Neutrino parameters and N_2-dominated leptogenesis

Michele Re Fiorentin

UNIVERSITY OF Southampton
School of Physics and Astronomy

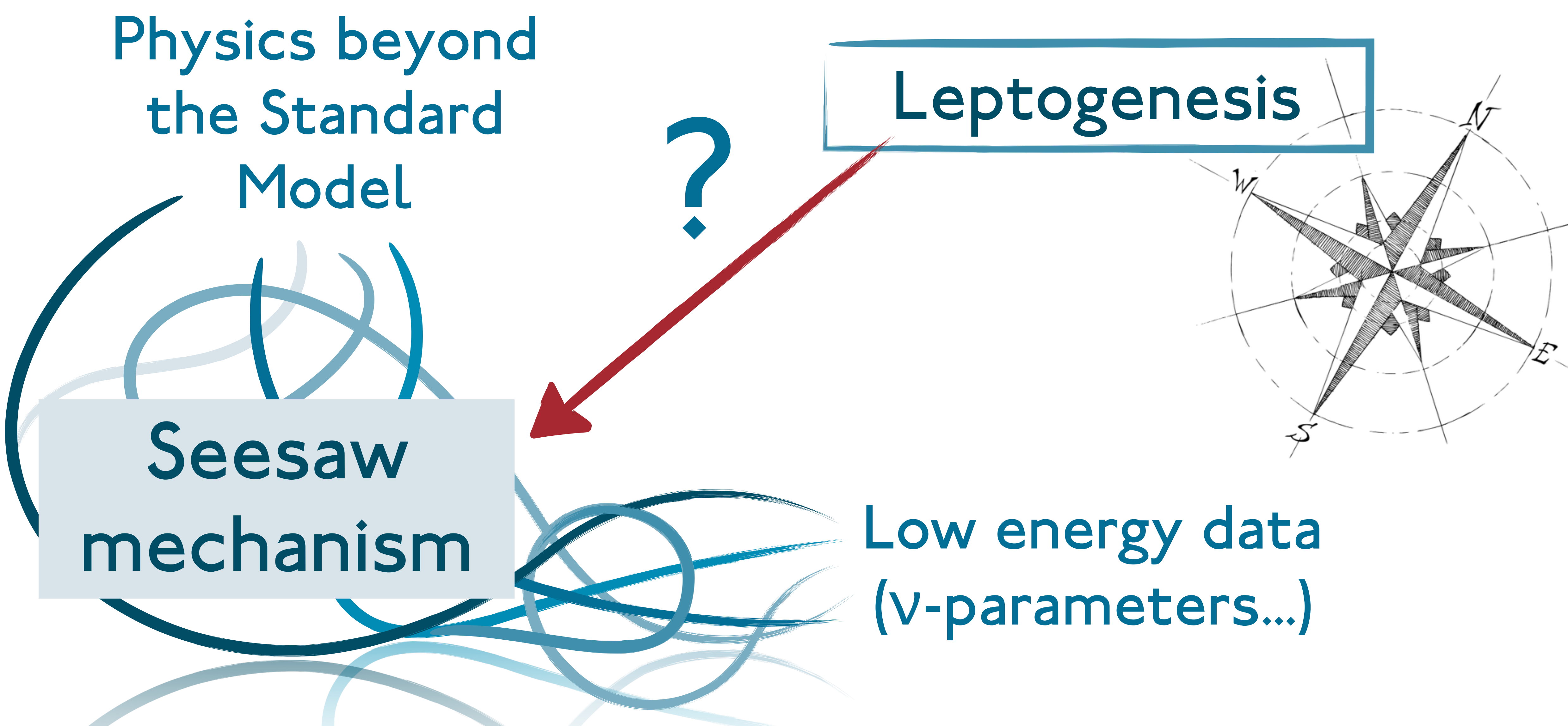
SHEP Southampton High Energy Physics

Based on: arXiv 1401.6185 with Pasquale Di Bari and Sophie E. King
arXiv 1409.xxxx with Pasquale Di Bari and Luca Marzola

Why leptogenesis?

Mechanism able to dynamically produce the baryon asymmetry

Link between cosmology, neutrino & new physics



Seesaw mechanism

Too many unconstrained parameters

Some theoretical inputs

New phenomenology: Baryon asymmetry

Leptogenesis

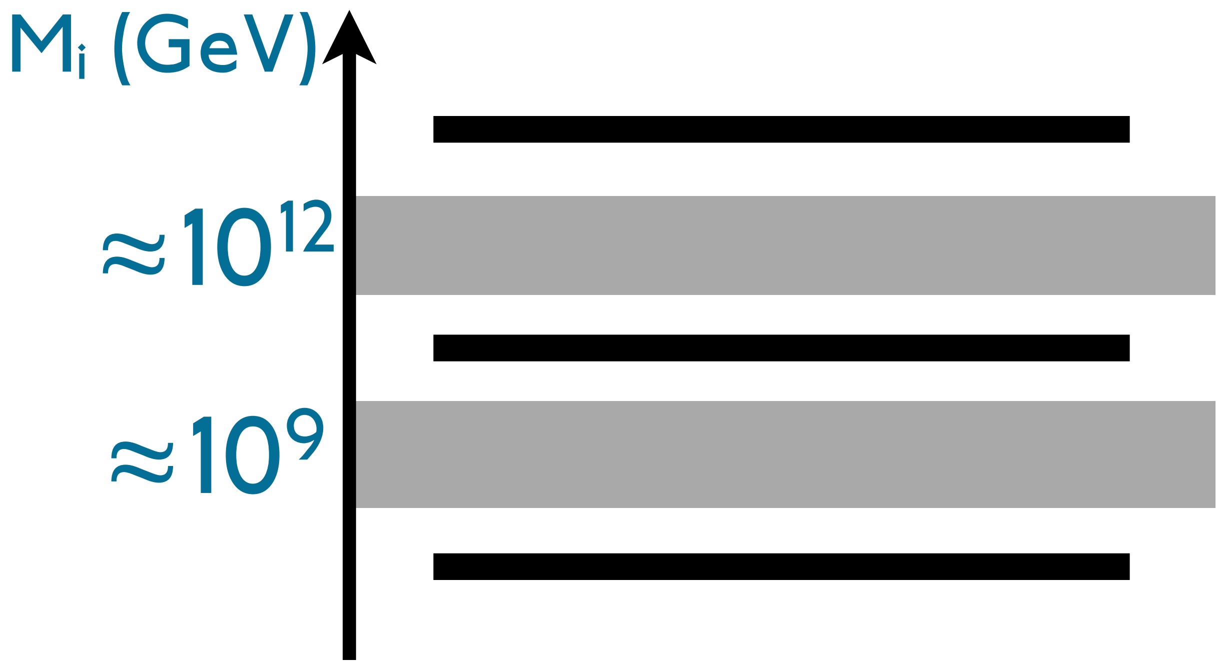
- Can leptogenesis provide an explanation and predictions on neutrino data?

Input from known low-energy neutrino data AND baryon asymmetry can provide info on unknown LE parameters and also constrain HE parameters

- Can LE neutrino data support/disprove leptogenesis?

Making leptogenesis predictive means making it "testable"

The N_2-dominated scenario



$$M_3 \gg 10^{12}\,\mathrm{GeV}$$

$$10^9\,\mathrm{GeV} \lesssim M_2 \lesssim 10^{12}\,\mathrm{GeV}$$

$$M_1 \lesssim 10^9\,\mathrm{GeV}$$

High reheating temperature, in line with BICEP2 (to be confirmed...)

(1) This scenario can become predictive

The requirement of independence of any pre-existing asymmetry highly constrains the LE parameters

(2) It is naturally realised in SO(10)-inspired models

(Branco et al. 2002; Nezri, Orloff 2002; Akhmedov, Frigerio, Smirnov 2003)

Strong thermal leptogenesis

- Full independence of initial conditions

$N_{B-L}^{\rm p,i}$ **Initial** asymmetry **pre-existing** to leptogenesis

$N_{B-L}^{\rm p,f}$ **Final** pre-existing asymmetry, **after** leptogenesis

Asymmetry produced by leptogenesis

$$N_{B-L}^{\rm lep,f} \gg N_{B-L}^{\rm p,f}$$

- Condition on the (hierarchical) RH neutrino mass spectrum:

N_2-dominated scenario is required

(Barbieri, Creminelli, Strumia 2000; Engelhard, Grossman, Nardi, Nir 2007;Bertuzzo, Di Bari, Marzola 2010)

- Condition on the low-energy neutrino parameters:

Lower bound on the lightest neutrino mass m_1

Lower bound on m_1

- Flavoured decay parameters

$$K_{i\alpha} = \left| \sum_j \sqrt{\frac{m_j}{m_*}} U_{\alpha j} \Omega_{ji} \right|^2$$

