Minimal Dark Matter Freeze-in with Low Reheating Temperatures & Implications for Direct Detection

Gabriele Montefalcone

Weinberg Institute for Theoretical Physics, University of Texas at Austin

Based on work with Katherine Freese, Kimberly Boddy & Barmak Shams Es Haghi (arXiv:2405.06226)

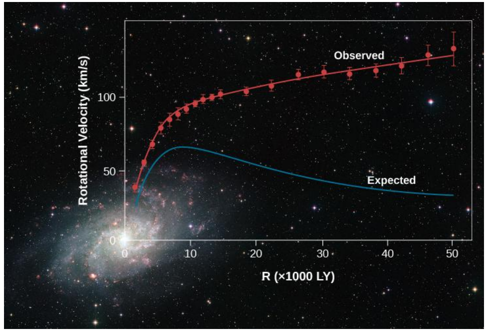
TEXAS

The University of Texas at Austin

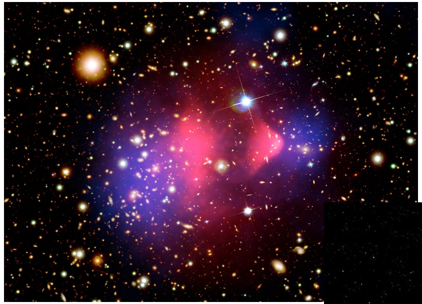
Evidence for Dark Matter (DM)

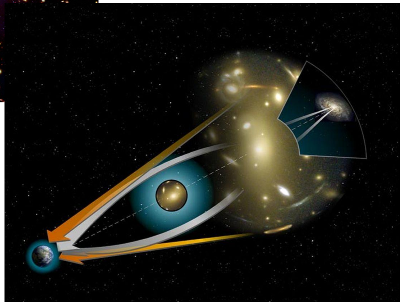
Huge amount of evidence from all scales (only from gravitational interaction)

Galactic scales

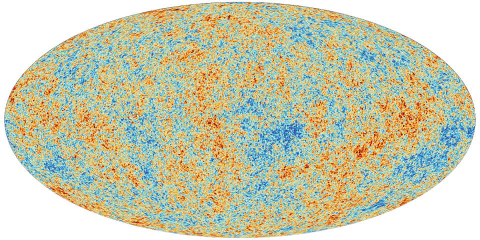


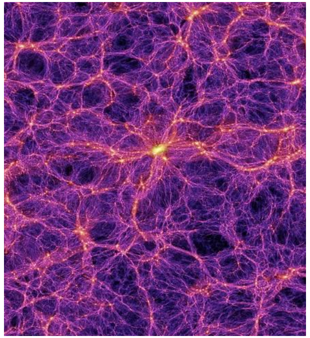
Cluster scales





Cosmological scales





What we know about DM

- Cold and Massive
- Stable/long lived
- No/weak interactions with the Standard Model (SM)
- No/weak SM charge (electric and color)
- Abundance: DM corresponds to **%25** of the energy budget in the universe today (**~5x** the amount of ordinary matter)

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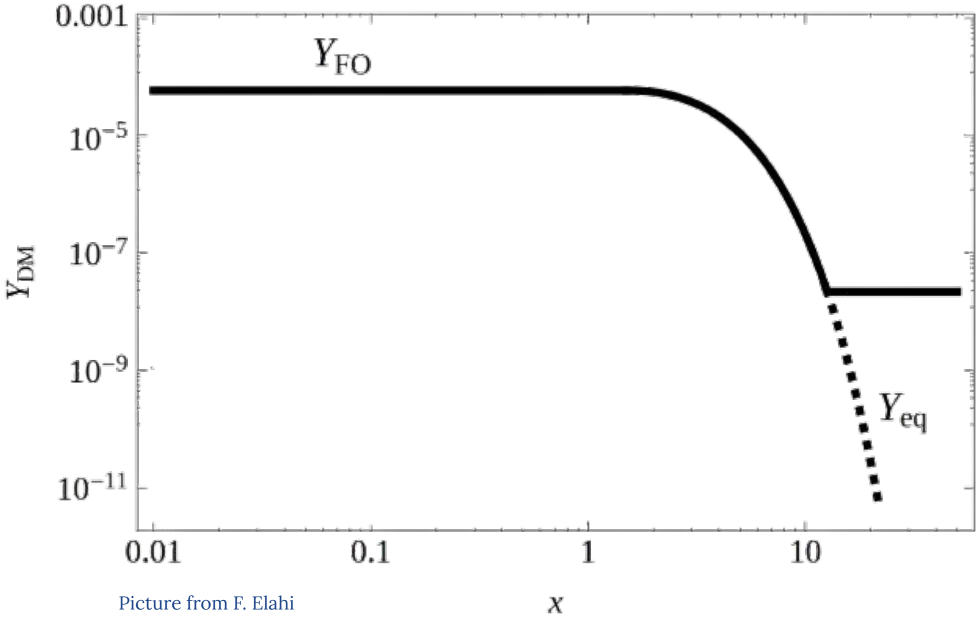
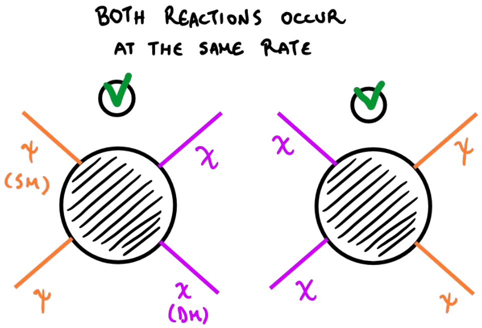
How was DM produced in the early universe?

