New Materials for Light Dark Matter Searches

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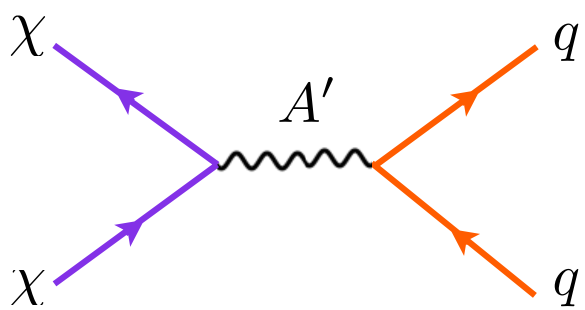
Scattering Interaction

Dark photon interactions lead to thermal relics with ~MeV masses

For light dark matter, nuclear recoils are undetectable, but electron recoils are promising

Nuclear Recoil

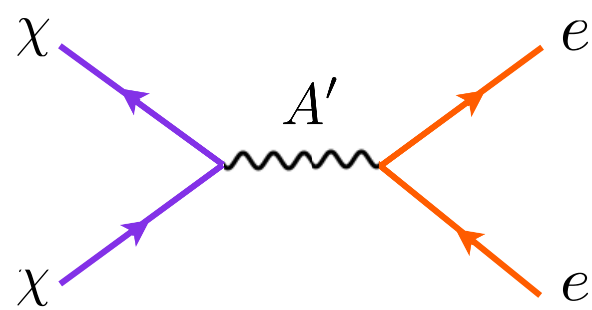


$$E_{\rm nr} \sim \ {\rm eV}$$

$$(m_\chi = 100\ {\rm MeV})$$

Nuclear recoil energy is below experimental thresholds

Electron Recoil



$$E_{\rm er} \sim 50\ {\rm eV}$$

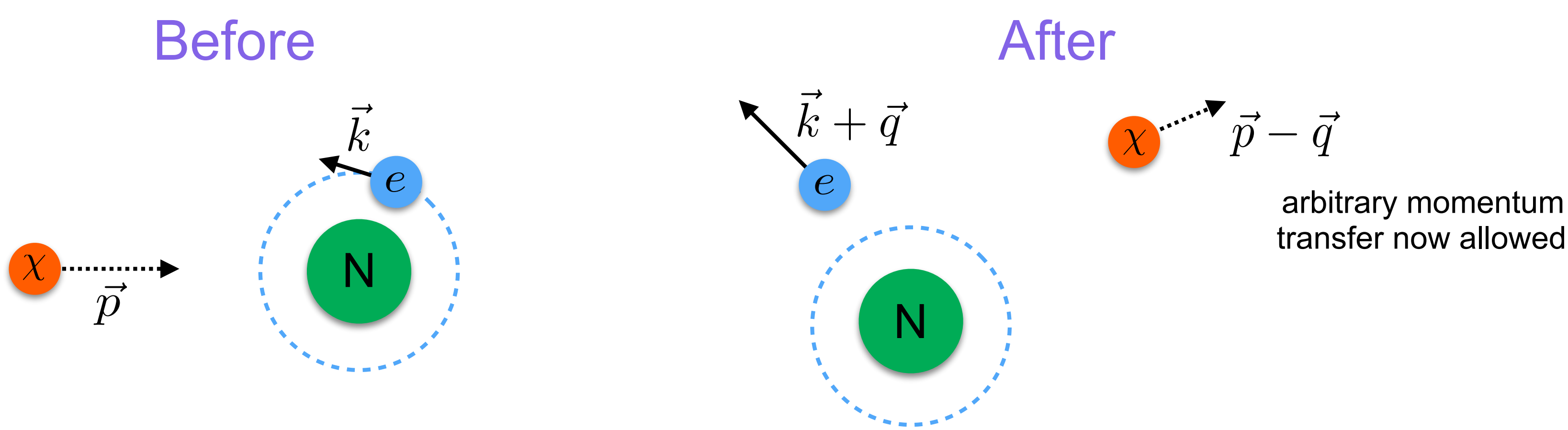
$$(m_\chi = 100\ {\rm MeV})$$

Enough energy available to excite or ionize an electron

Electron Scattering

Scattering with DM particle results in electron excitation/ionization

Kinematics differ from nuclear-scattering case because the bound-state electron does not have definite momentum



Observable energy transfers to the electron are feasible

$$\Delta E_{\rm e} \sim \frac{p^2}{2m_\chi} - \frac{|\vec{p}-\vec{q}|^2}{2m_\chi} \lesssim \frac{1}{2}\ \mathrm{eV} \times \left(\frac{m_\chi}{\mathrm{MeV}}\right)$$

