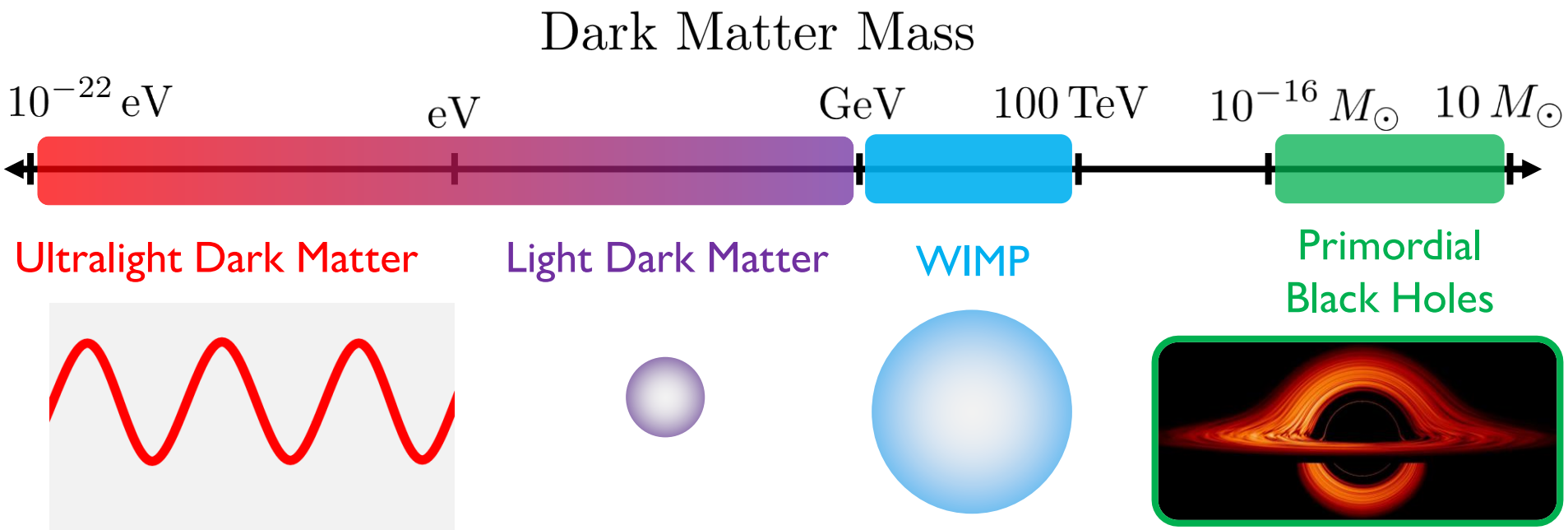
The Search For Light Dark Matter

Tanner Trickle

15th Conference on the Intersections of Particle and Nuclear Physics
University of Wisconsin Madison
June 11th, 2025

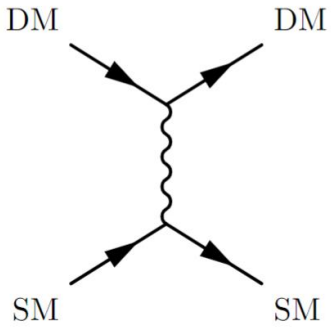
New Paradigms For Dark Matter

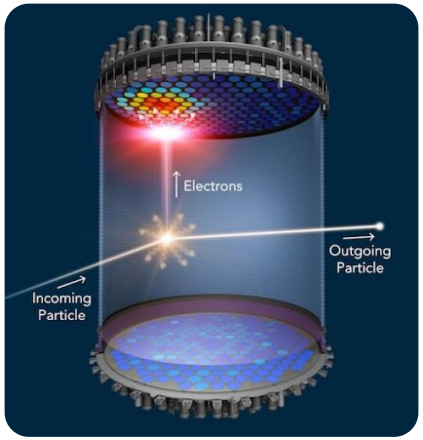


Today's focus

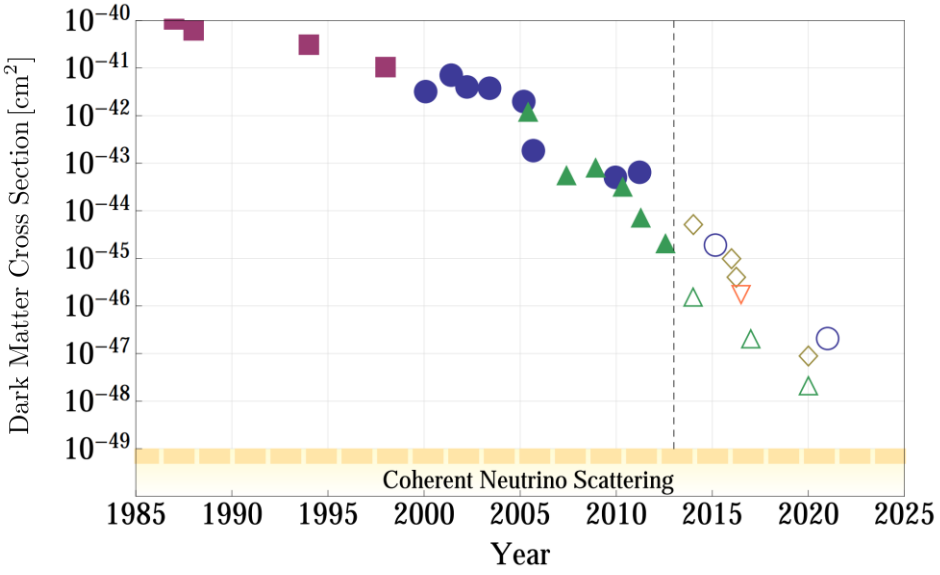
$$\mathrm{keV} \lesssim m_{\mathrm{DM}} \lesssim \mathrm{GeV}$$

Direct Detection of WIMPs

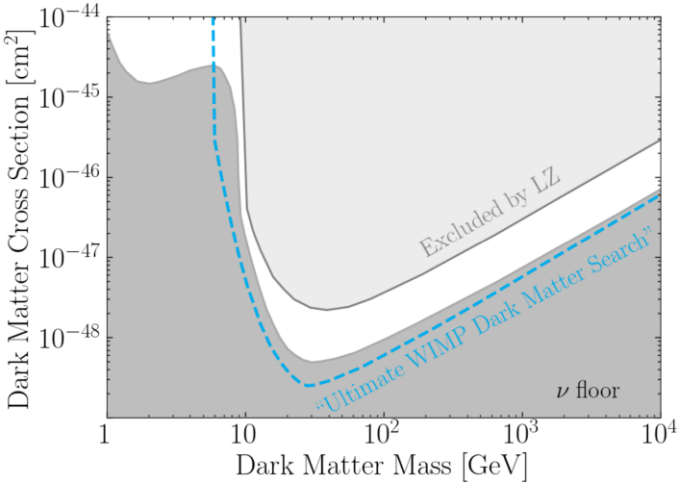




History of WIMP Direct Detection



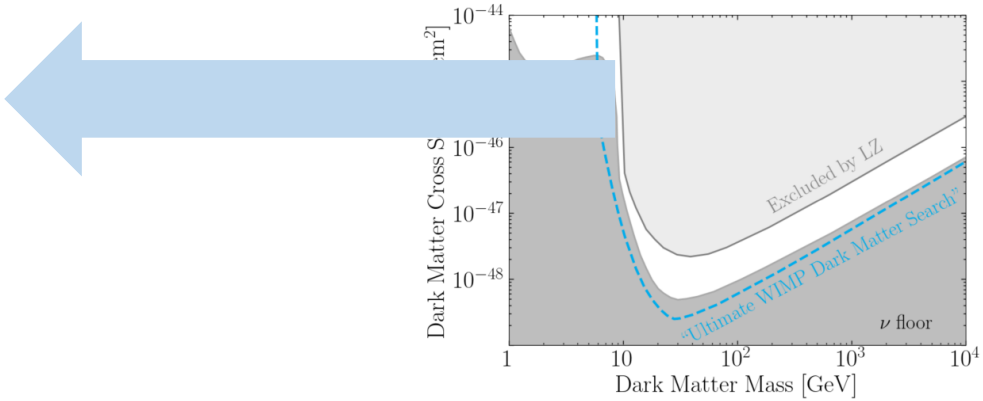
WIMP Direct Detection Today



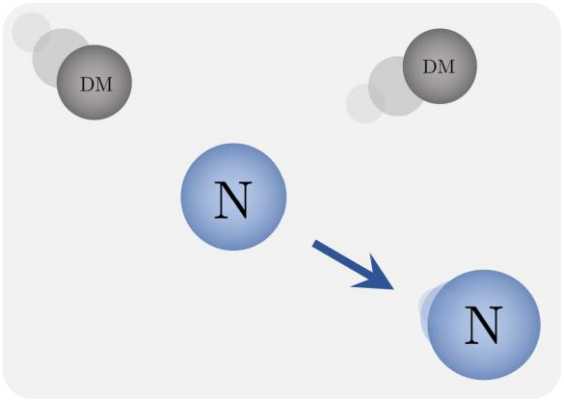
Illuminate the Hidden Universe
Determine the Nature of Dark Matter

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

Kinematic Limitations of Nuclear Recoil



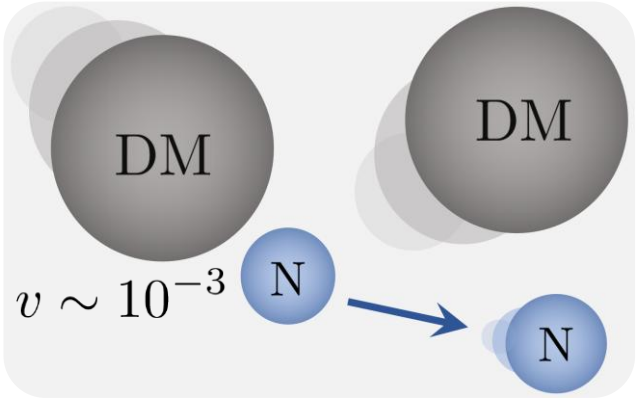
Light Dark Matter



$$q \sim m_{\rm DM} v$$

$$\omega \sim m_{\rm N} v^2 \left(\frac{m_{\rm DM}}{m_N}\right)^2 \sim 10\,{\rm keV} \left(\frac{m_{\rm DM}}{m_N}\right)^2$$

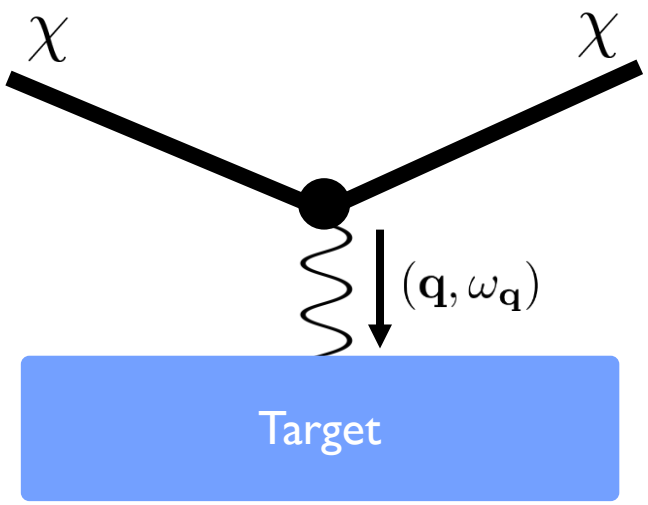
Heavy Dark Matter



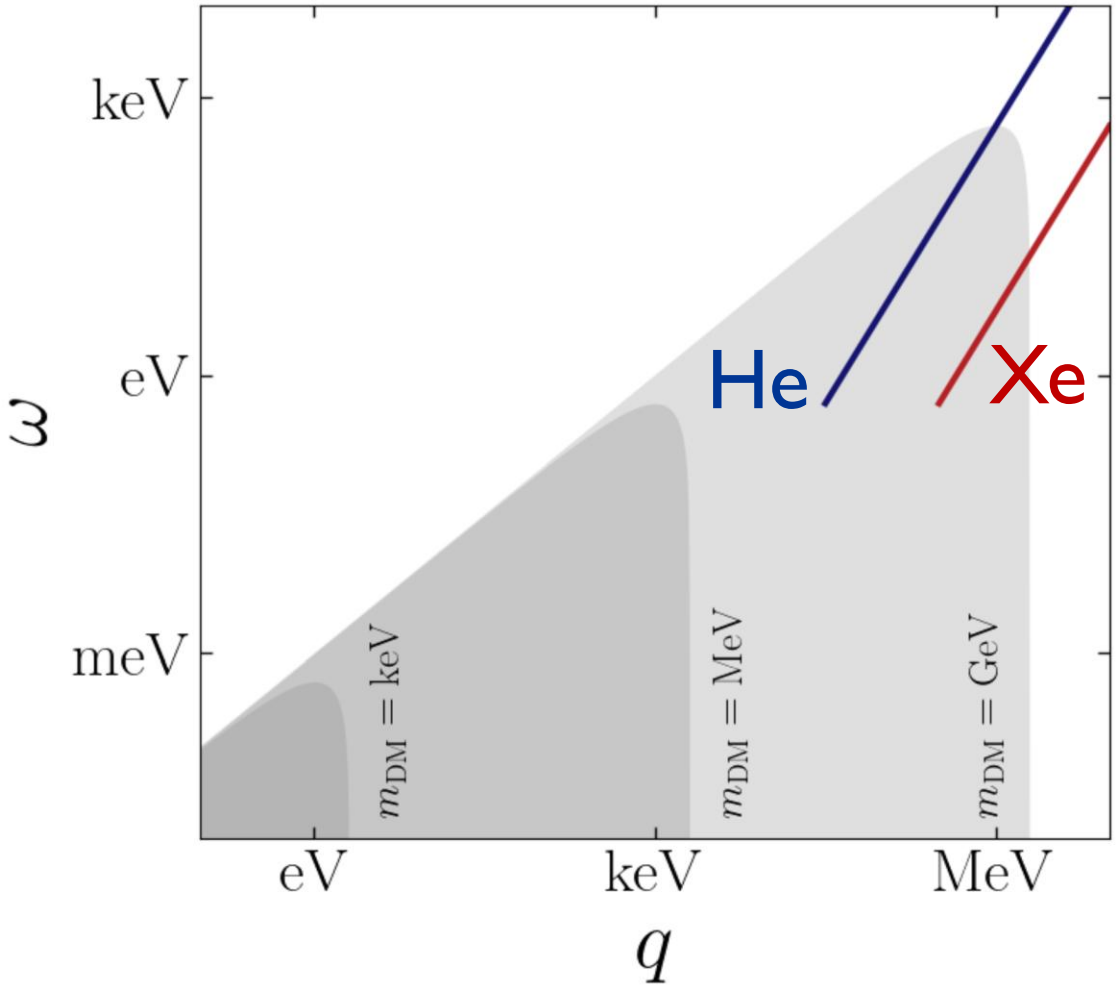
$$q \sim m_N v$$

$$\omega \sim m_N v^2 \sim 10\,{\rm keV}$$

How To Search For Light Dark Matter?