- Imposing $K_{1\tau} \ll 1, \quad K_{2\tau}, K_{1e}, K_{1\mu} \geq K_{\rm st}$

Lower bound on m1

- Flavoured decay parameters

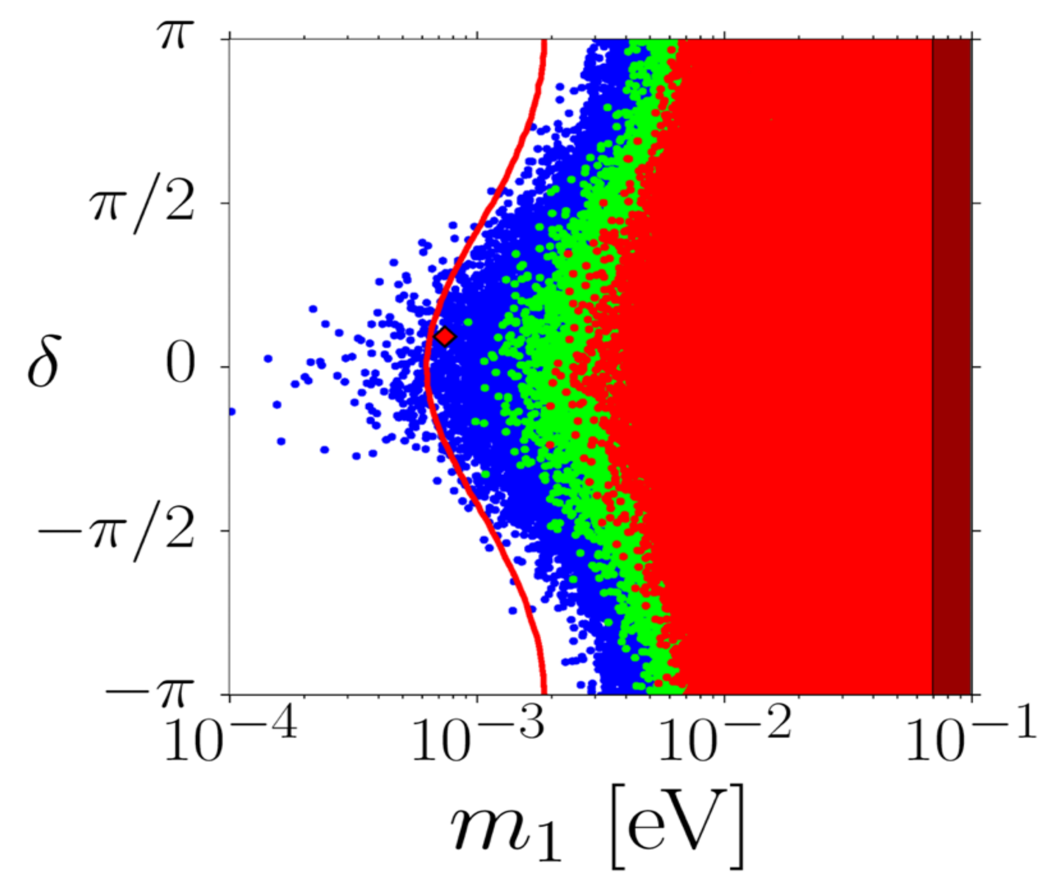
$$K_{i\alpha} = \left| \sum_j \sqrt{\frac{m_j}{m_*}} U_{\alpha j} \Omega_{ji} \right|^2$$

- Imposing $K_{1\tau} \ll 1, \quad K_{2\tau}, K_{1e}, K_{1\mu} \geq K_{\rm st}$

$$m_1 > m_1^{\rm lb} \equiv m_* \max_\alpha \left[\left(\frac{\sqrt{K_{\rm st}} - \sqrt{K_{1\alpha}^{0,\rm max}}}{\max\left[|\Omega_{21}|\right] \left| U_{\alpha 1} - \frac{U_{\tau 1}}{U_{\tau 3}} U_{\alpha 3} \right|} \right)^2 \right]$$

$$K_{\rm st} \propto \ln \left| N_{B-L}^{\rm p,i} \right|$$

$$K_{1\alpha}^{0,\rm max} \propto \max\left[|\Omega_{21}|^2 \right]$$



Lower bound on m₁

- **Flavoured decay parameters**

$$K_{i\alpha} = \left| \sum_j \sqrt{\frac{m_j}{m_*}} U_{\alpha j} \Omega_{ji} \right|^2$$

- **Imposing** $K_{1\tau} \ll 1, \quad K_{2\tau}, K_{1e}, K_{1\mu} \geq K_{\rm st}$

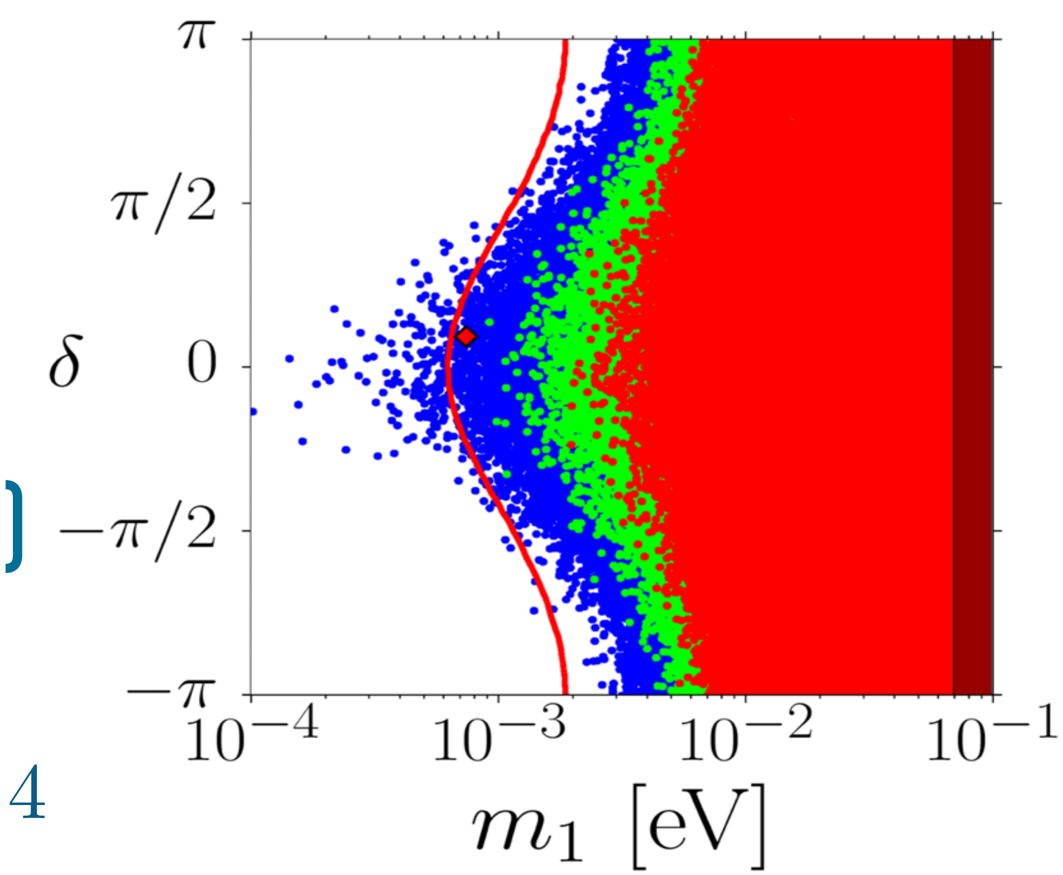
$$m_1 > m_1^{\rm lb} \equiv m_* \max_\alpha \left[\left(\frac{\sqrt{K_{\rm st}} - \sqrt{K_{1\alpha}^{0,\max}}}{\max\left[|\Omega_{21}|\right] \left| U_{\alpha 1} - \frac{U_{\tau 1}}{U_{\tau 3}} U_{\alpha 3} \right|} \right)^2 \right]$$

$$K_{\rm st} \propto \ln \left| N_{B-L}^{\rm p,i} \right|$$

$$K_{1\alpha}^{0,\max} \propto \max\left[|\Omega_{21}|^2 \right]$$

- **The lower bound exists if max[|Ω₂₁|²] is not too large**

$$\sqrt{K_{\rm st}} \geq \sqrt{K_{1\alpha}^{0,\max}} \quad \rightsquigarrow \quad \max\left[|\Omega_{21}|^2\right] \lesssim 4$$



SO(10)-inspired models

- Inherit conditions inspired to SO(10) grand unified models.

Neutrino Dirac mass matrix: $m_D = V_L^\dagger \, D_{m_D} \, U_R$

(1) $D_{m_D} \equiv (\alpha_1 m_u, \, \alpha_2 m_c, \, \alpha_3 m_t)$

(2) $\mathbb{1} \leq V_L \leq V_{\rm CKM}$

with $\begin{cases} \alpha_i = \mathcal{O}(1 \div 10) \\ m_u, \, m_c, \, m_t \end{cases}$ up-quark masses

SO(10)-inspired models

- Inherit conditions inspired to SO(10) grand unified models.

Neutrino Dirac mass matrix: $m_D = V_L^\dagger \, D_{m_D} \, U_R$

(1) $D_{m_D} \equiv (\alpha_1 m_u, \, \alpha_2 m_c, \, \alpha_3 m_t)$

(2) $\mathbb{1} \leq V_L \leq V_{\rm CKM}$

with $\begin{cases} \alpha_i = \mathcal{O}(1 \div 10) \\ m_u, \, m_c, \, m_t \end{cases}$ up-quark masses

- Matrix U_R is obtained analytically

SO(10)-inspired models

- Inherit conditions inspired to SO(10) grand unified models.

Neutrino Dirac mass matrix: $$m_D = V_L^\dagger \, D_{m_D} \, U_R$$

(1) $D_{m_D} \equiv (\alpha_1 m_u, \, \alpha_2 m_c, \, \alpha_3 m_t)$

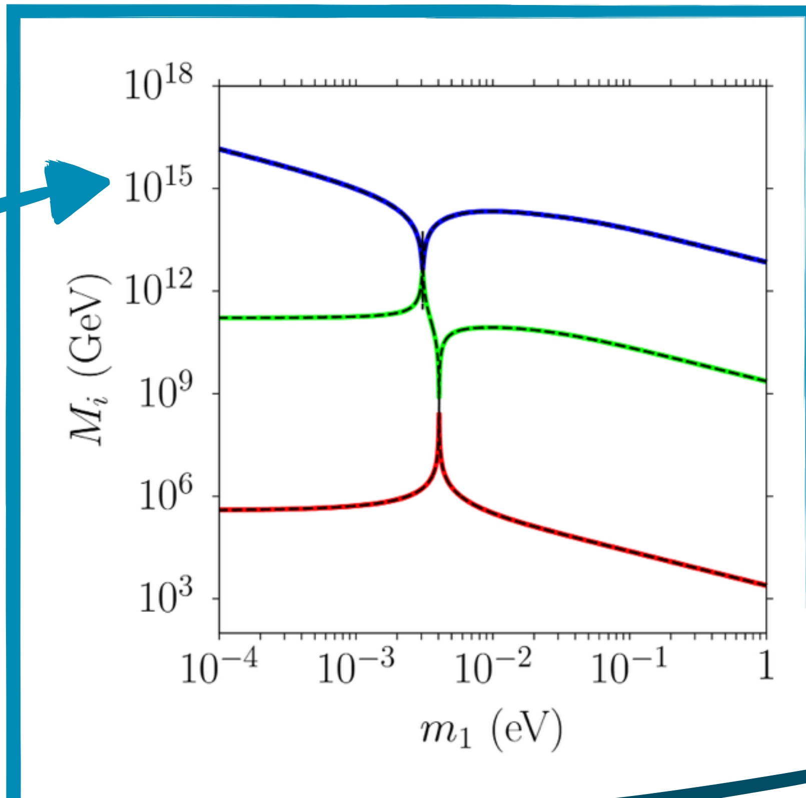
(2) $\mathbb{1} \leq V_L \leq V_{\rm CKM}$

