First High-Throughput Search for Dark Matter Detector Materials

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Hitoshi Gets Two Birthday Conferences 🎉

Outline

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

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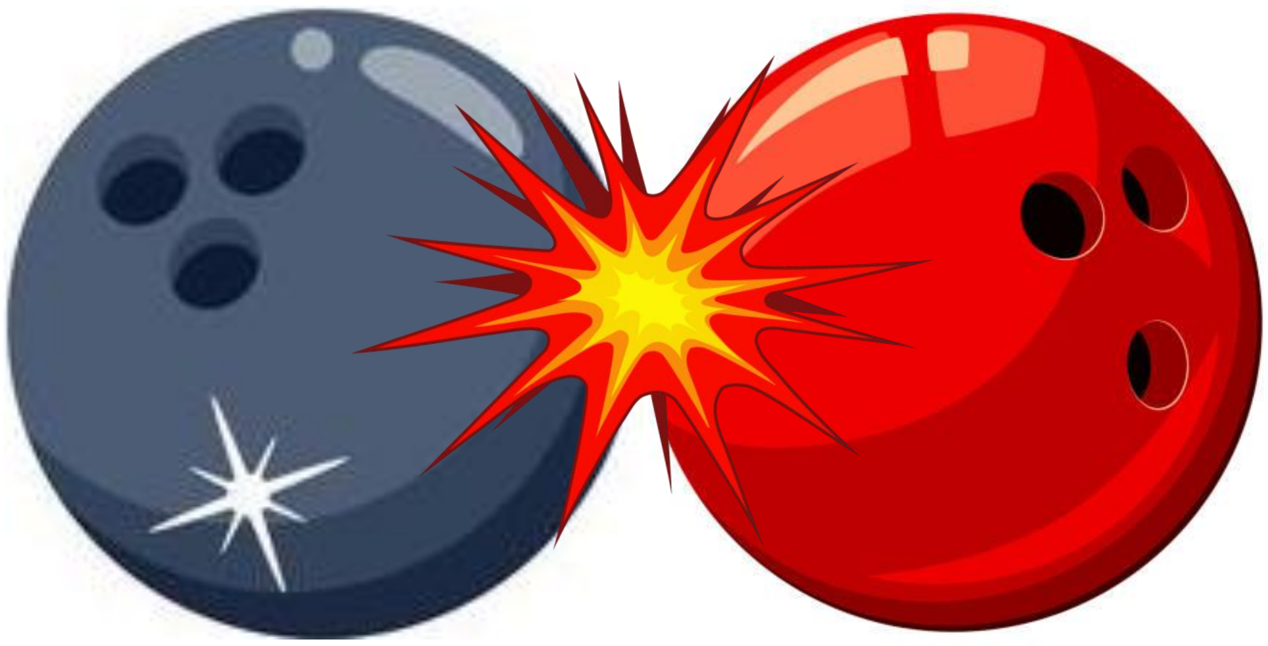
Kinematic Matching: Nuclear Recoil