The Canonical Freeze-out story

- DM is in thermal equilibrium with SM when **$T \gg m_{DM}$**
- DM freezes out at **T□m_{DM}/20**



Picture from F. Elahi



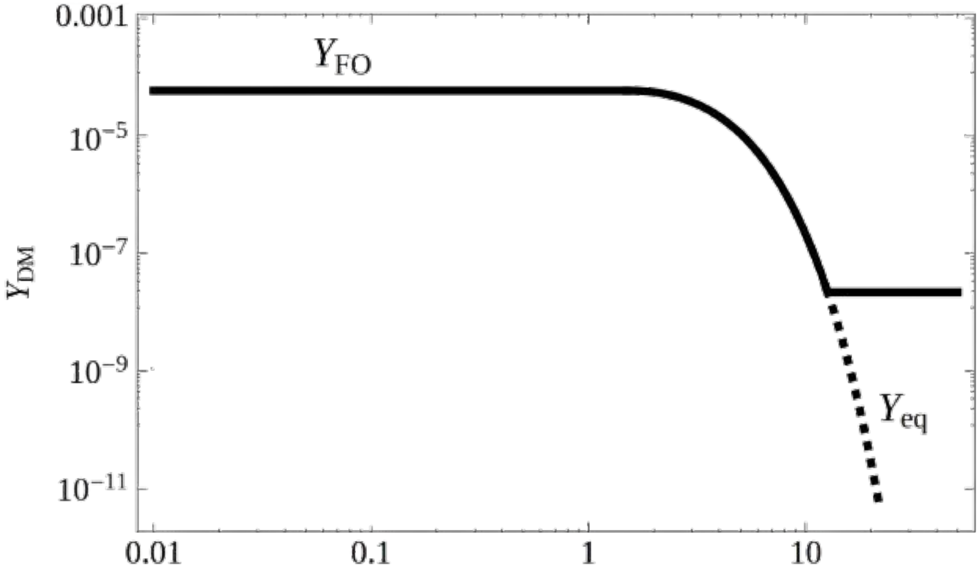
$$Y_{\rm DM} \equiv \frac{n_{\rm DM}}{s}$$

$$x \equiv \frac{m_{\rm DM}}{T}$$

The Canonical Freeze-out story

The WIMP miracle!

$m_{\rm DM}$□m_W and $\boldsymbol{\sigma}_{\rm DM}$□$\alpha_W{}^2/m_W{}^2$ reproduces the observed DM abundance **(α_W□10^{-2}, m_W□100 GeV)**



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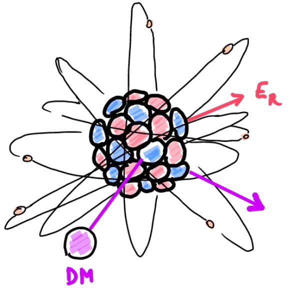
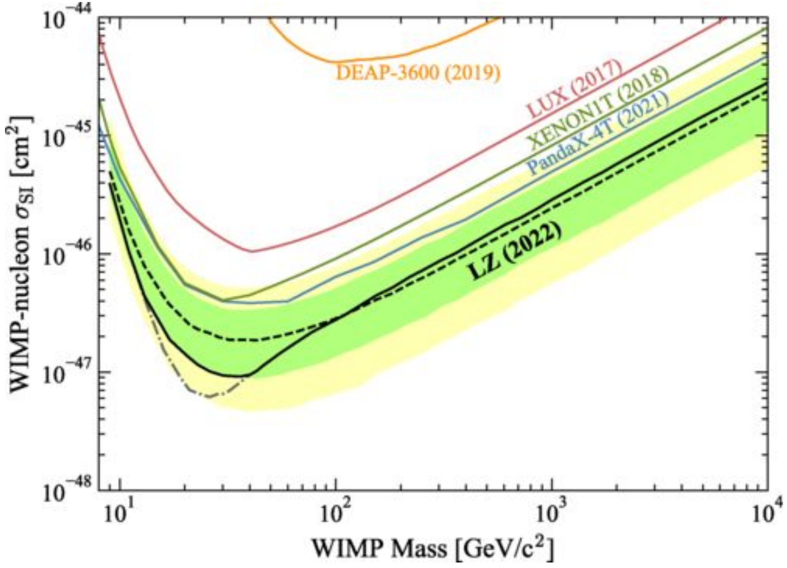
Constraints on WIMPs from Direct Detection

Nuclear Recoil



- Over the last three decades a wide-range of experimental programs have targeted the WIMP parameter space
  - increasingly constrained due to the lack of a direct detection.
  - multi-ton-scale target masses and a clear path for even larger detectors to reach the neutrino fog



LZ Collaboration 2022

Constraints on WIMPs from Direct Detection
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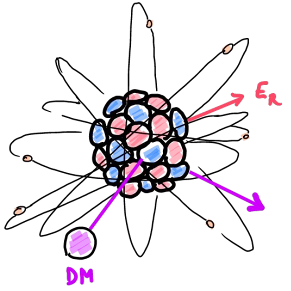

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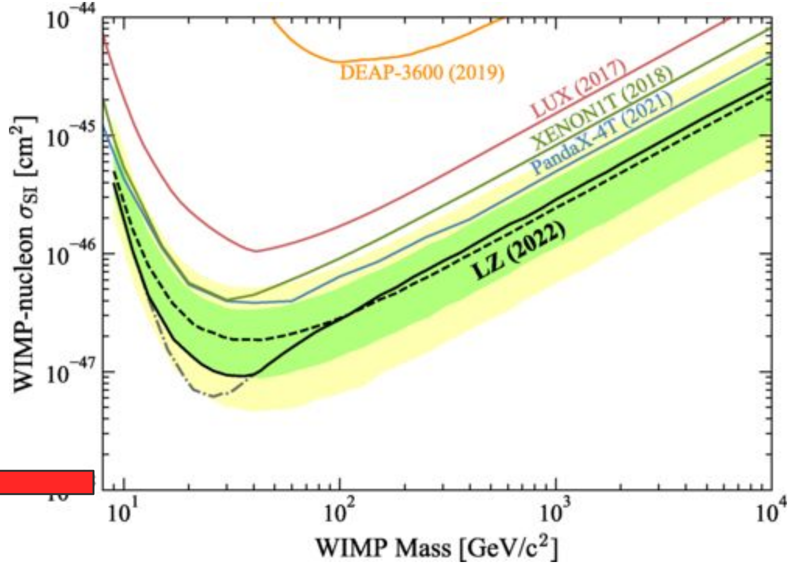


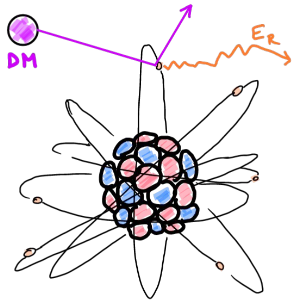
LZ Collaboration 2022

Motivates search for **lighter** DM candidates

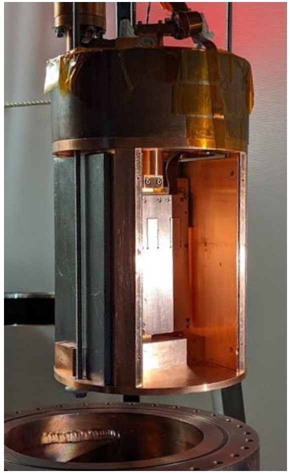
Direct Detection of sub-GeV Dark Matter

Electron Recoil

- New technology allowed recent experiments to extend their reach to sub-GeV DM masses by searching for **electronic recoils**



