Dark Universe Workshop: Early Universe Cosmology, Baryogenesis, and Dark Matter

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A unified model of

neutrino masses

dark matter

leptogenesis

(testable at neutrino telescopes)

Pasquale Di Bari

(University of Southampton)

Why going beyond the SM?

Even ignoring:

- (more or less) compelling theoretical motivations (quantum gravity theory, flavour problem, hierarchy and naturalness problems,…) 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***

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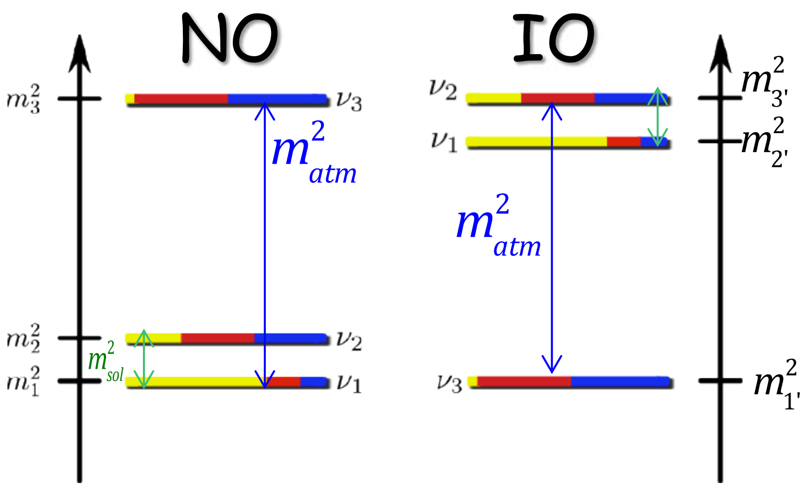
- *Neutrino masses and mixing*

⟹ It is reasonable to look for extensions of the SM providing a unified picture of neutrino masses and mixing and cosmological puzzles

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



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

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

$m_{sol} = (8.6 \pm 0.1)\ meV$

$m_{atm} = (50.3 \pm 0.3)\ meV$

(νfit 2019)

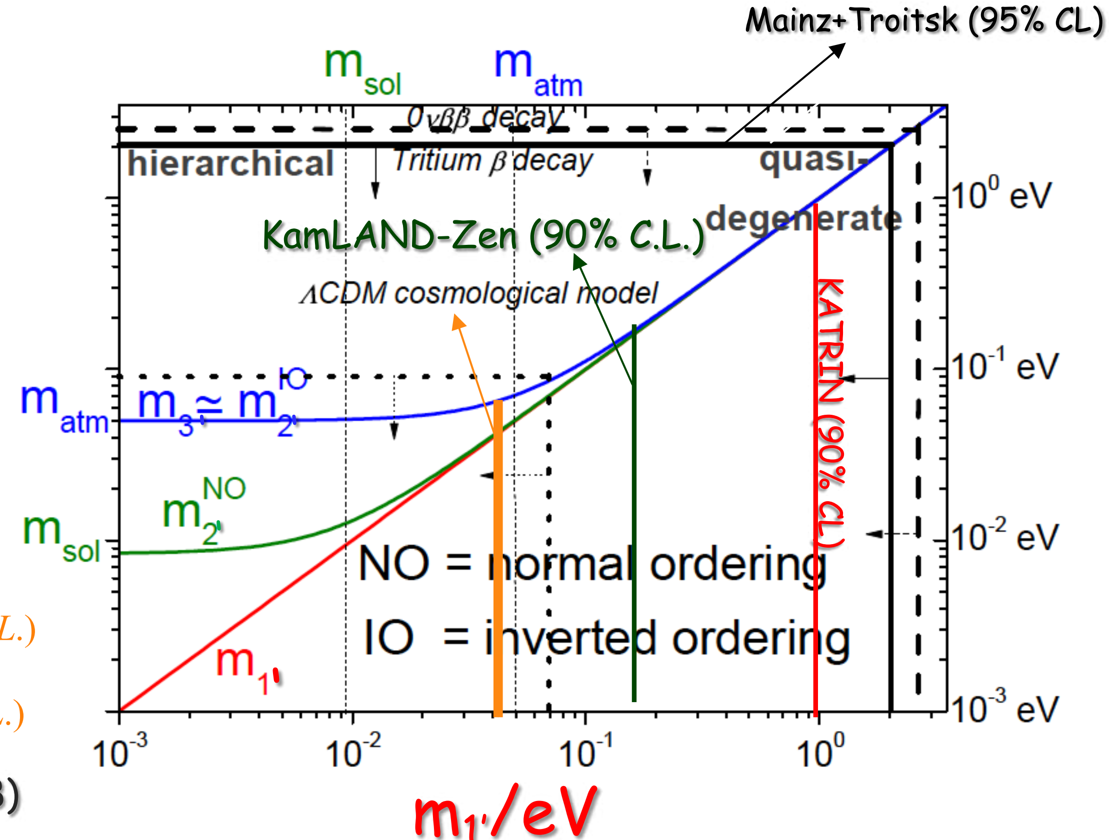
$$\sum_i m_i < 0.23\, eV \ (95\% C.L.)$$

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

$$\sum_i m_i < 0.146\, eV \Rightarrow m_{1'} \le 0.041\, \mathrm{eV} \quad (\mathrm{NO}, 95\% C.L.)$$

$$\sum_i m_i < 0.172\, eV \Rightarrow m_{1'} \le 0.042\, \mathrm{eV} \quad (\mathrm{IO}, 95\% C.L.)$$

(Choudury, Hannestad 1907.12598)



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

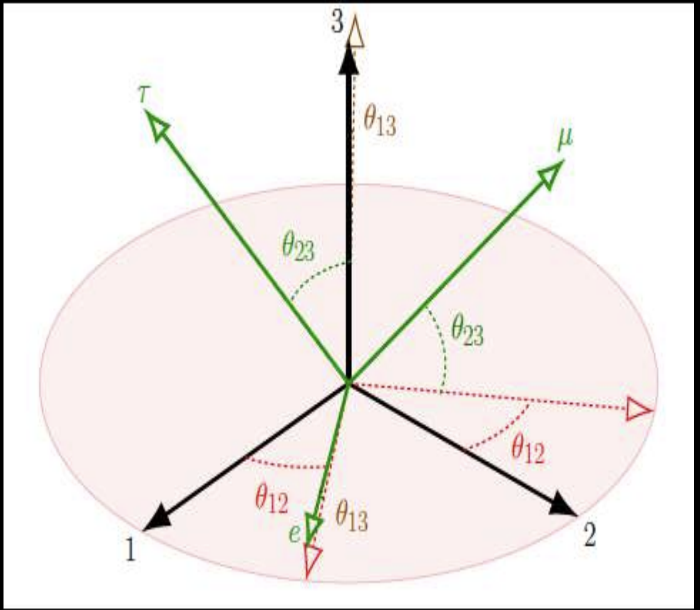
$$U_{\alpha i} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta}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

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

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)=10.4

Minimally extended SM

$$\mathcal{L}=\mathcal{L}_{SM}+\mathcal{L}_Y^\nu \qquad -\mathcal{L}_Y^\nu=\overline{\nu}_L h^\nu \nu_R \phi \Rightarrow -\mathcal{L}_Y^\nu=\overline{\nu}_L m_D^\nu \nu_R$$

Dirac Mass

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

diagonalising m_D : $m_D = V_L^\dagger D_{m_D} U_R$

$$D_{m_D} \equiv \begin{pmatrix} m_{D1} & 0 & 0 \\ 0 & m_{D2} & 0 \\ 0 & 0 & m_{D3} \end{pmatrix}$$

$\Rightarrow$ 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)

violates lepton number

$$-\mathcal{L}^{\nu}_{\rm mass} = \overline{\nu_L}\, m_D\, \nu_R + \frac{1}{2}\,\overline{\nu_R^c}\, M\, \nu_R + \text{h.c.} \quad = -\frac{1}{2}\left[(\bar{\nu}_L^c, \bar{\nu}_R) \begin{pmatrix} 0 & m_D^T \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} \right] + h.c.$$

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

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

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

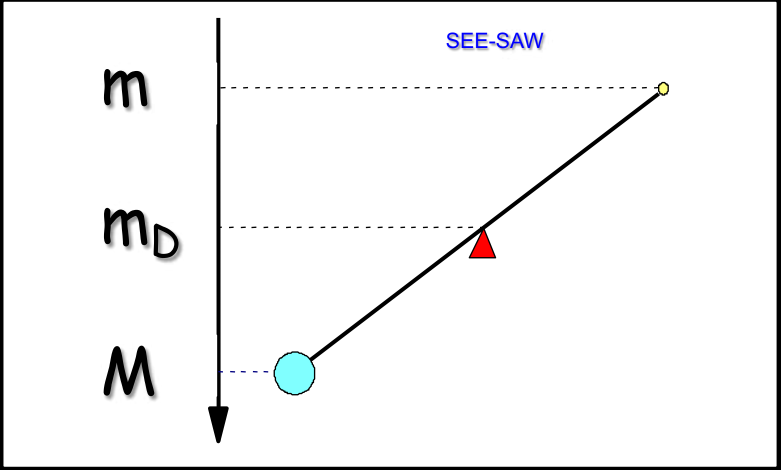
- 3(?) very heavy Majorana neutrinos N_1, N_2, N_3 with $M_3 > M_2 > M_1 \gg m_D$

