THEORY TARGETS FOR DARK MATTER EXPERIMENTS:

THE CASE OF MAGNETIC DIPOLE DARK MATTER

Based on arXiv:2512.07927 with Asher Berlin and Tanner Trickle

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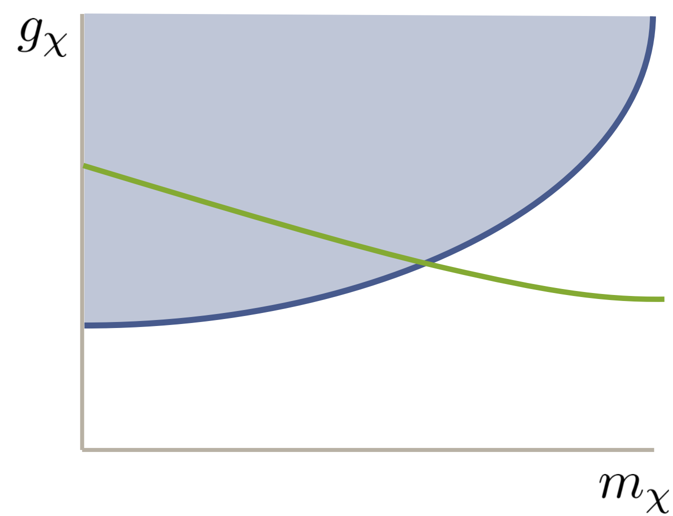
Sensitivity and Theory Target

χ : Dark Matter

m_χ : DM mass

g_χ : Coupling to the SM



Experimental sensitivity

What can the detector reach?

Theory target

What parameter space gives a physical motivation?

Experimental sensitivity aims to reach theory targets

What Defines a Theory Target?

A theory target is a parameter relation predicted by a specific origin of dark matter

Origin of DM

Particle model + **Production mechanism** + **Observed abundance** $\Omega_\chi h^2 \approx 0.12$

↓

Theory Target $g_{\chi,\mathrm{target}}(m_\chi)$ → **Experiments**

A link between the origin of DM and experiments

What Makes a Good Theory Target?

- **Predictive:** Production and detection are controlled by the same interactions, so the abundance implies a definite target

- **Robust:** Insensitive to initial conditions and the early history of the universe

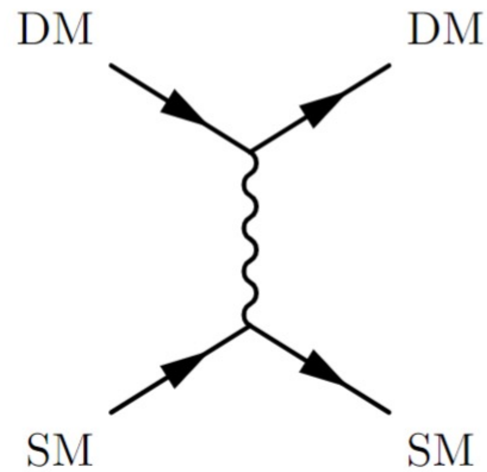
- **Reachable:** Within the sensitivity of realistic (future) experiments

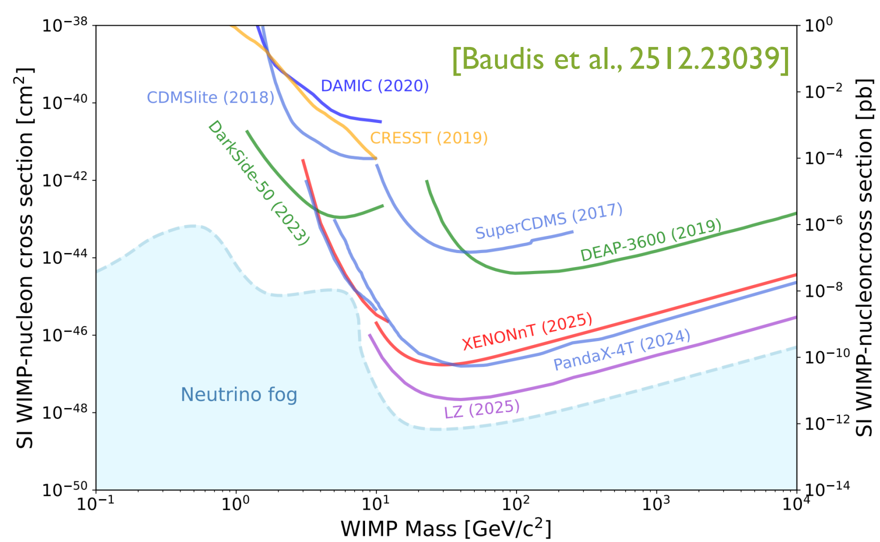
A Good Theory Target: WIMP

- Weak-scale freeze-out naturally yields the observed abundance (WIMP Miracle)

- Predictive ✓
  Robust ✓
  Reachable ✓

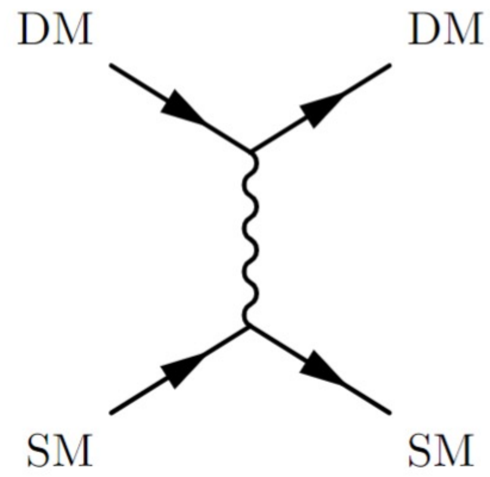
- This target drove decades of nuclear recoil searches

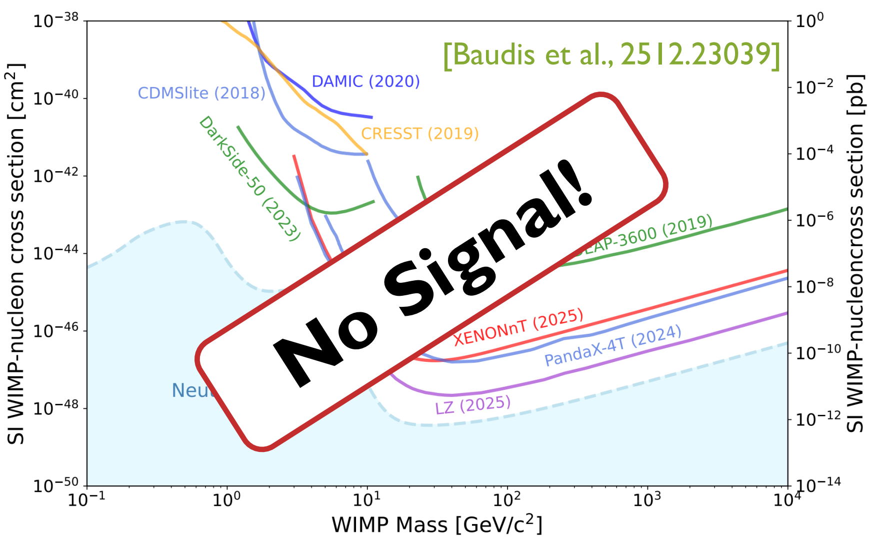




Testing the WIMP Target

- Nearly complete coverage down to the neutrino fog
- No signal, but a decisive result
- A good theory target does its job even without a signal
- Time to look elsewhere: new masses, new interactions

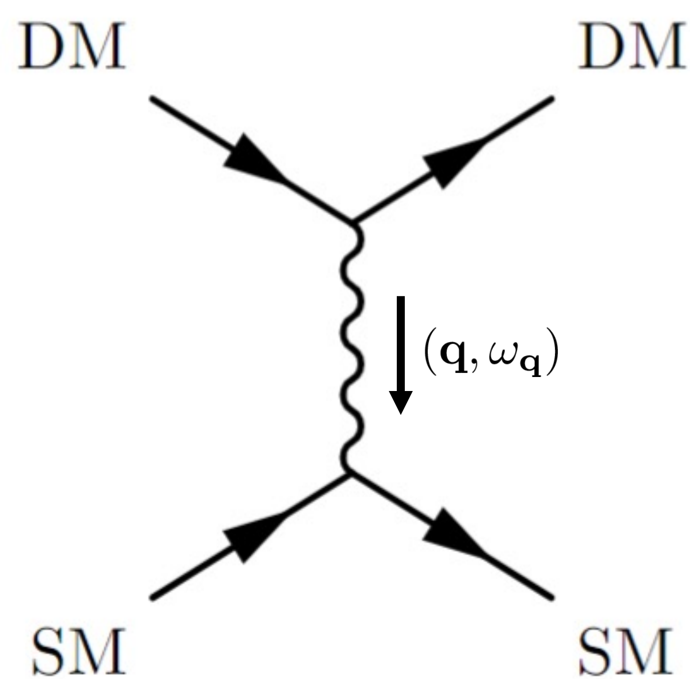


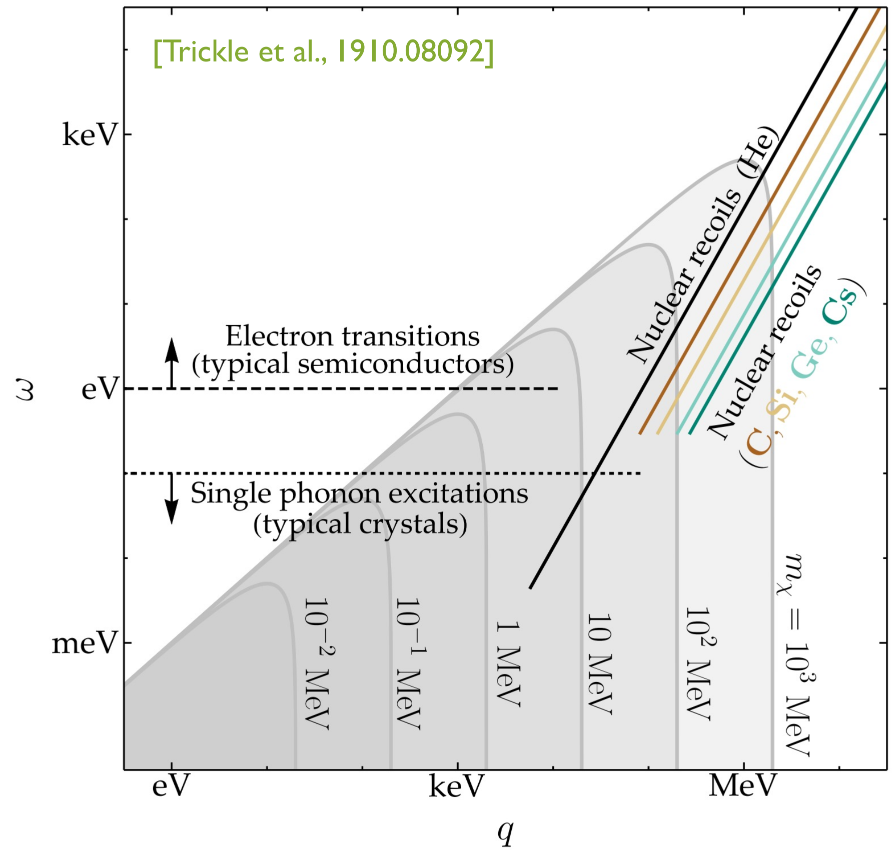


Theory Targets and Experiments Motivate Each Other

- Theory targets tell experiments where to look
- Experimental results and new technologies tell theory where to think
- The history of DM searches has been built on this interplay

