Strong thermal SO(10)-inspired leptogenesis in the light of recent results from long-baseline neutrino experiments

Marco Chianese

Conference PLANCK 2018
Bonn, May 23

Based on:

- M.C. and P. Di Bari, JHEP 1805
- Buccella, M.C., Mangano, Miele, Morisi, Santorelli, JHEP 1704

UNIVERSITY OF Southampton

Neutrino oscillations data

Neutrino oscillations are due to the mismatch between the flavour and the mass bases, which is encoded in the matrix:

$$\mathcal{U}_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

NuFIT 3.2 (2018)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.14$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$	$31.42 \to 36.05$	$33.62^{+0.78}_{-0.76}$	$31.43 \to 36.06$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.418 \to 0.613$	$0.554^{+0.023}_{-0.033}$	$0.435 \to 0.616$
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.9}$	$40.3 \to 51.5$	$48.1^{+1.4}_{-1.9}$	$41.3 \to 51.7$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.01981 \to 0.02436$	$0.02227^{+0.00074}_{-0.00074}$	$0.02006 \to 0.02452$
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	$8.09 \to 8.98$	$8.58^{+0.14}_{-0.14}$	$8.14 \to 9.01$
$\delta_{\text{CP}}/^\circ$	234^{+43}_{-31}	$144 \to 374$	278^{+26}_{-29}	$192 \to 354$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.494^{+0.033}_{-0.031}$	$+2.399 \to +2.593$	$-2.465^{+0.032}_{-0.031}$	$-2.562 \to -2.369$

Squared mass differences:

$$\Delta m^2_{21} = m^2_2 - m^2_1$$

$$\Delta m^2_{3\ell} = m^2_3 - m^2_1$$

Two possible orderings:

- **Normal Ordering (NO)**

$$m_1 < m_2 < m_3$$

- **Inverted Ordering (IO)**

$$m_3 < m_1 < m_2$$

See also: Capozzi et al., arXiv:1804.09678; Salas et al., arXiv:1708.01186

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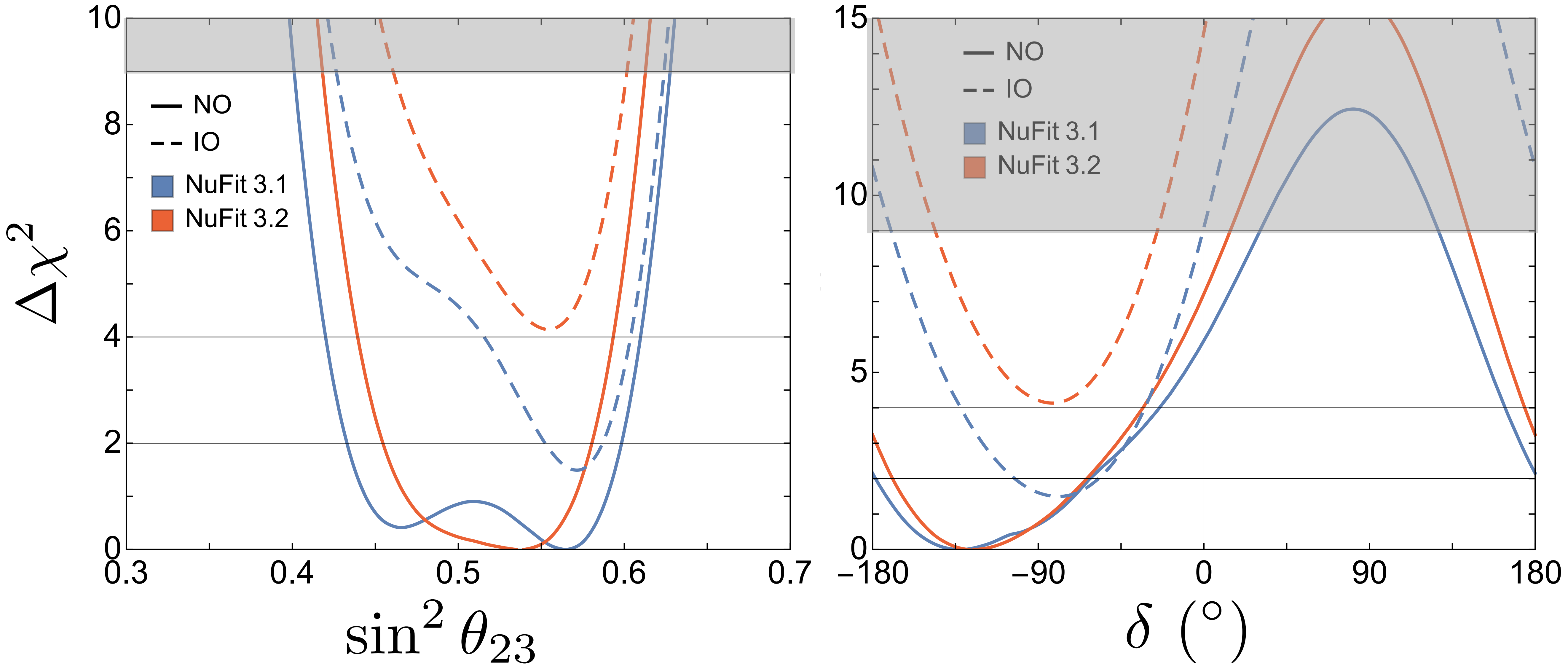
NuFIT 3.1 *vs* NuFIT 3.2



Highlights:

- NOνA—T2K agreement with $\sin^2\theta_{23} \gtrsim 0.5$
- more precise measurement $\delta \lesssim 0^\circ$
- Normal Ordering at 2σ

