The Search for Light Dark Matter

Tanner Trickle

August 25th, 2026

5th Workshop on
Symmetry and
Structure of the Universe
SSU 2026 BUSAN

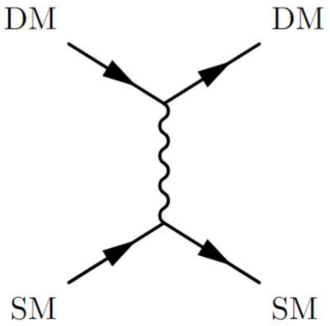
Outline

I. **Current Status of Direct Detection**

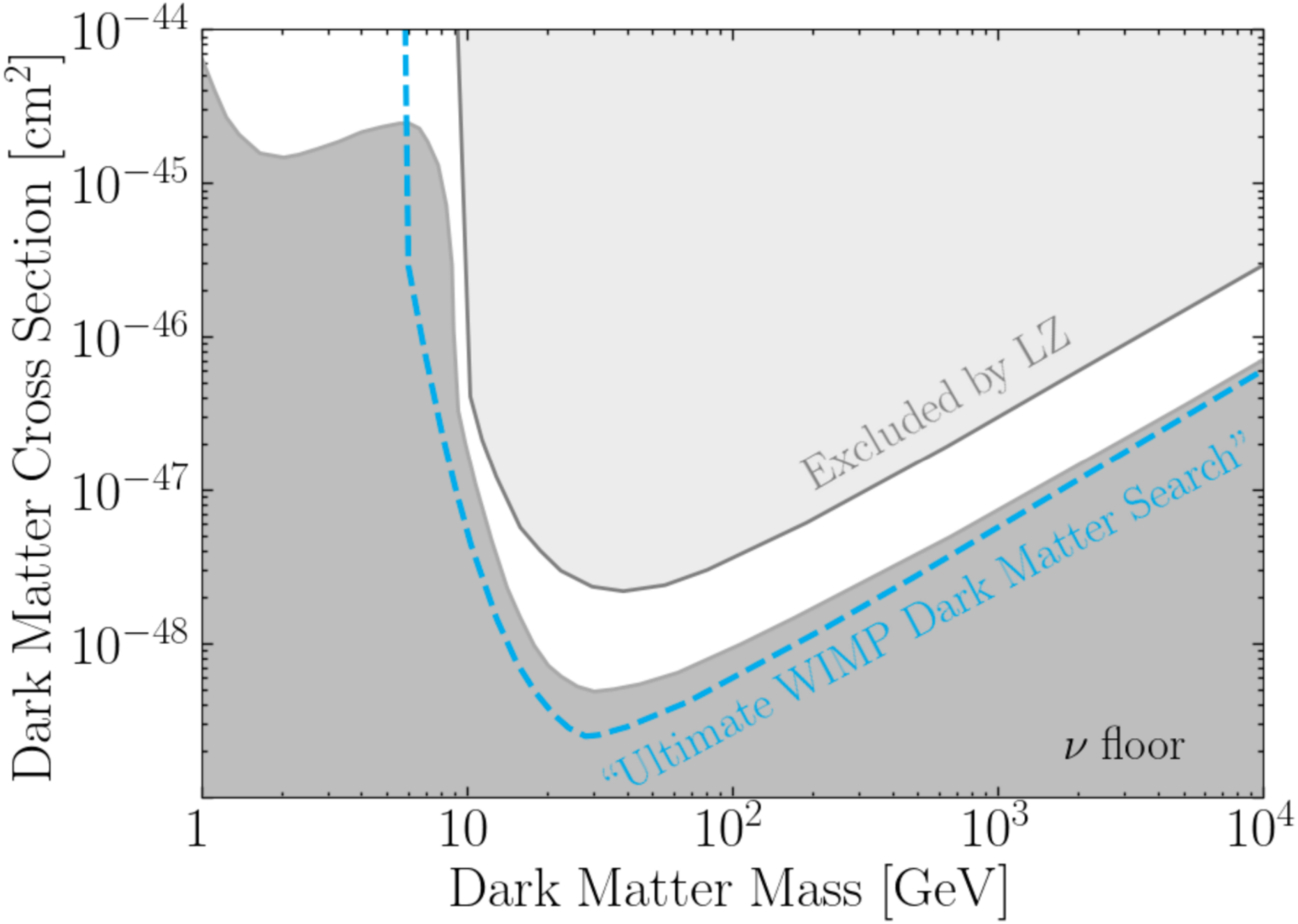
I. **Infrared Freeze-In of Magnetic Dipole Dark Matter**

II. **Magnon-Based Direct Detection**

Nuclear Recoil Direct Detection



LUX-ZEPLIN (LZ) detector



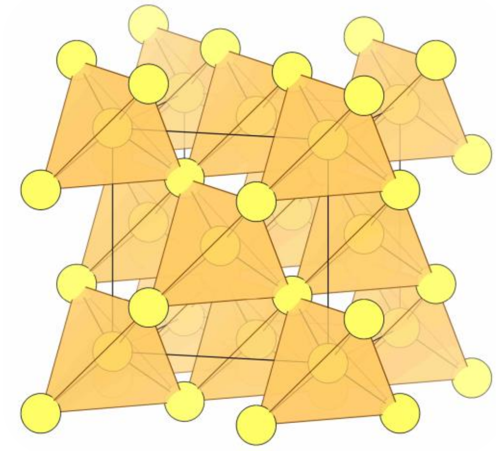
Illuminate the Hidden Universe

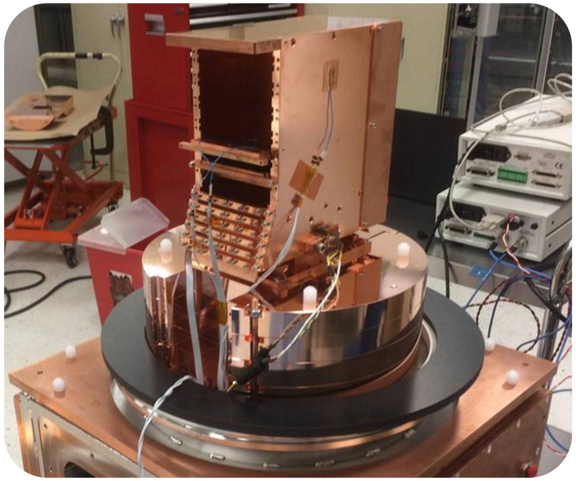
Determine the Nature of Dark Matter

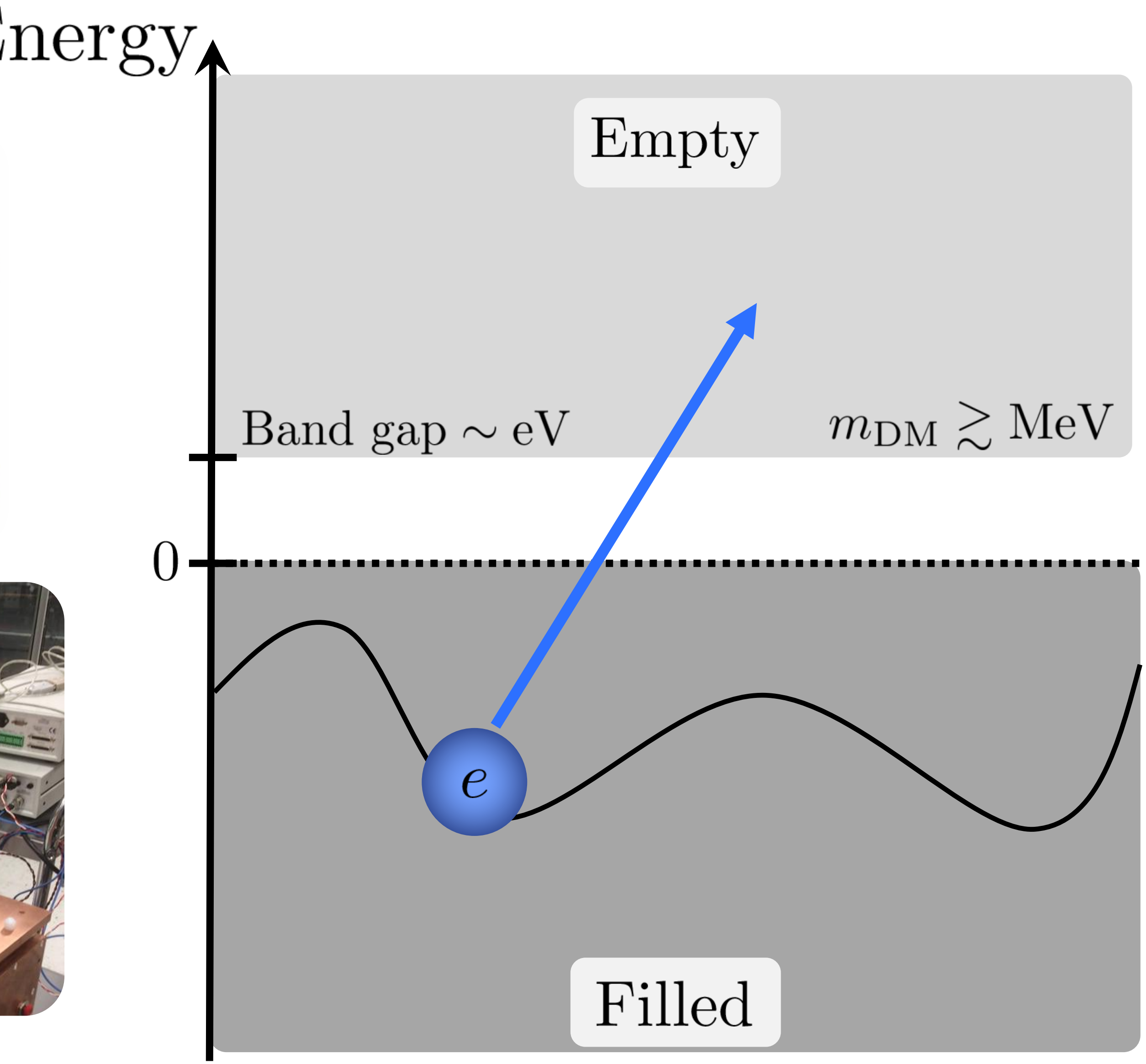
***Major Initiative**: G3, the Ultimate WIMP Dark Matter Search*

2023 P5 Report: Exploring the Quantum Universe | Pathways to Innovation and Discovery in Particle Physics.

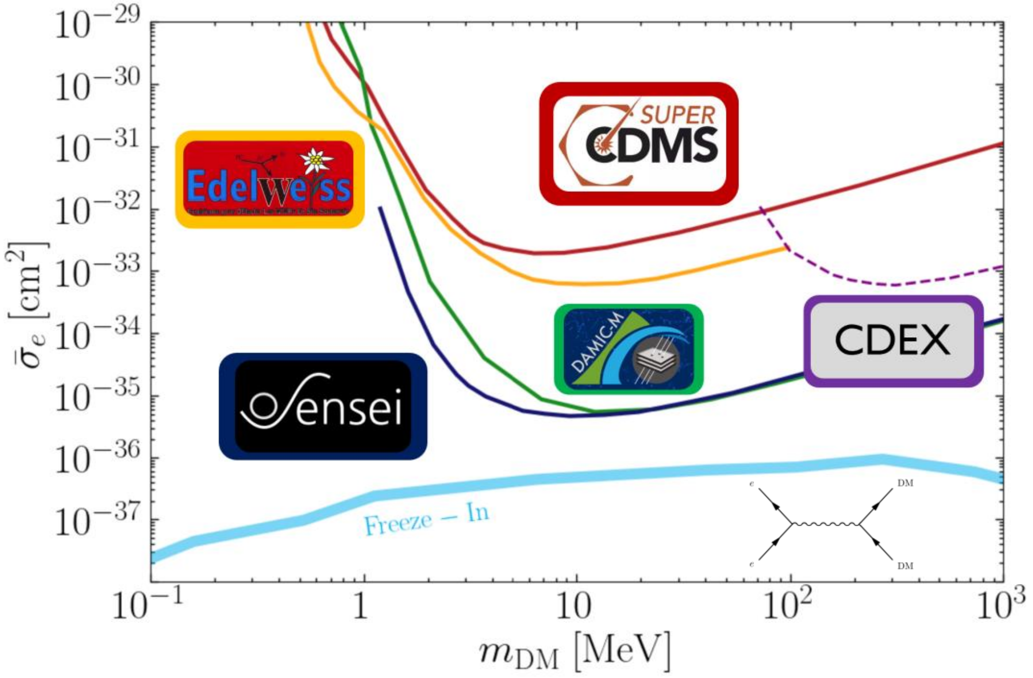
Electronic Excitations



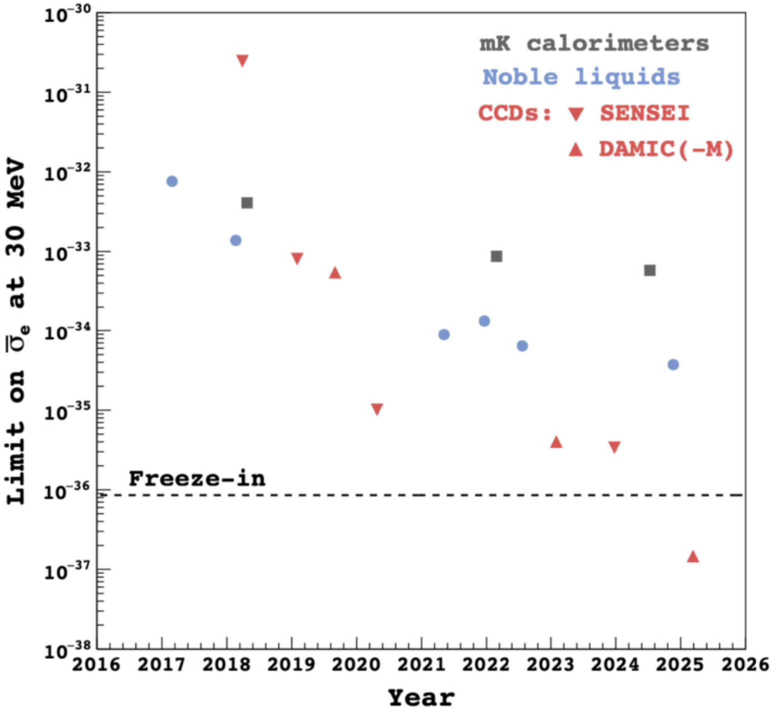




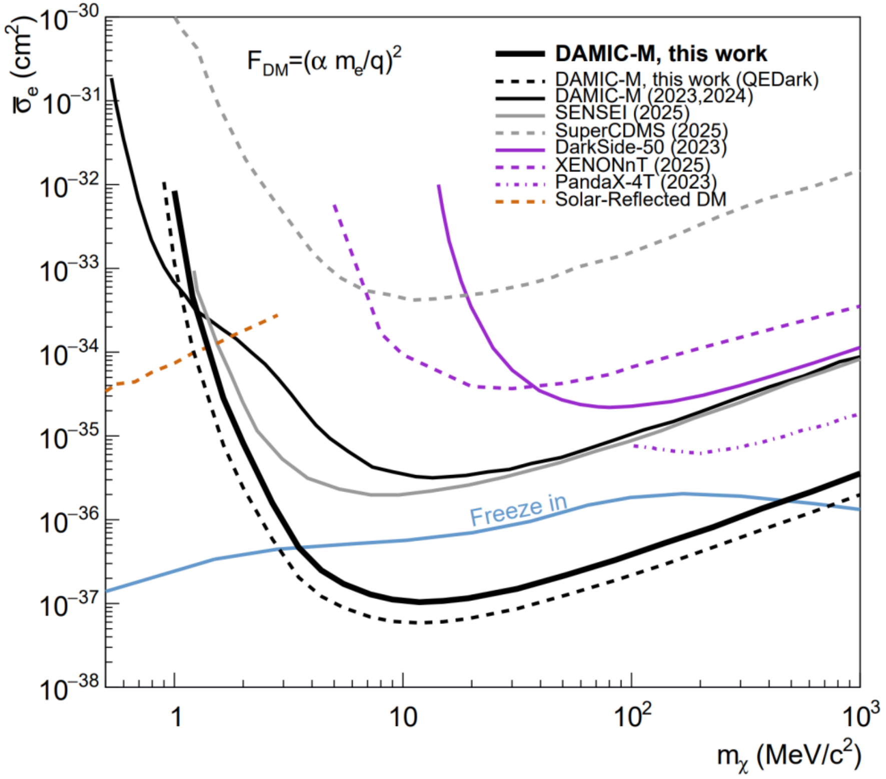
Experimental Sensitivity

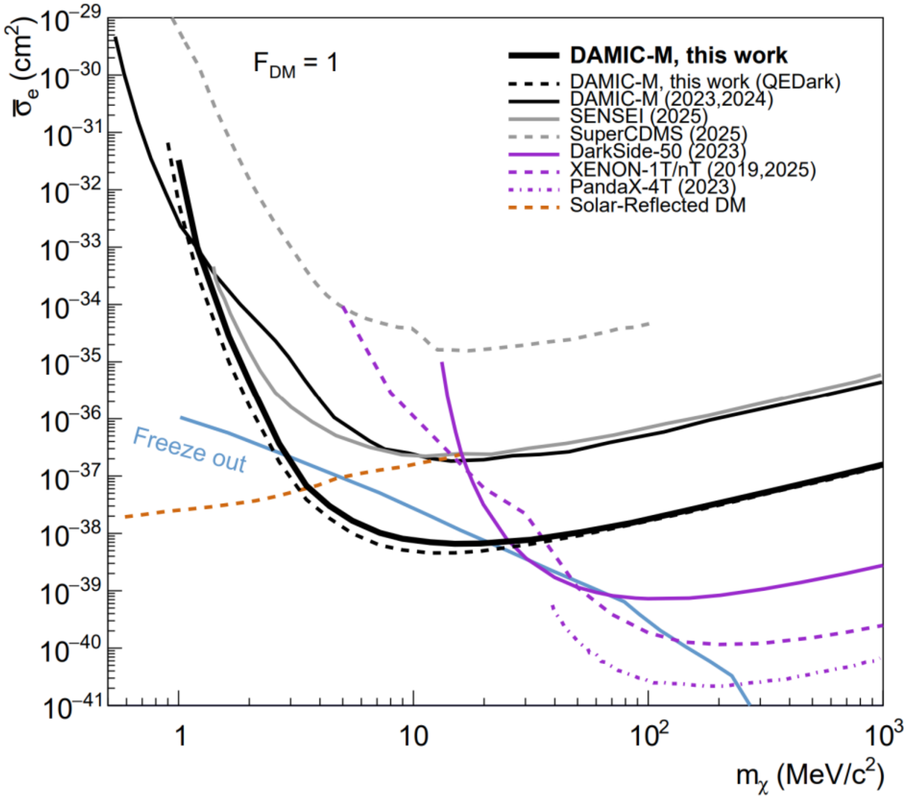


History of Light DM Direct Detection



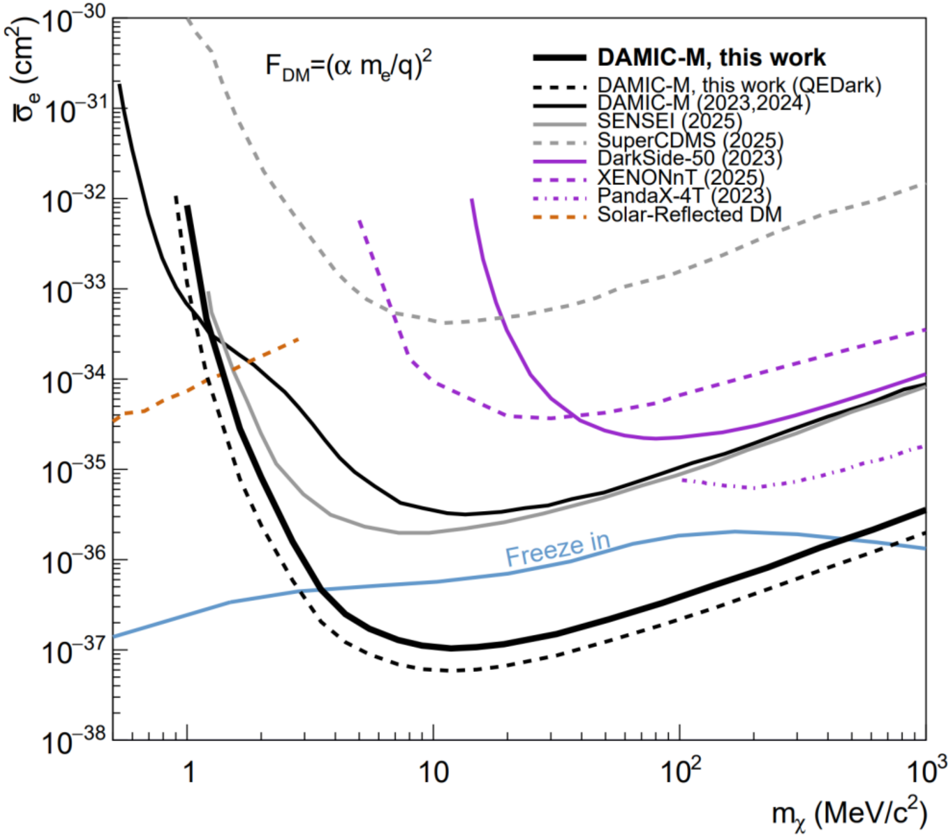
New Results From DAMIC





[2503.14617] Probing Benchmark Models of Hidden-Sector Dark Matter with DAMIC-M

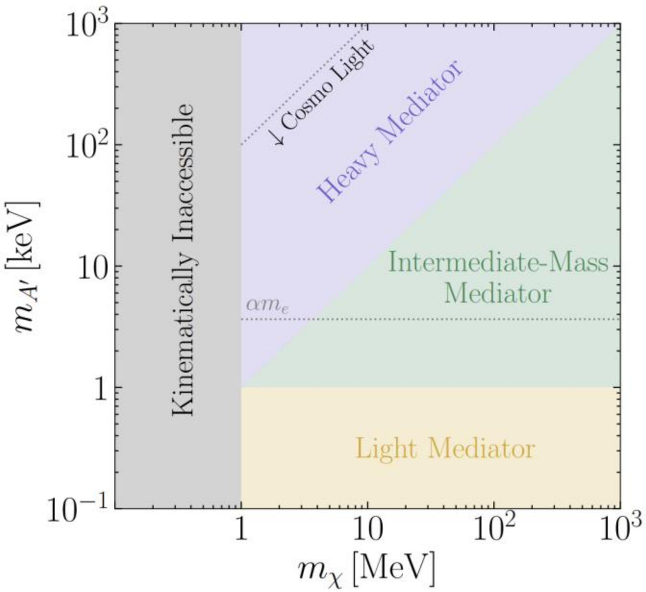
DAMIC Results Motivate New Questions



What new detector technologies must be developed for discovery?