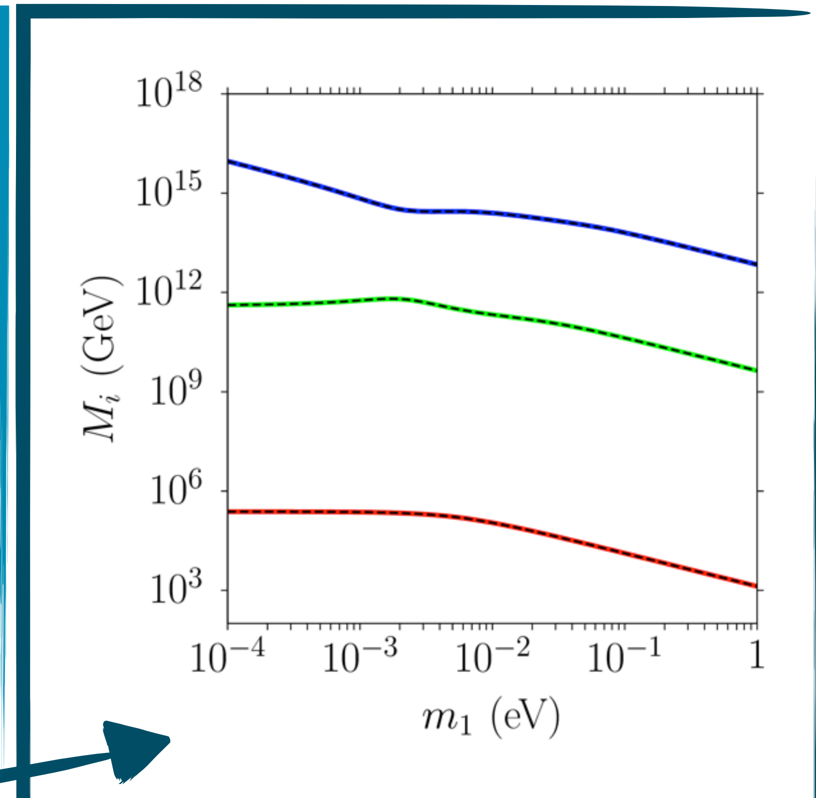
with $\begin{cases} \alpha_i = \mathcal{O}(1 \div 10) \\ m_u, \, m_c, \, m_t \end{cases}$ up-quark masses

- Matrix U_R is obtained analytically

- Barring crossing-level solutions, heavy neutrino spectrum is hierarchical

[Akhmedov, Frigerio, Smirnov 2003]





- Study the $V_L = \mathbb{1}$ case first.

$$\varepsilon_{2\tau} : \varepsilon_{2\mu} : \varepsilon_{2e} = \alpha_3^2\, m_t^2 : \alpha_2^2\, m_c^2 : \alpha_1^2\, m_u^2\, \frac{\alpha_3 m_t}{\alpha_2 m_c}\, \frac{\alpha_1 m_u^2}{\alpha_2^2\, m_c^2}$$

$$m_\nu = -m_D\, D_M^{-1}\, m_D^T$$
$$D_m = -U^\dagger\, m_\nu\, U^*$$

Final asymmetry: $N_{B-L}^{\rm lep,f} \simeq \varepsilon_{2\tau}\, \kappa(K_{2\tau})\, e^{-\frac{3\pi}{8}\, K_{1\tau}}$

$$N_{B-L}^{\rm lep,f} \simeq \frac{3}{16\pi}\, \frac{\alpha_2 m_c^2}{v^2}\, \frac{|m_{\nu ee}| \left(\left|(m_\nu^{-1})_{\tau\tau}\right|^2 + \left|(m_\nu^{-1})_{\mu\tau}\right|^2\right)^{-1}}{m_1\, m_2\, m_3}\, \frac{\left|(m_\nu^{-1})_{\tau\tau}\right|^2}{\left|(m_\nu^{-1})_{\mu\tau}\right|^2} {\rm Im}\left\{ \frac{\left((m_\nu^{-1})^*_{\mu\tau}\right)^2}{\left|(m_\nu^{-1})_{\mu\tau}\right|^2}\, \frac{m_{\nu ee}}{|m_{\nu ee}|}\, e^{-2i(\rho+\sigma)}\, e^{i\pi} \right\}$$
$$\times\, \kappa\left(\frac{m_1\, m_2\, m_3}{m_*}\, \frac{\left|(m_\nu^{-1})_{\mu\tau}\right|^2}{|m_{\nu ee}|\, \left|(m_\nu^{-1})_{\tau\tau}\right|} \right) \exp\left[-\frac{3\pi}{8}\, \frac{|m_{e\tau}|^2}{m_*\, |m_{\nu ee}|} \right]$$

- Study the $V_L = \mathbb{1}$ case first.

$$m_\nu = -m_D\, D_M^{-1}\, m_D^T$$
$$D_m = -U^\dagger\, m_\nu\, U^*$$

$$\varepsilon_{2\tau} : \varepsilon_{2\mu} : \varepsilon_{2e} = \alpha_3^2\, m_t^2 : \alpha_2^2\, m_c^2 : \alpha_1^2\, m_u^2\, \frac{\alpha_3 m_t}{\alpha_2 m_c}\, \frac{\alpha_1 m_u^2}{\alpha_2^2\, m_c^2}$$

Final asymmetry: $N_{B-L}^{\rm lep,f} \simeq \varepsilon_{2\tau}\, \kappa(K_{2\tau})\, e^{-\frac{3\pi}{8} K_{1\tau}}$

CP-asymmetry

$$N_{B-L}^{\rm lep,f} \simeq \frac{3}{16\pi}\, \frac{\alpha_2 m_c^2}{v^2}\, \frac{|m_{\nu ee}| \left(\left|(m_\nu^{-1})_{\tau\tau}\right|^2 + \left|(m_\nu^{-1})_{\mu\tau}\right|^2\right)^{-1}}{m_1\, m_2\, m_3}\, \frac{\left|(m_\nu^{-1})_{\tau\tau}\right|^2}{\left|(m_\nu^{-1})_{\mu\tau}\right|^2}\, \mathrm{Im}\left\{ \frac{\left((m_\nu^{-1})^*_{\mu\tau}\right)^2}{\left|(m_\nu^{-1})_{\mu\tau}\right|^2}\, \frac{m_{\nu ee}}{|m_{\nu ee}|}\, e^{-2i(\rho+\sigma)}\, e^{i\pi} \right\}$$
$$\times\, \kappa\left(\frac{m_1\, m_2\, m_3}{m_*}\, \frac{\left|(m_\nu^{-1})_{\mu\tau}\right|^2}{|m_{\nu ee}|\, \left|(m_\nu^{-1})_{\tau\tau}\right|} \right) \exp\left[-\frac{3\pi}{8}\, \frac{|m_{e\tau}|^2}{m_*\, |m_{\nu ee}|} \right]$$

Efficiency factor

Washout by N_1

- Study the $V_L = \mathbb{1}$ case first.

$$\varepsilon_{2\tau} : \varepsilon_{2\mu} : \varepsilon_{2e} = \alpha_3^2\, m_t^2 : \alpha_2^2\, m_c^2 : \alpha_1^2\, m_u^2\, \frac{\alpha_3 m_t}{\alpha_2 m_c} \frac{\alpha_1 m_u^2}{\alpha_2^2\, m_c^2}$$

$$m_\nu = -m_D\, D_M^{-1}\, m_D^T$$
$$D_m = -U^\dagger\, m_\nu\, U^*$$

Final asymmetry: $N_{B-L}^{\mathrm{lep,f}} \simeq \varepsilon_{2\tau}\, \kappa(K_{2\tau})\, e^{-\frac{3\pi}{8} K_{1\tau}}$

CP-asymmetry

Effective phase

$$N_{B-L}^{\mathrm{lep,f}} \simeq \frac{3}{16\pi} \frac{\alpha_2 m_c^2}{v^2} \frac{|m_{\nu ee}| \left(\left|(m_\nu^{-1})_{\tau\tau}\right|^2 + \left|(m_\nu^{-1})_{\mu\tau}\right|^2\right)^{-1}}{m_1\, m_2\, m_3} \frac{\left|(m_\nu^{-1})_{\tau\tau}\right|^2}{\left|(m_\nu^{-1})_{\mu\tau}\right|^2} \mathrm{Im}\left\{ \frac{\left((m_\nu^{-1})^*_{\mu\tau}\right)^2}{\left|(m_\nu^{-1})_{\mu\tau}\right|^2} \frac{m_{\nu ee}}{|m_{\nu ee}|} e^{-2i(\rho+\sigma)} e^{i\pi} \right\}$$
$$\times\, \kappa\left(\frac{m_1\, m_2\, m_3}{m_*} \frac{\left|(m_\nu^{-1})_{\mu\tau}\right|^2}{|m_{\nu ee}|\, \left|(m_\nu^{-1})_{\tau\tau}\right|} \right) \exp\left[-\frac{3\pi}{8} \frac{|m_{e\tau}|^2}{m_*\, |m_{\nu ee}|} \right]$$

Efficiency factor

Washout by N_1

- Study the $V_L = \mathbb{1}$ case first.

$$\varepsilon_{2\tau} : \varepsilon_{2\mu} : \varepsilon_{2e} = \alpha_3^2\, m_t^2 : \alpha_2^2\, m_c^2 : \alpha_1^2\, m_u^2 \, \frac{\alpha_3 m_t}{\alpha_2 m_c} \, \frac{\alpha_1 m_u^2}{\alpha_2^2\, m_c^2}$$

$$m_\nu = -m_D\, D_M^{-1}\, m_D^T$$
$$D_m = -U^\dagger\, m_\nu\, U^*$$

Final asymmetry: $N_{B-L}^{\rm lep,f} \simeq \varepsilon_{2\tau}\, \kappa(K_{2\tau})\, e^{-\frac{3\pi}{8} K_{1\tau}}$

