Strong thermal leptogenesis and the N_2-dominated scenario

Investigating neutrino data with leptogenesis

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

Why leptogenesis?

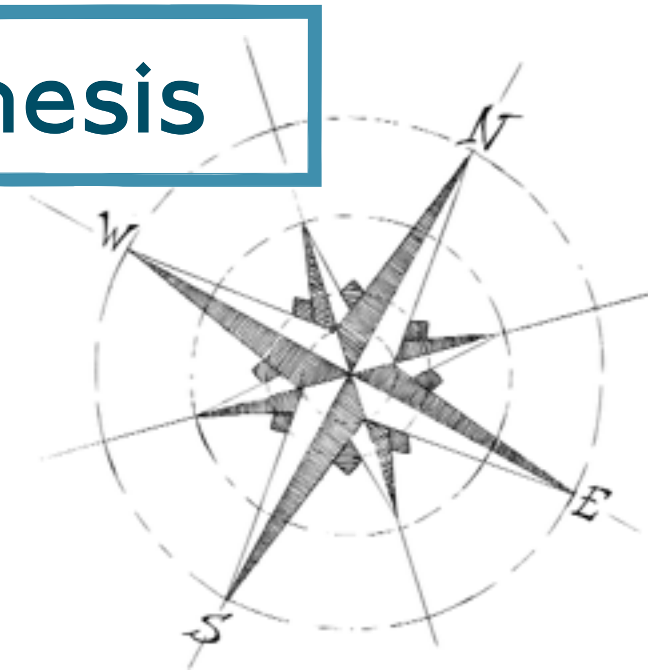
Mechanism able to dynamically produce the baryon asymmetry

Link between cosmology, neutrino & new physics

Physics beyond the Standard Model

?

Leptogenesis



See-saw mechanism

Low energy data (ν-parameters...)

• 3 RH neutrinos → 18 free parameters

$$\mathcal{L} = -\, Y^{\nu}_{\alpha k}\, \bar{L}_{\alpha} \tilde{\Phi} N_k + \frac{1}{2} N_j^T \mathcal{C}^{\dagger} D_{M\,j} N_j + h.c.$$

Light neutrino mass matrix:

$$D_m = v^2\, U^{\dagger}\, Y\, D_M^{-1} Y^t\, U^*$$

Complex orthogonal matrix:

$$\Omega \equiv v\, D^{-1}_{\sqrt{m}} U^{\dagger} Y\, D^{-1}_{\sqrt{M}}$$

[Casas, Ibarra 2001]

18 ← 6 3 6 3

9 low-energy (LE) neutrino parameters: testable at experiments

9 high-energy (HE) neutrino parameters: ???

- Too many parameters are still unconstrained

"Raw" see-saw models are NOT predictive

Some theoretical inputs

New phenomenology: leptogenesis

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

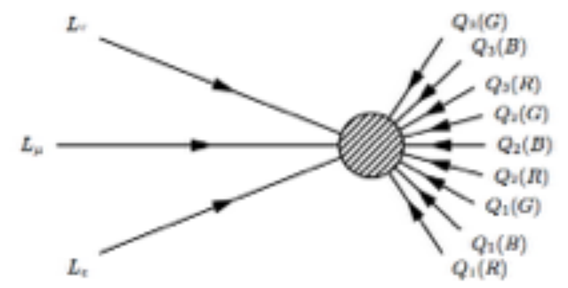
Input from known low-energy neutrino data AND baryon asymmetry can provide info on unknown LE parameters and also constrain HE parameters

- Can LE neutrino data support/disprove leptogenesis?

Making leptogenesis predictive means making it "testable"

Core ideas of leptogenesis

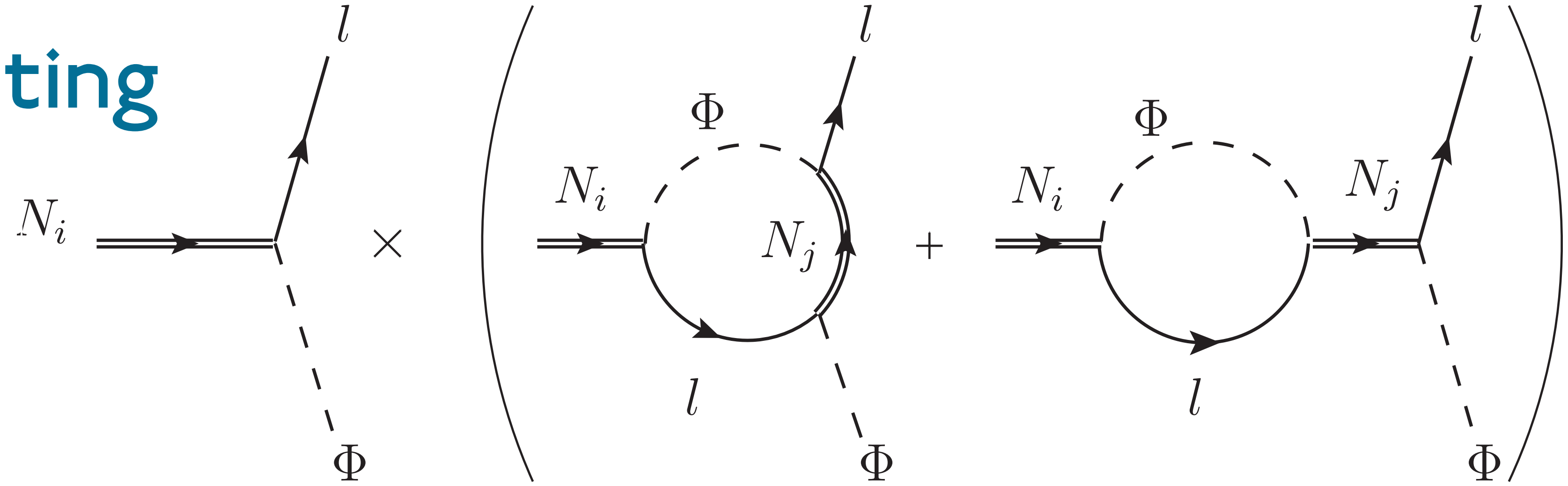
Produce lepton asymmetry → Sphalerons → Obtain baryon asymmetry



