Revisiting Dark Matter Freeze-in and Freeze-out through Phase-Space Distribution

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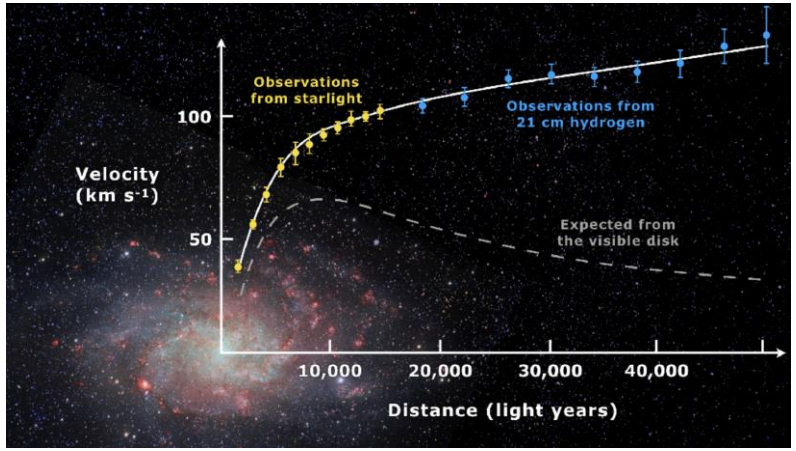
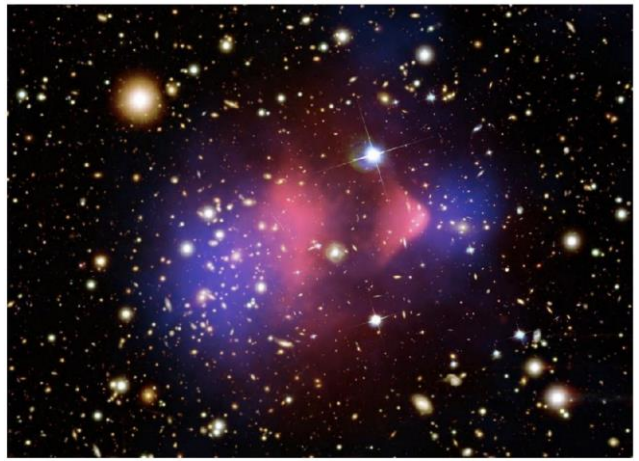
Yong Du, Fei Huang, Hao-Lin Li, Yuan-Zhen Li and Jiang-Hao Yu

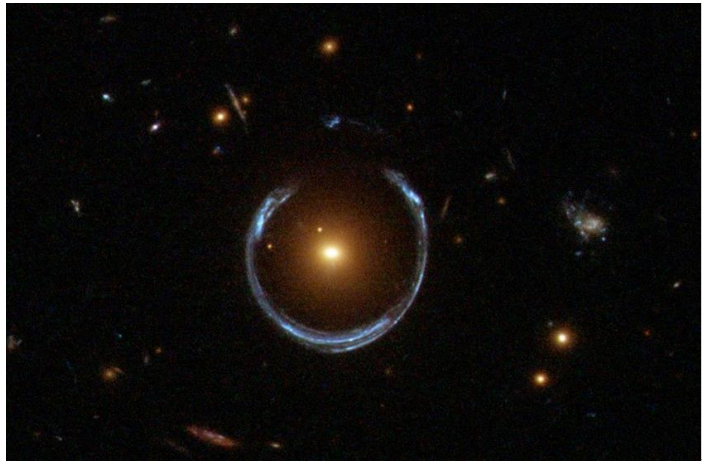
Observational evidence of DM

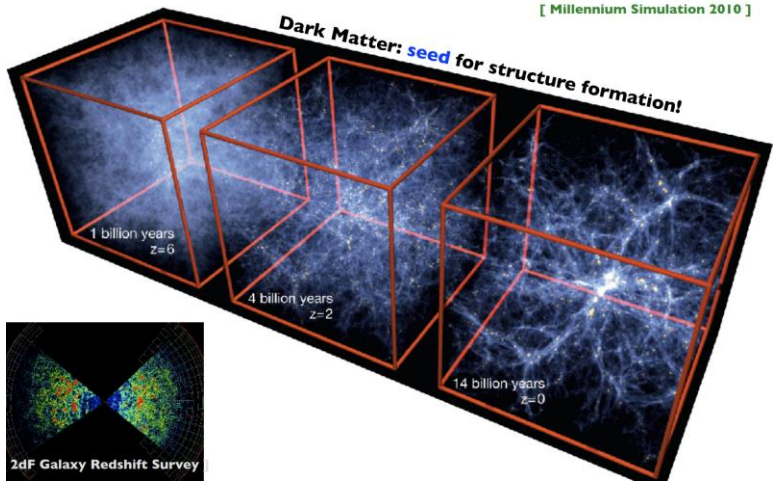
There is ample evidence for dark matter at different scales!

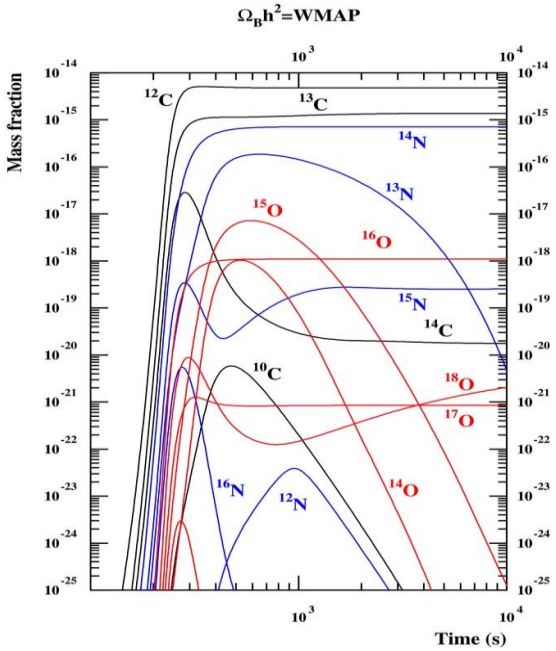


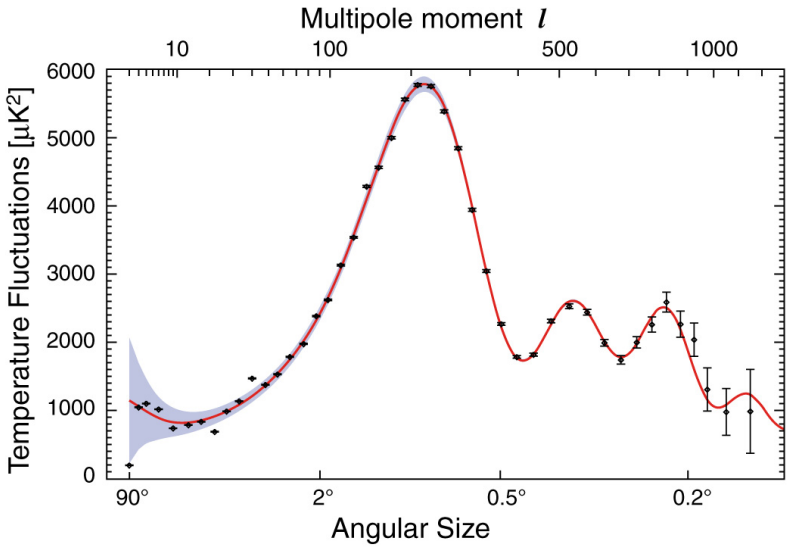


X-ray image (gas), visible light image (galaxy), gravitational lensing image (matter)



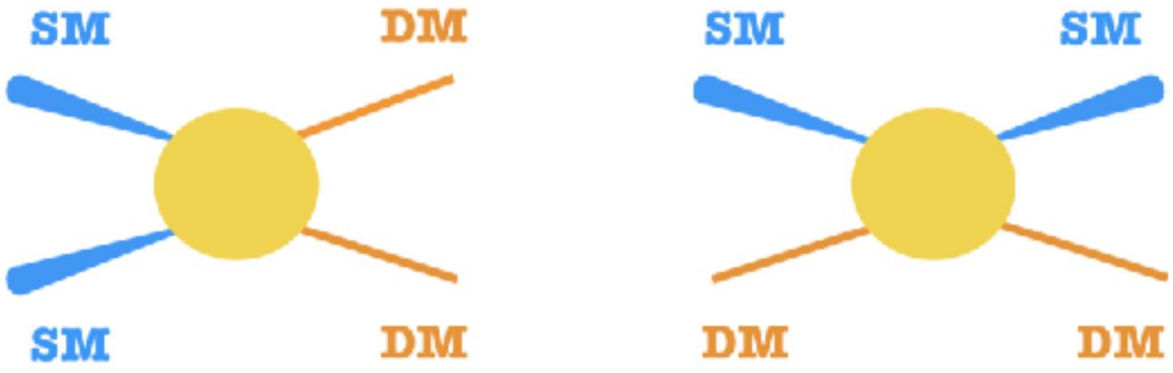




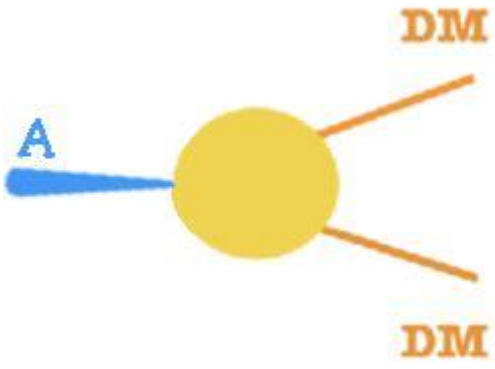


Possible particle-physics processes in early universe

Dark matter may have 2-to-2 annihilation or scattering processes with particles in the thermal bath.

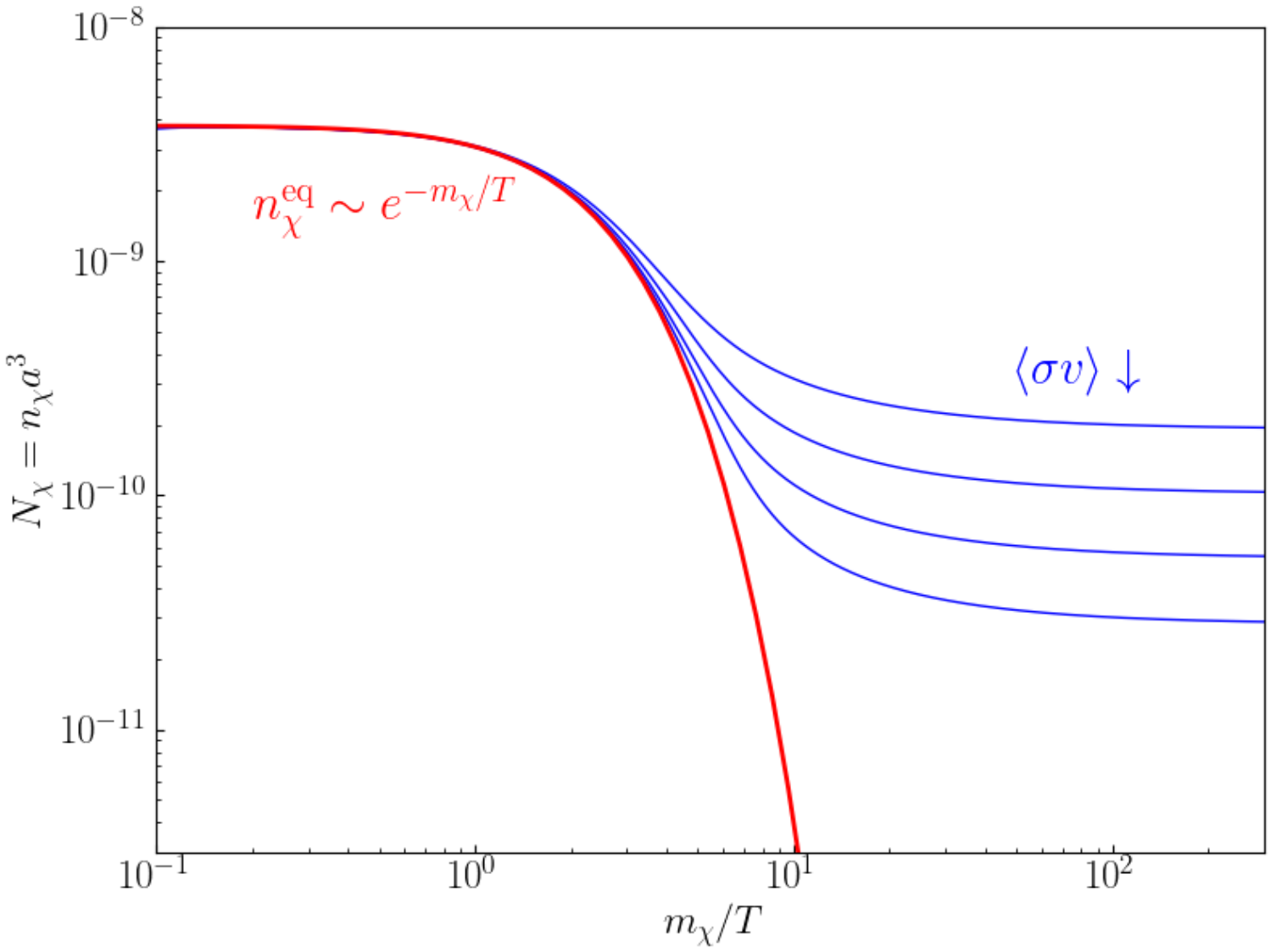


Dark matter may also be produced by particle decays.



