Dark matter direct detection with dielectrics

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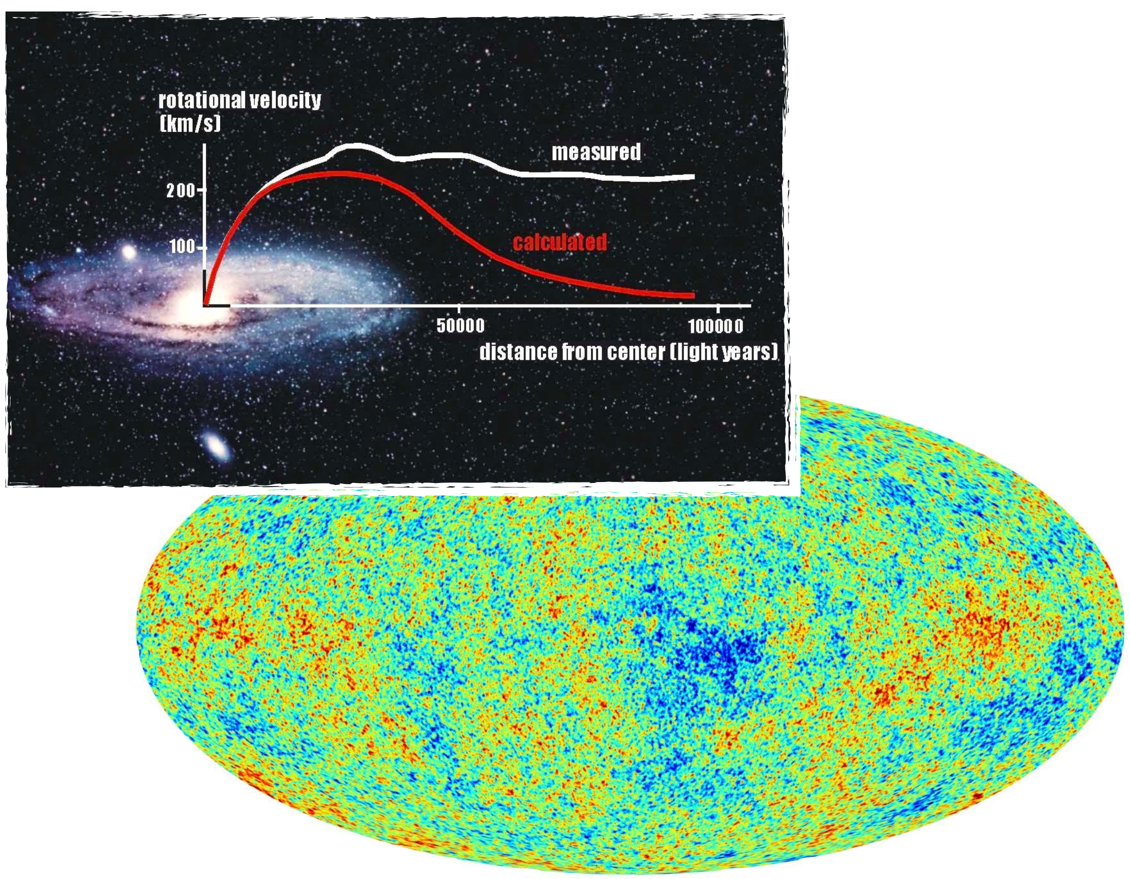
January 24, 2022
Heidelberg

Based on work with Simon Knapen and Jonathan Kozaczuk
2003.12077, 2011.09496, 2101.08275, 2104.12786

Dark matter: evidence and searches

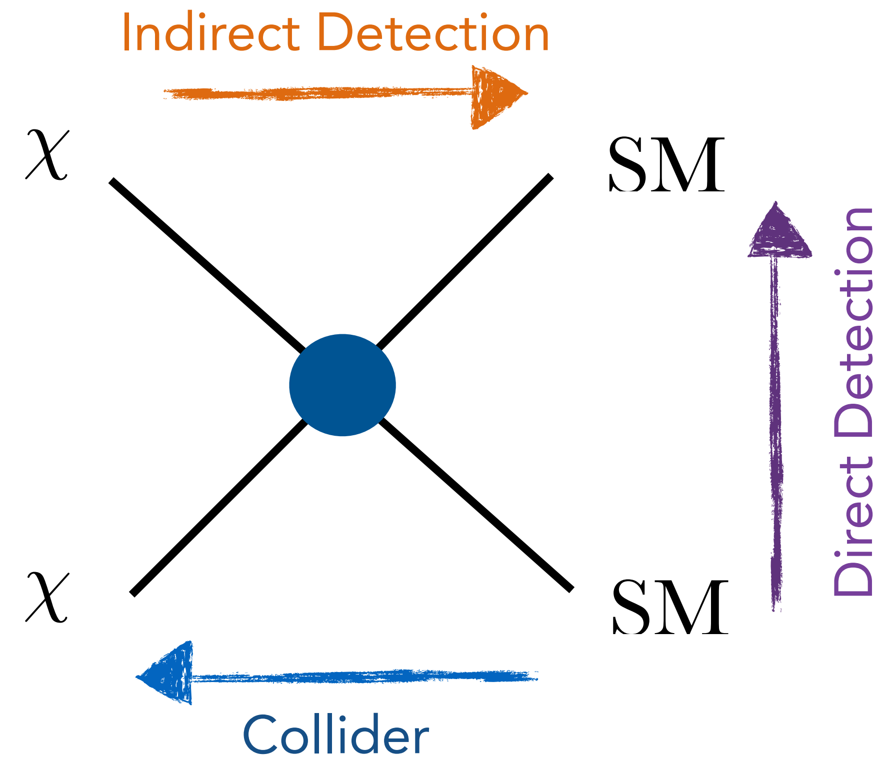
Gravitational evidence



Cosmic Microwave Background

Particle searches

- ⭐ Self-interactions
- ⭐ Many cosmo/astro probes



- ⭐ Electron scattering
- ⭐ Condensed mat systems

- ⭐ High Luminosity
- ⭐ Accelerator experiments

Motivation

Traditional approach to direct detection of dark matter: DM-nucleus scattering

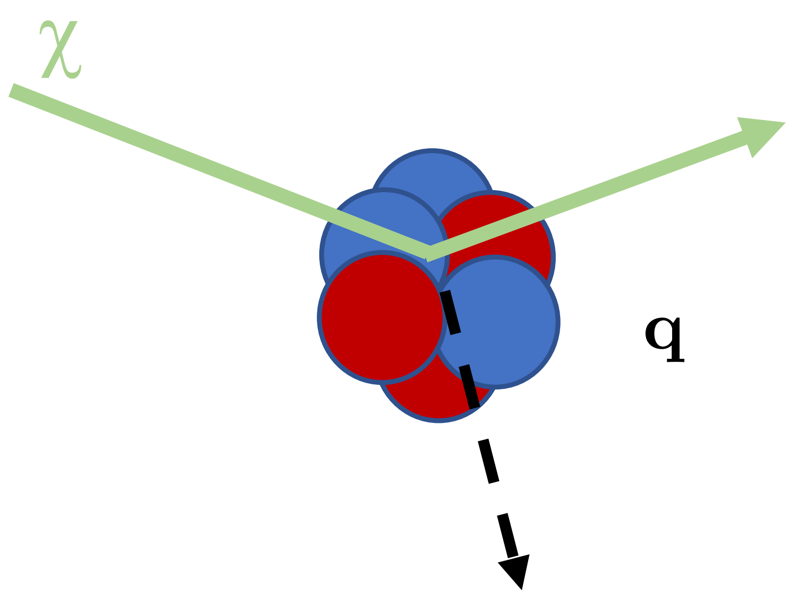
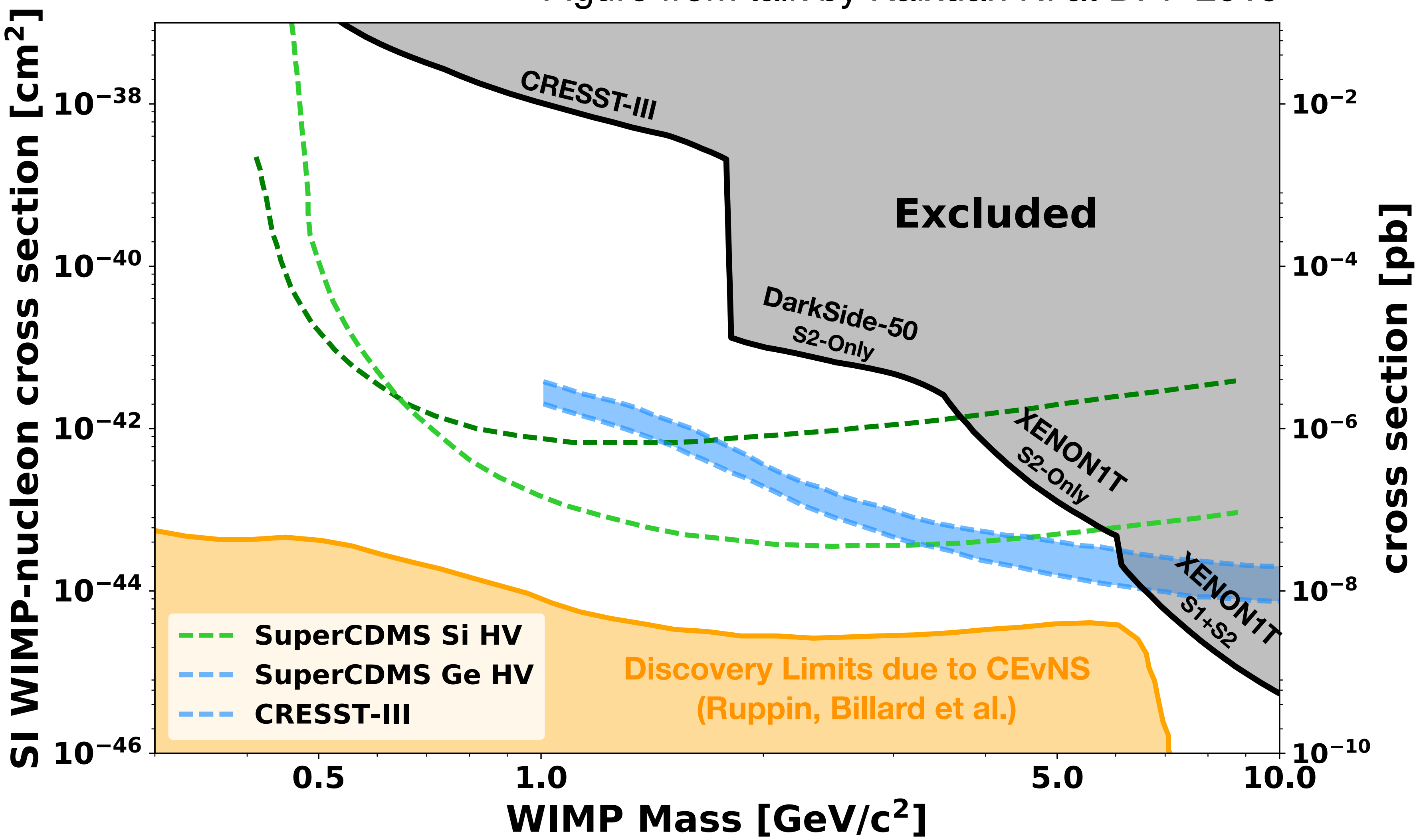


