Luca Marzola







#### **Features and predictions**

Reference papers:

- •E. Bertuzzo, P. Di Bari, L.M. Nucl.Phys.B849:521-548,2011
- •P. Di Bari, L. M. in preparation
- •P. Di Bari, L. M., S. Huber, S. Peeters in preparation

Two problems:

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**>CMBR:**  $\eta_B^{CMBR} := \frac{n_B - n_{\bar{B}}}{n_{\gamma}} = (6.20 \pm 0.15) \times 10^{-10}$ 

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One solution:

$$\mathscr{L} = \mathscr{L}_{SM} + i\overline{N_{Ri}}\gamma_{\mu}\partial^{\mu}N_{Ri} - h_{\alpha i}\overline{\ell_{L\alpha}}N_{Ri}\tilde{\phi} - \frac{1}{2}\overline{N_{Ri}^{c}}M_{ij}^{R}N_{Rj} + H.c$$

eptosenesis

1, 2, 5  $\alpha = e, \mu, \tau$ 

eprosenesis

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$$\begin{aligned} & \text{S.B.} \quad + \quad \text{Heavy R.H.N.} \\ -m_{\alpha i}^{D} \overline{\nu_{L\alpha}} N_{Ri} \qquad [M^{R}] \gg [m^{D}] \\ & \text{Type I Seesaw:} \\ M_{\text{light}} \simeq -m^{D} (M^{R})^{-1} (m^{D})^{T} \\ & M_{\text{heavy}} \simeq M^{R} \end{aligned}$$

eprosenesis

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$$UD_m U^T = m^D D_{M^R}^{-1} (m^D)^T \qquad D_{m^D} = V_L m^D U_R^{\dagger}$$

$$M^{-1} := D_{m^D}^{-1} V_L U D_m U^T V_L^T D_{m^D}^{-1} \equiv U_R D_{M^R}^{-1} U_R^T$$

$$\begin{aligned} & > \text{Seesaw mechanism:} \qquad m^{\nu} = -m^{D} D_{M^{R}}^{-1} (m^{D})^{T} \\ & > \text{Takagi factorisation:} \qquad m^{\nu} = -U D_{m} U^{T} \qquad D_{m} = \begin{pmatrix} m_{1} & 0 & 0 \\ 0 & m_{2} & 0 \\ 0 & 0 & m_{3} \end{pmatrix} \\ & U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \\ & \bullet \qquad U D_{m} U^{T} = m^{D} D_{M^{R}}^{-1} (m^{D})^{T} \qquad D_{m} D = V_{L} m^{D} U_{R}^{\dagger} \\ & M^{-1} := D_{m^{D}}^{-1} V_{L} U D_{m} U^{T} V_{L}^{T} D_{m^{D}}^{-1} \equiv U_{R} D_{M^{R}}^{-1} U_{R}^{T} \\ & \bullet \qquad \text{Diagonalising } M^{-1} (M^{-1})^{\dagger} \text{ gives: } U_{R} \\ & \bullet \qquad D_{M^{R}} = \begin{pmatrix} M_{1} & 0 & 0 \\ 0 & M_{2} & 0 \\ 0 & 0 & M_{3} \end{pmatrix} \end{aligned}$$

#### Seesaw type I, 3 RHN: 18 new parameters $h_{\alpha i}, M_i \rightarrow U, V_L, m_i, m^{D_i}$ $15+3 \rightarrow 6+6+3+3$

> v experiments: measure 5 parameters (pre T2K)

T. Schwetz et al.;2008

Parameter:	$\Delta m^2_{12} \ (10^{-5} { m eV^2})$	$ \Delta m^2_{13}  \; (10^{-3} { m eV}^2)$	$\sin^2  heta_{12}$	$\sin^2 heta_{13}$	$\sin^2  heta_{23}$
68% Confidence Interval:	$7.65\substack{+0.23\\-0.20}$	$2.40\substack{+0.12\-0.11}$	$0.304\substack{+0.022\\-0.016}$	$0.01\substack{+0.016\-0.011}$	$0.50\substack{+0.07 \\ -0.06}$

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•V<sub>L</sub> between I and CKM •light neutrino Dirac masses proportional to the up-type quark ones:  $(\alpha_1 m_m = 0 = 0)$ 

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 $\eta_B(SO(10))$ -inspired +  $\nu \exp(r) \simeq \eta_B^{CMBR}$ ?

