Dark matter direct detection with quasiparticles

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Workshop: Low Energy Recoils from Deep Underground

Challenges for sub-GeV DM

Kinematics of nuclear recoils from light dark matter

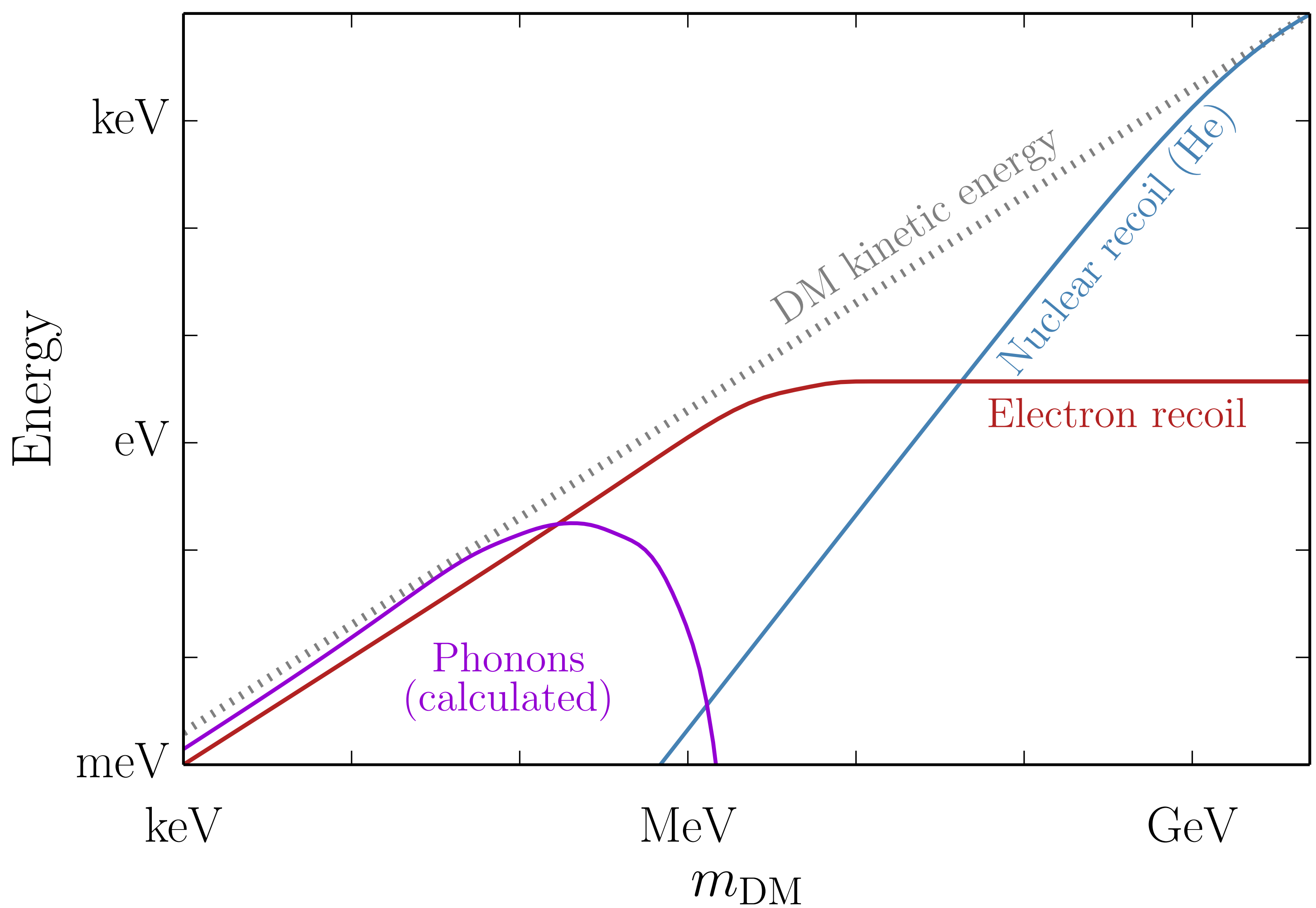
$$E_R = \frac{|\mathbf{q}|^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v^2}{m_N}$$

Drops quickly below $m_\chi \sim 10$ GeV

Best nuclear recoil threshold is currently $E_R > 30$ eV (CRESST-III) with DM reach of $m_\chi > 160$ MeV.

The kinematics of DM scattering against **free** nuclei is inefficient, and it does not accurately describe target response.

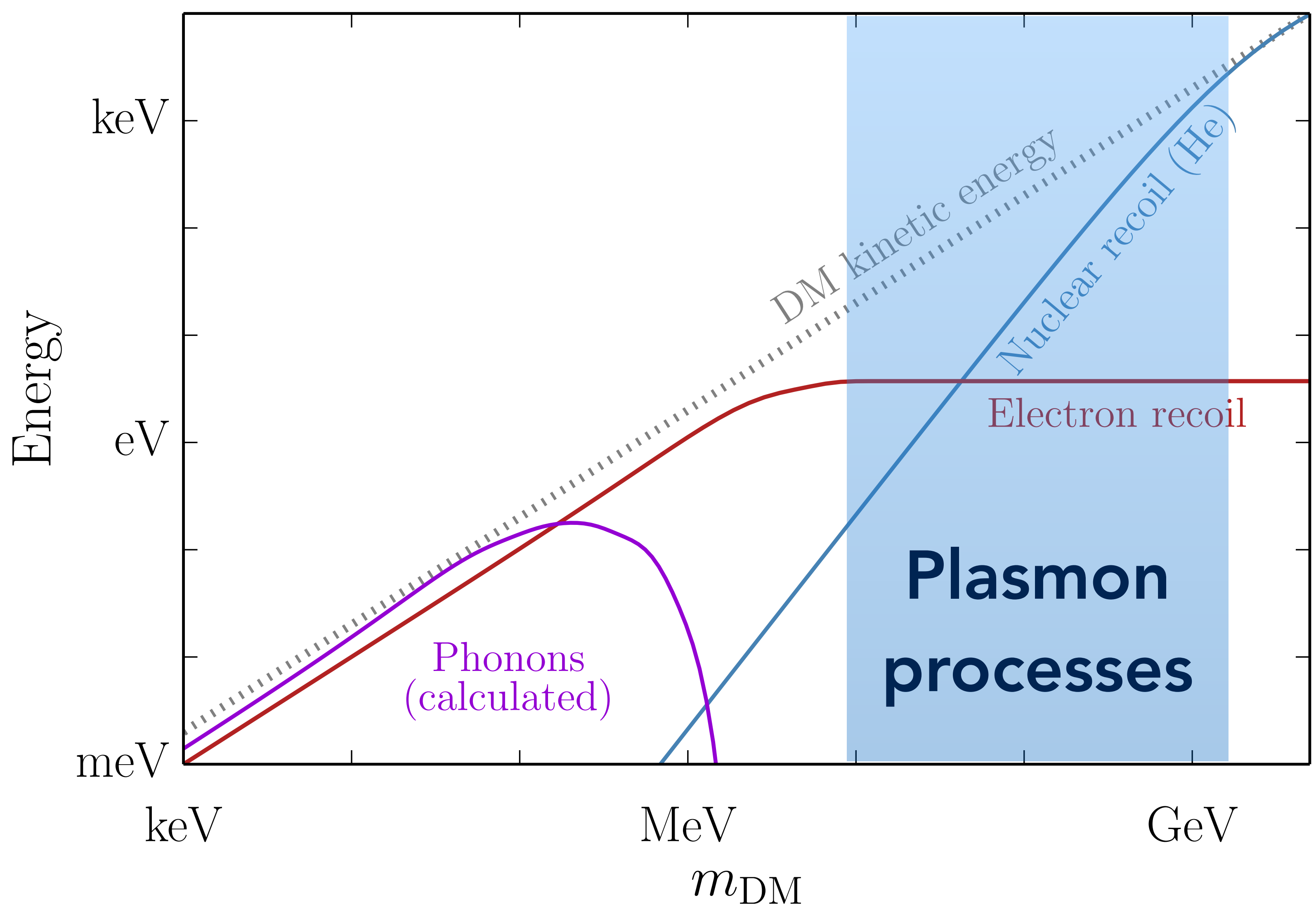
Material properties matter



Nuclear response is phonon-dominated at low energies.

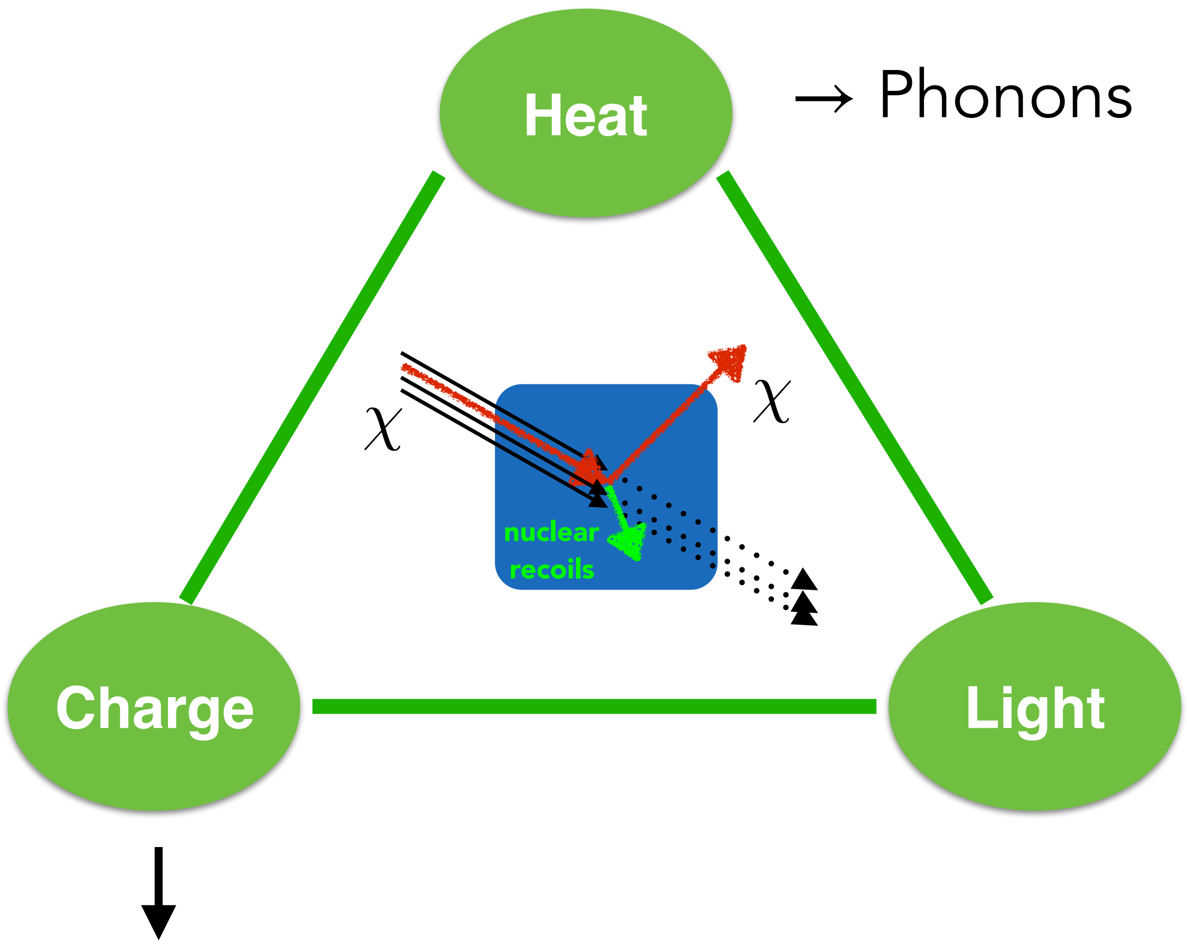
Electronic response depends on details of band structure/eigenstates.

