Royal Society Yusuf Hamied virtual Workshop for India and the UK

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Dark Matter from sterile-sterile neutrino mixing

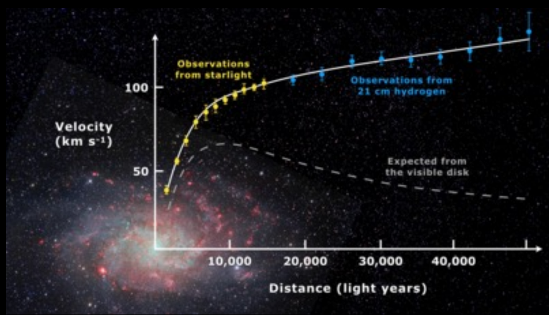
Pasquale Di Bari

(University of Southampton)

Dark Matter

At the present time dark matter acts as a cosmic glue keeping together

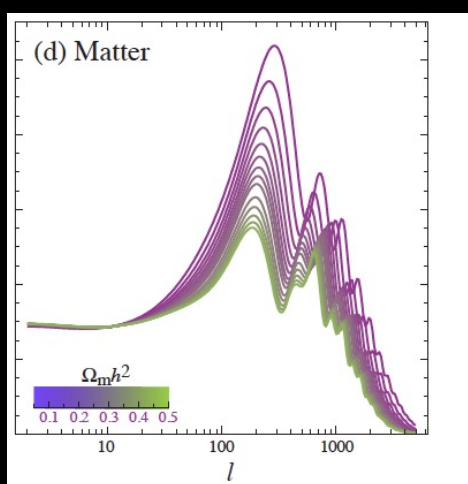
stars in galaxies and ..... galaxies in clusters of galaxies



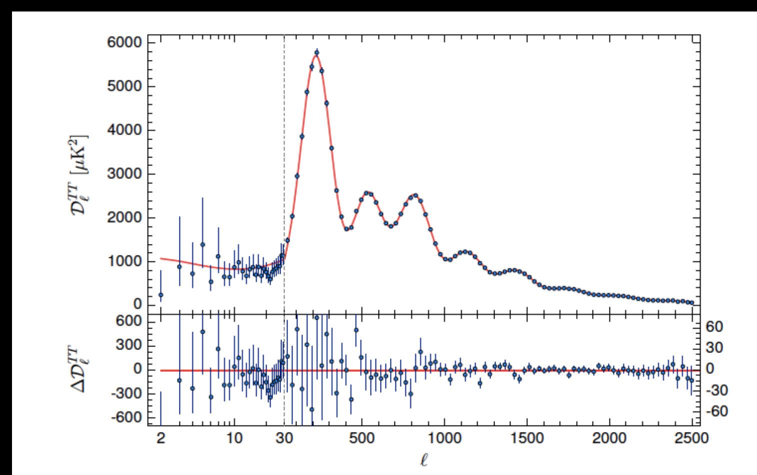
Coma cluster

...it also explains gravitational lensing+Xray observations in bullet cluster

...but it also has to be primordial to understand structure formation and CMB anisotropies



(Hu, Dodelson, astro-ph/0110414)



CMB + BAO

(Planck 2018, 1807.06209)

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

Massive neutrinos as dark matter?

Neutrino abundance freezes out when neutrinos are still ultra-relativistic ⇒

$$\Omega_{\nu 0} = \frac{n_{\nu 0} \sum_i m_i}{\varepsilon_{c0}} \Rightarrow \sum_i m_i \simeq 93\,\mathrm{eV}\,\Omega_{\nu 0} h^2$$

Imposing $\Omega_{\nu 0}h^2 \leq \Omega_{DM0}h^2 \simeq 0.12 \Rightarrow \sum_i m_i = 11\mathrm{eV}\, f_\nu$ $\quad (f_\nu \equiv \Omega_{\nu 0}/\, \Omega_{DM0})$

- Massive neutrinos do not seem to play any role in structure formation.
- In fact neutrino masses are even detrimental contributing to unwanted hot dark matter and for this reason (combining CMB + BAO) one obtains an upper bound $f_\nu \lesssim 0.02$ translating into an upper bound $\sum_i m_i \lesssim 0.2$ eV

Combining the upper bound from cosmology with the lower bound from neutrino oscillation experiments, one has a narrow window:

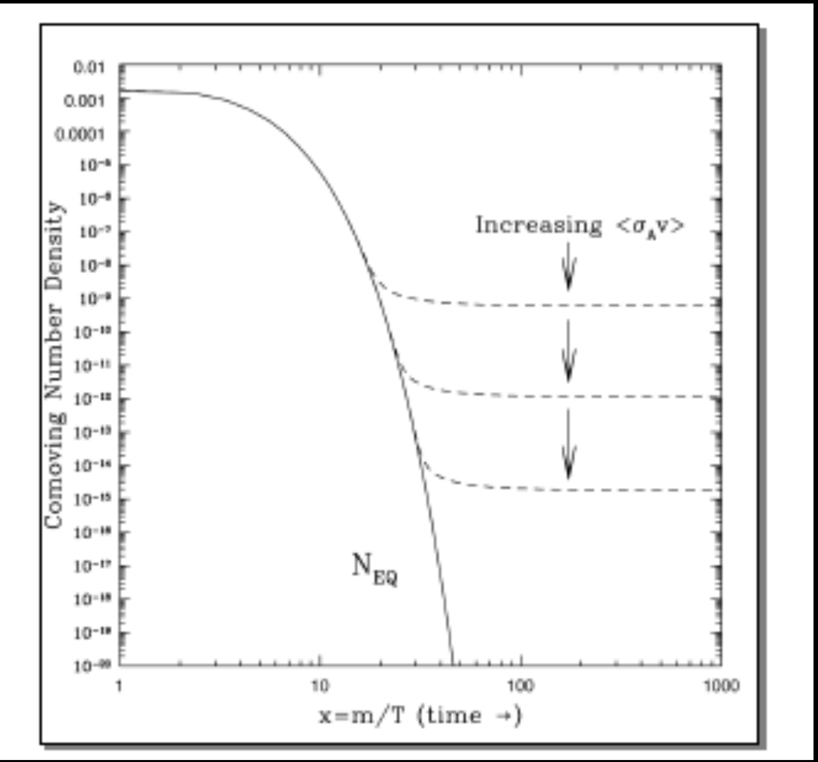
$$0.06\,\mathrm{eV} \leq \sum_i m_i \leq 0.17\,\mathrm{eV} \quad (95\%\ \mathrm{C.L.})$$

In next years cosmology should be able to measure $\sum_i m_i$ with $\delta(\sum_i m_i) \simeq 0.015$eV

Curiosity: neutrino contribution to matter today is comparable to that of stars

$$\Omega_{\mathrm{stars},0}/3 \leq \Omega_{\nu 0} \leq \Omega_{\mathrm{stars},0} \simeq 0.004$$

Non-relativistic freeze-out



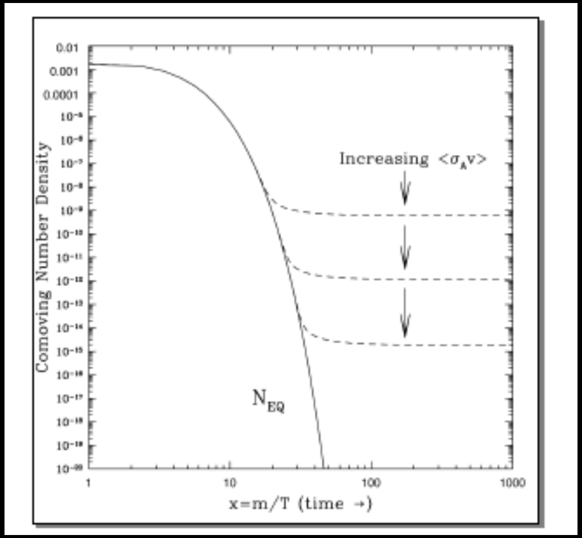
$$\Omega_X h^2 \simeq \frac{4\times 10^{-10}}{\langle\sigma_{\rm ann}\,\beta_{\rm rel}\rangle}\left(\frac{\hbar c}{\rm GeV}\right)^2 \simeq \frac{1.6\times 10^{-37}\,{\rm cm}^2}{\langle\sigma_{\rm ann}\,\beta_{\rm rel}\rangle_f},$$

WIMP miracle

$$\langle\sigma_{\rm ann}^{\rm weak}\beta_{\rm rel}\rangle \simeq \frac{\alpha_{\rm weak}^2}{m_X^2} \simeq 4\times 10^{-37}\,{\rm cm}^2\left(\frac{100\,{\rm GeV}}{m_X}\right)^2 \Rightarrow (\Omega_X h^2)_{\rm WIMP} \sim \mathcal{O}(0.1)\left(\frac{100\,{\rm GeV}}{m_X}\right)^2$$

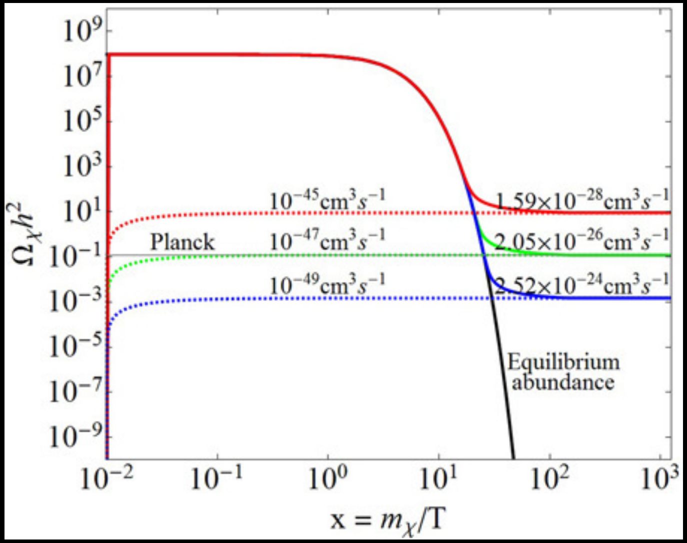
Freeze-out vs. freeze-in solutions

Freeze-out (WIMPs)



$$\Omega_X\, h^2 \simeq \frac{4\times10^{-10}}{\langle\sigma_{\rm ann}\,\beta_{\rm rel}\rangle}\left(\frac{\hbar\, c}{\rm GeV}\right)^2 \simeq \frac{1.6\times10^{-37}\,{\rm cm}^2}{\langle\sigma_{\rm ann}\,\beta_{\rm rel}\rangle_{\rm f}}\,,$$

