26 August 2024

TeV Particle Astrophysics 2024
Chicago, IL

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

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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)

TeVPA Chicago 2024

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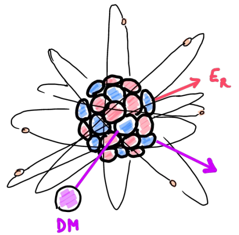
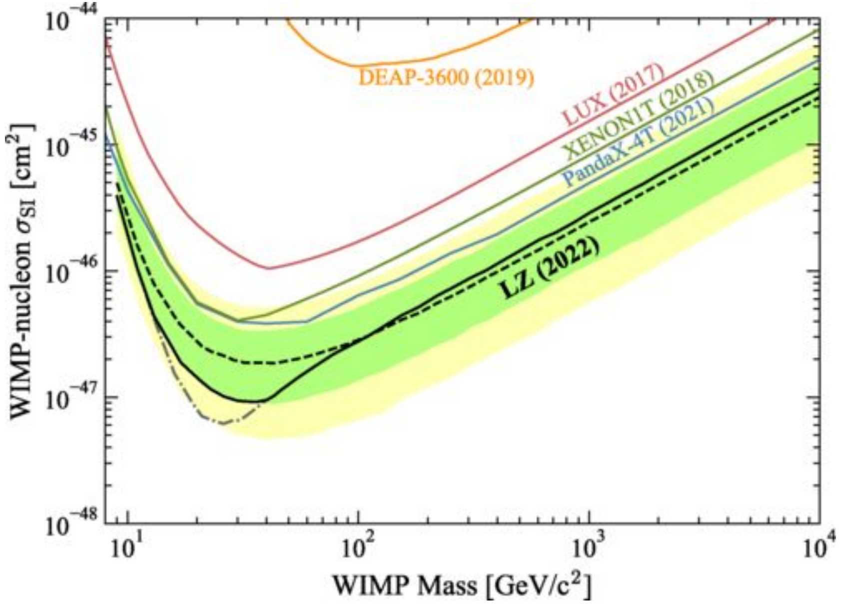
The Current State of DM Direct Detection

Nuclear Recoil:
GeV-TeV DM

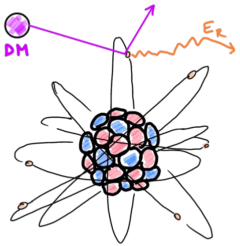




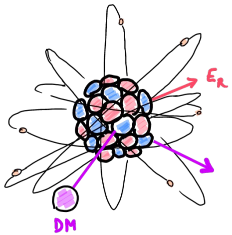
LZ Collaboration 2022

The Current State of DM Direct Detection

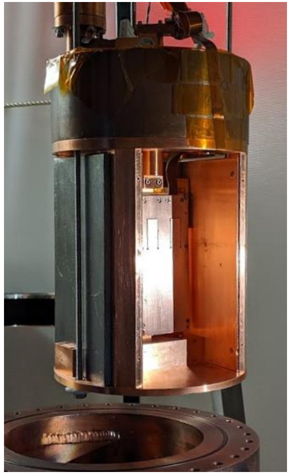
Electron Recoil:
sub-GeV DM



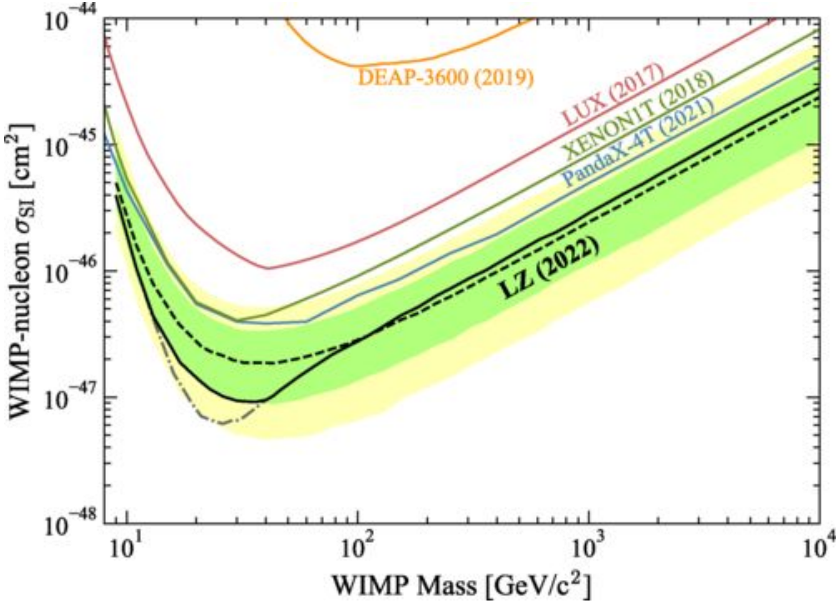
Nuclear Recoil:
GeV-TeV DM



SENSEI Collaboration



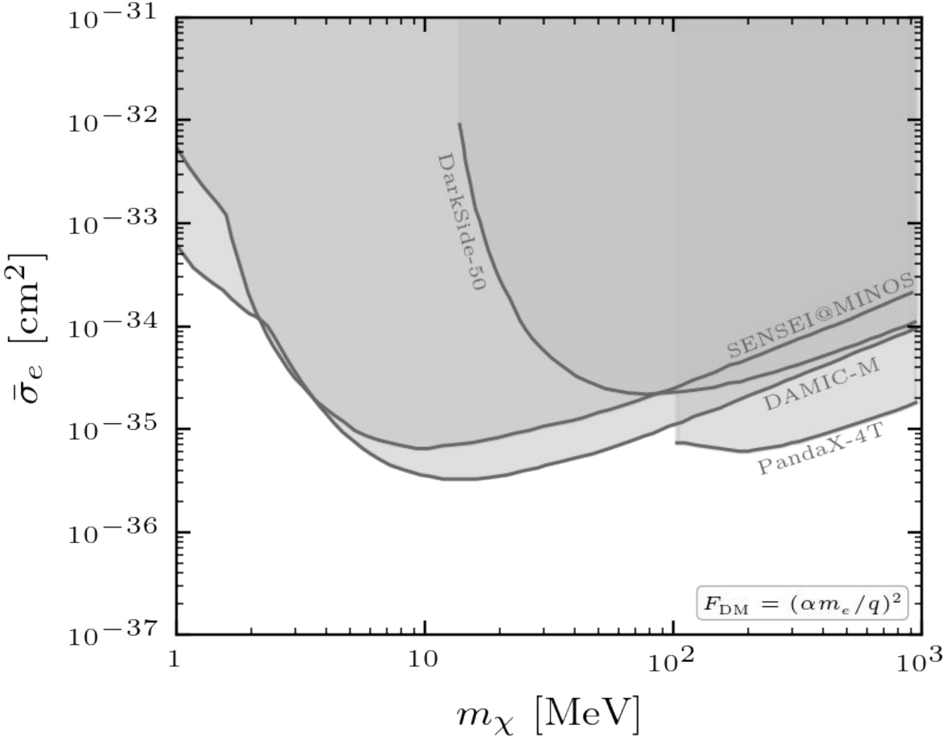
Pushing search to **lighter** DM candidates