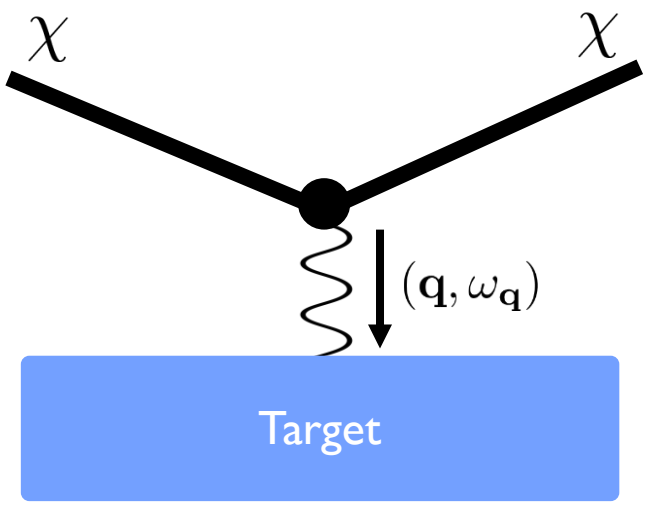
$$\omega_{\mathbf{q}} = \mathbf{q} \cdot \mathbf{v} - \frac{q^2}{2m_\chi}$$
$$\leq q v_{\max} - \frac{q^2}{2m_\chi}$$



[1910.08092] Multi-Channel Direct Detection of Light Dark Matter: Theoretical Framework

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

How To Search For Light Dark Matter?



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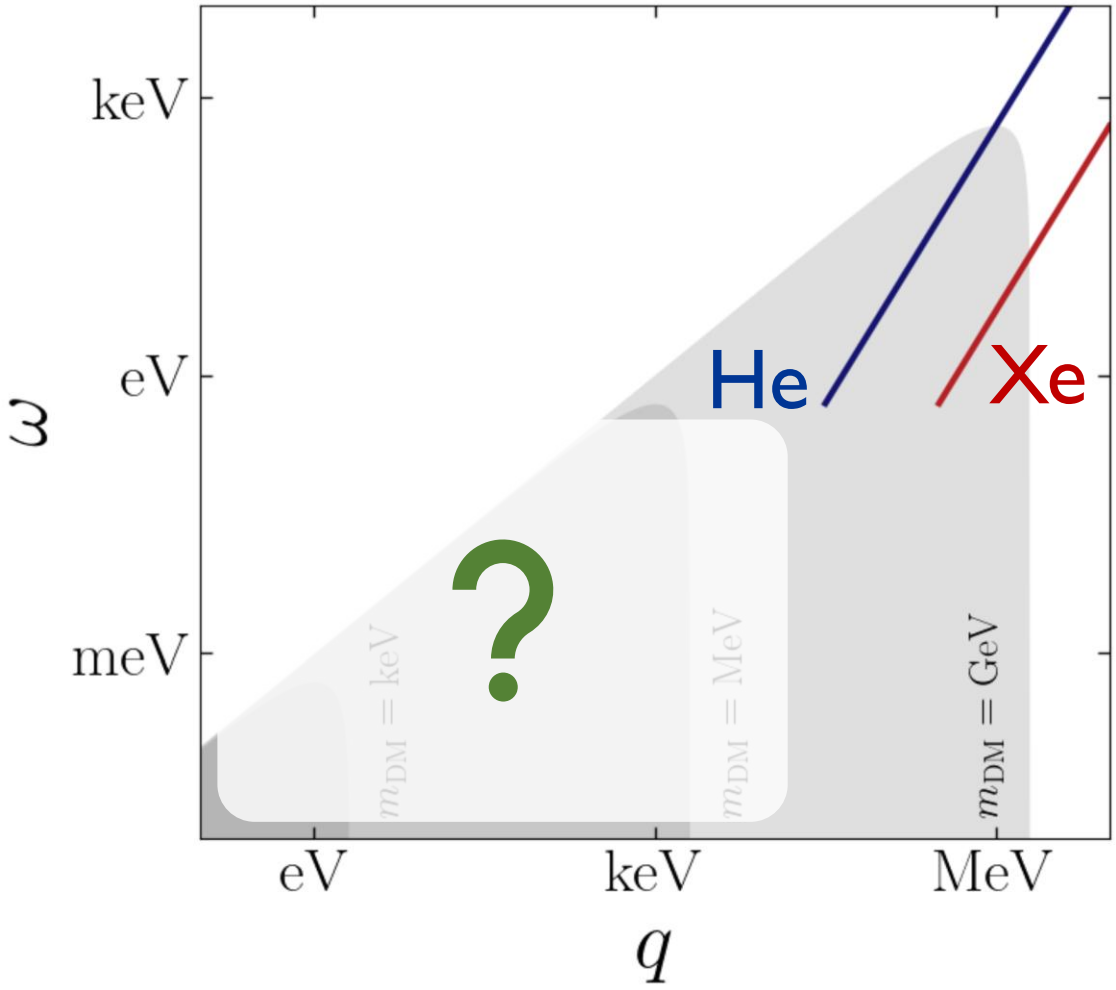
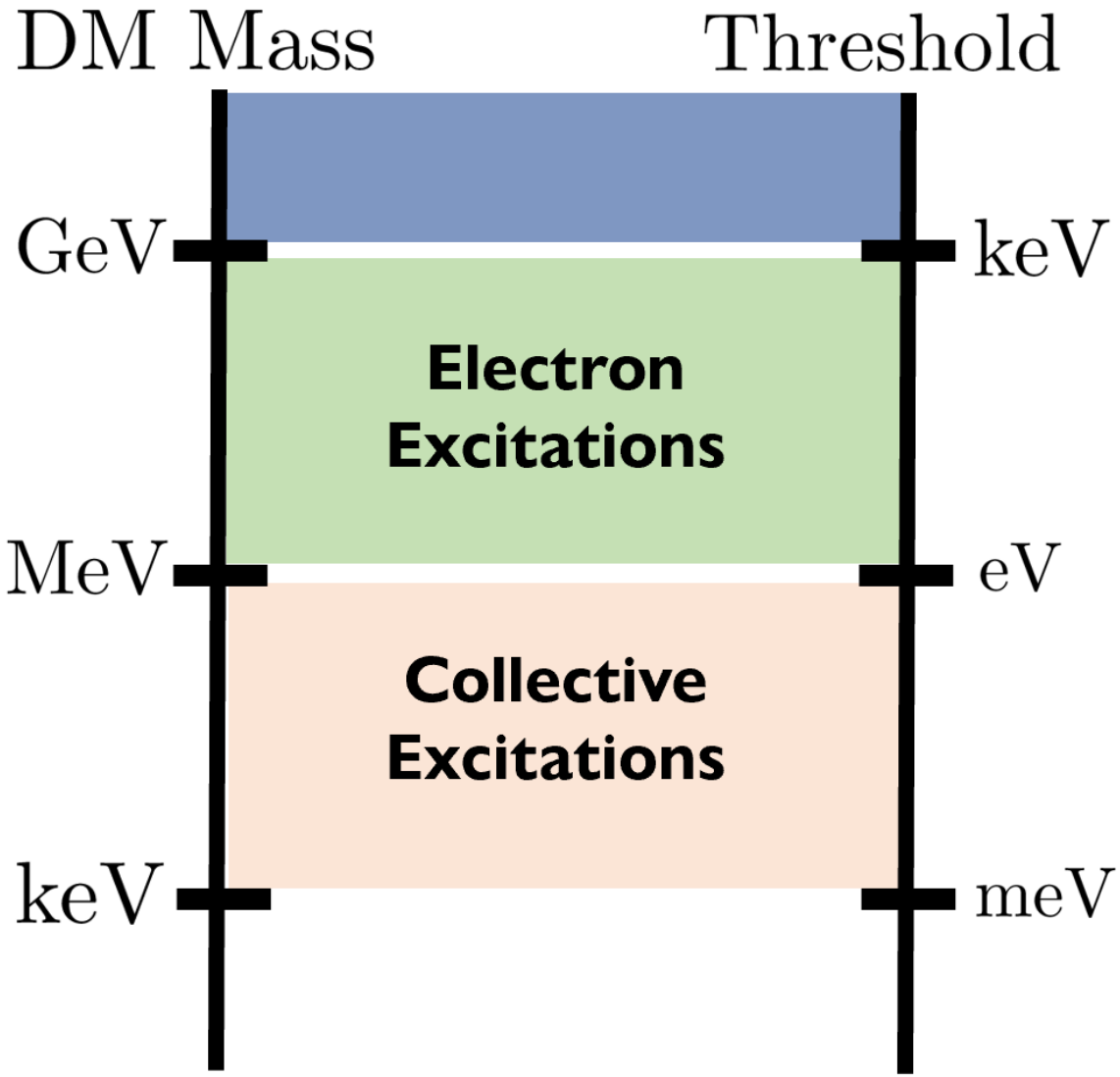


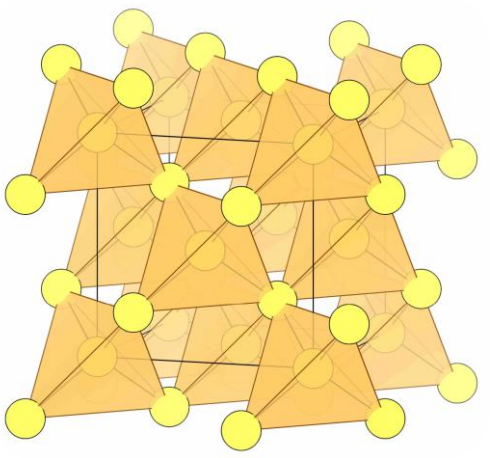
[1910.08092] Multi-Channel Direct Detection of Light Dark Matter: Theoretical Framework

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

Outline

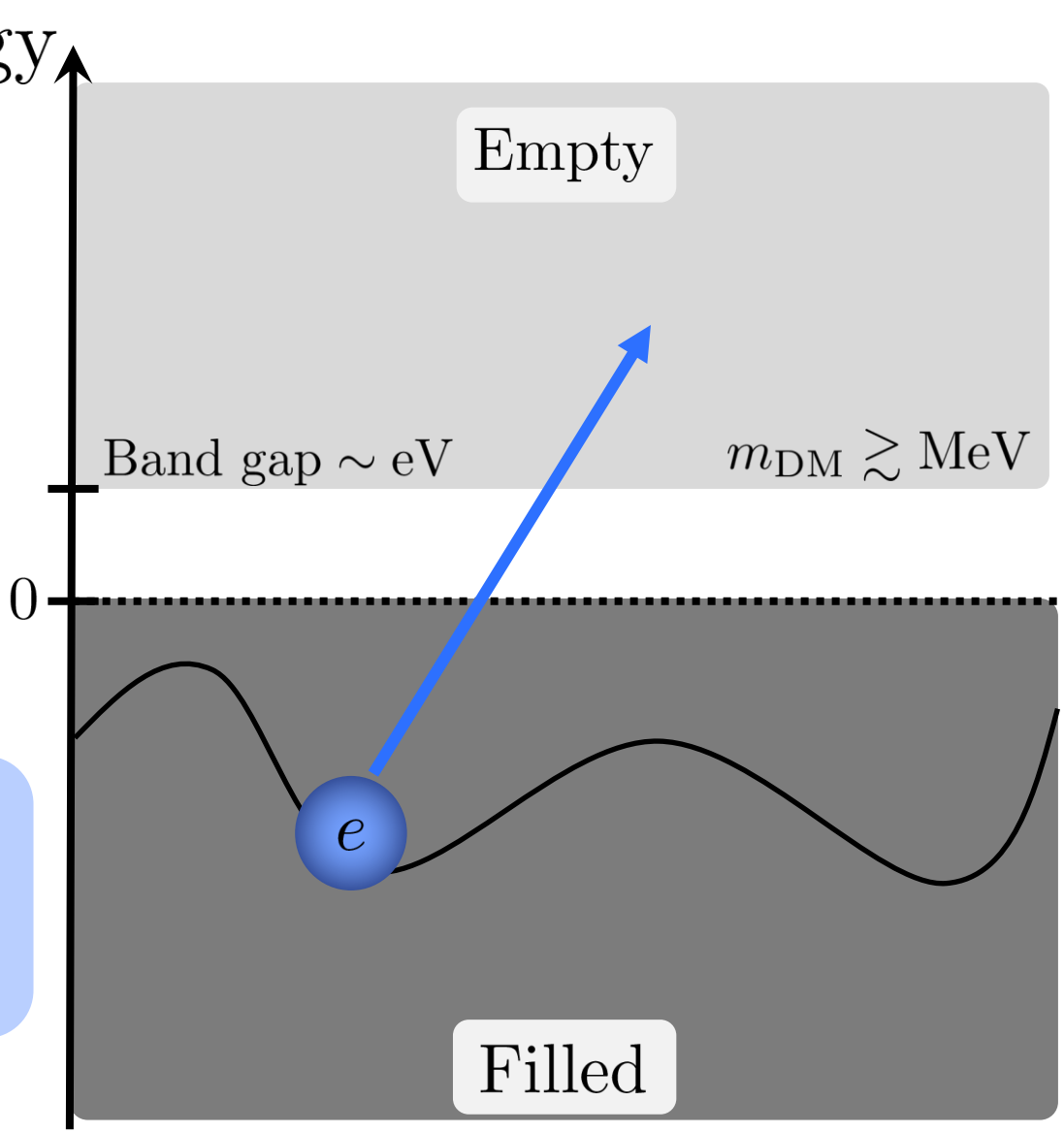

DM Mass
Threshold
GeV
keV
Electron Excitations
MeV
eV
Collective Excitations
keV
meV