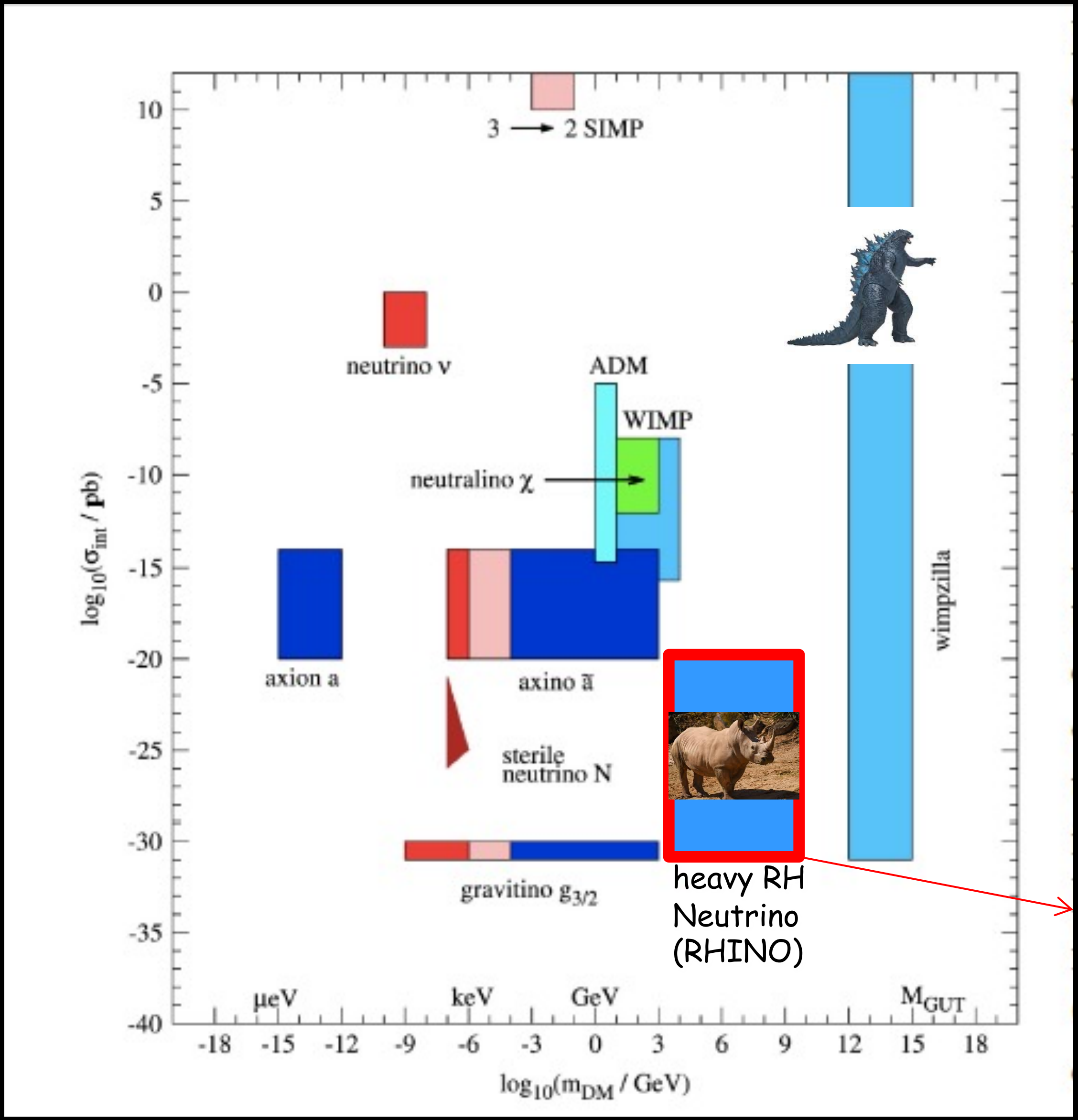
Freeze-in solution (FIMPs)



$$\Omega_{DM0}\, h^2 \propto \langle\sigma_{\rm ann}\beta_{\rm rel}\rangle$$

Beyond the WIMP paradigm

(from Baer et al.1407.0017)

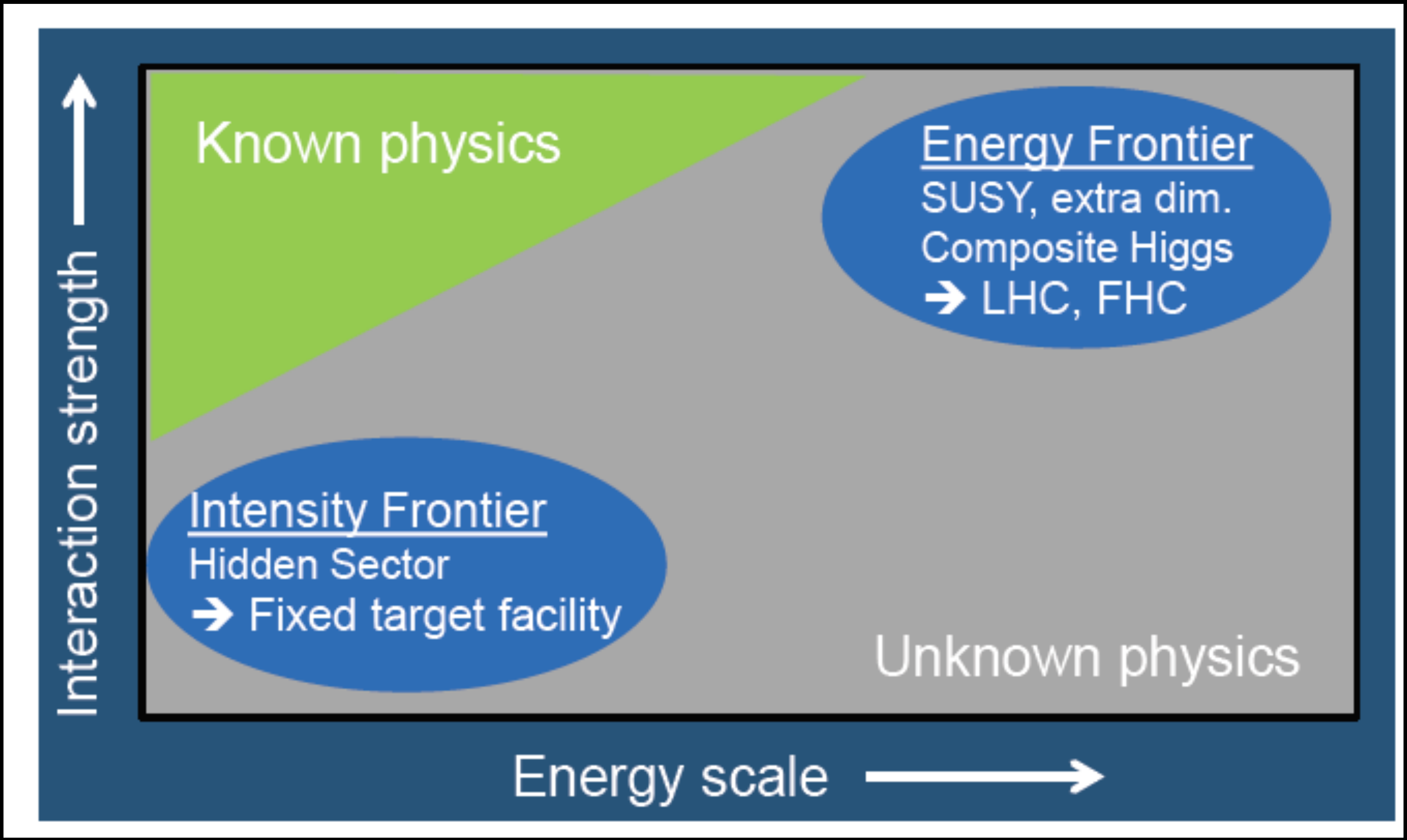


(PDB, Anisimov '08)

The more we know the less we understand?

Right-handed neutrino laboratory searches

(SHIP proposal, 1504.04855)



Dark matter from active-sterile neutrino mixing

(Dodelson Widrow '94; Shi, Fuller '99; Dolgov and Hansen '00; Asaka, Blanchet,Shaposhnikov '05)

- Type-I seesaw Lagrangian $-\mathcal{L}^{\nu}_{mass} = \overline{\nu}_L m_D \nu_R + \frac{1}{2}\overline{\nu^c_R} M \nu_R + h.c. = -\frac{1}{2}(\overline{\nu_L}\ \overline{\nu^c_R})\begin{pmatrix} 0 & m_D^T \\ m_D & M \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu^c_R \end{pmatrix} + h.c.$

$$\nu_{1L} \simeq U^{\dagger}_{1\alpha}\left(\nu_{L\alpha} - \frac{m_{D\alpha 1}}{M_1}\nu^c_{R1}\right)$$

- LH-RH neutrino mixing

$$N_{1R} \simeq \nu_{1R} + \frac{m_{D\alpha 1}}{M_1}\nu^c_{L\alpha}$$

- For $M_1 \ll m_e$ $\Rightarrow$ $\tau_1 = 5\times 10^{26}\,s\left(\frac{M_1}{keV}\right)^{-5}\left(\frac{10^{-8}}{\theta^2}\right) \gg t_0$ $\qquad \theta^2 \equiv \frac{\sum_\alpha |m_{D\alpha 1}|^2}{M_1^2}$

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

$$\Omega_{N_1} h^2 \sim 0.1\,\frac{\theta^2}{10^{-8}}\left(\frac{M_1}{keV}\right)^2 \sim \Omega_{DM,0} h^2$$

- The lightest neutrino mass $m_1 \lesssim 10^{-5}$ 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
- L ~10^{-4} (3.5 keV line?). (Horiuchi et al. '14; Bulbul at al. '14; Abazajian '14)

Heavy RH neutrino as dark matter ?