Figure from talk by Kaixuan Ni at DPF 2019



Challenges for sub-GeV DM

Kinematics of nuclear recoils from light dark matter

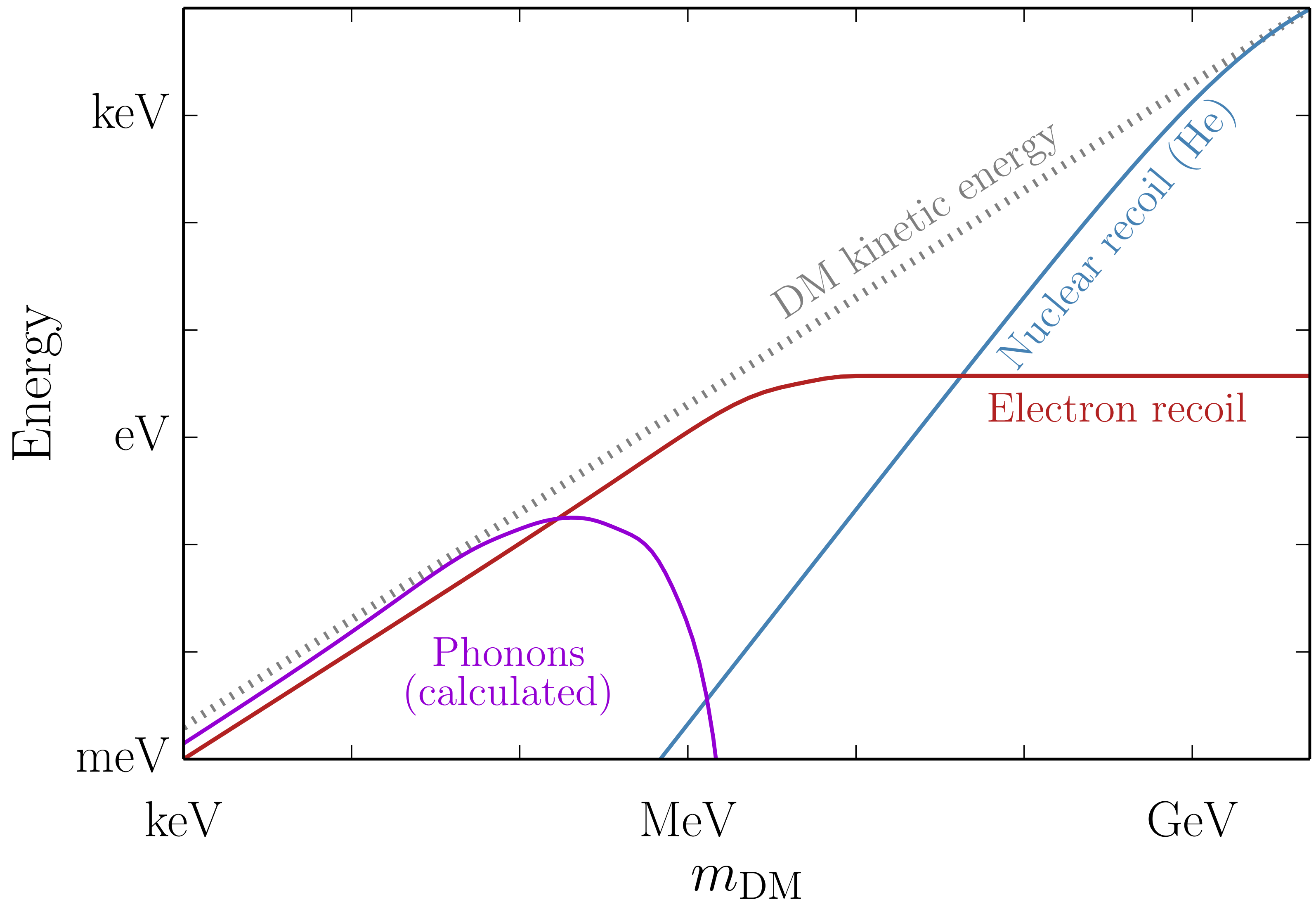
$$E_R = \frac{|\mathbf{q}|^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v^2}{m_N}$$

Drops quickly below $m_\chi \sim 10$ GeV

Best nuclear recoil threshold is currently $E_R > 30$ eV (CRESST-III) with DM reach of $m_\chi > 160$ MeV.

The kinematics of DM scattering against **free** nuclei is inefficient, and it does not describe target response accurately at low energies.

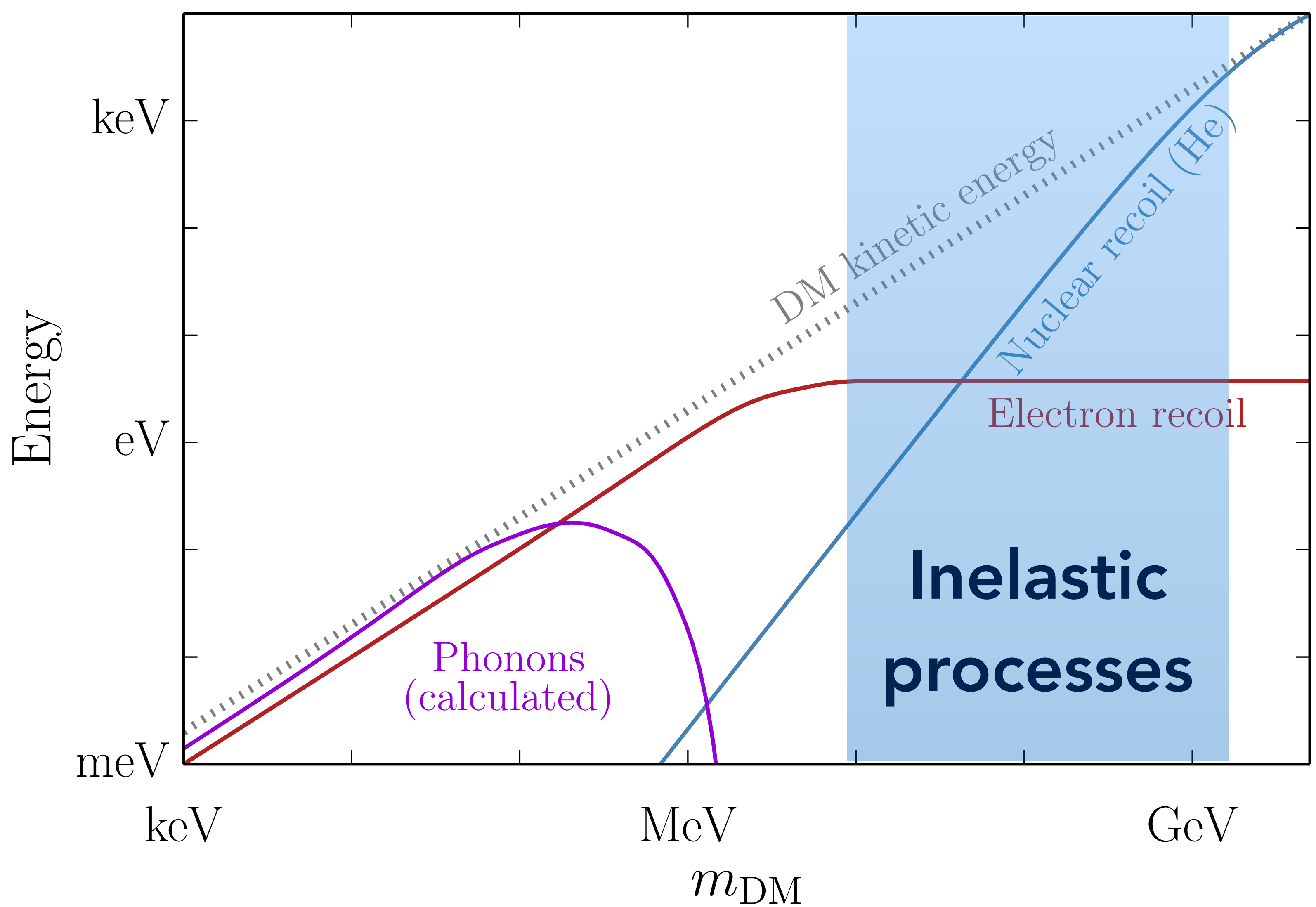
Material response to DM



Nuclear response is phonon-dominated at low energies.

Electronic response depends on details of band structure/eigenstates.

Material response to DM



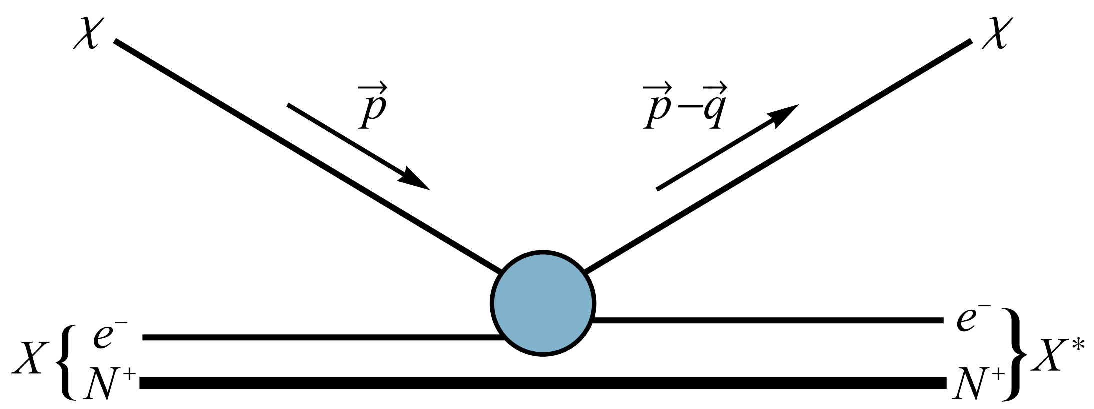
Inelastic nuclear recoils or 2 → 3 processes can extract more DM kinetic energy, and give charge signals from nuclear recoils.

Outline

Describing DM-electron scattering in terms of dielectric response $\epsilon(\omega, \mathbf{k})$

Inelastic processes: describing the Migdal effect in terms of $\epsilon(\omega, \mathbf{k})$

