Neutrino signals from dark matter spikes

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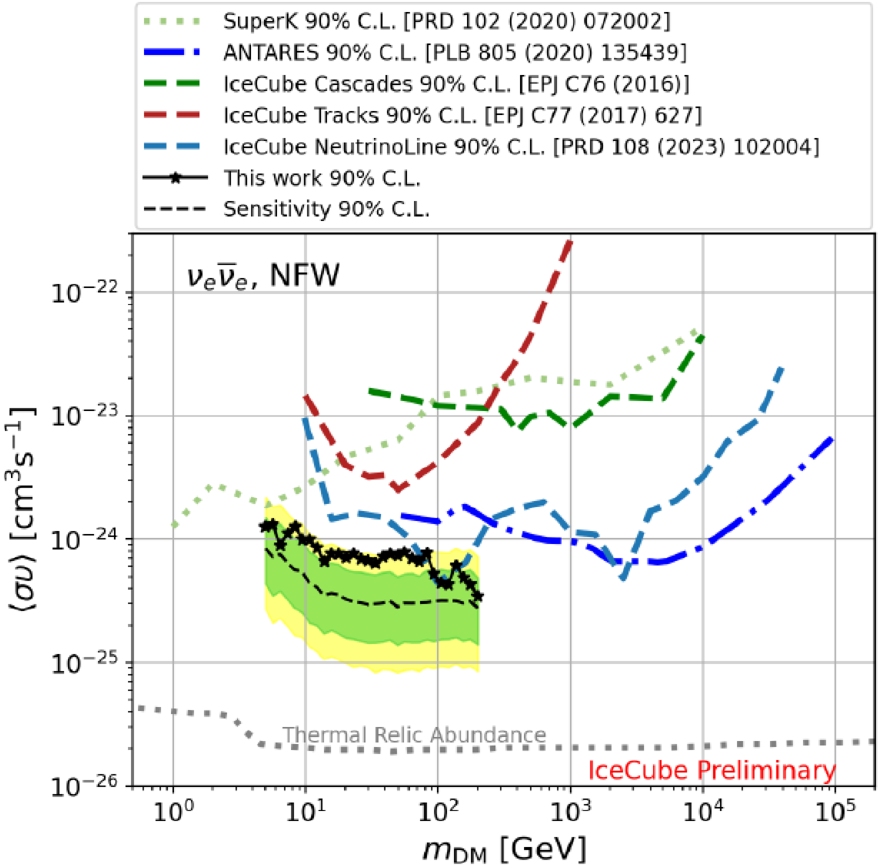
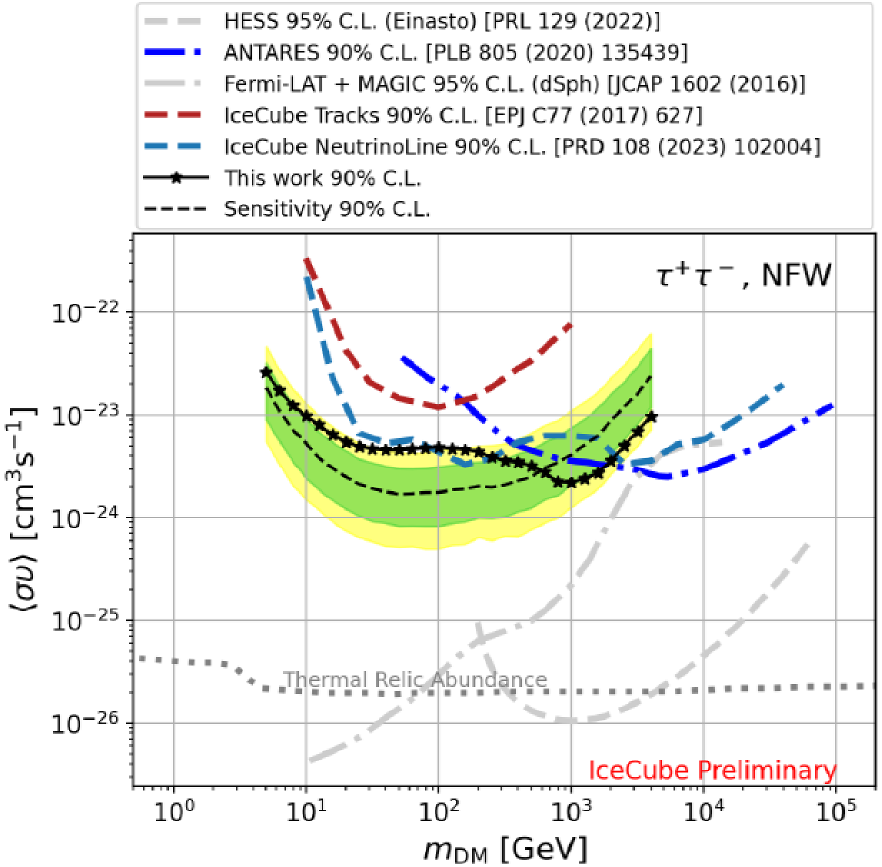
Dark matter searches with neutrinos

For 20+ years, neutrino telescopes have been searching for dark matter annihilation into neutrinos in the Milky Way center.





