ν-lines produced by DM: a phenomenological perspective for neutrino telescopes

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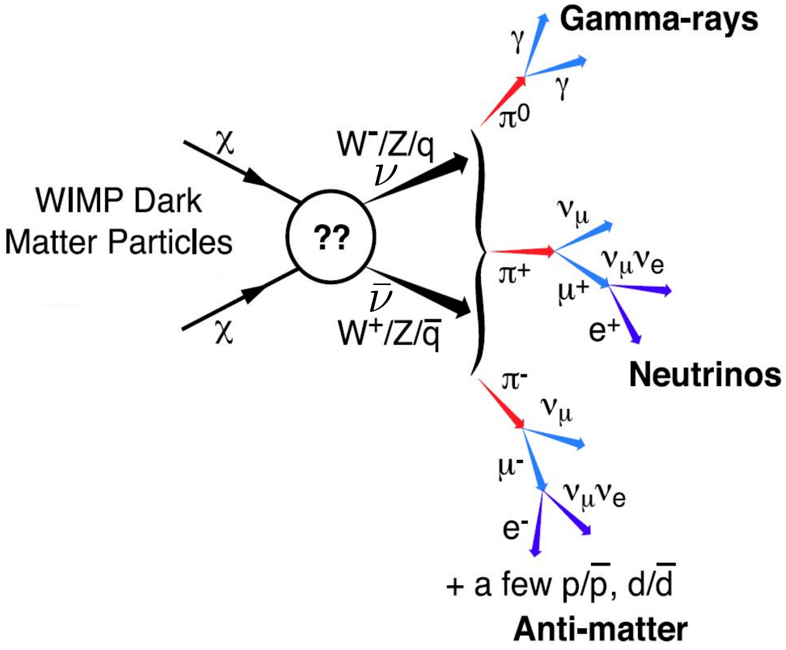
Based on: C. El Aisati, C. Garcia-Cely, TH, L. Vanderheyden, arXiv:1706.06600
C. El Aisati, M. Gustafsson, TH, arXiv:1506.02657
C. El Aisati, M. Gustafsson, TH, T. Scarna, arXiv:1510.05008
C. El Aisati, TH, T. Scarna, arXiv:1403.1280

Dark ghosts, 13/11/2018

DM indirect detection with neutrinos

DM annihilation or decay in the galactic center and halo

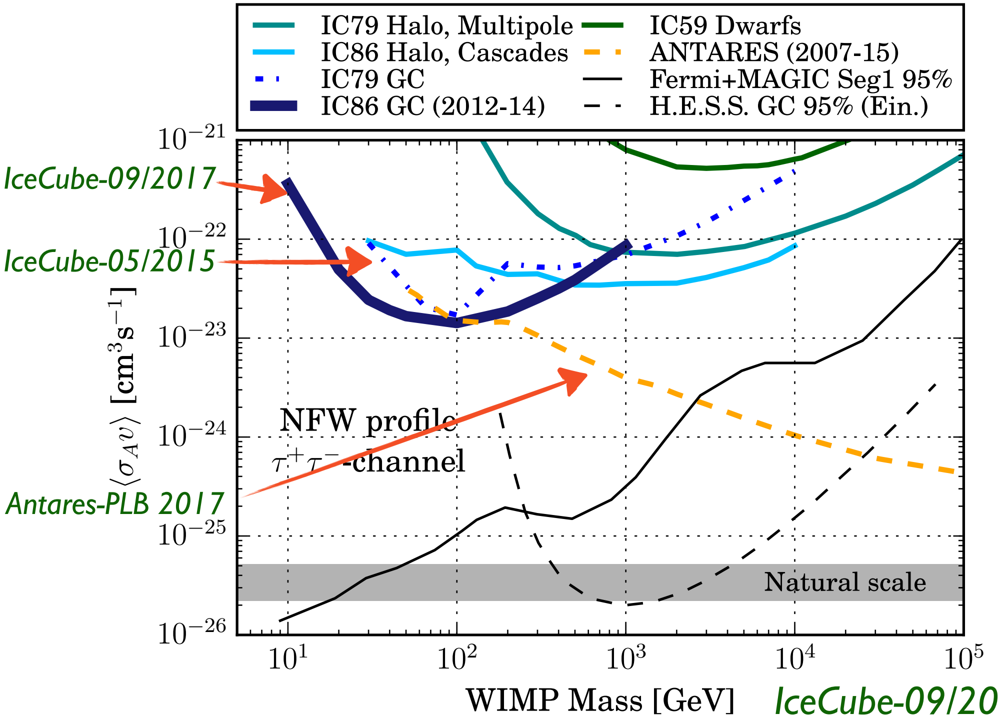


⇒ sets upper limits on a DM annihilation cross sections and lower limits on DM decay lifetime

DM indirect detection with neutrinos: charged particle channels

Most neutrino telescope analysis so far study annihilation channels where neutrinos are secondary particles: $DM\,DM \to \tau^+\tau^-,\, b\bar{b},\, W^+W^-, ...$

$DM\,DM \to \tau^+\tau^-$ example:



IceCube-09/2017

IceCube-05/2015

Antares-PLB 2017

IceCube-09/2017

⇒ limited discovery expectations in most straightforward frameworks:

- better limits on same channels from γ-ray telescopes except for $m_{DM} \gtrsim 10 - 20\,\mathrm{TeV}$
- thermal DM freeze-out typically requires $m_{DM} \lesssim 10 - 20\,\mathrm{TeV}$
- cross section sensitivity far from reaching the value required by thermal freeze-out

$\langle\sigma_{annih.} v\rangle \simeq 3 \cdot 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$

DM indirect detection with neutrinos: ν-lines

annihilation: $DM\,DM \to \nu\,\bar{\nu}$ and/or $DM\,DM \to \nu\,\nu$

decay: $DM \to \nu\bar{\nu},\ \nu\nu,\ \nu + X$

$\Rightarrow$ monochromatic ν's

$\Downarrow$

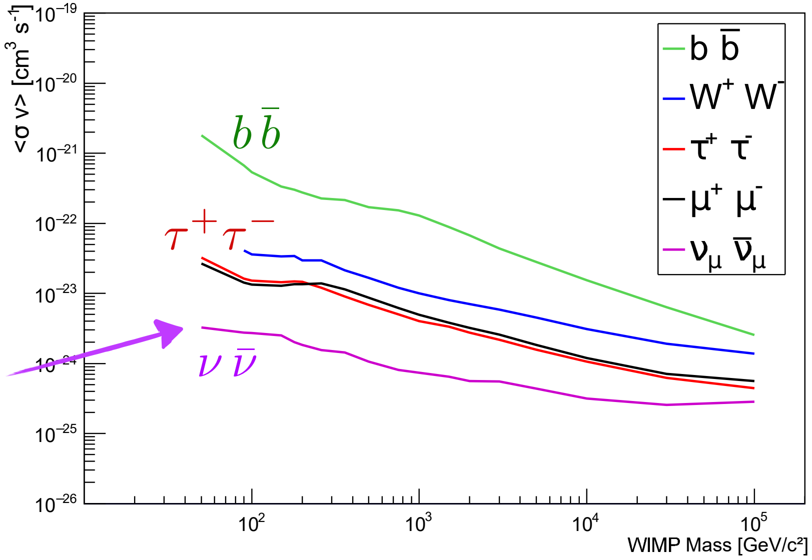
more possibilities of discoveries:

- 1) monochromatic signal: much cleaner: no astrophysical background expected!

  DM smoking gun!

- 2) better sensitivities than for secondary neutrino channels

Antares- PLB 2017



"primary' neutrinos

DM indirect detection with neutrinos: ν-lines

- 3) limits on ν channel from γ telescopes weaker than from ν telescopes!

⇓

the ν channel is competitive!

- 4) to produce a γ-line out of neutral DM one needs a loop suppressed process, unlike for producing a pair of neutrinos: boosts the ν-line % γ-line (model dependent)

- 5) further possibilities of improvements: so far the sharp spectral feature property was not exploited: a line in the ν energy spectrum

↑

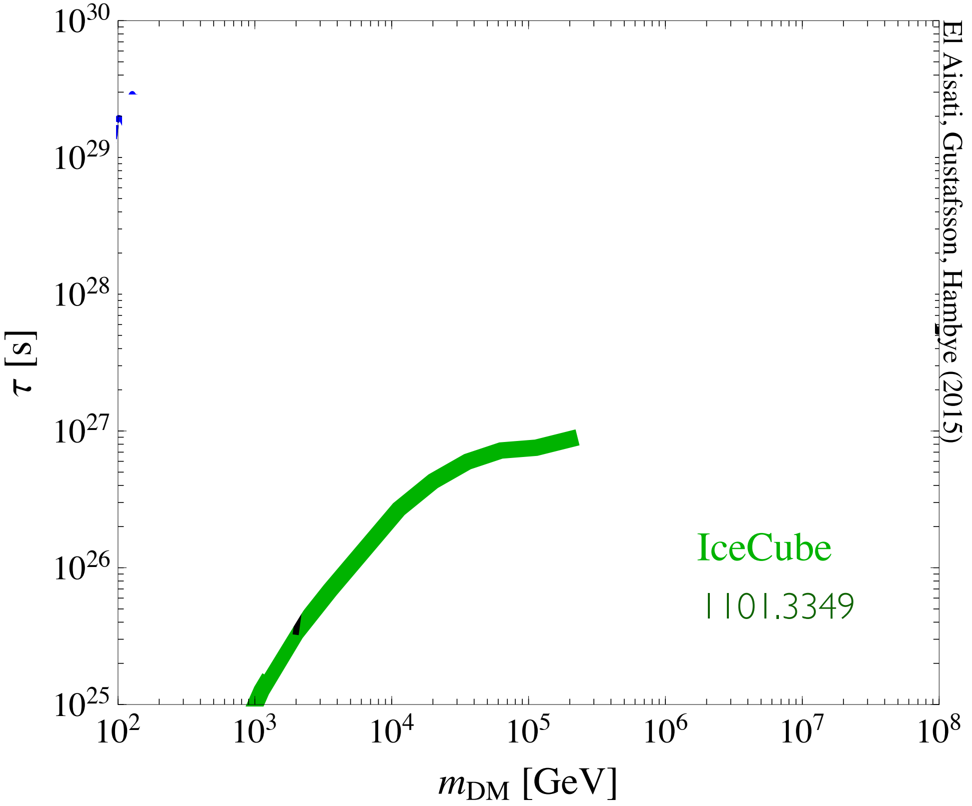
from γ telescopes the limit on γ-line channel is 2-3 orders of magnitude better than on channels with secondary photons

- 6) the decay scenario presents the further advantage that decay width not bounded from above by thermal cross section value, unlike annihilation process

Monochromatic flux of ν from DM decay: experimental limits

Observational situation for a decay: $\Gamma_{DM\to\nu+X}$

Long standing lower limit on DM lifetime:

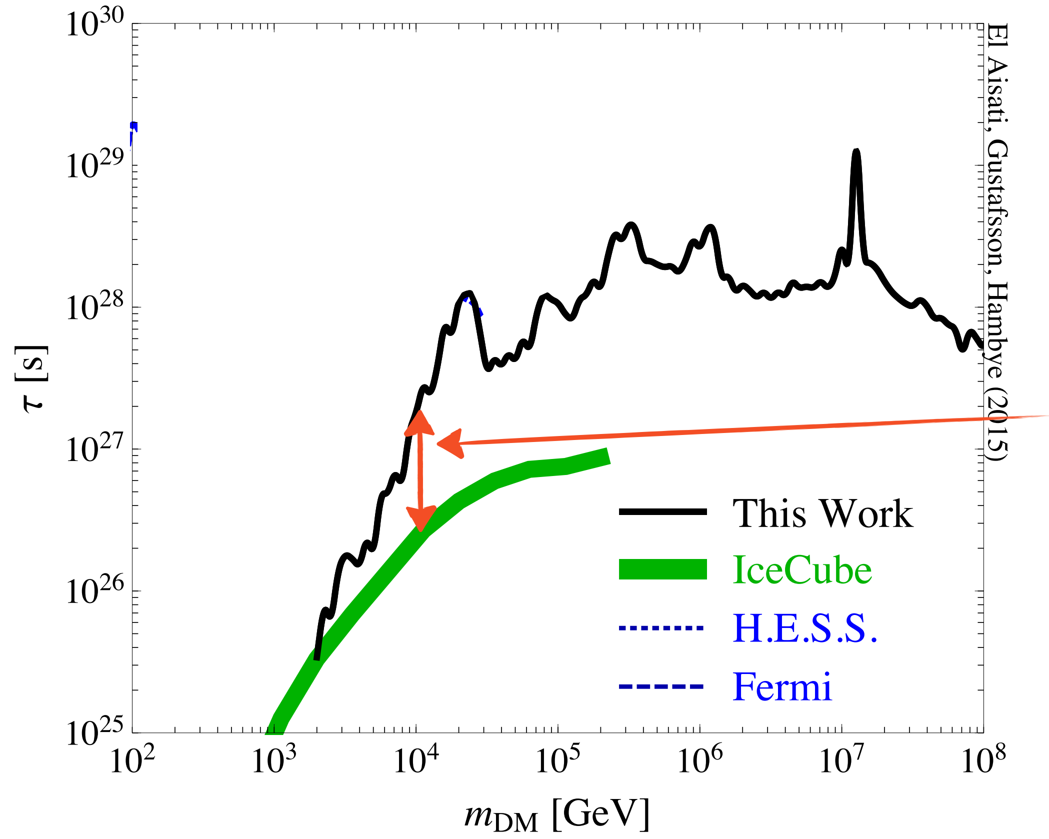


clear possibilities of improvements were to be expected: bigger detector, more statistic, better identification of events, …, and also from exploiting the sharp spectral feature property

Monochromatic flux of ν from DM decay: experimental limits

Observational situation for a decay: $\Gamma_{DM\rightarrow\nu+X}$

Exploiting the sharp spectral feature property from one year Icecube public data sample:



El Aisati, Gustafsson, Hambye (2015)

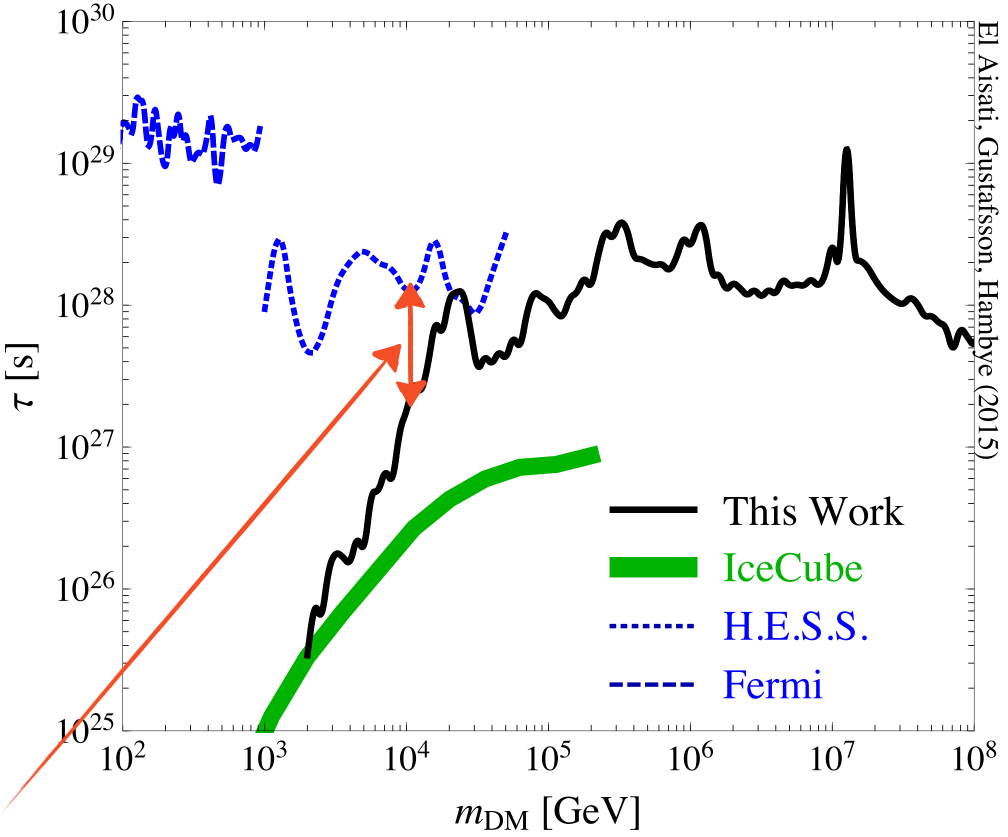
~ an order of magnitude improvement from few TeV to 100 TeV

even if one year only data sample and with no directional information in this sample!

