Neutrinos: the quest for a new physics scale

CERN 27-31 March 2017

# Unifying dark matter, leptogenesis and high energy neutrinos (with right-handed neutrino mixing)

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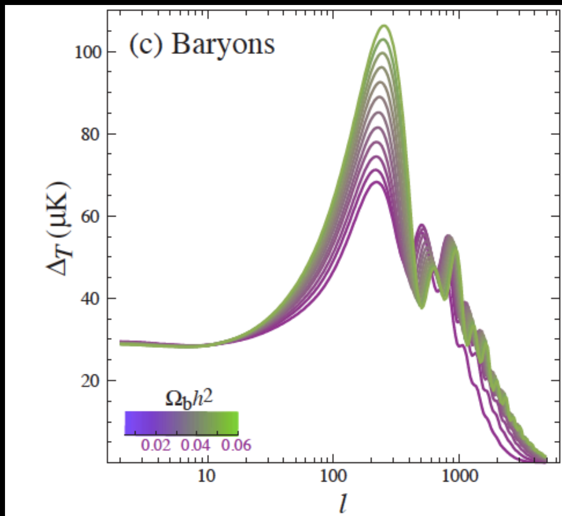
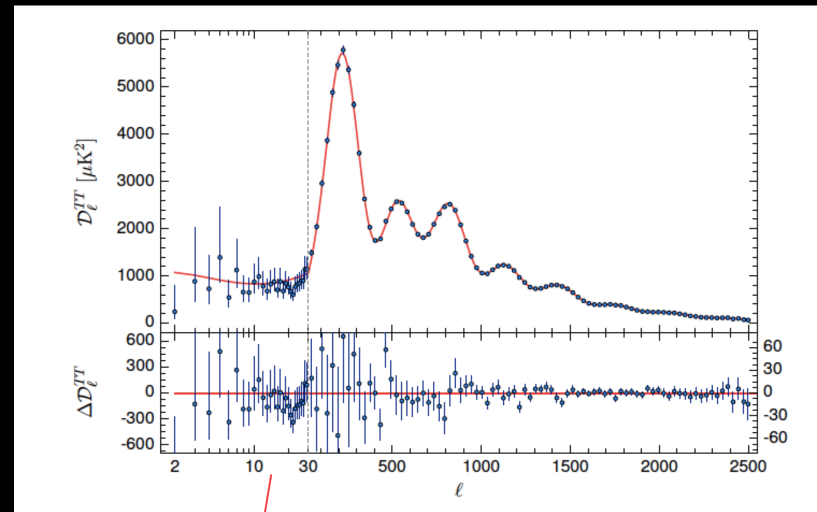
# The baryon asymmetry of the Universe

(Hu, Dodelson, astro-ph/0110414 )




(Planck 2015, 1502.10589 )



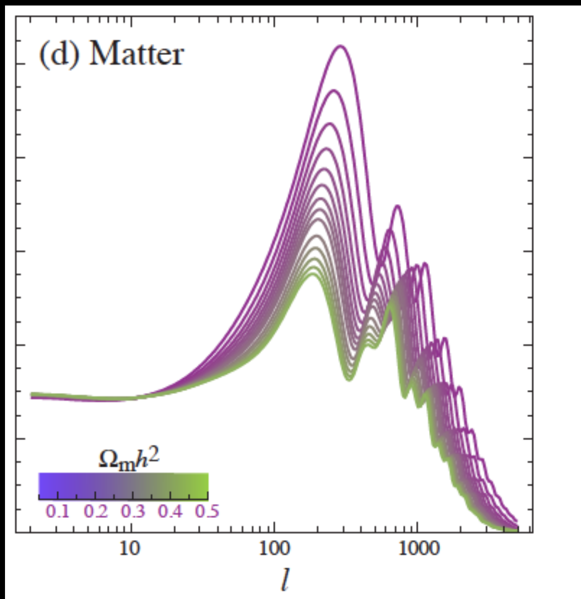

$$\Omega_{B0} h^2 = 0.02222 \pm 0.00023$$

$$\boxed{\eta_{B0} \equiv \frac{n_{B0} - \bar{n}_{B0}}{n_{\gamma 0}} \simeq \frac{n_{B0}}{n_{\gamma 0}} \simeq \frac{\rho_{c0} h^{-2}}{m_N n_{\gamma 0}} \simeq 273.5\,\Omega_{B0} h^2 \times 10^{-10} = (6.05 \pm 0.04) \times 10^{-10}}$$