SENSEI Collaboration



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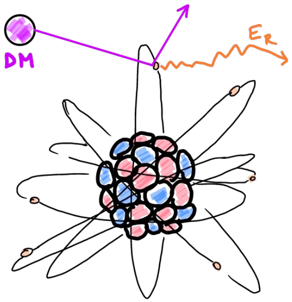
Direct Detection of sub-GeV Dark Matter
Electron Recoil

- New technology allowed recent experiments to extend their reach to sub-GeV DM masses by searching for **electronic recoils**

- Model Building **Challenges**:
  - light DM requires dark sectors
  - Thermal production of MeV DM is disallowed by BBN

Krnjaic, McDermott, 2019; An, Gluscevic, Calabrese, Hill, 2022



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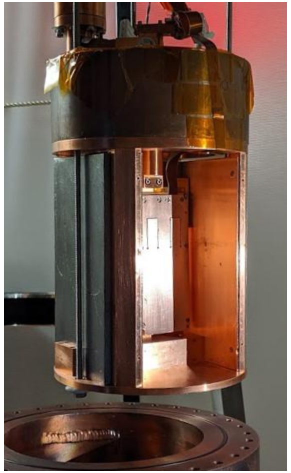

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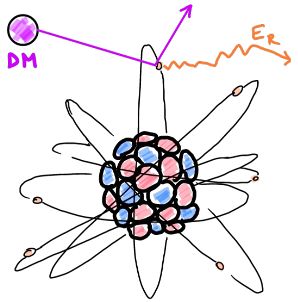
Alternative: Freeze-in!



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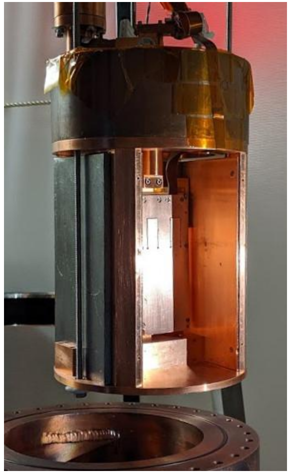
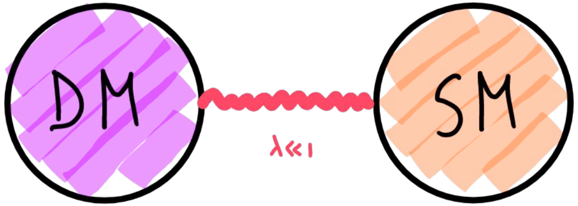


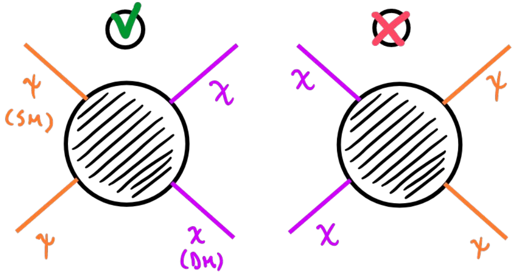
An alternative Scenario: Freeze-in

Hall, Jedamzik, March-Russell, West 2010

DM from a feeble interaction with SM

- **Feeble** interaction between DM and the SM so that DM is never in thermal equilibrium with the SM bath
    - Through a renormalizable operator with very small dimensionless coupling $\lambda_{\text{SM-DM}}$
- Initial DM abundance is negligible (i.e. inflaton reheats primarily the SM)
- The DM abundance is built up gradually (no inverse process!)



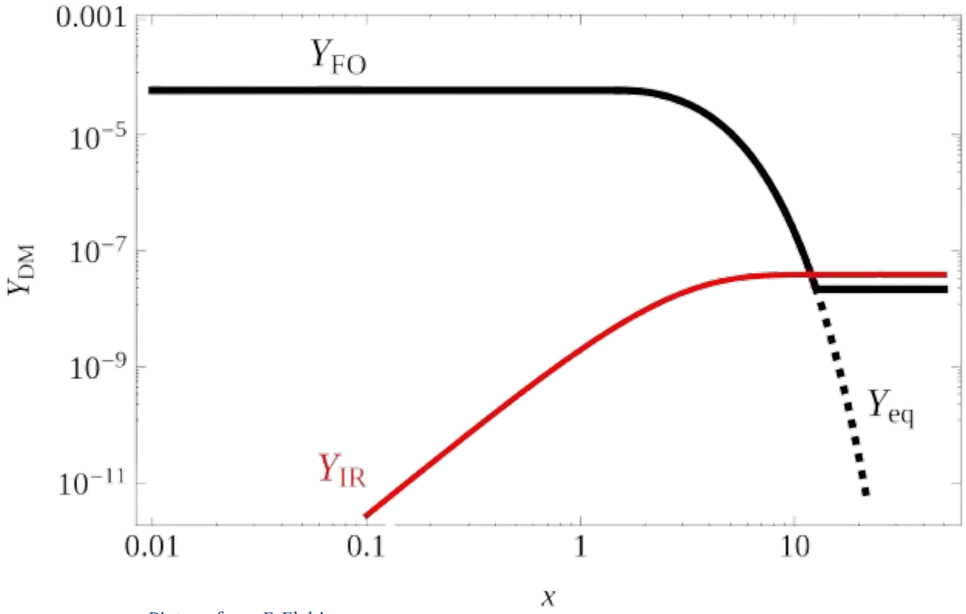


Freeze-in

DM from a feeble interaction with SM

Hall, Jedamzik, March-Russell, West 2010

- The process is insensitive to temperatures above the DM mass
    - The DM abundance is set by lowest T, i.e. **T□m$_{\mathrm{DM}}$**



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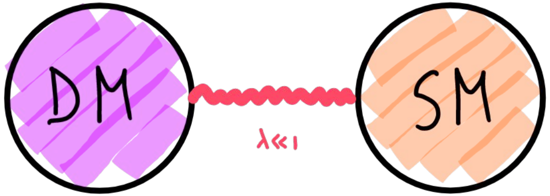


$$Y_{\mathrm{DM}} \sim \lambda^2 \frac{M_{\mathrm{pl}}}{T} \sim \lambda^2 \frac{M_{\mathrm{pl}}}{m_{\mathrm{DM}}}$$

