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The impact of dark matter self-scatterings on its relic abundance

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Based on 2204.07078

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DARK SIDE OF THE UNIVERSE

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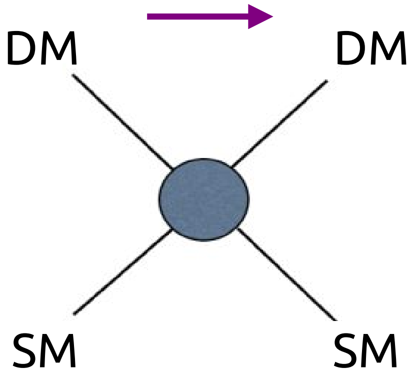
Self-scatterings of DM in the early Universe

Self-scatterings are usually neglected during the calculation of the DM relic abundance

The equilibrium shape of DM momentum distribution is established via ***elastic scatterings*** on SM particles in the plasma

$$f_i = \frac{n_i}{n_i^{\rm eq}}\, f_i^{\rm eq}(E_i, T_{\rm SM})$$



WIMPs typically go out of *kinetic equilibrium* much later than the freeze-out

T ~ 1-10 MeV (x >> 100)

Bringmann, 0903.0189

Boltzmann equation

With this assumption, one solves the Boltzmann equation for the DM number density (nBE)

$$\frac{dY}{dx} = \frac{s(x)}{x\,\tilde{H}(x)} \langle \sigma v \rangle(x) \left[Y_{\rm eq}^2(x) - Y^2 \right]$$

(for 2 → 2 annihilations)

$$\langle \sigma v \rangle = \frac{g_\chi^2}{n_\chi^{\rm eq} \cdot n_\chi^{\rm eq}} \int \frac{d^3 p}{(2\pi)^3} \frac{d^3 \tilde{p}}{(2\pi)^3} \sigma_{\rm ann} v \, f_\chi^{\rm eq}(p) f_\chi^{\rm eq}(\tilde{p})$$

Can also include decays, coannihilations, etc.

Works both for freeze-out and freeze-in

Early kinetic decoupling

If the *annihilation rate* >> the rate of *scatterings on SM* an early kinetic decoupling can occur → the assumption about the shape of f doesn't hold!

Example: scalar singlet model (Z_2)

