Neutrino Lines from Dark Matter

Camilo Garcia Cely

NuCo 2021: Neutrinos en Colombia

July 30, 2021

Prospects for discovering a neutrino line induced by dark matter annihilation

Chaimae El Aisati[1], Camilo Garcia-Cely[1], Thomas Hambye[1] and Laurent Vanderheyden[1]

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Indirect dark matter detection:

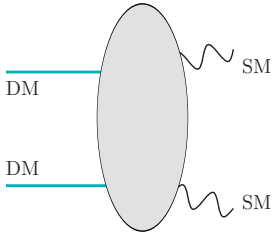
Dark matter annihilates or decays into some particles and these in turn produce a flux of γ, $e^{\pm}$, p, $\overline{p}$, and (anti-)neutrinos. Subsequently, these propagate from the point where they are produced until they reach the earth.

This talk: DM $\rightarrow \nu\nu$ or DM DM $\rightarrow \nu\nu$.

- Neutrinos point to the direction where they come from.
- Neutrinos are not subject to energy loses $\rightarrow$ The observation of a line would allow to infer the DM mass.
- Neutrino telescopes are expected to improve their sensitivities in the near future.

Indirect Searches of WIMPs

Look at the sky and search for



$$\frac{d\phi_\gamma}{dE_\gamma} = \frac{\bar{J}}{8\pi m_{\rm DM}^2}\frac{d(\sigma v)_\gamma}{dE_\gamma} \qquad \bar{J} = \frac{1}{\Delta\Omega}\int_{\Delta\Omega}\int_{\rm l.o.s.} \rho_{\rm DM}^2\, ds\, d\Omega\,.$$

- From $\Omega h^2 = 0.12$, we expect $\sigma v \sim 1\,\mathrm{pb} \sim 3\times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$.

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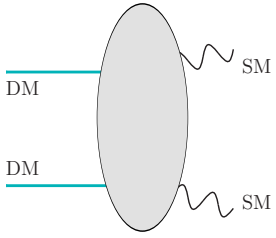

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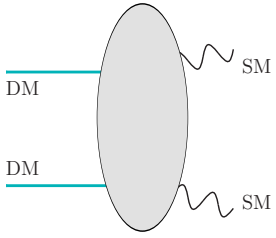

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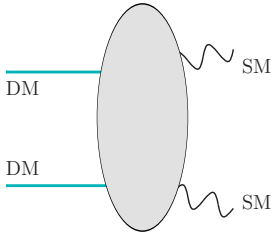

