Workshop on grand-unified theories:Phenomenology and Cosmology
HIAS, 8 – 12 April 2024

Dark matter from a (bright) sterile – (dark) sterile neutrino mixing

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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., $(g\text{-}2)_\mu$, R_K, R_K^*,…)

Standard physics (SM+GR) cannot explain:

- *Cosmological Puzzles :*

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

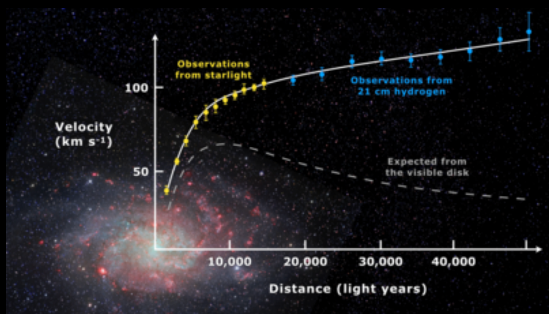
- *Neutrino masses and mixing*

problem of the origin of matter in the universe

Dark Matter

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

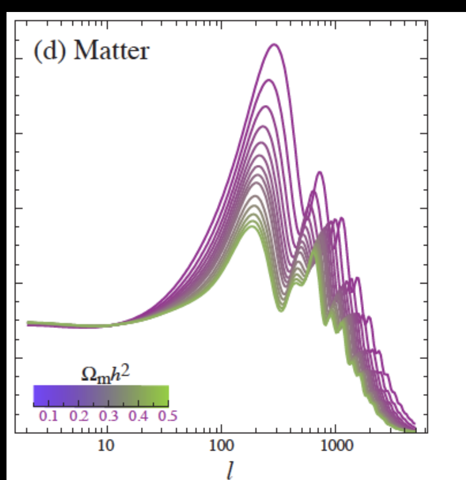
stars in galaxies and …..



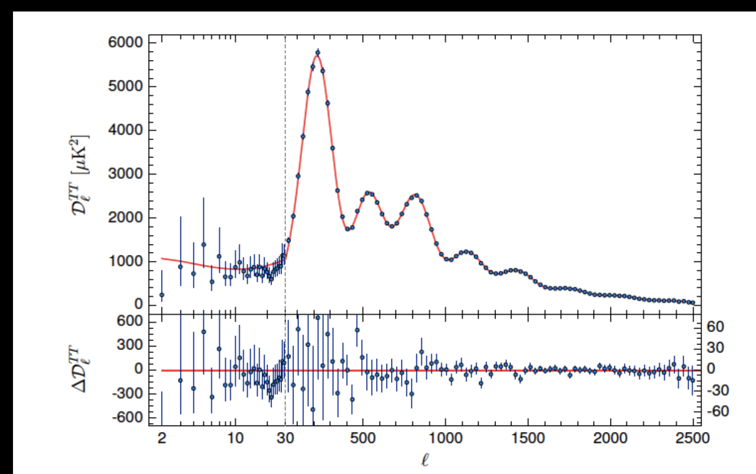
galaxies in clusters of galaxies

bullet cluster

…but it also needs to be primordial to understand structure formation and CMB anisotropies



(Hu, Dodelson, astro-ph/0110414)

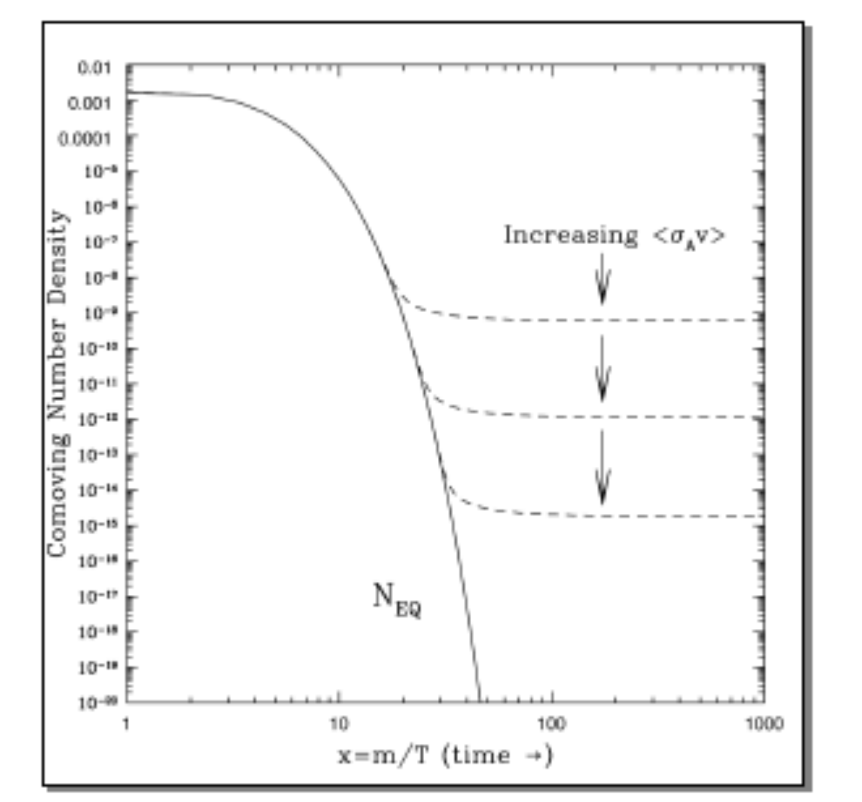


CMB + BAO

(Planck 2018, 1807.06209)

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

WIMP miracle



Freeze-out + WIMP ⇒ EW scale (WIMP miracle)

$$< \sigma_{\rm ann} v >_{\rm th} \simeq 3\times10^{-26} {\rm cm}^3\, s^{-1}$$

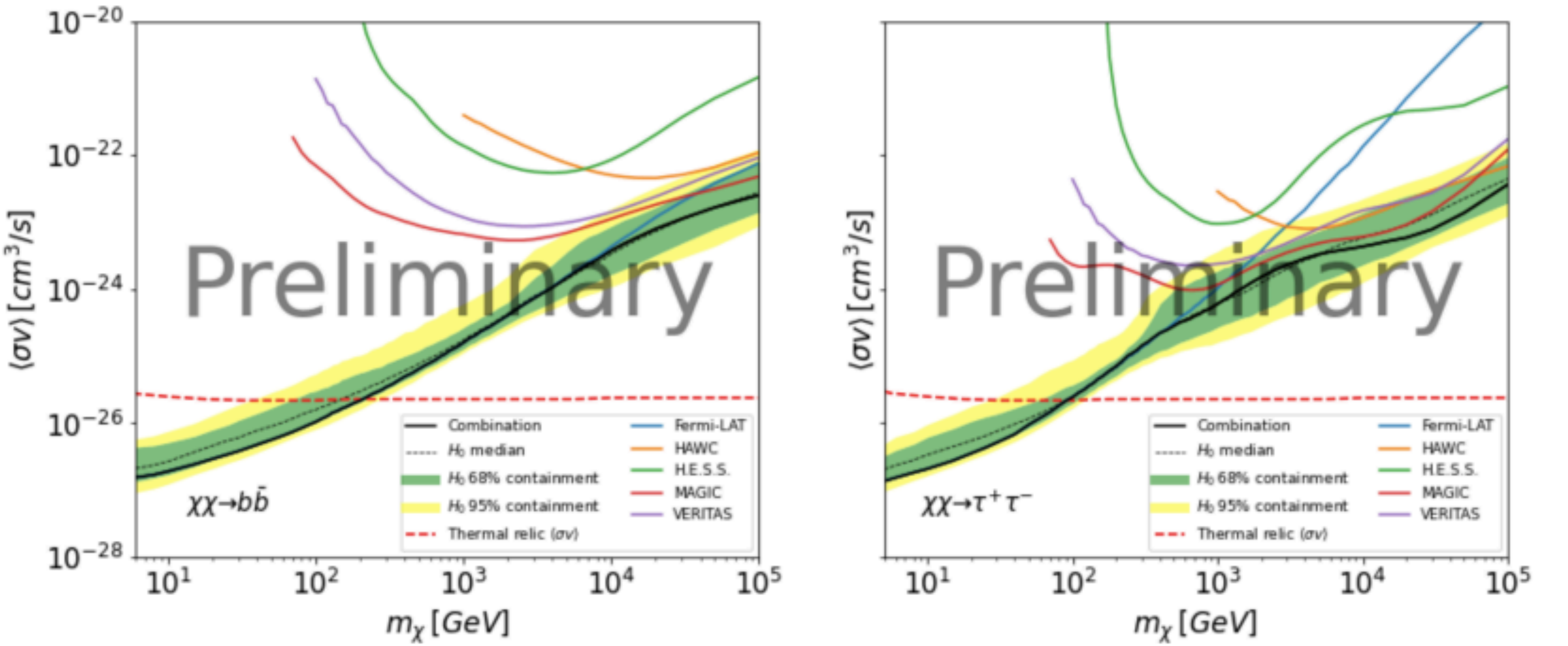
$$< \sigma_{\rm ann}^{\rm weak} v > = \frac{\alpha_{\rm weak}^2}{m_X^2} = < \sigma_{\rm ann} v >_{\rm th}$$

$\Rightarrow m_X \sim$ 100 GeV-1TeV ~ EW scale

- embeddable in models addressing naturalness+hierarchy problems
- ⇒ new physics at the 100 GeV - TeV scale
- The WIMP miracle has been for long time regarded as a strong argument in favour of WIMPs as dark matter particles.
- The lack of evidence of new physics at the TeV scale makes the WIMP miracle, if not completely ruled out, certainly less compelling.
- WIMPs are nowadays still a viable option but one out of many possible ones

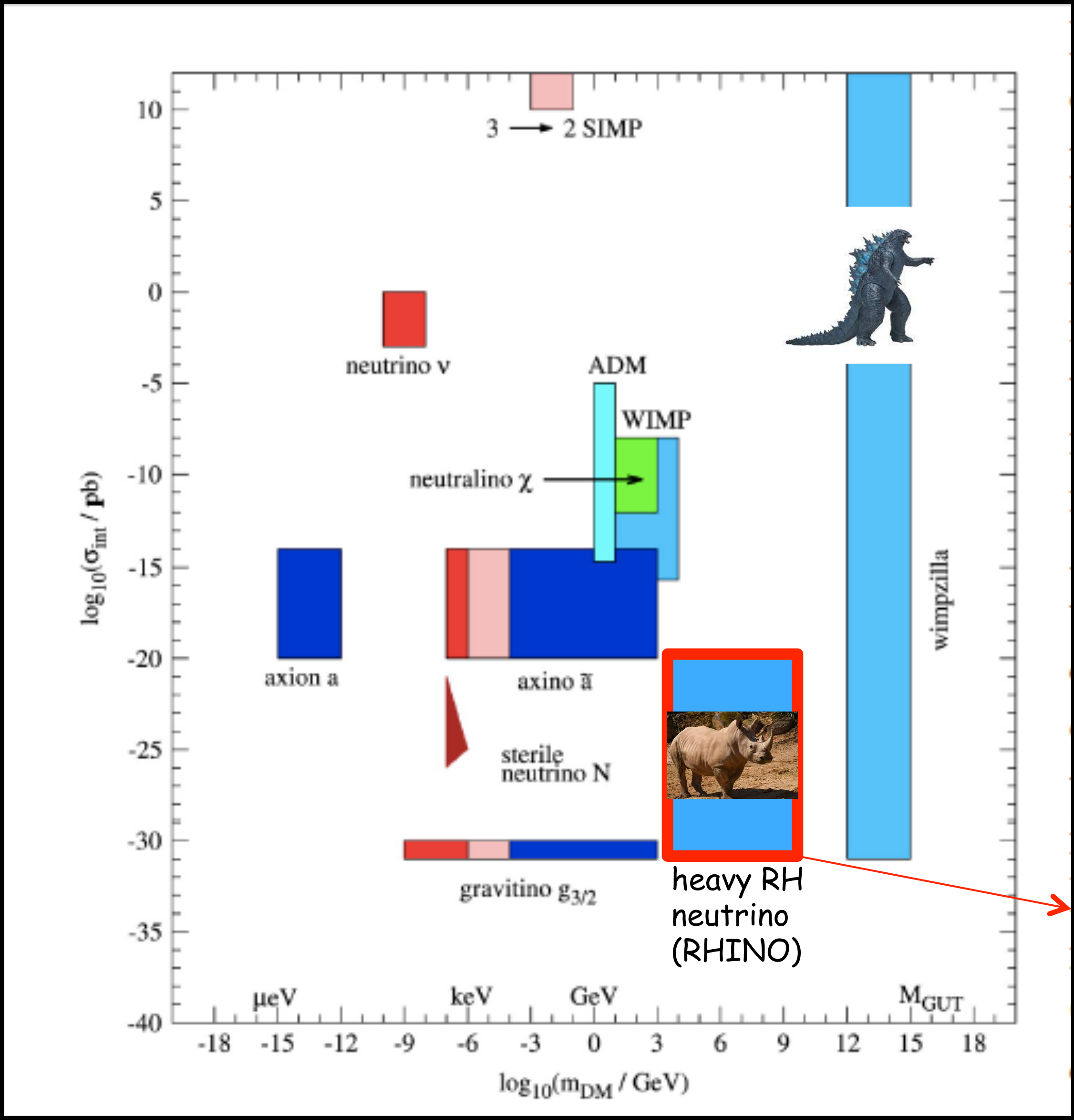
Indirect DM searches with γ-ray experiments

(from Aldo Morselli @ CORFU 2022)



Beyond the WIMP paradigm: the DM particle zoo

(from Baer et al.1407.0017)



(PDB, Anisimov '08)

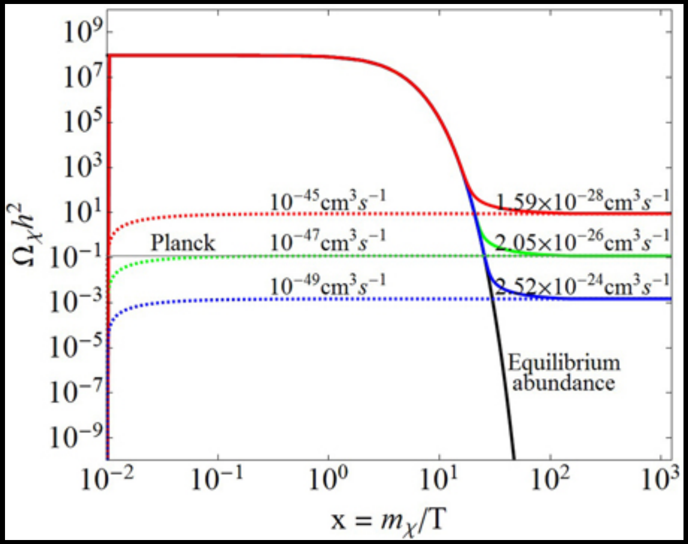
A new miracle?

