Dark matter spikes with (or without) strongly self-interacting particles

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In collaboration with Boris Betancourt, Motoko Fujiwara, Takashi Toma, Kensuke Akita and Robert Zimmermann

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Introduction

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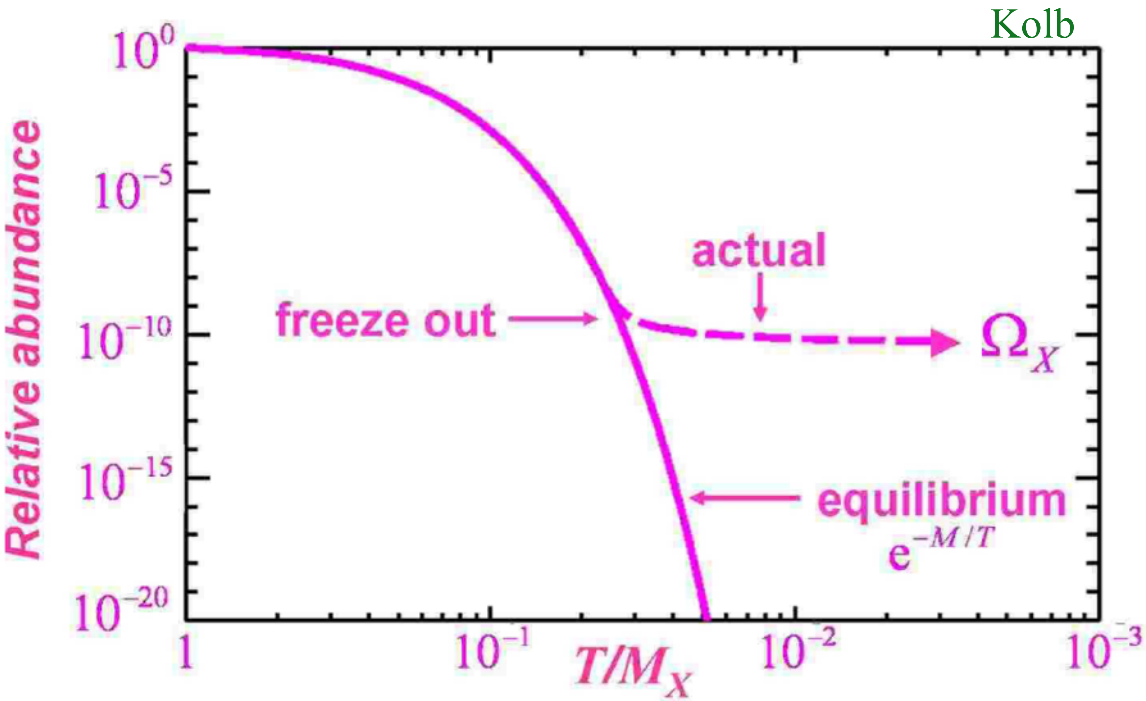

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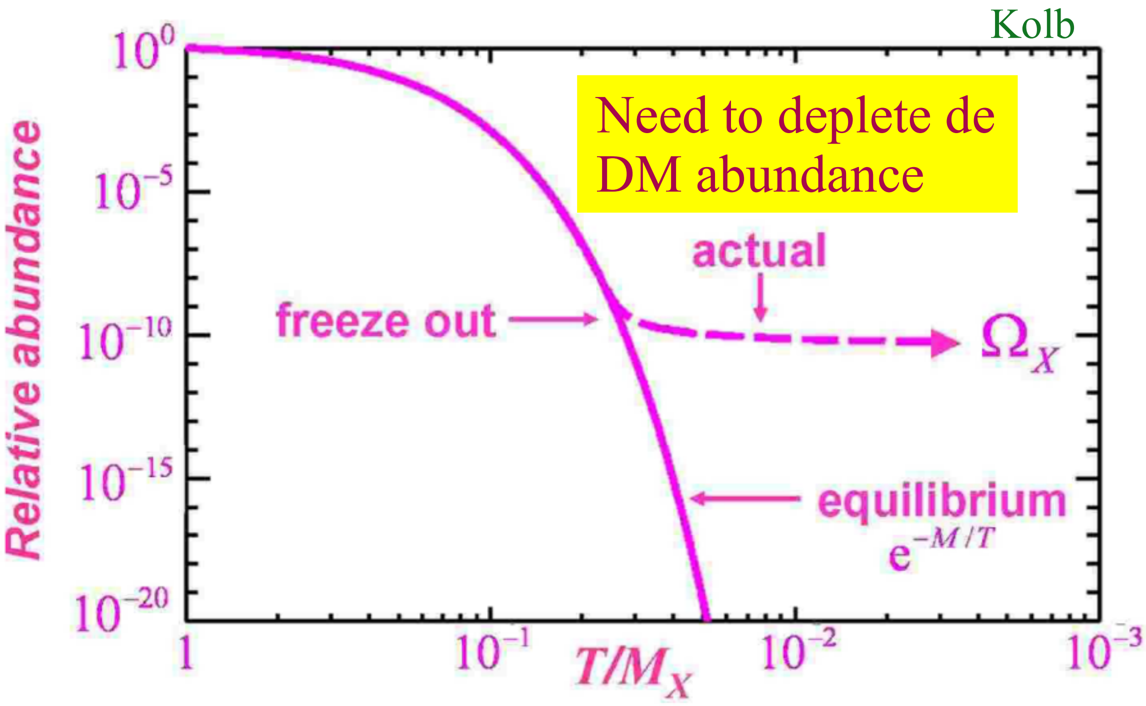

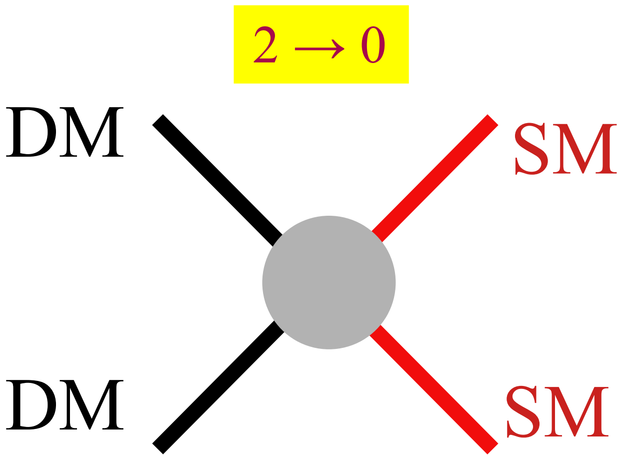

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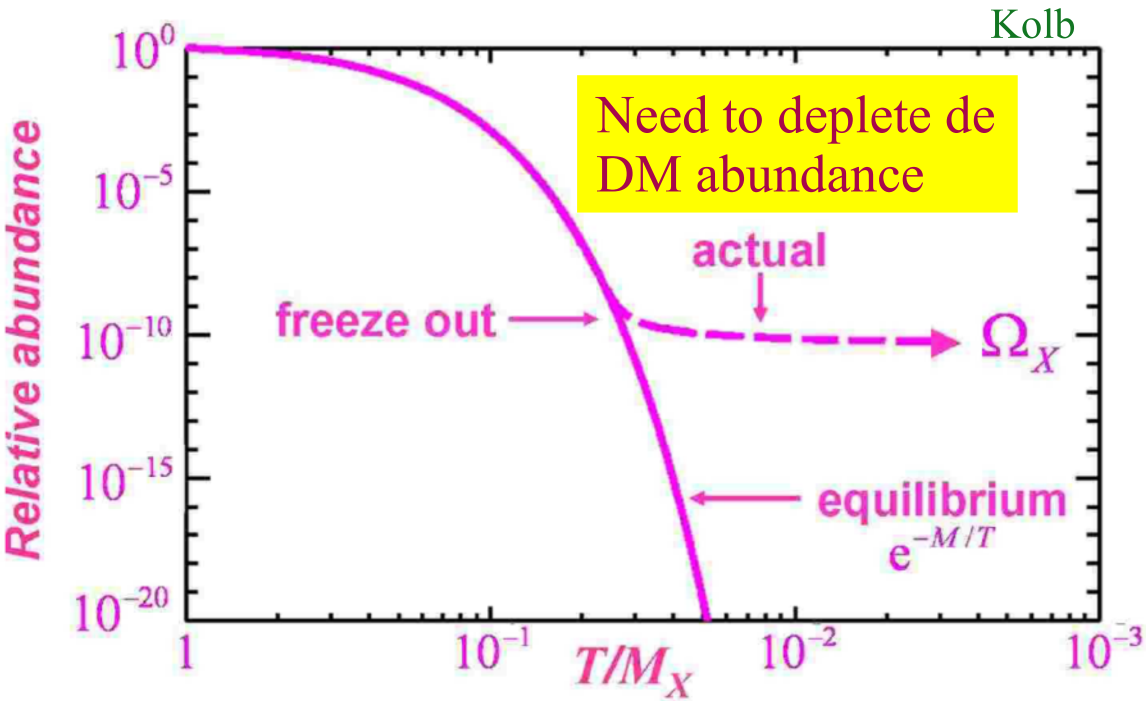

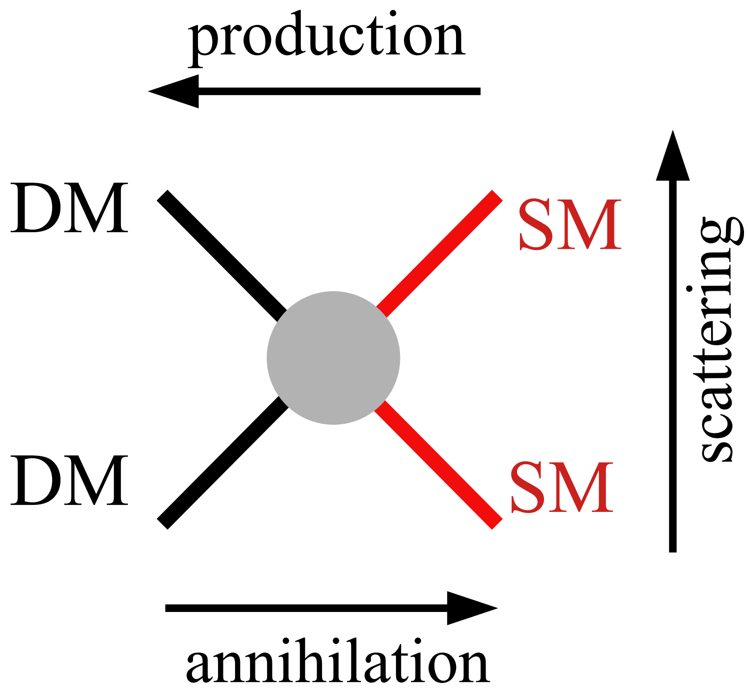

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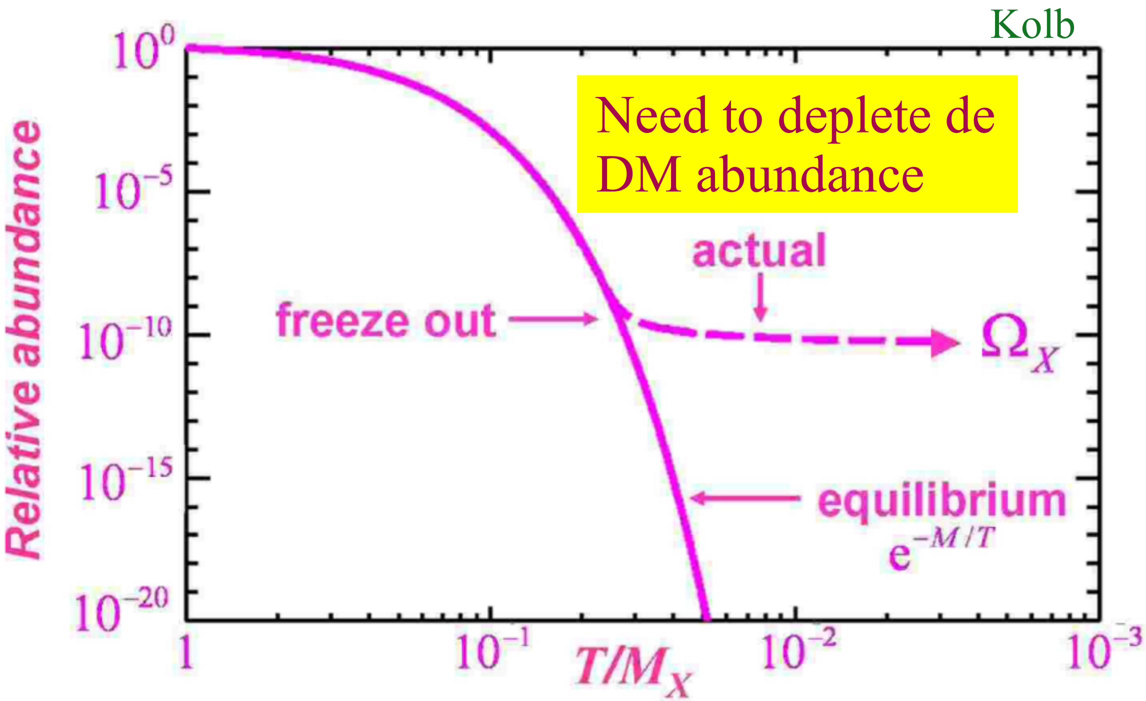