Benchmark Freeze-in Model

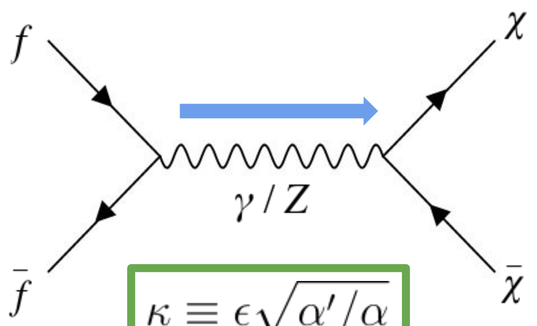
The Kinetic Mixing Portal

Hall, Jedamzik, March-Russell, West 2010
Chu, Hambye, Tytgat, 2012
Essig, Mardon, Volansky, 2012

- An ultralight dark photon **γ ' kinetically-mixed** with the SM hypercharge

$$\mathcal{L} \supset \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

$$\dot{n}_\chi + 3Hn_\chi = \sum_B \langle \sigma_{B\overline{B}\to\chi\overline{\chi}} v \rangle (n_\chi^{\mathrm{eq}})^2,$$



$$\boxed{\kappa \equiv \epsilon\sqrt{\alpha'/\alpha}}$$

- **Target of direct detection** program!
    - Ultralight mediator leads to large enhancement of the direct detection cross section at low momentum transfers.

$$\boxed{\overline{\sigma}_e = \frac{16\pi \mu_{\chi e}^2 \alpha^2 \kappa^2}{(\alpha m_e)^4},}$$

Benchmark Freeze-in Model

The Kinetic Mixing Portal

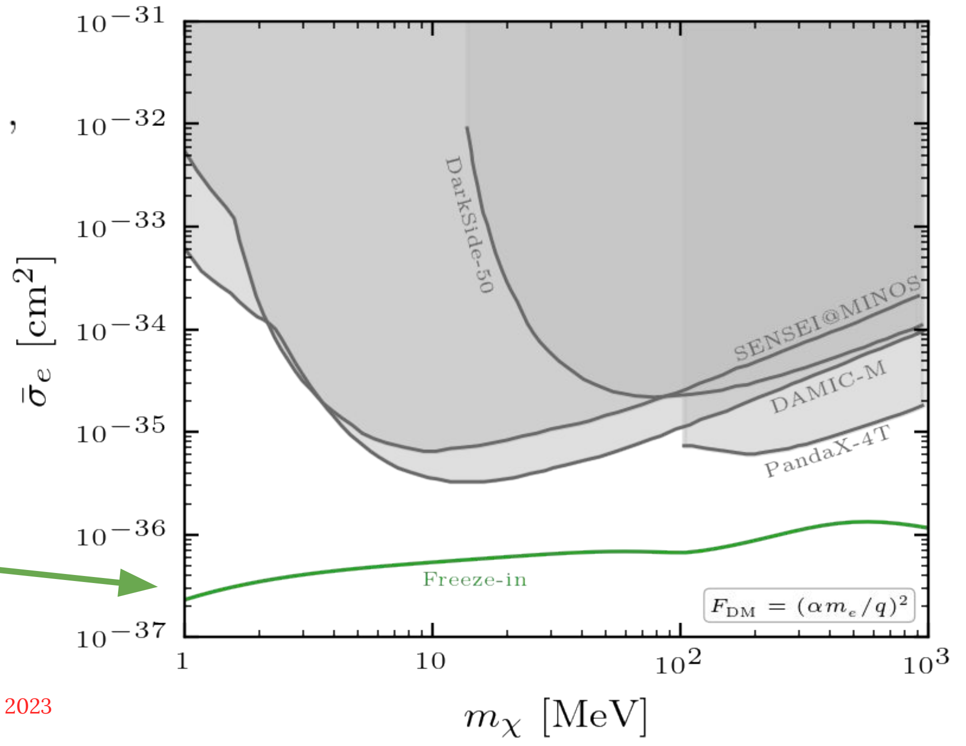
$$\overline{\sigma}_e = \frac{16\pi\mu_{\chi e}^2\alpha^2\kappa^2}{(\alpha m_e)^4},$$

$$Y_\chi(x) = \int_{x_{\rm rh}}^{x} dx' \frac{s}{Hx'}\left[\sum_B \langle\sigma_{B\overline{B}\to\chi\overline{\chi}}v\rangle (Y_\chi^{\rm eq})^2\right],$$

$$x \equiv m_\chi/T$$

- Previous work assumes $T_{rh} >> m_\chi$: $x_{rh} = 0$.
- Then, matching to the observed relic abundance today leads to

$$\kappa \equiv \epsilon\sqrt{\alpha'/\alpha} \approx \mathcal{O}(10^{-11})$$



Corrected prediction for the freeze-in benchmark by Bhattiprolu, McGehee, Pierce 2023

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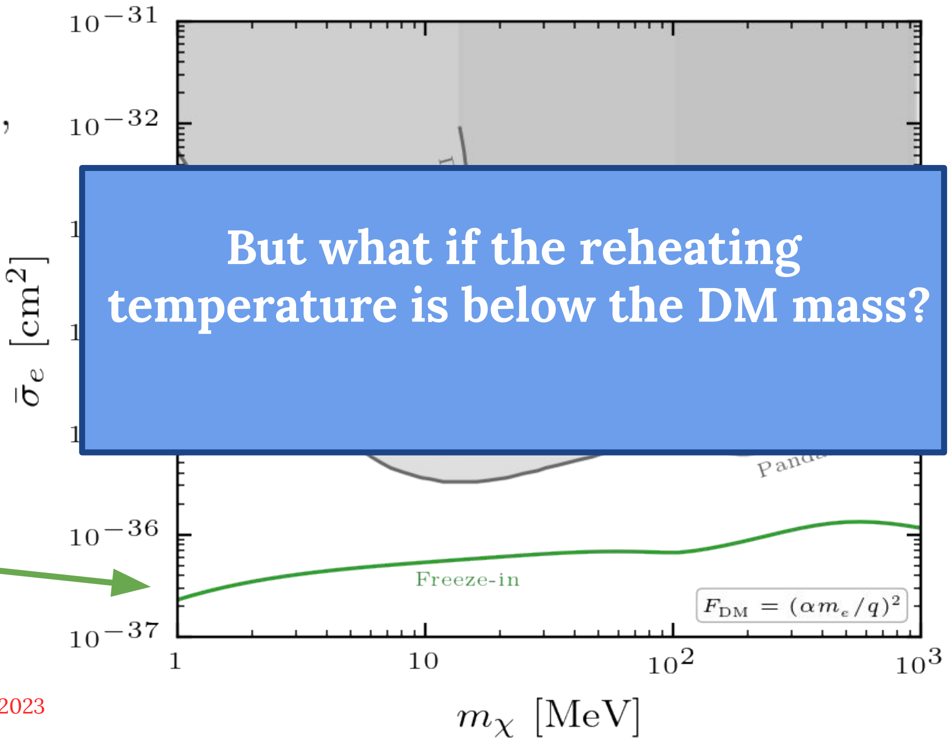


But what if the reheating temperature is below the DM mass?