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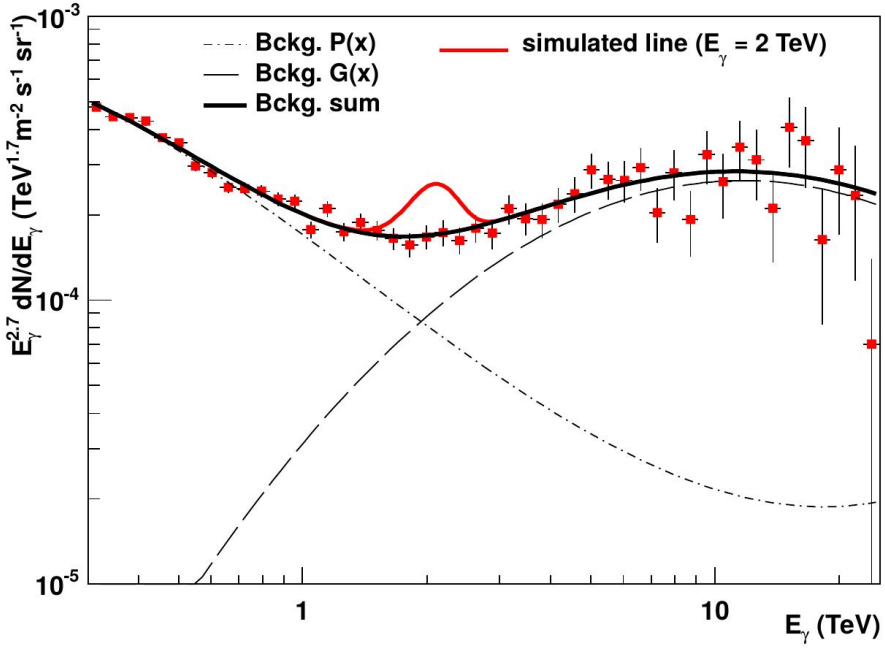
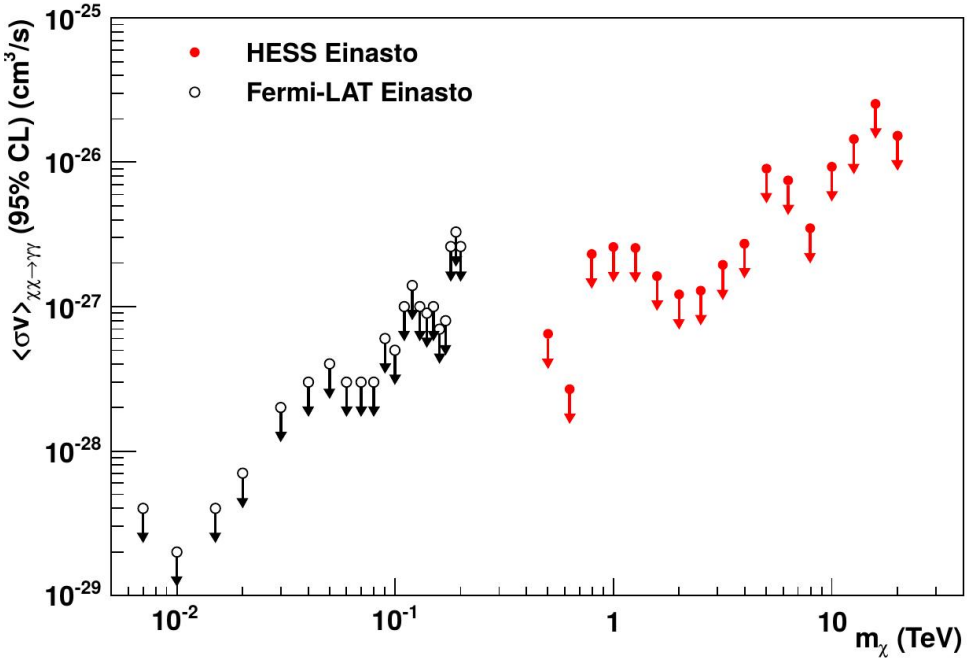
H.E.S.S. searches for line-like features

- Target region: a circle of 1 degree radius centered in the Milky Way Center, excluding Galactic plane $|b| \geq 0.3$ degrees.
- Adopt a phenomenological background model.

