Perspectives in Astroparticle physics
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Probing the origin of matter from right-handed neutrinos with IceCube

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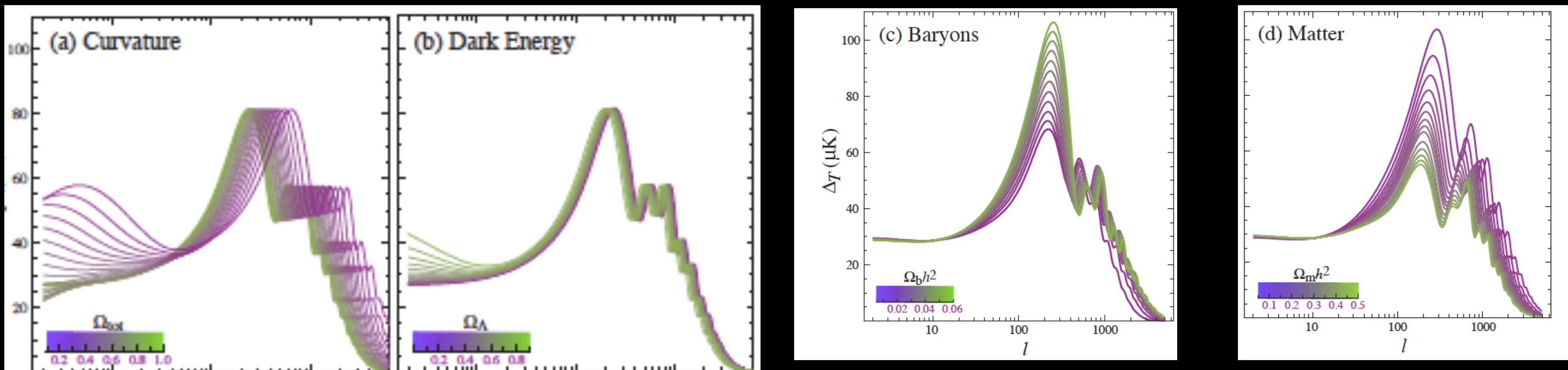
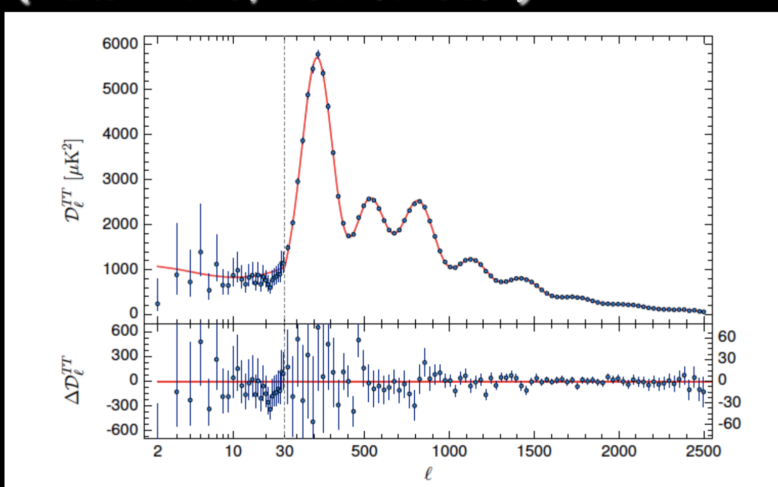
Cosmic ingredients

(Hu, Dodelson, astro-ph/0110414)



$\Omega_0 = 1.005 \pm 0.005$ $\Omega_\Lambda = 0.685 \pm 0.013$ $\Omega_{B0} h^2 = 0.02222 \pm 0.00023$ $\boxed{\Omega_{CDM,0} h^2 = 0.1198 \pm 0.0015 \sim 5\Omega_{B,0} h^2}$