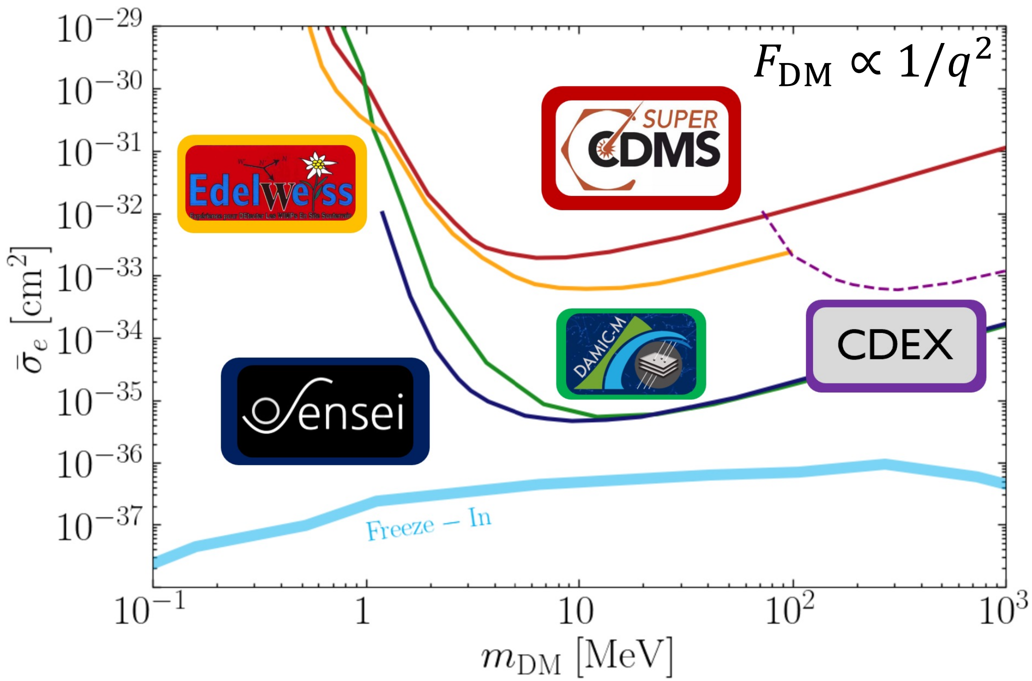
Light DM Direct Detection

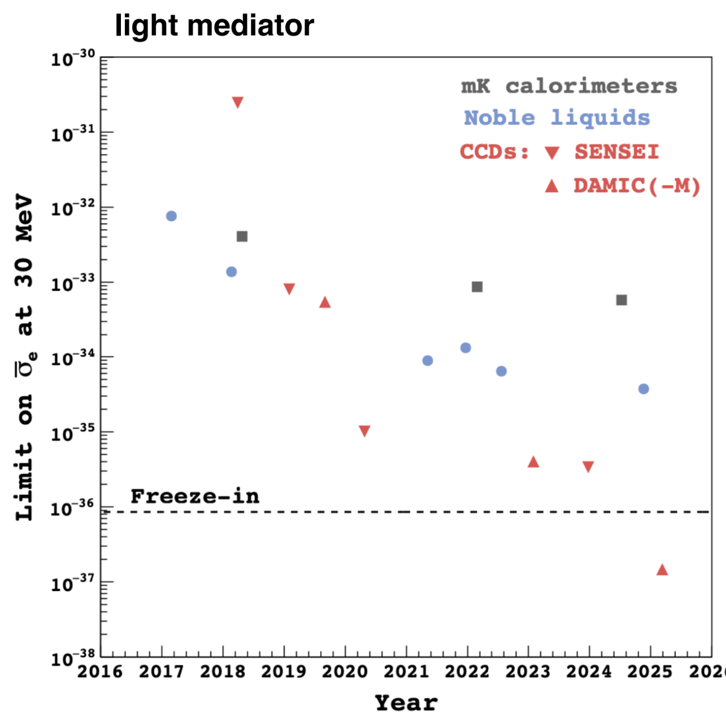




Multiple approaches to light DM detection

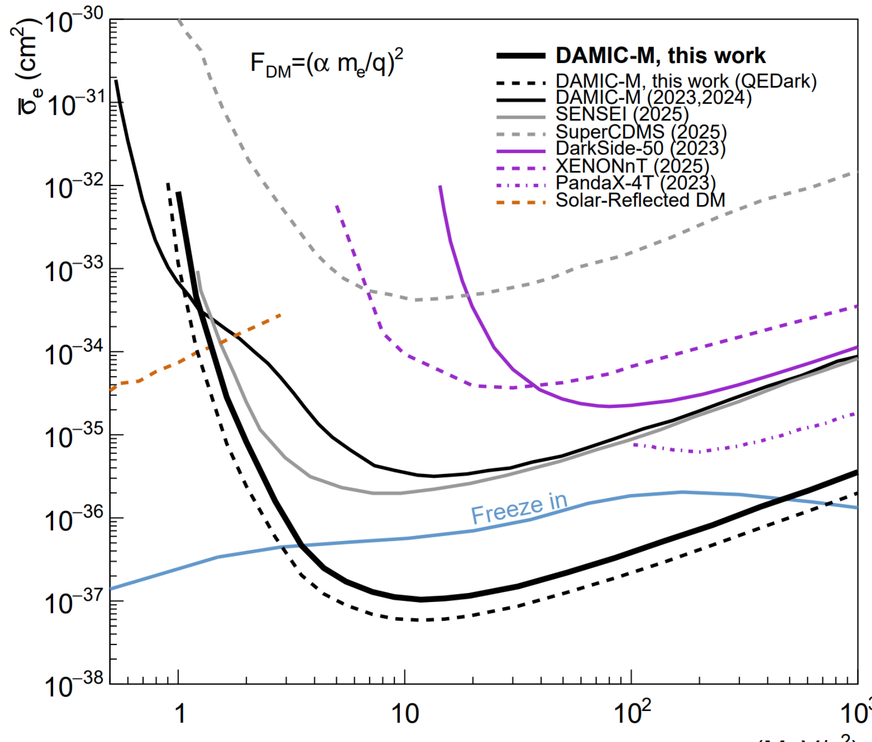
Theory Target for Light DM: Freeze-in





- Freeze-out is already ruled out for spin-independent (SI) interactions with a light mediator
- Freeze-in benchmark is being tested
- Predictive ✓ Robust ✓ Reachable ✓

New Results From DAMIC-M



[DAMIC-M Collaboration, 2503.14617]

- SI freeze-in parameter space is significantly constrained
- The natural next direction is spin-dependent (SD) interactions

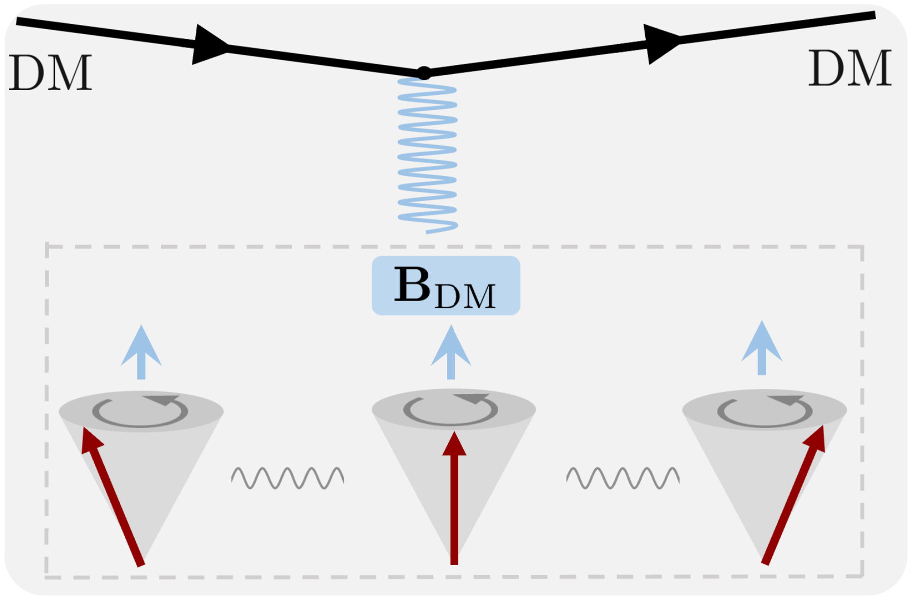
Detection of spin-dependent DM

- **Electron excitation**
  paired spins cancel
  → SD suppressed

- **Magnon**
  quantized collective spin precession in ferromagnetically aligned spins
  → coherent SD response

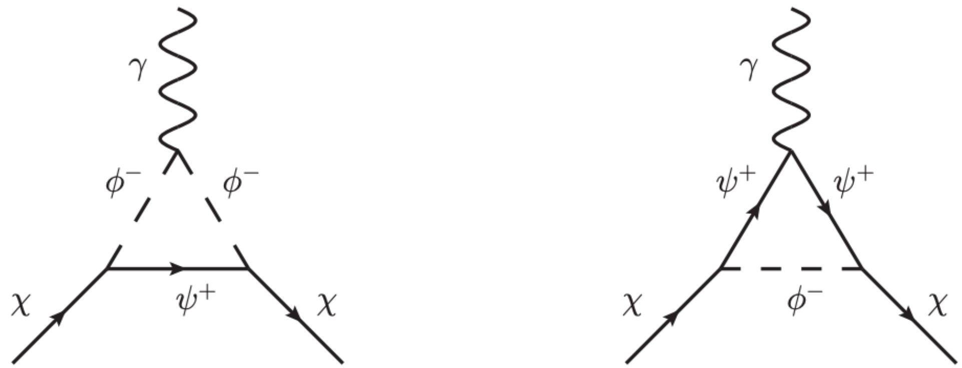
- Single-magnon detection is within reach of current quantum technology