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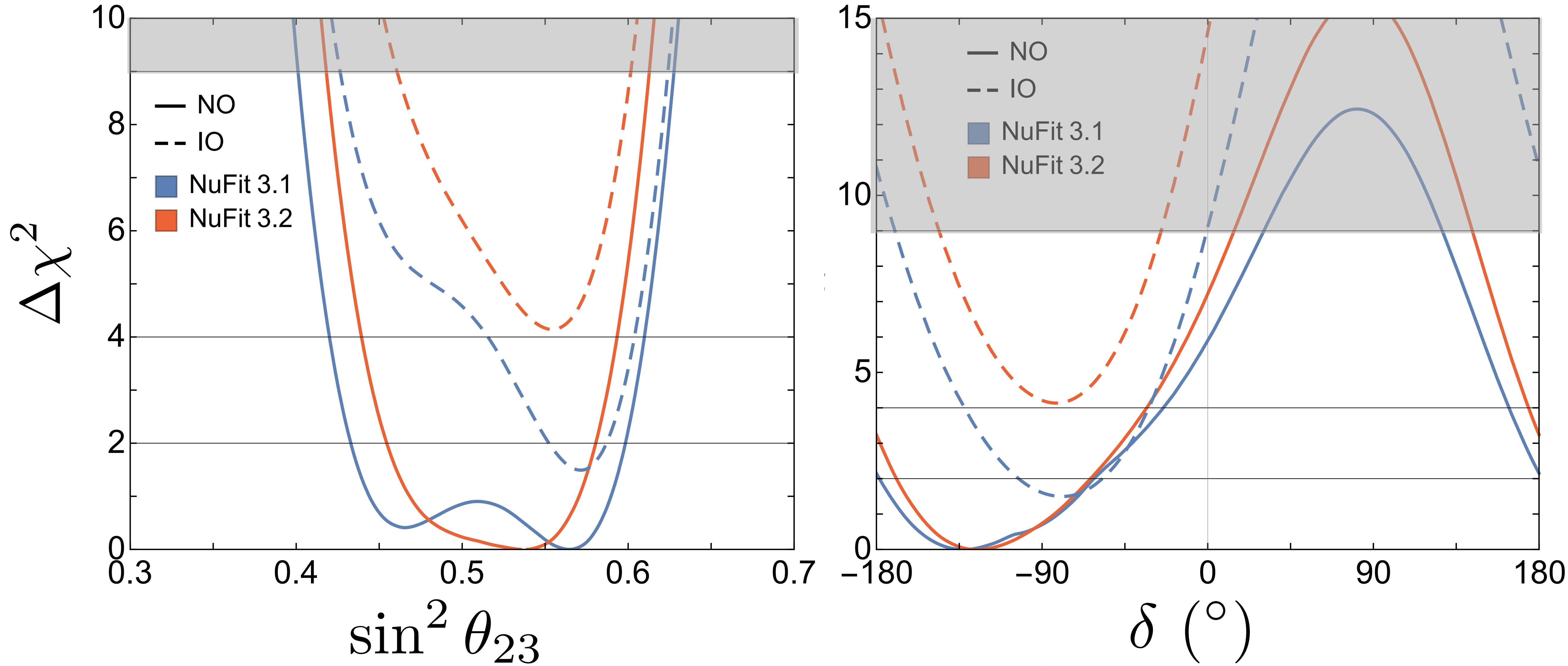

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Strong Thermal SO(10)-inspired Leptogenesis (STSO10)

SO(10)-inspired model

In minimal SO(10) GUT, neutrino masses and mixings are naturally explained by type-I seesaw mechanism, while the type-II contribution is in general subdominant.

$$m_\nu = -m_D \frac{1}{M_R} m_D^T$$

Assuming a particular Higgs scalar sector, the neutrino Dirac mass matrix has approximatively the same structure of up-quark mass matrix:

$$m_D = V_L^\dagger D_{m_D} U_R \quad \text{with} \quad D_{m_D} = (\alpha_1 m_{\text{up}},\, \alpha_2 m_{\text{charm}},\, \alpha_3 m_{\text{top}})$$

SO(10)-inspired condition

Parameters	$I \leq V_L \leq V_{\text{CKM}}$	$\alpha_i = \mathcal{O}(0.1 - 10)$
Benchmark values	$\theta_{12}^L \leq 13^\circ$ $\quad -\pi \leq \delta_L \leq \pi$ $\theta_{23}^L \leq 2.4^\circ$ $\quad -\pi \leq \alpha_L \leq \pi$ $\theta_{13}^L \leq 0.2^\circ$ $\quad -\pi \leq \beta_L \leq \pi$	$\alpha_{1,3} = 1 \quad \alpha_2 = 5$

Strong Thermal Leptogenesis

We impose two independent conditions to the paradigm of thermal leptogenesis:

Fukugita and Yanagida, PLB 174 (1986)

- *successful condition*

$$\eta_B = \alpha_{\rm sph} \frac{N_{B-L}^{\rm f}}{N_\gamma^{\rm rec}} = (6.10 \pm 0.04) \times 10^{-10}$$

Planck Collaboration, Astron.Astrophys. 594 (2016)

- *strong thermal condition (or independence of initial conditions)*

$$N_{B-L}^{\rm f} = N_{B-L}^{\rm lep,f} + N_{B-L}^{\rm p,f} \simeq N_{B-L}^{\rm lep,f}$$

contribution from thermal leptogenesis

contribution from a pre-existing asymmetry that has to be **washed-out!**

- *GUT bosons decays [Yoshimura, PRL 41 (1978)]*
- *Affleck-Dine mechanism [Affleck and Dine, Nucl. Phys. B (1985)]*
- *Gravity [Kallosh et al., PRD 52 (1995)]*

Tauonic N_2-dominated scenario

The strong thermal leptogenesis naturally works for **hierarchical** RH mass spectrum:

$$M_{R_3} \gg 10^{12}\ \mathrm{GeV}\,, \quad 10^{12}\ \mathrm{GeV} \gg M_{R_2} \gg 10^{9}\ \mathrm{GeV}\,, \quad 10^{9}\ \mathrm{GeV} \gg M_{R_1}$$

leptogenesis scale — wash-out scale

The two contributions read

$$N_{B-L}^{\mathrm{p,f}} = \left[p_e e^{-\frac{3\pi}{8}K_{1e}} + p_\mu e^{-\frac{3\pi}{8}K_{1\mu}} + p_\tau e^{-\frac{3\pi}{8}(K_{1\tau}+K_{2\tau})}\right] N_{B-L}^{\mathrm{p,i}}$$

$$N_{B-L}^{\mathrm{lep,f}} = f_1\left(K_{2e}, K_{2\mu}\right) e^{-\frac{3\pi}{8}K_{1e}} + f_2\left(K_{2e}, K_{2\mu}\right) e^{-\frac{3\pi}{8}K_{1\mu}}$$

$$+\varepsilon_{2\tau}\kappa\left(K_{2\tau}\right) e^{-\frac{3\pi}{8}K_{1\tau}}$$

Definitions:

$K_{i\alpha} \equiv$ flavoured decay rates

$\varepsilon_{i\alpha} \equiv$ flavoured CP asymmetries

$\kappa \equiv$ efficiency factor

$p_\alpha \equiv$ flavour ratios

$f_{1,2} \equiv$ suitable functions

Bertuzzo, Di Bari, Marzola, NPB 849 (2011)
Di Bari, King, Re Fiorentin, JCAP 1403
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We have to require **tauonic N$_2$-dominated scenario**:

$$N_{B-L}^{\mathrm{p,f}} \ll N_{B-L}^{\mathrm{lep,f}} \quad \Longrightarrow \quad K_{1e}, K_{1\mu}, K_{2\tau} \gg 1 \text{ and } K_{1\tau} \lesssim 1$$