Corrected prediction for the freeze-in benchmark by Bhattiprolu, McGehee, Pierce 2023

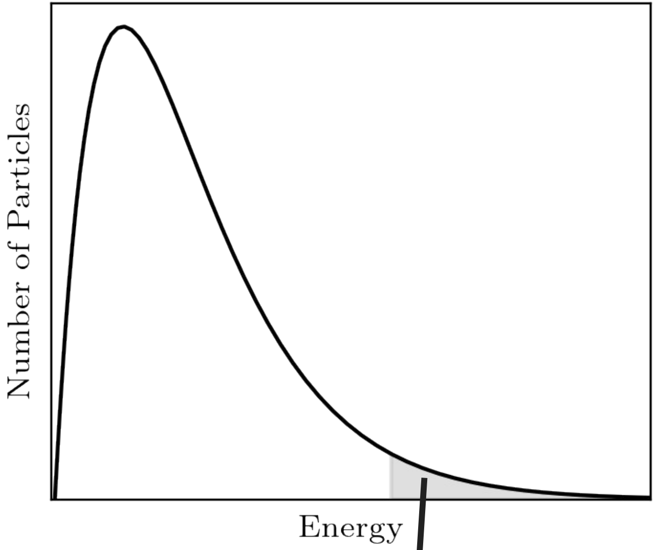
Benchmark Freeze-in Model

The Impact of the Reheating Temperature

- For $T_{rh} << m_\chi$: $\Gamma_{production} \sim \exp(-2m_\chi/T)$

  Kuzmin, Rubakov, 1998; Cosme, Costa, Lebedev, 2023

  - only SM particles in the **tail** of their velocity distributions have enough energy to annihilate into DM particles with $m_\chi >> T$



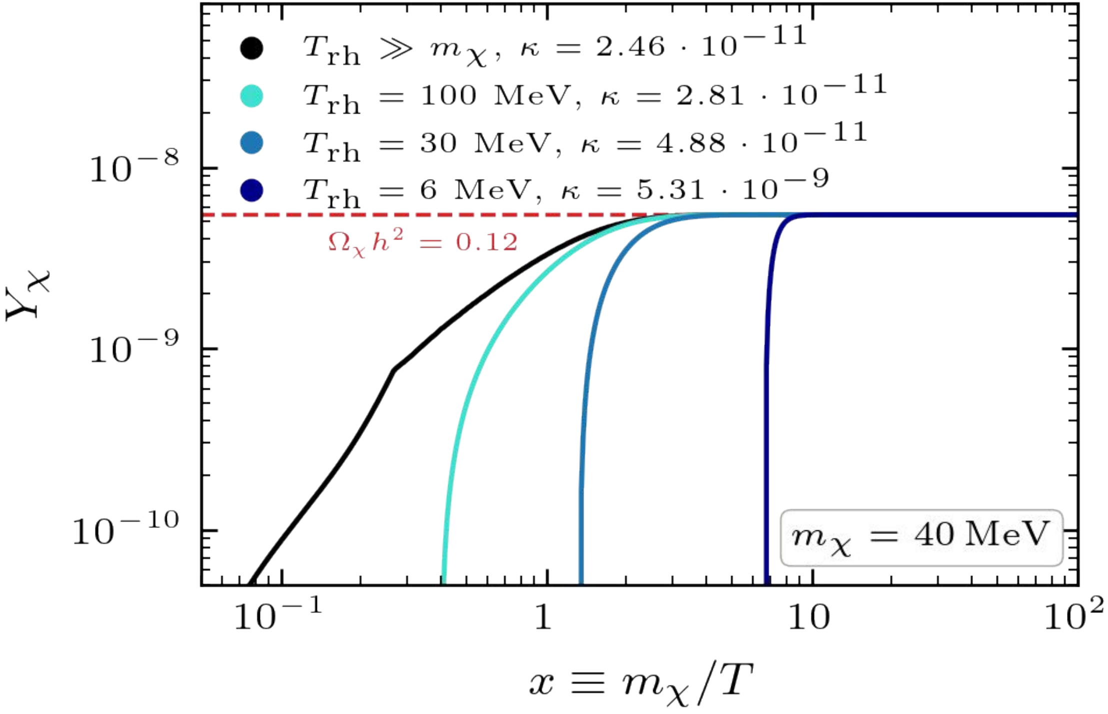
- To counteract the suppressed production and obtain the observed DM abundance today, we need:

a larger portal coupling →a larger scattering cross section

$$Y_\chi(x) = \int_{x_{\rm rh}}^{x} dx' \frac{s}{\overline{H}x'} \left[\sum_B \langle \sigma_{B\overline{B}\to\chi\overline{\chi}} v \rangle (Y_\chi^{\rm eq})^2 \right] ,$$

