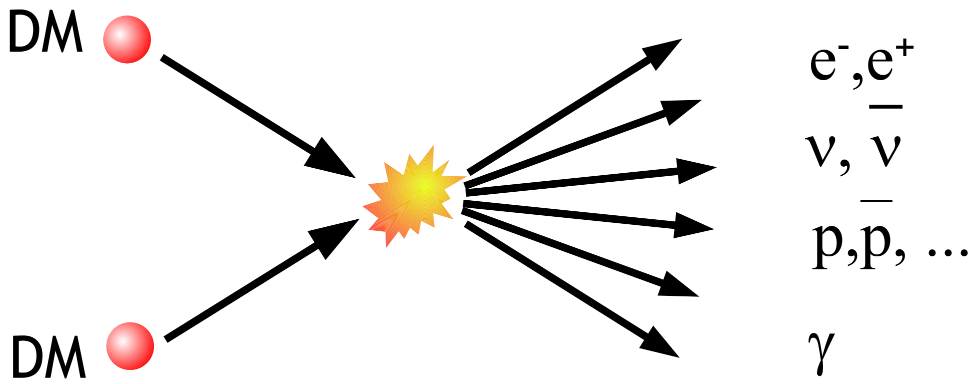
Probing the DM annihilation cross-section using neutrinos

Indirect dark matter searches



Dark matter particles annihilate into ordinary particles, such as electrons and positrons, antiprotons, neutrinos, photons…

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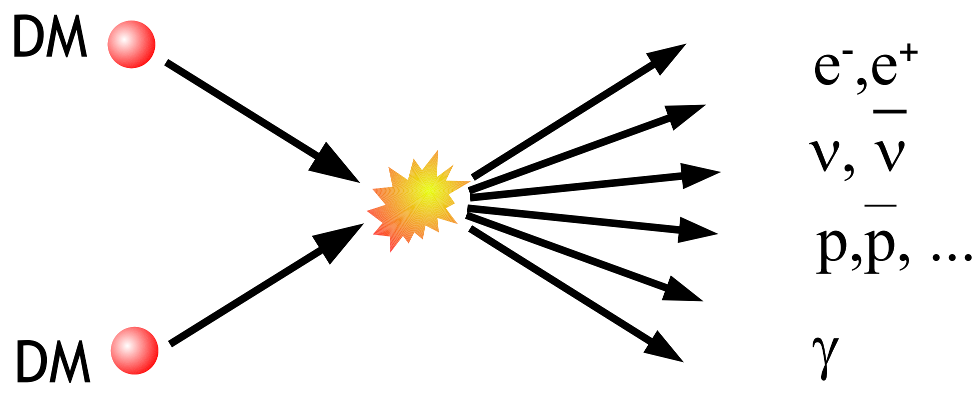

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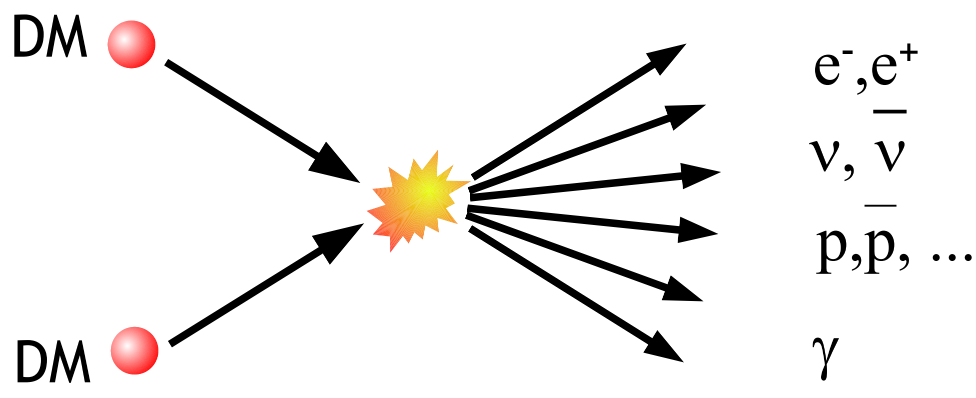
$$\frac{dJ_{\rm halo}}{dE_\nu} = \frac{1}{4\pi}\left[\frac{\langle\sigma_{\rm ann}v\rangle}{2m_{\rm DM}^2}\sum_f \frac{dN_\nu^f}{dE_\nu}B_f\right] \times \int_{\rm l.o.s.} \rho^2(\vec{l})\, d\vec{l}$$

Source term (particle physics) — Line-of-sight integral (astrophysics)

Indirect dark matter searches



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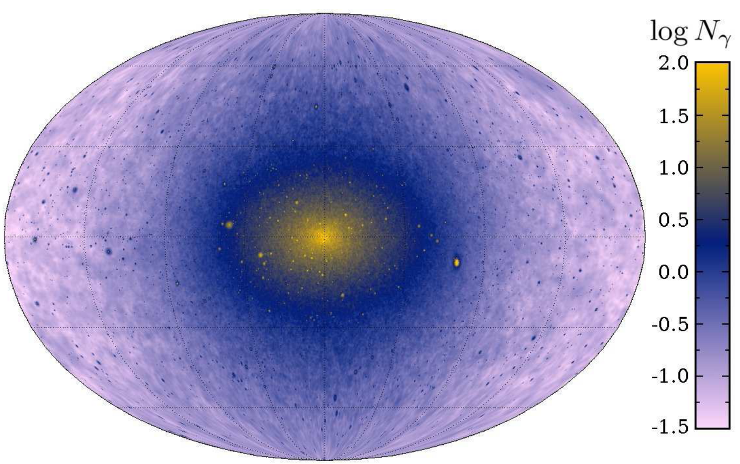
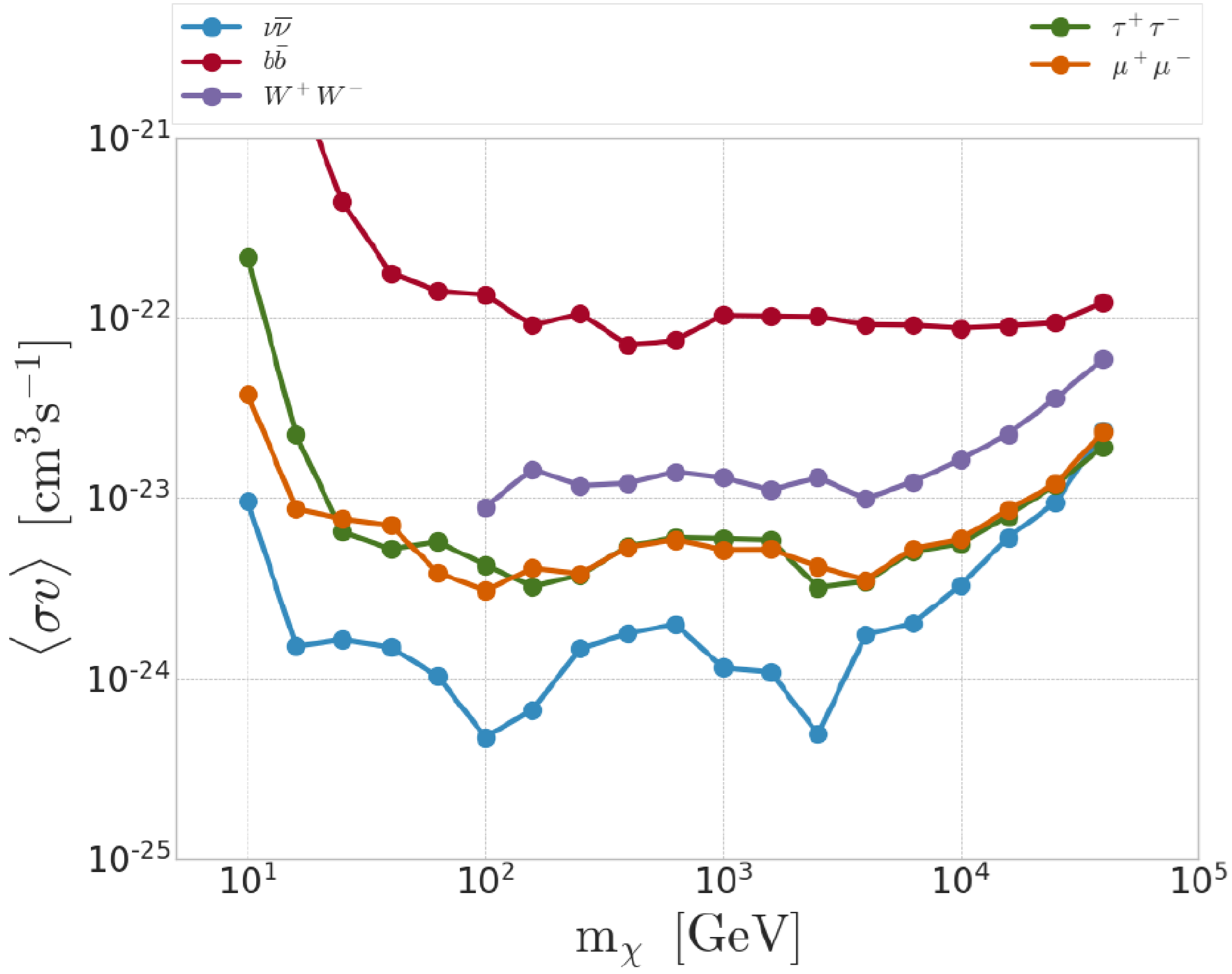


Limits on the annihilation cross-section

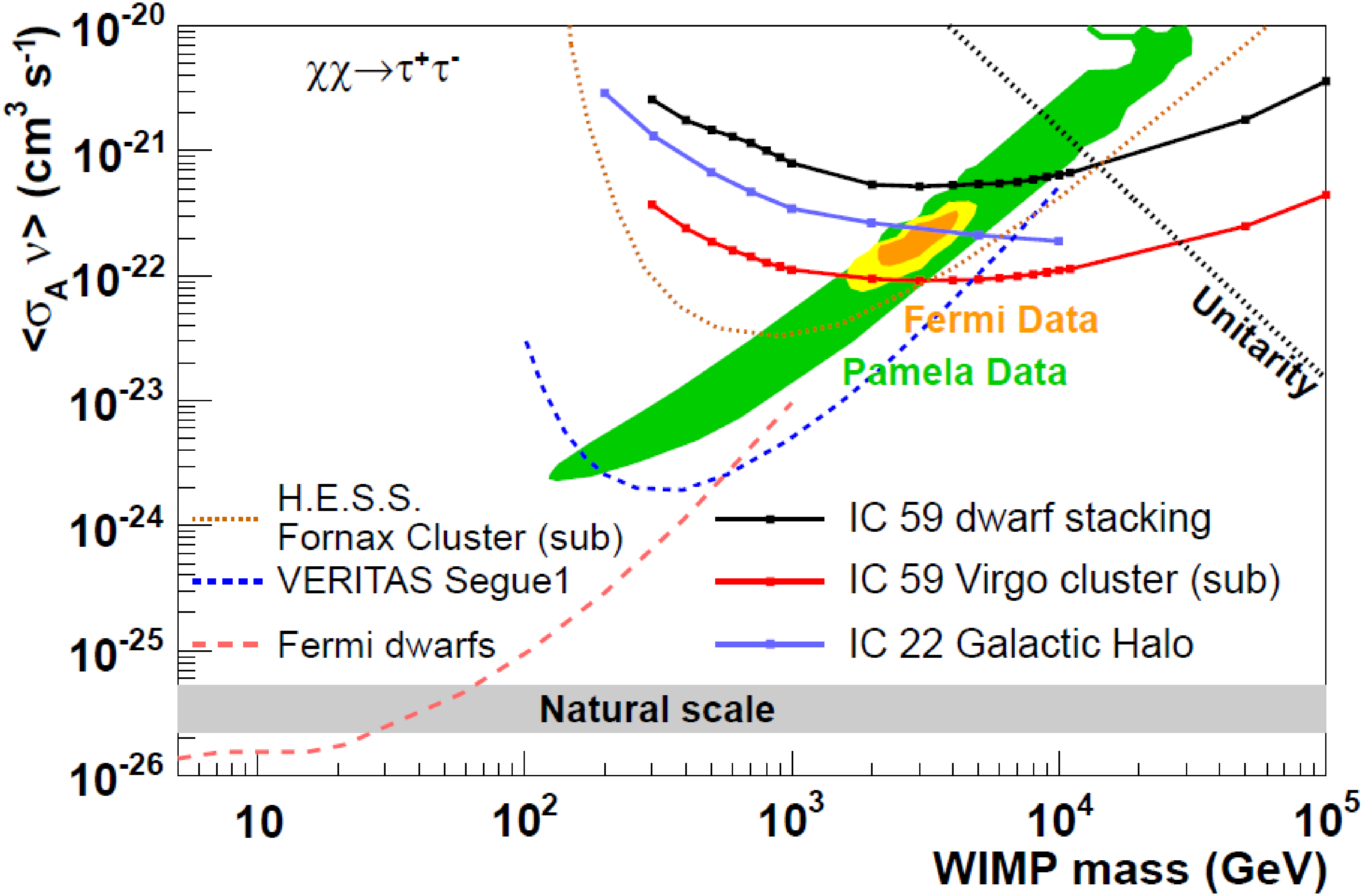
Neutrinos from dark matter annihilations in the Milky Way halo



IceCube 2023

Limits on the annihilation cross-section

Neutrinos from dark matter annihilations in dwarf galaxies & galaxy clusters.

