Neutrino parameters and N_2-dominated leptogenesis

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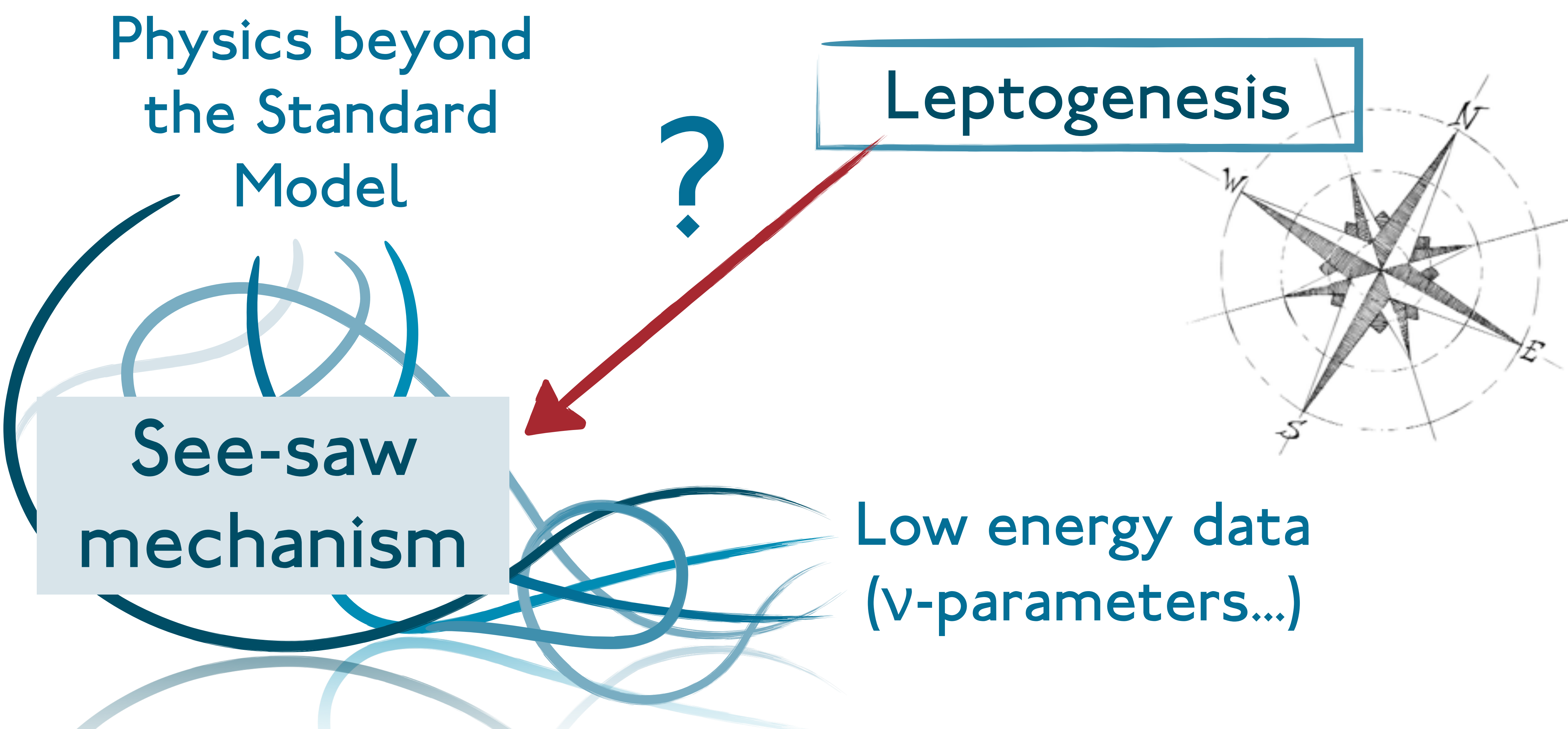
Based on: arXiv 1401.6185 with Pasquale Di Bari and Sophie E. King

Why leptogenesis?

Mechanism able to dynamically produce the baryon asymmetry

Link between cosmology, neutrino & new physics



See-saw 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?

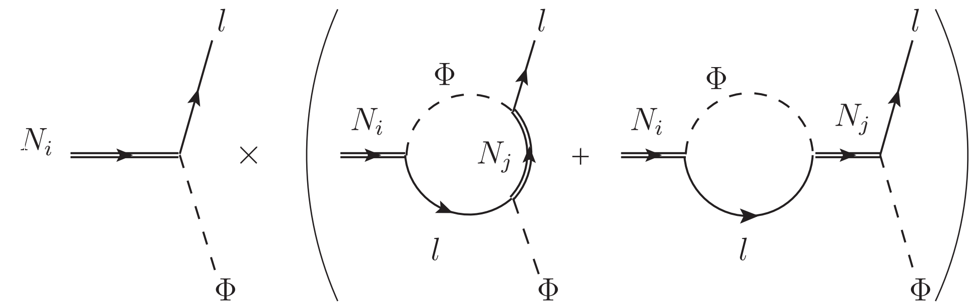
Making leptogenesis predictive means making it "testable"

(e.g. talk by Julia Harz)