LZ Collaboration 2022

Constraints on sub-GeV Dark Matter

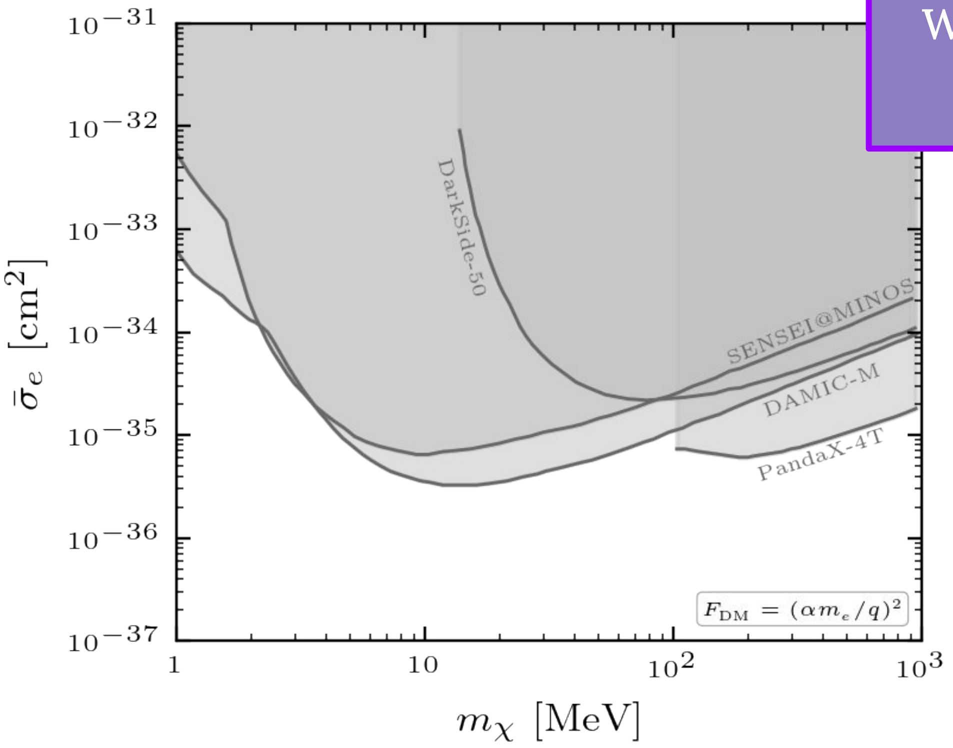
Direct detection reference DM-electron cross section



Constraints on sub-GeV Dark Matter

What DM models are we actually probing?

Direct detection reference DM-electron cross section



Constraints on sub-GeV Dark Matter

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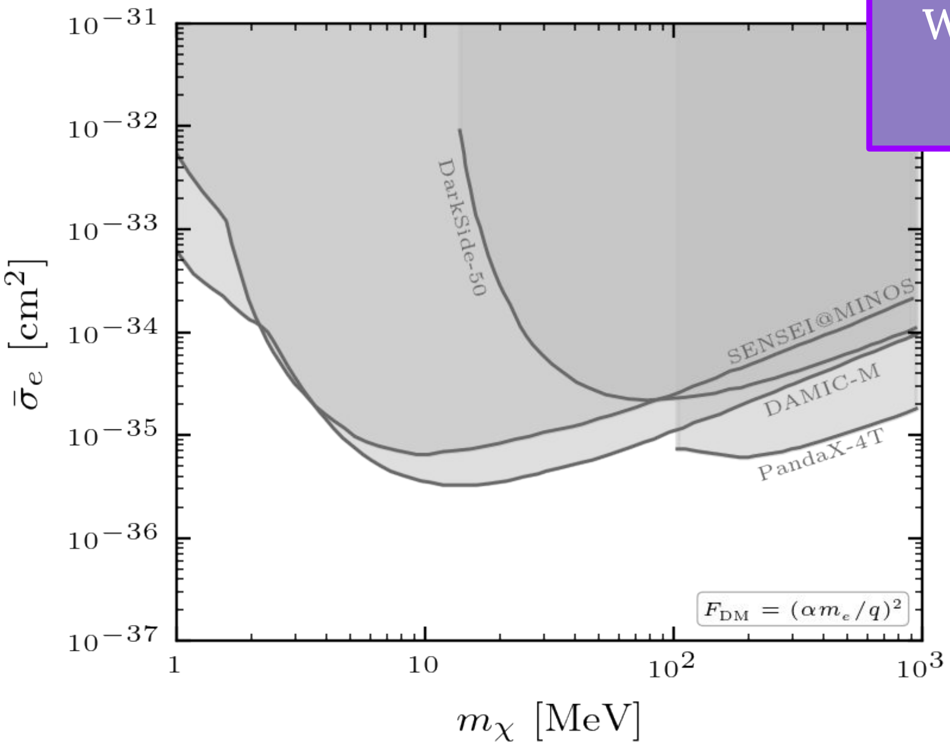


What DM models are we actually probing?

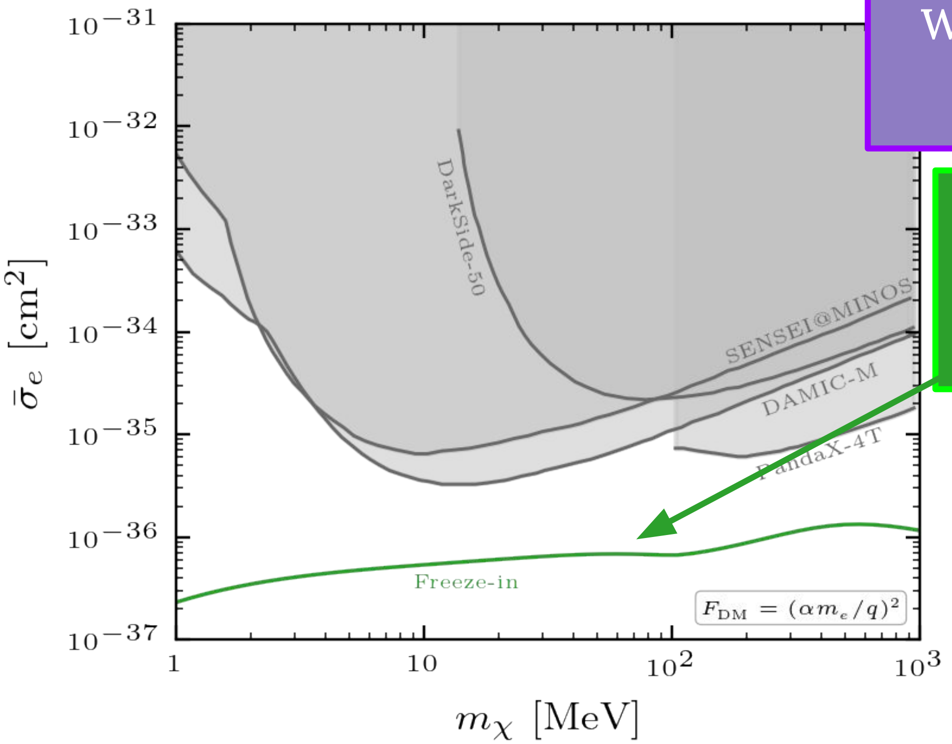
Model Building **Challenges**:

- light DM requires dark sectors
- Thermal production of MeV DM is disallowed by BBN

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

Constraints on sub-GeV Dark Matter

Direct detection reference
DM-electron cross section



What DM models are we actually probing?

