Distinguishing Dark Matter Properties through Large Scale Structure

JCAP 01 (2024) 023

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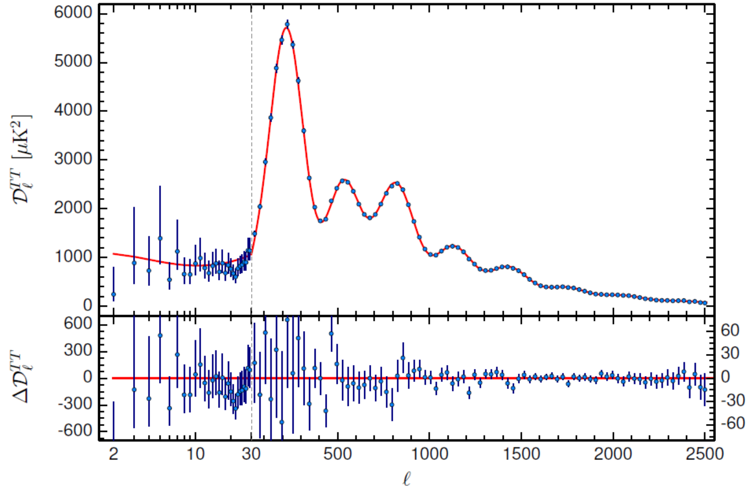
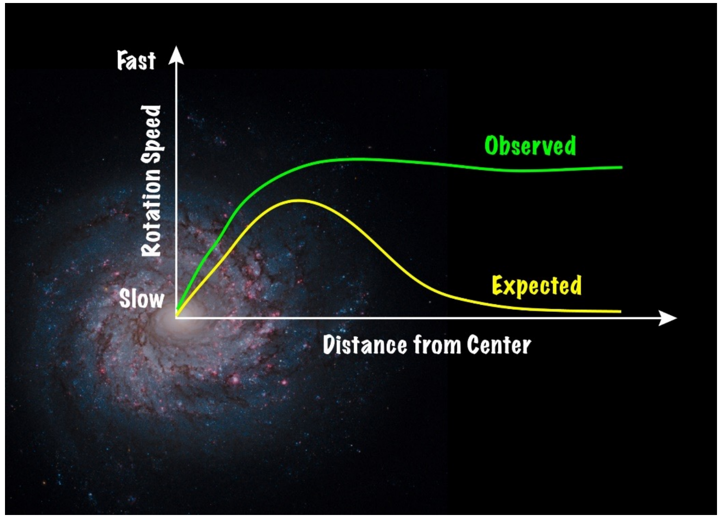
14th CosPa Meeting

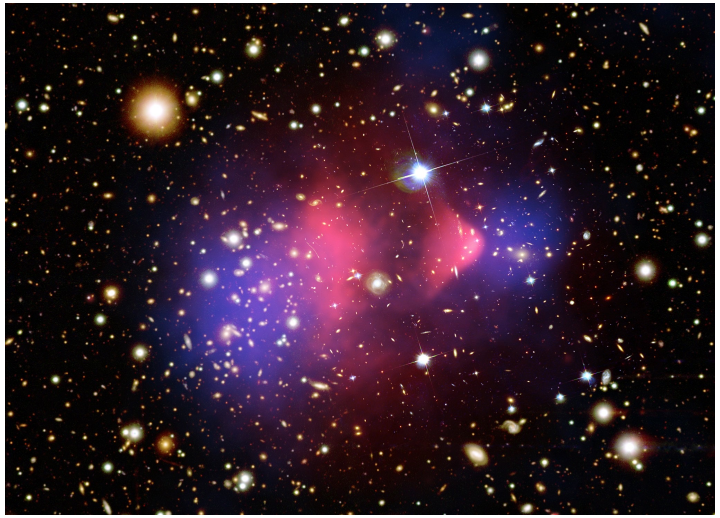
UCLouvain

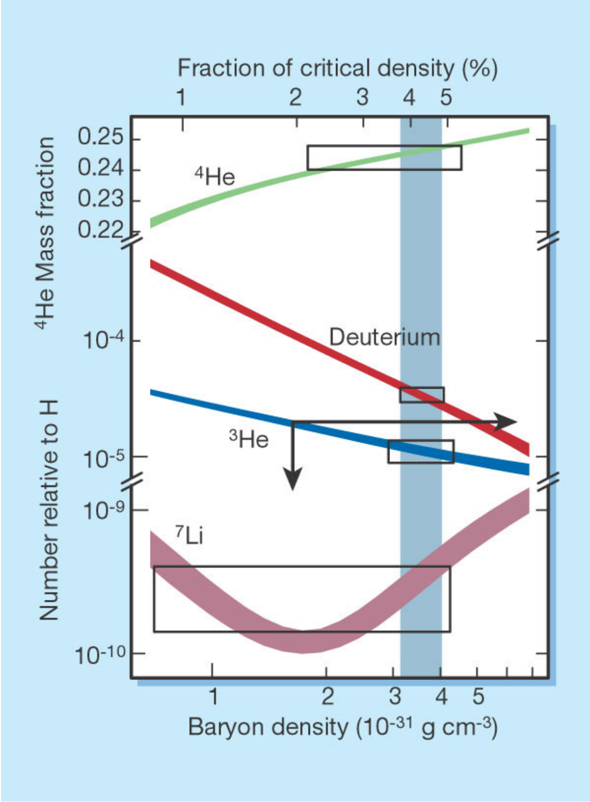
In collaboration with **Fei Huang (Weizmann Institute, Israel)** and **Jiang-Hao Yu (ITP, CAS, China)**

The existence of dark matter is supported by observations across many different scales

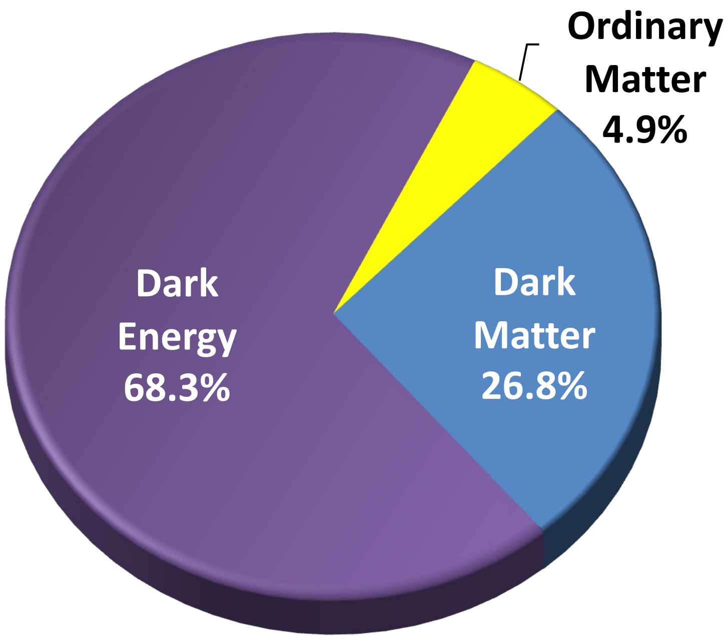








What have we learnt?

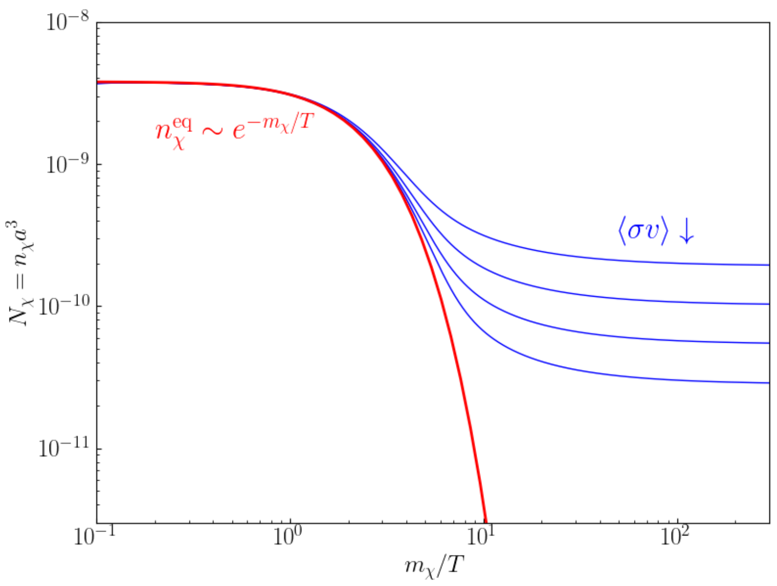


- **Abundance:** ~26% of the universe
- **Cold**: Non-relativistic, massive
- **Dark**: Negligible nongravitational interaction with Standard Model fields
- **Nonbaryonic**: Baryonic matter is simply not enough
- **BSM**: Not Standard Model particle

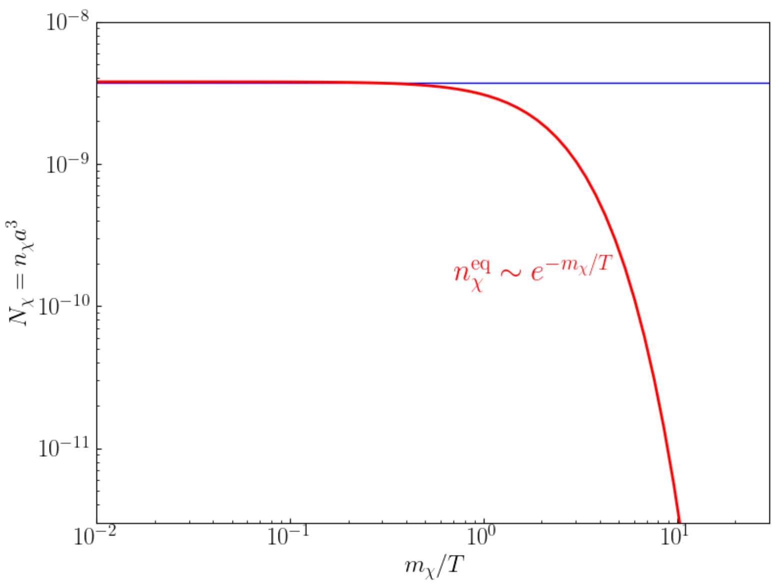
We still don't know:

- **Particle properties**: mass, spin, fundamental or composite, single-component or multi-component, etc.
- **Production mechanism**: freeze-out, freeze-in, decays, misalignment?

