New dark matter signals from semi-annihilations

Alejandro Ibarra

In collaboration with Boris Betancourt Kamenetskaia, Motoko Fujiwara, Takashi Toma, Kensuke Akita, Robert Zimmermann, Alessia Musumeci and Merlin Reichard

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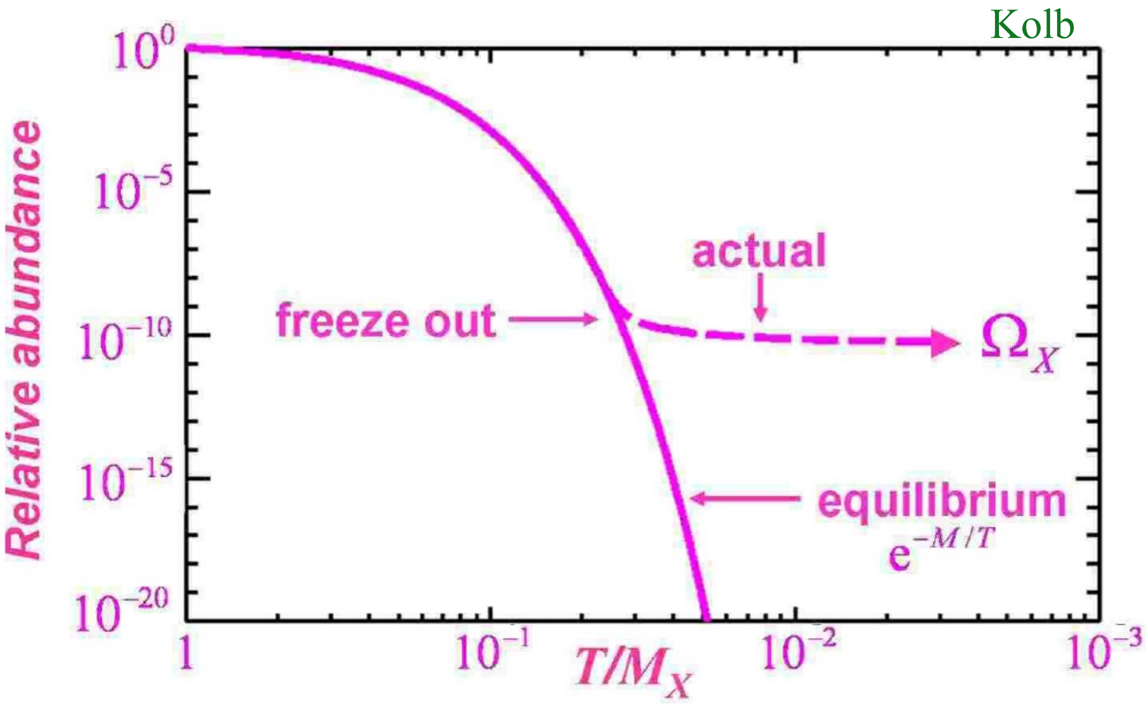
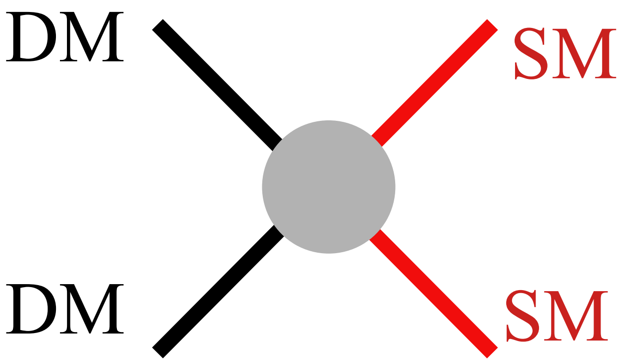
Introduction

Thermal freeze-out stands out as a plausible mechanism to generate the DM in our Universe (analogous to photon decoupling, neutron decoupling)





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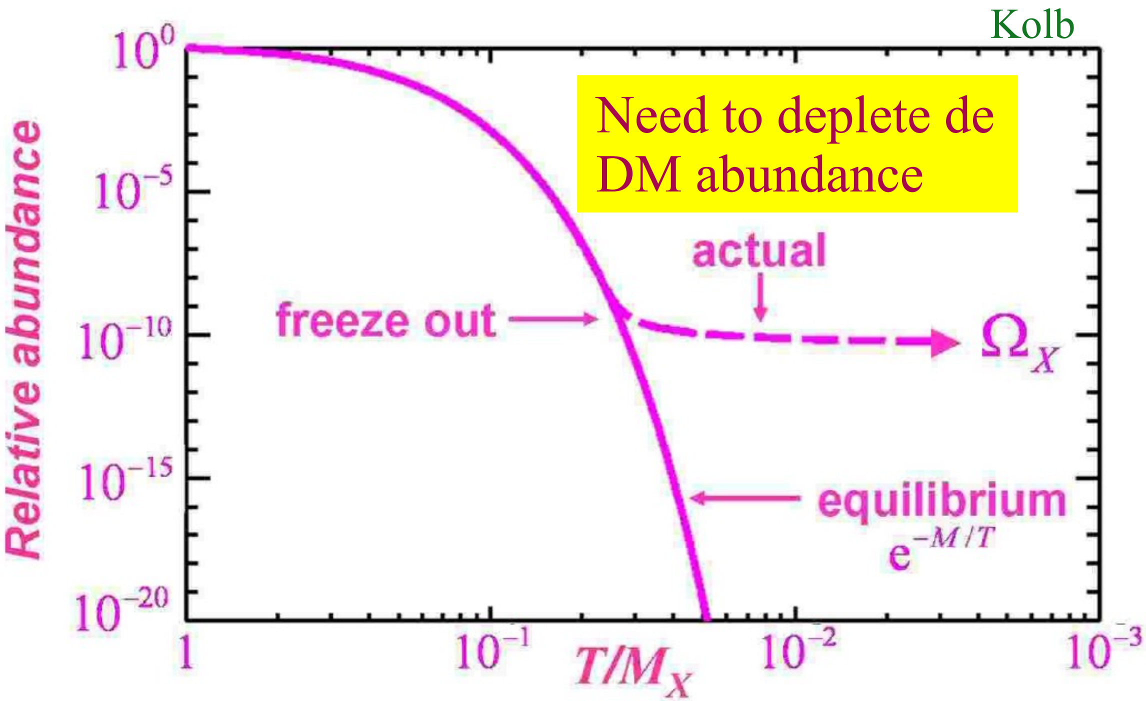

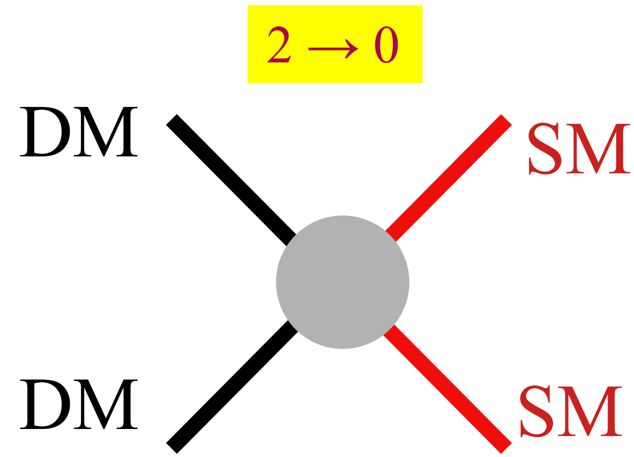

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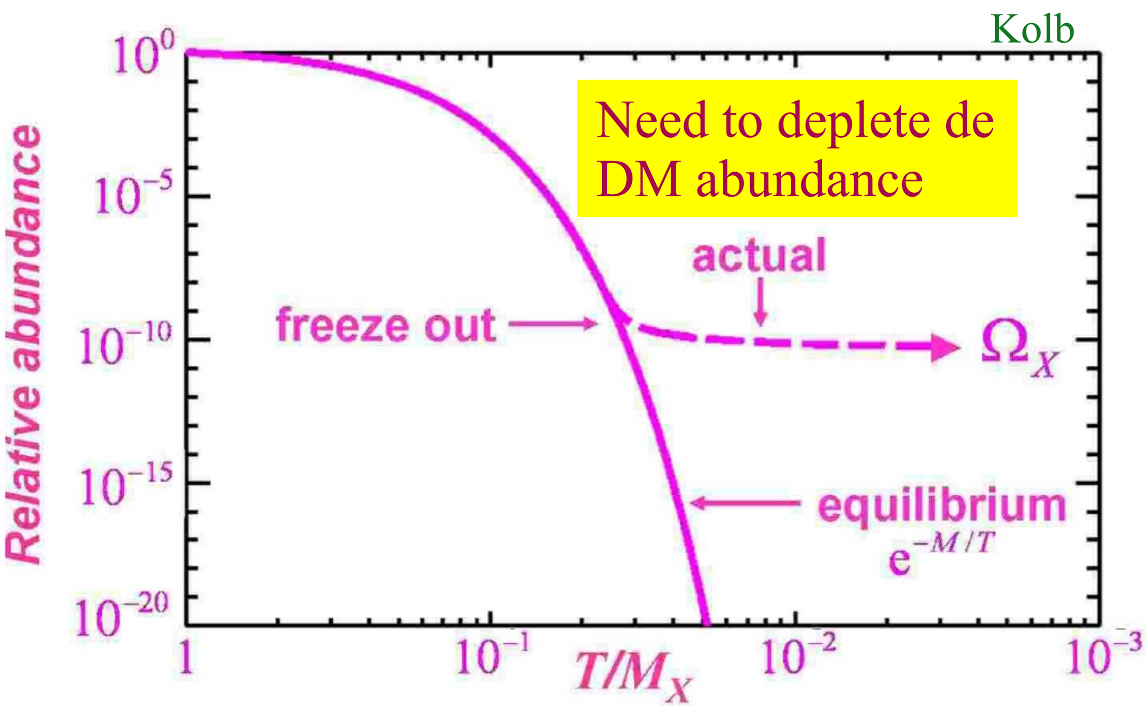

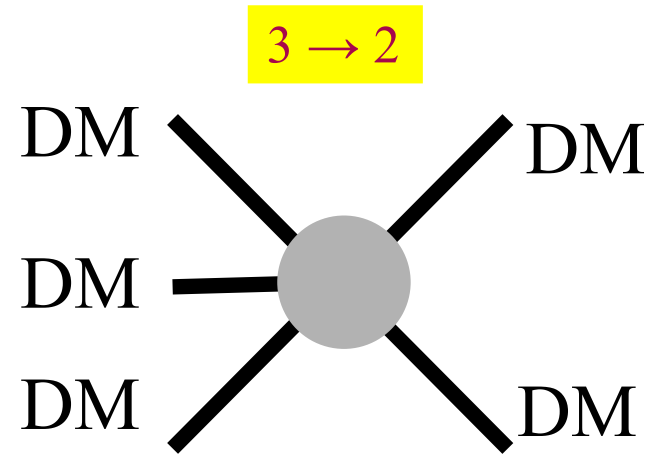

Carlson, Machacek, Hall
Hochberg, Kuflik, Volansky, Wacker

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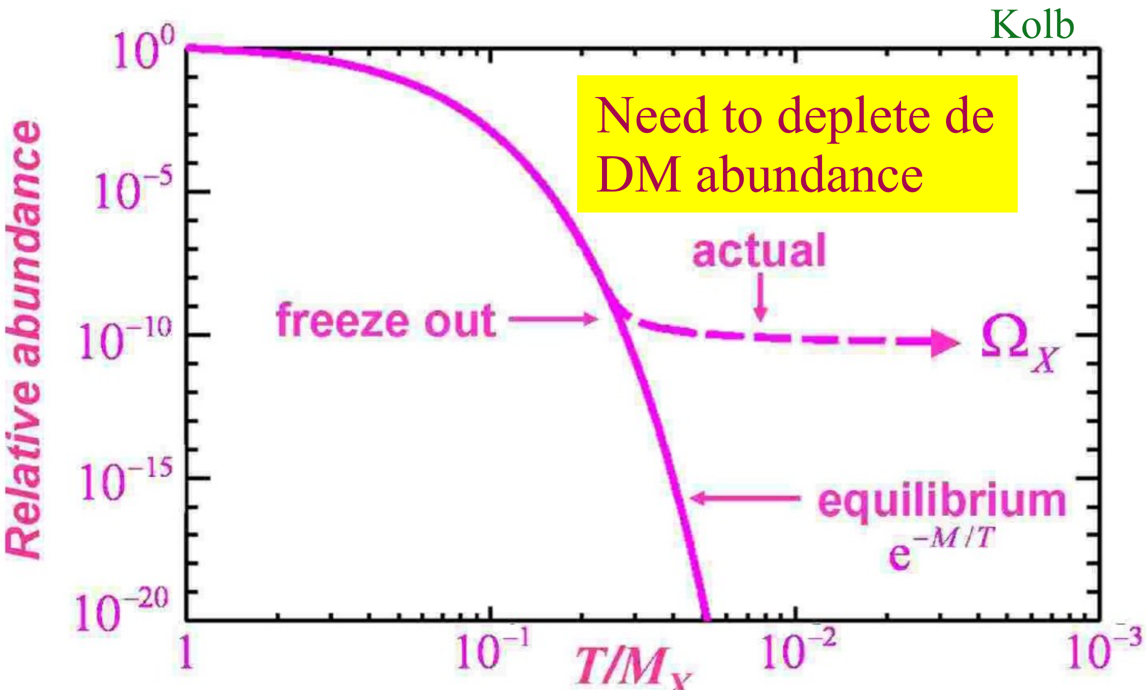

