Theory overview of DM-induced phonon excitations

Tongyan Lin
UCSD

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For extended discussion of theory framework, see:
TL, 1904.07915 (lecture notes);
Griffin, Knapen, TL, Zurek 1807.10291 (crystals);
Knapen, TL, Zurek 1611.06228 (superfluid He);
additional refs cited throughout this talk

Outline

Why phonons?

Calculating DM-phonon excitations

Lessons and future work

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

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

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

Why phonons?

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

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

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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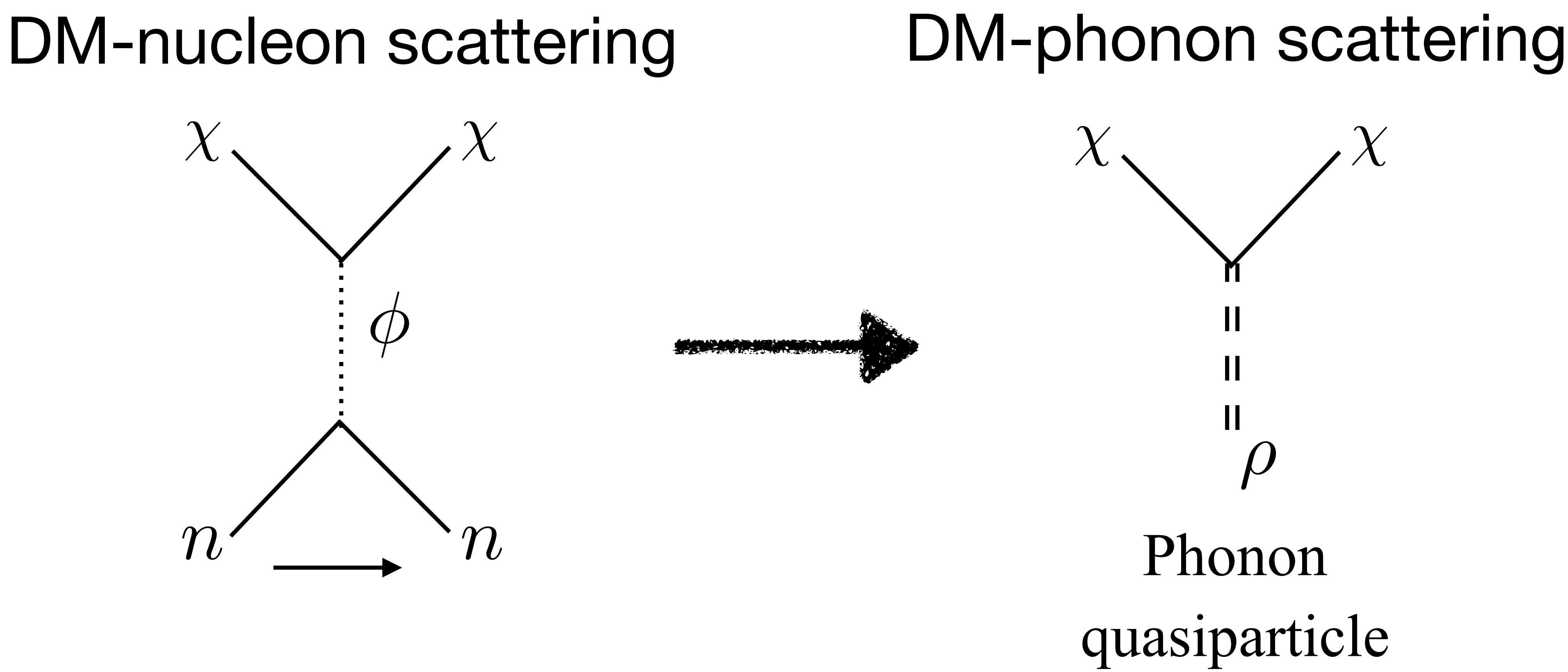
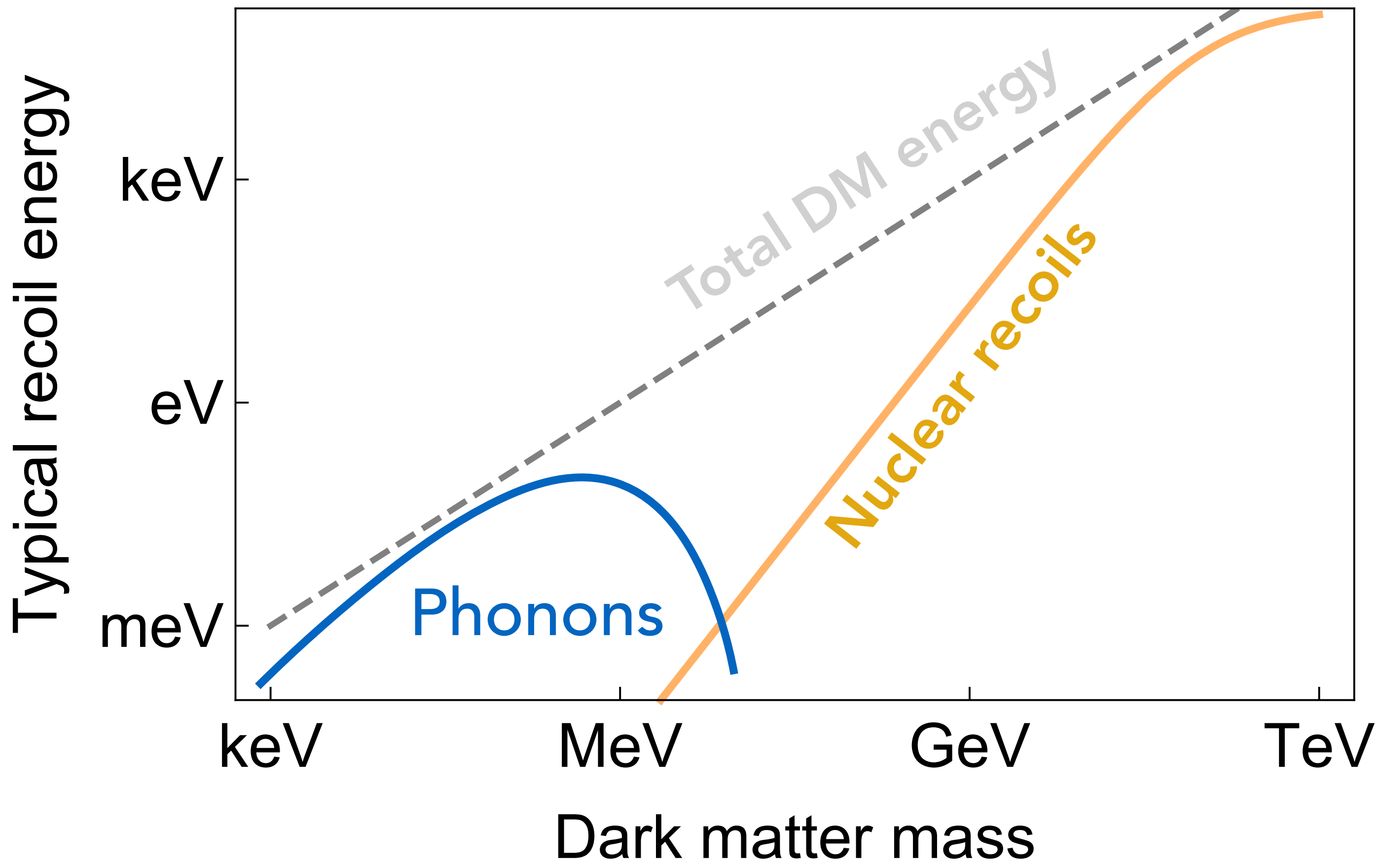
Why phonons?