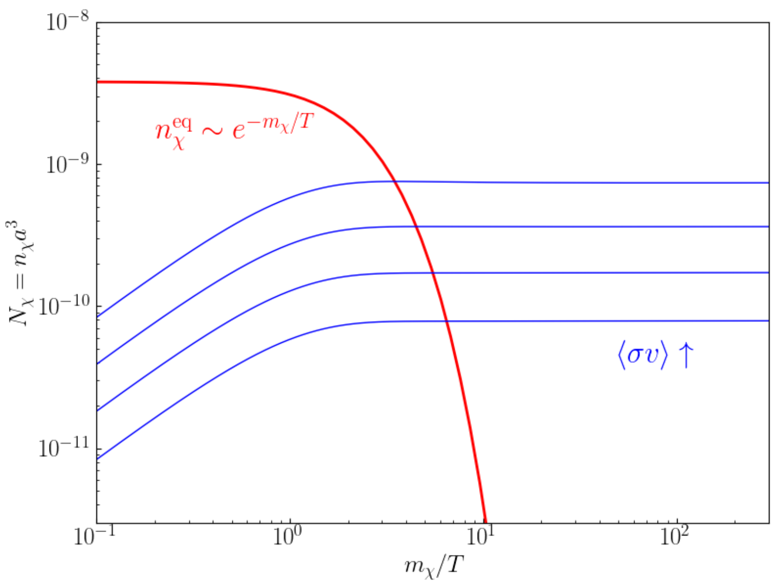
Possible Production mechanism of DM



Non-relativistic freeze-out
(WIMP)



Relativistic freeze-out
(Warm Dark Matter)



Freeze-in

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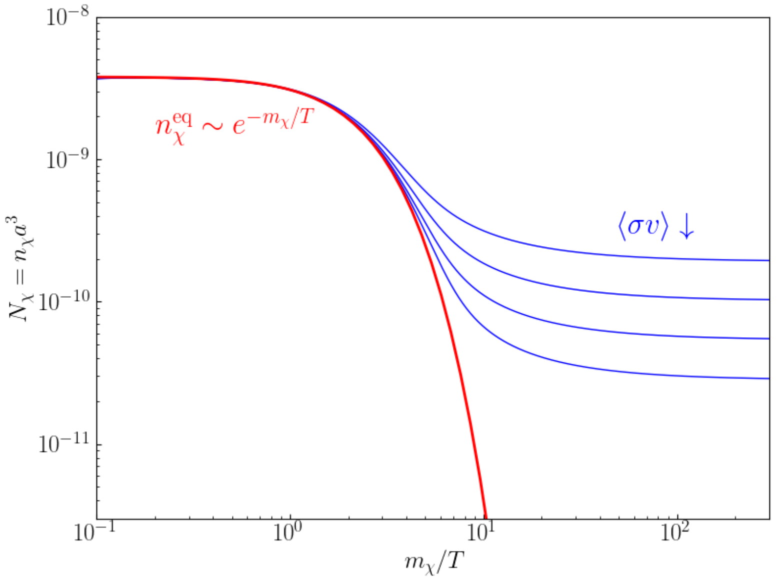

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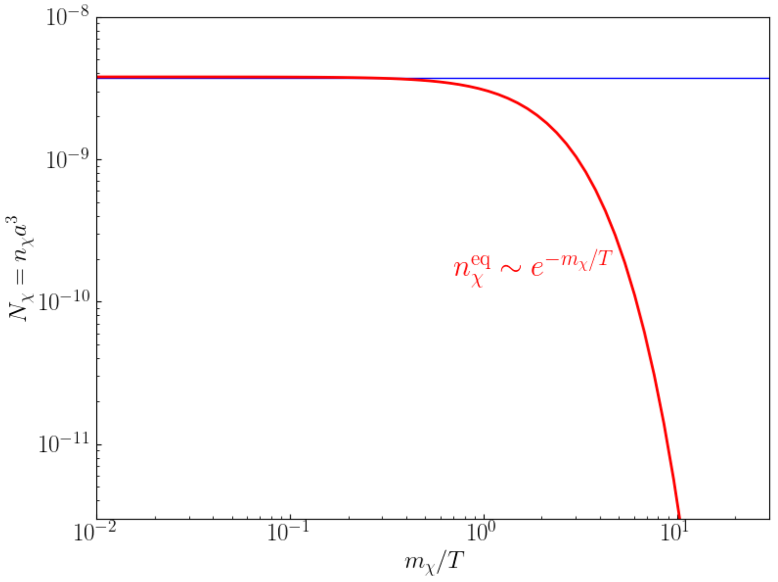

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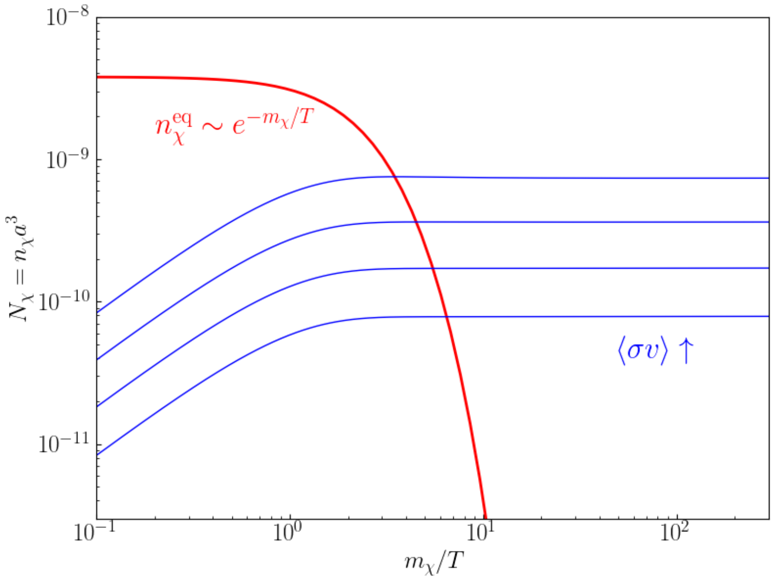

Freeze-in

Different thermal histories of DM result in different phase space distributions!

$$f_\chi(p) \approx \exp\left(-\frac{p^2}{2mT_\chi}\right)$$

$$f_\chi(p) \approx \exp\left(-\frac{p}{T_\chi}\right)$$

$$f_\chi(p) \approx C\,\frac{\exp(-p/T_\chi)}{\sqrt{p/T_\chi}}$$

f_χ will then be encoded in the cosmic structures.

F. D'Eramo & A. Lenoci
JCAP 10 (2021) 045

A little exercise with WDM

DM freezes-out relativistically: $f_\chi(p) \approx \exp(-p/T_\chi)$

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$$\rho_\chi \sim \int d^3p\, E\, f_\chi(p) \sim m_\chi T_\chi^3$$

Average velocity:

$$\langle v \rangle \sim \frac{1}{m_\chi} \int d^3p\, E\, f_\chi(p) \sim \frac{T_\chi}{m_\chi}$$

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well-measured

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Entropy conservation
+
cosmological redshift

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Entropy conservation + cosmological redshift

physical quantities at production time

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Entropy conservation + cosmological redshift

physical quantities at production time

DM velocity is constrained by structure formation!

$$m_\text{WDM} \geq 3.5\text{ keV}$$
$$\geq 5.3\text{ keV}$$

V. Iršič et al.
Phys. Rev. D 96 (2017) 023522

Constraints on decoupling temperatures

$$m_{\rm WDM} \geq 3.5\ \mathrm{keV}$$
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$$\langle v \rangle_0 \lesssim 2.1\times10^{-8}$$
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$$m_\chi \approx 1.9\times10^{-3}\ \mathrm{keV} \times \frac{\Omega_\chi}{0.25}\frac{g_{*,s}(T_{\mathrm{dec}})}{g_\chi}\eta_{\mathrm{dec}}^{-3}$$

- Mass contours are also velocity contours

Relativistic Freeze-Out

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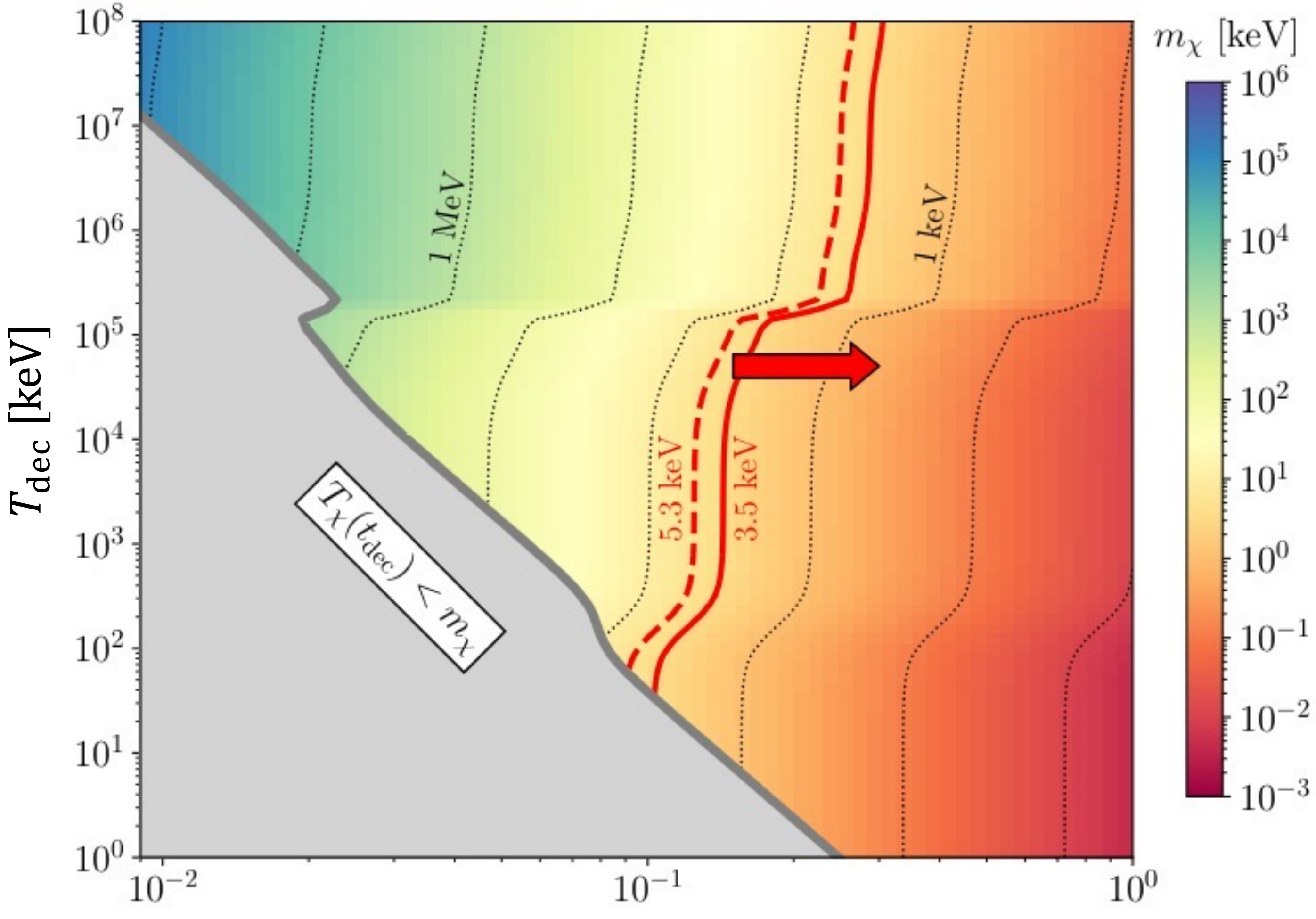