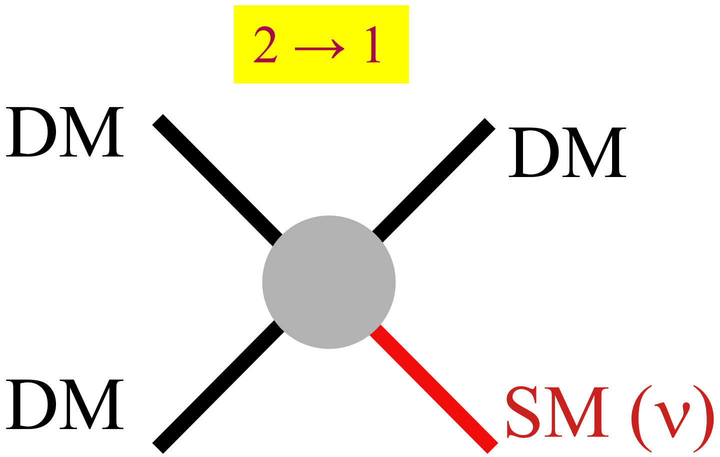

Hambye et al.
D'Eramo, Thaler

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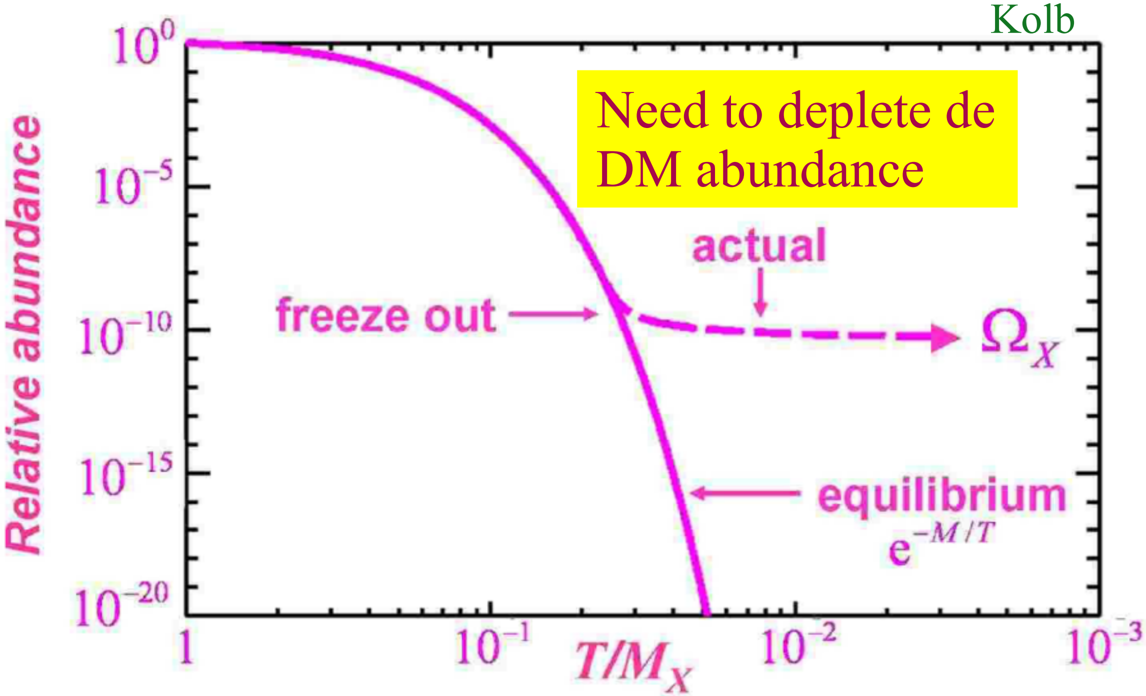

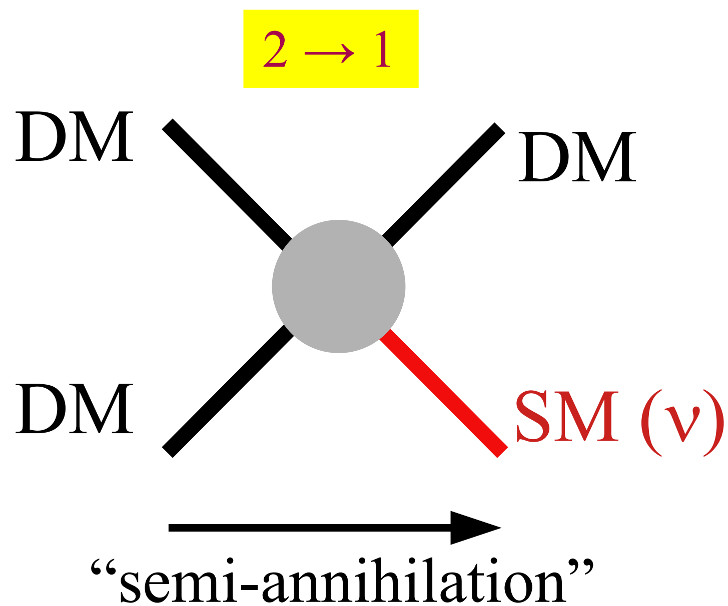

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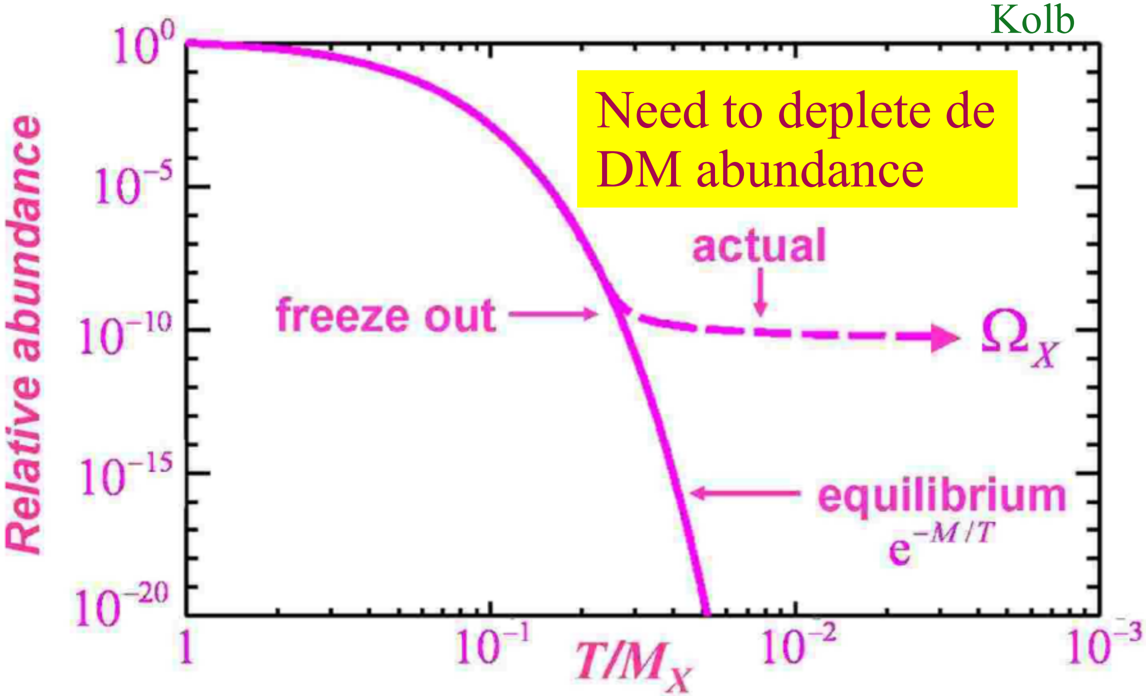
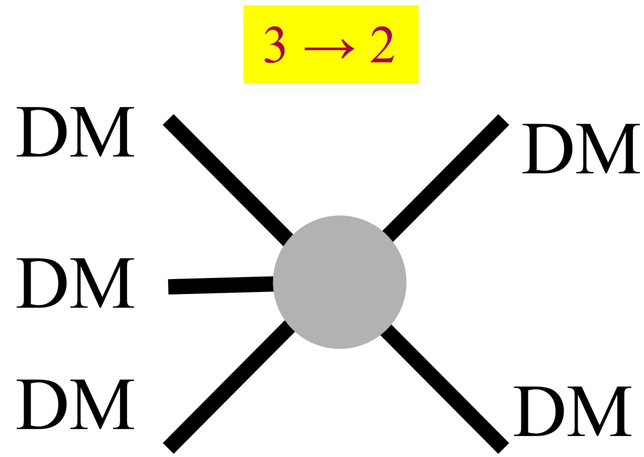
Kolb





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

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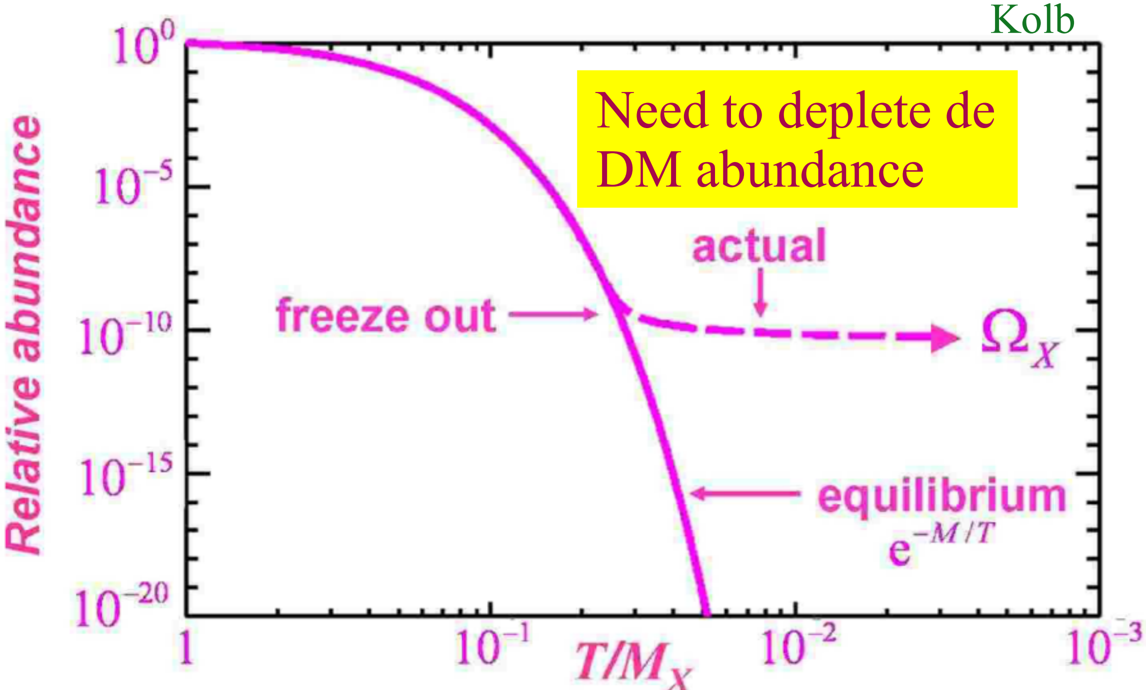
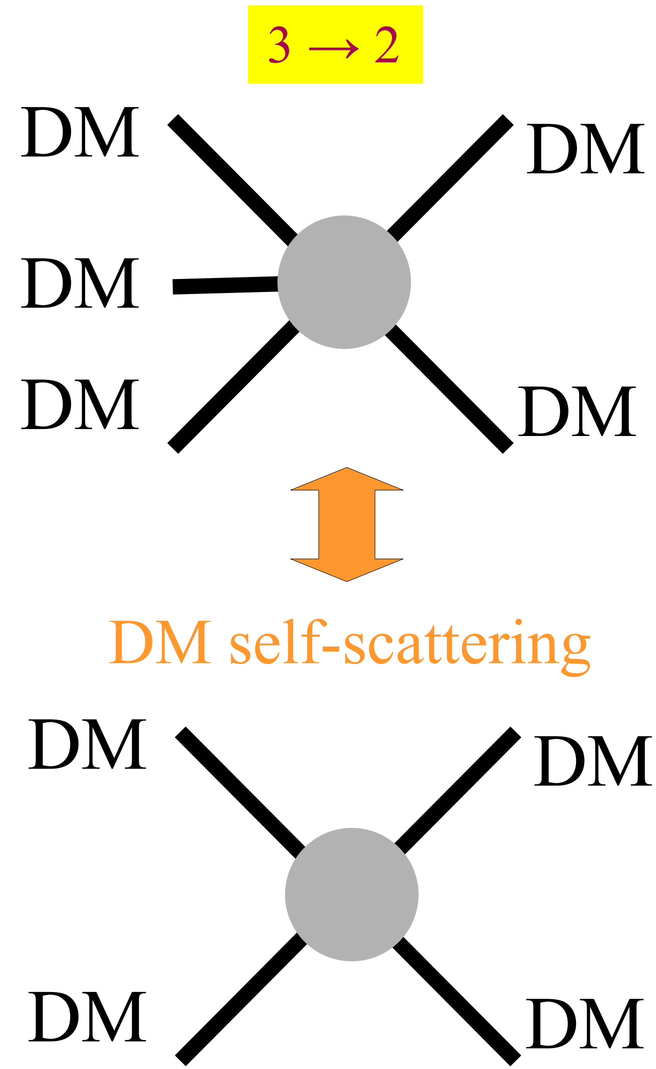
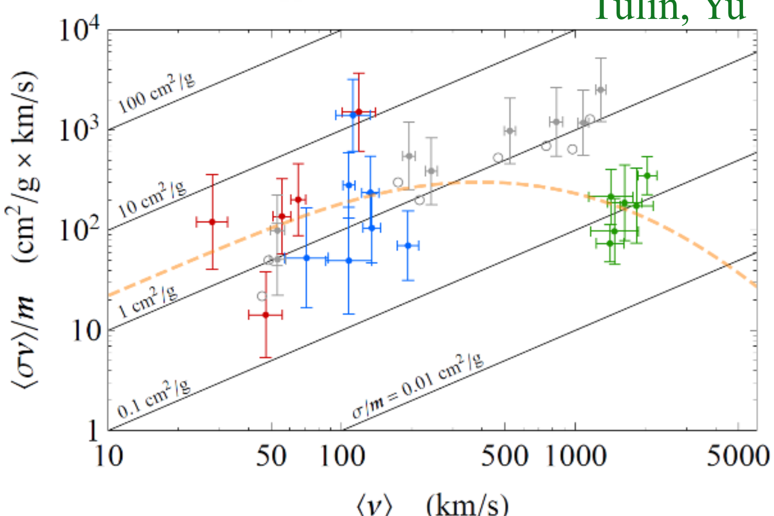