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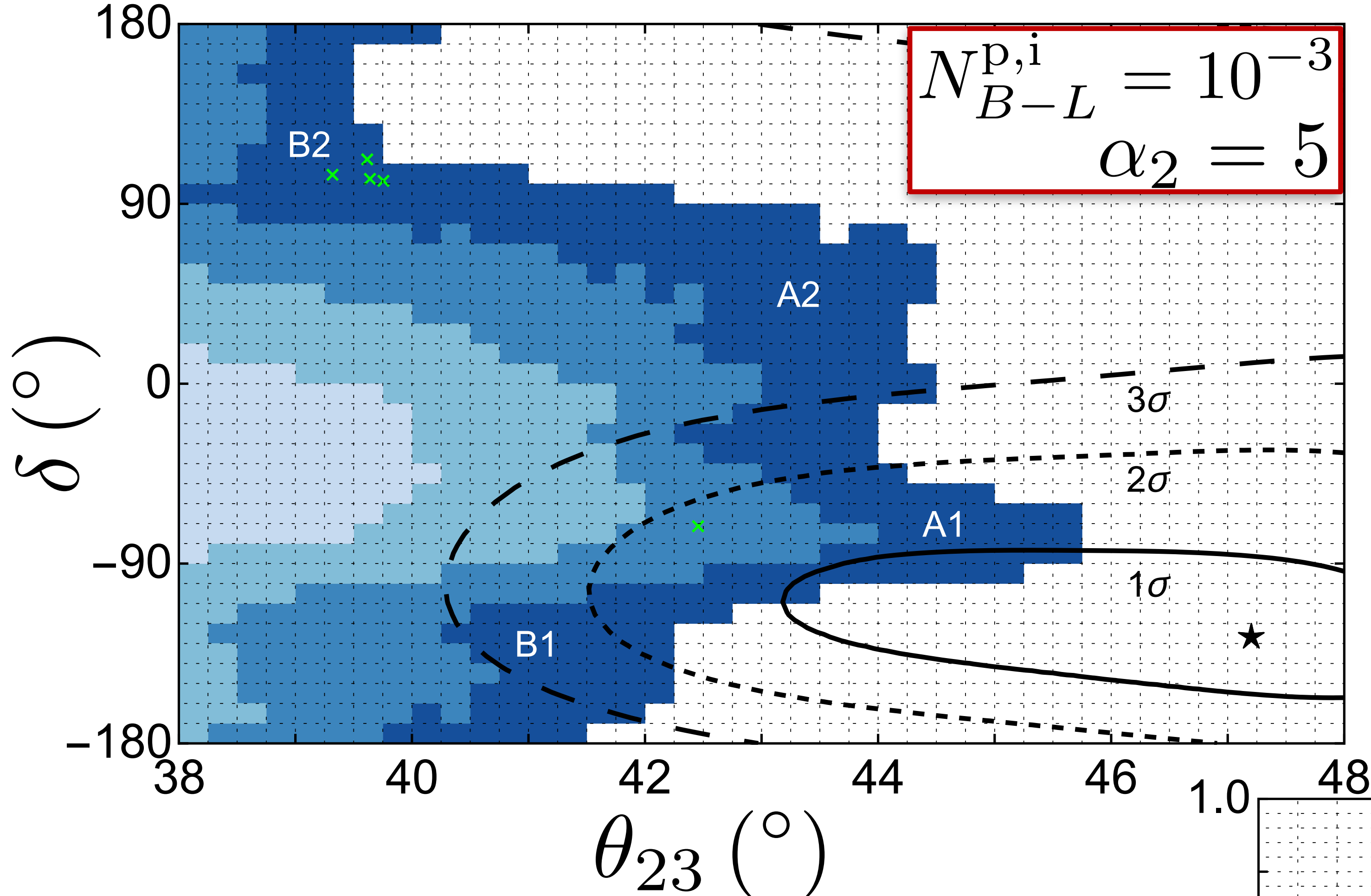
We perform a MonteCarlo procedure to obtain the allowed regions in the parameters space, providing *successful strong thermal* leptogenesis.

Benchmark results



From lightest to darkest blue, the regions contain 68%, 95%, 99.7% and 100% of the solutions.

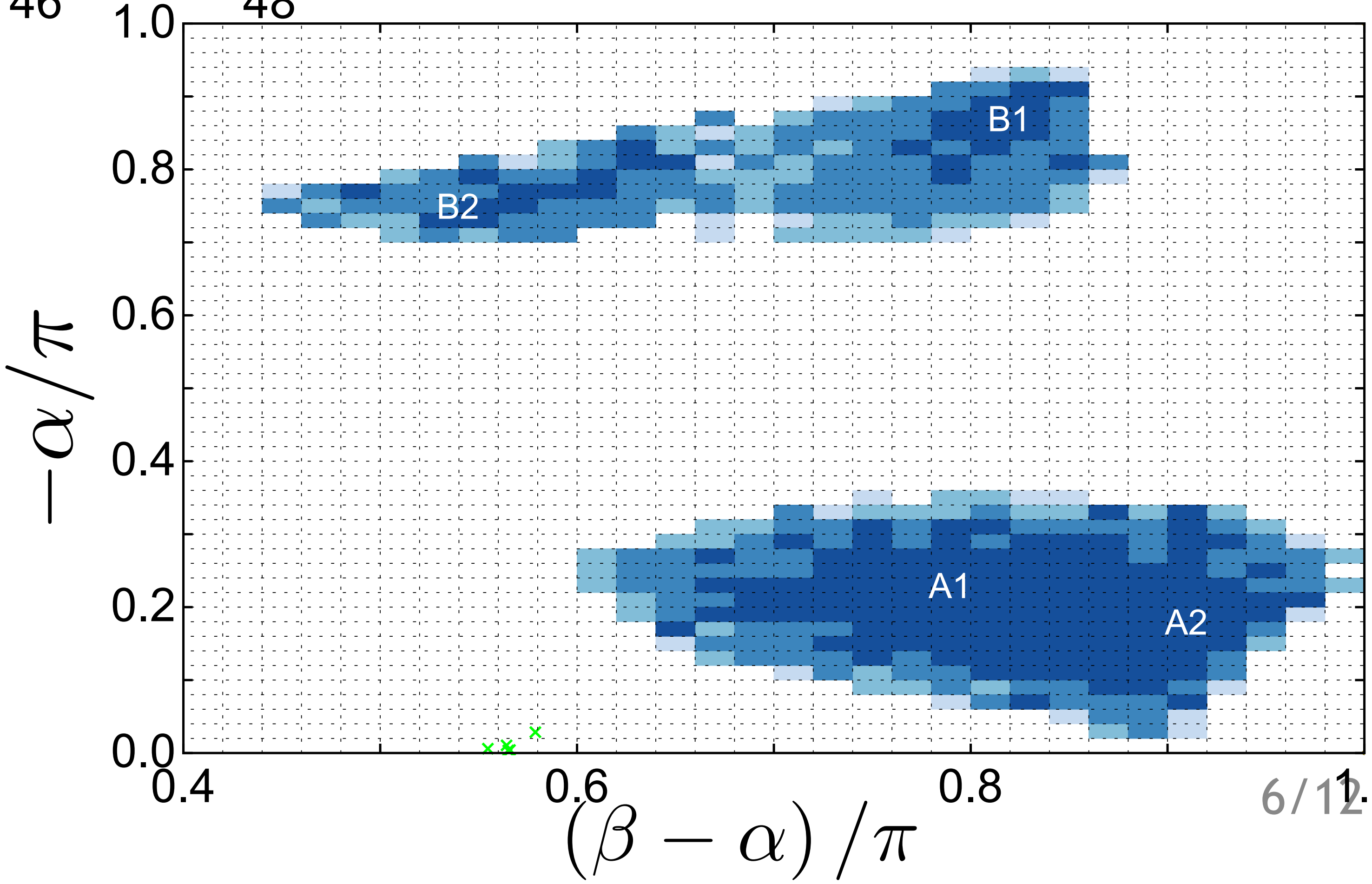
We have found a few **muonic solutions**, highlighted with green crosses.