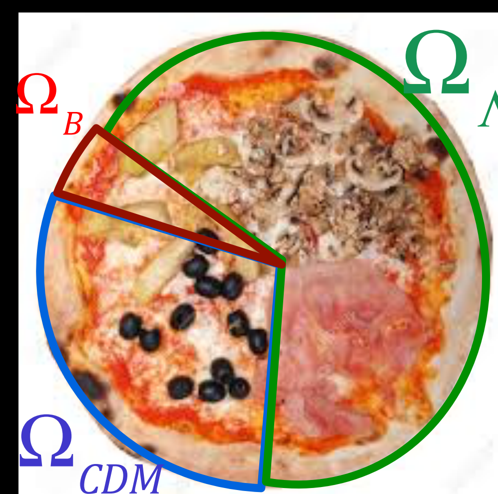
(Planck 2015, 1502.01589)



$h = 0.67 \pm 0.1$

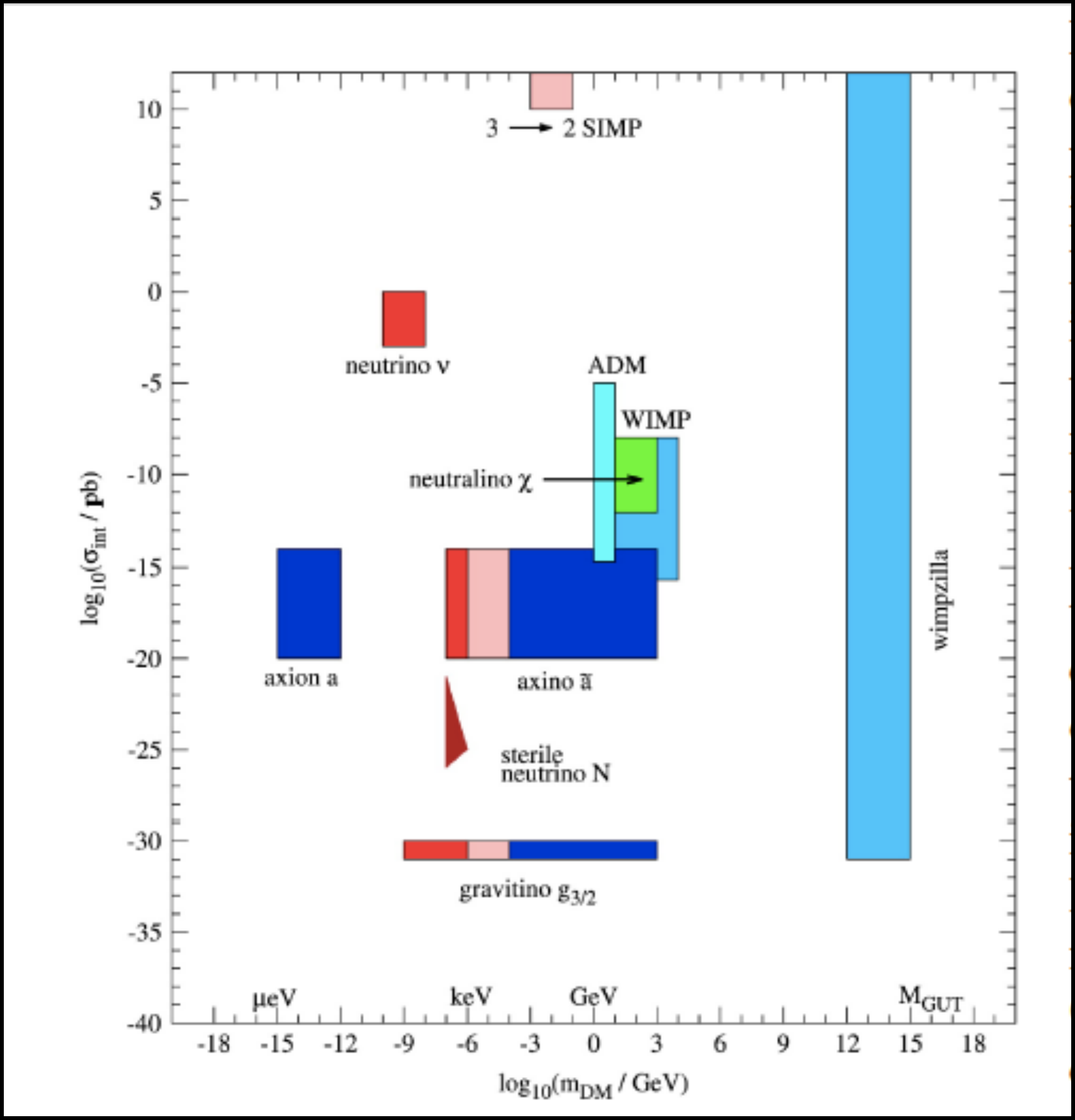
$\Omega_B \simeq 0.05$

$\Omega_{CDM} \simeq 0.265$



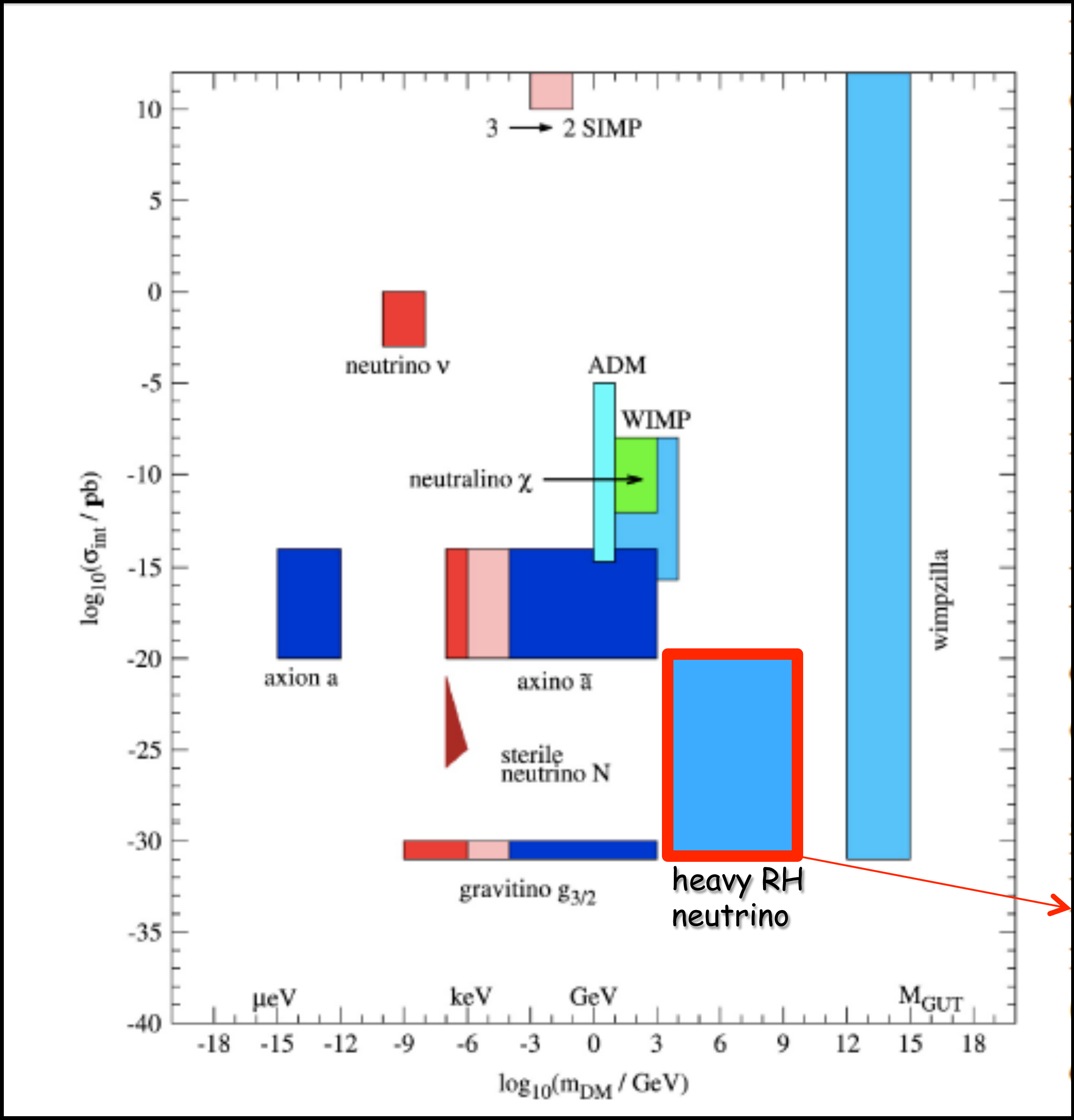
Beyond the WIMP paradigm

(Baer et al.1407.0017)



Beyond the WIMP paradigm

(from Baer et al.1407.0017)



(PDB, Anisimov '08)

Traditional 3 RH neutrino type-I seesaw

• Dirac + (Right-Right) Majorana mass term

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

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

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

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

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

- 3 very heavy Majorana RH neutrinos N_1, N_2, N_3 with masses $M_3 > M_2 > M_1 \gg \max[m_{Di}] \sim 100$ GeV and all "coupled" (cosmologically):

  decay parameters $K_i \equiv \Gamma_i/H(T=M_i) = v^2 (m_D^{\dagger}\, m_D)_{ii}/(M_i\, m_\star) \Rightarrow \min[K_i] \gtrsim O(10^{-1})$

- The decays of the 3 RH neutrinos can explain the matter-antimatter asymmetry with leptogenesis via decays (Fukugita, Yanagida '86)

- The 3 RH neutrinos decay with lifetimes comparable to the age of the Universe when they become non-relativistic: no DM candidate

