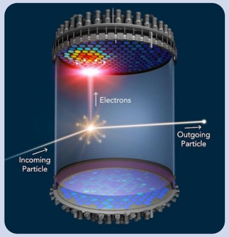
Theory Of Direct Detection For The Next Generation

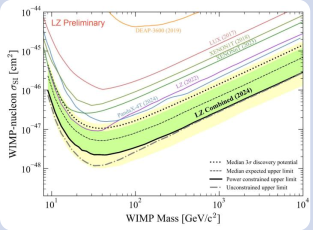
Tanner Trickle

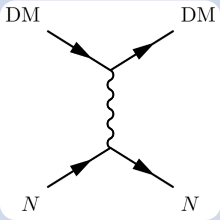
Dark Interactions Workshop – October 16th, 2024

Outline

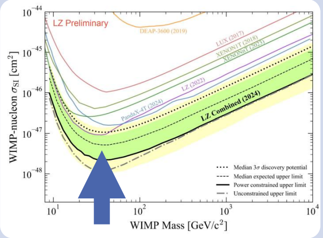
- **Background**

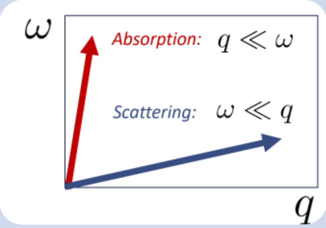


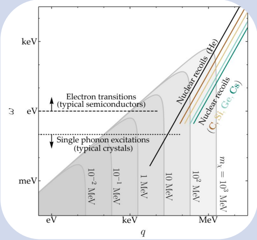




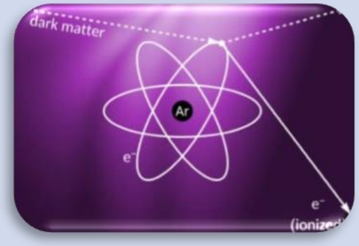
- **Kinematics**

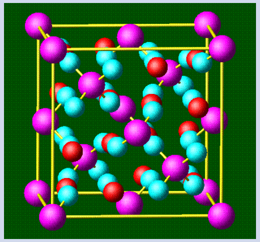


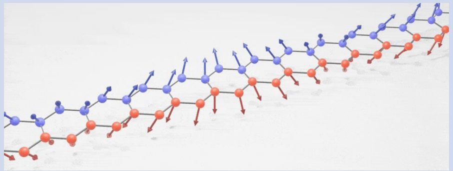




- **Target Excitations**







- **Effective Field Theory**

$$\delta\mathcal{L}_{\rm UV} \longrightarrow \delta\mathcal{L}_{\rm NR} \longrightarrow \text{Observables}$$

UV/High-Energy ($E \gg m_e$) Theory NR/Low-Energy ($E \ll m_e$) Theory

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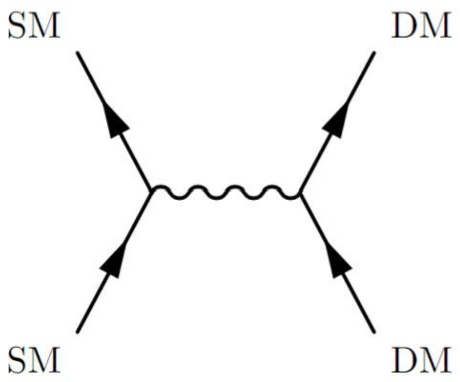
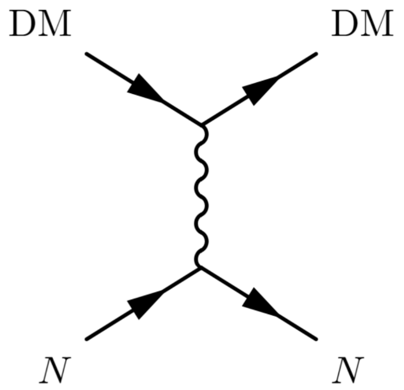
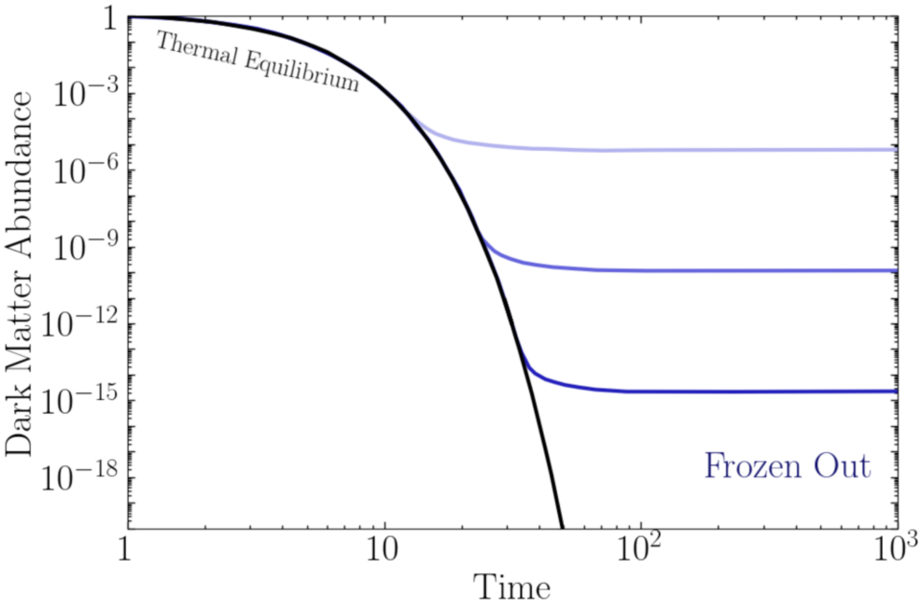
Classic Nuclear Recoil Direct Detection

Production

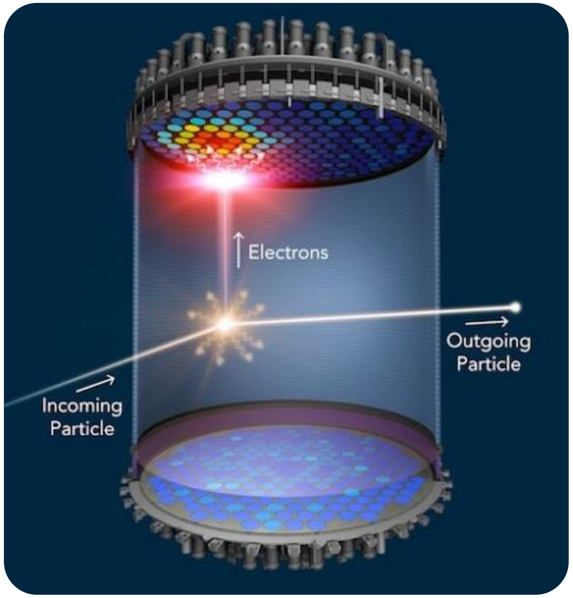


Detection





Thermal Freeze-Out



LZ Detector

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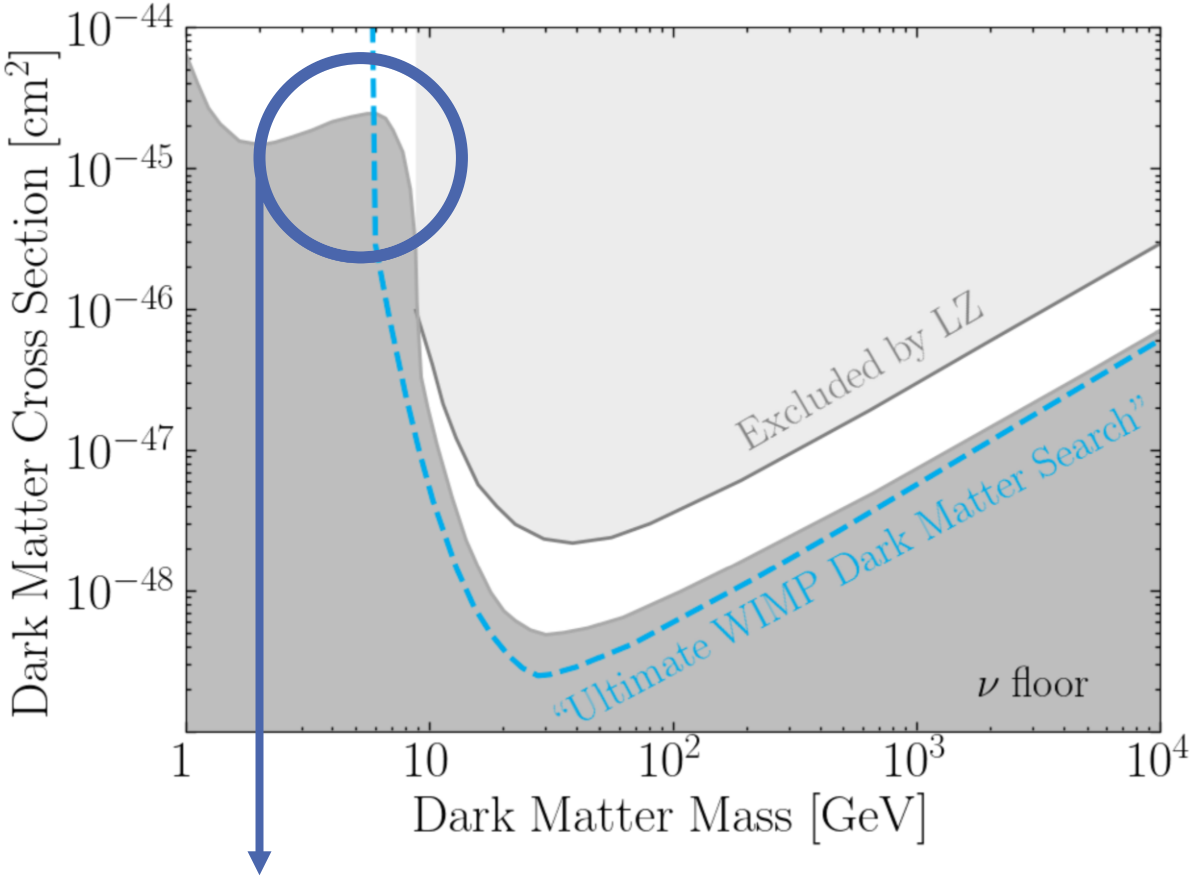
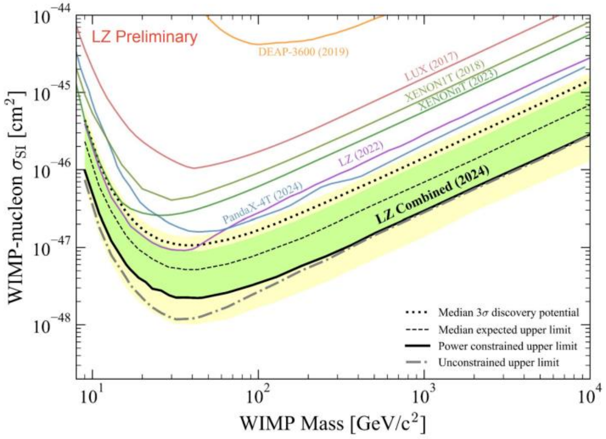
NR Detectors Approaching Neutrino Floor





