The dark matter-phonon coupling and sub-MeV direct detection

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Dark matter direct detection

- Strong limits for "traditional" WIMPs: $10\ \mathrm{GeV} \lesssim m_{DM} \lesssim 10\ \mathrm{TeV}$
- Significant recent progress in lowering energy thresholds, especially for DM-electron scattering, with sensitivity to $m_{DM} \gtrsim \mathrm{MeV}$
- New technologies needed/being developed to probe $m_{DM} \lesssim \mathrm{MeV}$

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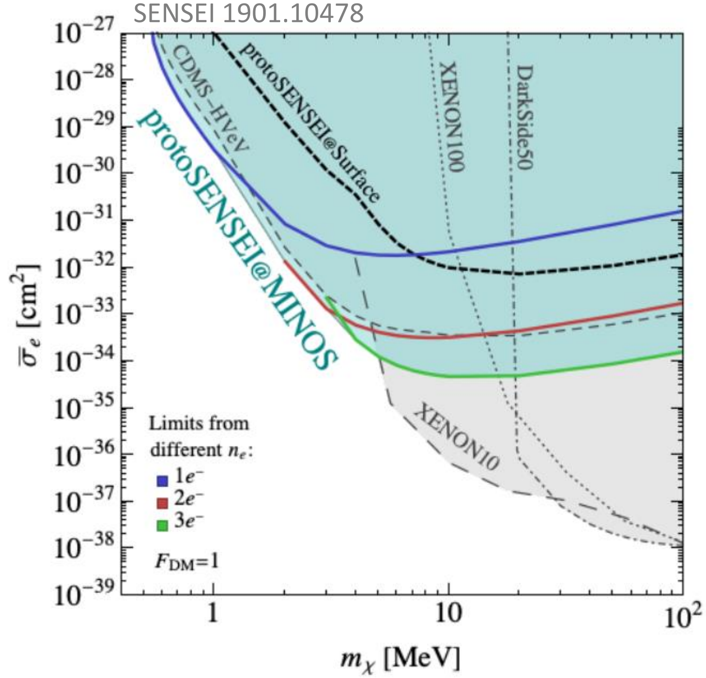

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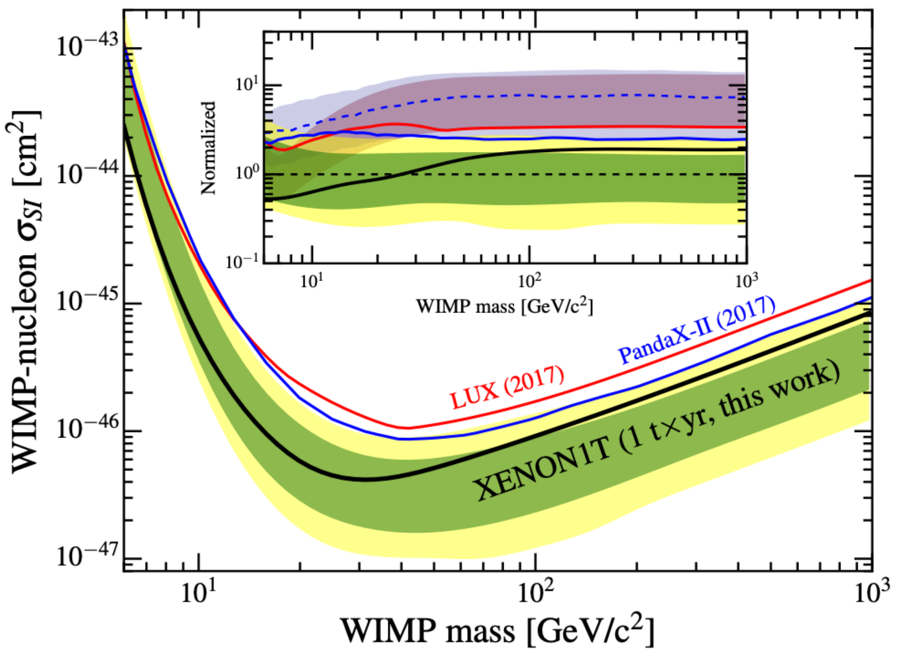