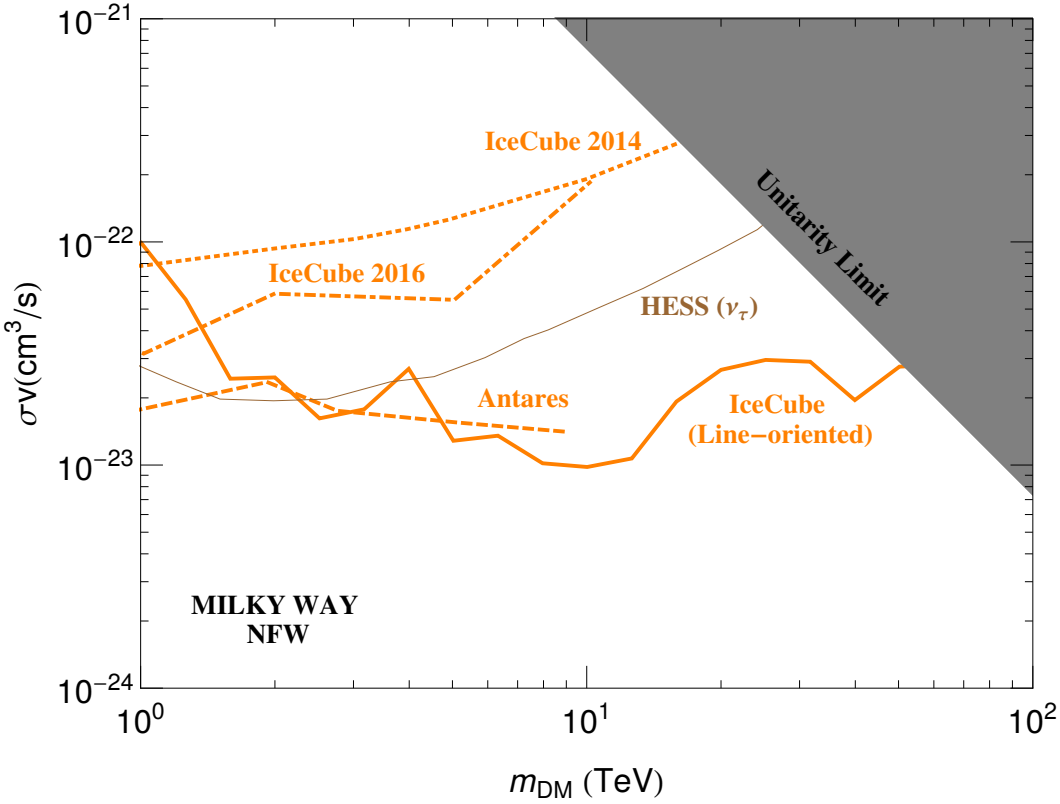
H.E.S.S. Collaboration 2013





Dark matter indirect searches with neutrino lines

- Neutrinos are similar to photons. They point to the direction where they were produced.
- With current resolutions, neutrino lines can be disentangled from the atmospheric and astrophysical background.

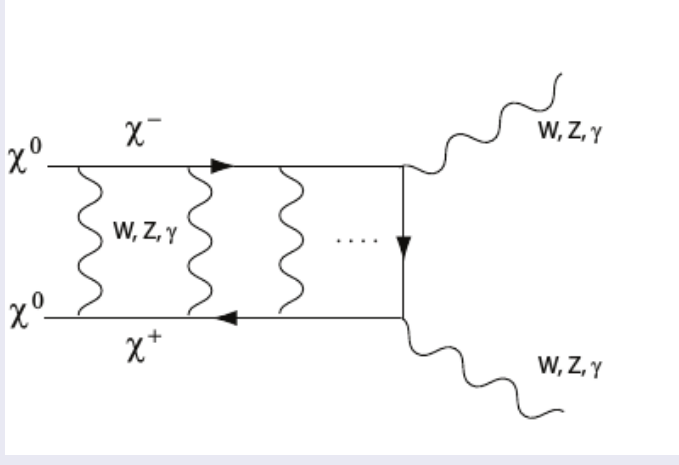


El Aisati, CGC, Hambye, Vanderheyden, 2017

Dark matter indirect searches with neutrino lines

What sort of models can be probed in the near future?

- Question partially addressed. Lindner, Merle, Niro, 2010.
- Consider *simple* models where the annihilation into neutrinos fixes the freeze-out process: $\sigma v \sim 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$ in the Early Universe.
- Calculate the Sommerfeld effect and see what are the neutrino indirect detection prospects.



Hisano et al, 2004

In practice, this means that today $\sigma v \gg 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$.

The importance of s-wave annihilations

$$\sigma v = \sigma v\Big|_{\text{L=0 (s-wave)}} + \sigma v\Big|_{\text{L=1 (p-wave)}} + \ldots$$

p-wave

It is generally suppressed.

- No Sommerfeld effect $\rightarrow$ proportional to v^2.
- Sommerfeld effect $\rightarrow$ proportional to α^2. Cassel, 2010

s-wave

In order to observe an indirect detection signal, it must not vanish

- Of order $10^{-26}\,\mathrm{cm}^3/\mathrm{s}$ at freeze-out.
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Annihilation channels

We must separately analyze two final states: $\nu\nu$ or $\nu\overline{\nu}$.

Putting everything together

Final state $\nu\bar{\nu}$

Lepton Number	Hypercharge	Angular Momentum J
0	0	≥ 1

- It does not work for scalar or Majorona DM.
- The simplest possibility is Dirac DM.

Final state $\nu\nu$

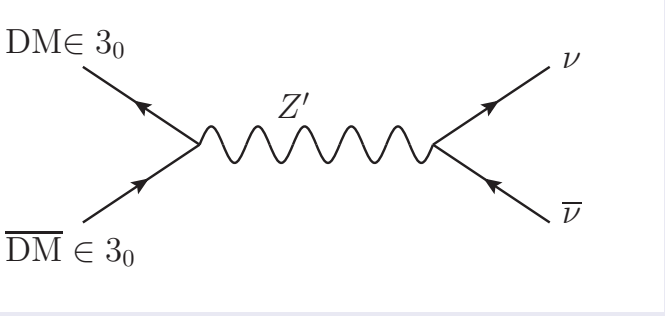
Lepton Number	Hypercharge	Angular Momentum J
2	2	≥ 0

- At the TeV scale, it requires a DM particle with hypercharge
- Too large neutrino masses might be induced by the same process leading to DM annihilations.