(Assuming negligible nuclear recoil)

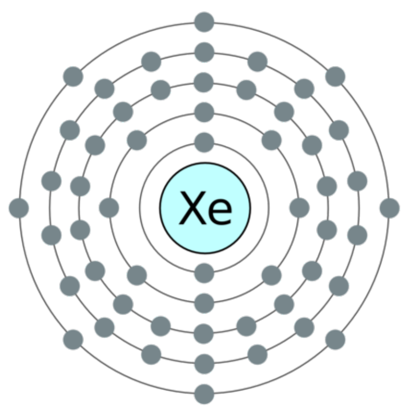
Mass Sensitivity

Sensitivity to dark matter mass is set by the ionization energy of the electron

Atomic Target

Ionize electrons in outermost atomic orbitals

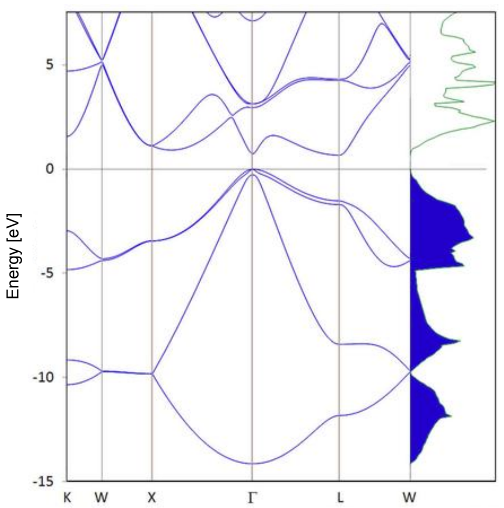
$$\Delta E_e \sim 10 \text{ eV} \Rightarrow m_\chi \gtrsim 10 \text{ MeV}$$



Semiconductor Target

Excite an electron from valence to conduction band

$$\Delta E_e \sim 1 \text{ eV} \Rightarrow m_\chi \gtrsim 1 \text{ MeV}$$



Scattering Rate

Rate to scatter electron from state 1 to 2 is given by:

DM velocity distribution

$$R_{1\to 2} = \frac{\rho_\chi}{m_\chi} \int d^3v \; f(\vec{v})\, \sigma v_{1\to 2}$$

DM number density

Scattering cross section

$\sigma v_{1\to 2}$ depends on the initial and final-state electron wavefunctions via

$$\langle \chi_{\vec{p}-\vec{q}}, e_2 |\, H_{\text{int}} \,| \chi_{\vec{p}}, e_1 \rangle \propto \int \frac{d^3k}{(2\pi)^3}\, \widetilde{\psi}_2^*(\vec{k}+\vec{q})\; \widetilde{\psi}_1(\vec{k})$$

For ionization process, final state is a plane wave

Essig, Mardon, and Volansky [1108.5383]

Semiconductors

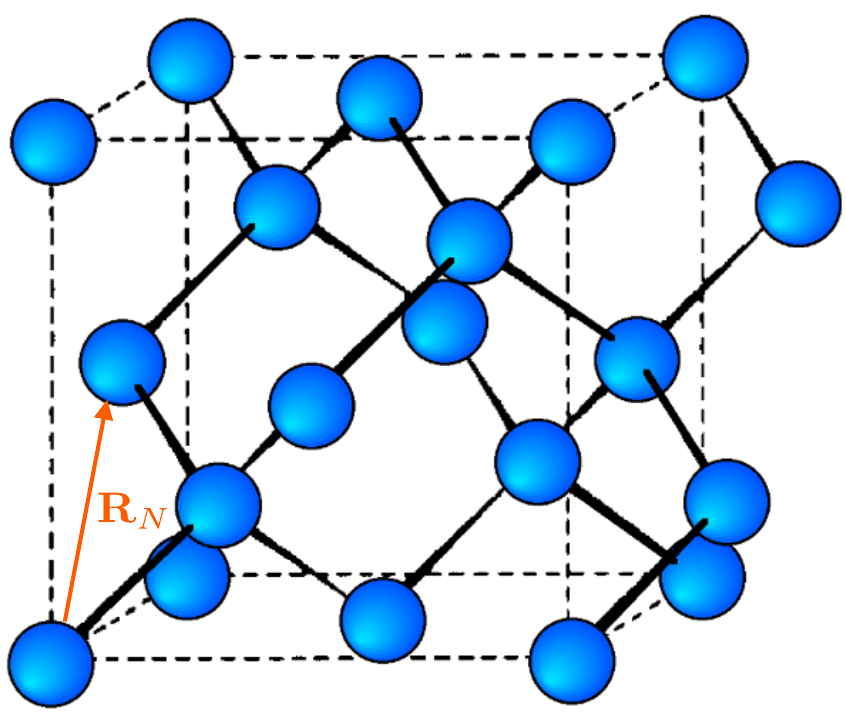
Lee, **ML**, Mishra-Sharma, and Safdi [1508.07361]