A simple solution:

Freeze-in!

- **Feeble** DM-SM interaction: DM is never in thermal equilibrium with the SM
- No initial DM abundance

Hall, Jedamzik, March-Russell, West 2010

Benchmark Freeze-in Model

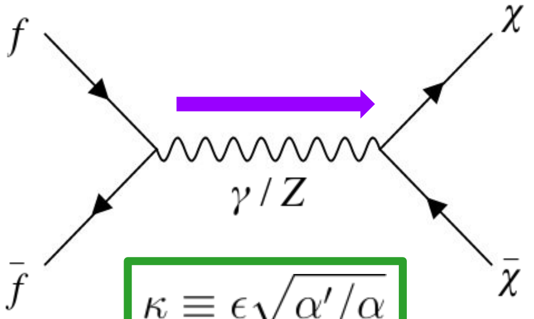
The Kinetic Mixing Portal

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

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

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



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

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

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

Benchmark Freeze-in Model

The Kinetic Mixing Portal

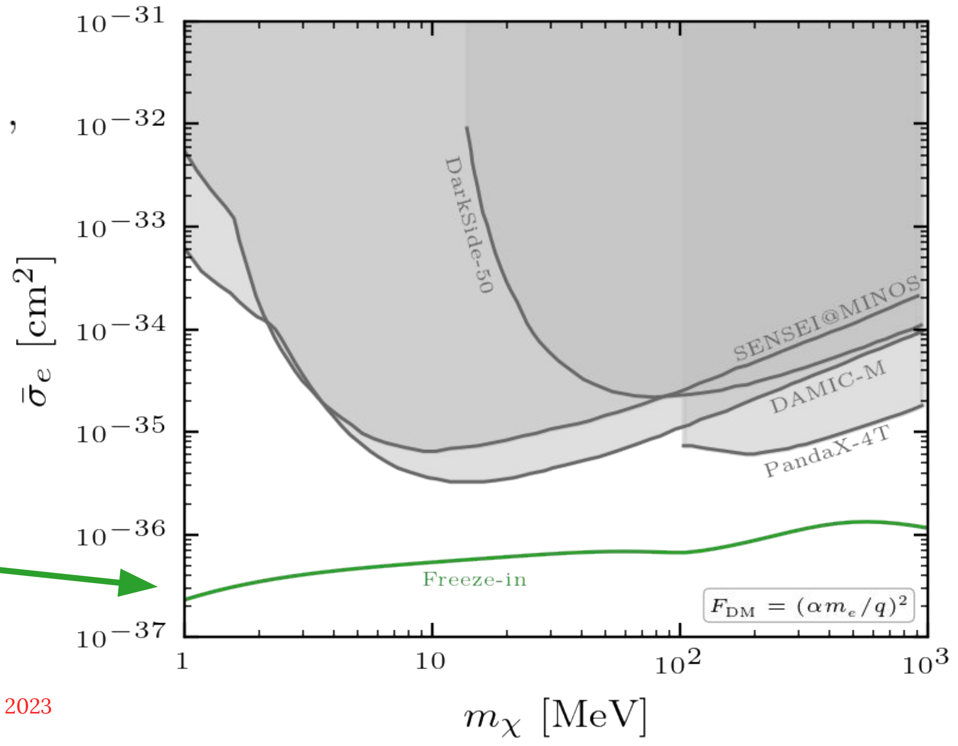
$$Y_\chi(x) = \int_{x_{\rm rh}}^{x} dx' \frac{s}{\overline{H} x'} \left[\sum_B \langle \sigma_{B\overline{B}\to\chi\overline{\chi}} v \rangle (Y_\chi^{\rm eq})^2 \right],$$

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

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

- 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

Benchmark Freeze-in Model

The Kinetic Mixing Portal

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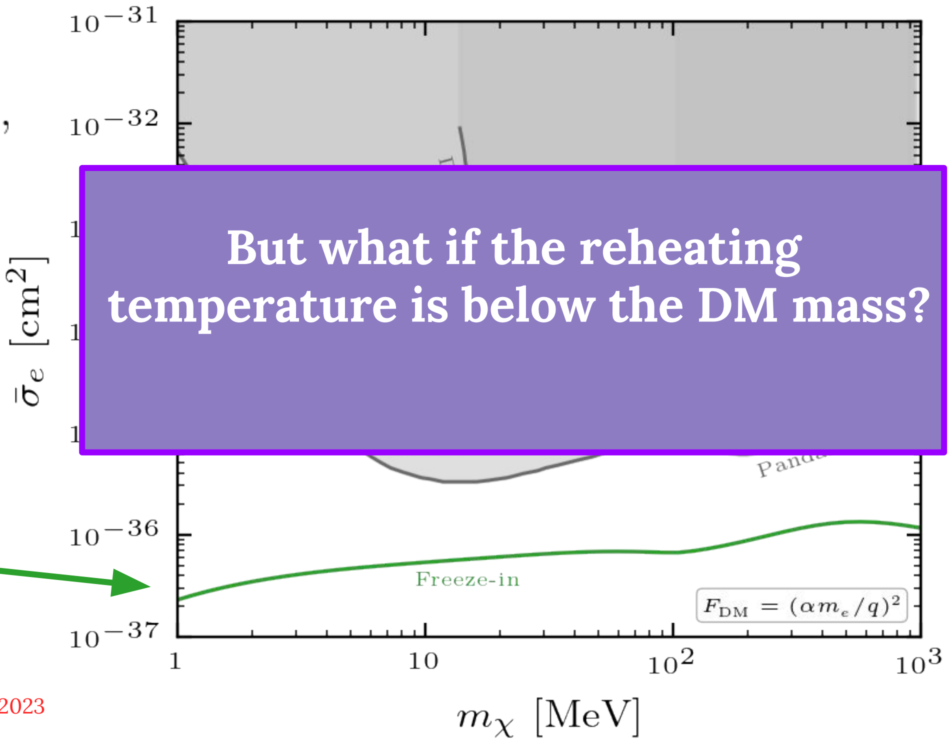


But what if the reheating temperature is below the DM mass?