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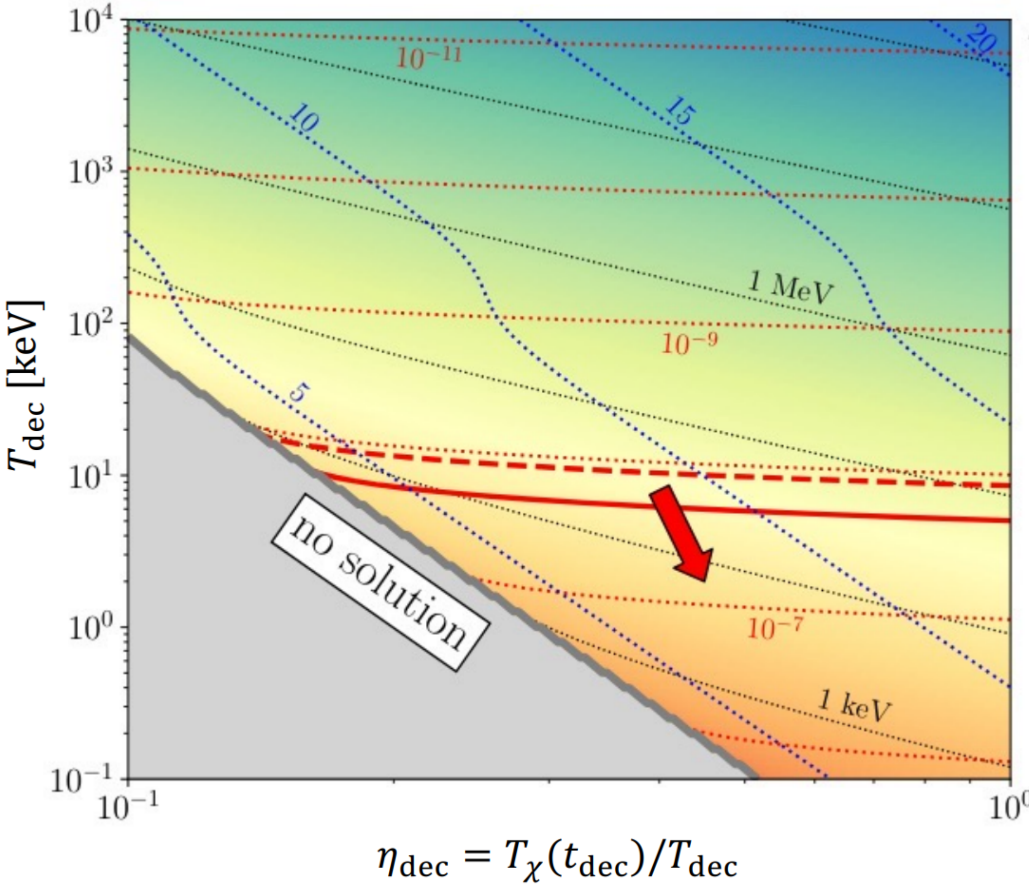

Freeze-In

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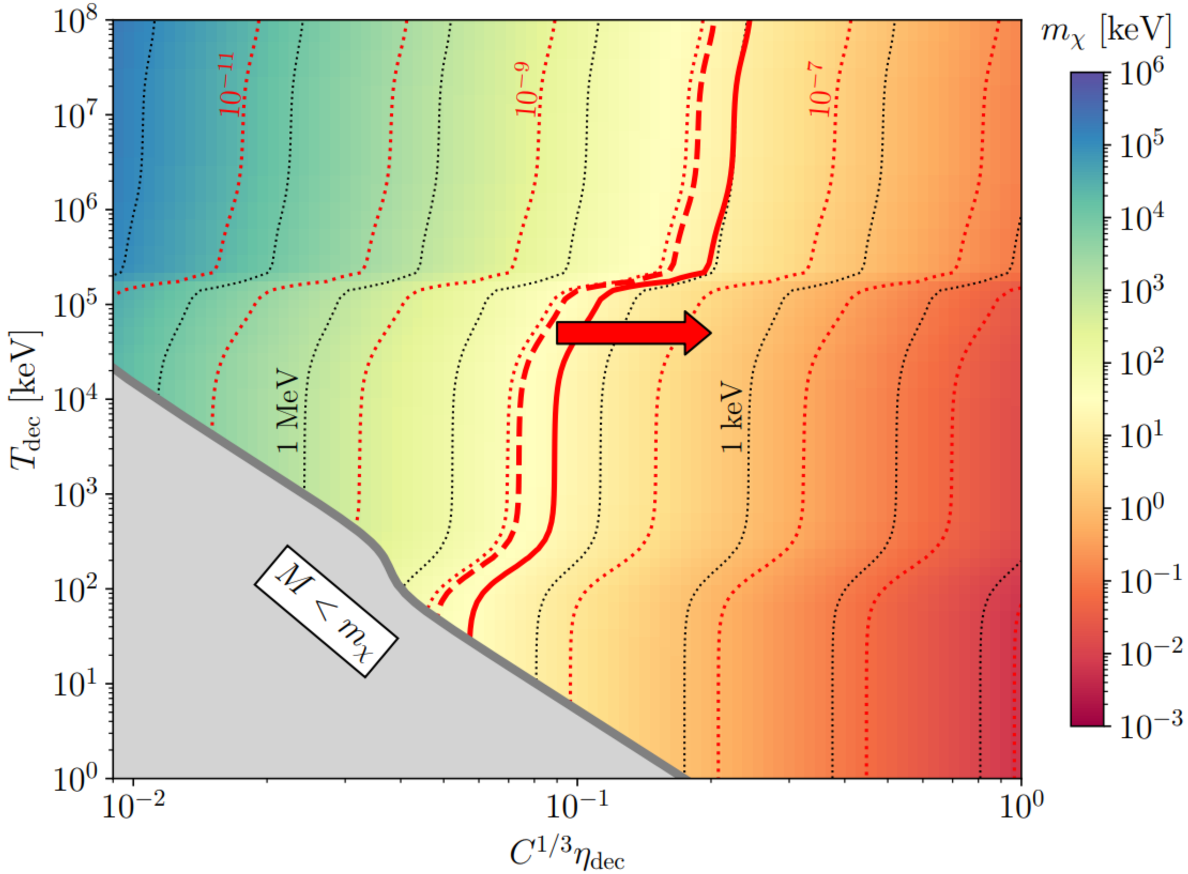

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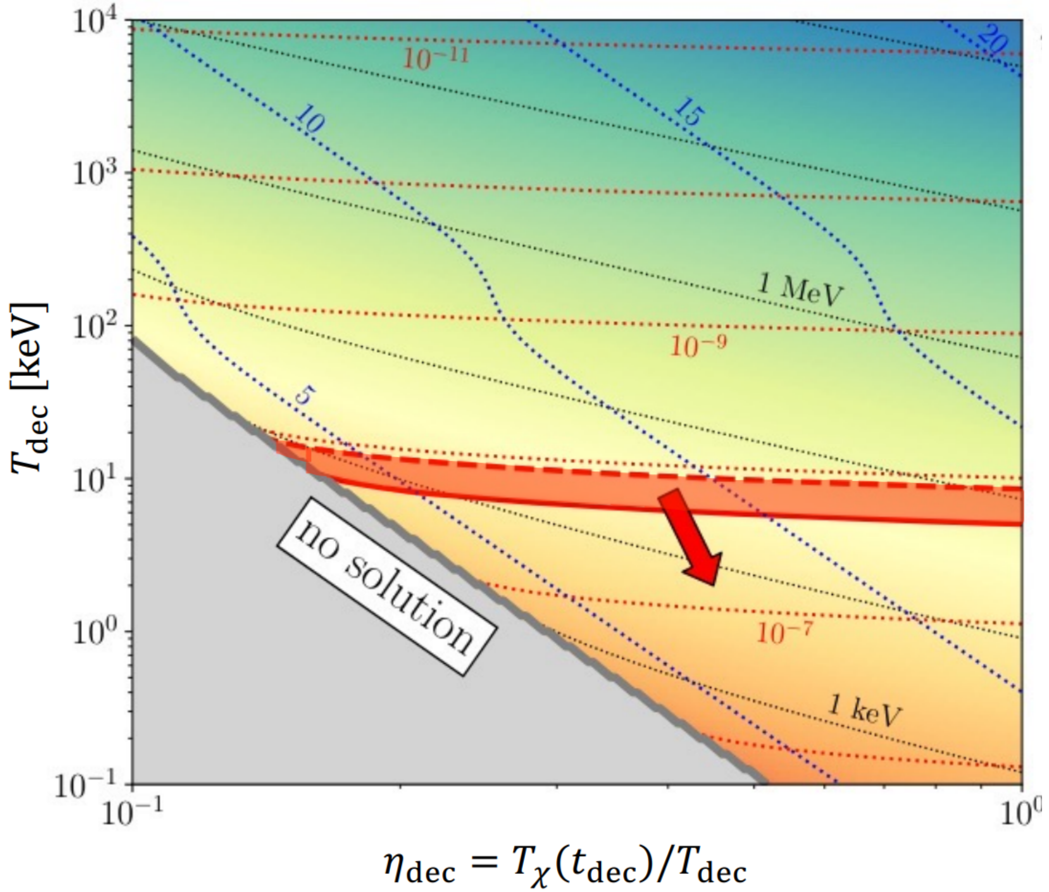

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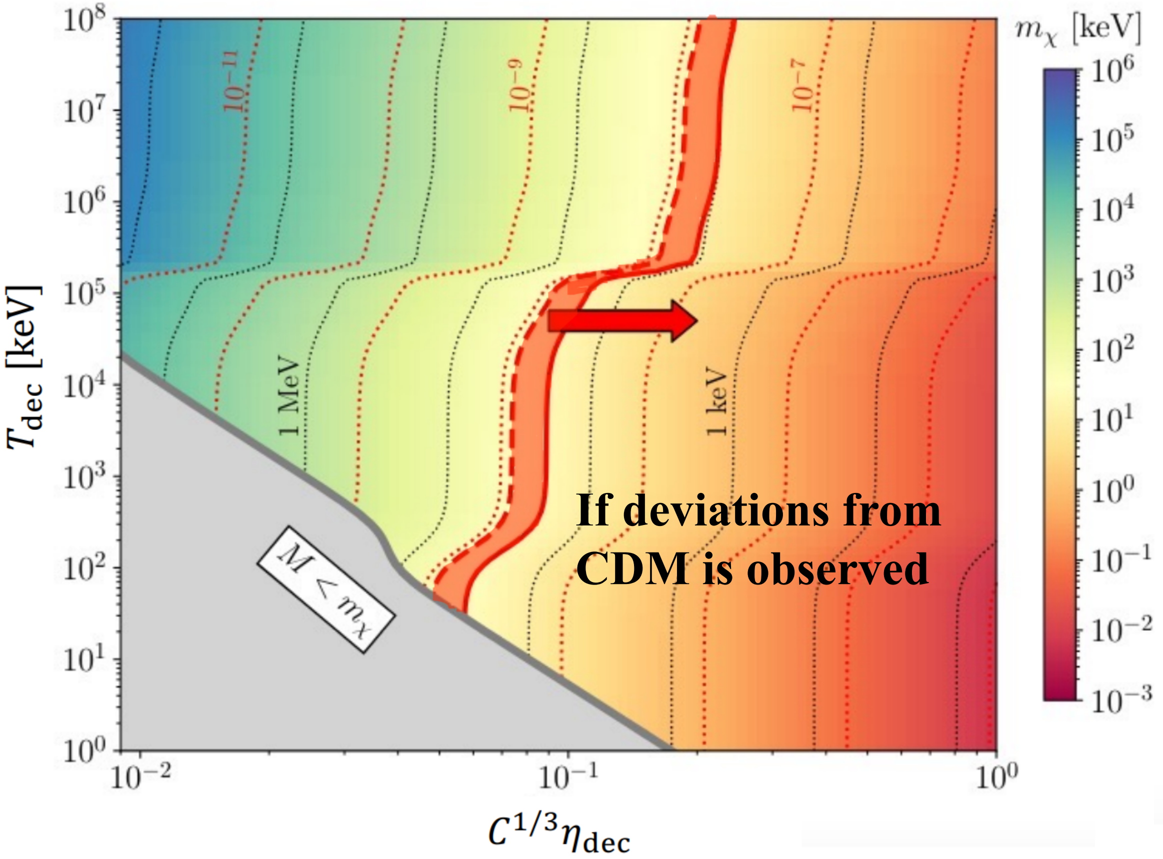

