Thermal Evolution of the Excited States in Inelastic Dark Matter Models

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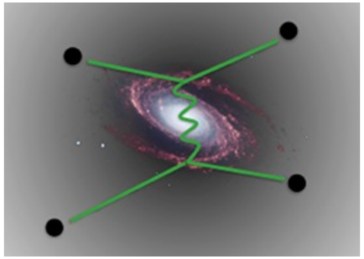
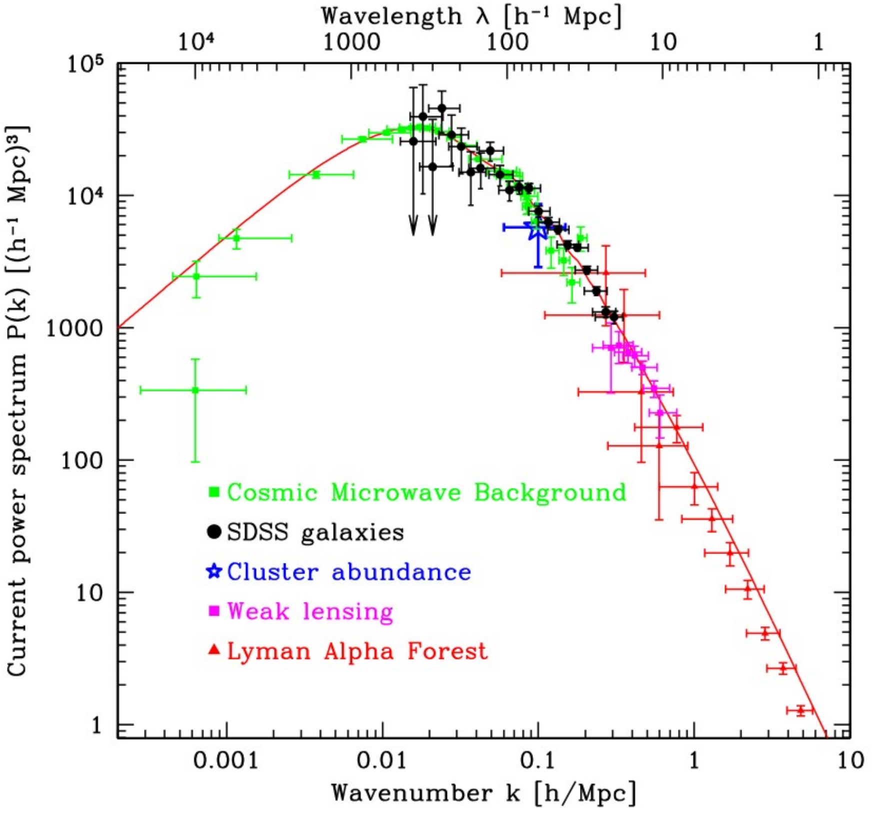


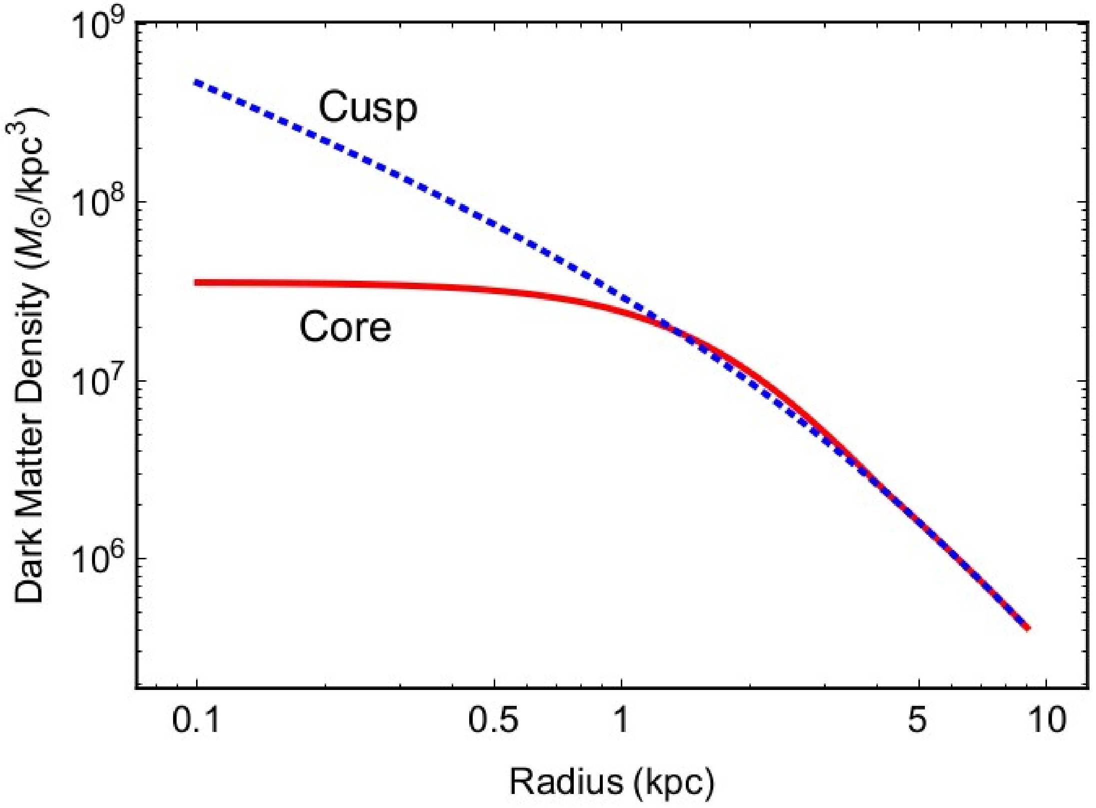
Introduction



The standard **cold and collisionless dark matter model** (CDM) successfully describes the universe on large scales. However, N-body simulations reveal discrepancies between CDM predictions and observations on small scales, such as the **core-cusp problem**

Tegmark, 2004

Introduction



Tulin, Yu, 2017

Core – Cusp problem

Standard CDM predicts cuspy halo profiles with $\rho \propto r^{-1}$ (NFW), but observations of dwarf galaxies and clusters favor cored profiles with approximately constant central density $\rho \sim \rho_0$