IceCube collaboration, ICRC2025

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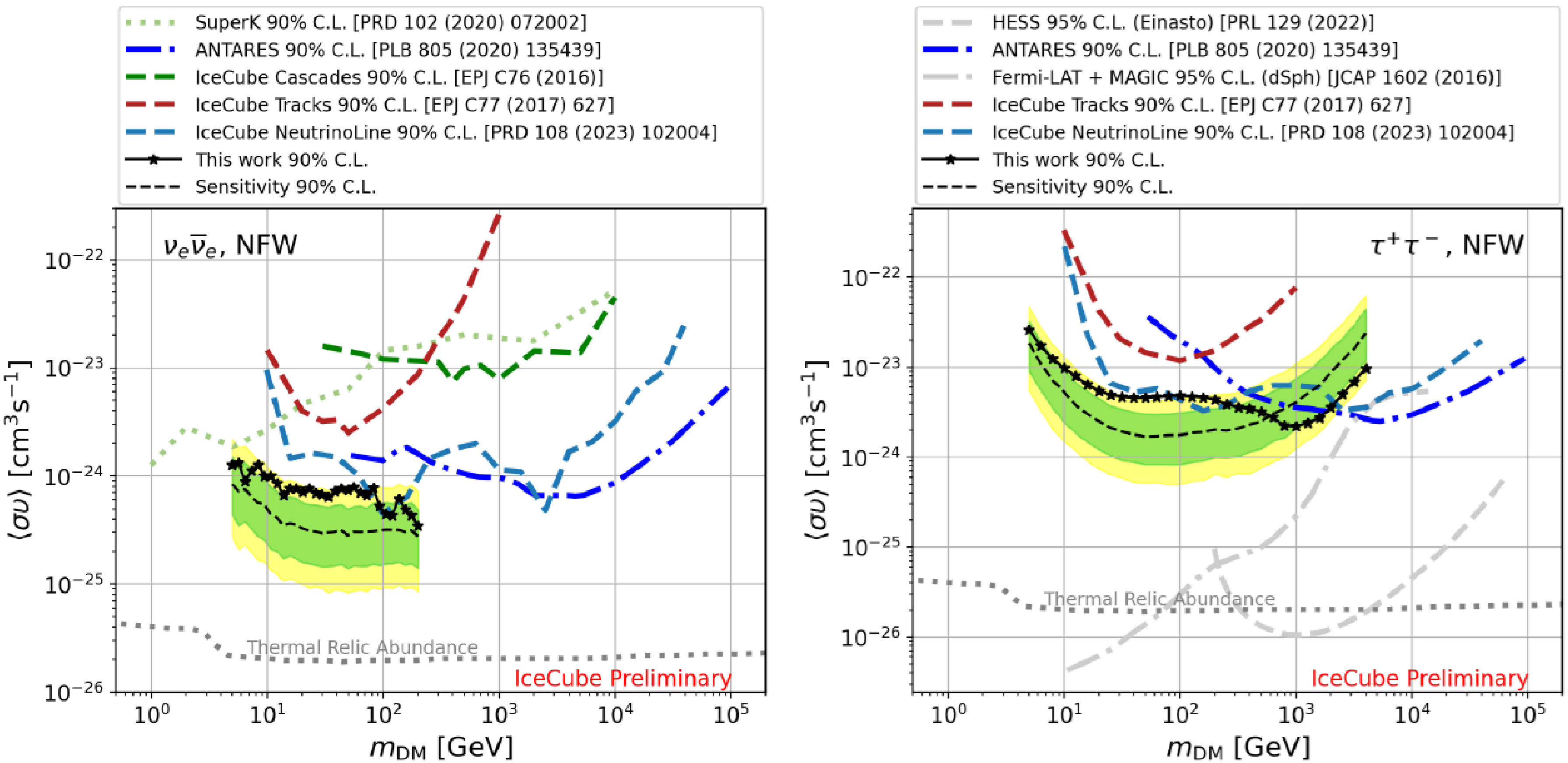

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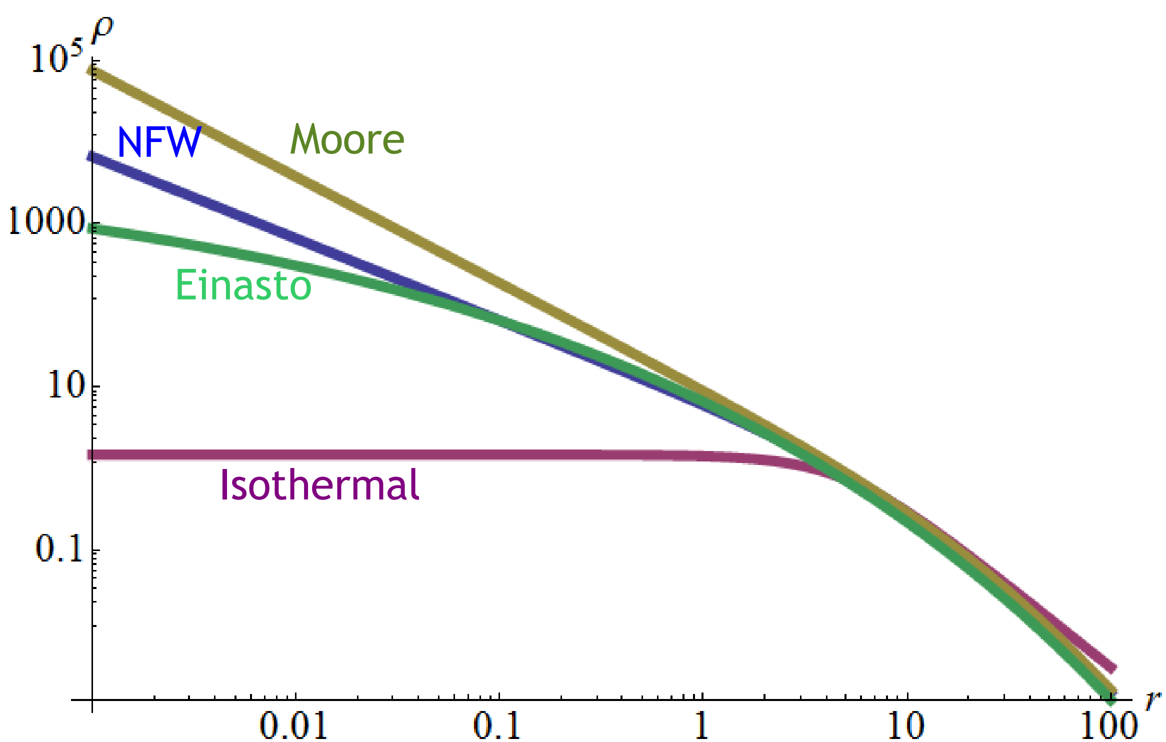
Note: DM could carry lepton number (⇒ automatically stable for scalar DM).
If this is the case, only the annihilation $\nu\nu$ can occur, but not $\tau^+\tau^-$.

Dark matter searches with neutrinos

A crucial assumption in the calculation of the fluxes is the DM halo profile.

Universal shape derived from numerical N-body simulations, and free parameters determined from astronomical observations.



$$\rho(r) = \frac{\rho_0}{(r/r_c)^\gamma [1 + (r/r_c)^\alpha]^{(\beta-\gamma)/\alpha}}$$

Halo model	α	β	γ	r_c (kpc)
Navarro, Frenk, White	1	3	1	20
Isothermal	2	2	0	3.5
Moore	1.5	3	1.5	28

Einasto

$$\rho(r) = \rho_0 \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^\alpha - 1\right)\right]$$