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With this setup the *natural* scenario is  $N_2$ -dominated > heavy neutrinos' hierarchical mass spectrum:  $M_3 > 10^{12} \text{ GeV} > M_2 > 10^9 \text{ GeV} \gg M_1$  $> N_3$  does not contribute to the asymmetry. Furthermore:  $M_3/M_2 > 10$  no resonant enhancement to  $\epsilon_2$ > B-L asymmetry produced in a 2-flavours regime for  $T \sim M_2$ :  $N_{B-L}(T \sim M_2) \simeq \epsilon_{2\tau} \kappa(K_2, K_{2\tau}) + \epsilon_{2e+\mu} \kappa(K_2, K_{2e+\mu})$ > N<sub>I</sub> does washout in three flavour regime. No B-L production:  $\eta_B^{N_1} \sim \eta_B^{CMBR} \Leftrightarrow M_1 \ge 10^9 \text{ GeV}$  $N_{B-L}^{f} \simeq \frac{p_{2e}}{p_{2e+\mu}} \epsilon_{2e+\mu} \kappa(K_{2e+\mu}) e^{-\frac{3\pi}{8}K_{1e}} + \frac{p_{2\mu}}{p_{2e+\mu}} \epsilon_{2e+\mu} \kappa(K_{2e+\mu}) e^{-\frac{3\pi}{8}K_{1\mu}} + \frac{p_{2\mu}}{p_{2e+\mu}} \epsilon_{2e+\mu} \kappa(K_{2e+\mu}) e^{-\frac{3\pi}{8}K_{1\mu}} + \frac{p_{2\mu}}{p_{2e+\mu}} \epsilon_{2e+\mu} \kappa(K_{2e+\mu}) e^{-\frac{3\pi}{8}K_{1\mu}} + \frac{p_{2\mu}}{p_{2e+\mu}} \epsilon_{2e+\mu} \kappa(K_{2e+\mu}) e^{-\frac{3\pi}{8}K_{1e}} + \frac{p_{2\mu}}{p_{2e+\mu}} \epsilon_{2e+\mu} \kappa(K_{2e+\mu}) e^{-\frac{3\pi}{8}K_{1e}} + \frac{p_{2\mu}}{p_{2e+\mu}} \epsilon_{2e+\mu} \kappa(K_{2e+\mu}) e^{-\frac{3\pi}{8}K_{1e}} + \frac{p_{2\mu}}{p_{2e+\mu}} \epsilon_{2e+\mu} \kappa(K_{2e+\mu}) e^{-\frac{3\pi}{8}K_{1\mu}} + \frac{p_{2\mu}}{p_{2e+\mu}} \epsilon_{2e+\mu} \kappa(K_{2e+\mu}) e^{-\frac{3\pi}{8}K_{1\mu}} + \frac{p_{2\mu}}{p_{2e+\mu}} \epsilon_{2e+\mu} \kappa(K_{2e+\mu}) e^{-\frac{3\pi}{8}K_{1e}} + \frac{p_{2\mu}}{p_{2e+\mu}} \epsilon_{2e+\mu} \kappa(K_{2e+\mu}) e^{-\frac{3\pi}{8}K_{1\mu}} + \frac{p_{2\mu}}{p_{2$  $+\epsilon_{2\tau}\kappa(K_{2\tau})e^{-\frac{3\pi}{8}K_{1\tau}}$ 

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- ) scan the parameter space and calculate  $\eta_{B}^{SO(10)}$ :
  - $I \leq V_L \leq CKM$ , normal and inverted order
  - • $\alpha_2 \sim O(I)$
  - •2 $\sigma$  experimental ranges for  $\theta_{12}, \theta_{23}, \theta_{13}$
  - •U⊃σ,ρ,δ∈[0,360°]
  - •m<sub>1</sub> < IeV, best fits for  $\Delta m^2_{sol}$ ,  $\Delta m^2_{atm}$

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End of leptogenesis

←→ Strong thermal leptogenesis independence of the initial conditions

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Unflavoured case, strong leptogenesis: K<sub>1</sub>>>

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W. Buchmuller, P. Di Bari, M. Plumacher - 2004

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- > 3 RHN: mass spectrum  $M_3 > 10^{12} \text{ GeV} > M_2 > 10^9 \text{ GeV} > M_1$
- > N<sub>2</sub>: strong washout along the au flavour  $K_{2 au} >> 1$
- > N<sub>1</sub>: asymmetric washout, strong along e,  $\mu$ ; weak along  $\tau$ 
  - preexisting asymmetry is completely washed out and strong thermal Leptogenesis is realised along the  $\tau$  flavour direction



independence of the initial conditions

W. Buchmuller, P. Di Bari, M. Plumacher - 2004

E. Bertuzzo, P. Di Bari, L.M. - 201

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preexisting asymmetry is completely washed out and strong thermal Leptogenesis is realised along the  $\tau$  flavour direction