Decay of heavy RH Majorana neutrinos

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

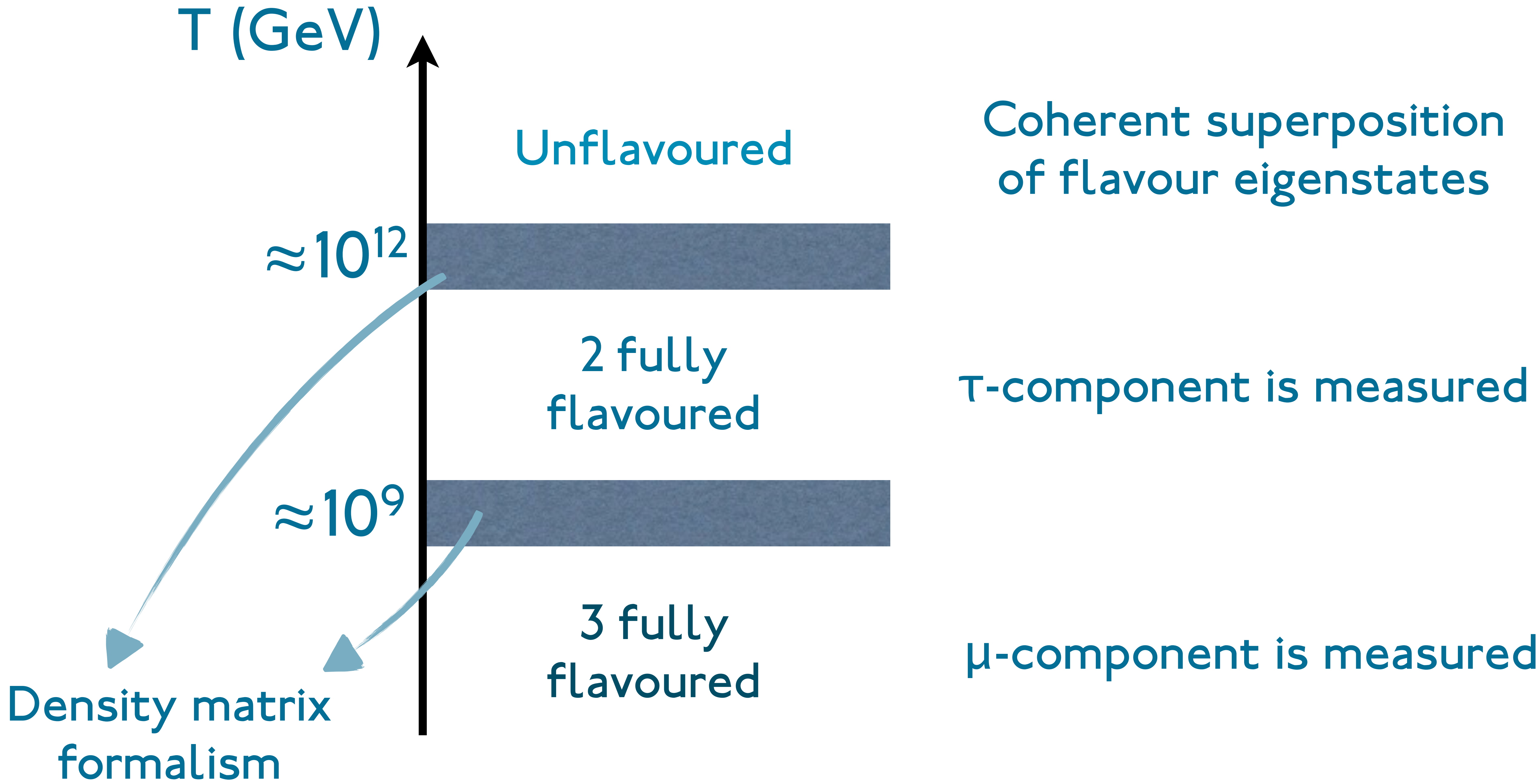
- Lepton number violating
- CP-violating
- Out of equilibrium



Adding flavour

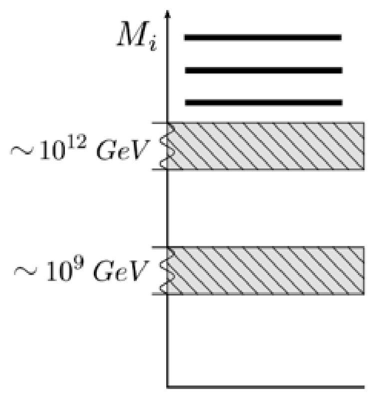
[Abada et al. 2006; Nardi, Nir, Roulet, Racker 2006; Blanchet, Di Bari, Raffelt '06; Riotto, De Simone 2006]

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

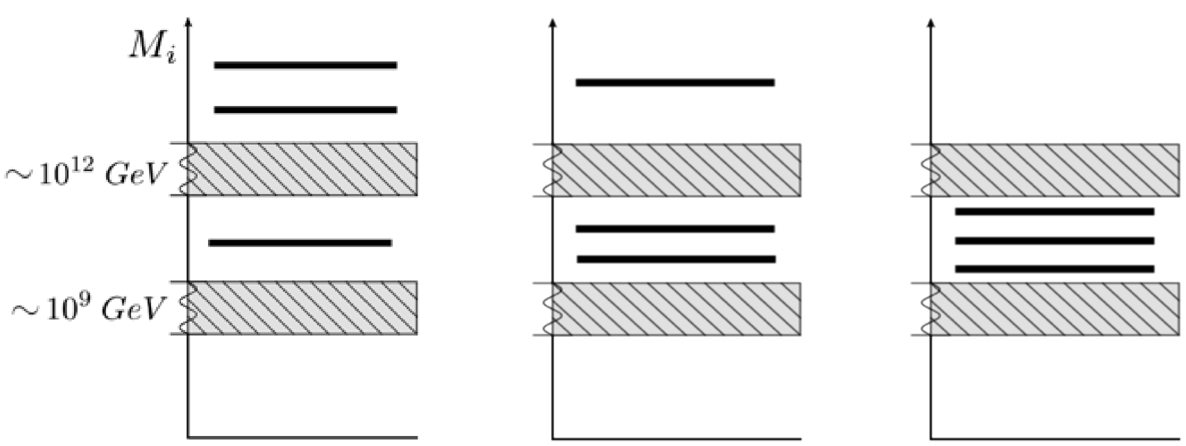


Guess who?

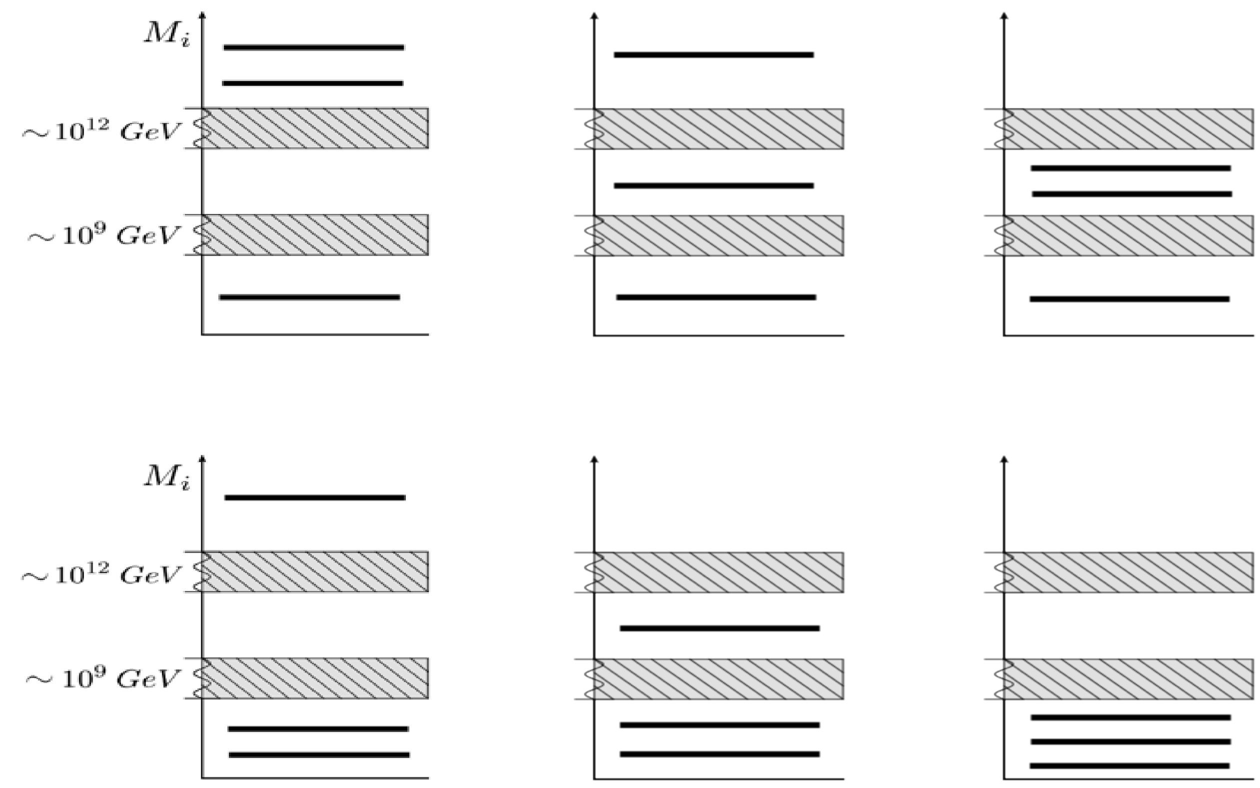
- Several ways to choose the RH neutrino spectrum.
  - Comply with the two "scales": 10^9, 10^{12} GeV.