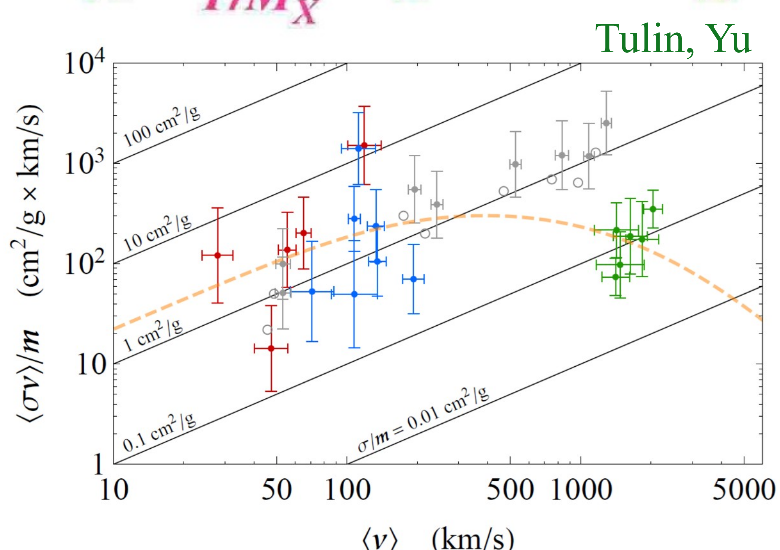

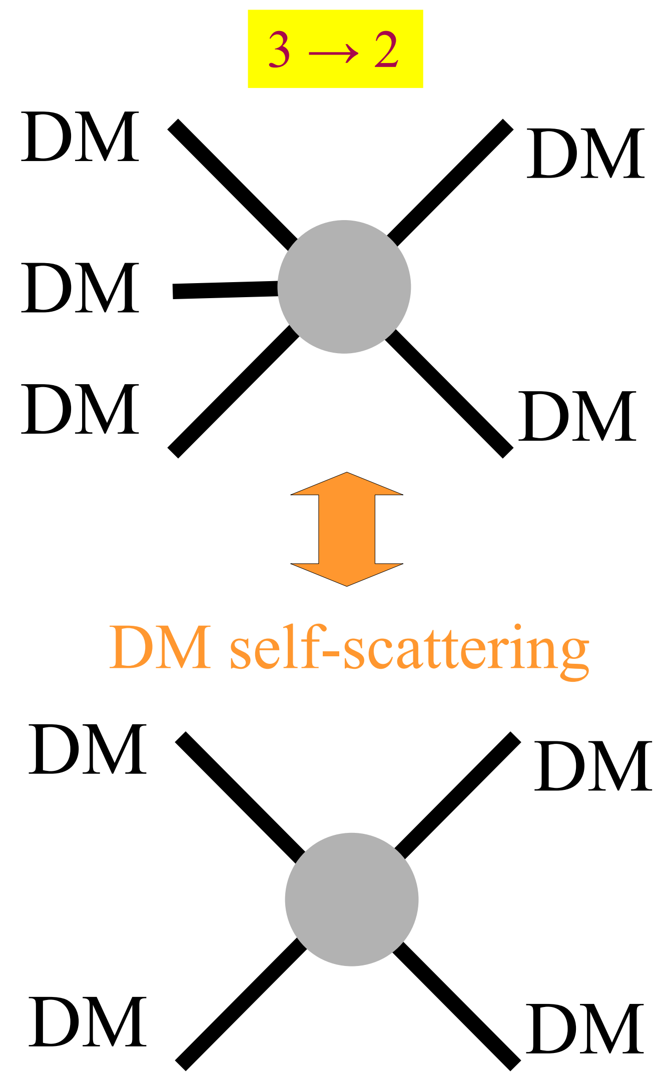

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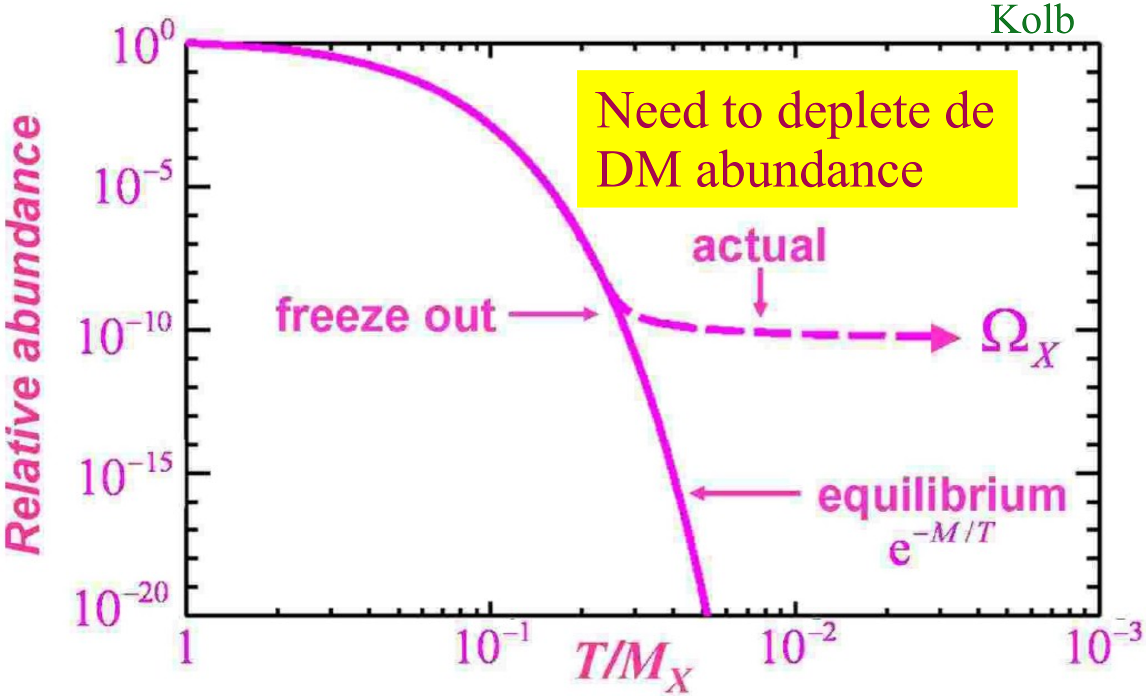
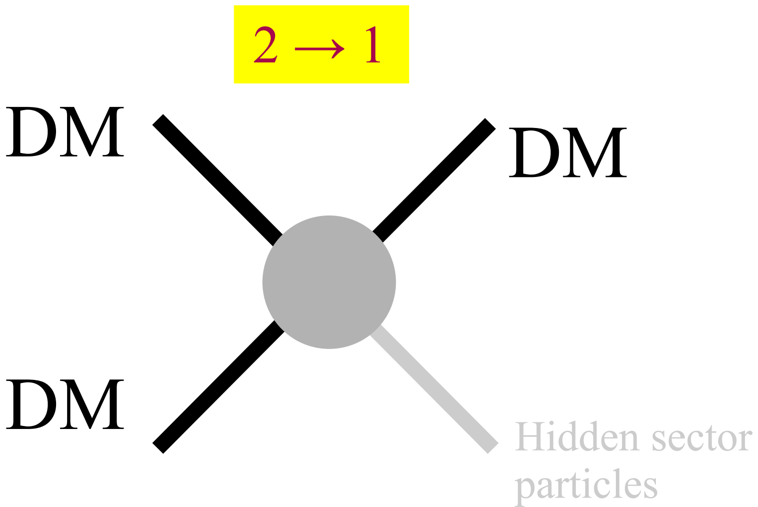
Kolb





Hambye (et al.)
D'Eramo, Thaler

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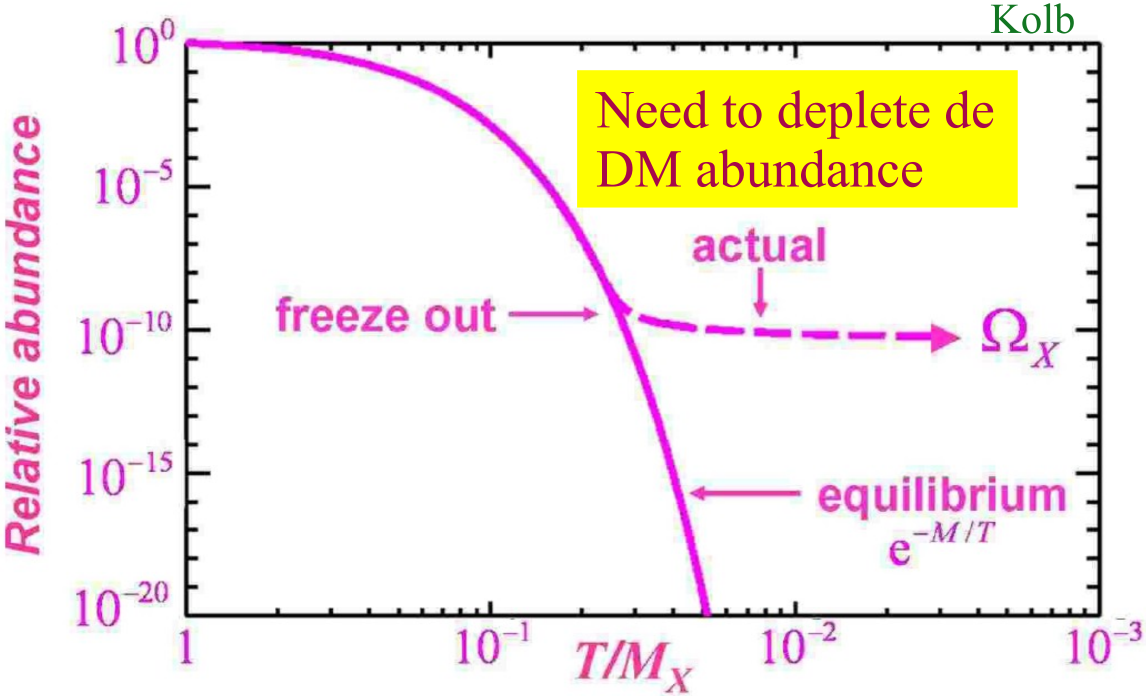

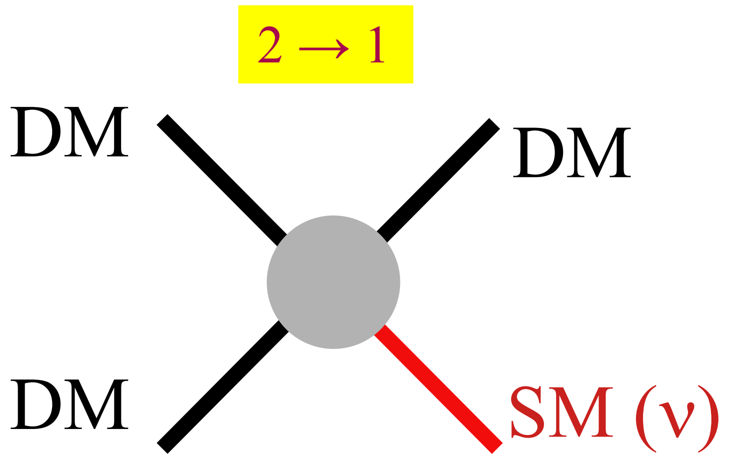

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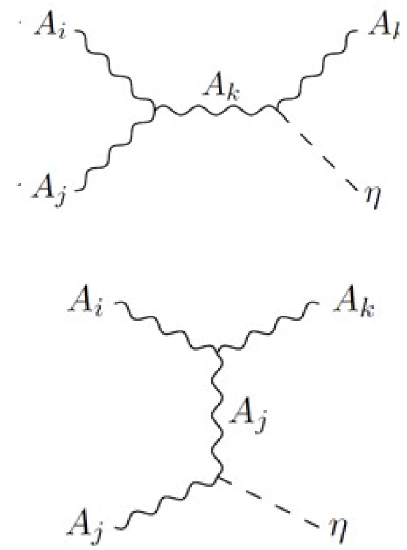
Some simple models

• Gauge bosons of a spontaneously broken SU(2) symmetry, with no fermion interactions Hambye '08; Arina, Hambye, AI, Weniger '09

$$A_\mu^a \to A_\mu^a + \tfrac{1}{g}\partial_\mu \alpha^a - \epsilon^{abc}\alpha^b A_\mu^c$$

$$\phi(x) \to \phi(x) + \frac{i}{2}\alpha^a(x)\tau^a\phi(x)$$



Lagrangian:

$$\mathcal{L} \supset -\frac{1}{4}F'^{\,\mu\nu}\cdot F'_{\mu\nu} + (D_\mu\phi)^\dagger (D^\mu\phi) - \mu_\phi^2\,\phi^\dagger\phi - \lambda_\phi\left(\phi^\dagger\phi\right)^2$$

A_μ^a stable due to an accidental SO(3) symmetry

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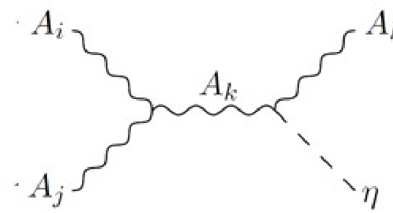

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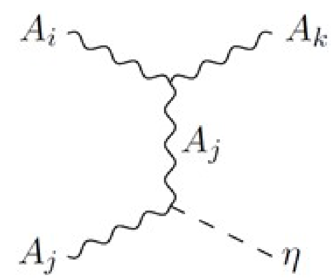


A^a_μ stable due to an accidental SO(3) symmetry

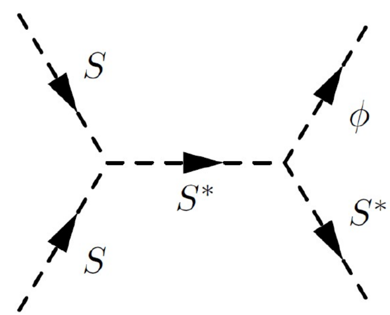
- Scalars S, ϕ, and a Z_3 symmetry. D'Eramo, Thaler '10; Belanger, Kannike, Pukhov, Raidal'12; Guo, Wu, Zhu '23 ...

$$S \to e^{2\pi i/3}S$$

$$\phi \to \phi$$

Lagrangian:

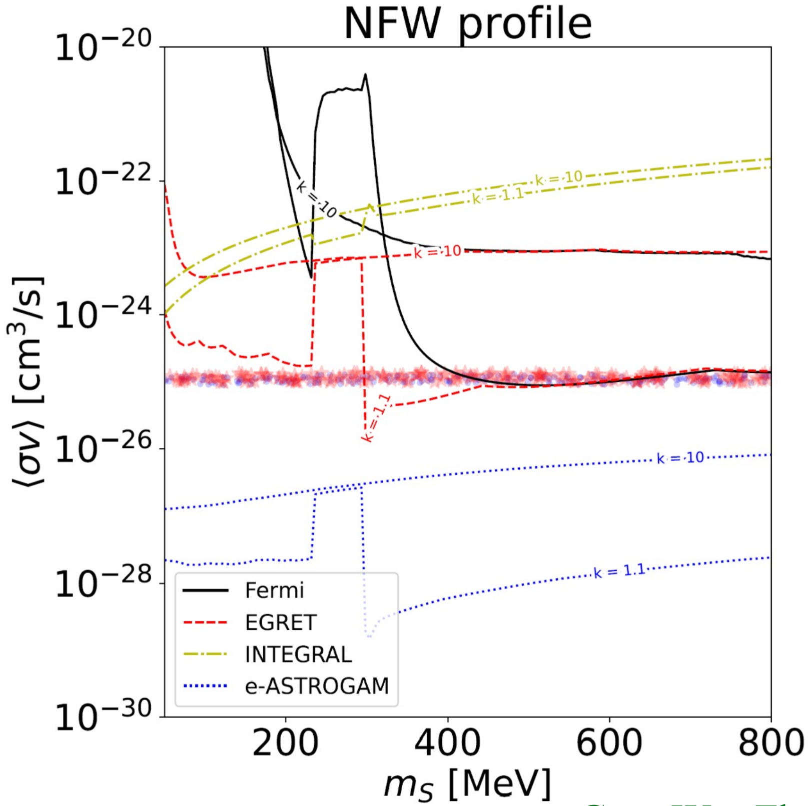
$$\mathcal{L} \supset -\mu_S S^3 - \mu_{S\phi}|S|^2\phi + \text{h.c.}$$



S stable if the Z_3 is exact

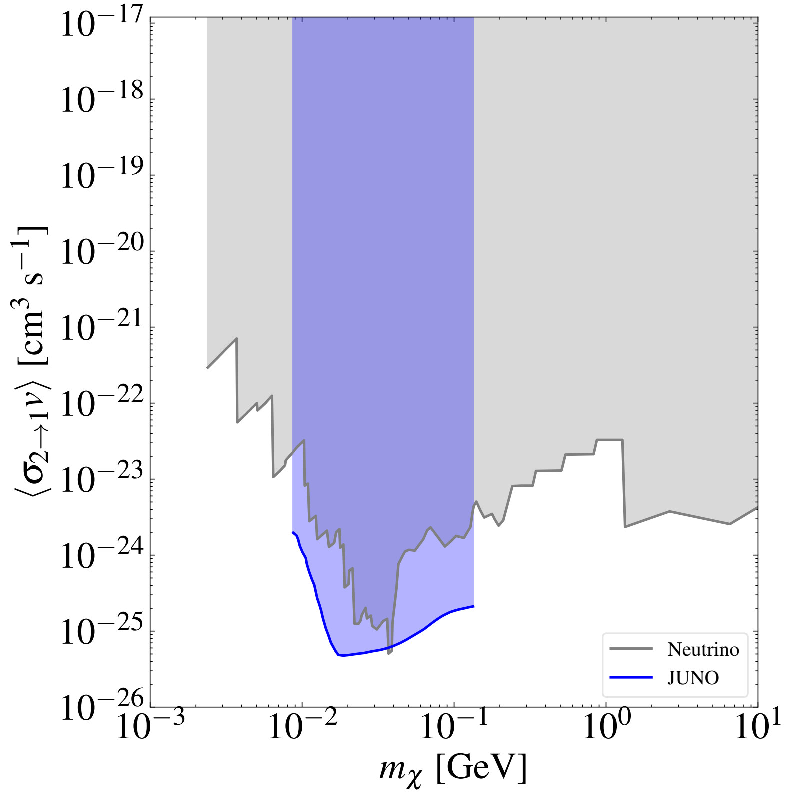
Annihilation signals

$\chi\chi \to \chi^c\phi,$ and $\phi \to$ visible



Guo, Wu, Zhu '23

$\chi\chi \to \chi^c\nu$



Betancourt Kamenetskaia et al '26.