Tulin, Yu



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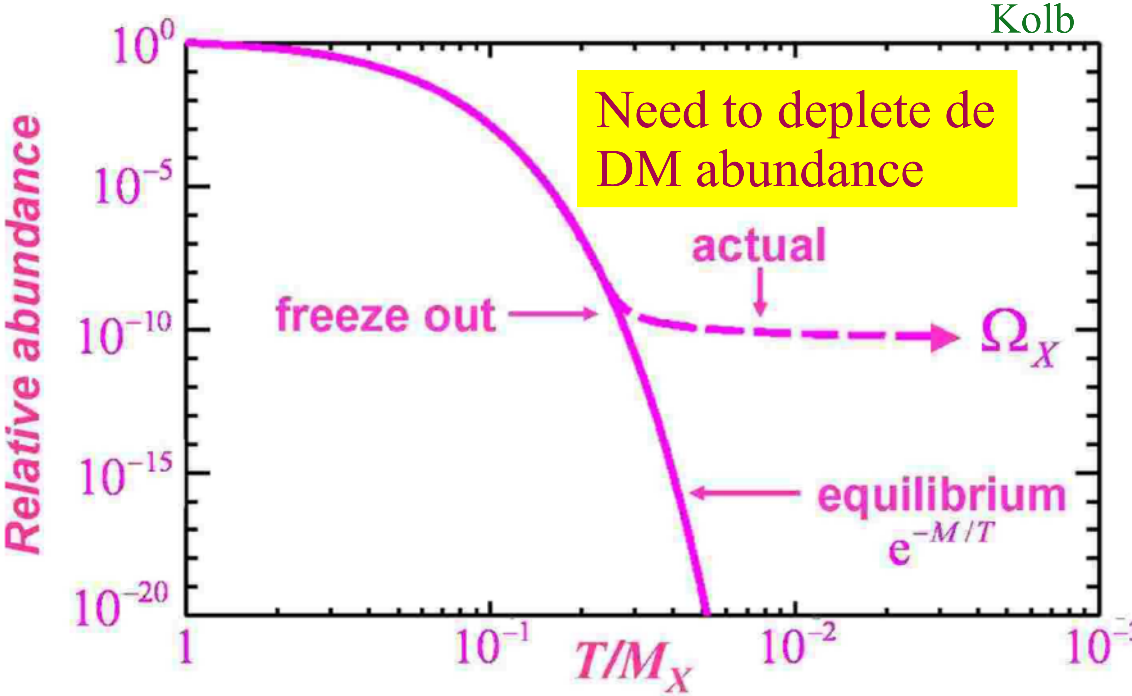

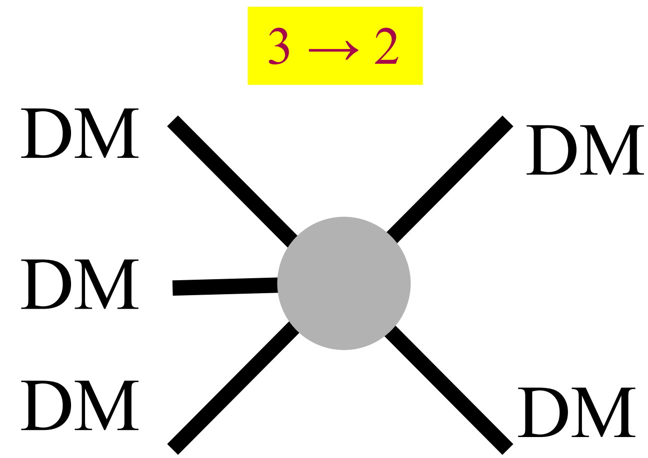

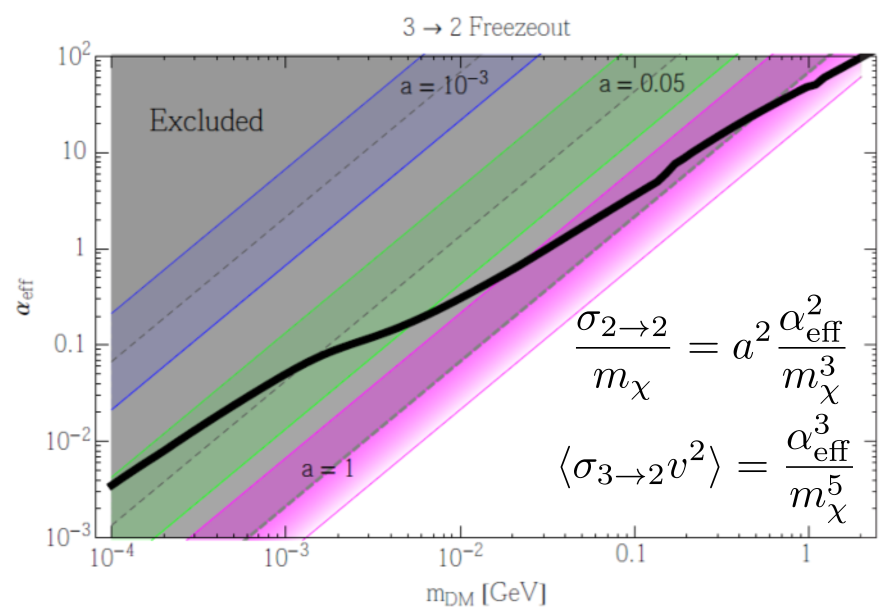

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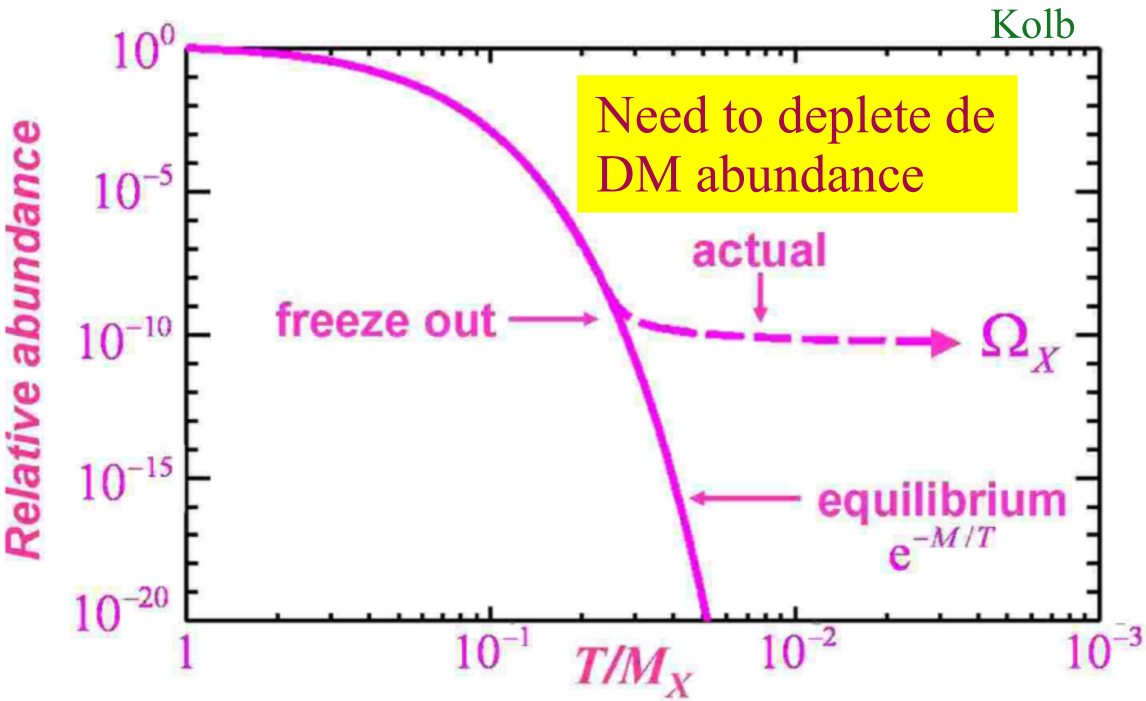
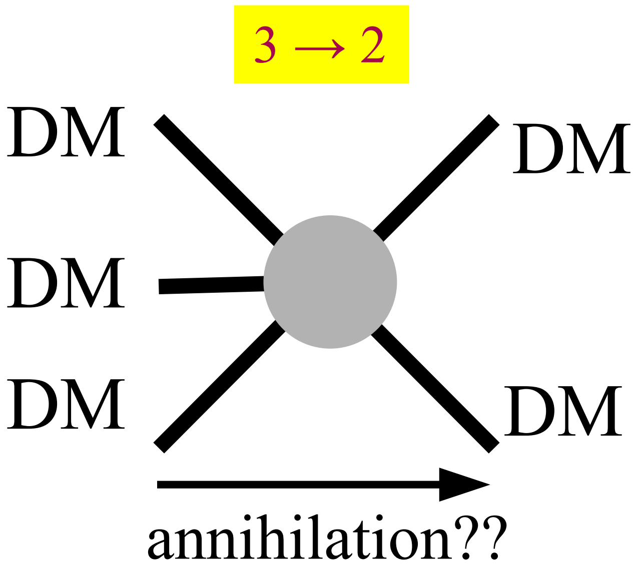




DM density at freeze-out

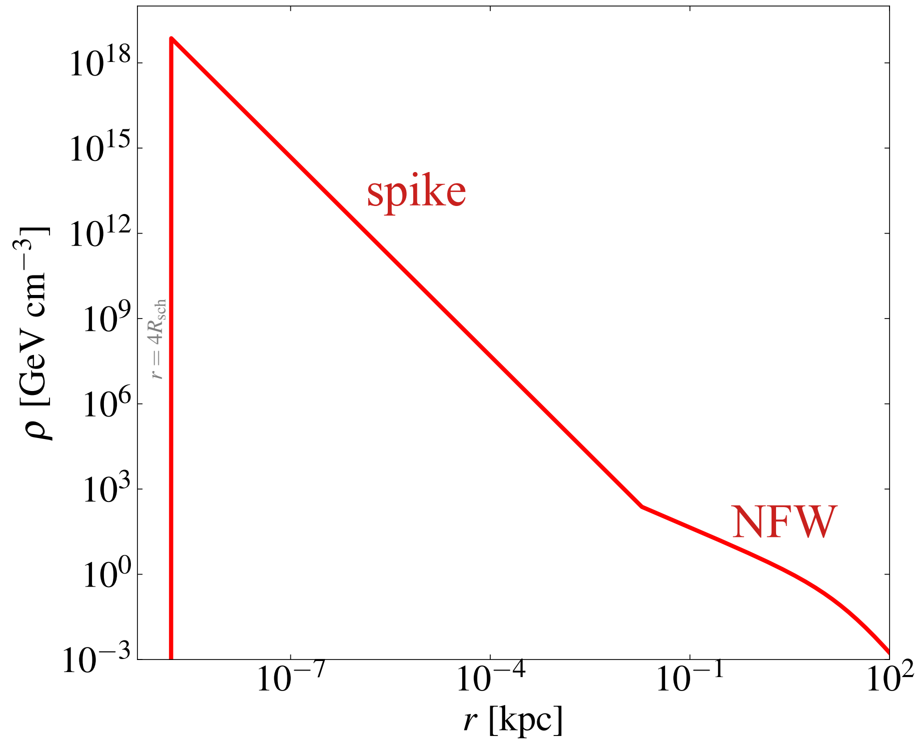
$$\rho_\chi \sim 6 \times 10^{22}\,\mathrm{GeV/cm^3} \left(\frac{m_\chi}{100\,\mathrm{MeV}}\right)^{-3} \left(\frac{\alpha_{\rm eff}}{0.1}\right)$$

