Exploring new landscapes in dark matter direct detection

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Bay Area Particle Theory Seminar
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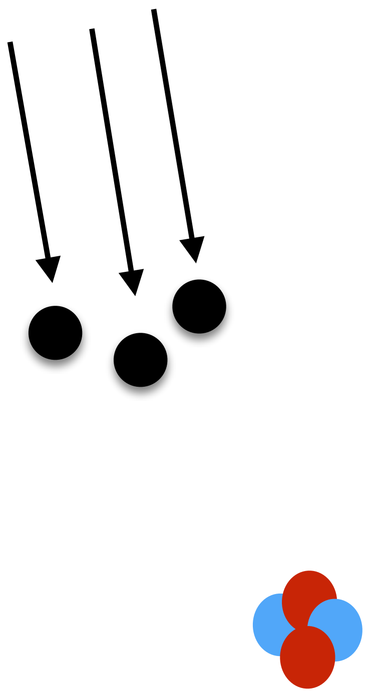
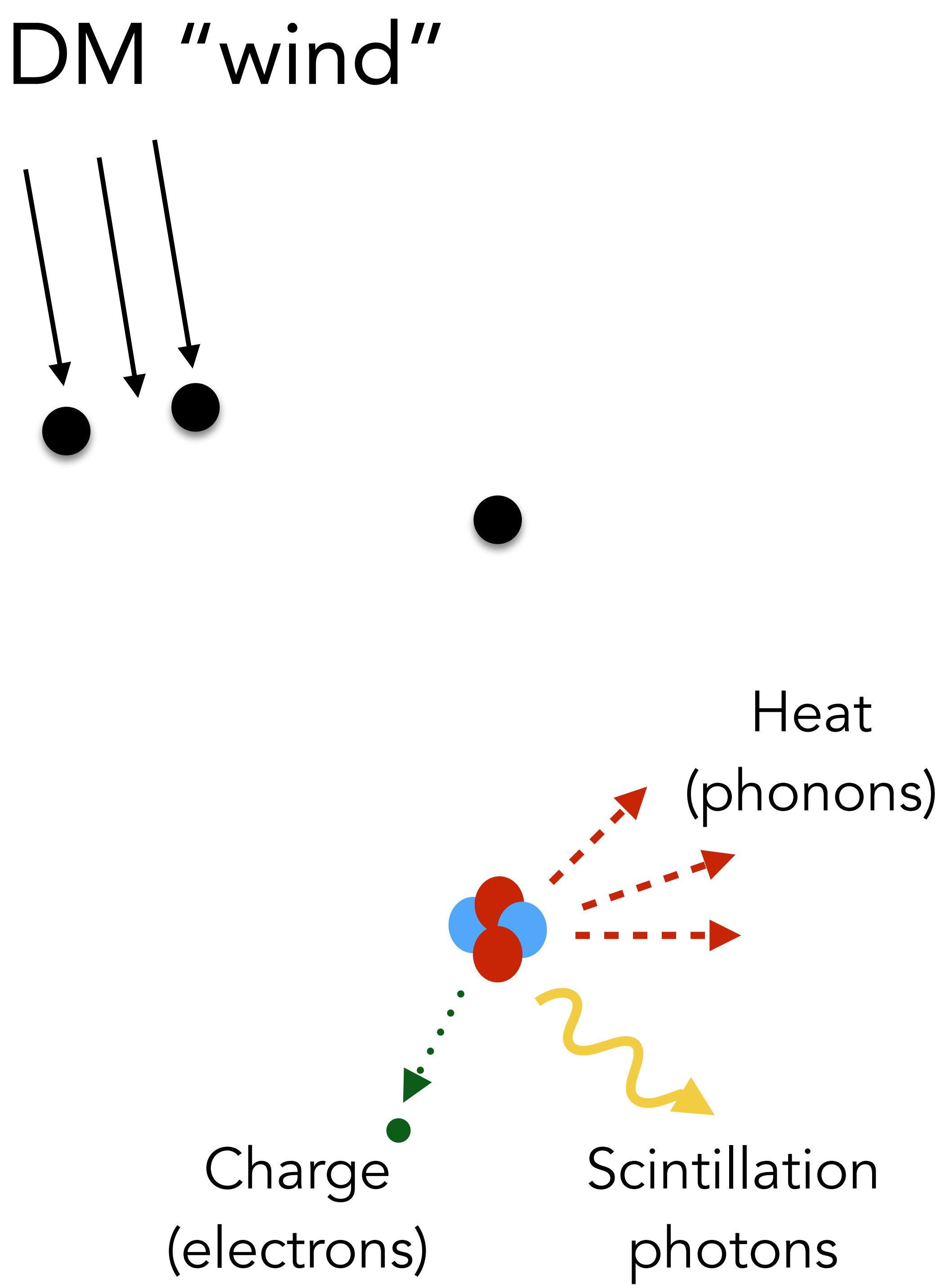
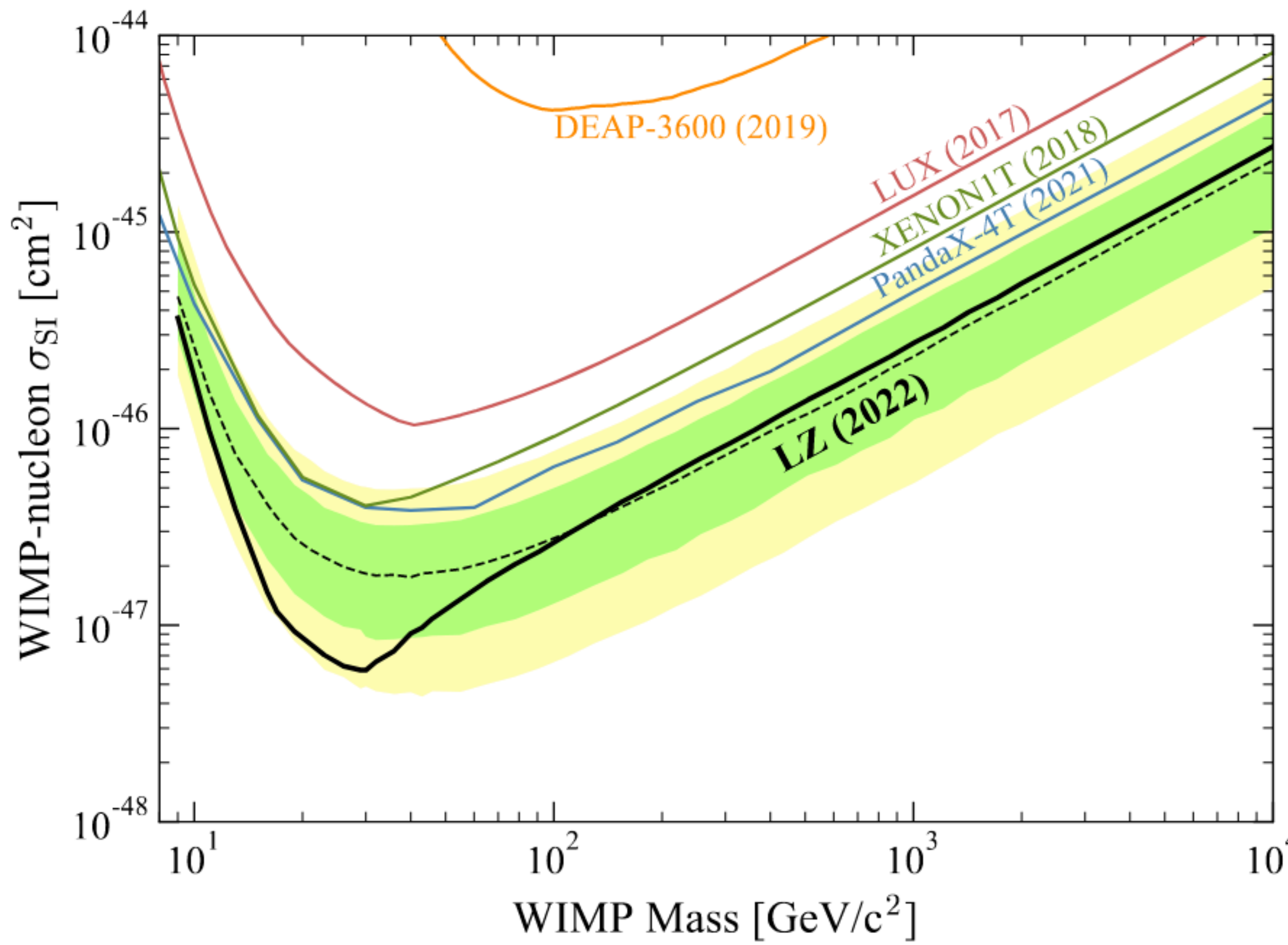
DM “wind”



Direct detection of nuclear recoils



Strong constraints on interaction cross section when DM mass comparable to nucleus mass



(Proton mass = 0.938 GeV)

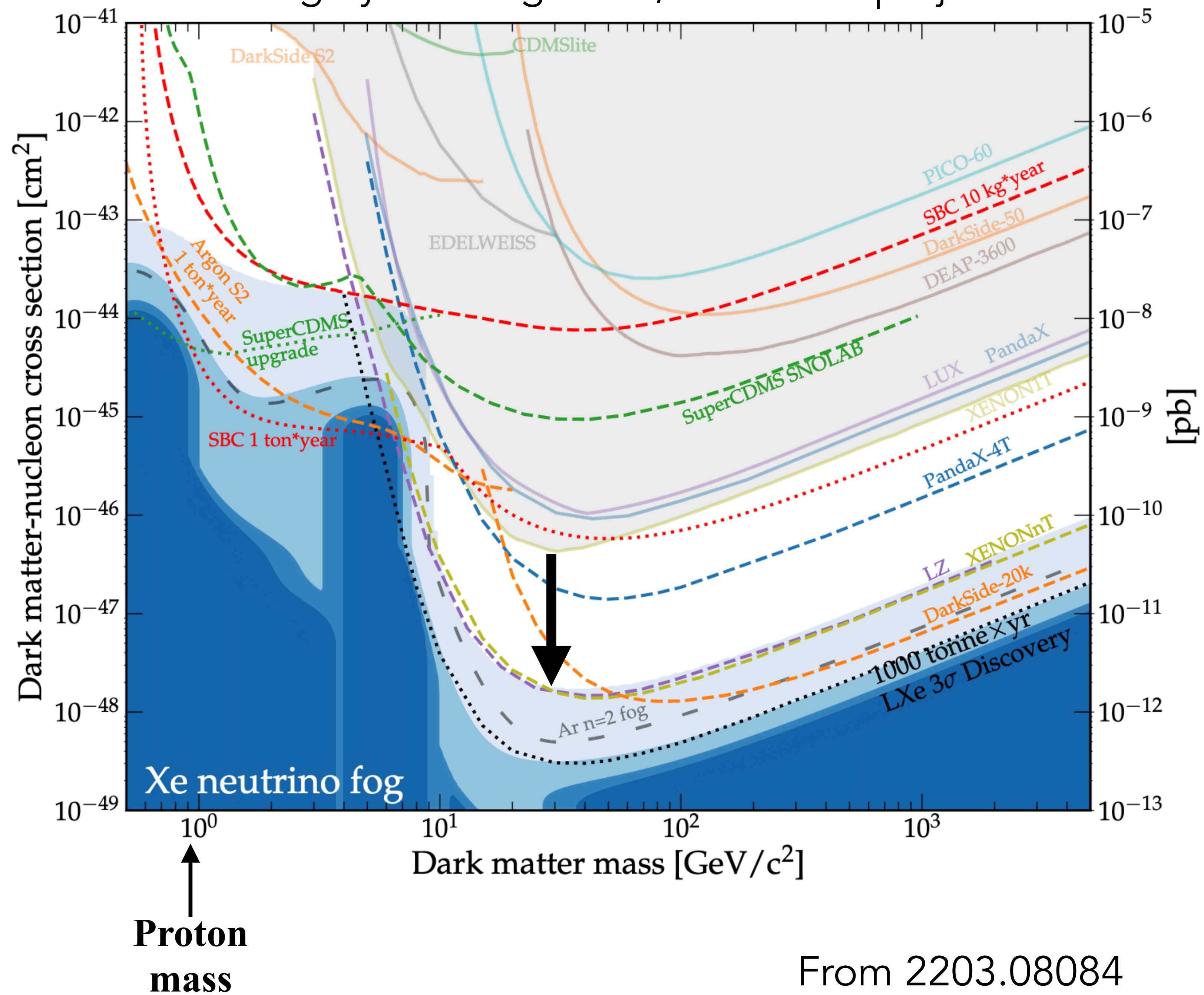
Direct detection of nuclear recoils

Landscape of direct detection above 1 GeV

XENON-nT

Many decades of progress searching for nuclear recoils

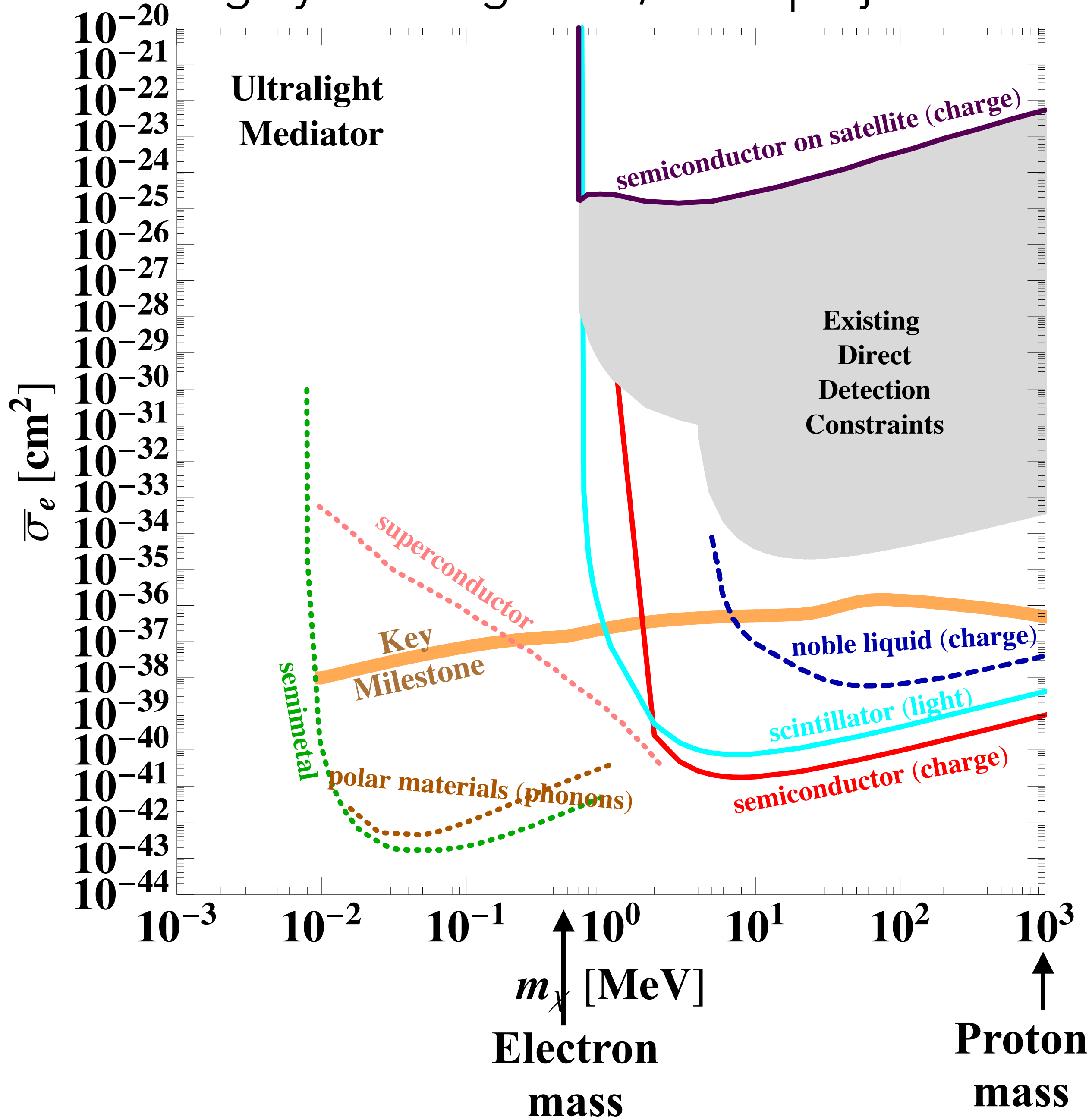
Shaded gray: existing limits; others are projections



From 2203.08084

Landscape of direct detection below 1 GeV

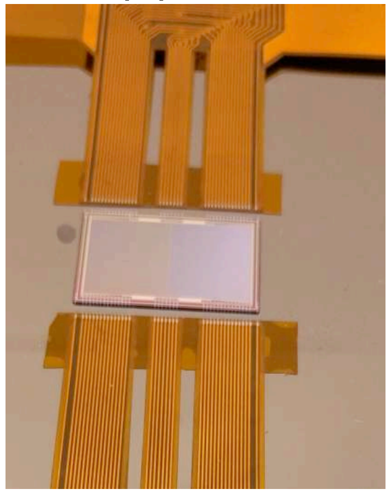
Shaded gray: existing limits; lines: projections

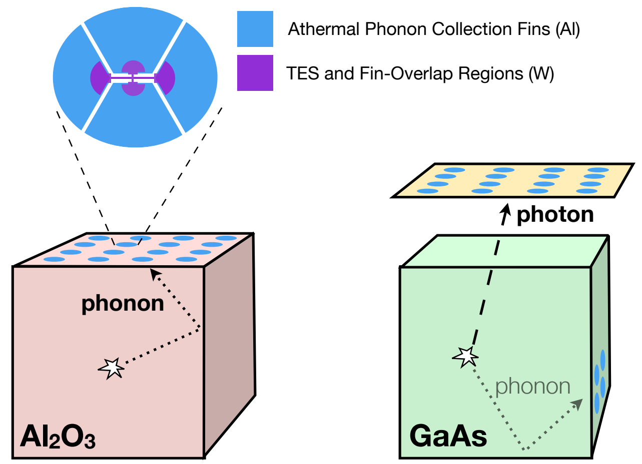


Rapid development in recent decade

- New particle candidates
- New experiments
- **New theory for direct detection**

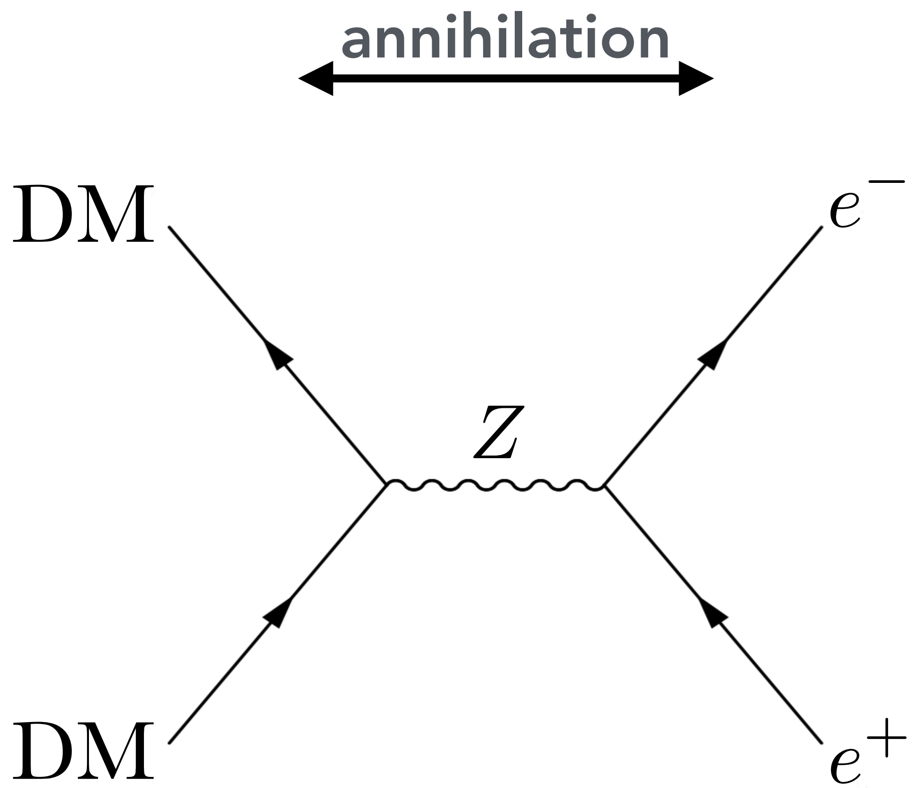
Skipper CCD

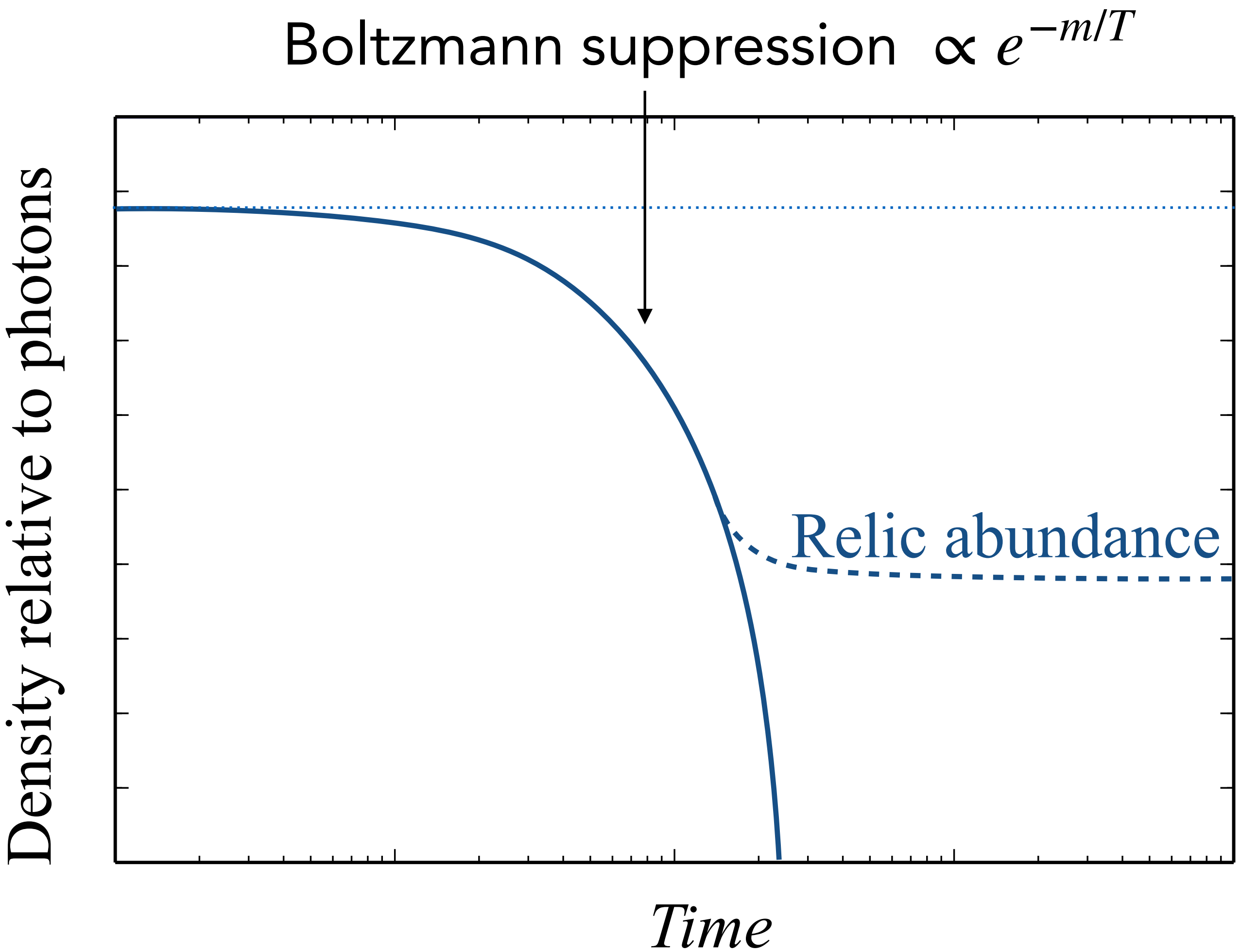




Basic Research Needs Report:
“Dark Matter Small Projects New Initiatives”

