$\Delta m^2_{31} < 0$	$\nearrow$	$\searrow$

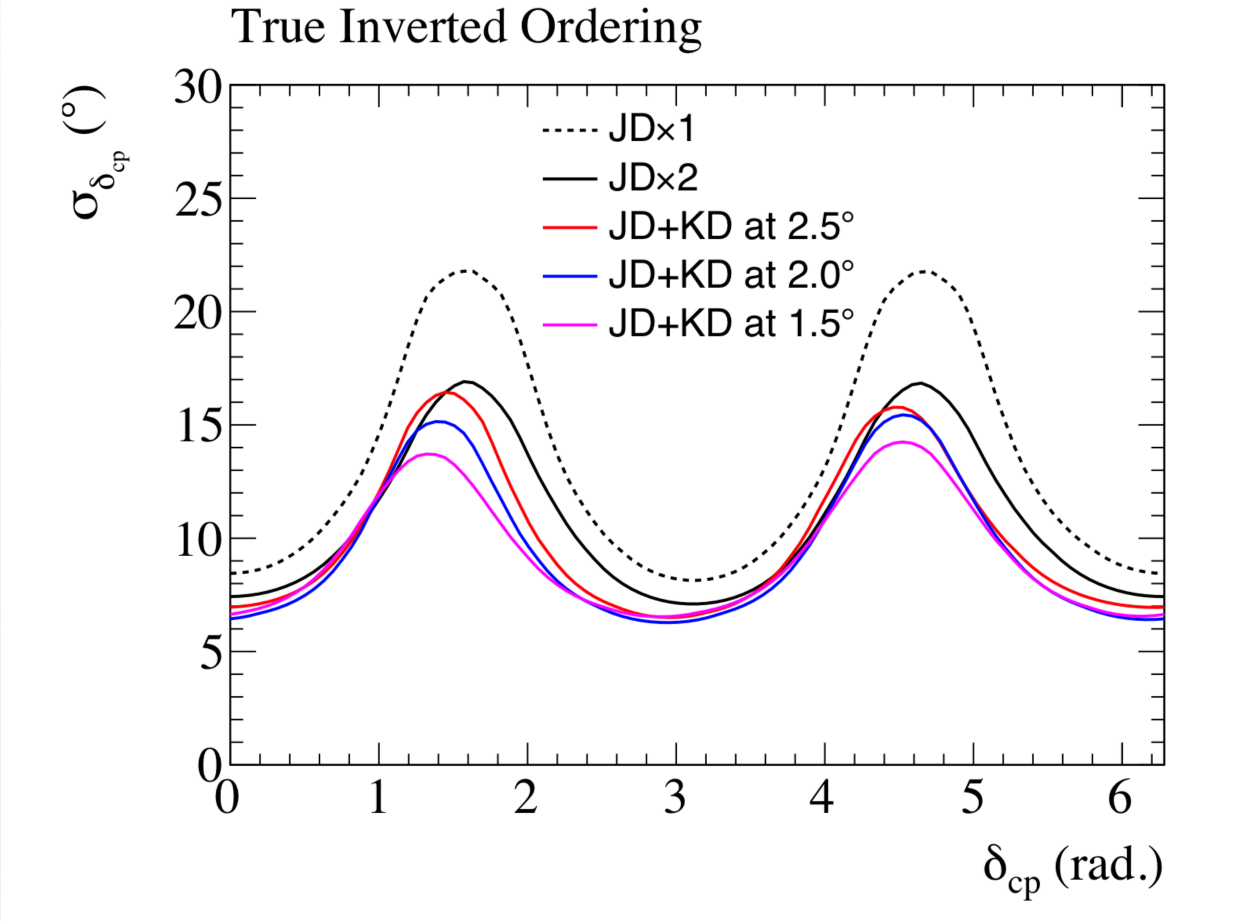
Correlations including mass observables

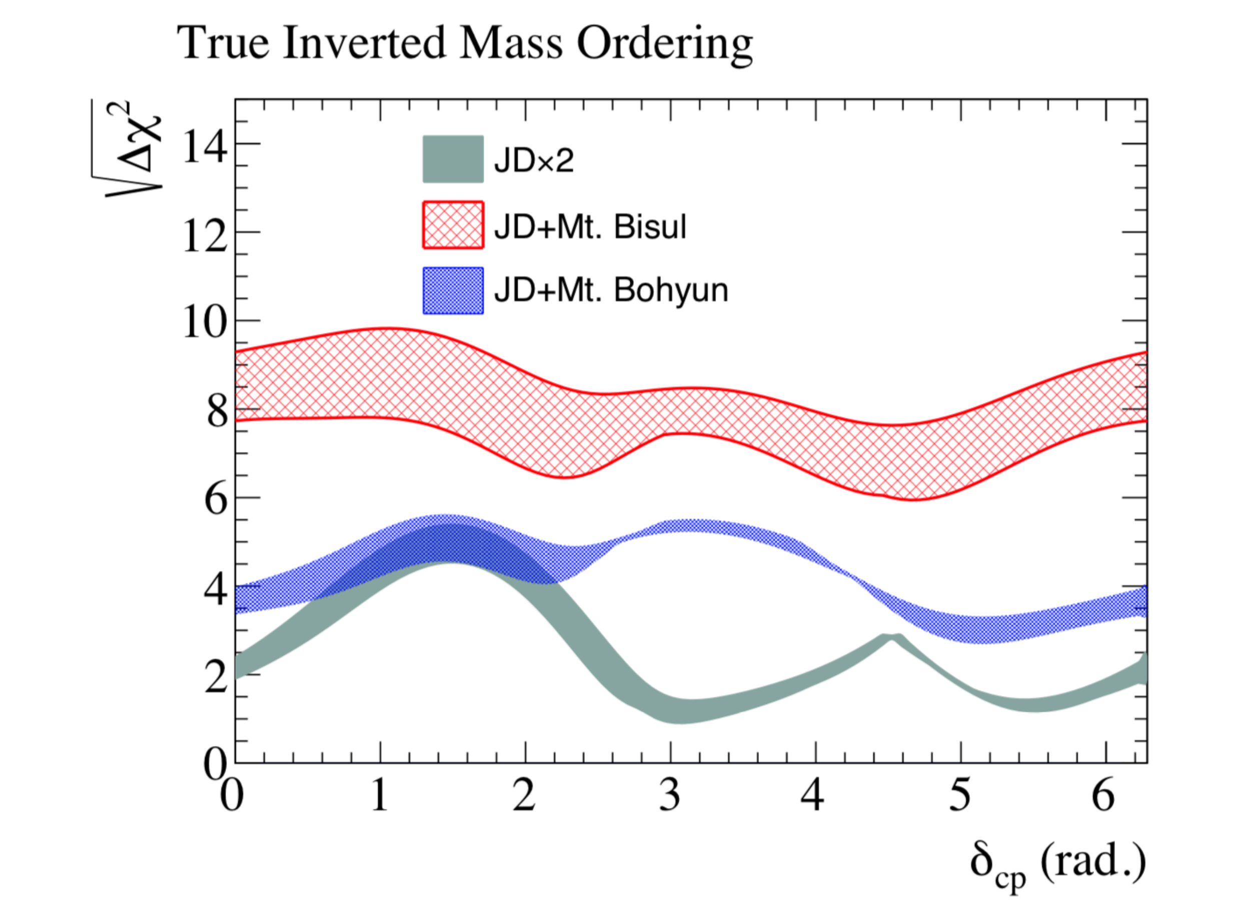






T2HKK





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