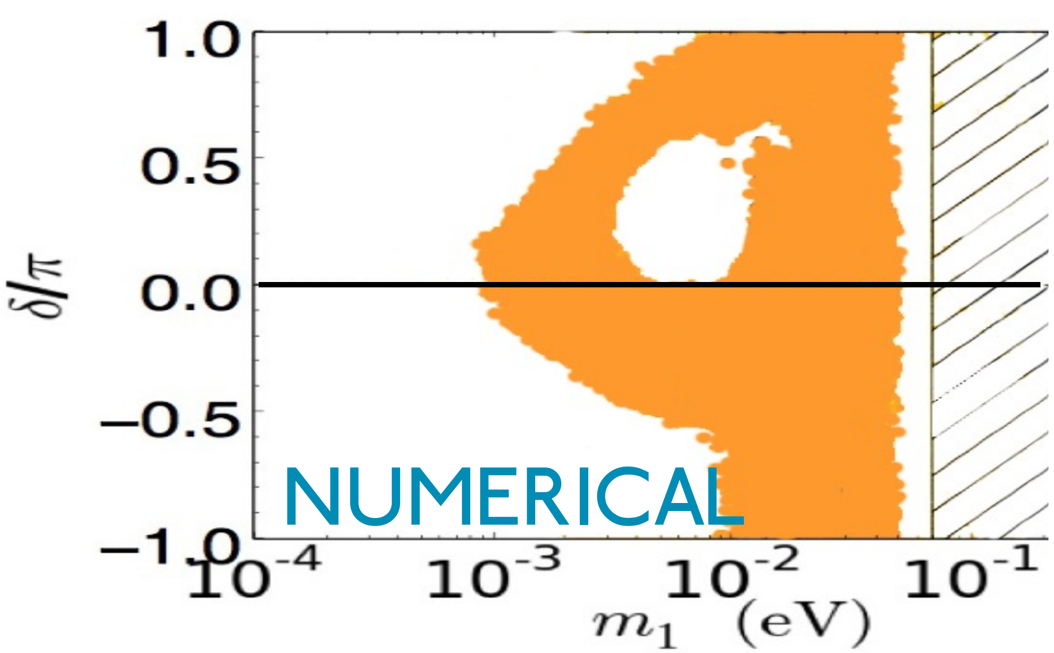
CP-asymmetry

Effective phase

$$N_{B-L}^{\rm lep,f} \simeq \frac{3}{16\pi}\, \frac{\alpha_2 m_c^2}{v^2}\, \frac{|m_{\nu ee}| \left(\left|(m_\nu^{-1})_{\tau\tau}\right|^2 + \left|(m_\nu^{-1})_{\mu\tau}\right|^2\right)^{-1}}{m_1\, m_2\, m_3}\, \frac{\left|(m_\nu^{-1})_{\tau\tau}\right|^2}{\left|(m_\nu^{-1})_{\mu\tau}\right|^2}\, \mathrm{Im}\left\{ \frac{\left((m_\nu^{-1})^*_{\mu\tau}\right)^2}{\left|(m_\nu^{-1})_{\mu\tau}\right|^2}\, \frac{m_{\nu ee}}{|m_{\nu ee}|}\, e^{-2i(\rho+\sigma)}\, e^{i\pi} \right\}$$
$$\times\, \kappa\left(\frac{m_1\, m_2\, m_3}{m_*}\, \frac{\left|(m_\nu^{-1})_{\mu\tau}\right|^2}{|m_{\nu ee}|\, \left|(m_\nu^{-1})_{\tau\tau}\right|} \right) \exp\left[-\frac{3\pi}{8}\, \frac{|m_{e\tau}|^2}{m_*\, |m_{\nu ee}|} \right]$$

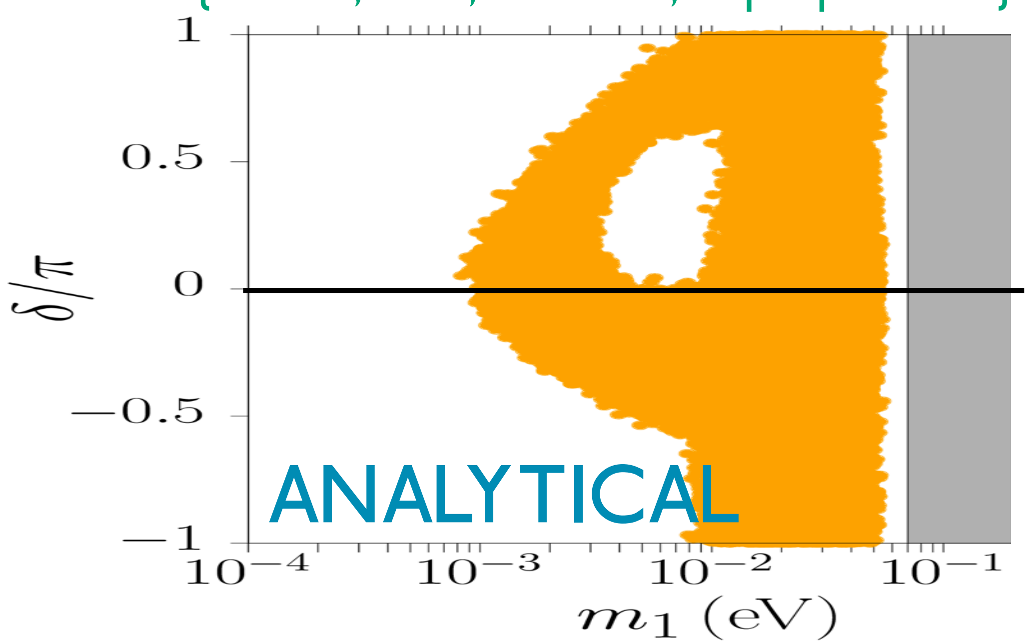
Efficiency factor

Washout by N_1



$$\eta_B^{\rm lep,f} \gtrsim \eta_B^{\rm CMB}$$

(Di Bari, MRF, Marzola, in preparation)



- **Study the $V_L = \mathbb{1}$ case first.**

$$\varepsilon_{2\tau} : \varepsilon_{2\mu} : \varepsilon_{2e} = \alpha_3^2\, m_t^2 : \alpha_2^2\, m_c^2 : \alpha_1^2\, m_u^2\, \frac{\alpha_3 m_t}{\alpha_2 m_c}\, \frac{\alpha_1 m_u^2}{\alpha_2^2\, m_c^2}$$

$$m_\nu = -m_D\, D_M^{-1}\, m_D^T$$
$$D_m = -U^\dagger\, m_\nu\, U^*$$

Final asymmetry: $N_{B-L}^{\rm lep,f} \simeq \varepsilon_{2\tau}\, \kappa(K_{2\tau})\, e^{-\frac{3\pi}{8} K_{1\tau}}$

CP-asymmetry

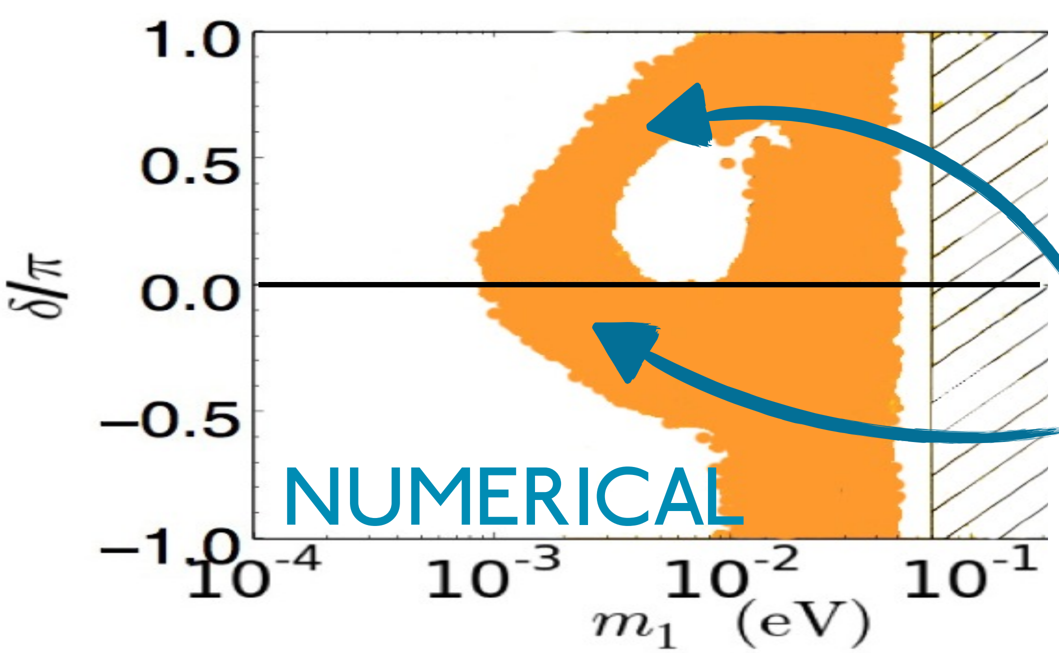
Effective phase

$$N_{B-L}^{\rm lep,f} \simeq \frac{3}{16\pi}\, \frac{\alpha_2 m_c^2}{v^2}\, \frac{|m_{\nu ee}| \left(\left|(m_\nu^{-1})_{\tau\tau}\right|^2 + \left|(m_\nu^{-1})_{\mu\tau}\right|^2 \right)^{-1}}{m_1\, m_2\, m_3}\, \frac{\left|(m_\nu^{-1})_{\tau\tau}\right|^2}{\left|(m_\nu^{-1})_{\mu\tau}\right|^2} \mathrm{Im}\left\{ \frac{\left((m_\nu^{-1})^*_{\mu\tau}\right)^2}{\left|(m_\nu^{-1})_{\mu\tau}\right|^2}\, \frac{m_{\nu ee}}{|m_{\nu ee}|}\, e^{-2i(\rho+\sigma)}\, e^{i\pi} \right\}$$
$$\times\, \kappa\left(\frac{m_1\, m_2\, m_3}{m_*}\, \frac{\left|(m_\nu^{-1})_{\mu\tau}\right|^2}{|m_{\nu ee}|\, \left|(m_\nu^{-1})_{\tau\tau}\right|} \right) \exp\left[-\frac{3\pi}{8}\, \frac{|m_{e\tau}|^2}{m_*\, |m_{\nu ee}|} \right]$$

Efficiency factor

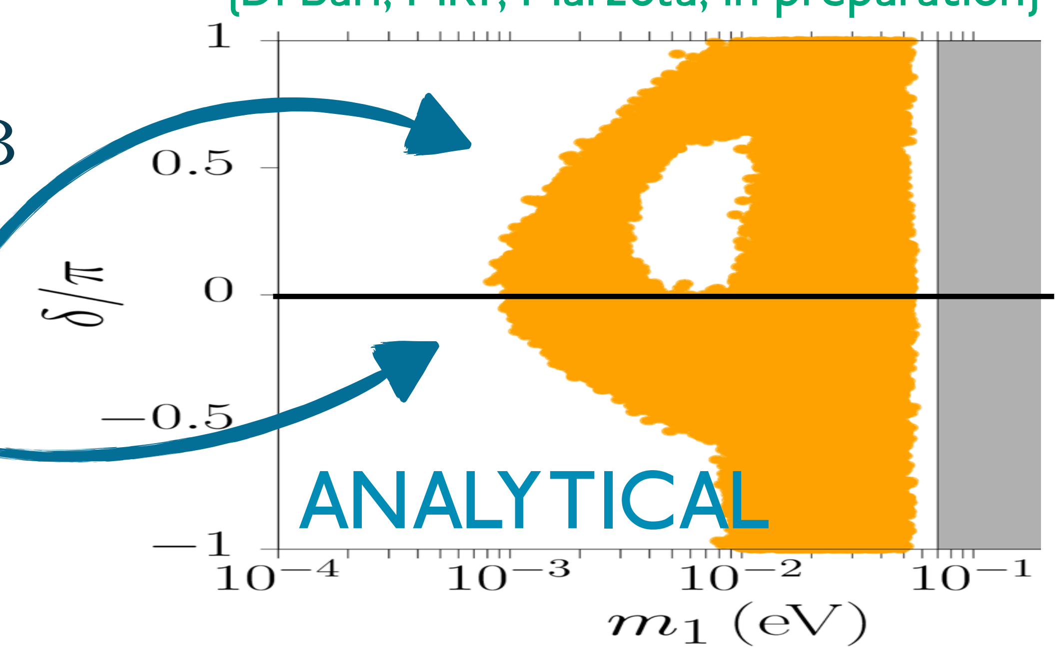
Washout by N₁

(Di Bari, MRF, Marzola, in preparation)



$$\eta_B^{\rm lep,f} \gtrsim \eta_B^{\rm CMB}$$

Asymmetry!

