High energy neutrino lines induced by DM: search and possible links with the seesaw

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Based on: R. Coy, A. Gupta, TH, arXiv:2104:00042
R. Coy, TH, arXiv:2012.05272
C. El Aisati, C. Garcia-Cely, TH, L. Vanderheyden, arXiv:1706.06600
C. El Aisati, M. Gustafsson, TH, arXiv:1506.02657
C. El Aisati, M. Gustafsson, TH, T. Scarna, arXiv:1510.05008
C. El Aisati, TH, T. Scarna, arXiv:1403.1280
M. Gustafsson, TH, T. Scarna, arXiv:1303.4423

NuT Madrid, 17/05/2022

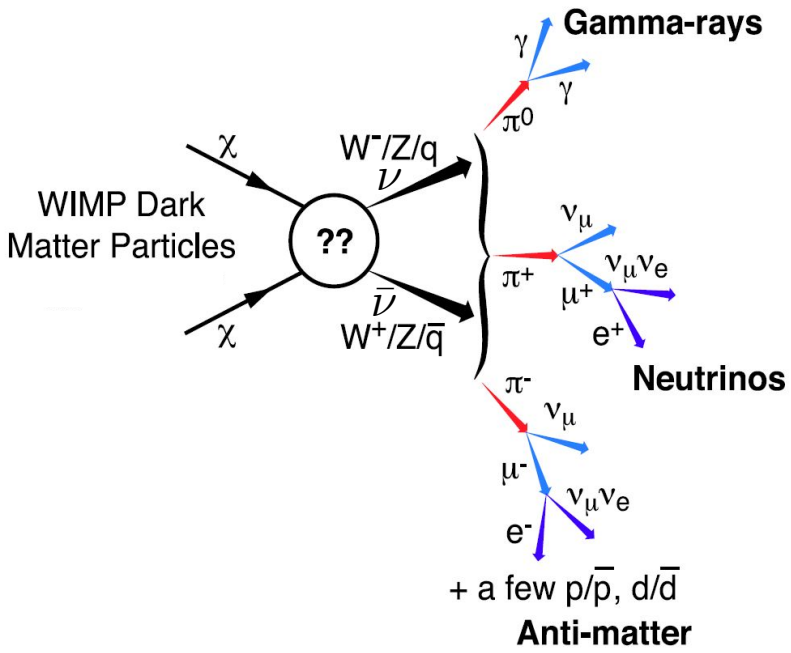
Outline

- ν - line search: motivations and new IceCube results
- determination of minimal DM models leading to observable ν-lines from DM annihilation
  - links with seesaw???
- 2 examples of DM setups predicting seesaw induced ν-lines from DM decay

Neutrino line search: new IceCube results

Probing DM with neutrinos: neutrino telescopes

DM annihilation or decay in the galactic center and halo can produce neutrinos



⇒ 2 kinds of signals:

- diffuse ν flux
- primary ν flux

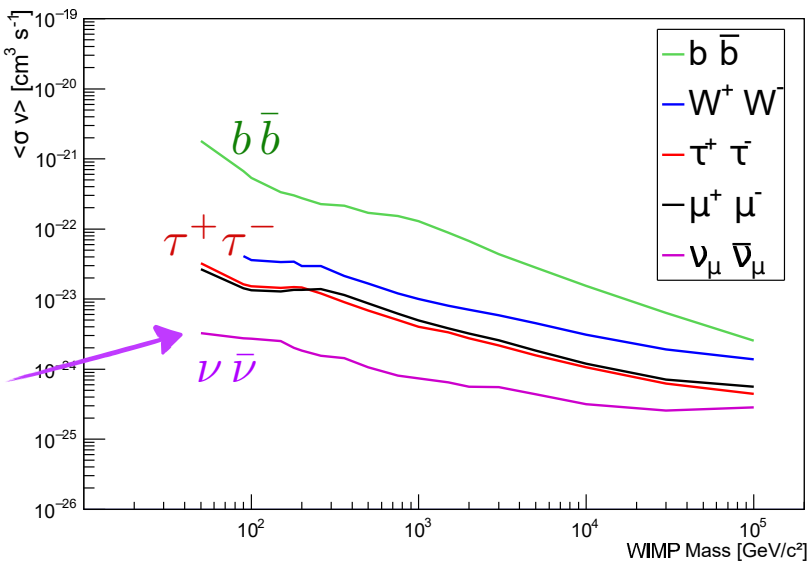
The 5 motivations for the search of ν-lines

↳ $DM\,DM \to \nu\,\bar{\nu}$ or $DM \to \nu + X$: monochromatic flux of ν: "ν-line"

↳ no astrophysical background: DM smoking gun!

↳ ν-channel: most sensitive channel for ν-telescopes

Antares- PLB 2017



"primary' neutrinos

(primary neutrinos)

↳ for the ν-channel: neutrino telescopes have better sensitivity than γ-telescopes

↳ unlike for other channels: $DMDM \to \tau^+\tau^-,\ \mu^+\mu^-,\ e^+e^-,\ W^+W^-,\ q\bar{q},\ \ldots$

(secondary neutrinos)

The 5 motivations for the search of ν-lines

↳ a ν-line can be produced from a tree level annihilation unlike a γ-line

↳ a line can be very well distinguished from background: in neutrino energy spectrum

↳ well known for γ-rays

from γ telescopes the limit on γ-line channel is 2-3 orders of magnitude better than on channels with secondary photons

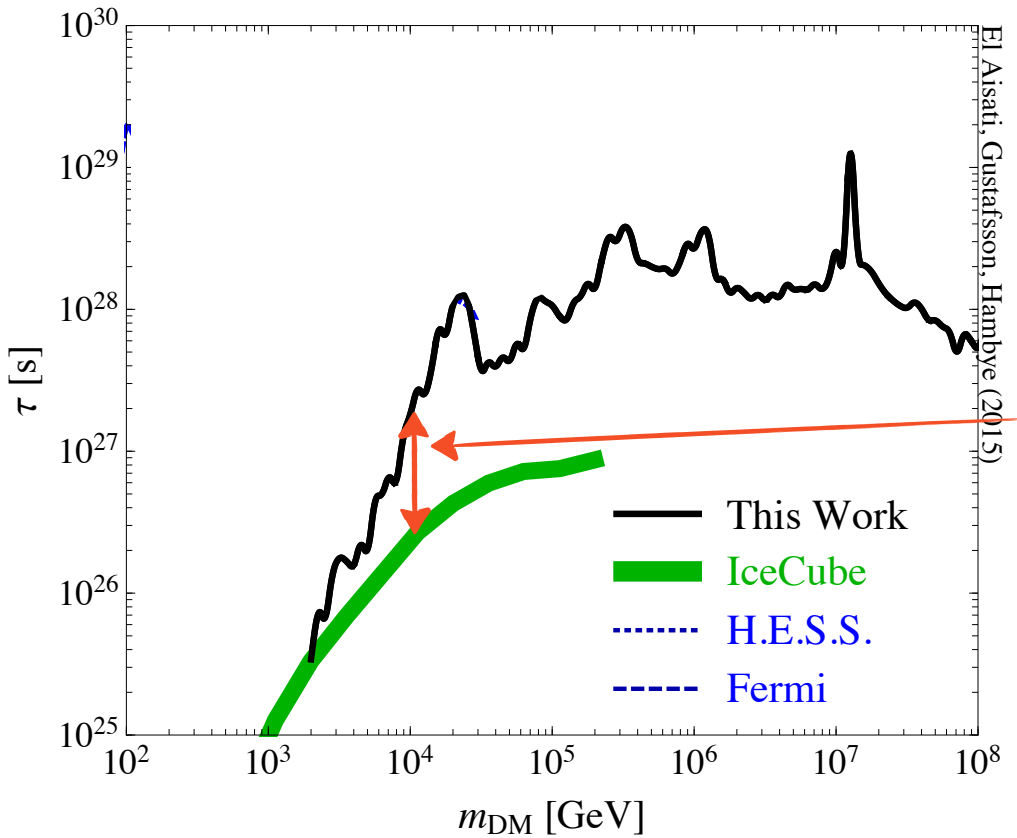
but so far all neutrino telescope limits on channel were not exploiting the energy information of the neutrino events!!!