Dark Matter Production: Vanilla freeze-out and freeze-in

Number density level: Freeze-out



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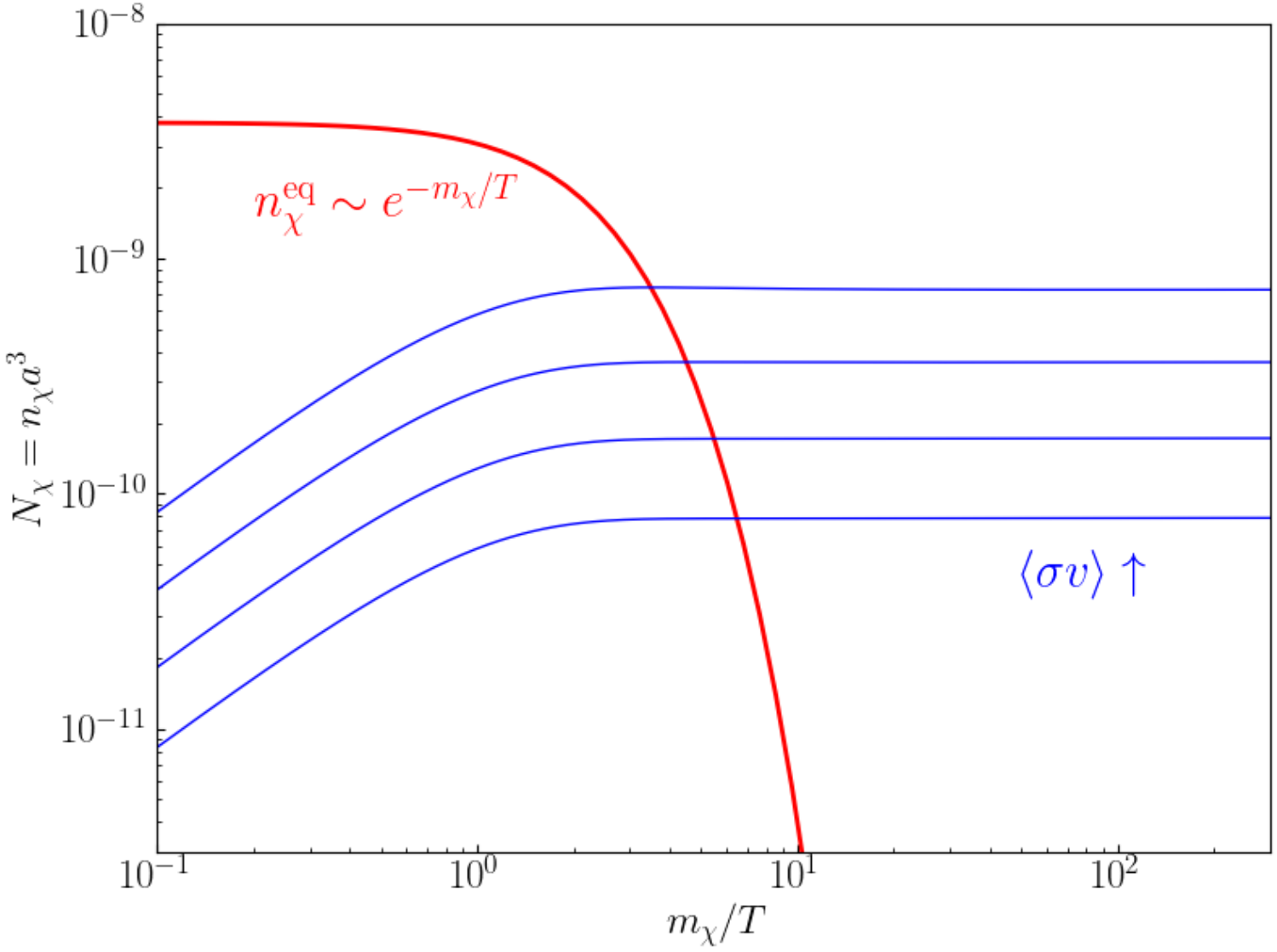
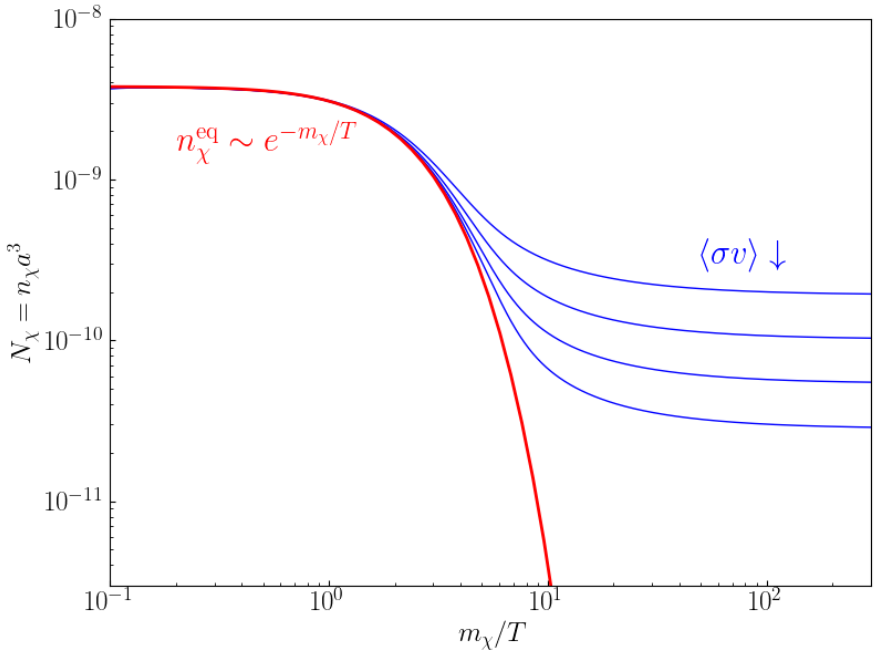
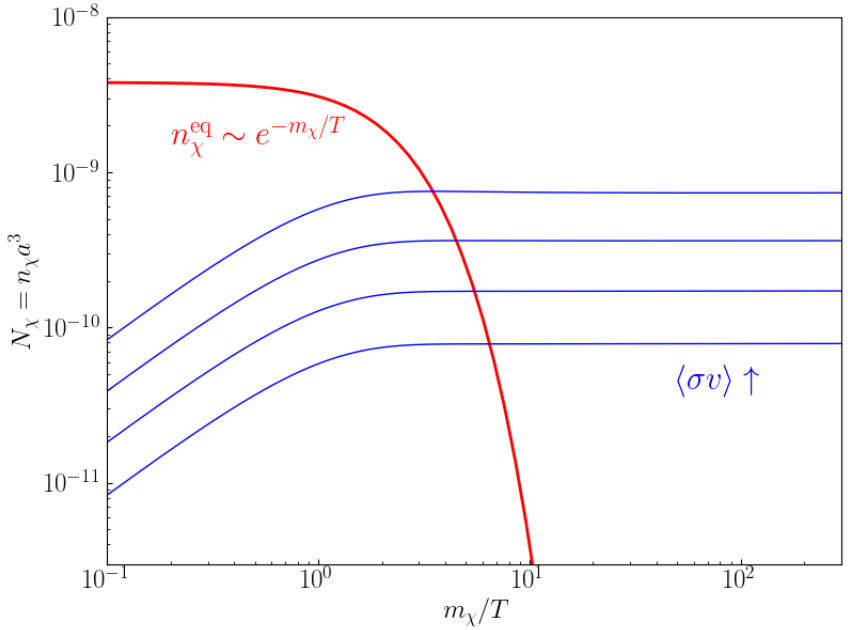


Dark Matter Production: Vanilla freeze-out and freeze-in

Number density level:

$$\frac{dn_\chi}{dt} + 3Hn_\chi \simeq (n_\chi^{\mathrm{eq}2} - n_\chi^2)\,\langle\sigma_{\mathrm{ann}}v\rangle_T \ ,$$





Dark Matter Production: Vanilla freeze-out and freeze-in

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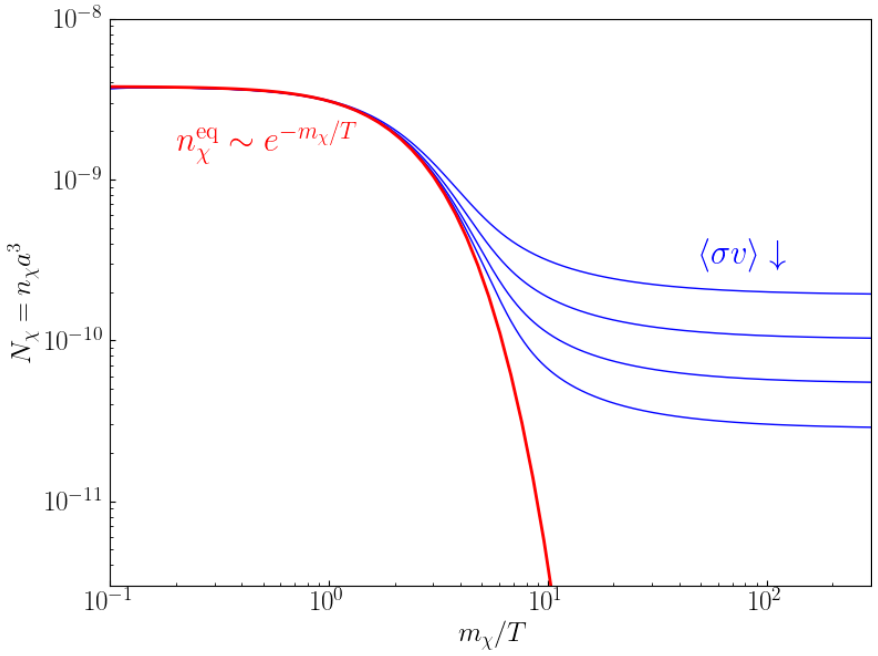
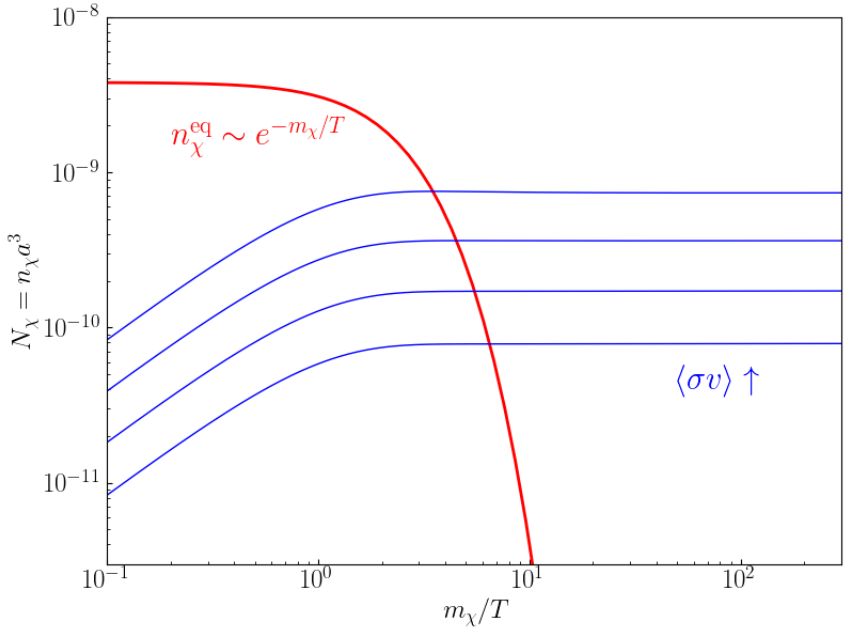
$$\frac{dn_\chi}{dt} + 3Hn_\chi \simeq (n_\chi^{\mathrm{eq}2} - \cancel{n_\chi^2})\,\langle\sigma_{\mathrm{ann}}v\rangle_T \ ,$$