Heavy DM

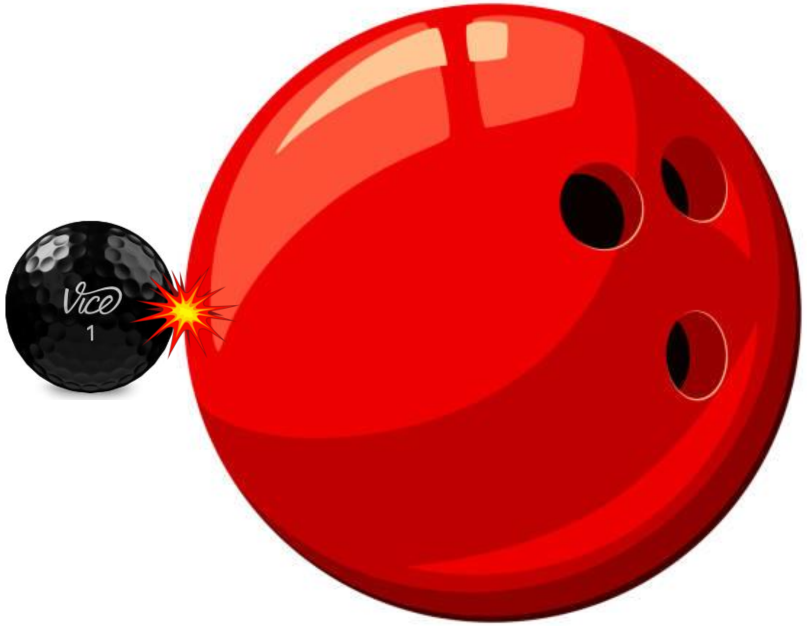
Nucleon



Kinematic Matching

Light DM

Nucleon



Kinematic Matching: Electron-DM

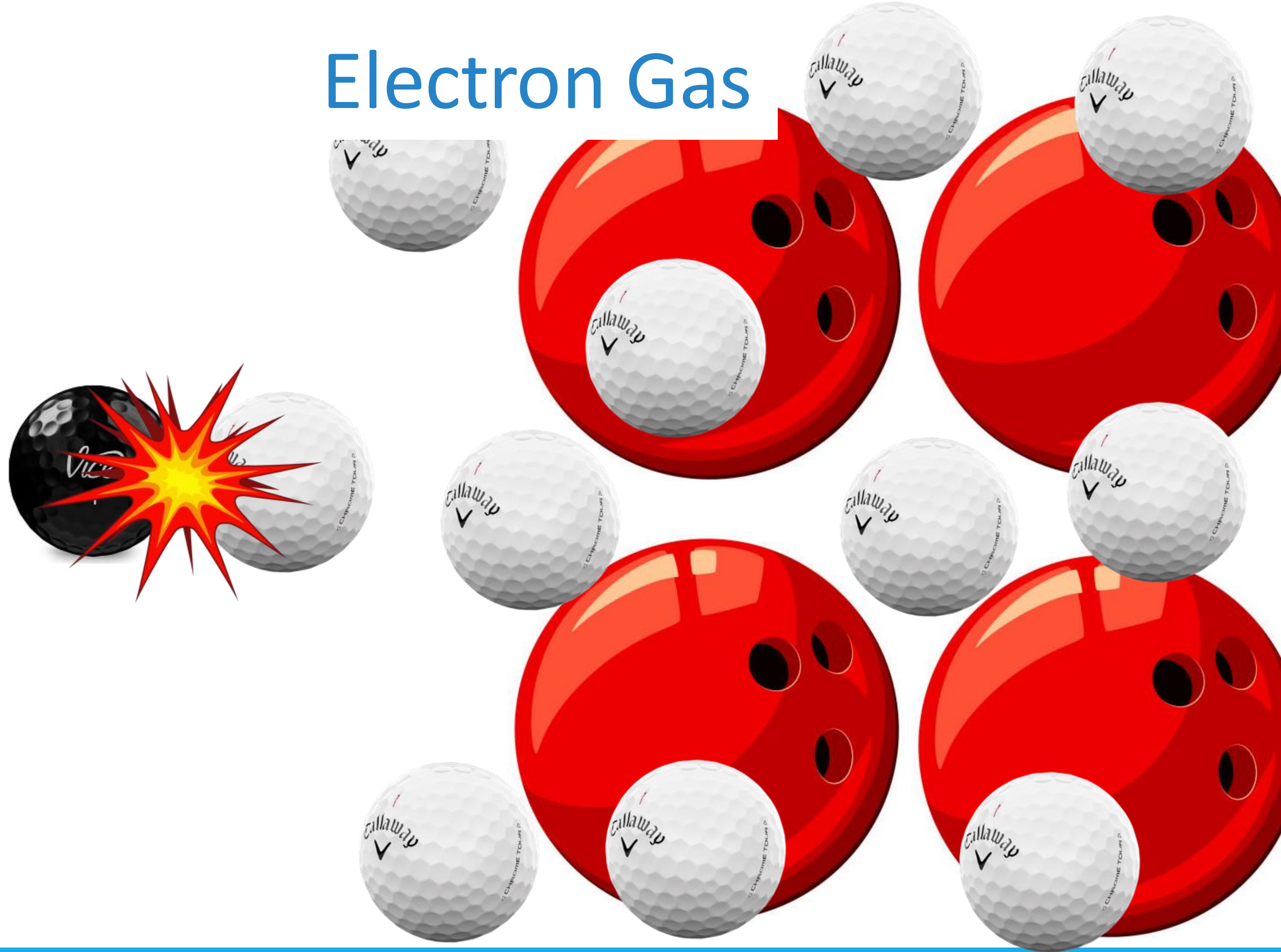
Light DM

Electron

Electronic Screening: DM

Light DM

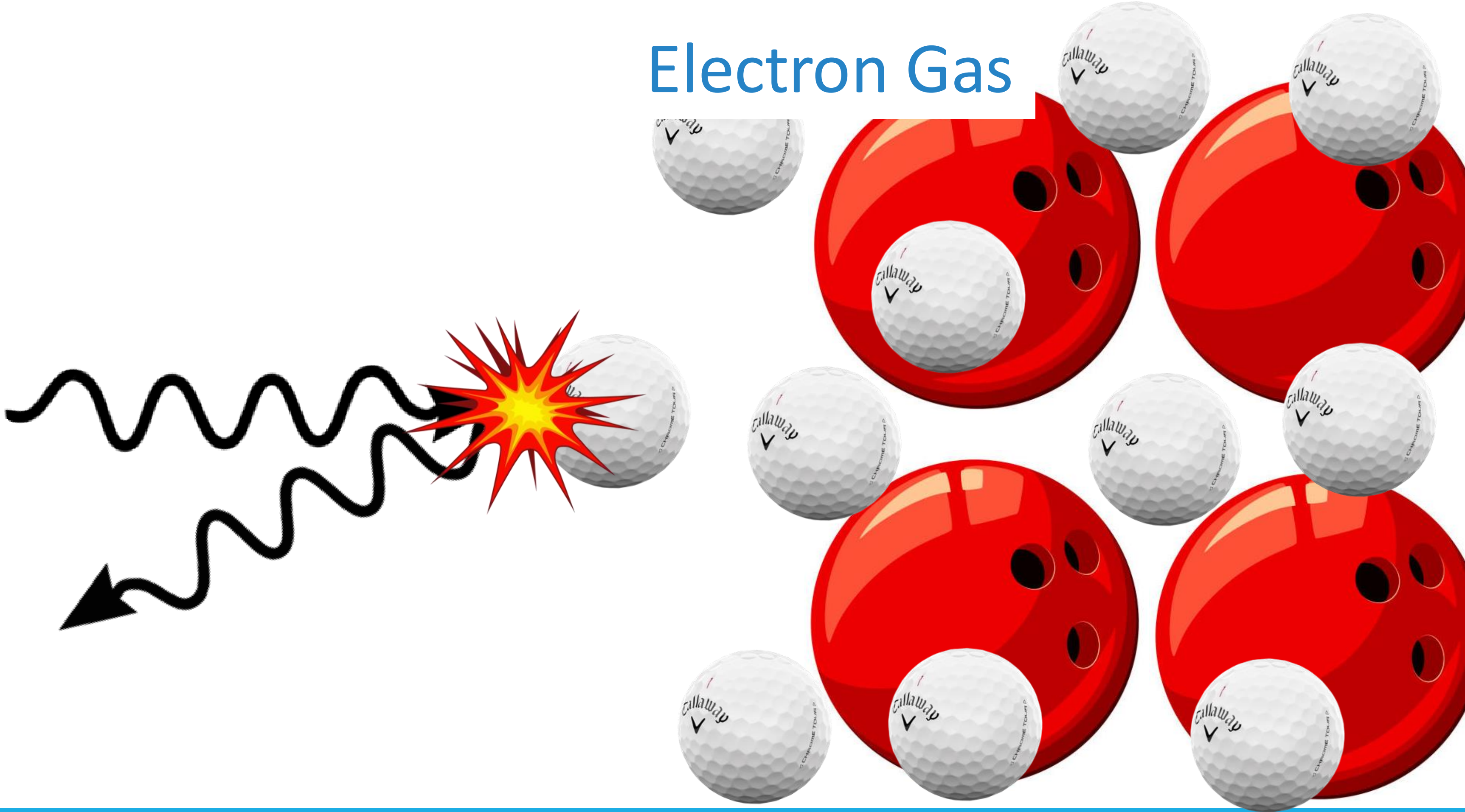
Electron Gas



Electronic Screening: Dielectric Function

Photon

Electron Gas

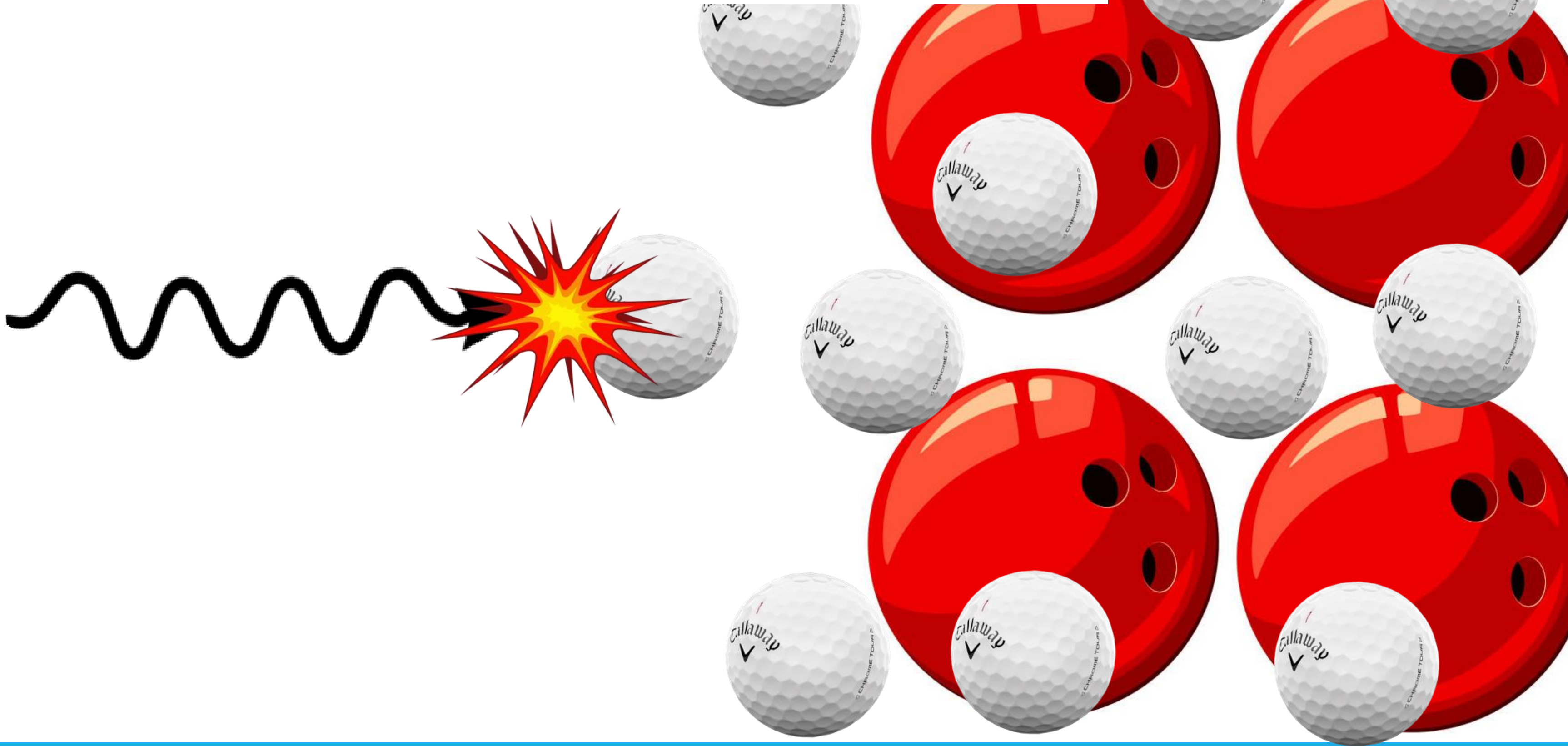


Scattering

Electronic Screening: Dielectric Function

Photon