What are other theoretically-motivated light dark matter models?

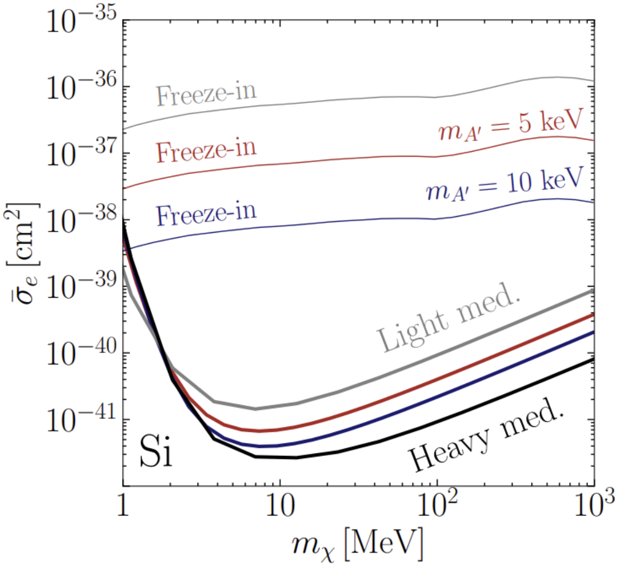
Intermediate-Mass Mediators

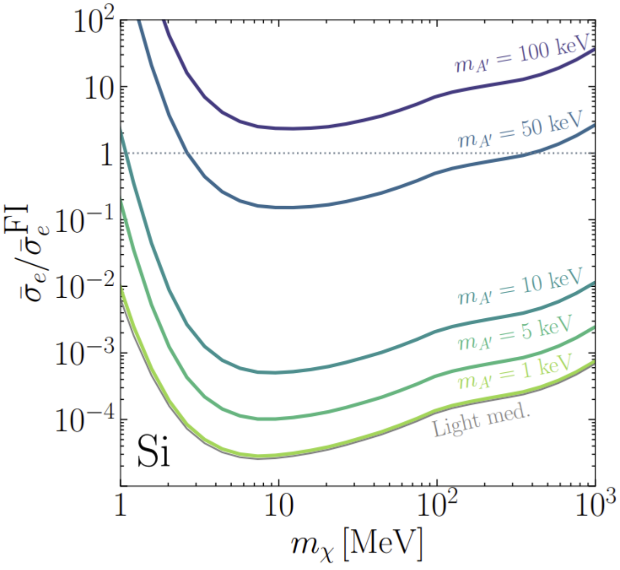


$$m_{A'} \ll \frac{\omega_{\rm th}}{v_{\rm max}} \qquad \text{Light Mediator}$$

$$\frac{\omega_{\rm th}}{v_{\rm max}} \lesssim m_{A'} \lesssim 2 m_\chi v_{\rm max} \qquad \text{Intermediate-Mass Mediator}$$

$$2 m_\chi v_{\rm max} \ll m_{A'} \qquad \text{Heavy Mediator}$$





[2605.11063] Electronic Direct Detection of Light Dark Matter with Intermediate-Mass Mediators

- C. Stratman, **T. Trickle**

Outline

I. Current Status of Direct Detection

I. Infrared Freeze-In of Magnetic Dipole Dark Matter

II. Magnon-Based Direct Detection

A Minimal Model of Light Dark Matter

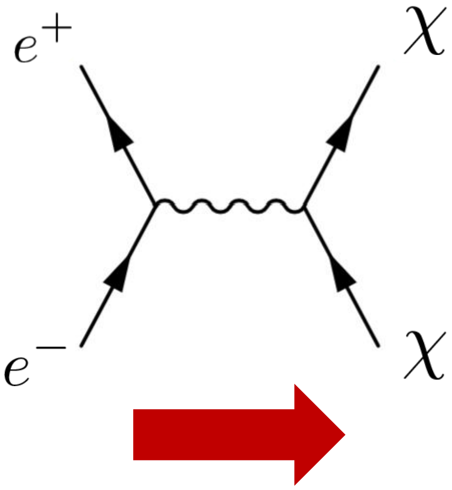
$$\mathcal{L} \supset \underbrace{\bar{\chi}(\not{\partial} - m_{\chi})\chi + g_{\chi}\, A'_{\mu}\bar{\chi}\gamma^{\mu}\chi}_{\text{Dark sector}} + \underbrace{\frac{\varepsilon}{2} F'_{\mu\nu} F^{\mu\nu}}_{\text{Interaction (Kinetic mixing)}}$$

$$\mathcal{L} \supset A'_{\mu}\left[g_{\chi}\left(\bar{\chi}\gamma^{\mu}\chi\right) + \varepsilon e\left(\bar{e}\gamma^{\mu}e\right)\right]$$

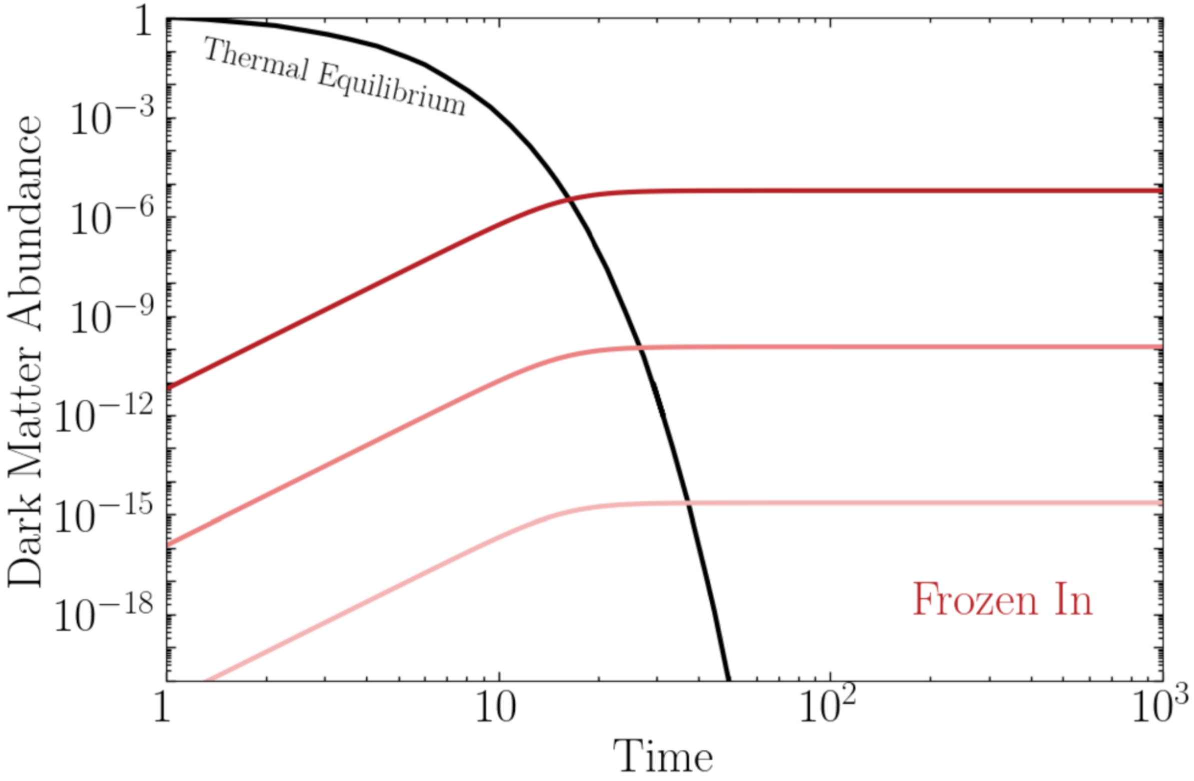
Interaction Lagrangian

Freeze-In

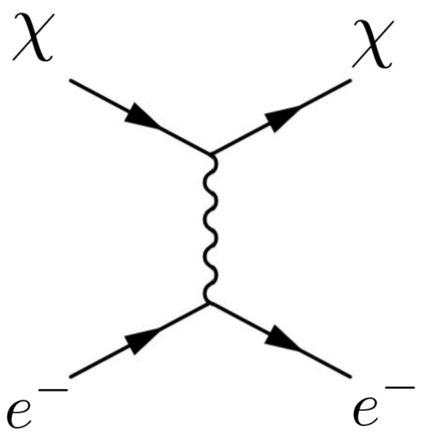
$$\mathcal{L} \supset A'_\mu \left[g_\chi \left(\bar{\chi} \gamma^\mu \chi \right) + \varepsilon e \left(\bar{e} \gamma^\mu e \right) \right]$$

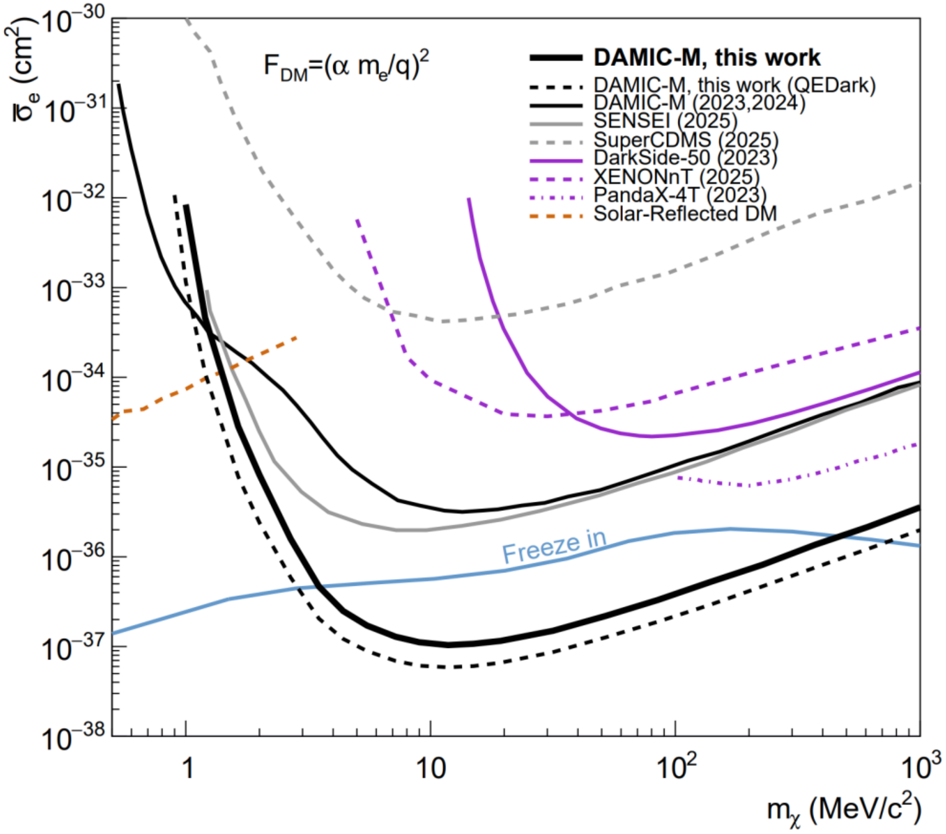


Freeze-in Production

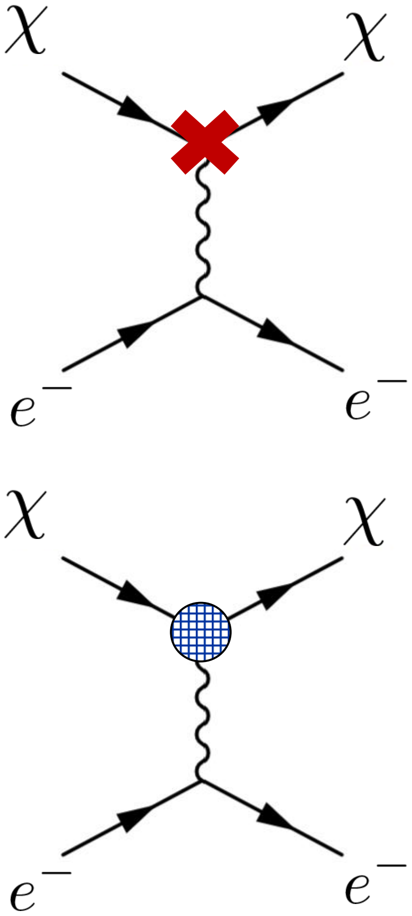


Freeze-In


χ
χ
e^-
e^-


$F_{DM}=(\alpha m_e/q)^2$
DAMIC-M, this work
DAMIC-M, this work (QEDark)
DAMIC-M (2023,2024)
SENSEI (2025)
SuperCDMS (2025)
DarkSide-50 (2023)
XENONnT (2025)
PandaX-4T (2023)
Solar-Reflected DM
Freeze in
$\bar{\sigma}_e$ (cm^2)
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
1
10
10^2
10^3
m_χ (MeV/c^2)

Magnetic Dipole-Coupled Dark Matter



$$\mathcal{L} \supset A'_\mu \Big[g_\chi \cancel{(\bar{\chi}\gamma^\mu\chi)} + \varepsilon e \left(\bar{e}\gamma^\mu e\right) \Big]$$

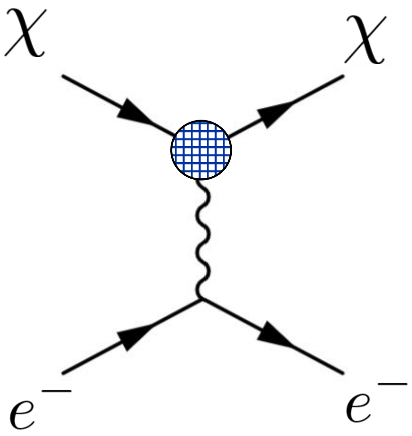
“Dark electron”

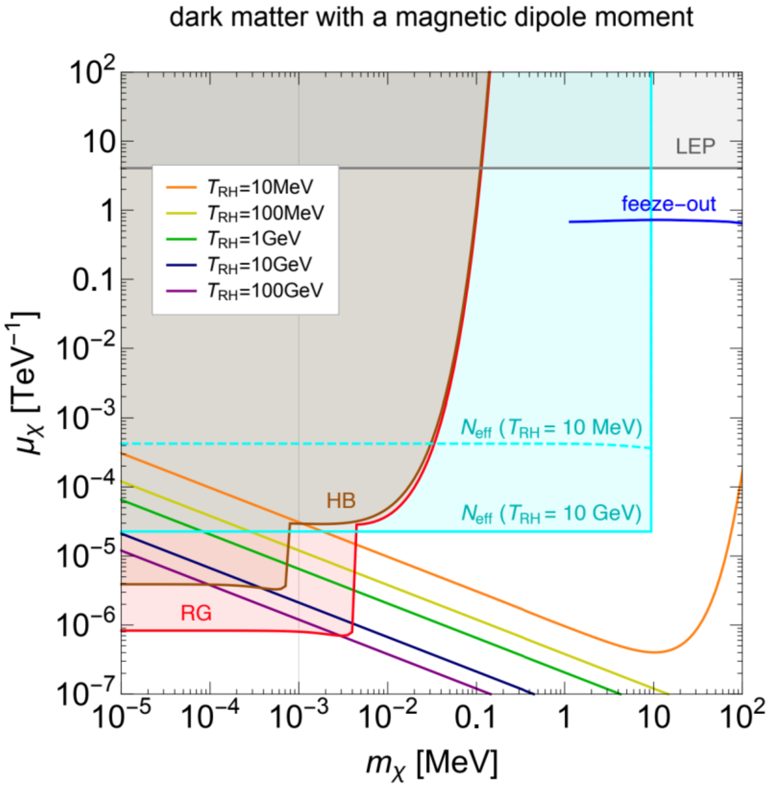
↓

“Dark neutron”

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

Freeze-In of Magnetic Dipole Dark Matter





dark matter with a magnetic dipole moment

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

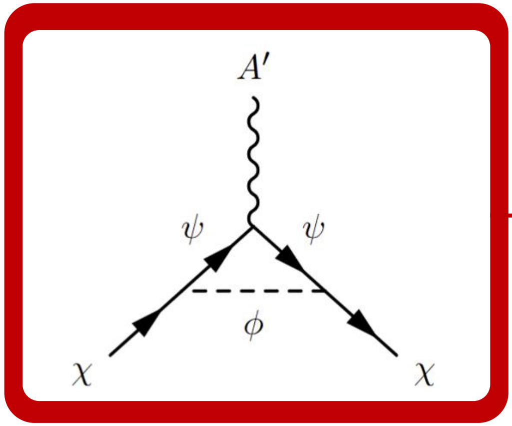
[1911.03389] Light(ly)-coupled Dark Matter in the keV Range: Freeze-In and Constraints

[1410.6157] UltraViolet Freeze-in

Problem: production is UV dominated

Magnetic Dipole-Coupled Dark Matter

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



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

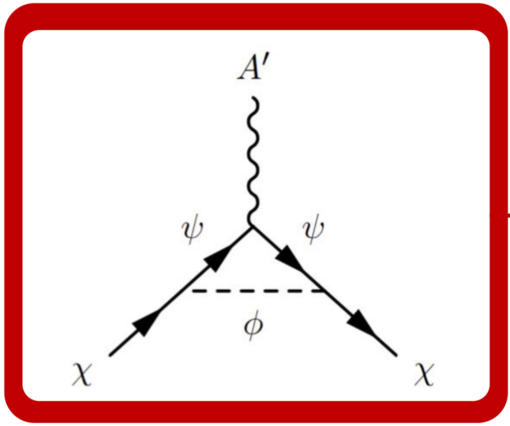
$$\mathcal{L} \supset \frac{\mu'_\chi}{2} F'_{\mu\nu} \left(\bar{\chi}\sigma^{\mu\nu}\chi\right)$$

