Dark Matter Induced Power in Quantum Devices

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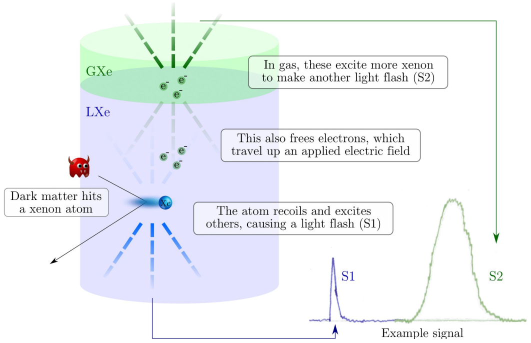
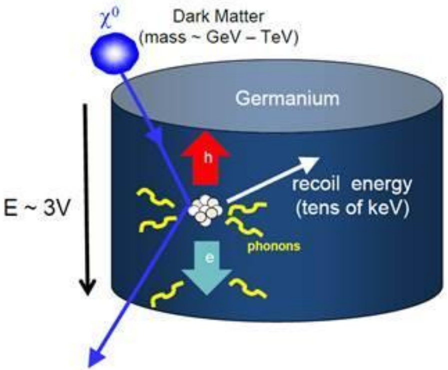
arXiv:2210.09313 w/ R. Leane & N. Kurinsky

TAUP 2023
Vienna

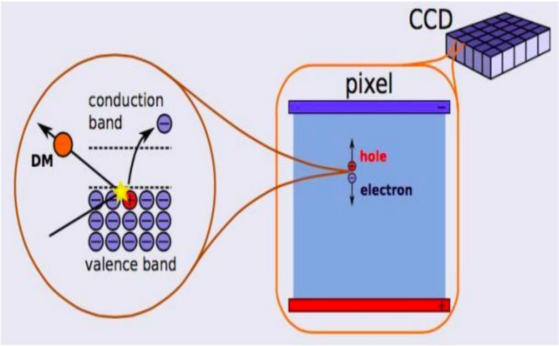
Conventional Direct Detection Experiments