Main Results

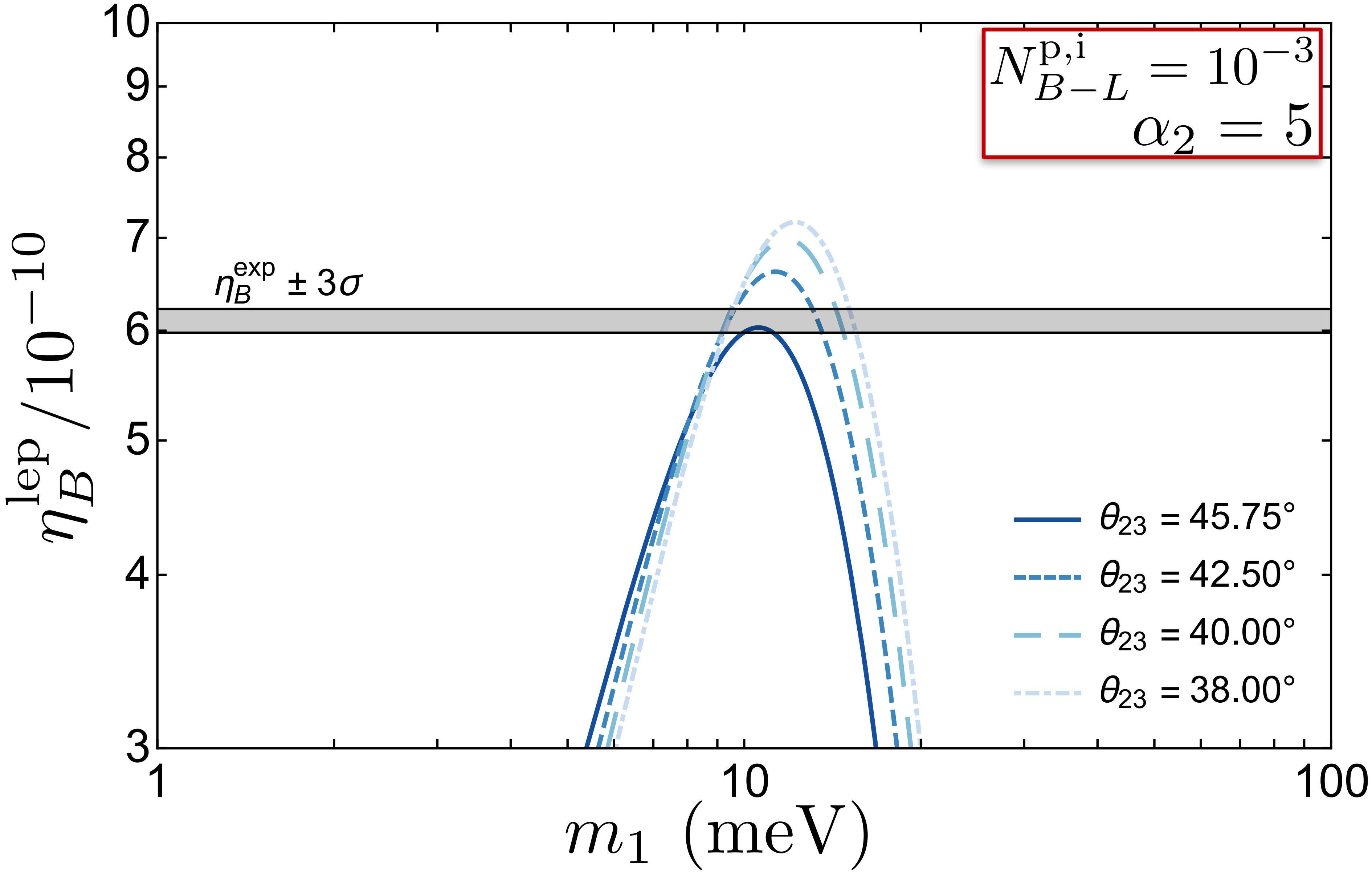
- The maximum allowed value is

$$\theta_{23}^{\max} \simeq 45.75^\circ \quad \text{for} \quad \delta \simeq -75^\circ$$

- Only the region A_1 is in agreement with experimental neutrino data at 2σ.