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



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: $m_i = \dfrac{m_{Di}^2}{M_I}$

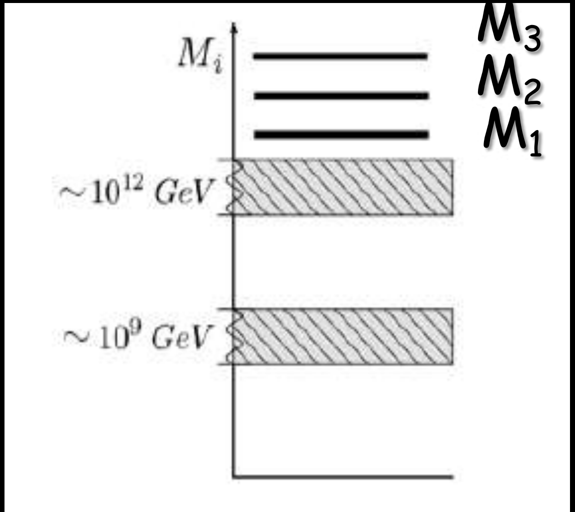
If also $m_{D1}=m_{D2}=m_{D3}=\lambda$ then simply: $M_I = \dfrac{\lambda^2}{m_i}$

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

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

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

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



M_3
M_2
M_1

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

A SECOND (LESS EASY) LIMIT: ALL MIXING FROM THE RH SECTOR

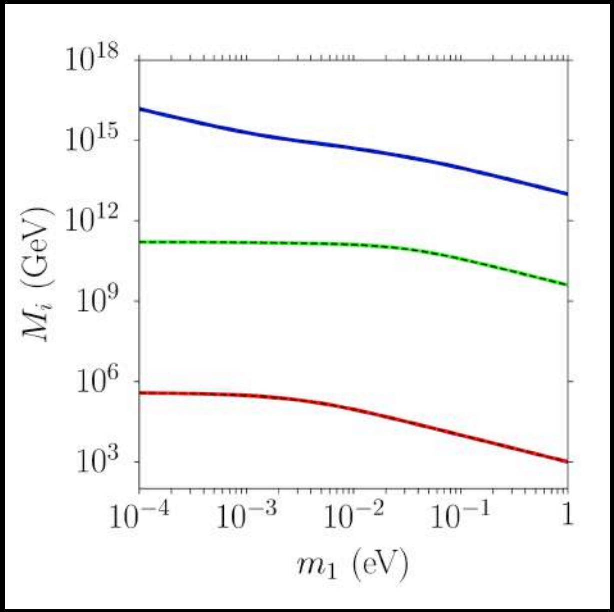
(Branco et al. '02; Nezri, Orloff '02; Akhmedov, Frigerio, Smirnov '03; PDB, Riotto '08; PDB, Re Fiorentin '12)

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

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

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

very hierarchical RH neutrino mass spectrum

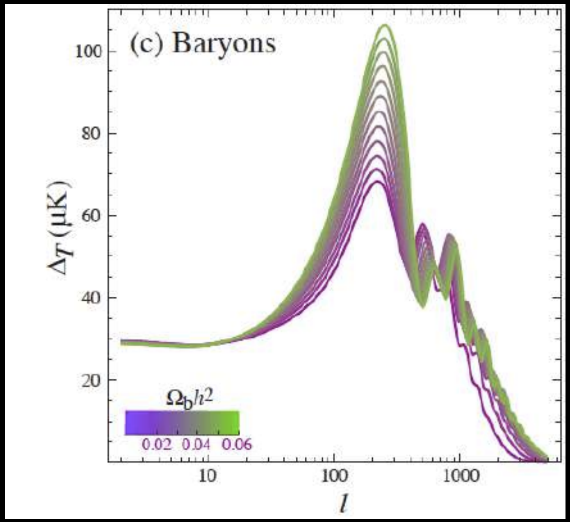


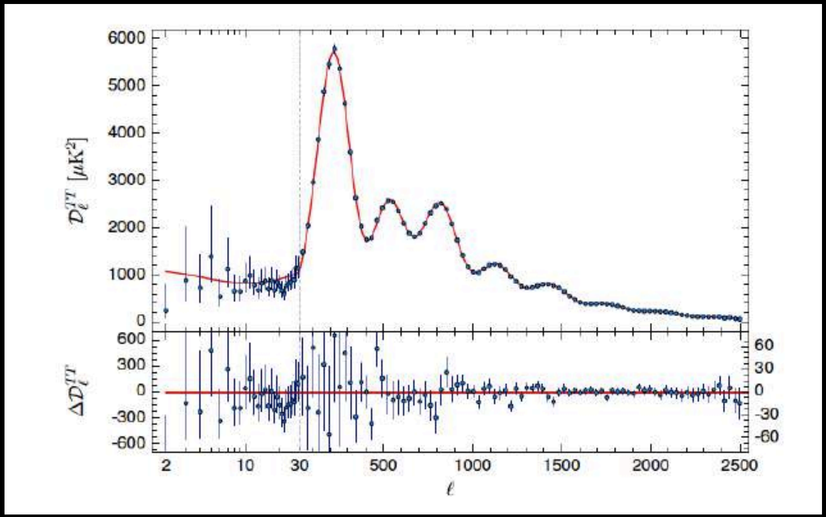
WHAT CAN HELP UNDERSTANDING WHICH IS THE RIGHT MODEL OR CLASS OF MODELS?

Baryon asymmetry of the universe

(Hu, Dodelson, astro-ph/0110414)

(Planck 2018, 1807.06209)





(CMB+BAO)

$$\Omega_{B0} h^2 = 0.02242 \pm 0.00014$$

$$\boxed{\eta_{B0} \equiv \frac{n_{B0} - \bar{n}_{B0}}{n_{\gamma 0}} \simeq \frac{n_{B0}}{n_{\gamma 0}} \simeq 273.5\,\Omega_{B0} h^2 \times 10^{-10} = (6.12 \pm 0.04) \times 10^{-10} = \eta_{B0}^{CMB}}$$

- Consistent with (older) BBN determination but more precise and accurate
- Asymmetry coincides with matter abundance since there is no evidence of primordial antimatter
- Though all 3 Sakharov conditions are satisfied in the SM, any attempt to reproduce the observed value fails by many orders of magnitude $\Longrightarrow$ it requires NEW PHYSICS!

Minimal scenario of leptogenesis

(Fukugita, Yanagida '86)

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

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

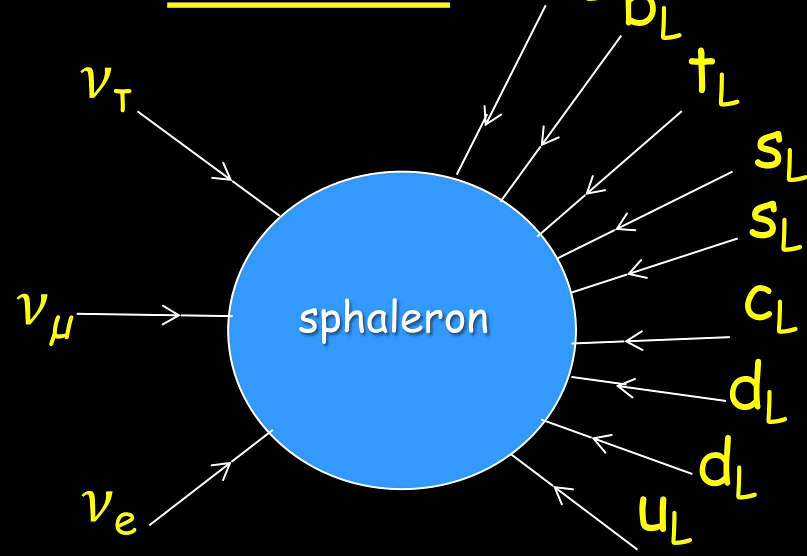
total CP asymmetries $\varepsilon_I \equiv -\dfrac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}$ $\Rightarrow$ N_{B-L} production

- Sphaleron processes in equilibrium

$\Rightarrow \; T_{lep} \gtrsim T^{off}_{sphalerons} \sim$ **140 GeV**

(Kuzmin, Rubakov, Shaposhnikov '85)

