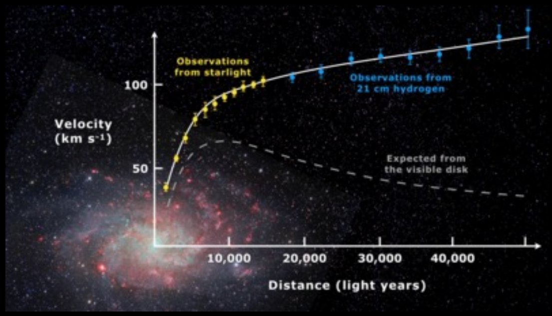
Dark Matter

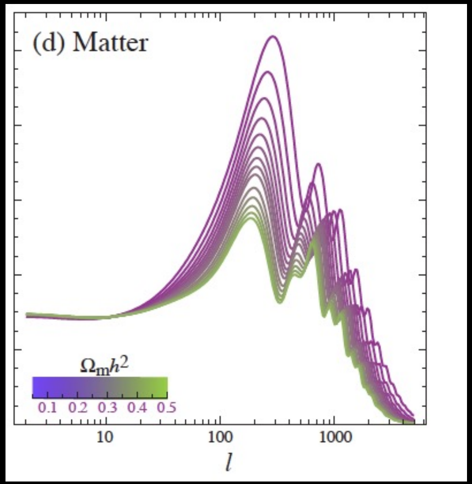
At the present time dark matter acts as a cosmic glue keeping together

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

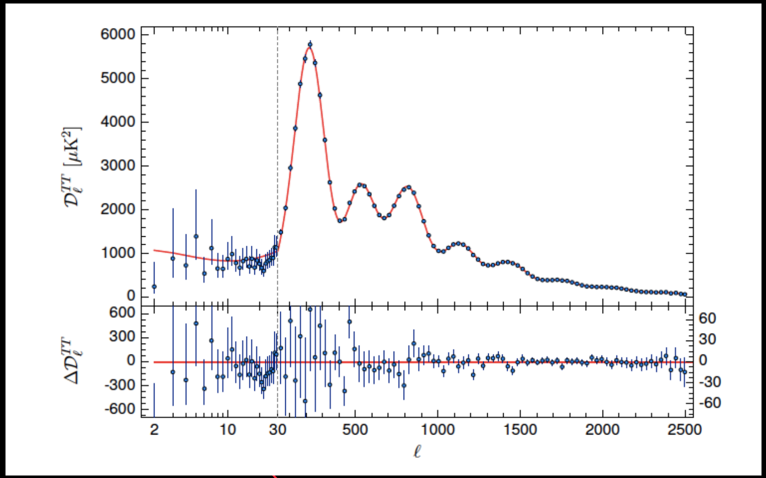


bullet cluster

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



(Hu, Dodelson, astro-ph/0110414)

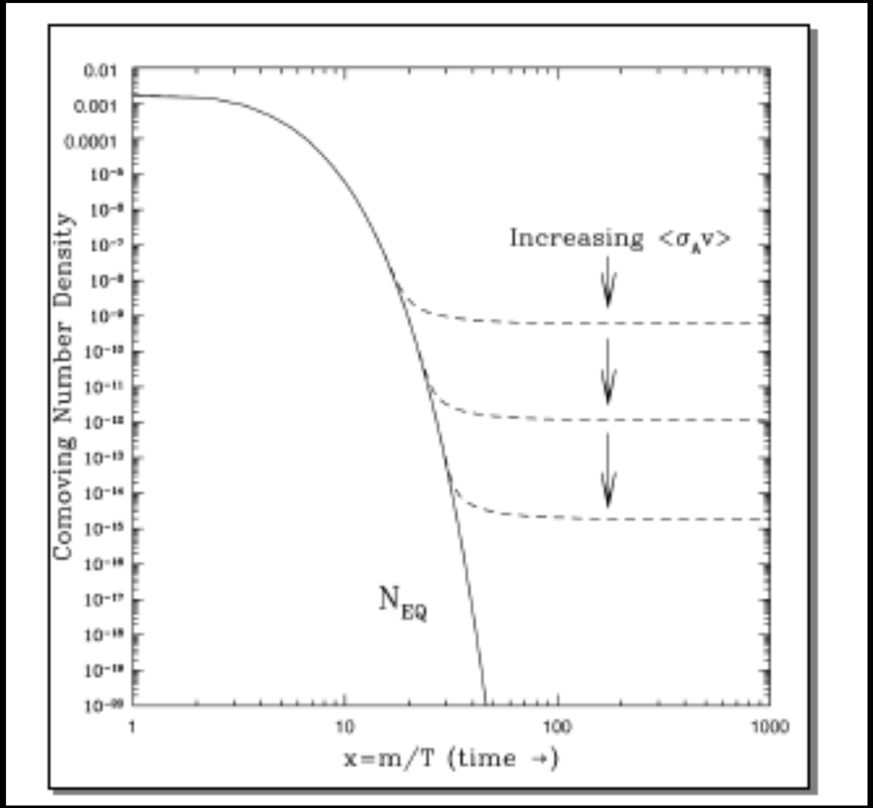


CMB + BAO

(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)

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

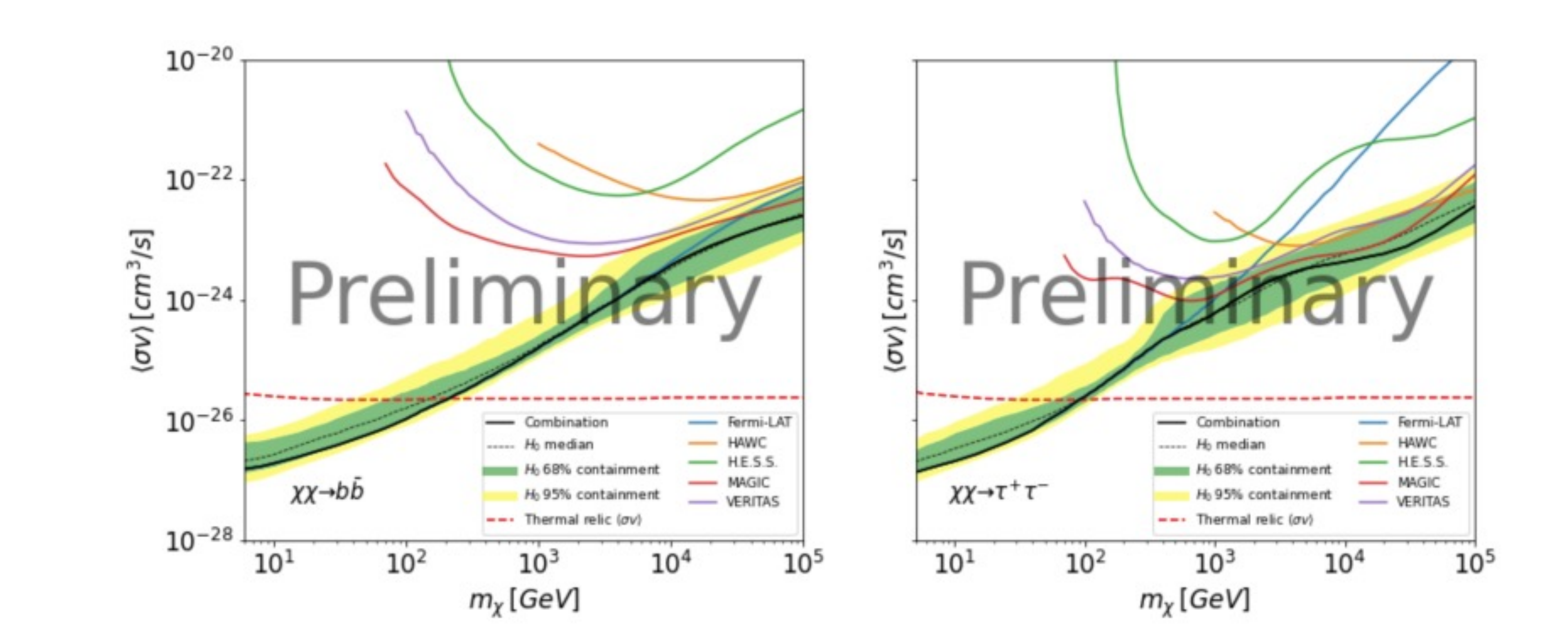
$$< \sigma_{ann}^{weak} v > = \frac{\alpha_{weak}^2}{m_X^2} = < \sigma_{ann} v >_{th}$$