- Cosmic rays + CMB thermal spectrum fix the sign of $\eta_B$
  (Cohen, De Rujula, Glashow astro-ph/9707087)
- Consistent with (older) BBN determination but more precise and accurate

# The Dark Matter of the Universe

(Hu, Dodelson, astro-ph/0110414 )

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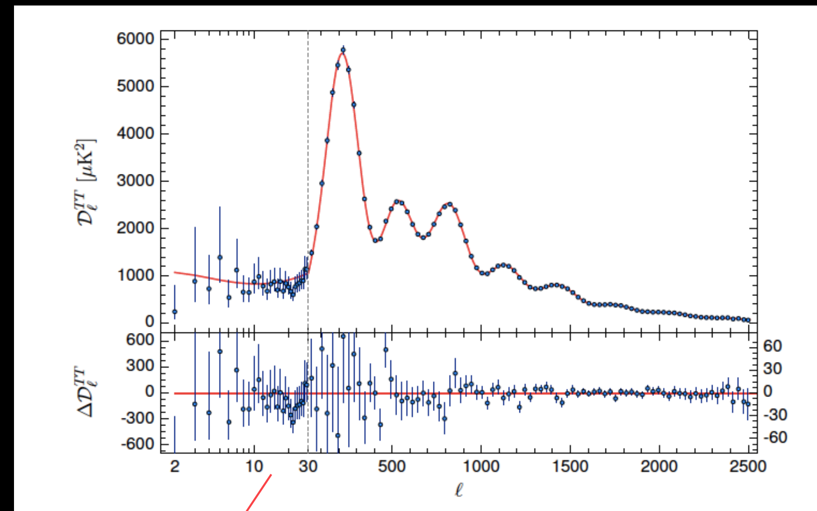
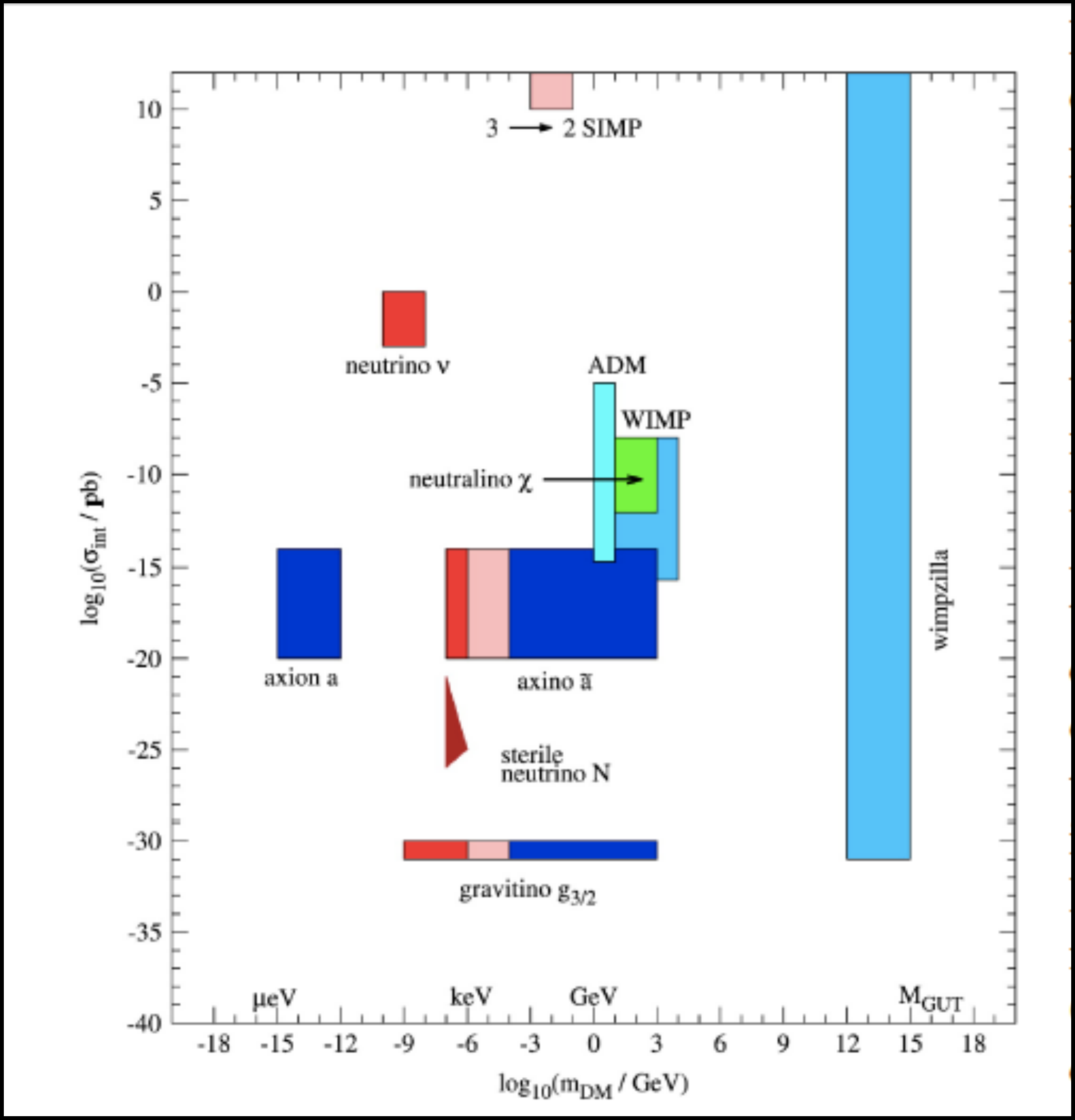