(Anisimov,PDB '08)

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

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

Suppose a RH neutrino has tiny Yukawa couplings (e.g., proportional to a small symmetry breaking parameter):

$$m_D \simeq \begin{pmatrix} \varepsilon_{e1} & m_{De2} & m_{De3} \\ \varepsilon_{\mu 1} & m_{D\mu 2} & m_{D\mu 3} \\ \varepsilon_{\tau 1} & m_{D\tau 2} & m_{D\tau 3} \end{pmatrix} \text{ or } m_D \simeq \begin{pmatrix} m_{De1} & \varepsilon_{e2} & m_{De3} \\ m_{D\mu 1} & \varepsilon_{\mu 2} & m_{D\mu 3} \\ m_{D\tau 1} & \varepsilon_{\tau 2} & m_{D\tau 3} \end{pmatrix} \text{ or } m_D \simeq \begin{pmatrix} m_{De1} & m_{De2} & \varepsilon_{e3} \\ m_{D\mu 1} & m_{D\mu 2} & \varepsilon_{\mu 3} \\ m_{D\tau 1} & m_{D\tau 2} & \varepsilon_{\tau 3} \end{pmatrix}$$

$$m_D = V_L^\dagger D_{m_D} U_R \qquad D_{m_D} \equiv v\, diag(h_A, h_B, h_C) \text{ with } h_A \le h_B \le h_C$$

$$\boxed{\tau_{DM} = \frac{4\pi}{h_A^2\, M_{DM}} = 0.87\, h_A^2\, 10^{-26} \frac{\mathrm{TeV}}{M_{DM}} s} \Rightarrow \boxed{\tau_{DM} > \tau_{DM}^{\min} \simeq 10^{28} s \Rightarrow h_A < 10^{-27} \sqrt{\frac{\mathrm{TeV}}{M_{DM}} \times \frac{10^{28}\,\mathrm{s}}{\tau_{DM}^{\min}}}}$$

Too small to reproduce the correct abundance with any production mechanism within a minimal type-I seesaw extension

Many proposed production mechanisms

Recently many production mechanisms have been proposed especially to address IceCube initially seemingly anomalous PeV neutrino events:

•from $SU(2)_R$ extra-gauge interactions (LRSM) (Fornengo,Niro, Fiorentin);

•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)

A 5-dimensional Higgs portal operator as a way out

(Anisimov hep-ph/0612024, Anisimov,PDB 0812.5085)

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}^{\nu}_{Y+M} + \mathcal{L}_{A}$$

Type-I Seesaw Lagrangian

$$-\mathcal{L}^{\nu}_{Y+M} = \overline{L}_{\alpha} h_{\alpha I} N_{I} \tilde{\phi} + \frac{1}{2} \overline{N^{c}_{I}} M_{I} N_{I} + h.c.$$

Anisimov operator(s)

$$\mathcal{L}_{A} = \sum_{I,J} \frac{\lambda_{IJ}}{\Lambda} \phi^{\dagger}\phi \, \overline{N^{c}_{I}} N_{J} + h.c.$$

$$= \frac{\lambda_{DS}}{\Lambda} \phi^{\dagger}\phi \, \overline{N^{c}_{D}} N_{S} + \frac{\lambda_{SS}}{\Lambda} \phi^{\dagger}\phi \, \overline{N^{c}_{S}} N_{S} + \frac{\lambda_{DD}}{\Lambda} \phi^{\dagger}\phi \, \overline{N^{c}_{D}} N_{D} + h.c. \quad (N_{D} = N_{3}; N_{S} = N_{2})$$

Remarks:

- from SMEFT to νSMEFT
- They are kind of Weinberg operators but a further step up
- They extend Higgs portal renormalizable operator (Patt,Wilczek hep-ph/0605188)

RHINO dark matter

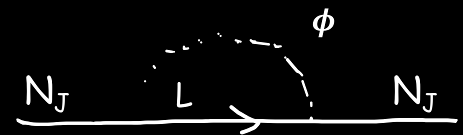
(Anisimov '06, Anisimov,PDB '08)

Consider the RH Higgs-induced neutrino mixing (RHINO) A. operator:

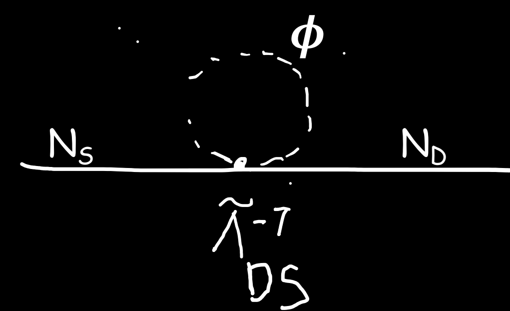
$$\mathcal{L}_A = \frac{\lambda_{DS}}{\Lambda}\phi^\dagger\phi\,\overline{N_D^c}N_S$$

In general, $\lambda_{DS} \neq 0$ this generates a dark-source RH neutrino mixing. The Yukawa and Anisimov interactions both generate effective potentials from self-energies:

From Yukawa interactions $\quad V_S^Y = \frac{T^2}{8p}h_S^2$



From mixing $\quad V_{DS}^\Lambda = \frac{T^2}{12\Lambda}\lambda_{DS}$



$$\tilde{\Lambda}_{DS} = \Lambda / \lambda_{DS}$$

Effective mixing Hamiltonian :

$$\Delta H \simeq \begin{pmatrix} -\frac{\Delta M^2}{4p} - \frac{T^2}{16p}h_S^2 & \frac{T^2}{12\tilde{\Lambda}_{DS}} \\ \frac{T^2}{12\tilde{\Lambda}_{DS}} & \frac{\Delta M^2}{4p} + \frac{T^2}{16p}h_S^2 \end{pmatrix}$$

$$\Delta M^2 \equiv M_S^2 - M_D^2$$

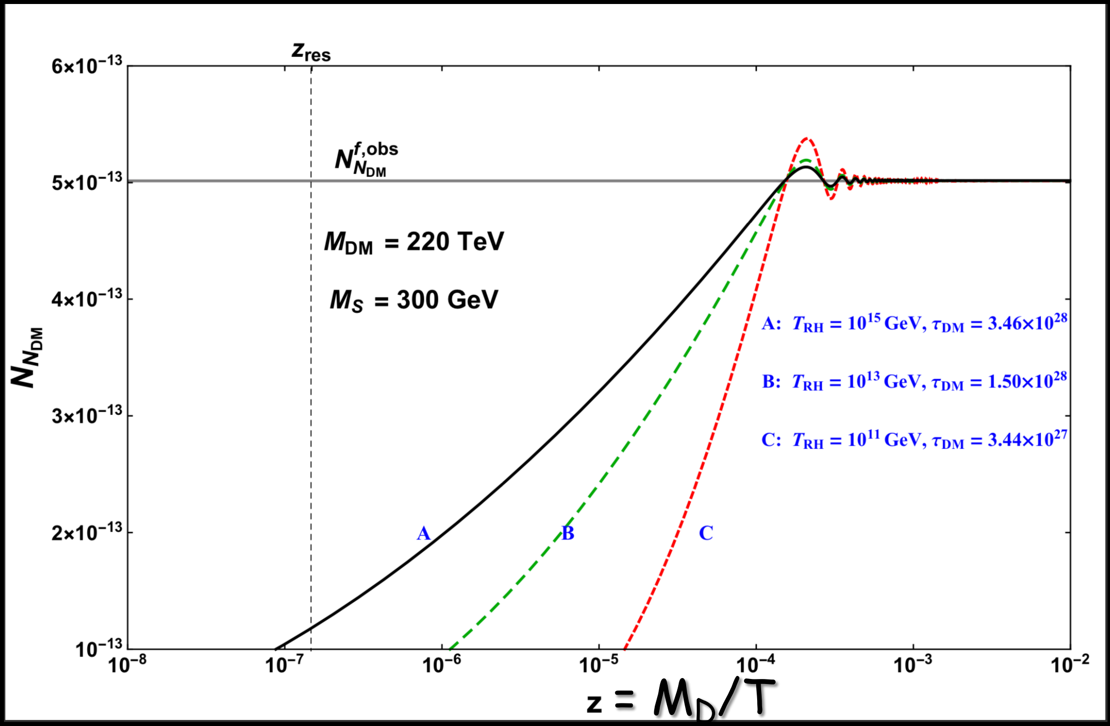
Density matrix calculation of the relic abundance

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

Density matrix equation for the dark-source RH neutrino system (using a monocromatic approximation p~3T)

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

Example for initial N_S thermal abundance

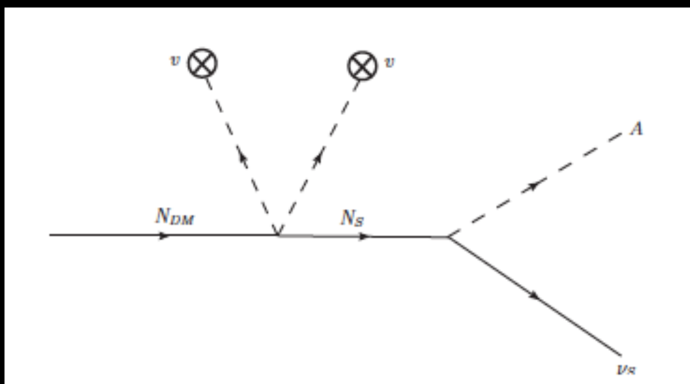


Constraints from decays

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

2 body decays (M_S>M_W)