XENON, LZ, PandaX



SuperCDMS

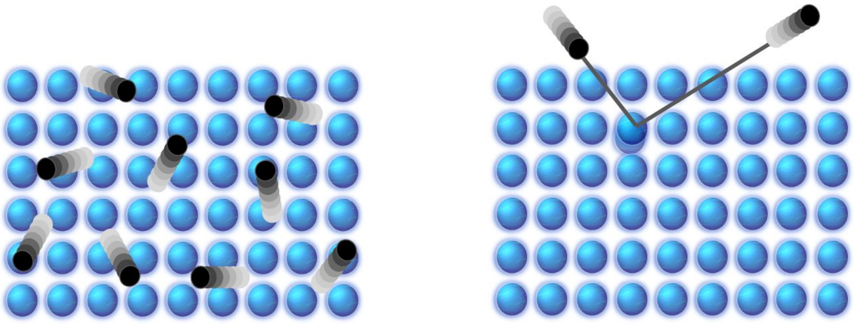


SENSEI, DAMIC-M

All looking for single scattering events from DM

Power Deposited by Dark Matter Scattering

Instead of individual events, use power/heat deposited by DM

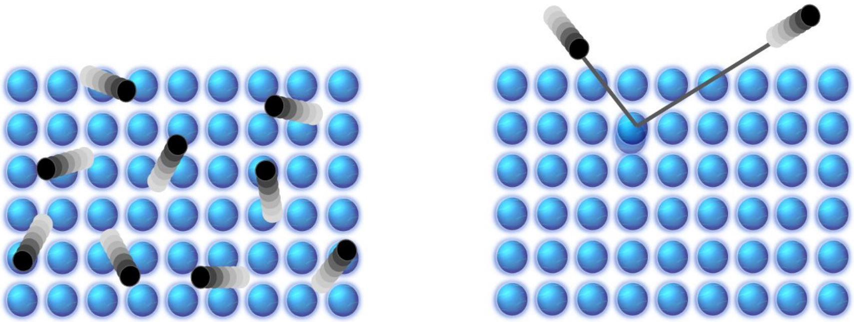


Noise from DM　　　　Recoil from DM

arXiv:2210.09313

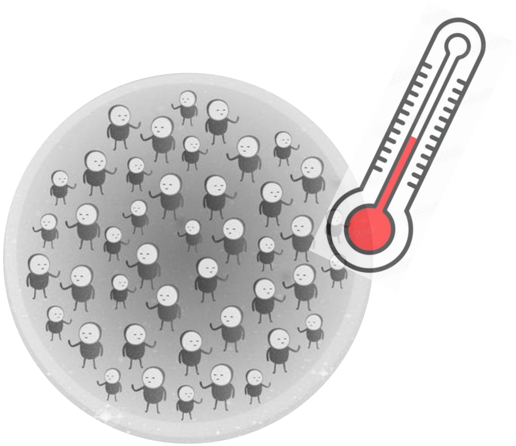
Power Deposited by Dark Matter Scattering

Instead of individual events, use power/heat deposited by DM



Noise from DM

Recoil from DM

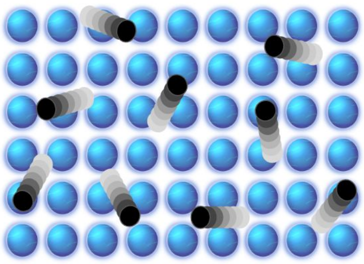


Using a very sensitive bolometers

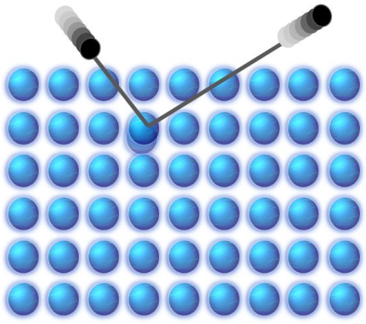
arXiv:2210.09313

Power Deposited by Dark Matter Scattering

Instead of individual events, use power/heat deposited by DM



Noise from DM



Recoil from DM

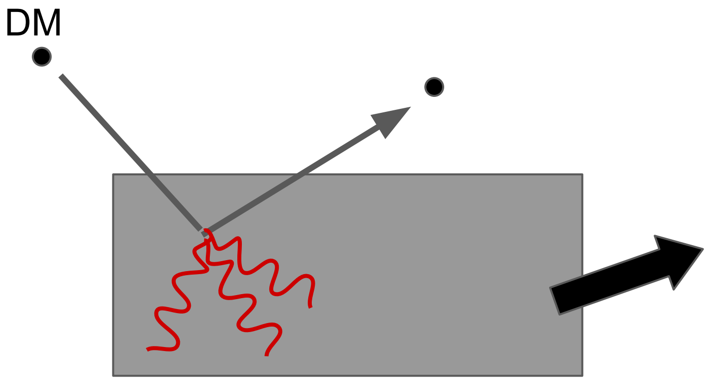
$$P_{\rm DM} = \int d\omega\, \omega \frac{d\Gamma}{d\omega}$$

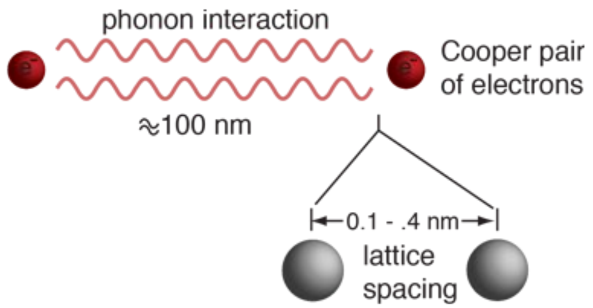
Scattering rate

arXiv:2210.09313

Power Deposition Mechanism

DM scattering creates phonons in this low mass regime: MeV - GeV





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

Power Deposited by Dark Matter Scattering

The excited phonons could directly be detected

or

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

We already have devices that can measure very small power deposition in this way

Captured Dark Matter on Earth

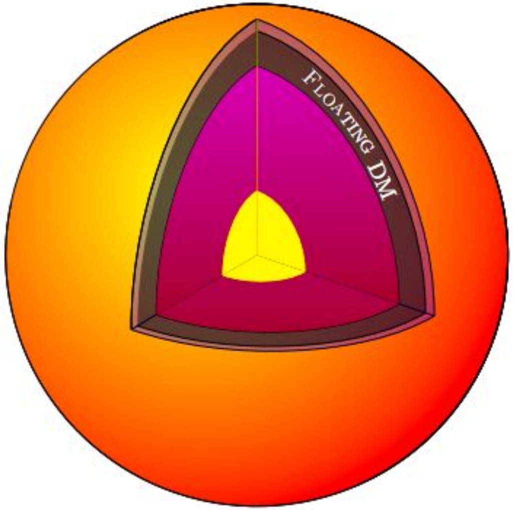


FIG. 1. Schematic of floating DM on the outer region of the celestial object as found in this work (dark shaded shell).