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

- ❑ embeddable in models addressing naturalness+hierarchy problems
- ❑ ⇒ it predicts new physics just at the electroweak scale (WIMP miracle)
- ❑ 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

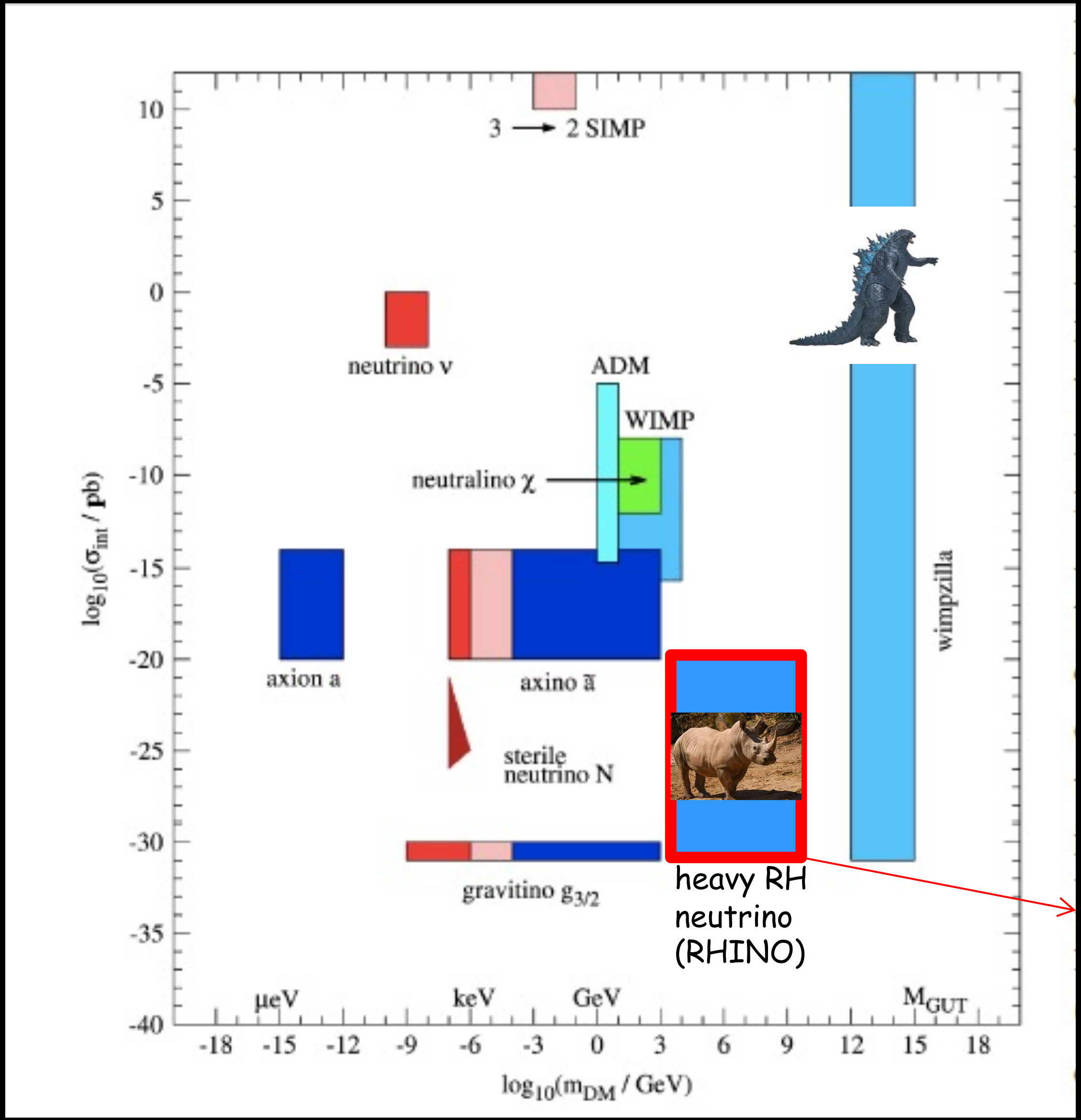
(from Aldo Morselli @ CORFU 2024)



Combination of the observation results towards
20 dwarf spheroidal galaxies (dSphs)

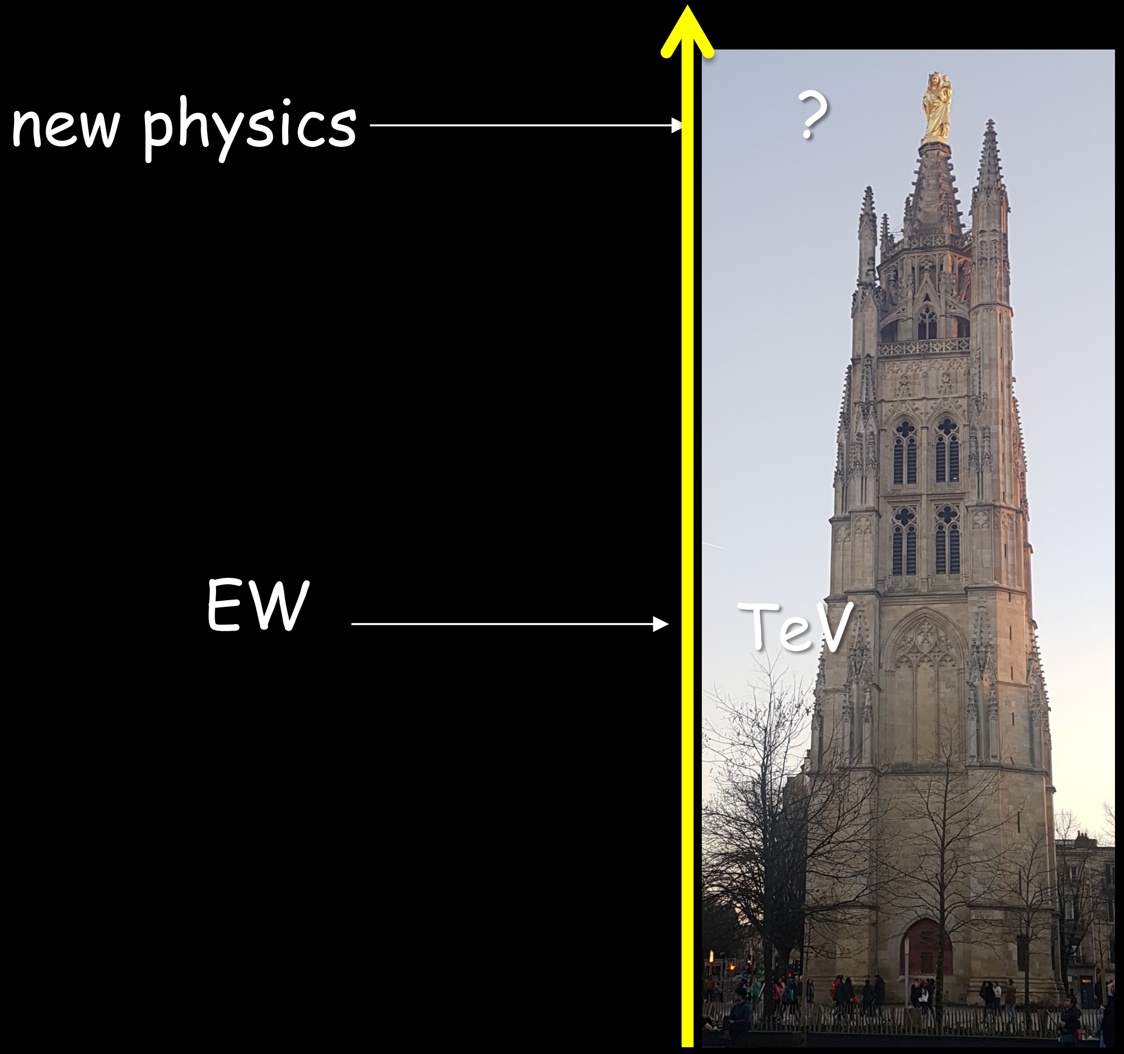
Beyond the WIMP paradigm: the DM particle zoo

(from Baer et al.1407.0017)



(PDB, Anisimov '08)

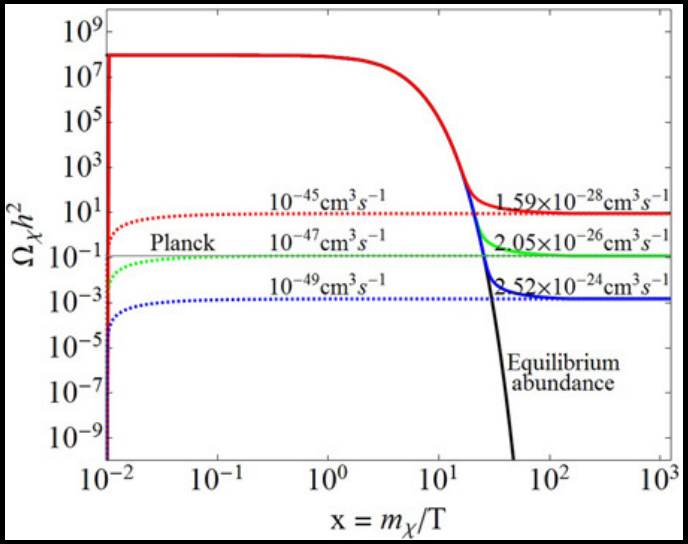
A new miracle?



