Mesoscopic Quantum Systems to Detect Light Dark Matter

Anirban Das

Seoul National University

August 17, 2023

KIAS HEP seminar

AN what is the future of dark matter search experiments?

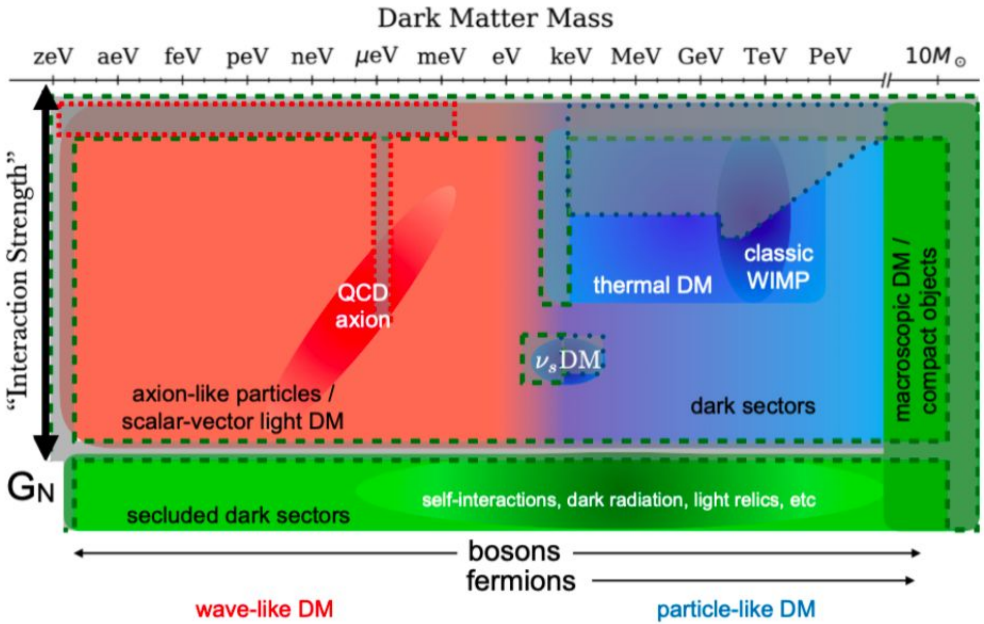
1. **Increasing Sensitivity**: Experiments will continue to push the boundaries of sensitivity, aiming to detect even weaker interactions between dark matter and ordinary matter. This involves developing more sophisticated detectors, shielding techniques, and data analysis methods to minimize background noise and improve signal detection.
2. **Diverse Detection Strategies**: Researchers will explore a wide range of dark matter detection strategies, including direct detection, indirect detection, and collider experiments. Each approach provides complementary information about the nature of dark matter particles.
3. **Light Dark Matter and Axions**: Efforts to detect light dark matter particles and axions will intensify. New experimental setups and technologies will be developed to enhance sensitivity to low-mass particles, which could have a significant impact on our understanding of dark matter.
4. **Advanced Detectors and Materials**: Continued advancements in detector technologies, such as cryogenic detectors, time projection chambers, and quantum sensors, will enable more efficient and accurate measurements, allowing for the detection of weaker signals.
5. **Global Collaboration**: Collaborations between research groups, institutions, and countries will play a crucial role in accelerating progress. Sharing knowledge, data, and expertise will lead to more efficient utilization of resources and a better chance of discovery.

ChatGPT

Outline:

- Light dark matter detection channels
- Dark matter power deposition & sensing
- Electron scattering in graphene
- Synergy with quantum computer research

Dark matter mass range is vast
anything between 10^{-22} and 10^{67} eV is possible



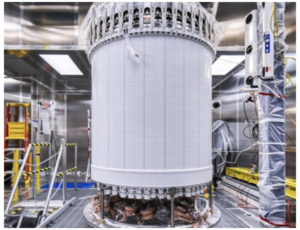
Snowmass 2021

Different mass regimes ask for different search strategies

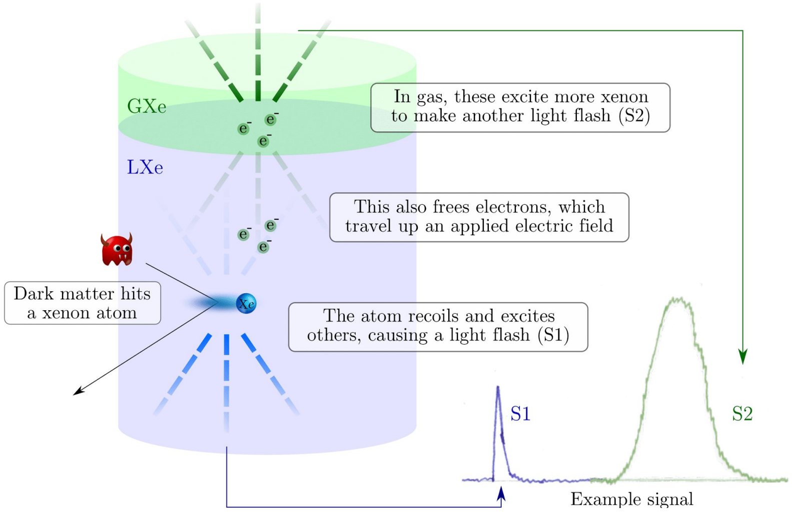
Direct Search for 'Classic' WIMP Dark Matter

~ 10 GeV - 10 TeV

XENONnT

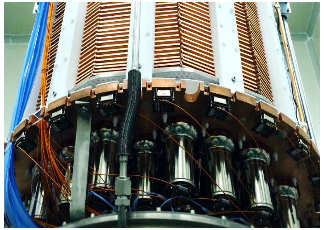


LZ



XENON

Nuclear recoil signal from DM scattering



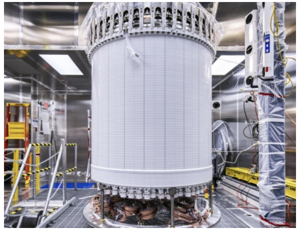
PandaX

COSINE

and more …

Direct Search for 'Classic' WIMP Dark Matter

XENONnT



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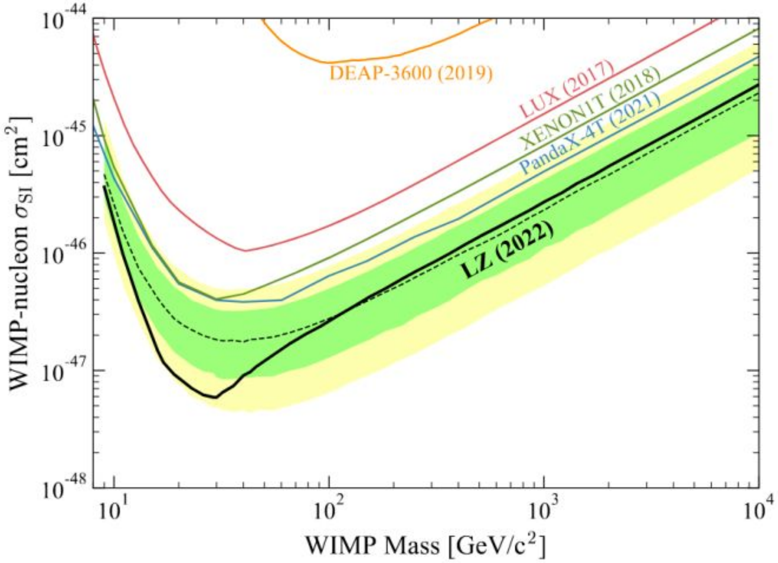
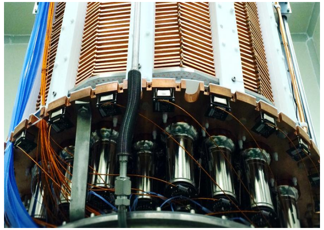