First spectrum based search of a 'ν-line' from IceCube data

↪ using a 2010-2012 public IceCube data sample: for DM decay: $\Gamma_{DM\to\nu+X}$

Lifetime lower limit exploiting the sharp spectral feature property:

El Aisati, Gustafsson, TH 15'



~ an order of magnitude improvement from few TeV to 100 TeV

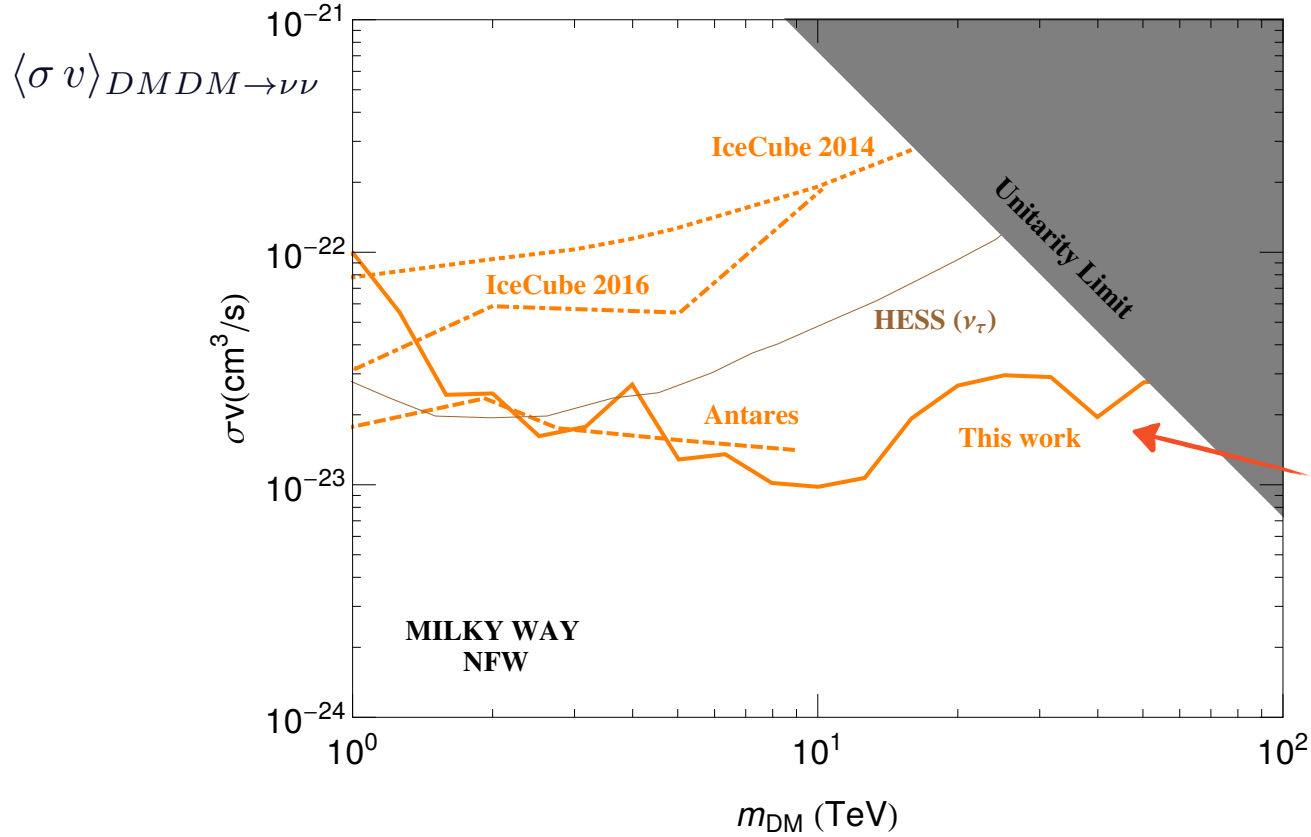
Above 100 TeV there are other limits: Rott, Kohri, Park , 14'
Esmaili, Kang, Serpico 14'

Monochromatic flux of ν from DM annihilation: experimental limits

↳ Observational situation for an annihilation: $\langle \sigma\, v \rangle_{DMDM \to \nu\nu}$

Annihilation cross section upper limit:

El Aisati, Garcia-Cely, T.H., Vanderheyden 17



from line dedicated search using same 1-year data sample than for the decay

decay: $n_\nu \propto \rho_{DM}$

⇒ only illustrative: based on sample of only one year and with no angular information:

crucial for annihilation: $n_\nu \propto \rho_{DM}^2$

↳ annihilation signal largely peaked on galactic center unlike for a decay

⇒ need also to see the galactic center with good angular resolution

Neutrino Line Searches with IceCube

J. A. Aguilar , Thomas Hambye, Michael Gustafsson
on behalf of IceCube

ULB

Dark Ghosts 2022

iihe

From J.-A. Aguilar talk, 31/03/2022

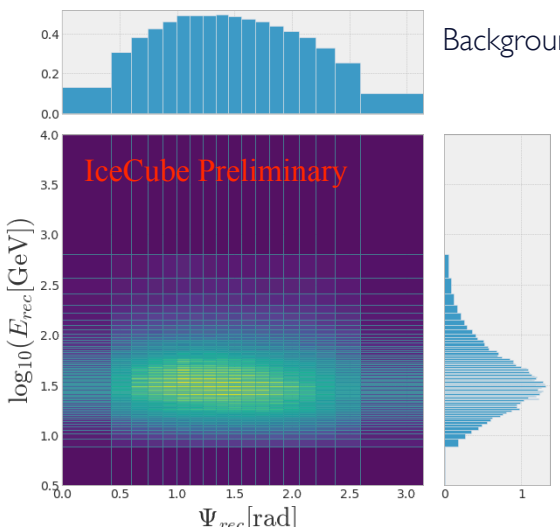
First neutrino telescope dedicated search for neutrino lines

IceCube collaboration + C. El Aisati, M. Gustafsson, T.H.: to appear

using the energy information of the neutrino events on top of angular information

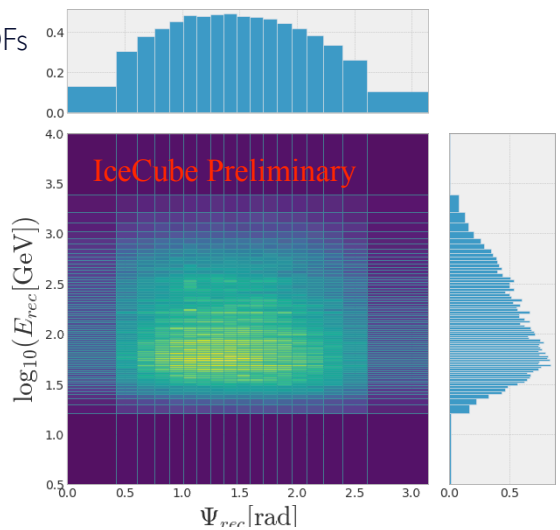
to look for a sharp spectral feature

LE Sample

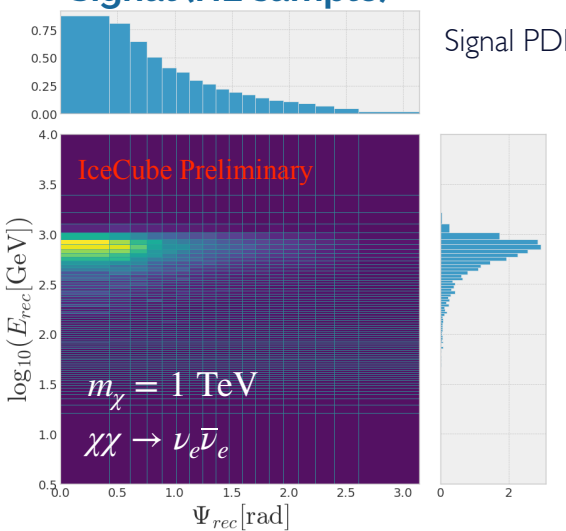


Background PDFs

HE Sample

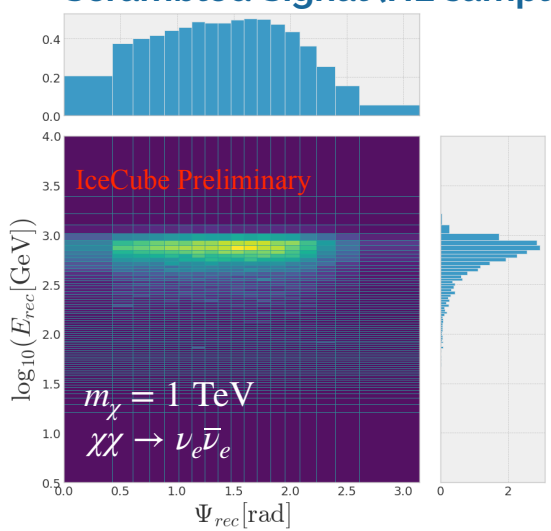


Signal (HE sample)



Signal PDFs

Scrambled Signal (HE sample)



5-years data sample

Double binning likelihood method

Background pdf obtained from scrambling data (in right ascension)

Signal Substraction Likelihood: to correct for signal contamination in the background pdf

Irregular binning

First neutrino telescope dedicated search for neutrino lines

Results annihilation: $\chi\chi \to \nu\bar{\nu}$ channel:

First neutrino telescope dedicated search for neutrino lines

Results decay: $\chi \to \nu\bar{\nu}$ channel:

Results : other channels: annihilation and decay

⇒ Given this exciting experimental situation:

could we expect on the theoretical side signals
at the level of present and future sensitivities??