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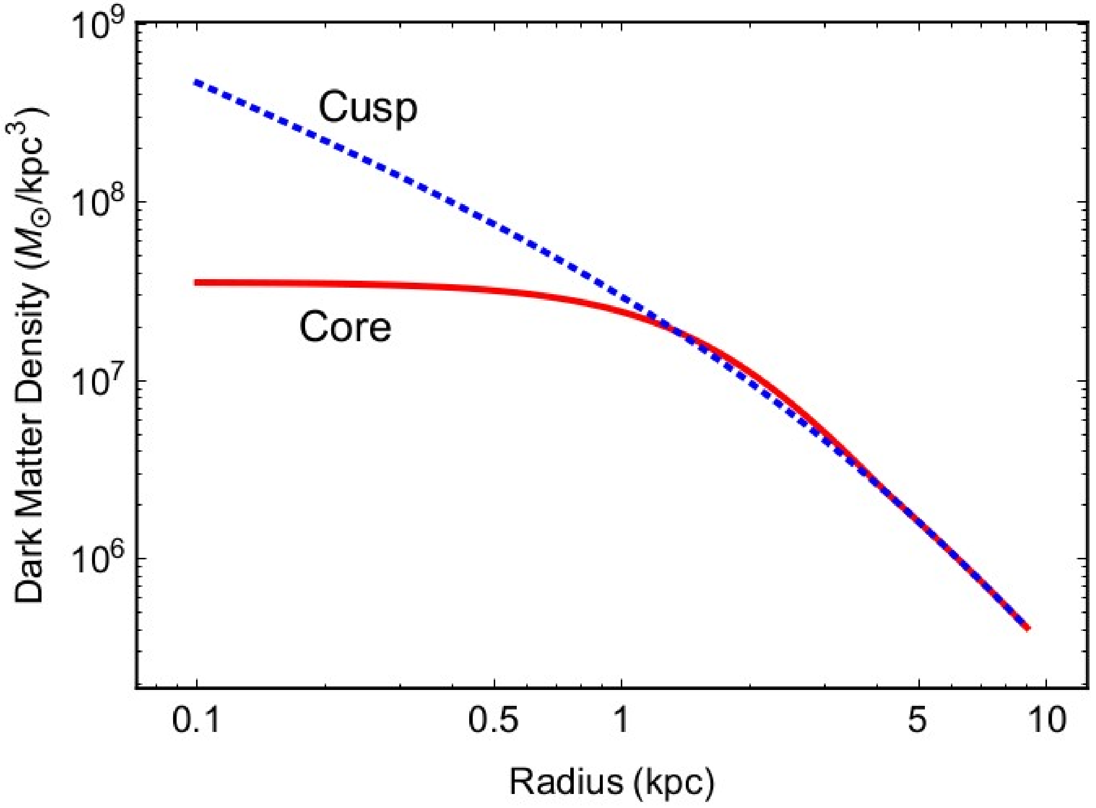

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Self-interacting DM offers a possible solution to this and other problems.

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- Light mediators must decay before BBN and are constrained by direct detection.
- Sommerfeld enhanced s-wave annihilations can conflict with CMB and indirect detection.

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- Light mediators must decay before BBN and are constrained by direct detection.
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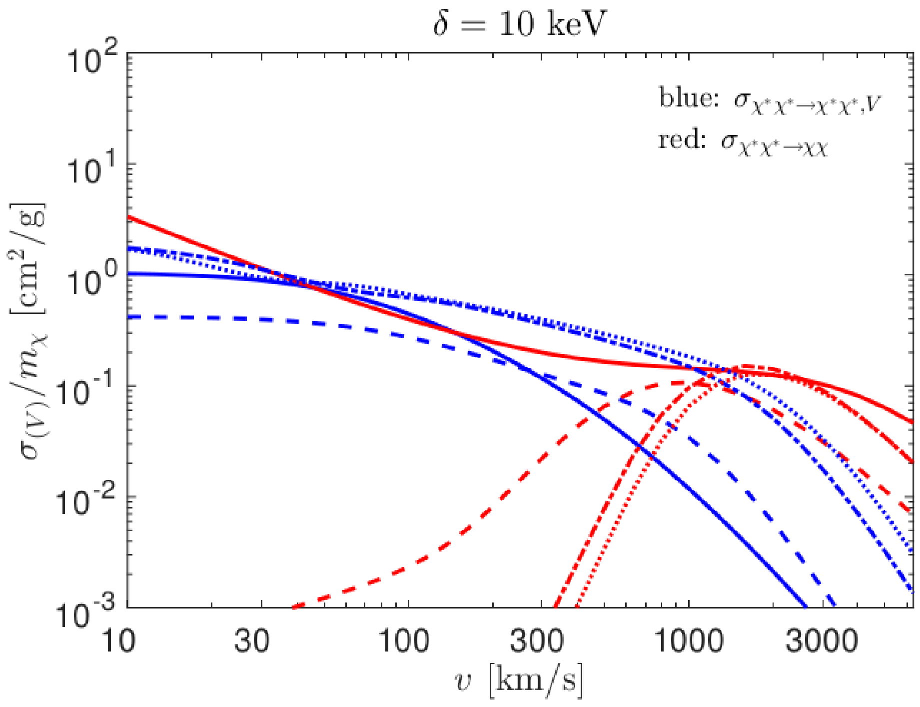
A phenomenologically viable alternative is inelastic dark matter (iDM)



Blennow et al. (2017)

Inelastic Dark Matter Model

The dark sector contains a U(1)‘ gauge symmetry with a gauge boson A’ with mass $m_{A'}$.

$$\mathcal{L}_{\text{NP}} = \mathcal{L}_\chi + \mathcal{L}_V \,,$$

$$\mathcal{L}_\chi = i\bar{\chi}_L \not{D} \chi_L + i\bar{\chi}_R \not{D} \chi_R - m_D \bar{\chi}_L \chi_R - \frac{1}{2} m_L \bar{\chi}_L^c \chi_L - \frac{1}{2} m_R \bar{\chi}_R^c \chi_R + \text{h.c.}$$

$$\mathcal{L}_V = -\frac{1}{4} A'^{\mu\nu} A'_{\mu\nu} - \frac{1}{2} \frac{\epsilon}{\cos\theta_W} B^{\mu\nu} A'_{\mu\nu} \,,$$