Electron Gas



Absorption

DM-Electron 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

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

Kinematic constraint

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

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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.

Our Dataset

- 1019 Materials with DFT computed, energy dependent, dielectric tensors
- 295 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 limit of transferred momentum q -> 0
  - Scattering rate calculation requires $q \neq 0$ data 😔

How to Extract Momentum Dependence

- The 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

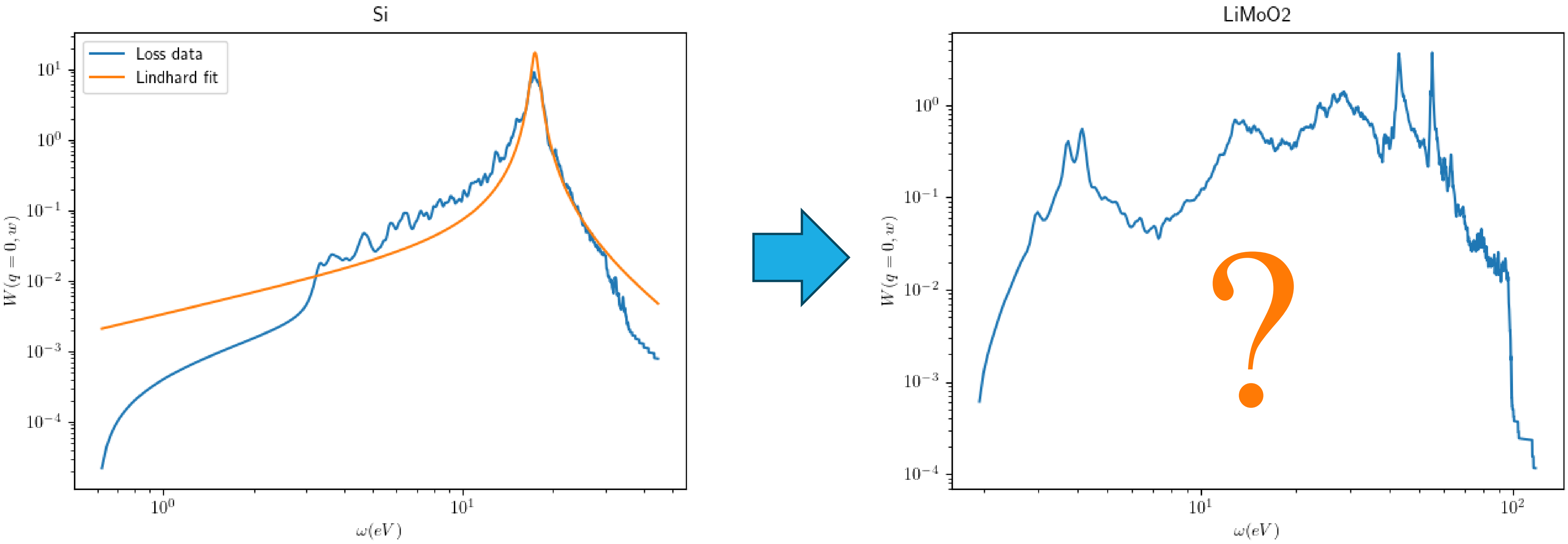
$$Q_\pm = \frac{q}{2k_f} \pm \frac{\omega + i\,\Gamma_p}{q v_f}$$

- We can fit the $q \to 0$ limit to the Materials Project dielectric functions 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