new physics

EW

Examples of DM beyond the standard WIMPs:

- Freeze-in solution (FIMPs)



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

- Dark matter could decay after freeze-out
  example: gravitino dark matter with R parity breaking
  (Buchmuller, Covi, Hamaguchi Ibarra, Yanagida hep--ph/0702184)

- Or both: freeze-in and decaying DM!
  (example: keV seesaw neutrino solution)

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:

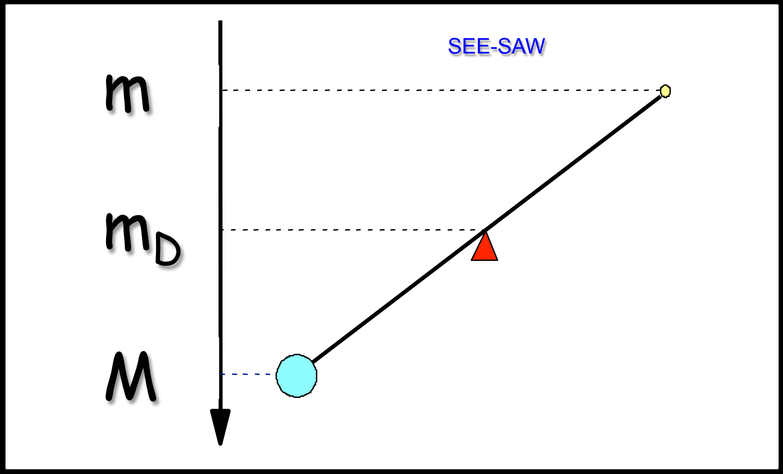
- 3 light **Majorana neutrinos** with masses (seesaw formula): $m_\nu = -m_D M^{-1} m_D^T \Rightarrow \mathrm{diag}(m_1, m_2, m_3) = -U^\dagger m_\nu U^*$
- 3(?) very heavy Majorana neutrinos **N_1, N_2, N_3** with **$M_3 > M_2 > M_1 \gg m_D$**

1 generation toy model :

$m_D \sim m_{top}$,

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

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



Dark matter from active-sterile neutrino mixing

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

- LH-RH (active-sterile) neutrino mixing

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

$$N_{1R} \simeq \nu_{1R} + \frac{m_{D\alpha 1}}{M_1}\nu^c_{L\alpha}$$ ⟶ 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 ~10^{-4} : 3.5 keV line? (Horiuchi et al. '14; Bulbul at al. '14; Abazajian '14)
The XRISM satellite (launched last Summer) should soon 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:

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

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 :

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

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

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

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, Bezrukov, Gorbunov, Shaposhnikov 0812.3622 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)

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

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

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

Remarks:

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

RHINO dark matter

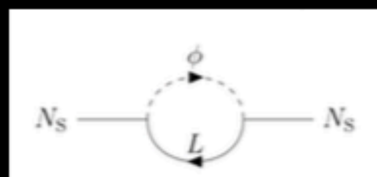
(Anisimov '06, Anisimov,PDB '08)

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

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

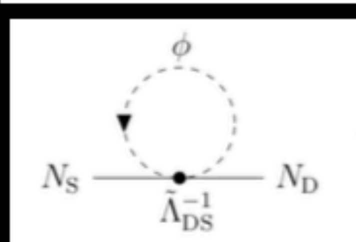
In general, $\lambda_{DS} \neq 0$ generates a dark-source RH neutrino mixing. The Yukawa and Anisimov interactions both generate effective potentials from self-energies:

From Yukawa interactions



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

From mixing



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

Effective mixing Hamiltonian :

mixing term

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

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

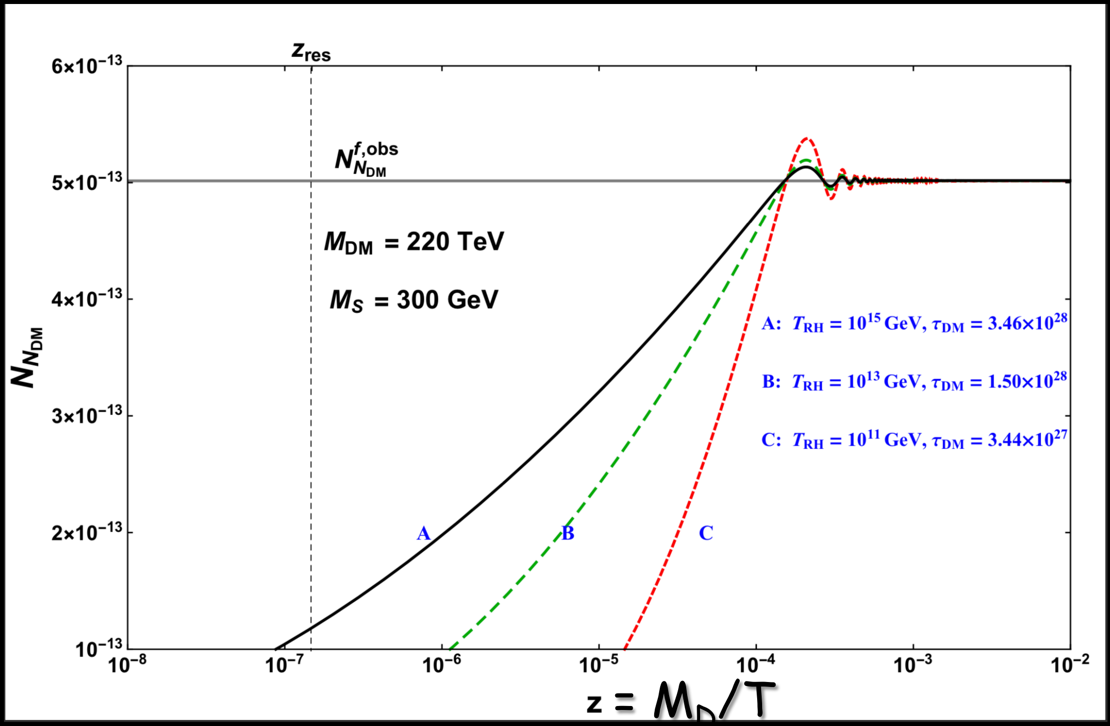
Density matrix calculation of the relic abundance

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

Density matrix equation for the dark-bright mixed RH neutrinos (using a monocromatic approximation p~3T)

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

Assuming an initial thermal N_S-abundance

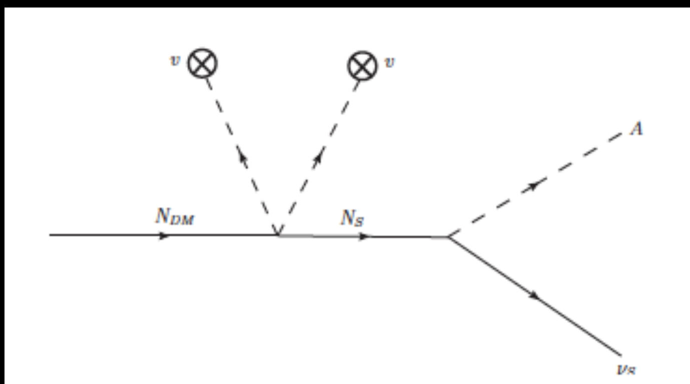


Dark neutrinos are necessarily unstable

(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



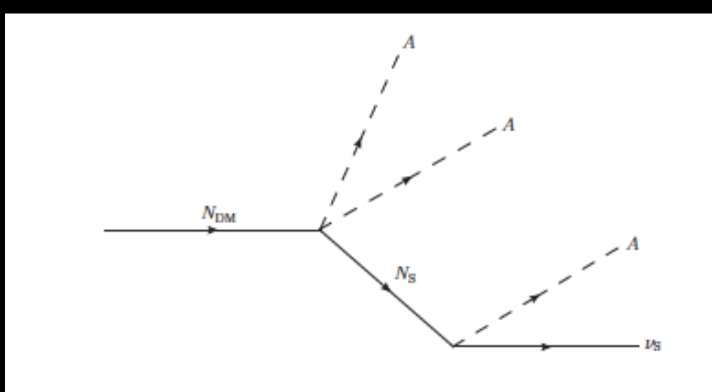
$$\theta_{\Lambda 0} = \frac{2\, v^2/\widetilde{\Lambda}_{\rm DS}}{M_{\rm D}\,(1 - M_{\rm S}/M_{\rm D})}$$

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



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

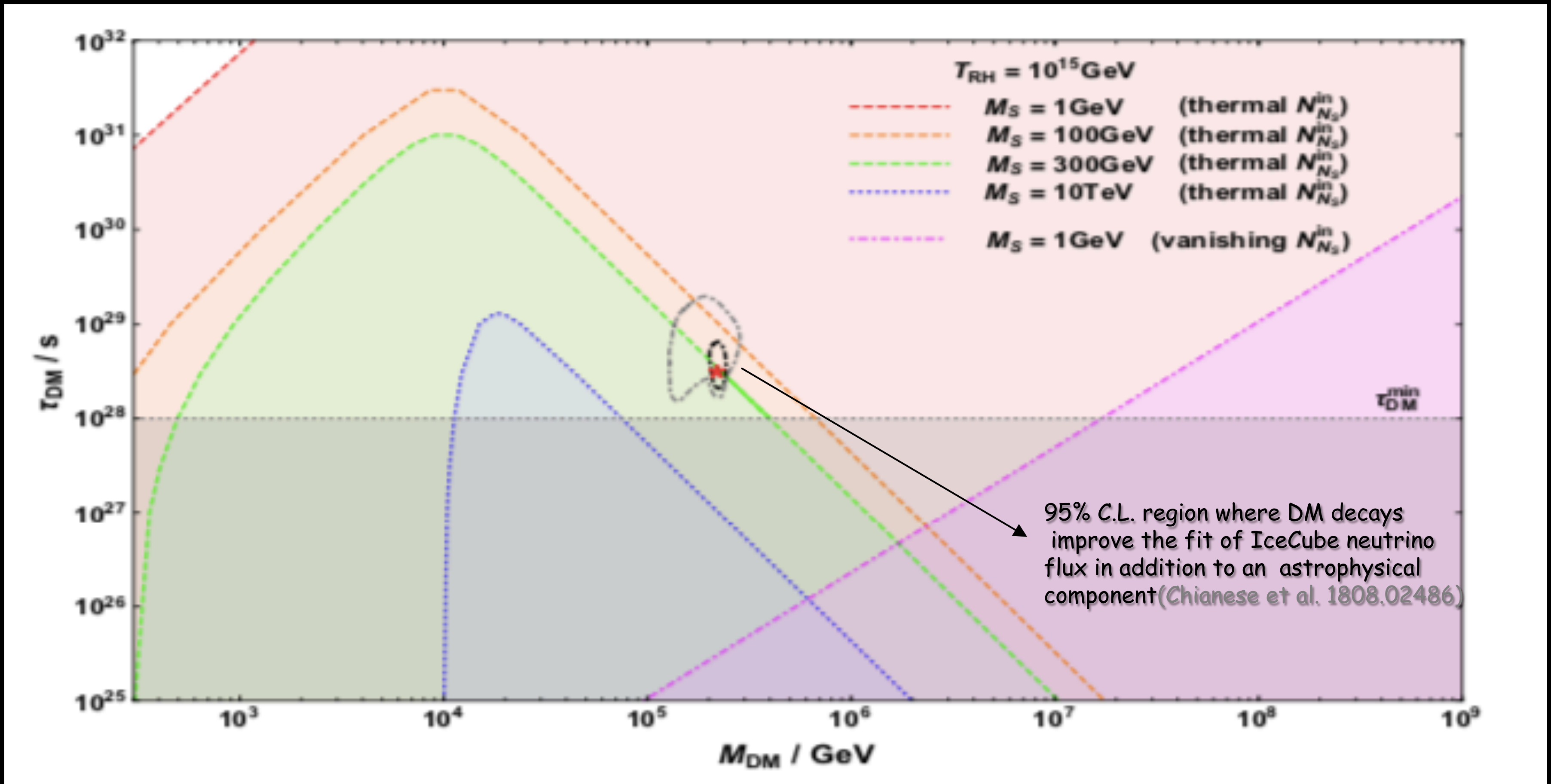
$$\Gamma_{{\rm D}\to 3A+\ell_{\rm S}} = \frac{\Gamma_{\rm S}}{15\cdot 2^{11}\cdot \pi^4}\,\frac{M_{\rm D}}{M_{\rm S}}\left(\frac{M_{\rm D}}{\widetilde{\Lambda}_{\rm DS}}\right)^2$$

⇒ Upper bound on M_D

3 body decays and annihilations can also 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