Thermal freeze-out

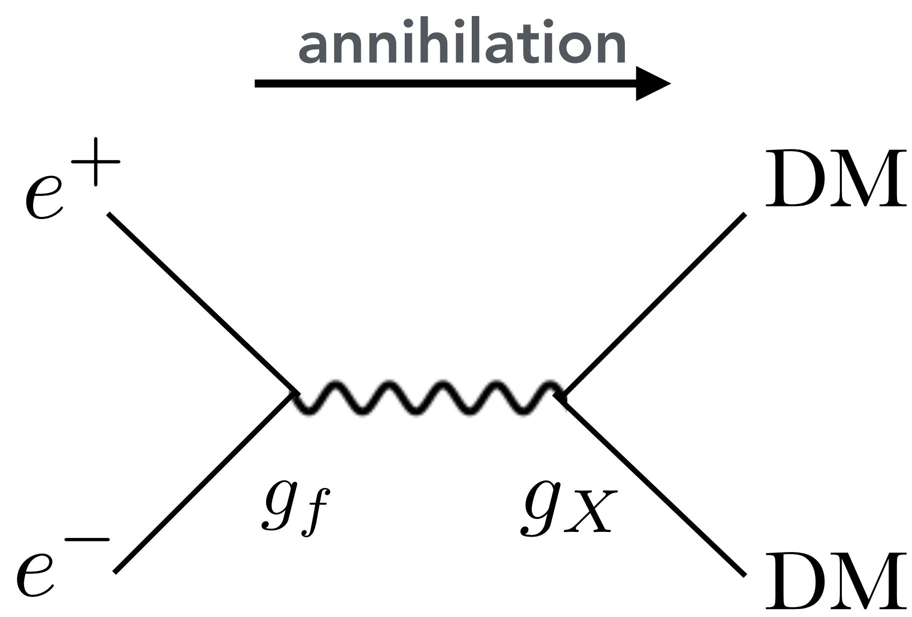




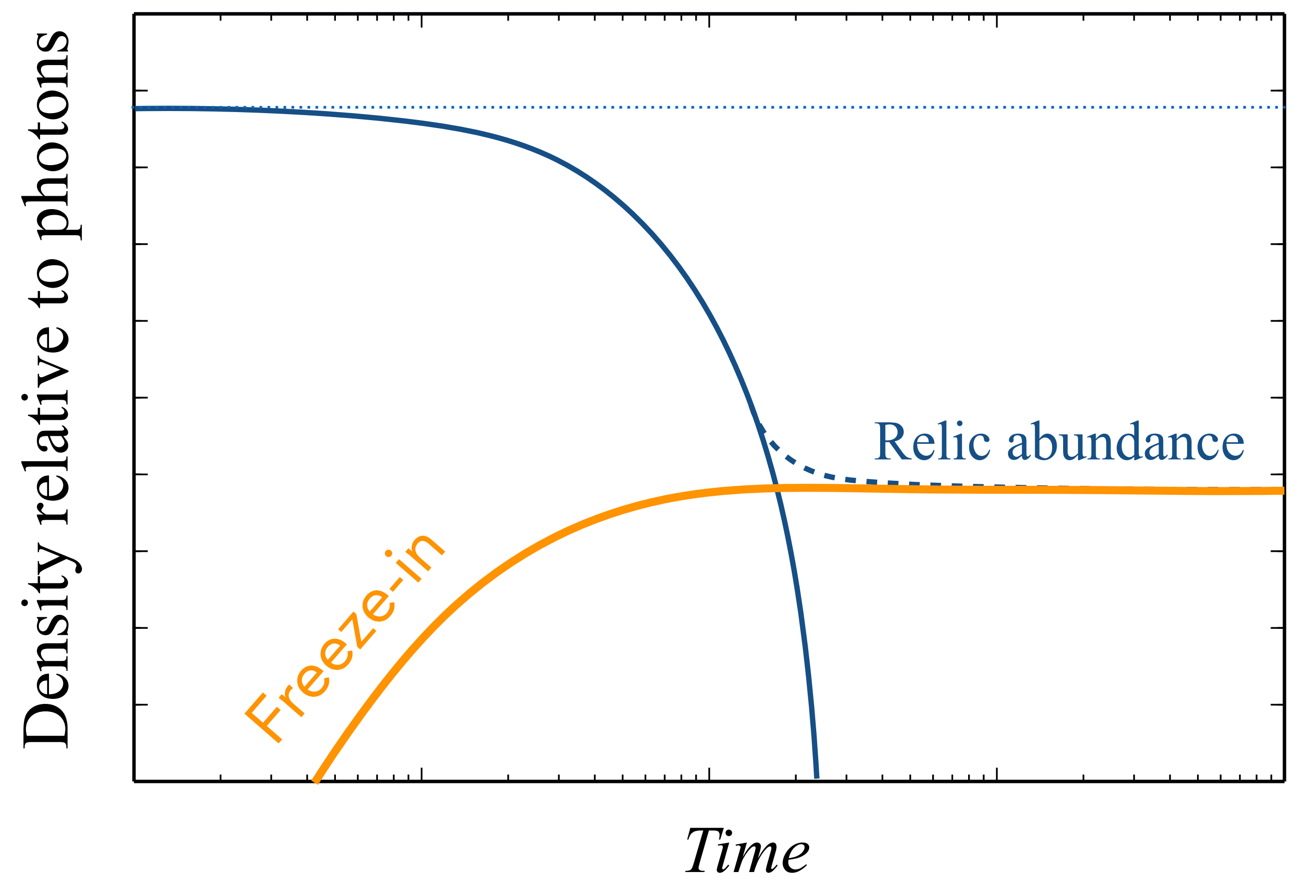
(Part of) the motivation for WIMPs with mass 10-100 GeV

This hypothesis works in a broad mass range of ~MeV up to 100 TeV

Freeze-in



See also: sterile neutrino

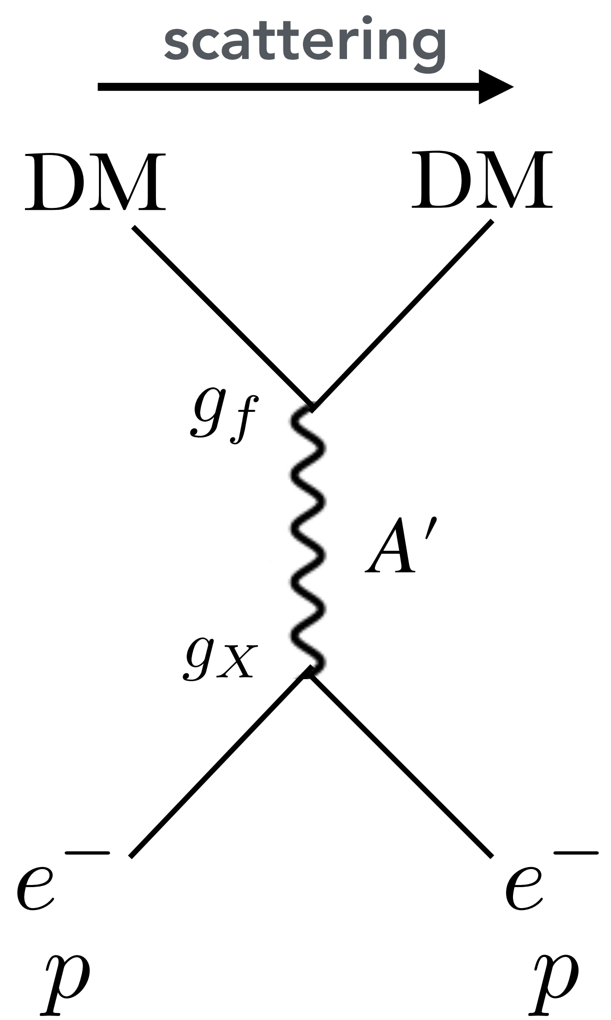


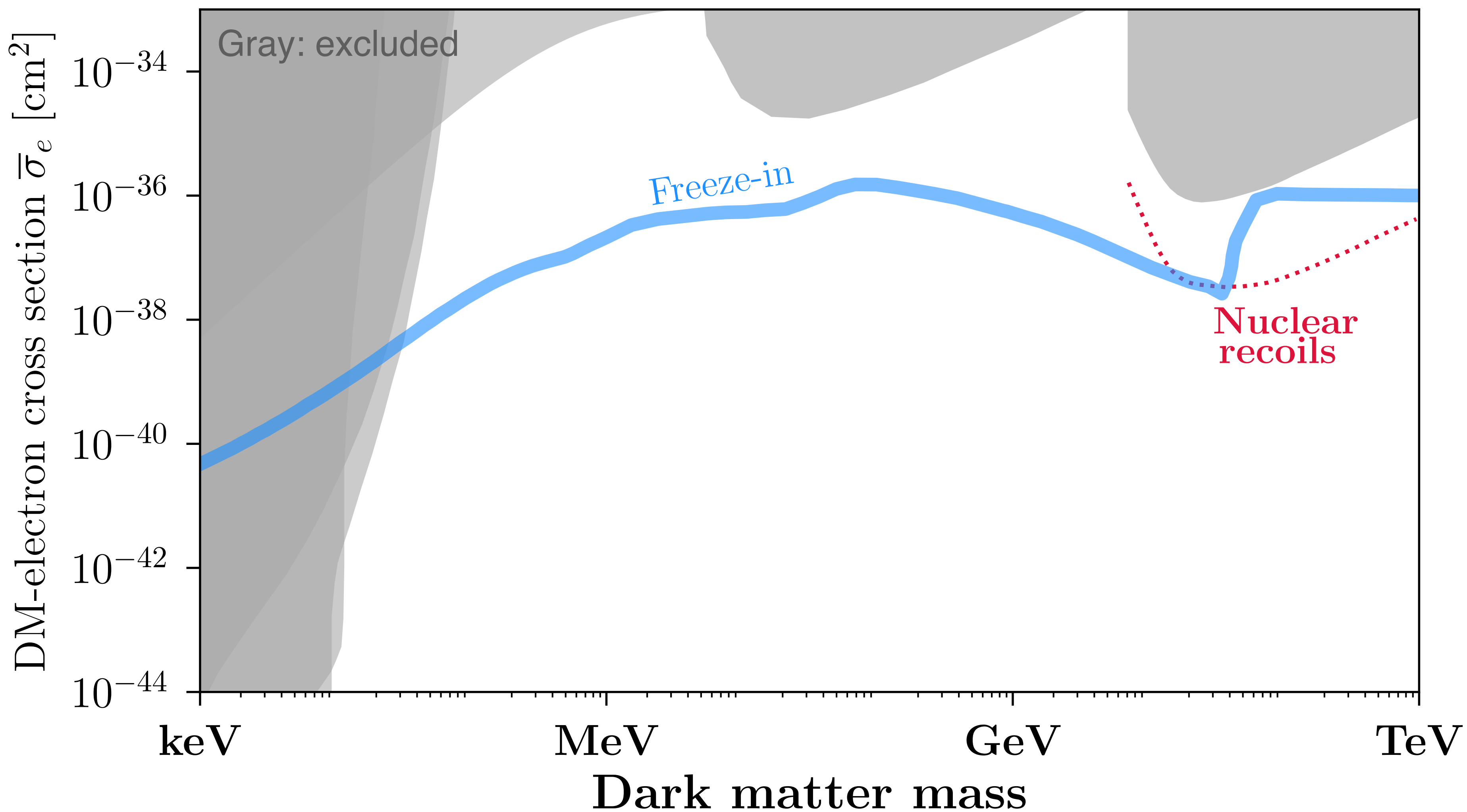
Dark matter populated by out-of-equilibrium annihilations

This also works for a broad mass range down to ~keV

Dodelson and Widrow 1993
Hall et al. 2009
Bernal et al. 2017 (review)

Assumption: A' is a dark photon with equal & opposite coupling to e^-, p



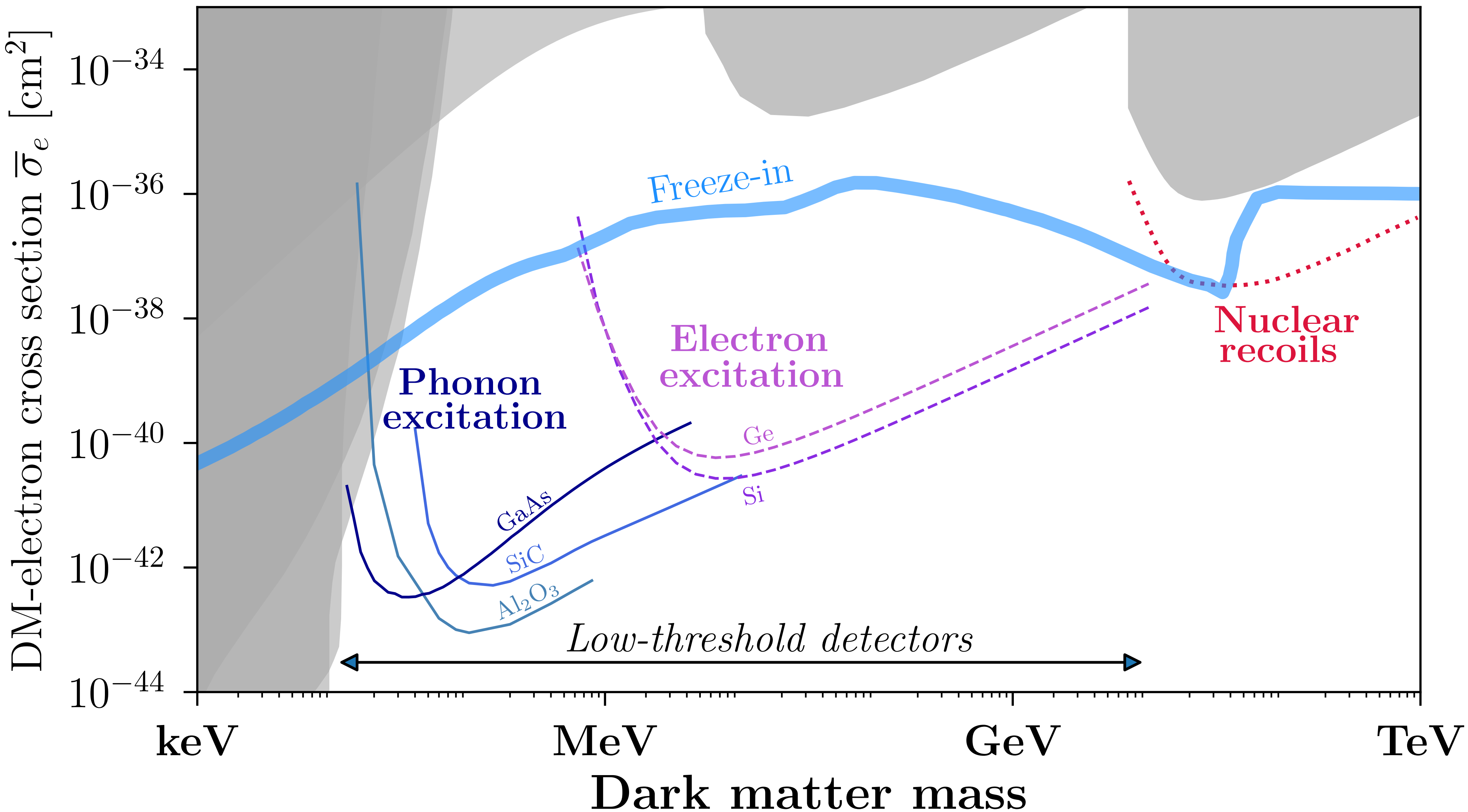


Matching the observed DM density predicts a scattering rate

Dvorkin, TL, Schutz PRD 2019, PRL 2021
Chu, Hambye, Tytgat 2011
Essig, Mardon, Volansky 2011

Why sub-GeV dark matter?

Thermal(ish) dark matter candidates + wide open parameter space that can be probed with small-scale experiments



Small targets can have a large impact

1. Rate goes as 1/mass

$$R \sim \frac{\rho_{\rm DM}}{m_{\rm DM}} \bar{\sigma}_e v \quad \text{with} \;\; \rho_{\rm DM} \approx 0.4\,{\rm GeV/cm^3}$$

2. Kinematic matching with DM scattering

Energy deposited $\omega = \frac{1}{2} m_{\rm DM} v^2 - \frac{(m_{\rm DM}\mathbf{v} - \mathbf{q})^2}{2 m_{\rm DM}}$