Minimal models leading to observable γ-line from DM annihilation

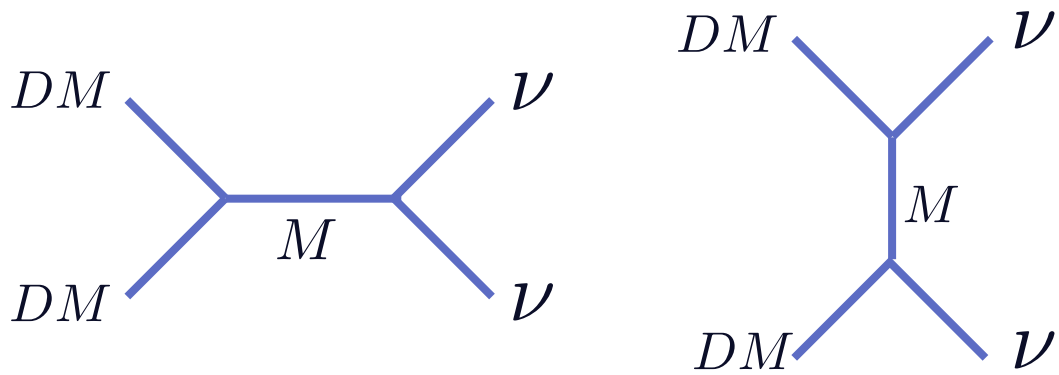
Determination of minimal models leading to observable ν-line from DM annihilation

El Aisati, Garcia-Cely, TH, Vanderheyden 17

↪ for spin 0 or 1/2 DM

↪ with DM out of single multiplet of $SU(3)_c \times SU(2)_L \times U(1)_Y$

↪ with $DM\,DM \to \nu\nu$ mediated by single mediator multiplet



⇒ systematic study of these minimal models

⇒ which ones of these models can lead to an observable ν-line???

List of simple candidate models for an observable ν flux

20 models: surviving direct detection, s-wave annihil., …

DM and mediator up to triplets

only Dirac DM for $\nu\bar{\nu}$ channel →

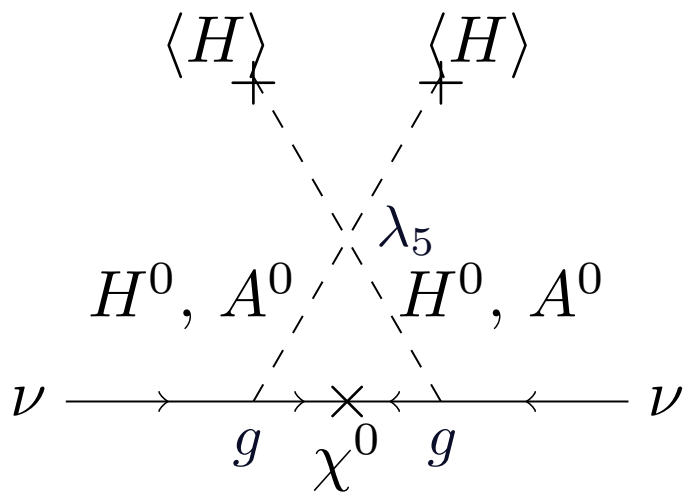
$\nu\nu$ channel →

Annihilation Channel	DM		Mediator		m_ν OK at 1-loop?	Suppressed by $v_{\rm EW}/m_{\rm DM}$?	$\ell^+\ell^-$	Model
$\overline{\rm DM}{\rm DM} \to \bar{\nu}\nu$	Dirac	T_0	s-chann. vector	S	Yes	No	=	F_1
		T_0	t-chann. scalar	D				F_2
		S	s-chann. vector	S				F_3
		S	t-chann. scalar	D				F_4
${\rm DMDM} \to \nu\nu$	Real Scalar	D	s-chann. scalar	T_2	$\pm$	No	/	S_1^r
		S	t-chann. Majorana	D	No	Yes		S_2^r
		D		S		No		S_3^r
		D		T_0		No		S_4^r
		D		T_2		Yes		S_5^r
		T_0		D		Yes		S_6^r
		T_2		D		Yes		S_7^r
	Majorana	D	s-chann. scalar	T_2	$\pm$	No		F_1^m
		S	t-chann. scalar	D	No	Yes		F_2^m
		D		S		No		F_3^m
		D		T_0		No		F_4^m
		D		T_2		Yes		F_5^m
		T_0		D		Yes		F_6^m
		T_2		D		Yes		F_7^m
	Complex Scalar	S	t-chann. Majorana	D	Yes	Yes		S_1
		T_0		D				S_2
	Dirac	S	t-chann. scalar	D	Yes	Yes		F_4
		T_0		D				F_2

El Aisati, Garcia-Cely, T.H., Vanderheyden '17
See also related table in Lindner, Merle, Niro '10

ν mass constraint: kills many $\nu\nu$ channel possibilities

example: inert doublet DM:



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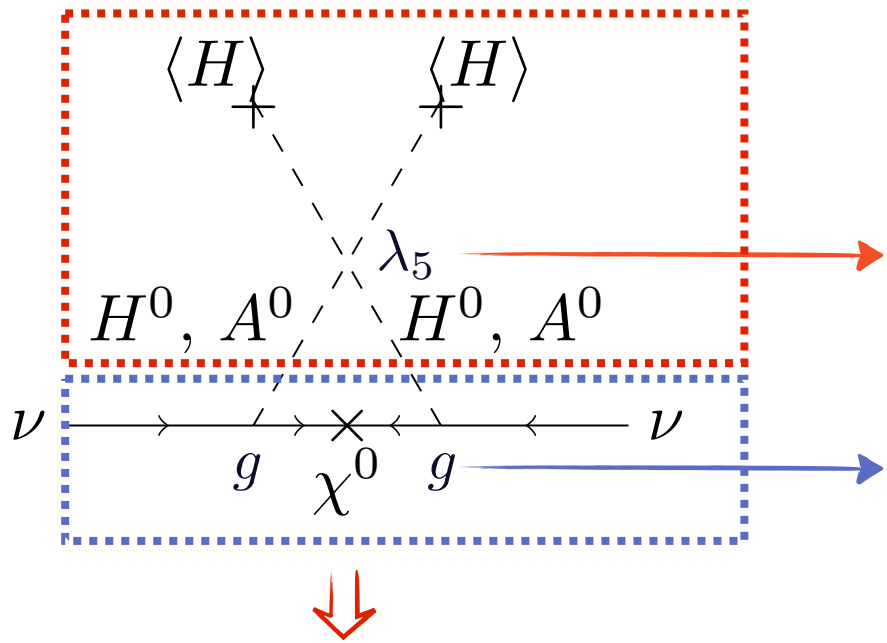

minimum value from direct detection constraint

minimum value to get an observable ν-line

too large neutrino masses! $m_\nu \gtrsim 100$ keV

El Aisati, Garcia-Cely, T.H., Vanderheyden '17

7 simple models leading to observable ν flux at ν telescopes

surviving neutrino mass constraint, other indirect detection limits, perturbativity….

Annihilation Channel	DM		Mediator		m_ν OK at 1-loop?	Suppressed by $v_{\rm EW}/m_{\rm DM}$?	$\ell^+\ell^-$	Model
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${\rm DMDM} \to \nu\nu$	Real Scalar	D	s-chann. scalar	T_2	$\pm$	No		S_1^r
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		D		T_0		No		S_4^r
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		T_2		D		Yes		S_7^r
	Majorana	D	s-chann. scalar	T_2	$\pm$	No	/	F_1^m
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		D		S		No		F_3^m
		D		T_0		No		F_4^m
		D	t-chann. scalar	T_2	No	Yes		F_5^m
		T_0		D		Yes		F_6^m
		T_2		D		Yes		F_7^m
	Complex Scalar	S	t-chann. Majorana	D	Yes	Yes		S_1
		T_0		D				S_2
	Dirac	S	t-chann. scalar	D	Yes	Yes		F_4
		T_0		D				F_2

possible only for $m_{DM} \gtrsim$ TeV not to induce too large l^+l^- flux because these models predict $\Phi_{\nu\bar{\nu}} = \Phi_{l^+l^-}$

excluded: give too many diffuse W^+W^- or too intense γ-line

possible only for $m_{DM} \lesssim$ TeV due to perturbativity:

El Aisati, Garcia-Cely, T.H., Vanderheyden '17

there exist simple models leading to observable neutrino flux at neutrino telescopes

ν-line cross section results including Sommerfeld effect

present ν -line sensitivity $\langle\sigma v\rangle_{DM\,DM\to\nu\nu} \sim \text{few}\,10^{-25}$ doesn't reach the thermal freeze out total cross section value $\langle\sigma v\rangle_{Tot} \sim 3\cdot 10^{-26}$

↳ need for a boost of the cross section from freeze out epoch to today

astrophysical boost particle physics boost: Sommerfeld effect

non relativistic DM particles today can exchange many lighter mediators before annihilating