The DM spike around supermassive black holes

Many 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

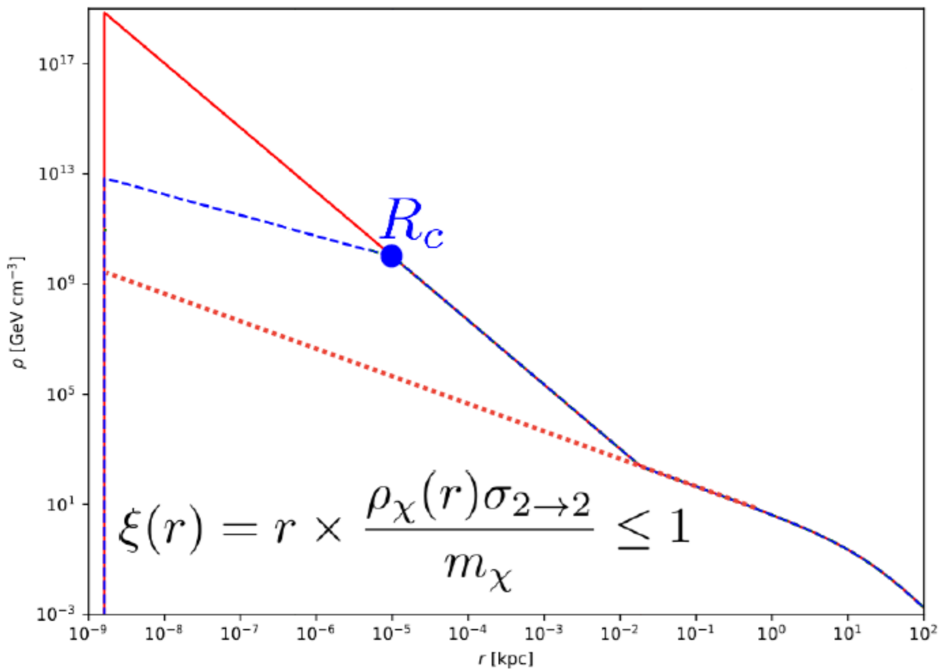
$$\rho(r) \sim \rho_0 \left(\frac{r_0}{r}\right) \longrightarrow \rho_{\rm sp} \sim \rho_R \left(\frac{R_{\rm sp}}{r}\right)^{7/3}$$



The DM spike around supermassive black holes

Different effects can soften the spike:

- Self-interactions: momentum exchange produce a core (depends on $\sigma_{2\to 2}$)



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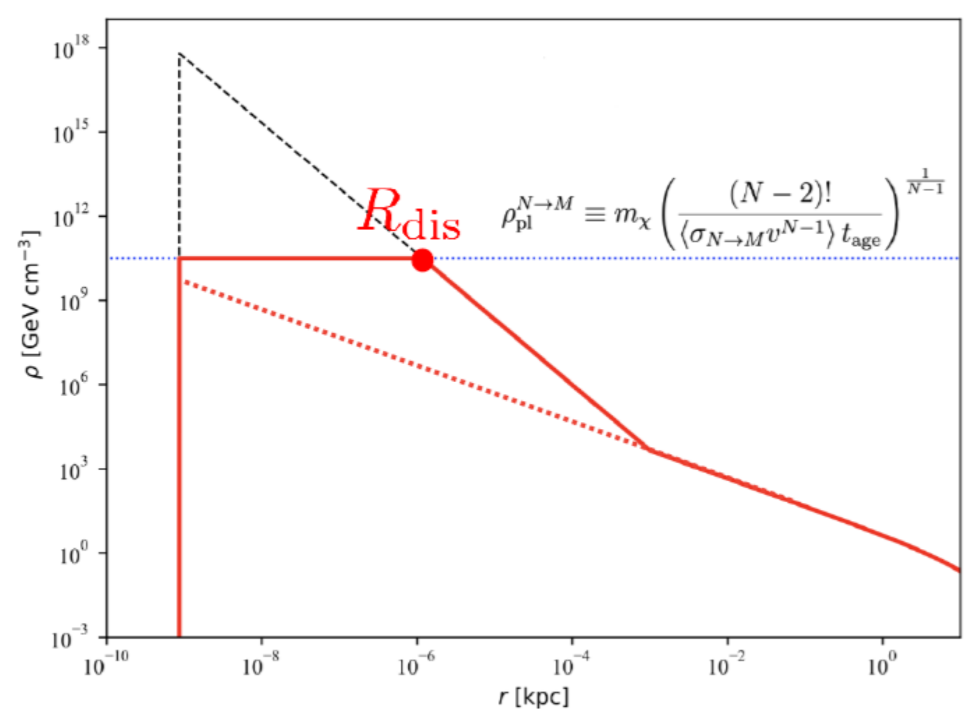
- n→m processes (n>m): deplete the number of DM particles in the spike (depends on $\sigma_{n\to m}$)

$$\dot{n}_\chi(r,t) = -\langle\sigma_{2\to0}v\rangle\,(n_\chi(r,t))^2 - \frac{n}{n!}\left\langle\sigma_{n\to m}v^{n-1}\right\rangle(n_\chi(r,t))^n$$



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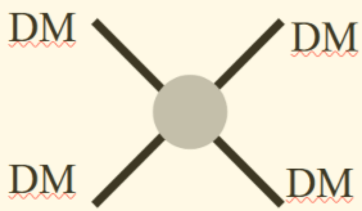
The n→m process produces a highly boosted DM particle.

Implications for direct DM searches?

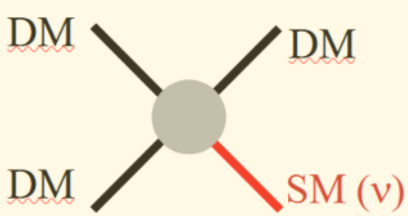
The DM spike around supermassive black holes

Large parameter space: $\{m_\chi, \sigma_{2\to2}/m_\chi, \langle\sigma_{2\to0}v\rangle, \langle\sigma_{2\to1}v\rangle, \langle\sigma_{3\to2}v^2\rangle, \ldots\}$

- Example 1: Only 2→2 and 2→1

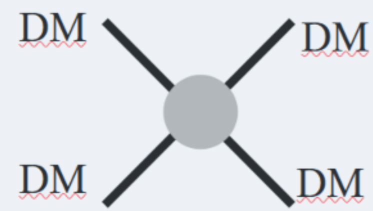


$$\sigma_{2\to2}/m_\chi = \frac{\alpha_{2\to2}^2}{m_\chi^3}$$



$$\langle\sigma_{2\to1}v\rangle = \frac{\alpha_{2\to1}^2}{m_\chi^2}$$

- Example 2: Only 2→2 and 3→2



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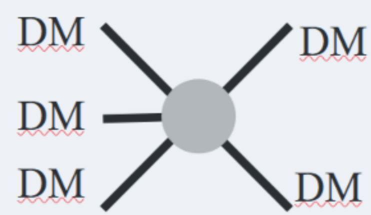
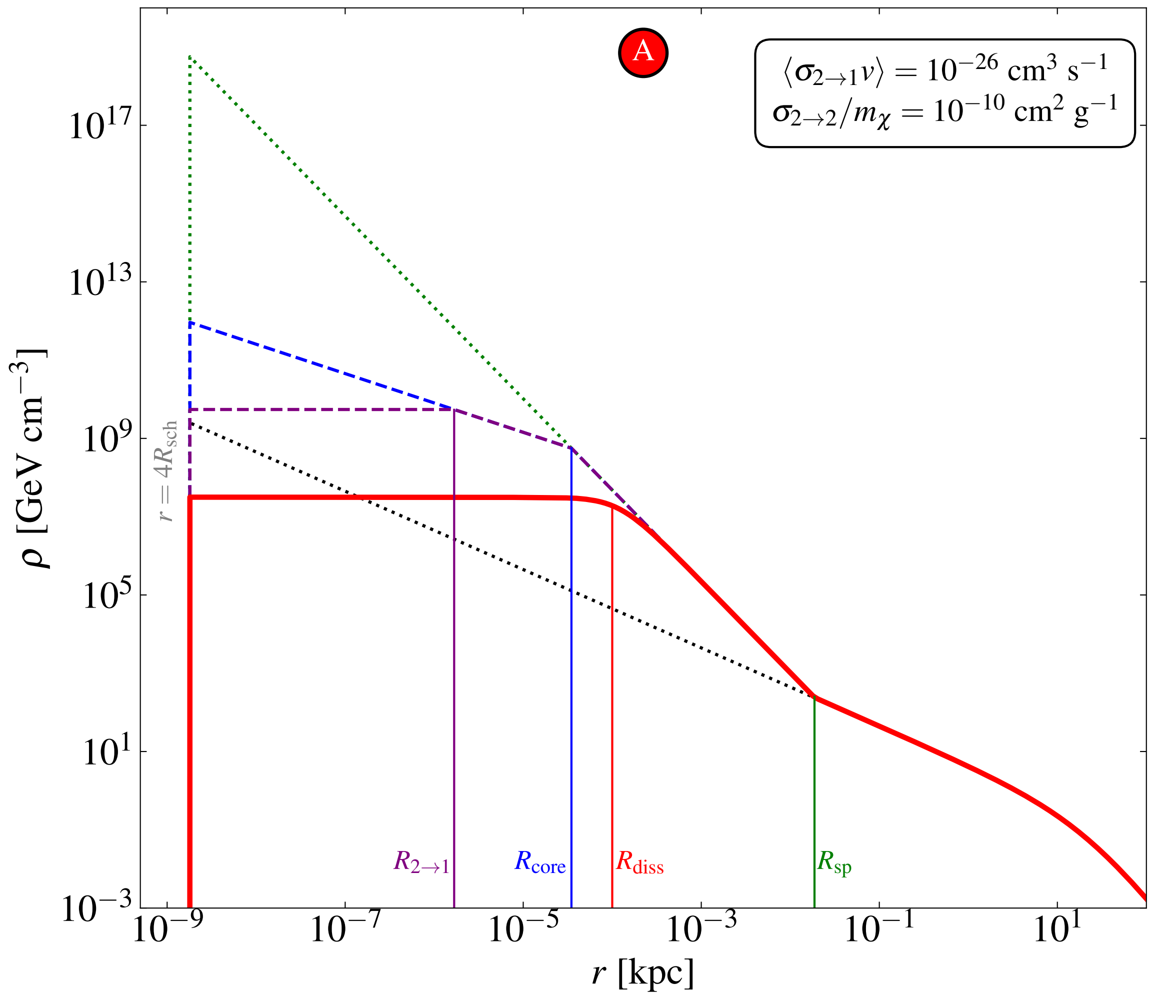