Electron is now described by Bloch wavefunction in a periodic lattice

$$\Psi(\ell, \mathbf{r}) = \sum_N e^{i\ell\cdot\mathbf{R}_N}\,\underbrace{\phi(\mathbf{r} - \mathbf{R}_N)}_{\text{Wavefunction at lattice site}}$$

ℓ = lattice momentum

Wavefunctions can be simplified using a series of well-motivated assumptions



Semiconductors

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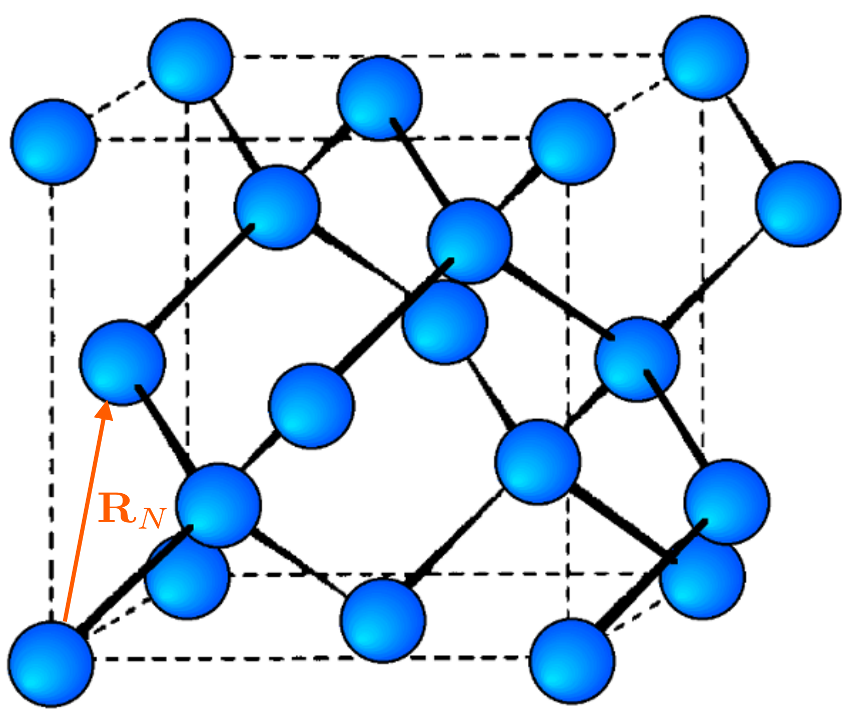
Electron is now described by Bloch wavefunction in a periodic lattice

$$\Psi(\ell, \mathbf{r}) = \sum_N e^{i\ell\cdot\mathbf{R}_N} \underbrace{\phi_{4\mathrm{p}}(\mathbf{r} - \mathbf{R}_N)}_{\text{Free atomic orbital}}$$

$\ell =$ lattice momentum

Wavefunctions can be simplified using a series of well-motivated assumptions



Tight-binding Approximation

electrons at different lattice sites
have limited interactions

Semiconductors

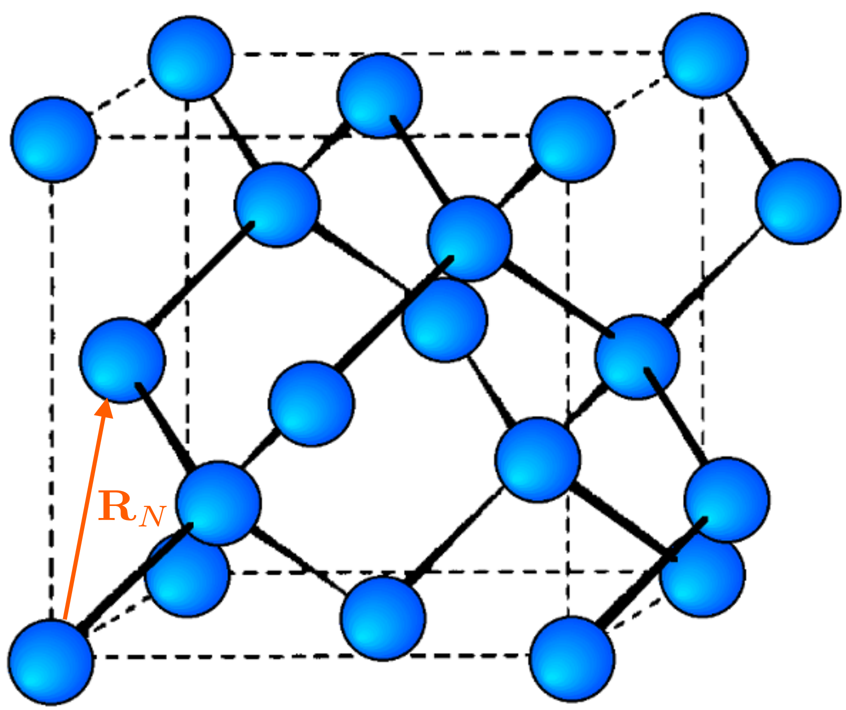
Lee, **ML**, Mishra-Sharma, and Safdi [1508.07361]