ψ, ϕ Dark Charged Particles

χ Dark Matter

Magnetic Dipole-Coupled Dark Matter

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

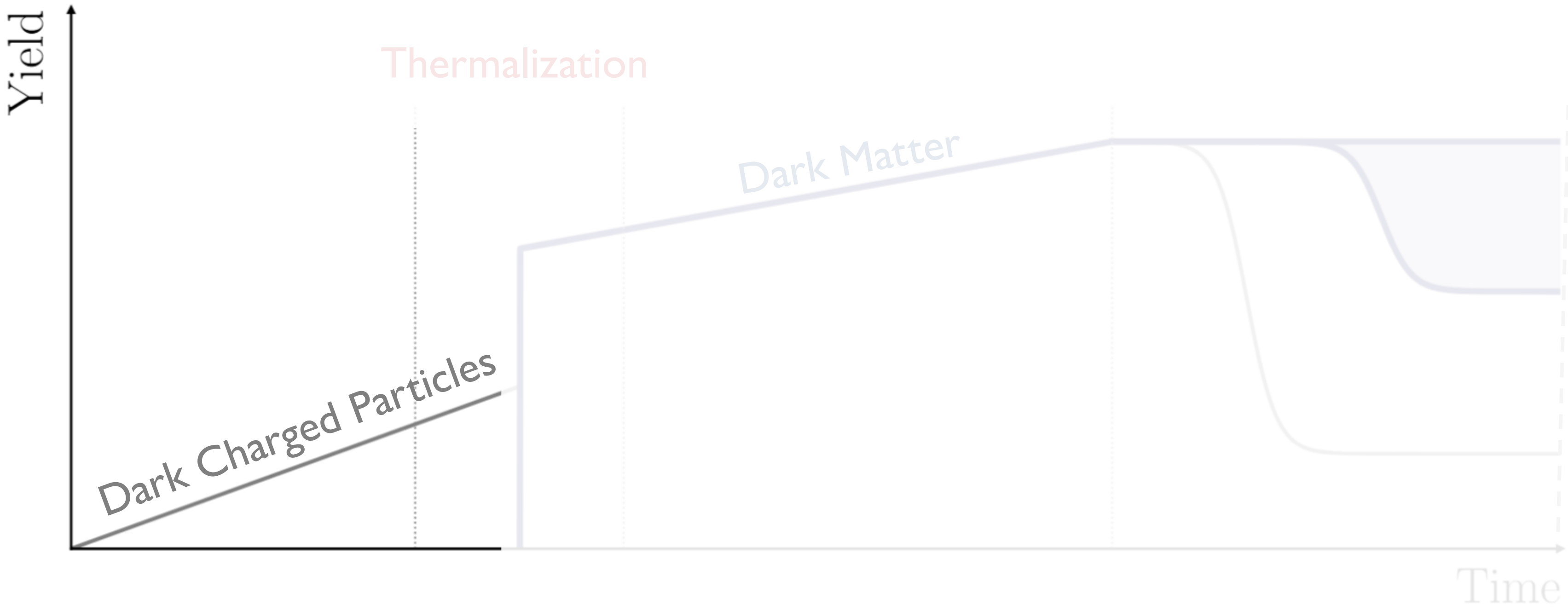


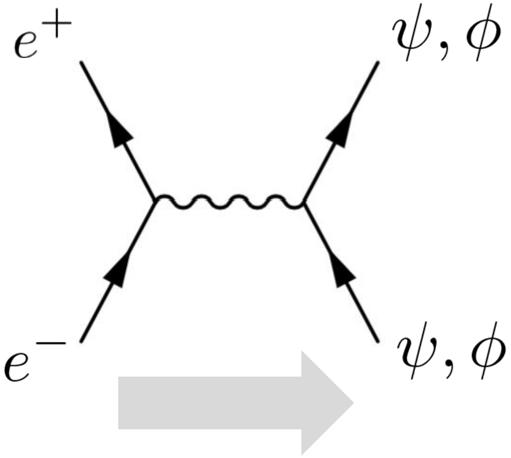
$$\mu'_\chi = \frac{g'y'^2}{32\pi^2 M}$$

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

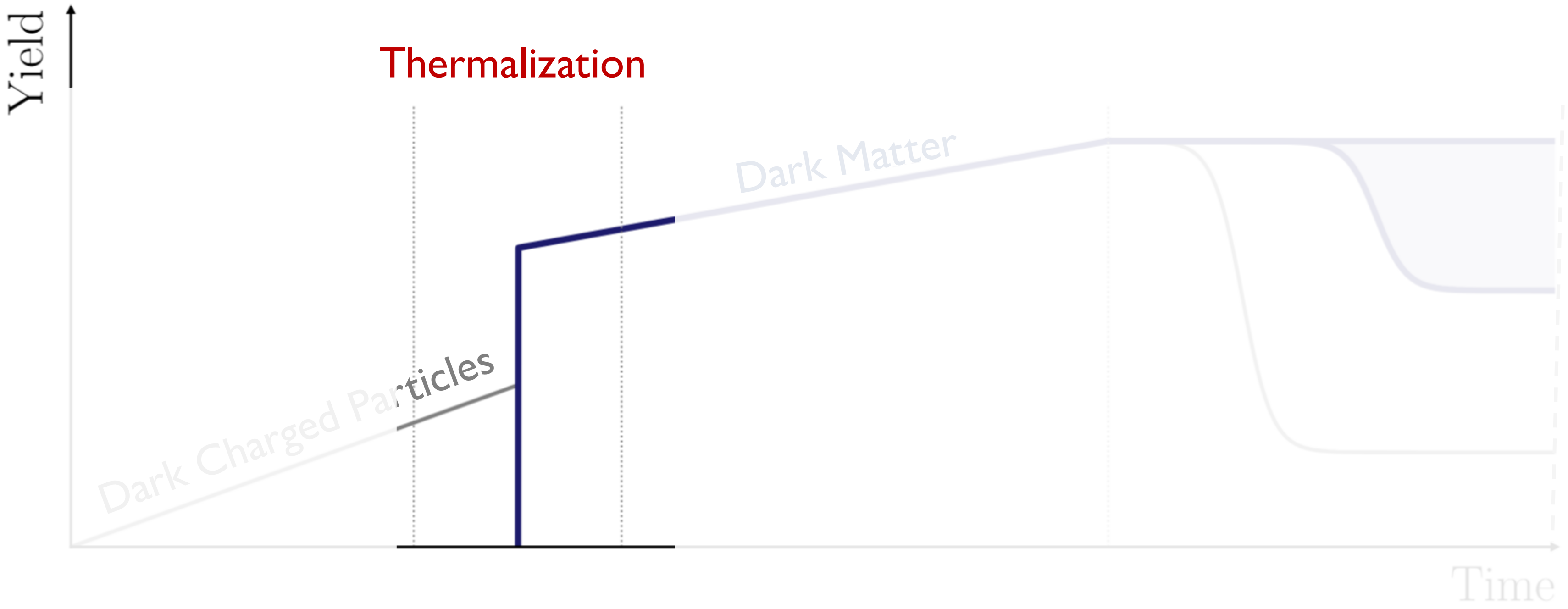
Magnetic Dipole-Coupled Interaction Lagrangian

Pre-Thermalization





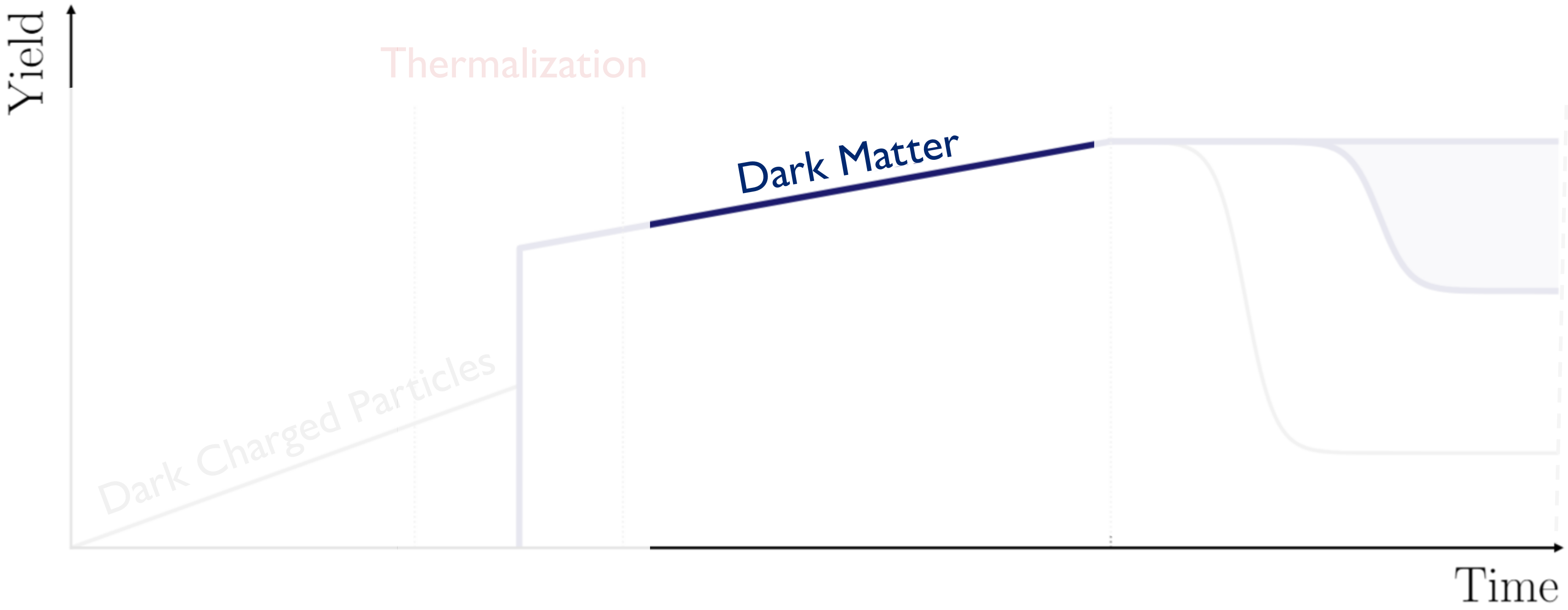
Thermalization

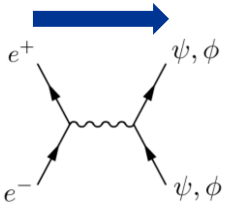


$$\phi \leftrightarrow \psi\chi \quad , \quad \phi\phi \leftrightarrow A'A' \quad , \quad \psi\psi \leftrightarrow A'A' \quad , \quad \phi\phi \leftrightarrow \chi\chi$$

All processes must be faster than Hubble.

Post-Thermalization



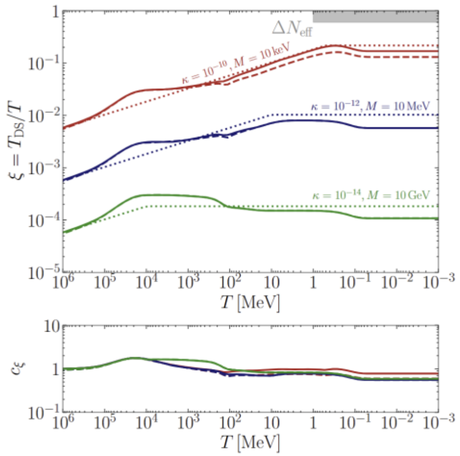


$$\frac{d(\rho_{\rm DS}/s^{4/3})}{dT} \propto -(e^2\kappa)^2 \frac{M_{\rm Pl}}{T^2}$$

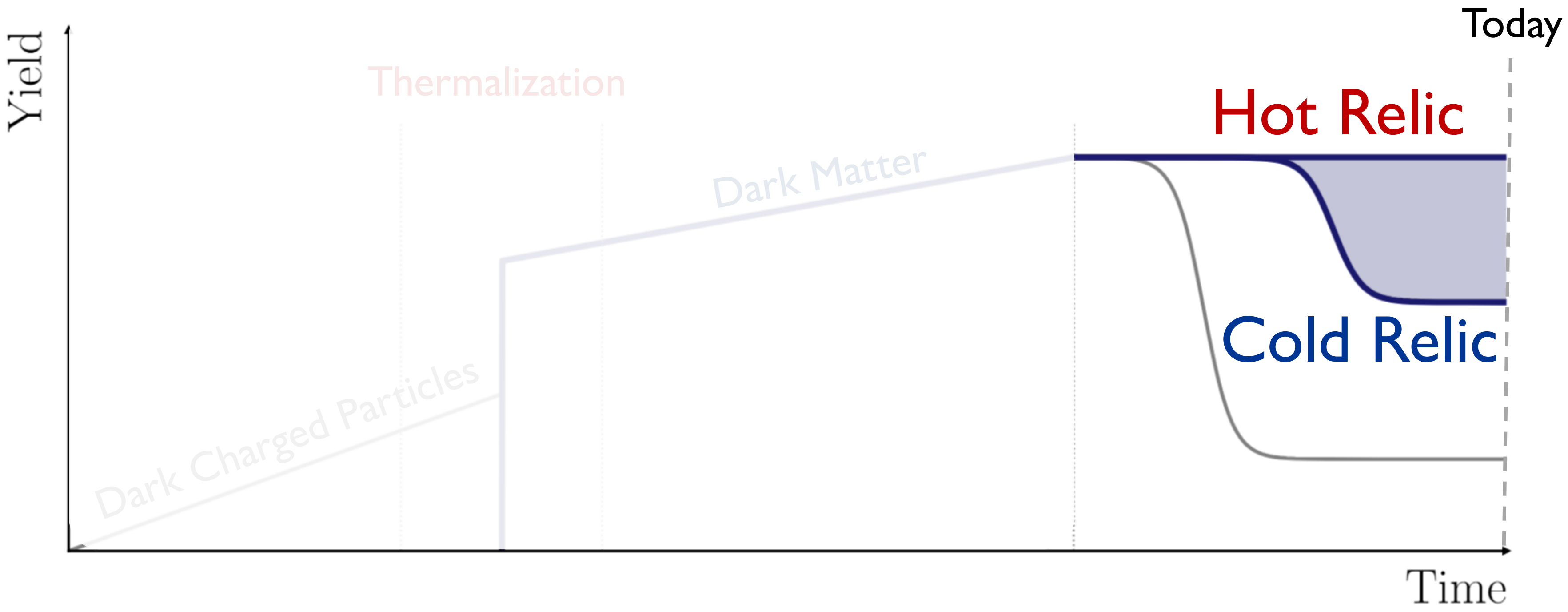
Energy density

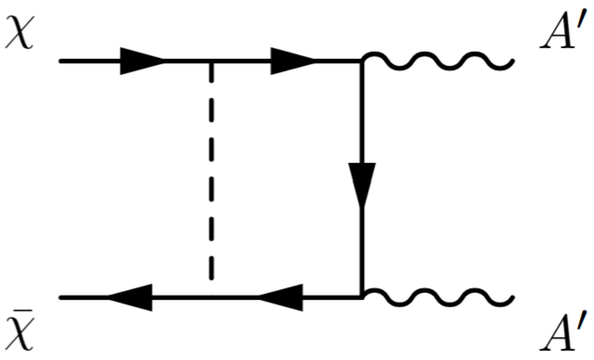
Boltzmann equation

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



Dark Matter Decoupling





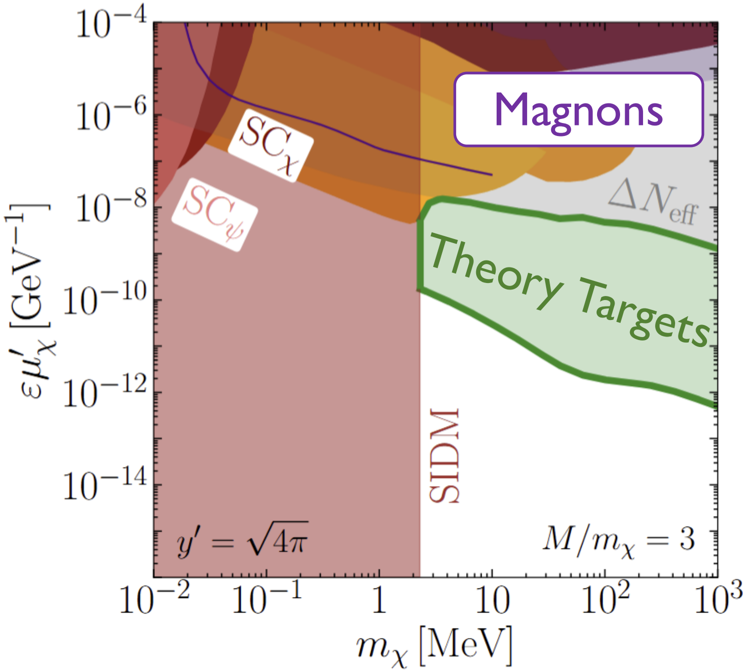
$$n_\chi \langle \sigma v \rangle_{\chi\chi\to A'A'} \lessgtr H \quad @ \quad T_{\rm DS} \sim m_\chi$$

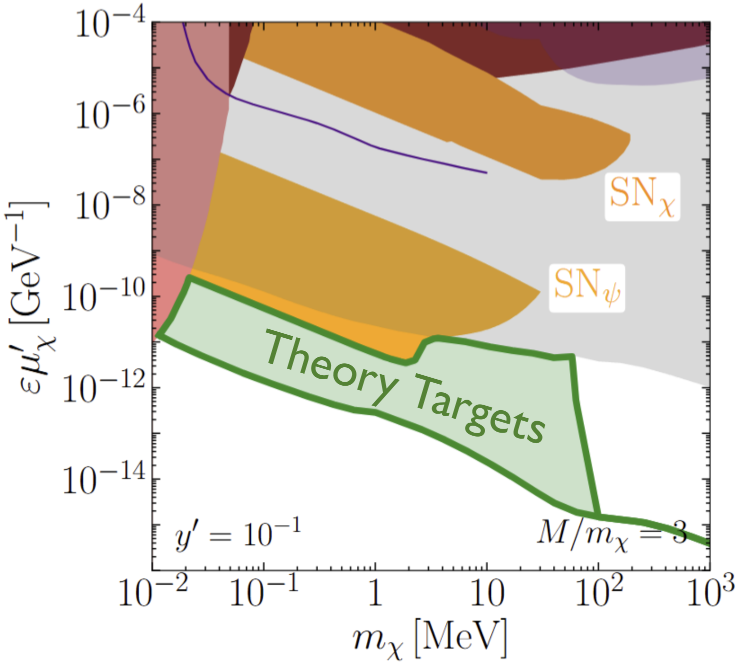
$$\langle \sigma v \rangle_{\chi\chi\to A'A'} \sim \frac{y'^4 g'^4}{768\pi^5}\frac{m_\chi^4}{M^6}$$

Hot Relic : **smaller** dark sector couplings

Cold Relic: **larger** dark sector couplings

Direct Detection Theory Targets





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

Example model parameter space ranges from optimistically detectable to un-detectable.

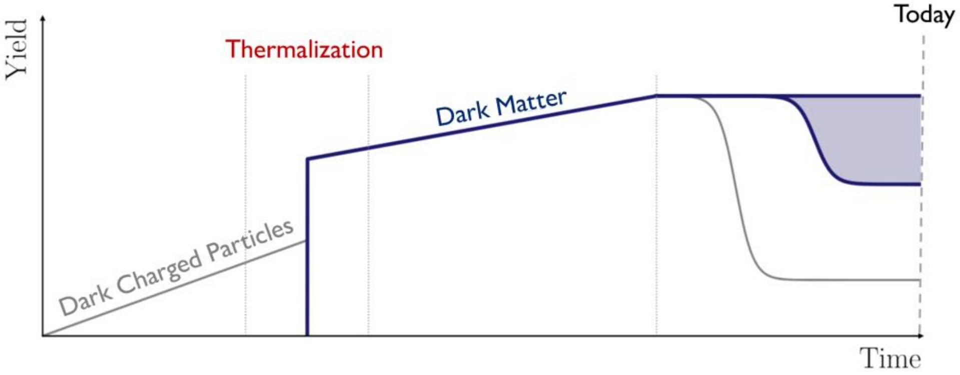
Thermalizing Freeze-In Summary

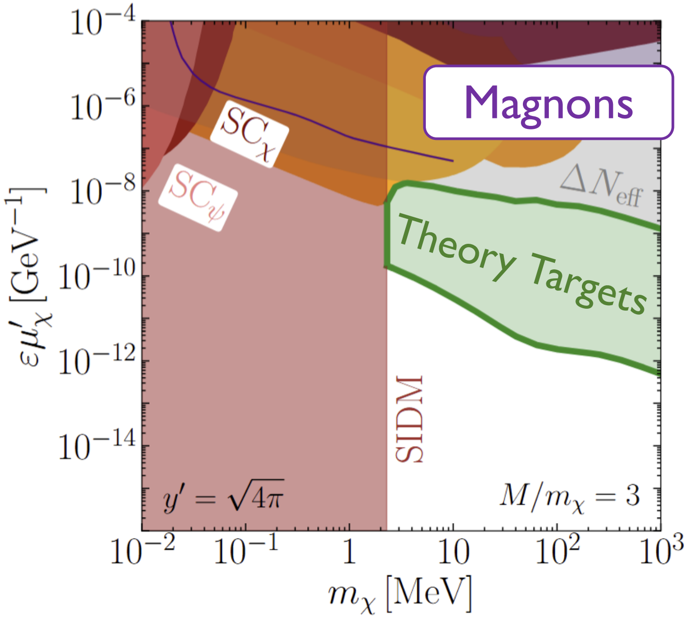
A simple dark sector…

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

thermalizing in the early universe…

realizes detectable magnetic dipole-couplings.