The semi-annihilation $\chi\chi \to \chi^c\phi$ produces a dark matter particle with $T_\chi = m_\chi/4$.

Scenario of boosted dark matter

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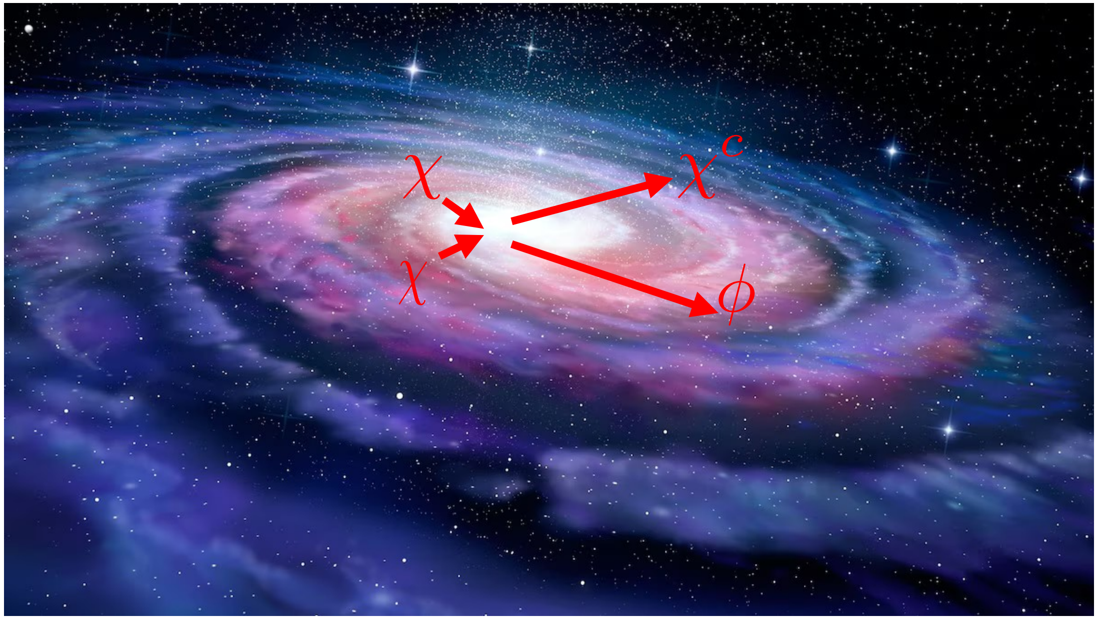
Scenario of boosted dark matter

Outline:

- Semi-annihilations in the MW center
- Semi-annihilations at high-redshift
- Semi-annihilations in dark matter spikes

Boosted dark matter from semi-annihilations in the Milky Way center



$$\frac{d\Phi_{\rm MW}}{dT_\chi} = \frac{4\Phi_{\rm MW}}{m_\chi}\delta\left(\frac{4T_\chi}{m_\chi} - 1\right)$$

$$\Phi_{\rm MW} = 3.2\times 10^{-3}{\rm cm}^{-2}{\rm s}^{-1}\left(\frac{m_\chi}{100~{\rm MeV}}\right)^{-2}\left(\frac{\langle\sigma_{2\to 1}v\rangle}{10^{-26}~{\rm cm}^3{\rm s}^{-1}}\right).$$

However, much larger fluxes expected at Earth from the motion of DM particles in the halo

Boosted dark matter from semi-annihilations in the Milky Way center

For example, take $m_\chi = 100\ \mathrm{MeV}$

$$\frac{d\Phi_{\rm halo}}{dT_\chi} \simeq 3.7 \times 10^6 \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{MeV}^{-1} \left(\frac{T_\chi}{2.7\times 10^{-5}\,\mathrm{MeV}}\right) \exp\left(-\frac{T_\chi}{2.7\times 10^{-5}\,\mathrm{MeV}}\right)$$

$$\frac{d\Phi_{\rm MW}}{dT_\chi} = 1.3 \times 10^{-4}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{MeV}^{-1}\,\delta\left(\frac{T_\chi}{25\,\mathrm{MeV}} - 1\right)$$

Much smaller fluxes…

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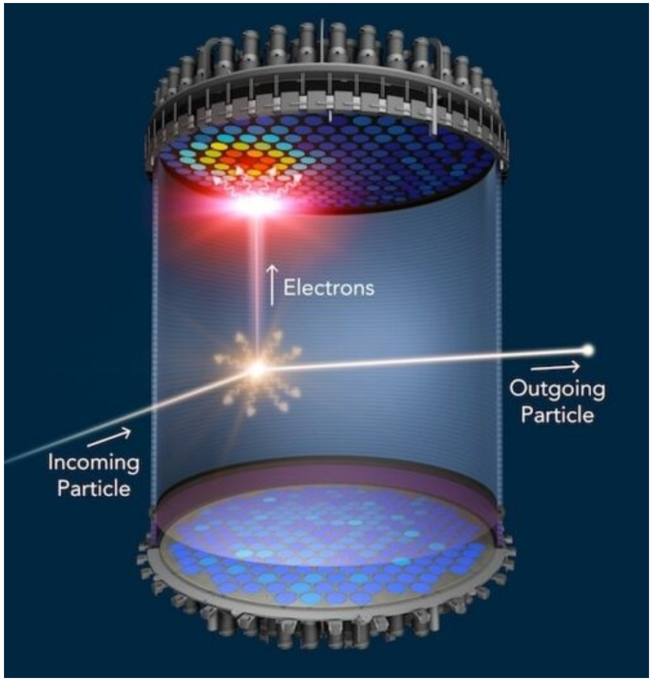
Much smaller fluxes… But at very different kinetic energies

- Current detectors using xenon as target can detect nuclear recoils with $T_T \gtrsim$ few keV, which requires $v \gtrsim 0.07\,c$
- At the peak of the distribution $v \sim 7.3\times 10^{-4}\,c$ which is undetectable.
- In fact, the velocity distribution of DM particles in the MW halo is truncated at $v_{\text{esc}} \simeq 1.8\times 10^{-3}\,c$

A 100 MeV dark matter particle moving in the MW halo is undetectable



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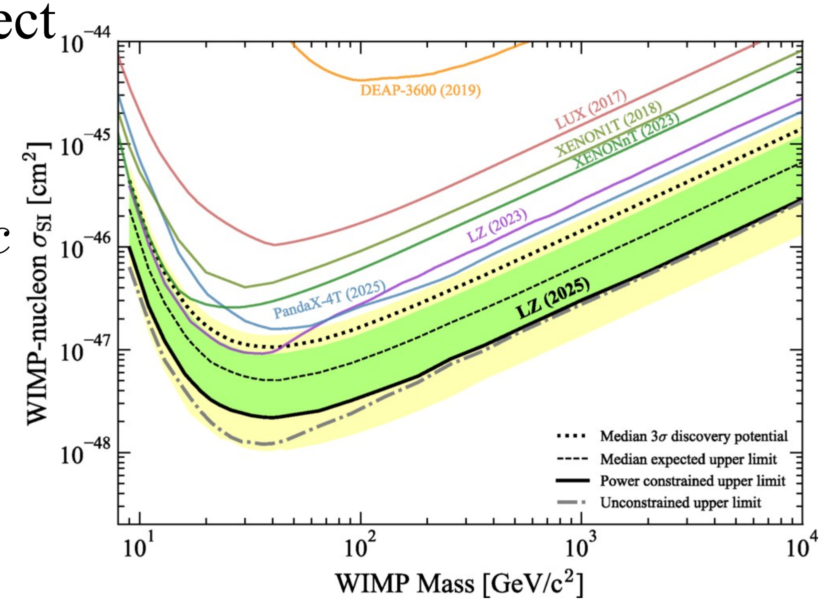

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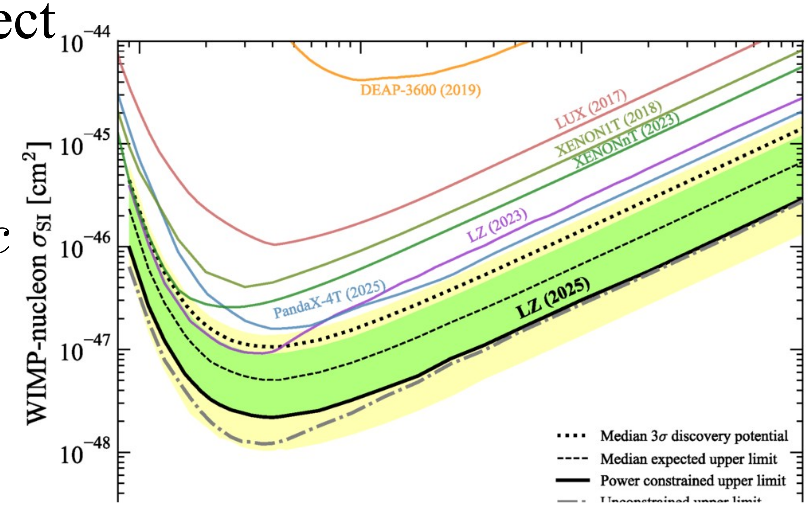

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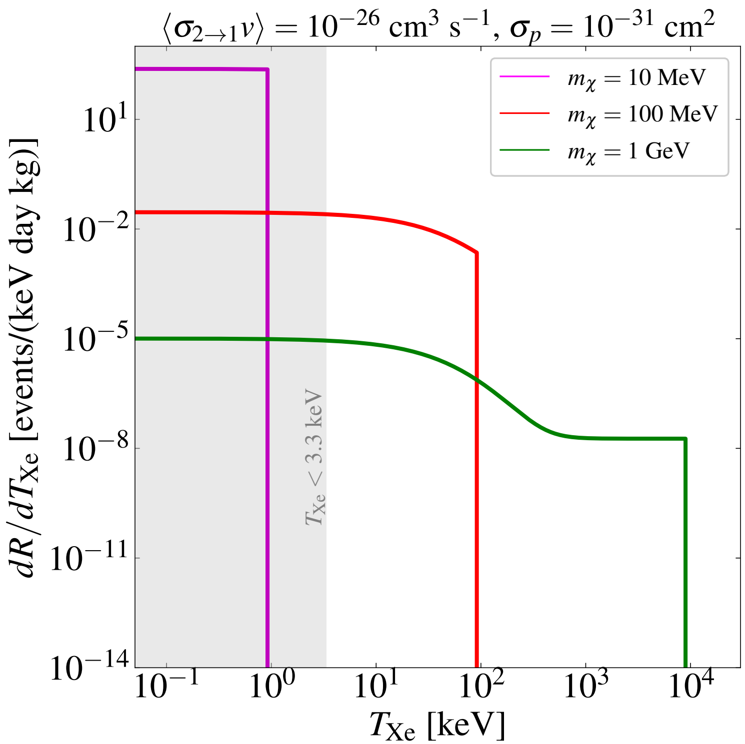
A 100 MeV dark matter particle from semi-annihilations has $v = 0.6\,c$ and could be detected

Boosted dark matter from semi-annihilations in the Milky Way center



Betancourt Kamenetskaia et al, 25

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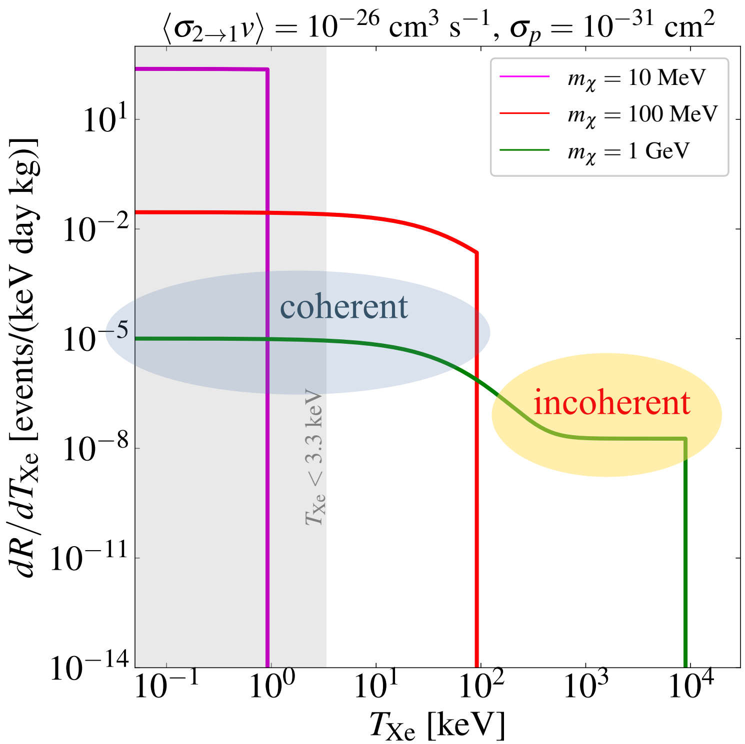

Betancourt Kamenetskaia et al, 25

$$\frac{d\sigma_{\chi\mathcal{T}}}{dT_{\mathcal{T}}} = \left(\frac{d\sigma_{\chi\mathcal{T}}}{dT_{\mathcal{T}}}\right)_{\rm coh} + \left(\frac{d\sigma_{\chi\mathcal{T}}}{dT_{\mathcal{T}}}\right)_{\rm inc},$$

$$\left(\frac{d\sigma_{\chi\mathcal{T}}}{dT_{\mathcal{T}}}\right)_{\rm coh} = \frac{\sigma^{\rm coh}_{\rm SI,\mathcal{T}}}{T^{\rm max}_{\mathcal{T}}}|F_{\rm SI,\mathcal{T}}(q)|^2,$$

$$\left(\frac{d\sigma_{\chi\mathcal{T}}}{dT_{\mathcal{T}}}\right)_{\rm inc} = \frac{\sigma^{\rm inc}_{\rm SI,\mathcal{T}}}{T^{\rm max}_{\mathcal{T}}}\left(1 - |F_{\rm SI,\mathcal{T}}(q)|^2\right).$$

Bednyakov, Naumov '18

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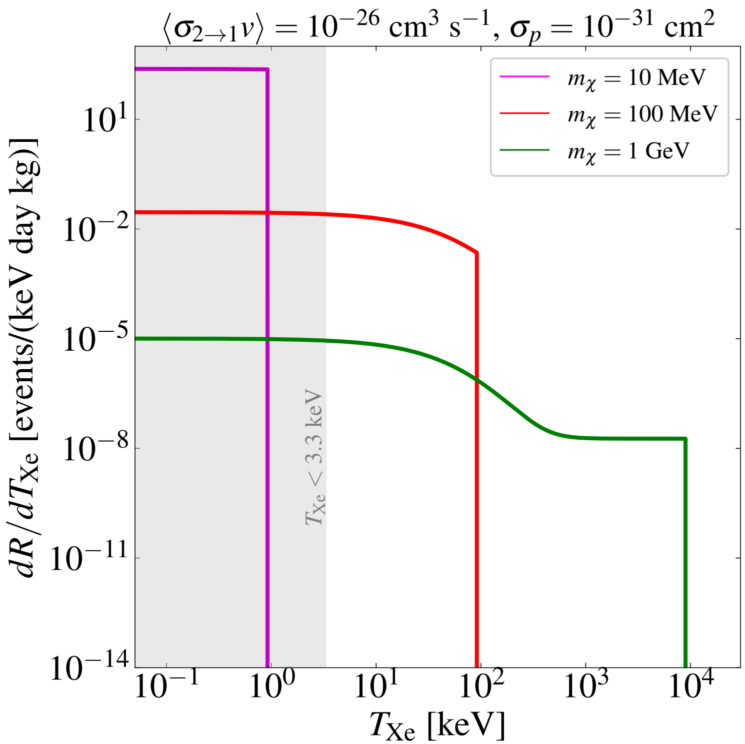