arXiv:2012.03957, 2209.09834, 2303.01516

Over time, halo DM may get captured in the Earth and can get thermalized

Conventional direct detection experiments do not have low enough threshold to probe thermalized DM

Halo DM

$$m_\chi = 1\,\mathrm{GeV}$$
$$E_{\mathrm{kin}} = \mathcal{O}(\mathrm{keV})$$
$$v_\chi = 230\,\mathrm{km\,s^{-1}}$$

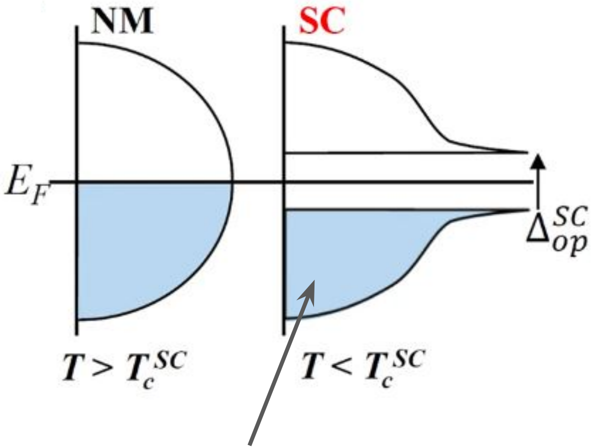
Thermalized DM

$$m_\chi = 1\,\mathrm{GeV}$$
$$E_{\mathrm{kin}} = \mathcal{O}(10\,\mathrm{meV})$$
$$v_\chi = 1\,\mathrm{km\,s^{-1}}$$

