DM Direct Detection: From Particle Physics to Material Science

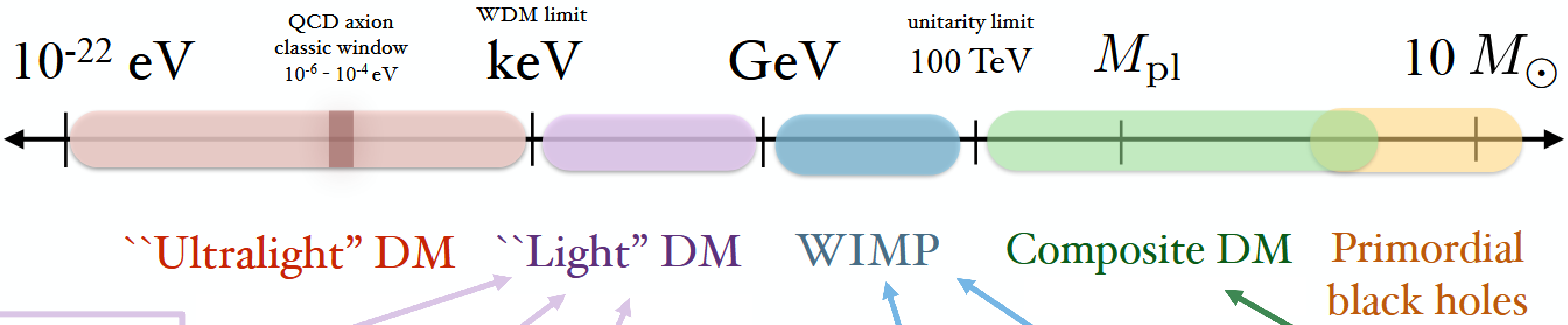
BETHANY SUTER | UC BERKELEY

EXPERIMENT MEETS THEORY, GGI

NOVEMBER 17, 2025

Image credit: Shutterstock

What I’ve worked on (and future work)



Mirror DM at a Muon Collider
arXiv:26XX.XXXXX

First High-Throughput Search for Dark Matter Detector Materials
arXiv:2506.19905

Multiphonon Processes in Spin-Dependent Dark-Matter Scattering
arXiv:2506.11191

WIMP-like Asymmetric DM Model
arXiv:2107.03398

A Bayesian statistical approach to supersymmetry
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AMSB applied to chiral gauge theories
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Fig from:
arXiv:1904.07915

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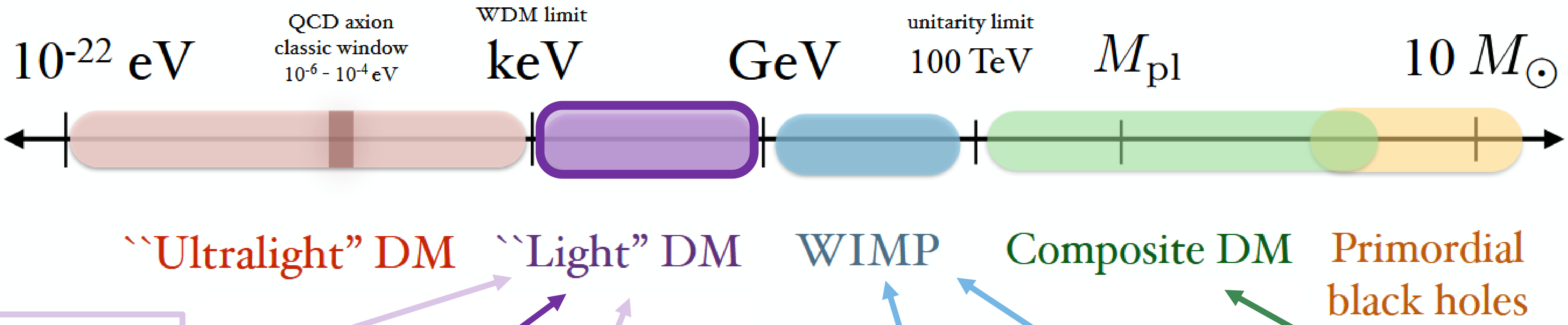

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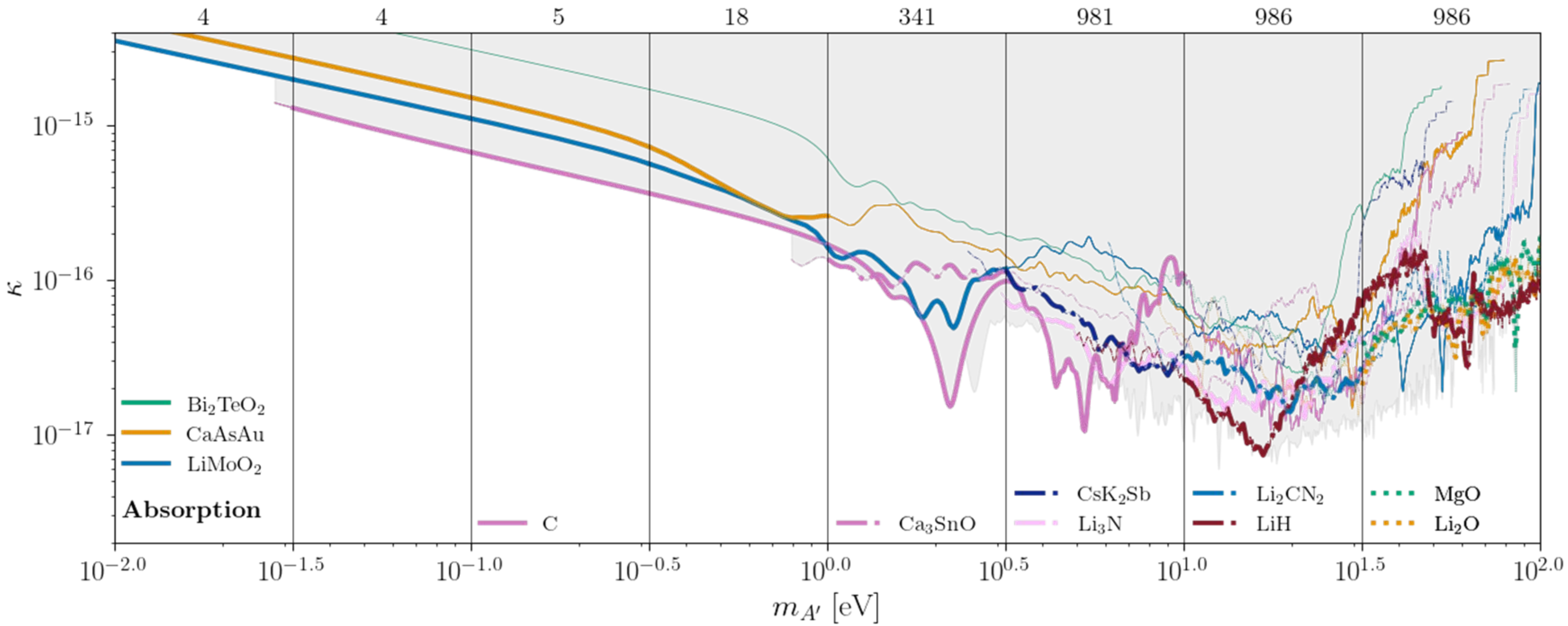
First High-Throughput Search for Dark Matter Detector Materials

- Dielectric function → absorption & scattering rate of DM in a material
- Materials Project
  - Open-source database of dielectric functions for over 1000 materials
- Analyze materials to find “best” potential materials for future light DM experiments

Absorption



4
4
5
18
341
981
986
986
10^{-15}
10^{-16}
10^{-17}
κ
Bi_2TeO_2
CaAsAu
$LiMoO_2$
Absorption
C
Ca_3SnO
CsK_2Sb
Li_3N
Li_2CN_2
LiH
MgO
Li_2O
$10^{-2.0}$
$10^{-1.5}$
$10^{-1.0}$
$10^{-0.5}$
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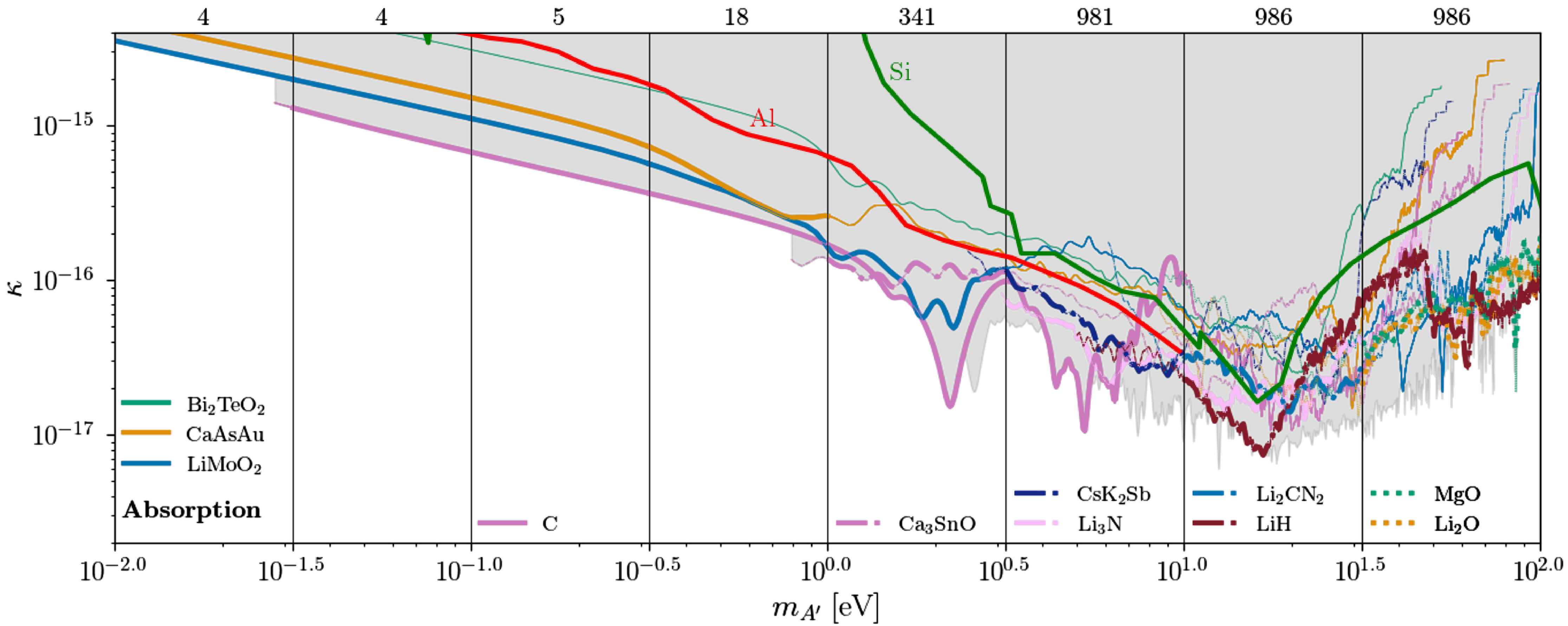
$10^{1.5}$
$10^{2.0}$
$m_{A'}$ [eV]

Absorption



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$10^{2.0}$
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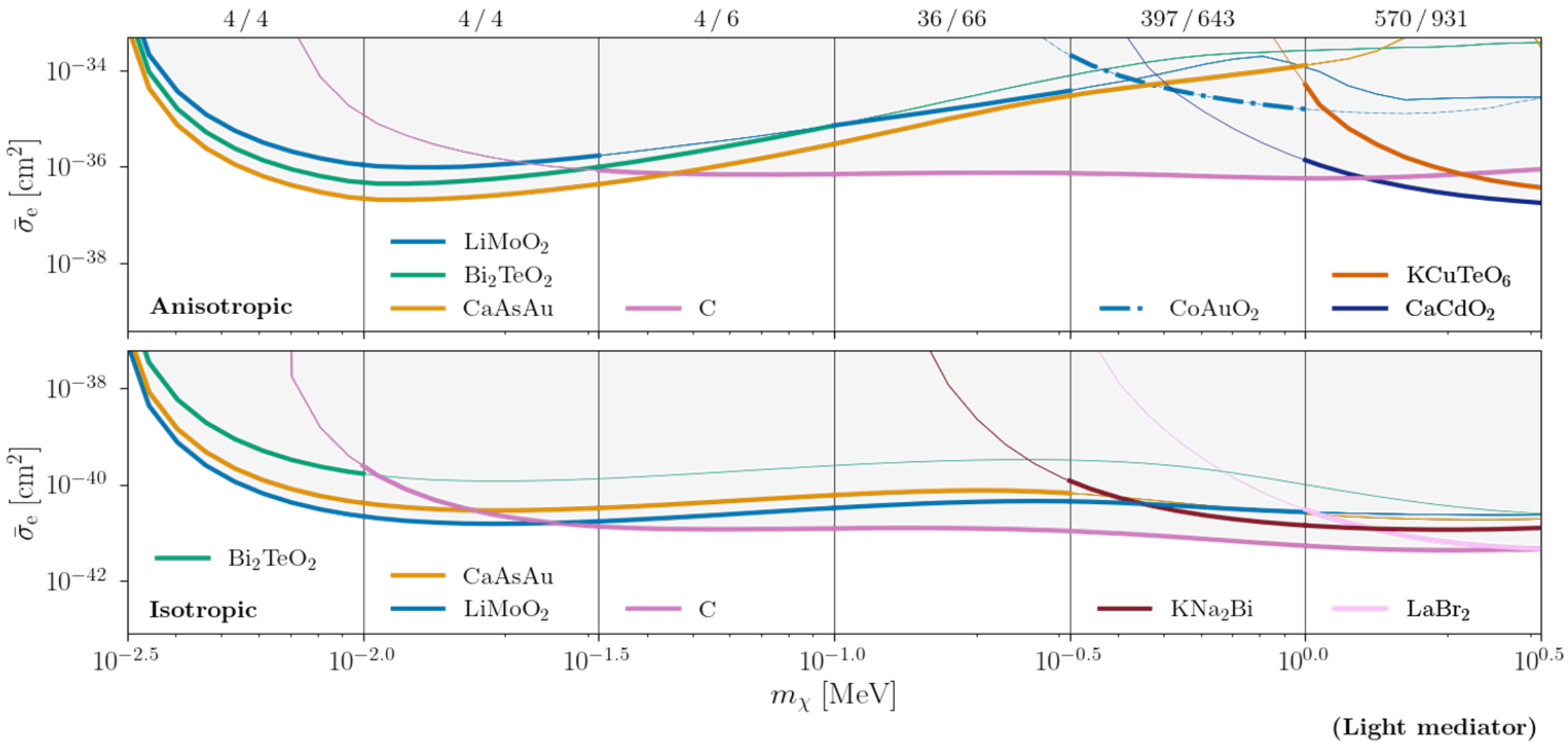
Light Mediator



$E_{th} = 10\ meV$

Backup Slides

The Materials Project

Harnessing the power of supercomputing and state-of-the-art methods, the Materials Project provides open web-based access to computed information on known and predicted materials as well as powerful analysis tools to inspire and design novel materials.

Conclusions: Part 1

We've performed the first high-throughput materials search for dark matter direct detection based on the dielectric properties of the materials (material informatics)

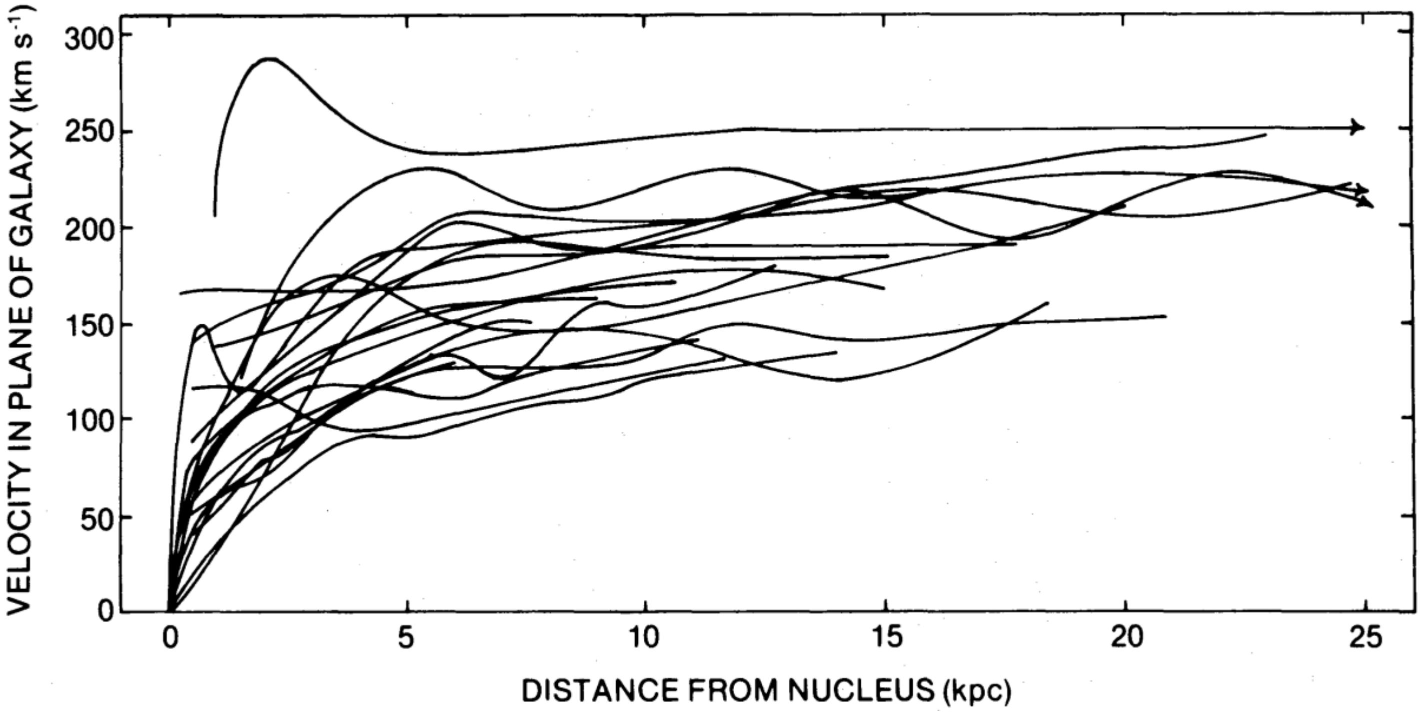
We utilized a model of the electron – DM scattering rate which correctly accounts for electron screening and depends on the particular material's dielectric tensor

We took dielectric tensor data from the Materials Project and modeled each material via a sum of Drude-Lindhard dielectric functions in order to approximate momentum dependence

We show the top three materials in many energy bands for absorption and scattering with both heavy and light mediators. We also show daily modulation for several exceptional materials.