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



Why phonons?

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



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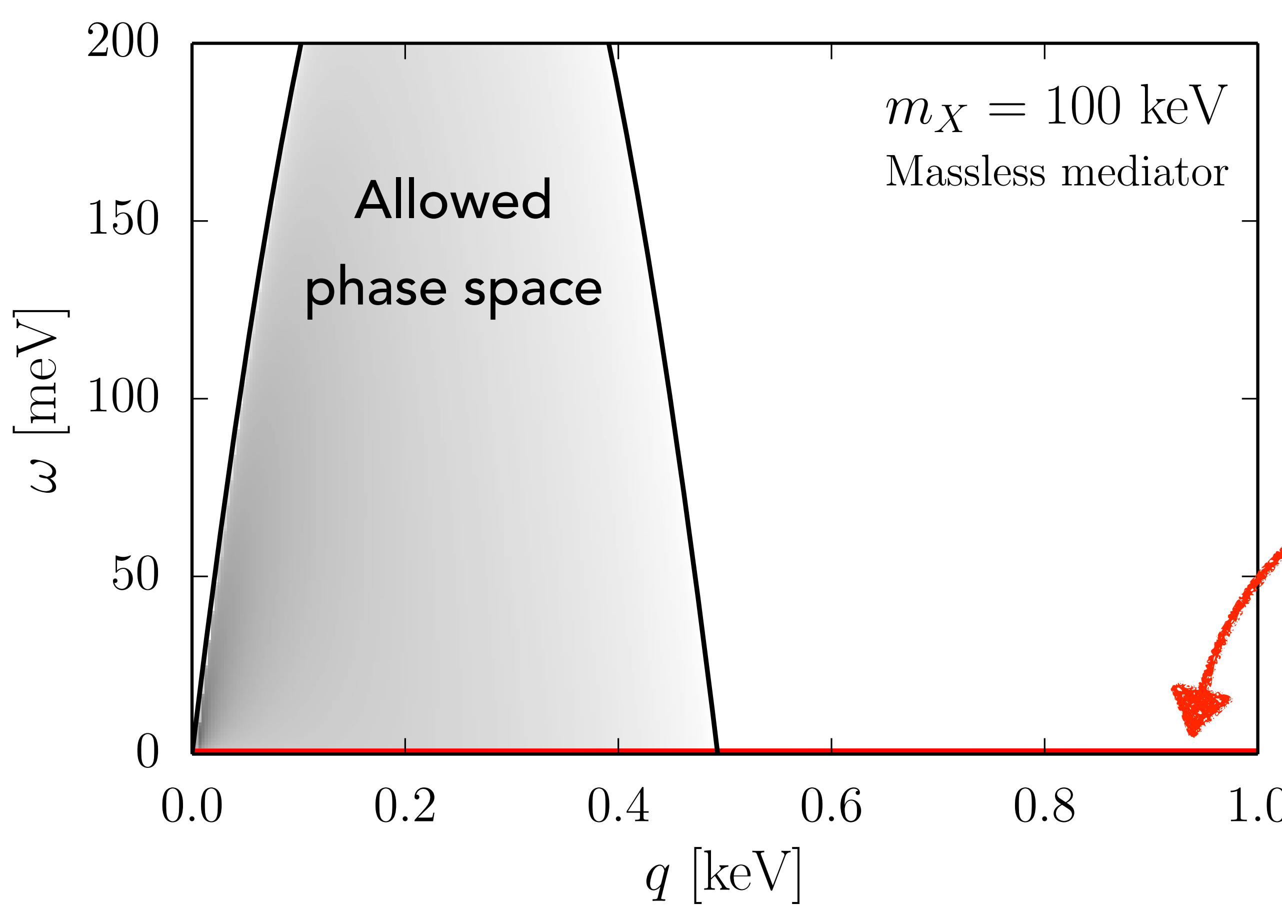
Initial DM velocity

