Plasmon production from dark matter scattering

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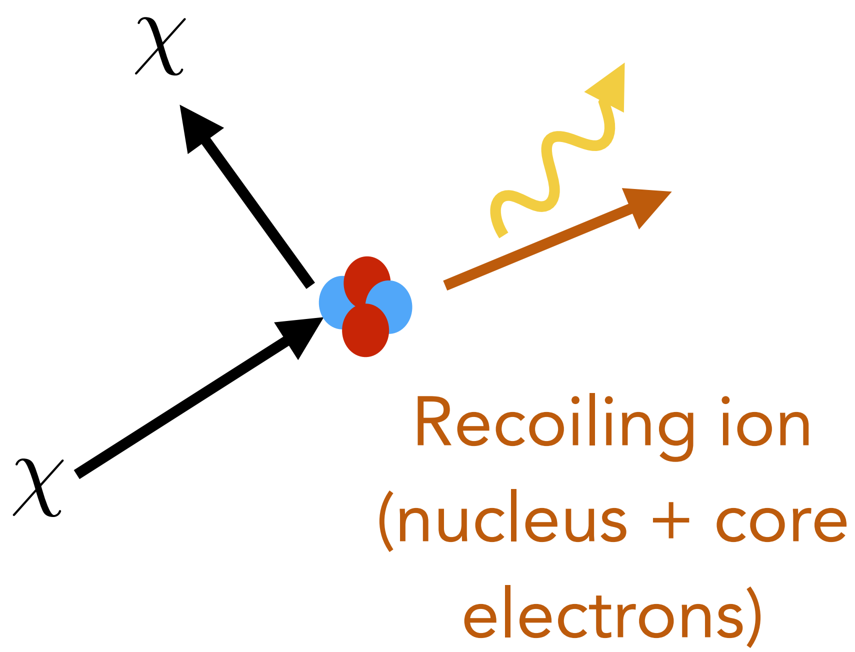
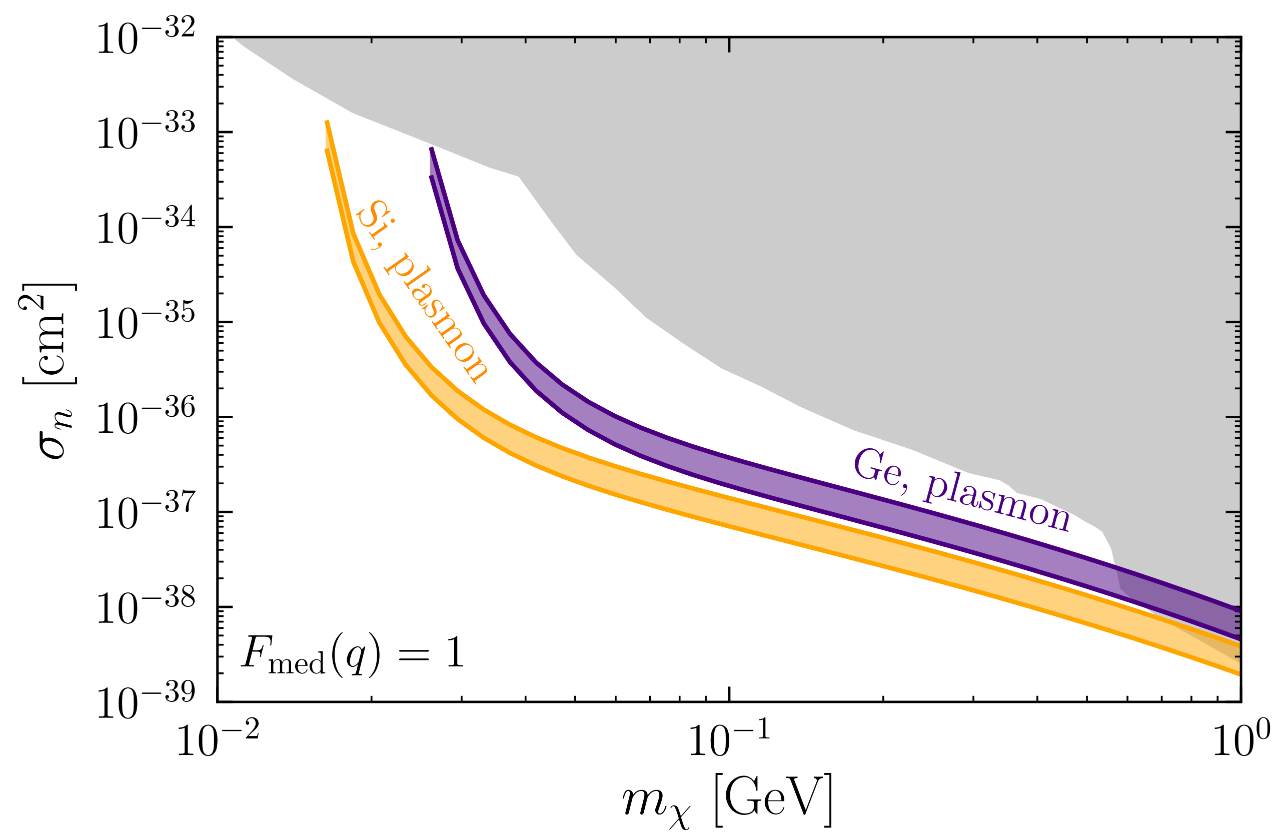
Based on 2003.12077 with Jonathan Kozaczuk

One-slide summary

Plasmons are longitudinal EM modes with typical energy $\omega_p \approx 16 - 17$ eV in Si, Ge semiconductors





Plasmons can be produced by bremsstrahlung of recoiling nuclei. For sub-GeV dark matter, this provides a new way to observe nuclear recoils that would otherwise be too low in energy to detect.

Motivation

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

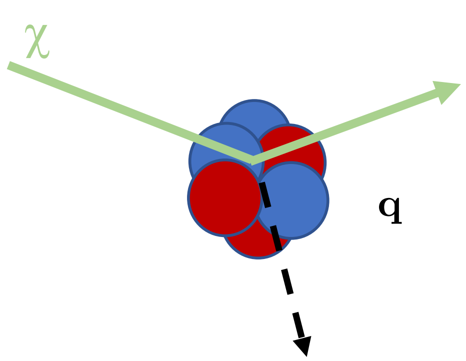
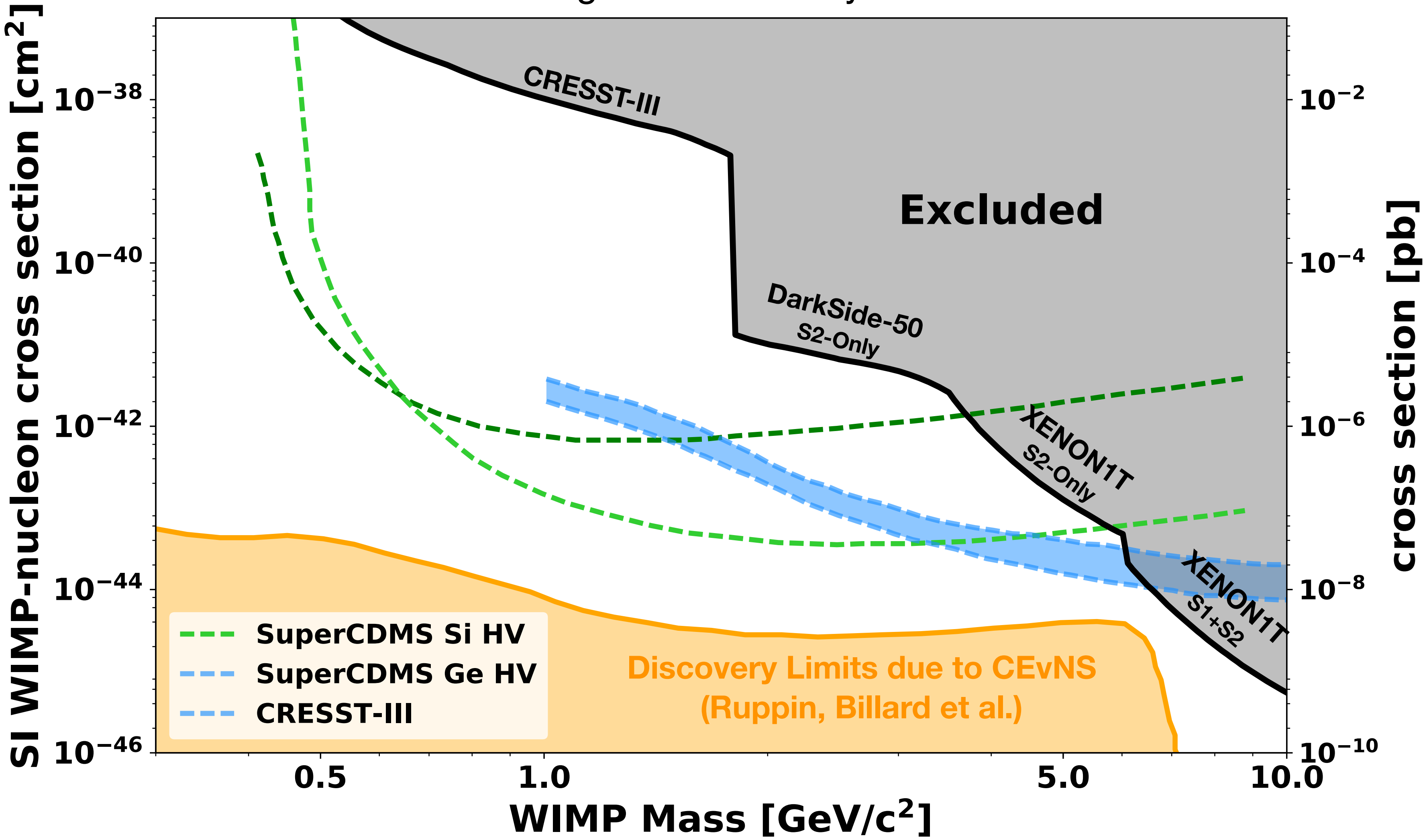