Magnons



[Trickle, Zhang, Zurek, 1905.13744, 2009.13534]
[Esposito, Pavaskar, 2210.13516]
[Marocco, Wheater, 2501.18120]

Magnetic Dipole DM



[Graham, Kaplan, Rajendran, Walters, 1203.2531]

$$\mathcal{L}_{\rm MDM} = -\frac{1}{2}\mu_\chi \bar{\chi}\sigma_{\mu\nu}\chi F^{\mu\nu}$$

- Naturally generated by heavy charged particles in a loop $\left(\mu_\chi \sim \frac{ey^2}{32\pi^2 M}\right)$
- EDM $\left(\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F^{\mu\nu}\right)$ can be obtained from the same diagram with a CP-violating phase
- MDM operator is $\vec{S}_\chi \cdot \vec{B}$ in the non-relativistic limit → spin-dependent

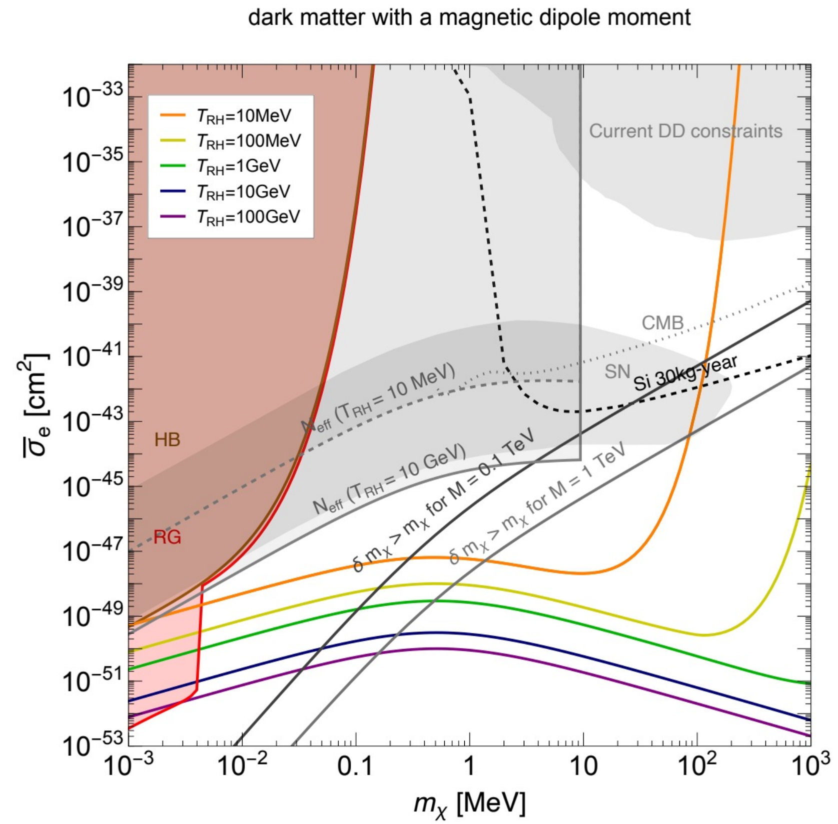
Production of Magnetic Dipole DM

$$\mathcal{L}_{\rm MDM} = -\frac{1}{2}\mu_\chi \bar{\chi}\sigma_{\mu\nu}\chi F^{\mu\nu}$$

- Dimension-5 operator
- UV Freeze-in
  $\rightarrow$ Depends on $T_{\rm RH}$
- Predictive ✔

  Robust ✗

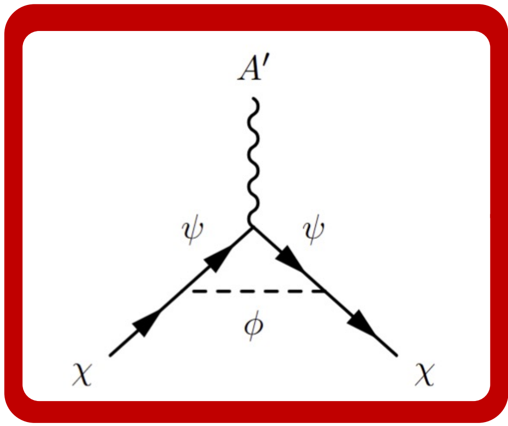
  Reachable △



[**JHC**, Essig, Reinert, 1911.03389]

Magnetic Dipole DM Model in this Work

$$\mathcal{L} \supset \underbrace{A'_\mu\left[g'(\bar{\psi}\gamma^\mu\psi) + g'(\phi^*\partial^\mu\phi)\right] + y'\phi\bar{\psi}\chi}_{\text{Dark sector}}$$



$$\mu'_\chi = \frac{g' y'^2}{32\pi^2 M}$$

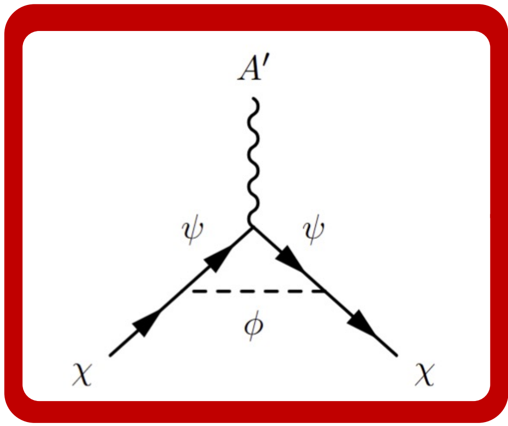
ψ, ϕ Dark Charged Particles

χ Dark Matter

$$\mathcal{L} \supset \frac{\mu'_\chi}{2} F'_{\mu\nu}\left(\bar{\chi}\sigma^{\mu\nu}\chi\right)$$

Magnetic Dipole DM Model in this Work

$$\mathcal{L} \supset \underbrace{A'_\mu\left[g'(\bar{\psi}\gamma^\mu\psi) + g'(\phi^*\partial^\mu\phi)\right] + y'\phi\bar{\psi}\chi}_{\text{Dark sector}} + \underbrace{\frac{\varepsilon}{2}F'_{\mu\nu}F^{\mu\nu}}_{\text{Interaction (Kinetic mixing)}}$$



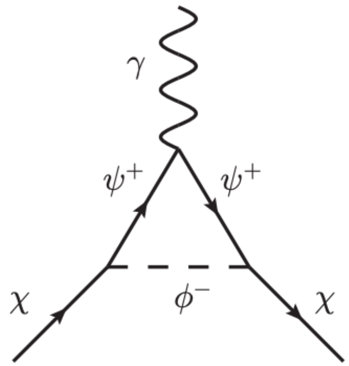
$$\mu'_\chi = \frac{g'y'^2}{32\pi^2 M}$$

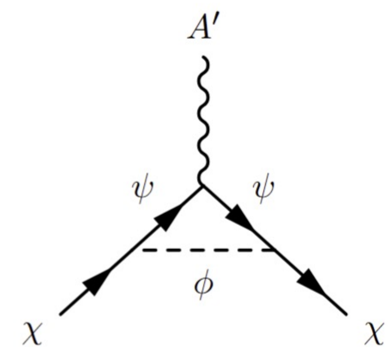
$$\mu_\chi = \varepsilon\mu'_\chi$$

$$\mathcal{L} \supset \frac{\mu'_\chi}{2}F'_{\mu\nu}\left(\bar{\chi}\sigma^{\mu\nu}\chi\right) + \varepsilon e\, A'_\mu\left(\bar{e}\gamma^\mu e\right)$$