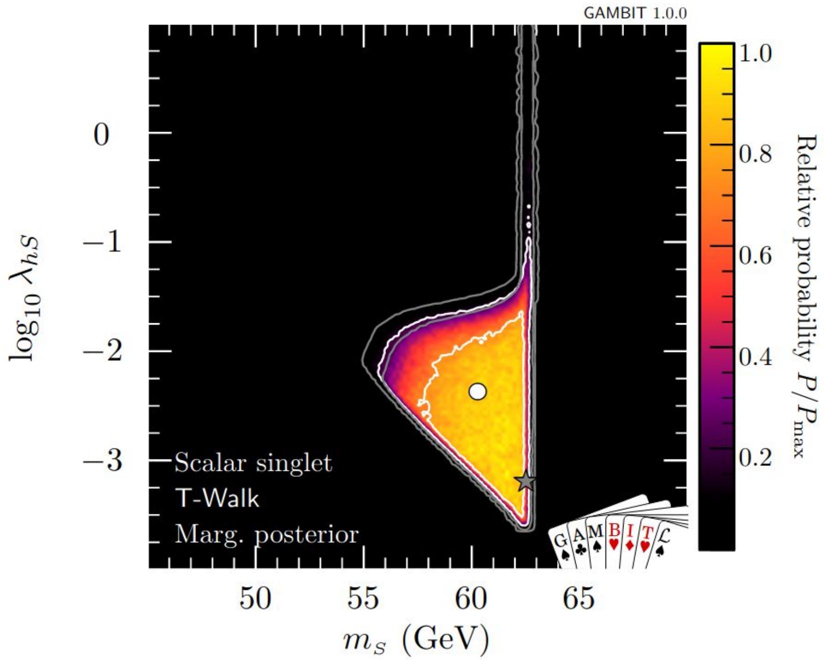
Binder et al., 1706.07433

- **Resonant** annihilation into SM fermions

$$\sigma v \propto \frac{\lambda_S^2}{(s - m_h^2)^2 + m_h^2 \Gamma_h^2}$$

- Elastic scattering

$$|\mathcal{M}|^2 \propto \frac{\lambda_S^2}{(t - m_h^2)^2}$$

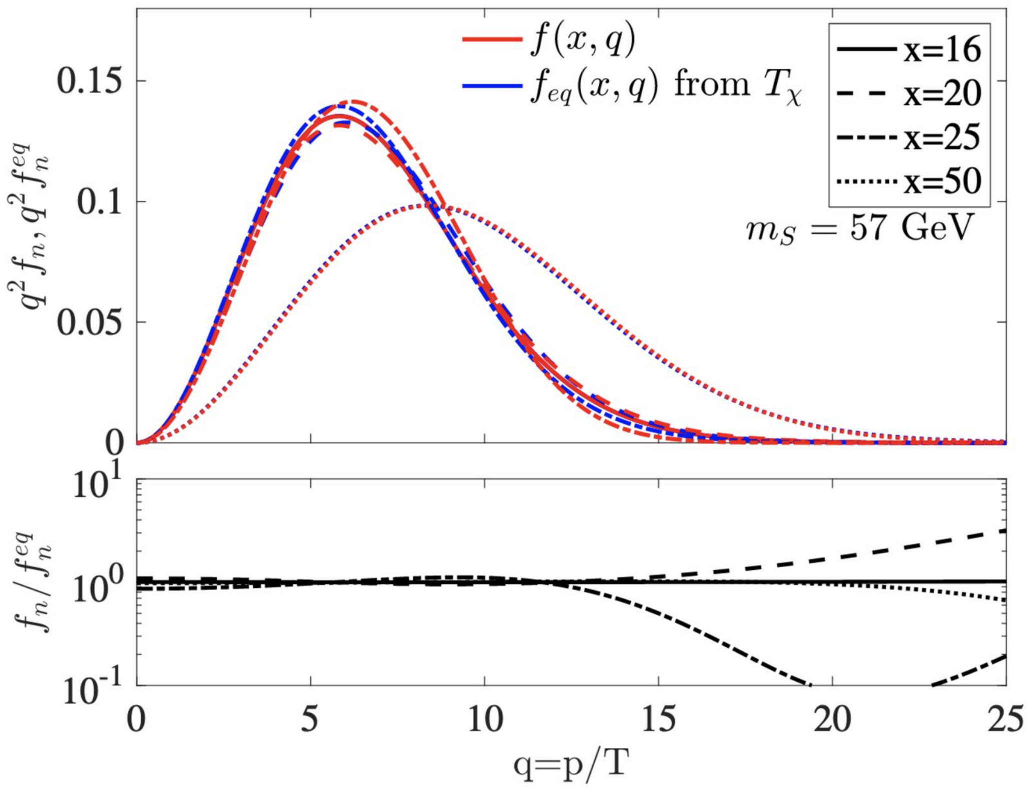


The best-fit region obtained by GAMBIT Collaboration, 1705.07931

Deviation from equilibrium shape

The **high-momentum tail** of the real distribution enhances the rate of annihilations

Binder et al., 1706.07433



Works for models with strong *velocity-dependence*:

- Resonance
- Sommerfeld
- Threshold
- Etc.

$$\langle \sigma v \rangle = \frac{g_\chi^2}{n_\chi^{eq} \cdot n_\chi^{eq}} \int \frac{d^3 p}{(2\pi)^3} \frac{d^3 \tilde{p}}{(2\pi)^3} \sigma_{ann} v f_\chi^{eq}(p) f_\chi^{eq}(\tilde{p})$$