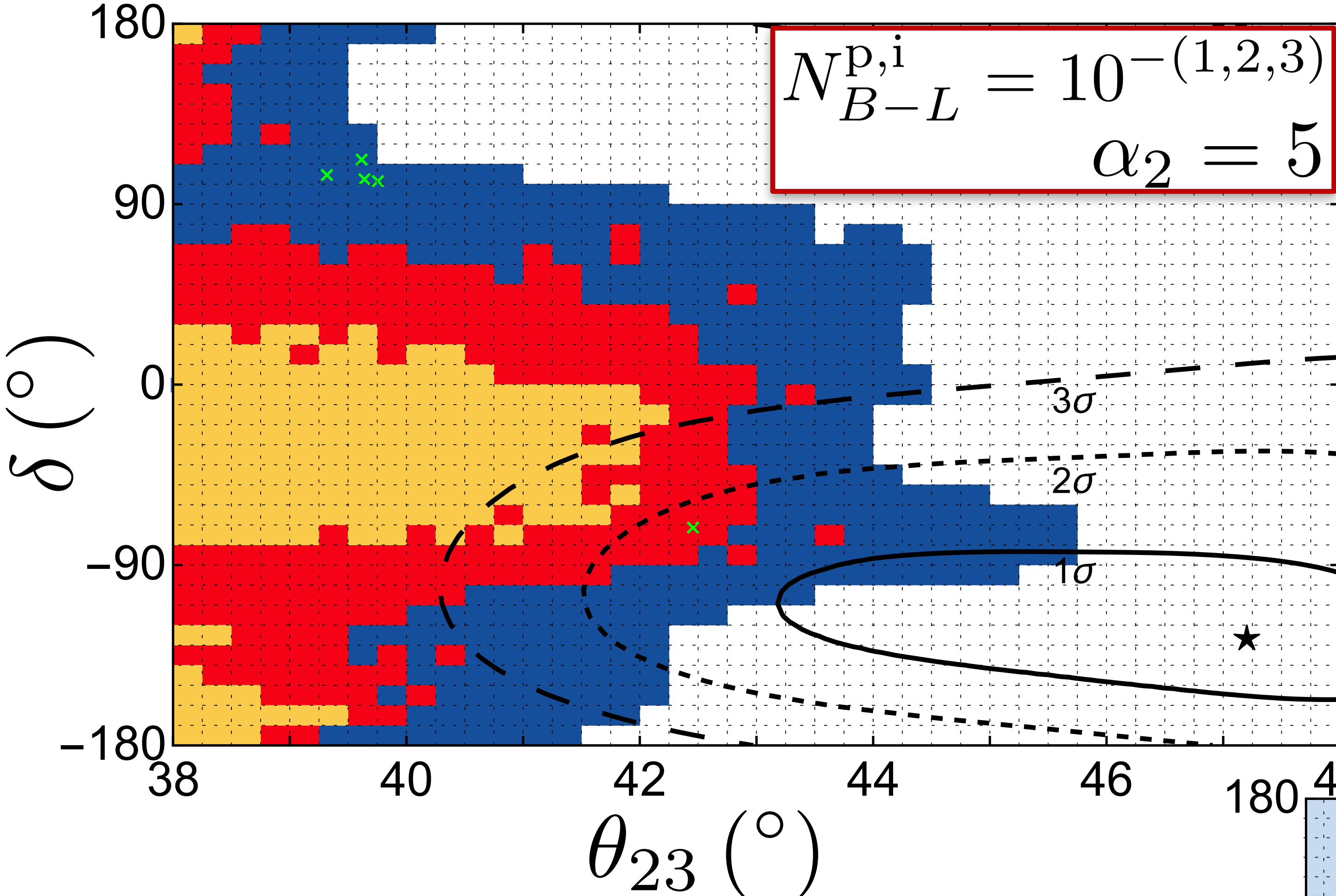
Fine-tuning



Increasing the values of the atmospheric angle implies a higher and higher **fine-tuning** of all parameters.

$$\varepsilon_{2\tau} \simeq \frac{3}{16\pi}\frac{m_{D_2}^2}{v_{\rm SM}^2}\frac{m_1}{m_{\rm sol}m_{\rm atm}}\frac{\left|m_{\rm sol}s_{12}^2c_{13}^2 + m_{\rm atm}s_{13}^2\,e^{2i(\beta-\alpha-\delta)}\right|\sin\theta_L}{s_{12}^4}\frac{1-s_{23}^2}{s_{23}^4}$$

Relaxing the assumptions



The three colours represent:

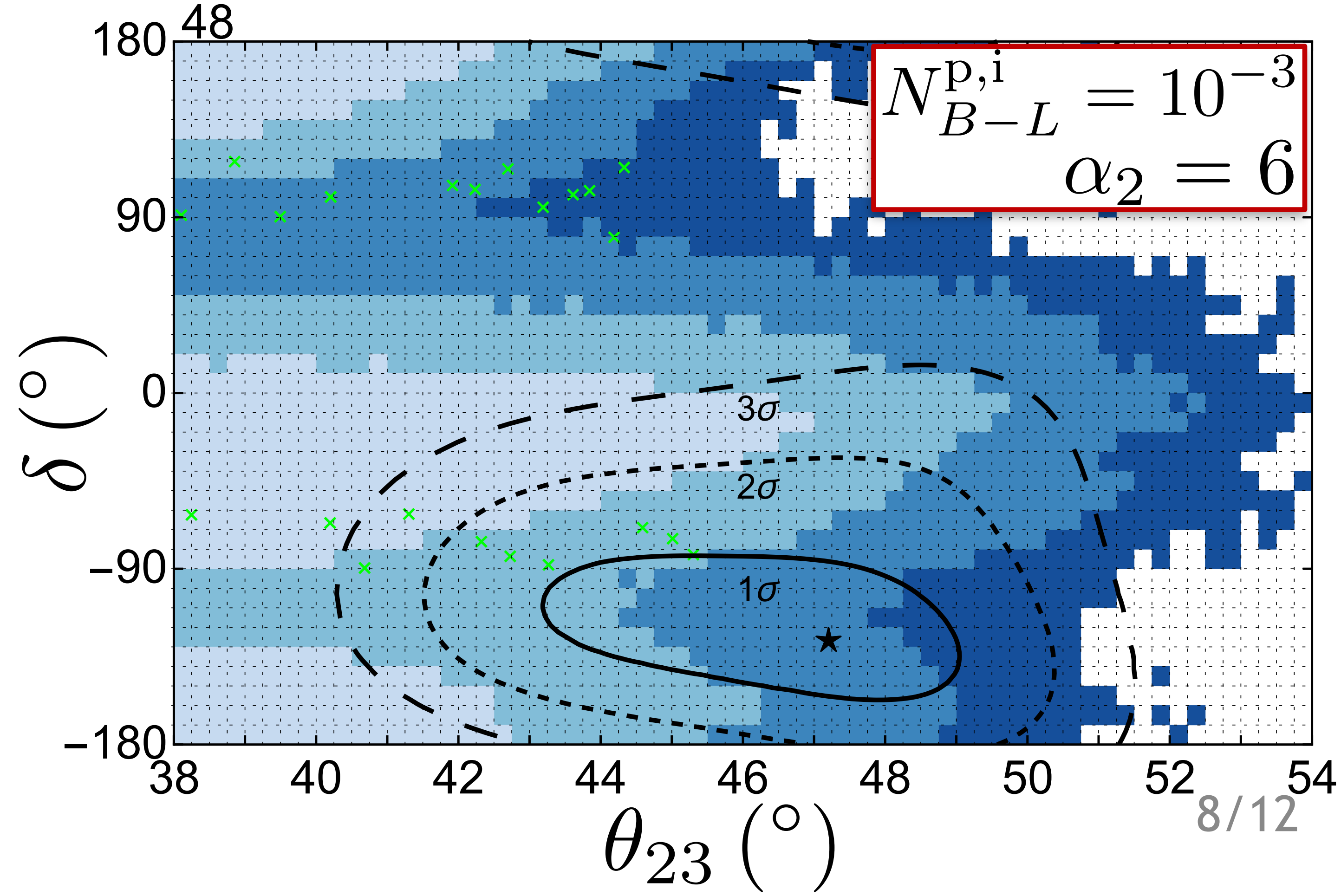
- $N^{\rm p,i}_{B-L} = 10^{-1}$
- $N^{\rm p,i}_{B-L} = 10^{-2}$
- $N^{\rm p,i}_{B-L} = 10^{-3}$

The larger the initial pre-existing asymmetry, the smaller the allowed regions.

The scenario is strongly dependent on α_2, while it is almost independent of $\alpha_{1,3}$.