What is Dark Matter?

- Dark, cold, collision-less, stable(ish) particle(s) making up 85% of matter in the universe
- Evidence for DM is strong
  - Galaxy rotation curves
  - CMB
  - Gravitational lensing
  - The Bullet Cluster
  - And many more
- Astrophysics tells us a lot about DM, but one major unknown – DM's mass



V. Rubin et al., 1980

Why Light Dark Matter?

- Well motivated theoretically
  - Sterile neutrinos, asymmetric dark matter, axion-like particles, dark sectors, etc.
- Well motivated experimentally
  - Builds off WIMP searches
  - Technology like SQUIDs and TES promise improved noise reduction and low energy thresholds
- Many exciting methods to detect dark matter
  - Scintillation, electron recoil, phonon excitations, the Migdal effect, etc.

Part 1
arXiv:2506.19905

Part 2
arXiv:2506.11191

WITH Y. HOCHBERG, B. LEHMANN, R. OVADIA, S. GRIFFIN, R.X. YANG, & W. ZHAO

First High-Throughput Search for Dark Matter Detector Materials

Outline: Part 1

1. DM-Electron Scattering
2. Materials Project & Big Data
3. Results!

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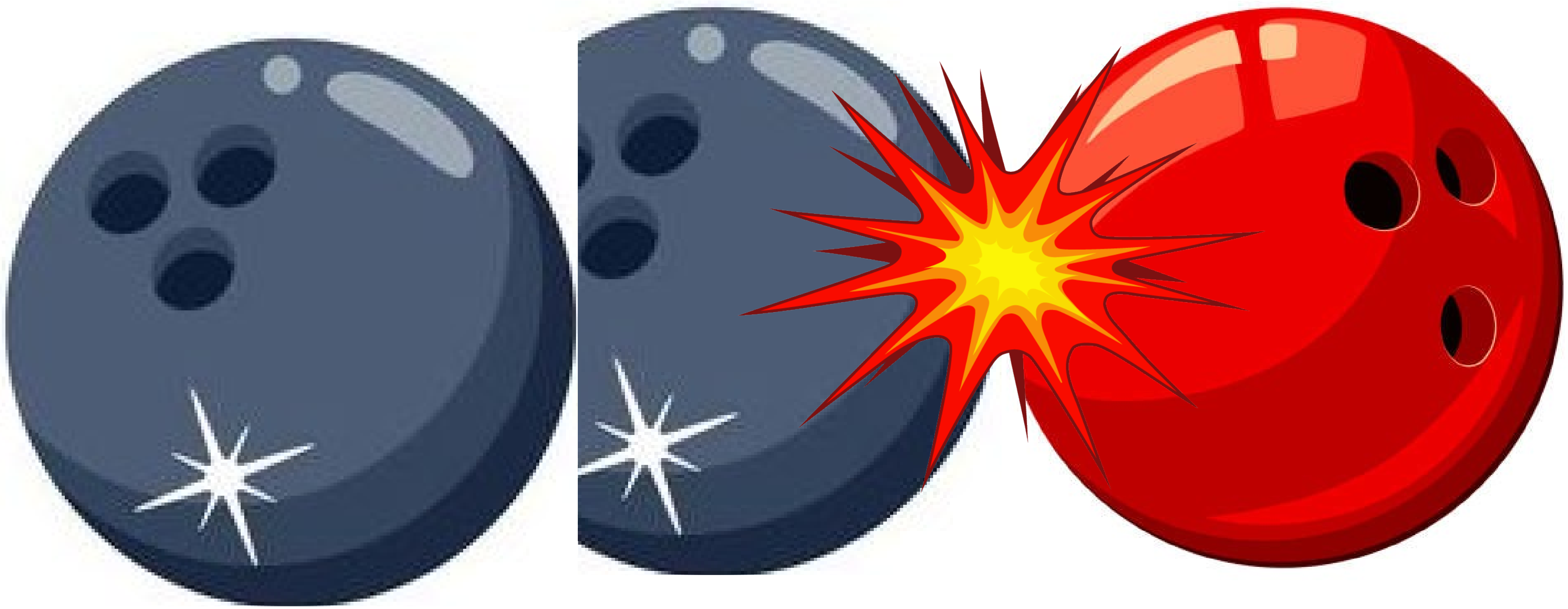
Kinematic Matching: Nuclear Recoil

Heavy DM

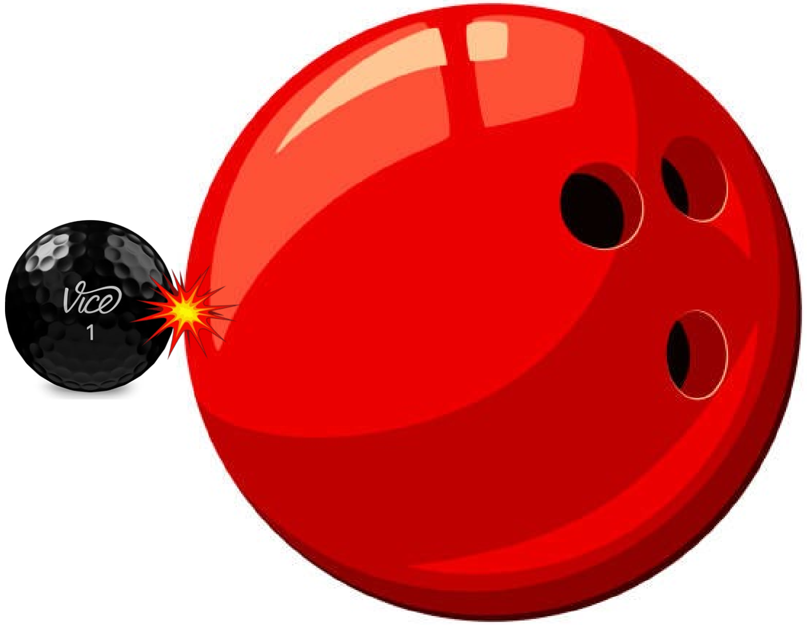
Nucleon



Kinematic Matching

Light DM

Nucleon



Kinematic Matching: Electron-DM

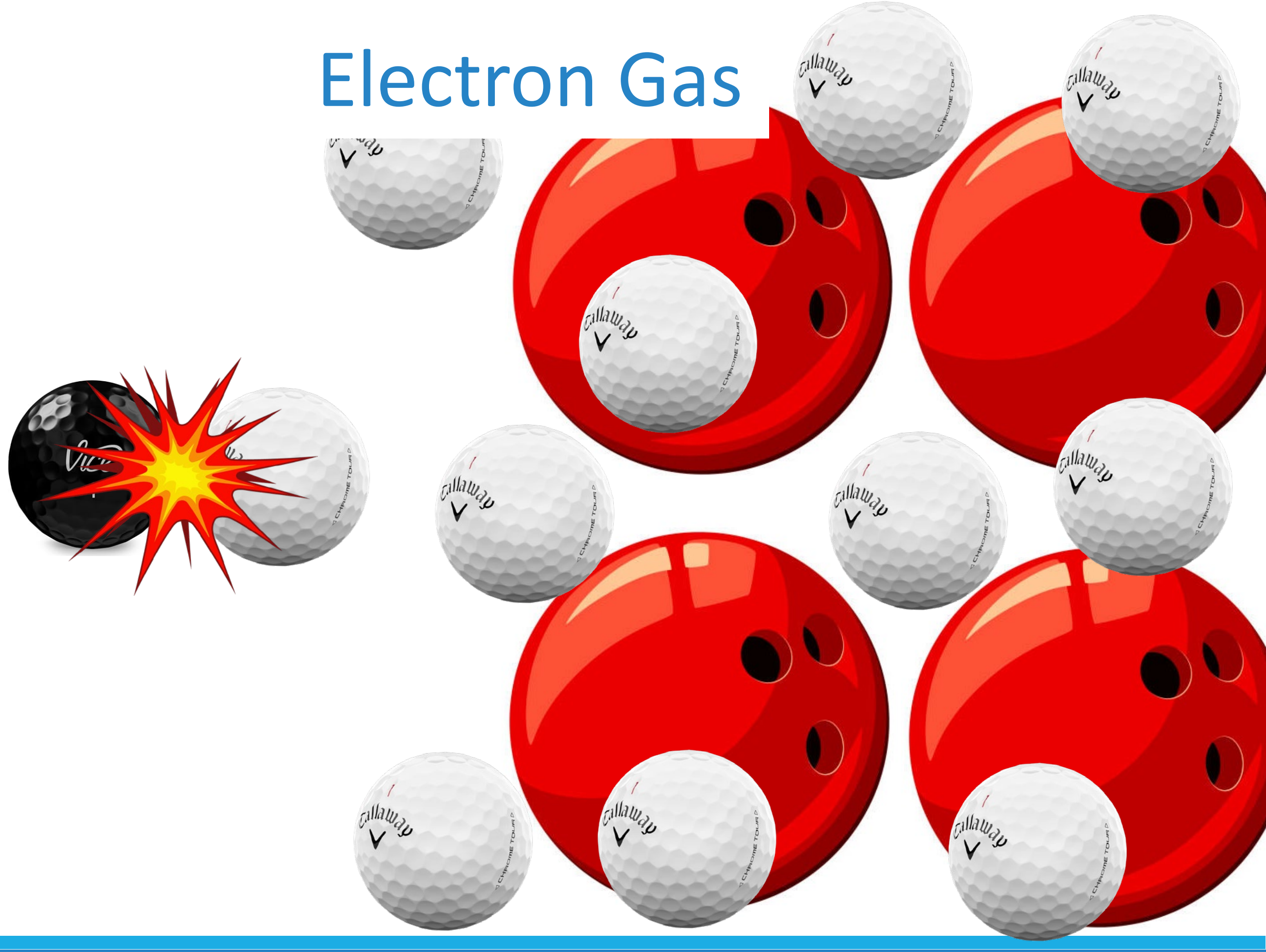
Light DM

Electron

Electronic Screening: DM

Light DM

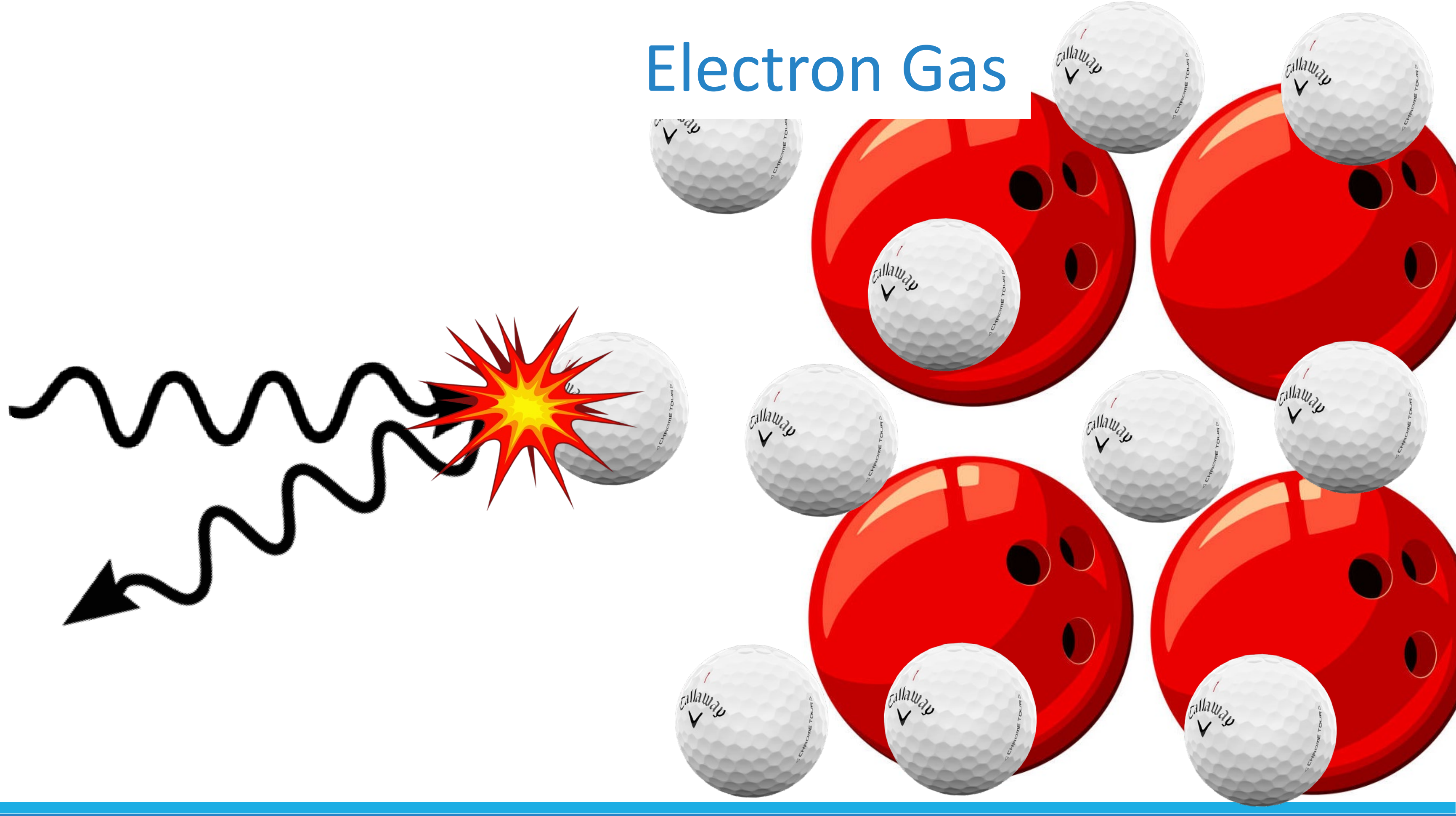
Electron Gas



Electronic Screening: Dielectric Function

Photon

Electron Gas

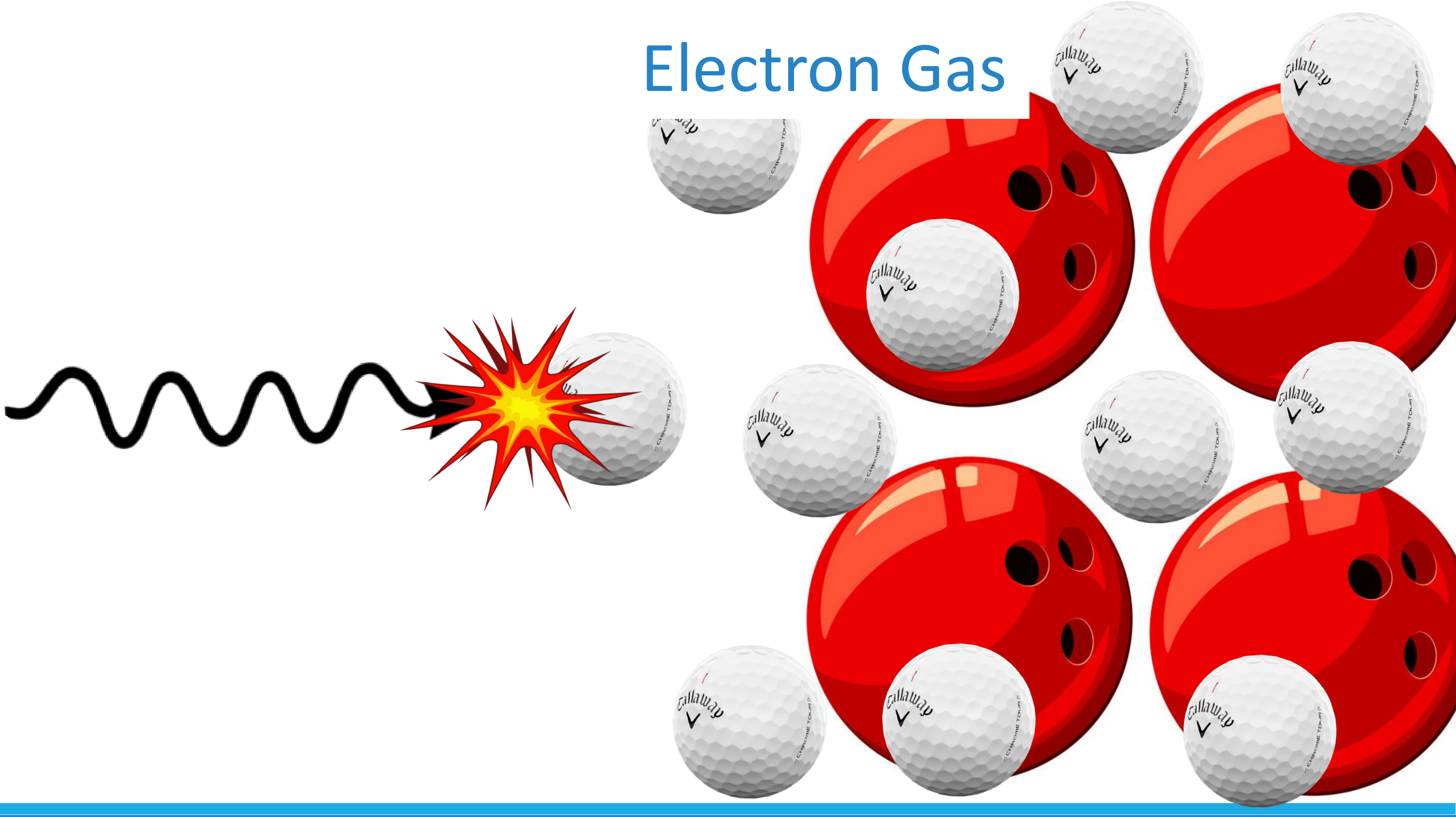


Scattering

Electronic Screening: Dielectric Function

Photon

Electron Gas



Absorption

DM-Electron Absorption Rate

Kinetic mixing coupling between dark photon and SM photon

Dark matter mass

$q \to 0$ is the optical limit

$$\Gamma_A = \kappa^2 m_\chi \mathcal{W}(q \approx 0, \omega)$$

For relativistic particles, $\omega \approx q \approx eV \approx 0$

Loss function of the material

$$\mathcal{W}(q,\omega) = \mathrm{Im}\left(-\frac{1}{\epsilon(q \approx 0, \omega)}\right)$$

Dielectric Function:
Parametrizes a material's response to deposits of energy/momentum