Planck TT,TE,EE+lowP

$$\boxed{\Omega_{CDM,0}h^2 = 0.1198 \pm 0.0015 \sim 5\Omega_{B,0}h^2}$$

# Beyond the WIMP paradigm

(Baer et al.1407.0017)



# Beyond the WIMP paradigm

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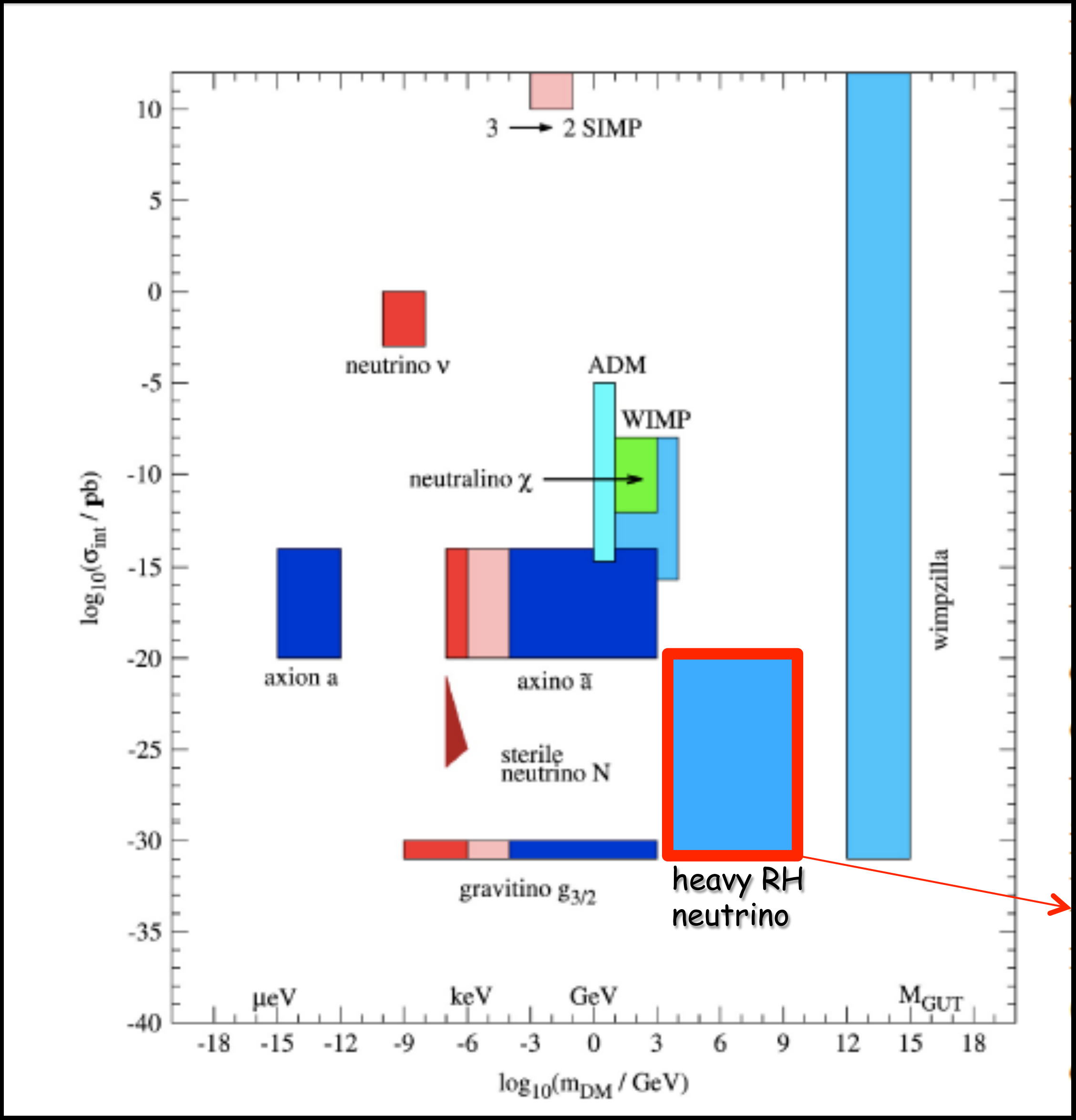


(PDB, Anisimov '08)

# Traditional 3 RH neutrino type-I seesaw

• Dirac + (Right-Right) Majorana mass terms

(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):

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

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

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 $N_1$ decays also radiatively and this produces constraints from X-rays (or opportunities to observe it). Currently a combination with structure formation constraints forces 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)

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

(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:

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

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

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

One could think of an abundance induced by RH neutrino mixing, after all consider that:

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

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

# RH neutrino mixing from Higgs portal

(Anisimov,PDB '08)

New interactions with the standard Higgs:

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

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

effective mixing Hamiltonian (in monocromatic approximation)

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

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

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

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

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

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Consider a 2 RH neutrino mixing for simplicity (A ←→ S=B or C) and consider medium effects:

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From the new interactions:

$$V_{JK}^\Lambda \simeq \frac{T^2}{12\,\Lambda}\,\lambda_{JK}$$

$$\widetilde{\Lambda} \equiv \Lambda/\lambda_{AS} \qquad \Delta M^2 \equiv M_{\rm S}^2 - M_{\rm DM}^2 \qquad v_{\rm S}^Y \equiv T^2\,h_{\rm S}^2/(4\,\Delta M^2) \qquad \sin 2\theta_\Lambda(T) \equiv T^3/(\widetilde{\Lambda}\,\Delta M^2)$$

effective mixing Hamiltonian (in monocromatic approximation)

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

# Non-adiabatic conversion

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

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

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

Adiabaticity parameter at the resonance

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

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 $\gamma_{res} \lll 1$)