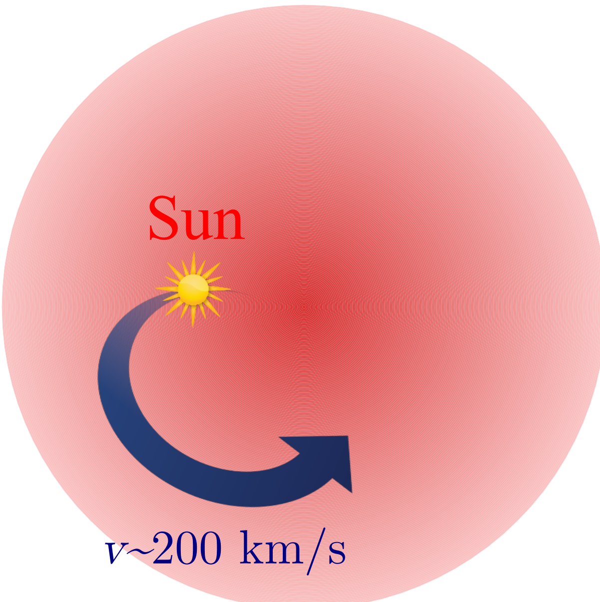


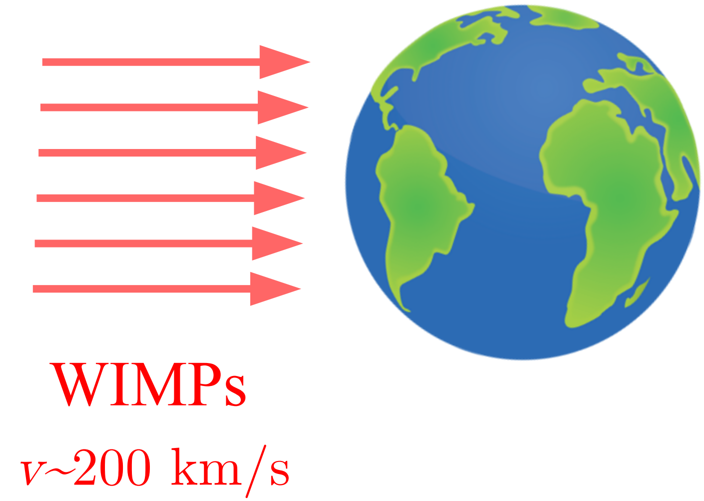
Aartsen et al., arXiv:1307.3473

Probing the DM-nucleon scattering cross-section using neutrinos

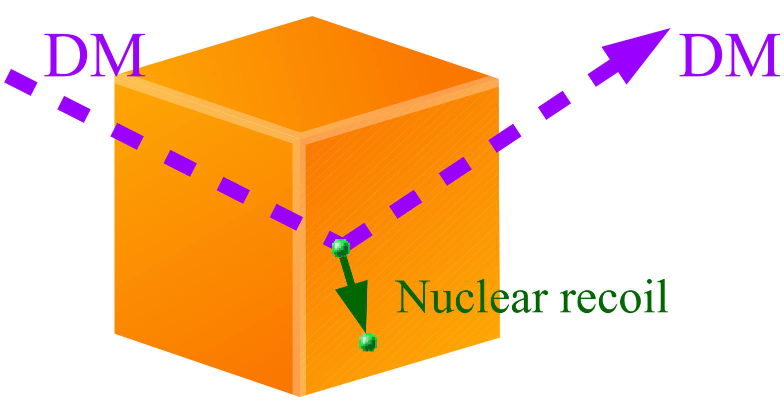
Standard method: "direct detection" experiments

The Sun (and the Earth) might be moving through a "gas" of dark matter particles.

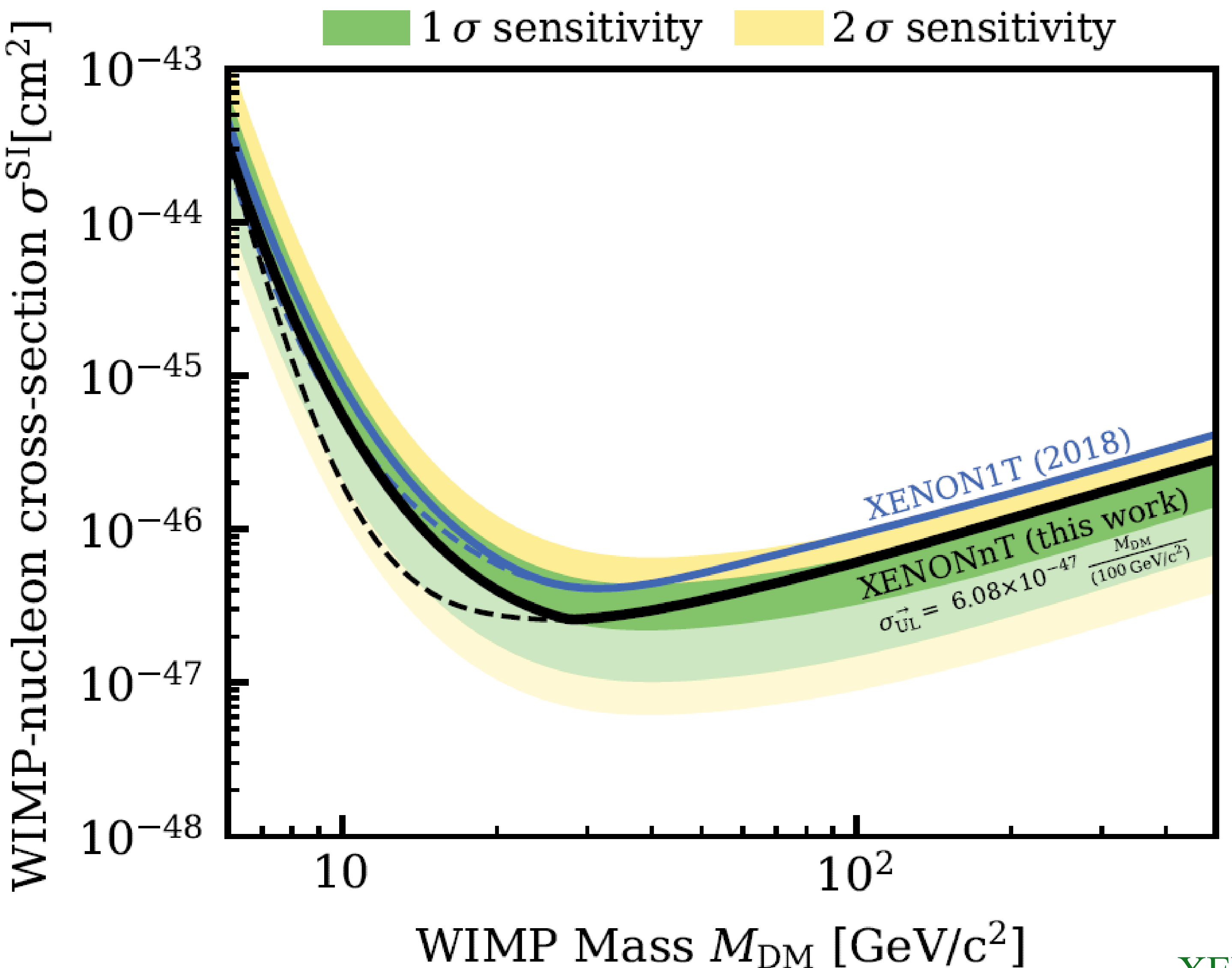




Once in a while a dark matter particle will interact with a nucleus. The nucleus then recoils, producing vibrations, ionizations or scintillation light in the detector.

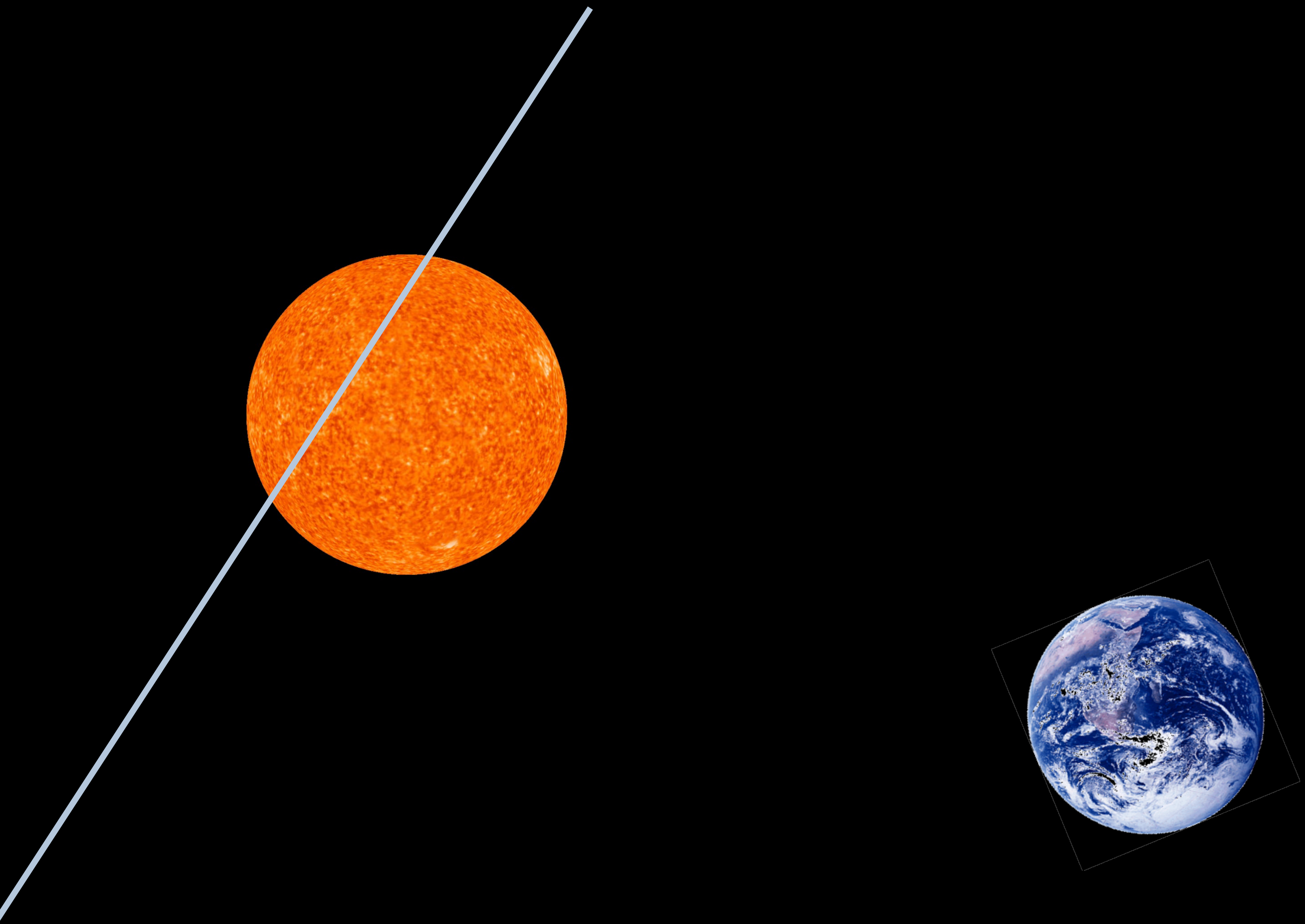


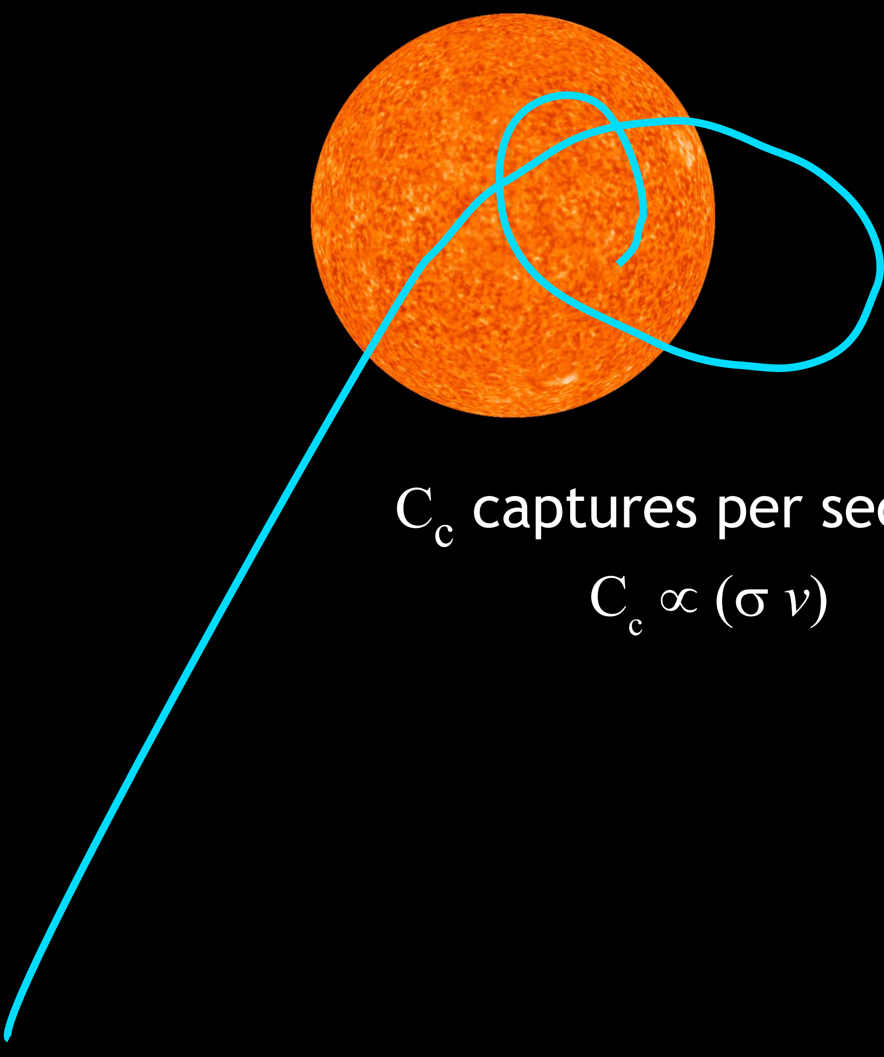
No significant excess detected so far



1 σ sensitivity
2 σ sensitivity
WIMP-nucleon cross-section σ^{SI}[cm^2]
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
XENON1T (2018)
XENONnT (this work)
$\sigma_{UL} = 6.08\times10^{-47}\ \frac{M_{DM}}{(100\ GeV/c^2)}$
10
10^2
WIMP Mass M_{DM} [GeV/c^2]

XENONnT'23

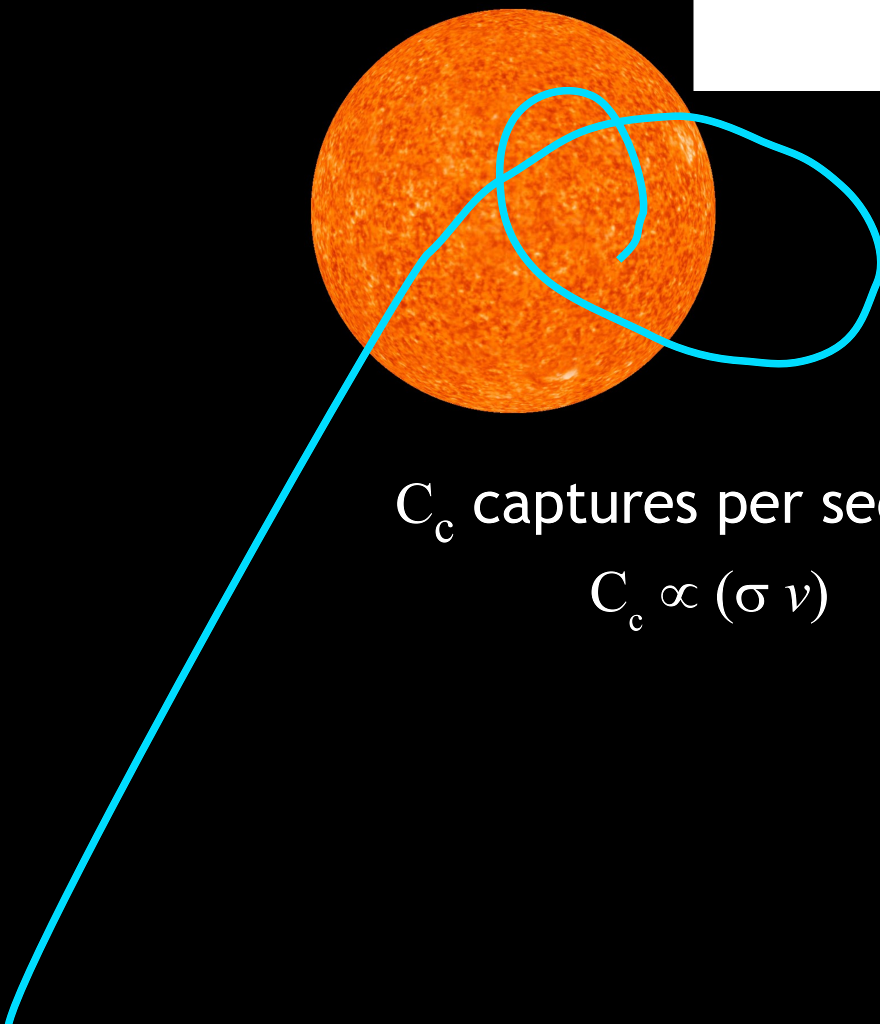




C_c captures per second,

$C_c \propto (\sigma v)$

$$C = \int_0^{R_\odot} 4\pi r^2 \mathrm{d}r \, \frac{\rho_{\mathrm{loc}}}{m_{\mathrm{DM}}} \int_{v \le v_{\mathrm{max}}^{(\mathrm{Sun})}(r)} \mathrm{d}^3 v \, \frac{f(\vec{v})}{v} \left(v^2 + [v_{\mathrm{esc}}(r)]^2\right) \times \int_{m_{\mathrm{DM}} v^2/2}^{2\mu_A^2 \left(v^2 + [v_{\mathrm{esc}}(r)]^2\right)/m_A} \mathrm{d}E_R \, \frac{\mathrm{d}\sigma}{\mathrm{d}E_R}$$