$$\langle\sigma_{3\to2}v^2\rangle = \frac{\alpha_{3\to2}^3}{m_\chi^5}$$

The fate of the DM spike

- Example 1: Only 2→2 and 2→1



The fate of the DM spike

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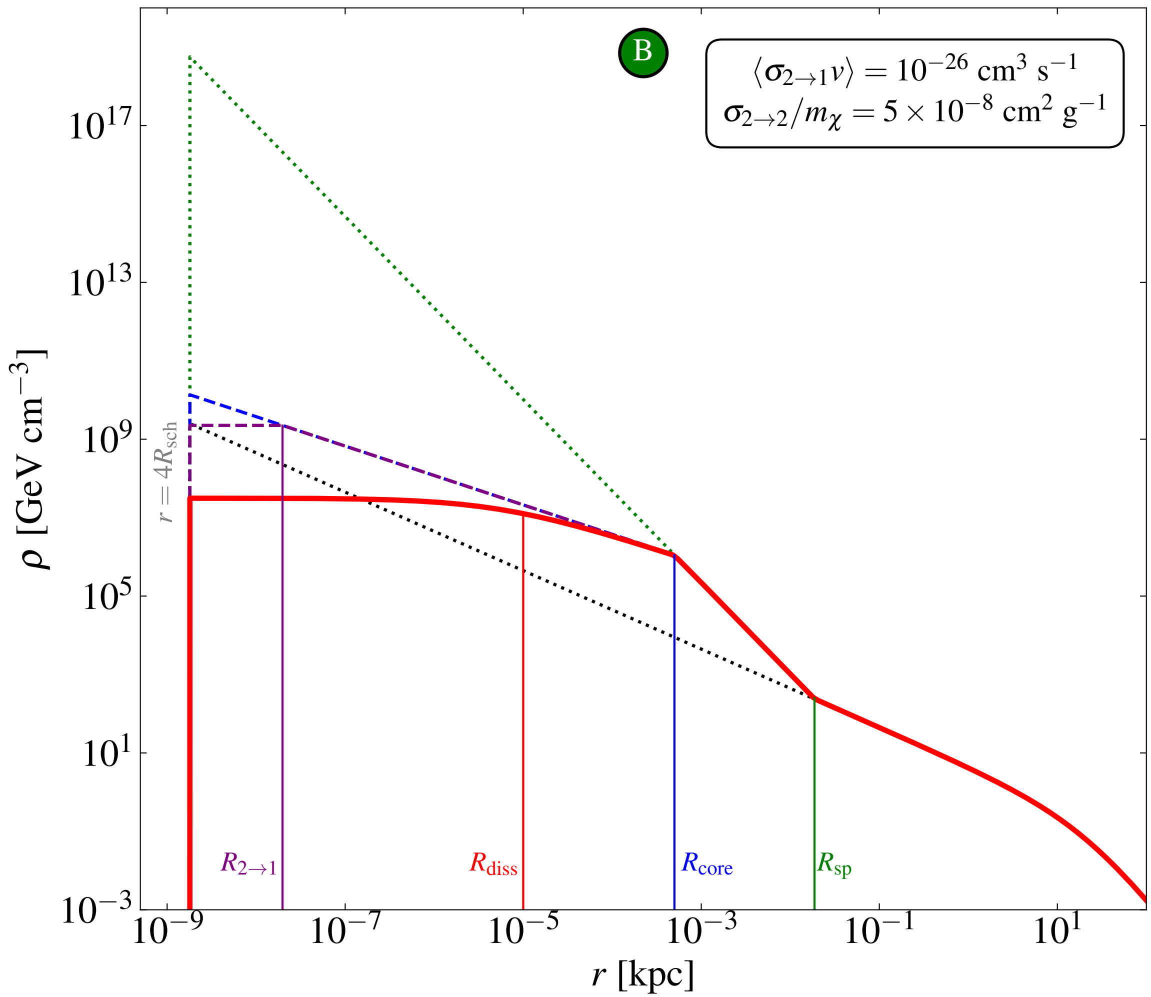

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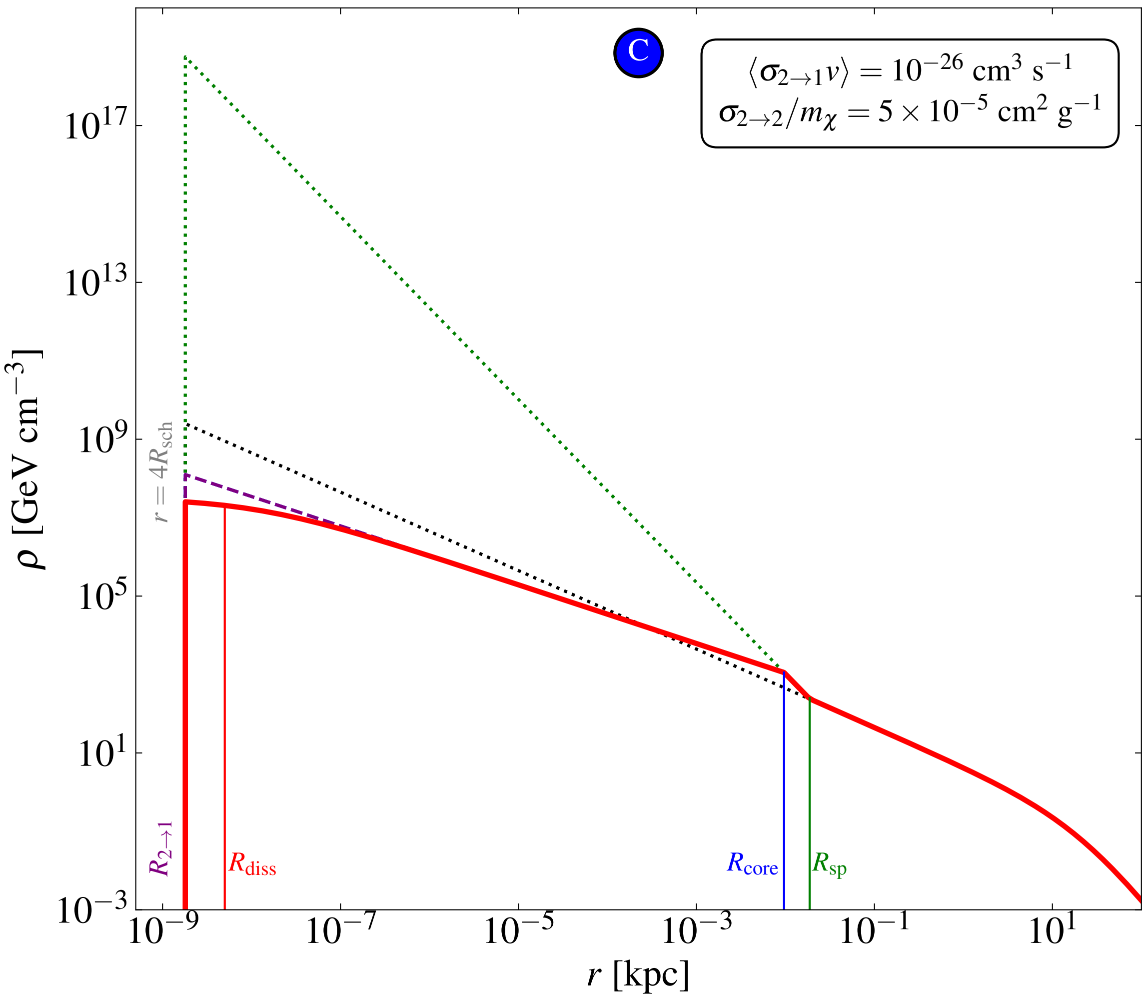

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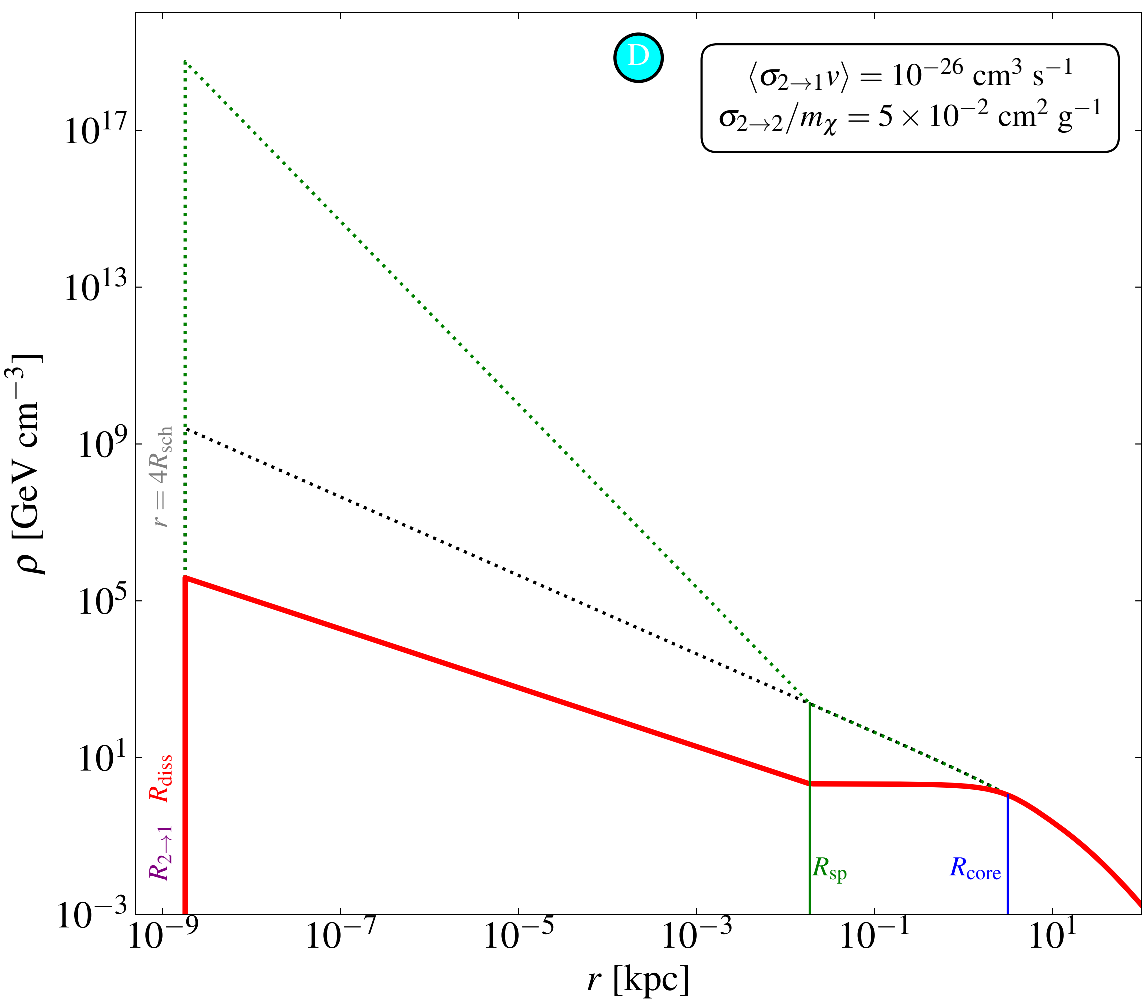
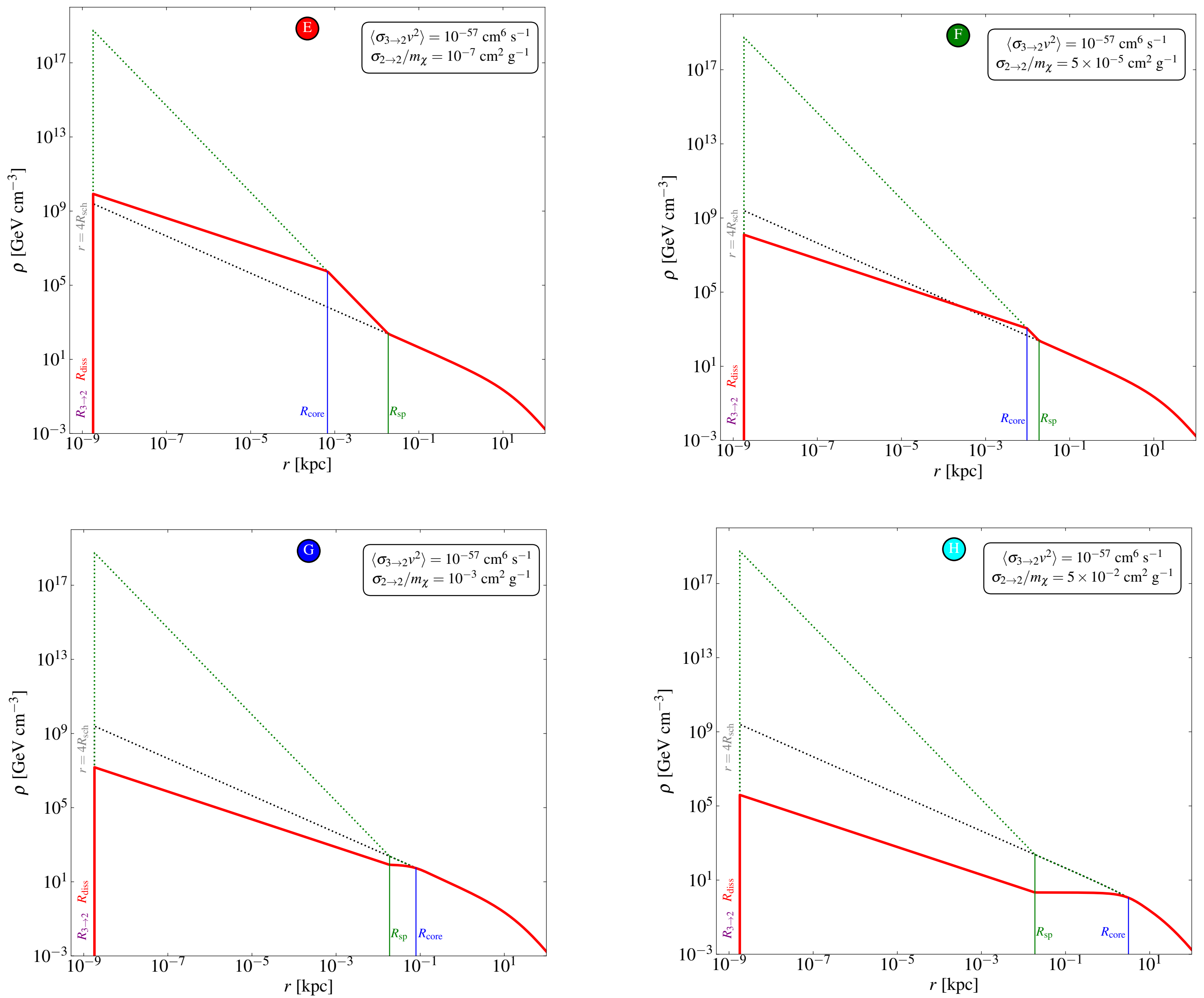
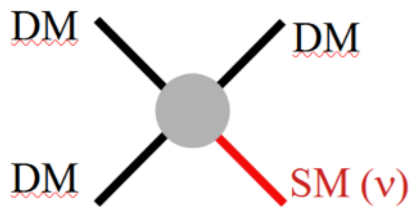