Unflavoured



2 fully flavoured



3 fully flavoured

Guess who?

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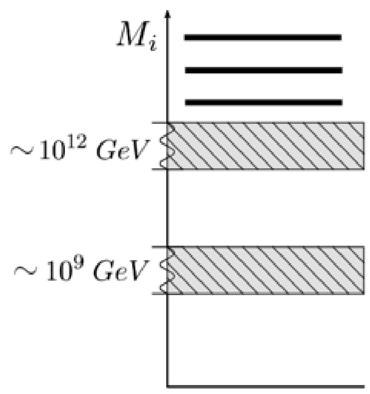
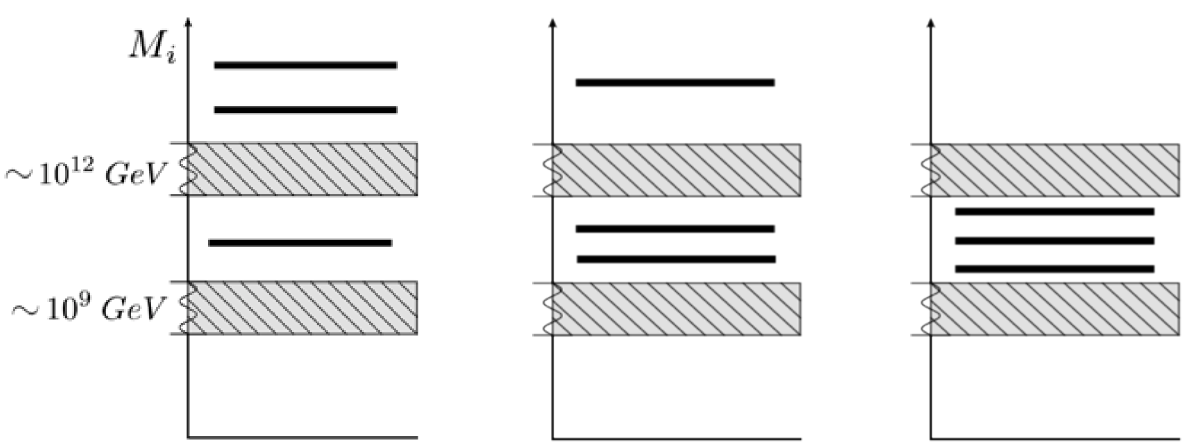
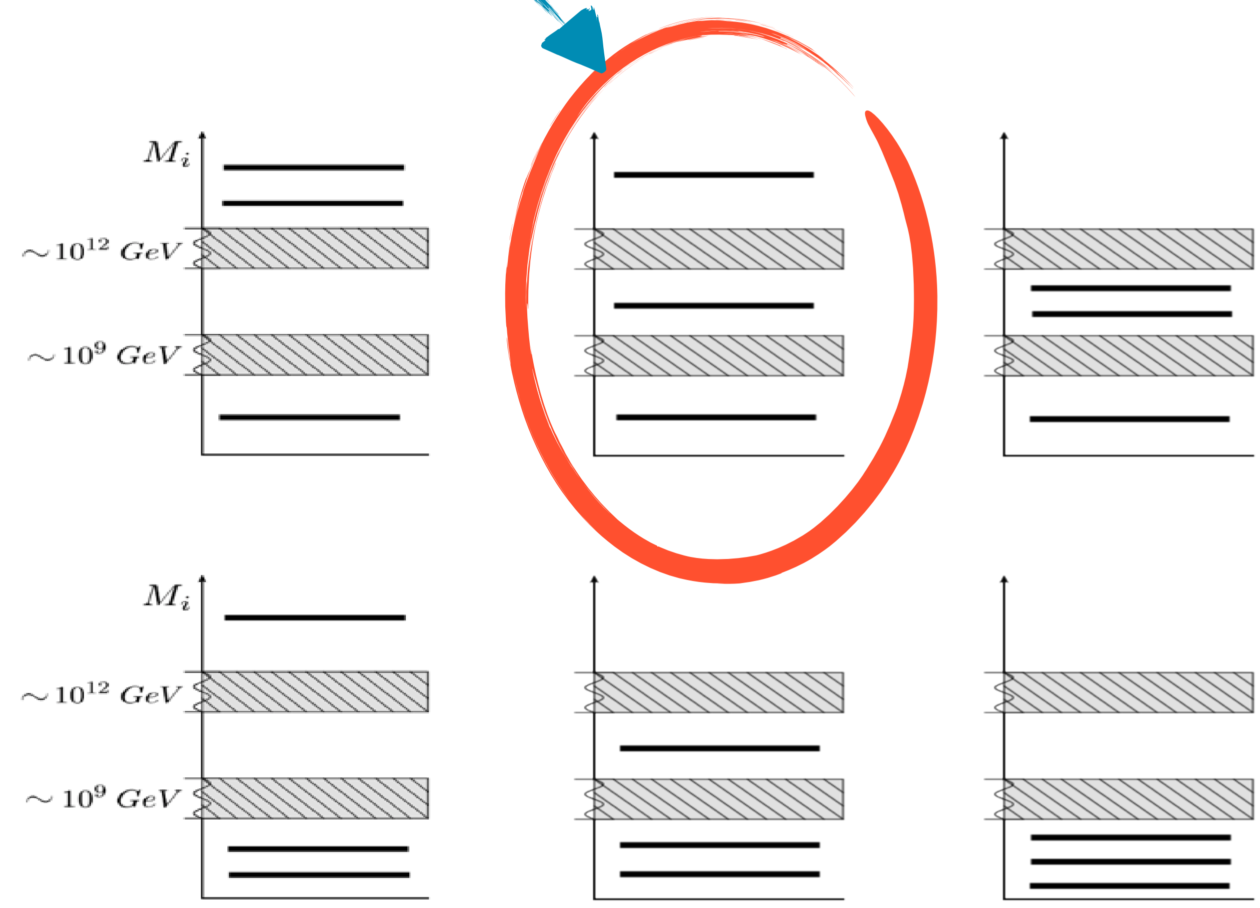
Flavoured N_2-dominated scenario