Electronic Excitations

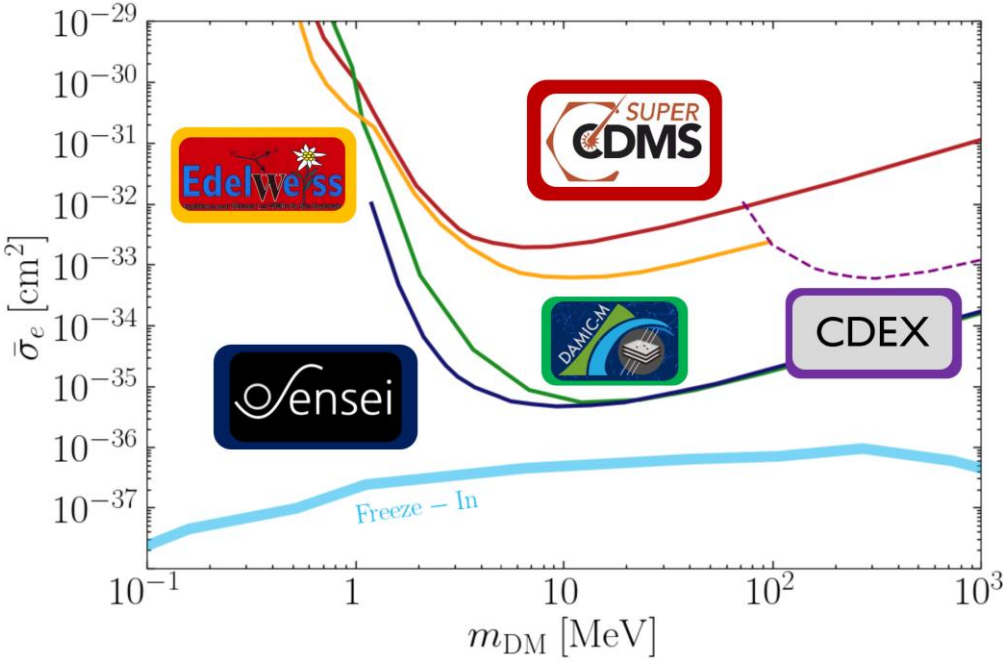


Semiconductor (Si, Ge, …)

$$m_{\rm DM} \gtrsim {\rm MeV} \underbrace{\left(\frac{\Delta E_{I\to F}}{\rm eV}\right)}_{\text{“Band Gap”}}$$

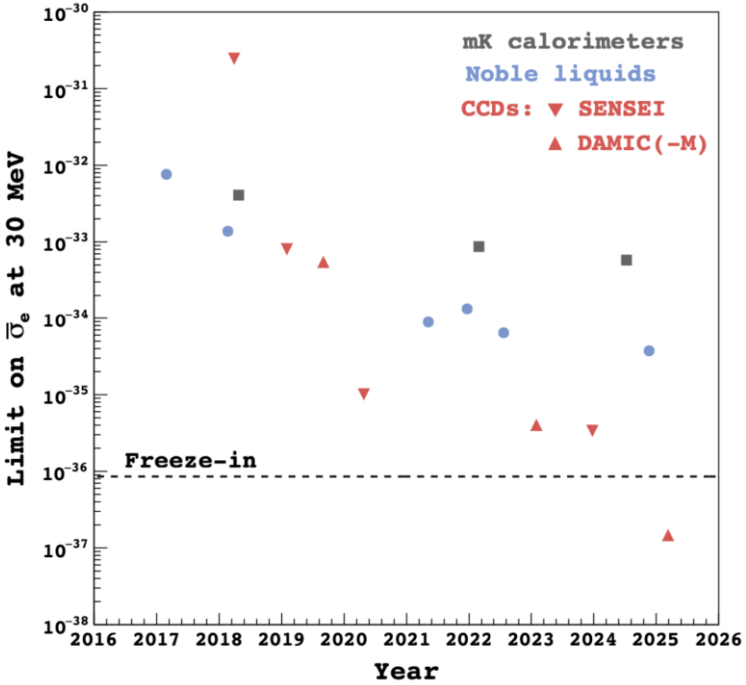


Ongoing Searches For Electron Excitations

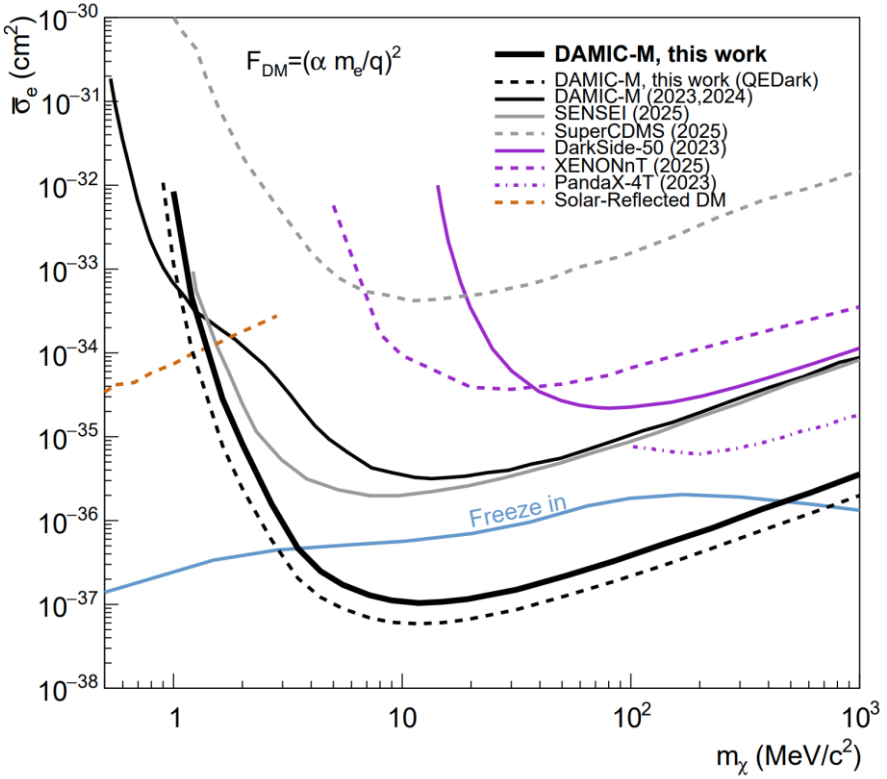


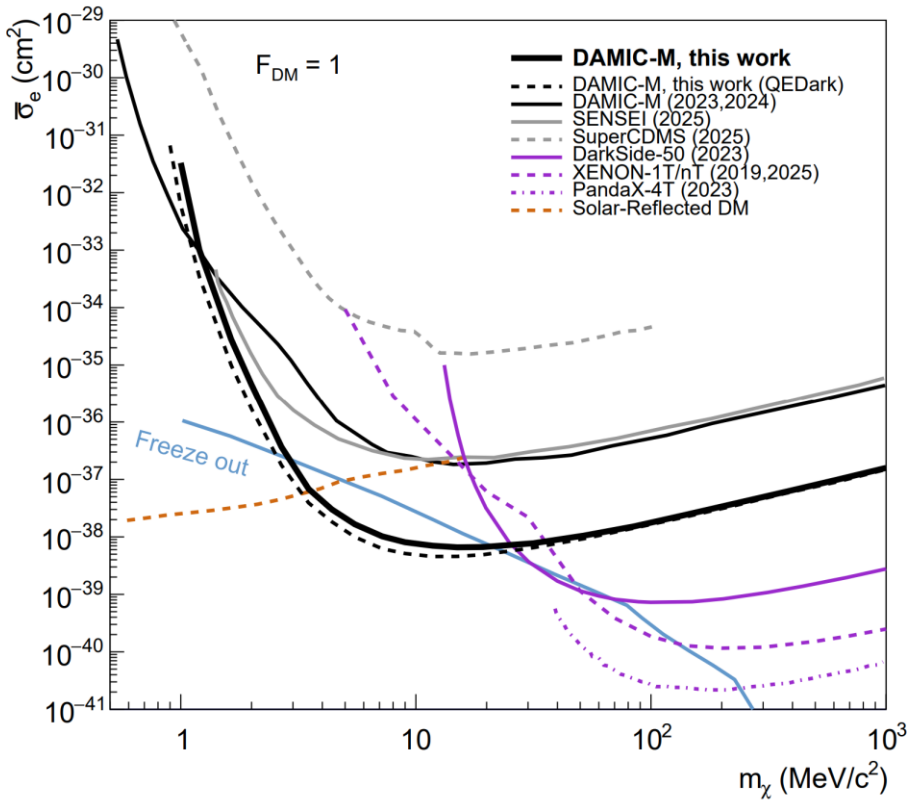
DAMIC

History of Light DM Direct Detection



New Results From DAMIC





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

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

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

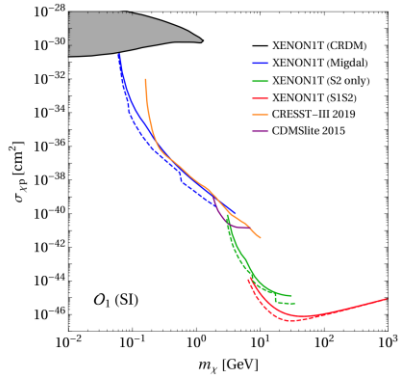
measurable

Other physical effects

Migdal Effect

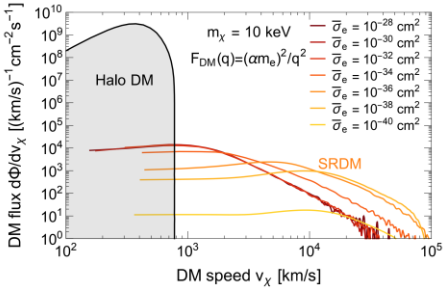
[1908.10881] On the relation between Migdal effect and dark matter-electron scattering in isolated atoms and semiconductors

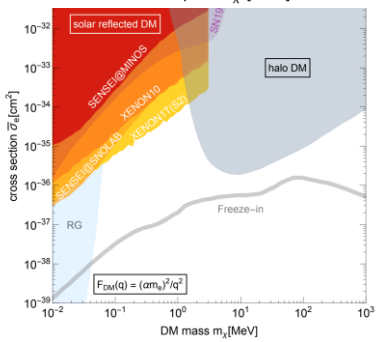
[2210.06490] The Migdal Effect in Semiconductors for Dark Matter with Masses below $\sim \,$100 MeV



Boosted Dark Matter

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



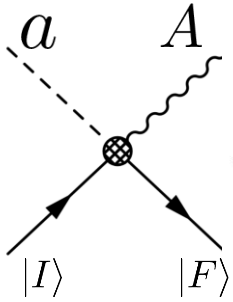


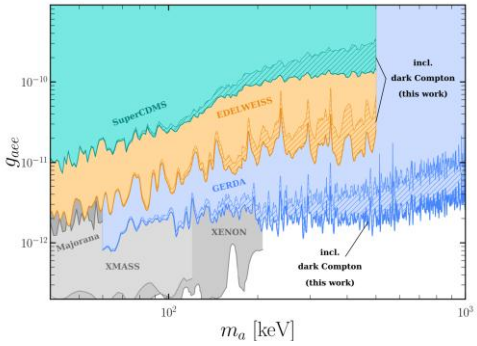
Dark Thomson

[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**



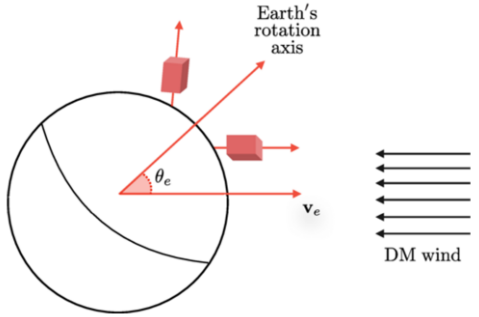


Daily Modulation

[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

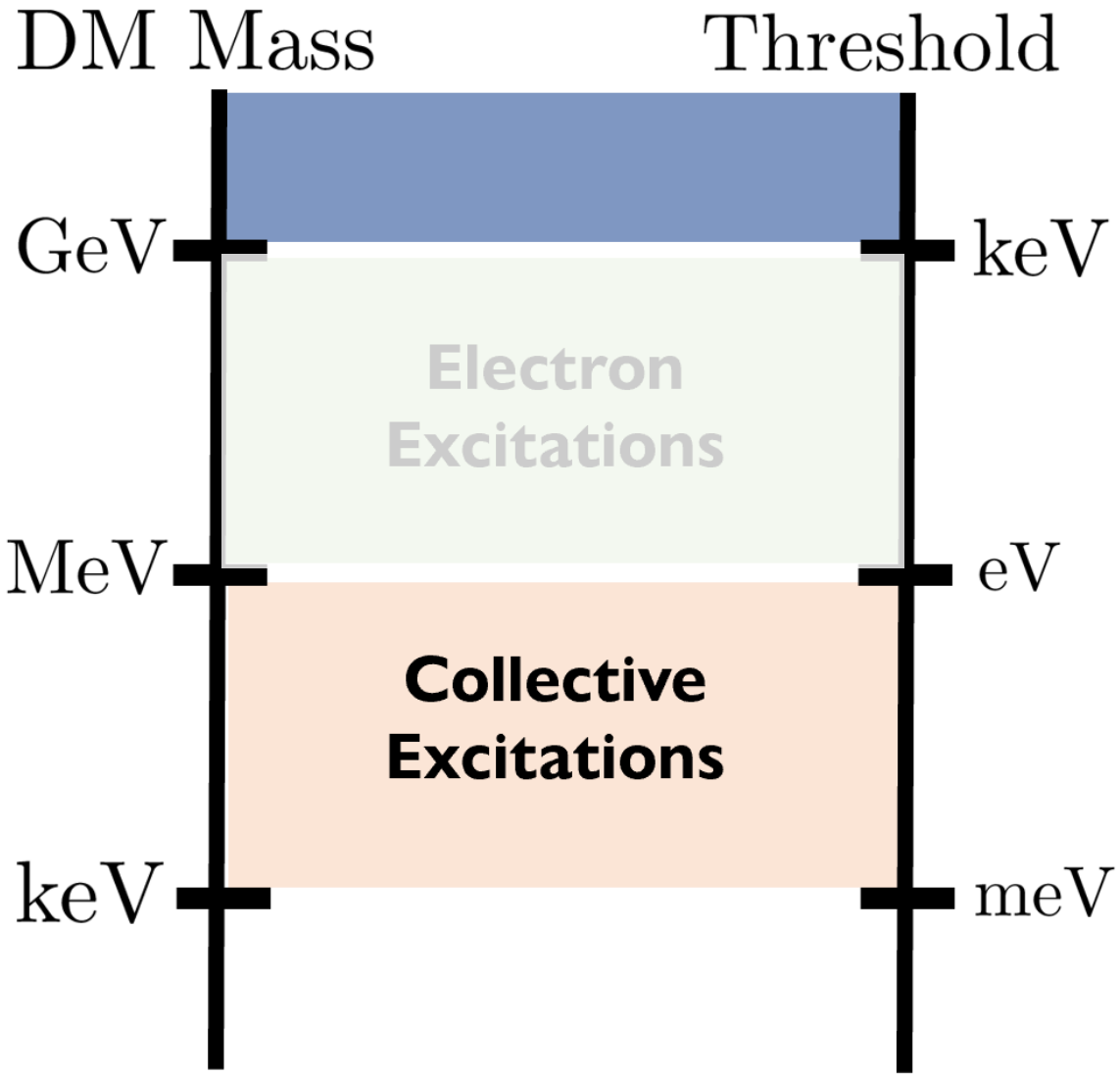


High-Frequency GWs

[2311.17147] Searching for High Frequency Gravitational Waves with Phonons

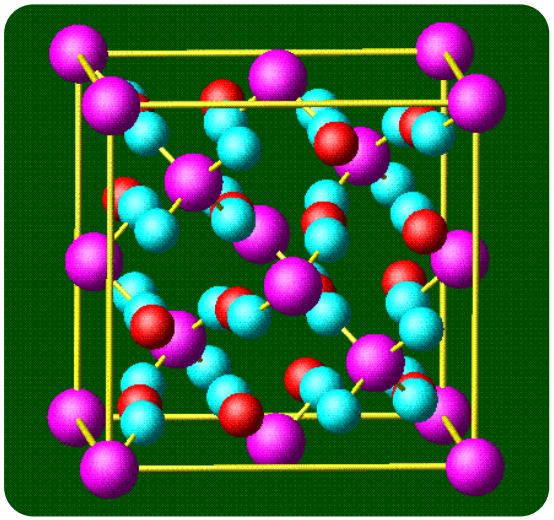
- Y. Kahn, J. Schutte-Engel, **T. Trickle**