$\alpha = 0.17, \ r_s = 20$ kpc

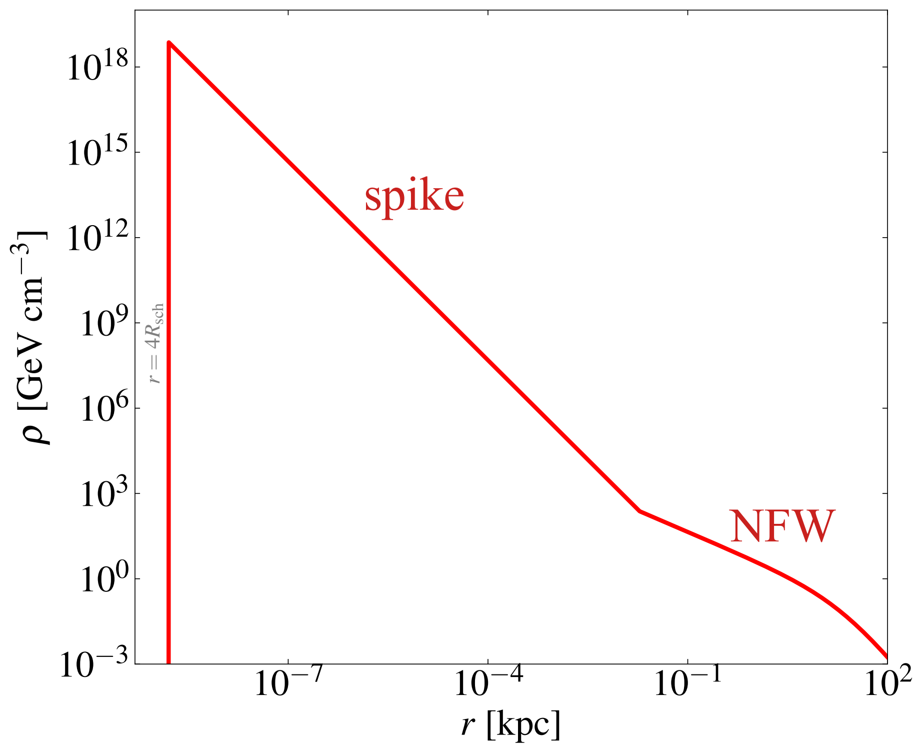
However, DM simulations cannot resolve the innermost parts of the galaxy

The DM spike around supermassive black holes

Most galaxies contain a supermassive black hole at its center.

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

$$\rho(r) \sim \rho_0 \left(\frac{r_0}{r}\right) \longrightarrow \rho_{\rm sp} \sim \rho_R \left(\frac{R_{\rm sp}}{r}\right)^{7/3}$$



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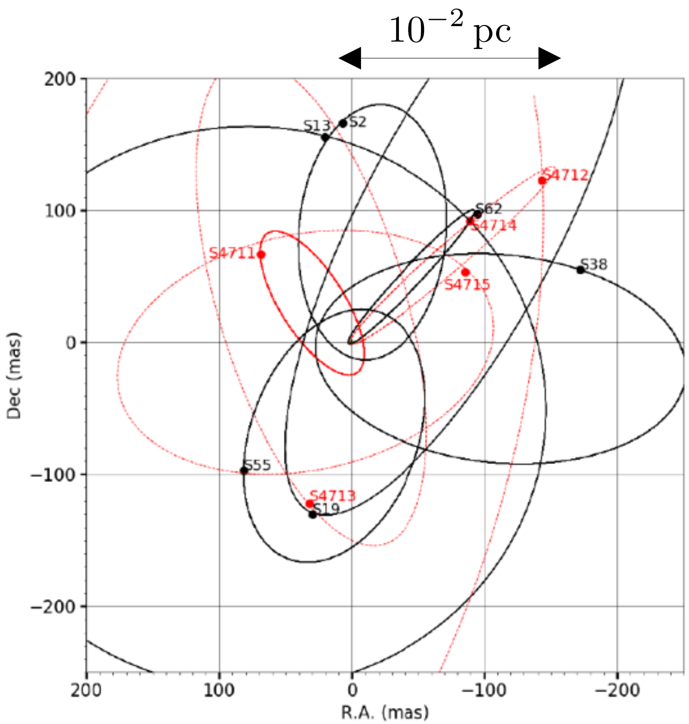
Dark matter annihilations soften the spike to a saturation density, $\rho_{\rm sat} = m_{\rm DM}/(\langle\sigma v\rangle t_{\rm BH})$

$$\rho(r) = \begin{cases} 0 & r \leq 4R_S \\ \dfrac{\rho_{\rm sp}(r)\rho_{\rm sat}}{\rho_{\rm sp}(r) + \rho_{\rm sat}} & 4R_S \leq r \leq R_{\rm sp} \\ \rho_0 \left(\dfrac{r}{r_0}\right)^{-1} \left(1 + \dfrac{r}{r_0}\right)^{-2} & r \geq R_{\rm sp} \end{cases}$$

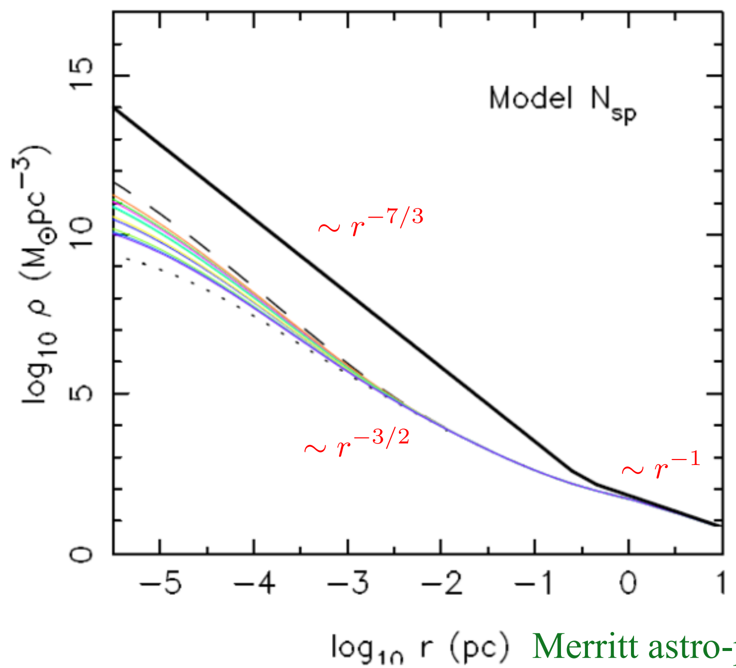
Larger annihilation rate than when assuming just NFW

The Milky Way dark matter spike

The Milky Way is known to contain stars orbiting very close to the supermassive black hole. Stellar heating significantly softens the spike.



Peißker et al, arXiv:2008.04764



Merritt astro-ph/0311594
Bertone, Merritt astro-ph/0501555

The DM spike at the MW center leads to an annihilation boost factor.

Relevant when the angular resolution of the instrument is very good.