Monochromatic flux of ν from DM decay: experimental limits

Observational situation for a decay: $\Gamma_{DM\rightarrow\nu+X}$

Exploiting the sharp spectral feature property from one year Icecube public data sample:



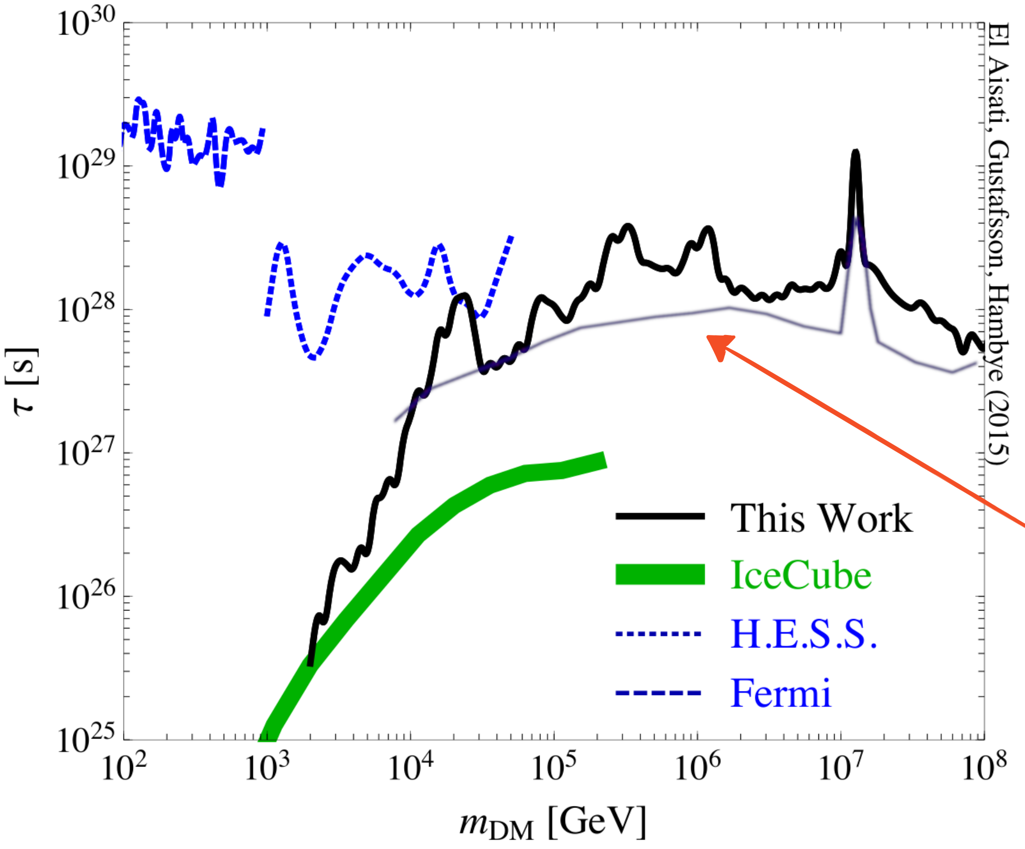
El Aisati, Gustafsson, Hambye (2015)

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

Monochromatic flux of ν from DM decay: experimental limits

Observational situation for a decay: $\Gamma_{DM \to \nu + X}$

With more statistics but still without exploiting the sharp feature property: Icecube 2018



El Aisati, Gustafsson, Hambye (2015)

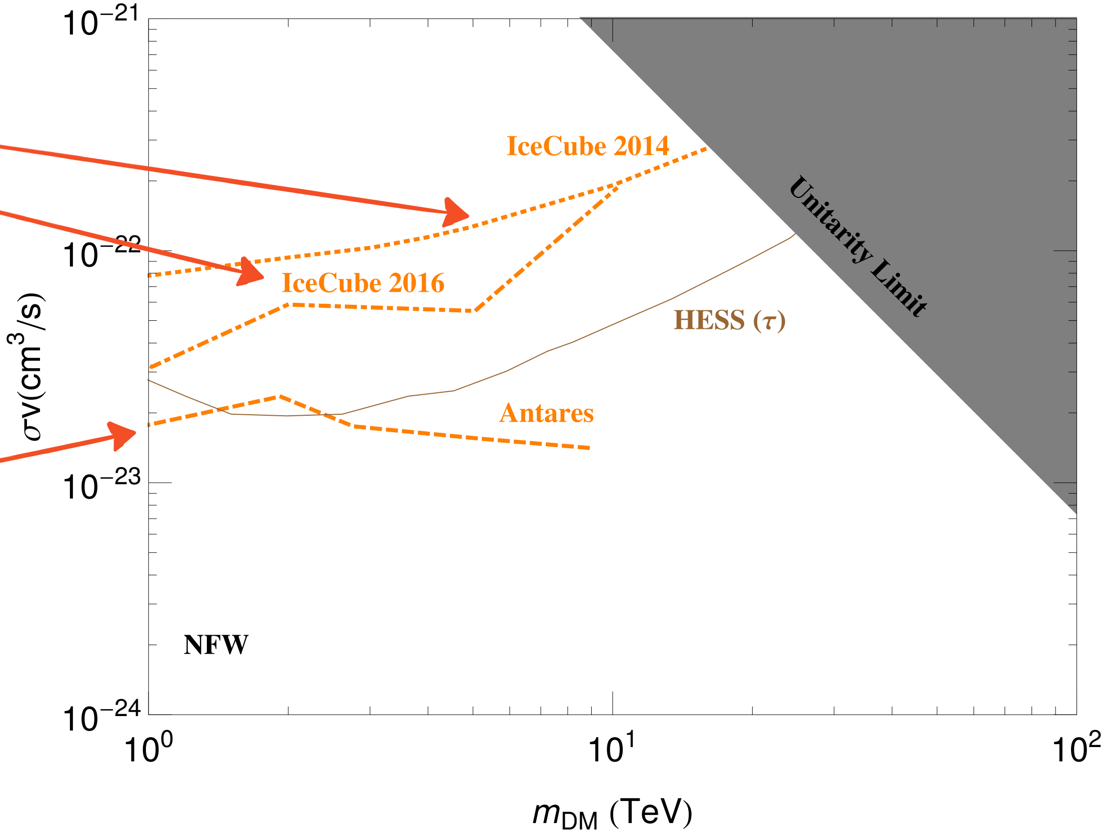
IceCube 2018

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 limits:

$\langle \sigma \, v \rangle_{DMDM \to \nu\nu}$



IceCube limits

not dedicated line searches

Antares limit (2015)

Monochromatic flux of ν from DM annihilation: experimental limits

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

Annihilation cross section upper limit:

$\langle\sigma\, v\rangle_{DM DM\to\nu\nu}$

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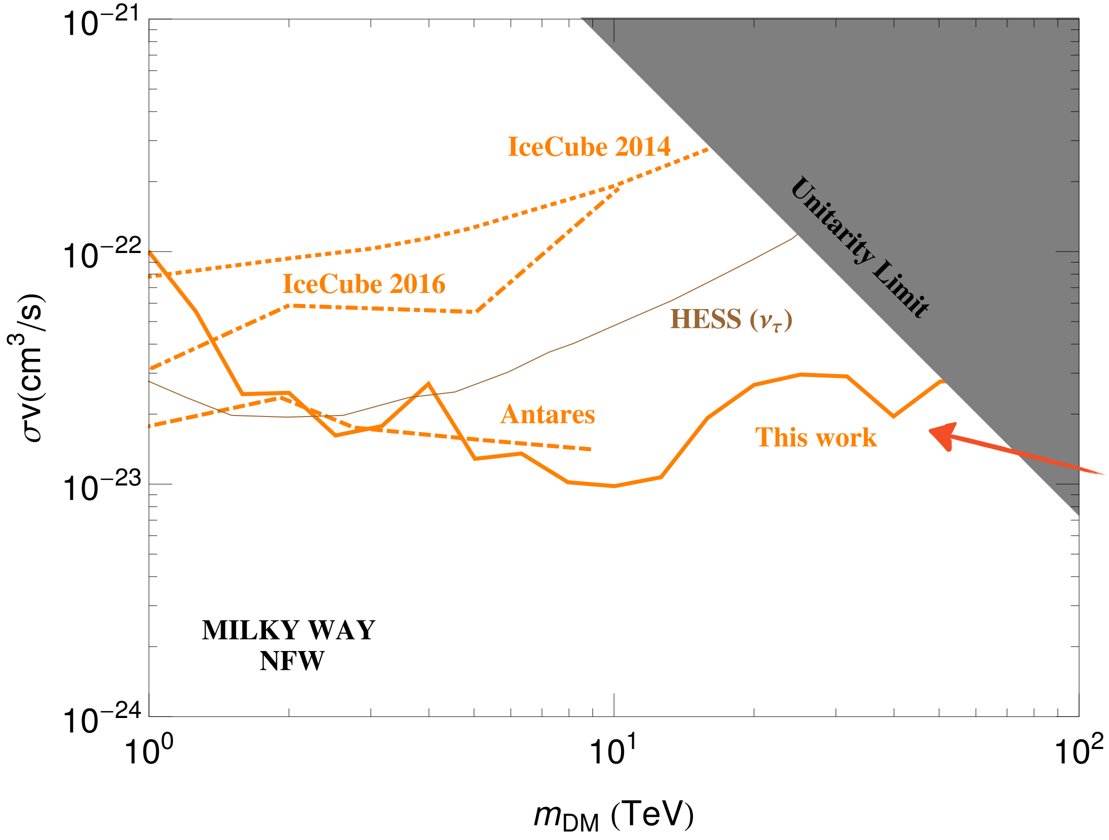


from line dedicated search using same 1-year data sample than for the decay

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

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

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

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

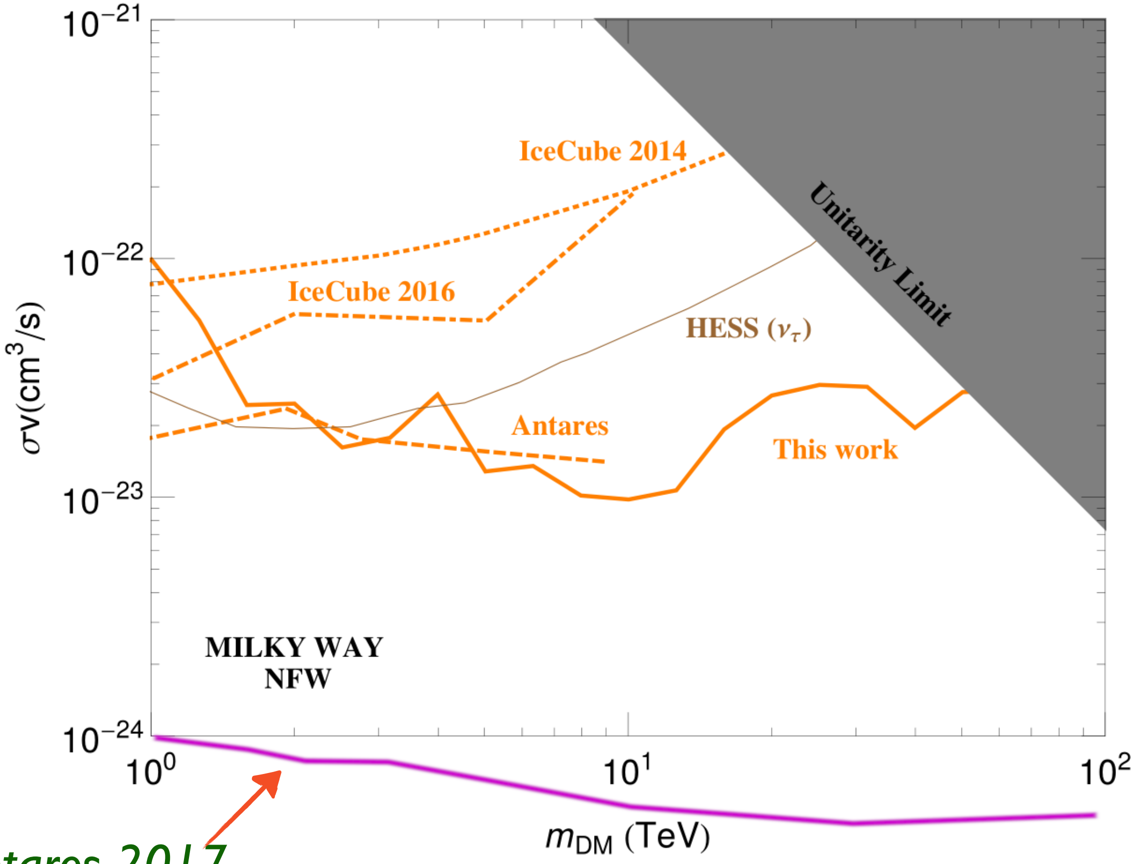
⇒ need also to see the galactic center with good angular resolut.

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:

$\langle \sigma\, v \rangle_{DMDM \to \nu\nu}$



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with still the sharp spectral feature property not exploited

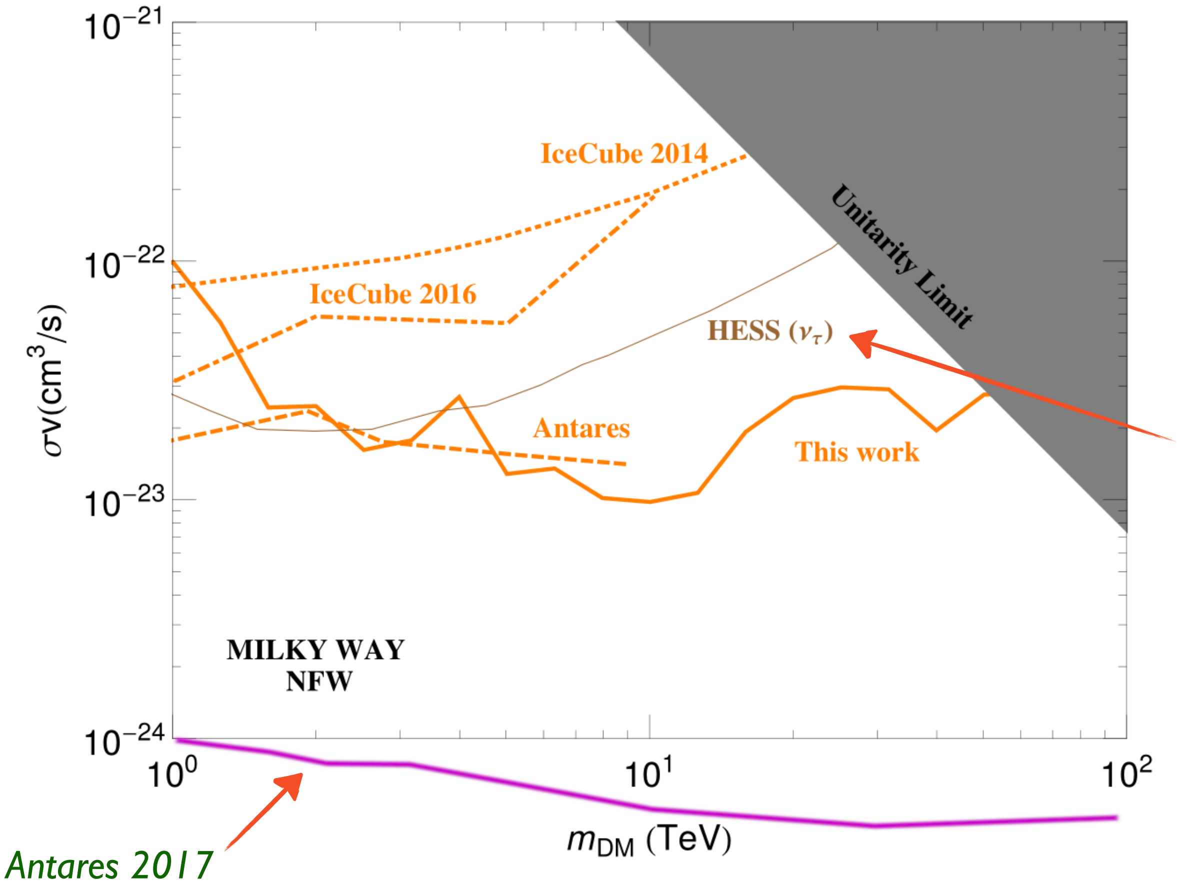
possibilities of further improvements!

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:

$$\langle \sigma \, v \rangle_{DMDM \to \nu\nu}$$



indirect limit from emission of cosmic rays by the monochromatic ν

Queiroz, Weniger, Yaguna 15

Antares 2017

→ with still the sharp spectral feature property not exploited (?)

⇒ possibilities of further improvements?? Antares energy resolution??

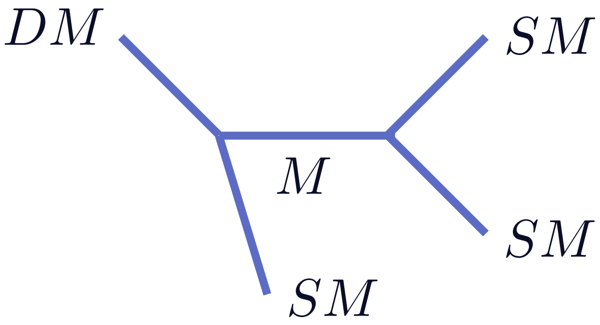
⇒ Given this exciting experimental situation:

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

DM decay: experimental sensitivity reachable??