Beyond the average velocity

Solve Boltzmann equations numerically to obtain the distribution function (assuming $\eta_{\mathrm{dec}} = 1$)

$$\left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right) f_\chi(p,t) = \mathcal{C}[f]$$

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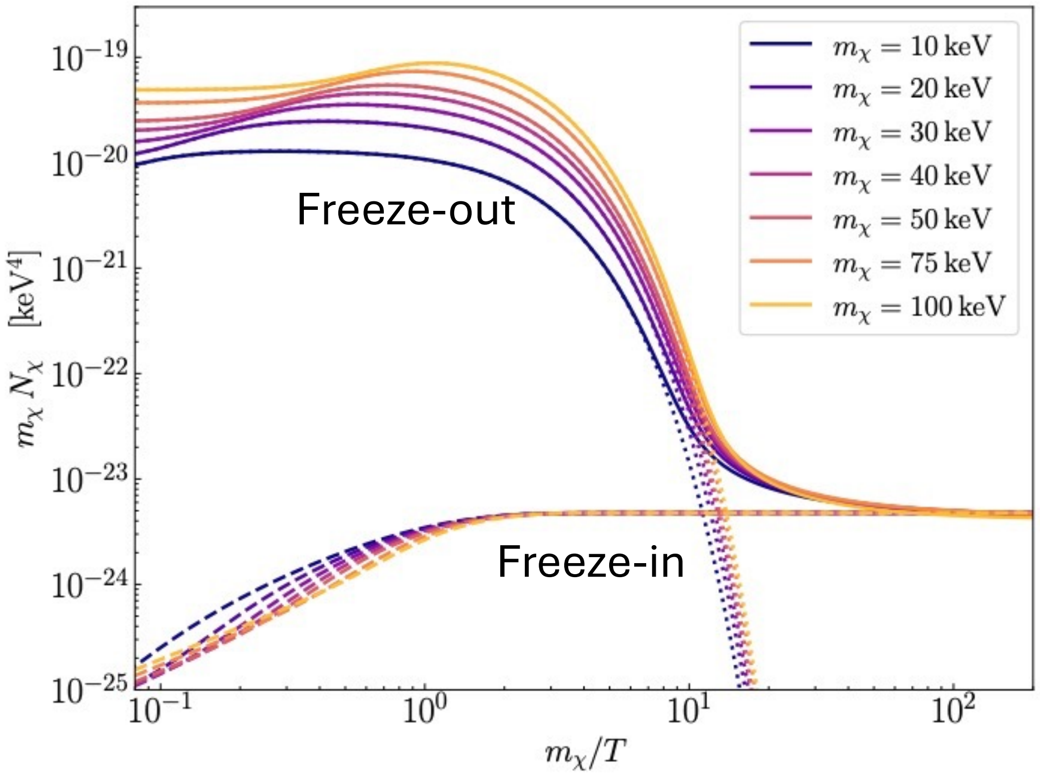

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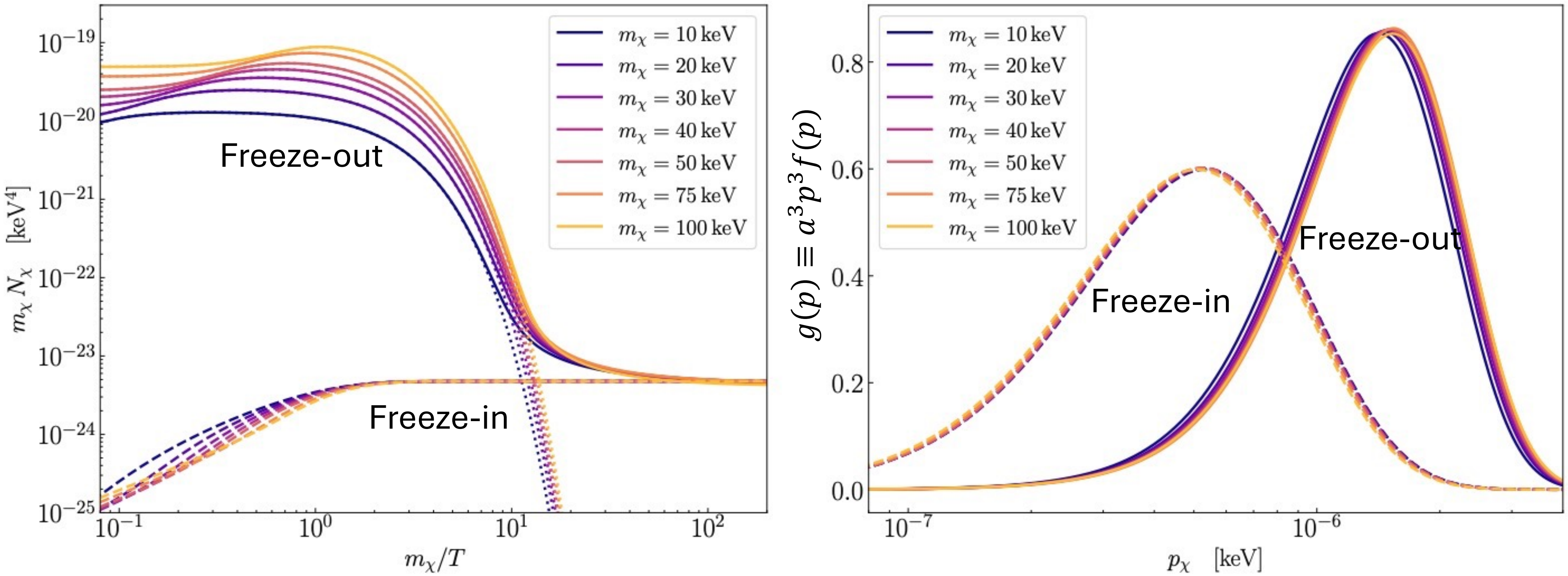

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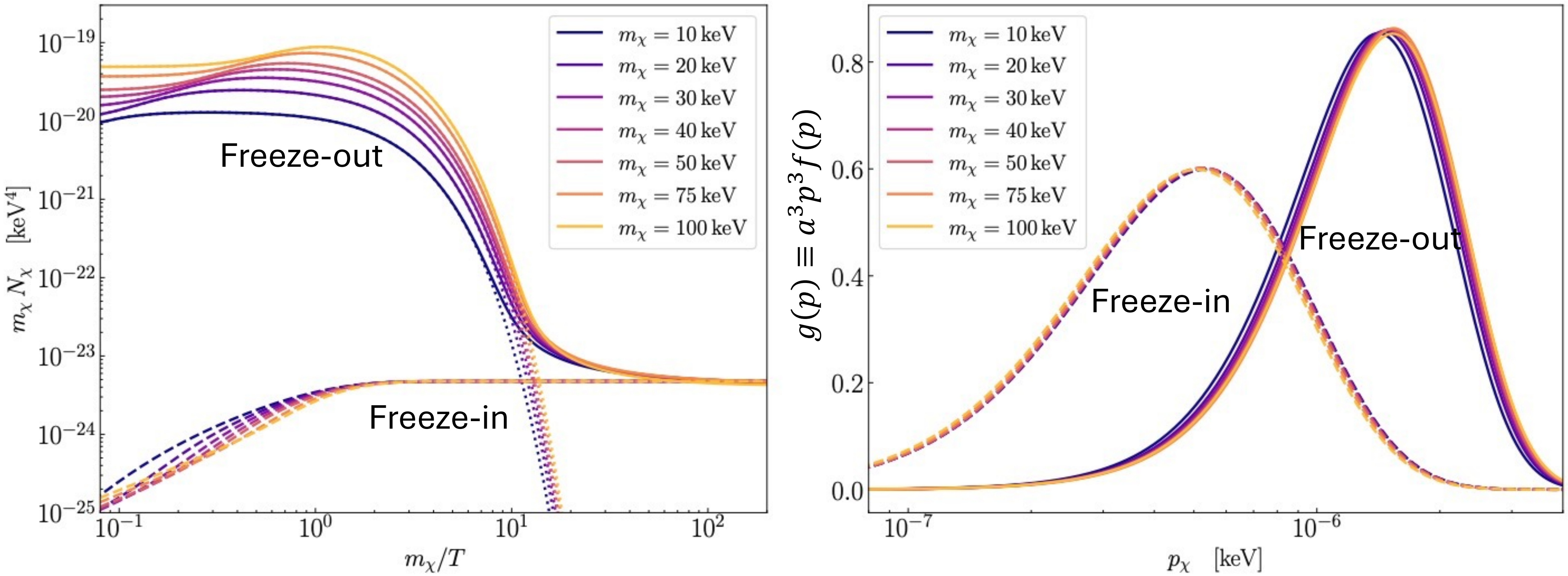
- For the ***same*** production mechanism → ***similar*** distributions
  - ***Larger mass*** → ***Smaller overall velocity***
- Distributions from freeze-in and freeze-out are ***distinct***
  - ***same mass*** → freeze-in distribution is ***colder***
  - Even if same average velocity → ***different shape***



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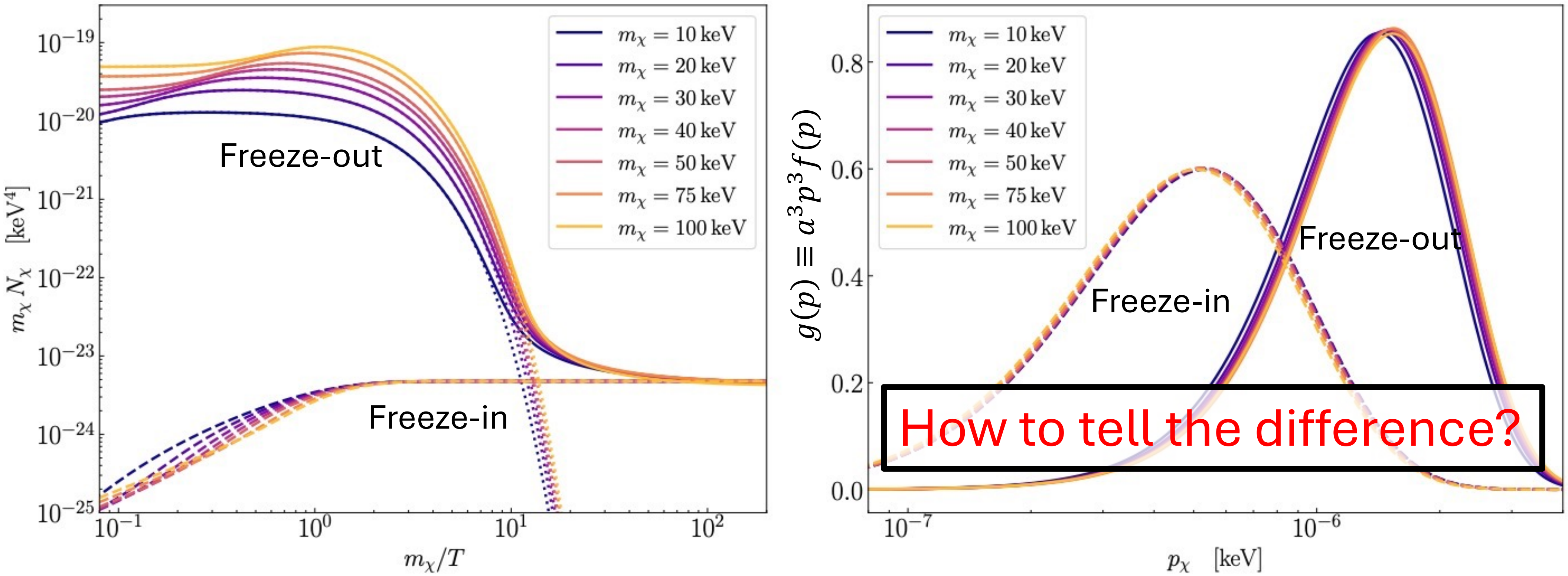


