Distinguishing Thermal Histories of Dark Matter from Structure Formation

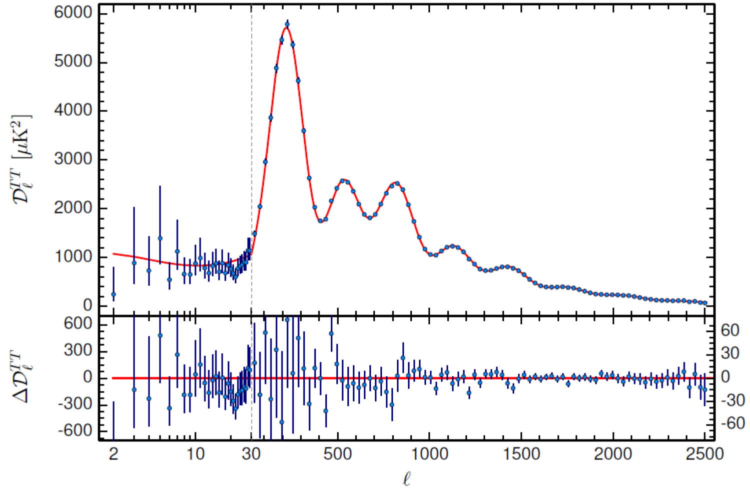
JCAP 01 (2024) 023

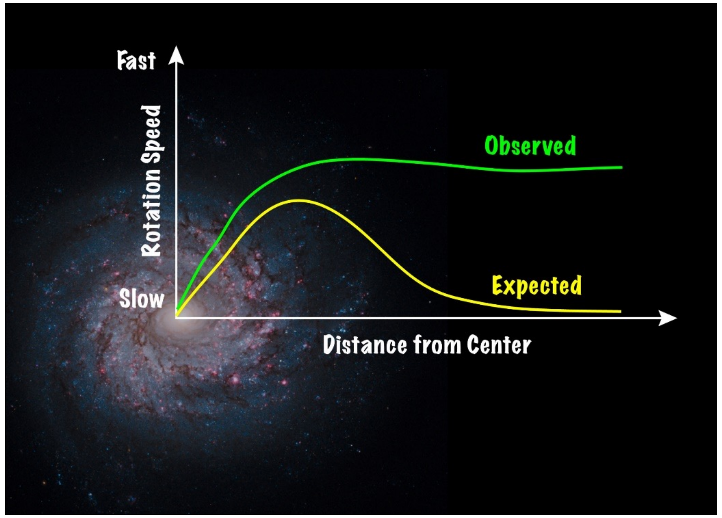
Fei Huang

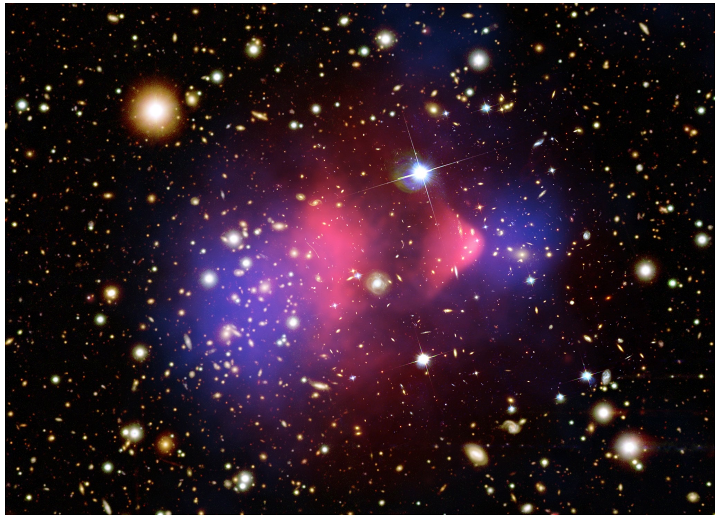
with Yuan-Zhen Li and Jiang-Hao Yu

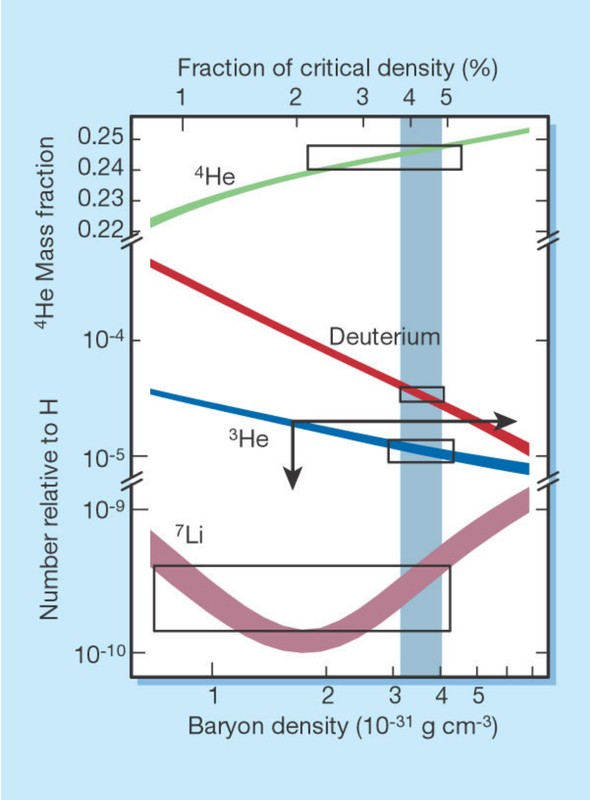
May 13, 2024

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

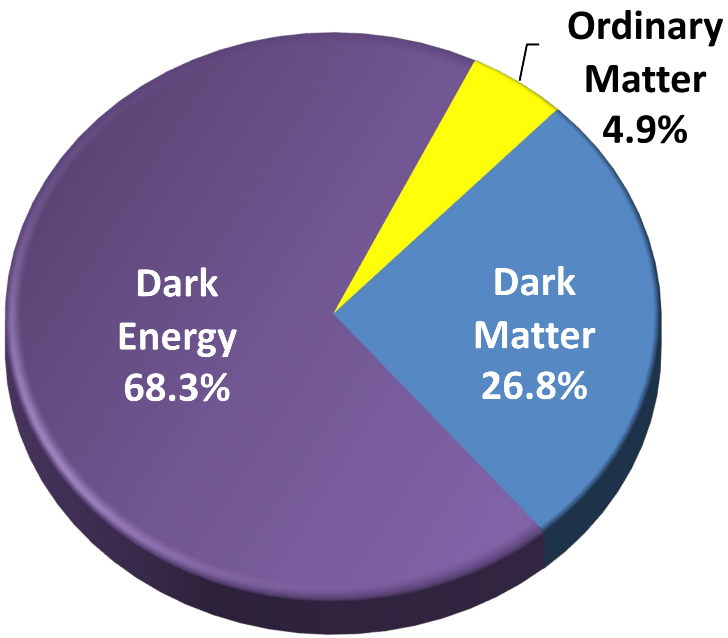








What have we learnt?



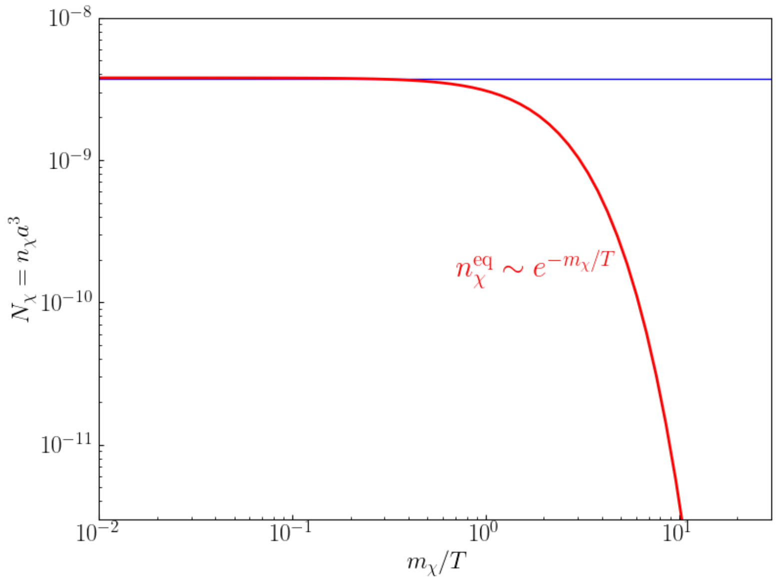
- **<u>Abundance:</u>** ~26% of the universe
- **<u>Cold</u>**: Non-relativistic, massive
- **<u>Dark</u>**: Negligible nongravitational interaction with Standard Model fields
- **<u>Nonbaryonic</u>**: Baryonic matter is simply not enough
- **<u>BSM</u>**: Not Standard Model particle

We still don't know:

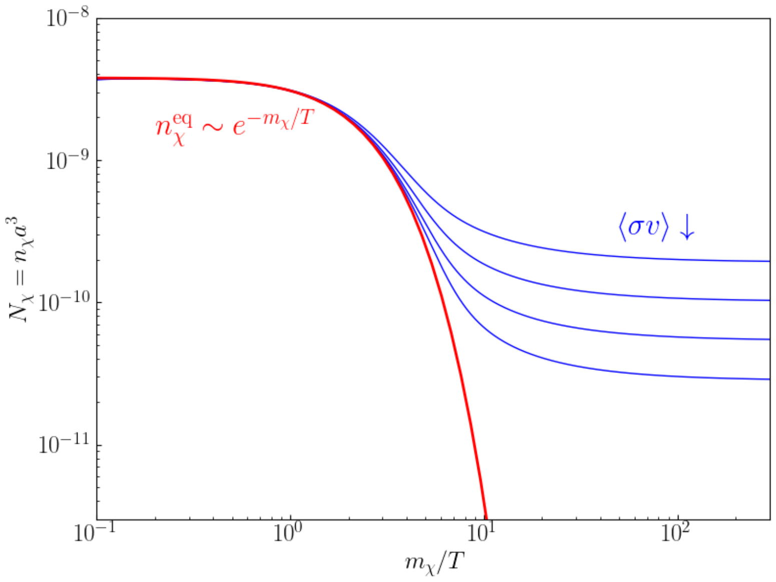
- **<u>Particle properties</u>**: mass, spin, fundamental or composite, single-component or multi-component, etc.
- **<u>Production mechanism</u>**: freeze-out, freeze-in, decays, misalignment?

DM Production from a Thermal Bath

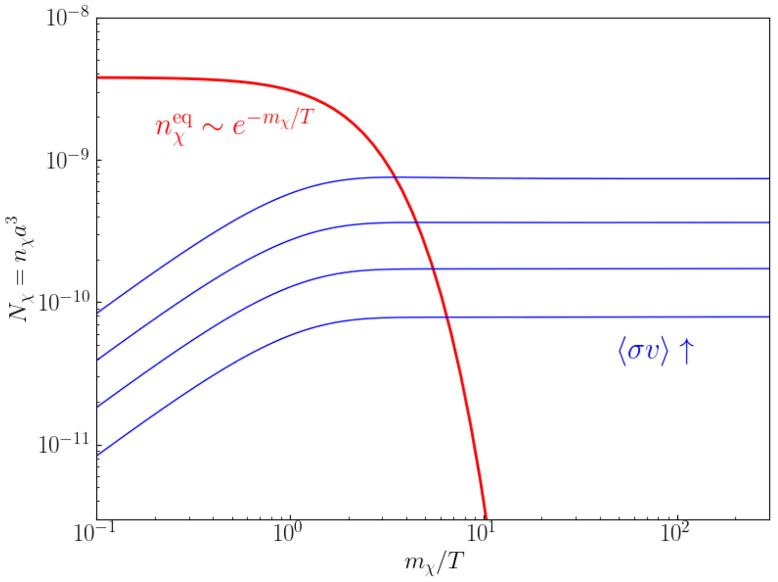
Relativistic freeze-out "Warm Dark Matter"



Non-Relativistic Freeze-Out



Freeze-In



Phase-Space Distribution

For any mechanism, there is a DM distribution function

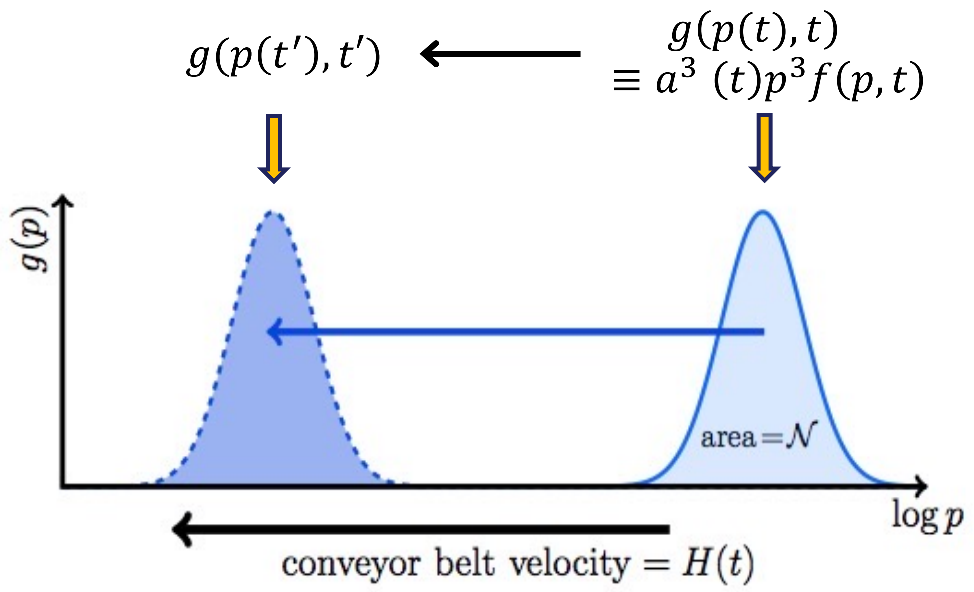
$$f(p,t)$$

After DM production is complete, the evolution of $f(p,t)$ is only subject to cosmological redshift:

$$p \sim a^{-1}$$

For ***freeze-out***, DM was in thermal equilibrium.
At decoupling:

$$f_\chi(p,t_{dec}) = \left[\exp\left(\frac{E-\mu_{dec}}{T_\chi(t_{dec})}\right) \pm 1\right]^{-1}$$



Relativistic freeze-out: $T_\chi(t_{dec}) \gg m_\chi,\; E \sim p$

At later times
$$f_\chi(p,t) \approx \left[\exp\left(-\frac{p-\mu}{T_\chi}\right) \pm 1\right]^{-1}$$

$$T_\chi(t) = T_\chi(t_{dec})\frac{a_{dec}}{a(t)}, \qquad \mu(t) = \mu_{dec}\frac{a_{dec}}{a(t)}$$

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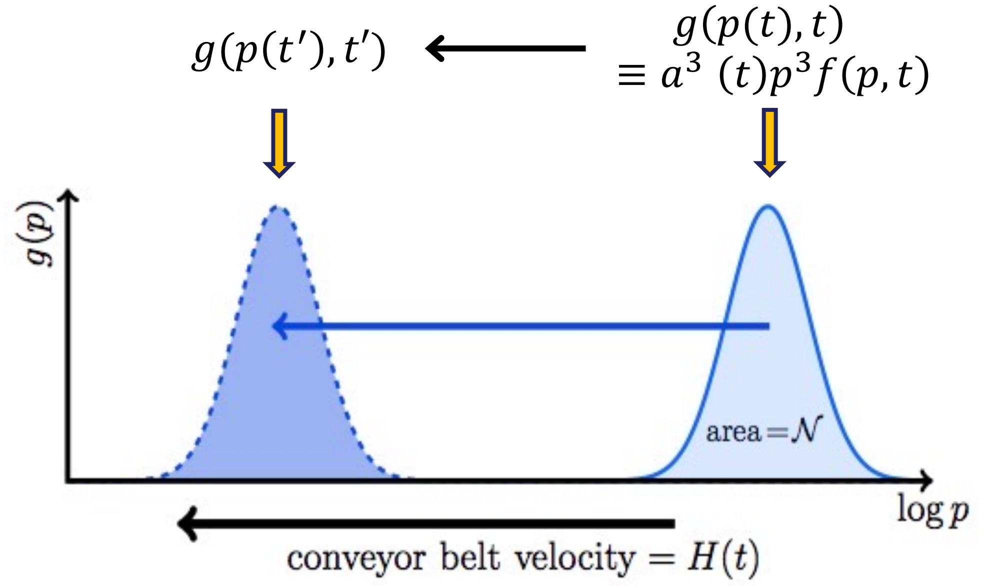

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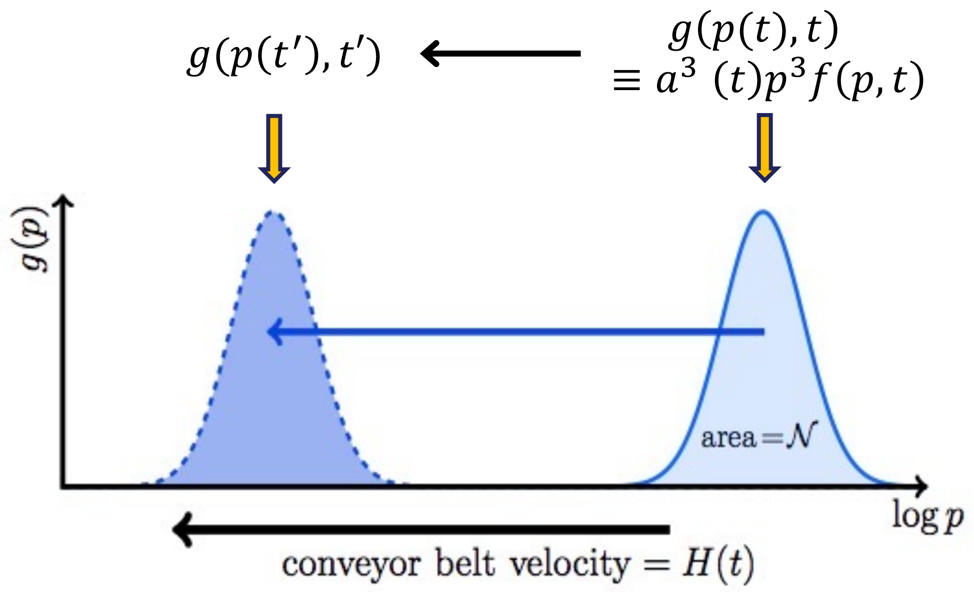