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



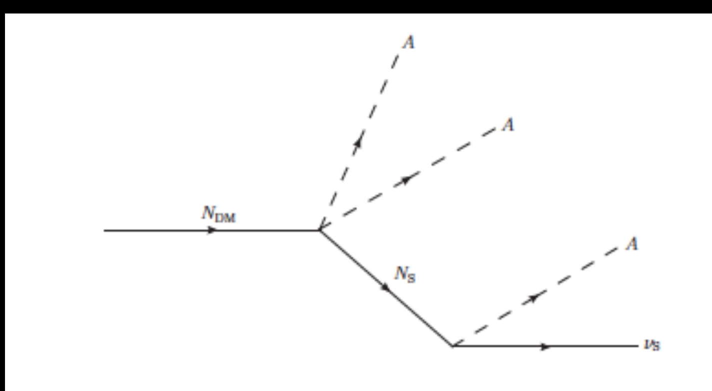
$$\theta_{\Lambda 0} = \frac{2\, v^2/\widetilde{\Lambda}_{\rm DS}}{M_{\rm D}\,(1 - M_{\rm S}/M_{\rm D})}$$

mixing angle today (for $\theta_{\Lambda 0}$ <<1)

$$\Gamma_{{\rm D}\to A+\ell_{\rm S}} = \frac{h_{\rm S}^2}{\pi}\left(\frac{v^2}{\widetilde{\Lambda}}\right)^2 \frac{M_{\rm D}}{(M_{\rm D}-M_{\rm S})^2}\,.$$

⇒ Lower bound on M_{DM}

4 body decays



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

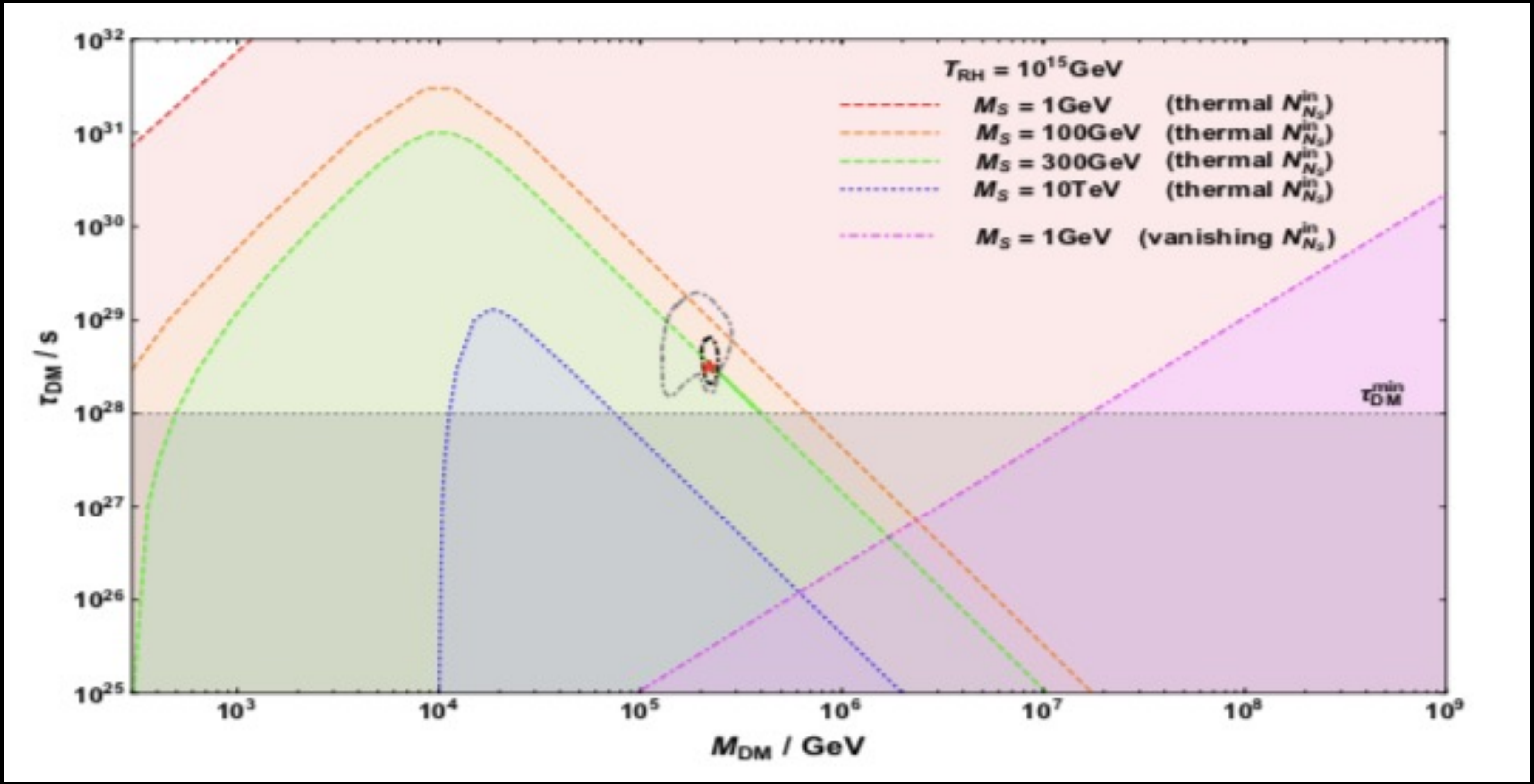
$$\Gamma_{{\rm D}\to 3A+\ell_{\rm S}} = \frac{\Gamma_{\rm S}}{15\cdot 2^{11}\cdot\pi^4}\,\frac{M_{\rm D}}{M_{\rm S}}\left(\frac{M_{\rm D}}{\widetilde{\Lambda}_{\rm DS}}\right)^2$$

⇒ Upper bound on M_{DM}

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

DM lifetime vs. mass plane: allowed regions

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



Solutions only for initial thermal N_S abundance, unless $M_S \sim 1$ GeV and $M_D \gtrsim 10^7$ GeV

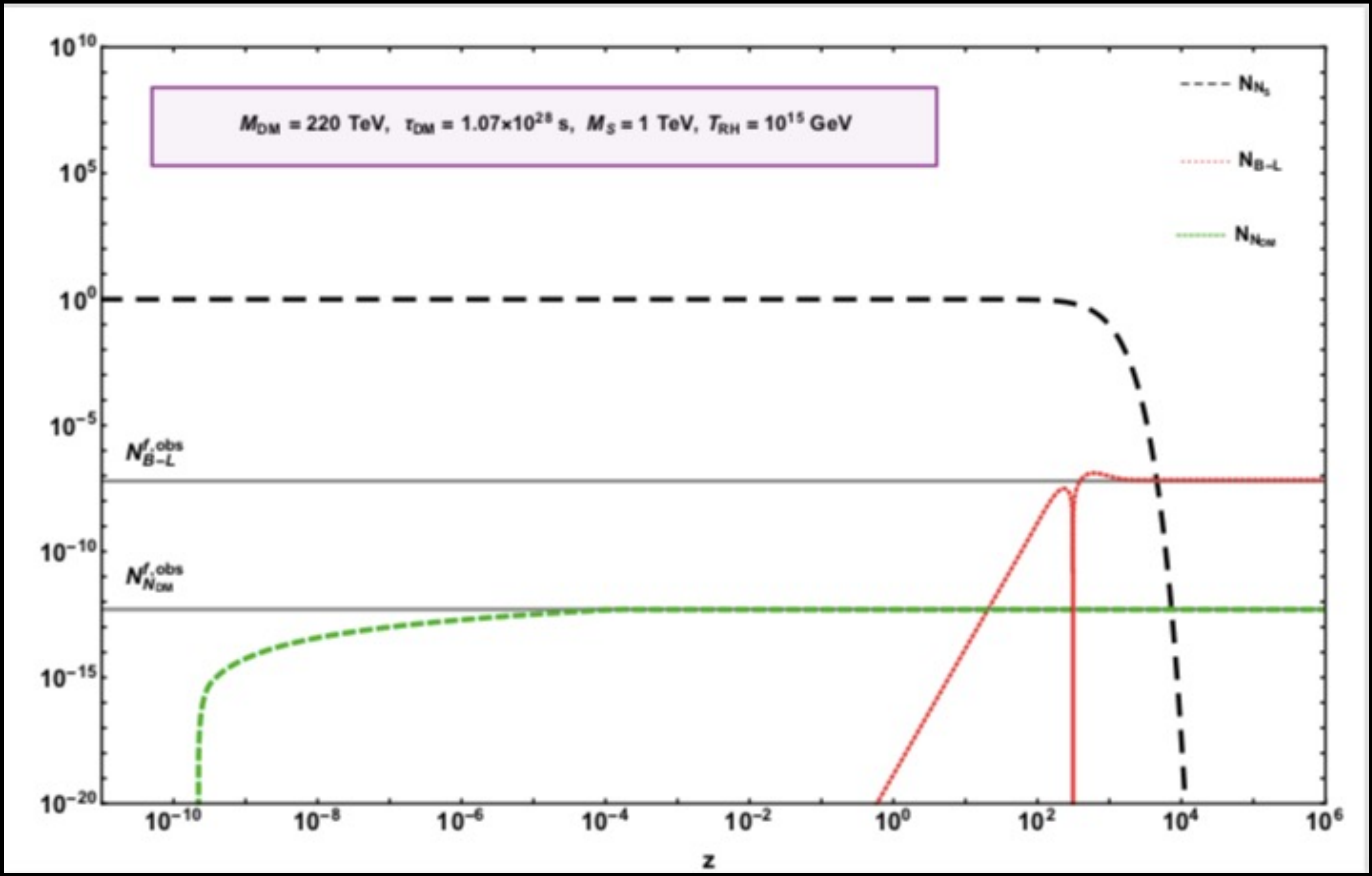
Can one think of processes able to thermalize the N_S abundance prior to the oscillations?

