Detection of Light Dark Matter With Optical Phonons in Polar Materials

Dark Matter Journal Club

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Phonons?

Optical Phonons?

Introduction

- DM in the 10 keV-GeV mass range, freeze-in DM interacting with ultralight dark photon, or asymmetric DM.
- Light DM: target must have a sufficiently small gap to excitations.
- This letter: Polar Materials excellent target for sub-MeV DM, especially for scattering through an ultralight dark photon mediator.
- Specifically Gallium Arsenide (GaA): excellent sensitivity to scattering via dark photon and scalar mediators, and dark photon absorption.

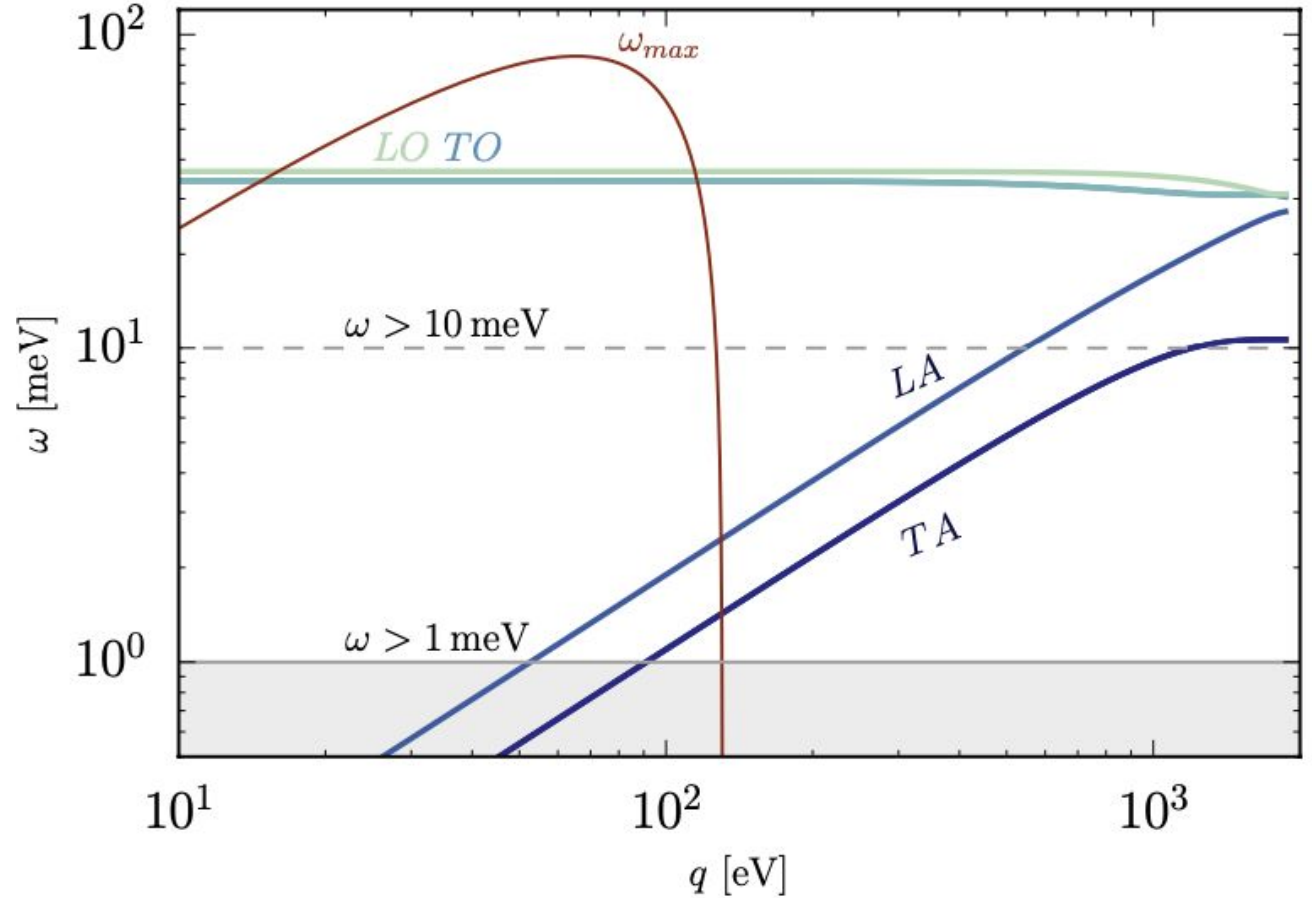
Reasons for Polar Materials (e.g. GaA) being a great target:

- These feature gapped optical phonons, can think as oscillating dipoles having a sizable coupling to kinetically mixed dark photons, weaker screening.
- Optical phonons are gapped excitations with energies of ~ 30meV-100meV---- kinetically favorable for sub-MeV DM, allowing >> meV energy depositions.
- Anisotropy of crystal induces a directional dependence in DM scattering rate.
- Similar to germanium and silicon, technology already exists to make ultrapure polar materials.