Material properties matter



Inelastic or 2 → 3 processes on the target side can also extract more DM kinetic energy.

Challenges for sub-GeV DM



→ Phonons

→ Scintillation photons

ionized atoms or electron-hole pairs in semiconductors (e.g. previous talk)

The charge and light yield for nuclear recoils below few hundred eV is not well understood, but expected to be ~0 on average.

Graphic from talk by Kaixuan Ni

Strategies for detecting nuclear recoils from sub-GeV DM

1. Decreasing the heat threshold

- Detectors in development to reach heat/phonon thresholds of ~ eV and below (e.g. SuperCDMS SNOLAB)

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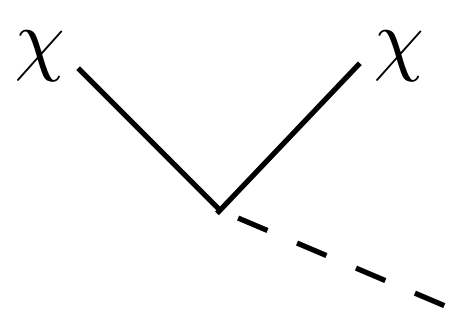
- **Direct phonon excitations from DM scattering**
  At low enough energies, cannot treat as free nucleus; harmonic potential matters. $\omega \approx 1 - 100 \text{ meV}$ for acoustic and optical phonons in crystals. (many works, e.g. Griffin, Knapen, TL, Zurek 2018; Cox, Melia, Rajendran 2019)

DM-phonon scattering

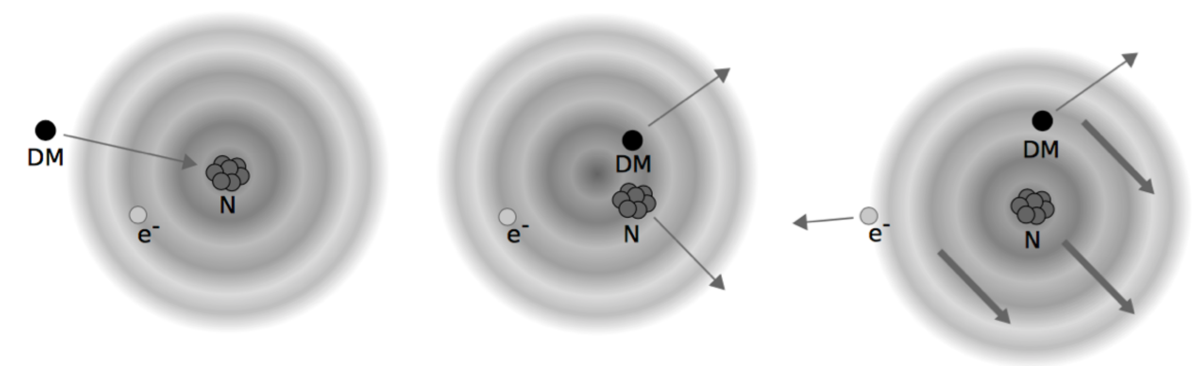


Kinematics of phonons relevant (and advantageous) for sub-MeV dark matter

Strategies for detecting nuclear recoils from sub-GeV DM

2. Increasing the charge signal

- Atomic Migdal effect
  Ionization of electrons
  which have to 'catch up'
  to recoiling nucleus
  (e.g. Ibe, Nakano, Shoji, Suzuki 2017)



From 1711.09906

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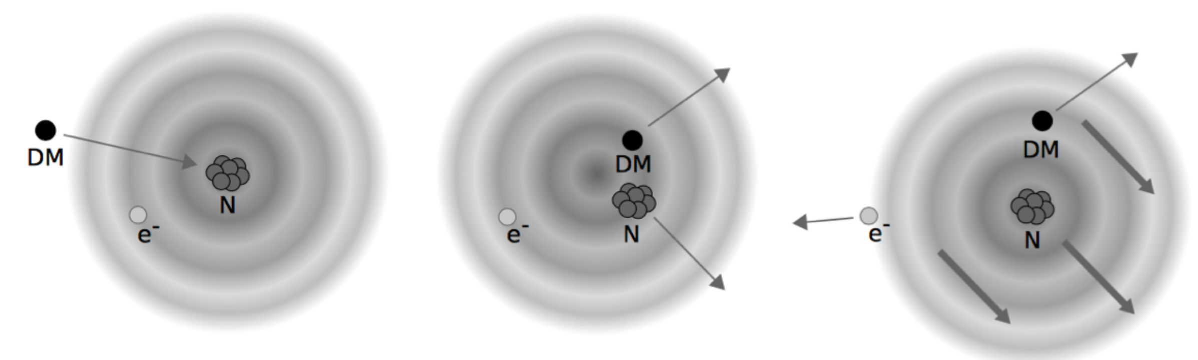


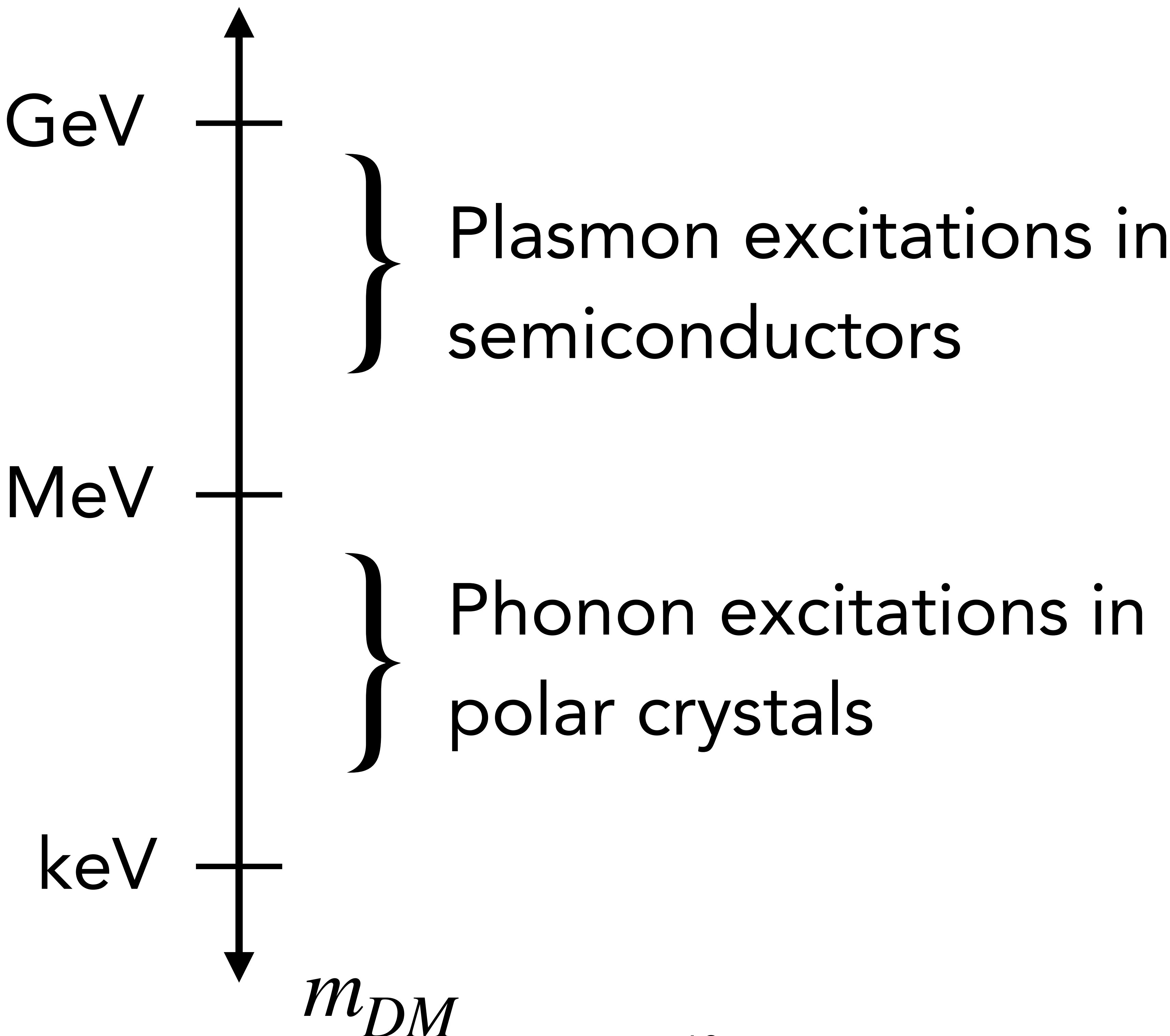
From 1711.09906

- Bremsstrahlung of (transverse) photons in LXe
  Kouvaris & Pradler 2016

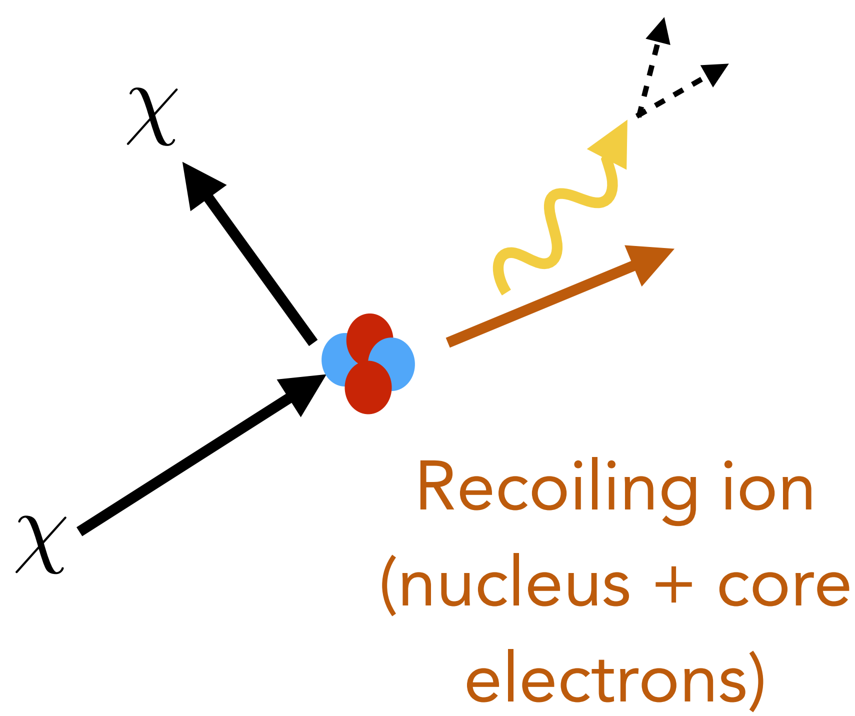
- **Plasmons (+ionization signals) in semiconductors**

Many-body effects are relevant in many of these cases!

