La Thuille 2023 - Les Rencontres de Physique de la Vallée d'Aoste

5 – 11 March 2023

Right-handed neutrinos and IceCube events

Pasquale Di Bari

(University of Southampton)

Why new physics?

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+GR cannot explain:

- ***Cosmological Puzzles*** :

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

- ***Neutrino masses and mixing***

problem of the origin of matter in the universe

Why new physics?

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+GR cannot explain:

- ***Cosmological Puzzles*:**

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

- ***Neutrino masses and mixing***

right-handed (RH) neutrinos provide a unified solution

Minimally extended SM: Dirac neutrinos

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

$$-\mathcal{L}_Y^\nu = \overline{\nu_L} h \nu_R \phi \Rightarrow SSB \Rightarrow -\mathcal{L}_{Dirac}^\nu = \overline{\nu_L} m_D \nu_R; \; m_D = vh$$

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: $U = V_L^\dagger$

many unanswered questions:

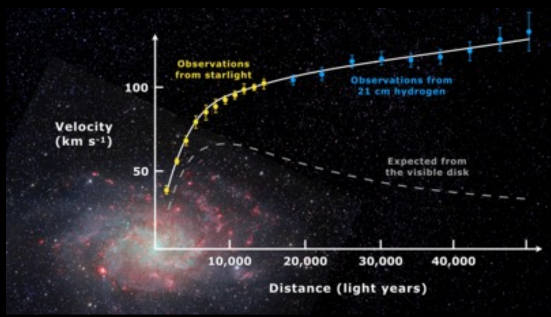
- Why neutrinos are much lighter than all other fermions?
- Why large mixing angles (differently from CKM angles)?

- Cosmological puzzles?

Dark Matter

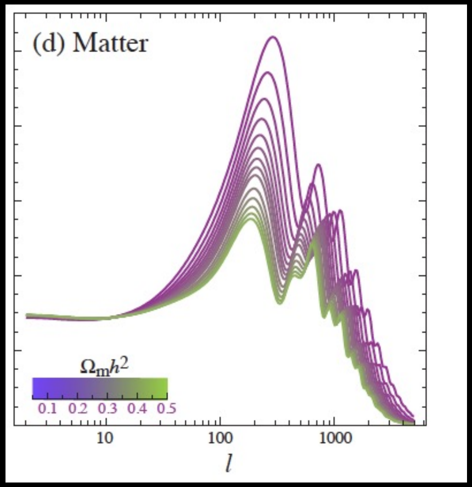
At the present time dark matter acts as a cosmic glue keeping together

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

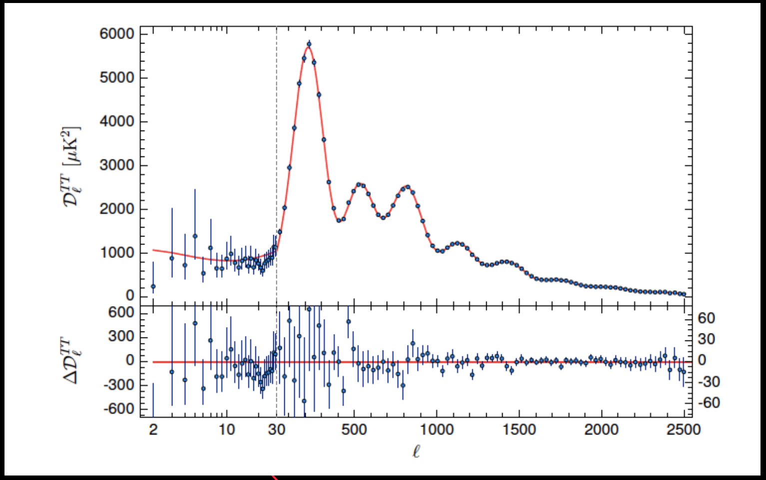


bullet cluster

...but it also needs 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 (ordinary) neutrinos as dark matter?

Ordinary left-handed neutrinos decouple relativistically $\Rightarrow n_{\nu 0} \sim n_{\gamma 0}$

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

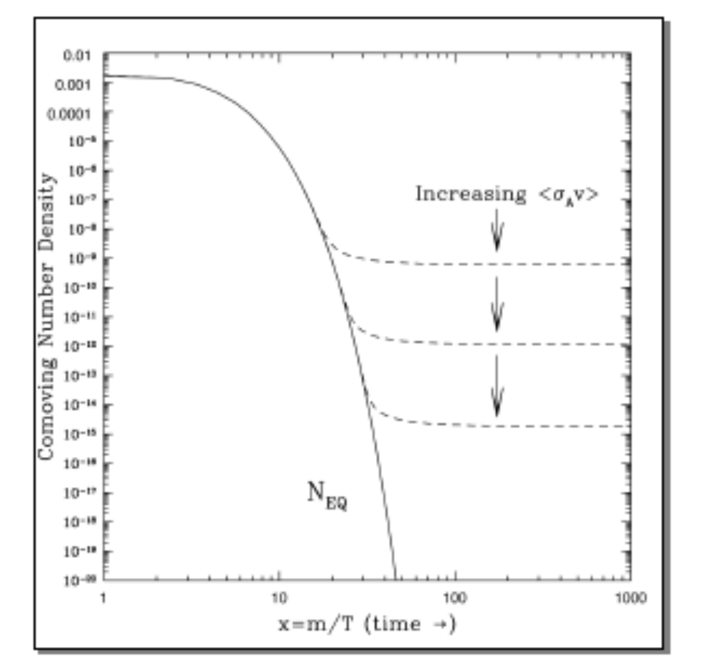
Imposing $\Omega_{\nu 0} h^2 \leq \Omega_{DM0} h^2 \simeq 0.12 \Rightarrow \sum_i m_i = 11\mathrm{eV}\, f_\nu$ $\quad (f_\nu \equiv \Omega_{\nu 0} / \Omega_{DM0})$

- However, 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 in the ΛCDM model $\Rightarrow$ for this reason (combining CMB + BAO) one obtains an upper bound $f_\nu \lesssim 0.02$ translating into

$$\sum_i m_i \lesssim 0.23\ \mathrm{eV}$$

Non-relativistic freeze-out



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

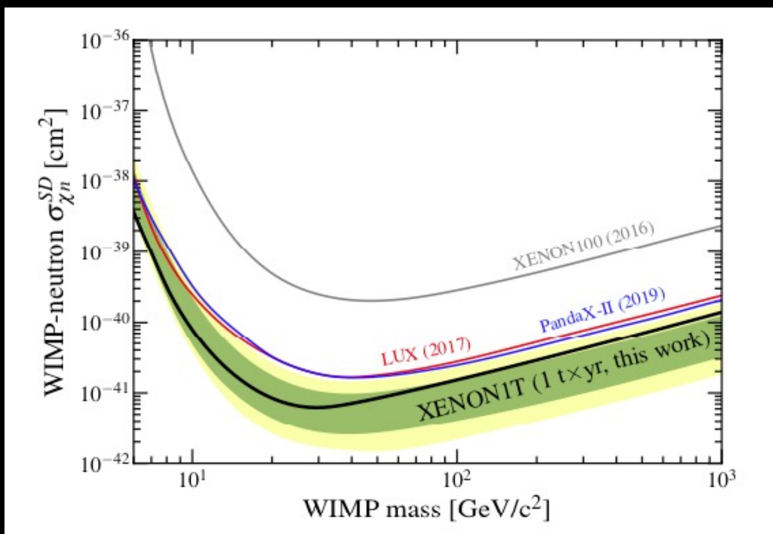
A WIMP miracle ?

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

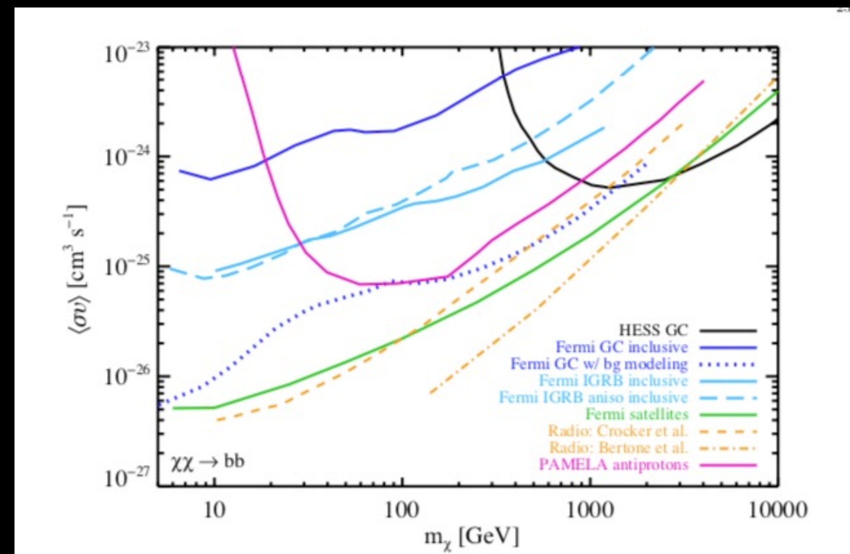
- The WIMP miracle has been for long time regarded as a standard solution to address the problem of dark matter: embeddable in models addressing naturalness+hierarchy problems ⇒ new physics at the 100 GeV - TeV scale

WIMP non-miracle

Dark matter direct searches (1902.03234)



Dark matter indirect searches (1604.00014)