Electron is now described by Bloch wavefunction in a periodic lattice

$$\Psi(\ell, \mathbf{r}) = \underbrace{\phi_{4\mathrm{p}}(\mathbf{r} - \mathbf{R}_N)}_{\text{Germanium wavefunction}}$$

$\ell = \text{lattice momentum}$

Wavefunctions can be simplified using a series of well-motivated assumptions



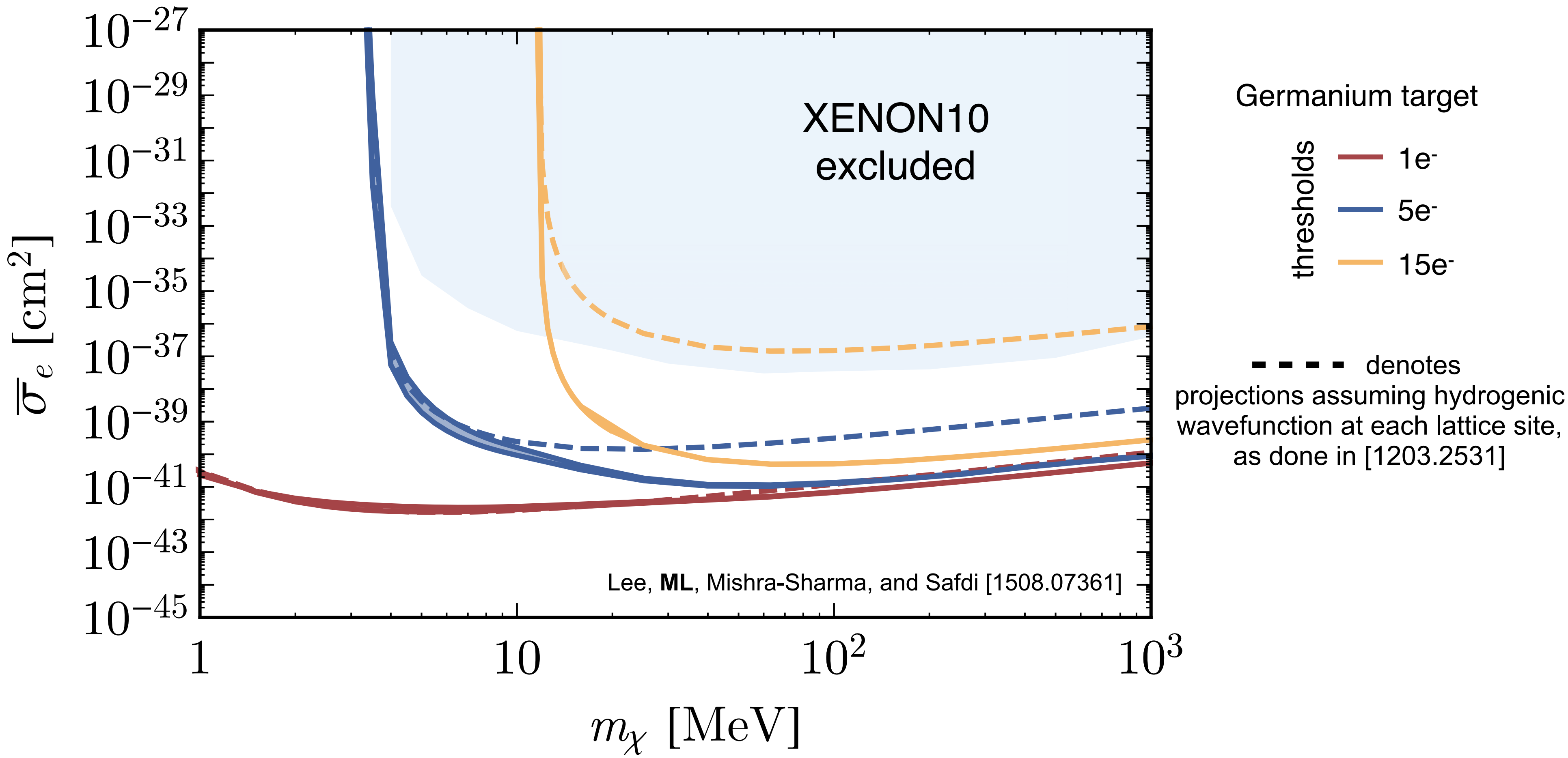
Tight-binding Approximation

electrons at different lattice sites have limited interactions

Assume DM-electron interaction is isolated to single lattice site

Projected Sensitivities

Germanium target can push sensitivities to lower dark matter masses, as compared to a Xenon target



Essig, Mardon, and Volansky [1108.5383]; Graham, Kaplan, Rajendran, and Walters [1203.2531]; Essig *et al.* [1206.2644]; Essig *et al.* [1509.01598]

