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

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Why leptogenesis?

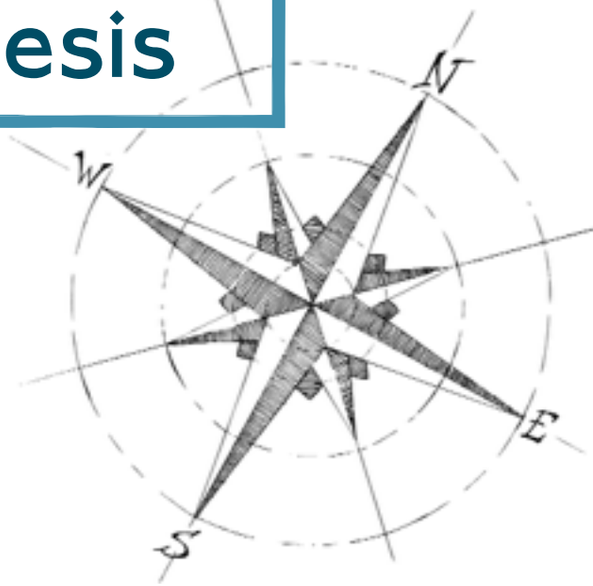
Mechanism able to dynamically produce the baryon asymmetry

Link between cosmology, neutrino & new physics

Physics beyond the Standard Model

?

Leptogenesis



See-saw mechanism

Low energy data (ν-parameters...)

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?

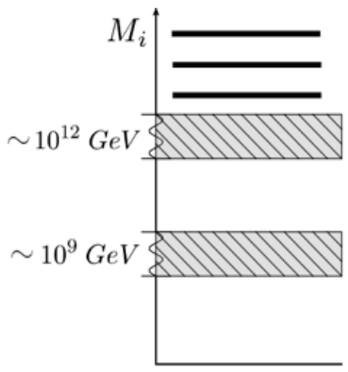
  Input from known low-energy neutrino data AND baryon asymmetry can provide info on unknown parameters.

- Can low-energy neutrino data support/disprove leptogenesis?

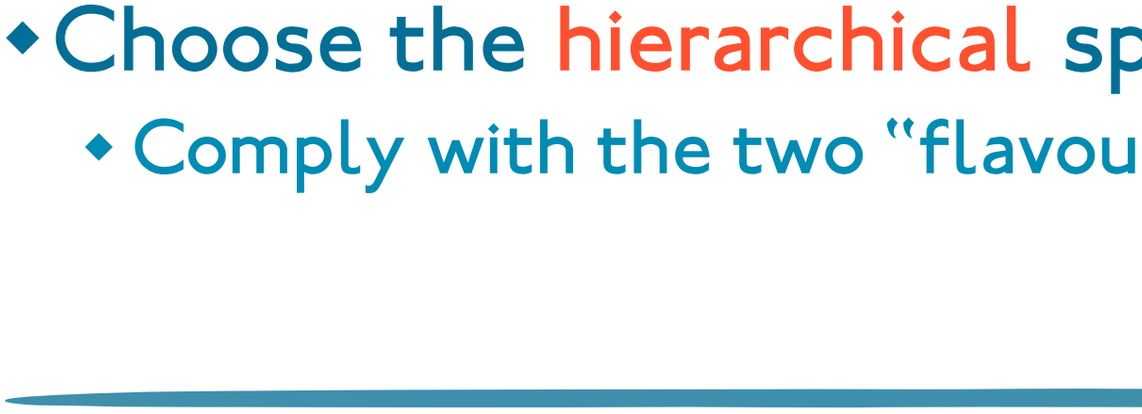
  Making leptogenesis predictive means making it "testable"