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

Benchmark Freeze-in Model

The Impact of the Reheating Temperature

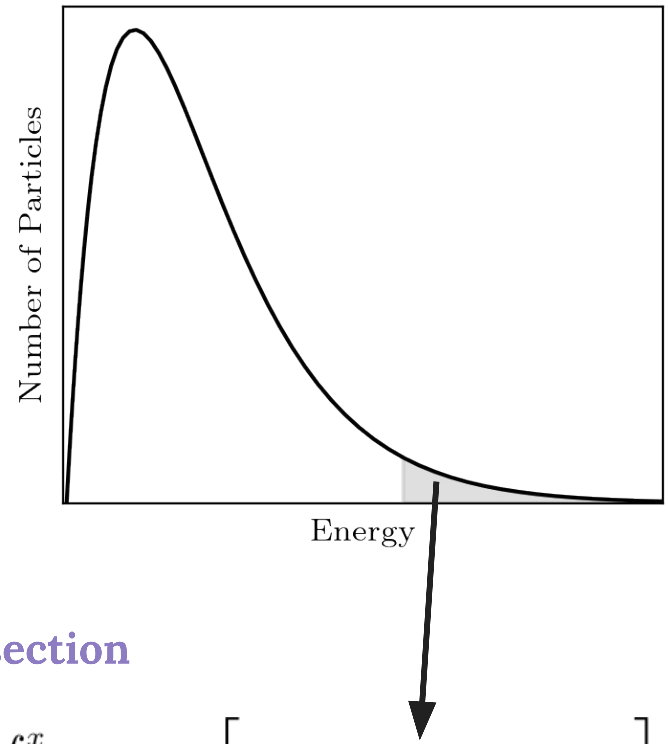
- For $T_{rh} << m_\chi$: $\Gamma_{production} \sim \exp(-2m_\chi/T)$

  Kuzmin, Rubakov, 1998;
  Bringmann, Heeba, Kahlhoefer, Vangsnes 2021, 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

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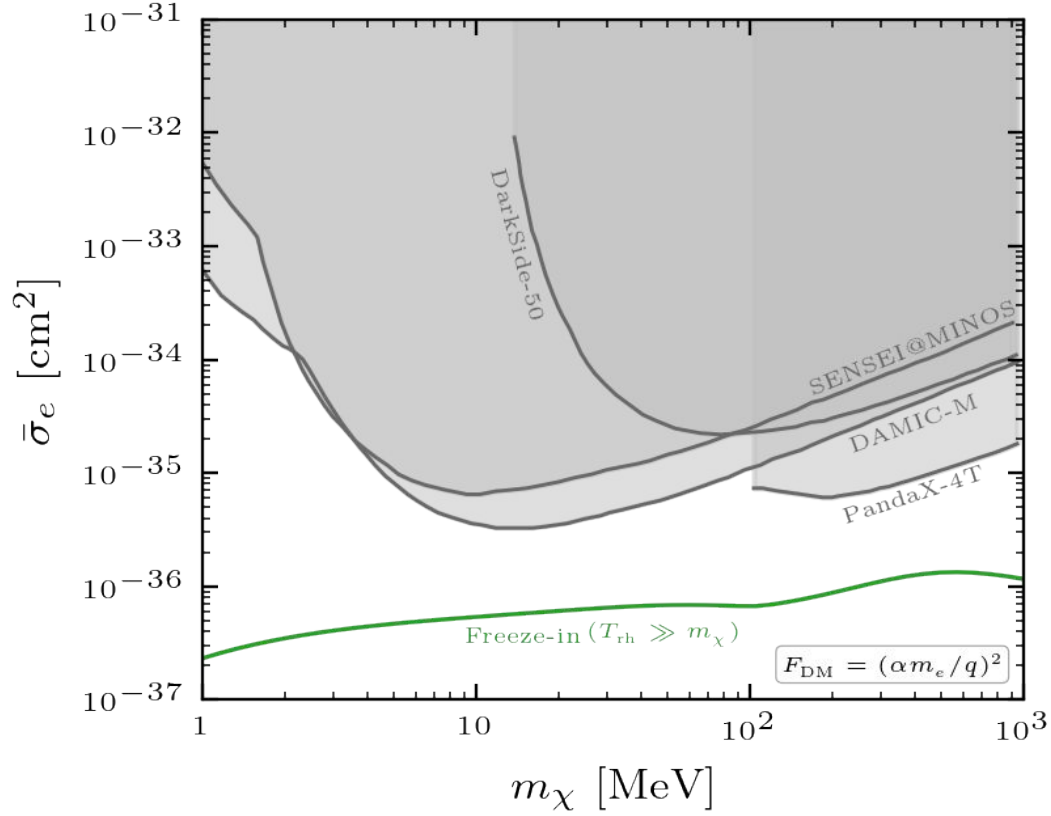