Flavours

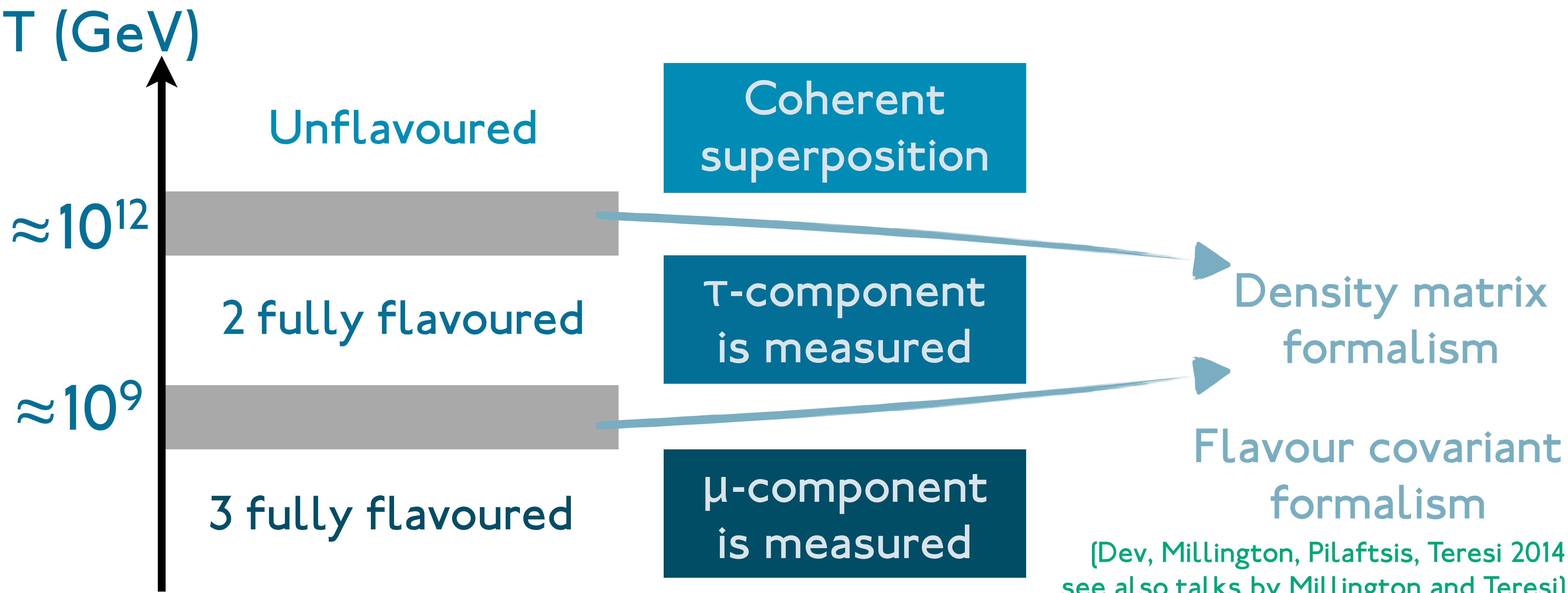
- Decay of RH neutrinos

$$N_i \xrightarrow{\Gamma_i} l_i\,\Phi^\dagger \qquad N_i \xrightarrow{\bar{\Gamma}_i} \bar{l}_i\,\Phi$$



- For T≲10^{12} GeV, τ-interactions are fast enough to break the coherence of $|l_i\rangle, \ |\bar{l}_i\rangle$

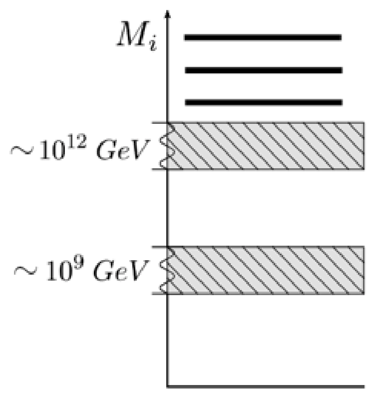
[Abada et al. 2006; Nardi, Nir, Roulet, Racker 2006; Blanchet, Di Bari, Raffelt '06; Riotto, De Simone 2006]



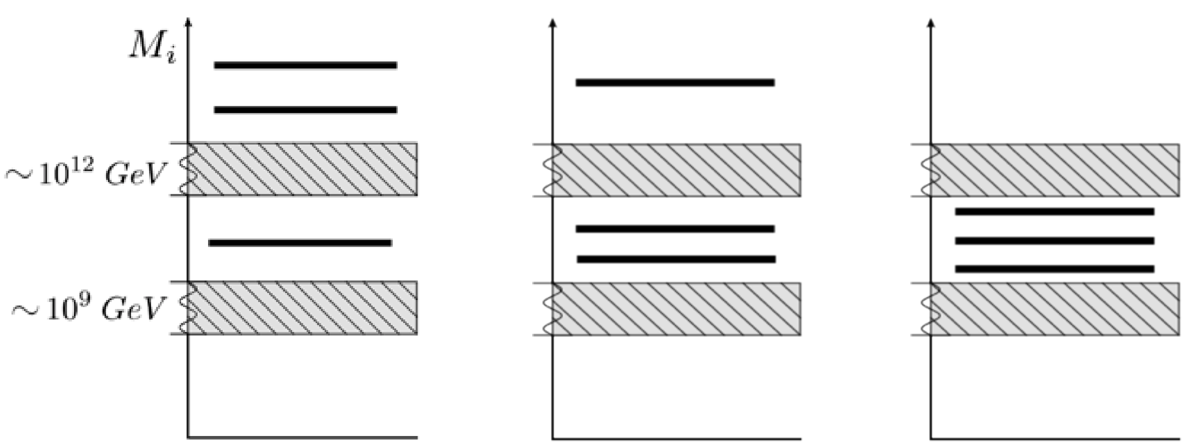
[Dev, Millington, Pilaftsis, Teresi 2014 see also talks by Millington and Teresi]

Hierarchical spectrum

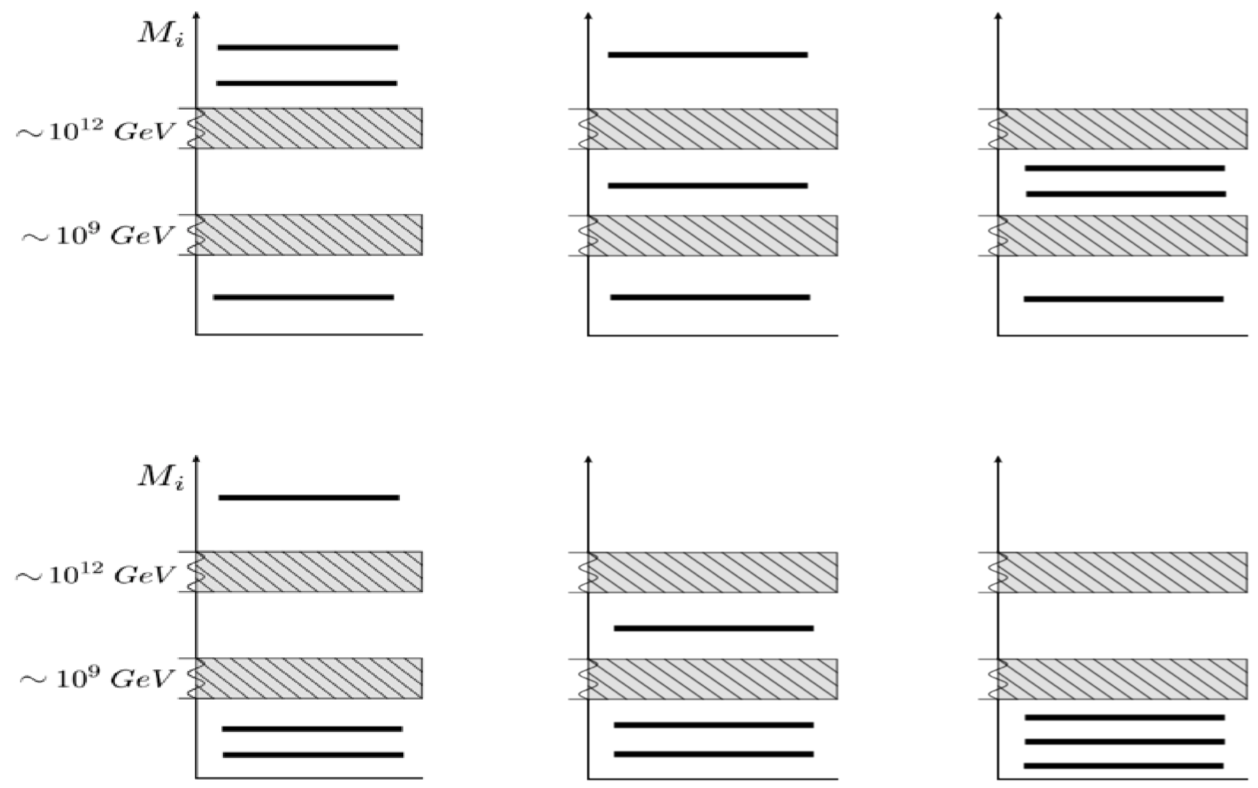
- Choose the hierarchical spectrum of 3 RH neutrinos.
  - Comply with the two "scales": 10^9, 10^{12} GeV.



