The fate of dark matter spikes and new sources of boosted DM

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In collaboration with Boris Betancourt, Motoko Fujiwara and Takashi Toma
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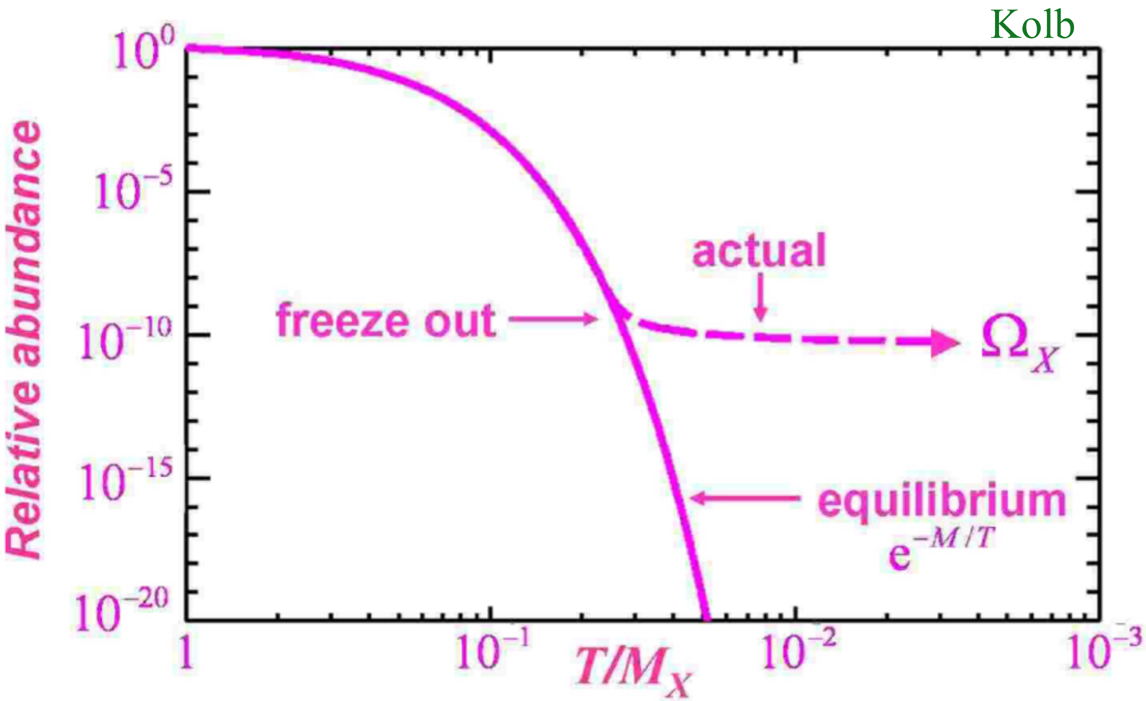
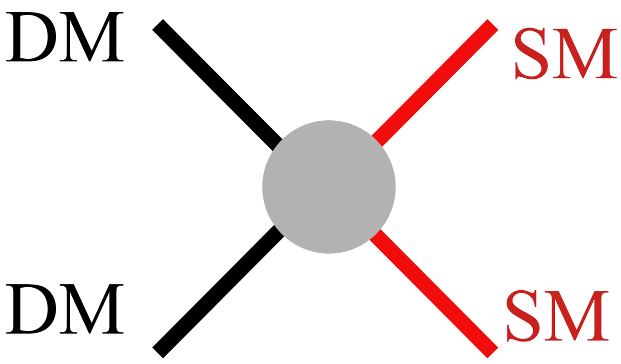
Introduction

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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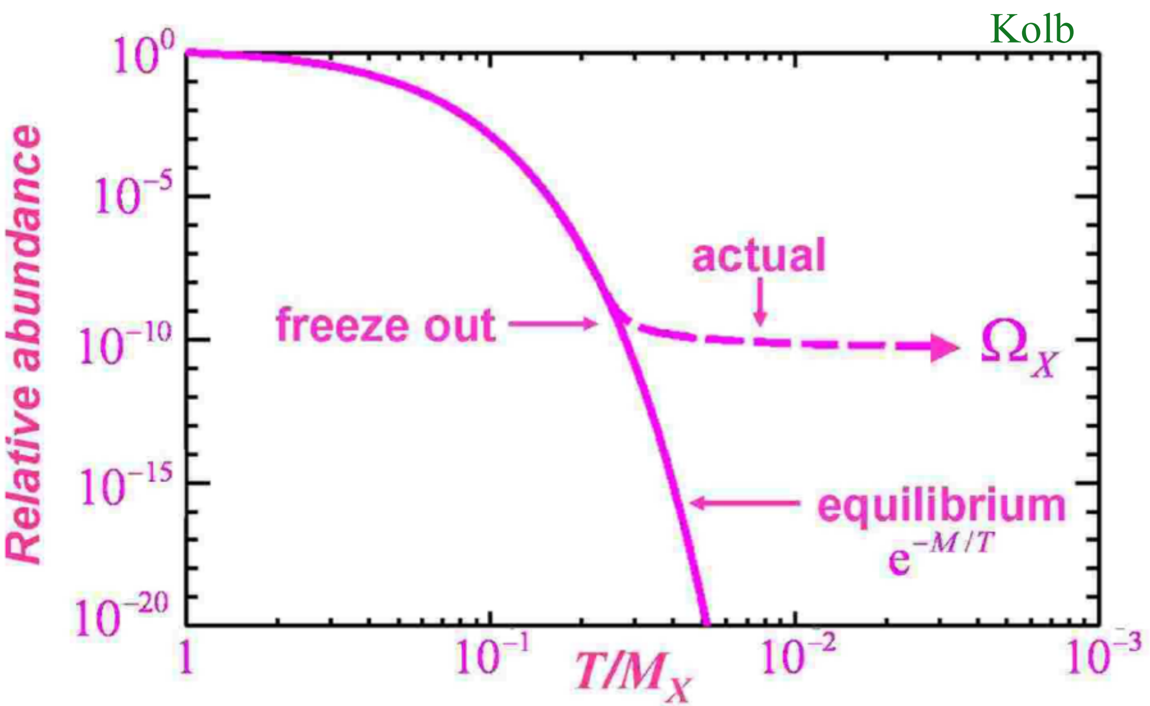

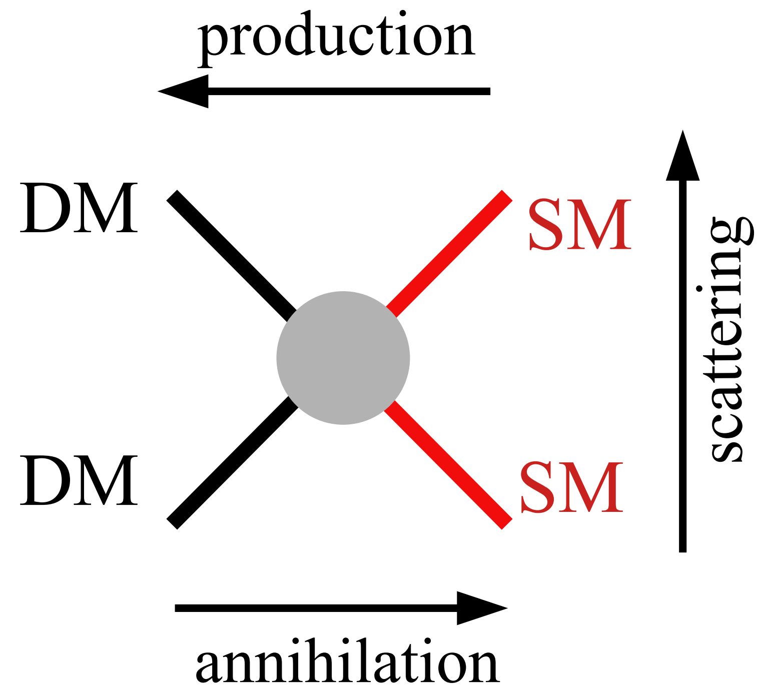

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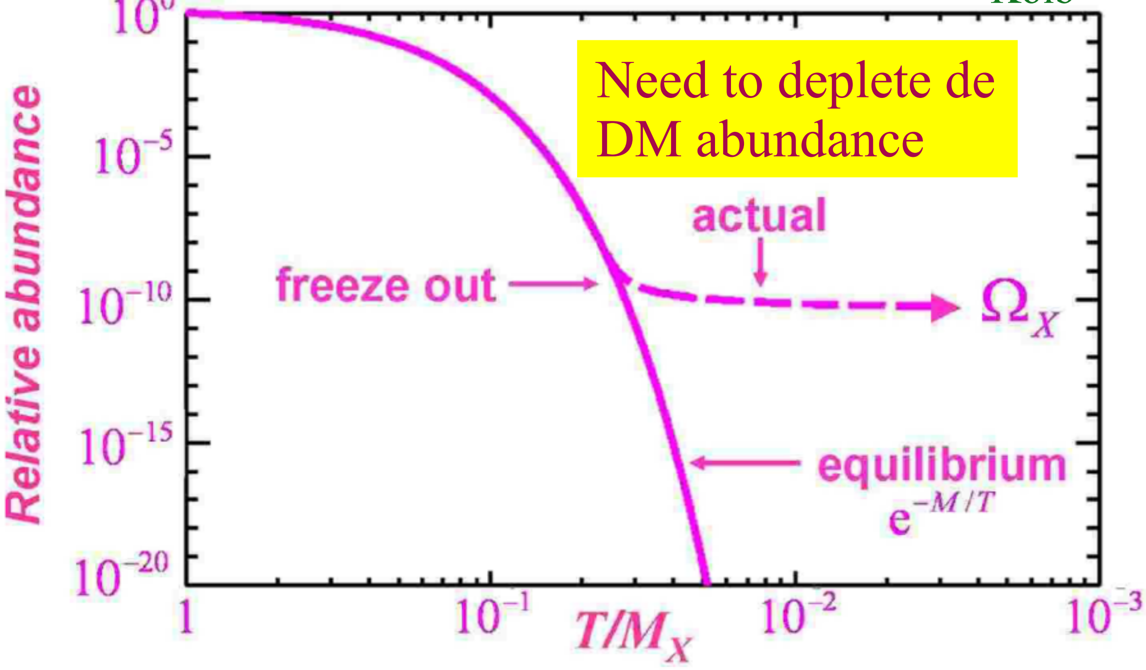