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Non-Relativistic freeze-out: $E_{dec}\sim m_\chi + \frac{p_{dec}^2}{2m_\chi}$

At later times
$$f_\chi(p,t) \approx \left[\exp\left(-\frac{m_\chi + p^2/(2m_\chi) - \mu}{T_\chi}\right) \pm 1\right]^{-1}$$

$$T_\chi(t) = T_\chi(t_{dec})\frac{a_{dec}^2}{a^2(t)}, \qquad \mu(t) = m_\chi - (m_\chi - \mu_{dec})\frac{a_{dec}^2}{a^2(t)}$$

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After DM production is complete, the evolution of $f(p,t)$ is only subject to cosmological redshift:

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For ***freeze-in***, DM was never in equilibrium

$$f_\chi(p, t_{dec}) = C\,\frac{\exp(-p/M)}{\sqrt{p/M}}$$

F. D'Eramo & A. Lenoci
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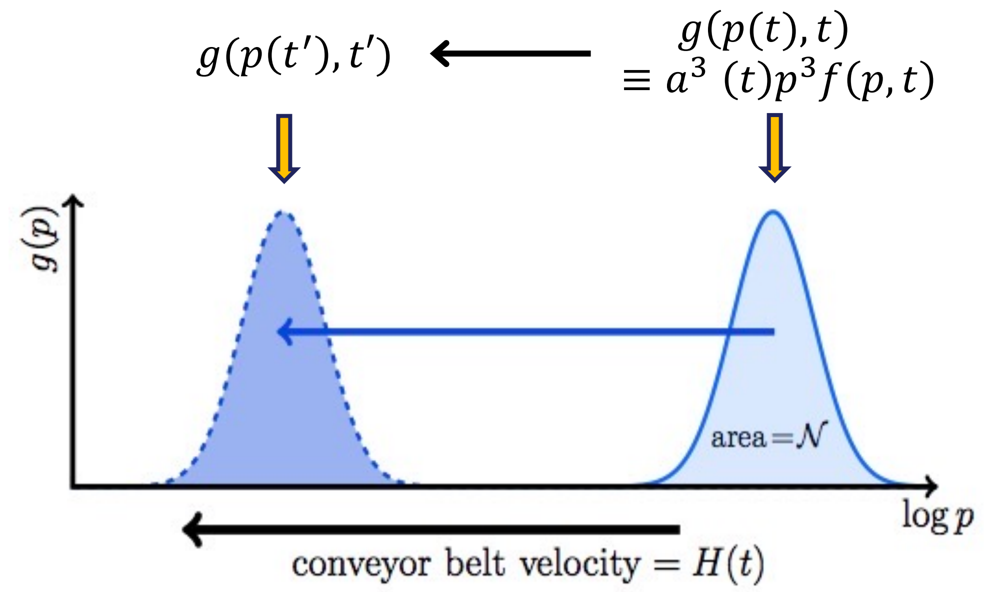
suitable for 2 → 2 processes, e.g.,

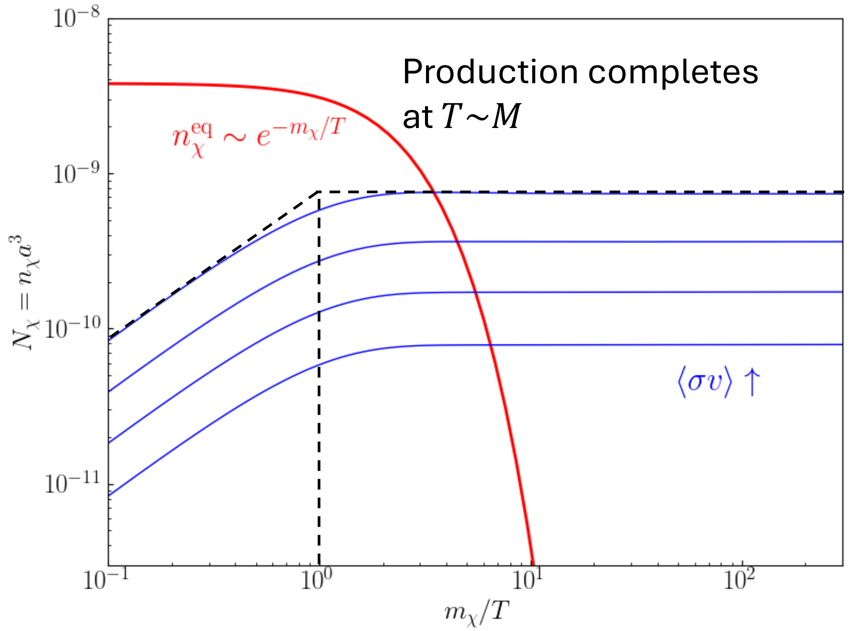
$$\psi + \psi \rightarrow \chi + \chi$$

Define an ***effective*** temperature:

$$T_\chi(t) = M\,\frac{a_{dec}}{a(t)}$$

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





A little exercise with WDM

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relativistic form, even
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Energy density :

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$$\langle v \rangle_0 \approx 1.1 \times 10^{-7} \times \left(\frac{2}{g_\chi}\right)^{1/3} \left(\frac{\Omega_\chi}{0.25}\right)^{1/3} \left(\frac{1\,\mathrm{keV}}{m_\chi}\right)^{4/3}$$

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$1/a$ (for T_χ)

\+

entropy conservation

$a^3 T^3 g_{*,s}(T) = const.$

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physical quantities at production time

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physical quantities at production time

e.g., Lyman-α constraint

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

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

DM velocity is constrained by structure formation!

Constraints on decoupling temperatures

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

$$\langle v \rangle_0 \lesssim 2.1\times10^{-8}$$
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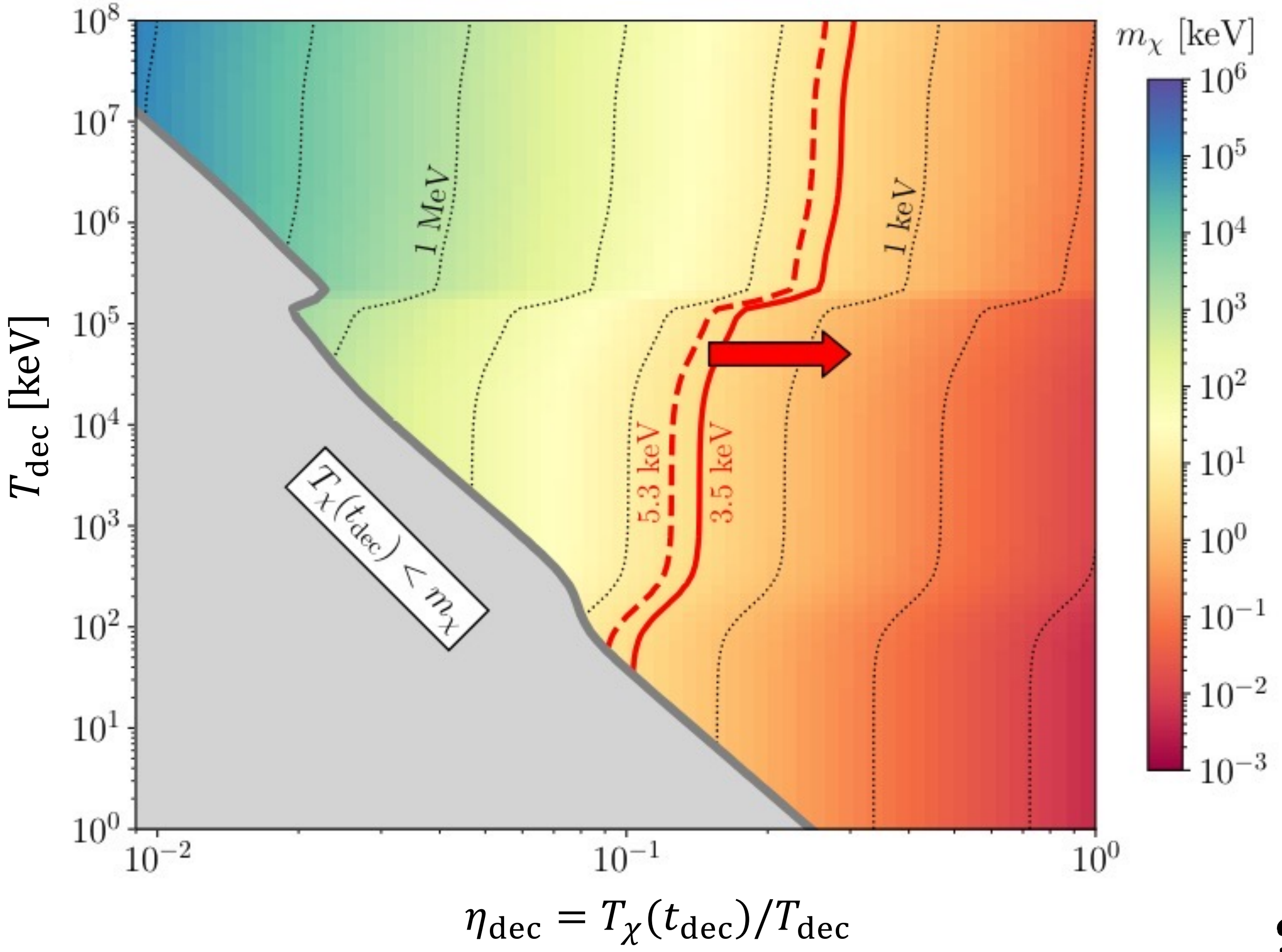
Relativistic Freeze-Out

$$m_\chi \approx 1.9\times10^{-3}\ \text{keV} \times \frac{\Omega_\chi}{0.25}\frac{g_{*,s}(T_{\rm dec})}{g_\chi}\eta_{\rm dec}^{-3}$$



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

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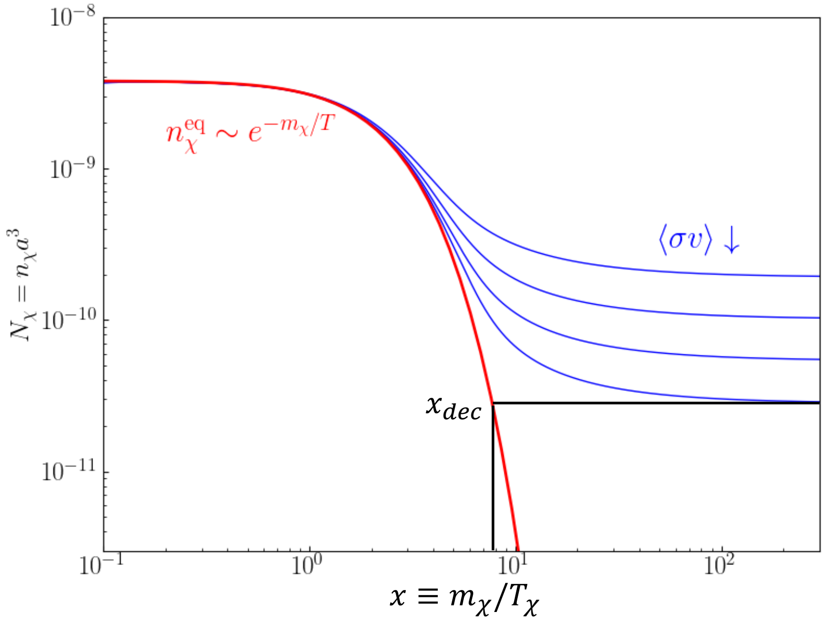
- Additional dependence on $x_{\rm dec}$
- $\eta_{\rm dec} = 1$ allowed



Non-**R**elativistic **F**reeze-**O**ut

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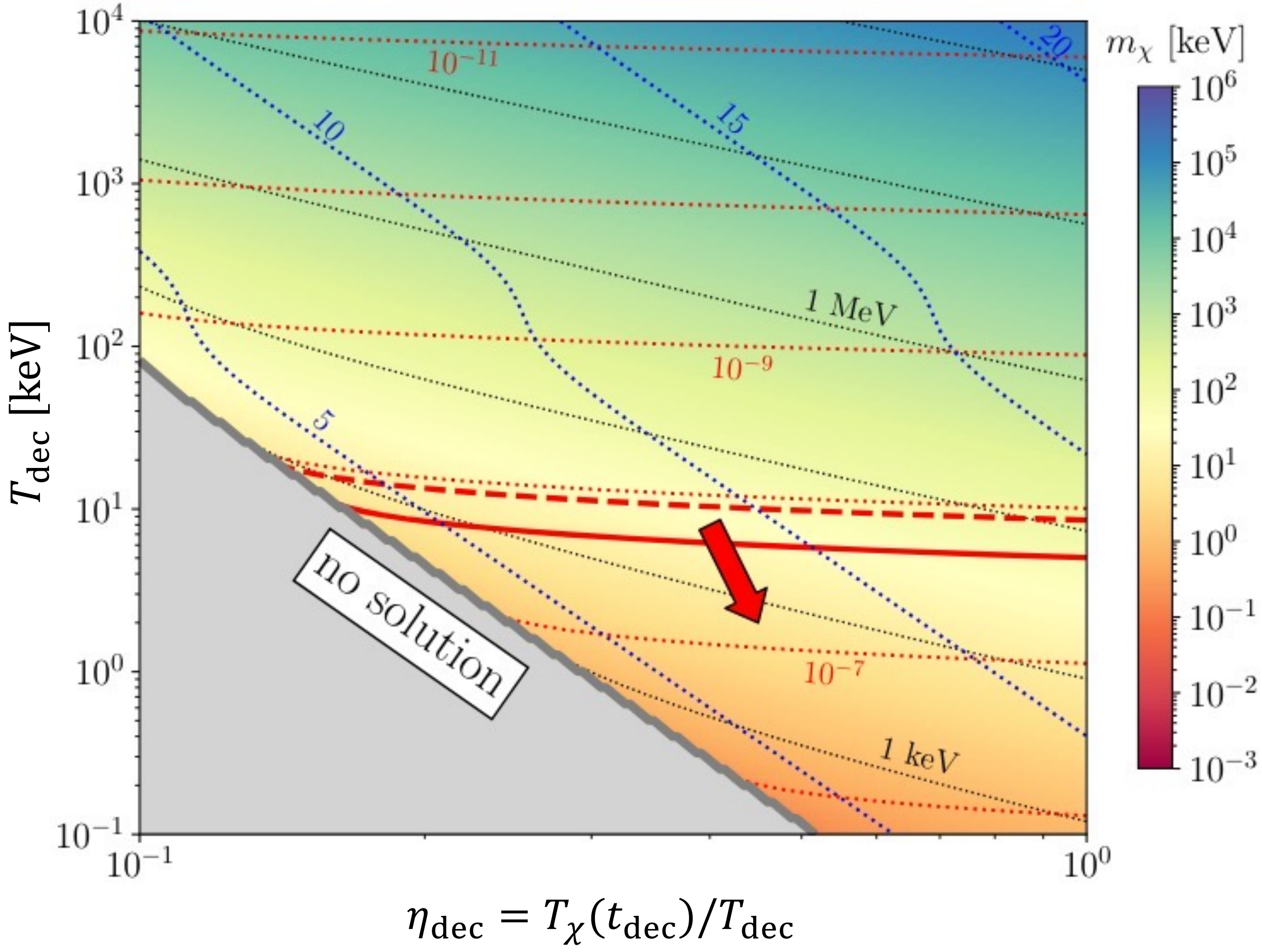