Unflavoured



2 fully flavoured



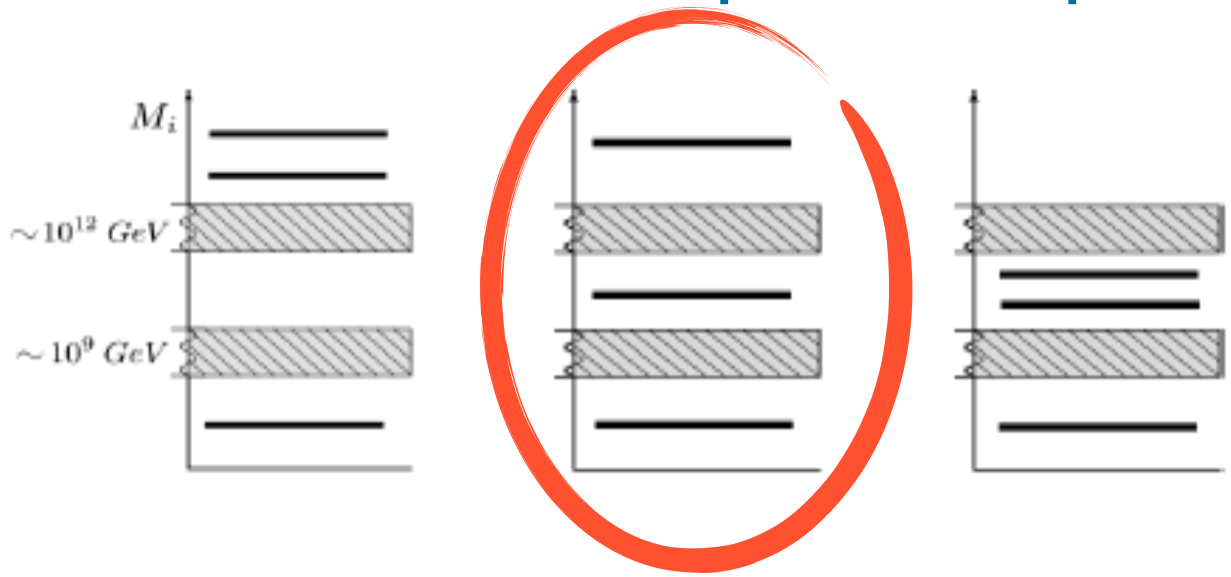
3 fully flavoured

Why should flavoured N_2 be interesting?

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

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

These models predict a precise spectrum of RH neutrinos:



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

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

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

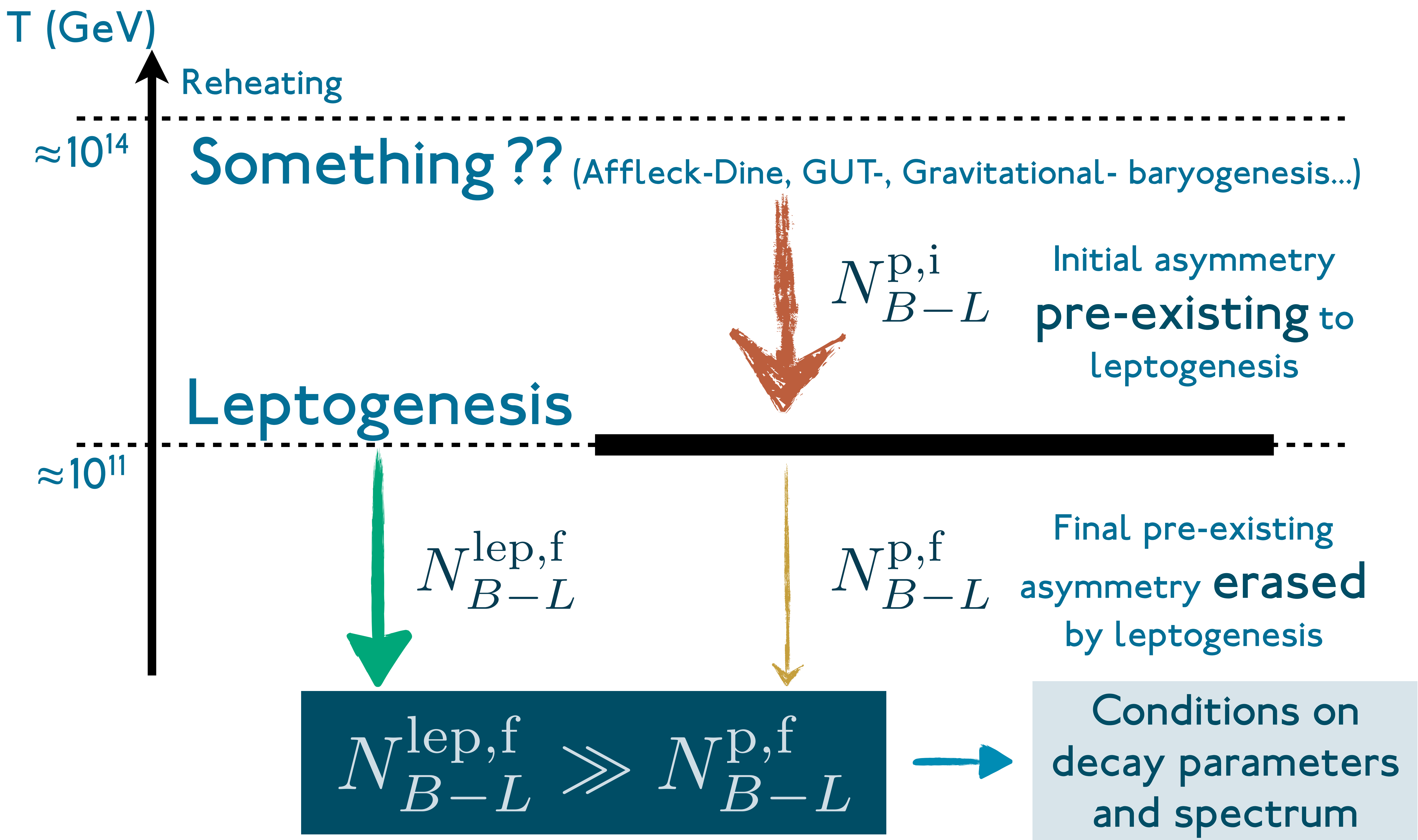
High reheating temperature, in line with BICEP2 (to be confirmed...)