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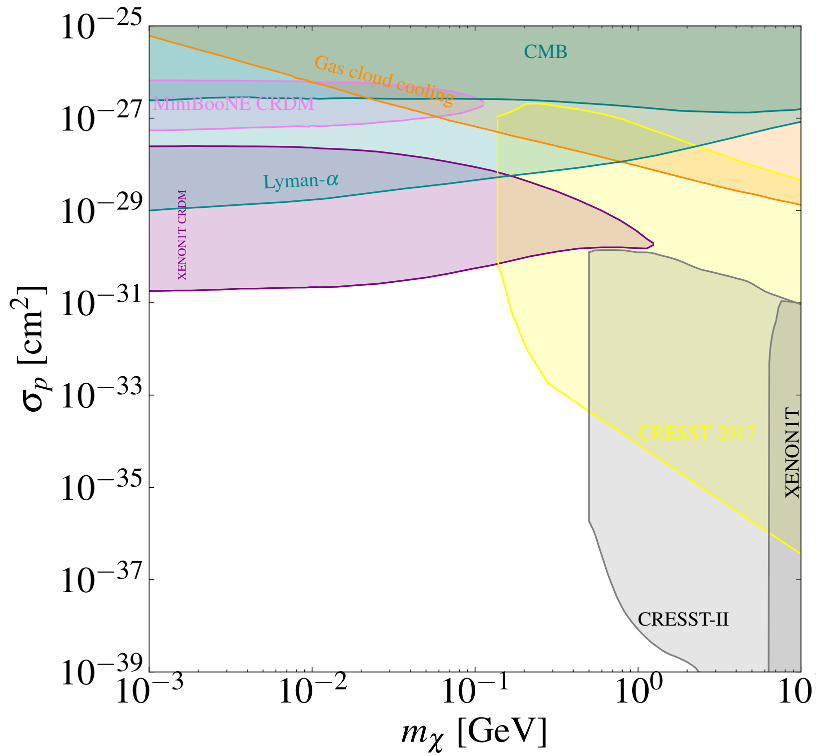

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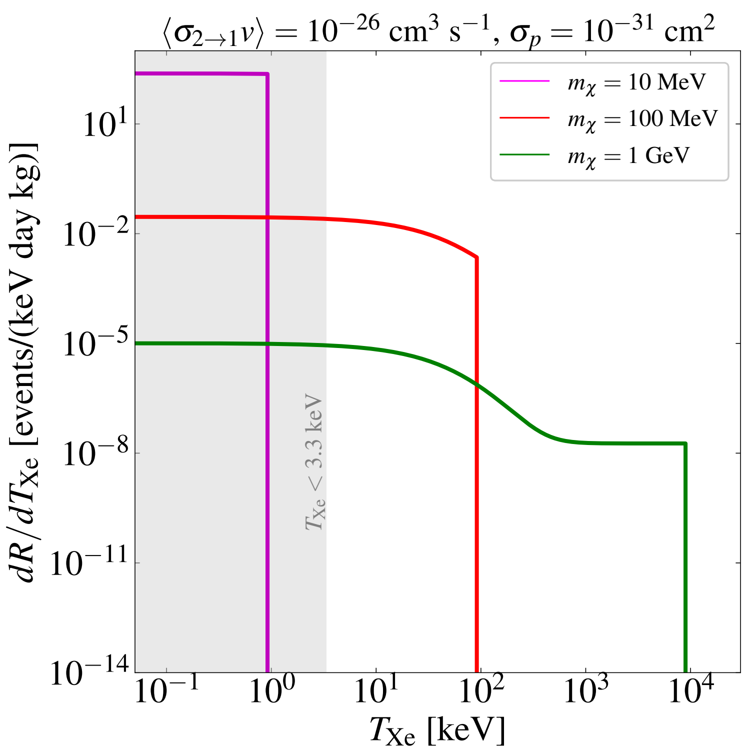

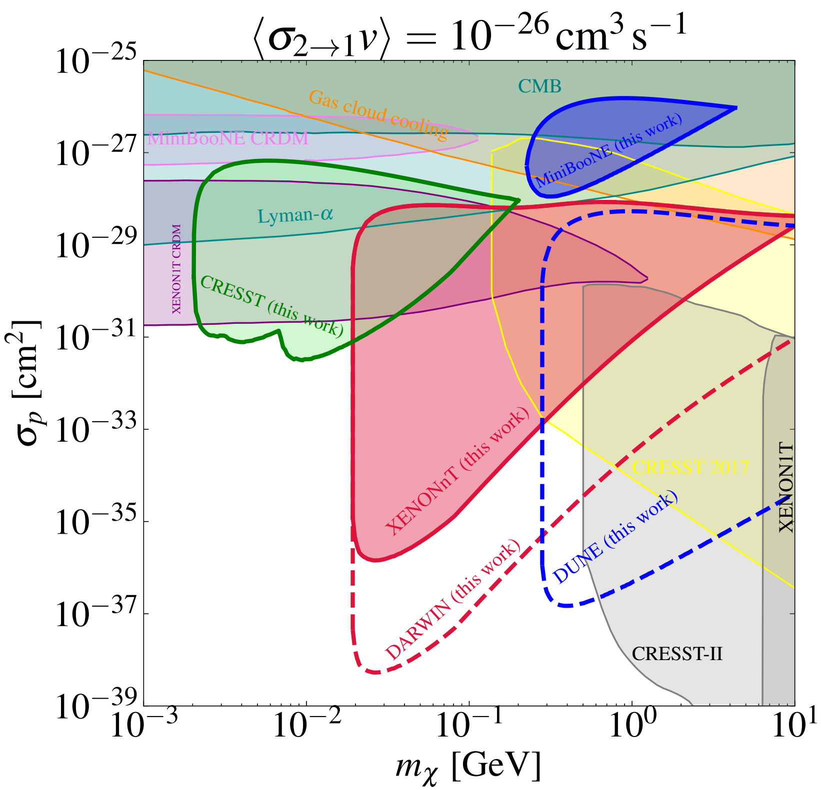

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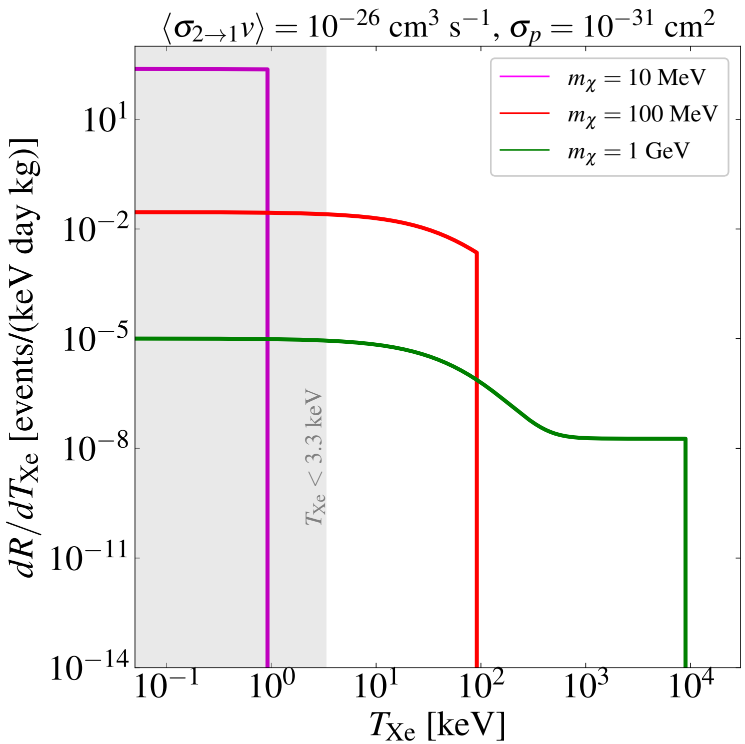
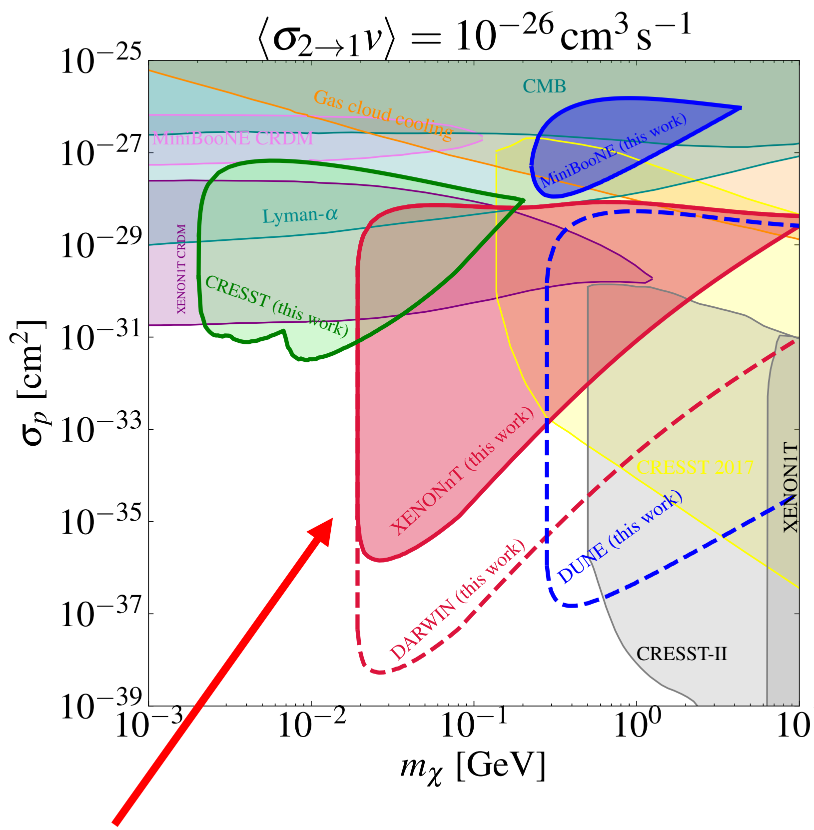


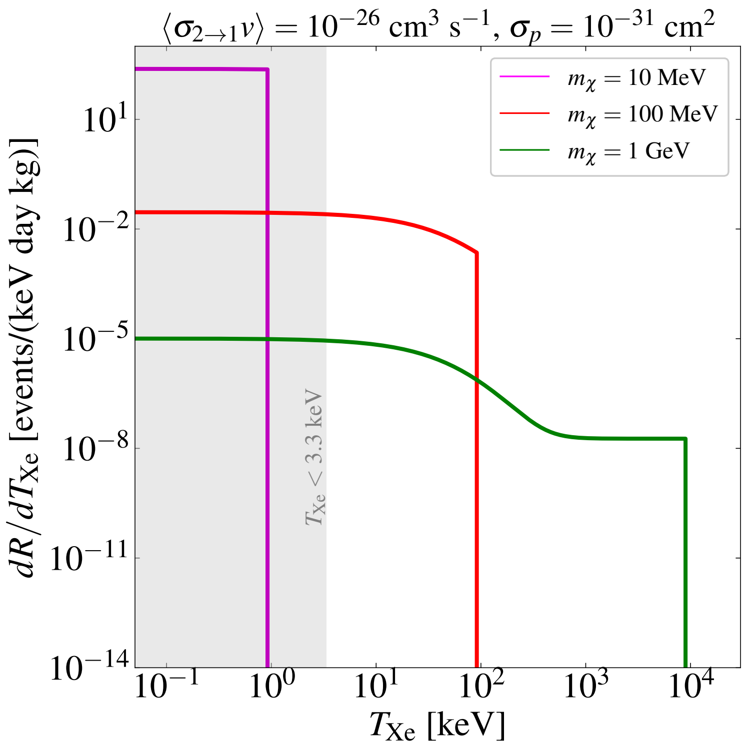


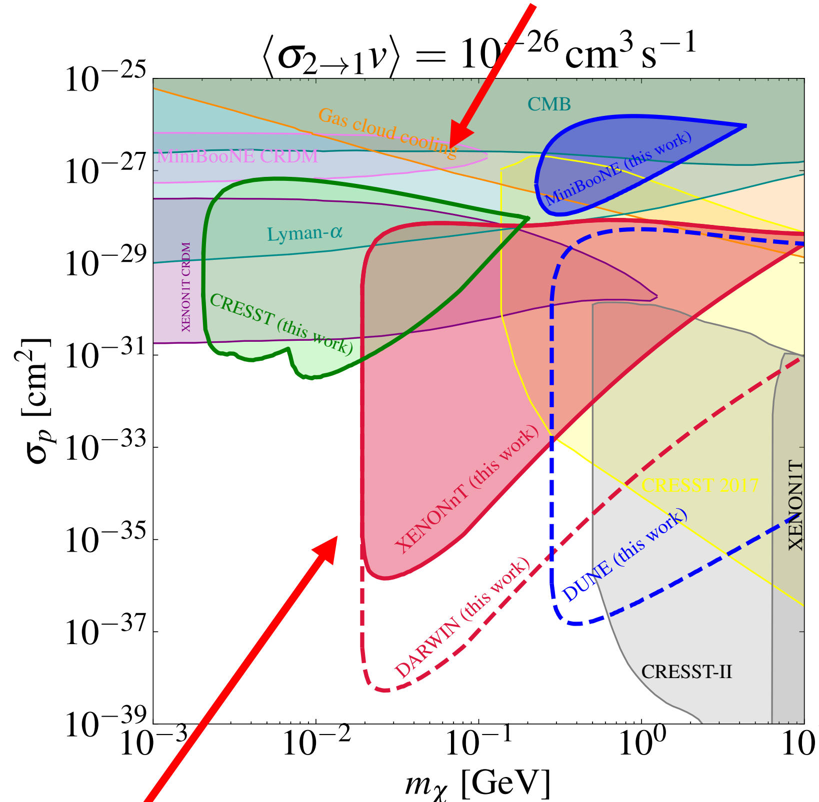
Betancourt Kamenetskaia et al, 25

No sensitivity to very small masses. Nuclear recoils below the detection threshold.