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

$\mathbf{q}$: momentum transfer



Nuclear recoil

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

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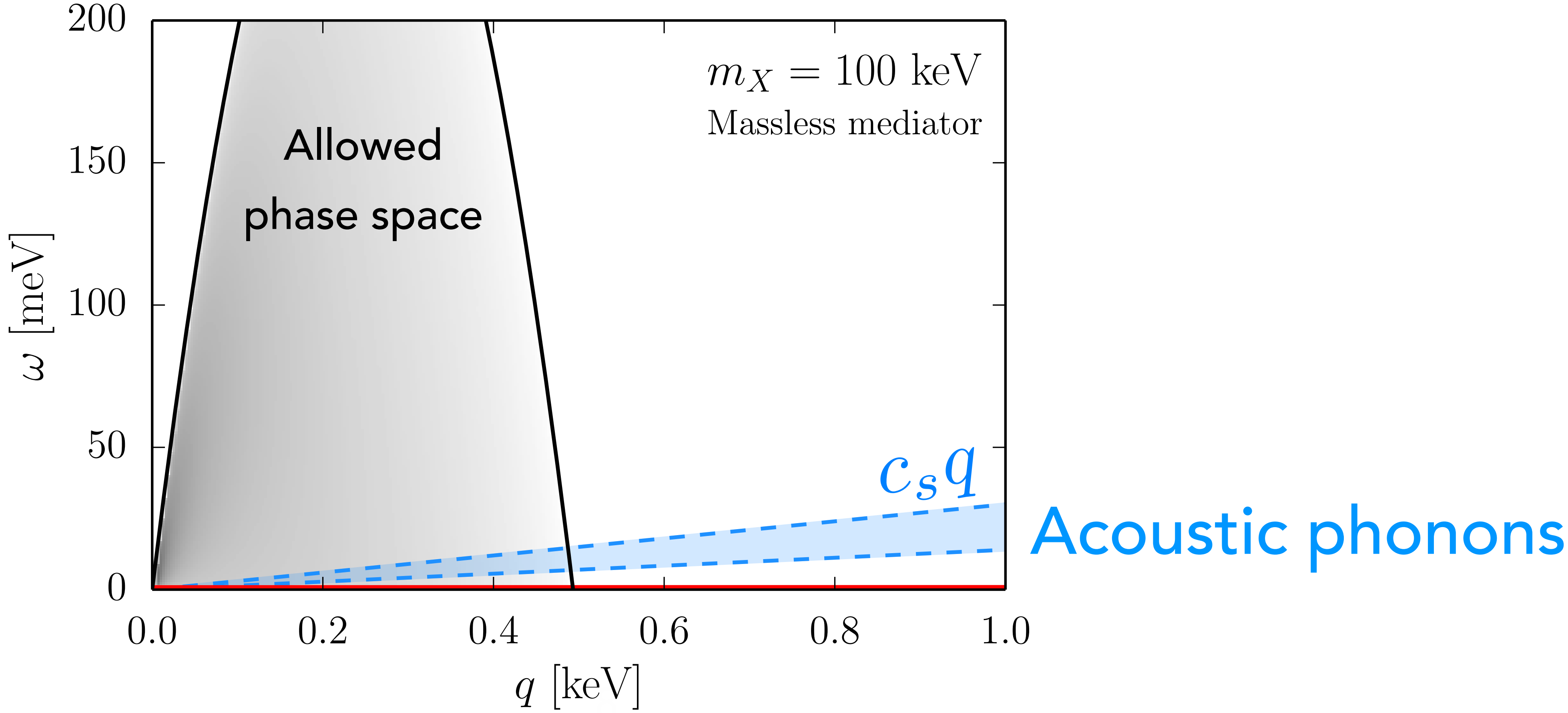

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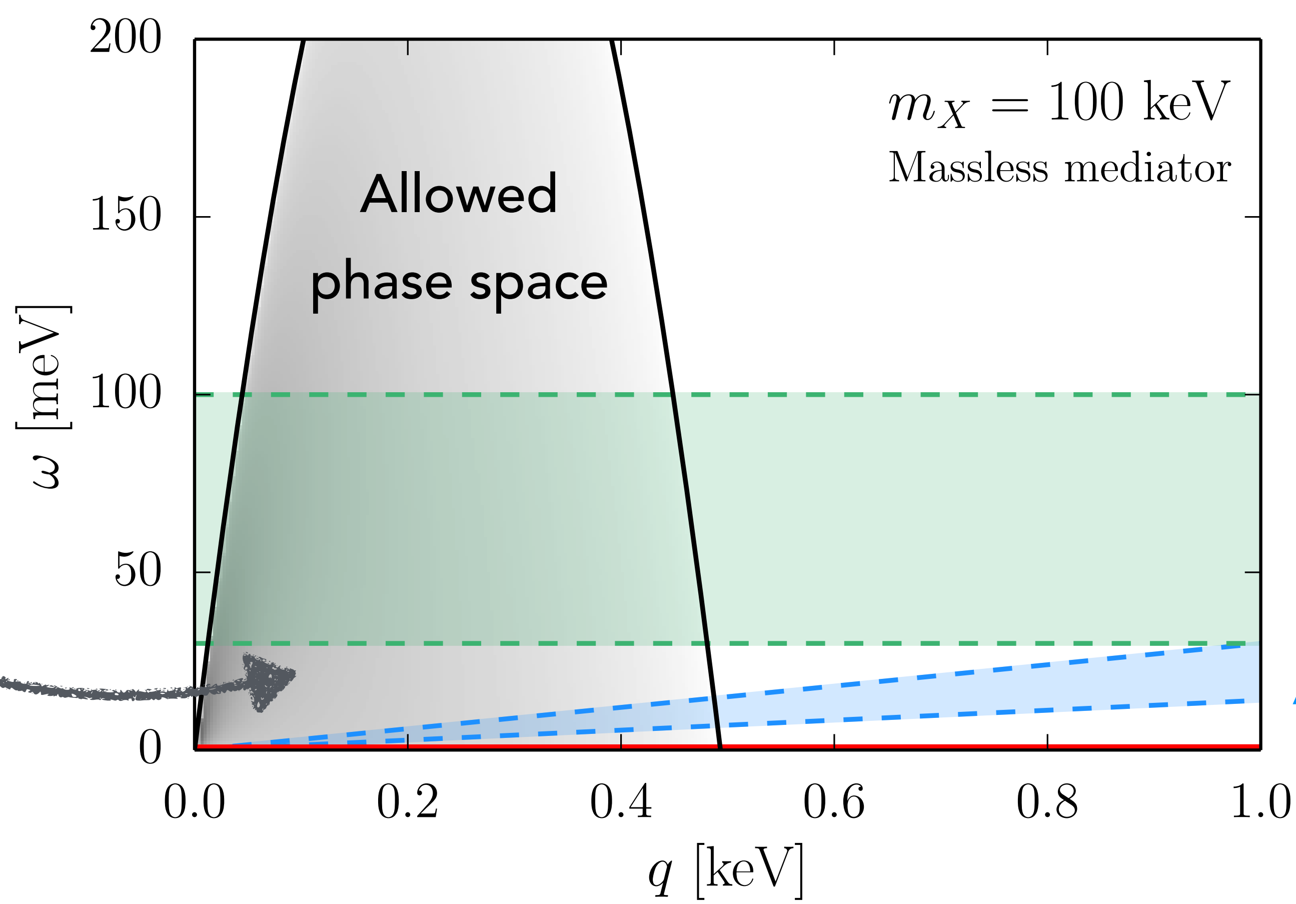
Multiphonons also possible in this phase space