Successful strong thermal leptogenesis ← (τ N<sub>2</sub>-dominated scenario)  $\eta_{B}^{SO(10)} \ge 5.9 \times 10^{-10}$ 

$$\begin{split} \eta_B^{preex} &= 0.0096 \times N_{B-L}^{preex} | < 10^{-10} \\ & \text{End of leptogenesis} \end{split}$$



W. Buchmuller, P. Di Bari, M. Plumacher -	2004
E. Bertuzzo, P. Di Bari, L.M 2011	

independence of the initial conditions



 $\alpha_2 = 5$ ,  $I \leq V_L \leq CKM$ , *n.o.* 

 $N_{B-L}^{0,preex}=0, |0^{-3}, |0^{-2}, |0^{-1}$ 

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 $10^{0}$ 

#### $\alpha_2 = 5$ , $I \leq V_L \leq CKM$ , n.o.

P. Di Bari, L.M. - Work in progress

θ

10

8

0└─ 10<sup>-4</sup>

ρνς

¦¦ = 1.0

0.5

0.0

 $\theta_{13}$ 

 $N_{B-L}^{0,preex}=0, |0^{-3}, |0^{-2}, |0^{-1}$ 

 $10^{0}$ 

#### arXiv:1106.2822v1 [hep-ex] 14 Jun 2011

Indication of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam

(The T2K Collaboration)

#### Abstract

The T2K experiment observes indications of  $\nu_{\mu} \rightarrow \nu_{e}$  appearance in data accumulated with  $1.43 \times 10^{20}$  protons on target. Six events pass all selection criteria at the far detector. In a three-flavor neutrino oscillation scenario with  $|\Delta m_{23}^2| = 2.4 \times 10^{-3} \text{ eV}^2$ ,  $\sin^2 2\theta_{23} = 1$  and  $\sin^2 2\theta_{13} = 0$ , the expected number of such events is  $1.5 \pm 0.3$ (syst.). Under this hypothesis, the probability to observe six or more candidate events is  $7 \times 10^{-3}$ , equivalent to  $2.5\sigma$  significance. At 90% C.L., the data are consistent with  $0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$  for  $\delta_{\rm CP} = 0$  and normal (inverted) hierarchy.

 $\pi/2$ 

-π/2

 $\pi/2$ 

 $-\pi/2$ 

 $\delta_{\rm CP}$ 

 $\delta_{CP}$ 

 $\Delta m_{23}^2 > 0$ 

est fit to T2K data

 $\Delta m_{23}^2 < 0$ 

68% CL

90% CL

T2K

 $1.43 \times 10^{20}$  p.o.t.

0.5

0.6

#### $\alpha_2 = 5$ , $I \leq V_L \leq CKM$ , *n.o.*

 $\sigma/\pi$ 

P. Di Bari, L.M. - Work in progress

 $\theta$ 

10

8

0└─ 10<sup>-4</sup>

ρ vs

1.5

¦¦ = 1.0

0.5

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 $\theta_{13}$ 



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#### Abstract

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hierarchy

P. Di Bari, L.M. - Work in progress

10  $\theta$ 

8

( 1

ρ

<sup>⊭</sup>⊲ 1.0

0.5

0.0

 $\theta_{13}$ 



#### arXiv:1106.6028v1 [hep-ph] 29 Jun 2011

#### Evidence of $\theta_{13} > 0$ from global neutrino data analysis

G.L. Fogli,<sup>1,2</sup> E. Lisi,<sup>2</sup> A. Marrone,<sup>1,2</sup> A. Palazzo,<sup>3</sup> and A.M. Rotunno<sup>1</sup>

The neutrino mixing angle  $\theta_{13}$  is at the focus of current neutrino research. From a global analysis of the available oscillation data in a  $3\nu$  framework, we previously reported [Phys. Rev. Lett. 101, 141801 (2008)] hints in favor of  $\theta_{13} > 0$  at the 90% C.L. Such hints are consistent with the recent indications of  $\nu_{\mu} \rightarrow \nu_{e}$  appearance in the T2K and MINOS long-baseline accelerator experiments. Our global analysis of all the available data currently provides  $> 3\sigma$  evidence for nonzero  $\theta_{13}$ , with  $1\sigma$  ranges  $\sin^{2} \theta_{13} = 0.021 \pm 0.007$  or  $0.025 \pm 0.007$ , depending on reactor neutrino flux systematics. Updated ranges are also reported for the other  $3\nu$  oscillation parameters ( $\delta m^{2}$ ,  $\sin^{2} \theta_{12}$ ) and ( $\Delta m^{2}$ ,  $\sin^{2} \theta_{23}$ ).

