Direct detection of sub-GeV dark matter

Tongyan Lin
UCSD

HKUST IAS Mini-workshop on theory
January 2022

Traditional approach to direct detection relies on at least two channels, with recoil energy thresholds of ~keV

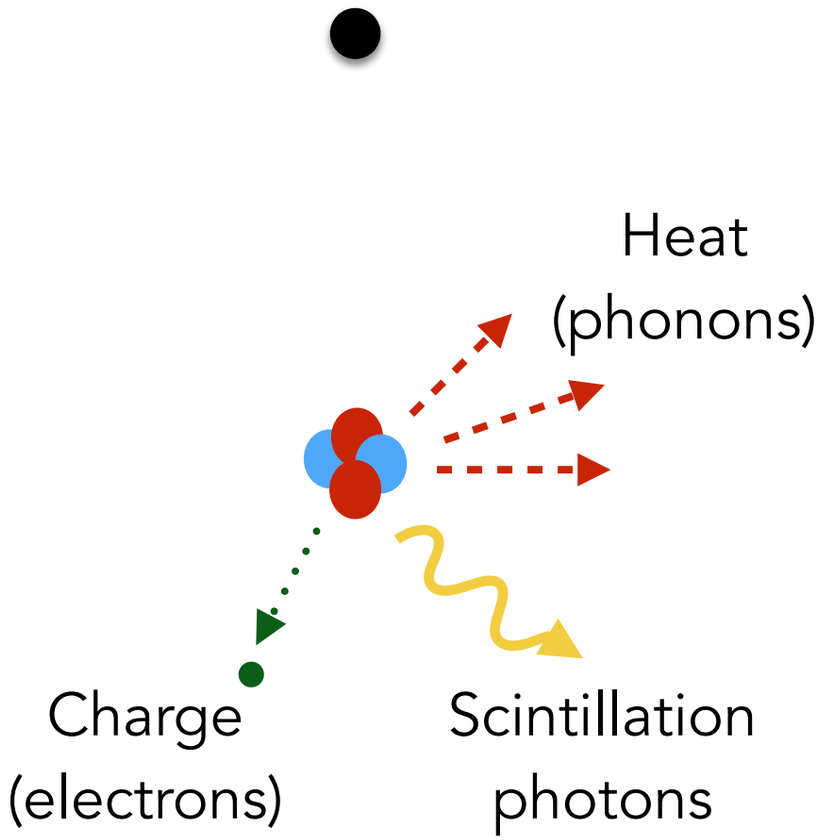
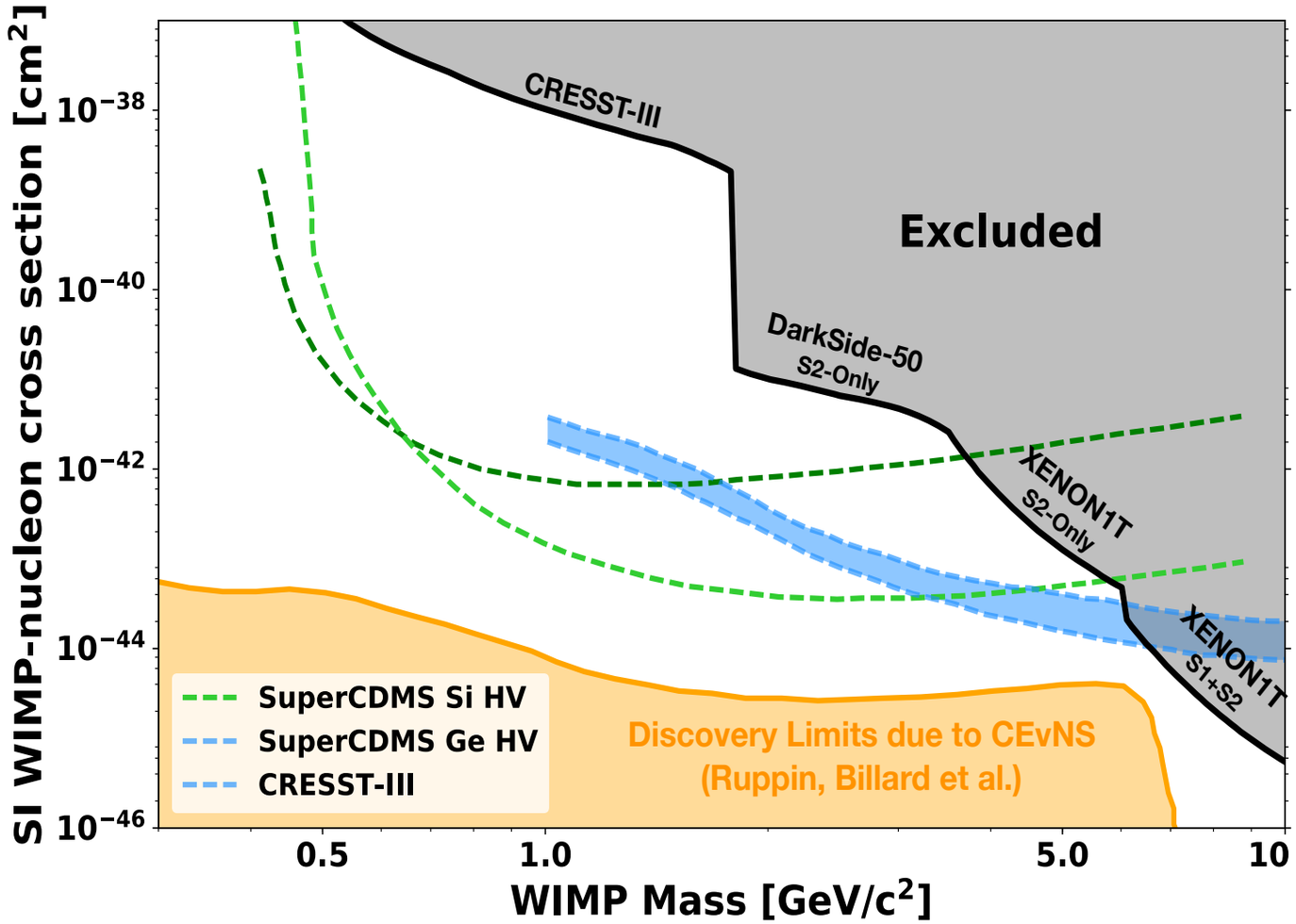
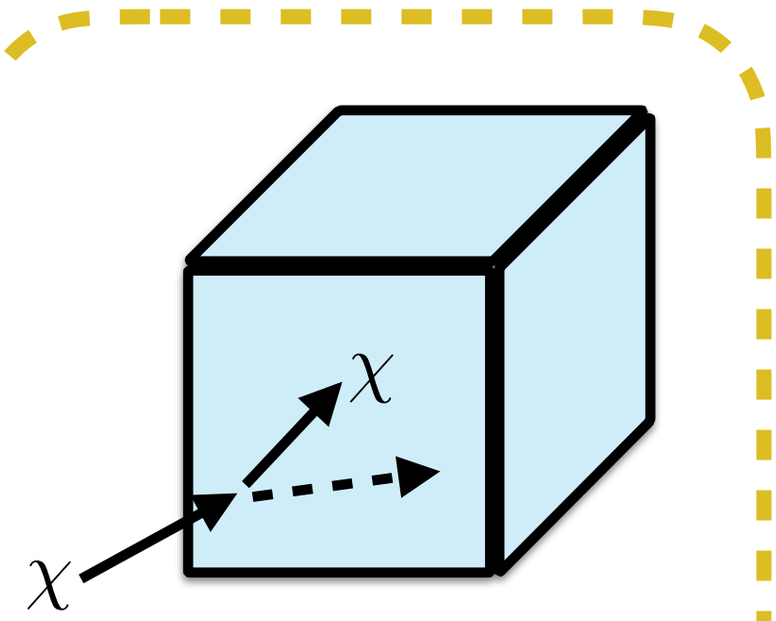


Figure from talk by Kaixuan Ni at DPF 2019



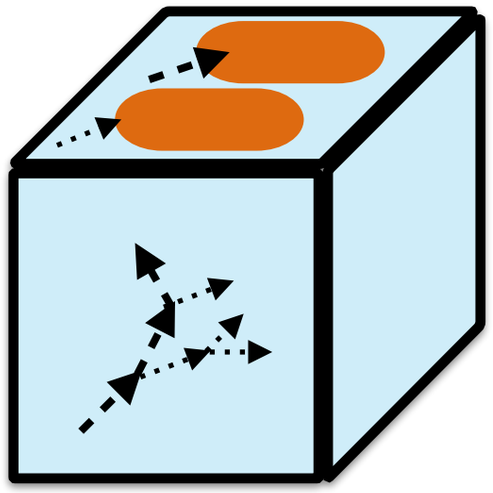
Direct detection of > GeV mass DM

Direct detection of sub-GeV DM

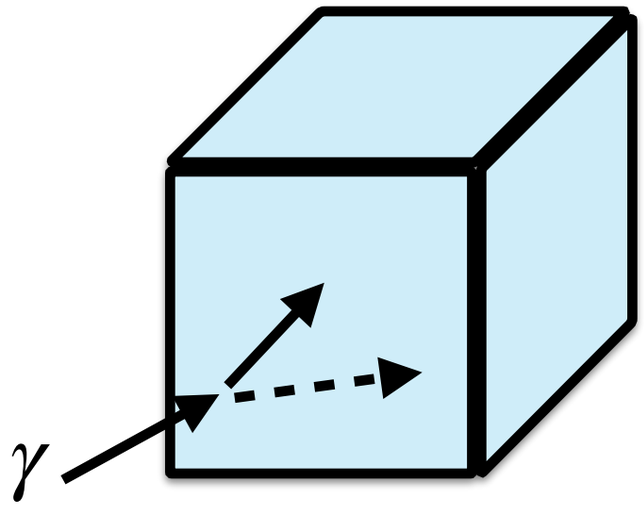


Bulk target
(~mg-g mass)