Direct detection with quasiparticles



Detecting nuclear recoils via plasmon excitations



Based on: Kozaczuk, TL 2019; Knapen, Kozaczuk, TL (to appear)

Plasmons

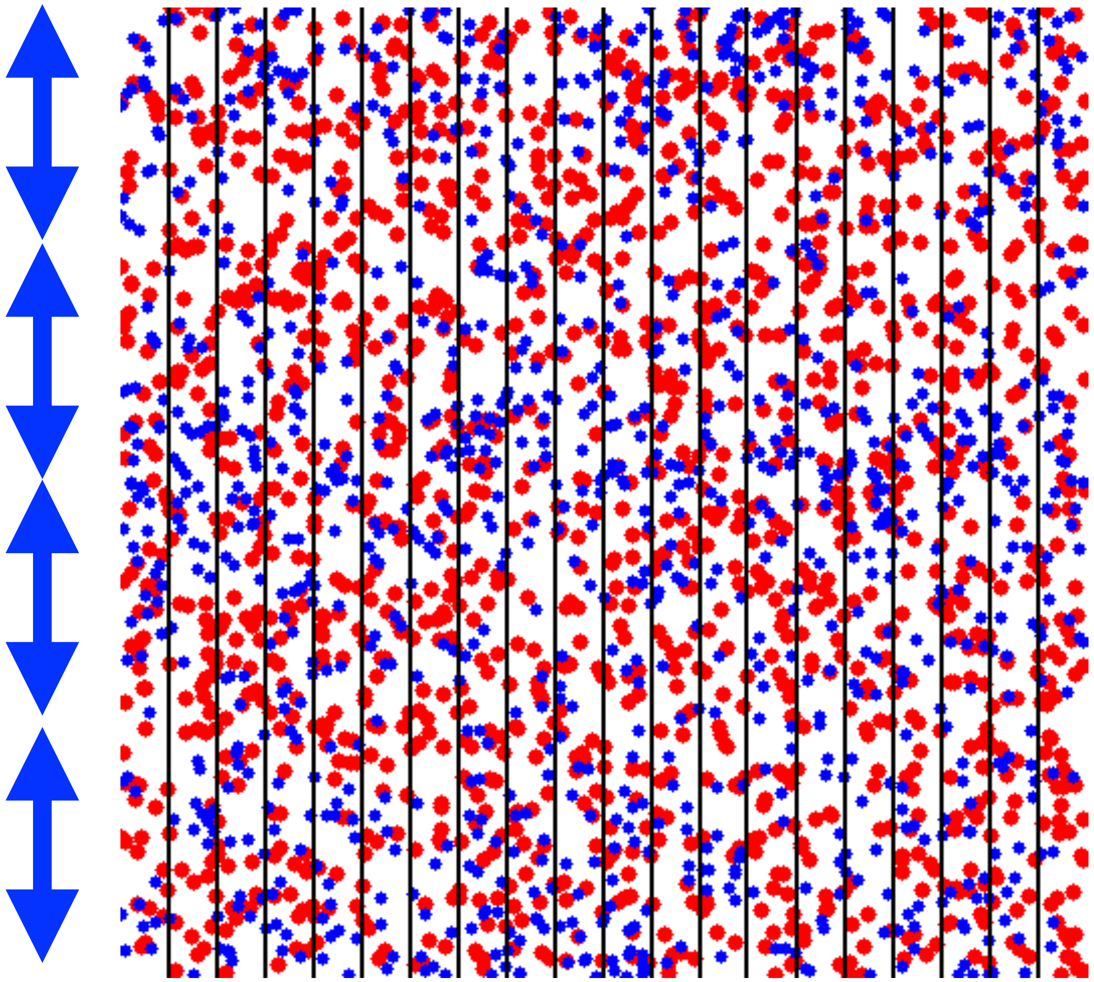
- Simple picture: uniform displacement of electrons by $\mathbf{r}$

$$-e\mathbf{E} = 4\pi\alpha_{em} n_e \mathbf{r}$$
$$\ddot{\mathbf{r}} = -\omega_p^2 \mathbf{r}$$

Plasma frequency $$\omega_p^2 \equiv \frac{4\pi\alpha_{em} n_e}{m_e}$$

- Plasmons are quantized longitudinal E-field excitations in the medium (contrast with “transverse photons”)

Electron gas in fixed ion background

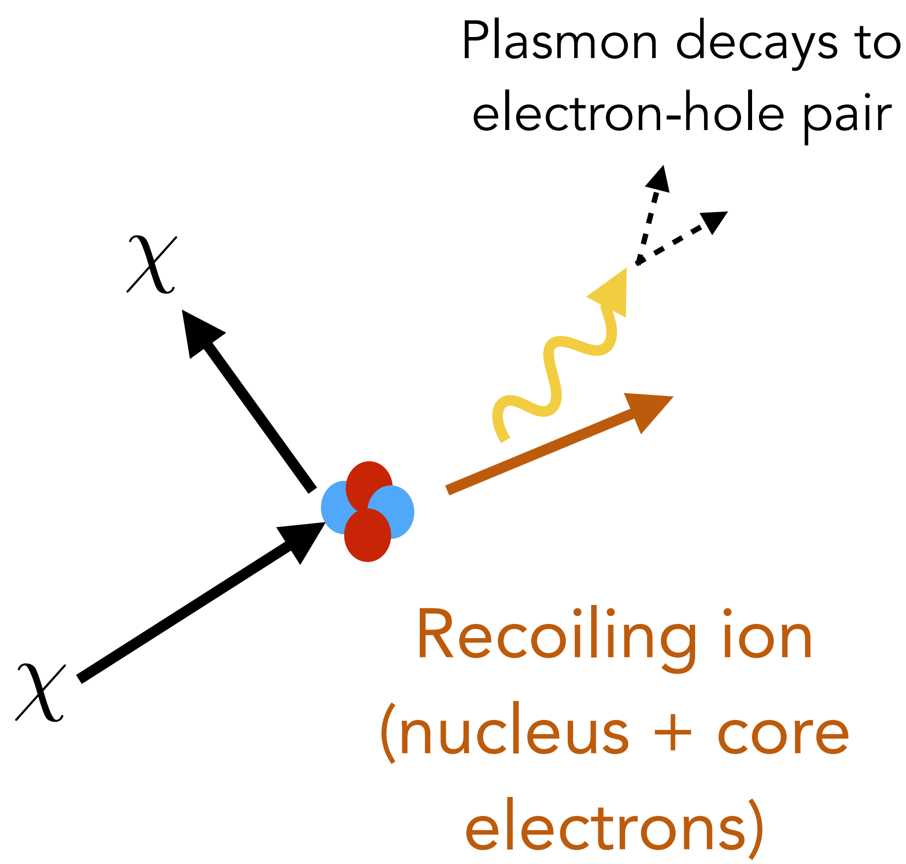


red: ion blue: electron

Plasmons from dark matter?

Proposed by Kurinsky, Baxter, Kahn, Krnjaic as an explanation of low-energy rates in semiconductor DD experiments.

Our goal: calculate the plasmon excitation rate from nuclear recoils in semiconductors. This is an additional charge signal that should be included and can improve reach for sub-GeV DM.



Assumptions

For nuclear recoil energy

$$\omega_{\text{phonon}} \ll E_R \lesssim E_{\text{core}}$$

treat as a free nucleus with tightly bound core electrons. Valid for $10 \text{ MeV} \lesssim m_\chi \lesssim 1 \text{ GeV}$.

Electron gas model

- Toy model: bremsstrahlung of a longitudinal mode in a metal (degenerate electron gas in fixed ion background)

- Plasmon appears as a zero of the dielectric function

Gauss's law without external source

$$\hat{\epsilon}_L(\omega, \mathbf{k})\mathbf{k} \cdot \mathbf{E} = 0 \rightarrow \mathbf{k} \cdot \mathbf{E} \neq 0 \text{ when } \hat{\epsilon}_L(\omega, \mathbf{k}) = 0$$

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- Or as a pole in the longitudinal propagator

$$D^{00}(\omega, \mathbf{k}) = \frac{1}{k^2 \hat{\epsilon}_L(\omega, \mathbf{k})} = \frac{1}{k^2 - \Pi_L(\omega, \mathbf{k})}$$

(Coulomb gauge)

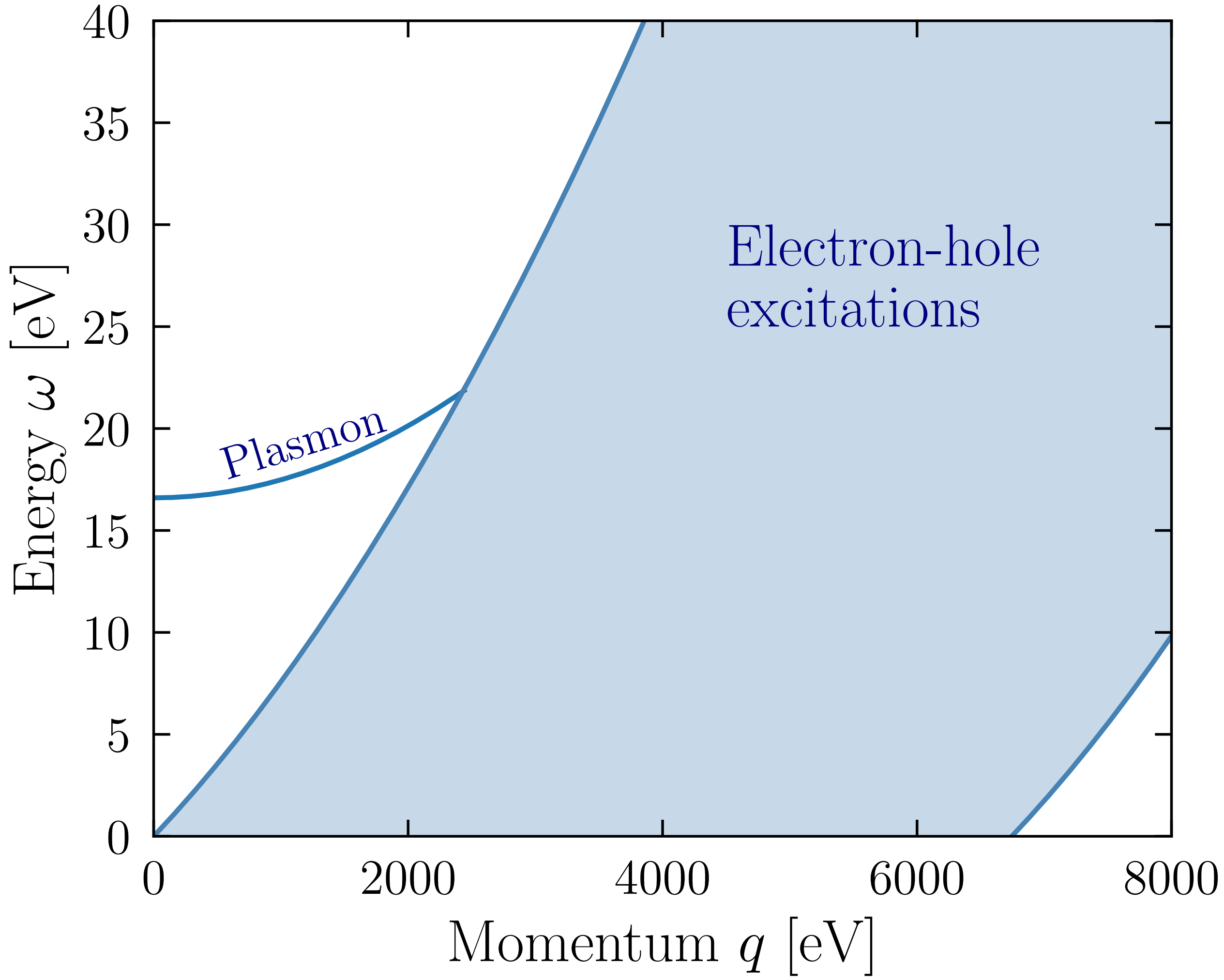
$$\hat{\epsilon}_L(\omega, \mathbf{k}) = 1 - \frac{\Pi_L(\omega, \mathbf{k})}{k^2}$$