It includes a Dirac fermion $\chi_D = \chi_L + \chi_R$

Inelastic Dark Matter Model

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$\delta \equiv m_{\chi^*} - m_\chi$

$$m_{\chi^*} = \sqrt{m_D^2 + \frac{1}{4}(m_R - m_L)^2} + \frac{1}{2}(m_R + m_L)$$

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In our work, we consider that

$$m_{A'} > m_\chi \gg \delta$$

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The coupling to A' is off-diagonal

$$\mathcal{L}_\chi \supset ie' A'_\mu \bar{\chi}^* \gamma^\mu \chi + \mathcal{O}(\delta/m_\chi)$$

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Inelastic Dark Matter Model

Phenomenologically Viable iDM

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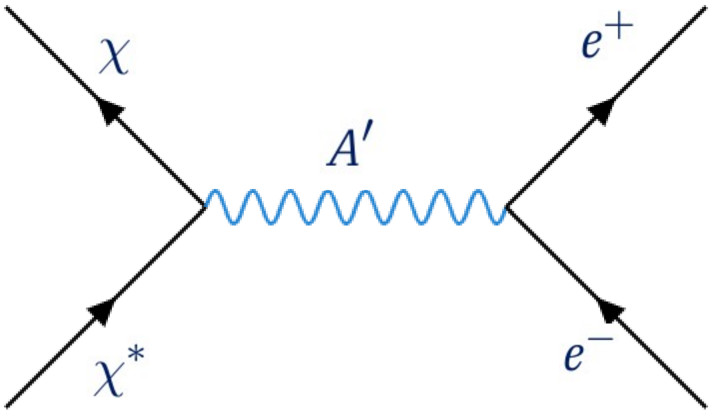
- The total relic abundance can be generated through thermal DM production (freeze-out).



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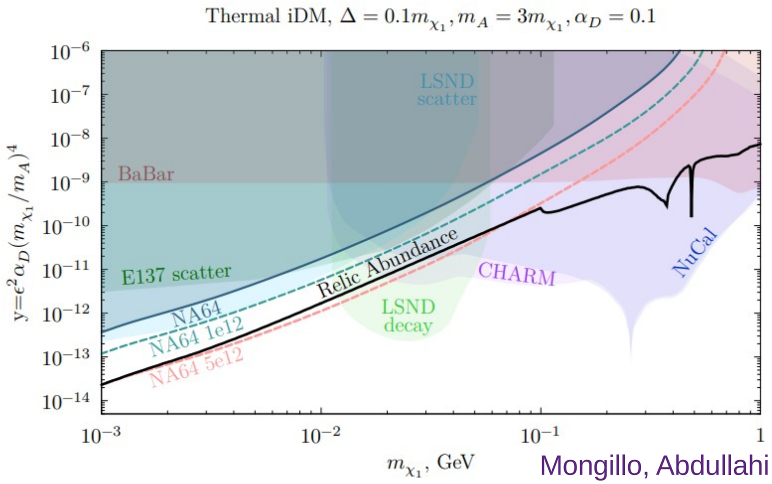
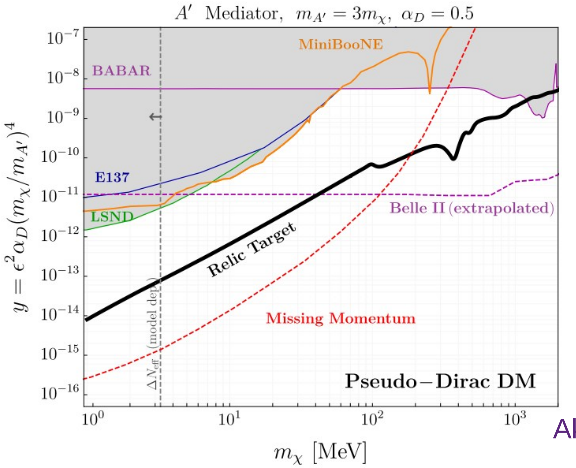
- The total relic abundance can be generated through thermal DM production (freeze-out).
- Several experiments projections (e.g., NA64, LDMX, Belle II) are sensitive to off-diagonal interactions.



Mongillo, Abdullahi, 2023

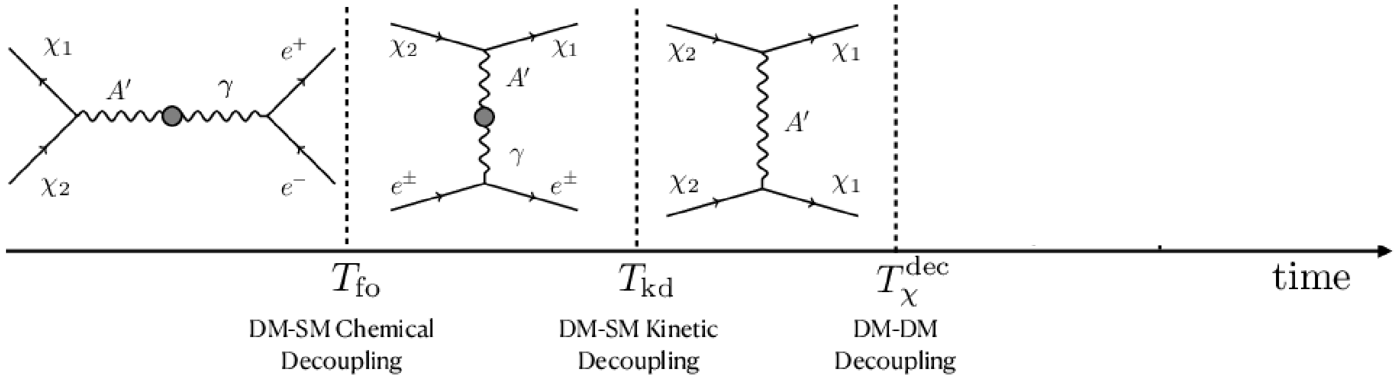


Akesson, Berlin, 2018

Cosmic evolution of iDM

Time evolution of iDM

$\chi \equiv \chi_1$
$\chi^* \equiv \chi_2$



Berlin, Krnjaic, 2023

Evolution of Excited-States Abundance

After the total freeze-out, the time evolution of the number density of χ^*

$$\dot{n}_{\chi^*} + 3Hn_{\chi^*} = -\langle\sigma_{\chi^* e^\pm \to \chi e^\pm}\, v\rangle n_{\chi^*} n_{e^\pm} + \langle\sigma_{\chi e^\pm \to \chi^* e^\pm}\, v\rangle n_\chi n_{e^\pm}$$
$$- \langle\sigma_{\chi^*\chi^* \to \chi\chi}\, v\rangle n_{\chi^*}^2 + \langle\sigma_{\chi\chi \to \chi^*\chi^*}\, v\rangle n_\chi^2$$