$$\omega \leq vq - \frac{q^2}{2 m_{\rm DM}}$$

for a given momentum transfer q and DM velocity $v \approx 10^{-3} c$

DM scattering kinematics

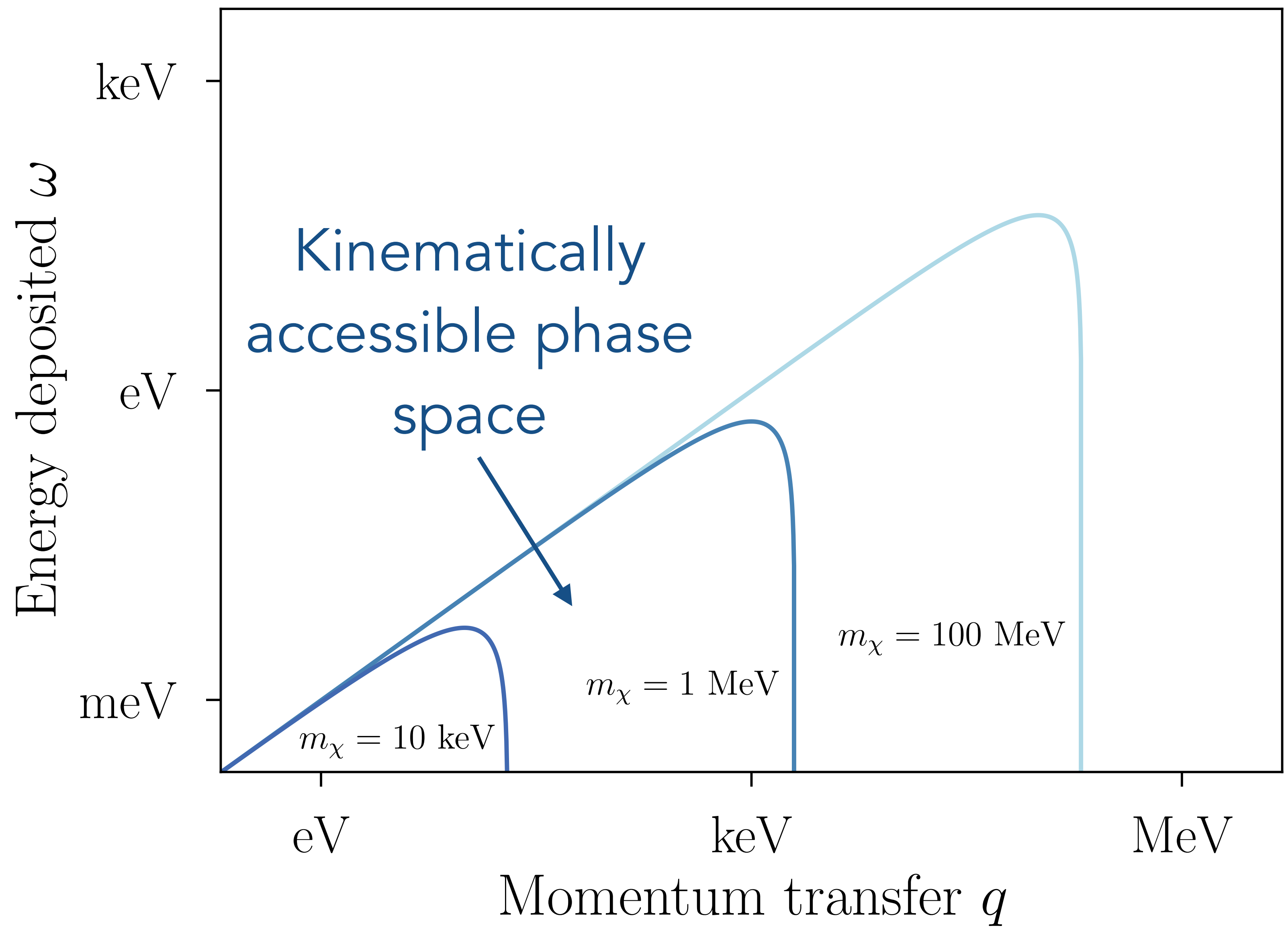
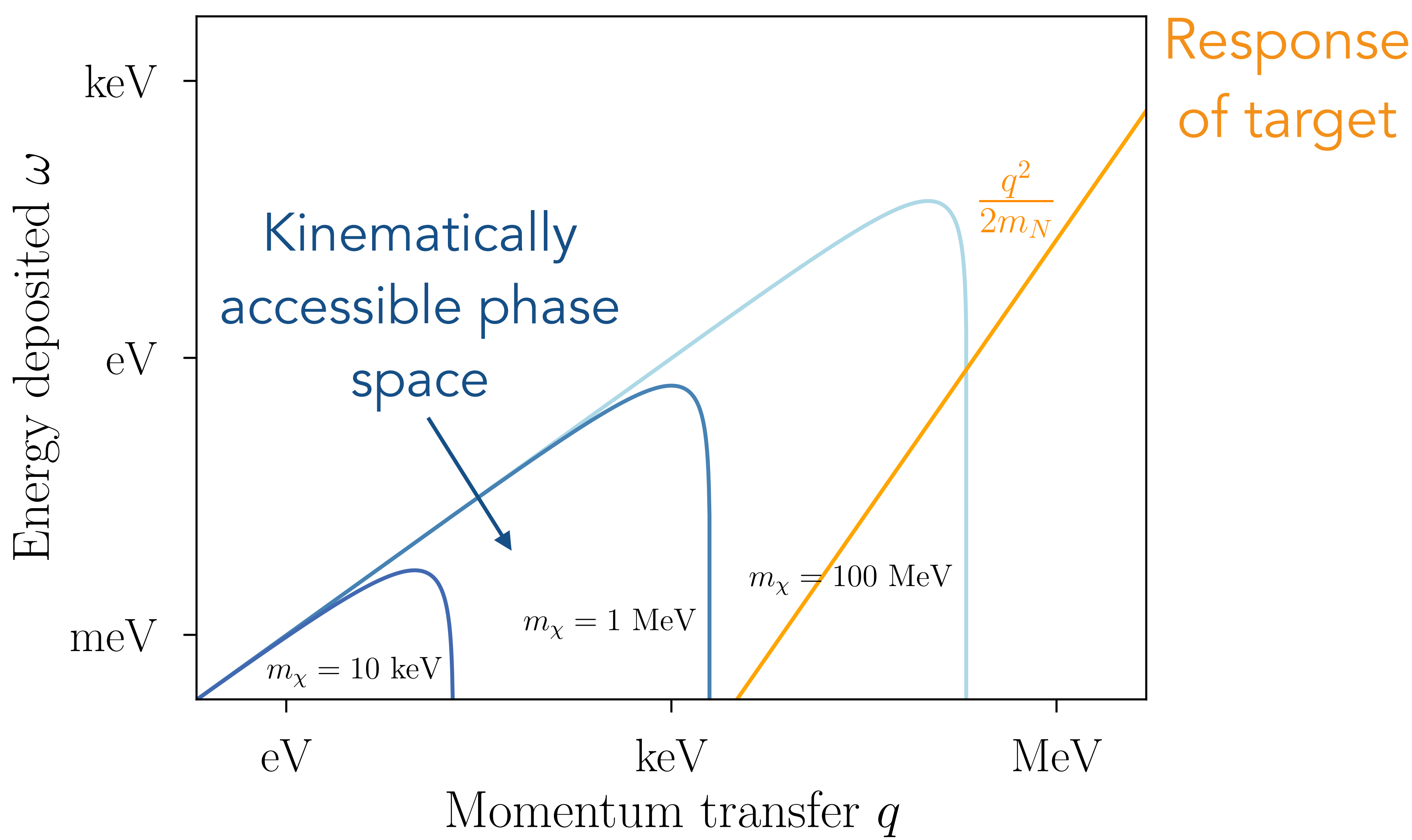


Fig from Kahn, TL 2108.03239
Trickle, Zhang, Zurek, Inzani, Griffin 1910.08092

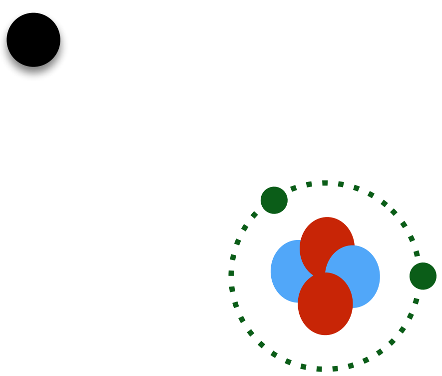
DM scattering kinematics



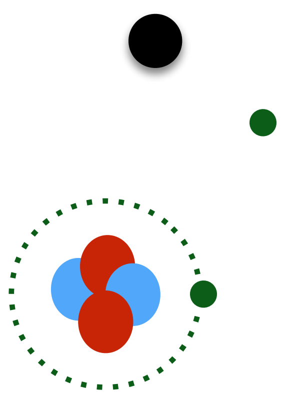
* Kinematic mismatch of nuclear recoils for sub-GeV DM
* Free nucleus approximation no longer valid

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

Energy & momentum scales for sub-GeV dark matter

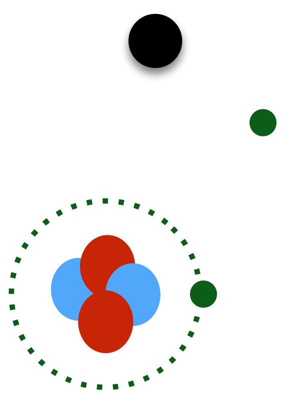


Energy & momentum scales for sub-GeV dark matter

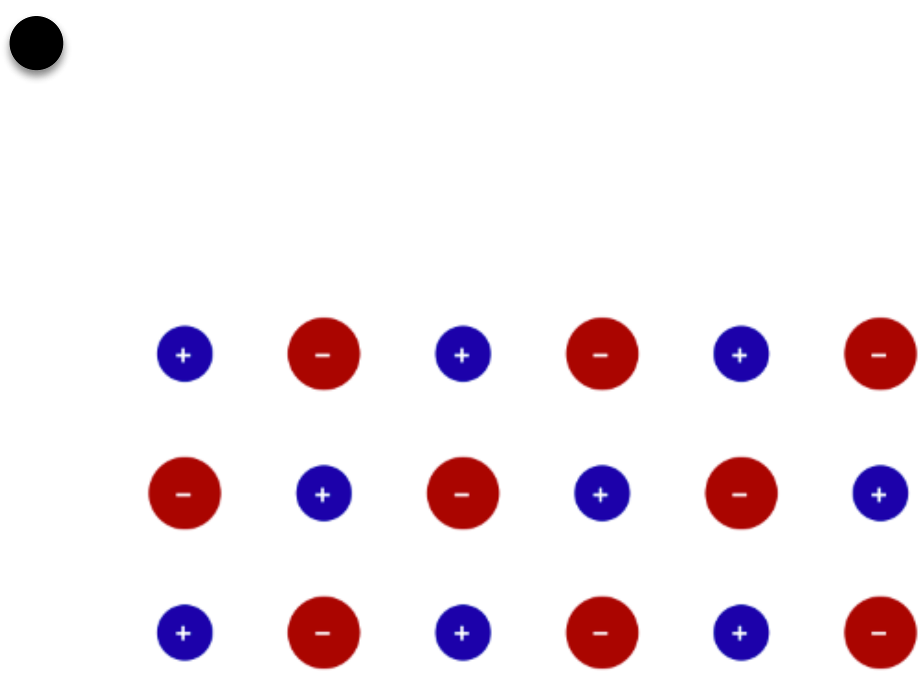


DM-electron scattering

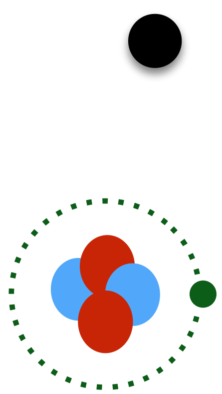
Energy & momentum scales for sub-GeV dark matter



DM-electron
scattering



Energy & momentum scales for sub-GeV dark matter



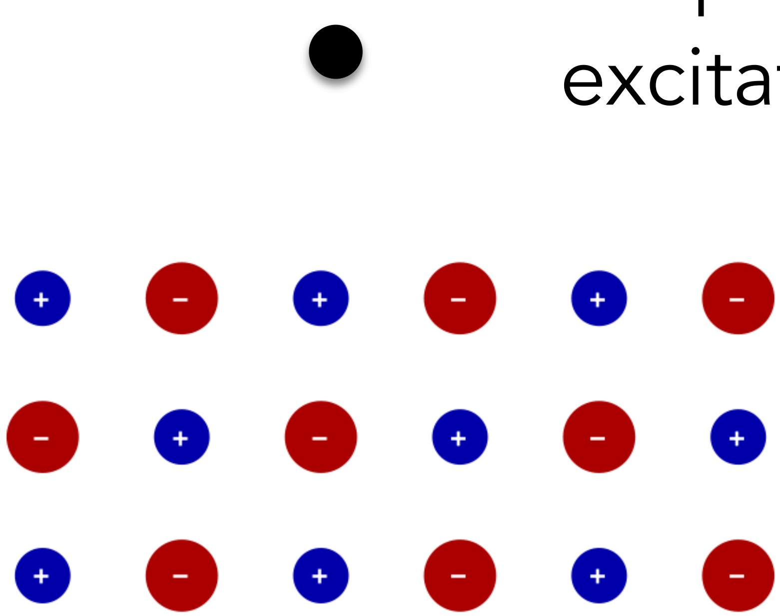
DM-electron scattering

MeV-scale DM:

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

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

In conventional insulators, semiconductors:



DM phonon excitations

Electron excitations:

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

Single phonon excitations:

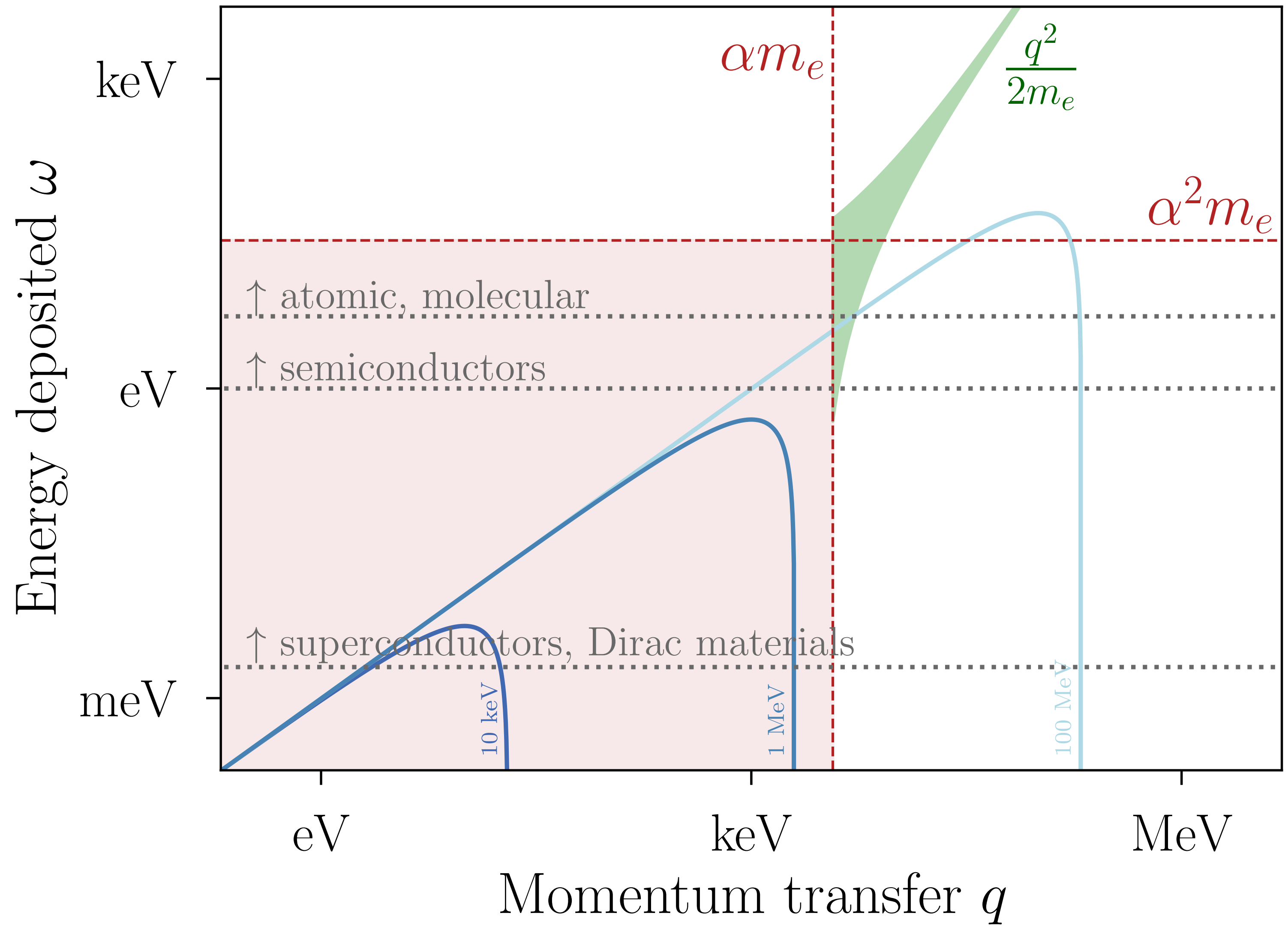
$$\omega \lesssim 0.2\,\mathrm{eV}, q \lesssim \mathrm{keV}$$

"Kinematic matching" with available modes in solid state systems

(Reviews: TL 2019, Kahn, TL 2021)

DM-electron scattering

Opportunity: constrained by available energy eigenstates rather than free-particle kinematics.



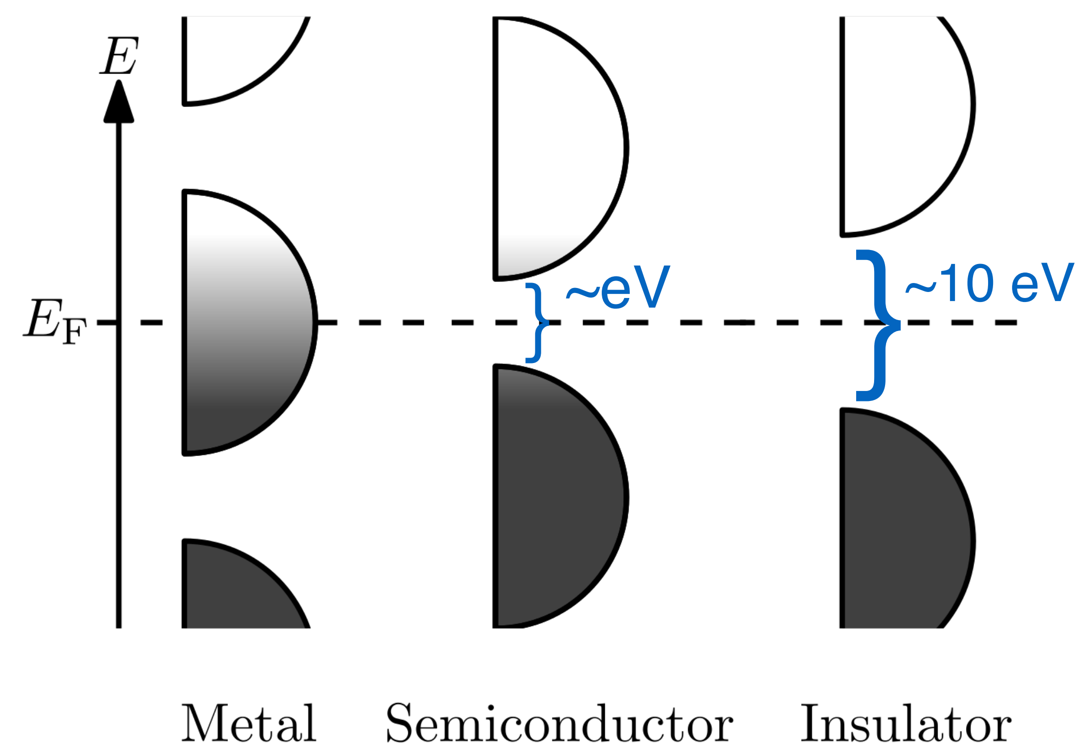
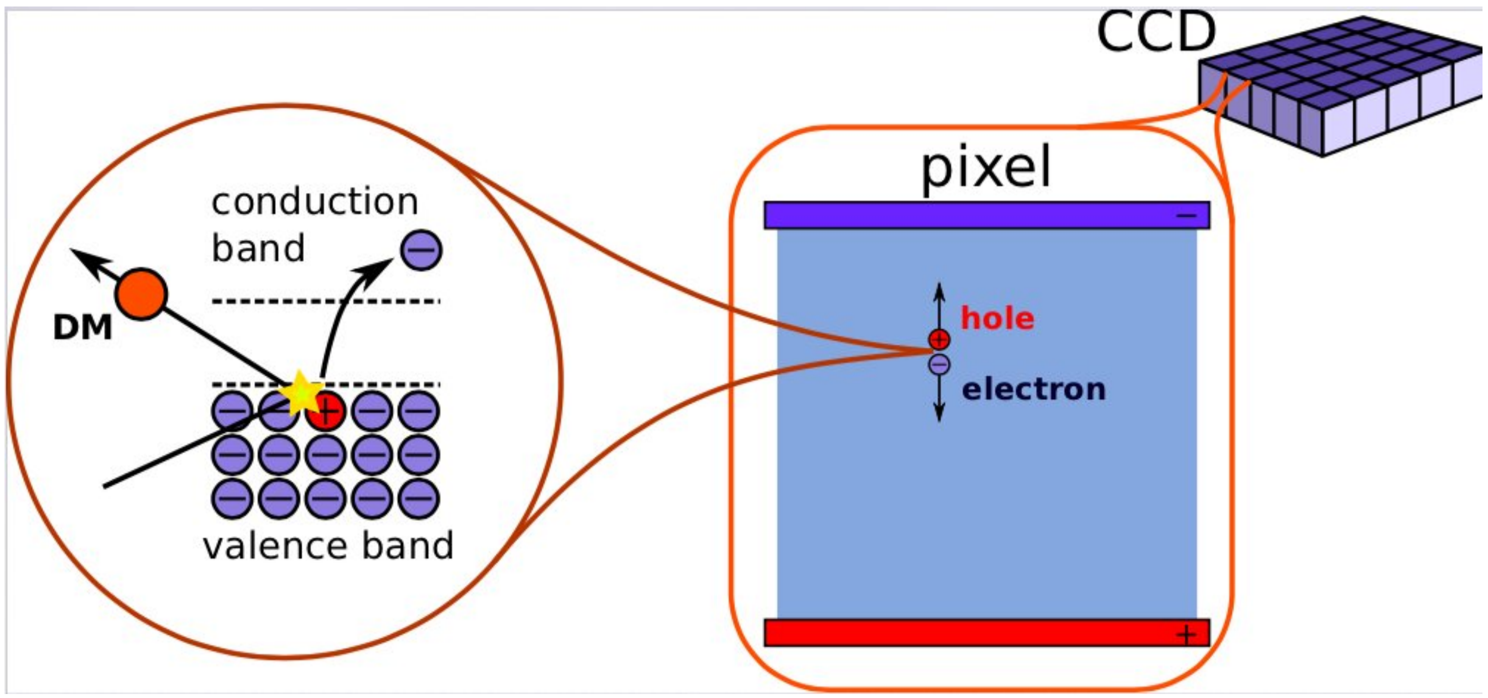


Fig from Kahn, TL 2108.03239
Trickle, Zhang, Zurek, Inzani, Griffin 1910.08092

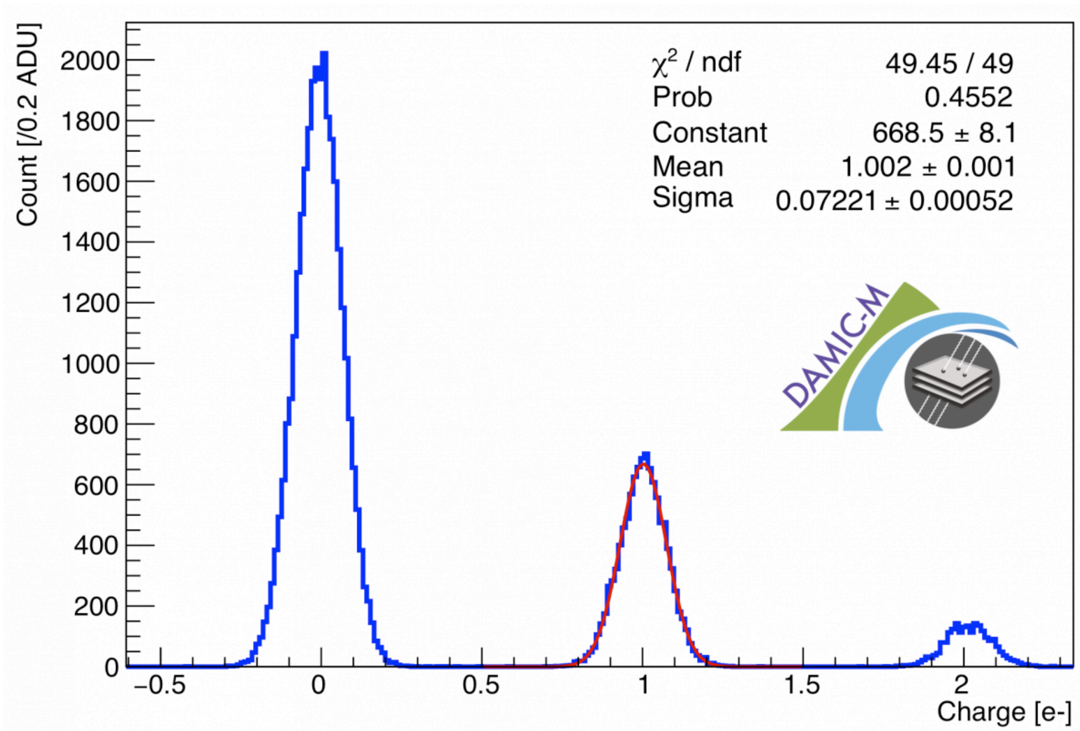
DM scattering in a semiconductor

Charge readout from CCDs with O(eV) band gaps



2004.11378

Low noise skipper CCD can resolve single charges (SENSEI, DAMIC-M)