Low threshold experiments are ideal for them

Quantum Devices Based on Superconductor

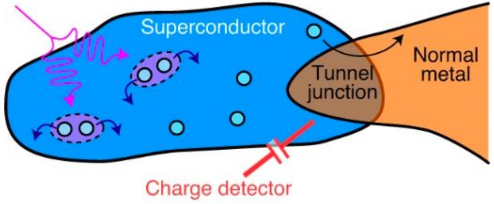
Electron DoS

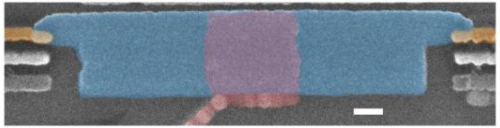


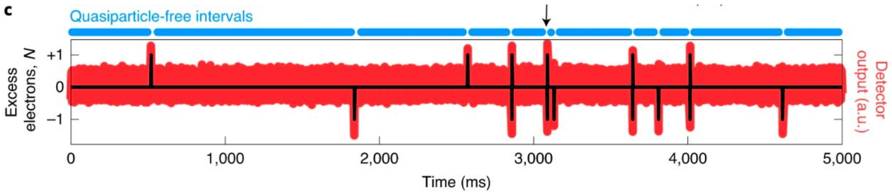
BCS ground state:
sea of Cooper pairs

Δ_{Al} = 0.34 meV

Low quasiparticle bkg device





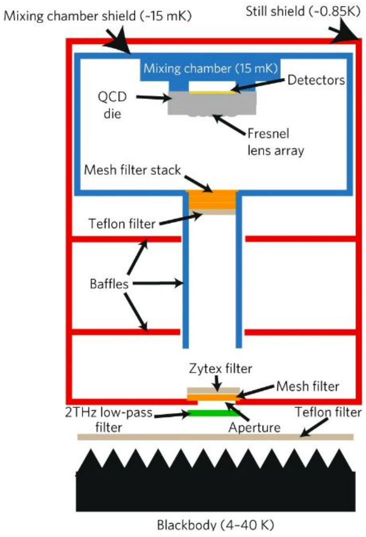


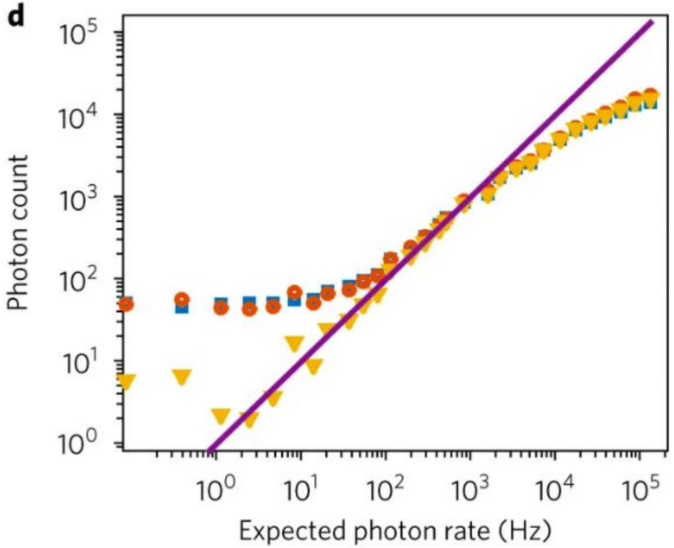
***P* = 6 x 10^{-25} Wμm^{-3}**

Nature Physics 18, 145-148 (2022)

Quantum Devices Based on Superconductor

Low noise bolometer, Cryogenic infrared sensor



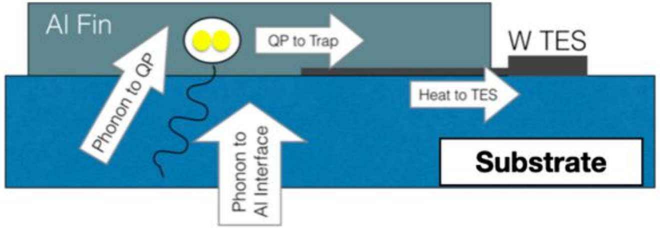


$P = 1.7 \times 10^{-20}\ \mathrm{W\mu m^{-3}}$

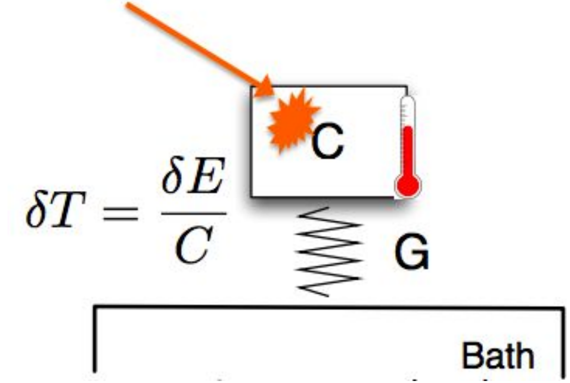
Nature Astronomy 2, 90-97 (2018)