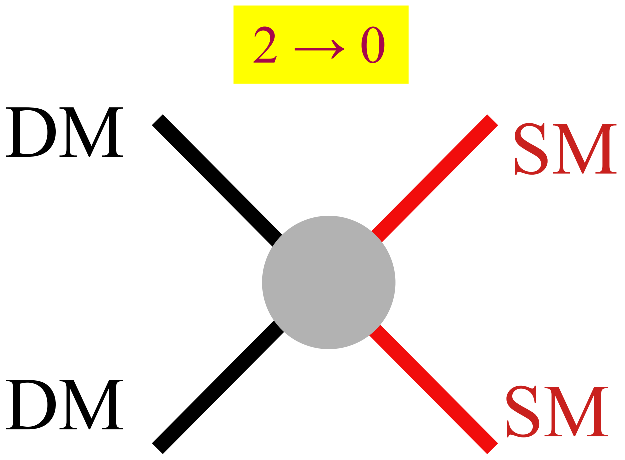

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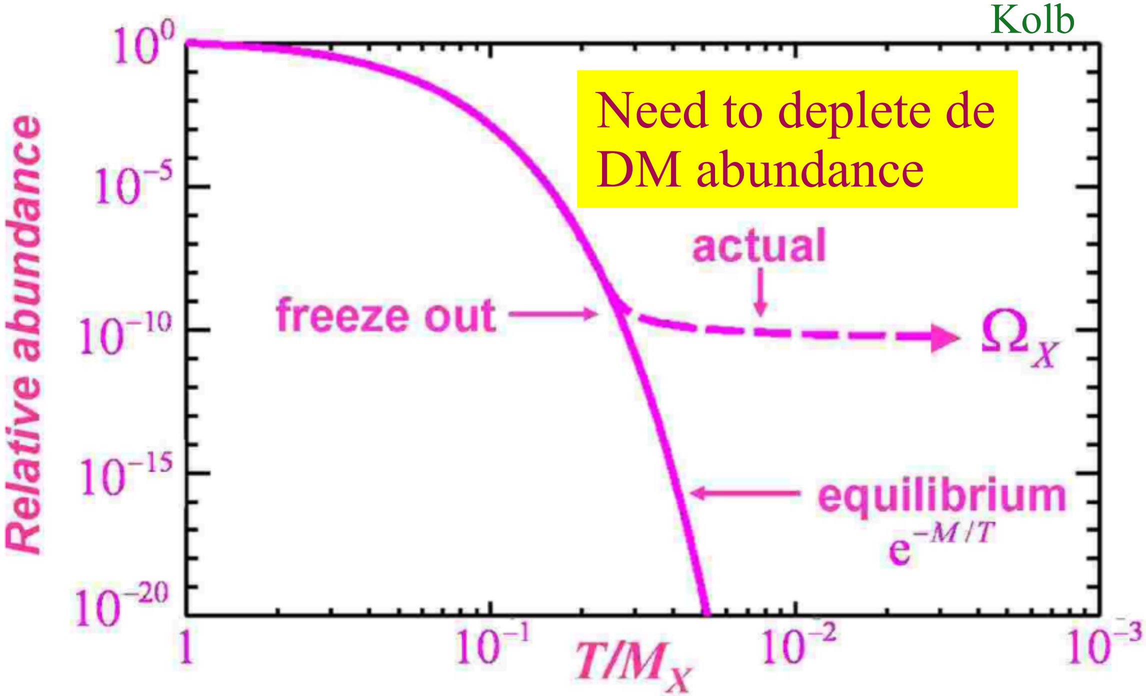

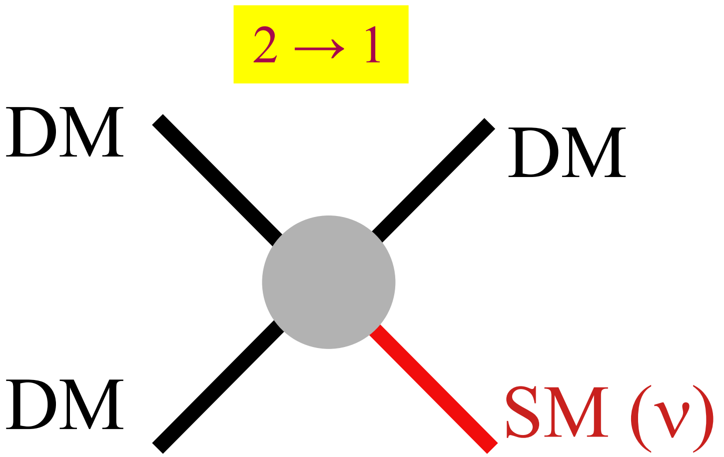

D'Eramo, Thaler

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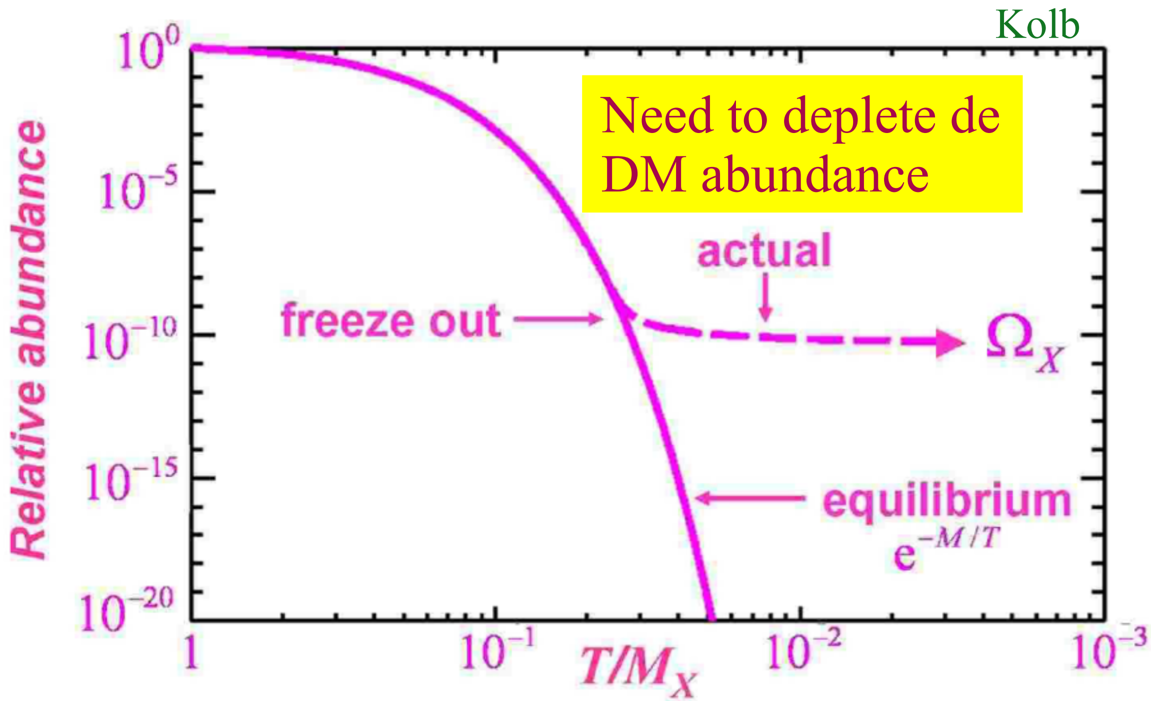