Electron recoils



e- in materials are not free or isolated particles

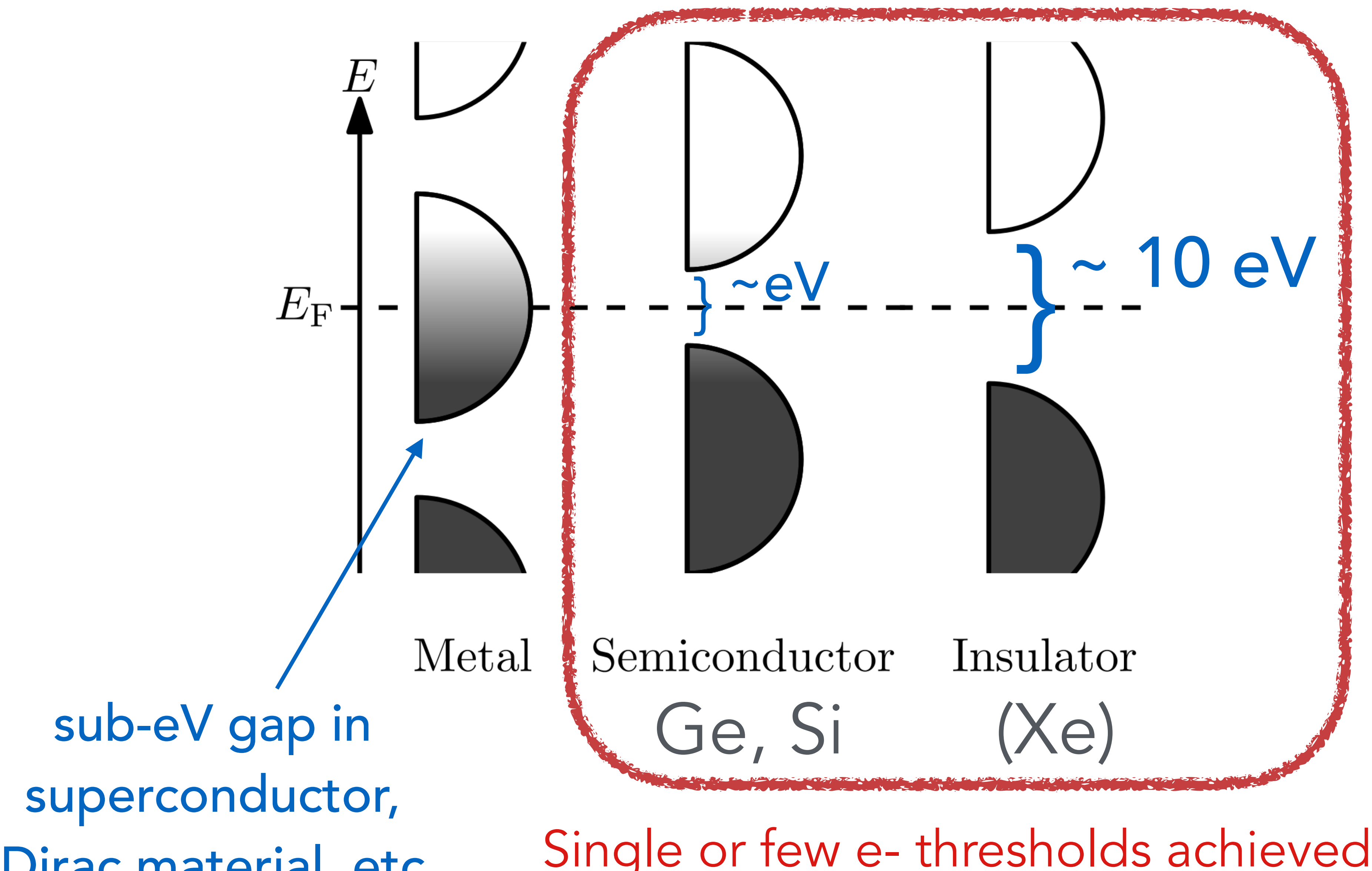
Opportunity: constrained by available energy eigenstates rather than free-particle kinematics.

Complication: need to know eigenstates and wavefunctions in a many-body system.

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

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

Electronic band structure

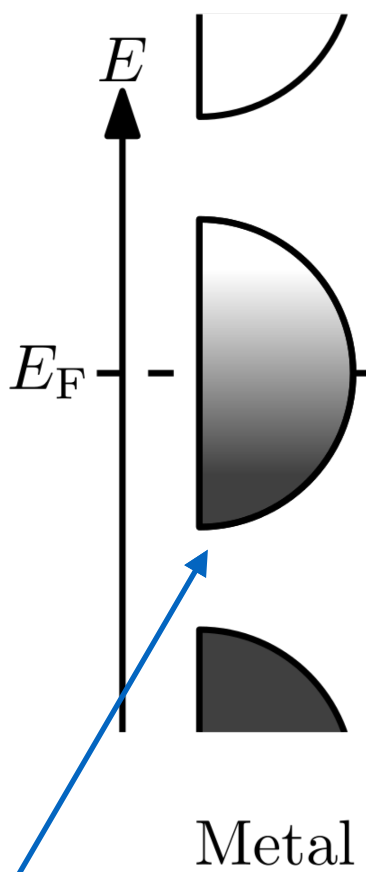


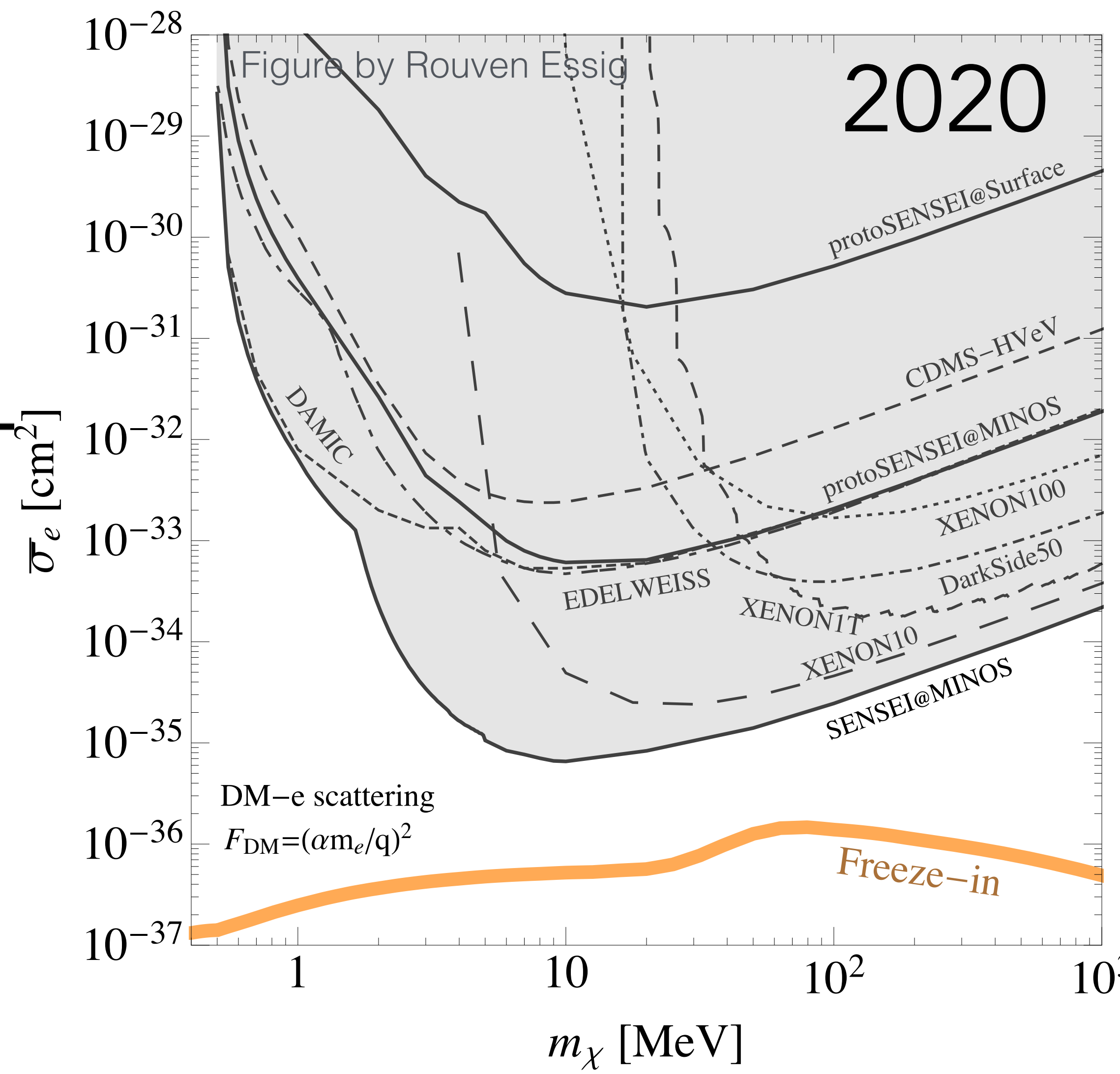
[Hochberg, Pyle, Zhao, Zurek 2015
Dirac: 1708.08929, 1910.02091, etc]

Single or few e- thresholds achieved in a number of experiments

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

Electronic band structure





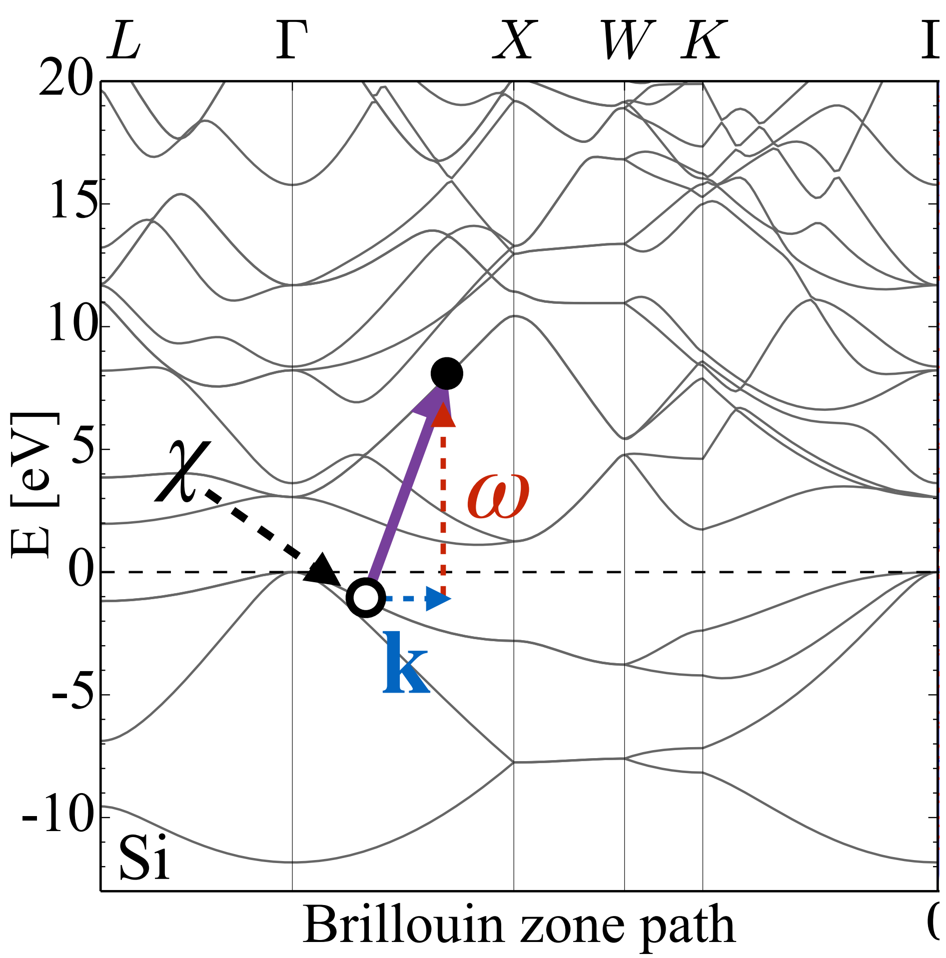
sub-eV gap in superconductor, Dirac material, etc

[Hochberg, Pyle, Zhao, Zurek 2015
Dirac: 1708.08929, 1910.02091, etc]

Single or few e- thresholds achieved in a number of experiments

Complication: need to know about excitations in a many-body system.