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

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

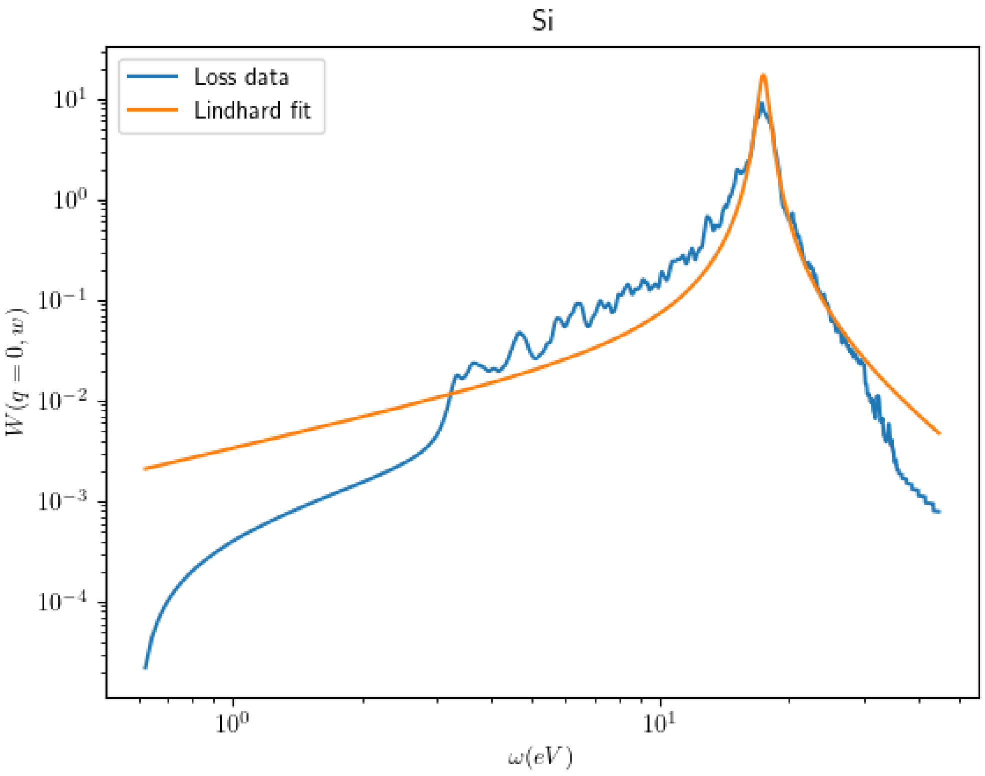
features not described by Lindhard plasmons are independent of q

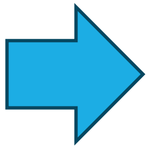
4. We calculate the scattering rate using

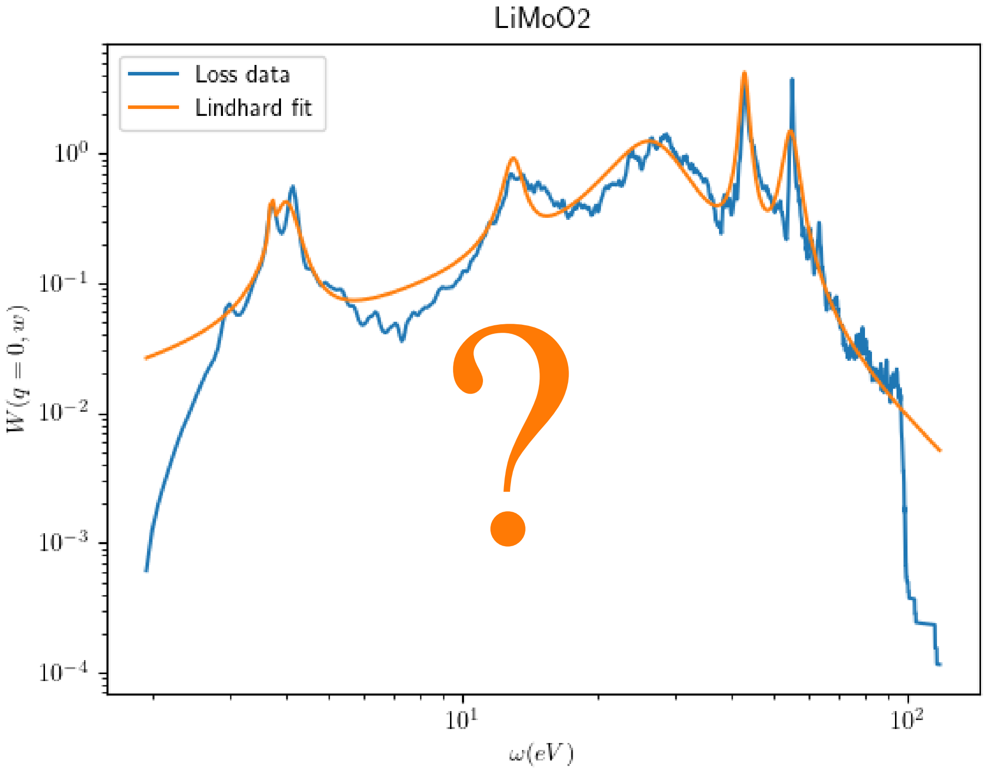
$$\epsilon(q,\omega) = r(\omega)\,\epsilon_{fit}(q,\omega)$$