DM-phonon scattering

- Several proposals to detect sub-MeV DM using *DM-phonon* interactions

  (e.g. Schutz et. al. ‘16, Hochberg et. al. ’16, Bunting et. al. ‘17, Knapen et. al. ’17)

- Optical phonons with energies $\mathrm{O}(10\text{-}100)\ \mathrm{meV}$ have the correct kinematics for efficient scattering of sub-MeV DM

- DM couples coherently to the entire atom, hence for many models the effective coupling scales with the number of constituents

- The effective coupling is then (almost) *proportional to the mass of the atom*

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The coupling-to-mass effect:

If the coupling to each atom is proportional to its mass, the leading contribution to inelastic scattering off optical phonons at small momentum transfer vanishes.

Coupling-to-mass effect

Consider DM scattering off an array of atoms via a potential:

$$\mathcal{V} = \sum_{l=1}^{N} g_l V(\mathbf{r} - \mathbf{r}_l)$$

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Expand at linear order for inelastic scattering at low momentum transfer ($q \to 0$).
Then, if coupling is proportional to mass $g_l = g m_l$:

$$iV(\mathbf{q})\, g\, \mathbf{q} \cdot \langle \Phi_f | \left(\sum_l m_l \hat{\mathbf{r}}_l \right) | \Phi_i \rangle$$

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- Can apply same argument for a dipole operator: $D = -\sum_{l=1}^{N} g_l\, \mathbf{r}_l \cdot \mathbf{A}$

When is this effect relevant?

General systems (e.g. molecules):

$1/q >$ (size of system)

$$\langle \Phi_f | V(\mathbf{q}) \sum_l g_l e^{i\mathbf{q}\cdot\hat{\mathbf{r}}_l} | \Phi_i \rangle$$

Periodic systems (e.g. crystals):

Use Bloch's theorem to restrict sum to the unit cell

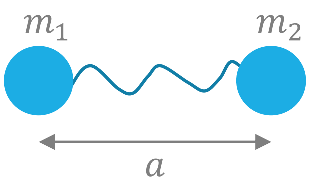
- Optical phonons
  $1/q >$ (size of unit cell)

- Acoustic phonons (i.e. translations of the unit cell)
  $1/q >$ (size of system)

→ Coupling-to-mass effect becomes relevant for $q \lesssim \mathrm{keV}$ ($m_{DM} \lesssim \mathrm{MeV}$)

Example : diatomic molecule

Consider diatomic molecule, modelled as a harmonic oscillator



Form factor for inelastic scattering off vibrational mode, $\sigma \propto |\mathcal{F}|^2$

$M = m_1 + m_2$
$\mu = m_1 m_2 / M$

$$|\mathcal{F}(q)|^2 = \frac{q^2}{M}\left(\frac{g_1^2 m_2}{m_1} + \frac{g_2^2 m_1}{m_2} - 2 g_1 g_2 \cos qa\right)$$

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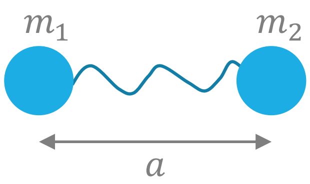

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Parameterise the coupling-to-mass limit as: $g_1 = g m_1 (1 + \epsilon/2)$ $\quad g_2 = g m_2 (1 - \epsilon/2)$

Expanding in small ε and qa :

$$|\mathcal{F}(q)|^2 = q^2 g^2 \mu \left(\epsilon^2 + (qa)^2 + \dots\right)$$

Leading $O(q^2)$ term vanishes in coupling ∝ mass limit ($\varepsilon \to 0$)