Semiconductor target



Independent particle approximation:

Wavefunction overlap

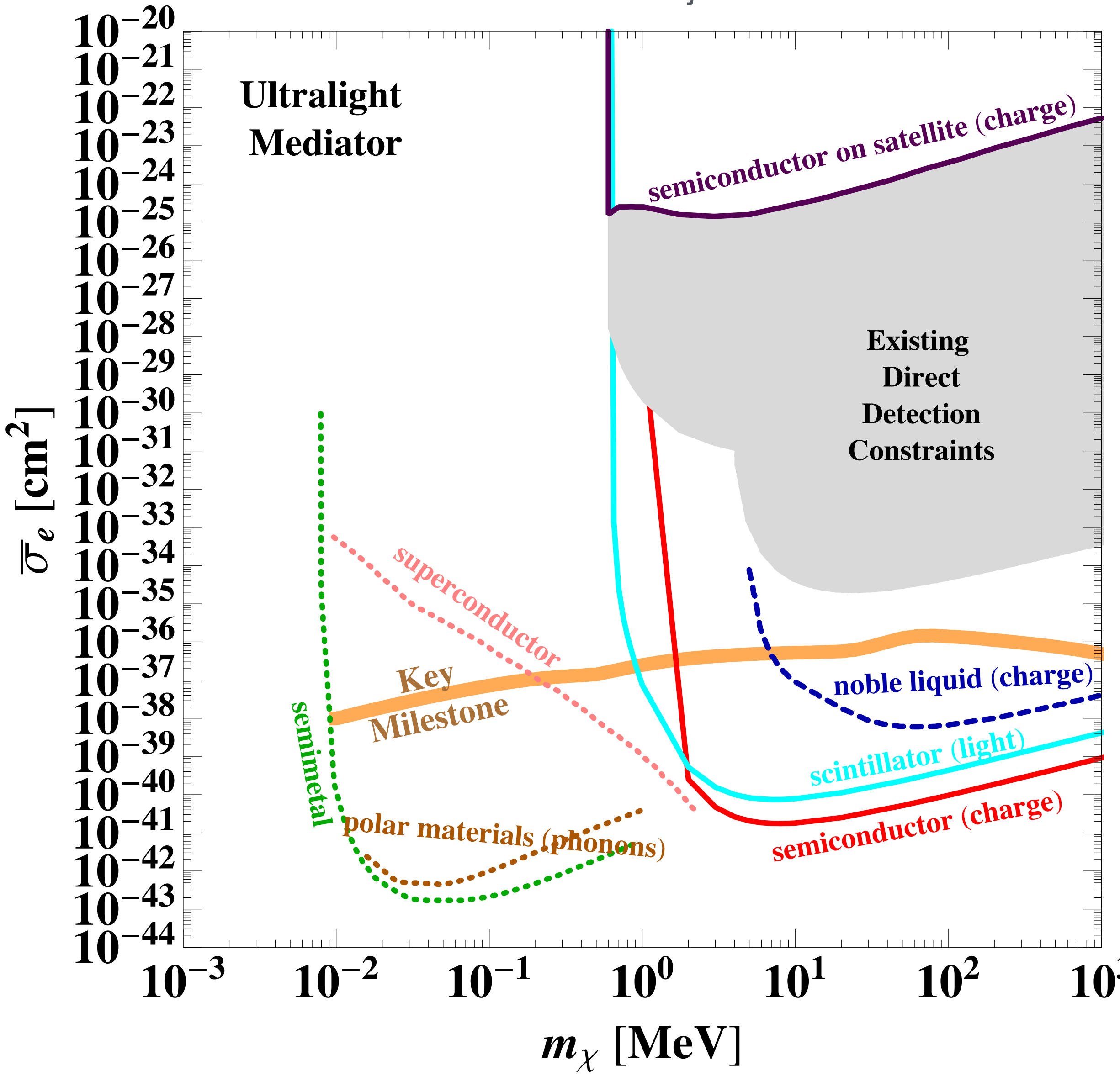
$$\frac{d\sigma}{d^3\mathbf{k}d\omega} \propto \bar{\sigma}_e F^2_{\mathrm{med}}(k) \sum_{\ell,\ell'} \sum_{\mathbf{p},\mathbf{p}'} |\langle \mathbf{p}',\ell' | e^{i\mathbf{k}\cdot\mathbf{r}} | \mathbf{p},\ell\rangle|^2$$
$$\times f^0(\omega_{\mathbf{p},\ell})\big(1-f^0(\omega_{\mathbf{p}',\ell'})\big)\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

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

Does this capture all many-body effects?

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

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

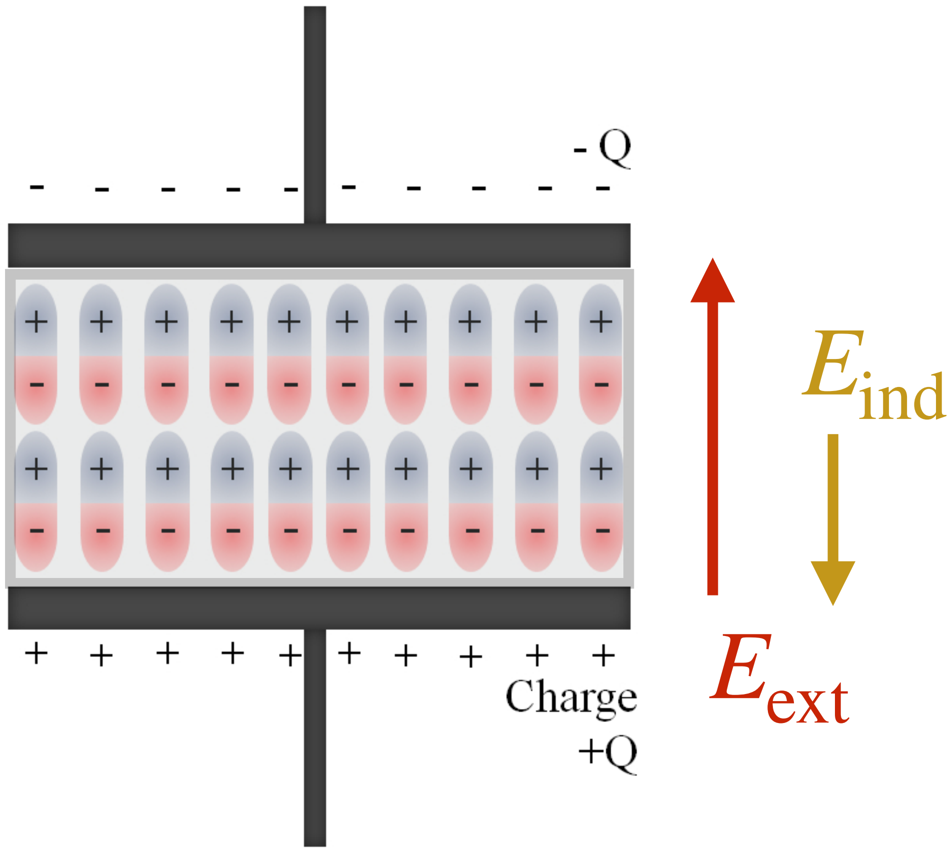


Now many papers studying different targets, proposed experiments, and new experiments in development.

All dielectrics

Today: how to describe DM-electron scattering in all these materials in terms of dielectric response function.

Dielectric response



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

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

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:

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

Dissipation

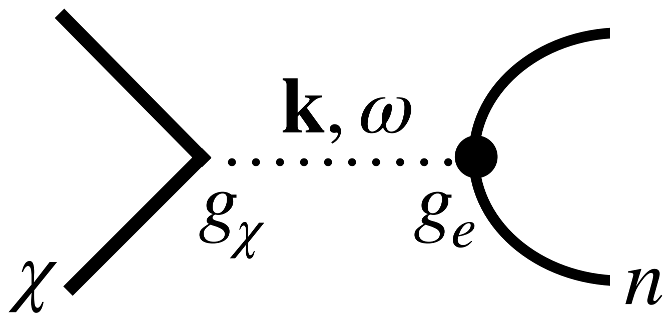
DM-electron scattering rate is determined by ELF:

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

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

ELF for Dark Matter

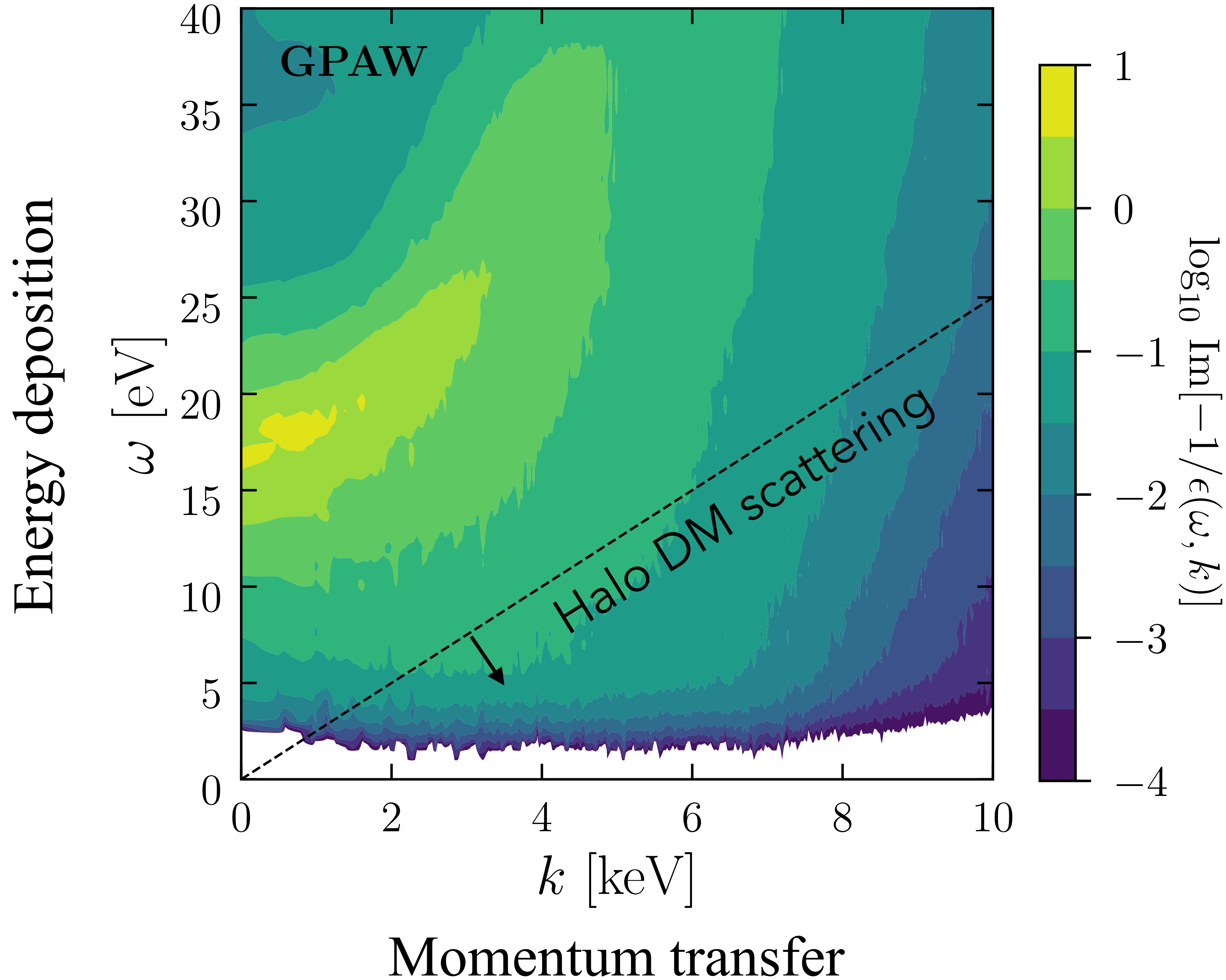
DM-electron scattering with scalar or vector mediators:



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

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

Response of Silicon semiconductor to electron interactions



Knapen, Kozaczuk, TL 2101.08275, 2104.12786

Screening effects

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

$$\propto \bar{\sigma}_e F^2_{\text{med}}(\mathbf{k})\frac{\text{Im}\,\epsilon(\omega,\mathbf{k})}{|\epsilon(\omega,\mathbf{k})|^2}$$