Benchmark Freeze-in Model

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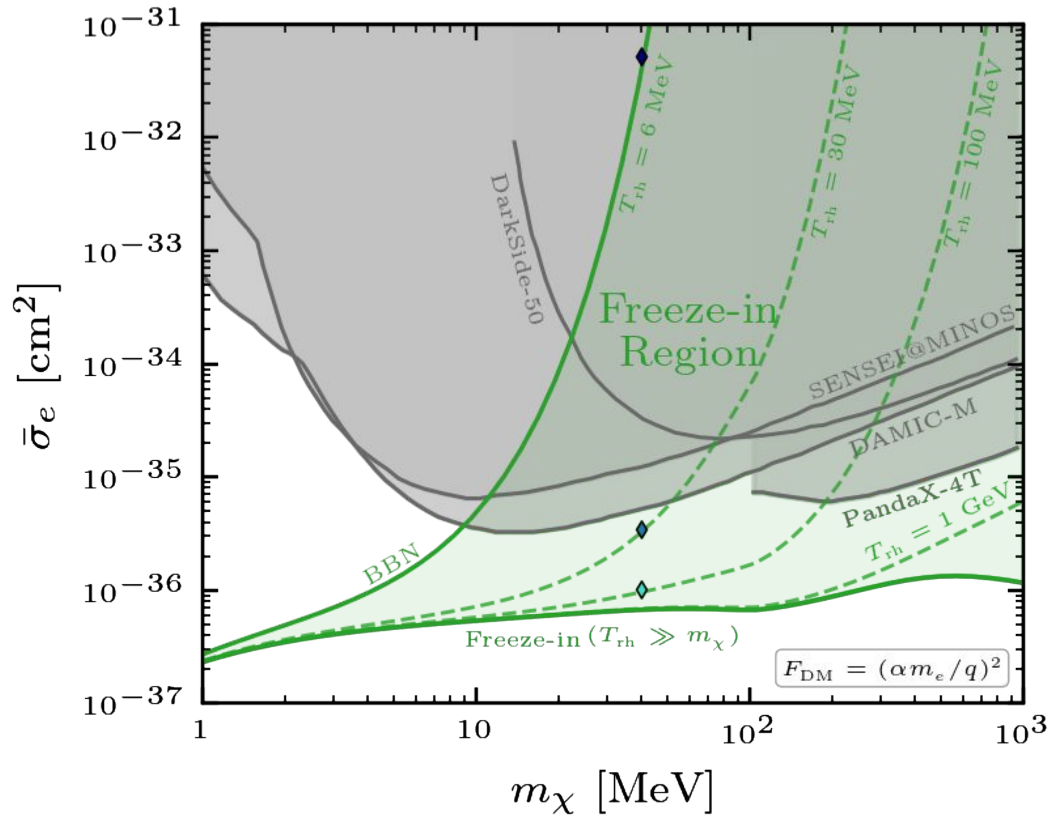
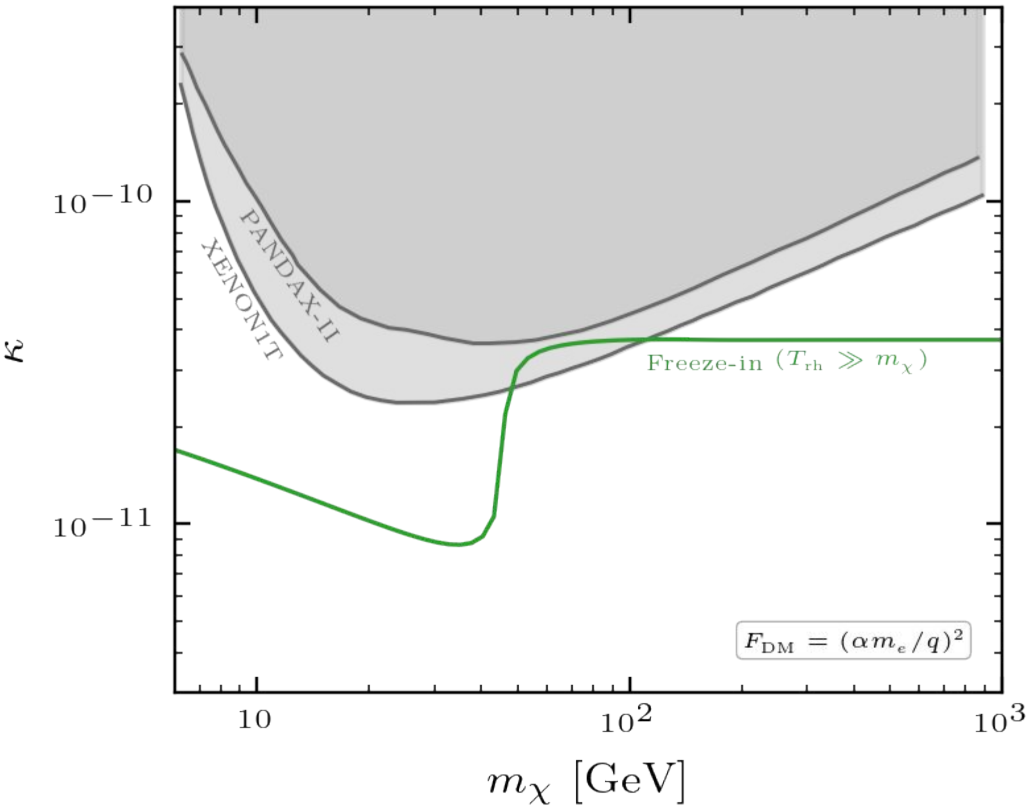


$$\frac{\kappa(T_{\rm rh} \ll m_\chi)}{\kappa(T_{\rm rh} \gg m_\chi)} \sim \sqrt{x_{\rm rh}}e^{x_{\rm rh}}$$

- The 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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Benchmark Freeze-in Model

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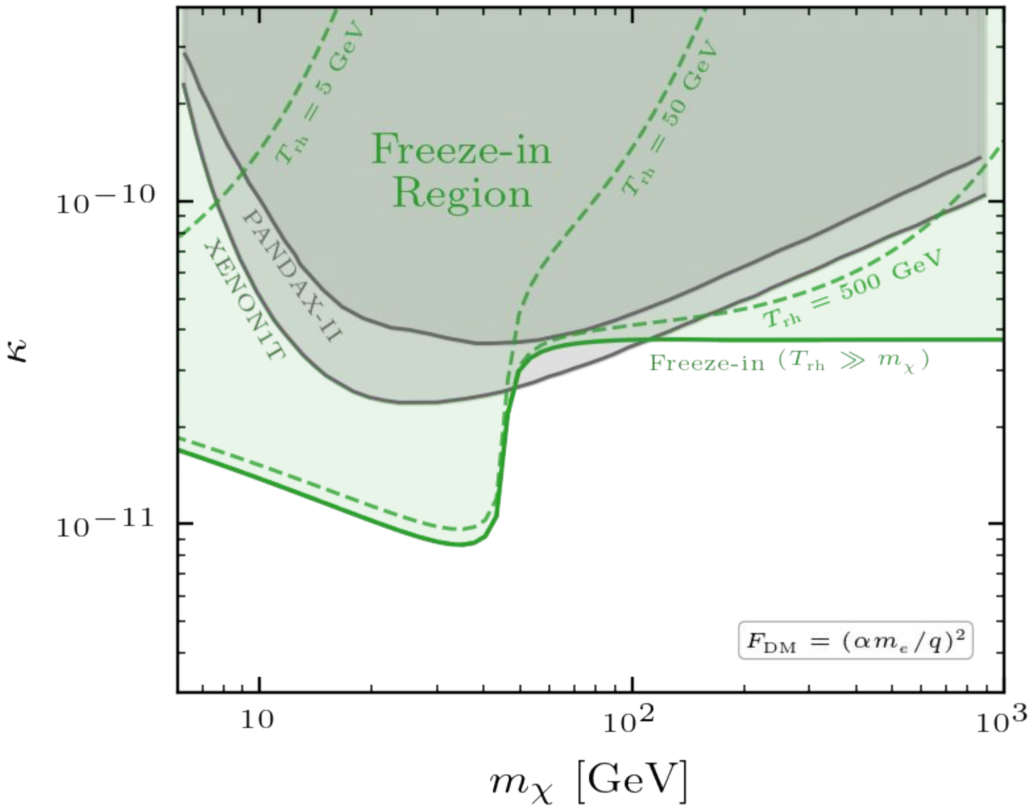


$$\frac{\kappa(T_{\rm rh} \ll m_\chi)}{\kappa(T_{\rm rh} \gg m_\chi)} \sim \sqrt{x_{\rm rh}}\, e^{x_{\rm rh}}$$

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

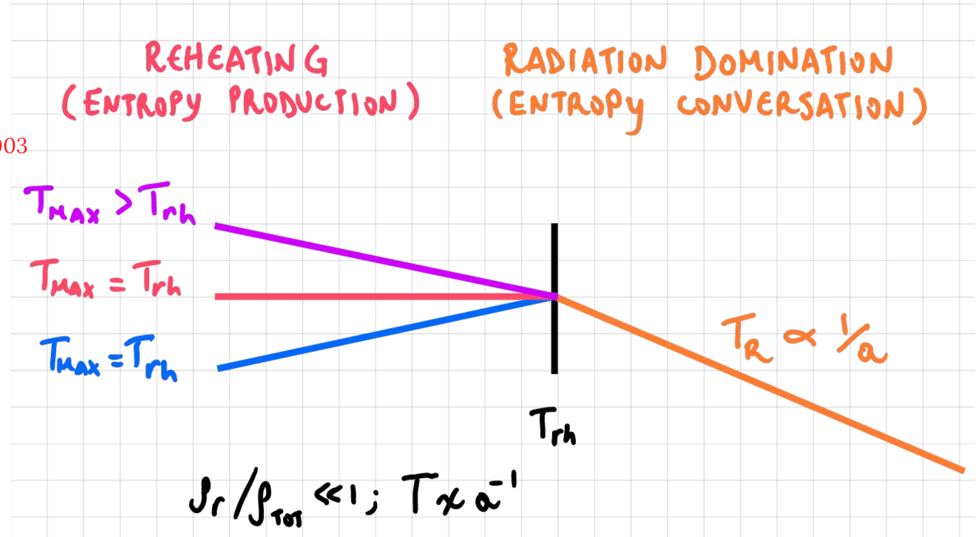
Cosme, Costa, Lebedev, 2024

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 the 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

Conclusions

Grazie per l’attenzione!