DM-Electron Scattering Rate

Non-relativistic DM-electron potential

$$V(q) = \frac{g_\chi g_e}{q^2 + m_{\phi,V}^2}$$

Mean inverse DM speed (via SHM)

$$\eta(v_{min}) = \int_{v_{min}} d^3\boldsymbol{v}_\chi \frac{f(\boldsymbol{v}_\chi)}{v_\chi}$$

$$\frac{dR}{d\omega} = \frac{\rho_\chi}{2\pi^2 e^2 \rho_T m_\chi} \int dq\, q^3 |V(q)|^2 \mathcal{W}(q,\omega)\, \eta(v_{min}(q,\omega))$$

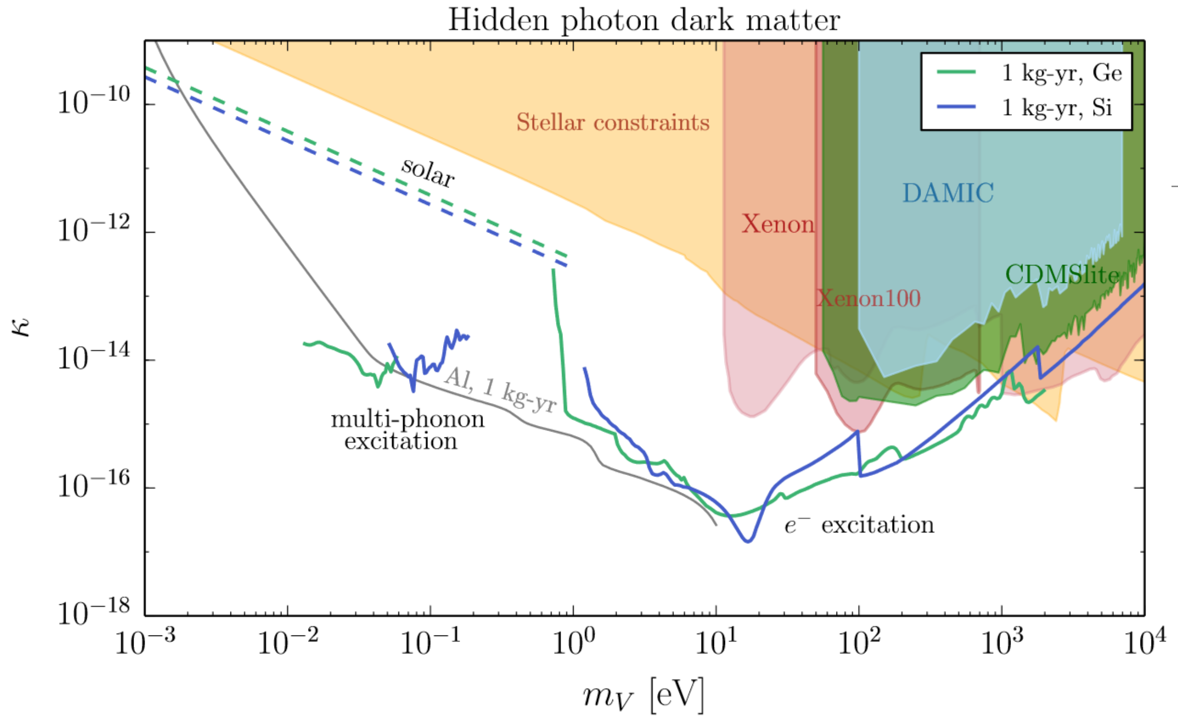
Mass density of the target material

Loss function of the material

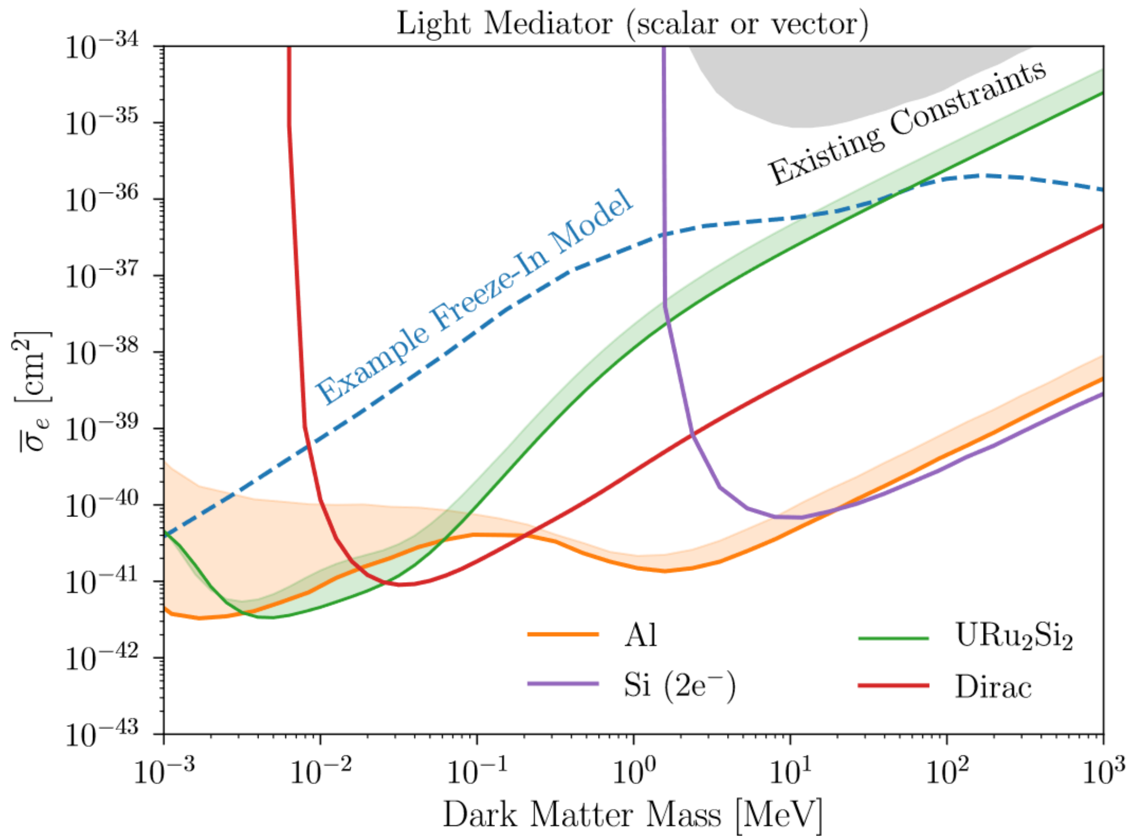
$$\mathcal{W}(q,\omega) = \mathrm{Im}\left(-\frac{1}{\hat{q}.\overleftrightarrow{\epsilon}(q,\omega).\hat{q}}\right)$$

Kinematic constraint

$$v_{min} = \frac{\omega}{q} + \frac{q}{2m_\chi}$$



arXiv:1608.01994



arXiv:2101.08263

Current DM-Electron Absorption/Scattering

Outline: Part 1

1. DM-Electron Scattering
2. Materials Project & Big Data
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Our Dataset

- 1019 Materials with DFT computed, energy dependent, dielectric tensors
- 593 materials have anisotropic responses in at least 1 axis
  - We can do both an isotropic and anisotropic scattering analysis
  - Anisotropic scattering eliminates the background for a streaming DM signal, at the cost of requiring more DM interactions.
- Calculated in the optical limit (transferred momentum q -> 0)
  - Scattering rate calculation requires $q \neq 0$ data 😞

How to Extract Momentum Dependence

- The Drude-Lindhard Dielectric Function has momentum dependence:

$$\epsilon_{RPA}(q,\omega) = 1 + \frac{3\omega_p^2}{q^2 v_F^2}\left\{\frac{1}{2} + \frac{k_F}{4q}(1 - Q_-^2)\mathrm{Log}\left(\frac{Q_- + 1}{Q_- - 1}\right) + \frac{k_F}{4q}(1 - Q_+^2)\mathrm{Log}\left(\frac{Q_+ + 1}{Q_+ - 1}\right)\right\}$$

  - Derived using perturbation theory and the Random Phase Approximation (RPA)
  - Models materials with one plasmon peak very well

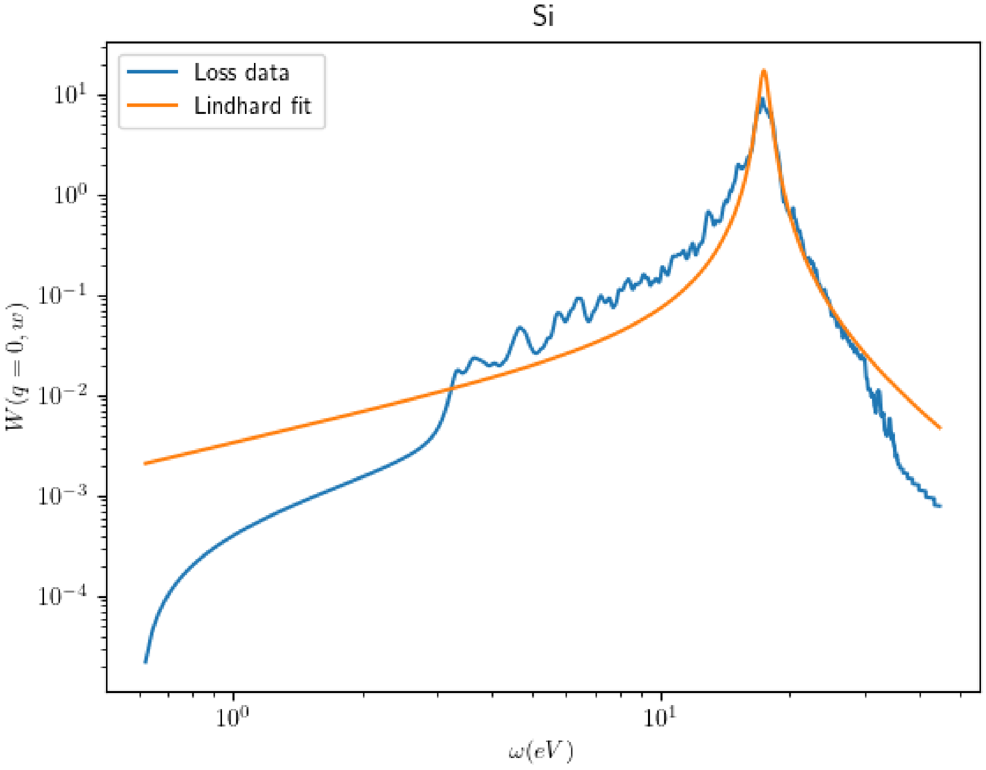
$$Q_\pm = \frac{q}{2k_f} \pm \frac{\omega + i\,\Gamma_p}{q v_f}$$

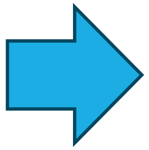
- We can fit the $q \to 0$ limit to the Materials Project dielectric tensors and extract ω_p and Γ_p:

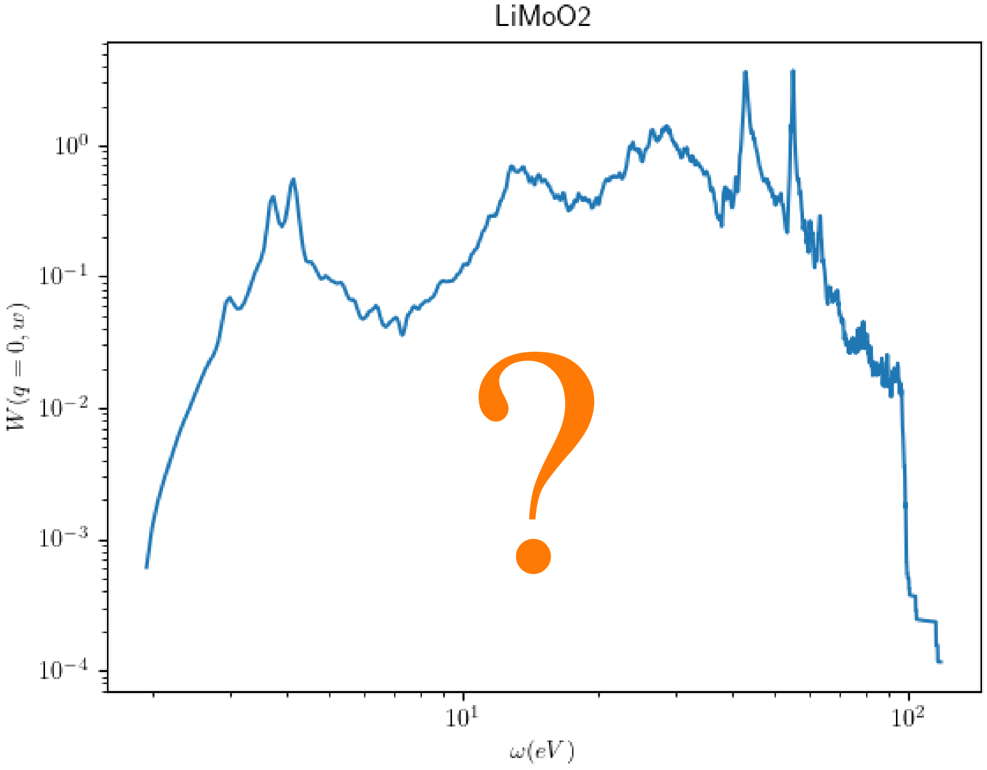
$$\epsilon_{RPA}(q \to 0, \omega) = 1 + \frac{\omega_p^2}{\left(\Gamma_p - i\omega\right)^2}$$

k_f, v_f can be derived from ω_p

Fitting Difficult Dielectric Functions







Full Pipeline

Oscillator Method

1. Locations of peaks, ω_p, are determined by zeros in Re(ϵ)
2. We fit a sum of Lindhards at q=0:

$$\frac{1}{\quad}\sum^{n_{peaks}}$$

This methodology is only a proxy for the true (unknown) q dependence. A more complete DFT or experimental analysis is required for any materials of interest

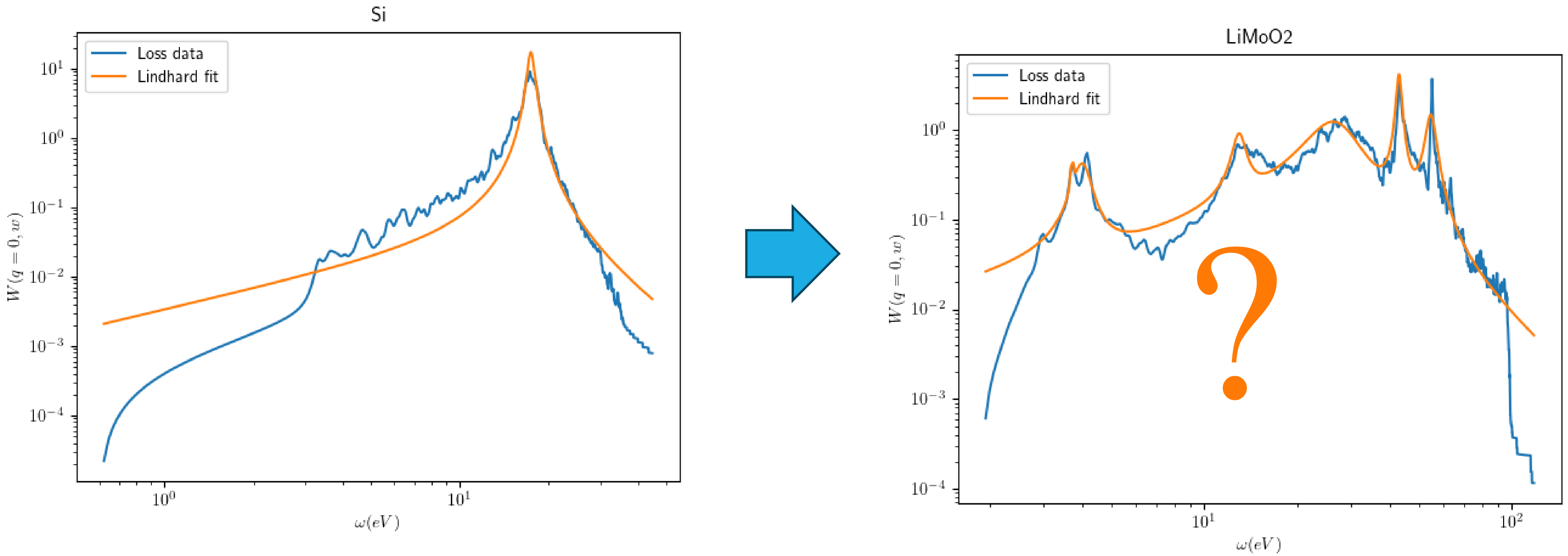
are independent of q

4. We calculate the scattering rate using

$$\epsilon(q,\omega) = r(\omega)\,\epsilon_{fit}(q,\omega)$$

For anisotropic materials, repeat this process for $\hat{q}.\overleftrightarrow{\epsilon}(q,\omega).\hat{q}$ with $\hat{q}$ pointing uniformly around the unit sphere