Evolution of Excited-States Abundance

Time evolution of the number density of χ^*

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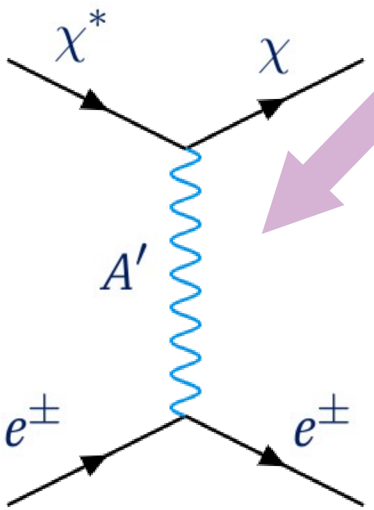

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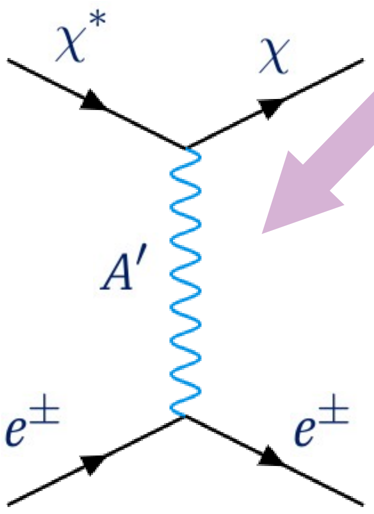

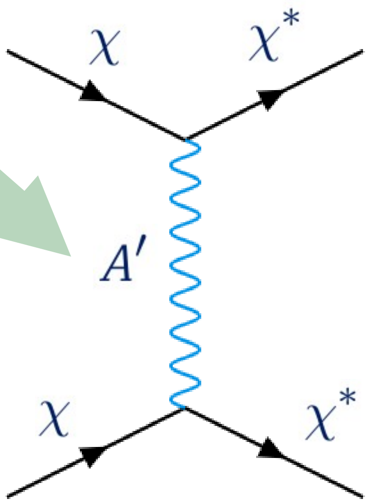

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$$- \langle\sigma_{\chi^*\chi^* \to \chi\chi}\, v\rangle n_{\chi^*}^2 + \langle\sigma_{\chi\chi \to \chi^*\chi^*}\, v\rangle n_\chi^2$$

We fixed the total number density as $n_{\chi,\mathrm{tot}} \equiv n_{\chi^*} + n_\chi$

We defined the fraction of excited states $f \equiv \dfrac{n_{\chi^*}}{n_{\chi,\mathrm{tot}}}\,,\qquad 0 \leq f \leq 0.5$

Evolution of the Fraction of Excited states

Time evolution of f

$$\frac{\mathrm{d}f}{\mathrm{d}t} = -\left(\Gamma_{\downarrow}^{\mathsf{SM}} f + \Gamma_{\downarrow}^{\mathsf{DS}} f^2\right) + \left[\Gamma_{\uparrow}^{\mathsf{SM}}(1-f) + \Gamma_{\uparrow}^{\mathsf{DS}}(1-f)^2\right]$$

with

$$\Gamma_{\uparrow}^{\mathsf{SM}} \equiv \left\langle \sigma_{\chi e^{\pm} \to \chi^* e^{\pm}}\, v \right\rangle n_{e^{\pm}} \;,$$
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$\chi \to \chi^*$ Up-scattering (endothermic)

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$\chi^* \to \chi$ Down-scattering (exothermic)

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→

$$\Gamma_{\uparrow}^{\mathrm{SM}} \sim \Gamma_{\downarrow}^{\mathrm{SM}} \times e^{-\delta/T_{\mathrm{sm}}}$$
$$\Gamma_{\uparrow}^{\mathrm{DS}} \sim \Gamma_{\downarrow}^{\mathrm{DS}} \times e^{-2\delta/T_{\chi}}$$

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After kinetic decoupling $(\Gamma_{\uparrow\downarrow}^{\mathrm{SM}} < H)$, the dark sector and the SM evolve with different temperatures.

Evolution of the Fraction of Excited states

$$\frac{\mathrm{d}f}{\mathrm{d}t} = -\left(\Gamma^{\mathrm{SM}}_{\downarrow} f + \Gamma^{\mathrm{DS}}_{\downarrow} f^2\right) + \left[\Gamma^{\mathrm{SM}}_{\uparrow}(1-f) + \Gamma^{\mathrm{DS}}_{\uparrow}(1-f)^2\right]$$

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$$\Gamma^{\mathrm{DS}}_{\downarrow} \equiv \left\langle \sigma_{\chi^*\chi^* \to \chi\chi}\, v \right\rangle n_{\chi,\mathrm{tot}}\ .$$