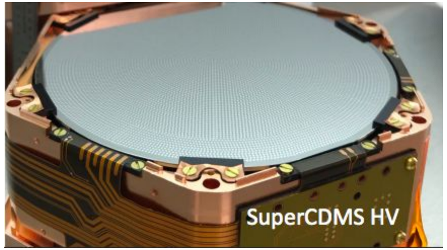
Quantum Devices Based on Superconductor

SuperCDMS Si detector covered with SC Al fins coupled to W TES



Athermal phonon sensor



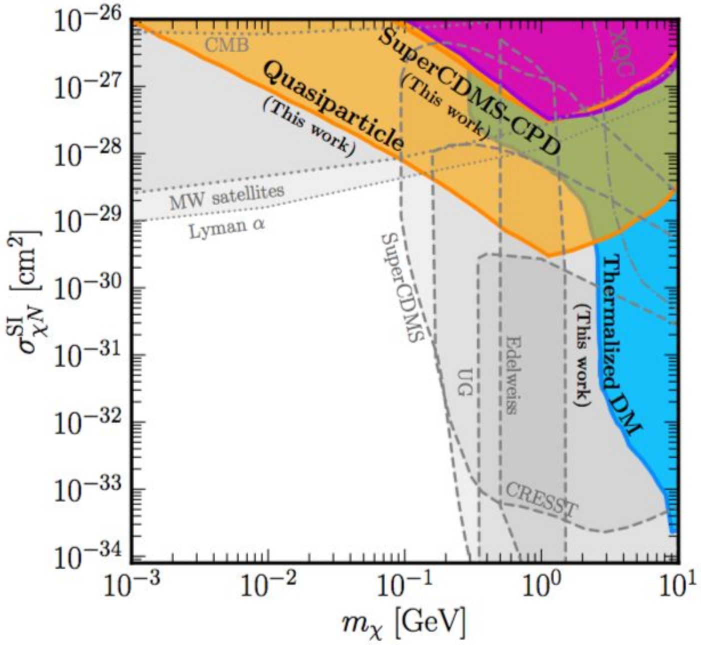


***P* = 3 x 10^{-21} W*μ*m^{-3}**

PRD 104, 032010 (2021)
Matt Pyle, 2022

New Limits on DM-nuclear cross section

$$P_{\rm DM} = \int d\omega\, \omega \frac{d\Gamma}{d\omega} \leq P_{\rm limit}$$



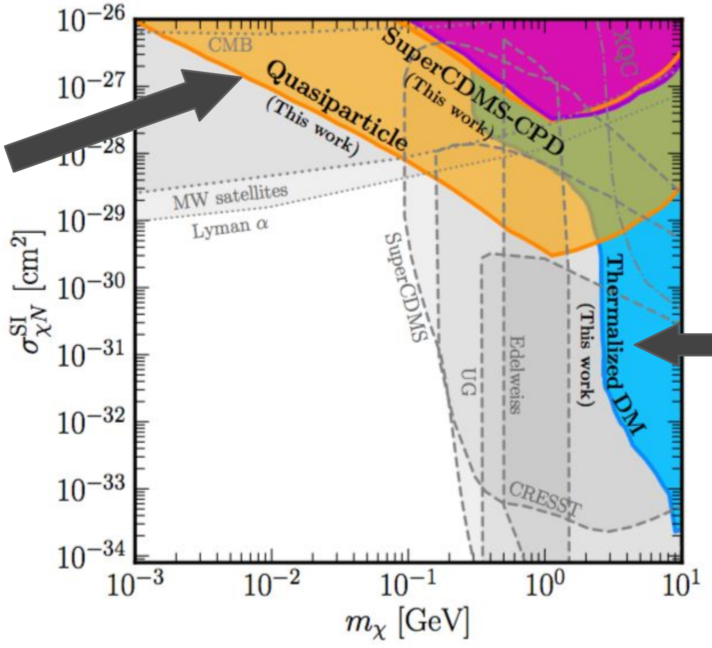
arXiv:2210.09313

Unprecedented power sensitivity helps us put new limits on DM-nucleon cross section for both thermalized and halo population

New Limits on DM-nuclear cross section

competitive limit for
halo DM

$$P_{\rm DM} = \int d\omega\, \omega \frac{d\Gamma}{d\omega} \leq P_{\rm limit}$$

