15th Rencontres du Vietnam: 3 Neutrinos and beyond
ICISE, Quy Nhon, 4-10 August, 2019

Neutrino masses leptogenesis and dark matter

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Why going beyond the SM?

Even ignoring:

- ❑ (more or less) compelling theoretical motivations (quantum gravity theory, flavour problem, hierarchy problem, naturalness(?),…) and
- ❑ Experimental anomalies (e.g., $(g-2)_\mu$, R_K, R_K^*,…)

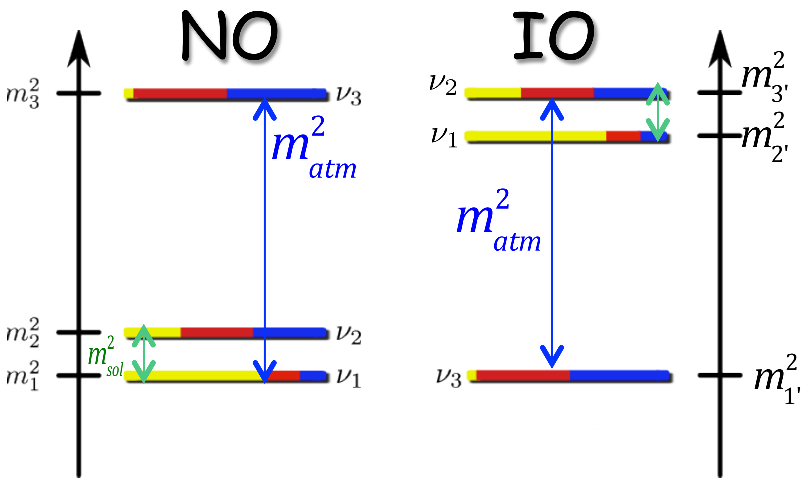
The SM cannot explain:

- *Cosmological Puzzles :*

1. Dark matter
2. Matter - antimatter asymmetry
3. Inflation
4. Accelerating Universe

- *Neutrino masses and mixing*

Neutrino masses ($m_{1'} < m_{2'} < m_{3'}$)



$$NO: m_2 = \sqrt{m_1^2 + m_{sol}^2}, \quad m_3 = \sqrt{m_1^2 + m_{atm}^2}$$

$$IO: m_{2'} = \sqrt{m_{1'}^2 + m_{atm}^2 - m_{sol}^2}, \quad m_{3'} = \sqrt{m_{1'}^2 + m_{atm}^2}$$

m_{sol} = (8.6 ± 0.1) meV

m_{atm} = (50.3 ± 0.3) meV

(νfit 2019)

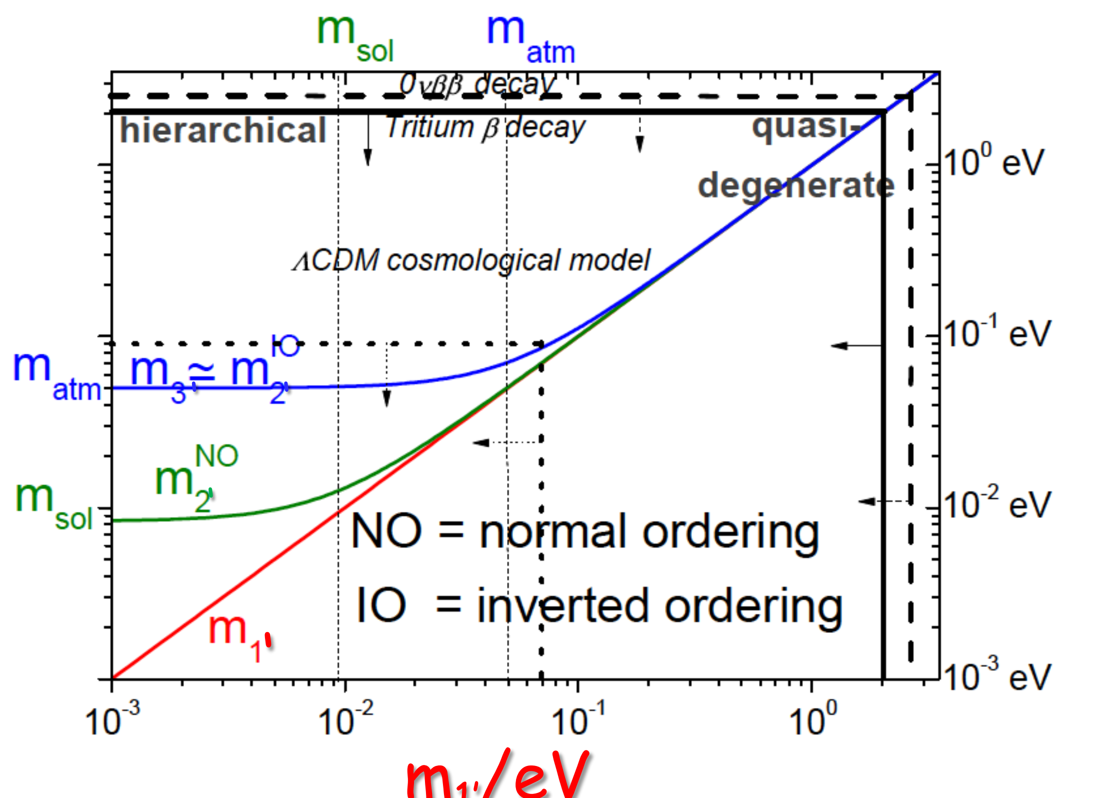
$$\sum_i m_i < 0.23\,eV \ (95\% C.L.)$$

$$\Rightarrow m_{1'} \leq 0.07\,eV$$ (Planck 2015)

$$\sum_i m_i < 0.12\,eV \ (95\% C.L.)$$

$$\Rightarrow m_{1'} \leq 0.03\,eV \quad (NO)$$

$$m_{1'} \leq 0.016\,eV \quad (IO)$$ (Planck 2018)



Neutrino mixing: $\nu_\alpha = \sum_i U_{\alpha i} \nu_i$

$$U_{\alpha i} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\sigma} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\sigma} \end{pmatrix}$$

PDG:
$\alpha_{31} = 2(\sigma - \rho)$
$\alpha_{21} = -2\rho$

Atmospheric, LB | Reactors, Accel., LB CP violating phase | Solar, Reactors | ββ0ν decay

$c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$

3σ ranges (NO)

(νfit July 2019)

$\theta_{12} = [31.6^\circ, 36.3^\circ]$

$\theta_{13} = [8.2^\circ, 9.0^\circ]$

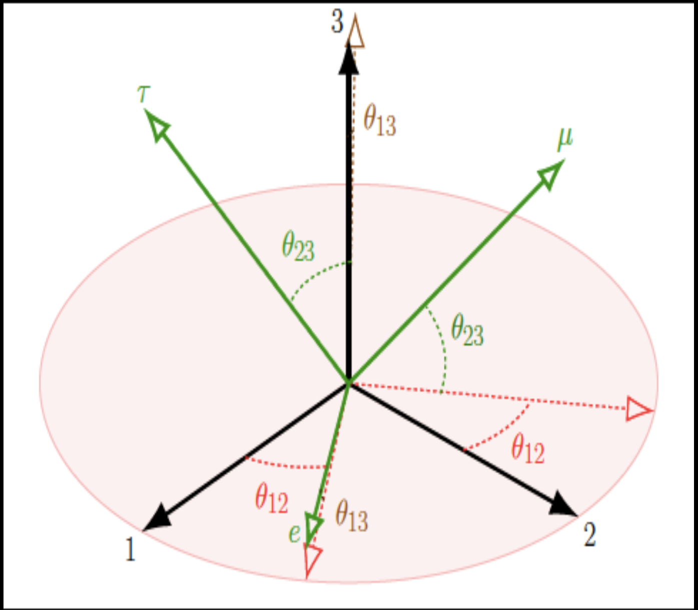
$\theta_{23} = [41.1^\circ, 51.3^\circ]$

$\delta = [144^\circ, 357^\circ]$

$\rho, \sigma = [0, 360^\circ]$

NO favoured over IO:

$\Delta\chi^2$ (IO-NO)=10.6



Minimally extended SM

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_Y^\nu$$

$$-\mathcal{L}_Y^\nu = \overline{\nu_L}\, h^\nu\, \nu_R\, \phi \Rightarrow -\mathcal{L}_{\rm mass}^\nu = \overline{\nu_L}\, m_D\, \nu_R$$

Dirac Mass

(in a basis where charged lepton mass matrix is diagonal)

diagonalising m_D : $$m_D = V_L^\dagger D_{m_D} U_R \qquad D_{m_D} \equiv \begin{pmatrix} m_{D1} & 0 & 0 \\ 0 & m_{D2} & 0 \\ 0 & 0 & m_{D3} \end{pmatrix}$$

$\Rightarrow$ neutrino masses: $m_i = m_{Di}$

leptonic mixing matrix: $U = V_L^\dagger$

<u>But many unanswered questions:</u>

- Why neutrinos are much lighter than all other fermions?
- Why large mixing angles (differently from CKM angles)?
- Cosmological puzzles?
- Why not a Majorana mass term as well?

Minimal seesaw mechanism (type I)

• Dirac + (right-right) Majorana mass terms

(Minkowski '77; Gell-mann, Ramond, Slansky; Yanagida; Mohapatra, Senjanovic '79)

$$-\mathcal{L}^{\nu}_{\rm mass} = \overline{\nu_L}\, m_D\, \nu_R + \frac{1}{2}\,\overline{\nu^c_R}\, M\, \nu_R + \text{h.c.}$$

violates lepton number

In the see-saw limit ($M \gg m_D$) the mass spectrum splits into 2 sets:

- 3 light **Majorana neutrinos** with masses (seesaw formula):

$$\text{diag}(m_1, m_2, m_3) = -U^{\dagger}\, m_D\, \frac{1}{M}\, m_D^T\, U^{\star}$$

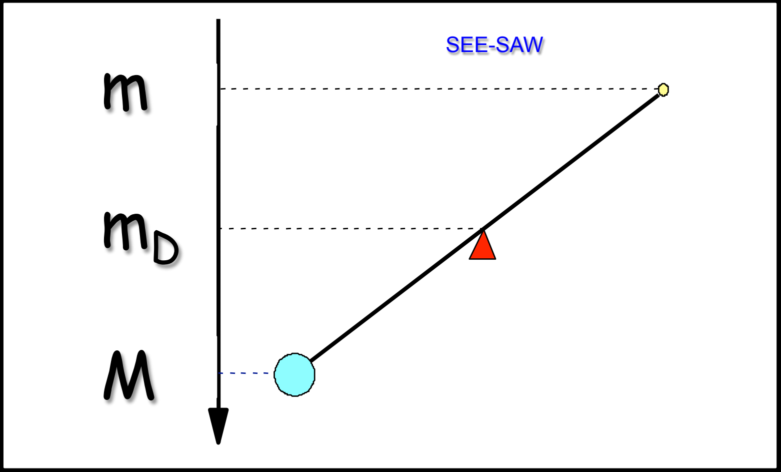
- 3(?) very heavy Majorana neutrinos N_I, N_{II}, N_{III} with $M_{III} > M_{II} > M_I \gg m_D$

1 generation toy model :

$m_D \sim m_{top}$,

$m \sim m_{atm} \sim 50$ meV

$\Rightarrow M \sim M_{GUT} \sim 10^{16}$GeV



Theory prediction:

$M \sim 10^{16}$ GeV

Experimentalist reaction

3 generation seesaw models: two extreme limits

In the flavour basis (both charged lepton mass and Majorana mass matrices are diagonal):

$$-\mathcal{L}^{\nu+\ell}_{\rm mass} = \overline{\alpha_L}\, m_\alpha\, \alpha_R + \overline{\nu_{L\alpha}}\, m_{D\alpha I}\, \nu_{RI} + \frac{1}{2}\,\overline{\nu^c_{RI}}\, M_I\, \nu_{RI} + \text{h.c.}$$