A new miracle should not be searched but it should appear……well, miraculously!

Examples of DM beyond the standard WIMPs:

- Freeze-in solution (FIMPs, super WIMPs, RH neutrinos)



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

- 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)

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 ~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:

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

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 :

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

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

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

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, 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

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

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

RHINO dark matter

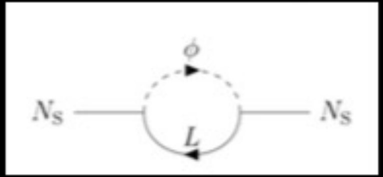
(Anisimov '06, Anisimov,PDB '08)

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

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

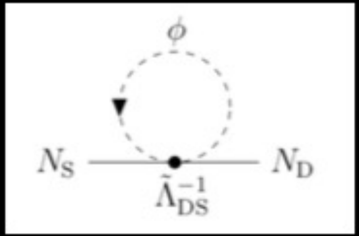
In general, $\lambda_{DS} \neq 0$ generates a dark-source RH neutrino mixing. The Yukawa and Anisimov interactions both generate effective potentials from self-energies:

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

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

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

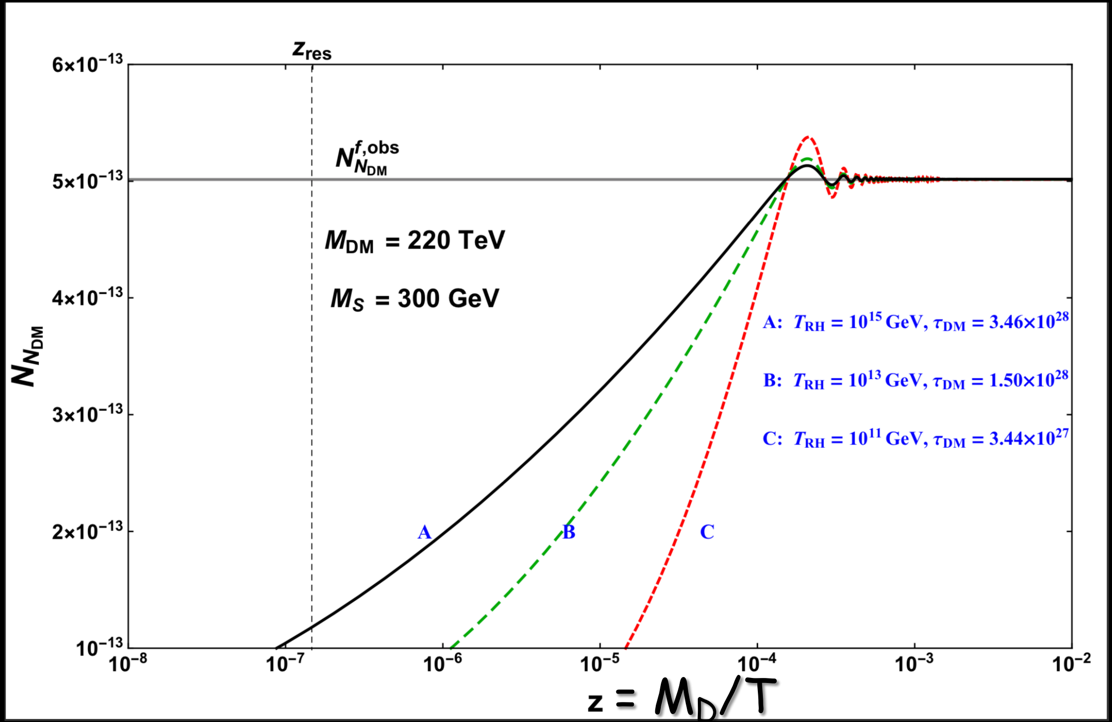
Density matrix calculation of the relic abundance

(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

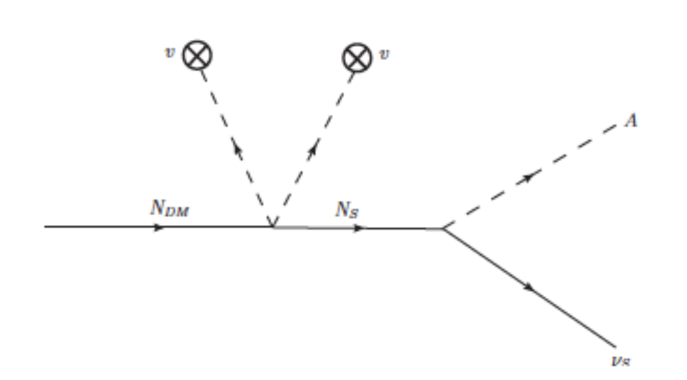


Dark neutrinos are necessarily unstable

(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



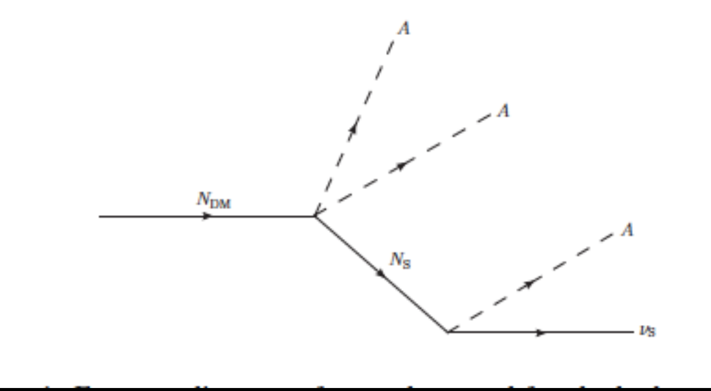
$$\theta_{\Lambda 0} = \frac{2\, v^2/\widetilde{\Lambda}_{\rm DS}}{M_{\rm D}\,(1 - M_{\rm S}/M_{\rm D})}$$