$\Delta B = \Delta L = 3$



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

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

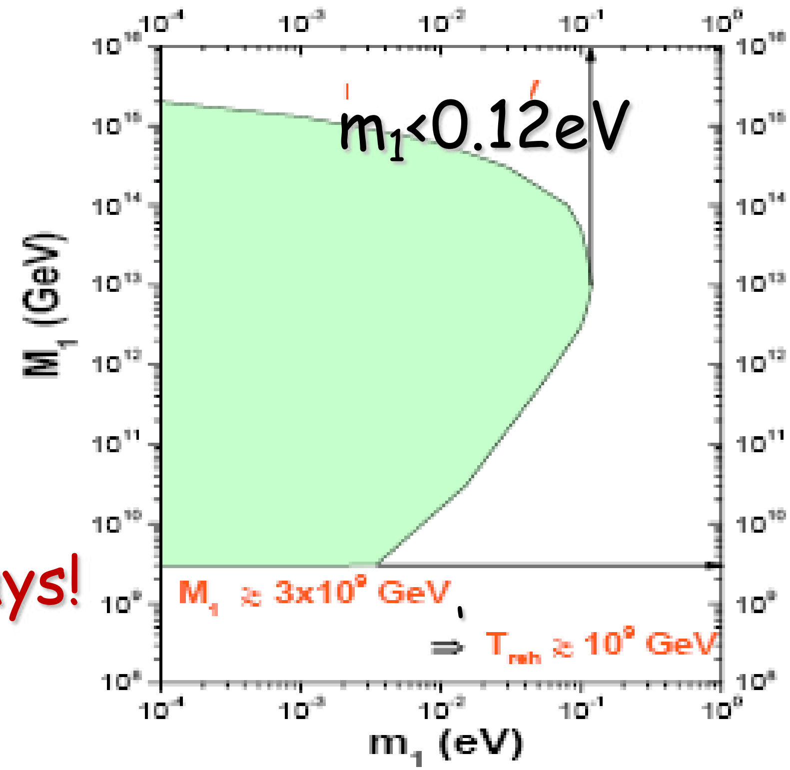
All the asymmetry is generated by the lightest RH neutrino decays!

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 ?

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 to break the coherent evolution of $|l_1\rangle$ and $|\bar{l}'_1\rangle$

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

- ❑ T << 10^9 GeV then also ∝-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

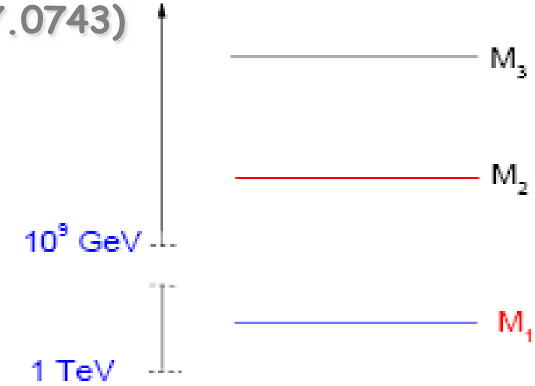
2 Flavour regime (τ, e+μ) $\qquad \varepsilon_{1\tau}\kappa_1^{fin}(K_{1\tau}) + \varepsilon_{1e+\mu}\kappa_1^{fin}(K_{1e+\mu})$

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

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

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 $\Rightarrow$ much weaker

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

- 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!

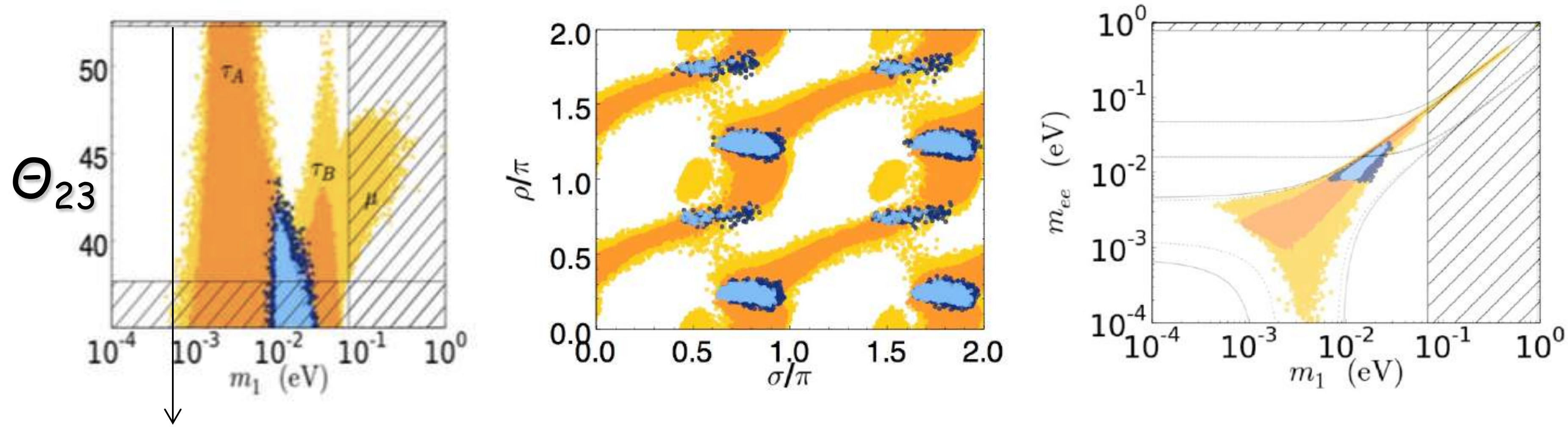
  $V_L \sim V_{CKM}$; $m_{D1}=\alpha_1\, m_{up}$; $m_{D2}=\alpha_2\, m_{charm}$; $m_{D3}=\alpha_3\, m_{top}$

N_2 leptogenesis rescues SO(10)-inspired leptogenesis

(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 $I \leq V_L \leq V_{CKM}$ $V_L = I$



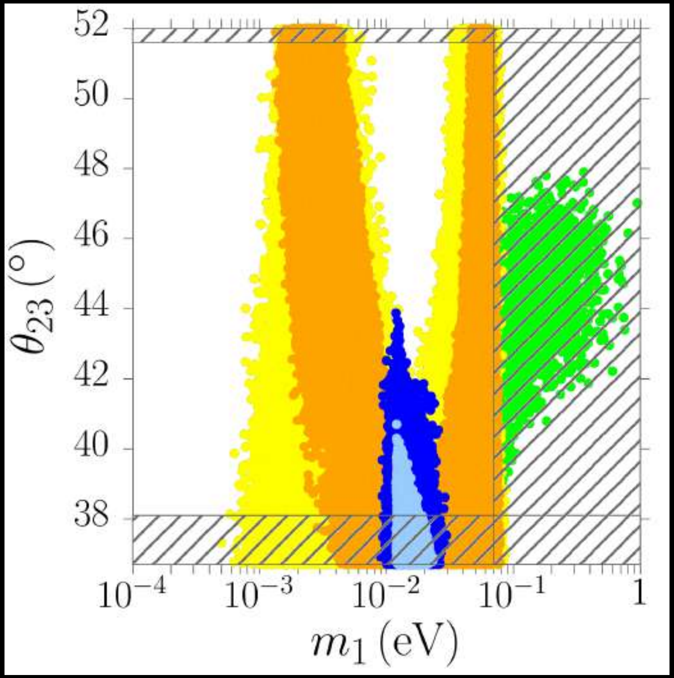
- Lower bound $m_1 \gtrsim 10^{-3}$ eV
- θ_{23} upper bound

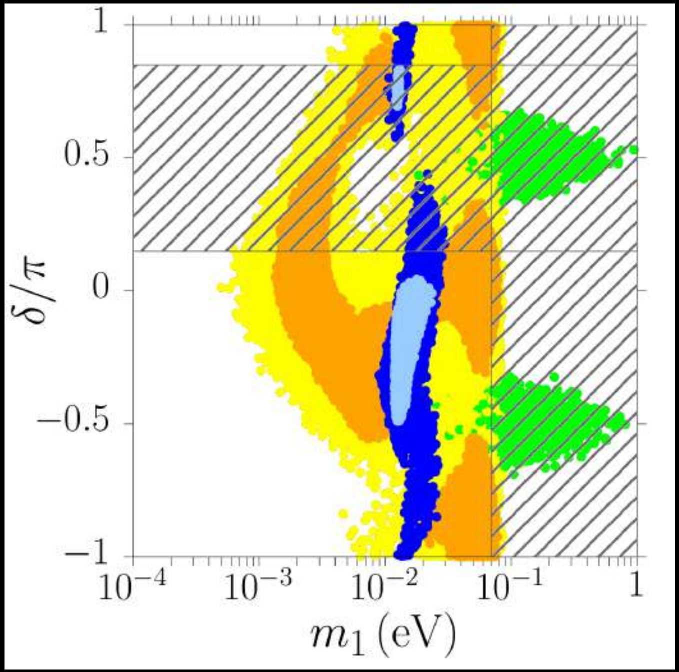
- Majorana phases constrained about specific regions

- Effective $0\nu\beta\beta$ mass can still vanish but bulk of points above meV

- INVERTED ORDERING IS EXCLUDED
- What are the blue regions? It is a subset of solutions allowing `strong' thermal leptogenesis

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)

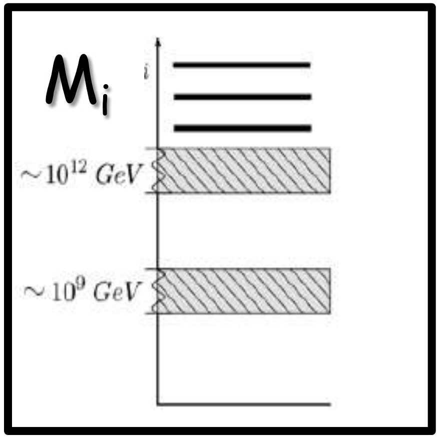
In particular current best fit values of δ and θ_{23} would imply $m_{ee} \gtrsim$ 10 meV $\Rightarrow$ testable signal at $0\nu\beta\nu$ experiments