	γ_c	γ_{sp}	r_c	$\rho(R_\odot)$	$\log_{10} \bar{J}_3$ $(\bar{J}_5)$ $\tau = 0$	$\tau = 10$	$\tau = 10$
N	1.0	–	–	0.3	2.56 (3.51)	2.56 (3.50)	2.56 (3.50)
N_c	1.0	–	10	0.3	2.54 (3.33)	2.54 (3.33)	2.54 (3.33)
N_{sp}	1.0	2.33	–	0.3	9.21 (11.2)	3.86 (5.84)	2.56 (3.52)
$N_{c,sp}$	1.0	2.29	10	0.3	6.98 (8.98)	2.61 (3.88)	2.54 (3.33)

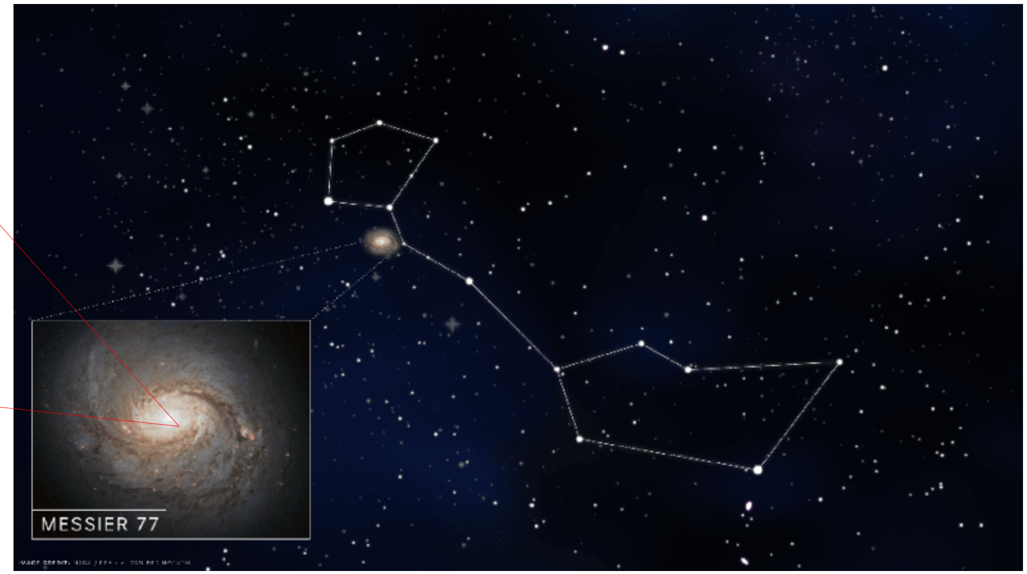
Other galaxies might <u>not</u> host stars orbiting close to their centers.

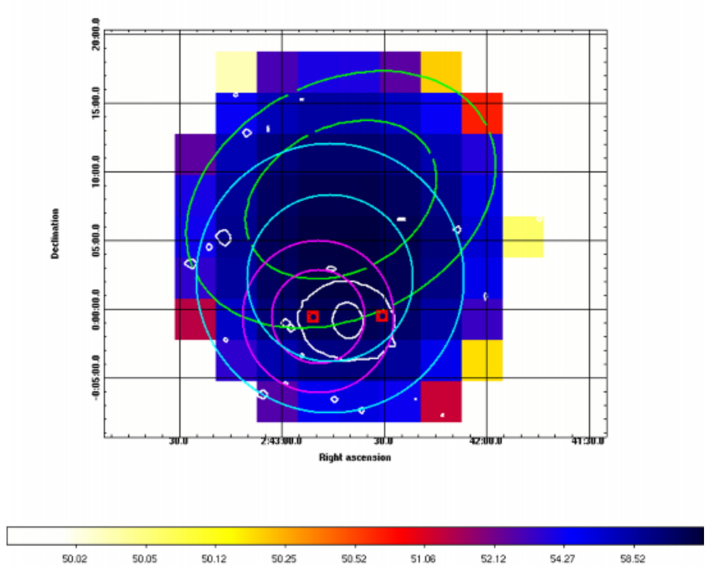
Their dark matter spike might remain intact today

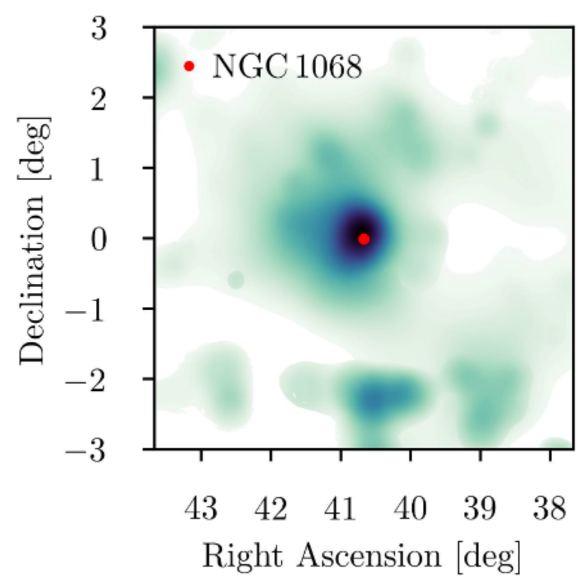
The larger rate of annihilation could compensate for their larger distance, and become potential targets for dark matter detection.

A dark matter signal from NGC 1068?

IceCube has detected a 4.2σ neutrino excess in the range 1.5-15 TeV in the direction of the Seyfert galaxy NGC 1068, located at 14.4 Mpc from the Earth.







