Transmon Qubit Constraints on Light Dark Matter

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with R. Leane & N. Kurinsky

IDM 2024
L'Aquila

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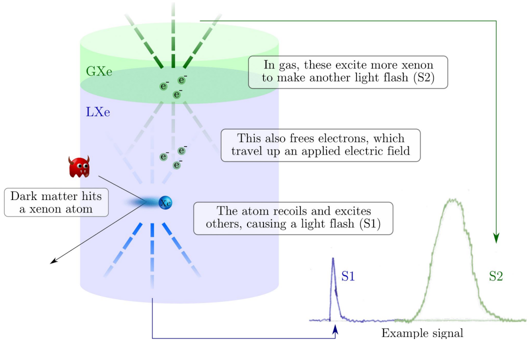
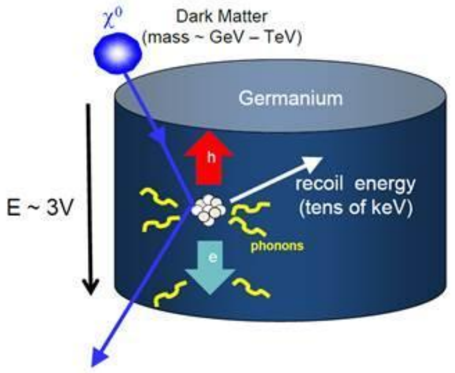
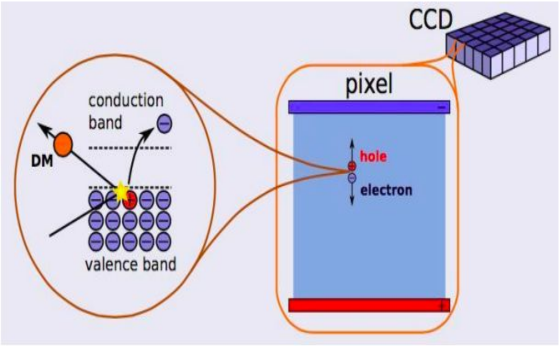
Conventional Direct Detection Experiments



XENON, LZ, PandaX



SuperCDMS



SENSEI, DAMIC-M

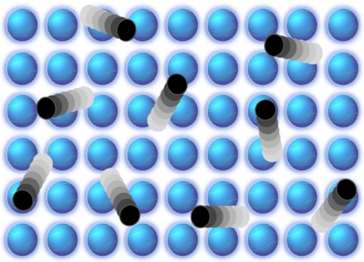
All looking for individual scattering events from DM

Power Deposited by Dark Matter Scattering

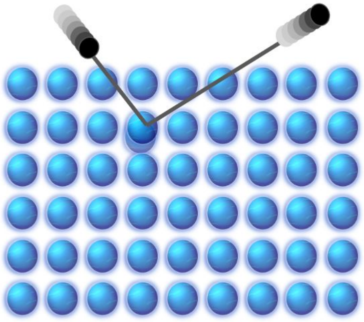
Instead of individual recoil, use power measurement of quantum devices to probe thermal DM

$$P_{\mathrm{DM}} = \int d\omega \, \omega \frac{d\Gamma}{d\omega} \qquad R_{\mathrm{DM}} = \int d\omega \, \frac{d\Gamma}{d\omega}$$