Figure from talk by Kaixuan Ni at DPF 2019



Challenges for sub-GeV DM

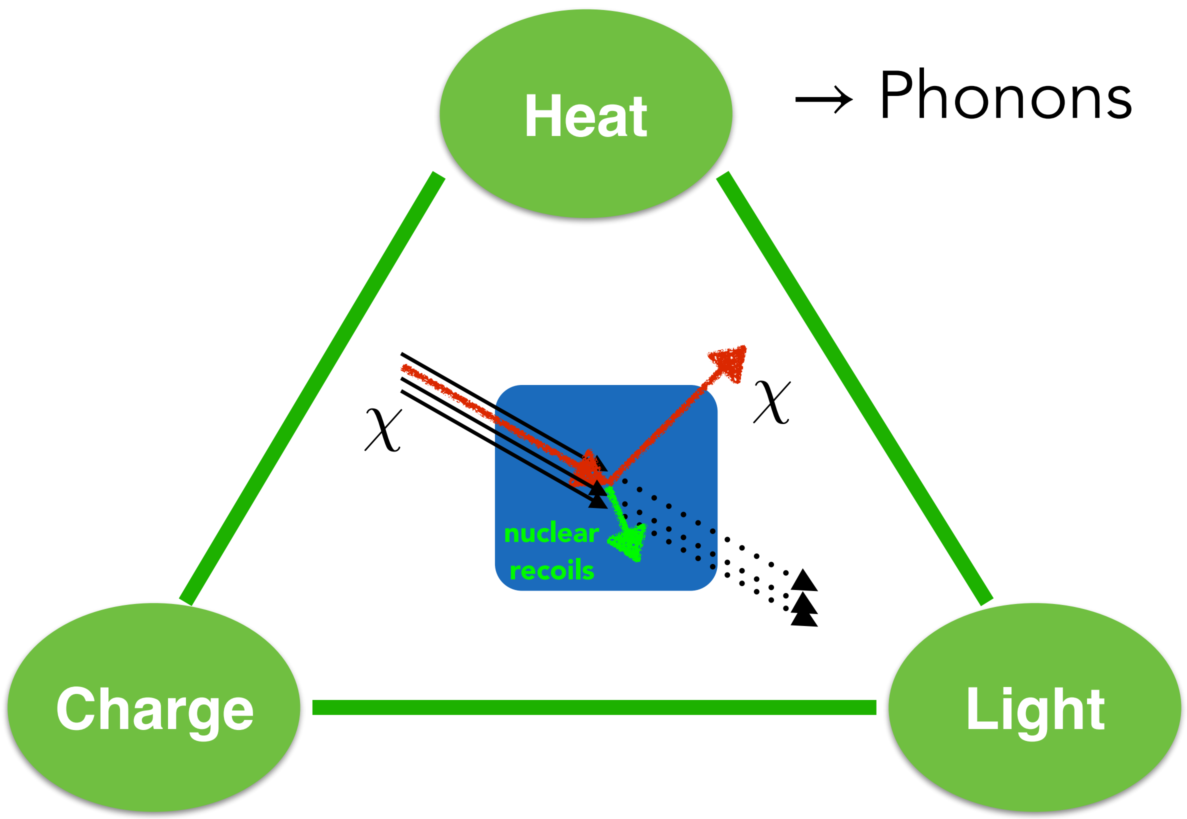
Kinematics of nuclear recoils from light dark matter

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

Drops quickly below $m_\chi \sim 10 \text{ GeV}$

Best nuclear recoil threshold is currently $E_R > 30 \text{ eV}$ (CRESST-III) with DM reach of $m_\chi > 160 \text{ MeV}$. Large unknown backgrounds at these energies.

Challenges for sub-GeV DM



→ Phonons

Best threshold of $E_R > 30\ \mathrm{eV}$ (CRESST-III) from phonons and photons.

→ Scintillation photons

ionized atoms or electron-hole pairs in semiconductors; many experiments have shown sensitivity to O(1) or few e-, corresponding to as low as ~eV electronic energy.

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)

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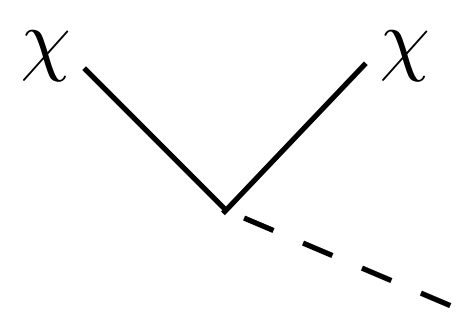
- Direct phonon excitations from DM scattering
  At low enough energies, cannot treat as free nucleus; harmonic potential matters. $\omega \approx 1 - 100 \text{ meV}$ for acoustic and optical phonons in crystals. (many works, e.g. Griffin, Knapen, TL, Zurek 2018; Cox, Melia, Rajendran 2019)

DM-phonon scattering

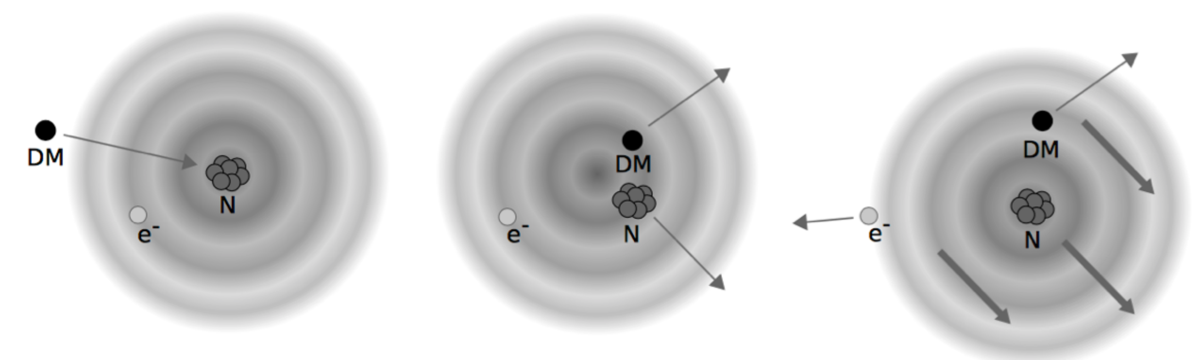


Kinematics of phonons relevant (and advantageous) for sub-MeV dark matter

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

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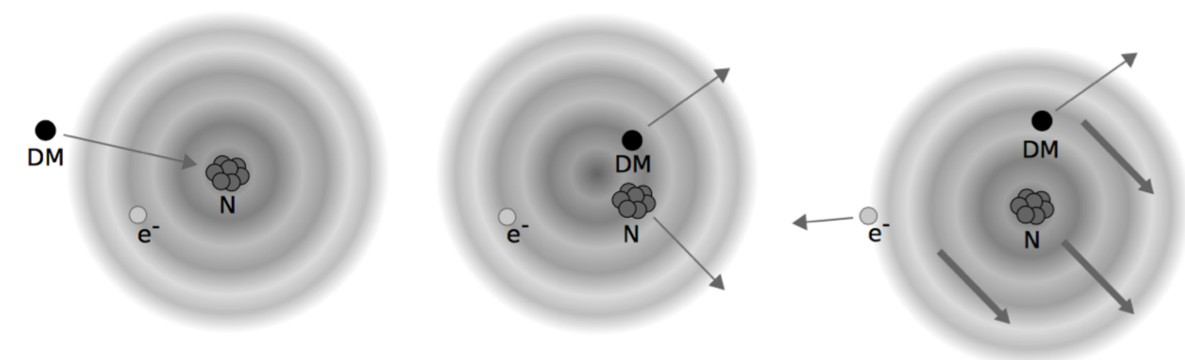


From 1711.09906

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

- **Plasmons (+ionization signals) in semiconductors**

Many-body effects are relevant in many of these cases!