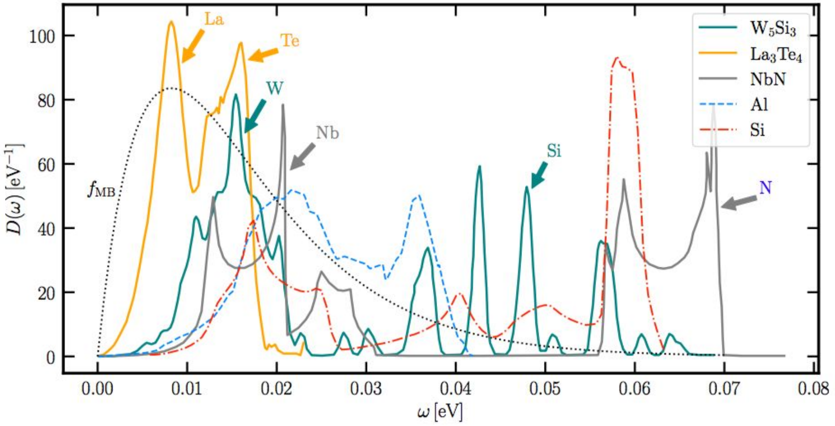


arXiv:2210.09313

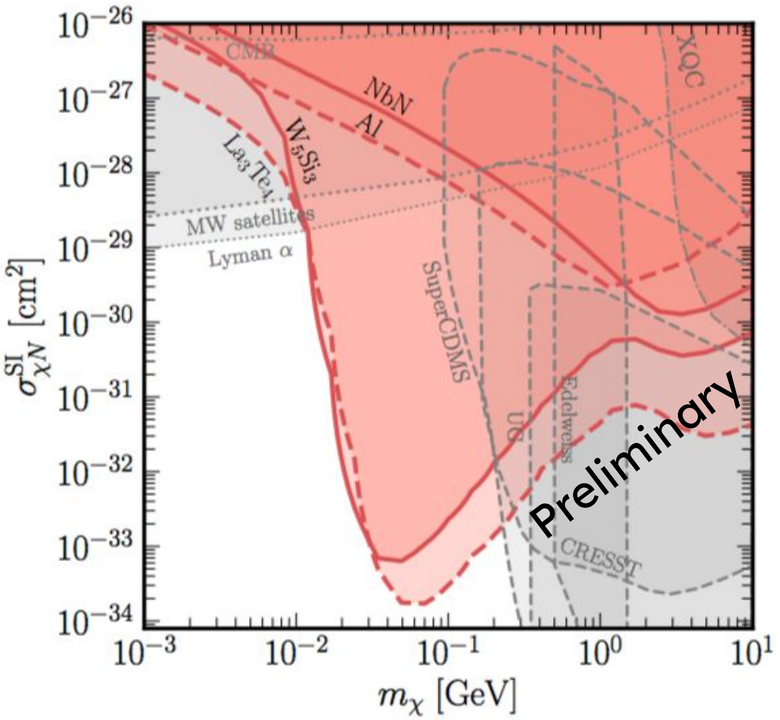
Limit on thermalized DM
(only limited by DM evap.)

Unprecedented power sensitivity helps us put new limits on DM-nucleon cross section for both thermalized and halo population

Optimizing the absorber material



Better overlap with thermalized DM distribution

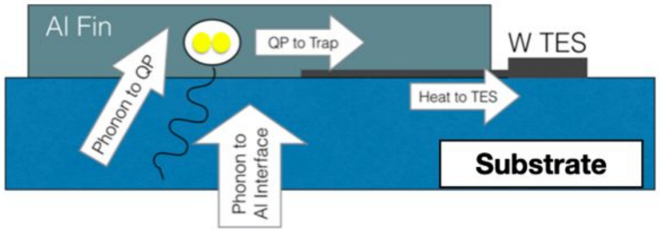


New materials with more phonon states at low energy

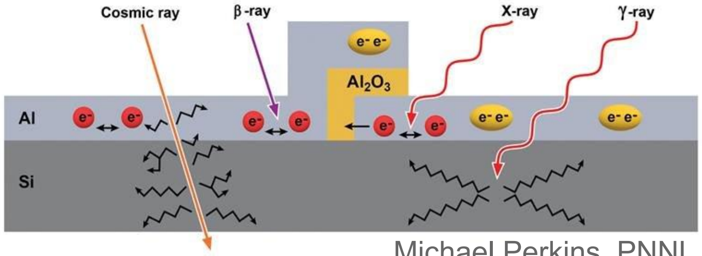
Challenges for detection:

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

Similarity w/ superconductor-based Qubit



Athermal phonon sensor used in SuperCDMS



SC Al-based Qubit chip

Technological similarity between Quantum sensors & Qubit chips

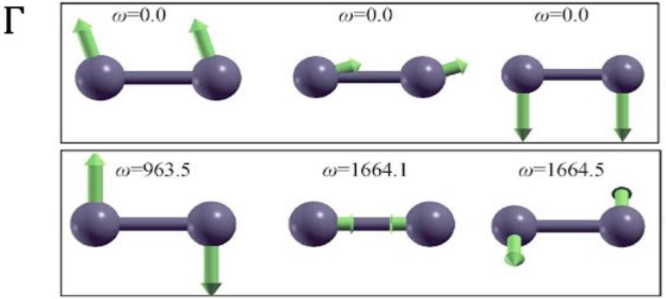
Cross-community collaboration will be critical