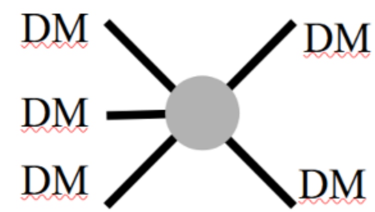
The fate of the DM spike

- Example 2: Only 2→2 and 3→2



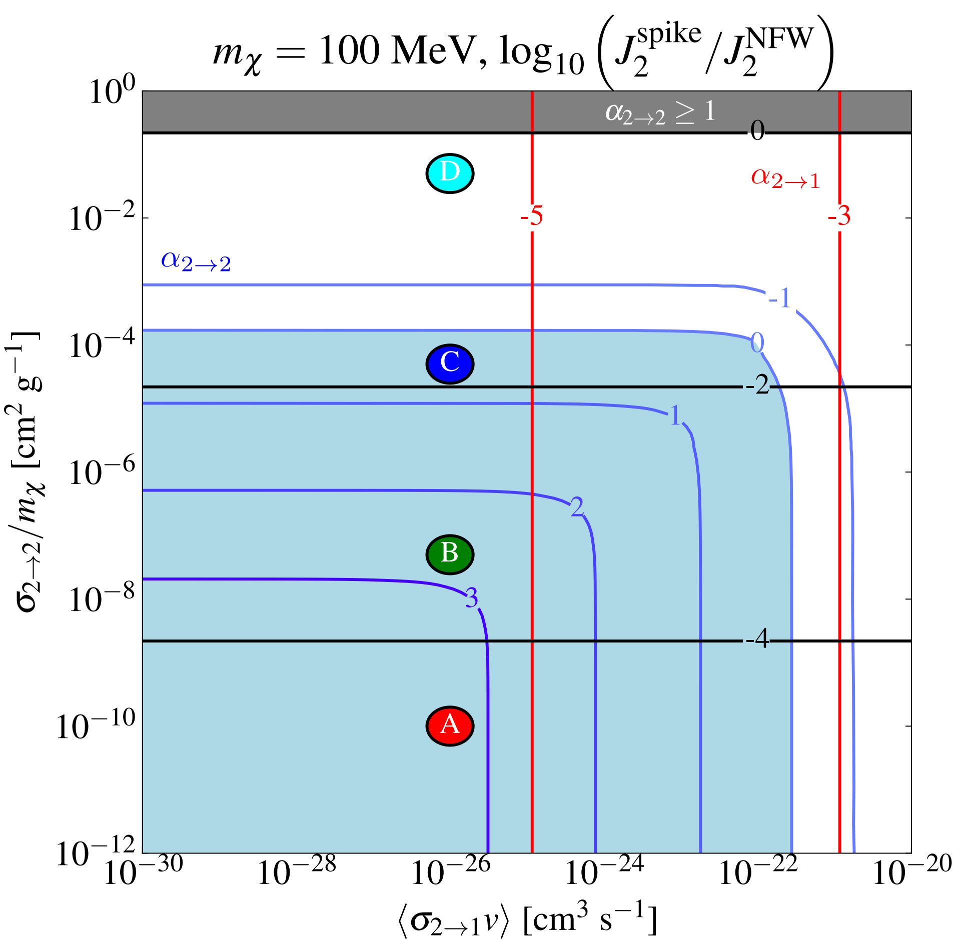
Implications for J-factors

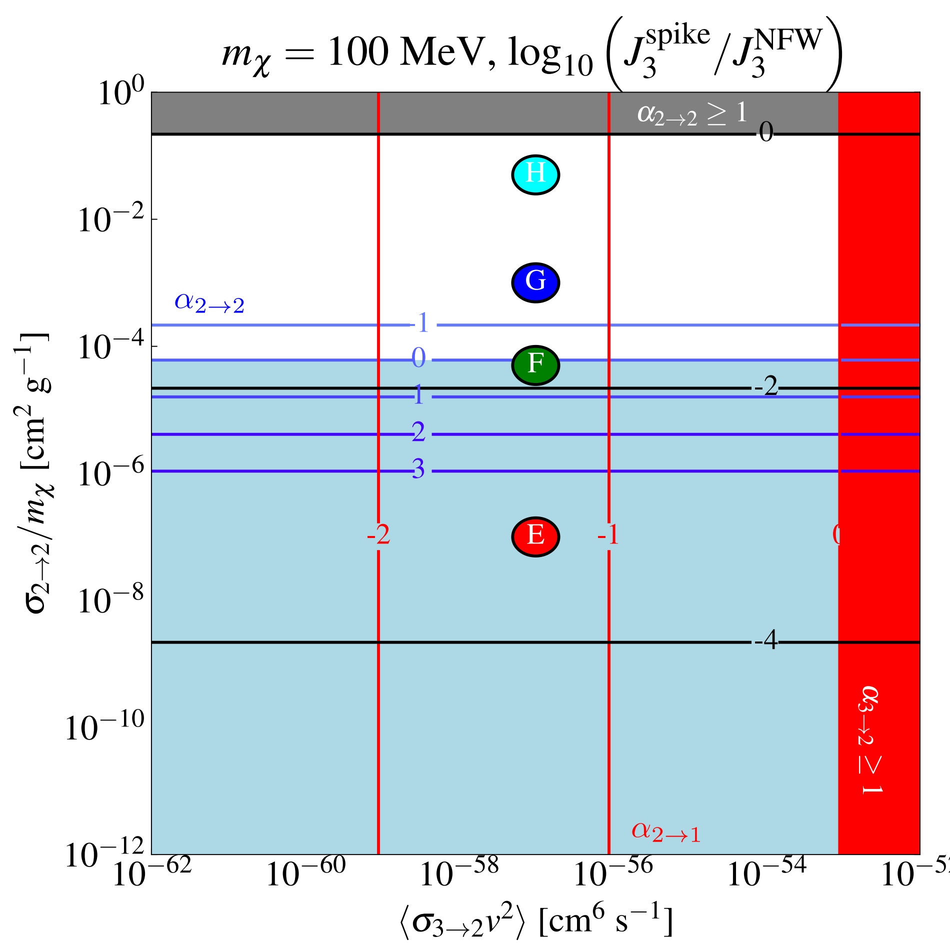




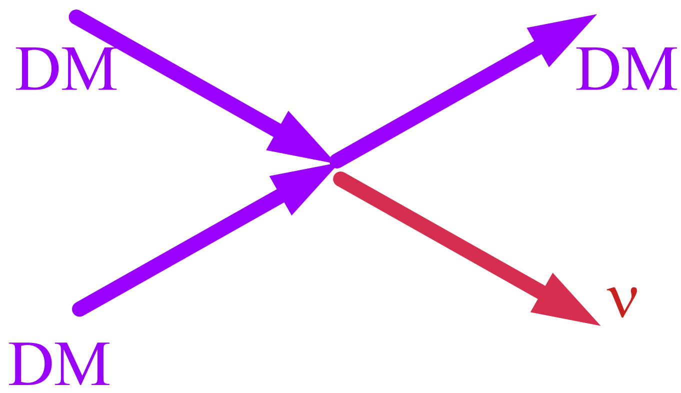
$$J_2^{\rm spike} \equiv 4\pi \int_0^{R_{\rm sp}} dr\ r^2 \big(\rho_\chi(r)/m_\chi\big)^2.$$

$$J_3^{\rm spike} \equiv 4\pi \int_0^{R_{\rm sp}} dr\ r^2 \big(\rho_\chi(r)/m_\chi\big)^3$$



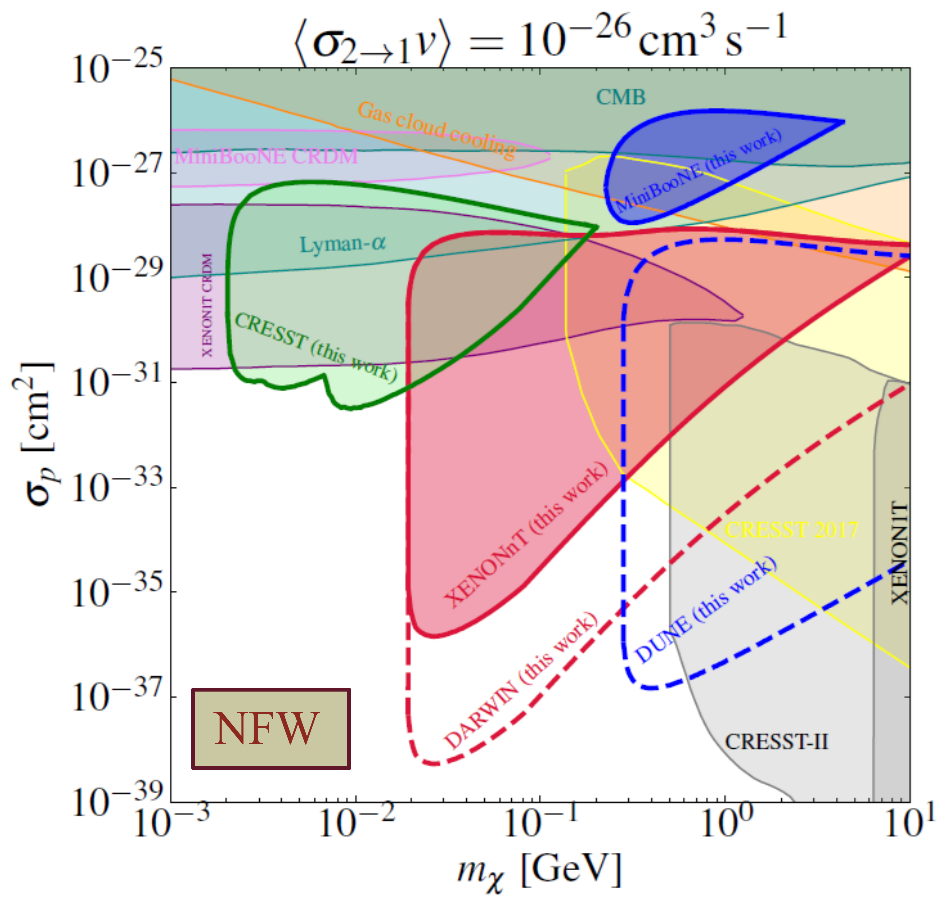


Implications for direct detection experiments



Flux of boosted DM particles, with $T_\chi = m_\chi/4$

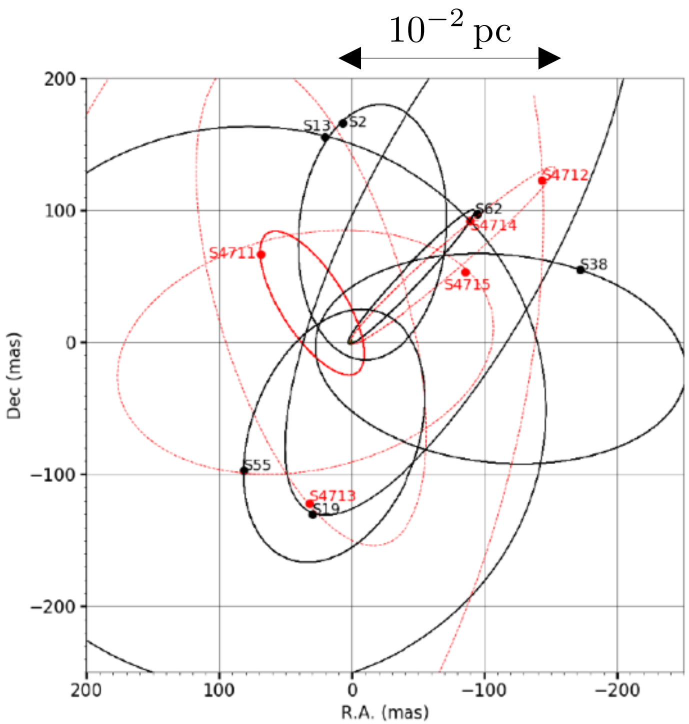
$$\Phi_{\rm BDM} \simeq 3.2\times10^{-3}\ {\rm cm}^{-2}\ {\rm s}^{-1}\ \left(\frac{m_\chi}{100\,{\rm MeV}}\right)^{-2}\left(\frac{\langle\sigma_{2\to1}v\rangle}{10^{-26}\,{\rm cm}^3{\rm s}^{-1}}\right)$$



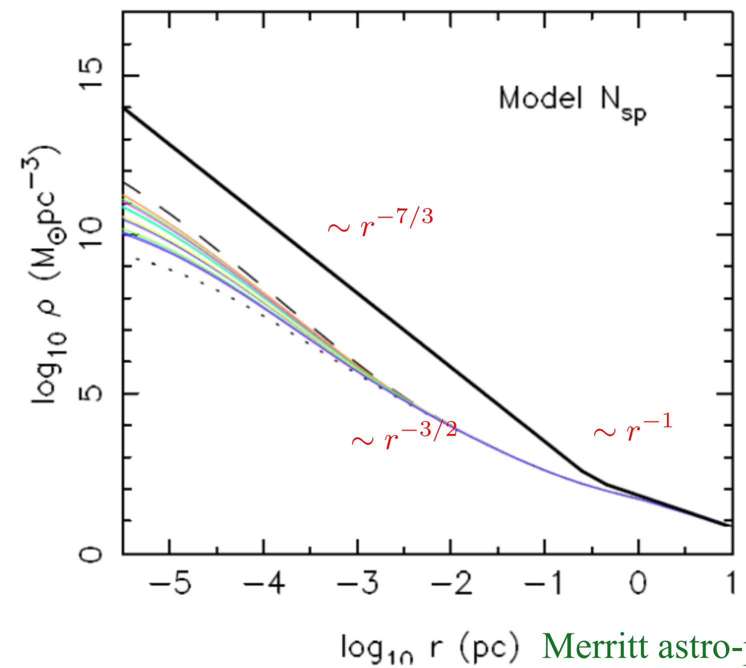
Enhancement due to the DM spike?