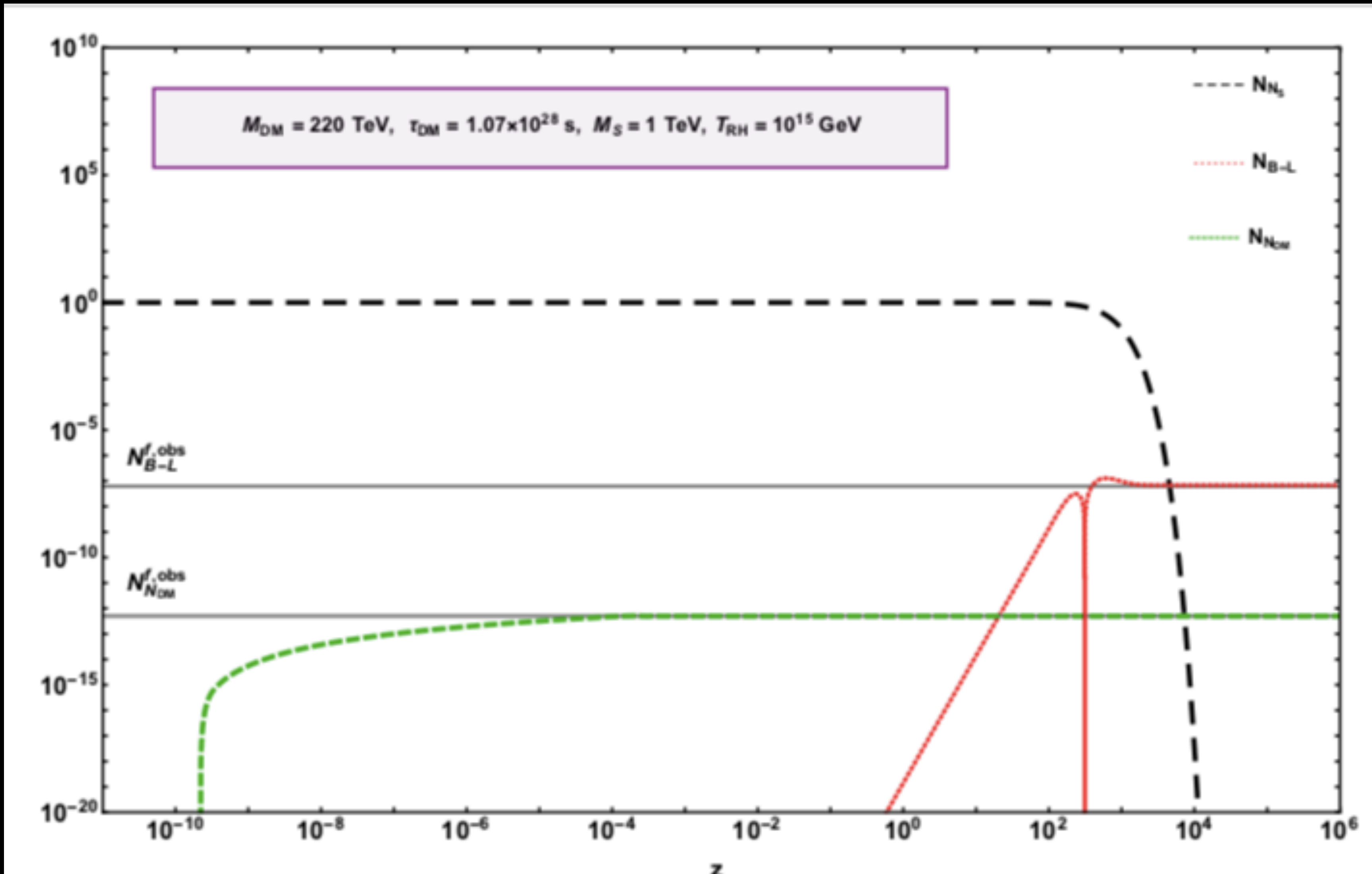
Can one think of processes able to thermalize the N_S abundance prior to the oscillations?

Two good motivations

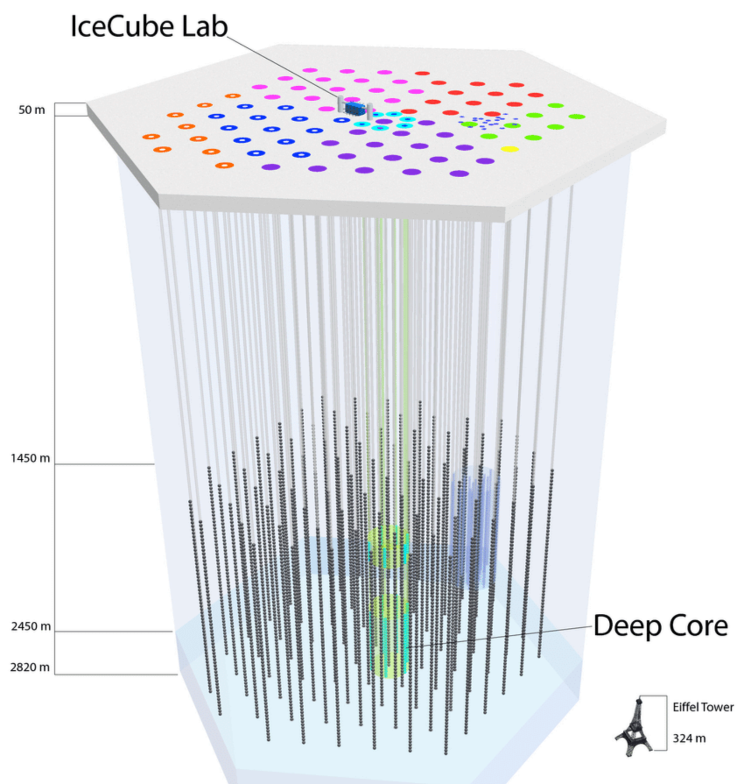
Unifying Leptogenesis and Dark Matter

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

A solution for initial thermal N_S abundance:



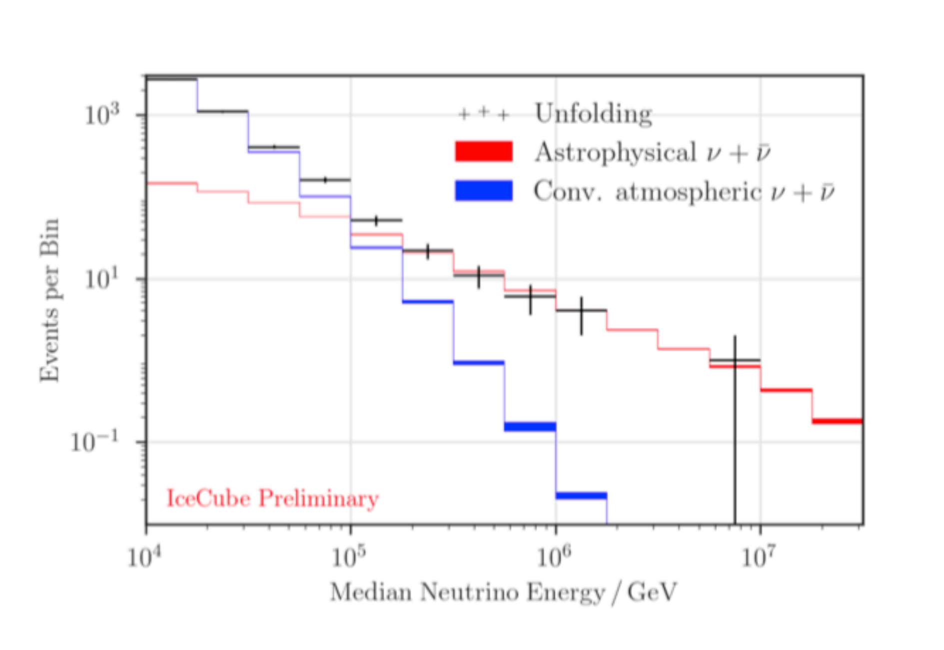
IceCube



- 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

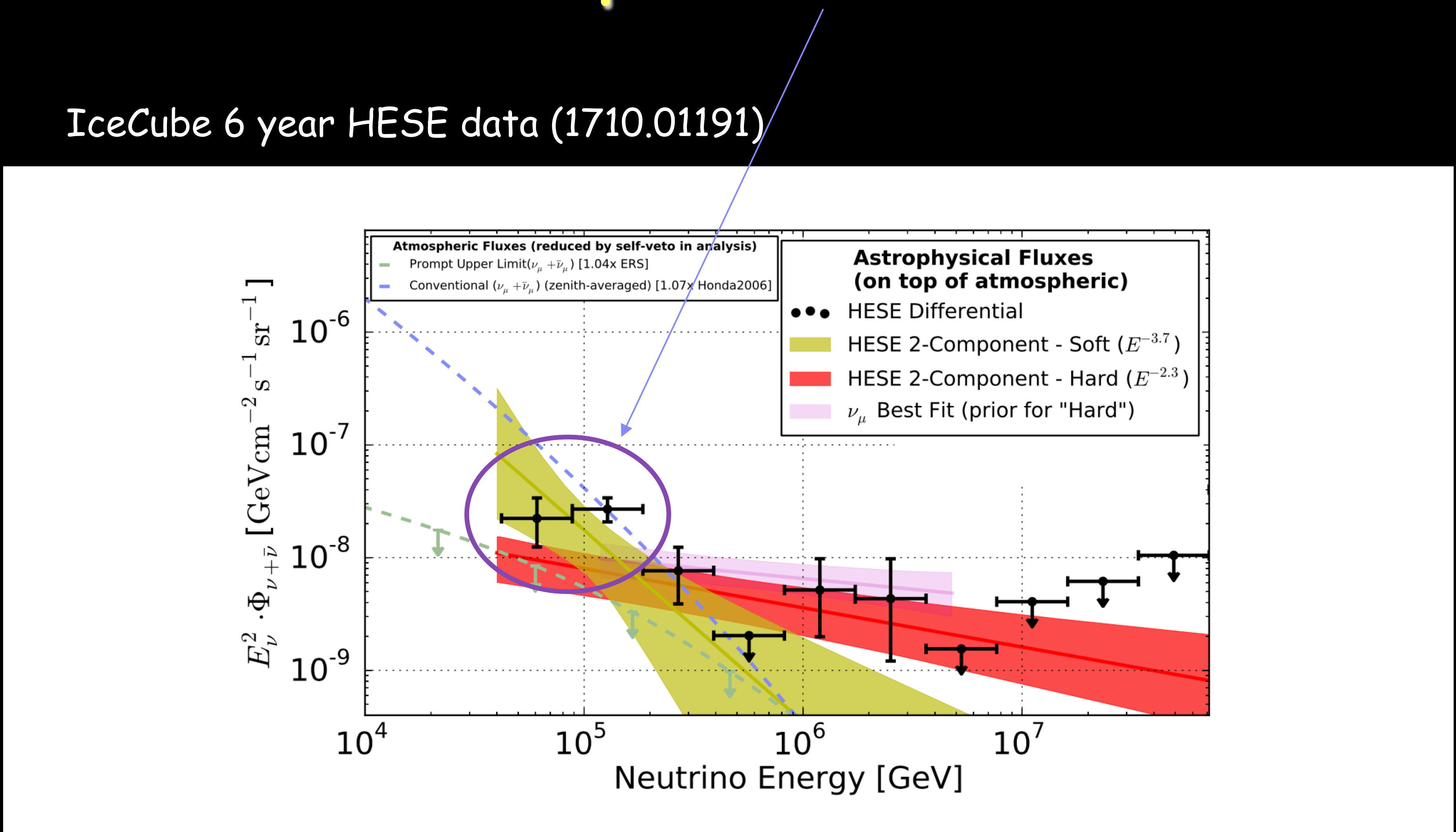
$$\frac{d\Phi}{dE} = \Phi_0 \cdot \left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{-\gamma_{astro}}$$

Best fit

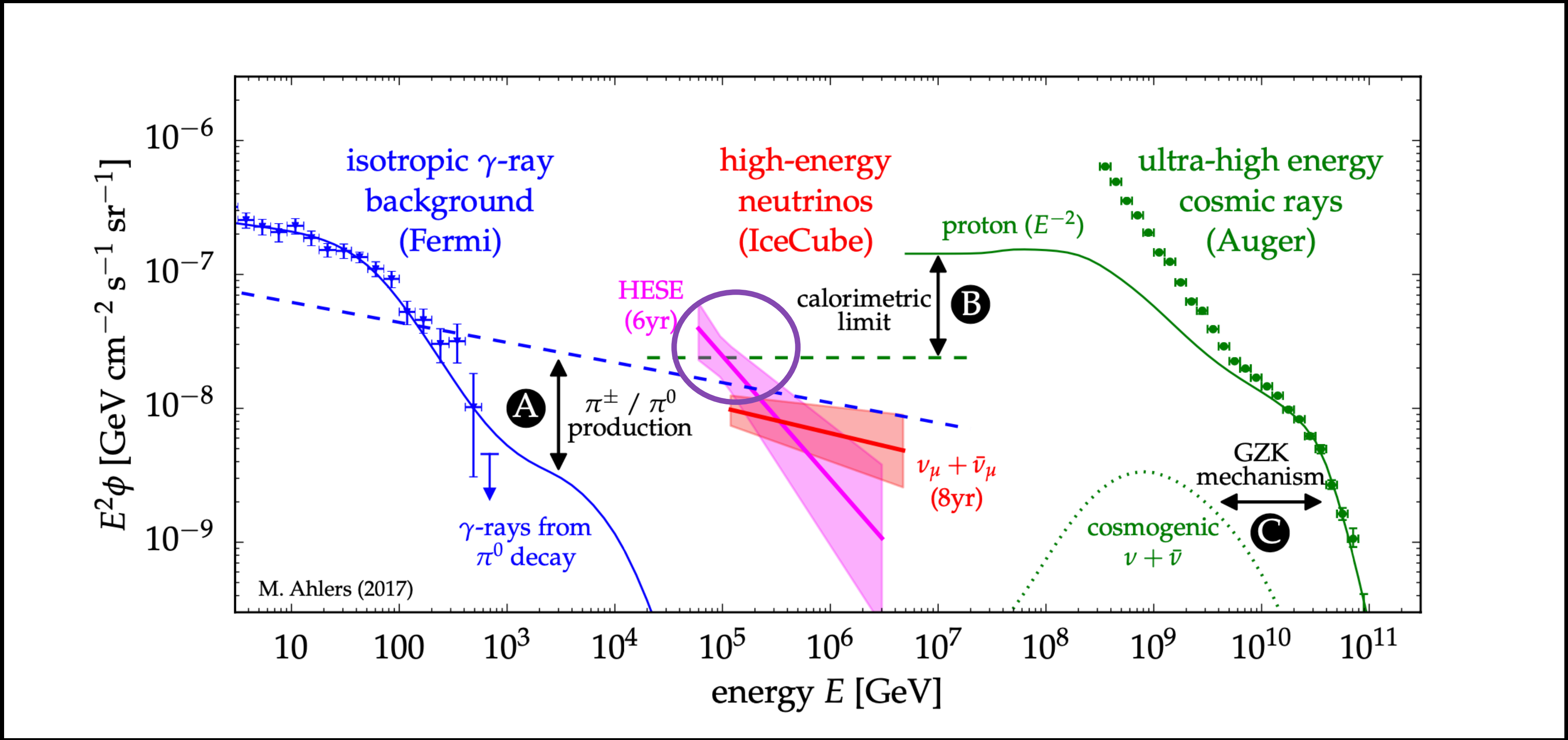
$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE} = (1.01 \pm^{0.26}_{0.23}) \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-2.19 \pm 0.10} \cdot 10^{-18} \mathrm{GeV}^{-1} cm^{-2} s^{-1} sr^{-1}.$$

An extra component at ~100 TeV ?