↳ example: model F_2 : a $Y=0$ fermion DM triplet + a scalar doublet mediator

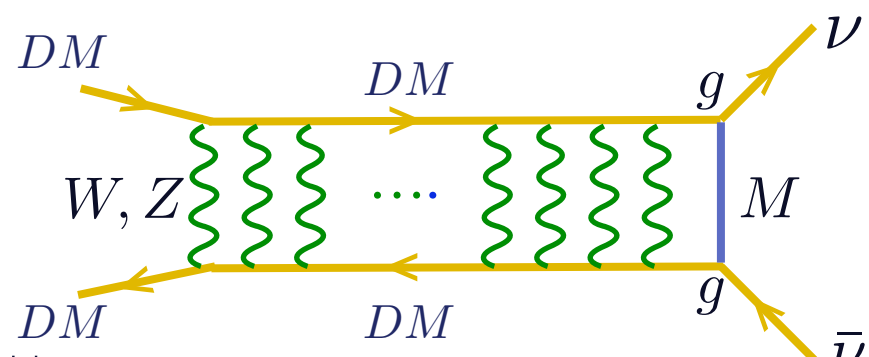
⇓

Sommerfeld for free and known: E-W interactions

as models $F_1,\ S_1^r,\ F_1^m$

⇓

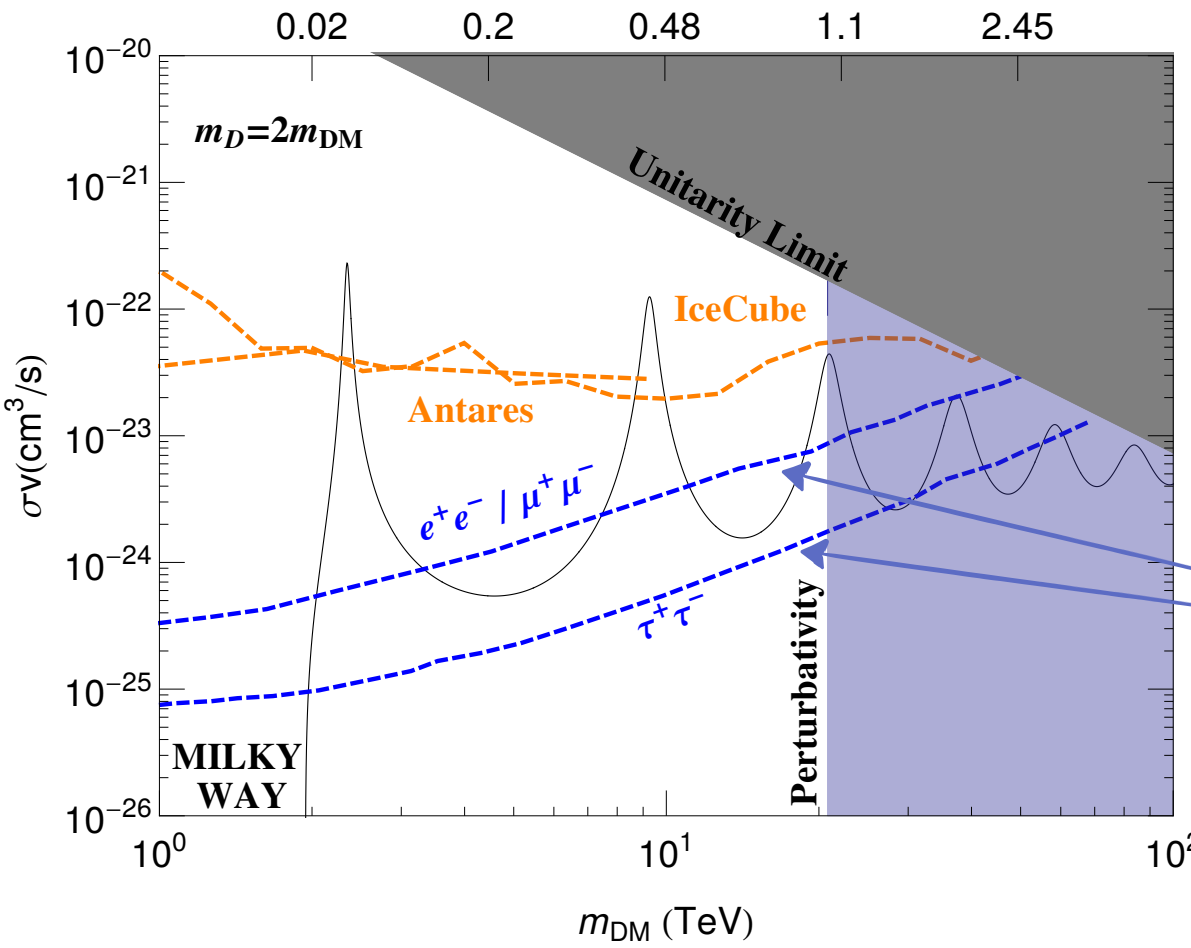
ν-line is predicted as a function of m_{DM} and $DM-Med-\nu$ coupling g



⇑ can be fixed by DM relic density

ν-line cross section results including Sommerfeld effect

example: model F_2 : a $Y = 0$ fermion DM triplet + a scalar doublet mediator



El Aisati, Garcia-Cely, T.H., Vanderheyden '17

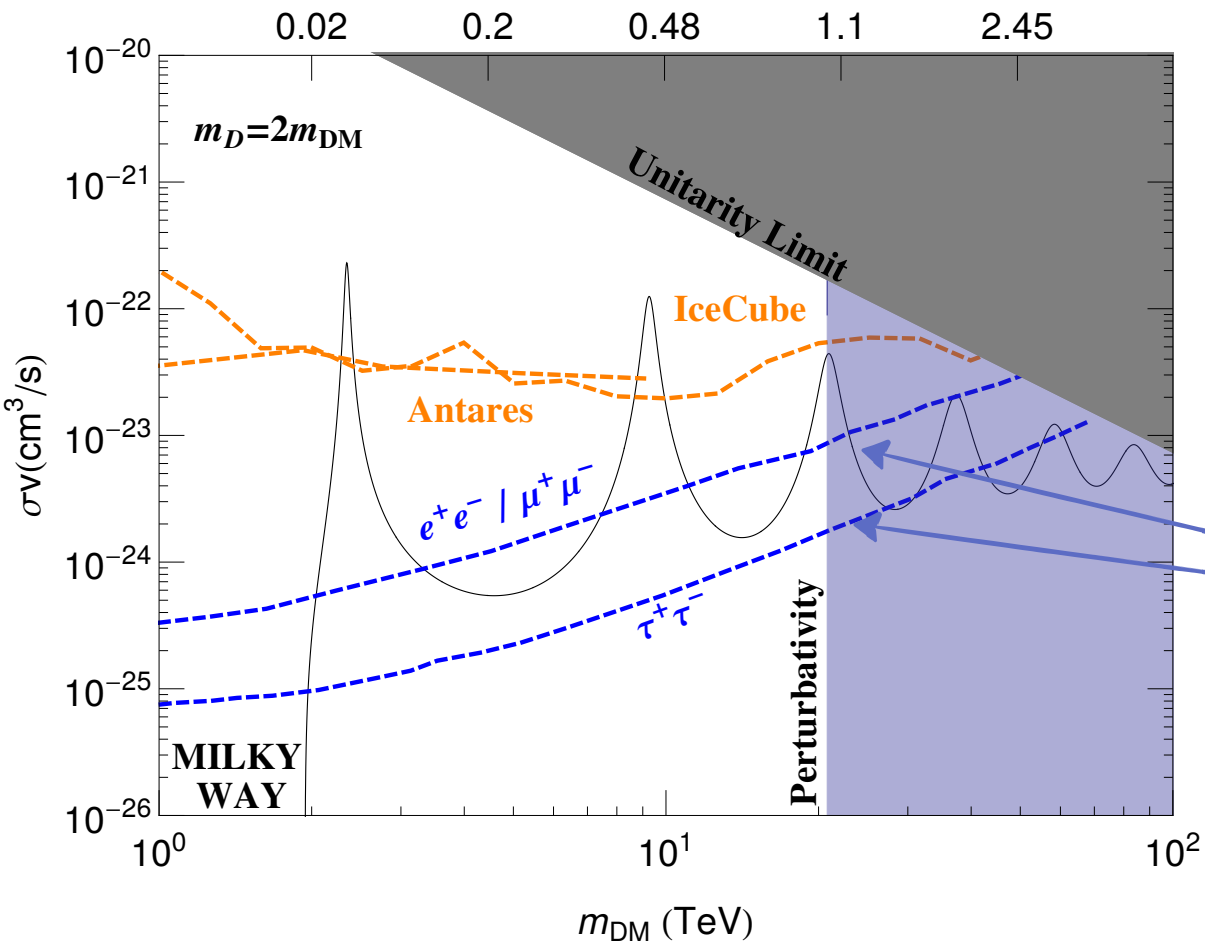
$\Phi_{\nu\bar{\nu}} = \Phi_{l^+l^-}$
charged lepton flux constraint

⇒ all fluxes predicted: ν-line and associated charged lepton flux around the corner

discrimination of the models

ν-line cross section results including Sommerfeld effect

example: model F_2 : a $Y = 0$ fermion DM triplet + a scalar doublet mediator



El Aisati, Garcia-Cely, T.H., Vanderheyden '17

$\Phi_{\nu\bar{\nu}} = \Phi_{l^+l^-}$
charged lepton flux constraint

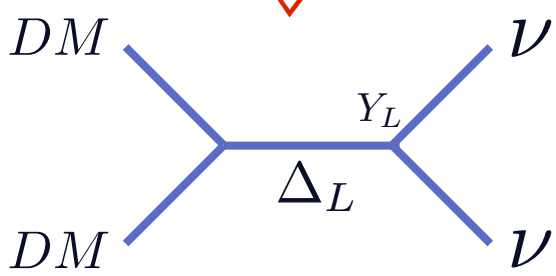
⇒ various multi-TeV models with electroweak interactions are in fact already excluded: give a too large Sommerfeld boost ⇒ neutrino telescopes are already excluding thermal scenarios!
but still allowed at lower scale or if annihilation channel to neutrinos subleading in freeze-out

Probing the seesaw???

one surviving model involve the type-II seesaw scalar triplet state

model S_1^r : real scalar DM from doublet + scalar $Y = 2$ triplet mediator

a type-II seesaw state Δ_L



El Aisati, Garcia-Cely, T.H., Vanderheyden '17

Probing the seesaw???