Plasmons

- Simple picture: uniform displacement of electrons by $\mathbf{r}$

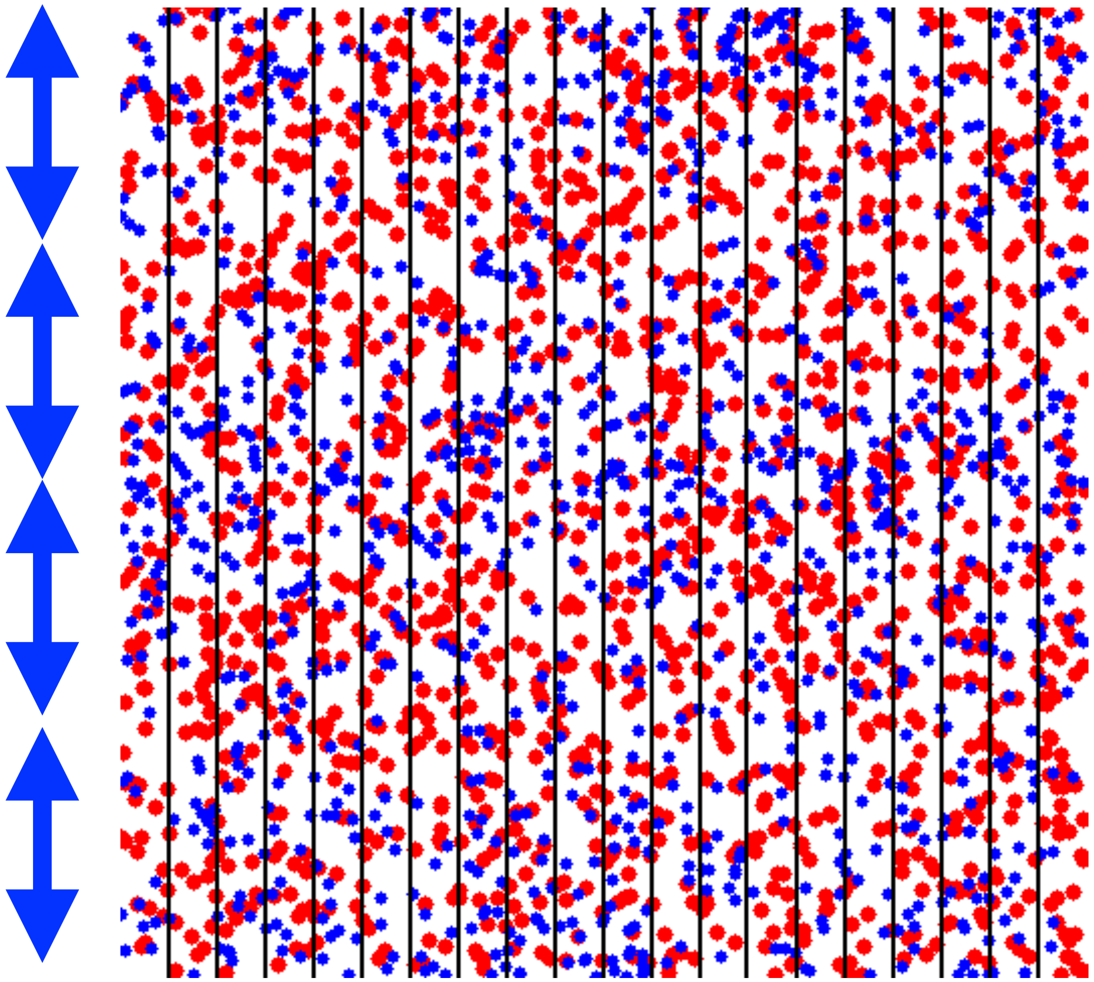
$$-e\mathbf{E} = 4\pi\alpha_{em}n_e\mathbf{r}$$

$$\ddot{\mathbf{r}} = -\omega_p^2\mathbf{r}$$

Plasma frequency $\quad \omega_p^2 \equiv \dfrac{4\pi\alpha_{em}n_e}{m_e}$

- Plasmons are quantized longitudinal E-field excitations in the medium (contrast with "transverse photons")

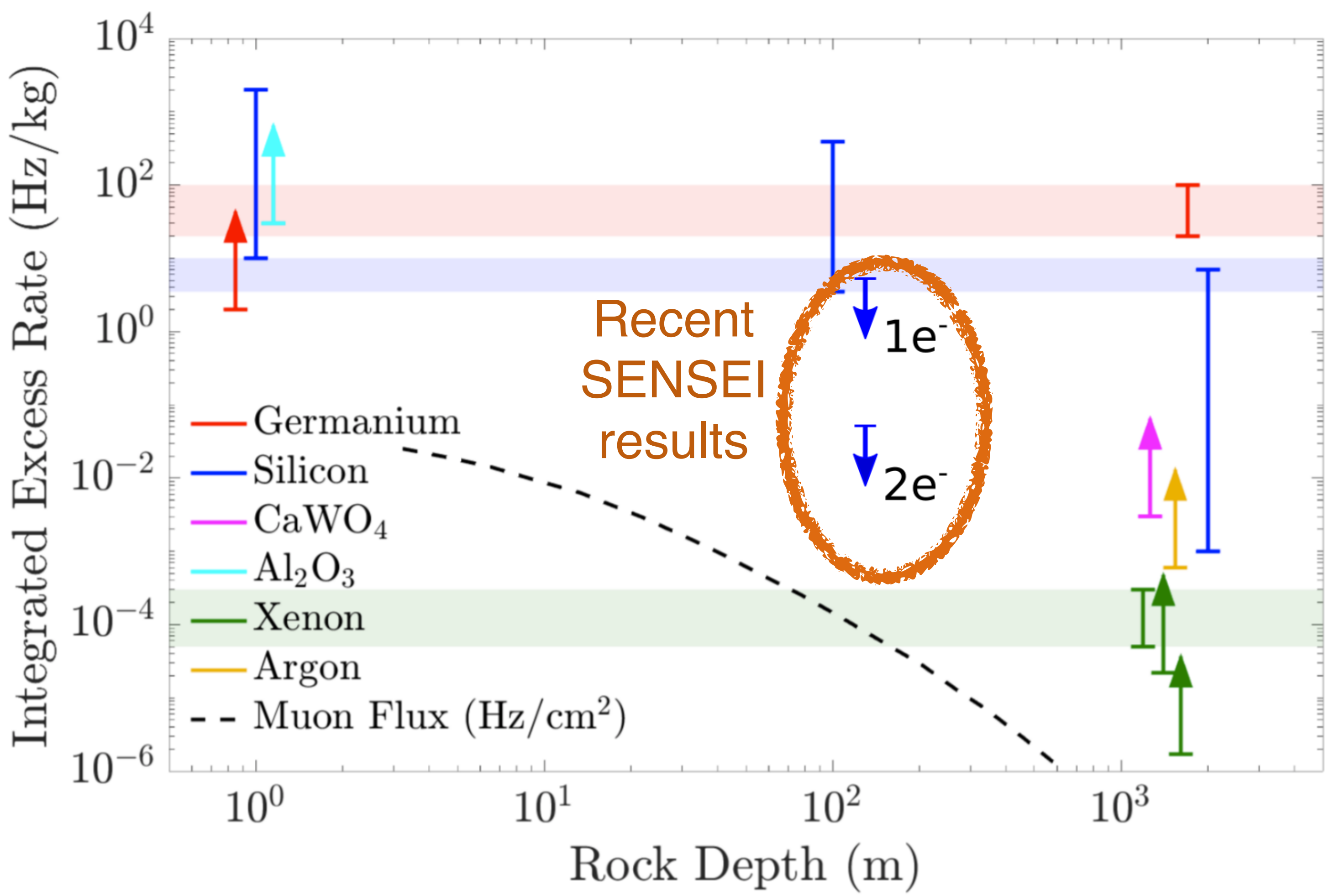
Electron gas in fixed ion background



red: ion blue: electron

Plasmons from dark matter?