Unflavoured



2 fully flavoured



3 fully flavoured

Hierarchical spectrum

- Choose the hierarchical spectrum of 3 RH neutrinos.
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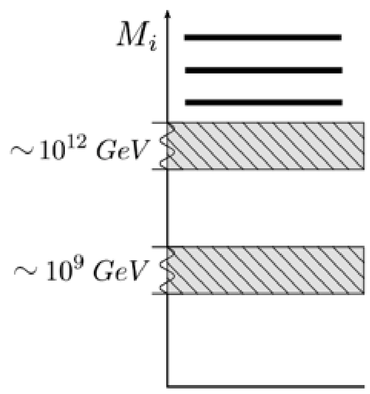
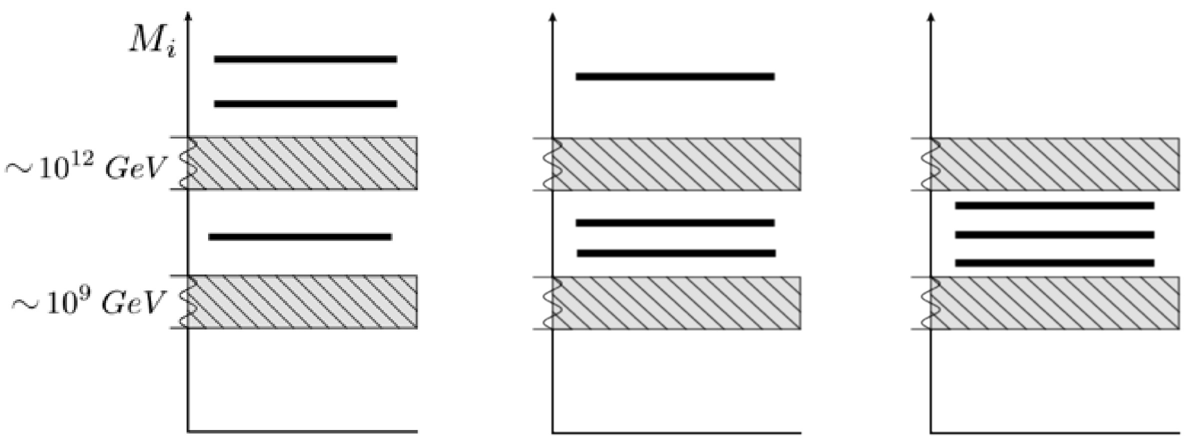
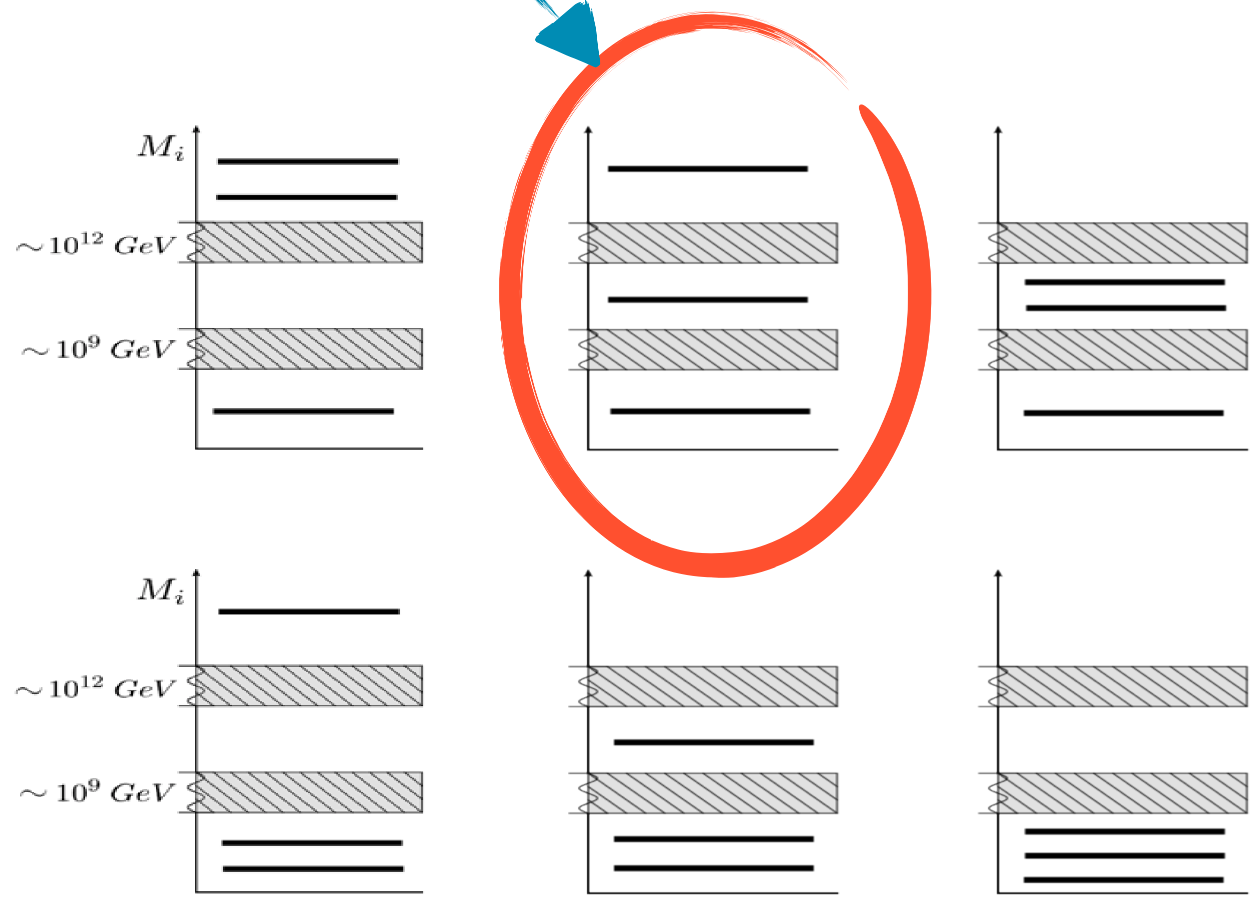
Flavoured N_2-dominated scenario