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



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

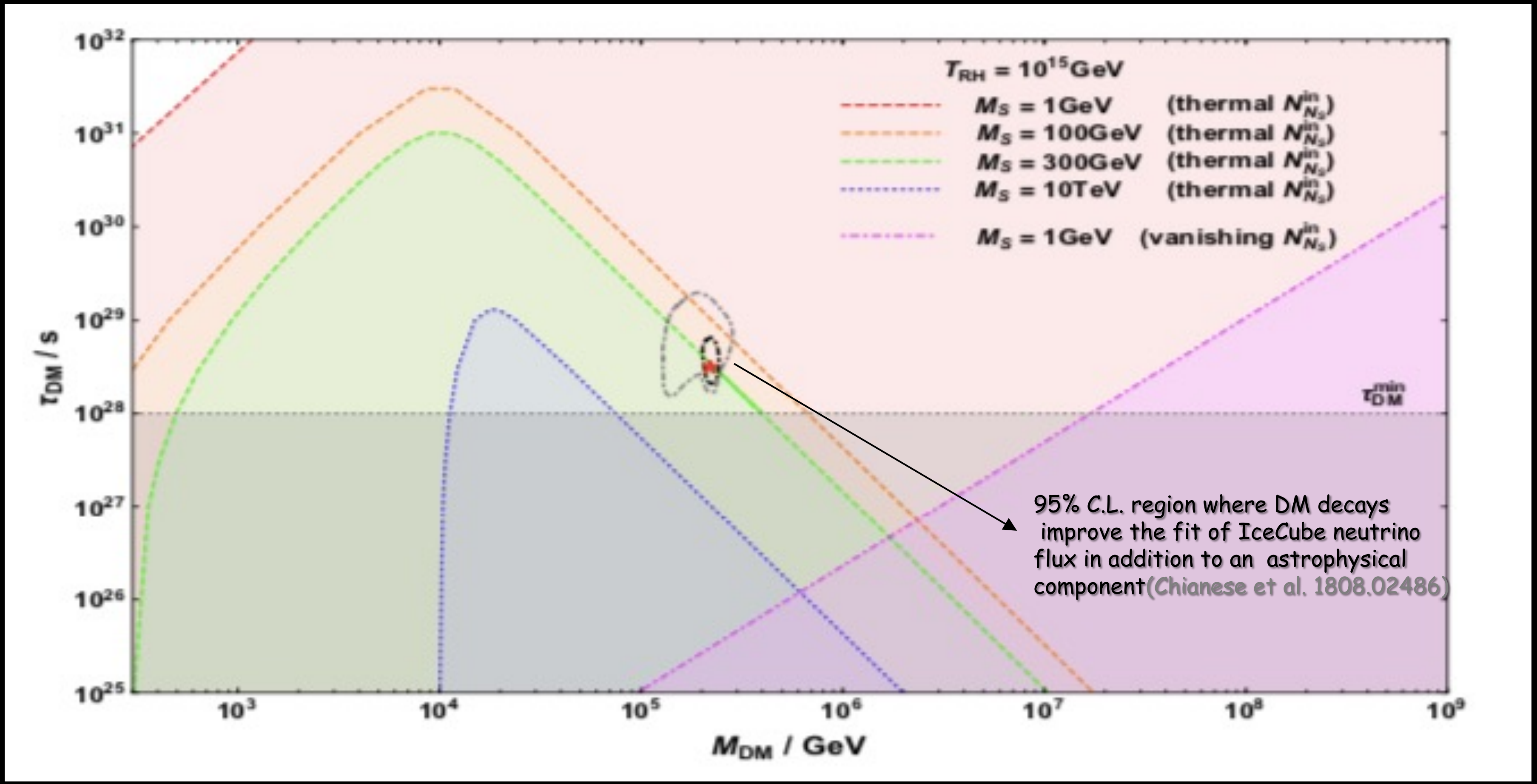
$$\Gamma_{{\rm D}\to 3A+\ell_{\rm S}} = \frac{\Gamma_{\rm S}}{15 \cdot 2^{11} \cdot \pi^4}\,\frac{M_{\rm D}}{M_{\rm S}}\left(\frac{M_{\rm D}}{\widetilde{\Lambda}_{\rm DS}}\right)^2$$

⇒ 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

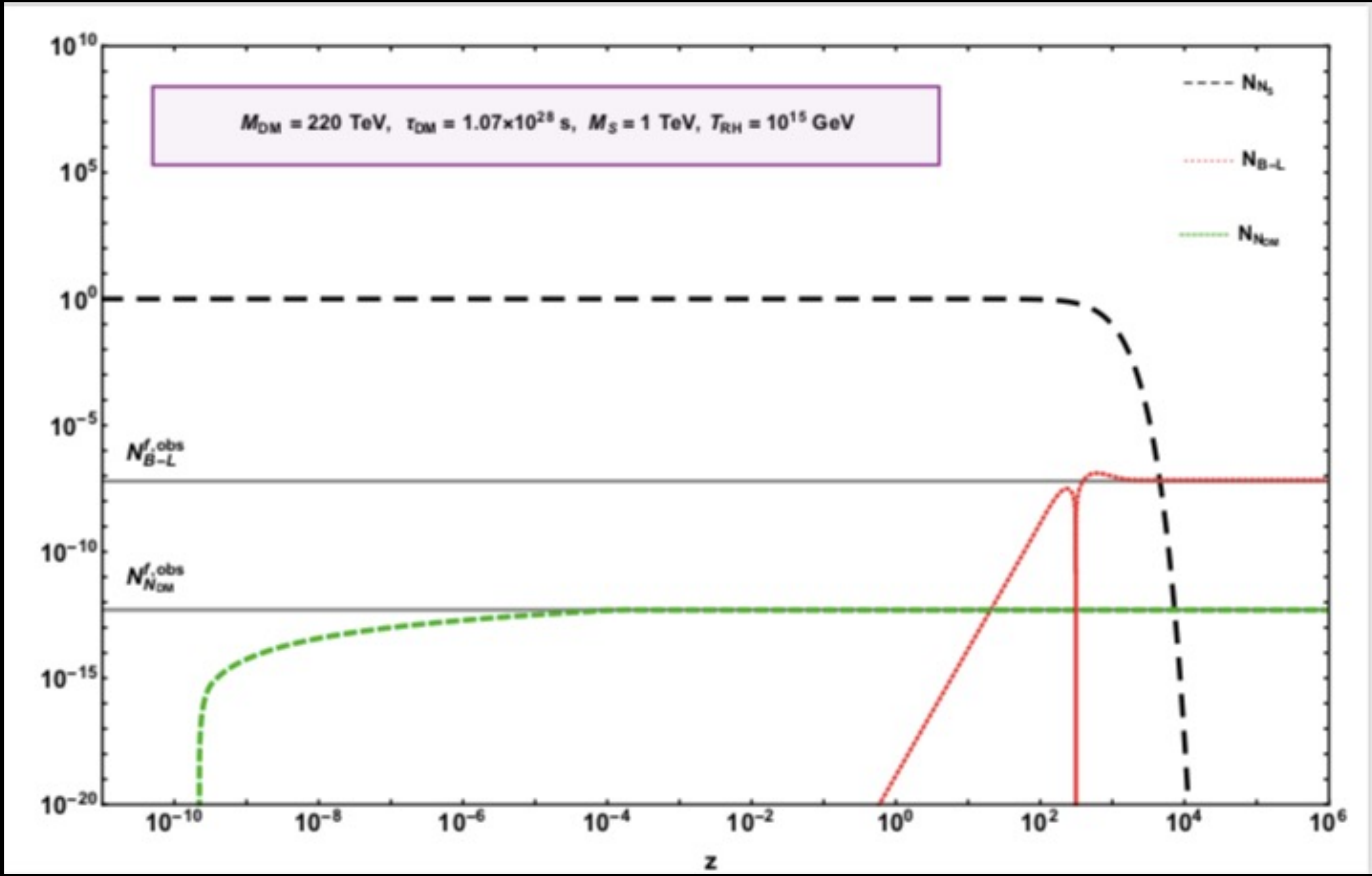
Can one think of processes able to thermalize the N_S abundance prior to the oscillations?