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

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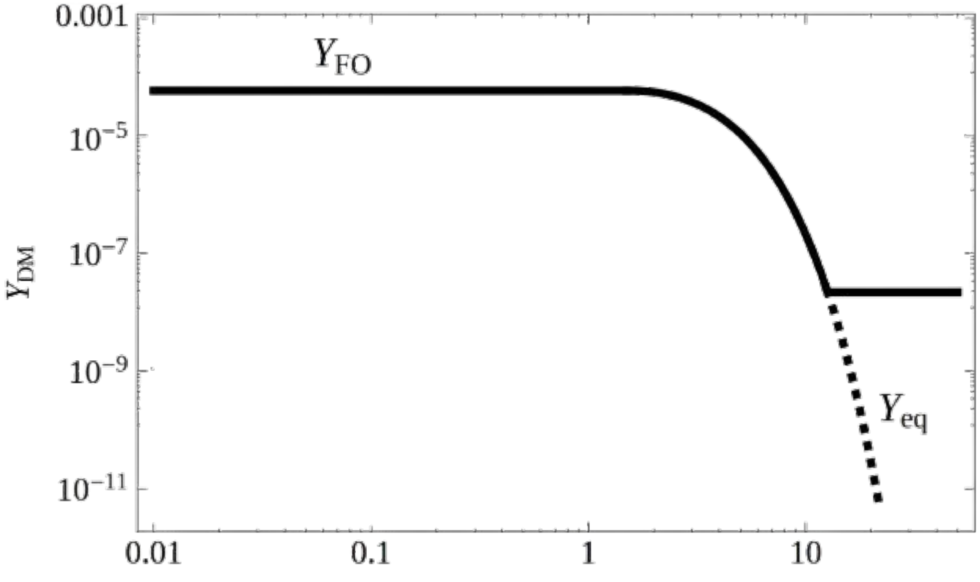
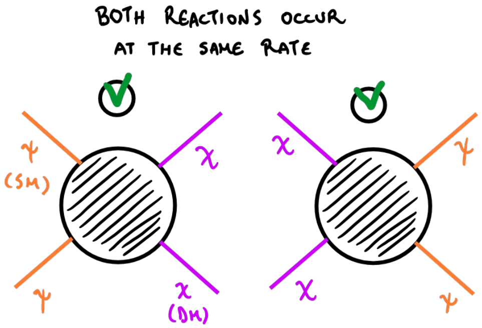
BACK-UP SLIDES

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



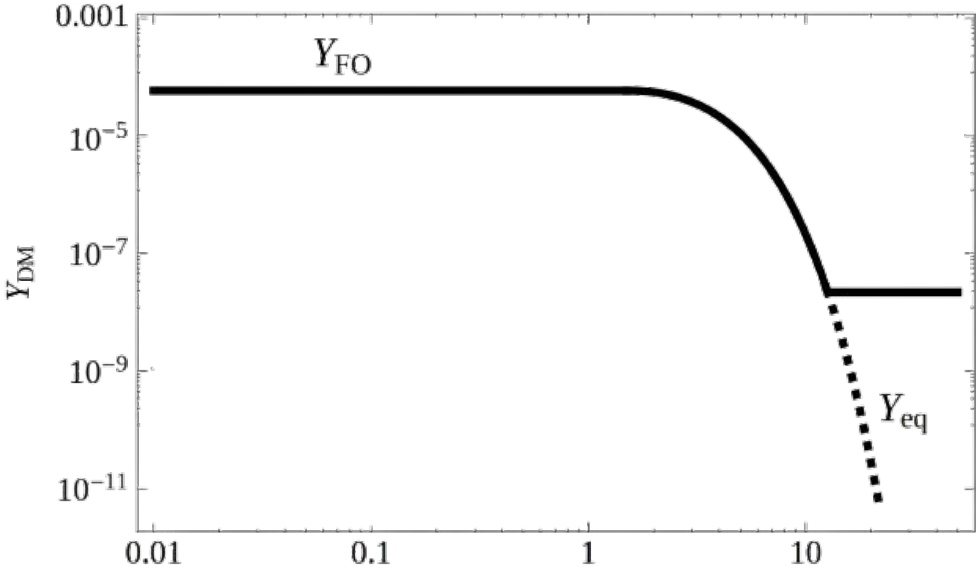
$$Y_{\rm DM} \equiv \frac{n_{\rm DM}}{s}$$

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

The Canonical Freeze-out story

The WIMP miracle!

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



Picture from F. Elahi

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

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

Model Building Challenges of Light Dark Matter

Necessity of a Dark Sector

- Lee-Weinberg bound: Weak scale couplings lead to an overabundance of DM for $\mathbf{m}_{\chi} < 1$ GeV

Lee, Weinberg 1977

⟹ **New BSM mediators** below the weak scale are required!

- For a sub-GeV DM candidate, if the dark sector is thermally coupled to SM, it is hard to evade CMB injection constraints.
  - Either asymmetric DM; or models with p-wave or kinematic suppression.

⟹ We can have a **secluded** sector (with no to negligible SM coupling)

See TASI lectures by Tongyan Lin for a review of all these constraints and the corresponding relevant papers on the subject.

Model Building Challenges of Light Dark Matter

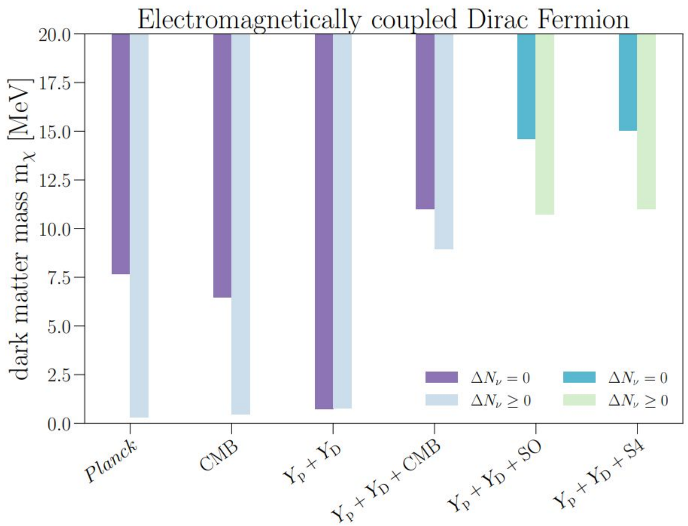
Krnjaic, McDermott, 2019;
An, Gluscevic, Calabrese, Hill, 2022