IceCube 6 year HESE data (1710.01191)



A multimessenger analysis confirms an 100 TeV excess



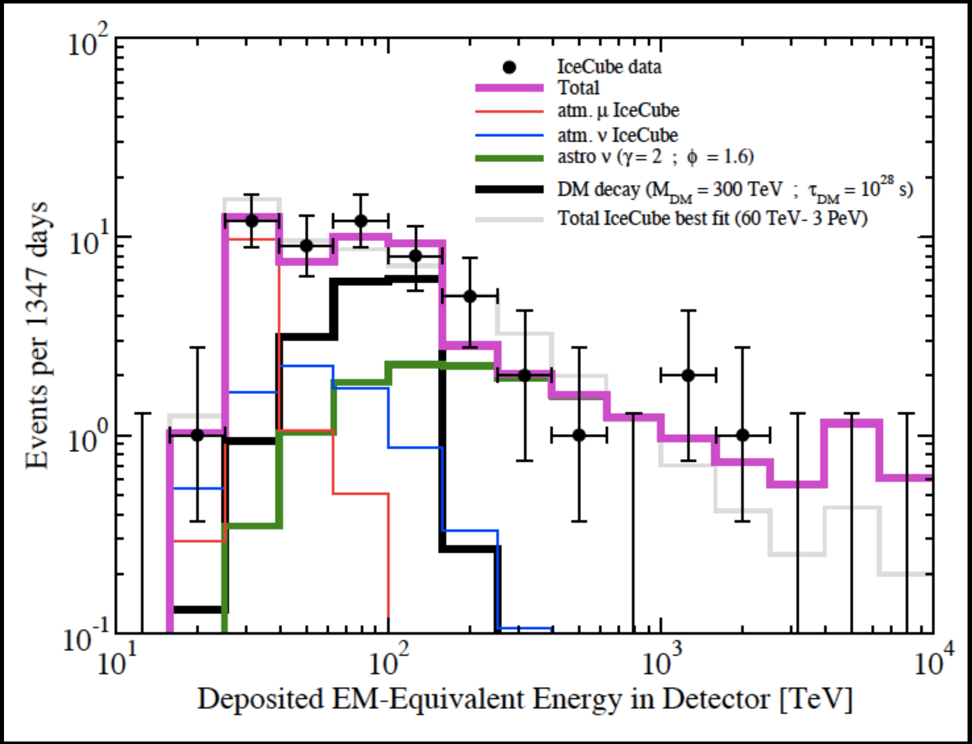
IceCube 6 year HESE data (1710.01191)

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

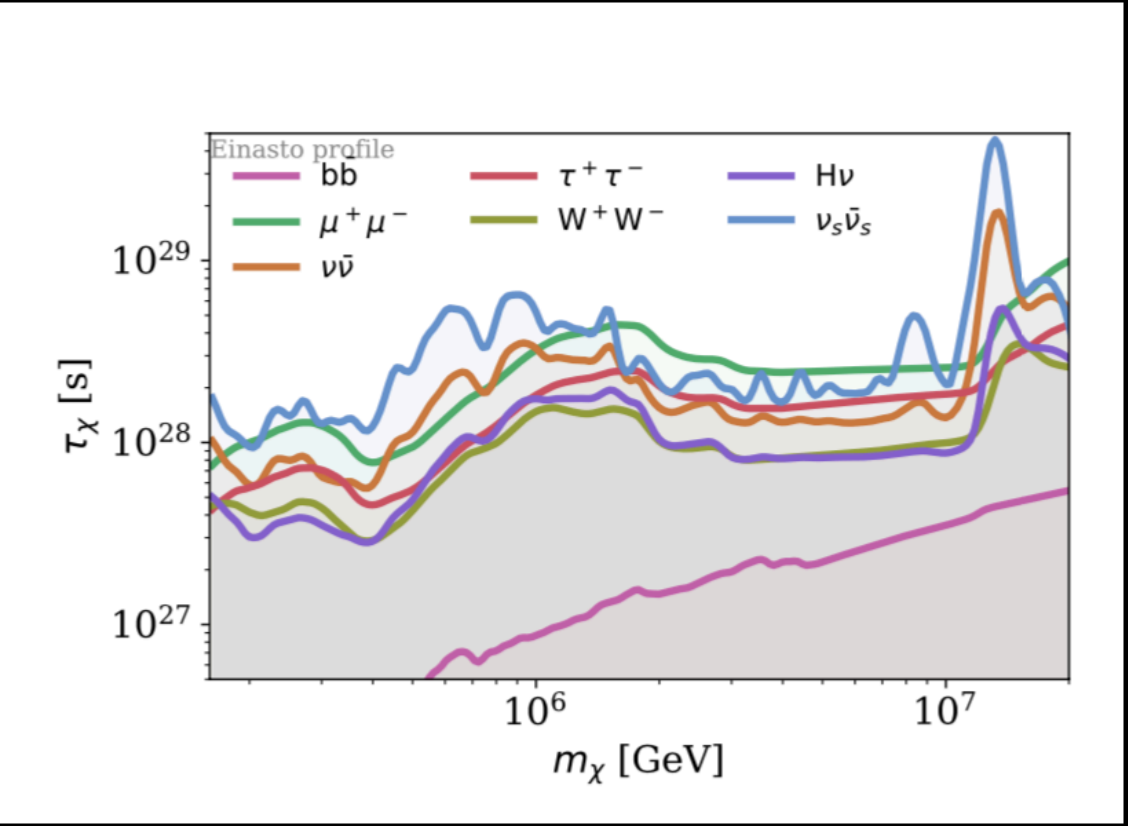


(from 1606.06238)

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

Lower bound on the lifetime of decaying DM

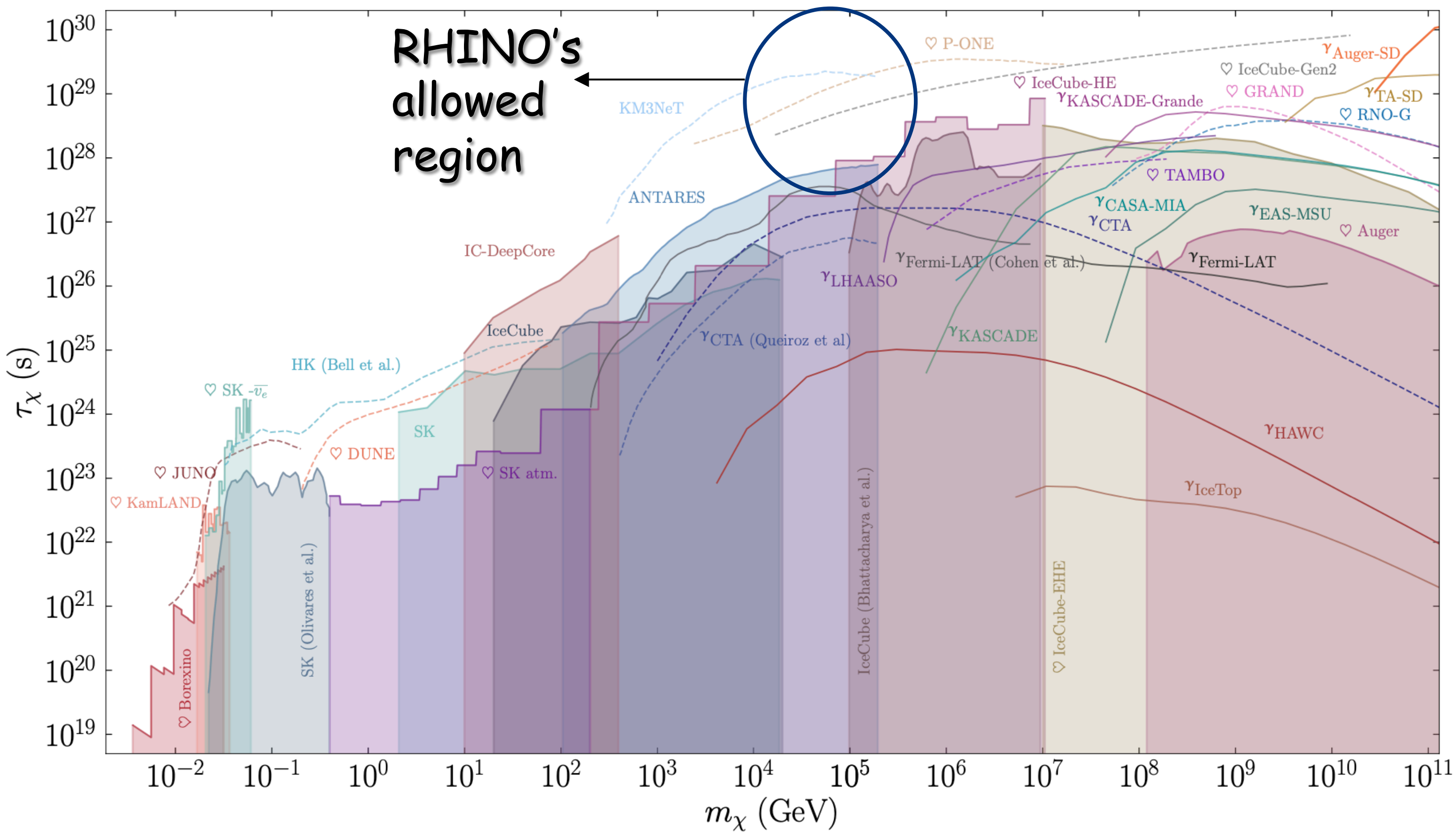
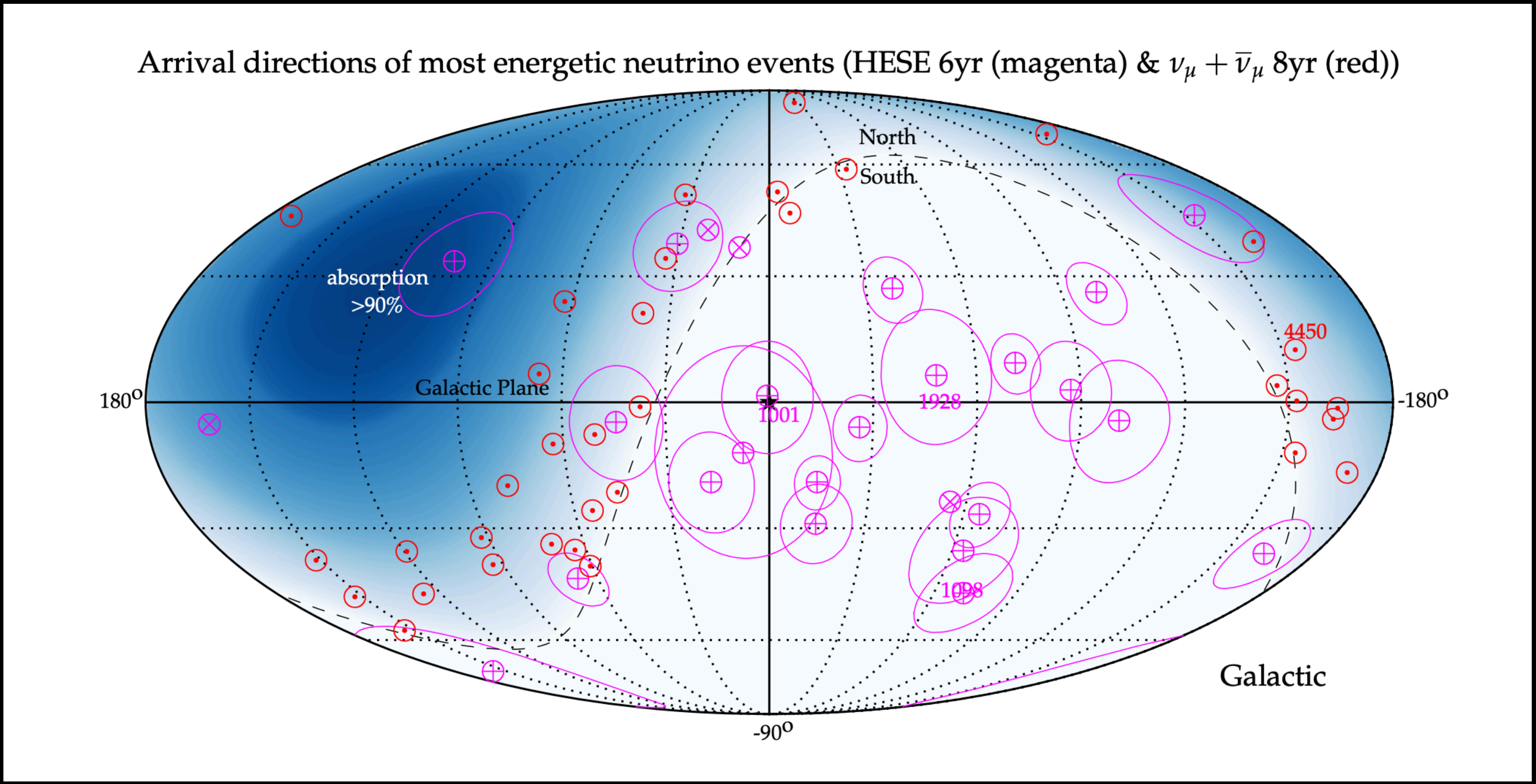


FIG. 2: ***Constraints on the lifetime of dark matter decaying to neutrinos $\chi \to \bar{\nu}\nu$.*** Solid lines bordering shaded regions represent limits from existing neutrino telescope data, solid lines without shading correspond to limits from existing gamma-ray observatories (as shown in Fig. 3), and dashed lines show the reach of future experiments. Labels with a heart symbol (♡) correspond to limits derived for this work.