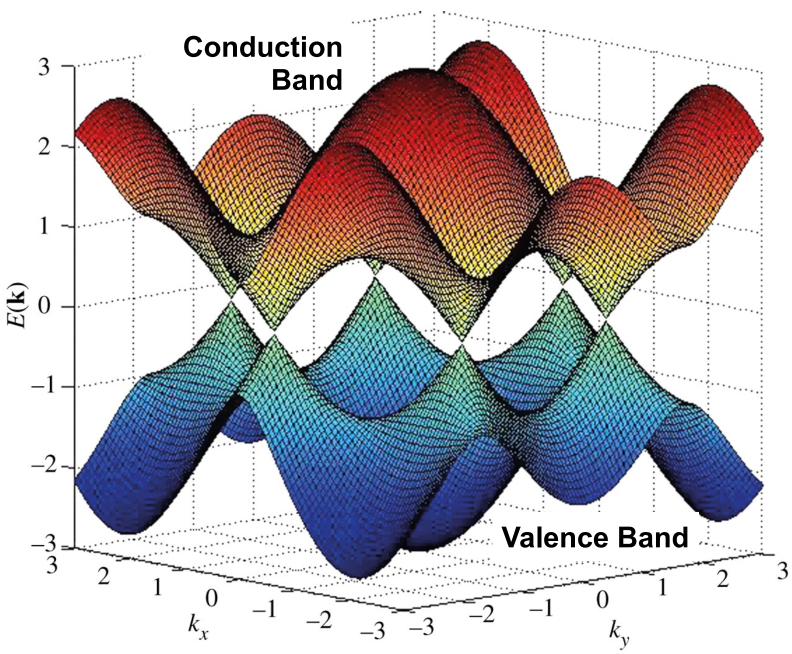
Considerations for Target Choice

Material Property	Why We Care
Band gap	Minimum dark matter mass
Lattice spacing	Localization of scattering

Graphene

Graphene is an example of a 2D material with a vanishing band gap

Lattice symmetries allow us to write down analytic wavefunctions, making dark matter scattering calculation tractable



Minimum mass set by the energy needed to excite the electron to the conduction band, and then eject it

$$\Delta E_e \sim E_{\rm BG} + \Phi \sim \text{ eV}$$

$$\Rightarrow m_\chi \gtrsim 1 \text{ MeV}$$

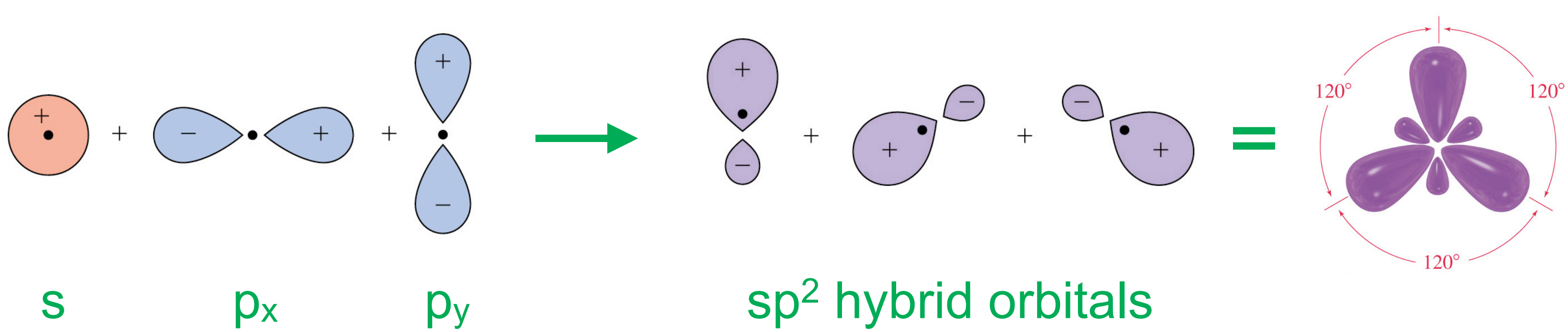
Band Gap	Work Function
E_{BG} = 0 eV	ϕ = 4 eV