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

$$I = 1,2,3$$

bi-unitary parameterisation: $m_D = V_L^\dagger D_{m_D} U_R \qquad D_{m_D} \equiv diag(m_{D1}, m_{D2}, m_{D3})$

FIRST (EASY) LIMIT: ALL MIXING FROM THE LEFT-HANDED SECTOR

- $U_R = I \Rightarrow$ again $U = V_L^\dagger$ and neutrino masses: $m_i = \dfrac{m_{Di}^2}{M_I}$

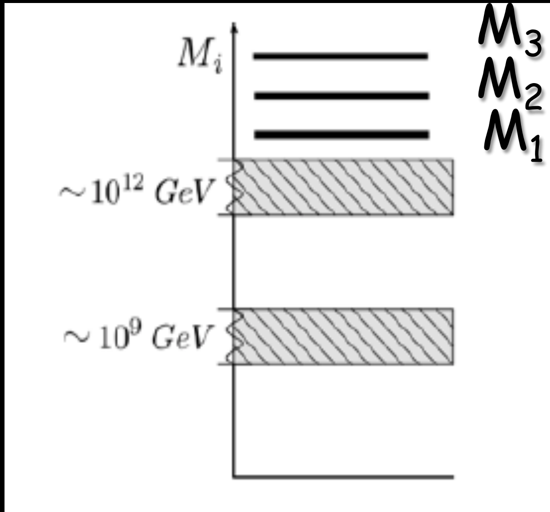
If also $m_{D1}=m_{D2}=m_{D3}=\lambda$ then simply: $M_I = \dfrac{\lambda^2}{m_i}$

Exercise: $\lambda \sim 100\, GeV$

$m_1 \sim 10^{-4}\, eV \Rightarrow M_3 \sim 10^{17}\, GeV$

$m_2 = m_{sol} \sim 10\, meV \Rightarrow M_2 \sim 10^{15}\, GeV$

$m_3 = m_{atm} \sim 50\, meV \Rightarrow M_1 \sim 10^{14}\, GeV$



Typically RH neutrino mass spectrum emerging in simple discrete flavour symmetry models

A SECOND (NOT SO EASY) LIMIT: ALL MIXING FROM THE RH SECTOR

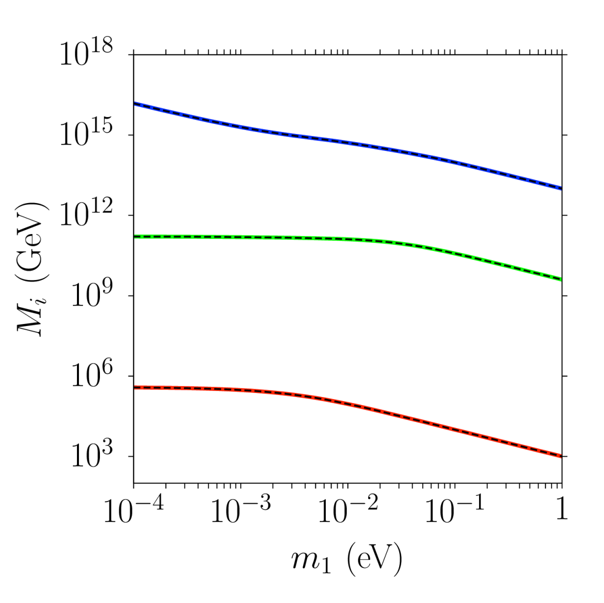
(Branco et al. '02; Nezri, Orloff '02; Akhmedov, Frigerio, Smirnov '03; PDB, Riotto '08; PDB, Re Fiorentin '12)

- $V_L = I \;\Rightarrow\; M_1 = \dfrac{m_{D1}^2}{m_{\beta\beta}};\quad M_2 = \dfrac{m_{D2}^2}{m_1 m_2 m_3}\dfrac{m_{\beta\beta}}{|(m_\nu^{-1})_{\tau\tau}|};\quad M_3 = m_{D3}^2\,|(m_\nu^{-1})_{\tau\tau}|$

If one also imposes (SO(10)-inspired models)

$$m_{D1} = \alpha_1\, m_{up};\quad m_{D2} = \alpha_2 m_{charm};\; m_{D3} = \alpha_3 m_{top};\quad \alpha_i = O(1)$$

Barring very fine-tuned solutions, one obtains a very hierarchical RH neutrino mass spectrum



Combining discrete flavour + grand unified symmetries one can obtain basically all mass spectra between these two limits (we will be back on this)

WHAT CAN HELP UNDERSTANDING WHICH IS THE RIGHT MODEL OR CLASS OF MODELS??

Minimal scenario of leptogenesis

- Type I seesaw mechanism (Fukugita, Yanagida '86)
- Thermal production of RH neutrinos: $T_{RH} \gtrsim T_{lep} \simeq M_i / (2 \div 10)$

heavy neutrinos decay $N_I \xrightarrow{\Gamma_I} L_I + \phi^\dagger \qquad N_I \xrightarrow{\overline{\Gamma}} \overline{L}_I + \phi$

total CP asymmetries $\varepsilon_I \equiv -\dfrac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}$ $\Rightarrow N_{B-L}^{fin} = \sum_{I=1,2,3} \varepsilon_I \times \kappa_I^{fin}$ → efficiency factors

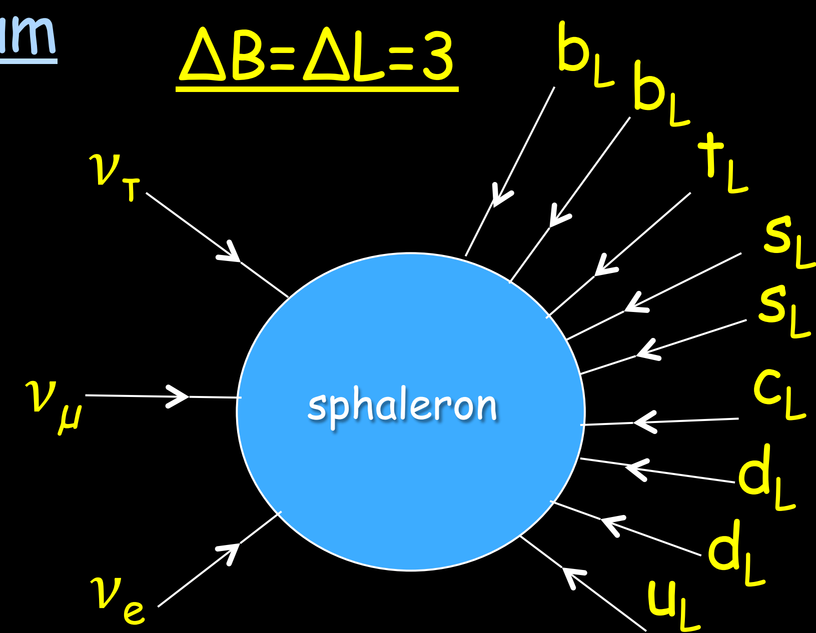
- Sphaleron processes in equilibrium

$\Rightarrow T_{lep} \gtrsim T_{sphalerons}^{off} \sim$ **100 GeV**

(Kuzmin, Rubakov, Shaposhnikov '85)

$$\Rightarrow \boxed{\eta_{B0}^{lep} = \frac{a_{sph} N_{B-L}^{fin}}{N_\gamma^{rec}} \simeq 0.01 N_{B-L}^{fin}}$$

$\Delta B = \Delta L = 3$



Seesaw parameter space

Combining $\eta_{B0}^{lep} \simeq \eta_{B0}^{CMB} \simeq 6\times 10^{-10}$ with low energy neutrino data can we test seesaw and leptog.? Problem: too many parameters

(Casas, Ibarra'01) $m_\nu = -m_D \frac{1}{M} m_D^T \Leftrightarrow \boxed{\Omega^T \Omega = I}$ Orthogonal parameterisation

$$\boxed{m_D} = \boxed{U \begin{pmatrix} \sqrt{m_1} & 0 & 0 \\ 0 & \sqrt{m_2} & 0 \\ 0 & 0 & \sqrt{m_3} \end{pmatrix} \Omega \begin{pmatrix} \sqrt{M_1} & 0 & 0 \\ 0 & \sqrt{M_2} & 0 \\ 0 & 0 & \sqrt{M_3} \end{pmatrix}}$$

(in a basis where charged lepton and Majorana mass matrices are diagonal)

light neutrino parameters

heavy neutrino parameters escaping experimental information

- Popular solution: "low-scale" leptogenesis, though no signs so far of new physics at the TeV scale or below supporting this picture (talk by Juric Klaric)

- High scale leptogenesis is challenging to test but there are a few strategies able to reduce the number of parameters in order to obtain testable predictions on low energy neutrino parameters

Vanilla leptogenesis ⇒ upper bound on ν masses

(Buchmüller, PDB, Plümacher '04; Blanchet, PDB '07)

1) Lepton flavor composition is neglected

2) Hierarchical spectrum ($M_2 \gtrsim 2M_1$)

3) Strong lightest RH neutrino wash-out

$$\eta_{B0} \simeq 0.01 N_{B-L}^{final} \simeq 0.01 \varepsilon_1 \kappa_1^{fin}(K_1, m_1)$$

decay parameter: $K_1 \equiv \dfrac{\Gamma_{N_1}(T=0)}{H(T=M_1)}$

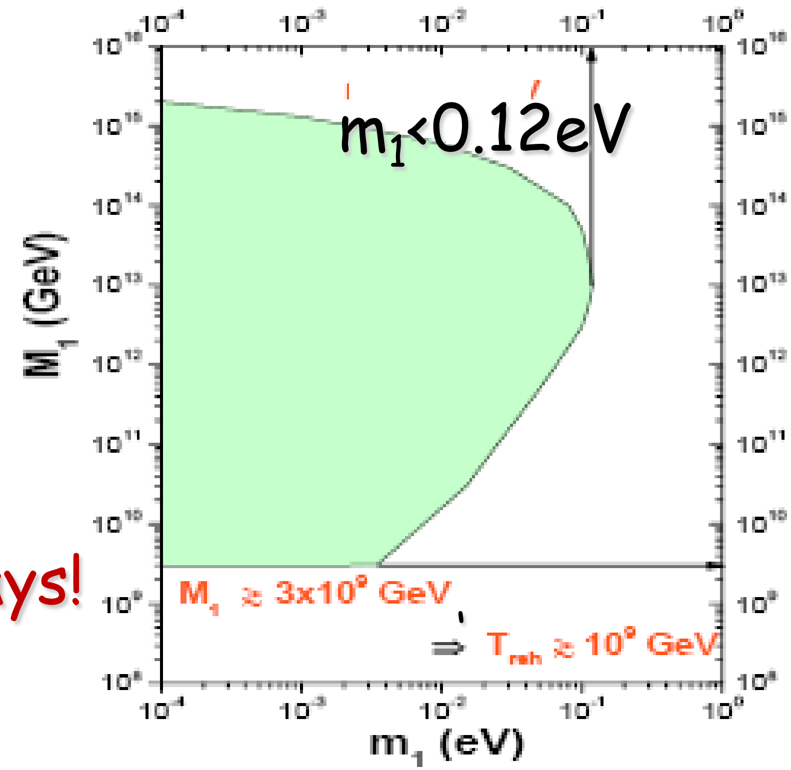
All the asymmetry is generated by the lightest RH neutrino decays!

4) Barring fine-tuned cancellations

(Davidson, Ibarra '02)

$$\varepsilon_1 \leq \varepsilon_1^{\max} \simeq 10^{-6} \left(\frac{M_1}{10^{10}\,\mathrm{GeV}}\right) \frac{m_{\rm atm}}{m_1 + m_3}$$

$$\eta_B^{\max}(m_1, M_1) \geq \eta_B^{CMB}$$



No dependence on the leptonic mixing matrix U: it cancels out!