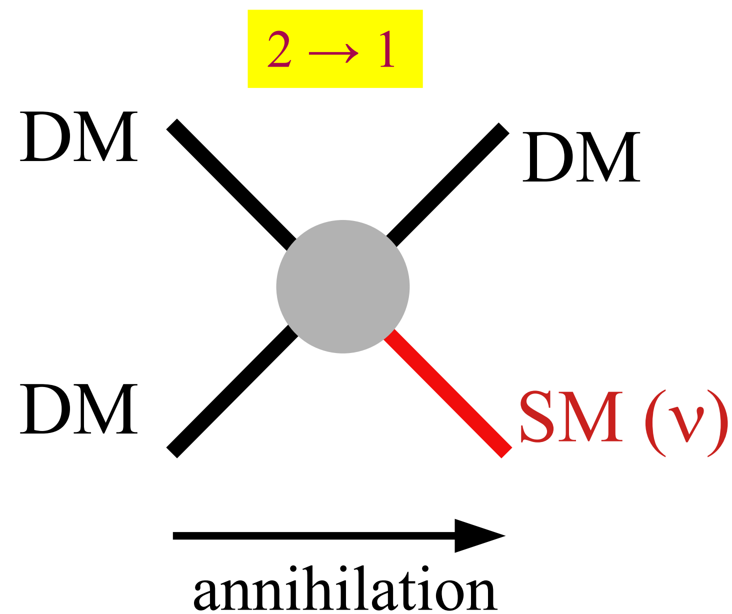

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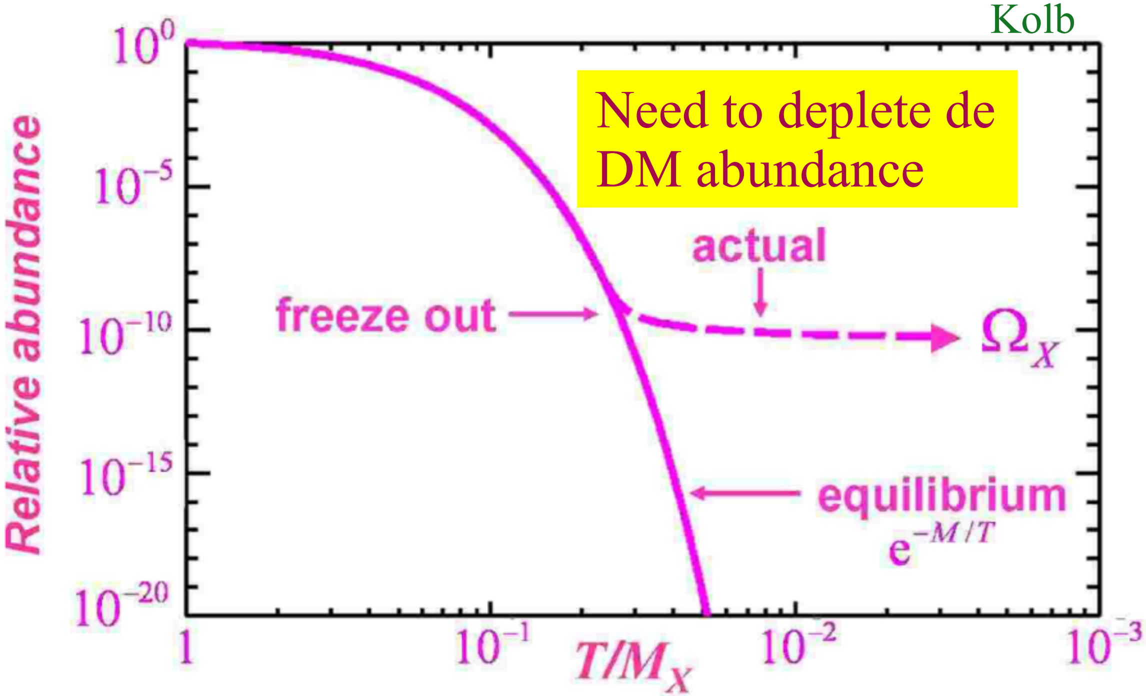

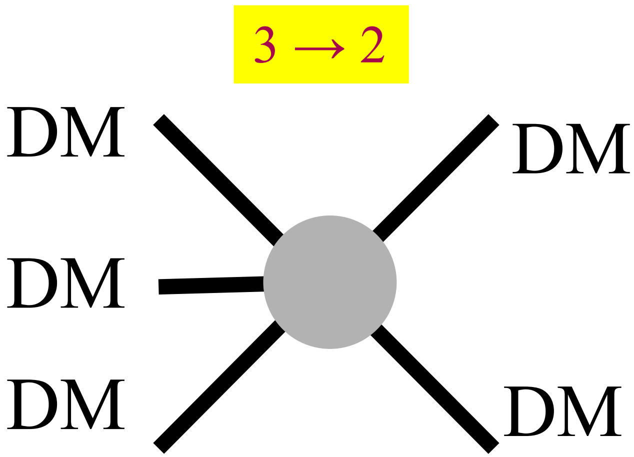

Carlson, Machacek, Hall
Hochberg, Kuflik, Volansky, Wacker

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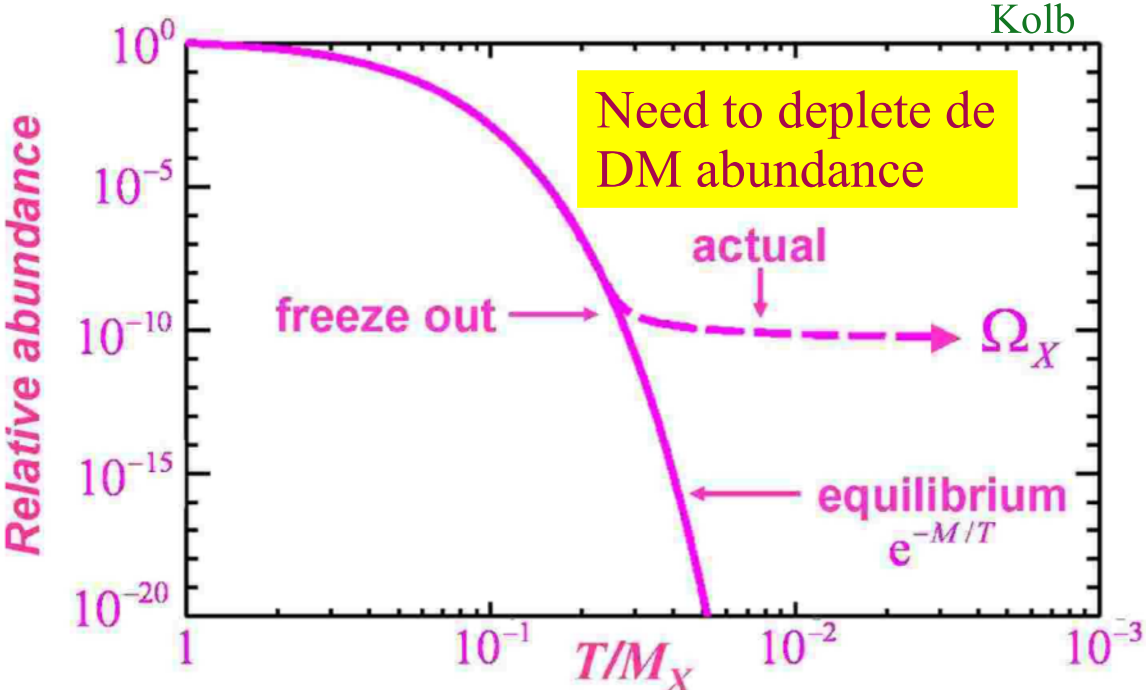
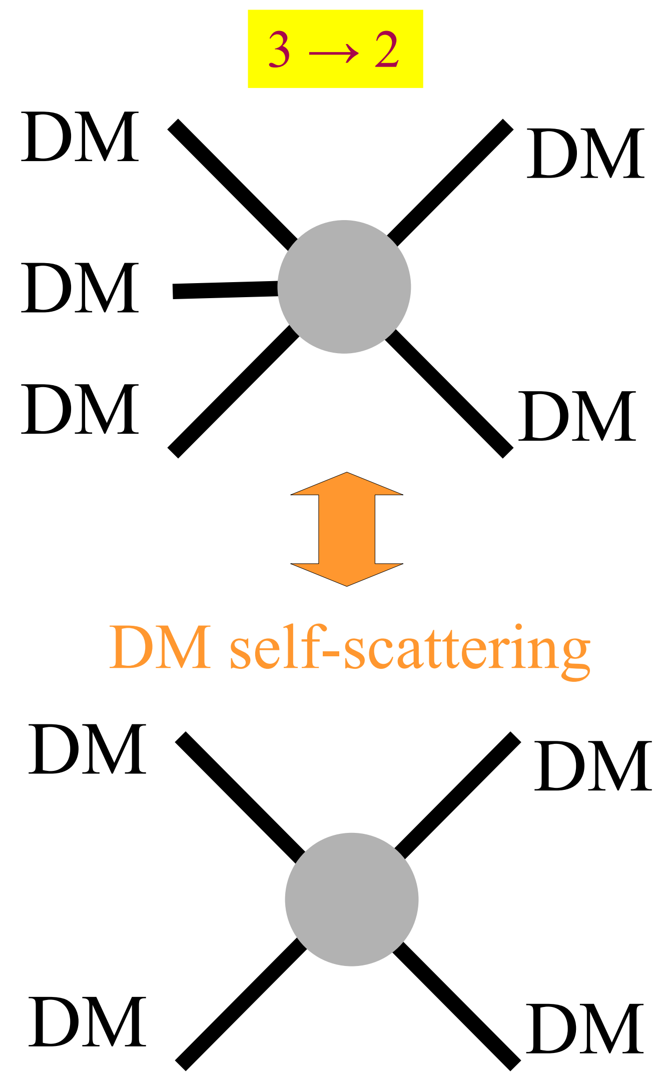
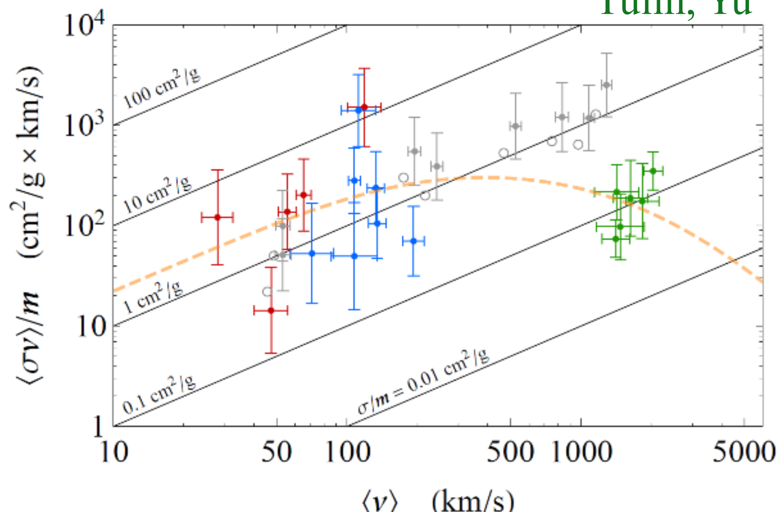