Two benchmark models

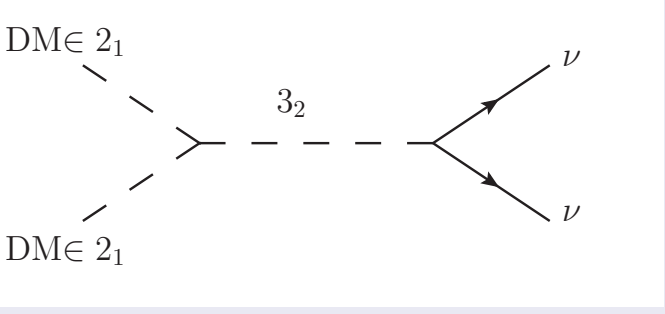
Model F_1: Dirac DM coupled to a heavier Z'

We want Sommerfeld effect $\rightarrow$ Take DM in a triplet with $Y = 0$.



Model S_1^r: Scalar DM coupled to a scalar triplet with $Y = 2$.

We want Sommerfeld effect $\rightarrow$ Take DM as an Inert Higgs.



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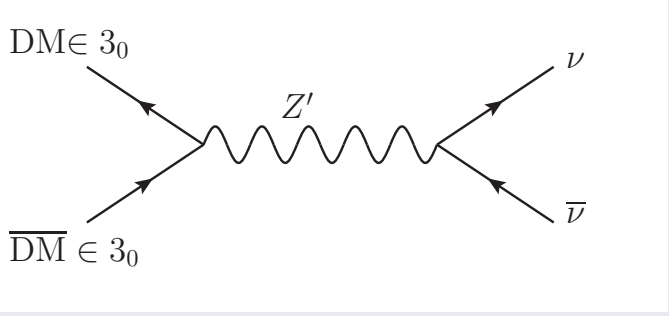

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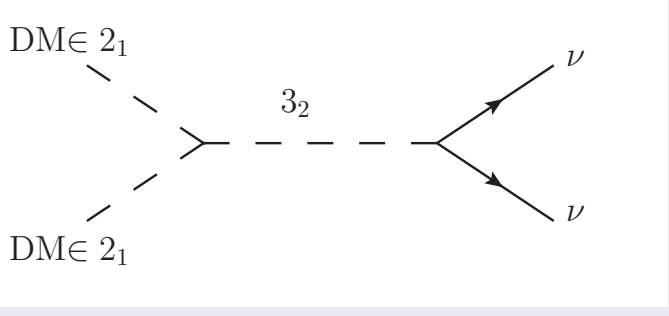


Type-II seesaw mechanism $\rightarrow$ Neutrino masses at tree level.

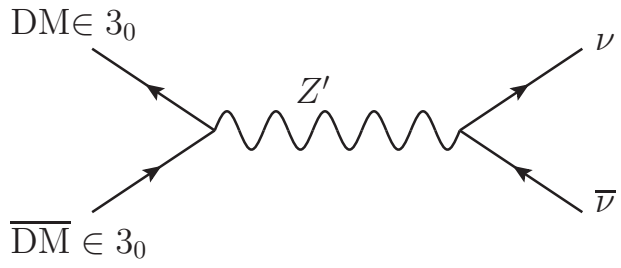
El Aisati, CGC, Hambye, Vanderheyden, 2017