IS SO(10)-INSPIRED LEPTOGENESIS RULED OUT ?

Independence of the initial conditions (strong thermal leptogenesis)

(Buchmüller, PDB, Plümacher '04)

wash-out of a pre-existing asymmetry $N_{B-L}^{p,initial}$

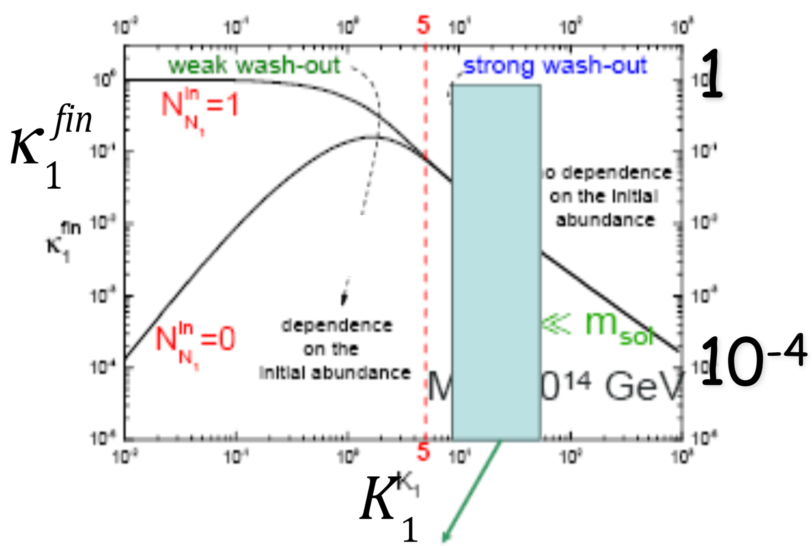
Just a coincidence?

$$\boxed{N_{B-L}^{\rm p,final} = N_{B-L}^{\rm p,initial}\, e^{-\frac{3\pi}{8}\,K_1} \ll N_{B-L}^{\rm f,N_1}}$$

decay parameter: $K_1 \equiv \dfrac{\Gamma_{N_1}}{H(T=M_1)} \sim \dfrac{m_{\rm sol,atm}}{m_\star \sim 10^{-3}\,{\rm eV}} \sim 10 \div 50$

equilibrium neutrino mass: $m_* = \dfrac{16\pi^{5/2}\sqrt{g_*}}{3\sqrt{5}}\dfrac{v^2}{M_{\rm Pl}} \simeq 1.08\times 10^{-3}\ {\rm eV}.$

independence of the initial N_1-abundance as well



$$\boxed{K_{\rm sol} \simeq 9 \lesssim K_1 \lesssim 50 \simeq K_{\rm atm}}$$

Charged lepton flavour effects

(Abada et al '06; Nardi et al. '06; Blanchet, PDB, Raffelt '06; Riotto, De Simone '06)

Flavor composition of lepton quantum states matters!

$$|l_1\rangle = \sum_\alpha \langle l_\alpha | l_1 \rangle \, |l_\alpha\rangle \qquad (\alpha = e, \mu, \tau)$$

$$|\bar{l}'_1\rangle = \sum_\alpha \langle l_\alpha | \bar{l}'_1 \rangle \, |\bar{l}_\alpha\rangle$$

- **T << 10^{12} GeV** ⇒ τ-Yukawa interactions are fast enough break the coherent evolution of $|l_1\rangle$ and $|\bar{l}'_1\rangle$

⇒ incoherent mixture of a τ and of a μ+e components ⇒ 2-flavour regime

- T << 10^9 GeV then also μ-Yukawas in equilibrium ⇒ **3-flavour regime**

M_1

UNFLAVOURED $\qquad N_{B-L}^{final} = \varepsilon_1 \kappa_1^{fin}$

~ 10^{12} GeV — TRANSITION REGIME: DENSITY MATRIX APPROACH NEEDED

2 Flavour regime (τ, e+μ) $\qquad \varepsilon_{1\tau}\kappa_1^{fin}(K_{1\tau}) + \varepsilon_{1e+\mu}\kappa_1^{fin}(K_{1e+\mu})$

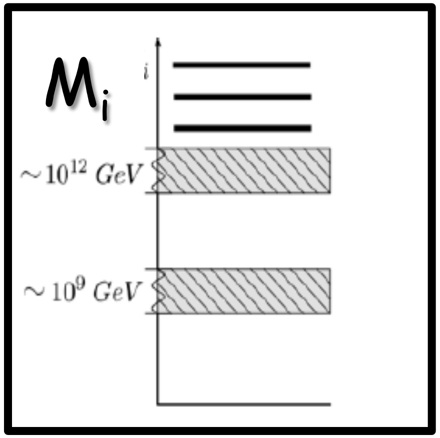
~ 10^9 GeV — TRANSITION REGIME: DENSITY MATRIX APPROACH NEEDED

3 Flavour regime (e, μ, τ) $\qquad \varepsilon_{1\tau}\kappa_1^{fin}(K_{1\tau}) + \varepsilon_{1\mu}\kappa_1^{fin}(K_{1\mu}) + \varepsilon_{1e}\kappa_1^{fin}(K_{1e})$

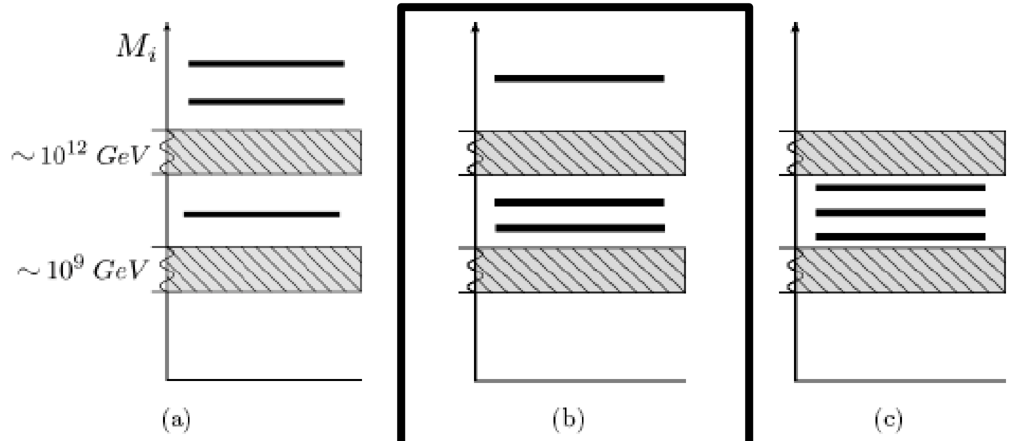
Heavy neutrino lepton flavour effects: 10 scenarios

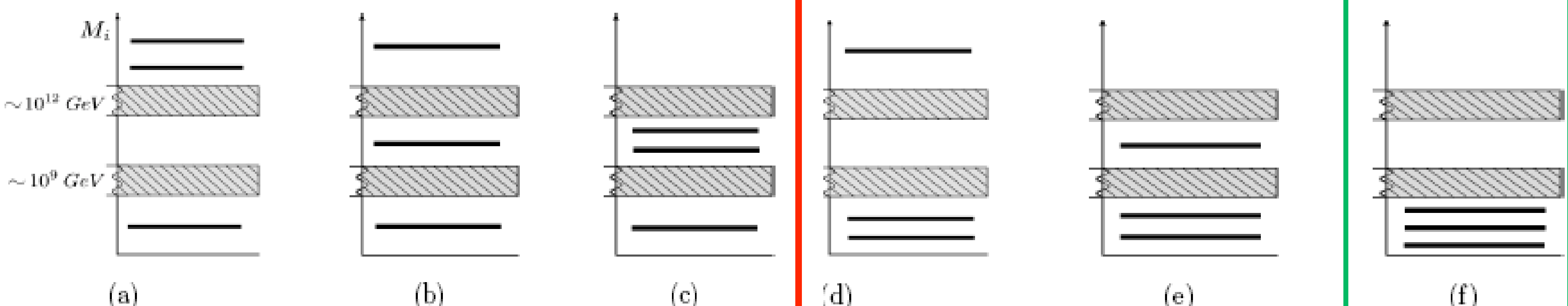
Typically rising in discrete flavour symmetry models

Heavy neutrino flavored scenario



2 RH neutrino scenario





N_2 -dominated scenario:

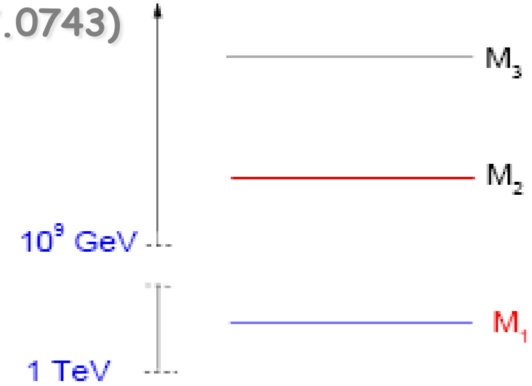
☛N_1 produces negligible asymmetry;

Low scale leptogenesis

Example: ARS leptog, (talk by Juraj Klaric)

N_2 leptogenesis

(PDB hep-ph/0502082, Vives hep-ph/0512160;Blanchet,PDB 0807.0743)



- **Unflavoured case:** asymmetry produced from N_2 - RH neutrinos is typically washed-out

$$\eta_{B0}^{lep(N_2)} \simeq 0.01 \cdot \varepsilon_2 \cdot \kappa^{fin}(K_2) \cdot e^{-\frac{3\pi}{8}K_1} << \eta_{B0}^{CMB}$$

- **Adding flavour effects:** lighest RH neutrino wash-out acts on individual flavour ⇒ much weaker

$$\boxed{N_{B-L}^{\rm f}(N_2) = P_{2e}^0\,\varepsilon_2\,\kappa(K_2)\,e^{-\frac{3\pi}{8}\,K_{1e}} + P_{2\mu}^0\,\varepsilon_2\,\kappa(K_2)\,e^{-\frac{3\pi}{8}\,K_{1\mu}} + P_{2\tau}^0\,\varepsilon_2\,\kappa(K_2)\,e^{-\frac{3\pi}{8}\,K_{1\tau}}}$$

- With flavor effects the domain of successful N_2 dominated leptogenesis greatly enlarges: the probability that $K_1 < 1$ is less than 0.1% but the probability that either K_{1e} or $K_{1\mu}$ or $K_{1\tau}$ is less than 1 is ~23%

  (PDB, Michele Re Fiorentin, Rome Samanta)

- Existence of the heaviest RH neutrino N_3 is necessary for the $\varepsilon_{2\alpha}$'s not to be negligible

- It is the only hierarchical scenario that can realise strong thermal leptogenesis (independence of the initial conditions) if the asymmetry is tauon-dominated and if $m_1 \gtrsim 10$ meV (corresponding to $\Sigma_i m_i \gtrsim 80$meV)

  (PDB, Michele Re Fiorentin, Sophie King arXiv 1401.6185)

- N_2-leptogenesis rescues SO(10)-inspired models!