(Arguelles et al., 2210.01303)

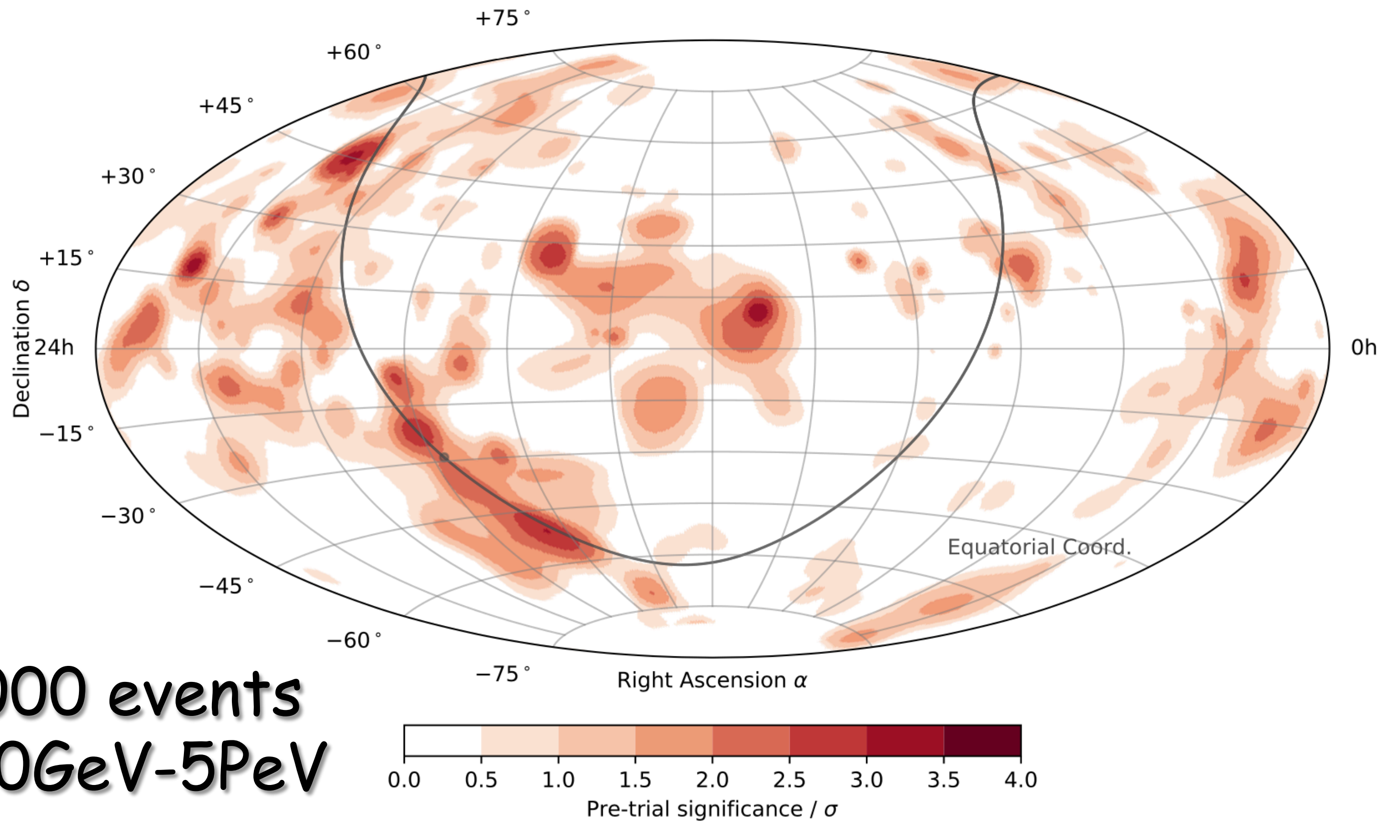
Absence of strong anisotropies



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

Observation of high energy neutrinos from the Galactic plane

(IceCube 10 years data 2011-2021 2307.04427)

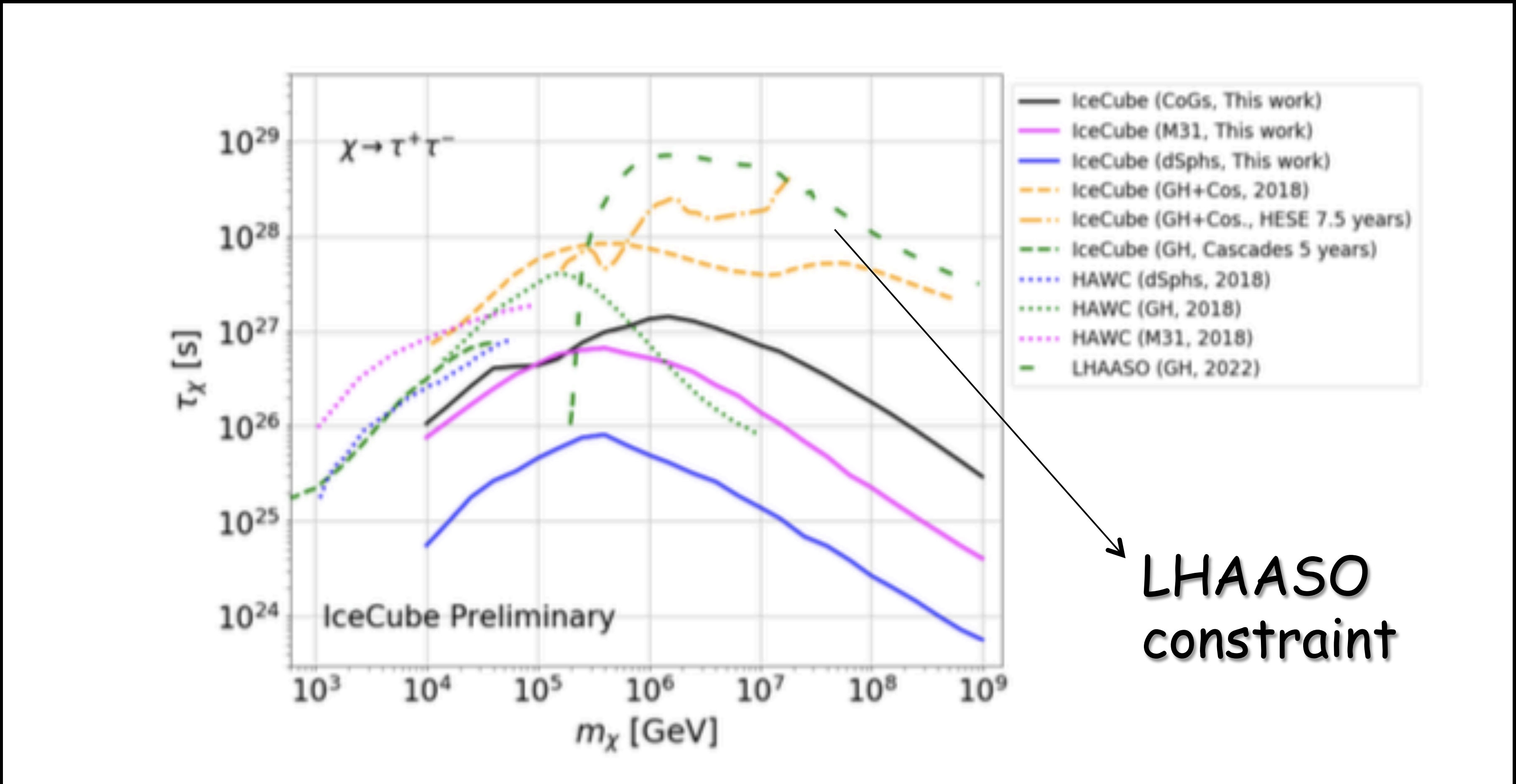


~60,000 events
E~500GeV-5PeV

Figure 4: **All-sky point source search.** The best-fitting pre-trial significance for the all-sky search is shown as a function of direction in an Aitoff projection of the celestial sphere, in equatorial coordinates (J2000 equinox). The Galactic plane is indicated by a grey curve, and the Galactic Center as a dot. Although some locations appear to have significant emission, the trial factor for the number of points searched means these points are all individually statistically consistent with background fluctuations.

Search for DM decays in nearby galaxy clusters and galaxies with IC

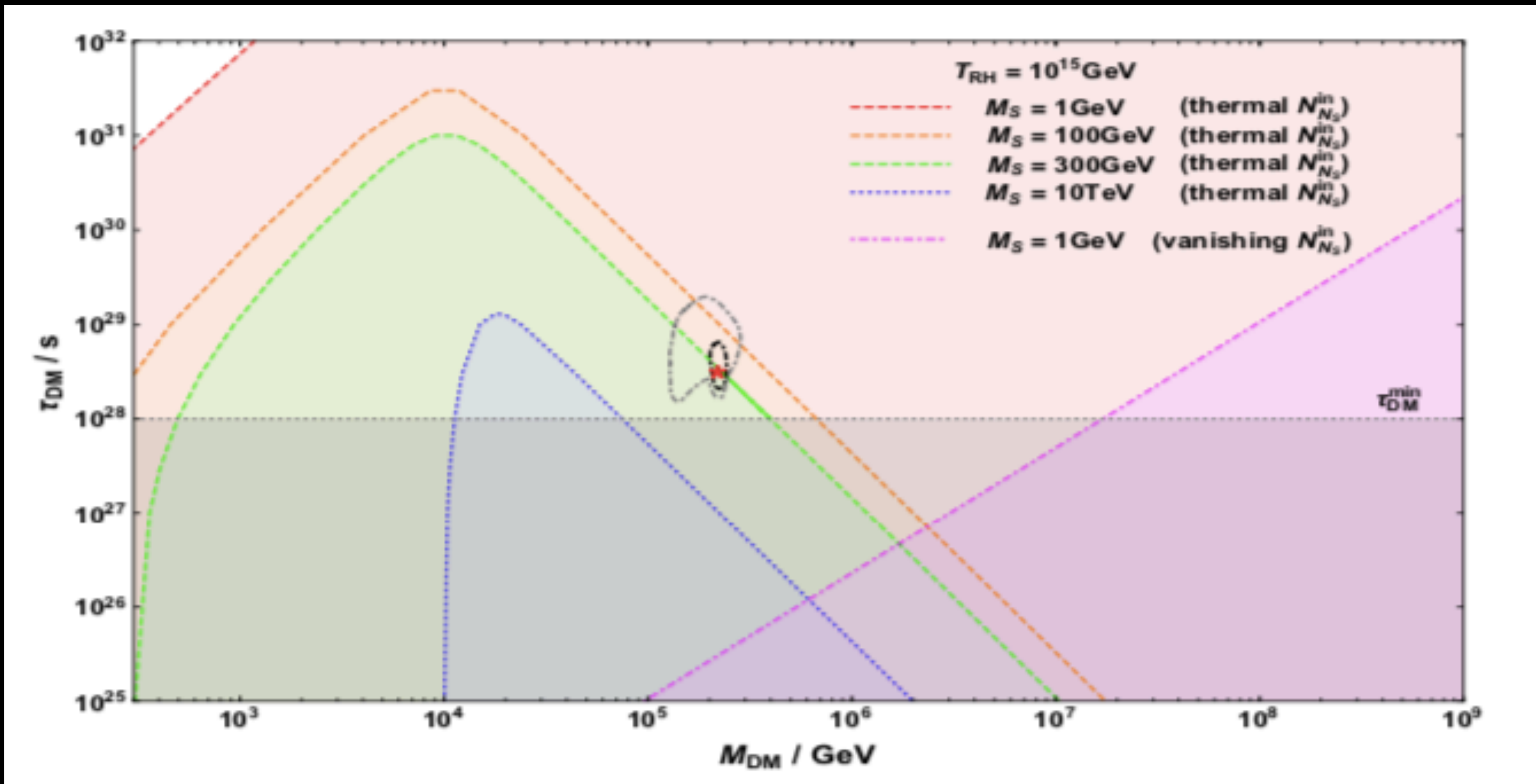
(IceCube 2308.04833)



LHAASO = Large High Altitude Air Shower Observatory

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)

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

<u>effective scales</u>

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

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

Can these interactions thermalise the source neutrinos prior to oscillations?

Let us modify the kinetic equations including these processes:

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

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

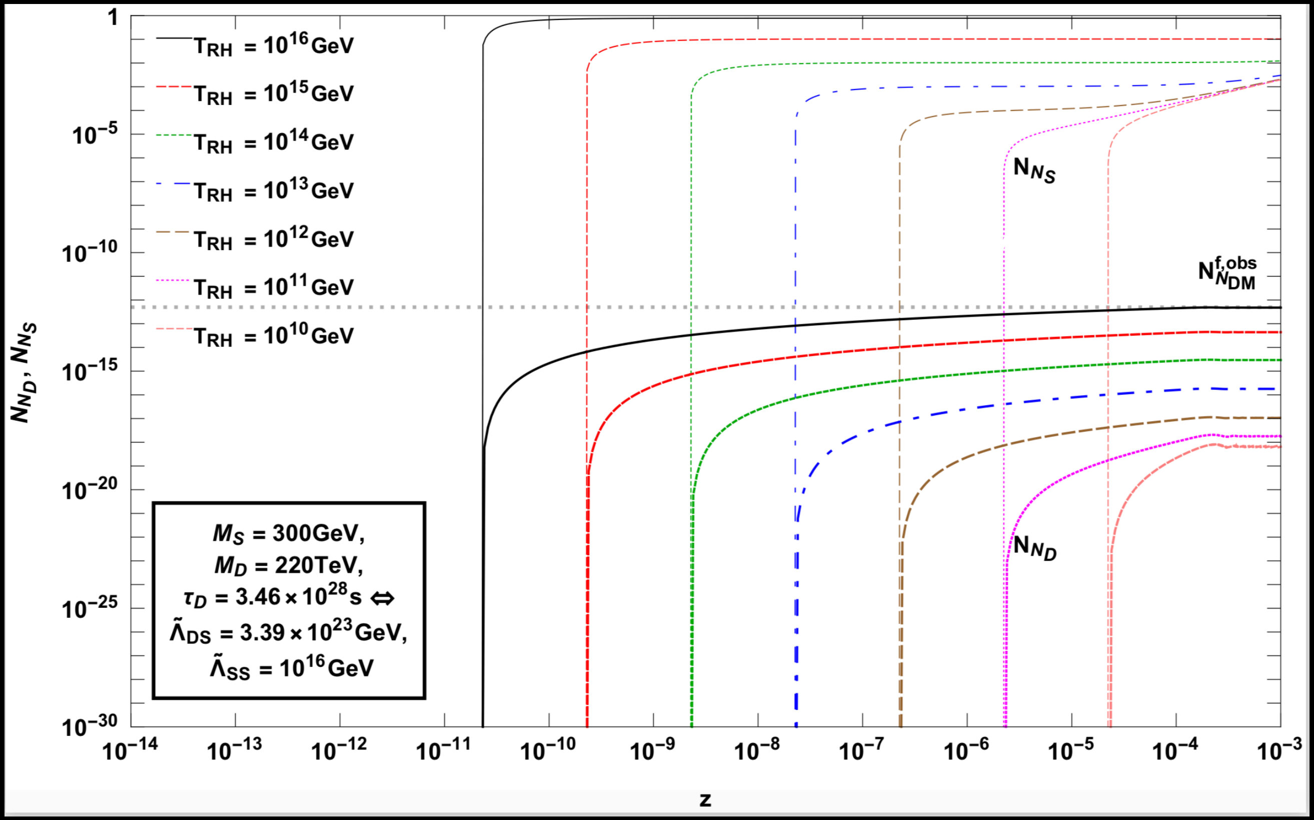
(Kolb, Long, 1708.04293)