Fitting Difficult Dielectric Functions



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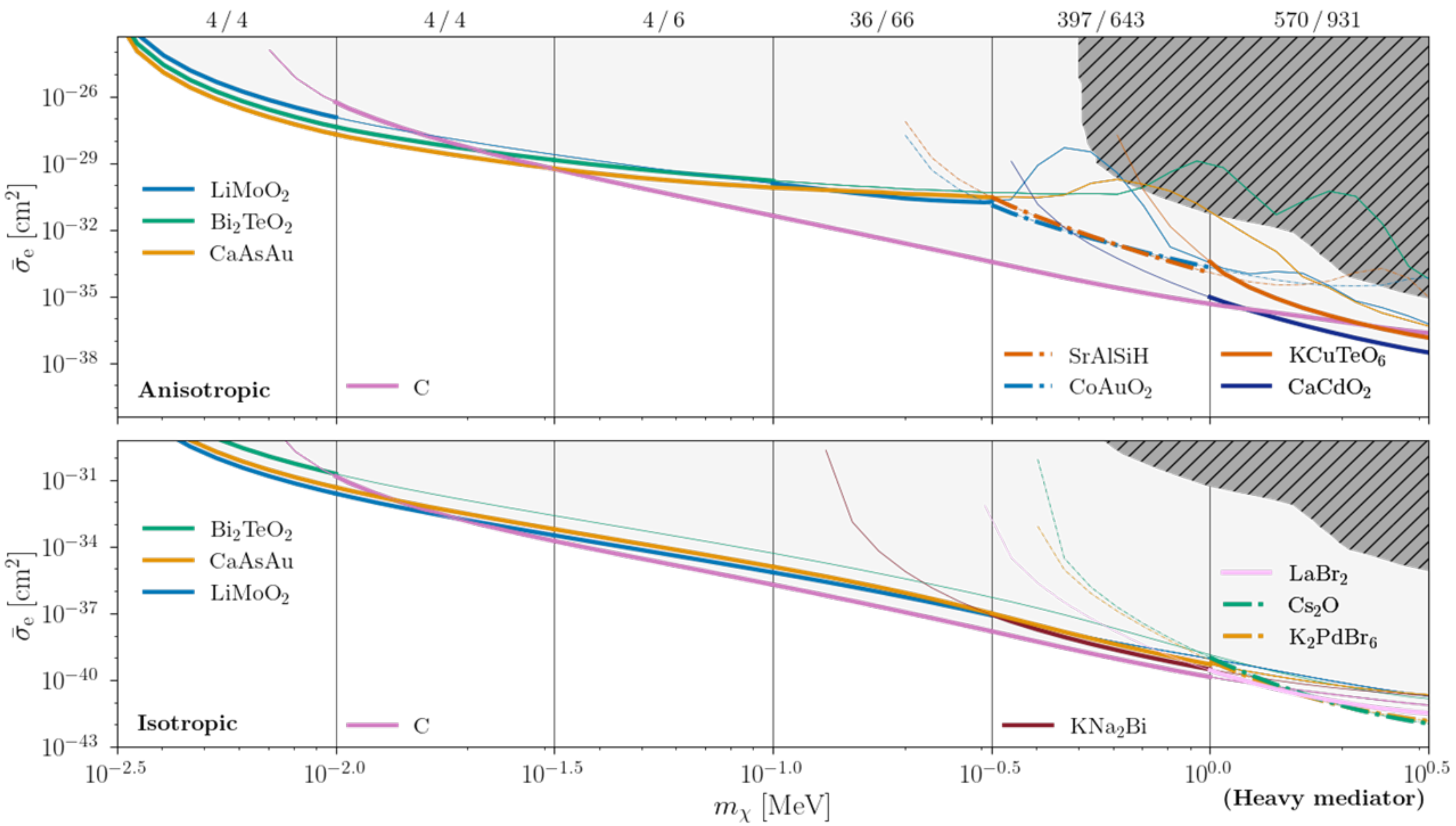
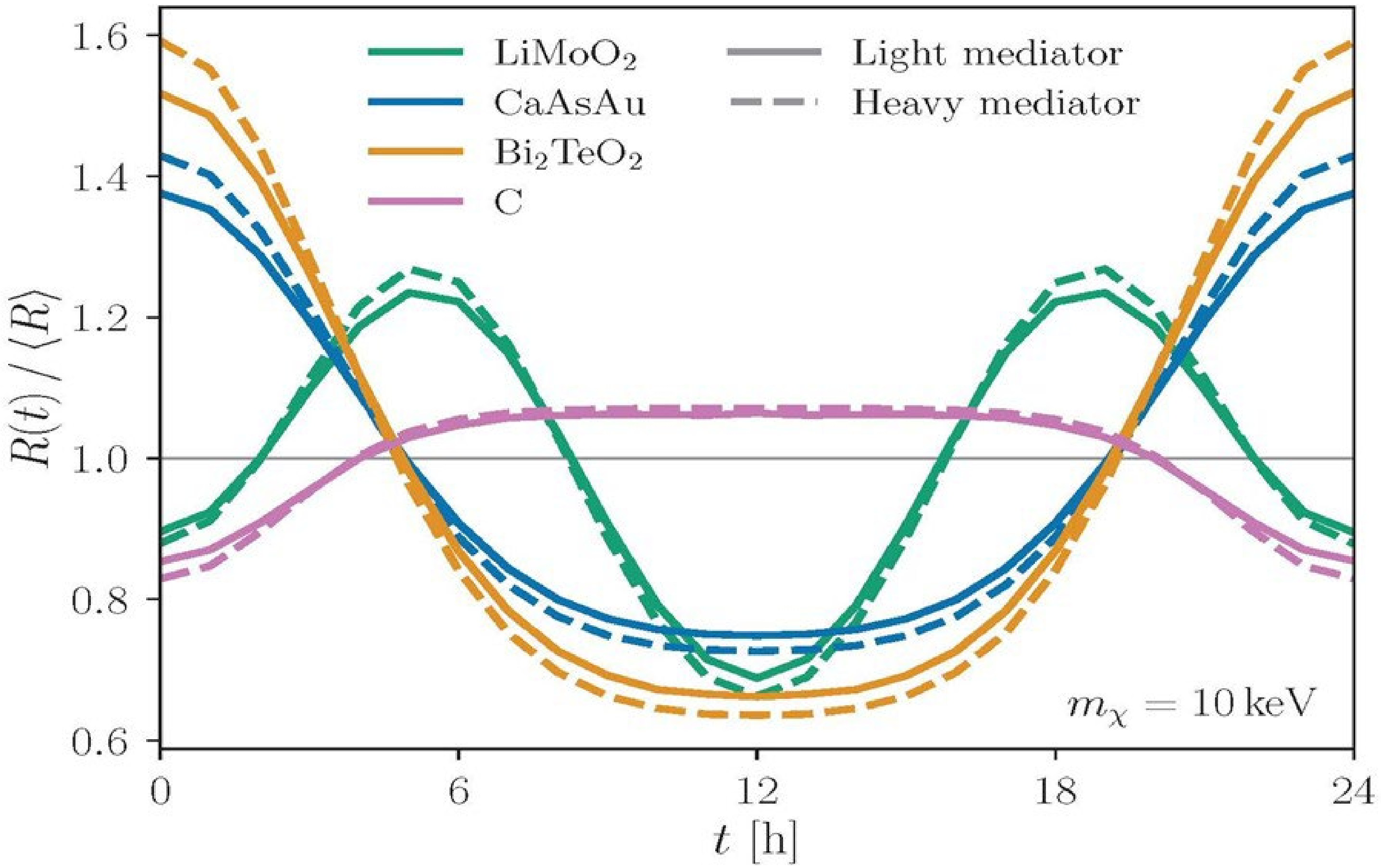
Heavy Mediator



$E_{th} = 10\ meV$

Daily Modulation



WITH S. GORI , S. KNAPEN, T. LIN, & P. MUNBODH

Multiphonon Processes in Spin-Dependent Dark-Matter Scattering

Outline: Part 2

1. Why phonons + DM
2. Derivation of multiphonon scattering
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Kinematic Matching

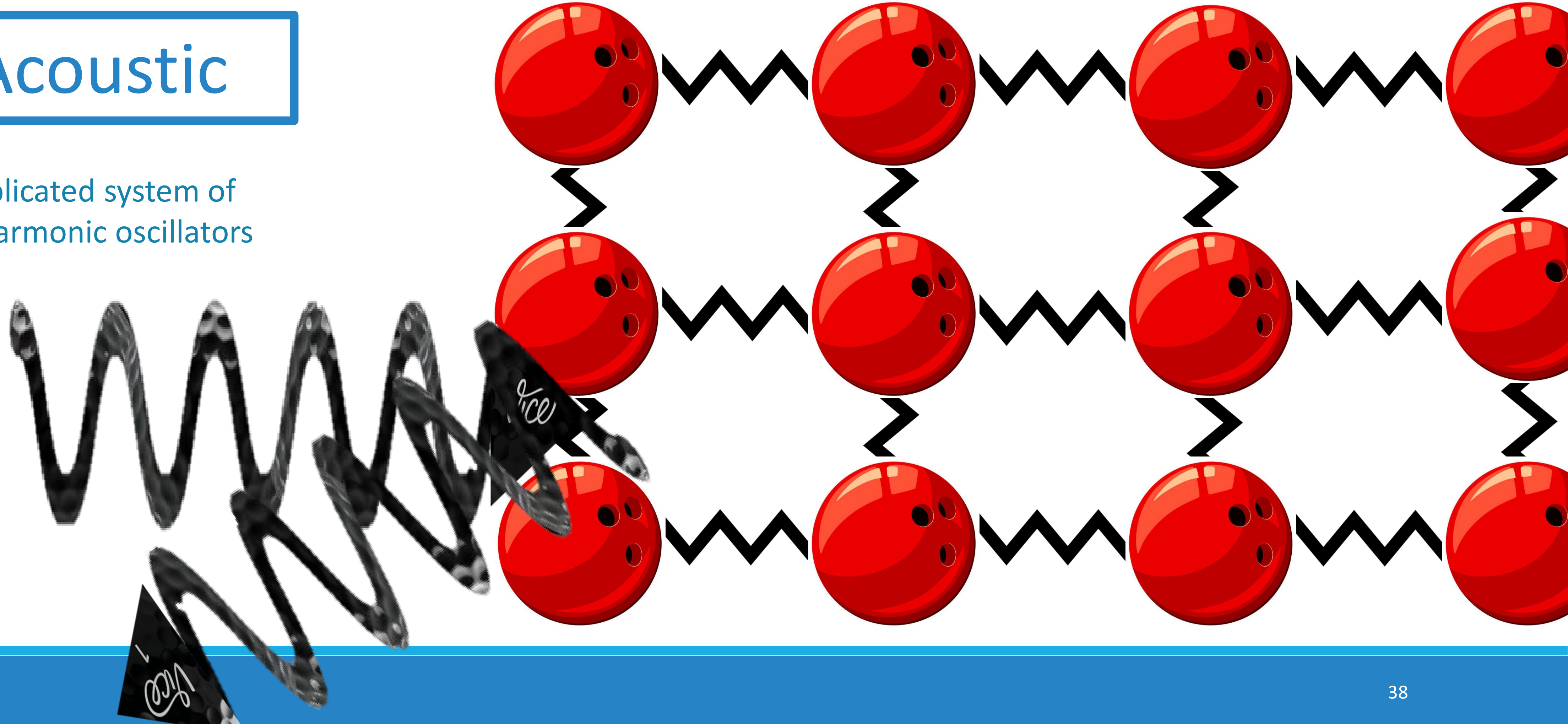
Light DM

Nucleon

Nuclear Scattering: Phonons

Acoustic

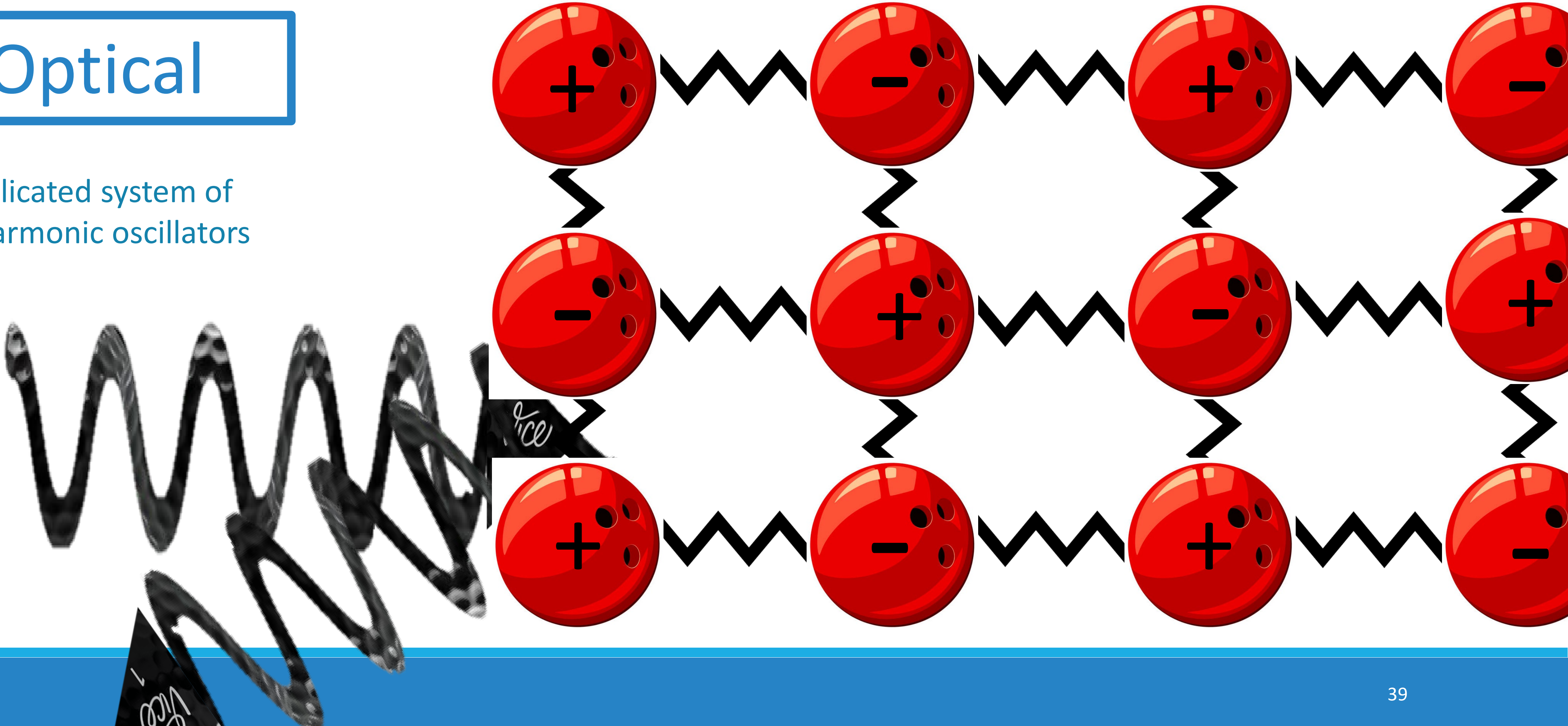
Very complicated system of
coupled harmonic oscillators



Nuclear Scattering: Phonons

Optical

Very complicated system of
coupled harmonic oscillators



Acoustic vs Optical

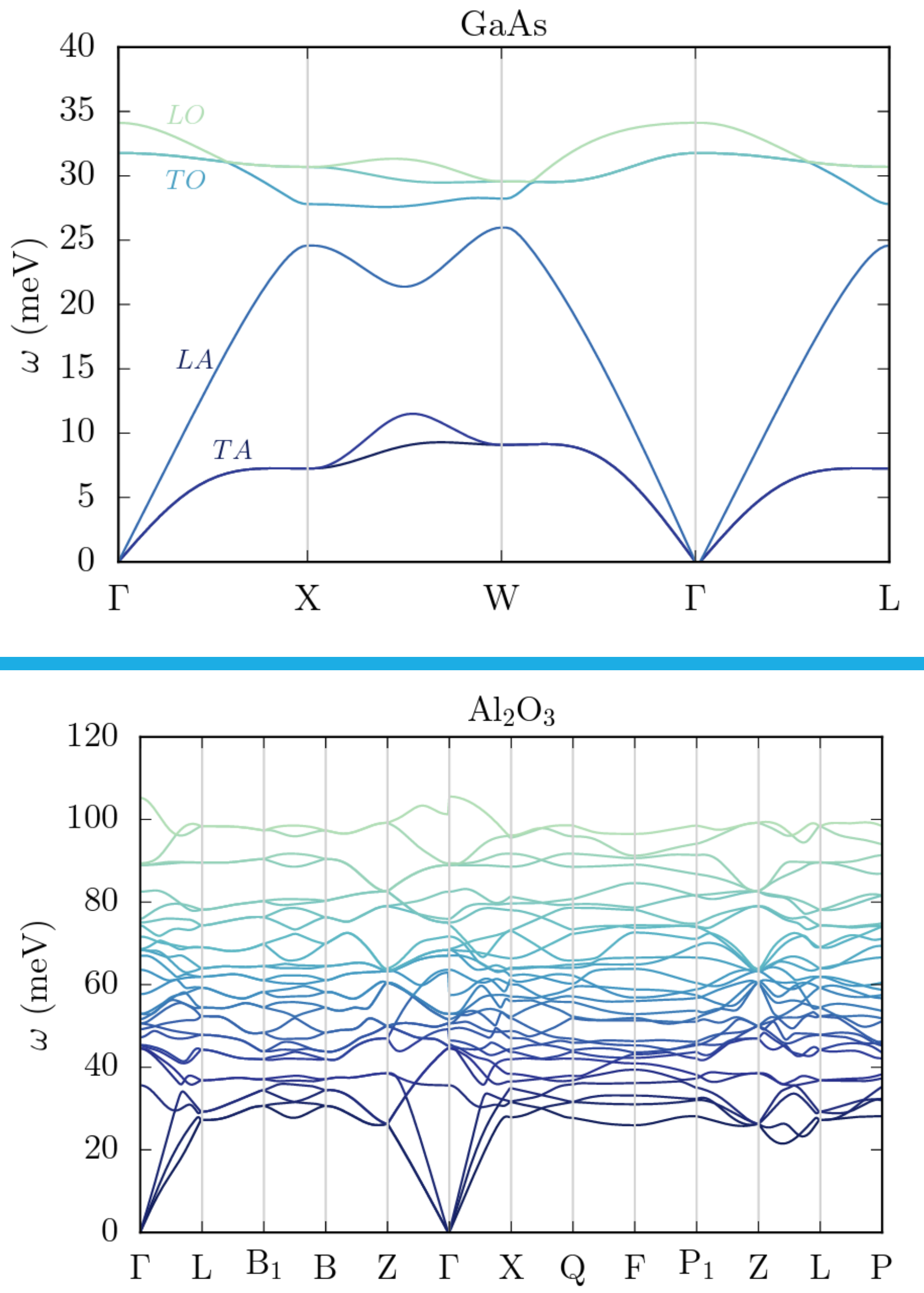
- As discussed in 1807.10291, low momentum transfer = only excite acoustic phonon in 1st Brillouin zone

$$\omega = c_s|q| \approx 2c_s v m_X \sim 7\ meV \times \frac{m_X}{100keV}$$

- Best experimental threshold is in 10 – 100 meV range, so difficult or impossible to detect

- Optical modes don't have this scaling:

$$\omega \sim 30\ meV \text{ as } |q| \to 0$$

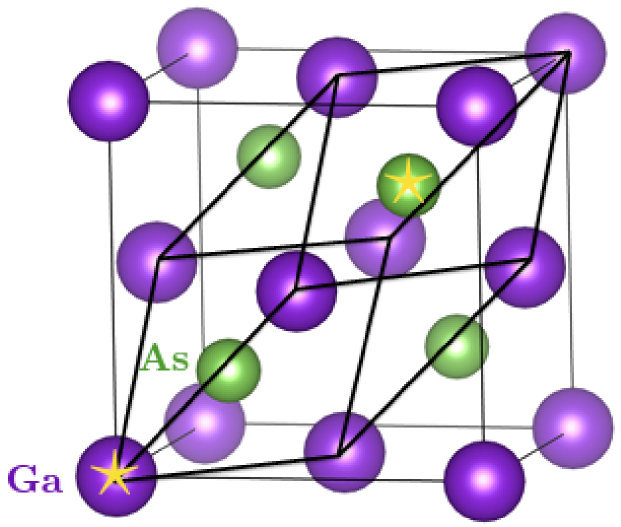


1807.10291

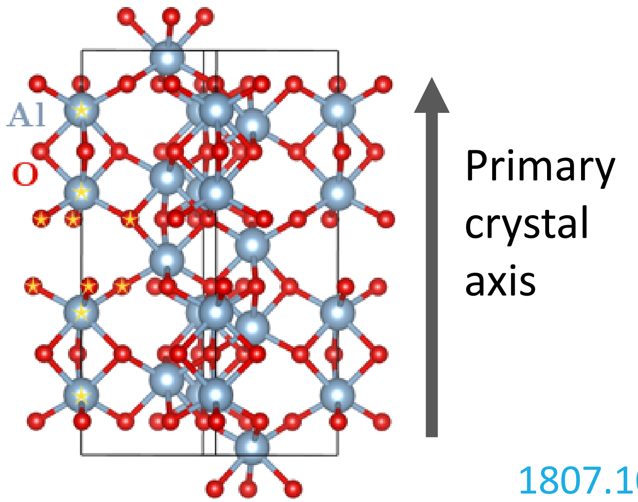
Polar Materials

- At least two different atoms with **different** effective charges
- Each unit cell forms an electric dipole
- E field or dark photon causes vibrations
  - → Optical phonons
- **GaAs**
  - 2 atoms in unit cell
  - 3 acoustic phonons, 3 optical phonons
- **Sapphire**
  - 10 atoms in unit cell
  - 3 acoustic phonons, 27 optical phonons

GaAs



Al_2O_3 (Sapphire)



1807.10291

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1. Why phonons + DM
2. Derivation of multiphonon scattering
3. Results!