- for the decay case: easy to have an observable flux!
- models based on accidental DM stability:

low energy accidental symmetry broken
at high energy as for proton decay:



⇒ higher dimens. operator

$$\Gamma_{DM} \sim \frac{m_{DM}^{2n+1}}{M^{2n}}$$

for instance for dimension 6 operator (n=2) and $m_{DM} \sim \mathrm{TeV}$:
$\tau_{DM} \sim 10^{28}\,\mathrm{sec}$ for $M \sim M_{GUT}$

⇒ the decay case can be fully scanned and parametrized by writing down the full list of higher dimens. operators linear in the DM field

Decay mode example: $DM \to \nu + \gamma$

El Aisati, Gustafsson, TH, Scarna '16

ν-line + γ-line: double monochromatic smoking gun!!

very few possible effective operator structures up to dim-6:

one dim-5 structure:
$$\mathcal{O}^{(5)Y} \equiv \bar{L}\sigma_{\mu\nu}\psi_{DM}F_Y^{\mu\nu},$$
$$\mathcal{O}^{(5)L} \equiv \bar{L}\sigma_{\mu\nu}\psi_{DM}F_L^{\mu\nu},$$

3 dim-6 structure:
$$\mathcal{O}^{1Y} \equiv \bar{L}\sigma_{\mu\nu}\psi_{DM}F_Y^{\mu\nu}\phi,$$
$$\mathcal{O}^{1L} \equiv \bar{L}\sigma_{\mu\nu}\psi_{DM}F_L^{\mu\nu}\phi,$$
$$\mathcal{O}^{2Y} \equiv D_\mu\bar{L}\gamma_\nu\psi_{DM}F_Y^{\mu\nu},$$
$$\mathcal{O}^{2L} \equiv D_\mu\bar{L}\gamma_\nu\psi_{DM}F_L^{\mu\nu},$$
$$\mathcal{O}^{3Y} \equiv \bar{L}\gamma_\mu D_\nu\psi_{DM}F_Y^{\mu\nu},$$
$$\mathcal{O}^{3L} \equiv \bar{L}\gamma_\mu D_\nu\psi_{DM}F_L^{\mu\nu},$$

⇒ varying over possible DM quantum numbers:

Operator Structure	DM field (*n-plet*, Y)	Fields contract. (*n-plet*)	*Operator*
$\bar{L}\sigma_{\mu\nu}\psi_{DM}F_Y^{\mu\nu}$	$(2,-1)$		$\mathcal{O}^{(5)Y}_{2\text{-let}}$
$\bar{L}\sigma_{\mu\nu}\psi_{DM}F_L^{\mu\nu}$	$(2,-1)$		$\mathcal{O}^{(5)L}_{2\text{-let}}$
	$(4,-1)$		$\mathcal{O}^{(5)L}_{4\text{-let}}$
$\bar{L}\sigma_{\mu\nu}\psi_{DM}F_Y^{\mu\nu}H$	$(1,0)$		$\mathcal{O}^{1Y}_{H,1\text{-let}}$
	$(3,0)$		$\mathcal{O}^{1Y}_{H,3\text{-let}}$
$\bar{L}\sigma_{\mu\nu}\psi_{DM}F_L^{\mu\nu}H$	$(1,0)$		$\mathcal{O}^{1L}_{H,1\text{-let}}$
	$(3,0)$	a: $(\bar{L}H)=1$	$\mathcal{O}^{1L,a}_{H,3\text{-let}}$
	$(3,0)$	c: $(\psi_{DM}H)=2$	$\mathcal{O}^{1L,c}_{H,3\text{-let}}$
	$(3,0)$	d: $(\psi_{DM}H)=4$	$\mathcal{O}^{1L,d}_{H,3\text{-let}}$
	$(3,0)$	e: $(\bar{L}\psi_{DM})=2$	$\mathcal{O}^{1L,e}_{H,3\text{-let}}$
	$(3,0)$	f: $(\bar{L}\psi_{DM})=4$	$\mathcal{O}^{1L,f}_{H,3\text{-let}}$
	$(5,0)$		$\mathcal{O}^{1L}_{H,5\text{-let})}$
$\bar{L}\sigma_{\mu\nu}\psi_{DM}F_Y^{\mu\nu}\tilde{H}$	$(3,-2)$		$\mathcal{O}^{1Y}_{\tilde{H},3\text{-let}}$
$\bar{L}\sigma_{\mu\nu}\psi_{DM}F_L^{\mu\nu}\tilde{H}$	$(3,-2)$	b: $(\bar{L}\tilde{H})=3$	$\mathcal{O}^{1L,b}_{\tilde{H},3\text{-let}}$
	$(3,-2)$	c: $(\psi_{DM}\tilde{H})=2$	$\mathcal{O}^{1L,c}_{\tilde{H},3\text{-let}}$
	$(3,-2)$	d: $(\psi_{DM}\tilde{H})=4$	$\mathcal{O}^{1L,d}_{\tilde{H},3\text{-let}}$
	$(3,-2)$	e: $(\bar{L}\psi_{DM})=2$	$\mathcal{O}^{1L,e}_{\tilde{H},3\text{-let}}$
	$(3,-2)$	f: $(\bar{L}\psi_{DM})=4$	$\mathcal{O}^{1L,f}_{\tilde{H},3\text{-let}}$
	$(5,-2)$		$\mathcal{O}^{1L}_{\tilde{H},5\text{-let}}$
$D_\mu\bar{L}\gamma_\nu\psi_{DM}F_Y^{\mu\nu}$	$(2,-1)$		$\mathcal{O}^{2Y}_{2\text{-let}}$
$D_\mu\bar{L}\gamma_\nu\psi_{DM}F_L^{\mu\nu}$	$(2,-1)$		$\mathcal{O}^{2L}_{2\text{-let}}$
	$(4,-1)$		$\mathcal{O}^{2L}_{4\text{-let}}$
$\bar{L}\gamma_\mu D_\nu\psi_{DM}F_Y^{\mu\nu}$	$(2,-1)$		$\mathcal{O}^{3Y}_{2\text{-let}}$
$\bar{L}\gamma_\mu D_\nu\psi_{DM}F_L^{\mu\nu}$	$(2,-1)$		$\mathcal{O}^{3L}_{2\text{-let}}$
	$(4,-1)$		$\mathcal{O}^{3L}_{4\text{-let}}$

full list of operators up to quintuplet

⇒ ν-line and γ-line correlated:

- same energy
- ratio of line intensities fixed by operator
- associated flux of cosmic rays fixed by operator and around the corner

for other decay channel operators see also Feldstein, Kusenko, Matsumoto, Yanagida, 13'

DM annihilation: experimental sensitivity reachable??

for the annihilation case: possibilities to have an observable flux!

remember the 2 issues:

- ν-line sensitivity much weaker than γ-line sensitivity

  not necessarily a problem because ν-line can proceed easily at tree level unlike γ-line

- ν-line sensitivity on $\sigma_{DM\,DM\rightarrow\nu\bar{\nu}}$ doesn't reach the thermal freeze out total cross section value $\langle\sigma v\rangle_{Tot}\sim 3\cdot 10^{-26}$

  this excludes an observable ν-line for many models but not necessarily: 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

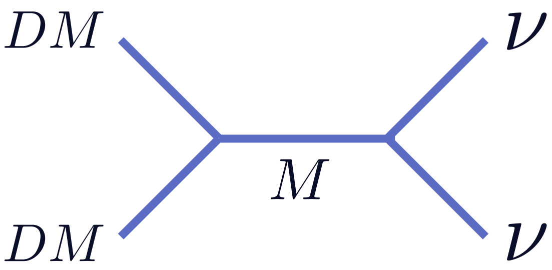
Determination of minimal models leading to observable ν-line from DM annihilation

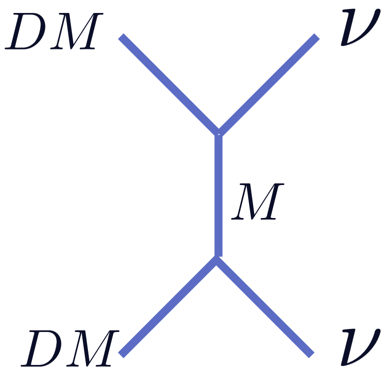
El Aisati, Garcia-Cely, TH, Vanderheyden 17

↪ 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 from DM annihilation through the Sommerfeld effect????

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

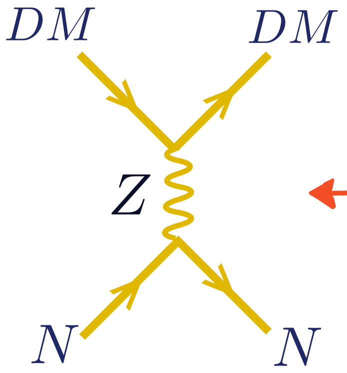
many constraints:

- constraint 2: direct detection constraint:

big issue for DM multiplet with non-zero hypercharge

$\Downarrow$

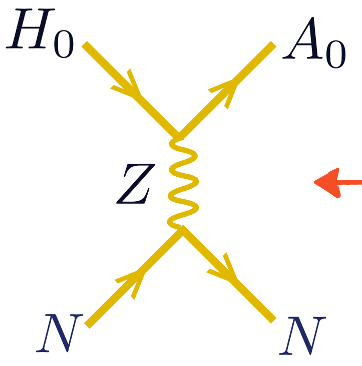
need to split in mass the neutral components of the DM multiplet



far too large

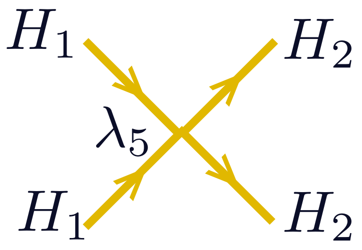
example: DM is neutral component of scalar doublet: ``inert'' doublet

$$H_2 = \begin{pmatrix} H^+ \\ \frac{H_0 + iA_0}{\sqrt{2}} \end{pmatrix}$$



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

possible from λ_5 interaction



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

s-wave + direct detection surviving models

20 models:

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 $v_{\mathrm{EW}}/m_{\mathrm{DM}}$?	$\ell^+\ell^-$	Model
$\overline{\mathrm{DM}}\mathrm{DM} \to \bar{\nu}\nu$	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
$\mathrm{DMDM} \to \nu\nu$	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

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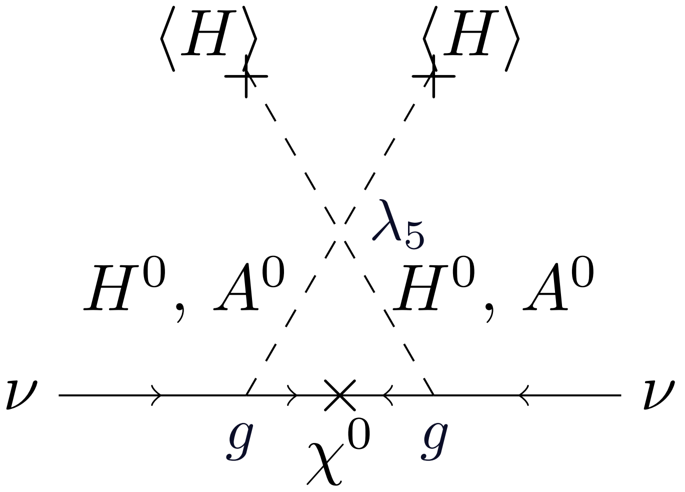
See also related table in Lindner, Merle, Niro '10

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

$\Downarrow$

constraint 3:

example: inert doublet DM:



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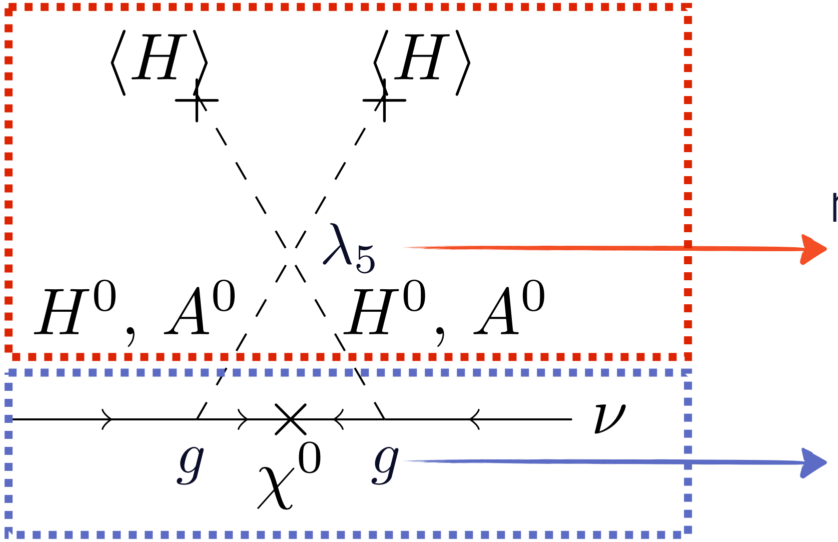

minimum value from direct detection constraint

minimum value to get an observable ν-line

$\Downarrow$

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

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s-wave + direct detection + ν mass surviving models

8 models:

DM and mediator up to triplets

Annihilation Channel	DM		Mediator		m_ν OK at 1-loop?	Suppressed by $v_{\mathrm{EW}}/m_{\mathrm{DM}}$?	$\ell^+\ell^-$	Model
$\overline{\mathrm{DM}}\mathrm{DM} \to \bar{\nu}\nu$	Dirac	T_0	s-chann. vector	S	Yes	No	=	F_1
		T_0	t-chann. scalar	D				F_2
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		S	t-chann. scalar	D				F_4
$\mathrm{DMDM} \to \nu\nu$	Real Scalar	D	s-chann. scalar	T_2	±	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	±	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

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

$$\Phi_{\nu\bar{\nu}} = \Phi_{l^+l^-}$$

constraint 4

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

constraint 5

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

constraint 6

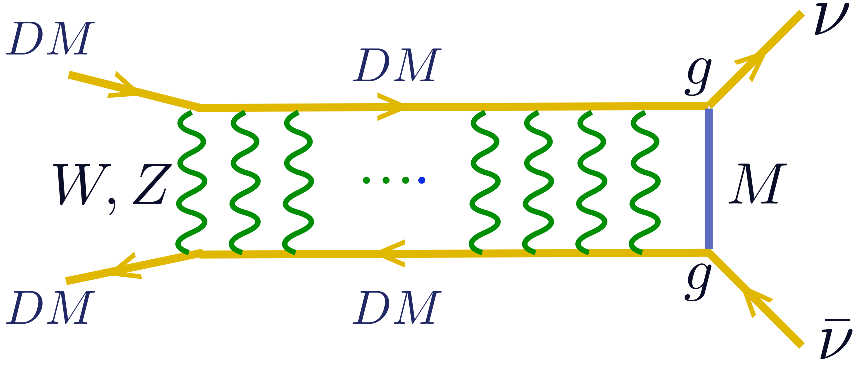
ν-line cross section results including Sommerfeld effect

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

⇓

Sommerfeld for free and known: E-W interactions

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



⇓

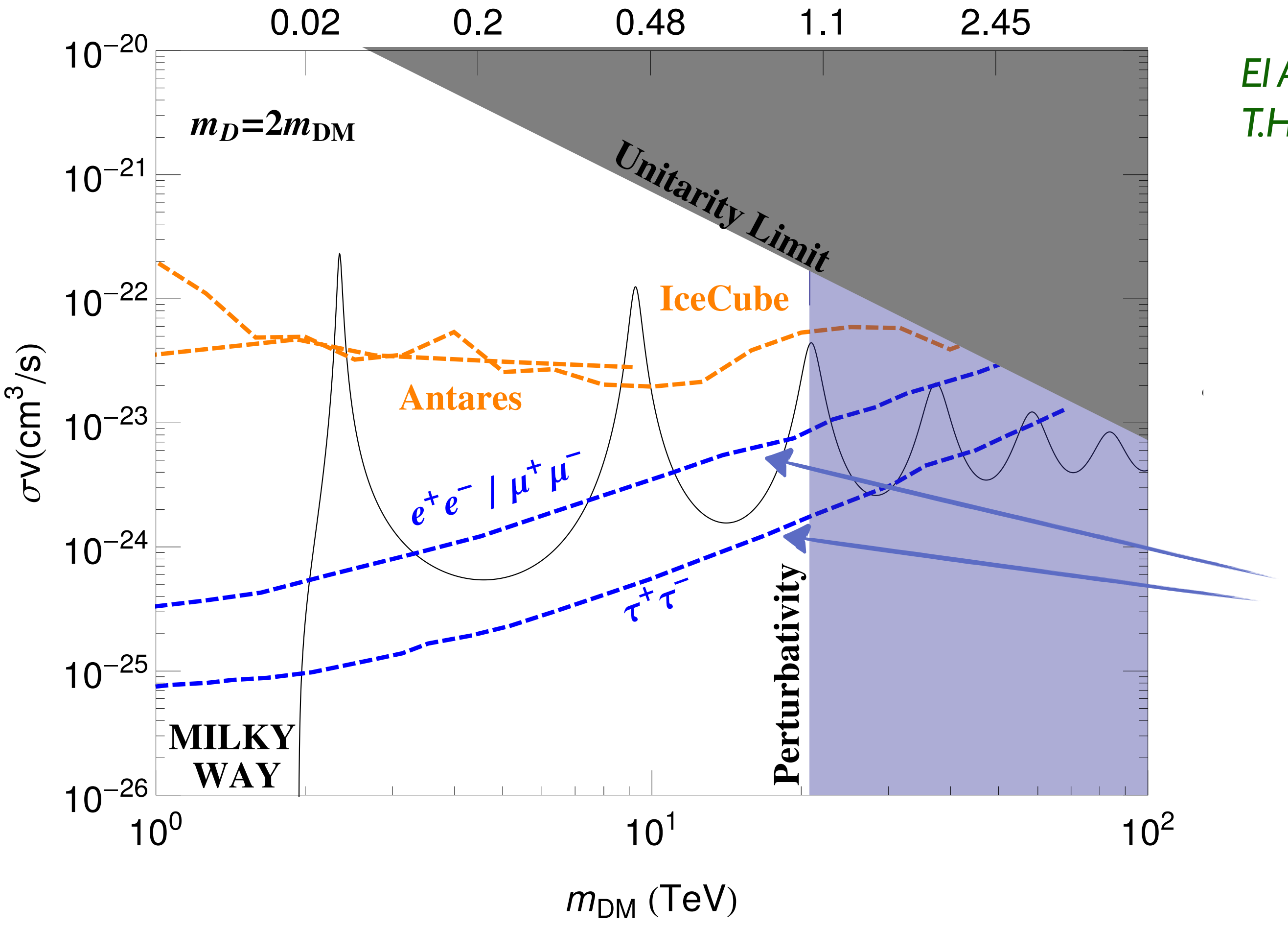
ν-line is predicted as a function of
m_{DM} and $DM-Med-\nu$ coupling g