(2) This scenario can become predictive

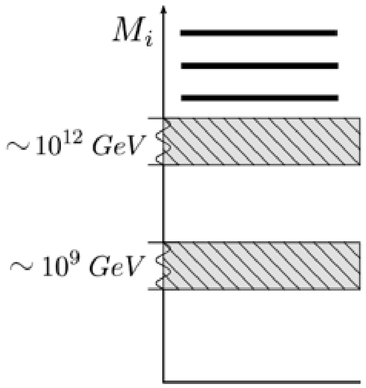
The requirement of independence of any pre-existing asymmetry highly constrains the LE parameters

Strong thermal leptogenesis

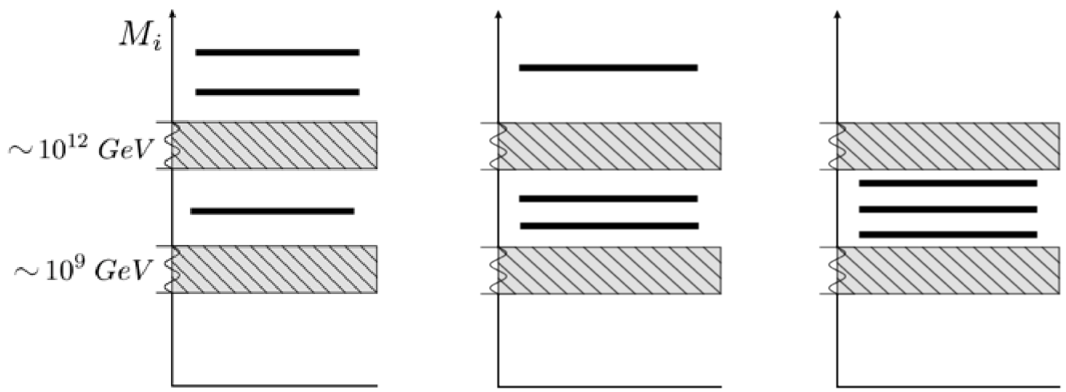
- Full independence of initial conditions



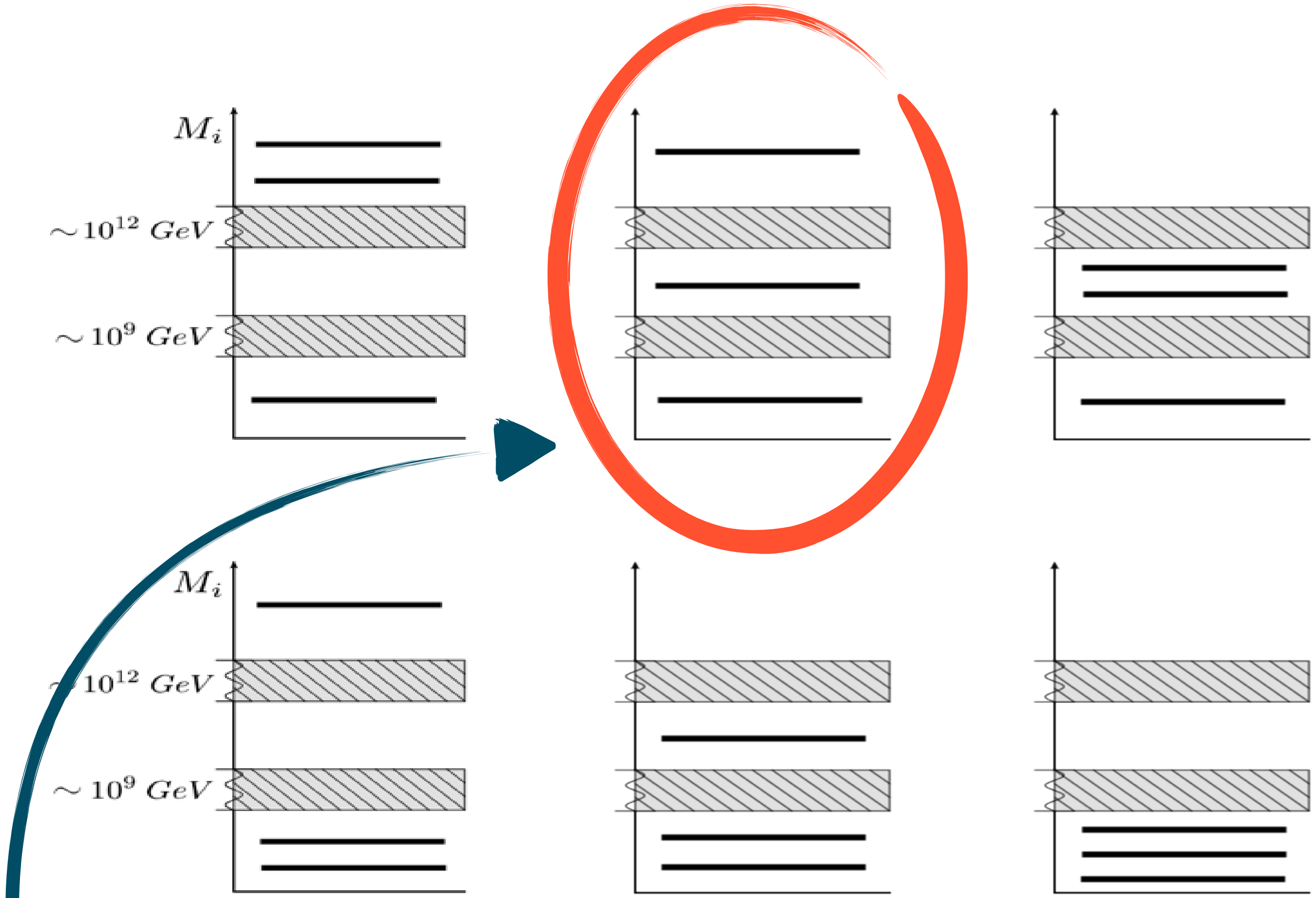
How?



Unflavoured



2 fully flavoured



3 fully flavoured

- Strong thermal leptogenesis can be realised ONLY within a N_2-dominated scenario with this pattern

(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

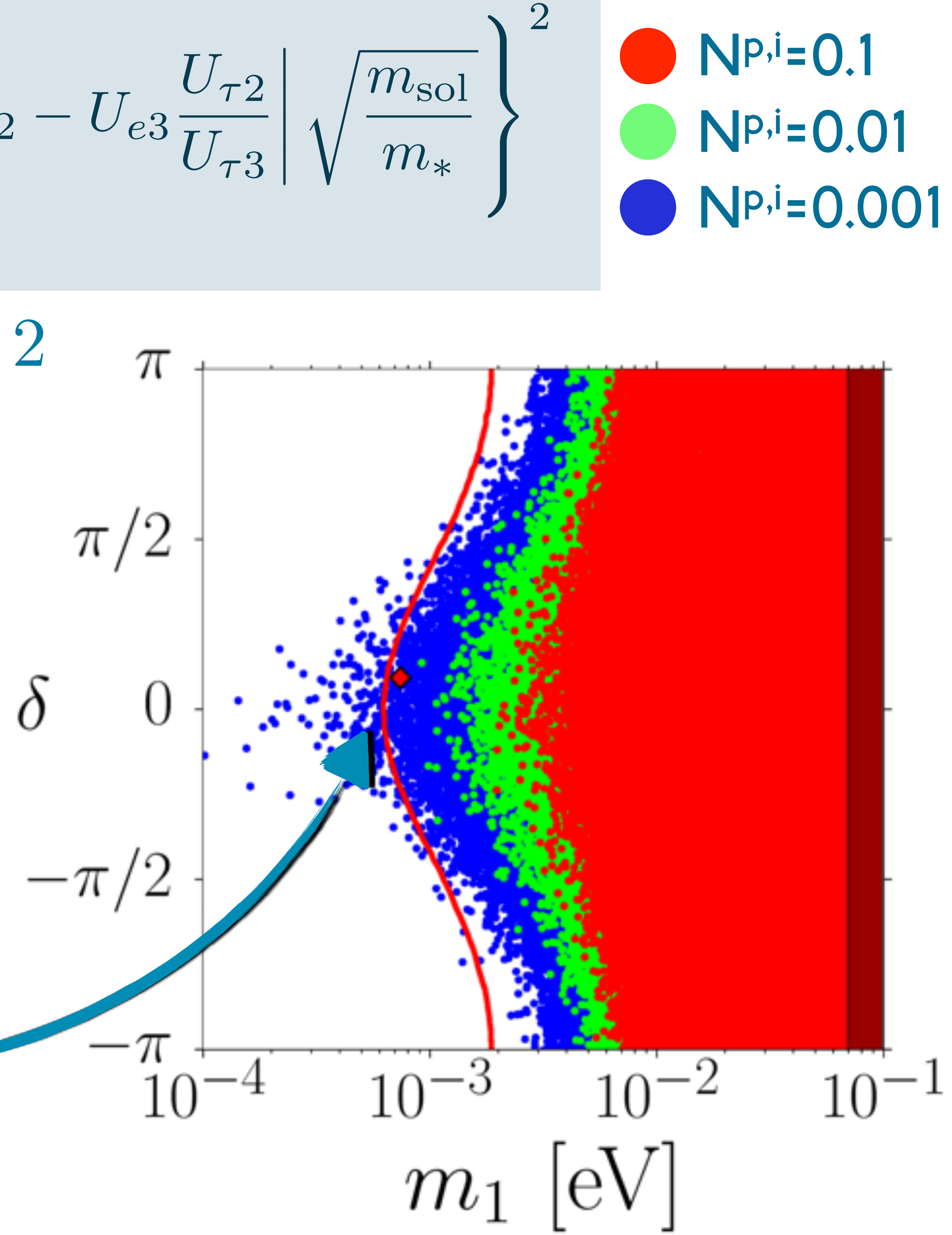
$$m_1 \geq \frac{m_*}{\left| U_{e1} - U_{e3}\frac{U_{\tau 1}}{U_{\tau 3}} \right|} \left\{ \sqrt{\frac{K_{1e}^{\min}}{M_\Omega}} - \left| U_{e2} - U_{e3}\frac{U_{\tau 2}}{U_{\tau 3}} \right| \sqrt{\frac{m_{\rm sol}}{m_*}} \right\}^2$$