Constraints on decoupling temperatures

$m_{\rm WDM} \gtrsim 3.5$ keV
$\gtrsim 5.3$ keV

$\langle v \rangle_0 \lesssim 2.1\times10^{-8}$
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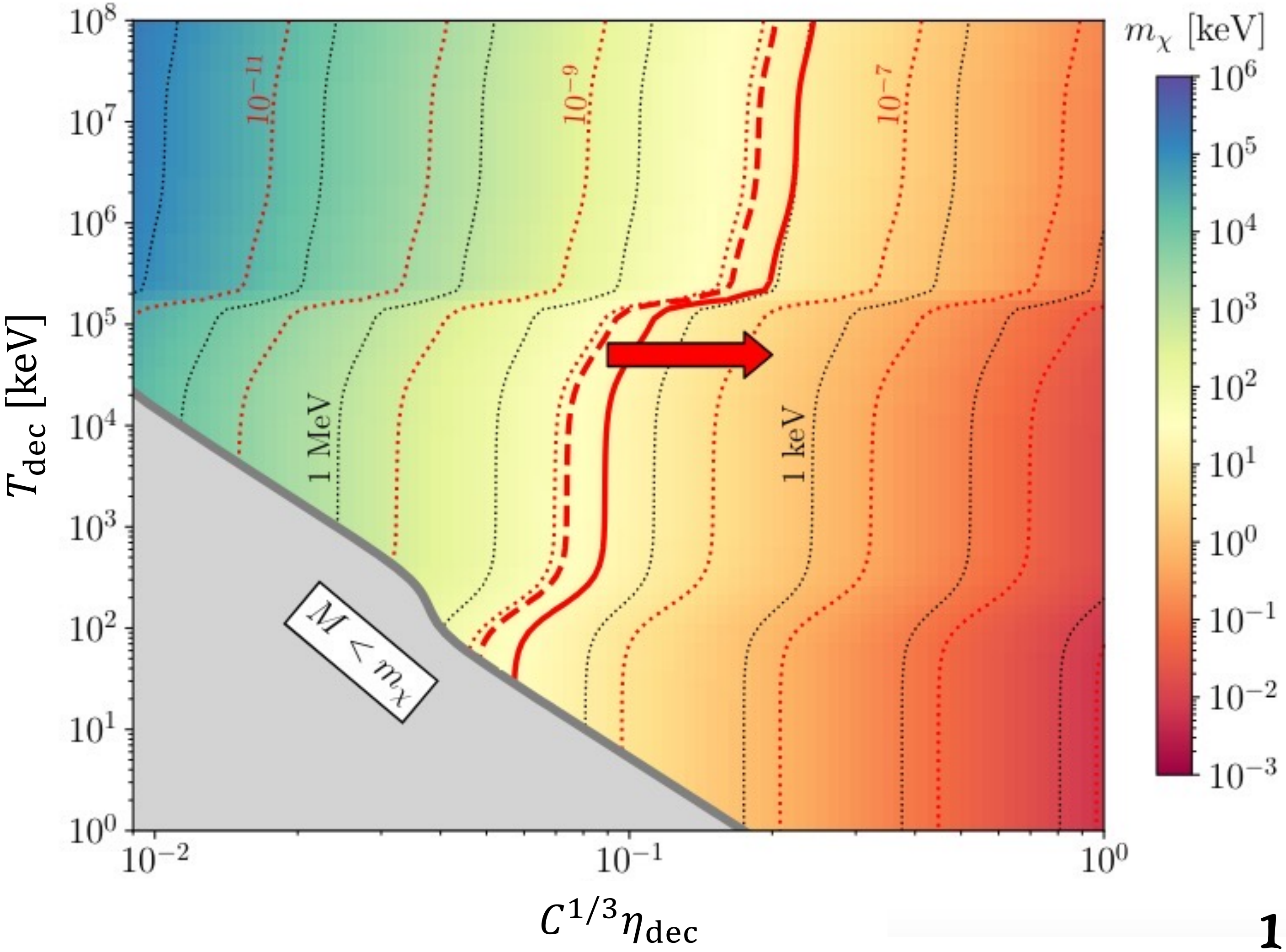
- Additional degeneracy from C
  - $f_\chi(p,t) = C\,\frac{\exp(-p/T_\chi)}{\sqrt{p/T_\chi}}$
  - Mass and velocity contours identical only if C fixed
- $\eta_{\rm dec} = 1$ also allowed

Freeze-In

$$m_\chi \approx 2.7\times 10^{-3}\ \text{keV} \times \frac{\Omega_\chi}{0.25}\,\frac{g_{*,s}(T_{\rm dec})}{g_\chi}\,C^{-1}\eta_{\rm dec}^{-3}$$



An optimistic possibility

What if

- **deviation** from CDM is observed in **future** observations
- consistent with free-streaming effects from **non-negligible primordial velocity** of DM

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- A lower bound on DM velocities

The allowed region will become a band

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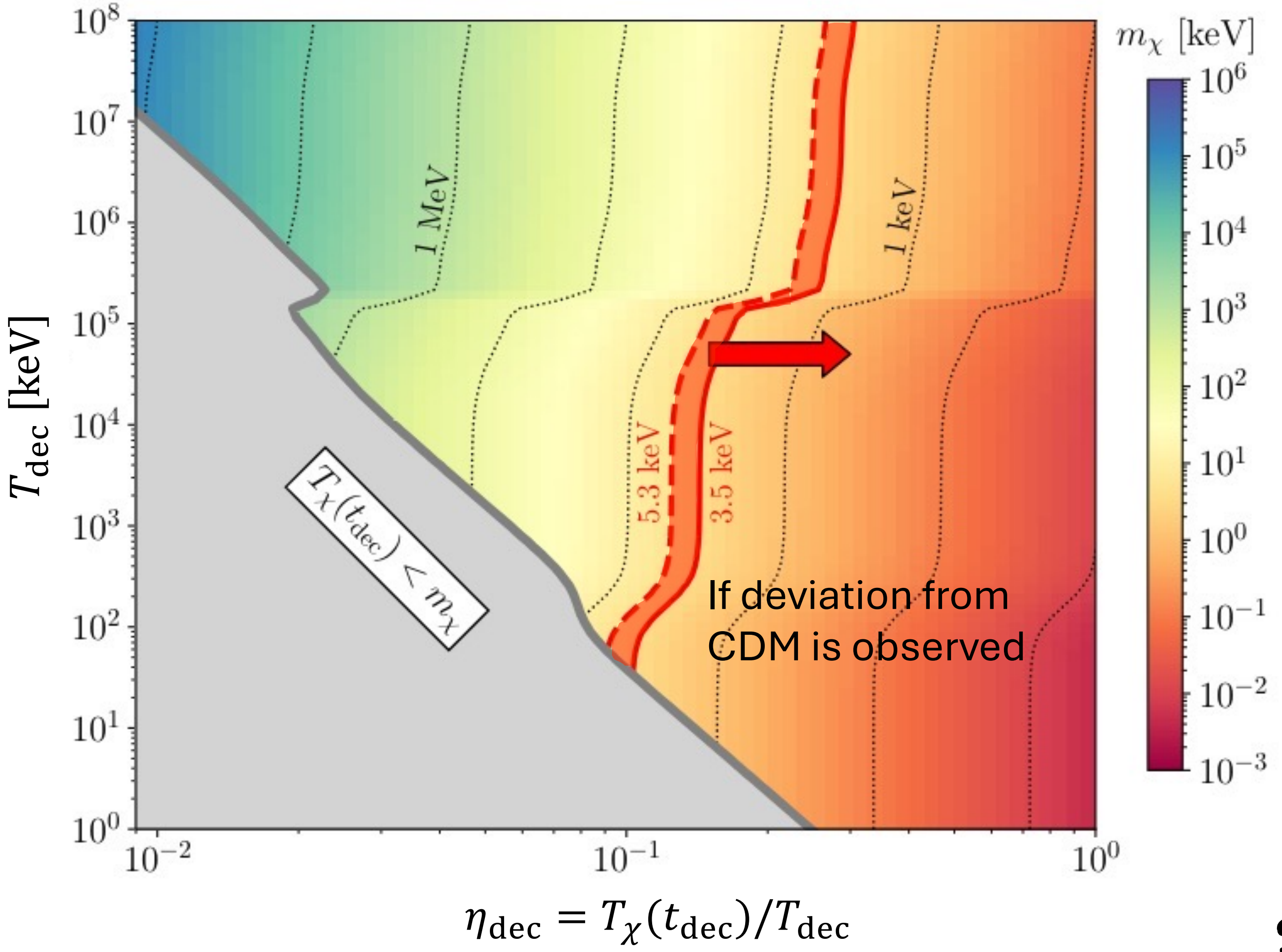

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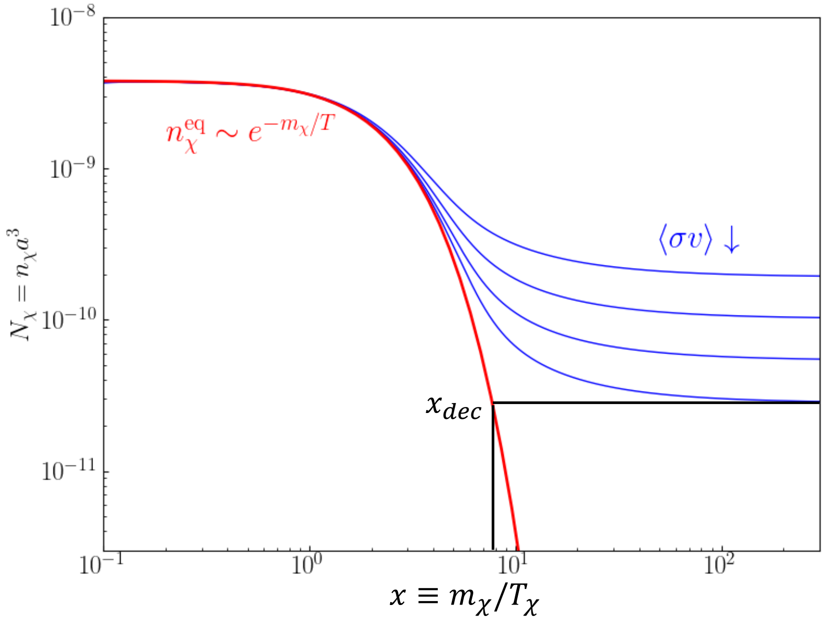

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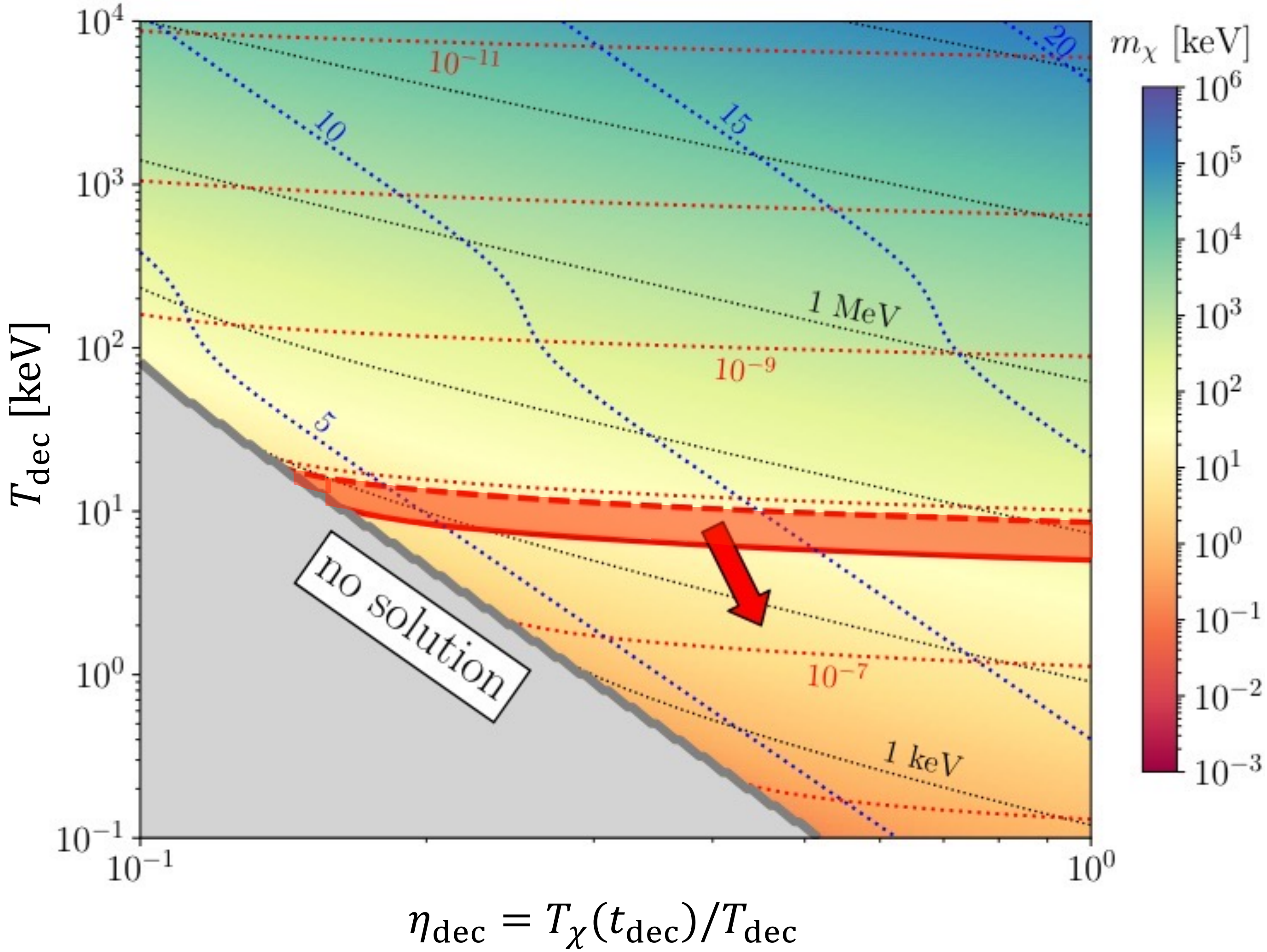

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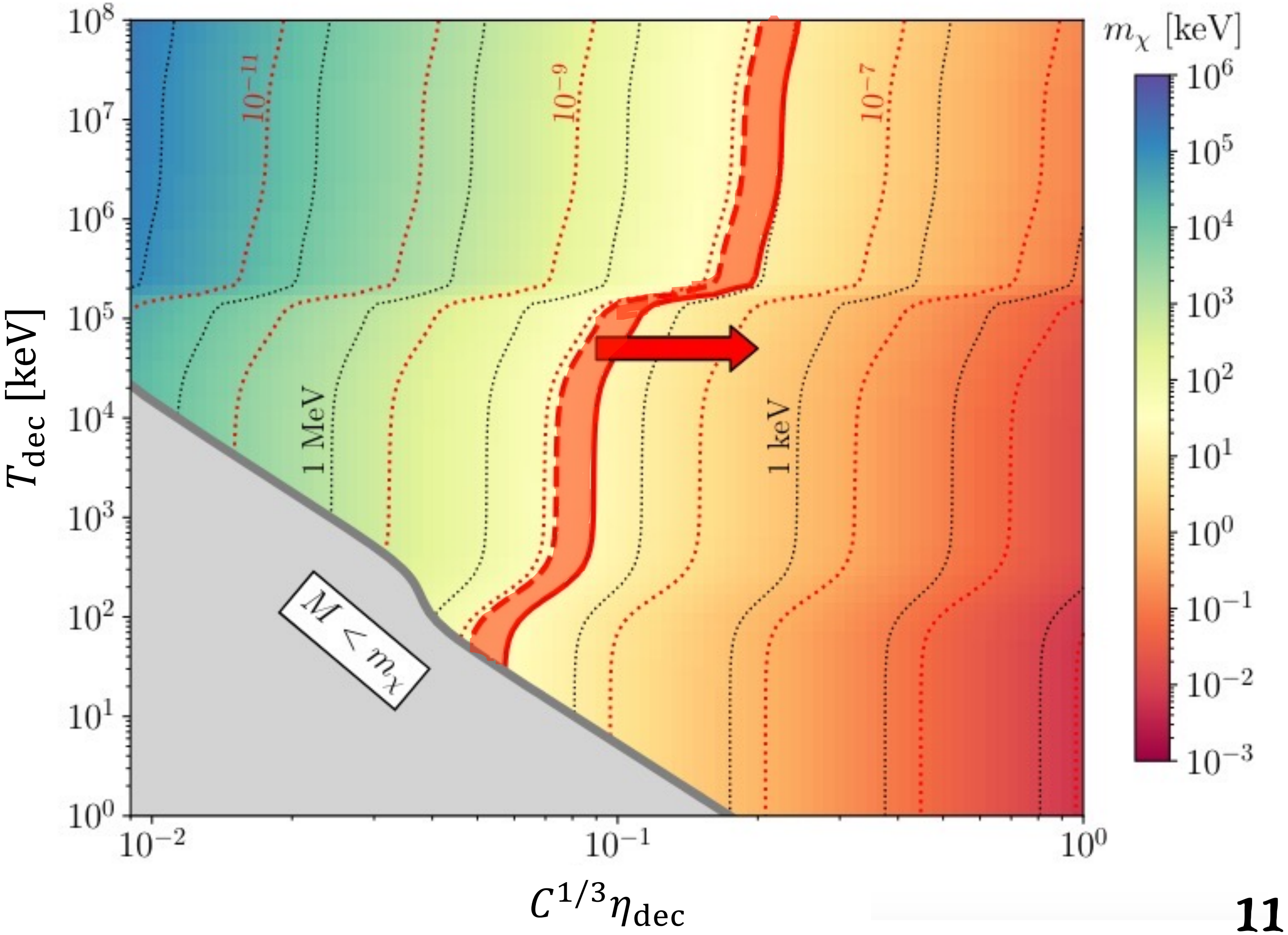

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Straightforward expectations

- A lower bound on DM velocities — *The allowed region will become a band*
- Different implications for different production mechanisms

Can we do more?

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Can we do more?

- **Differences between different production mechanisms?**
  - Different production mechanisms can give rise to the same average velocity today
  - Need to go beyond the average velocity and look at the full distribution function!