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:

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

- 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} (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

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):

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

What production mechanism? Turning on tiny Yukawa couplings?

Yukawa basis:

$$m_D = V_L^\dagger \, D_{m_D} \, U_R \, .$$

$$D_{m_D} \equiv v \, \mathrm{diag}(h_A, h_B, h_C), \text{ with } h_A \leq h_B \leq h_C .$$

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

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

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

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

Proposed production mechanisms

Starting from a 2 RH neutrino seesaw model

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

many production mechanisms have been proposed:

- from $SU(2)_R$ extra-gauge interactions (LRSM) (talk by V. Niro);
- 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)

RH neutrino mixing from Higgs portal

(Anisimov,PDB '08)

Assume new interactions with the standard Higgs:

$$\mathcal{L} = \frac{\lambda_{IJ}}{\Lambda}\,\phi^\dagger\,\phi\,\overline{N_I^c}\,N_J \qquad \text{(I,J=A,B,C)}$$

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: $V_J^Y = \dfrac{T^2}{8\,E_J}\,h_J^2$

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

effective mixing Hamiltonian (in monocromatic approximation)

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

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

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

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

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

Non-adiabatic conversion

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

Adiabaticity parameter at the resonance

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

Landau-Zener formula

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

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

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

For successful dark-matter genesis $\Rightarrow$

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

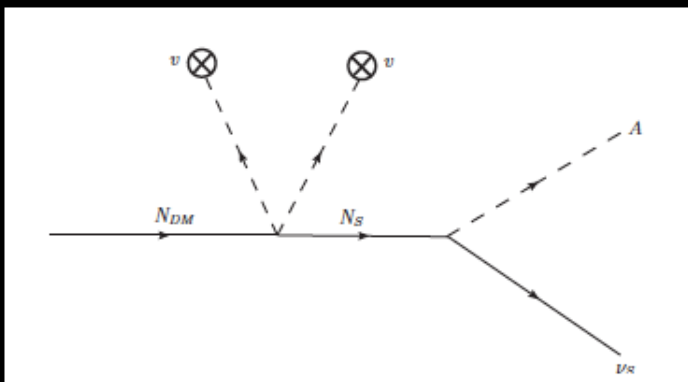
2 options: either Λ<M_{Pl} and λ_{AS}<<< 1 or λ_{AS}~ 1 and Λ>>>M_{Pl} :
it is possible to think of models in both cases.