Current scenario above ~ 10 GeV

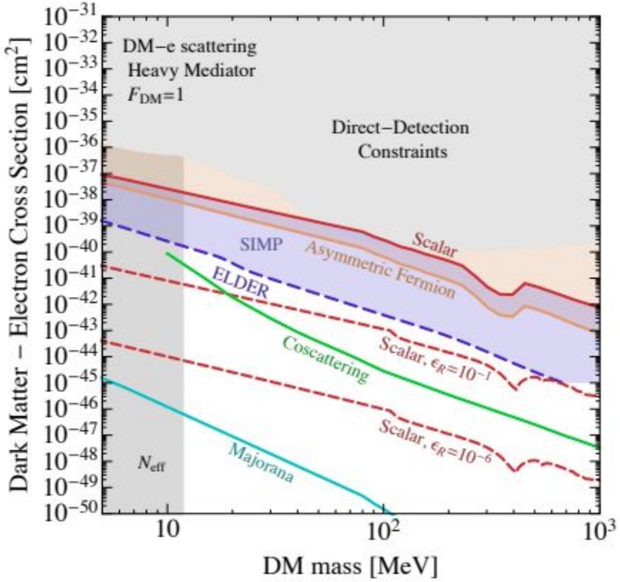


PANDA

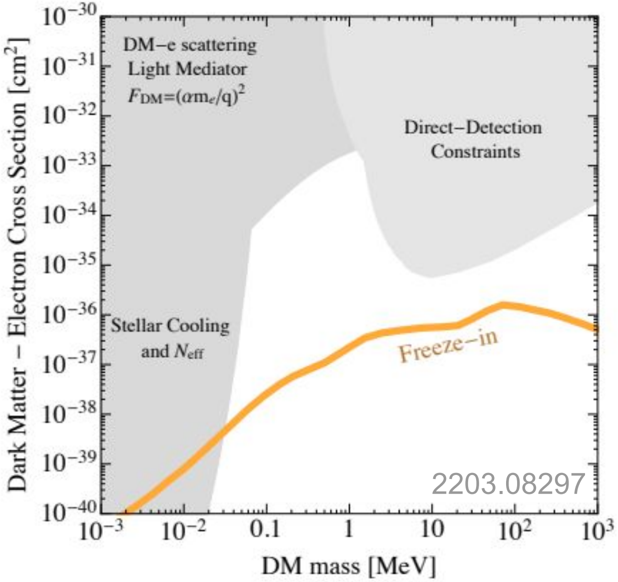
COSINE

and more …

Sub-GeV Mass Range: Models



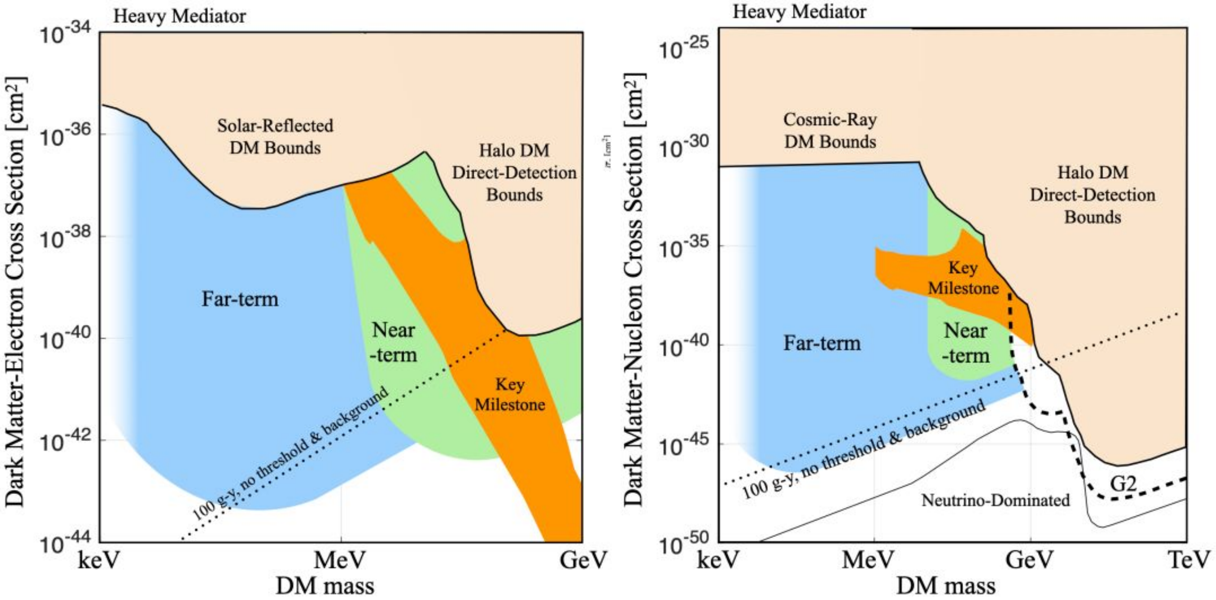
Freeze-out (heavy mediator)



Freeze-in (light mediator)

Portals: Vector, Scalar, Electric & Magnetic dipole

Sub-GeV Mass Range: The landscape



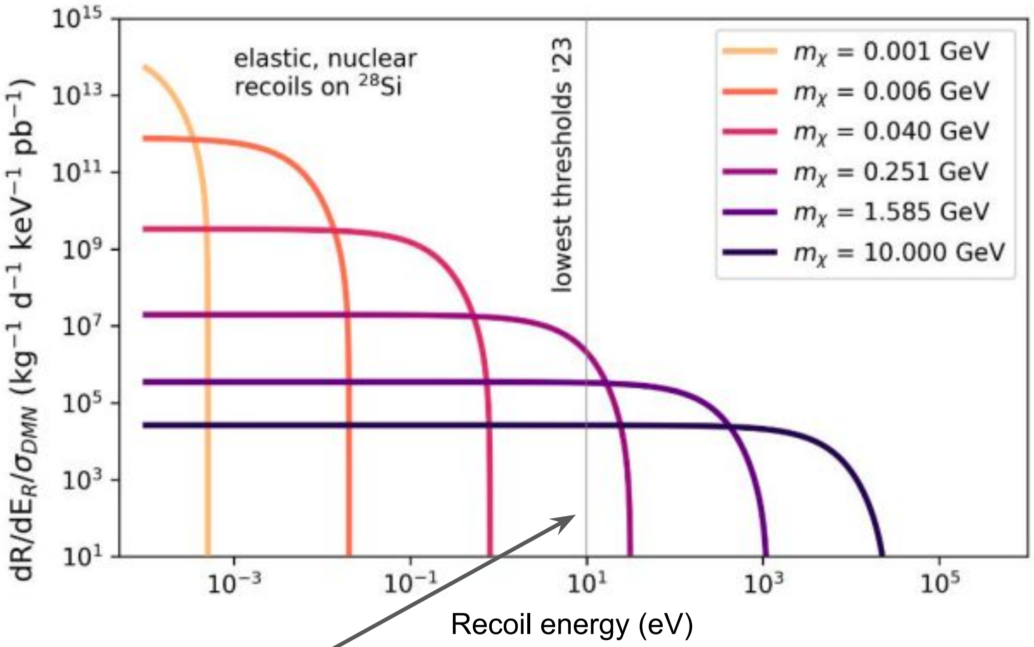
2203.08297

Below ~ 100 MeV, nuclear & electron recoil based experiments lose sensitivity & the parameter space is significantly less explored

Sub-GeV Mass Range: Recoil energies

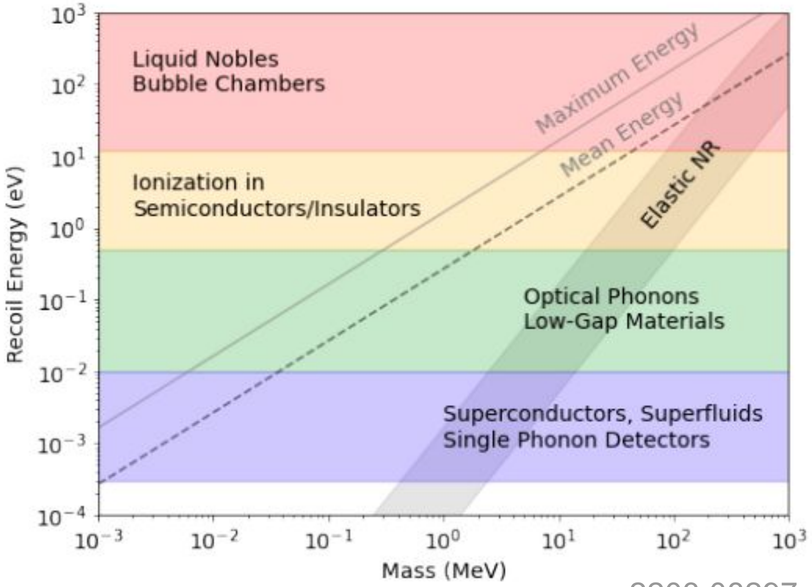
Recoil energy is proportional to the Nonrelativistic DM mass

$$E_\chi \simeq 0.3\,\mathrm{eV}\left(\frac{m_\chi}{\mathrm{MeV}}\right)$$



Lowest achieved energy threshold

Sub-GeV Mass Range: Exploration techniques



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Depending on the typical DM energy, different detection methods needed