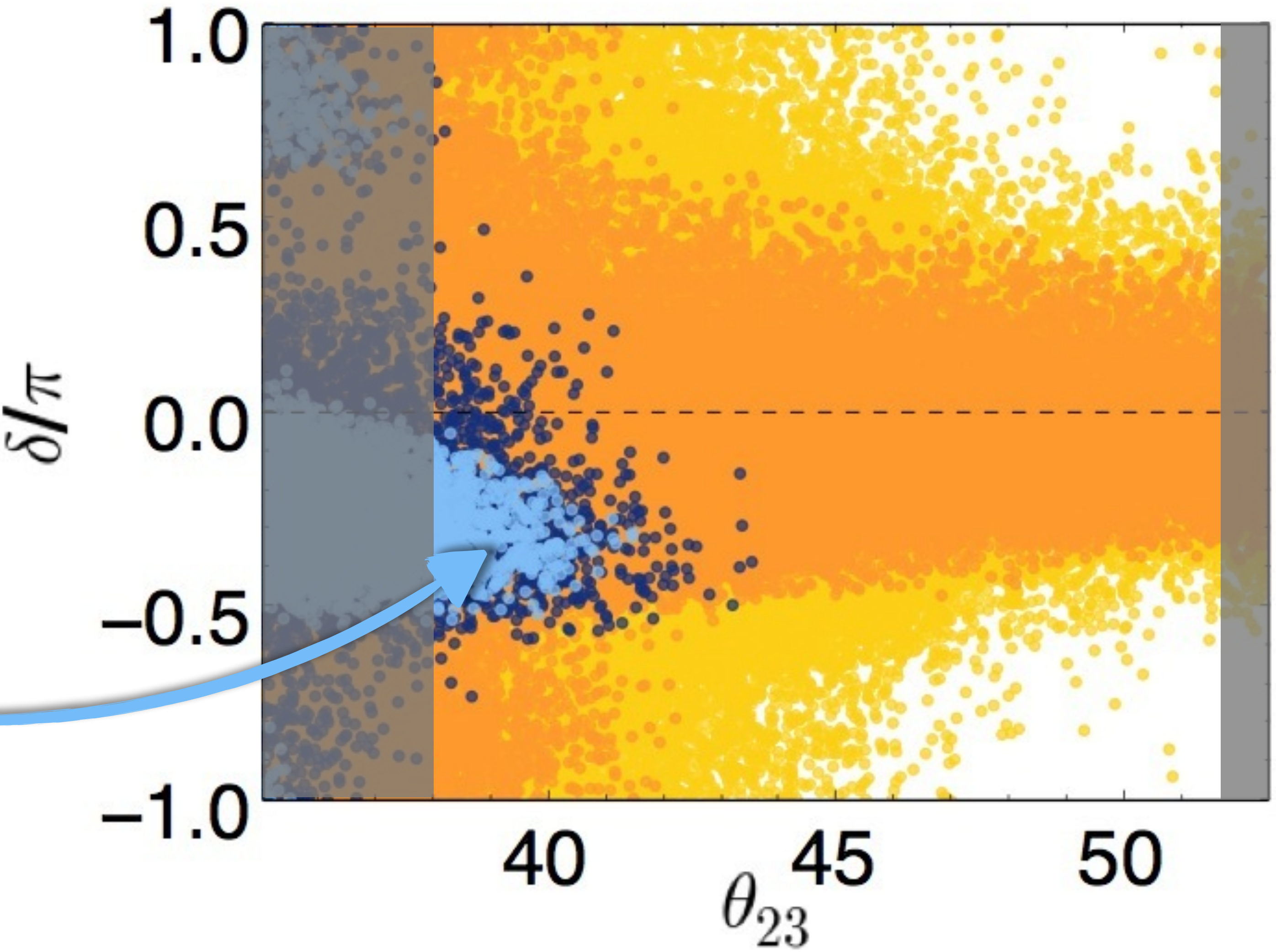


SO(10)-inspired + Strong thermal lep.

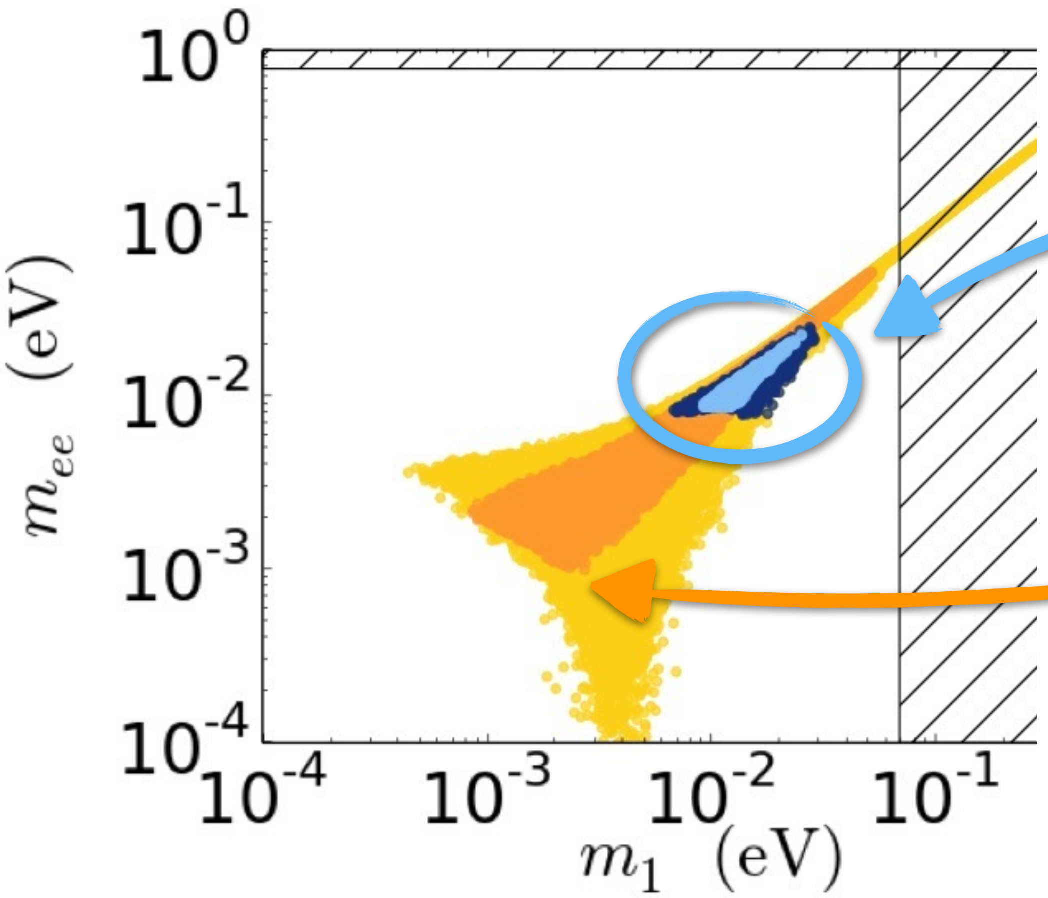
- Numerical predictions
  (Di Bari, Marzola, 2013)
- Analytical proof on the way
  (Di Bari, MRF, Marzola, in preparation)

$1 \leq V_L \leq V_{CKM}$, $N^{p,i}=0$
$V_L=1$, $N^{p,i}=0$
$1 \leq V_L \leq V_{CKM}$, $N^{p,i}=10^{-3}$
$V_L=1$, $N^{p,i}=10^{-3}$

	Predictions
m_1	$\approx$ 20 meV
Ordering	NORMAL
θ_{13}	$\gtrsim 2^\circ$
δ	$\approx -45^\circ$
θ_{23}	$\lesssim 41^\circ$