Proportional to DM-electron scattering form factor in the independent-electron approximation (RPA)

$$\text{Im}\,\epsilon^{\text{RPA}}(\omega,\mathbf{k}) = \frac{4\pi^2\alpha_{em}}{Vk^2}\sum_{\ell,\ell'}\sum_{\mathbf{p},\mathbf{p}'}|\langle\mathbf{p}',\ell'|e^{i\mathbf{k}\cdot\mathbf{r}}|\mathbf{p},\ell\rangle|^2$$
$$\times f^0(\omega_{\mathbf{p},\ell})\big(1-f^0(\omega_{\mathbf{p}',\ell'})\big)\;\delta(\omega+\omega_{\mathbf{p},\ell}-\omega_{\mathbf{p}',\ell'})$$

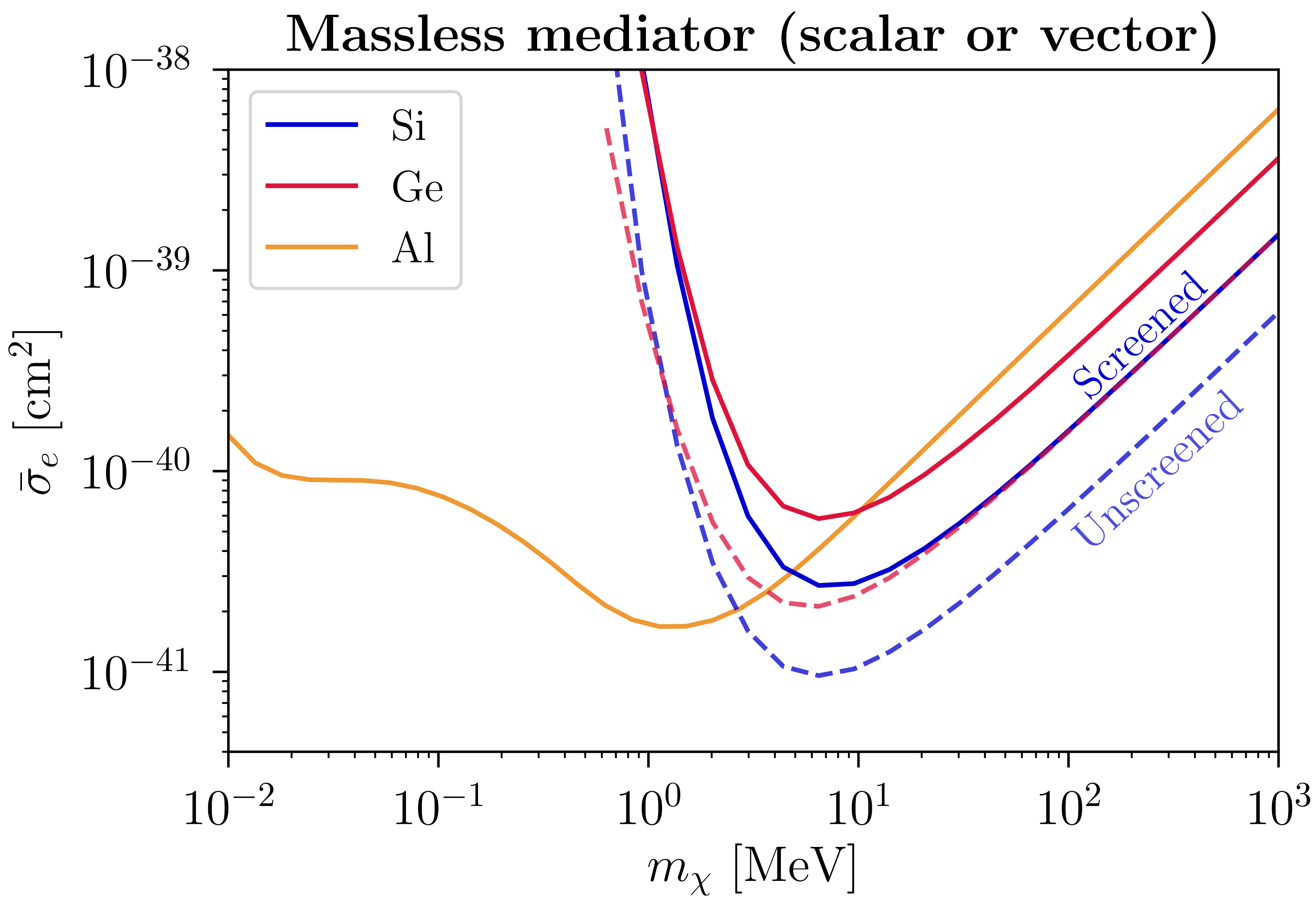
$|\epsilon(\omega,\mathbf{k})|^2$ screening for vector mediators considered in superconductors, Dirac materials.

Not previously included in signal rates for semiconductors.

Also not previously included for scalar mediators.

Impact for DM-electron scattering

Using the ELF automatically incorporates screening effects:



Knapen, TL, Kozaczuk 2101.08275

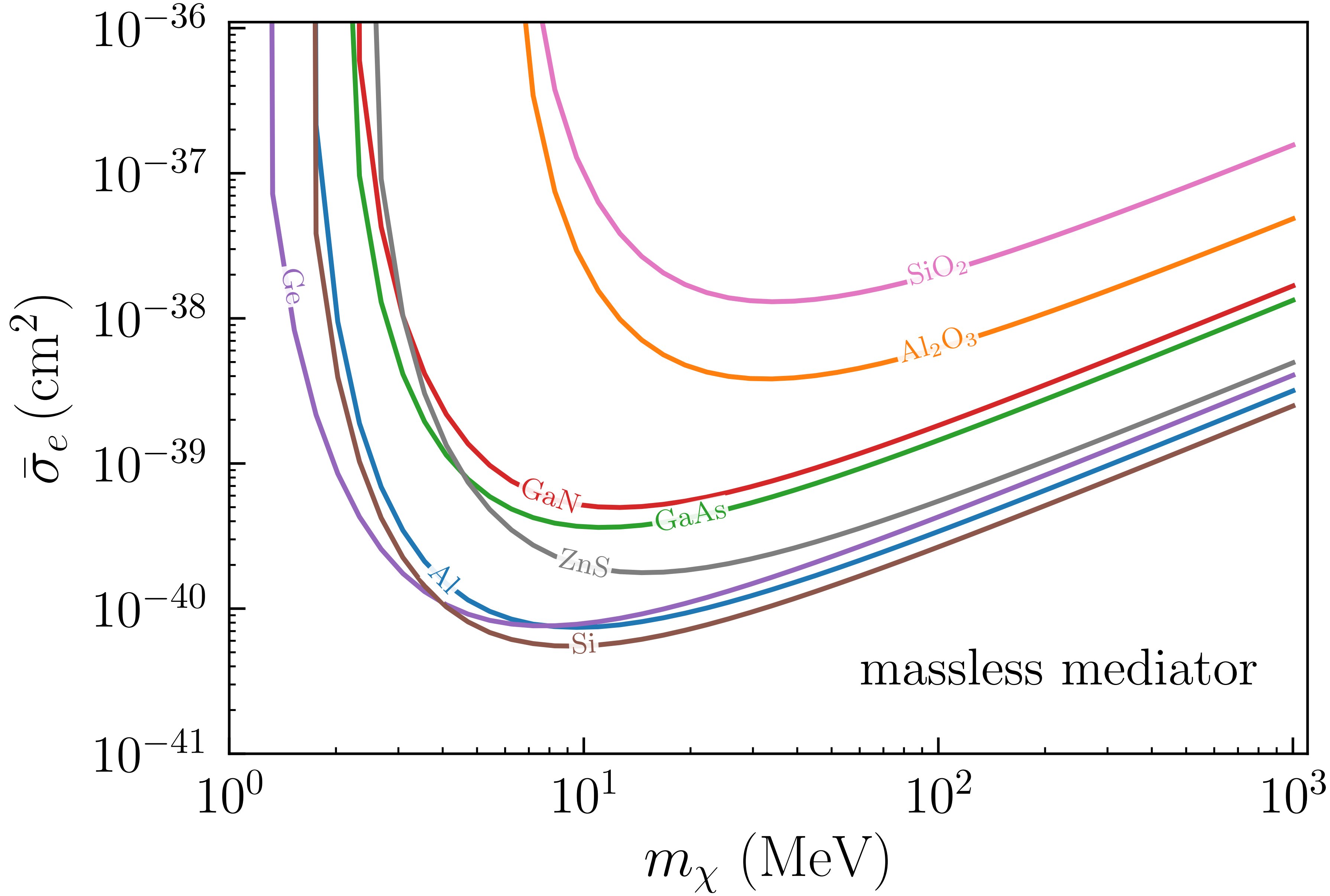
Additional effects of core electrons included in Griffin, Inzani, Trickle, Zhang, Zurek 2105.05253

The energy loss function (ELF)

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

Theory	Experiment
Many established approaches to ϵ	Optical measurements
Include screening, local field effects	X-ray scattering
Include electron-electron interactions	Fast electron scattering (EELS)

Fast target material comparison



2e- threshold using data-driven Mermin method for ELF

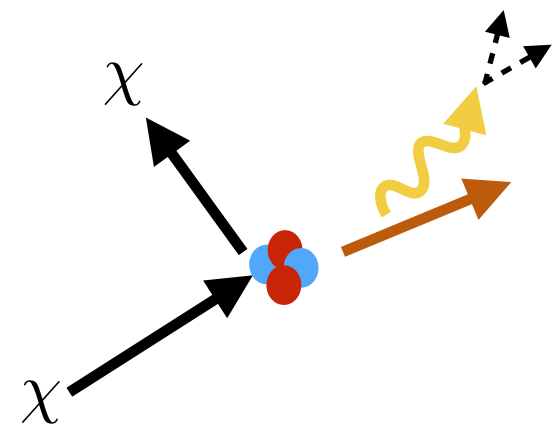
Si, Ge particularly good due to lower thresholds

Knapen, TL, Kozaczuk, 2104.12786

ELF for Dark Matter

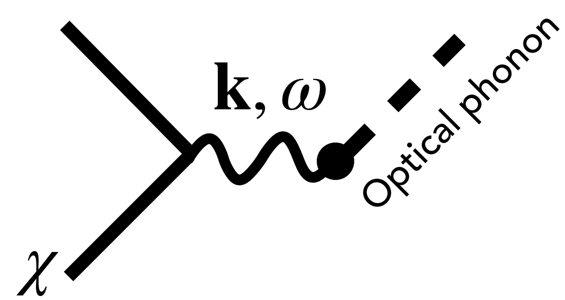
DarkELF: python package for dark matter energy loss processes with tabulated ELFs for a variety of materials (incl. Si, Ge, GaAs)
https://github.com/tongylin/DarkELF

DM-nucleus scattering via Migdal effect



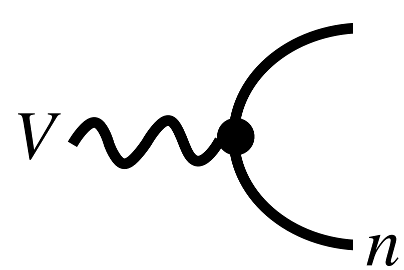
$$\frac{dP}{d^3\mathbf{k}d\omega} \propto \frac{4\pi\alpha_{em}Z_{\text{ion}}^2}{\omega^4}\frac{|\mathbf{v_N}\cdot\mathbf{k}|^2}{k^2}\text{Im}\left(\frac{-1}{\epsilon(\omega,\mathbf{k})}\right)$$