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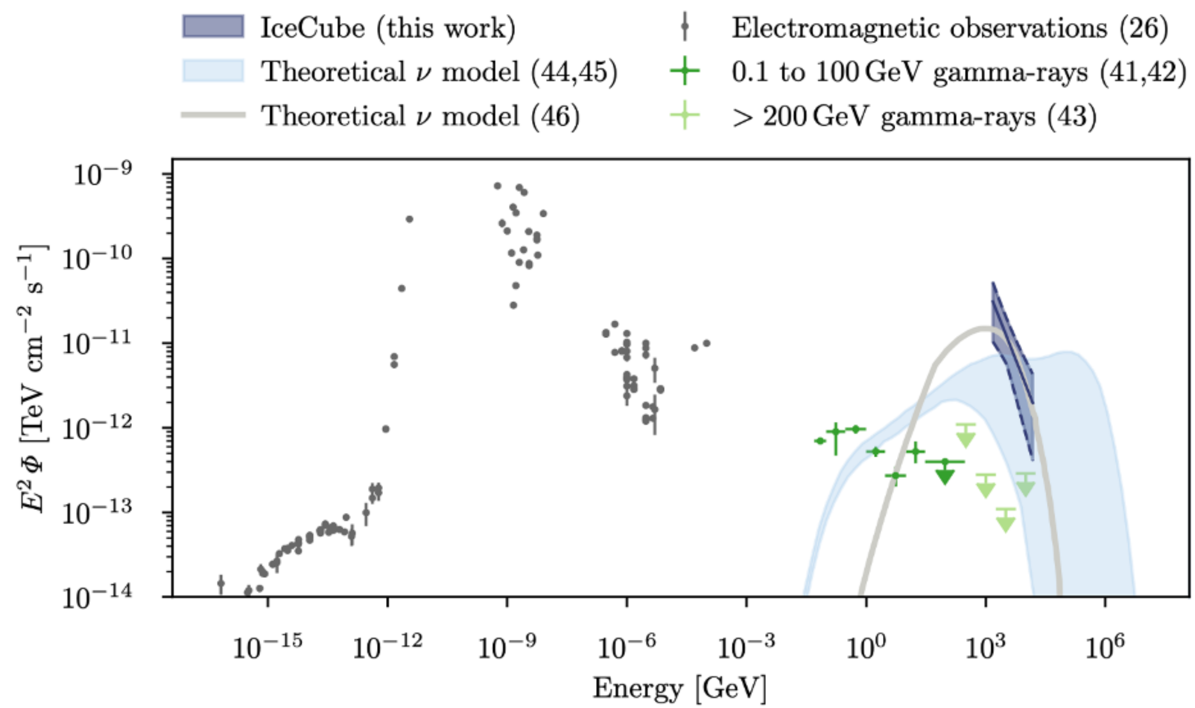
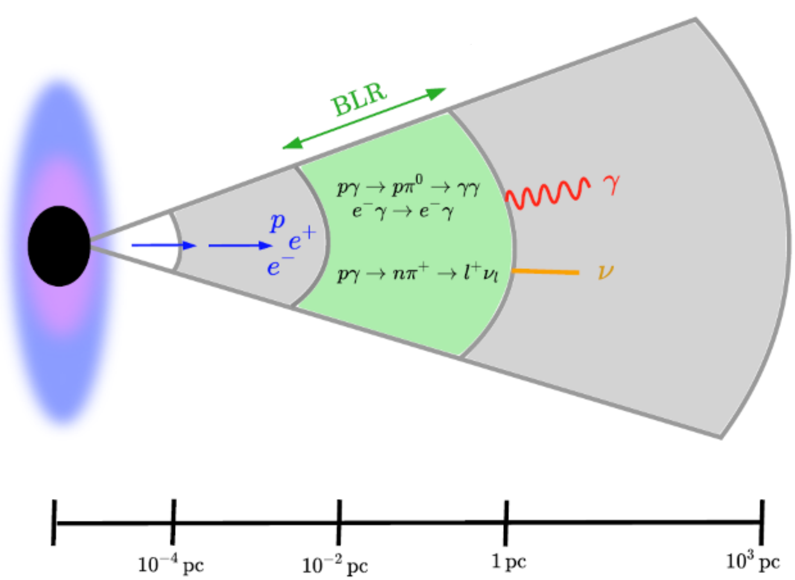
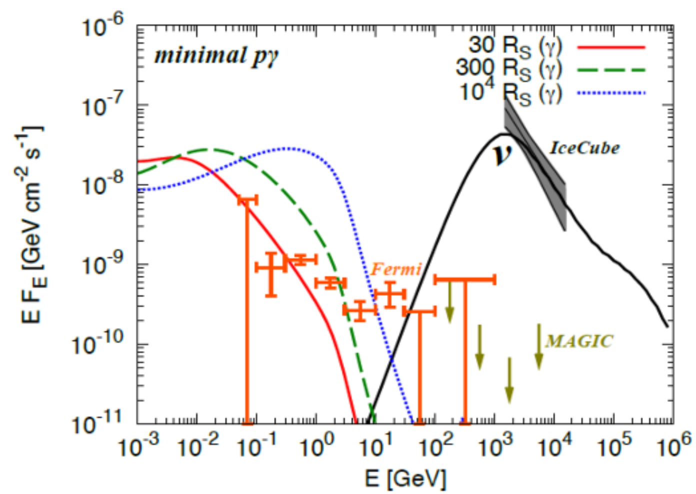


IceCube coll'22





Murase'22

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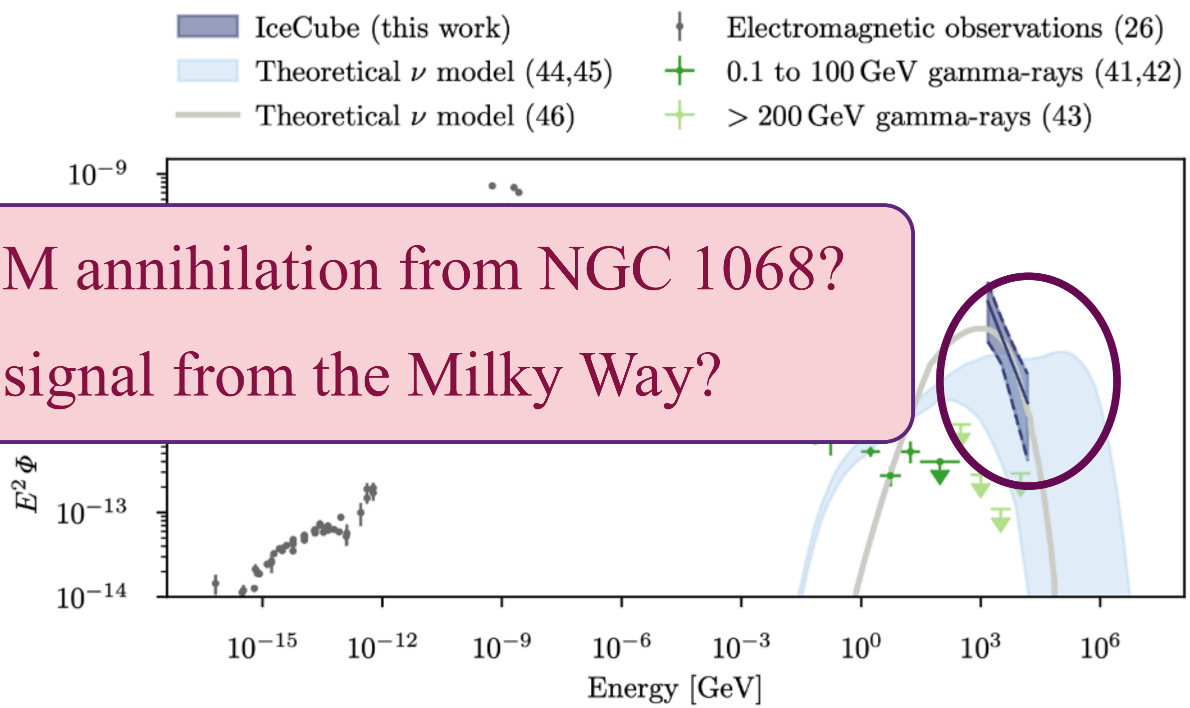
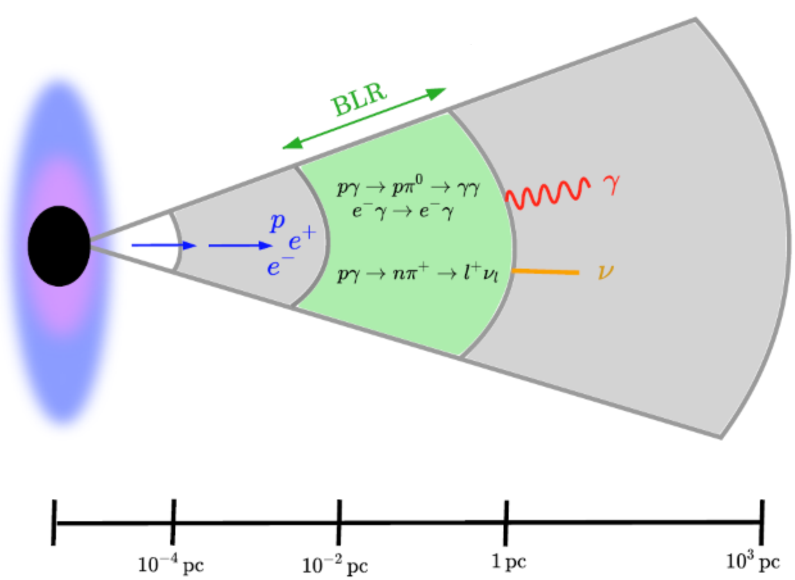
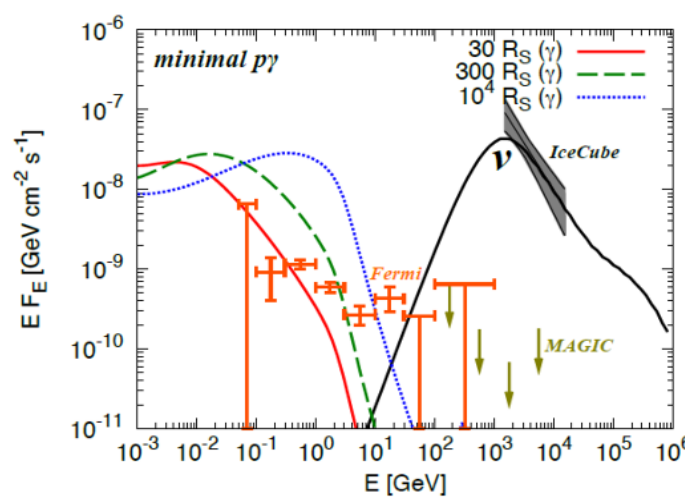