Experimental tests on the way

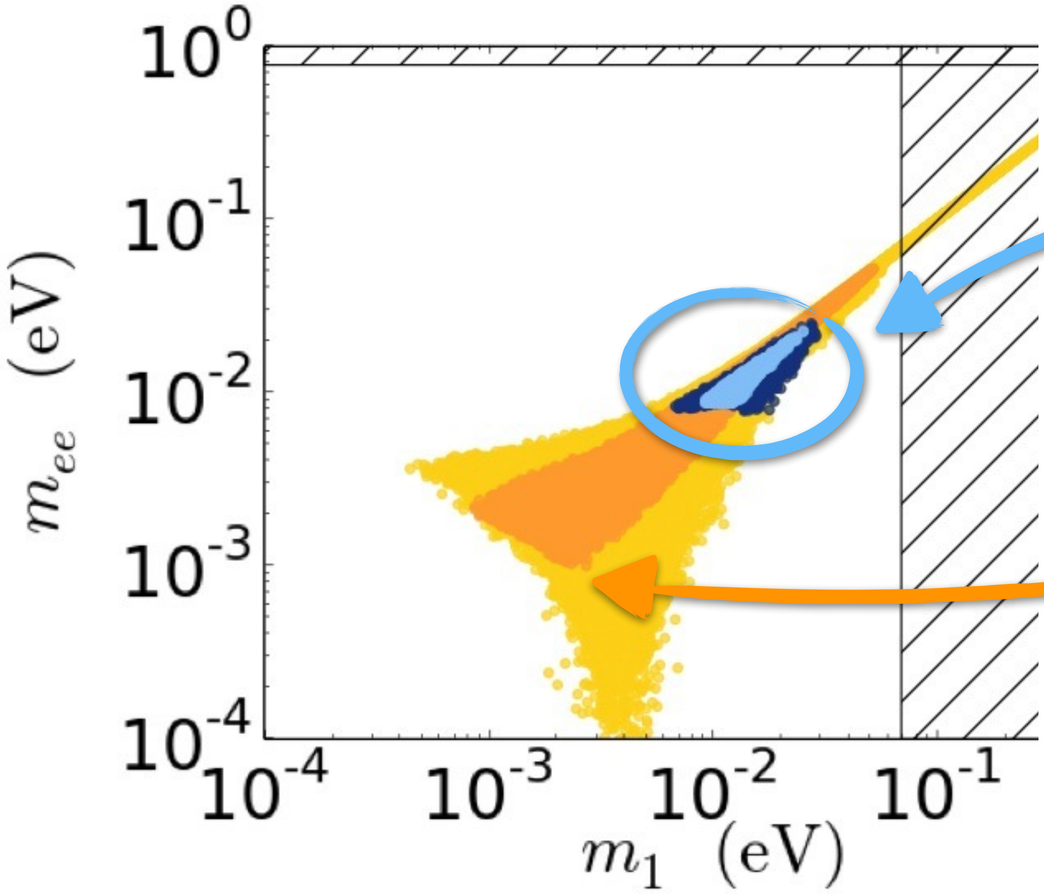


- Effective 0β2ν neutrino mass

$$|m_{\nu ee}| \simeq 15\,\mathrm{meV}$$

For V_L=1 $\quad M_2 \propto |m_{\nu ee}| \;\Rightarrow\; |m_{\nu ee}| \neq 0$

Experimental tests on the way



- Effective 0β2ν neutrino mass

$$|m_{\nu ee}| \simeq 15\,\mathrm{meV}$$

For V_L=1 $\quad M_2 \propto |m_{\nu ee}| \;\Rightarrow\; |m_{\nu ee}| \neq 0$

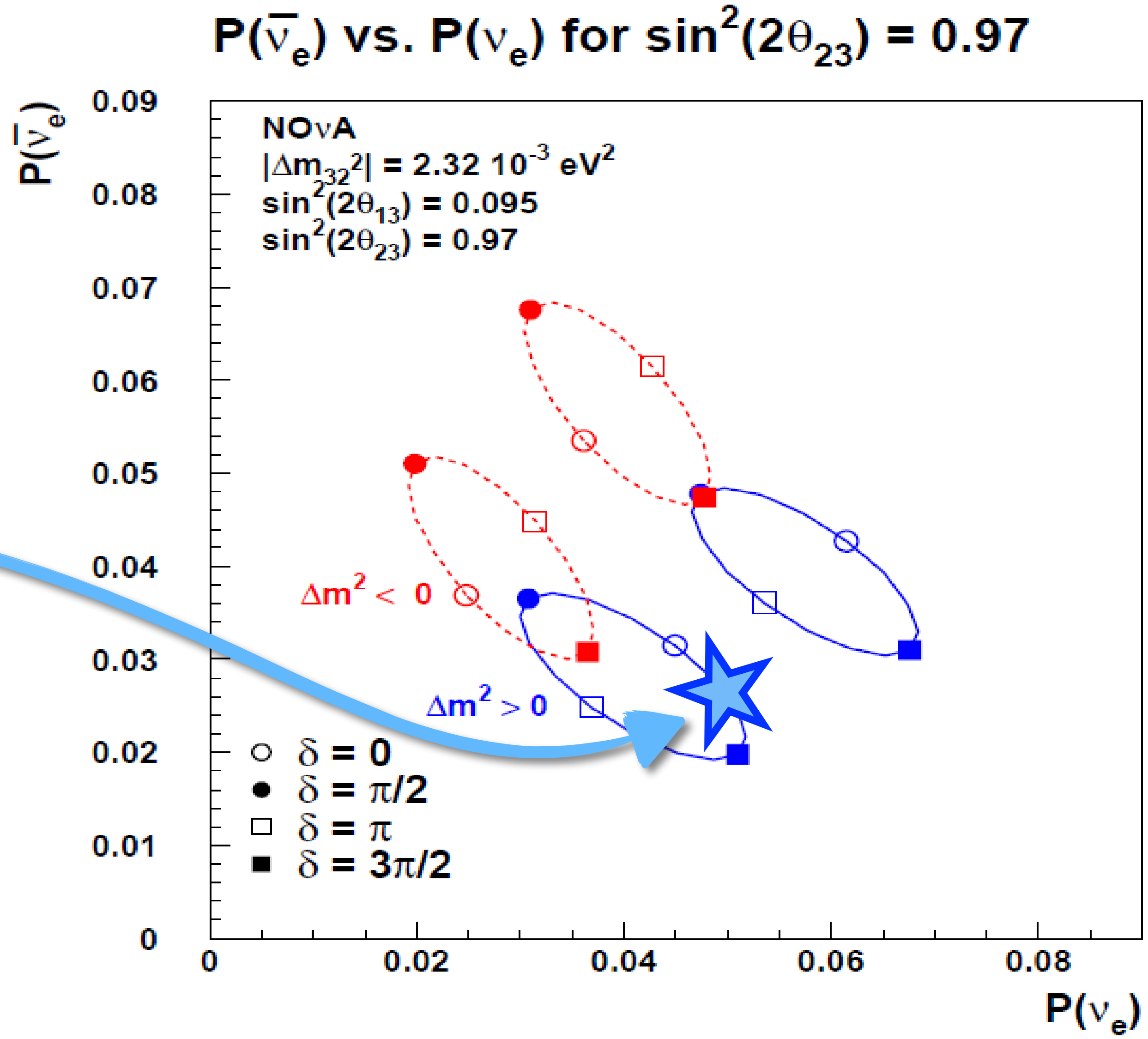
- NOνA experiment

SO(10)+STL solution

$$\theta_{23} \lesssim 41^\circ$$

$$\delta \simeq -\pi/4$$

Very important test of the model.



Conclusions

Leptogenesis links cosmology and neutrino physics.

Flavoured N_2-dominated

- Predictive with strong thermal leptogenesis:
  - low m_1 highly disfavoured
    (though quantitatively it may depend on the chosen parameterisation)

$$m_1 \gtrsim 1\,\mathrm{meV}$$

- Naturally realised in SO(10)-inspired models
  - Highly predictive on low-energy neutrino parameters

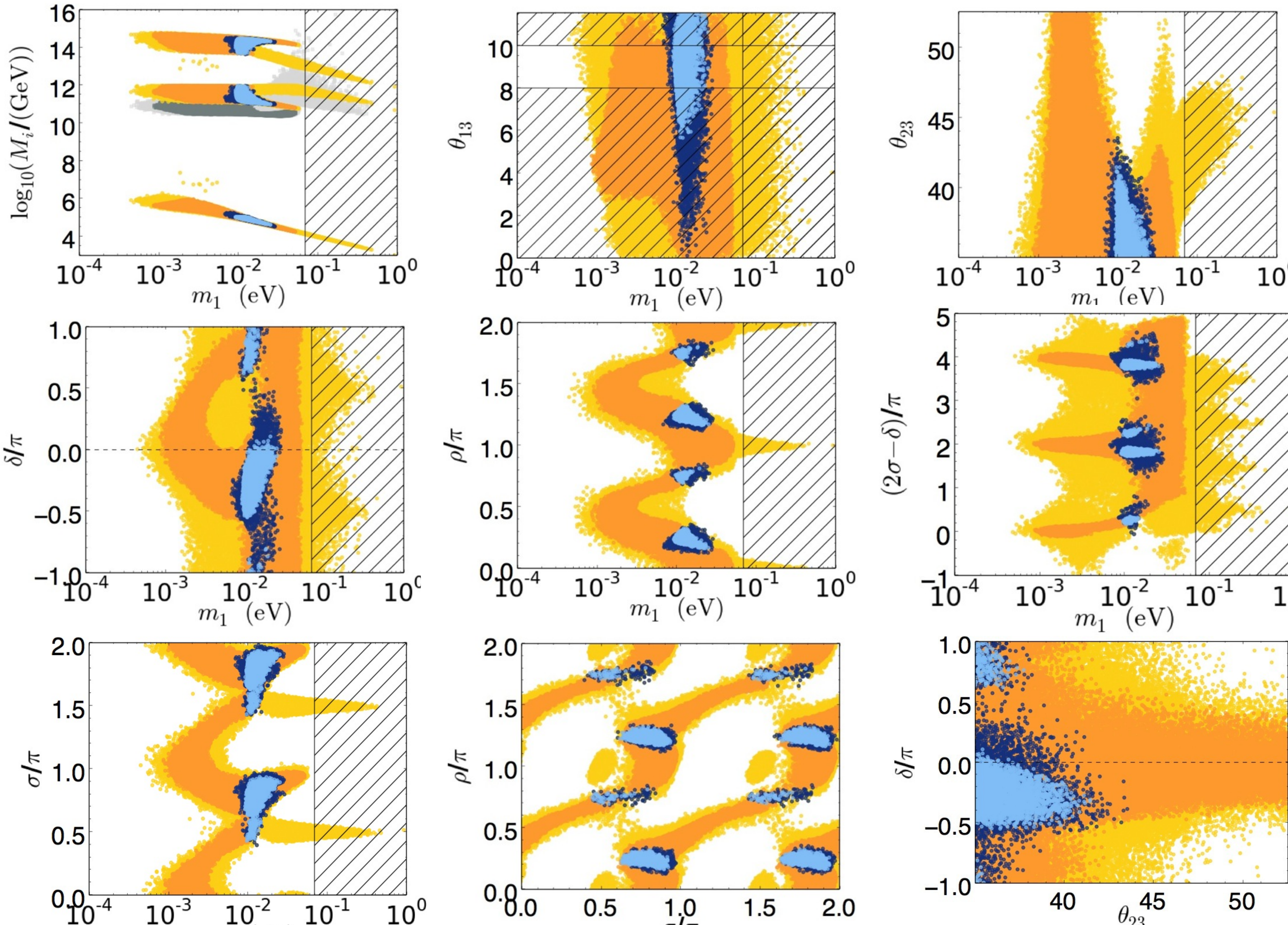
$$\theta_{23} \lesssim 41^\circ, \quad \delta \simeq -\pi/4$$

- Testable at forthcoming neutrino experiments

We are entering an exciting era of new experimental results that leptogenesis will have to face.