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

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

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

95% C.L.



Statistics

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

- **99%** of points with

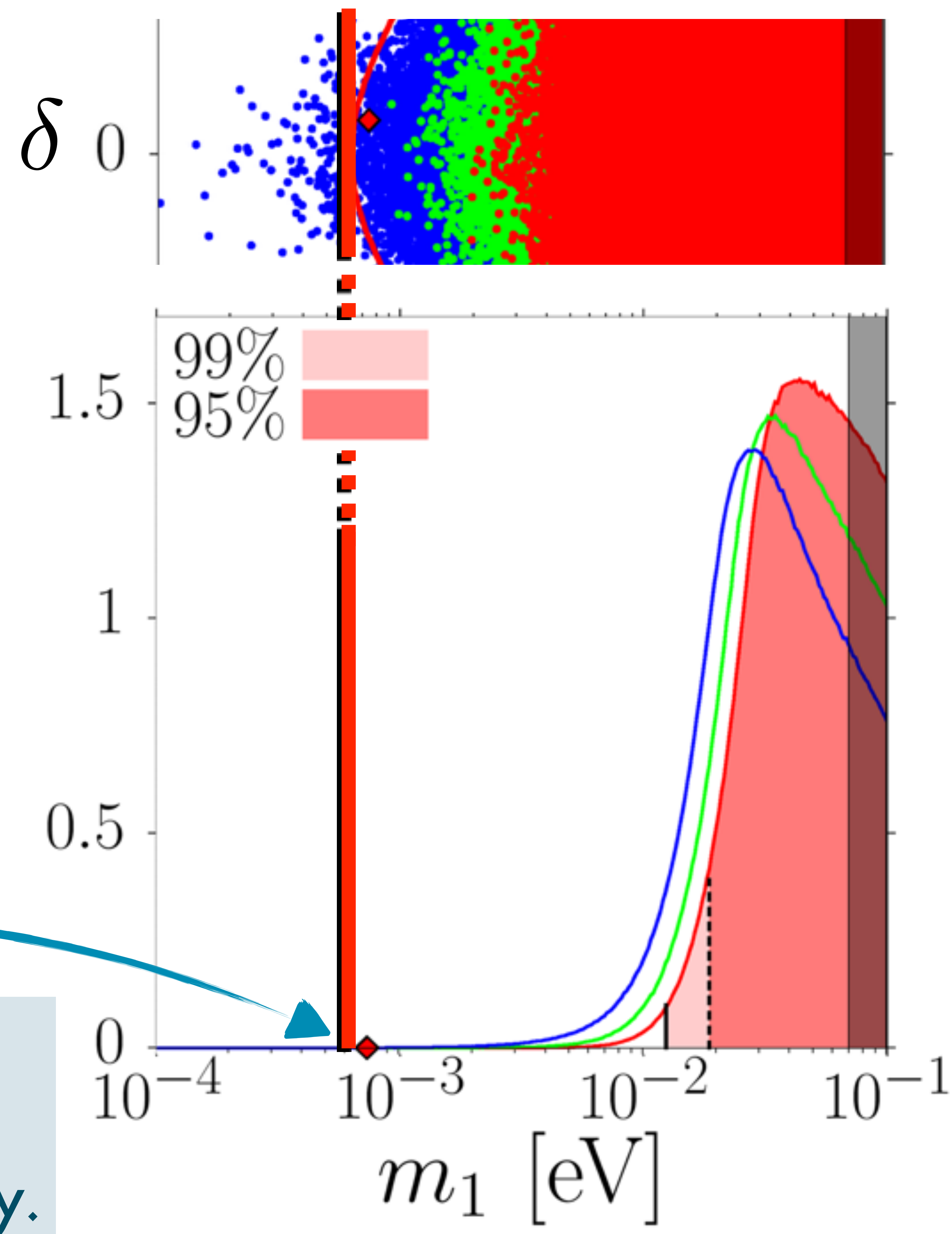
  $$m_1 \gtrsim 11\,\mathrm{meV}$$

- **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.

Experiments? 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]