DM scattering in a semiconductor

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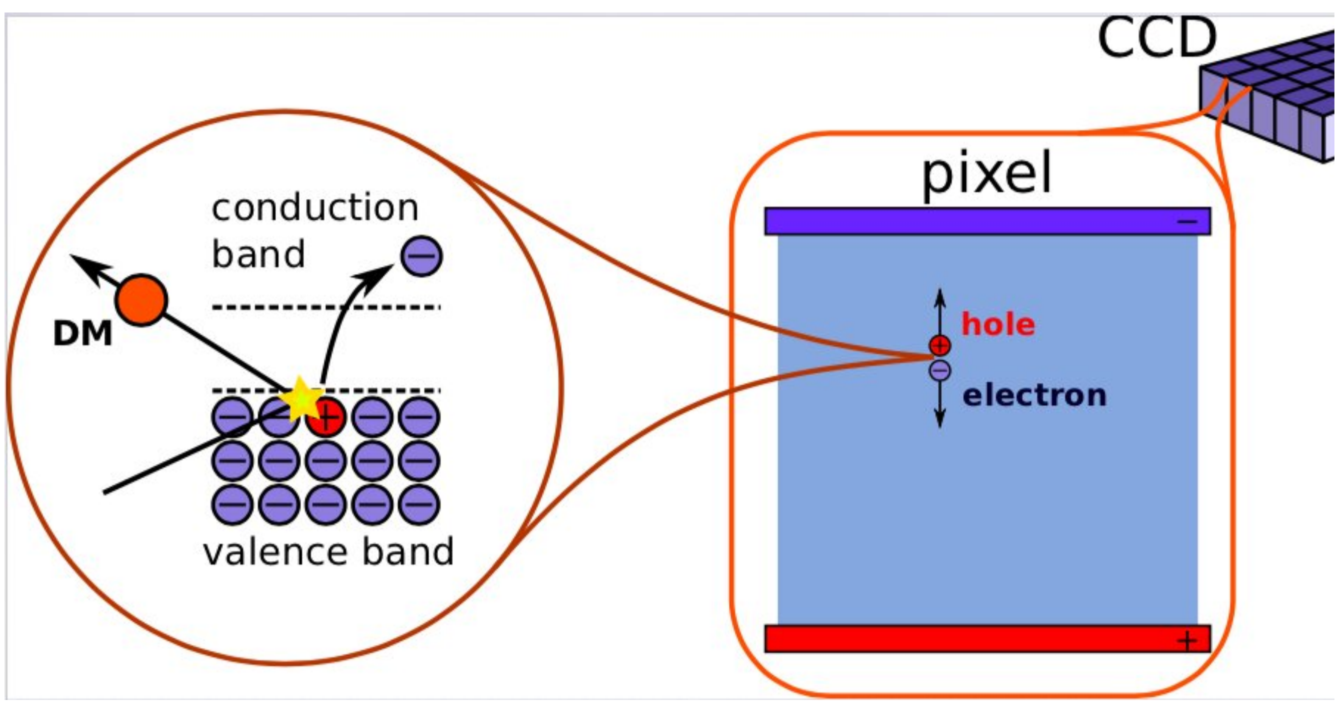


2004.11378

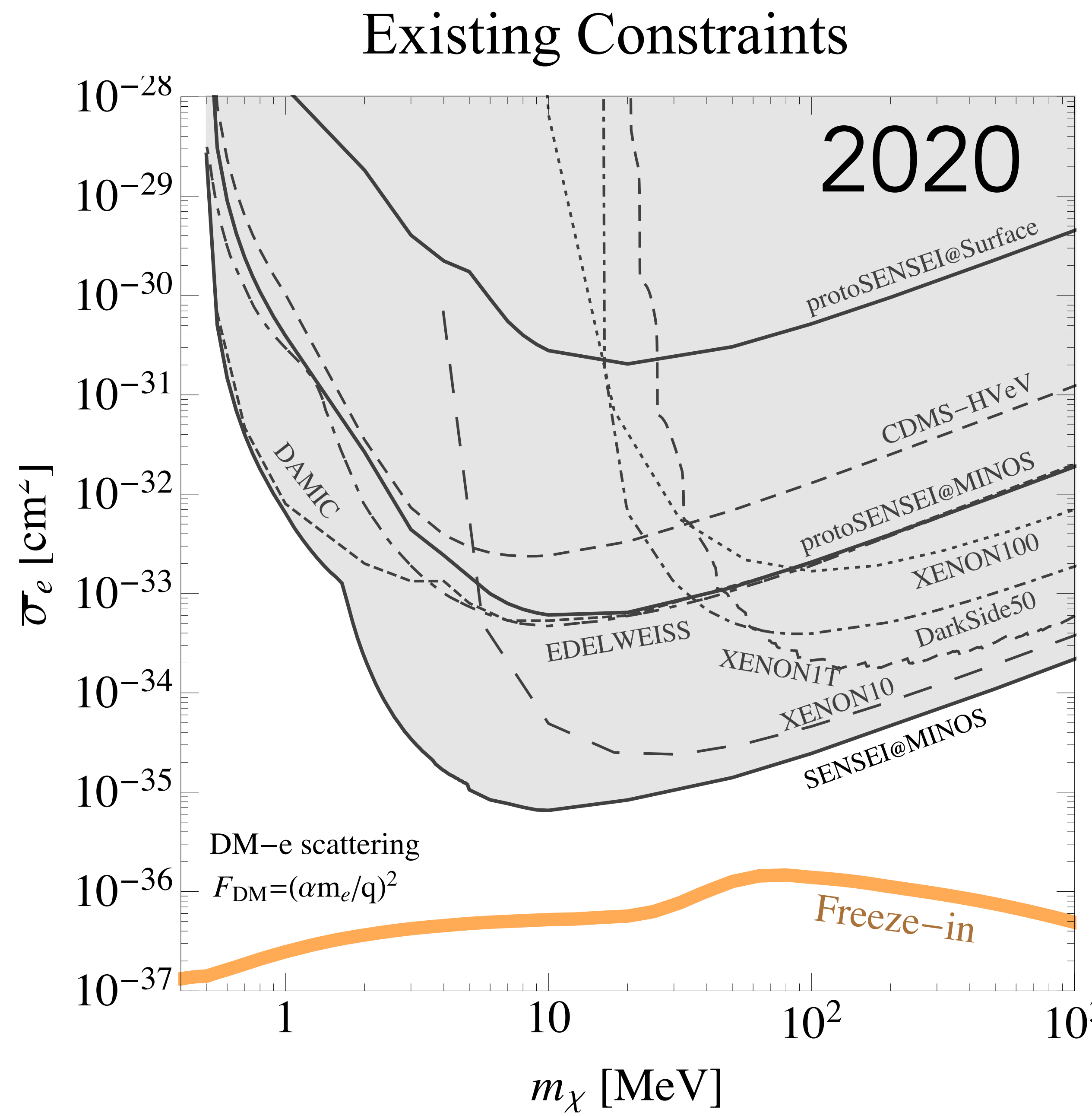
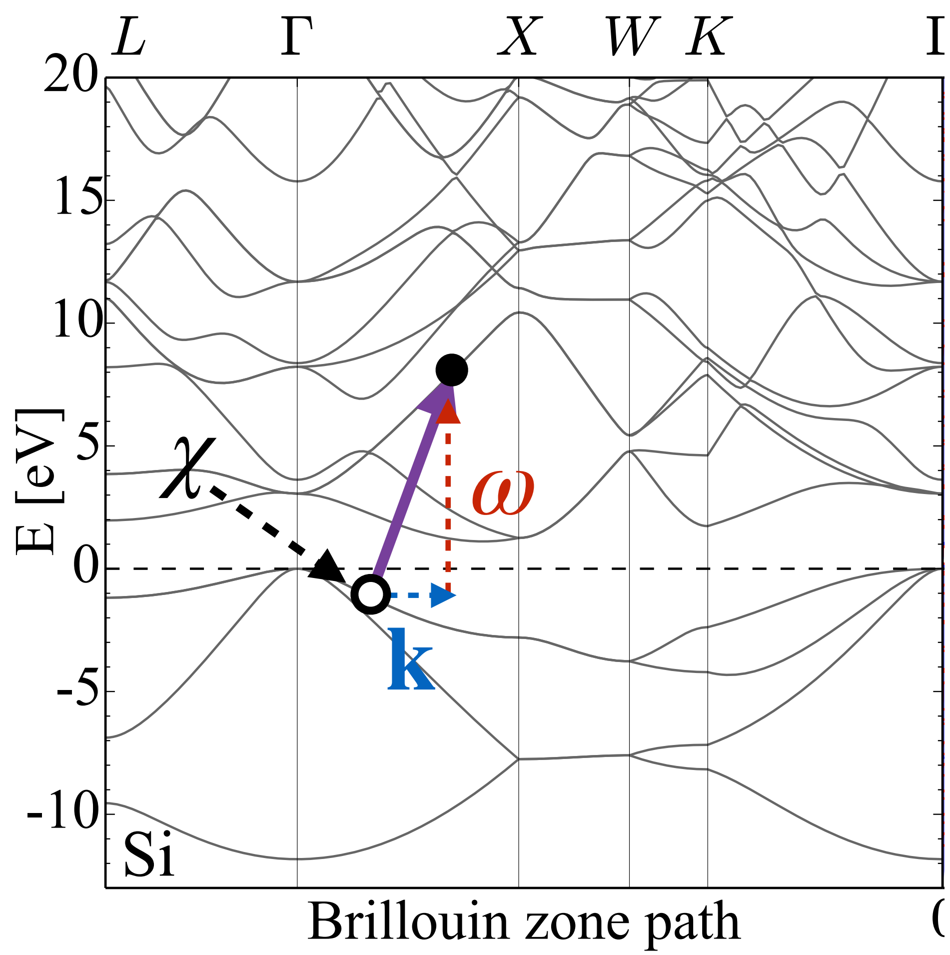


Figure by Rouven Essig

DM scattering in a semiconductor



Independent particle approximation:

Wavefunction overlap

$$\frac{d\sigma}{d^3\mathbf{k}\,d\omega} \propto \bar{\sigma}_e F_{\rm med}^2(k) \sum_{\ell,\ell'} \sum_{\mathbf{p},\mathbf{p}'} |\langle \mathbf{p}', \ell' | e^{i\mathbf{k}\cdot\mathbf{r}} | \mathbf{p}, \ell \rangle|^2$$

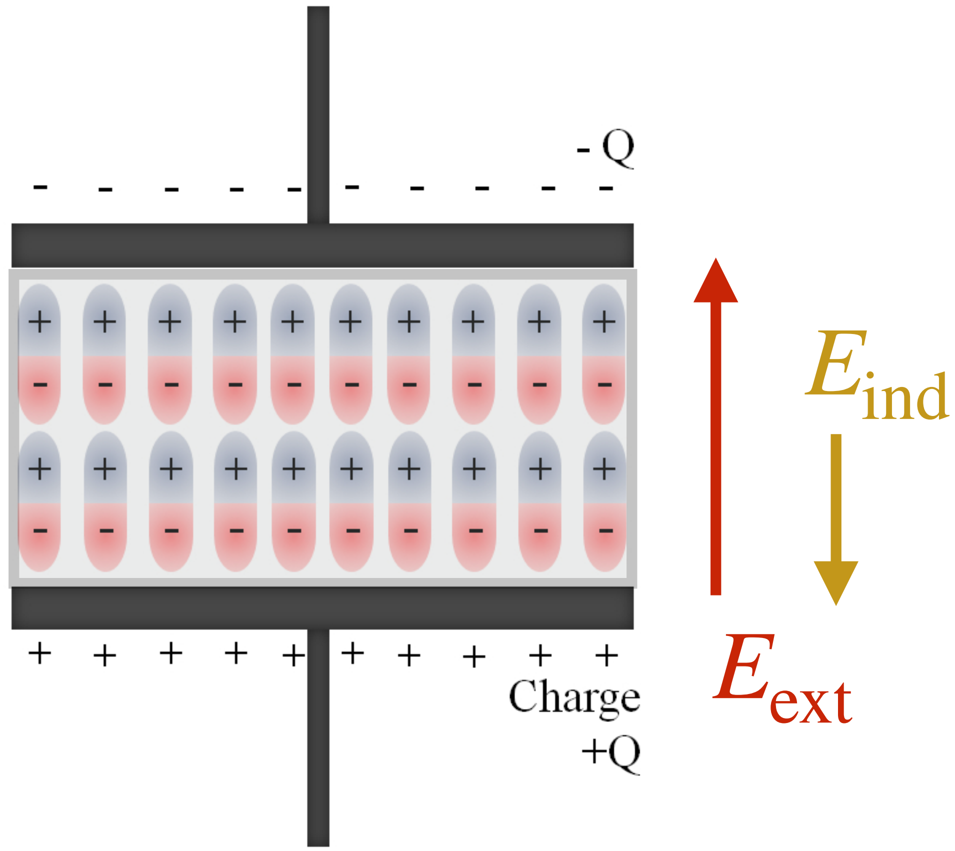
$$\times f^0(\omega_{\mathbf{p},\ell})\left(1 - f^0(\omega_{\mathbf{p}',\ell'})\right)\, \delta(\omega + \omega_{\mathbf{p},\ell} - \omega_{\mathbf{p}',\ell'})$$

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

Complications: not clear how different materials compare; collective effects?

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

Energy loss function (ELF)



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

More generally:

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

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

Pines 1956

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:

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

Dissipation

ELF

DM-electron scattering rate is determined by ELF:

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

Knapen, Kozaczuk, TL 2021a, 2021b
Hochberg, Kahn, Kurinsky, Lehmann, Yu, and Berggren 2021

DM-electron scattering

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

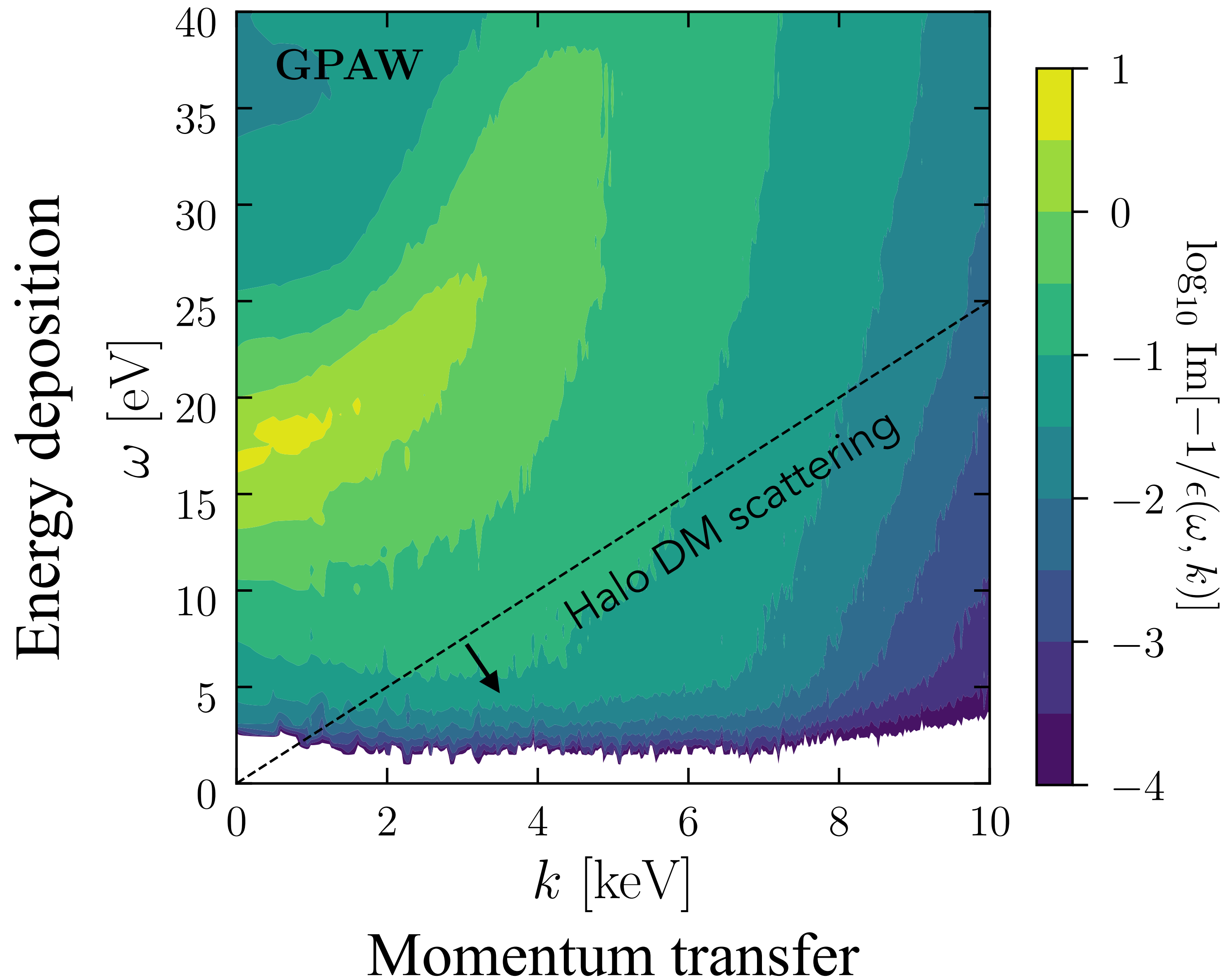
Energy loss function (ELF)

Packages details of material in one function

Many existing materials science approaches

Accounts for previously missed screening effects

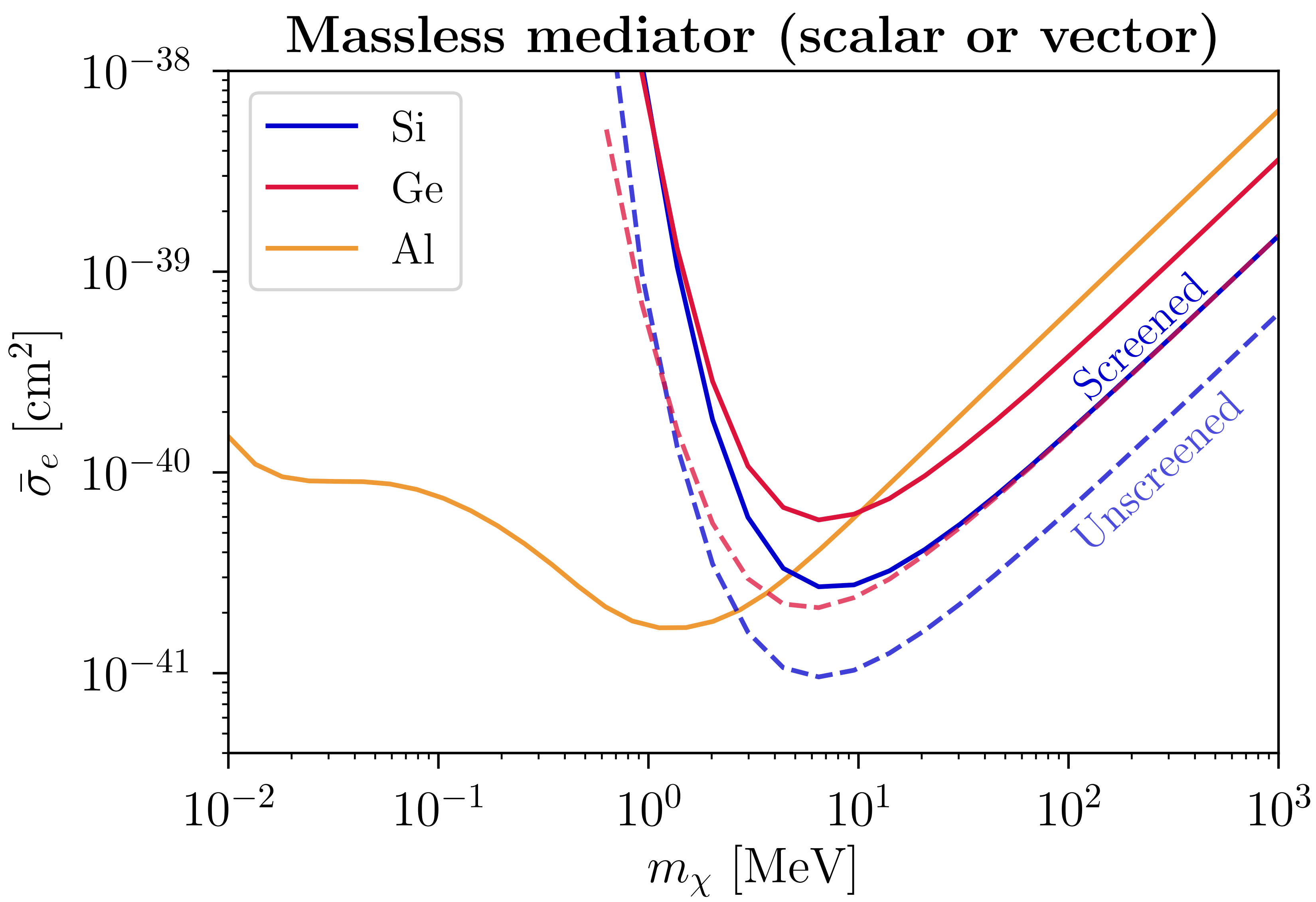
Energy loss function (ELF) of Silicon semiconductor