Benchmark Freeze-in Model

The Impact of the Reheating Temperature



Benchmark Freeze-in Model

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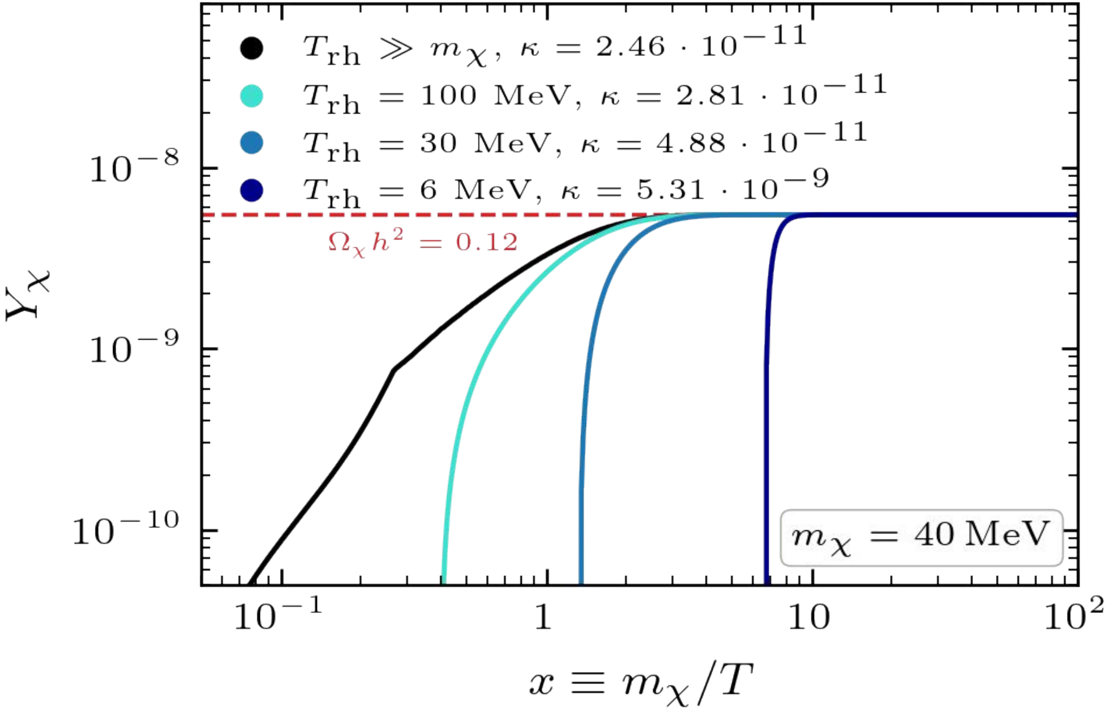


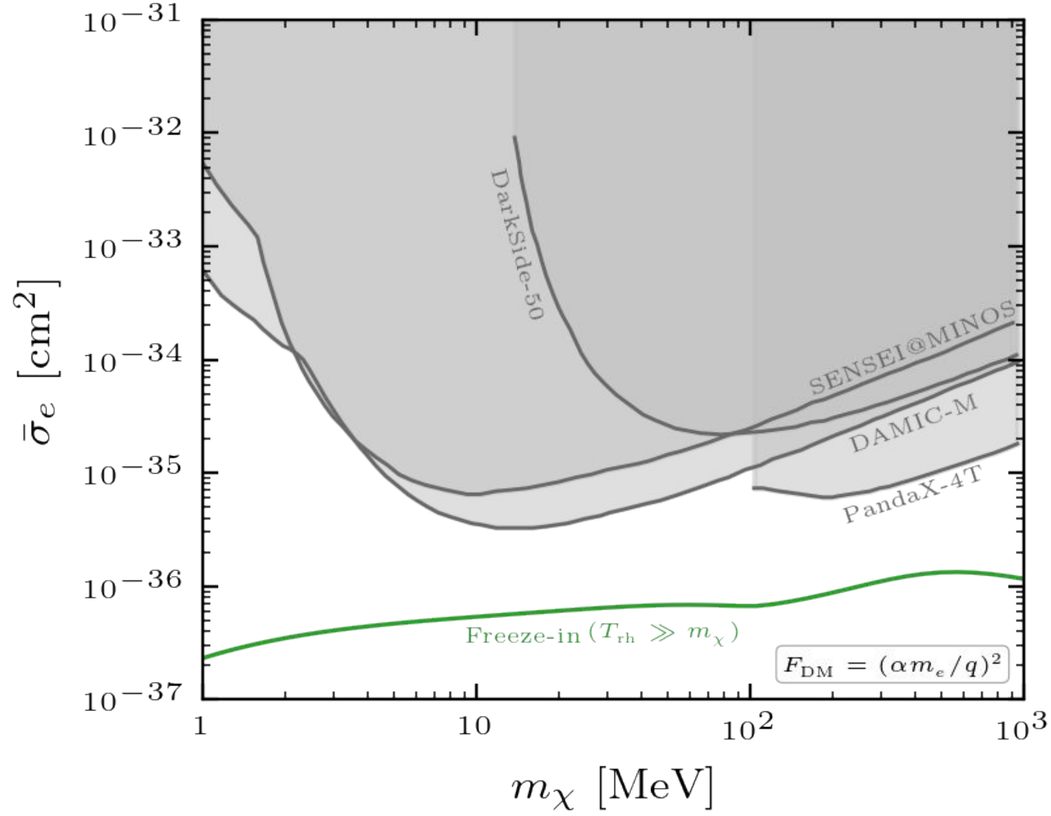
For $T_{rh} << m_\chi$:

final DM abundance becomes very sensitive to T_{rh}

$$\frac{\kappa(T_{\rm rh} \ll m_\chi)}{\kappa(T_{\rm rh} \gg m_\chi)} \sim \sqrt{x_{\rm rh}} e^{x_{\rm rh}}$$