Kurinsky, Baxter, Kahn, Krnjaic (2002.06937) propose plasmons from DM as an explanation of low-energy excess rates seen in semiconductor-target experiments



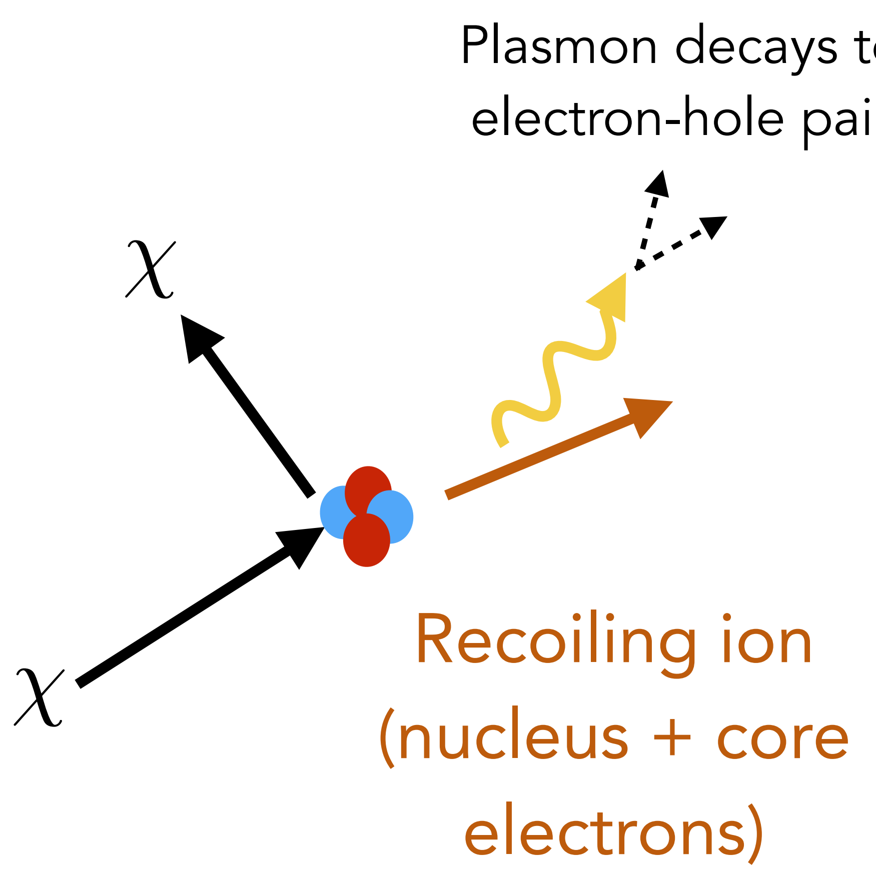
Slide from SENSEI talk, based on figure from Kurinsky et al.

- Excess in 1e- or 2e- bins (assumption requiring plasmon decays to phonons)
- If nuclear recoil, requires $O(10^{-3} - 1)$ probability to produce plasmons
- Could also be excited by large flux of fast-moving millicharged DM

(more on this later)

Plasmons from dark matter?

Our goal: calculate the plasmon excitation rate from nuclear recoils in semiconductors. This is an additional charge signal that should be included and can improve reach for sub-GeV DM.



For nuclear recoil energy

$$\omega_{\text{phonon}} \ll E_R \lesssim E_{\text{core}}$$

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

Bremsstrahlung of a longitudinal mode, or a current source which loses energy to plasmon mode in the material.

Electron gas model

- First approach: bremsstrahlung of a longitudinal mode in a simplified model of a metal (degenerate electron gas in fixed ion BG)

- Plasmon appears as a zero of the dielectric function

Gauss's law without external source

$$\hat{\epsilon}_L(\omega, \mathbf{k})\mathbf{k} \cdot \mathbf{E} = 0 \rightarrow \mathbf{k} \cdot \mathbf{E} \neq 0 \text{ when } \hat{\epsilon}_L(\omega, \mathbf{k}) = 0$$

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- Or as a pole in the longitudinal propagator

$$D^{00}(\omega, \mathbf{k}) = \frac{1}{k^2 \hat{\epsilon}_L(\omega, \mathbf{k})} = \frac{1}{k^2 - \Pi_L(\omega, \mathbf{k})}$$

(Coulomb gauge)

$$\hat{\epsilon}_L(\omega, \mathbf{k}) = 1 - \frac{\Pi_L(\omega, \mathbf{k})}{k^2}$$

Electron gas model

- Dielectric function for non-interacting electrons (Lindhard formula) at zero temperature:

$$\hat{\epsilon}_L(\omega, \mathbf{k}) = 1 + \lim_{\eta \to 0} \frac{4\pi\alpha_{em}}{V|\mathbf{k}|^2} \sum_{\mathbf{p}} \left\{ \frac{|\langle \mathbf{p}+\mathbf{k}|e^{i\mathbf{k}\cdot\mathbf{r}}|\mathbf{p}\rangle|^2}{\omega_{\mathbf{p}+\mathbf{k}} - \omega_{\mathbf{p}} - \omega - i\eta} + \frac{|\langle \mathbf{p}-\mathbf{k}|e^{-i\mathbf{k}\cdot\mathbf{r}}|\mathbf{p}\rangle|^2}{\omega_{\mathbf{p}-\mathbf{k}} - \omega_{\mathbf{p}} + \omega + i\eta} \right\}$$

Sum over occupied electron states $|\mathbf{p}\rangle$

$\omega_{\mathbf{p}}$ = energy of state $|\mathbf{p}\rangle$

(can be obtained from virtual electron excitations, or from forward scattering calculation)

- Can be evaluated analytically for plane-wave states and spherical Fermi surface (with Fermi velocity $v_F \approx .007$ in Si)

$$\hat{\epsilon}_L(\omega, k) \approx 1 - \frac{\omega_p^2}{\omega^2}\left(1 + \frac{3}{5}\frac{k^2 v_F^2}{\omega_p^2} + \ldots\right)$$