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

For successful dark-matter genesis

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

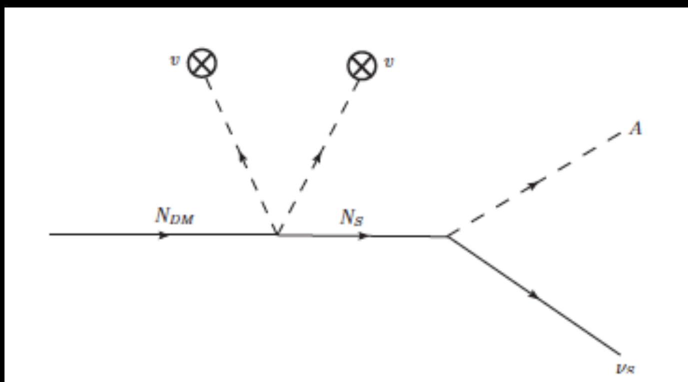
2 options: either $\Lambda < M_{Pl}$ and $\lambda_{AS} \lll 1$ or $\lambda_{AS} \sim 1$ and $\Lambda \ggg M_{Pl}$ :
it is possible to think of models in both cases.

# 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




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

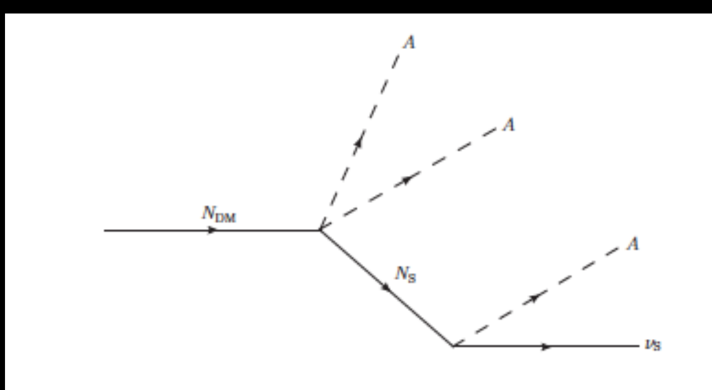
mixing angle today

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

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

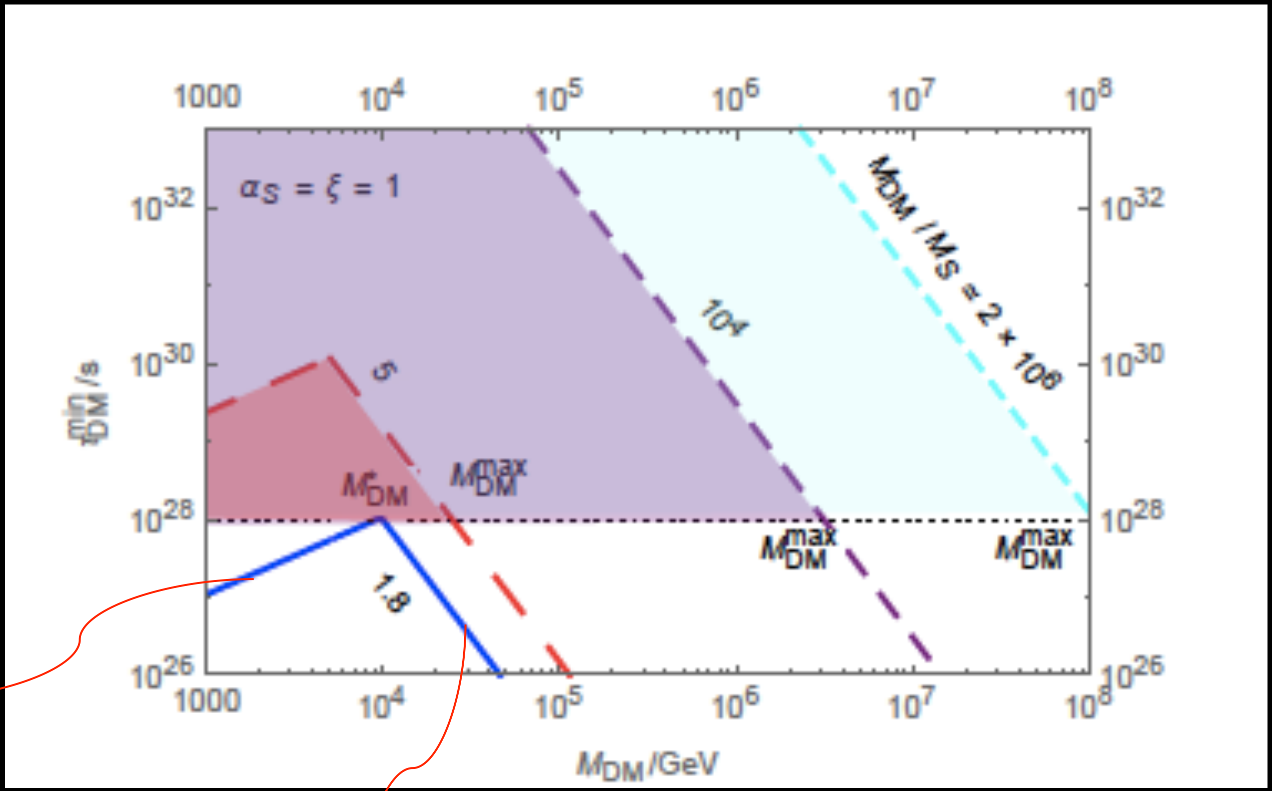