Two good motivations

Unifying Leptogenesis and Dark Matter

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

A solution for initial thermal N_S abundance:

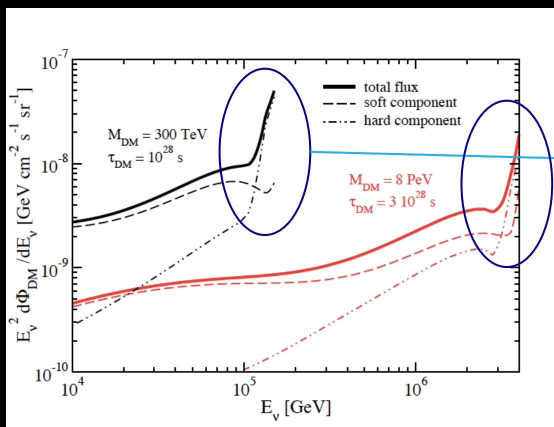


Very high energy neutrinos from decays

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

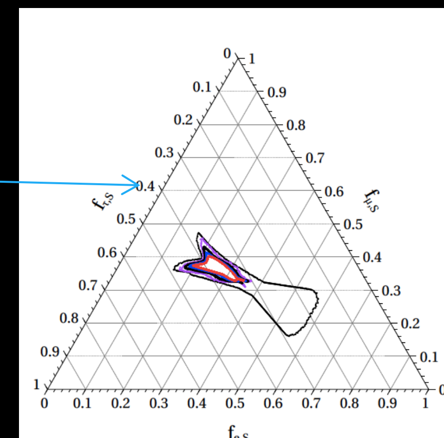
- DM neutrinos unavoidably decay today into A+leptons (A=H,Z,W) through the same mixing that produced them in the very early Universe
- Potentially testable high energy neutrino contribution

Energy neutrino flux



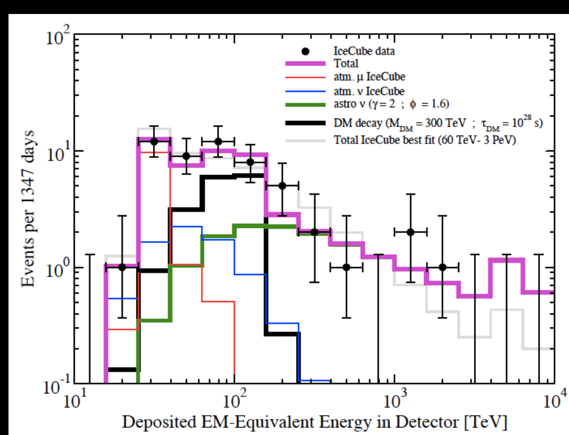
Hard component

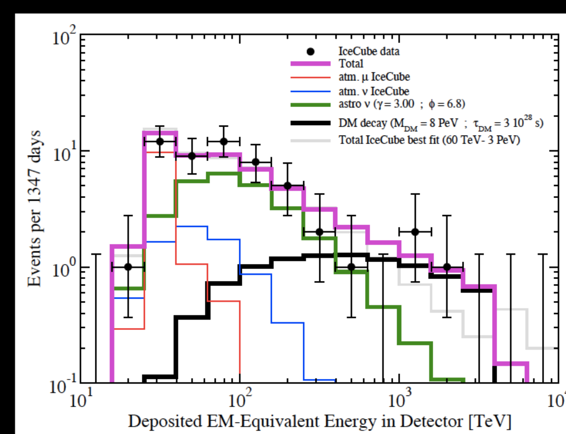
Flavour composition at the detector



Neutrino events at IceCube: 2 examples

M_{DM}=300TeV

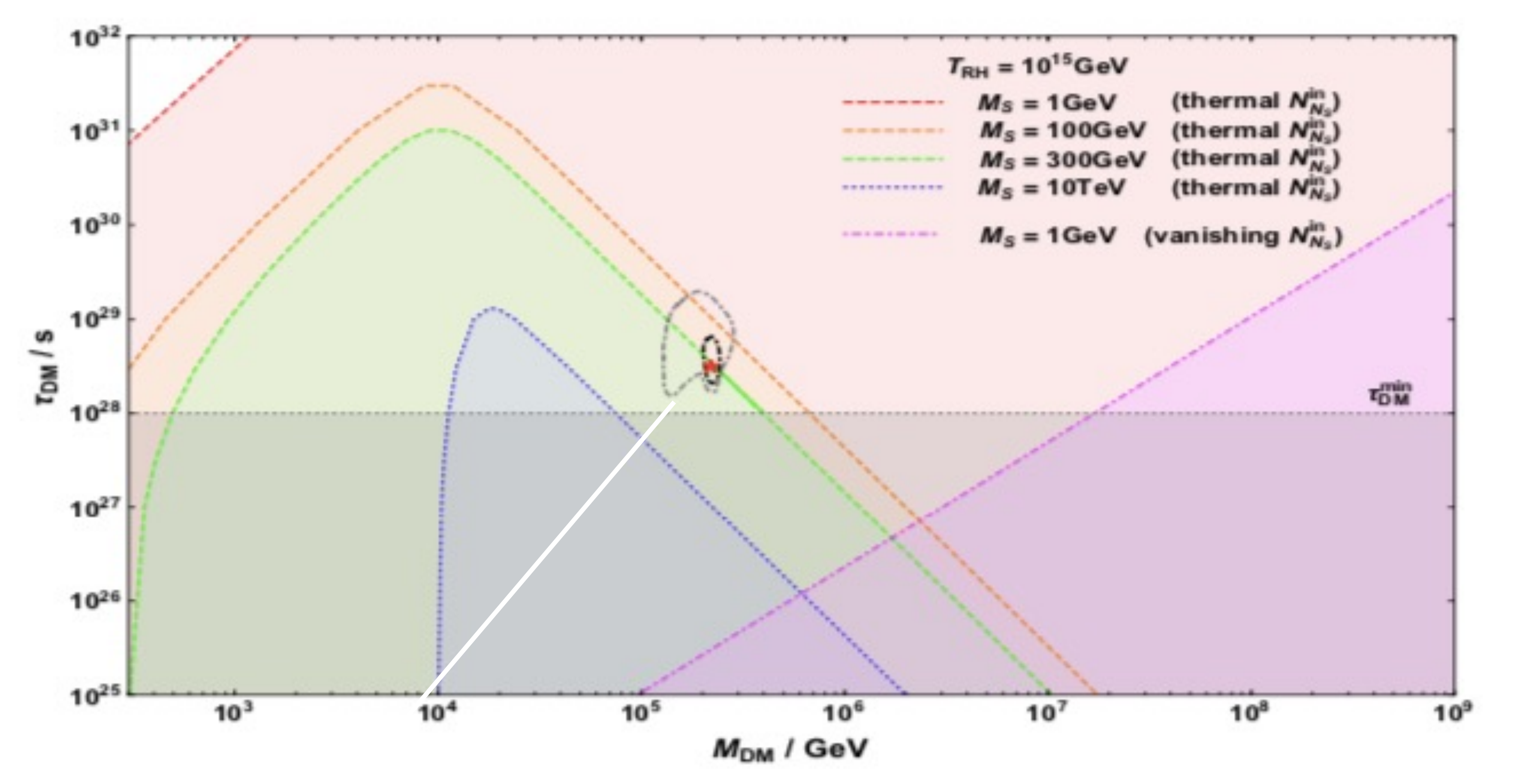




M_{DM}=8 PeV

DM lifetime vs. mass plane: allowed regions

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



95% C.L. region where neutrinophilic DM decays well fit an excess in the neutrino flux at ~100 TeV energies in addition to an astrophysical component (Chianese et al. 1808.02486)

Including Higgs portal interactions for N_S

(PDB, A. Murphy, arXiv 2210.10801)

$$\mathcal{L}_A = \frac{\lambda_{DS}}{\Lambda}\phi^\dagger\phi\,\overline{N^c_{DM}}N_S + \frac{\lambda_{SS}}{\Lambda}\phi^\dagger\phi\,\overline{N^c_S}N_S$$

Can these interactions thermalise the source neutrinos prior to the mixing?

Let us modify the kinetic equations including these processes:

$$\frac{dN_{IJ}}{dt} = -i\,[\Delta H, N]_{IJ} - \begin{pmatrix} 0 & \frac{1}{2}(\Gamma_D + \Gamma_S)N_{DS} \\ \frac{1}{2}(\Gamma_D + \Gamma_S)N_{SD} & (\Gamma_D + \Gamma_S)(N_{N_S} - N^{eq}_{N_S}) + \frac{\langle \sigma_{\phi\phi \to N_S N_S} v\rangle}{R^3}(N^2_{N_S} - N^{eq\,2}_{N_S}) \end{pmatrix}$$