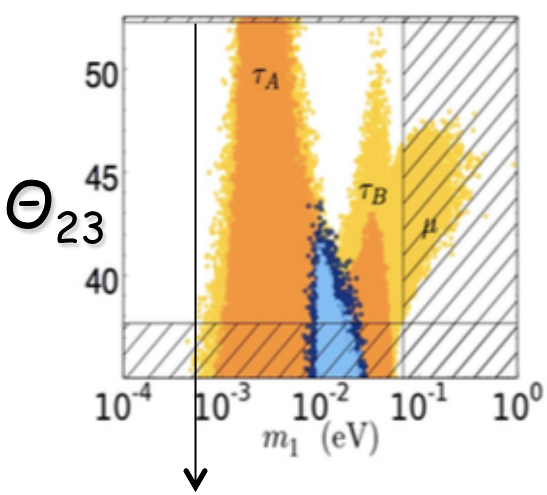
  $V_L \sim V_{CKM}$; $m_{D1}=\alpha_1\, m_{up}$; $m_{D2}=\alpha_2\, m_{charm}$; $m_{D3}=\alpha_3\, m_{top}$

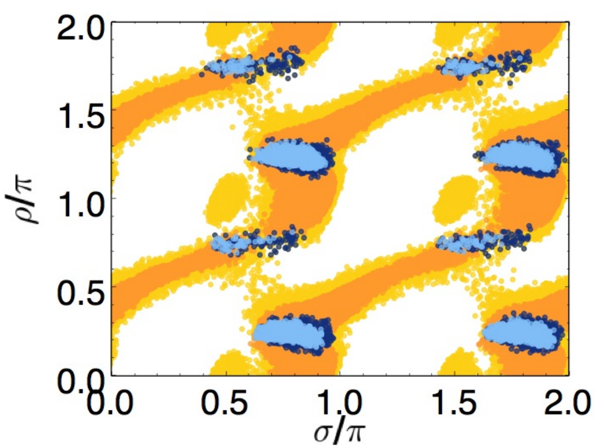
SO(10)-inspired leptogenesis is predictive

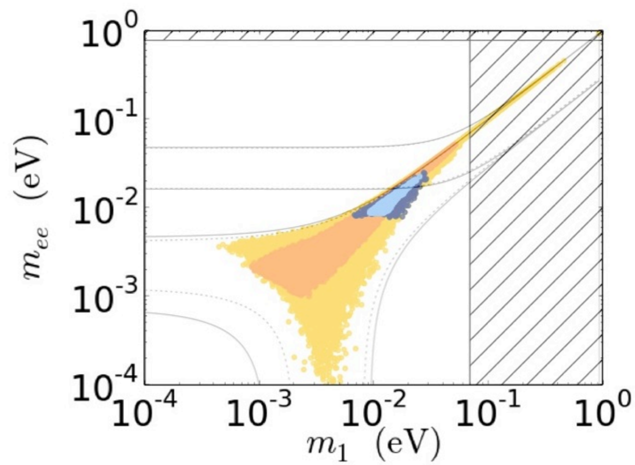
(PDB, Riotto 0809.2285;1012.2343;He,Lew,Volkas 0810.1104)

- dependence on α_1 and α_3 cancels out $\Rightarrow$ the asymmetry depends only on $\alpha_2 \equiv m_{D2}/m_{charm}$: $\eta_B \propto \alpha_2^2$

$\alpha_2=5$ NORMAL ORDERING $I \leq V_L \leq V_{CKM}$ $V_L = I$



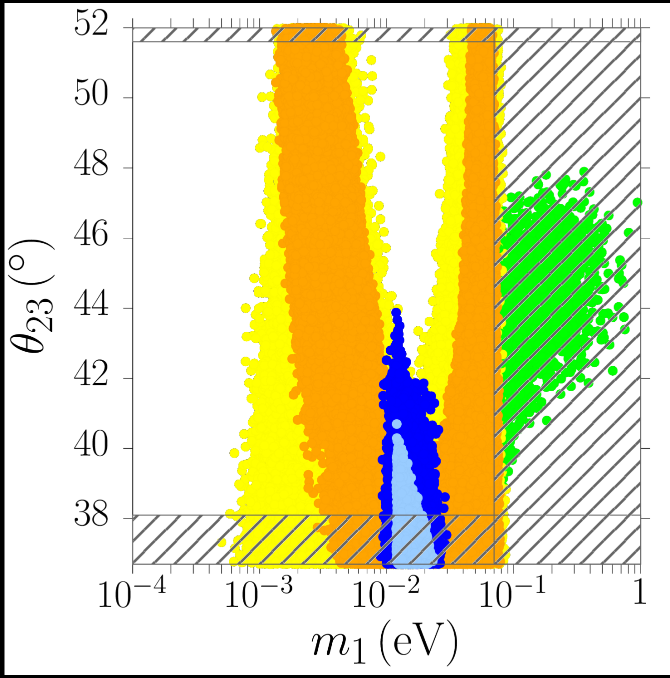


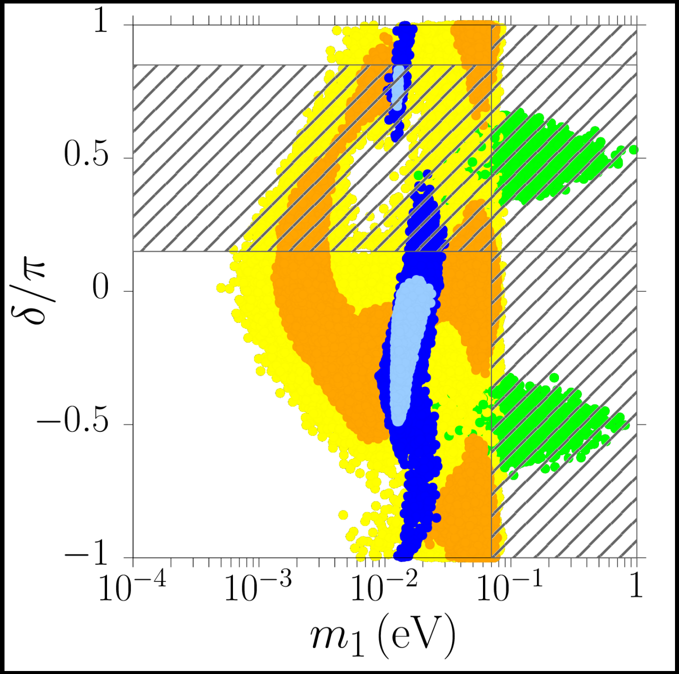


- Lower bound $m_1 \gtrsim 10^{-3}$ eV
- Θ_{23} upper bound
- Majorana phases constrained about specific regions
- Effective $0\nu\beta\beta$ mass can still vanish but bulk of points above meV

- INVERTED ORDERING IS EXCLUDED
- What are the blue regions?

SO(10)-inspired leptogenesis confronting long baseline and absolute neutrino mass experiments





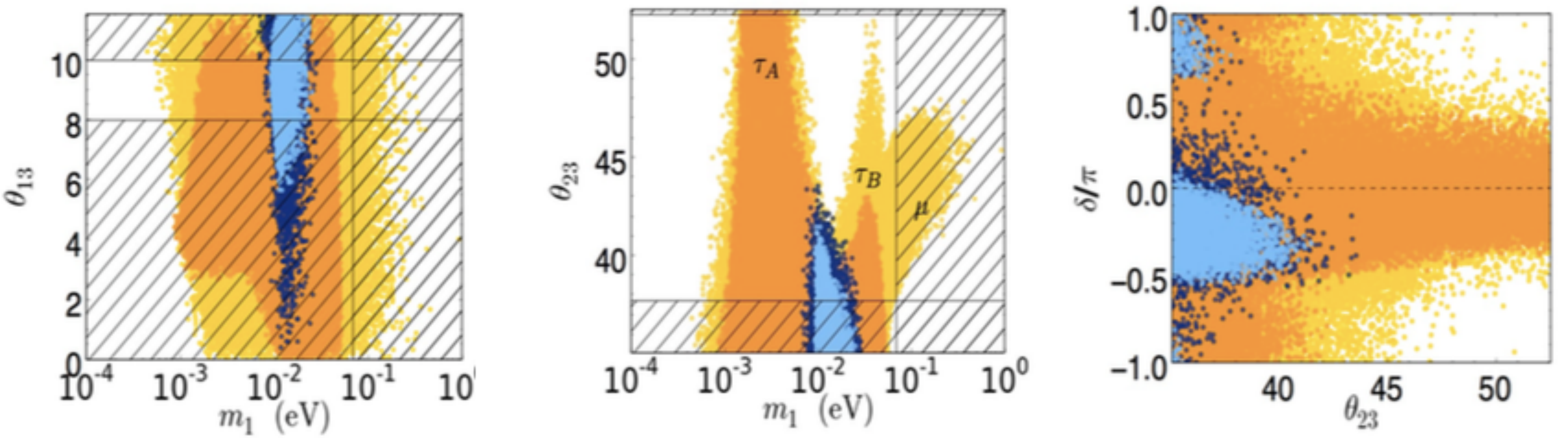
If the current tendency of data to favour second octant for θ_{23} is confirmed, then SO(10)-inspired leptogenesis predicts a deviation from the hierarchical limit that can be tested by absolute neutrino mass scale experiments (PDB, Samanta in preparation)

Strong thermal SO(10)-inspired (STSO10) solution

(PDB,Marzola 09/2011,DESY workshop;1308.1107;PDB,Re Fiorentin,Marzola 1411.5478)

- Strong thermal leptonesis condition can be satisfied for a subset of the solutions only for NORMAL ORDERING

$\alpha_2=5$ ❑ blue regions: $N_{B-L}^{pre-ex}=10^{-3}$ ($I\leq V_L \leq V_{CKM}$; $V_L=I$)



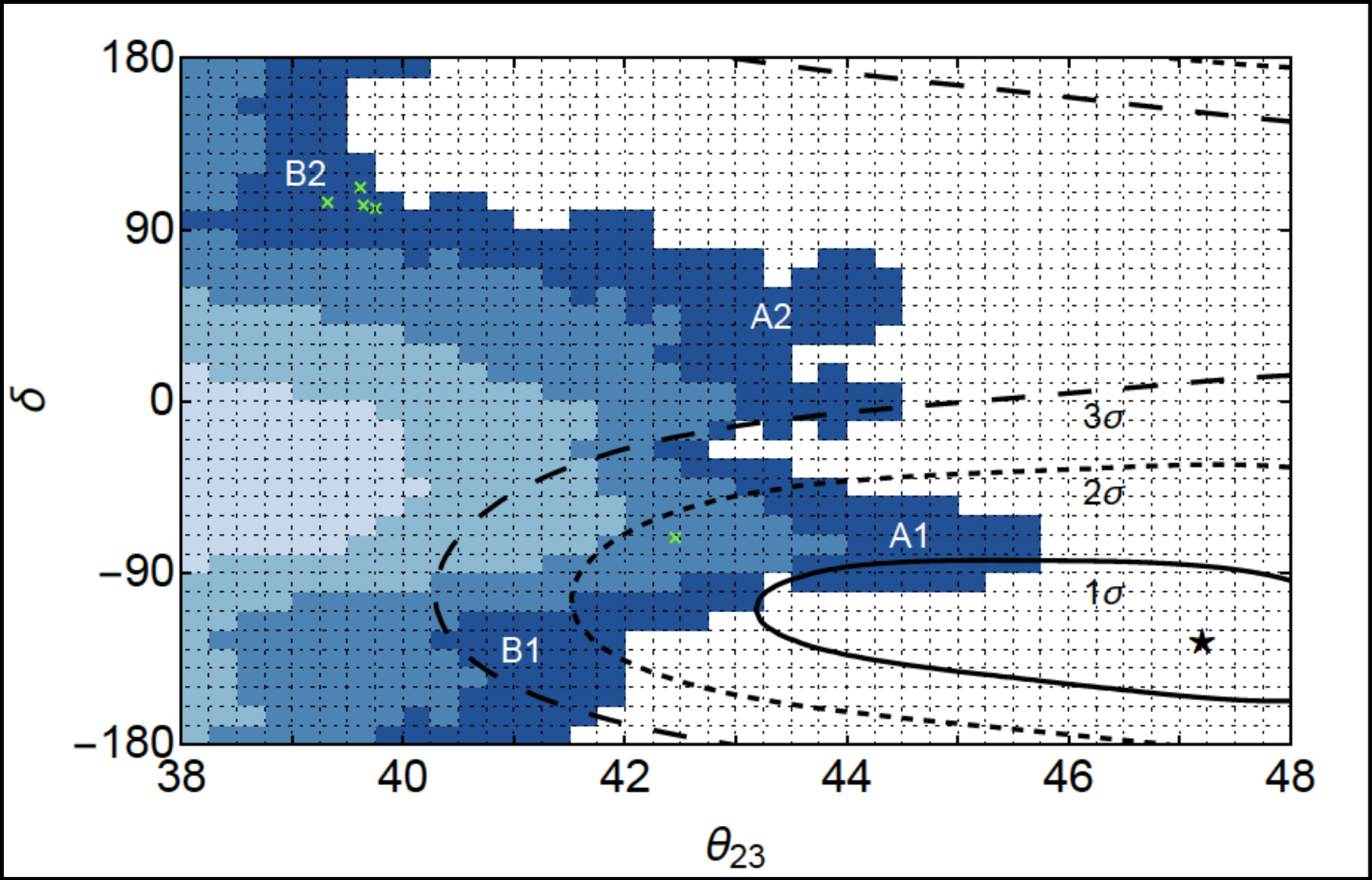
- Absolute neutrino mass scale: $8 \lesssim m_1/\text{meV} \lesssim 30 \Leftrightarrow 70 \lesssim \sum_i m_i/\text{meV} \lesssim 120$
- Non-vanishing Θ_{13};
- Θ_{23} strictly in the first octant;