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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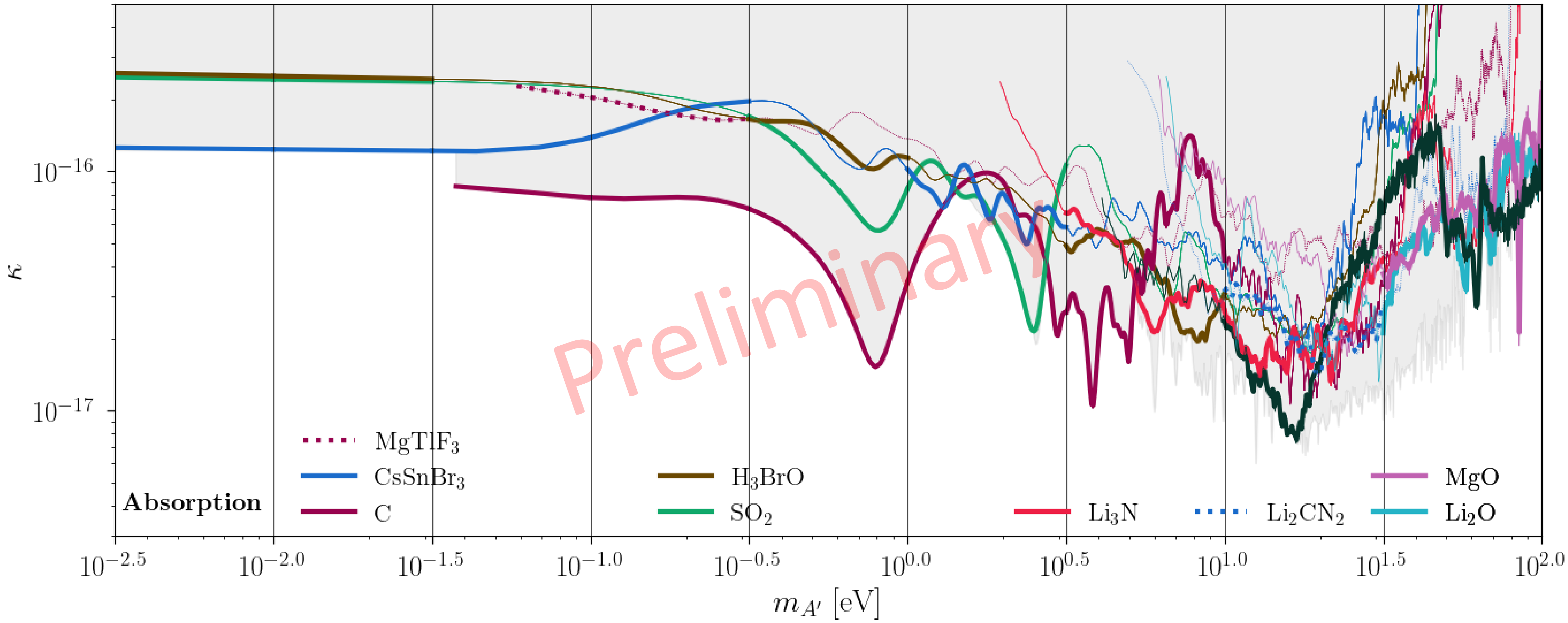
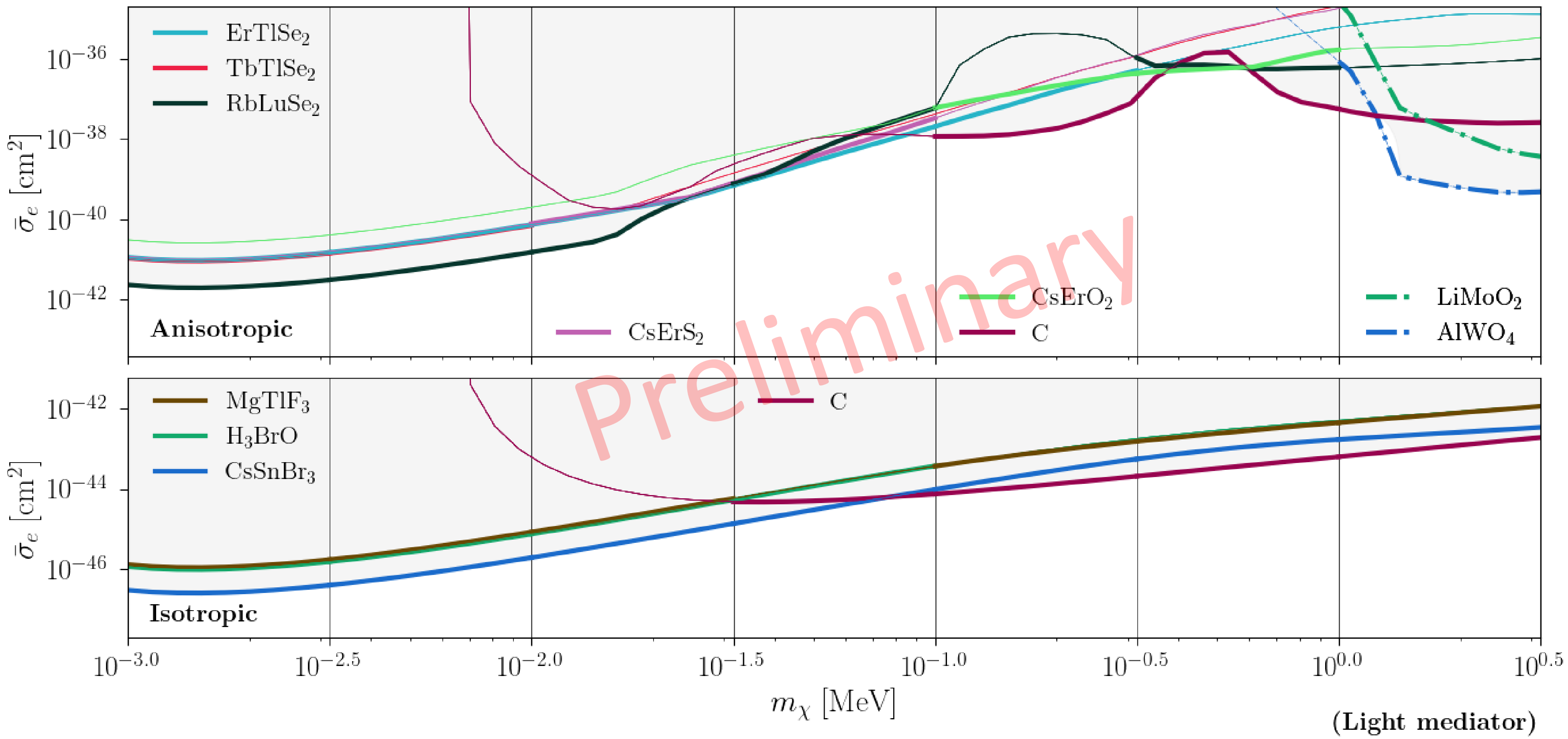
Absorption