The Milky Way dark matter spike

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



Peißker et al, arXiv:2008.04764



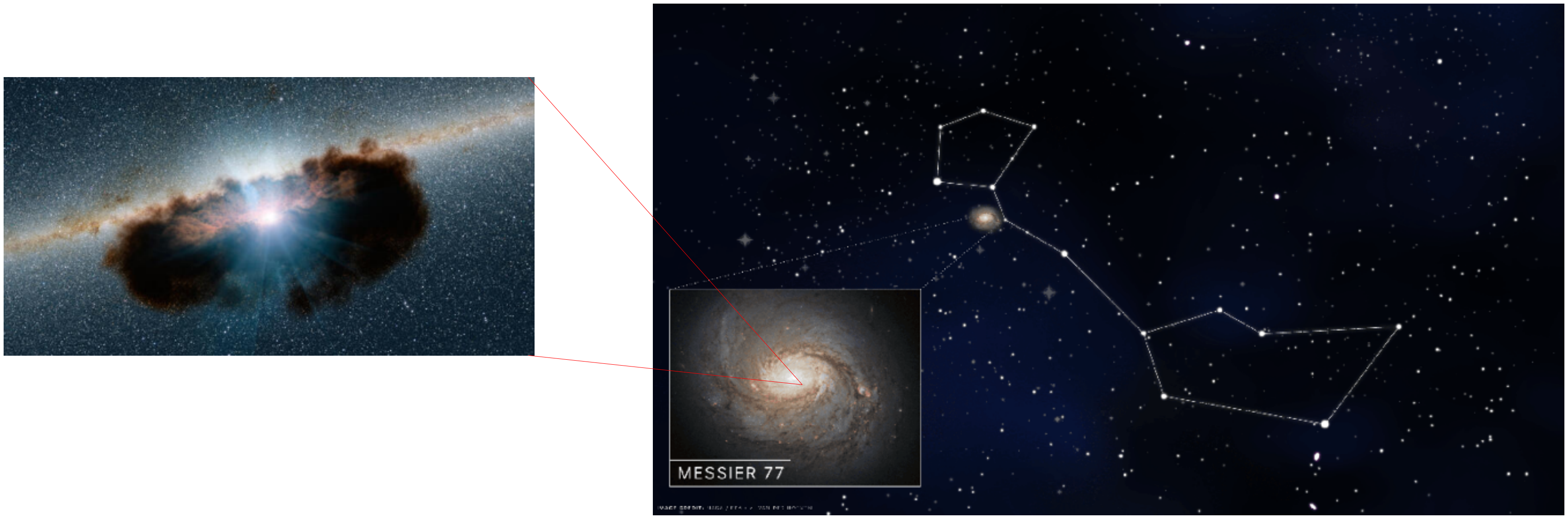
Merritt astro-ph/0311594
Bertone, Merritt astro-ph/0501555

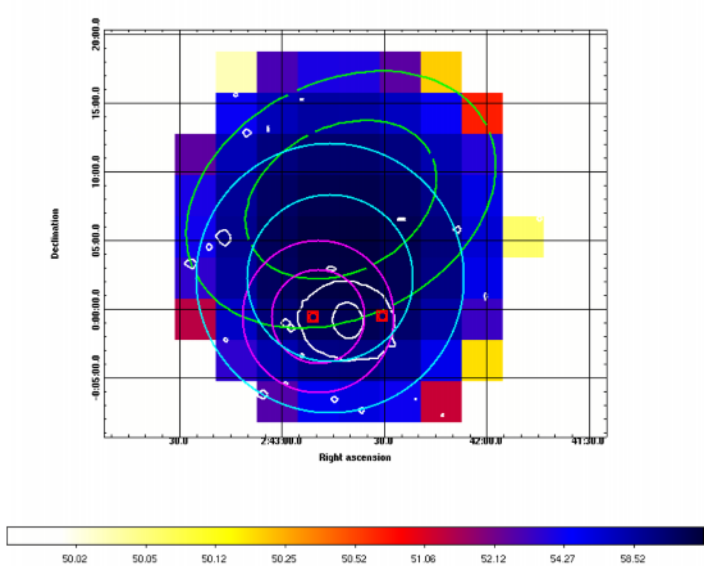
The DM spike at the MW center leads to an annihilation boost factor. Relevant when the angular resolution of the instrument is very good.

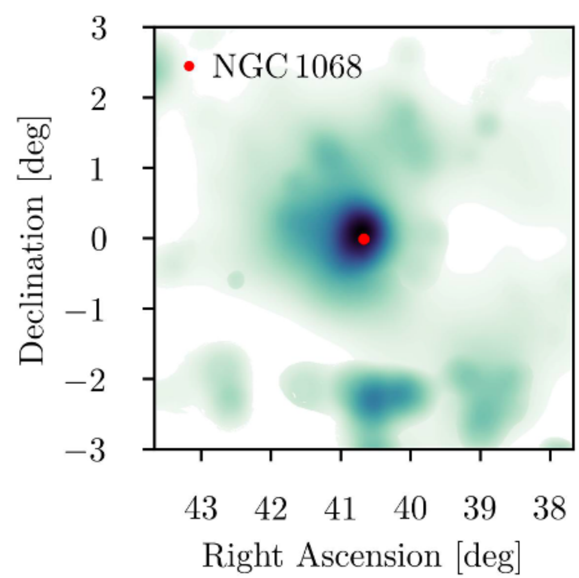
					$\log_{10} \overline{J}_3$ ($\overline{J}_5$)		
	γ_c	γ_{sp}	r_c	$\rho(R_\odot)$	$\tau = 0$	$\tau = 10$	$\tau = 10$
N	1.0	–	–	0.3	2.56 (3.51)	2.56 (3.50)	2.56 (3.50)
N_c	1.0	–	10	0.3	2.54 (3.33)	2.54 (3.33)	2.54 (3.33)
N_{sp}	1.0	2.33	–	0.3	9.21 (11.2)	3.86 (5.84)	2.56 (3.52)
$N_{c,sp}$	1.0	2.29	10	0.3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

A dark matter spike in 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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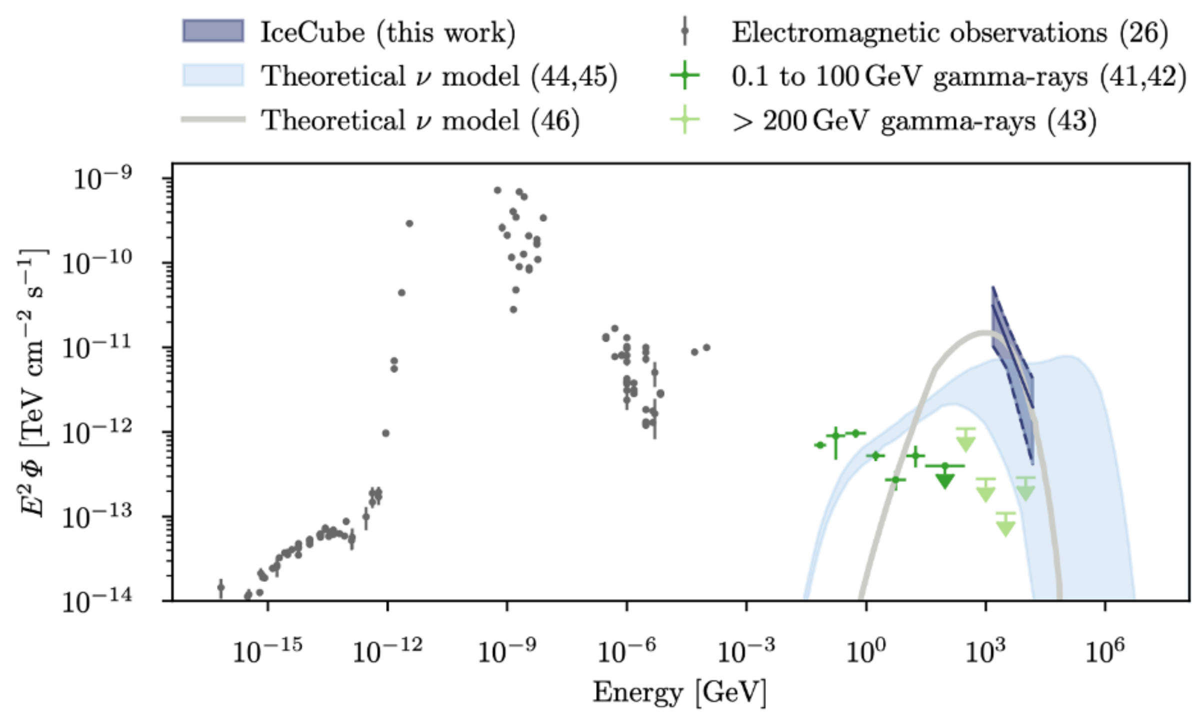