Strong SO(10)-inspired leptogenesis confronting long baseline experiments

(PDB, Marco Chianese 1802.07690)

Pre-existing initial asymmetry: $N_{B-L}^{p,i} = 10^{-3}$

$$\alpha_2 = m_{D2} / m_{charm} = 5$$

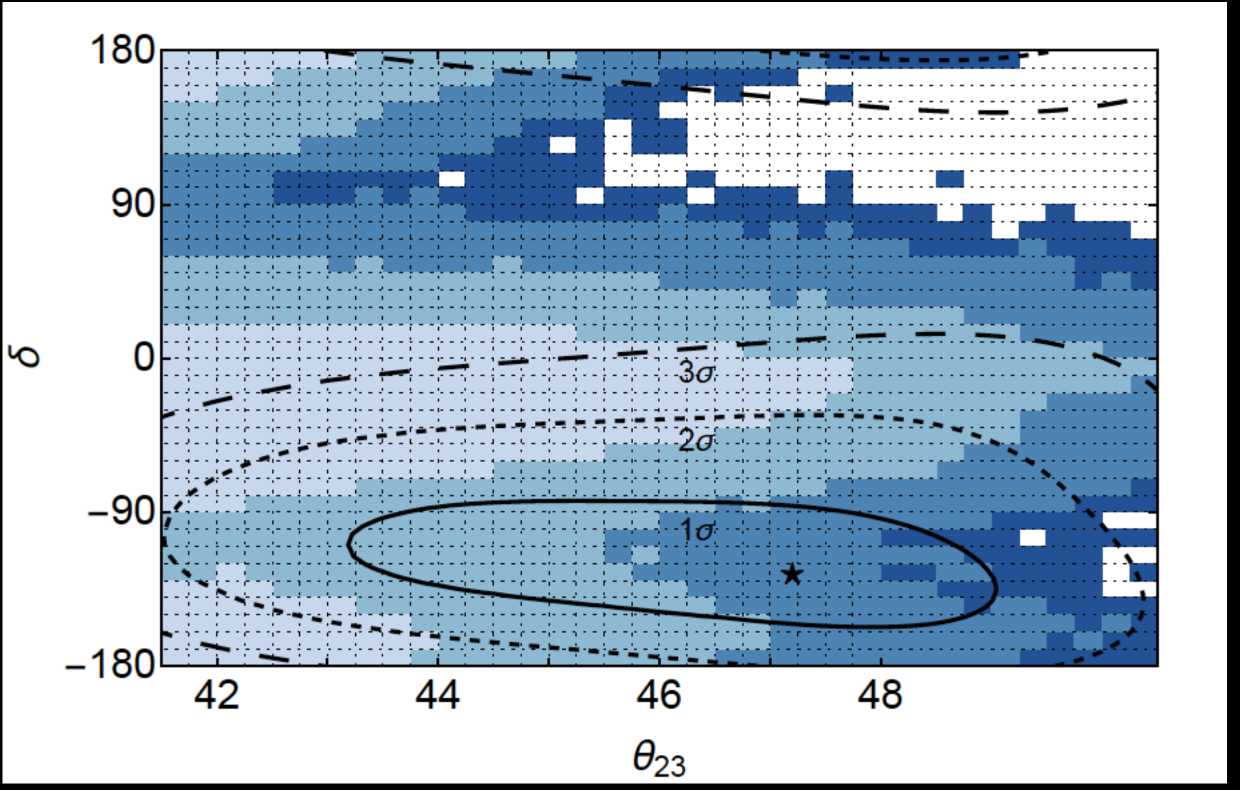


Strong SO(10)-inspired leptogenesis confronting long baseline experiments

(PDB, Marco Chianese 1802.07690)

Pre-existing initial asymmetry: $N^{p,i}_{B-L} = 10^{-3}$

$$\alpha_2 = m_{D2} / m_{charm} = 6$$



Second octant is compatible with strong thermal condition only if $\alpha_2 \gtrsim 6$: are there realistic models?

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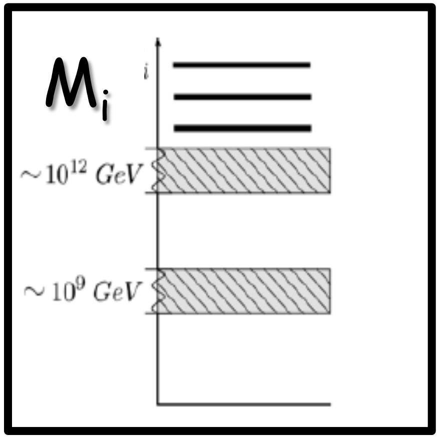
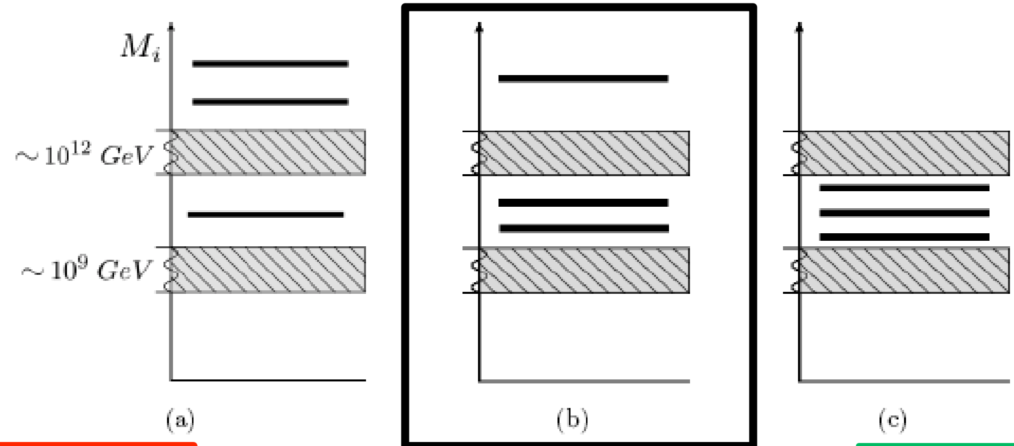
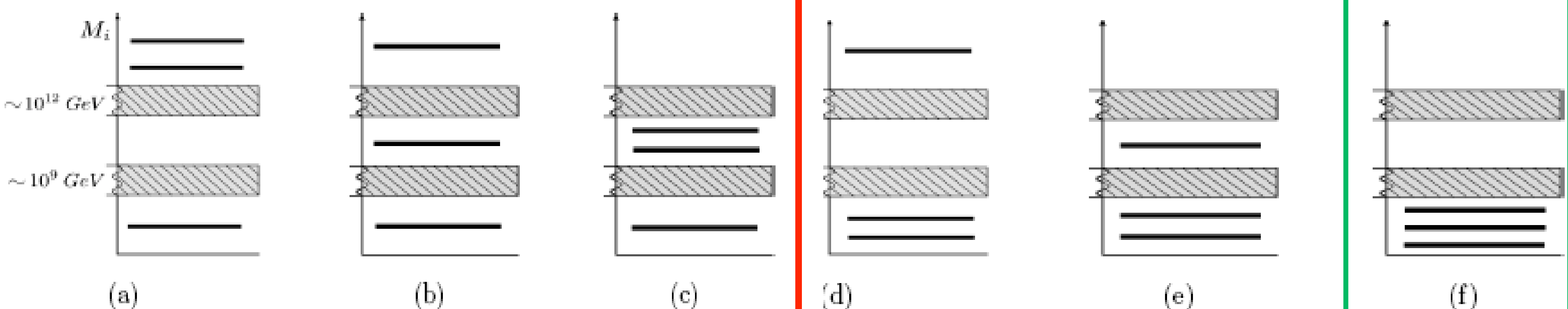


2 RH neutrino scenario





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2 RH neutrino models

(King hep-ph/9912492;Frampton,Glashow,Yanagida hep-ph/0208157;Ibarra,Ross2003; Antusch,King,Riotto'08; Antusch, PDB,Jones,King '11; King 1512.07531)

- They can be obtained from 3 RH neutrino models in the limit $M_3 \rightarrow \infty$;
- Number of parameters gets reduced to 11;
- Still further conditions needed to get predictions!
- Contribution to asymmetry from both 2 RH neutrinos:

the contribution from the lightest (N_1) typically dominates but the contribution from next-to-lightest (N_2) opens new regions that correspons to light sequential dominated neutrino mass models realised in some GUT models. In any case there is still a lower bound

$$M_1 \gtrsim 2\text{x}\ 10^{10}\ \text{GeV} \Rightarrow T_{RH} \gtrsim 6 \times 10^9\ \text{GeV}$$

- 2 RH neutrino model realised for example in A4 x SU(5) SUSY GUT model with interesting link between "leptogenesis phase" and Dirac phase

(F, Bjorkeroth, S.F. King 1505.05504)

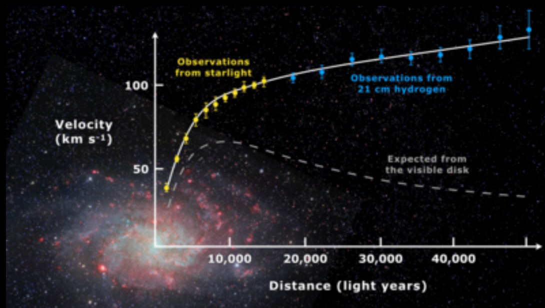
- 2 RH neutrino model can be also obtained from 3 RH neutrino models with 1 vanishing Yukawa eigenvalue ⇒ potential DM candidate

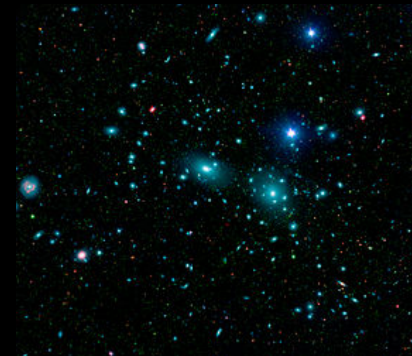
(A.Anisimov, PDB hep-ph/0812.5085)

Dark Matter

At the present time DM acts as a cosmic glue keeping together

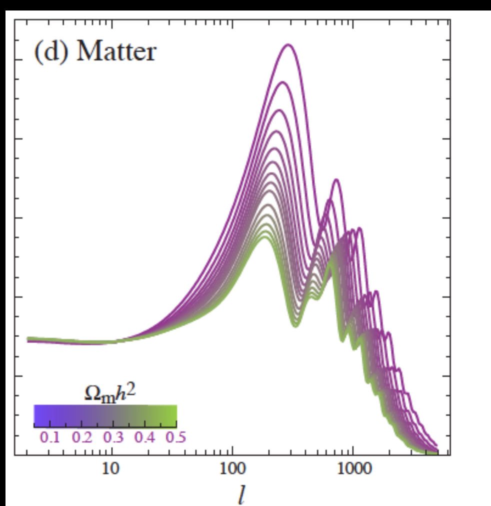
Stars in galaxies.... … and galaxies in clusters of galaxies (such as in Coma cluster)