Sub-GeV Mass Range: Exploration techniques

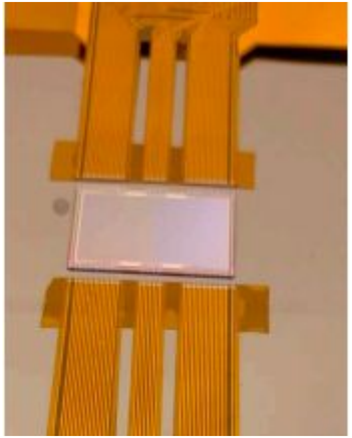
Low mass DM has larger number density

$$n_\chi = \frac{\rho_\chi}{m_\chi} = \frac{0.4\ \mathrm{GeV\ cm^{-3}}}{m_\chi}$$

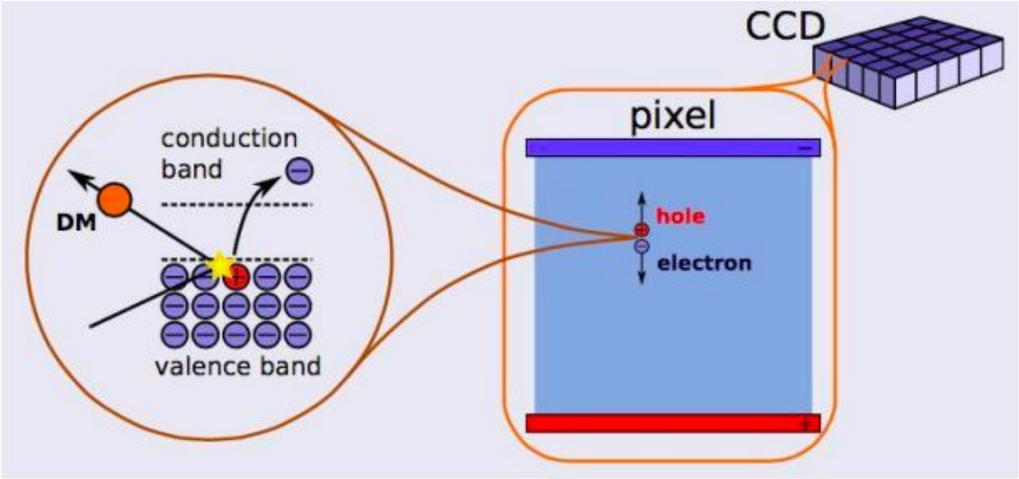
Relatively smaller scale experiments can have good reach

Charge Detectors

Charge Coupled Devices (Skipper-CCD) made of semiconductors look for free charges released from possible DM scattering



Skipper CCD

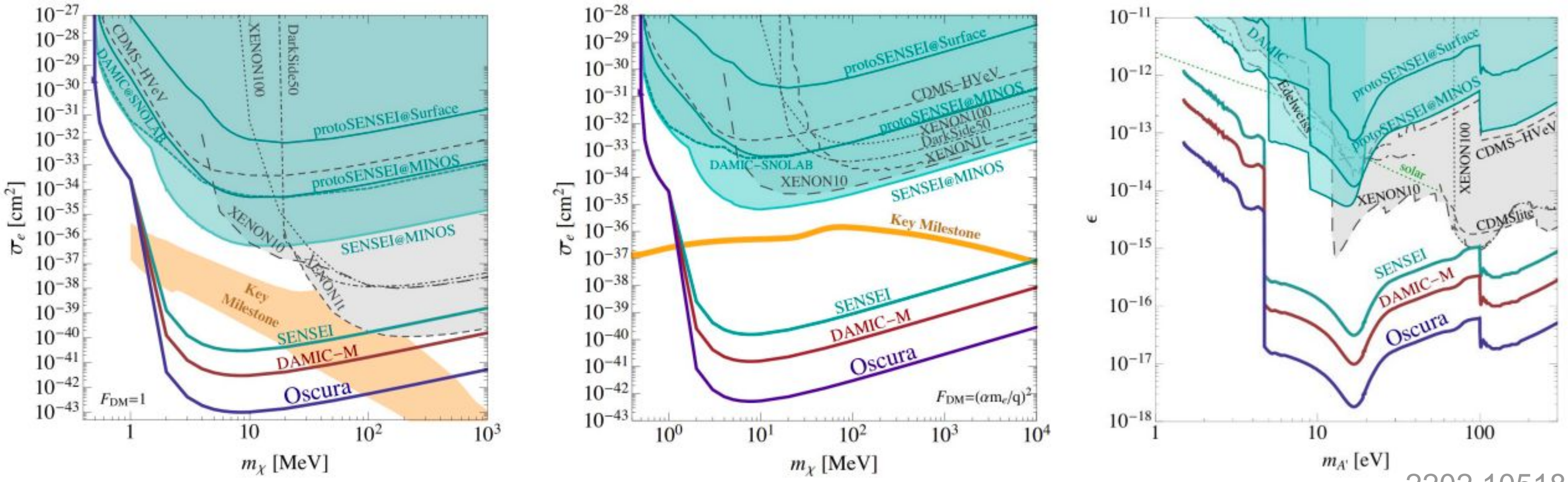


Nate Saffold 2022

SENSEI, DAMIC-M, Oscura

Charge Detectors

Charge Coupled Devices (Skipper-CCD) made of semiconductors look for free charges released from possible DM scattering



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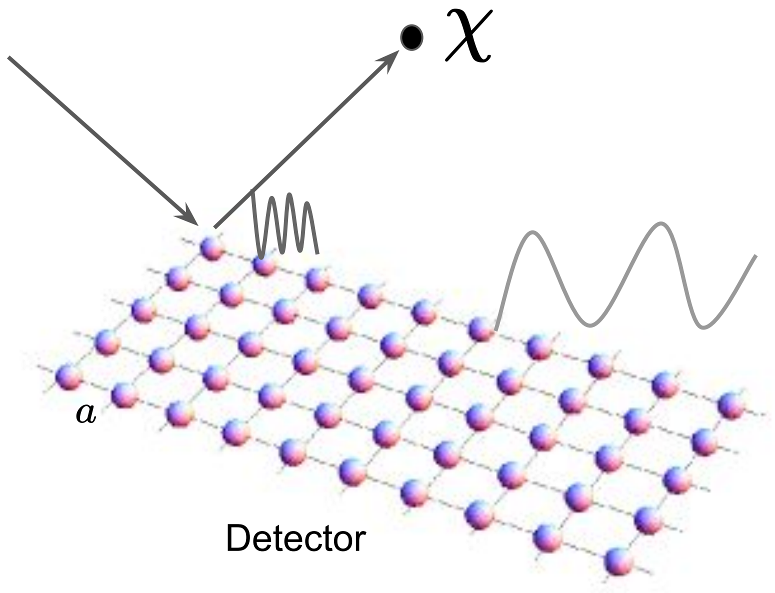
SENSEI, DAMIC-M, Oscura are set to cover benchmark models in future

Low momentum scattering:
Phonon excitation



When momentum transfer $q \simeq \frac{2\pi}{a} = \mathcal{O}(\mathrm{keV})$

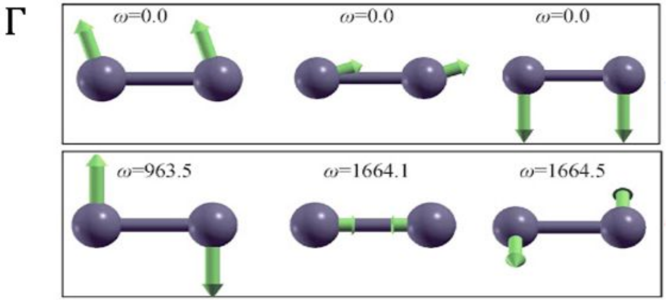
energy transfer $\omega < \mathcal{O}(100\,\mathrm{meV})$

Lattice vibration/phonons becomes the dominant mode of energy transfer

Need to compute phonon excitation rate

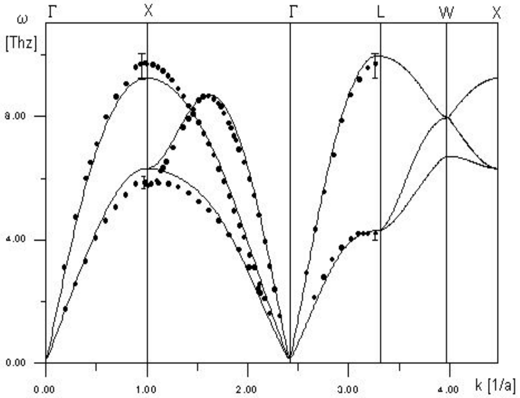
Phonons are quanta of crystal lattice oscillation