Backup

$1 \leq V_L \leq V_{CKM}, N^{p,i}=0$ $V_L=1, N^{p,i}=0$ $1 \leq V_L \leq V_{CKM}, N^{p,i}=10^{-3}$ $V_L=1, N^{p,i}=10^{-3}$



(Di Bari, Marzola, 2013; Di Bari, MRF, Marzola, in preparation)

SO(10)-inspired analytics

Takagi diagonalisation

$$M^{-1} = D_{m_D}^{-1}\, V_L\, U\, D_m\, U^T\, V_L^T\, D_{m_D}^{-1}$$
$$M^{-1} = U_R\, D_M^{-1}\, U_R^T$$

Heavy neutrino spectrum

$$M_1 \simeq \frac{m_{D1}^2}{|m_{\nu ee}|}$$
$$M_2 \simeq \frac{m_{D2}^2}{m_1\, m_2\, m_3}\,\frac{|m_{\nu ee}|}{\left|(m_\nu^{-1})_{\tau\tau}\right|}$$
$$M_3 \simeq m_{D3}^2\,\left|(m_\nu^{-1})_{\tau\tau}\right|$$

U_R matrix

$$U_R \simeq \begin{pmatrix} 1 & -\frac{m_{D1}}{m_{D2}}\frac{m_{\nu e\mu}^*}{m_{\nu ee}^*} & \frac{m_{D1}}{m_{D2}}\frac{(m_\nu^{-1})_{\mu\tau}^*}{(m_\nu^{-1})_{\tau\tau}^*} \\ \frac{m_{D1}}{m_{D2}}\frac{m_{\nu e\mu}}{m_{\nu ee}} & 1 & \frac{m_{d2}}{m_{D3}}\frac{(m_\nu^{-1})_{\mu\tau}^*}{(m_\nu^{-1})_{\tau\tau}^*} \\ \frac{m_{D1}}{m_{D3}}\frac{m_{\nu e\tau}}{m_{\nu ee}} & -\frac{m_{D2}}{m_{D3}}\frac{(m_\nu^{-1})_{\mu\tau}}{(m_\nu^{-1})_{\tau\tau}} & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{-i\phi_1/2} & & \\ & e^{-i\phi_2/2} & \\ & & e^{-i\phi_3/2} \end{pmatrix}$$

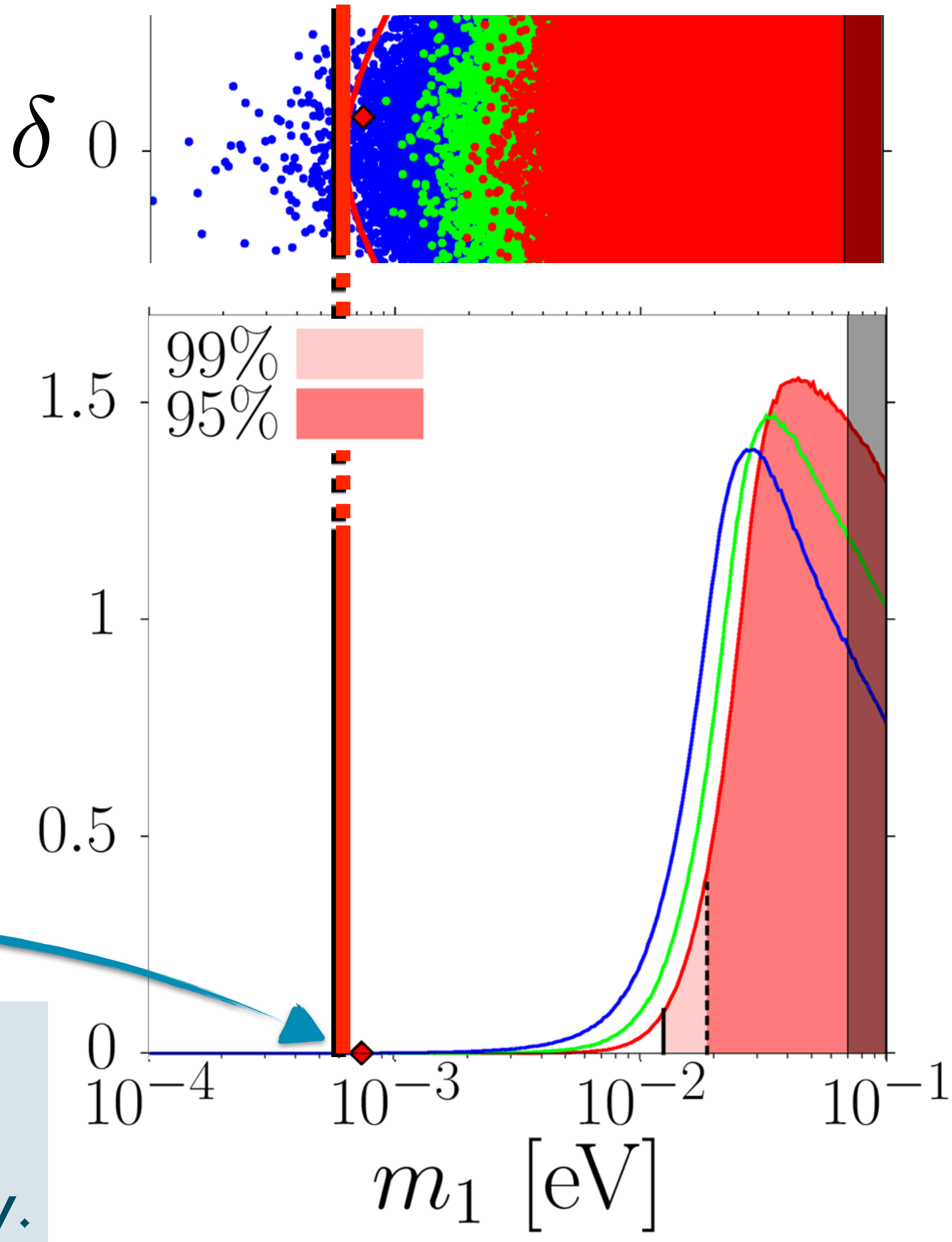
$$\phi_1 + \phi_2 + \phi_3 = -2(\rho + \sigma) \qquad \phi_1 = -\arg\{-m_{\nu ee}\} \qquad \phi_3 = \arg\{-(m_\nu^{-1})_{\tau\tau}\}$$

Statistics

For $N^{p,i}$=0.1, $|\Omega_{ij}|^2 \leq 2$:

- **99%** of points with
  $$m_1 \gtrsim 11\,\mathrm{meV}$$
- **95%** of points with
  $$m_1 \gtrsim 18\,\mathrm{meV}$$

- 100% of points larger than the analytical lower bound.
  $$m_1 \gtrsim 1\,\mathrm{meV}$$



Experiments can then exclude portions of parameter space accordingly.

Experimental test: Cosmology

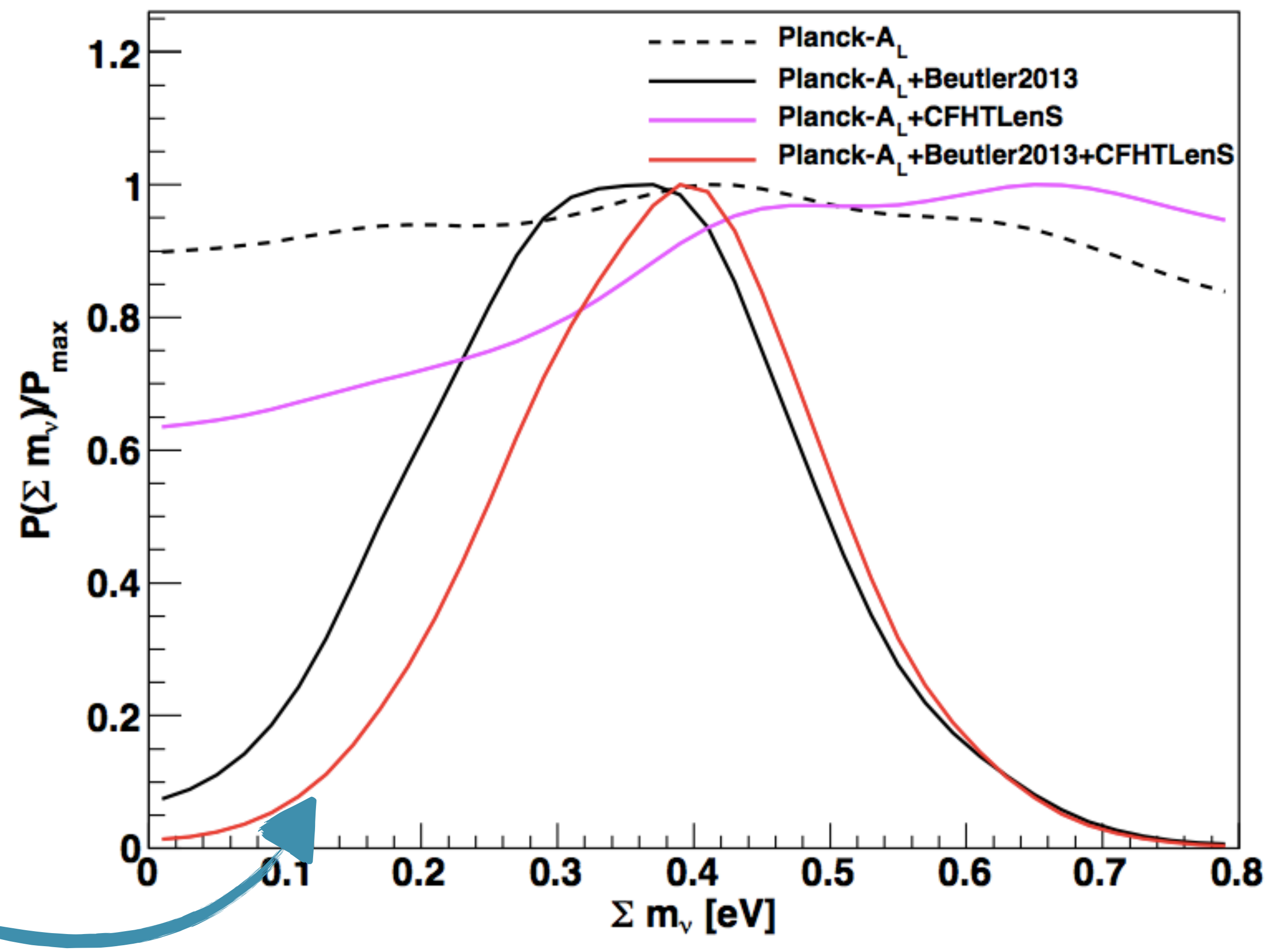
- CMB spectrum alone:

$$\sum m_\nu < 0.933\,\mathrm{eV}$$ [Planck XVI]

- CMB+SZ+BAO

$$\sum m_\nu = (0.22 \pm 0.09)\,\mathrm{eV}$$

[Planck XX]



- BOSS collaboration

$$\sum m_\nu = (0.36 \pm 0.10)\,\mathrm{eV}$$

at 3.4σ [Beutler et al. 2014]

are experiments pointing at $m_1 \neq 0$?