Optical phonons

Acoustic phonons

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

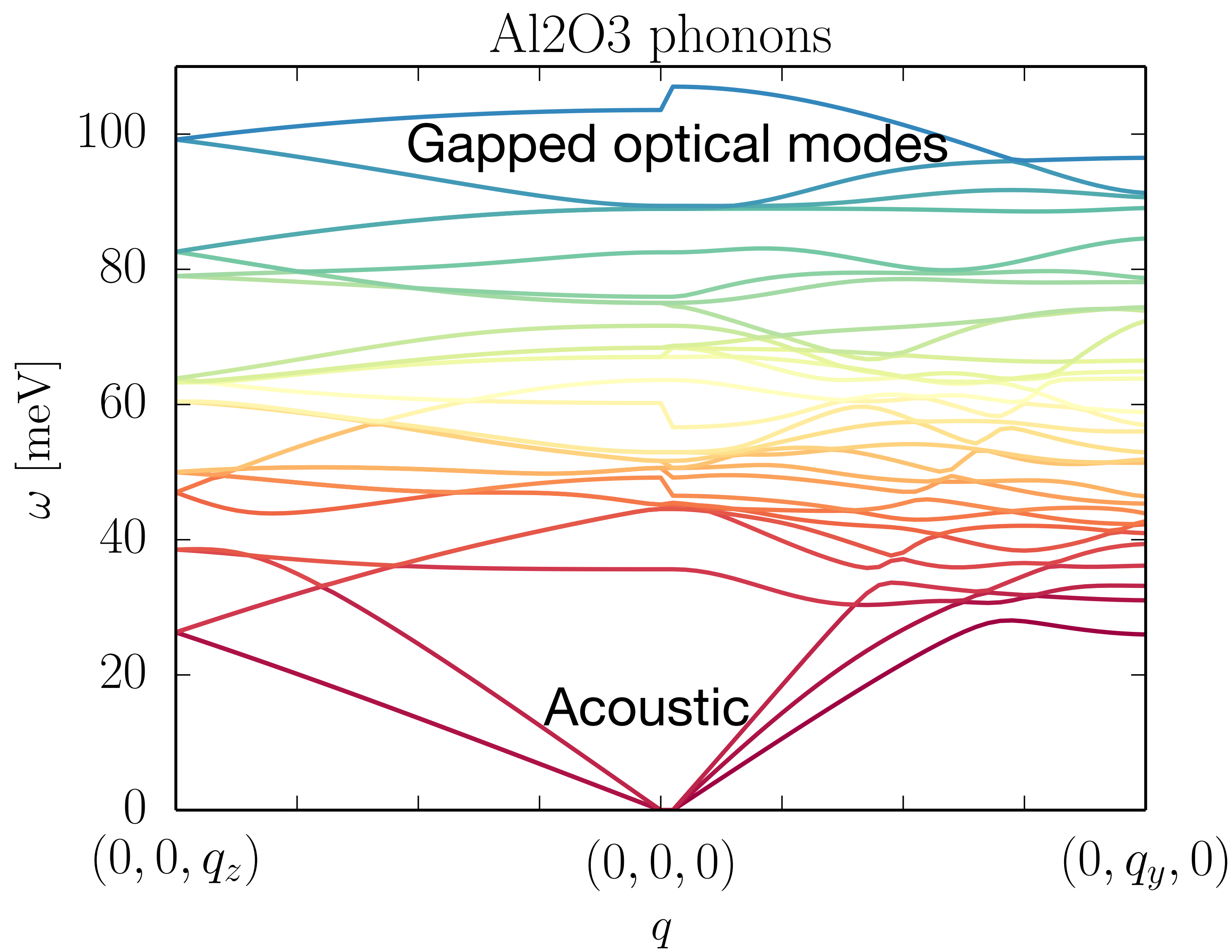
Interplay of DM-ion interaction and phonon modes allows for unique excitation spectrum in each crystal, possible background discrimination

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.

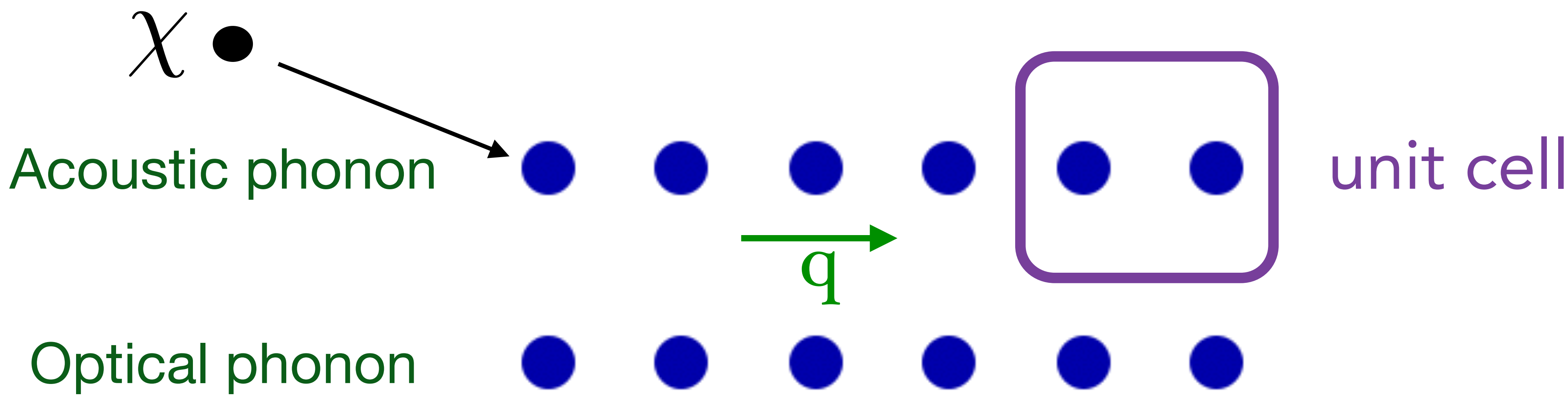


Example band structure

Griffin, Knapen, TL, Zurek 1807.10291

Theory framework for calculating DM-phonon excitations

Solve eigenvalue problem: $\sum_{j'} \mathbf{D}_{\mathbf{q},j,j'} \cdot \mathbf{e}_{\nu,j'}(\mathbf{q}) = \omega^2_{\nu,\mathbf{q}} \mathbf{e}_{\nu,j}(\mathbf{q})$