Knapen, Kozaczuk, TL PRD 2021a, 2021b

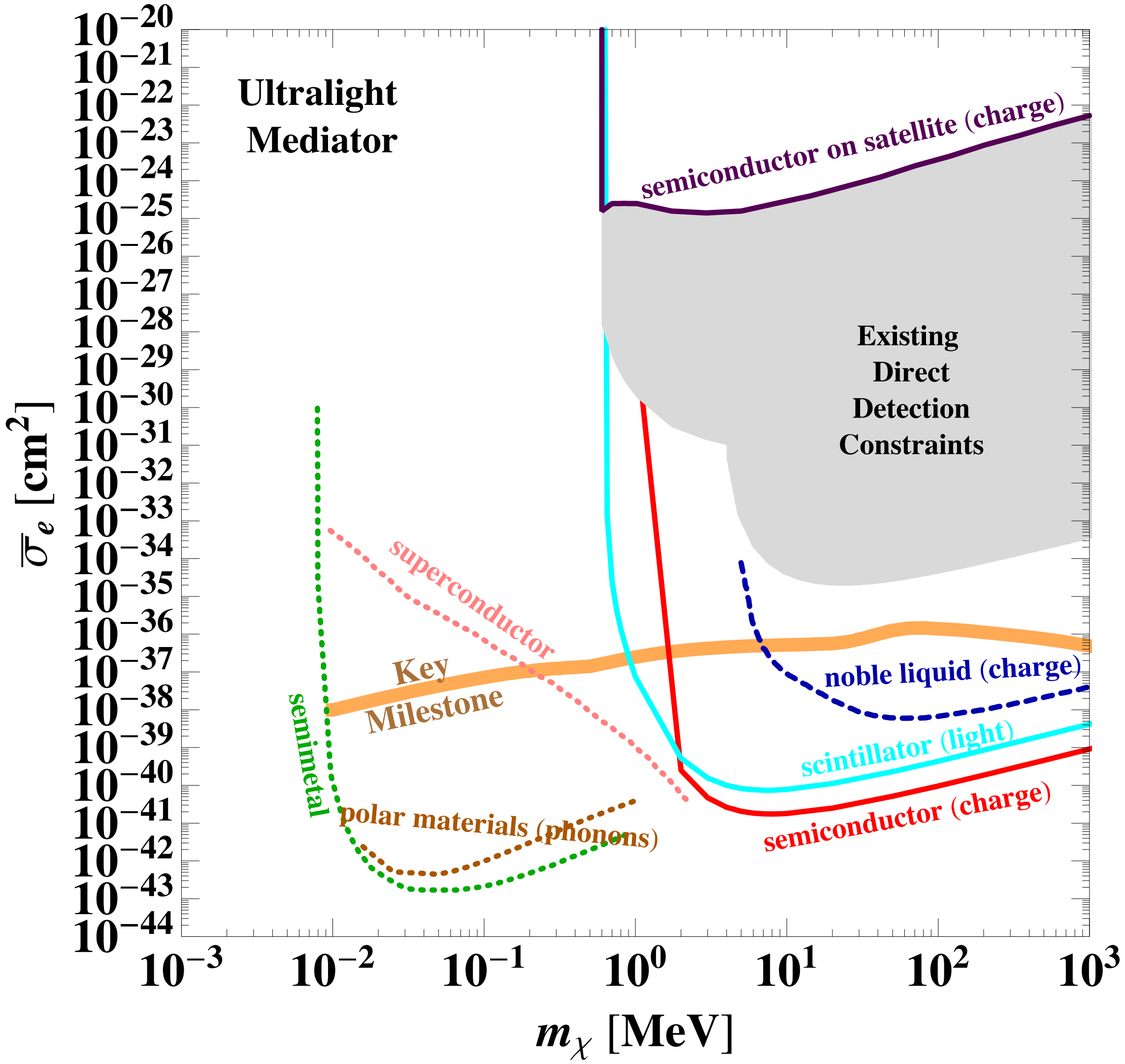
Impact for DM-electron scattering

Screening effects appear as $1/|\epsilon(\omega, \mathbf{k})|^2$

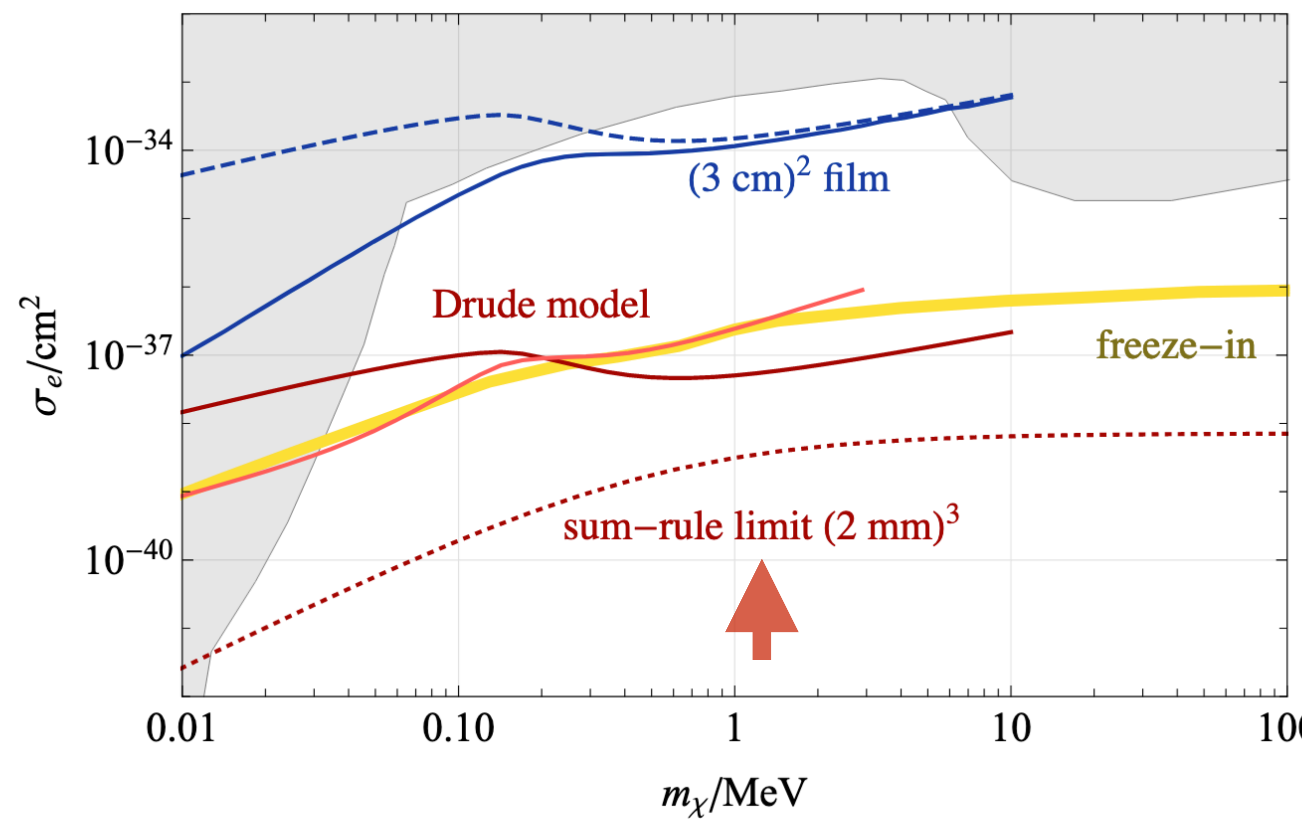


Knapen, Kozaczuk, TL PRD 2021a, 2021b

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



Many papers studying
different targets.
All dielectrics.

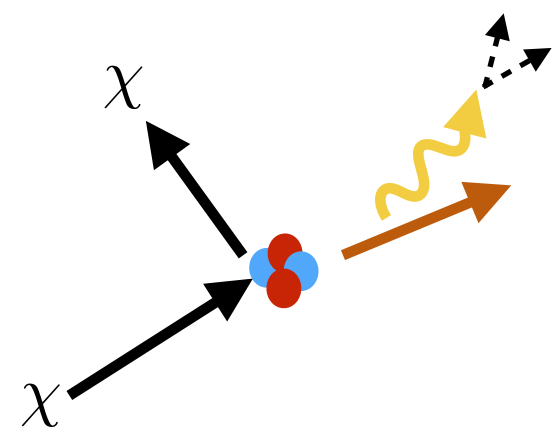


Theoretical constraints on the ELF

Lasenby & Prabhu 2110.01587

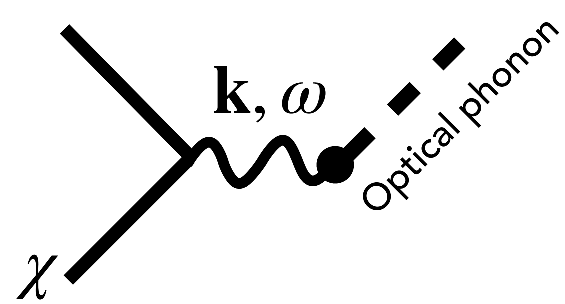
ELF for Dark Matter

DM-nucleus scattering via Migdal effect



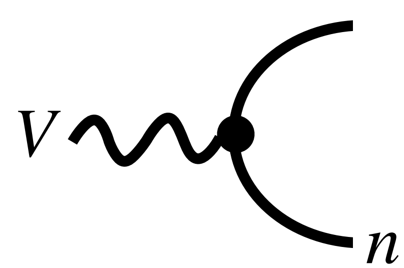
$$\frac{dP}{d^3\mathbf{k}d\omega} \propto \frac{4\pi\alpha_{em}Z_{\rm ion}^2}{\omega^4}\frac{|\mathbf{v}_\mathbf{N}\cdot\mathbf{k}|^2}{k^2}\mathrm{Im}\left(\frac{-1}{\epsilon(\omega,\mathbf{k})}\right)$$

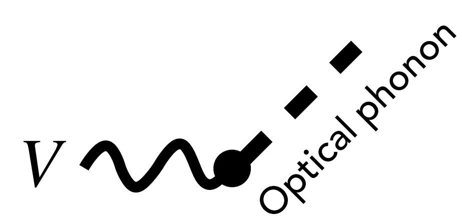
DM-phonon scattering



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

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)

Kozaczuk, TL PRD 2020, Knapen, Kozaczuk, TL PRL 2021
Knapen, Kozaczuk, TL PRD 2021a, 2021b

DM-nucleus scattering in a crystal

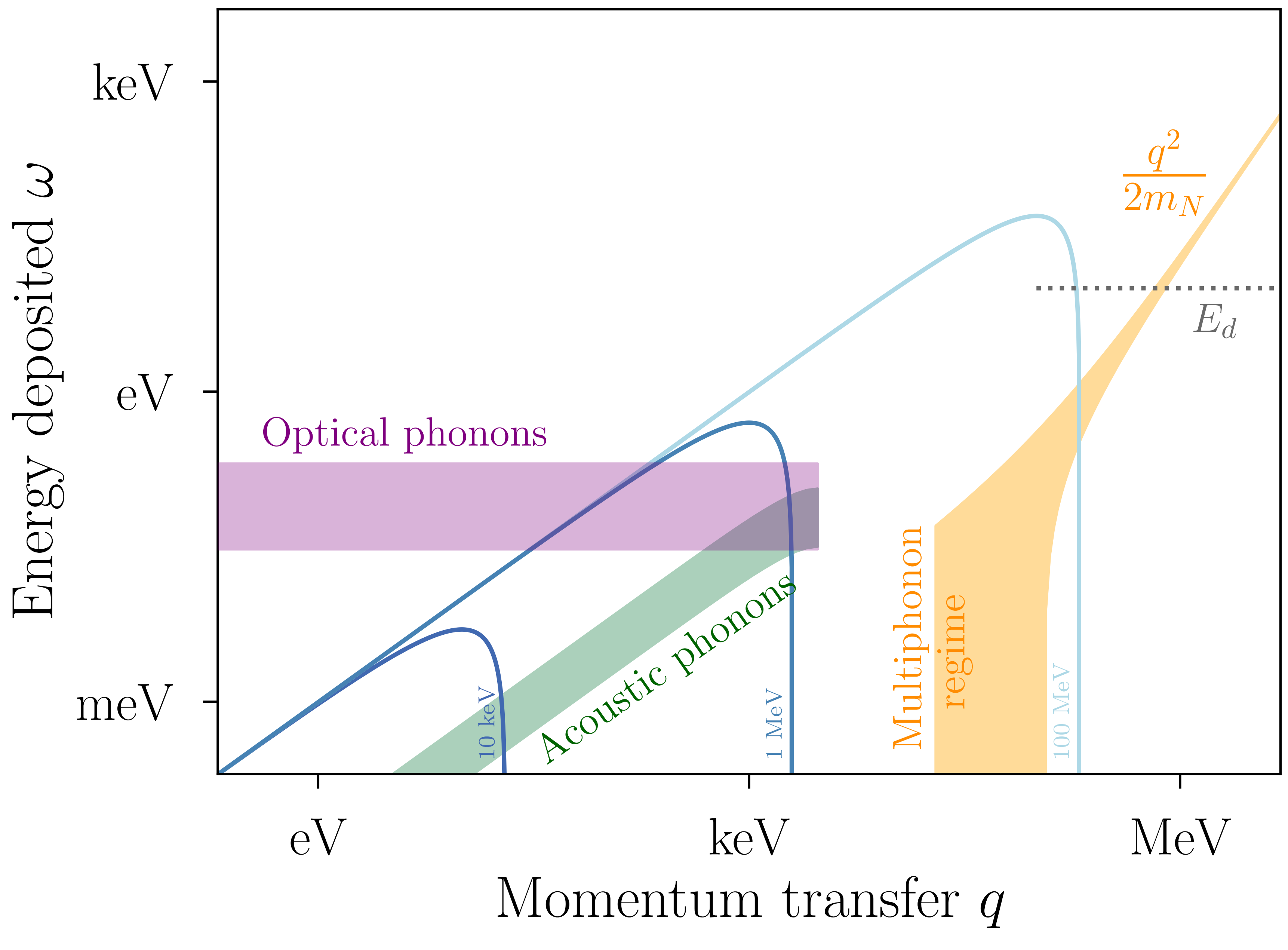
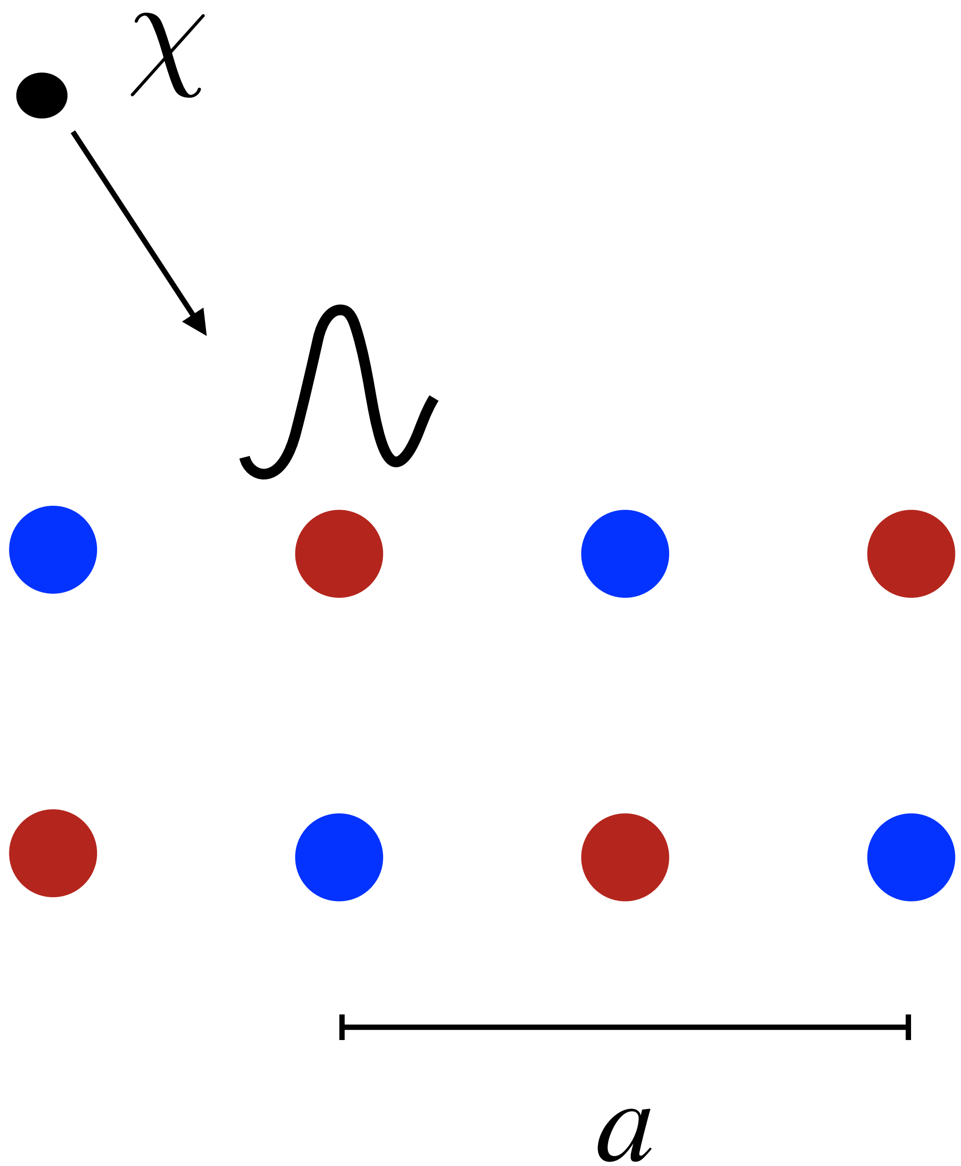


Fig from Kahn, TL 2108.03239
Trickle, Zhang, Zurek, Inzani, Griffin 1910.08092

What does DM-nucleus scattering look like in a crystal?



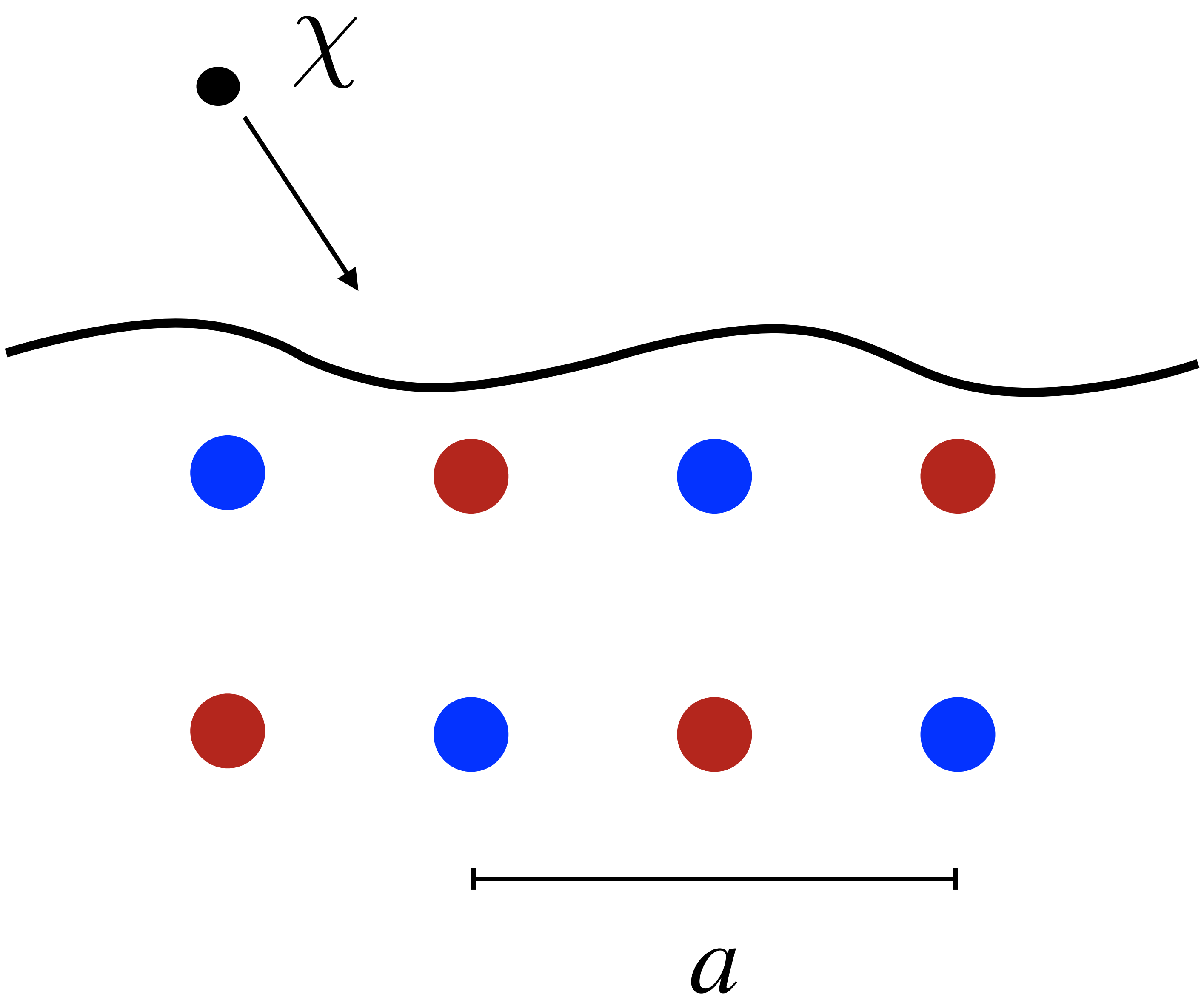
When momentum transfer

$$q \gg \frac{2\pi}{a} \sim \text{few keV}$$

and $\omega \gg \bar{\omega}_{\text{phonon}} \sim 10\text{-}100 \text{ meV}$

DM scatters off an individual nucleus

What does DM-nucleus scattering look like in a crystal?