Magnetic Dipole-Coupled Interaction Lagrangian

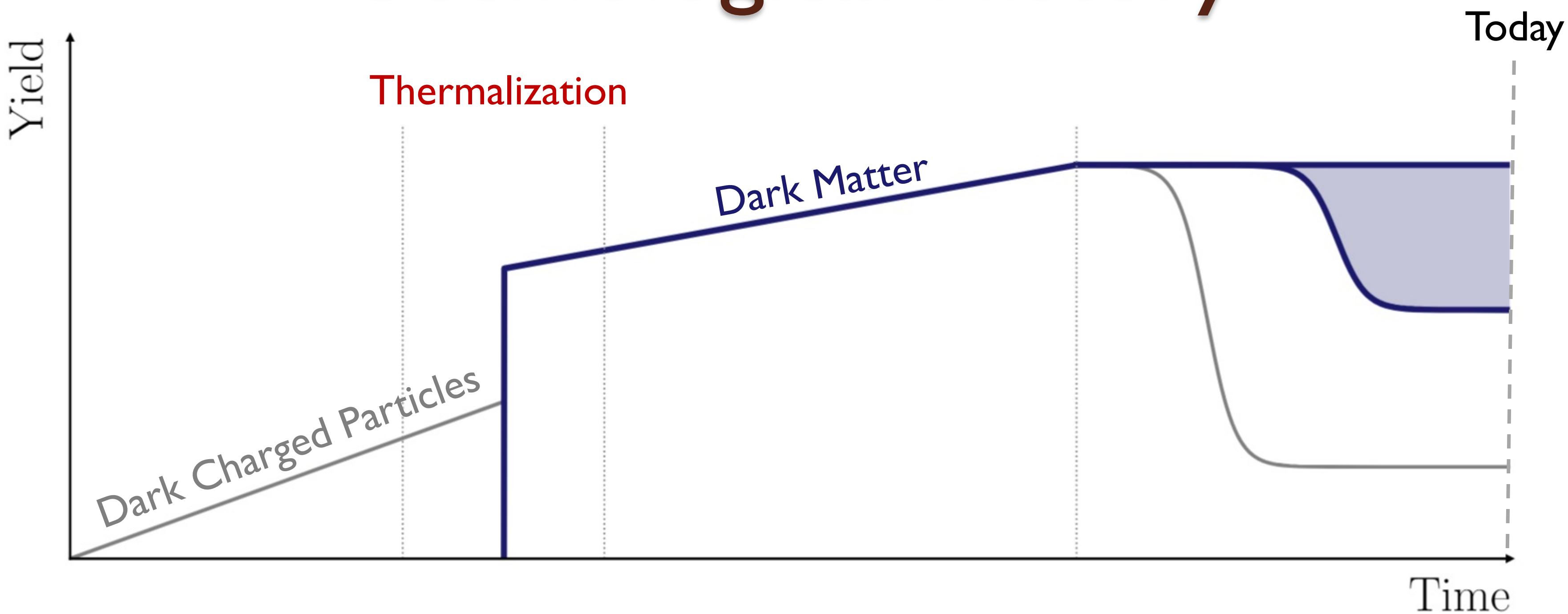
Magnetic Dipole DM Model in this Work





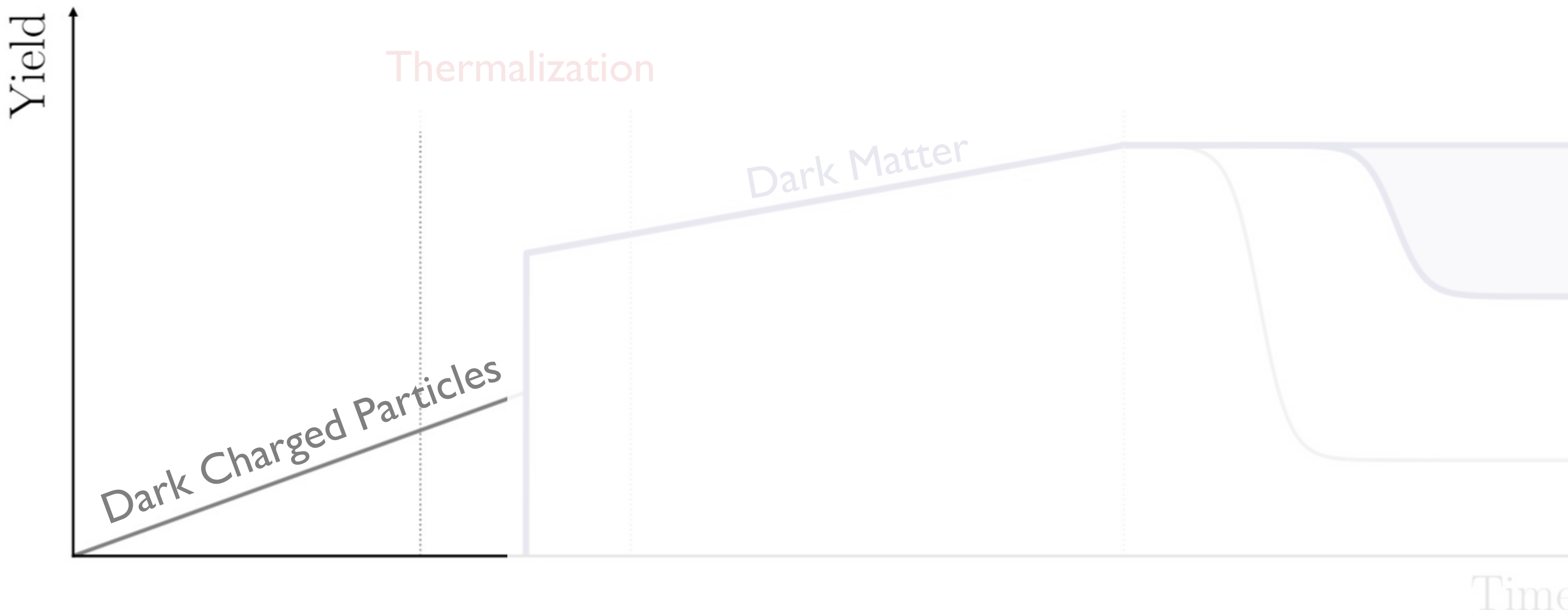
- In the massless A' limit, DCPs (ψ, ϕ) are millicharged particles
- DCPs can be light while χ acquires an MDM at low energies
- Smallness of MDM comes from the small mixing angle ε
- Predictive ✓ Robust ✓ Reachable ✓

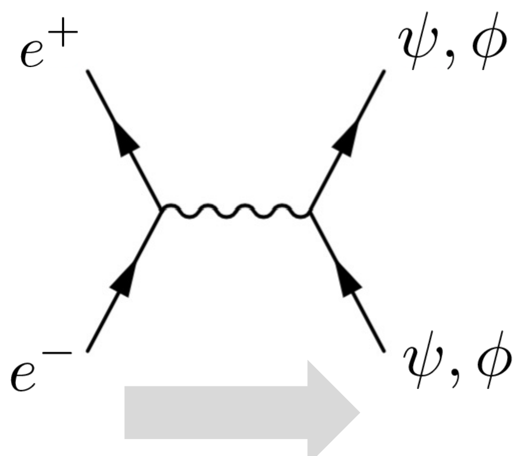
Cosmological History



- DCP Freeze-in → DS Thermalization → DS Evolution → DM Freeze-out
- This structure was first explored as "reannihilation" [Chu, Hambye, Tytgat, 1112.0493]
- Further developed in "glaciation" [2111.13709] and "dark sink" [2312.14152, 2408.07744]
- In this work, DM is produced through thermalization, not direct freeze-in

1. DCPs Freeze-in



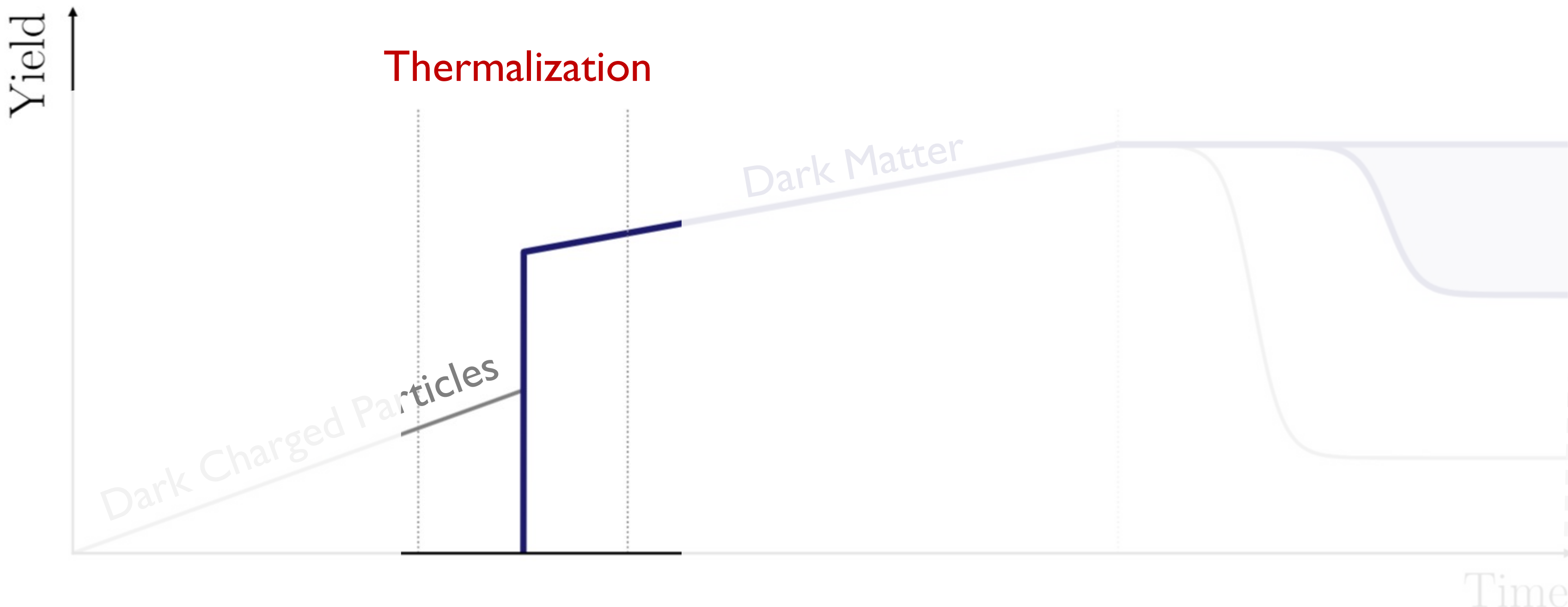


$$Y_X \sim 10^{-4}\, e^4 \kappa^2 \, \frac{M_{\rm Pl}}{T}$$

$$X = \psi, \phi \quad \kappa \equiv \frac{\varepsilon g'}{e}$$

$$m_\psi \approx \; m_\phi \equiv M > m_\chi$$

2. DS Thermalization



$$\phi \leftrightarrow \psi\chi \quad , \quad \phi\phi \leftrightarrow A'A' \quad , \quad \psi\psi \leftrightarrow A'A' \quad , \quad \phi\phi \leftrightarrow \chi\chi$$

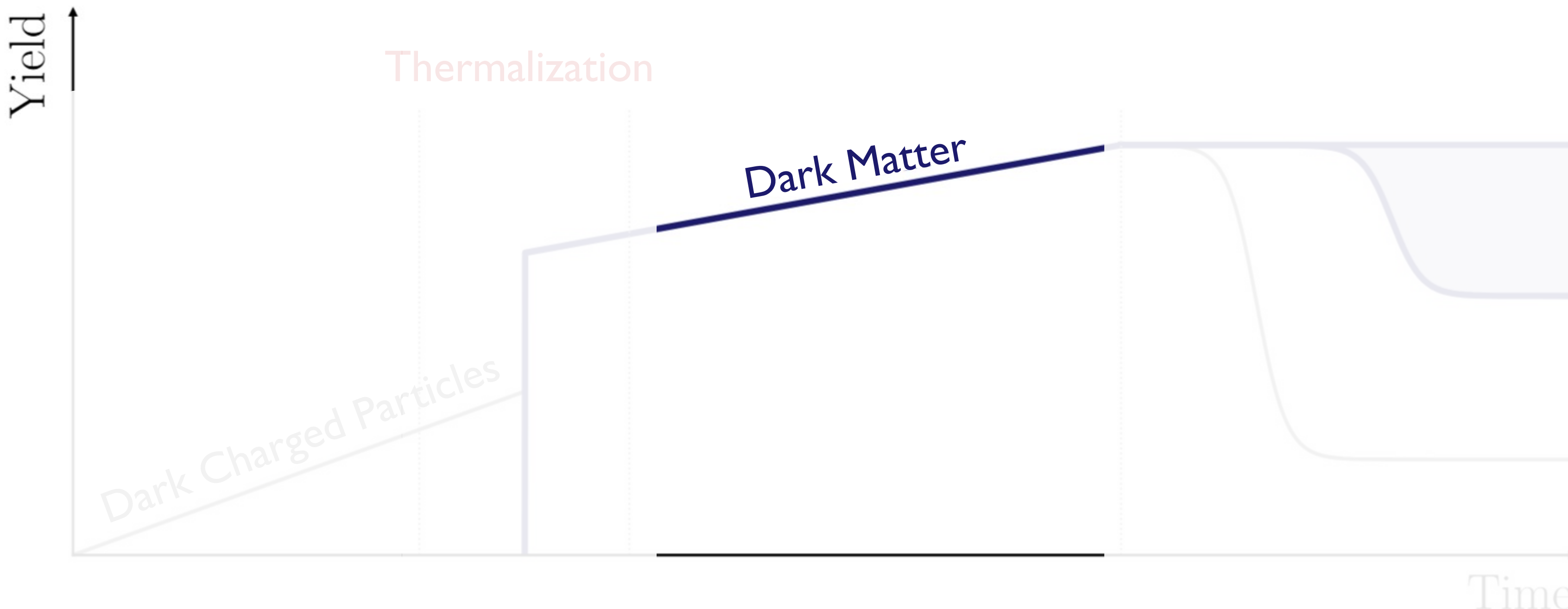
All processes must be faster than Hubble $\Gamma > H$