Imprints on cosmic structure

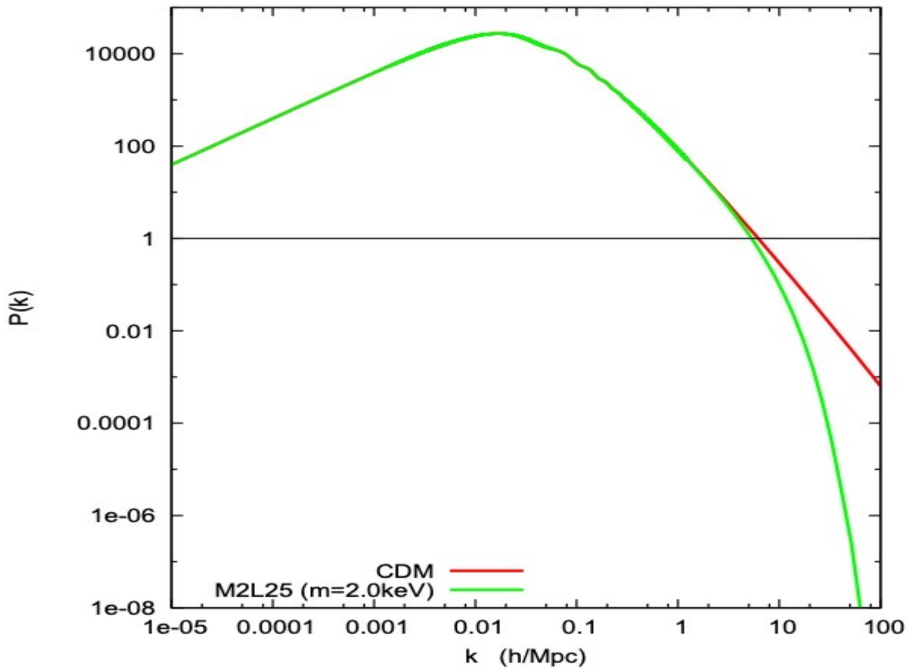
- Non-negligible velocities suppresses structure formation, reflected in the ***matter power spectrum***

$$P(k)$$

- Often represented by the ***squared transfer function***

$$T^2(k) \equiv P(k)/P_{\mathrm{CDM}}(k)$$

- The shape of $T^2(k)$ ***contains the information*** of the distribution function



J. Lesgourgues and T. Tram
JCAP 09 (2011) 032

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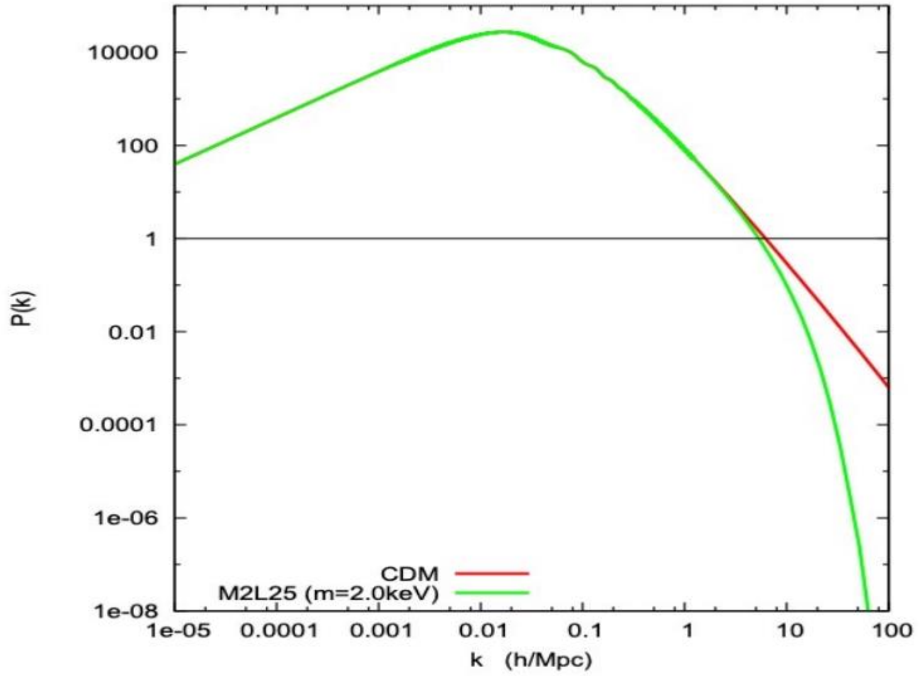

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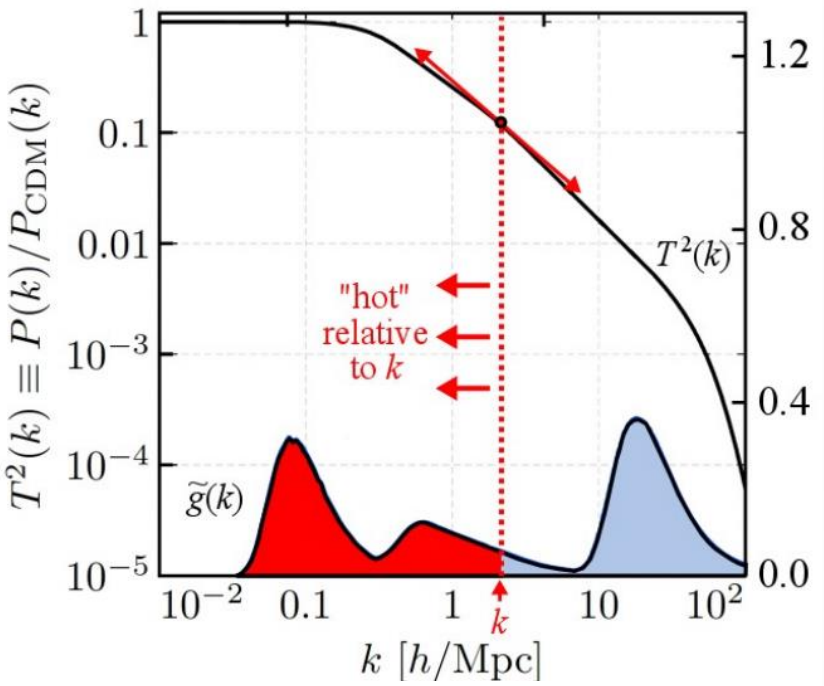

K. Dienes,F. Huang,J. Kost,S. Su,B. Thomas
Phys.Rev.D 101 (2020) 12

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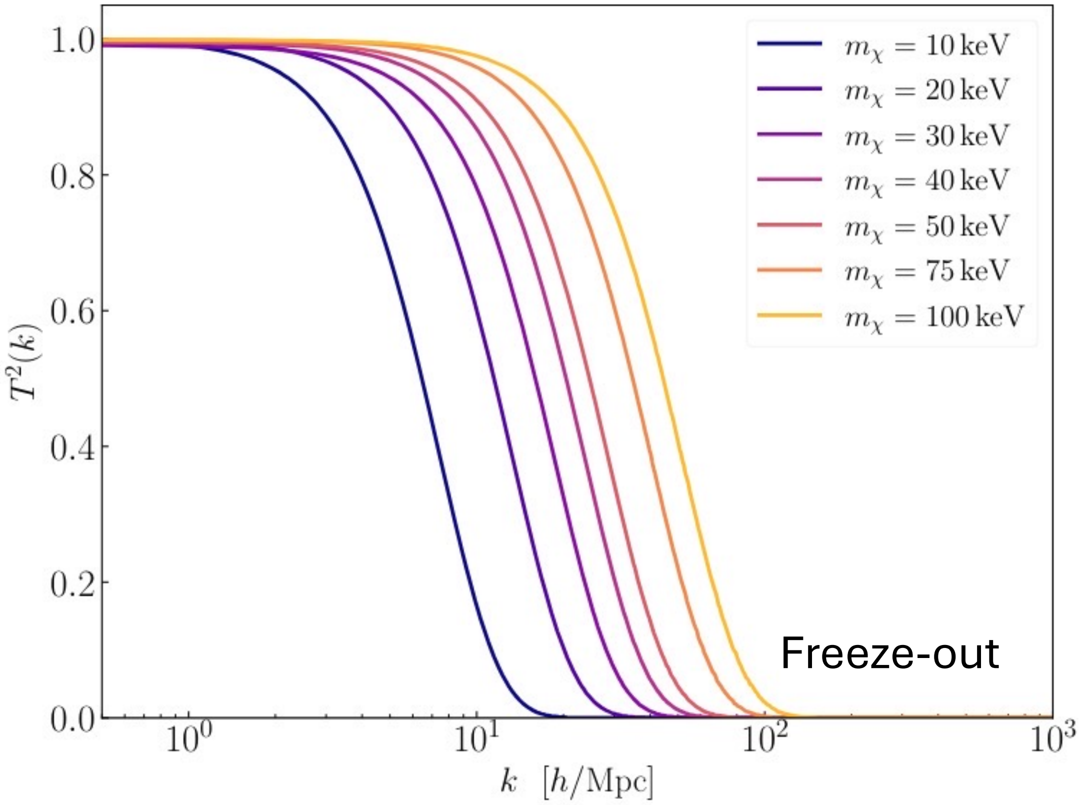