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

Condition for the thermalisation of the N_S abundance

(PDB, A. Murphy, arXiv 2210.10801)

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



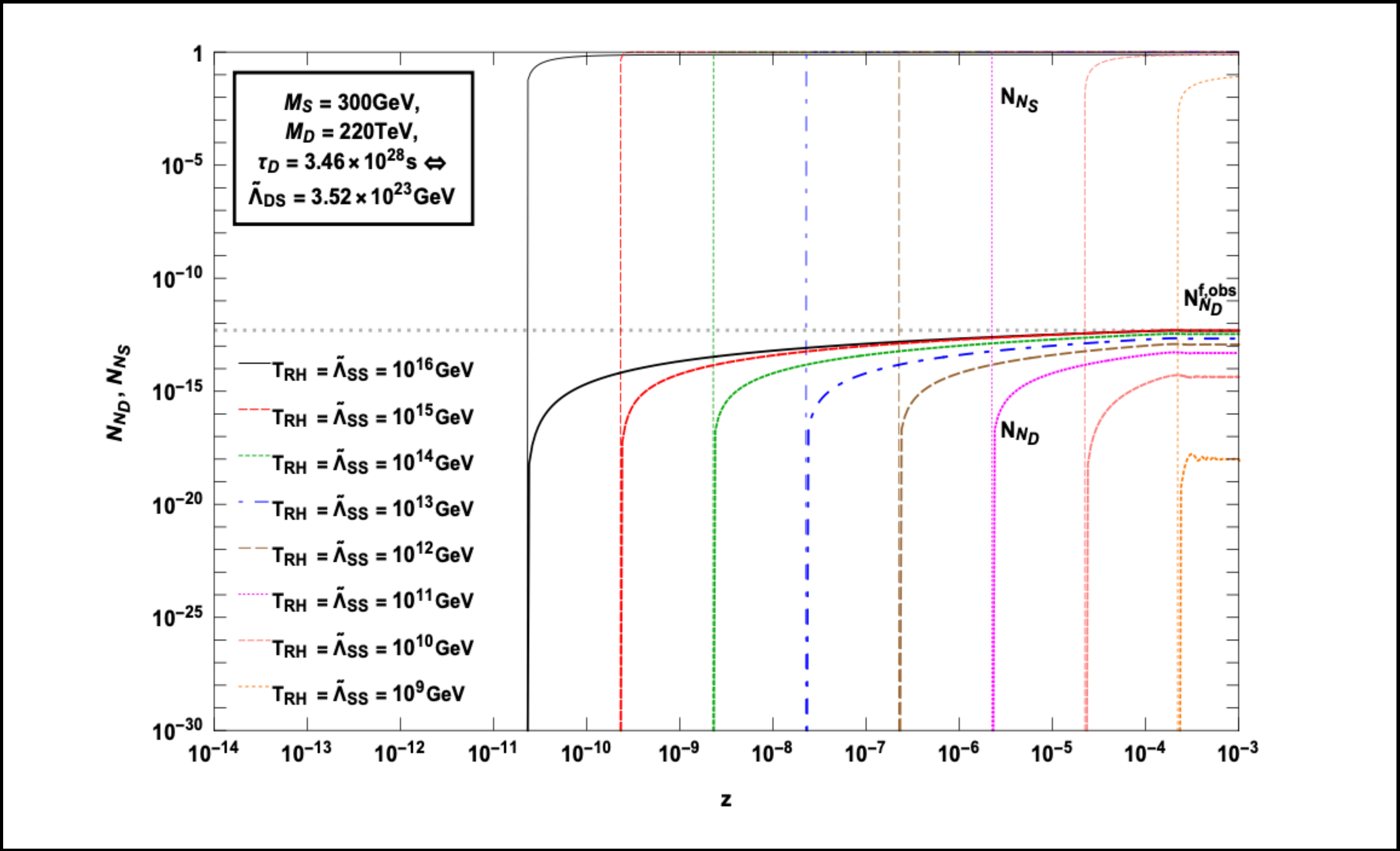
$\tilde{\Lambda}_{DS} \sim 10^{23}$ GeV

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

⇓

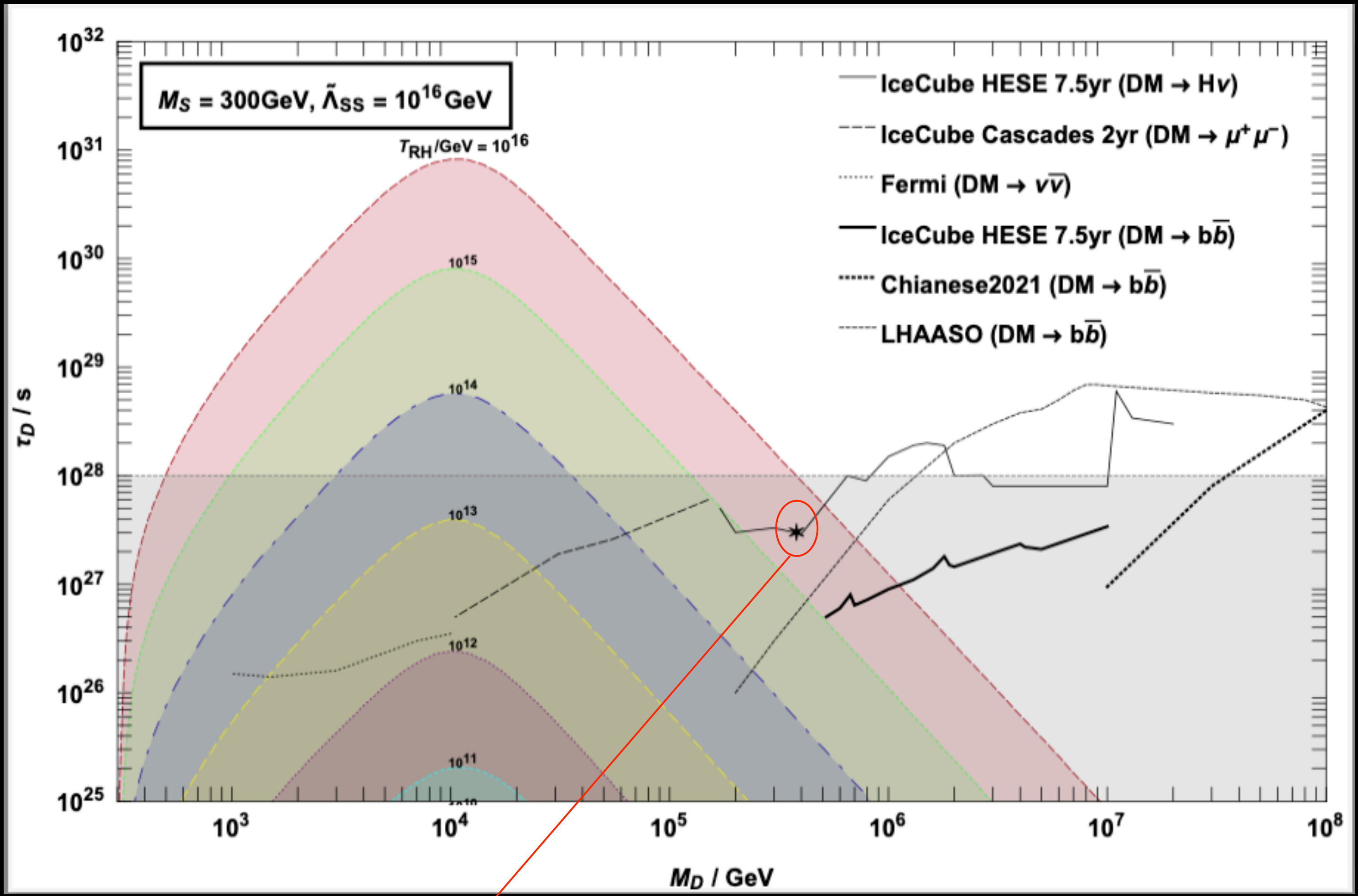
GUT scale !!

The scale 10^{16} GeV maximises the production of DM



DM lifetime vs. mass plane: allowed regions

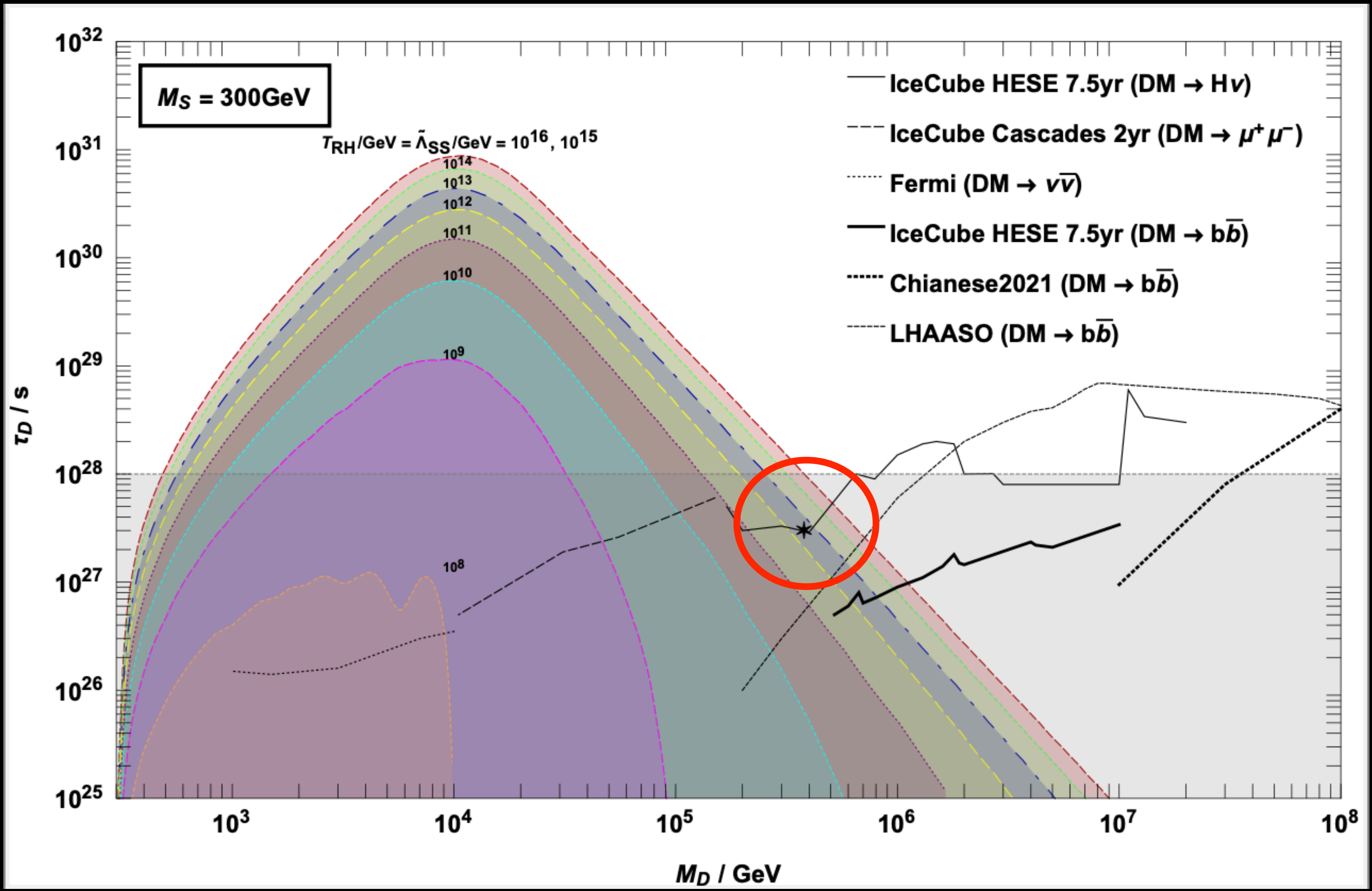
(PDB, A. Murphy, 2210.10801)