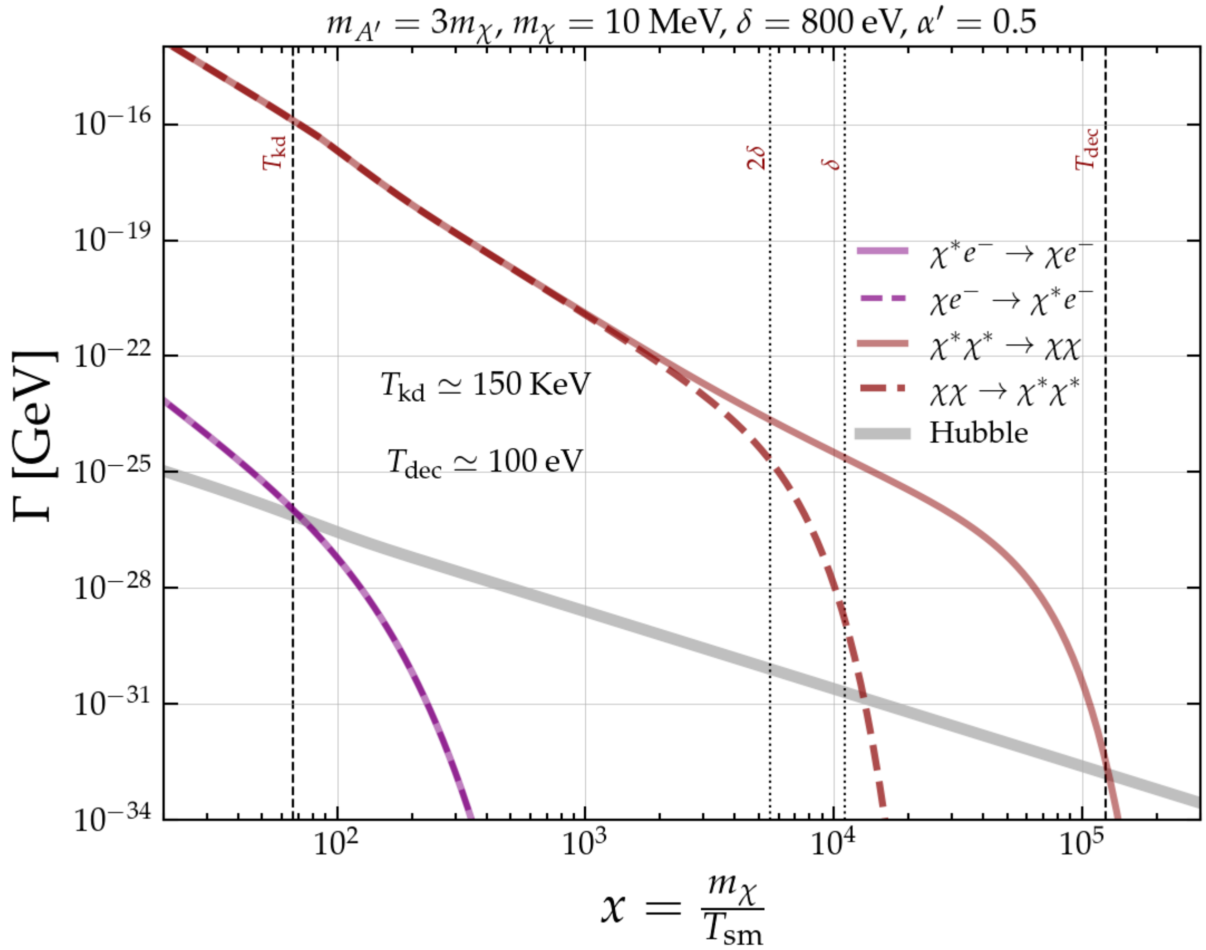
DS temperature Tx:

$$T_\chi = \begin{cases} T_{\mathrm{sm}} & \text{for } T_{\mathrm{sm}} > T_{\mathrm{kd}}, \\ f(T_{\mathrm{sm}}) & \text{for } T_{\mathrm{sm}} < T_{\mathrm{kd}}. \end{cases}$$

T_{kd} is defined as:

$$\left.\frac{\Gamma^{\mathrm{SM}}_{\uparrow\downarrow}}{H}\right|_{T=T_{\mathrm{kd}}} \simeq 1$$

Preliminary Results



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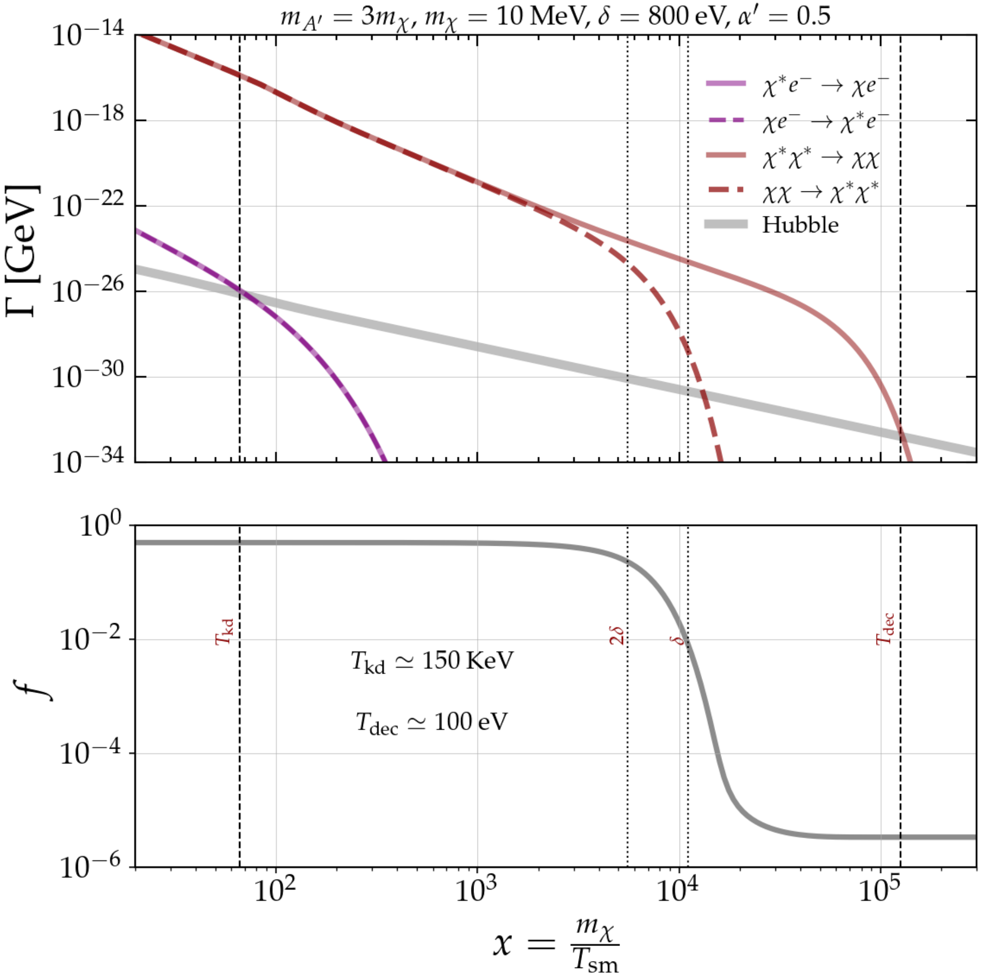