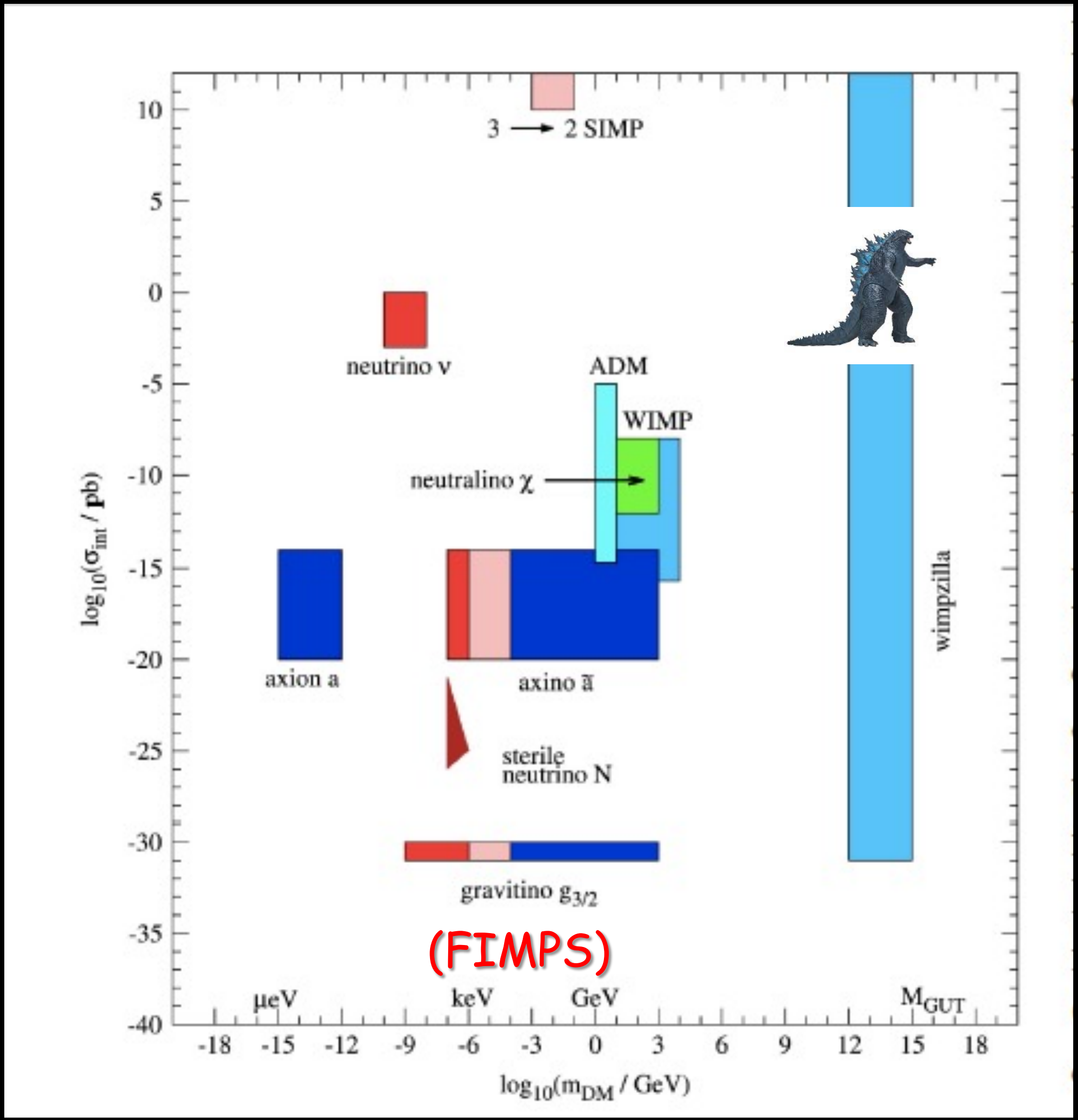


(XENONnT results exclude XENO1T ~keV excess 2207.11330)

These results do not rule out WIMPs but they are today not anymore considered as the standard option but one out of many possible ones

Beyond the WIMP paradigm

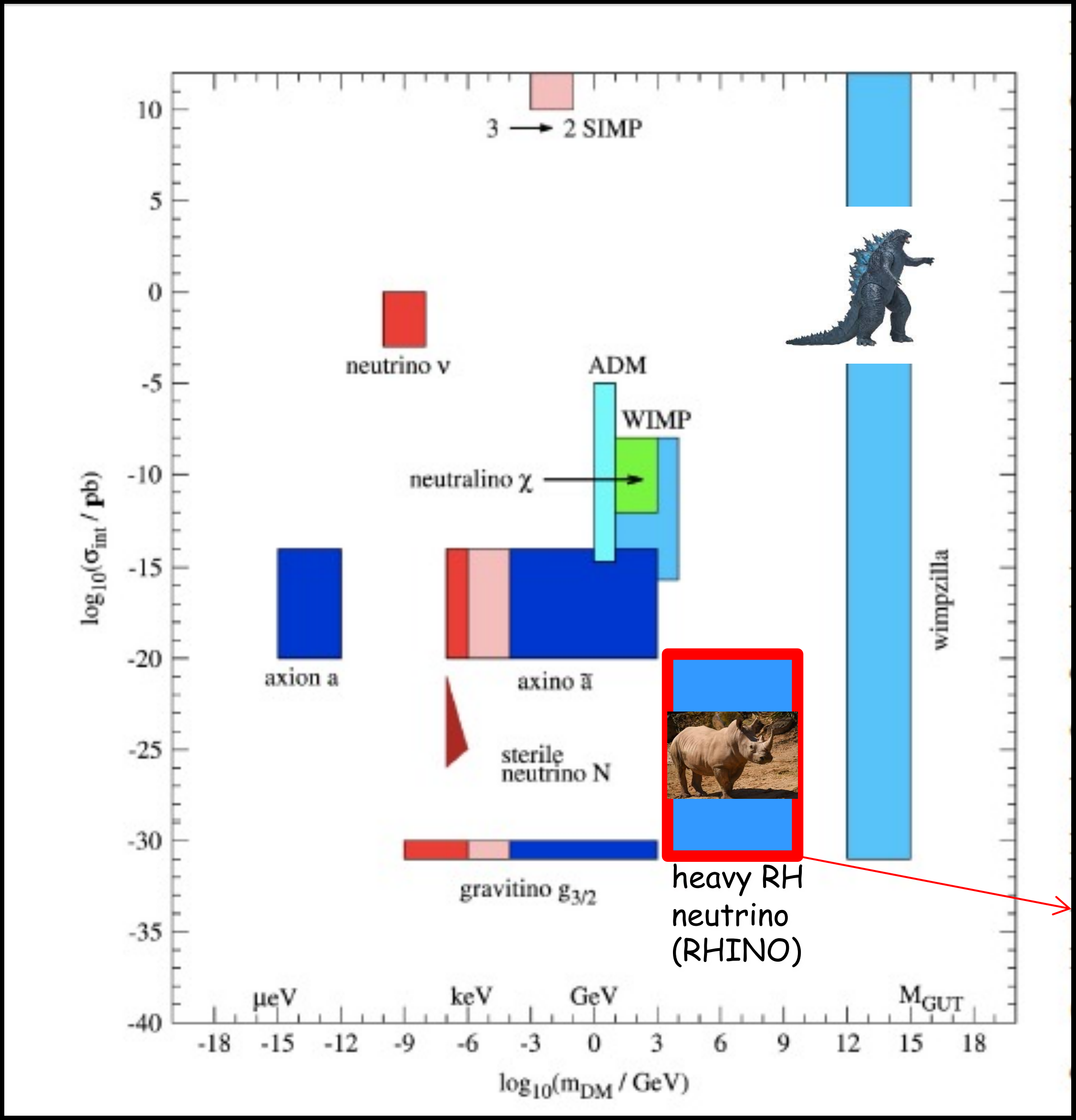
(from Baer et al.1407.0017)



The more we know the less we understand?

Beyond the WIMP paradigm: the DM particle zoo

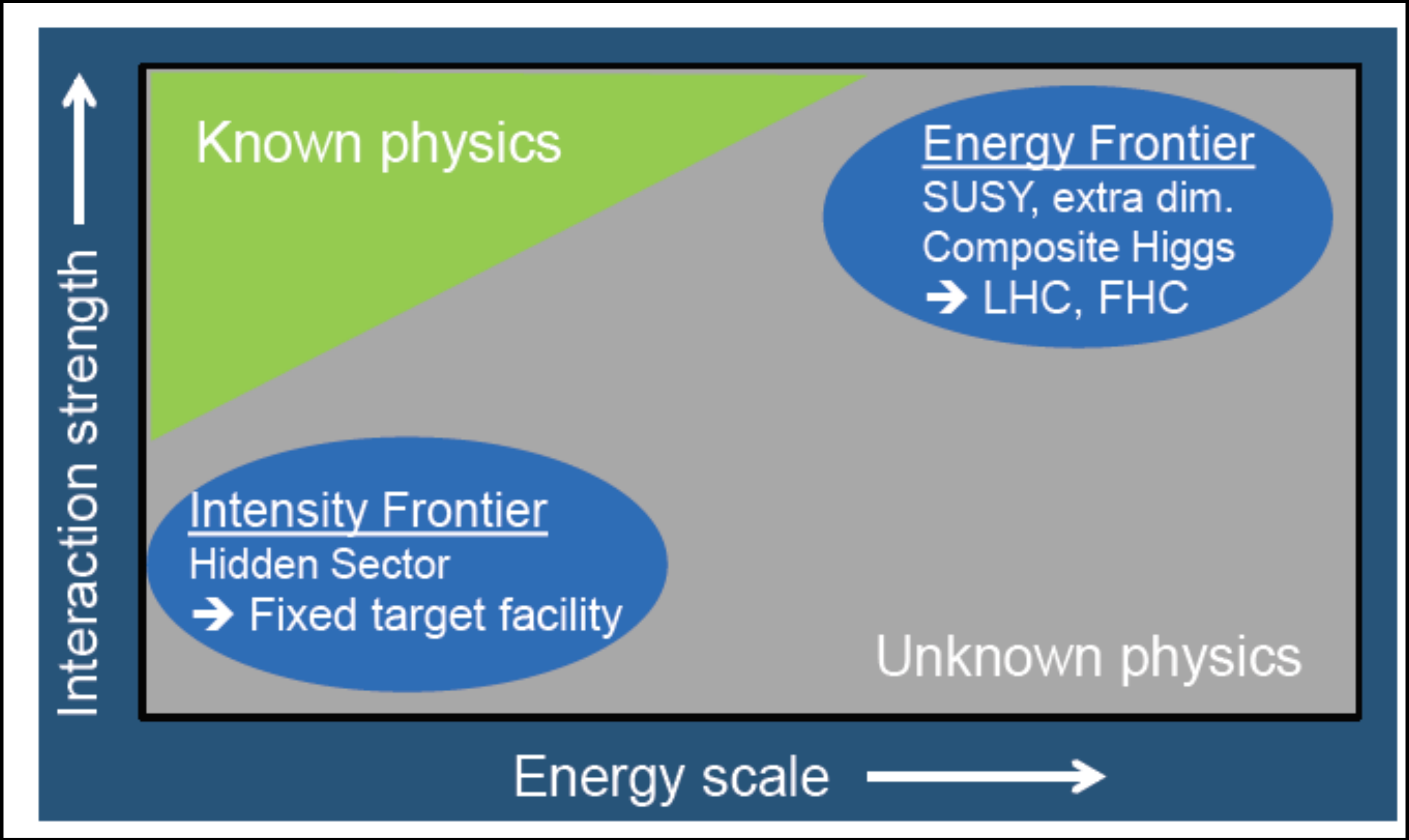
(from Baer et al.1407.0017)



(PDB, Anisimov '08)

New frontiers

(SHIP proposal, 1504.04855)



Minimal seesaw mechanism (type I)

- Dirac + (right-right) Majorana mass term

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

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

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

- 3 light **Majorana neutrinos** with masses (seesaw formula): $m_\nu = -m_D M^{-1} m_D^T \Rightarrow \mathrm{diag}(m_1, m_2, m_3) = -U^\dagger m_\nu U^*$

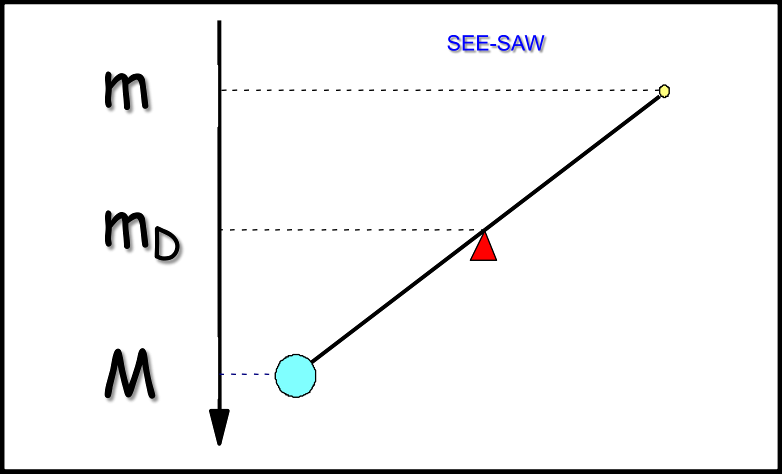
- 3(?) very heavy Majorana neutrinos N_1, N_2, N_3 with $M_3 > M_2 > M_1 \gg m_D$