Electron gas model

- Plasmon is infinitely long lived for small *k* in this toy model
- For $k \gtrsim \omega_p / v_F$ (~2.4 keV in Si,Ge) there is a large plasmon decay width into electron-hole pairs.
- Plasmons cannot be directly produced by DM with typical halo velocities v ~ 1e-3:

$$\omega = \mathbf{k}\cdot\mathbf{v} - \frac{k^2}{2m_\chi} \quad \rightarrow \quad k \geq \frac{\omega}{v} \sim 16\,\mathrm{keV}$$

Spectrum of longitudinal excitations in the electron gas



Electron gas model

Standard bremsstrahlung calculation in QFT but with final longitudinal mode

$$\chi(p) + N \to \chi(p') + N(q_N) + \omega_L(k)$$

In the limit of soft brem, $k \ll \sqrt{2m_N E_R}$ (valid for us):

$$\frac{d^2\sigma_{\text{plasmon}}}{dE_R dk} = \frac{2Z_{\text{ion}}^2 \alpha_{em}}{3\pi} \frac{Z_L(k)k^2}{\omega_L(k)^3} \frac{E_R}{m_N} \times \left.\frac{d\sigma}{dE_R}\right|_{\text{el}}$$

Elastic DM-nucleus scattering cross section

Roughly 4-6 orders of magnitude larger than brem of transverse photons

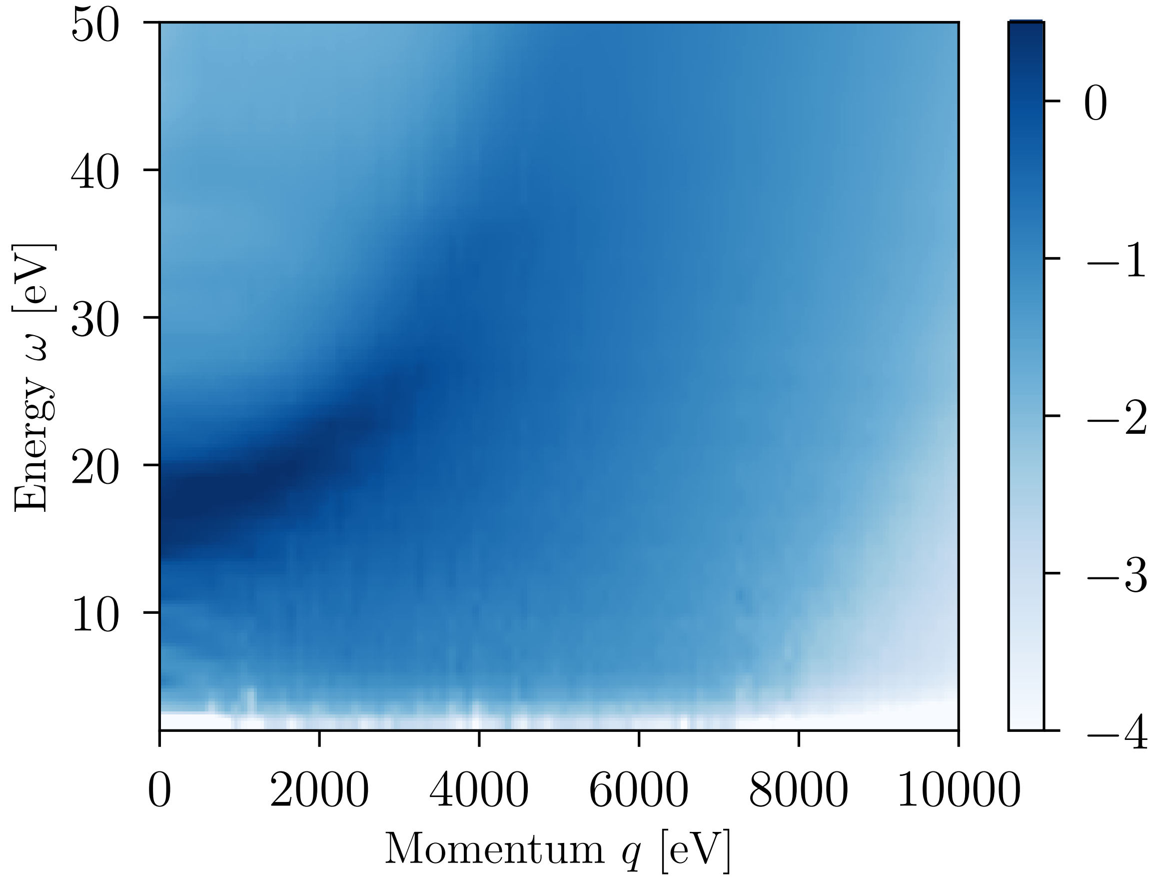
Bremsstrahlung of plasmons is low-probability, but may be the leading ionization signal for low-energy nuclear recoils in semiconductors.

Plasmon production in semiconductors

Differences from electron gas model:

- Band gap: $\omega_g \sim O(1)$ eV (but $\omega_g \ll \omega_p$)
- Electron wavefunctions: plane waves → Bloch waves
- Plasmon decays by interband transitions.

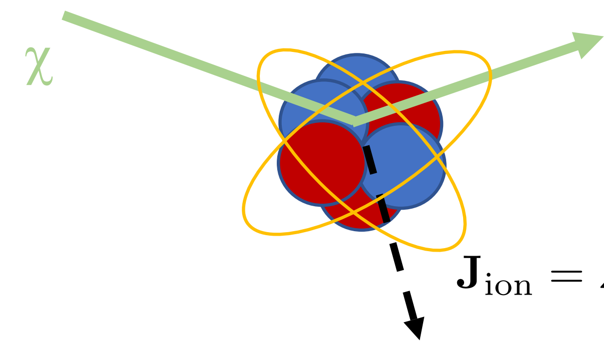
Longitudinal response in a semiconductor



These effects are all accounted for in the dielectric function of the material!
Rewrite plasmon production in terms of $\hat{\epsilon}_L$

Plasmon production in semiconductors

Current sourced by ion recoiling against DM:



$$\mathbf{J}_{\text{ion}} = Z_{\text{ion}}\, e\, \mathbf{v}_{\text{ion}}\, \Theta(t)\, \delta^3(\mathbf{x} - \mathbf{v}_{\text{ion}} t)$$

Energy transfer to material:

$$W = -\int d^3k \int_0^\infty \frac{d\omega}{(2\pi)^4} 2\,\text{Re}\left[\mathbf{J}^*_{\text{ion}}(\omega, \mathbf{k}) \cdot \mathbf{E}(\omega, \mathbf{k})\right]$$

Longitudinal part of Maxwell's equations:

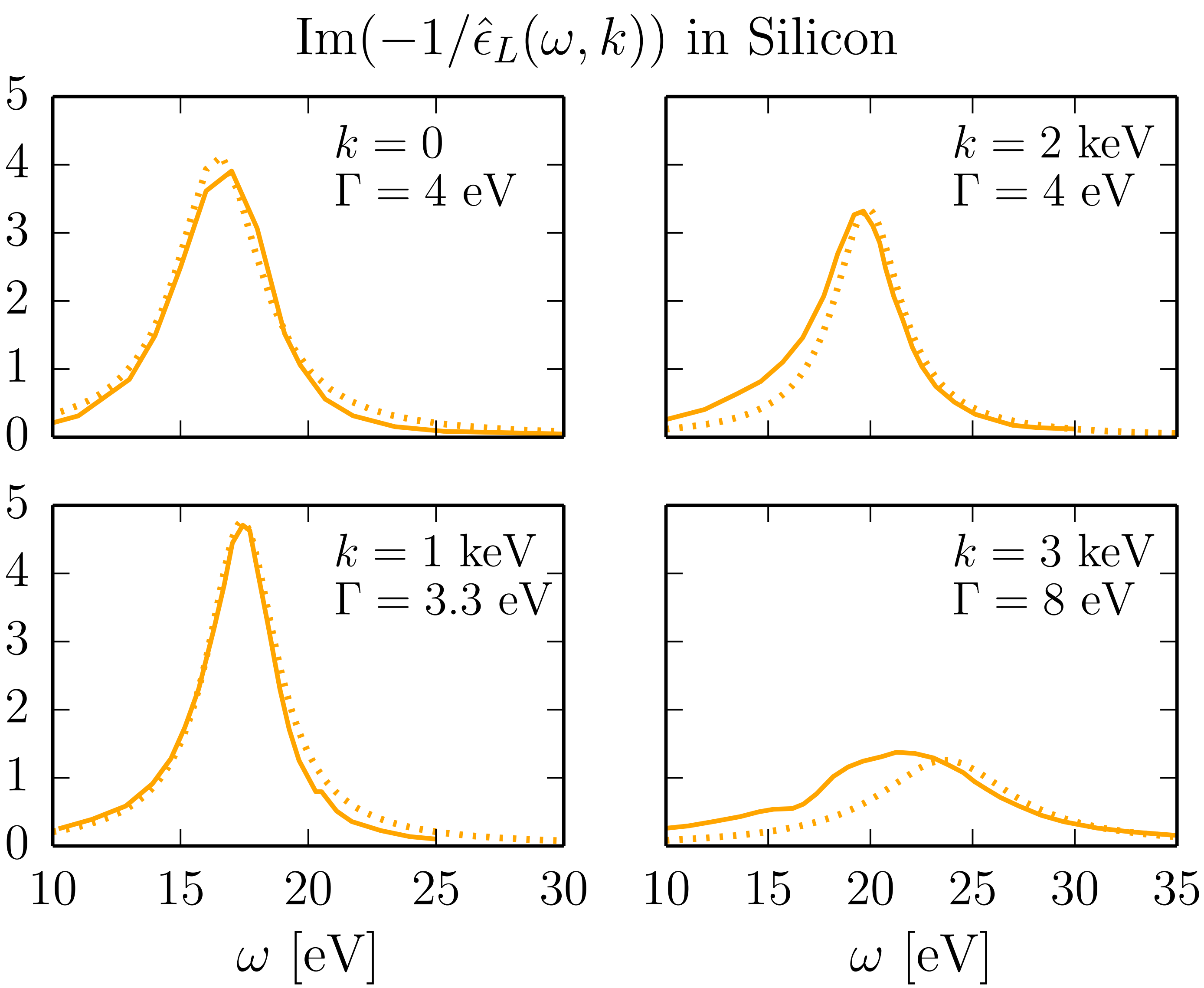
$$J_{\text{ion},L}(\omega, \mathbf{k}) = \frac{i}{\omega} Z_{\text{ion}}\, e\, \mathbf{v}_{\text{ion}} \cdot \frac{\mathbf{k}}{k}$$