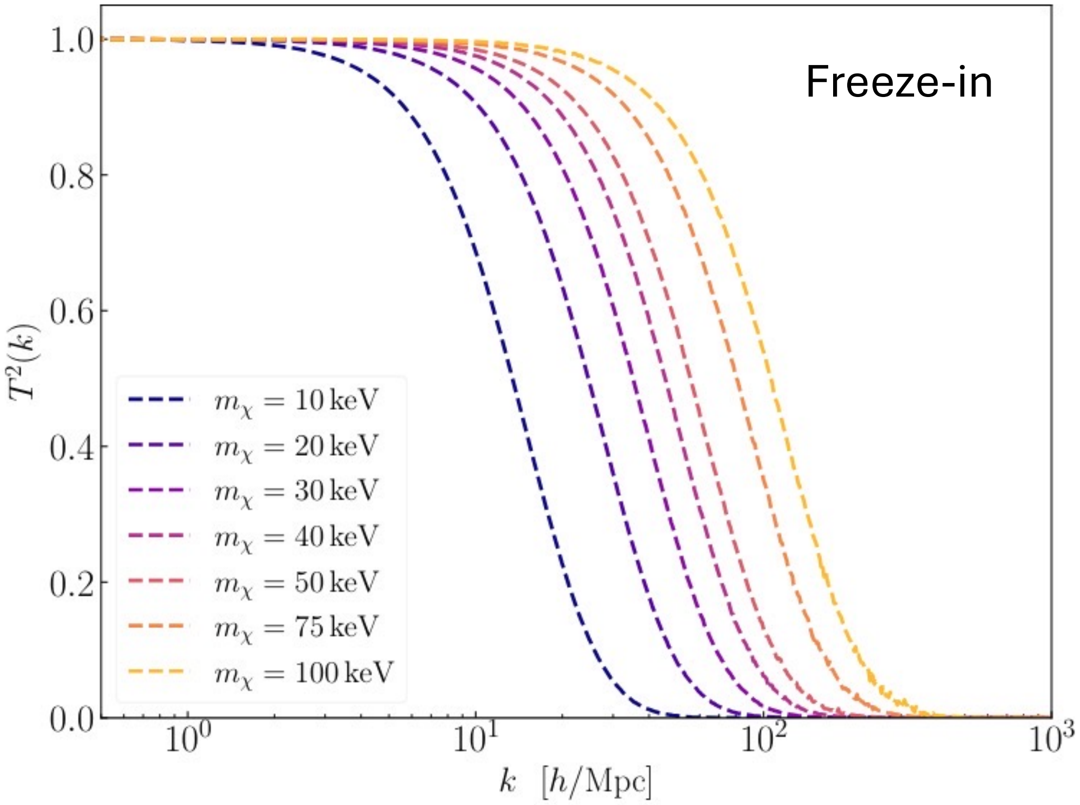

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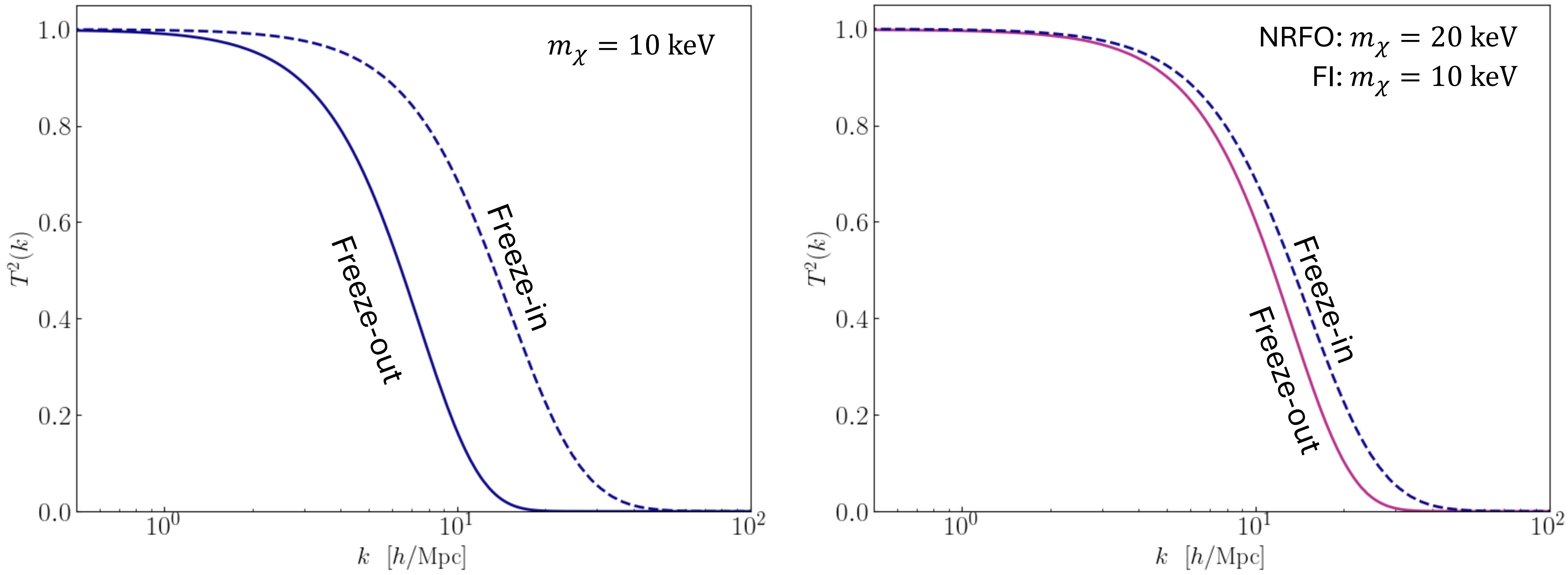

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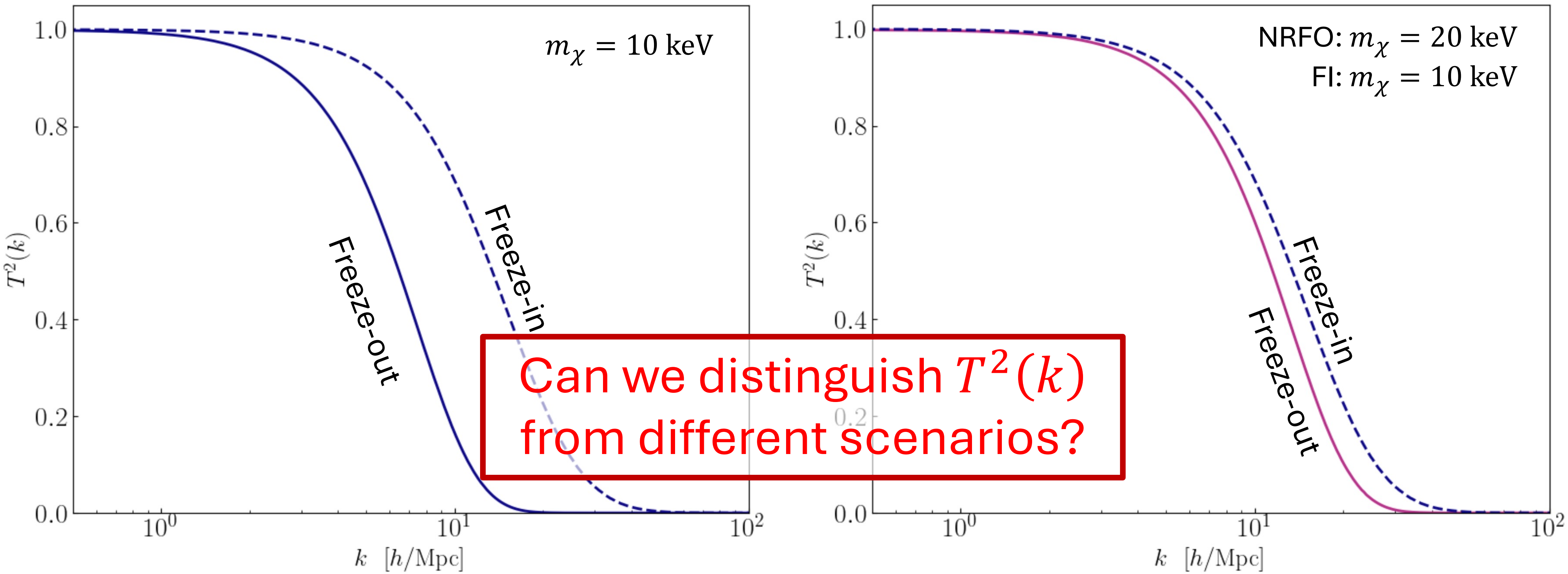

Can we distinguish $T^2(k)$ from different scenarios?

Distinguishing different scenarios

- If future measurements on $P(k)$ finds deviation from CDM, use WDM as a baseline model

$$P_{\mathrm{WDM}}(k)[1+\sigma_P^+(k)] > P(k) > P_{\mathrm{WDM}}(k)[1-\sigma_P^-(k)]$$

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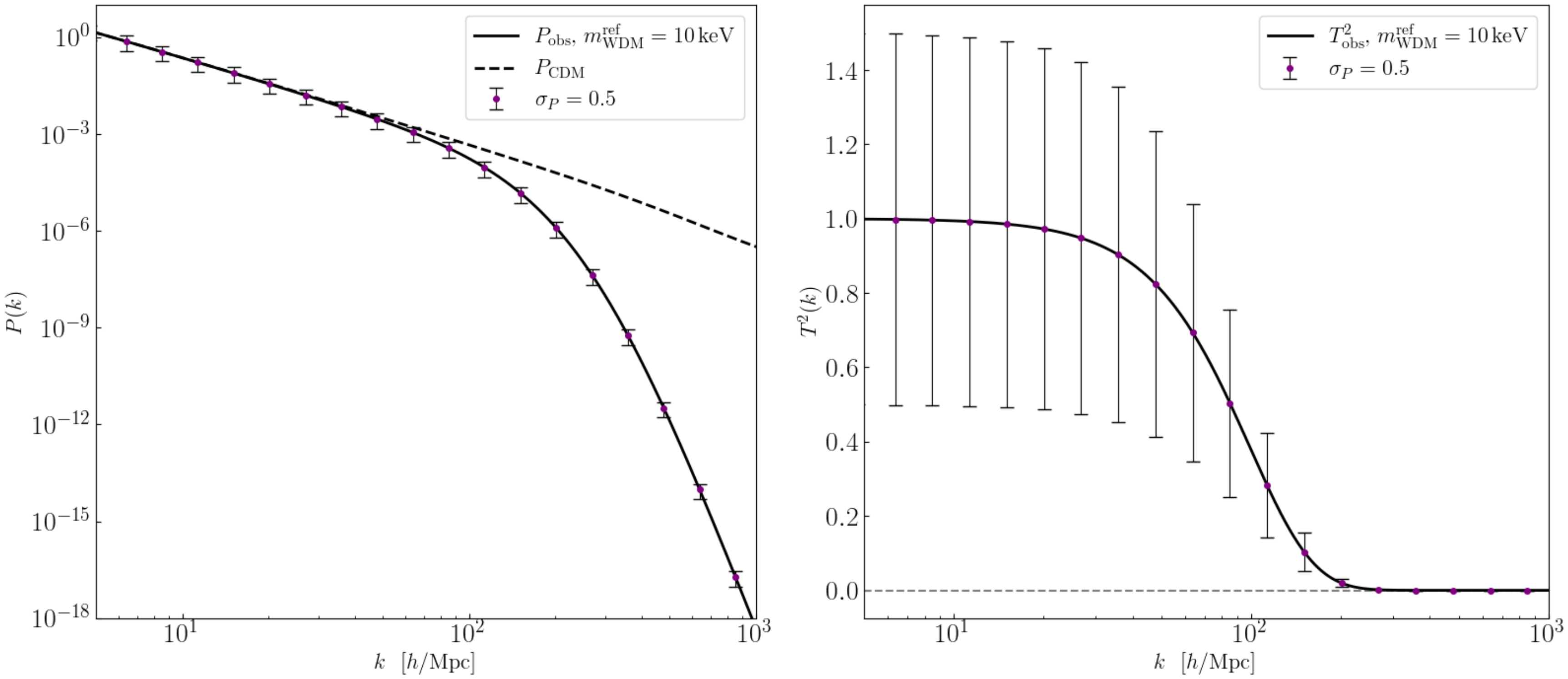
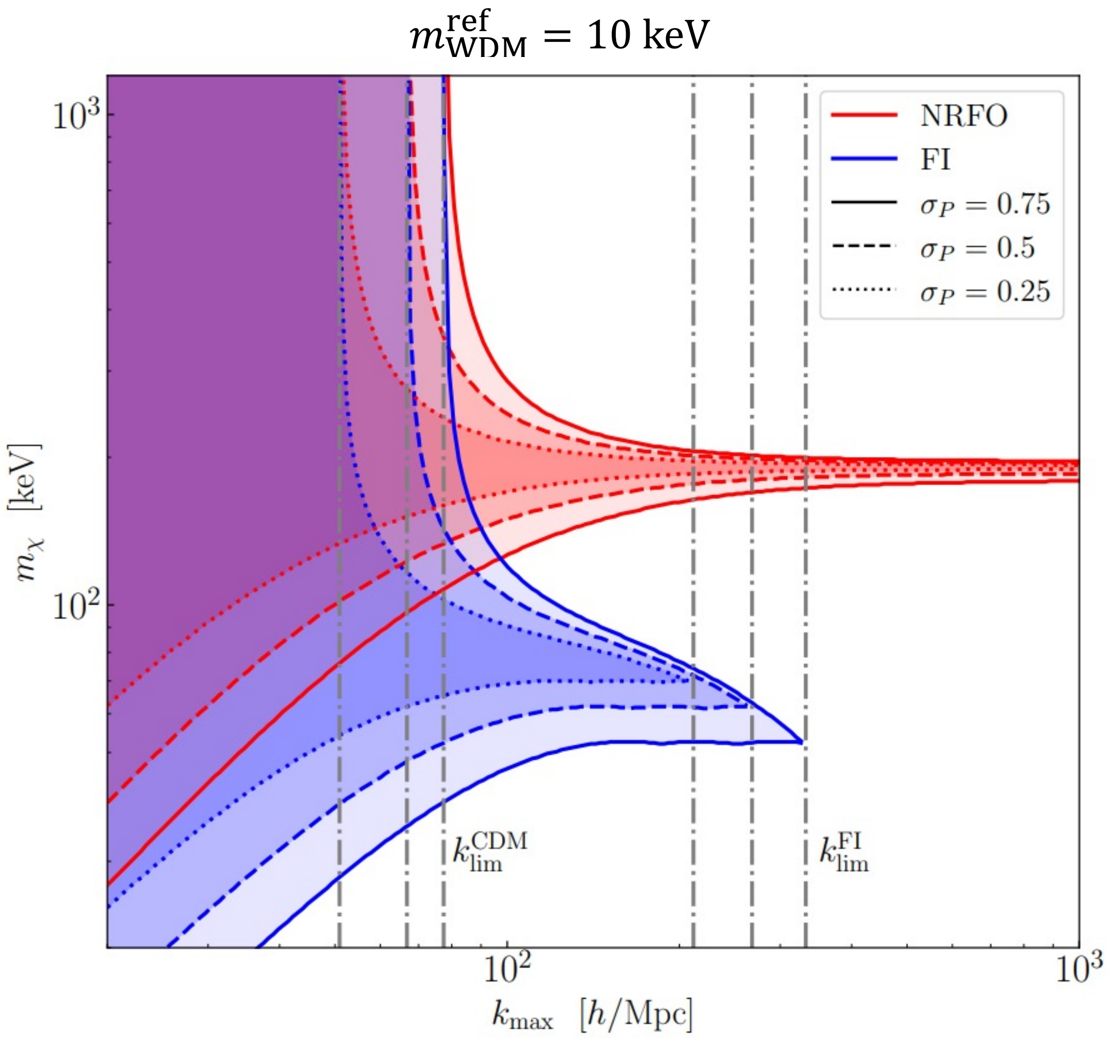
- Explore different possibilities: e.g., ***constant symmetric relative errors*** on $P(k)$