Beyond the average velocity

Solve Boltzmann equations numerically
to obtain the distribution function

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

Assuming $\psi + \psi \leftrightarrow \chi + \chi$, $m_\psi \ll m_\chi$

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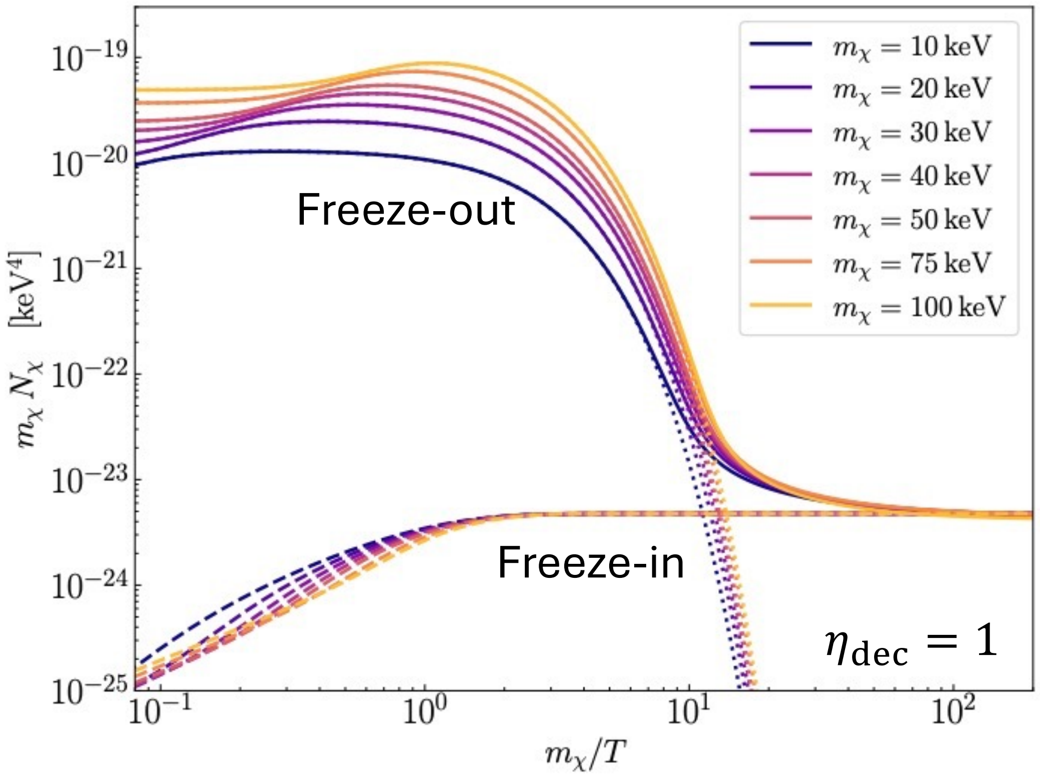

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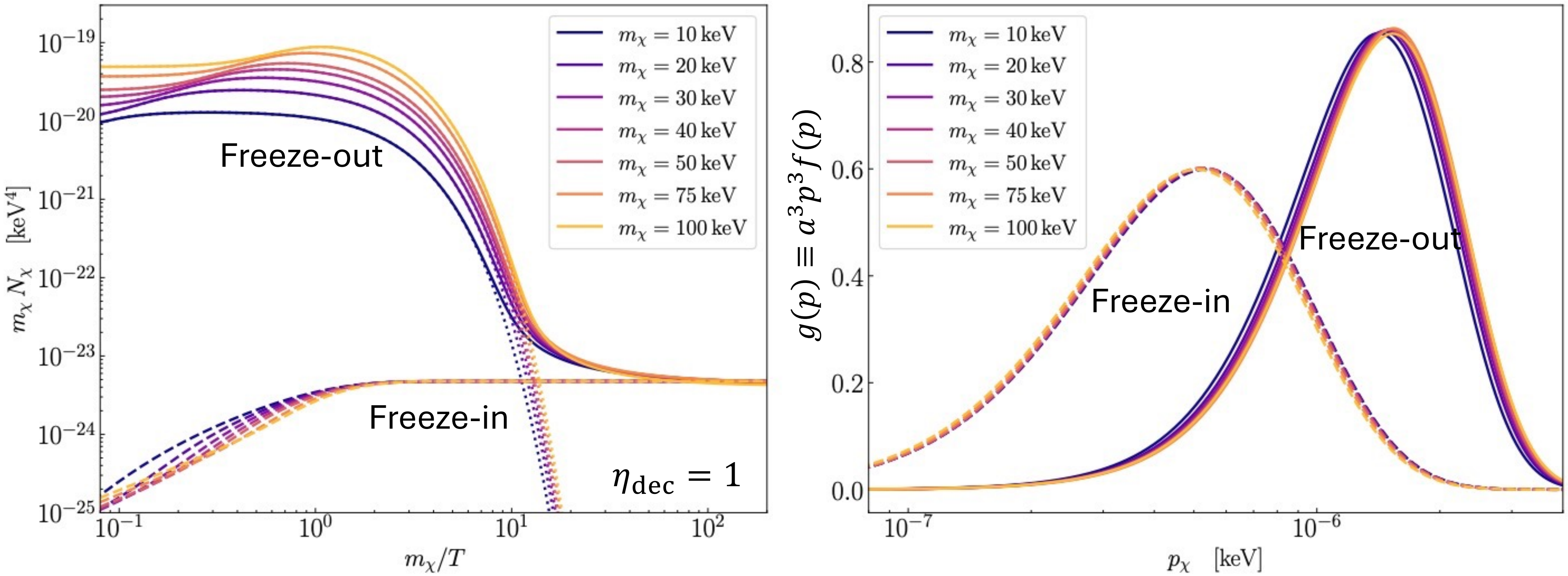

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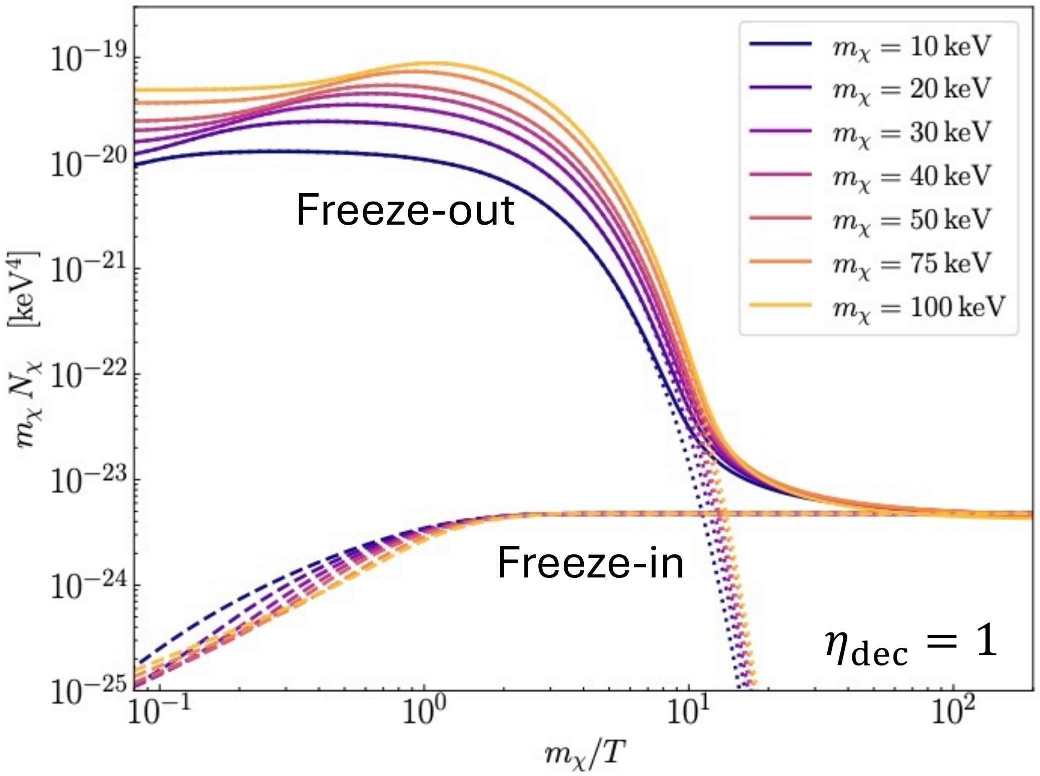
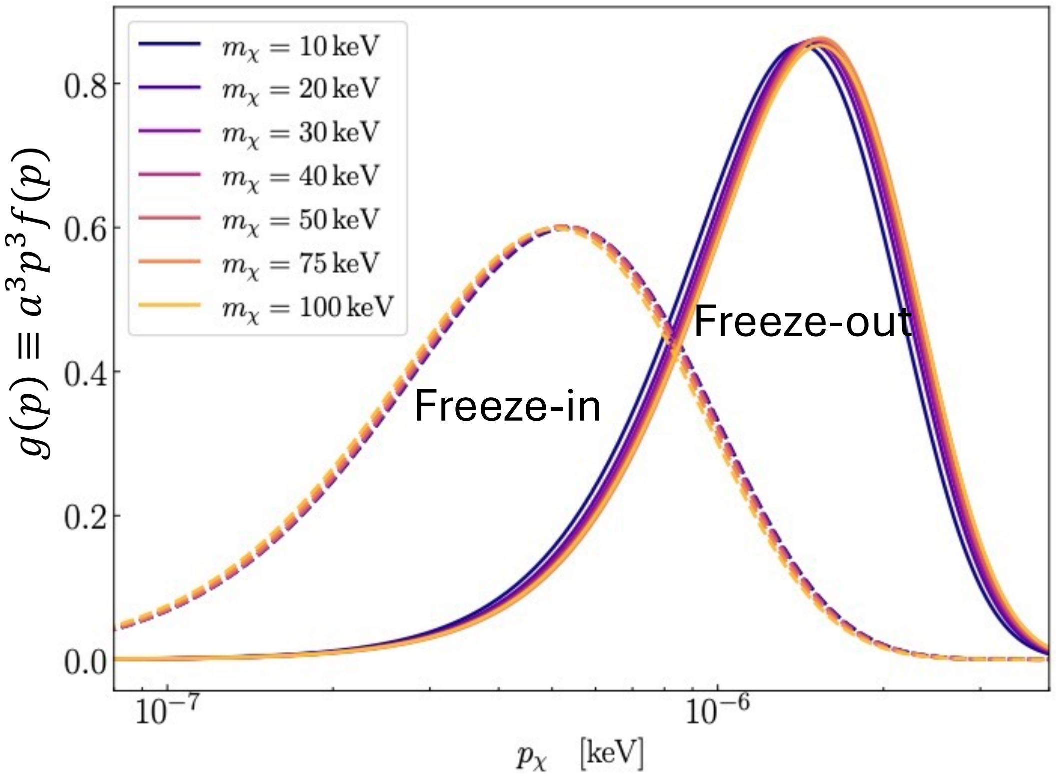
- For the ***same*** production mechanism → ***similar*** distributions
  - ***Larger mass*** → ***Smaller overall velocity***
- Distributions from freeze-in and freeze-out are ***distinct***
  - ***same mass*** → freeze-in distribution is ***colder***
  - Even if same average velocity → ***different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





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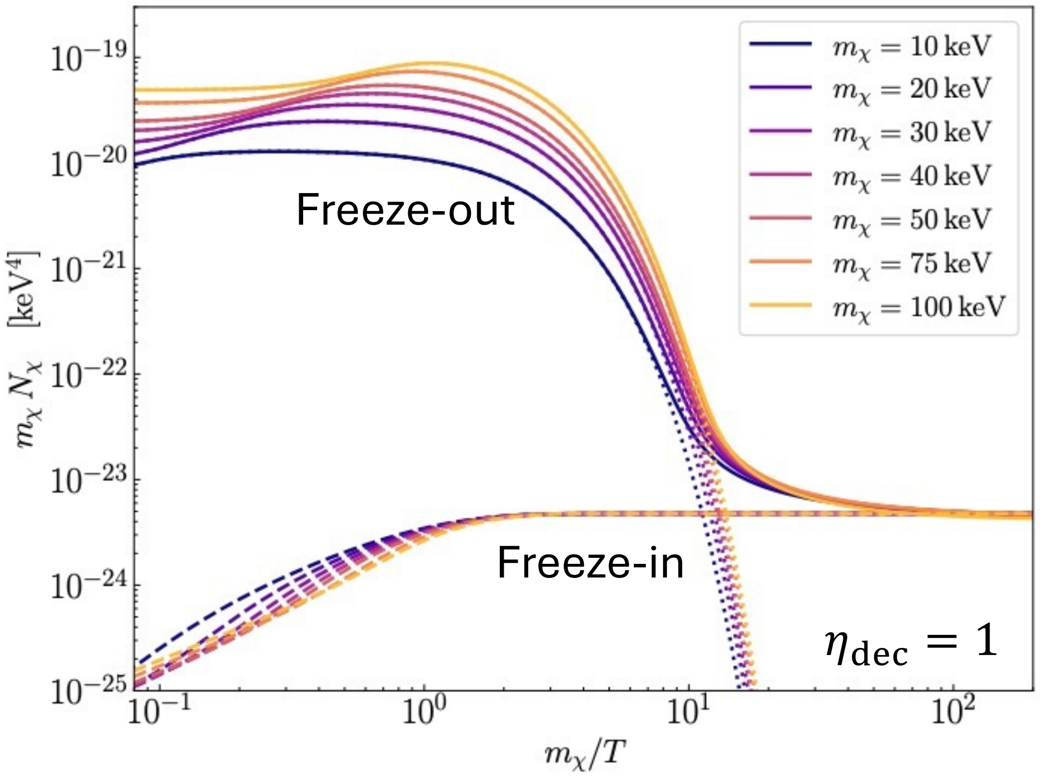
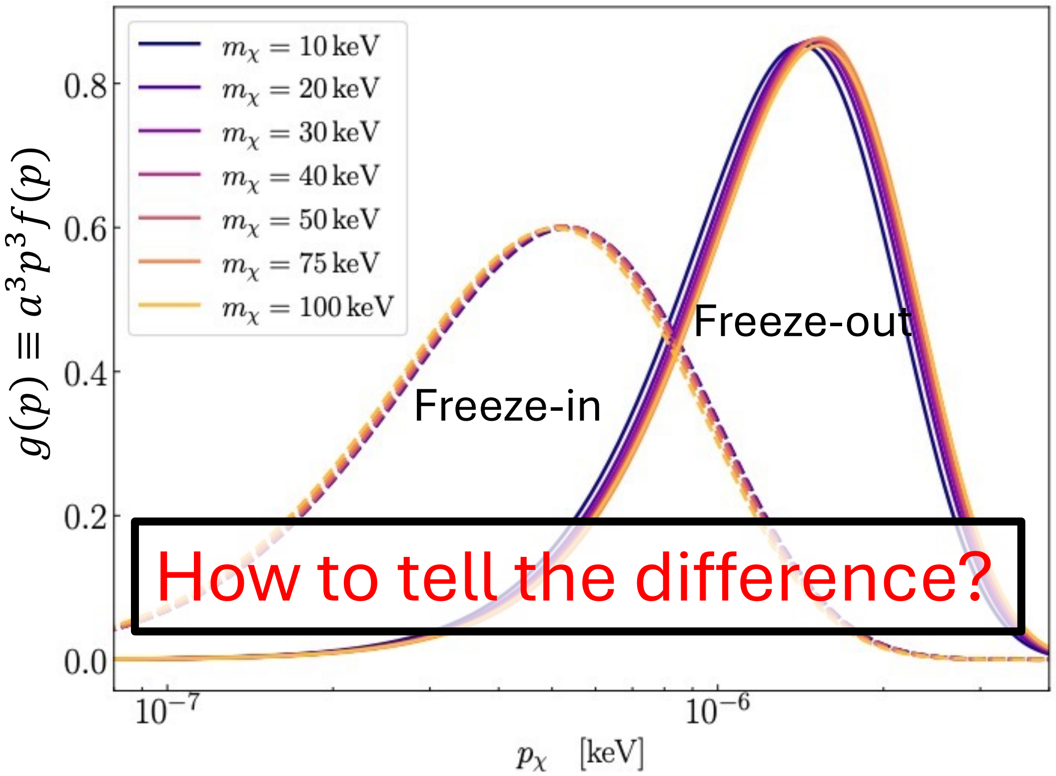
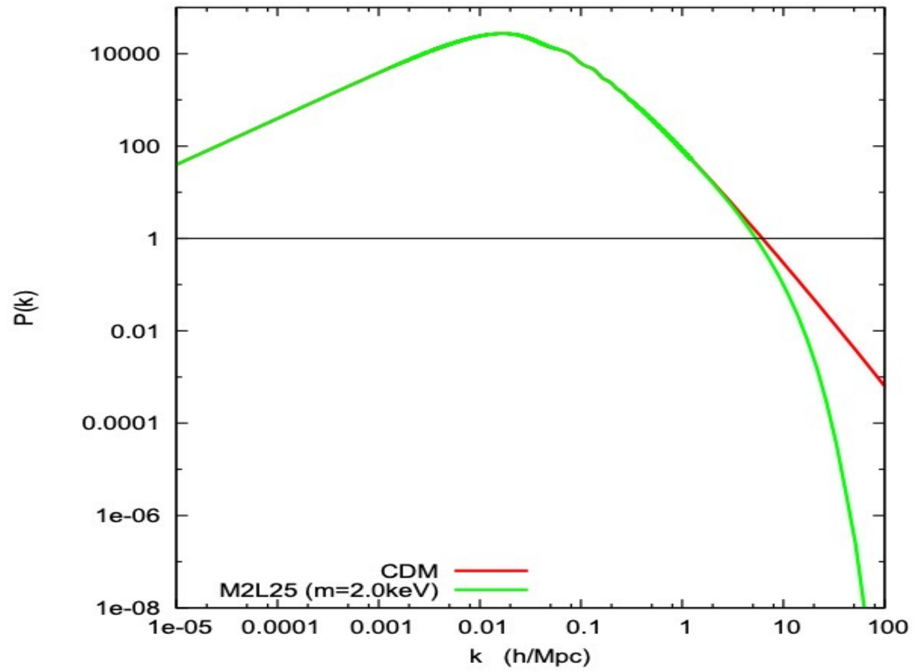