1 generation toy model :

$m_D \sim m_{top}$,

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

$\Rightarrow M \sim 10^{15}$ GeV



Matter-antimatter asymmetry with 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 $N_I \xrightarrow{\Gamma_I} L_I + \phi^\dagger \qquad N_I \xrightarrow{\bar{\Gamma}} \bar{L}_I + \phi$

total CP asymmetries $\varepsilon_I \equiv -\dfrac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$

$$\Rightarrow N_{B-L}^{fin} = \sum_{I=1,2,3} \varepsilon_I \times \kappa_I^{fin}$$

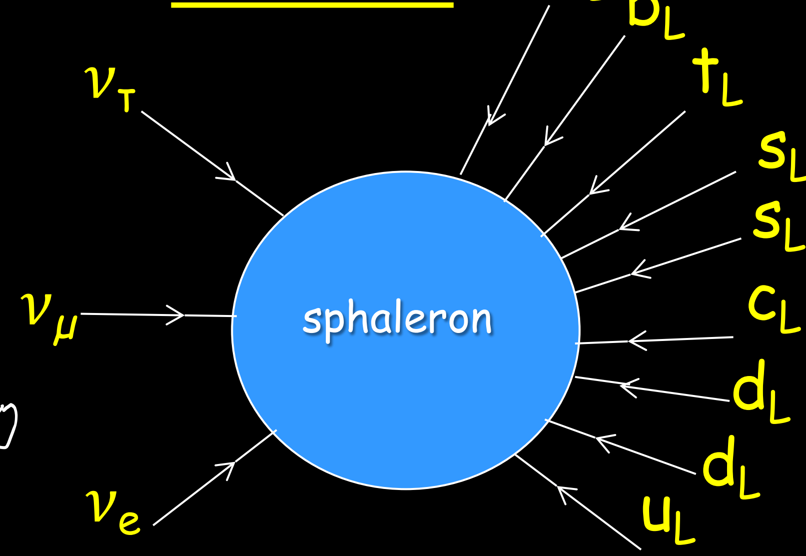
efficiency factors

- Sphaleron processes in equilibrium

$\Rightarrow T_{RH} \gtrsim T^{off}_{sphalerons} \simeq 132\ \text{GeV}$

(Kuzmin,Rubakov,Shaposhnikov '85
D'Onofrio, Rummukainen, Tranberg 1404.3565)

ΔB=ΔL=3



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

successful leptogenesis $\eta_{B0}^{lep} \simeq \eta_{B0}^{obs} \sim 6 \cdot 10^{-10}$

Dark matter from active-sterile neutrino mixing

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

- LH-RH (active-sterile) neutrino mixing

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

$$N_{1R} \simeq \nu_{1R} + \frac{m_{D\alpha 1}}{M_1}\nu^c_{L\alpha} \longrightarrow \text{lightest RH neutrino}$$

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

$$\Omega_{N_1} h^2 \sim 0.1\,\frac{\theta^2}{10^{-8}}\left(\frac{M_1}{\text{keV}}\right)^2 \sim \Omega_{DM,0}h^2 \qquad \theta^2 \equiv \frac{\sum_\alpha |m_{D\alpha 1}|^2}{M_1^2}$$

- For $M_1 \ll m_e$ $\Rightarrow$ $\tau_1 = 5\times 10^{26}\,s\left(\frac{M_1}{keV}\right)^{-5}\left(\frac{10^{-8}}{\theta^2}\right) \gg t_0$
- The lightest neutrino mass $m_1 \lesssim 10^{-5}$ eV $\Rightarrow$ hierarchical neutrino masses
- 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
- $L \sim 10^{-4}$: 3.5 keV line? (Horiuchi et al. '14; Bulbul at al. '14; Abazajian '14)

The XRISM satellite to be launched in 2023 should give a final answer

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 there is a RH neutrino with tiny Yukawa couplings (e.g., proportional to a small symmetry breaking parameter) referred to as dark neutrino N_D :

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

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

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

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

5-dimensional Higgs portal-like operators 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

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

Anisimov operator(s)

$$\mathcal{L}_A = \sum_{I,J} \frac{\lambda_{IJ}}{\Lambda} \phi^\dagger \phi \, \overline{N_I^c} N_J + h.c.$$

$$= \frac{\lambda_{DS}}{\Lambda}\phi^\dagger\phi\,\overline{N_D^c}N_S + \frac{\lambda_{SS}}{\Lambda}\phi^\dagger\phi\,\overline{N_S^c}N_S + \frac{\lambda_{DD}}{\Lambda}\phi^\dagger\phi\,\overline{N_D^c}N_D + h.c. \quad (N_D = N_3; N_S = N_2)$$

→ RH-RH (sterile-sterile) Higgs-induced neutrino mixing (RHINO)

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

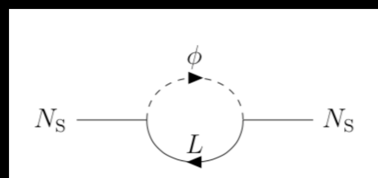
(Anisimov '06, Anisimov,PDB '08)

Focus on the RH-RH Higgs-induced neutrino mixing (RHINO) operator:

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

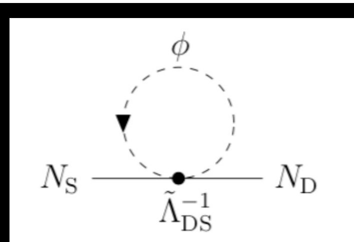
In general, $\lambda_{DS} \neq 0$ this generates a dark-source RH neutrino mixing. The Yukawa and Anisimov interactions both generate effective potentials from self-energies:

From Yukawa interactions



$$\Rightarrow \quad V_S^Y = \frac{T^2}{8p} h_S^2$$

From mixing



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

Effective mixing Hamiltonian :

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

mixing term

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

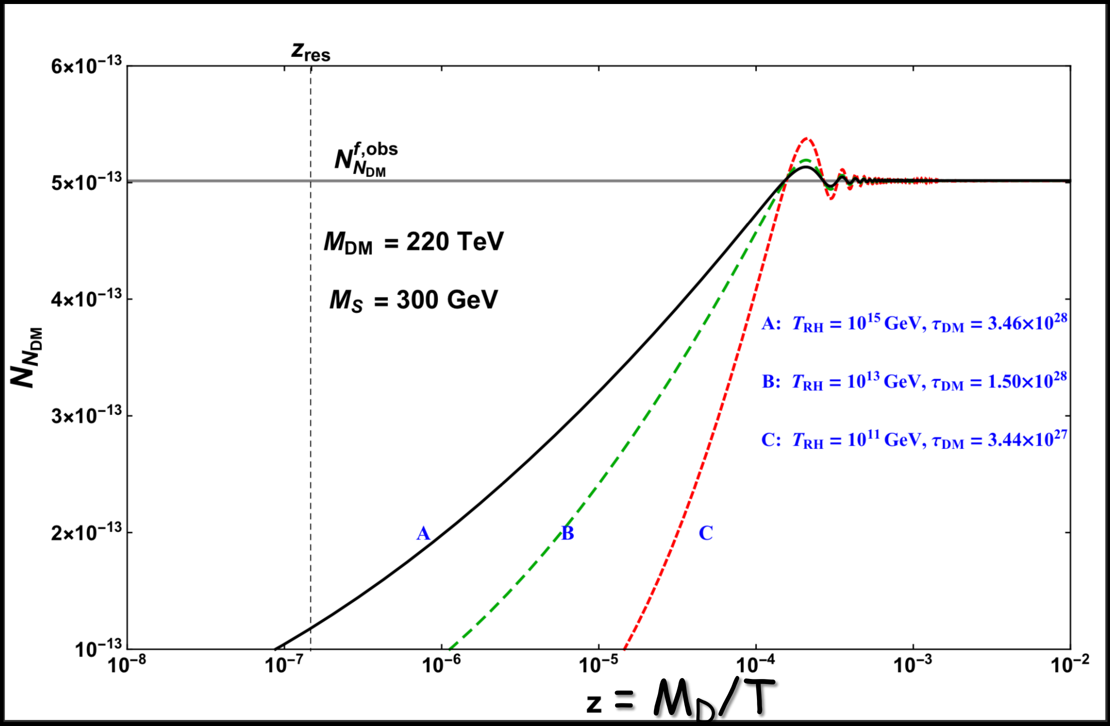
Density matrix calculation of the relic abundance

(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)

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

Assuming an initial thermal N_S-abundance

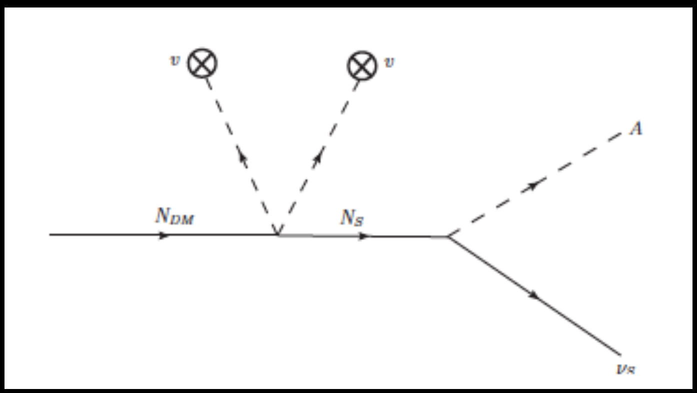


Dark neutrinos MUST decay ⇒ decaying DM

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

2 body decays ($M_S > M_W$)

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



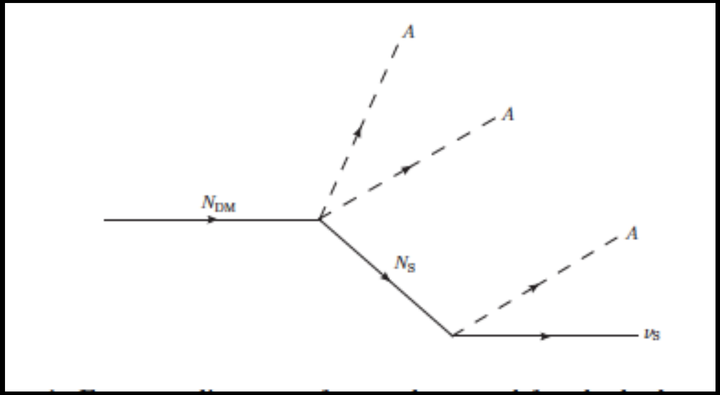
$$\theta_{\Lambda 0} = \frac{2\, v^2/\widetilde{\Lambda}_{\rm DS}}{M_{\rm D}\,(1 - M_{\rm S}/M_{\rm D})}$$