⇑

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



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$\Phi_{\nu\bar{\nu}} = \Phi_{l^+l^-}$

charged lepton
flux constraint

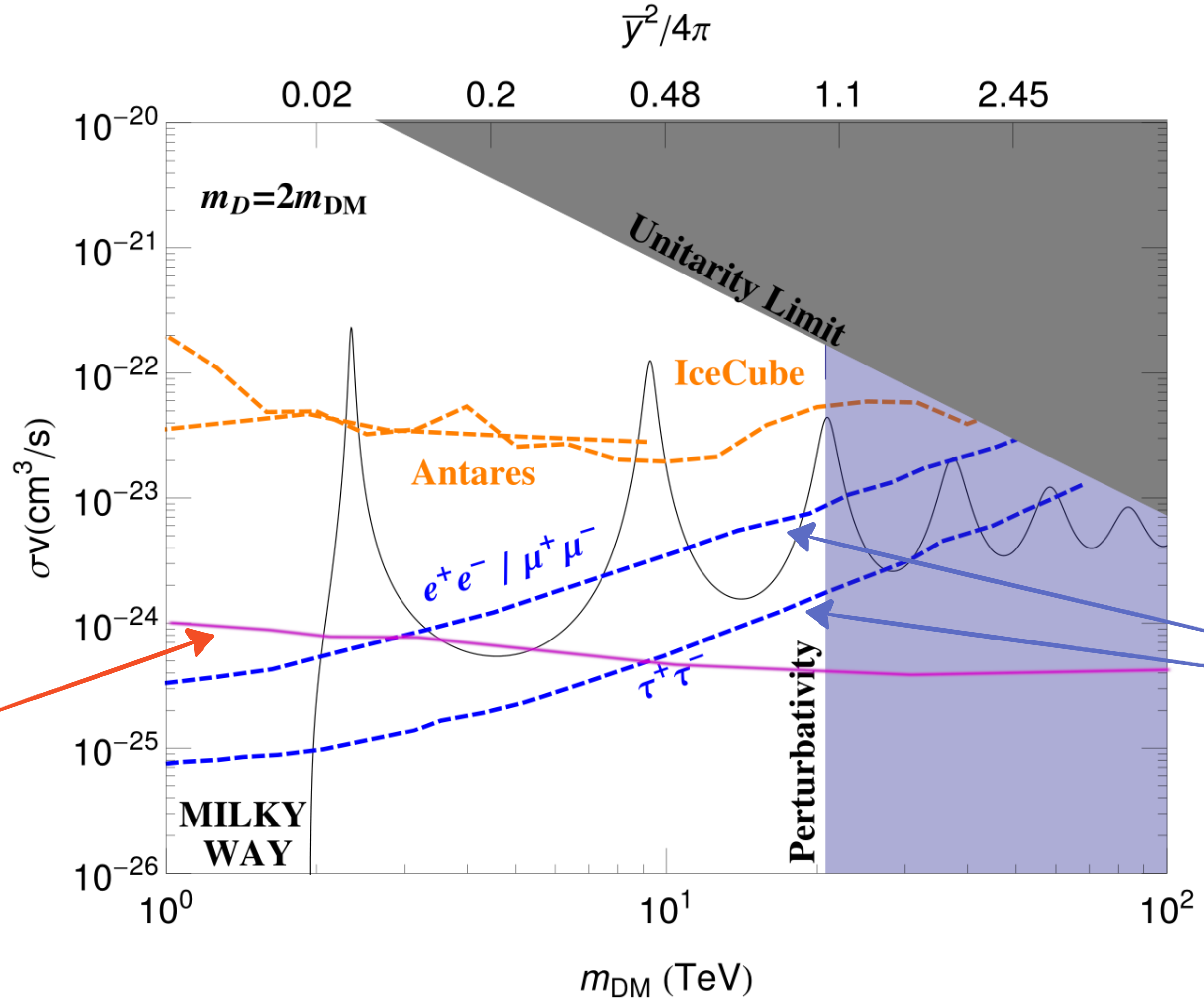
constraint 4

⇒ 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



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Antares 2017

$\Phi_{\nu\bar{\nu}} = \Phi_{l^+l^-}$

charged lepton flux constraint

constraint 4

⇒ 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 subheading in freeze-out

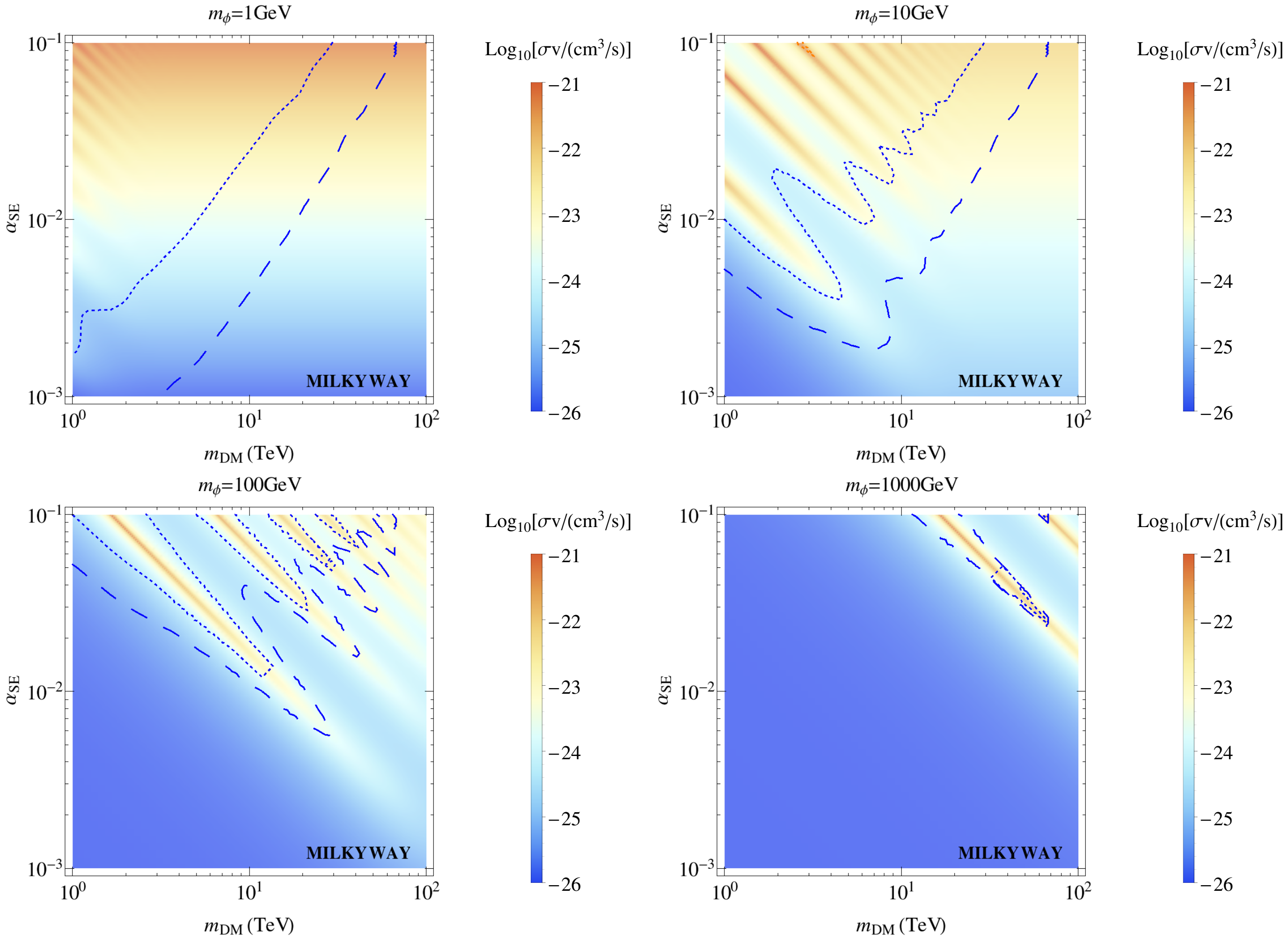
ν-line cross section results including Sommerfeld effect

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

Sommerfeld requires extra light BSM mediator

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

more freedom



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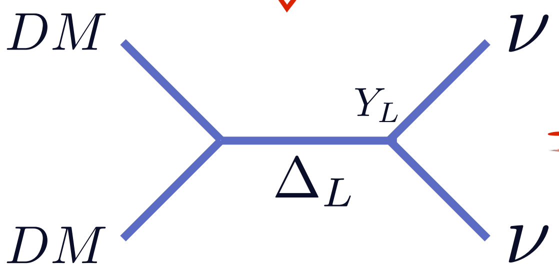
ν-line flavor composition

further possibility of model discrimination

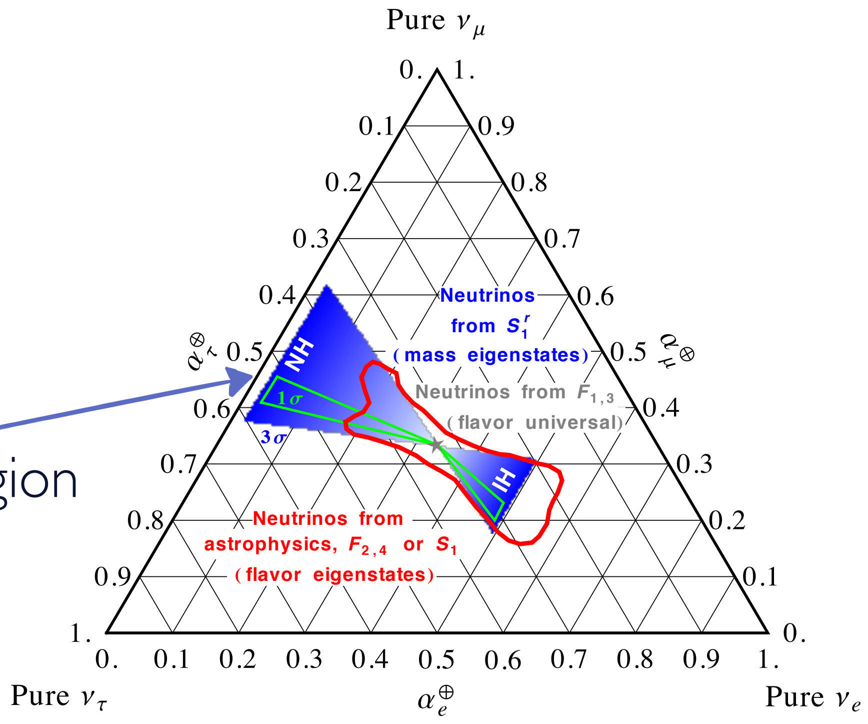
a type-II seesaw state Δ_L

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



⇒ neutrinos are produced as mass eigenstates

flavour flux composition outside oscillation region



Garcia-Cely, Heeck '16

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

DM annihilation: experimental sensitivity reachable??

→ longer term perspective:

it is not excluded anymore that in a not too long term the sensitivity reaches the thermal annihilation cross section value, in case no need for a Sommerfeld boost anymore ⇒ more models could give an observable ν-line

Summary

ν-telescope search for a line: many advantages with respect to other channels

↪ recent large improvement of sensitivity, expected to be still improved further soon!!

↪ DM decay case: - ν and γ line sensitivities of same order in multiTeV range

- many models could lead to observable ν-line including for interesting $DM \to \gamma + \nu$ scenario

↪ DM annihilation case: - ν-line sensitivity << γ-line sensitivity

- ν-line sensitivity doesn't reach freeze out value

↪ simple specific models leading to observable ν-line do exist thanks to Sommerfeld effect and can be studied in in a systematic way

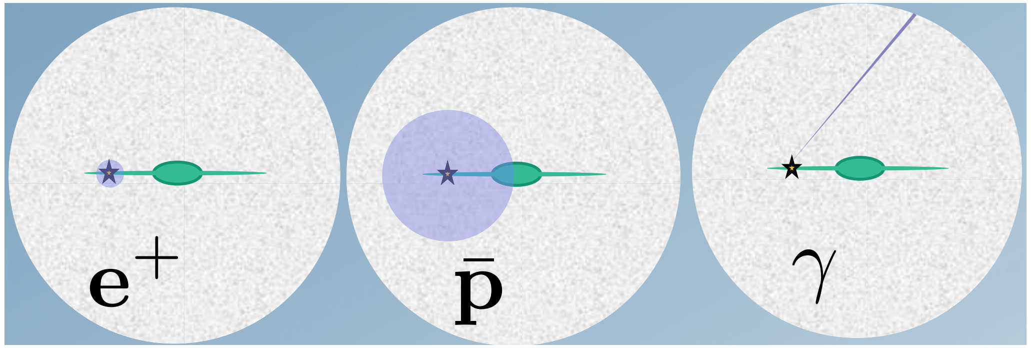
↪ possibilities of model discrimination from ν-line energy, intensity and flavor composition and associated diffuse cosmic ray emission

Monochromatic flux of γ : DM smoking gun

from DM annihilation or decay

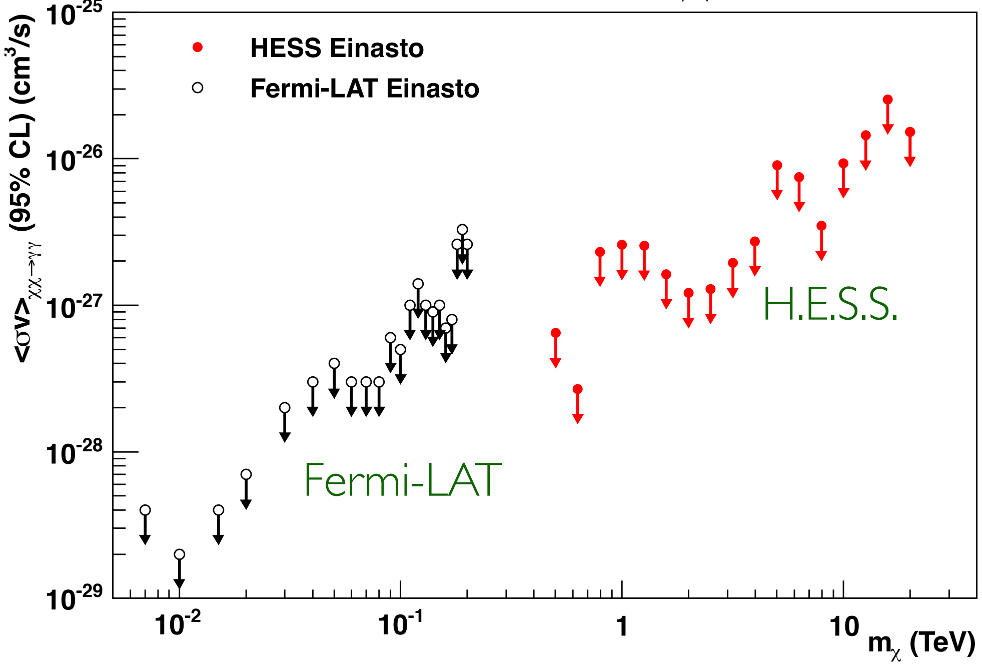
- no astrophysical background
- flux and direction basically unaffected during propagation
- very active experimental field: Fermi-LAT, HESS, CTA, Gamma400, Dampe, …

from Bergström, NJP 09



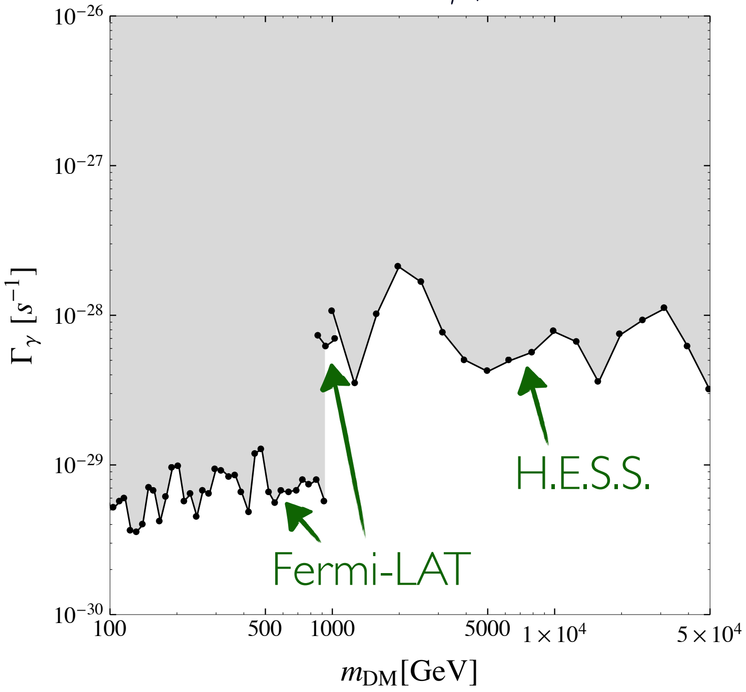
Annihilation cross section upper limit:

$\langle \sigma\, v\rangle_{DMDM\to\gamma\gamma}$



Decay width upper limit:

$\Gamma_{DM\to\gamma+X}$

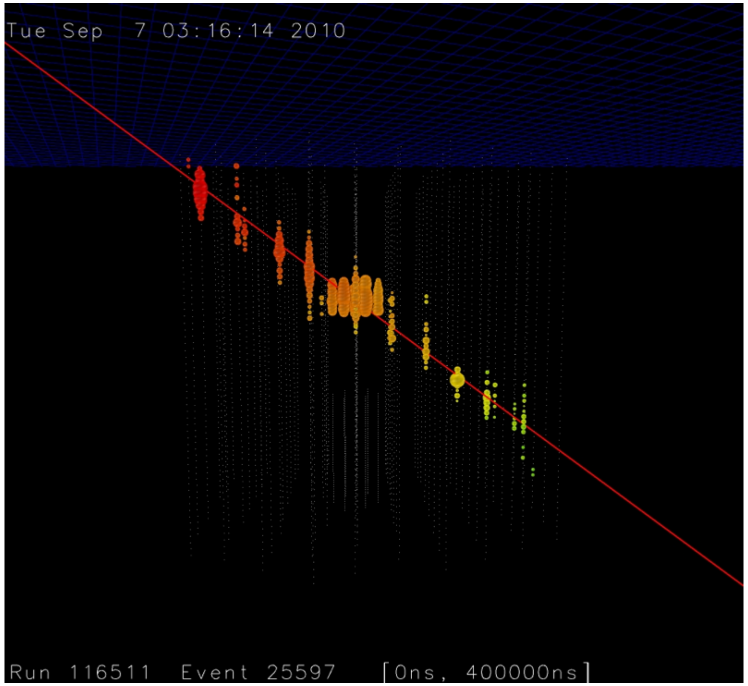


See also recent Hawc results

1301.1173

ν-line search from DM annihilation: need good energy resolution and good angular resolution towards galactic center

muon track:

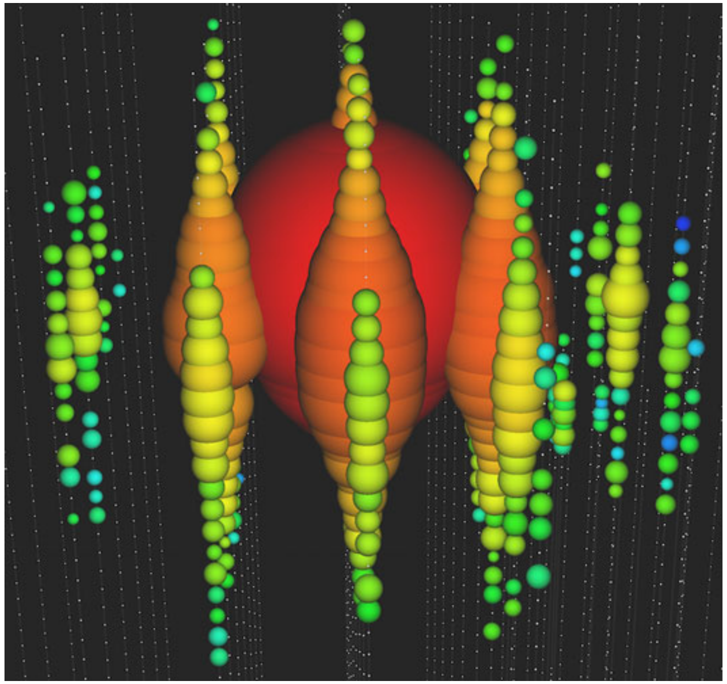


good angular resolut.: $\sim 0.2^\circ - 1^\circ$

poor energy resolut. unless fully contained

OK to see the galactic center for
starting inside events

cascade events:



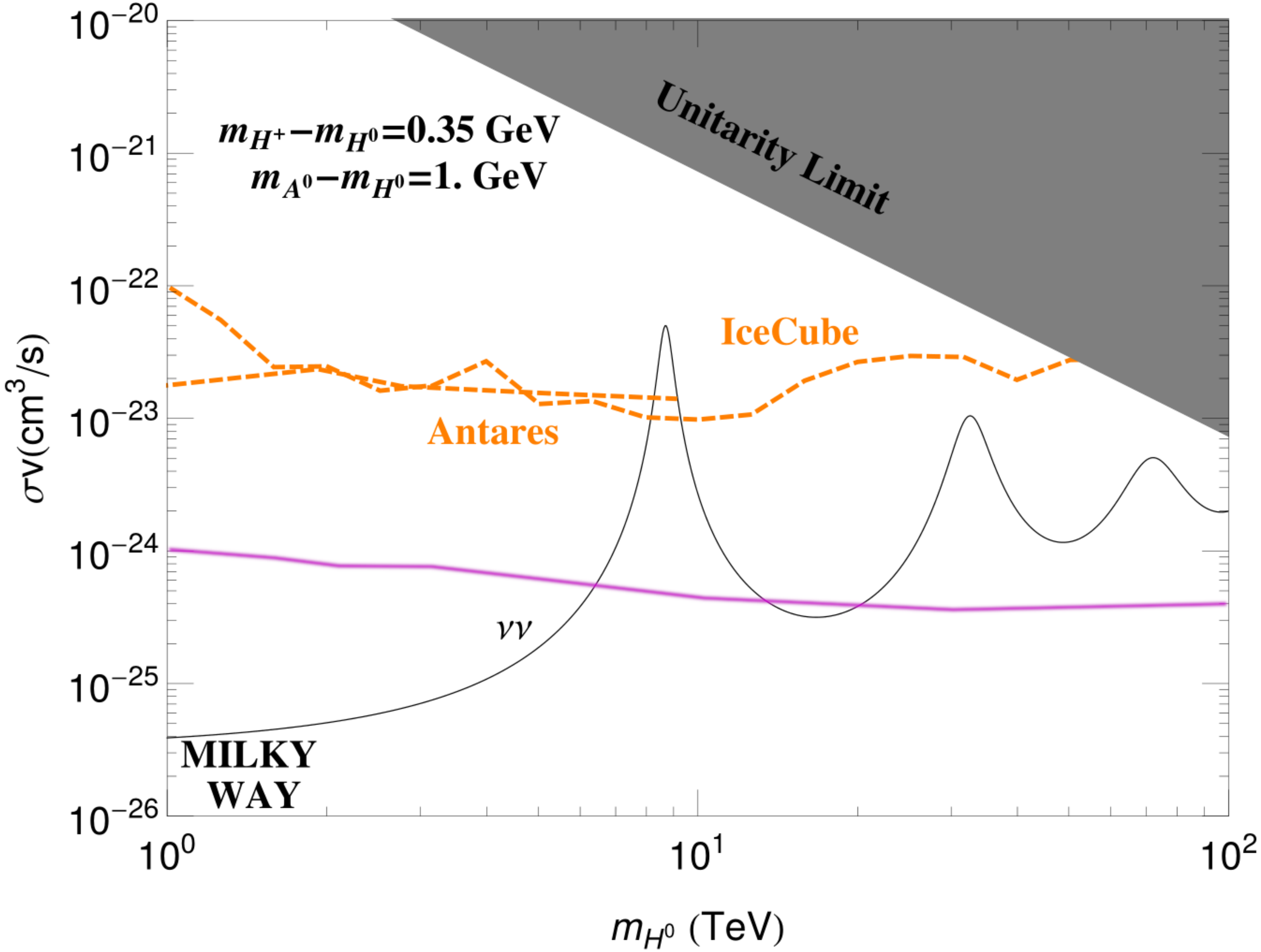
good energy resolut.: $\sim 15\%$

not so good ang. resol.: $\sim 10^\circ - 15^\circ$

good for galactic center events

$\Rightarrow$ very promising even if not as easy as for a decay and as for a γ-line

Model S_1^r



Unitarity Limit
$m_{H^+} - m_{H^0} = 0.35$ GeV
$m_{A^0} - m_{H^0} = 1.$ GeV
IceCube
Antares
$\nu\nu$
MILKY WAY
$\sigma v (\mathrm{cm}^3/\mathrm{s})$
m_{H^0} (TeV)
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^0
10^1
10^2

Decay bound from Icecube details

$DM \to \nu + X$: ν flux expected in detector for a given lifetime

Galactic component:

$$\frac{d\phi_h}{dE_\nu d\Omega}(b,l) = \underbrace{\frac{1}{4\pi\, m_{DM}\, \tau_{DM}}\frac{dN}{dE_\nu}}_{\text{particle physics factor}} \underbrace{\int_{l.o.s.} ds\, \rho_h[r(s,b,l)]}_{\text{galactic DM factor}}$$

NFW profile

Extragalactic component:

$$\frac{d\phi_{eg}}{dE_\nu d\Omega} = \underbrace{\frac{\Omega_{DM}\rho_c}{4\pi}\int dz\, \frac{c}{H(z)}}_{\text{cosmological factor}} \underbrace{\frac{1}{m_{DM}\tau_{DM}}\frac{dN}{dE}\Big|_{E=E_\nu(1+z)}}_{\text{particle physics factor}}$$

Flux in detector issues: flavor, ν vs $\bar{\nu}$, earth absorption, ...

- ν-oscillations: average ν flavor:

$$\begin{aligned} P(\nu_e \leftrightarrow \nu_e) &= 0.573, \quad & P(\nu_e \leftrightarrow \nu_\mu) &= 0.277 \\ P(\nu_e \leftrightarrow \nu_\tau) &= 0.150, \quad & P(\nu_\mu \leftrightarrow \nu_\mu) &= 0.348 \\ P(\nu_\mu \leftrightarrow \nu_\tau) &= 0.375, \quad & P(\nu_\tau \leftrightarrow \nu_\tau) &= 0.475 \end{aligned}$$

relatively small effect

results presented here are for democratic 1/3, 1/3, 1/3, $\nu + \bar{\nu}$ flux

- ν vs $\bar{\nu}$: relatively small effect too

- earth absorption effects.... taken into account

Number of events expected in detector for a given lifetime

↪ depends on instrument response for a given data sample

$\alpha = flavor\ index$

$$\frac{dN_\alpha}{dE_\nu d\Omega dE' d\cos\theta' d\phi'} = \underbrace{\frac{d(\phi_h + \phi_{eg})_\alpha}{dE_\nu d\Omega}}_{\text{theory flux}} \underbrace{\mathcal{E}_\alpha D_{eff,\alpha}}_{\text{instrument response:}}$$

↪ exposure:
$\mathcal{E}_\alpha = A_{eff,\alpha}(E_\nu, \theta) \times \Delta t$

↪ dispersion function:
$D^\alpha_{eff}(E', \theta', \phi'; E_\nu, \theta, \phi)$

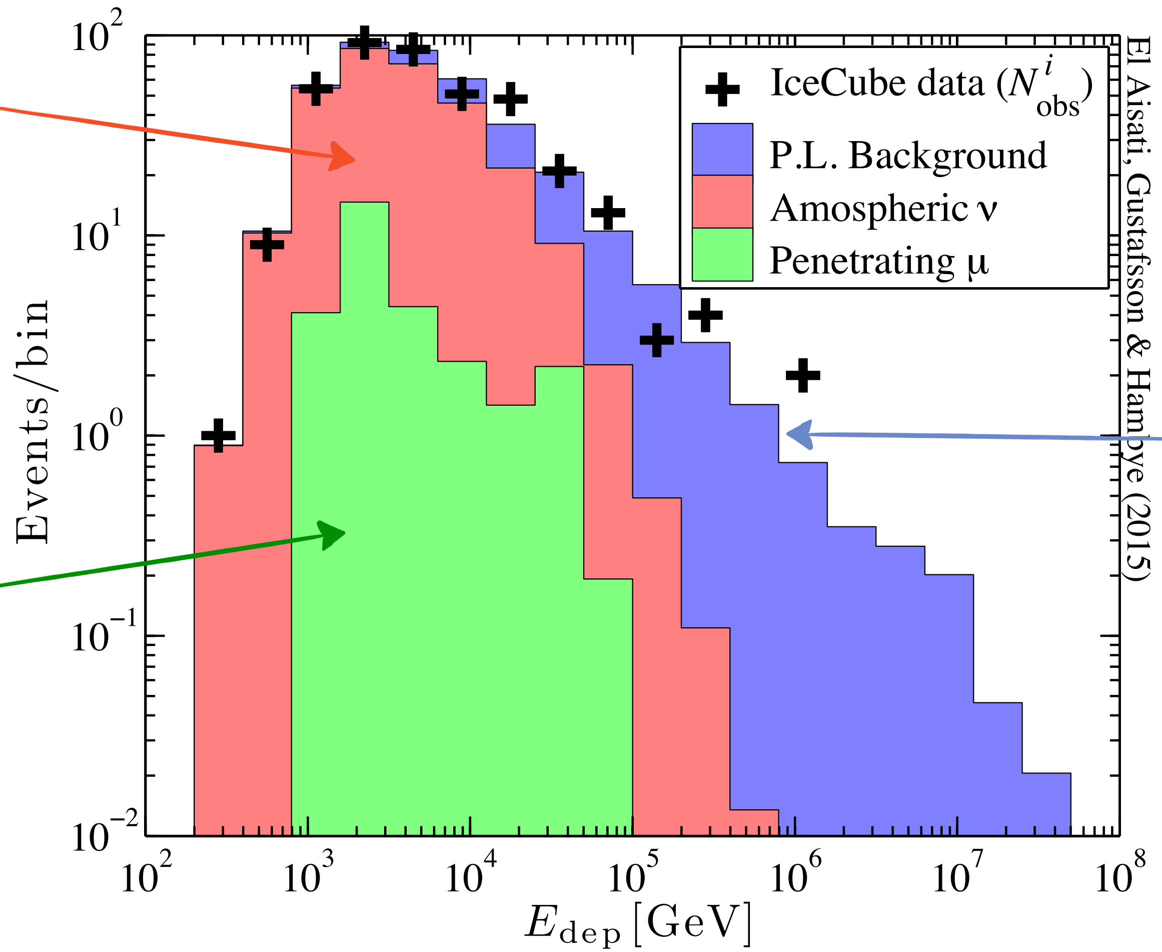
$$\Rightarrow N^i_{DM} = \int dE' \int d\cos\theta' \int d\phi' \int dE \int d\Omega \sum_{\alpha = e,\mu,\tau,\bar{e},\bar{\mu},\bar{\tau}} P_\alpha \frac{dN_\alpha}{dE_\nu d\Omega dE' d\cos\theta' d\phi'}$$

for a public 2010-2012 IceCube data sample
(78+8 strings, $100\ \mathrm{GeV} - 10^8\ \mathrm{GeV}$, 383 detected events)

Background

atmospheric neutrinos

penetrating muons



El Aisati, Gustafsson & Hampye (2015)

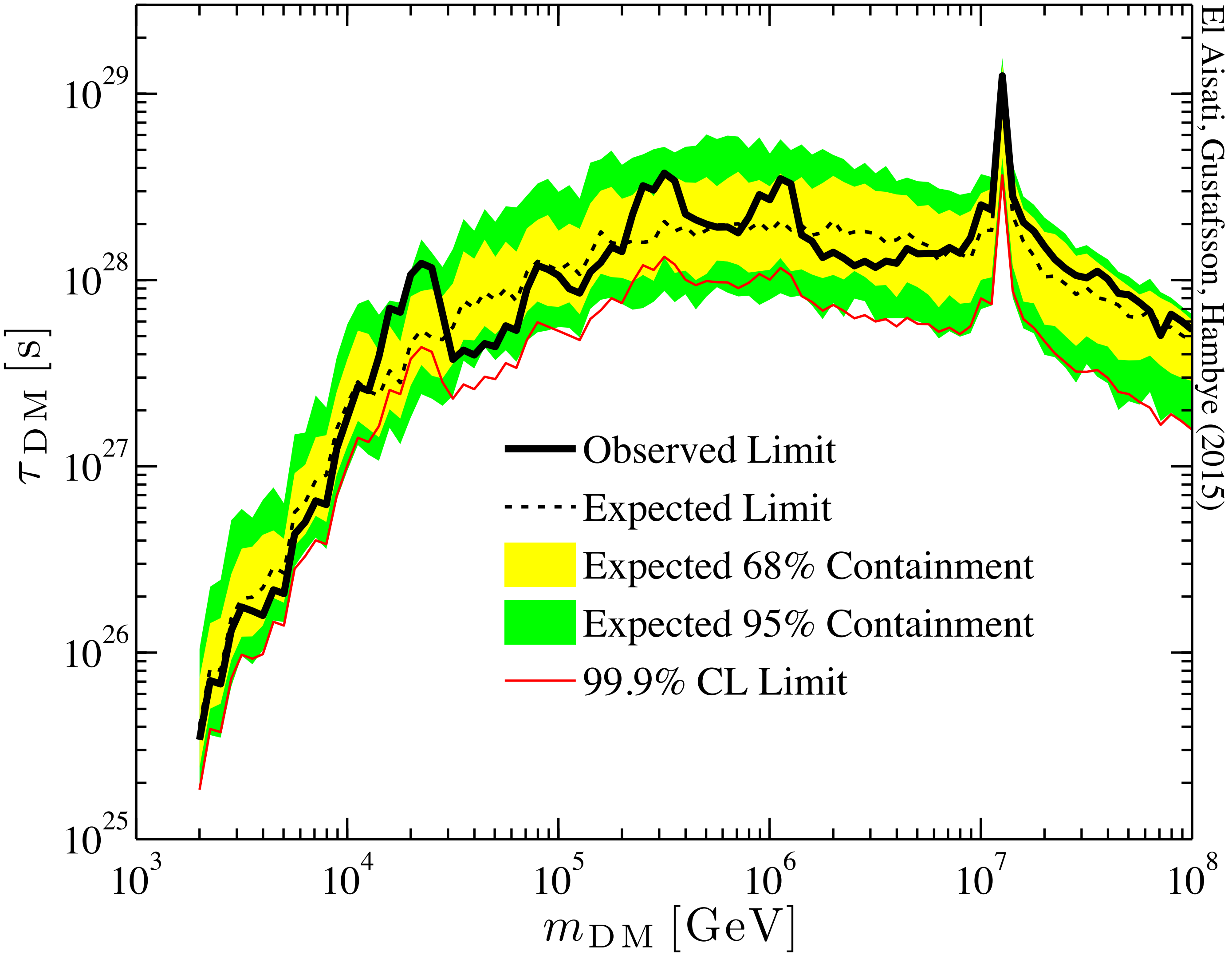
astrophysical neutrinos: we assume a power law with free power

$$\Rightarrow N^i_{tot} = n_{sig} N^i_{DM}(m_{DM}, \tau_{DM}) + n_1 N^i_{\mu} + n_2 N^i_{atm} + n_3 N^i_{astro}(\gamma)$$

free normalizations $n_{sig,1,2,3}$ and free power γ

⇒ statistical method: test statistic of profile likelihood ratio (as for Fermi γ-line)