Event rate spectrum



Noise from DM

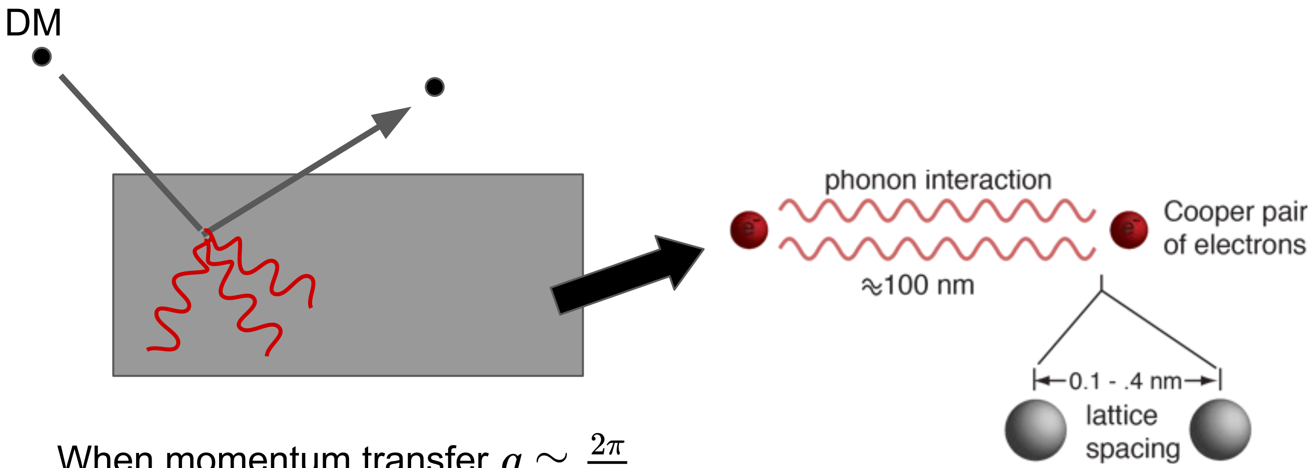


Recoil from DM

PRL 132(2024) 12, 121801

Power Deposition Mechanism

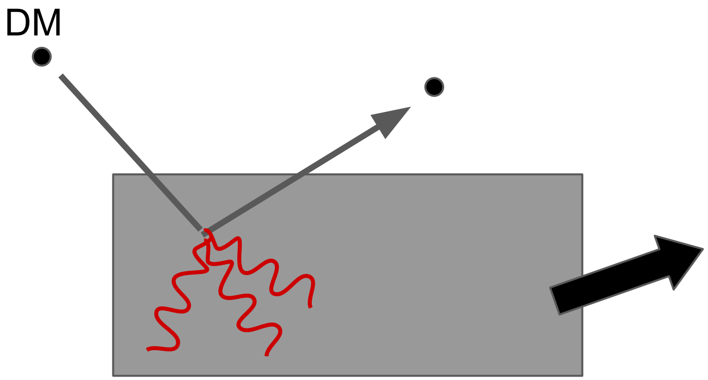
DM mostly excites phonons in this low mass regime: MeV - GeV

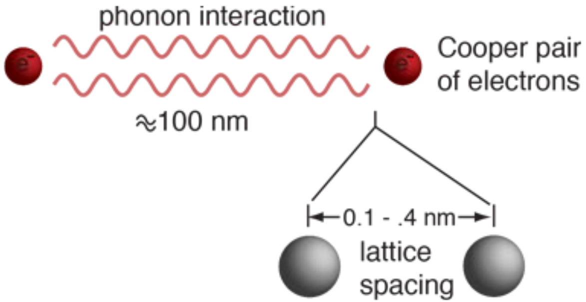


When momentum transfer $q \simeq \frac{2\pi}{a}$

Campbell-Deem et al. (PRD 2022)

Power Deposited by Dark Matter Scattering





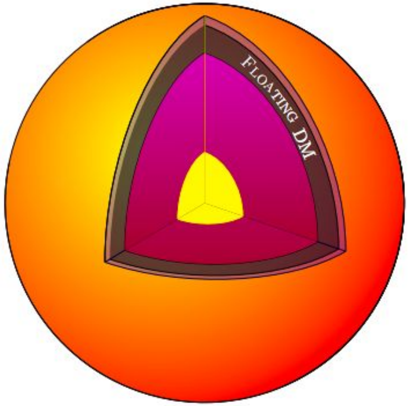
When momentum transfer $q \simeq \frac{2\pi}{a}$