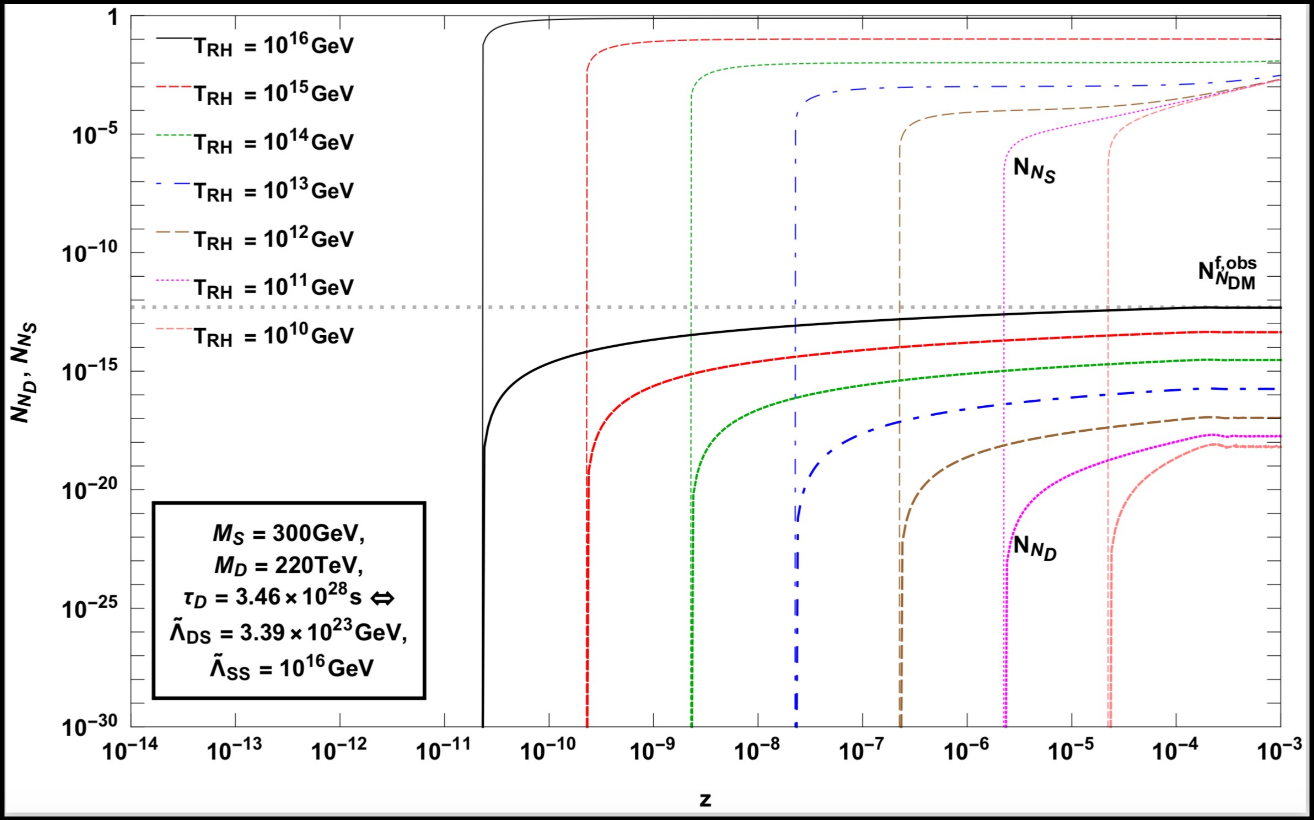
$$A(z) \equiv \frac{\langle \sigma_{\phi\phi\to N_S N_S} v\rangle}{R^3 H z} = \frac{A(z=1)}{z^2}; \qquad \langle \sigma_{\phi\phi\to N_S N_S} v\rangle_{T>>M_S} \simeq \frac{1}{4\pi \tilde{\Lambda}^2_{SS}}$$

$$\Rightarrow A(z=1) \simeq g_N \frac{3}{16}\frac{\xi(3)}{\pi^3}\sqrt{\frac{90}{8\pi^3 g_R}}\frac{M_D M_{Pl}}{\tilde{\Lambda}^2_{SS}}$$

Condition for the thermalisation of the N_S abundance

(PDB, A. Murphy, arXiv 2210.10801)

$$\Rightarrow N_{N_S}(z_{in} \ll z \ll 1) - N_{N_S}(z_{in}) \simeq \frac{A_1}{z_{in}} \simeq 1.0 \times \left(\frac{T_{in}}{10^{16}\,\mathrm{GeV}}\right)\left(\frac{10^{16}\,\mathrm{GeV}}{\tilde{\Lambda}_{SS}}\right)^2 \simeq 1$$

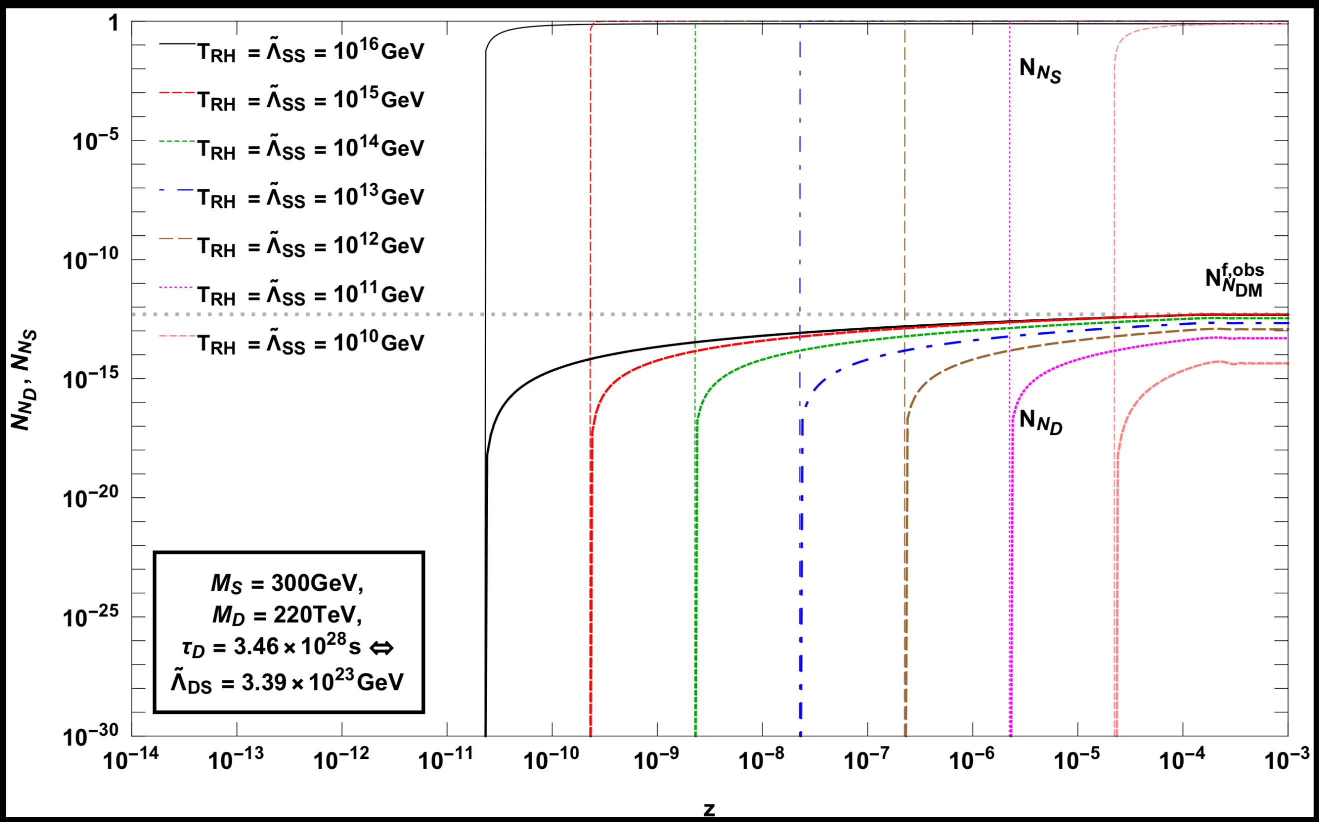


The emerging effective scale for the thermalization coincides with the grandunified scale: a RHINO miracle ?

Condition for the thermalisation of the N_S abundance

(PDB, A. Murphy, arXiv 2210.1081)

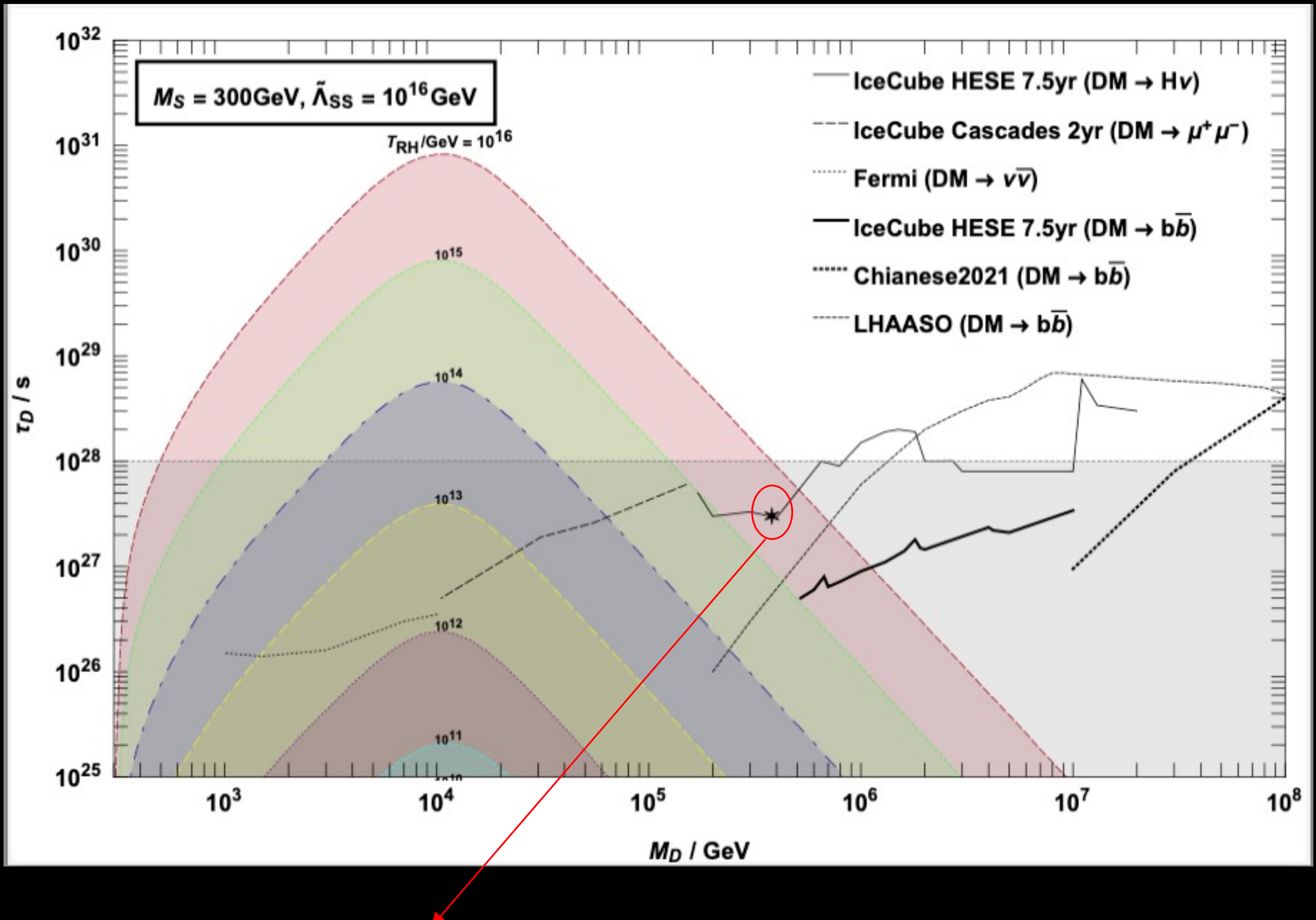
$$\Rightarrow N_{N_S}(z_{in} \ll z \ll 1) - N_{N_S}(z_{in}) \simeq \frac{A_1}{z_{in}} \simeq 1.0 \times \left(\frac{T_{in}}{10^{16}\,\mathrm{GeV}}\right)\left(\frac{10^{16}\,\mathrm{GeV}}{\tilde{\Lambda}_{SS}}\right)^2 \simeq 1$$