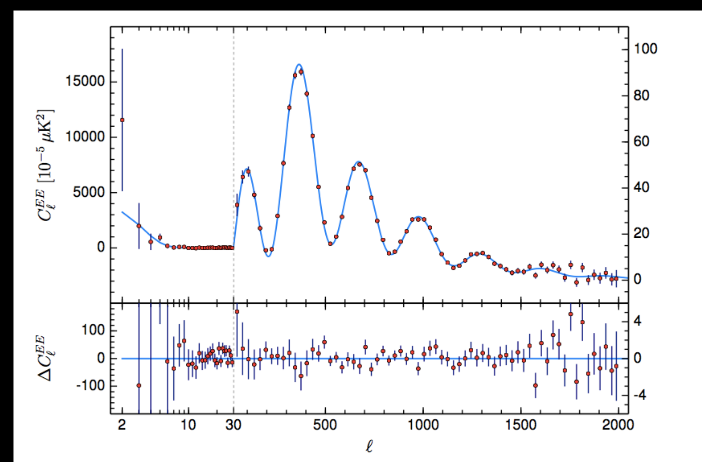




But it has to be primordial to understand structure formation and CMB anisotropies

(Hu, Dodelson, astro-ph/0110414) (Planck 2018, 1807.06209)





CMB +"ext"

$$\boxed{\Omega_{CDM,0}h^2 = 0.11933 \pm 0.0009 \sim 5\Omega_{B,0}h^2}$$

A first solution : lowering the scale of the 3 RH neutrinos masses (νMSM)

(Asaka, Blanchet, Shaposhnikov '05)

For $M_1 \ll m_e \Rightarrow$ $\tau_{N_1} = 5 \times 10^{26}\,\mathrm{sec}\left(\frac{M_1}{1\ \mathrm{keV}}\right)^{-5}\left(\frac{\overline{\Theta}^2}{10^{-8}}\right)^{-1}$ $\gg t_0$ $\left(|\overline{\theta}|^2 \equiv \sum_\alpha |m_{D\alpha 1}/M_1|^2\right)$

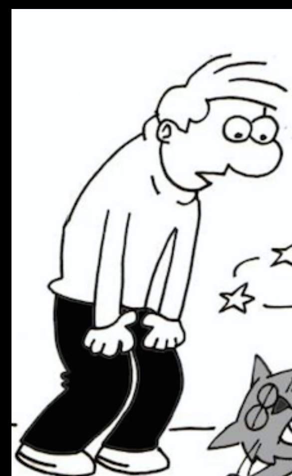
The production is induced by (non-resonant) RH-LH mixing at T~100 MeV (Dodelson-Widrow mechanism hep-ph/9303287):

$$\Omega_{N_1} h^2 \sim 0.1 \left(\frac{\overline{\theta}}{10^{-4}}\right)^2 \left(\frac{M_1}{keV}\right)^2 \sim \Omega_{DM,0} h^2$$

- The N_1's decay also radiatively and this produces constraints from X-rays (or opportunities to observe it).
- Considering also structure formation constraints, one is forced to consider a resonant production induced by a large lepton asymmetry L ~10^{-4} (Shi and Fuller astro-ph/9810076)
- 3.5 keV line? (Horiuchi et al. '14; Bulbul at al. '14; Abazajian '14)
- Not clear whether such a large lepton asymmetry can be produced by the same (heavier) RH neutrino decays (next talk!!!)

WARM

WIMP



WIMPZILLA

keV=10^{-6}GeV

10GeV

10^{6}GeV

10^{13}GeV

M_{DM}

WARM

WIMP

RHINO

WIMPZILLA

keV=10^{-6}GeV

10GeV

10^{6}GeV

10^{13}GeV

M_{DM}

An alternative solution: decoupling 1 RH neutrino ⇒ 2 RH neutrino seesaw

(Babu, Eichler, Mohapatra '89; Anisimov, PDB '08)

1 RH neutrino has vanishing Yukawa couplings (enforced by some symmetry such as Z_2):

$$m_D \simeq \begin{pmatrix} 0 & m_{De2} & m_{De3} \\ 0 & m_{D\mu 2} & m_{D\mu 3} \\ 0 & m_{D\tau 2} & m_{D\tau 3} \end{pmatrix}, \text{ or } \begin{pmatrix} m_{De1} & 0 & m_{De3} \\ m_{D\mu 1} & 0 & m_{D\mu 3} \\ m_{D\tau 1} & 0 & m_{D\tau 3} \end{pmatrix}, \text{ or } \begin{pmatrix} m_{De1} & m_{De2} & 0 \\ m_{D\mu 1} & m_{D\mu 2} & 0 \\ m_{D\tau 1} & m_{D\tau 2} & 0 \end{pmatrix},$$

What production mechanism? Turning on tiny Yukawa couplings?

Yukawa basis: $m_D = V_L^\dagger \, D_{m_D} \, U_R \, .$ $\quad D_{m_D} \equiv v \, \mathrm{diag}(h_A, h_B, h_C)$, with $h_A \leq h_B \leq h_C$.

$$\tau_{\rm DM} = \frac{4\pi}{h_A^2 \, M_{\rm DM}} \simeq 0.87 \, h_A^{-2} \, 10^{-23} \left(\frac{\rm GeV}{M_{\rm DM}}\right) \, {\rm s} \quad \Rightarrow \quad \tau_{DM} > \tau_{DM}^{\min} \simeq 10^{28} s \Rightarrow h_A < 3\times 10^{-26} \sqrt{\frac{GeV}{M_{DM}} \times \frac{10^{28} s}{\tau_{DM}^{\min}}}$$

One could think of an abundance induced by RH neutrino mixing, considering that:

$$\left(\frac{N_{DM}}{N_\gamma}\right)_{prod} \simeq 10^{-6} (\Omega_{DM,0} h^2) \frac{GeV}{M_{DM}} \sim 10^{-7} \frac{GeV}{M_{DM}} \Rightarrow n_{DM,0} \sim 1\, m^{-3} \frac{GeV}{M_{DM}}$$

It would be enough to convert just a tiny fraction of ("source") thermalised RH neutrinos but it does not work with standard Yukawa couplings

Proposed production mechanisms

Starting from a 2 RH neutrino seesaw model

$$m_D \simeq \begin{pmatrix} 0 & m_{De2} & m_{De3} \\ 0 & m_{D\mu 2} & m_{D\mu 3} \\ 0 & m_{D\tau 2} & m_{D\tau 3} \end{pmatrix}, \text{ or } \begin{pmatrix} m_{De1} & 0 & m_{De3} \\ m_{D\mu 1} & 0 & m_{D\mu 3} \\ m_{D\tau 1} & 0 & m_{D\tau 3} \end{pmatrix}, \text{ or } \begin{pmatrix} m_{De1} & m_{De2} & 0 \\ m_{D\mu 1} & m_{D\mu 2} & 0 \\ m_{D\tau 1} & m_{D\tau 2} & 0 \end{pmatrix},$$

many production mechanisms have been proposed:

- from $SU(2)_R$ extra-gauge interactions (LRSM) ;
- from inflaton decays (Anisimov,PDB'08; Higaki, Kitano, Sato '14);
- from resonant annihilations through SU(2)' extra-gauge interactions (Dev, Kazanas,Mohapatra,Teplitz, Zhang '16);
- From new $U(1)_Y$ interactions connecting DM to SM (Dev, Mohapatra,Zhang '16);
- From $U(1)_{B-L}$ interactions (Okada, Orikasa '12);
- …………………

In all these models IceCube data are fitted through fine tuning of parameters responsible for decays (they are post-dictive)

Higgs induced RH neutrino mixing DM (RHiNo DM)

(Anisimov,PDB '08; PDB,Ludl,Palomarez-Ruiz 2016; PDB,Farrag,Samanta,Zhou 2019)

Assume new interactions with the standard Higgs:

Anisimov operator
(hep-ph 0612024)

$$\mathcal{L} = \frac{\lambda_{IJ}}{\Lambda}\,\phi^\dagger\,\phi\,\overline{N_I^c}\,N_J$$

(I,J=A,B,C)

In general they are non-diagonal in the Yukawa basis: this generates a RH neutrino mixing.
Consider a 2 RH neutrino mixing for simplicity (I,J=DM,S) and consider medium effects:

From the Yukawa interactions:

$$V_S^Y \equiv \frac{T^2}{8E_S} h_S^2$$

From the new interactions:

$$V_{IJ}^\Lambda \equiv \frac{T^2}{12\,\Lambda}\lambda_{IJ}$$

(I,J=DM,S)

define:

$$\Delta M^2 \equiv M_{\rm S}^2 - M_{\rm DM}^2.$$

$$\tilde{\Lambda} \equiv \frac{\Lambda}{\lambda_{DM-S}}$$

$$\sin 2\theta_\Lambda \equiv \frac{T^3}{\tilde{\Lambda}\,\Delta M^2}$$

Mixing angle

effective mixing Hamiltonian (in monocromatic approximation)

$$\Delta H \simeq \begin{pmatrix} -\frac{\Delta M^2}{4p} - \frac{T^2}{16p} h_{\rm S}^2 & \frac{T^2}{12\tilde{\Lambda}} \\ \frac{T^2}{12\tilde{\Lambda}} & \frac{\Delta M^2}{4p} + \frac{T^2}{16p} h_{\rm S}^2 \end{pmatrix} \Rightarrow$$

$$\sin 2\theta_\Lambda^{\rm m} = \frac{\sin 2\theta_\Lambda}{\sqrt{(1+v_{\rm S}^Y)^2 + \sin^2 2\theta_\Lambda}}$$

$$v_{\rm S}^Y \equiv T^2\,h_{\rm S}^2/(4\,\Delta M^2)$$

If $\Delta m^2 < 0$ ($M_{DM} > M_S$) there is a resonance for $v_S^Y = -1$ at:

$$z_{\rm res} \equiv \frac{M_{\rm DM}}{T_{\rm res}} = \frac{h_{\rm S}\,M_{\rm DM}}{2\sqrt{M_{\rm DM}^2 - M_{\rm S}^2}}$$

Non-adiabatic conversion

(Anisimov,PDB '08; P.Ludl.PDB,S.Palomarez-Ruiz '16)

Adiabaticity parameter at the resonance

$$\gamma_{\rm res} \equiv \left.\frac{|E^{\rm m}_{\rm DM} - E^{\rm m}_{\rm S}|}{2\,|\dot{\theta}_m|}\right|_{\rm res} = \sin^2 2\theta_\Lambda(T_{\rm res})\,\frac{|\Delta M^2|}{12\,T_{\rm res}\,H_{\rm res}}\,,$$

Landau-Zener formula

$$\left.\frac{N_{N_{\rm DM}}}{N_{N_{\rm S}}}\right|_{\rm res} \simeq \frac{\pi}{2}\,\gamma_{\rm res}$$

(remember that we need only a small fraction to be converted so necessarily γ_{res}<<<1)

$$\Rightarrow \quad \Omega_{\rm DM}\,h^2 \simeq \frac{0.15}{\alpha_{\rm S}\,z_{\rm res}}\left(\frac{M_{\rm DM}}{M_{\rm S}}\right)\left(\frac{10^{20}\,{\rm GeV}}{\widetilde{\Lambda}}\right)^2\left(\frac{M_{\rm DM}}{\rm GeV}\right)$$

For successful dark-matter genesis

$$\Rightarrow \quad \widetilde{\Lambda}_{\rm DM} \simeq 10^{20}\sqrt{\frac{1.5}{\alpha_{\rm S}\,z_{\rm res}}\,\frac{M_{\rm DM}}{M_{\rm S}}\,\frac{M_{\rm DM}}{\rm GeV}}\,{\rm GeV}$$

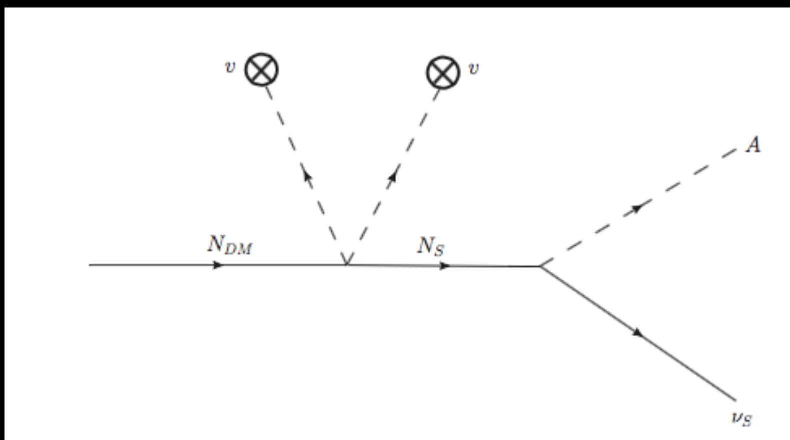
2 options: either Λ<M_{Pl} and λ_{AS}<<< 1 or λ_{AS}~ 1 and Λ>>>M_{Pl} :

it is possible to think of models in both cases.