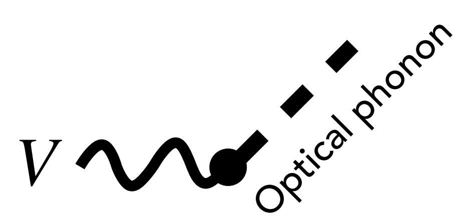
DM-phonon scattering



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

Bosonic DM absorption

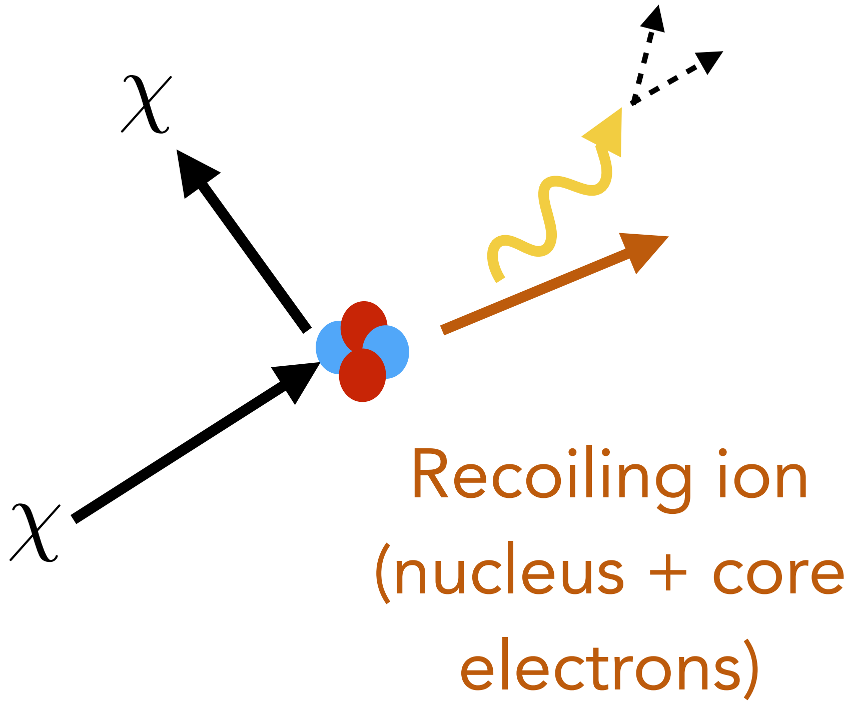




$$R = \frac{1}{\rho_T}\frac{\rho_{\text{DM}}}{m_V}\kappa^2 m_V\,\text{Im}\left(\frac{-1}{\epsilon(\omega,\mathbf{k})}\right)$$

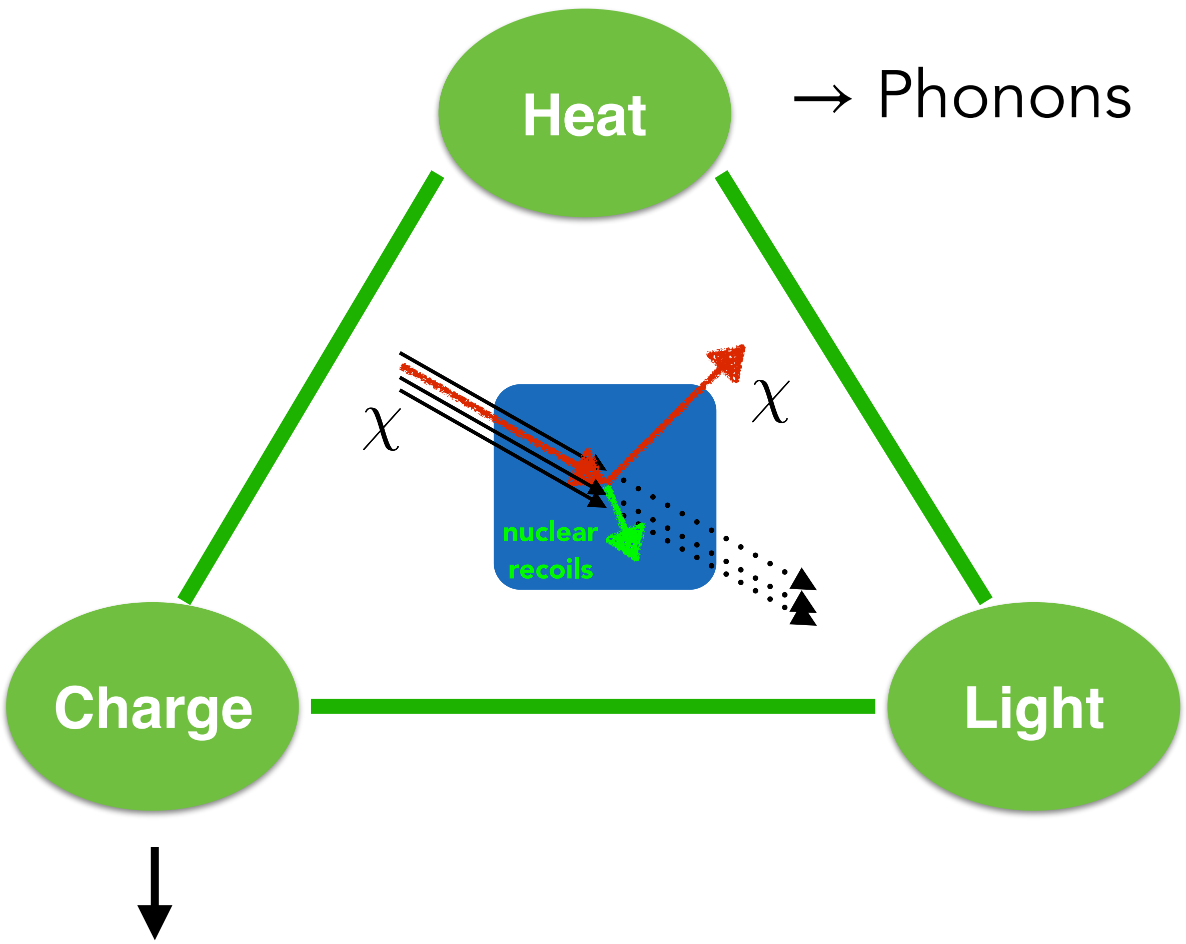
Knapen, Kozaczuk, TL 2101.08275, 2104.12786
Knapen Kozaczuk, TL 2003.12077, 2011.09496

Detecting nuclear recoils via the Migdal effect



With Jonathan Kozaczuk (2003.12077)
and with Jonathan Kozaczuk and Simon Knapen (2011.09496)

Challenges of low-energy nuclear recoils



→ Phonons

→ Scintillation photons

ionized atoms or electron-hole pairs in semiconductors

The charge and light yield for nuclear recoils below few hundred eV is not well understood, but expected to be ~0 on average.

Graphic from talk by Kaixuan Ni

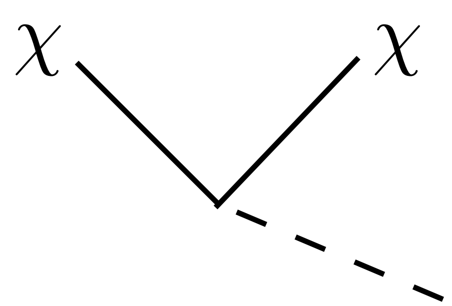
Strategies for detecting nuclear recoils from sub-GeV DM

1. Decreasing the heat threshold

- Detectors in development to reach heat/phonon thresholds of ~ eV and below (e.g. SuperCDMS SNOLAB)

- Direct phonon excitations from DM scattering
  $\omega \approx 1 - 100$ meV for acoustic and optical phonons in crystals
  (e.g. phonons: Griffin, Knapen, TL, Zurek 2018; molecules: Essig, Perez-Rios, Ramani, Slone 2019)

DM-phonon scattering

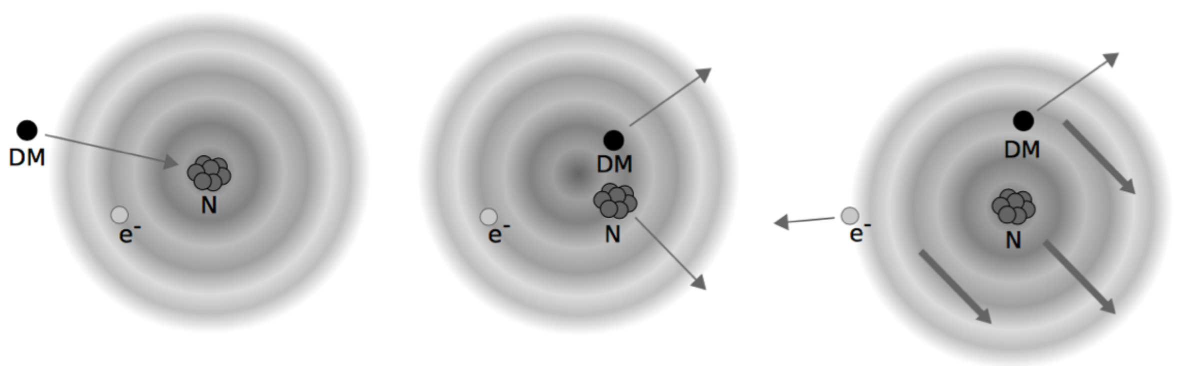


Kinematics of phonons relevant (and advantageous) for sub-MeV dark matter

Strategies for detecting nuclear recoils from sub-GeV DM

2. Increasing the charge signal

- Atomic Migdal effect
  Ionization of electrons
  which have to 'catch up'
  to recoiling nucleus
  (e.g. Ibe, Nakano, Shoji, Suzuki 2017)



From 1711.09906 (Dolan et al.)