NOTICE THAT SO(10)-inspired leptogenesis clearly disproves the statement that high scale leptogenesis is "untestable"

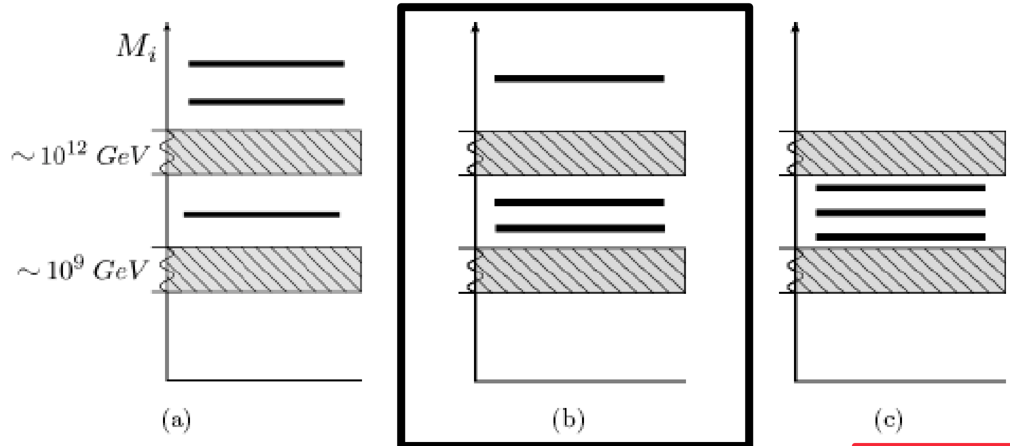
Which heavy neutrino spectrum?

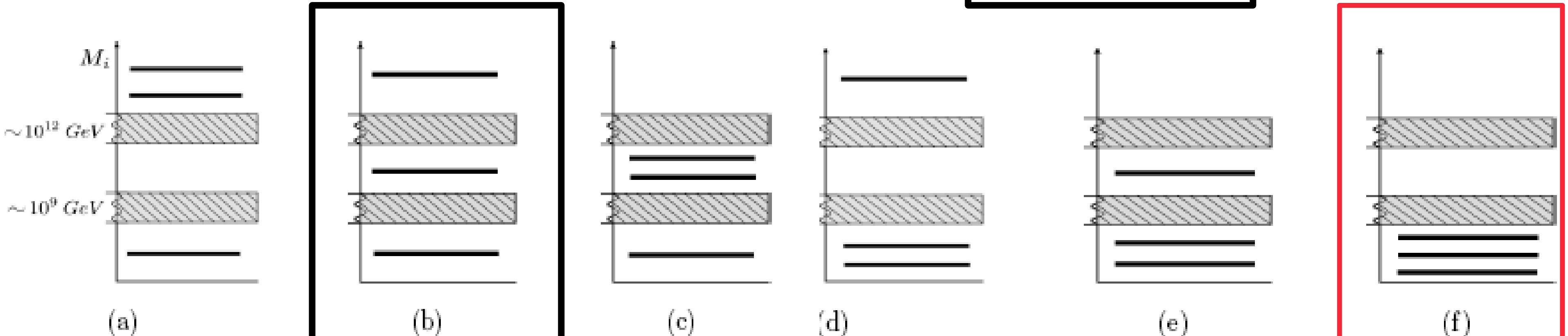
Typically rising in discrete flavour symmetry models

Heavy neutrino flavored scenario



2 RH neutrino scenario





☛It emerges in SO(10)-inspired models

Low scale see-saw models

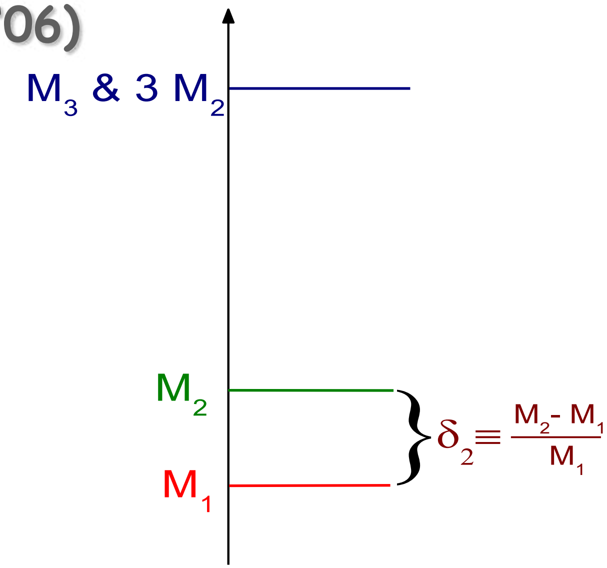
The degenerate limit

(Covi, Roulet, Vissani '96; Pilaftsis ' 97; Blanchet, PDB '06)

Different possibilities, for example:

- partial hierarchy: $M_3 \gg M_2$, M_1

$\Rightarrow \quad |\varepsilon_3| \ll |\varepsilon_2|, |\varepsilon_1| \quad$ and $\quad \kappa_3^{\rm fin} \ll \kappa_2^{\rm fin}, \kappa_1^{\rm fin}$



CP asymmetries get enhanced $\propto 1/\delta_2$

$$\Rightarrow \mathbf{N}_{\mathbf{B-L}}^{\rm fin} \nearrow$$

For $\delta_2 \lesssim 0.01$ (**degenerate limit**) :

$$(M_1^{\rm min})_{\rm DL} \simeq 4\times 10^9\,{\rm GeV}\left(\frac{\delta_2}{0.01}\right) \quad \text{and} \quad (T_{\rm reh}^{\rm min})_{\rm DL} \simeq 5\times 10^8\,{\rm GeV}\left(\frac{\delta_2}{0.01}\right)$$

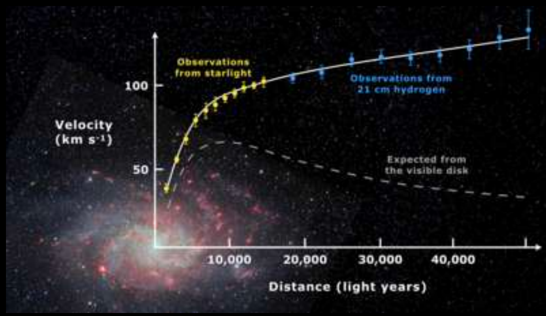
The reheating temperature lower bound is relaxed

The required tiny value of δ_2 can be obtained e.g. in ***radiative leptogenesis*** (Branco, Gonzalez, Joaquim, Nobre'04,'05)

Dark Matter

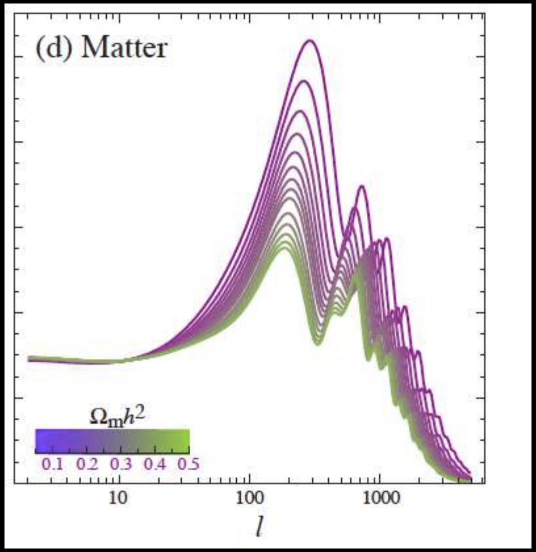
At the present time DM acts as a cosmic glue keeping together

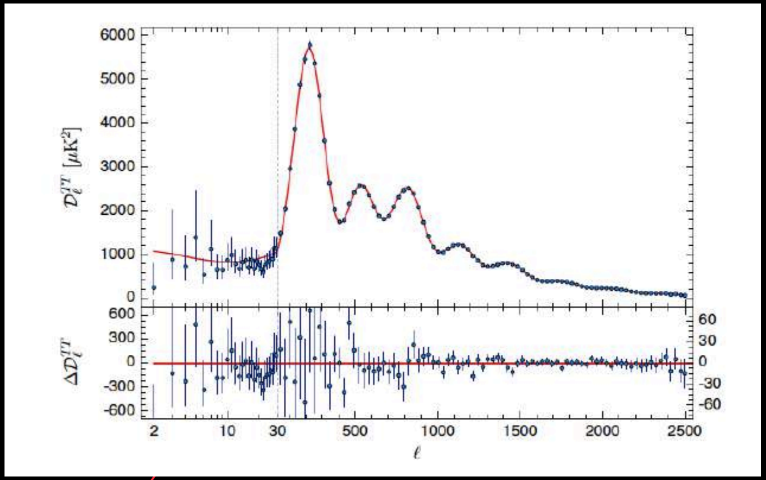
Stars in galaxies…. … and galaxies in cluseters of galaxies (such as in Coma cluster)