Full Boltzmann equation

In fact, the nBE is derived from the general **Full Boltzmann equation** (**fBE**)

$$2E_i\left(\partial_t - H\, p\partial_p\right) f_i(p) = C\left[f_i\right]$$

Collision term

DM **distribution function**

The collision term takes into account all the processes

Equilibrating processes (affect the shape)

$$C[f_\chi] = C_{\text{ann}} + C_{\text{dec}} + C_{\text{el}} + C_{\text{self}} + \ldots$$

Number-changing processes (*mainly* affect the density)

Collision term

For DM + DM → SM + SM :

$$C_{\text{ann}}[f_\chi] = \frac{1}{2g_\chi}\int \frac{d^3\tilde{p}}{(2\pi)^3\tilde{E}}\int \frac{d^3k}{(2\pi)^3\omega}\int \frac{d^3\tilde{k}}{(2\pi)^3\tilde{\omega}}$$

All momenta configurations

$$\times(2\pi)^4\delta^{(4)}(E+\tilde{E}-\omega-\tilde{\omega})$$

Energy and momenta conservation

$$\times\Big[|\mathcal{M}|^2_{\text{SM}\to\text{DM}}\, f_{\text{SM}}(\omega)f_{\text{SM}}(\tilde{\omega})[1\pm f_\chi(E)][1\pm f_\chi(\tilde{E})]$$

$$-|\mathcal{M}|^2_{\text{DM}\to\text{SM}}\, f_\chi(E)f_\chi(\tilde{E})[1\pm f_{\text{SM}}(\omega)][1\pm f_{\text{SM}}(\tilde{\omega})\Big]$$

Probability x number of states

Unknown function

Leads to an integro-differential equation

Numerical difficulties

Collision terms have the following structure

$$C[f_\chi] \propto f_\chi(p) \int \dots \int \frac{d^3k}{(2\pi)^3\, 2\omega} \dots$$

Distribution function is not integrated over
Can be solved explicitly

$$C[f_\chi] \propto \int \dots \int \frac{d^3k}{(2\pi)^3\, 2\omega} f_\chi(k) \dots$$

Distribution function has to be integrated over
Integro-differential equation

fBE → system of fBEs

$$f_\chi(k) \to \{ f_1(k_1), \dots, f_n(k_n) \} \qquad \int \frac{dk}{E_k} \to \sum_i \frac{(\Delta k)}{E_k^i}$$

Numerical integration

Self-scattering inevitably has 2 unknown functions in the *lowest order* in f_χ

Why are self-scatterings important?

Self-scatterings can be more important than elastic scatterings in ***shaping*** the distribution:

- Momentum transfer $\Delta p/p \sim 1$ (for elastic $\Delta p/p \ll 1$) → less collisions required
- Couplings and vertices can be different (enhanced)
- Less constrained by observations

$$\sigma_{\rm el}/m \lesssim 10^{-34}\ {\rm cm}^2/{\rm GeV}$$

On electrons, from structure formation
Nguyen+, 2107.12380

$$\sigma_{\rm self}/m \lesssim 10^{-24}\ {\rm cm}^2/{\rm GeV}$$

From cluster collisions
Kim+, 1608.08630

Setting

We study the role of self-scatterings on the example of a DM model with long-range interaction and a decaying long-lived heavier state

- Freeze-out
- Early kinetic decoupling
- (Late-time) DM injection from decays

The model

Decaying scalar singlet + DM fermion + dark U(1)*

$$\mathcal{D}_\mu = \partial_\mu - ie'A'_\mu$$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)^2 - V(S,H) + yS\bar{\chi}\chi + m_{\rm DM}\bar{\chi}\chi + \bar{\chi}i\mathcal{D}_\mu\gamma^\mu\chi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_A^2 A'_\mu A'^\mu$$

$$V(H,S) = -\mu_H^2|H|^2 - \frac{1}{2}m_S^2S^2 + \lambda_H|H|^4 + \frac{\lambda_S}{4}S^4 + \frac{\lambda_{HS}}{2}|H|^2S^2$$

Scalar decays → non-thermal component of DM

Dark U(1) → self- and elastic-scatterings + annihilation into SM

* this model without dark U(1) was studied in a similar context in Ala-Mattinen+, 2201.06456