Primary excitation

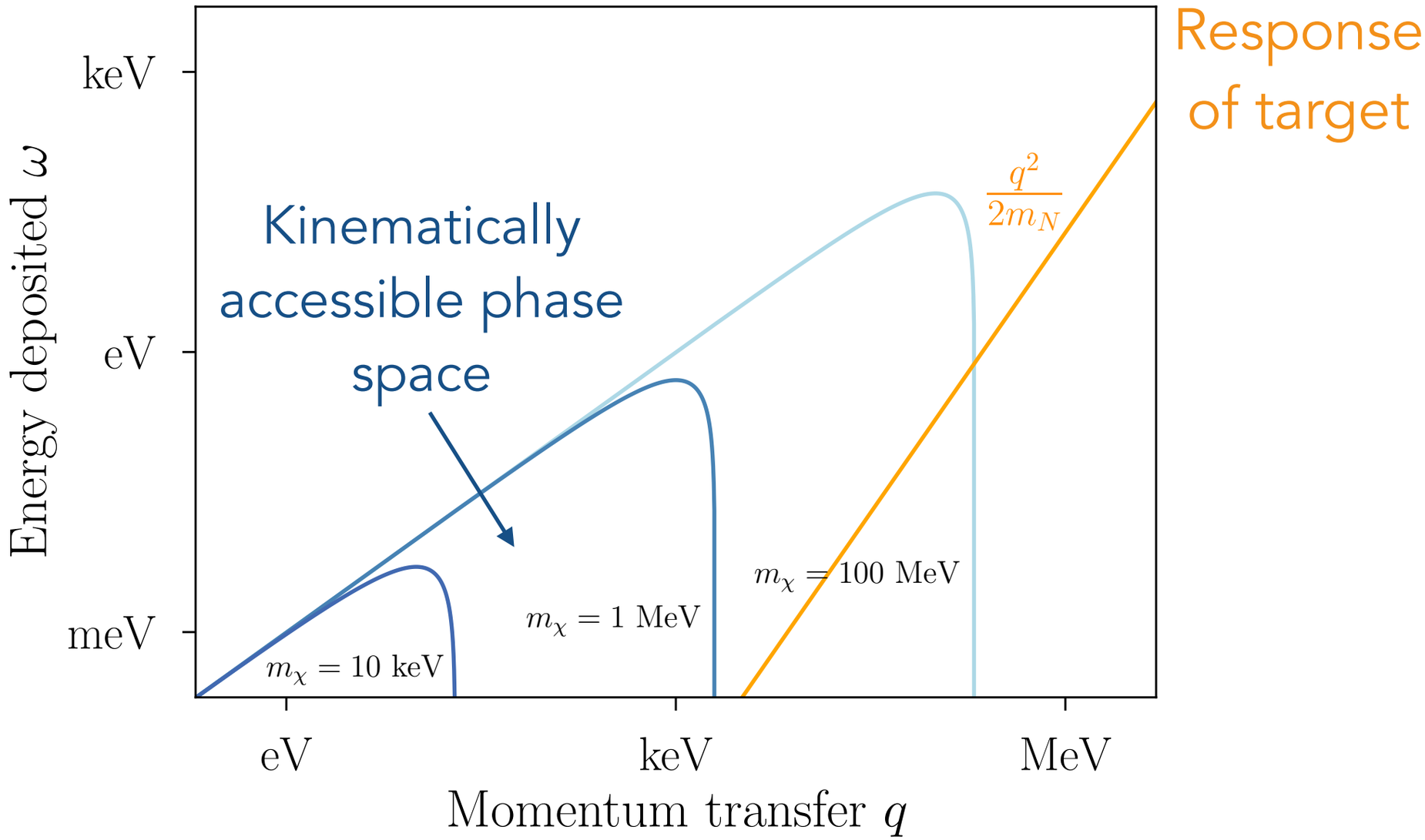


Conversion of primary excitation to secondaries
+
detection of secondaries



Backgrounds

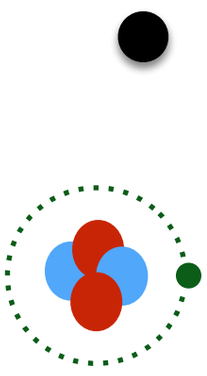
DM scattering off free nuclei



* Kinematic mismatch for sub-GeV DM
* Free nucleus approximation no longer valid

Fig from Kahn, TL 2108.03239
Trickle, Zhang, Zurek, Inzani, Griffin 1910.08092

Energy & momentum scales for sub-GeV dark matter



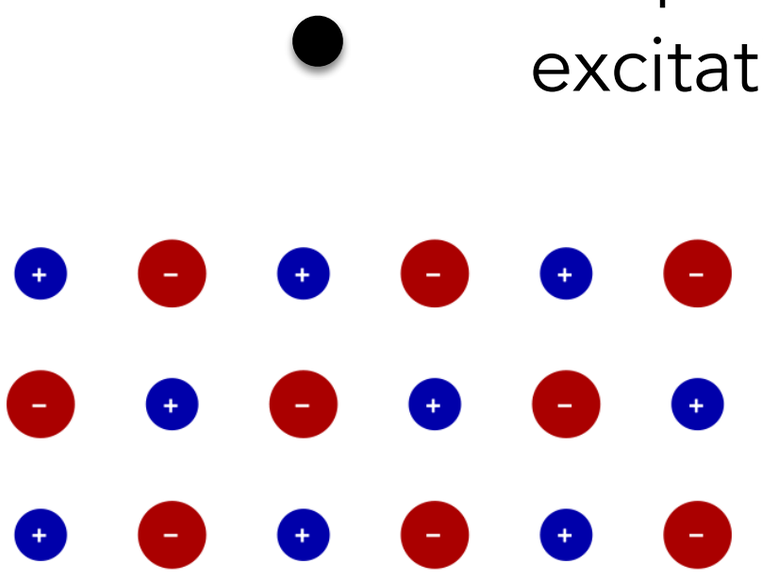
DM-electron scattering

MeV-scale DM:

Energy deposition: $\omega \sim m_\chi v^2/2 \sim \mathrm{eV}$

Momentum transfer: $k \sim m_\chi v \sim \mathrm{keV}$

In conventional insulators, semiconductors:



DM phonon excitations

Electron excitations:

$\omega \sim 1 - 14\,\mathrm{eV}, k \sim \alpha m_e = 3.7\,\mathrm{keV}$

Single phonon excitations:

$\omega \lesssim 0.2\,\mathrm{eV}, k \lesssim \mathrm{keV}$

"Kinematic matching" with available modes in condensed matter systems

(Recent review: Kahn, TL 2021)