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

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

⇒ Lower bound on M_D

4 body decays



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

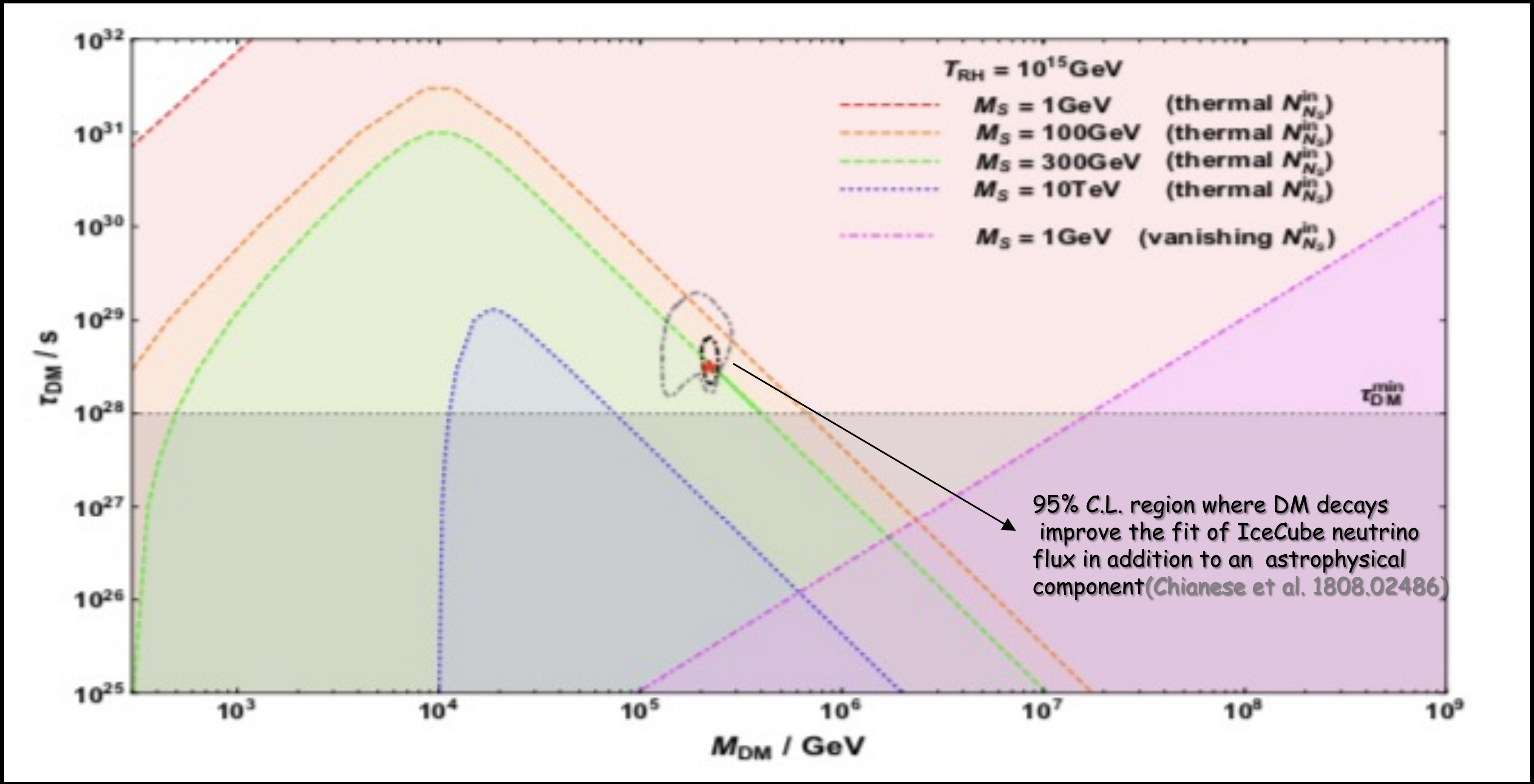
$$\Gamma_{{\rm D}\to 3A+\ell_{\rm S}} = \frac{\Gamma_{\rm S}}{15\cdot 2^{11}\cdot \pi^4}\,\frac{M_{\rm D}}{M_{\rm S}}\left(\frac{M_{\rm D}}{\widetilde{\Lambda}_{\rm DS}}\right)^2$$

⇒ Upper bound on M_D

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)



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

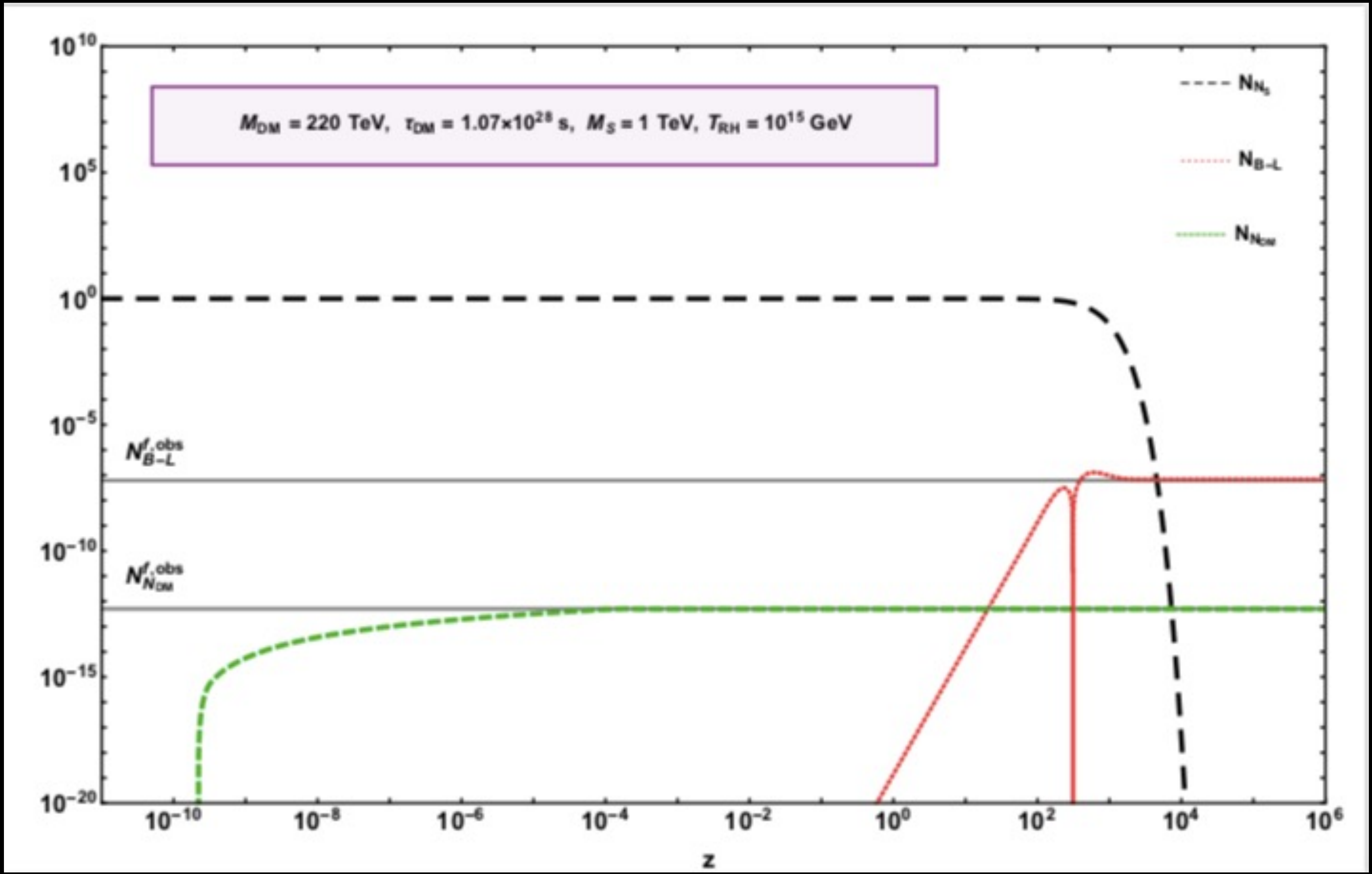
Can one think of processes able to thermalize the N_S abundance prior to the oscillations?

Two good motivations

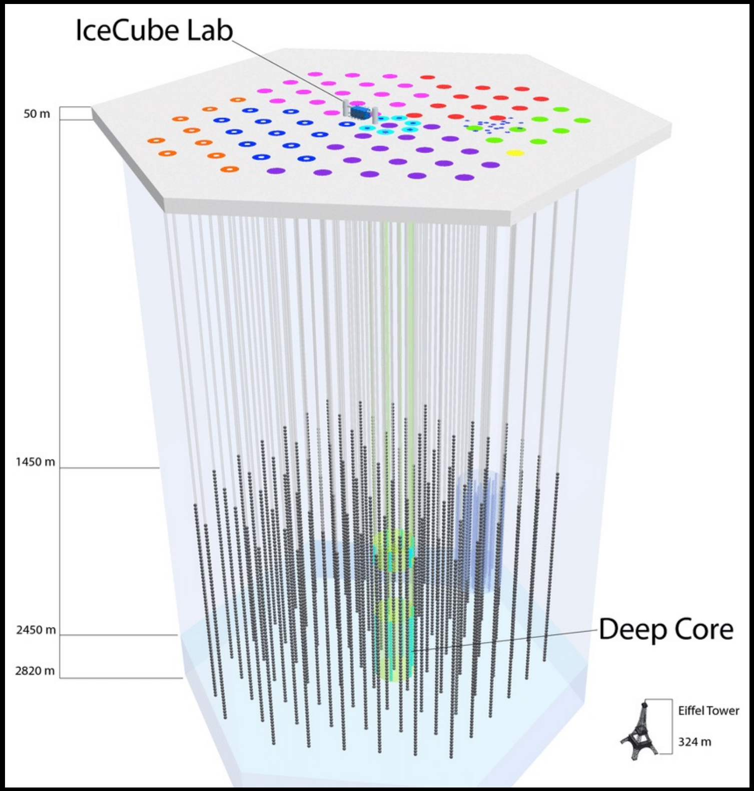
Unifying Leptogenesis and Dark Matter

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

A solution for initial thermal N_S abundance:



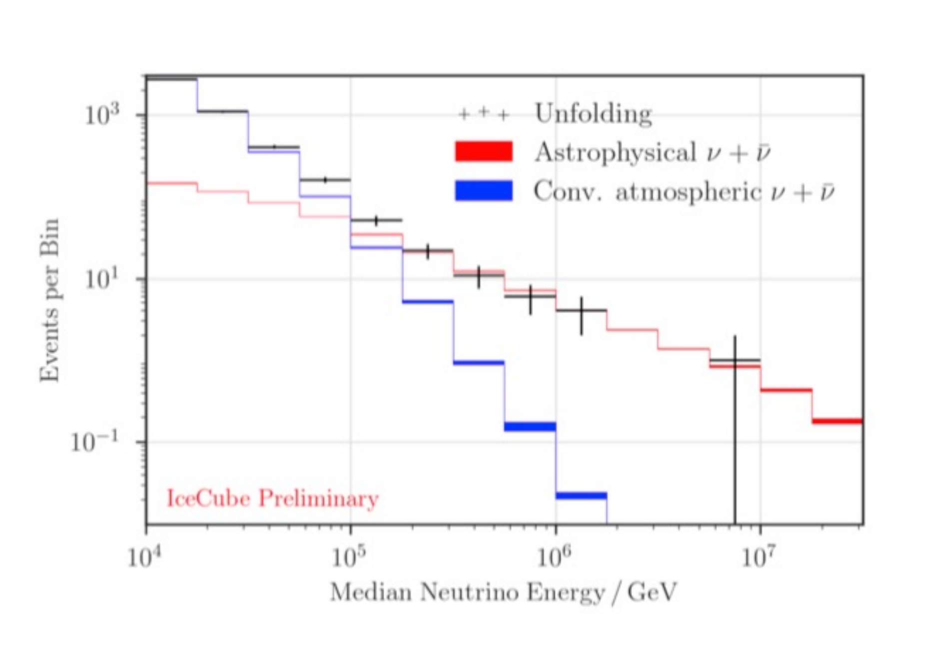
IceCube



- Neutrinos are perfect astronomical messengers (from the edge of the universe)
- In the range 10 TeV - 10 EeV only neutrinos are unabsorbed and undeflected
- 2013: IceCube discovered cosmic VHE neutrinos (30 TeV – 1 PeV range)
- Some observed in coincidence with blazar γ-ray flare: extragalactic origin
- High Energy Starting Events (HESE) veto to reduce overwhelming atmospheric background at energies $\lesssim$ 300 TeV $\Rightarrow$ first evidence of cosmic neutrinos
- Up-going muon data set has confirmed the existence of cosmic neutrinos but ….