The model

Decaying scalar singlet + DM fermion + dark U(1)

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)^2 - V(S,H) + yS\bar{\chi}\chi + m_{\rm DM}\bar{\chi}\chi + \bar{\chi}i\mathscr{D}_\mu\gamma^\mu\chi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_A^2 A'_\mu A'^\mu$$

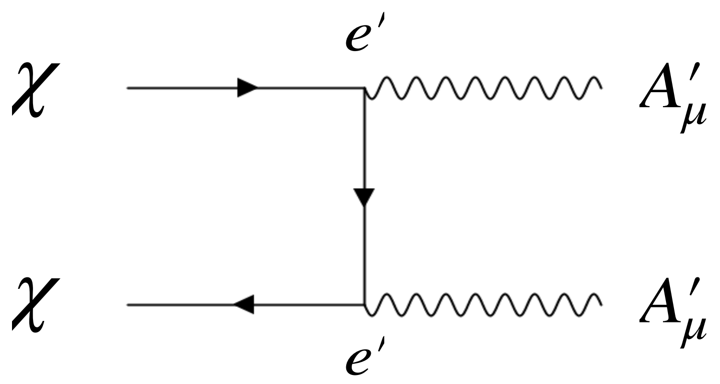
$$V(H,S) = -\mu_H^2|H|^2 - \frac{1}{2}m_S^2S^2 + \lambda_H|H|^4 + \frac{\lambda_S}{4}S^4 + \frac{\lambda_{HS}}{2}|H|^2S^2 \qquad \mathscr{D}_\mu = \partial_\mu - ie'A'_\mu$$

Z2 symmetry slightly broken:

- Small value of y → **long lifetime** (late injection)
- Loop-supressed to SM → **no entropy dilution**
- Coupling to Higgs → always in thermal equilibrium

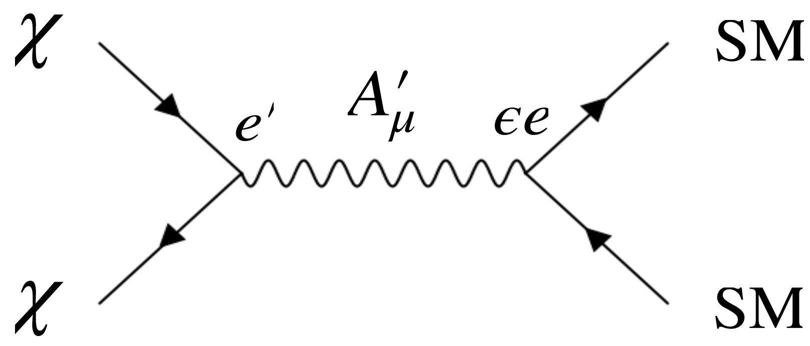
The model

Decaying scalar singlet + DM fermion + dark U(1)



Sub-threshold annihilation

$m_\chi < m_{A'_\mu}$



Resonant annihilation
(suppressed by the small ϵ)

Two DM annihilation processes are possible

<u>In our case</u> the strong velocity dependence comes from sub-threshold

How is fBE solved?

DRAKE code for the calculation of DM abundance

Written in *Mathematica* language

DRAKE
Dark matter Relic Abundance beyond Kinetic Equilibrium

https://drake.hepforge.org Binder+, 2103.01944

The current version solves **nBE** and **fBE** for the freeze out of 2-2 annihilation processes