Graphene Basics

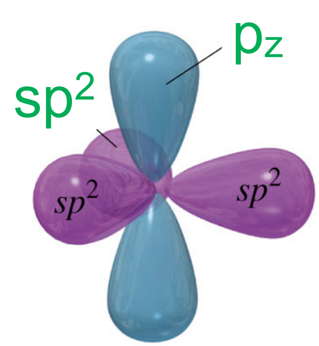
Graphene consists of Carbon atoms in honeycomb lattice

Carbon has four valence electrons occupying $(2s)(2p)^3$ orbitals

Hybridized orbitals form in-plane σ bonds



Remaining p_z orbital is unhybridized and forms covalent π bond



Wavefunctions

The Bloch wavefunction for the π electron is given by

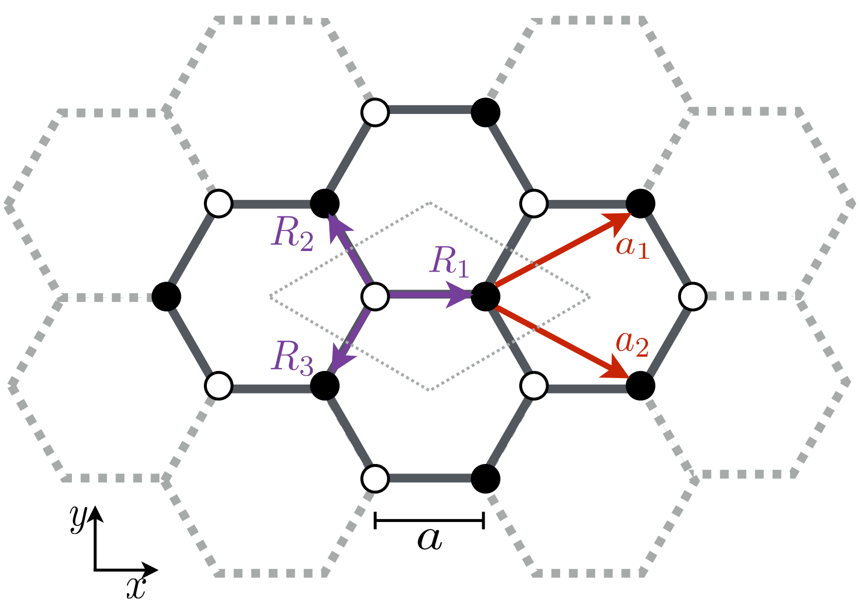
$$\Psi_\pi(\boldsymbol{\ell}, \mathbf{r}) \propto \phi_{2\mathrm{p}_z}(\mathbf{r}) + e^{i\varphi_{\boldsymbol{\ell}}} \sum_{j=1}^{3} e^{i\boldsymbol{\ell}\cdot\mathbf{R}_j} \phi_{2\mathrm{p}_z}(\mathbf{r} - \mathbf{R}_j)$$

Atomic wavefunctions: $\phi_{2\mathrm{p}_z}(\mathbf{r})$ and $\phi_{2\mathrm{p}_z}(\mathbf{r} - \mathbf{R}_j)$

Phase factors from nearest neighbors: $e^{i\varphi_{\boldsymbol{\ell}}}$ and $e^{i\boldsymbol{\ell}\cdot\mathbf{R}_j}$