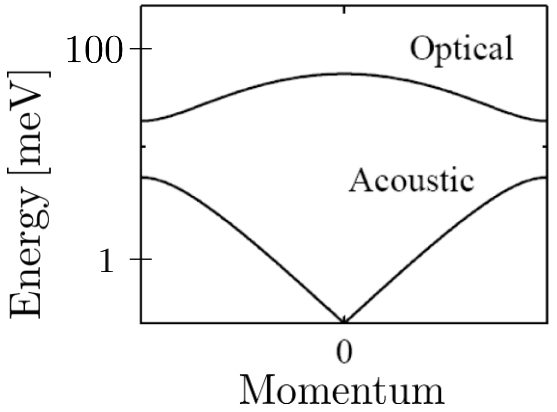
Outline


DM Mass
Threshold
GeV
keV
Electron Excitations
MeV
eV
Collective Excitations
keV
meV

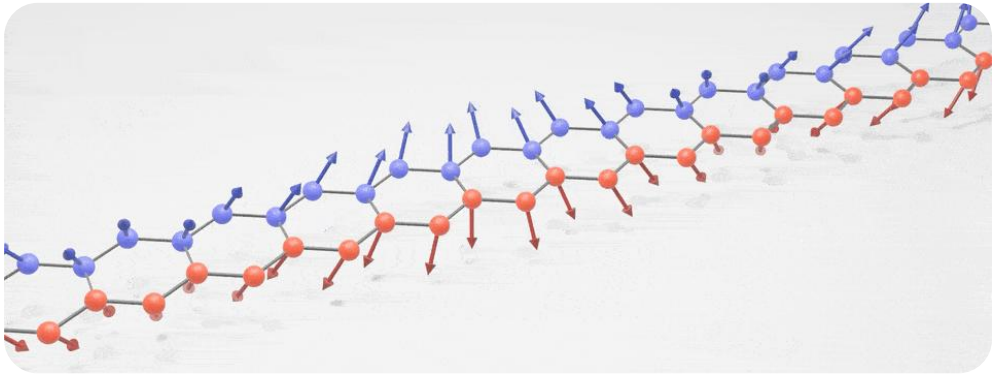
Collective Excitations

Phonons





Magnons



$$\omega \sim 1 - 100\,\mathrm{meV}$$

$$m_{\mathrm{DM}} \gtrsim 1\,\mathrm{keV}$$

Multi-Channel Direct Detection of Light Dark Matter: Target Comparison

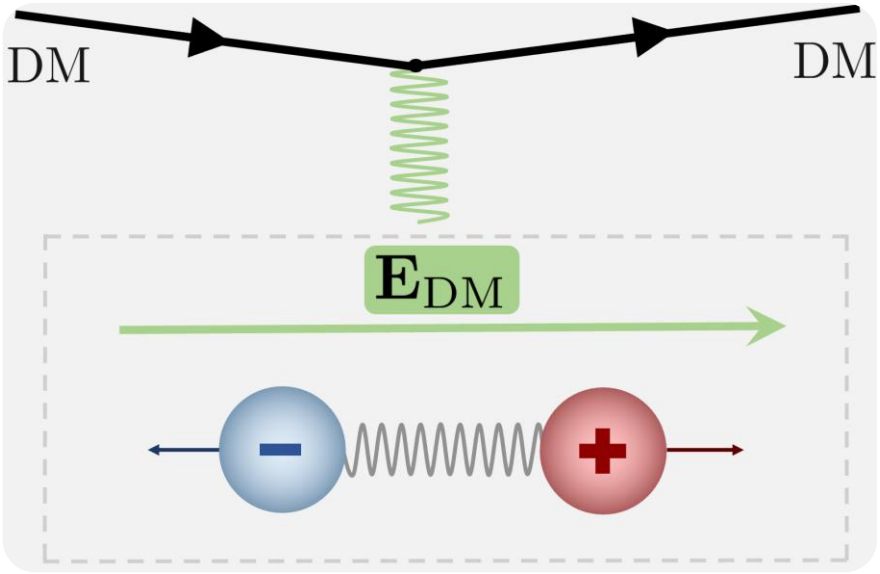
- **T. Trickle**, et. al., **PRD**

Detecting Light Dark Matter with Magnons

- **T. Trickle**, et. al., **PRL**

Dark Matter Interacting With Collective Excitations

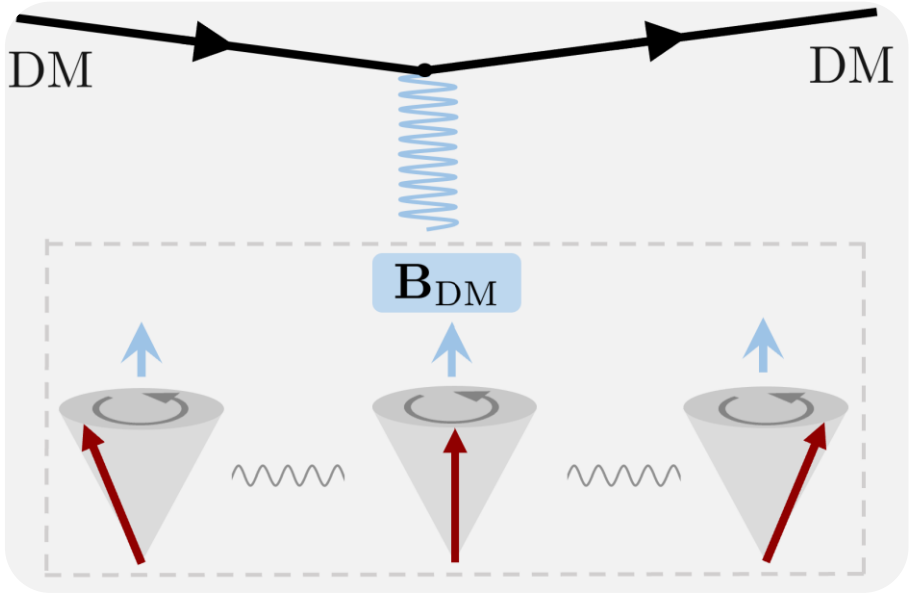
Phonons



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

"Spin-**independent** coupling"

Magnons



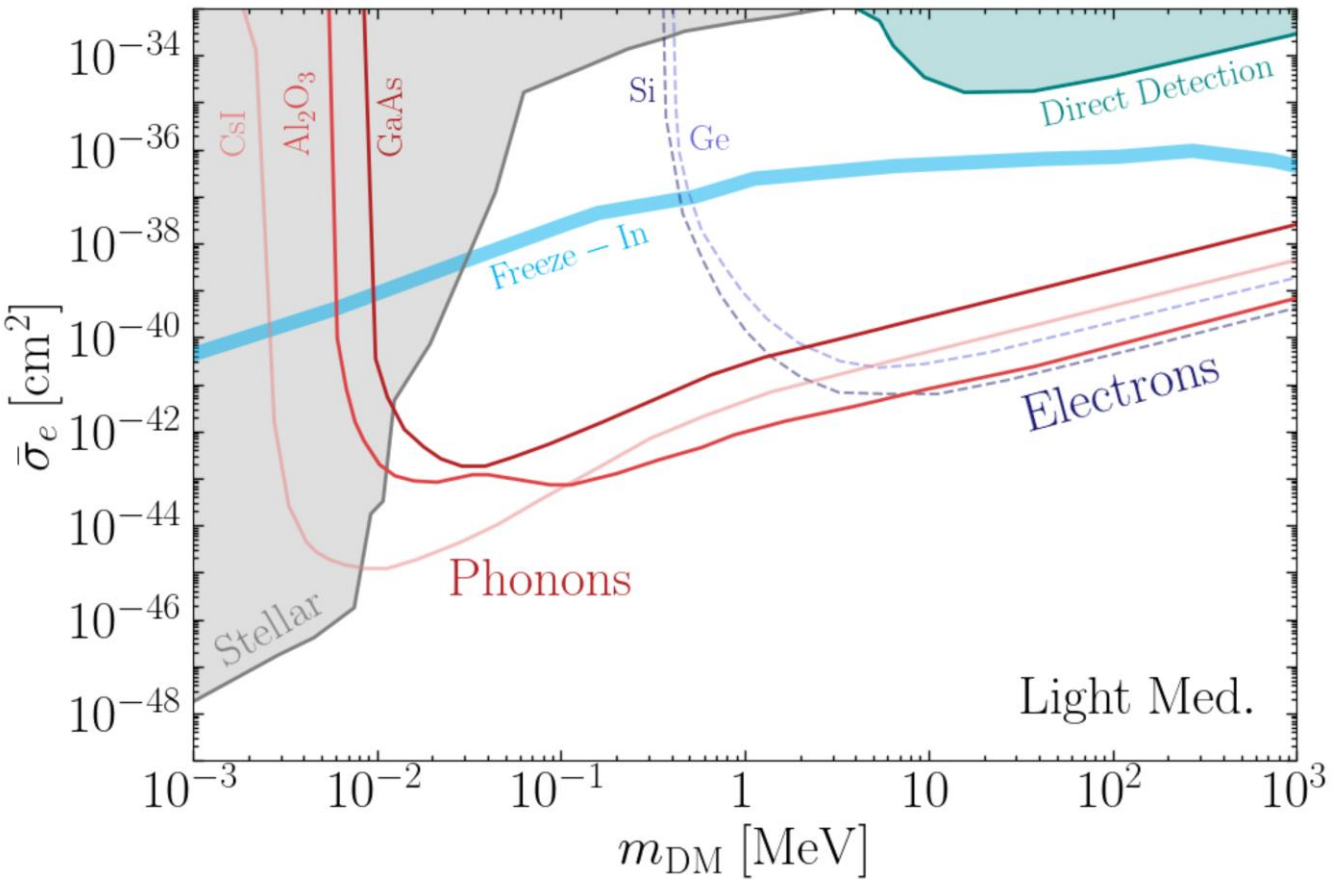
$$\mathcal{L} \supset g_\chi V_\mu \bar{\chi}\gamma^\mu\gamma^5\chi + g_e V_\mu \bar{e}\gamma^\mu\gamma^5 e$$

"Spin-**dependent** coupling"

Effective Field Theory of Dark Matter Direct Detection With Collective Excitations

- **T. Trickle**, et. al. **PRD**

Direct Detection with Phonons



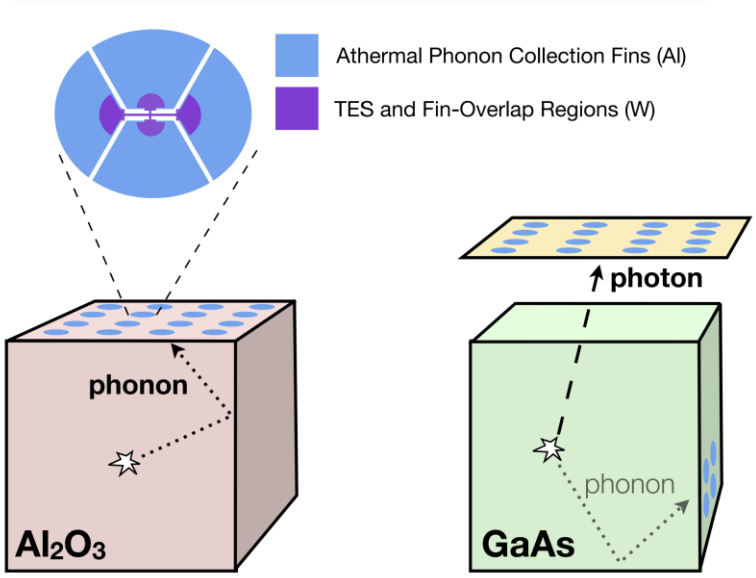
Multi-Channel Direct Detection of Light Dark Matter: Target Comparison [1910.10716]

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

Experiments sensitive to single phonon excitations will be powerful probes of light dark matter.