(Pure freeze-in)





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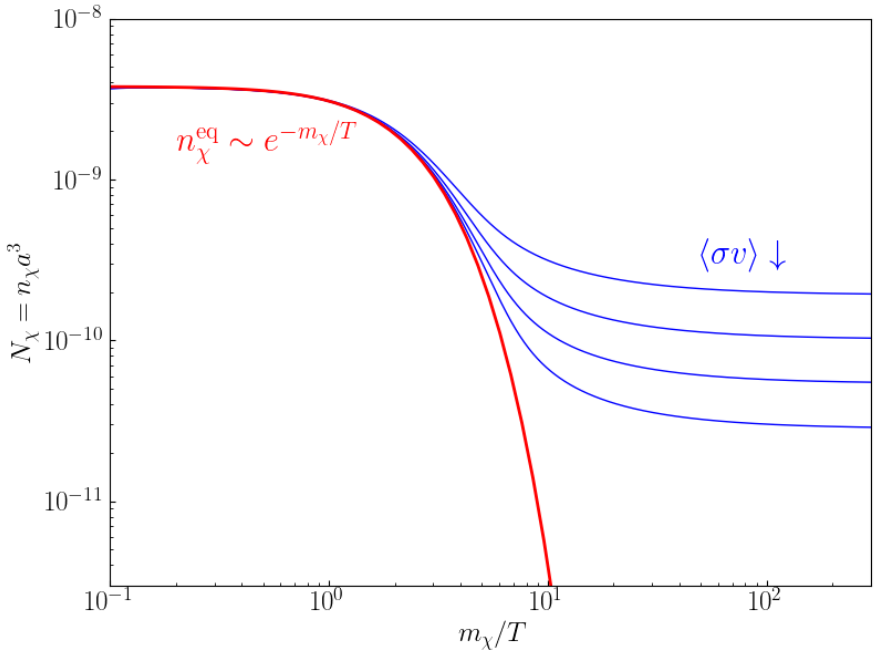
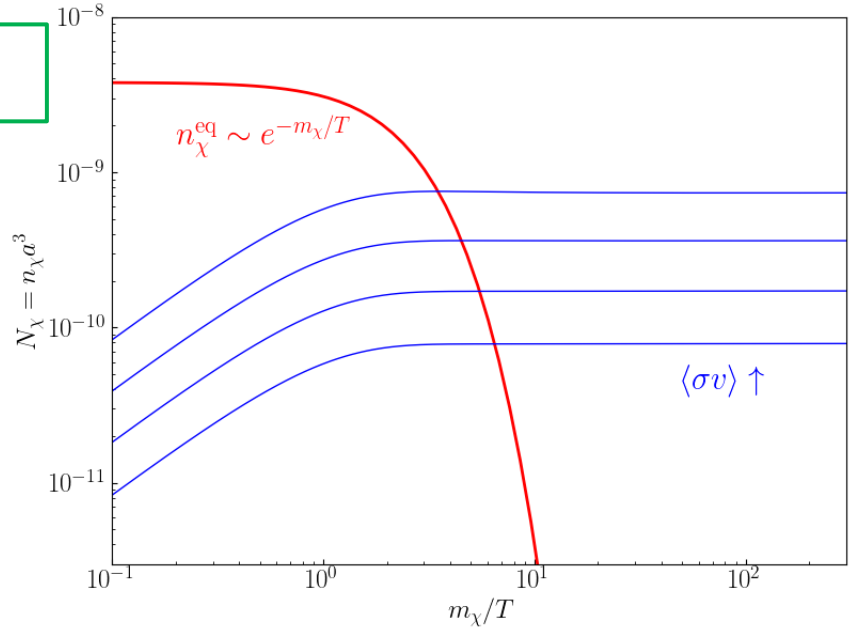


Dark matter velocities, very important for structure formation.



Dark Matter Production: Vanilla freeze-out and freeze-in

Number density level:

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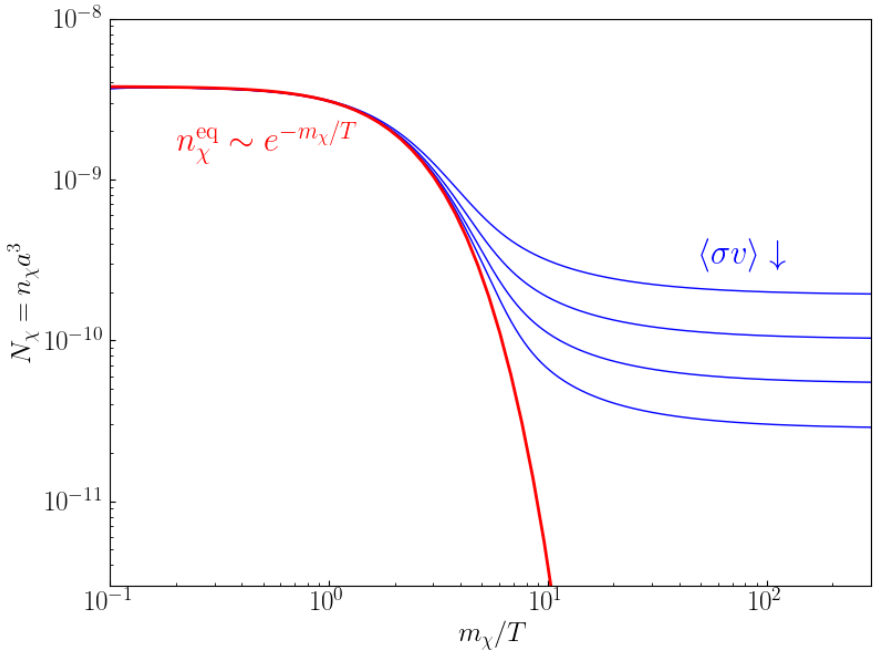
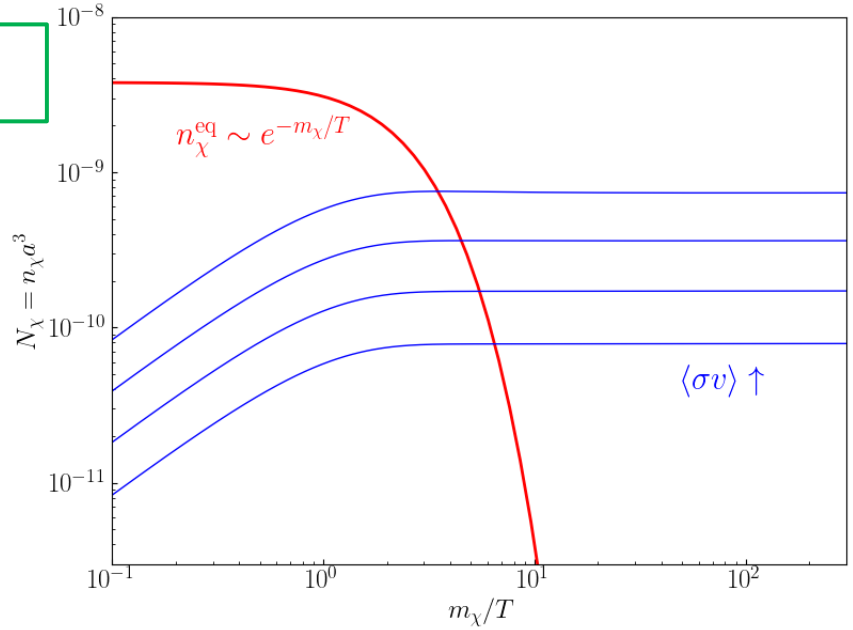


Dark matter velocities, very important for structure formation.

Phase space distribution level:

$$\frac{\partial f_\chi}{\partial t} - Hp\frac{\partial f_\chi}{\partial p} = C[f_\chi]$$



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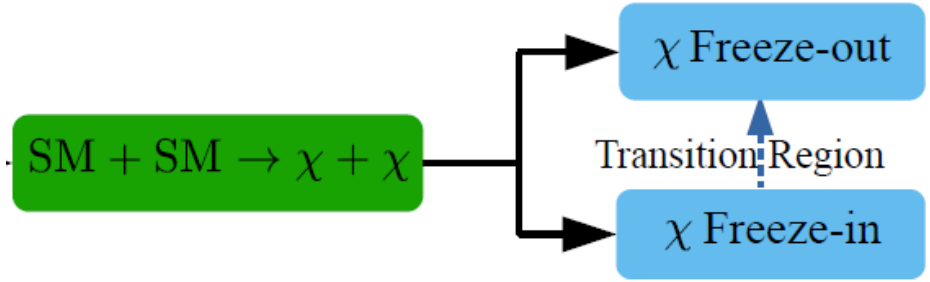
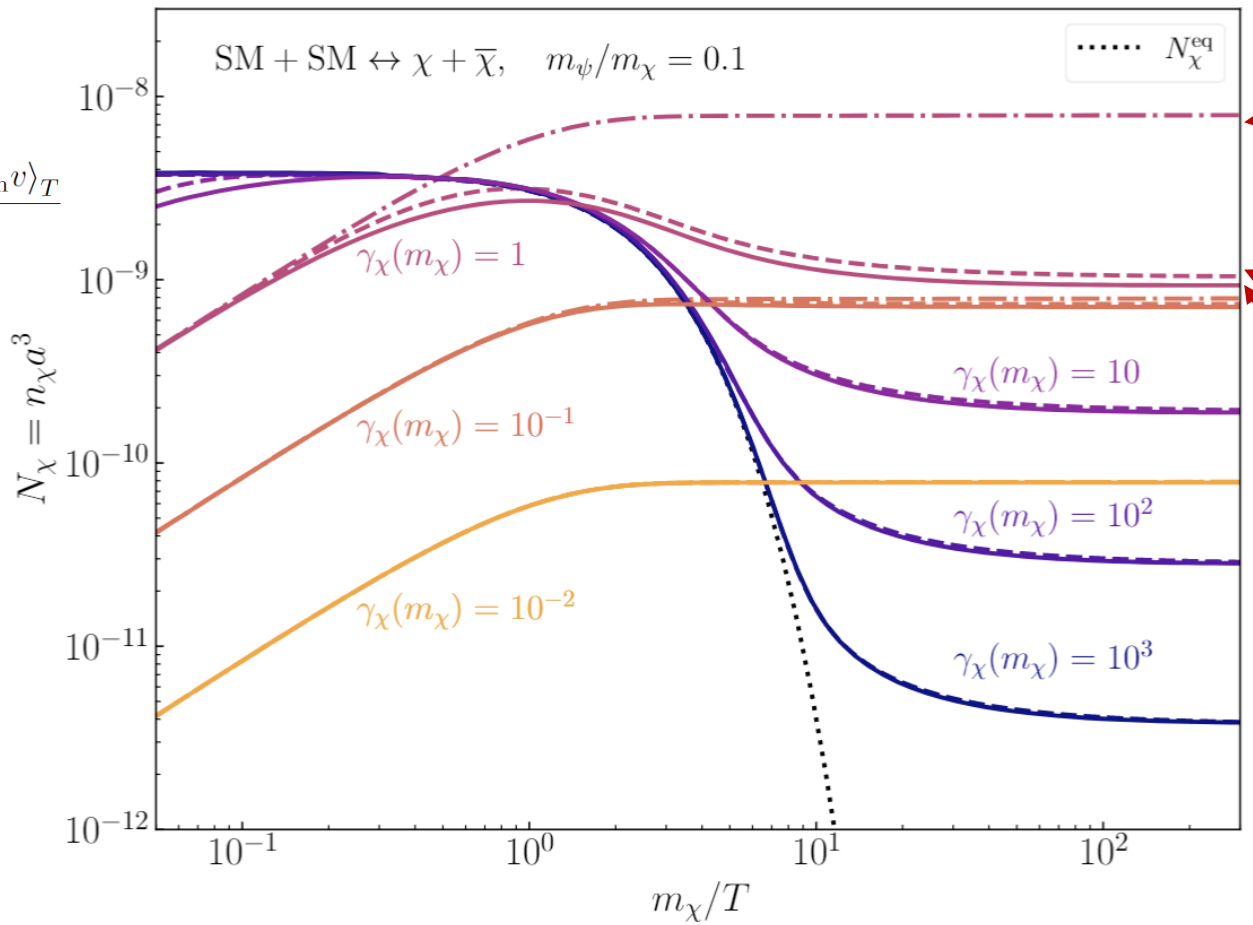
Production channel via 2→2 annhilation: SM+SM → χ + χ



$$\gamma(T) \equiv \frac{n_\chi^{\mathrm{eq}}(T)\,\langle\sigma_{\mathrm{ann}} v\rangle_T}{H(T)}$$