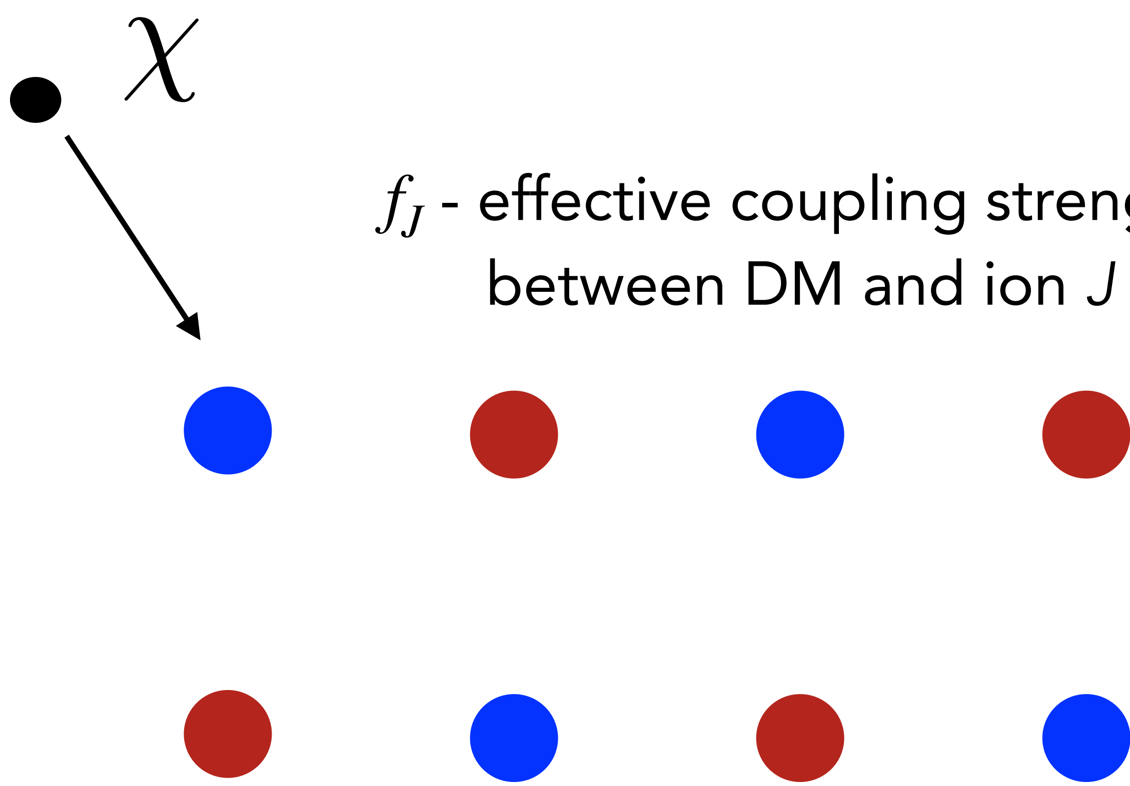
When momentum transfer

$$q \ll \frac{2\pi}{a}$$

and $\omega \sim \bar{\omega}_{\rm phonon}$

DM excites collective excitations = phonons

DM-nucleus interaction



f_J - effective coupling strength between DM and ion J

Short range SI interaction

$$\sigma_{\chi p} = 4\pi b_p^2$$

Scattering potential in Fourier space

$$V(\mathbf{q}) \propto b_p \sum_J f_J \, e^{i\mathbf{q}\cdot\mathbf{r}_J}$$

Dynamic structure factor

$$S(\mathbf{q},\omega) \equiv \frac{2\pi}{V} \sum_f \left| \sum_J \langle \Phi_f | f_J e^{i\mathbf{q}\cdot\mathbf{r}_J} | 0 \rangle \right|^2 \delta\left(E_f - \omega\right)$$

$$= \frac{1}{V} \sum_{J,\,J'}^{N} f_J f_{J'}^* \int_{-\infty}^{\infty} dt \, \langle e^{-i\mathbf{q}\cdot\mathbf{r}_{J'}(0)} e^{i\mathbf{q}\cdot\mathbf{r}_J(t)} \rangle e^{-i\omega t}$$

Contains interference terms between different atoms → single phonon excitations

Theory of neutron scattering: Squires 1996, Schober 2014

Dynamic structure factor

Phonon comes into play through positions of ions:

$$\mathbf{r}_J(t) = \mathbf{r}_J^0 + \mathbf{u}_J(t)$$

$$\uparrow$$

Quantized displacement field $\mathbf{u}_J(t) \sim \sum_{\mathbf{q}} \frac{1}{\sqrt{2m_N\omega_{\mathbf{q}}}} \left(\hat{a}_{\mathbf{q}}^{\dagger}\mathbf{e}_{\mathbf{q}}e^{-i\mathbf{q}\cdot\mathbf{r}_J+i\omega_{\mathbf{q}}t} + \text{h.c.}\right)$

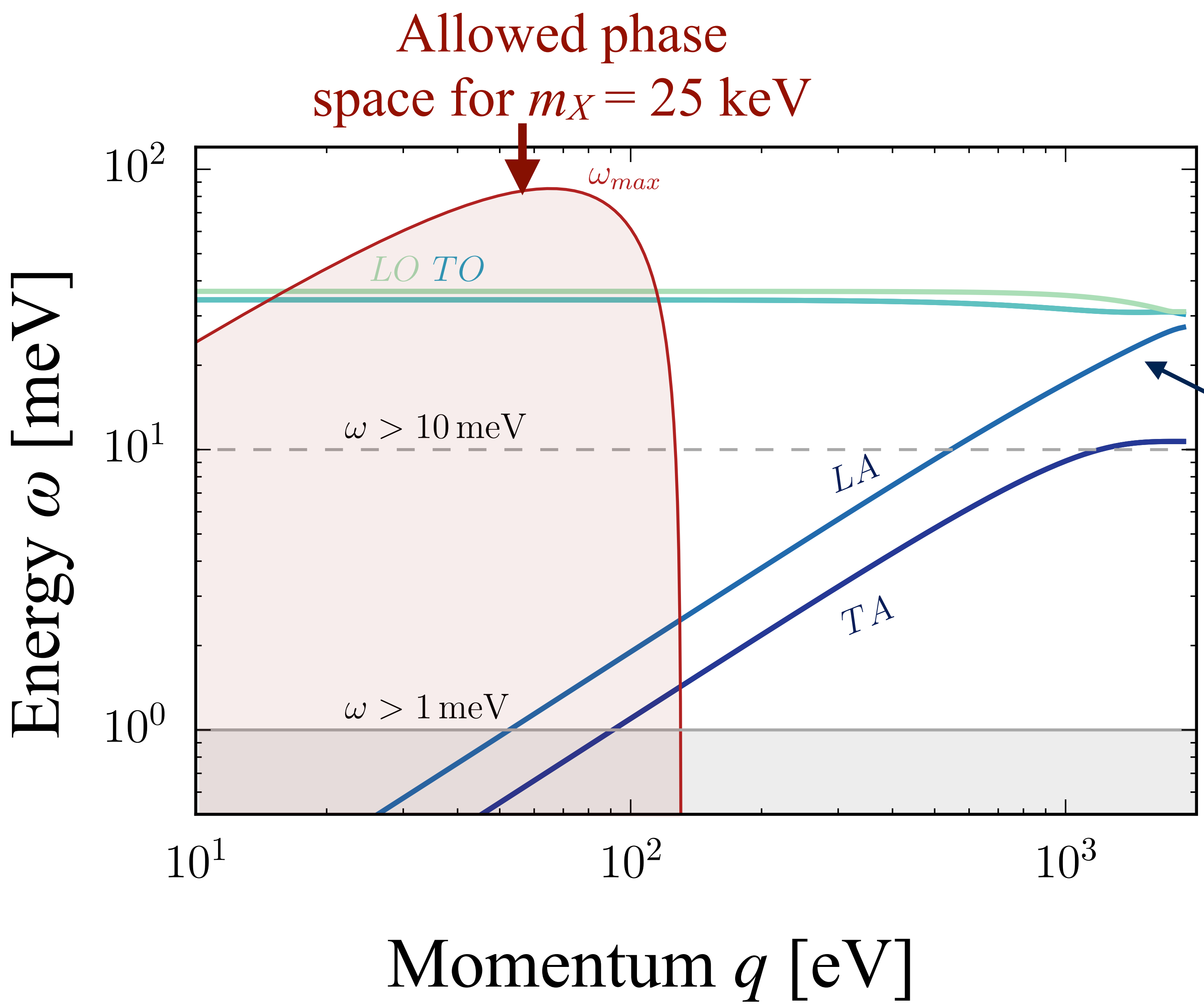
Phonon dispersions $\omega_{\mathbf{q}}$ and eigenvectors $\mathbf{e}_{\mathbf{q}}$ calculated by first-principles approaches (density functional theory)

Single phonon contribution has been studied extensively in literature

$$S^{n=1}(\mathbf{q},\omega) \sim \sum_{J,J'} f_J f_{J'} \int dt \, \langle \mathbf{q}\cdot\mathbf{u}_J(0) \; \mathbf{q}\cdot\mathbf{u}_{J'}(t)\rangle e^{-i\omega t}$$

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

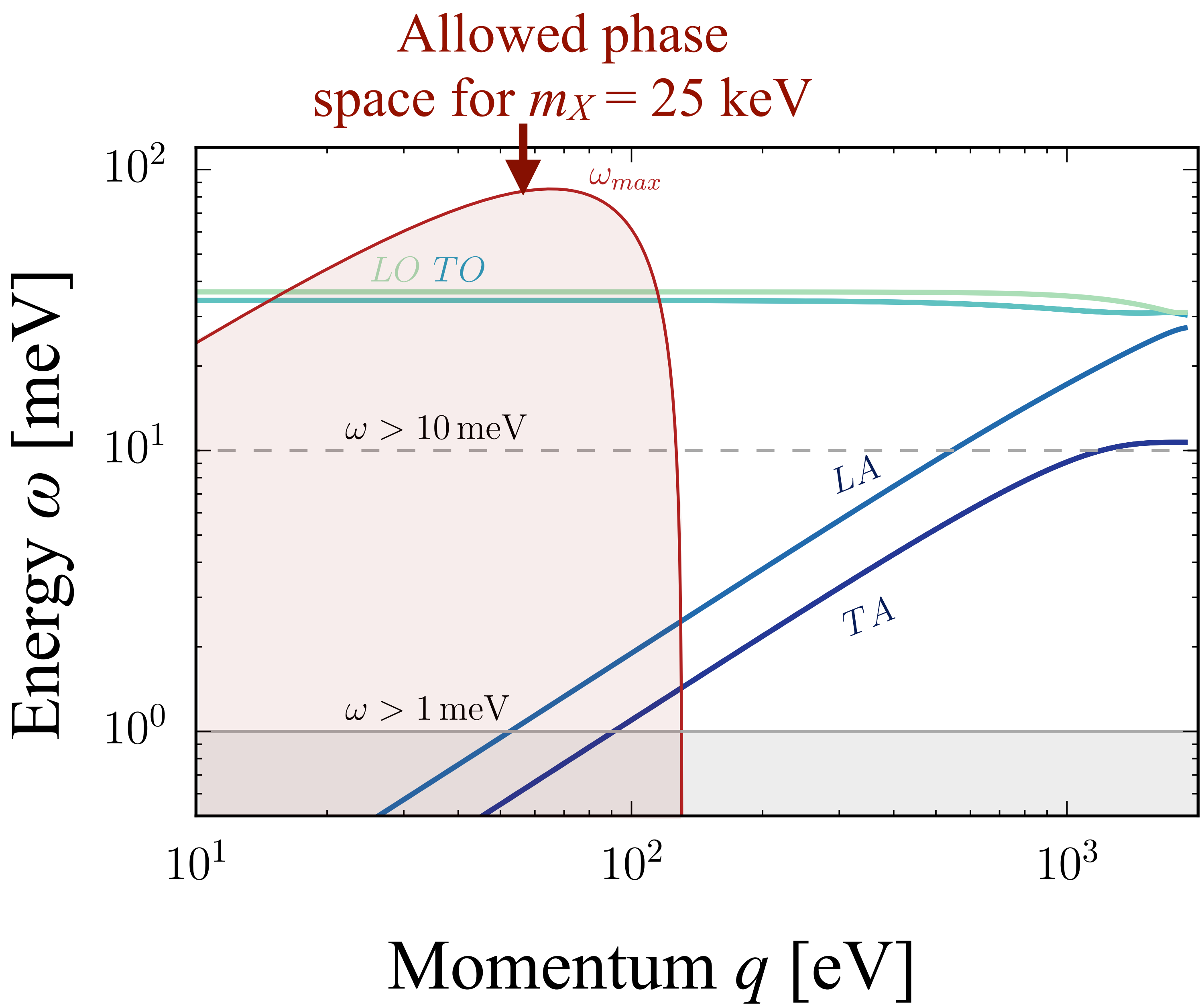
Single phonon excitations

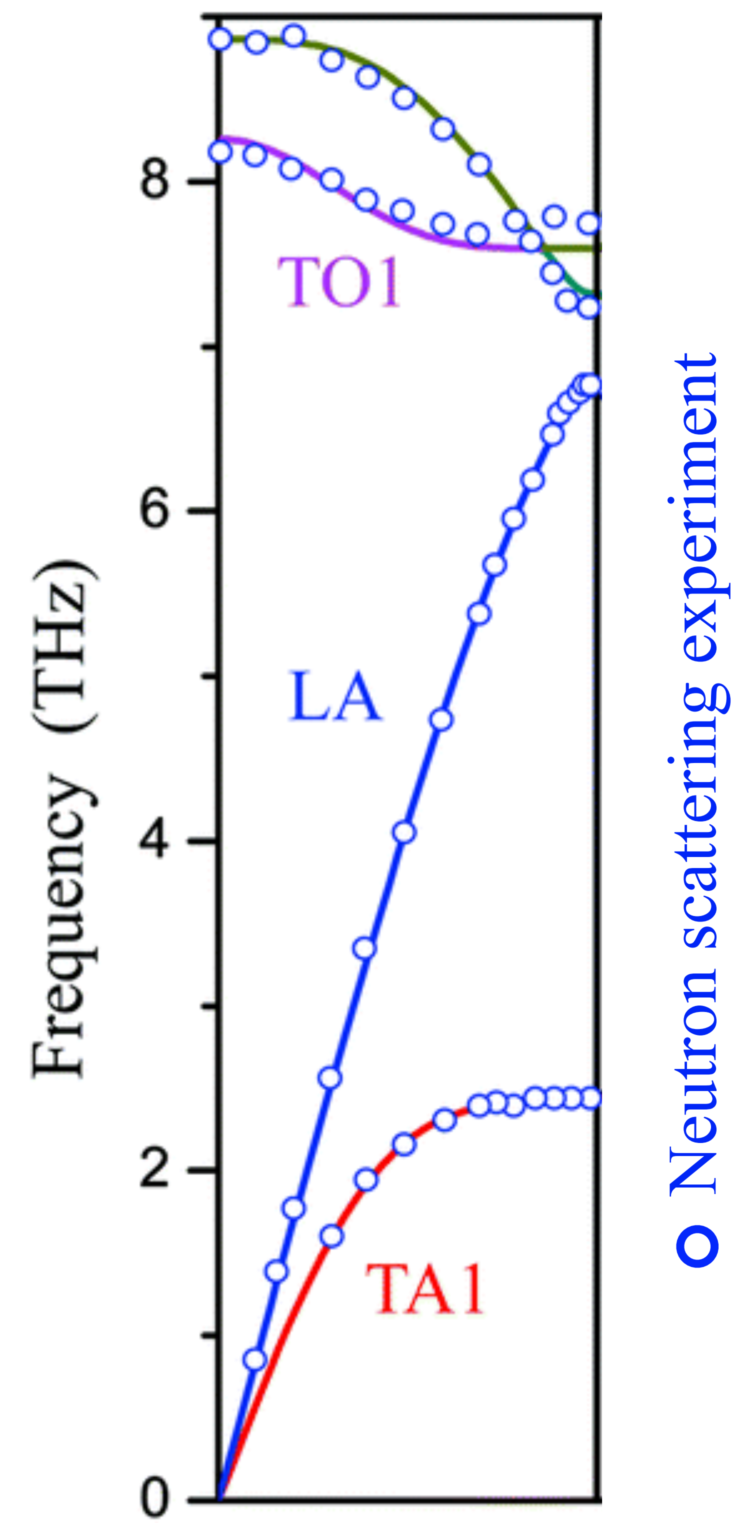


Resonant response of material at single-phonon dispersions (calculated with DFT)

Knapen, TL, Pyle, Zurek PRB 2018
Griffin, Knapen, TL, Zurek PRD 2020

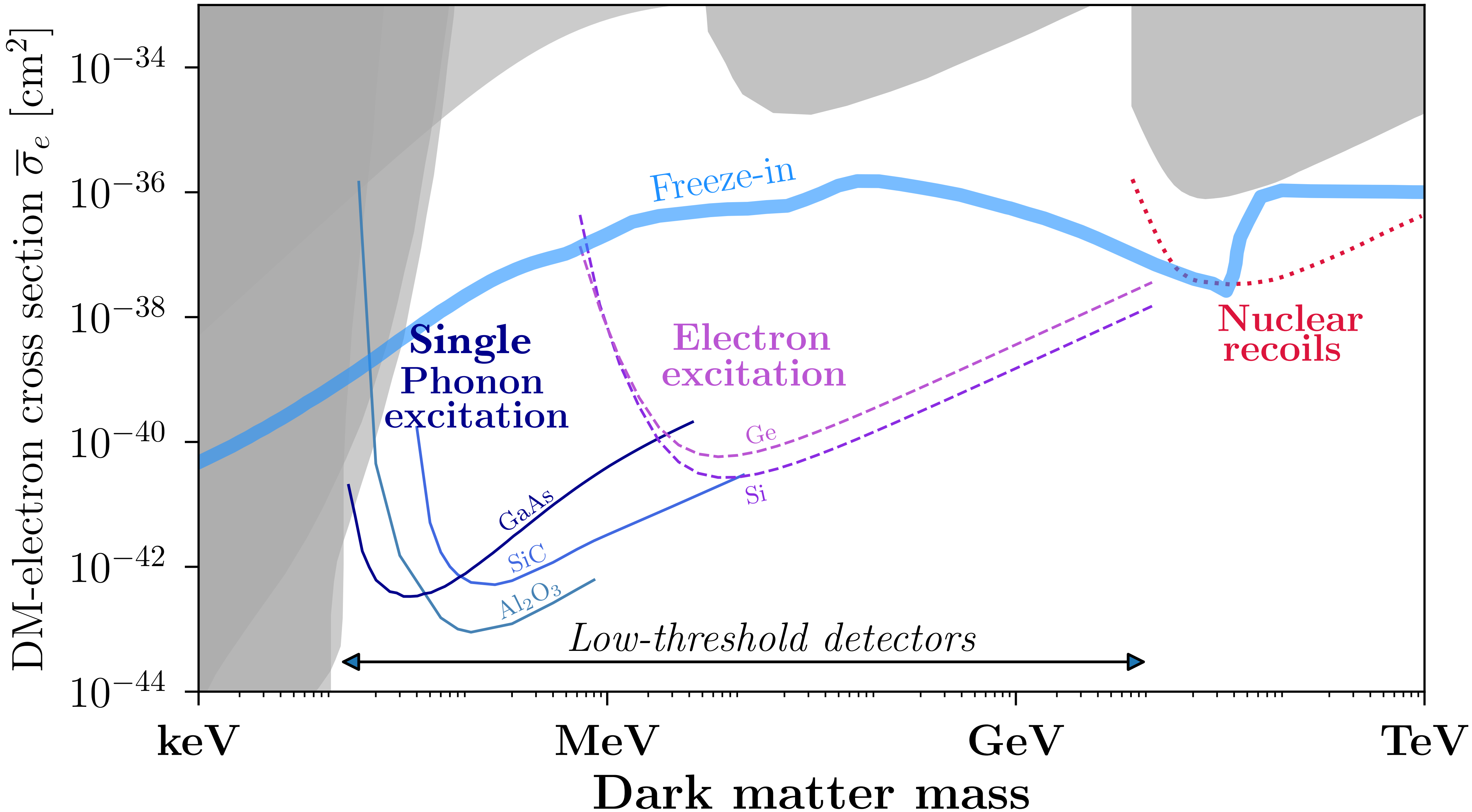
Single phonon excitations





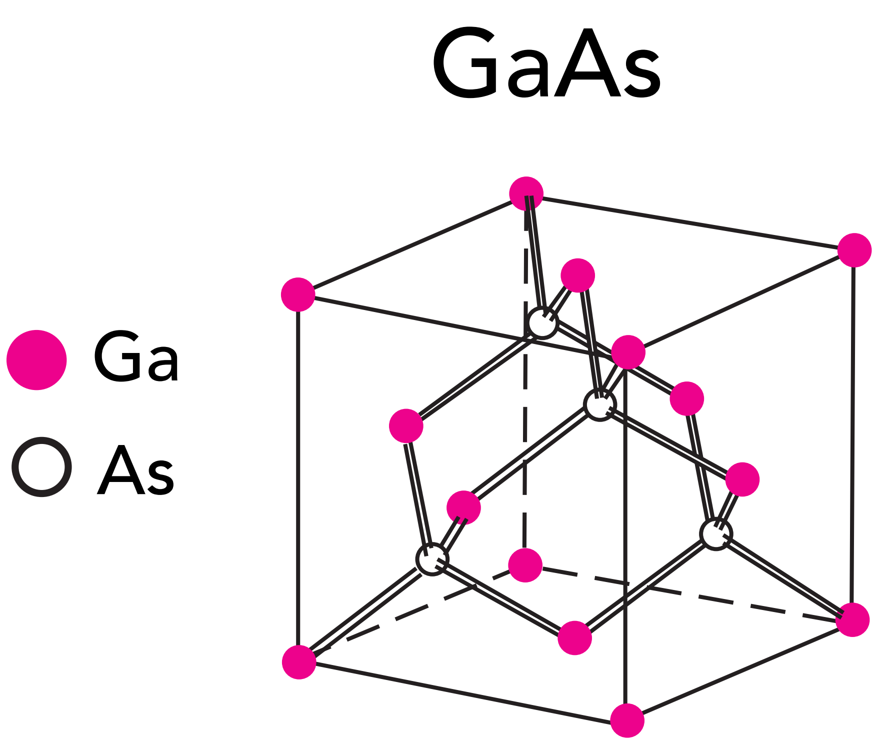
Knapen, TL, Pyle, Zurek PRB 2018
Griffin, Knapen, TL, Zurek PRD 2020

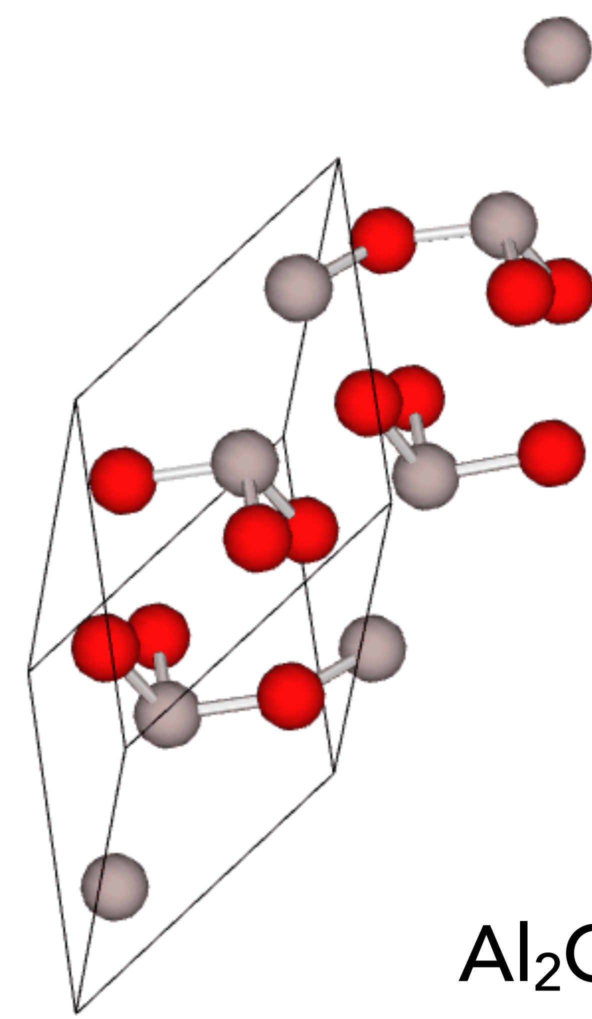
Single phonon excitations



Materials properties for DM

Use different materials to maximize sensitivity to particular models, discriminate signal vs. background, and for directional detection.