El Aisati, Garcia-Cely, T.H., Vanderheyden '17

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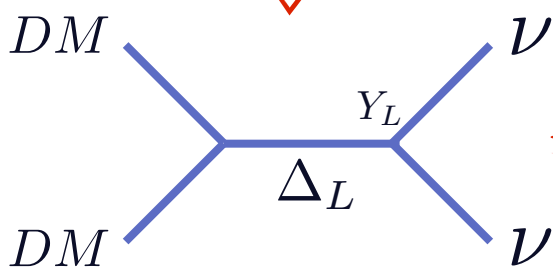
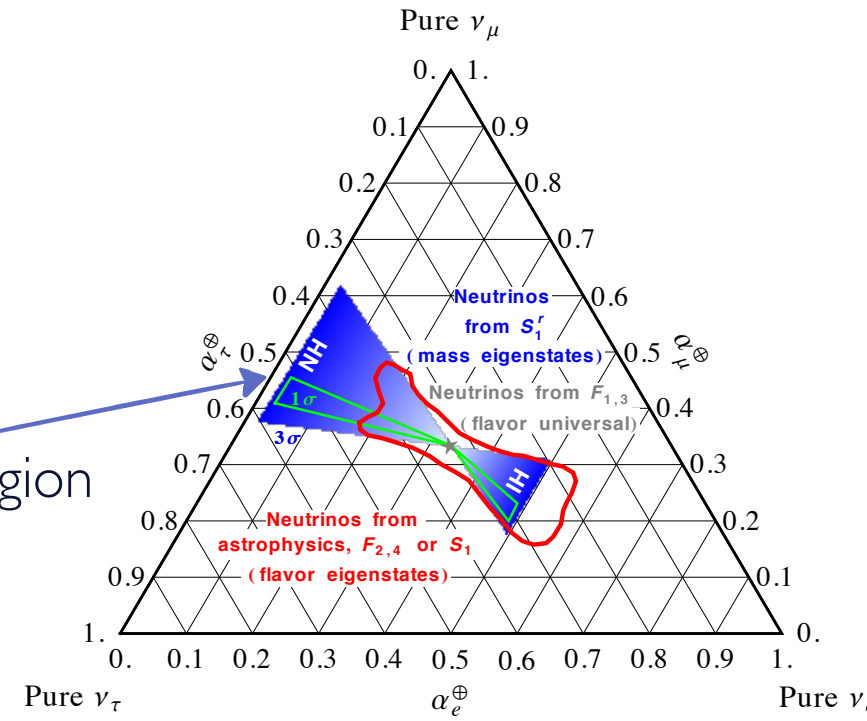


$\Rightarrow$ neutrinos are produced as mass eigenstates

flavour flux composition outside oscillation region



Garcia-Cely, Heeck '16
El Aisati, Garcia-Cely, TH, Vanderheyden '17

Probing the seesaw???

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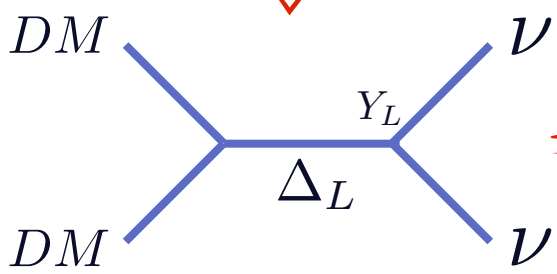
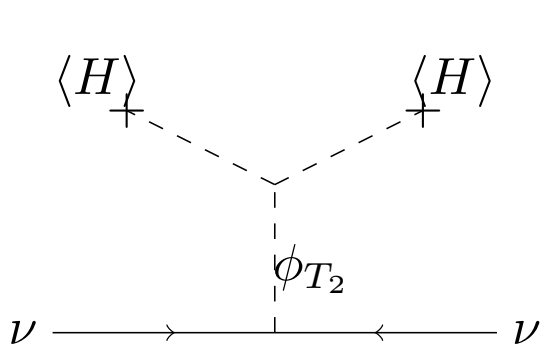
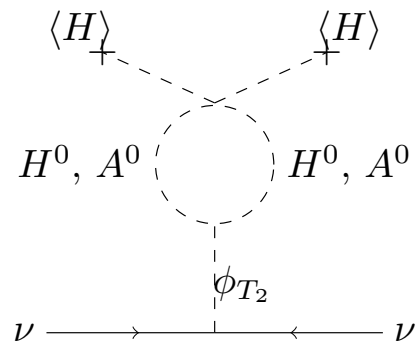


$\Rightarrow$ neutrinos are produced as mass eigenstates

but some tuning is necessary between tree level and loop contribution not to induce not to induce too large neutrino masses:





Seesaw induced ν-line from DM decay

DM slow decay?

$$\tau_{DM} > \tau_U \sim 10^{18}\ \text{sec}$$

$$\tau_{DM} > 10^{24-29}\ \text{sec} \quad \Leftarrow \text{ not to produce too large fluxes of } e^+, \bar{p}, \gamma, \nu, \ldots$$

↳ 2 main options

↙ suppressed by powers of a very heavy scale

↘ suppressed by very tiny couplings

DM slow decay from heavy scale suppression

dimension 5 operator suppression: $\tau_{DM} \sim \frac{1}{8\pi}\frac{m_{DM}^3}{\Lambda_{UV}^2} \Rightarrow \Lambda_{UV} \sim 10^{29}\ \mathrm{GeV}$

$\tau_{DM} \sim 10^{27}\ \mathrm{sec} \quad m_{DM} \sim \mathrm{TeV}$

dimension 6 operator suppression: $\tau_{DM} \sim \frac{1}{8\pi}\frac{m_{DM}^5}{\Lambda_{UV}^4} \Rightarrow \Lambda_{UV} \sim 10^{16}\ \mathrm{GeV}$

opportunity to probe the GUT scale!!

and seesaw physics!

A simple DM setup leading to dim-6 seesaw induced ν-line

Coy, TH, '20

↪ a massive QED structure on top of the SM: $U(1)_X$ gauge structure with SSB

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} F^X_{\mu\nu} F^{X\mu\nu} + \bar{\chi}(i \not{D} - m_\chi)\chi + D_\mu \phi^\dagger D^\mu \phi - \lambda_m \phi^\dagger \phi H^\dagger H - V(\phi)$$

TH '08 + χ

↪ the χ fermion is stable, as well as the $U(1)_X$ gauge boson if $m_A < 2m_\chi$

+ seesaw type-I interactions:

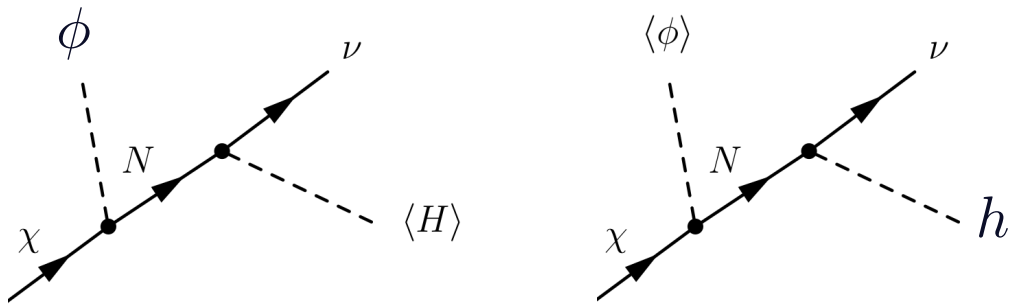
$$\mathcal{L}_{\rm seesaw} = i\overline{N_R} \not{\partial} N_R - \frac{1}{2} m_N \left(\overline{N_R} N_R^c + \overline{N_R^c} N_R \right) - \left(Y_\nu \overline{N_R} \tilde{H}^\dagger L + h.c. \right) .$$

⇒ possibility a neutrino portal: $\delta\mathcal{L} = -\left(Y_L \overline{N_R} \phi \chi_L + Y_R \overline{N_R^c} \phi \chi_R + h.c. \right)$

Destabilization of the fermion DM component by the neutrino portal interactions

Coy, TH, '20

χ decays: $\chi \to \nu\phi$ $\chi \to \nu h$ $\chi \to W^{\pm} l^{\mp}$ $\chi \to Z\nu$ $\chi \to A'\nu$



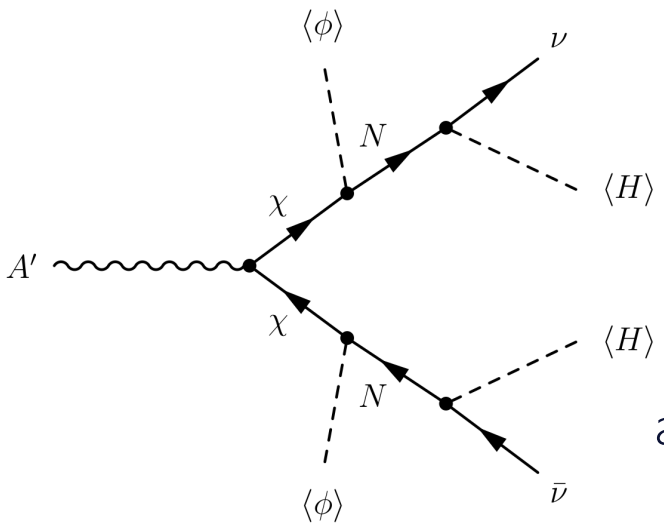
all suppressed by 2 powers of m_N: χ fastly decays $\Rightarrow$ no χ DM anymore