DM-electron scattering

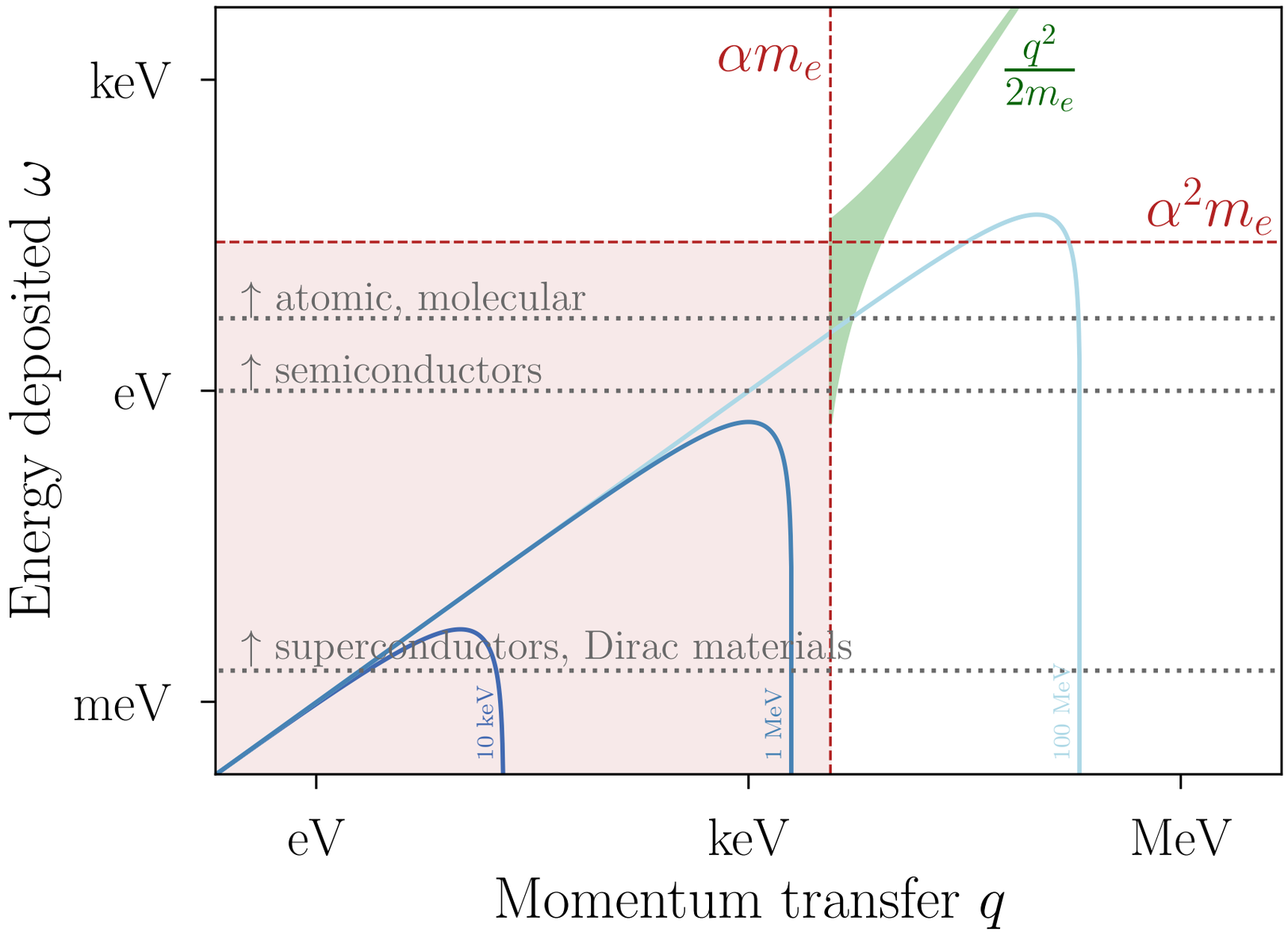


Fig from Kahn, TL 2108.03239
Trickle, Zhang, Zurek, Inzani, Griffin 1910.08092

DM-nucleus scattering in a crystal

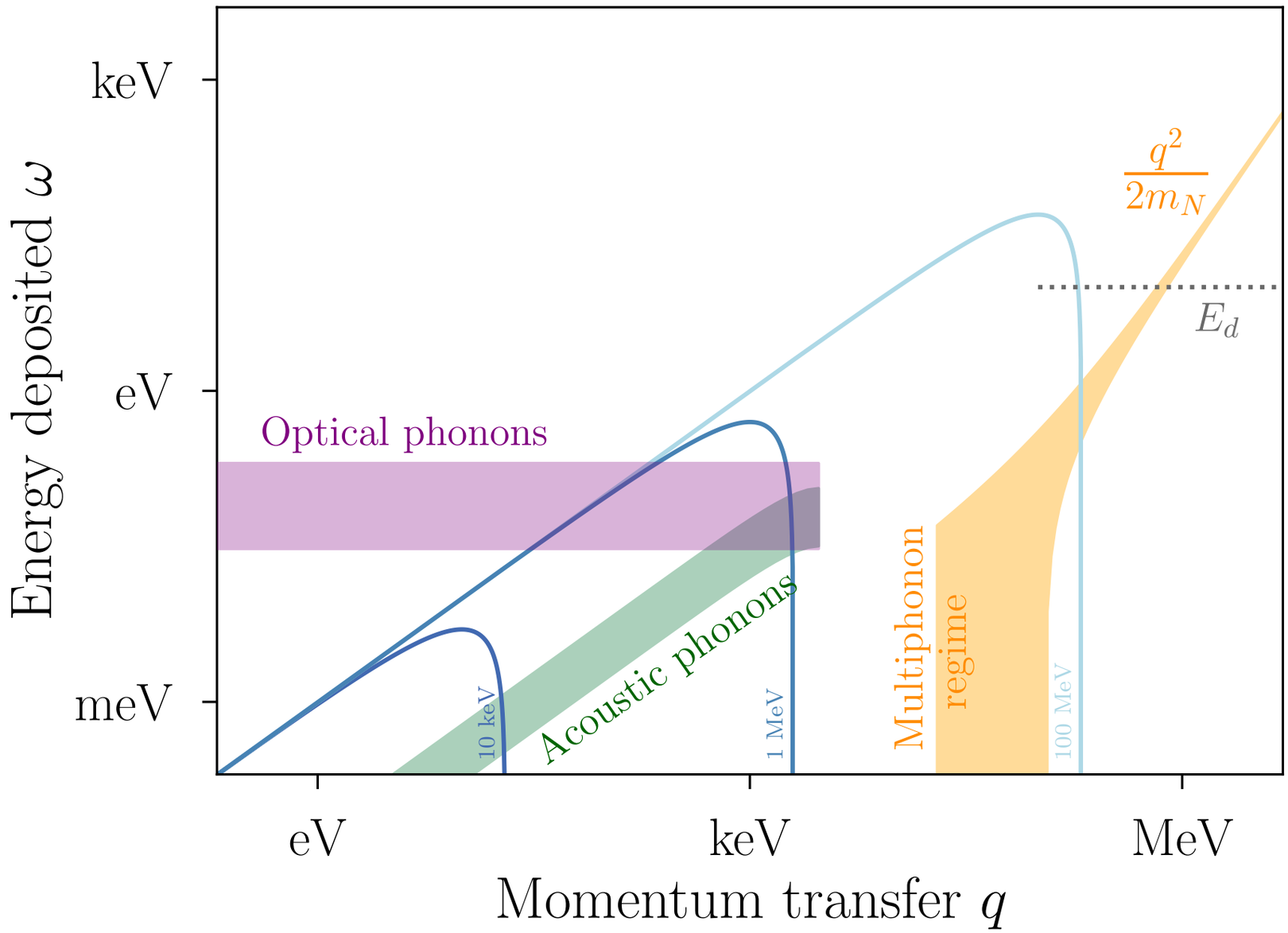
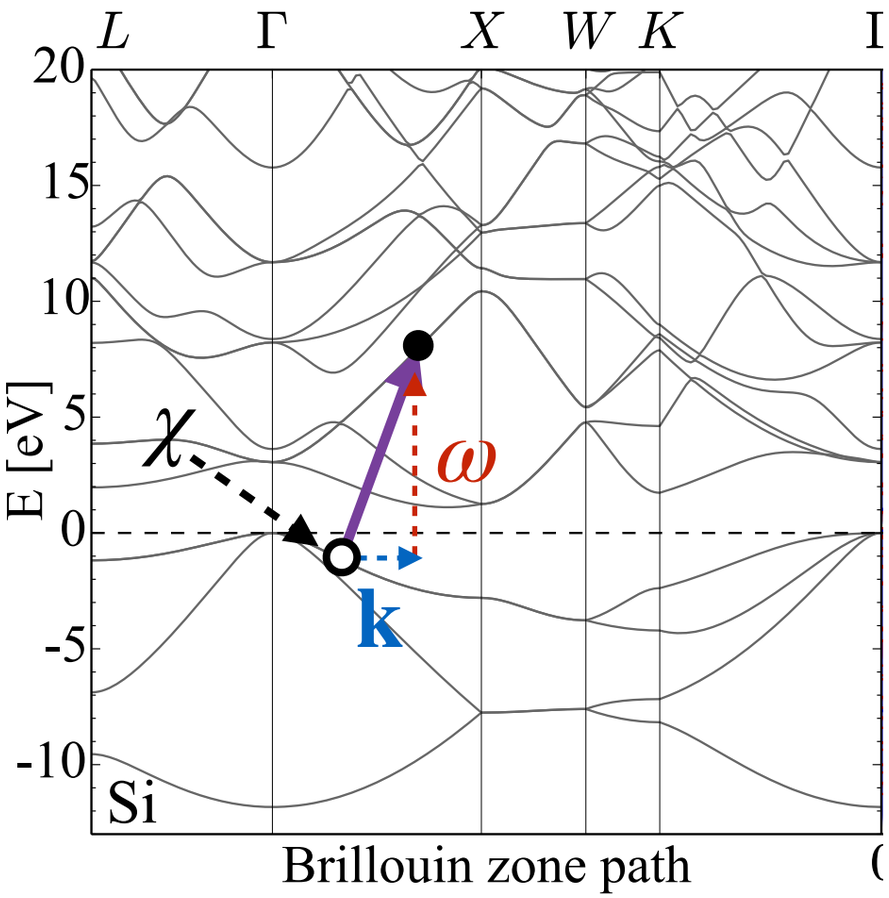


Fig from Kahn, TL 2108.03239
Trickle, Zhang, Zurek, Inzani, Griffin 1910.08092

Electronic signals

DM scattering in a semiconductor



Independent particle approximation:

Wavefunction overlap

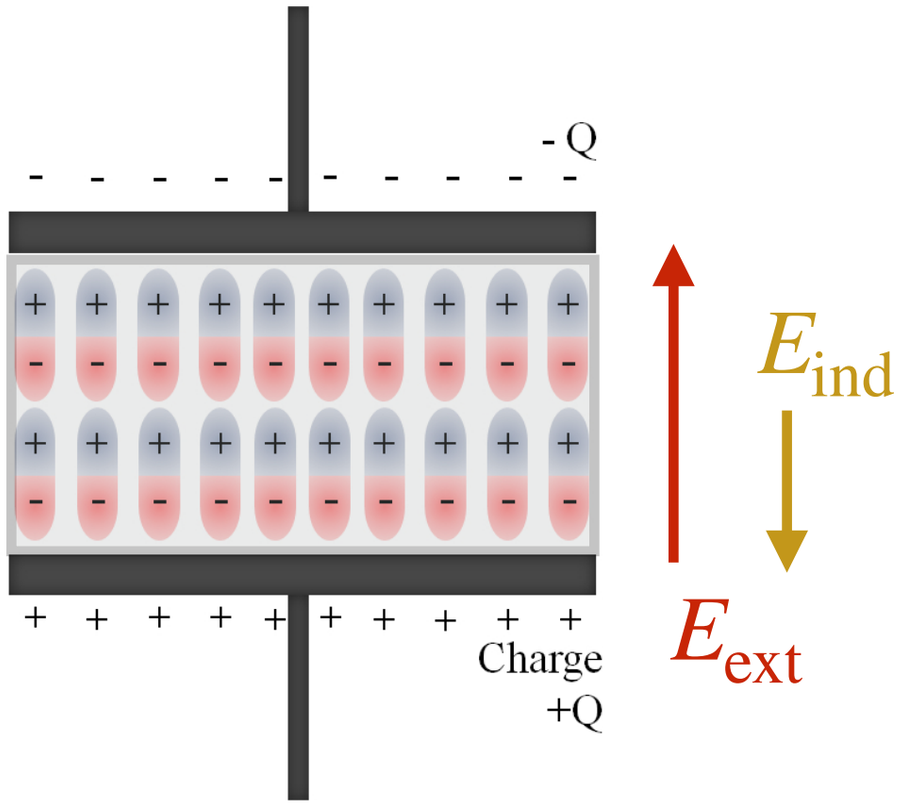
$$\frac{d\sigma}{d^3\mathbf{k}d\omega} \propto \bar{\sigma}_e F_{\rm med}^2(k) \sum_{\ell,\ell'} \sum_{\mathbf{p},\mathbf{p}'} |\langle \mathbf{p}', \ell' | e^{i\mathbf{k}\cdot\mathbf{r}} | \mathbf{p}, \ell \rangle|^2$$
$$\times f^0(\omega_{\mathbf{p},\ell})\left(1 - f^0(\omega_{\mathbf{p}',\ell'})\right)\ \delta(\omega + \omega_{\mathbf{p},\ell} - \omega_{\mathbf{p}',\ell'})$$

Sum over occupied bands ℓ and Bloch momentum $\mathbf{p}$ to excited state $|\mathbf{p}', \ell'\rangle$

Complication: many body effects are important!

Essig, Mardon, Volansky 2011;
Essig, Fernandez-Serra, Mardon, Soto, Volansky, Yu 2015

Energy loss function (ELF)



$$\nabla \cdot \mathbf{E} = \frac{4\pi \rho_{\text{ext}}}{\epsilon} \qquad \mathbf{E} = \frac{\mathbf{E}_{\text{ext}}}{\epsilon}$$

More generally:

$$\mathbf{E}(\omega, \mathbf{k}) = \frac{\mathbf{E}_{\text{ext}}(\omega, \mathbf{k})}{\epsilon(\omega, \mathbf{k})}$$

Amount of screening is related to induced charge:

$$\frac{1}{\epsilon(\omega, \mathbf{k})} = 1 + \frac{4\pi e^2}{k^2} \chi(\omega, \mathbf{k})$$

Susceptibility, charge density response

Energy loss function (ELF)

$$\frac{1}{\epsilon(\omega, \mathbf{k})} = 1 + \frac{4\pi e^2}{k^2}\chi(\omega, \mathbf{k})$$

External probe that couples to charge density:

$$S(\omega, \mathbf{k}) \propto \underbrace{2\,\mathrm{Im}\left(-\chi(\omega, \mathbf{k})\right)}_{\text{Dissipation}} = \frac{k^2}{2\pi\alpha_{em}} \underbrace{\mathrm{Im}\left(\frac{-1}{\epsilon(\omega, \mathbf{k})}\right)}_{\text{ELF}}$$

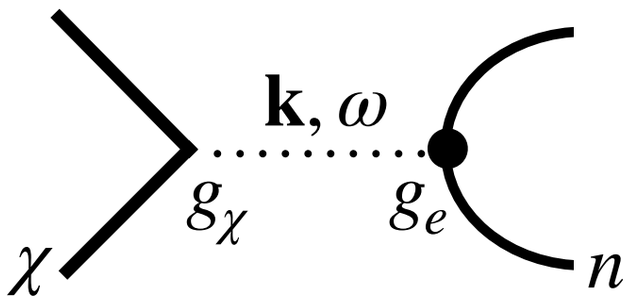
DM-electron scattering rate is determined by ELF:

$$\frac{d\sigma}{d^3\mathbf{k}d\omega} \propto \bar{\sigma}_e F_{\mathrm{med}}^2(\mathbf{k})\,\mathrm{Im}\left(\frac{-1}{\epsilon(\omega, \mathbf{k})}\right)$$