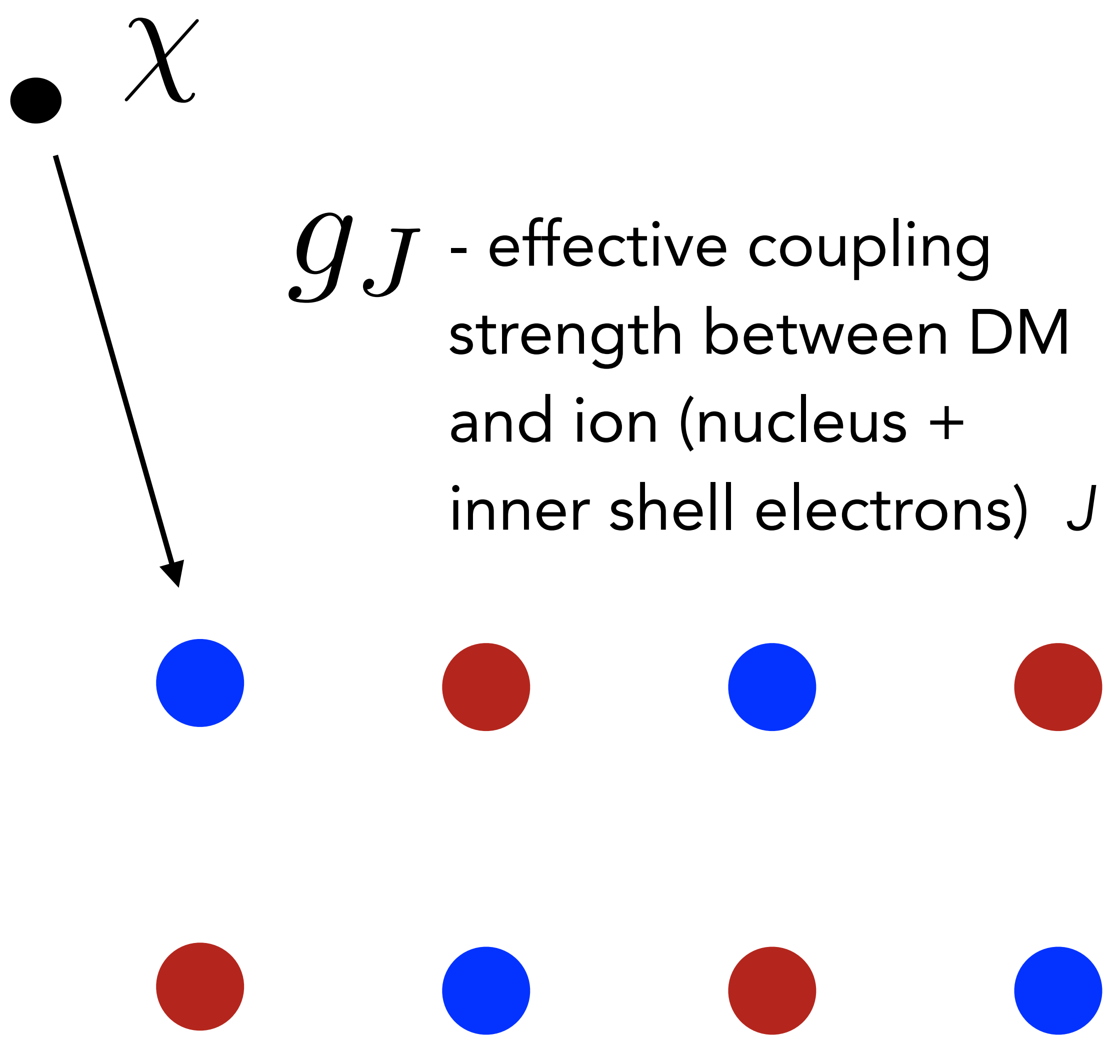


Dark matter can excite a given phonon when forces on all the ions constructively interfere in the right way.

In particle physics language, we have to match interactions with individual ions to the EFT of phonon excitations.

DM-ion interaction

Assuming spin-independent interactions to ion



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

Short range potential

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

$$V(\mathbf{r}) = \frac{2\pi b_{\chi p}}{g_p m_\chi} \sum_J g_J \delta(\mathbf{r} - \mathbf{r}_J)$$

In Fourier space

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

DM-ion interaction

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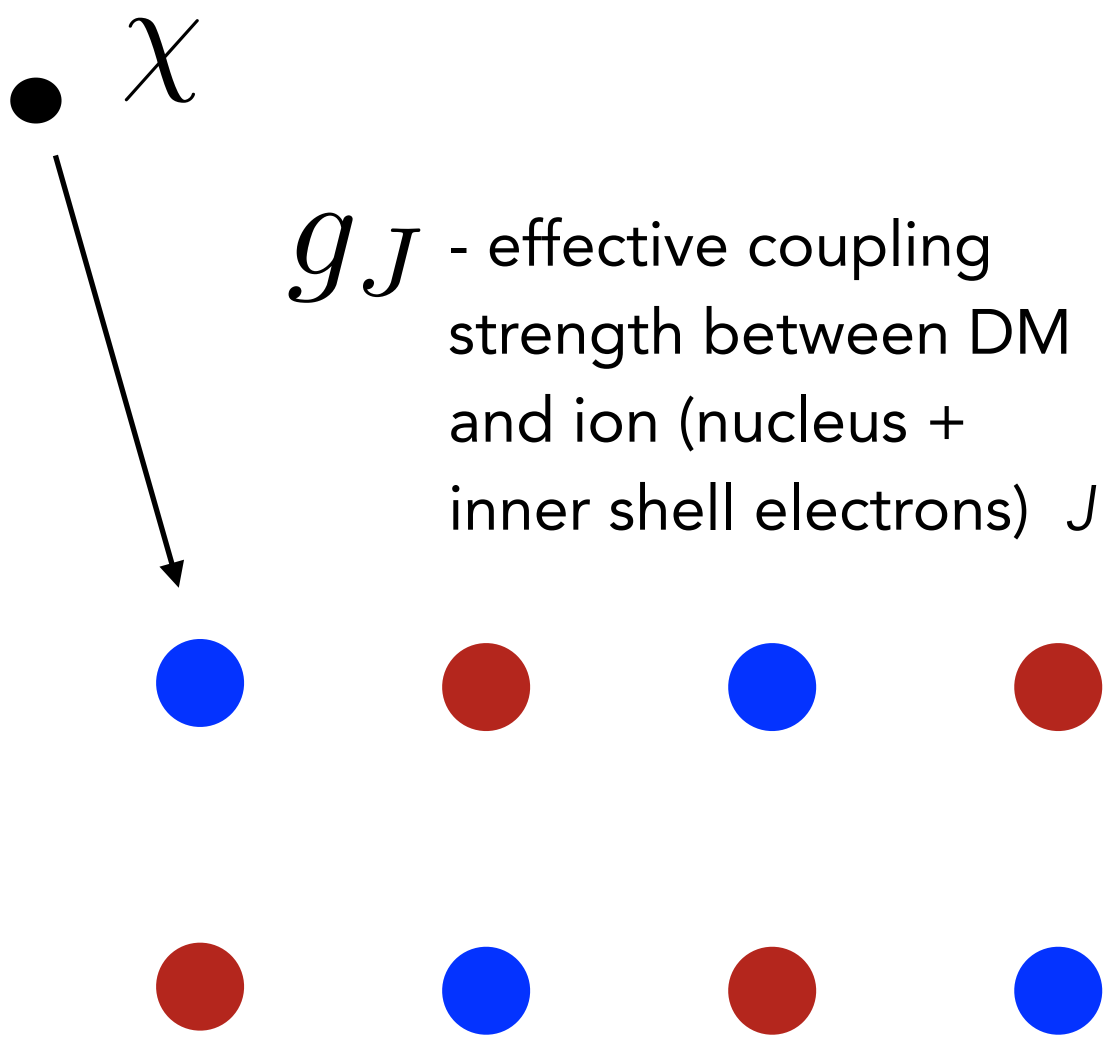


g_J - effective coupling strength between DM and ion (nucleus + inner shell electrons) J