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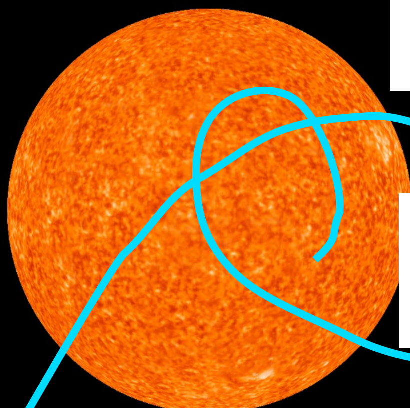

$$C \simeq 10^{20}\,\mathrm{s}^{-1} \left(\frac{\rho_0}{0.3\,\mathrm{GeV/cm}^3}\right) \left(\frac{1\,\mathrm{TeV}}{m_{\mathrm{DM}}}\right)^2 \frac{2.77\,\sigma_p^{(\mathrm{SD})} + 4.27 \cdot 10^3\,\sigma_p^{(\mathrm{SI})}}{10^{-40}\,\mathrm{cm}^2},$$

C_c captures per second,

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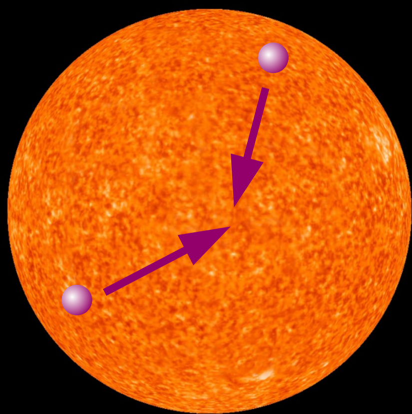
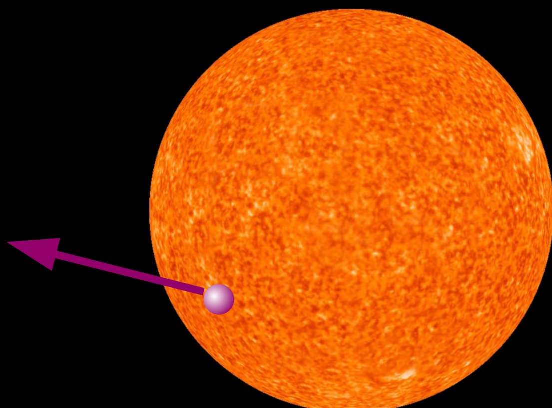


Γ_A annihilations per second

$$\Gamma_A = \frac{1}{2} C_A N^2$$

$$C_{A,\odot} \simeq 1.2 \cdot 10^{-52}\,\mathrm{s}^{-1} \left(\frac{\langle \sigma v \rangle}{2.2 \cdot 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}} \right) \left(\frac{m_{\mathrm{DM}}}{\mathrm{TeV}} \right)^{3/2}$$



C_e evaporations (or decays) per second

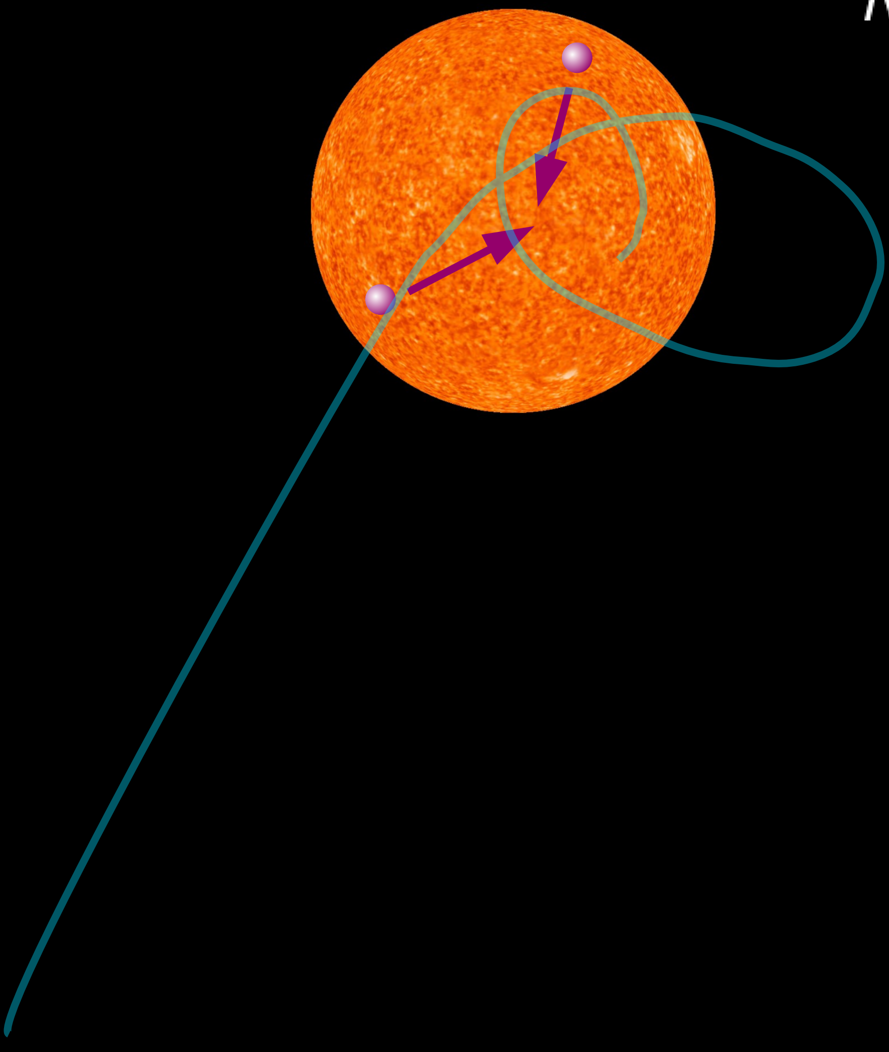
Negligible

Evolution of the number of WIMPs

$$\frac{dN}{dt} = C_c - C_a N^2$$

$$N(t) = \sqrt{\frac{C_c}{C_a}} \tanh\left(\frac{t}{\tau}\right), \text{ with } \tau = 1/\sqrt{C_c C_a}$$

$$\Gamma_A = \frac{C_a}{2} N^2 = \frac{C_c}{2} \tanh^2\left(\frac{t}{\tau}\right)$$



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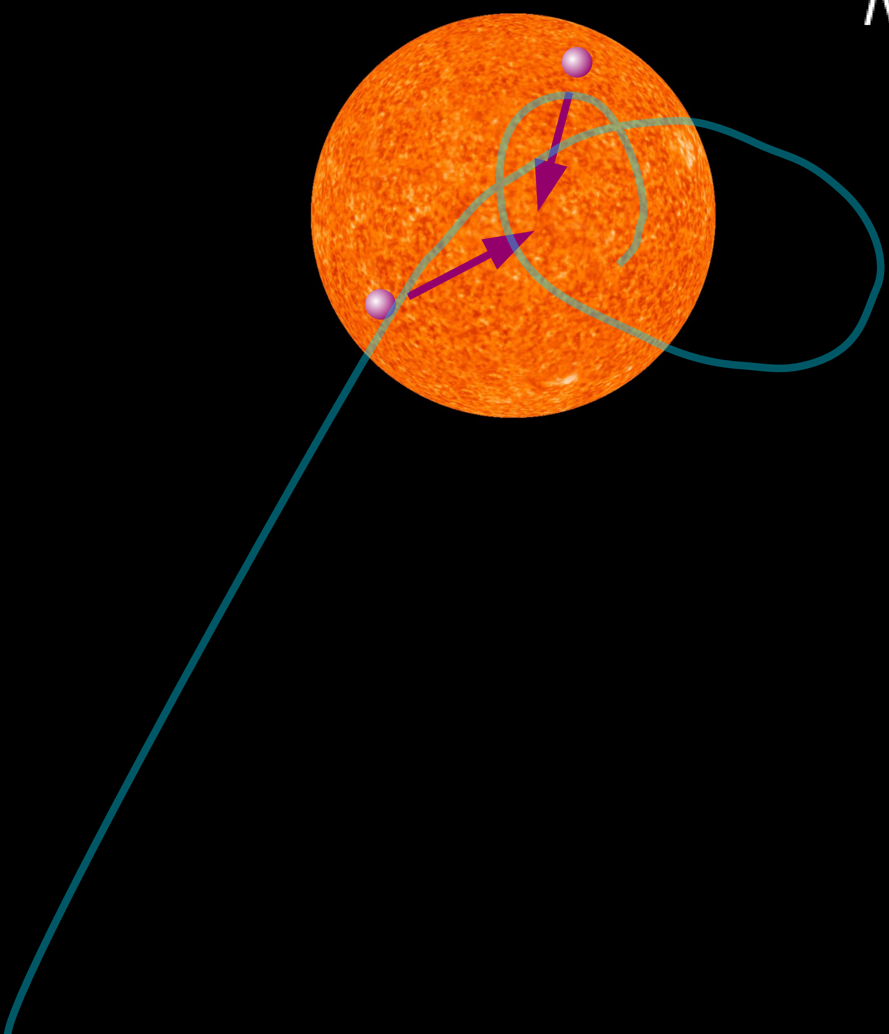
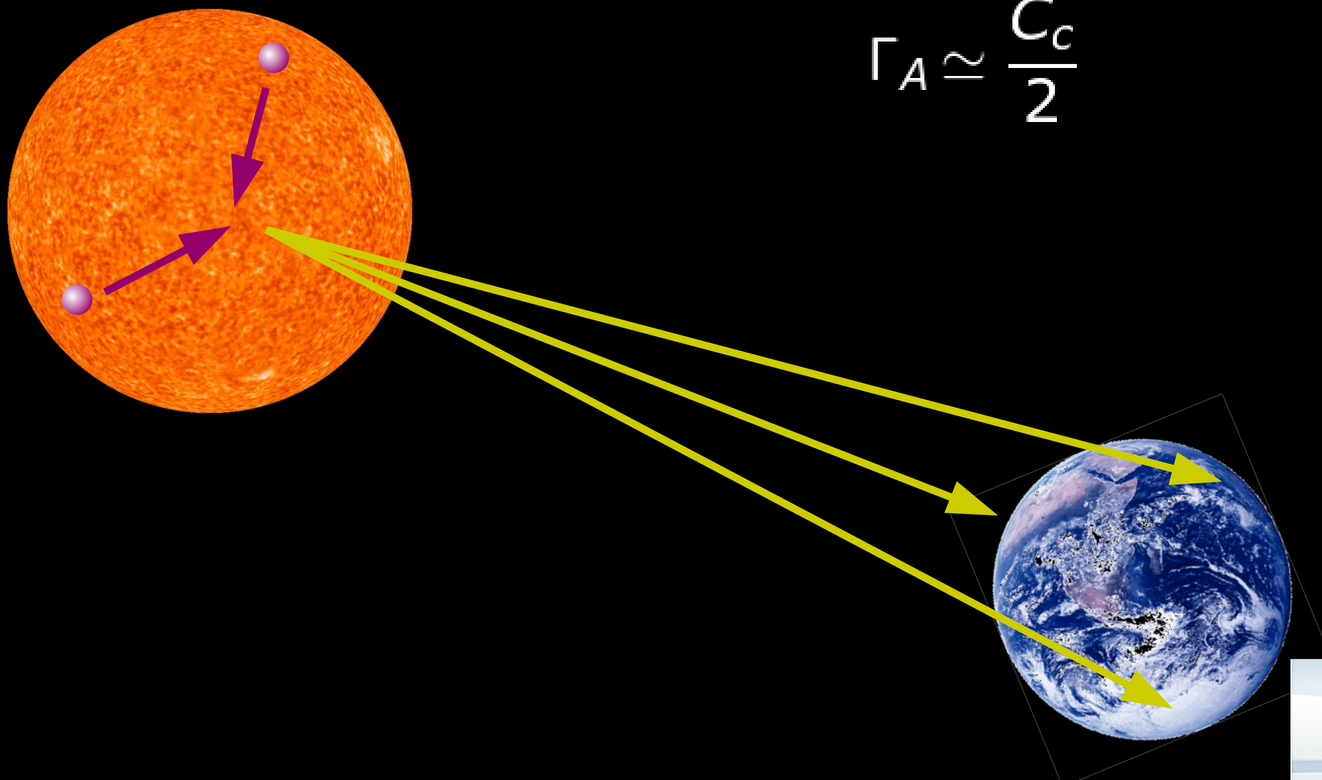
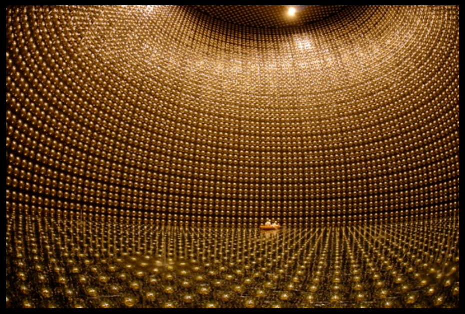
$$\Gamma_A = \frac{C_a}{2} N^2 \simeq \frac{C_c}{2}, \text{ if } t \gg \tau$$