The excited phonons could directly be detected

or

In a SC, the phonons will break Cooper pairs & release quasiparticles that can be detected

Captured Dark Matter on Earth can be probed too



Much lower energy relative to halo DM

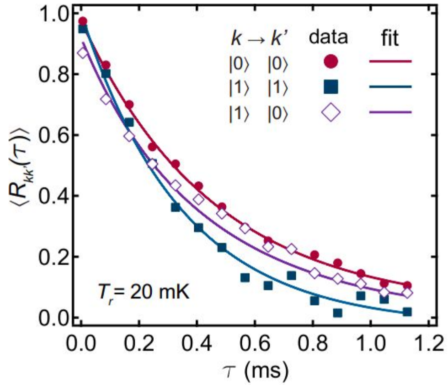
$$m_\chi = 1\,\mathrm{GeV}$$
$$T_\chi \approx 300\,\mathrm{K}$$
$$E_{\mathrm{kin}} = \mathcal{O}(10\,\mathrm{meV})$$

Low threshold experiments are essential

2012.03957, 2209.09834, 2303.01516

Superconductor-based Quantum Devices

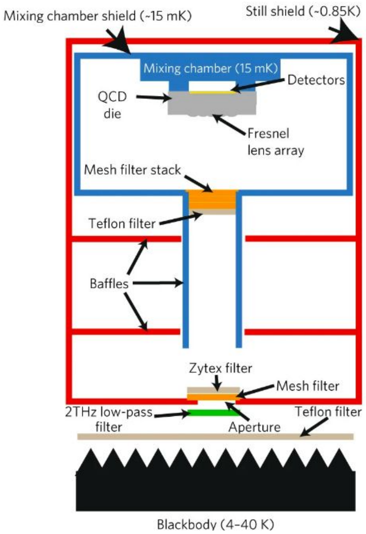
Quasiparticle-induced decoherence in transmon qubit



P = 5.7 x 10^{-24} Wμm^{-3}

Nature Comm. 4, 1913 (2013)

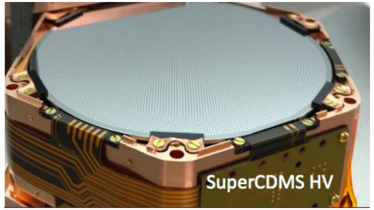
Low noise bolometer
Infrared sensor

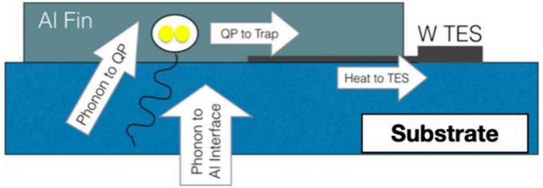


P = 1.7 x 10^{-20} Wμm^{-3}

Nature Astronomy 2, 90-97 (2018)

SuperCDMS Si detector





P = 3 x 10^{-21} Wμm^{-3}

PRD 104, 032010 (2021)