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

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





(CMB + BAO)

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

Dark matter from LH-RH neutrino mixing

(Asaka, Blanchet, Shaposhnikov '05)

- LH-RH neutrino mixing

$$\nu = (\nu_L + \nu_L^c) + \frac{m_D}{M}(\nu_R + \nu_R^c)$$

$$N = (\nu_R + \nu_R^c) - \frac{m_D}{M}(\nu_L + \nu_L^c)$$

- For $M_1 \ll m_e \Rightarrow$ $\tau_1 = 5\times 10^{28} s \left(\frac{M_1}{keV}\right)^{-5}\left(\frac{10^{-8}}{\theta^2}\right) \gg t_0$ $\left(|\theta|^2 \equiv \sum_\alpha |m_{D\alpha 1}/M_1|^2\right)$

- Solving Boltzmann equations abundance is produced at T~100 MeV:

(Dodelson Widrow '94) $$\Omega_{N_1} h^2 \sim 0.1\left(\frac{\bar{\theta}}{10^{-4}}\right)^2\left(\frac{M_1}{keV}\right)^2 \sim \Omega_{DM,0} h^2$$

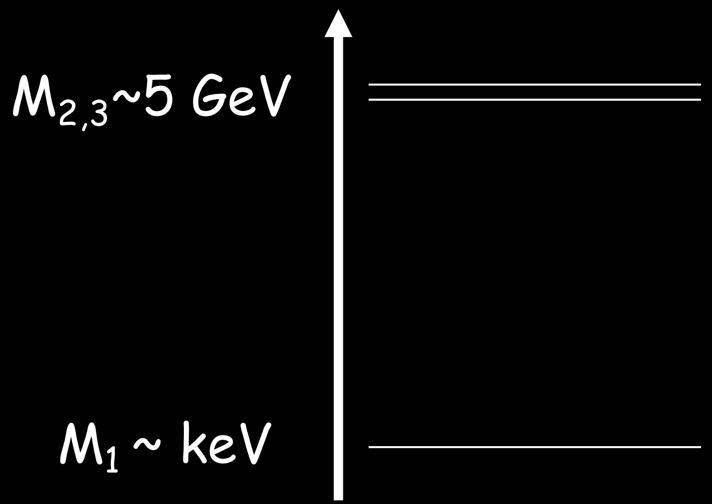
- The lightest neutrino mass is $\lesssim 10^{-5}$ eV $\Rightarrow$ hierarchical limit
- The N_1's also radiatively decay and this produces constraints from X-rays (or opportunities to observe it).
- Considering also structure formation constraints, one is forced to consider a resonant production induced by a large lepton asymmetry (Shi, Fuller '99, Dolgov and Hansen '00)
- $L \sim 10^{-4}$ (3.5 keV line?). (Horiuchi et al. '14; Bulbul at al. '14; Abazajian '14)

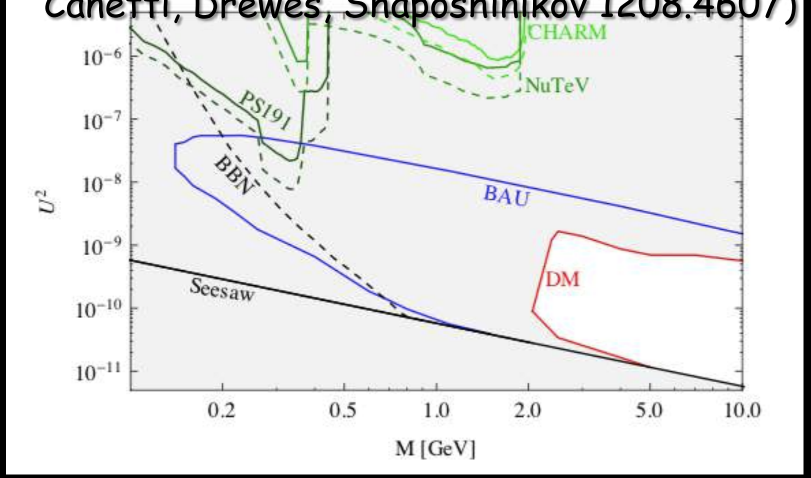
νMSM model

(Asaka,Blanchet,Shaposhnikov '05; Asaka,Shaposhinikov '06; Canetti, Drewes, Shaposhinikov 1208.4607)

- In addition to DM from resonant production in the presence of large asymmetry also the observed BAU is explained by leptogenesis from oscillations (Akhmedov, Rubakov, Smirnov '99)

- The mixing of the two heavier RH neutrinos with quasi-degenerate masses $M_{2,3}$~ 1GeV and ΔM~1eV can reproduce BAU and produce the large asymmetry after sphaleron freeze-out necessary for DM resonant production. Moreover if $M_{2,3} \lesssim$ 5 GeV direct tests from meson decays are possible at SHiP .





Canetti, Drewes, Shaposhinikov 1208.4607)

- However, recent analyses fails to reproduce both asymmetry and DM for such low $M_{2,3}$ masses and M_1 = 7 keV (M.Laine 1905.08814)

An alternative solution

(Anisimov, PDB '08)

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

$$m_D \simeq \begin{pmatrix} 0 & m_{De2} & m_{De3} \\ 0 & m_{D\mu2} & m_{D\mu3} \\ 0 & m_{D\tau2} & m_{D\tau3} \end{pmatrix}, \text{ or } \begin{pmatrix} m_{De1} & 0 & m_{De3} \\ m_{D\mu1} & 0 & m_{D\mu3} \\ m_{D\tau1} & 0 & m_{D\tau3} \end{pmatrix}, \text{ or } \begin{pmatrix} m_{De1} & m_{De2} & 0 \\ m_{D\mu1} & m_{D\mu2} & 0 \\ m_{D\tau1} & m_{D\tau2} & 0 \end{pmatrix},$$

What production mechanism? For high masses just a tiny abundance is needed:

$$N_{DM} \simeq 10^{-9} (\Omega_{DM,0} h^2) N_\gamma^{prod} \frac{TeV}{M_{DM}}$$

Turning on tiny Yukawa couplings?

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

$$\boxed{\tau_{DM} = \frac{4\pi}{h_A^2\, M_{DM}} = 0.87 h_A^2\, 10^{-23} \frac{\text{GeV}}{M_{DM}} s} \Rightarrow \boxed{\tau_{DM} > \tau_{DM}^{\min} \simeq 10^{28} s \Rightarrow h_A < 3\times 10^{-26} \sqrt{\frac{GeV}{M_{DM}} \times \frac{10^{28} s}{\tau_{DM}^{\min}}}}$$

Too small to reproduce the correct abundance with any production mechanism

Higgs portal RH neutrino mixing DM

(Anisimov '06, Anisimov,PDB '08)

Assume new interactions with the standard Higgs:

Anisimov Operator $$L_{5\dim} = \frac{\lambda_{IJ}}{\Lambda}\phi^\dagger\phi\,\overline{N_J^c}N_I \qquad (I,J=A,B,C)$$

In general they are non-diagonal in the Yukawa basis: this generates a RH neutrino mixing.
Consider a 2 RH neutrino mixing for simplicity and consider medium effects:

From the Yukawa interactions: $V_J^Y = \frac{T^2}{8\,E_J}h_J^2$

From the new interactions: $V_{JK}^\Lambda \simeq \frac{T^2}{12\,\Lambda}\lambda_{JK}$

Mixing from misalignment: $\sin 2\theta_\Lambda(T) \equiv T^3/(\tilde{\Lambda}\,\Delta M^2)$ $\quad \tilde{\Lambda} = \Lambda/\lambda_{DM-S}$

effective mixing Hamiltonian (in monocromatic approximation):

$$\Delta H \simeq \begin{pmatrix} -\frac{\Delta M^2}{4p} - \frac{T^2}{16p}h_S^2 & \frac{T^2}{12\tilde{\Lambda}} \\ \frac{T^2}{12\tilde{\Lambda}} & \frac{\Delta M^2}{4p} + \frac{T^2}{16p}h_S^2 \end{pmatrix} \Rightarrow \sin 2\theta_\Lambda^{m} = \frac{\sin 2\theta_\Lambda}{\sqrt{(1+v_S^Y)^2 + \sin^2 2\theta_\Lambda}}$$

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

$v_S^Y \equiv T^2\,h_S^2/(4\,\Delta M^2)$

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

$$z_{res} \equiv \frac{M_{DM}}{T_{res}} = \frac{h_S\,M_{DM}}{2\sqrt{M_{DM}^2 - M_S^2}}$$

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 (more accurate calculation employing density matrix Solution is needed)

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

(remember that we need only a small fraction to be converted so necessarily $\gamma_{res} \lll 1$)