Optical Phonons in Polar Materials: gapped dispersion

- Optical phonons arise when there is more than one atom per primitive unit cell of a crystal.
- For GaAs, with two atoms in primitive cell, phonons consist of two transverse acoustic modes (TA), one longitudinal acoustic mode (LA), and two transverse gapped optical (TO) and longitudinal gapped optical (LO) modes.
- Acoustic modes have linear dispersion $\omega \propto q \text{ as } q \to 0$

Optical modes have non-zero frequencies $\omega_{\mathrm{LO,TO}}$ as $q \to 0.$



Phonon modes in GaAs, with q the momentum transfer.

Optical Phonons in Polar Materials: dipole and low screening

- Also, in GaAs, the ions have net Born effective charges of ±2.1, resulting from the polar GaAs bond, giving rise to coherently oscillating dipole moments, which allow a coupling of the LO phonons to charged particles, including conduction electrons and DM coupled to an ultra-light dark photon mediator.
- For energies below the electron band gap: $\omega < \omega_g$,

  Permittivity of GaAs: $\hat{\epsilon}(\omega) = \epsilon_\infty \frac{\omega_{\mathrm{LO}}^2 - \omega^2 + i\omega\gamma_{\mathrm{LO}}}{\omega_{\mathrm{TO}}^2 - \omega^2 + i\omega\gamma_{\mathrm{TO}}}$ ~ O(1) ---small

  with damping parameters $\gamma_{\mathrm{TO,LO}}$
- Permittivity determines the screening of electric (and dark photon) fields (mild effect of electric field of ions reduced by conduction electrons)

Optical Phonons in Polar Materials: summary

- Combined, the gapped dispersion (discrete), dipole moment, and relatively mild screening achieves sensitivity to dark photon interactions.

Experimental Concept

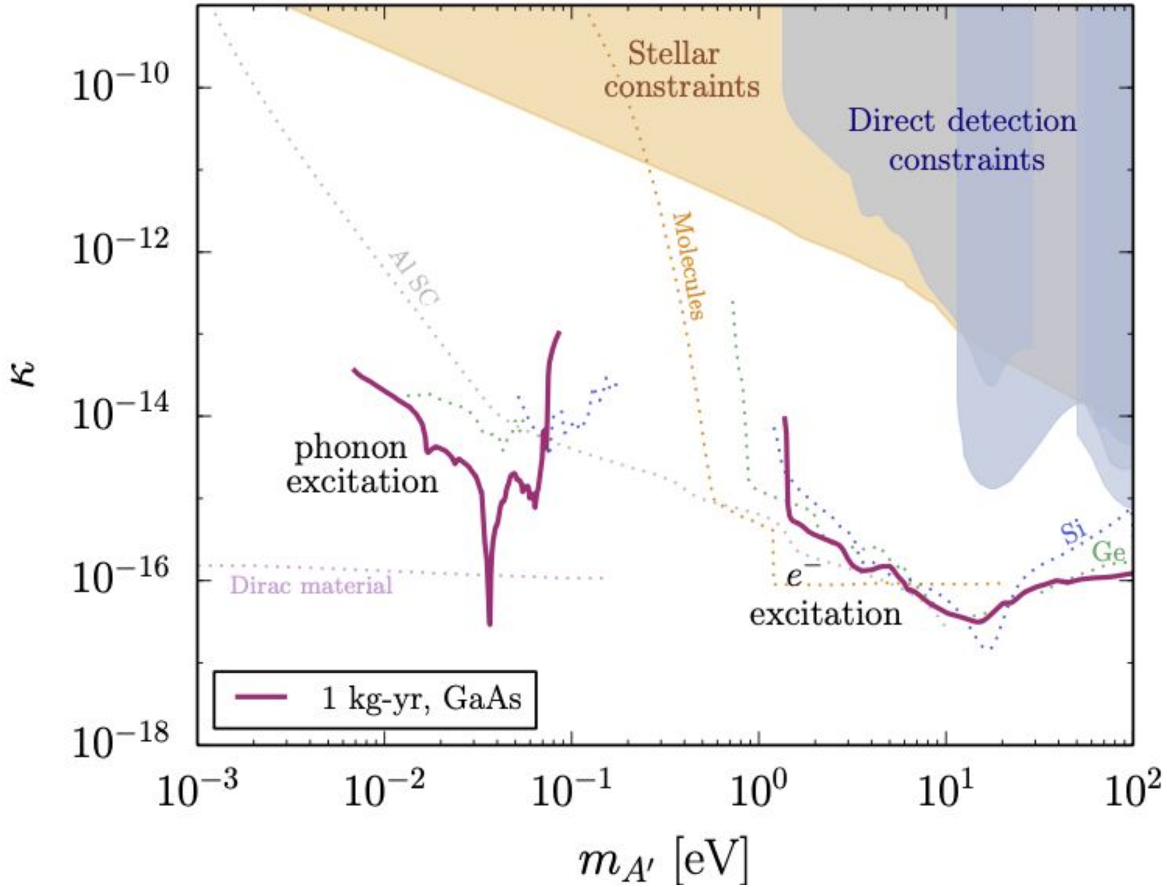
- Require detection technology that can trigger on 30 meV - 100 meV of vibrational excitations with minimal dark count rate.
- Need to collect and sense athermal phonon excitations before thermalization are viable:
  - absorb athermal phonons into a few monolayer thick layer of superfluid He film.
  - instrument the surface of a polar absorber with athermal phonon sensors- employed by CDMS . High energy phonons produced by DM interactions quickly decay into O(10^2) acoustic phonons with energies around O(meV), a scale which both isotopic scattering and anharmonic decay timescales become long compared to travel time across crystal.