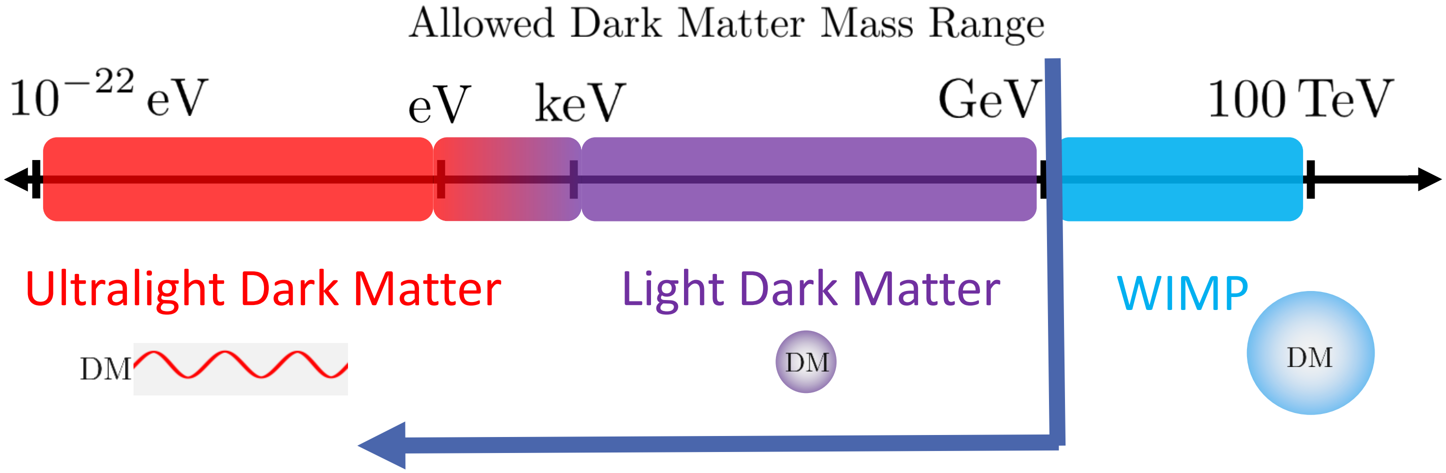
LZ Results TeVPA 2024

XENONnT

[2408.02877] First Measurement of Solar ^{8}B Neutrinos via Coherent Elastic Neutrino-Nucleus Scattering with XENONnT

[2409.17868] First Search for Light Dark Matter in the Neutrino Fog with XENONnT

Direct Detection Of Light Dark Matter

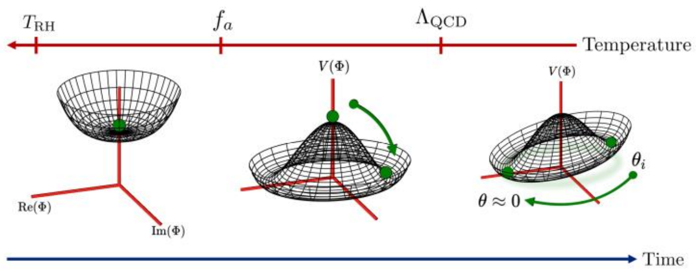


Ultralight Dark Matter

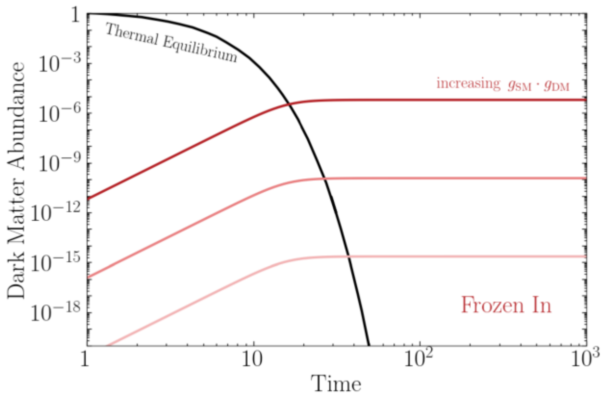
Light Dark Matter

WIMP

Production



Misalignment Mechanism



Thermal Freeze-In

- *Modified Freeze-Out*
  - *SIMP*
  - *ELDER*
- *Asymmetric DM*
- *Inflationary Production*

⋮

How do we search for sub-GeV mass dark matter?

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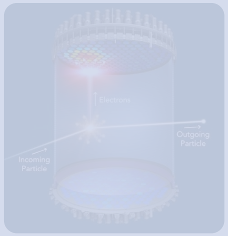
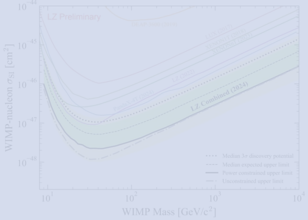
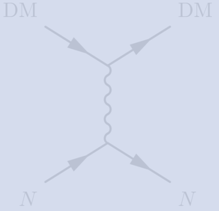
Outline

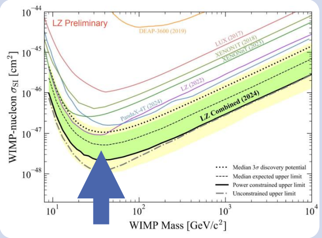
- Background

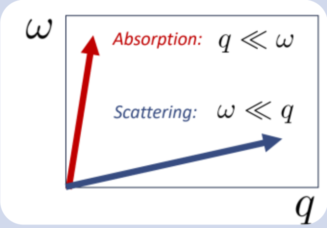


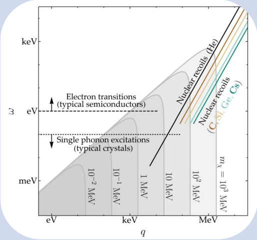




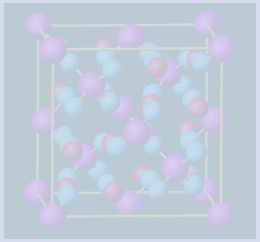
- **Kinematics**

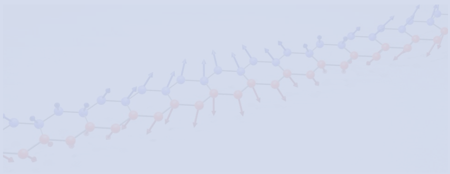






- Target Excitations





- Effective Field Theory

$$\delta\mathcal{L}_{\rm UV} \longrightarrow \delta\mathcal{L}_{\rm NR} \longrightarrow \text{Observables}$$

UV/High-Energy ($E \gg m_e$) Theory   NR/Low-Energy ($E \ll m_e$) Theory

Scattering Kinematics: Nuclear Recoil

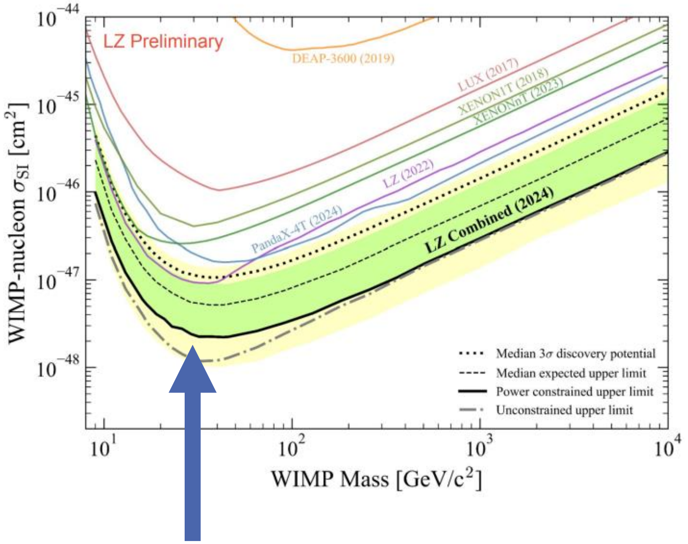
1D Billard Ball Mechanics

Energy conservation

$$\frac{1}{2}m_{\rm DM}v^2 = \frac{1}{2}m_{\rm DM}v'^2 + \frac{1}{2}m_N v_N^2$$

Momentum conservation

$$m_{\rm DM}v = m_{\rm DM}v' + m_N v_N$$



$$m_{\rm DM} \sim m_N$$

$$\text{Energy Deposited} = \begin{cases} 2m_N\, v^2 \sim \text{keV} & m_{\rm DM} \gg m_N \\ \dfrac{2m_{\rm DM}^2}{m_N}\, v^2 \sim \left(\dfrac{m_{\rm DM}}{m_N}\right)^2 \times \text{keV} & m_{\rm DM} \ll m_N \end{cases}$$

A solution: Lighter nuclei, still limited to $m_N \sim \text{GeV}$

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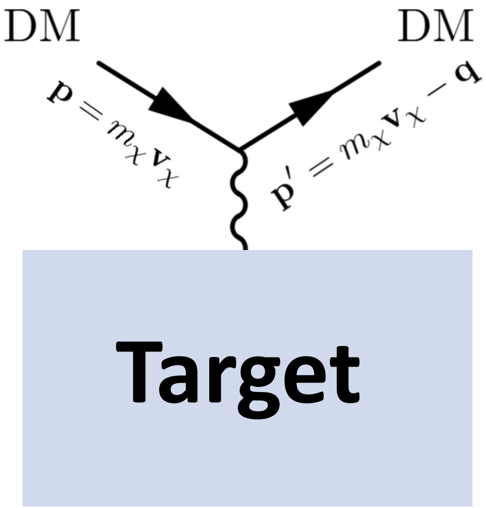
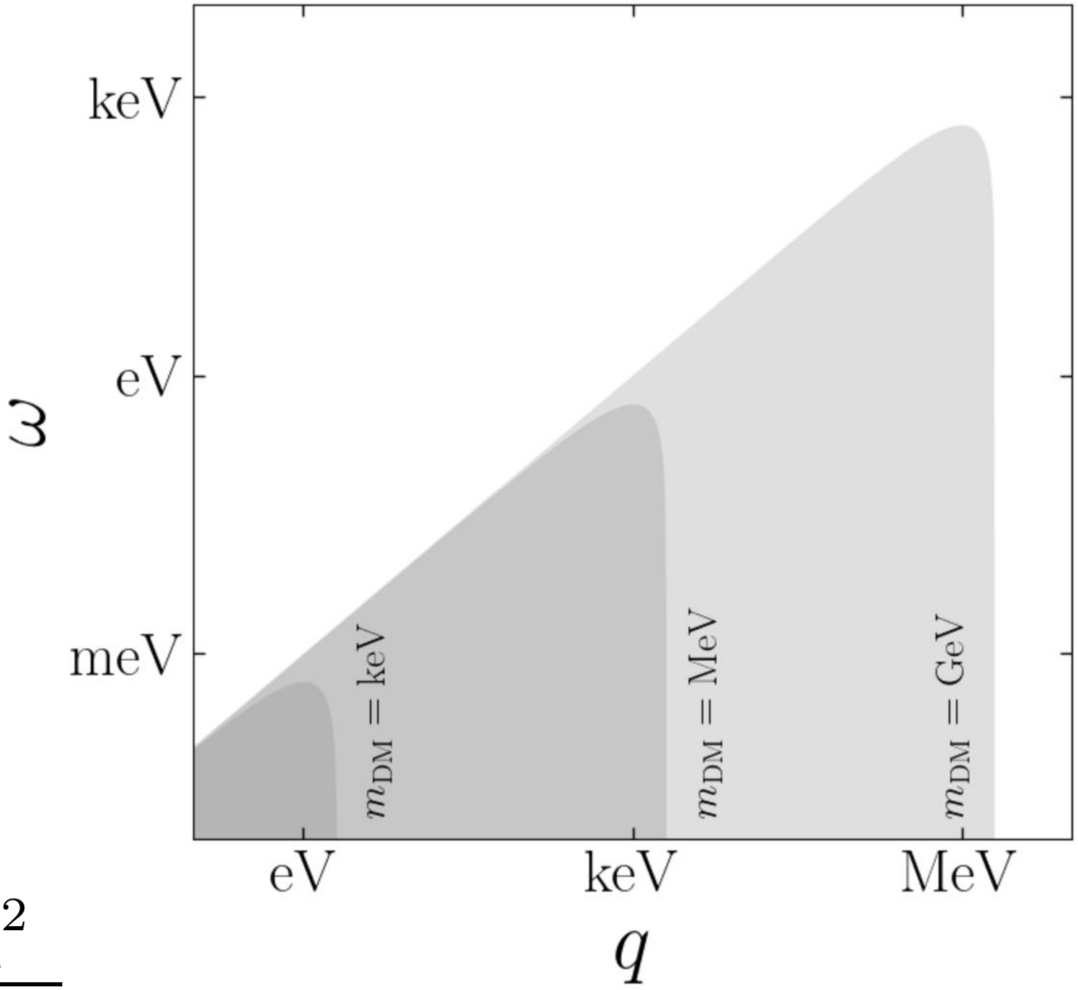
Scattering Kinematics



$$E_i = \frac{1}{2} m_\chi \mathbf{v}_\chi^2$$

$$E_f = \frac{1}{2m_\chi} (m_\chi \mathbf{v}_\chi - \mathbf{q})^2$$

$$E_i - E_f = \omega = \mathbf{q} \cdot \mathbf{v}_\chi - \frac{\mathbf{q}^2}{2m_\chi}$$