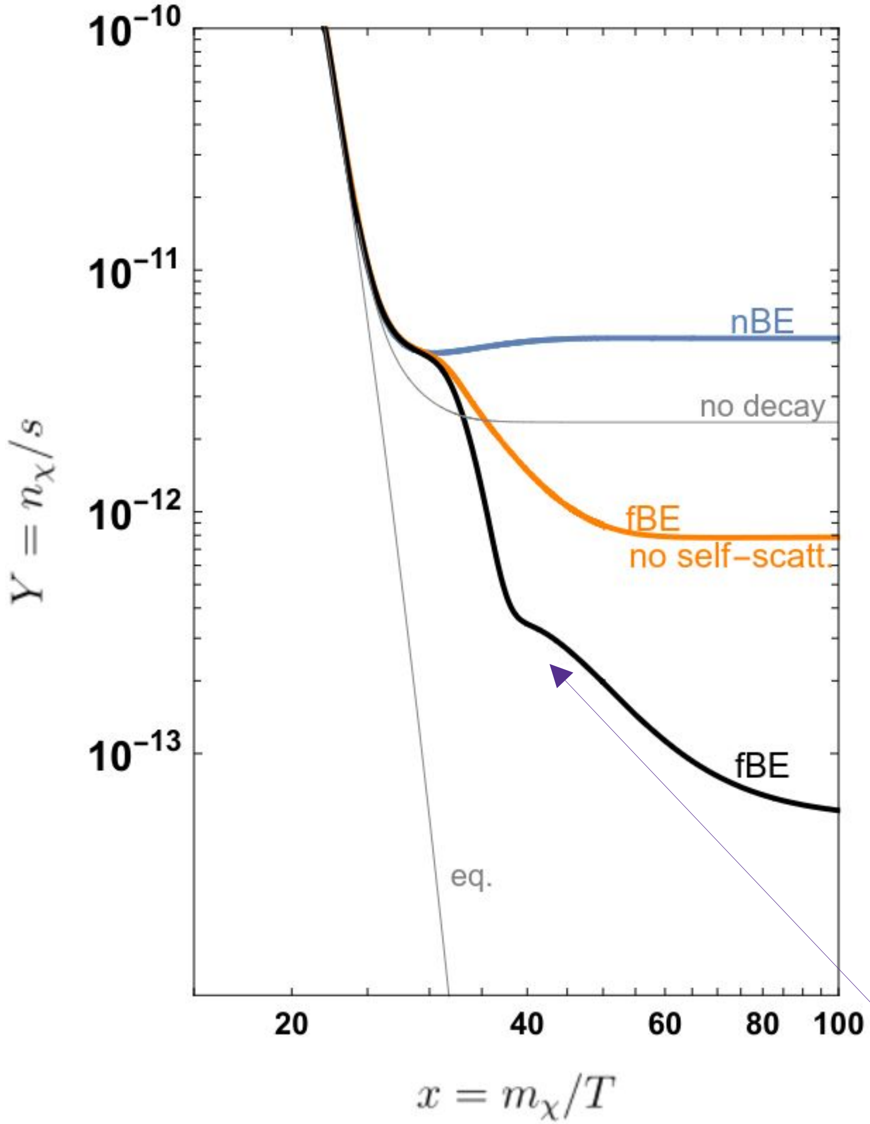
For our study we included:

- Decays
- Self-scatterings – implemented a C++ patch for fast numerical intergration of the collision term integrals

$$C_{\rm self}[f_\chi(p)] \propto \int d^3k \int d^3\tilde{p} \int d^3\tilde{k} \quad f_\chi(\tilde{k}) f_\chi(\tilde{p})$$

Backward term for self-scattering

Density evolution



Kinetic equilibrium:

No decay – standard freeze-out

nBE – the density is increased by the late-time decay products

Early kinetic decoupling (fBE):