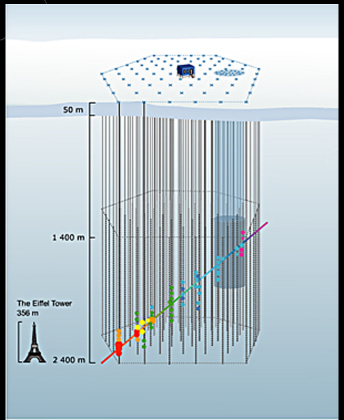


- The annihilation of dark matter particles produces Standard Model particles.
- Most of them are absorbed in their propagation inside the Sun.
- Only neutrinos can escape.
- The neutrino flux measures in fact the *capture rate*

$$\Gamma_A \simeq \frac{C_c}{2}$$

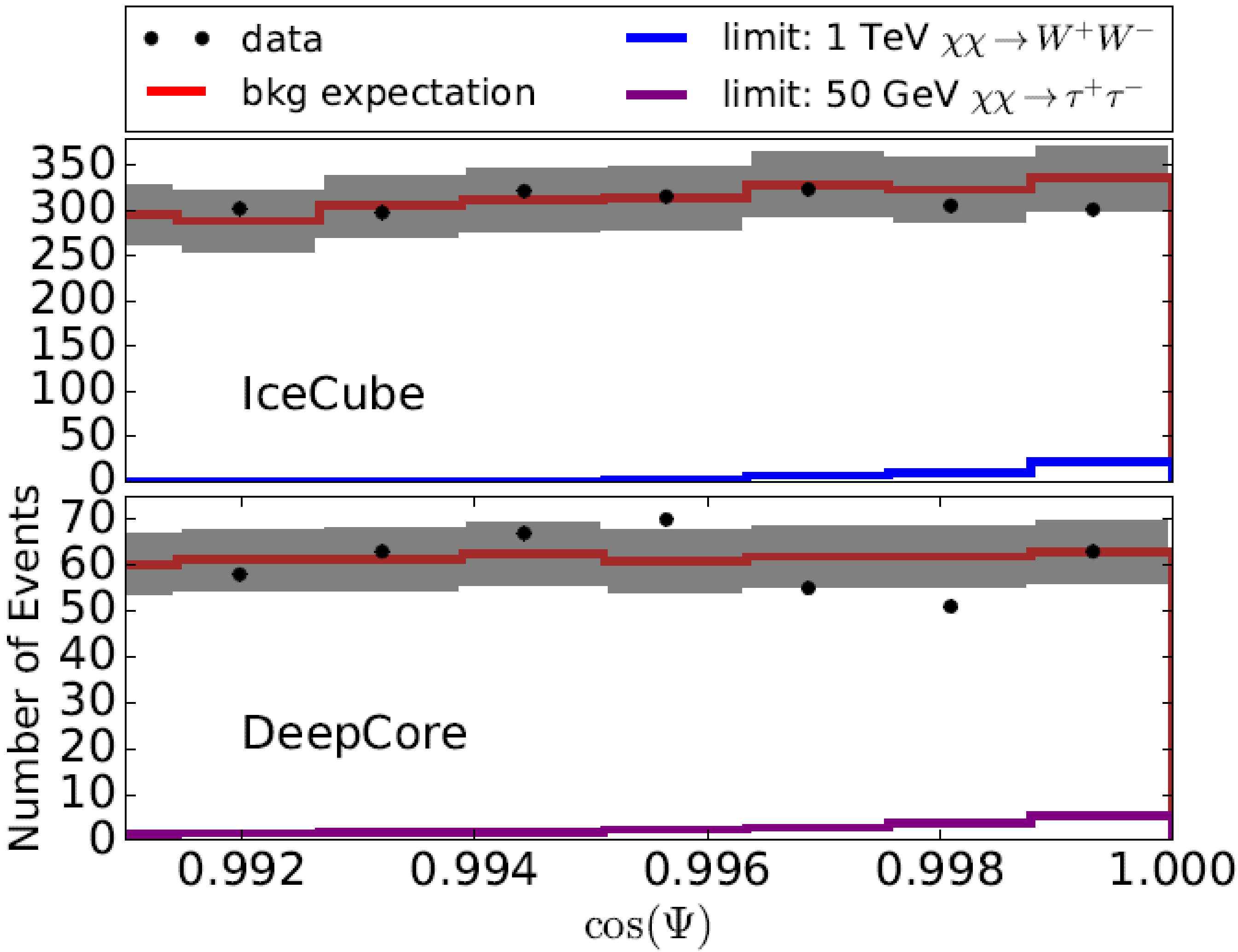






Neutrinos from annihilations in the Sun

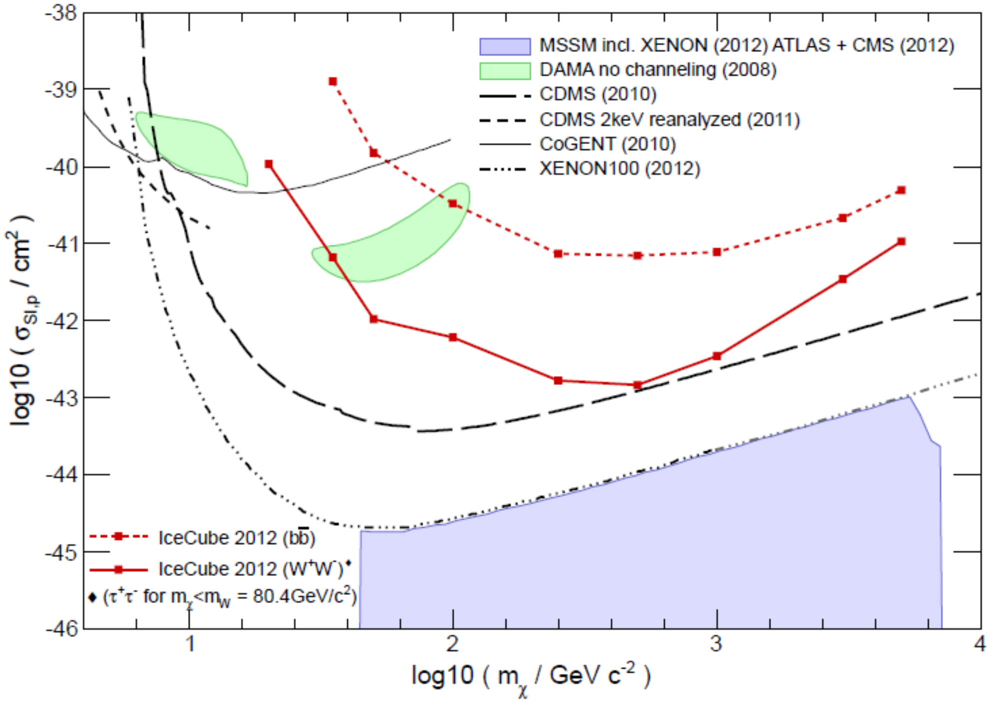
Observations consistent with the background-only hypothesis

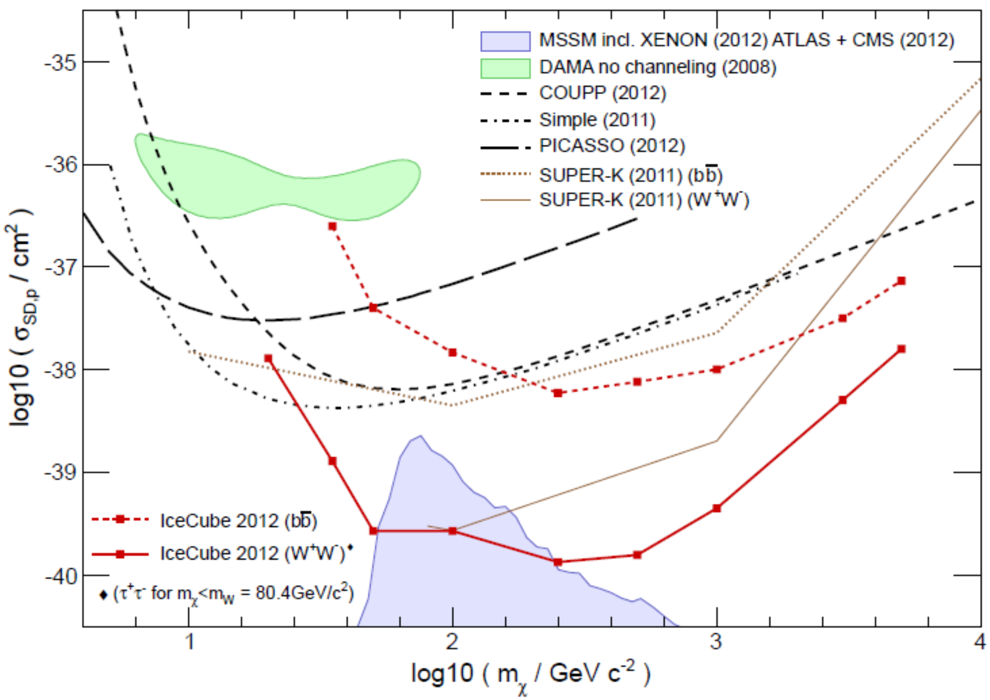


IceCube collaboration
ArXiv:1612.05949

Limits on the scattering cross-section

Limits on the spin-dependent and spin-independent scattering cross section of dark matter particles with protons.





IceCube Collaboration
arXiv:1212.4097

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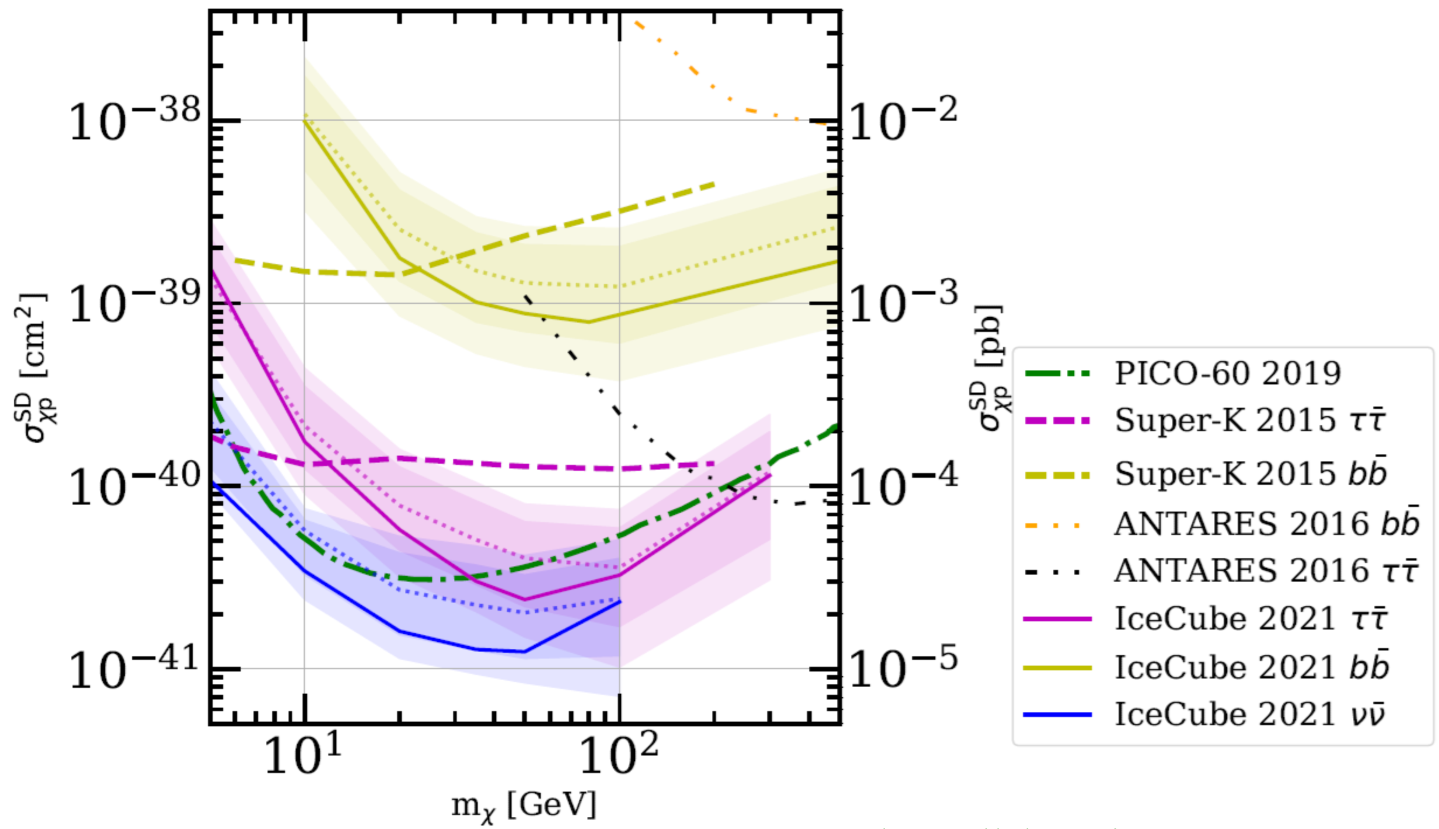


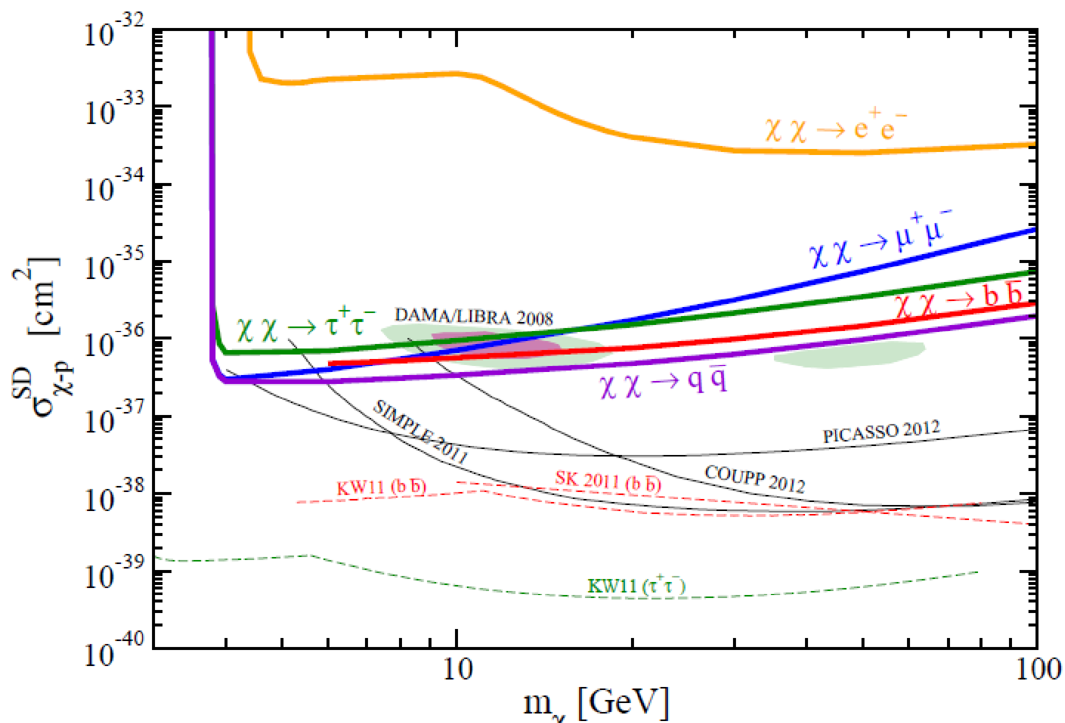
IceCube Collaboration'21

Limits on the scattering cross-section

Limits on annihilations channels into light fermions.