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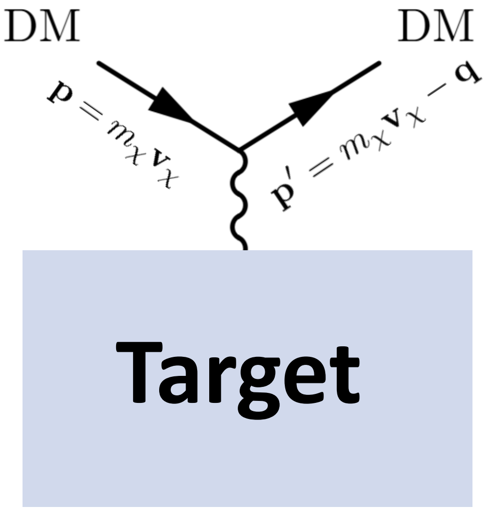
Scattering Kinematics



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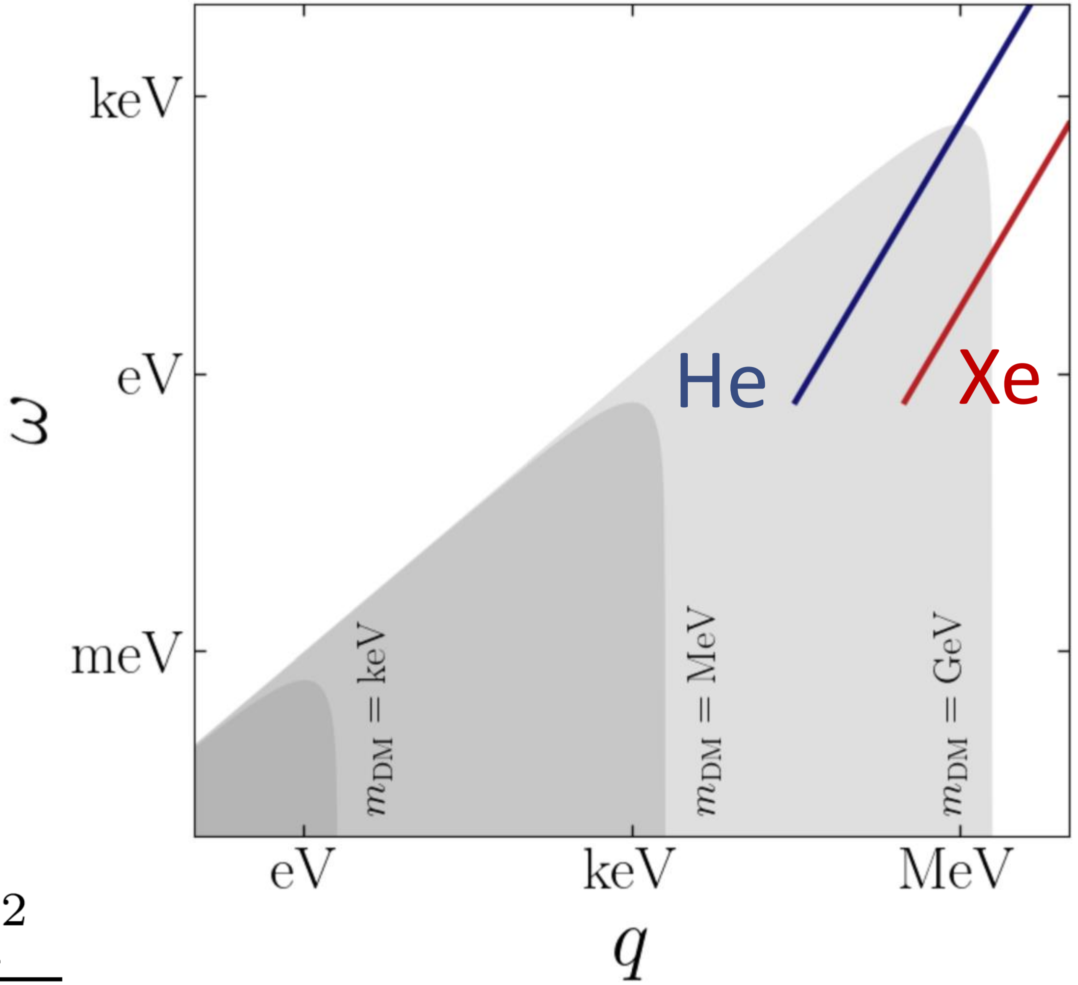
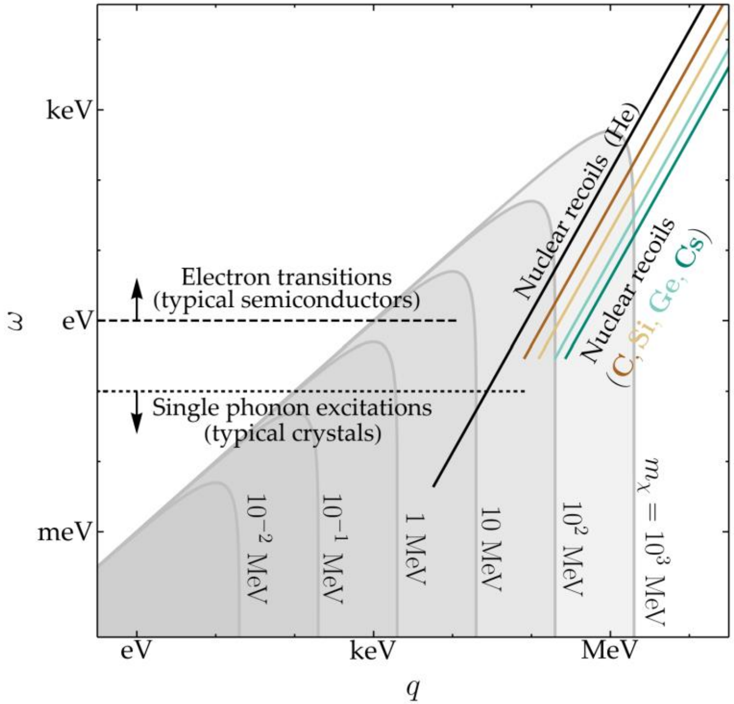


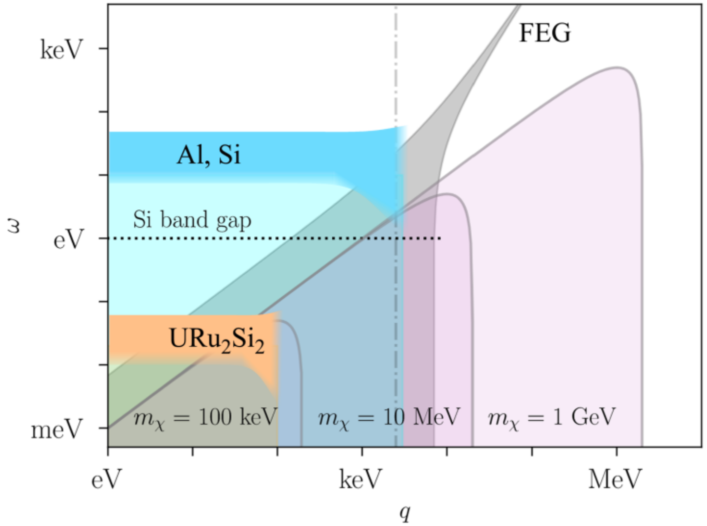
Scattering Kinematics



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

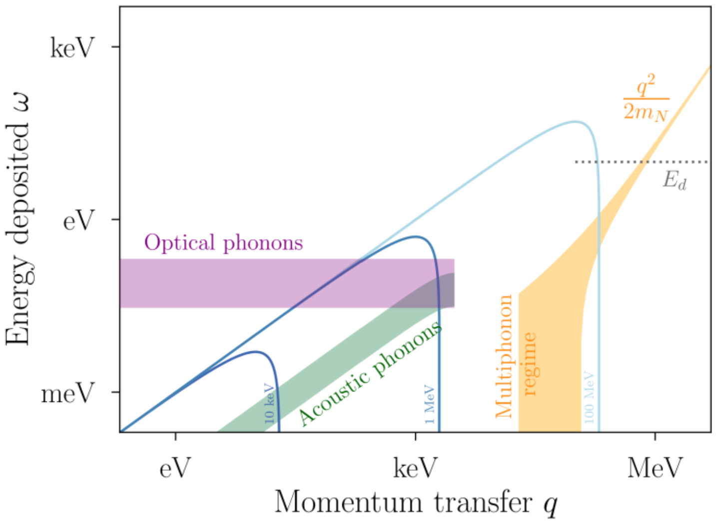
- **T. Trickle**, Z. Zhang, K. Zurek, K. Inzani, S. Griffin

Electrons



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

Phonons



[2108.03239] Searches for light dark matter using condensed matter systems

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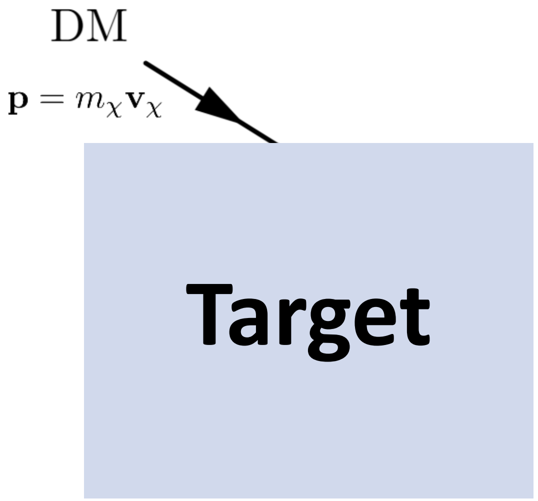
Absorption Kinematics