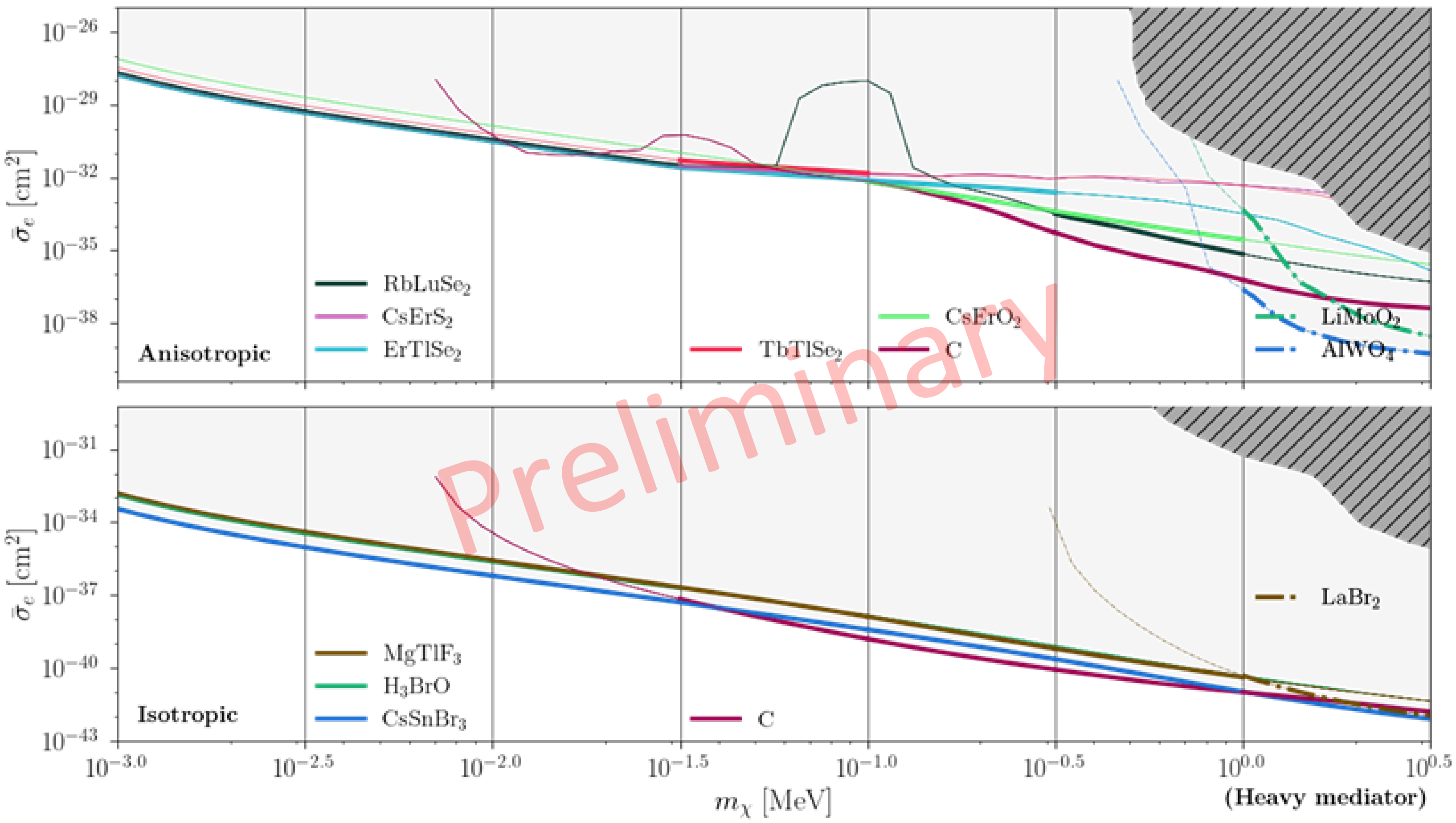
Preliminary
Absorption
MgTlF3
CsSnBr3
C
H3BrO
SO2
Li3N
Li2CN2
MgO
Li2O
κ
10^−16
10^−17
10^−2.5
10^−2.0
10^−1.5
10^−1.0
10^−0.5
10^0.0
10^0.5
10^1.0
10^1.5
10^2.0
m_A′ [eV]