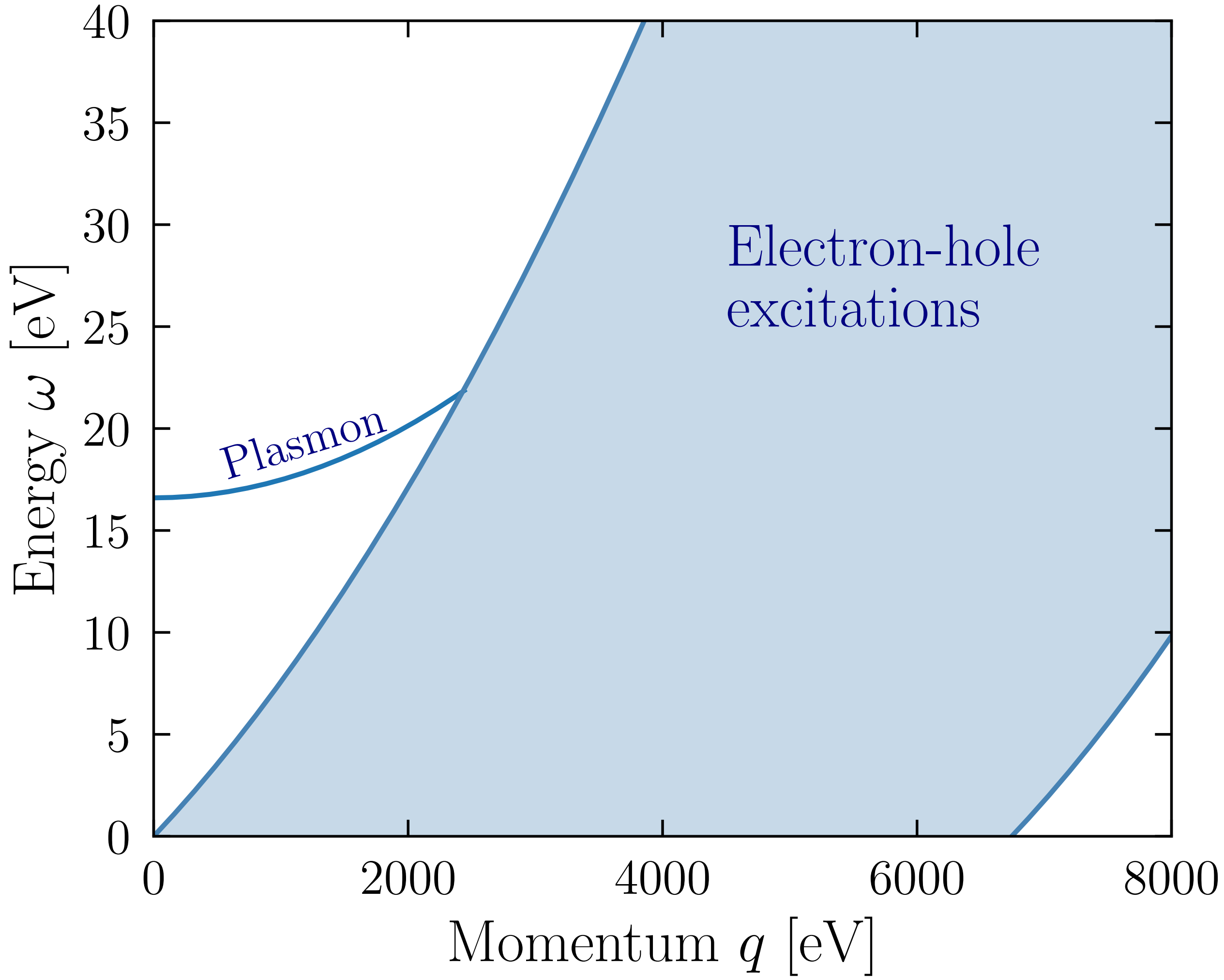
Plasmon mode near classical plasmon frequency, with weak dispersion

Electron gas model

- Plasmon is infinitely long lived for small *k* in this toy model
- For $k \gtrsim \omega_p / v_F$ (~2.4 keV in Si,Ge) the plasmon dispersion matches onto single electron excitations and there is a large plasmon decay width.
- Plasmons cannot be directly produced by DM with typical halo velocities v ~ 1e-3:

$$\omega = \mathbf{k} \cdot \mathbf{v} - \frac{k^2}{2m_\chi} \quad \rightarrow \quad k \geq \frac{\omega}{v} \sim 16\,\mathrm{keV}$$

Spectrum of longitudinal excitations in the electron gas



Electron gas model

Standard bremsstrahlung calculation in QFT

$$\chi(p) + N \to \chi(p') + N(q_N) + \omega_L(k)$$

With an external longitudinal mode

$$\varepsilon_L^\mu = \sqrt{Z_L(k)}\frac{\omega_L(k)}{k}(1,0,0,0)$$

$$Z_L(k) \approx 1 - \frac{3}{5}\frac{k^2 v_F^2}{\omega_p^2} + \ldots \quad \text{(for } k \ll \omega_p/v_F \text{)}$$

Using analytic approximations in Braaten and Segel '93

In the limit of soft brem, $k \ll \sqrt{2m_N E_R}$ (valid for us):

$$\frac{d^2\sigma_{\text{plasmon}}}{dE_R dk} = \frac{2Z_{\text{ion}}^2\alpha_{em}}{3\pi}\frac{Z_L(k)k^2}{\omega_L(k)^3}\frac{E_R}{m_N} \times \boxed{\left.\frac{d\sigma}{dE_R}\right|_{\text{el}}}$$

Elastic DM-nucleus scattering cross section

Electron gas model

In the limit of soft brem, $k \ll \sqrt{2m_N E_R}$ (valid for us):

$$\frac{d^2\sigma_{\text{plasmon}}}{dE_R dk} = \underbrace{\frac{2Z_{\text{ion}}^2 \alpha_{em}}{3\pi} \frac{Z_L(k)k^2}{\omega_L(k)^3} \frac{E_R}{m_N}}_{\sim 10^{-5} - 10^{-4}} \times \left.\frac{d\sigma}{dE_R}\right|_{\text{el}}$$

Contrast with soft brem of transverse photons:

$$\frac{d^2\sigma_{\gamma}}{dE_R dk} = \underbrace{\frac{4Z_{\text{ion}}^2 \alpha_{em}}{3\pi} \frac{Z_T(k)k^2}{\omega_T(k)^3} \frac{E_R}{m_N}}_{\sim 10^{-10} - 10^{-9}} \times \left.\frac{d\sigma}{dE_R}\right|_{\text{el}}$$

Bremsstrahlung of plasmons is low-probability, but may be the leading ionization signal for low-energy nuclear recoils

Plasmon production in semiconductors

Differences from simplified electron gas picture:

- Band gap: $\omega_g \sim O(1)$ eV (but $\omega_g \ll \omega_p$)
- Electron wavefunctions: plane waves → Bloch waves
- Interband transitions

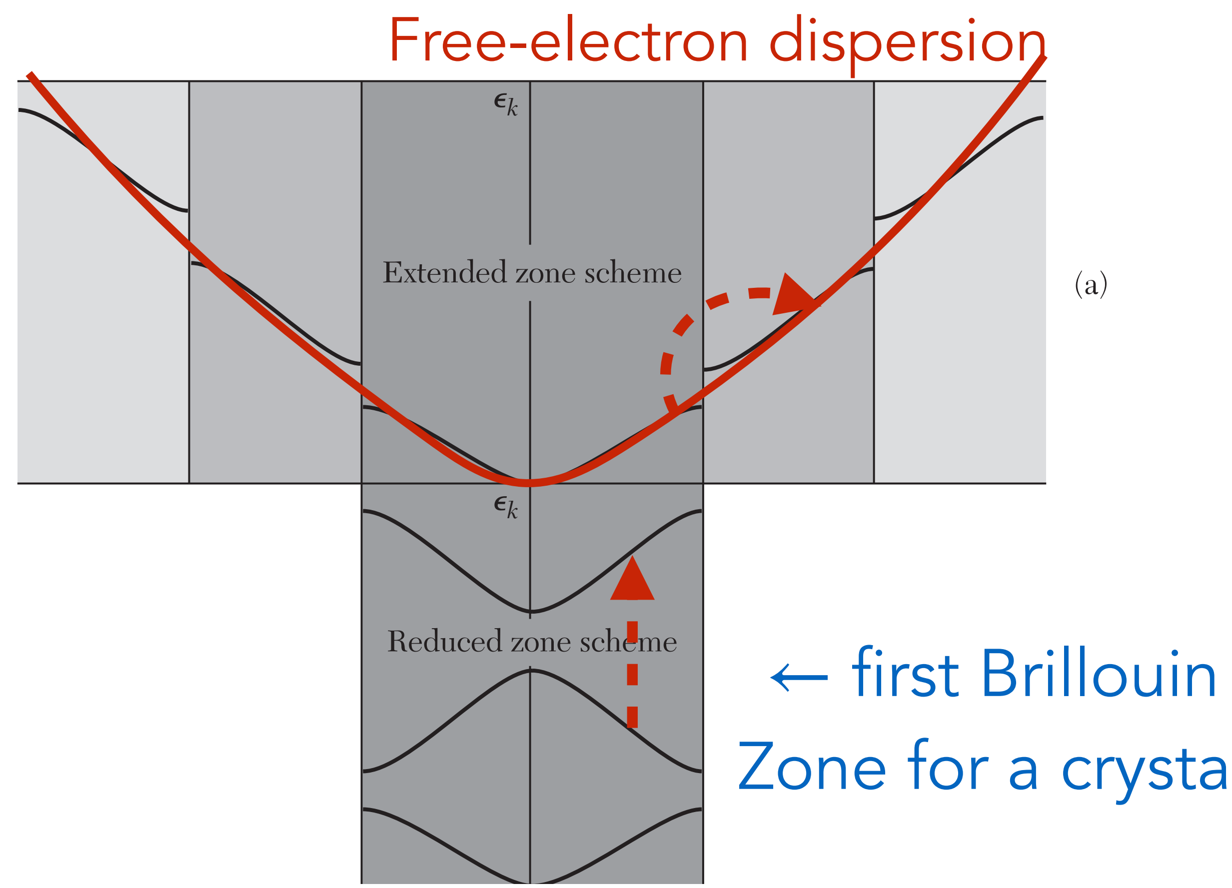
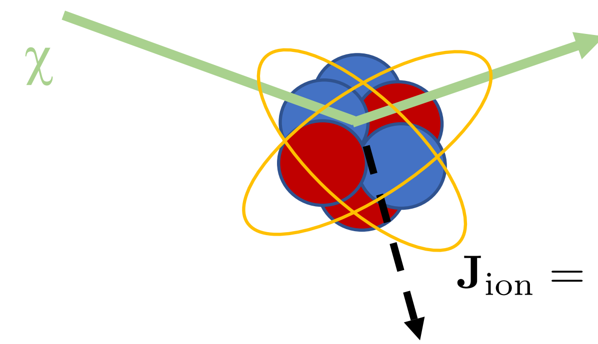