Unflavoured



2 fully flavoured



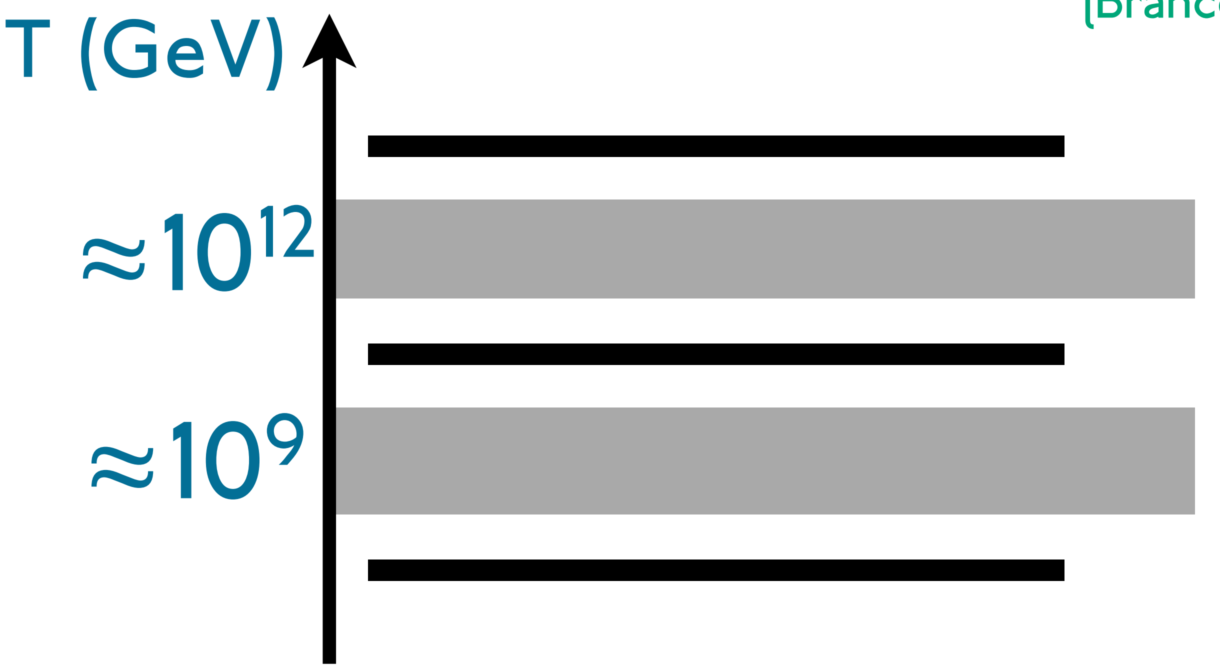
3 fully flavoured

Why should flavoured-N_2 be interesting?

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

These models predict a precise spectrum of RH neutrinos:

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



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

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

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

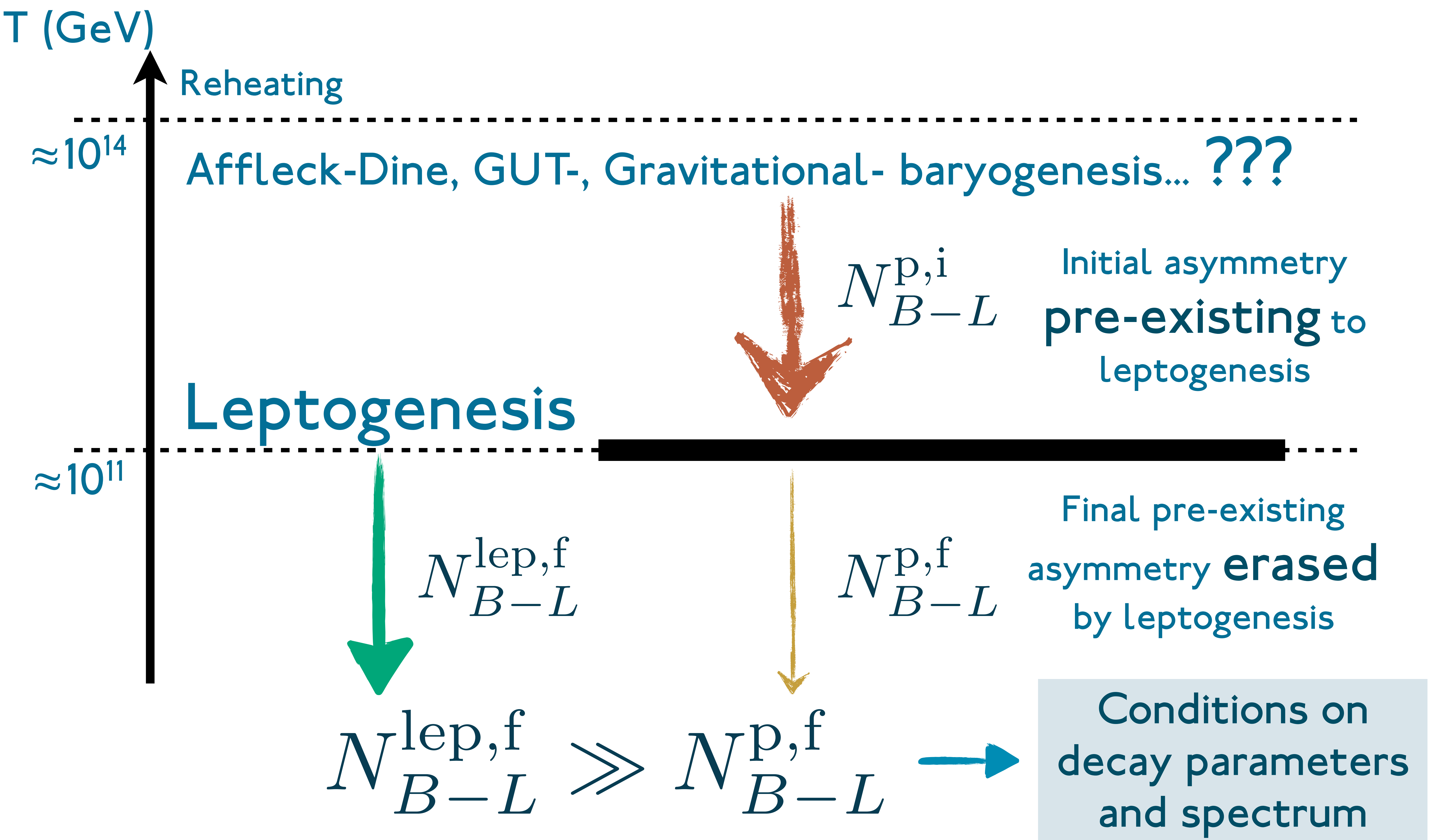
High reheating temperature, in line with BICEP2 (to be confirmed...)

(2) This scenario can become predictive

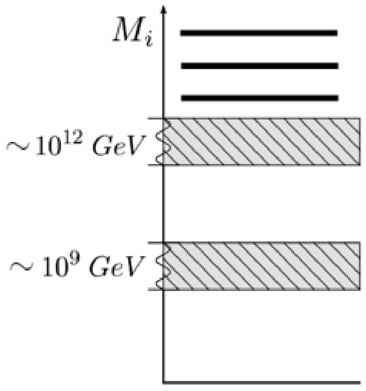
The requirement of independence of any pre-existing asymmetry highly constrains the LE parameters

Strong thermal leptogenesis

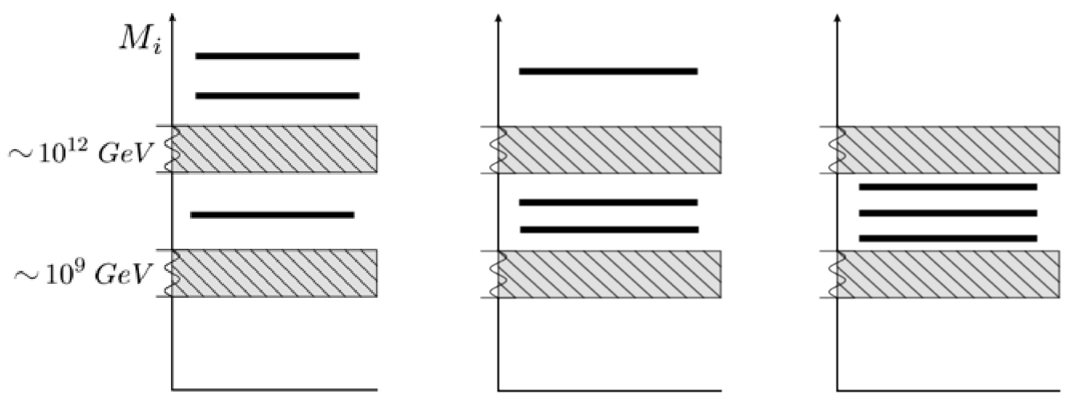
- Full independence of initial conditions