Imprints on cosmic structure

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

$$P(k)$$



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

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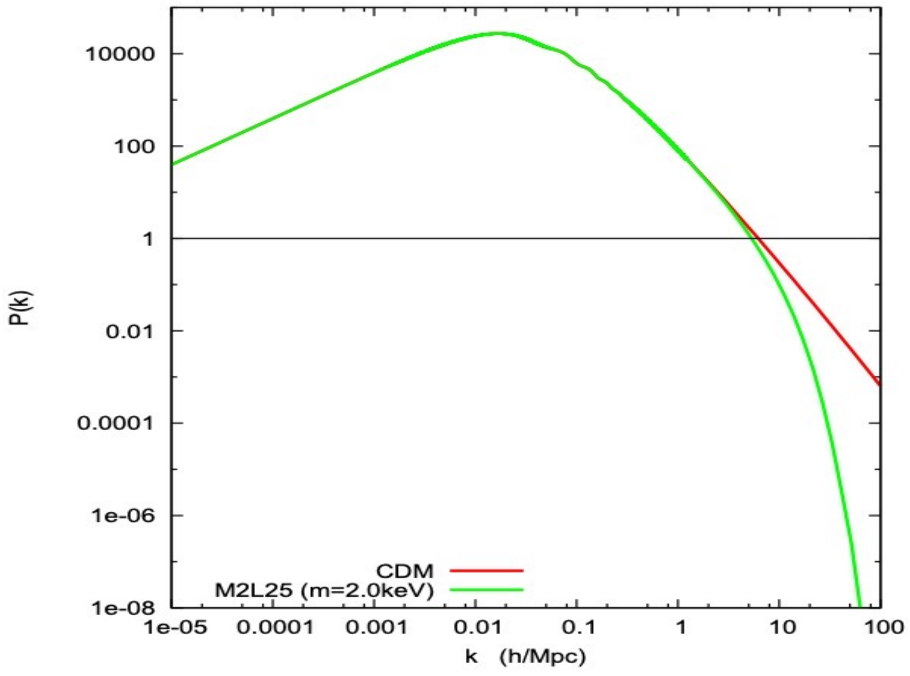
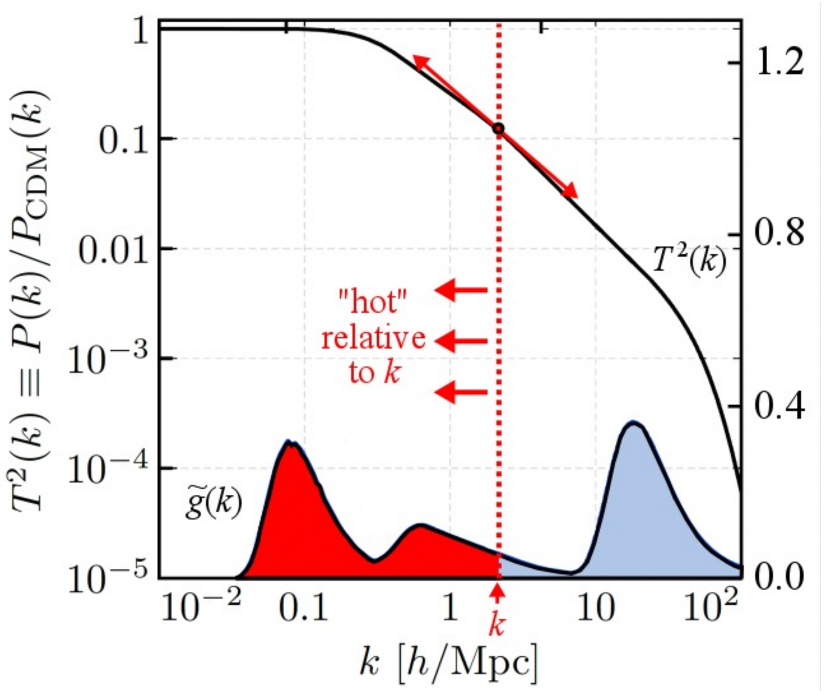
- Often represented by the ***squared transfer function***

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

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



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



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

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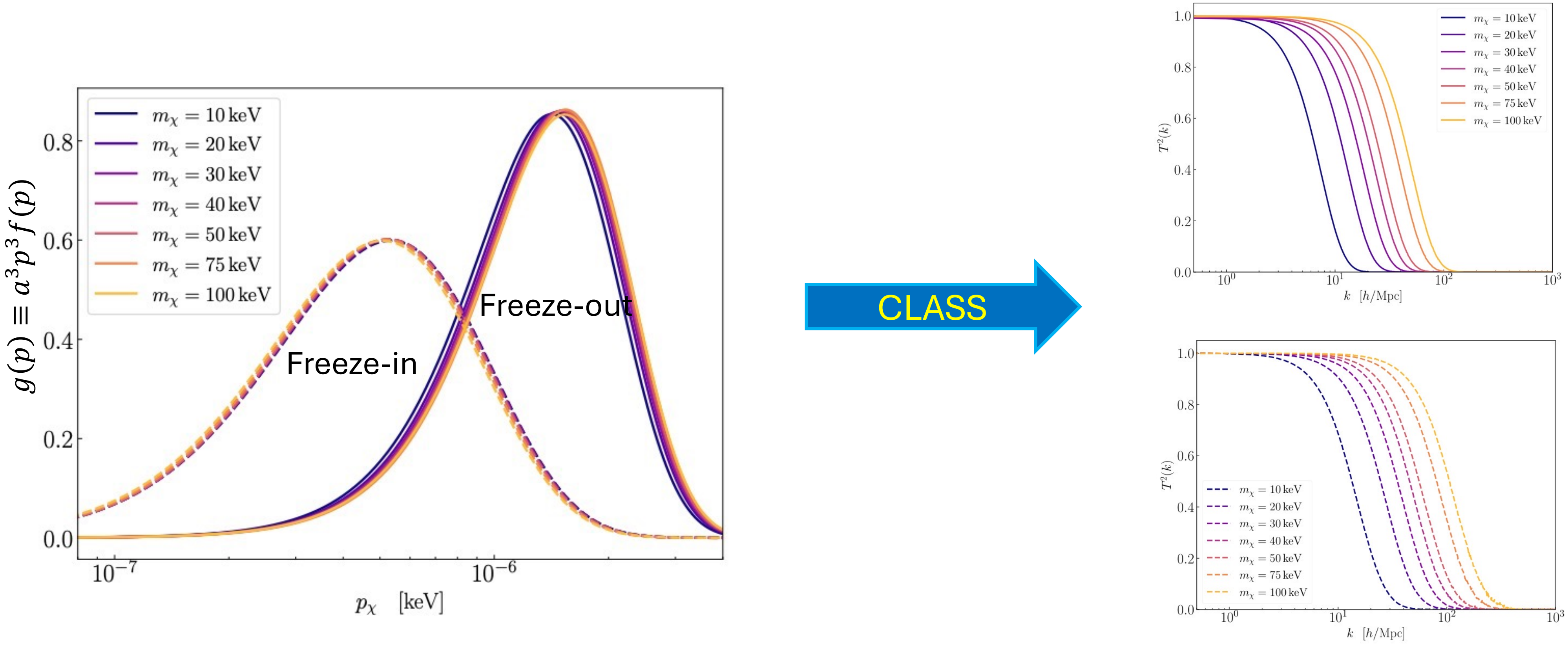

Freeze-out

Freeze-in

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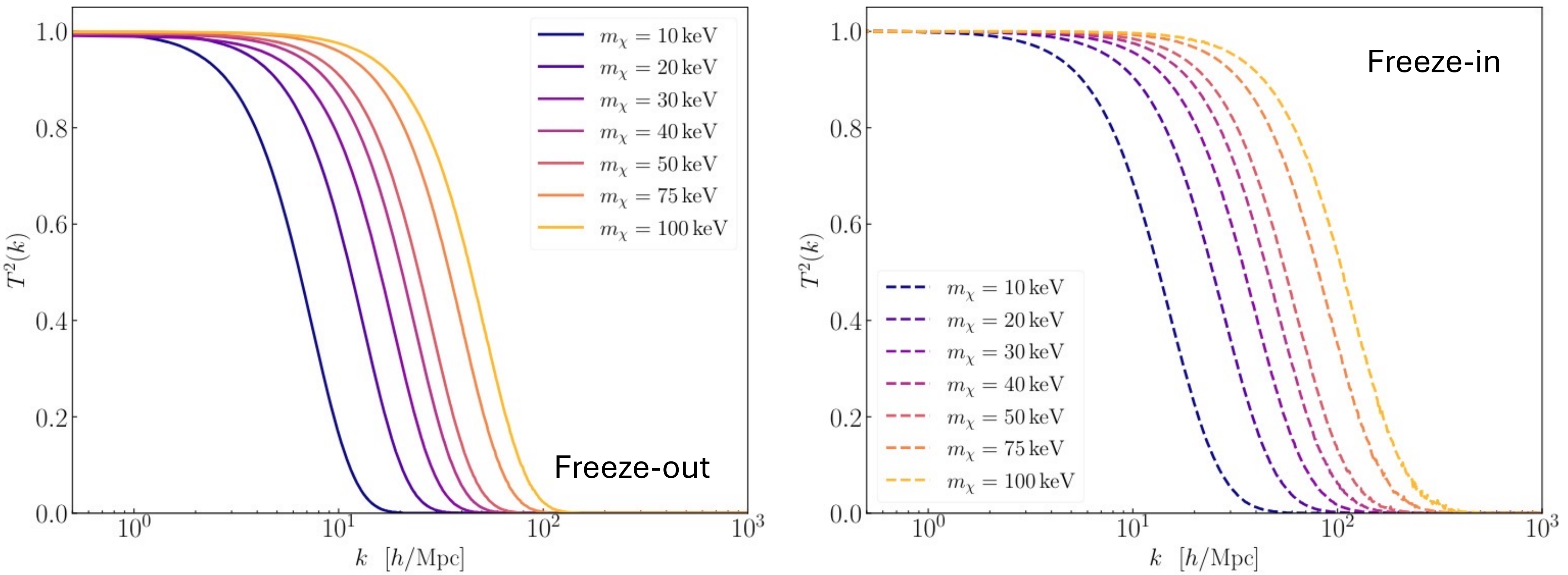

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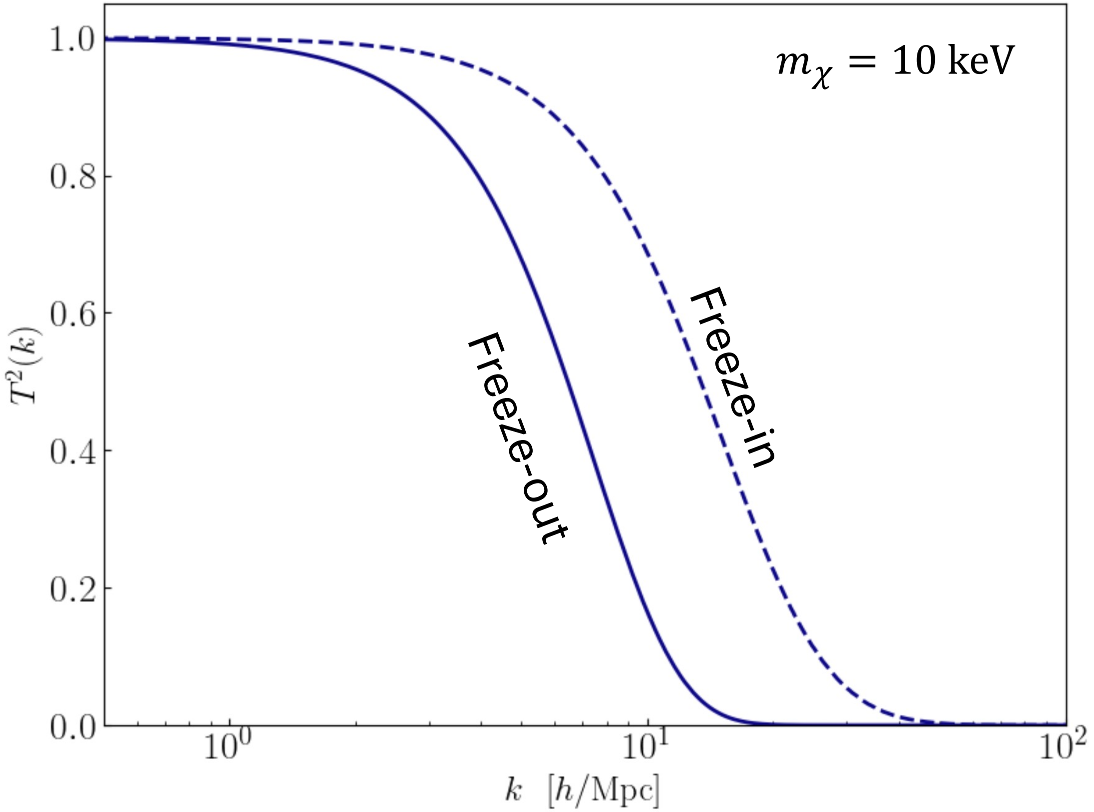

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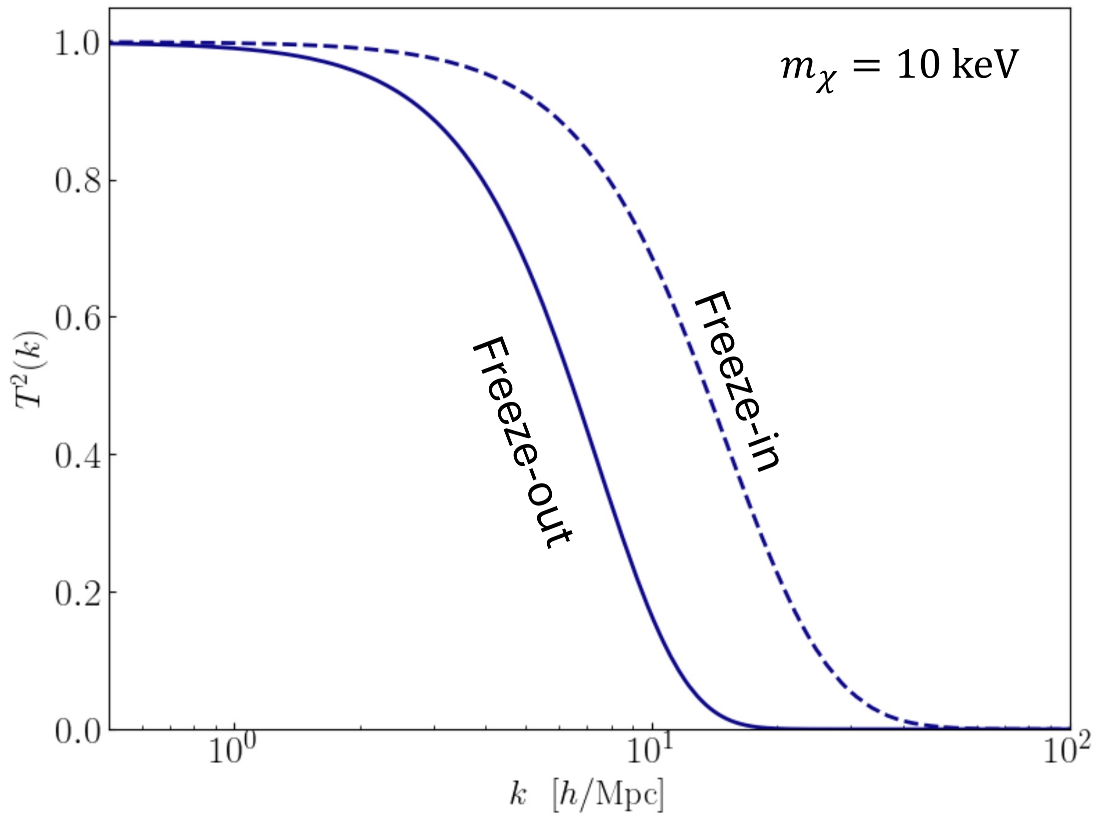