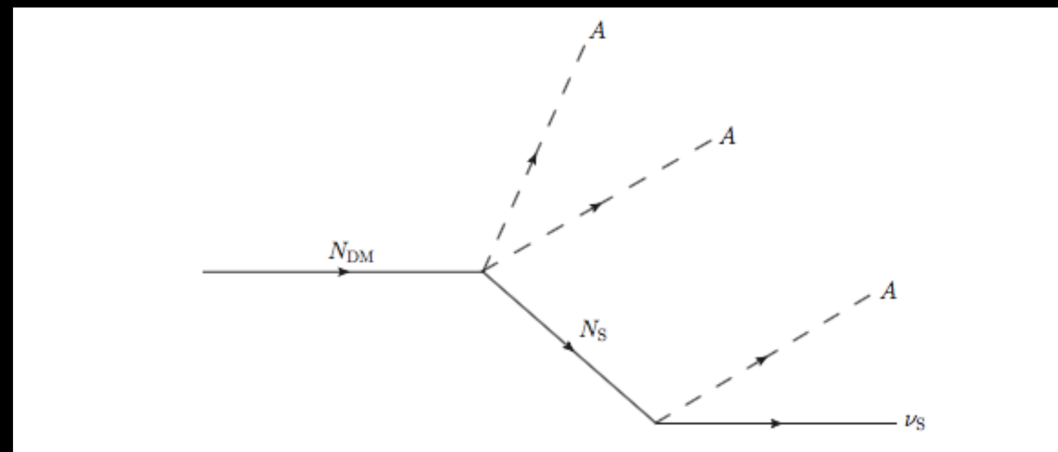
Decays: a natural allowed window on M_{DM}

The same Higgs induced interaction are also responsible for decays!

2 body decays



4body decays



$$\Gamma^{-1}_{\mathrm{DM}\to A+\ell_{\mathrm{S}}} = \frac{\pi}{h_{\mathrm{S}}^2}\left(\frac{\widetilde{\Lambda}}{v^2}\right)^2 M_{\mathrm{DM}}$$

$$\Gamma^{-1}_{DM\to 3A+\nu} \propto M^{-3}_{DM}$$

2 body decays lead to a lower bound on M_{DM}

4 body decays lead to an upper bound on M_{DM}

IceCube data require

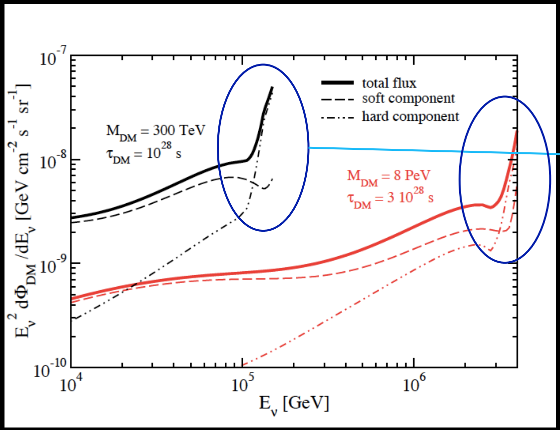
$$\tau \simeq \left(\Gamma_{\mathrm{DM}\to A+\ell_{\mathrm{S}}} + \Gamma_{\mathrm{DM}\to 3A+\ell_{\mathrm{S}}}\right)^{-1} > \tau^{\mathrm{min}}_{\mathrm{DM}} \simeq 10^{28}\,\mathrm{s}\,,$$

DM decays might help fitting IceCube data

(Anisimov,PDB,0812.5085;PDB, P.Ludl,S. Palomarez-Ruiz 1606.06238)

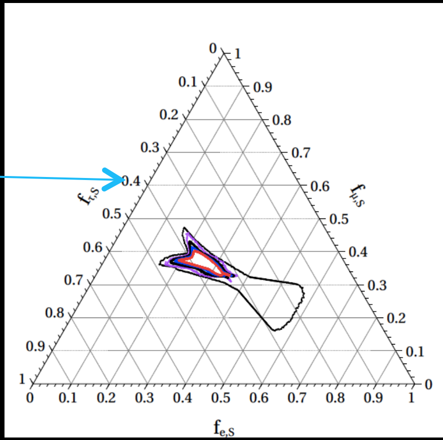
- DM neutrinos unavoidably decay today into A+leptons (A=H,Z,W) through the same mixing that produced them in the very early Universe
- Potentially testable high energy neutrino contribution

Energy neutrino flux



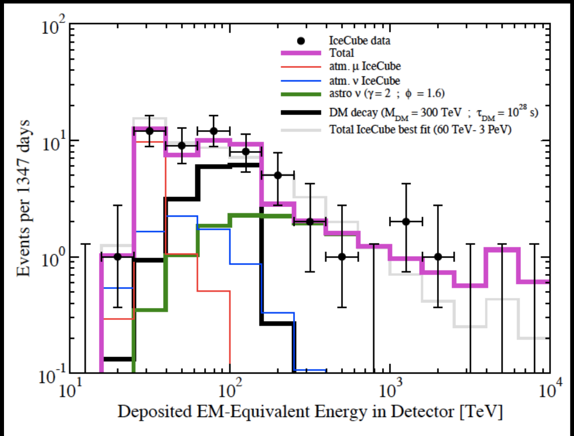
Hard component

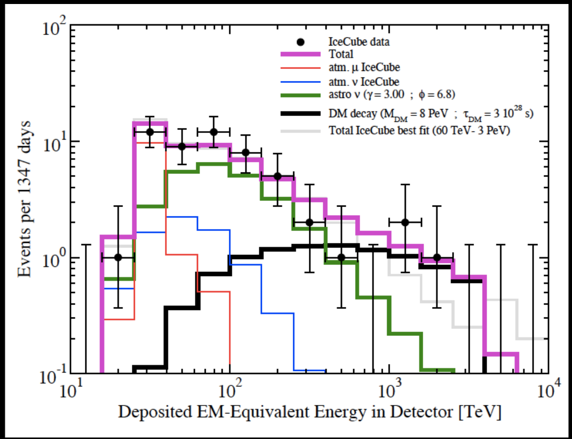
Flavour composition at the detector



Neutrino events at IceCube: 2 examples

M_{DM}=300TeV





M_{DM}=8 PeV

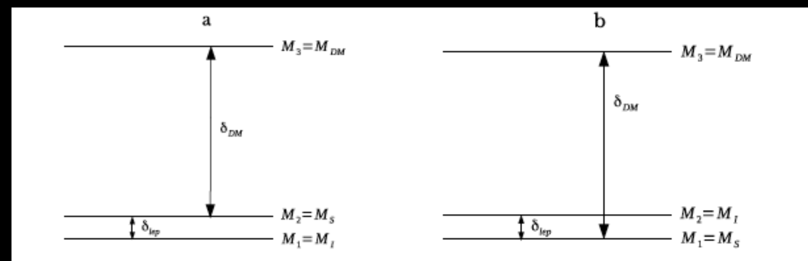
Unifying Leptogenesis and Dark Matter

(PDB, NOW 2006;Anisimov,PDB,0812.5085;PDB, P.Ludl,S. Palomarez-Ruiz 1606.06238+see recent v3)

- Interference between N_A and N_B can give sizeable CP decaying asymmetries able to produce a matter-antimatter asymmetry but since $M_{DM}>M_S$ necessarily $N_{DM}=N_3$ and $M_1 \simeq M_2$ ⇒ leptogenesis with quasi-degenerate neutrino masses

$\delta_{DM} \equiv (M_3 - M_S)/M_S$

$\delta_{lep} \equiv (M_2 - M_1)/M_1$



$$\varepsilon_{i\alpha} \simeq \frac{\overline{\varepsilon}(M_i)}{K_i} \left\{ \mathcal{I}_{ij}^{\alpha}\, \xi(M_j^2/M_i^2) + \mathcal{J}_{ij}^{\alpha}\, \frac{2}{3(1 - M_i^2/M_j^2)} \right\}$$

(Covi,Roulet,Visssani '96)

$$\overline{\varepsilon}(M_i) \equiv \frac{3}{16\,\pi} \left(\frac{M_i\, m_{\rm atm}}{v^2} \right) \simeq 1.0 \times 10^{-6} \left(\frac{M_i}{10^{10}\,{\rm GeV}} \right),$$

$$\xi(x) = \frac{2}{3} x \left[(1+x) \ln\left(\frac{1+x}{x} \right) - \frac{2-x}{1-x} \right],$$

Analytical expression for the asymmetry:

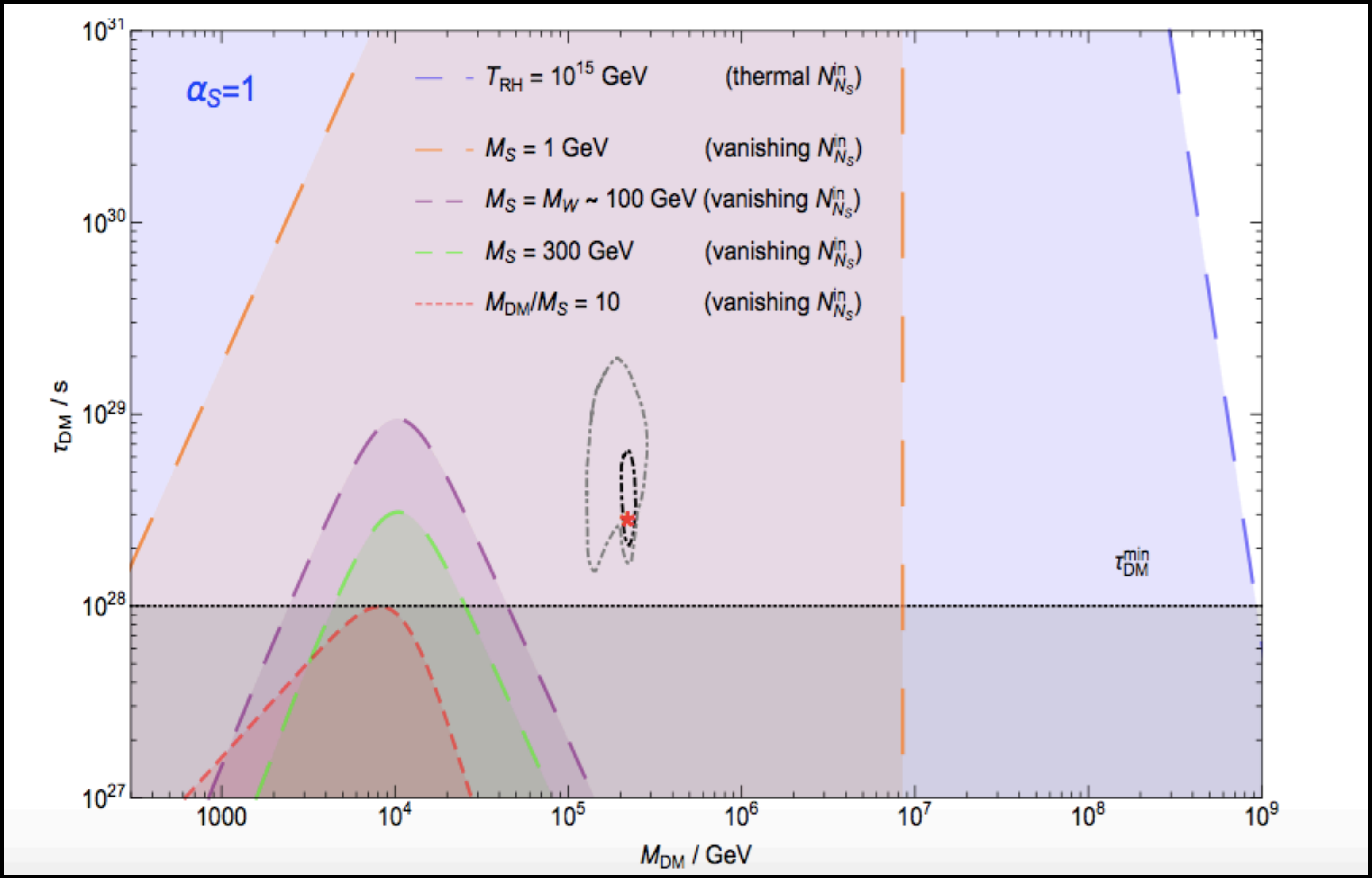
$$\eta_B \simeq 0.01\, \frac{\overline{\varepsilon}(M_1)}{\delta_{\rm lep}}\, f(m_\nu, \Omega),$$

Efficiency factor

$$f(m_\nu, \Omega) \equiv \frac{1}{3} \left(\frac{1}{K_1} + \frac{1}{K_2} \right) \sum_\alpha \underbrace{\kappa(K_{1\alpha} + K_{2\alpha})}_{\text{Efficiency factor}} \left[\mathcal{I}_{12}^{\alpha} + \mathcal{J}_{12}^{\alpha} \right],$$

- $M_S \gtrsim 2\, T_{sph} \simeq 300$ GeV ⇒ $10\ \text{TeV} \lesssim M_{DM} \lesssim 1\ \text{PeV}$
- $M_S \lesssim 10$ TeV
- $\delta_{lep} \sim 10^{-5}$ ⇒ leptogenesis is not fully resonant

Allowed regions (from Landau-Zener)

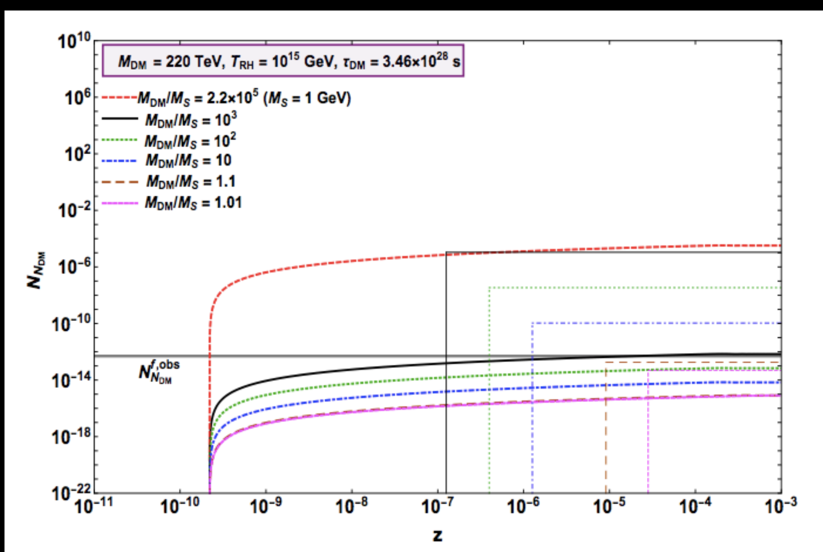


Necessity of solving density matrix equation

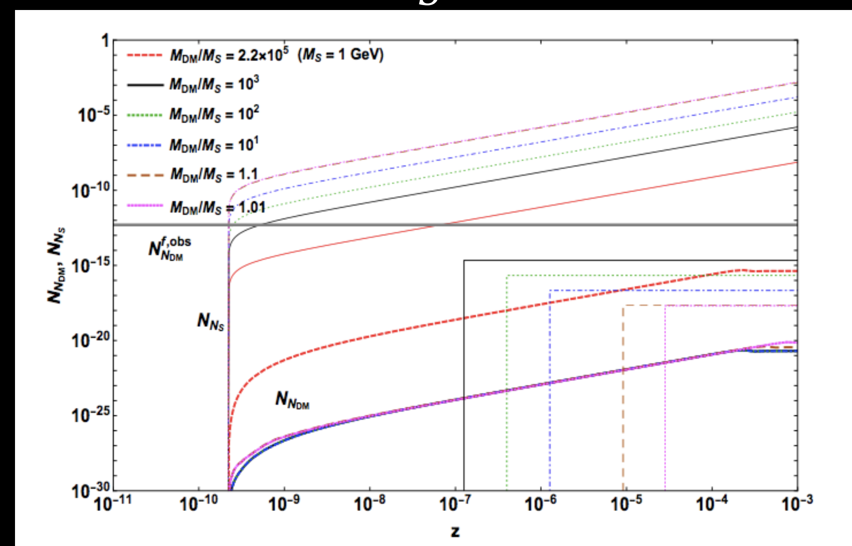
(PDB, Farraf, Samanta, Zhou 1908.00521)

$$\frac{dN_{IJ}}{dt} = -i\,[\mathcal{H}, N]_{IJ} - \begin{pmatrix} 0 & \frac{1}{2}(\Gamma_D + \Gamma_S)\, N_{\mathrm{DM-S}} \\ \frac{1}{2}(\Gamma_D + \Gamma_S)\, N_{\mathrm{S-DM}} & (\Gamma_D + \Gamma_S)\,(N_{N_{\mathrm{S}}} - N_{N_{\mathrm{S}}}^{\mathrm{eq}}) \end{pmatrix}$$

$N_{N_S}^{in} = 1$

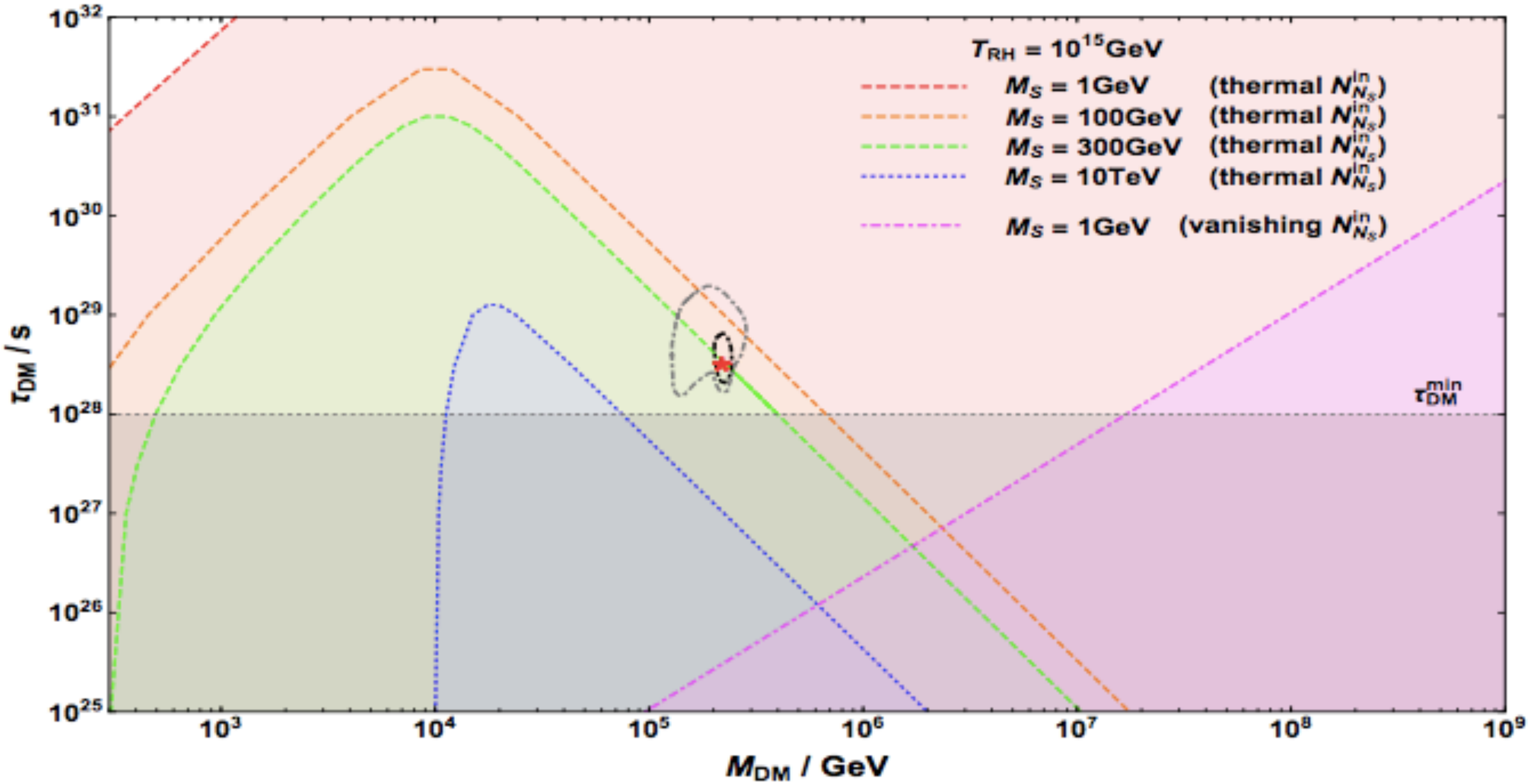


$N_{N_S}^{in} = 0$



Density matrix solutions show that LZ approximation does not work: the Production is not resonant and much less efficient at least in the hiierarchical case However, production occurs at lower temperattures and this opens a new solution

Allowed regions (density matrix equation)



If one wants to combine DM with leptogenesis from deycas then a thermalisation of the source rH neutrinos has to be assumed…..otheriwse one might think of combining DM production with ARS leptogenesis (talk by Juric)

SUMMARY

- Seesaw neutrino mass models are an attractive explanation of neutrino masses and mixing easily embaddable in realistic grandunified models (with or without flavour symmetries)
- However they contain great number of parameters and typically high scale….cosmology helps in this respect: reproducing BAO with leptogenesis imposes important constraints and within specific classes of models can lead to predictions on low energy neutrino parameters (alternatively one can go to low scale leptogenesis, next talk)
- Absolute neutrino mass scale experiments combined with neutrino mixing will in the next year test SO(10)-inspired leptogenesis predicting some deviation from the hierarchical limit
- If no deviation from the hierarchical limit is observed then two RH neutrino models will be favoured, in this case an intriguing unified picture of neutrino masses+ leptogenesis + dark matter is possible with the help of Higgs induced RH neutrino mixing (Anisimov operator)
- Density matrix calculations are crucial and seem to suggest new possibilities that are currently explored….soon new results!