Indeed, we have

$$\varepsilon_{2\tau} \propto m^2_{D_2} \quad \Longrightarrow \quad \eta^{\rm lep}_B \propto \alpha_2^2\, m^2_{\rm charm}$$



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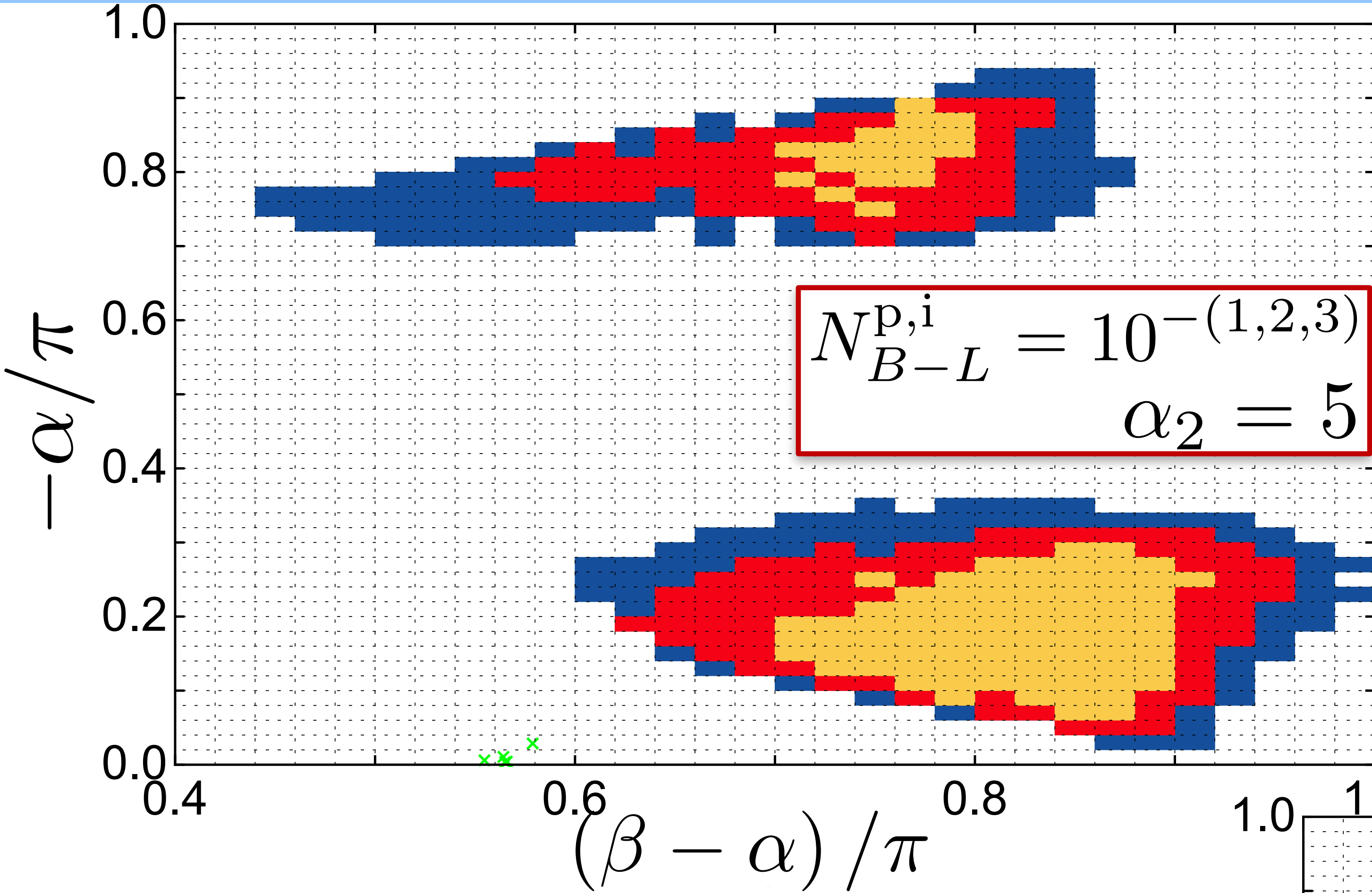

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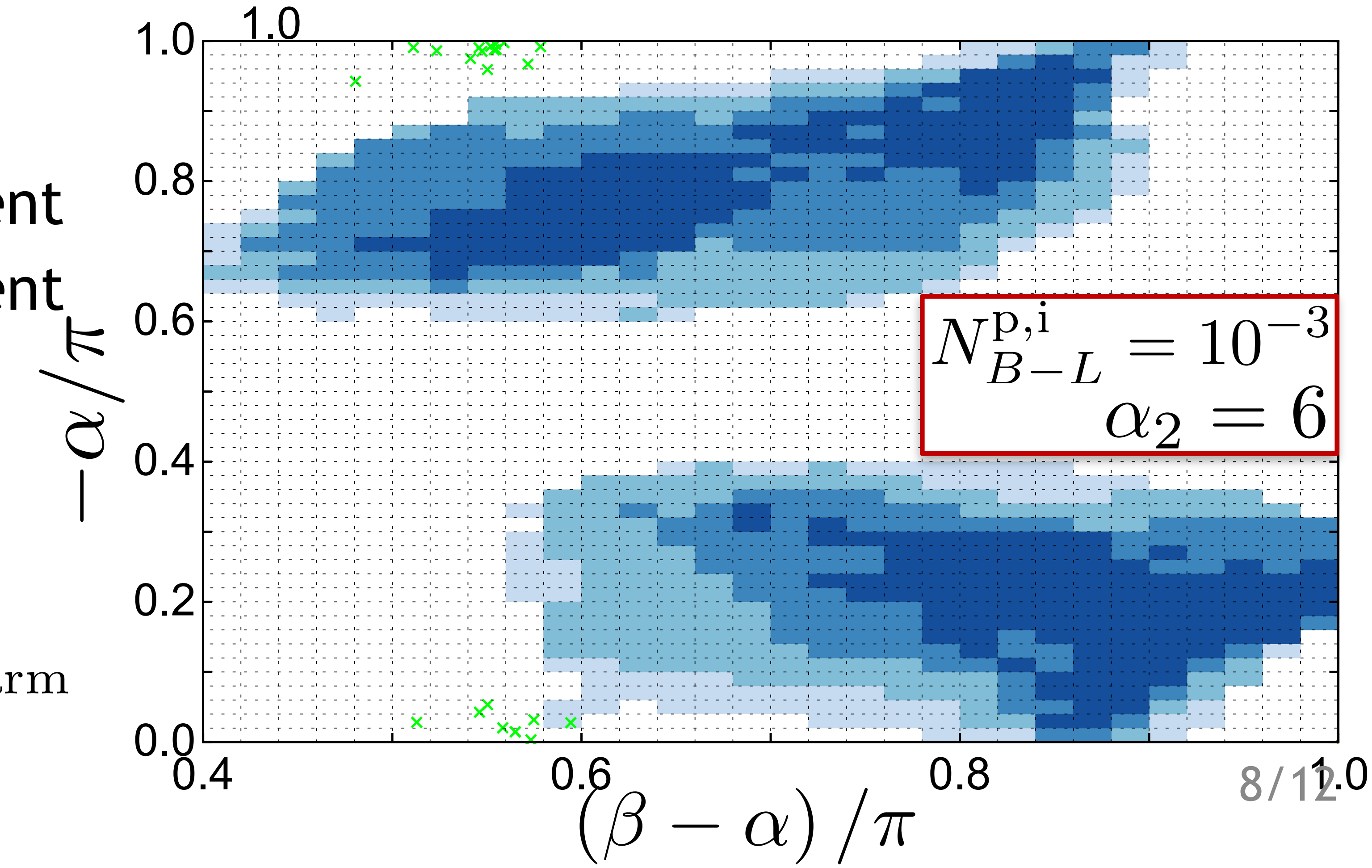