Two good motivations

Unifying Leptogenesis and Dark Matter

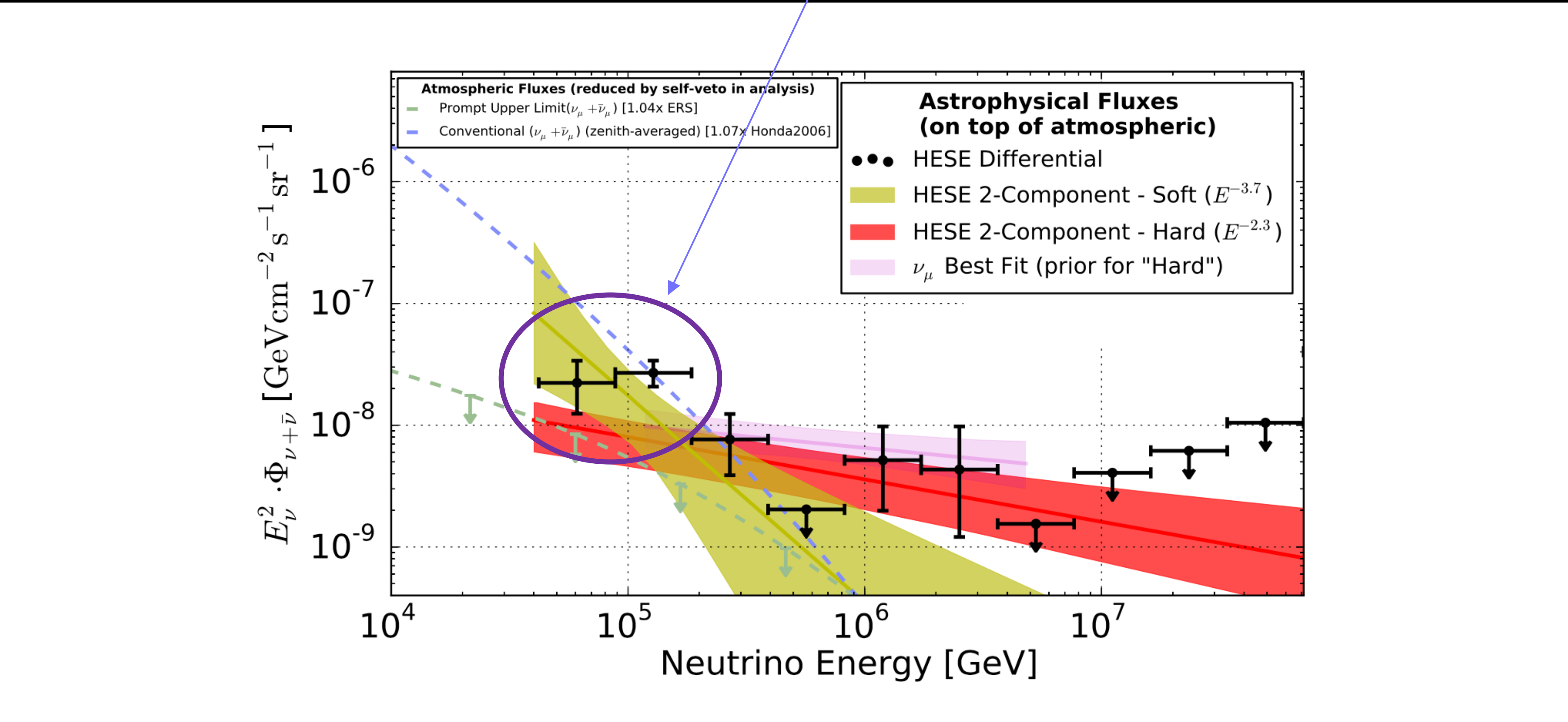
(PDB, K. Farrag, R. Samanta, Y. Zhou, 1908.00521)

A solution for initial thermal N_S abundance:

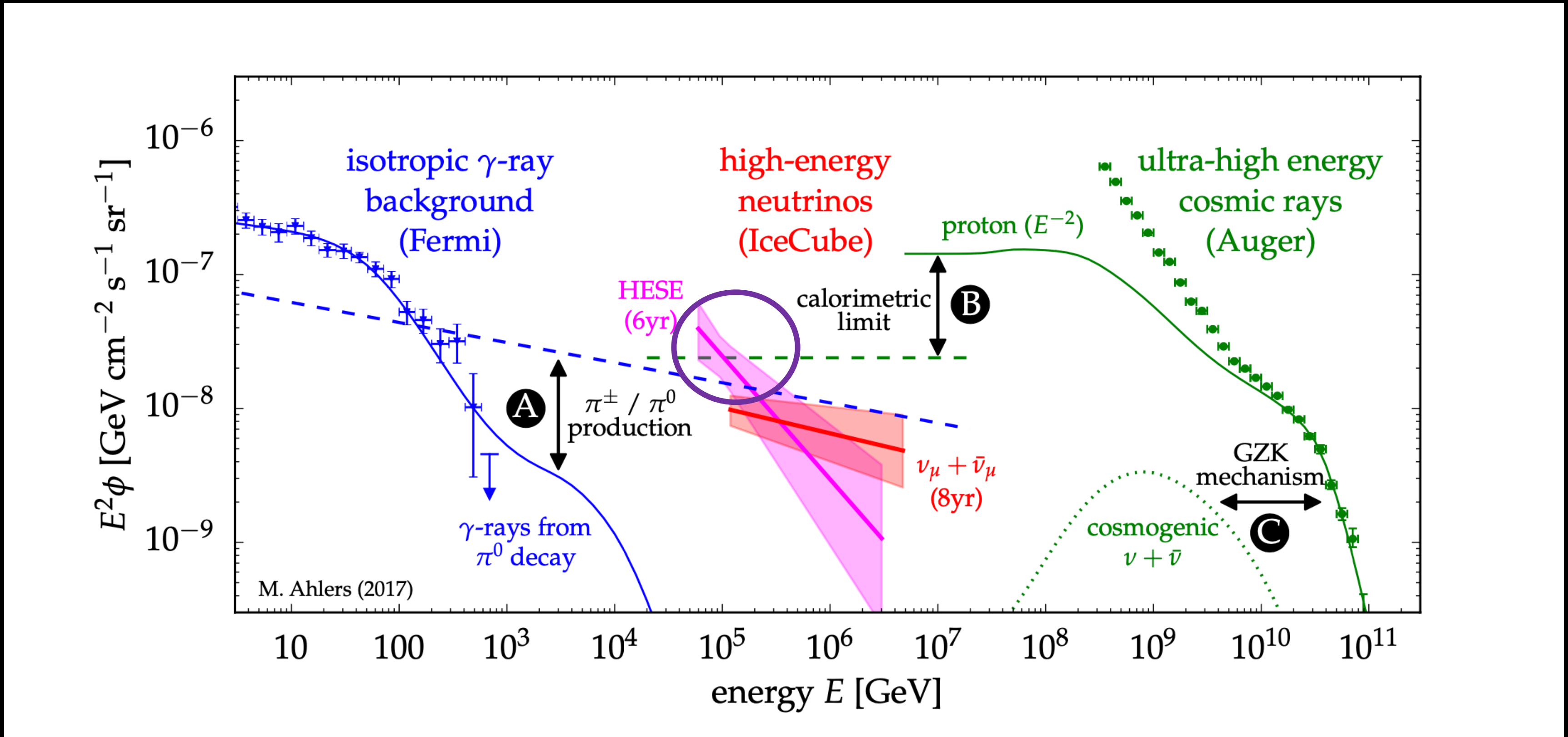


An extra component at ~100 TeV ?

IceCube 6 year HESE data (1710.01191)



A multimessenger analysis confirms an 100 TeV excess

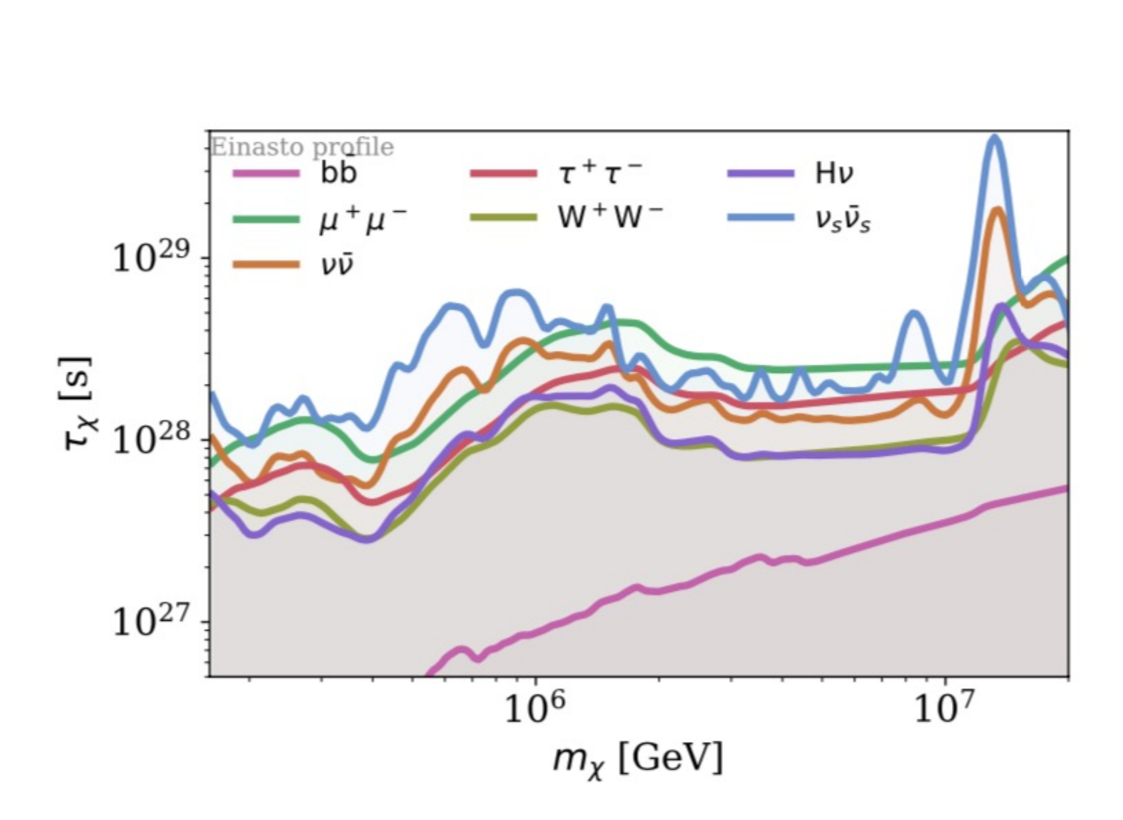


IceCube 6 year HESE data (1710.01191)