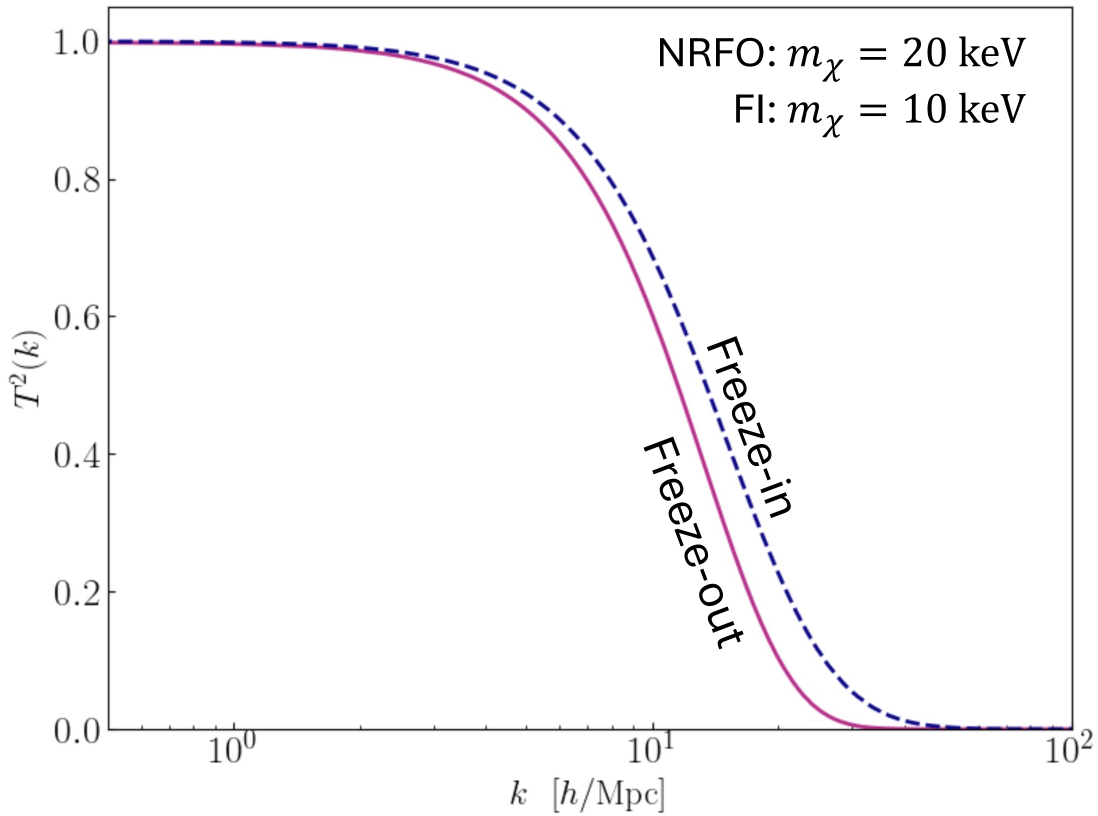

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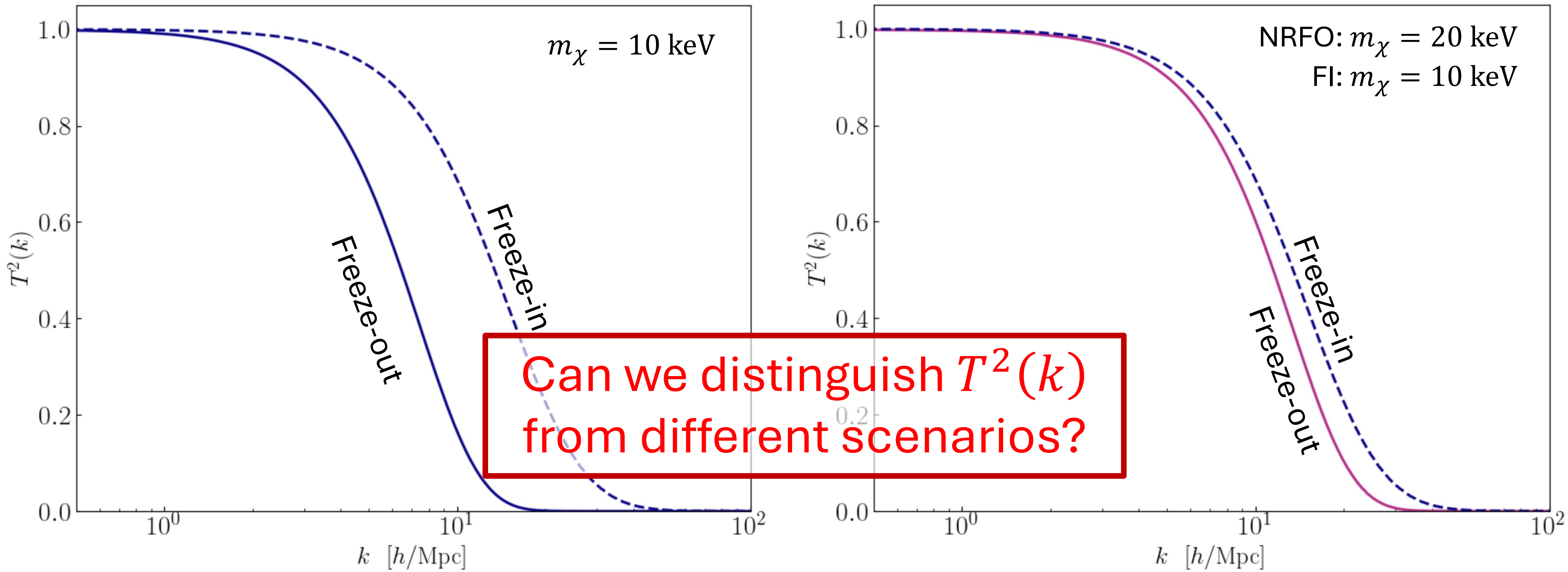

Can we distinguish $T^2(k)$ from different scenarios?

Distinguishing different scenarios

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

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

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- Explore different possibilities

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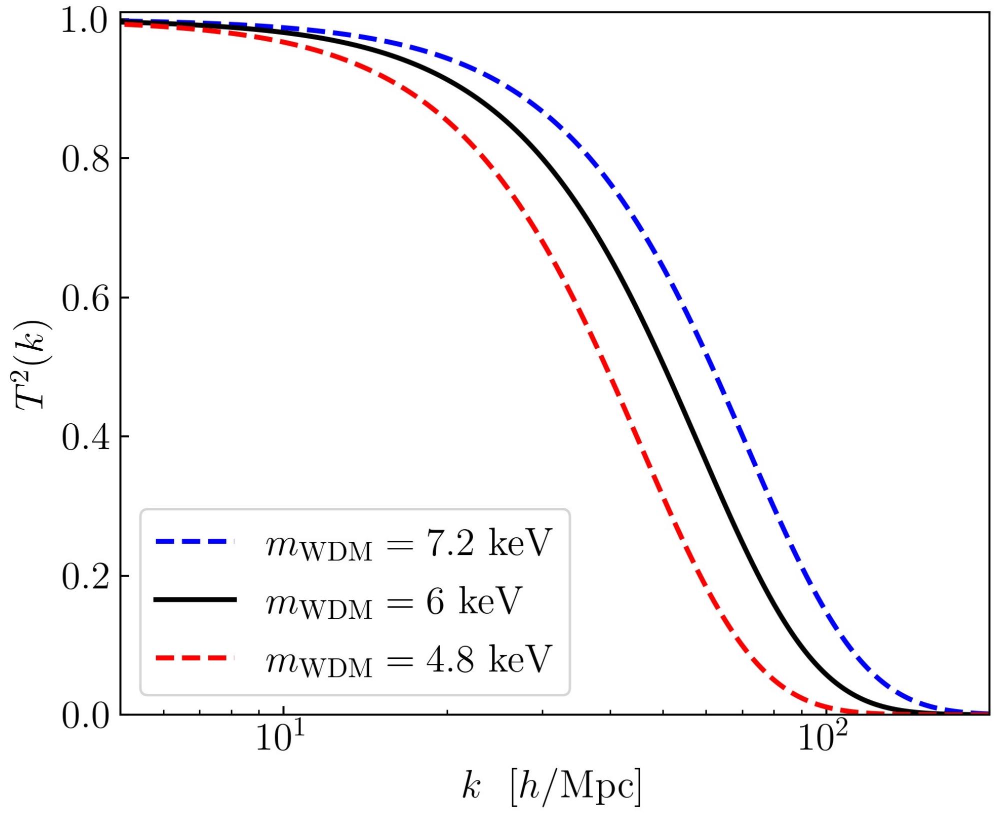
- Explore different possibilities: e.g., $P(k)$ characterized by a ***WDM mass range***

$$m_{\rm WDM}^{\rm ref}(1+\sigma_{m_{\rm WDM}}) > m_{\rm WDM} > m_{\rm WDM}^{\rm ref}(1-\sigma_{m_{\rm WDM}})$$



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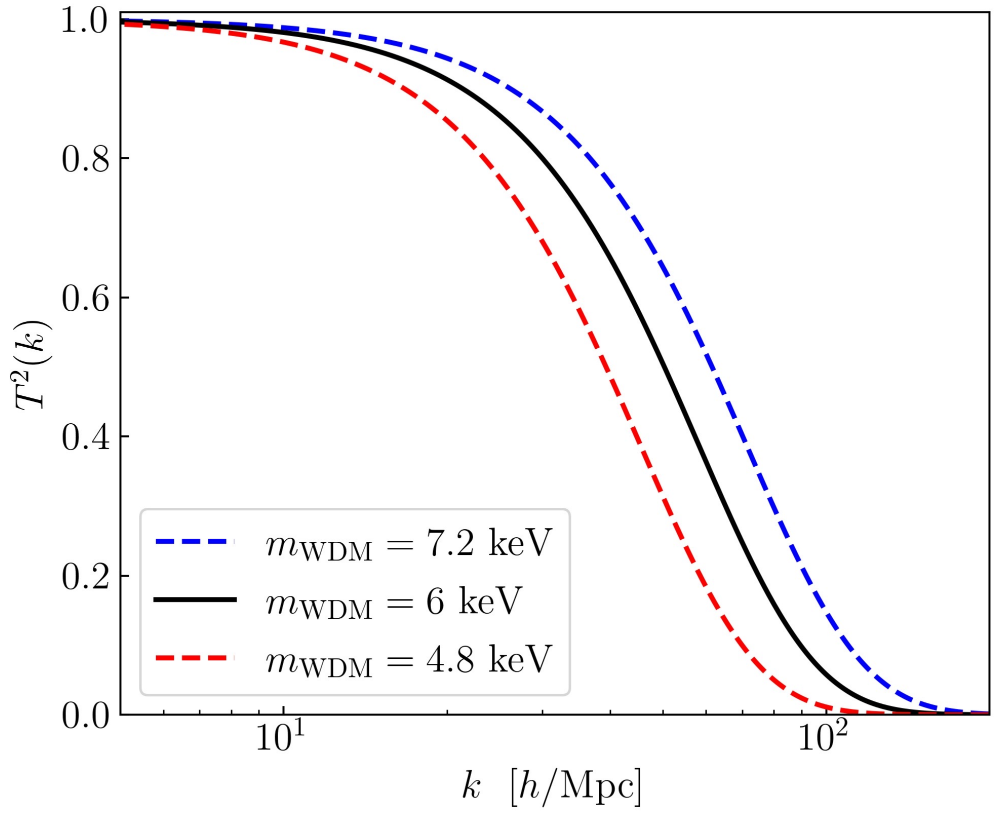

δA analysis: R. Murgia et al. JCAP 11 (2017) 046

$$P_{\rm 1D}(k) \equiv \frac{1}{2\pi}\int_k^\infty dk'\ k' P(k')$$

$$A \equiv \int_{k_{\rm min}}^{k_{\rm max}} dk\ \frac{P_{\rm 1D}(k)}{P_{\rm 1D}^{\rm CDM}(k)}$$

$k_{max} = 20\ h/Mpc$

$k_{min} = 0.5\ h/Mpc$

$$\delta A \equiv 1 - A/A_{\rm CDM}$$

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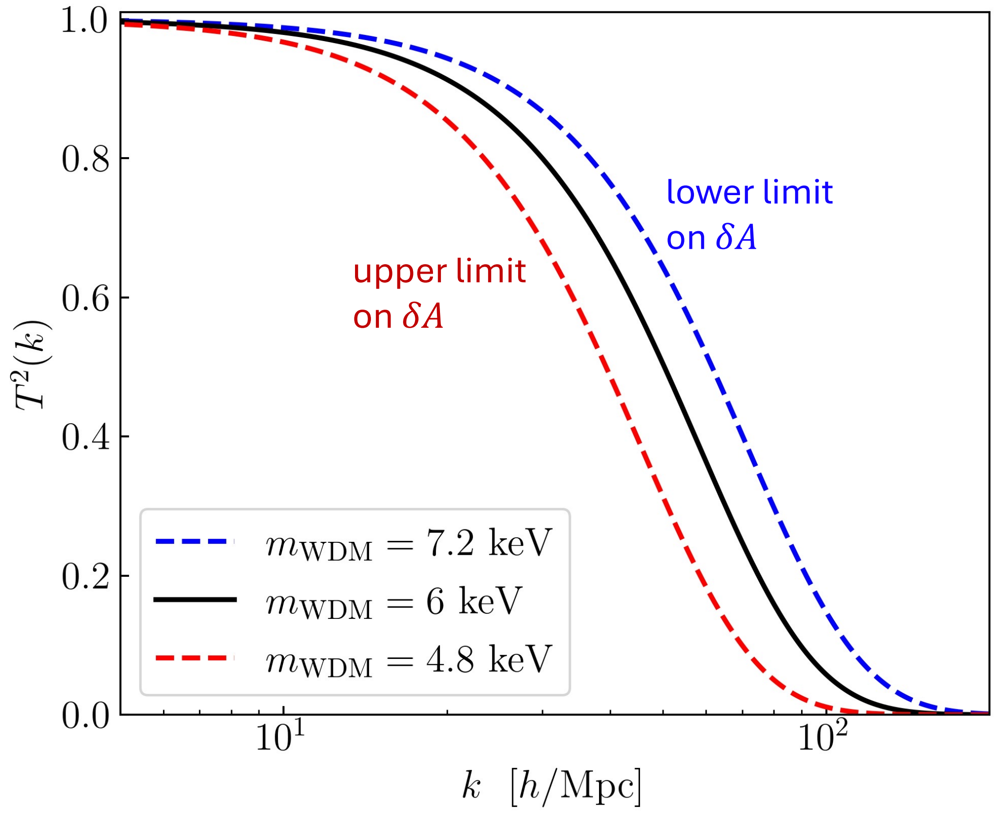

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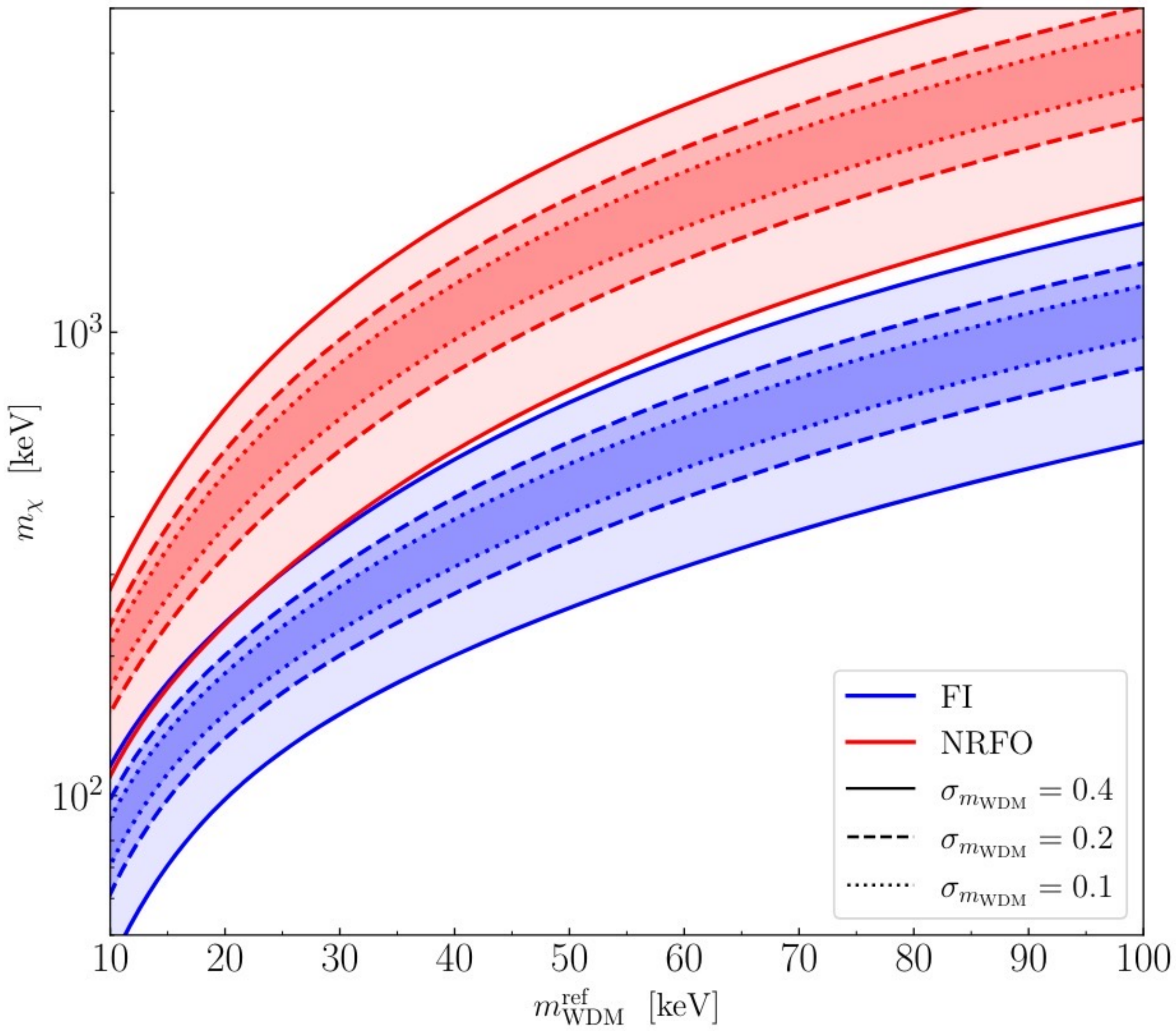
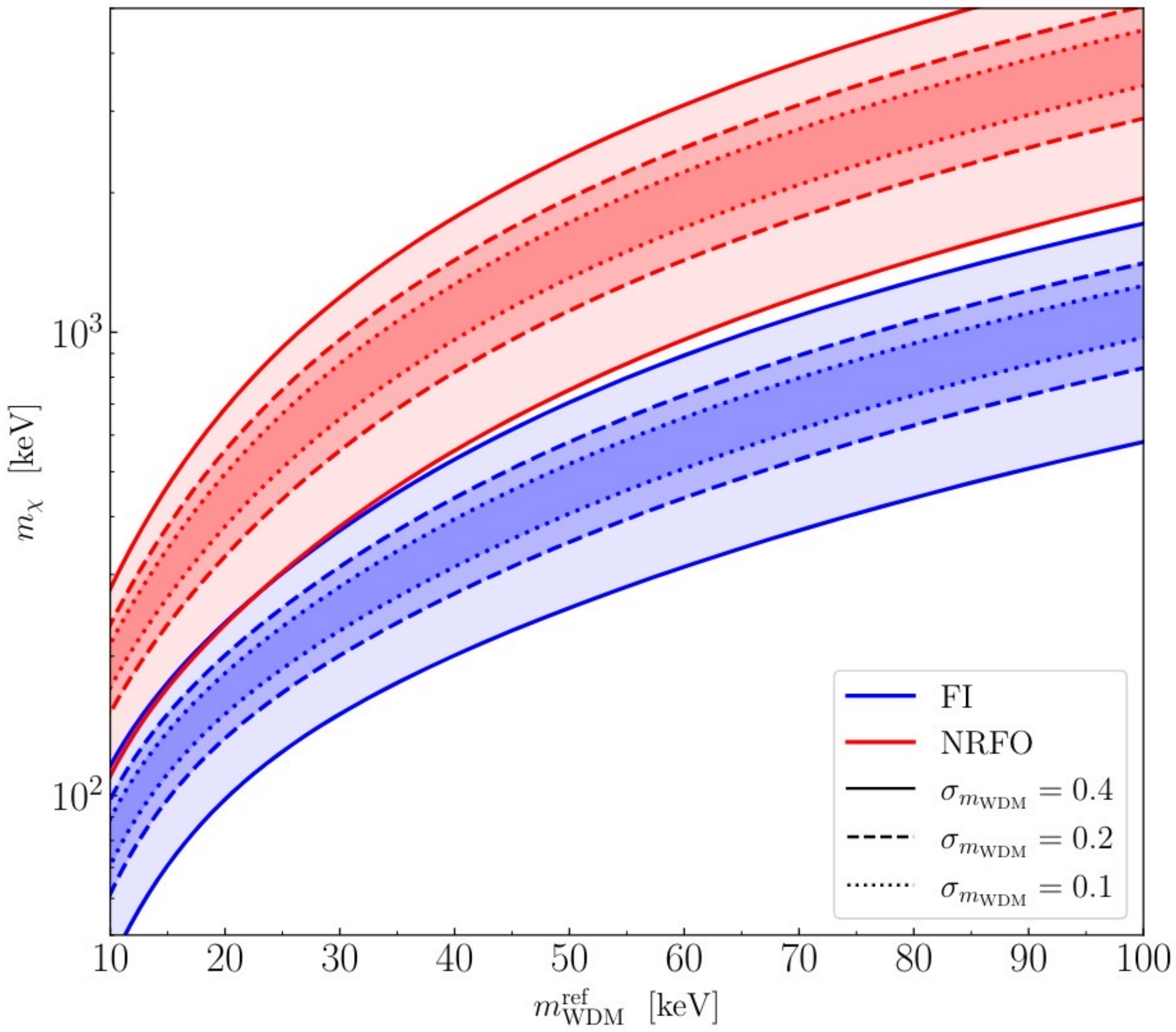
- Different allowed mass ranges for FI and NRFO
- Allowed regions are completely separated given sufficiently small uncertainties