Knapen, Kozaczuk, TL 2101.08275, 2104.12786
Hochberg, Kahn, Kurinsky, Lehmann, Yu, and Berggren 2021

ELF for Dark Matter

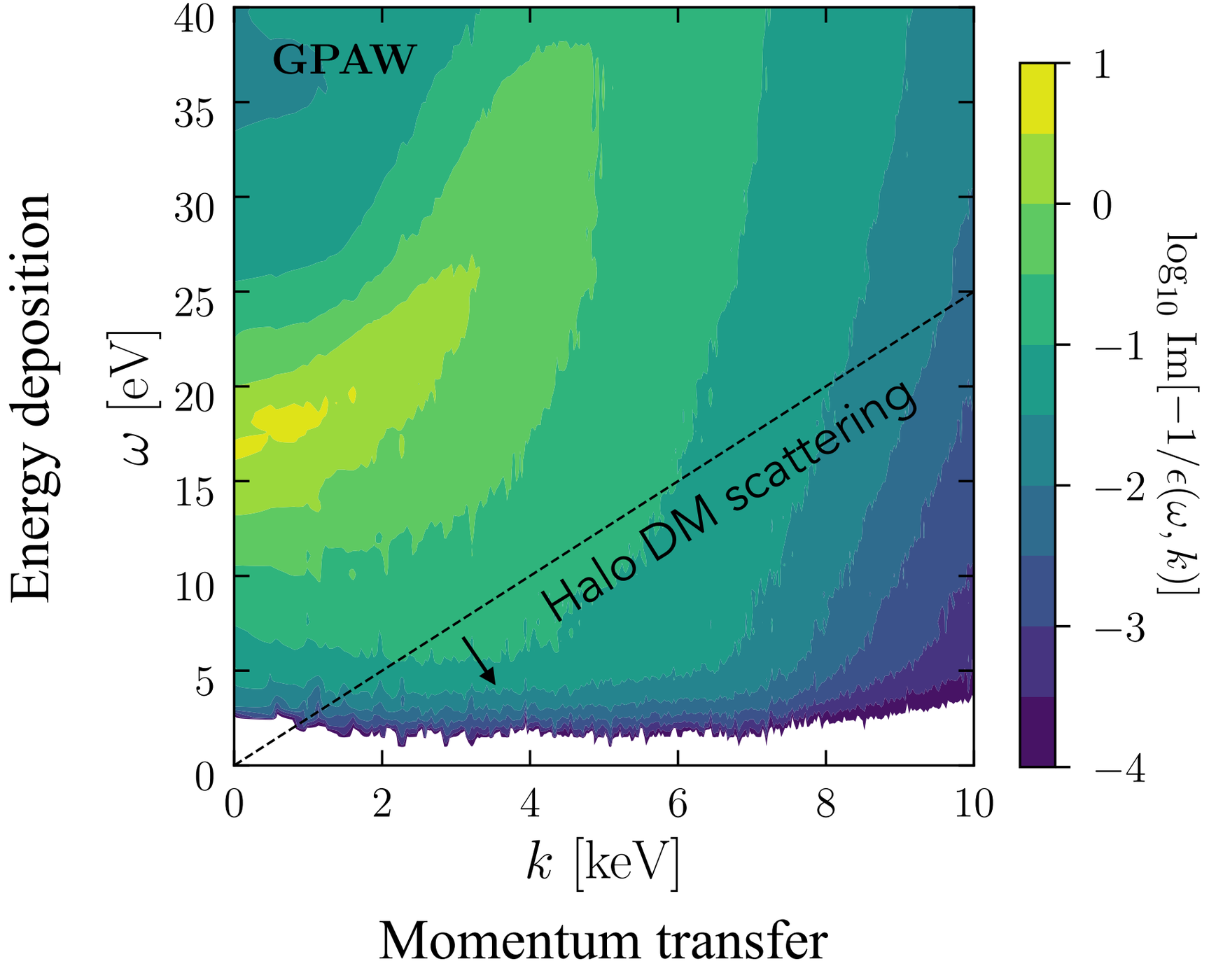
DM-electron scattering



$$\frac{d\sigma}{d^3\mathbf{k}d\omega} \propto \bar{\sigma}_e F_{\rm med}^2(\mathbf{k})\,{\rm Im}\left(\frac{-1}{\epsilon(\omega,\mathbf{k})}\right)$$

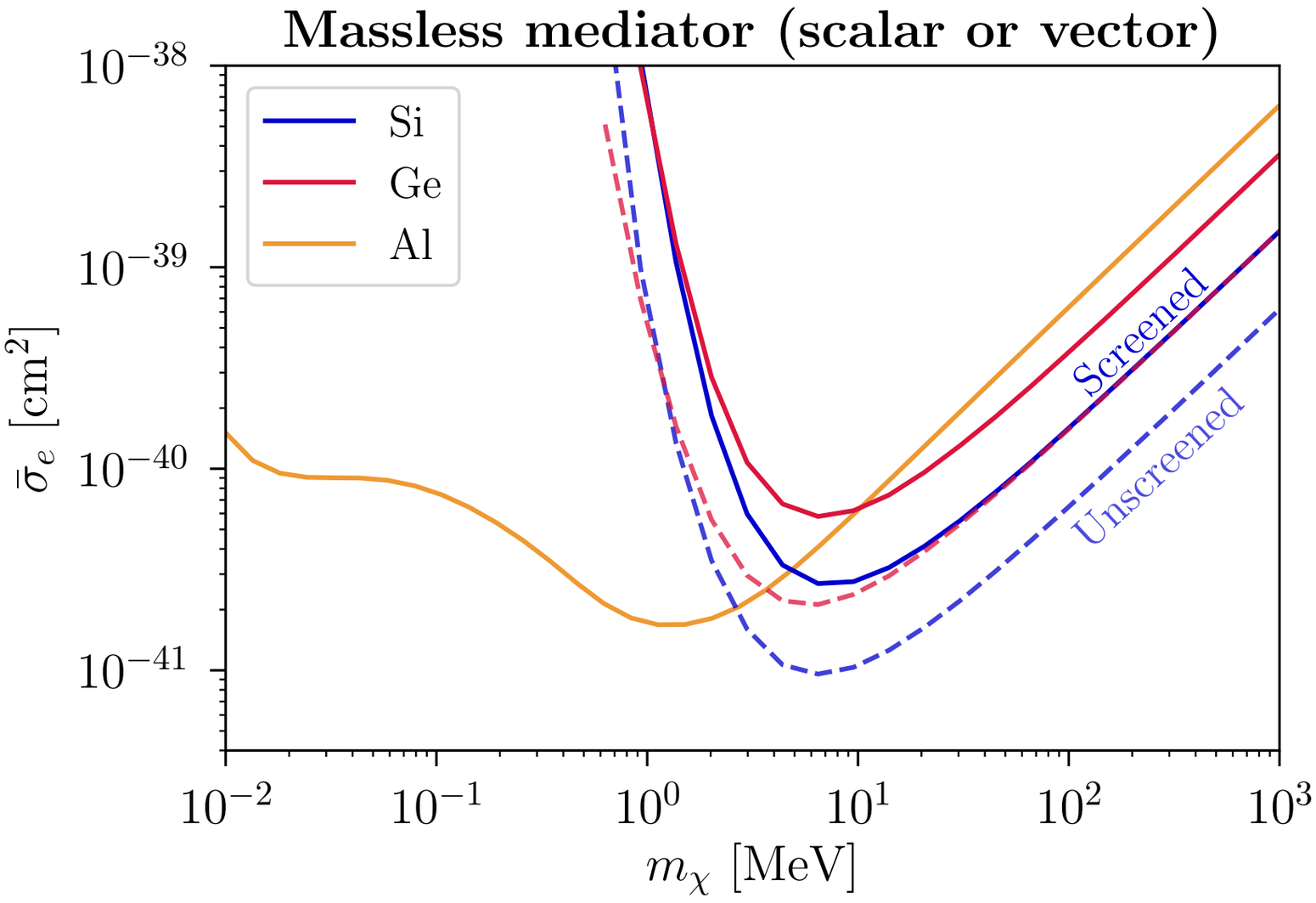
- Packages details of material in one function
- Includes additional screening effects not captured in original approach (impact on rates)
- Describes response to SM probes — many existing materials science approaches to calculating or calibrating the ELF

Response of Silicon semiconductor to electron interactions



Impact for DM-electron scattering

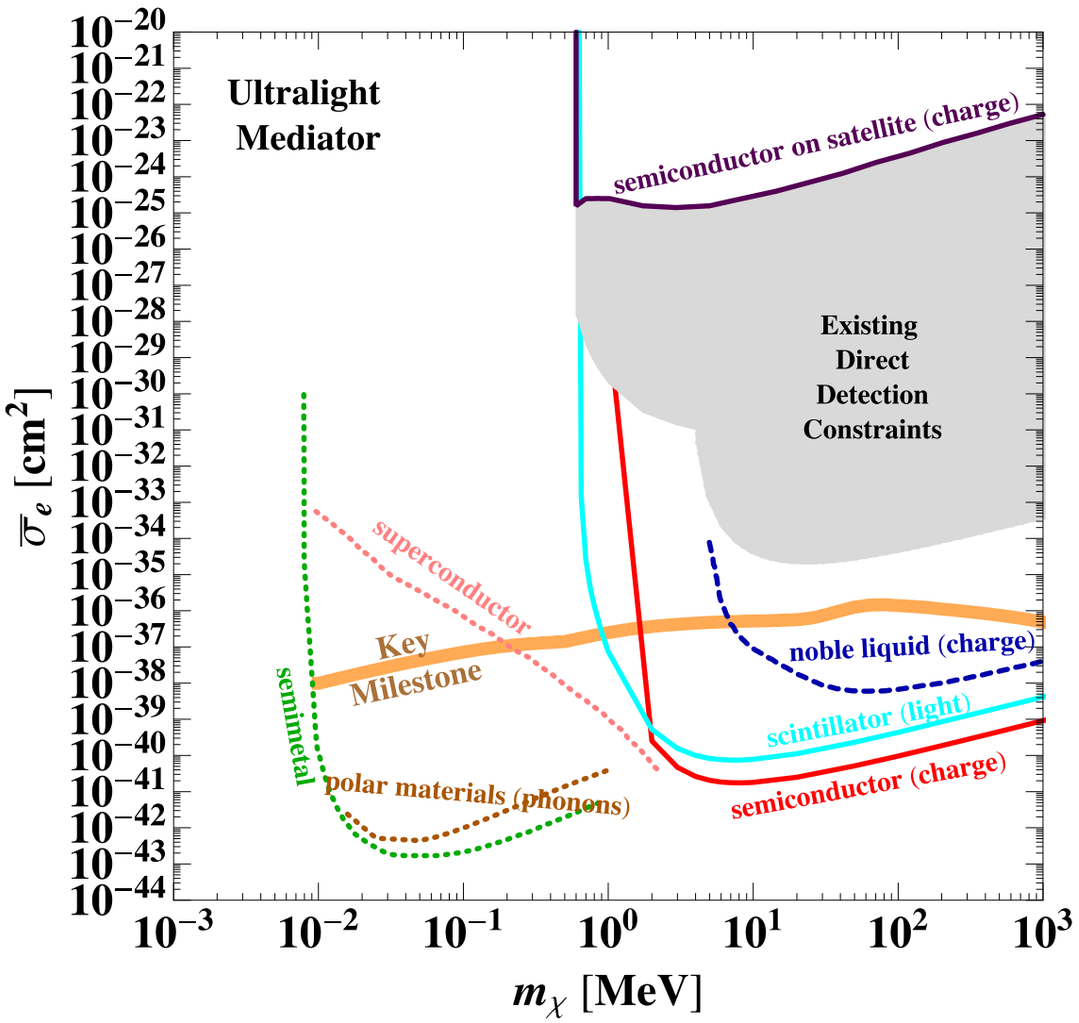
Using the ELF automatically incorporates screening effects:



Knapen, TL, Kozaczuk 2101.08275

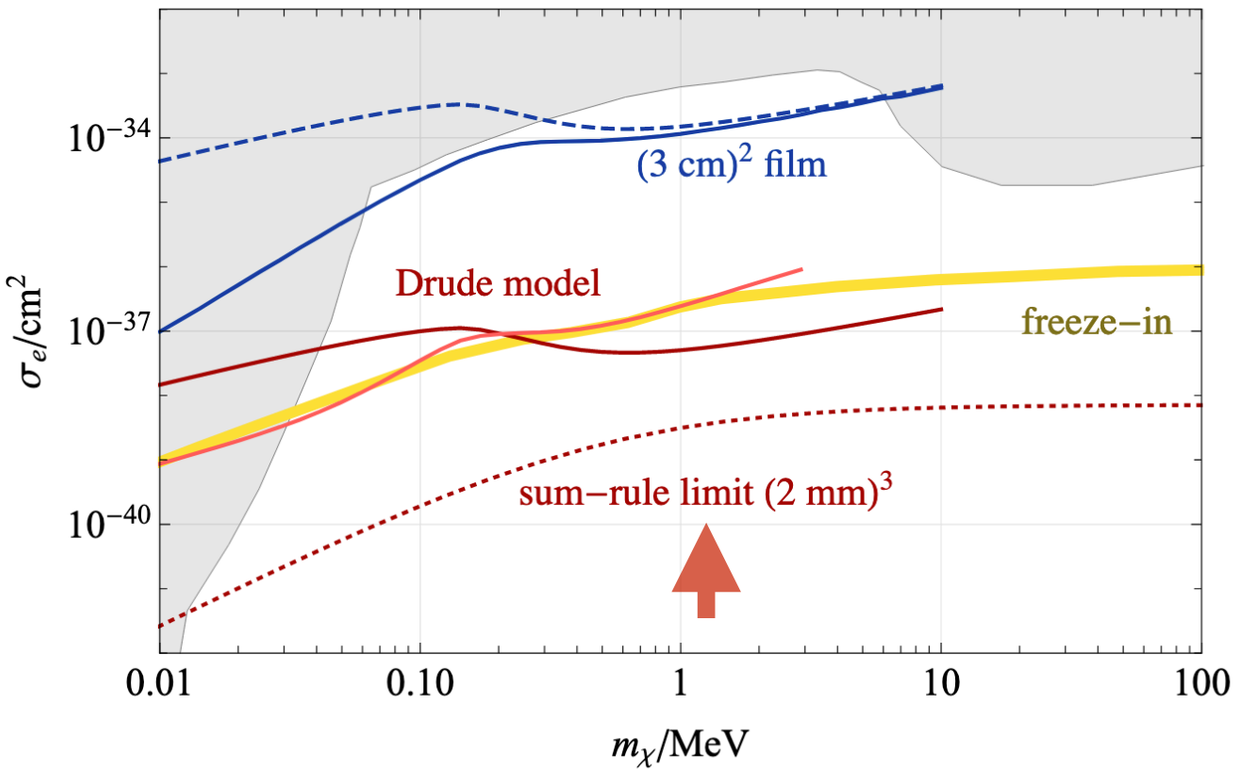
Additional effects of core electrons included in Griffin, Inzani, Trickle, Zhang, Zurek 2105.05253

From Basic Research Needs Report:
"Dark Matter Small Projects New Initiatives"



Many papers studying different targets.

All dielectrics.

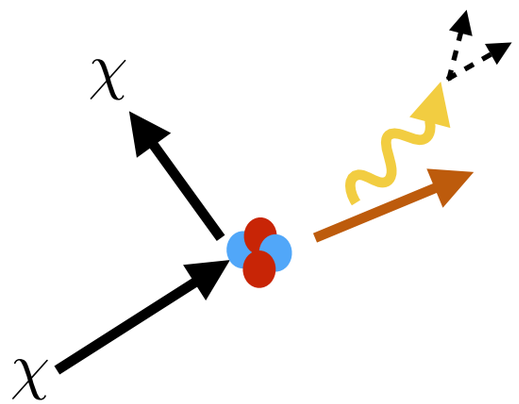


Theoretical constraints on the ELF

Lasenby & Prabhu 2110.01587

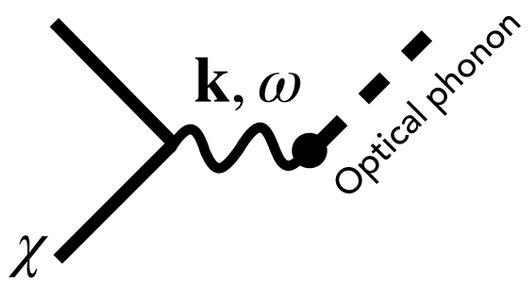
ELF for Dark Matter

DM-nucleus scattering via Migdal effect



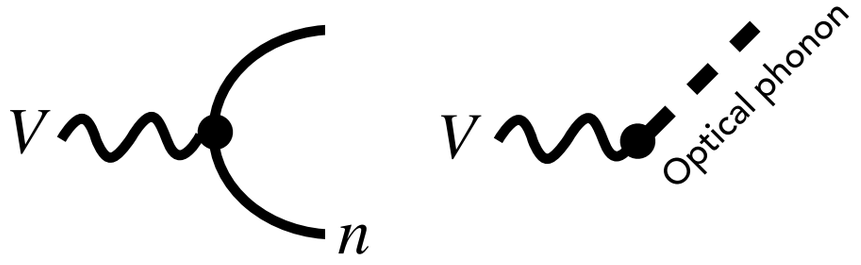
$$\frac{dP}{d^3\mathbf{k}d\omega} \propto \frac{4\pi\alpha_{em}Z_{\rm ion}^2}{\omega^4}\frac{|\mathbf{v_N}\cdot\mathbf{k}|^2}{k^2}\mathrm{Im}\left(\frac{-1}{\epsilon(\omega,\mathbf{k})}\right)$$

DM-phonon scattering



$$\frac{d\sigma}{d^3\mathbf{k}d\omega} \propto \bar{\sigma}_e F_{\rm med}^2(\mathbf{k})\,\mathrm{Im}\left(\frac{-1}{\epsilon(\omega,\mathbf{k})}\right)$$

Bosonic DM absorption



$$R = \frac{1}{\rho_T}\frac{\rho_{\rm DM}}{m_V}\kappa^2 m_V\,\mathrm{Im}\left(\frac{-1}{\epsilon(\omega,\mathbf{k})}\right)$$

DarkELF: python package for dark matter energy loss processes with tabulated ELFs for a variety of materials (incl. Si, Ge, GaAs)
https://github.com/tongylin/DarkELF

Knapen, Kozaczuk, TL 2101.08275, 2104.12786
Knapen Kozaczuk, TL 2003.12077, 2011.09496