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

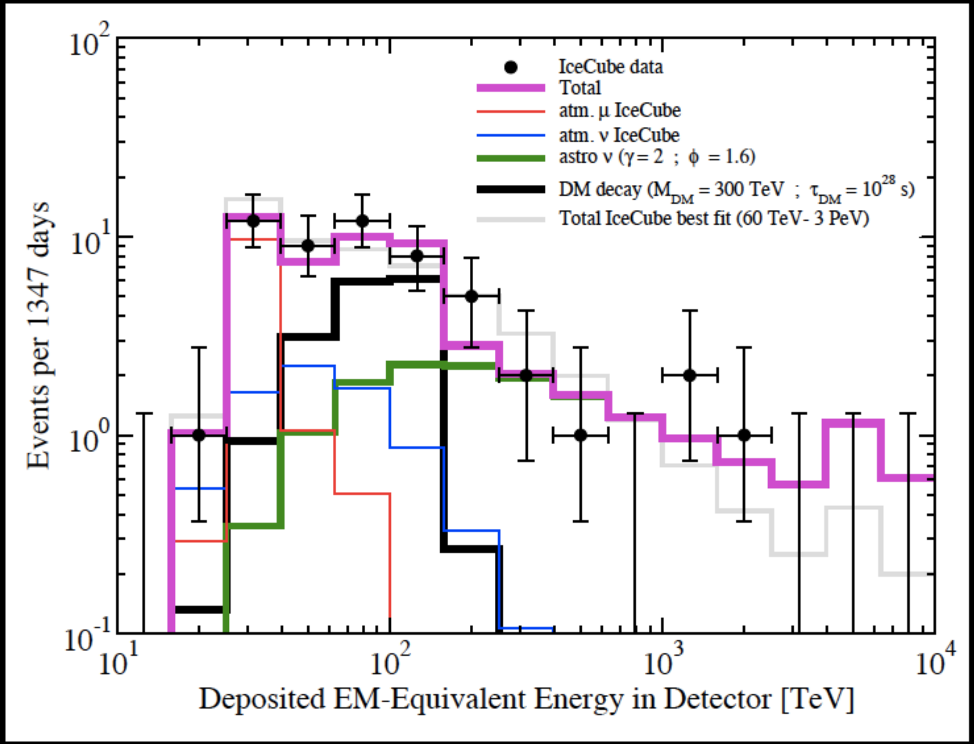
Very high energy neutrinos from N_D decays

(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)

Lower bound on the lifetime of decaying DM

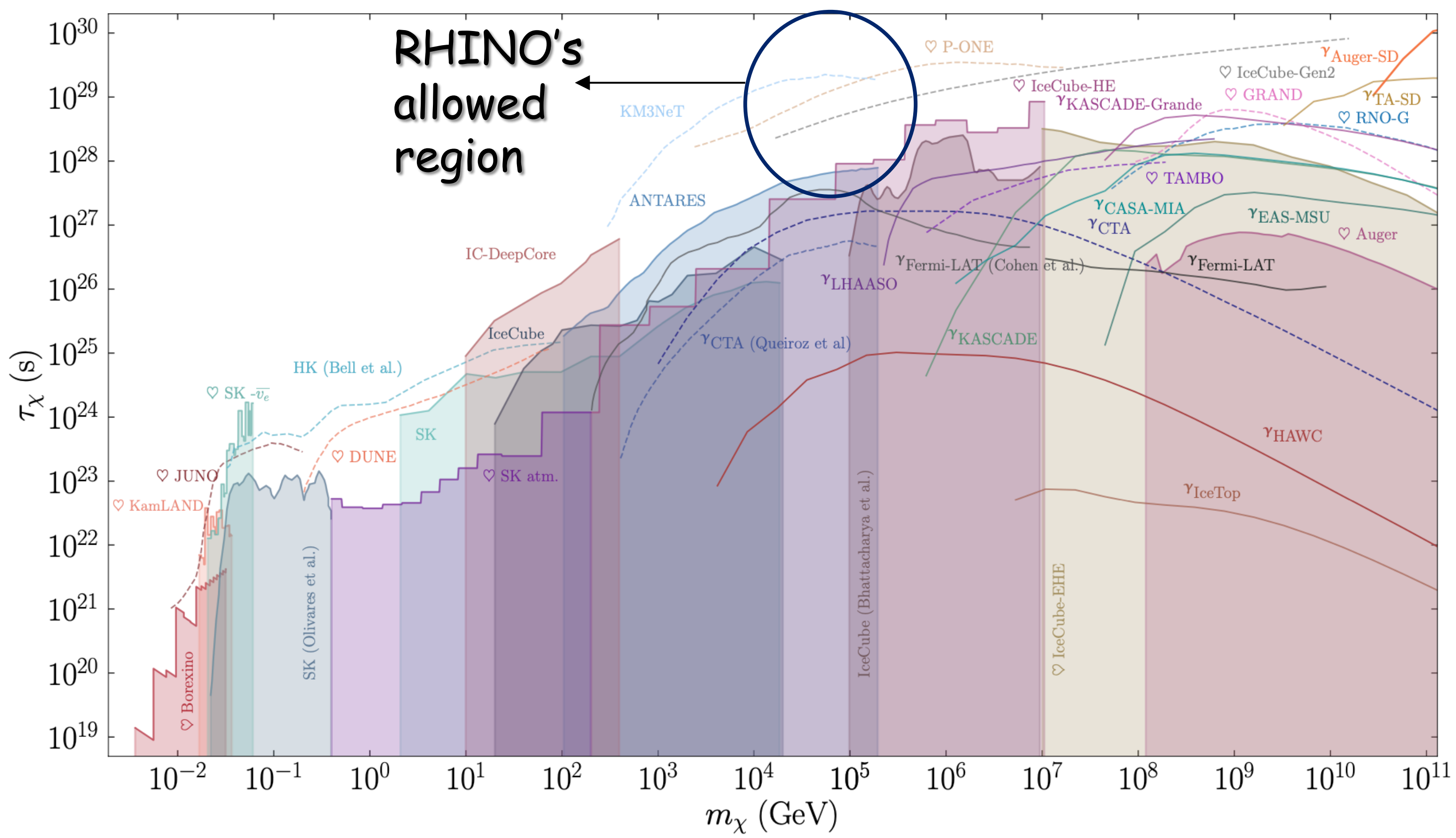
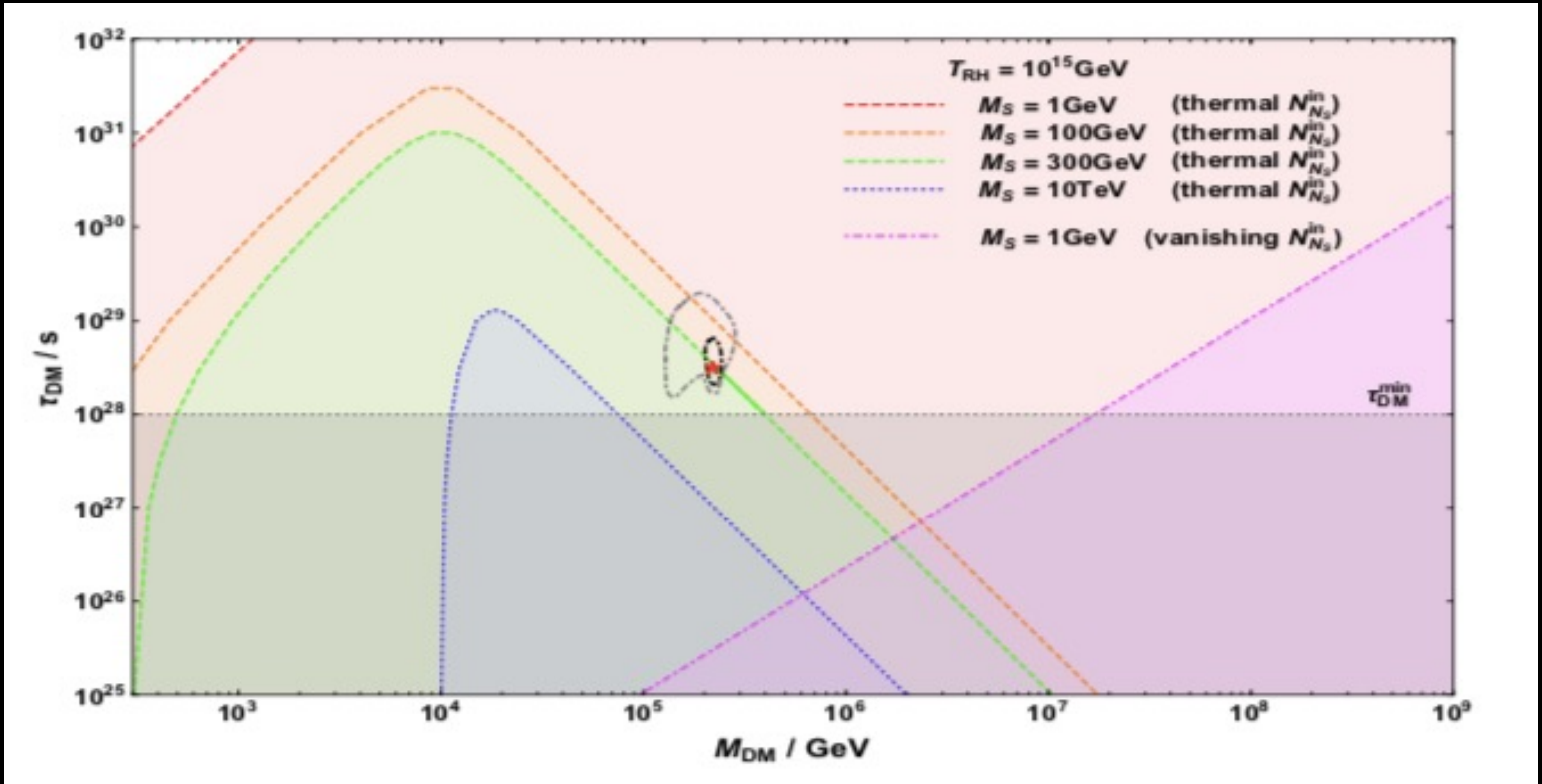