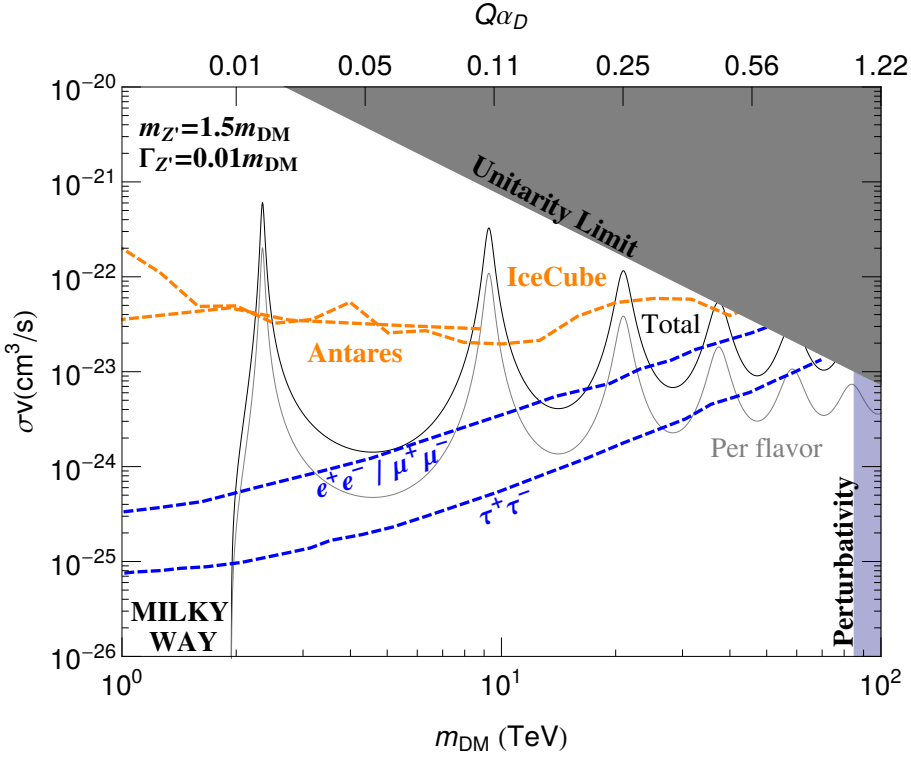
Model F_1

DM belongs to $\psi \sim 3_0$

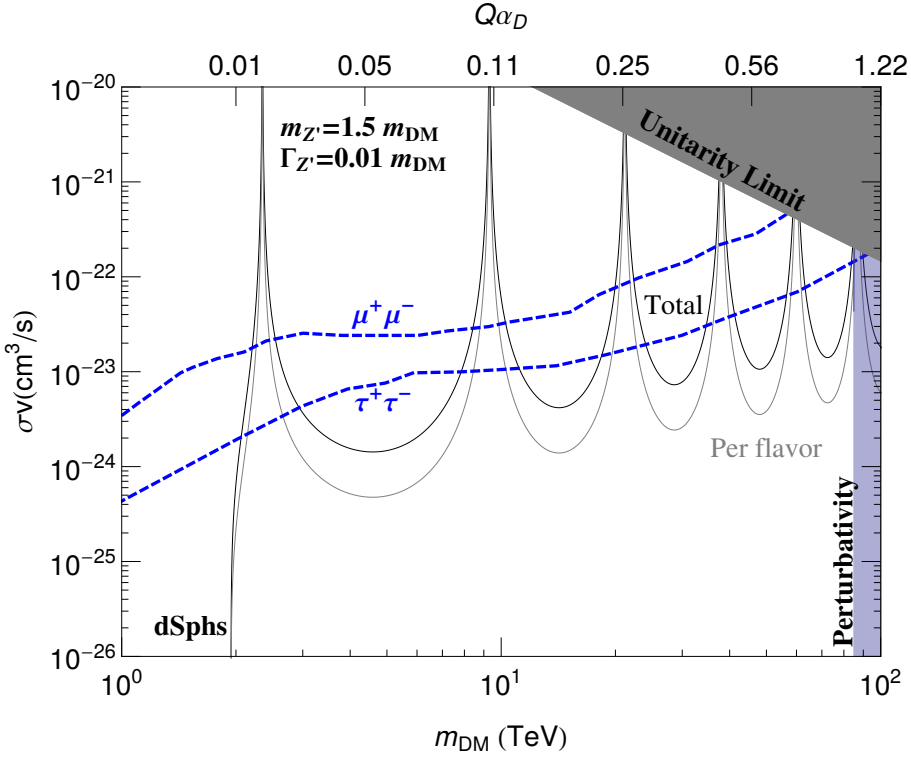
$$\mathcal{L}_{Z'} \supset g_D Z'_\mu \left(\overline{\psi}\gamma^\mu\psi + Q\overline{L_\alpha}\gamma^\mu L_\alpha\right) .$$

At freeze-out $\sigma v \sim 2.3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$.