Hierarchical spectrum

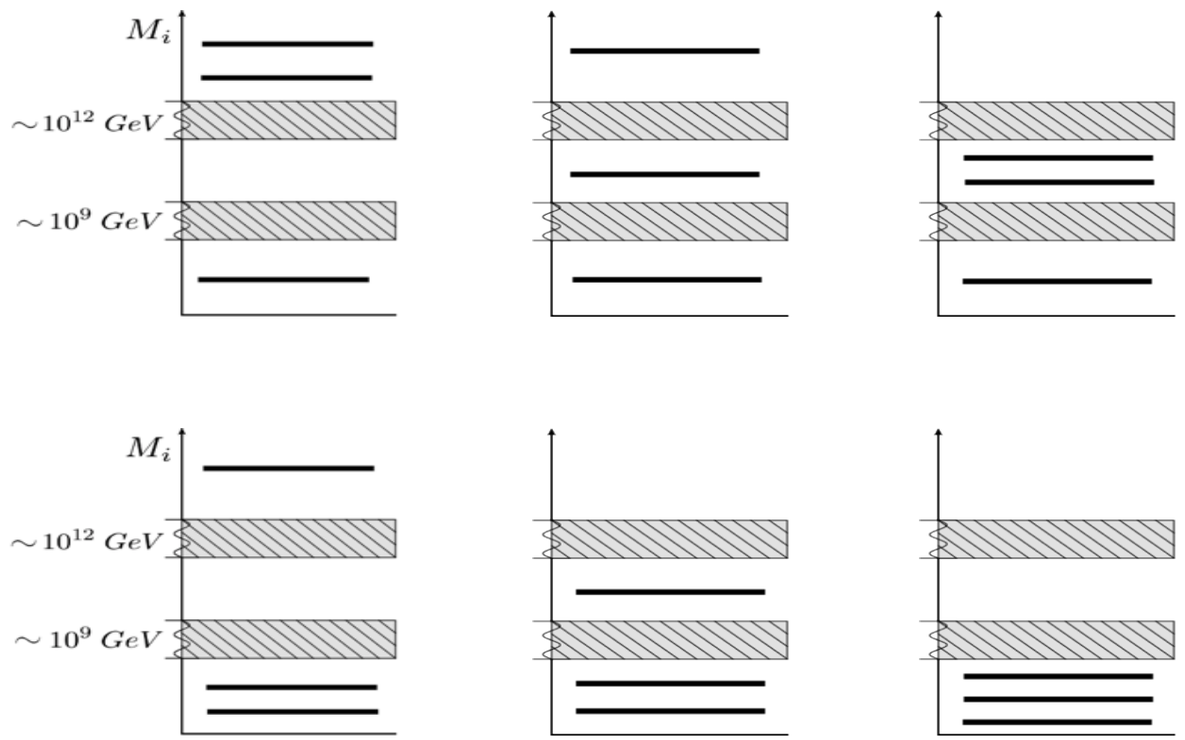
- Choose the hierarchical spectrum of 3 RH neutrinos.
  - Comply with the two "flavour-scales": 10^9, 10^{12} GeV.