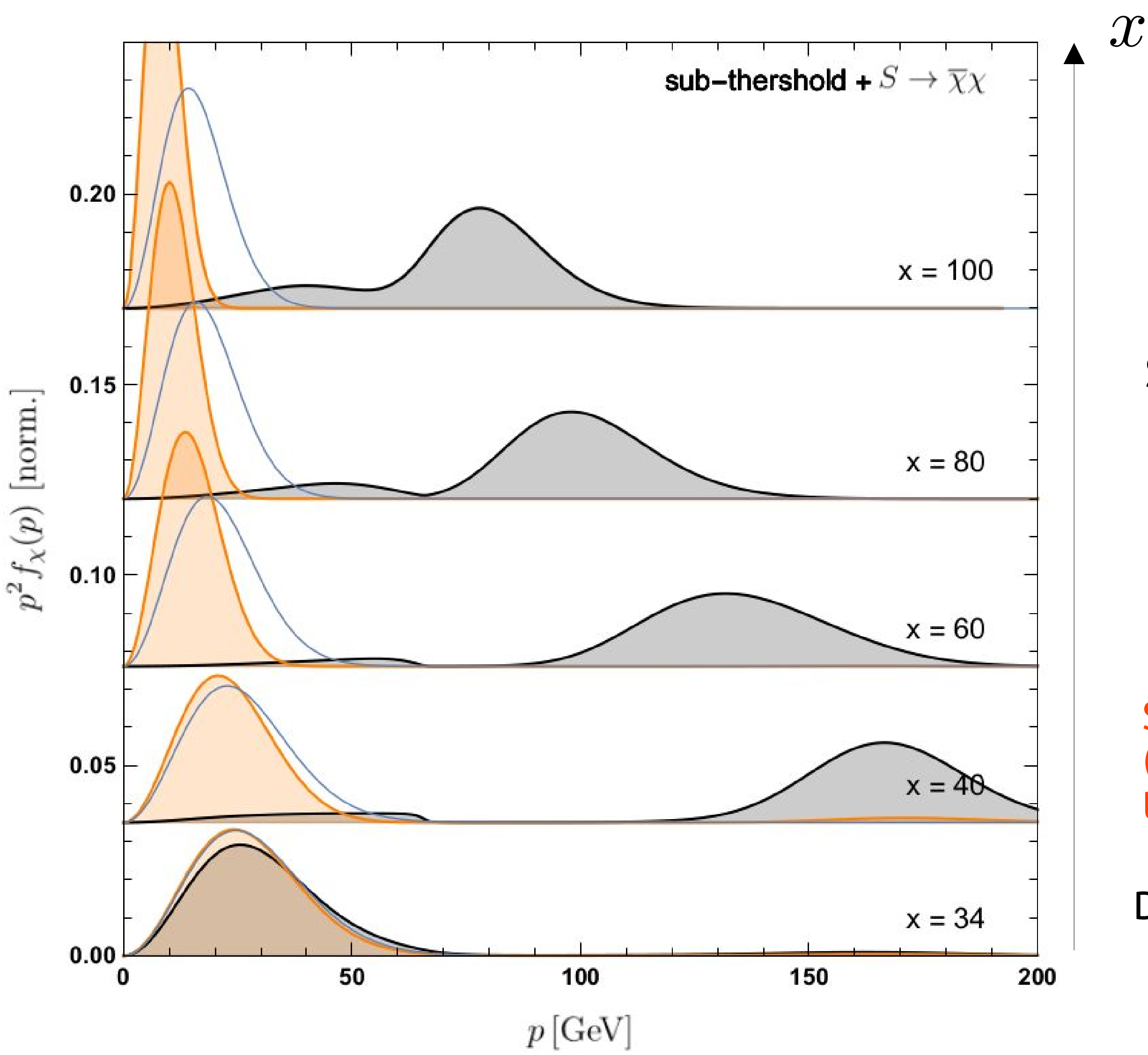
No self-scatterings – hot particles from decays extend the annihilation into SM and deplete the density

Self-scatterings *redistribute the energy* from decaying particles and extend the annihilation even longer

sub–threshold + $S \to \bar{\chi}\chi$
$m_\chi = 100\,\mathrm{GeV}$
$m_A = 108\,\mathrm{GeV}$
$m_S = 400\,\mathrm{GeV}$
$e' = 1.$
$\epsilon = 0.001$