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



$$\theta_\Lambda^0 = \left(\frac{v^2}{\widetilde{\Lambda}}\right)^2 \frac{1}{\Gamma_S^2/4 + M_S^2\,\delta_{\rm DM}^2}$$

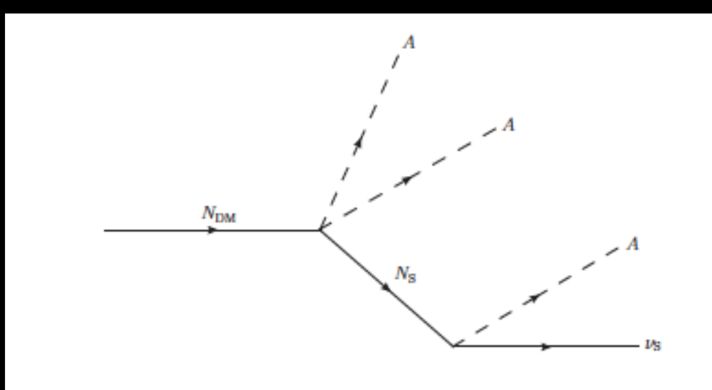
mixing angle today

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

$$M_{\rm DM} \geq M_{\rm DM}^{\rm min} \simeq 2.5 \times 10^{12}\, z_{\rm res}^{5/3}\, \tau_{28}^{1/3} \left[\frac{(1 + M_{\rm S}/M_{\rm DM})^2}{4\, M_{\rm DM}/M_{\rm S}}\right]^{1/3} {\rm GeV}$$