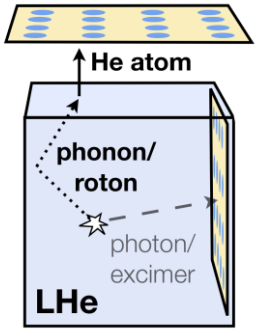
Single Phonon-Based Experiments

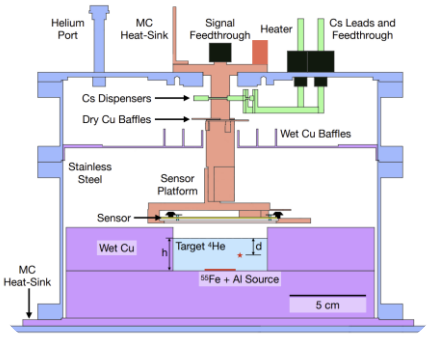
Funded



SPICE

Sub-eV **P**olar **I**nteractions **C**ryogenic **E**xperiment





HeRALD

Helium **R**oton **A**pparatus for **L**ight **D**ark Matter

Applying Superfluid Helium to Light Dark Matter Searches: Demonstration of the HeRALD Detector Concept [2307.11877]

Single Phonon Detection for Dark Matter via Quantum Evaporation and Sensing of Helium-3 [2201.00738]

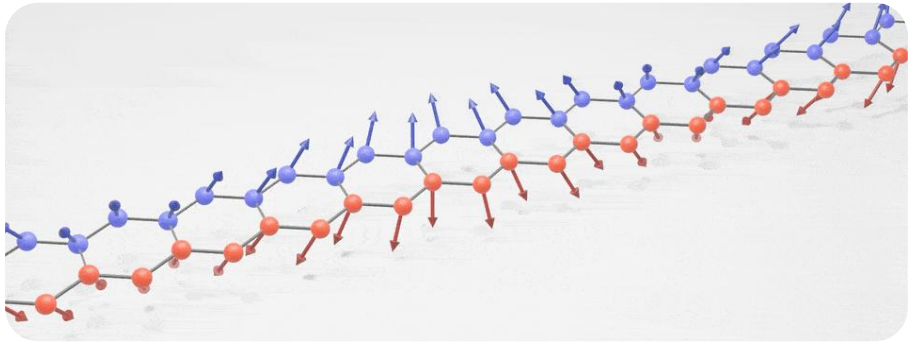
Proposed

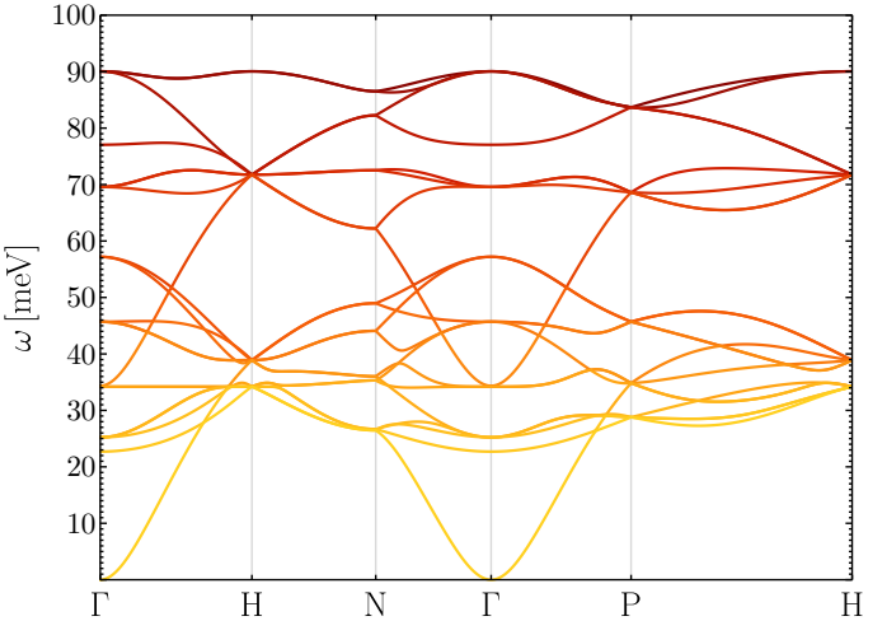
[2301.04778] Broad-Range Directional Detection of Light Dark Matter in Cryogenic Ice

Phys. Rev. Research 5, 043262 (2023) - Chiral phonons as dark matter detectors

Magnons

Collective spin excitations



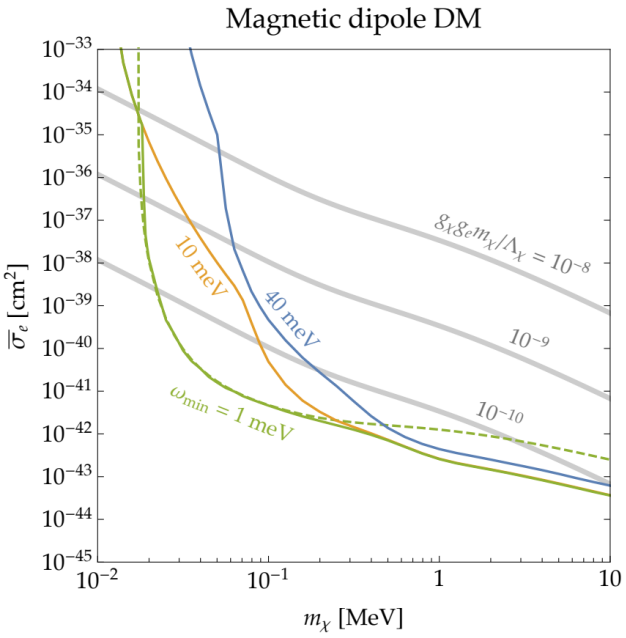


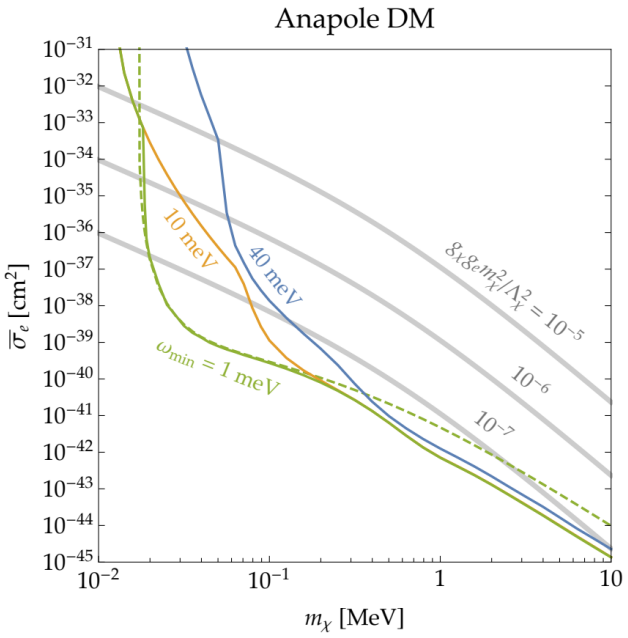
[1905.13744] Detecting Light Dark Matter with Magnons

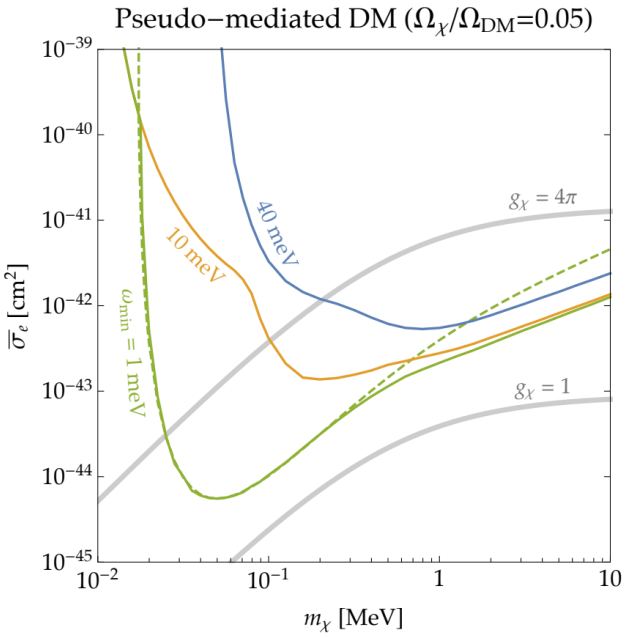
- **T. Trickle**, Zhang, Zurek

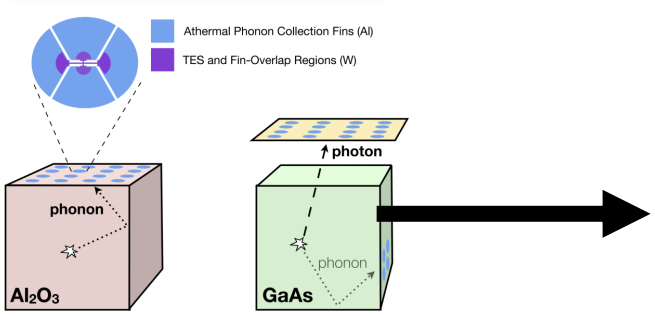
Sensitivity To Dark Matter Scattering

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

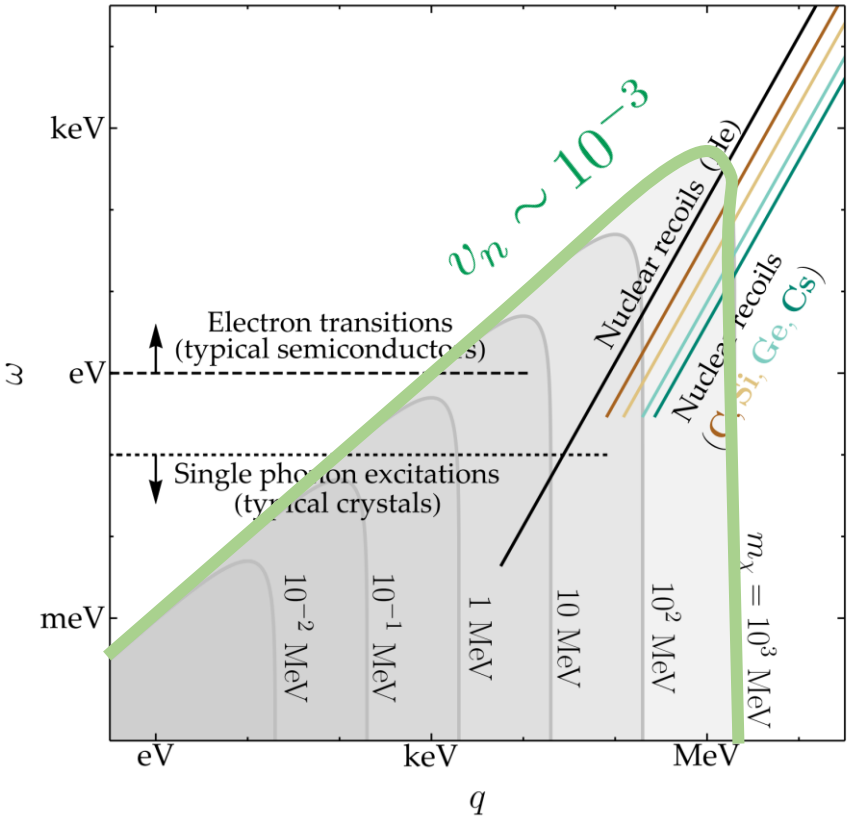
Data-Driven Understanding With Neutron Scattering

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

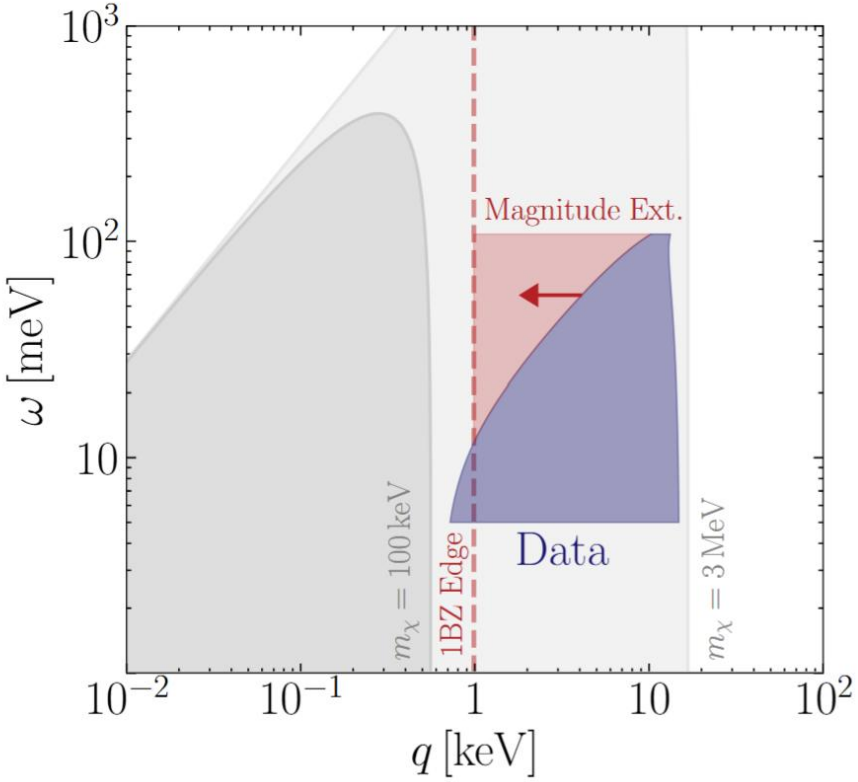
$$\mathcal{L} \supset \frac{g_\chi}{4m_\chi}\,\bar{\chi}\sigma^{\mu\nu}\chi\,F_{\mu\nu} + g_e A'_\mu\,\bar{e}\gamma^\mu e$$