Upper bound on $M_{DM}$ ($\tau_{28} \equiv \tau_{DM}^{min}/10^{28}$s)

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

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

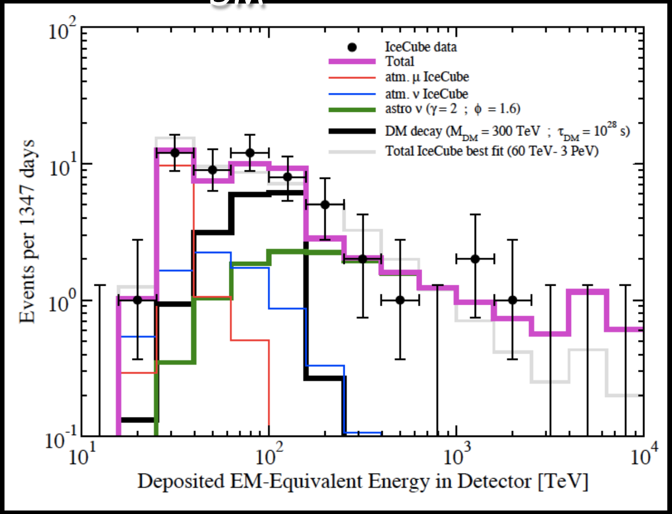
# Decays:very high energy neutrinos at IceCube

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

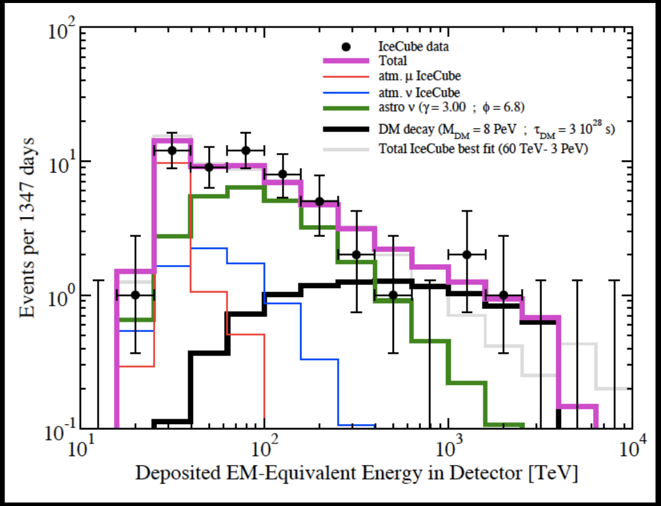
- Since the same interactions responsible for production also unavoidably induce decays ⇒ the model predicts high energy neutrino flux component at some level ⇒ testable at neutrino telescopes (Anisimov,PDB '08)

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 $\gamma$ 's in FERMI? Multimessenger analysis is crucial.