Boosted dark matter from semi-annihilations in the Milky Way center

No sensitivity to large cross-sections
DM particles are stopped by rock and don't reach the detector





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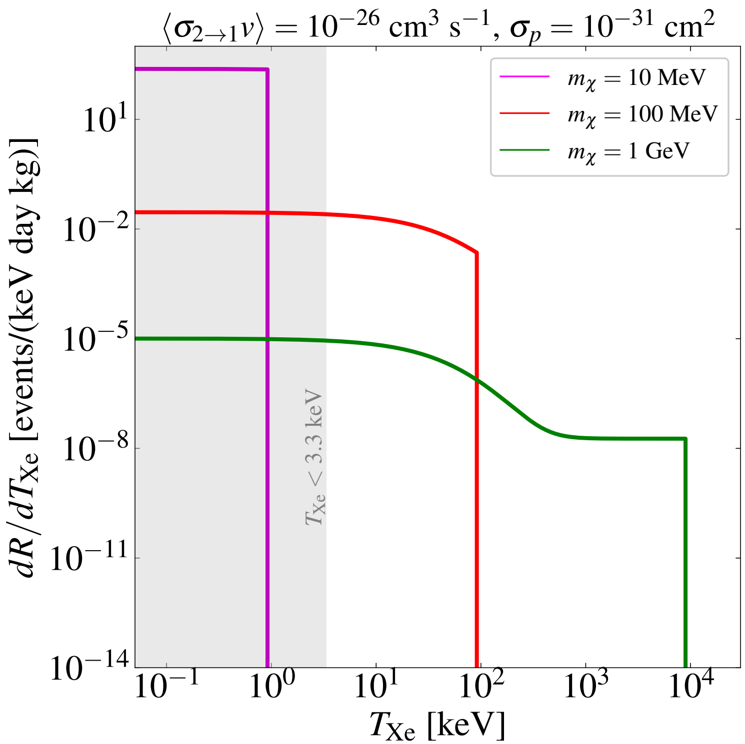
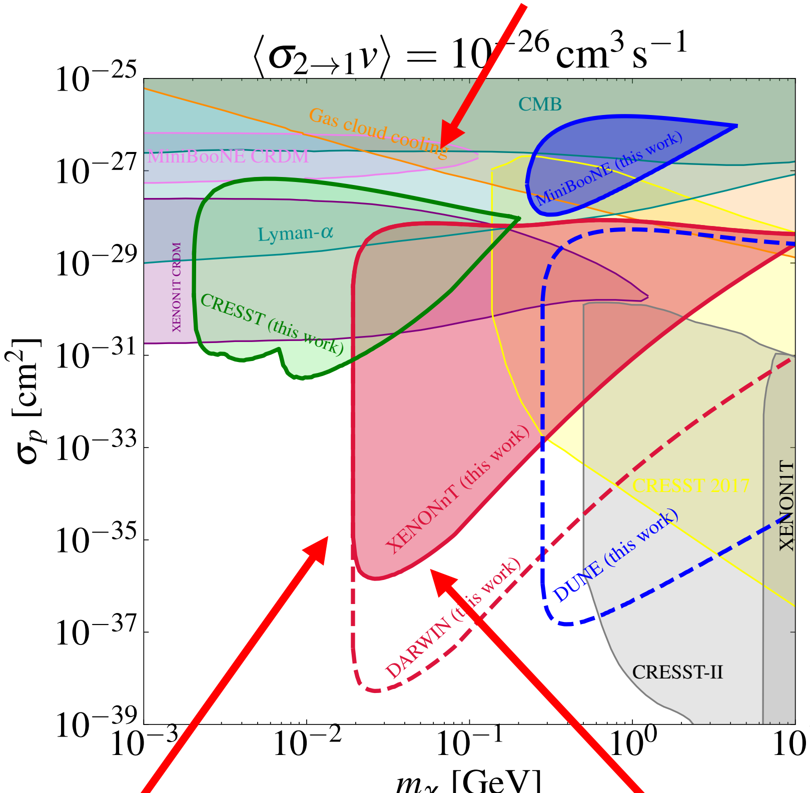




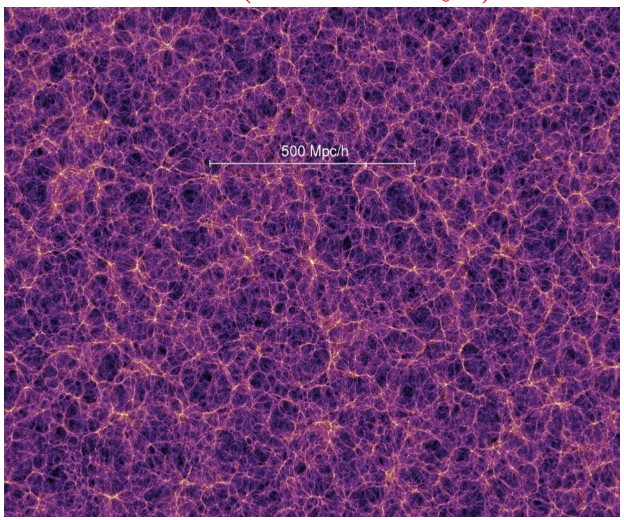
Betancourt Kamenetskaia et al, 25

No sensitivity to very small masses. Nuclear recoils below the detection threshold.

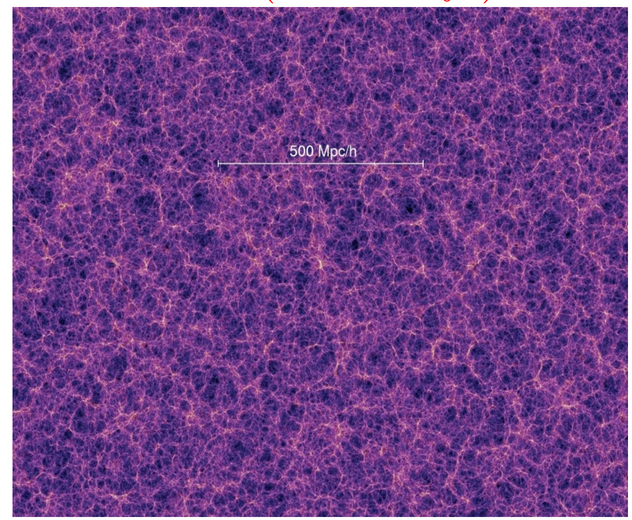
Significant improvement in sensitivity for $m_\chi \sim 20\,\mathrm{MeV}$. Sensitivity scales as m_χ^{-2}

Boosted dark matter from semi-annihilations at high redshift

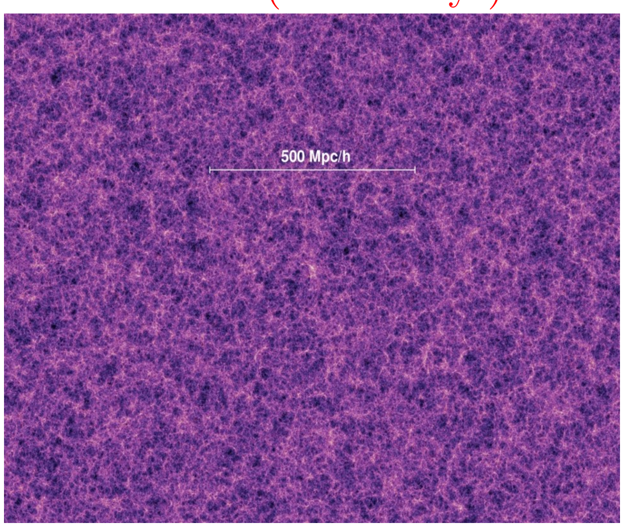
$z = 0 \quad (t = 13.6\,\mathrm{Gyr})$



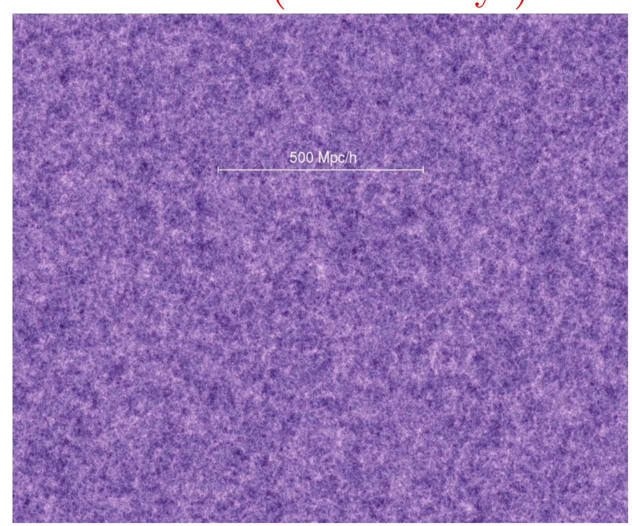
$z = 1.4 \quad (t = 4.7\,\mathrm{Gyr})$



$z = 5.7 \quad (t = 1.0\,\mathrm{Gyr})$



$z = 18.3 \quad (t = 0.21\,\mathrm{Gyr})$

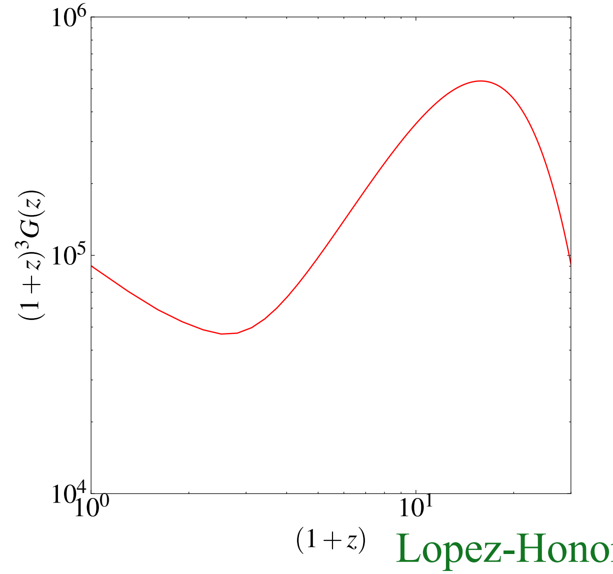


Millenium simulation

Boosted dark matter from semi-annihilations at high redshift

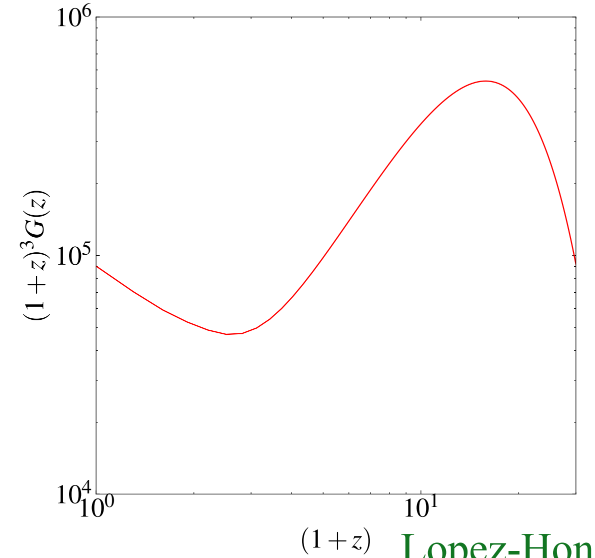
- Number of BDM particles produced at redshift z per unit volume, unit time and unit kinetic energy:

$$Q_{\rm cosmo}(T_z, z) = \frac{1}{2}\,\langle \sigma_{2\to 1} v\rangle \frac{\rho_\chi^2(z)}{m_\chi^2}\, G(z)\, \delta\left(T_z - \frac{m_\chi}{4}\right)$$



Lopez-Honorez et al, 13

Boosted dark matter from semi-annihilations at high redshift



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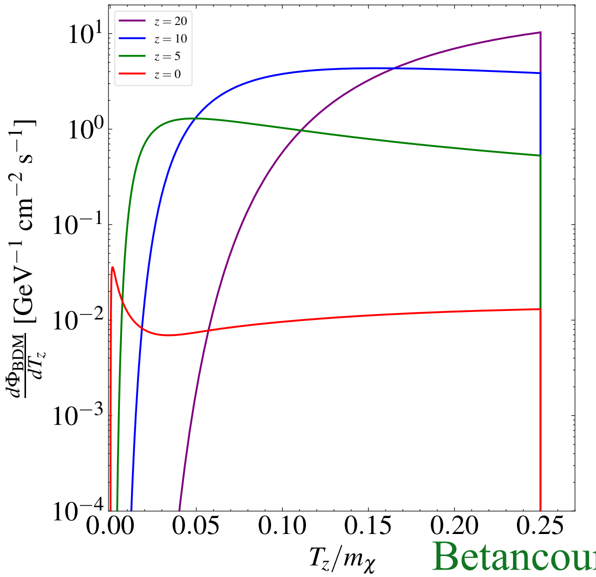
- Flux of BDM particles at redshift z from annihilations at higher redshift:

$$\frac{d\Phi_{\rm cosmo}}{dT_z}(T_z, z) = (1+z)^2 \int_z^\infty \frac{dz'}{H(z')(1+z')^3} \sqrt{1 - \left(\frac{m_\chi}{T_{z'} + m_\chi}\right)^2}\, Q_{\rm cosmo}\left(T_{z'}, z'\right)$$

$m_\chi = 100\,\mathrm{MeV}, \langle \sigma v\rangle = 10^{-26}\,\mathrm{cm}^3/s$



Betancourt Kamenetskaia et al, 26

1) Sizable flux at high z. Implications for structure formation?

2) At z=0, the flux is comparable to the one from the MW center

$$\frac{d\Phi_{\rm MW}}{dT_\chi} = 1.3\times 10^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{MeV}^{-1}\,\delta\left(\frac{T_\chi}{25\,\mathrm{MeV}} - 1\right)$$

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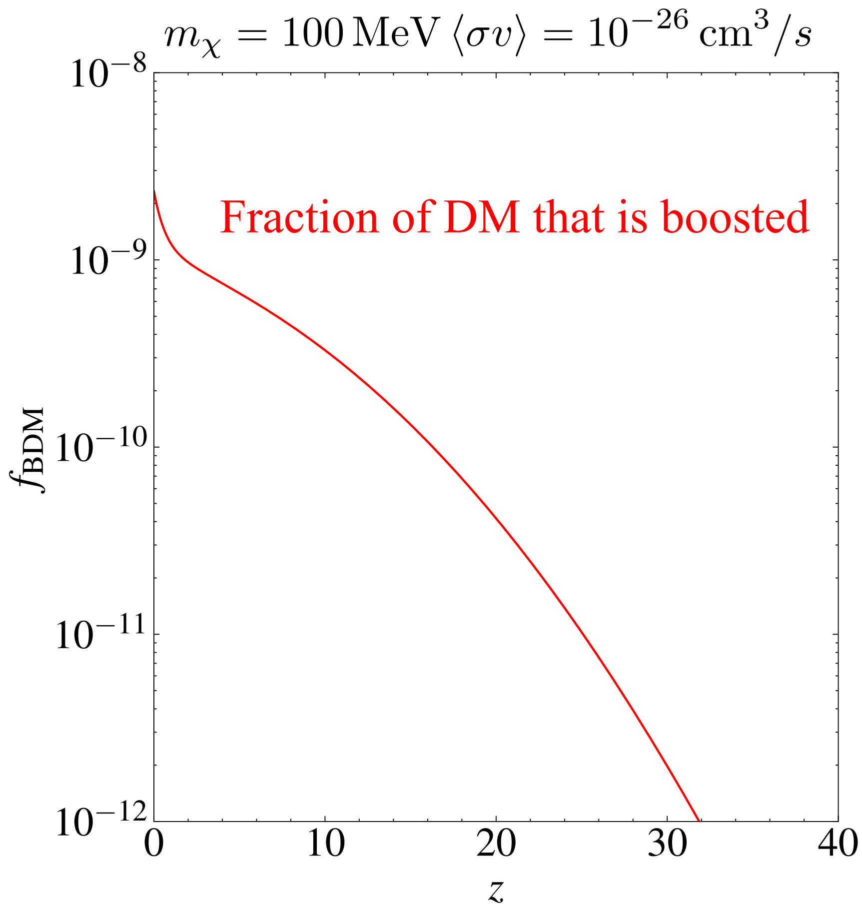
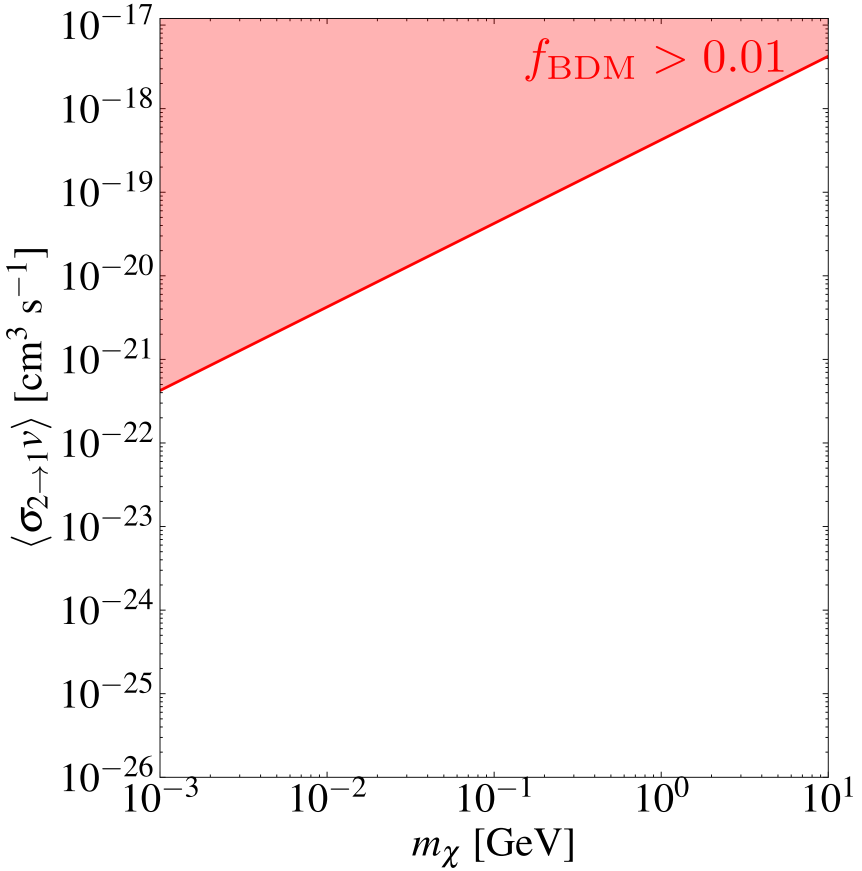
Implications for direct search experiments?