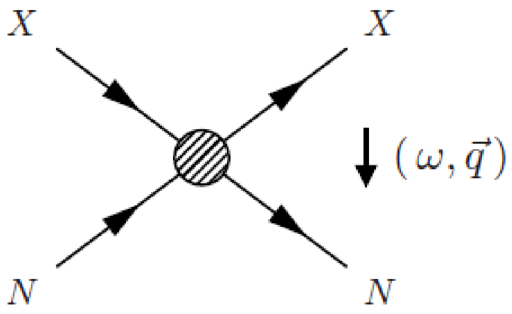
arXiv:1712.06598
arXiv:1807.10291
arXiv:1911.03482
arXiv:2205.02250

DM Multiphonon Expansion

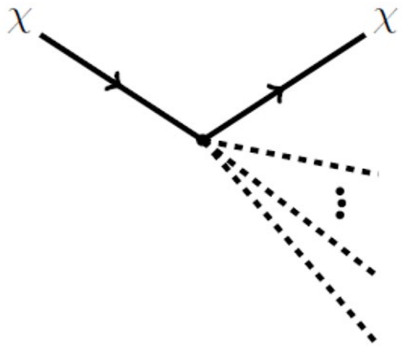
Large m_χ & q → **Small m_χ & q**

Short λ → **Long λ**

Momentum is a good expansion parameter $q \ll \sqrt{2m_N\omega}$



$$\omega = \frac{q^2}{2m_N}$$



$$\mathcal{R} \sim \mathcal{O}\left(\frac{q^{2n}}{2m_N}\right)$$

$$\mathcal{R} \sim \mathcal{O}\left(\frac{q^2}{2m_N}\right)$$

Multiphonon Scattering Rate

Fermi's Golden Rule

λ_i & λ_f denote initial & final spin & phonon states

$$\frac{d\sigma}{d^3q\,d\omega} \sim \sum_{i,f} \left| \sum_{d}^{N} \langle \lambda_f | \mathcal{O}(q) e^{iq\cdot r_d} | \lambda_i \rangle \right|^2 \delta(E_f - \omega)$$

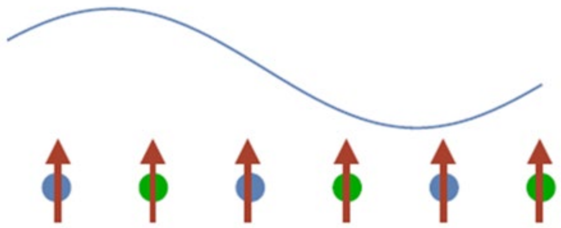
r_d is the position of each atom

d labels each atom in the crystal

$\mathcal{O}(q)$ is some spin dependent operator

$\mathcal{O}(q)$ = 1 is spin independent
(already been done: 2205.0225)

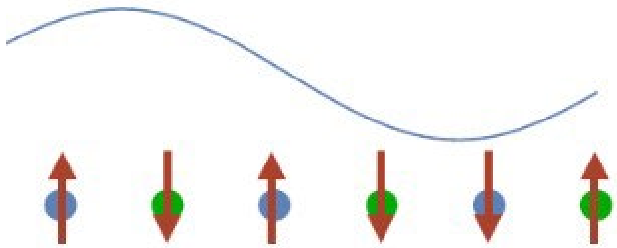
Spin Dependent Interactions



Nuclear Spin Polarized

Similar to spin independent case, with a form factor correction

(see T. Trickle et. al. 2009.13534)



Nuclear Spin Unpolarized

Cross section doesn't average away:

$d = d'$ (incoherent) terms contribute $\sim \langle S_N^2 \rangle$

Modify spin independent calculation!

Figures by S. Knapen

Approximations

- Harmonic Approximation:
  - Decompose into a sum of harmonic oscillators weighted by the phonon density of states
  - Neglect anharmonic contributions to the crystal potential
- Isotropic crystal
- Unpolarized Spins
  - Nuclei spins have equal probabilities of being pointed in any direction – no net B field

Multiphonon Rate

$s_{med}(q)$ is a spin factor depending on the EFT operator $\sim 1, \mathrm{q}^2, \mathrm{q}^4$

Expansion order by order in $\frac{q^2}{2m_d}$

n labels each phonon in the expansion

$$\frac{d\sigma}{d^3q\,d\omega} \sim \sum_d^N s_{med}(q)\,\underbrace{e^{-2W_d(q)} \sum_n \left(\frac{q^2}{2m_d}\right)^n \frac{1}{n!} \left(\prod_{i=1}^{n} \int d\omega_i \frac{D_d(\omega_i)}{\omega_i}\right) \delta\left(\sum_j \omega_j - \omega\right)}_{\text{Same as in the spin independent calculation}}$$

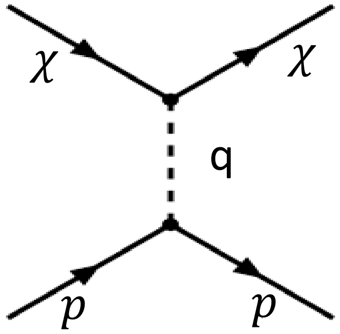
d labels each atom in the crystal

Debye Waller factor

Same as in the spin independent calculation

Partial density of states (from DFT)

Model Dependence: EFT operators



Scalar mediator ϕ

$$\mathcal{L} \supset g_\chi \phi \bar{\chi}\chi + g_p \phi \bar{N}\gamma^5 N$$
$$\mathcal{L}_{NR} \sim (q \cdot S_N)$$

$\longrightarrow$ $$s_\phi \sim \frac{q^2}{m_N^2}\left(\overline{f_d^2 \langle S_d^2 \rangle}\right)$$

Pseudoscalar mediator a

$$\mathcal{L} \supset g_\chi a \bar{\chi}\gamma^5\chi + g_p a\, \bar{N}\gamma^5 N$$
$$\mathcal{L}_{NR} \sim (q \cdot S_N)(q \cdot S_\chi)$$

$\longrightarrow$ $$s_a \sim \frac{q^4}{m_N^2 m_\chi^2}\langle S_\chi^2 \rangle \left(\overline{f_d^2 \langle S_d^2 \rangle}\right)$$

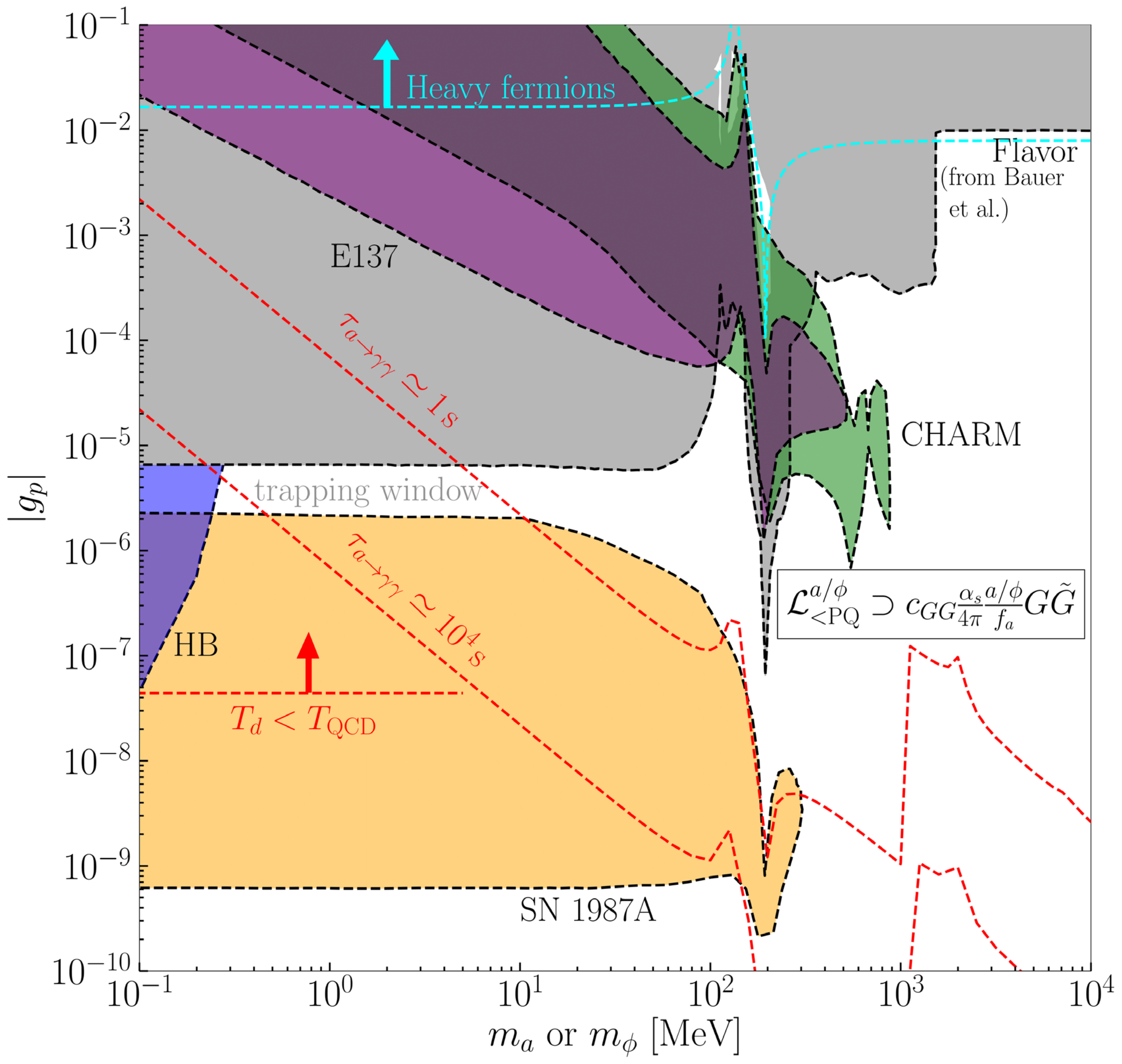
Pseudovector mediator A'_μ

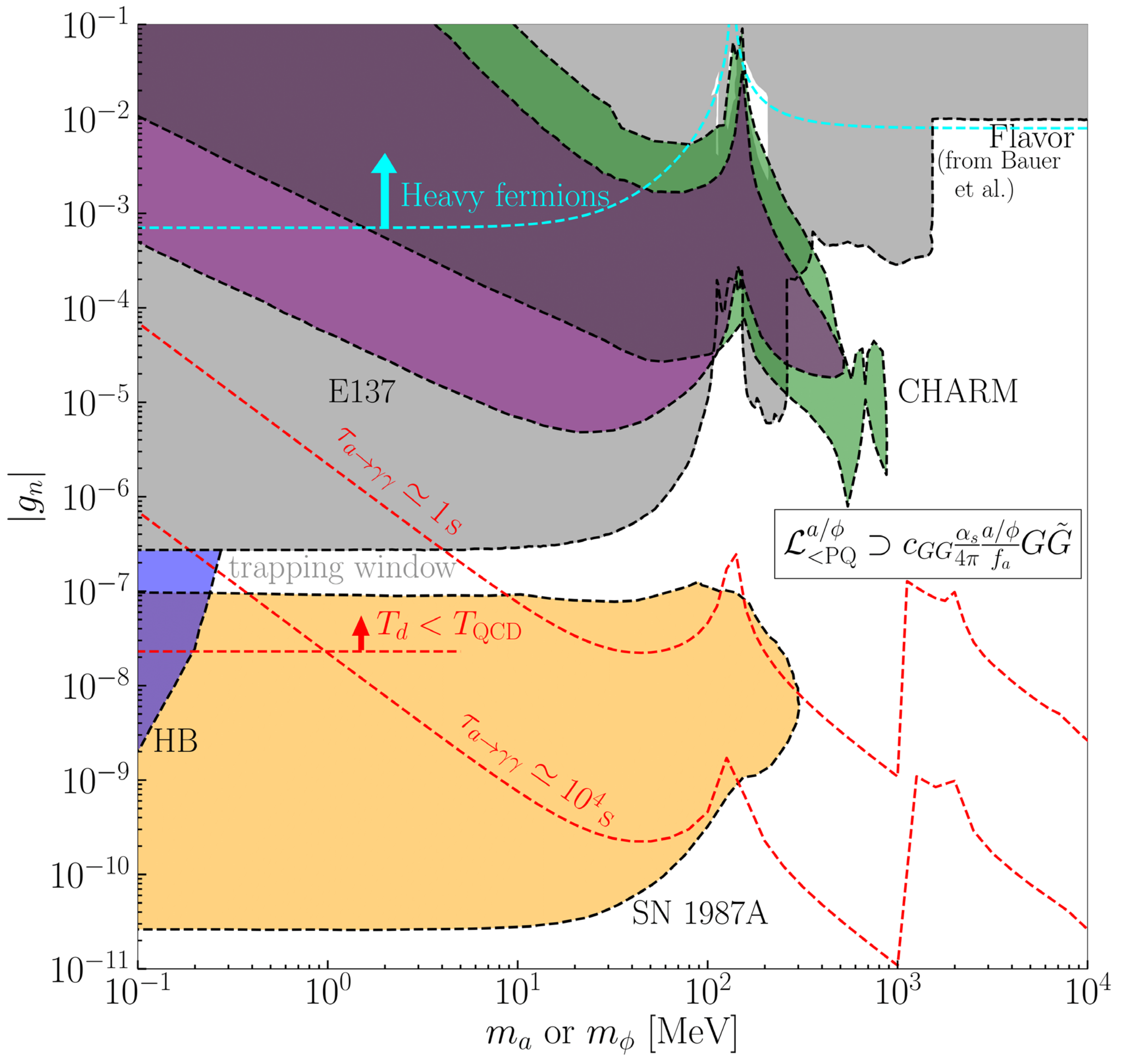
$$\mathcal{L} \supset g_\chi A'_\mu \bar{\chi}\gamma^\mu\gamma^5\chi + g_p A'_\mu\, \bar{N}\gamma^\mu\gamma^5 N$$
$$\mathcal{L}_{NR} \sim (S_N \cdot S_\chi)$$

$\longrightarrow$ $$s_{A'_\mu} \sim \langle S_\chi^2 \rangle \left(\overline{f_d^2 \langle S_d^2 \rangle}\right)$$

Outline: Part 2

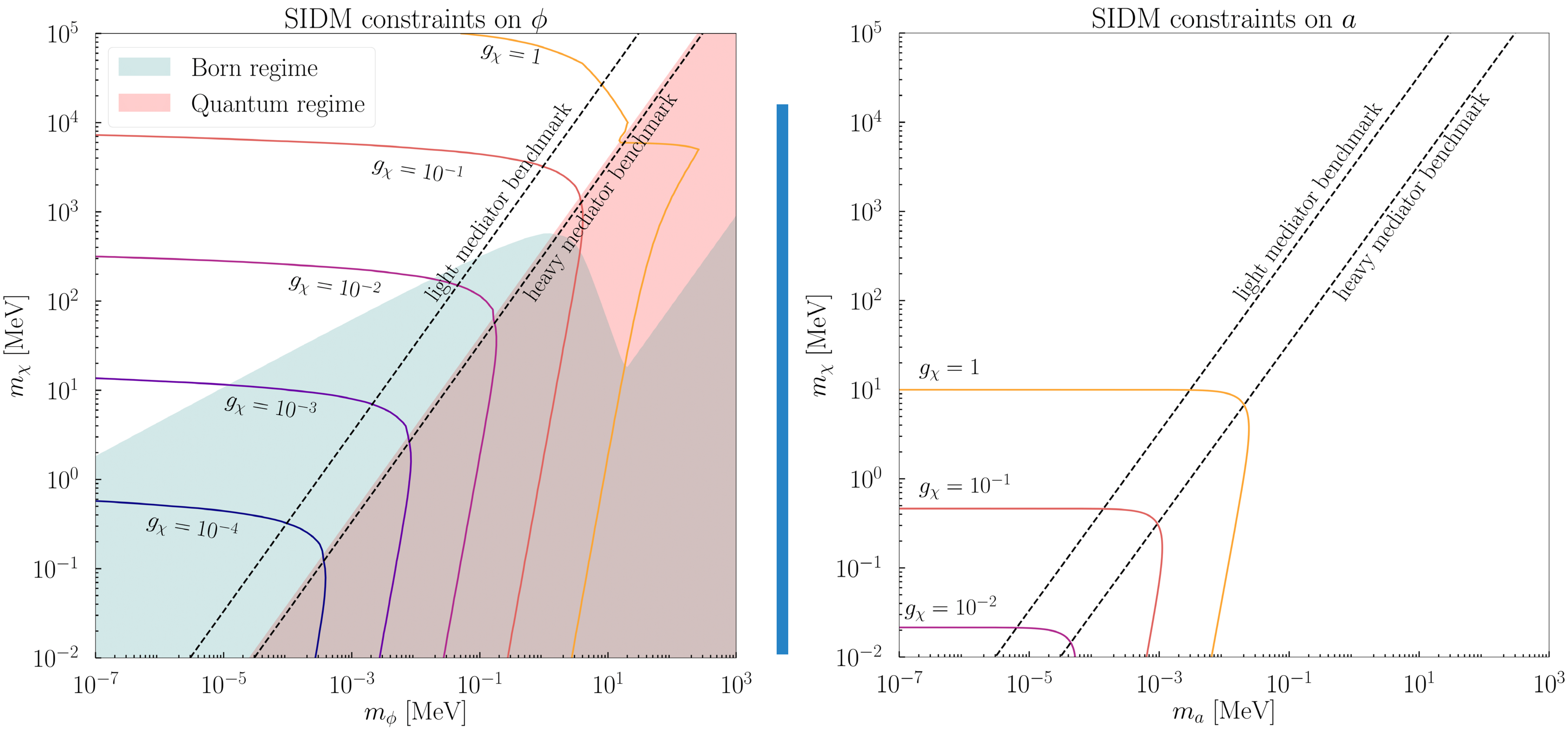
1. Why phonons + DM
2. Derivation of multiphonon scattering
3. Constraints & Results