4 body decays

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

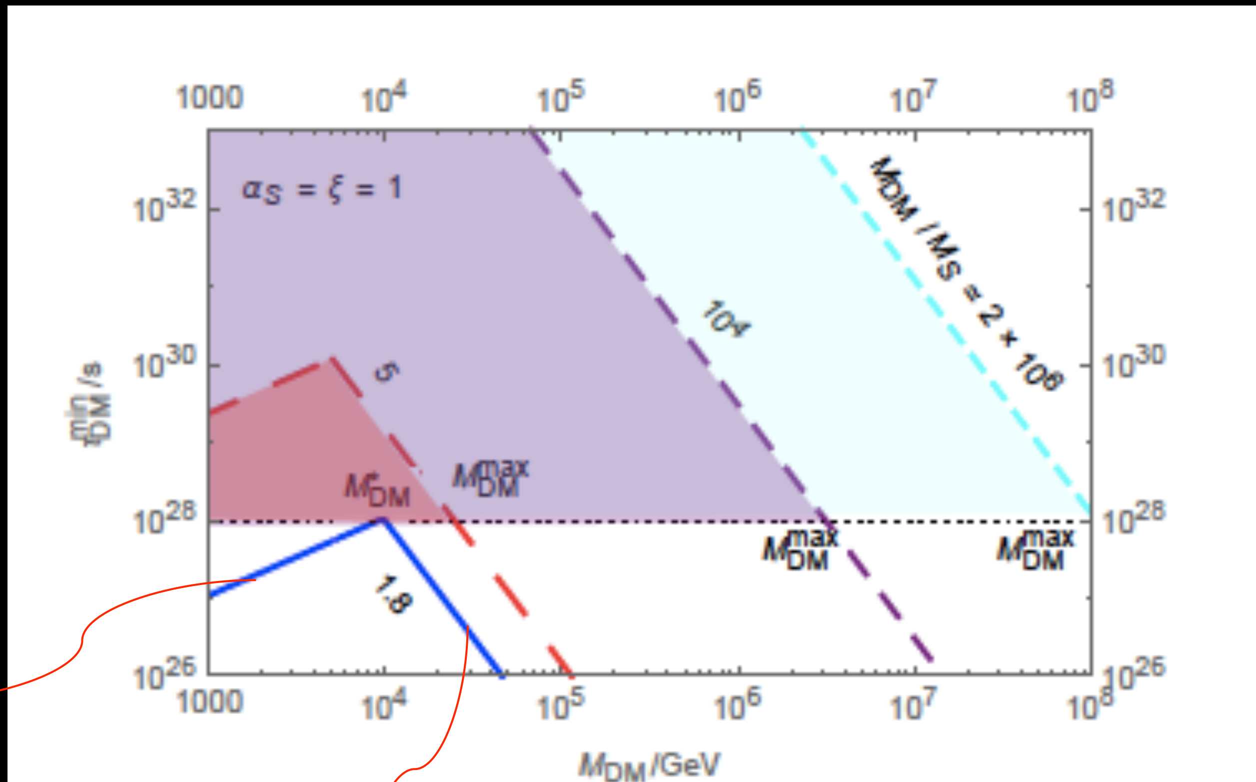


Upper bound on M_{DM} ($\tau_{28} \equiv \tau_{DM}^{min}/10^{28}$s)

$$M_{\rm DM} \lesssim M_{\rm DM}^{{\rm max}(A)} \simeq \frac{5 \times 10^3\,{\rm GeV}}{\alpha_{\rm S}^{2/3}\, z_{\rm res}^{1/3}\, \tau_{28}^{1/3}} \left(\frac{M_{\rm DM}}{M_{\rm S}}\right)^{2/3}$$

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} (⇒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.

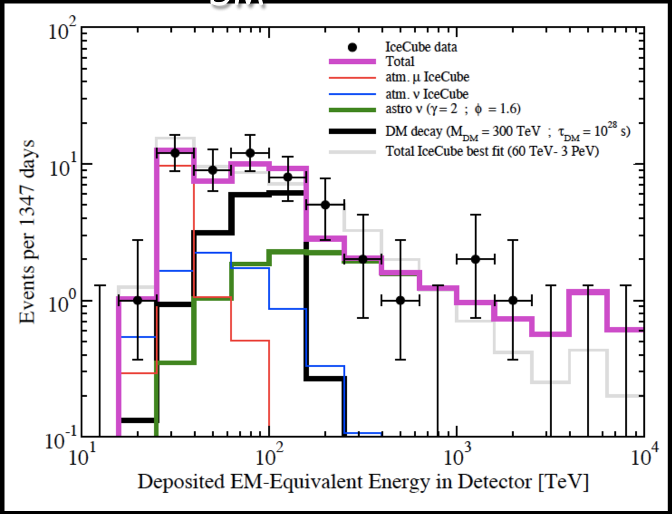
Decays:very high energy neutrinos at IceCube

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

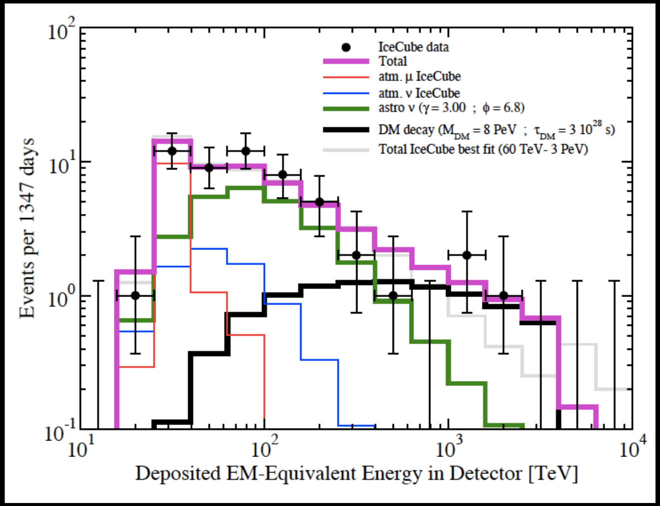
- Since the same interactions responsible for production also unavoidably induce decays ⇒ the model predicts high energy neutrino flux component at some level ⇒ testable at neutrino telescopes (Anisimov,PDB '08)