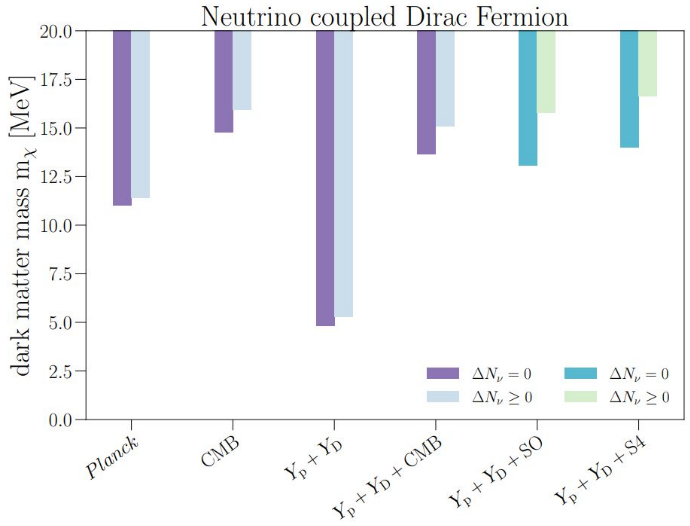
BBN constraints on thermal DM

Thermal production of **MeV DM is disallowed** by BBN

Only assumption is that DM is thermally coupled to SM

Precise constraints depend on the nature of DM particle



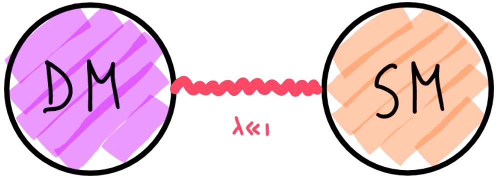


A Lighting Review of Freeze-in

DM from a feeble interaction with SM

Hall, Jedamzik, March-Russell, West 2010

- **Feeble** interaction between DM and the SM so that DM is never in thermal equilibrium with the SM bath
- Initial DM abundance is negligible (i.e. inflaton reheats primarily the SM)
- The DM abundance is built up gradually (no inverse process!)
- The process is insensitive to temperatures above the DM mass
  - The DM abundance is set by lowest T, i.e. **T□m**$_{DM}$



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

Benchmark Freeze-in Model

The Kinetic Mixing Portal

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} + \frac{\epsilon_Y}{2}\hat{X}_{\mu\nu}\hat{B}^{\mu\nu} - e'\hat{X}_\mu\bar{\chi}\gamma^\mu\chi.$$

Dark U'(1); SM hypercharge; dirac fermionic DM

Diagonalizing the gauge basis $\{\hat{A}_\mu, \hat{Z}_\mu, \hat{X}_\mu\}$ in terms of the mass basis $\{A_\mu, Z_\mu, A'_\mu\}$ we get

$$\begin{aligned}
\hat{Z}_\mu &= Z_\mu \\
\hat{A}_\mu &= A_\mu + \epsilon A'_\mu \\
\hat{X}_\mu &= A'_\mu - \epsilon \tan\theta_W Z_\mu
\end{aligned}$$

$$\begin{aligned}
\mathcal{L} \supset &- \epsilon e A'_\mu J^\mu_{\rm EM} - e' J^\mu_{\rm DM}\left(A'_\mu - \epsilon\tan\theta_W Z_\mu\right) \\
&+ i\epsilon e\left[F'^{\mu\nu}W^+_\mu W^-_\nu - \left(\partial_\mu W^+_\nu - \partial_\nu W^+_\mu\right)A'^\mu W^{-\nu}\right. \\
&\left. + \left(\partial_\mu W^-_\nu - \partial_\nu W^-_\mu\right)A'^\mu W^{+\nu}\right]
\end{aligned}$$

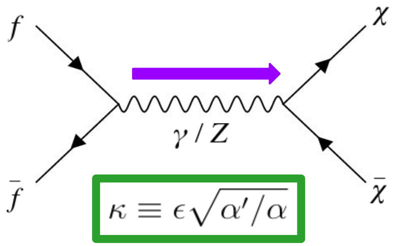
The effective kinetic mixing parameter is $\epsilon \equiv \epsilon_Y \cos\theta_W$

Below EW phase transition, we simply have: $\mathcal{L} \supset \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$

Following prescription of Bhattiprolu, McGehee, Pierce 2023

Benchmark Freeze-in Model

The Kinetic Mixing Portal



$$-\frac{\bar{H}T}{s}\frac{dY_\chi}{dT} = \sum_B \langle \sigma_{B\bar{B}\to\chi\bar{\chi}} v \rangle (Y_\chi^{\rm eq})^2,$$

$$H/\bar{H} = 1 + \frac{1}{3}\frac{d\ln g_{*,s}}{d\ln T}$$ (accounts for varying number of relativistic degrees of freedom)

Thermally averaged cross section:

$$\langle \sigma_{B\bar{B}\to\chi\bar{\chi}} v \rangle = \frac{T}{(n_\chi^{\rm eq})^2}\frac{4g_i^2}{(4\pi)^5}\int_{s_{\rm min}}^{\infty} ds\, \overline{|\mathcal{M}|}^2_{B\bar{B}\to\chi\bar{\chi}} \sqrt{1-\frac{4m_i^2}{s}}\sqrt{1-\frac{4m_\chi^2}{s}}\sqrt{s}\,K_1(\sqrt{s}/T),$$

➡ We sum over all SM particles B that produce DM at tree level:

- $\{e,\ \mu,\ \tau\}$
- $\{\nu_e,\ \nu_\mu,\ \nu_\tau\}$
- $\{u,\ c,\ t,\ d,\ s,\ b\}$
- $\{\pi^\pm, K^\pm\}$
- $W^\pm$

Following prescription of Bhattiprolu, McGehee, Pierce 2023

Benchmark Freeze-in Model

The Kinetic Mixing Portal

$$-\frac{\bar{H}T}{s}\frac{dY_\chi}{dT} = \sum_B \langle\sigma_{B\bar{B}\to\chi\bar{\chi}}v\rangle (Y_\chi^{\rm eq})^2, \quad \langle\sigma_{B\bar{B}\to\chi\bar{\chi}}v\rangle = \frac{T}{(n_\chi^{\rm eq})^2}\frac{4g_i^2}{(4\pi)^5}\int_{s_{\rm min}}^\infty ds\, \overline{|\mathcal{M}|}^2_{B\bar{B}\to\chi\bar{\chi}}\sqrt{1-\frac{4m_i^2}{s}}\sqrt{1-\frac{4m_\chi^2}{s}}\sqrt{s}\,K_1(\sqrt{s}/T),$$