IceCube up-going muon neutrinos

IceCube 8 years data



Standard single power-law spectrum for an astrophysical flux

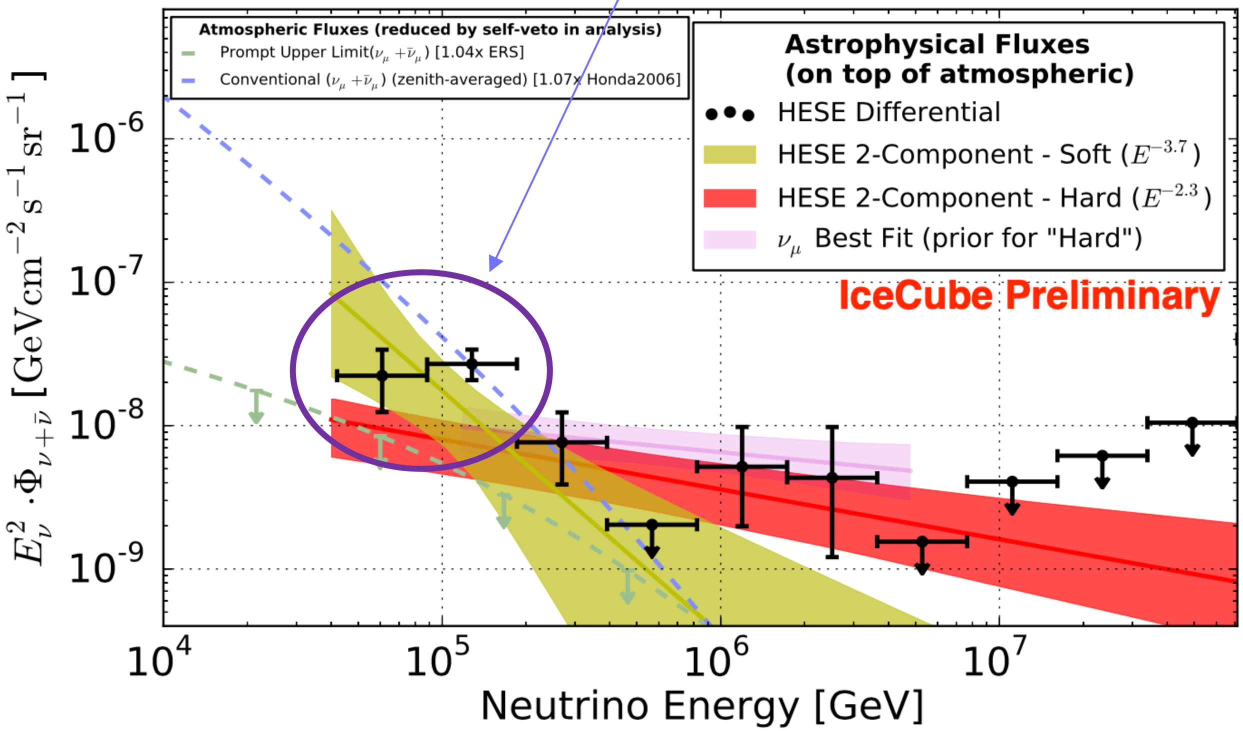
$$\frac{d\Phi}{dE} = \Phi_0 \cdot \left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{-\gamma_{astro}}$$

Best fit

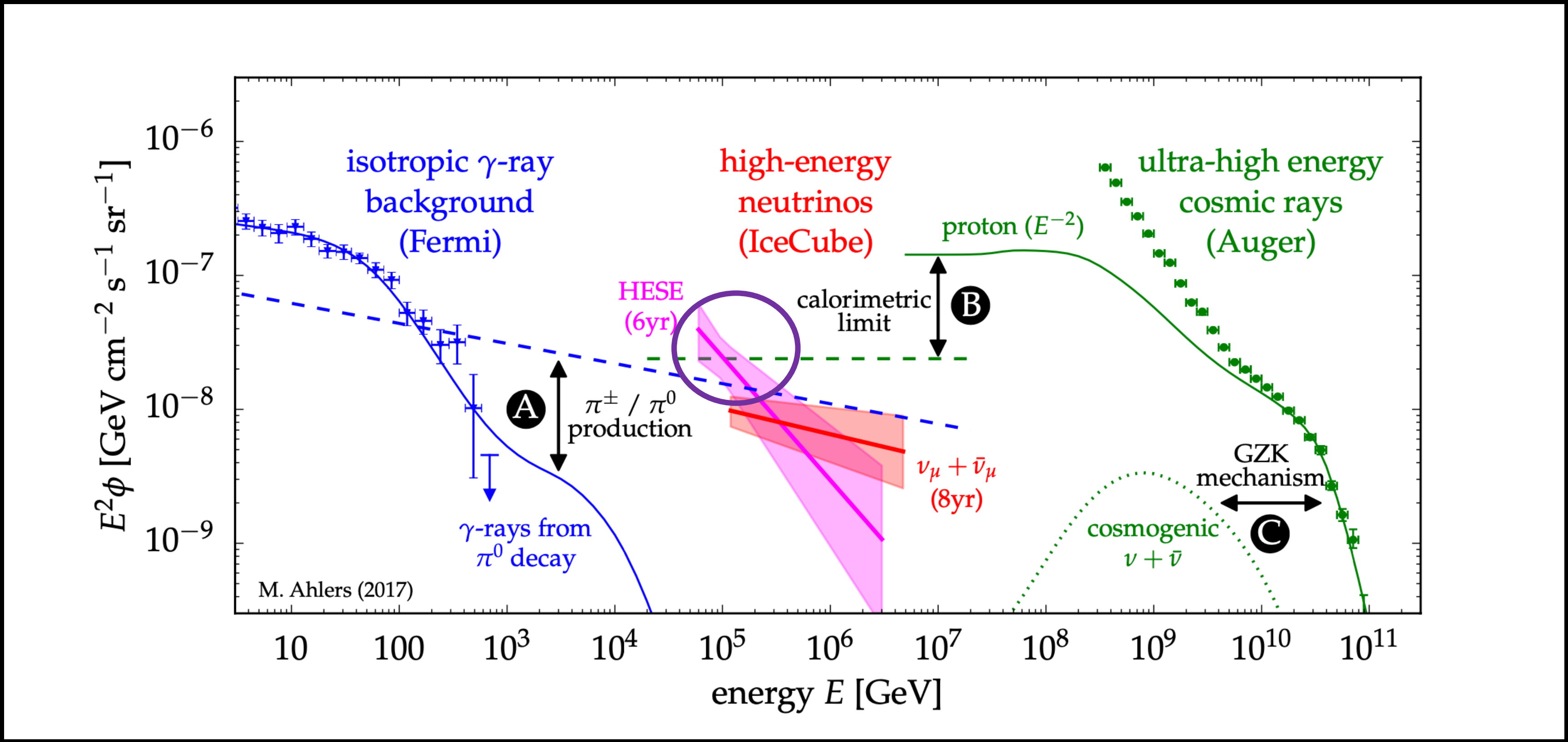
$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE} = (1.01 \pm^{0.26}_{0.23}) \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-2.19 \pm 0.10} \cdot 10^{-18} \mathrm{GeV}^{-1} cm^{-2} s^{-1} sr^{-1}.$$

An extra component at ~100 TeV ?

IceCube 6 year HESE data (1710.01191)

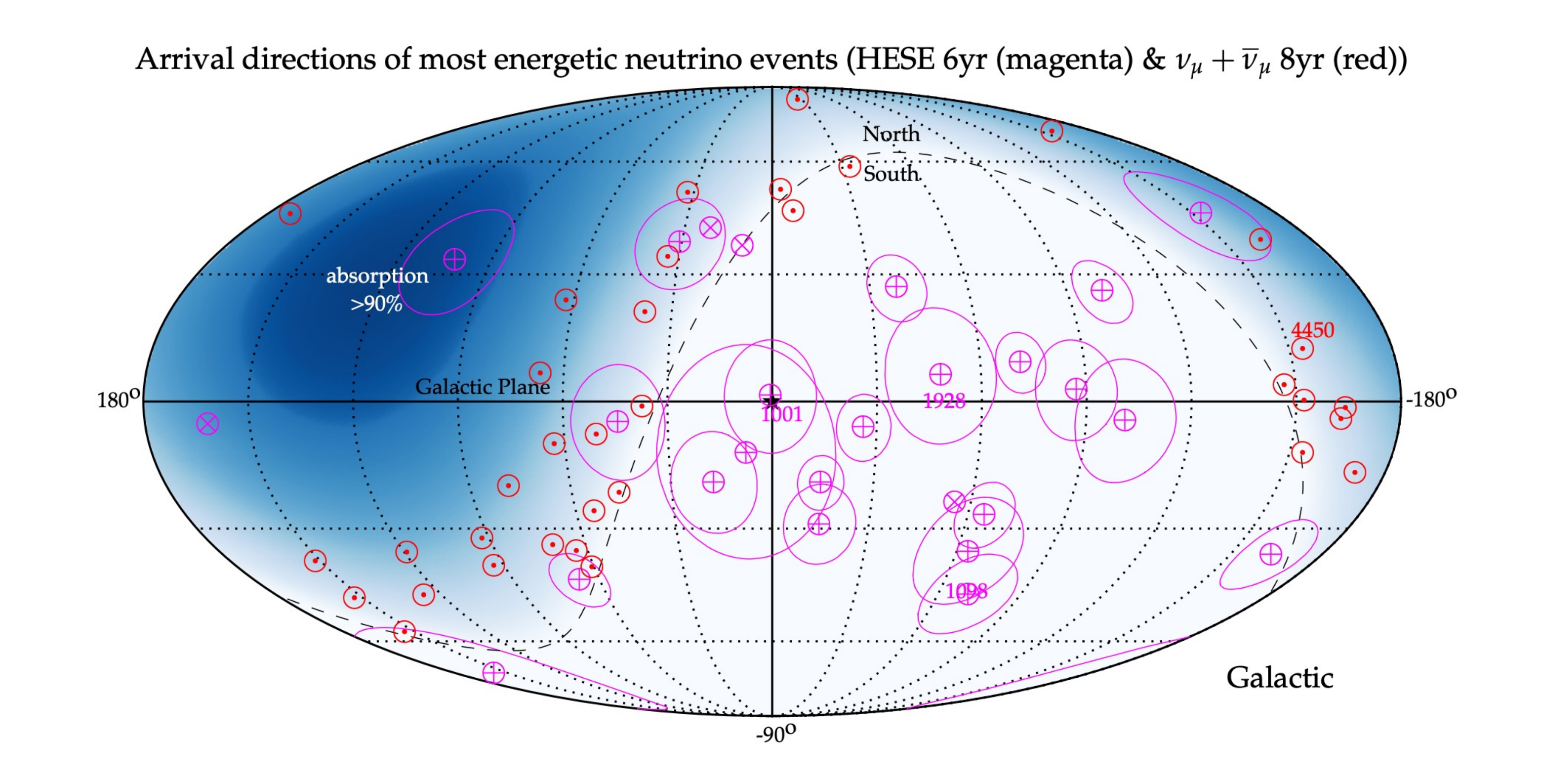


A multimessenger analysis confirms an 100 TeV excess



IceCube 6 year HESE data (1710.01191)