Unflavoured



2 fully flavoured

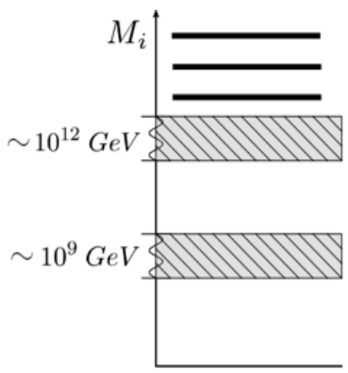


3 fully flavoured

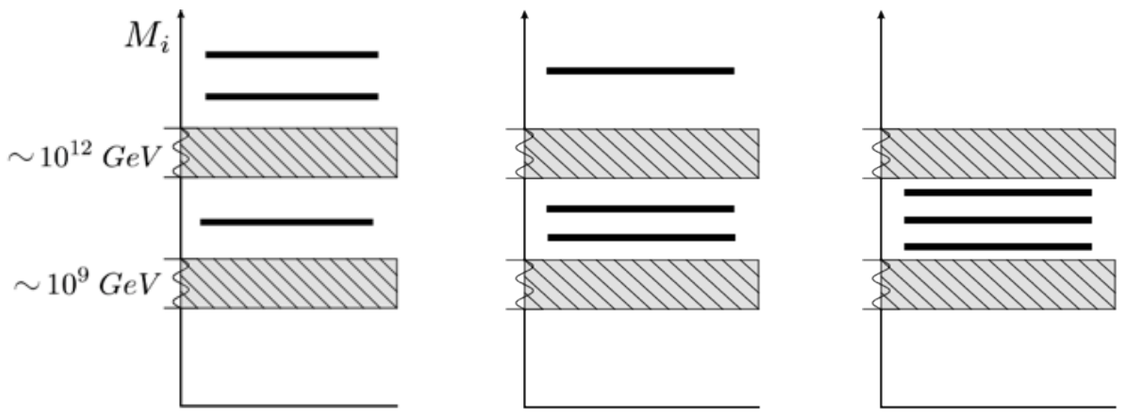
Hierarchical spectrum

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

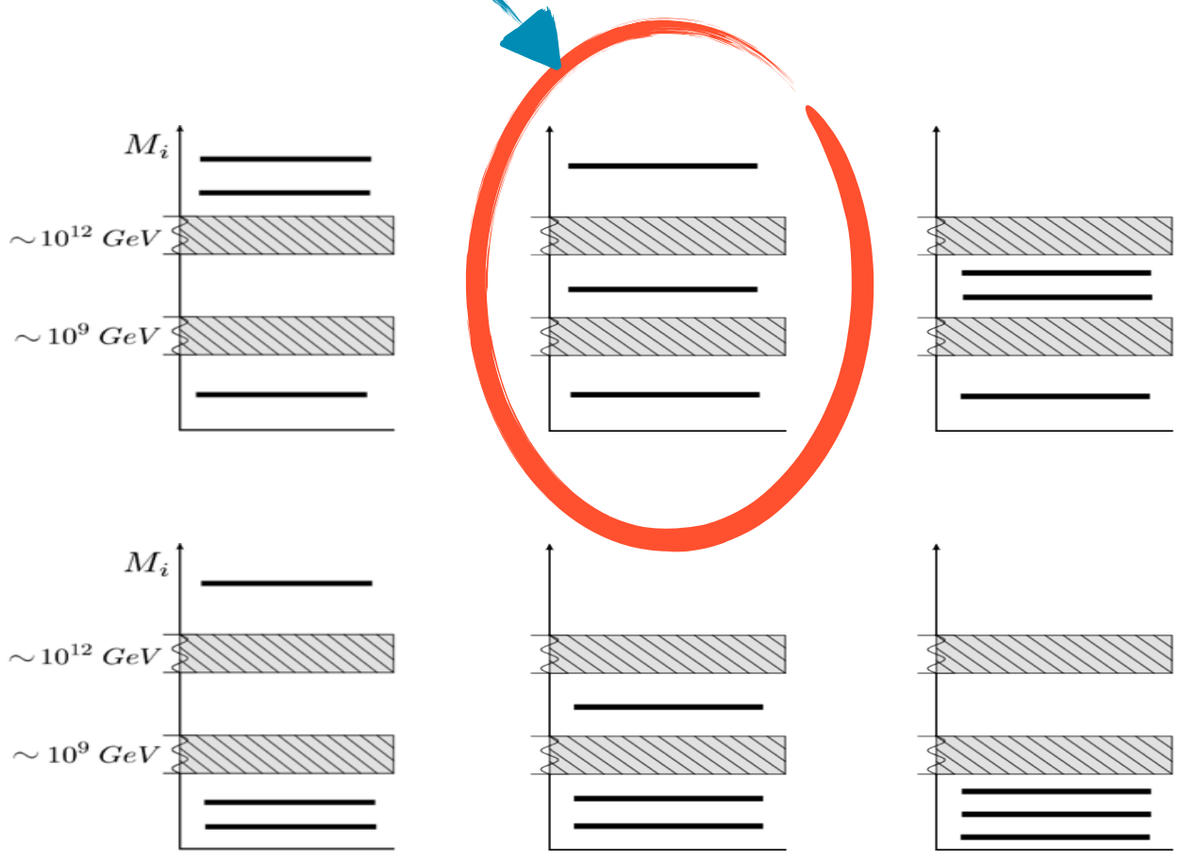
Flavoured N_2-dominated scenario



Unflavoured



2 fully flavoured



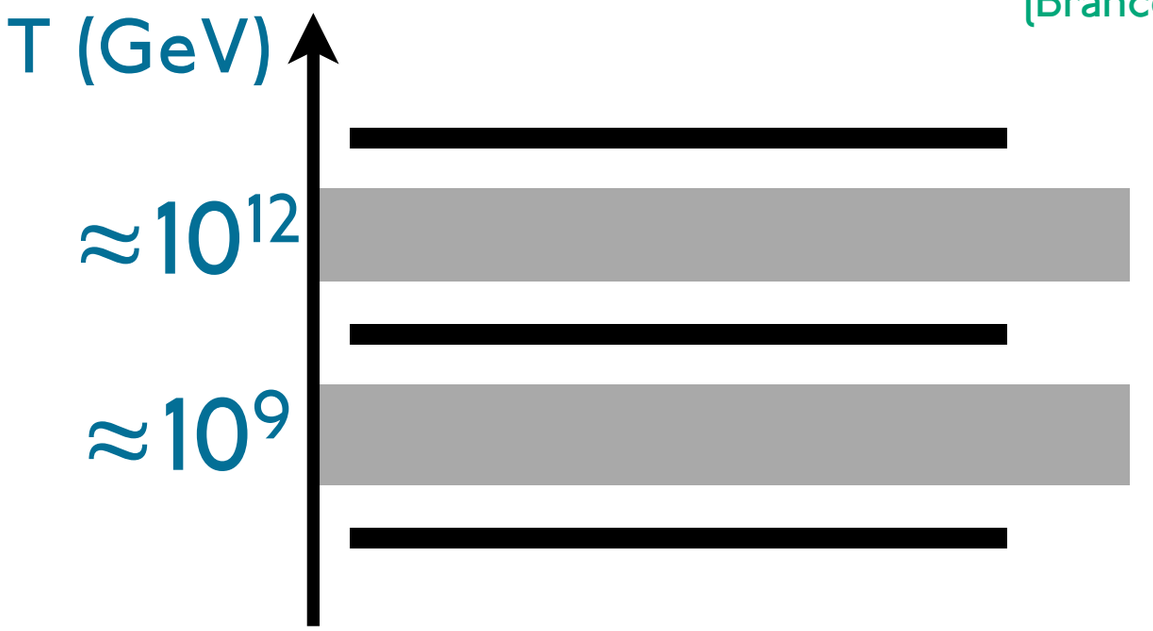
3 fully flavoured

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

T (GeV)