Light Mediator



$E_{th} = 1\ eV$

Heavy Mediator



$E_{th} = 1\ eV$

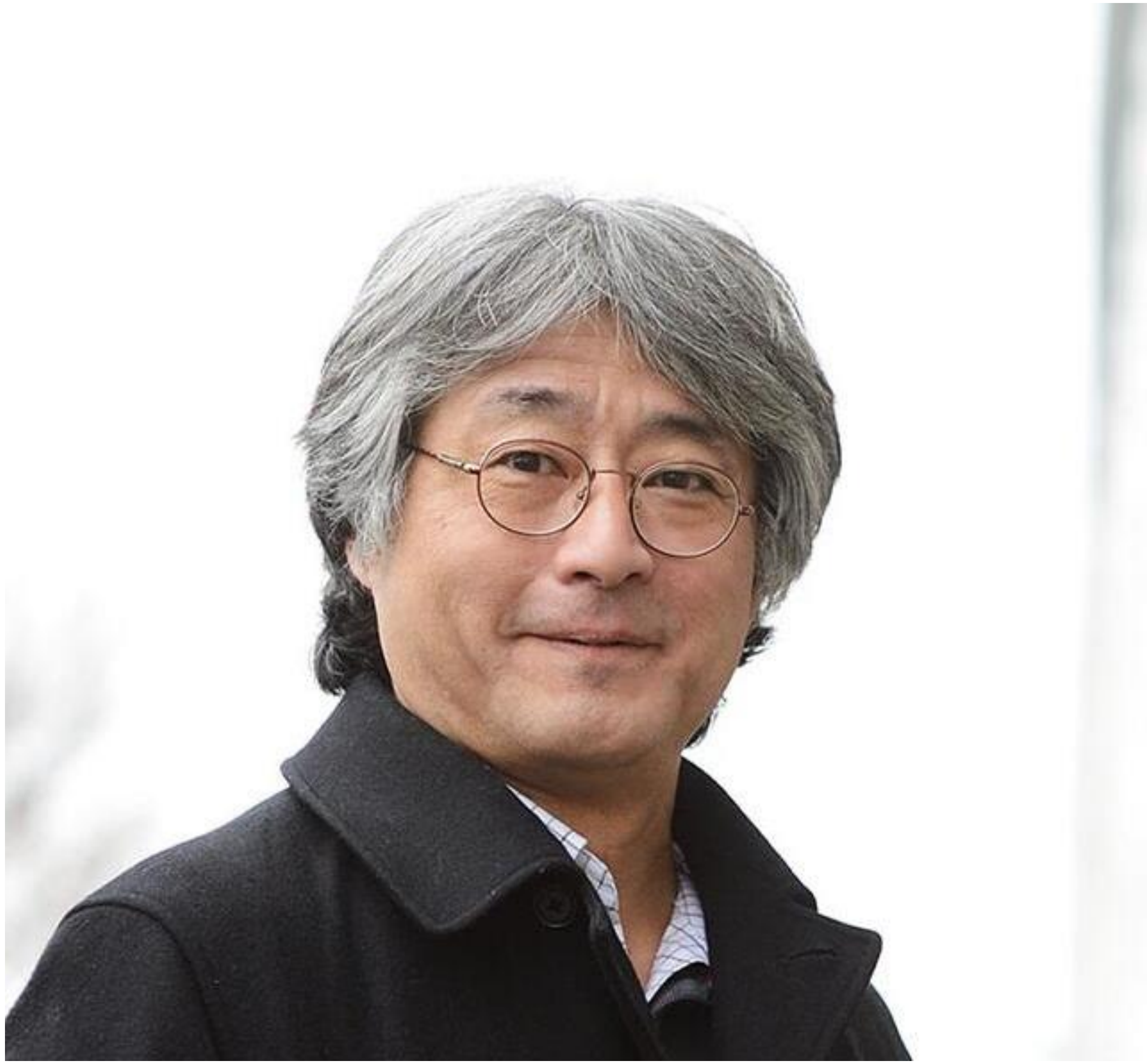
Conclusions

We’ve performed the first high throughput search for optimal materials with which to search for dark matter via direct detection

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

We took dielectric tensor data from the Materials Project and modeled each material via a sum of 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.



Happy Birthday Hitoshi