Experimental Concept: Backgrounds

- Radiogenic backgrounds (compton, H, Pb decay products) have higher energy scales and is not of interest here.
- *pp* neutrinos: a few events per kg-year
- Coherent scattering of high-energy photons

Dark photon absorption

- Consider: DM in mass range of ~meV- 100eV, consisting of nonthermally produced dark photons, with kinetic mixing $-\kappa F'_{\mu\nu} F^{\mu\nu}/2$
- The DM can be detected through absorption, where all of the mass-energy of the DM goes into the excitation.
- Absorption rate $R = \frac{1}{\rho}\frac{\rho_{\rm DM}}{m_{A'}}\kappa_{\rm eff}^2 \sigma_1$
- In-medium coupling of A' with EM current: $\kappa_{\rm eff}^2 = \frac{\kappa^2 m_{A'}^4}{\left[m_{A'}^2 - {\rm Re}\,\Pi(\omega)\right]^2 + {\rm Im}\,\Pi(\omega)^2}$
- Photon polarization tensor: $\Pi(\omega) = -i\sigma\omega$
- Optical conductivity: $\sigma_1 = -\frac{{\rm Im}\Pi(\omega)}{\omega}$, Permittivity: $\hat{\epsilon} = \hat{n}^2 = 1 + i\sigma/\omega$



Reach for absorption of dark photon DM, in terms of the kinetic mixing parameter for kg-year exposure

DM scattering via ultralight dark photon

- Assume a fermionic DM interaction $g_X \overline{X} \gamma^\mu X A'_\mu$, in addition to kinetic mixing.
- X is effectively millicharged; the interaction of X with an LO phonon is effectively that o a test charge with electric charge.
- Fröhlich Hamiltonian (interactions of electrons with LO phonons in the long wavelength and isotropic limit:

$$\mathcal{H}_I = i\frac{\kappa g_X}{e} C_F \sum_{\mathbf{k},\mathbf{q}} \frac{1}{|\mathbf{q}|} \left[c^\dagger_{\mathbf{q}} a^\dagger_{\mathbf{k}-\mathbf{q}} a_{\mathbf{k}} - \text{c.c.} \right]$$