Reheating

$\approx 10^{14}$

Affleck-Dine, GUT-, Gravitational- baryogenesis... ???

$N_{B-L}^{\mathrm{p,i}}$

Initial asymmetry **pre-existing** to leptogenesis

Leptogenesis

$\approx 10^{11}$

$N_{B-L}^{\mathrm{lep,f}}$

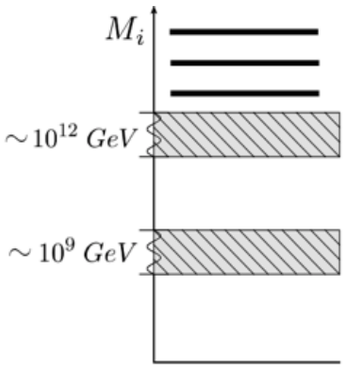
$N_{B-L}^{\mathrm{p,f}}$

Final pre-existing asymmetry **erased** by leptogenesis

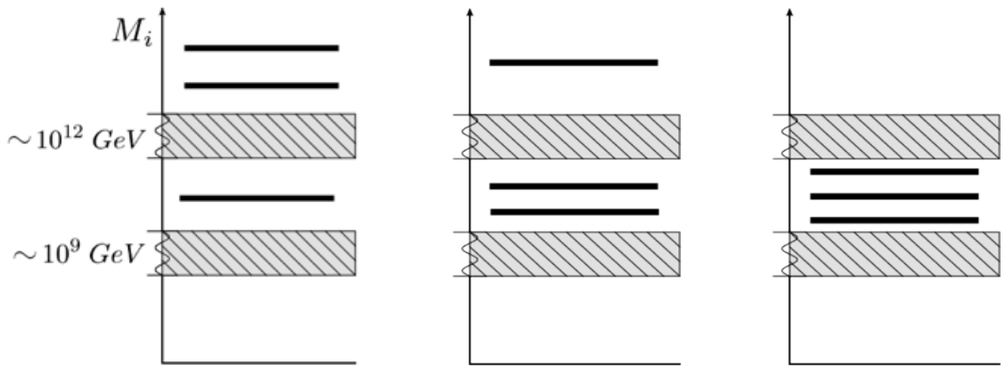
$$N_{B-L}^{\mathrm{lep,f}} \gg N_{B-L}^{\mathrm{p,f}}$$