Fig from Kittel

These effects are all accounted for in the dielectric function of the material! Rewrite plasmon production in terms of $\hat{\epsilon}_L$

Plasmon production in semiconductors

Current sourced by ion recoiling against DM:



$$\mathbf{J}_{\rm ion} = Z_{\rm ion}\, e\, \mathbf{v}_{\rm ion}\, \Theta(t)\, \delta^3(\mathbf{x} - \mathbf{v}_{\rm ion} t)$$

Energy transfer to material:

$$W = -\int d^3k \int_0^\infty \frac{d\omega}{(2\pi)^4} 2\,\mathrm{Re}\left[\mathbf{J}^*_{\rm ion}(\omega, \mathbf{k}) \cdot \mathbf{E}(\omega, \mathbf{k})\right]$$

Longitudinal part of Maxwell's equations:

$$J_{{\rm ion},L}(\omega, \mathbf{k}) = \frac{i}{\omega} Z_{\rm ion}\, e\, \mathbf{v}_{\rm ion} \cdot \frac{\mathbf{k}}{k}$$

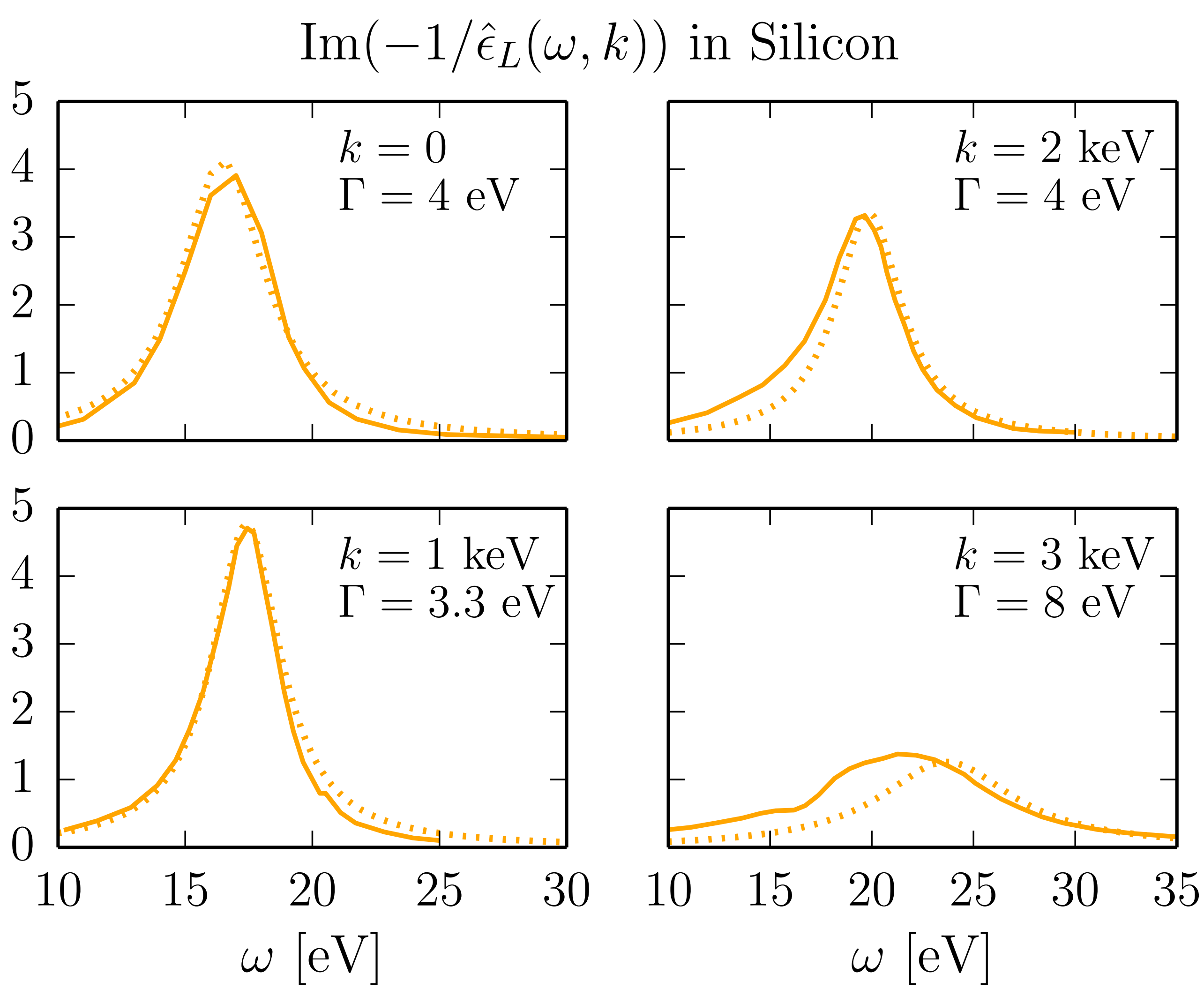
$$i\,\omega D_L(\omega, \mathbf{k}) = i\,\omega \hat{\epsilon}_L(\omega, \mathbf{k}) E_L(\omega, \mathbf{k}) = J_{{\rm ion},L}(\omega, \mathbf{k})$$

Energy loss rate to longitudinal electronic excitations (not only plasmons)

$$\frac{dW_L}{dk} = \int_0^\infty d\omega \frac{2 Z_{\rm ion}^2 \alpha_{em}}{3\pi^2} \left|\mathbf{v}_{\rm ion}\right|^2 \frac{k^2}{\omega^3}\, \mathrm{Im}\left(\frac{-1}{\hat{\epsilon}_L(\omega, \mathbf{k})}\right)$$

Energy loss function

Despite differences for semiconductors, the electron gas picture provides a reasonable approximation of the plasmon pole for simple semiconductor like Si.



Solid: X-ray scattering from Weissker et al. 2010
Dashed: Modified electron gas model

Including a finite width Γ for electron gas

$$\mathrm{Im}\left(\frac{-1}{\hat{\epsilon}_L(\omega, \mathbf{k})}\right) \simeq Z_L(\omega, k) \frac{\omega_L(k)^2 \omega \Gamma}{\left(\omega^2 - \omega_L(k)^2\right)^2 + \omega^2 \Gamma^2}$$

Approximating the Lorentzian as a delta function:

$$\frac{dN_{\text{plasmon}}}{dk} \simeq \frac{2Z_{\text{ion}}^2 \alpha_{em}}{3\pi} \frac{Z_L(k) k^2}{\omega_L(k)^3} \frac{E_R}{m_N}$$

This is equivalent to the result obtained in the electron gas model

Energy loss function

Numerical calculations of the full dielectric function of Si, using state-of-art electron wave functions and accounting for electron-electron interactions, also agree with this picture.