FIG. 2: ***Constraints on the lifetime of dark matter decaying to neutrinos $\chi \to \bar{\nu}\nu$.*** Solid lines bordering shaded regions represent limits from existing neutrino telescope data, solid lines without shading correspond to limits from existing gamma-ray observatories (as shown in Fig. 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)

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:

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

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

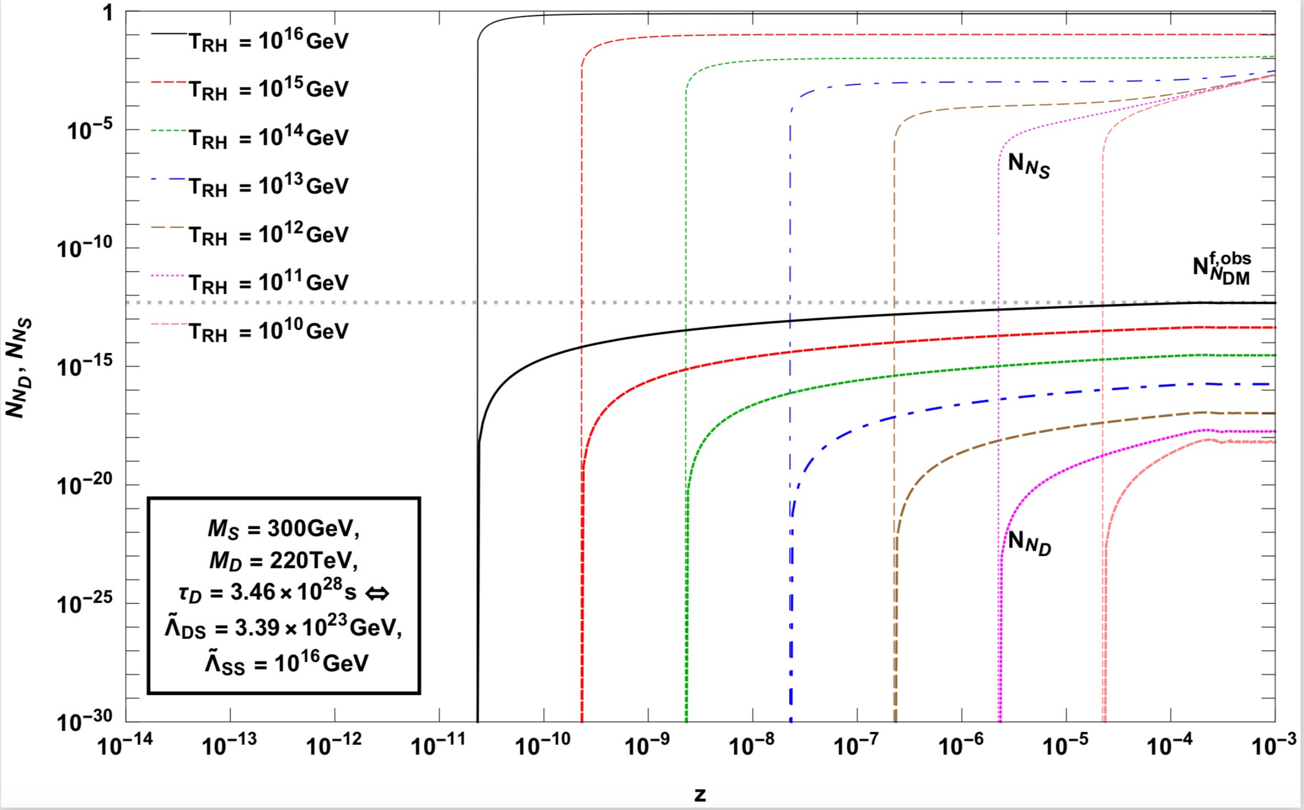
(Kolb, Long, 1708.04293)

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

Condition for the thermalisation of the N_S abundance

(PDB, A. Murphy, arXiv 2210.10801)