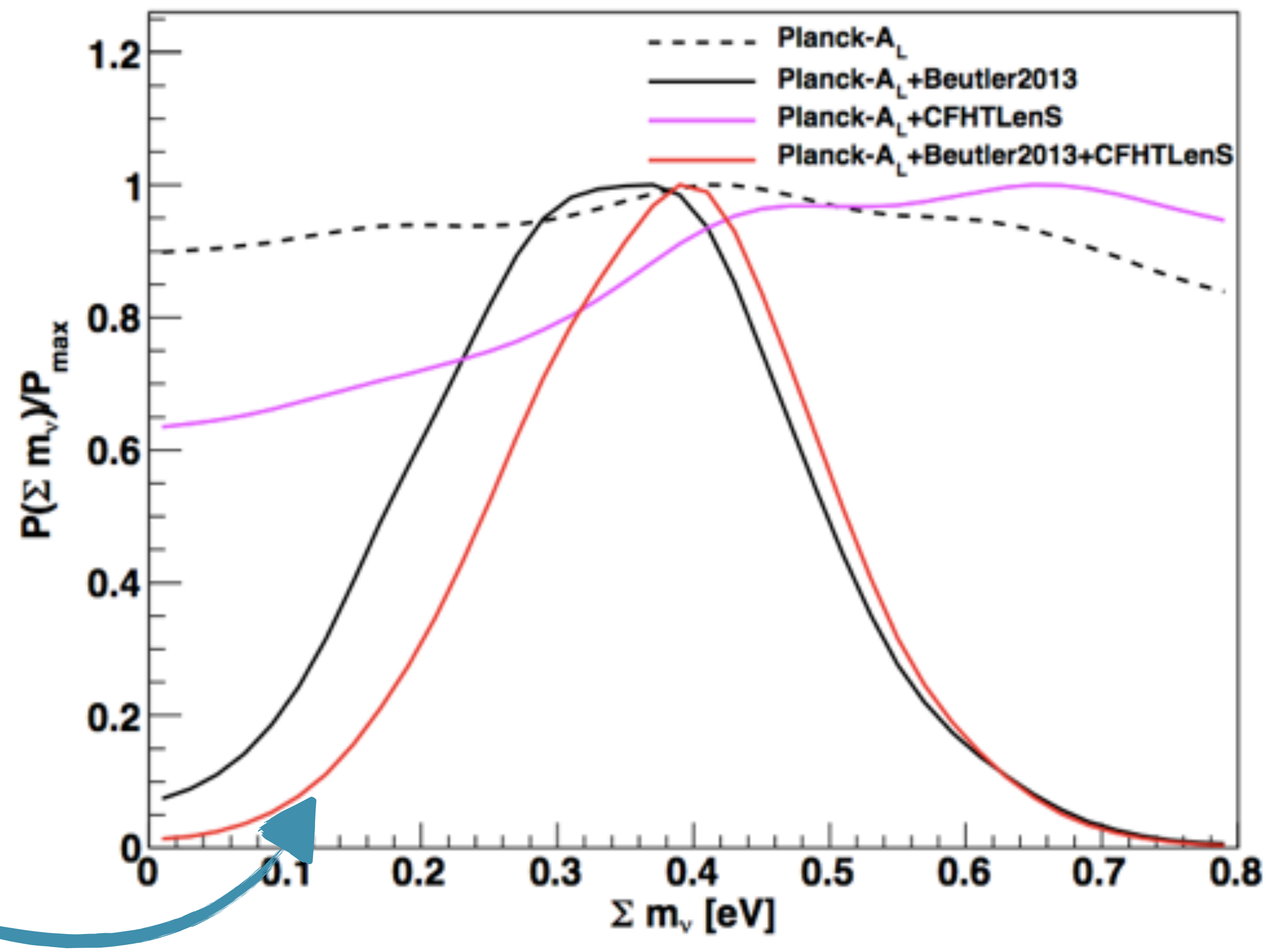
- BOSS collaboration

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

at 3.4σ [Beutler et al. 2014]

$$m_1 = (0.127 \pm 0.032)\,\mathrm{eV} \quad \text{NO}$$

$$m_1 = (0.117 \pm 0.032)\,\mathrm{eV} \quad \text{IO}$$



are experiments pointing at $m_1 \neq 0$?

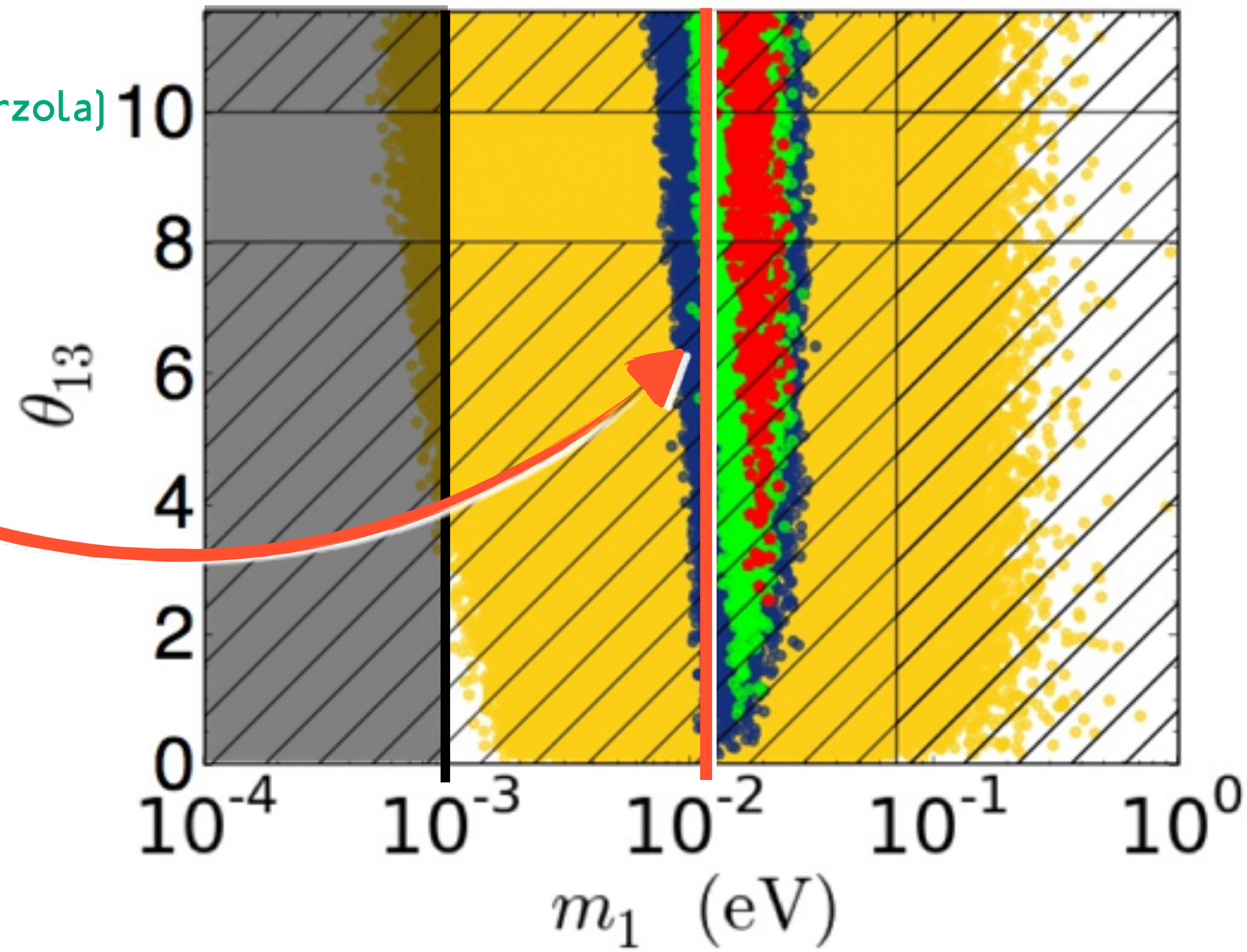
Long Baseline experiments must determine the ordering!

An example: SO(10)-inspired

SO(10)-inspired + Strong thermal leptogenesis

- Numerical predictions (Di Bari, Marzola)
- Analytical proof on the way

	Predictions
m	≈ 20 meV
m	
Ordering	NORMAL
θ	≳ 2°
δ	≈ -45°
θ	≲ 41°



2011 ▸ Daya Bay 2012

05/2013 ▸ Fogli et al., 12/2013

▸ Waiting for NOvA...

Conclusions

- Leptogenesis can link cosmology and neutrino physics.
- Predictions on LE and HE neutrino parameters?