Conditions on decay parameters and spectrum

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

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

$N^{p,i}$=0.1

$N^{p,i}$=0.01

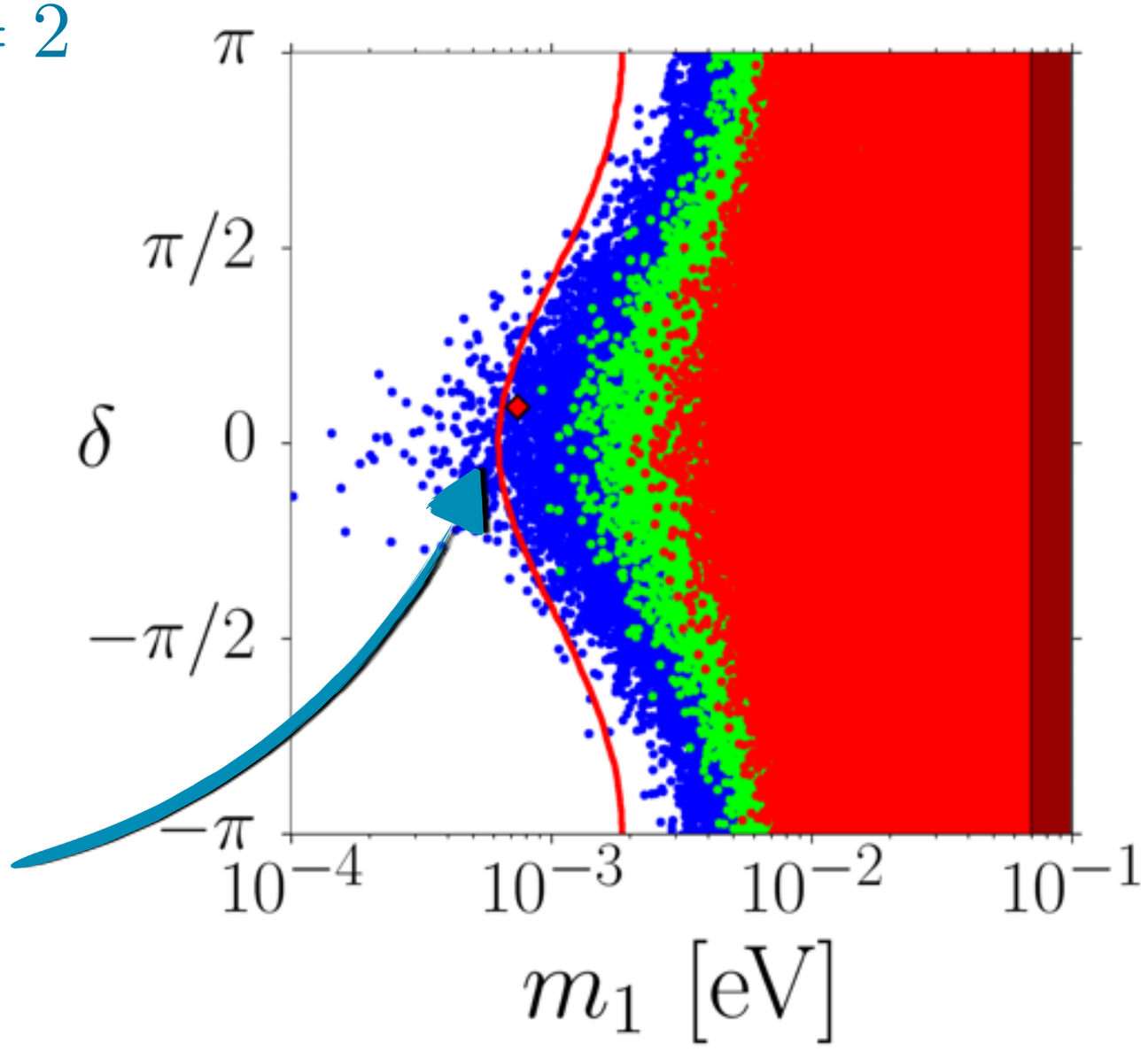
$N^{p,i}$=0.001

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

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

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

95% C.L.



Experiments? Cosmology!

- CMB spectrum alone:

$$\sum m_\nu < 0.933\,\mathrm{eV}$$ (Planck XVI)