Superconductor-based Quantum Devices

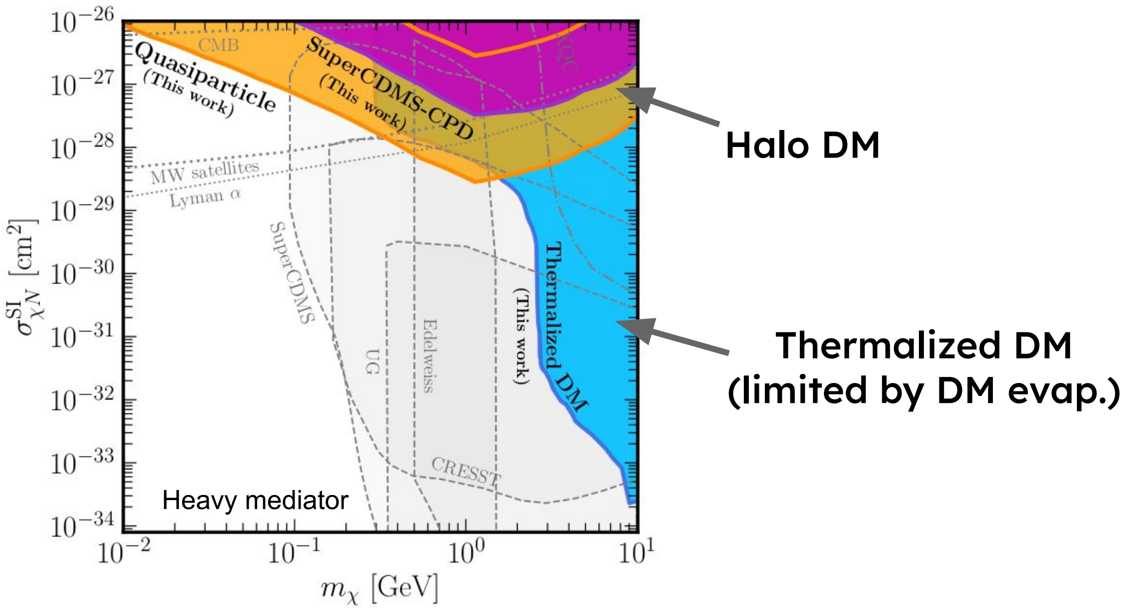
Boltzmann equation for quasiparticles in a superconductor

$$\frac{dn_{\mathrm{qp}}}{dt} = -\bar{\Gamma} n_{\mathrm{qp}}^2 - \Gamma_T n_{\mathrm{qp}} + \frac{P_{\mathrm{DM}}}{2\Delta}$$

In equilibrium: $$\frac{P_{\mathrm{DM}}}{2\Delta} = \bar{\Gamma} n_{\mathrm{qp}}^2 + \Gamma_T n_{\mathrm{qp}}$$

$$n_{\mathrm{qp}} \approx \left(\frac{P_{\mathrm{DM}}}{3.6 \times 10^{-21}\,\mathrm{W}\,\mu\mathrm{m}^{-3}} \right) \mu\mathrm{m}^{-3}$$

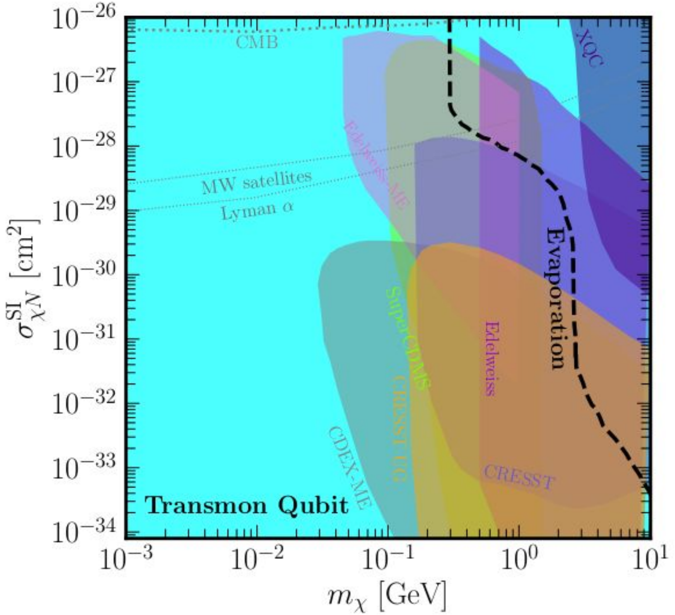
New Limits on DM-nuclear cross section



We put new limits on DM-nucleon cross section using the unprecedented power sensitivity for both halo & thermalized populations

Das, Kurinsky, Leane (PRL 2024)