$\ell = \text{lattice momentum}$

Wavefunctions for σ electrons are still tractable, though more complicated



Kinematically-allowed scattering is localized to only a few lattice sites:

$$q_{\mathrm{min}} \lesssim \frac{2\pi}{a} \sim 9\ \mathrm{keV}$$

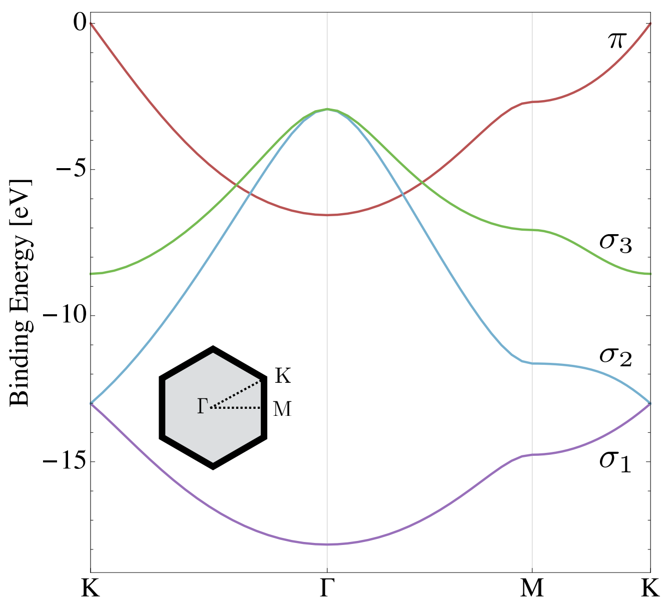
Interference from different lattice sites can lead to diffraction patterns in observed signal

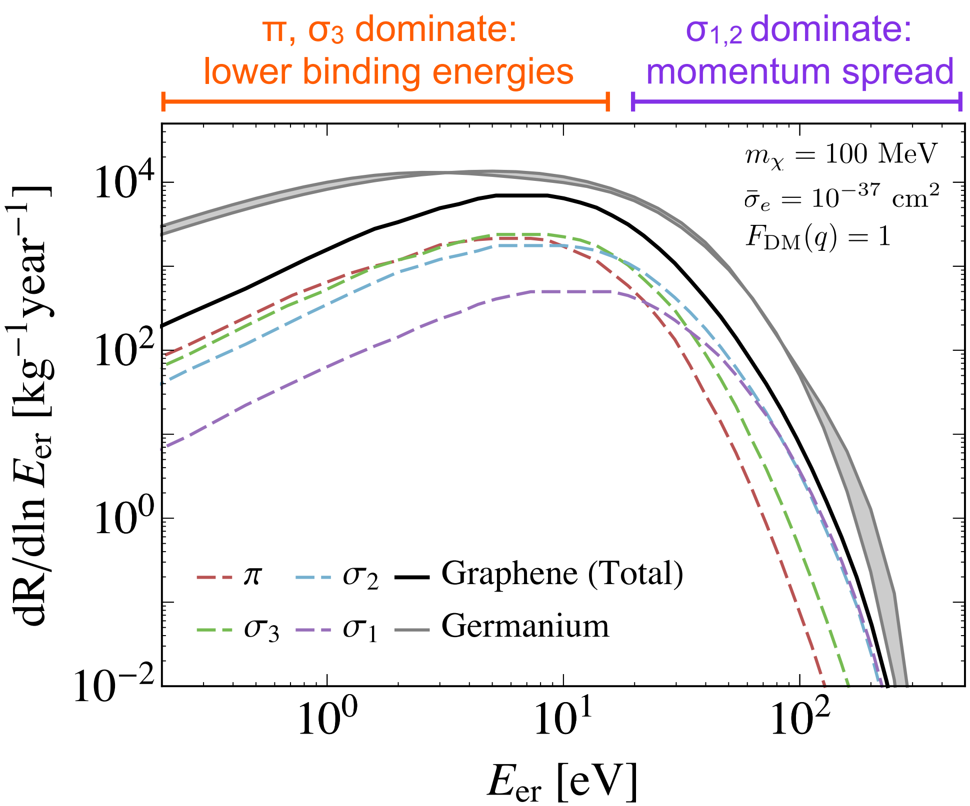
Scattering Rate

Hochberg, Kahn, **ML**, Tully, and Zurek [1606.08849]

Electrons from both the π and σ bands contribute to the total scattering rate

For a given electron energy, the binding energy and associated momentum spread of the electron wavefunction sets its contribution to the rate