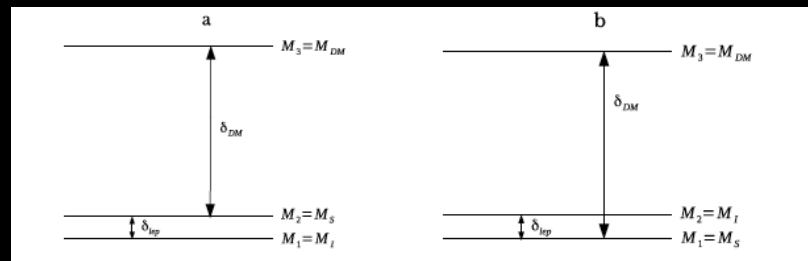
# Unifying Leptogenesis and Dark Matter

(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 $M_1 \simeq M_2 \Rightarrow$ 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:

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

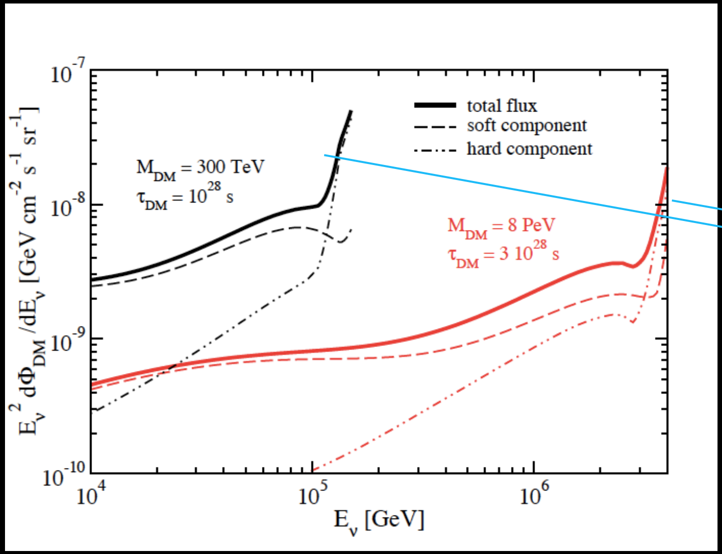
Efficiency factor

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

- $M_S \gtrsim 2\,T_{sph} \simeq 300$ GeV $\Rightarrow$ 10 TeV $\lesssim M_{DM} \lesssim$ 10 PeV
- $M_S \lesssim$ 10 TeV
- $\delta_{lep} \sim 10^{-5} \Rightarrow$ leptogenesis is not fully resonant (talk by D. Teresi)

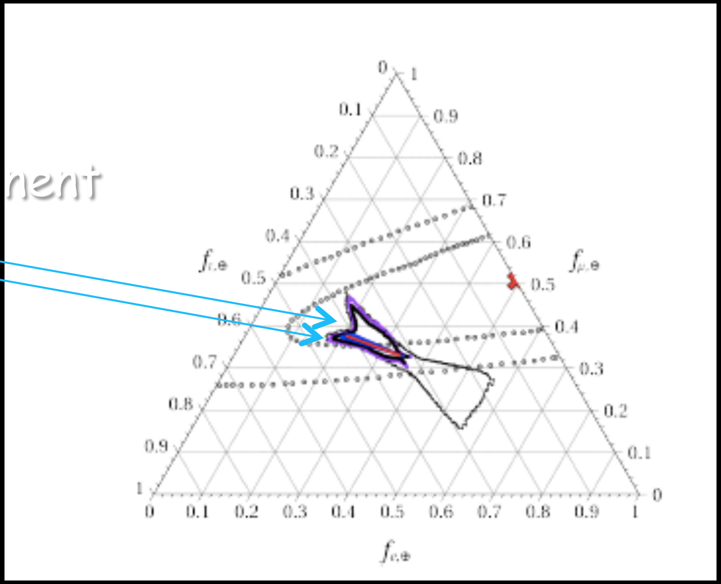
# Decays: a distinct flavour composition

Energy neutrino flux




Hard component

Flavour composition at the detector (Normal Hierarchy)




For NH 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.