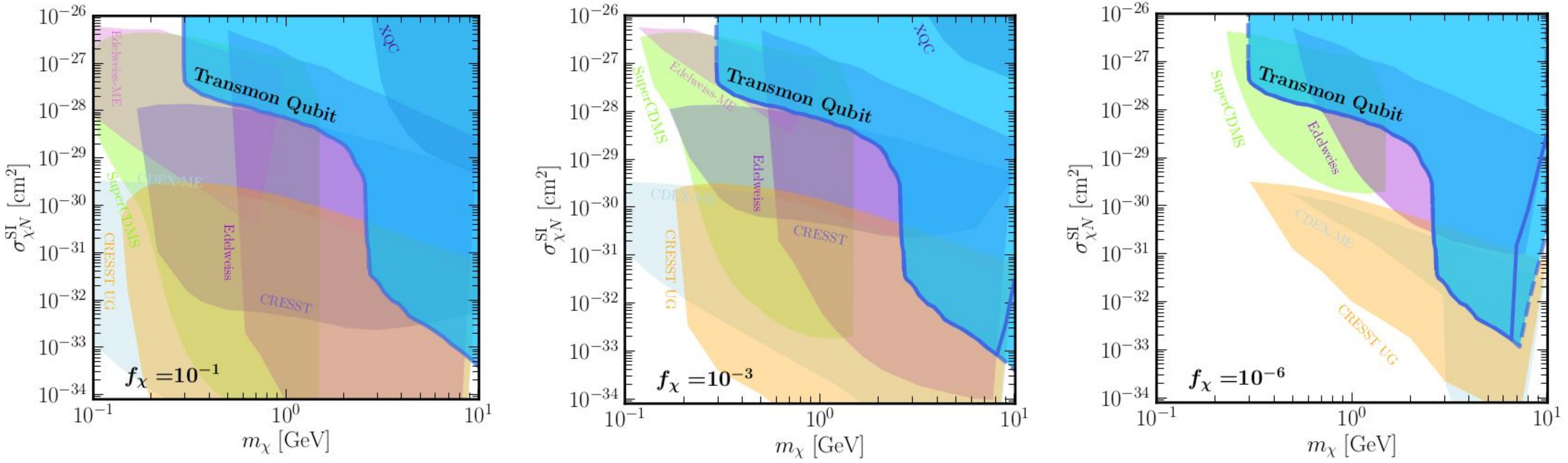
New Limits on DM-nuclear cross section



We put new limits on DM-nucleon cross section using the unprecedented power sensitivity for both halo & thermalized populations

Das, Kurinsky, Leane (2405.00112)

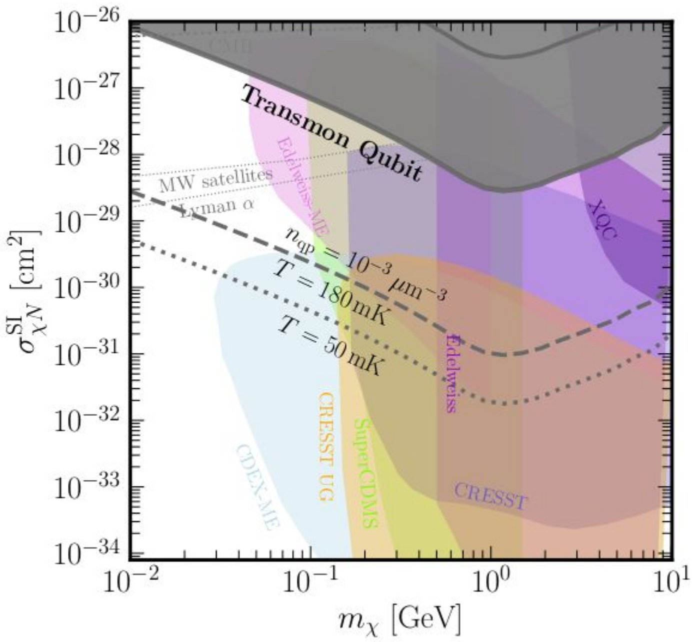
Strong Limits for sub-fraction DM



Qubit measurements are sensitive to small fractional DM outperforming other underground experiments