Outline

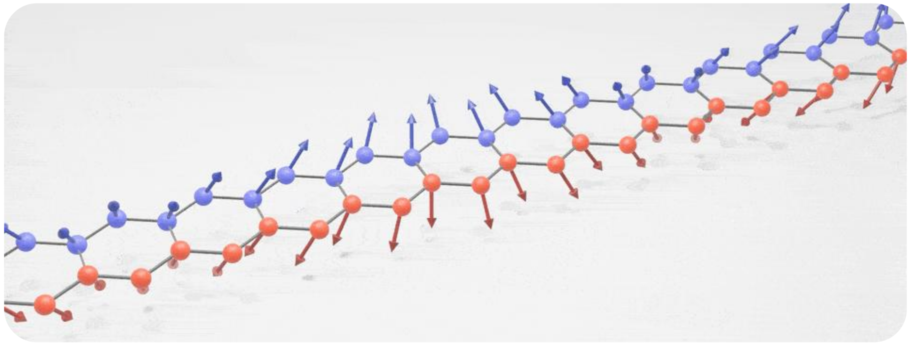
I. Current Status of Direct Detection

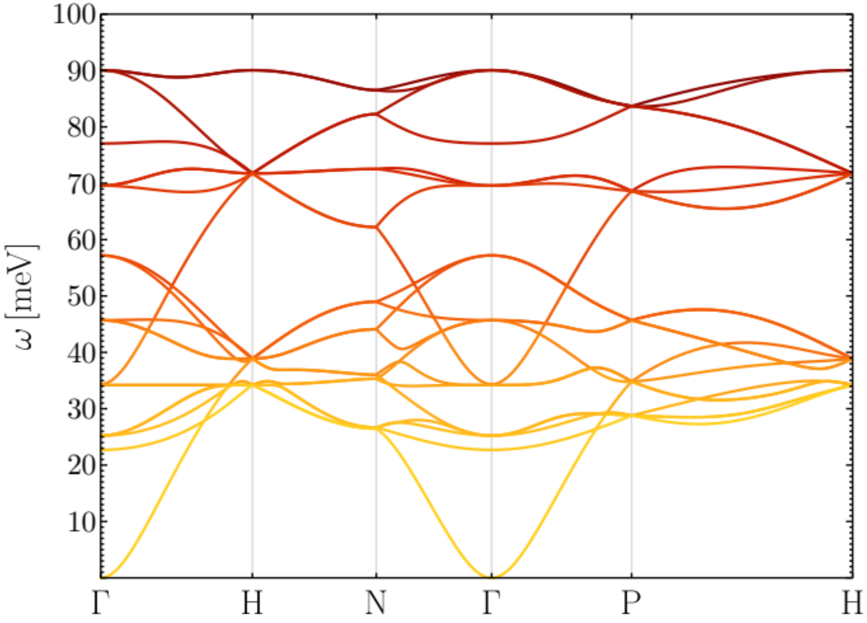
I. Infrared Freeze-In of Magnetic Dipole Dark Matter

II. Magnon-Based Direct Detection

Magnons

Collective spin excitations



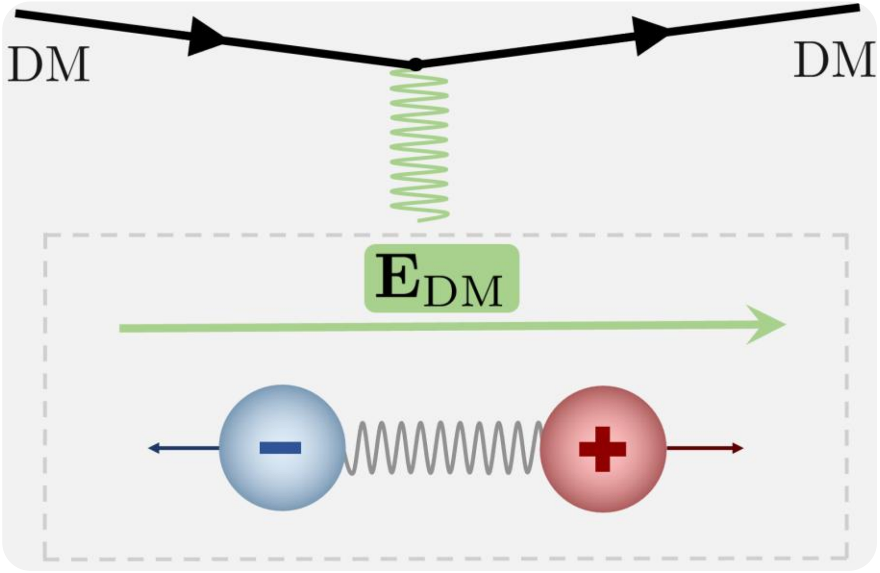


[1905.13744] Detecting Light Dark Matter with Magnons

- **T. Trickle**, Zhang, Zurek

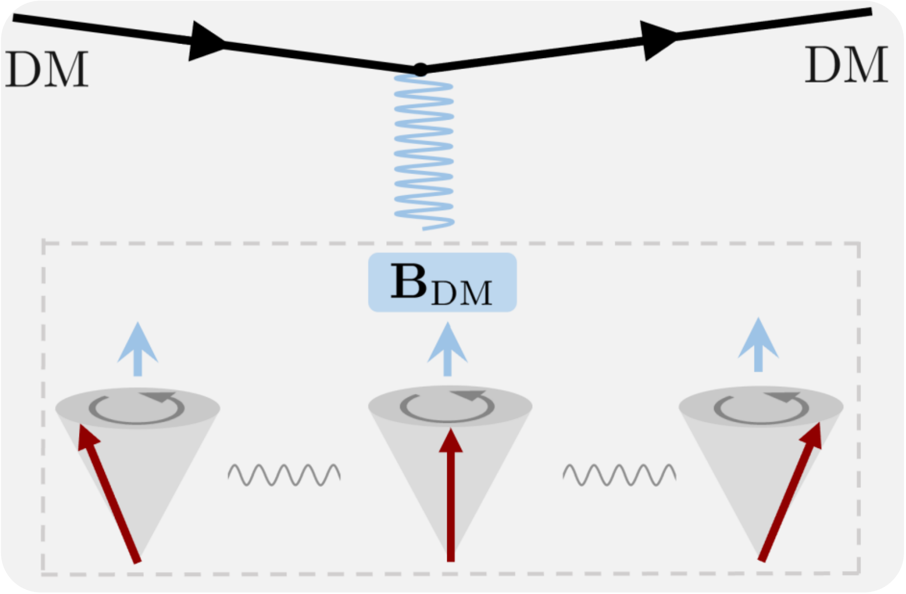
Phonon vs. Magnon Scattering

Phonons



“Spin-**independent** coupling”

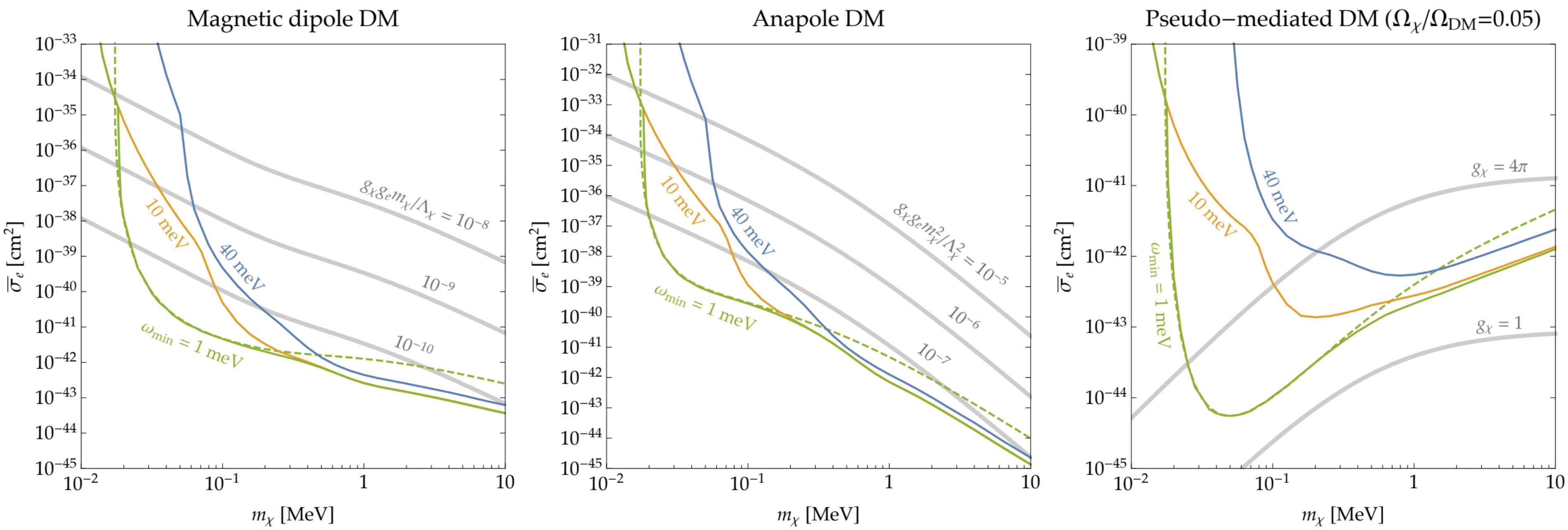
Magnons

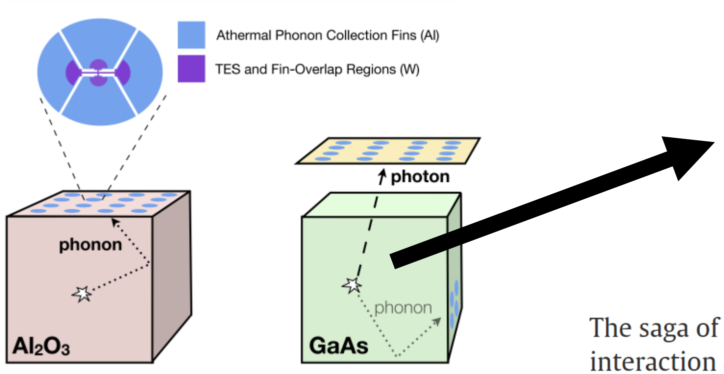


“Spin-**dependent** coupling”

Sensitivity To Dark Matter Scattering

First-Principles





The saga of YIG: Spectra, thermodynamics, interaction and relaxation of magnons in a complex magnet

Vladimir Cherepanov [*1 a], Igor Kolokolov [b], Victor L'vov [*1 c]

[1905.13744] Detecting Light Dark Matter with Magnons

- **T. Trickle**, Zhang, Zurek

The Dark Matter Scattering Rate

Data-Driven Approach

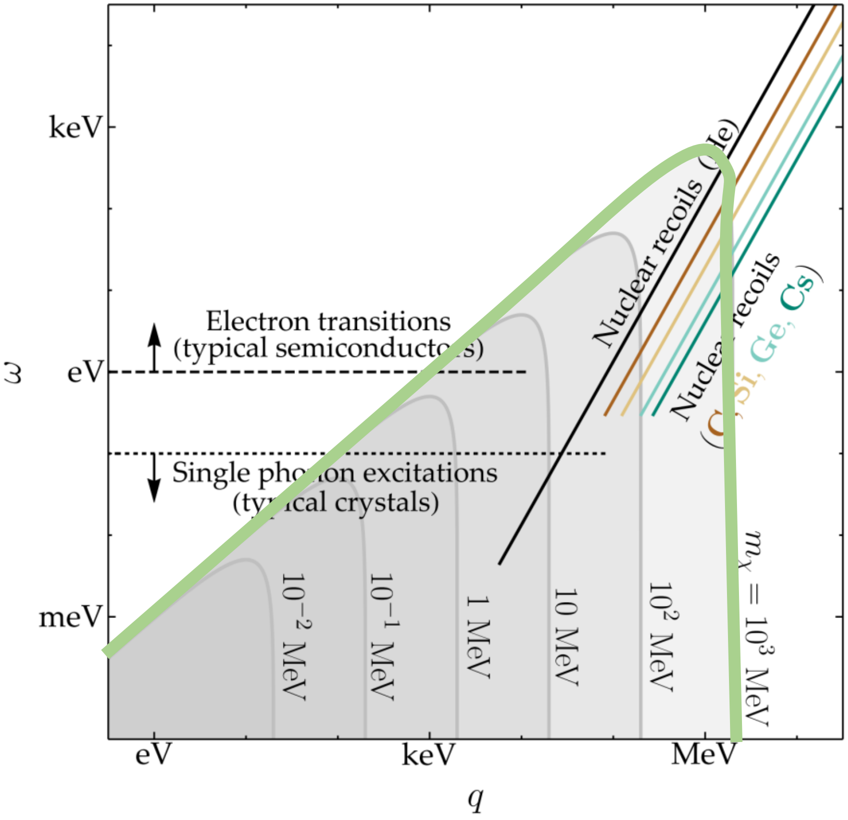
Similarities With Neutron Scattering

Effective neutron-electron interaction

$$\mathcal{L} \supset \frac{\gamma_n e}{4m_n}\,\bar{n}\sigma^{\mu\nu}n\,F_{\mu\nu} - eA_\mu\,\bar{e}\gamma^\mu e$$

Dark magnetic dipole dark matter

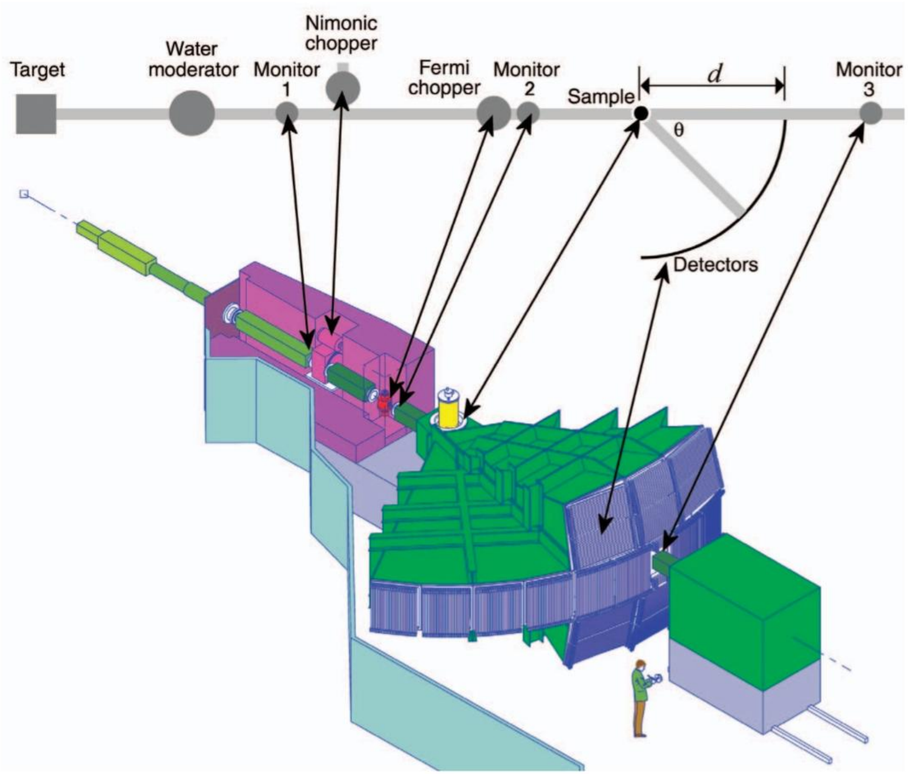
$$\mathcal{L} \supset \frac{\mu'_\chi}{2}F'_{\mu\nu}\,(\bar{\chi}\sigma^{\mu\nu}\chi) + \varepsilon e\,A'_\mu\,(\bar{e}\gamma^\mu e)$$



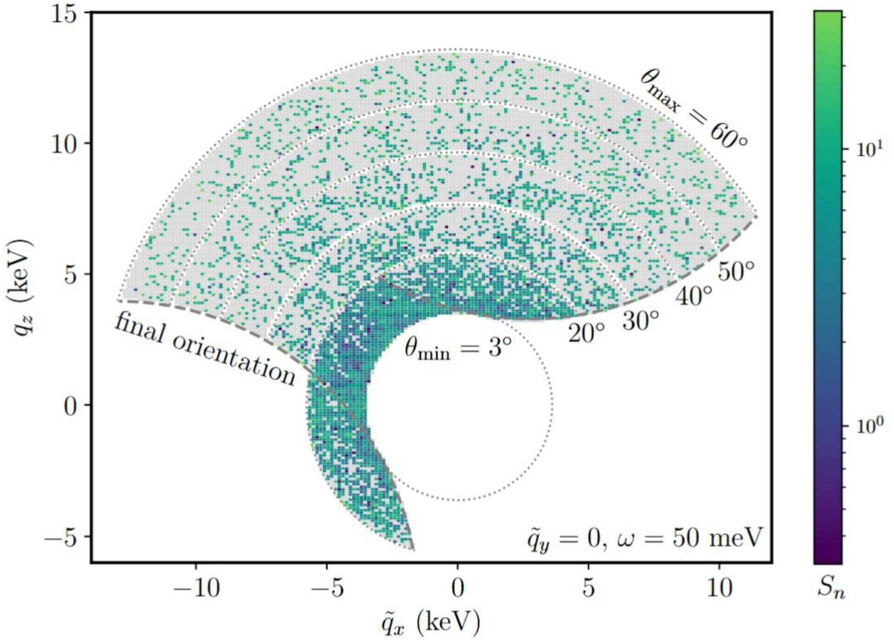
☑ Interaction structure

☑ Kinematics

A Neutron Scattering Dataset



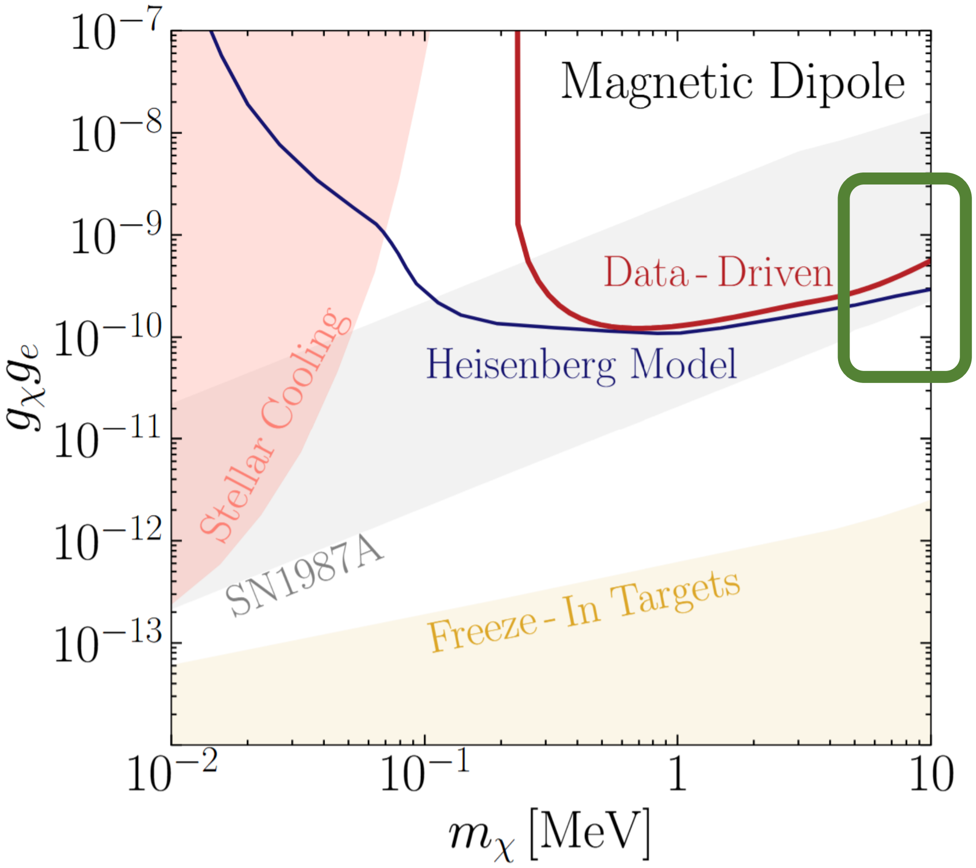
The MAPS Spectrometer



A 2D slice of the data

ISIS Neutron and
Muon Source

Comparison of First-Principles and Data-Driven Sensitivity



$$\mathcal{L} \supset \frac{g_\chi}{4m_\chi}\bar{\chi}\sigma^{\mu\nu}\chi\, F'_{\mu\nu} + g_e A'_\mu\,\bar{\Psi}\gamma^\mu\Psi$$

- Data-driven enhanced by *phonon* contribution
- First-principles enhanced by neglecting *magnetic form factors*

[2501.18120] Spin-dependent dark matter scattering in quasi-two-dimensional magnets