Example: sapphire

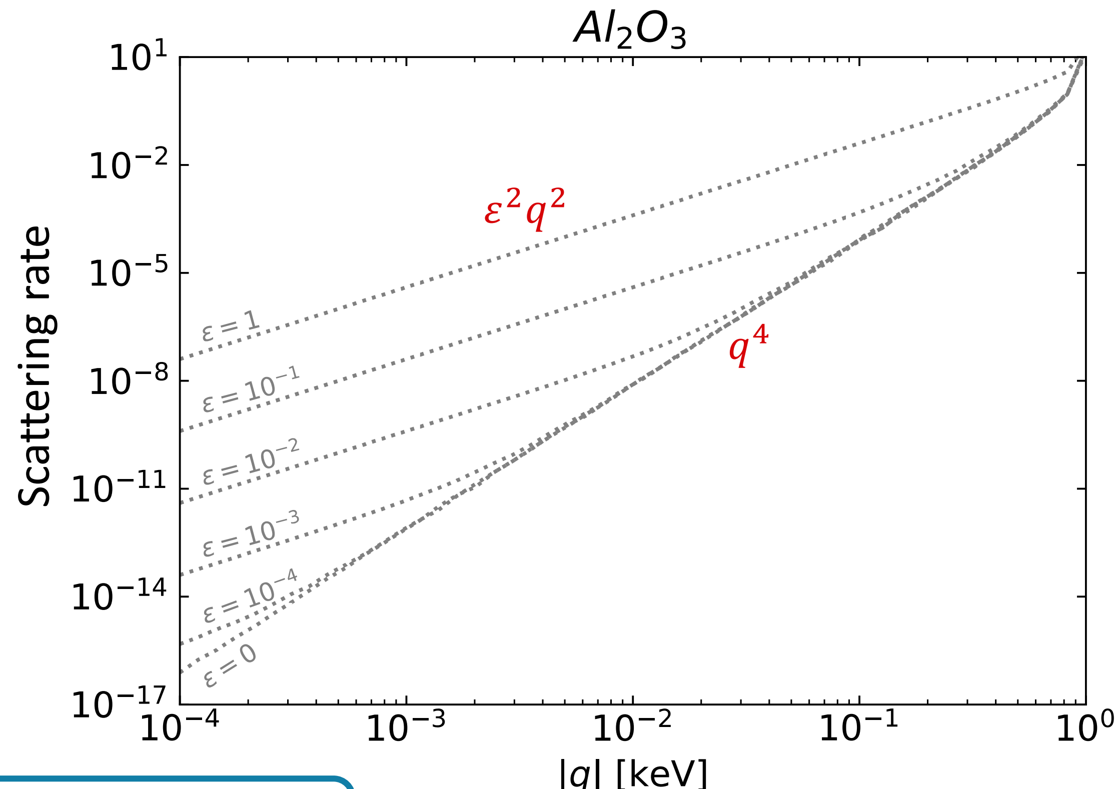
$$V = \sum_l g_l \, \delta^{(3)}(\mathbf{r} - (\mathbf{X}_l + \mathbf{x}_l))$$

- Sapphire has been proposed as a potential detector material for sub-MeV DM (Knapen et. al. '17)
- For crystals, use ab-initio calculations of the phonon band structure and numerically calculate inelastic structure factor

Deviation from coupling ∝ mass:

$$g_{Al} = g\, m_{Al}(1 + \varepsilon/2)$$

$$g_O = g\, m_O\, (1 - \varepsilon/2)$$



Again, leading $O(q^2)$ contribution suppressed by ε^2

Deviations from coupling-to-mass

For a generic model with DM coupling to protons and neutrons:

$$g_i = g_p Z_i + g_n (A_i - Z_i) = A_i \left((g_p - g_n) \frac{Z_i}{A_i} + g_n \right)$$

$g_p = g_n$ (i.e. coupling to baryon number)

- Always in the coupling ∝ mass limit
- Deviations of $\varepsilon \sim O(10^{-3})$ due to nuclear binding energy and proton-neutron mass difference