Tulin, Yu



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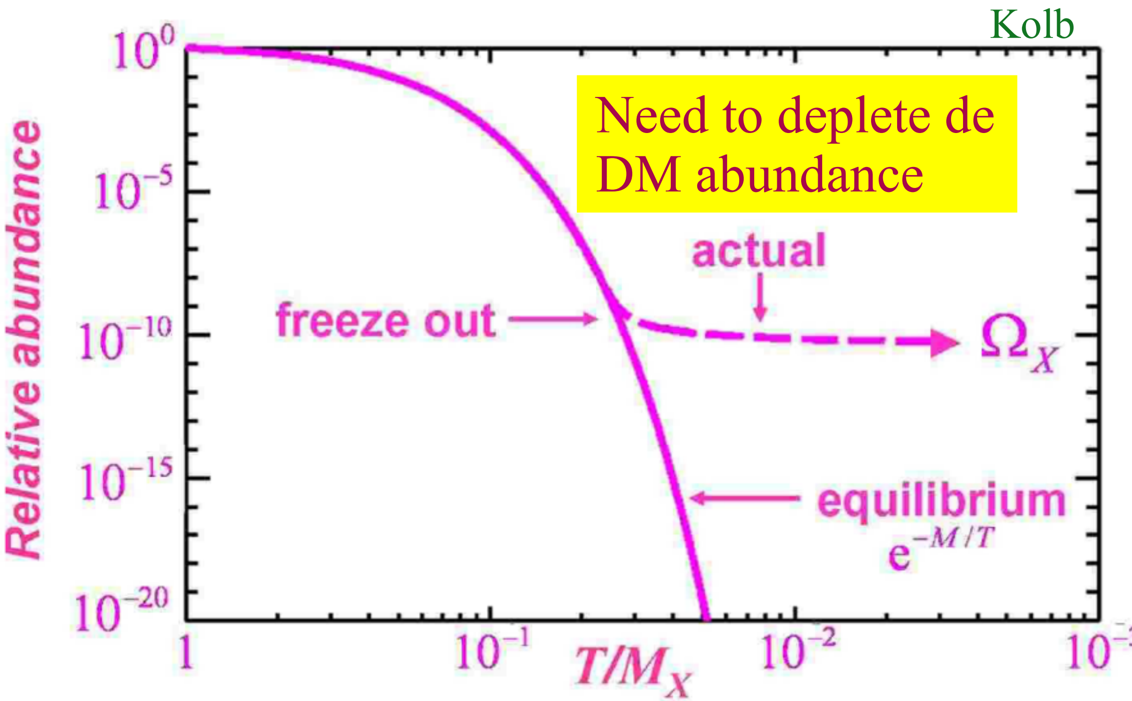

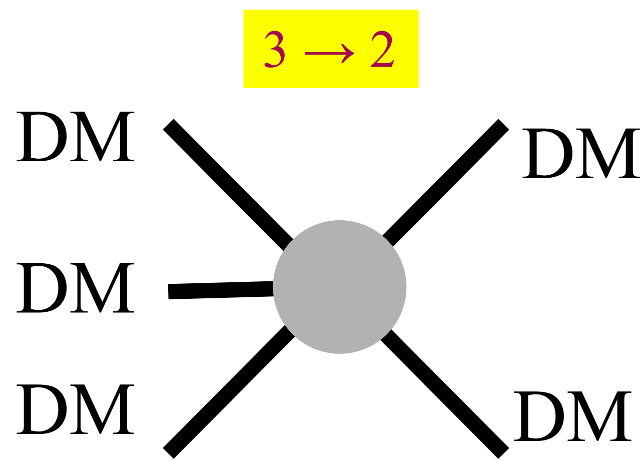

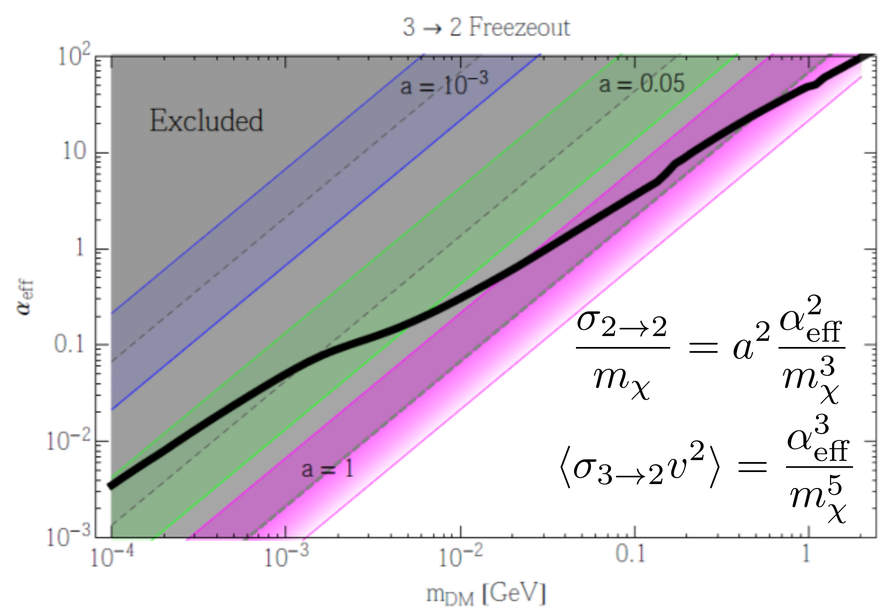

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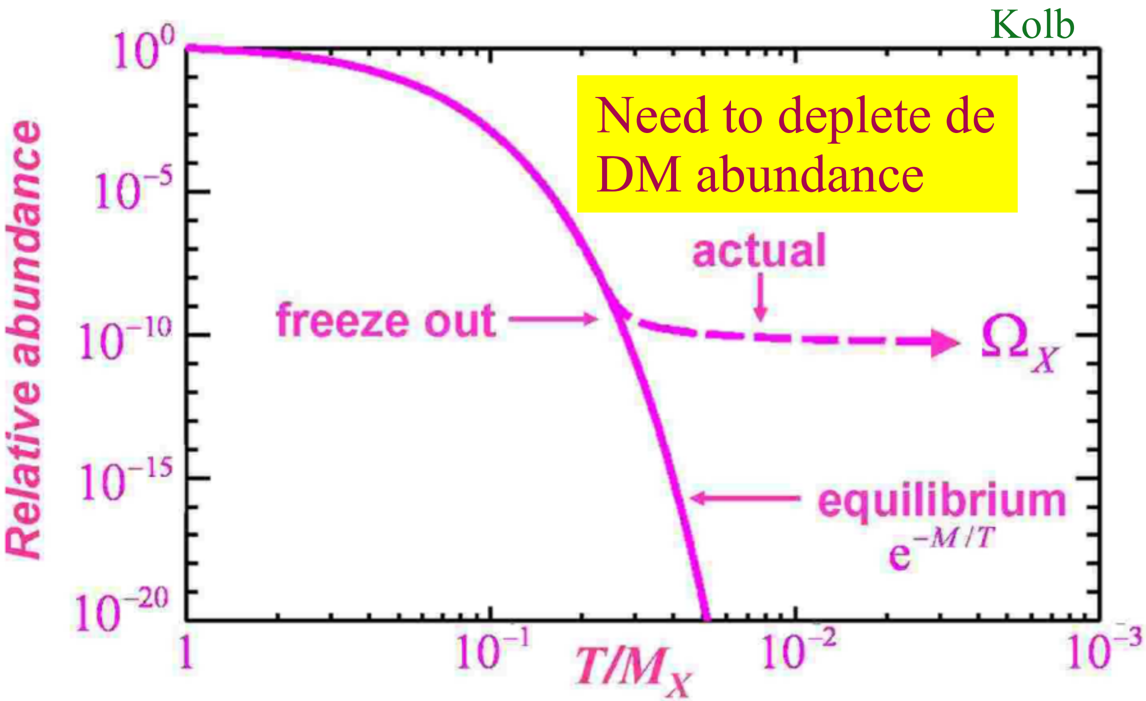
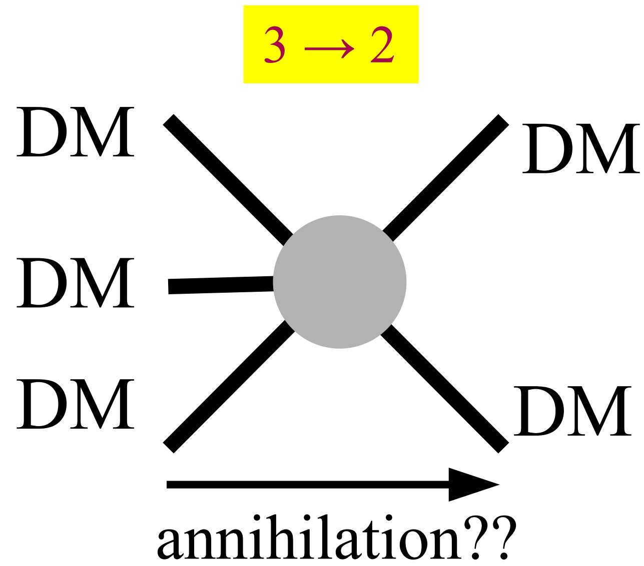