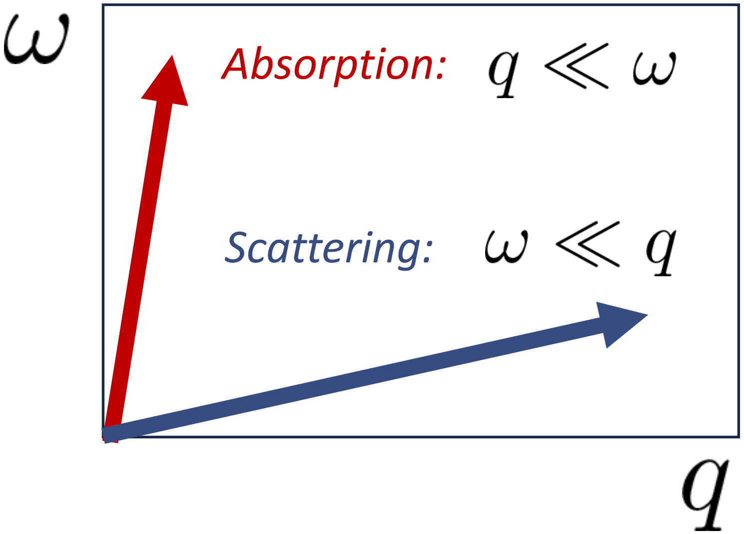
DM

$\mathbf{p} = m_\chi \mathbf{v}_\chi$

Target

$$\omega \approx m_{\mathrm{DM}}$$

$$|\mathbf{q}| < 2 m_{\mathrm{DM}} v$$



ω

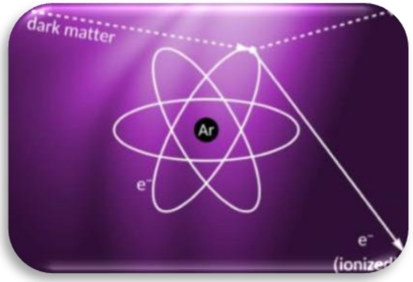
Absorption: $q \ll \omega$

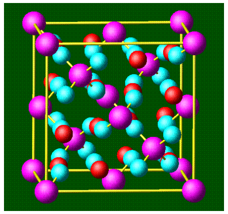
Scattering: $\omega \ll q$

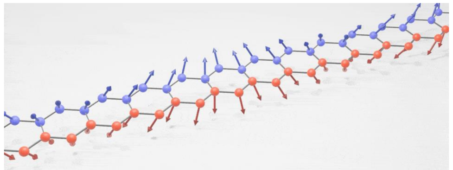
q

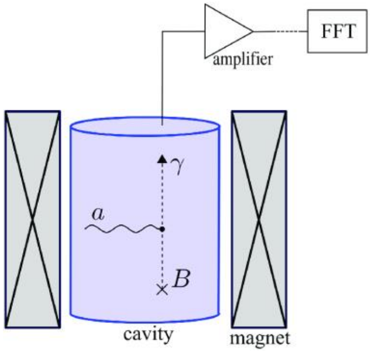
Energy eV meV μeV

GHz









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Outline

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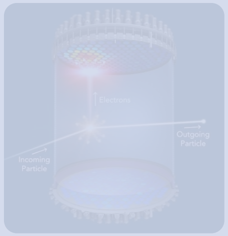
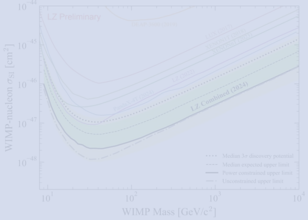
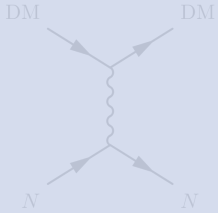
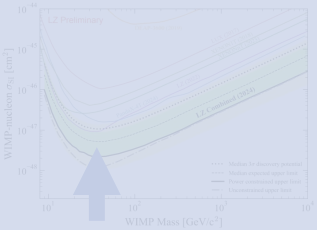
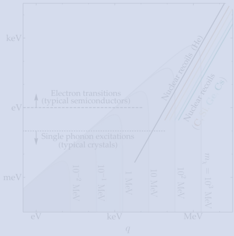






- Kinematics





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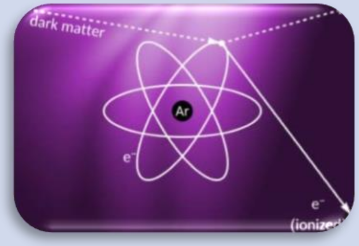

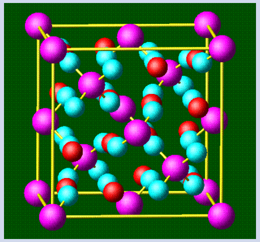

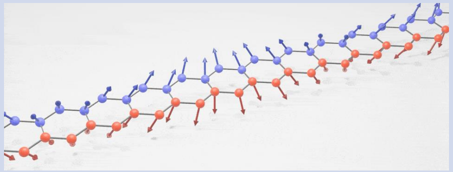

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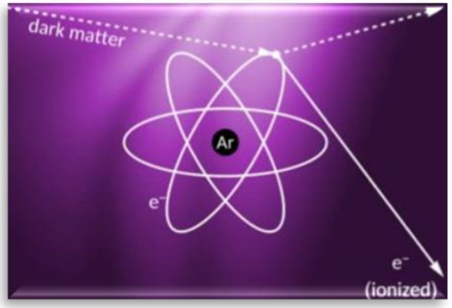
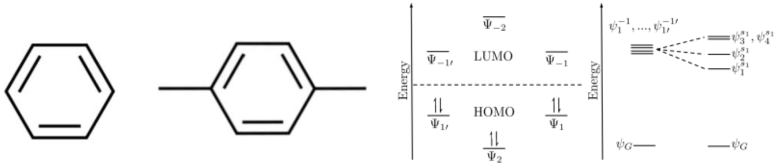
UV/High-Energy ($E \gg m_e$) Theory   NR/Low-Energy ($E \ll m_e$) Theory

Electrons

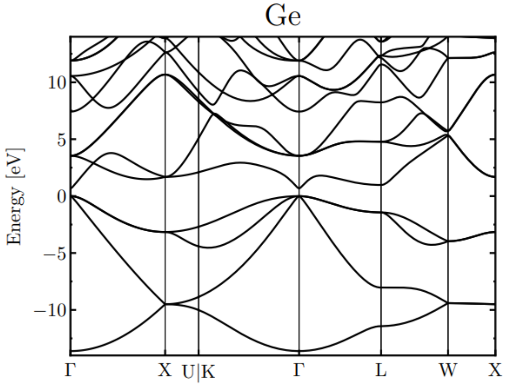
Atomic Targets

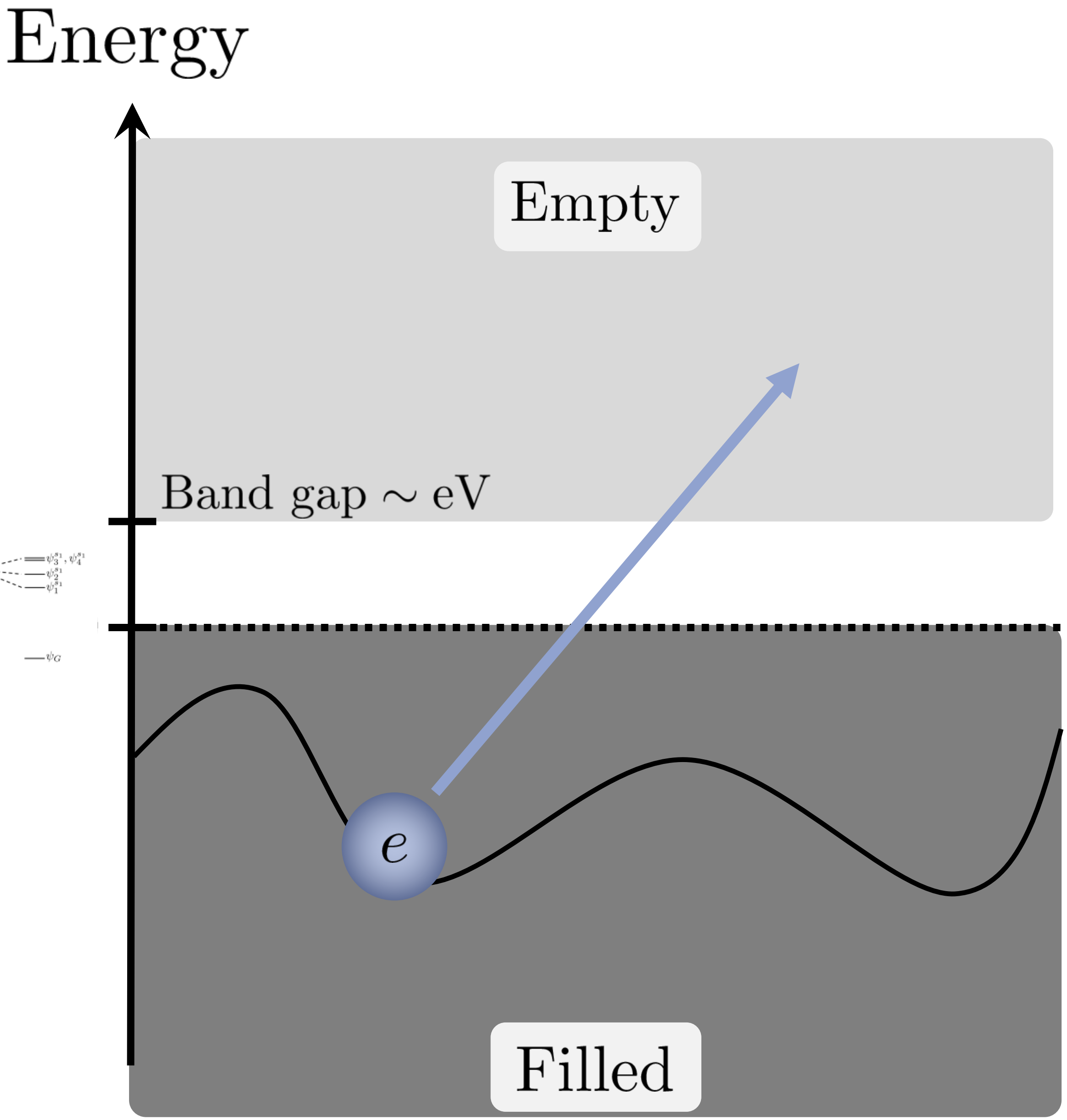


Molecular Targets

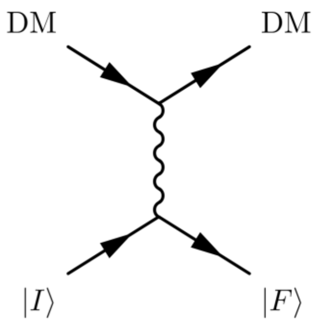


Semiconductor/Crystals

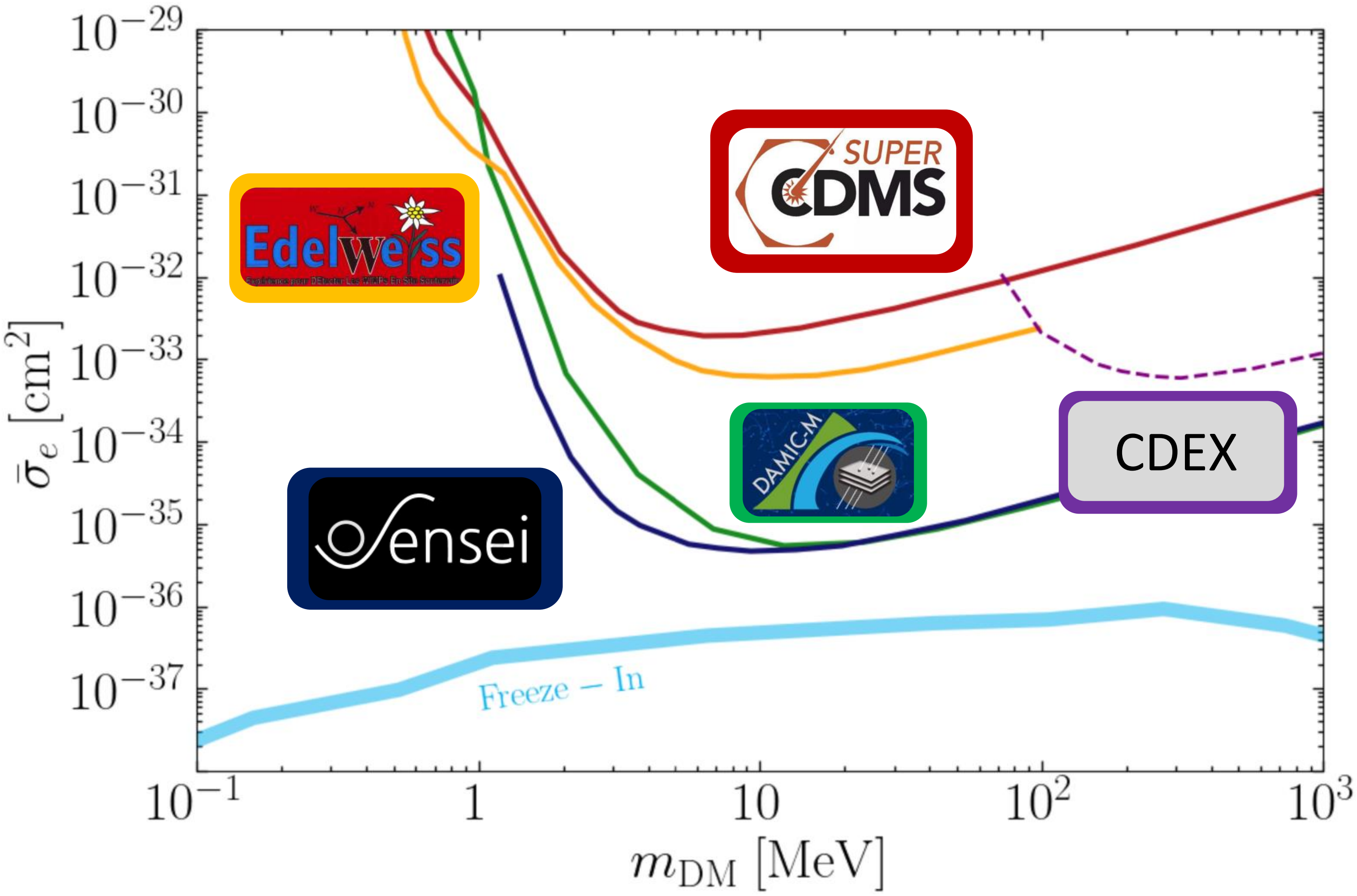




Current Electron Based Experiments



DAMIC



All use Silicon or Germanium as the target material

[2202.10518] The Oscura Experiment

(SENSEI + DAMIC)