Final takeaways

- As DM searches dig deeper into the parameter space, it becomes more challenging
- New technique of measuring the power deposited by DM could be more useful in future
- Mesoscopic quantum devices are set to improve further in measuring small energy deposit
- Close technical connection with qubit development research
- Collaborative strategy will be beneficial

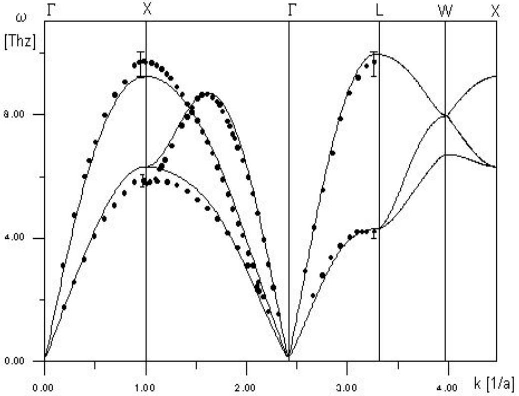
Phonons are quanta of crystal lattice oscillation

Total number of modes $3N$

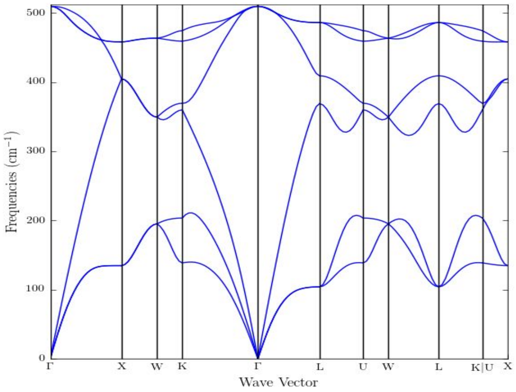


Acoustic modes

Optical modes



Aluminum



Silicon

Dark Matter Interaction Rate

Velocity-averaged interaction rate

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

Structure Factor: detector response

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

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

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.

$q < q_{\rm BZ}$

$$S_{\rm LA} \simeq \frac{2\pi}{V_c} \frac{\sum A_d q^2}{2m_p \omega_{\rm LA}} \delta(\omega - \omega_{\rm LA})$$

$$S_{\rm LO} \simeq \frac{2\pi}{V_c} \frac{a^2 q^4}{32 m_p \omega_{\rm LO}} \frac{A_1 A_2}{A_1 + A_2} \delta(\omega - \omega_{\rm LO})$$

Knowledge from neutron scattering

Incoherent Approx.