DM density at freeze-out

$$\rho_\chi \sim 10^{25}\,\mathrm{GeV/cm^3}\left(\frac{m_\chi}{40\,\mathrm{MeV}}\right)^{-3}\left(\frac{\alpha_{\rm eff}}{1}\right)$$

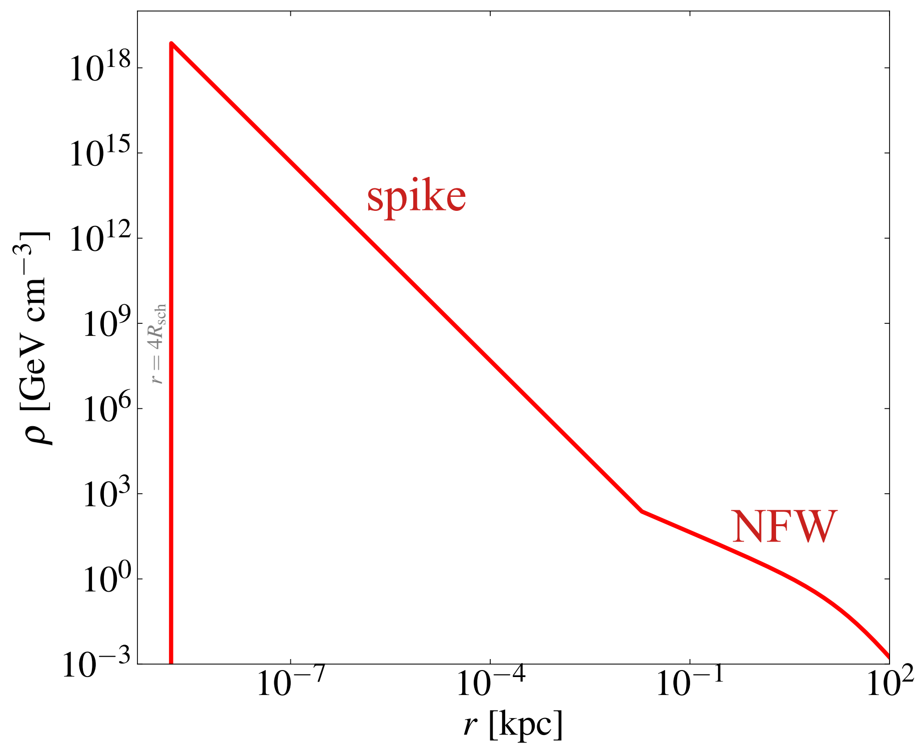
The DM spike around supermassive black holes

In the center of the Milky Way it is located a supermassive black hole, with mass ~ 4×10^6 M_{sun}.

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

$$\rho(r) = \rho_0 \left(\frac{r_0}{r}\right)^{\gamma} \longrightarrow \rho_{sp} \sim \rho_R \left(\frac{R_{sp}}{r}\right)^{\gamma_{sp}}$$

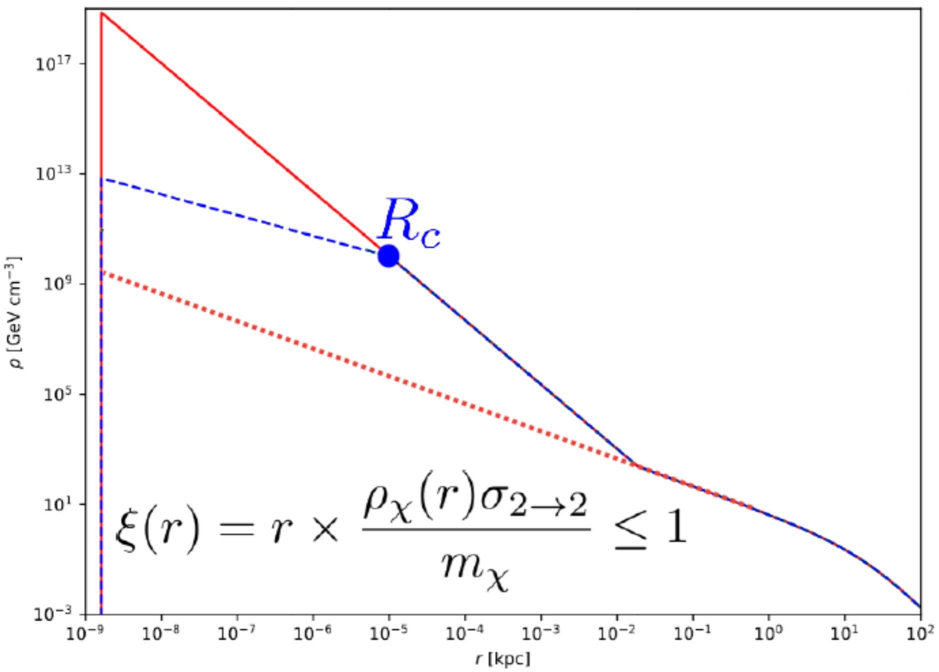
$R_{sp} \sim 18.7\,\mathrm{pc}$
$\rho_R \sim 240\,\mathrm{GeV/cm^3}$
$\gamma_{sp} \sim 2.3$



The DM spike around supermassive black holes

Different effects can soften the spike:

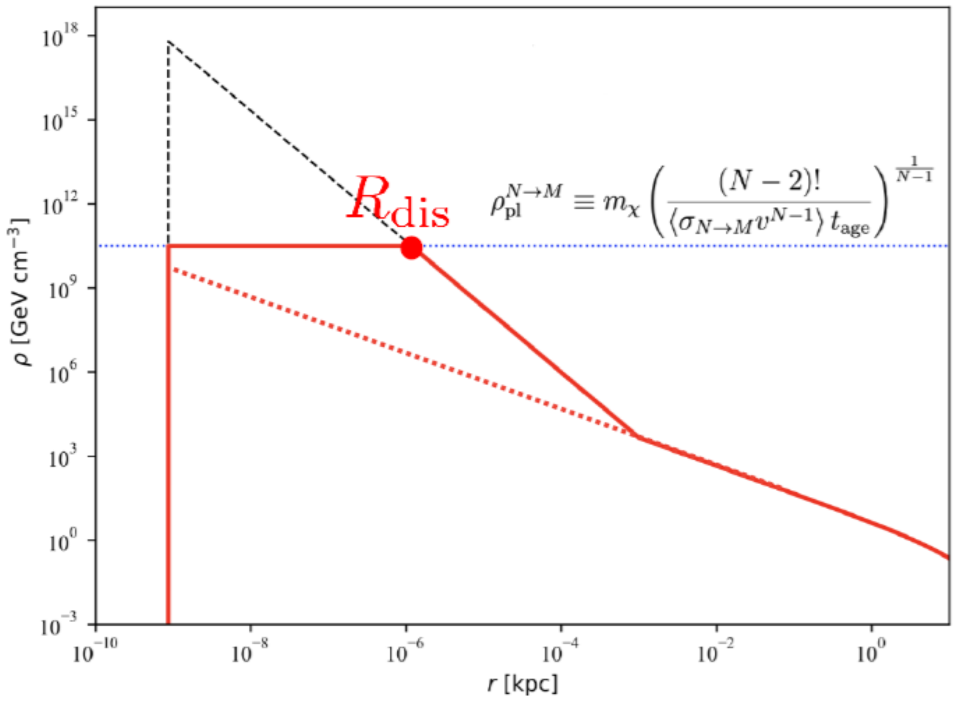
- Self-interactions: momentum exchange produce a core (depends on $\sigma_{2\to2}$)



The DM spike around supermassive black holes

Different effects can soften the spike:

- Self-interactions: momentum exchange produce a core (depends on $\sigma_{2\to 2}$)
- n→m processes (n>m): deplete the number of DM particles in the spike (depends on $\sigma_{n\to m}$)



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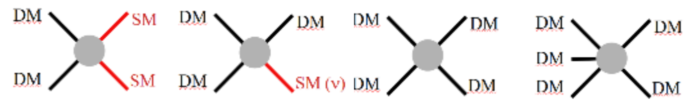
The n→m process produces a highly boosted DM particle.

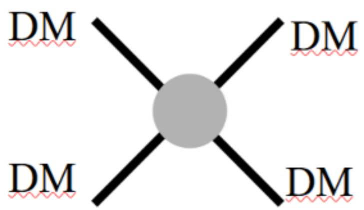
Implications for direct DM searches?