Total number of modes 3*N*

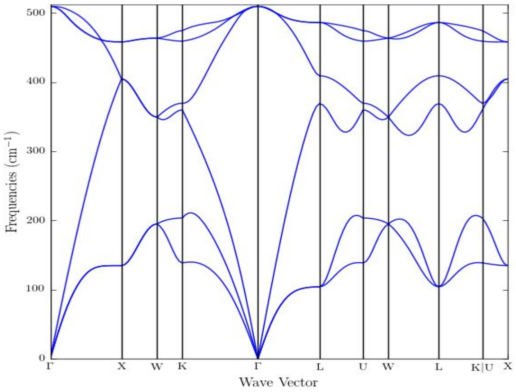


Acoustic modes

Optical modes



Aluminum



Silicon

Dark Matter Interaction Rate

Velocity-averaged interaction rate

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

Structure Factor:
detector response

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

$$\omega_{\mathbf{q}} = \mathbf{q} \cdot \mathbf{v} - \frac{q^2}{2m_\chi} = E_f - E_i$$ Energy transfer in a single scattering

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

Heavy mediator

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

Light mediator

Single & Multi-phonon Structure Factor

Coherent Approx.

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

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

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

Knowledge from neutron scattering

Incoherent Approx.

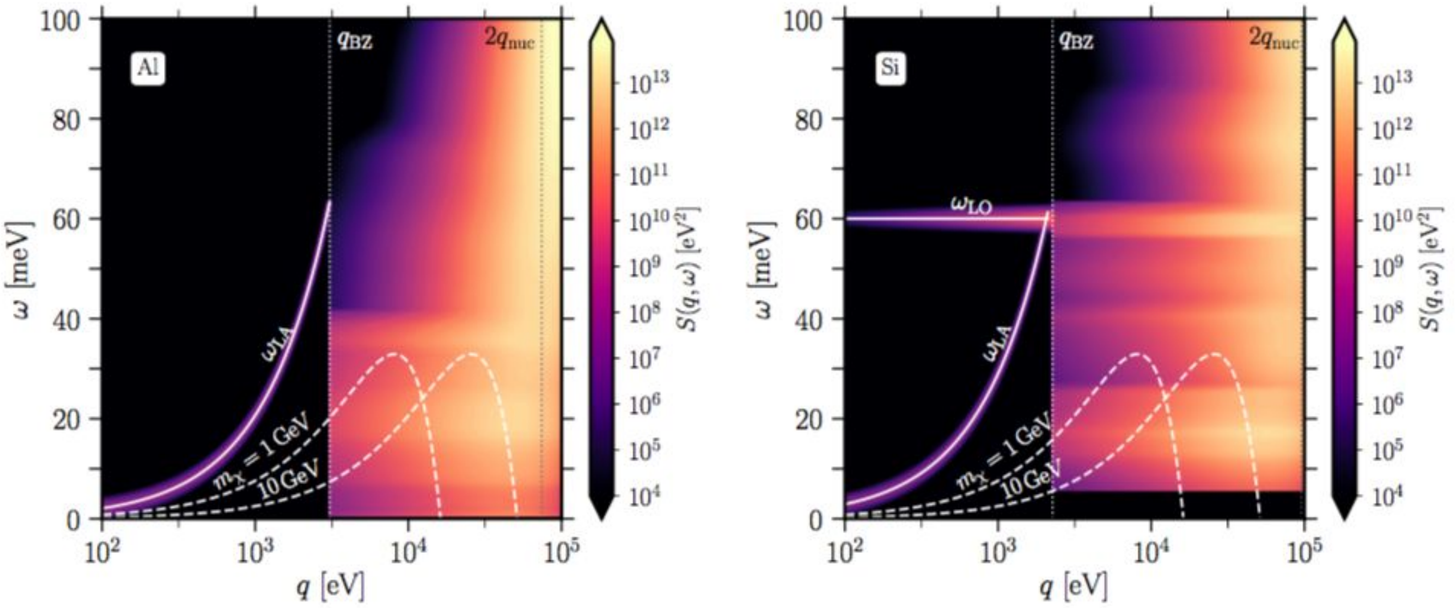
$q > q_{\mathrm{BZ}}$

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

Approaches nuclear recoil in large ω and q limit

2205.02250

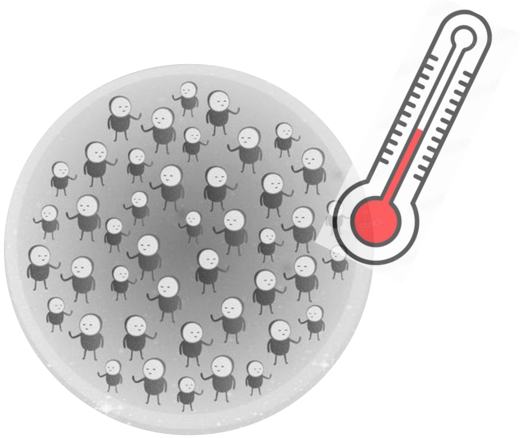
Structure factors of Al & Si



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

arXiv:2210.09313

Power Measurement by Quantum Devices

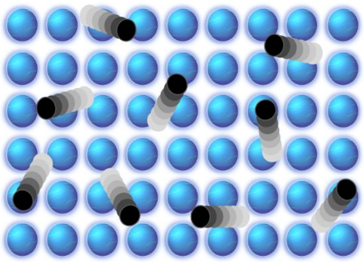


AD, N. Kurinsky, R. Leane
arXiv:2210.09313

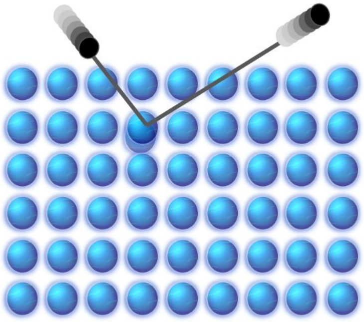
Power Deposited by Dark Matter Scattering

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

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



Noise from DM



Recoil from DM

arXiv:2210.09313

Captured Dark Matter on Earth

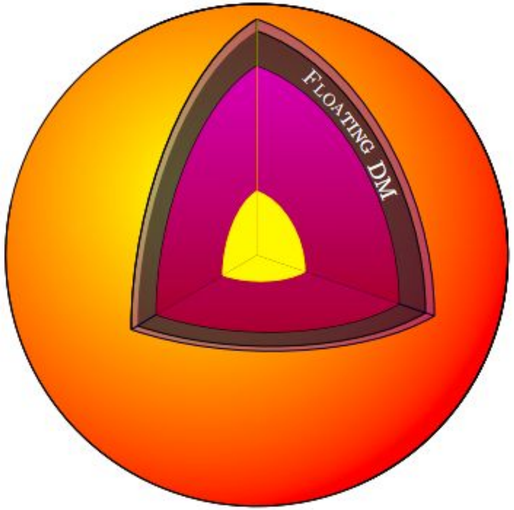


FIG. 1. Schematic of floating DM on the outer region of the celestial object as found in this work (dark shaded shell).