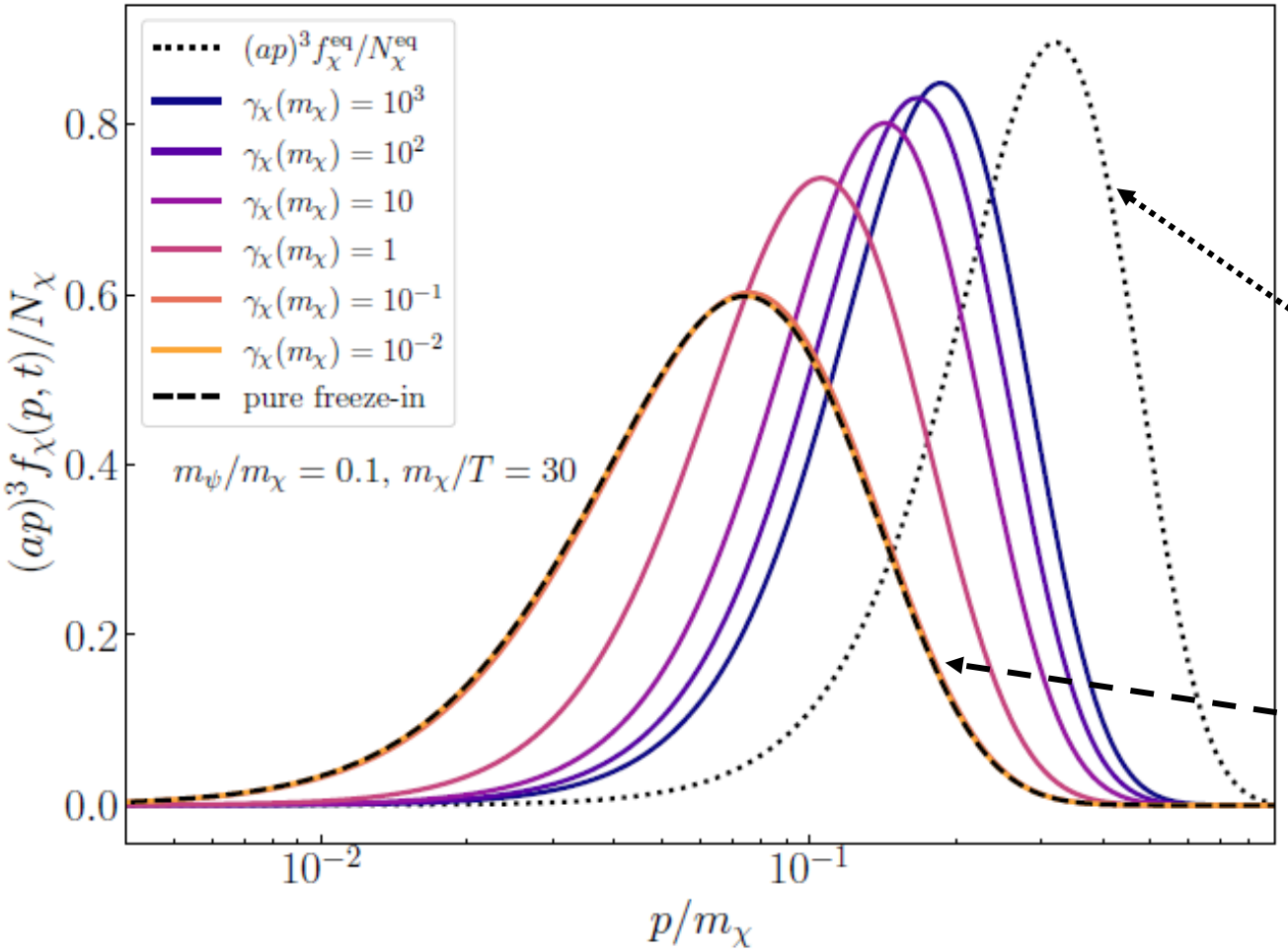
$$\frac{dn_\chi}{dt} + 3Hn_\chi \simeq (n_\chi^{\mathrm{eq}2})\,\langle\sigma_{\mathrm{ann}} v\rangle_T \,.$$

$$\frac{dn_\chi}{dt} + 3Hn_\chi \simeq (n_\chi^{\mathrm{eq}2} - n_\chi^2)\,\langle\sigma_{\mathrm{ann}} v\rangle_T \,,$$

$$\frac{\partial f_\chi}{\partial t} - Hp\frac{\partial f_\chi}{\partial p} = C_{\mathrm{ann}}(t, p_\chi)\,,$$

Production channel: 2→2 annhilation

As one increases the interaction strength continuously , the shape of the distribution function after production also deforms continuously between two limits --- it shifts towards the higher momentum.



Distribution in thermal equilibrium.

Limited distribution in pure freeze-in.

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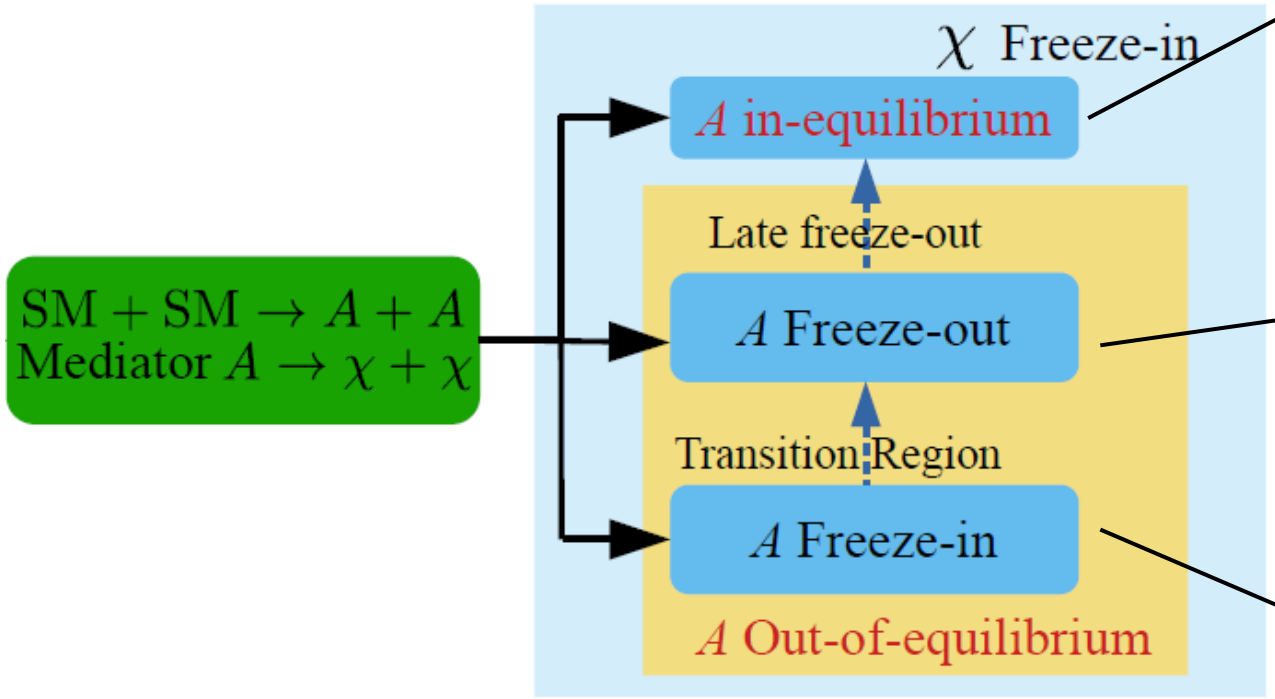
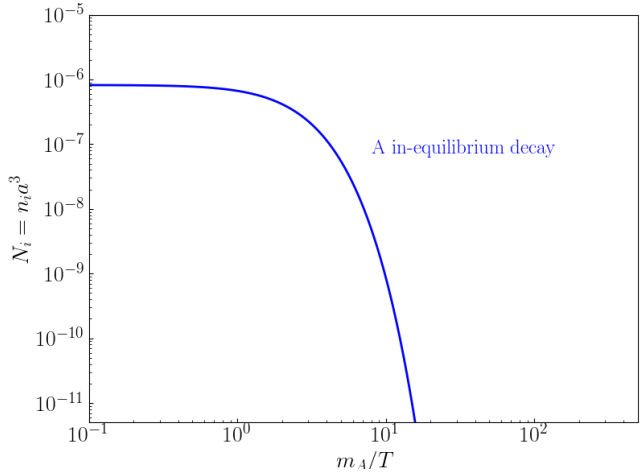
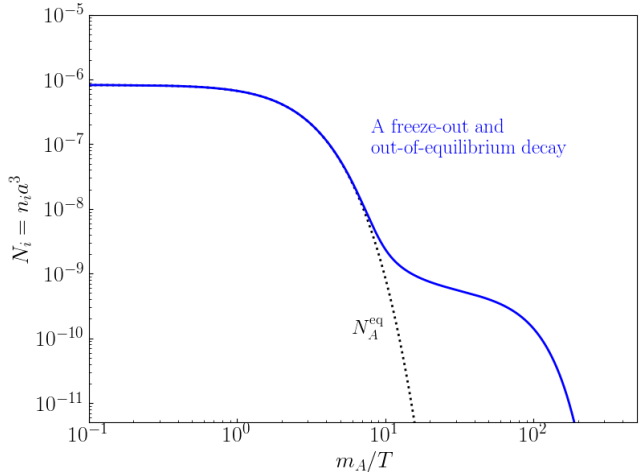
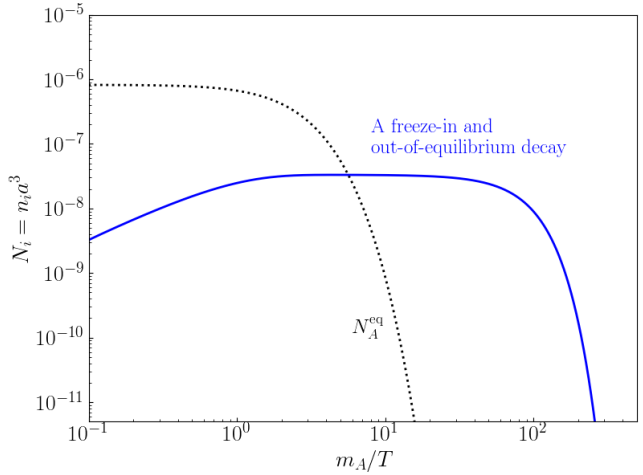
Production channel: SM+SM→ A+A, A→ χ + χ