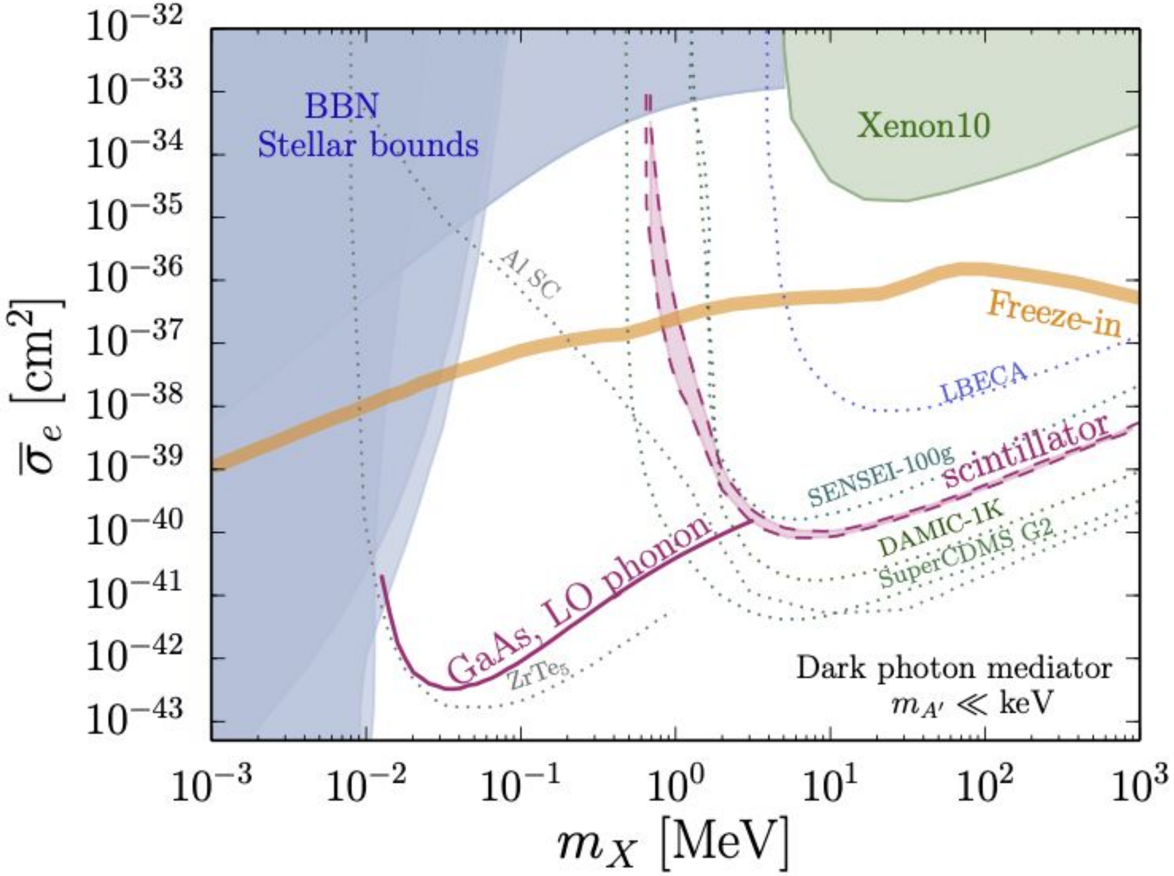
with coupling:

$$C_F = e \left[\frac{\omega_{\text{LO}}}{2V_{\text{cell}}} \left(\frac{1}{\epsilon_\infty} - \frac{1}{\epsilon_0} \right) \right]^{1/2}$$

DM scattering via ultralight dark photon (cont'nd)

- Scattering rate for X: $\Gamma(\mathbf{p_i}) = 2\pi \int \frac{d^3\mathbf{p}_f}{(2\pi)^3} \delta(E_f - E_i - \omega) |\mathcal{M}_\mathbf{q}|^2$,

  with matrix element $|\mathcal{M}_\mathbf{q}|^2 = \frac{\kappa^2 g_X^2}{e^2} \frac{C_F^2}{q^2}$
- The total rate per unit time: $R = \frac{1}{\rho} \frac{\rho_{\text{DM}}}{m_X} \int d^3\mathbf{v} f(\mathbf{v}) \Gamma(m_\chi \mathbf{v})$
- Sensitivity in terms of DM cross section: $\bar{\sigma}_e \equiv \frac{4\mu_{Xe}^2 \kappa^2 g_X^2 \alpha_{em}}{(\alpha_{em} m_e)^4}$
- Restrict to keV-MeV mass range for now, otherwise outside the first Brillouin zone