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

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

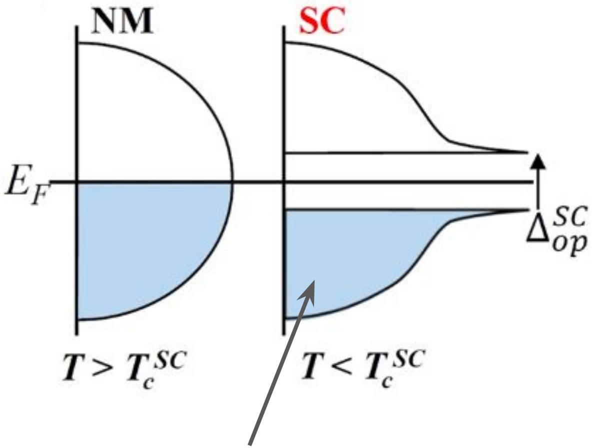
Thermalized DM

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

Low threshold experiments needed for them too

Quantum Devices Based on Superconductor

Electron DoS

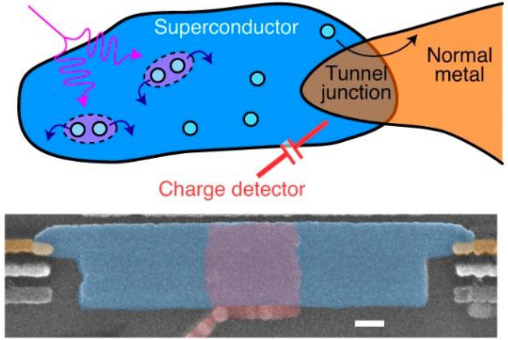


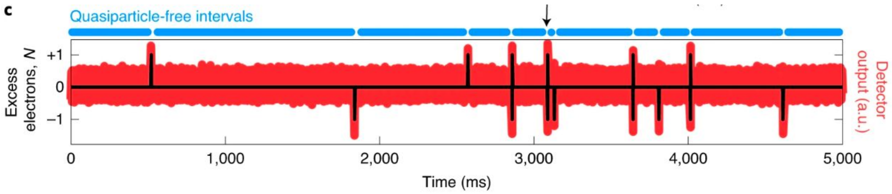
BCS ground state:
sea of Cooper pairs

Δ_{Al} = 0.34 meV

P = 6 x 10^{-25} Wμm^{-3}

Low bkg quasiparticle device

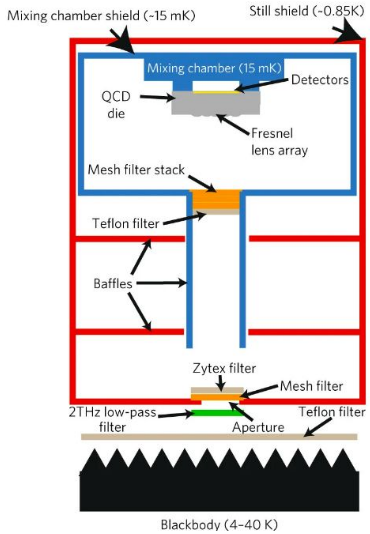


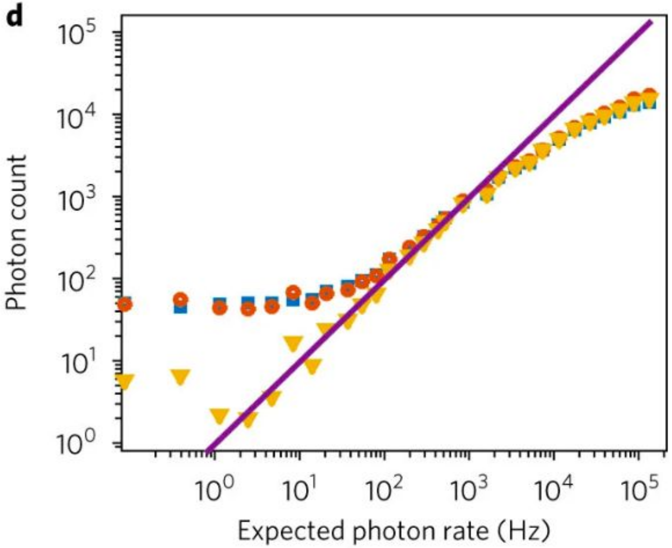


Nature Physics 18, 145-148 (2022)

Quantum Devices Based on Superconductor

Low noise bolometer, Cryogenic infrared sensor



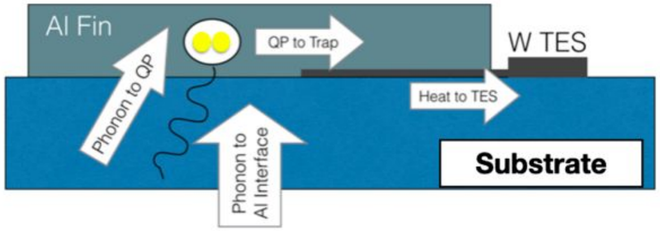


P = 1.7 x 10^{-20} Wμm^{-3}

Nature Astronomy 2, 90-97 (2018)

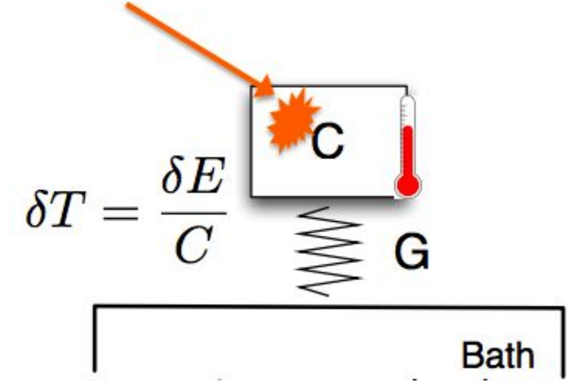
Quantum Devices Based on Superconductor

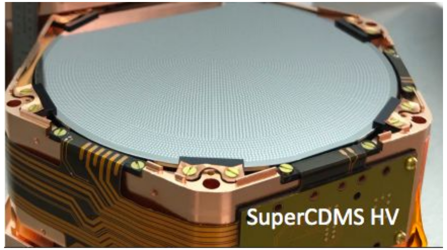
SuperCDMS Si detector covered with SC Al fins coupled to W TES



Athermal phonon sensor

External agent





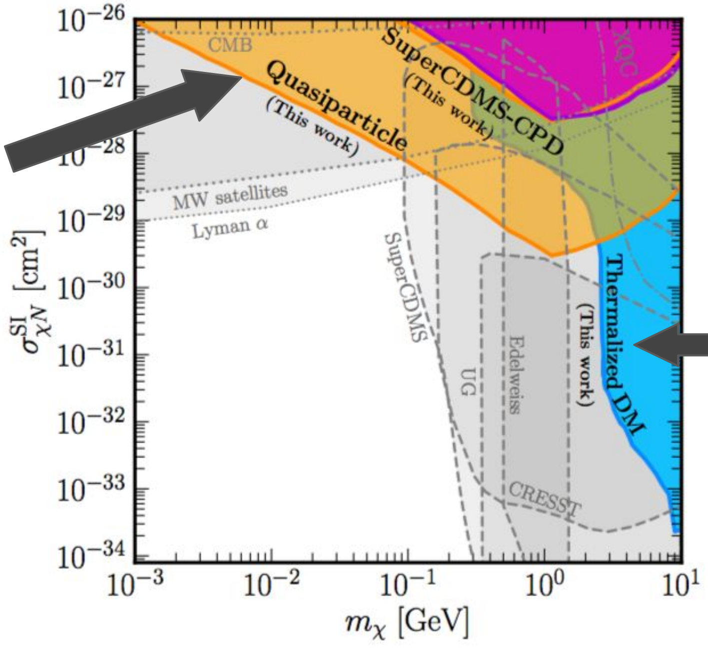
$P = 3 \times 10^{-21}$ Wμm^{-3}

PRD 104, 032010 (2021)
Matt Pyle, 2022

New Limits on DM-nuclear cross section

competitive limit for halo DM

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

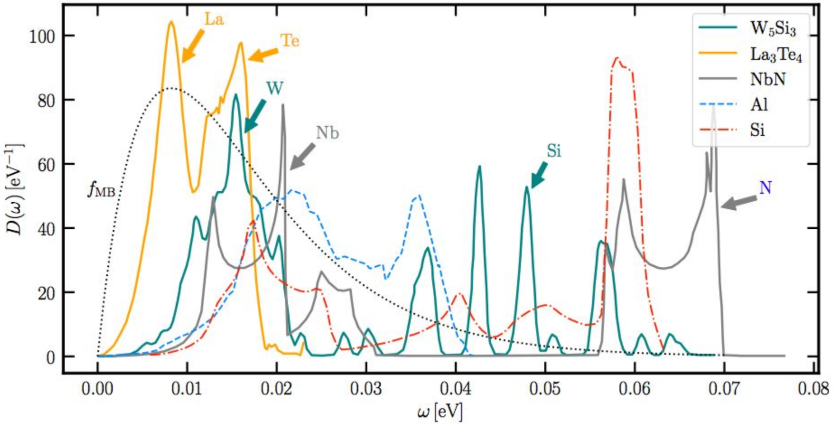


arXiv:2210.09313

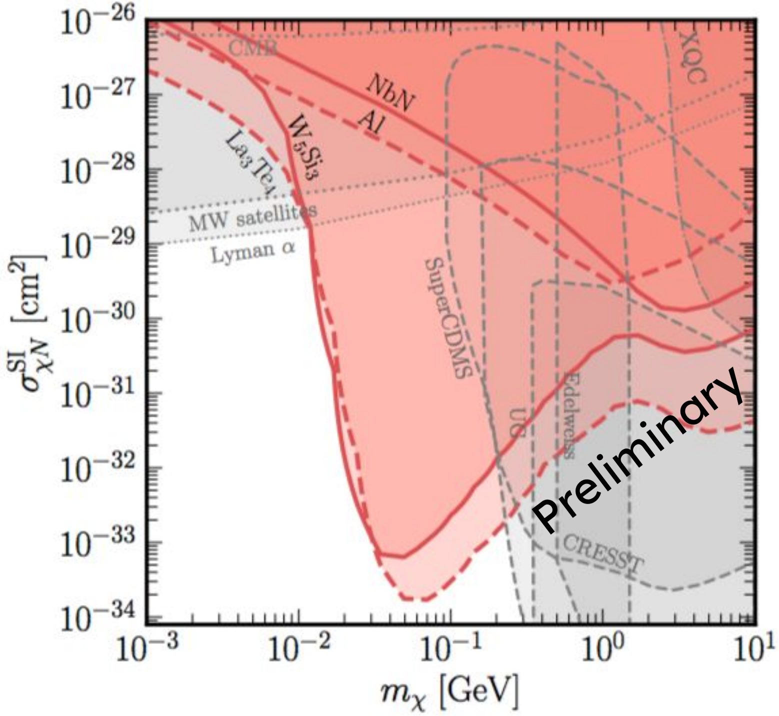
Limit on thermalized DM (only limited by DM evap.)