Absence of strong anisotropies



This disfavours scenarios with strong Galactic emissions, the dominant component is of extra-galactic origin

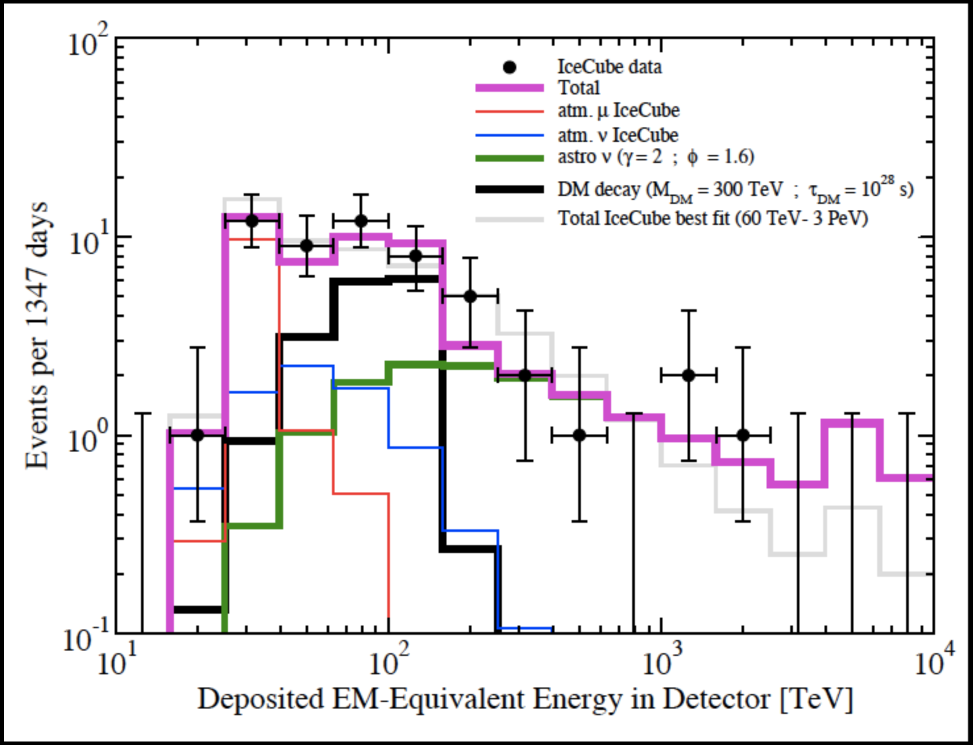
Very high energy neutrinos from N_D decays

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

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

- The produced neutrinos can be responsible for the excess at ~100 TeV in IceCube

Example: M_{DM}=300TeV

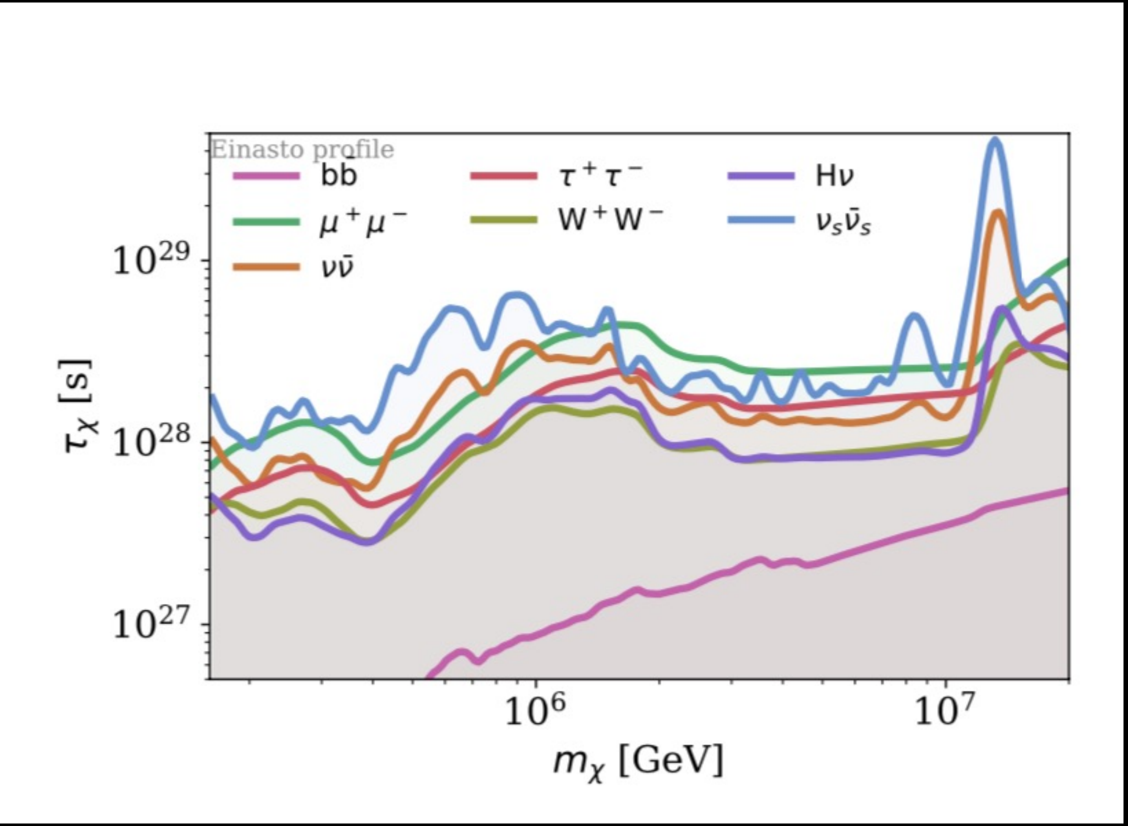


(from 1606.06238)

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

Many proposed production mechanisms

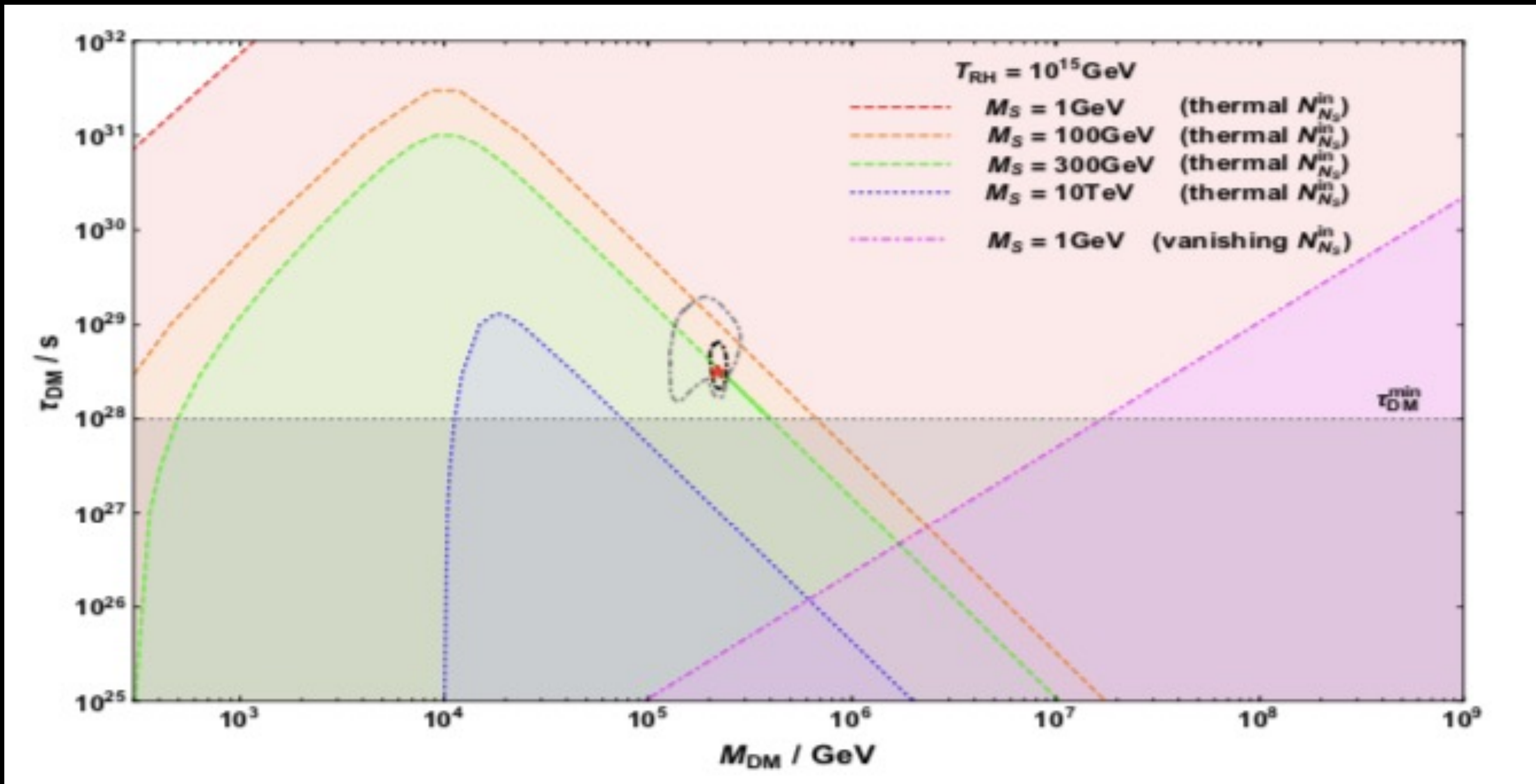
Many production mechanisms have been proposed especially to address IceCube initially seemingly anomalous PeV neutrino events:

- 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)

DM lifetime vs. mass plane: allowed regions

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



What processes can thermalize the N_S-abundance prior to the oscillations?

Including Higgs portal interactions for N_S

(PDB, A. Murphy, arXiv 2210.10801)

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

effective scales

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

$$\tilde{\Lambda}_{SS} \equiv \Lambda/\lambda_{SS}$$

Can these interactions thermalise the source neutrinos prior to oscillations?