A few high-energy particles $\rightarrow$ Many low-energy particles

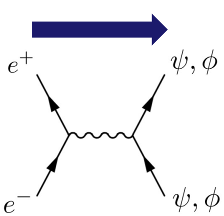
(DS Thermalization from the Sun: Dark Solar Wind)

[**JHC**, Kaplan, Rajendran, Ramani, Tanin, 2205.11527]

3. DS Evolution



$$\rho_{\mathrm{DS}} \sim T_{\mathrm{DS}}^{4}$$



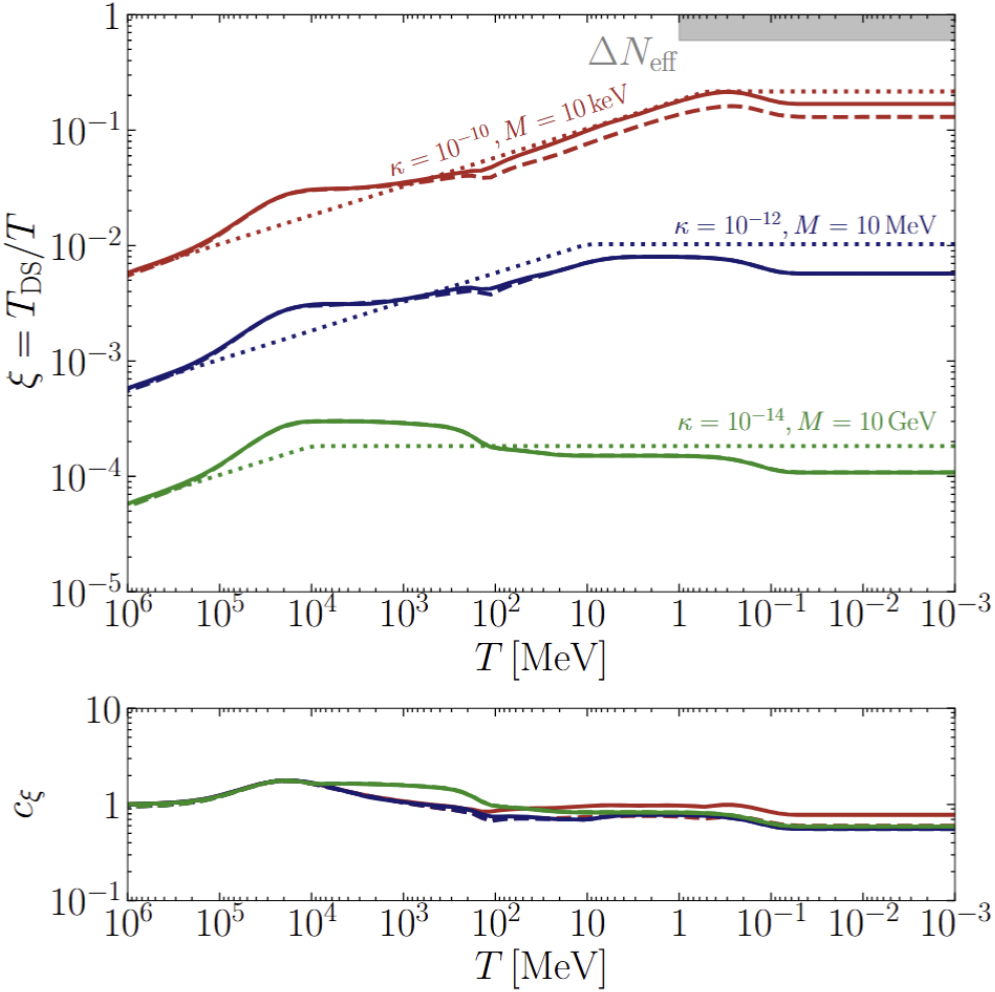
$$\frac{d(\rho_{\mathrm{DS}}/s^{4/3})}{dT} \propto -(e^2\kappa)^2 \frac{M_{\mathrm{Pl}}}{T^2}$$

Energy density

Boltzmann equation

$$\frac{T_{\mathrm{DS}}}{T} \sim \sqrt{e^2\kappa}\left(\frac{M_{\mathrm{Pl}}}{T}\right)^{1/4}$$

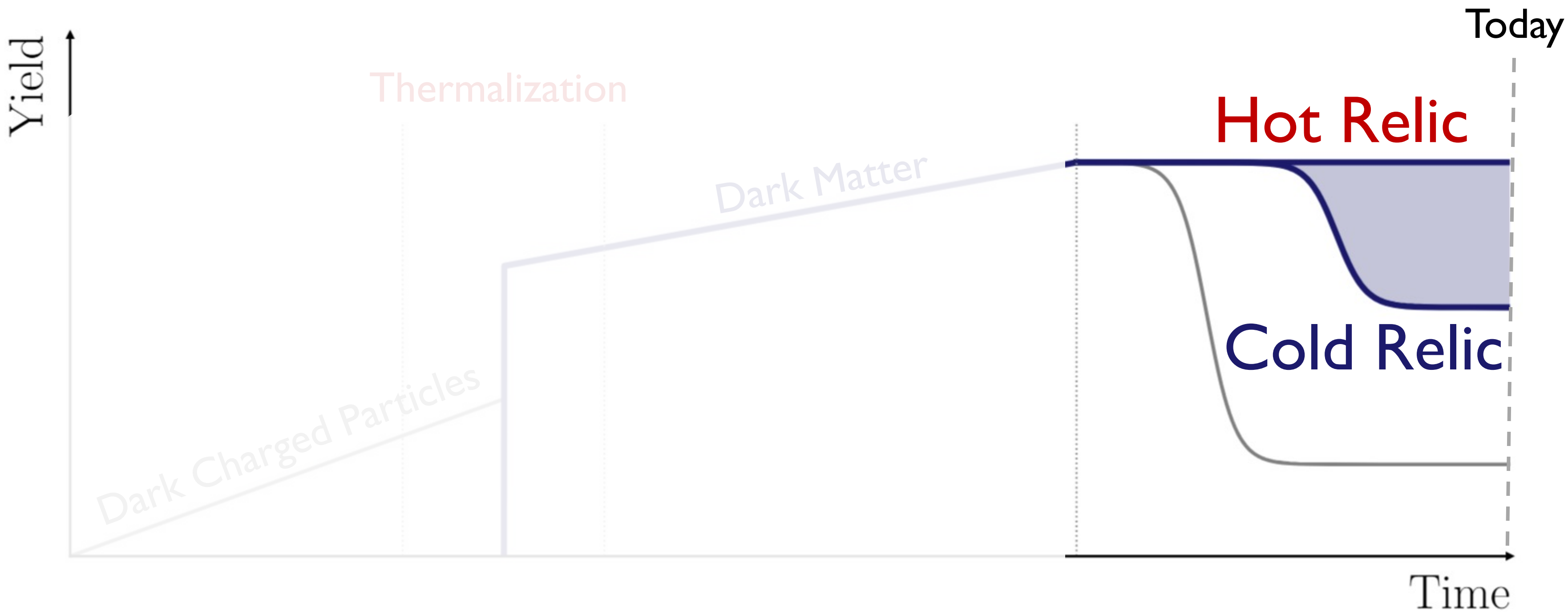
3. DS Evolution

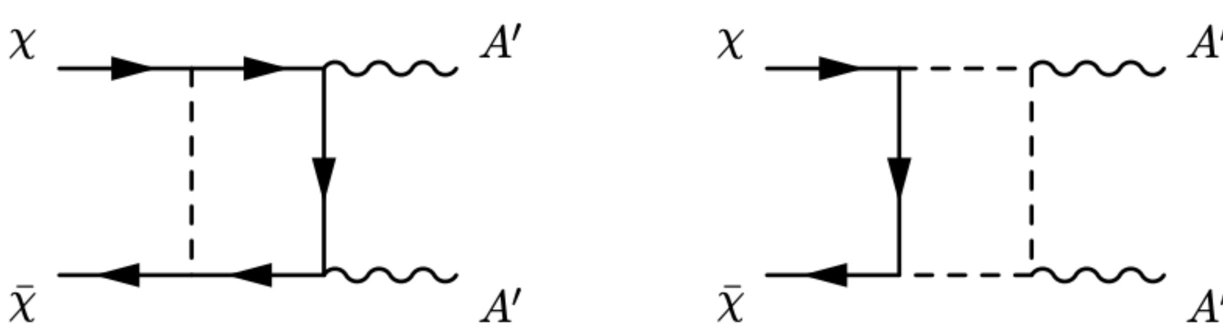


- DS is always colder than SM ($\xi < 1$)
- The the exact shape is determined by various processes and $g_\star$
- Energy injection stops if SM cannot produce DCPs

$$\frac{\rho_{\rm DS}}{s^{4/3}} = 10^{-4}\, c_\rho\, e^4 \kappa^2 \left(\frac{M_{\rm Pl}}{\max\{T, M, m_e\}} \right)$$