Decays essentially stop contributing

Distribution function



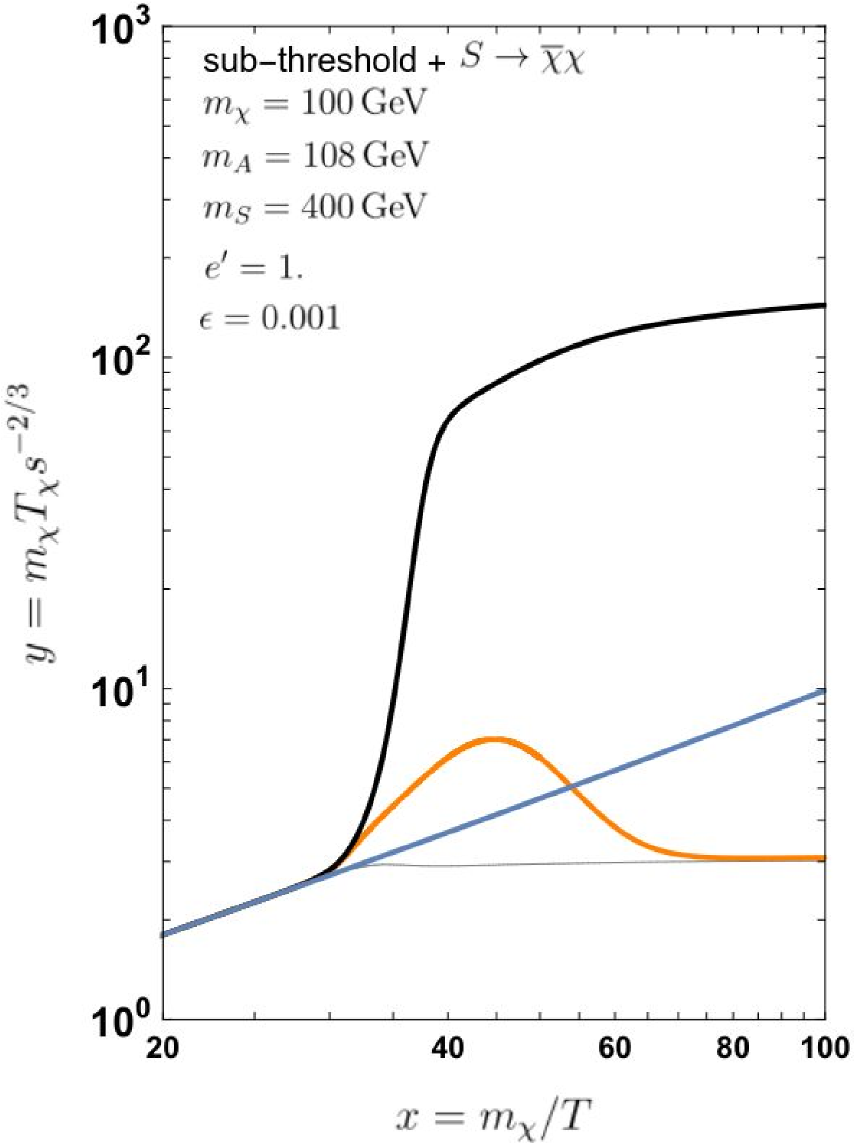
- nBE
- fBE (no scatterings)
- fBE (active scatterings)

Self-scatterings redistribute the heat and "move" the distribution towards larger momenta → larger $\langle \sigma v \rangle$

Small component of high-energy particles (most of the energy is dumped into SM through annihilations)