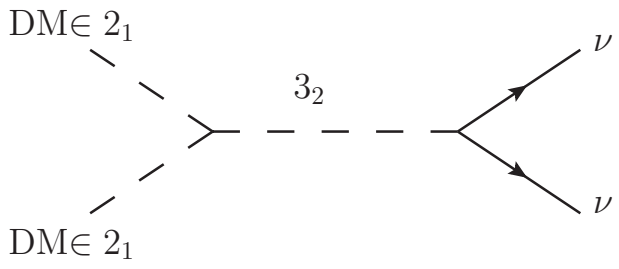
In the Milky way ($v \sim 2 \times 10^{-3} c$)



In dwarf galaxies ($v \sim \times 10^{-5} c$)

Model S_1^r

DM belongs to $\phi_D \sim 2_1 = \begin{pmatrix} H^+ \\ (H^0 + iA^0)/\sqrt{2} \end{pmatrix}$



$$\mathcal{L} = \mu\, \phi_D \phi_T \phi_D - Y^L_{\alpha\beta}\, \overline{L_\alpha} \phi_T L^c_\beta + h.c.$$

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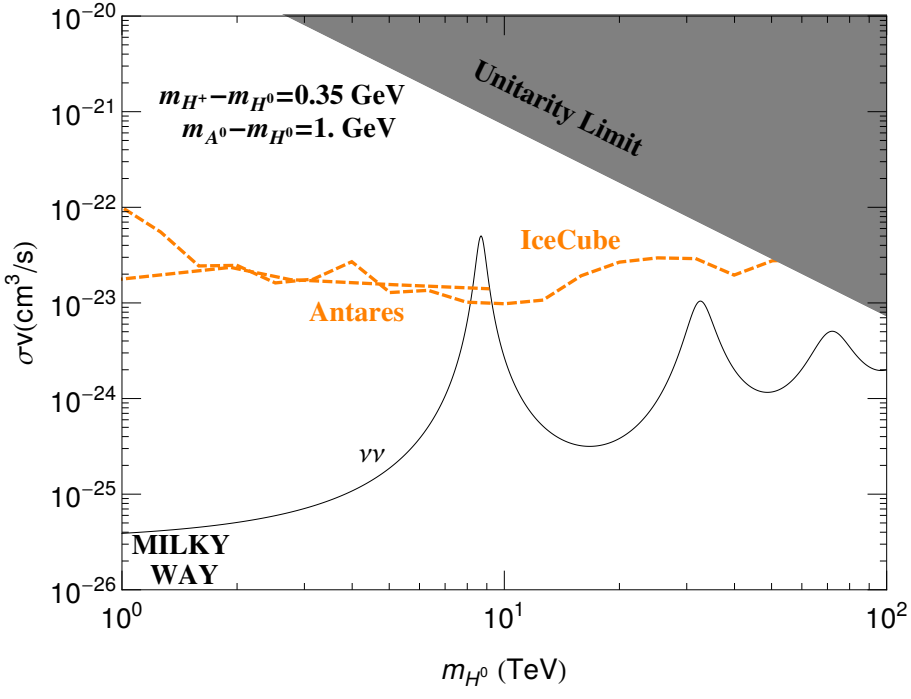

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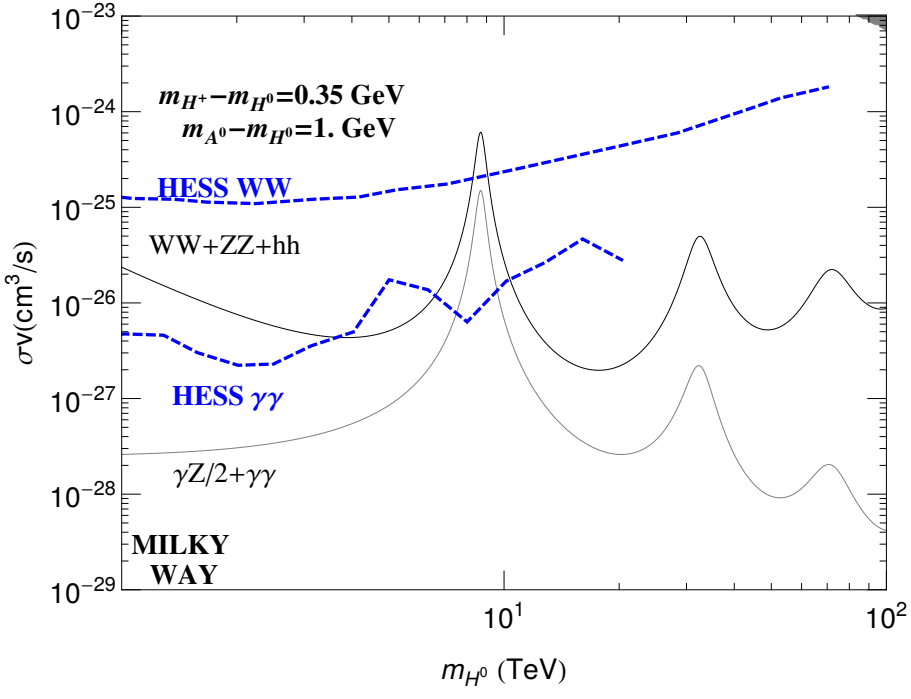

No charged leptons.