4. DM Freeze-out



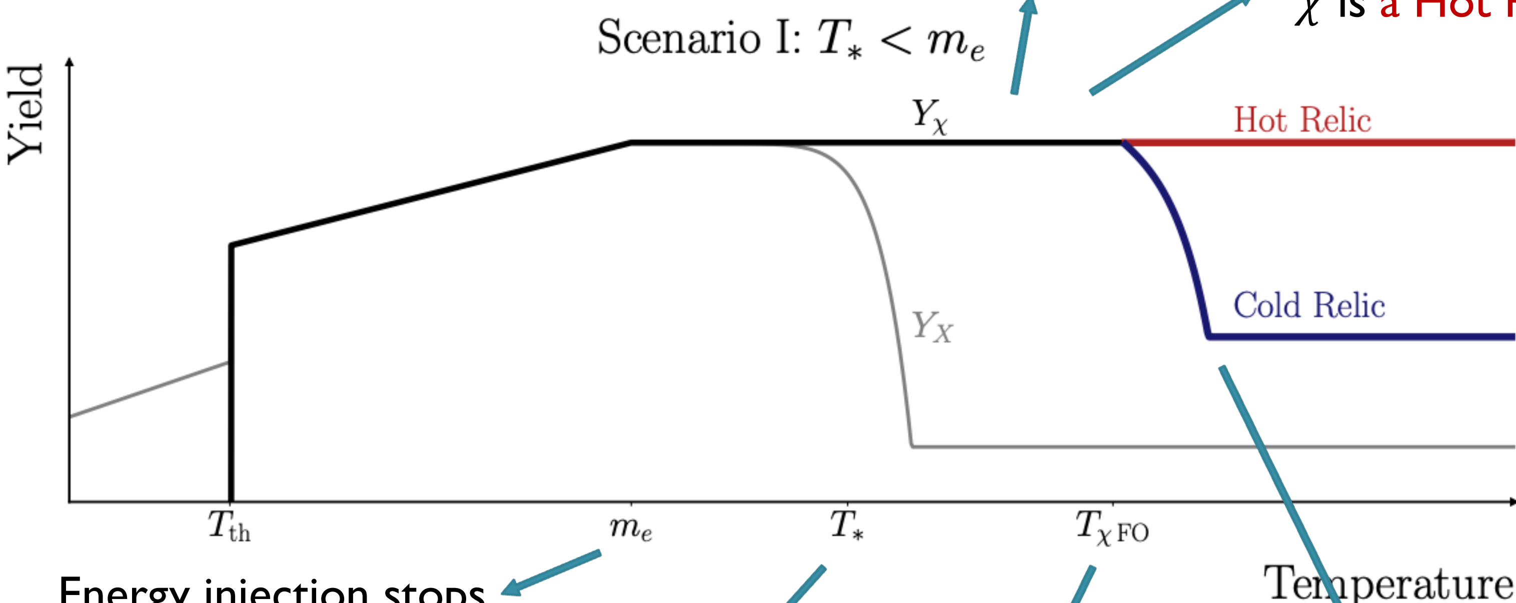


$$\langle \sigma v \rangle_{\chi\chi \to A'A'} \sim \frac{y'^4 g'^4}{768\pi^5} \frac{m_\chi^4}{M^6}$$

4. DM Freeze-out

$$\xi \equiv \frac{T_{\rm DS}}{T} \sim \sqrt{e^2\kappa}\left(\frac{M_P}{m_e}\right)^{1/4}$$

If $\chi - A'$ decouples earlier, χ is a Hot Relic



Final yield depends on the coupling

Energy injection stops

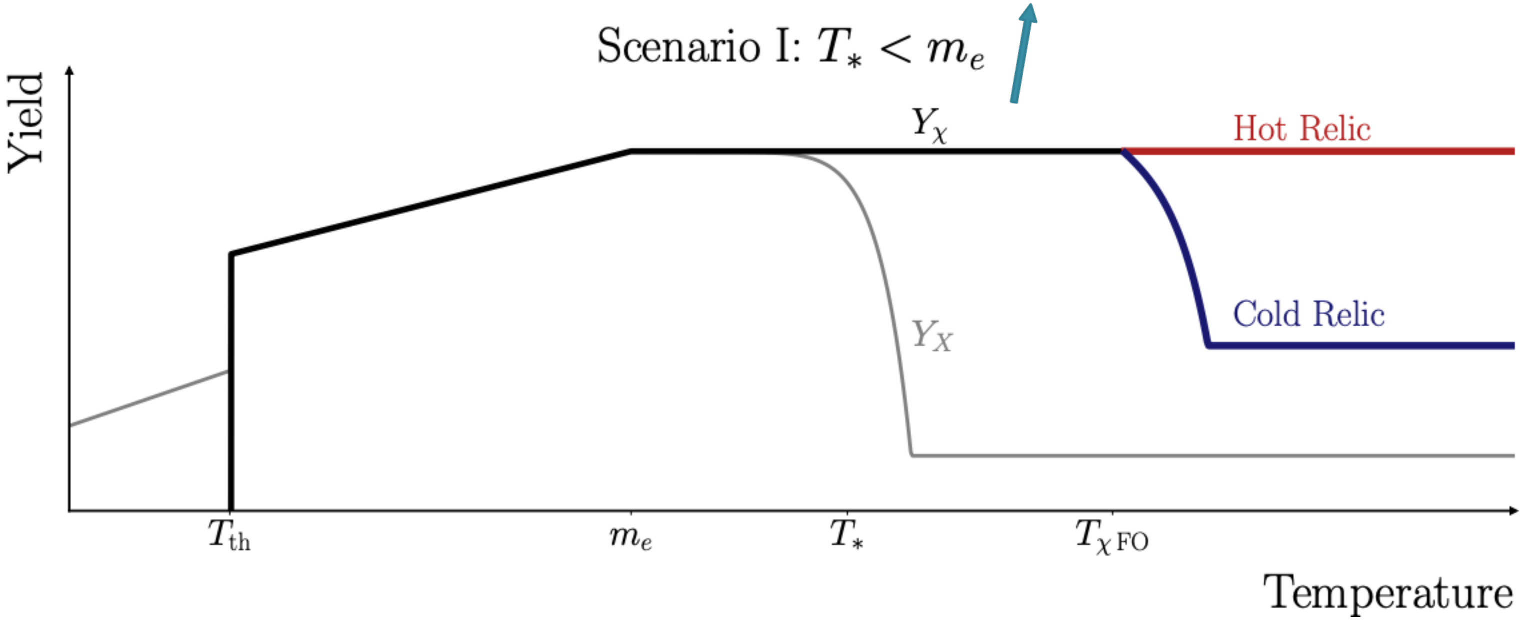
$T_* \equiv T(T_{\rm DS} = M)$
DCPs start to deplete

$$T_{\chi\,\rm FO} = T\left(T_{\rm DS} = \frac{m_\chi}{10}\right)$$

If $\chi - A'$ decouples later, χ is a Cold Relic

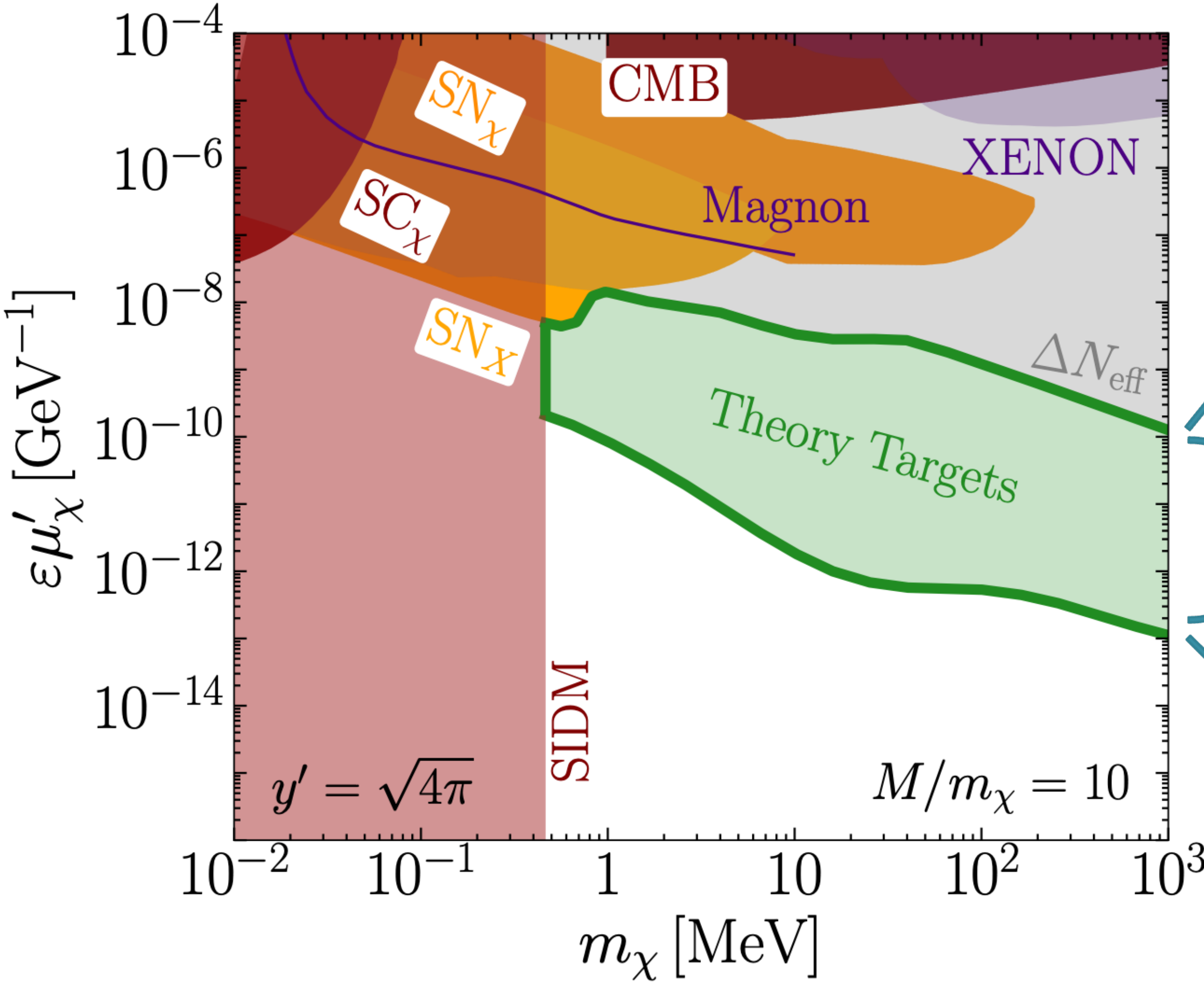
4. DM Freeze-out

$$\xi \equiv \frac{T_{\rm DS}}{T} \sim \sqrt{e^2\kappa}\left(\frac{M_P}{m_e}\right)^{1/4}$$



$$Y_\chi \simeq \begin{cases} \dfrac{90}{\pi^4 g_{*s}(m_e)}\xi_e^3 \sim 10^{-3}\,\left(e^2\kappa\right)^{3/2}\left(\dfrac{M_{\rm Pl}}{m_e}\right)^{3/4} & \text{(HR)} \\ \left.\dfrac{H}{s\langle\sigma v\rangle'_{\chi\chi\to A'A'}}\right|_{T_{\chi\,\rm FO}} \sim 10^6\,\dfrac{\sqrt{e^2\kappa}}{y'^4 g'^4}\left(\dfrac{M_{\rm Pl}}{m_e}\right)^{1/4}\left(\dfrac{m_\chi}{M_{\rm Pl}}\right)\left(\dfrac{M}{m_\chi}\right)^6 & \text{(CR)} \end{cases}$$