Let us modify the kinetic equations including these processes:

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

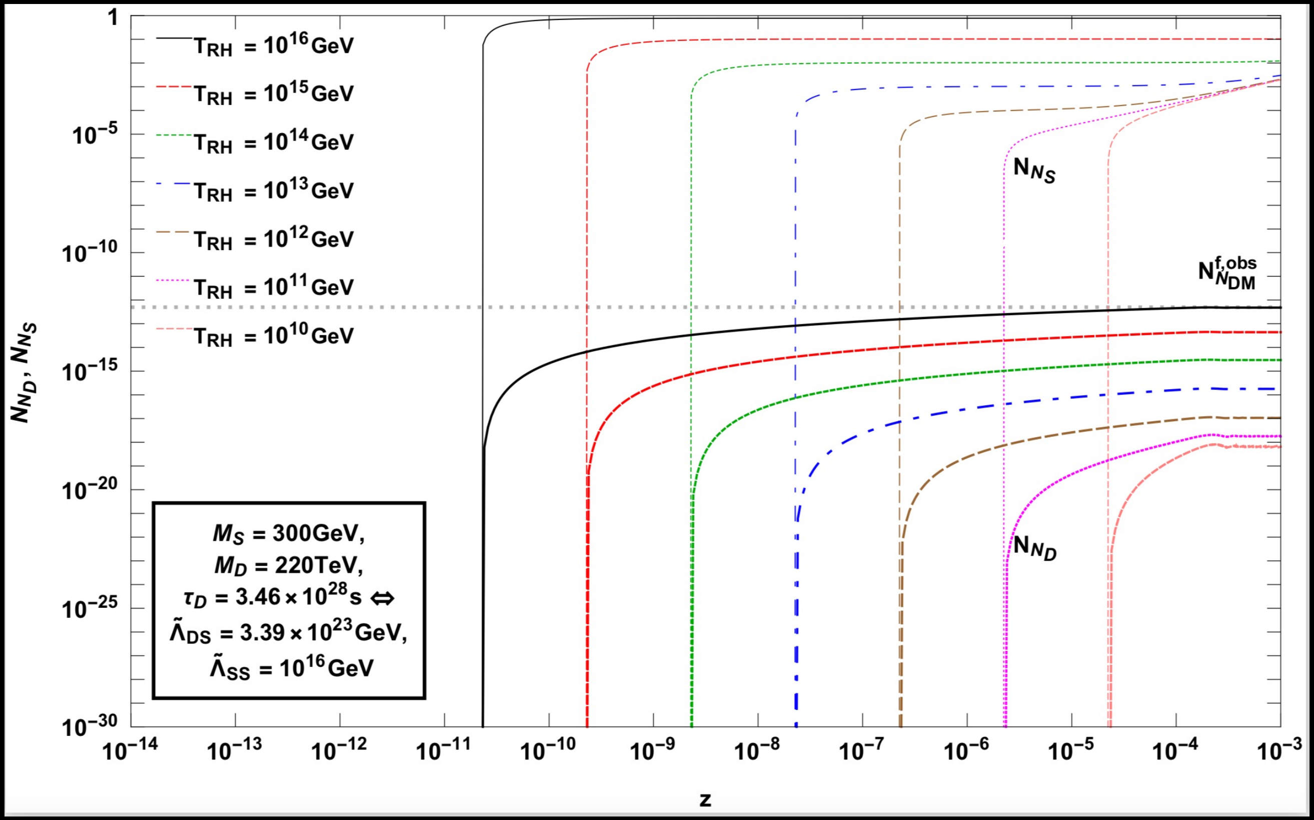
$$A(z) \equiv \frac{\langle\sigma_{\phi\phi\to N_S N_S}v\rangle}{R^3 H z} = \frac{A(z=1)}{z^2}; \qquad \langle\sigma_{\phi\phi\to N_S N_S}v\rangle_{T\gg M_S} \simeq \frac{1}{4\pi\tilde{\Lambda}^2_{SS}}$$

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

Condition for the thermalisation of the N_S abundance

(PDB, A. Murphy, arXiv 2210.10801)

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



$\tilde{\Lambda}_{DS} \sim 10^{23}$ GeV

$\tilde{\Lambda}_{SS} \sim 10^{16}$ GeV

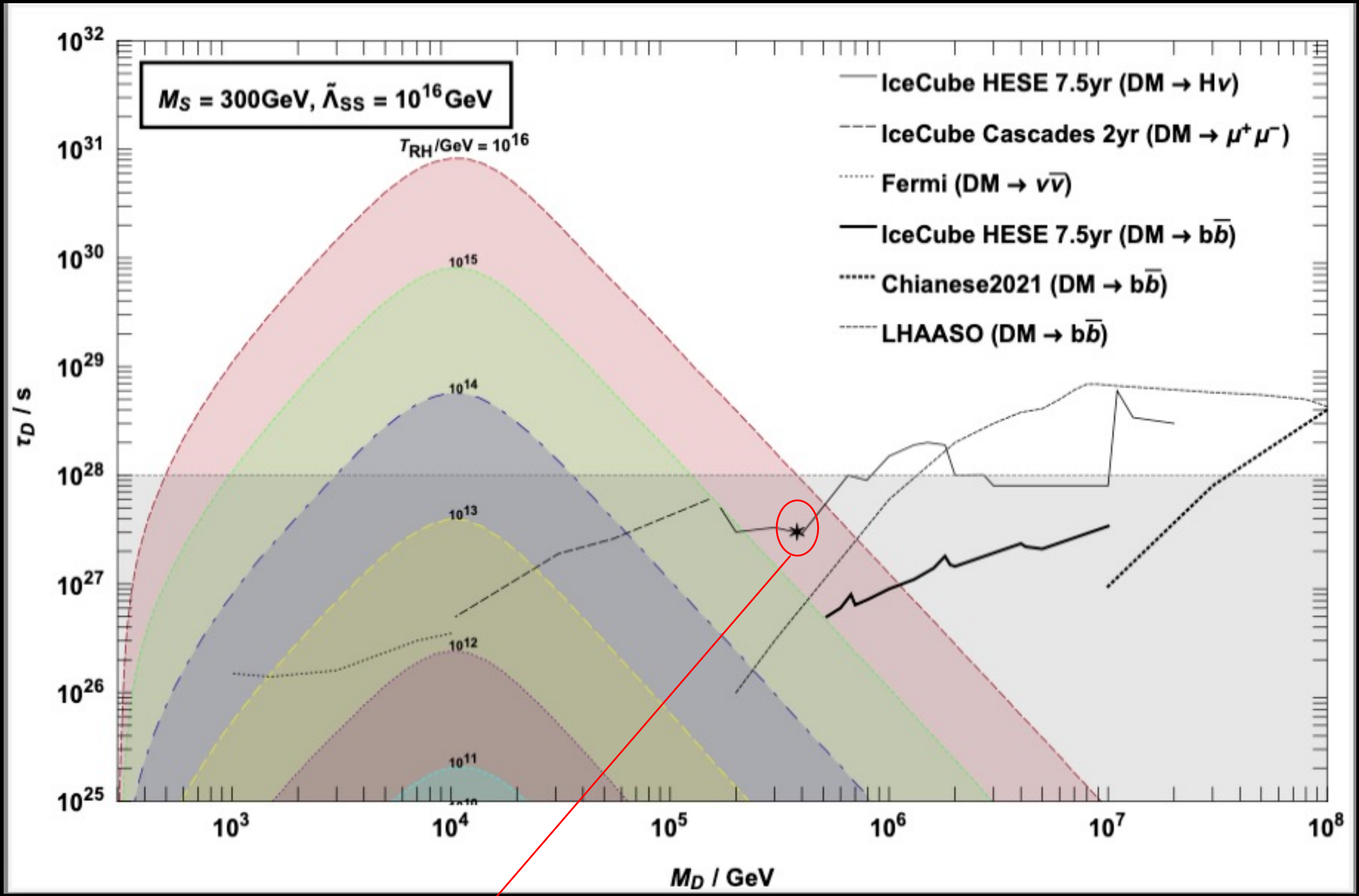
↓

GUT scale !!

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

DM lifetime vs. mass plane: allowed regions

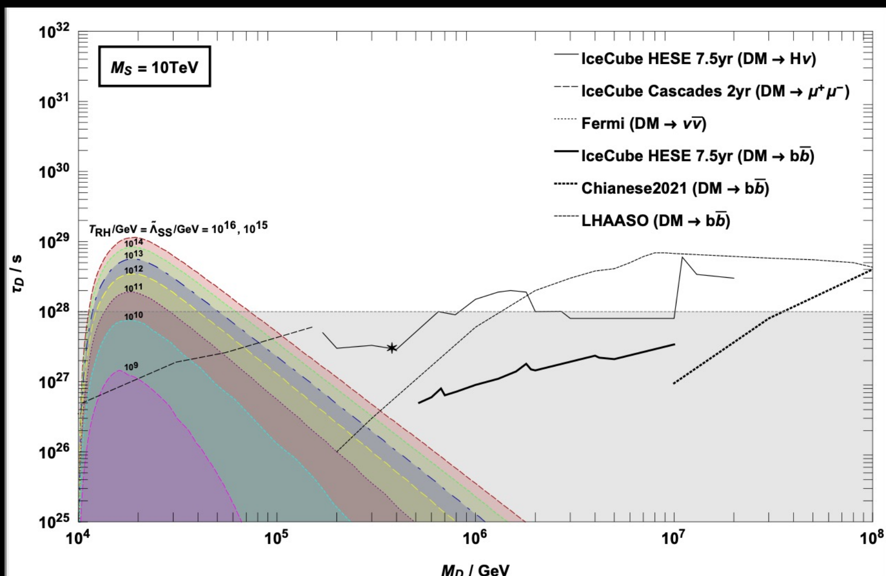
(PDB, A. Murphy, arXiv 2210.10801)

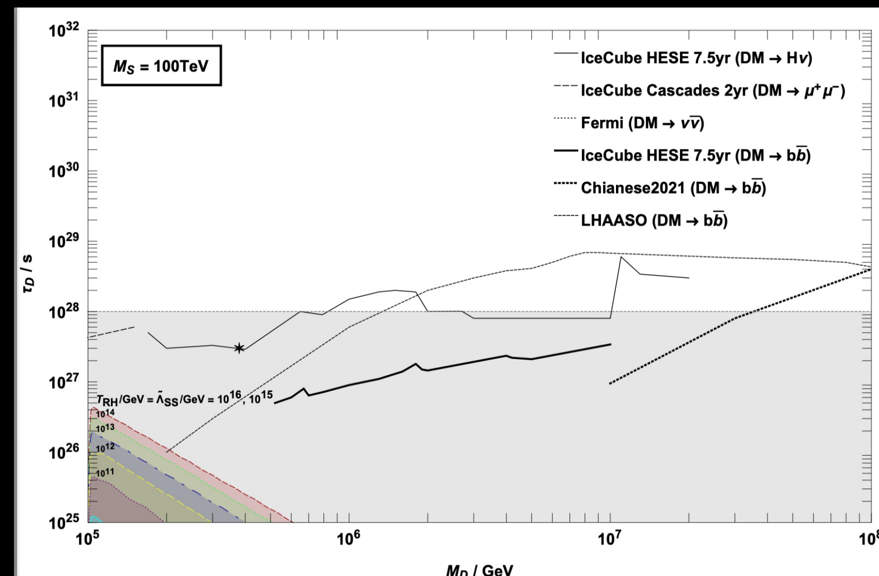


Decaying DM best fit (2.5σ) from IceCube 7.5 year data (2205.12950)

Upper bound on the seesaw (=leptogenesis) scale

(PDB, A. Murphy, arXiv 2210.10801)