For the validity of the EFT: $T_{RH} \lesssim \tilde{\Lambda}_{SS}$

DM lifetime vs. mass plane: allowed regions

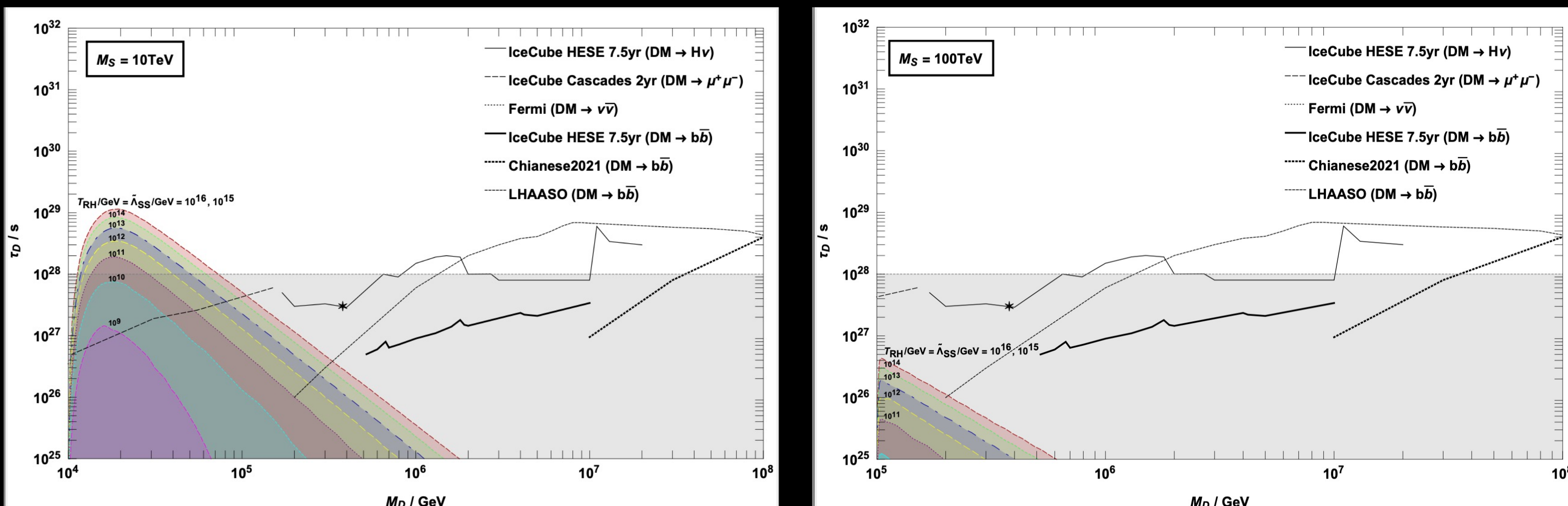
(PDB, A. Murphy, arXiv 2210.10801)



Decaying DM best fit (2.5σ) from IceCube 7.5 year data (2205.12950)

Upper bound on the seesaw (=leptogenesis) scale

(PDB, A. Murphy, arXiv 2210.10801)

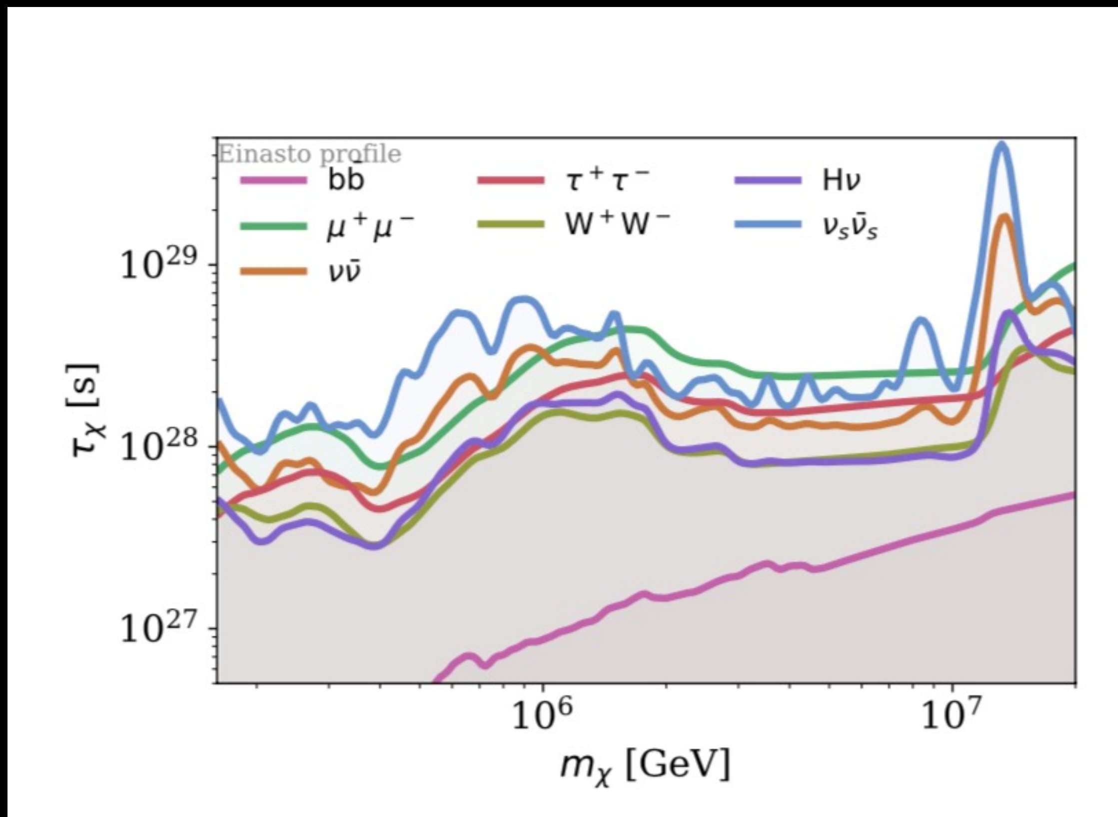


The mechanism is compatible with (resonant) leptogenesis at a scale upto ~ 100 TeV

Searches for Connections between Dark Matter and High-Energy Neutrinos with IceCube