Direct Detection Theory Targets



Upper boundary comes from various constraints

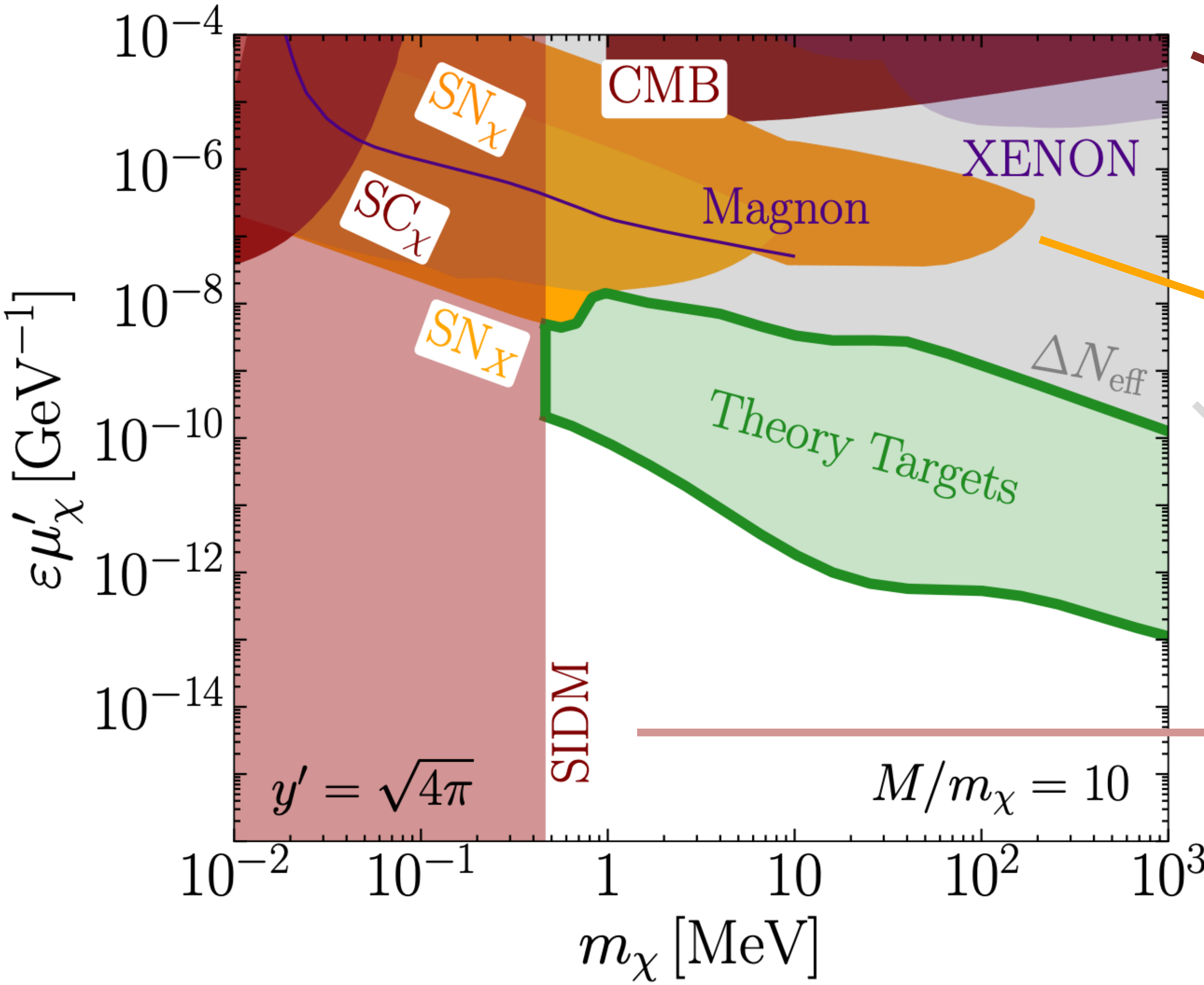
The region in between corresponds to the Cold Relic case