The DM spike around supermassive black holes

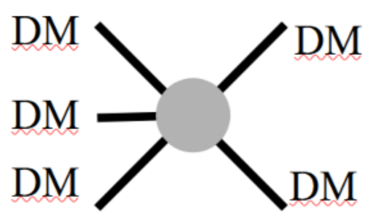
Large parameter space: $\{m_\chi, \sigma_{2\to0}, \sigma_{2\to1}, \sigma_{2\to2}, \sigma_{3\to2}, \ldots\}$



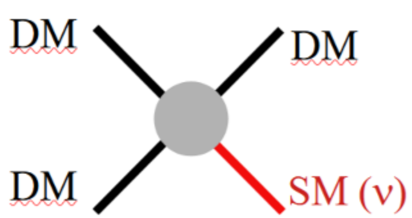
Model independent parametrization of the cross-sections:



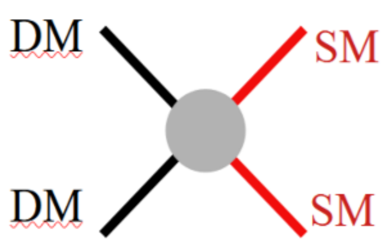
$$\sigma_{2\to2} = a^2 \frac{\alpha_{\rm eff}^2}{m_\chi^2} \qquad a \sim 1$$



$$\sigma_{3\to2} = \frac{\alpha_{\rm eff}^3}{m_\chi^5}$$



$$\sigma_{2\to1} = b^2 \frac{\alpha_{\rm eff}^2}{m_\chi^2} \qquad b \sim \begin{cases} (\alpha_{\rm SM}/\alpha_{\rm eff})^{1/2} & \text{for tree level} \\ (\alpha_{\rm SM}\alpha_{\rm eff})^{-1/2} & \text{for one loop} \end{cases}$$



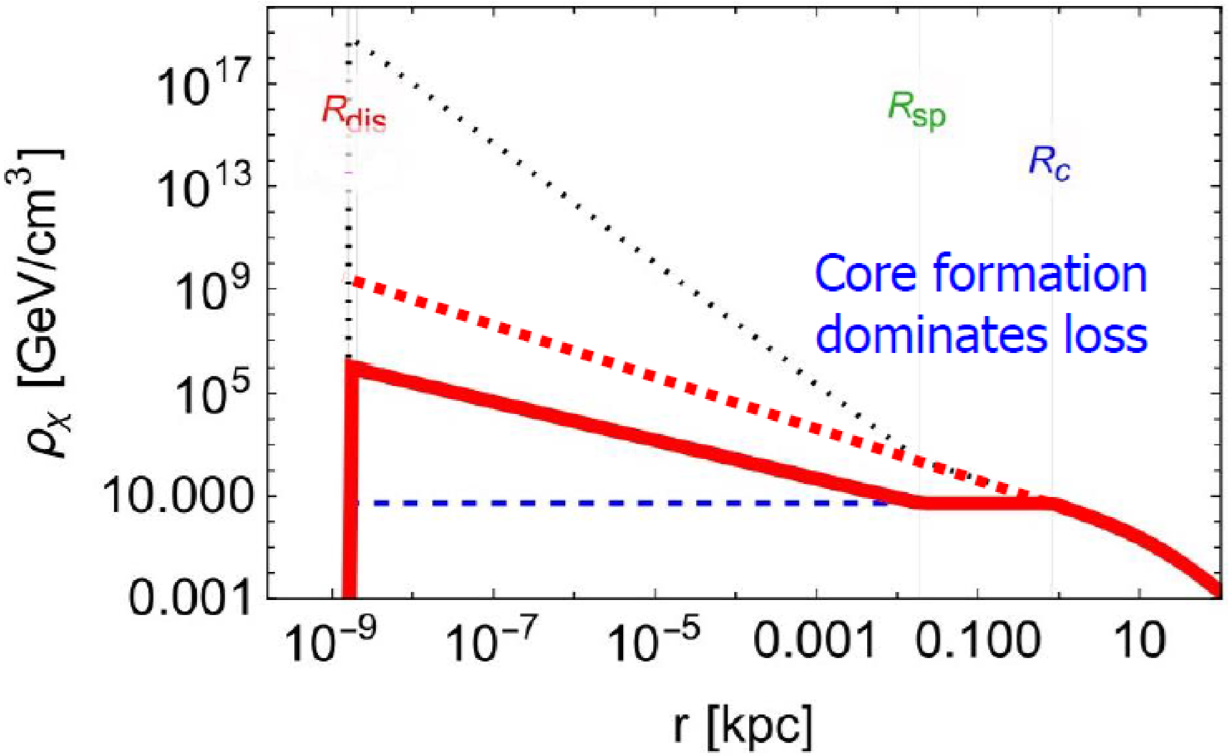
$\sigma_{2\to0}$

The fate of the DM spike

- Example 1: Only 2→2 and 3→2 (inspired by SIMP)

$m_\chi = 100\,\mathrm{MeV}\,,\alpha_{\mathrm{eff}} = 0.22\,, a = 1$

$\sigma_{2\to2} = 1.1\times10^{-1}\,\mathrm{cm}^2/\mathrm{g}\,,\langle\sigma_{3\to2}v^2\rangle = 10^{-55}\,\mathrm{cm}^6/s$

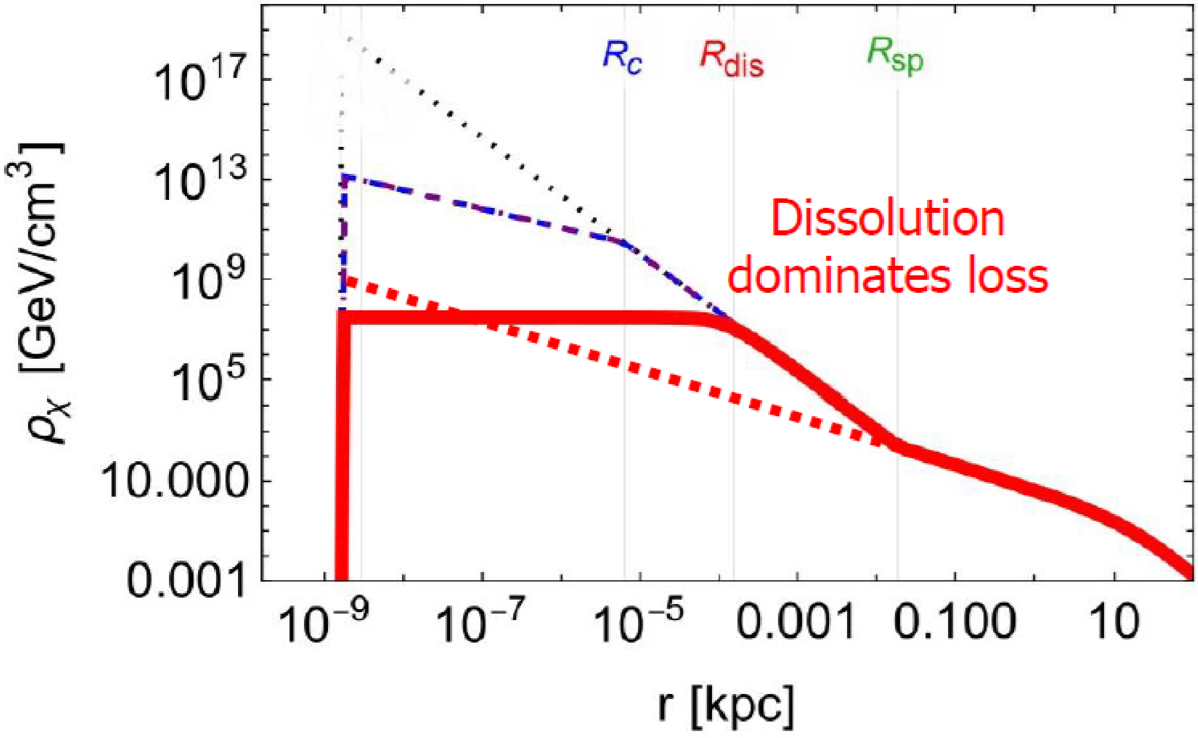


In the framework of the SIMP mechanism, no significant spike is expected today. If a spike is detected (GW, astronomical observations), SIMP would be ruled out.