Long range potential

$$V(\mathbf{r}) = \sum_J \frac{g_J}{|\mathbf{r} - \mathbf{r}_J|}$$

In Fourier space

$$V(\mathbf{q}) = \frac{1}{\mathbf{q}^2} \sum_J g_J e^{-i\mathbf{q}\cdot\mathbf{r}_J}$$

Need to characterize expectation value of this in material

Dynamic structure factor

Scattering off a cold target in ground state:

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

Total DM scattering rate:

$$\Gamma(\mathbf{v}_i) \propto \int d^3\mathbf{q}\, \sigma_{\chi p}(\mathbf{q}) S(\mathbf{q},\omega)$$

Called the dynamic structure factor for neutron scattering where $g_J = A_J$

Need more general class of dark matter structure factors depending on models & form of interactions

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

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

$$+ \ \text{(1-phonon)} \quad \longleftarrow \quad \sim \langle \mathbf{q}\cdot\mathbf{u}_J \ \mathbf{q}\cdot\mathbf{u}_{J'} \rangle \times \delta\left(\omega - \omega_\nu(\mathbf{q})\right)$$

$$+ \ \text{(2-phonon)} + \cdots$$

Expansion in $q^2/(M_N\omega)$ and in anharmonic phonon interactions

Single phonon excitations

Debye-Waller factor ≈ 0

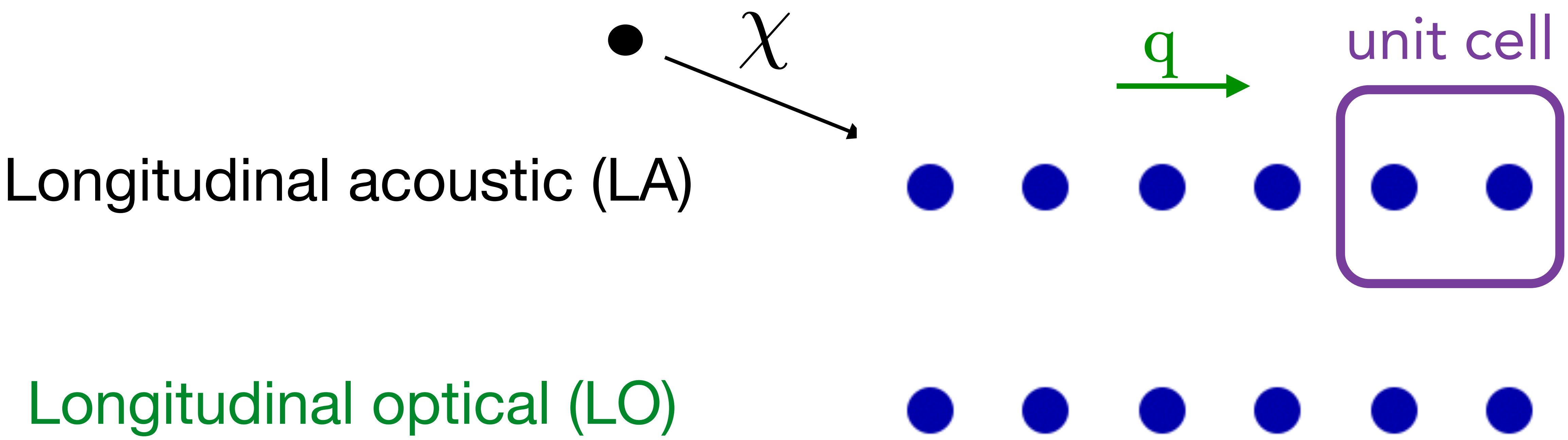
$$\underset{[\text{1-phonon}]}{S(\mathbf{q},\omega)} \approx \sum_{\nu} \frac{1}{\omega_\nu(\mathbf{q})} \left| \sum_{\substack{\text{atoms } j \\ \text{in unit cell}}} g_j \, \mathbf{q} \cdot \mathbf{e}_{\nu,j}(\mathbf{q}) \frac{e^{-W_j(q)}}{\sqrt{m_j}} \right|^2 \delta\left(\omega - \omega_\nu(\mathbf{q})\right)$$

Form factor for spin-independent interaction to excite a phonon in branch ν with momentum q