A signal of DM annihilation from NGC 1068?

Why no signal from the Milky Way?

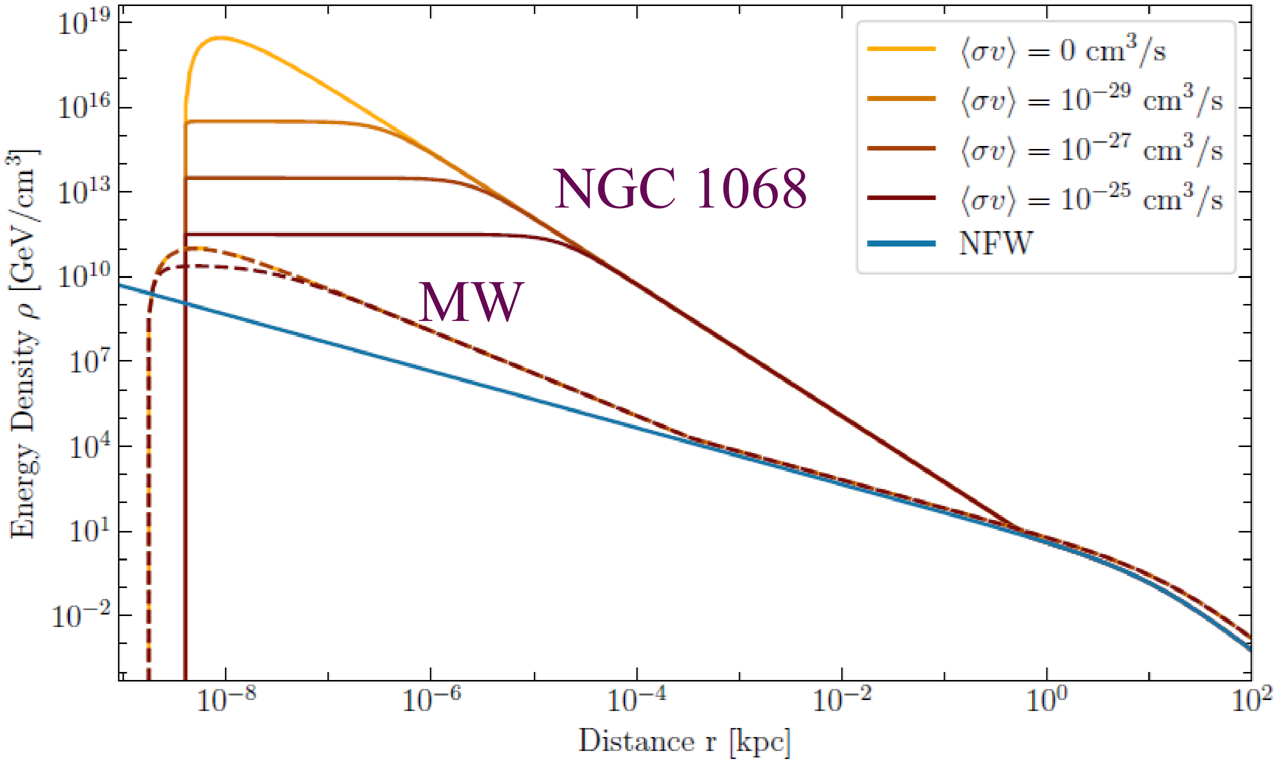
IceCube coll'22





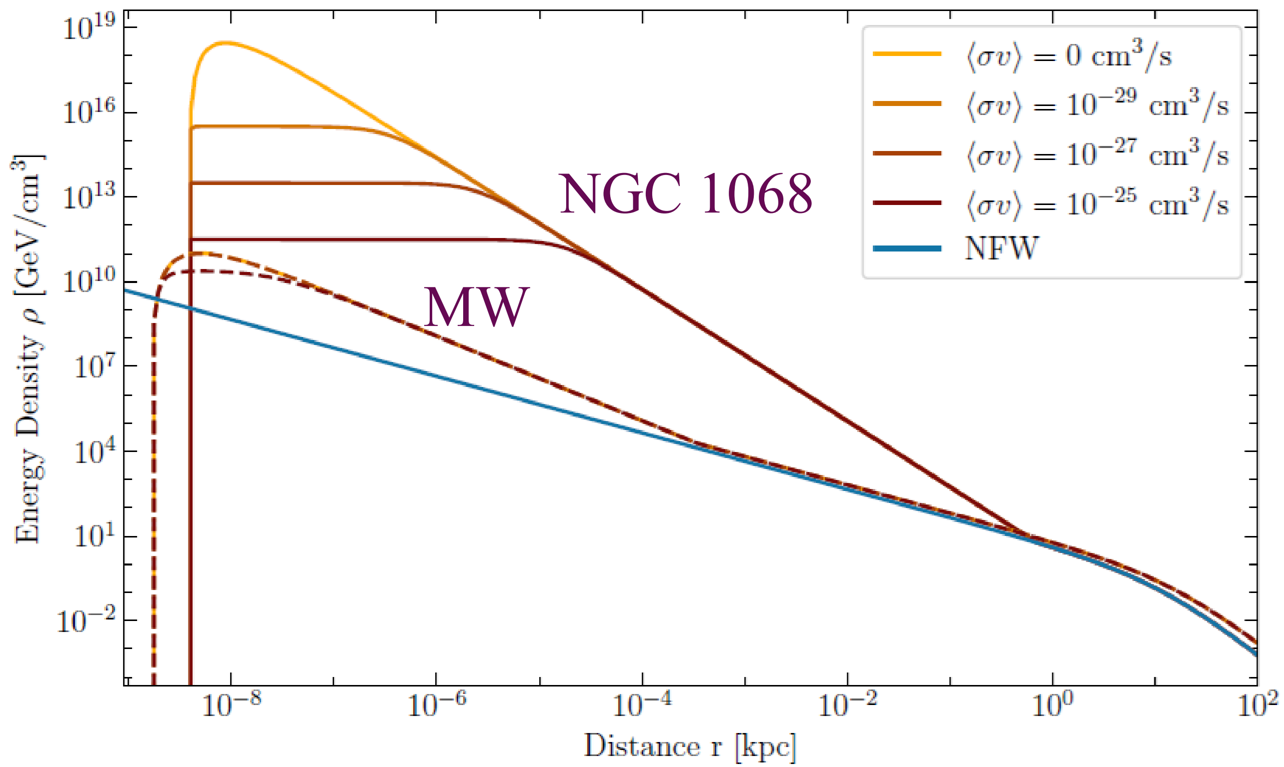
Murase'22

Dark matter profiles of NGC 1068 and the MW



The spike of the MW is for sure affected by stellar heating. We assume that the spike of NGC 1068 is not.

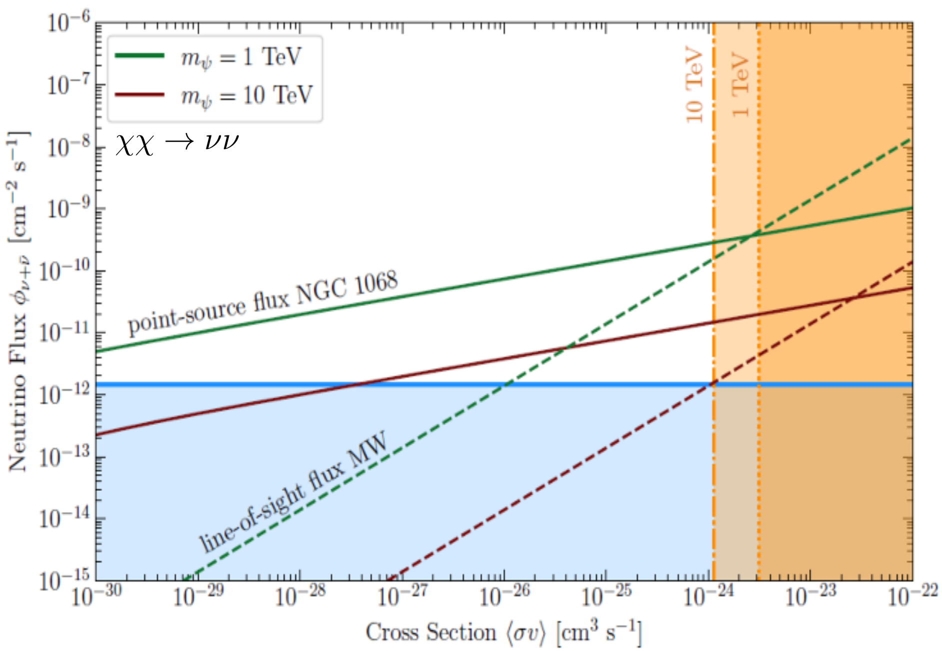
Dark matter profiles of NGC 1068 and the MW

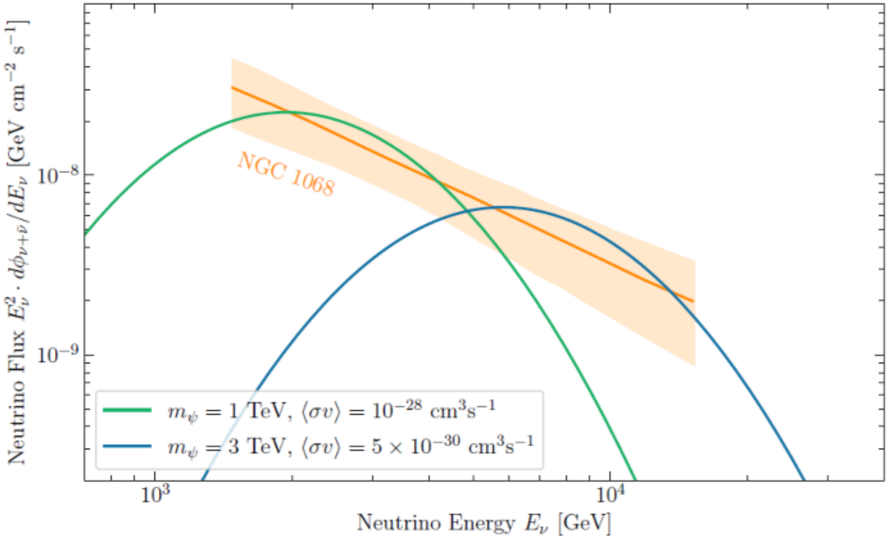


The spike of the MW is for sure affected by stellar heating. We assume that the spike of NGC 1068 is not.

- NGC 1068 has an active nucleus, but not the Milky Way.
- The radiation and winds from the active nucleus heat up the gas and expel cold gas from the center of the galaxy, preventing star formation.

Implications for neutrino fluxes





- Dark matter annihilations in the spike could produce a neutrino flux detectable at Earth as a point source (for reasonable values of the cross-section).
- The neutrino flux produced in the Milky Way center could be below the sensitivity of current experiments due to the effect of the stellar heating on the spike.

Nearby galaxies (especially active galaxies) are potentially interesting targets for dark matter annihilation.