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

New Limits on DM-nuclear cross section

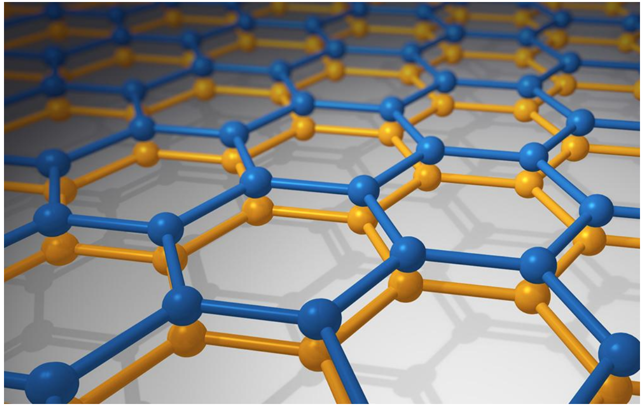


Better overlap with thermalized DM

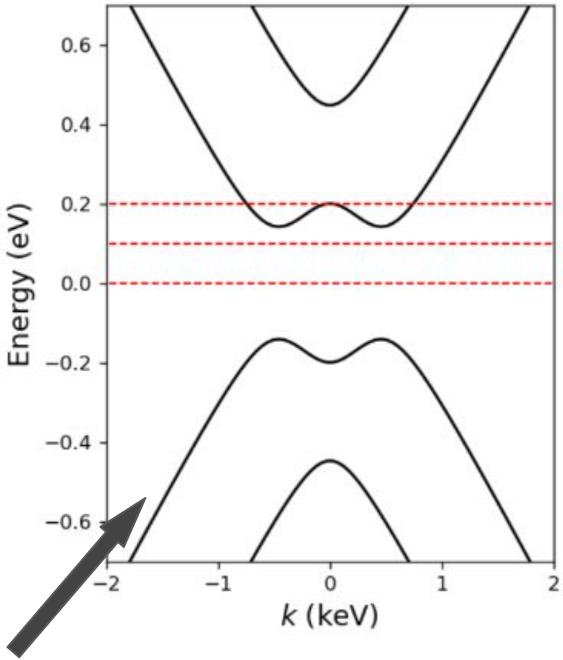


New materials with more phonon states at low energy

Bi-layer Graphene (BLG)



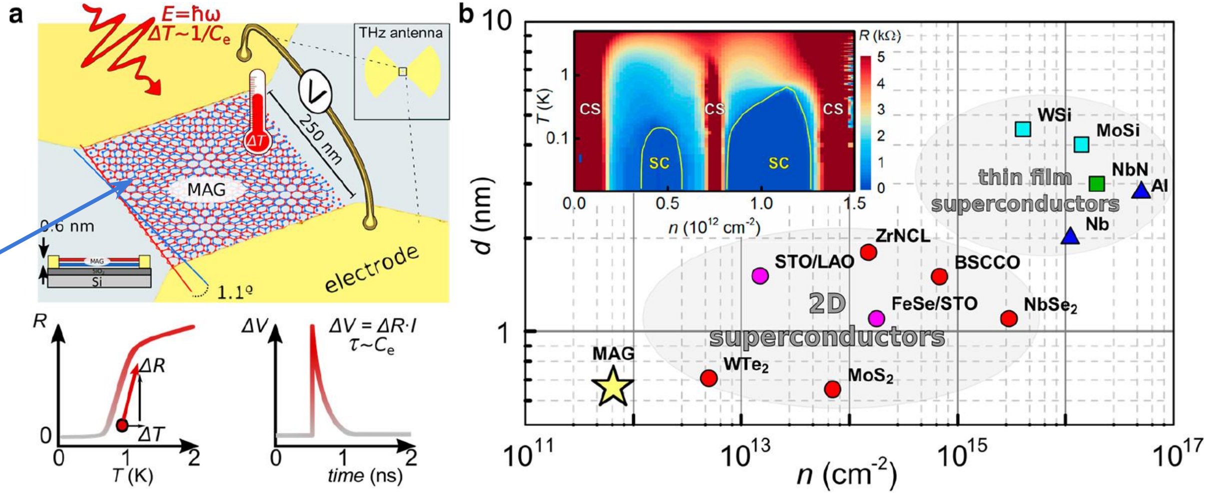
In BLG, intra- and inter-layer electrons interact to create distinct band structure



A tunable energy gap between the bands can be created by gating the BLG with appropriate voltage

Twisted Bi-layer Graphene (tBLG)

Single Photon Detector



Twisted bi-layer graphene (tBLG) shows superconductivity at certain twist angles known as the Magic Angles $(\theta \simeq 1.05^\circ)$

Nano Lett. 2020, 20, 5, 3459–3464

Dark Matter-Electron Scattering

Sub-MeV DM may not have enough energy to liberate an electron

But it can excite perturbations in the electron sea in a metal/semiconductor

$$\underbrace{\frac{1}{\epsilon(q,\omega)}}_{\text{Dielectric function}} = 1 + \underbrace{V_c(q)}_{\text{Coulomb potential}}\,\underbrace{\chi(q,\omega)}_{\text{Linear response}}$$

In the linear regime, dielectric function contains all information about the medium

arXiv:2101.08263

Dark Matter-Electron Scattering

Sub-MeV DM may not have enough energy to liberate an electron

But it can excite oscillations in the electron sea in a metal/semiconductor

$$S(q,\omega) \propto 2\,\mathrm{Im}(-\chi(q,\omega)) = \frac{2}{V_c(q)}\mathrm{Im}\left(\frac{-1}{\epsilon(q,\omega)}\right)$$

Energy Loss Function (ELF)

DM-e scattering rate becomes proportional to the ELF of the material which is experimentally measurable

Applicable to scalar, vector, fermionic DM

arXiv:2101.08263

Dark Matter-Electron Scattering

$$S(q,\omega) \propto 2\,\mathrm{Im}(-\chi(q,\omega)) = \frac{2}{V_c(q)}\mathrm{Im}\underbrace{\left(\frac{-1}{\epsilon(q,\omega)}\right)}_{\text{Energy Loss Function (ELF)}}$$

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

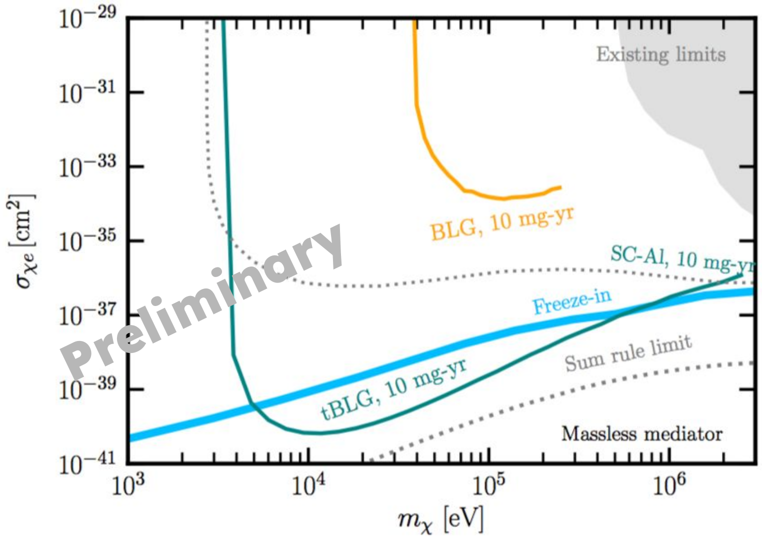
DM-e scattering rate becomes proportional to the ELF of the material which is experimentally measurable