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

For successful dark-matter genesis $\Rightarrow$

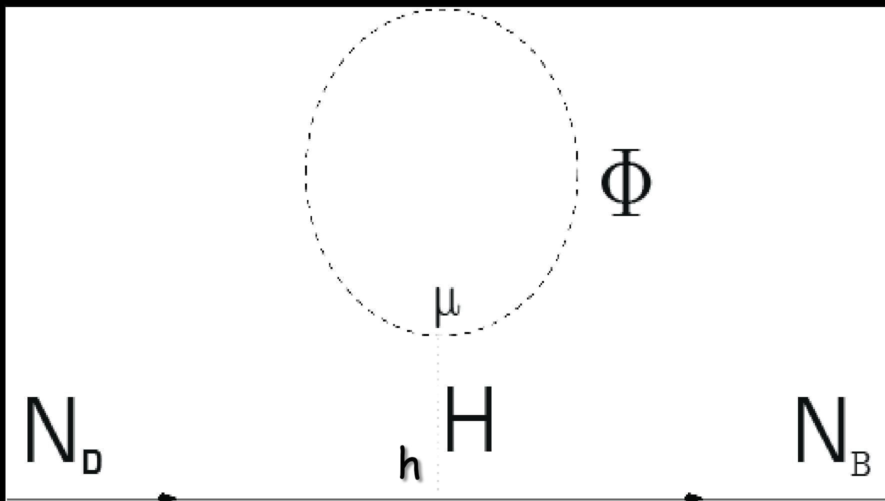
$$\widetilde{\Lambda}_{\rm DM} \simeq 10^{20}\sqrt{\frac{1.5}{\alpha_{\rm S}\,z_{\rm res}}\,\frac{M_{\rm DM}}{M_{\rm S}}\,\frac{M_{\rm DM}}{\rm GeV}}\;{\rm GeV}$$

2 options: either $\Lambda < M_{Pl}$ and $\lambda_{AS} \lll 1$ or $\lambda_{AS} \sim 1$ and $\Lambda \ggg M_{Pl}$:

it is possible to think of models in both cases.

A possible GUT origin

(Anisimov,PDB, 2010, unpublished)



$$\frac{1}{\Lambda_{\rm eff}} = \frac{h\mu}{M_{\rm GUT}^2}$$

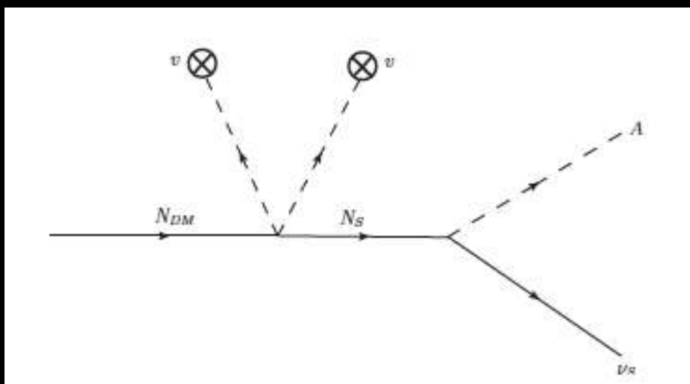
$$\Lambda_{\rm eff} >> M_{\rm GUT}\,!$$

Constraints from decays

(Anisimov,PDB '08; Anisimov,PDB'10; P.Ludl.PDB,S.Palomarez-Ruiz'16)

2 body decays

DM neutrinos unavoidably decay today into A+leptons (A=H,Z,W) through the same mixing that produced them in the very early Universe



$$\theta_{\Lambda 0} = \frac{2\, v^2/\widetilde{\Lambda}}{M_{\rm DM}\,(1 - M_{\rm S}/M_{\rm DM})}.$$

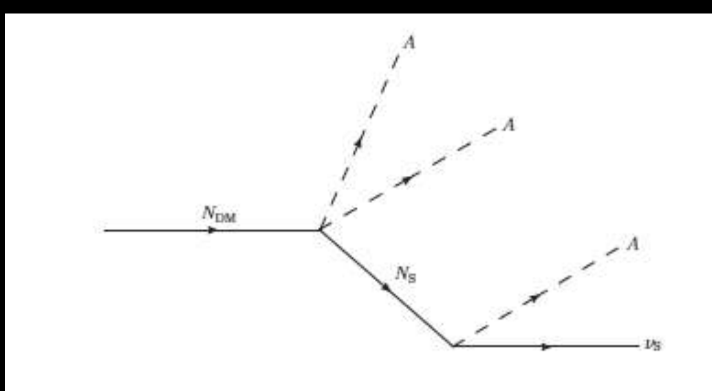
mixing angle today

Lower bound on M_{DM} ($\tau_{28} \equiv \tau_{DM}^{min}/10^{28}$s)

$$M_{\rm DM} \geq M_{\rm DM}^{\rm min} \simeq 54\,{\rm TeV}\,\alpha_{\rm S}\,\tau_{28}\,\left(\frac{M_{\rm S}}{M_{\rm DM}}\right)$$

4 body decays

$$N_{\rm DM} \to 2\,A + N_{\rm S} \to 3\,A + \nu_{\rm S}\ (A = W^{\pm}, Z, H).$$

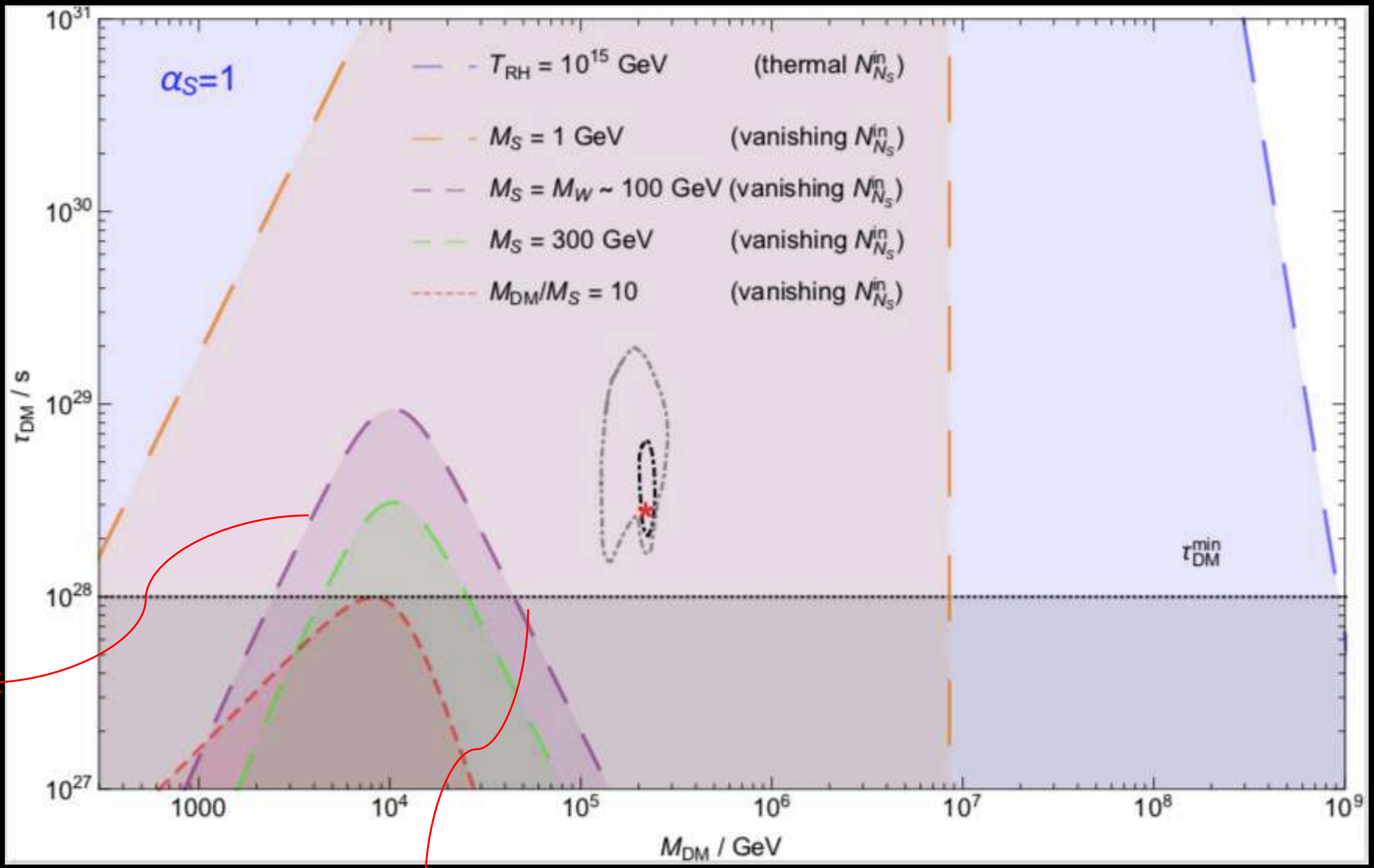


Upper bound on M_{DM} ($\tau_{28} \equiv \tau_{DM}^{min}/10^{28}$s)

$$M_{\rm DM} \lesssim 5.3\,{\rm TeV}\,\alpha_{\rm S}^{-\frac{2}{3}}\, z_{\rm res}^{-\frac{1}{3}}\, \tau_{28}^{-\frac{1}{3}} \left(\frac{N_{N_{\rm S}}}{N_\gamma}\right)_{\rm res}^{\frac{1}{3}} \left(\frac{M_{\rm DM}}{M_{\rm S}}\right)^{\frac{2}{3}}$$

3 body decays and annihilations also can occur but yield weaker constraints

Decays: a natural allowed window on M_{DM}



Lower bound from 2 body decays

Upper bound from 4 body decays

Increasing M_{DM}/M_S relaxes the constraints since it allows higher T_{res} ($\Rightarrow$more efficient production) keeping small N_S Yukawa coupling (helping stability)! But there Is an upper limit to T_{res} from usual upper limit on reheat temperature.