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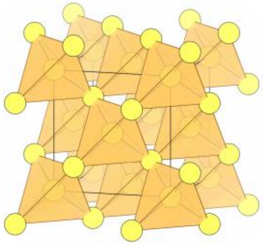
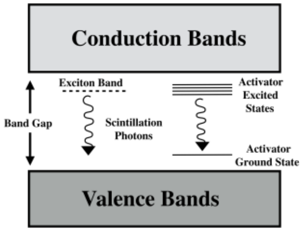
Many Ideas For Future Detectors

Other Semiconductors/Dielectrics



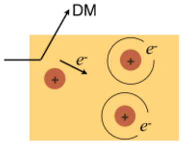
- SNOWMASS21-CF1_CF2-IF1_IF8-120.pdf (TESSARACT: GaAs, Sapphire)
- [2101.08275] Dark matter-electron scattering in dielectrics
- [2101.08263] Determining Dark Matter-Electron Scattering Rates from the Dielectric Function
- [2008.08560] SiC Detectors for Sub-GeV Dark Matter

Scintillators

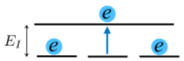


- [1607.01009] Direct Detection of sub-GeV Dark Matter with Scintillating Targets
- [2402.01395] Dark Matter-Electron Scattering Search Using Cryogenic Light Detectors

Doped Semiconductors

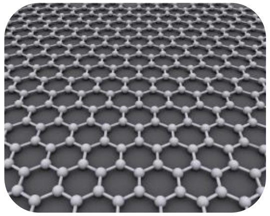


n-type semiconductor



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

Low Band Gap (~meV) Targets

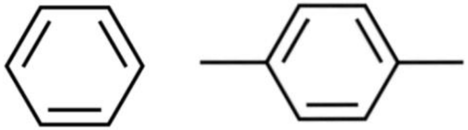


- [1909.09170] Directional Dark Matter Detection in Anisotropic Dirac Materials
- [2202.11716] Dark Matter Direct Detection in Materials with Spin-Orbit Coupling

Organic Aromatics

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

⋮



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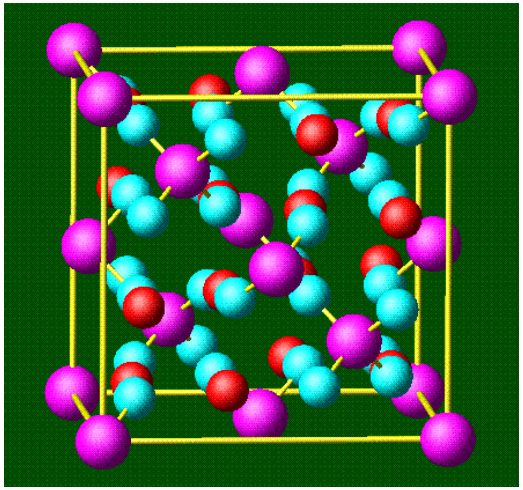
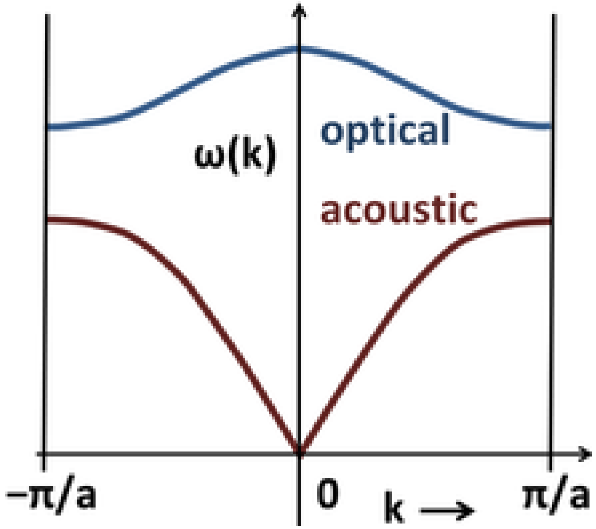
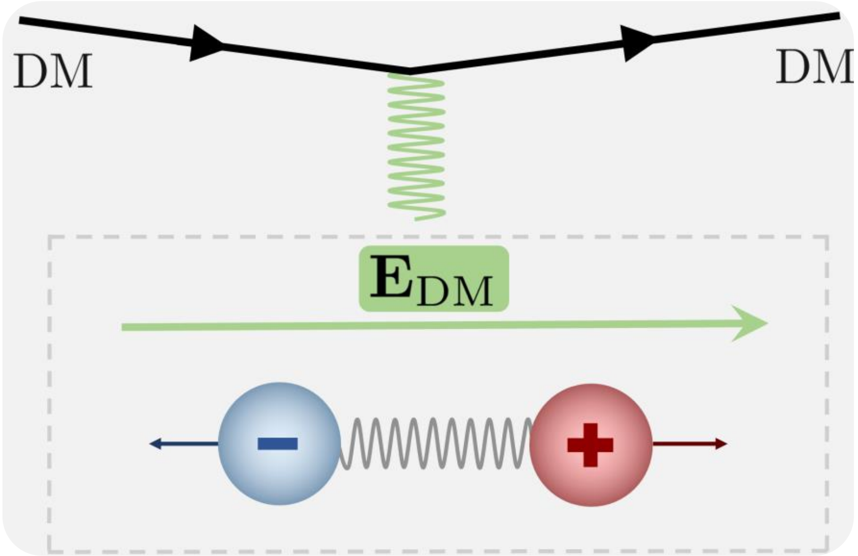
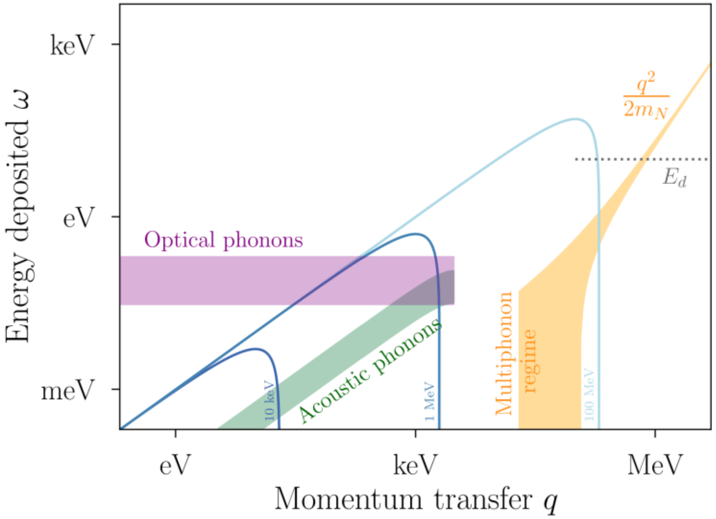
Phonons









[2108.03239] Searches for light dark matter using condensed matter systems

Phonon Scattering Rate

Fermi's golden rule

$$\Gamma(\boldsymbol{v}) = \frac{1}{V}\int \frac{d^3q}{(2\pi)^3} \sum_f \left| \langle f |\, \widetilde{\mathcal{V}}(-\boldsymbol{q}, \boldsymbol{v})\, | i \rangle \right|^2 2\pi\, \delta\big(E_f - E_i - \omega_{\boldsymbol{q}}\big)$$

Fermi's golden rule for phonon excitations

$$\Gamma(\boldsymbol{v}) = \frac{1}{V}\int \frac{d^3q}{(2\pi)^3} \sum_{\nu,\boldsymbol{k}} \left| \sum_{l,j} \boxed{\langle \nu, \boldsymbol{k} |} \boxed{e^{i\boldsymbol{q}\cdot\boldsymbol{x}_{lj}}}\, \widetilde{\mathcal{V}}_{lj}(-\boldsymbol{q}, \boldsymbol{v}) | 0 \rangle \right|^2 2\pi\, \delta\big(\omega_{\nu,\boldsymbol{k}} - \omega_{\boldsymbol{q}}\big)$$

$$|\nu, \mathbf{k}\rangle = a^\dagger_{\nu\mathbf{k}} |0\rangle$$

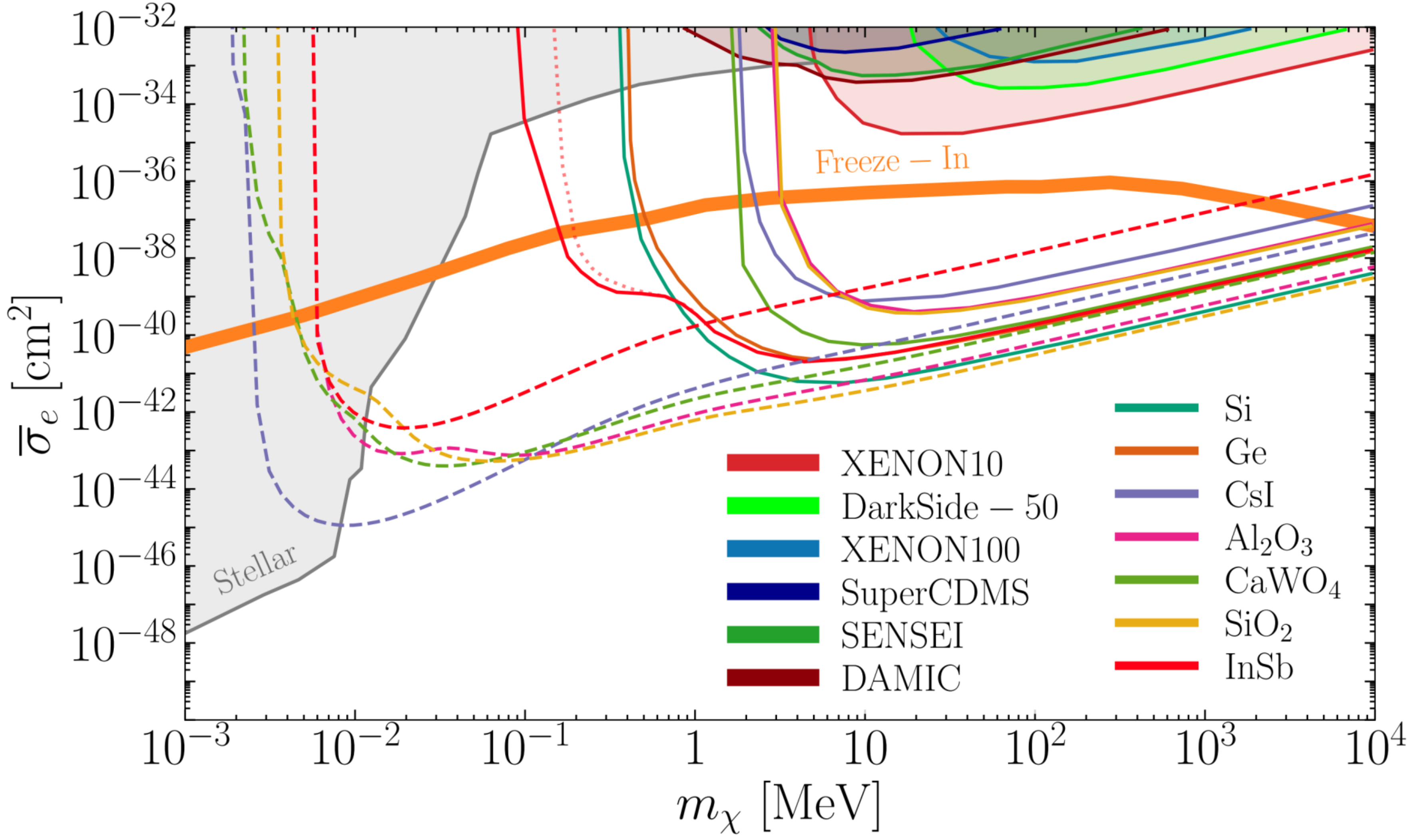
$$\boldsymbol{u}_{lj} = \boldsymbol{x}_{lj} - \boldsymbol{x}^0_{lj} = \sum_{\nu=1}^{3n} \sum_{\boldsymbol{k}\in 1\mathrm{BZ}} \frac{1}{\sqrt{2N m_j \omega_{\nu,\boldsymbol{k}}}} \left(\hat{a}_{\nu,\boldsymbol{k}}\, \boldsymbol{\epsilon}_{\nu,\boldsymbol{k},j}\, e^{i\boldsymbol{k}\cdot\boldsymbol{x}^0_{lj}} + \hat{a}^\dagger_{\nu,\boldsymbol{k}}\, \boldsymbol{\epsilon}^*_{\nu,\boldsymbol{k},j}\, e^{-i\boldsymbol{k}\cdot\boldsymbol{x}^0_{lj}} \right)$$