Das, Kurinsky, Leane (2405.00112)

Promising Future Outlook



- Significant progress in Qubit research in last few years to achieve low QP bkg
- We can realistically probe $\sigma = 10^{-32}\ cm^2$ within next few years

Das, Kurinsky, Leane (2405.00112)

Challenges for detection:

- ➔ Power calibration of the calorimeter
- ➔ Neutron scattering
- ➔ Radioactivity & cosmic rays
- ➔ Unknown systematics

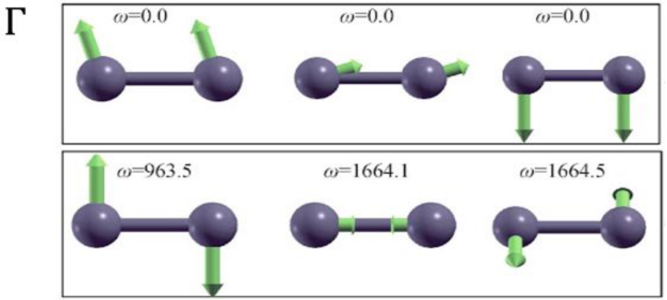
Summary

- ➔ As we try to probe lighter mass DM, experiments become more challenging
- ➔ Mesoscopic quantum devices are promising to probe lighter DM and feeble interaction
- ➔ Good sensitivity for small sub-fractional DM too
- ➔ Constraints are set to improve by a few orders of magnitude within next few years

Papers ➔

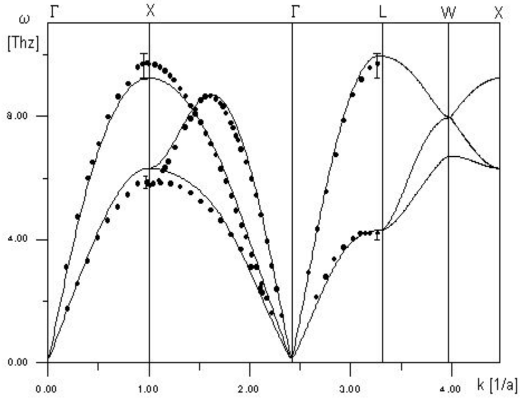
Phonons are quanta of crystal lattice oscillation

Total number of modes $3N$

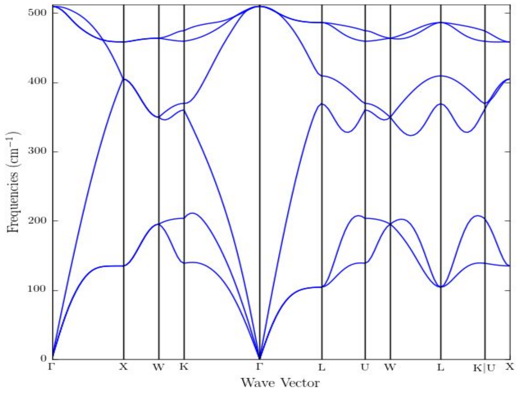


Acoustic modes

Optical modes



Aluminum



Silicon

Dark Matter Interaction Rate

Velocity-averaged interaction rate

$$\Gamma = \frac{\pi \sigma_N n_\chi}{\rho_T \mu^2} \int d^3 v f_\chi(\mathbf{v}) \int \frac{d^3 q}{(2\pi)^3} F_{\text{med}}^2(q) \underline{S(\mathbf{q}, \omega_{\mathbf{q}})}$$

Structure Factor:
detector response

$$\frac{d\Gamma}{d\omega} = \frac{\pi \sigma_N n_\chi}{\rho_T \mu^2} \int d^3 v f_\chi(\mathbf{v}) \int \frac{d^3 q}{(2\pi)^3} F_{\text{med}}^2(q) S(\mathbf{q}, \omega) \delta(\omega - \omega_{\mathbf{q}})$$

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

Energy transfer in a single scattering

$$F_{\text{med}} = 1$$

Heavy mediator

$$F_{\text{med}} = (\alpha m_e / q)^2$$

Light mediator

Single & Multi-phonon Structure Factor

Coherent Approx.