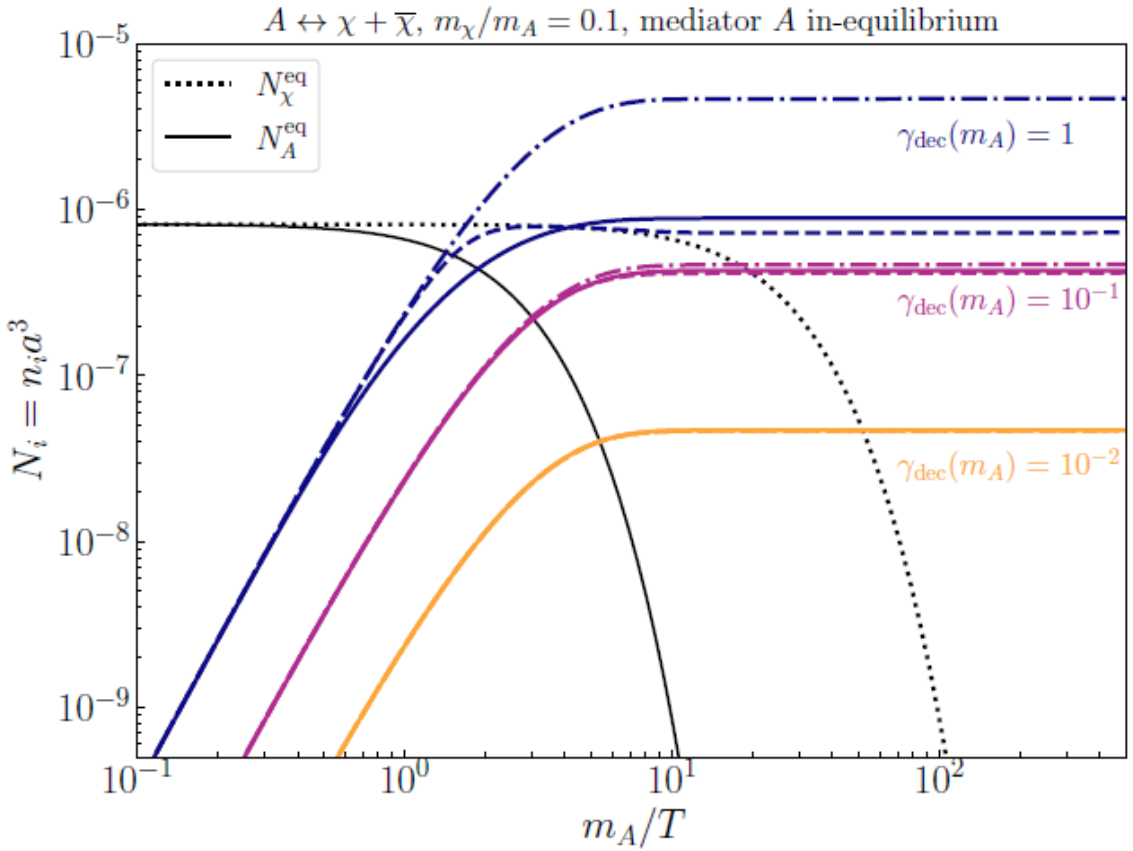




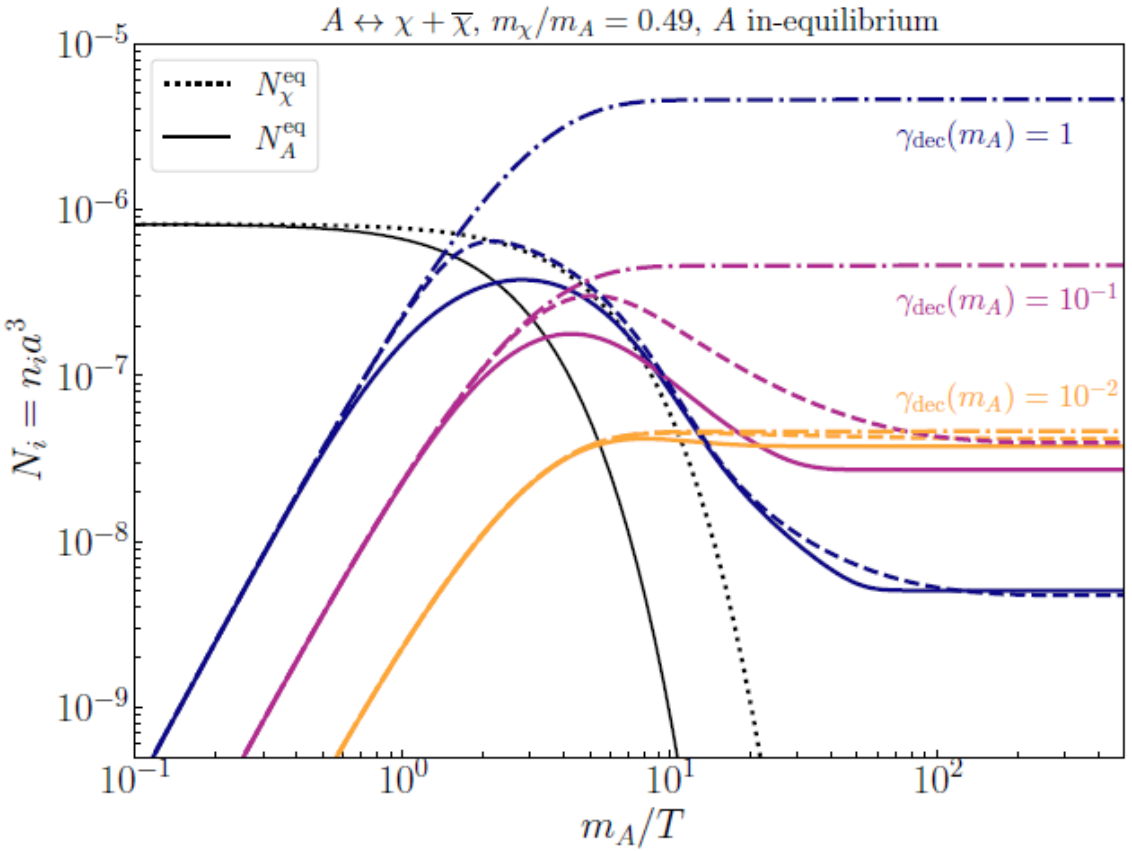


Production channel: A→ χ + χ for A in-equilibrium

$$m_\chi << m_A$$



$$m_\chi \sim m_A/2$$

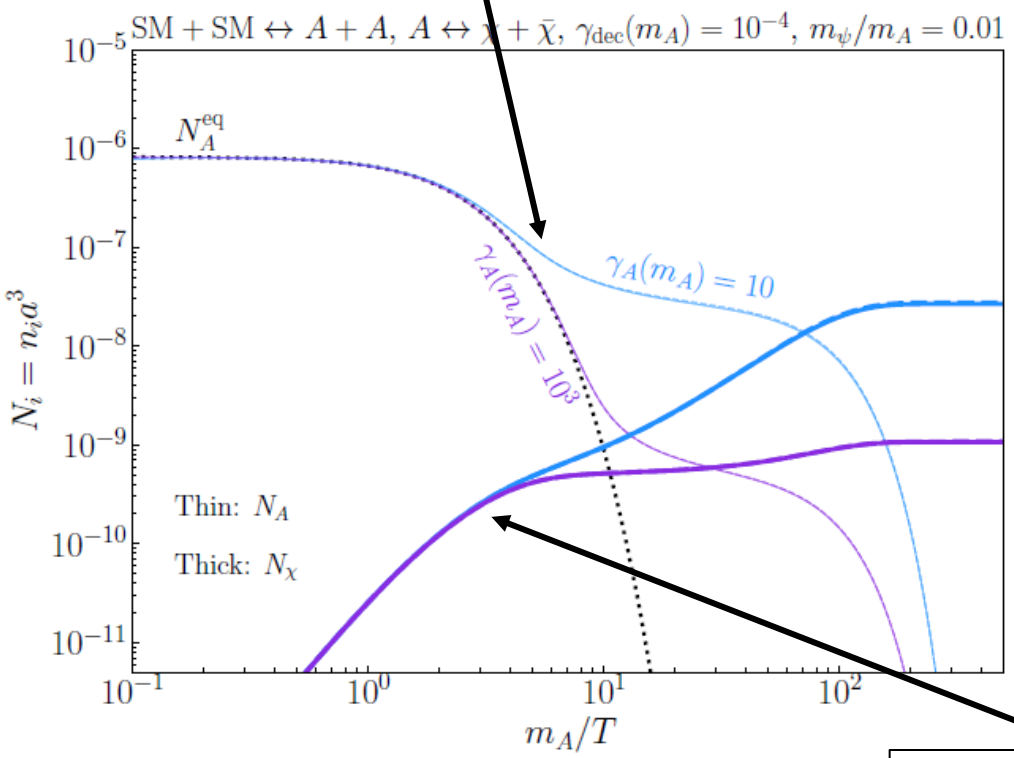


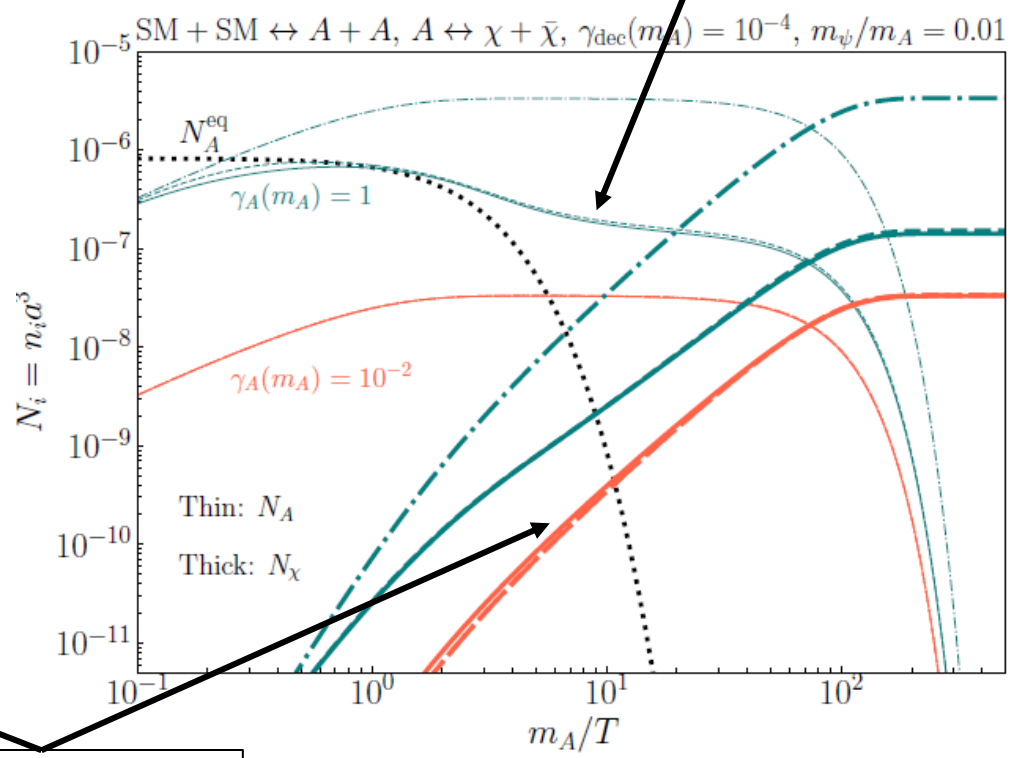
Production channel: A→ χ + χ for A out-of-equilibrium

$$\frac{\partial f_A}{\partial t} - Hp\frac{\partial f_A}{\partial p} = C^A_{\rm ann}[f_A] + C^A_{\rm dec}[f_A, f_\chi]\,,$$
$$\frac{\partial f_\chi}{\partial t} - Hp\frac{\partial f_\chi}{\partial p} = C^\chi_{\rm dec}[f_A, f_\chi]\,.$$