Benchmark Freeze-in Model

The Impact of the Reheating Temperature



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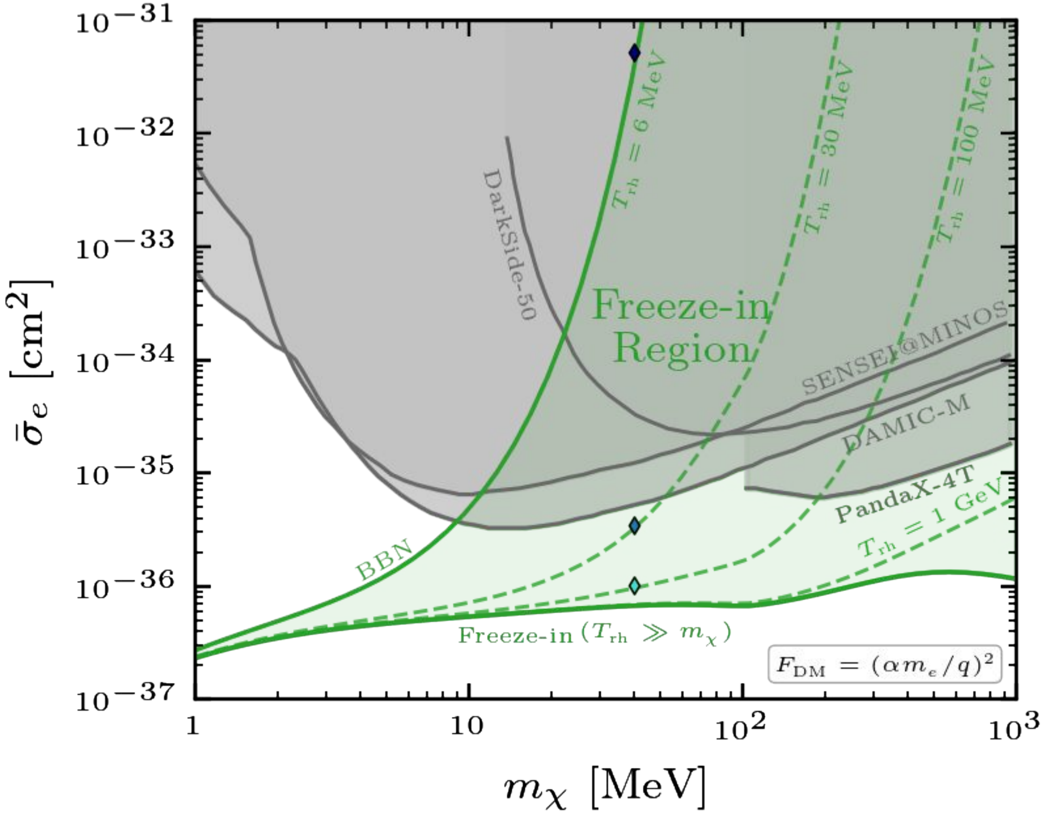
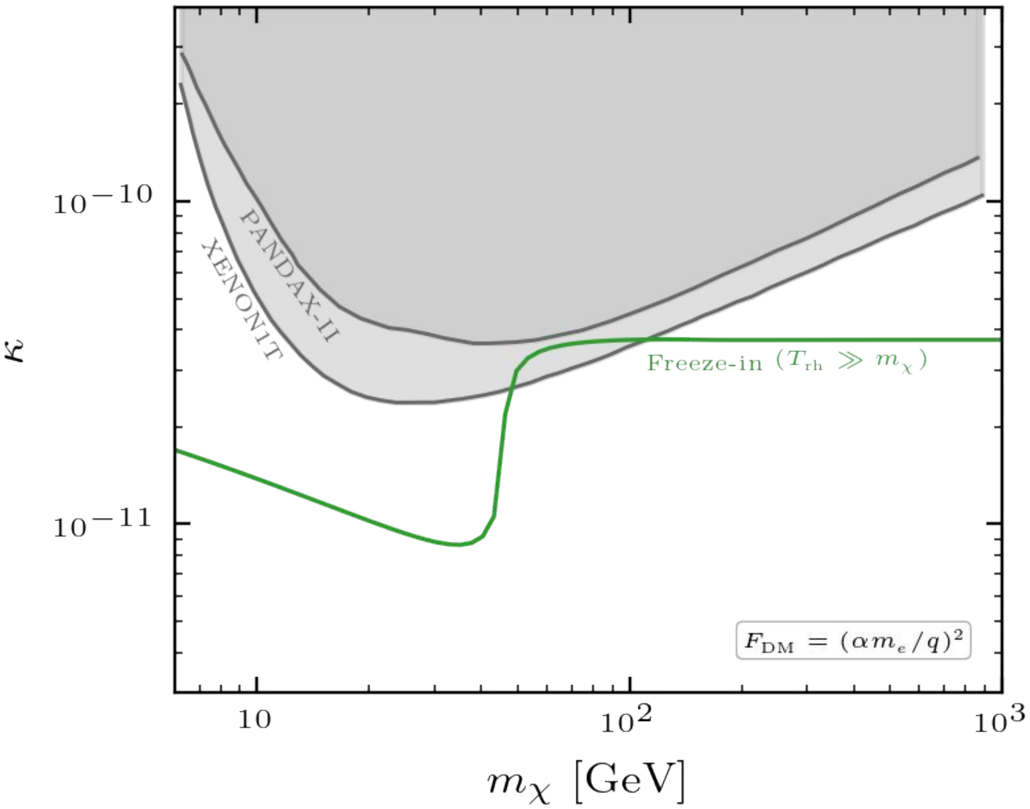


$$\boxed{\frac{\kappa(T_{\rm rh} \ll m_\chi)}{\kappa(T_{\rm rh} \gg m_\chi)} \sim \sqrt{x_{\rm rh}}\, e^{x_{\rm rh}}}$$

- The freeze-in benchmark should be regarded as an **extended region** defined by the reheating temperature, rather than a single curve.
- A large portion of parameter space is currently being **probed by direct detection!**

Benchmark Freeze-in Model

The Impact of the Reheating Temperature



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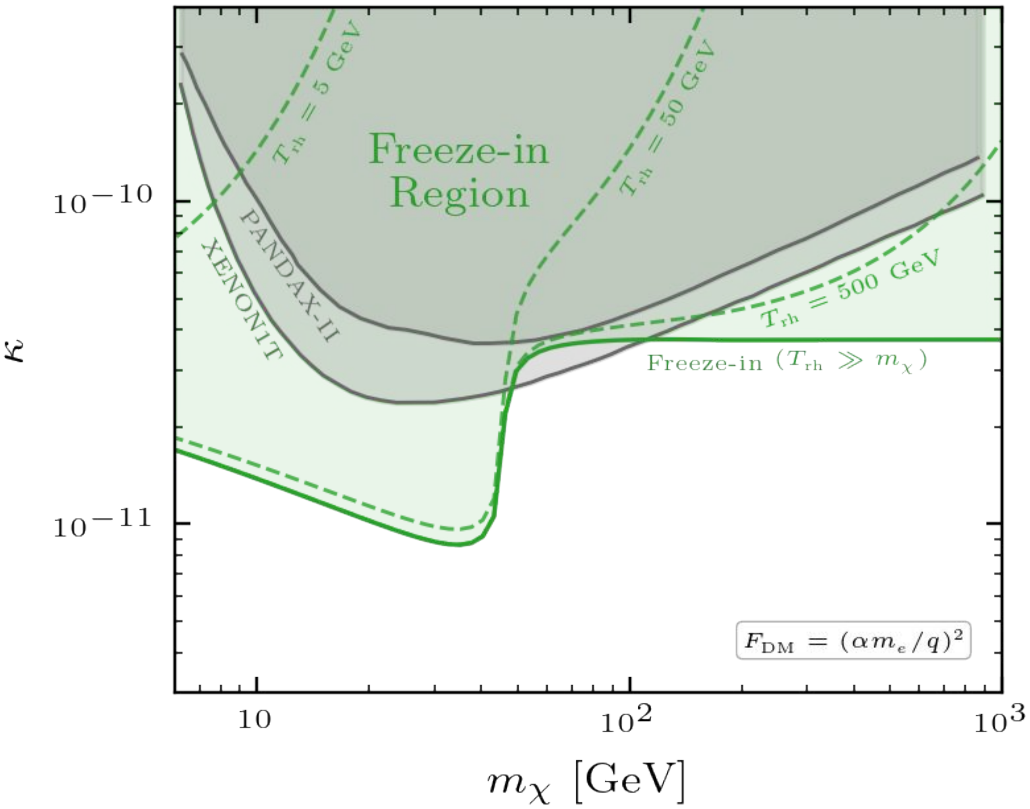


$$\frac{\kappa(T_{\rm rh} \ll m_\chi)}{\kappa(T_{\rm rh} \gg m_\chi)} \sim \sqrt{x_{\rm rh}}\, e^{x_{\rm rh}}$$