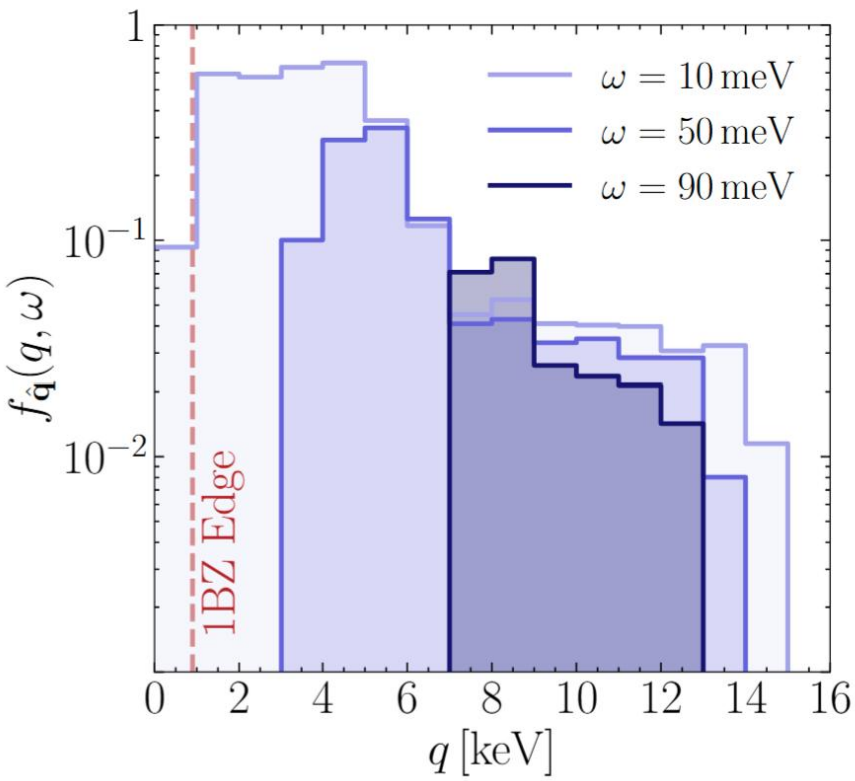
☑ Interaction structure

☑ Kinematics

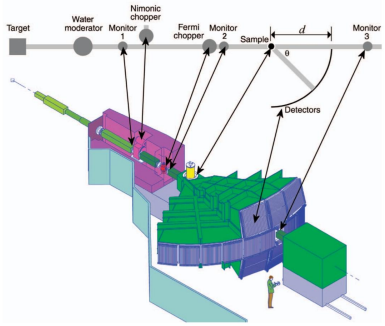
A Neutron Scattering Dataset



Kinematic coverage



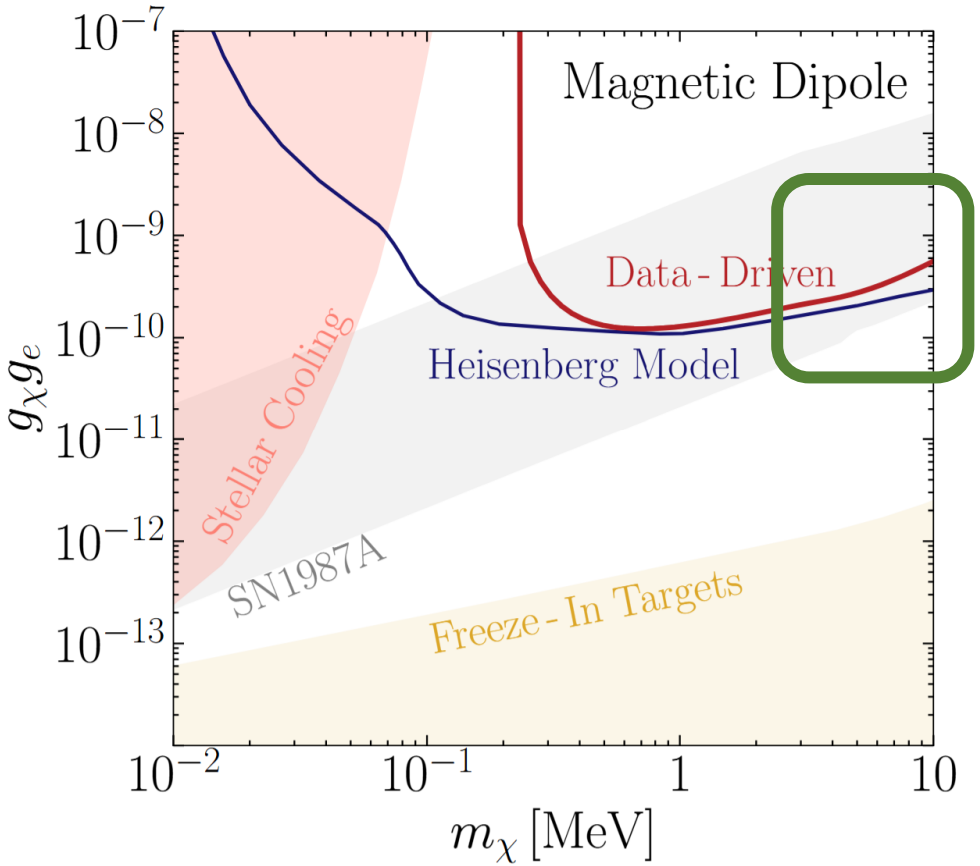
Angular coverage



The MAPS Spectrometer

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

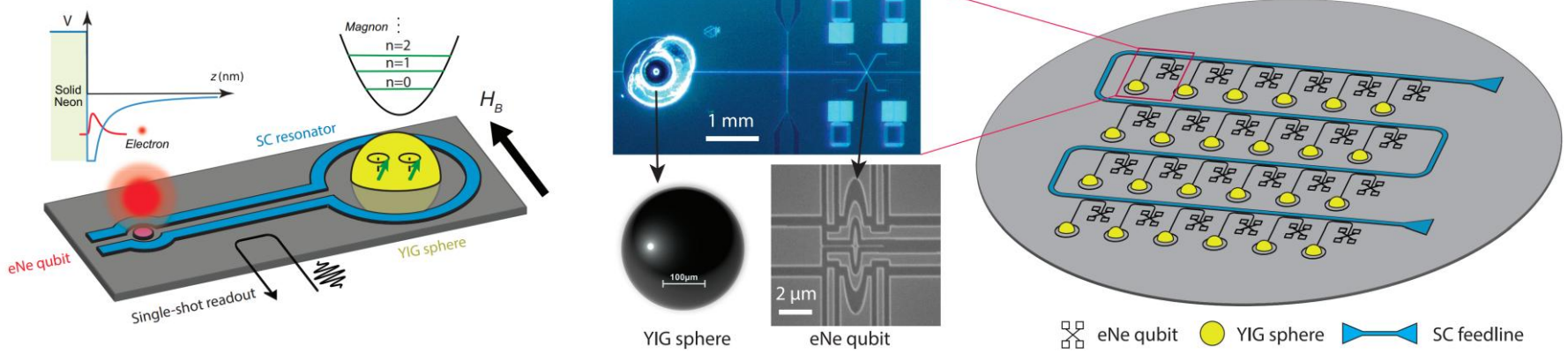
- Berlin, Millar, **T. Trickle**, Zhou

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)

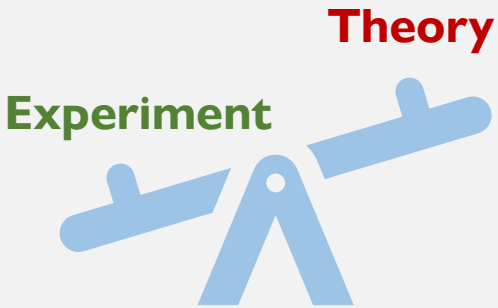


[2504.16160] MOSAIC: Magnonic Observations of Spin-dependent Axion-like InteraCtions

- Chang, Hobbs, Jin, Lisovenko, Novosad, Saleem, **T. Trickle**, Wang

Summary

Direct detection is searching for light dark matter with detectors at the interface of condensed matter and particle physics.

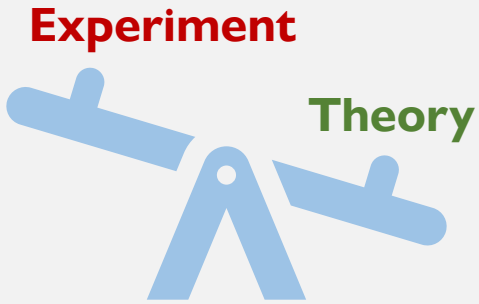


$\mathrm{MeV} \lesssim m_{\mathrm{DM}} \lesssim \mathrm{GeV}$

Recent DAMIC results constrain sub-GeV freeze-in dark matter for the first time.

What theories live below the freeze-in line?

How can we use effective field theories to understand the sensitivity of these experiments to *any* dark matter signal?



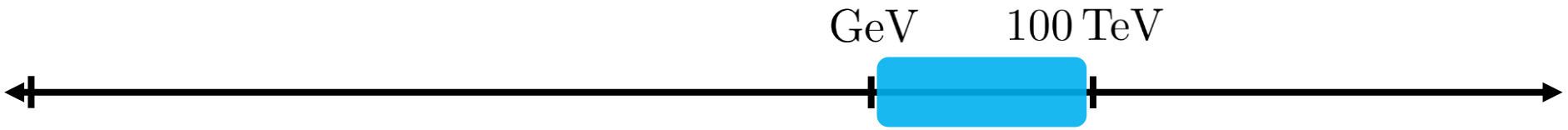
$\mathrm{keV} \lesssim m_{\mathrm{DM}} \lesssim \mathrm{MeV}$

Collective excitations will allow us to search for the lightest possible fermionic dark matter candidates.

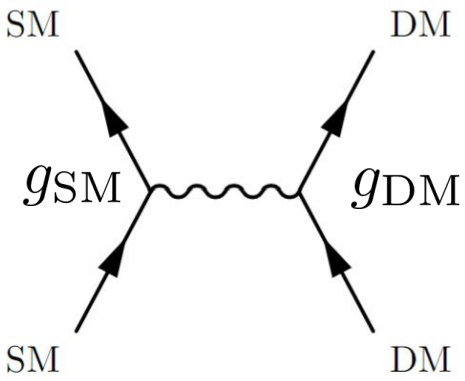
Thank you

The WIMP Paradigm

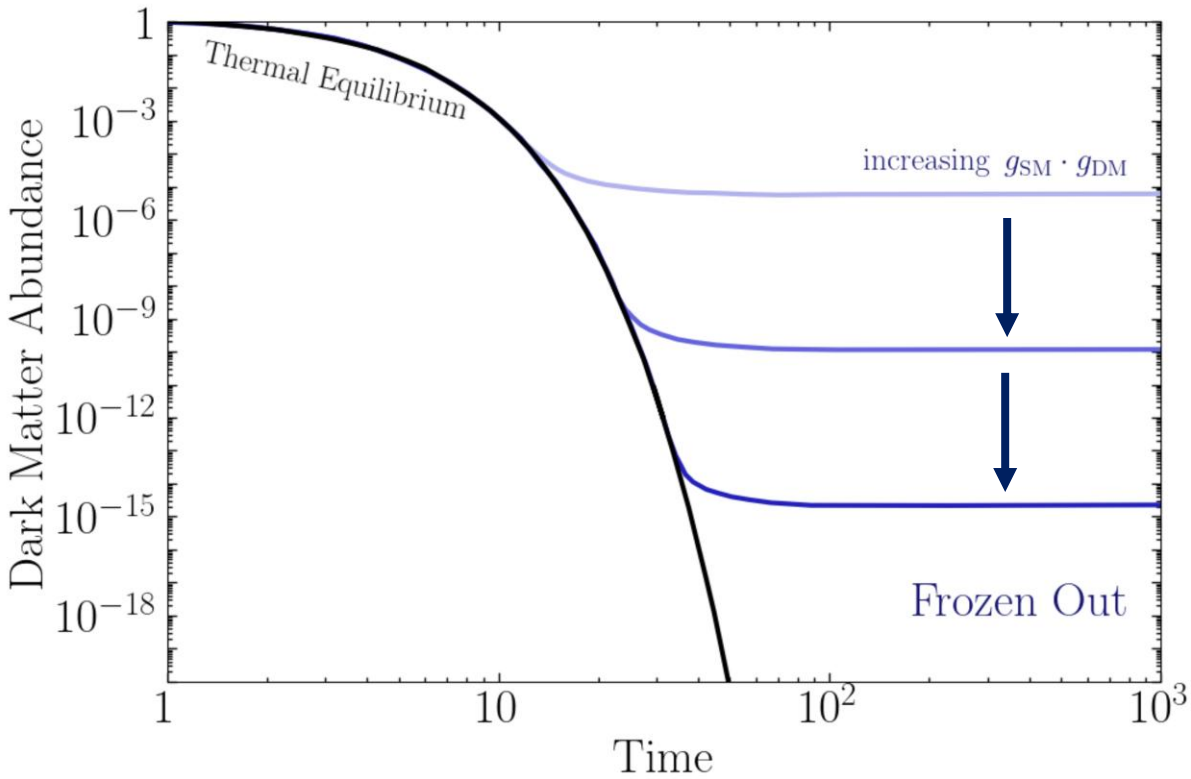
Dark Matter Mass



Weakly-Interacting Massive Particle (WIMP)



Freeze-out Production Mechanism

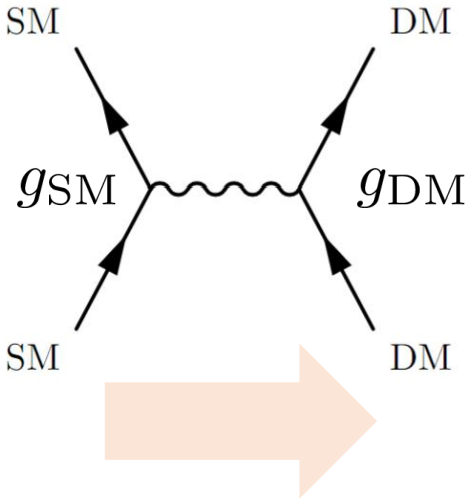


Kolb and Turner, *The Early Universe*

Why Search For Light Dark Matter?

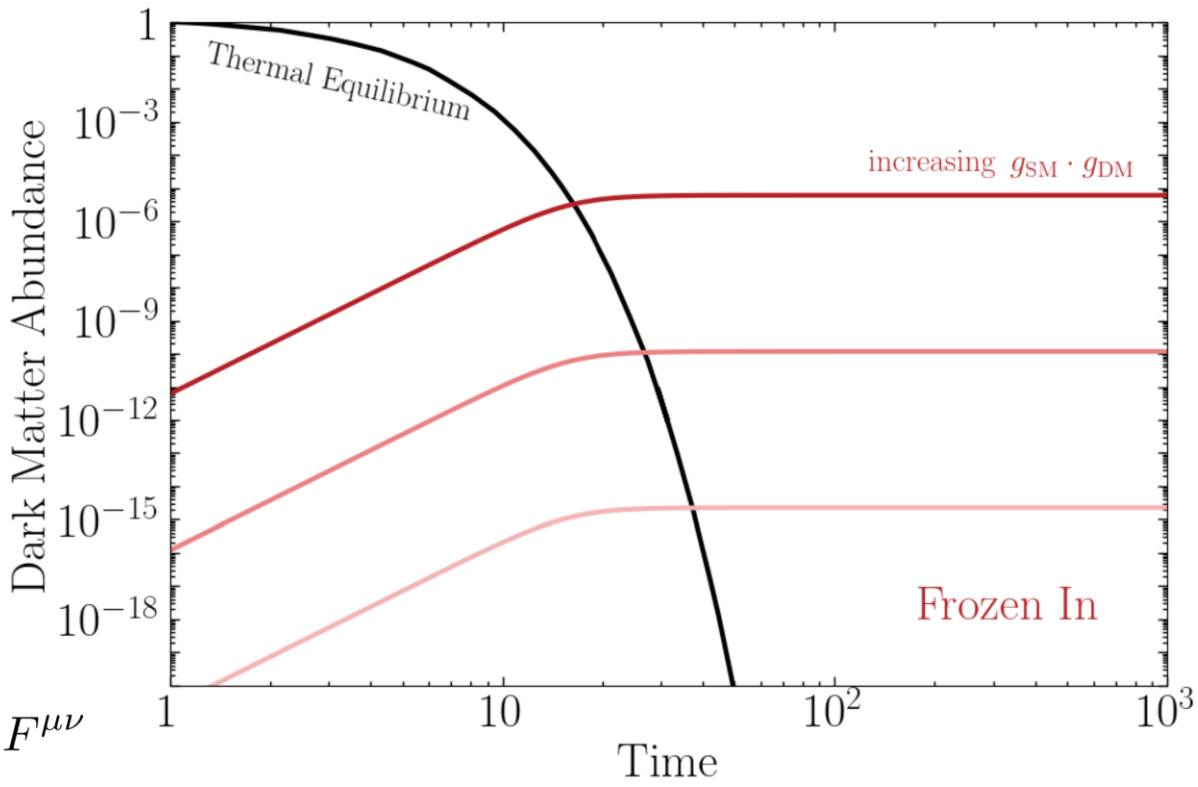
*Because there are **many** theoretically well-motivated dark matter models outside of WIMPs.*