Plasmon width in semiconductors well-explained by interband transitions (i.e., decays to kinematically accessible electron-hole transition)

Corresponds to ~4-5 observed e- once cascade effects accounted for (see e.g. Alig et al 1980)

Walter & Cohen 1971

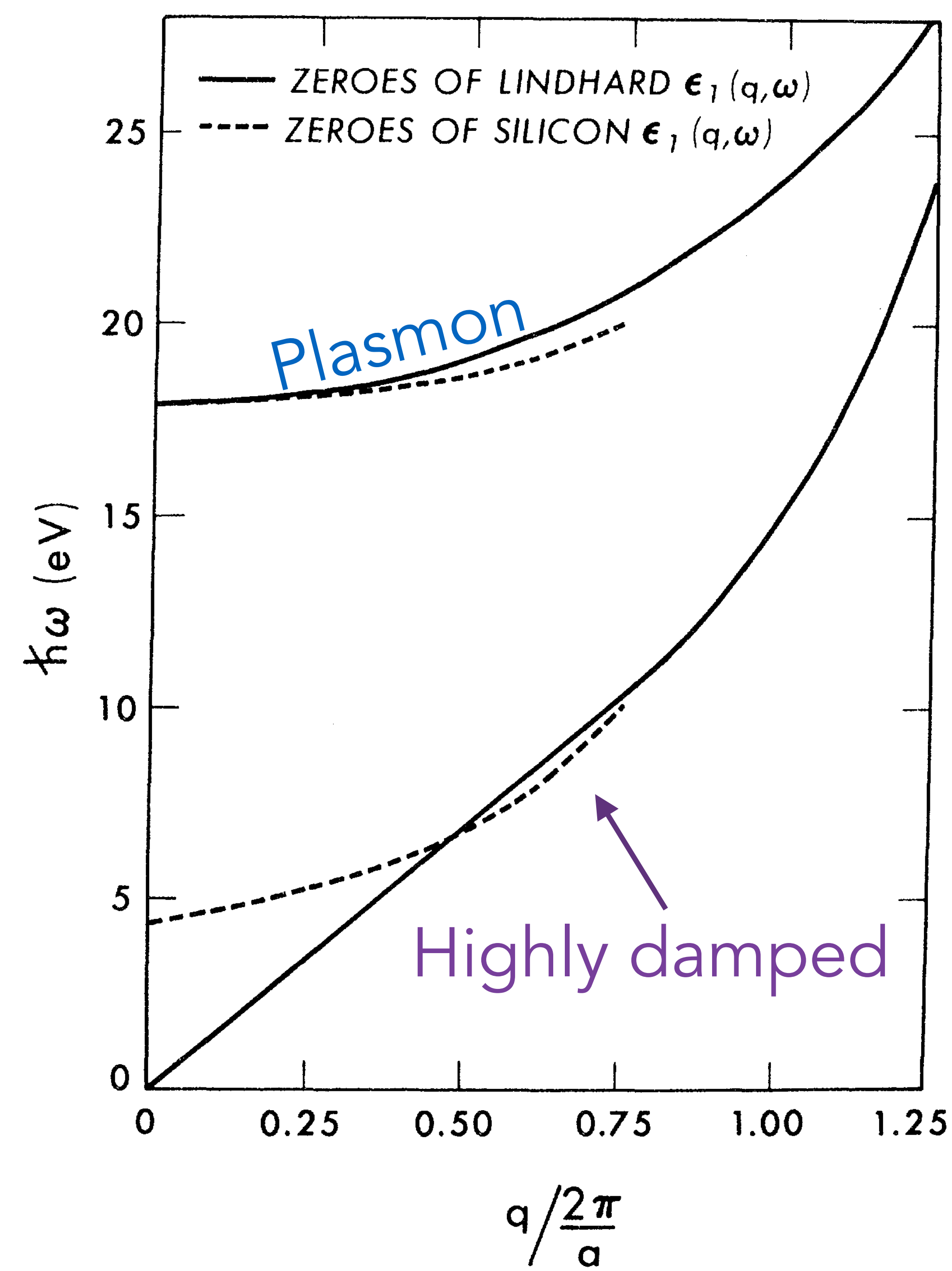


FIG. 13. Plots of the zeros of $\epsilon_1(\vec{q}, \omega)$ for silicon and a free-electron gas in the $(\vec{q}, \omega)$ plane.

Ionization signals from nuclear recoils

$$\frac{dN_L}{d\omega dk} = \frac{4Z_{\text{ion}}^2 \alpha_{em}}{3\pi^2} \frac{E_R}{m_N} \frac{k^2}{\omega^3} \,\mathrm{Im}\left(\frac{-1}{\hat{\epsilon}_L(\omega, \mathbf{k})} \right)$$

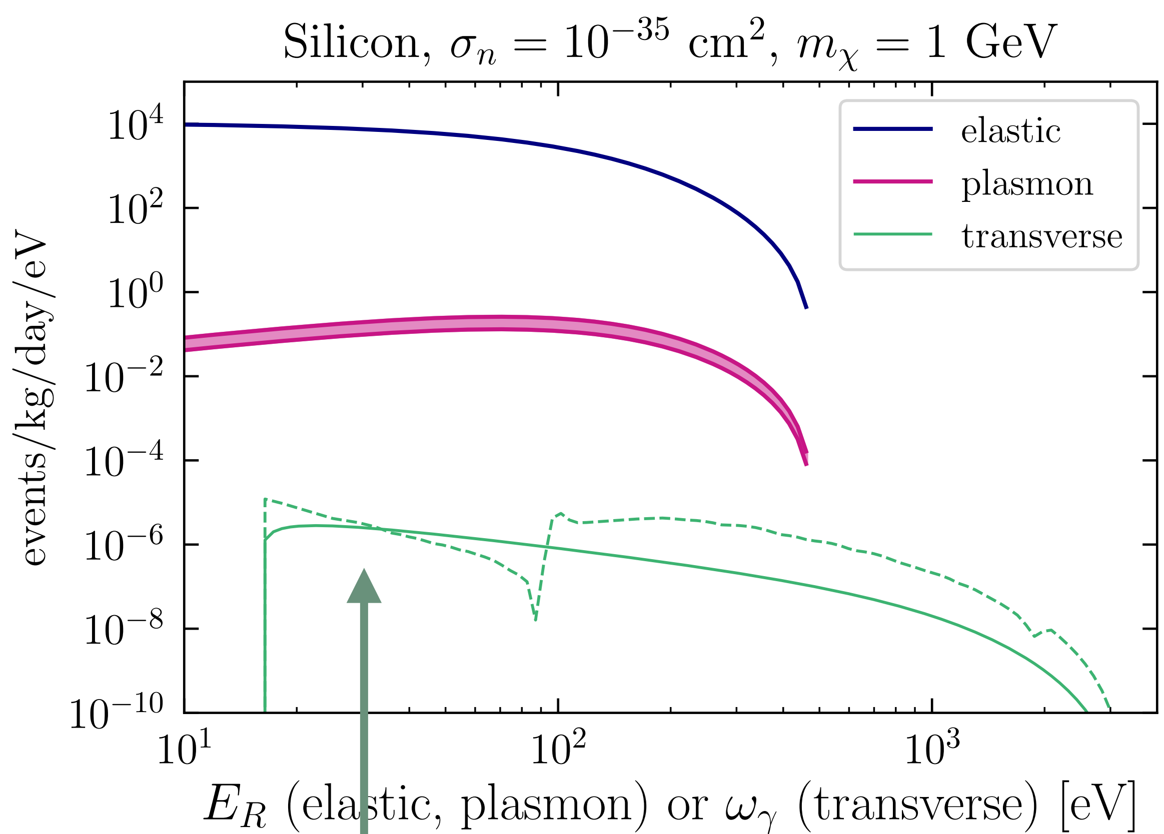
Energy loss function contains information about all electronic excitations (charge signals), even away from plasmon pole. This is analog of the atomic Migdal effect in semiconductors.