# 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

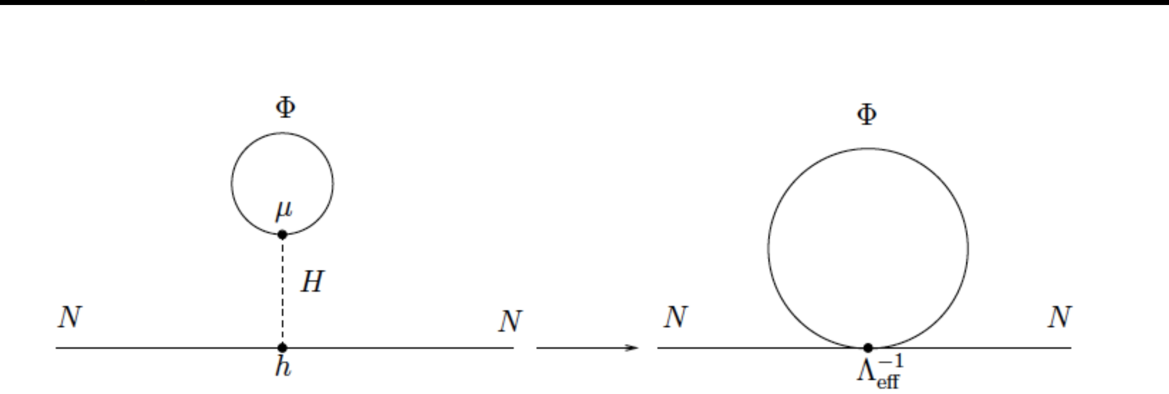
- The scenario is also compatible with leptogenesis

- A natural allowed window for the mass of Dark Matter in TeV-10 PeV range and some contribution to high energy neutrino flux in that renge of energies is an unavoidable feature ⇒ the model is testable with neutrino telescopes…. a multimessenger analysis should yield even stronger constraints (Cohen, Murase, Rodd,Safdi,Soreq 1612.05638)

# Possible models

(Anisimov,PDB, 2010, unpublished)

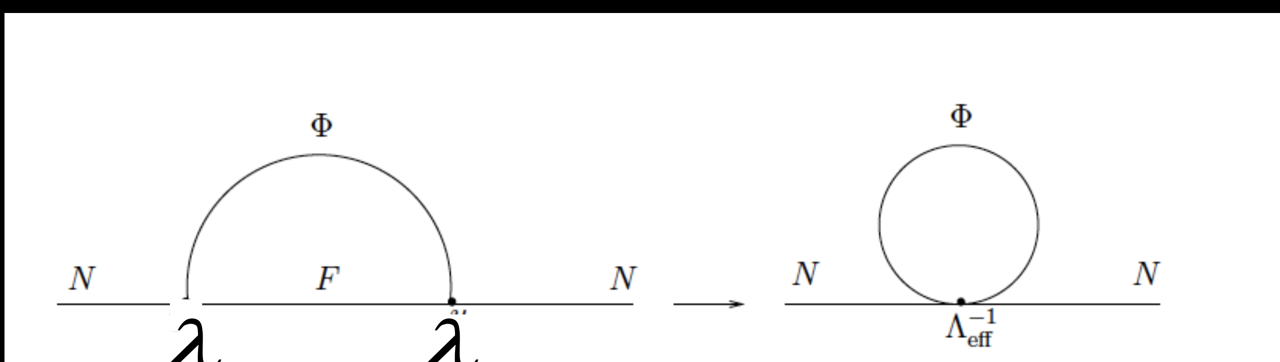
## Option 1: $\lambda$ ~ 1




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

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

## Option 2: $\lambda$ <<< 1




$$\Lambda_{eff} \sim \lambda^{-2} M_F$$