A freeze-out and out-of-equilibrium decay

A freeze-in and out-of-equilibrium decay





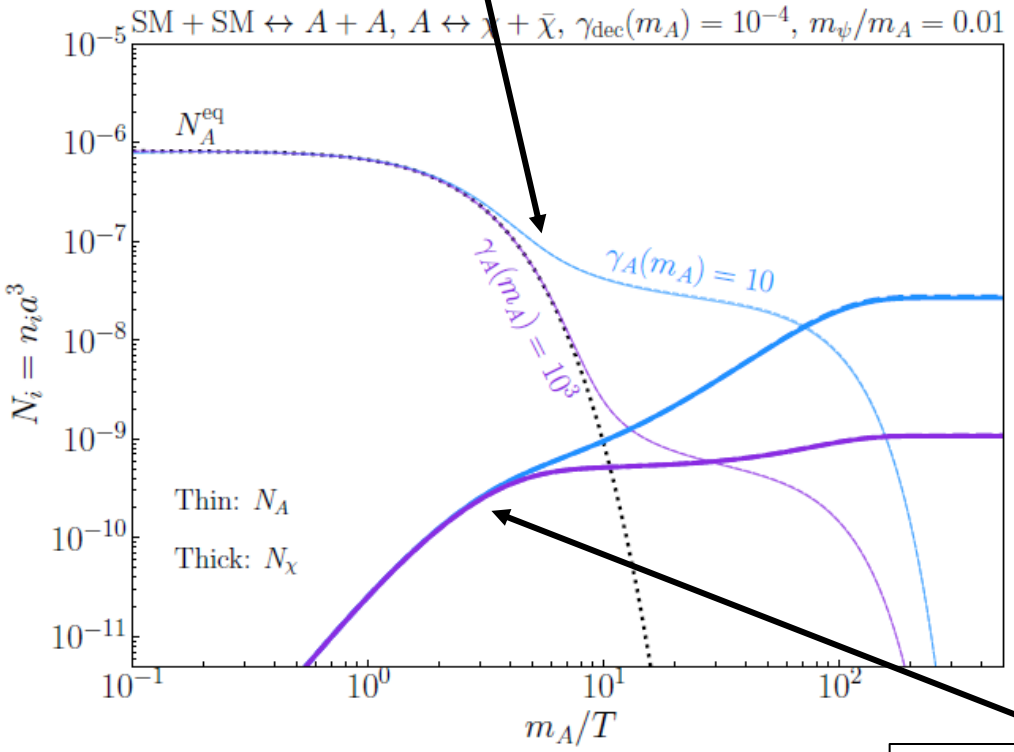
DM freeze-in

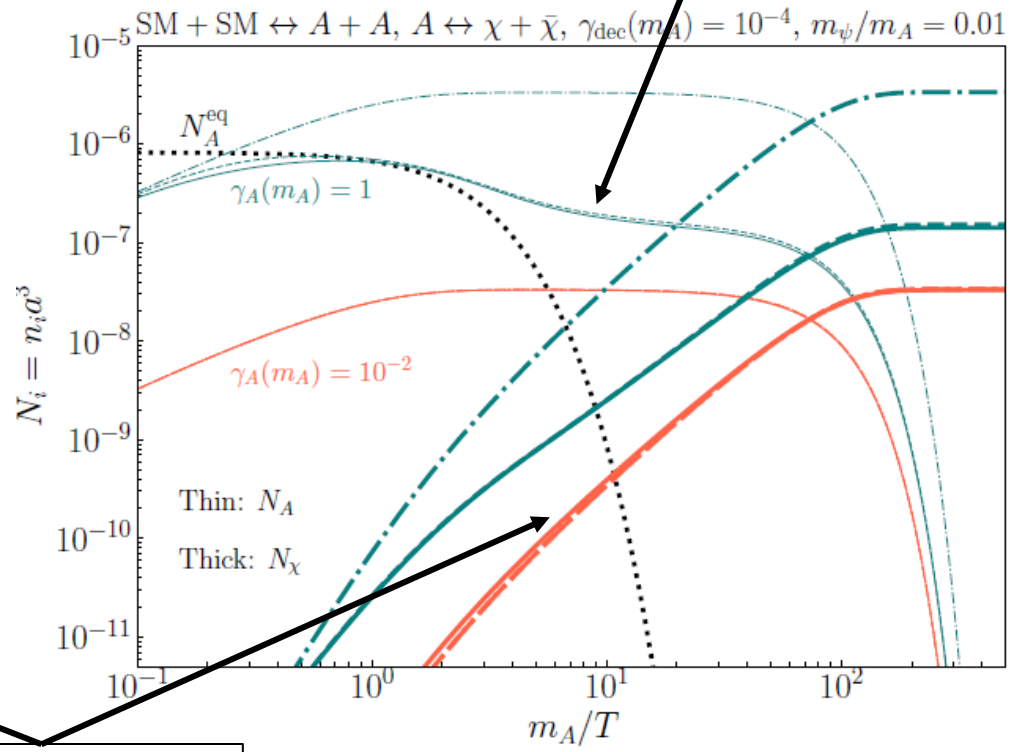
Production channel: A→ χ + χ for A out-of-equilibrium

$$\frac{\partial f_A}{\partial t} - Hp\frac{\partial f_A}{\partial p} = C^A_{\rm ann}[f_A] + C^A_{\rm dec}[f_A, f_\chi]\,,$$
$$\frac{\partial f_\chi}{\partial t} - Hp\frac{\partial f_\chi}{\partial p} = C^\chi_{\rm dec}[f_A, f_\chi]\,.$$