The general goal is to find the interaction potential in terms of excitation operators.

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

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

Projected Sensitivity Of Single Phonon Detectors

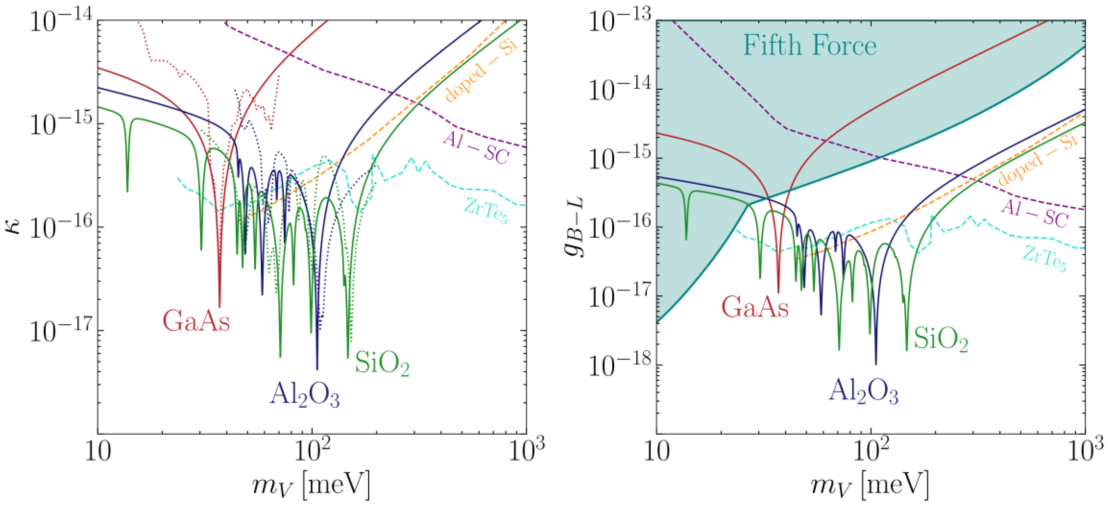


[1910.10716] Multi-Channel Direct Detection of Light Dark Matter: Target Comparison

- S. Griffin, K. Inzani, **T. Trickle**, Z. Zhang, K. Zurek

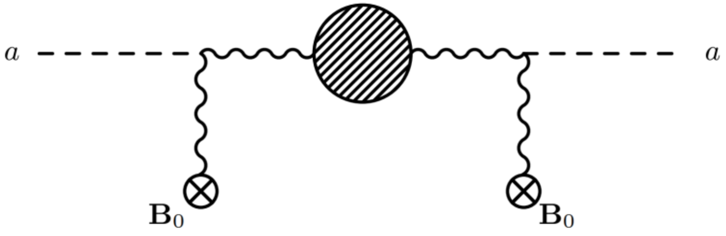
ttrickle@fnal.gov

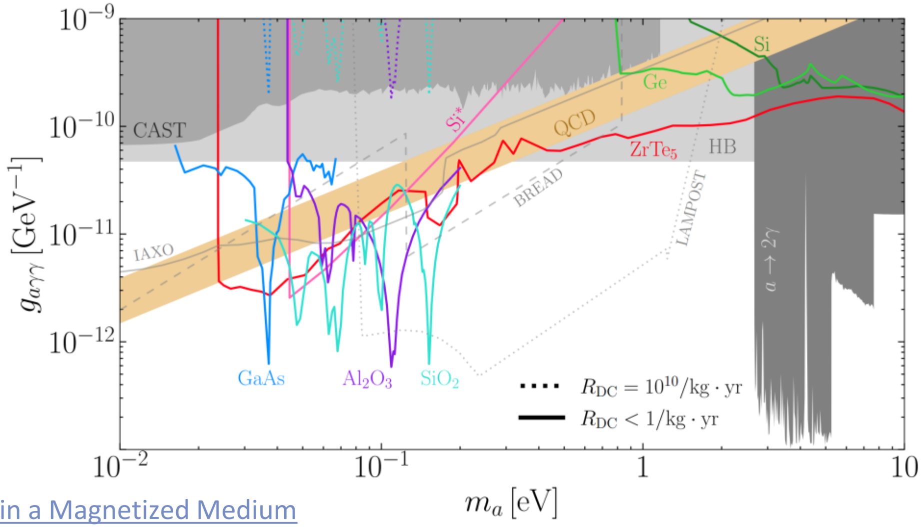
Projected Sensitivity Of Single Phonon Detectors



[2308.06314] Effective Field Theory for Dark Matter Absorption on Single Phonons

- A. Mitridate, K. Pardo, **T. Trickle**, K. Zurek



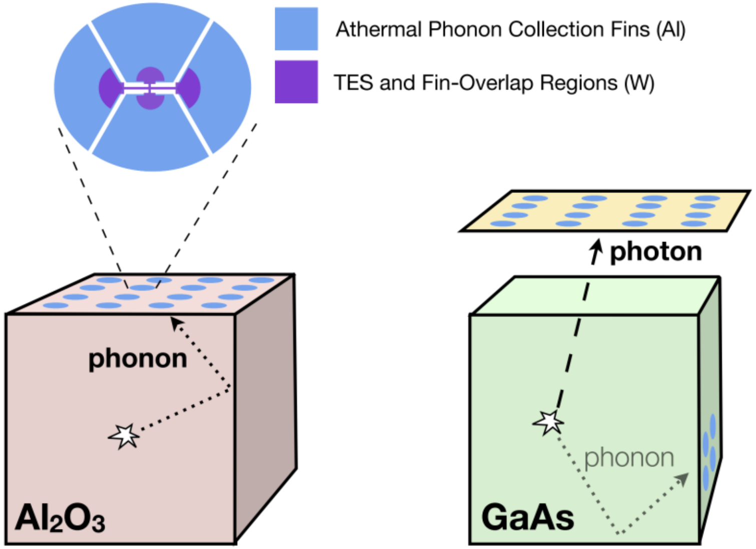


[2305.05681] Absorption of Axion Dark Matter in a Magnetized Medium

- A. Berlin, **T. Trickle**

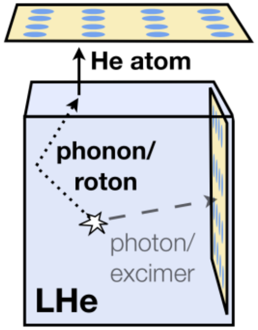
Phonon-Based Experiments

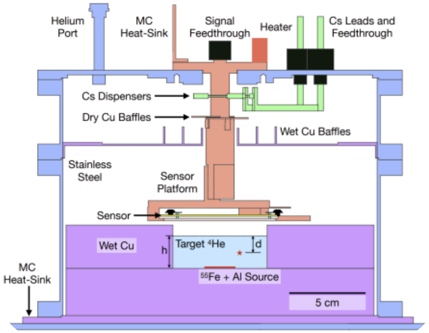
Funded



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]

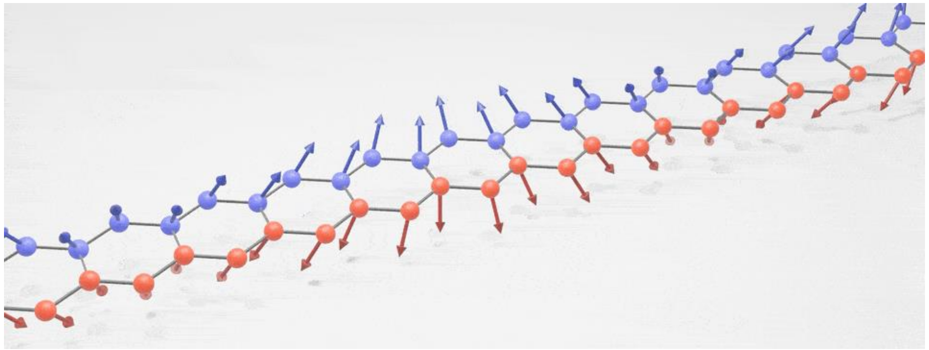
Single Phonon Detection for Dark Matter via Quantum Evaporation and Sensing of Helium-3 [2201.00738]

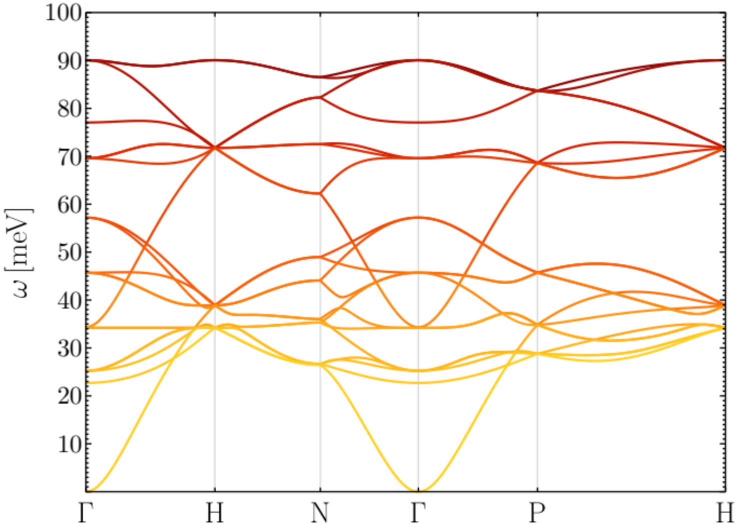
Proposed

[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





$$\Gamma(\boldsymbol{v}) = \frac{1}{V}\int \frac{d^3q}{(2\pi)^3} \sum_{\nu,\boldsymbol{k}} \left| \sum_{l,j} \boxed{\langle \nu, \boldsymbol{k}|} \boxed{e^{i\boldsymbol{q}\cdot\boldsymbol{x}_{lj}}\, \widetilde{\mathcal{V}}_{lj}(-\boldsymbol{q},\boldsymbol{v})} |0\rangle \right|^2 2\pi\,\delta\left(\omega_{\nu,\boldsymbol{k}} - \omega_{\boldsymbol{q}}\right)$$