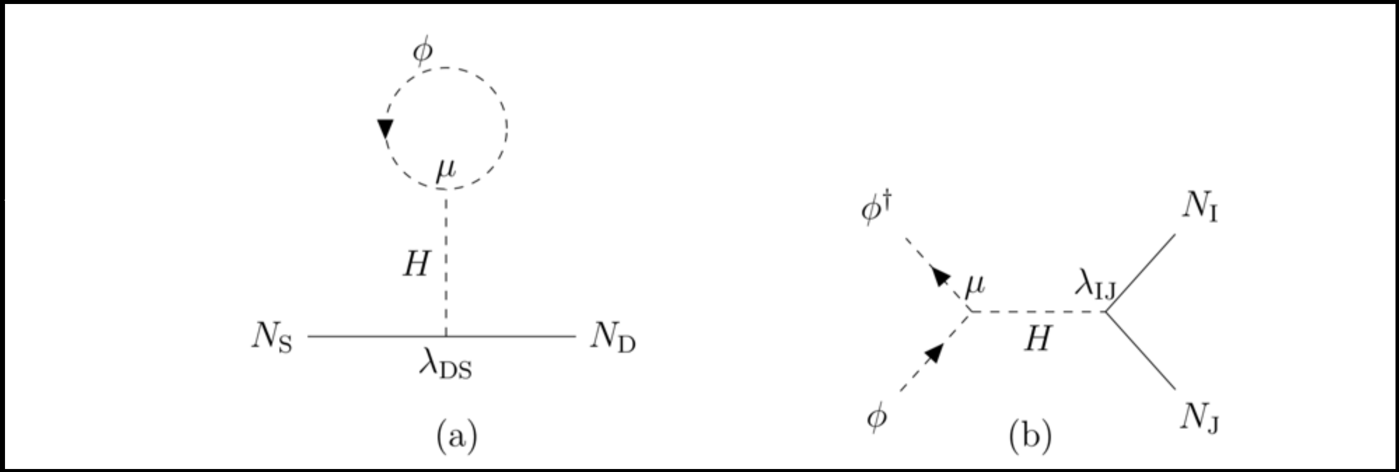


The mechanism is compatible with (resonant) leptogenesis at a scale upto ~ 100 TeV

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)

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



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

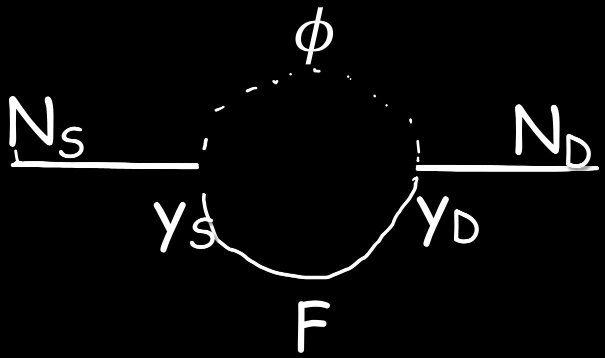
$\Longrightarrow$ $\widetilde{\Lambda}_{IJ} = \Lambda/\lambda_{IJ}$, and $\Lambda = M_H^2/\mu$.

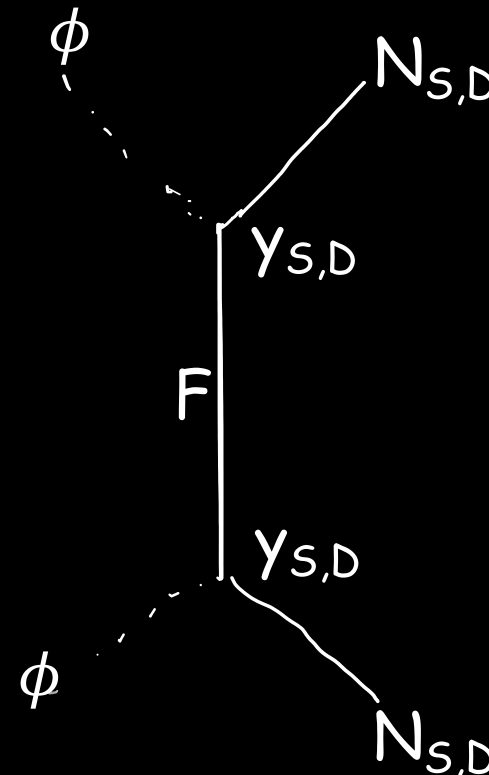
For $\mu \sim 10^9$GeV one can have $\tilde{\Lambda}_{DS} \sim 10^{23}$ GeV and $\lambda_{DS} \sim O(1)$ but one cannot reproduce simultaneously $\tilde{\Lambda}_{SS} \sim 10^{16}$GeV with the same scale Λ

A possible GUT origin ? Heavy fermion F as mediator

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

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





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

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

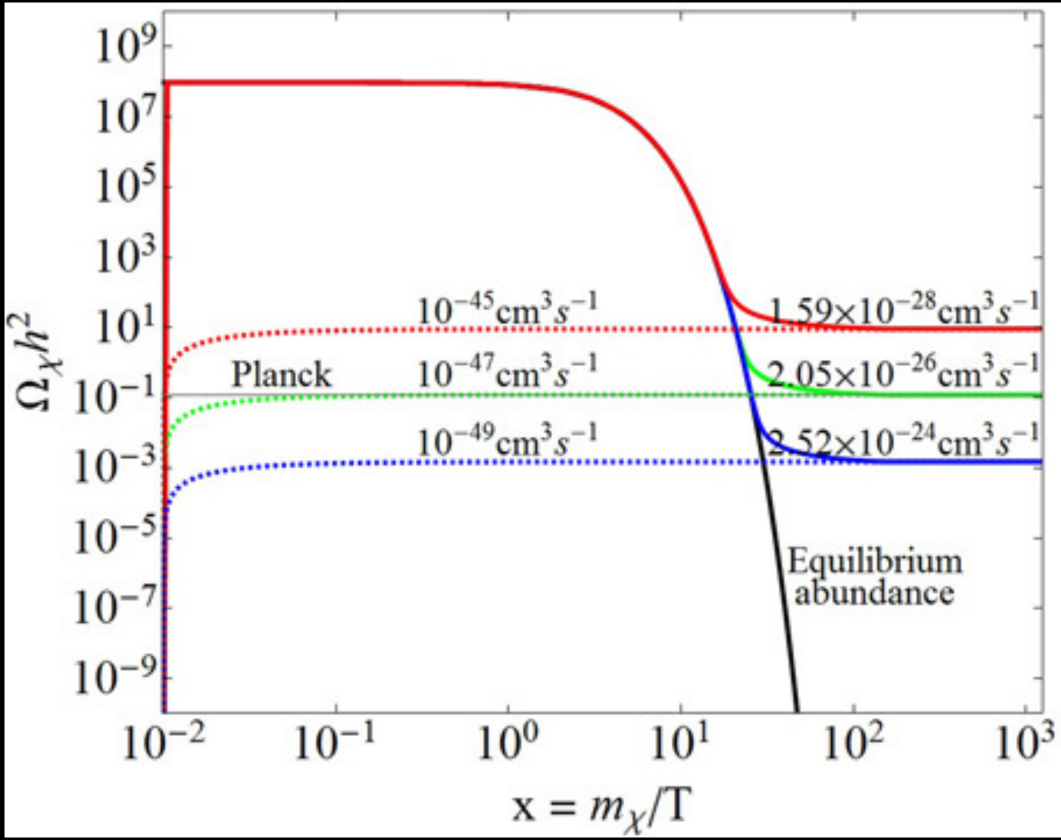
$$\tilde{\Lambda}_{DS} = \frac{\Lambda}{y_D y_S} \sim 10^{23}\,\text{GeV} \qquad \tilde{\Lambda}_{SS} = \frac{\Lambda}{y_S y_S} \sim \Lambda \sim 10^{16}\,\text{GeV} \qquad \tilde{\Lambda}_{DD} = \frac{\Lambda}{y_D y_D} \sim 10^{30}\,\text{GeV}$$

$y_D \sim 10^{-7}$ 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 traditionally explored so far and….
- ….RH neutrinos provide a very intriguing solution. An heavy 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 up to 100 TeV.
- Interestingly, the IceCube collaboration find an excess in the neutrino flux at energies well explained by RHINO DM decays (with M_D~100 TeV) and further support comes from multimessenger astronomy
- Soon (?) new analysis of anisotropies in the IceCube high energy neutrino flux might provide a crucial test for heavy decaying DM

Freeze-in solution for annihilating particles (FIMPs)



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

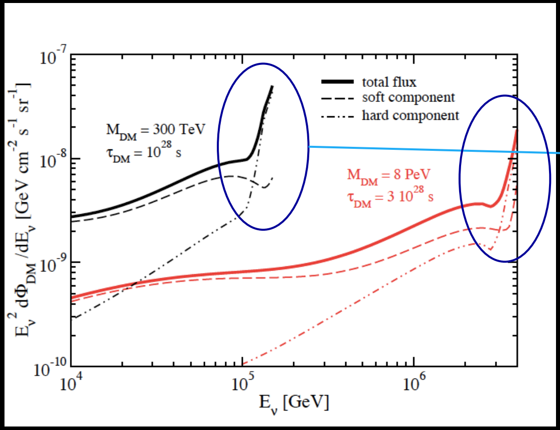
FIMPs evade all constraints, even too much: they are typically untestable!

Very high energy neutrinos from N_D decays

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

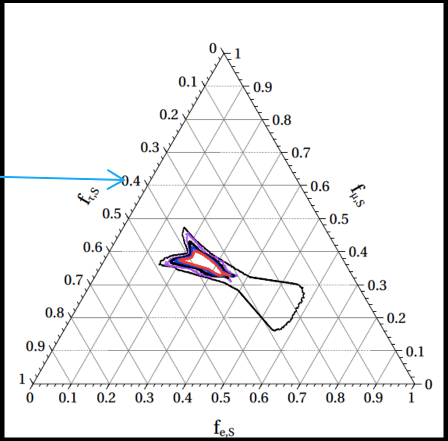
- DM neutrinos unavoidably decay today into A+leptons (A=H,Z,W) through the same mixing that produced them in the very early Universe
- Potentially testable high energy neutrino contribution

Energy neutrino flux



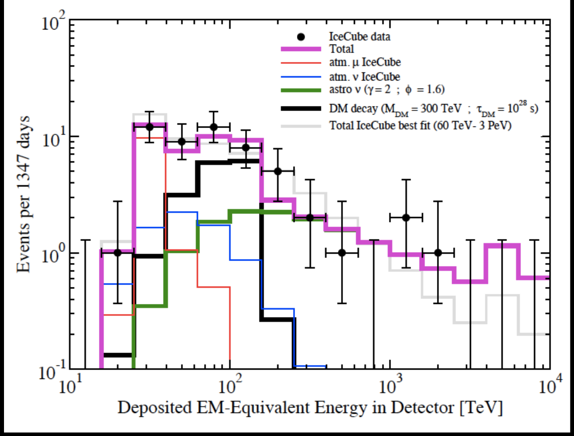
Hard component

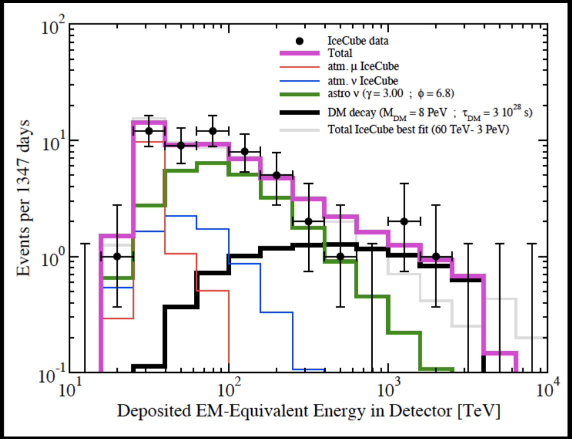
Flavour composition at the detector



Neutrino events at IceCube: 2 examples

M_{DM}=300TeV





M_{DM}=8 PeV