A freeze-out and out-of-equilibrium decay

A freeze-in and out-of-equilibrium decay

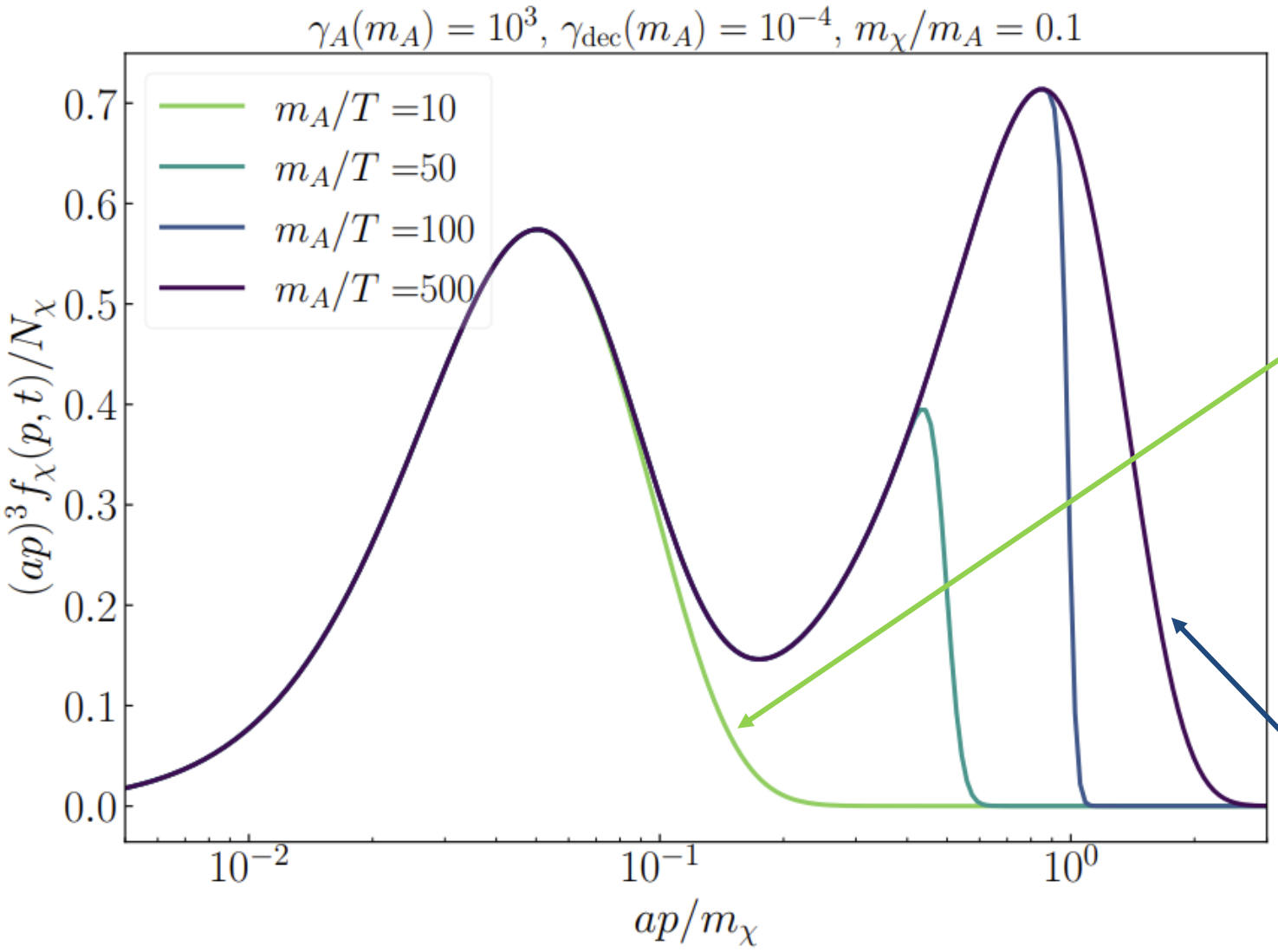




DM freeze-in

Production channel: A→ χ + χ for A frzeezes out and decays

$m_\chi << m_A$

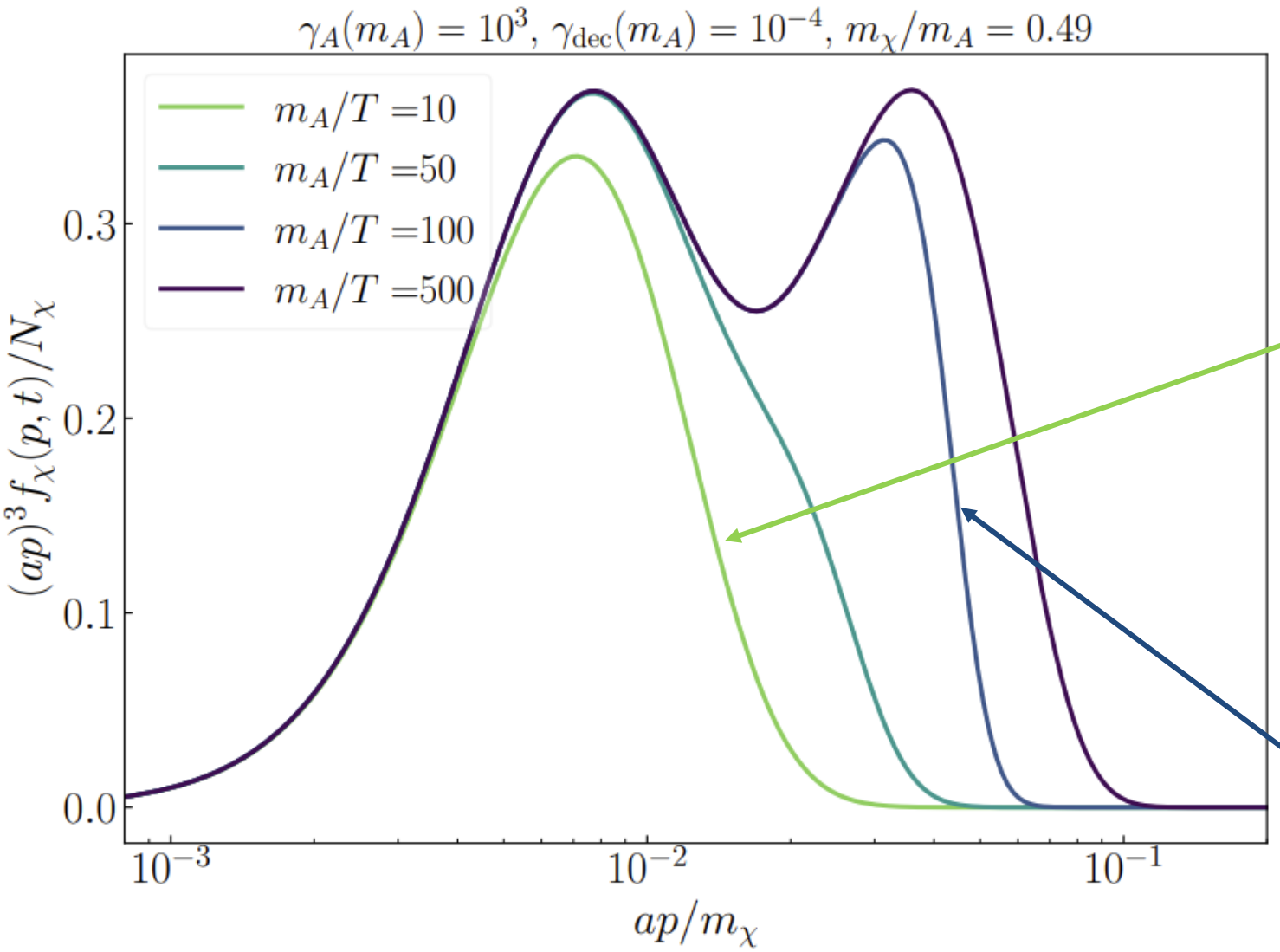


Formation of the first peak at early: In-equilibrium decay

Formation of the second peak at later: Out-of-equilibrium decay

Production channel: A→ χ + χ for A frzeezes out and decays

$$m_\chi \sim m_A/2$$



Formation of the first peak at early: In-equilibrium decay

Formation of the second peak at later: Out-of-equilibrium decay

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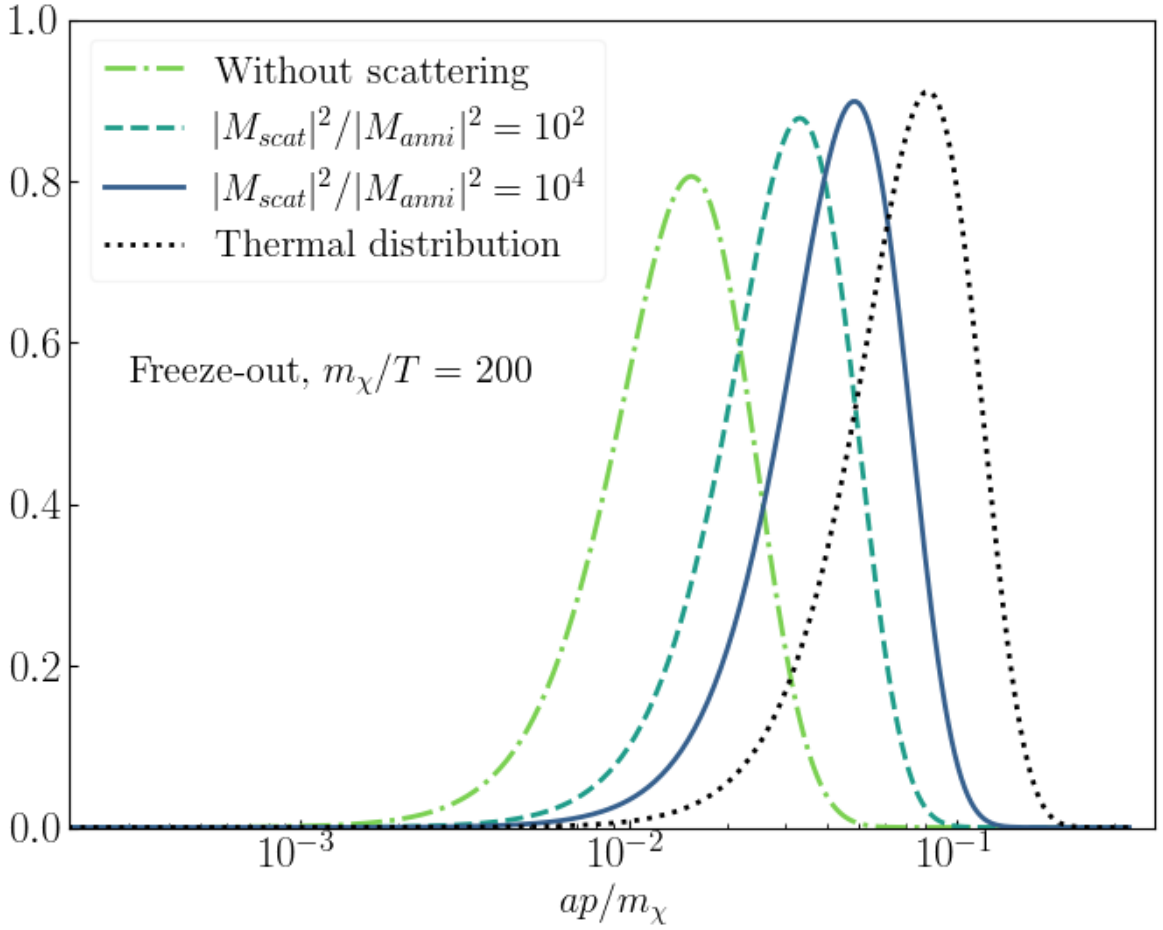
Effects of elastic scattering: for 2→2 annhilation

The one with a larger elastic-scattering rate has a larger average mentum and tends to be closer to the thermal distribution.



Freeze-out

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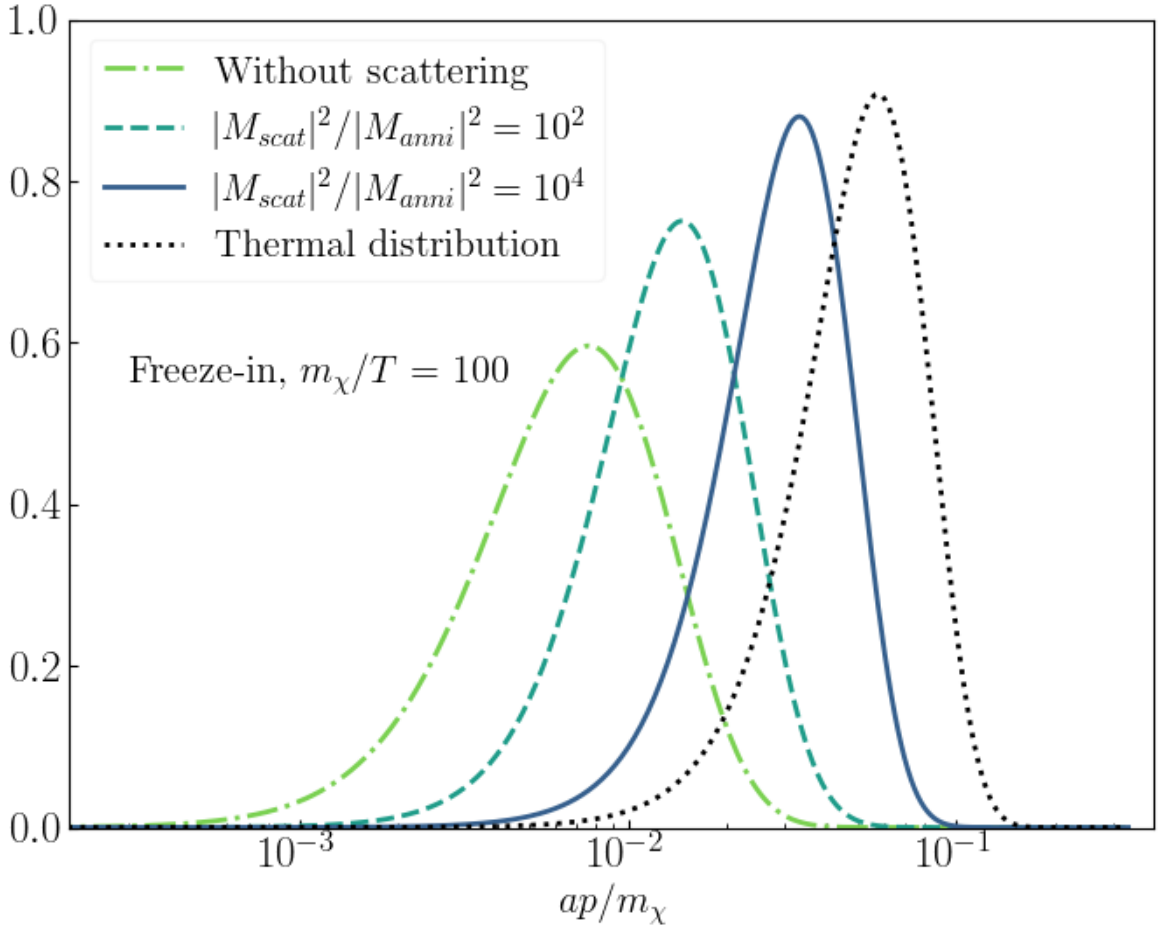
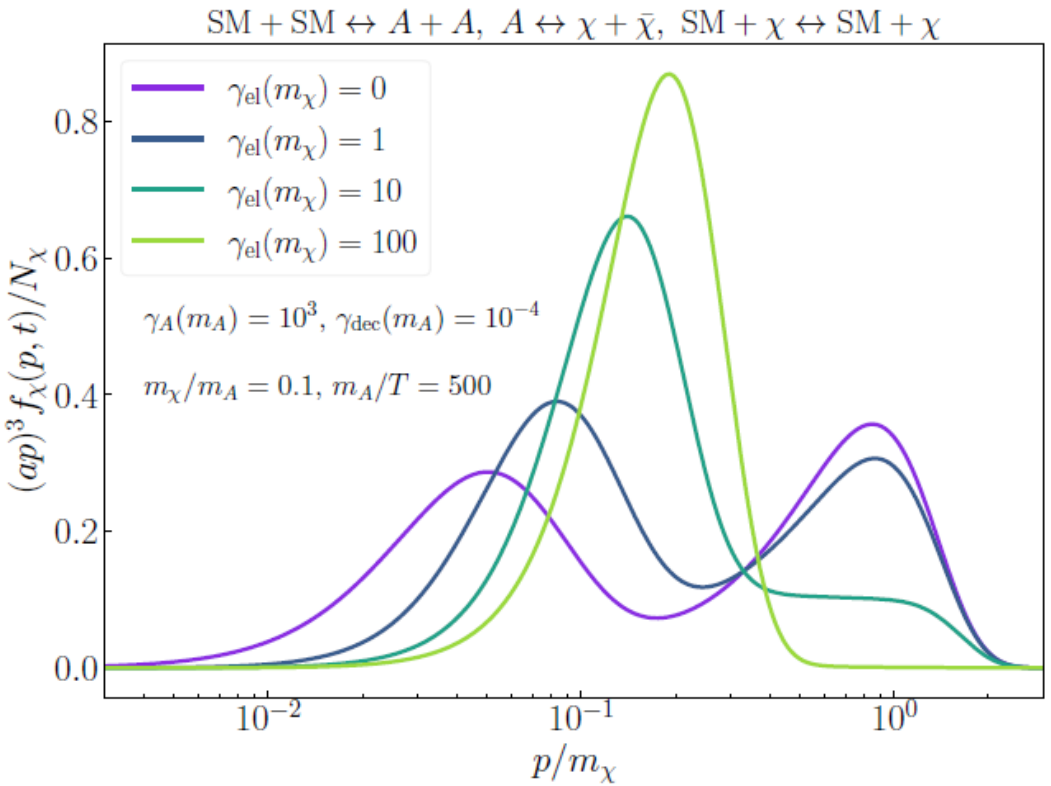


Freeze-in

Effects of elastic scattering: for 1→2 out-of-equilibrium decay

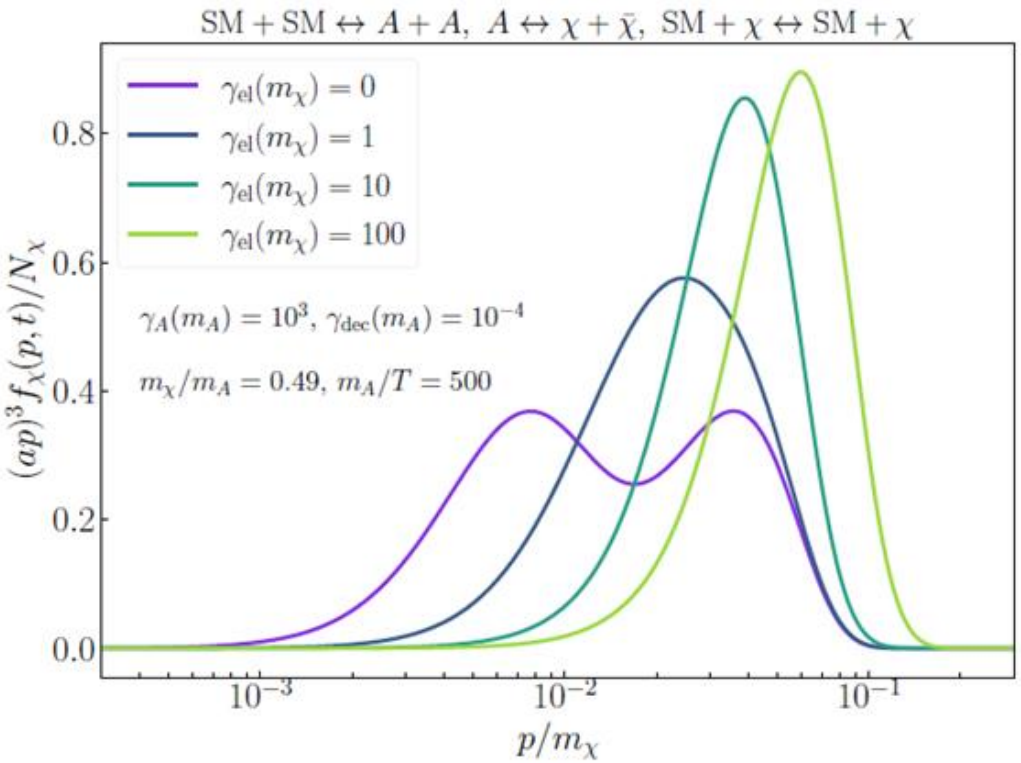
In general, elastic scatterings tend to deform the distribution from bimodal to unimodal, which may cause significant difference for the structure formation.