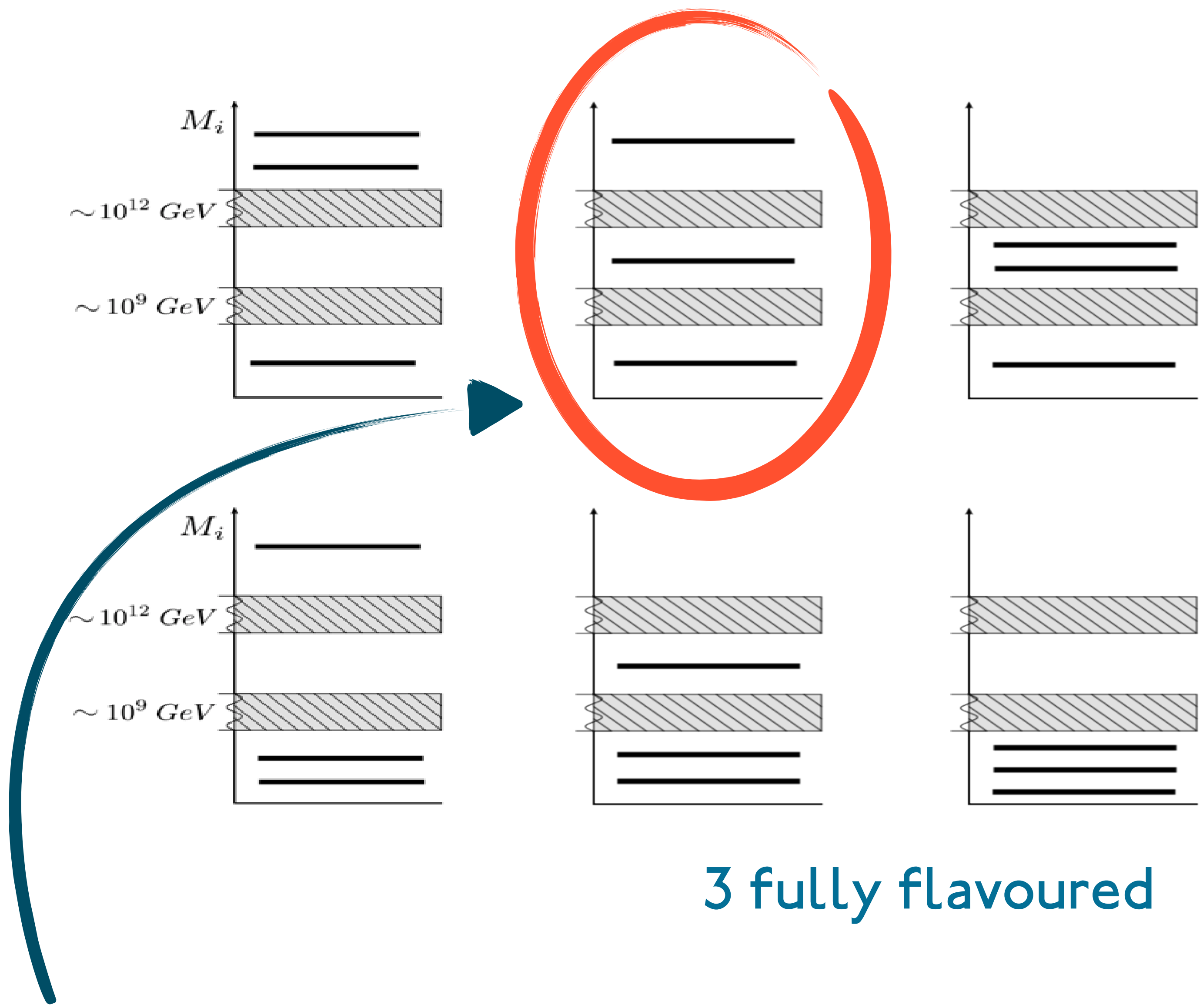
How?



Unflavoured



2 fully flavoured



3 fully flavoured

- With a hierarchic spectrum, strong thermal leptogenesis realised ONLY in this case.