Applicable to scalar, vector, fermionic DM

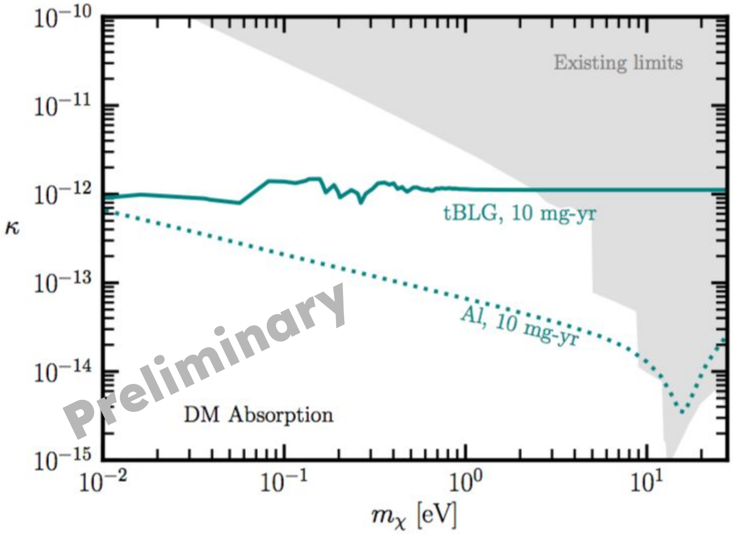
arXiv:2101.08263

Dark Matter-Electron Scattering in Graphene

Competitive limit can be obtained by using bi-layer graphene



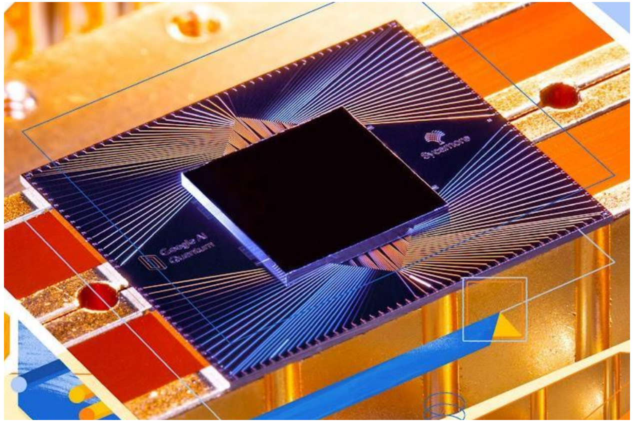
Scattering

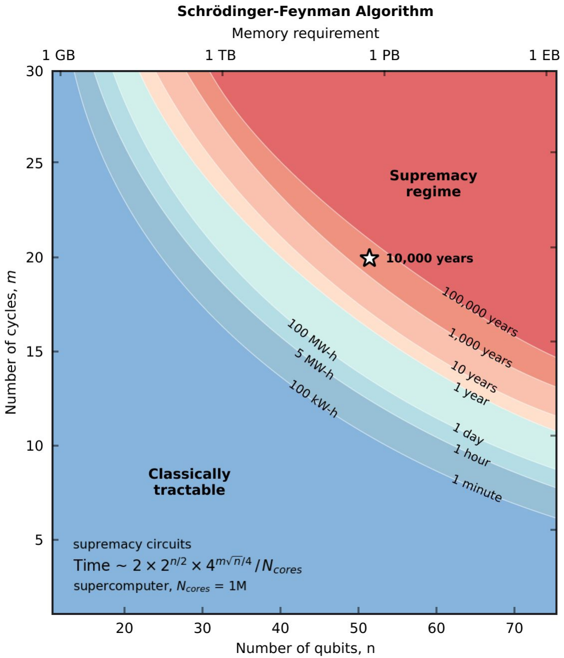


Absorption

Synergy between DM search & Quantum Computer

Sycamore processor has 54 qubits on its chip



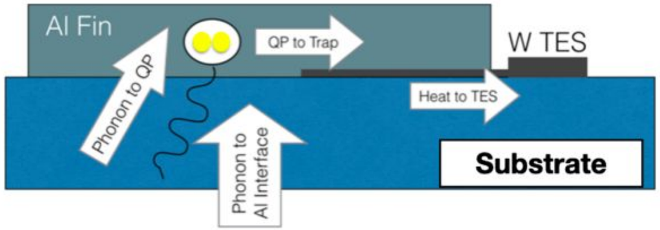


A key goal in developing future quantum processor is to achieve

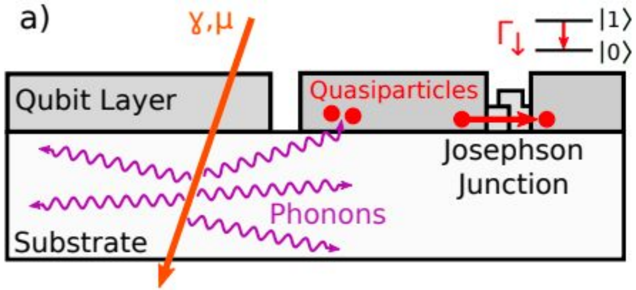
long term coherence over a large number of qubits

Google quantum AI, https://quantumai.google/hardware

Synergy between DM search & Quantum Computer



Athermal phonon sensor of SuperCDMS



Qubit chip used by Sycamore

2104.05219

Qubits are small quantum systems with two definite states

Isolation from external perturbations is essential to maintain long range coherence between qubits

Synergy between DM search & Quantum Computer

Two areas have different motivations but similar technical goals

Collaboration between the two groups will bring in expertise in different areas

Already started – e.g. NEXUS at Fermilab, . . .

Check out UT physics colloquium:

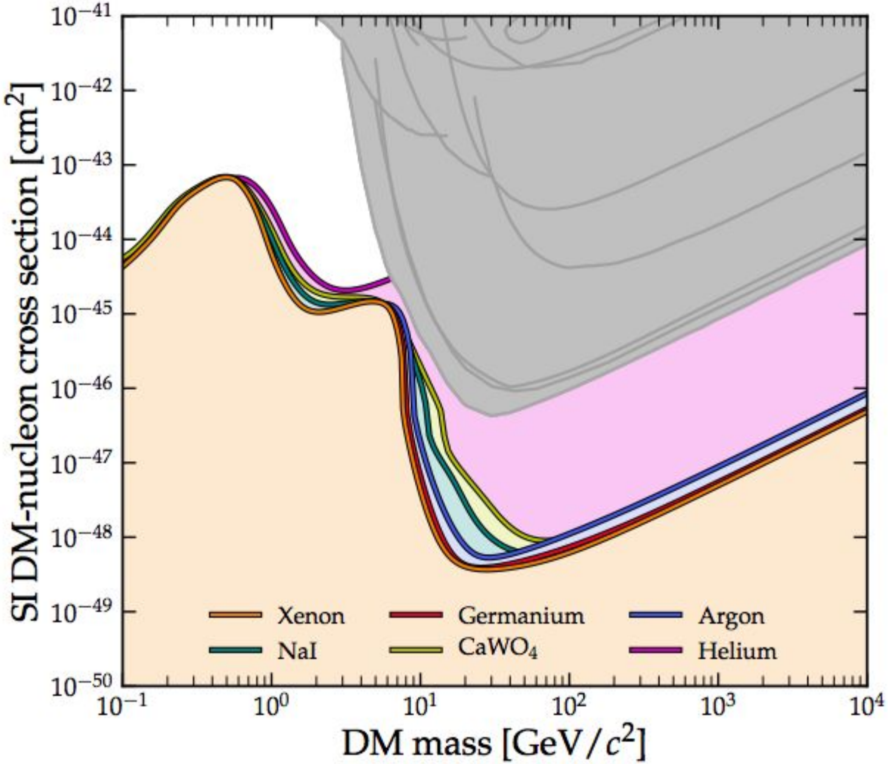
https://www.youtube.com/watch?v=mKMO0OgWVN0

Final words

- ➢ DM theory space is vast and sub-GeV DM is relatively less explored. We need different strategies to probe its different regions
- ➢ As we probe deeper into the parameter space, it becomes more challenging to look for any signature of DM
- ➢ Innovative and state-of-the-art technology is needed to design experiments with high sensitivity
- ➢ Collaborative strategy with quantum computer research could be beneficial