Electron recoil experiments

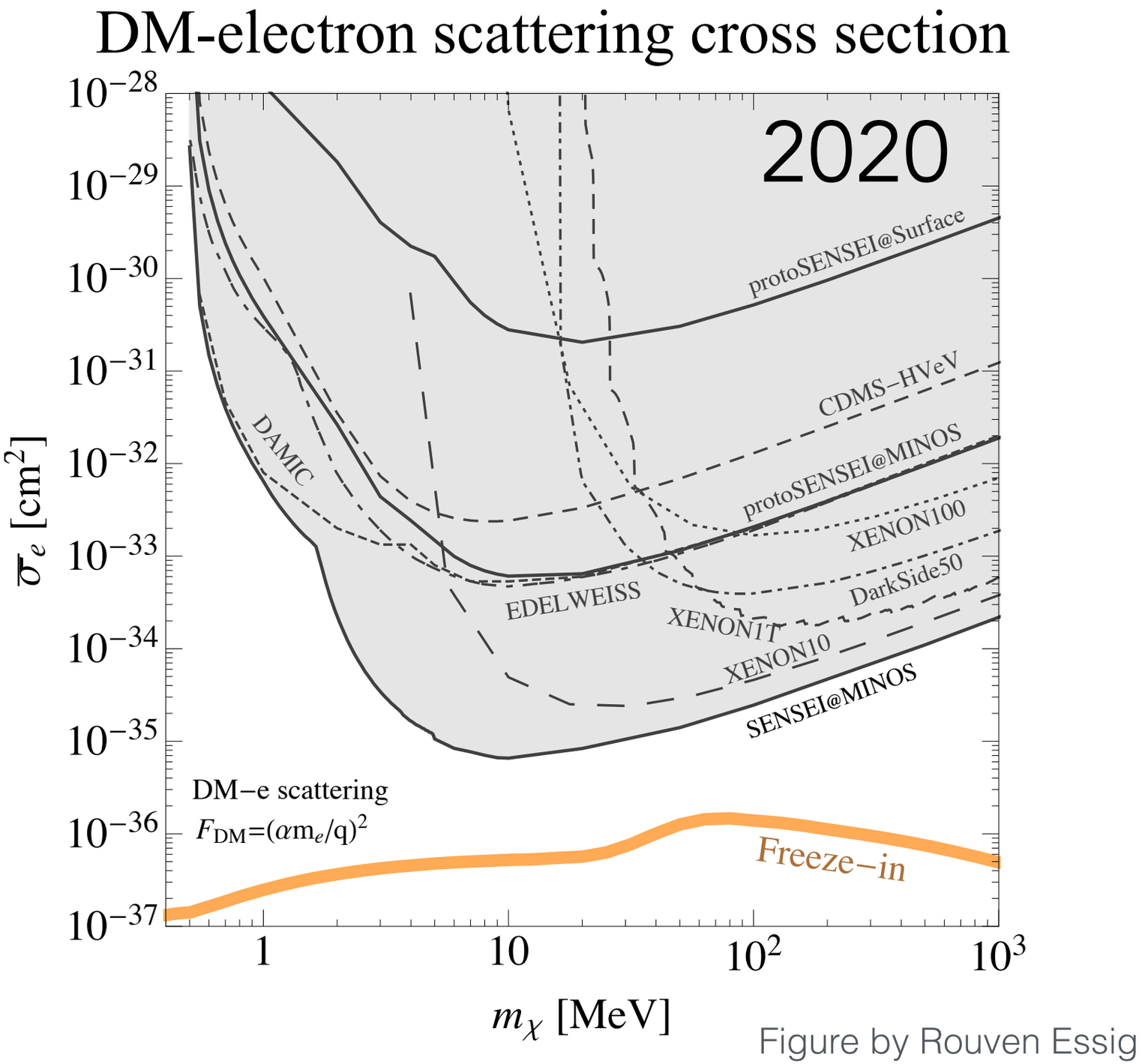


Figure by Rouven Essig

Phonons from sub-GeV DM

DM-nucleus scattering in a crystal

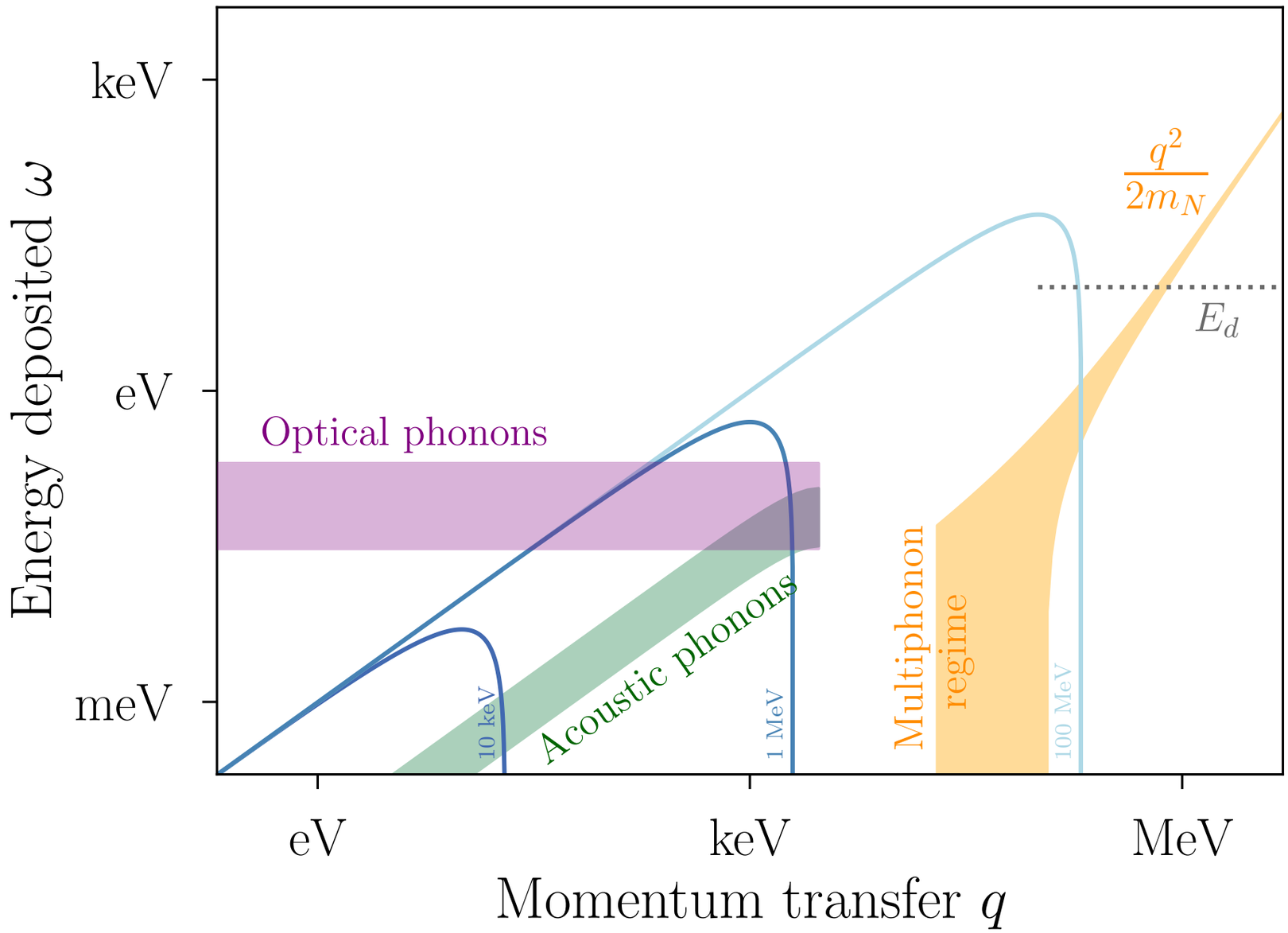
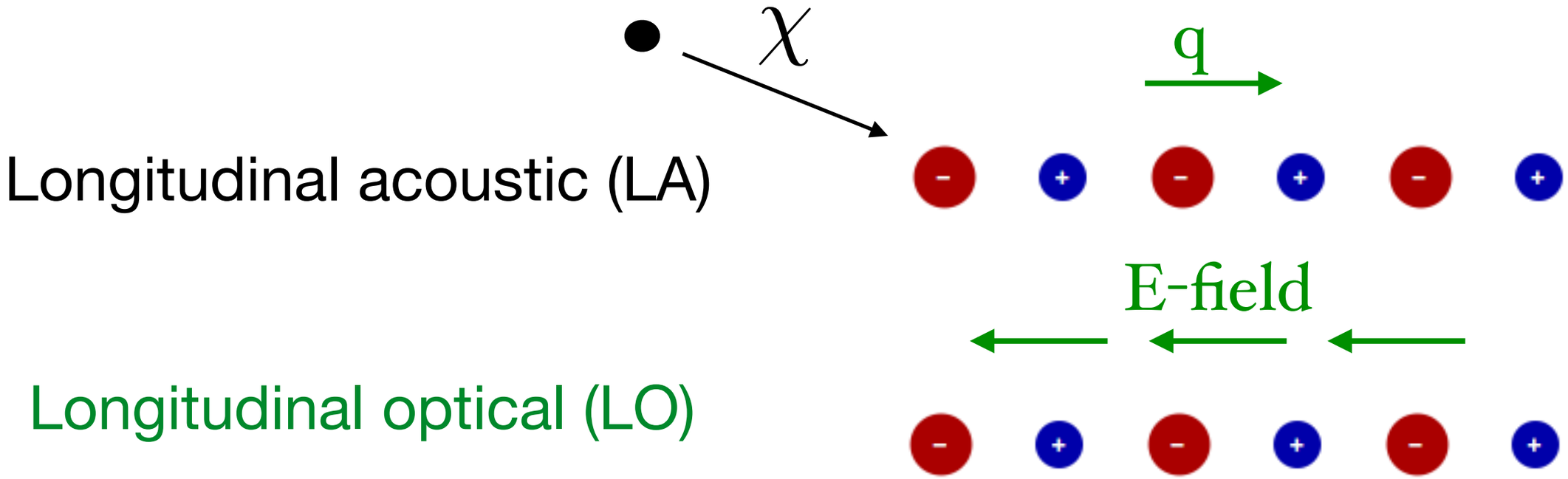


Fig from Kahn, TL 2108.03239
Trickle, Zhang, Zurek, Inzani, Griffin 1910.08092

DM-phonon interactions

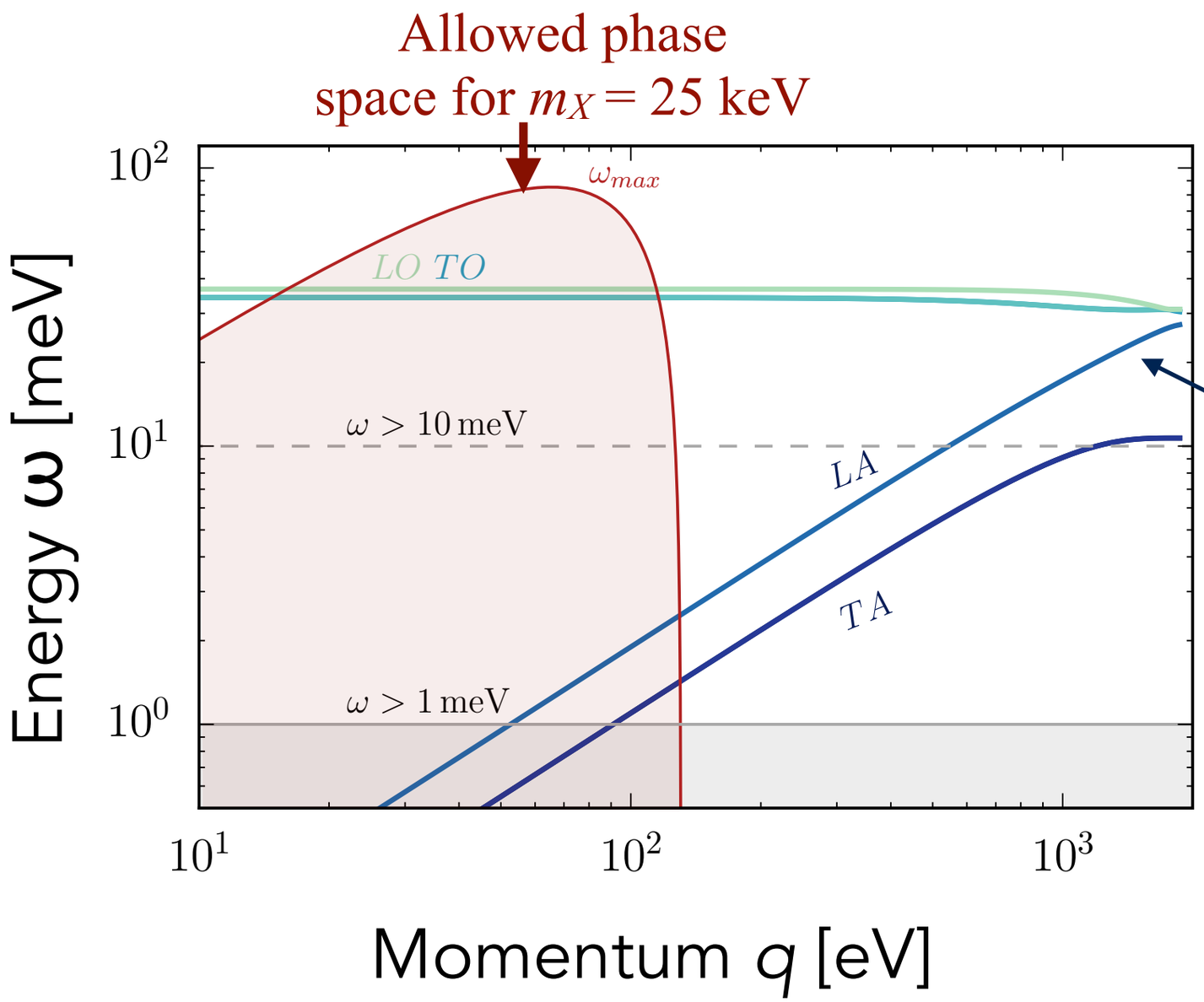


= Oppositely charged ions in crystal

DM that interacts via dark photon mediator excites **optical phonons in polar materials** through a dipole coupling.