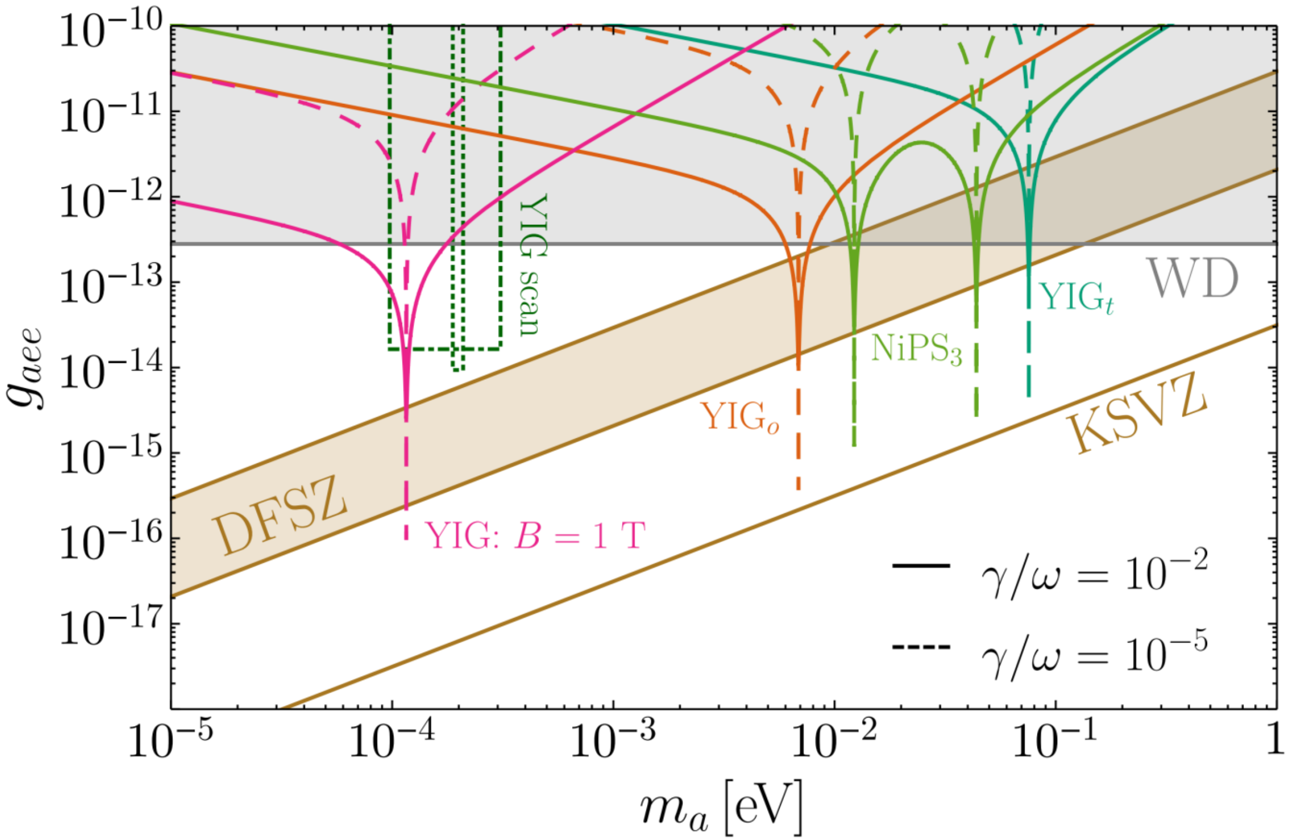
[2504.02927] Determining Spin-Dependent Light Dark Matter Rates from Neutron Scattering

- Berlin, Millar, **T. Trickle**, Zhou

Axion Absorption Into Magnons

The saga of YIG: Spectra, thermodynamics, interaction and relaxation of magnons in a complex magnet

Vladimir Cherepanov [*1 a], Igor Kolokolov [b], Victor L'vov [*1 c]

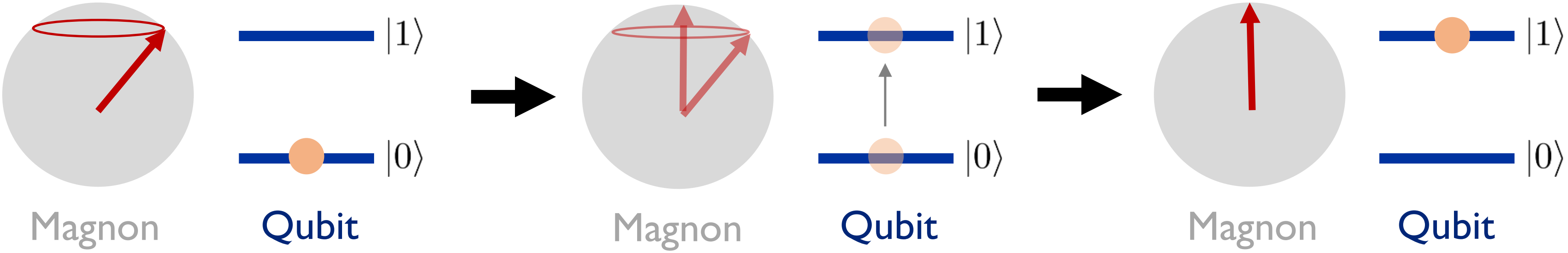


[2005.10256] Detectability of Axion Dark Matter with Phonon Polaritons and Magnons

- Mitridate, **T. Trickle**, Zhang, Zurek

How To Detect Single Magnons?

Single Magnon Counting With Qubits



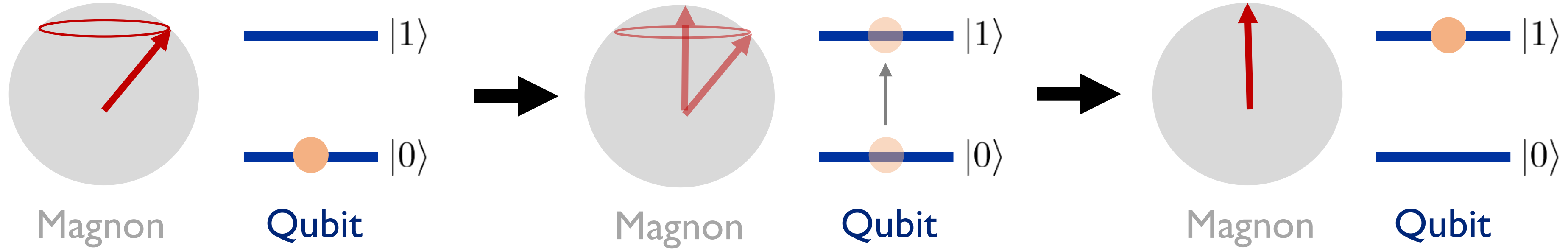
$$\frac{\omega_{|1\rangle} - \omega_{|0\rangle}}{2\pi} \sim 6\,\mathrm{GHz}$$

If $\omega_{\mathrm{m}} \sim (\omega_{|1\rangle} - \omega_{|0\rangle})$ then resonant conversion between magnon-qubit states.

Similar idea with phonons: [2410.17308] Listening For New Physics With Quantum Acoustics

- Linehan, **T. Trickle**, Conner, Ghosh, Lin, Sholapurkar, Cleland

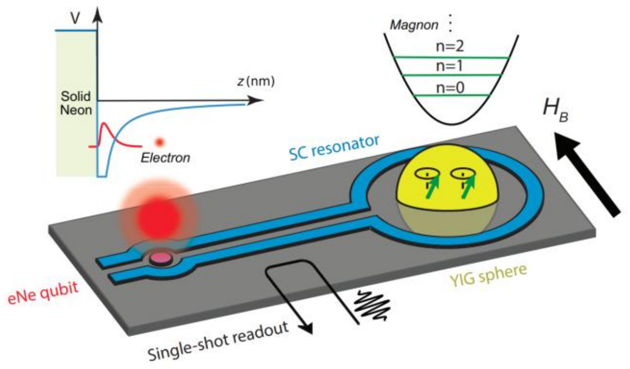
Single Magnon Detection With Quantum Magnonics

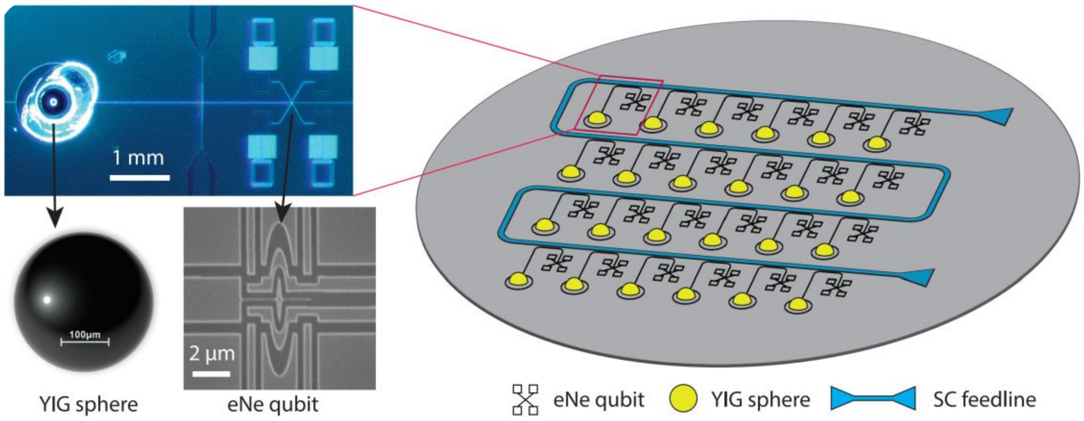


Quantum Information Science Enabled Discovery (QuantISED) 2.0

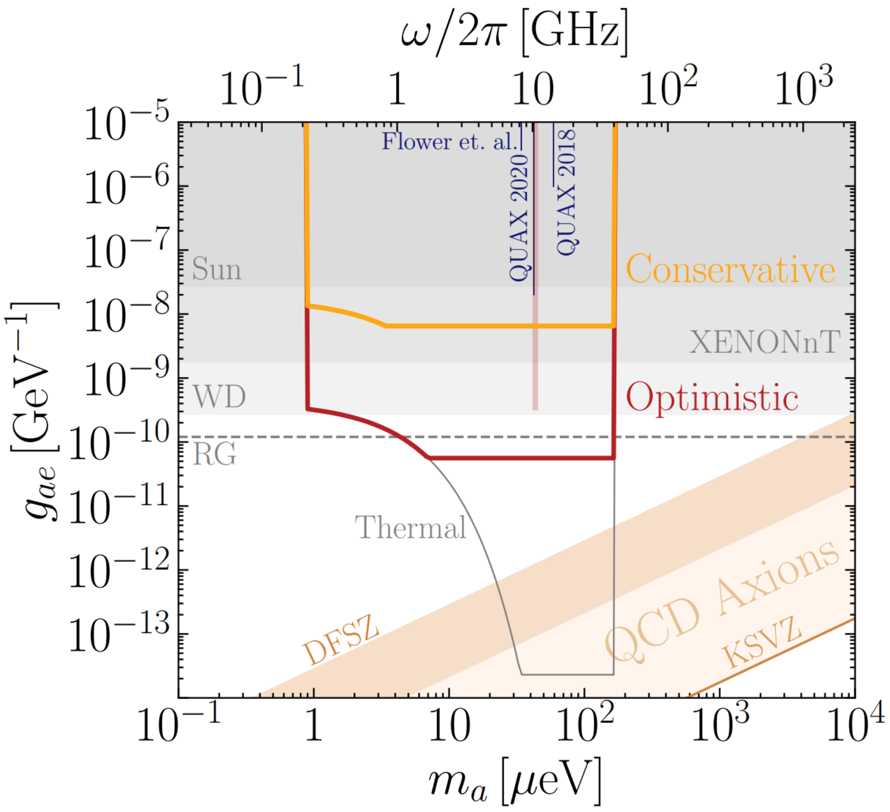
Quantum Magnonics For Spin-Dependent BSM Physics

Argonne National Laboratory – Notre Dame – **T. Trickle** (Co-PI)





Projected MOSAIC Sensitivity



$$g_{ae} \sim \frac{10^{-8}}{\text{GeV}} \underbrace{N_s^{-\frac{1}{4}}}_{\text{Number of spheres}} \underbrace{\left(\frac{2.7\,\text{mg}}{m_{\text{YIG}}}\right)^{\frac{1}{2}}}_{\text{Mass of sphere}} \underbrace{\left(\frac{p_{\text{dc}}}{3\times 10^{-4}}\right)^{\frac{1}{4}}}_{\text{Dark count probability}}$$

Conservative – achievable today

$$N_s \sim 10^3\,,\; m_{\text{YIG}} \sim 2.7\,\text{mg}$$

Optimistic – improvements to $N_s, m_{\text{YIG}}, p_{\text{dc}}$

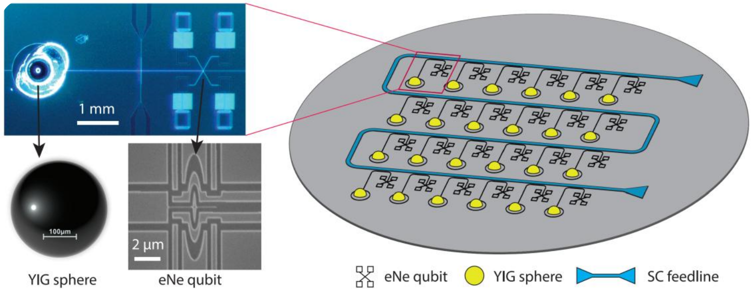
$$N_s \sim 10^4\,,\; m_{\text{YIG}} \sim 2.7\,\text{g}$$

Each tile can achieve sensitivity beyond SQL

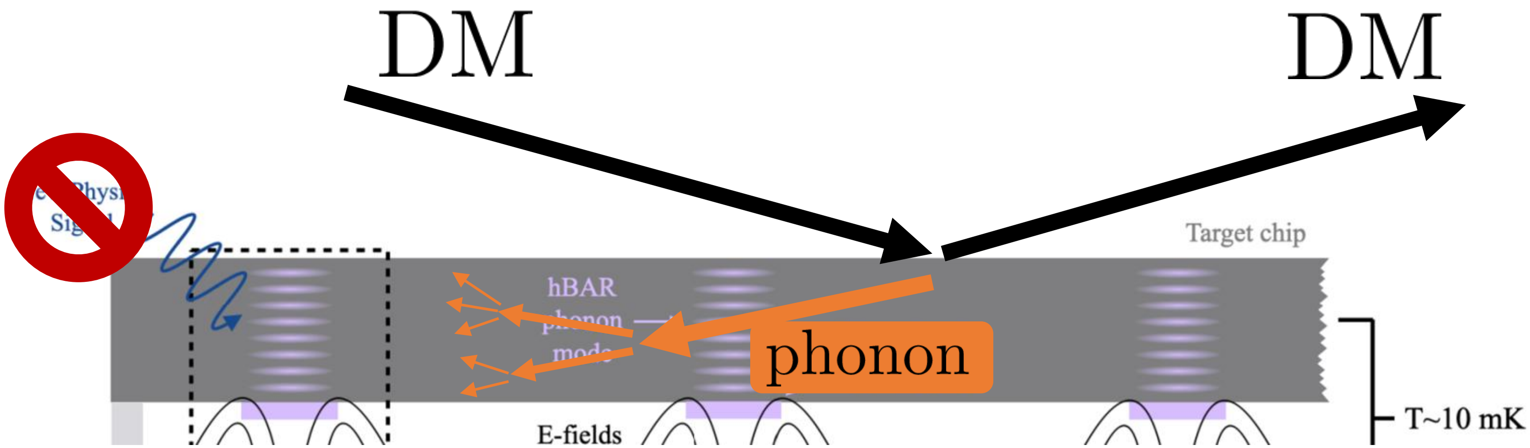
$$\frac{\text{SNR}}{\text{SNR}_{\text{SQL}}} \sim \left(\frac{10^{-4}}{p_{\text{dc}}}\right)^{\frac{1}{2}} \left(\frac{m_a}{10\,\mu\text{eV}}\right)^{\frac{1}{2}}$$

Many open questions…

- *Improvements to dark count probability?*
- *Use axion coherence?*
- *Magnon down-conversion?*

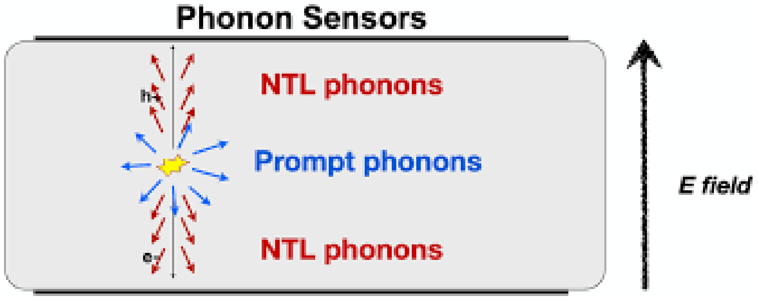


Down-Conversion Detection



[2410.17308] Listening For New Physics With Quantum Acoustics

- Linehan, **T. Trickle**, Conner, Ghosh, Lin, Sholapurkar, Cleland



Analogous idea with magnons

Summary

I. Current Status of Direct Detection
    - ***DAMIC results motivate thinking about new models and new detection technologies.***

I. Infrared Freeze-In of Magnetic Dipole Dark Matter
    - ***Dark sector thermalization allows for IR dominated freeze-in of light, magnetic dipole-coupled dark matter.***

II. Magnon-Based Direct Detection
    - ***Magnons are exceptionally sensitive to light, spin-dependent dark matter, including axions. Quantum magnonics is a promising approach for single magnon readout.***

Axion-like Particles

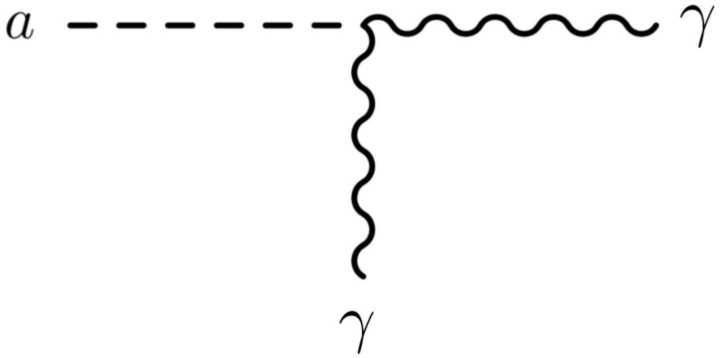
QCD Axion: gluon coupling mandatory, solves strong CP problem

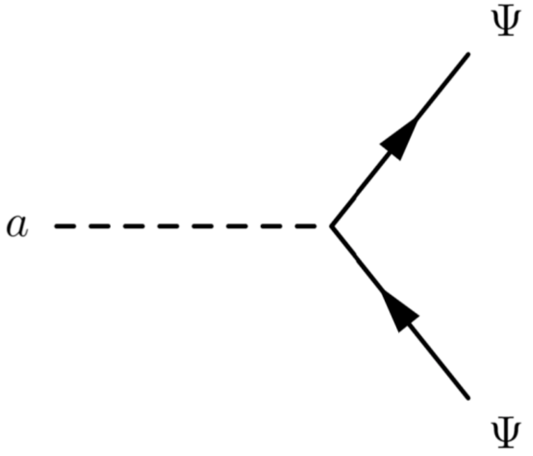
$$\mathcal{L} \supset \frac{a}{f_a}\frac{g^2}{32\pi^2} G^a_{\mu\nu}\widetilde{G}^{\mu\nu}_a \qquad m_a = \sqrt{\frac{m_u m_d}{(m_u+m_d)^2}}\frac{m_\pi f_\pi}{f_a} \sim 6\,\mu\mathrm{eV}\left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right)$$

Axion-like particles: pNG bosons of broken PQ, more diverse phenomenology

$$\mathcal{L} \supset g_{a\gamma\gamma}\, a\, F^{\mu\nu}\widetilde{F}_{\mu\nu}$$

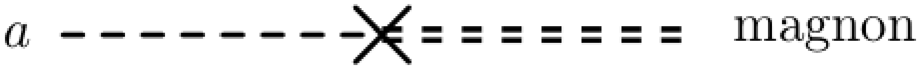
$$\mathcal{L} \supset g_{a\Psi}\,\partial_\mu a\,\bar{\Psi}\gamma^\mu\gamma^5\Psi \qquad (\Psi \in \{e,p,n\})$$



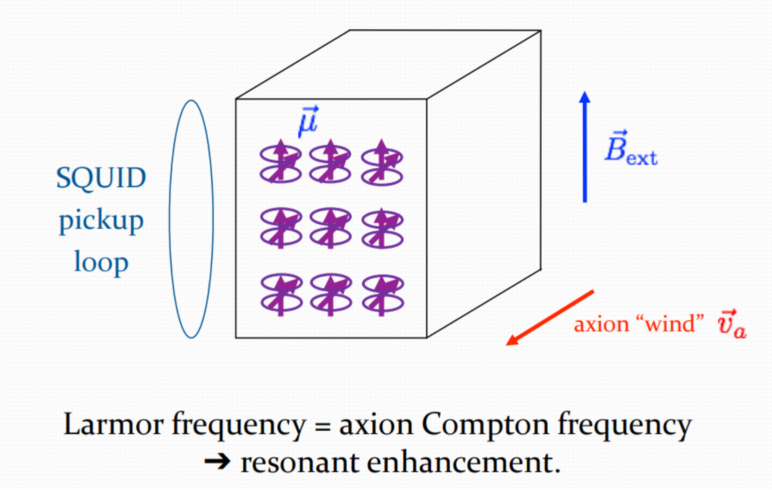


Axion Absorption Into Magnons

$$\mathcal{L} \supset g_{ae}\partial_\mu a\,\bar{e}\,\gamma^\mu\gamma^5\, e \longrightarrow \delta H \supset g_{ae}\,\vec{\nabla}a\cdot\vec{S}_e$$



CASPEr Wind – but with electrons



Larmor frequency = axion Compton frequency
➔ resonant enhancement.