$$i\,\omega D_L(\omega, \mathbf{k}) = i\,\omega \hat{\epsilon}_L(\omega, \mathbf{k}) E_L(\omega, \mathbf{k}) = J_{\text{ion},L}(\omega, \mathbf{k})$$

Energy loss rate to longitudinal electronic excitations (not only plasmons)

$$\frac{dW_L}{dk} = \int_0^\infty d\omega \frac{2 Z^2_{\text{ion}} \alpha_{em}}{3\pi^2} |\mathbf{v}_{\text{ion}}|^2 \frac{k^2}{\omega^3} \text{Im}\left(\frac{-1}{\hat{\epsilon}_L(\omega, \mathbf{k})}\right)$$

Energy loss function



Solid: X-ray scattering from Weissker et al. 2010
Dashed: Modified electron gas model

Electron gas picture provides a reasonable approximation of the plasmon pole for simple semiconductor like Si.

Including a finite width Γ for electron gas

$$\mathrm{Im}\left(\frac{-1}{\hat{\epsilon}_L(\omega, \mathbf{k})}\right) \simeq Z_L(\omega, k)\frac{\omega_L(k)^2\omega\Gamma}{\left(\omega^2 - \omega_L(k)^2\right)^2 + \omega^2\Gamma^2}$$

Ionization signals from nuclear recoils

Rate for inelastic process with plasmon production:

$$\frac{dN_L}{d\omega dk} = \frac{4Z_{\text{ion}}^2 \alpha_{em}}{3\pi^2} \frac{E_R}{m_N} \frac{k^2}{\omega^3} \text{Im}\left(\frac{-1}{\hat{\epsilon}_L(\omega, \mathbf{k})} \right)$$

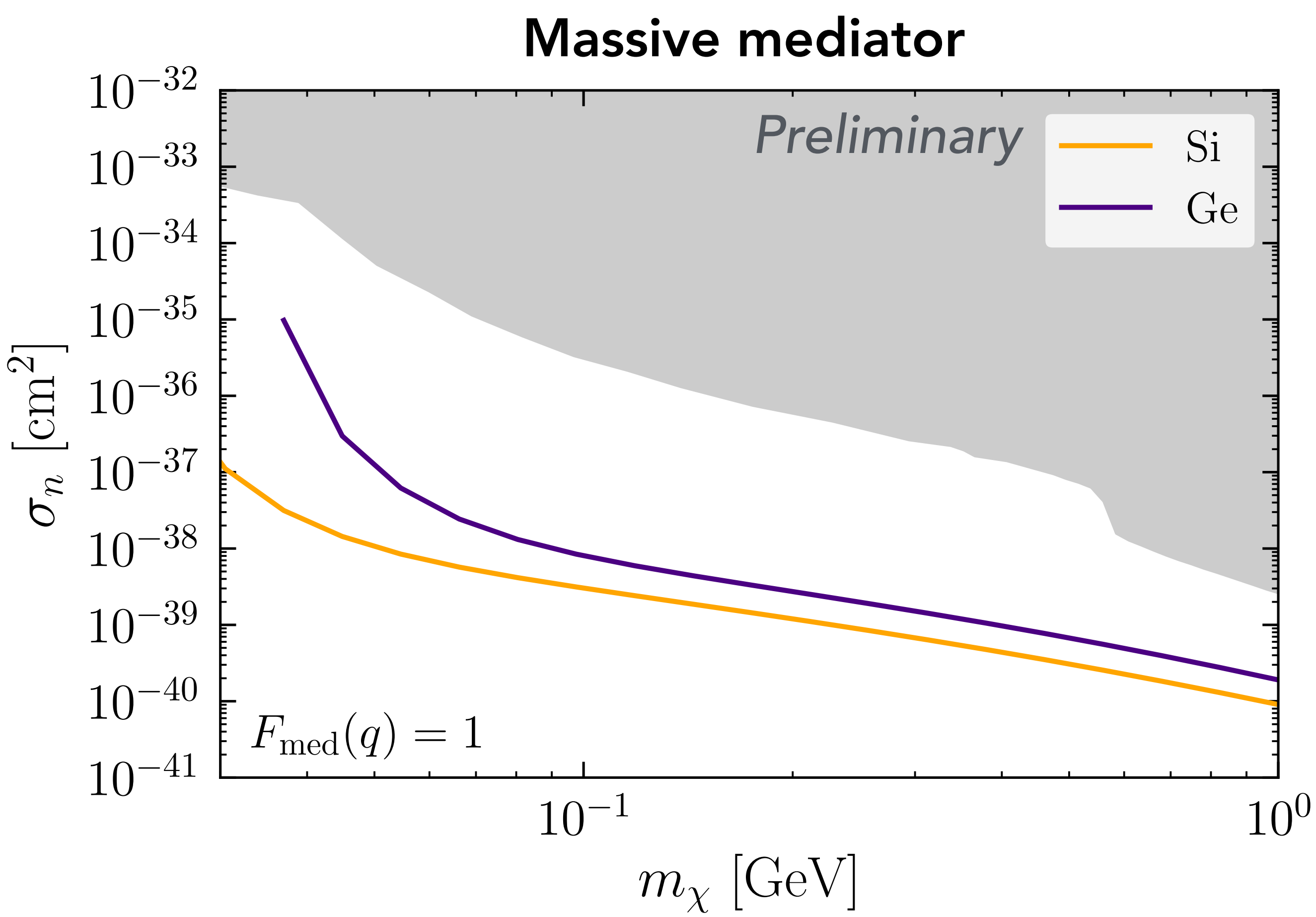
Expect a plasmon resonance at ~16 eV (5-6 electrons). Possible even when expected nuclear recoil is well below 16 eV.

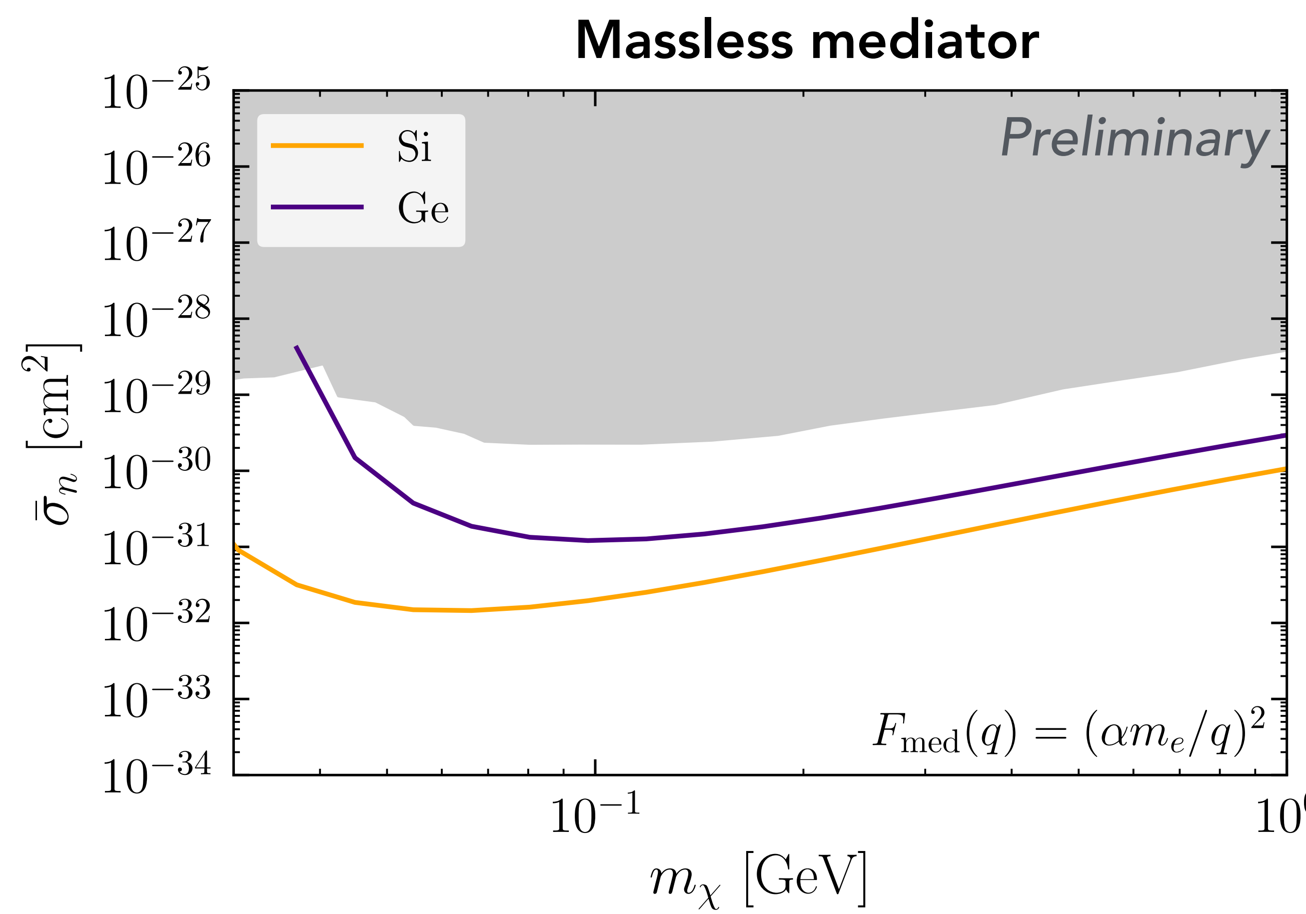
But energy loss function contains **all** electronic excitations (charge signals), even away from plasmon pole.

We can use methods from condensed matter theory to numerically compute the full energy loss function (in progress).