$m_\chi << m_A$



Elastic scatterings dissipate the kinetic energy of dark matter.

$m_\chi \sim m_A/2$



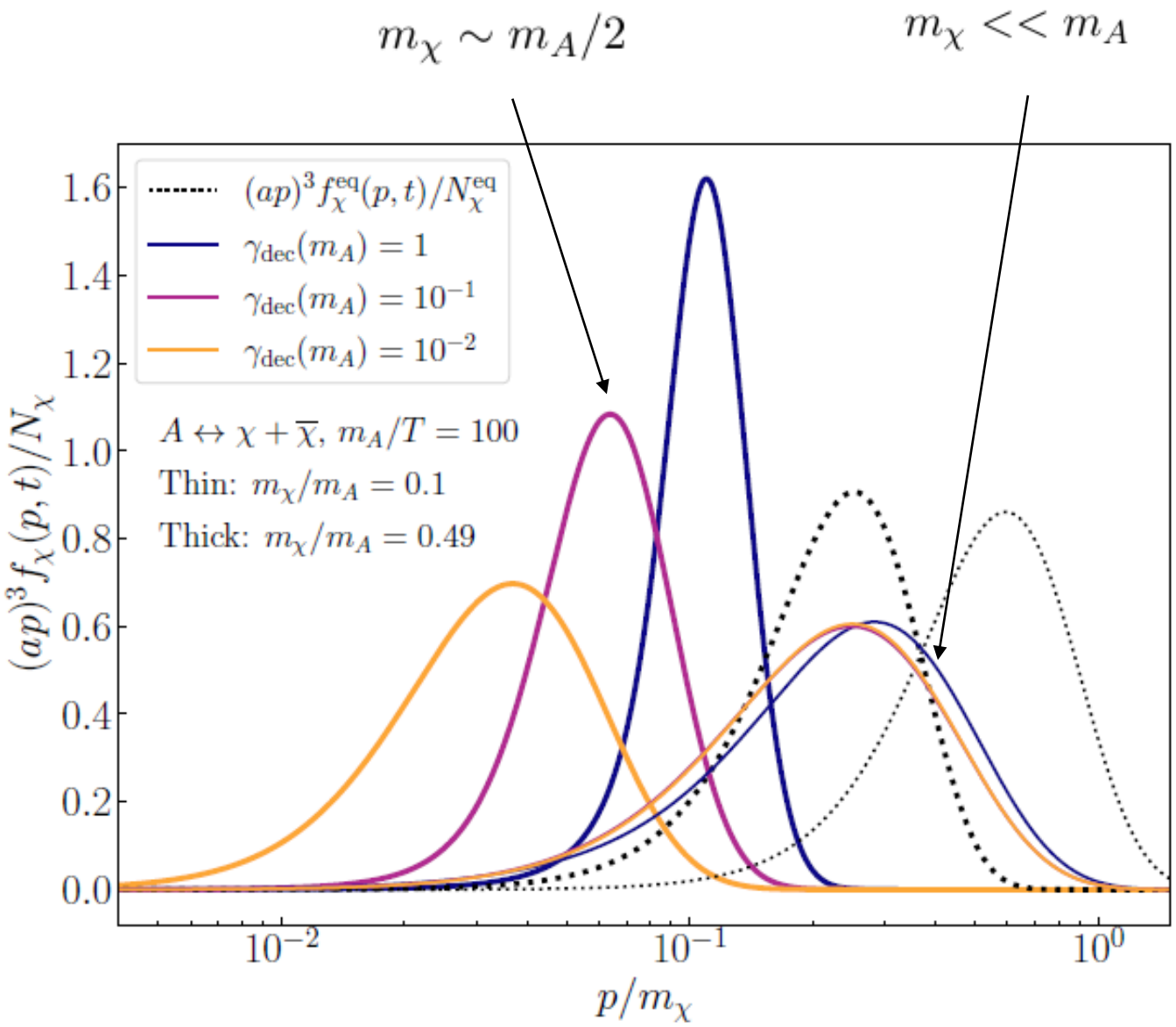
Elastic scatterings extract kinetic energy from thermal bath.

Conclusion

1. Using the 2→2 annihilation and the 1→2 decay processes for illustration, we compare the resulting dark-matter relic abundance from the distribution approach with that from the number-density approach. In the transition regime between freeze-in and freeze-out, we find the difference can be quite significant.
2. We also find that the freeze-in production in the 2→2 and the 1→2 processes can also result in non-thermal phase-space distributions, or even multi-modal ones with out-of-equilibrium decay, which can potentially affect structure formation at late times.
3. We find that the inclusion of the elastic scattering tends to alter the phase-space distribution towards the thermal one, and even can erase the multi-modal pattern of the multi-modal phase-space distributions.

Thank you!

Production channel: A→ χ + χ for A in-equilibrium

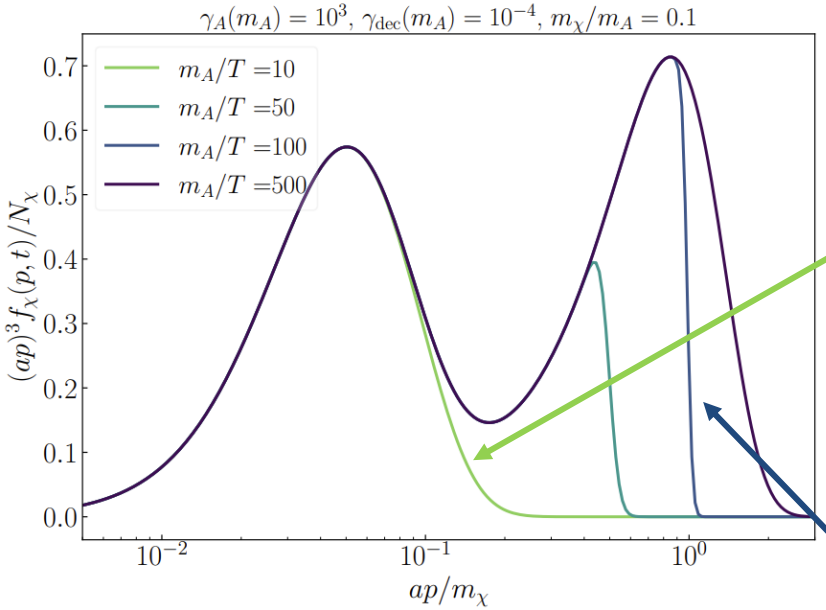


- Non-thermal distributions
- Overall coder than thermal distribution
- Highly non-thermal when $m_\chi \sim m_A/2$.

Production channel: A→ χ + χ for A out-of-equilibrium

$m_\chi << m_A$

A freeze out and out-of-equilibrium decay



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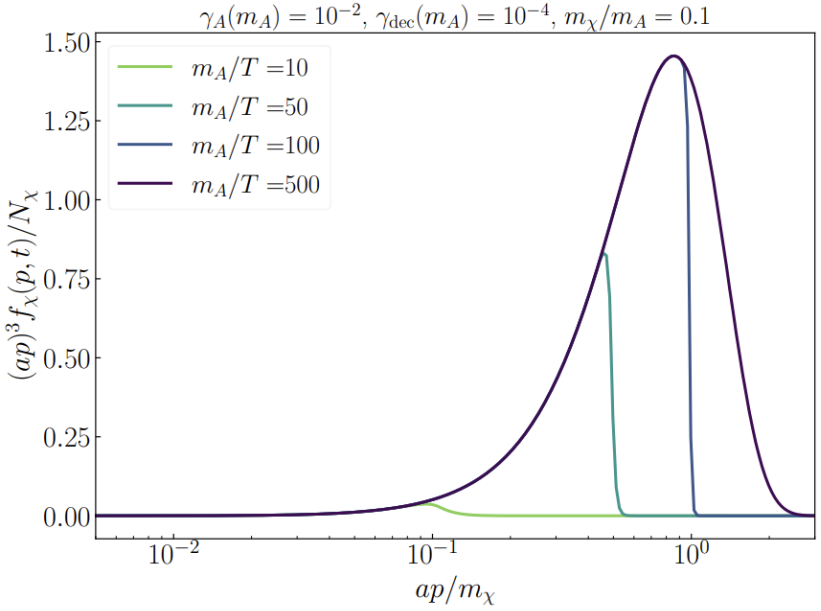
A freeze in and out-of-equilibrium decay

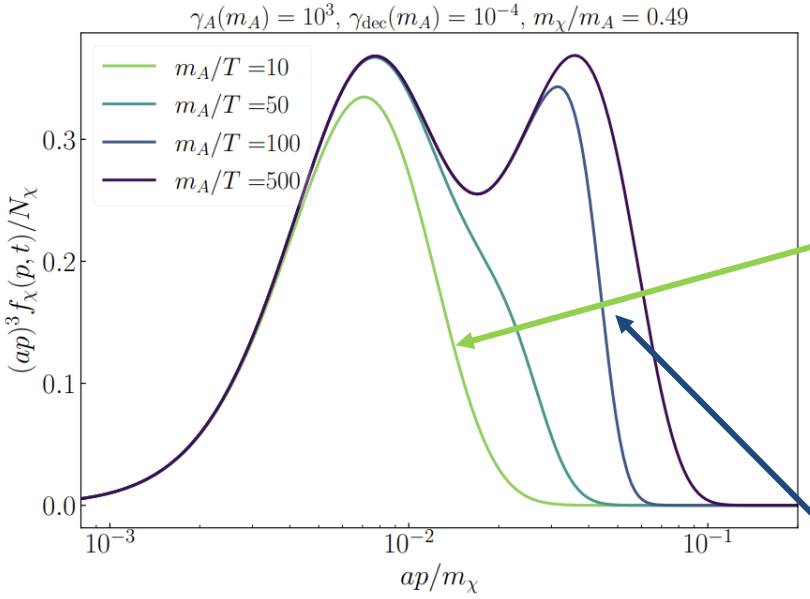


Out-of-equilibrium decay is dominated.

Production channel: A→ χ + χ for A out-of-equilibrium

$$m_\chi \sim m_A/2$$

A freeze out and out-of-equilibrium decay



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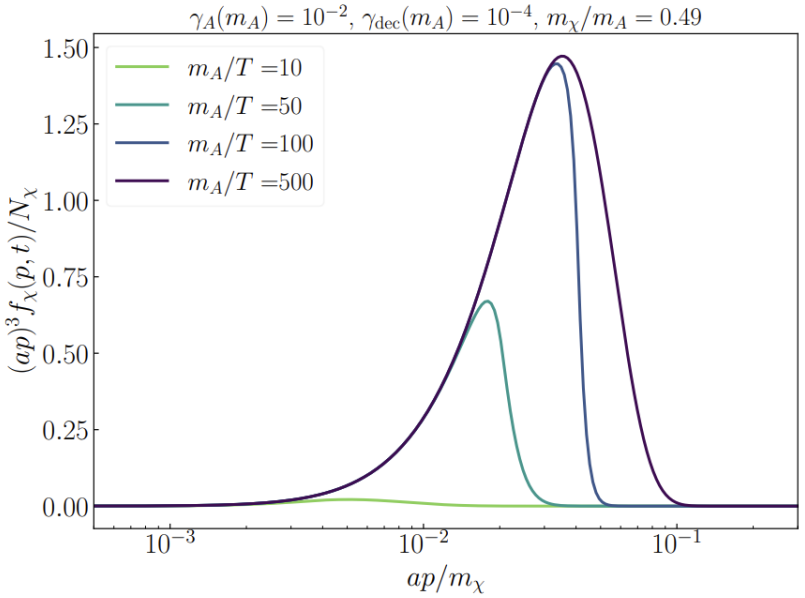
A freeze in and out-of-equilibrium decay



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