(before BBN)

Seesaw induced slow decay of the gauge boson DM component

Coy, TH, '20

A' decays: $A' \to \nu\bar{\nu}$

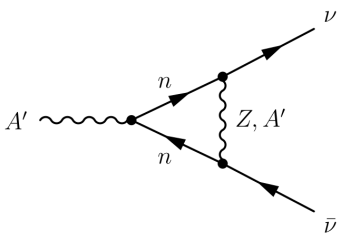


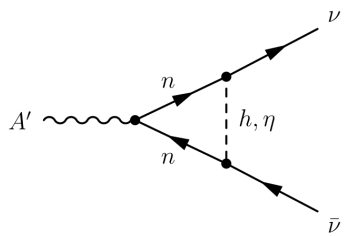
⇒ suppressed by 4 powers of m_N

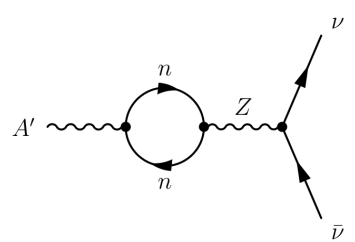
a ν-line around the corner if all couplings of order unity!

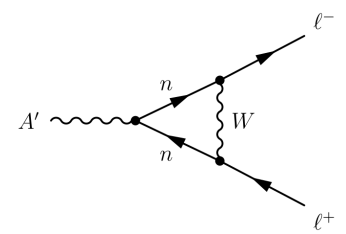
$$\Gamma(A' \to \nu\bar{\nu})_{\rm tree} \simeq \frac{g_X^2 Y_\nu^4 (Y_L^2 - Y_R^2)^2 v^4 v_\phi^4 m_{A'}}{96\pi m_\chi^4 m_N^4}$$

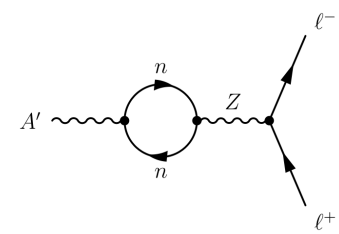
All one-loop induced decays also suppressed by 4 powers of m_N ! (unlike Majoron DM)







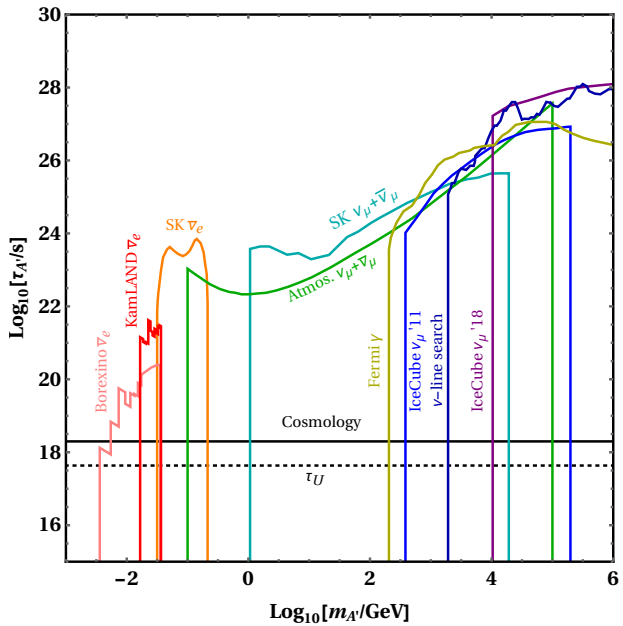




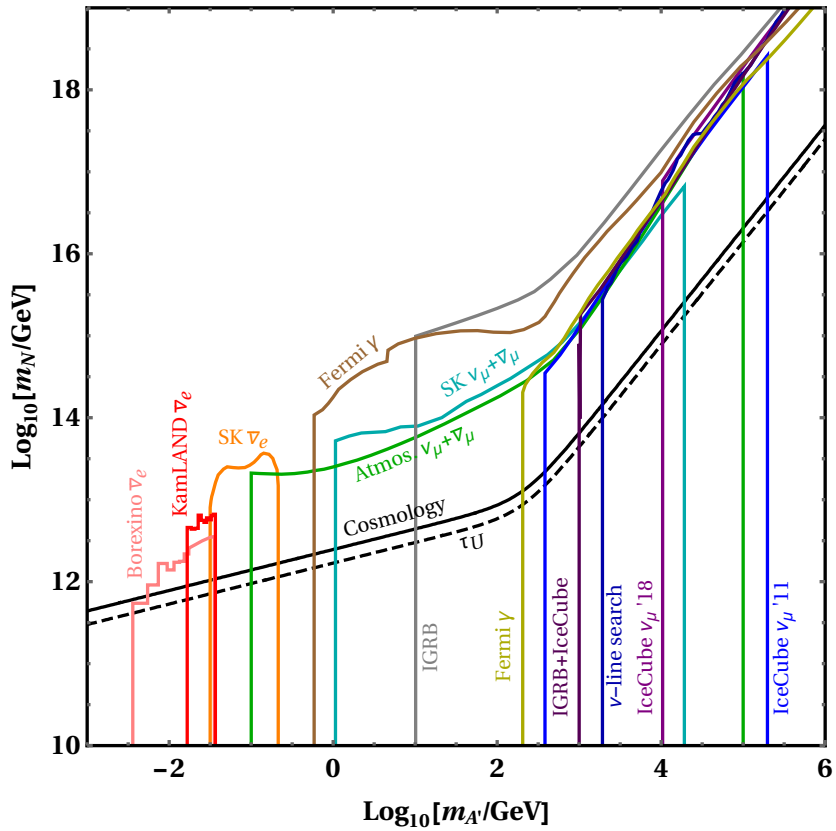
Seesaw induced slow decay of the gauge boson DM component

Coy, TH, '20

compilation of experimental lower bounds on DM lifetime for $DM \to \nu\nu$



lower bound on m_N for all couplings of order unity



also includes 3 and 4 body tree level decays

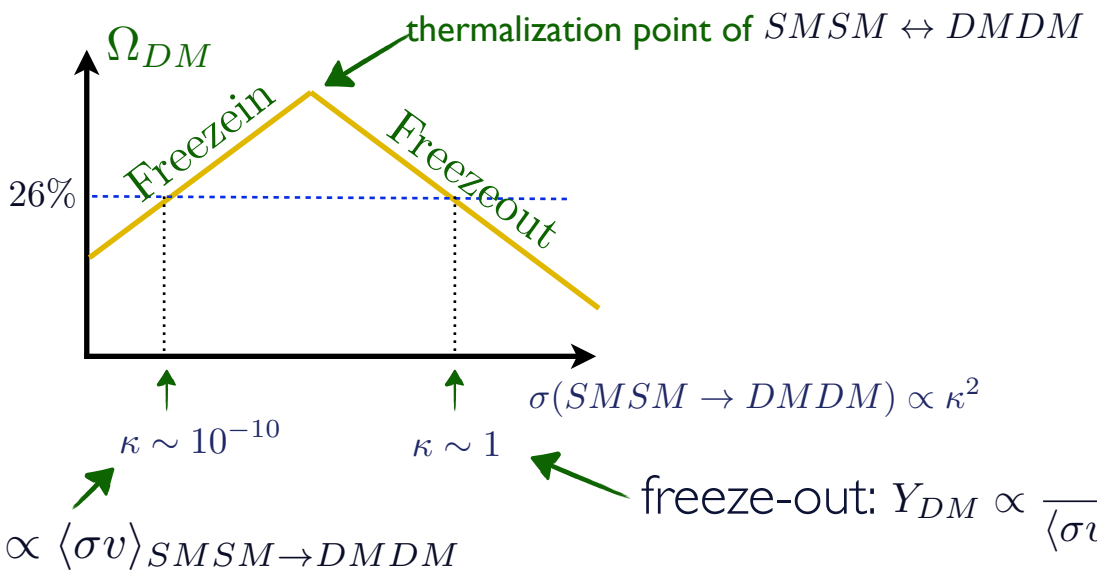
+ related emission of charged lepton: to be seen soon too if a neutrino line is observed!!

A low scale seesaw induced decaying DM setup

a simple question: could the seesaw interactions set the DM relic density, even though DM is not a sterile neutrino??

from a thermal bath the 2 most straightforward ways to account for the observed DM relic density are the freeze-out and freeze-in

slow out-of-equilibrium production of DM: requires tiny coupling



freeze-out: $Y_{DM} \propto \dfrac{1}{\langle\sigma v\rangle_{SMSM\to DMDM}}$

Mc Donald 02'
Hall, Jedamzik, March-Russell, West 09'

a framework which involve small couplings is the low scale seesaw:
could low scale seesaw be responsible for DM relic density through freeze-in???