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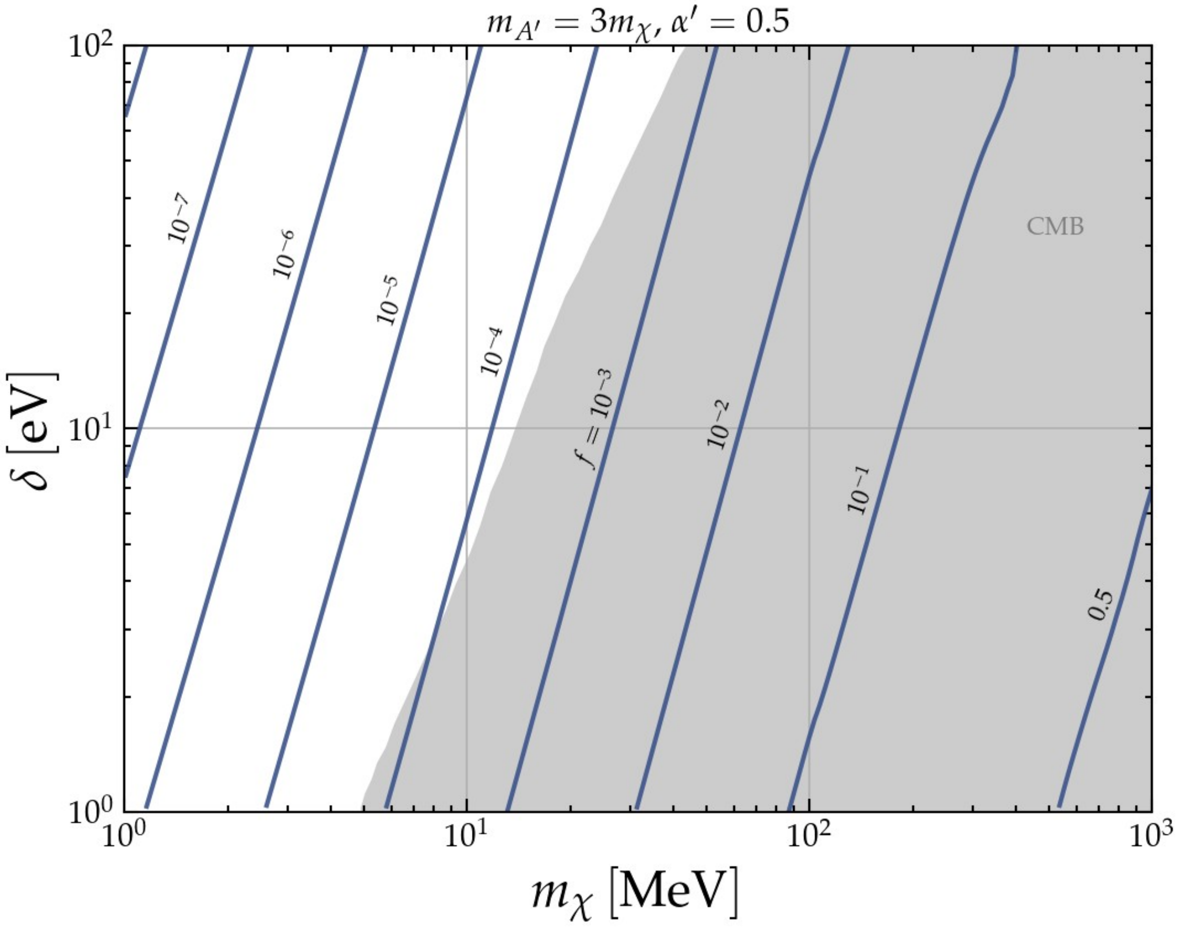
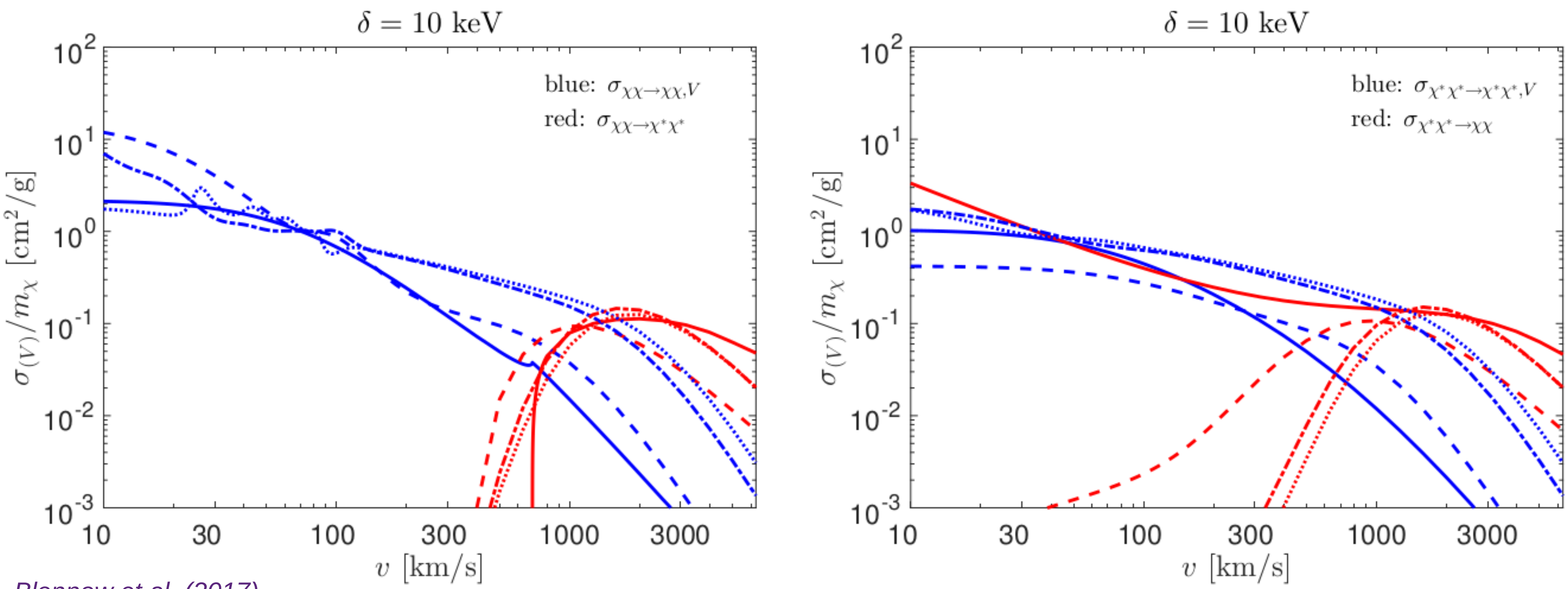