$$|\nu, \mathbf{k}\rangle = a^\dagger_{\nu\mathbf{k}}|0\rangle$$

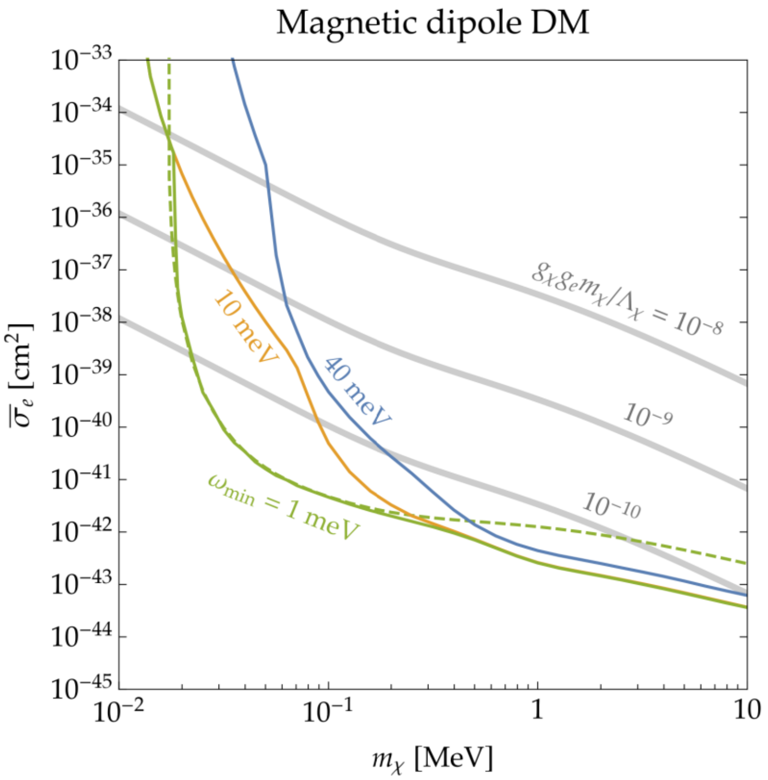
$$H = \sum_{\ell\ell' jj'} \mathbf{S}_{\ell' j'} \cdot \mathbf{J}_{\ell\ell' jj'} \cdot \mathbf{S}_{\ell j}$$

$$\langle \nu, \boldsymbol{k}| \widetilde{\mathcal{V}}(-\boldsymbol{q},\boldsymbol{v})|0\rangle = \sum_{l,j} e^{i\boldsymbol{q}\cdot\boldsymbol{x}_{lj}} \boldsymbol{f}_j(-\boldsymbol{q},\boldsymbol{v}) \cdot \langle \nu, \boldsymbol{k}|\boldsymbol{S}_{lj}|0\rangle$$

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

Projected Sensitivity of Single Magnon Detectors

Scattering

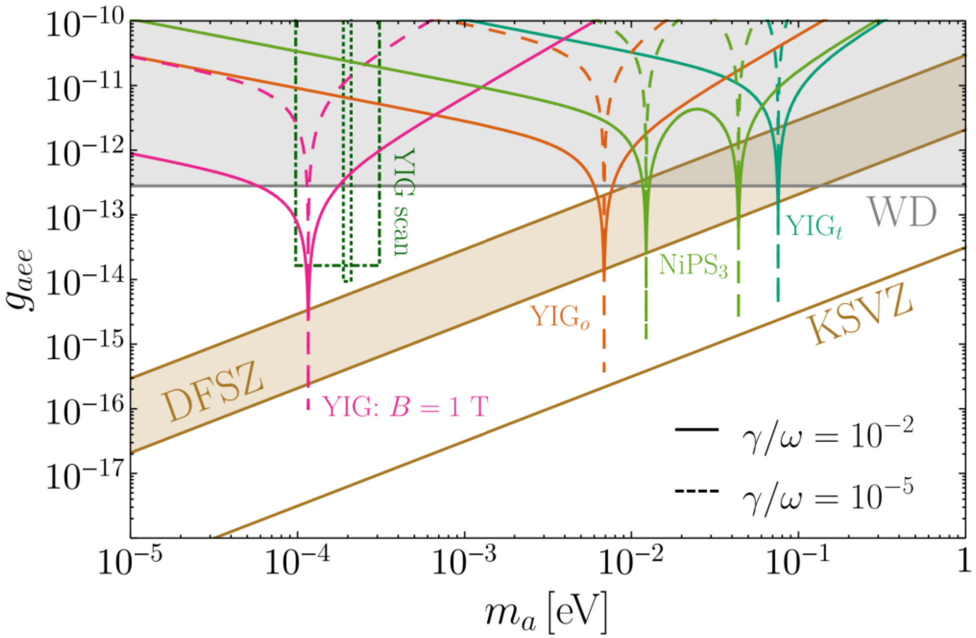


$$\mathcal{L} = \frac{g_\chi}{\Lambda_\chi}\bar{\chi}\sigma^{\mu\nu}\chi\, V_{\mu\nu} + g_e \bar{e}\gamma^\mu e\, V_\mu$$

[1905.13744] Detecting Light Dark Matter with Magnons

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

Absorption



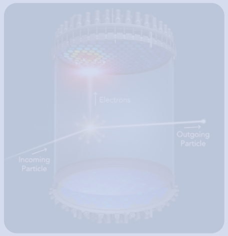
$$\mathcal{L} \supset \frac{g_{aee}}{2m_e}(\partial_\mu a)\bar{\psi}\gamma^\mu\gamma^5\psi$$

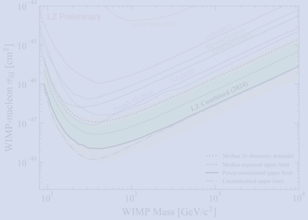
[2005.10256] Detectability of Axion Dark Matter with Phonon Polaritons and Magnons

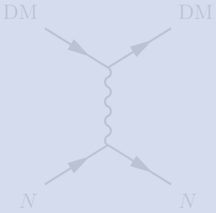
- A. Mitridate, **T. Trickle**, Z. Zhang, K. Zurek

Outline

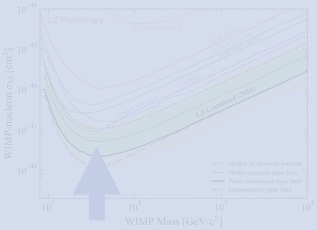
- Background

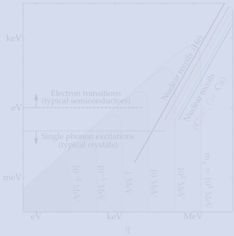




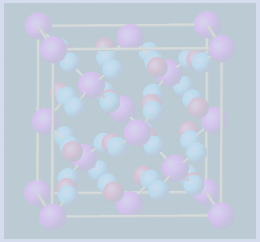


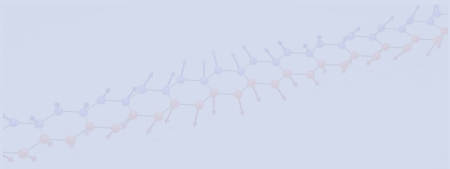
- Kinematics





- Target Excitations





- **Effective Field Theory**

$$\underset{\text{UV/High-Energy } (E \gg m_e) \text{ Theory}}{\delta\mathcal{L}_{\text{UV}}} \longrightarrow \underset{\text{NR/Low-Energy } (E \ll m_e) \text{ Theory}}{\delta\mathcal{L}_{\text{NR}}} \longrightarrow \text{Observables}$$

Nuclear Recoil Effective Field Theory

[1203.3542] The Effective Field Theory of Dark Matter Direct Detection

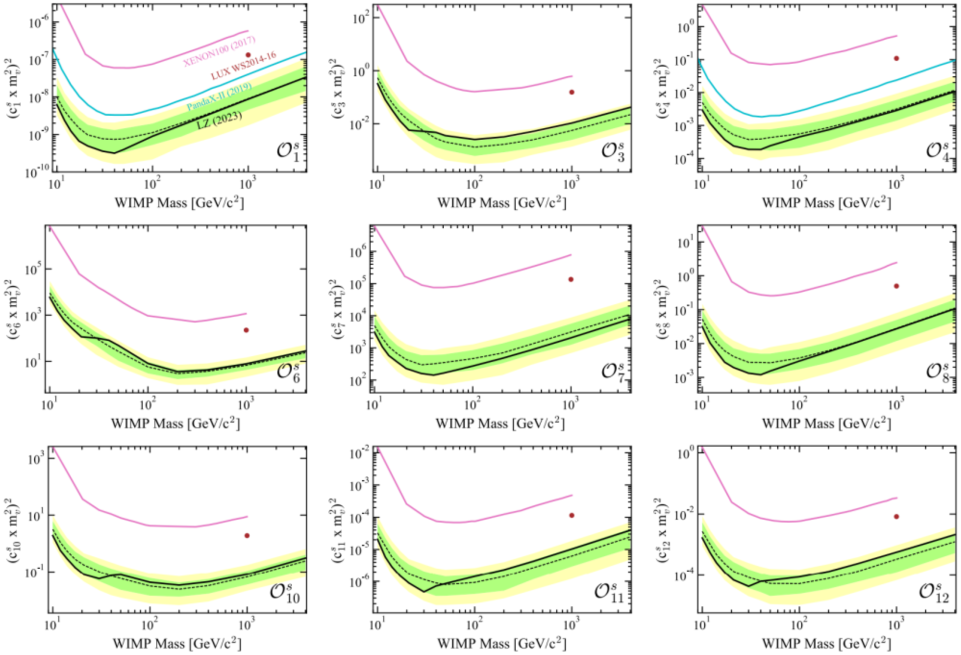
$$\mathcal{L}_{\text{int}} = \sum_{N=n,p} \sum_i c_i^{(N)} \mathcal{O}_i \chi^+ \chi^- N^+ N^-$$

$$\mathcal{O}_1 = \mathbf{1}$$

$$\mathcal{O}_2 = (v^\perp)^2$$

$$\mathcal{O}_3 = i\vec{S}_N \cdot (\vec{q} \times \vec{v}^\perp)$$

$$\vdots$$



Phys. Rev. D 109, 092003 (2024) - First constraints on WIMP-nucleon effective field theory couplings in an extended energy region from LUX-ZEPLIN

Phys. Rev. D 109, 112017 (2024) - Effective field theory and inelastic dark matter results from XENON1T

Effective Field Theories

	Scattering	Absorption	Dark Thomson Scattering
Nuclear Recoil	[1203.3542] The Effective Field Theory of Dark Matter Direct Detection		
Electron	[1912.08204] Atomic responses to general dark matter-electron interactions [2105.02233] Crystal responses to general dark matter-electron interactions [2407.14598] The Non-Relativistic Effective Field Theory Of Dark Matter-Electron Interactions • G. Krnjaic, D. Rocha, **T. Trickle**		
Phonon	[2009.13534] Effective Field Theory of Dark Matter Direct Detection With Collective Excitations • **T. Trickle**, Z. Zhang, K. Zurek	[2308.06314] Effective Field Theory for Dark Matter Absorption on Single Phonons • A. Mitridate, K. Pardo, **T. Trickle**, K. Zurek	
Magnon			

NR EFT Of Dark Matter-Electron Interactions

UV/High-Energy ($E \gg m_e$) Theory

NR/Low-Energy ($E \ll m_e$) Theory

$$\delta\mathcal{L}_{\mathrm{UV}} \longrightarrow \delta\mathcal{L}_{\mathrm{NR}} \longrightarrow \text{Observables}$$

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

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

NR EFT Of Dark Matter-Electron Interactions

UV/High-Energy ($E \gg m_e$) Theory

NR/Low-Energy ($E \ll m_e$) Theory

$$\delta\mathcal{L}_{\rm UV} = \bar{\Psi}\,\mathcal{O}_{\rm UV}\,\Psi \longrightarrow \delta\mathcal{L}_{\rm NR} = \psi^\dagger\,\mathcal{O}_{\rm NR}\,\psi$$