The same story holds for **m_χ > 1 GeV**

➡ A large portion of parameter space is currently being **probed by direct detection!**

Aside: Max vs Reheat Temperature

- Our work assumes that the maximum temperature of the thermal bath is equal to the reheating temperature
    - Always valid in the instantaneous reheating approximation!
    - Many examples also in the case of **finite** reheating (,)

Inflaton decays to radiation directly

Chung, Kolb, Riotto, 1998; Giudice, Kolb, Riotto, 2000; Kolb, Notari, Riotto, 2003

Inflaton decays to an unstable particle which then decays to radiation

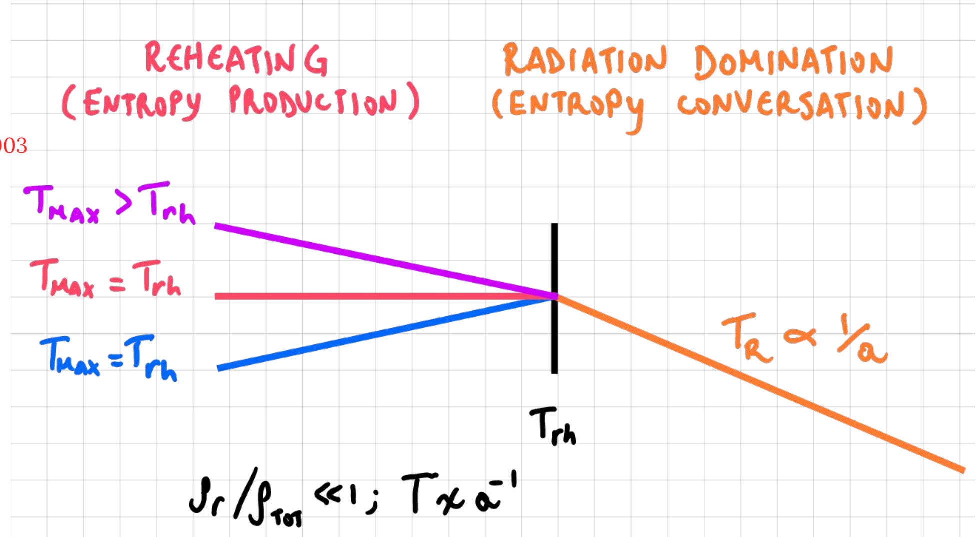
Cosme, Costa, Lebedev, 2024

Inflaton has generic dissipation rate dependent on temperature and scale factor

Co, Gonzalez, Harigaya, 2021

Resonant reheating: s-channel inflaton annihilation

Barman, Bernal, Xu, 2024



Conclusions

- We cannot neglect the impact of the reheating temperature on the benchmark freeze-in model

- For **$T_{rh} << m_\chi$** , DM production rate is exponentially suppressed, so that to achieve the observed relic abundance we need:

  a larger portal coupling → a larger DM-electron scattering cross section

- The freeze-in benchmark target is a **region** defined by reheating temperature rather than a single curve.

  - A large portion of parameter space is currently being **tested by direct detection!**

  - A potential future detection that lies between the current observational upper limits and the traditional freeze-in benchmark would directly probe the reheating temperature and the conditions of the universe in its earliest moments

Grazie per l’attenzione

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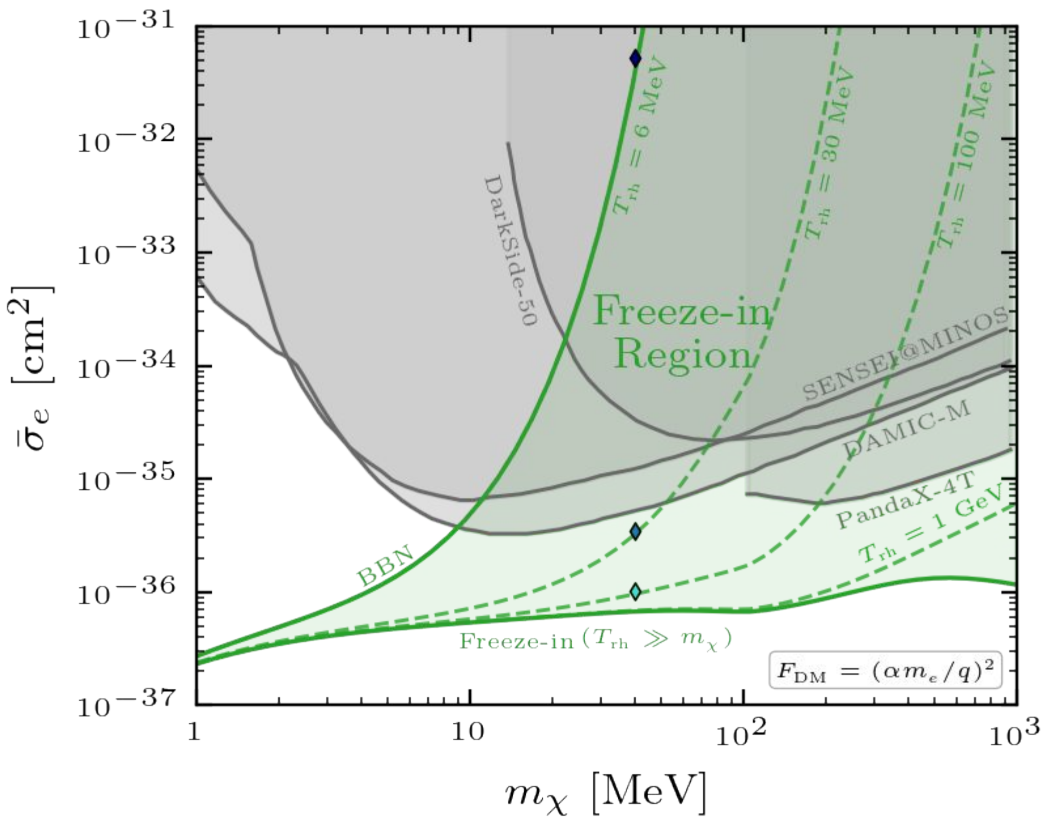

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