Sensitivity in semiconductors

1 kg-year exposure, assuming E_R > 200 meV to avoid phonon regime





Inelastic charge signal from plasmons + off-resonance
can enhance sensitivity to nuclear recoils from sub-GeV dark matter!

Direct detection with phonons in polar materials

Based on: Pyle, Knapen, TL, Zurek 2018; Griffin, Knapen, TL, Zurek 2018; Griffin, Hochberg, Inzani, Kurinsky, TL, Yu 2020

Why phonons?

1. Two most common elementary excitations in solid state materials: electrons and phonons. Phonons must be considered for low mass dark matter

Momentum transfer $q < 2m_\chi v_{\rm max} \sim 4 \text{ keV} \times (m_\chi/\text{MeV})$

Energy deposited $\omega < \frac{1}{2}m_\chi v_{\rm max}^2 \sim 2 \text{ eV} \times (m_\chi/\text{MeV})$

1/(interparticle spacing)

↓

q >> O(1-10) keV → recoil against individual nuclei

q << O(1-10) keV → excite phonons (lattice/fluid vibrations), most relevant for sub-MeV dark matter

*Numbers are material dependent

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ω >> O(0.1) eV → multiphonon excitations, nuclear recoil

ω << O(0.1) eV → excite single phonons (lattice/fluid vibrations), most relevant for sub-MeV dark matter

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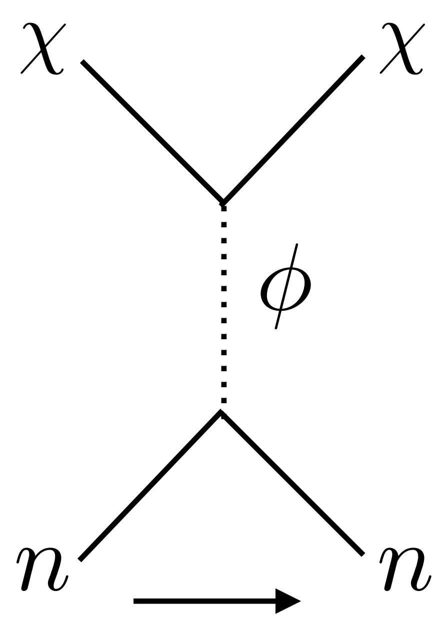
DM-nucleon scattering



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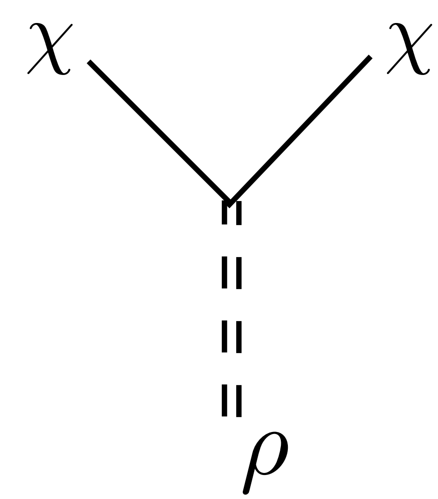


Phonon quasiparticle

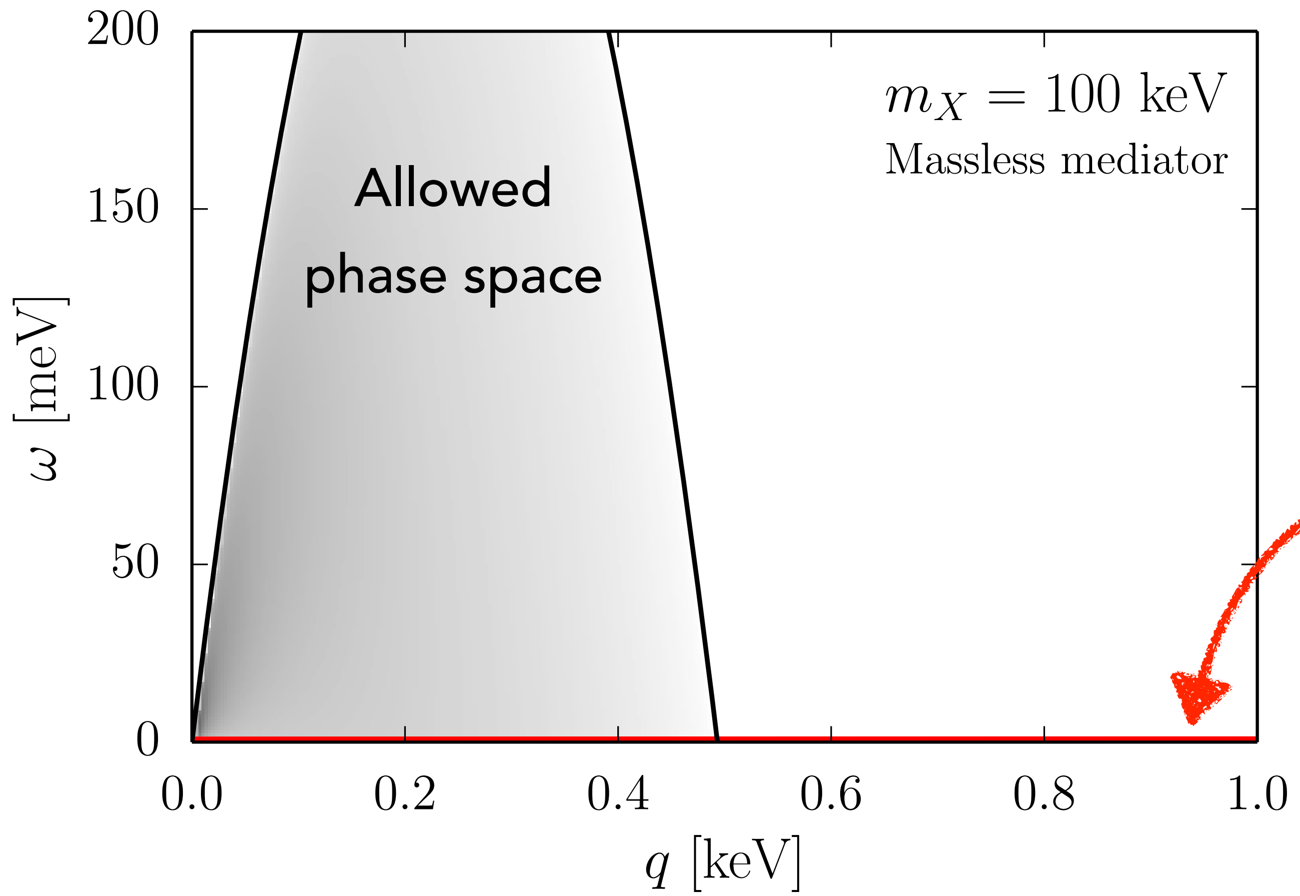
Why phonons?

2. Kinematics of phonon excitation is suited to ~10 keV-MeV dark matter. Phonon energies ~1-100 meV

Initial DM velocity

Energy deposited $$\omega = \mathbf{q} \cdot \mathbf{v}_i - \frac{\mathbf{q}^2}{2m_\chi}$$

q: momentum transfer



Nuclear recoil

$$\omega = \frac{q^2}{2m_N}$$

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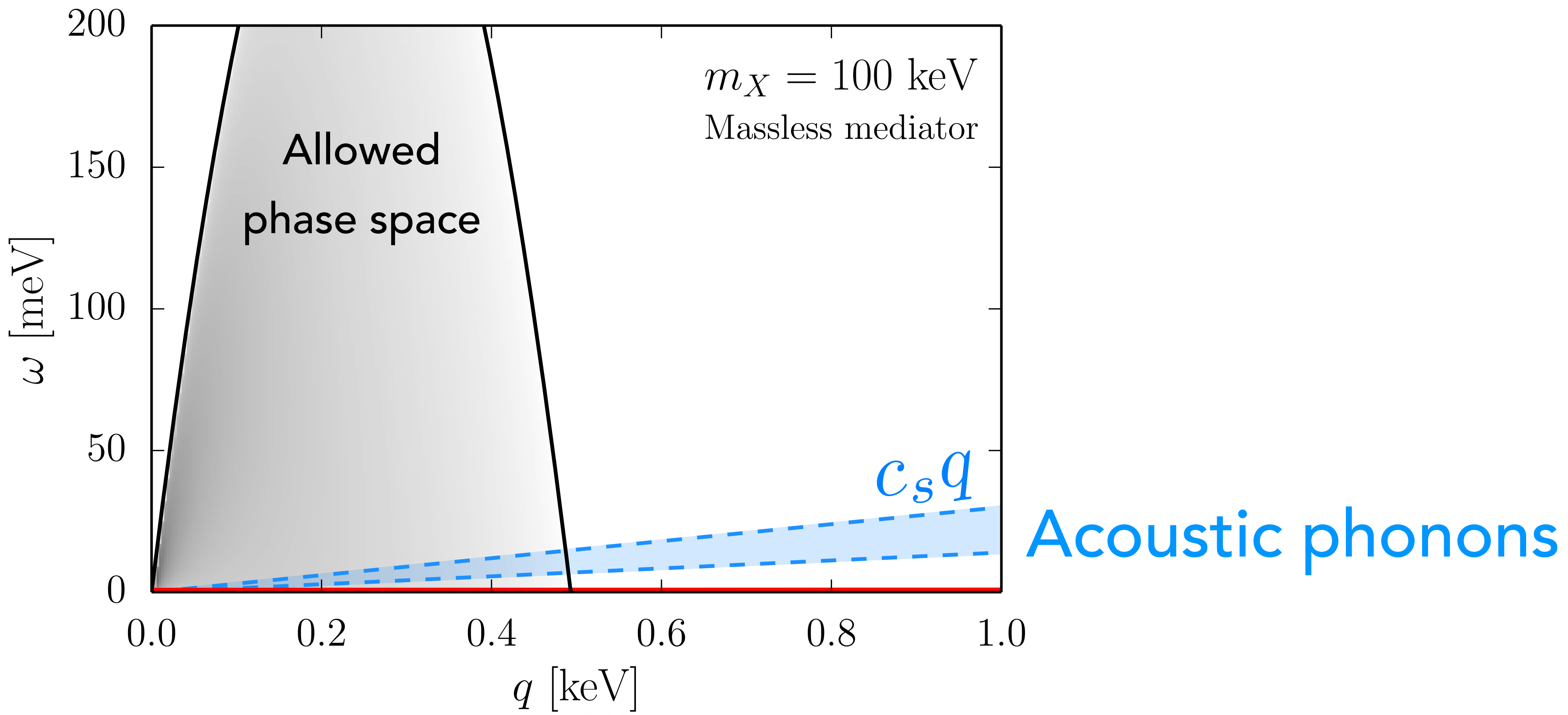