Boosted dark matter from semi-annihilations at high redshift

1) Implications for structure formation?





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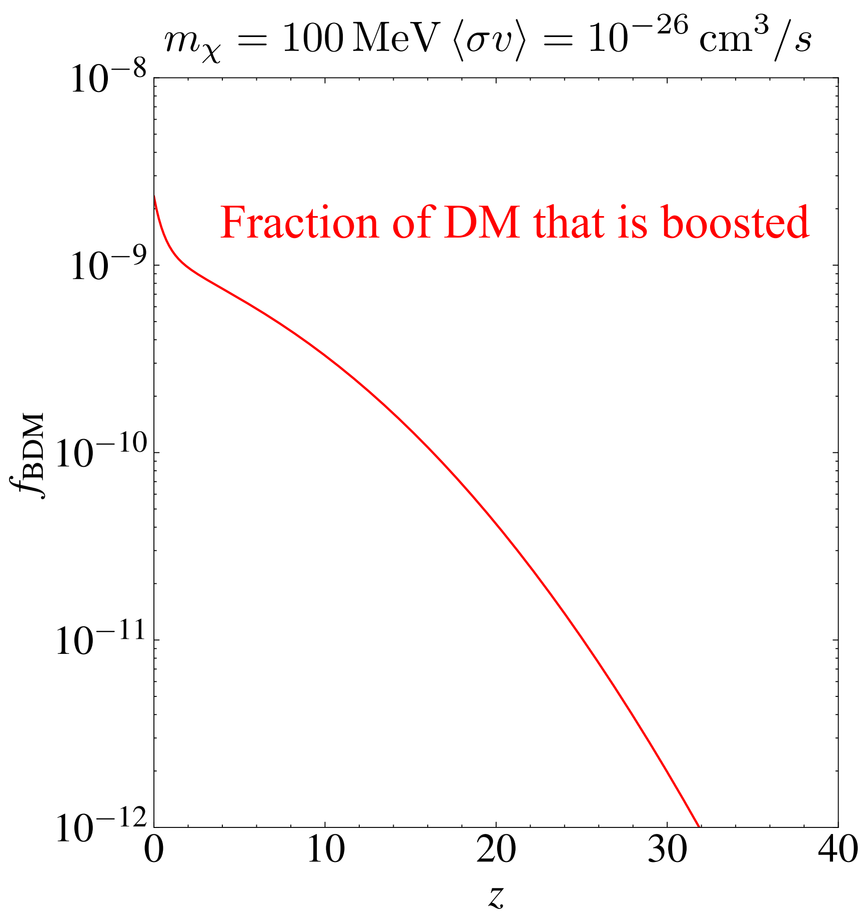
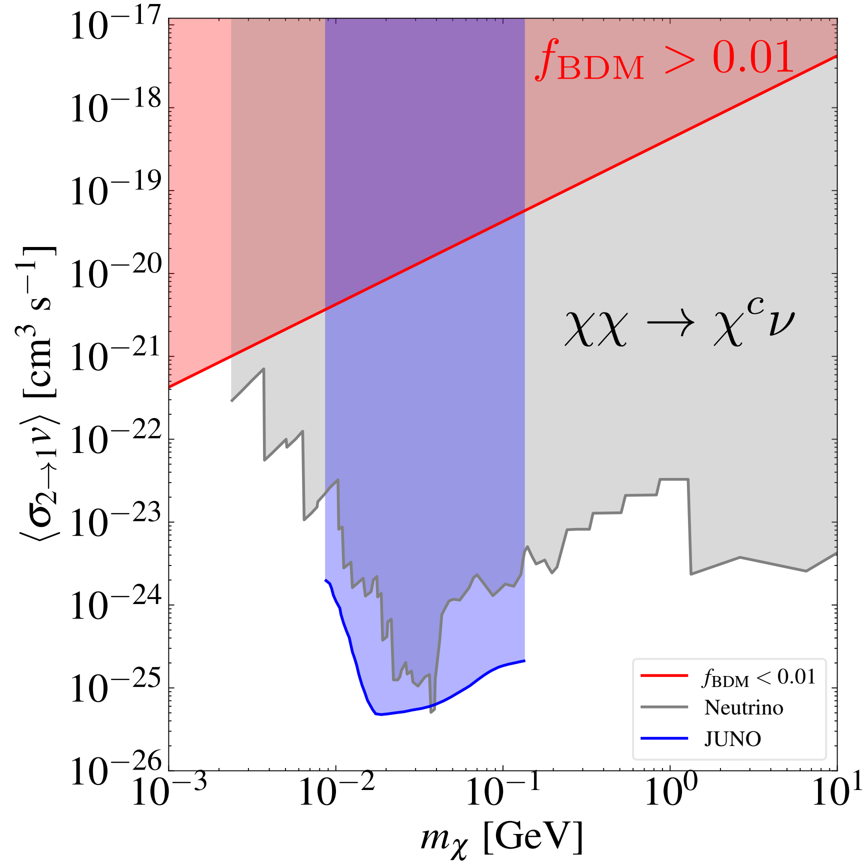
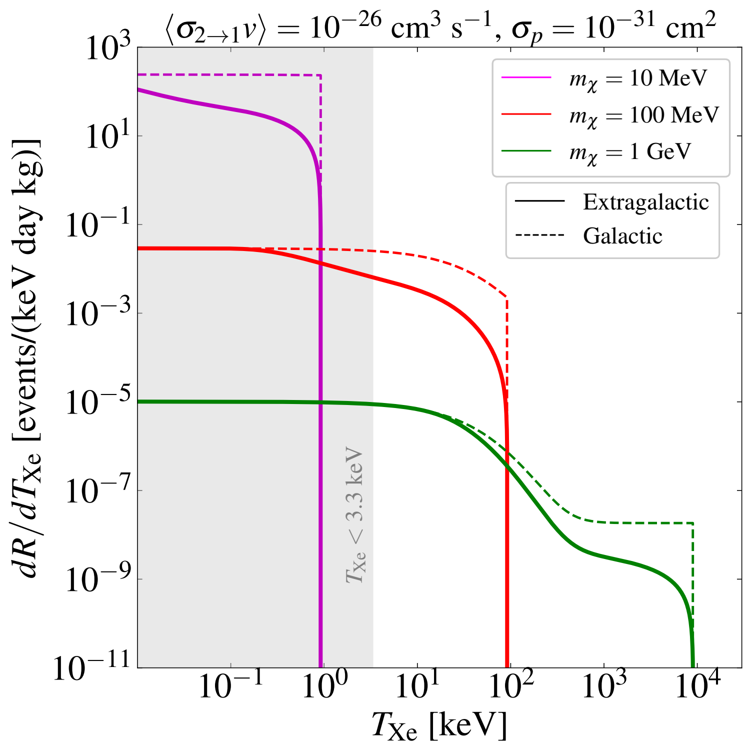


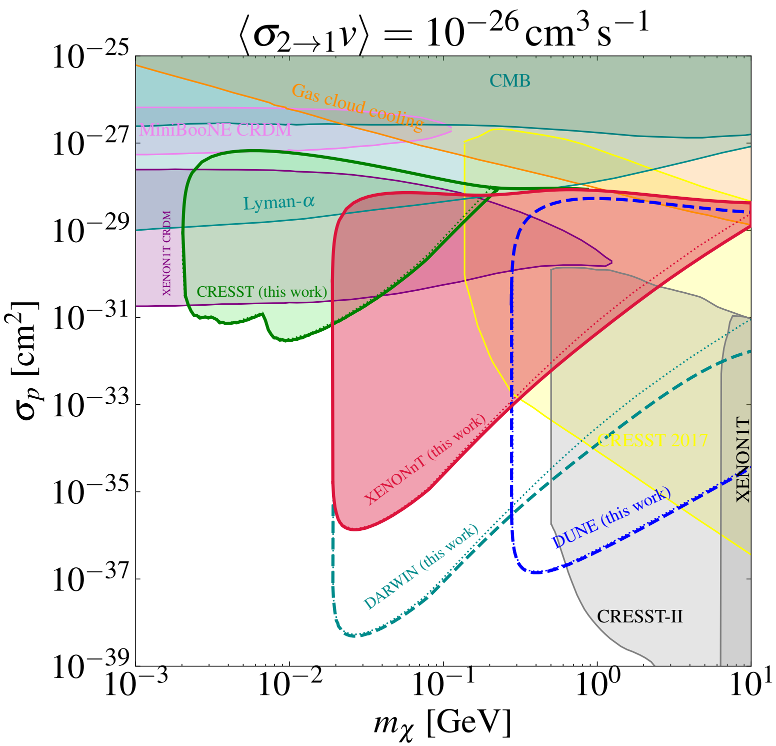


Boosted dark matter from semi-annihilations at high redshift

2) Implications for direct search experiments?



Betancourt Kamenetskaia et al, 26



Boosted dark matter from semi-annihilations at high redshift

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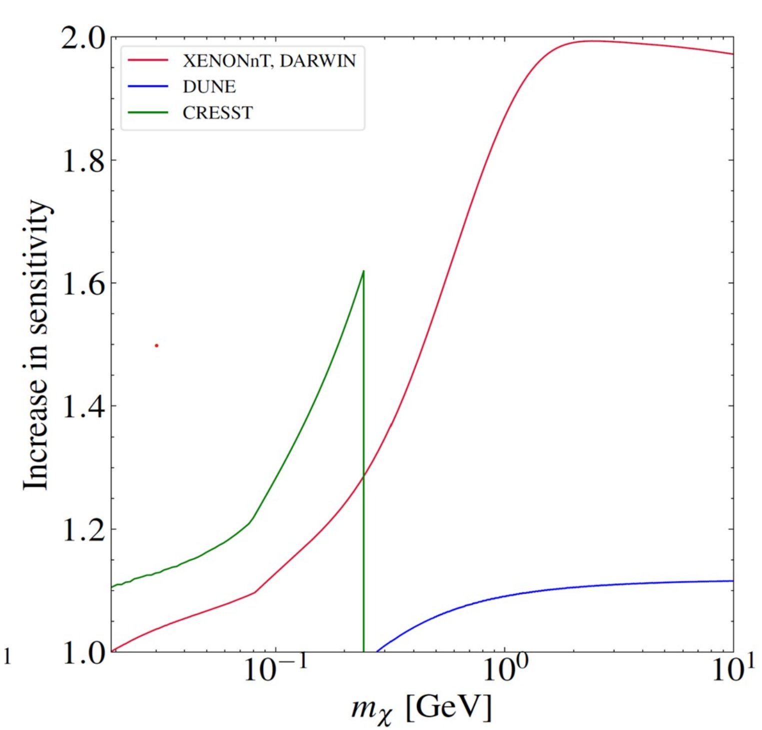
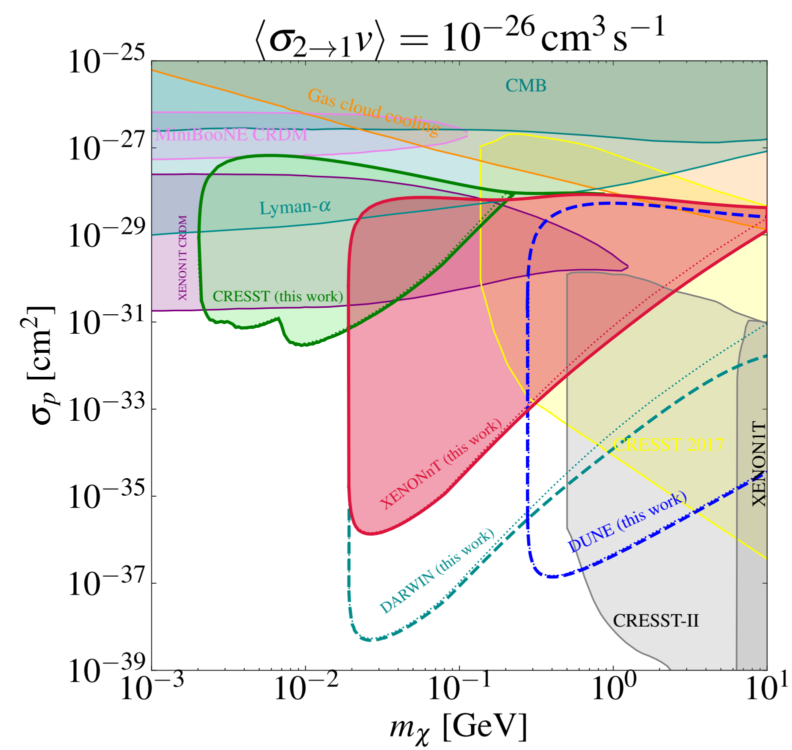


Betancourt Kamenetskaia et al, 26

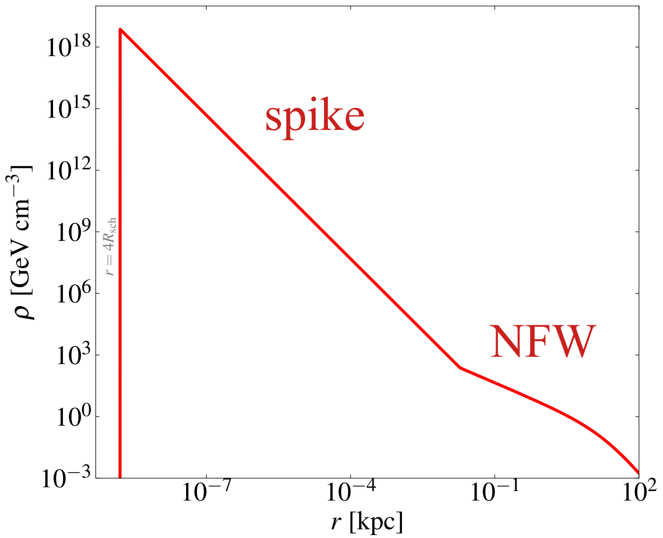


Boosted dark matter from semi-annihilations in Active Galactic Nuclei?

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

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

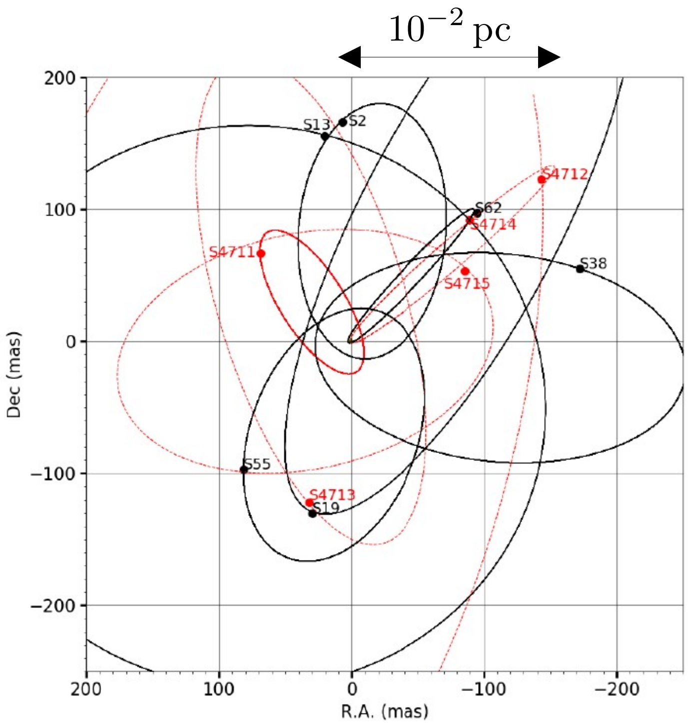


Enhancement in the (semi-)annihilation rate.