Neutrinos also carry flavor...

Astrophysical neutrinos (produced as flavor eigenstates)

$$\rho^S = \overbrace{\begin{pmatrix} \alpha_e^S & 0 & 0 \\ 0 & \alpha_\mu^S & 0 \\ 0 & 0 & \alpha_\tau^S \end{pmatrix}}^{\text{flavor-eigenstate basis}},$$

$$H \simeq E\,\mathbb{1} + \overbrace{\begin{pmatrix} \frac{m_1^2}{2E} & 0 & 0 \\ 0 & \frac{m_2^2}{2E} & 0 \\ 0 & 0 & \frac{m_3^2}{2E} \end{pmatrix}}^{\text{mass-eigenstate basis}}$$

CGC, Heeck (2017)

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$$\rho^\oplus = e^{-iHL}\rho^S e^{iHL} \xrightarrow{L \gg \frac{E}{\Delta m_i^2}} \overbrace{\begin{pmatrix} \alpha_e^\oplus & \cdot & \cdot \\ \cdot & \alpha_\mu^\oplus & \cdot \\ \cdot & \cdot & \alpha_\tau^\oplus \end{pmatrix}}^{\text{flavor-eigenstate basis}}$$

with $\alpha^\oplus \simeq P\alpha^S$

$$P_{\ell\ell'} = \sum_i |U_{\ell i}|^2 |U_{\ell' i}|^2$$

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Pure ν_μ