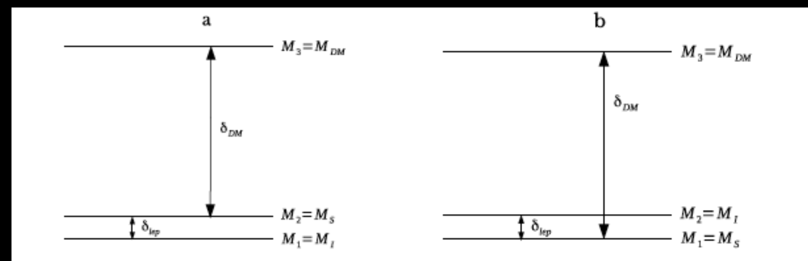
Unifying Leptogenesis and Dark Matter

(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 $M_1\simeq M_2 \Rightarrow$ 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

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

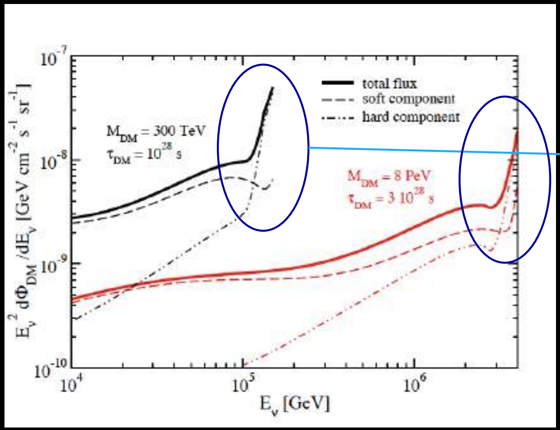
- $M_S \gtrsim 2\,T_{sph} \simeq 300$ GeV $\Rightarrow$ 10 TeV $\lesssim M_{DM} \lesssim$ 1 PeV
- $M_S \lesssim$ 10 TeV
- $\delta_{lep} \sim 10^{-5} \Rightarrow$ leptogenesis is not fully resonant

Nicely predicted a signal at IceCube

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

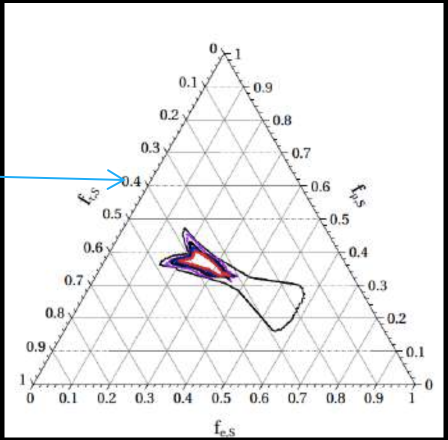
- DM neutrinos unavoidably decay today into A+leptons (A=H,Z,W) through the same mixing that produced them in the very early Universe
- Potentially testable high energy neutrino contribution

Energy neutrino flux



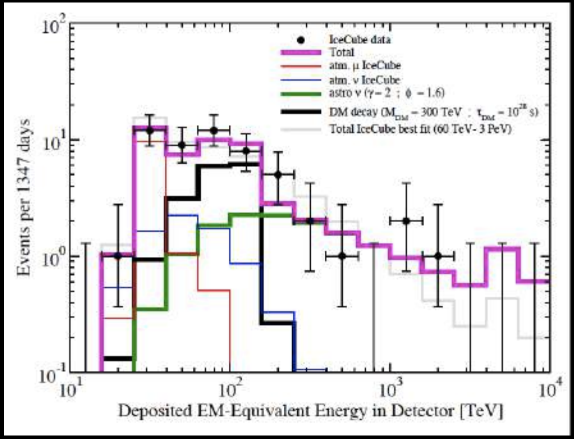
Hard component

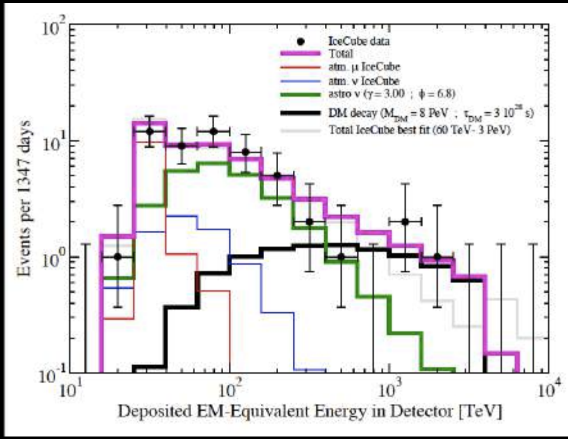
Flavour composition at the detector



Neutrino events at IceCube: 2 examples

M_{DM}=300TeV





M_{DM}=8 PeV

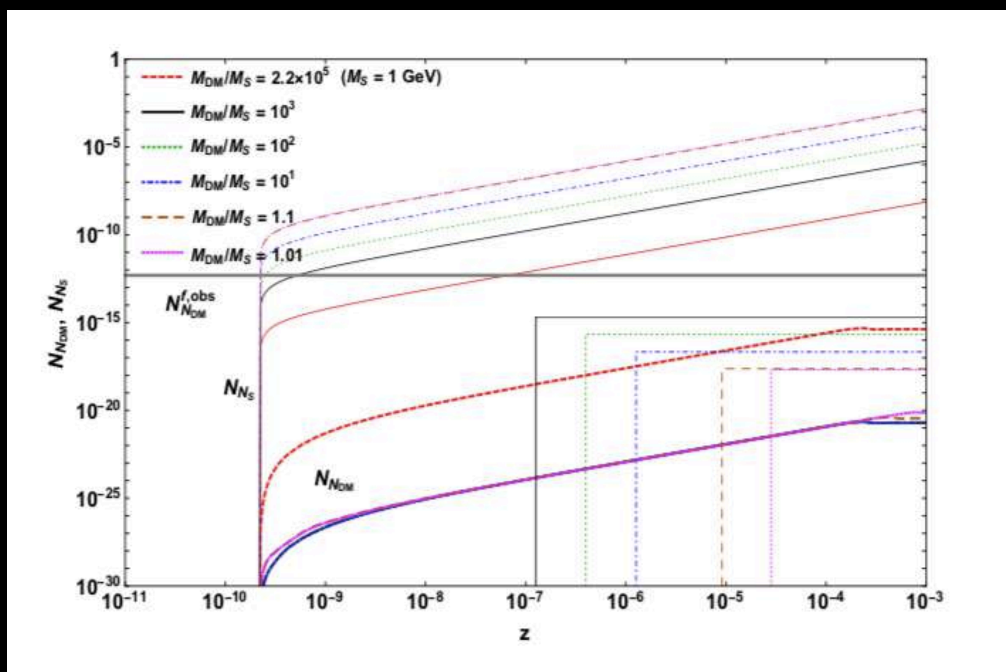
Density matrix calculation of the relic abundance

(P.Di Bari, K. Farrag, R. Samanta, Y. Zhou, 1908.00521)

Density matrix equation for the DM-source RH neutrino system

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

A numerical solution shows that a Landau-Zener overestimated the relic Abundance by a few orders of magnitude (especially in the hierarchical case)