The annihilation DM DM $\rightarrow q\,\bar{q}$, with q a light quark, does not produce high energy neutrinos. The light quark produces pions which are quickly stopped in the solar interior before decaying. This annihilation channel produces only MeV neutrinos.

The MeV neutrinos could be detected at Super-Kamiokande



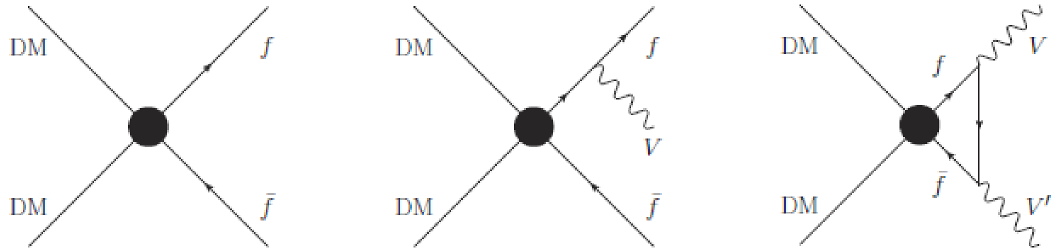
Bernal, Martín-Albo, Palomares-Ruiz, arXiv:1208.0834

See also Rott, Siegal-Gaskins, Beacom, arXiv:1208.0827

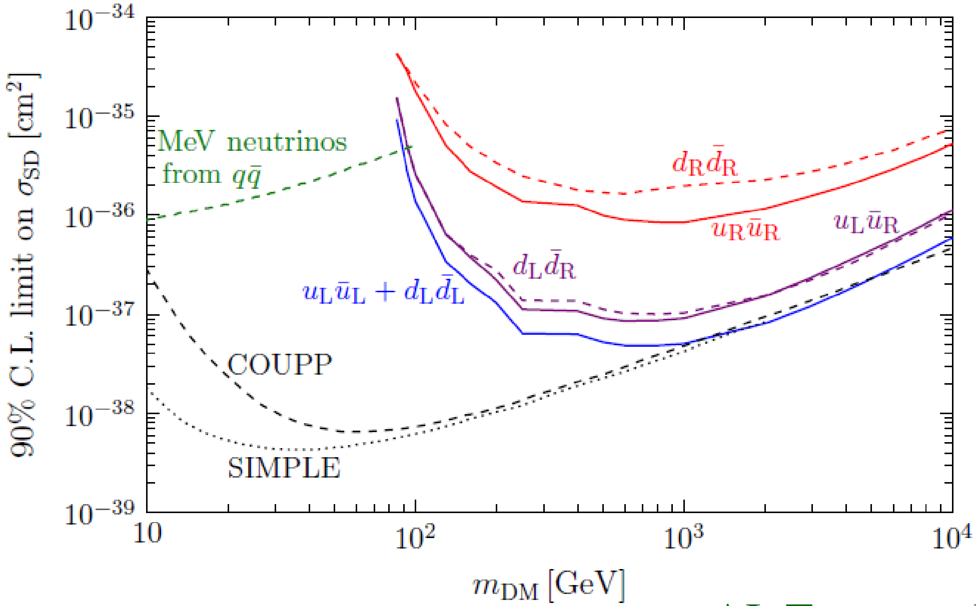
Limits on the scattering cross-section

Limits on annihilations channels into light fermions.

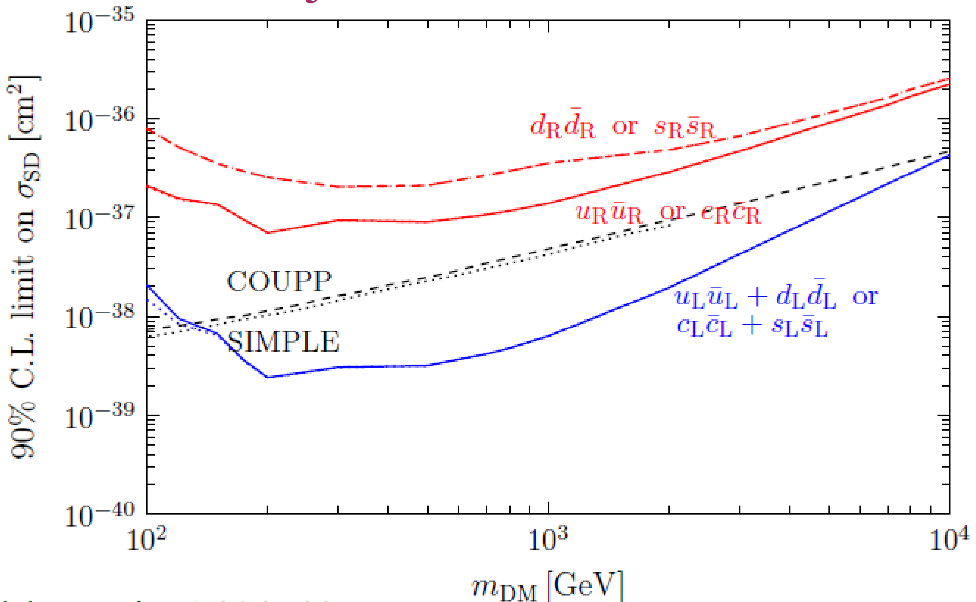
The higher order annihilations DM DM → q $\bar{q}$ Z or DM DM → Z Z do produce high energy neutrinos via the decay of the Z boson



Dirac dark matter



Majorana/scalar dark matter



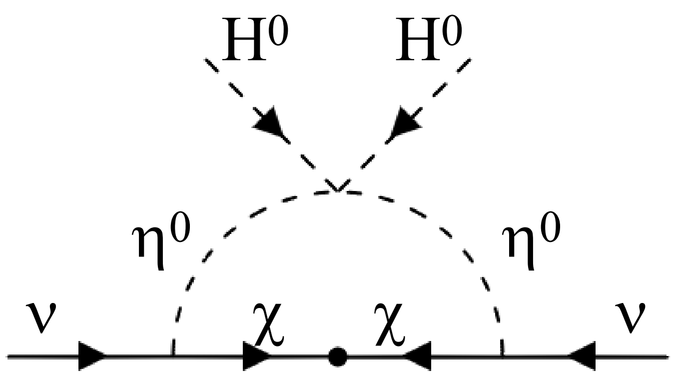
AI, Totzauer, Wild, arXiv:1402.4375

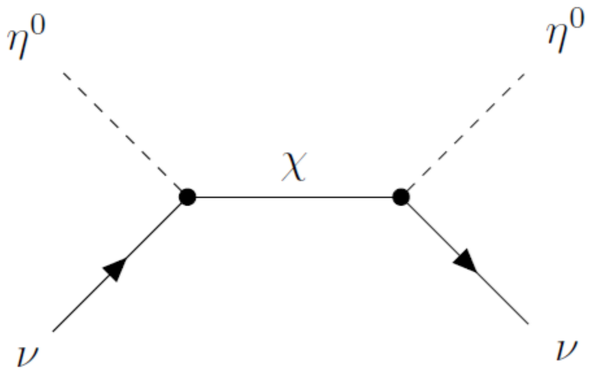
Probing the DM-neutrino scattering cross-section using neutrinos

DM-neutrino scattering

Much less studied. But natural in some models

♦ “Scotogenic” neutrino mass models: neutrino masses arise from interactions with the DM.

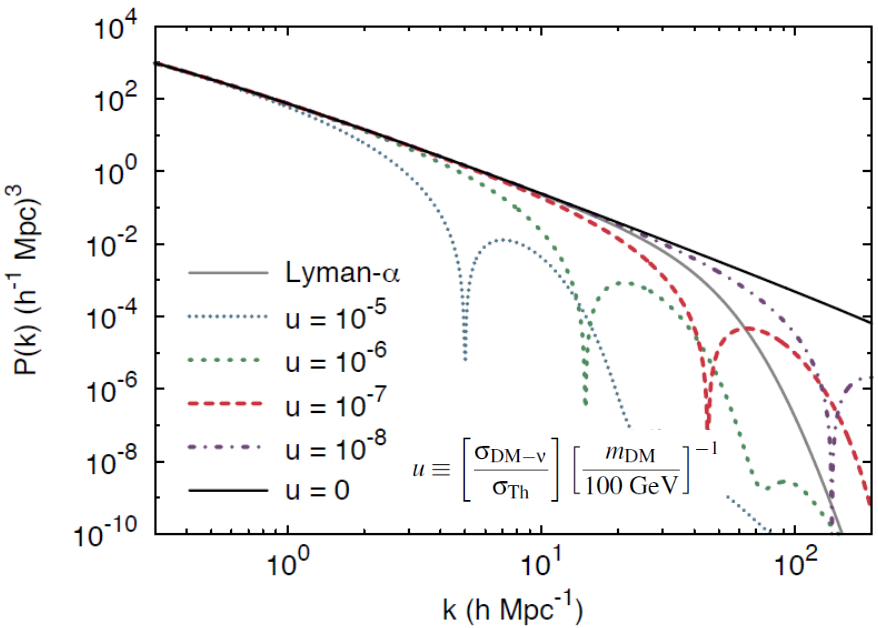




DM-neutrino scattering

- DM scattering with neutrinos?

Constraints from cosmology



Wilkinson, Boehm, Lesgourgues'13,14

$$\sigma_{DM-\nu} \lesssim 10^{-33}\,(m_{DM}/\mathrm{GeV})\ \mathrm{cm}^2$$

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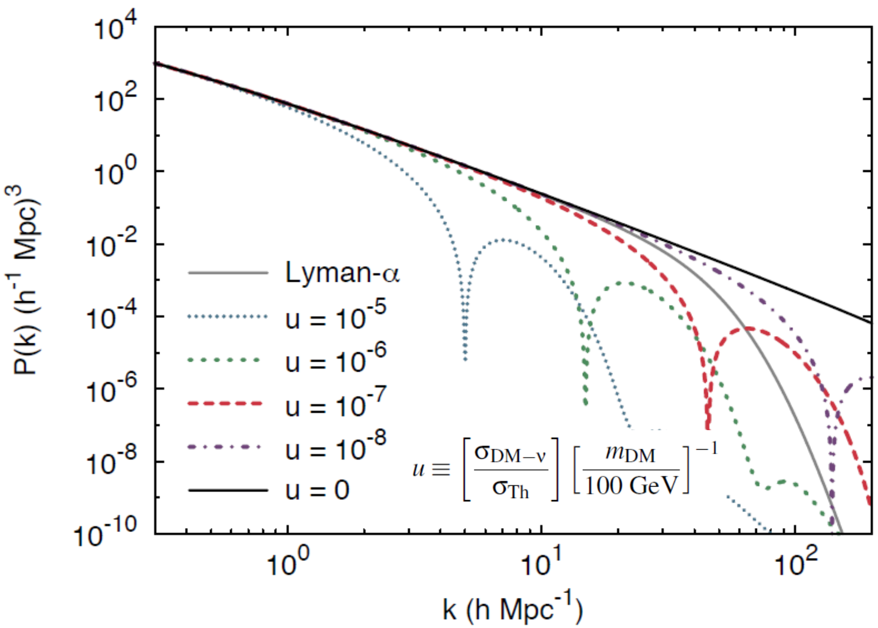