#### $\alpha_2 = 5$ , $I \leq V_L \leq CKM$ , n.o.

 $N_{B-L}^{0,preex}=0, |0^{-3}, |0^{-2}, |0^{-1}$ 









 $10^{0}$ 

#### Going further: $PDFs; V_L = I, n.o.$

#### P. Di Bari, L. M., S. Huber, S. Peeters - work in progress





### Going further: $PDFs; V_L = I, n.o.$

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#### 68% C.L. 95% C.L.







#### Going further: $PDFs; V_L = I, n.o.$

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# Again on $\theta_{13}$

Input distribution: uniform on [0°, 14°]

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### Epilogue and future prospects:

About leptogenesis and the SO(10)-inspired model:

Future prospects:

## Epilogue and future prospects:

About leptogenesis and the SO(10)-inspired model:

- > Leptogenesis can explain the observed BAU and, via the seesaw mechanism, the neutrino mass scale in a natural way
- > The SO(10)-inspired model allows for successful strong leptogenesis proposing a tauon-N<sub>2</sub> dominated scenario, n.o.
- > Sharp predictions for n.o. requiring strong thermal leptogenesis!
- ) Statistical analyses appears in line with new results on  $\theta_{13}$  and  $\theta_{23}$

Future prospects:

> Complete set of one parameter PDFs for  $V_L \neq I$ , i.o. & n.o.

> more on SO(10)-inspired: possible future scenarios.

# Encore:

- N<sub>1</sub> leptogenesis as an example
- Correlations between  $\theta_{13}$  and  $\theta_{23}$
- Inverted order in the SO(10) inspired model
- Details on the statistical analyses
- Strong thermal leptogenesis in steps

 $N_{N_1}$  evolution:

 $N_{B-L}$  evolution:

 $N_{N_1}$  evolution:

$$\frac{dN_{N_1}}{dz} = -D_1(N_{N_1} - N_{N_1}^{eq}) \qquad z := M_1/T$$

 $N_{B-L}$  evolution:



 $N_{N_1}$  evolution:

$$\frac{dN_{N_1}}{dz} = -D_1(N_{N_1} - N_{N_1}^{eq}) \qquad z := M_1/T$$

 $N_{B-L}$  evolution:

**Connection to neutrino oscillation parameters!** 

#### $N_{N_1}$ evolution: $N_{B-L}$ evolution:

$$\frac{dN_{N_1}}{dz} = -D_1(N_{N_1} - N_{N_1}^{eq})$$
$$\frac{dN_{B-L}}{dz} = \epsilon_1 D_1(N_{N_1} - N_{N_1}^{eq}) - N_{B-L} W_1(z)$$



The three stages of N<sub>1</sub> leptogenesis, strong washout regime:  $K_1 = 100$ ;  $|\epsilon_1| = 10^{-6}$ 

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# Correlations between $\theta_{23}$ & $\theta_{13}$

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For high values of  $\theta_{13}$  Leptogenesis and the seesaw mechanism select increasing values of  $\theta_{23}$ 

#### Inverted order; $\alpha_2=5$ , $I \leq V_L \leq CKM$

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Going a step further:

P. Di Bari, L. M., S. Huber, S. Peeters - work in progress

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#### Implementation: python code

#### **>** populate the sample space: $V_L = 1$ normal ordering only

Parameter:	$m_{sol}~(\mathrm{eV})$	$m_{atm} (eV)$	$\sin^2  heta_{12}$	$ heta_{13}$	$\sin^2  heta_{23}$
Assumed values:	$8.75 \times 10^{-3}$	$5.0 \times 10^{-2}$	Gauss(0.304; 0.019)	$unif[0^{\circ}; 14^{\circ}]$	Gauss(0.50; 0.06)

 $m_1: uniform[0; 10^{-4}] \, \mathrm{eV} \qquad lpha_1 = 1 \qquad lpha_2 = 5 \qquad lpha_3 = 1 \qquad \delta, 
ho, \sigma: uniform[0; 2\pi]$ 

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This is the only scenario allowing for strong thermal leptogenesis!