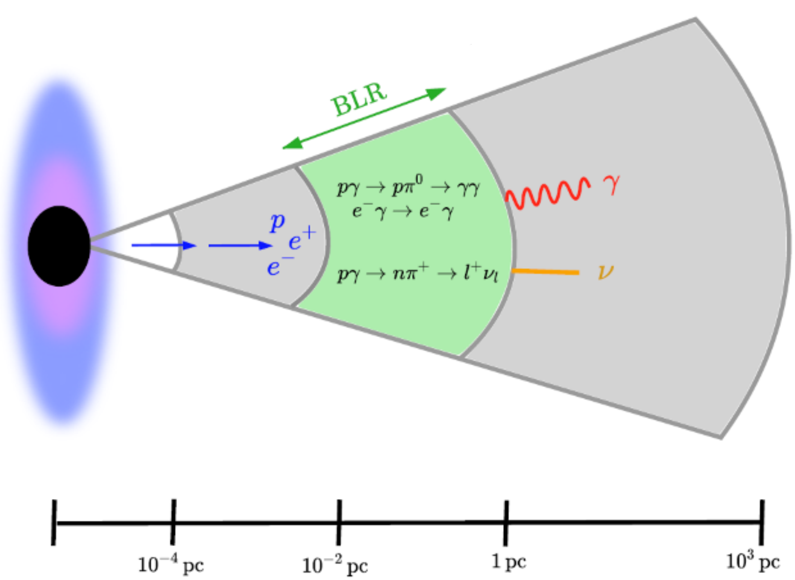

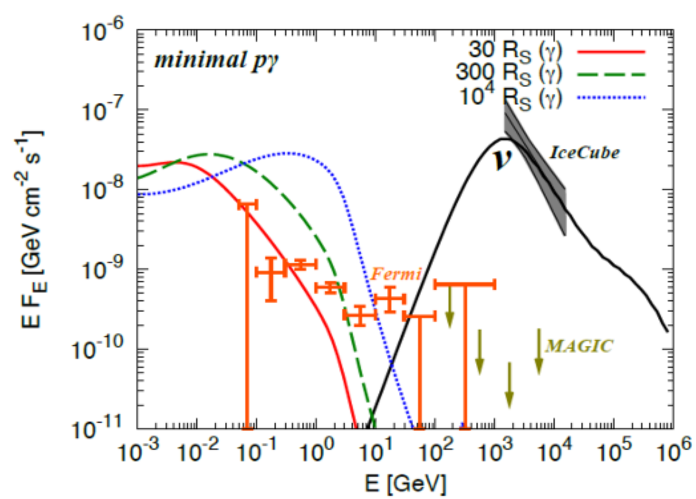

Murase'22

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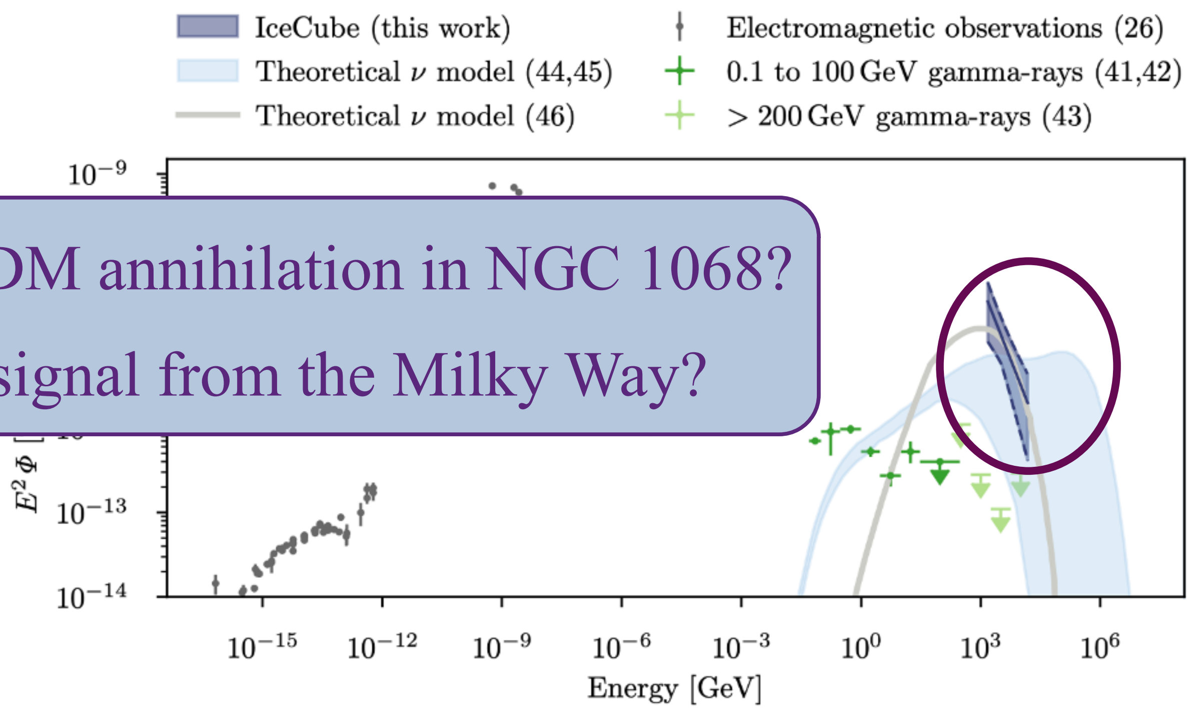
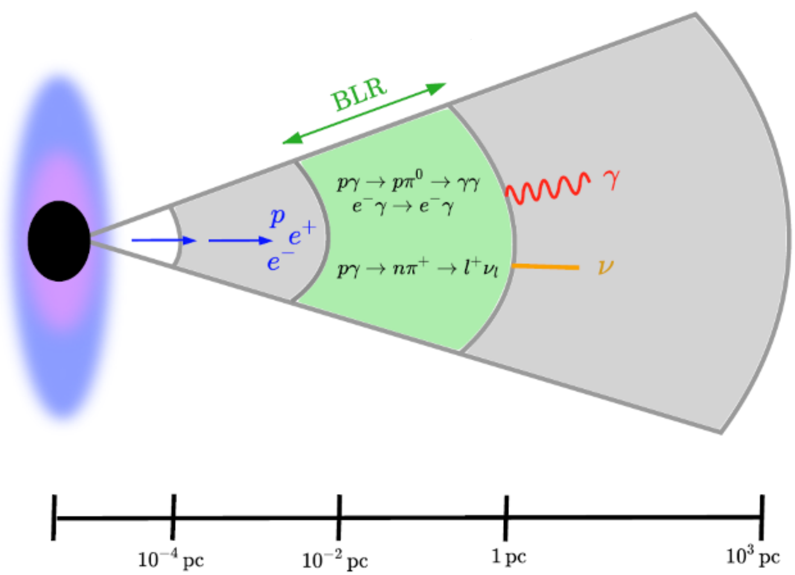
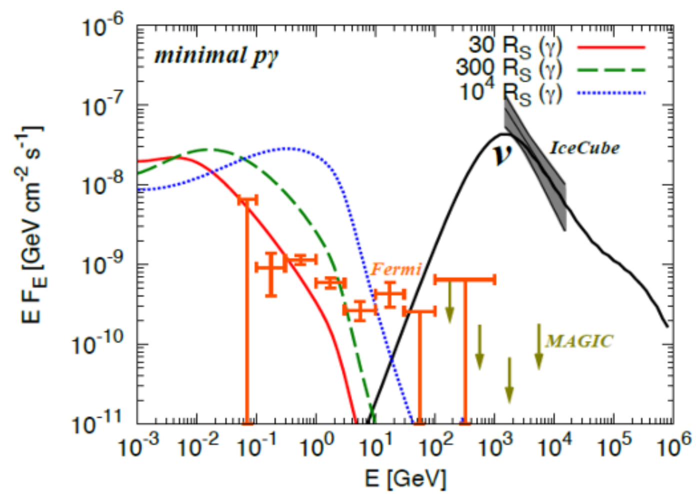


A signal of DM annihilation in NGC 1068?

Why no signal from the Milky Way?

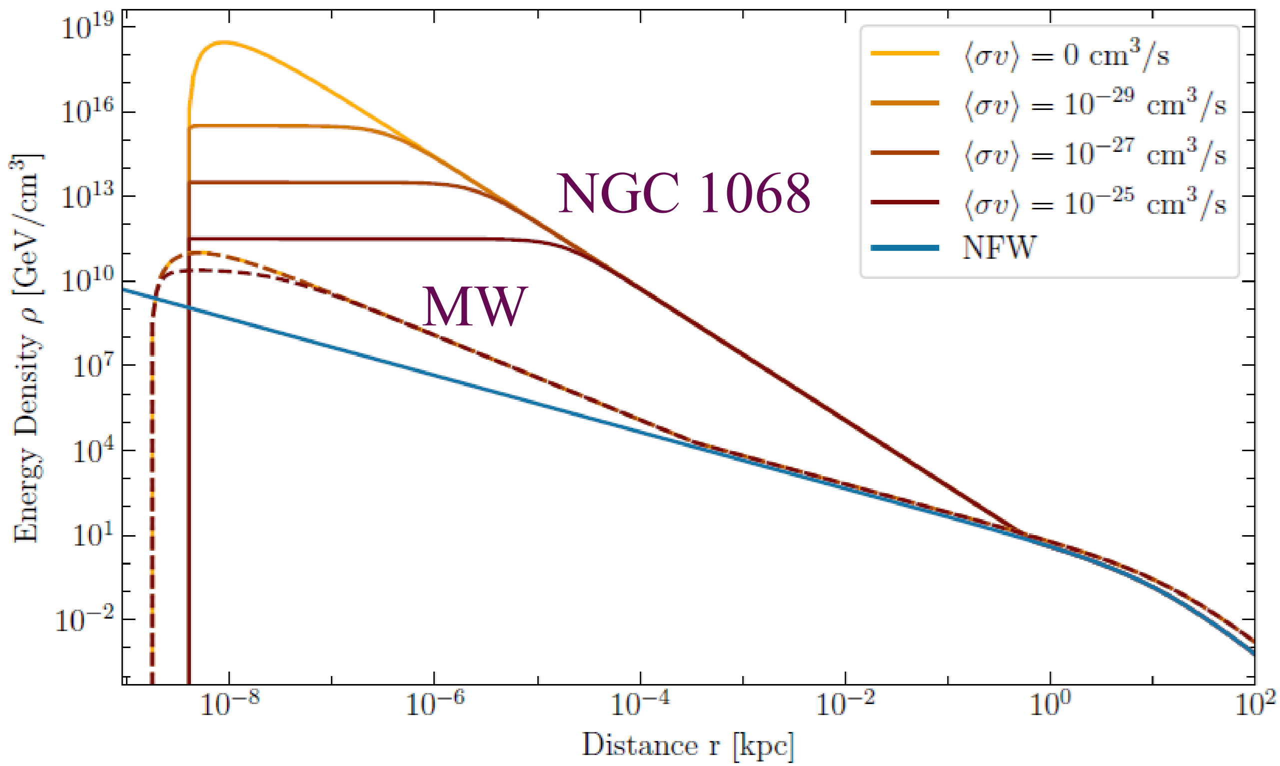




Murase'22

A dark matter spike in NGC 1068?

- 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.
- Assume that the spike in NGC 1068 is not significantly affected by the stellar heating. Dark matter annihilations in the spike could produce a neutrino flux detectable at Earth as a point source.



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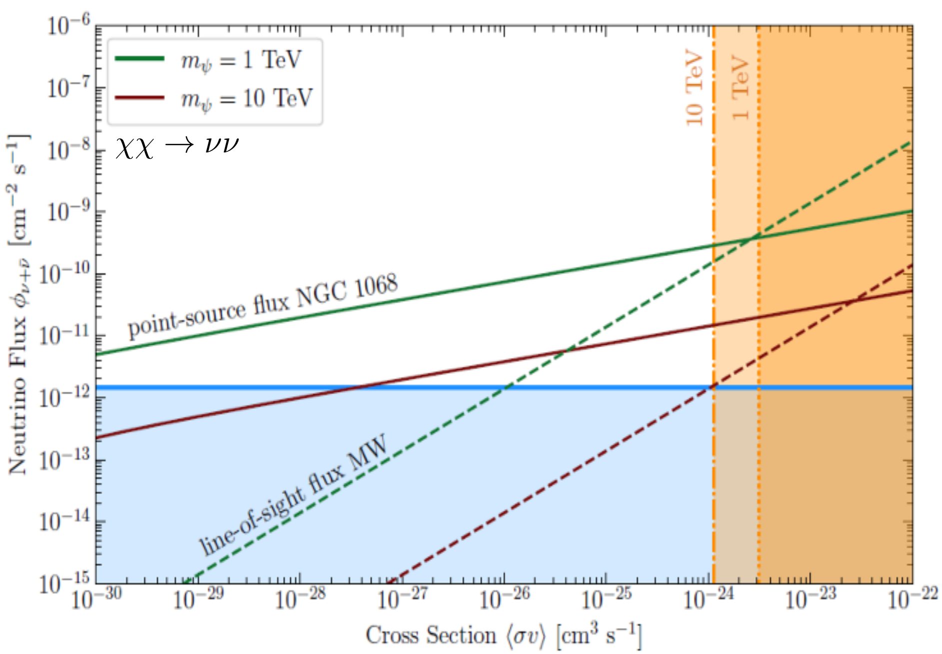

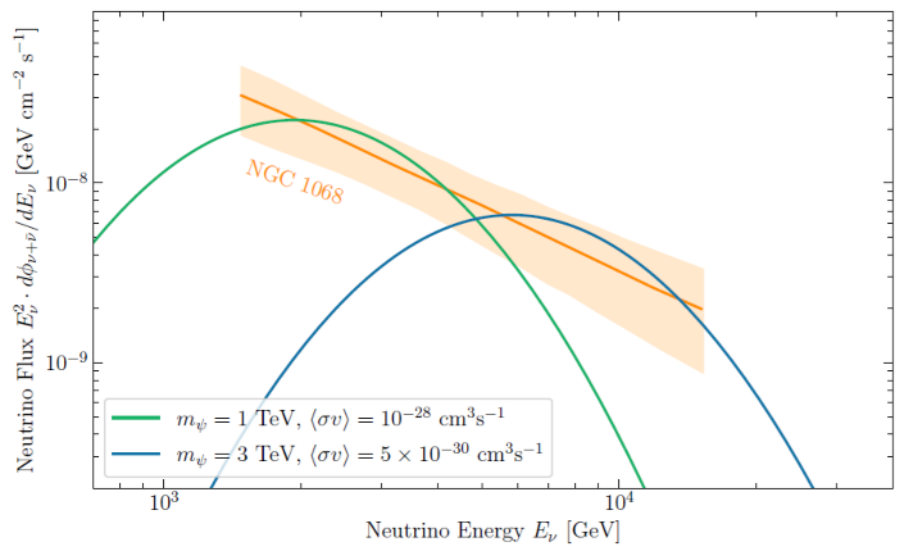

Conclusions

- The structure of the dark matter spike surrounding a black hole can be significantly affected by dark matter processes (scatterings, annihilations, semi-annihilations, $3 \to 2$ processes, etc.)
- Semi-annihilations in the Galactic Center are a source of boosted dark matter. This flux component could be detected in experiments when the DM mass is in the sub-GeV scale, with a characteristic recoil spectrum.
- The neutrino emission from NGC 1068 detected by IceCube could be due to dark matter annihilations if its DM spike remains intact until today. A neutrino flux from other galaxies could be detected in the future (if their spikes are not affected by stellar heating).