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

DM lifetime vs. mass plane: allowed regions

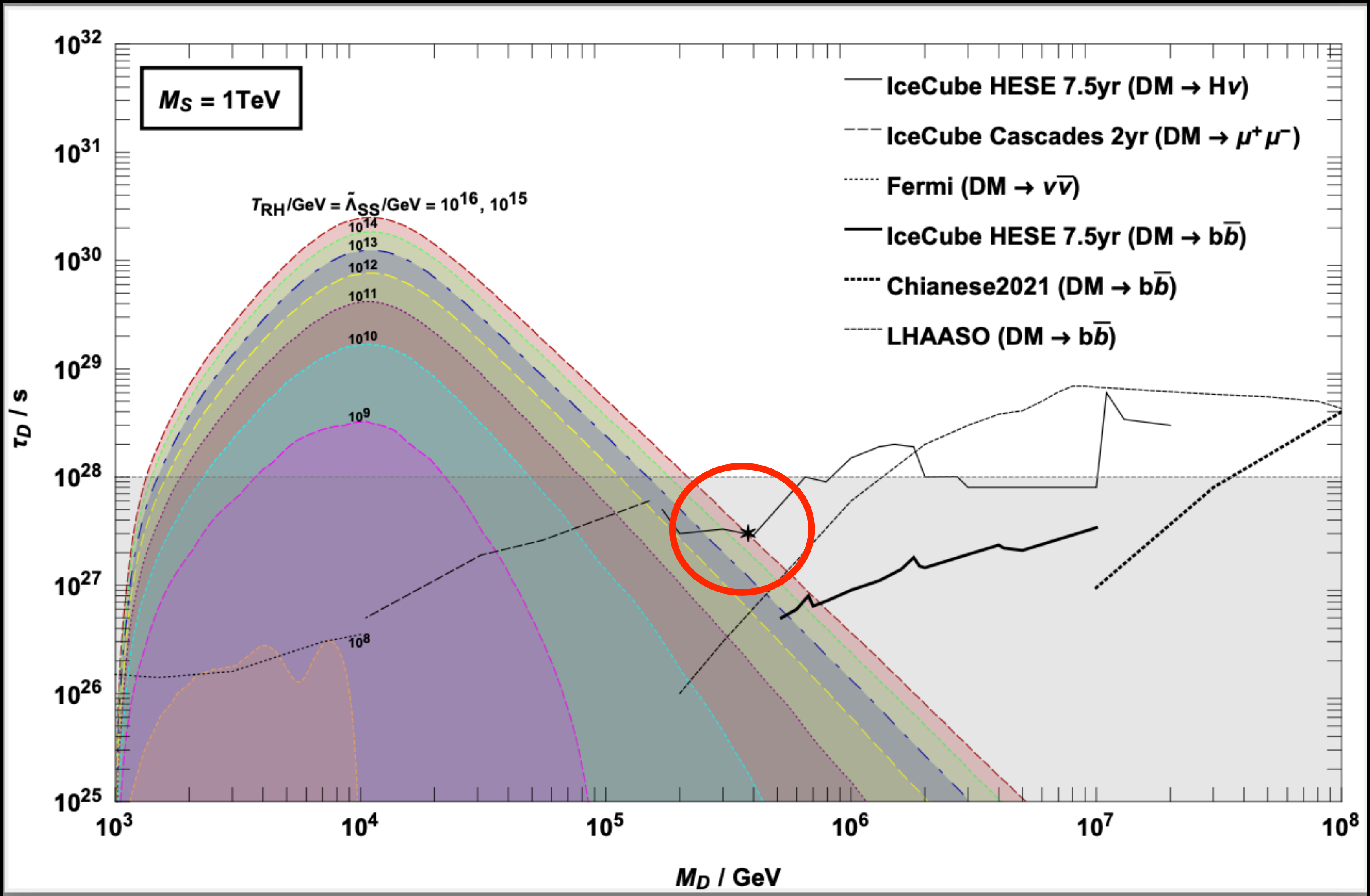
(PDB, A. Murphy, 2210.10801)



The scale of new physics cannot be made too much lower the GUT scale in order to explain the IceCube excess (respecting the LHAASO lower bound)

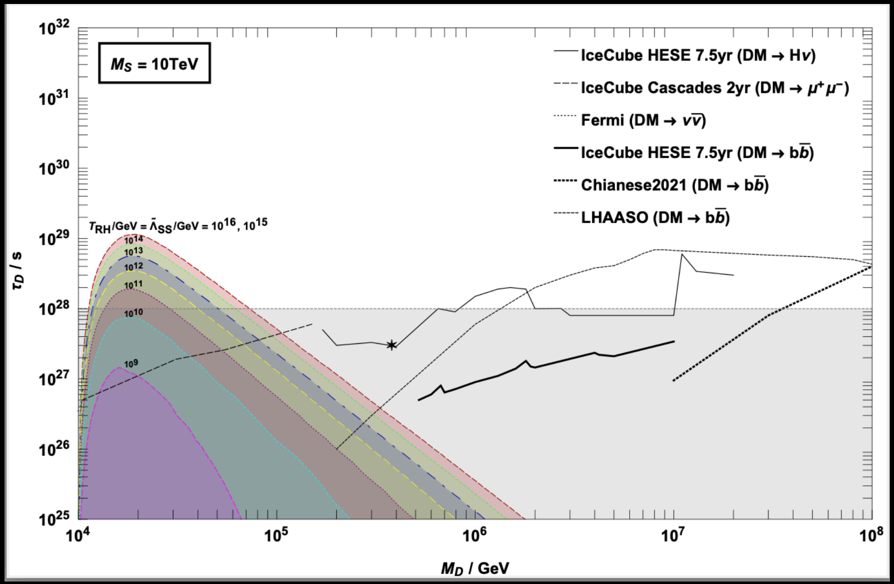
DM lifetime vs. mass plane: allowed regions

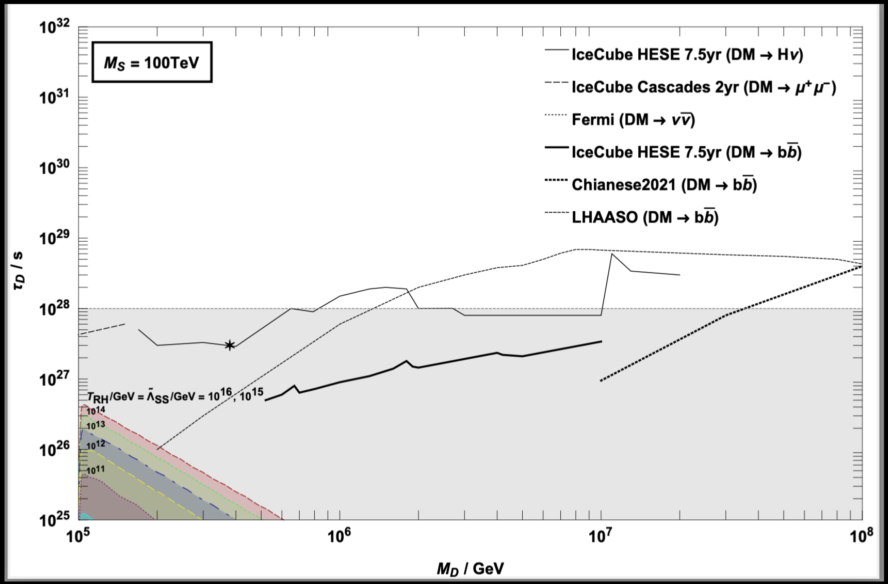
(PDB, A. Murphy, 2210.10801)



Upper bound on the seesaw (=leptogenesis) scale

(PDB, A. Murphy, 2210.10801)



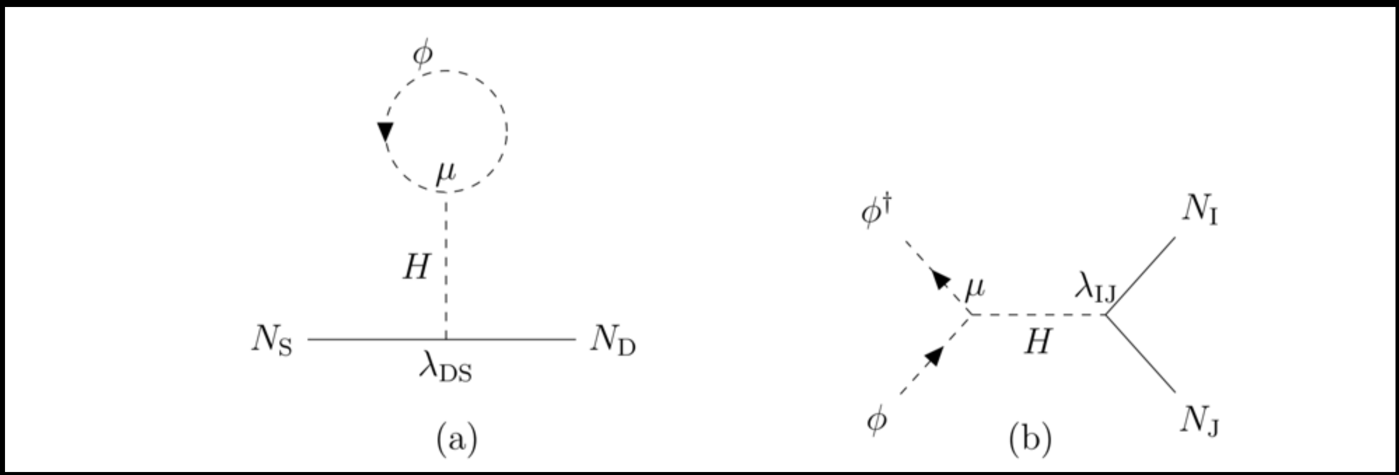


The mechanism is compatible with (resonant) leptogenesis at a scale between 10 and 100 TeV

A possible GUT origin ? Heavy scalar H as mediator

(Anisimov,PDB, 2008; PDB, P. Ludl, S. Palomarez-Ruiz 2016; Kolb and Long 1708.04293; PDB, A. Murphy, 2210.10801)

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



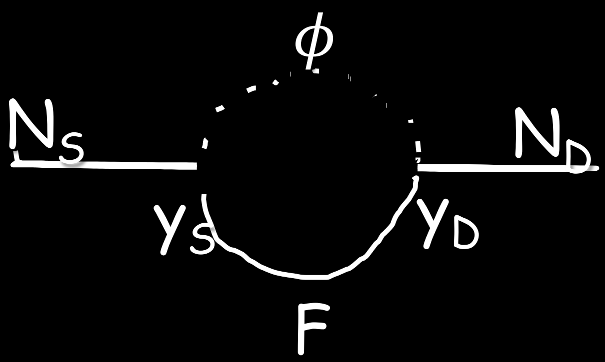
$$\mathcal{L}_H^{\rm eff} = \frac{1}{2} \sum_{I,J,K,L} \frac{\lambda_{IJ}\lambda_{KL}}{M_H^2} (\overline{N_{\rm I}^c} N_J)(\overline{N_{\rm K}^c} N_L) + \frac{1}{2}\frac{\mu^2}{M_H^2}(\phi^\dagger \phi)^2 + \sum_{I,J} \frac{\mu \lambda_{IJ}}{M_H^2} \Phi^\dagger \Phi \overline{N_{\rm I}^c} N_{\rm J} \,.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

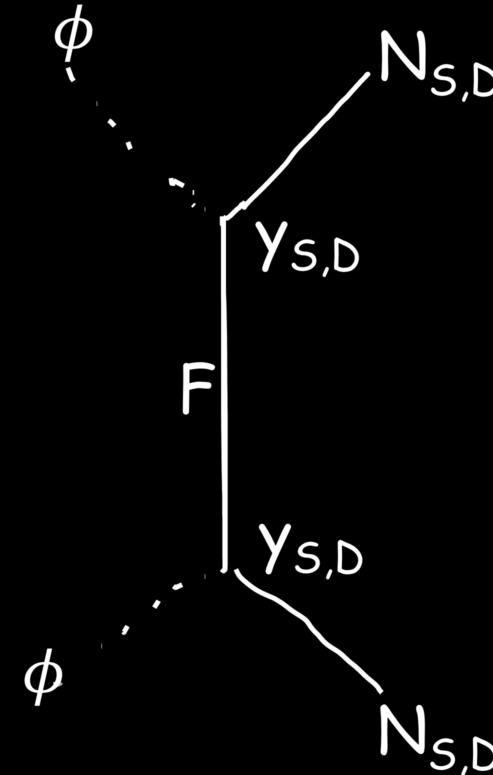
For $\mu \sim 10^9$GeV and $M_H \sim 10^{16}$GeV one can have $\tilde{\Lambda}_{DS} \sim 10^{23}$ GeV and $\lambda_{DS} \sim O(1)$ but one cannot reproduce simultaneously $\tilde{\Lambda}_{SS} \sim 10^{16}$GeV with the same scale Λ

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 $y_S\sim1$ and $y_D\sim10^{-7}$:

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

$y_D\sim10^{-7}$ can be understood as a small symmetry (e.g. Z_2) breaking parameter

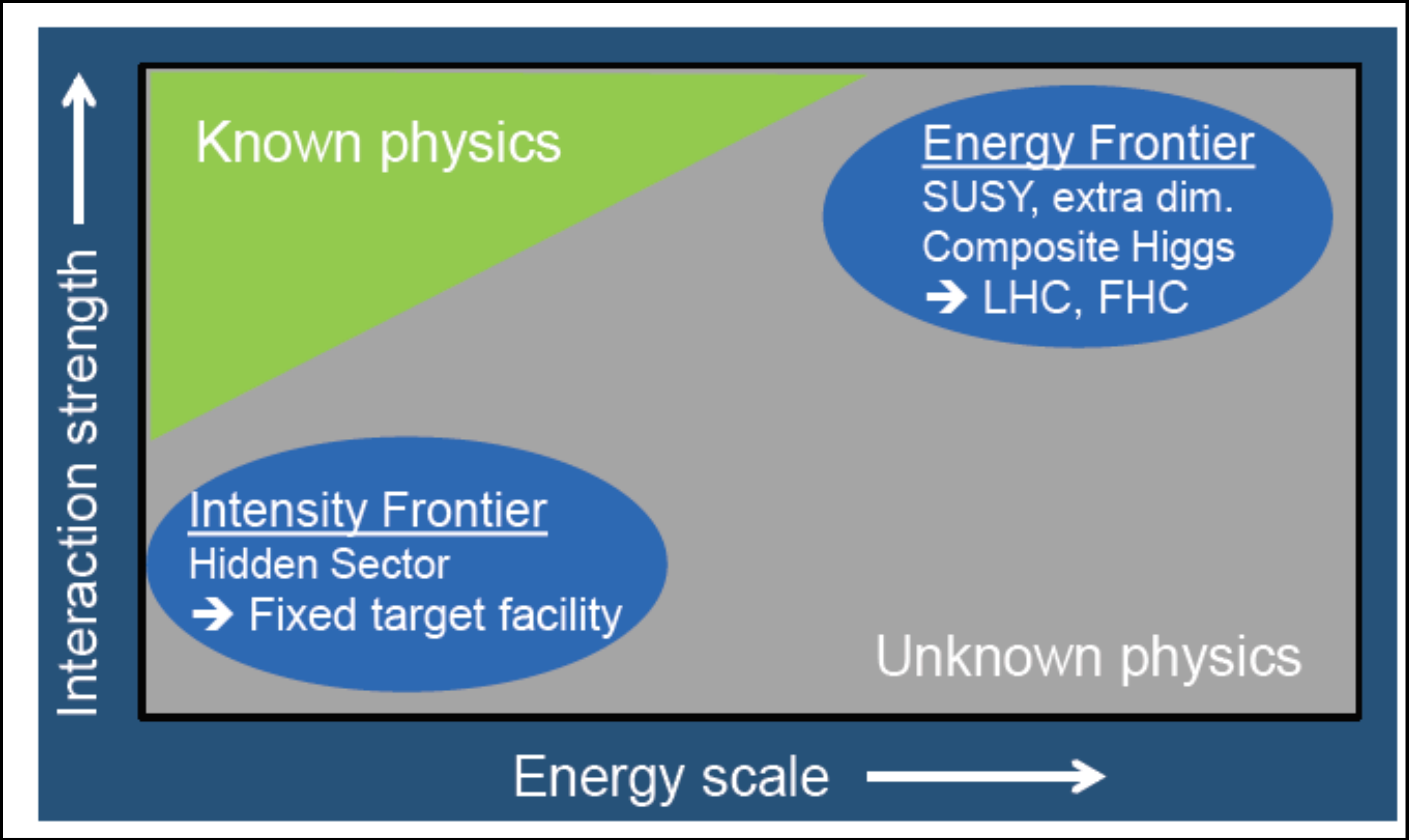
Summary

- The DM puzzle might have a solution at higher scales than those traditionally explored so far and….
- ….heavy RH neutrinos provide an interesting option. An heavy RH neutrino playing the role of DM requires an extension of the usual type-I seesaw Lagrangian
- 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 finds 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
- The emerging scale of new physics that can accommodate all constraints and also address the IceCube excess at ~ 100 TeV is $M_{GUT} \sim 10^{15}$ -10^{16} GeV:

a GUT RHINO miracle!