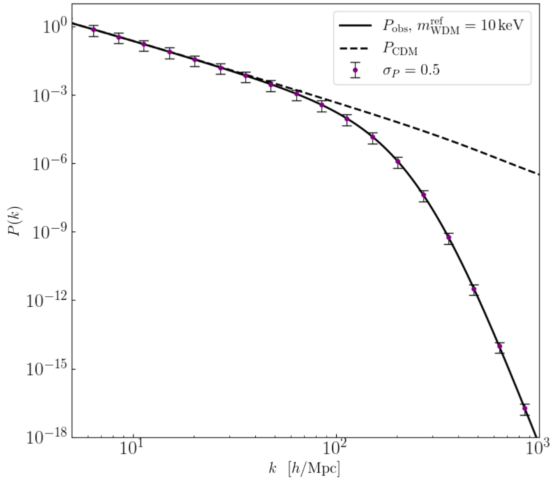
$$\sigma_P^{\pm}(k) = \sigma_P$$



Distinguishing different scenarios

- Assuming $N = 20$ data points evenly distributed on log-scale from $k_{\min} = 1\ h/\mathrm{Mpc}$ to $k_{\max}$





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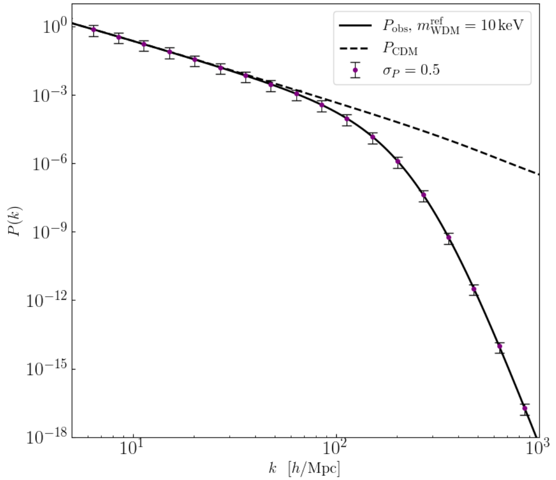
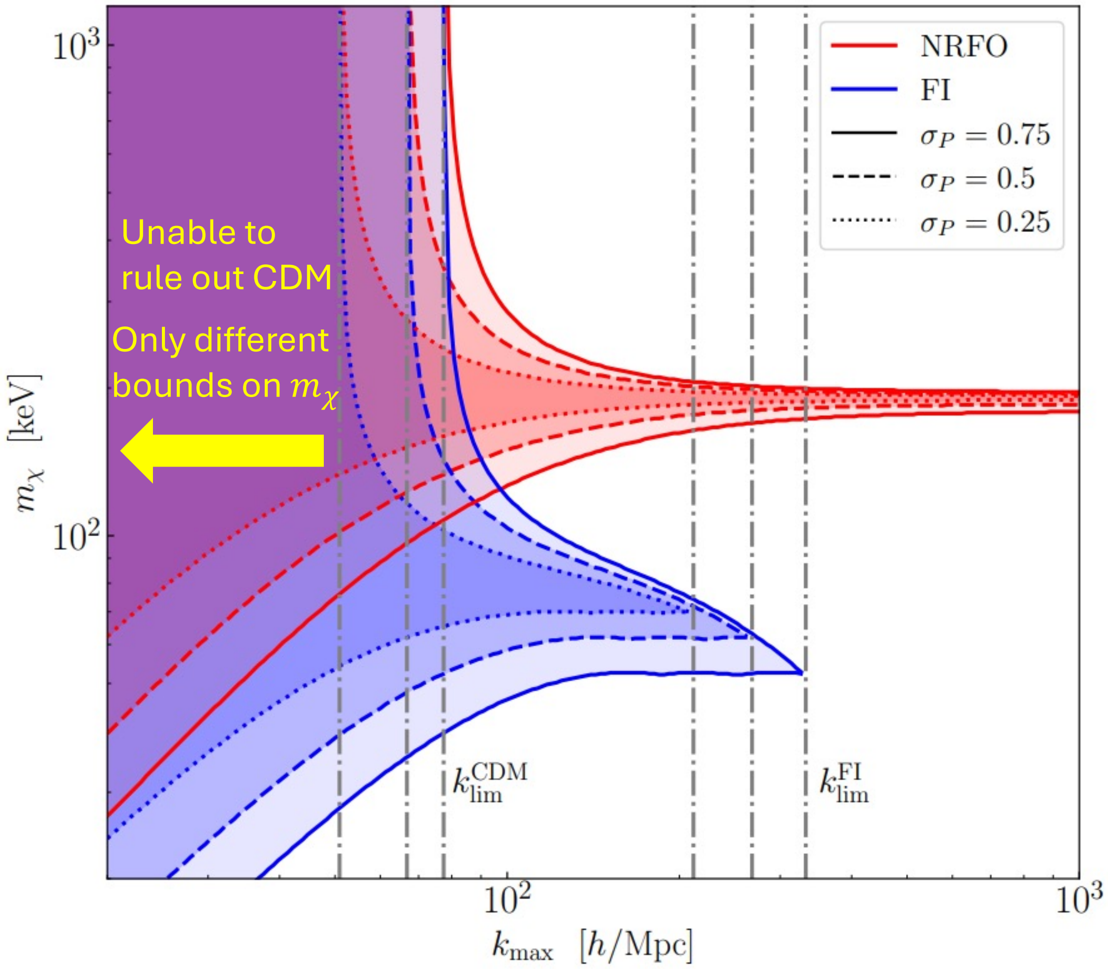


$m_{\mathrm{WDM}}^{\mathrm{ref}} = 10$ keV



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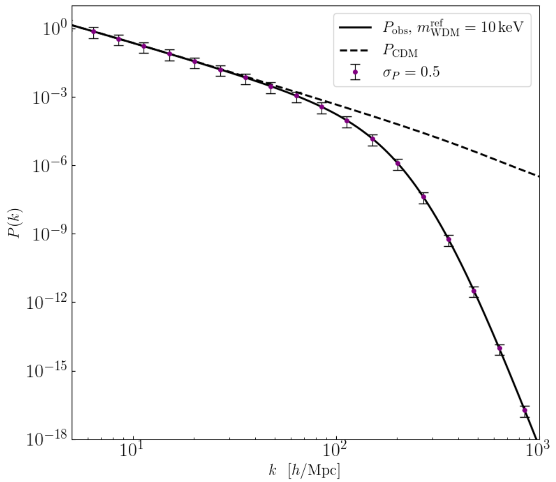

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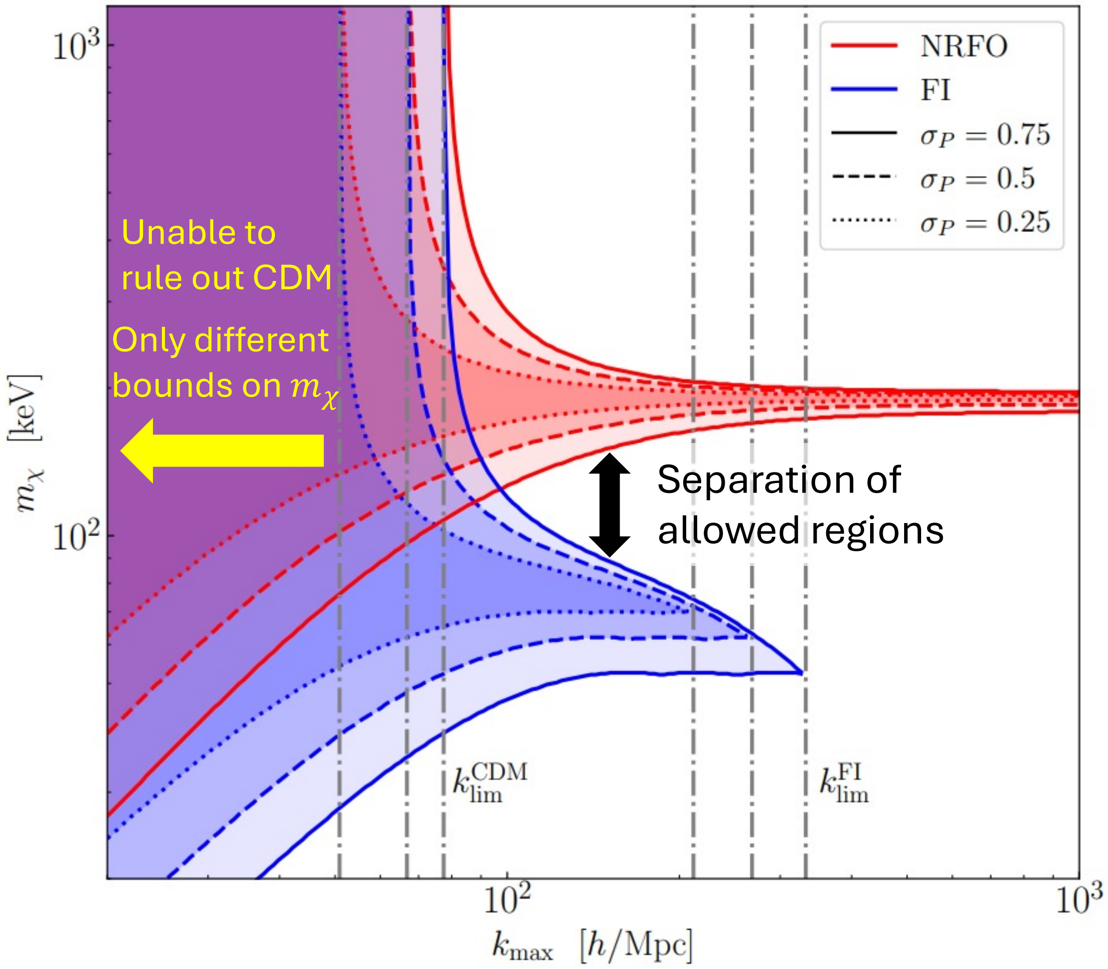