Result: lower limit on lifetime

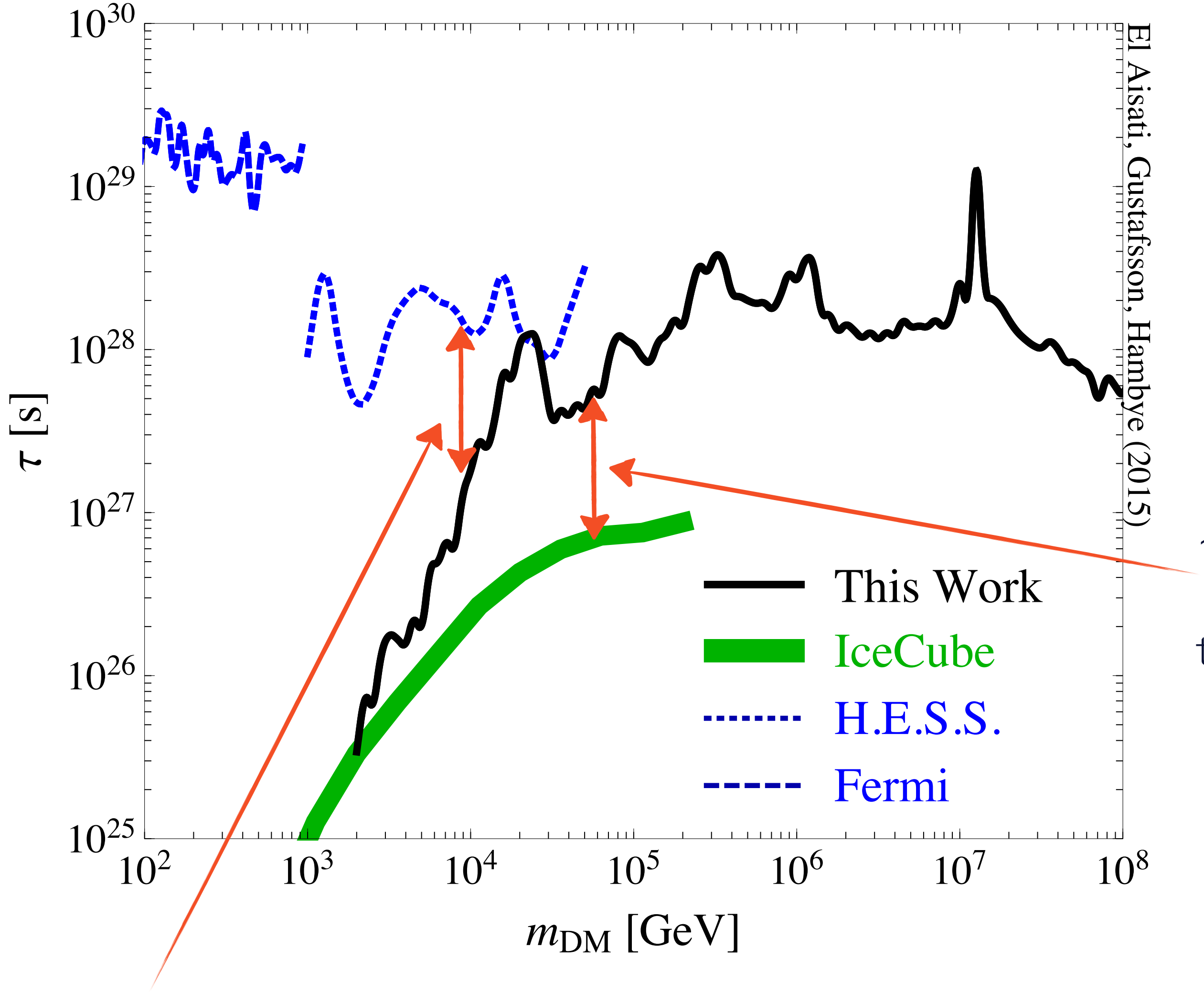


El Aisati, Gustafsson, Hambye (2015)

⇒ no evidence for a ν-line ← at most $1.5\,\sigma$ at $E \sim 40\,\mathrm{TeV}$

$m_{DM} \gtrsim 100\,\mathrm{TeV}$ bounds in Rott, Kohri, Park '14, Esmaili, Kang, Serpico '14 are similar

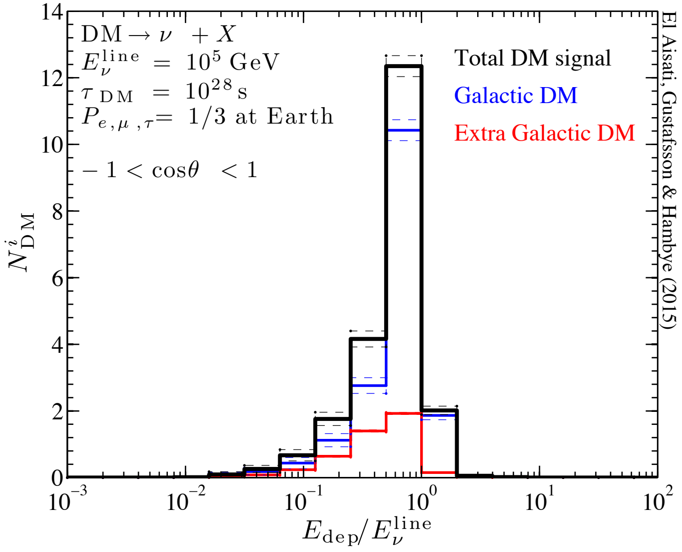
Comparison with previous limits and with γ-line limits



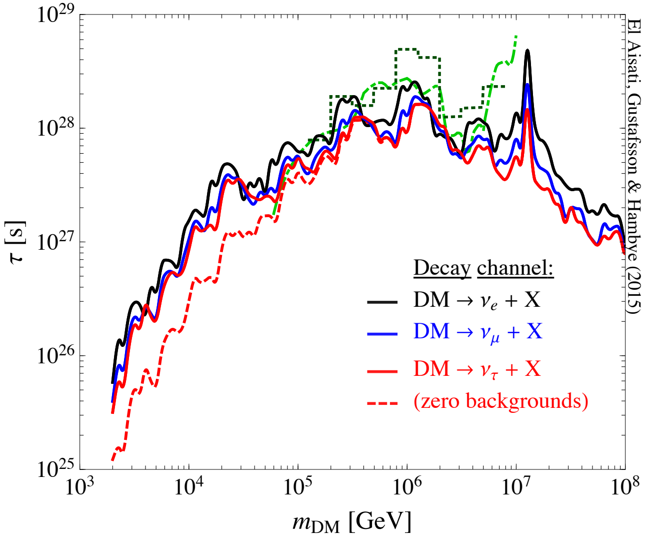
El Aisati, Gustafsson, Hambye (2015)

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

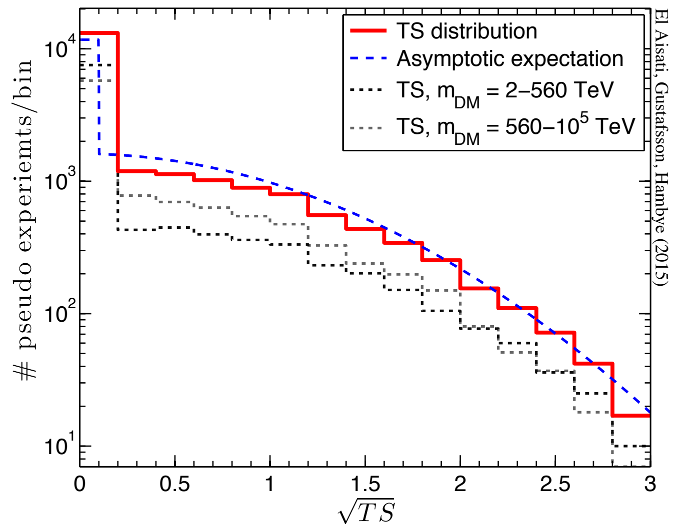
between few TeV and 50 TeV, γ and ν line sensitivities are similar! ← within a factor 1 to 20



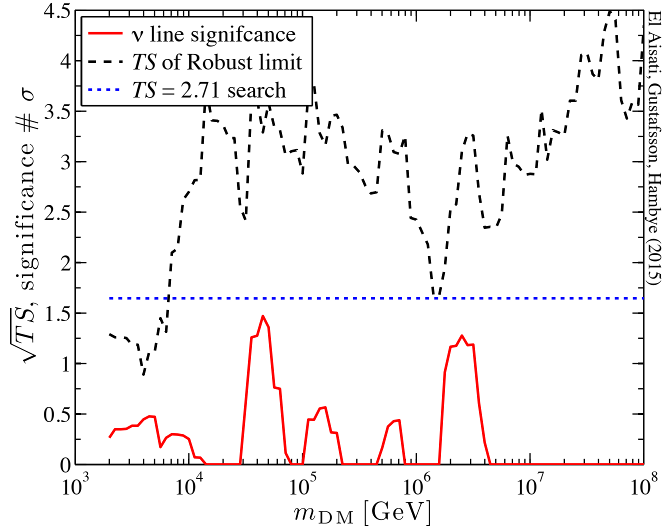
DM → ν + X
$E_\nu^{\rm line} = 10^5$ GeV
$\tau_{\rm DM} = 10^{28}$ s
$P_{e,\mu,\tau}$ = 1/3 at Earth
$-1 < \cos\theta < 1$
Total DM signal
Galactic DM
Extra Galactic DM
$N^i_{\rm DM}$
$E_{\rm dep}/E_\nu^{\rm line}$
0
2
4
6
8
10
12
14
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
El Aisati, Gustafsson & Hambye (2015)



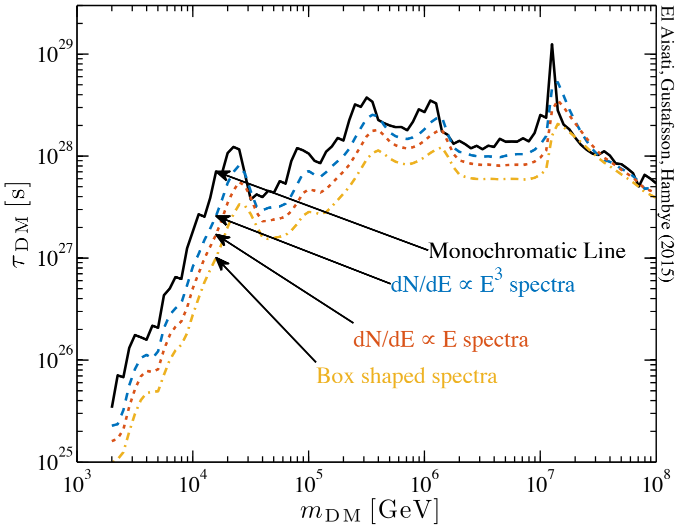
Decay channel:
DM → ν_e + X
DM → ν_μ + X
DM → ν_τ + X
(zero backgrounds)
τ [s]
$m_{\rm DM}$ [GeV]
10^{25}
10^{26}
10^{27}
10^{28}
10^{29}
10^3
10^4
10^5
10^6
10^7
10^8
El Aisati, Gustafsson & Hambye (2015)



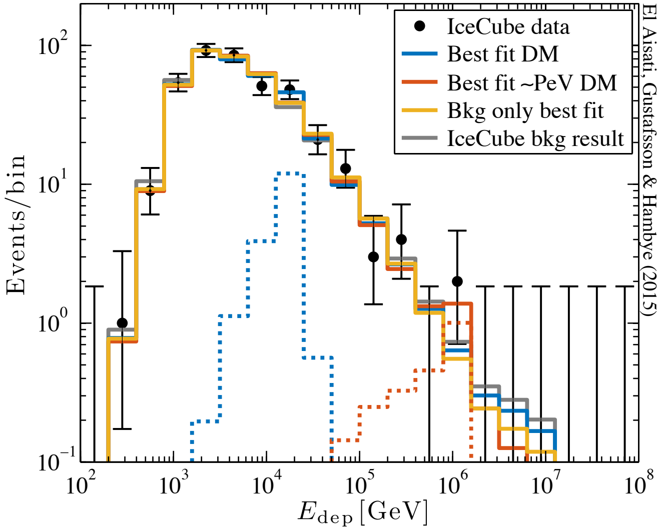
TS distribution
Asymptotic expectation
TS, $m_{\rm DM}$ = 2–560 TeV
TS, $m_{\rm DM}$ = 560–10^5 TeV
pseudo experiemts/bin
$\sqrt{TS}$
10^1
10^2
10^3
10^4
0
0.5
1
1.5
2
2.5
3
El Aisati, Gustafsson & Hambye (2015)



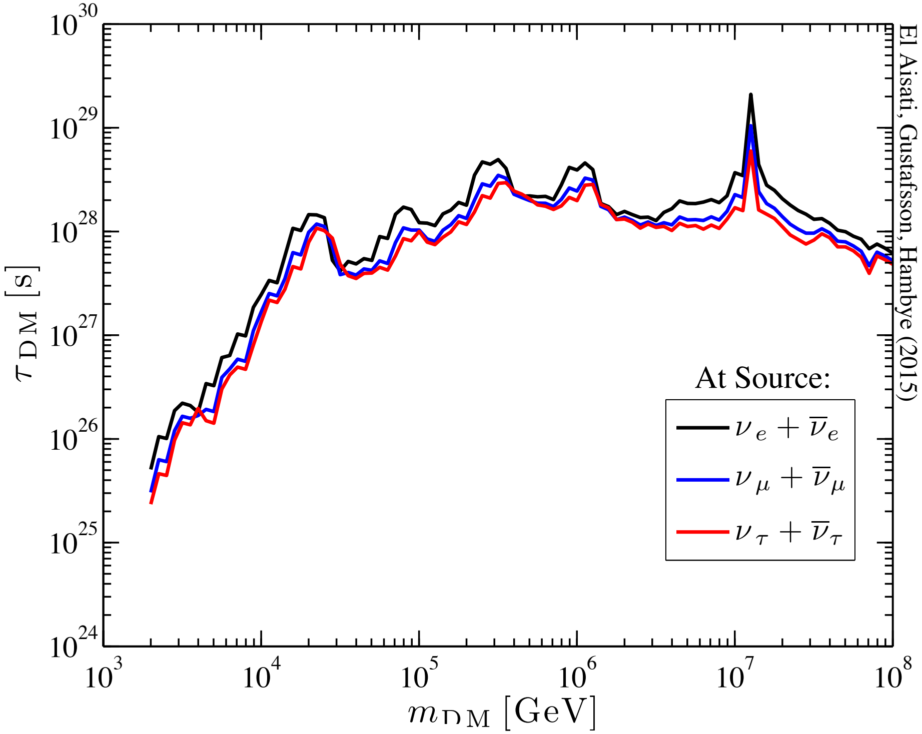
ν line signifcance
TS of Robust limit
TS = 2.71 search
$\sqrt{TS}$, significance # σ
$m_{\rm DM}$ [GeV]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
10^3
10^4
10^5
10^6
10^7
10^8
El Aisati, Gustafsson, Hambye (2015)

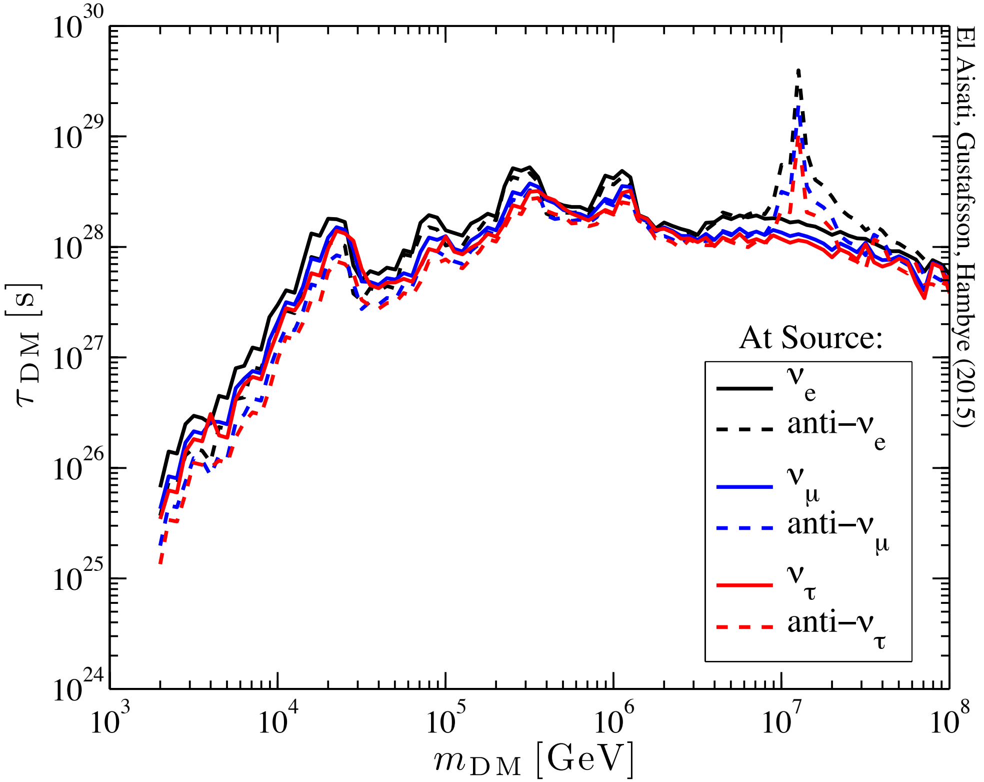


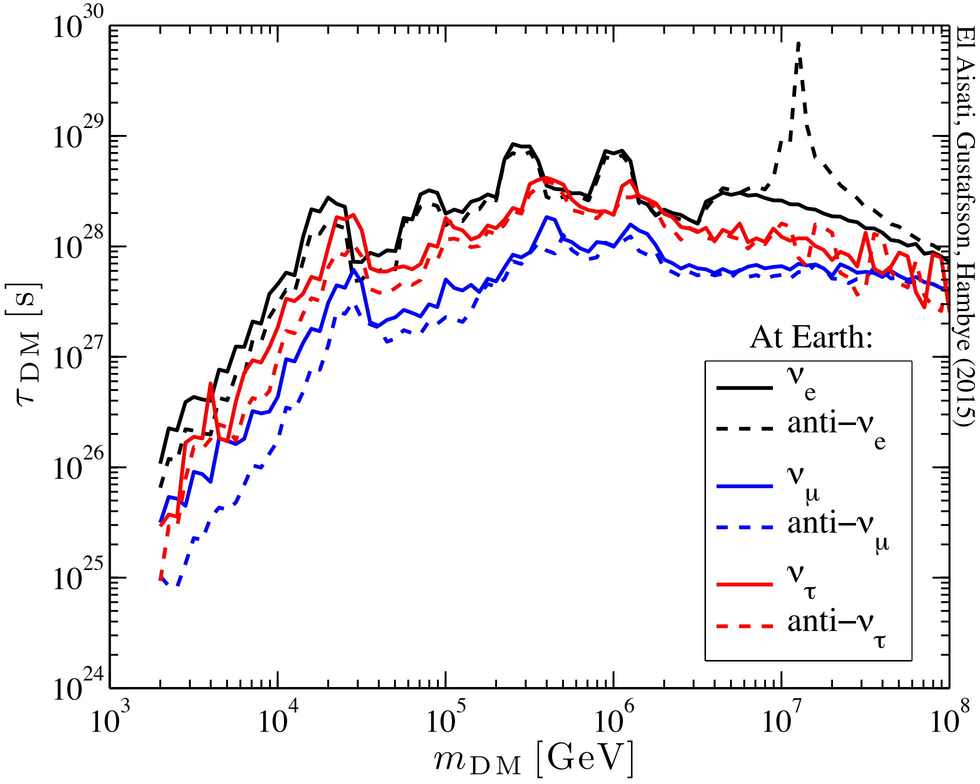
Monochromatic Line
dN/dE ∝ E^3 spectra
dN/dE ∝ E spectra
Box shaped spectra
$\tau_{\rm DM}$ [s]
$m_{\rm DM}$ [GeV]
10^{25}
10^{26}
10^{27}
10^{28}
10^{29}
10^3
10^4
10^5
10^6
10^7
10^8
El Aisati, Gustafsson, Hambye (2015)