DM that interacts via scalar mediator has strongest coupling with **acoustic phonons.**

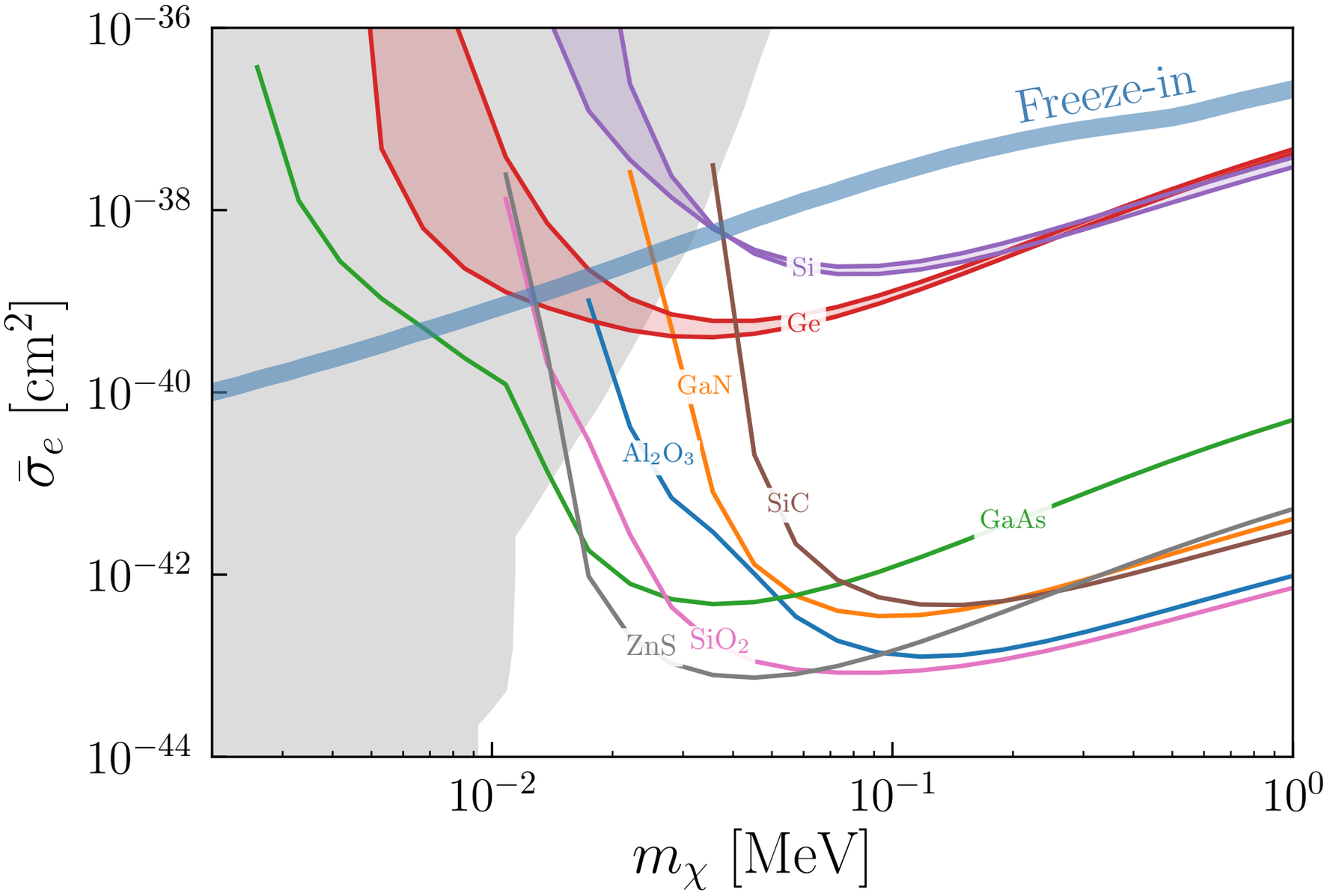
Polar materials such as GaAs are promising



Resonant response of material at single-phonon dispersions (calculated with DFT)

Knapen, TL, Pyle, Zurek 1712.06598
Griffin, Knapen, TL, Zurek 1807.10291

(Idealized) reach of single phonon excitations to DM with dark photon mediator



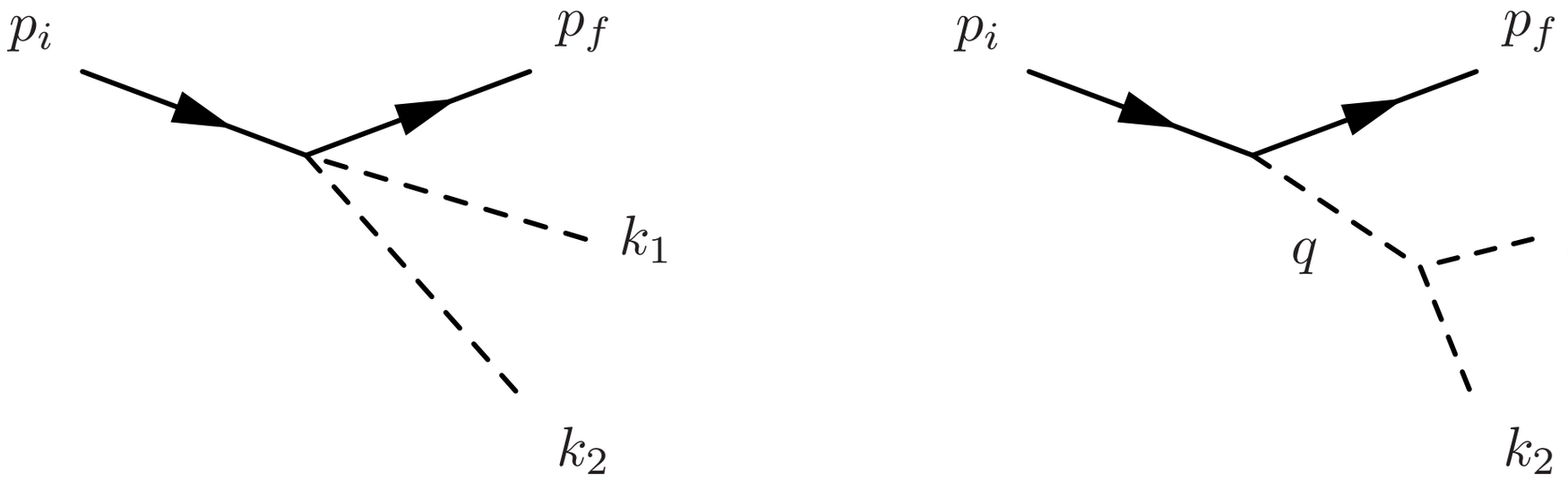
Thermal relic DM by freeze-in

Figure from Knapen, TL, Kozaczuk, 2104.12786
Griffin, Knapen, TL, Zurek 1807.10291;
Griffin, Inzani, Trickle, Zhang, Zurek 1910.10716
Griffin, Hochberg, Inzani, Kurinsky, TL, Yu 2020
Coskuner, Tickle, Zhang, Zurek 2102.09567

all projections assume kg-yr exposure

Multiphonon regime

With larger energy and momentum transfer, production of more phonons becomes relevant

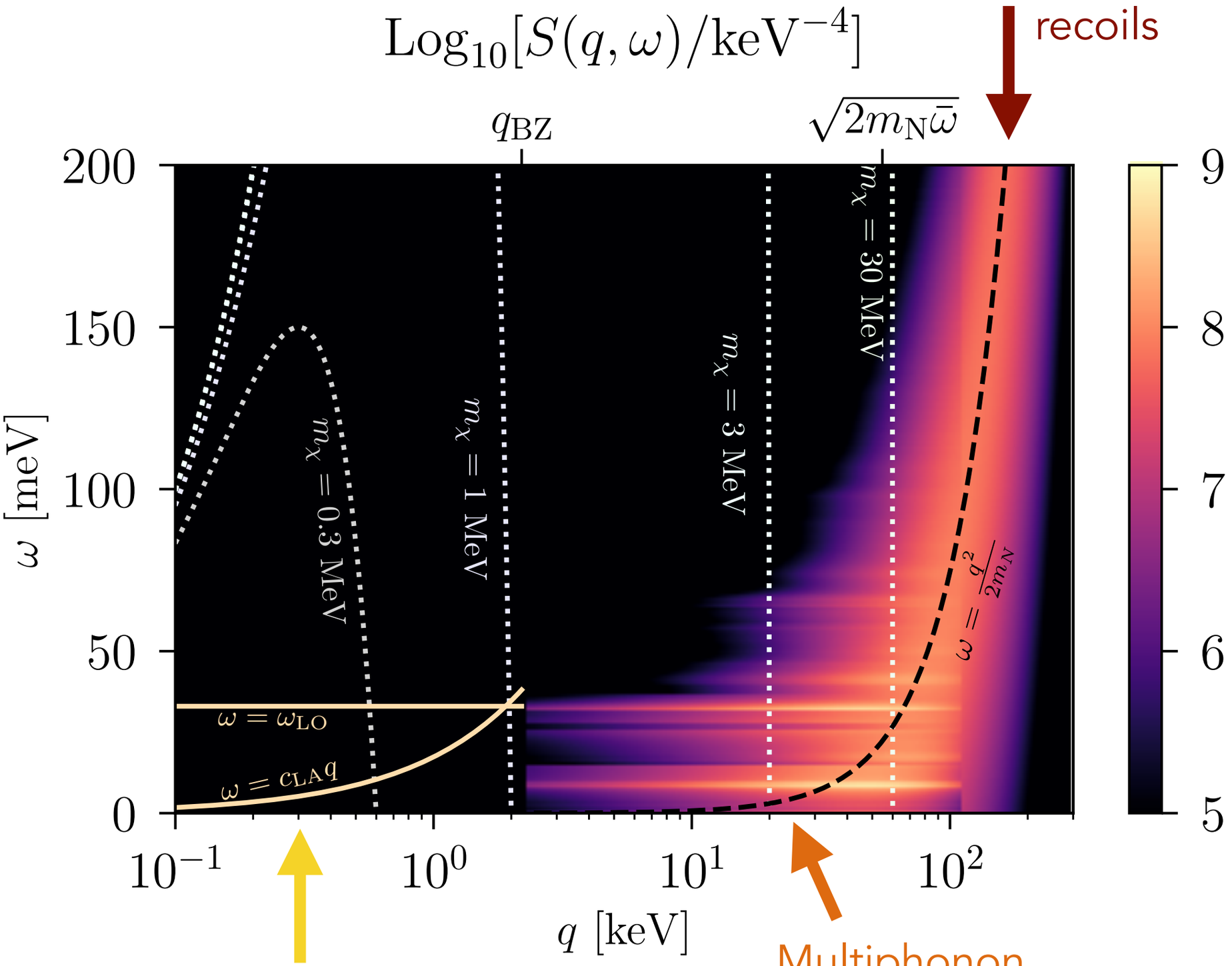


Response function $S(\mathbf{q},\omega) = (\text{0-phonon}) + (\text{1-phonon}) + (\text{2-phonon}) + \cdots$