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

This is precisely the same pattern predicted by SO(10)-inspired models

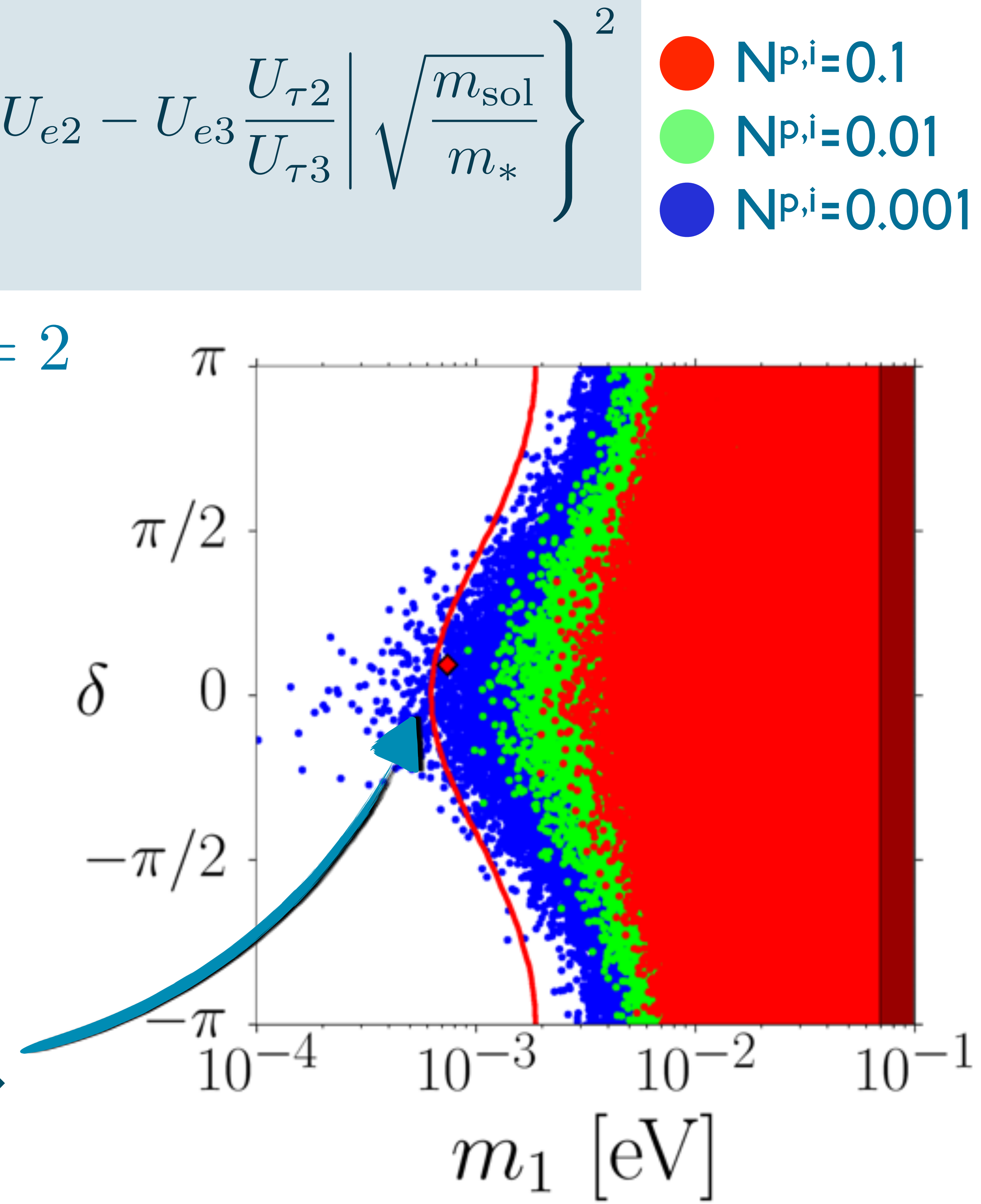
Lower bound on m_1

$$m_1 \geq \frac{m_*}{\left|U_{e1} - U_{e3}\frac{U_{\tau 1}}{U_{\tau 3}}\right|}\left\{\sqrt{\frac{K_{1e}^{\min}}{M_\Omega}} - \left|U_{e2} - U_{e3}\frac{U_{\tau 2}}{U_{\tau 3}}\right|\sqrt{\frac{m_{\rm sol}}{m_*}}\right\}^2$$

$m_* \simeq 10^{-3}\,\mathrm{eV}, \quad |\Omega_{ij}|^2 \leq M_\Omega = 2$

- Normal ordering
- Dependence on $N^{p,i}$
- Dependence on the experimental angles
- Dependence on Dirac phase δ

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



Statistics

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

- **99%** of points with

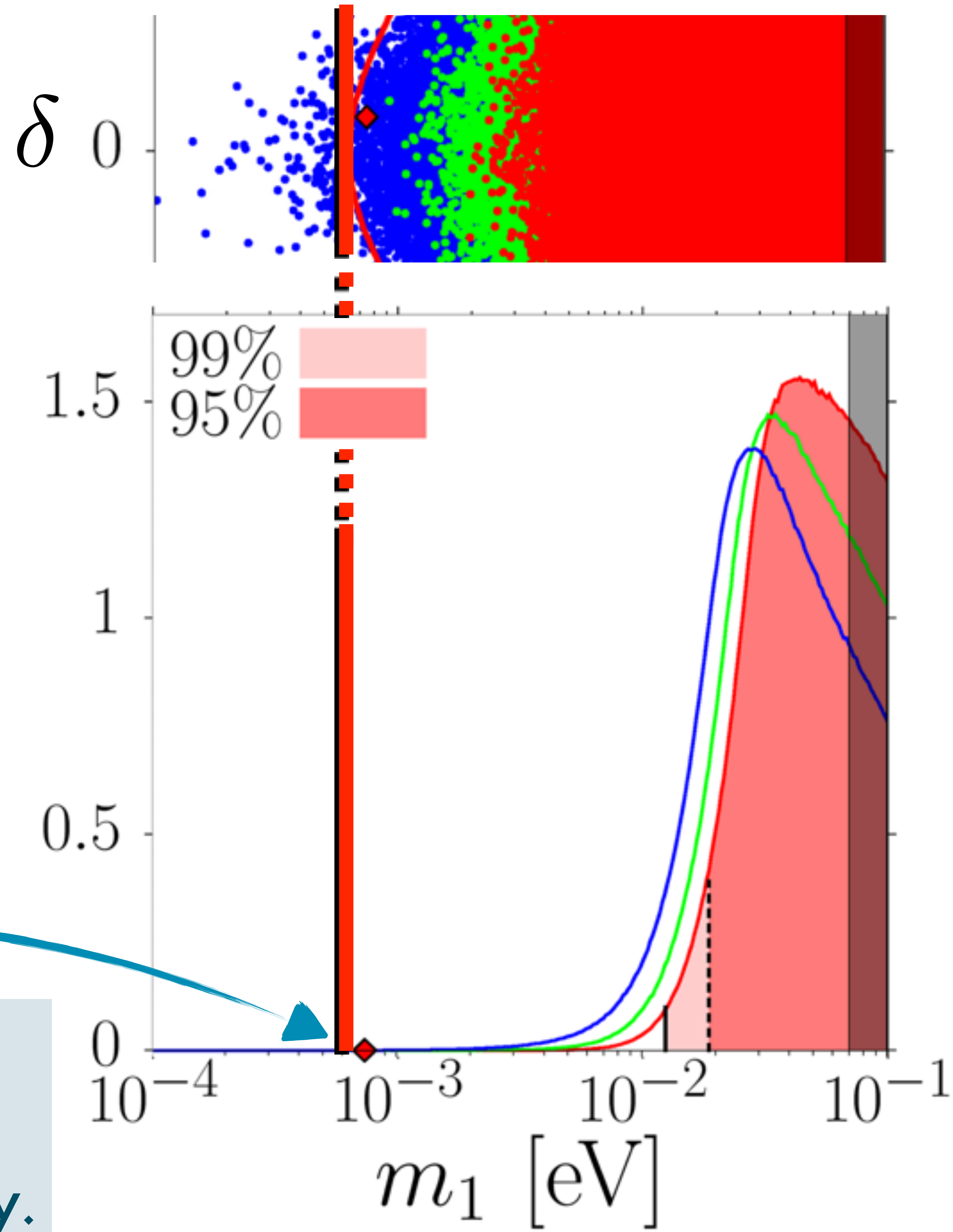
  $$m_1 \gtrsim 11\,\text{meV}$$

- **95%** of points with

  $$m_1 \gtrsim 18\,\text{meV}$$

- 100% of points larger than the analytical lower bound.

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



Experiments can then exclude portions of parameter space accordingly.

Experiments? Cosmology!

- CMB spectrum alone:

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

- CMB+SZ+BAO

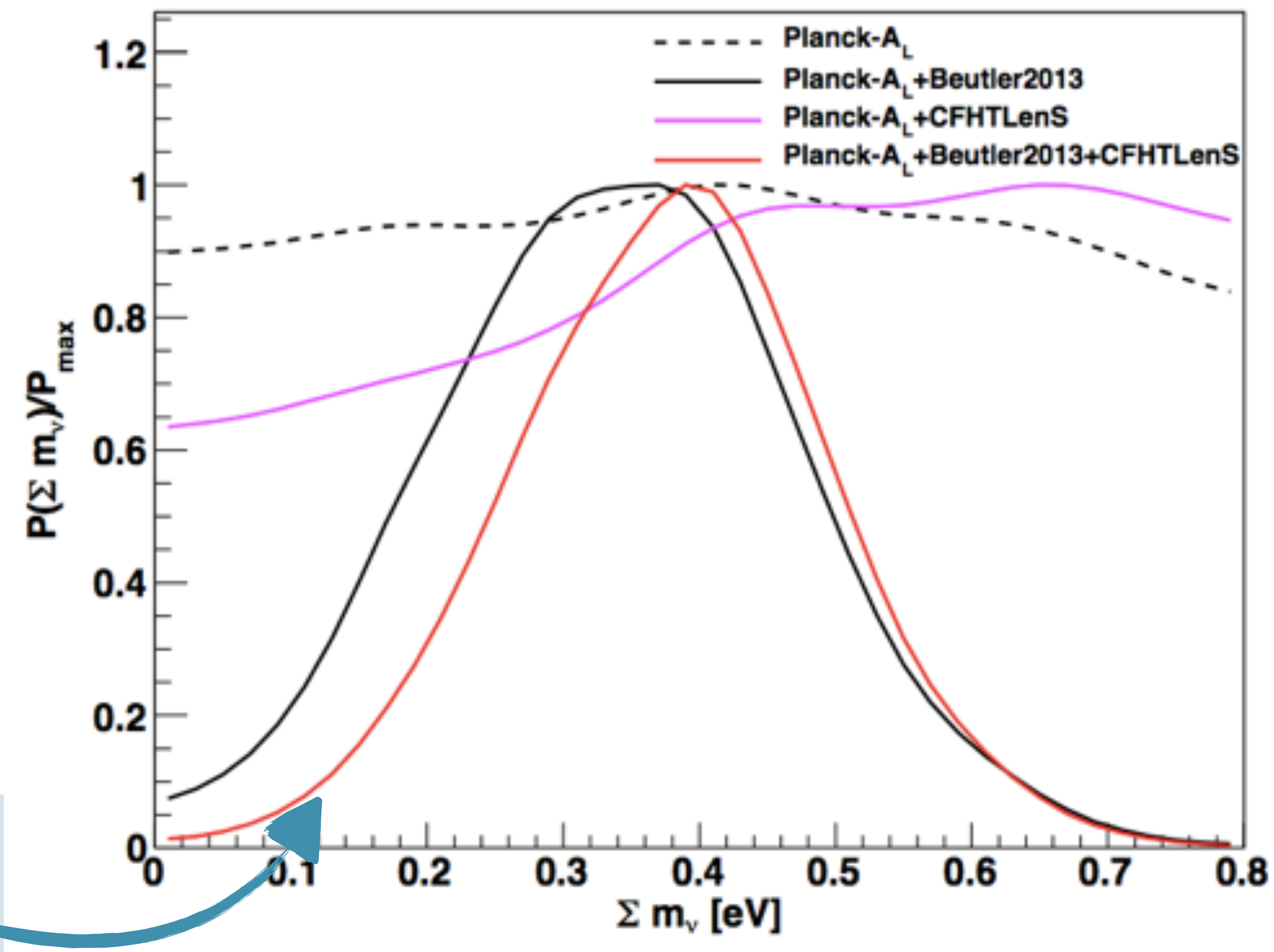
$$\sum m_\nu = (0.22 \pm 0.09)\,\text{eV}$$

[Planck XX]

- BOSS collaboration

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

at 3.4σ [Beutler et al. 2014]



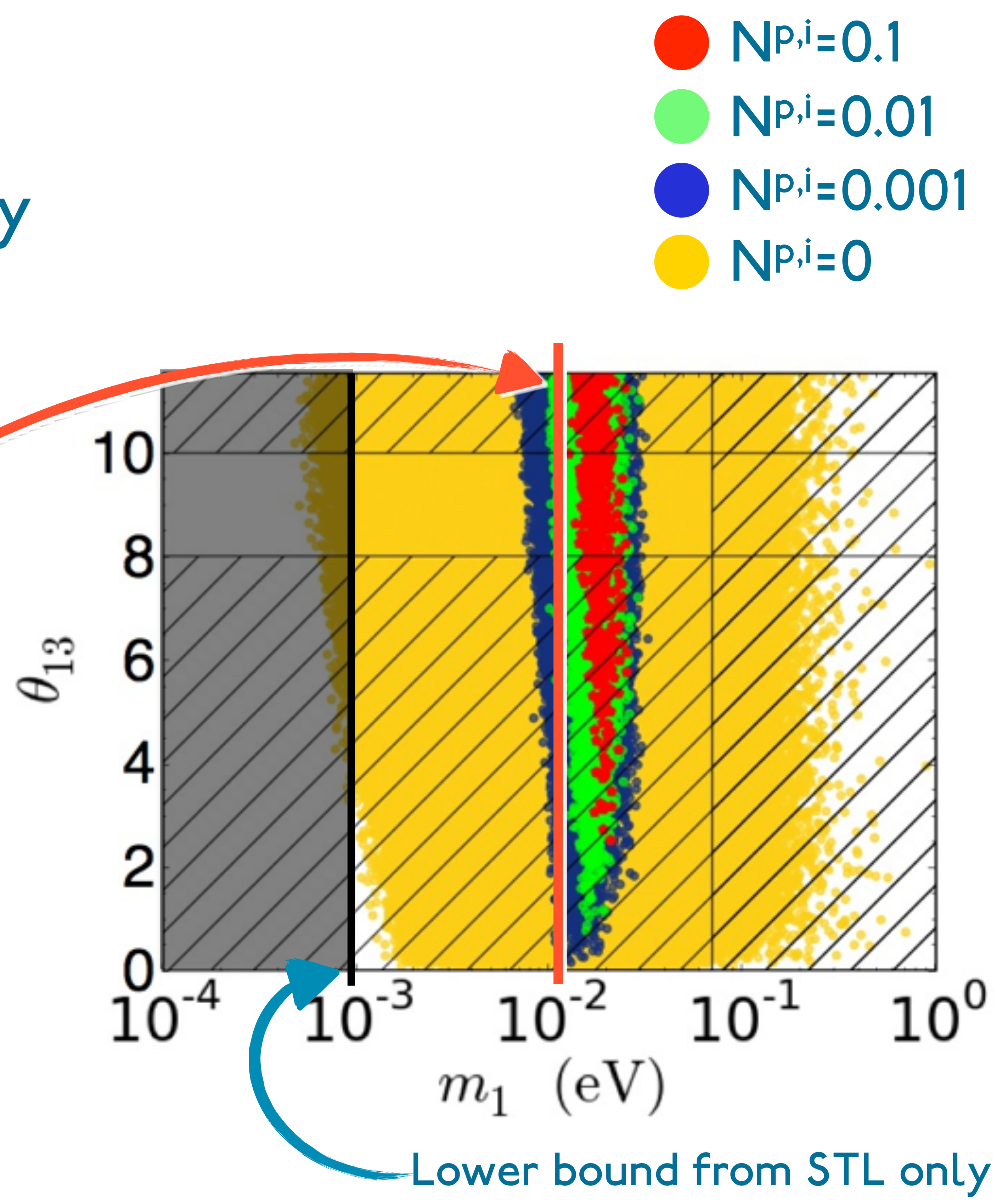
are experiments pointing at $m_1 \neq 0$?

Long Baseline experiments must determine the ordering!

SO(10)-inspired + Strong thermal lep.

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

	Predictions
m_1	≈ 20 meV
m_{ee}	≈ 15 meV
Ordering	NORMAL
θ_{13}	≳ 2°
δ	≈ -45°
θ_{23}	≲ 41°



Conclusions

Leptogenesis links cosmology and neutrino physics.