$q < q_{\mathrm{BZ}}$

$$\begin{cases} S_{\mathrm{LA}} \simeq \dfrac{2\pi}{V_c} \dfrac{\sum A_d q^2}{2m_p \omega_{\mathrm{LA}}} \delta(\omega - \omega_{\mathrm{LA}}) \\ S_{\mathrm{LO}} \simeq \dfrac{2\pi}{V_c} \dfrac{a^2 q^4}{32 m_p \omega_{\mathrm{LO}}} \dfrac{A_1 A_2}{A_1 + A_2} \delta(\omega - \omega_{\mathrm{LO}}) \end{cases}$$

Knowledge from neutron scattering

Incoherent Approx.

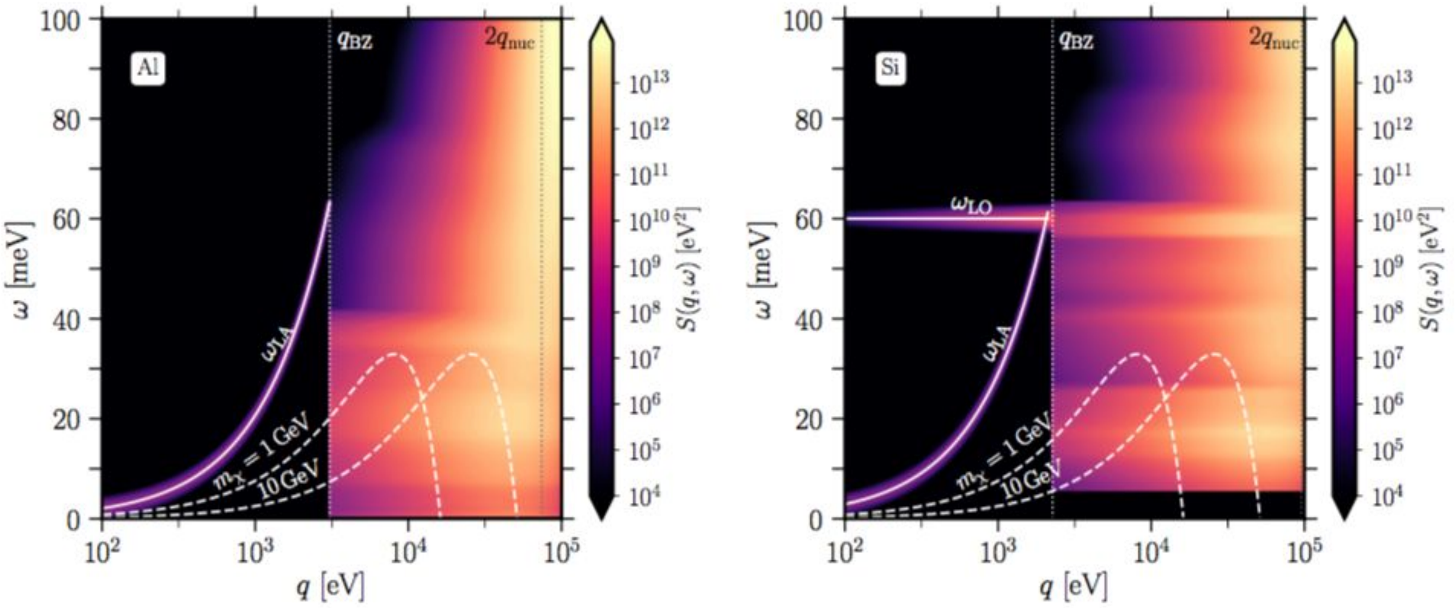
$q > q_{\mathrm{BZ}}$

$$S_N \simeq \frac{2\pi}{V_c} \sum_d f_d^2 e^{-2W_d(q)} \sum_n \left(\frac{q^2}{2m_d}\right)^2 \frac{1}{n!} \left(\prod_i \int d\omega_i \frac{D_d(\omega_i)}{\omega_i}\right) \delta(\omega - \sum_j \omega_j)$$