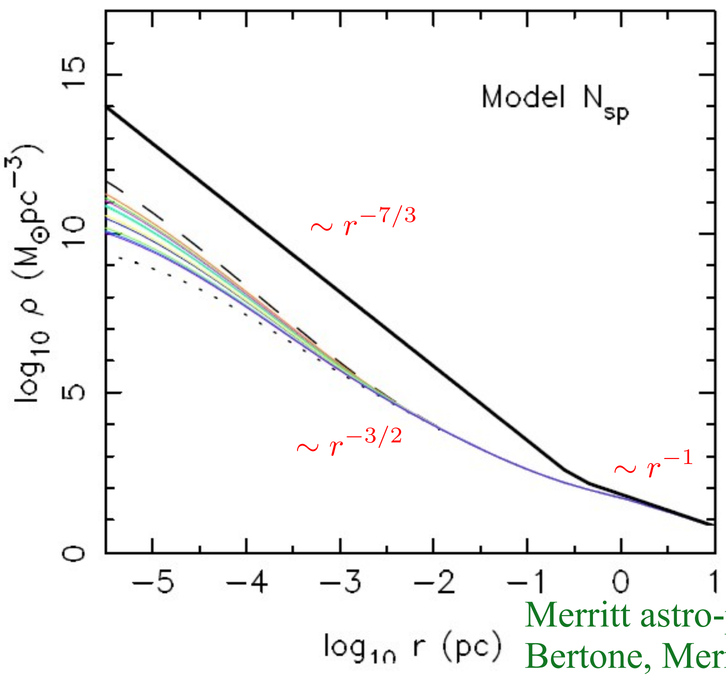
Why should AGNs be a better target for indirect searches than the Milky Way center, which is much closer?

Boosted dark matter from semi-annihilations in Active Galactic Nuclei?

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



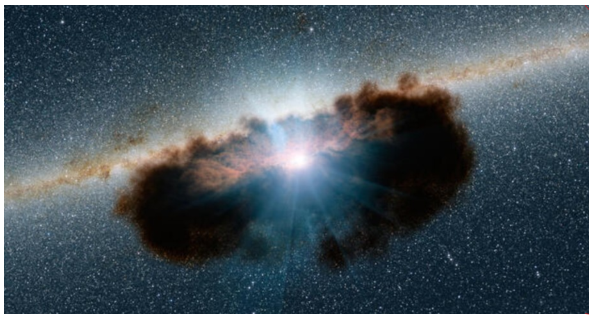
Merritt astro-ph/0311594
Bertone, Merritt astro-ph/0501555

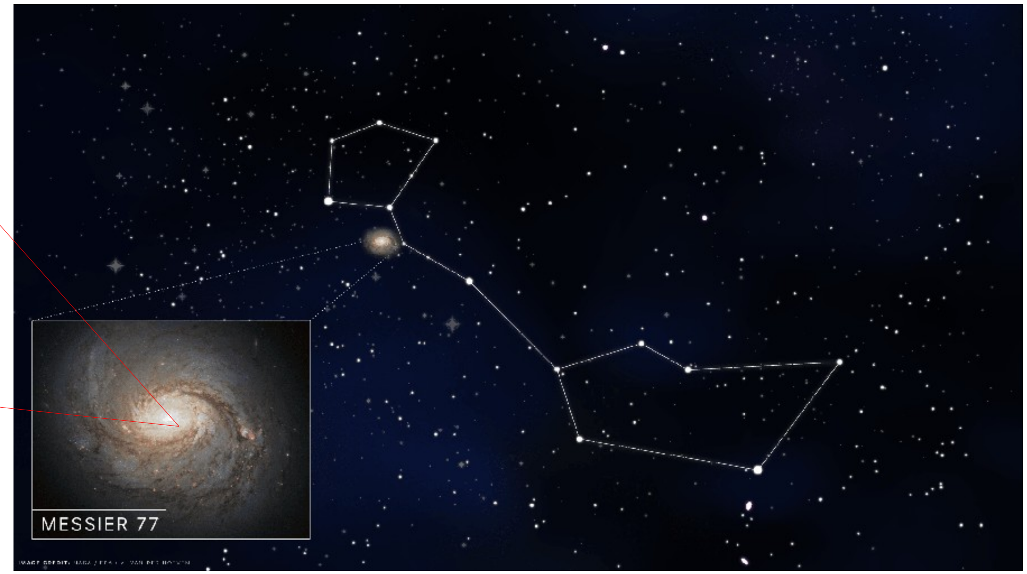
The spike on the MW is for sure affected by stellar heating.
What would happen if the spike in AGNs remains intact?

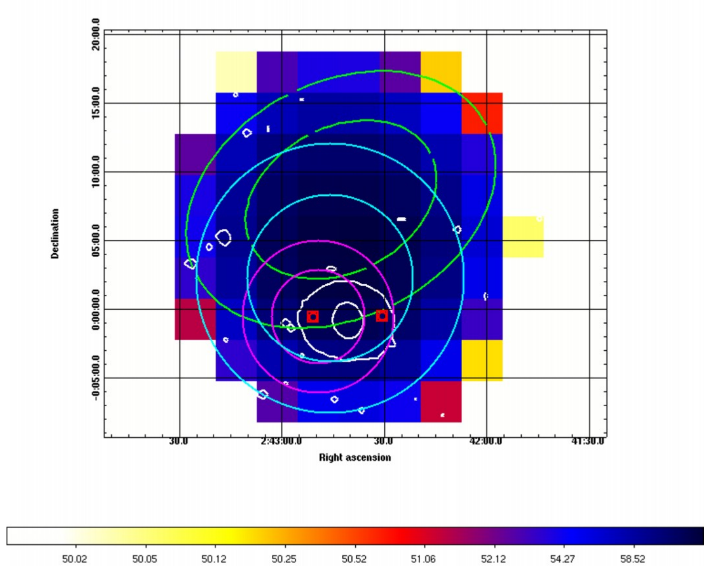
Akita, AI, Zimmermann, 2507.16539

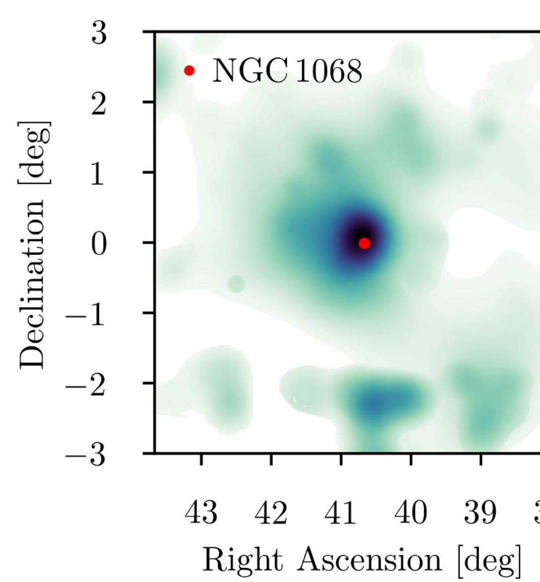
A dark matter signal from NGC 1068?

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.

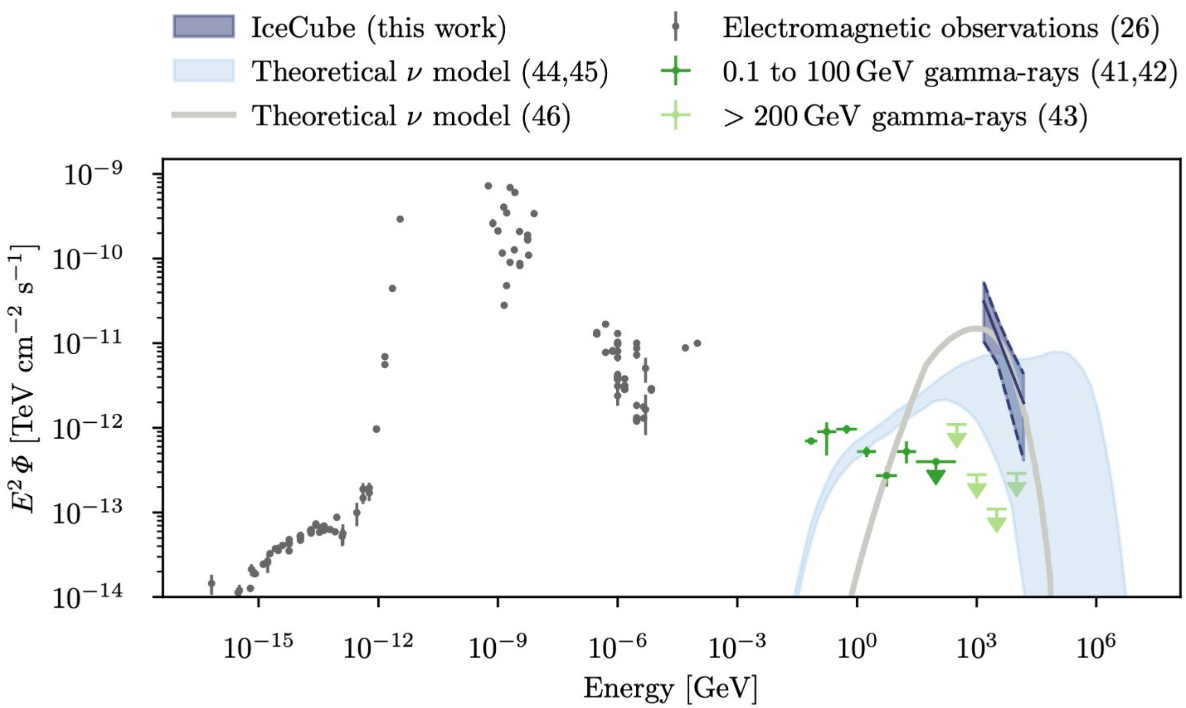




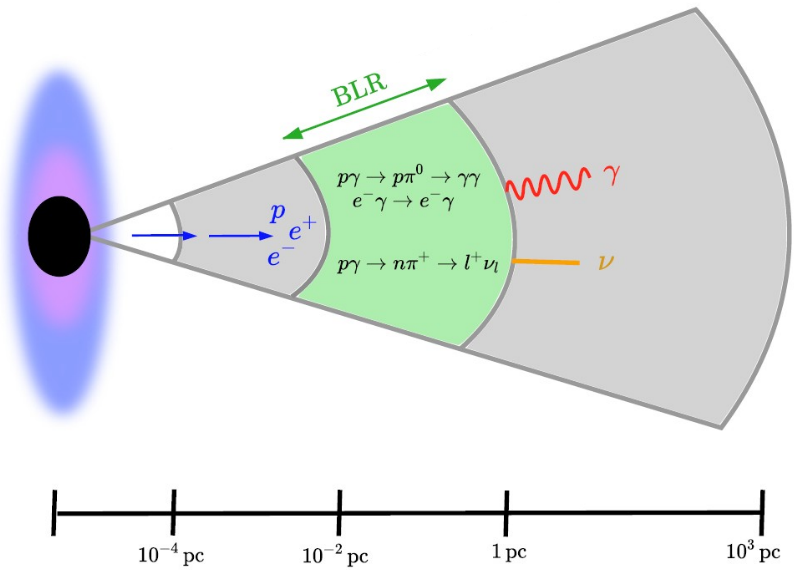


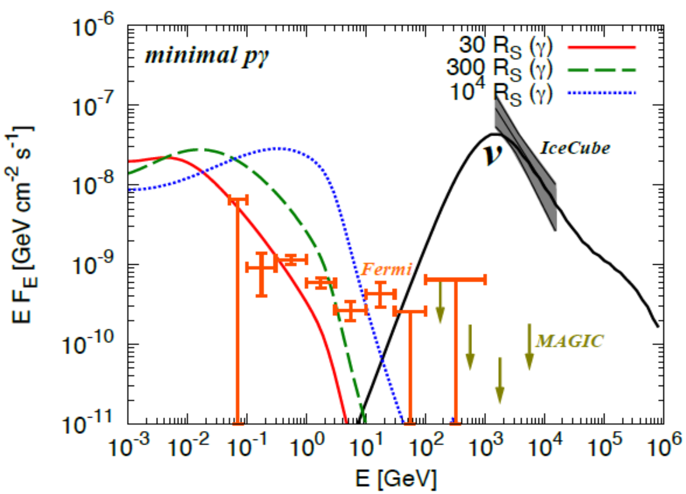


A dark matter signal from NGC 1068?



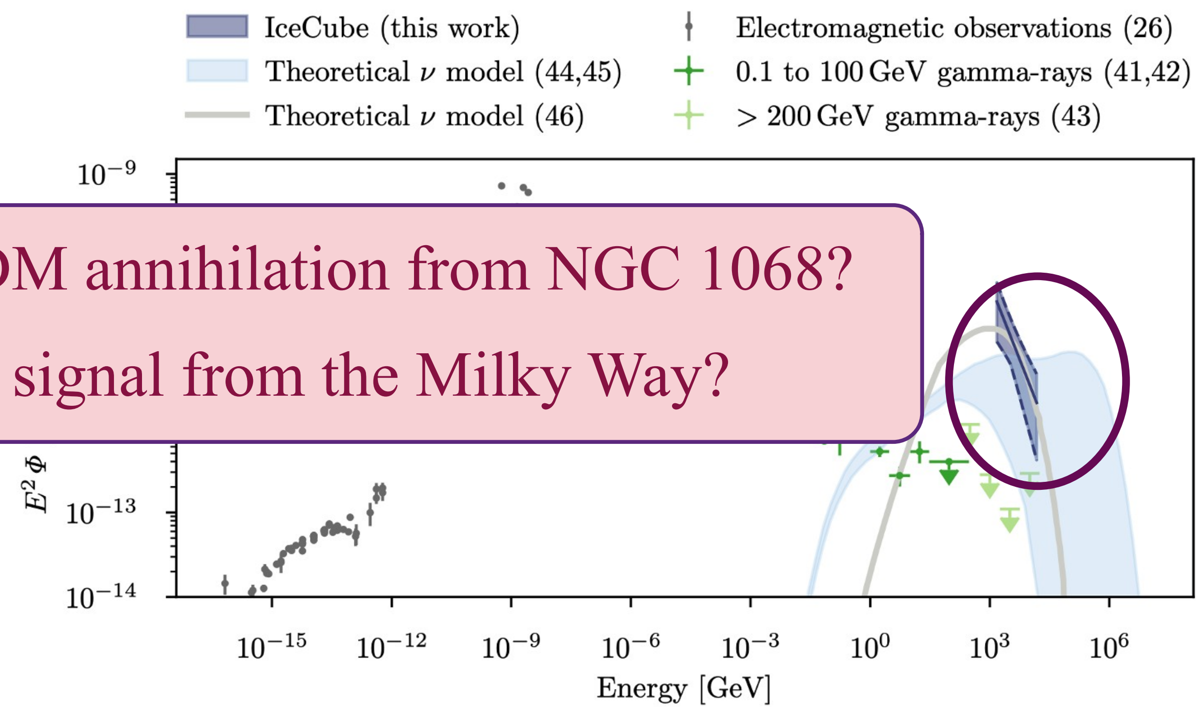
IceCube coll'22





Murase'22

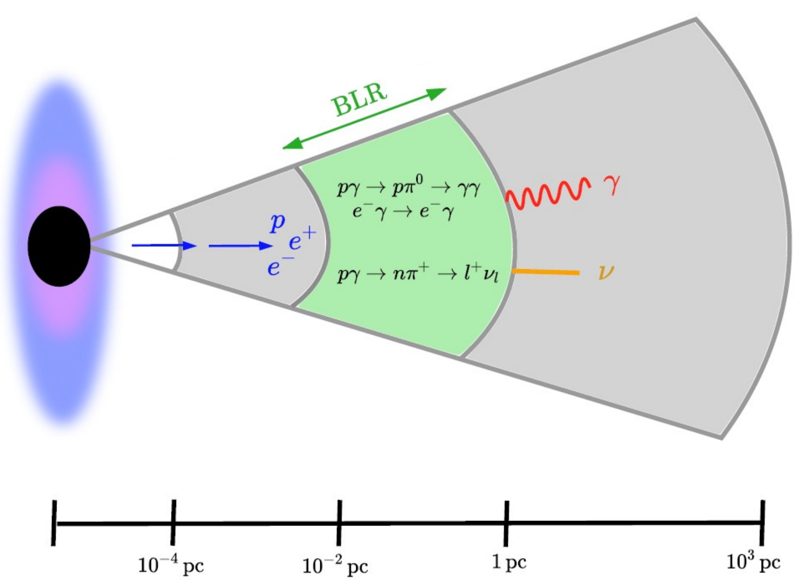
A dark matter signal from NGC 1068?