A simple DM setup whose relic density is determined by seesaw interactions

Coy, Gupta, TH, '21

seesaw type-I: $\mathcal{L}_{\rm seesaw} = i\overline{N_R}\partial\!\!\!/ N_R - \frac{1}{2}m_N(\overline{N_R}N_R^c + \overline{N_R^c}N_R) - (Y_\nu \overline{N_R}\tilde{H}^\dagger L + h.c.)$

neutrino portal: $\delta\mathcal{L} = -Y_\chi \overline{N}\phi\chi + h.c.$

→ DM is χ and/or ϕ ($\mathcal{Z}_2$ symmetry or extra $U(1)_X$, ...)

first step: if $m_N < m_{W,Z,h}$ freeze-in production of $N's$ from seesaw Yukawa induced decays of W, Z, h

$$\Gamma_{W^\pm \to N\, l_i^\pm} = \frac{1}{48\pi} m_W |Y_{\nu i}|^2 \, f(m_N^2/m_W^2)\,,$$

$$\Gamma_{Z\to \overline{N}\,\nu_i + N\bar{\nu}_i} = \frac{1}{48\pi} m_Z |Y_{\nu i}|^2 \, f(m_N^2/m_Z^2)\,,$$

$$\Gamma_{h\to \overline{N}\,\nu_i + N\bar{\nu}_i} = \frac{1}{16\pi} m_h |Y_{\nu i}|^2 \left(1 - \frac{m_N^2}{m_h^2}\right)^2$$

→ not in thermal equilibrium if $\sum_i |Y_{\nu i}|^2 \lesssim 1\cdot 10^{-16}\cdot \left(\frac{m_N}{10\,\text{GeV}}\right)^2$

A simple DM setup whose relic density is determined by seesaw interactions

Coy, Gupta, TH, '21

second step: decay of $N's$ through the neutrino portal: $N \to \chi\phi$

easily dominant because 2-body decay

$$Y_\chi = Y_\phi = Y_N\big|_{\text{before N decay}}$$

$$\Omega_{DM}h^2 \simeq 10^{23} \sum_i |Y_{\nu i}|^2 \left(\frac{m_\chi + m_\phi}{1\,\text{GeV}}\right)\left(\frac{10\,\text{GeV}}{m_N}\right)^2$$

from Yukawa couplings leading to lightest neutrino mass

$$\sum_i |Y_{\nu i}|^2 \simeq 10^{-24} \cdot \left(\frac{m_N}{10\,\text{GeV}}\right)^2 \left(\frac{1\,\text{GeV}}{m_\chi + m_\phi}\right)$$

$$m_{\nu_1} < \tilde{m}_1 = 4 \cdot 10^{-12}\,\text{eV} \cdot \frac{10\ \text{GeV}}{m_N} \cdot \left(\frac{1\,\text{GeV}}{m_\chi + m_\phi}\right)$$

⇒ the seesaw has the flexibility to produce DM in such a simple way from decays of SM bosons

Testability of the framework

Coy, Gupta, TH, '21

↳ lightest neutrino mass prediction: cannot be established but can be falsified

$$m_{\nu_1} < \tilde{m}_1 = 4 \cdot 10^{-12}\,\text{eV} \cdot \frac{10\ \text{GeV}}{m_N} \cdot \left(\frac{1\,\text{GeV}}{m_\chi + m_\phi} \right)$$

↳ observable neutrino line prediction:

↳ for instance if $m_\chi > m_\phi$ DM is dominated by χ component:

$\chi \to \phi\nu$ induced by neutrinos portal and N-ν seesaw mixing

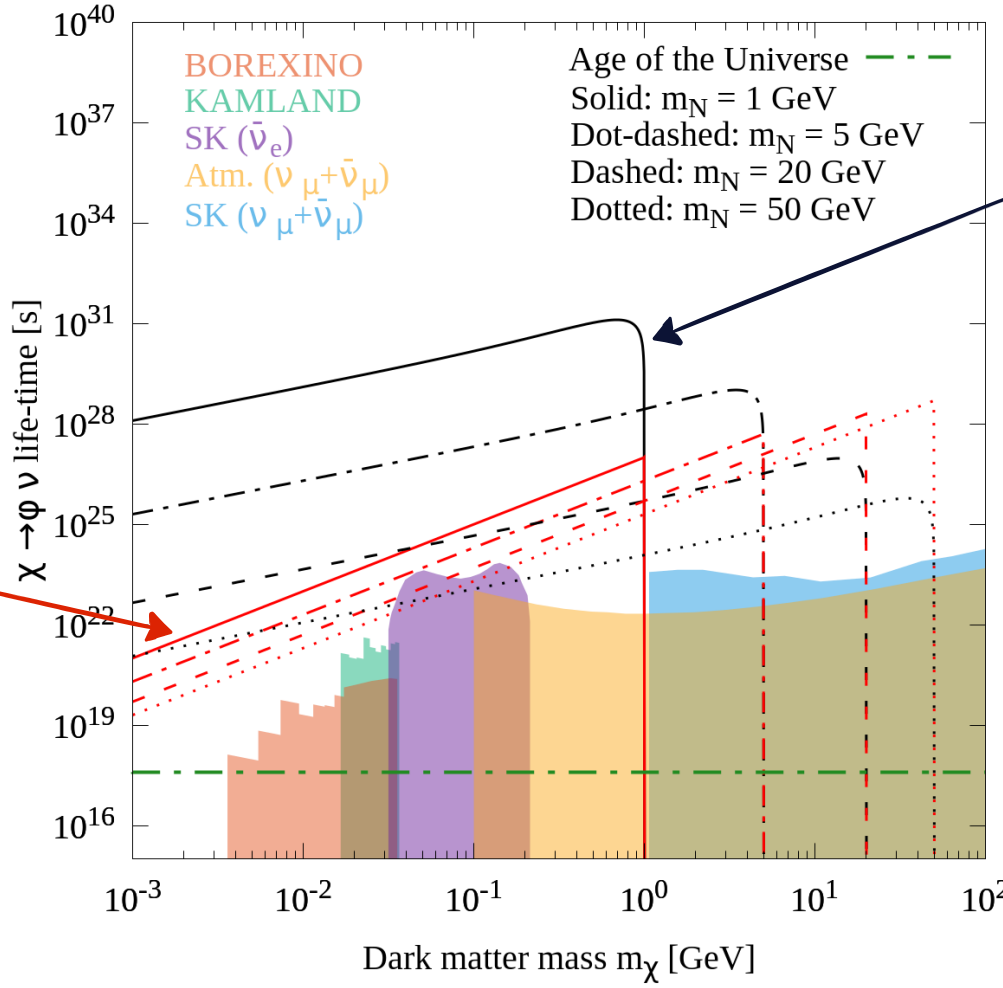
$$\Gamma_{\chi\to\phi\nu} = \frac{1}{32\pi} |Y_\chi|^2 \frac{\sum_i |Y_{\nu i}|^2 v^2}{m_N^2} m_\chi \left(1 - \frac{m_\phi^2}{m_\chi^2}\right)^2$$

⇓

ν-line if on top of tiny Y_ν coupling, the Y_χ coupling is also tiny

ν-line constraints

Coy, Gupta, TH, '21



upper bound to have 1-to-1 correspondance between Ω_{DM} and seesaw parameters (2-body N decay dominance)

upper bound from large scale structure formation

$$\tau_\chi \lesssim 10^{28}\,\mathrm{sec}\left(\frac{m_{DM}}{m_N}\right)^2\left(\frac{m_N}{10\,\mathrm{GeV}}\right)$$

Other option leading to 1-to-1 Ω_{DM}-seesaw correspondance

Coy, Gupta, TH, '21

→ relativistic decoupling of DM in the hidden sector thermal bath

if neutrino portal Y_χ large, χ disappears quickly: ϕ is the DM $\quad \chi \to \phi\nu$

N, χ, ϕ forms a thermalized (from Y_χ) hidden sector which does not thermalize with SM thermal bath (Y_ν small)

SM sector thermal bath: T $\quad$ hidden sector thermal bath: T'

in the hidden sector the ϕ DM particle decouples relativistically: $m_\phi < m_\chi << m_N$

$$\phi\phi \leftrightarrow \chi\chi$$

doesn't depend on annihilation cross section but only on T'/T:

TH, Lucca, Vanderheyden, '20

``relativistic floor hidden sector DM scenario''

T'/T is set by seesaw parameters ⇒ 1-to-1 Ω_{DM}-seesaw correspondance!