Axion Absorption Into Magnons

First-Principles

Setup

$$H = \sum_{\ell\ell' jj'} \mathbf{S}_{\ell' j'} \cdot \boxed{\mathbf{J}_{\ell\ell' jj'}} \cdot \mathbf{S}_{\ell j}$$

Fit to neutron scattering data

$$\delta H = g_{ae} \vec{\nabla} a \cdot \sum_{\ell j} \vec{S}^{e}_{\ell j}$$

Fermi's Golden Rule

$$\Gamma = 2\pi \sum_{\nu \mathbf{k}} \left| \langle \text{magnon} | \, \delta H \, | a \rangle \right|^2 \delta(m_a - \omega_{\nu \mathbf{k}})$$

[2005.10256] Detectability of Axion Dark Matter with Phonon Polaritons and Magnons

- A. Mitridate, **T. Trickle**, Z. Zhang, K. Zurek

Selection rules $[H, \delta H] = 0$

No absorption in simplest magnets!

1. External magnetic field
2. Anisotropic exchange interactions
3. Non-degenerate Lande g-factors

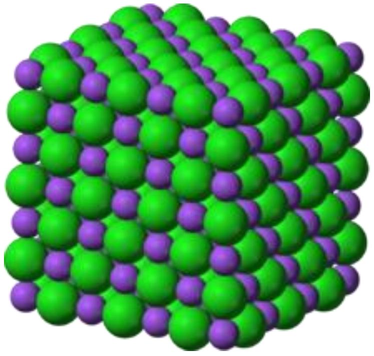
Data-Driven

$$R \simeq \left(\frac{g_{ae} \, v_{\text{DM}}}{\mu_B} \right)^2 \frac{\rho_{\text{DM}}}{\rho_{\text{T}}} \, \hat{\mathbf{q}} \cdot \text{Im} \left(-\mu^{-1} \right) \cdot \hat{\mathbf{q}}$$

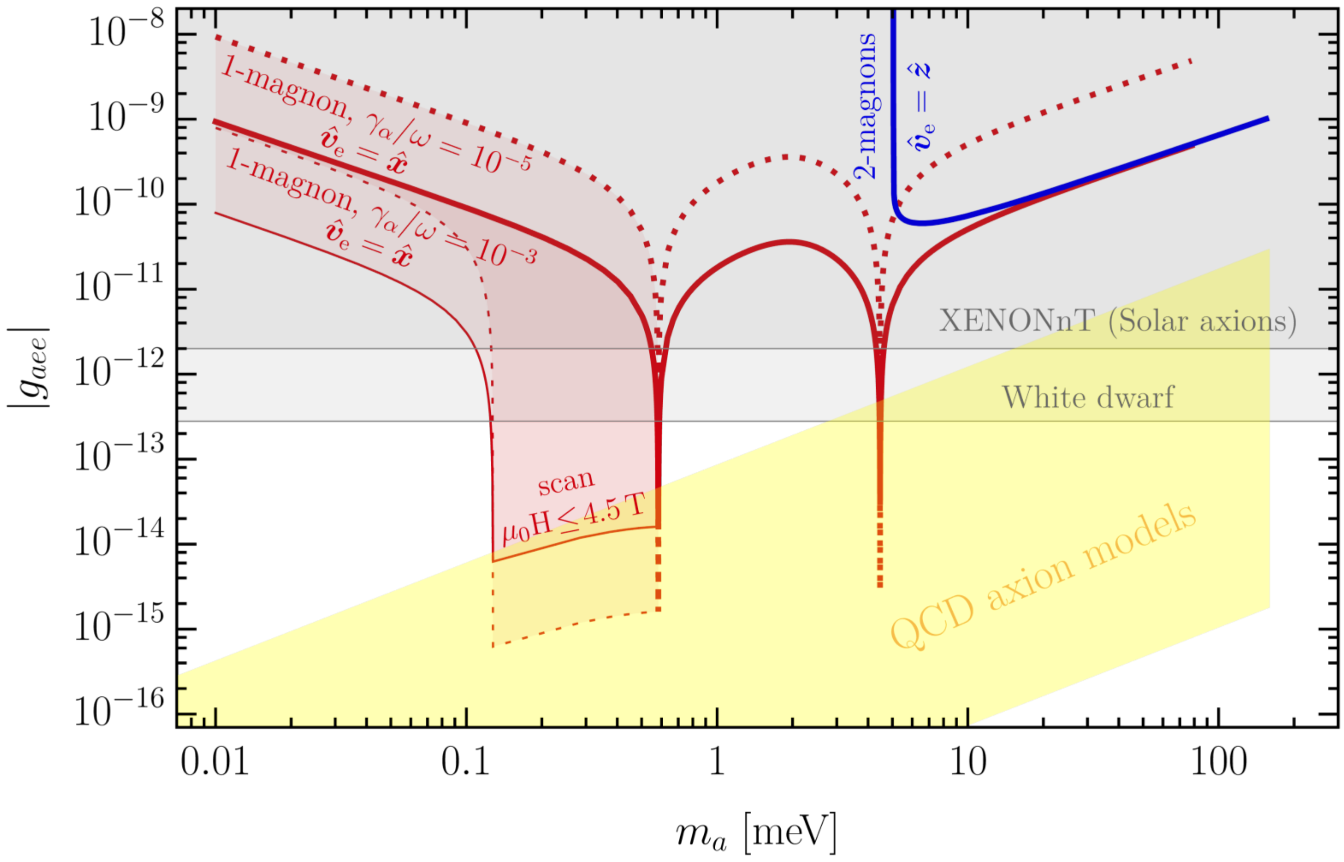
[2312.11601] Physical Signatures of Fermion-Coupled Axion Dark Matter

- A. Berlin, A. Millar, **T. Trickle**, K. Zhou

Axion Absorption Into Magnons

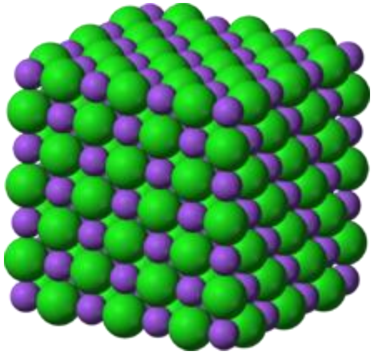


NiO

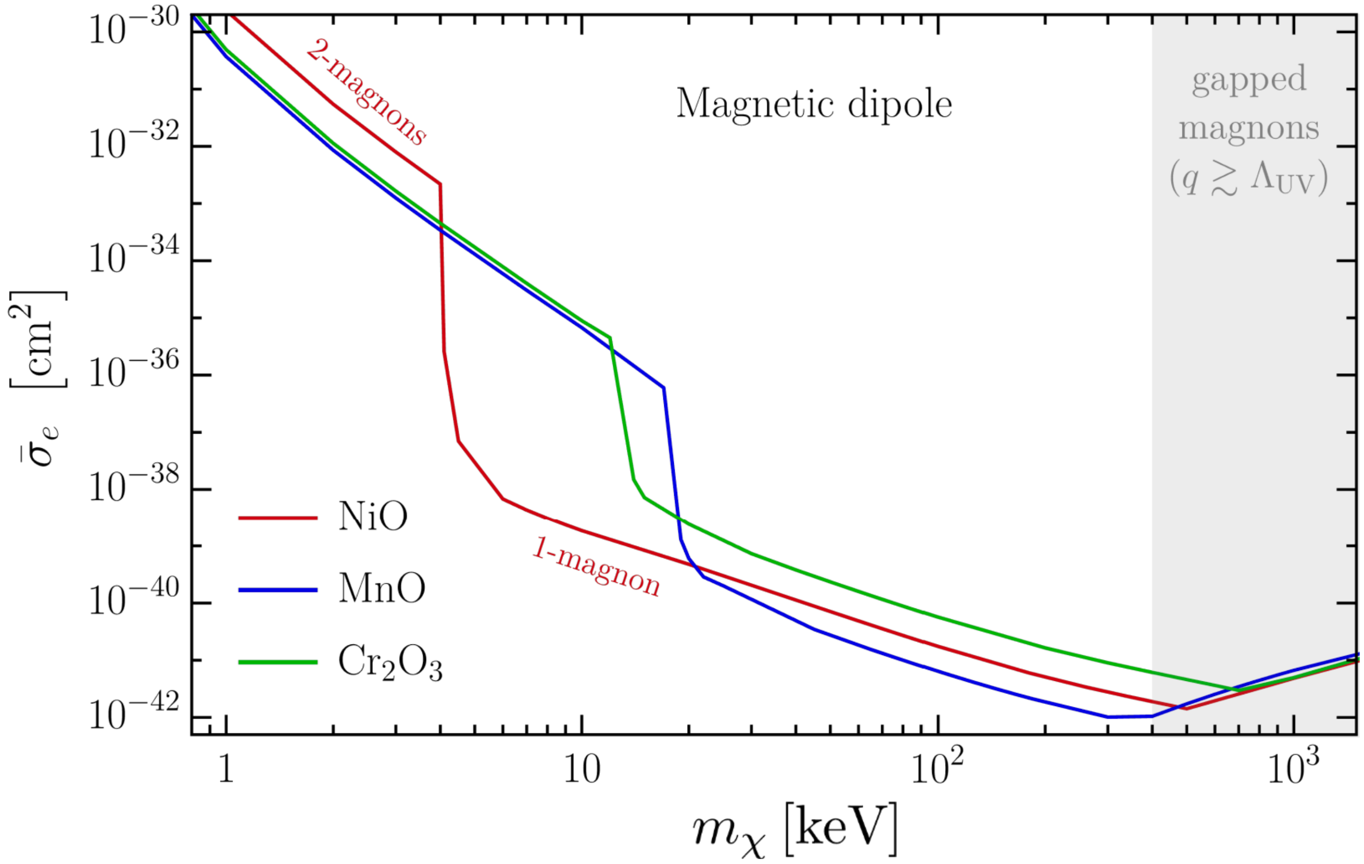


[2411.11971] Hunting axion dark matter with anti-ferromagnets: a case study with nickel oxide

Sensitivity To Dark Matter Scattering

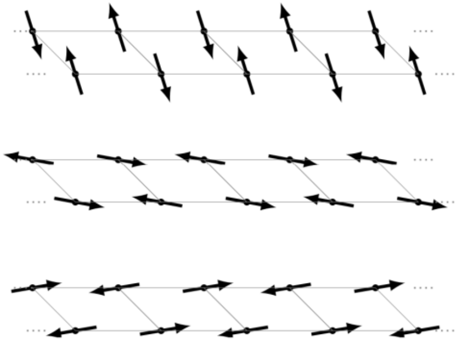


NiO



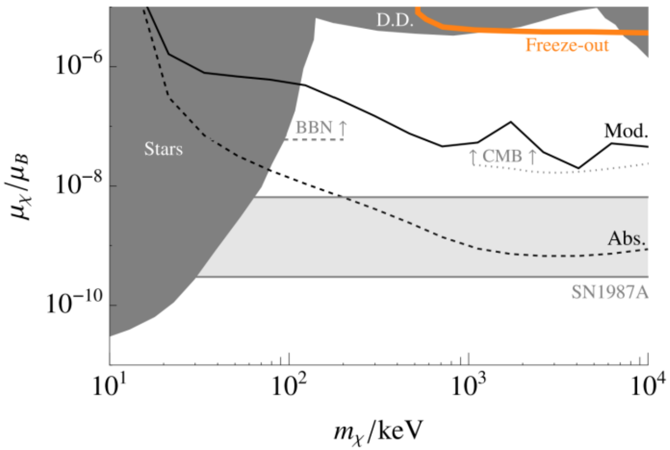
[2210.13516] Optimal anti-ferromagnets for light dark matter detection

Sensitivity To Dark Matter Scattering

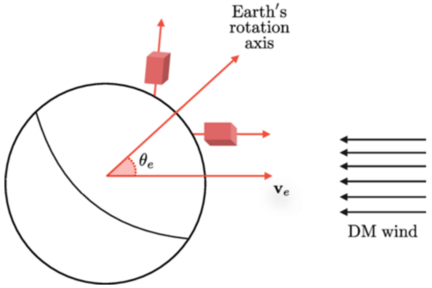


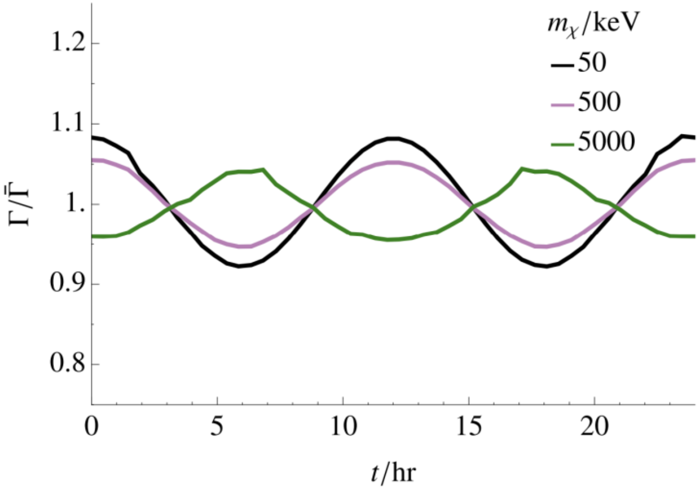
Quasi-2D material

Sensitivity



Daily modulation effects





[2501.18120] Spin-dependent dark matter scattering in quasi-two-dimensional magnets

The Dark Matter Scattering Rate

First-Principles

$$\Gamma = 2\pi \sum_{\nu \mathbf{k}} \left| \langle \nu \mathbf{k} | H_{\mathrm{int}} | 0 \rangle \right|^2 \delta(\omega_{\nu \mathbf{k}} - \omega_{\mathbf{q}})$$

+

$$H_{\mathrm{int}} \sim \sum_{\ell j} \boldsymbol{\mathcal{O}}^{\chi}_{\ell j} \cdot \mathbf{S}^{e}_{\ell j}$$

Derived from high-energy theory

Magnon modes derived from diagonalizing Heisenberg Hamiltonian

$$H = \sum_{\ell \ell' j j'} \mathbf{S}_{\ell' j'} \cdot \mathbf{J}_{\ell \ell' j j'} \cdot \mathbf{S}_{\ell j}$$

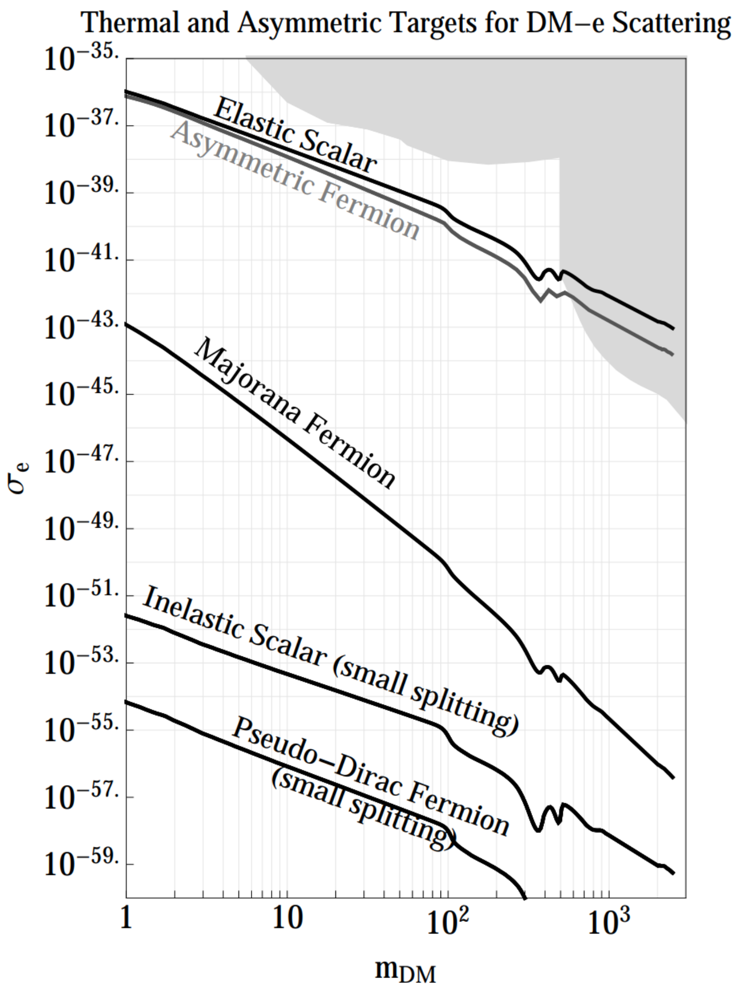
$$\boldsymbol{S}_{lj} = \mathbf{R}'(\boldsymbol{x}_{lj}) \left[\sqrt{\frac{S_j}{2}} \left(\boldsymbol{r}_j^* \hat{a}_{lj} + \boldsymbol{r}_j \hat{a}_{lj}^\dagger \right) + \boldsymbol{t}_j \left(S_j - \hat{a}_{lj}^\dagger \hat{a}_{lj} \right) \right]$$

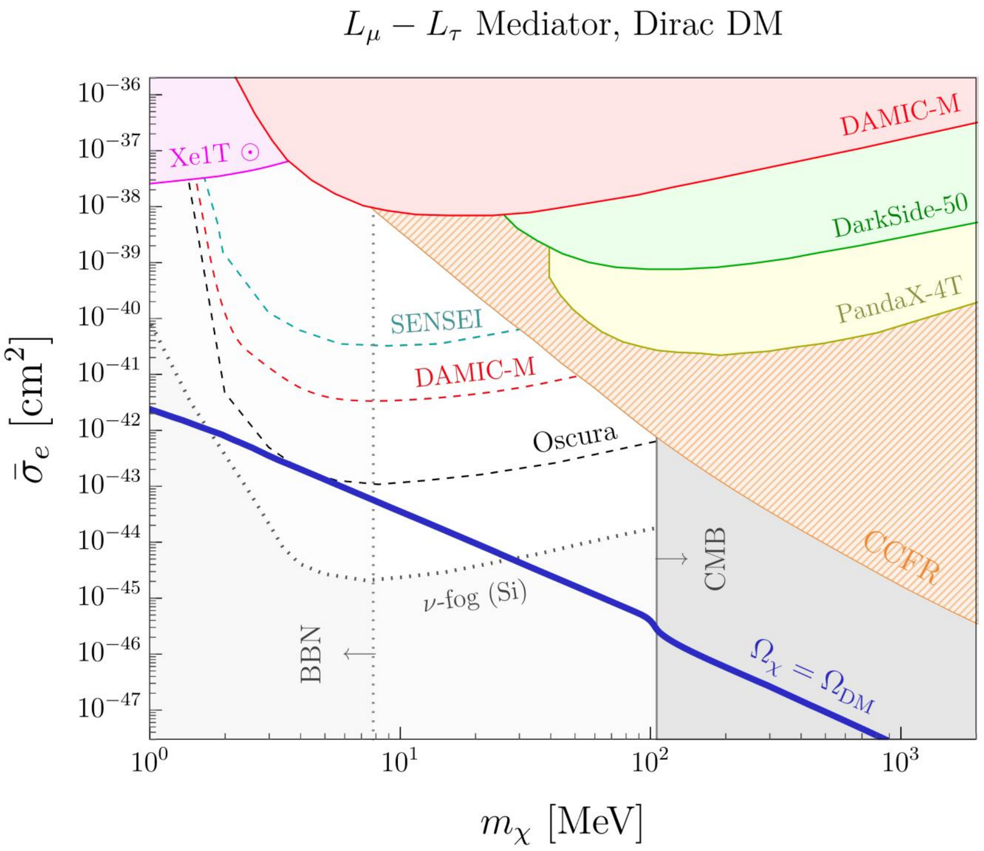
[1905.13744] Detecting Light Dark Matter with Magnons