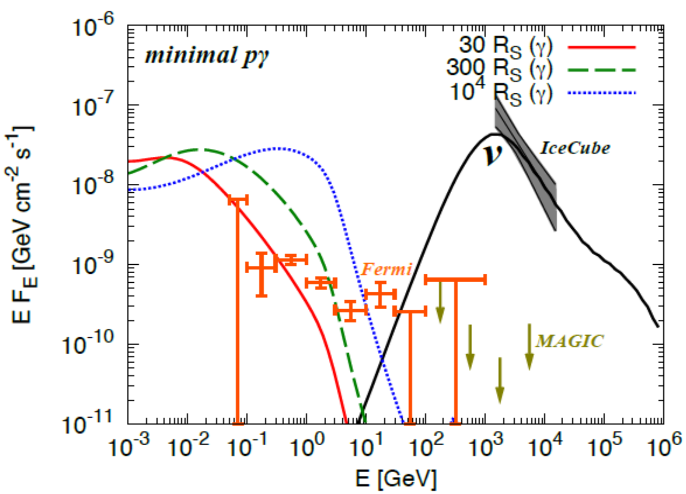


A signal of DM annihilation from NGC 1068?

Why no signal from the Milky Way?

IceCube coll'22

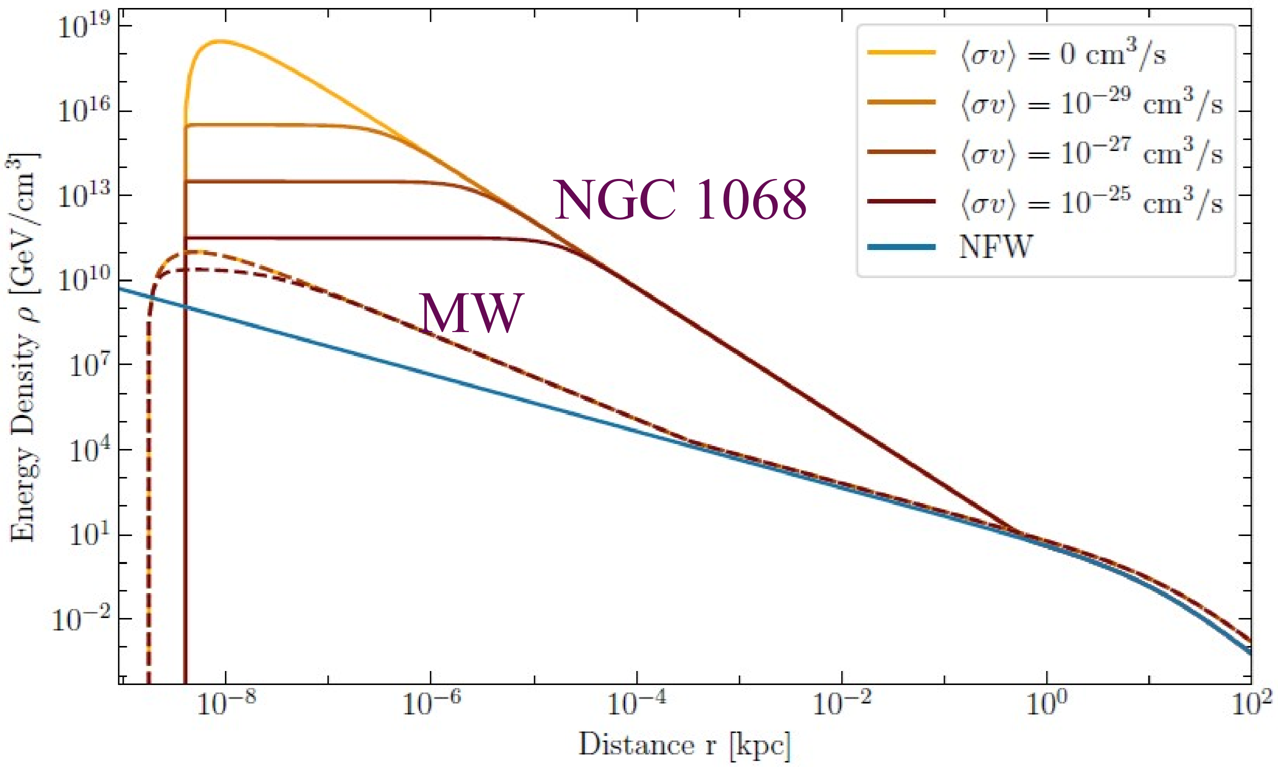




Murase'22

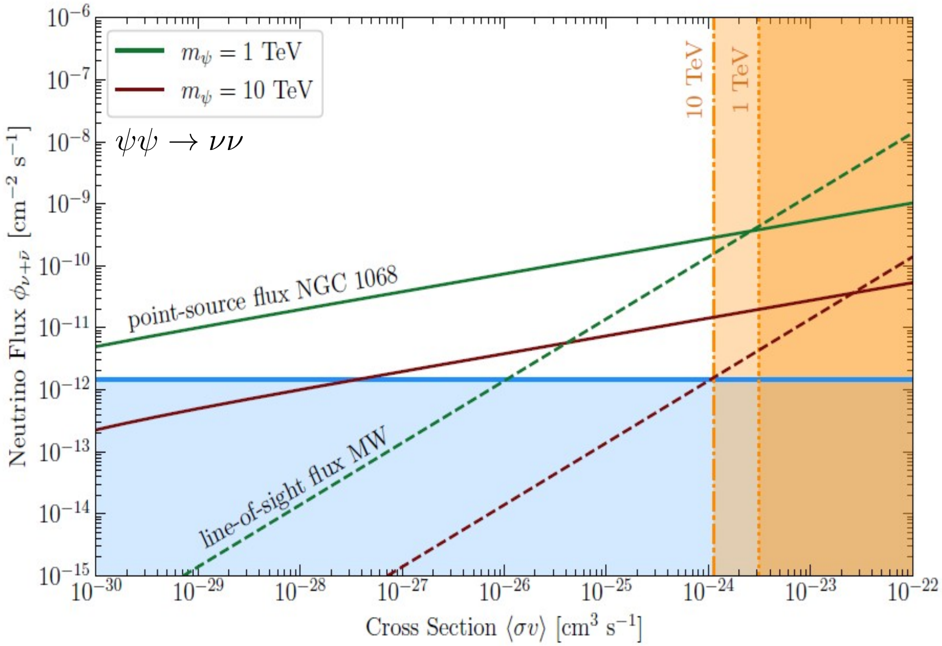
Boosted dark matter from semi-annihilations in Active Galactic Nuclei?

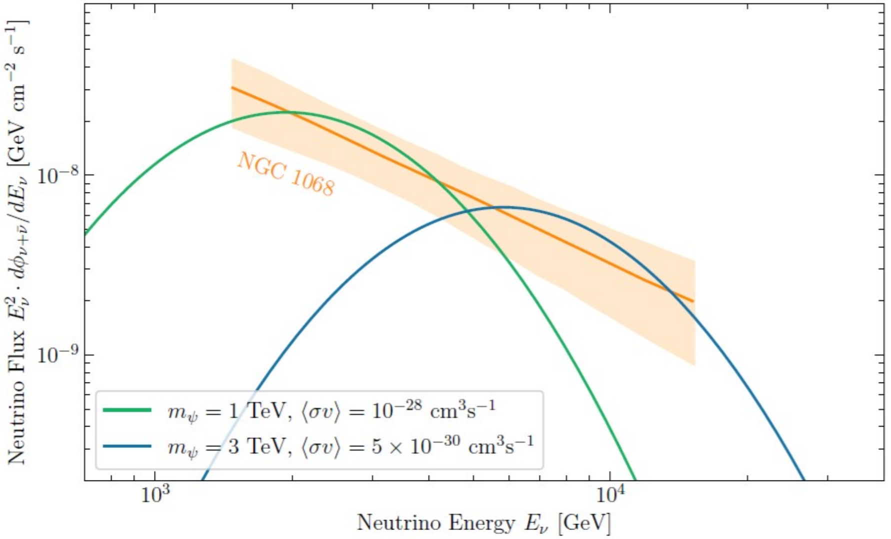
Dark matter profiles of NGC 1068 and the MW



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

A dark matter signal from NGC 1068?



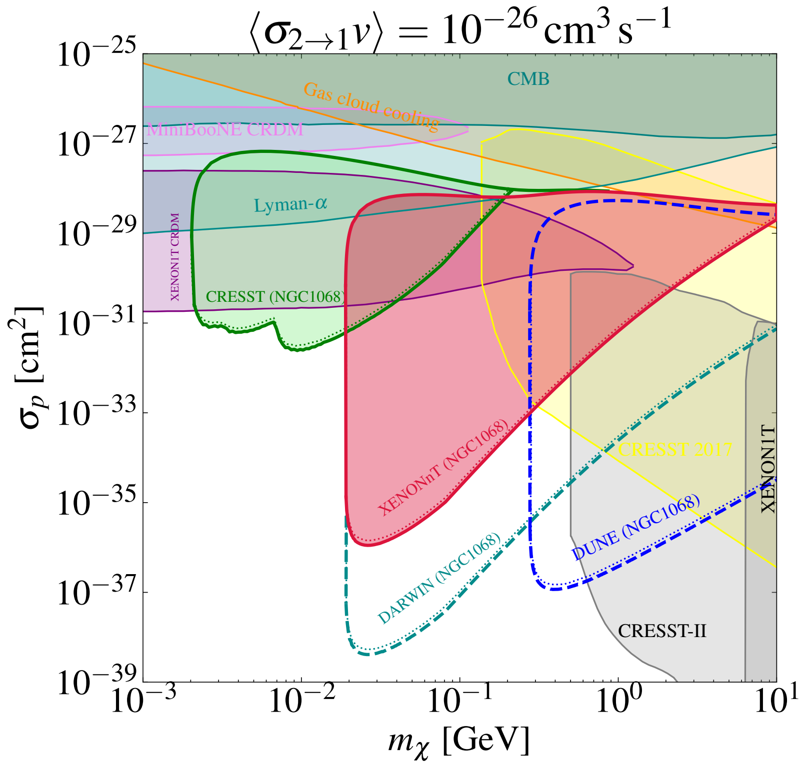


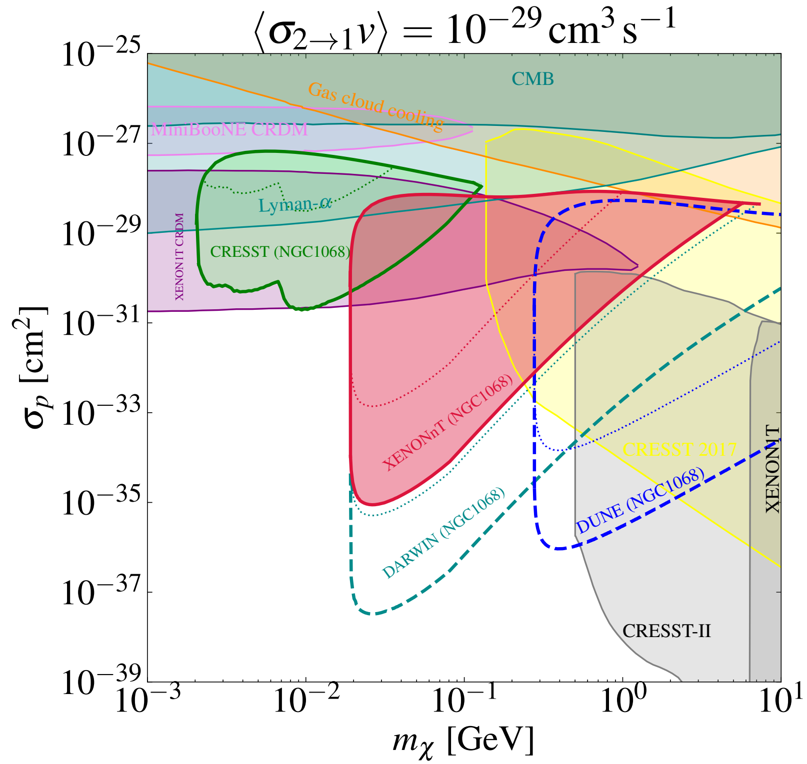
Akita, AI, Zimmermann

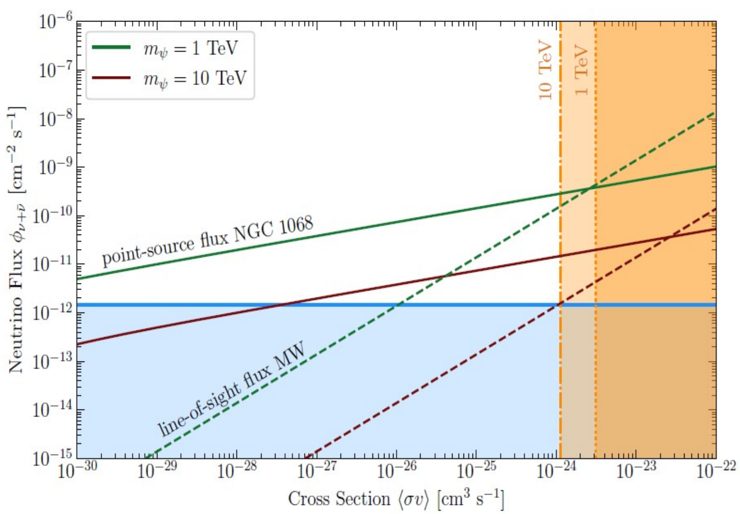
- Dark matter annihilations in the spike of NGC 1068 could produce a neutrino flux detectable at Earth as a point source (for reasonable values of the cross-section).
- The neutrino flux produced in the Milky Way center is below the sensitivity of current experiments, due to the effect of the stellar heating on the spike.

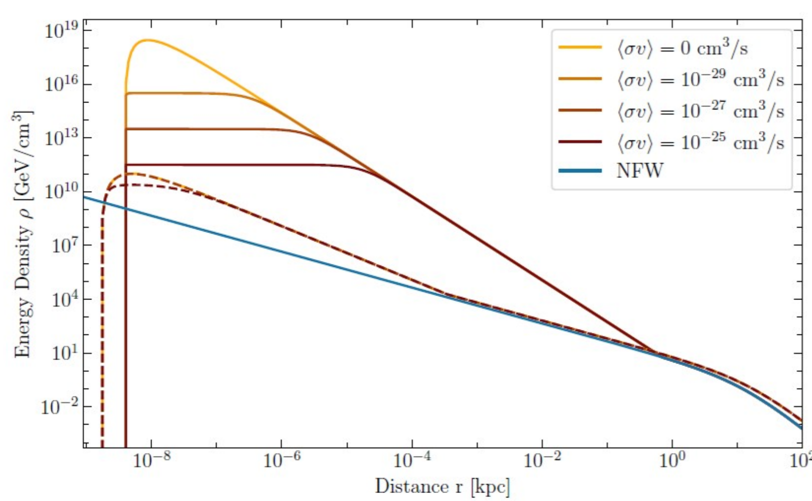
NGC 1068 (an other nearby active galaxies) are potentially interesting targets for dark matter annihilation.

Boosted dark matter from semi-annihilations In NGC1068?









Conclusions

- The dark matter semi-annihilation $\chi\chi \to \chi^c\phi$ is well motivated theoretically and constitutes a source of boosted dark matter.
- Annihilations in the Milky Way increase the sensitivity of current direct detection experiments to sub-GeV DM by orders of magnitude.
- Neutrino detectors such as MiniBooNe and DUNE cannot detect DM in the MW halo, but can detect signals from semi-annihilations.
- Other sources of boosted dark matter further increase the sensitivity of experiments to semi-annihilations. For small semi-annihilation cross-sections, NGC1068 may provide the largest contribution to the boosted DM flux.