The fate of the DM spike

- Example 2: Only 2→2 and 2→1 (inspired by semi-annihilations)

$$m_\chi = 100\,\mathrm{MeV}\,, \alpha_{\rm eff} = 3\times 10^{-7}\,, b = 1$$
$$\sigma_{2\to 2} = 1.9\times 10^{-12}\,\mathrm{cm}^2/\mathrm{g}\,, \langle\sigma_{3\to 2}v^2\rangle = 10^{-28}\,\mathrm{cm}^3/s$$



The fate of the DM spike

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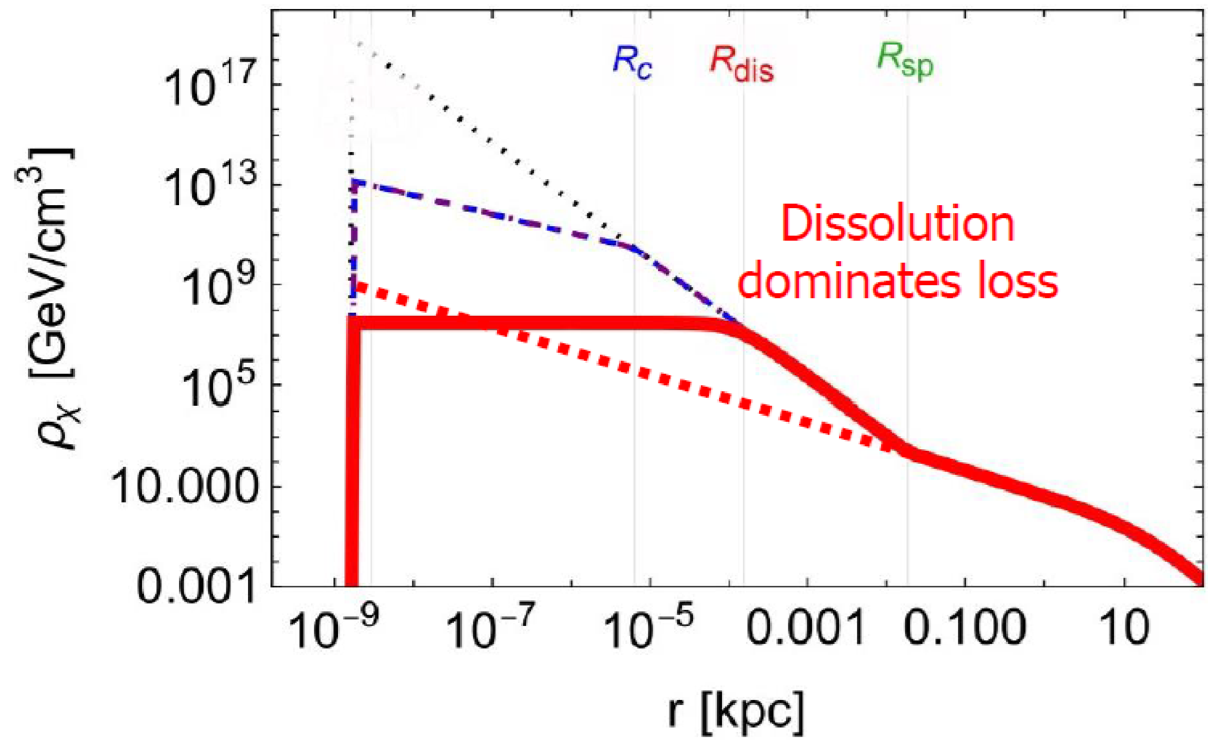
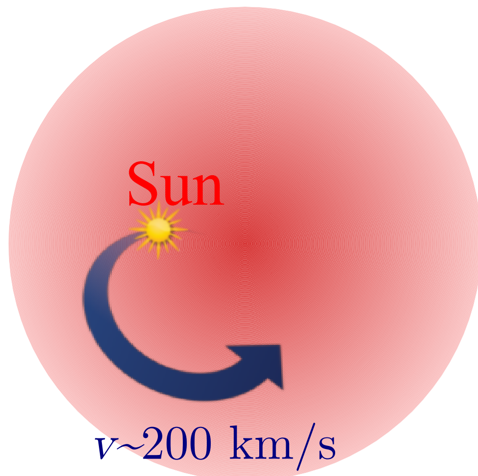


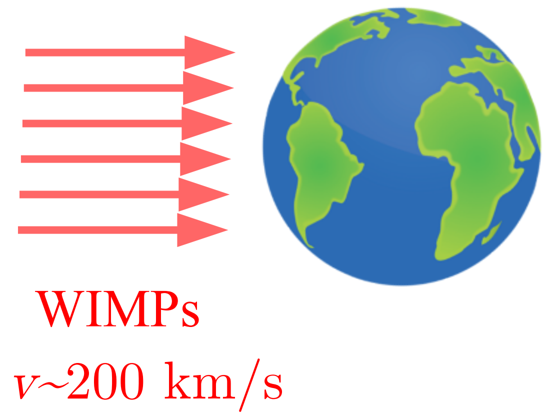
Flux of boosted DM particles, with $T_\chi = m_\chi/4$

$$\Phi \simeq 9\times 10^{-3}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\left(\frac{m_\chi}{100\mathrm{MeV}}\right)^{-2}\left(\frac{J_2}{100}\right)\left(\frac{\langle\sigma_{2\to 1} v\rangle}{10^{-26}\mathrm{cm}^3/\mathrm{s}}\right)$$

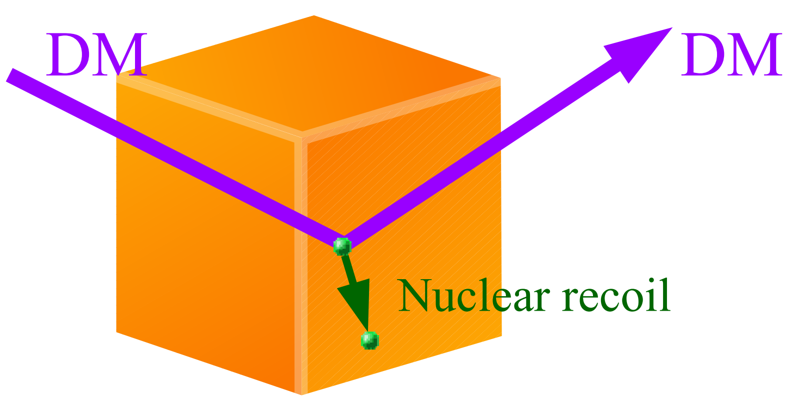
Direct detection

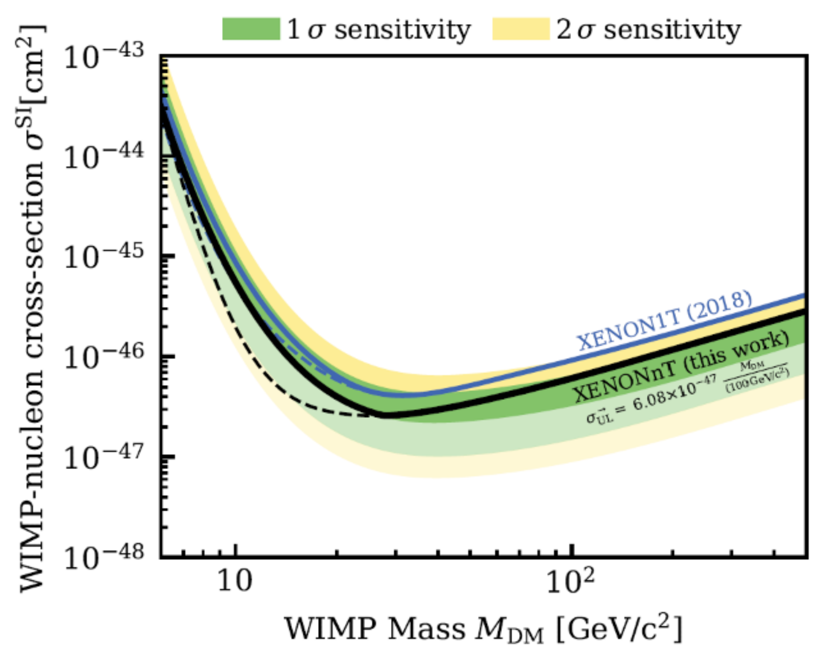
The Sun (and the Earth) might be moving through a “gas” of dark matter particles.



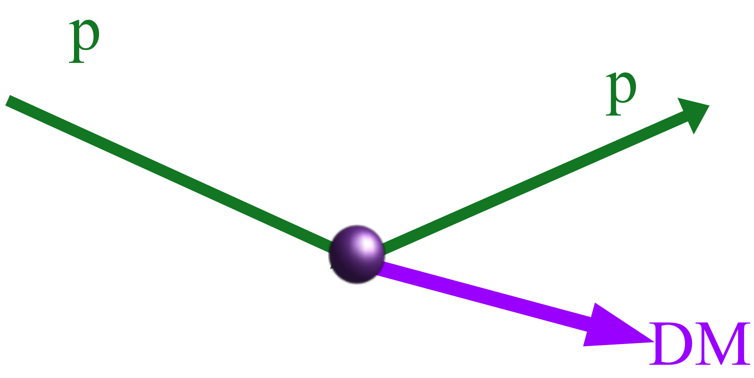


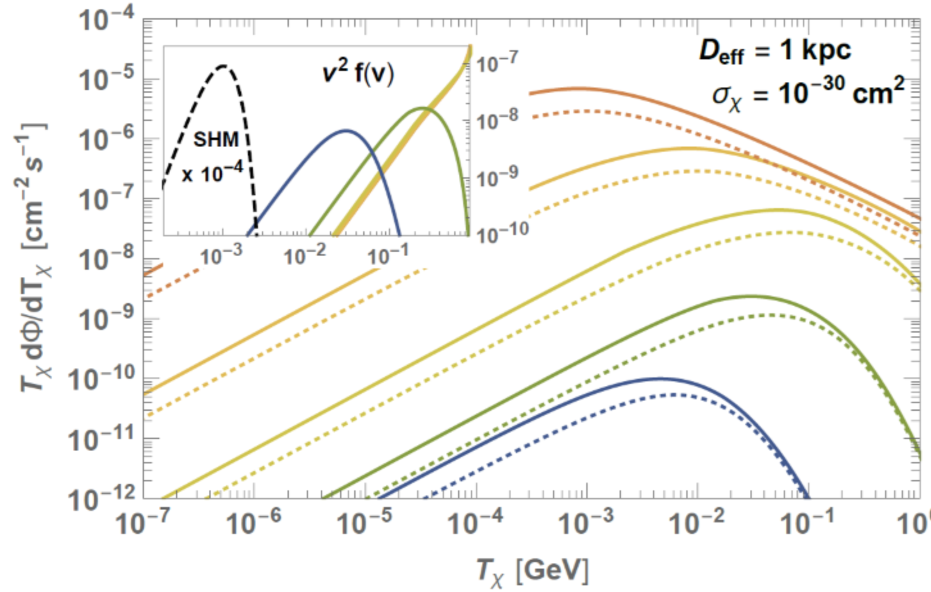
Once in a while a dark matter particle will interact with a nucleus. The nucleus then recoils, producing vibrations, ionizations or scintillation light in the detector.