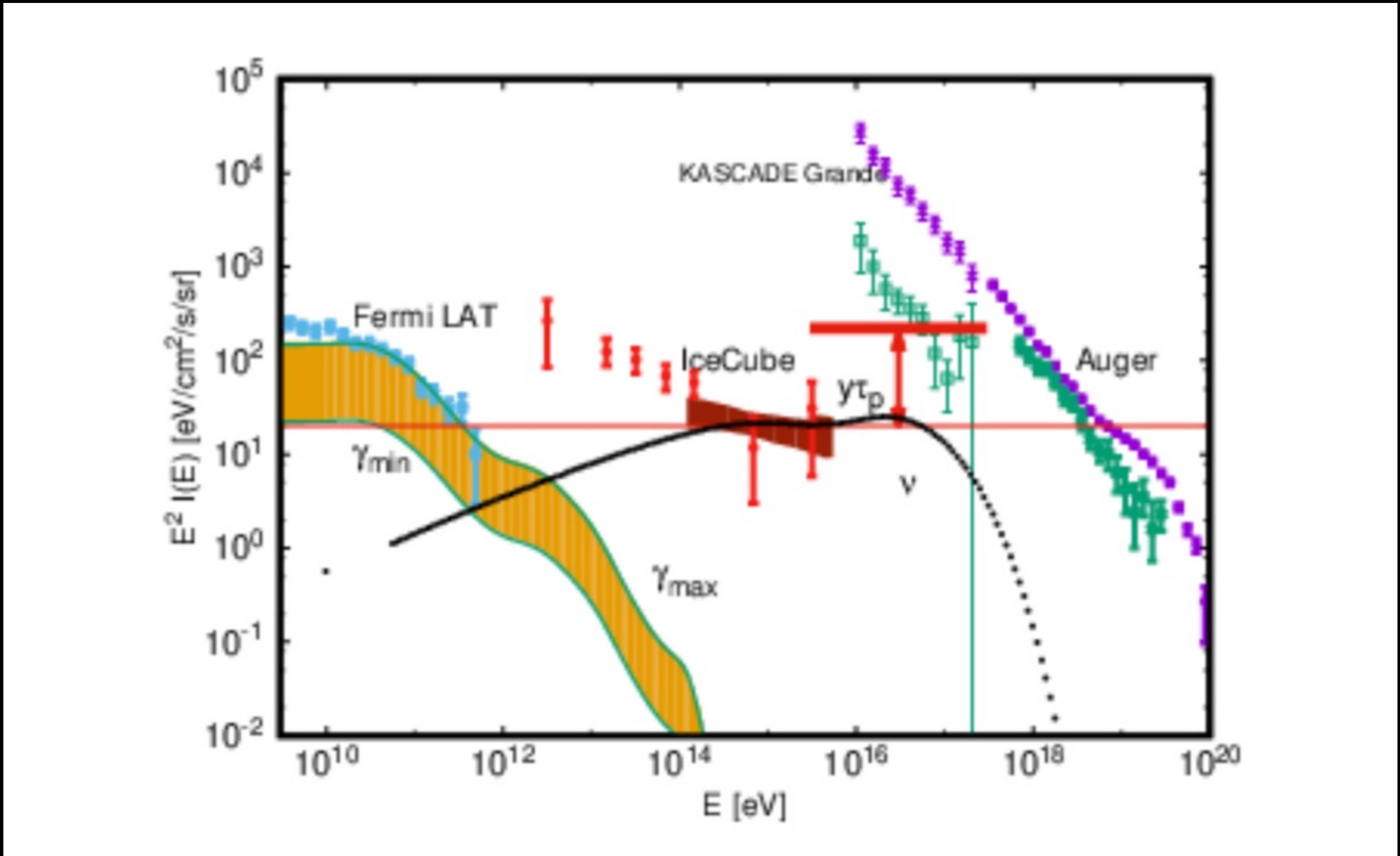
IceCube Collaboration

(2205.12950)



2.5σ significance when compared to the null hypothesis
best fit point: m_D=386 TeV, τ_D=2.8x10^{27} s

Multimessenger analysis

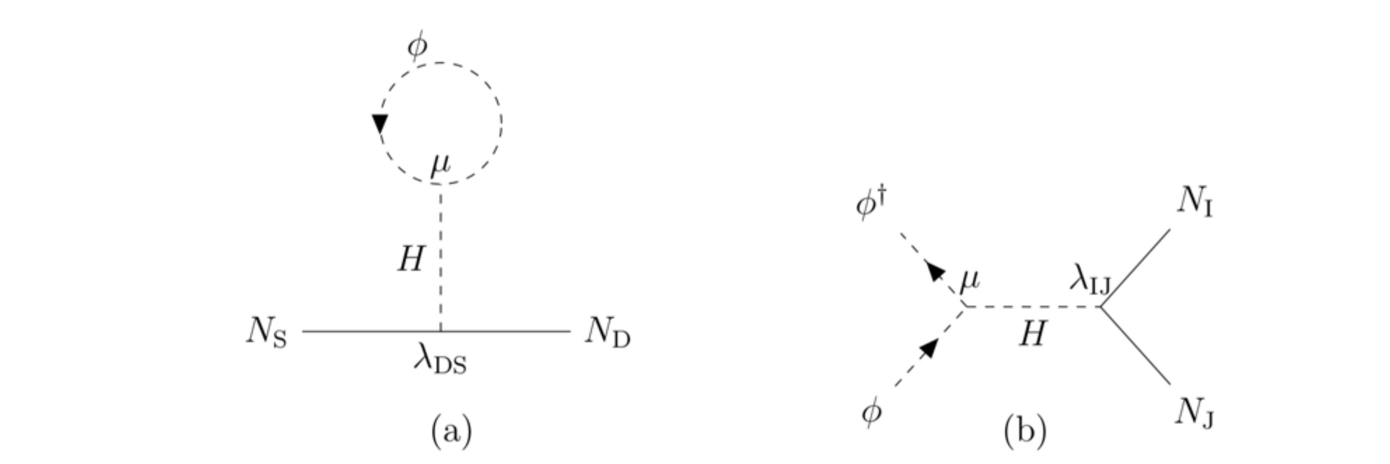


From Kachelriess 2201.04535 (IceCube 3 year data)

A possible GUT origin ? Heavy scalar H as mediator

(Anisimov,PDB, 2008; P.Ludl.PDB,S.Palomarez-Ruiz'16; Kolb and Long 1708.04293; PDB, A. Murphy, arXiv 2210.10801)

$$\mathcal{L}_H = \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2} M_H^2\, H^2 - \sum_{I,J} \lambda_{IJ}\, H\, \overline{N_{\rm I}^c}\, N_J - \mu\, H\, \phi^\dagger\, \phi\,.$$



$$\mathcal{L}_H^{\rm eff} = \frac{1}{2} \sum_{I,J,K,L} \frac{\lambda_{IJ}\lambda_{KL}}{M_H^2} (\overline{N_{\rm I}^c}\, N_J)\, (\overline{N_{\rm K}^c}\, N_L) + \frac{1}{2}\, \frac{\mu^2}{M_H^2}\, (\phi^\dagger\, \phi)^2 + \sum_{I,J} \frac{\mu\, \lambda_{IJ}}{M_H^2}\; \Phi^\dagger\, \Phi\, \overline{N_{\rm I}^c}\, N_{\rm J}\,.$$

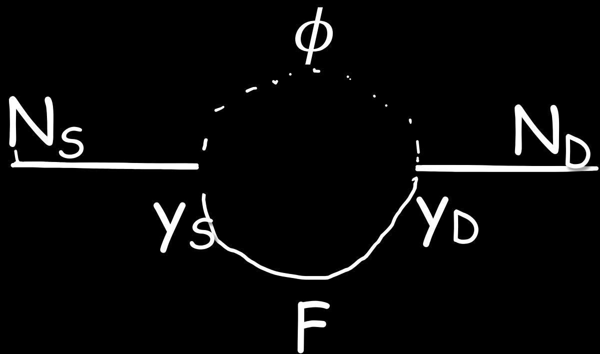
$\Longrightarrow$ $\widetilde{\Lambda}_{IJ} = \Lambda/\lambda_{IJ}$, and $\Lambda = M_H^2/\mu$.

For $\mu \sim 10^9$GeV one can have $\tilde{\Lambda}_{DS} \sim 10^{23}$ GeV and $\lambda_{DS} \sim O(1)$ but one cannot reproduce simultaneously $\tilde{\Lambda}_{SS} \sim 10^{16}$GeV with the same scale Λ

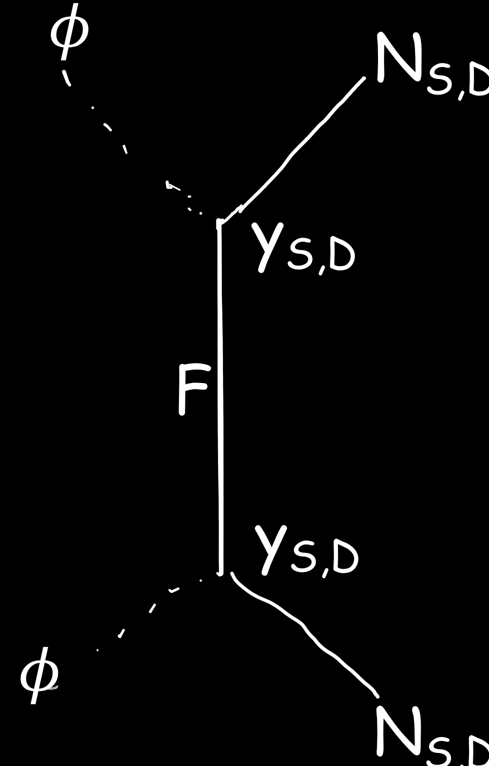
A possible GUT origin ? Heavy fermion F as mediator

(Anisimov,PDB, 2008; PDM, A. Murphy 2210.10801)

$$\mathcal{L}_F = \bar{F}\,(i\,\partial\!\!\!/ - M_{\rm F})\,F - \sum_I y_I\,(\bar{F}\,\phi\,N_I + \bar{N}_I\,\phi^\dagger\,F)$$



$$-\mathcal{L}_F^{\rm eff} = \sum_{I,J} \frac{y_I\,y_J}{M_F}\,\bar{N}_I\,N_J\,\phi^\dagger\,\phi\,, \Longrightarrow \quad \Lambda = M_{\rm F} \text{ and } \lambda'_{IJ} = y_I\,y_J.$$



This time one can have one scale $\Lambda = M_F \sim M_{GUT}$ and for $y_S \sim 1$ and $y_D \sim 10^{-7}$:

$$\tilde{\Lambda}_{DS} = \frac{\Lambda}{y_D y_S} \sim 10^{23}\,\text{GeV} \qquad \tilde{\Lambda}_{SS} = \frac{\Lambda}{y_S y_S} \sim \Lambda \sim 10^{16}\,\text{GeV} \qquad \tilde{\Lambda}_{DD} = \frac{\Lambda}{y_D y_D} \sim 10^{30}\,\text{GeV}$$

$y_D \sim 10^{-7}$ could be understood as a small symmetry (e.g. Z_2) breaking parameter

Summary

- The DM puzzle might have a solution at higher scales than those usually explored and….
- ….neutrino physics is a good place where to look for such a solution. A high scale RH neutrino playing the role of DM requires an extension of the usual type-I seesaw Lagrangian (able already to explain neutrino masses and mixing and the matter-antimatter asymmetry via leptogenesis).
- Higgs induced sterile-sterile neutrino mixing provides not only a way to produce dark neutrinos with the right abundance but also….it makes them detectable at neutrino telescopes.
- Higgs portal interactions for the seesaw (source) neutrino enhance the dark neutrino production and allow to lift the scale of leptogenesis certainly above 300 GeV but even higher,
- Interestingly, the IceCube collaboration find an excess in the neutrino flux at energies well explained by a RHINo DM (~100 TeV) and further support (or constraints) might come from multimessenger astronomy and anisotropies in te high energy neutrino flux (stay tuned!)i.