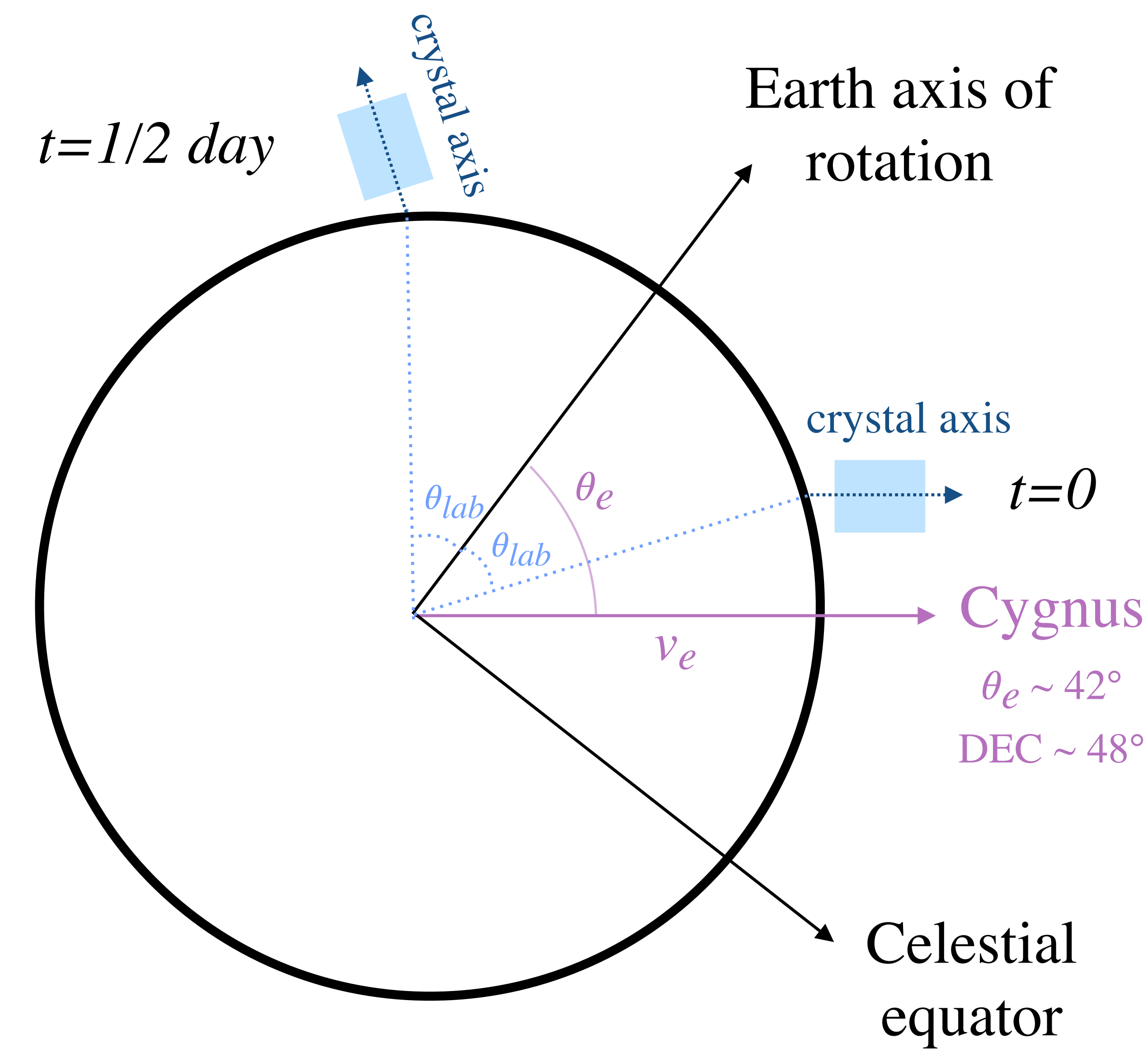


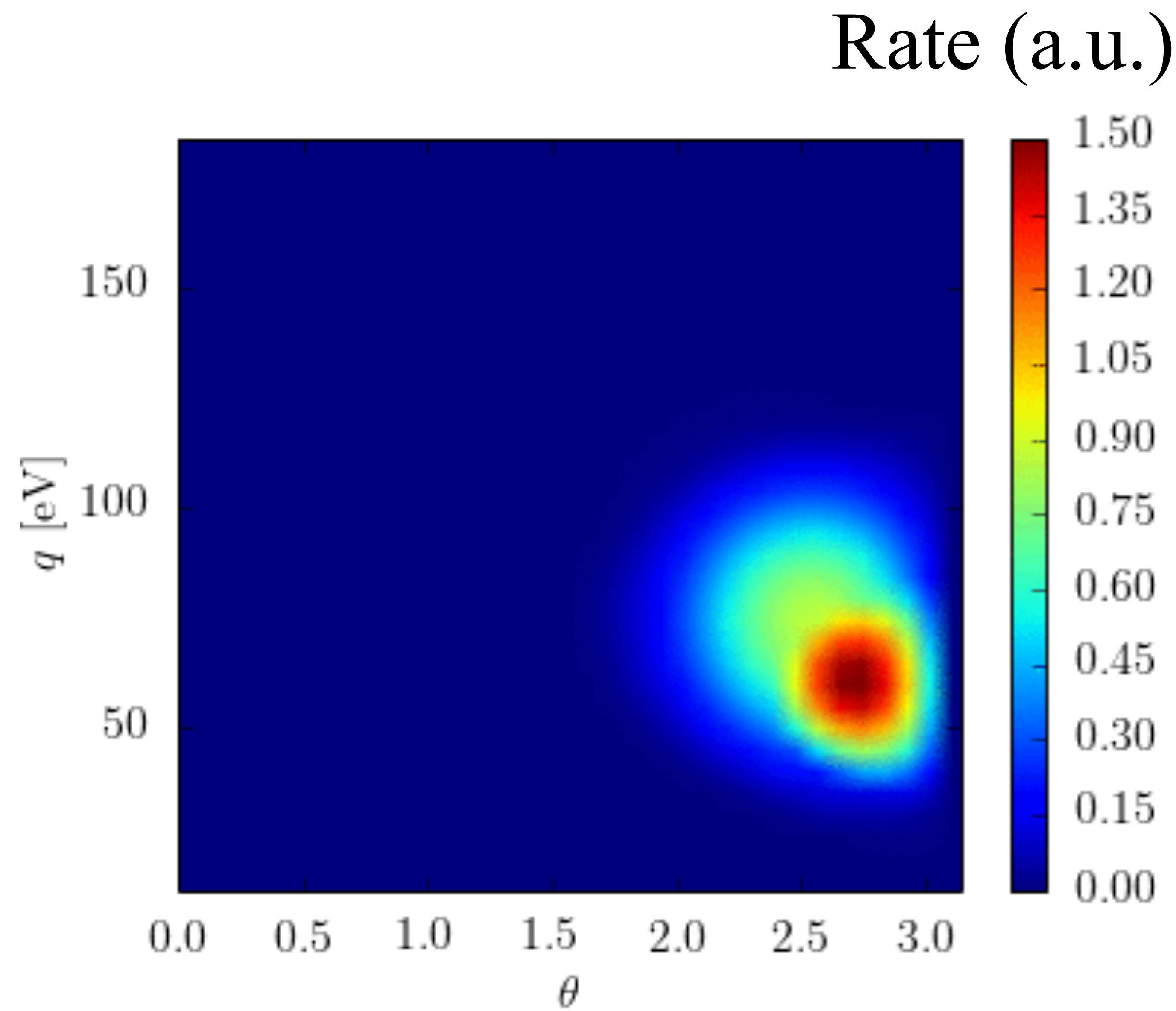


Al_2O_3
(Sapphire)

Knapen, TL, Pyle, Zurek PRB 2018; Griffin, Knapen, TL, Zurek PRD 2018; Griffin, Hochberg, Inzani, Kurinsky, TL, Yu PRD 2020;

Daily modulation





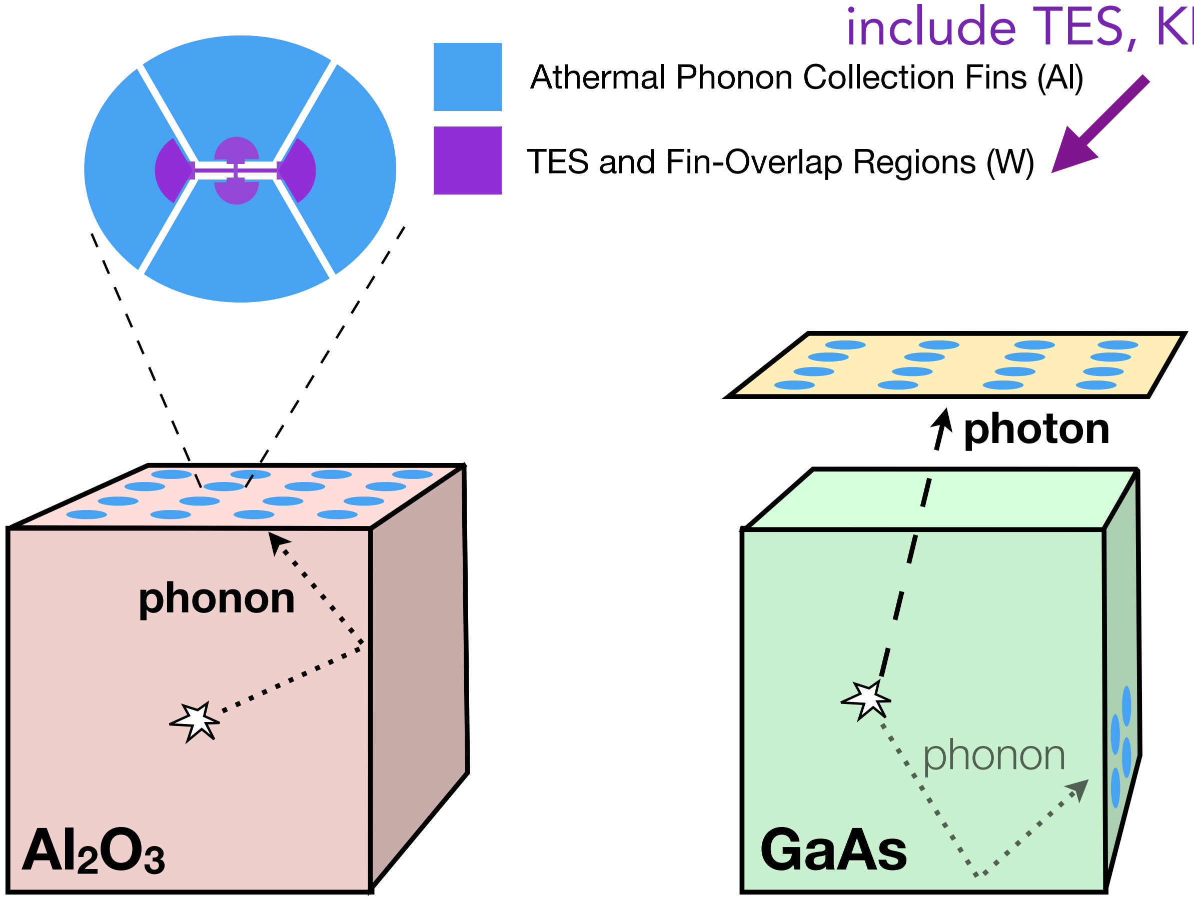
Angle with crystal axis

Griffin, Knapen, TL, Zurek PRD 2018

Phonon detection

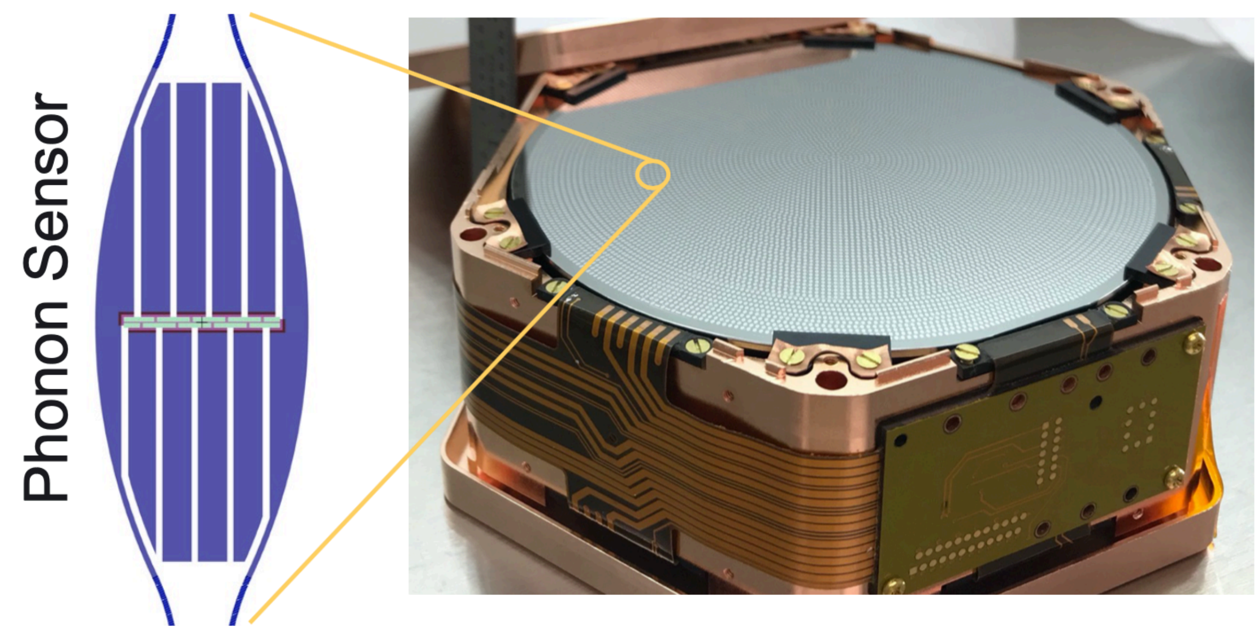
Single phonons excitations
with energy 1-100 meV

Technologies being explored
include TES, KID, Qubits



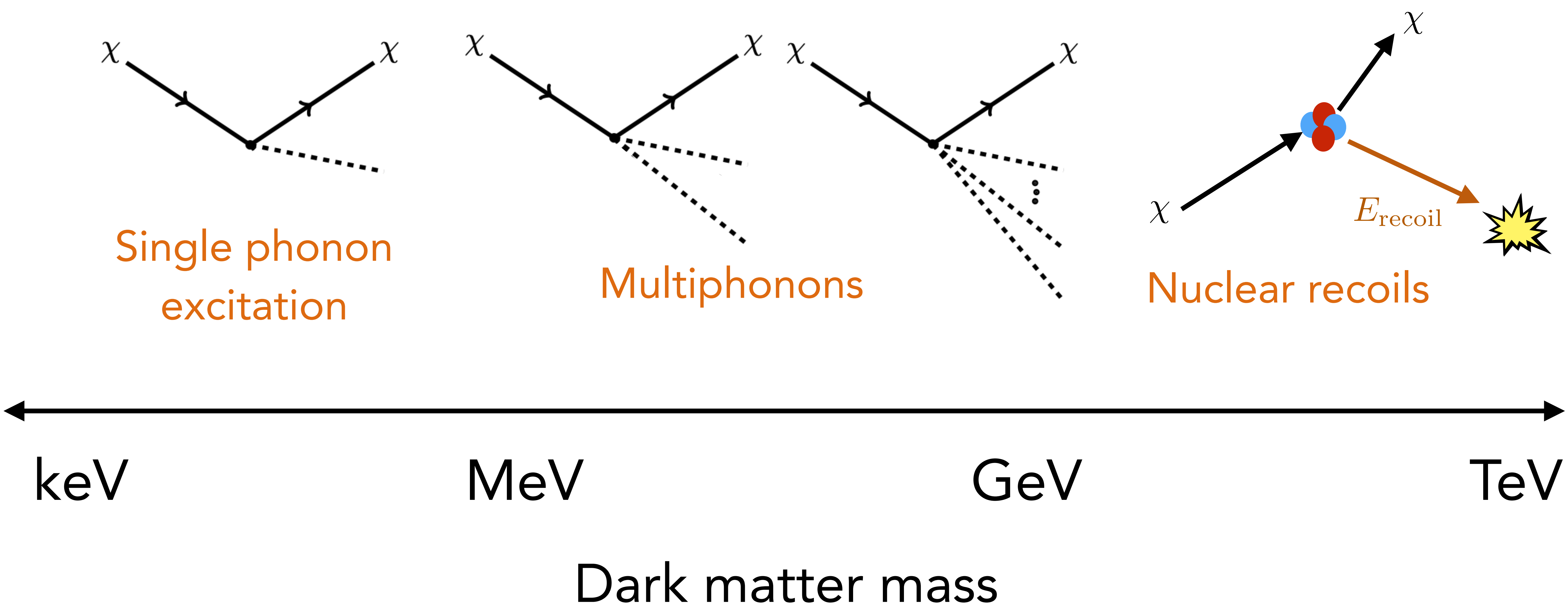
From TESSERACT white paper

Existing state of the art phonon detection at energies of 1-10 eV



SuperCDMS

DM-nucleus scattering in crystals

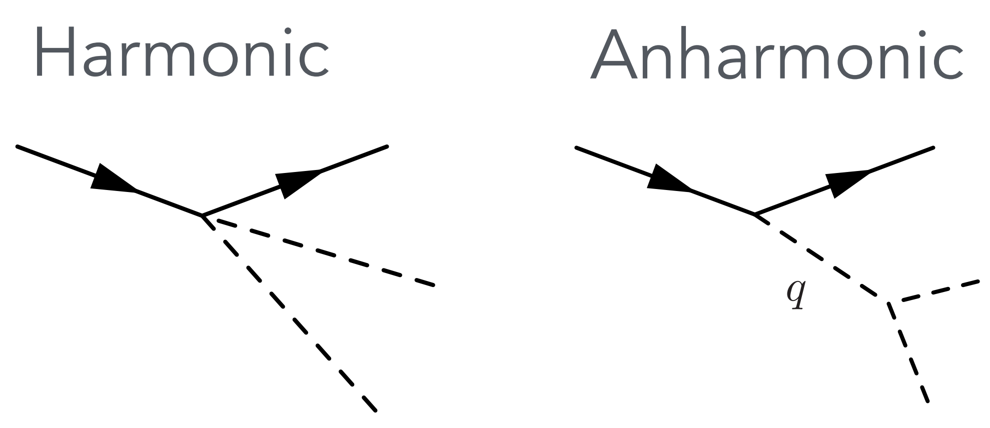


Campbell-Deem, Knapen, TL, Villarama PRD 2022
Campbell-Deem, Cox, Knapen, TL, Melia PRD 2020
Knapen, Kozaczuk, TL PRL 2021

Dynamic structure factor

Expansion in $q^2/(M_N\omega)$ (and anharmonic interactions):

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



Quickly becomes more complicated to evaluate for more than 1 phonon

Our approach: use harmonic & incoherent approximations

Campbell-Deem, Cox, Knapen, TL, Melia PRD 2020

Incoherent approximation for $q > q_{\text{BZ}}$ or $n > 1$ phonons

Neglect interference terms entirely:

$$S(\mathbf{q}, \omega) \approx \frac{1}{V} \sum_{J}^{N} (f_J)^2 \int_{-\infty}^{\infty} dt \, \langle e^{-i\mathbf{q}\cdot\mathbf{u}_J(0)} e^{i\mathbf{q}\cdot\mathbf{u}_J(t)} \rangle e^{-i\omega t}$$

Given in terms of auto-correlation function

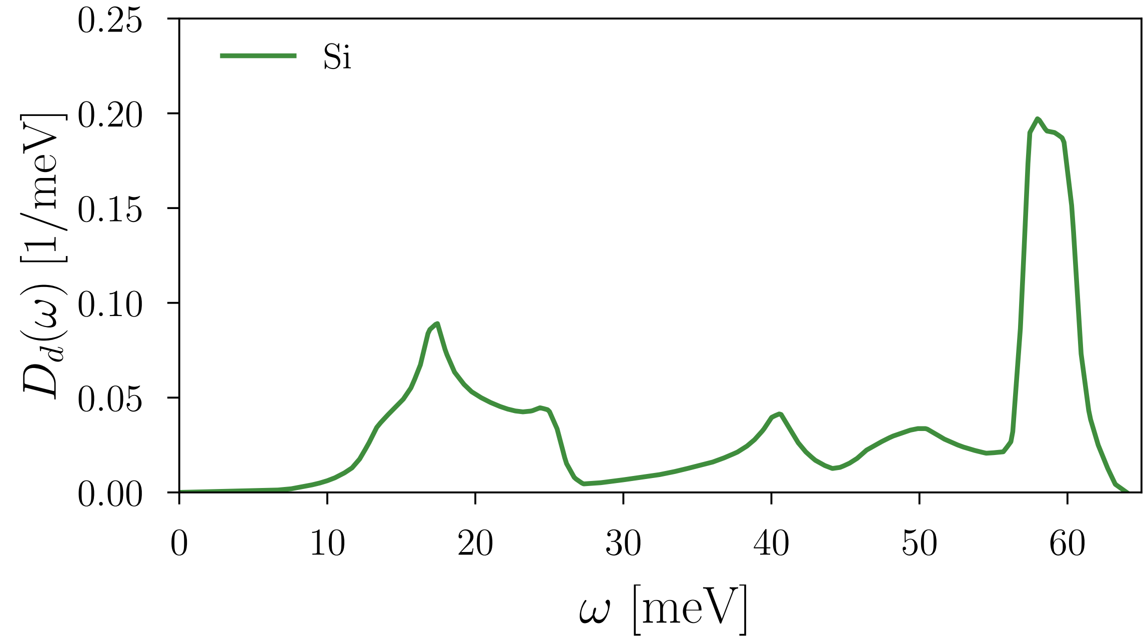
Motivation for $q > q_{\text{BZ}}$: scatter off individual nuclei at large q

Motivation for $n > 1$: momentum gets distributed over multiple phonons, and the motions of individual atoms will be less correlated.