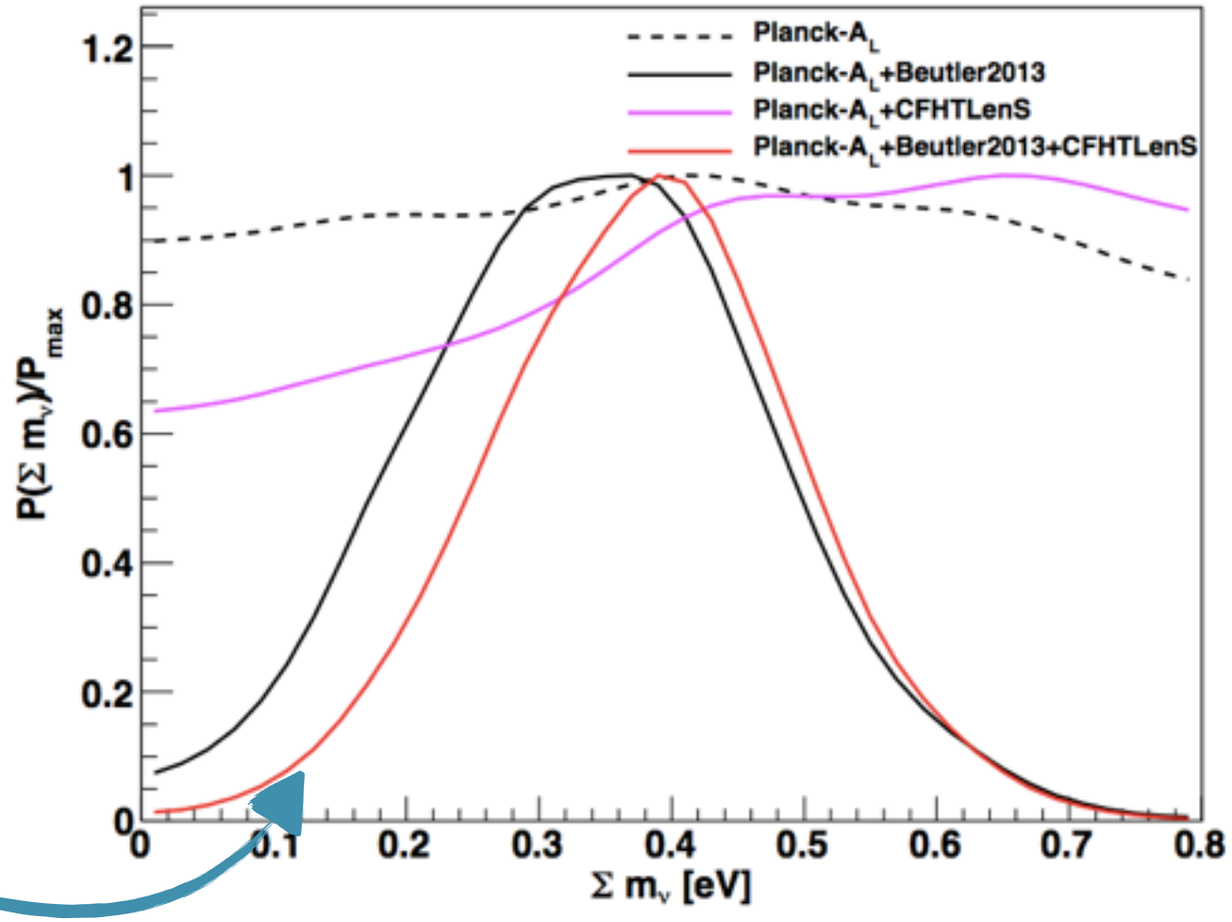
- CMB+SZ+BAO

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

- BOSS collaboration

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

at 3.4σ (Beutler et al. 2014)



are experiments pointing at $m_1 \neq 0$?

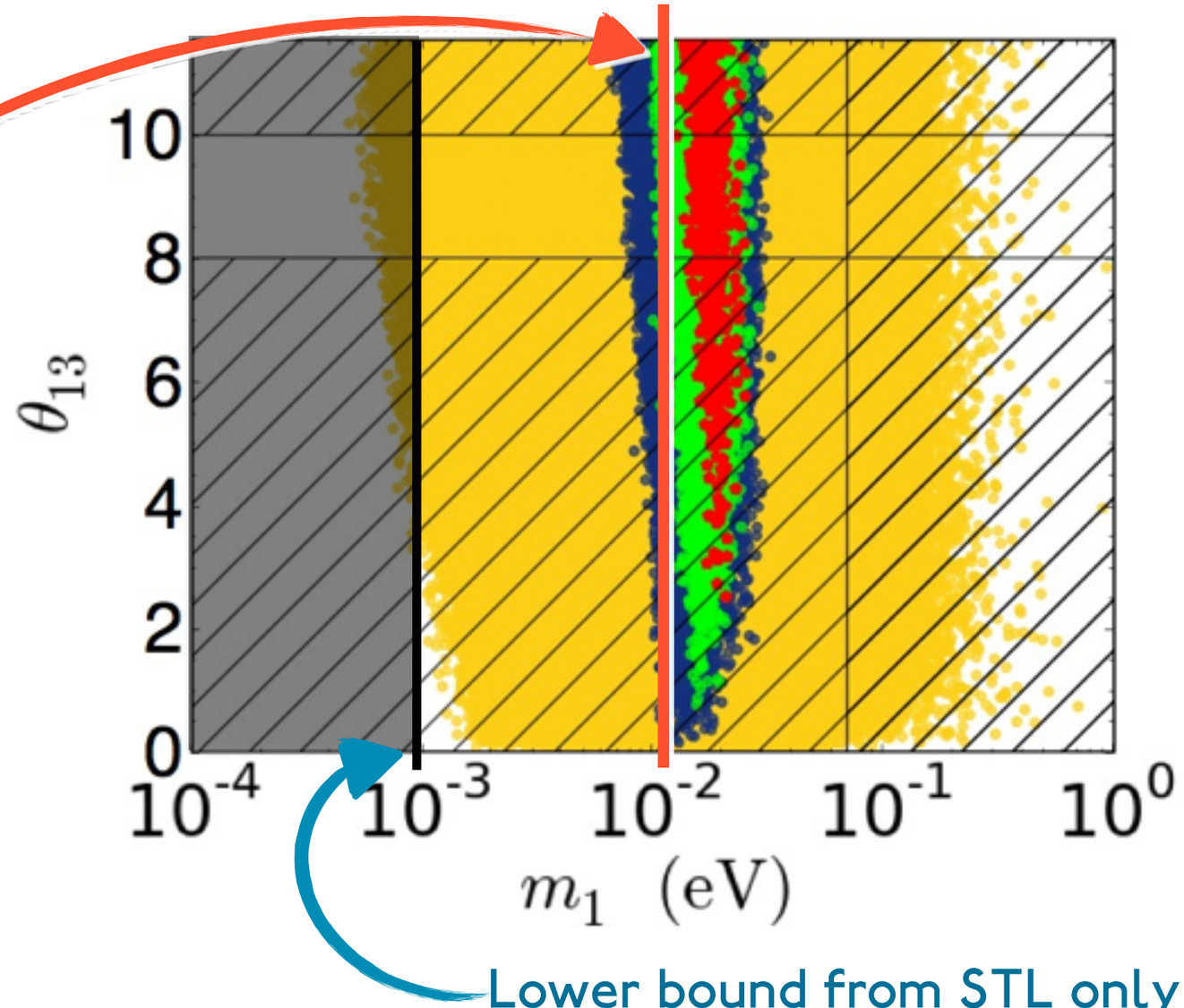
Long Baseline experiments must determine the ordering!