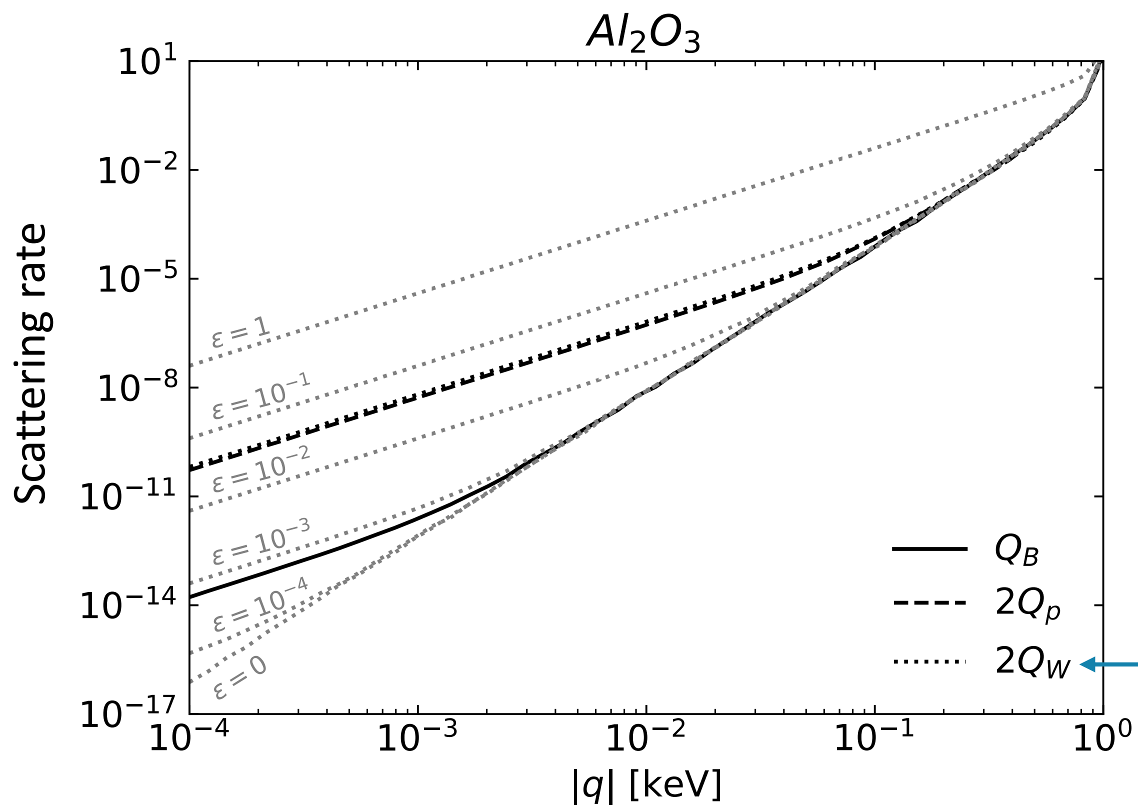
$g_p \neq g_n$

- Deviation from coupling-to-mass determined by differences in Z_i/A_i between atoms
- Expect $\varepsilon \sim O(0.01 - 0.1)$

Example: sapphire

- Coupling to baryon number gives $\varepsilon \sim O(10^{-3})$ as expected
  → Suppression of up to $O(10^6)$ compared to naïve expectation

- Coupling to proton number or neutron number (≈ weak charge) consistent with $\epsilon_{\mathrm{Al_2O_3}} \sim \mathcal{O}(|13/27 - 8/16|) \sim 0.02$



Also relevant for neutrino scattering

Implications for future experiments (I)

$g_p = g_n$

- Always deep in the coupling-to-mass limit
- Coupling-to-mass effect requires careful treatment in numerical calculations for crystals due to large cancellations
- Higher order q^4 terms dominate the scattering rate for $\mathrm{eV} \lesssim q \lesssim \mathrm{keV}$, and must be included when calculating projected sensitivities
- Two-phonon processes may become important → further study needed

Implications for future experiments (II)

$g_p \neq g_n$

- Scattering rate can be enhanced by choosing materials with larger variations in Z_i/A_i between atoms
- Materials with a mixture of light ($Z/A{\sim}0.5$) and heavy ($Z/A{\sim}0.4$) elements, or that include hydrogen atoms can give sensitivity gains of 10-100

Implications for future experiments (III)