Approaches nuclear recoil in large ω and q limit

2205.02250

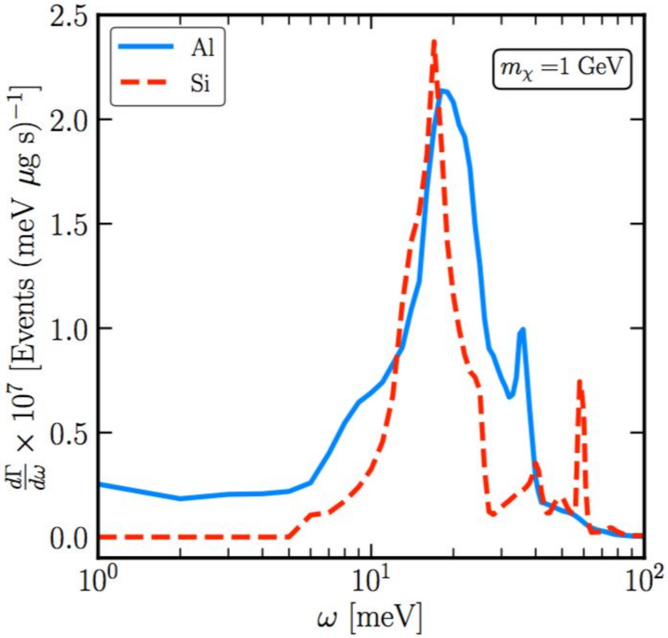
Structure factors of Al & Si



Phonon structure factors $S(q,\omega)$ in Al & Si are favorable for scattering with $O(10\text{ meV})$ energy DM

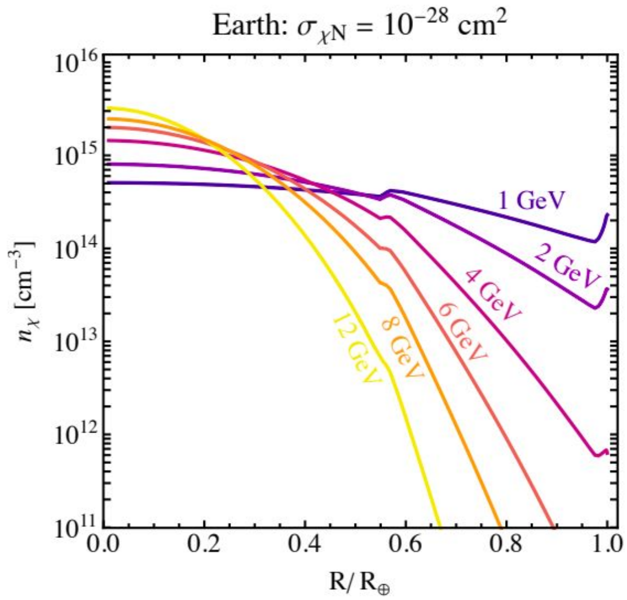
arXiv:2210.09313

Differential Scattering Rate in Al & Si



Phonon structure factors $S(q,\omega)$ in Al & Si are favorable for scattering with O(10 meV) energy DM arXiv:2209.09834

Floating Dark Matter on Earth



For DM mass 1-10 GeV and xsec > 10^{-35} cm^2, the thermalized population can get very dense near Earth's surface

However, these DM particles have very low energy, E_{DM}~ $O(10$ meV$)$