- Bremsstrahlung of (transverse) photons in LXe
  Kouvaris & Pradler 2016

Strategies for detecting nuclear recoils from sub-GeV DM

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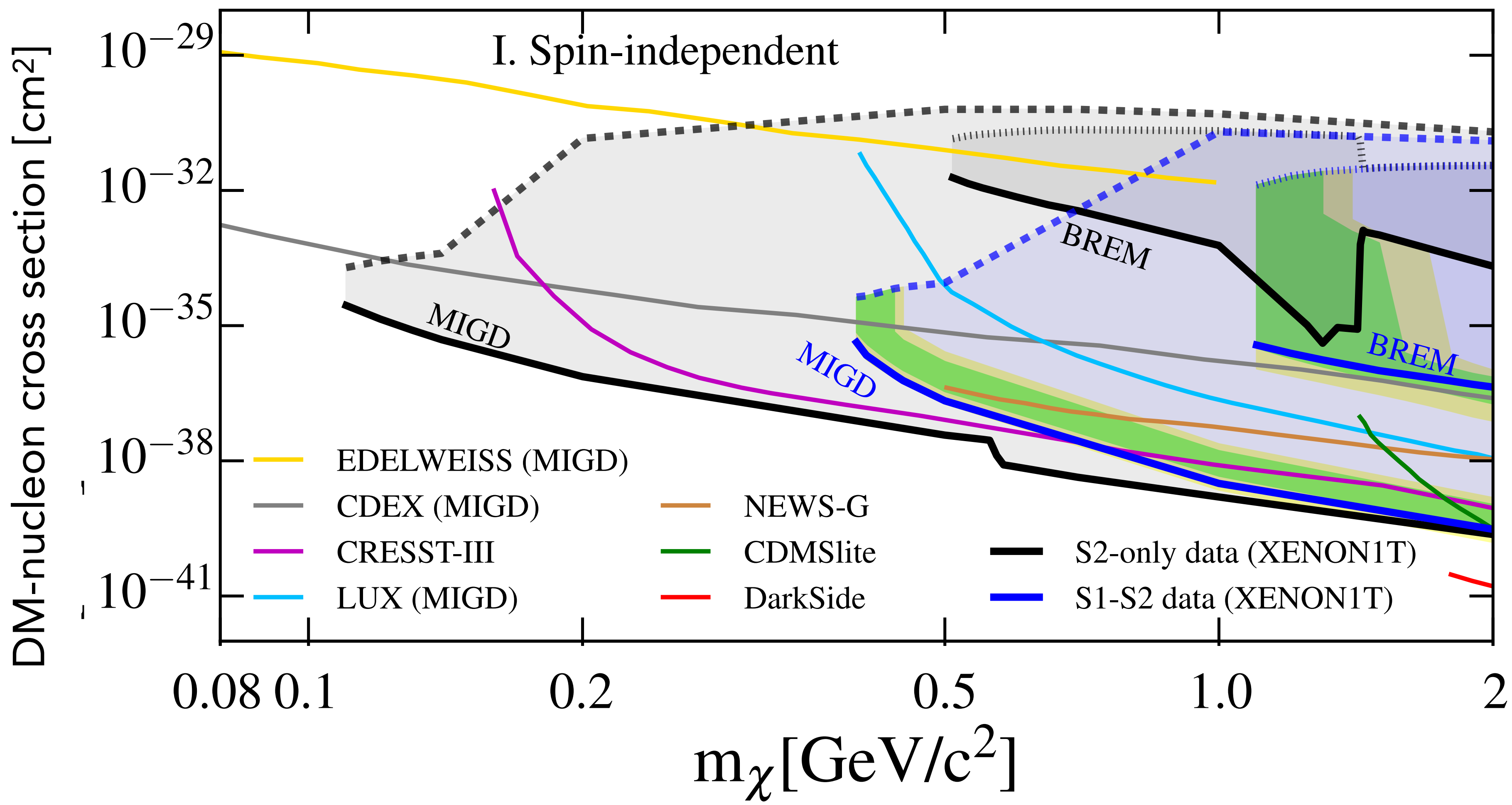

Results from XENON1T search (PRL 2019)

Strategies for detecting nuclear recoils from sub-GeV DM

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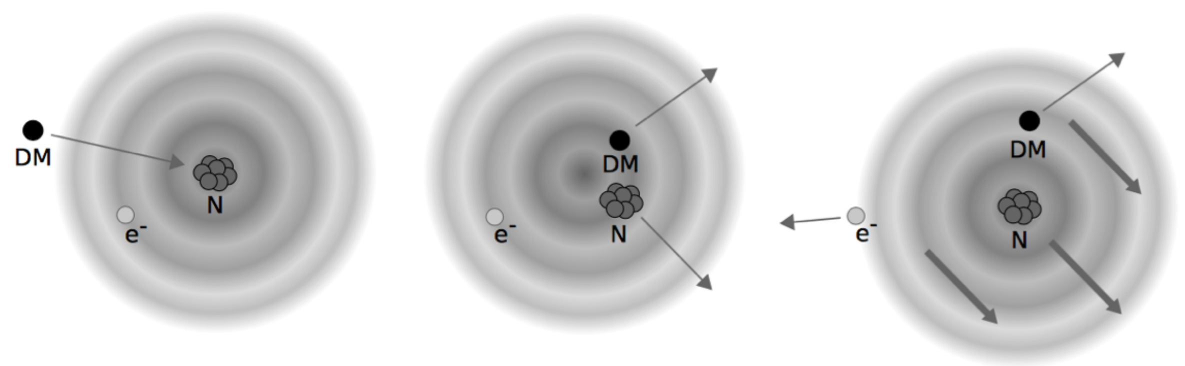


From 1711.09906 (Dolan et al.)

- Bremsstrahlung of (transverse) photons in LXe
  Kouvaris & Pradler 2016
- **Migdal effect in semiconductors with lower thresholds**

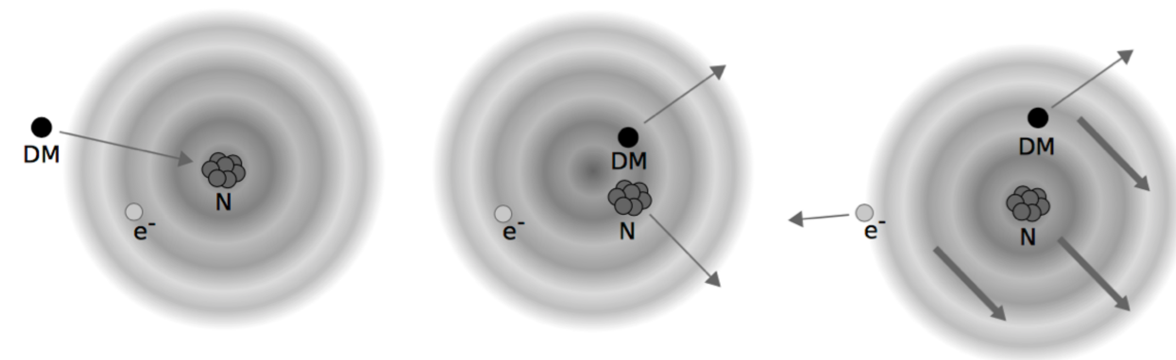
Atomic Migdal effect

Electrons have to 'catch up' to recoiling nucleus

Boost initial state to frame of moving nucleus:

$$|i\rangle \to e^{im_e \mathbf{v}_N \cdot \sum_\beta \mathbf{r}_\beta} |i\rangle$$

From 1711.09906 (Dolan, Kahlhoefer, McCabe)



Nucleus recoils with velocity $\mathbf{v}_N$

Transition probability $|\mathcal{M}_{if}|^2$

$$\mathcal{M}_{if} = \langle f | \, e^{im_e \mathbf{v}_N \cdot \sum_\beta \mathbf{r}_\beta} \, |i\rangle \approx i m_e \langle f | \, \mathbf{v}_N \cdot \sum_\beta \mathbf{r}_\beta \, |i\rangle$$

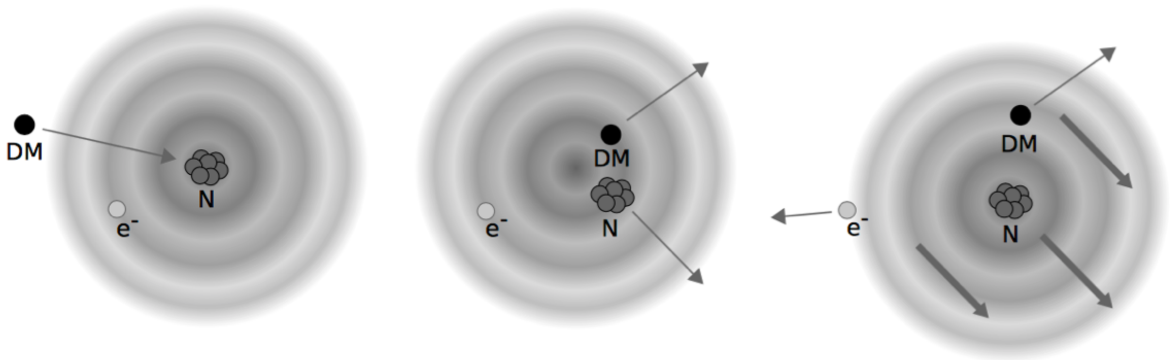
Small probability for "shake-off" electron, but allows low-energy nuclear recoil to be above the e- recoil threshold

Ibe, Nakano, Shoji, Suzuki 2017
Dolan, Kahlhoefer, McCabe 2017
Bell, Dent, Newstead, Sabharwal, Weiler 2019

Atomic Migdal effect

Boost initial state to frame of moving nucleus:

$$|i\rangle \to e^{im_e \mathbf{v}_N \cdot \sum_\beta \mathbf{r}_\beta} |i\rangle$$



Nucleus recoils with velocity $\mathbf{v}_N$

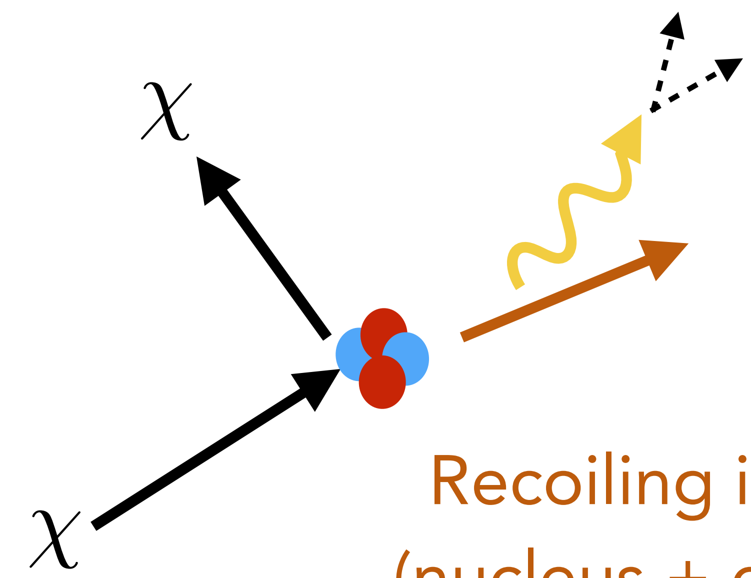
Problem: applying this to semiconductors does not work. Boosting argument does not apply because of crystal lattice.

The Migdal effect as bremsstrahlung

Bremsstrahlung calculation

$$\chi + N \to \chi + N + e^-$$

treating N as nucleus with tightly bound core electrons. Valid for $10 \text{ MeV} \lesssim m_\chi \lesssim 1 \text{ GeV}$.



Usual DM-nucleus scattering

$$\frac{d\sigma}{d\omega} = \frac{2\pi^2 A^2 \sigma_n}{m_\chi^2 v_\chi} \int \frac{d^3\mathbf{q}_N}{(2\pi)^3} \int \frac{d^3\mathbf{p}_f}{(2\pi)^3} \delta(E_i - E_f - \omega - E_N) \times \int \frac{d^3\mathbf{k}}{(2\pi)^3} F(\mathbf{p}_i - \mathbf{p}_f - \mathbf{q}_N - \mathbf{k})^2$$
$$\times 4\alpha_{em} Z_{\text{ion}}^2 \left[\frac{1}{\omega - \mathbf{q}_N \cdot \mathbf{k}/m_N} - \frac{1}{\omega} \right]^2 \text{Im}\left(\frac{-1}{\epsilon(\omega, \mathbf{k})} \right)$$

Form factor accounting for multiphonon response in a harmonic crystal

Differential probability of ion to excite an electron

Knapen Kozaczuk, TL 2011.09496

Relation with atomic Migdal effect

From boosting argument:

$$im_e \langle f| \mathbf{v}_N \cdot \sum_\beta \mathbf{r}_\beta |i\rangle$$
$$= \mathbf{v}_N \cdot \frac{1}{\omega}\langle f|\Sigma_\beta \mathbf{p}_\beta|i\rangle$$
$$= -\mathbf{v}_N \cdot \frac{1}{\omega^2}\langle f|\Sigma_\beta[\mathbf{p}_\beta, H_0]|i\rangle = \frac{-i}{\omega^2}\langle f|\sum_\beta \frac{Z_N\alpha \mathbf{v}_N \cdot \hat{\mathbf{r}}_\beta}{|\mathbf{r}_\beta - \mathbf{r}_N|^2}|i\rangle.$$