Expansion in $q^2/(2m_N\omega)$ and in anharmonic phonon interactions

Campbell-Deem, Cox, Knapen, TL, Melia 1911.03482

Response peaked about free nuclear recoils

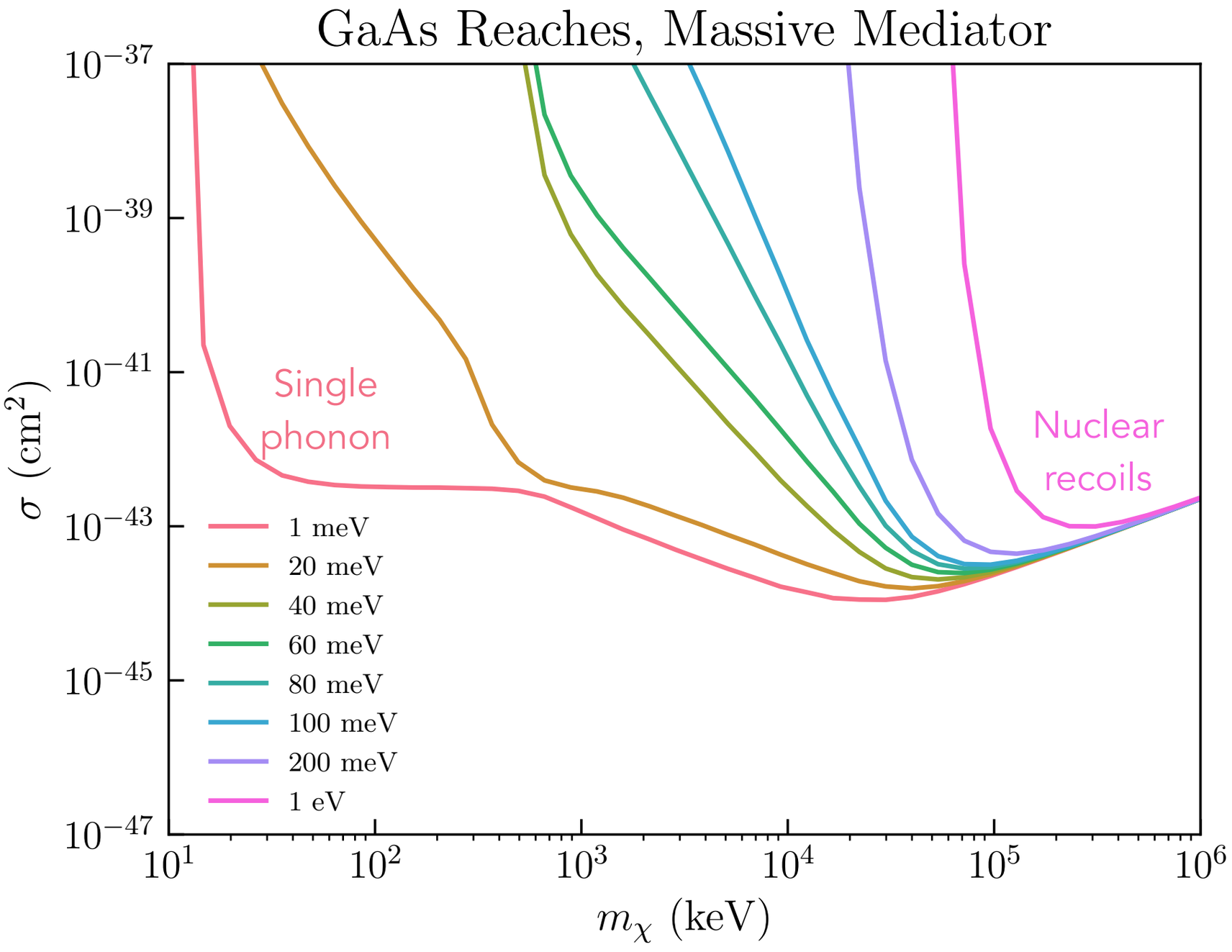


Single phonon, resonant response

Multiphonon response

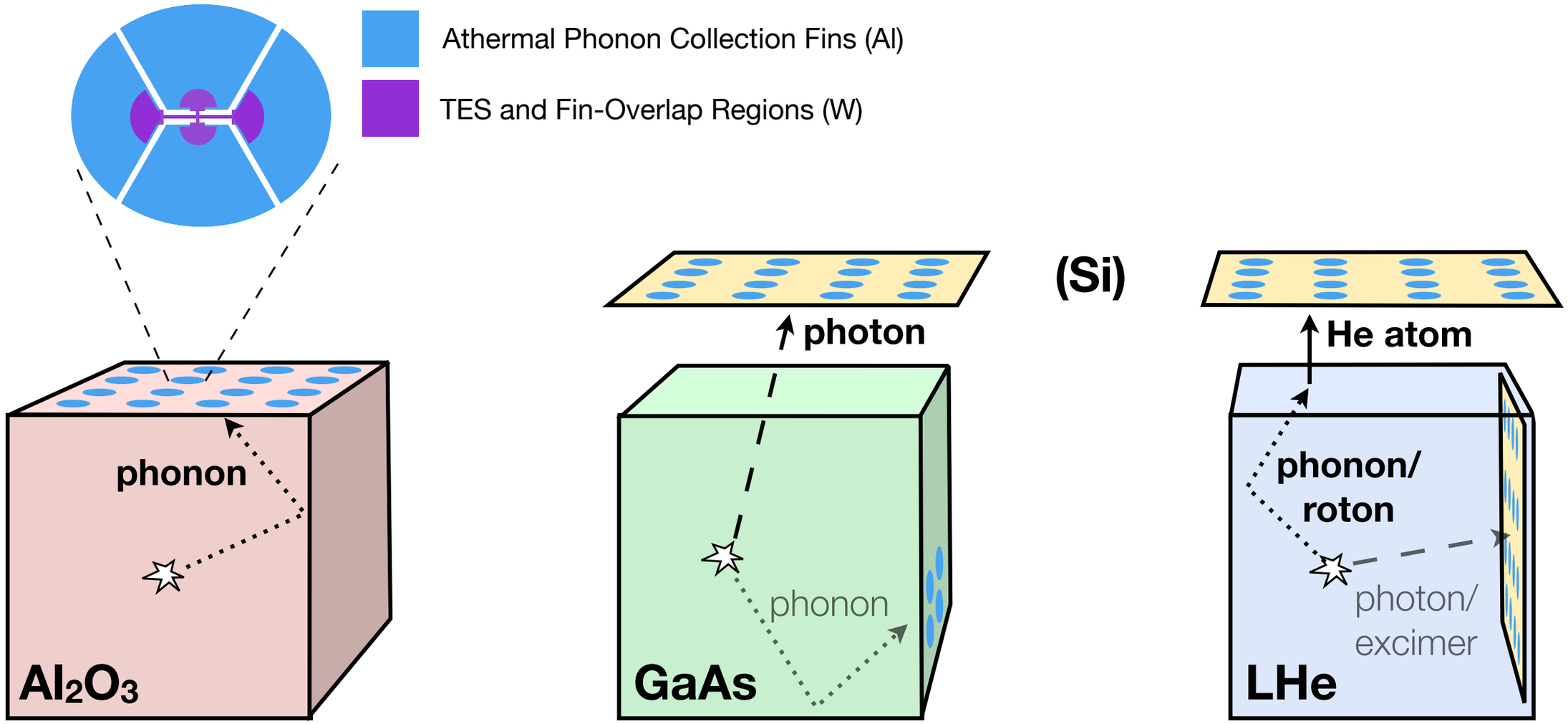
Campbell-Deem, Knapen, TL, Villarama, to appear

From the single phonon regime to free nuclear recoils



Campbell-Deem, Knapen, TL, Villarama, to appear
Kahn, Krnjaic, Mandava 2011.09477

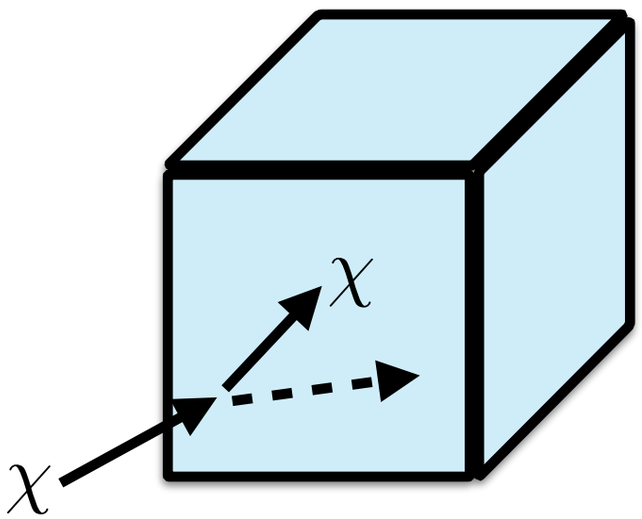
Detection



Phonon detection with SPICE/HeRALD

Direct detection of sub-GeV DM

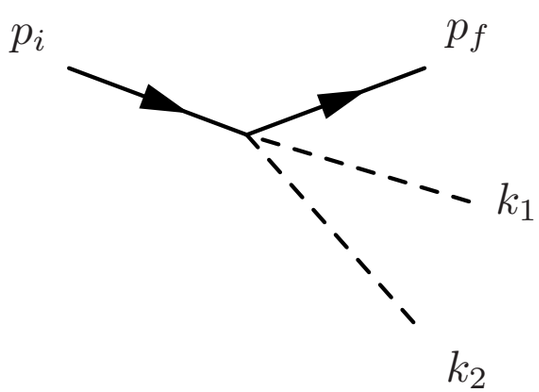
Theory progress in describing primary excitations of DM in condensed matter targets



Bulk target
(~mg-g mass)

$$\mathrm{Im}\left(\frac{-1}{\epsilon(\omega,\mathbf{k})}\right)$$

Energy loss function (ELF) for **DM-electron** interactions



Multi-**phonon** interactions: from single phonon to nuclear recoil regime