For example,



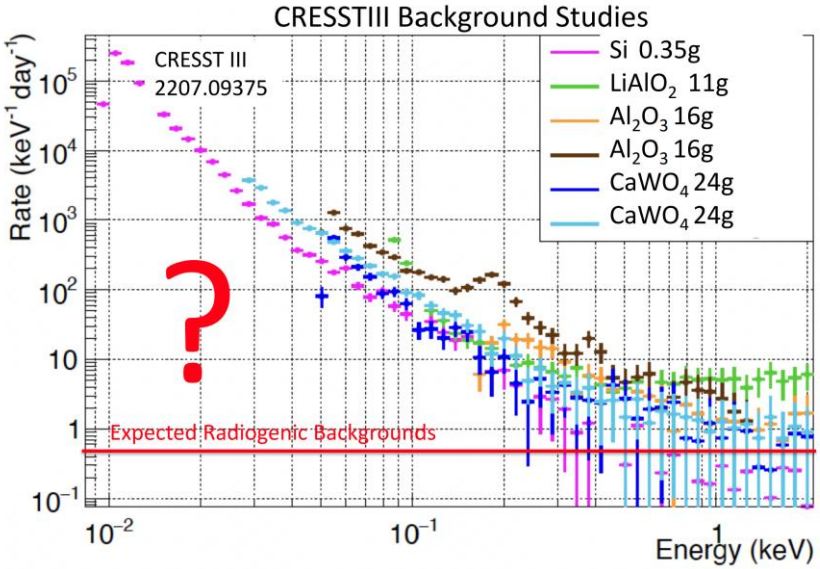
$$\mathcal{L} \supset \bar{\chi}\left(i\not{\partial}' - m_{\rm DM}\right)\chi + \kappa\, F'_{\mu\nu}F^{\mu\nu}$$

Freeze-in Production



Recent review: [2401.03025] Dark Matter Candidates of a Very Low Mass

Current Challenge: Low-Energy Excess



Matt Pyle, *The 10th LCTP Spring Symposium: Hunting For Particle Dark Matter*

[2202.05097] EXCESS workshop: Descriptions of rising low-energy spectra

Previous Editions:

EXCESS21

EXCESS22

EXCESS22@IDM

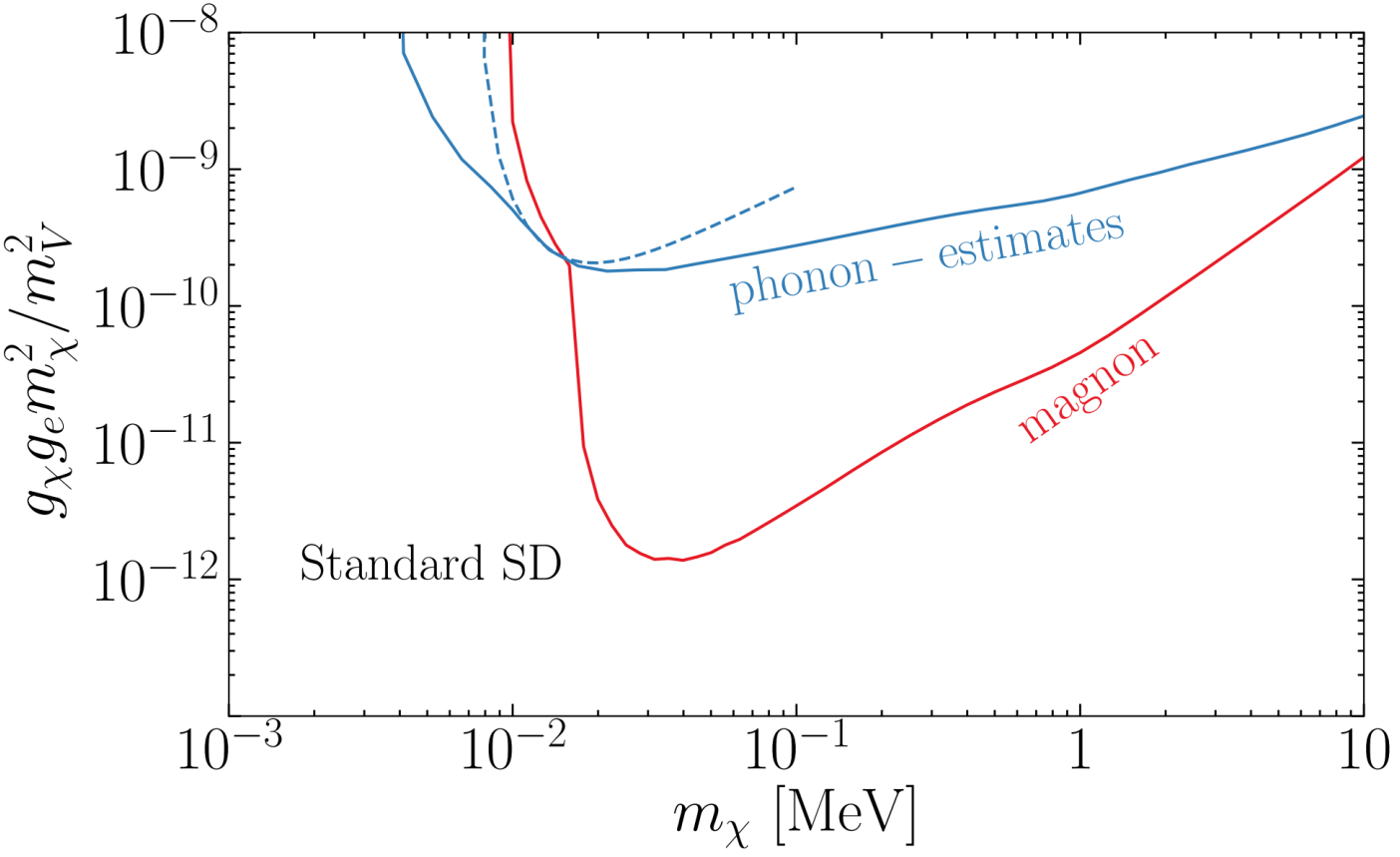
EXCESS23@TAUP

Mitigation strategies:

- Removing stress induced phonons
- Background discrimination techniques

SD Dominance of Magnon Scattering

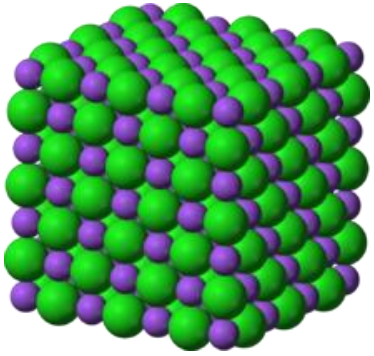
$$\mathcal{L} \supset g_\chi V_\mu \bar{\chi}\gamma^\mu\gamma^5\chi + g_e V_\mu \bar{e}\gamma^\mu\gamma^5 e$$



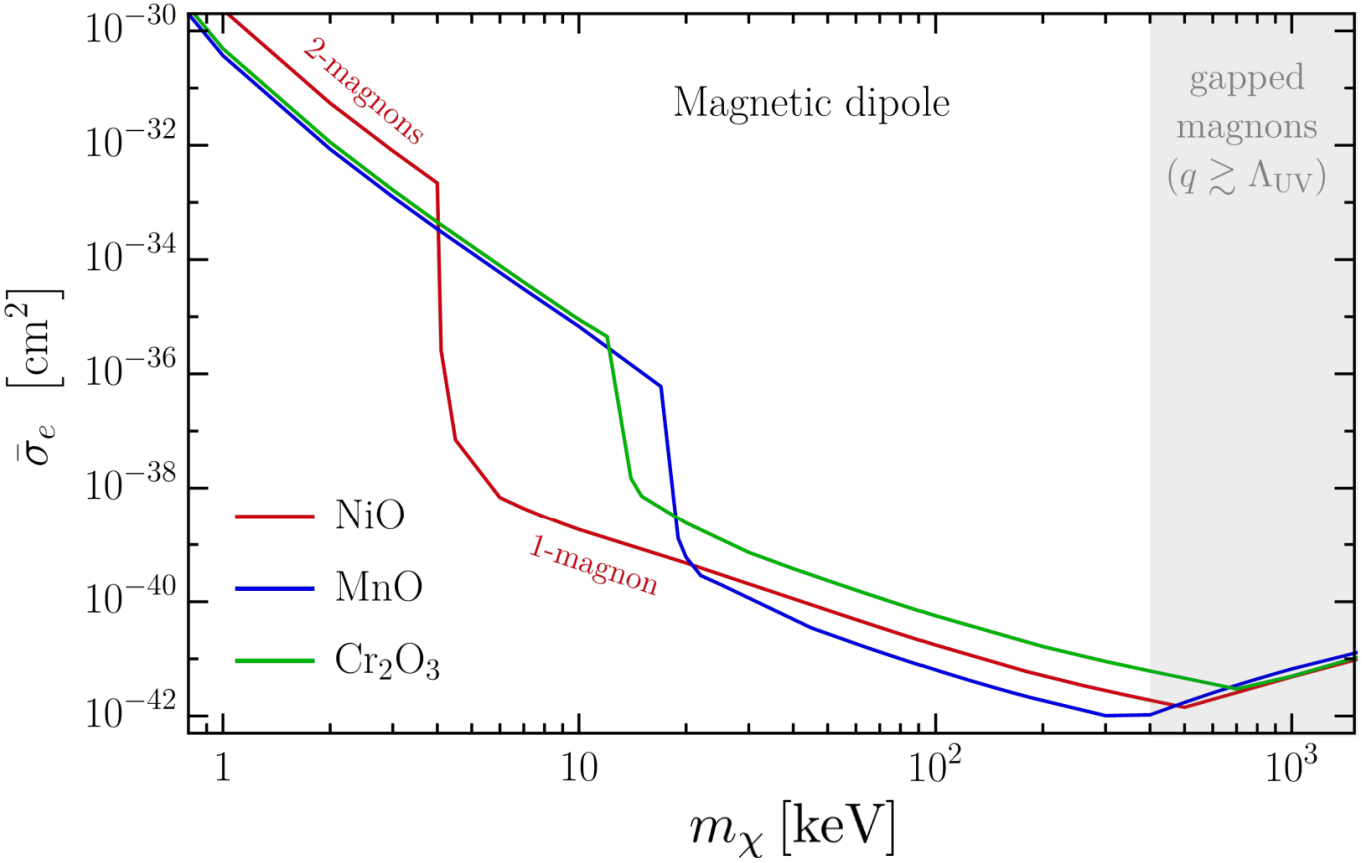
[2009.13534] Effective Field Theory of Dark Matter Direct Detection With Collective Excitations

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

Sensitivity To Dark Matter Scattering

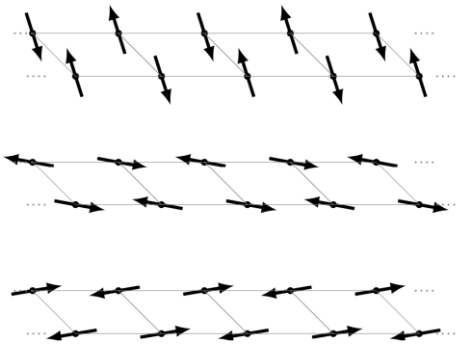


NiO



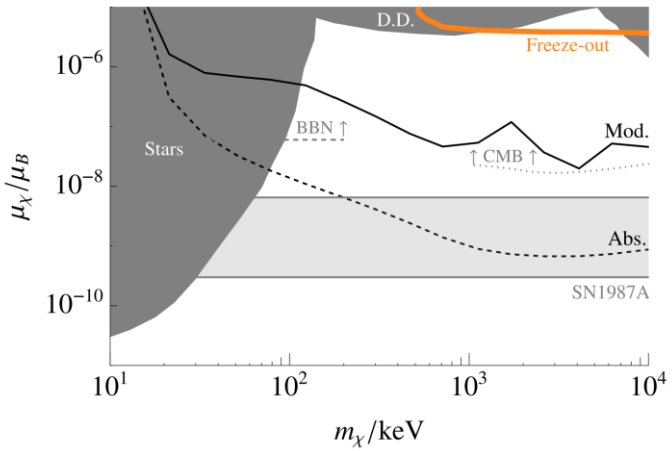
[2210.13516] Optimal anti-ferromagnets for light dark matter detection