- **T. Trickle**, Zhang, Zurek

ttrickle@fnal.gov

Some (Heavy Mediator) Motivated Models





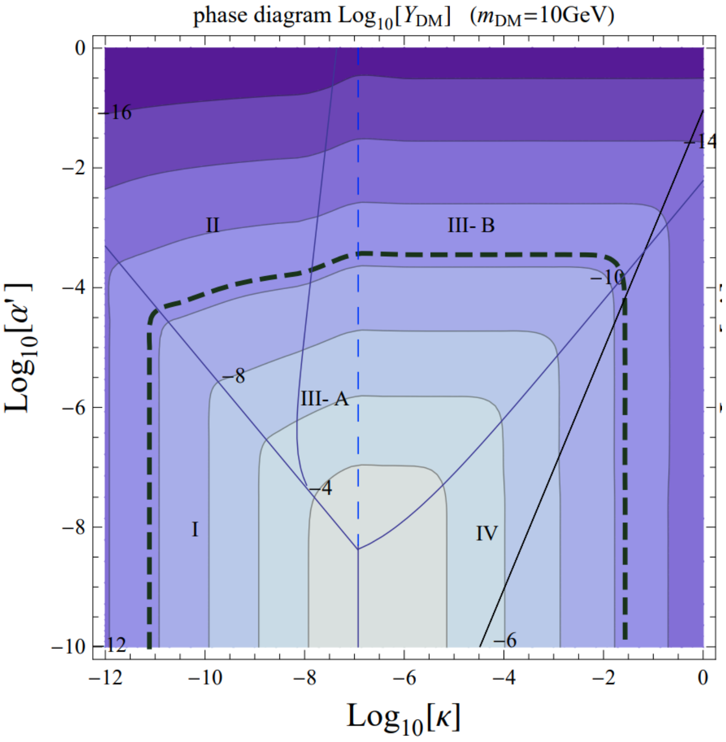
[1707.04591] US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report

[2505.04626] Testing Thermal-Relic Dark Matter with a Dark Photon Mediator

[2603.03444] New Thermal-Relic Targets for sub-GeV Dark Matter Direct Detection

The Mesa Diagram: Why Freeze-In Is Special

$$\mathcal{L} \supset A'_\mu \left[g_\chi \left(\bar{\chi} \gamma^\mu \chi \right) + \varepsilon e \left(\bar{e} \gamma^\mu e \right) \right]$$



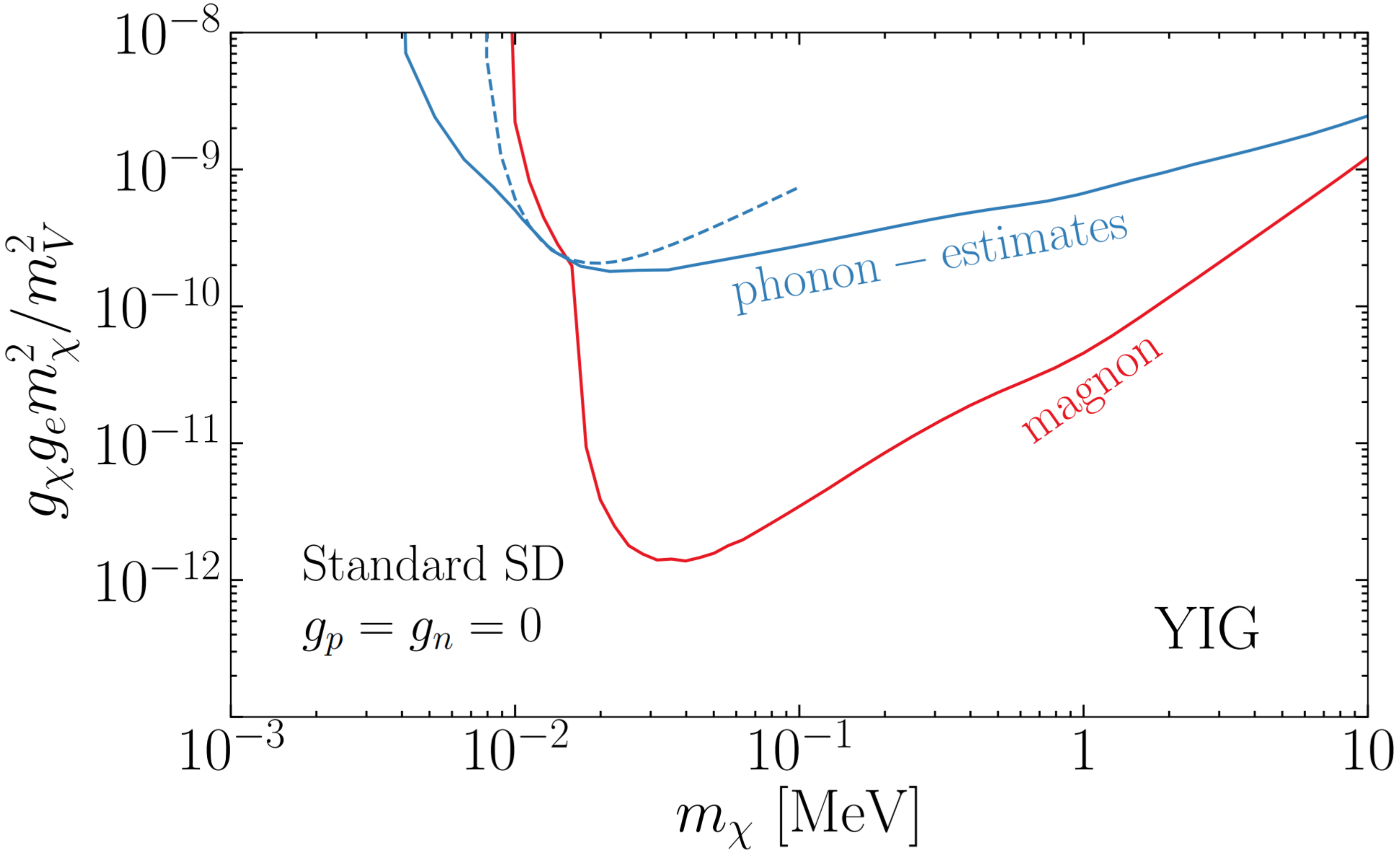
$$\kappa \propto \sqrt{\bar{\sigma}_e}$$

$$\alpha' = \frac{g_\chi^2}{4\pi}$$

[1112.0493] The Four Basic Ways of Creating Dark Matter Through a Portal

SD Dominance of Magnon Scattering

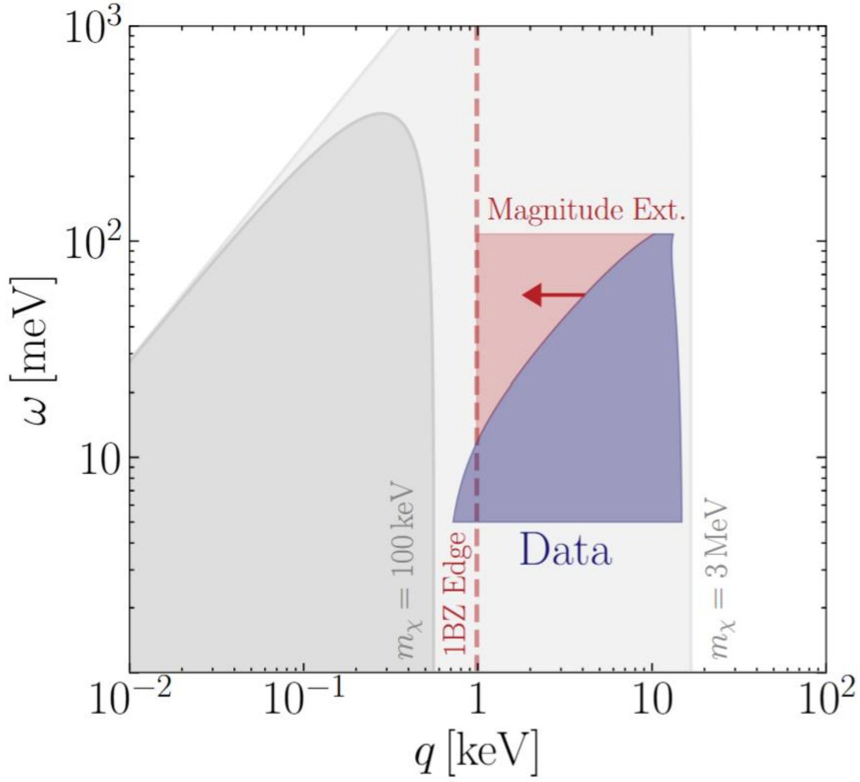
$$\mathcal{L} \supset g_\chi \, V_\mu \, \bar{\chi}\gamma^\mu\gamma^5\chi + g_e \, V_\mu \, \bar{e}\gamma^\mu\gamma^5 e$$



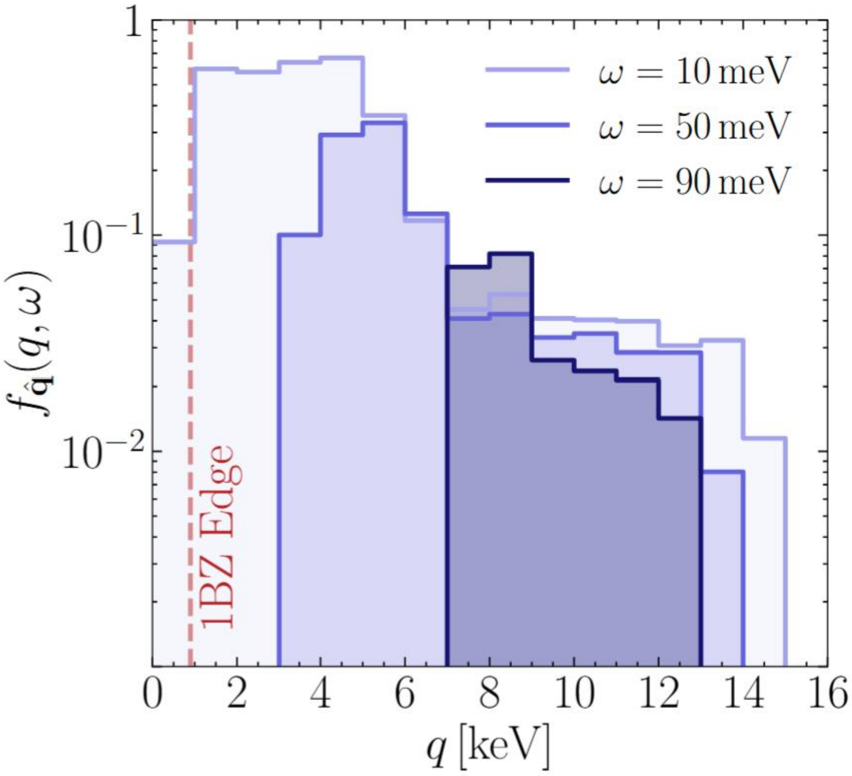
[2009.13534] Effective Field Theory of Dark Matter Direct Detection With Collective Excitations

- **T. Trickle**, Zhang, Zurek

A Neutron Scattering Dataset



Kinematic coverage



Angular coverage

Additional Interesting Directions

Calibrating results to data

[2101.08275] Dark matter-electron scattering in dielectrics

[2101.08263] Determining Dark Matter-Electron Scattering Rates from the Dielectric Function

Dark photon scattering rate

$$\Gamma(\mathbf{v}_\chi) = \int \frac{\mathrm{d}^3\mathbf{q}}{(2\pi)^3} |V(\mathbf{q})|^2 \left[2\frac{q^2}{e^2} \, \mathrm{Im} \boxed{\left(-\frac{1}{\epsilon(\mathbf{q}, \omega_\mathbf{q})} \right)} \right]$$

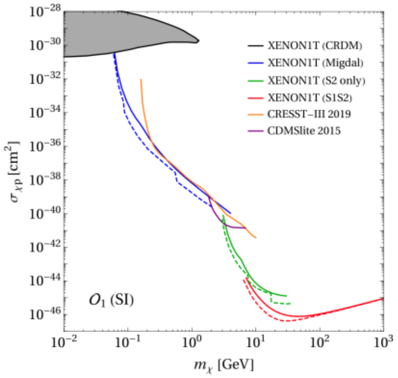
measurable

Other physical effects

Migdal Effect

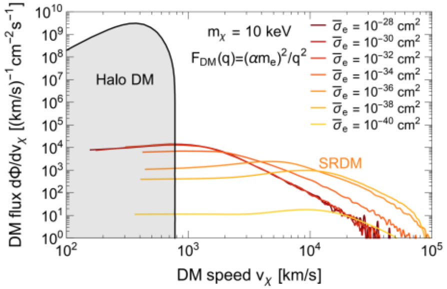
[1908.10881] On the relation between Migdal effect and dark matter-electron scattering in isolated atoms and semiconductors

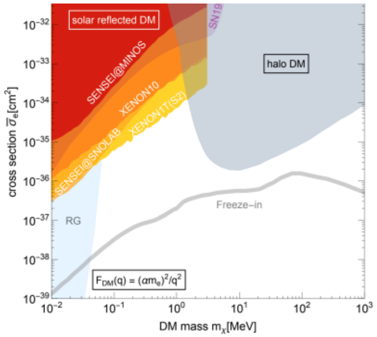
[2210.06490] The Migdal Effect in Semiconductors for Dark Matter with Masses below $\sim \,$100 MeV



Boosted Dark Matter

[2404.10066] Solar reflection of dark matter with dark-photon mediators



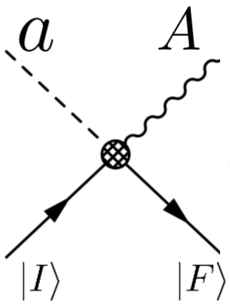


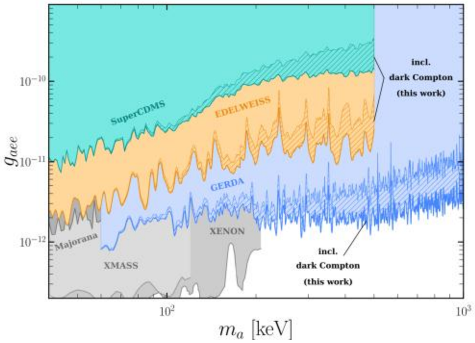
Dark Thomson

[2109.08168] Impact of Dark Compton Scattering on Direct Dark Matter Absorption Searches

[2407.14598] The Non-Relativistic Effective Field Theory Of Dark Matter-Electron Interactions

- G. Krnjaic, D. Rocha, **T. Trickle**



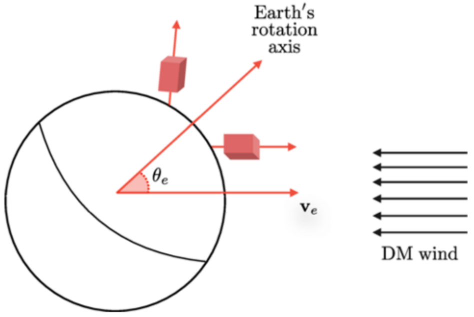


Daily Modulation

[2102.09567] Directional Detectability of Dark Matter With Single Phonon Excitations: Target Comparison

- A. Coskuner, **T. Trickle**, Z. Zhang, K. Zurek

[2212.04505] Directional detection of dark matter with anisotropic response functions

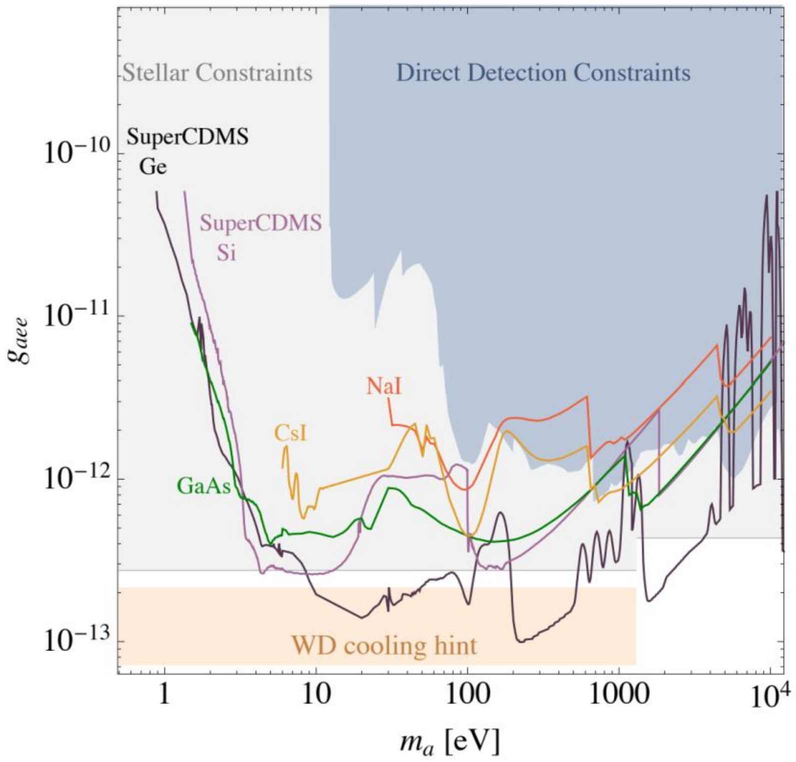


High-Frequency GWs

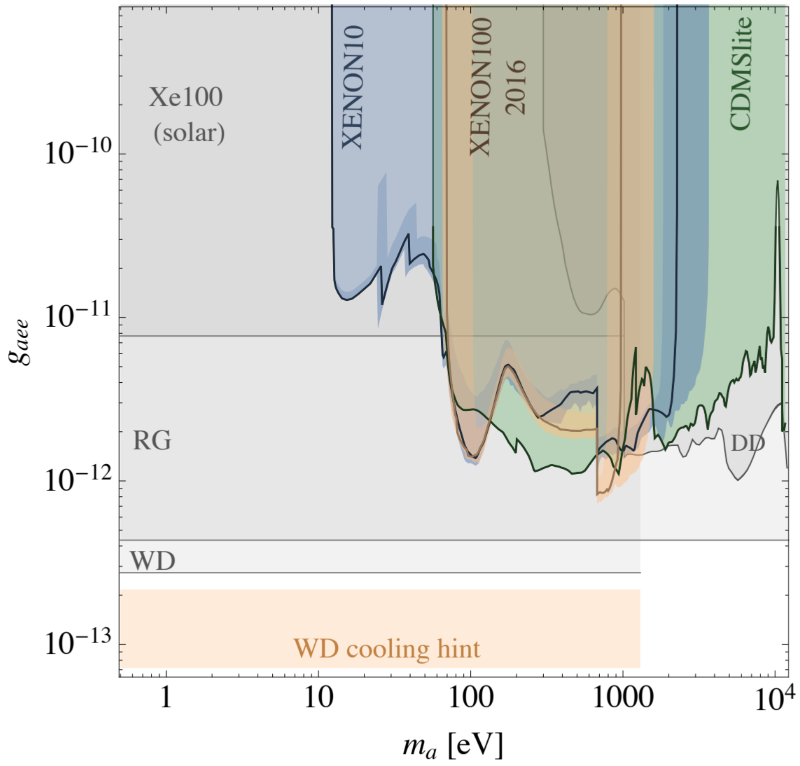
[2311.17147] Searching for High Frequency Gravitational Waves with Phonons