Lower boundary is set by the Hot Relic case

Predictive ✓

Robust ✓

Various Constraints

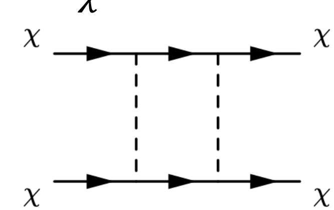


CMB energy injection from the annihilation to e^-e^+

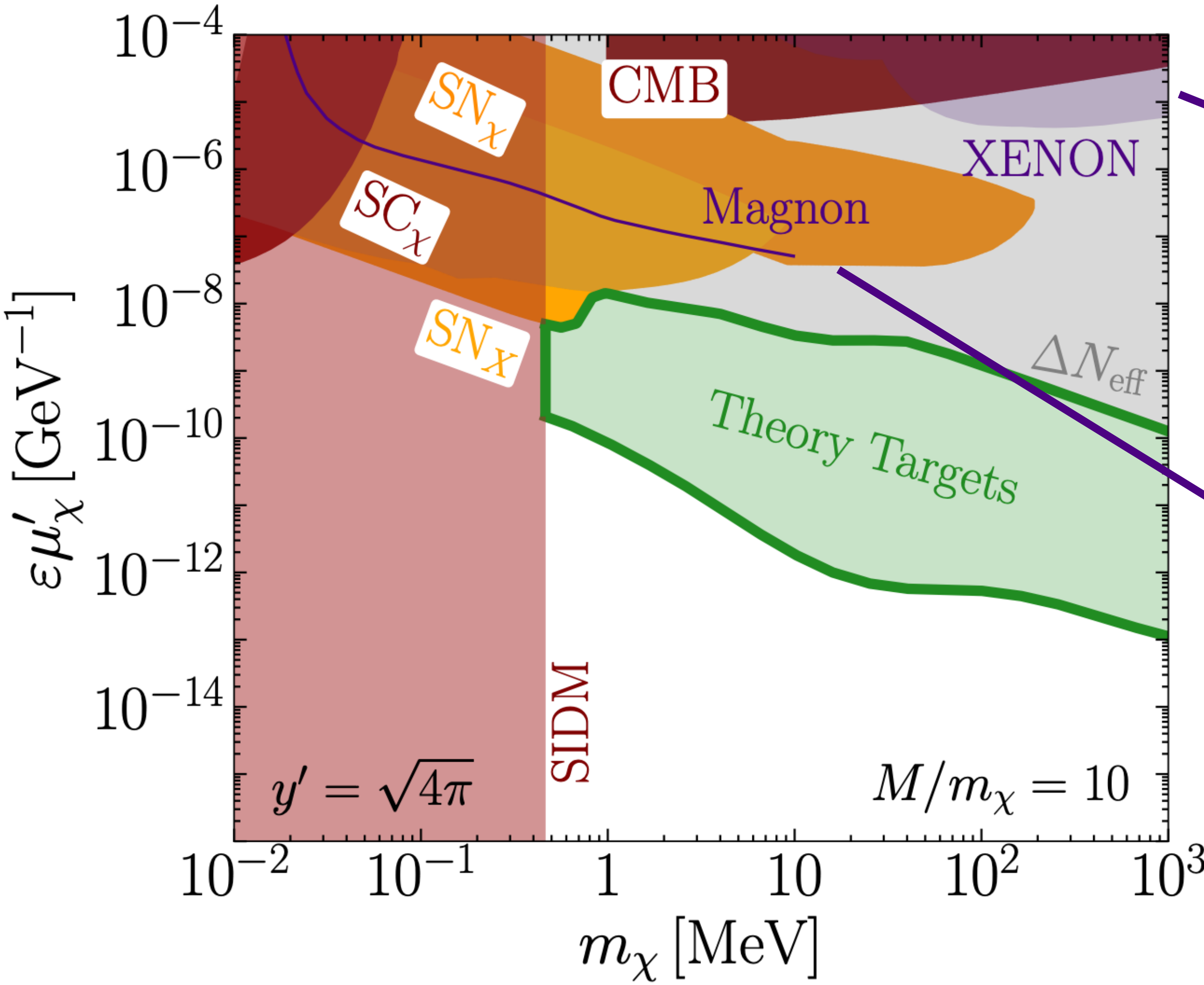
Stellar energy loss bounds from SN/RG

Radiation energy density from A'
$\Delta N_{\rm eff} < 0.17$

DM self-interaction
$$\frac{\sigma_T}{m_\chi} < 1\ \mathrm{cm}^2/\mathrm{g}$$



Direct Detection Sensitivity

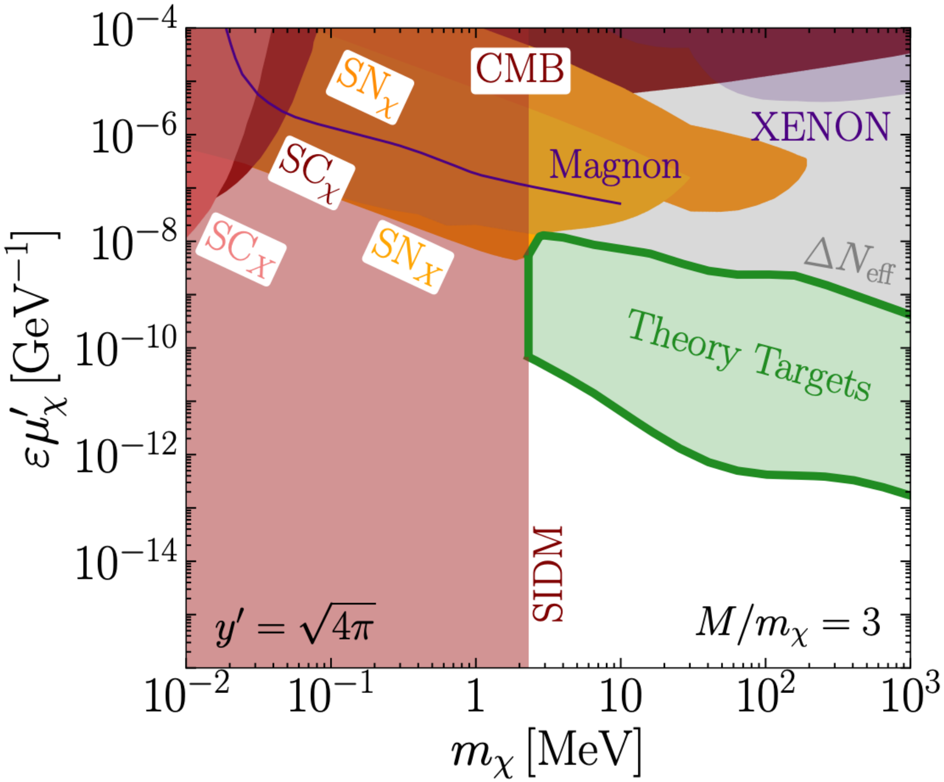


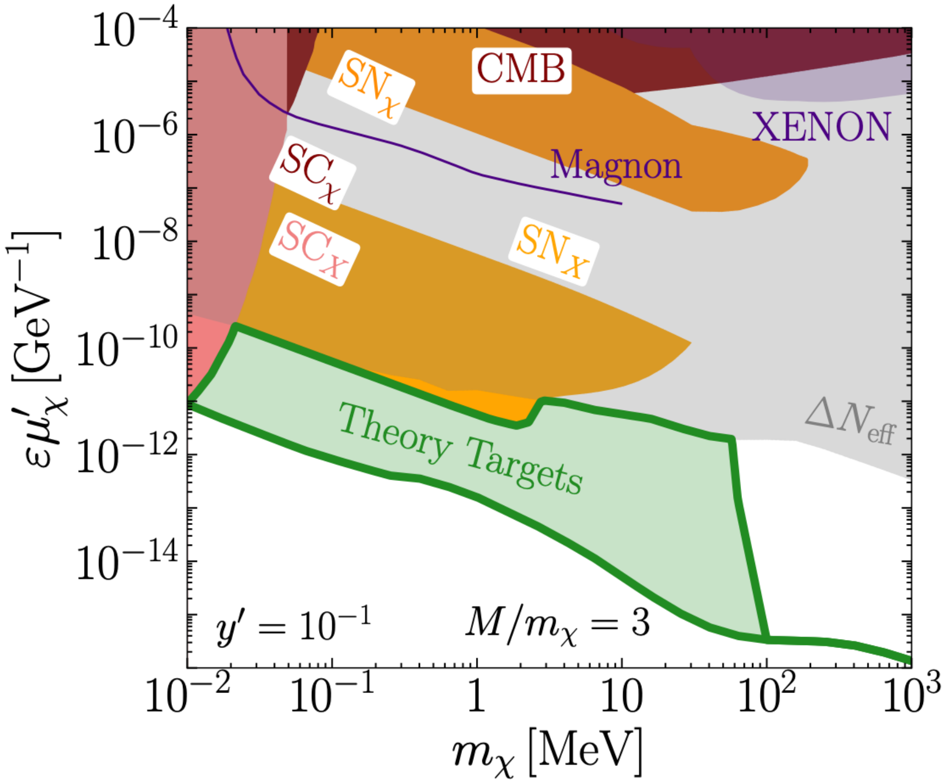
XENON electron-recoil
No coherent enhancement,
but no suppression either

Magnon experiments
Sensitive to SD
Within an order of magnitude of the theory target

Reachable ✓

Other parameters





Summary

- Magnon detectors open a new window: coherent sensitivity to spin-dependent DM

- We propose IR freeze-in of dark charged particles, which thermalize the dark sector

- The result is a theory target for magnon experiments:
  Predictive ✓
  Robust ✓
  Reachable ✓

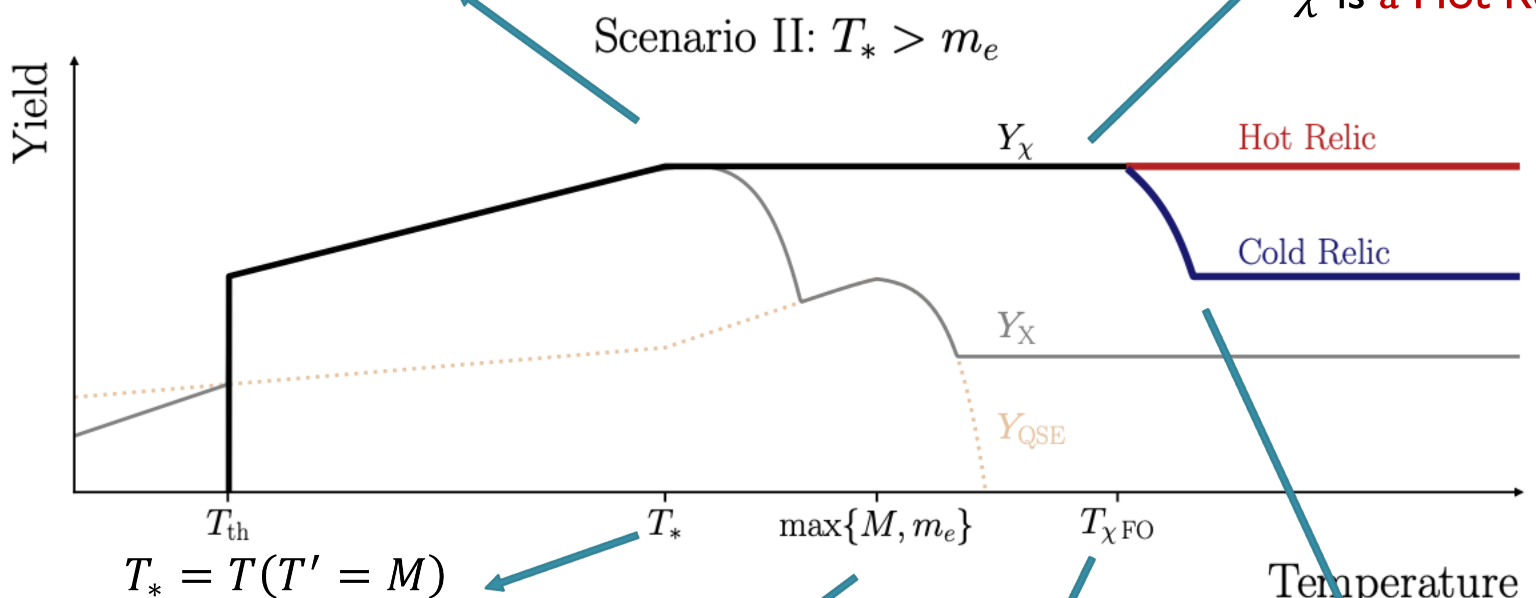
THANK YOU

BACK UP

4. DM Freeze-out: Scenario 2

$$\xi \sim (e^2\kappa)^{2/3}\left(\frac{M_P}{M}\right)^{1/3}$$

If $\chi - A'$ decouples earlier, χ is a Hot Relic



Final yield depends on the coupling

$T_* = T(T' = M)$
Number changing processes stop

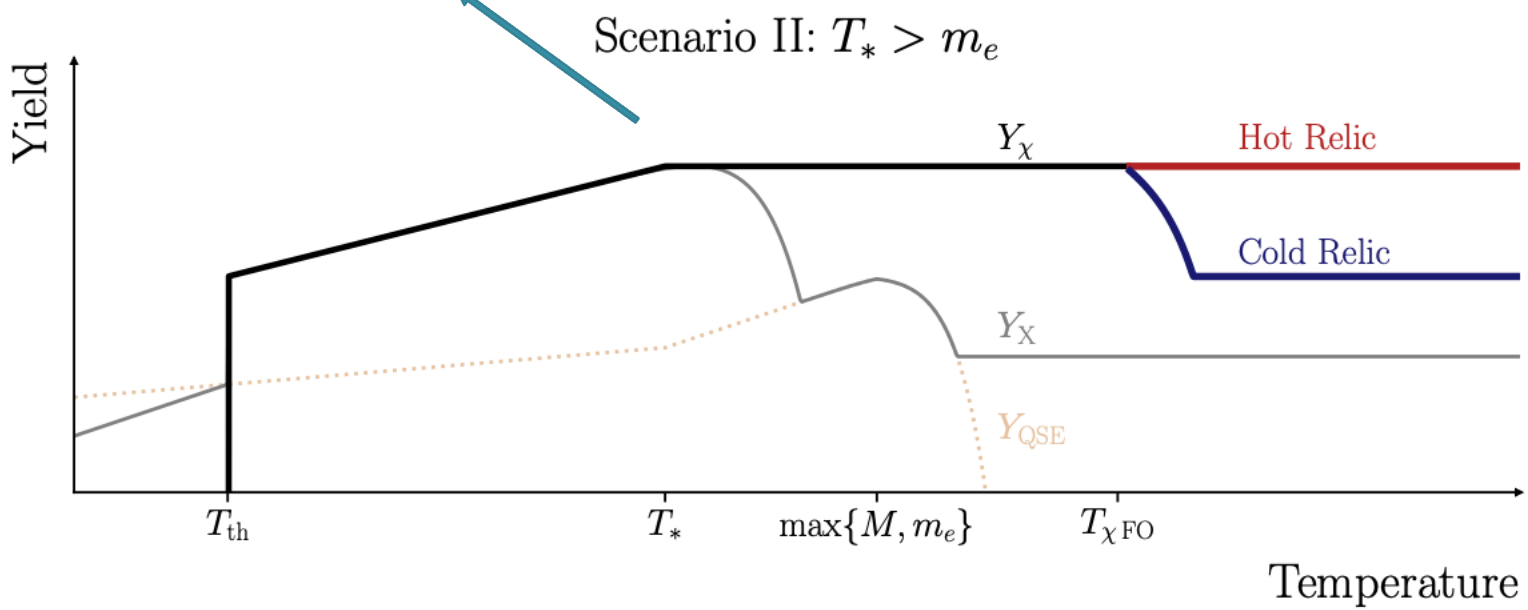
Energy injection is still active, and it generates high-energy X

$$T_{\chi\,\rm FO} = T\left(T_{\rm DS} = \frac{m_\chi}{10}\right)$$

If $\chi - A'$ decouples later, χ is a Cold Relic

4. DM Freeze-out: Scenario 2

$$\xi \sim (e^2\kappa)^{2/3}\left(\frac{M_P}{M}\right)^{1/3}$$



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