Short Summary

high energy ν-line search : - large recent improvements

- more in near future

ν-line from DM annihilation: - several possibilities at level of present sensitivity

- possible links with seesaw

↪ even if neutrino masses constraints kill in many cases the possibility of an intense ν-line

ν-line from DM decay: - many possibilities at level of present sensitivity

- can be induced by seesaw interactions

↪ high seesaw scale option (order unity couplings): allow to test GUT scale

↪ low seesaw scale option (tiny couplings)

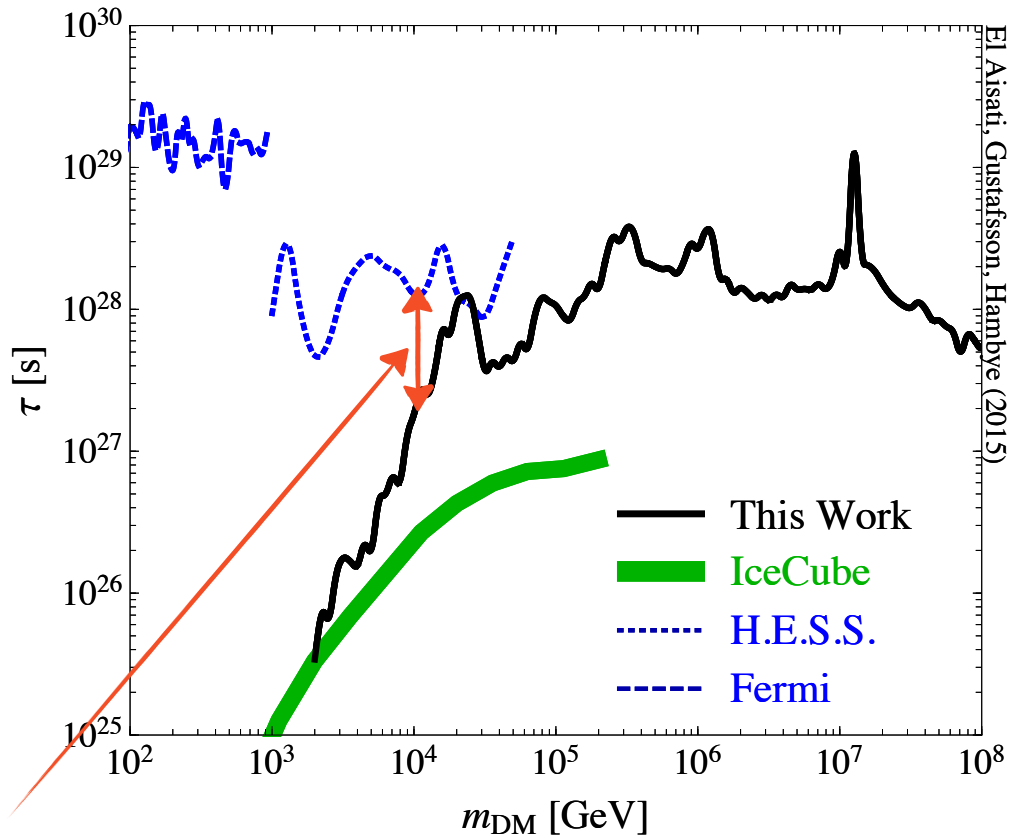
First spectrum based search of a 'ν-line' from IceCube data

↪ using a 2010-2012 public IceCube data sample: for DM decay: $\Gamma_{DM\to\nu+X}$

Lifetime lower limit exploiting the sharp spectral feature property:

El Aisati, Gustafsson, TH 15'

Lifetime lower limit:



between few TeV and 50 TeV, γ and ν line sensitivities are similar! ← within a factor 1 to 20

IceCube new analysis: Most significant result

More details about minimal models for nu-lines

Determination of minimal models leading to observable ν-line from DM annihilation

↳ many constraints:

- constraint 1: annihilation must proceed through s-wave

  not to be suppressed by velocity powers today

  ↳ for the $DM\,DM \to \nu\,\bar{\nu}$ channel this excludes all scalar and Majorana DM models

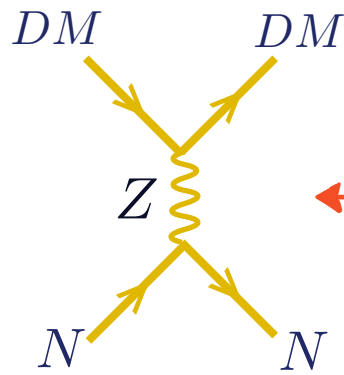
  but leaves open many possibilities in the $DM\,DM \to \nu\,\nu$ channel

Determination of minimal models leading to observable ν-line from DM annihilation

many constraints:

- constraint 2: direct detection constraint:

big issue for DM multiplet with non-zero hypercharge

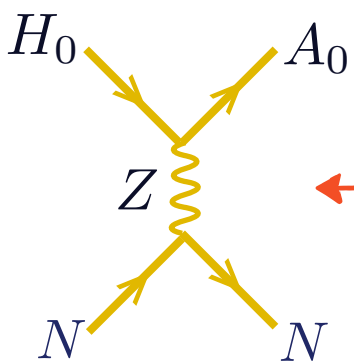


far too large

need to split in mass the neutral components of the DM multiplet

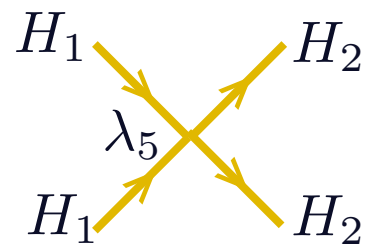
example: DM is neutral component of scalar doublet: ``inert'' doublet

$$H_2 = \begin{pmatrix} H^+ \\ \frac{H_0 + i A_0}{\sqrt{2}} \end{pmatrix}$$



kinematically forbidden if: $m_{A_0} - m_{H_0} \gtrsim 100$ keV

possible from λ_5 interaction



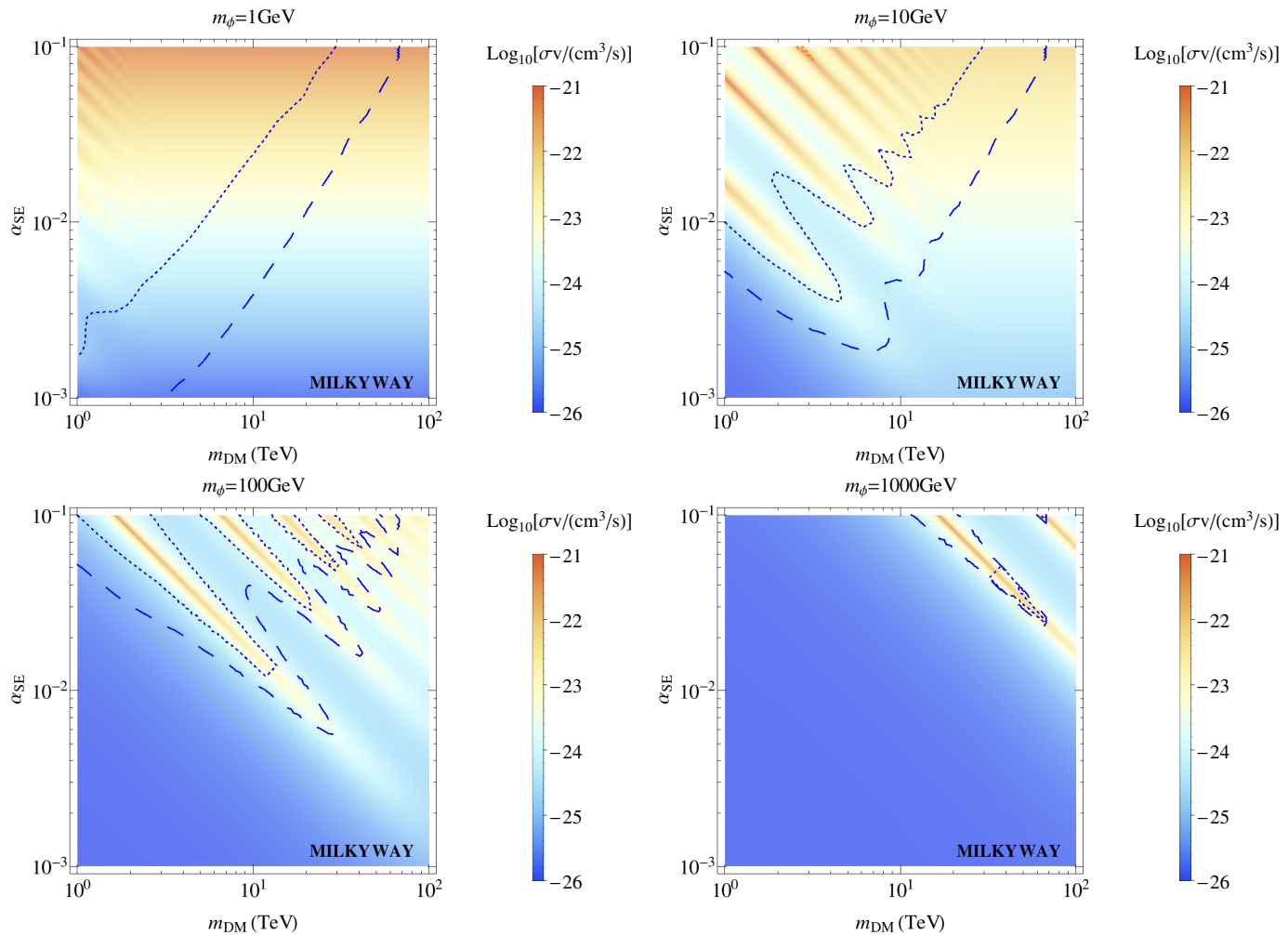
similarly $Y \neq 0$ DM Dirac fermion must be split into Majorana fermions

ν-line cross section results including Sommerfeld effect

other example: model F_4: a $Y = 0$ fermion DM singlet + a scalar doublet med.

Sommerfeld requires extra light BSM mediator

$\Rightarrow$ ν-line is predicted as a function of of m_{DM} and $DM - Med - \nu$ coupling g and Som. mediator mass and coupling



El Aisati, Garcia-Cely, T.H., Vanderheyden '17