For fermions **f**: $\{e,\ \mu,\ \tau\}$ (leptons) $\{\nu_e,\ \nu_\mu,\ \nu_\tau\}$ (neutrinos) $\{u,\ c,\ t,\ d,\ s,\ b\}$ (quarks)

$$\overline{\mathcal{M}}^2_{f\bar{f}\to\chi\bar{\chi}} = \frac{32}{3}\pi^2\alpha^2\kappa^2 N_f\left(s+2m_\chi^2\right)\left[\frac{Q_f^2}{s^2}\left(s+2m_f^2\right) - 2Q_fV_f\tan\theta_W\frac{\left(s+2m_f^2\right)\left(s-m_Z^2\right)}{s\left[\left(s-m_Z^2\right)^2+m_Z^2\Gamma_Z^2\right]} + \tan^2\theta_W\frac{V_f^2\left(s+2m_f^2\right)+A_f^2\left(s-4m_f^2\right)}{\left(s-m_Z^2\right)^2+m_Z^2\Gamma_Z^2}\right],$$

For scalars **ϕ**: $\{\pi^\pm, K^\pm\}$

$$\overline{\mathcal{M}}^2_{\phi^+\phi^-\to\chi\bar{\chi}} = \frac{32}{3}\pi^2\alpha^2\kappa^2\left(1+\frac{2m_\chi^2}{s}\right)\left(1-\frac{4m_\phi^2}{s}\right),$$

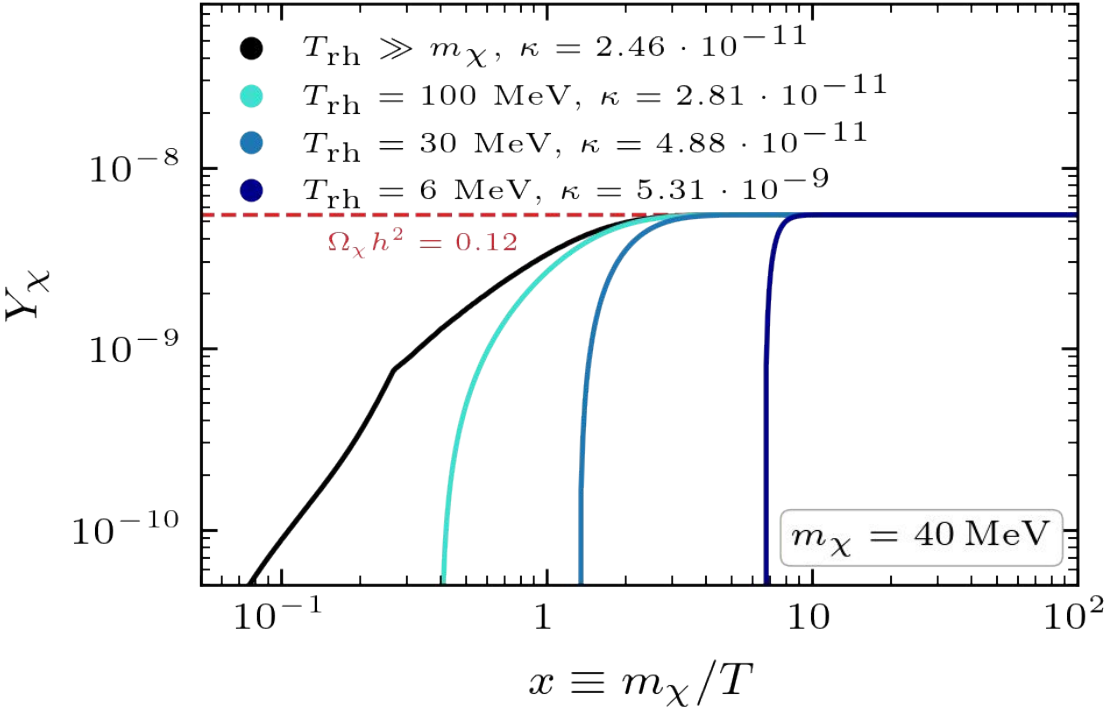
For the **W** boson:

$$\overline{\mathcal{M}}|^2_{W^+W^-\to\chi\bar{\chi}} = \frac{8}{27}\pi^2\alpha^2\kappa^2\left(\frac{m_Z}{m_W}\right)^4\frac{\left(s+2m_\chi^2\right)\left(s-4m_W^2\right)\left(s^2+20sm_W^2+12m_W^4\right)}{s^2\left[\left(s-m_Z^2\right)^2+m_Z^2\Gamma_Z^2\right]},$$

Following prescription of Bhattiprolu, McGehee, Pierce 2023

Benchmark Freeze-in Model

The Impact of the Reheating Temperature



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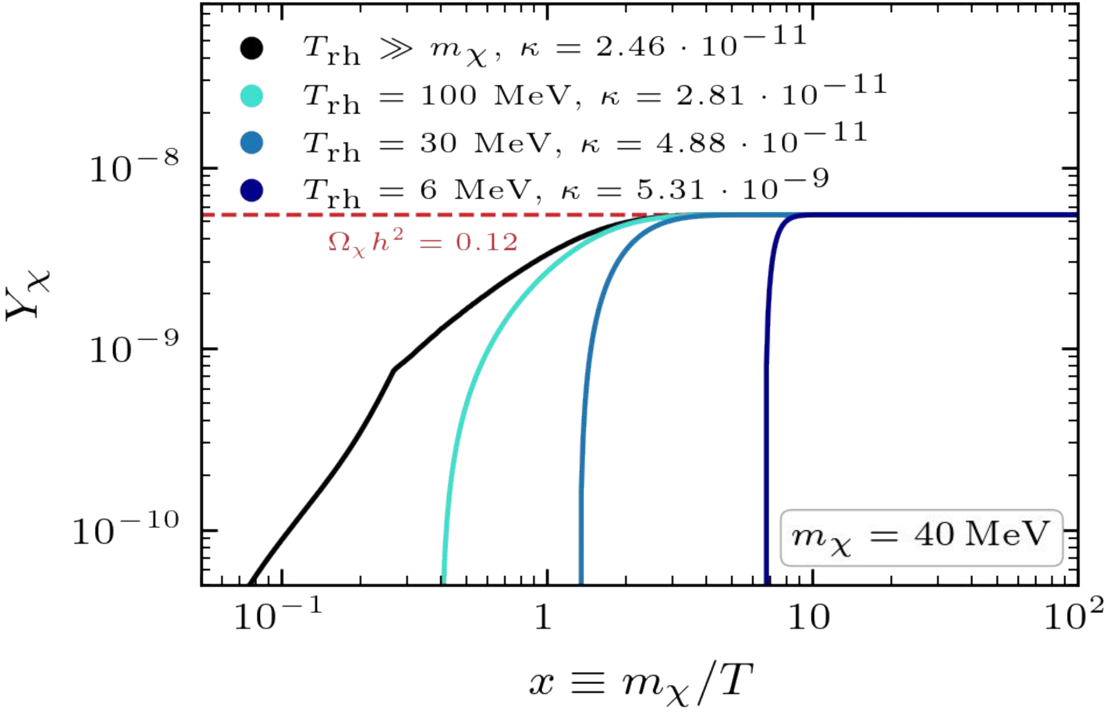

For $T_{rh} << m_\chi$:

final DM abundance becomes very sensitive to T_{rh}

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