How to map $\Psi \to \psi$ *?*

$$\mathcal{L}_{\rm UV} = \bar{\Psi}(i\not{D} - m_e)\Psi \longrightarrow \mathcal{L}_{\rm NR} = \psi^\dagger\left[i\partial_t - \frac{\mathbf{p}^2}{2m_e} - V + \cdots\right]\psi$$

more generally, NRQED

Applying the map,

$$\mathcal{O}_{\rm NR} \approx \mathrm{Tr}\left[P_+\left(\mathcal{O}_{\rm UV} + \frac{i}{2m_e}\{\gamma^i D_i, \mathcal{O}_{\rm UV}\} - \frac{1}{8m_e^2}\{\gamma^i D_i, \{\gamma^j D_j, \mathcal{O}_{\rm UV}\}\} - \frac{ie}{4m_e^2}\{\gamma^0\gamma^i F_{0i}, \mathcal{O}_{\rm UV}\}\right)\right]$$

$+$ Order m_e^{-3}

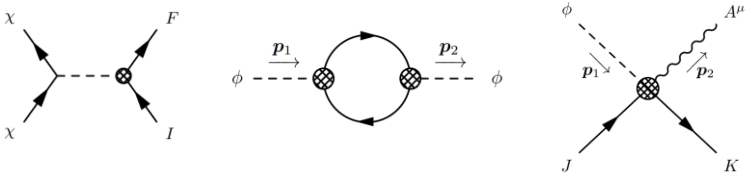
[2407.14598] The Non-Relativistic Effective Field Theory Of Dark Matter-Electron Interactions

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

NR EFT Of Dark Matter-Electron Interactions

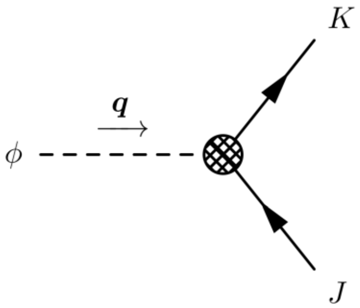
NR/Low-Energy ($E \ll m_e$) Theory

$$\delta\mathcal{L}_{\rm NR} \xrightarrow{\text{Feynman Rules}} \text{Observables}$$



Three Point Feynman Rule

$$\mathscr{L}_{\rm int}^{\rm NR} = \sum_{\ell=1}^{8}\left[C_{\phi,\ell}\,\phi + C_{\nabla\phi,\ell}\,\frac{(\nabla\phi)}{m_e} + \cdots\right]\left[\psi^\dagger\,\hat{\mathcal{O}}_\ell\,\psi\right] \Longrightarrow i\mathcal{M}_{\rm NR} = i\sum_{\ell=1}^{8}\underline{\left[C_{\phi,\ell} + C_{\nabla\phi,\ell}\left(\frac{i\boldsymbol{q}}{m_e}\right) + \cdots\right]}\,\underline{\left[\int d^3\boldsymbol{x}\,e^{i\boldsymbol{q}\cdot\boldsymbol{x}}\,\psi_K^\dagger(\boldsymbol{x})\,\hat{\mathcal{O}}_\ell\,\psi_J(\boldsymbol{x})\right]}$$



$$\Longrightarrow \quad i\sum_{\ell=1}^{8}\overline{f_{\phi,\ell}(\boldsymbol{q})}\;\overline{\hat{\mathcal{M}}_{JK,\ell}(\boldsymbol{q})}$$

Feynman rule **factorizes** to **DM-model dependent** and **target dependent** pieces.

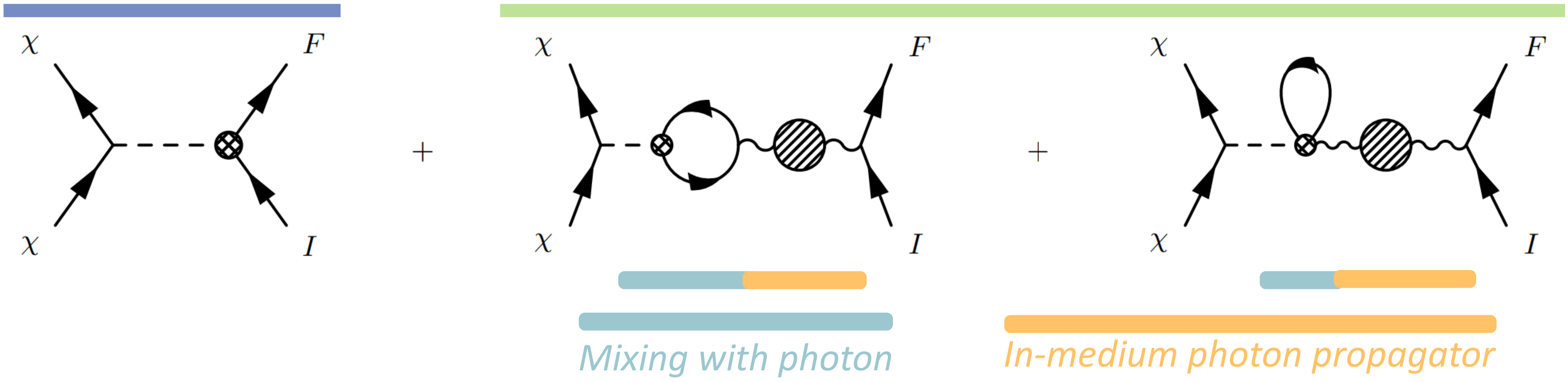
[2407.14598] The Non-Relativistic Effective Field Theory Of Dark Matter-Electron Interactions

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

Screening Effects in the EFT

Tree

Loop - ``Screening diagrams"

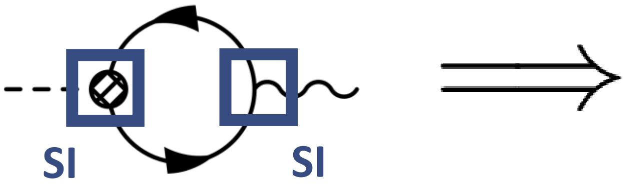


Mixing with photon

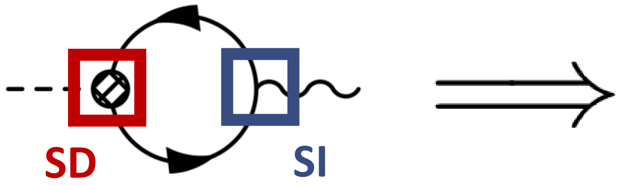
In-medium photon propagator

What models are screened?

Those with non-zero mixing with the photon.



Screened



Not screened

*in simple targets**

Other 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

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

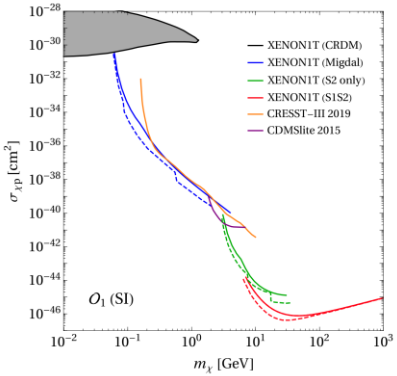
measurable

Other physical effects

Migdal Effect

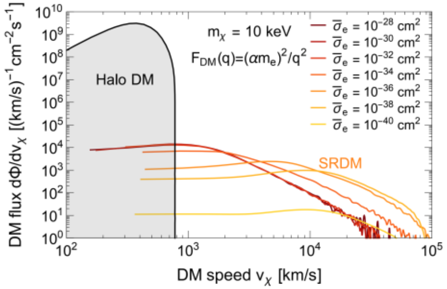
[1908.10881] On the relation between Migdal effect and dark matter-electron scattering in isolated atoms and semiconductors

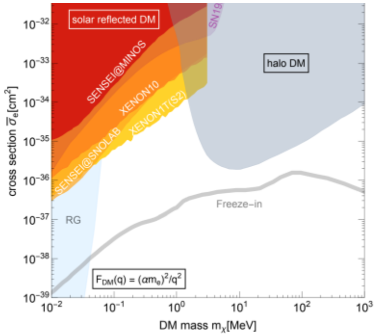
[2210.06490] The Migdal Effect in Semiconductors for Dark Matter with Masses below $\sim \,$100 MeV



Boosted Dark Matter

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



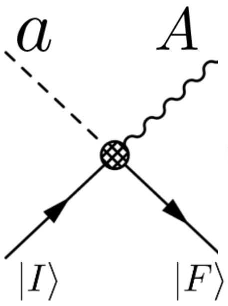


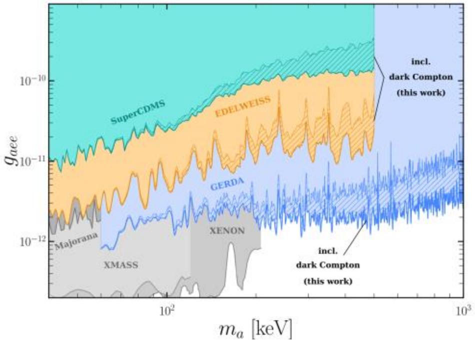
Dark Thomson

[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**



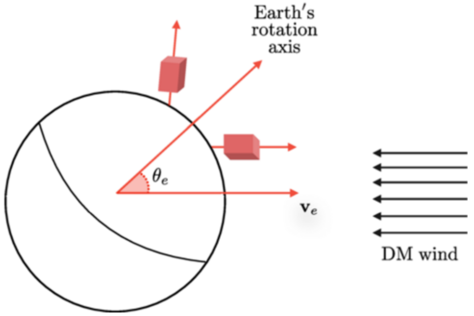


Daily Modulation

[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



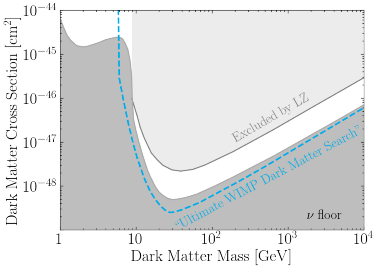
High-Frequency GWs

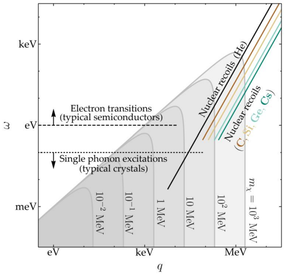
[2311.17147] Searching for High Frequency Gravitational Waves with Phonons

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

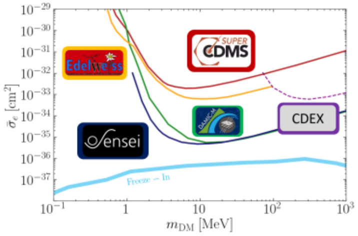
Summary

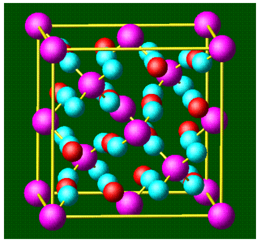
- **The next generation of direct detection experiments will rely on low-energy excitations.**

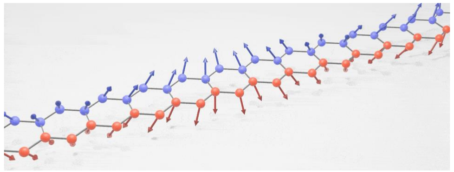




- **Electrons, phonons, and magnons are kinematically well-matched to light dark matter, and can probe complementary parts of parameter space.**







- **Effective field theory is a useful tool for parameterizing all potential signatures.**

$$\delta\mathcal{L}_{\rm UV} = \bar{\Psi}\,\mathcal{O}_{\rm UV}\,\Psi \longrightarrow \delta\mathcal{L}_{\rm NR} = \psi^\dagger\,\mathcal{O}_{\rm NR}\,\psi$$

$$\mathcal{O}_{\rm NR} \approx {\rm Tr}\left[P_+\left(\mathcal{O}_{\rm UV} + \frac{i}{2m_e}\{\gamma^i D_i, \mathcal{O}_{\rm UV}\} - \frac{1}{8m_e^2}\{\gamma^i D_i, \{\gamma^j D_j, \mathcal{O}_{\rm UV}\}\} - \frac{ie}{4m_e^2}\{\gamma^0\gamma^i F_{0i}, \mathcal{O}_{\rm UV}\}\right)\right]$$

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