IceCube data
Best fit DM
Best fit ~PeV DM
Bkg only best fit
IceCube bkg result
Events/bin
$E_{\rm dep}$ [GeV]
10^{-1}
10^0
10^1
10^2
10^2
10^3
10^4
10^5
10^6
10^7
10^8
El Aisati, Gustafsson & Hambye (2015)


10^{30}
10^{29}
10^{28}
10^{27}
10^{26}
10^{25}
10^{24}
$\tau_{\rm DM}$ [s]
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
$m_{\rm DM}$ [GeV]
At Source:
$\nu_e + \overline{\nu}_e$
$\nu_\mu + \overline{\nu}_\mu$
$\nu_\tau + \overline{\nu}_\tau$
El Aisati, Gustafsson, Hambye (2015)


10^{30}
10^{29}
10^{28}
10^{27}
10^{26}
10^{25}
10^{24}
$\tau_{\rm DM}$ [s]
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
$m_{\rm DM}$ [GeV]
At Source:
ν_e
anti−ν_e
ν_μ
anti−ν_μ
ν_τ
anti−ν_τ
El Aisati, Gustafsson, Hambye (2015)


10^{30}
10^{29}
10^{28}
10^{27}
10^{26}
10^{25}
10^{24}
$\tau_{\rm DM}$ [s]
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
$m_{\rm DM}$ [GeV]
At Earth:
ν_e
anti−ν_e
ν_μ
anti−ν_μ
ν_τ
anti−ν_τ
El Aisati, Gustafsson, Hambye (2015)

Double smoking gun scenario: details

Systematic study of $DM \to \nu + \gamma$ double smoking gun scenario: EFT

a 2-body radiative decay of a neutral particle is anyway given by non-renormalizable interactions

→ very slow decay: could be natural if the mediator inducing it is heavy, similar to proton case

→ stability due to accidental symmetry

a dim-6 operator mediated by GUT scale gives: $\tau_{DM} \sim 10^{28}$ sec

$$\mathcal{L}_{eff} = \sum_i \frac{c_i^{dim-5}}{\Lambda_{UV}} \mathcal{O}_i^{dim-5} + \sum_i \frac{c_i^{dim-6}}{\Lambda_{UV}^2} \mathcal{O}_i^{dim-6} + \ldots$$

→ very few operators: one dim-5 structure: $\mathcal{O}^{(5)Y} \equiv \bar{L}\sigma_{\mu\nu}\psi_{DM}F_Y^{\mu\nu}$,

$$\mathcal{O}^{(5)L} \equiv \bar{L}\sigma_{\mu\nu}\psi_{DM}F_L^{\mu\nu},$$

3 dim-6 structure: $\mathcal{O}^{1Y} \equiv \bar{L}\sigma_{\mu\nu}\psi_{DM}F_Y^{\mu\nu}\phi$,

$$\mathcal{O}^{1L} \equiv \bar{L}\sigma_{\mu\nu}\psi_{DM}F_L^{\mu\nu}\phi,$$

$$\mathcal{O}^{2Y} \equiv D_\mu\bar{L}\gamma_\nu\psi_{DM}F_Y^{\mu\nu},$$

$$\mathcal{O}^{2L} \equiv D_\mu\bar{L}\gamma_\nu\psi_{DM}F_L^{\mu\nu},$$

$$\mathcal{O}^{3Y} \equiv \bar{L}\gamma_\mu D_\nu\psi_{DM}F_Y^{\mu\nu},$$

$$\mathcal{O}^{3L} \equiv \bar{L}\gamma_\mu D_\nu\psi_{DM}F_L^{\mu\nu},$$

Systematic study of $DM \to \nu + \gamma$ double smoking gun scenario: EFT

taking into account possible DM quantum numbers DM can be a singlet, doublet, triplet, quadruplet or quintuplet (with $\phi = H$ or $\bar{H}$)

Operator Structure	DM field (n-*plet*, Y)	Fields contract. (n-*plet*)	*Operator*
$\bar{L}\sigma_{\mu\nu}\psi_{DM}F_Y^{\mu\nu}$	$(2,-1)$		$\mathcal{O}^{(5)Y}_{2\text{-let}}$
$\bar{L}\sigma_{\mu\nu}\psi_{DM}F_L^{\mu\nu}$	$(2,-1)$		$\mathcal{O}^{(5)L}_{2\text{-let}}$
	$(4,-1)$		$\mathcal{O}^{(5)L}_{4\text{-let}}$
$\bar{L}\sigma_{\mu\nu}\psi_{DM}F_Y^{\mu\nu}H$	$(1,0)$		$\mathcal{O}^{1Y}_{H,1\text{-let}}$
	$(3,0)$		$\mathcal{O}^{1Y}_{H,3\text{-let}}$
$\bar{L}\sigma_{\mu\nu}\psi_{DM}F_L^{\mu\nu}H$	$(1,0)$		$\mathcal{O}^{1L}_{H,1\text{-let}}$
	$(3,0)$	a: $(\bar{L}H) = 1$	$\mathcal{O}^{1L,a}_{H,3\text{-let}}$
	$(3,0)$	c: $(\psi_{DM}H) = 2$	$\mathcal{O}^{1L,c}_{H,3\text{-let}}$
	$(3,0)$	d: $(\psi_{DM}H) = 4$	$\mathcal{O}^{1L,d}_{H,3\text{-let}}$
	$(3,0)$	e: $(\bar{L}\psi_{DM}) = 2$	$\mathcal{O}^{1L,e}_{H,3\text{-let}}$
	$(3,0)$	f: $(\bar{L}\psi_{DM}) = 4$	$\mathcal{O}^{1L,f}_{H,3\text{-let}}$
	$(5,0)$		$\mathcal{O}^{1L}_{H,5\text{-let)}}$
$\bar{L}\sigma_{\mu\nu}\psi_{DM}F_Y^{\mu\nu}\tilde{H}$	$(3,-2)$		$\mathcal{O}^{1Y}_{\tilde{H},3\text{-let}}$
$\bar{L}\sigma_{\mu\nu}\psi_{DM}F_L^{\mu\nu}\tilde{H}$	$(3,-2)$	b: $(\bar{L}\tilde{H}) = 3$	$\mathcal{O}^{1L,b}_{\tilde{H},3\text{-let}}$
	$(3,-2)$	c: $(\psi_{DM}\tilde{H}) = 2$	$\mathcal{O}^{1L,c}_{\tilde{H},3\text{-let}}$
	$(3,-2)$	d: $(\psi_{DM}\tilde{H}) = 4$	$\mathcal{O}^{1L,d}_{\tilde{H},3\text{-let}}$
	$(3,-2)$	e: $(\bar{L}\psi_{DM}) = 2$	$\mathcal{O}^{1L,e}_{\tilde{H},3\text{-let}}$
	$(3,-2)$	f: $(\bar{L}\psi_{DM}) = 4$	$\mathcal{O}^{1L,f}_{\tilde{H},3\text{-let}}$
	$(5,-2)$		$\mathcal{O}^{1L}_{\tilde{H},5\text{-let}}$
$D_\mu\bar{L}\gamma_\nu\psi_{DM}F_Y^{\mu\nu}$	$(2,-1)$		$\mathcal{O}^{2Y}_{2\text{-let}}$
$D_\mu\bar{L}\gamma_\nu\psi_{DM}F_L^{\mu\nu}$	$(2,-1)$		$\mathcal{O}^{2L}_{2\text{-let}}$
	$(4,-1)$		$\mathcal{O}^{2L}_{4\text{-let}}$
$\bar{L}\gamma_\mu D_\nu\psi_{DM}F_Y^{\mu\nu}$	$(2,-1)$		$\mathcal{O}^{3Y}_{2\text{-let}}$
$\bar{L}\gamma_\mu D_\nu\psi_{DM}F_L^{\mu\nu}$	$(2,-1)$		$\mathcal{O}^{3L}_{2\text{-let}}$
	$(4,-1)$		$\mathcal{O}^{3L}_{4\text{-let}}$

Operator predictions: line energies and intensities

I) same line energies

II) correlated line intensities: more ν than γ

↳ gauge invariance: $F^{Y}_{\mu\nu}$ or $F^{L}_{\mu\nu}$ ⇒ $DM \to \nu\gamma,\, \nu Z,\, lW$

if operator has a $F^{Y}_{\mu\nu}$ and $m_{DM} >> m_Z$: $\frac{n_\nu}{n_\gamma} = \frac{1}{\cos^2\theta_W} = 1.3$

if operator has a $F^{L}_{\mu\nu}$ and $m_{DM} >> m_Z$: $\frac{n_\nu}{n_\gamma} = \frac{1}{\sin^2\theta_W} = 4.3$

if combination of operators: $\frac{n_\nu}{n_\gamma} \geq 1$ and of order 1 unless tuning

Operator predictions: additional continuum fluxes of cosmic rays

Z, W, l produce $\bar{p}$, γ_D, $e^{\pm}$, ...

It turns out that all operators can give only 5 possible line intensity to CR number ratios

operators with a $F^{Y}_{\mu\nu}$:

$$A: \quad R_{\gamma/CR} = \cos^2\theta_W / (\sin^2\theta_W \cdot n_{CR/Z}),$$

only $DM \to \gamma\nu, Z\nu$ channels

operators with a $F^{L}_{\mu\nu}$:

$$C: \quad R_{\gamma/CR} = \sin^2\theta_W / (\cos^2\theta_W \cdot n_{CR/Z}),$$

$$D, E, F: \quad R_{\gamma/CR} = \frac{\sin^2\theta_W}{\cos^2\theta_W \cdot n_{CR/Z} + c_W \cdot (n_{CR/W^+l^-} + n_{CR/W^-l^+})}$$

$$c_W = \frac{1}{4}, 1, \frac{9}{4}$$

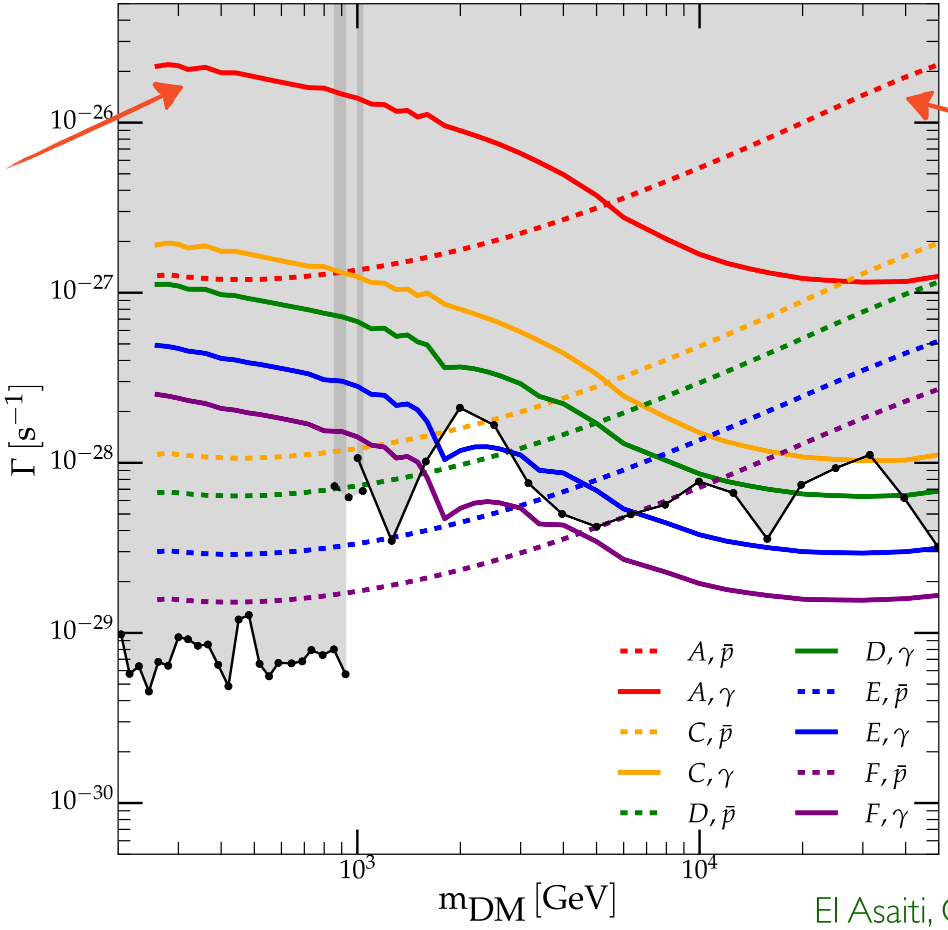
$DM \to \gamma\nu, Z\nu, Wl$ channels

DM field *n-plet,*	 *Y*	*Operator*	*Prediction* $R_{\nu/\gamma}$	 $R_{\gamma/CR}$
1	0	$\mathcal{O}_H^{1Y}$	1.3	A
		$\mathcal{O}_H^{1L}$	4.3	E
2	-1	$\mathcal{O}^{(5)Y}$, $\mathcal{O}^{2Y}$, $\mathcal{O}^{3Y}$	1.3	A
		$\mathcal{O}^{(5)L}$, $\mathcal{O}^{2L}$, $\mathcal{O}^{3L}$	4.3	E
3	0	$\mathcal{O}_H^{1Y}$	1.3	A
		$\mathcal{O}_H^{1L,a}$	4.3	C
		$\mathcal{O}_H^{1L,d}$, $\mathcal{O}_H^{1L,f}$	4.3	D
		$\mathcal{O}_H^{1L,c}$, $\mathcal{O}_H^{1L,e}$	4.3	E
3	-2	$\mathcal{O}_{\tilde{H}}^{1Y}$	1.3	A
		$\mathcal{O}_{\tilde{H}}^{1L,e}$	4.3	C
		$\mathcal{O}_{\tilde{H}}^{1L,b}$, $\mathcal{O}_{\tilde{H}}^{1L,d}$	4.3	D
		$\mathcal{O}_{\tilde{H}}^{1L,c}$	4.3	E
		$\mathcal{O}_{\tilde{H}}^{1L,f}$	4.3	F
4	-1	$\mathcal{O}^{(5)L}$, $\mathcal{O}^{2L}$, $\mathcal{O}^{3L}$	4.3	D
5	0	$\mathcal{O}_H^{1L}$	4.3	D
5	-2	$\mathcal{O}_{\tilde{H}}^{1L}$	4.3	D

Operator predictions: additional continuum fluxes of cosmic rays

upper bound on γ-line intensity from imposing that associated CR flux doesn't exceed observed ones

continuum flux
of γ constraint
(solid)



continuum flux
of $\bar{p}$ constraint
(dashed)

El Asaiti, Gustafsson, TH, Scarna 15

⇒ clear possibilities to have double monochromatic DM evidence + observation of associated CR excess!