Decays start to contribute to the density

Temperature evolution



$$y \propto T_\chi \cdot x^2$$

Significantly heated up

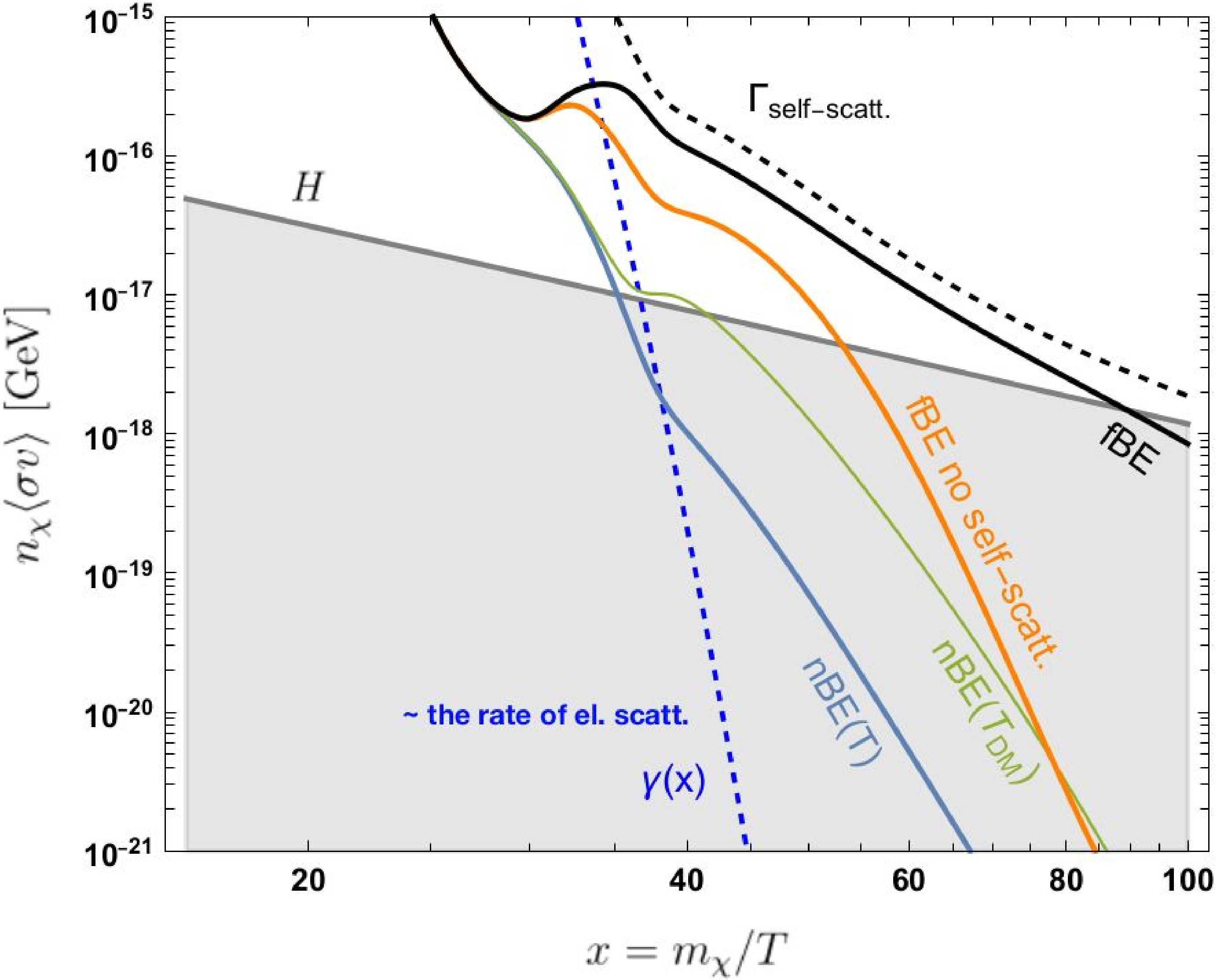
The heat from decays remains in the dark sector due to an efficient **redistribution by self-scatterings**

Temperature is equal to T_{SM} $\quad T_{\mathrm{SM}} \propto x^{-1}$

No self-scatterings – DM is slightly heated by decays and then the temperature decreases due to expansion

$$T_{\mathrm{non-rel}} \propto x^{-2}$$ (constant *y*)

Rates of processes



Conclusion

The interplay of different interactions in some DM models can lead to a deviation of the DM energy distribution from the equilibrium shape that can affect the relic density of DM

We studied a model in which

- the self-scattering plays a crucial role in shaping the energy distribution
- the relic density can decrease with an injection of additional DM particles due to a more efficient annihilation of high-momentum particles (velocity-dependent cross section)