Spin-independent interactions of low mass DM excite single longitudinal phonons

Which longitudinal phonons get excited depends on g_j

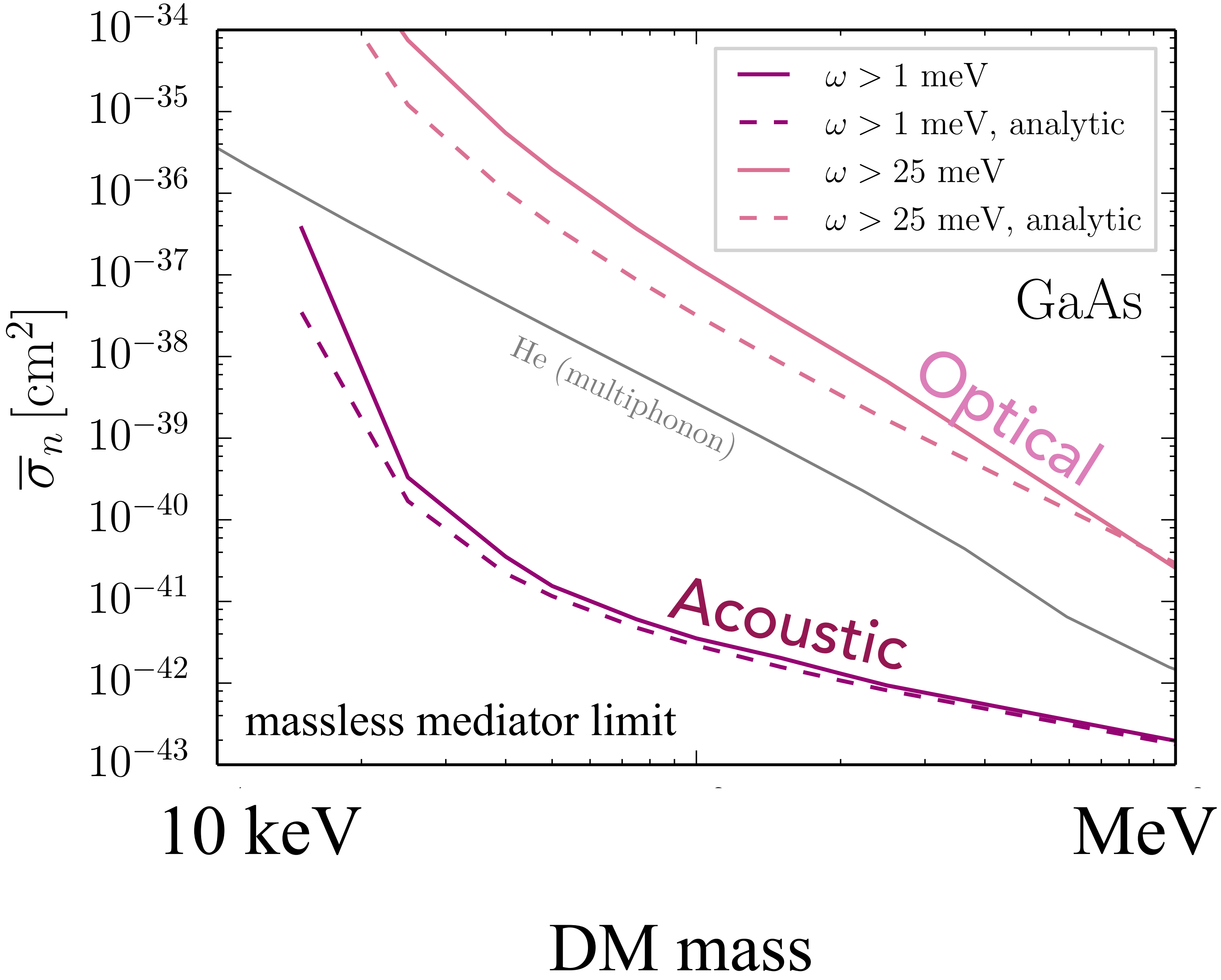
Single phonon excitations



Dark matter that couples to nucleon number excites acoustic phonons most easily (constructive interference). There is a large suppression in coupling to optical phonons (destructive interference).

Optical vs. acoustic

DM coupling to nucleon number

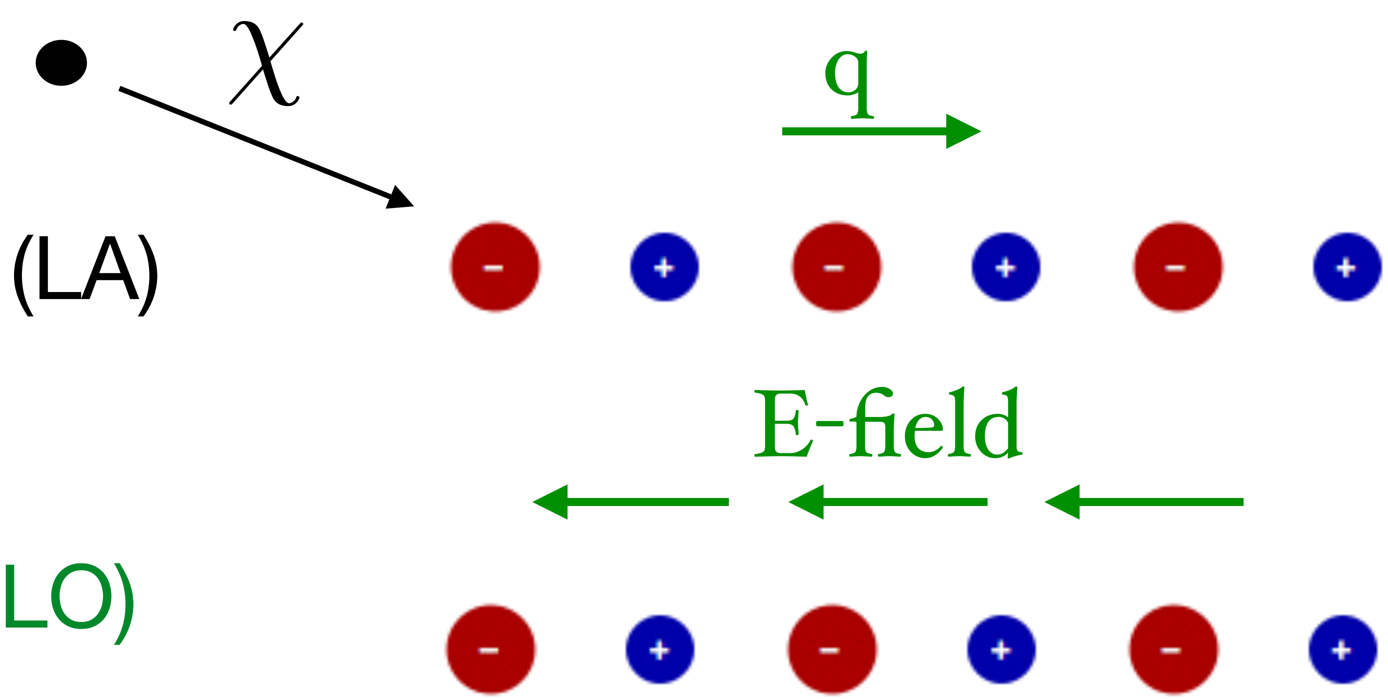


all projections assume kg-yr exposure
Superfluid He: Knapen, TL, Zurek 2017
See also Cox, Melia, Rajendran 1905.05575

DM coupling to charge

Longitudinal acoustic (LA)

Longitudinal optical (LO)