SO(10)-inspired + Strong thermal lep.

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

$N^{p,i}$=0.1
$N^{p,i}$=0.01
$N^{p,i}$=0.001
$N^{p,i}$=0

	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)

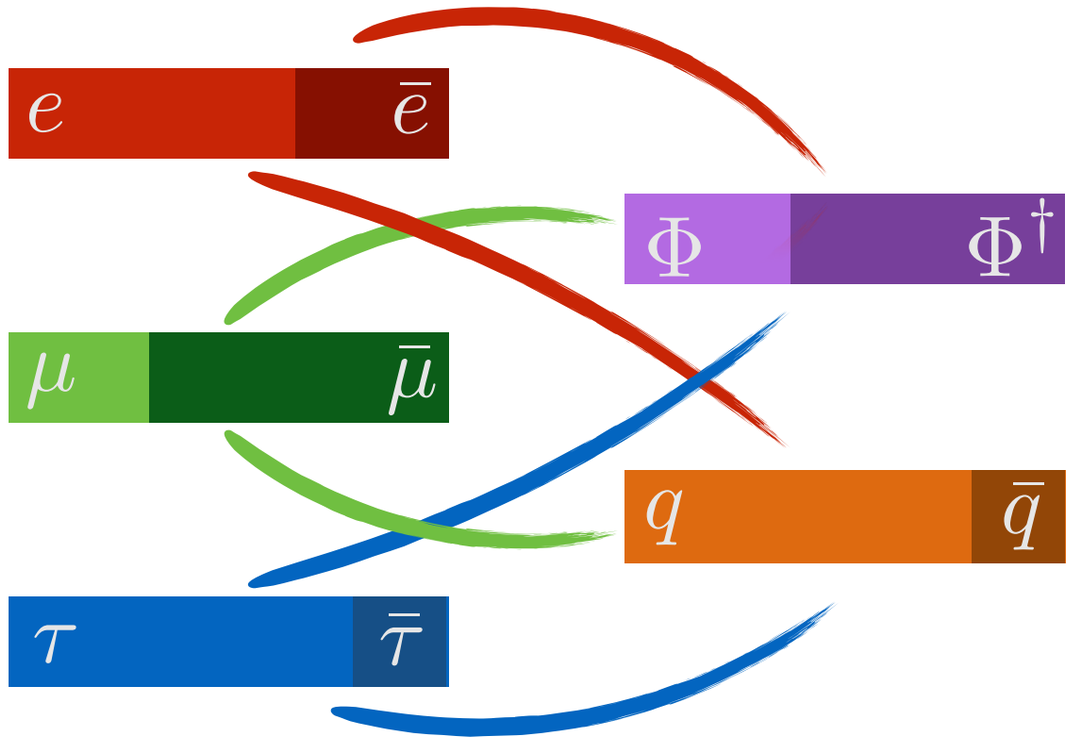
- Flavour asymmetries do not evolve independently
- Coupling through Higgs and quark asymmetries