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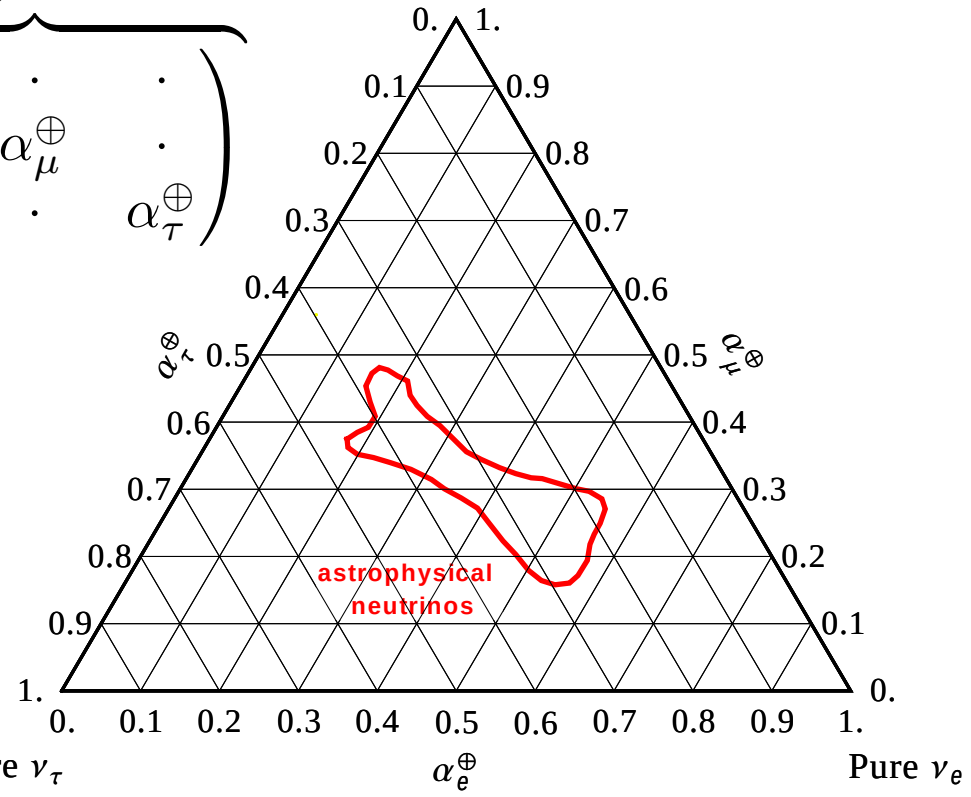
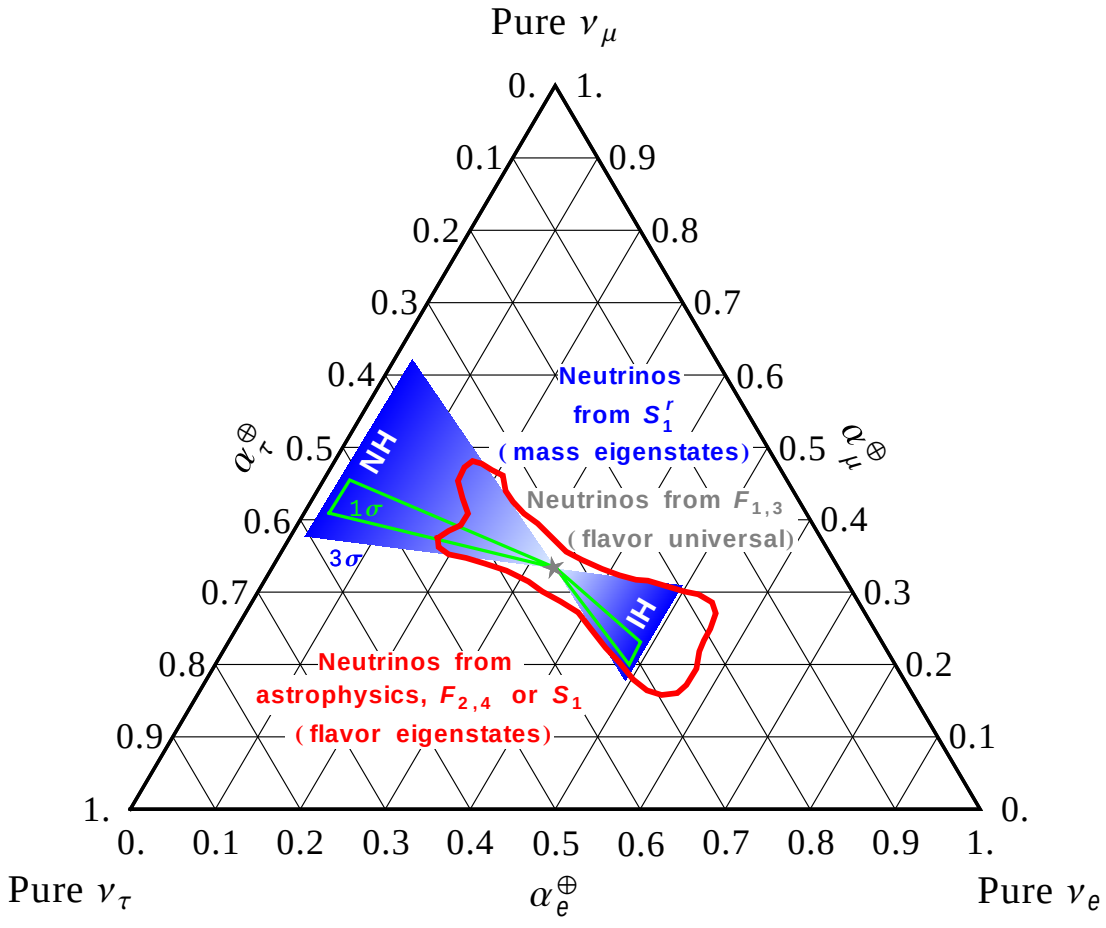


CGC, Heeck (2017)

Neutrinos also carry flavor...

The same is true for DM annihilations

- Process DM DM $\to \nu\nu$
- Process DM DM $\to \nu\bar{\nu}$ with a t-channel induced by a Yukawa interaction
- Process DM DM $\to \nu\bar{\nu}$ with a Z' in the s-channel



El Asaiti, CGC, Hambye, Vanderheyden (2017)

Conclusions

- Multi-TeV DM models predict significant annihilation rates due to the Sommerfeld effect. These typically correspond to cross sections well above the canonical thermal value.
- I discussed models whose main signature is the annihilation into neutrino lines. They can be probed in the near future.
- In certain cases, the flavor structure of the lines can not be mimicked by astrophysical neutrinos.

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Thanks for your attention