Summary

- SIDM remains a promising solution to small-scale structure problems.
- Elastic SIDM models face strong constraints from direct detection and CMB.
- Inelastic DM naturally avoids direct detection bounds, relaxes cosmological constraints, and maintains a viable relic density through freeze-out.
- A more detailed analysis is required to the dark sector temperature evolution.

Thanks

Back-up



Blennow et al. (2017)

	$\delta = 10$ keV		$\delta = 50$ keV		$\delta = 150$ keV	
Benchmark (line style)	m_χ	$m_{A'}$	m_χ	$m_{A'}$	m_χ	$m_{A'}$
A (solid)	15	1	40	1	51	1
B (dashed)	55	7	80	1.5	110	1
C (dash-dotted)	100	4	120	1	140	1
D (dotted)	140	4	160	2	180	1.5

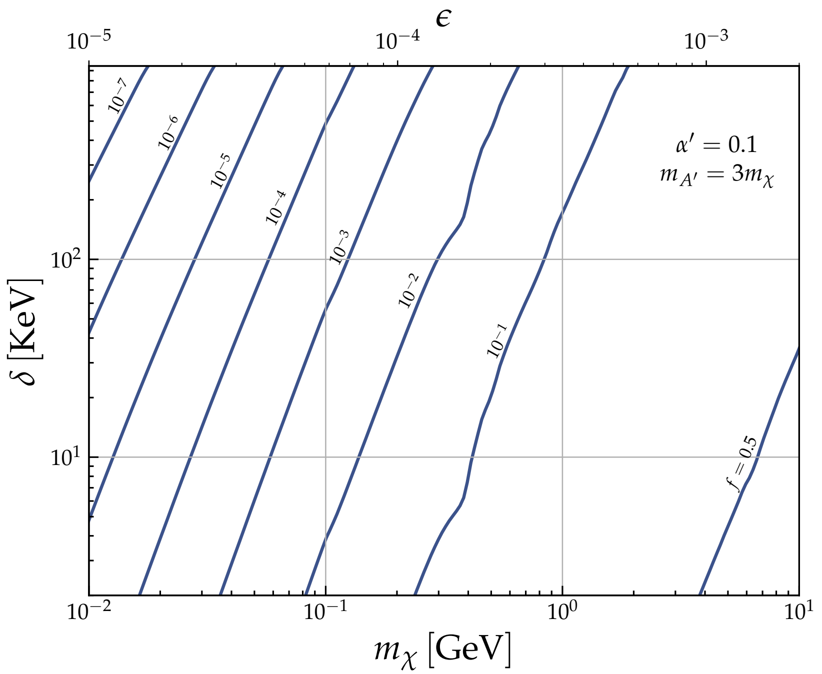
GeV

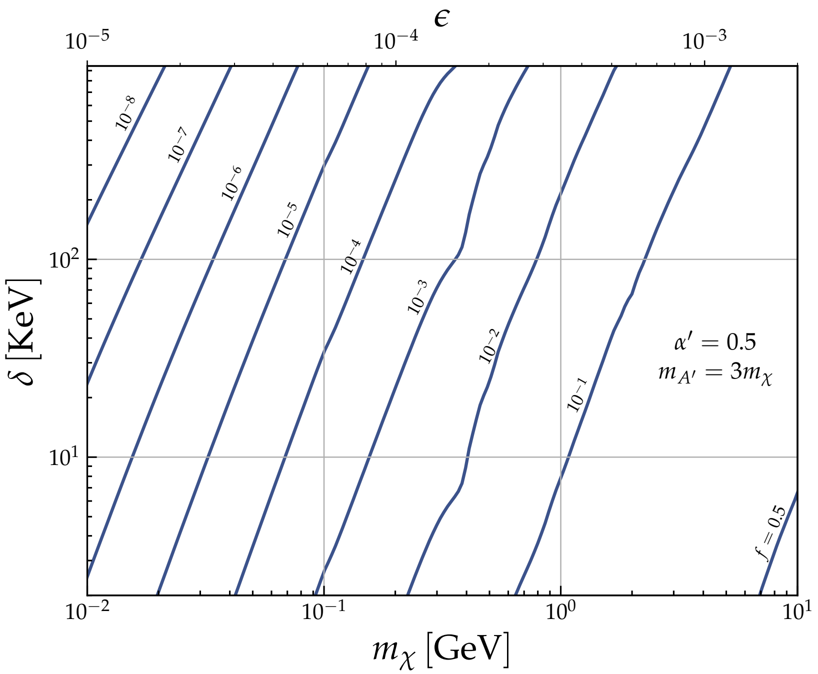
MeV

Observations and constraints on self-interaction cross section per DM mass

Positive observations	σ/m	$v_{\rm rel}$	Observation	Refs.
Cores in spiral galaxies (dwarf/LSB galaxies)	$\gtrsim 1\ \mathrm{cm^2/g}$	$30 - 200\ \mathrm{km/s}$	Rotation curves	[102, 116]
Too-big-to-fail problem				
Milky Way	$\gtrsim 0.6\ \mathrm{cm^2/g}$	$50\ \mathrm{km/s}$	Stellar dispersion	[110]
Local Group	$\gtrsim 0.5\ \mathrm{cm^2/g}$	$50\ \mathrm{km/s}$	Stellar dispersion	[111]
Cores in clusters	$\sim 0.1\ \mathrm{cm^2/g}$	$1500\ \mathrm{km/s}$	Stellar dispersion, lensing	[116, 126]