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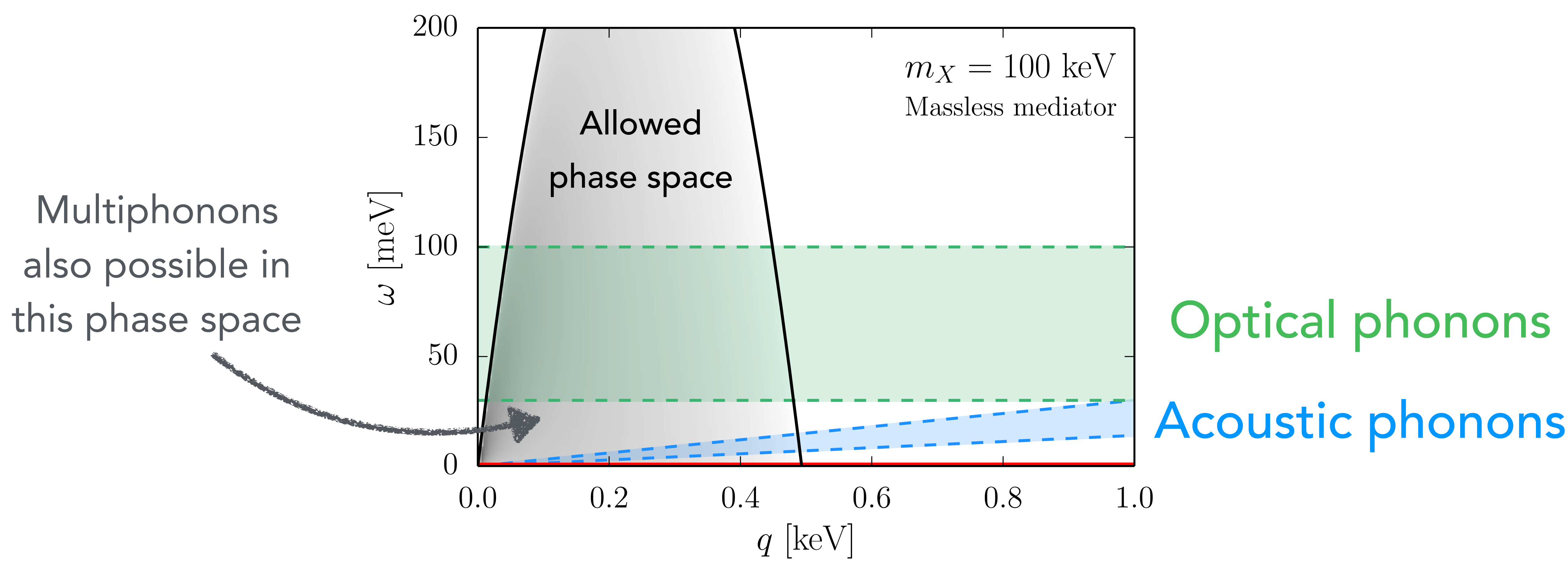


Why phonons?

3. DM-phonon couplings are material dependent, allowing for target & model complementarity

Spin-independent DM-phonon form factor in crystal

Phonon branch ν

$$|F_\nu(q)|^2 \propto \left| \sum_{\text{atoms } j} g_j \, \mathbf{q} \cdot \mathbf{e}_{\nu,j}(\mathbf{q}) \frac{e^{-W_j(q)}}{\sqrt{m_j}} \right|^2$$

DM effective interaction with ion = nucleus + inner shell electrons

$$g_j \approx g_p Z_j + g_n (A - Z)_j + g_e N_j^{e,\text{inner}}$$

phonon eigenmodes, band structure enters here

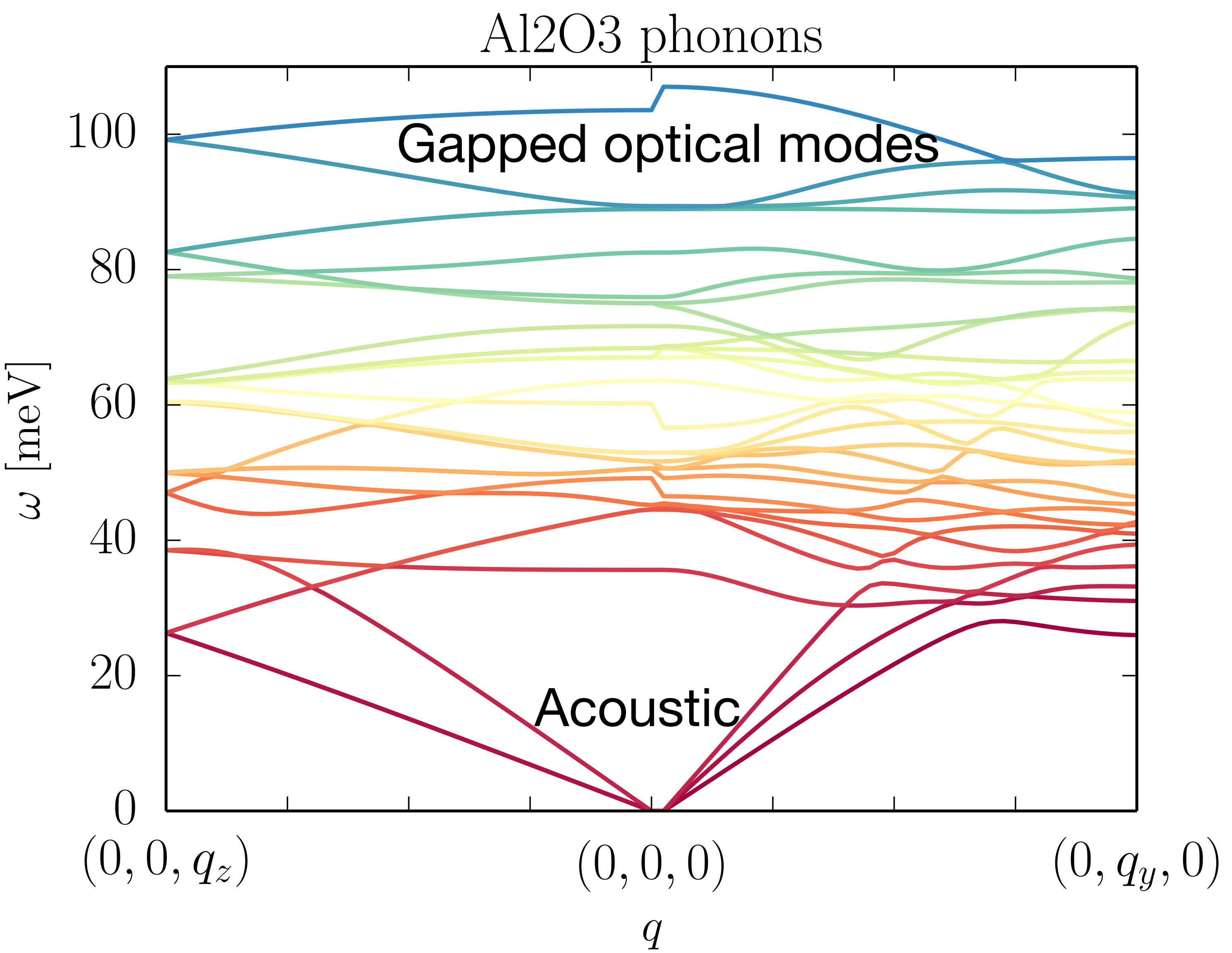
Interplay of DM-ion interaction and phonon modes allows for unique excitation spectrum in each crystal, possible background discrimination

Why phonons?

4. Possible directional signal in anisotropic material

Phonon couplings and energies depend on crystal direction.

Daily rate modulation as crystal rotates relative to DM wind.



Example band structure

Griffin, Knapen, TL, Zurek 1807.10291

Why polar materials?

Longitudinal acoustic (LA)

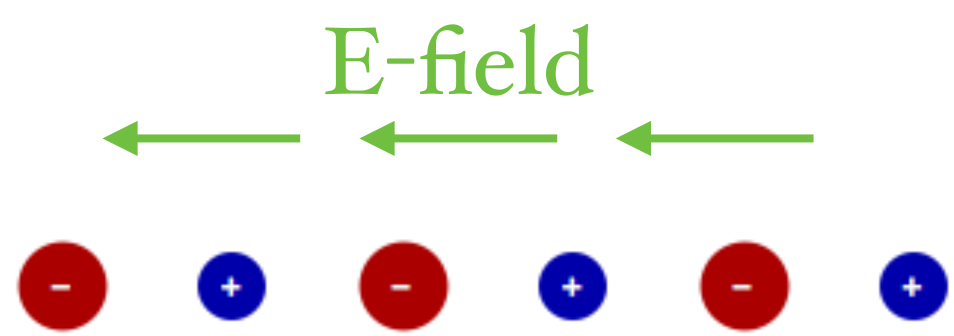
Problem: for dark photon mediator, destructive interference

Why polar materials?

Longitudinal acoustic (LA)

Problem: for dark photon mediator, destructive interference

Longitudinal optical (LO)



LO phonons ~ coherently oscillating dipoles

Dark photon mediator can couple to dipole moment (optical phonon) in a polar material

$$\mathcal{M} \propto \frac{Qe^2}{\epsilon_\infty |\mathbf{q}|^2} \mathbf{q} \cdot (Z\mathbf{u})$$

Ion displacement (dipole)

SiC for direct detection

Advantages of SiC:

1. Intermediate between Si and diamond, while retaining key advantages of diamond such as high sound speed

2. Cost effective!

3. Polar semiconductor where Si and diamond are not

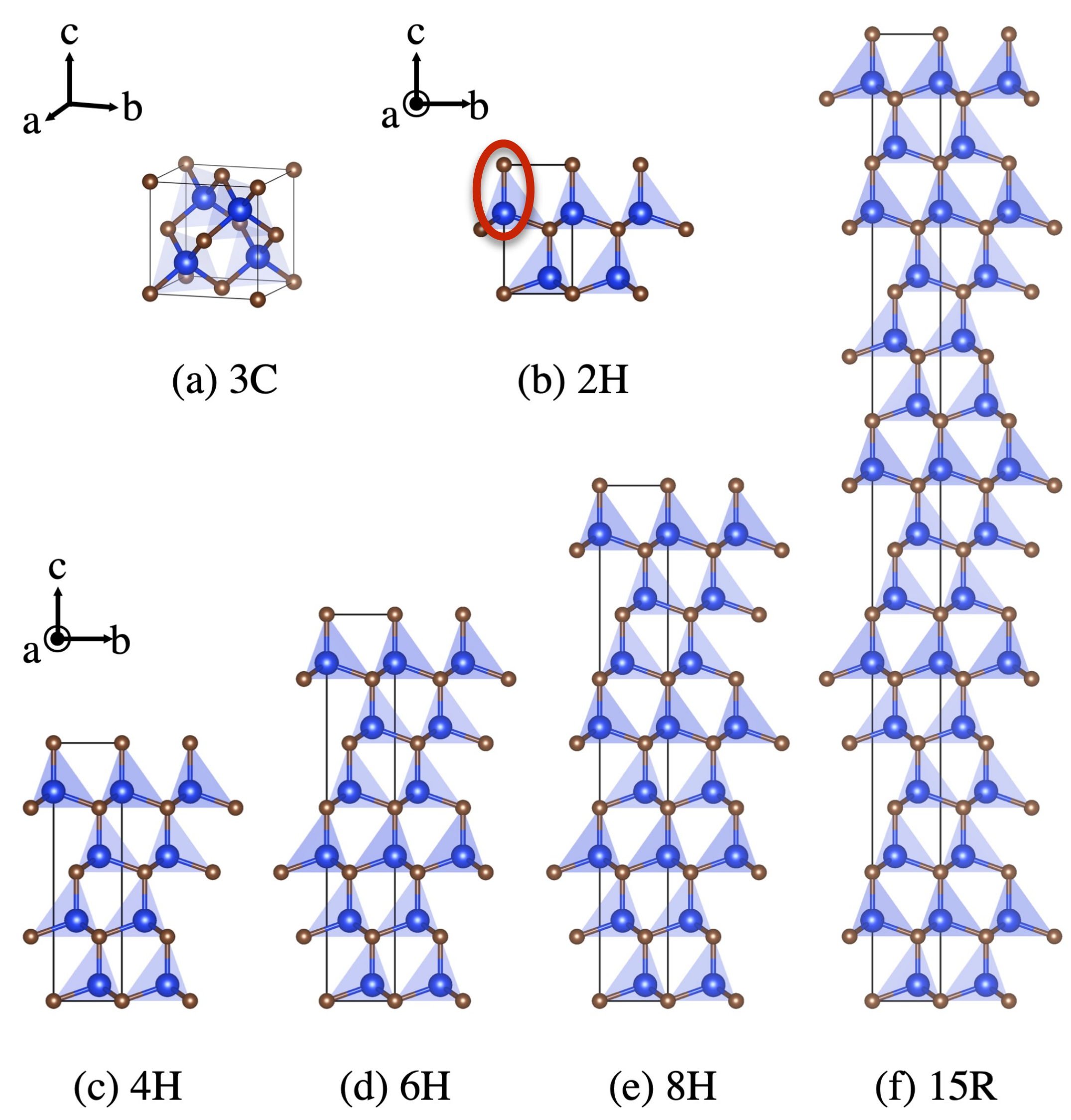
4. Many stable polytypes with tunable DM sensitivity

Griffin, Hochberg, Inzani, Kurinsky, TL, Yu 2020

SiC for direct detection

Many stable polytypes of SiC with little difference in energy — feature of the large charge asymmetry in the SiC bond.

Different polytypes and different crystal structures obtained by stacking layers in various ways.

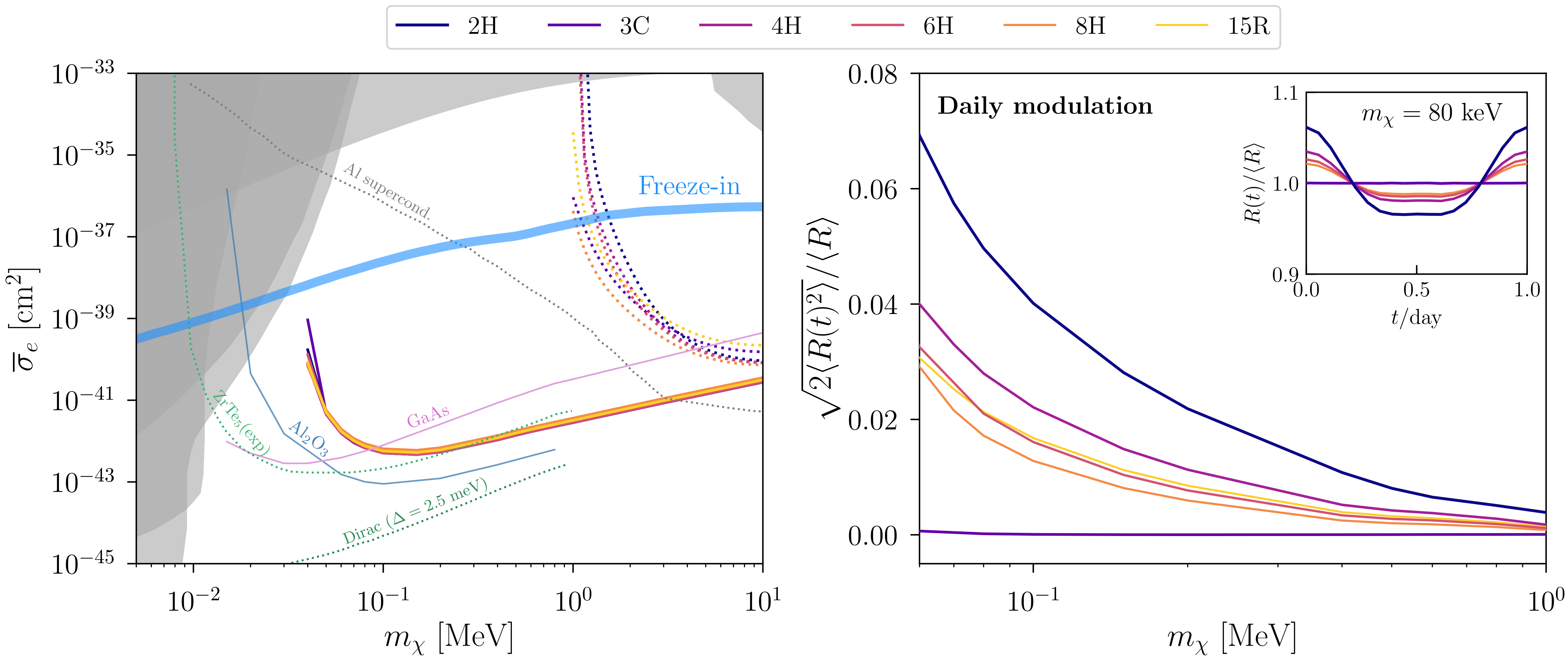


Blue: Si   Brown: C

Griffin, Hochberg, Inzani, Kurinsky, TL, Yu 2020

SiC for direct detection

Sensitivity to freeze-in with optical phonons



Maximum directionality for hexagonal 2H phase, minimum for cubic 3C phase

Modulation becomes smaller with more layers inside a unit cell

Can we design more optimal dark matter detection materials?

Griffin, Hochberg, Inzani, Kurinsky, TL, Yu 2020

Quasiparticle excitations beyond single phonon or plasmon

- **Multiphonon excitations** - less restrictive final phase space and larger energy deposition can compensate for penalty in emitting extra phonons.
  - **Superfluid He:** Schutz and Zurek 2016; Knapen, TL, Zurek 2016; Acanfora, Esposito, Polosa 2019; Baym, Beck, Filippini, Pethick, Shelton 2020
  - **Semiconductors:** Campbell-Deem, Cox, Knapen, TL, Melia 2019

- **Magnons -** spin-wave analog of phonon for spin-dependent interactions.
  Barbieri, Cerdonio, Fiorentini, Vitale 1989; Flower, Bourhill, Goryachev Tobar 2018; Trickle, Zhang, Zurek 2019; Chigusa, Moroi, Nakayama 2020

Summary

To understand sub-GeV DM scattering in materials, we need to understand the material response, including collective excitations or quasiparticles.

DM excitations of plasmons and phonons are promising ways to search for DM-nuclear recoils.

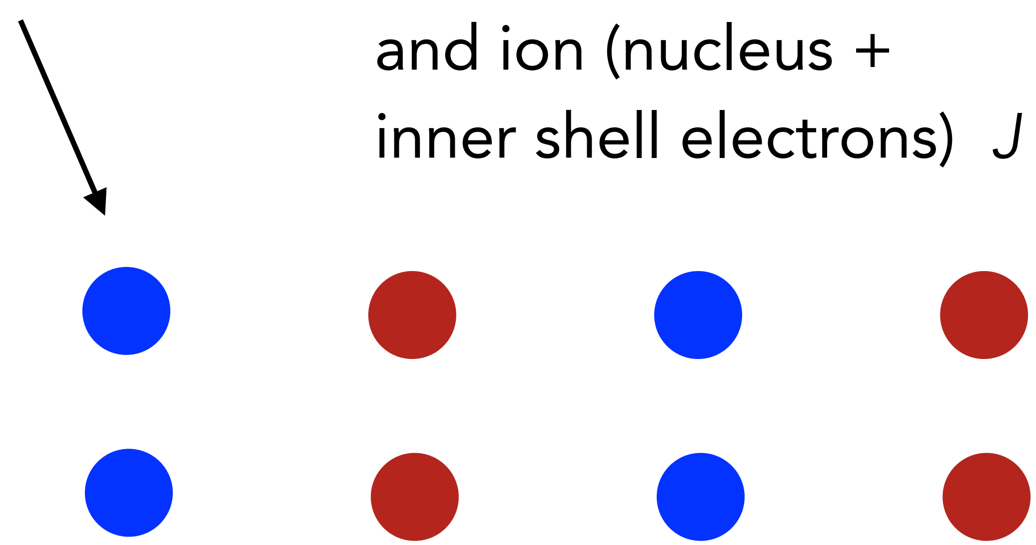
Thanks!

Extra

Dynamic structure factor

• χ

g_J - effective coupling strength between DM and ion (nucleus + inner shell electrons) J



Short range potential

$$\sigma_{\chi p} = 4\pi b_{\chi p}^2$$

$$V(\mathbf{q}) = \frac{2\pi b_{\chi p}}{g_p m_\chi} \sum_J g_J e^{-i\mathbf{q}\cdot\mathbf{r}_J}$$

Need to characterize expectation value of this in material

Scattering rate goes as

$$S(\mathbf{q},\omega) \equiv \frac{1}{N} \sum_{\lambda_f} \left| \sum_J g_J \langle \lambda_f | e^{-i\mathbf{q}\cdot\mathbf{r}_J} | 0 \rangle \right|^2 \delta(E_{\lambda_f} - \omega)$$

Dynamic structure factor

Phonon comes into play through positions of ions:

$$\mathbf{r}_J(t) = \mathbf{r}_J^0 + \mathbf{u}_J(t)$$

Quantized displacement field $\mathbf{u}_J(t) \sim \sum_{\mathbf{q}} \frac{1}{\sqrt{2NM_J\omega_{\mathbf{q}}}} \left(\hat{a}_{\mathbf{q}}^\dagger \mathbf{e}_{\mathbf{q}}^* e^{i\omega_{\mathbf{q}} t} + \text{h.c.}\right)$

Expansion in factors of the displacement

$$S(\mathbf{q}, \omega) = \text{(0-phonon)} + \text{(1-phonon)} + \text{(2-phonon)} + \cdots$$

Debye-Waller factor ≈ 0

$$S(\mathbf{q}, \omega) \approx \sum_{\nu} \frac{1}{\omega_\nu(\mathbf{q})} \left| \sum_{\substack{\text{atoms } j \\ \text{in unit cell}}} g_j \, \mathbf{q} \cdot \mathbf{e}_{\nu,j}(\mathbf{q}) \frac{e^{-W_j(q)}}{\sqrt{m_j}} \right|^2 \delta\left(\omega - \omega_\nu(\mathbf{q})\right)$$

[1-phonon]

Questions