Auto-correlation can be approximated using the phonon density of states

$$\langle \mathbf{q}\cdot\mathbf{u}_J(0)\mathbf{q}\cdot\mathbf{u}_J(t)\rangle \approx \frac{q^2}{2m_N}\int d\omega' \frac{D(\omega')}{\omega'} e^{i\omega' t}$$

In the harmonic, isotropic limit



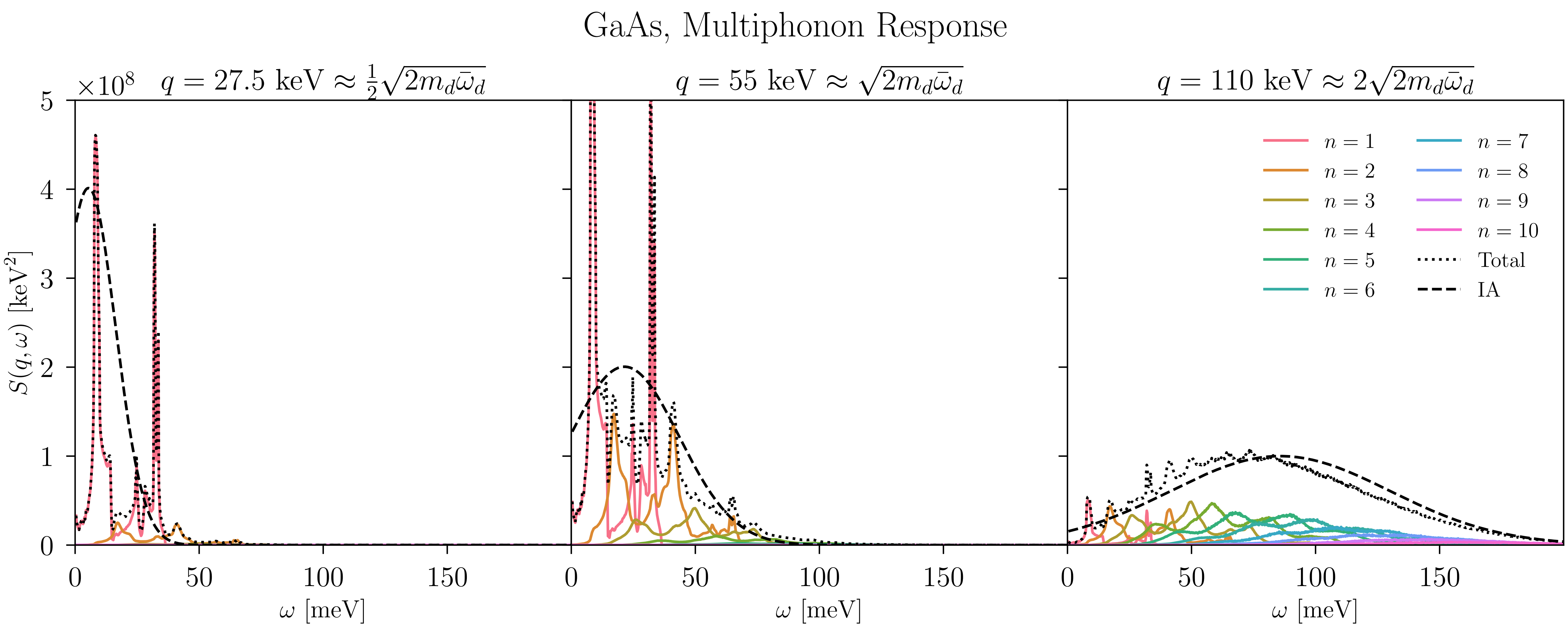
Dynamic structure factor with incoherent approximation:

$$S(q,\omega) \propto \sum_J e^{-2W_J(q)}(f_J)^2 \sum_n \frac{1}{n!}\left(\frac{q^2}{2m_N}\right)^n \left(\prod_{i=1}^n \int d\omega_i \frac{D(\omega_i)}{\omega_i}\right)\delta\left(\sum_j \omega_j - \omega\right)$$

$$\sim \left(\frac{q^2}{2m_N\bar{\omega}_{\rm ph}}\right)^n$$

$q \approx \sqrt{2m_N\bar{\omega}_{\rm ph}}$ for many phonons to contribute

Multiphonons become important around $q = \sqrt{2m_N\bar{\omega}_{\text{ph}}}$



$q = \frac{1}{2}\sqrt{2m_N\bar{\omega}_{\text{ph}}}$:
dominated by
n=1 phonon

$q = \sqrt{2m_N\bar{\omega}_{\text{ph}}}$:
contributions from
n=1,2,3,4…

$q = 2\sqrt{2m_N\bar{\omega}_{\text{ph}}}$:
can be approximated by
Gaussian envelope
(Impulse Approximation)

Campbell-Deem, Knapen, TL, Villarama PRD 2022

Impulse approximation

When $q \gg \sqrt{2m_N\bar{\omega}_{\rm ph}}$, "re-sum" the n-phonon contributions and directly evaluate by saddle-point approximation:

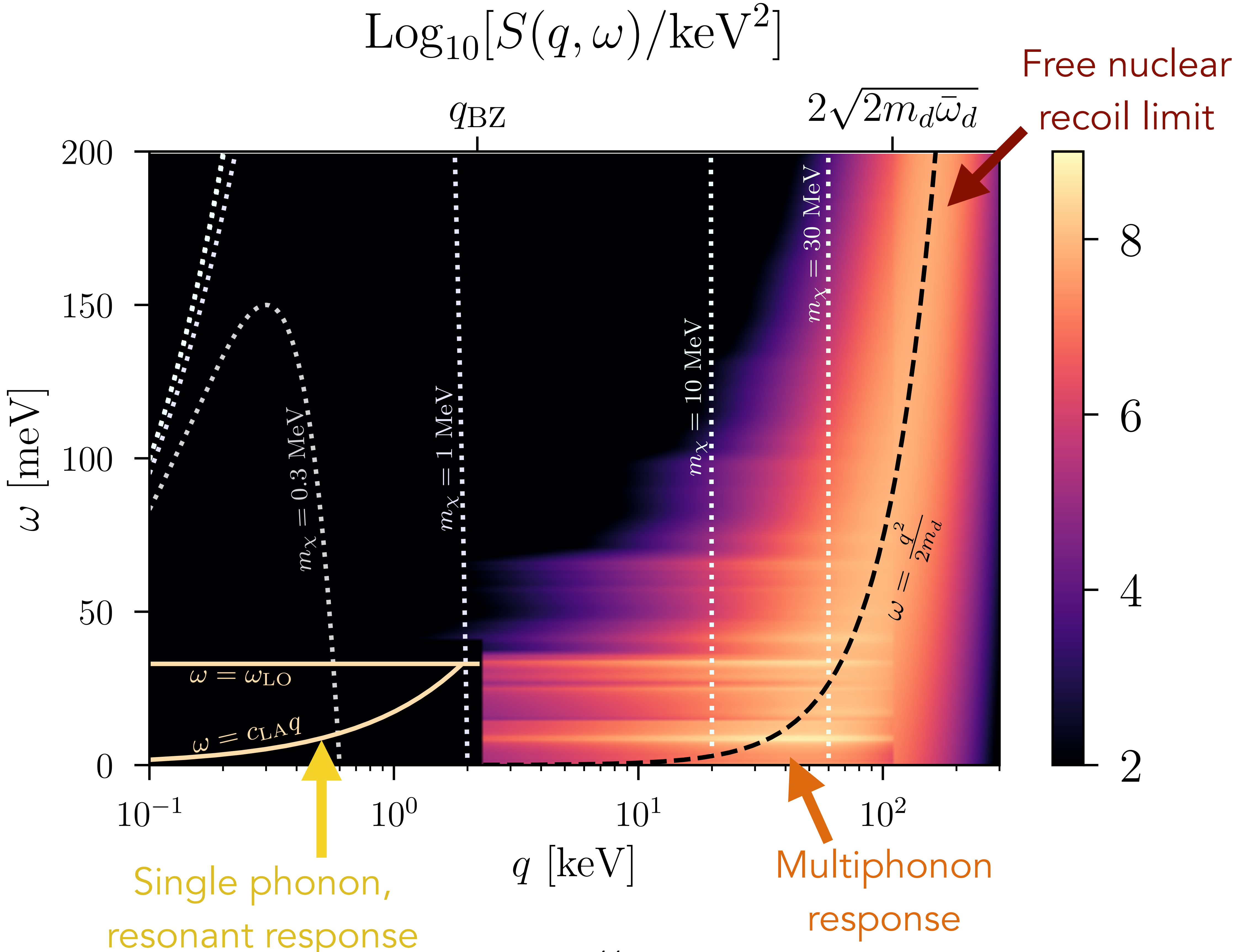
$$S^{\rm IA}(q,\omega) \propto \sum_J f_J^2 \sqrt{\frac{2\pi}{\Delta^2}} \exp\left(-\frac{(\omega - \frac{q^2}{2m_N})^2}{2\Delta^2}\right), \quad \Delta^2 = \frac{q^2\bar{\omega}_{\rm ph}}{2m_N}$$

As $\omega \gg \bar{\omega}_{\rm ph}$, $\Delta/\omega \to 0$, take narrow-width limit:

$$S(q,\omega) \propto \sum_J f_J^2 \; \delta\left(\omega - \frac{q^2}{2m_N}\right)$$

reproducing free nuclear recoils

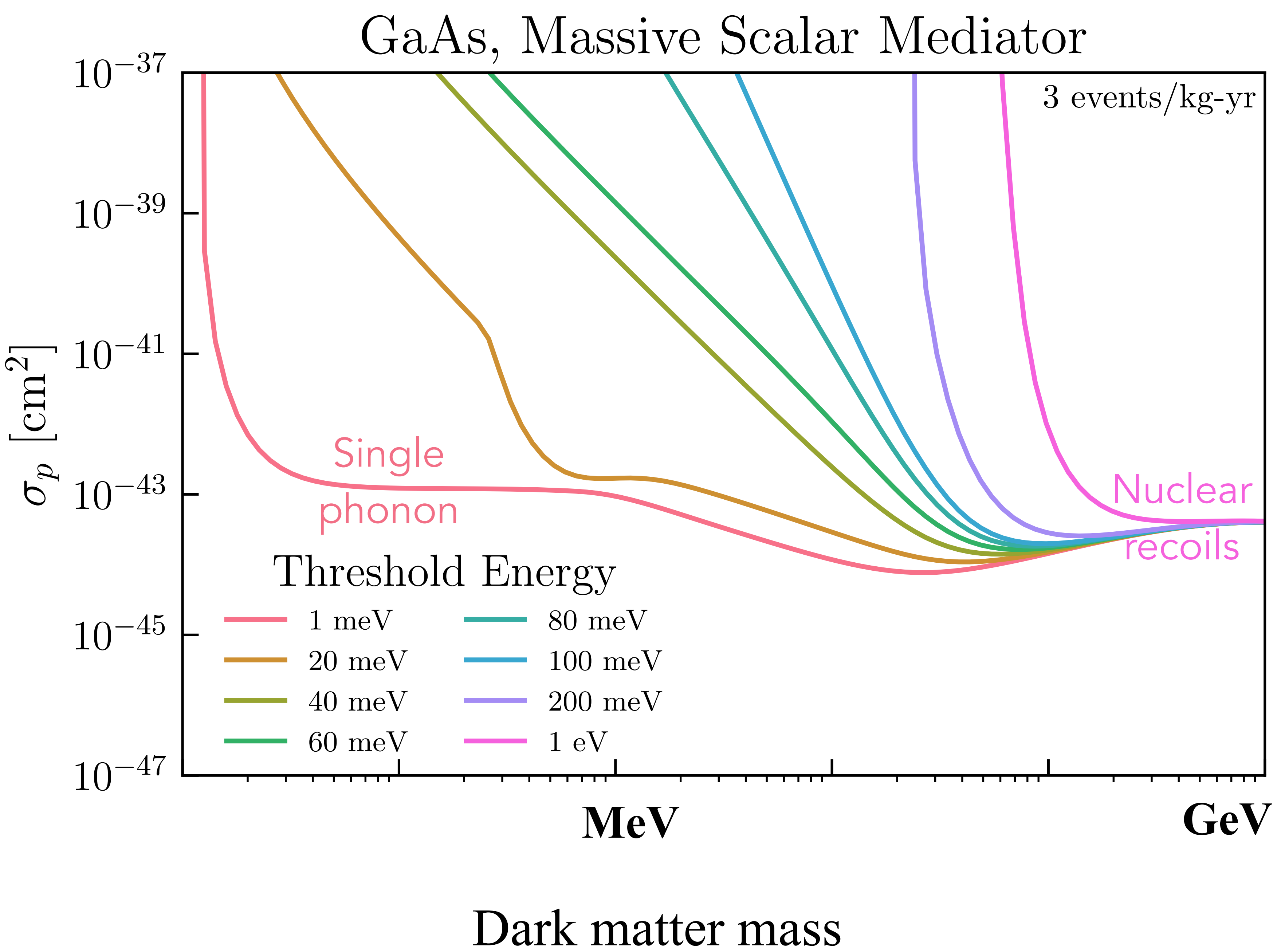
Response of GaAs semiconductor to DM-nucleus scattering



Campbell-Deem, Knapen, TL, Villarama PRD 2022

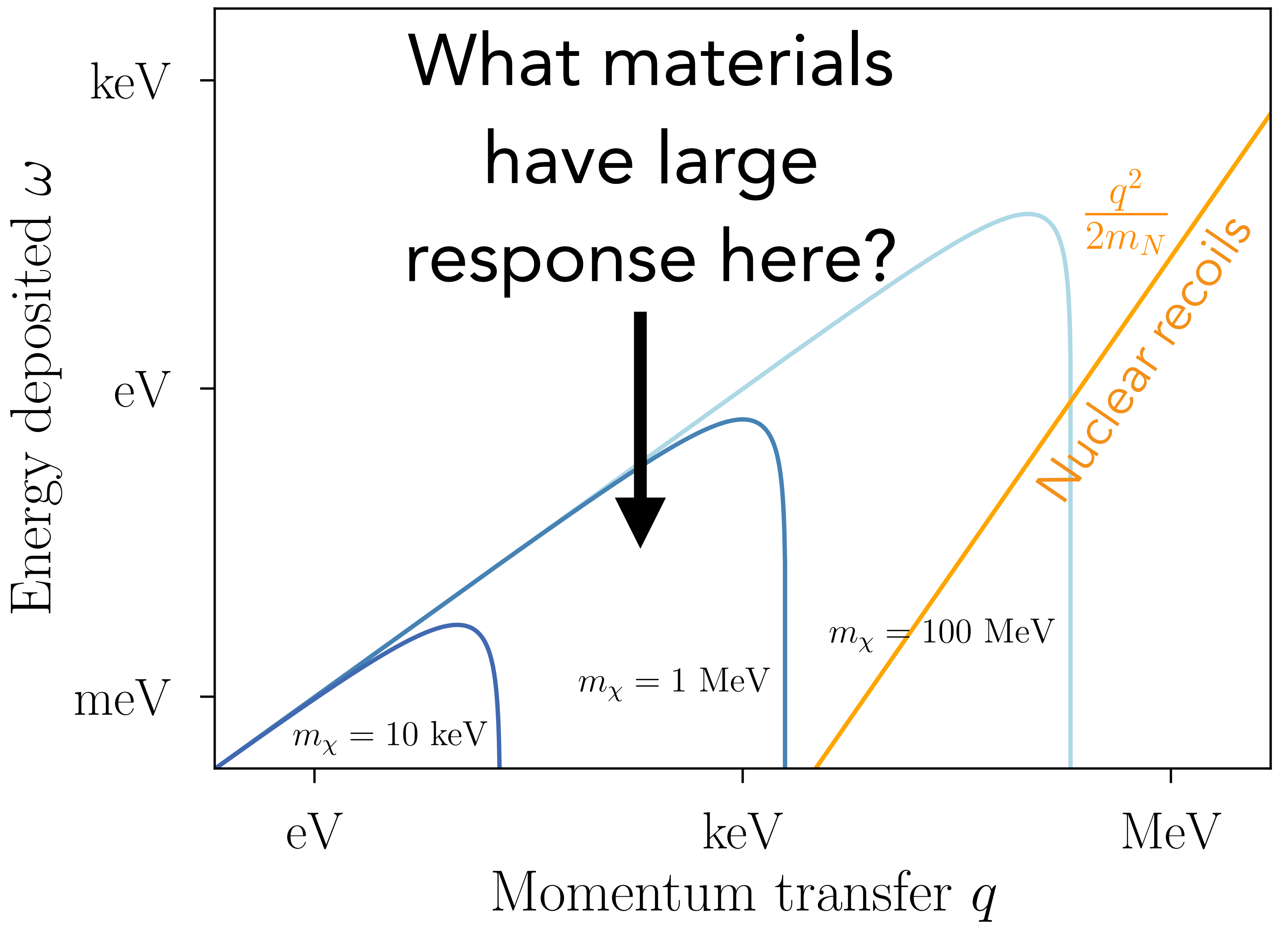
From single phonons to nuclear recoils

First steps towards describing DM-nucleus scattering into multiphonons.



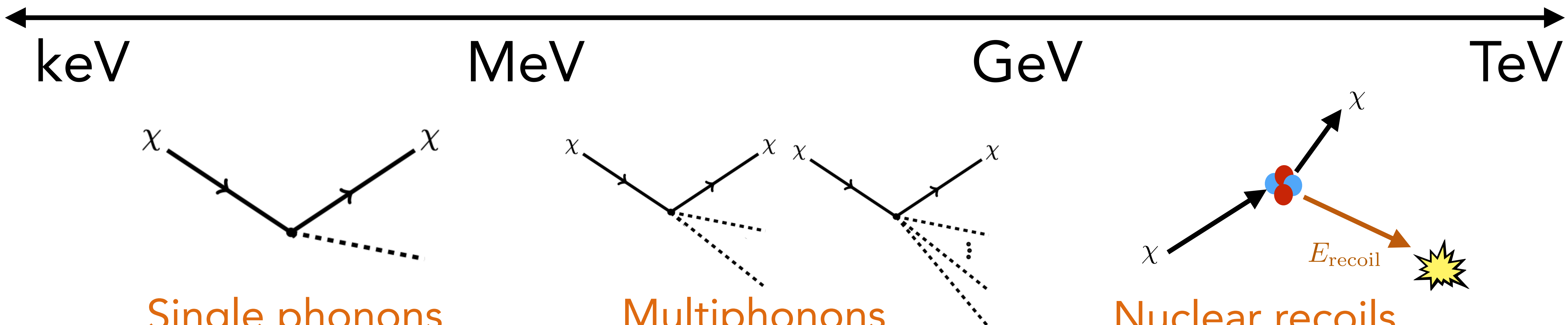
Campbell-Deem, Knapen, TL, Villarama PRD 2022
See also Kahn, Krnjaic, Mandava 2011.09477

Fruitful playground for DM searches and materials properties



A birds eye view of sub-GeV dark matter direct detection

Dark matter mass

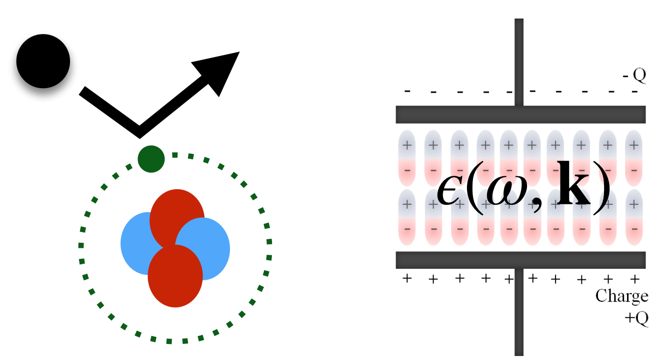


Single phonons

Multiphonons

Nuclear recoils

Semiconductors, polar crystals, superfluid helium, molecules, …



Electron excitations

Semiconductors, noble liquids (Xe), scintillators, superconductors, Dirac materials, organic scintillators, quantum dots, …