Distinguishing different scenarios

- Different allowed mass ranges for FI and NRFO
- Allowed regions are completely separated given sufficiently small uncertainties
- < 1 keV uncertainty from future global 21 cm measurement forecasted by J. Hibbard et al.

  Astrophys.J. 929 (2022) 2, 151



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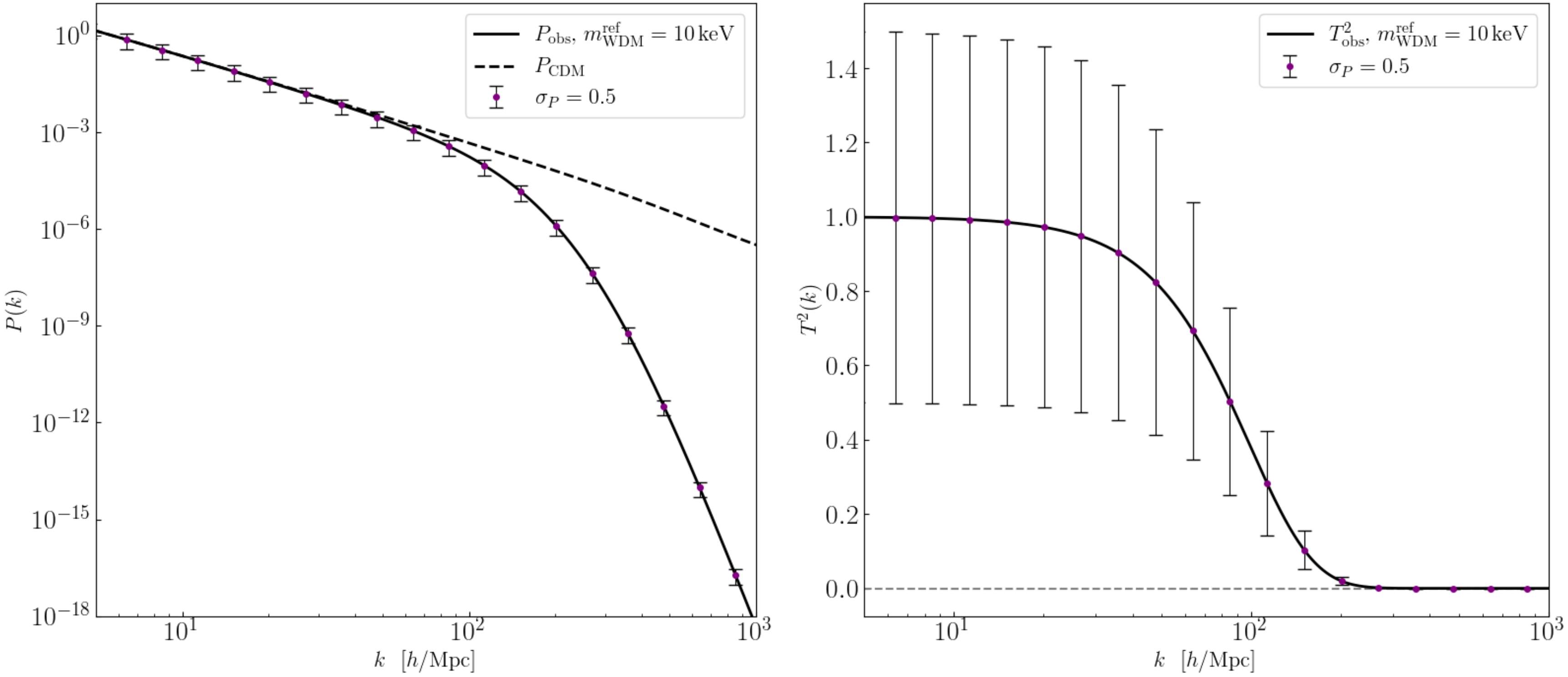
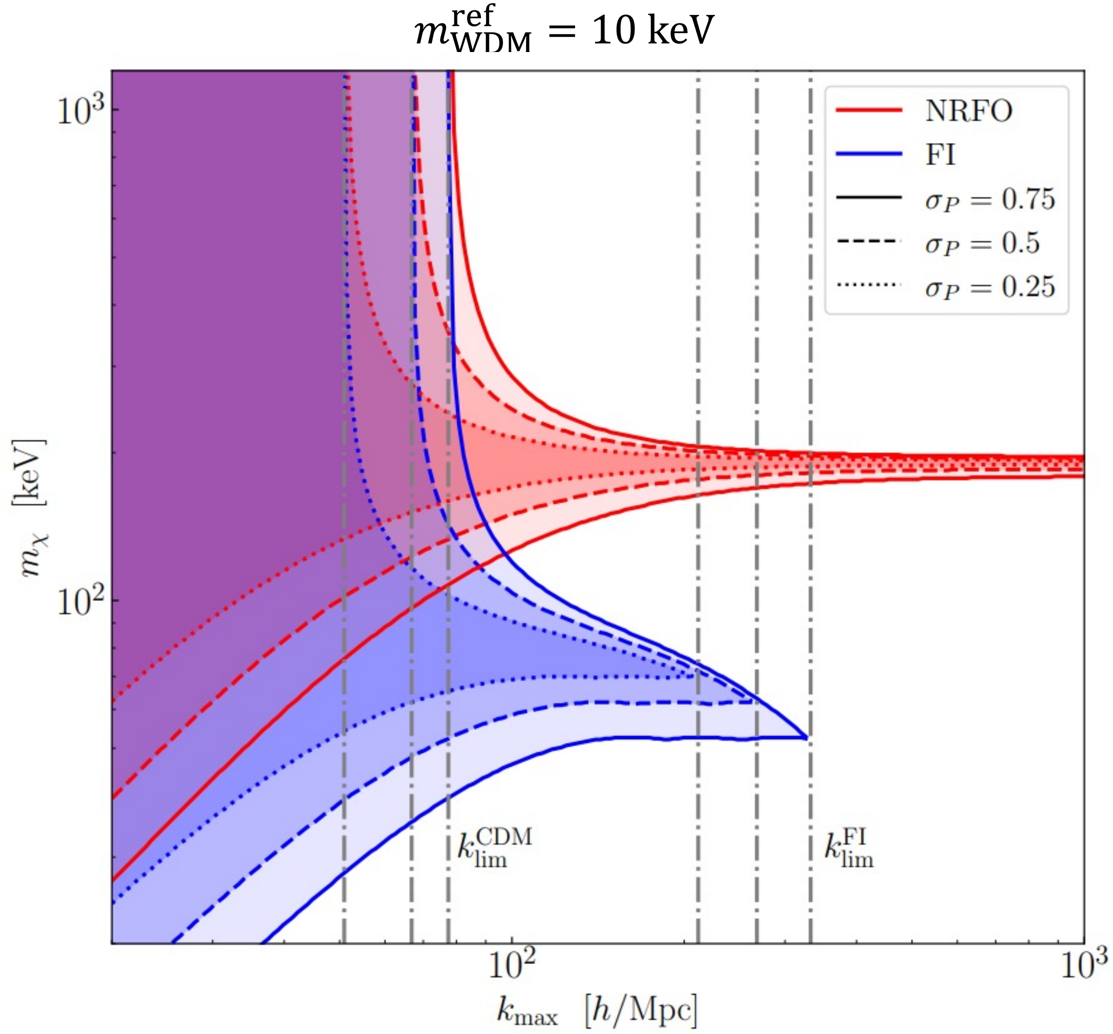
- Explore different possibilities: e.g., ***constant symmetric relative errors*** on $P(k)$

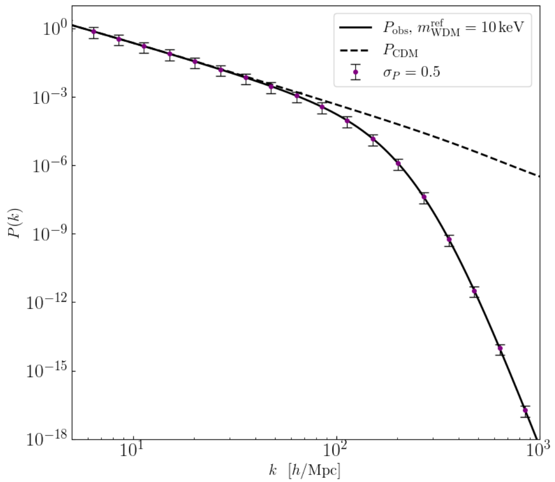
$$\sigma_P^{\pm}(k) = \sigma_P$$



Distinguishing different scenarios

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





constant symmetric relative errors on $P(k)$

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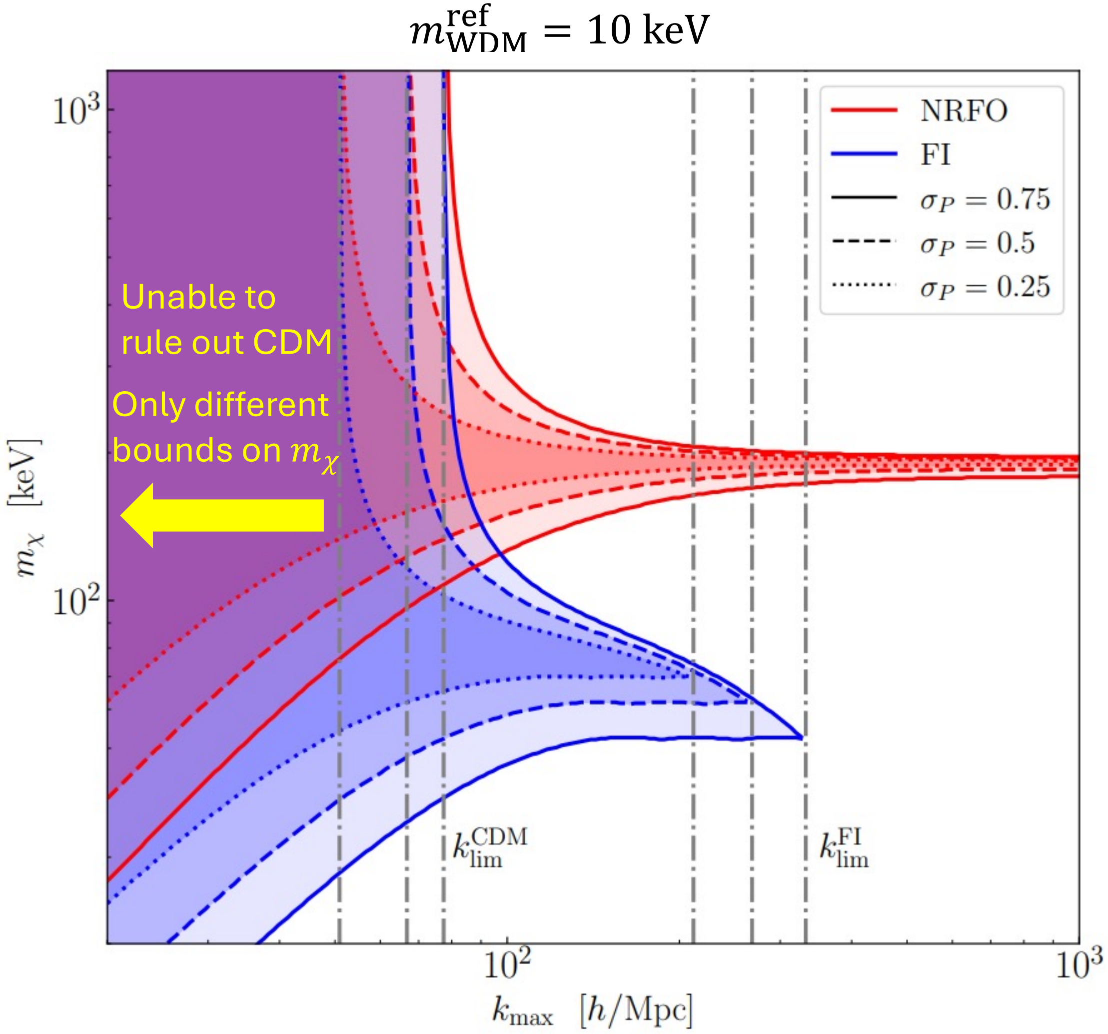