Strong thermal leptogenesis: Flavoured N_2-dominated

- Naturally realised in SO(10)-inspired models
  - Promising embedding of leptogenesis and GUT theory
- It is predictive on its own
  - $m_1 \gtrsim 1$ meV, but
  - low m_1 highly disfavoured
    (though quantitatively it may depend on the chosen parameterisation)
- It can be severely cornered by future 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]

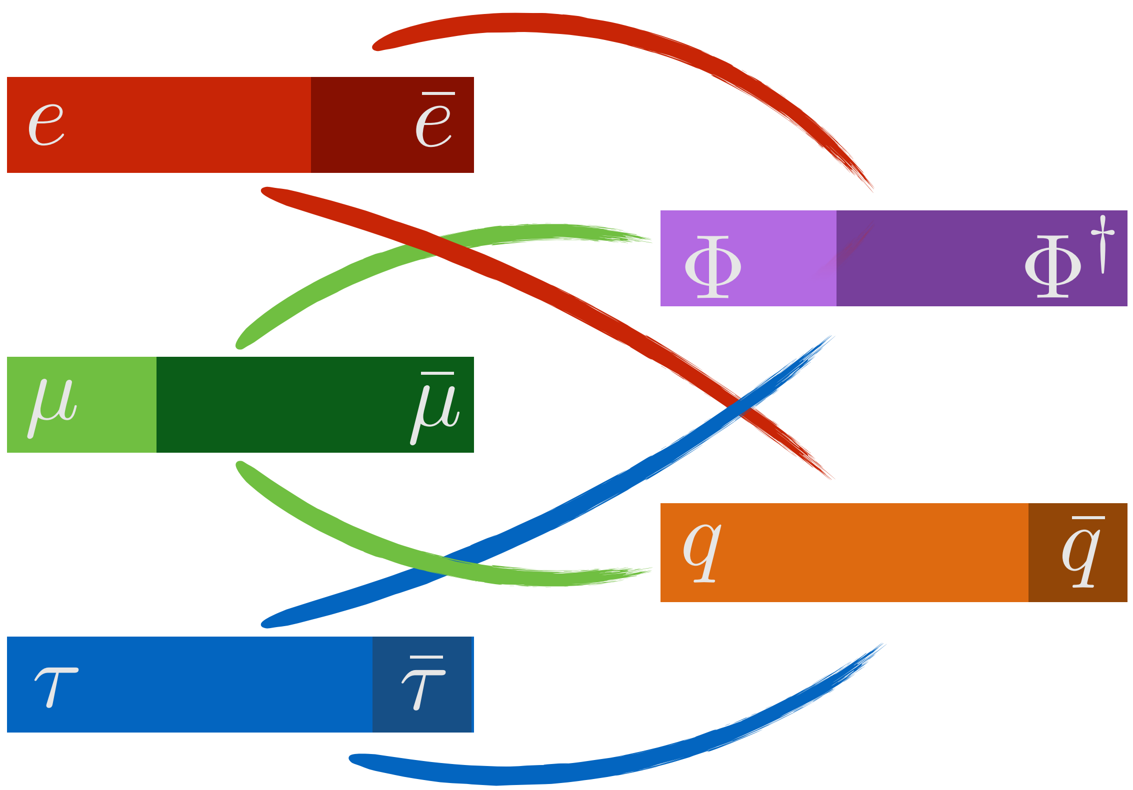
- Flavour asymmetries do not evolve independently
- Coupling through Higgs and quark asymmetries

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, $\alpha, \beta = e, \mu, \tau$

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



Modification of the final asymmetry

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

Modification of the statistical limits

(Work in progress...)

99% limit ≈×2 higher

Phantom terms

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

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

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

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

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

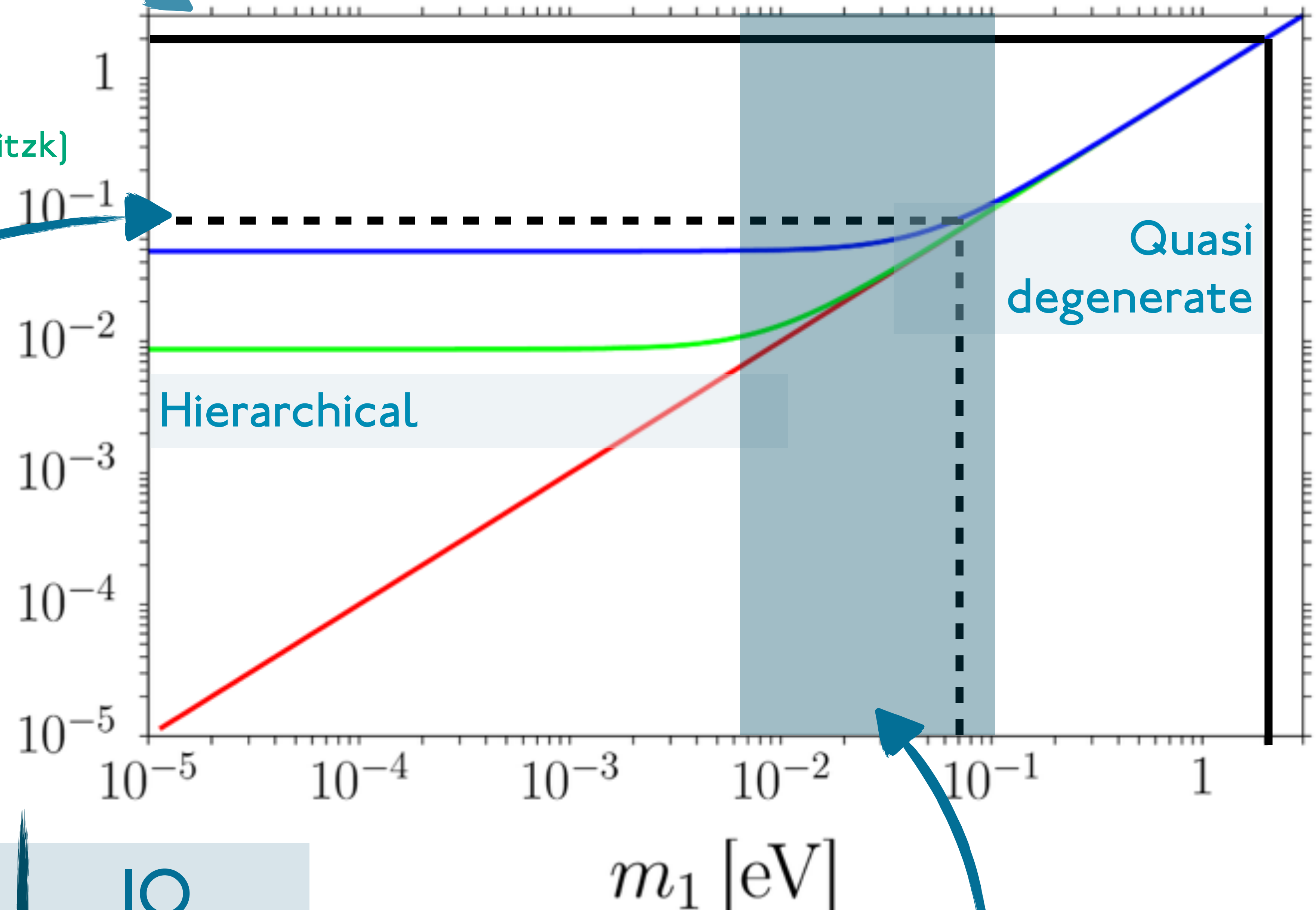
Light neutrino spectrum

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

	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