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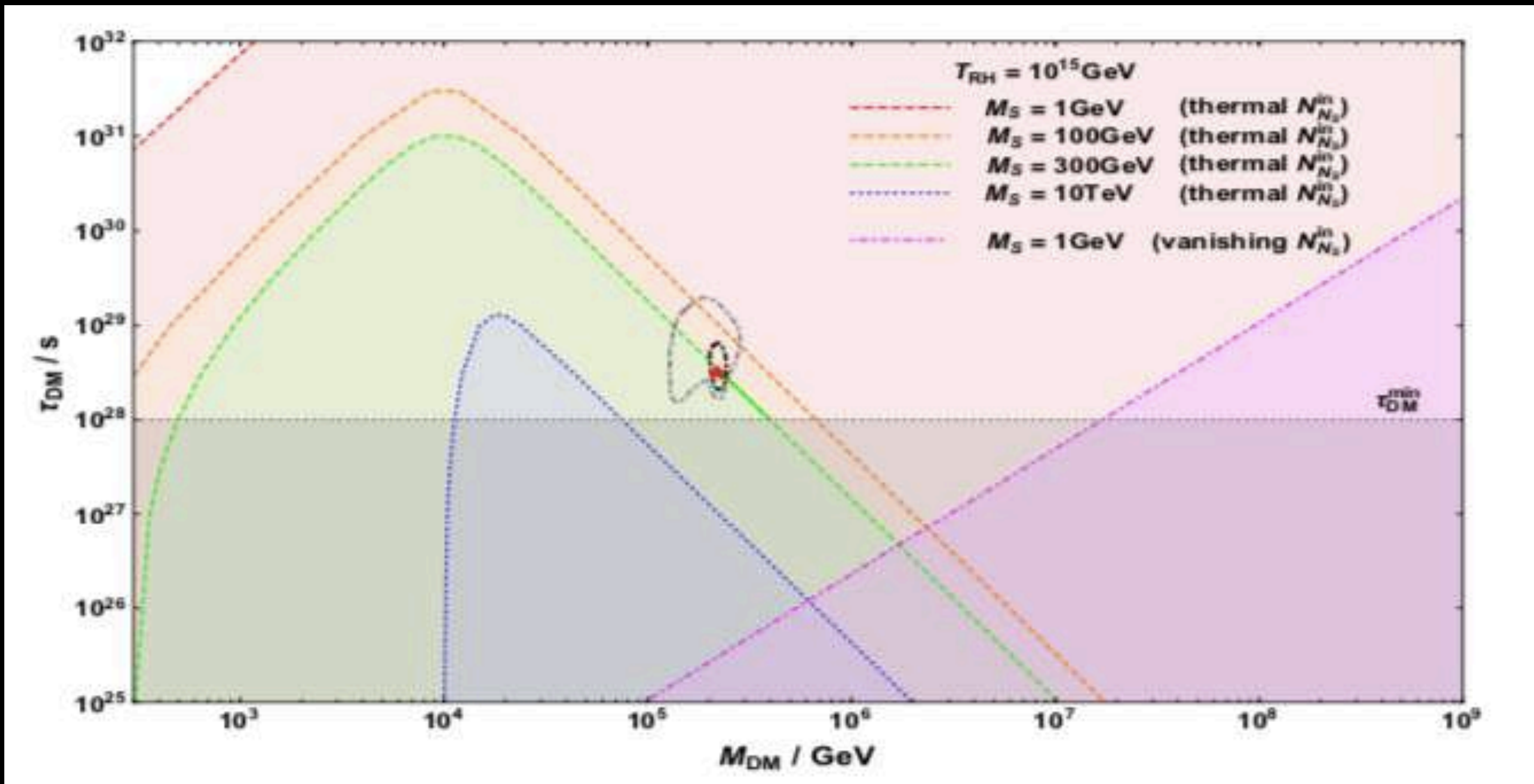
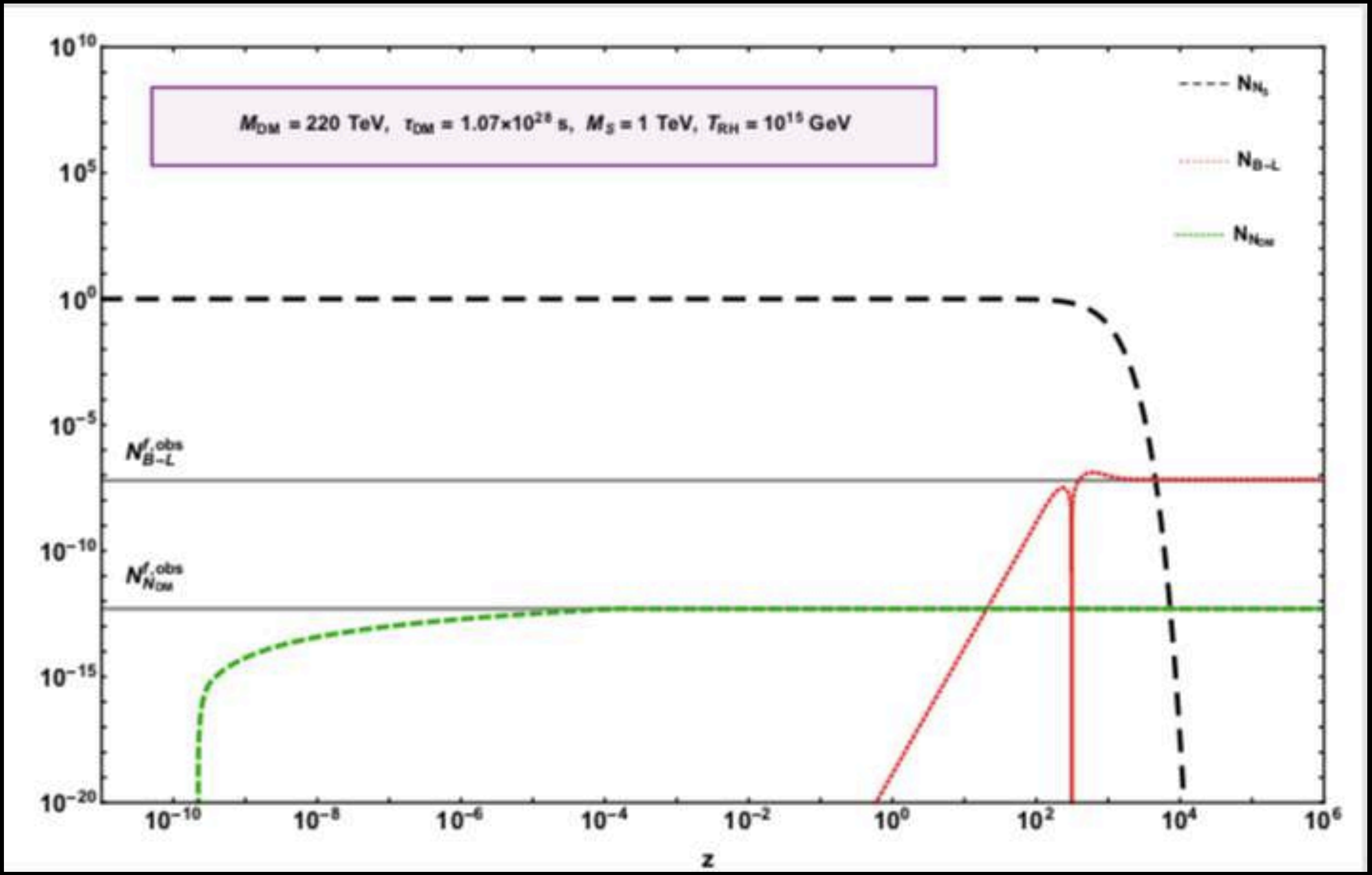


Solutions only for initial thermal N_S abundance, unless $M_S \sim 1$ GeV

Unifying Leptogenesis and Dark Matter

(PDB, K. Farrag, R. Samanta, Y. Zhou, 1908.00521)

A solution for initial thermal N_S abundance:



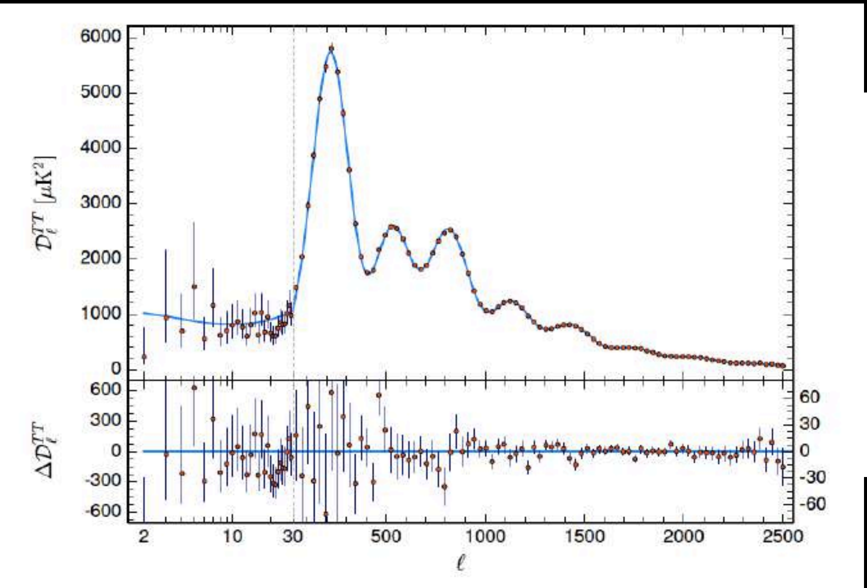
SUMMARY

- Seesaw neutrino mass models can not only reproduce neutrino masses and mixing but also address cosmological origin of matter.
- Moreover Cosmology helps to constraint neutrino models: reproducing matter-antimatter asymmetry and dark matter of the universe imposes important constraints and within specific classes of models can lead to predictions on low energy neutrino parameters and new signals (e.g., at neutrino telescopes)
- 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 $00\nu\beta$+CP violation is discovered, it would be a very strong case (discovery?) in favour of leptogenesis and would particularly favour SO(10)-inspired leptogenesis.
- 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.

ΛCDM model

It is a minimal flat cosmological model with only 6 parameters : baryon and cold dark matter abundances, angular size of sound horizon at recombination, reionization optical depth, amplitude and spectral index of primordial perturbations.

ΛCDM best fit to the *Planck* 2018 data (TT+TE+EE+low E+lensing)
(Planck Collaboration, *arXiv 1807.06209*)



Parameter	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038

(Planck 2018 results, 1807.06209)

Planck results are in good agreement with BAO, SNe and galaxy lensing observations. The only significant (~4σ) tension is with local measurement of the Hubble constant

In the ΛCDM model, expansion is described by a flat Friedmann-Lemaitre cosmological model