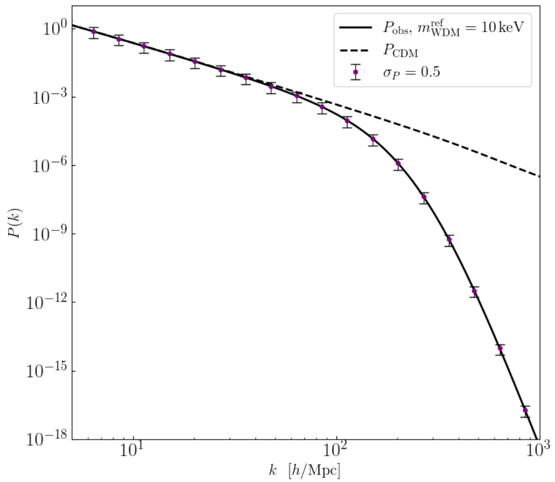

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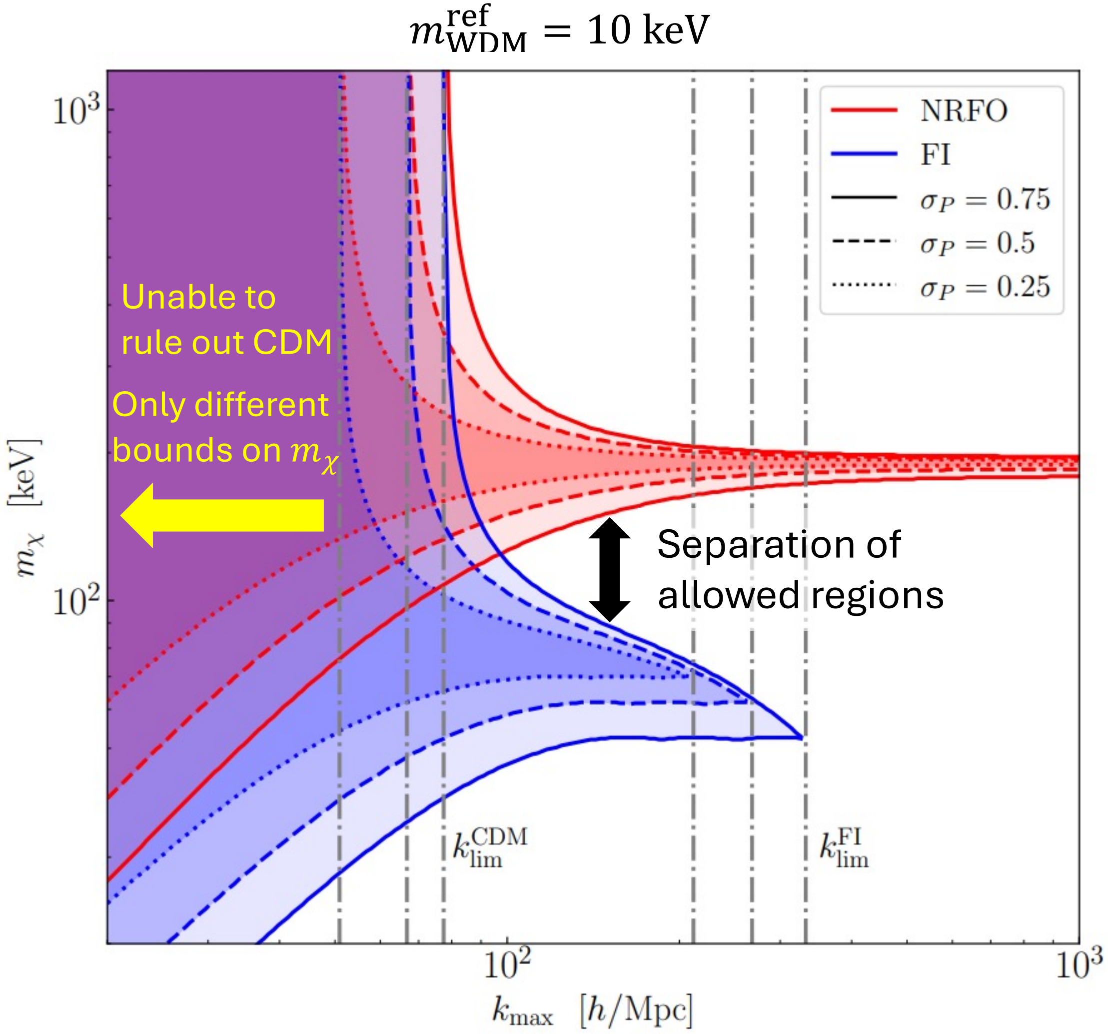

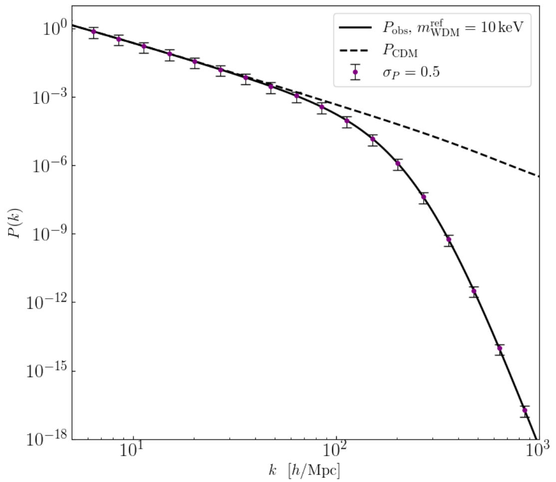

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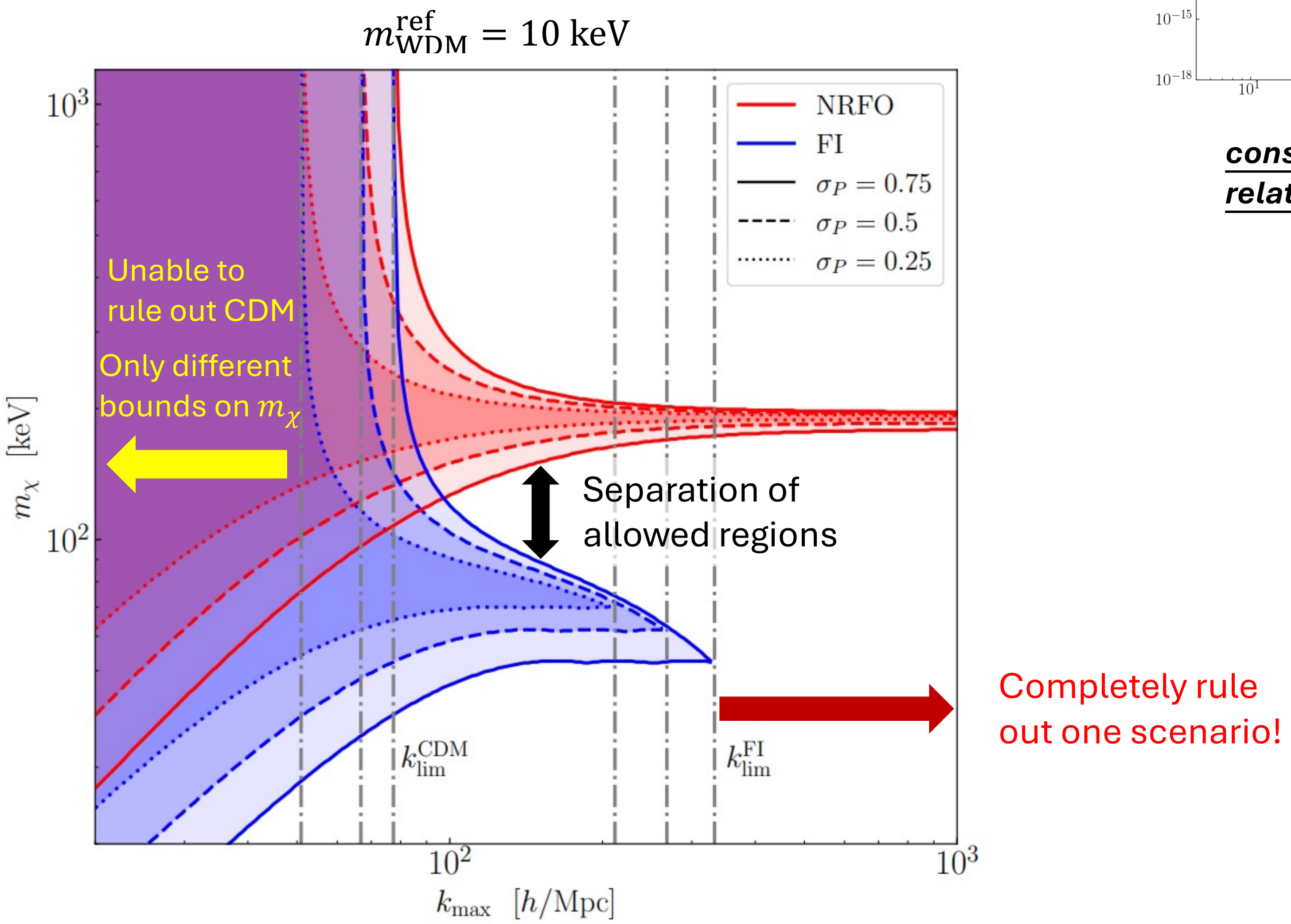

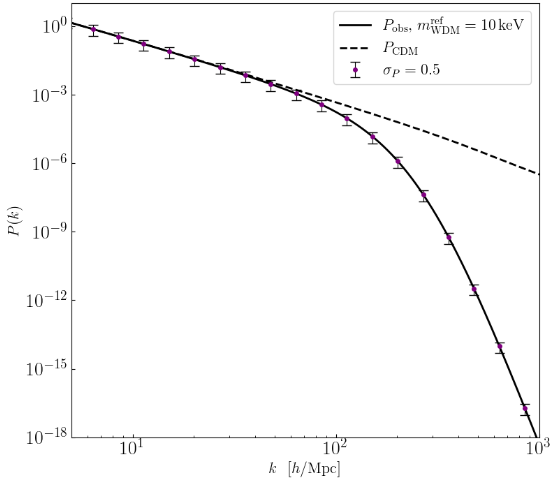

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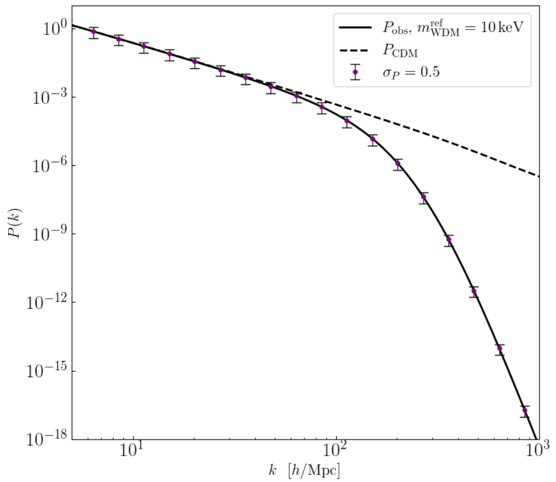
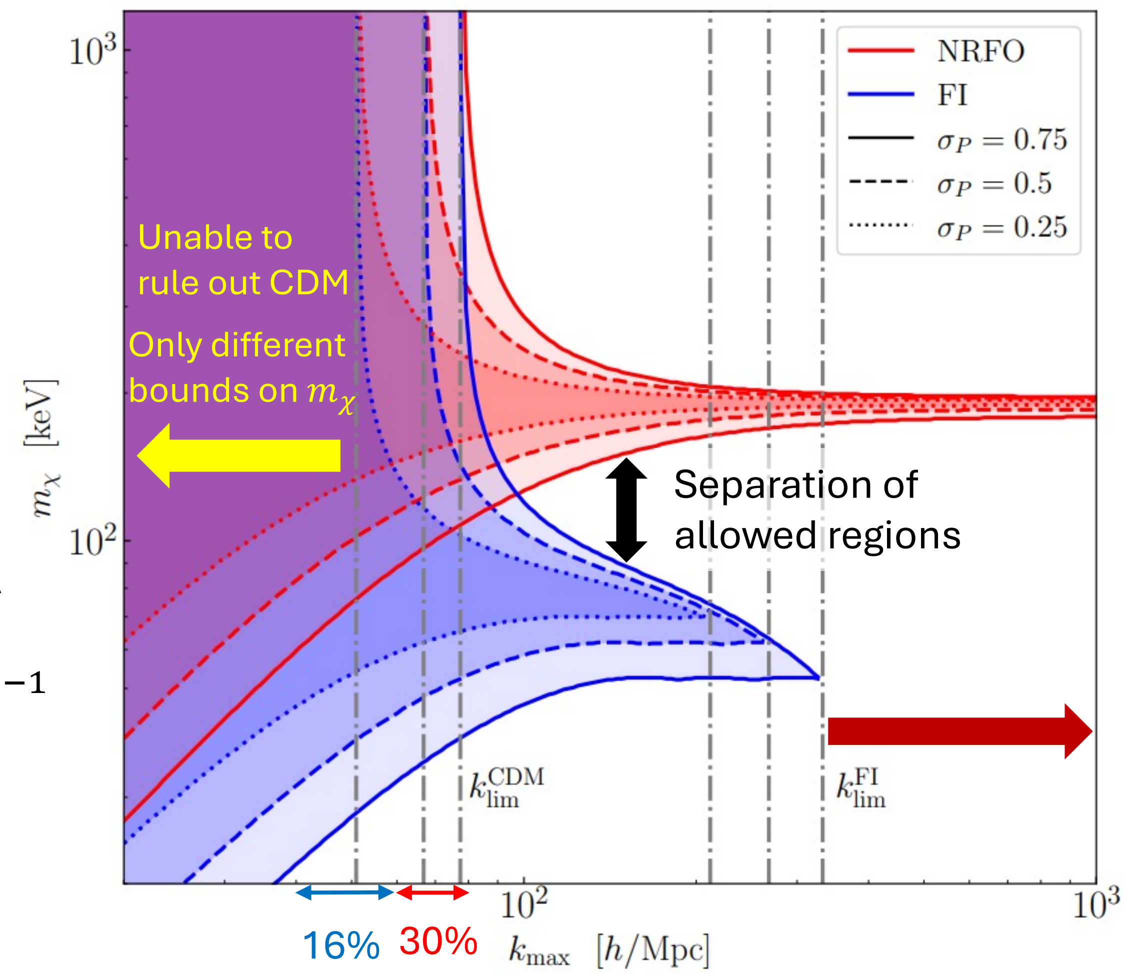


constant symmetric relative errors on $P(k)$

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



Completely rule out one scenario!

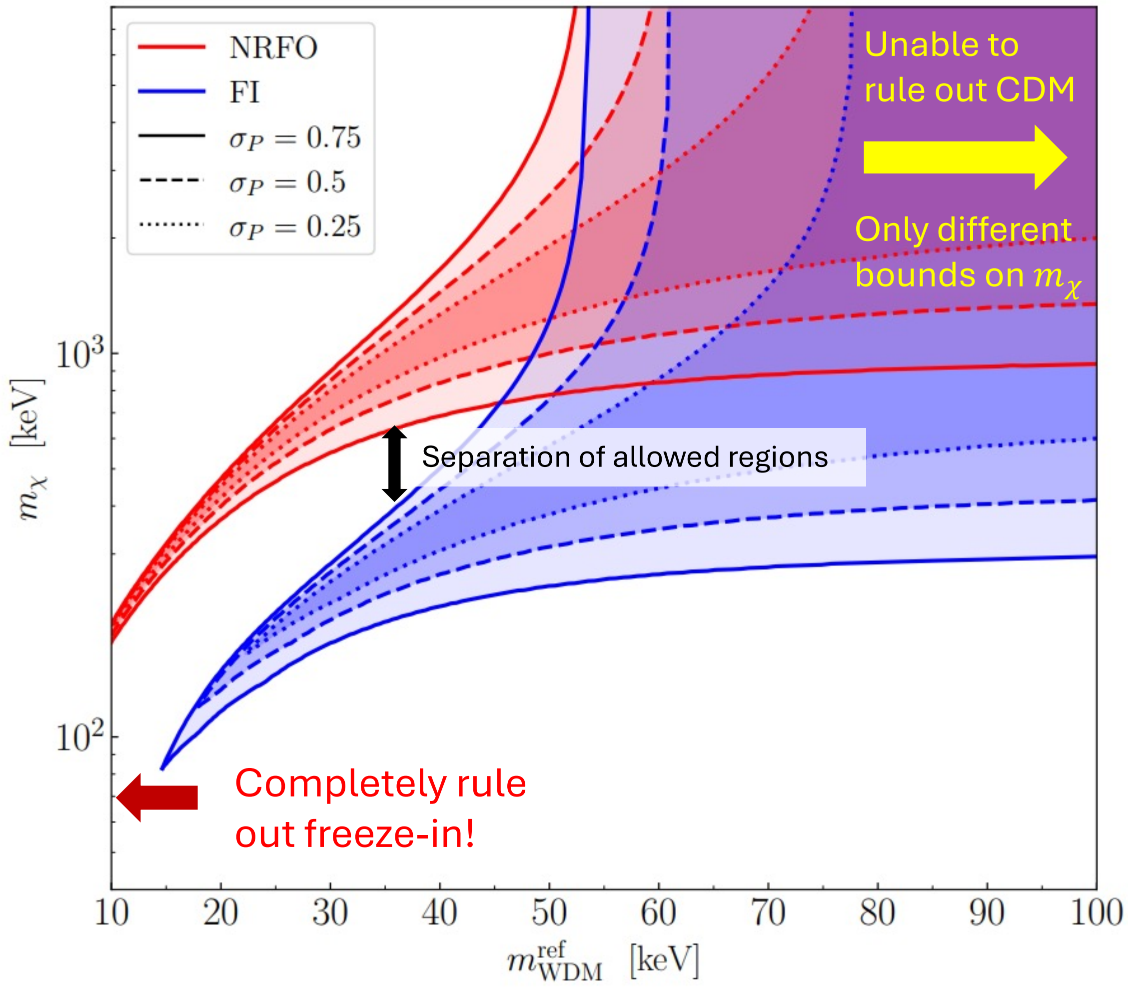
Forecasts on 21 cm fluctuation measurements show that HERA can measure matter power spectrum up to $k \approx 40{\sim}80\ \mathrm{Mpc}^{-1}$ with precision 16~30 %

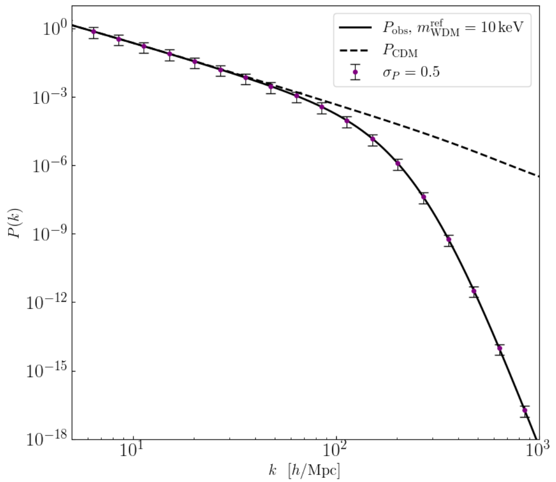
J. Muñoz, C. Dvorkin, F. Cyr-Racine
Phys.Rev.D 101 (2020) 6, 063526

Distinguishing different scenarios

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

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





constant symmetric relative errors on $P(k)$

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