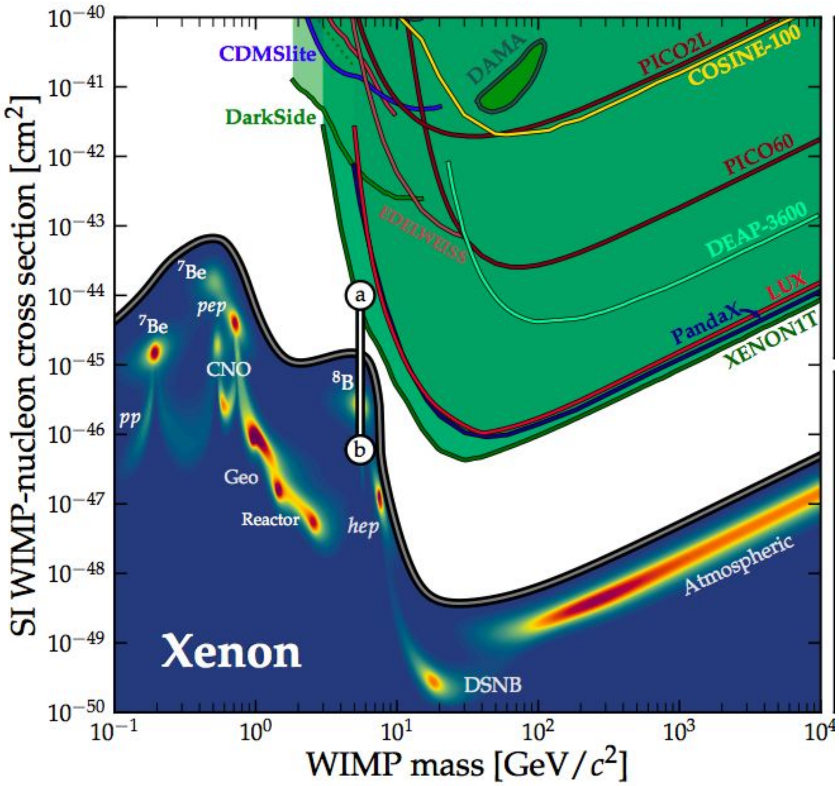
Back ups

Neutrino floor for various detectors



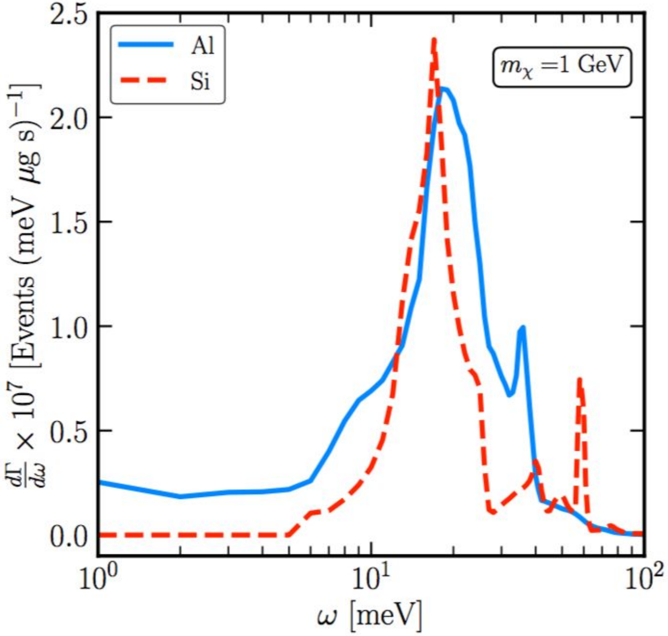
2109.03116

Neutrino floor for various detectors



2109.03116

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

DM Capture in Earth thru Scattering

arXiv:2209.09834

Floating Dark Matter in Celestial Bodies

Rebecca K. Leane[1,2,*] and Juri Smirnov[3,†]

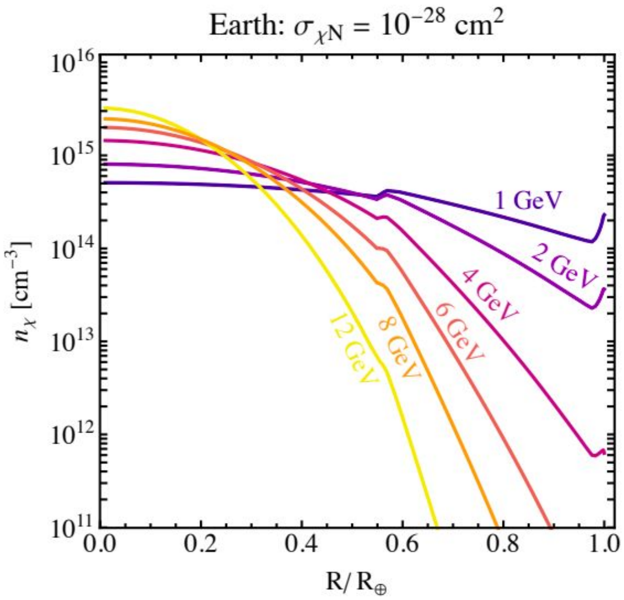
[1]SLAC National Accelerator Laboratory, Stanford University, Menlo Park, CA 94025, USA
[2]Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94305, USA
[3]Department of Mathematical Sciences, University of Liverpool, Liverpool, L69 7ZL, United Kingdom

(Dated: September 21, 2022)

Dark matter (DM) can be captured in celestial bodies after scattering and losing sufficient energy to become gravitationally bound. We derive a general framework that describes the current DM distribution inside celestial objects, which self-consistently includes the effects of concentration diffusion, thermal diffusion, gravity, and capture accumulation. For DM with sufficient interactions, we show that a significant DM population can thermalize and sit towards the celestial-body surface. This floating distribution allows for new phenomenology for DM searches in a wide range of celestial bodies, including the Sun, Earth, Jupiter, Brown Dwarfs, and Exoplanets.

arXiv:2209.09834

Floating Dark Matter on Earth

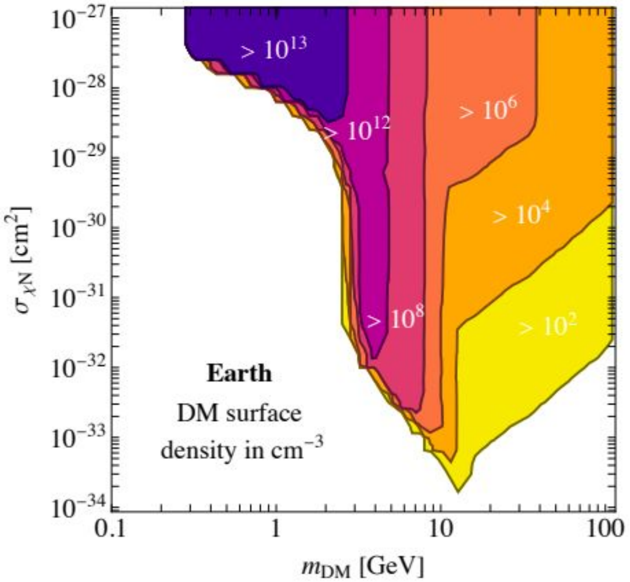


For DM mass 1-10 GeV and xsec > 10^{-35} cm^2, the thermalized population can get very dense near Earth's surface

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

arXiv:2209.09834

Floating Dark Matter on Earth

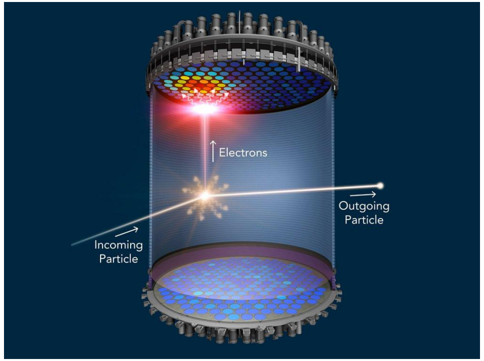


For DM mass 1-10 GeV and xsec > 10^{-35} cm^2, the thermalized population can get very dense near Earth's surface

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

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

XENON

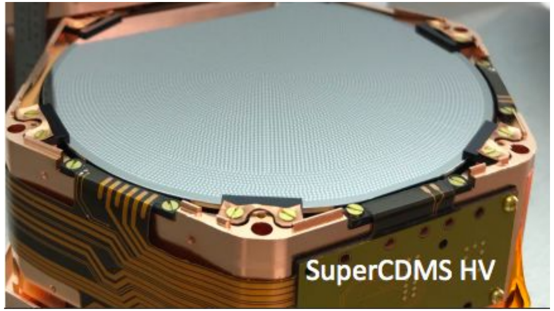


1 keV for e^- - recoil (Migdal)

CRESST

$O(100)$ eV

SuperCDMS-CPD



1 eV