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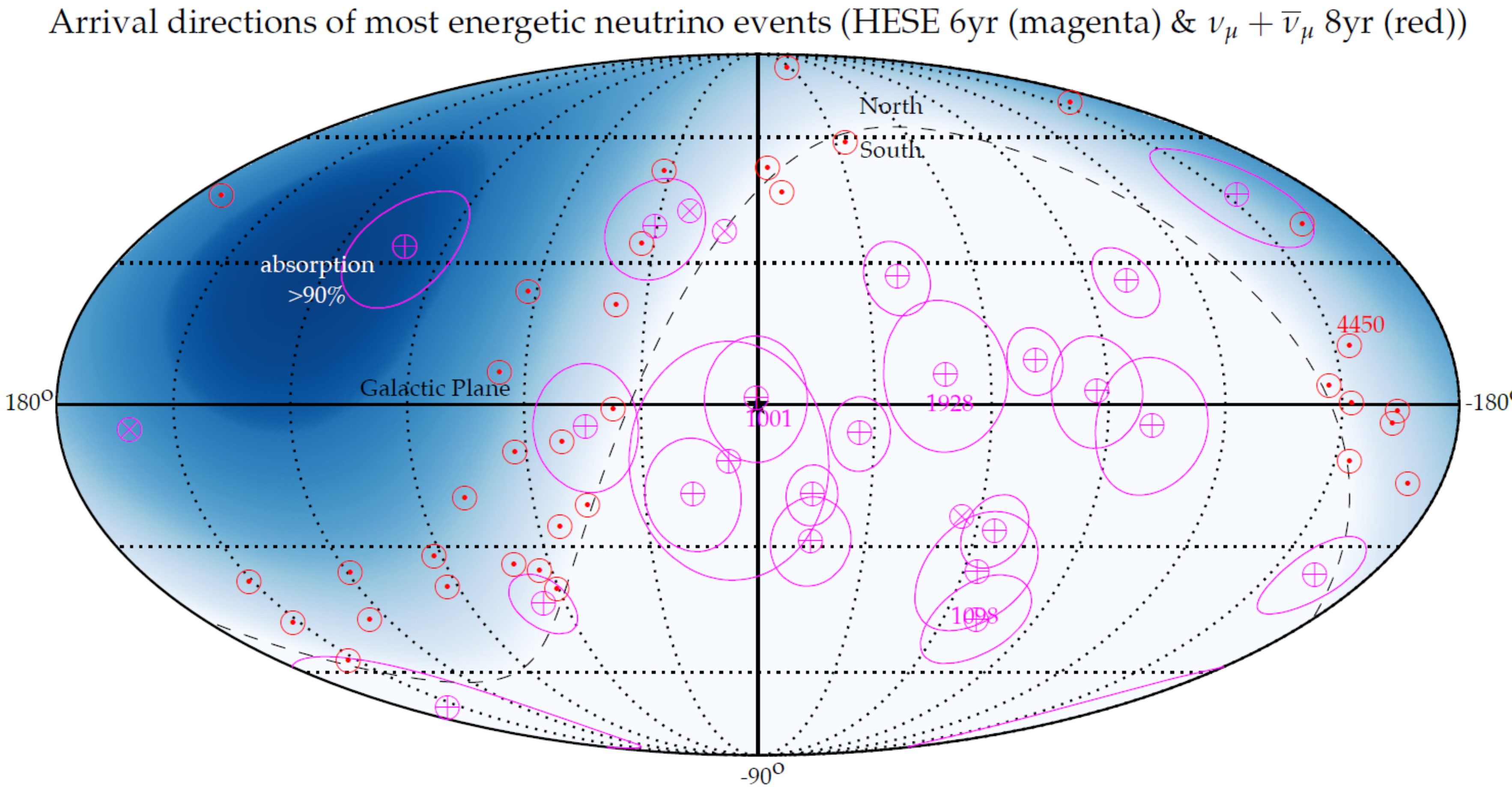
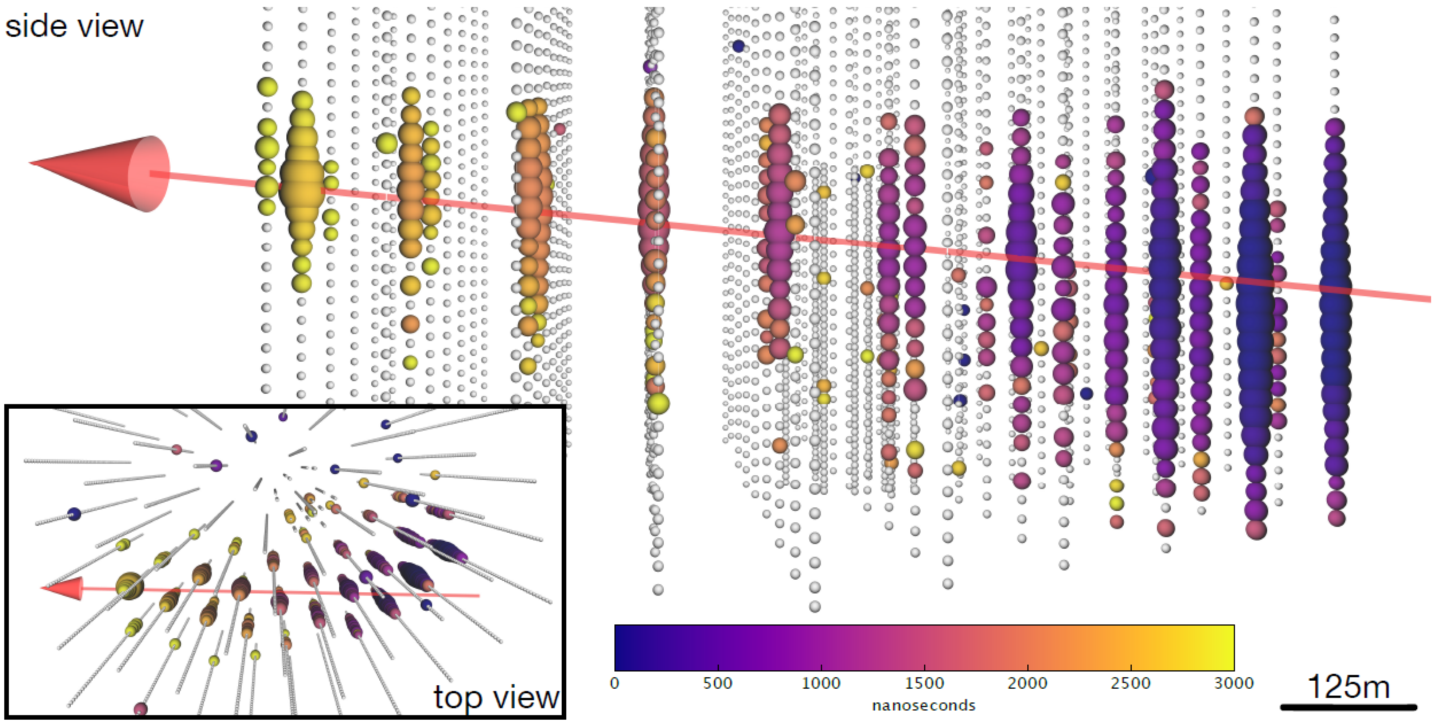
Other constraints from Astroparticle Physics?

A new era in neutrino astronomy



A new era in neutrino astronomy

- 22 September 2017: detection of the neutrino event IceCube-170922A, with an energy of 290 TeV



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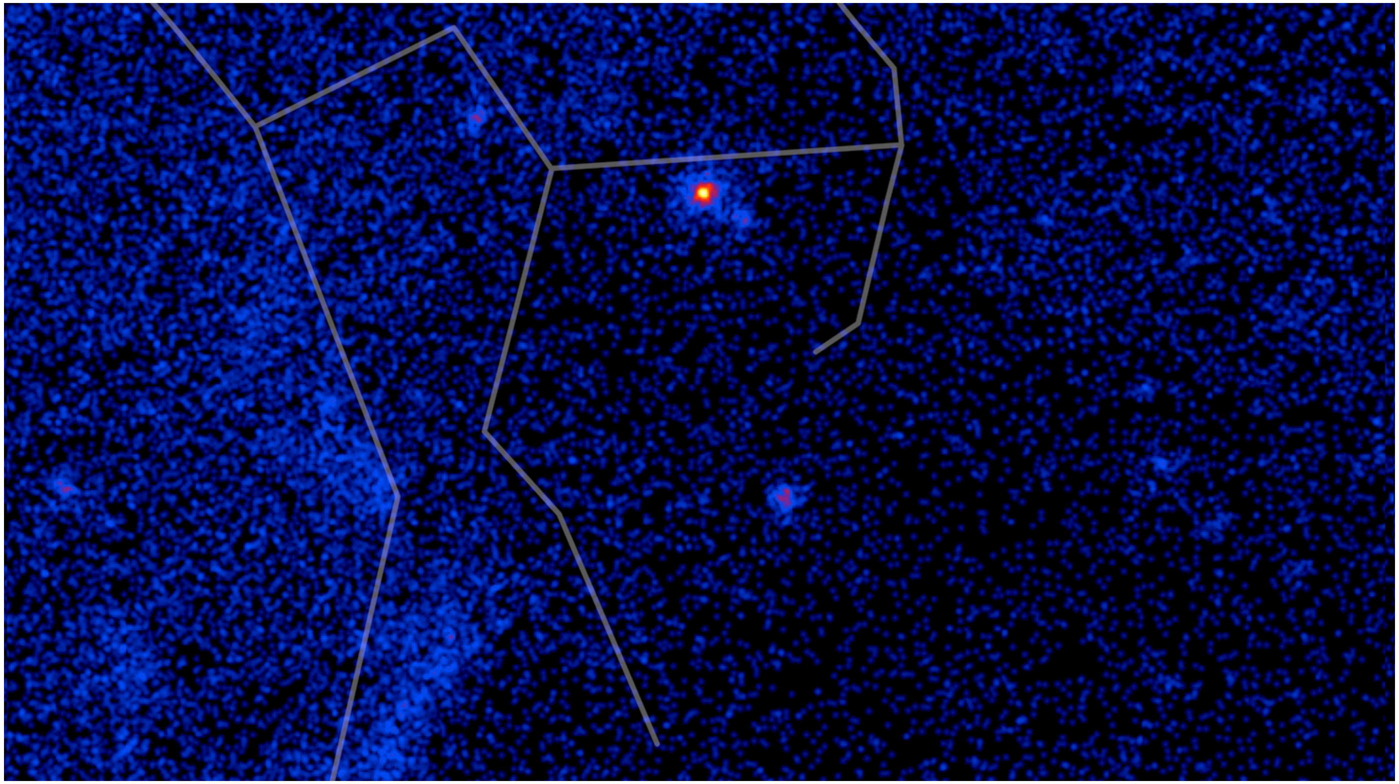
• The blazar TXS 0506+056 is located inside the error circle of IC-170922A. A multiwavelength observation campaign of TXS 0506+056 was initiated



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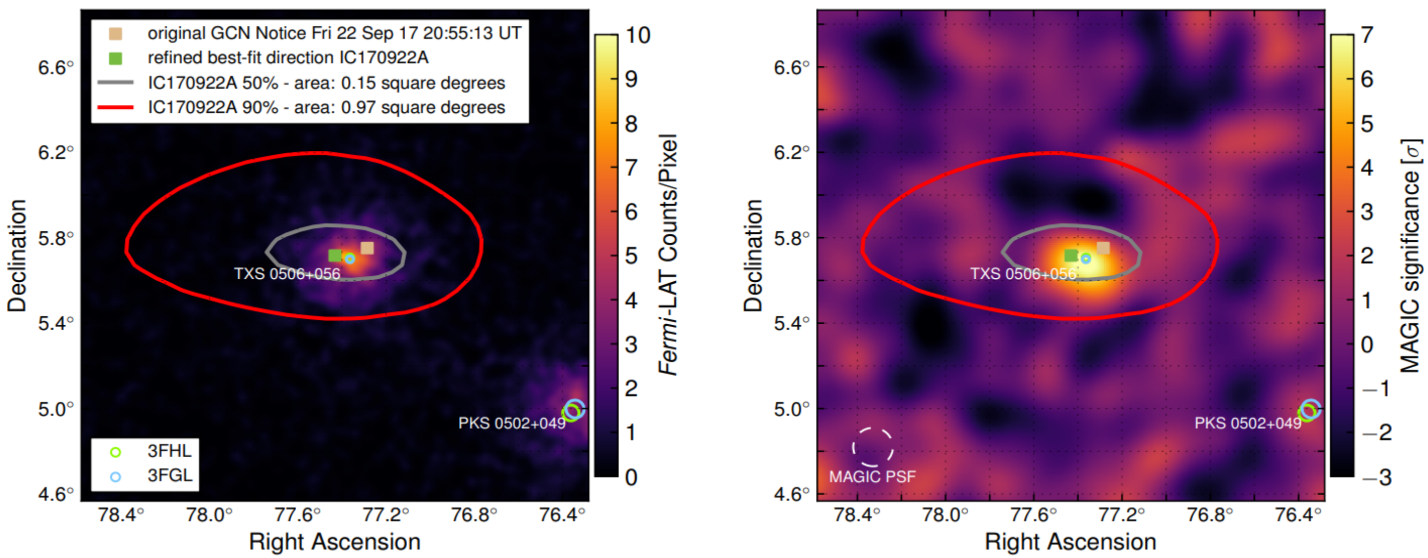

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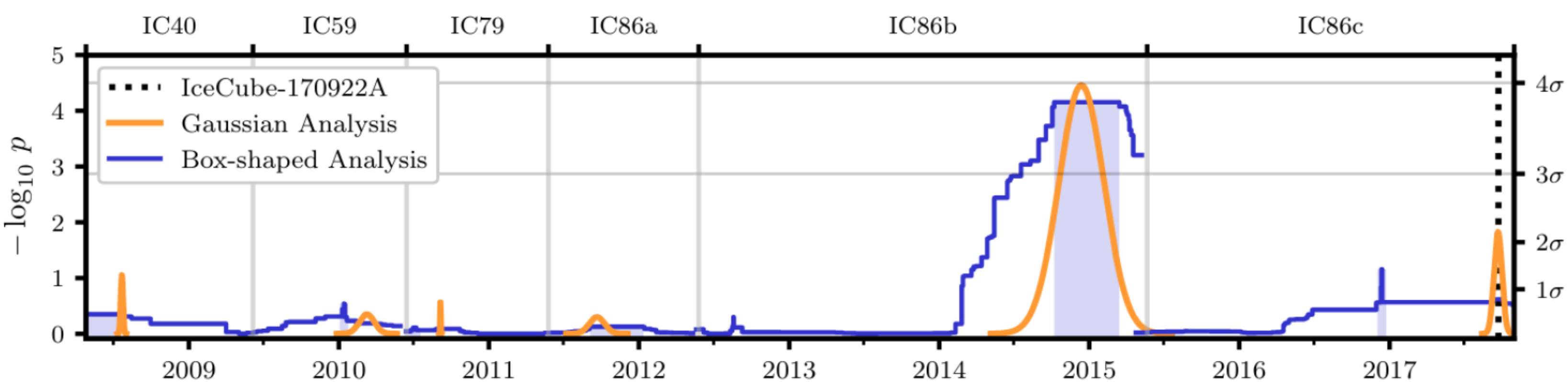

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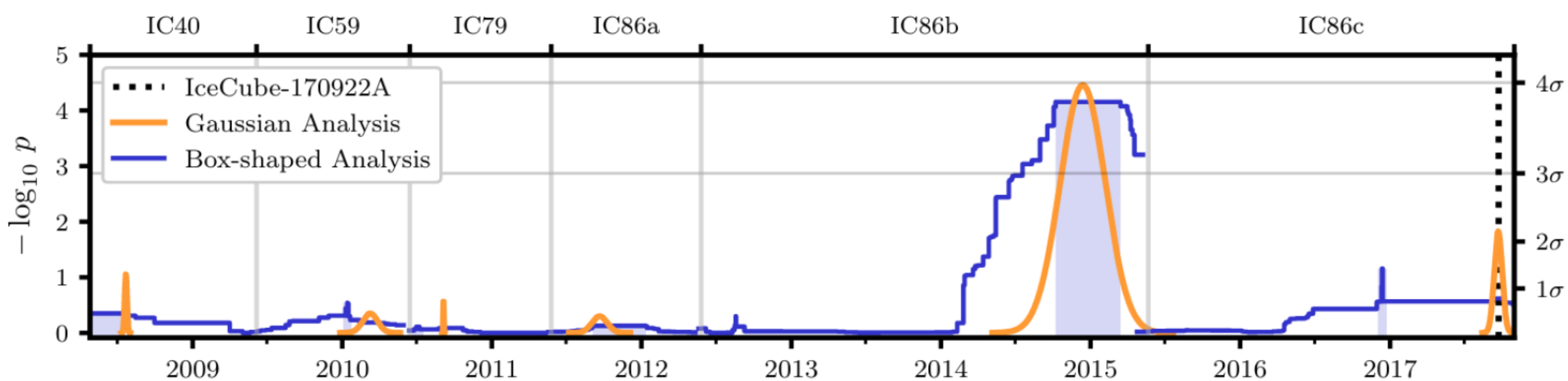
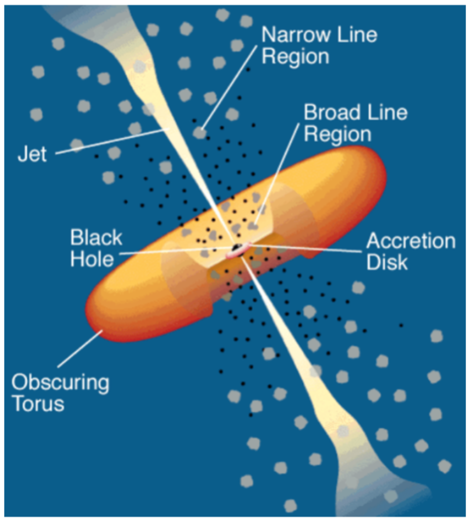
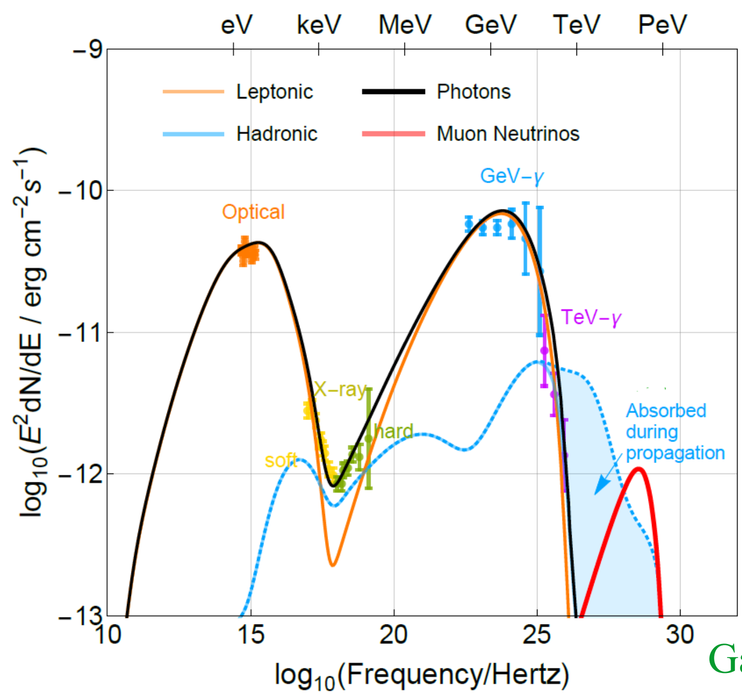