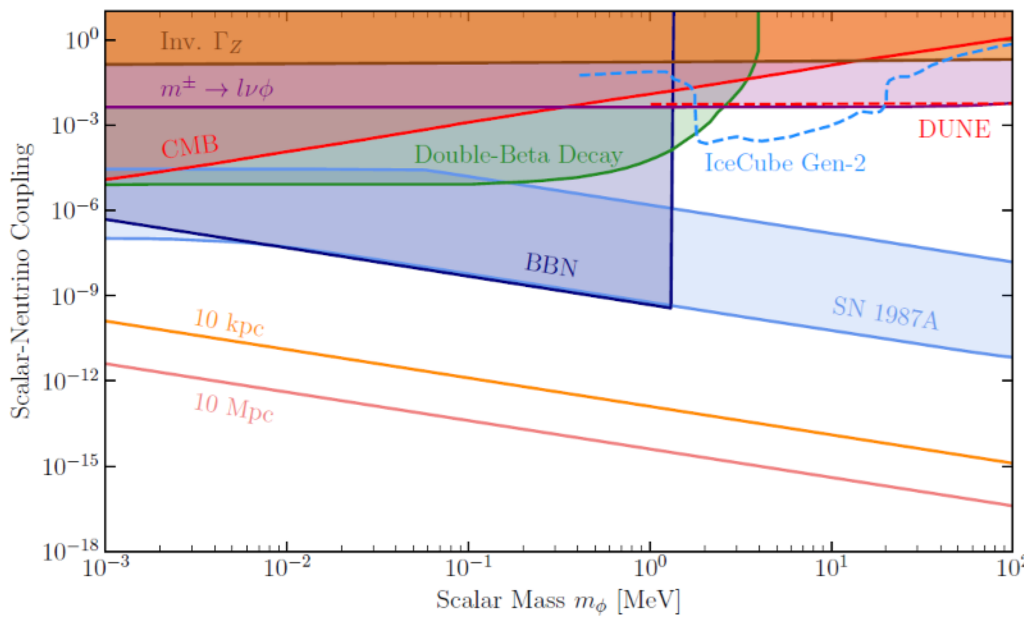
An alternative explanation

- Consider dark matter annihilation into a very light scalar: $\chi\chi \to \phi\phi$
- If ϕ is very light it can only decay into neutrinos, or into photons at one loop). The annihilation produces mostly neutrinos

- Since ϕ is light and is produced with a large boost, its decay length can be extremely long.

$$c\tau \simeq \frac{8\pi}{g^2}\frac{m_\psi}{m_\phi^2} \simeq 16\,\mathrm{kpc}\left(\frac{g}{10^{-12}}\right)^{-2}\left(\frac{m_\psi}{1\ \mathrm{TeV}}\right)\left(\frac{m_\phi}{100\ \mathrm{keV}}\right)^{-2}$$

- If the decay length is larger than ~10 kpc but smaller than ~10 Mpc, no signal from the MW center, but possible signals from NGC 1068.



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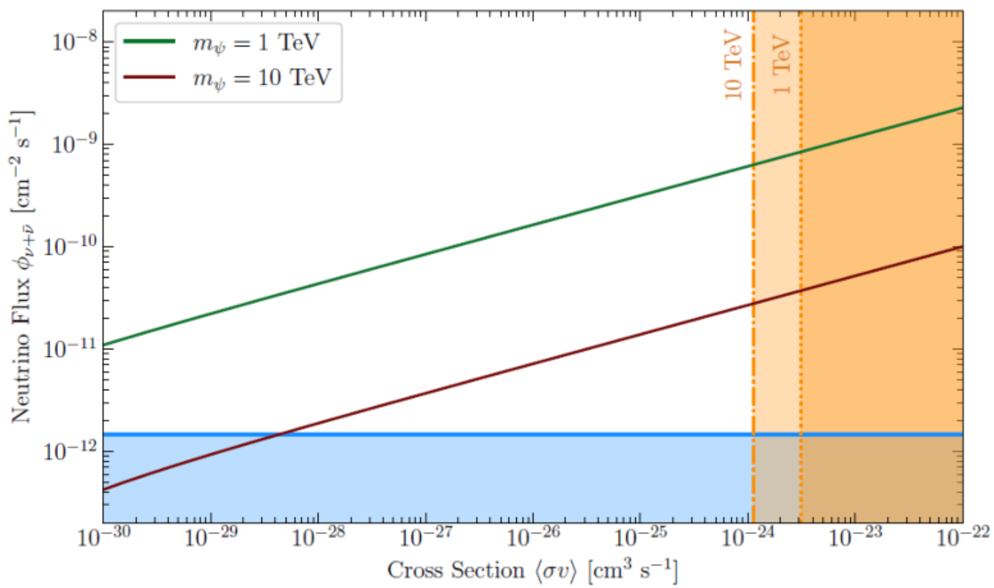

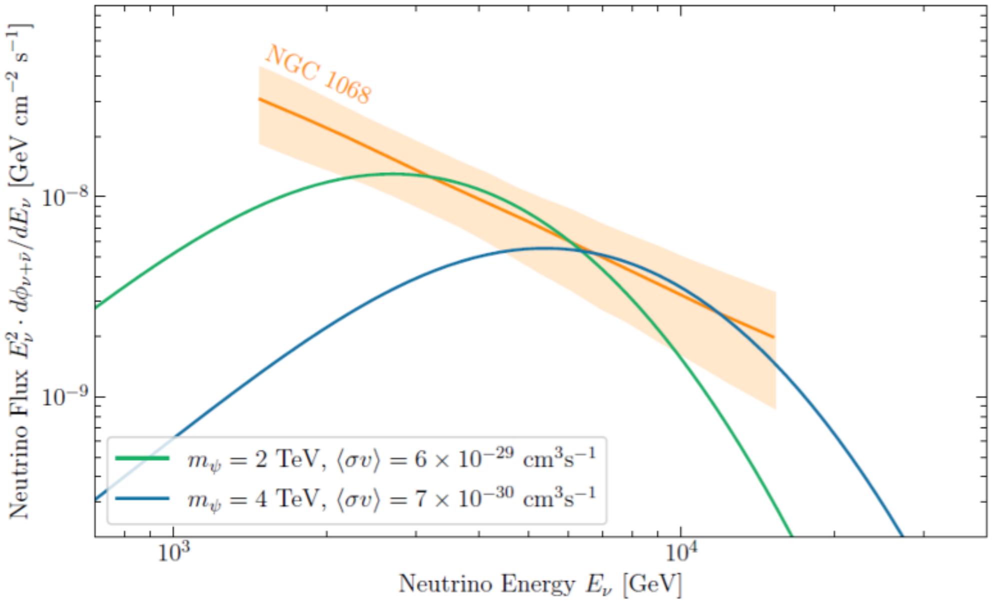

Conclusions

- The halo profile in the innermost part of galaxies is expected to present a spike as a result of the growth of the supermassive black hole at its center

- The shape of the spike is affected by several astrophysical and particle physics processes: stellar heating, self-scattering, self-annihilation, etc.

- The spike of the Milky Way is softened due to the heating by S-stars. Other galaxies may not host stars very close to the black hole, and their spikes might remain intact today. The enhancement of the annihilation rate might compensate for their larger distance, and become targets of dark matter detection.

- The neutrino emission from NGC 1068 could be explained by dark matter annihilations for cross-sections in the ballpark of the thermal value. The neutrino flux from the MW center is below the current limits.

- A neutrino flux from other galaxies could be detected in the future (NGC4945, Centaurus A, Circinus, etc)