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)

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

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

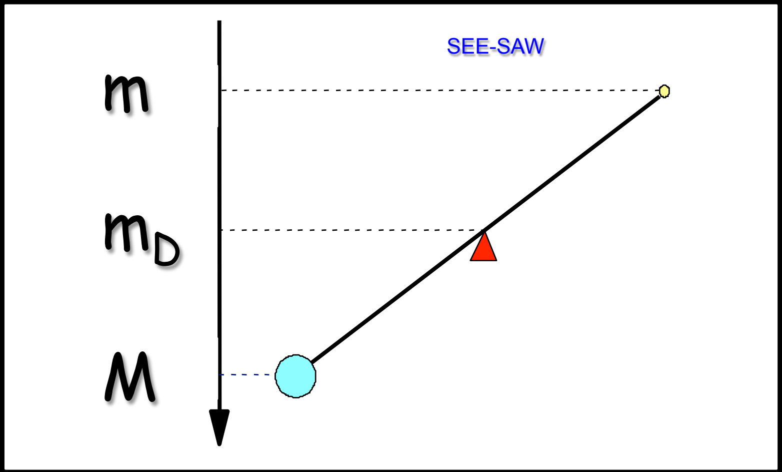
- 3 light **Majorana neutrinos** with masses (seesaw formula): $m_\nu = -m_D M^{-1} m_D^T \Rightarrow \mathrm{diag}(m_1, m_2, m_3) = -U^\dagger m_\nu U^*$
- 3(?) very heavy Majorana neutrinos **N_1, N_2, N_3** with **$M_3 > M_2 > M_1 \gg m_D$**

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 $N_I \xrightarrow{\Gamma_I} L_I + \phi^\dagger$ $\quad N_I \xrightarrow{\overline{\Gamma}} \overline{L}_I + \phi$

total CP asymmetries $\varepsilon_I \equiv -\dfrac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}$ $\Rightarrow N_{B-L}^{fin} = \sum_{I=1,2,3} \varepsilon_I \times \kappa_I^{fin}$ → efficiency factors

- Sphaleron processes in equilibrium

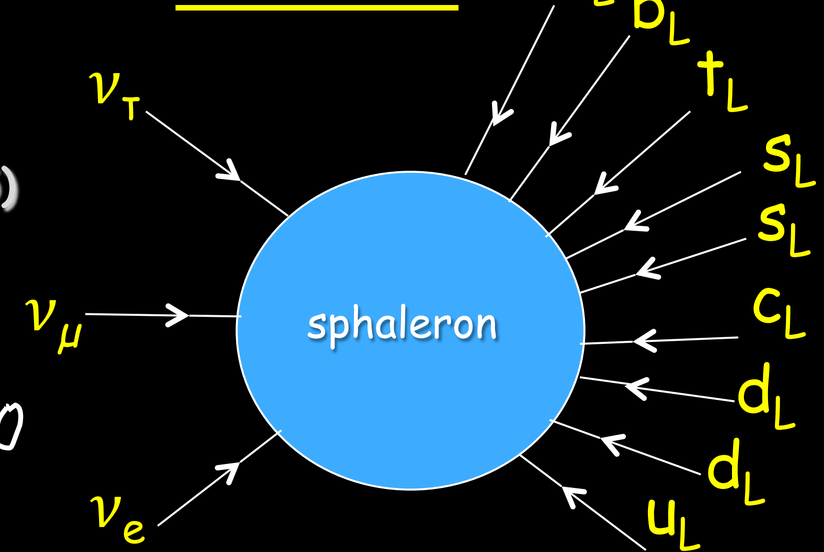
$\Rightarrow T_{RH} \gtrsim T_{sphalerons}^{off} \simeq$ 132 GeV

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

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

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

ΔB=ΔL=3



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);

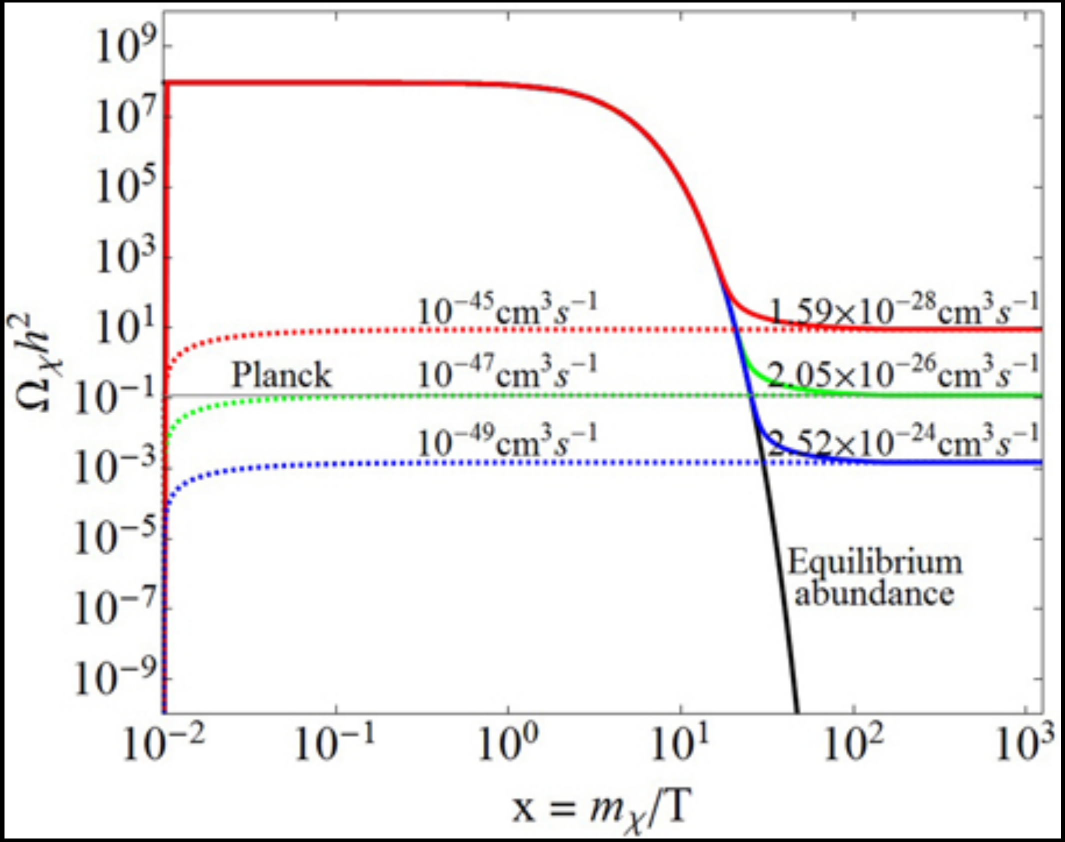
•From new $U(1)_Y$ interactions connecting DM to SM (Dev, Mohapatra,Zhang '16);

•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)

Freeze-in solution for annihilating particles (FIMPs)



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

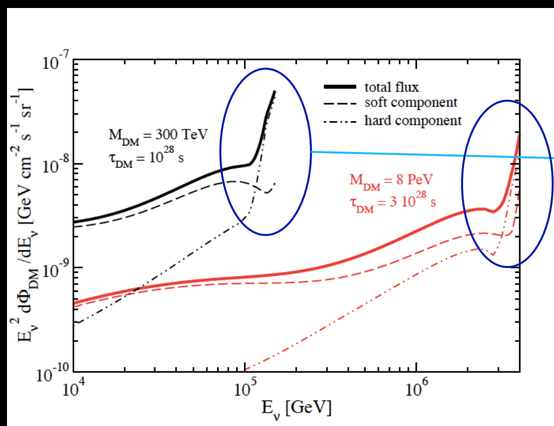
FIMPs evade all constraints, even too much: they are typically untestable!

Very high energy neutrinos from N_D decays

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

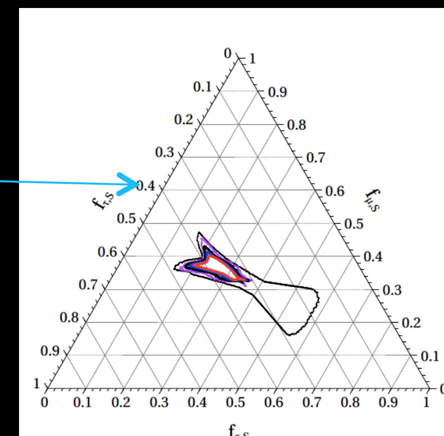
- DM neutrinos unavoidably decay today into A+leptons (A=H,Z,W) through the same mixing that produced them in the very early Universe
- Potentially testable high energy neutrino contribution

Energy neutrino flux



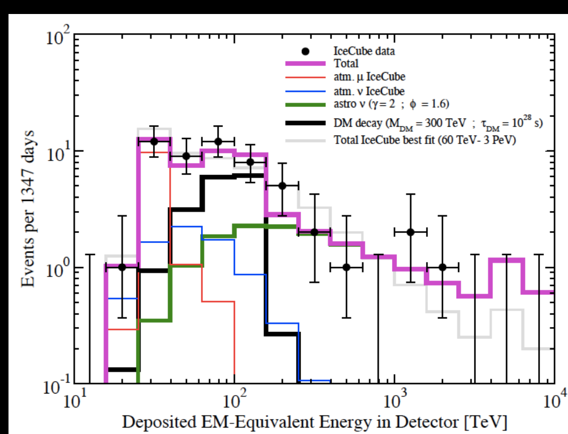
Flavour composition at the detector

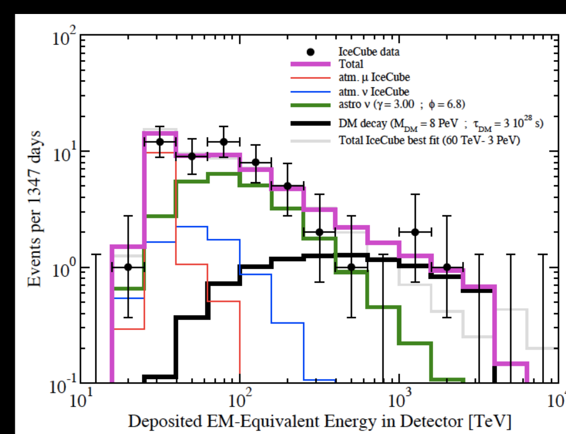
Hard component



Neutrino events at IceCube: 2 examples

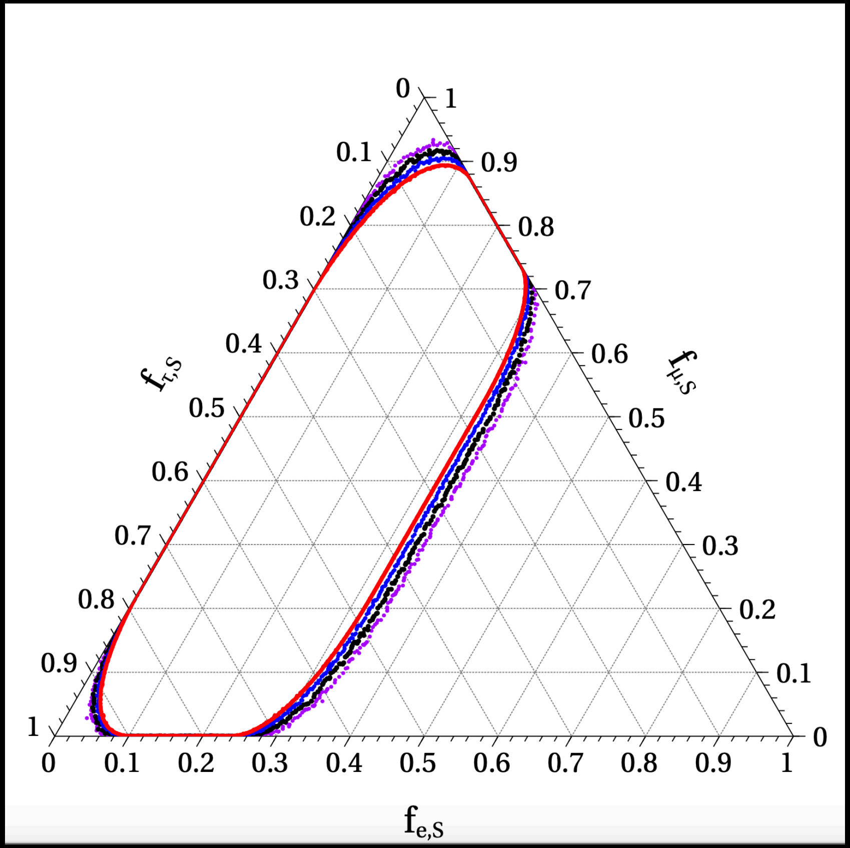
M_{DM}=300TeV





M_{DM}=8 PeV

Flavour composition at the production



Flavour composition at the detector