Models not in coupling-to-mass limit

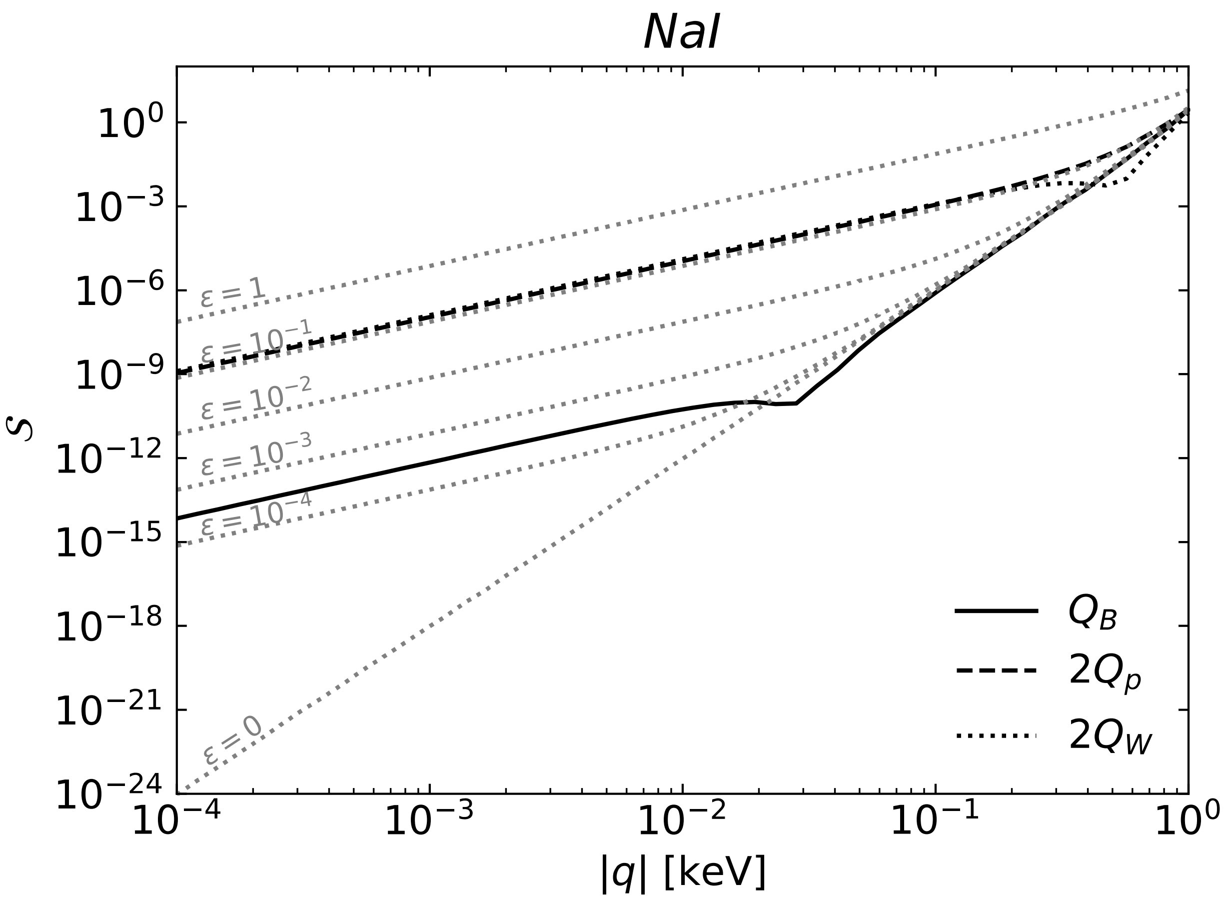
- Spin-dependent scattering or dark matter that interacts via a kinetically mixed dark photon are far from the coupling-to-mass limit
- Can take advantage of the coupling-to-mass effect to reduce neutrino scattering backgrounds (also true if DM couples to baryon number)
- Consider materials with equal Z_i/A_i for all atoms
  (e.g. homogeneous materials, or light elements with $Z/A = 1/2$)

Summary

- Excellent progress by direct detection experiments over recent years, now new approaches are needed/being developed to enter the sub-MeV DM mass regime
- Many proposals for sub-MeV DM detection based upon phonon excitations
- DM-phonon interactions are subject to the *coupling-to-mass effect*, which can significantly suppress the scattering rate
- This effect is important in obtaining accurate rate calculations for future experiments, and can influence the choice of detector material

Backup

Example: NaI



NaI
10^{0}
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
10^{-18}
10^{-21}
10^{-24}
$\mathcal{S}$
$\varepsilon = 1$
$\varepsilon = 10^{-1}$
$\varepsilon = 10^{-2}$
$\varepsilon = 10^{-3}$
$\varepsilon = 10^{-4}$
$\varepsilon = 0$
Q_B
$2Q_p$
$2Q_W$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
$|q|$ [keV]