Constraints on g_N

Valid for m_ϕ & m_a



Constraints on g_χ

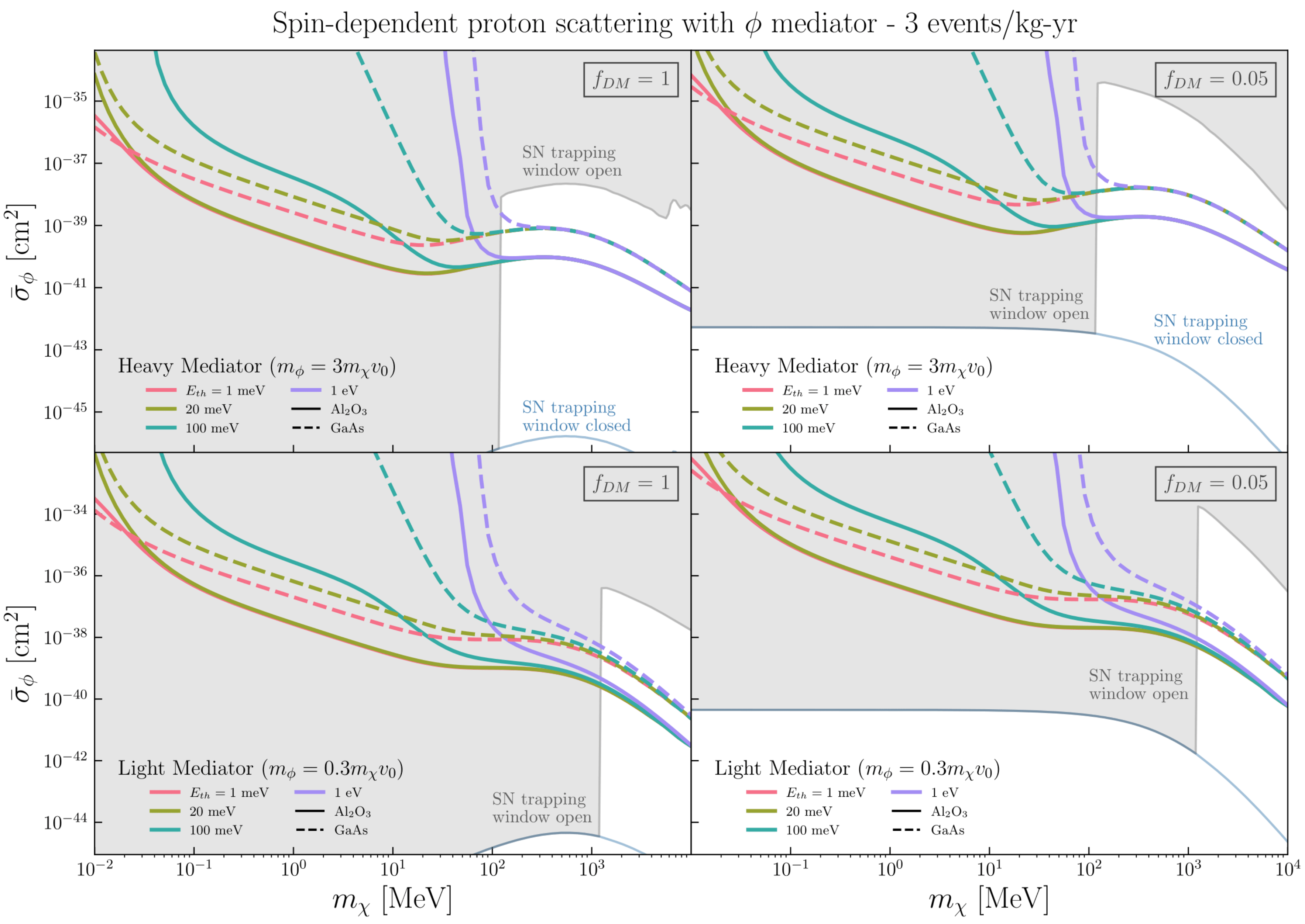
$$\boxed{\frac{\sigma}{m_\chi} \lesssim 1.1\ cm^2/g}$$

2006.12515

Results

- Most optimistic reach curves: ϕ
- $m_\phi = 10\, m_\chi v_0$
- Cliff occurs at the constraint from HB stars
- Left: SIDM constraints on g_χ; Right: $g_\chi = 1$

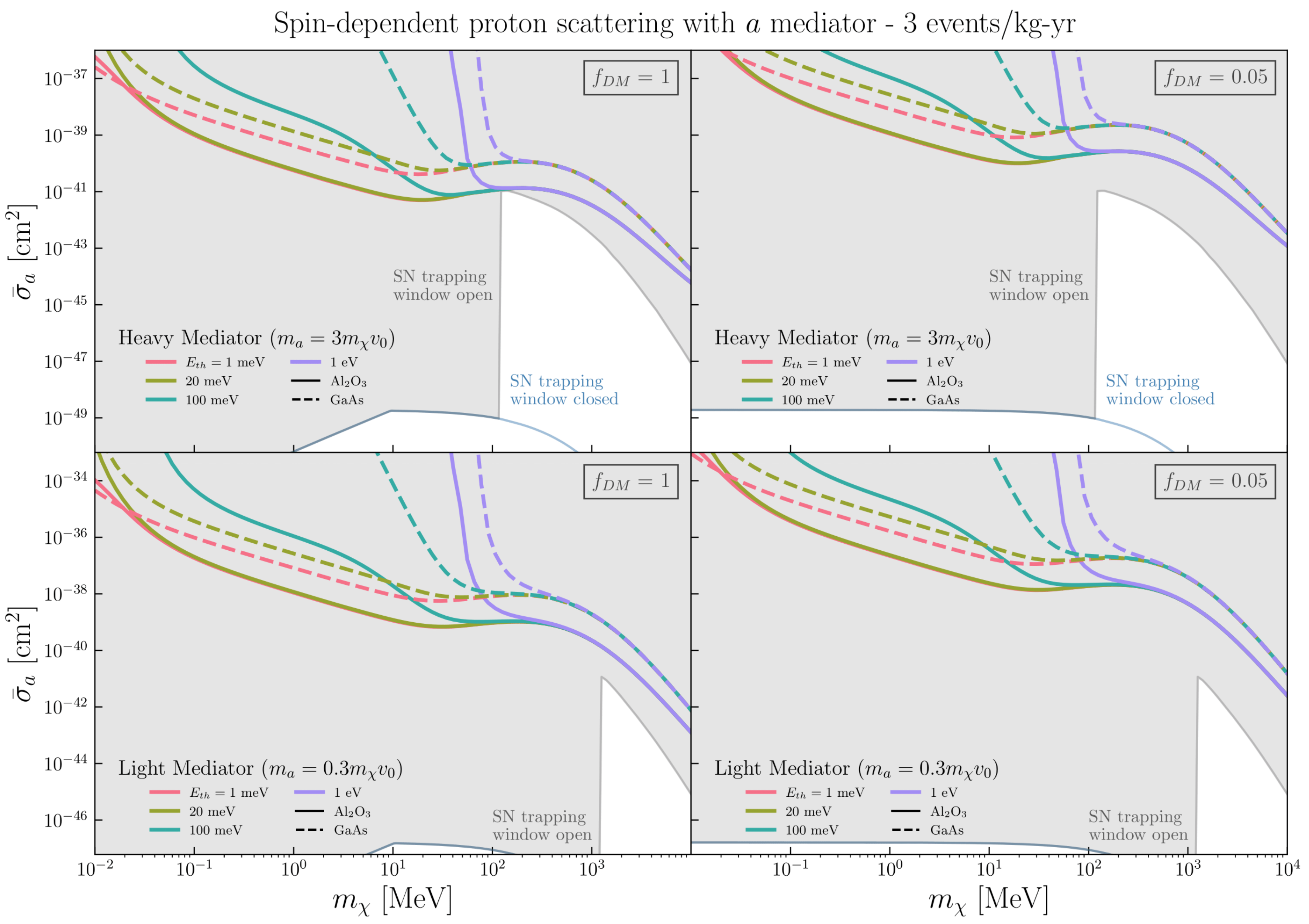
Cross sections needed for 3 events/kg-year rate for GaAs & sapphire using several threshold energies

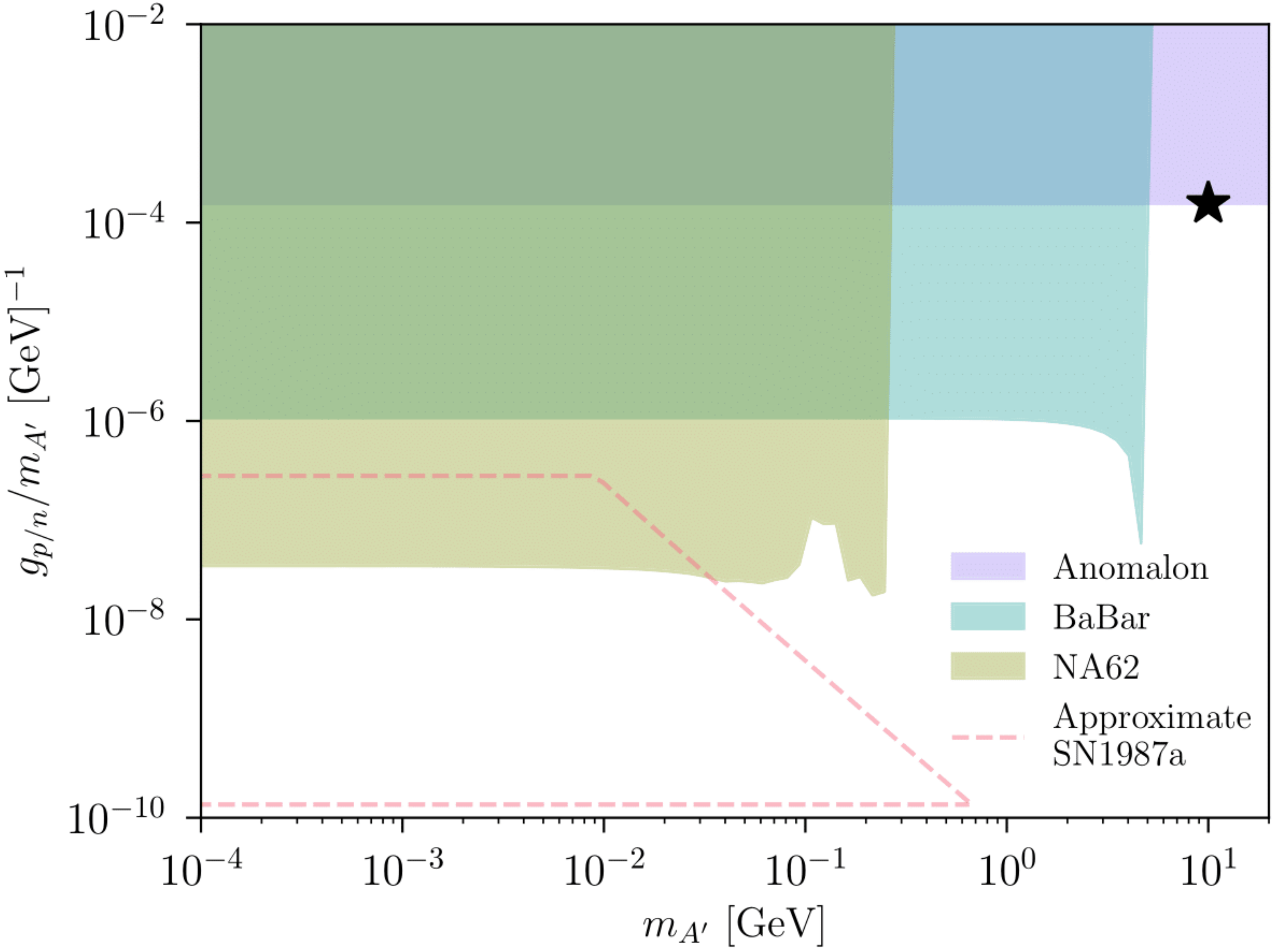


Results

- Potential reach for a is always worse than ϕ – momentum suppressed
- $m_a = 10\, m_\chi v_0$
- Cliff occurs at the constraint from HB stars
- Left: SIDM constraints on g_χ; Right: $g_\chi = 1$

Cross sections needed for 3 events/kg-year rate for GaAs & sapphire using several threshold energies





The star denotes the optimal choice of mediator mass to reduce the constraint.

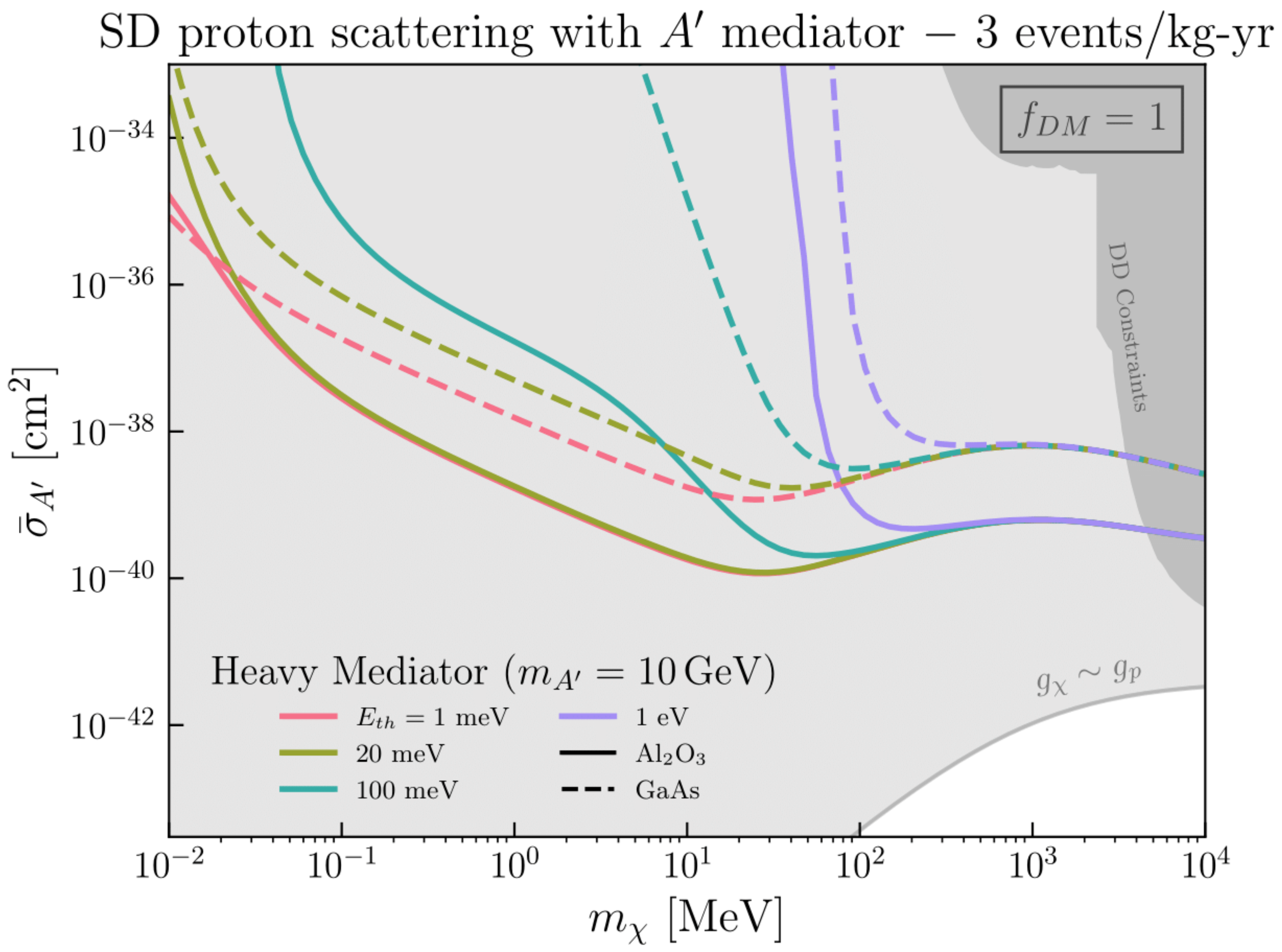
Constraints on g_N

Valid for $m_{A'}$

Results

- A' – axial vector case; often considered SD case
- $m_{A'} = 10\ GeV$
- $g_N \sim g_\chi$
  - Theoretical consistency
  - SIDM constraints are superseded

Cross sections needed for 3 events/kg-year rate for GaAs & sapphire using several threshold energies



Conclusions: Part 2

Multiphonon – DM interactions cover intermediate DM mass ranges between nuclear recoil and single phonon detection

Spin dependent multiphonon scattering utilizes similar methods as spin independent when crystal spins are randomly distributed

The reach of multiphonon experiments falls well short of current constraints on spin dependent DM interactions (SN, mesons, etc), except in a few possible cases