Abell 3827 subhalo merger	$\sim 1.5\ \mathrm{cm^2/g}$	$1500\ \mathrm{km/s}$	DM-galaxy offset	[127]
Abell 520 cluster merger	$\sim 1\ \mathrm{cm^2/g}$	$2000 - 3000\ \mathrm{km/s}$	DM-galaxy offset	[128, 129, 130]
Constraints				
Halo shapes/ellipticity	$\lesssim 1\ \mathrm{cm^2/g}$	$1300\ \mathrm{km/s}$	Cluster lensing surveys	[95]
Substructure mergers	$\lesssim 2\ \mathrm{cm^2/g}$	$\sim 500 - 4000\ \mathrm{km/s}$	DM-galaxy offset	[115, 131]
Merging clusters	$\lesssim$ few $\mathrm{cm^2/g}$	$2000 - 4000\ \mathrm{km/s}$	Post-merger halo survival (Scattering depth $\tau < 1$)	Table II
Bullet Cluster	$\lesssim 0.7\ \mathrm{cm^2/g}$	$4000\ \mathrm{km/s}$	Mass-to-light ratio	[106]

Tulin, Yu (2017)


ϵ
10−5
10−4
10−3
10−7
10−6
10−5
10−4
10−3
10−2
10−1
f = 0.5
α′ = 0.1
mA′ = 3mχ
δ [KeV]
10²
10¹
10−2
10−1
10⁰
10¹
mχ [GeV]


ϵ
10−5
10−4
10−3
10−8
10−7
10−6
10−5
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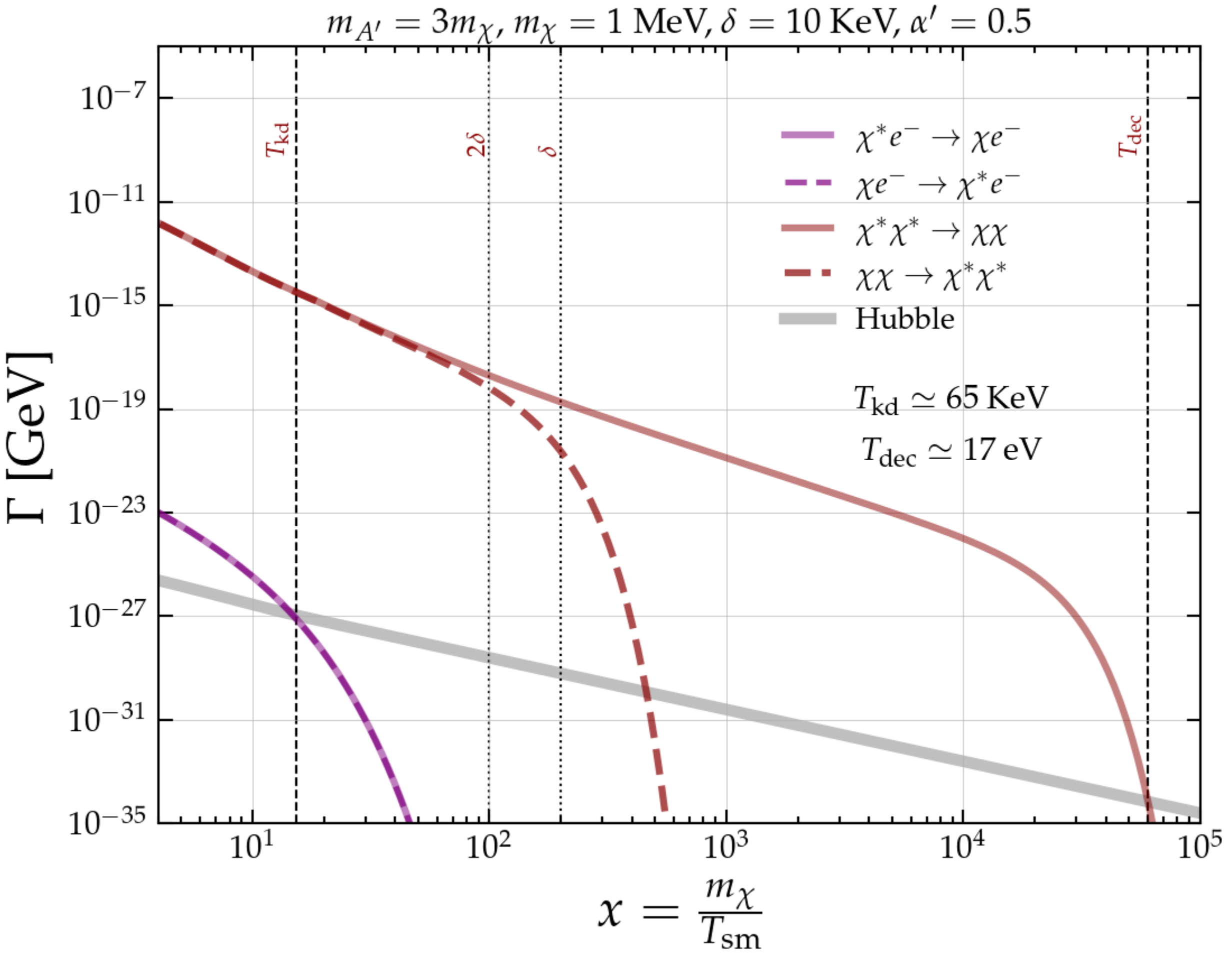
Results



$m_{A'} = 3m_\chi$, $m_\chi = 1$ MeV, $\delta = 10$ KeV, $\alpha' = 0.5$
Γ [GeV]
$x = \frac{m_\chi}{T_{sm}}$
10^{-7}
10^{-11}
10^{-15}
10^{-19}
10^{-23}
10^{-27}
10^{-31}
10^{-35}
10^1
10^2
10^3
10^4
10^5
T_{kd}
2δ
δ
T_{dec}
$\chi^* e^- \to \chi e^-$
$\chi e^- \to \chi^* e^-$
$\chi^* \chi^* \to \chi\chi$
$\chi\chi \to \chi^* \chi^*$
Hubble
$T_{kd} \simeq 65$ KeV
$T_{dec} \simeq 17$ eV