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

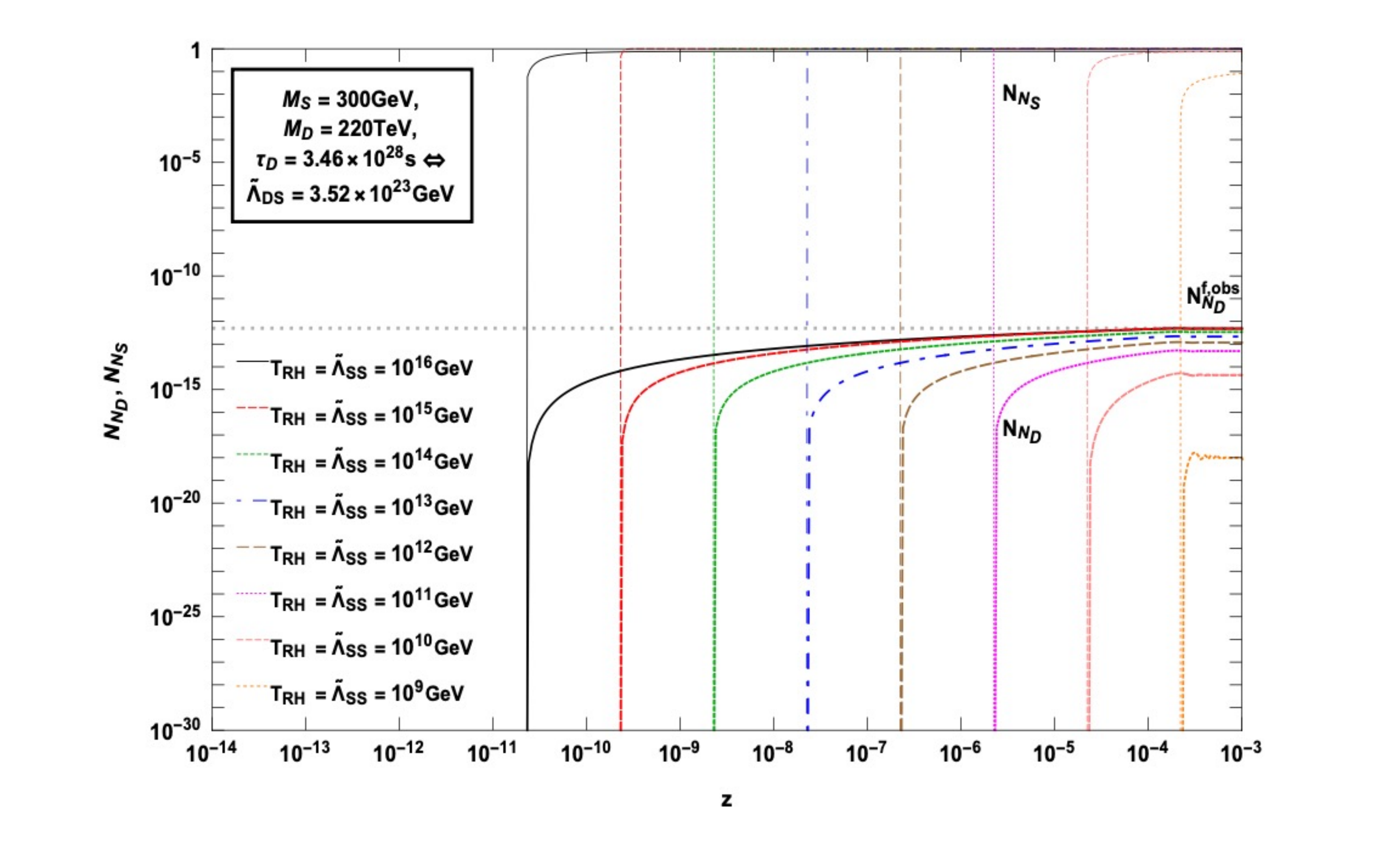


$\tilde{\Lambda}_{DS} \sim 10^{23}$ GeV

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

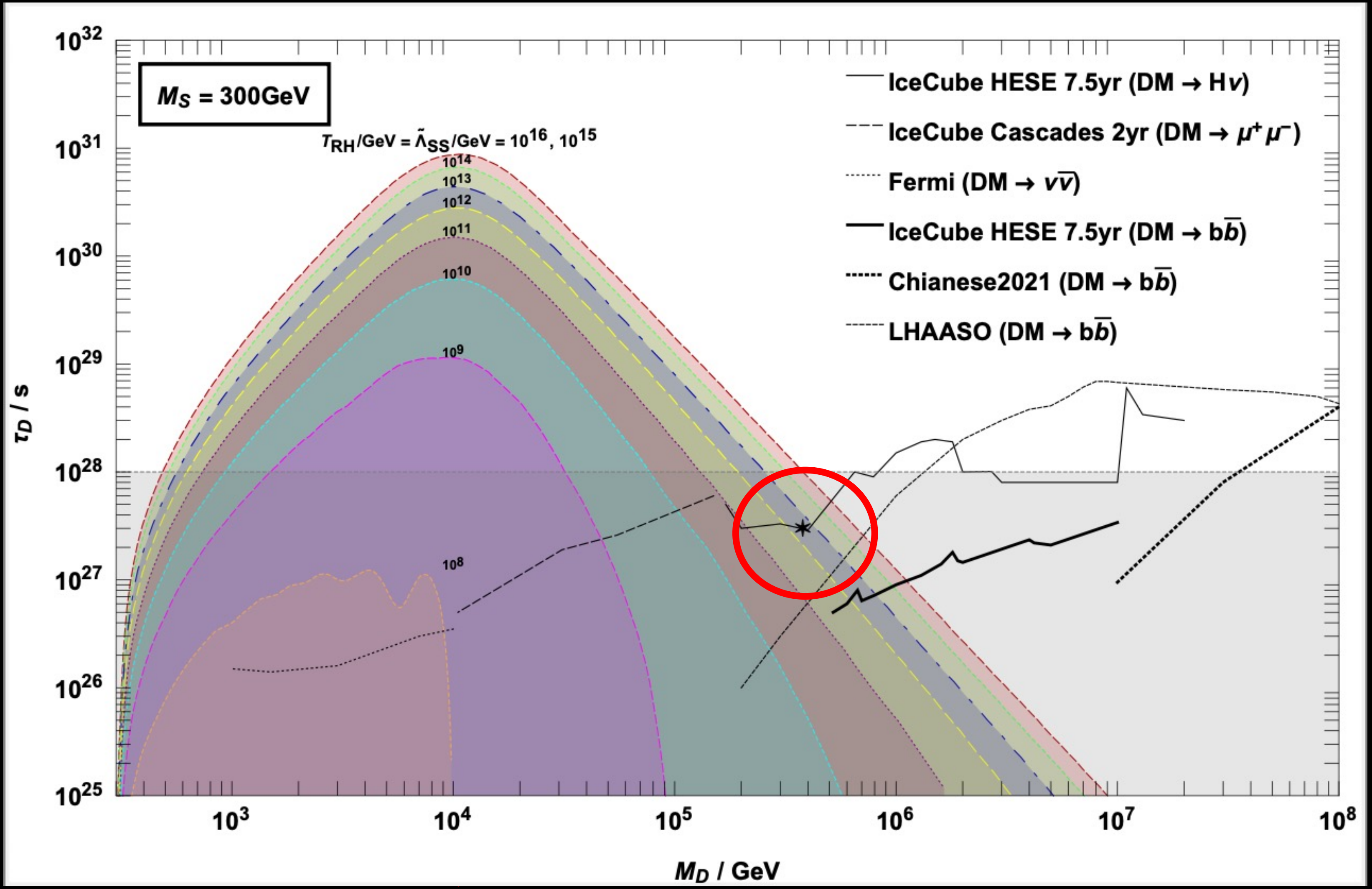
GUT scale !!

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



DM lifetime vs. mass plane: allowed regions

(PDB, A. Murphy, 2210.10801)



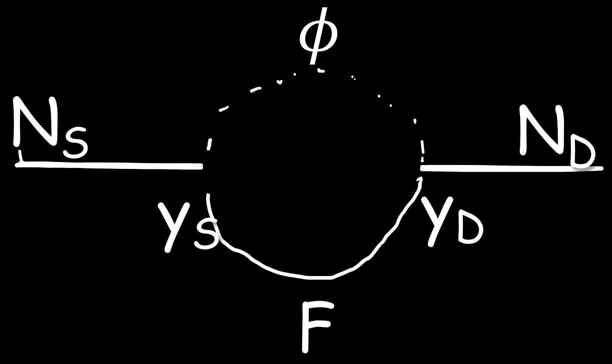
The scale of new physics cannot be made too much lower the GUT scale in order to explain the IceCube excess (respecting the LHAASO lower bound)

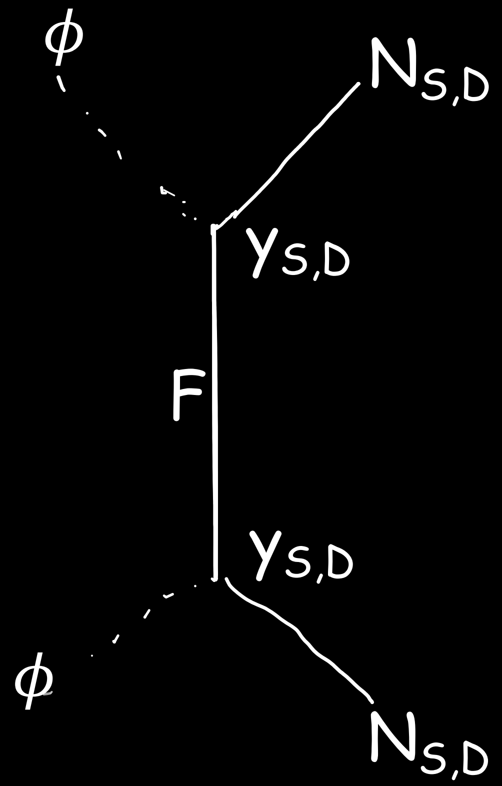
A RHINO miracle?

A possible GUT origin ? Heavy fermion F as mediator

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

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





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

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

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

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

Conclusions

- The matter-antimatter asymmetry puzzle might be related to an explanation of neutrino masses, this seems today the most attractive scenario. Discovery of $0\nu\beta\beta$ would be a strong evidence

- The dark matter puzzle has different solutions, some of which could also be related to neutrino physics.

- A solution of both puzzles seem to be nicely embeddable in grandunified models