Long Baseline experiments must determine the ordering!

Light neutrino spectrum

Tritium β decay:
$m_e < 2\,\mathrm{eV}$

(Mainz-Troitzk)

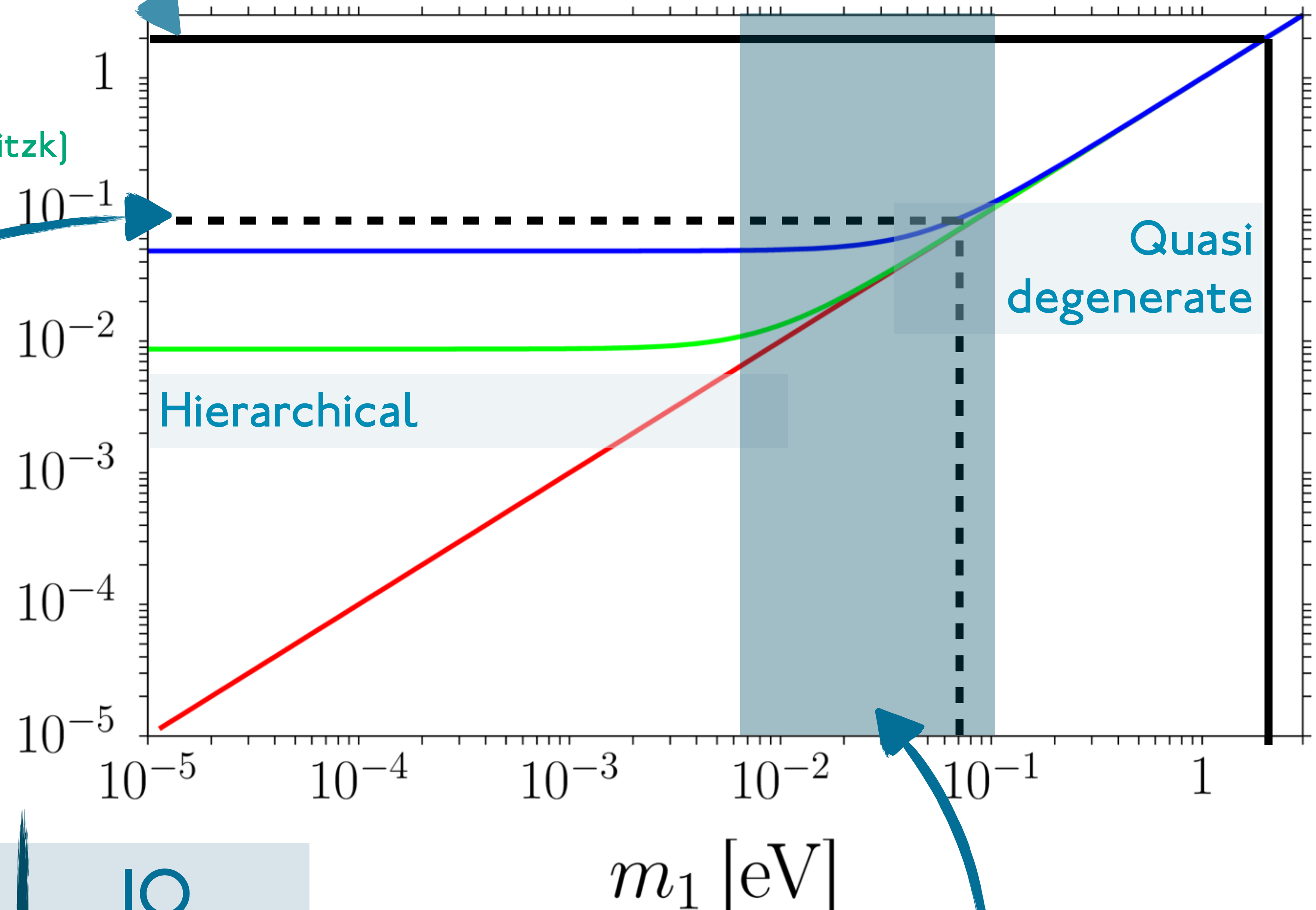
ΛCDM:
$m_1 < 0.07\,\mathrm{eV}$

(Planck+WP+BAO+highL)

$m_3 = m_2^{\mathrm{IO}}$

m_2^{NO}

m_1



	NO	IO
	$m_3^2 - m_2^2 = \Delta m^2_{\mathrm{atm}}$	$\Delta m^2_{\mathrm{sol}}$
	$m_2^2 - m_1^2 = \Delta m^2_{\mathrm{sol}}$	$\Delta m^2_{\mathrm{atm}}$

Semi-hierarchical spectrum

Flavour coupling

[Blanchet, Di Bari, 2006;
Antusch, Di Bari, Jones, SFKing, 2012]

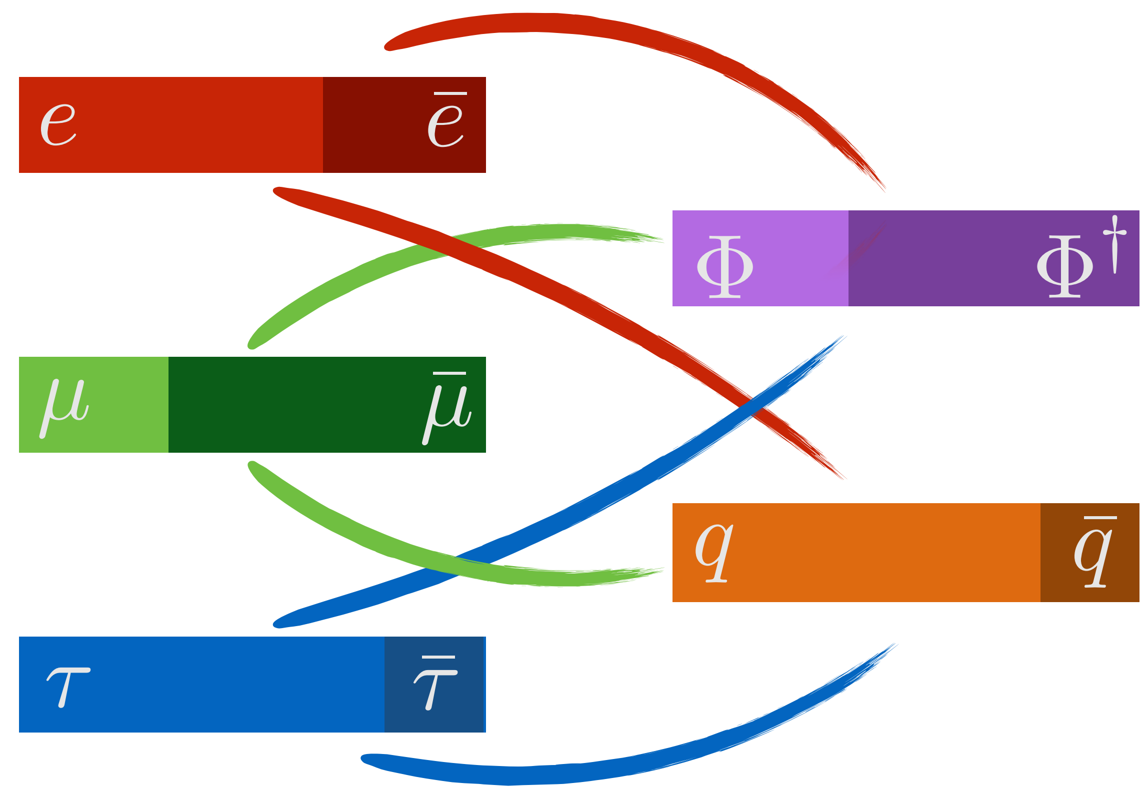
- Flavour asymmetries do not evolve independently
- Coupling through Higgs and quark asymmetries

2-flavoured regime: N_2's decay, $\gamma, \delta = (e+\mu), \tau$

$$\frac{dN_\gamma}{dz_2} = D_{N_2}\left(\varepsilon_{2\gamma}\right) - P^0_{2\gamma} W_2 \sum_\delta C^{(2)}_{\gamma\delta} N_\delta$$

3-flavoured regime: N_1's washout, $\alpha, \beta = e, \mu, \tau$

$$\frac{dN_\alpha}{dz_2} = -P^0_{1\alpha} \sum_\beta C^{(3)}_{\alpha\beta} W_1^{\mathrm{ID}} N_\beta$$



Modification of the final asymmetry

1 order of magnitude for ≈30% of the param. space

[SEKing, MRF 2014;
Work in progress...]

Modification of the statistical limits

99% limit ≈×2 higher

Phantom terms

(Nardi, Racker, Roulet '06;
Antusch, Di Bari, SFKing, Jones '10;
Blachet, Di Bari, Marzola, Jones '11,'12)

$\Gamma_2 \neq \bar{\Gamma}_2$ $\quad$ $|\bar{l}_2\rangle \neq CP|l_2\rangle$

$$\varepsilon_{2\alpha} = P^0_{1\alpha}\varepsilon_2 + \frac{\Delta P^0_{2\alpha}}{2}$$

$$N^{\rm lep,f}_{\delta} \simeq \left[\frac{P^0_{2\delta}}{P^0_{2(e+\mu)}}\varepsilon_{2(e+\mu)}\kappa\left(K_{2(e+\mu)}\right) + \left(\varepsilon_{2\delta} - \frac{P^0_{2\delta}}{P^0_{2(e+\mu)}}\varepsilon_{2(e+\mu)}\right)\kappa\left(K_{2(e+\mu)}/2\right)\right] e^{-3\pi/8K_{1\delta}}$$

- $\eta_B^{(c)} \simeq 10^{\pm 1}\,\eta_B^{(u)}$ in ≈30% of the parameter space (SEKing, MRF 2014; Work in progress)
- Assumed zero in strong thermal analysis