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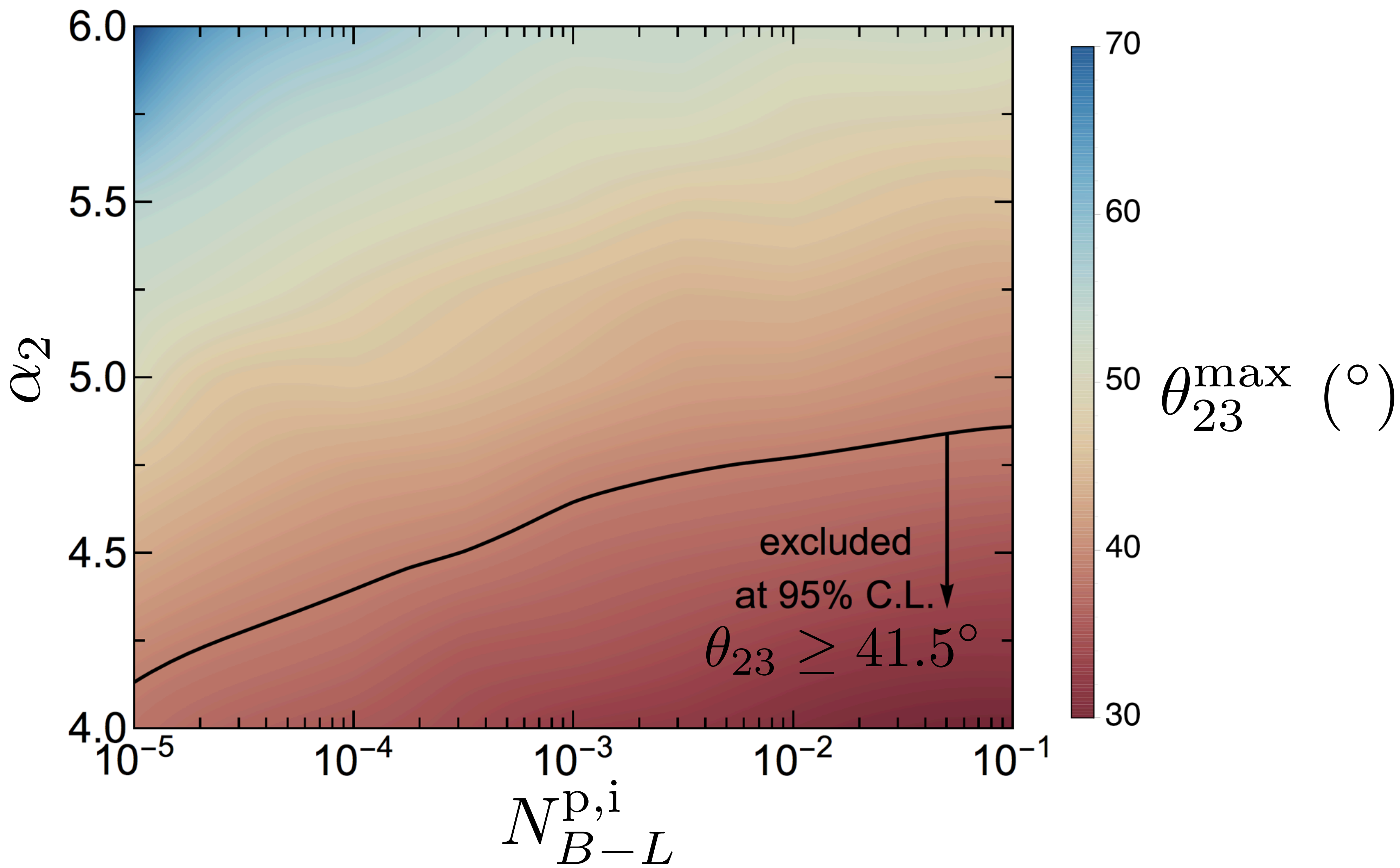

Latest neutrino oscillations data disfavour small values for α_2 in Strong Thermal SO(10)-inspired leptogenesis scenario, providing **additional constraints** to GUT global realistic fits of fermion masses.

$0\nu\beta\beta$ and SO(10) mass-mixing sum rule

The Majorana nature of neutrinos can be tested by looking for the neutrinoless double beta decay whose rate is proportional to

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

The **neutrino sum rules** are simple relations among neutrino oscillation parameters appearing once an additional symmetry is imposed.

Horizontal/Flavour →

Fields	1st family	2nd family	3rd family
Quarks	u	c	t
	d	s	b
Leptons	e	μ	τ
	ν_e	ν_μ	ν_τ

Mass and Mixing sum rules

$$\kappa_1 m_1^h + \kappa_2 \left(m_2\, e^{-2i\alpha}\right)^h + \kappa_3 \left(m_3\, e^{-2i\beta}\right)^h = 0$$

$$\left(1-\sqrt{2}\sin\theta_{23}\right) = \rho_{\rm atm} + \lambda\left(1-\sqrt{2}\sin\theta_{13}\right)\cos\delta$$

$$\theta_{12} = \rho_{\rm sol} + \theta_{13}\cos\delta$$

See Refs: King, JHEP 0508; Antusch and King, PLB 631 (2005); Barry and Rodejohann, Nucl. Phys. B 842 (2011); King et al., New J. Phys. 16 (2014)

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Mass-Mixing sum rule in SO(10)

$$\left| \frac{A^2}{m_1} + \frac{B^2}{m_2 \, e^{-2i\alpha}} + \frac{C^2}{m_3 \, e^{-2i\beta}} \right| \lesssim \varepsilon$$