Strong thermal leptogenesis: Flavoured N_2-dominated

- Naturally realised in SO(10)-inspired models
  - Promising embedding of leptogenesis in GUT theory
- Predictive on its own: $m_1 \gtrsim 1$ meV
  - low m_1 highly disfavoured
    (though quantitatively it may depend on the chosen parameterisation)
- Testable at forthcoming neutrino experiments

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

Flavour coupling

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

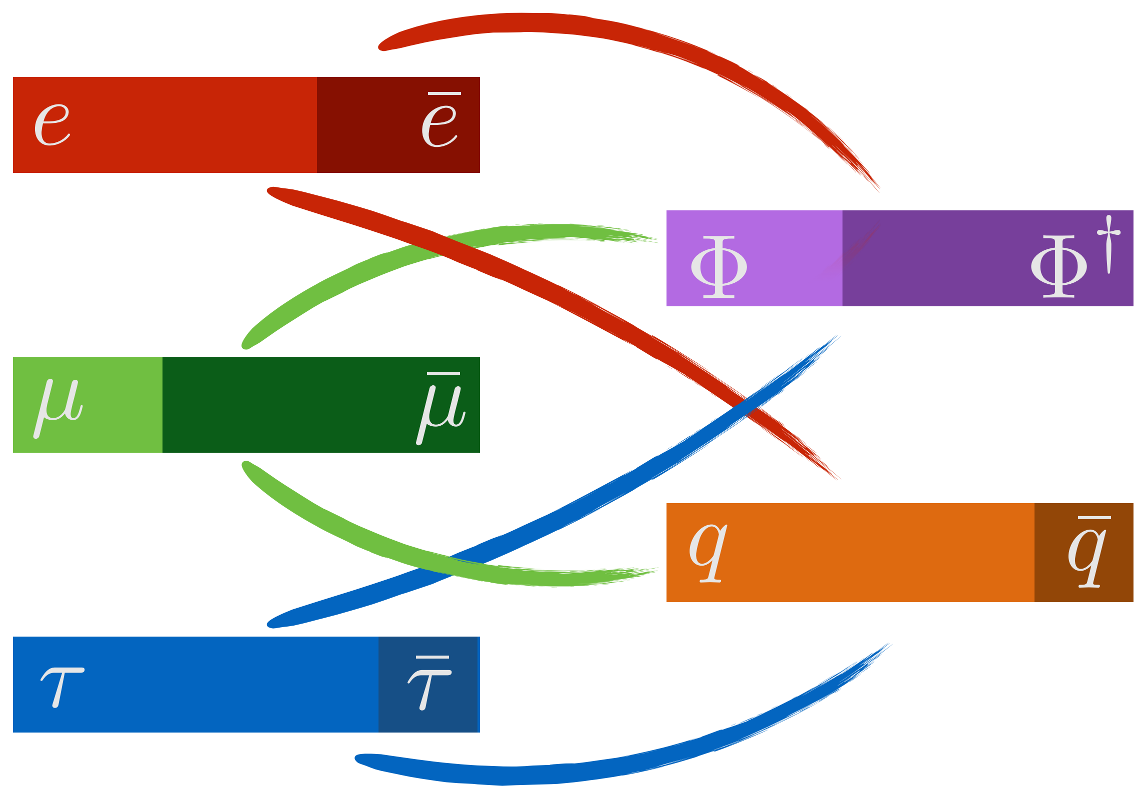
- Flavour asymmetries do not evolve independently
- Coupling through Higgs and quark asymmetries

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

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

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

$$\frac{dN_\alpha}{dz_2} = -P^0_{1\alpha} \sum_\beta C^{(3)}_{\alpha\beta} W^{\rm ID}_1 N_\beta$$



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]

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

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

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

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

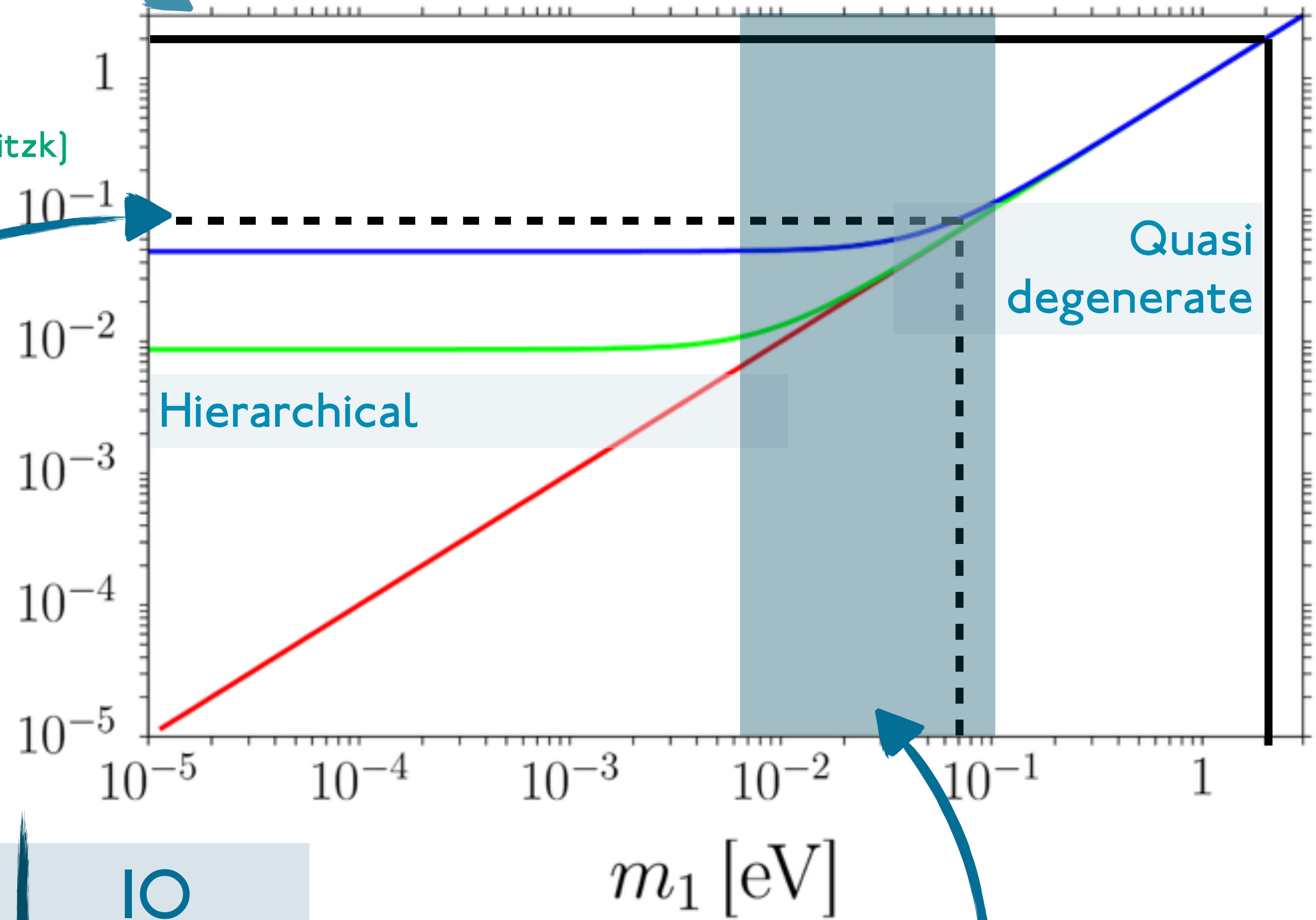
Light neutrino spectrum

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

Semi-hierarchical spectrum

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