First identified source of high energy astrophysical neutrinos

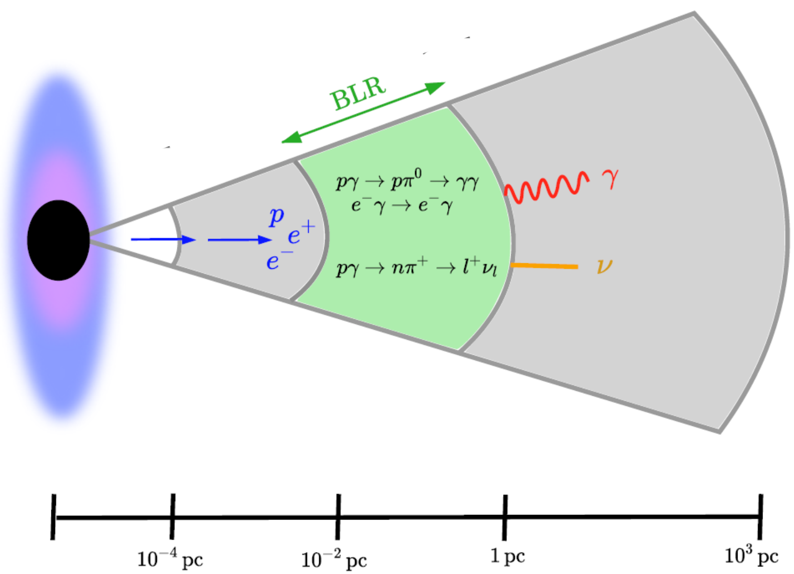
Photon and neutrino production in blazars

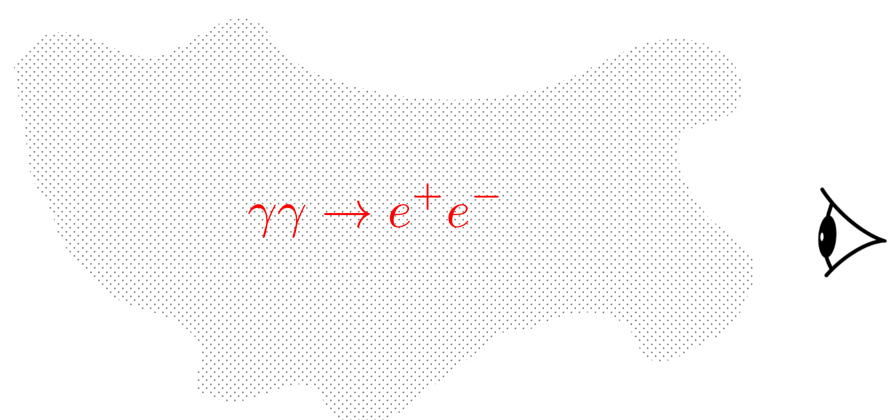
The neutrino and photon fluxes can be qualitatively well reproduced in leptohadronic models.





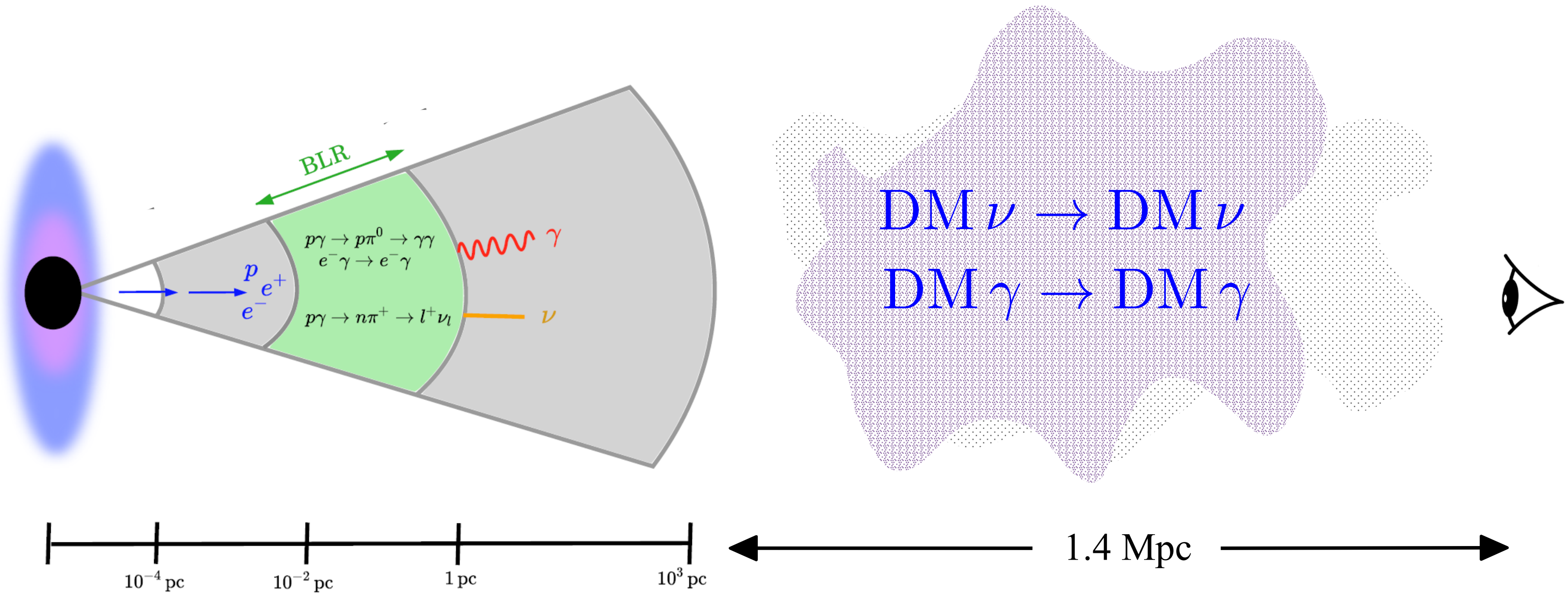
Gao et al'18





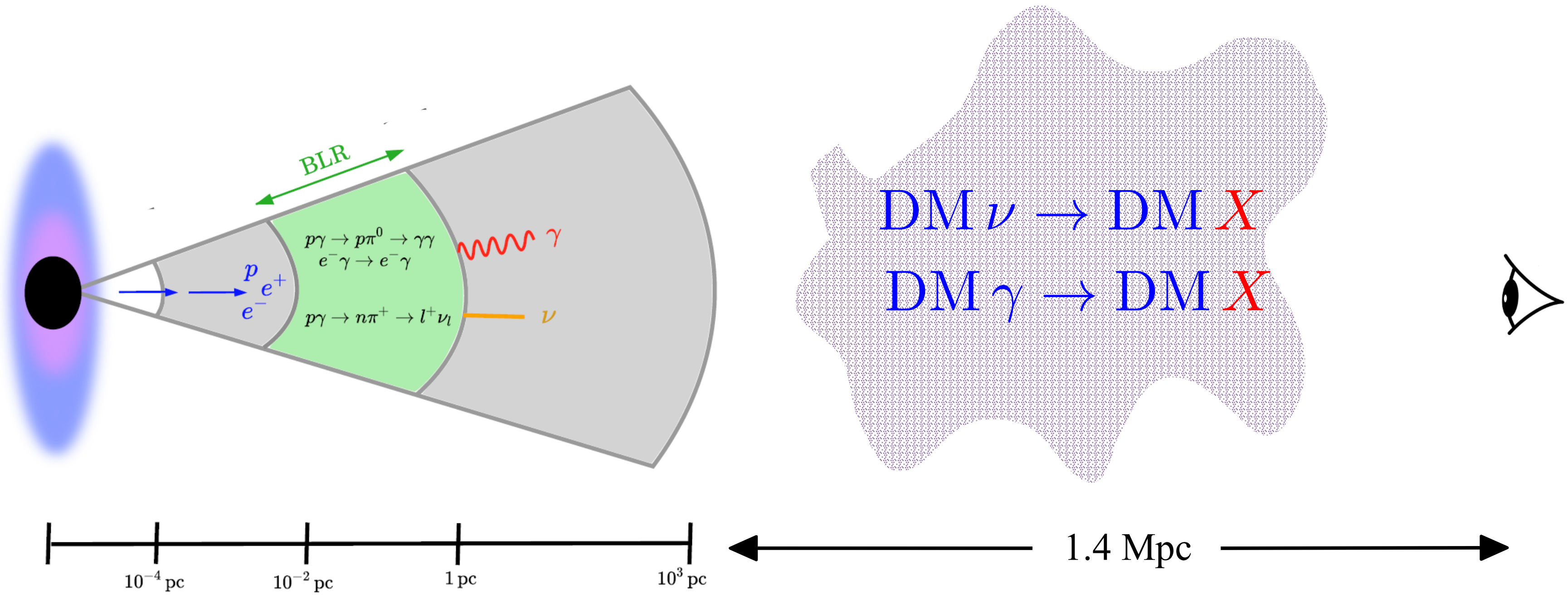
1.4 Mpc

Blazars as probes of the intergalactic medium



Neutrinos propagate through the intergalactic medium and through the Milky Way before reaching us. If the dark matter neutrino cross-section is large, the neutrino flux would be attenuated. Same with photons.

Blazars as probes of the intergalactic medium



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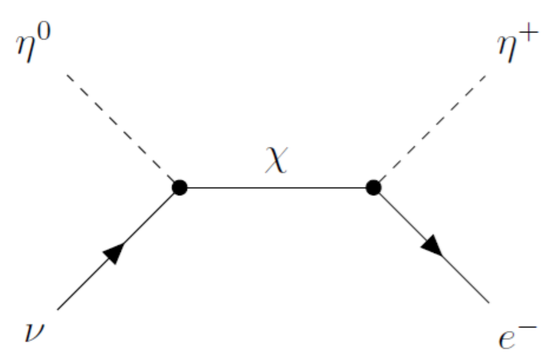
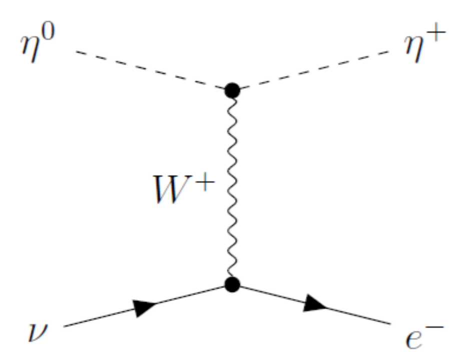
Note: the absorption could also be due to inelastic scatterings





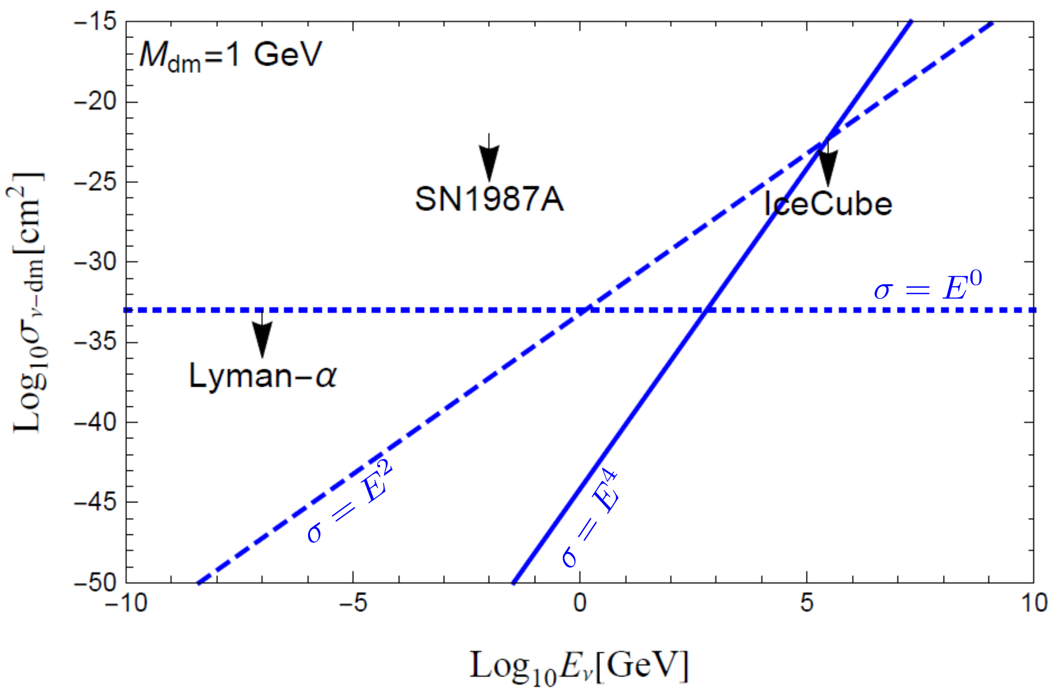
Blazars as probes of the intergalactic medium

- Flux attenuation $\frac{\Phi^{\rm obs}}{\Phi^{\rm em}} = \exp\left[-\sigma_{\rm DM-\nu}\Sigma_{\rm DM}\right]$

$\Sigma_{\rm DM} = \frac{1}{m_{\rm DM}}\int_{\rm path} dr\rho(\vec{r})$ is the number of DM particles along the path

- Require that the attenuation of the neutrino flux due to DM-neutrino scatterings is less than 90%:

$$\frac{\sigma_{\rm DM-\nu}}{m_{\rm DM}} \lesssim \frac{2.3}{\Sigma_{\rm DM}}$$



Choi, Kim, Rott'19
Kelly, Machado '19

The dark matter spike around TXS 0506+056

In the center of the blazar it is located a supermassive black hole, with mass ~ $3\times10^8\ M_{sun}$.