= Oppositely charged ions in crystal

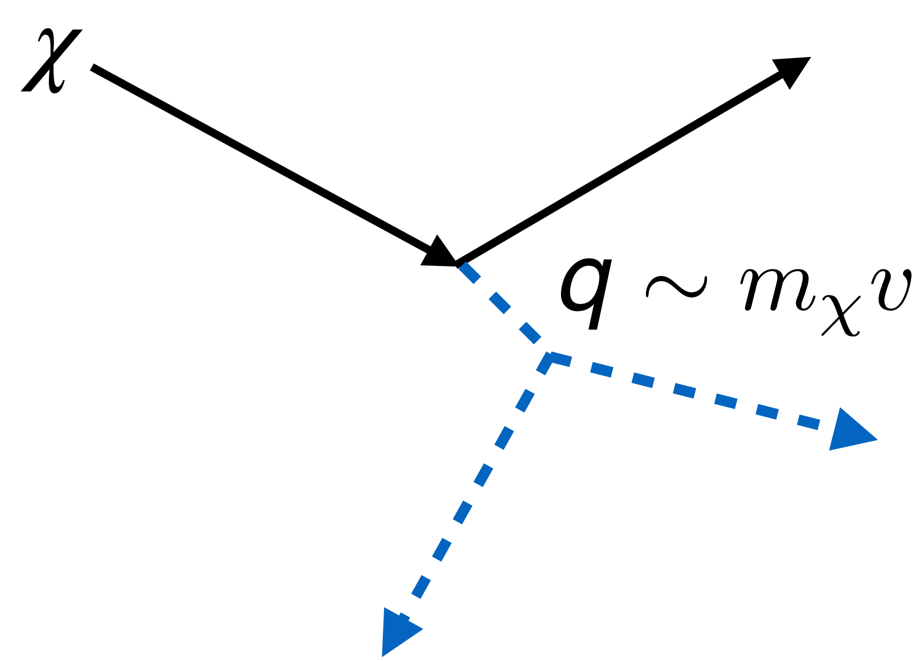
Dark matter that couples to electric charge (such as freeze-in benchmark) excites optical phonons in polar materials

(see talk by S. Griffin)

Knapen, Pyle, TL, Zurek 1712.06598
Griffin, Knapen, TL, Zurek 1807.10291

Multiphonon excitations

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



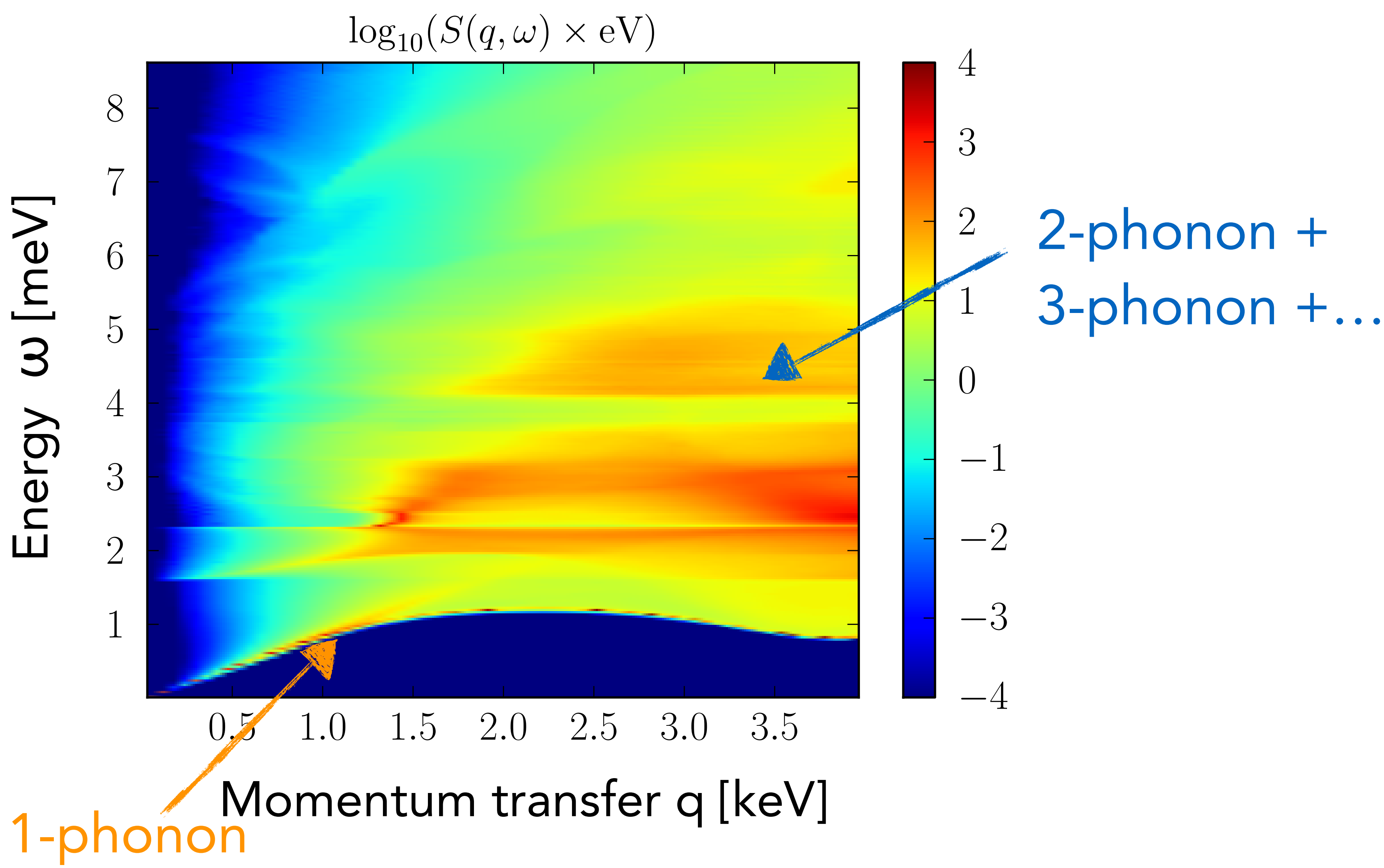
Expansion in $q^2/(M_N\omega)$ and in anharmonic phonon interactions

Less restrictive final space and larger energy deposition can compensate for penalty in emitting extra phonon

Schutz and Zurek 1604.08206
Knapen, TL, Zurek 1611.06228
Acanfora, Esposito, Polosa 1902.02361

Multiphonon excitations

Dynamic structure factor S(q,ω) in superfluid He



Resummed calculation from Campbell et al. 2015

To-do list & wish list

- Single and multiphonon excitations from neutron scattering or other sources, for calibrating DM signals and detectors?

- Dynamical structure factors in crystals with multiphonon excitations (in progress w/ S. Knapen,…)

- Promising quasiparticle excitations beyond phonons, for a variety of spin-independent, spin-dependent (talk by K. Zhang) or other interactions

Summary

DM-induced excitations of phonons (or any collective excitations in target) are a natural and promising avenue in direct detection of sub-MeV DM.

Basic theory ideas are in place, but many different directions to go!

Thanks!