Sensitivity To Dark Matter Scattering

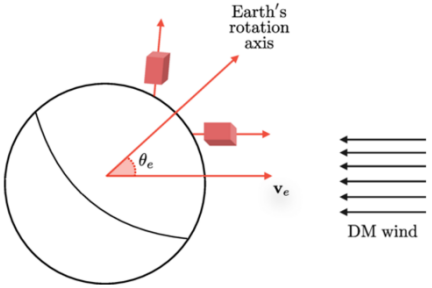


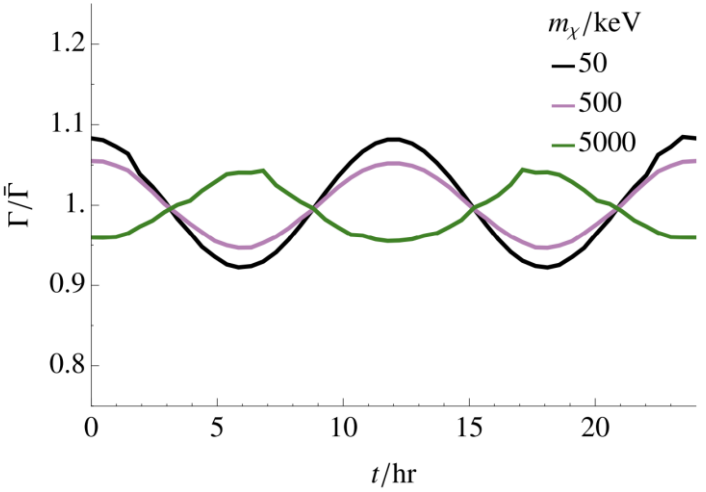
Quasi-2D material

Sensitivity



Daily modulation effects





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

Relationship With The Dynamic Structure Factor

Neutron scattering differential cross section

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

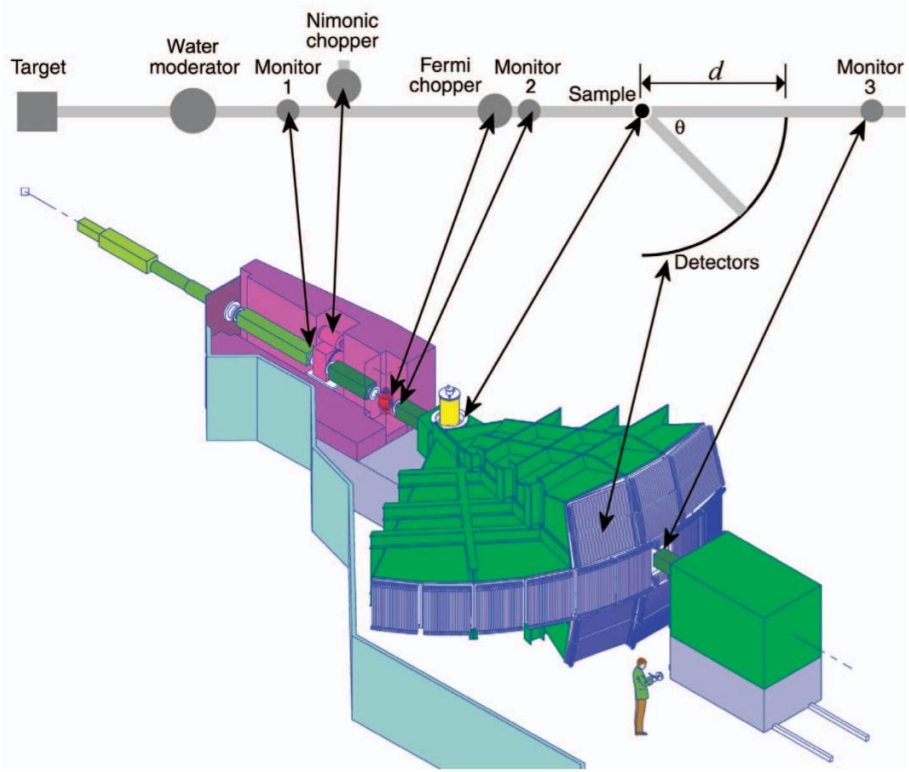
Measurable

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

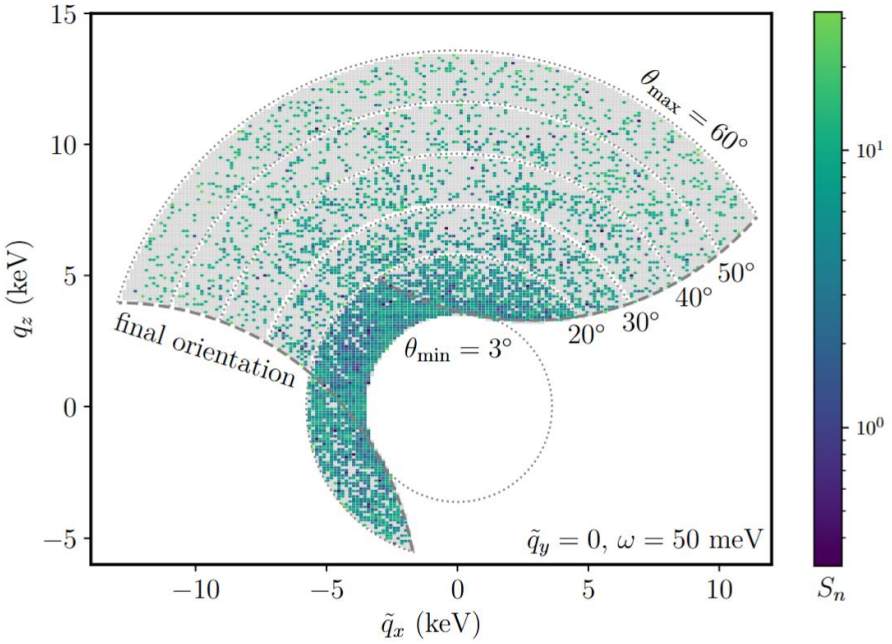
Kinematics

Magnetic dipole dark matter model scattering rate

A Neutron Scattering Dataset



The MAPS Spectrometer



A 2D slice of the data

ISIS Neutron and Muon Source

Recasting Other Dark Matter Models

Alternative reparameterization of general scattering rate

$$\Gamma_{\rm s}(\mathbf{v}) = \int \frac{{\rm d}^3\mathbf{q}}{(2\pi)^3}\, \mathcal{F}^{ij}(\mathbf{q},\omega_{\mathbf{q}})\, \chi''_{ij}(\mathbf{q},\omega_{\mathbf{q}})$$

Magnetic susceptibility

Model	Lagrangian	form factor $\mathcal{F}^{ij}$
Magnetic dipole DM	$\frac{g_\chi}{4\,m_\chi}\,\bar\Psi_\chi\sigma^{\mu\nu}\Psi_\chi\,F'_{\mu\nu} + g_e\,\bar\Psi_e\gamma^\mu\Psi_e A'_\mu$	$2\left(\frac{g_\chi g_e}{\lvert\mathbf{q}\rvert^2+m_{\rm med}^2}\right)^2\left(\frac{\lvert\mathbf{q}\rvert^2}{4\,m_\chi m_e}\right)^2(\delta^{ij}-\hat{\mathbf{q}}^i\hat{\mathbf{q}}^j)$
Anapole DM	$\frac{g_\chi}{4\,m_\chi^2}\,\bar\Psi_\chi\gamma^\mu\gamma^5\Psi_\chi\,\partial^\nu F'_{\mu\nu} + g_e\,\bar\Psi_e\gamma^\mu\Psi_e A'_\mu$	$2\left(\frac{g_\chi g_e}{\lvert\mathbf{q}\rvert^2+m_{\rm med}^2}\right)^2\left(\frac{\lvert\mathbf{q}\rvert^3}{8\,m_\chi^2 m_e}\right)^2(\delta^{ij}-\hat{\mathbf{q}}^i\hat{\mathbf{q}}^j)$
Axial vector mediator V_μ	$V_\mu\,(g_\chi\,\bar\Psi_\chi\gamma^\mu\gamma^5\Psi_\chi + g_e\,\bar\Psi_e\gamma^\mu\gamma^5\Psi_e)$	$2\left(\frac{g_\chi g_e}{\lvert\mathbf{q}\rvert^2+m_{\rm med}^2}\right)^2\delta^{ij}$
Pseudoscalar mediator ϕ	$\phi\,(g_\chi\,\bar\Psi_\chi i\gamma^5\Psi_\chi + g_e\,\bar\Psi_e i\gamma^5\Psi_e)$	$2\left(\frac{g_\chi g_e}{\lvert\mathbf{q}\rvert^2+m_{\rm med}^2}\right)^2\left(\frac{\lvert\mathbf{q}\rvert^2}{4\,m_\chi m_e}\right)^2\hat{\mathbf{q}}^i\hat{\mathbf{q}}^j$
CP violating scalar mediator ϕ	$\phi\,(g_\chi\,\bar\Psi_\chi\Psi_\chi + g_e\,\bar\Psi_e i\gamma^5\Psi_e)$	$2\left(\frac{g_\chi g_e}{\lvert\mathbf{q}\rvert^2+m_{\rm med}^2}\right)^2\left(\frac{\lvert\mathbf{q}\rvert}{2\,m_e}\right)^2\hat{\mathbf{q}}^i\hat{\mathbf{q}}^j$
Dark electron EDM	$g_\chi\,\bar\Psi_\chi\gamma^\mu\Psi_\chi A'_\mu + \frac{g_e}{4\,m_e}\,i\bar\Psi_e\sigma^{\mu\nu}\gamma^5\Psi_e\,F'_{\mu\nu}$	$2\left(\frac{g_\chi g_e}{\lvert\mathbf{q}\rvert^2+m_{\rm med}^2}\right)^2\left(\frac{\lvert\mathbf{q}\rvert}{2\,m_e}\right)^2\hat{\mathbf{q}}^i\hat{\mathbf{q}}^j$

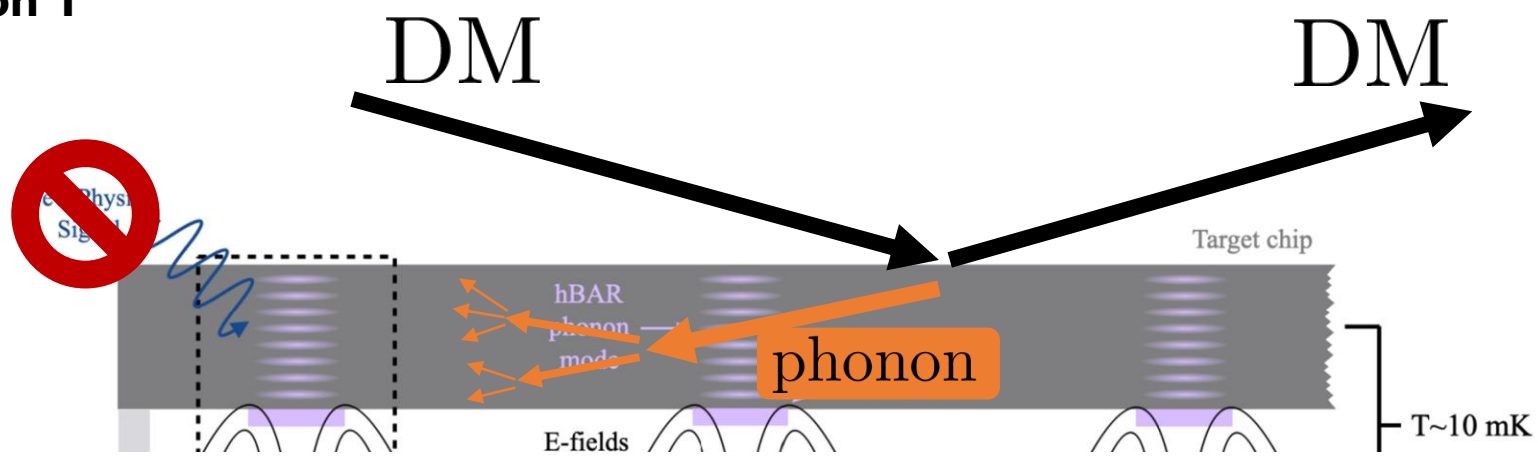
Generally, not all components of susceptibility available to neutron scattering.

$$S_n(\mathbf{q},\omega) = \frac{1}{N_{\rm f}}\frac{\gamma_n^2 e^4}{8\,m_e^2}\frac{\Omega_c}{(2\pi)^3}\,P_T^{ij}\,\chi''_{ij}(\mathbf{q},\omega_{\mathbf{q}})$$

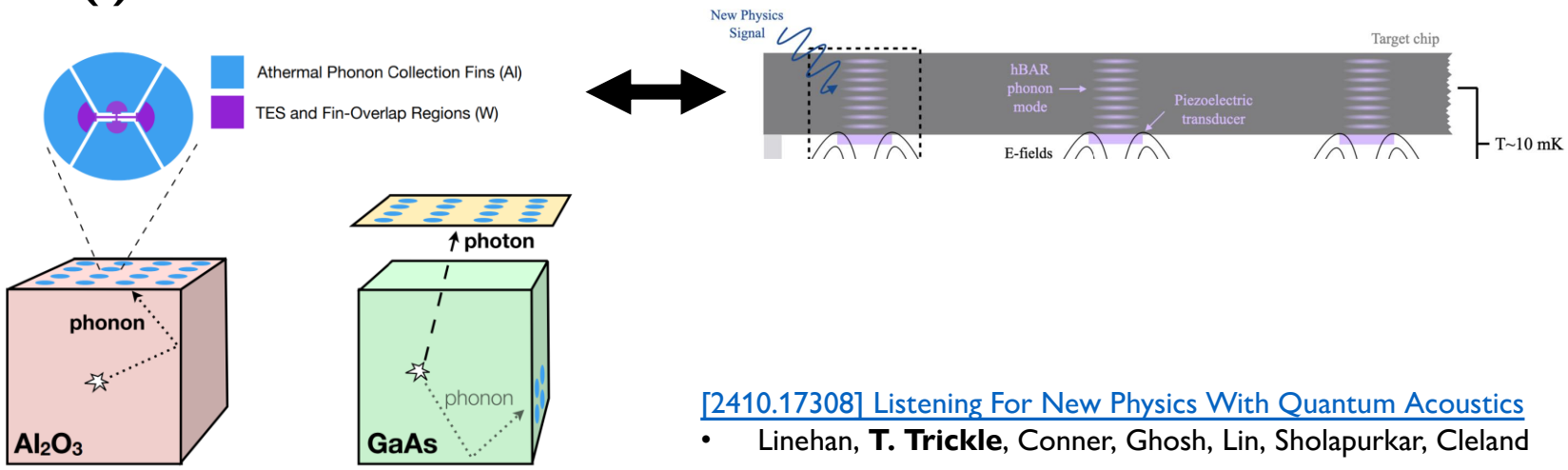
Components can be related with target specific information about susceptibility tensor structure

Down-Conversion Detection

Option 1



Option 2 (?)

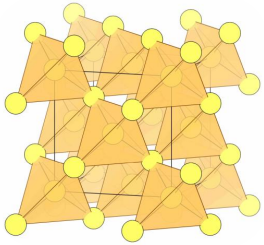


[2410.17308] Listening For New Physics With Quantum Acoustics

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

Many Other Target Ideas Using Electrons

Other Semiconductors/Dielectrics



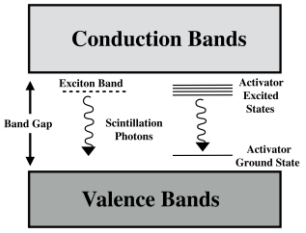
SNOWMASS21-CF1_CF2-IF1_IF8-120.pdf (TESSARACT: GaAs, Sapphire)

[2101.08275] Dark matter-electron scattering in dielectrics

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

[2008.08560] SiC Detectors for Sub-GeV Dark Matter

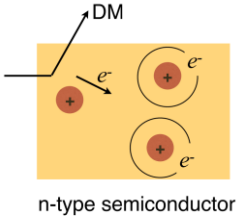
Scintillators



[1607.01009] Direct Detection of sub-GeV Dark Matter with Scintillating Targets

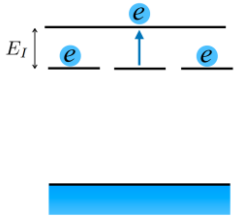
[2402.01395] Dark Matter-Electron Scattering Search Using Cryogenic Light Detectors

Doped Semiconductors



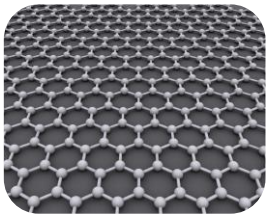
[2212.04504] Doped Semiconductor Devices for sub-MeV Dark Matter Detection

Low Band Gap (~meV) Targets



[1909.09170] Directional Dark Matter Detection in Anisotropic Dirac Materials

[2202.11716] Dark Matter Direct Detection in Materials with Spin-Orbit Coupling



Organic Aromatics

[1912.02822] Dark Matter-Electron Scattering from Aromatic Organic Targets