Neutrino events at IceCube: 2 examples of fits where a DM component in addition to an astrophysical component helps fitting HESE data:

M_{DM}=300TeV



M_{DM}=8 PeV



- Some authors claim there is an excess at (60-100) TeV taking into account also MESE data (Chianese,Miele,Morisi '16)

- But where are the γ 's in FERMI? Multimessenger analysis is crucial.

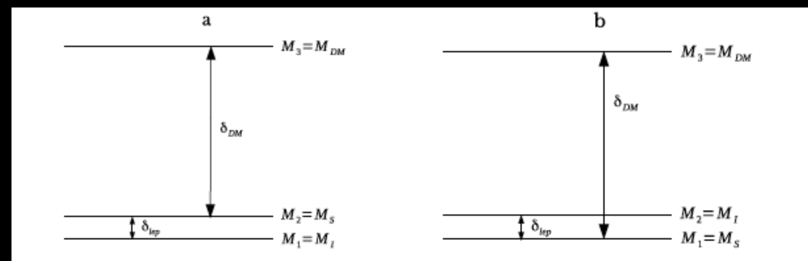
Unifying Leptogenesis and Dark Matter

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

- 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:

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

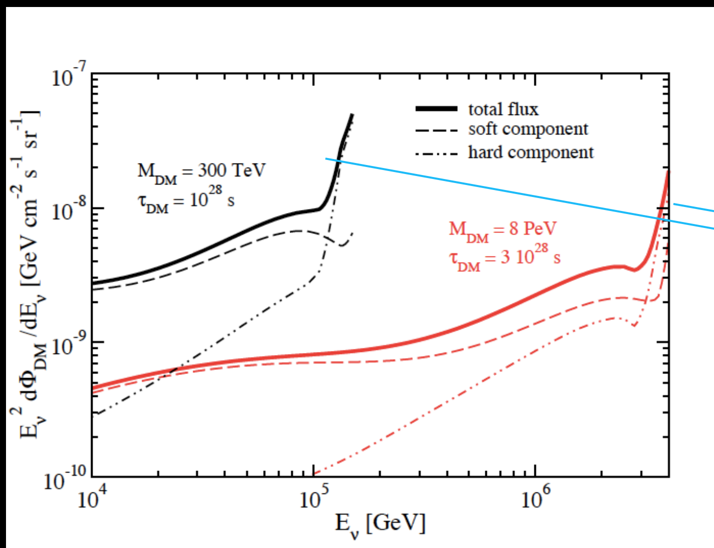
Efficiency factor

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

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

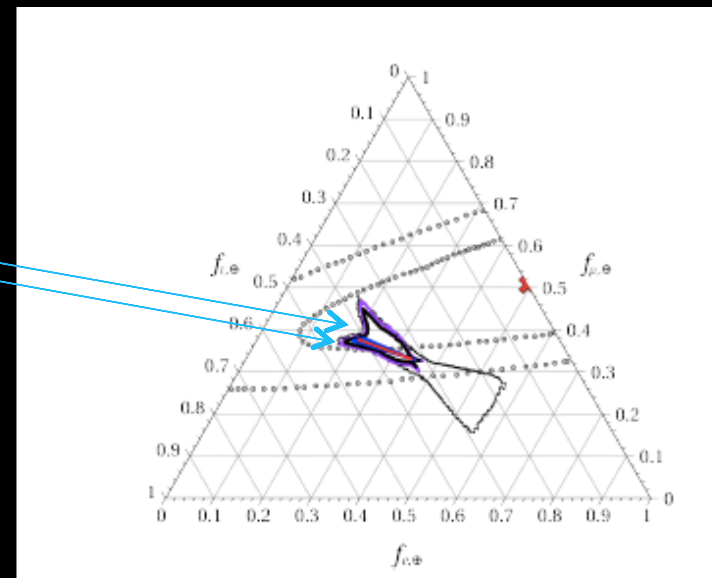
Decays: a distinct flavour composition

Energy neutrino flux



Hard component

Flavour composition
at the detector
(Normal Hierarchy)



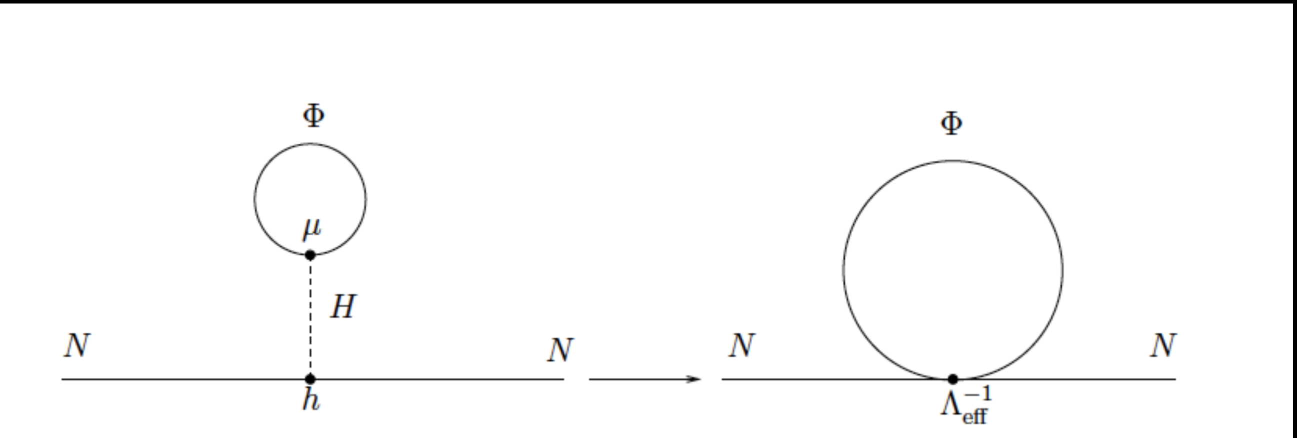
For Normal Hierarchy it is interesting that the electron neutrino hard component is strongly suppressed (it can be even vanishing).

At the detector this is smeared out by mixing but it might be still testable in future.

A possible model ?

(Anisimov,PDB, 2010)

$\underline{\lambda \sim 1}$



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

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

Unfortunately any UV extension seems to generate a Majorana mass term that Is equivalent to generate Yukawa couplings in the basis where the Majorana mass matrix is diagonal: the initial assumption can be realised but with a large amount of fine tuning (Chianese, PDB, King '17)

Summary

- DM might be produced from RH neutrino mixing within a standard typeI seesaw extension plus (Higgs portal) new interactions producing a non renormalizable operator responsible both for production and for decays

- The scenario is also compatible with leptogenesis

- Natural allowed window for the mass of Dark Matter in TeV-PeV range + contribution to high energy neutrino flux in the same range of energies is a prediction of the model ⇒ the model is testable with neutrino telescopes…. a multimessenger analysis can help placing even stronger Constraints

- More generally a TeV-PeV RH neutrino seems to be an attractive (rasonably well justified) candidate for decaying DM able to provide a signal at IceCube and helping fitting current data.