Dipole potential from recoiling nucleus

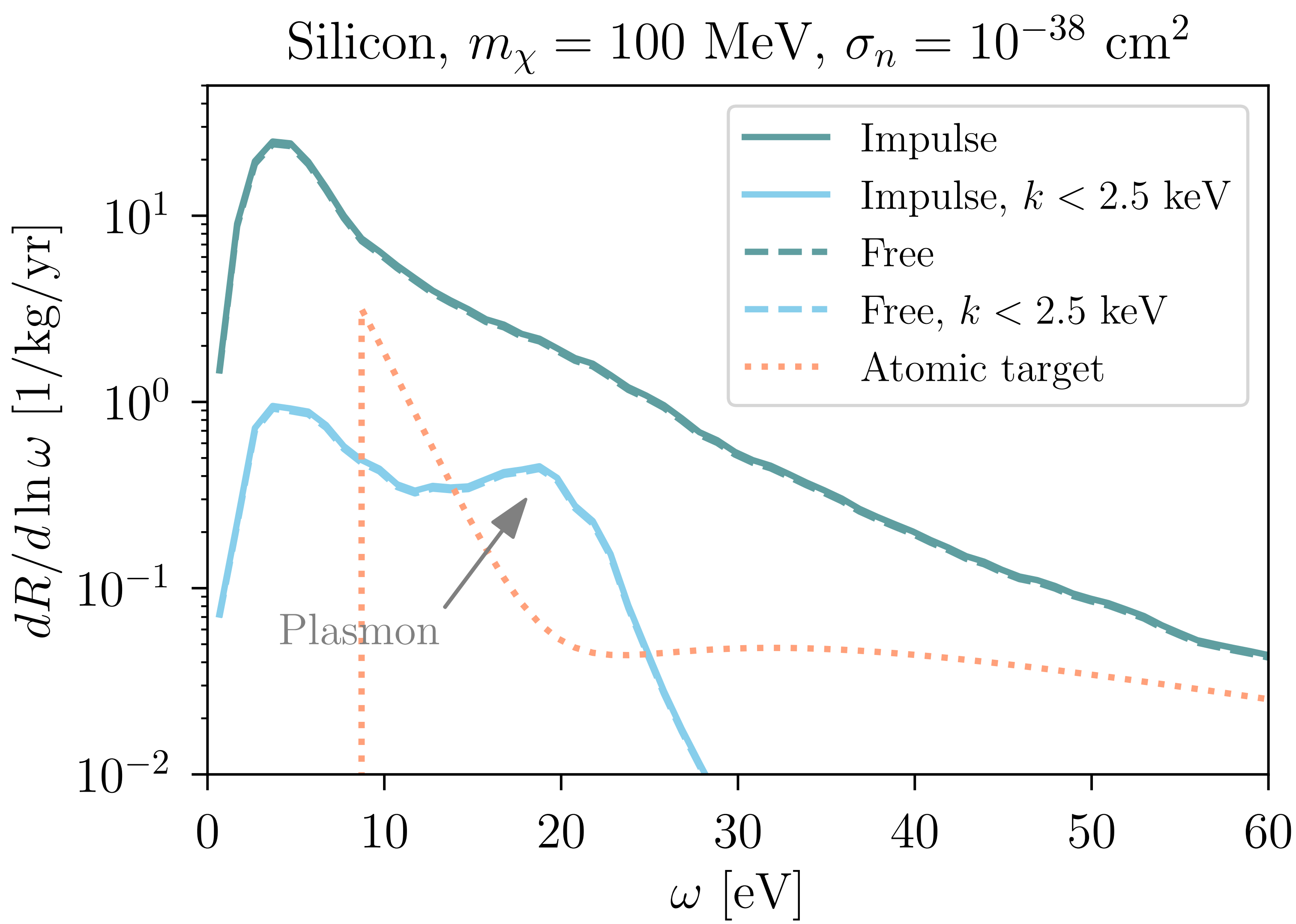
Atomic Migdal effect

$$\frac{dP(E_N)}{d\omega} \approx \left(\frac{4\pi Z_N\alpha}{\omega^2}\right)^2 \sum_{i,f} \left| \int \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{\mathbf{v}_N \cdot \mathbf{k}}{k^2} \langle f|e^{i\mathbf{k}\cdot\mathbf{r}}|i\rangle \right|^2 \delta\left(E_i + \omega - E_f\right)$$

Semiconductor Migdal effect

$$\frac{dP}{d\omega} \approx \frac{(4\pi Z_{\text{ion}}\alpha)^2}{\omega^4 V} \sum_{\mathbf{p}_e} \int \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{|\mathbf{v}_N \cdot \mathbf{k}|^2}{k^4} \frac{|[\mathbf{p}_e + \mathbf{k}|\mathbf{p}_e]_\Omega|^2}{|\epsilon(\mathbf{k},\omega)|^2} \times \left(f(\mathbf{p}_e) - f(\mathbf{p}_e + \mathbf{k})\right) \delta(\omega_{\mathbf{p}_e+\mathbf{k}} - \omega_{\mathbf{p}_e} - \omega)$$

Full rate in semiconductors

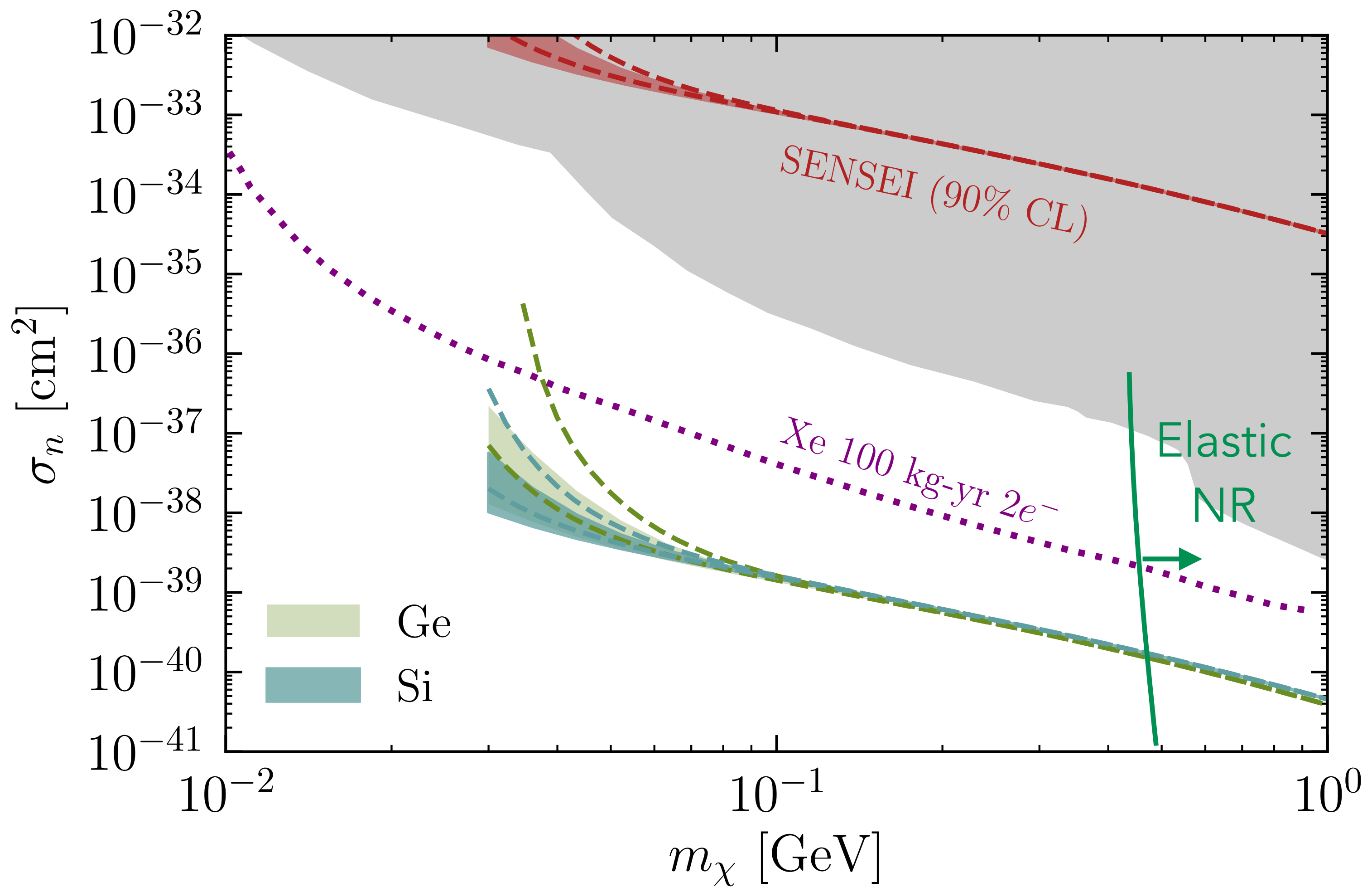


Migdal rate in semiconductors is much larger due to lower gap for excitations.

Knapen Kozaczuk, TL 2011.09496

Sensitivity in semiconductors

1 kg-year exposure, with Q > 2 (similar to proposed experiments)



The Migdal effect in semiconductors can enhance sensitivity to nuclear recoils from sub-GeV dark matter

Essig, Pradler, Sholapurkar, Yu 2020
Barak et al. 2020 (SENSEI)
Elastic NR reach from Agnese et al. 2017

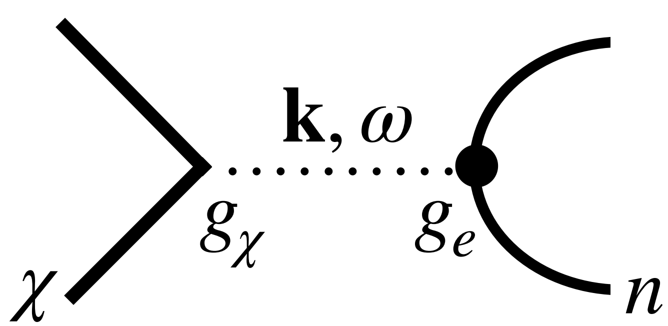
Knapen Kozaczuk, TL 2011.09496

Conclusions

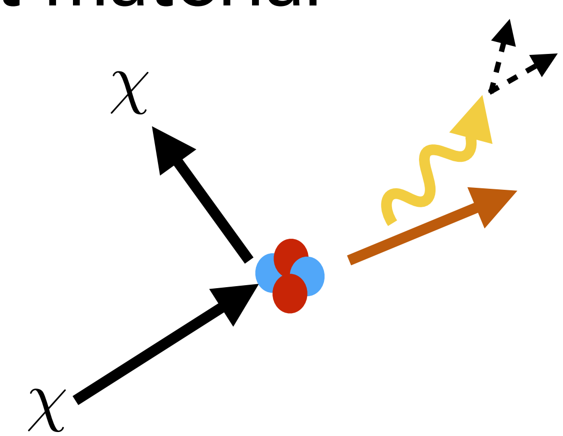
The energy loss function (ELF) in dielectric materials describes response to any electromagnetic probe (Standard Model or DM):

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

Appears in multiple types of DM interactions, applies for arbitrary target material



DM-electron scattering



DM-nucleus scattering via Migdal effect

Conclusions

The energy loss function (ELF) in dielectric materials describes response to any electromagnetic probe (Standard Model or DM):

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

Appears in multiple types of DM interactions, applies for arbitrary target material

We welcome use of DarkELF, a python package for DM interactions in terms of the ELF: https://github.com/tongylin/DarkELF