The growth of the black hole produces a "spike" in the dark matter distribution Gondolo, Silk'99, Peebles '72, Quinlan, Hernquist, Sigurdsson '95

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For TXS 0506+056, $R_{\rm sp} \sim 1\,{\rm pc}$

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Dark matter annihilations soften the spike to a saturation density, proportional to $\langle\sigma v\rangle$

$$\rho(r) = \begin{cases} 0 & r \leq 4R_S \\ \dfrac{\rho_{\rm sp}(r)\rho_{\rm sat}}{\rho_{\rm sp}(r)+\rho_{\rm sat}} & 4R_S \leq r \leq R_{\rm sp} \\ \rho_0\left(\dfrac{r}{r_0}\right)^{-\gamma}\left(1+\dfrac{r}{r_0}\right)^{-3+\gamma} & r \geq R_{\rm sp} \end{cases}$$

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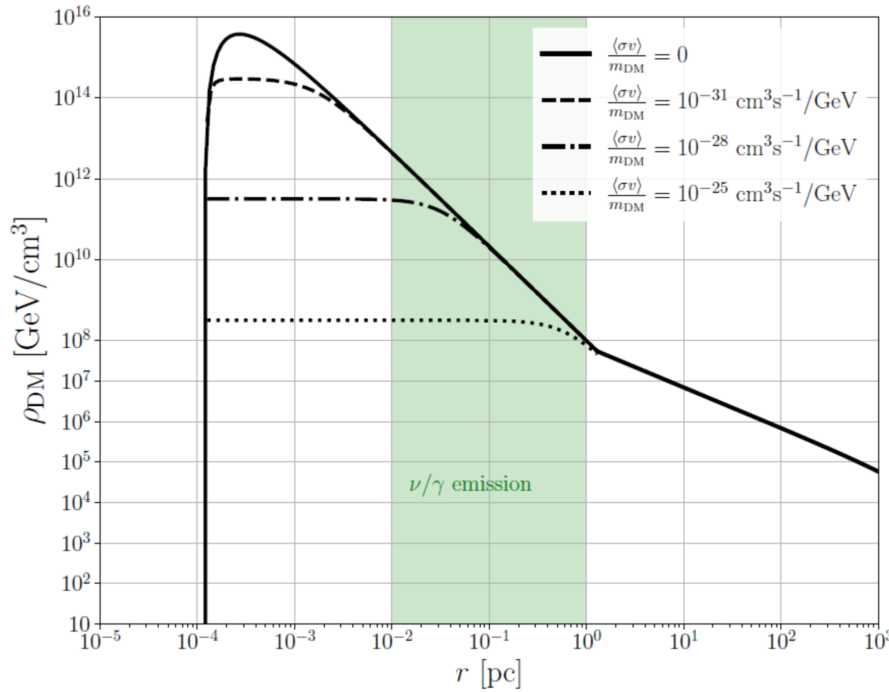
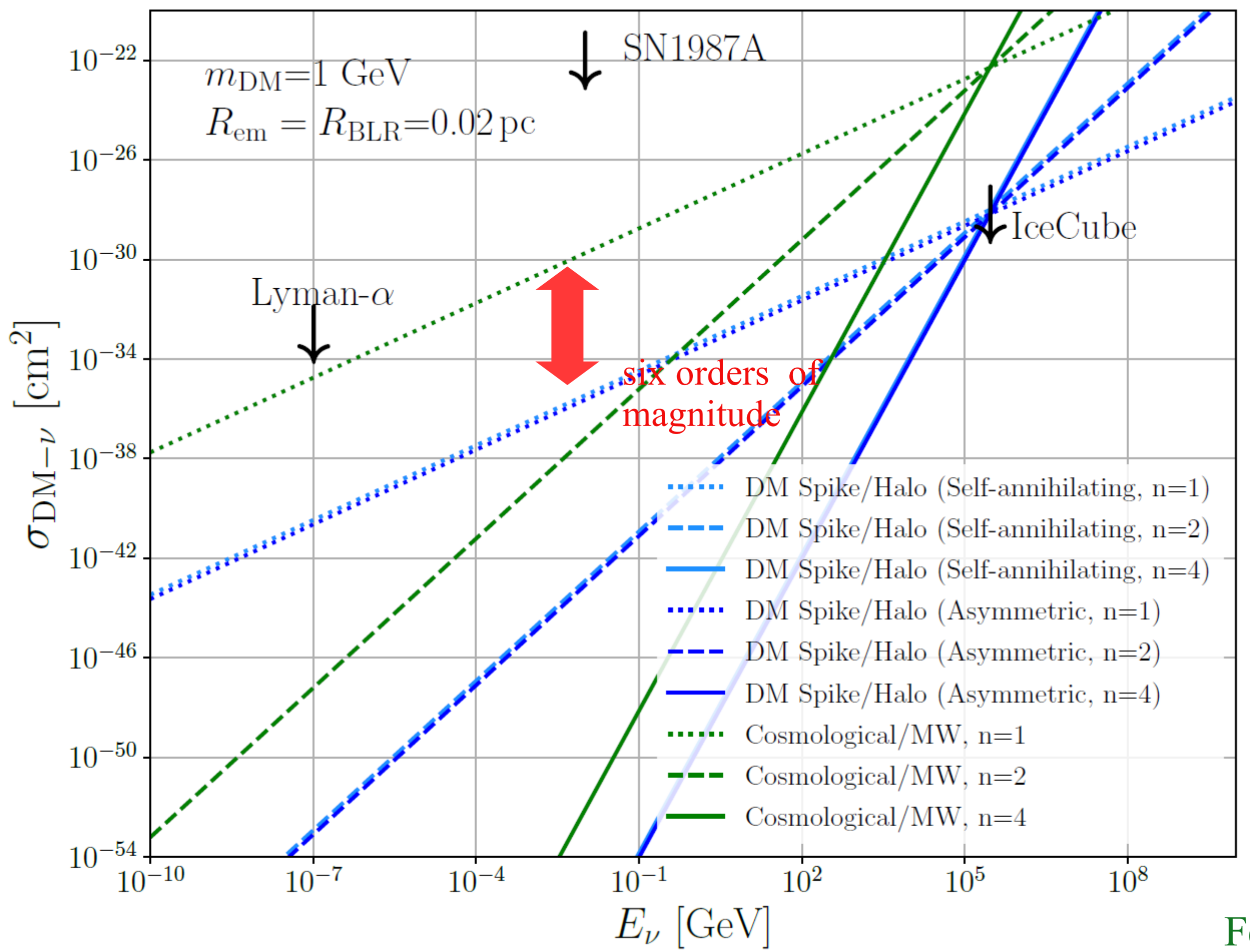


Ferrer, Herrera, AI'22

The region of emission of neutrinos and photons lies inside the dark matter spike ⇒ Increase in the column density.

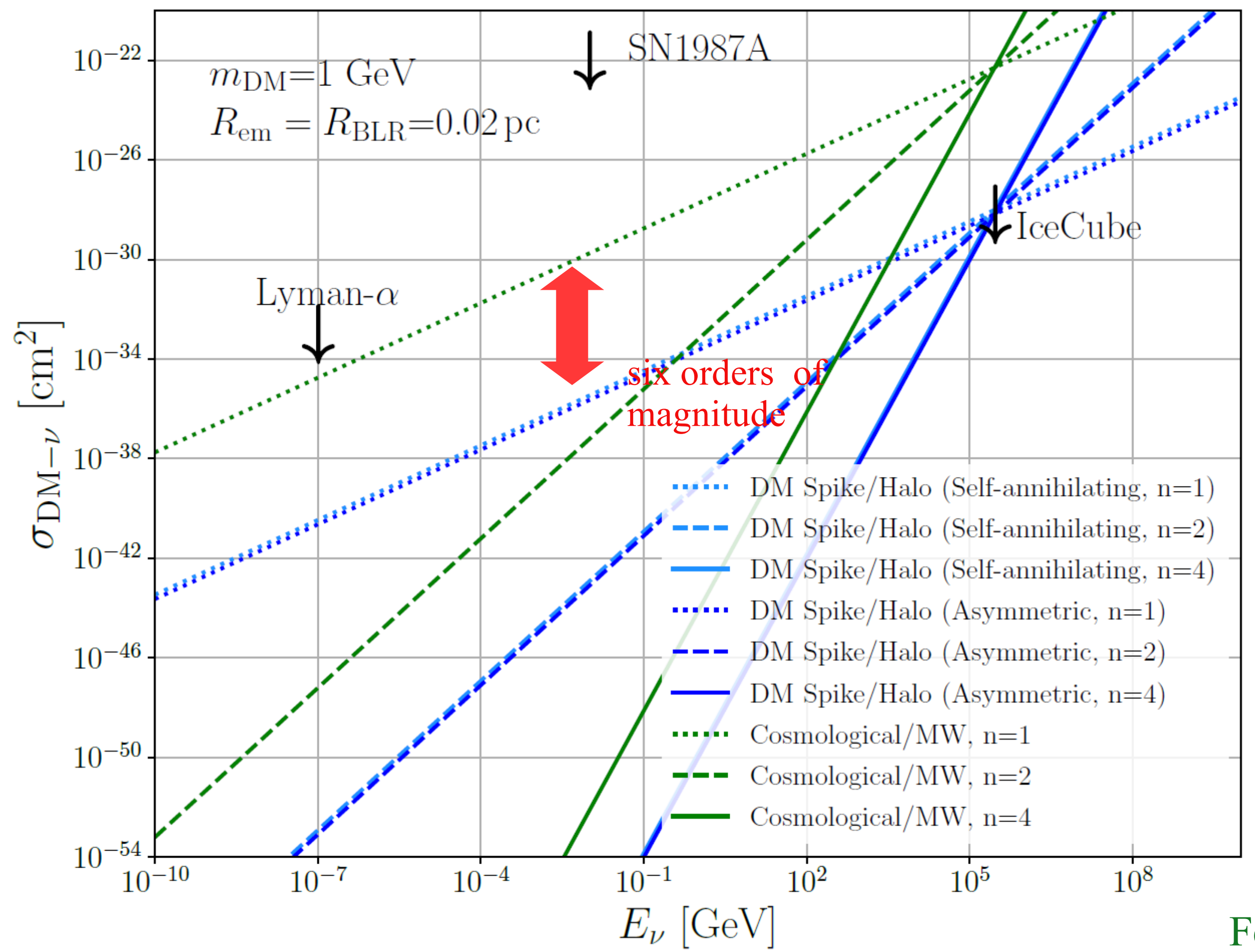
Probing the scattering cross-section with neutrinos



Ferrer, Herrera, AI'22
See also Cline et al'22

Complementarity with other searches?

Probing the scattering cross-section with neutrinos



Ferrer, Herrera, AI'22
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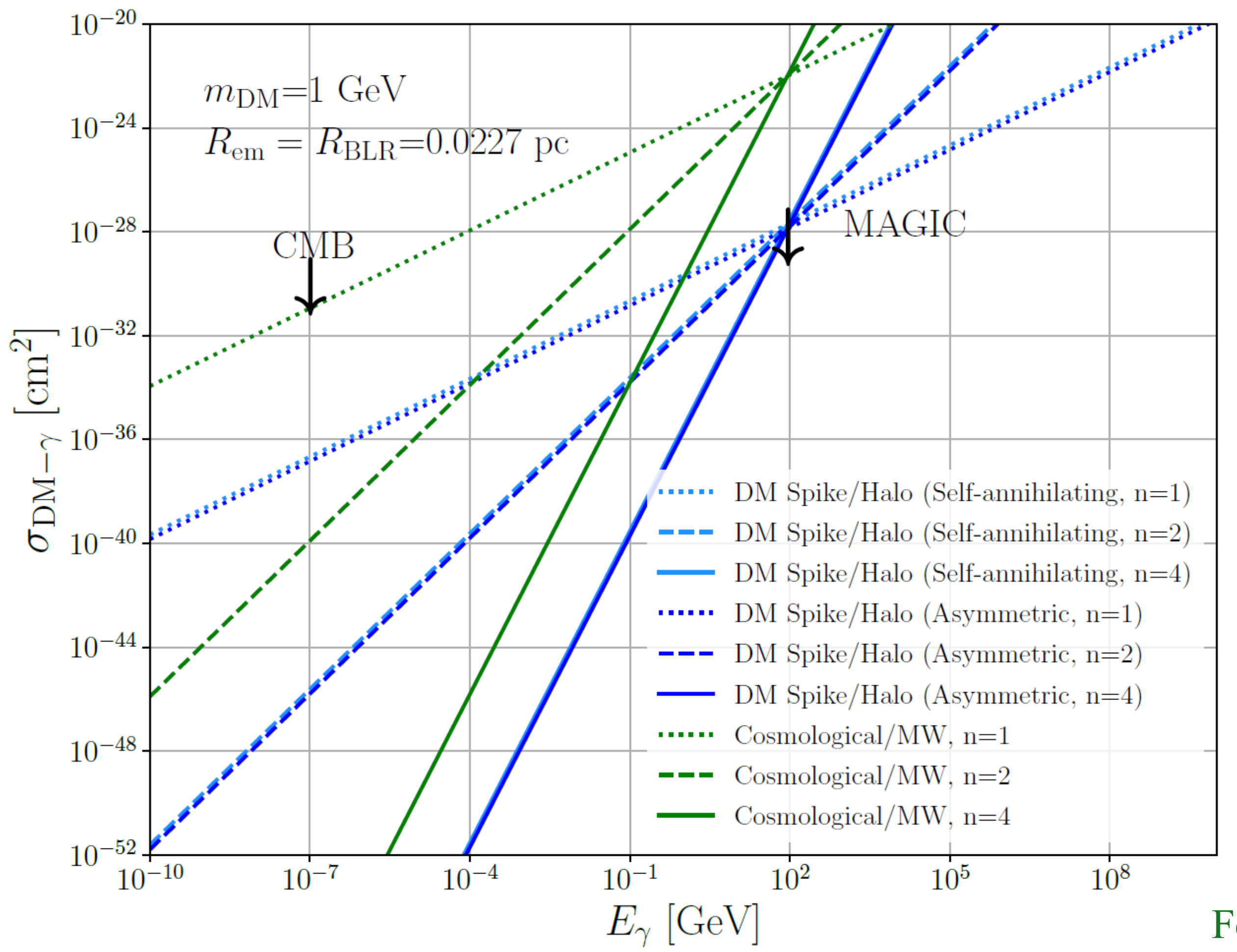
Complementarity with other searches?

Better and more robust limits could be obtained as more and more high energy ν sources are discovered.

Probing the scattering cross-section with photons



Ferrer, Herrera, AI'22

Conclusions

• After 40+ years of search, there is still no concluding evidence that dark matter is made of elementary particles.

• Neutrino telescopes could provide hints for dark matter, especially if dark matter annihilates mostly into neutrinos, and when dark matter interacts with nucleons via the spin-dependent interaction.

• The recent discovery of high energy astrophysical neutrino sources by IceCube opens new opportunities to probe dark matter properties, and new opportunities to probe neutrino mass models.