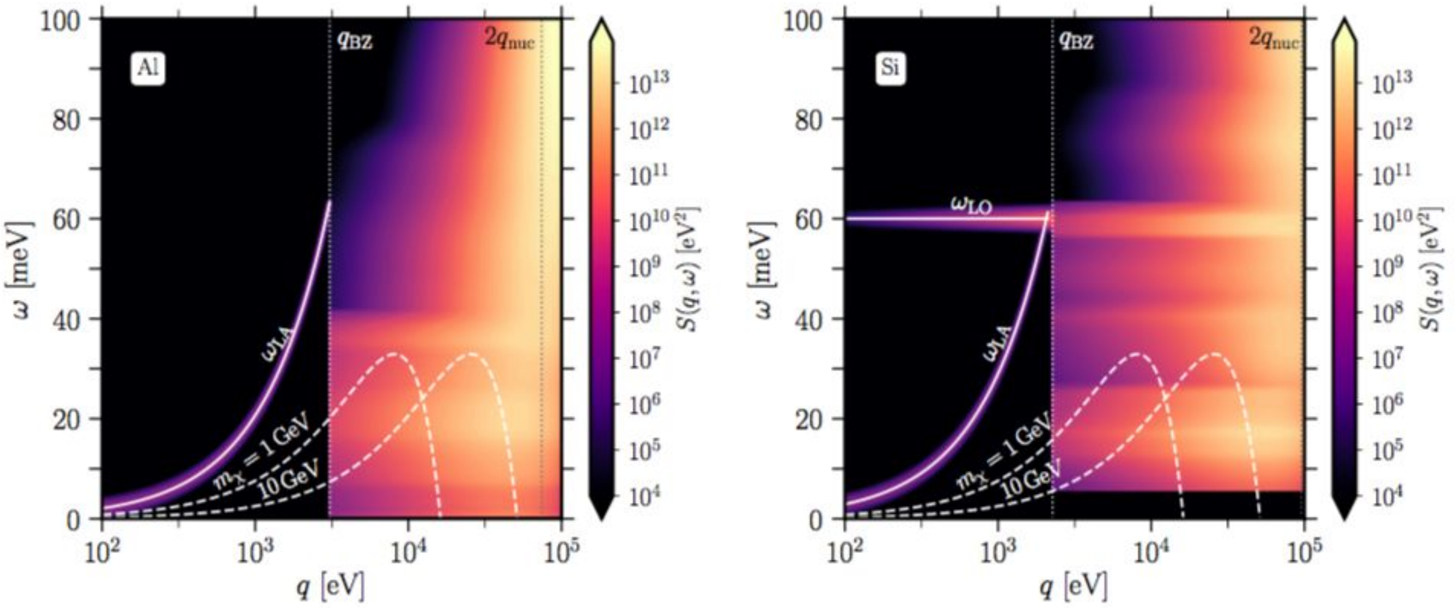
$q > q_{\rm BZ}$

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

Approaches nuclear recoil in large ω and q limit

2205.02250

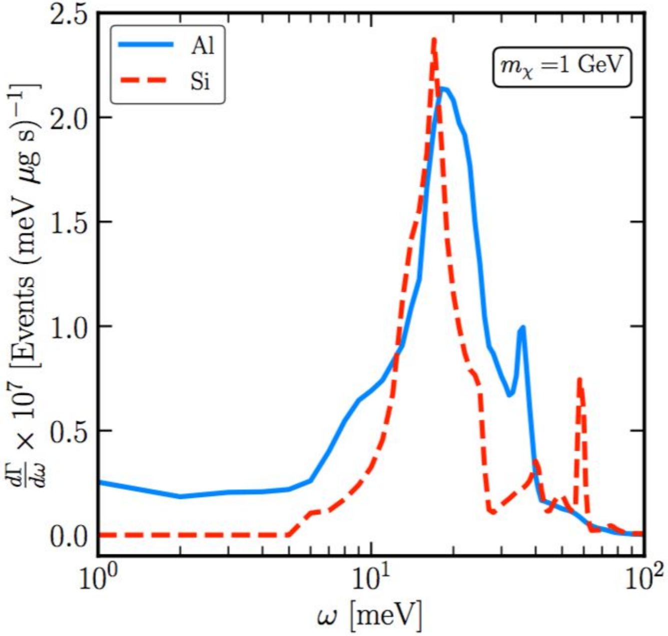
Structure factors of Al & Si



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

arXiv:2210.09313

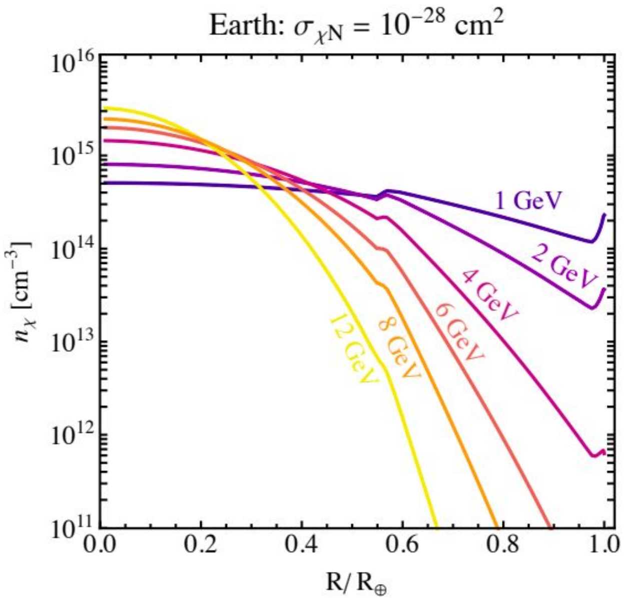
Differential Scattering Rate in Al & Si



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$)$