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

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

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

Modification of the statistical limits

(SEKing, MRF 2014;
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)

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

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

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

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

Light neutrino spectrum

Tritium β decay:

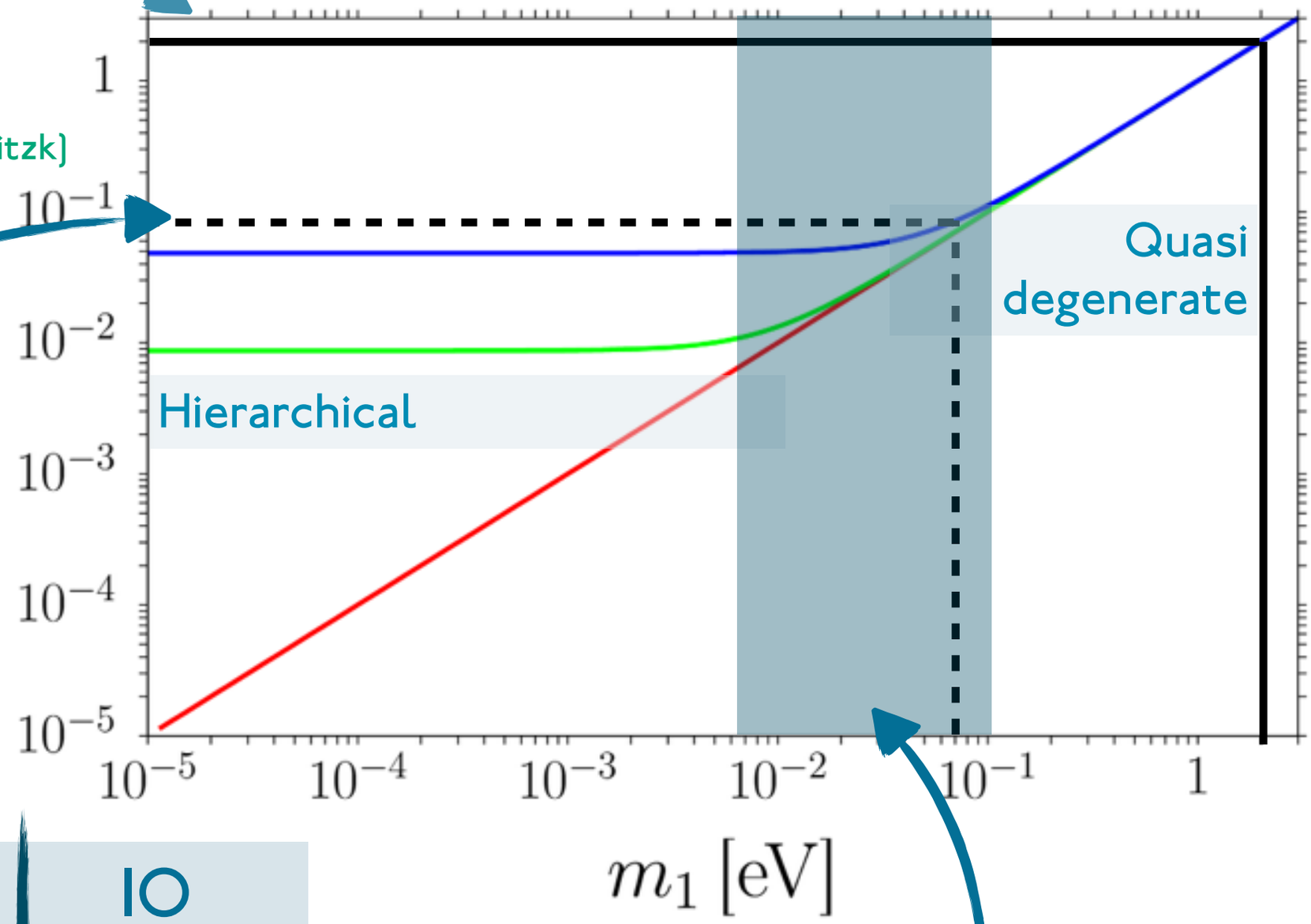
$$m_e < 2\,\mathrm{eV}$$

(Mainz-Troitzk)

ΛCDM:

$$m_1 < 0.07\,\mathrm{eV}$$

(Planck+WP+BAO+highL)



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

m_2^{NO}

m_1

	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