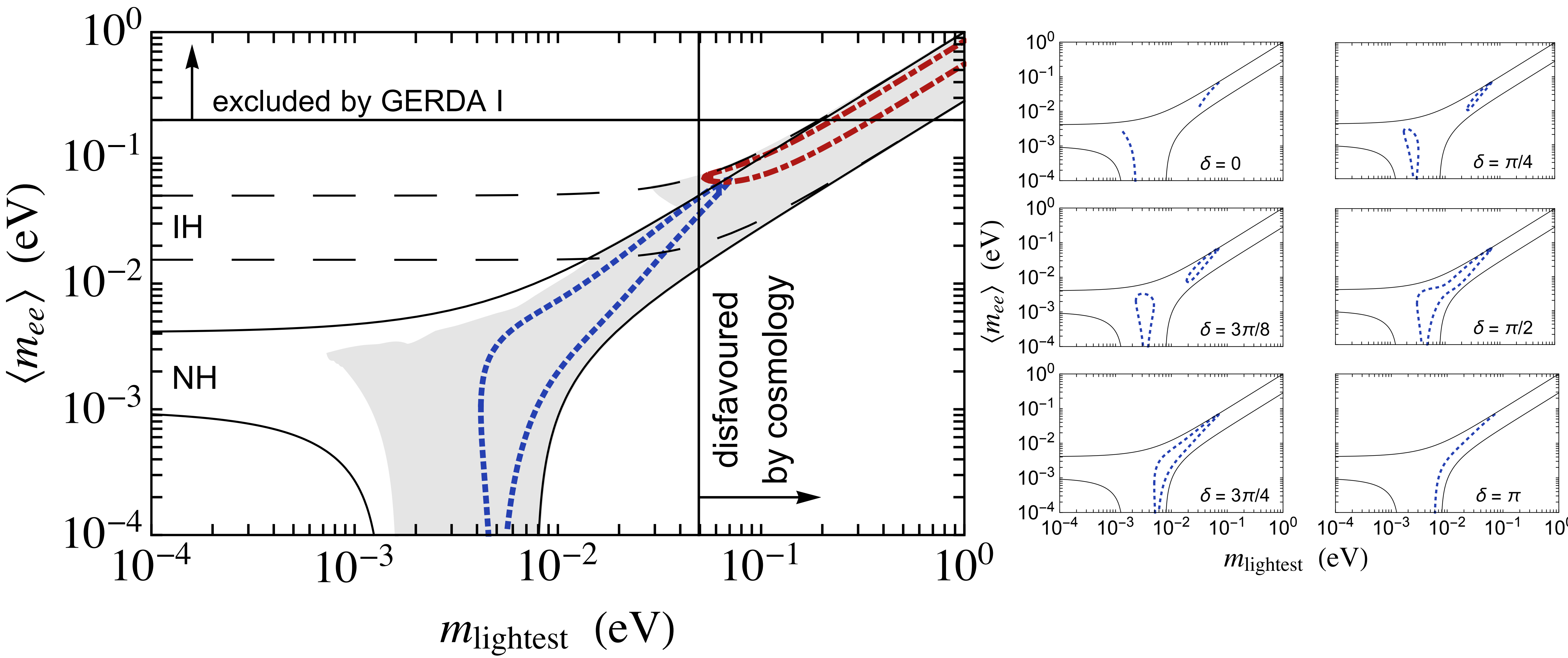
$$A = c_{12} \, c_{23} \, s_{13} \, e^{i\delta} - s_{12} \, s_{23}$$

$$B = s_{12} \, c_{23} \, s_{13} \, e^{i\delta} + c_{12} \, s_{23}$$

$$C = c_{13} \, c_{23}$$

Buccella, M.C., Mangano, Miele, Morisi, Santorelli, JHEP 1704

Predictions on 0νββ plane

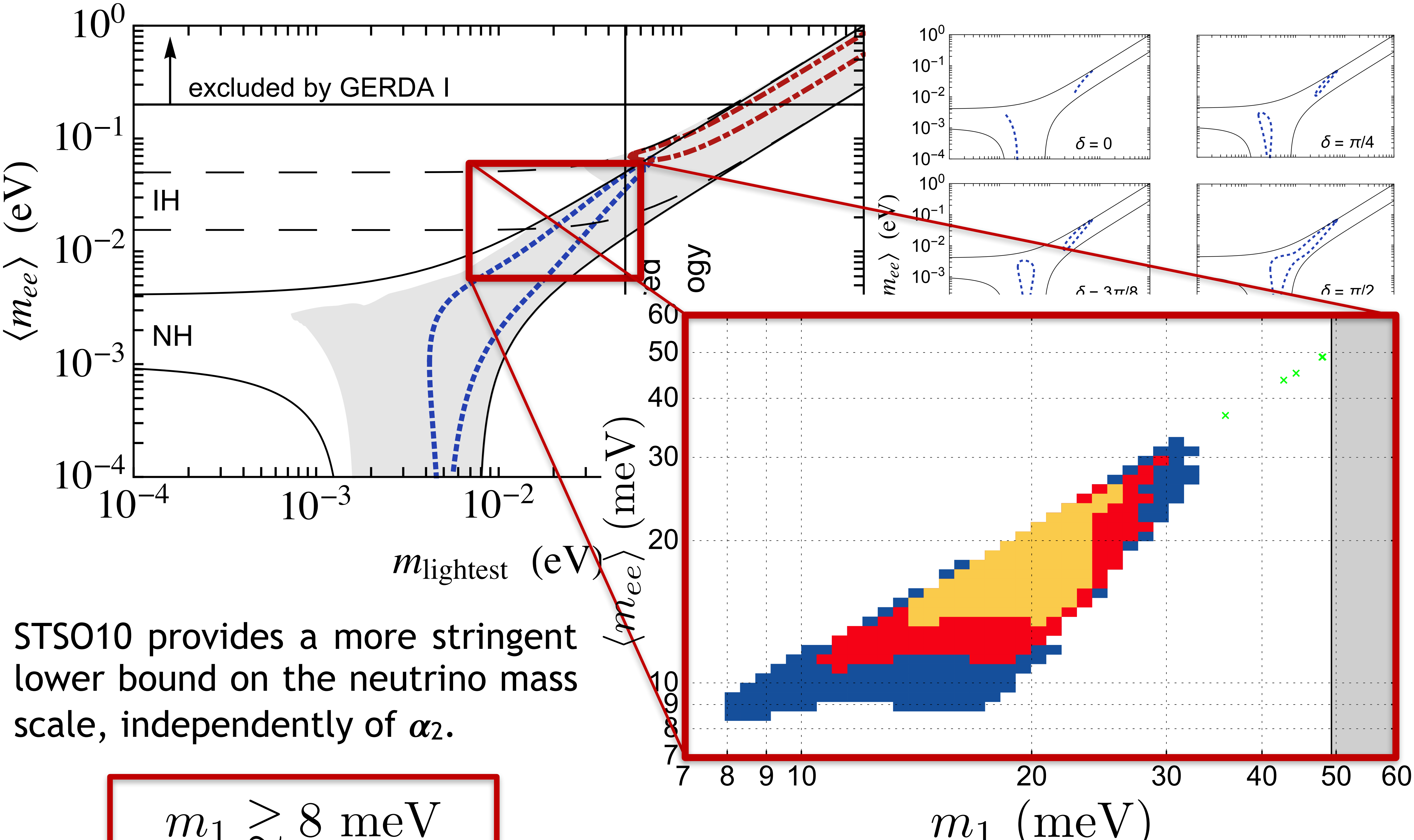


The mass-mixing neutrino sum rule predicts **Normal Ordering** and a lower limit for the lightest neutrino mass:

$$m_{\rm lightest} \gtrsim 0.75 \text{ meV} \quad \text{at} \quad 3\sigma$$

Buccella, M.C., Mangano, Miele, Morisi, Santorelli, JHEP 1704

Predictions on $0\nu\beta\beta$ plane



STSO10 provides a more stringent lower bound on the neutrino mass scale, independently of α_2.

$$m_1 \gtrsim 8 \text{ meV}$$

Conclusions

By using the latest neutrino data, we have determined the allowed regions in the parameter space satisfying Strong Thermal SO(10)-inspired (STSO10) leptogenesis.

The main results are:

- the benchmark scenario is still allowed at 2σ.
- the larger (smaller) the second Dirac neutrino mass (pre-existing asymmetry), the larger the maximum allowed value for θ_{23}.
- the $0\nu\beta\beta$ plane is further constrained with respect to the predictions of the SO(10) neutrino mass-mixing sum rule, providing

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The measurement of the neutrinoless double beta decay would be the ultimate powerful test of SO(10)-inspired models and STSO(10) leptogenesis.

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Thanks for your attention