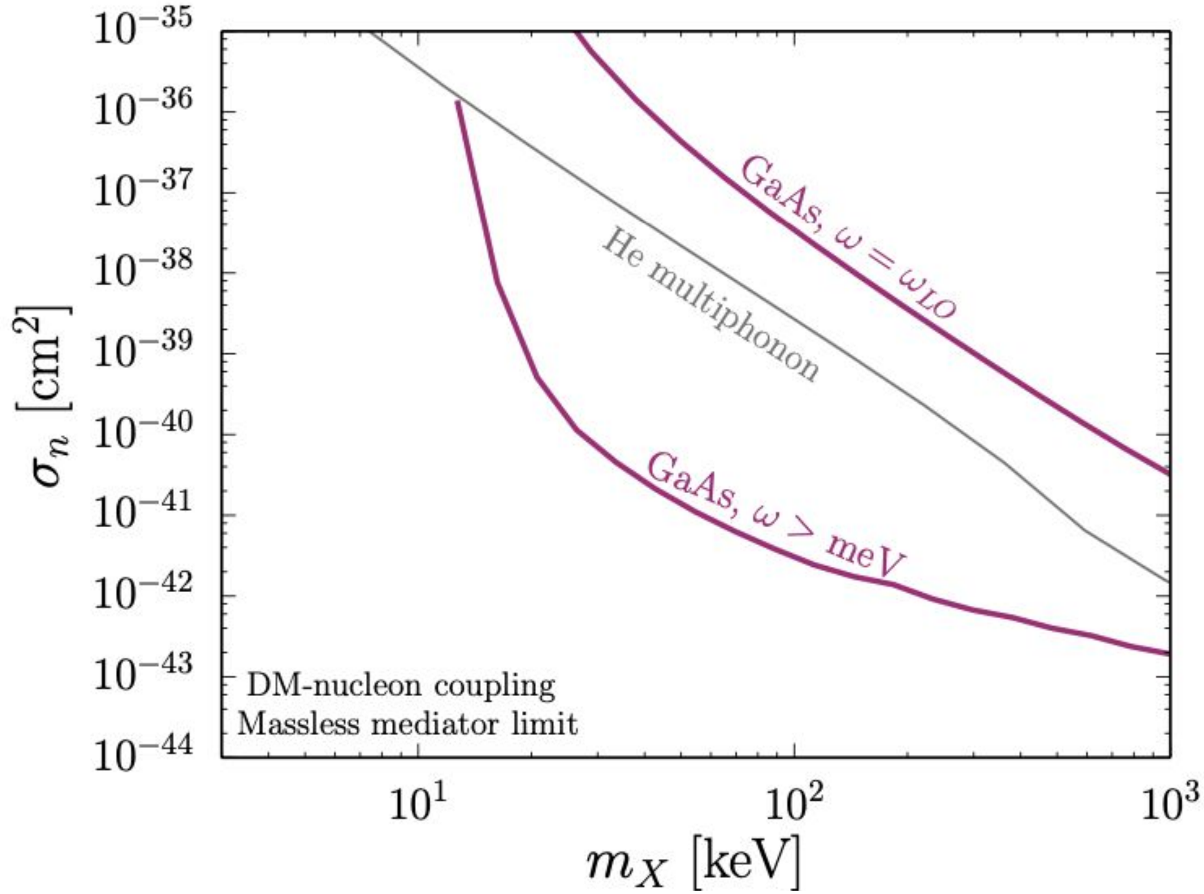


Sensitivity to DM scattering via an ultralight dark photon, for kg-yr exposure on GaAs

Scalar-mediated nucleon scattering

- sub-MeV DM with coupling to nucleons only, for multiphonon production in superfluid helium.
- Strength characterized by average DM-nucleaon scattering length $\bar{b}_n$
- Differential DM scattering rate $$\frac{d^2\Gamma}{dq\,d\omega} = \frac{4\pi}{V_{\rm cell}} \frac{q}{m_X p_i} S(\mathbf{q},\omega)$$
- Dynamical structure factor $$S(\mathbf{q},\omega) = \frac{1}{2}\sum_\nu \frac{|F_\nu(\mathbf{q})|^2}{\omega_{\nu,\mathbf{q}}}\delta(\omega_{\nu,\mathbf{q}}-\omega)$$
- Phonon form factor $$|F_\nu(\mathbf{q})|^2 = \left|\sum_d \frac{b_d}{\sqrt{m_d}} e^{-W_d(\mathbf{q})}\mathbf{q}\cdot\mathbf{e}_{\nu,d,\mathbf{q}} e^{-i\mathbf{q}\cdot\mathbf{r}_d}\right|^2$$ in limit Debye-Waller factor $W_d \sim 0$, $$\approx \frac{\bar{b}_n^2}{2m_n} q^2 \left|\sqrt{A_{\rm Ga}}e^{i\mathbf{r}_{\rm Ga}\cdot\mathbf{q}} \pm \sqrt{A_{\rm As}}e^{i\mathbf{r}_{\rm As}\cdot\mathbf{q}}\right|^2$$

Approximations break down $m_X \gtrsim 1$ MeV, will require description of multiphonon processes and phonons excited outside first Brillouin Zone.



Sensitivity of GaAs to scattering off nucleons via a scalar mediator, with kg-yr exposure.

References

[1] Simon Knapen, Tongyan Lin, Matt Pyle, & Kathryn M. Zurek. (2018). Detection of light dark matter with optical phonons in polar materials. Physics Letters. B, 785, 386-390.