- Y. Kahn, J. Schutte-Engel, **T. Trickle**

Searches For The Axion-Electron Coupling



Semiconductors



Noble Liquid

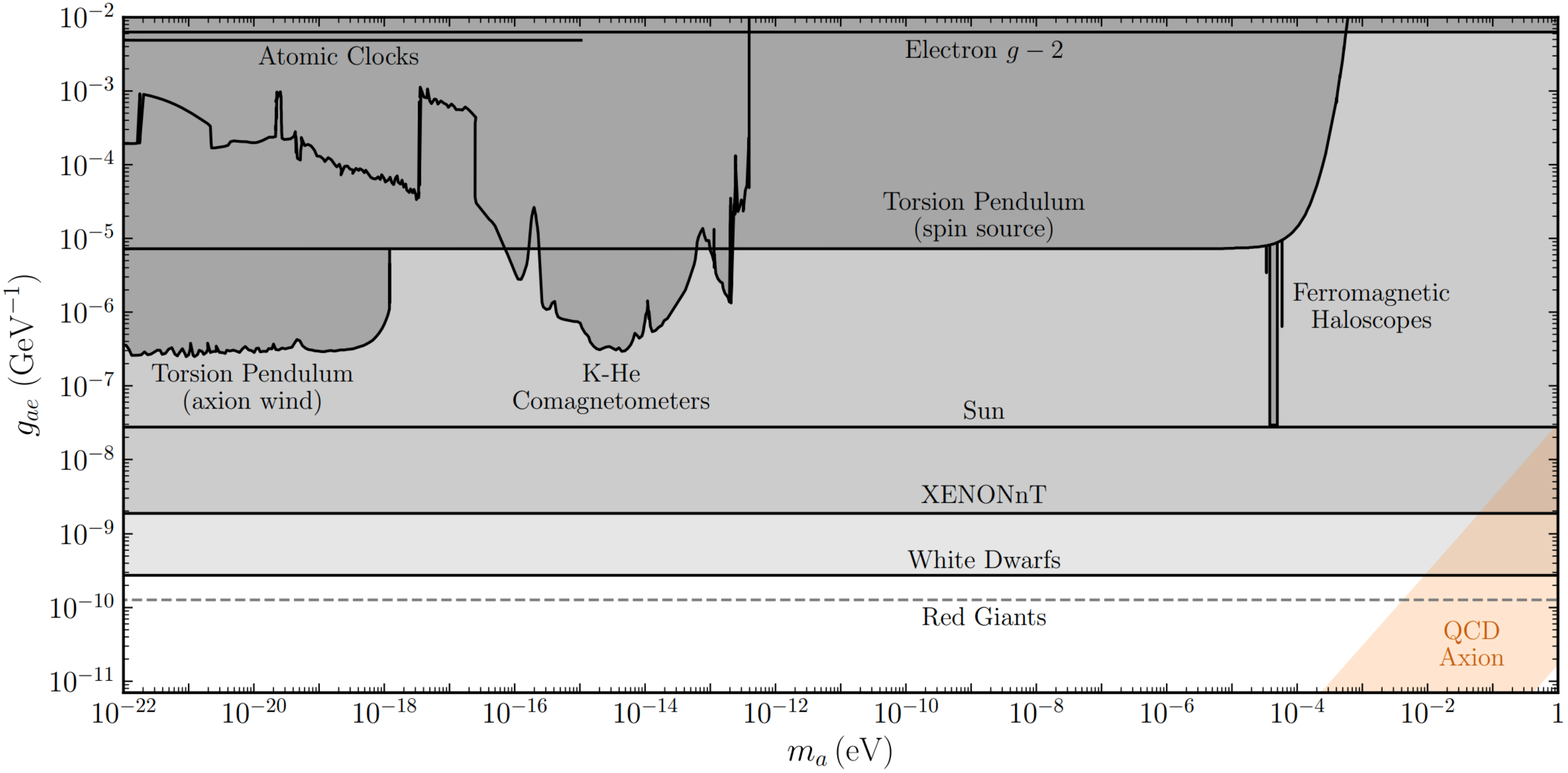
[1608.02123] Searching for Dark Absorption with Direct Detection Experiments

$$R \simeq \left(\frac{g_{ae}\, m_a}{e}\right)^2 \frac{\rho_{\mathrm{DM}}}{\rho_{\mathrm{T}}} \times \begin{cases} 3\ \mathrm{Im}\,[\,\varepsilon(m_a)\,] & \text{(unpolarized target)} \\ \mathrm{Im}\left[\dfrac{-1}{\varepsilon(m_a)}\right] & \text{(polarized target, spin splitting} \gg m_a\text{)} \end{cases}$$

[2312.11601] Physical Signatures of Fermion-Coupled Axion Dark Matter

- A. Berlin, A. Millar, **T. Trickle**, K. Zhou

Existing Limits on Axion-Electron Coupling

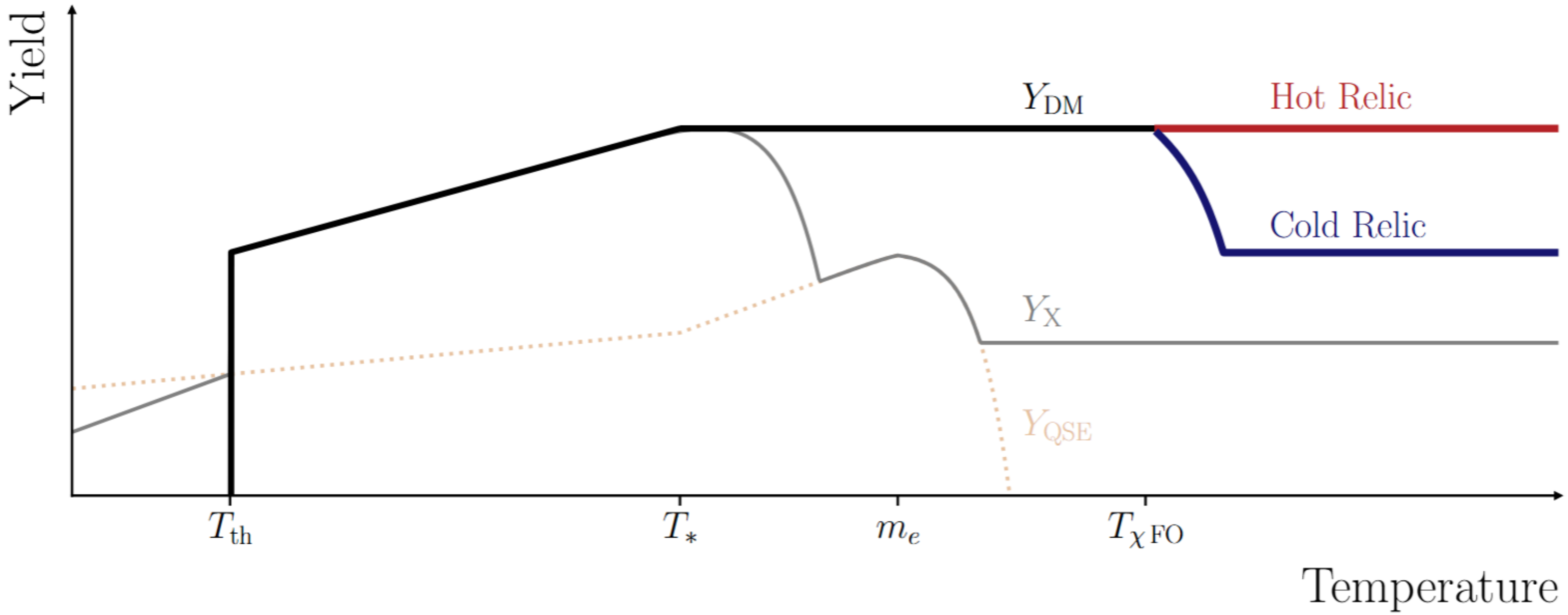


Currently no experiments sensitive enough to search for light axions below stellar cooling limits.

[2312.11601] Physical Signatures of Fermion-Coupled Axion Dark Matter

- Berlin, Millar, **T. Trickle**, Zhou

Quasi-static Equilibrium



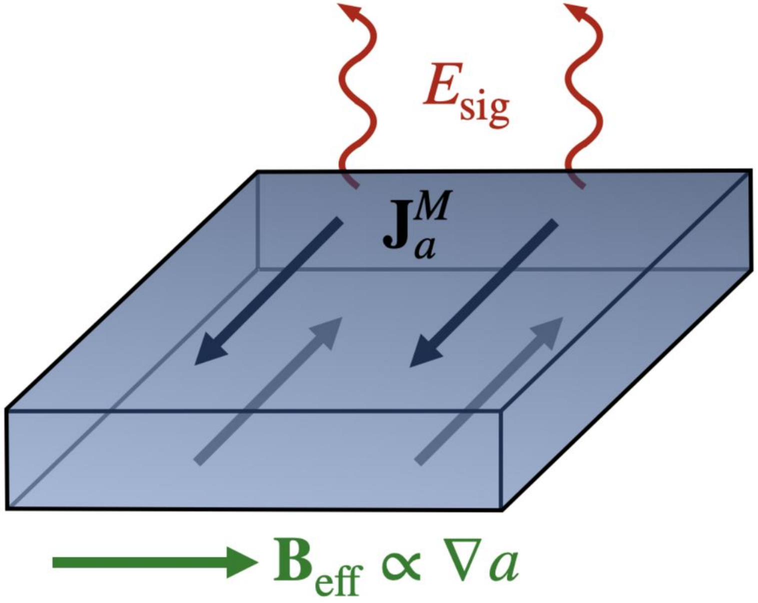
$$\frac{dY_X}{dT} \approx -\frac{c}{sHT}\left[\langle\sigma v\rangle_{XX\to\mathrm{SM}}\left(n_X^{\mathrm{eq}}\right)^2 + \langle\sigma v\rangle'_{XX\to\mathrm{DS}}\left(\left(n_X'^{\mathrm{eq}}\right)^2 - n_X^2\right)\right]$$

$$\frac{dY_X}{dT} \approx -\frac{cs}{HT}\langle\sigma v\rangle'_{XX\to\mathrm{DS}}\left[Y_{\mathrm{QSE}}^2 - Y_X^2\right]$$

Axion Induced Currents

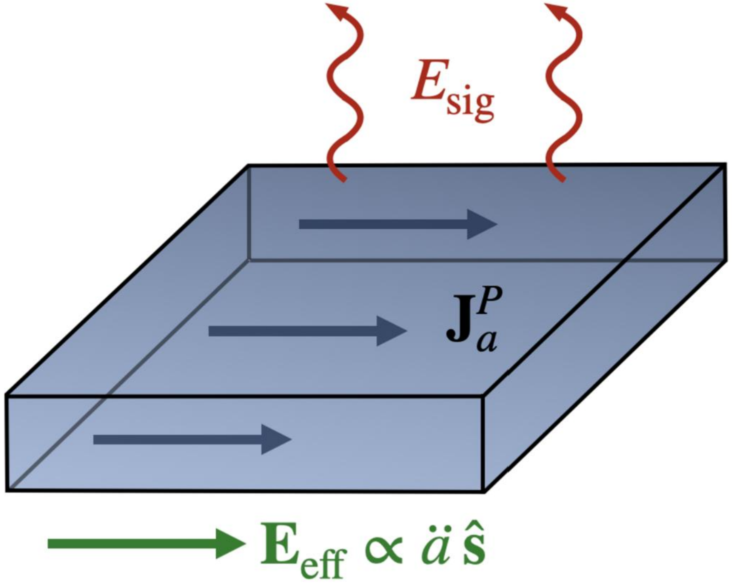
Axion wind term

$$\mathbf{J}_a^M = \nabla \times \left(\left(1 - \mu^{-1}\right) \mathbf{B}_{\text{eff}}\right)$$



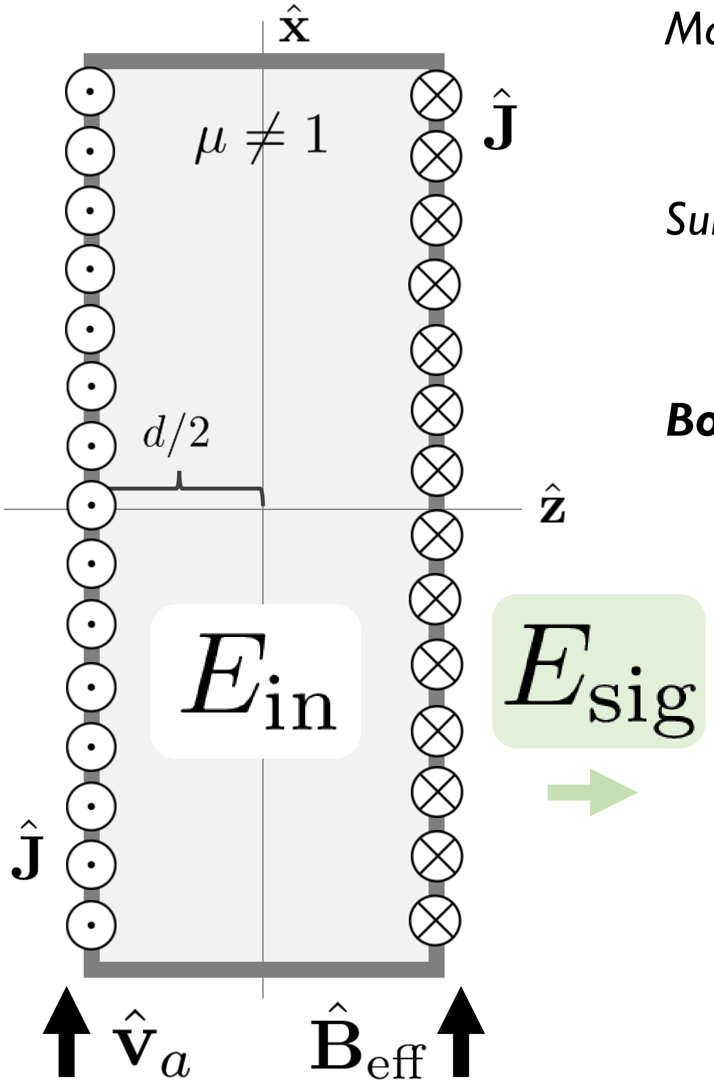
Axio-electric term

$$\mathbf{J}_a^P = (\varepsilon - 1)\, \partial_t \mathbf{E}_{\text{eff}}$$



Axion Wind Induced Signal

Focus on Axion wind induced currents.



Magnetization

$$M_x = \Theta\left(d/2 - z\right)\Theta(z + d/2)\, M_a$$

Surface Current

$$J_y = \left(\delta(z + d/2) - \delta(z - d/2)\right) M_a$$

Boundary Conditions

Electric field continuity

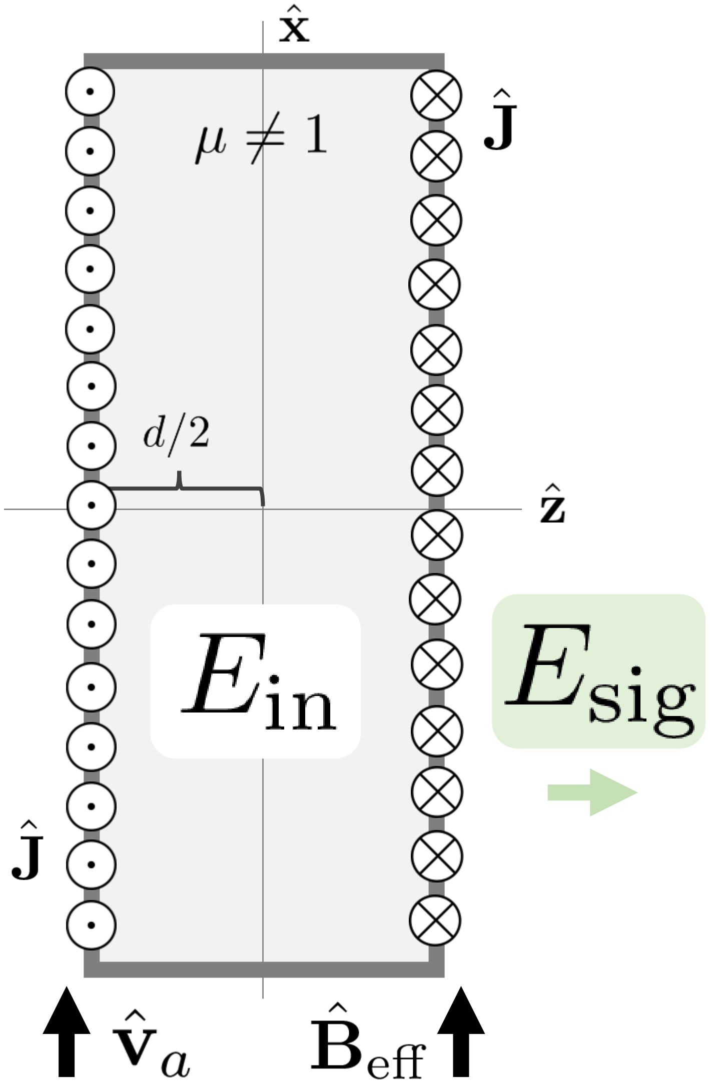
$$E^x_{\text{in}}\, \sin\left(n\, m_a d/2\right) = E^x_{\text{sig}}\, e^{i m_a d/2}$$

Magnetic field discontinuity (Amperian loop)

$$-\frac{in}{\mu}\, E^x_{\text{in}}\, \cos\left(n m_a d/2\right) = E^x_{\text{sig}}\, e^{i m_a d/2} + M_a$$

Axion Wind Induced Signal

Focus on Axion wind induced currents.



$$E_{\text{sig}} = \mathcal{F} \times B_{\text{eff}}$$

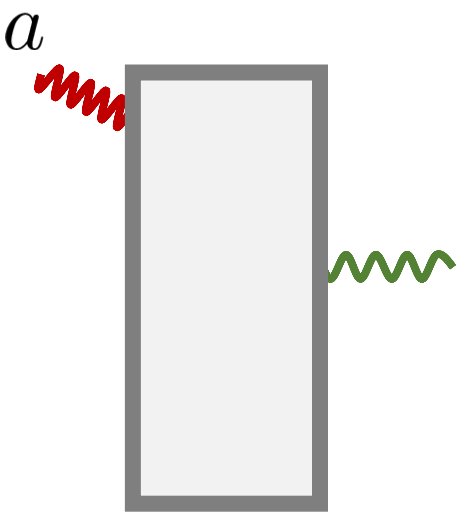
$$\mathcal{F} = \left| \frac{\mu - 1}{\mu + in\cot\left(n m_a d/2\right)} \right|$$

$$n^2 = \varepsilon\mu$$

Tunable with external magnetic field.

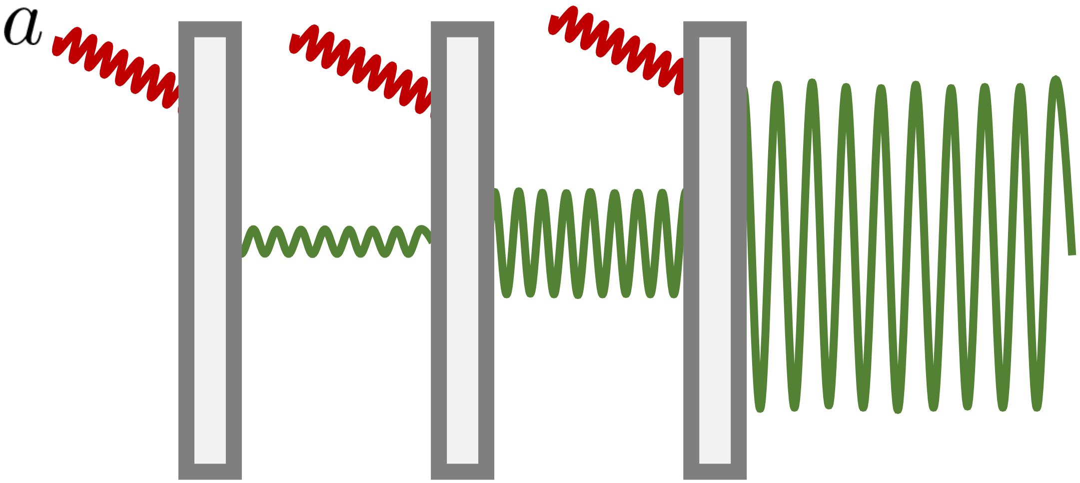
Multi-Layer Coherently Enhances Signal

Single Slab

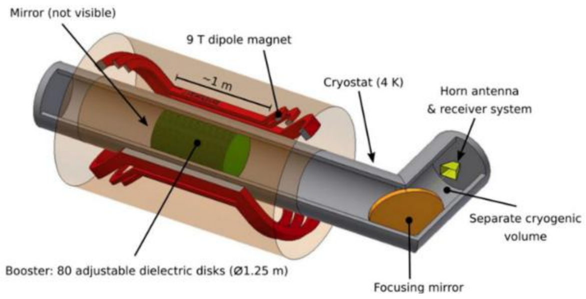


$$P_{\text{sig}} \sim |E_{\text{sig}}|^2 A$$

Many Slabs



$$P_{\text{sig}} \sim N^2 |E_{\text{sig}}|^2 A \qquad (\Delta\omega \sim 1/N)$$



Idea behind DALI, LAMPOST, MADMAX, and MuDHI experiments.

Relationship With The Dynamic Structure Factor

$$\frac{d\sigma_n(\mathbf{v})}{d\Omega dE'} = \frac{|\mathbf{p}'|}{|\mathbf{p}|} S_n(\mathbf{q}, \omega_{\mathbf{q}}) \quad \textit{Measurable}$$

Magnetic dipole dark matter model

$$R = \frac{\rho_\chi}{2\pi\rho_{\mathrm{T}}} \frac{g_\chi^2 g_e^2}{m_\chi^3 \gamma_n^2 e^4} \frac{N_{\mathrm{f}}}{\Omega_c} \int \mathrm{d}\omega \, \mathrm{d}^3\mathbf{q} \; \underset{\textit{Kinematics}}{\underline{g(\mathbf{q}, \omega)}} \boxed{S_n(\mathbf{q}, \omega)}$$

Sensitivity and Extrapolation Schemes