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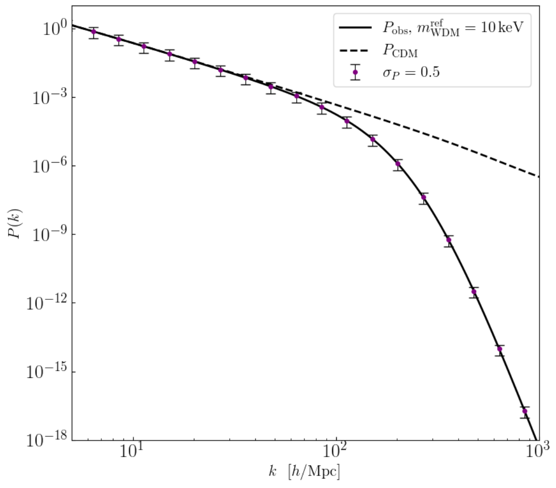

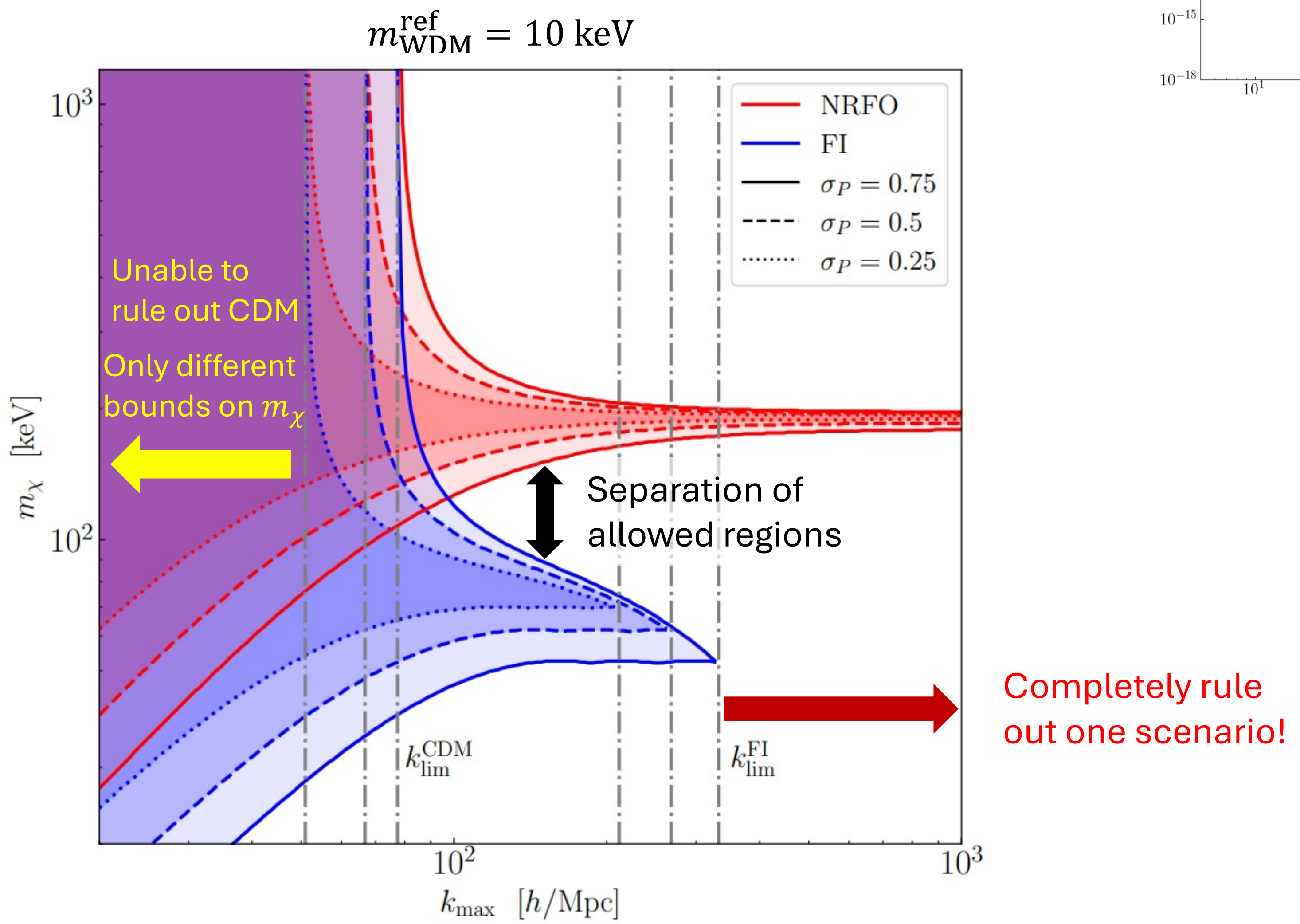

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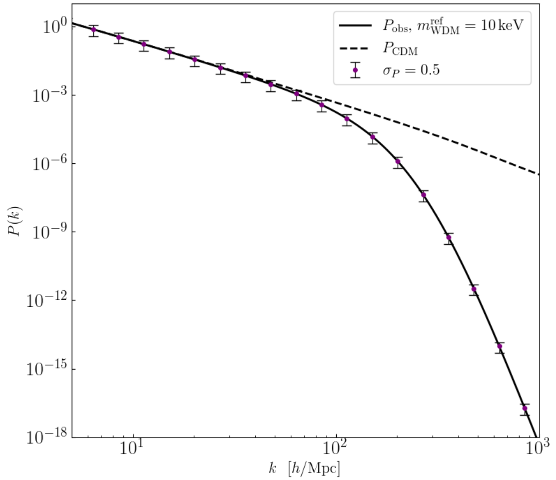
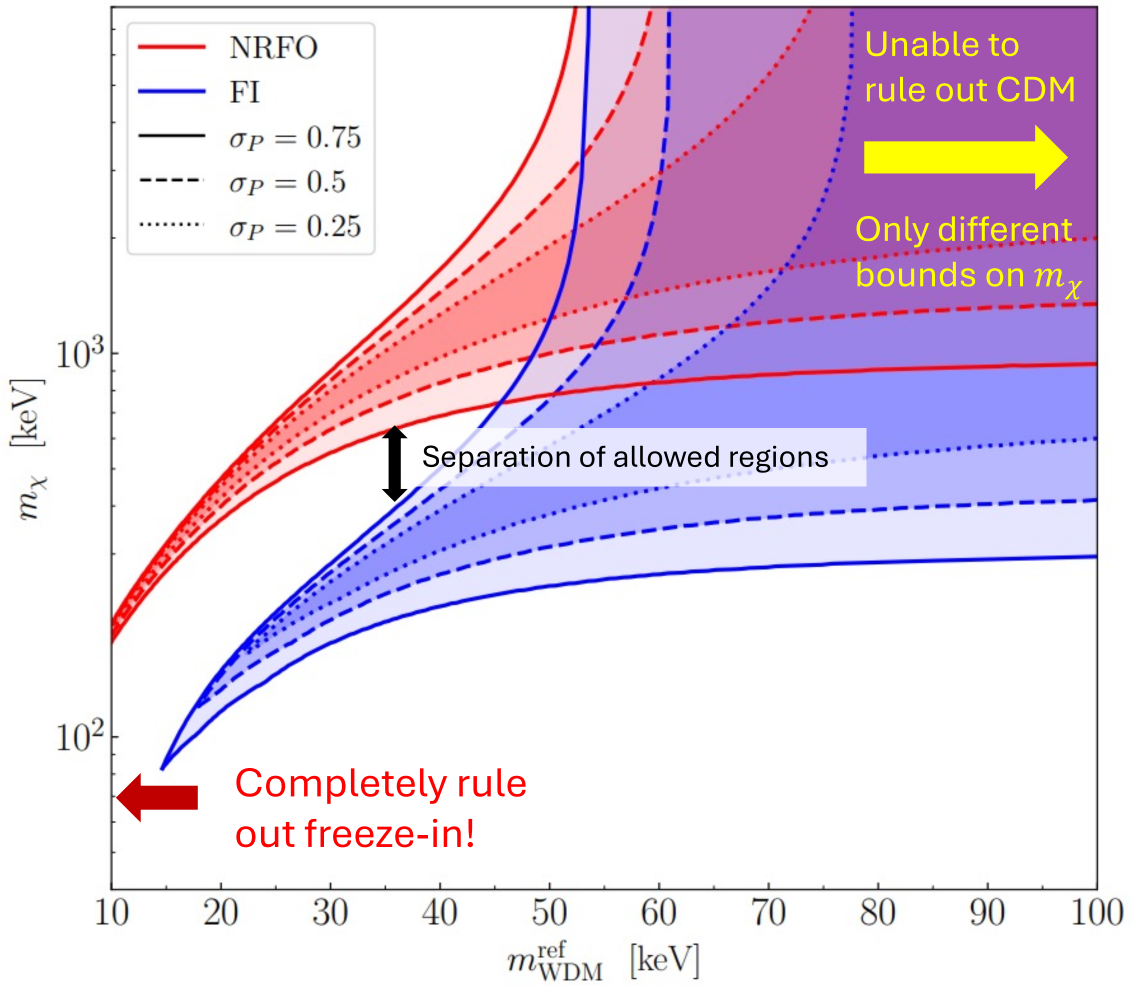


$k_{\mathrm{max}} = 500\ h/\mathrm{Mpc}$



Conclusion

- The cosmic structure contains information about the thermal history of dark matter
- Current WDM bounds can be re-interpreted to place constraints on decoupling temperatures (physical quantities relevant for the early universe) in different scenarios
- For different scenarios, these constraints imply different bounds on DM mass for different scenarios.
- If future data observes deviation from CDM predictions, it is potentially possible to discriminate different production mechanisms if there is sufficient precision