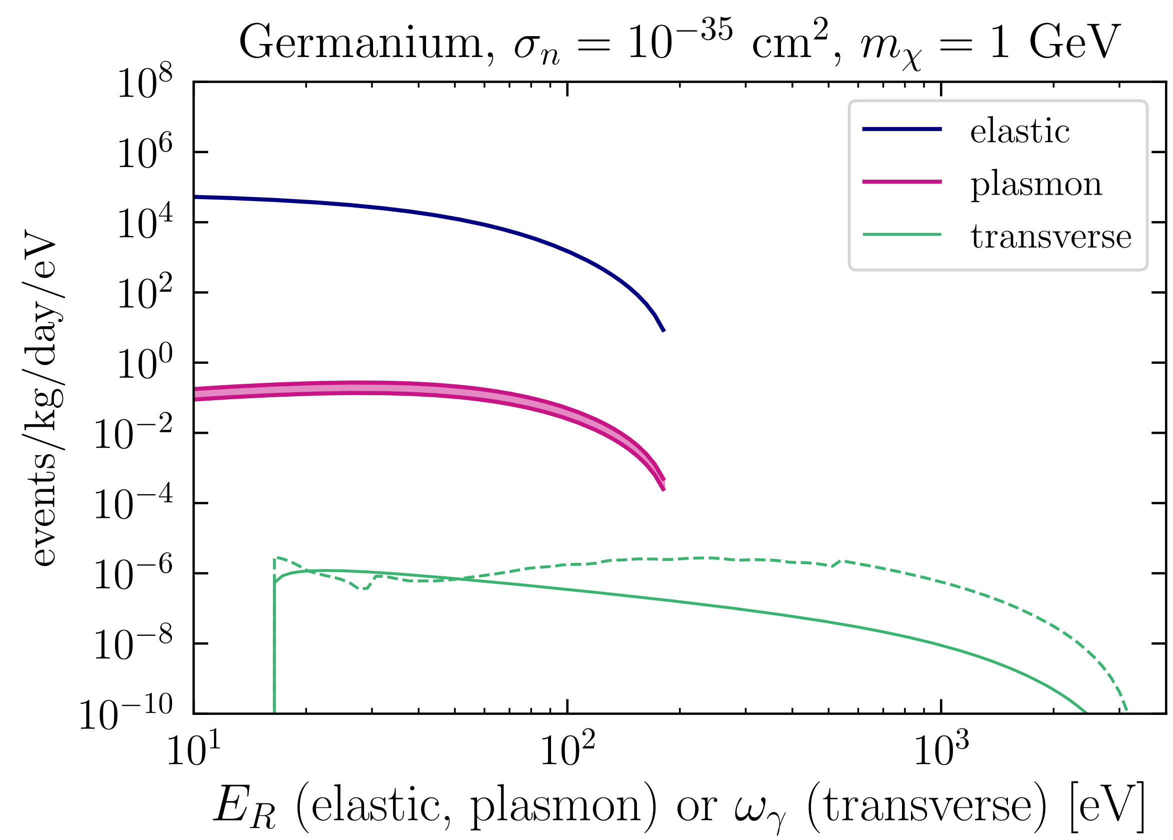
We are working on numerical calculations of the energy loss function using standard methods in condensed matter.

Expect there to be a resonance in the material response at plasmon pole → what I'll show today only includes plasmon pole. We are working on followup to include everything

Plasmon production rate

Assume universal coupling to nucleons $\left.\frac{d\sigma}{dE_R}\right|_{\mathrm{el}} = \frac{A^2 m_N \sigma_n}{2\mu_{\chi n}^2 v^2}$

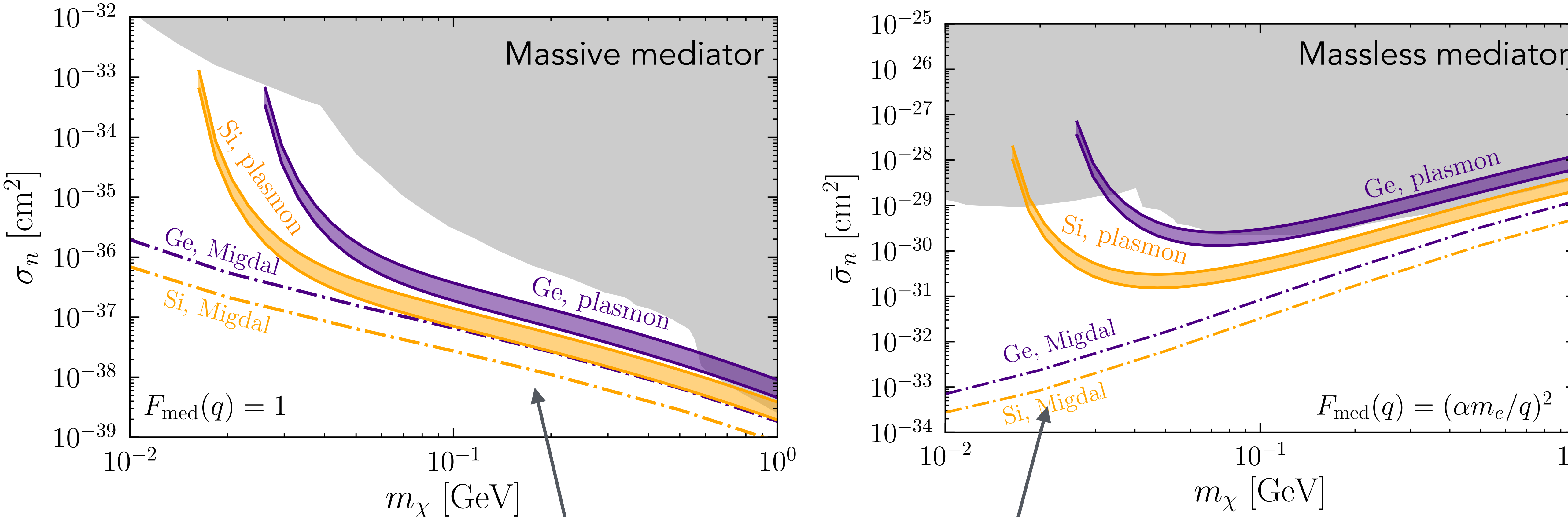




Solid: electron gas model — valid if ω_γ not too much larger than $\omega_{\mathrm{core}} \sim 100$ eV (Si) or 30 eV (Ge)
Dashed: atomic calculation from Kouvaris & Pradler 1607.01789

Plasmon production in semiconductors

Sensitivity for 1 kg-year exposure, assuming E_R > 100 meV to avoid phonon regime



Notes about Migdal curves (1908.10881): does not restrict in E_R (extrapolates free NR to phonon regime) and applies atomic picture to semiconductors (not valid for delocalized electrons?).

Plasmon search (peaked charge signal at 16-20 eV) can enhance sensitivity to nuclear recoils from sub-GeV dark matter!

Implications for excess rates?

Proposal from Kurinsky, Baxter, Kahn, Krnjaic (2002.06937)

- Excess in 1e- or 2e- bins (assumption requiring plasmon decays to phonons)

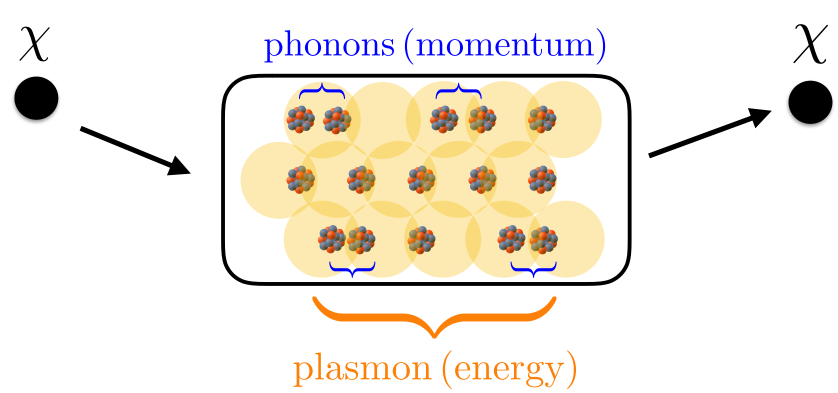
Plasmon decay products have not been directly measured. Other measurements + theory point to plasmon decay to electron excitation (4-5 e- measured)

- If nuclear recoil, requires O($10^{-3} - 1$) probability to produce plasmons

The probability to excite the plasmon via bremsstrahlung is much smaller, $10^{-5} - 10^{-4}$

- Could also be excited by large flux of fast-moving millicharged DM

Note Kurinsky et al. also propose mechanism where multiple phonons are produced in association with plasmon



This likely requires large phonon-plasmon coupling, and has not been studied so far.

Next steps

- Numerical studies of energy loss functions to obtain full inelastic ionization signal from nuclear recoils; revisit existing data to obtain limits on sub-GeV dark matter.

- We are computing ionization produced in the 'hard' process of the DM-nucleus scattering. Depending on E_R, there are additional contributions to charge yield from the subsequent nuclear recoil; complicated materials science problem.

- Extend our framework to the phonon regime, where effects of the ion potential are important.

Summary

Many body effects can be important for sub-GeV dark matter detection. Plasmons are an example of a collective mode that can be excited by DM.

Plasmon production yields a charge signal at ~16-20 eV that can be used to such for low-energy nuclear recoils. There are off-pole contributions too (in progress).

Thanks!