Importance of 3-body decays for operators involving a scalar field

$$\mathcal{O}^{1Y} \equiv \bar{L}\sigma_{\mu\nu}\psi_{DM}F_Y^{\mu\nu}\phi,$$
$$\mathcal{O}^{1L} \equiv \bar{L}\sigma_{\mu\nu}\psi_{DM}F_L^{\mu\nu}\phi,$$

$$\Gamma_{2-body} \propto \frac{1}{8\pi}\frac{v_\phi^2}{m_{DM}}$$
$$\Gamma_{3-body} \propto \frac{1}{128\pi^3}\, m_{DM}$$

↪ $\dfrac{\Gamma_{3-body}}{\Gamma_{2-body}} \sim \dfrac{1}{16\pi^2}\dfrac{m_{DM}^2}{v_\phi^2}$ $\Rightarrow$ 3-body channels dominate 2-body channels for $m_{DM} \gtrsim 4\,\mathrm{TeV}$

$(\text{with}\,\phi = H \text{ or } \bar{H})$

3-body channel consequences

$$\psi_{DM} \to \nu\gamma h,\ \nu\gamma Z_L,\ l\gamma W_L,\ \nu Z h,\ \nu Z Z_L,\ l Z W_L,\ l W h,\ l W Z_L,\ \nu W W_L$$

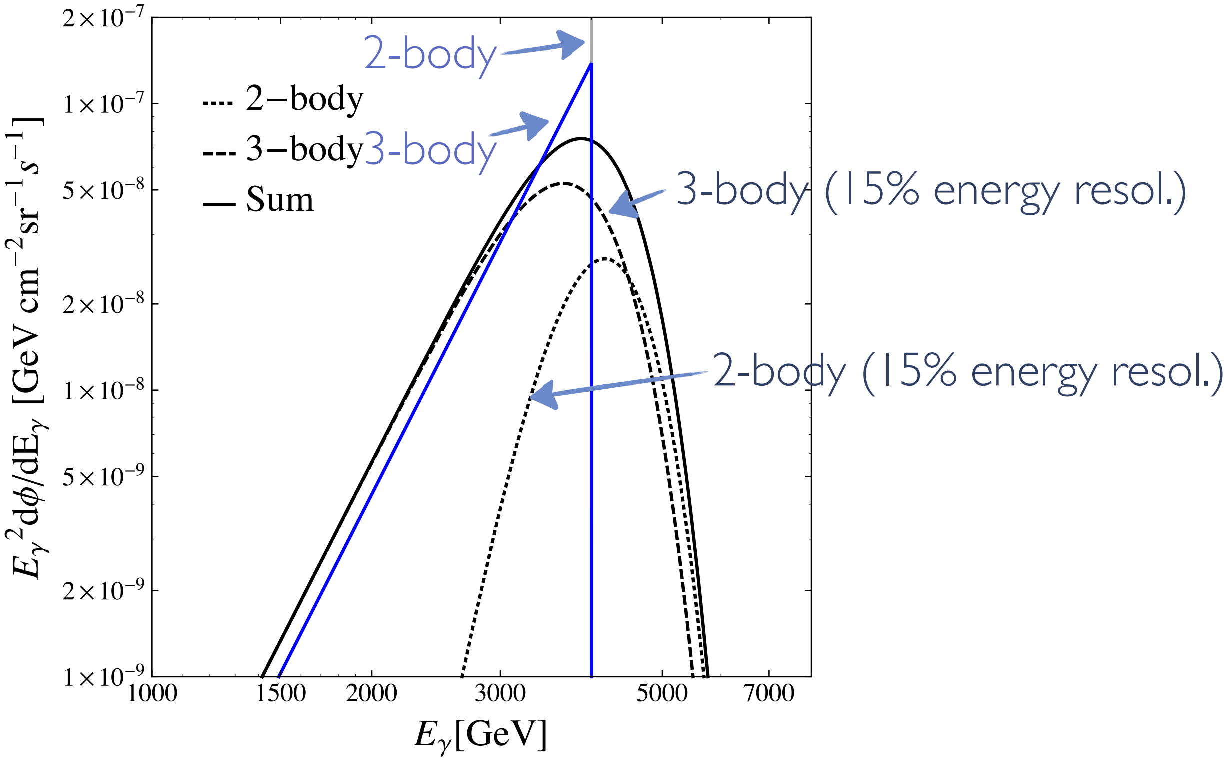
- additional cosmic rays

3-body channel consequences

$$\psi_{DM} \to \nu\gamma h,\ \nu\gamma Z_L,\ l\gamma W_L,\ \nu Z h,\ \nu Z Z_L,\ l Z W_L,\ l W h,\ l W Z_L,\ \nu W W_L$$

- additional cosmic rays
- additional γ sharp spectral features

  $DM \to \nu\,\gamma\,h$: similar to internal bremsstralung



2-body

3-body

3-body (15% energy resol.)

2-body (15% energy resol.)

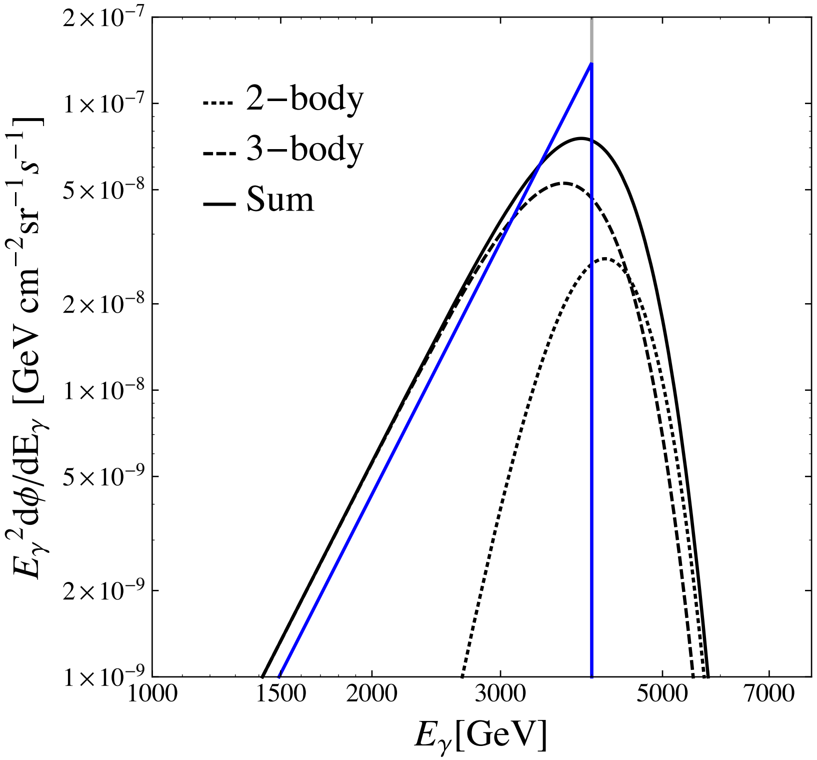
3-body channel consequences

$$\psi_{DM} \to \nu\gamma h,\ \nu\gamma Z_L,\ l\gamma W_L,\ \nu Z h,\ \nu Z Z_L,\ lZW_L,\ lWh,\ lWZ_L,\ \nu WW_L$$

- additional cosmic rays

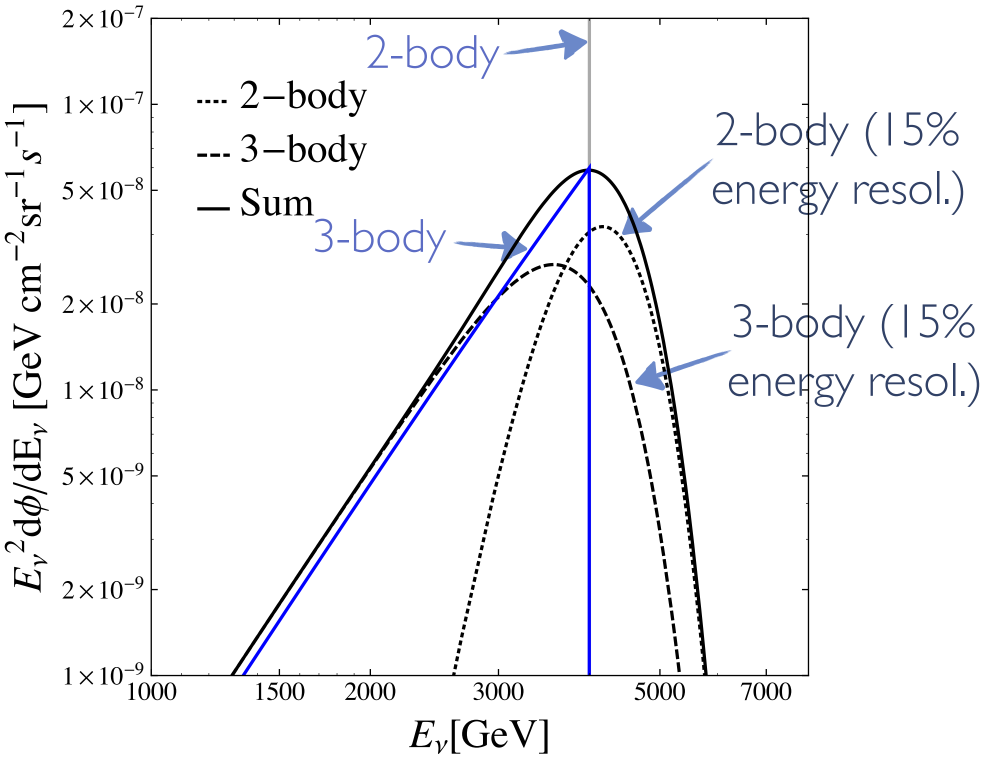
- additional γ sharp spectral features

  $DM \to \nu\gamma h$: similar to internal bremsstrahlung



- additional ν sharp spectral features!

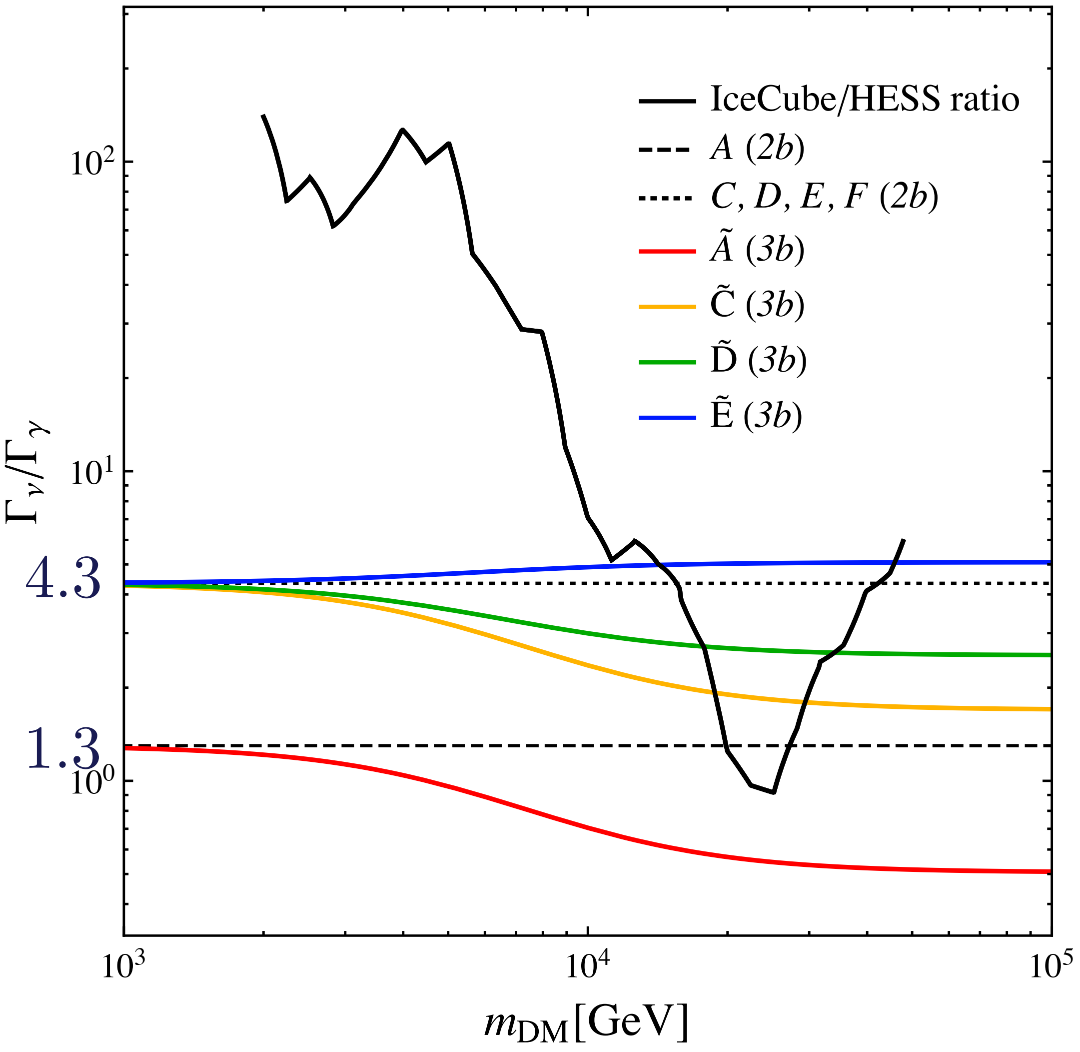
  $DM \to \nu\gamma h$: "neutrino internal bremsstrahlung"



must be looked for by Icecube too!

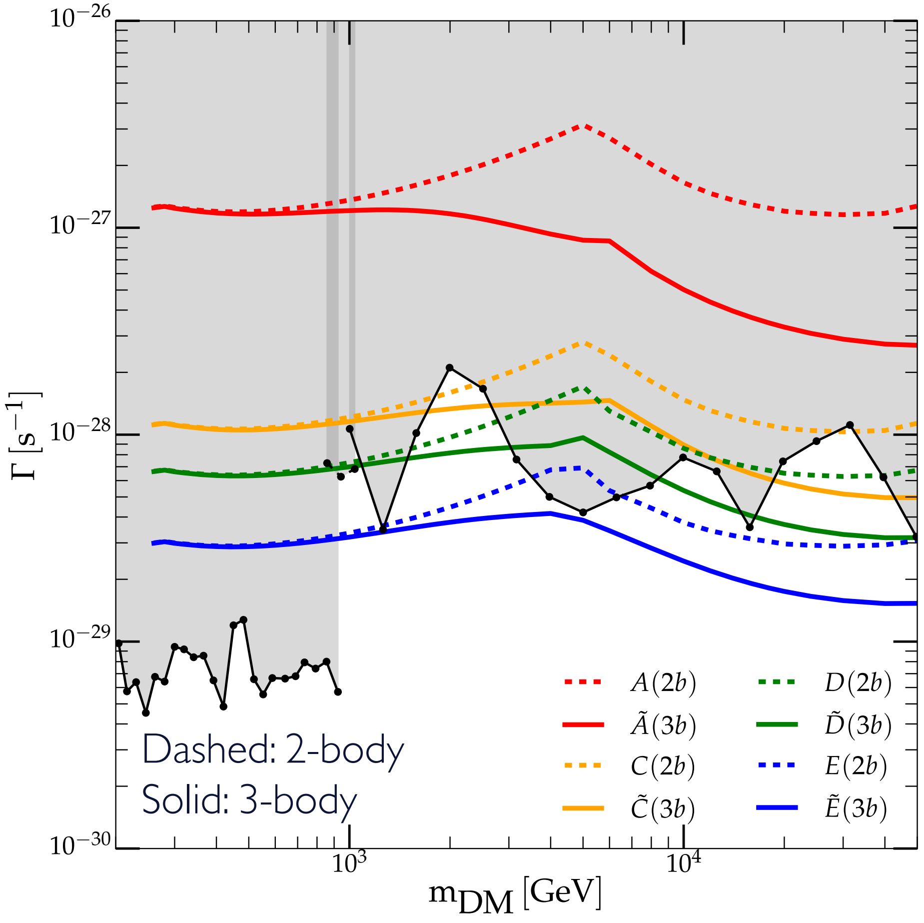
Summing 2 and 3 body sharp feature γ and ν

ratios of ν sharp feature intensity to γ sharp feature intensity

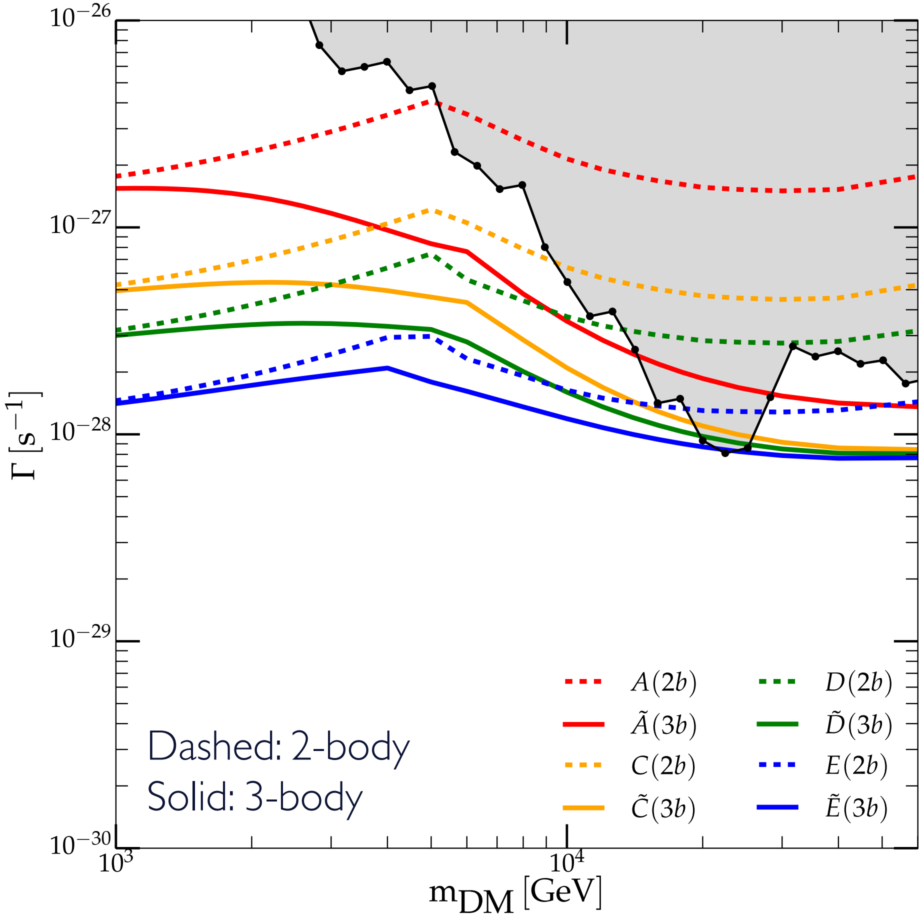


Summing 2 and 3 body sharp feature γ and ν: upper limits

Upper limits on γ spectral sharp feature intensity:



Upper limits on ν spectral sharp feature intensity:



clear possibilities to have double monochromatic DM
⇒ evidence + observation of associated CR excess!
and to distinguish classes of operators and scenarios