Conclusions

Part 1: arXiv:2506.19905

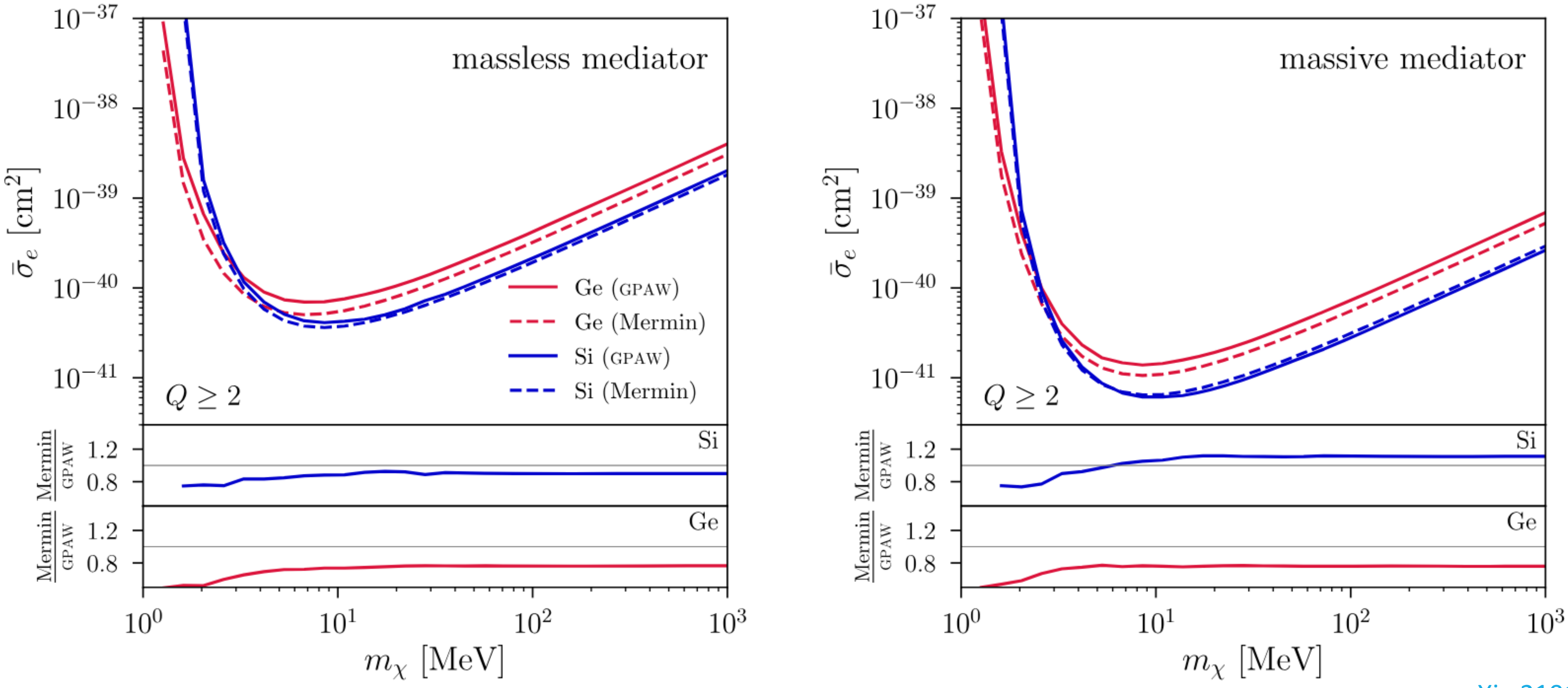
- Current electron recoil experiments focus on limited, well-known materials
- We can harness the ideas of Material Informatics and use a data-driven approach to find exceptional candidate materials for next-gen dark matter detectors
- Anisotropic materials provide a big boost by eliminating backgrounds in detectors

Part 2: arXiv:2506.11191

- We updated constraints on the spin-dependent DM-nucleon cross section for three representative operators
- We project the zero-background reach for upcoming phonon detectors
- Because of momentum suppression, and the strength of the constraints, very little parameter space remains open for these low DM masses.

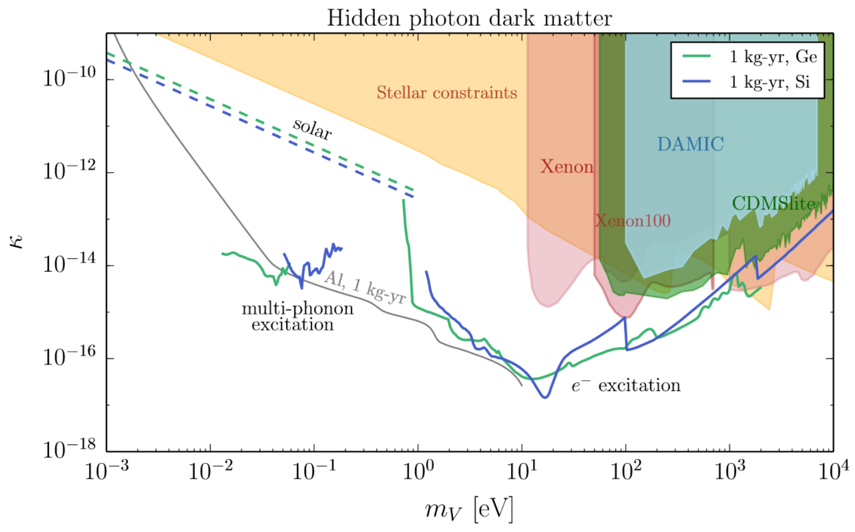
Questions?

Comparison between DFT (GPAW) and Mermin Oscillators



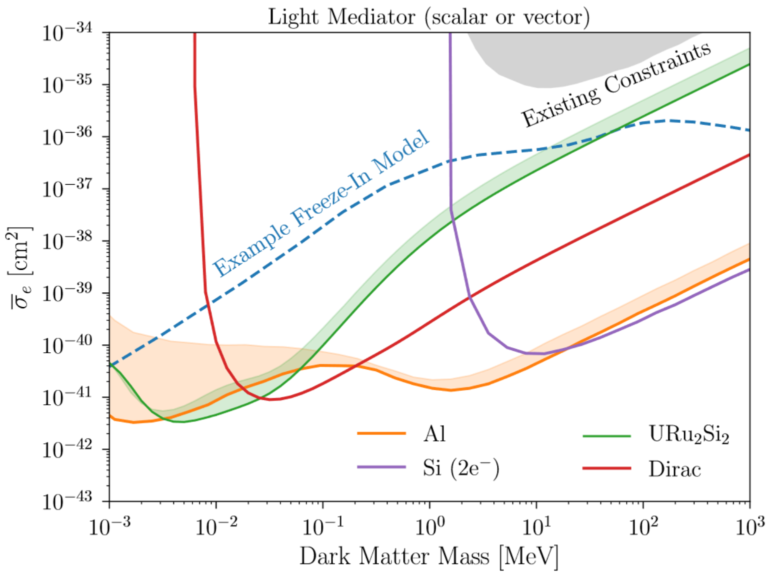
arXiv:2101.08275

DM-e^- Absorption



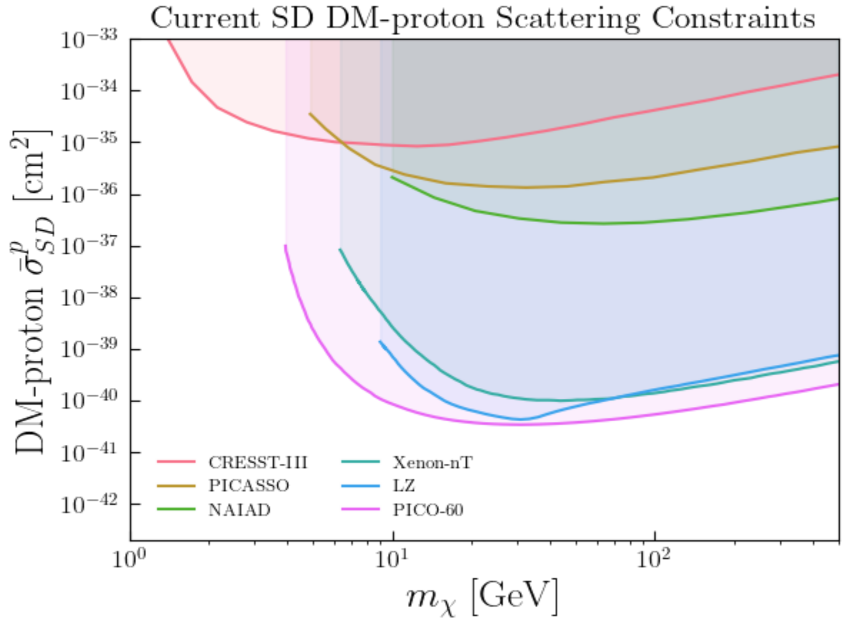
arXiv:1608.01994

DM-e^- Scattering



arXiv:2101.08263

DM-N Scattering



arXiv:2207.03764 arXiv:2303.14729
arXiv:2207.07640 arXiv:1702.07666
arXiv:1707.01632 arXiv:1611.01499

Current Experimental Constraints and Projections

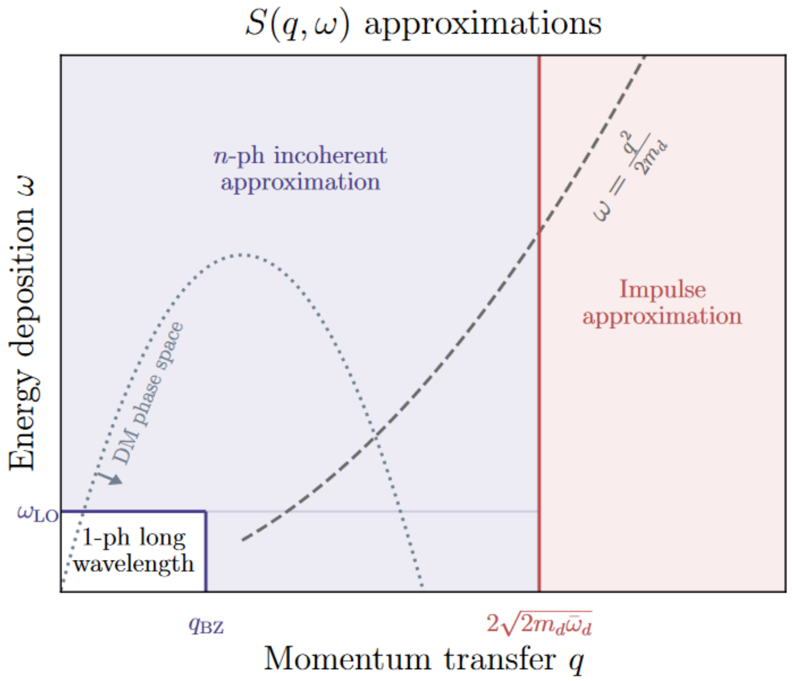
Benefits of Polar Materials

- Gapped dispersion of optical phonons
  - Single or multiphonon
- Anisotropic crystal structures
  - Daily modulation in rate
- Low screening
  - Required: few free electrons, high polarizability
  - Gap for electronic excitations $\sim O(1 - 10\ eV)$
  - Kinetic mixing with dark photon couples to dipole moment
- Easy to fabricate

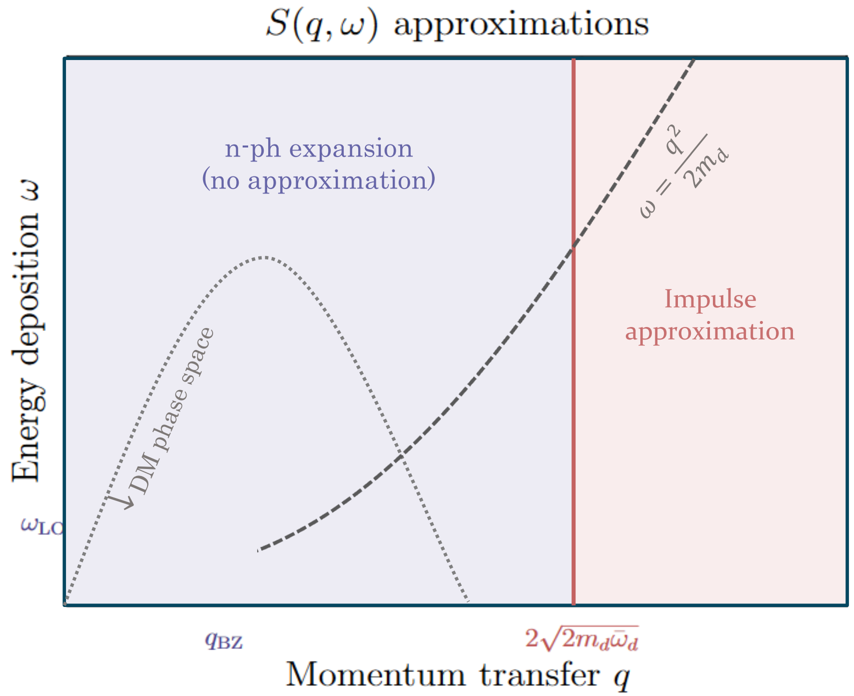
S. Griffin, S. Knapen, T. Lin, M. Pyle, K. Zurek: 1807.10291

Approximations

Spin Independent



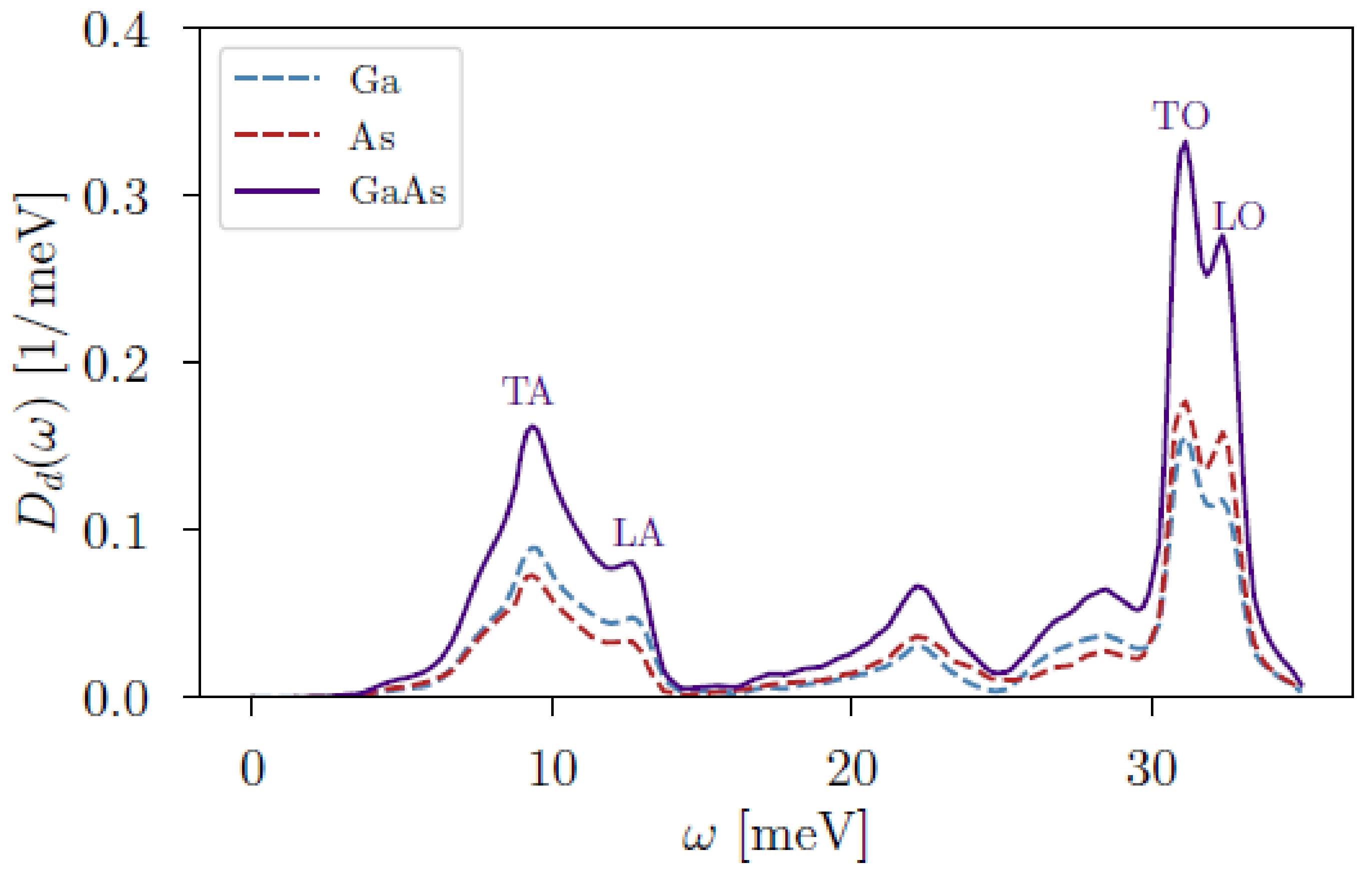
Spin Dependent



B. Campbell-Deem, S. Knapen, T. Lin, E. Villarama: 2205.02250

Density of States

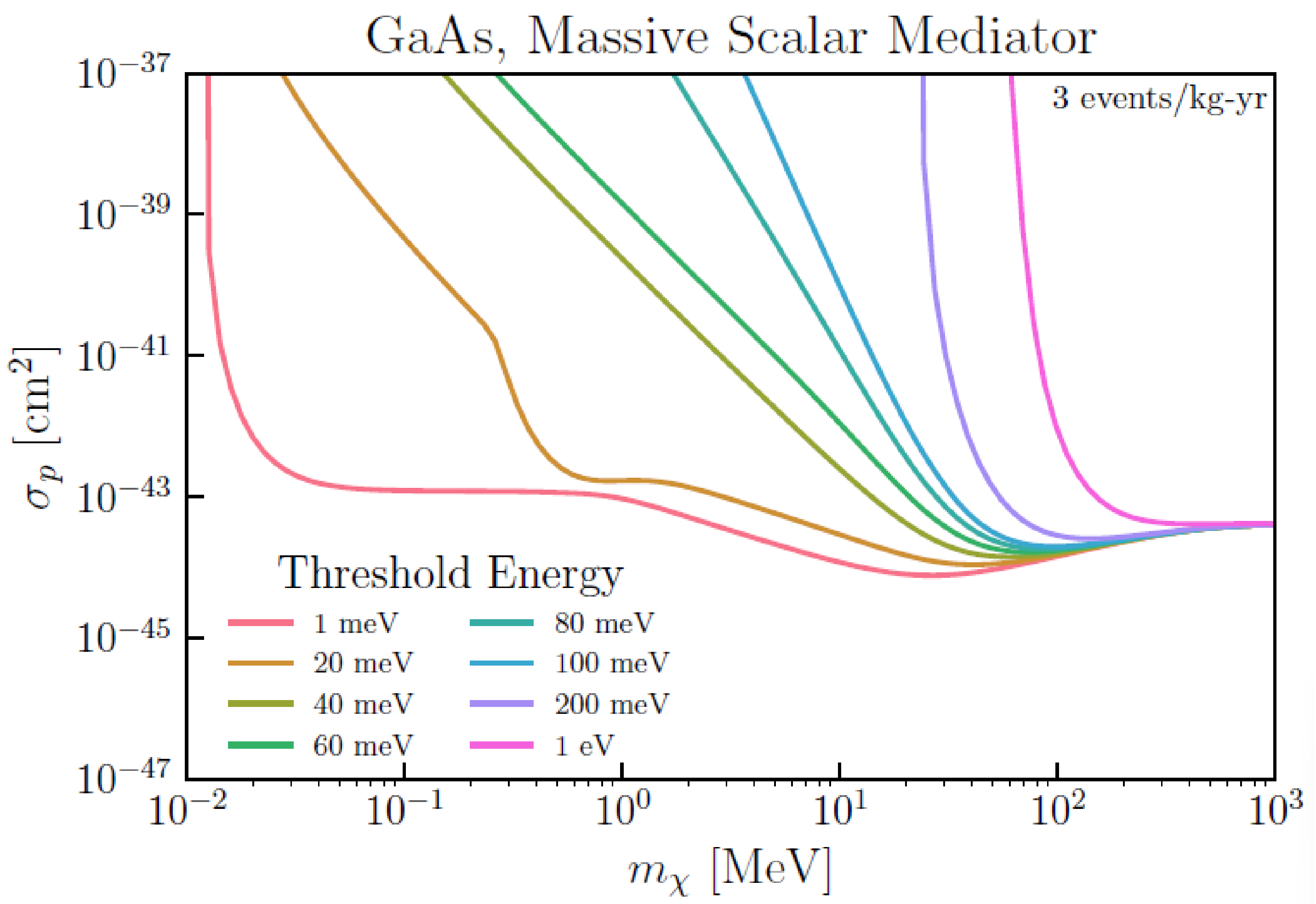
- The peaks from each phonon are visible
- The partial density of states are calculated using Density Effective Theory where data is not yet taken
- Many materials’ density of states can be taken from the Material Project data