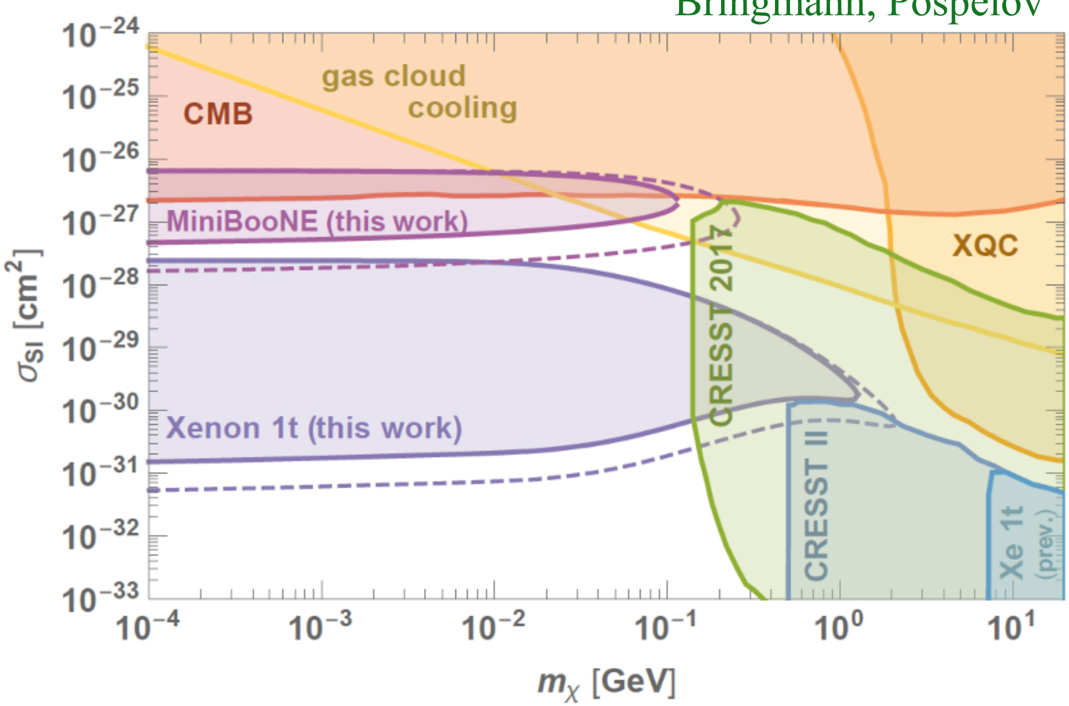


Direct detection of CR boosted dark matter

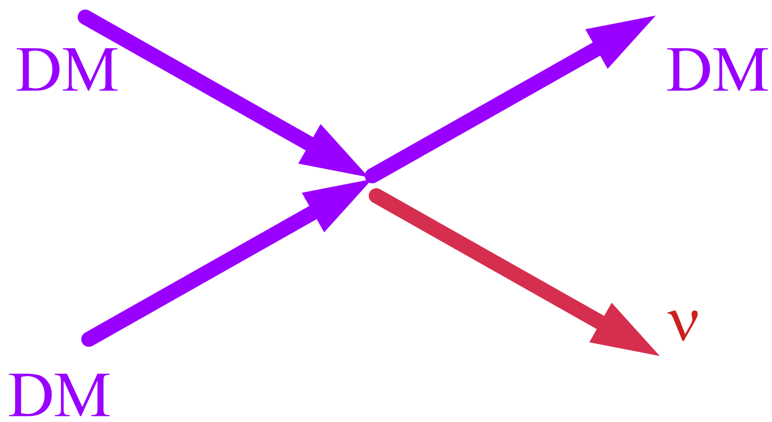




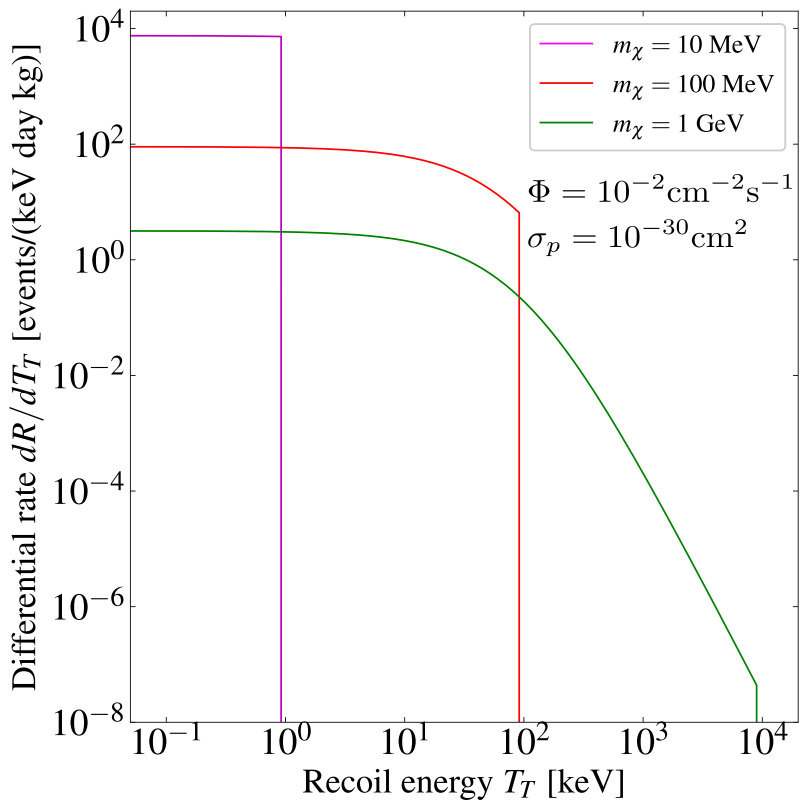
Bringmann, Pospelov

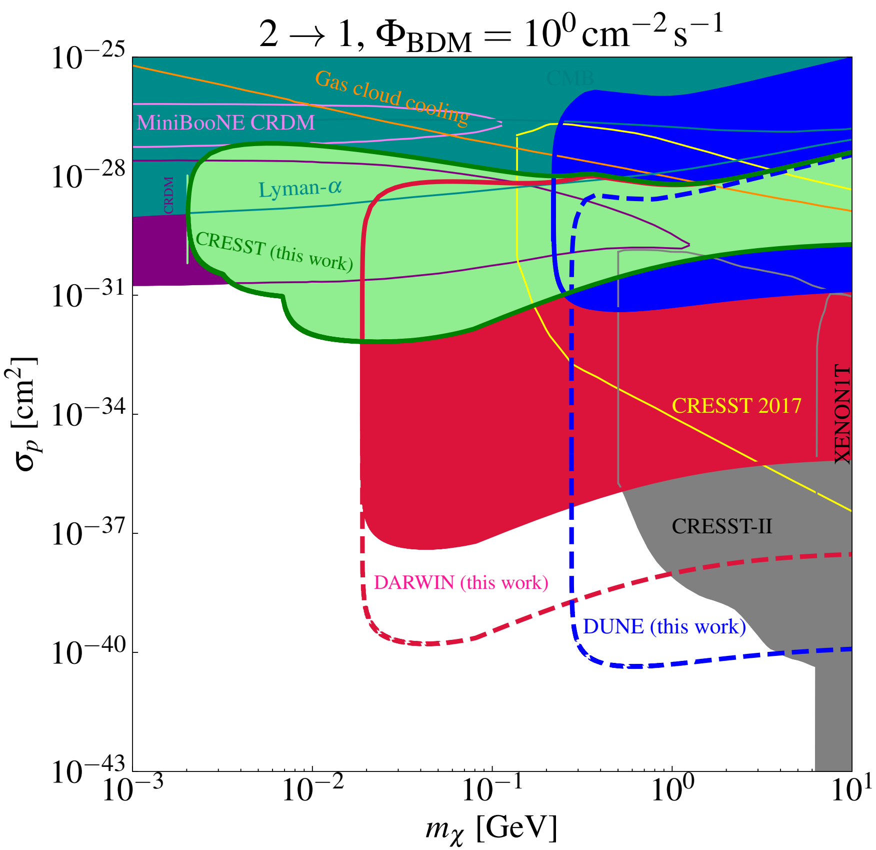


Direct detection of boosted DM in the GC



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





Conclusions

- The structure of the dark matter spike surrounding a black hole can be significantly affected by self-interactions, concretely by the unavoidable $3\to2$ or $4\to2$ processes (or $2\to1$ when semi-annihilations occur), due to the extremely high densities within the spike.
- The $n\to m$ processes are a source of boosted dark matter, which may allow to probe light dark matter in direct detection experiments.
- If semi-annihilations determine the dark matter relic abundance, the sensitivity of experiments to dark matter scatterings increases by up to six orders of magnitude.