A. Jain, Et. Al. https://doi.org/10.1063/1.4812323

Spin Independent Results

- Assumes a coupling $\sim A_d$
- Isotropic approximation
- Anharmonic corrections around $m_\chi \sim 1 - 10\ MeV$: 2309.10839



B. Campbell-Deem, S. Knapen, T. Lin, E. Villarama: 2205.02250

Multiphonon Rate (SI)

$$\frac{d\sigma}{d^3q\,d\omega} \sim \sum_d^N f_d^2 e^{-2W_d(q)} \sum \left(\frac{q^2}{2m_d}\right)^n \frac{1}{n!} \left(\prod_{i=1}^n \int d\omega_i \frac{D_d(\omega_i)}{\omega_i}\right) \delta\left(\sum_j \omega_j - \omega\right)$$

$q \gg \sqrt{2\omega m_d}$

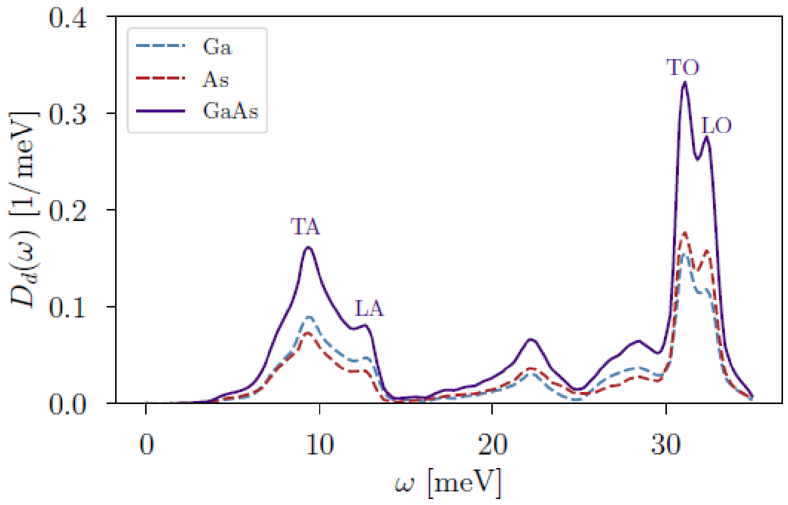
Impulse Approximation

Partial density of States

$$\frac{d\sigma}{d^3q\,d\omega} \sim \sum_d^N f_d^2 \sqrt{\frac{2\pi}{\Delta_d^2}} \exp\left(-\frac{\left(\omega - \frac{q^2}{2m_d}\right)^2}{2\Delta_d^2}\right)$$

$q \ggg \sqrt{2\omega m_d}$

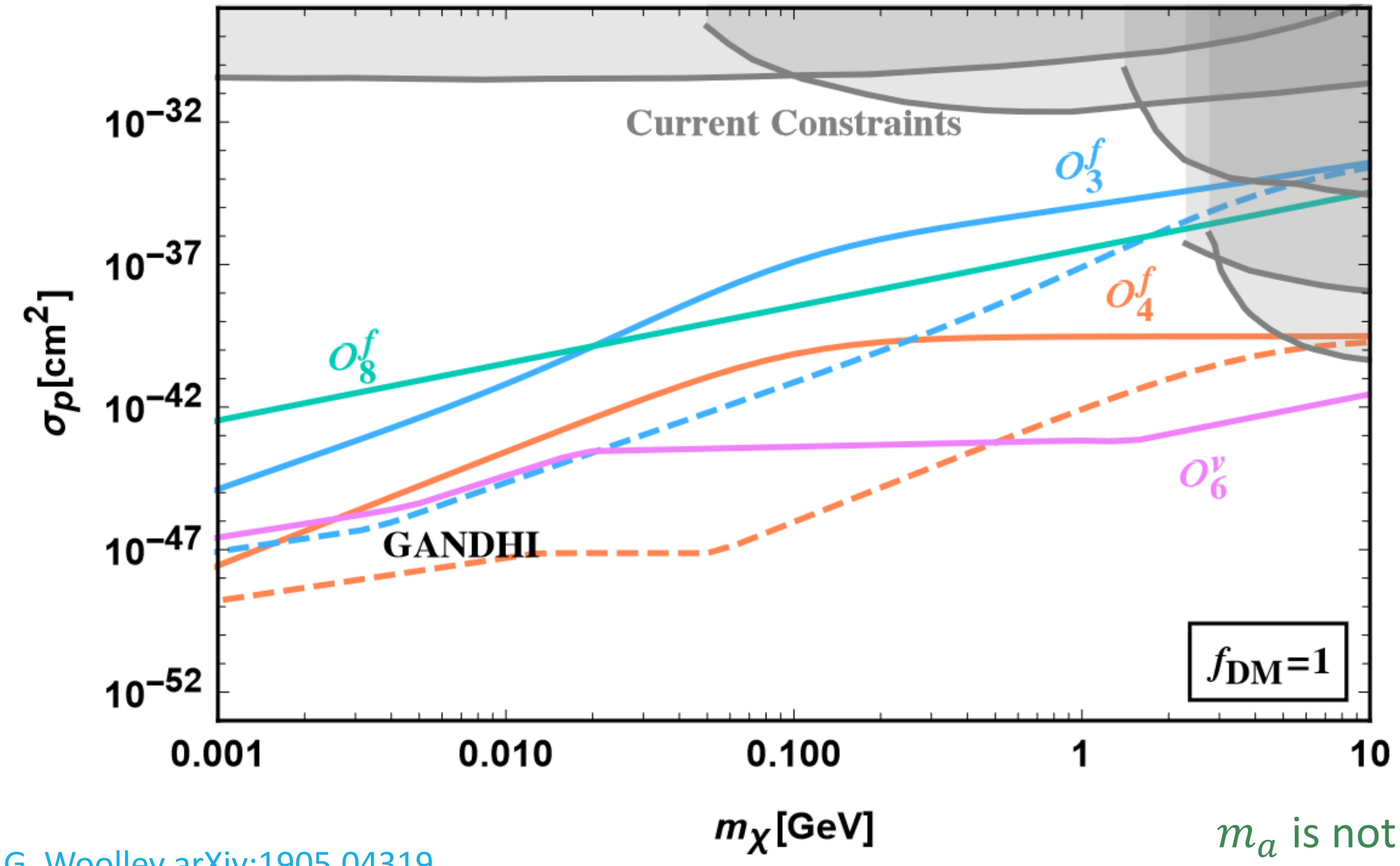
$$\frac{d\sigma}{d^3q\,d\omega} \sim \sum_d^N f_d^2 \times \delta\left(\omega - \frac{q^2}{2m_d}\right)$$



Free nuclear recoil limit!

B. Campbell-Deem, S. Knapen, T. Lin, E. Villarama: 2205.02250

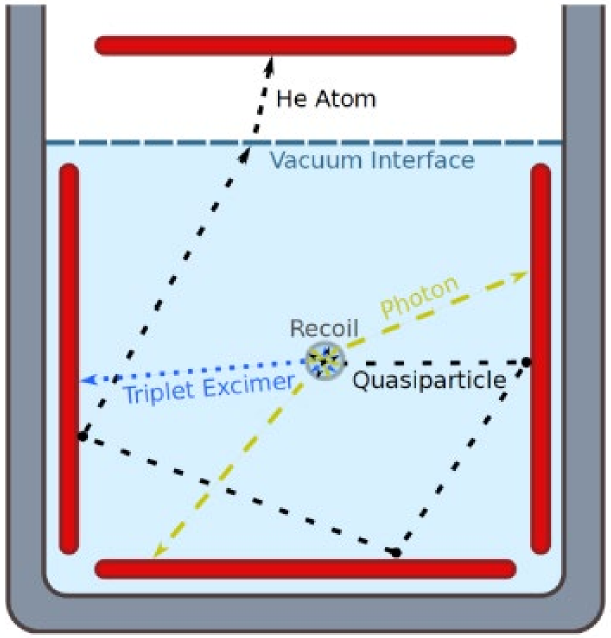
Spin Dependent Constraints

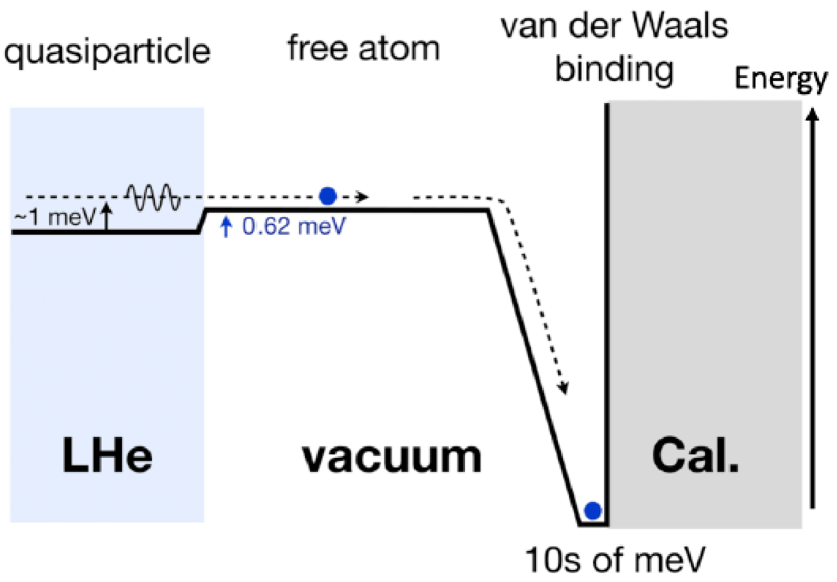


H. Ramani, G. Woolley arXiv:1905.04319

m_a is not fixed

Phonon Detector: HeRALD

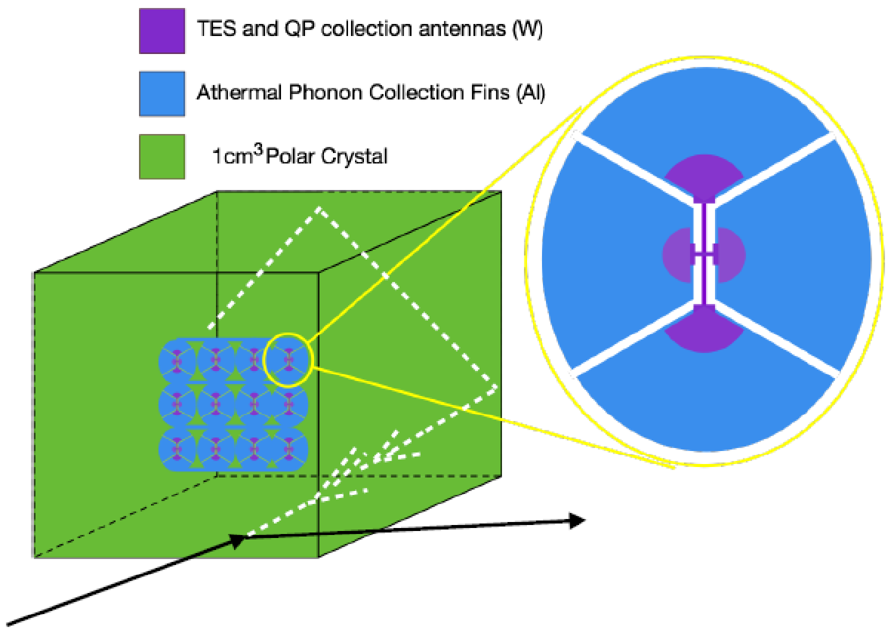




- Calorimeters with TES readout
- Quantum evaporation of He atoms

S. Hertel, A. Biekert, J.Lin, V.Velan, & D. McKinsey arXiv:1810.06283
Figures from J. Lin slides

Phonon Detector: SPICE



- Polar Materials: GaAs or Sapphire
- Scintillation & phonons
  - Background discrimination!
- Low energy TES
  - 10 meV threshold

3’’ sapphire detector

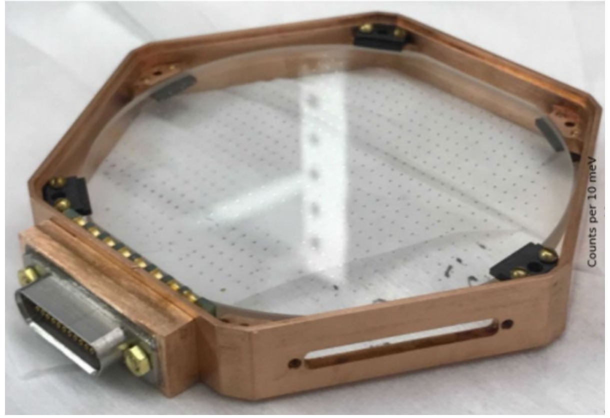
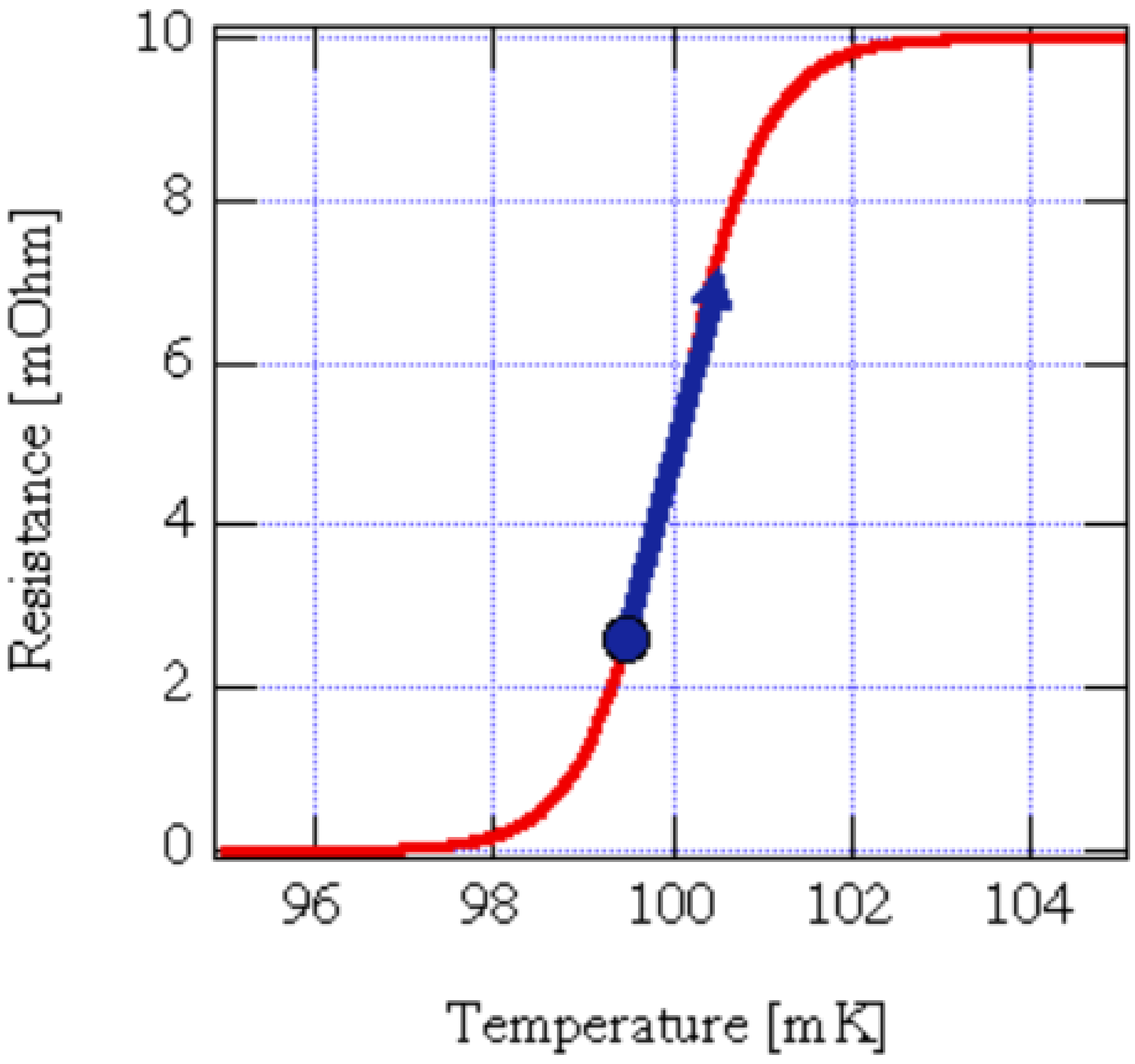


Figure from M. Pyle

Picture from TESSERACT Website

Transition Edge Sensors (TES)

- Superconducting film acting at the phase “transition edge”
- Large change in resistance with tiny shifts in temperature
- Smaller band widths → lower threshold energies



Kinematic Matching: Nuclear Recoil

Heavy DM

Nucleon