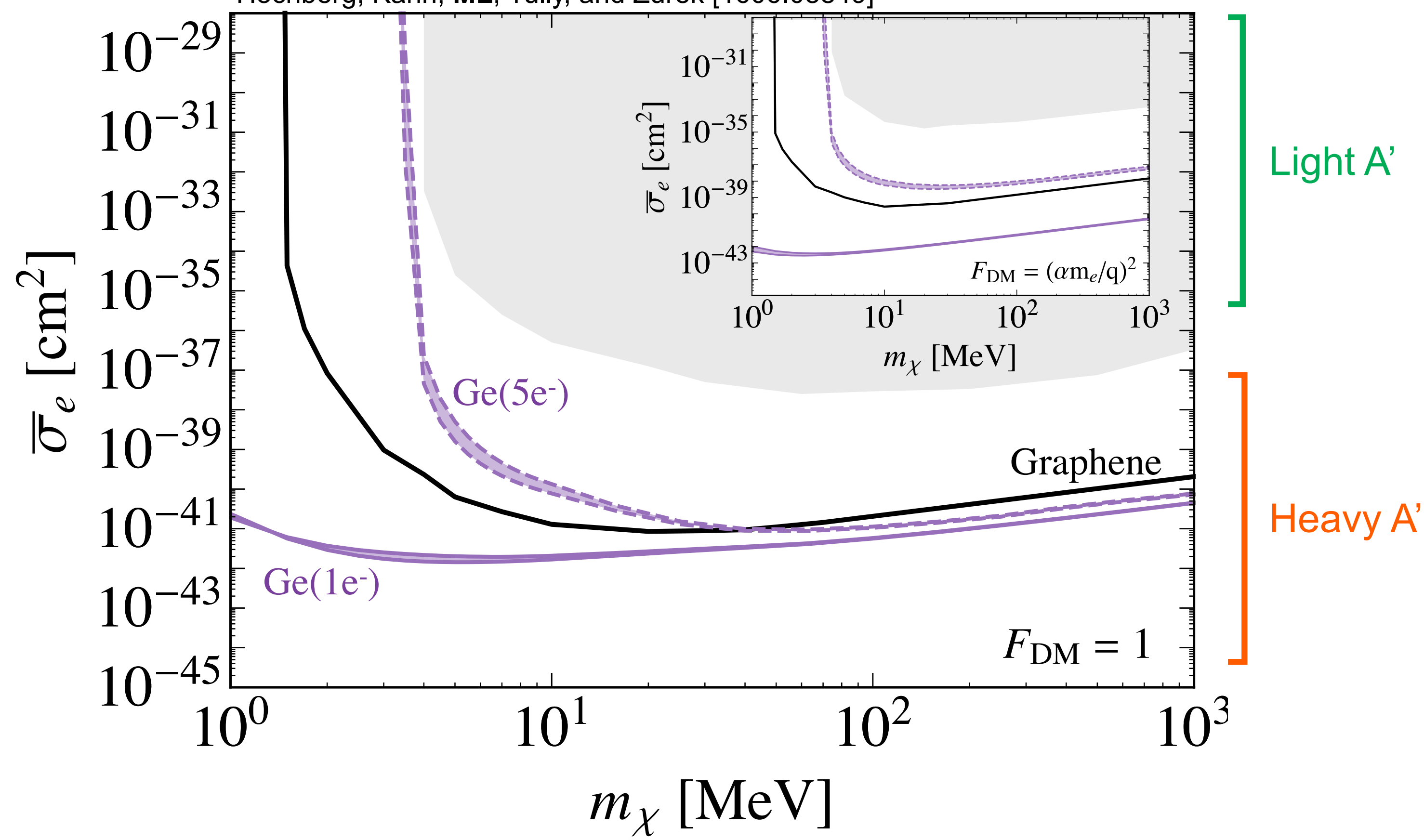
Projected Sensitivity

Graphene is competitive with semiconductor targets for MeV-GeV DM

Low-mass reach for graphene is set by the work function (ϕ = 4 eV), which can be engineered to be lower

Yuan *et al. Nano Letters* (2015).

Hochberg, Kahn, **ML**, Tully, and Zurek [1606.08849]



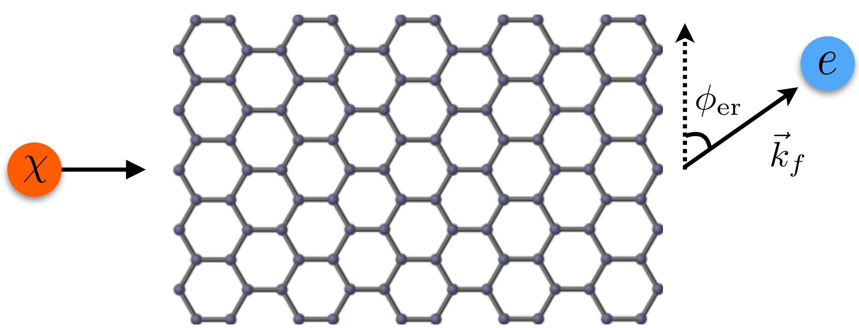
Dark Matter Diffraction

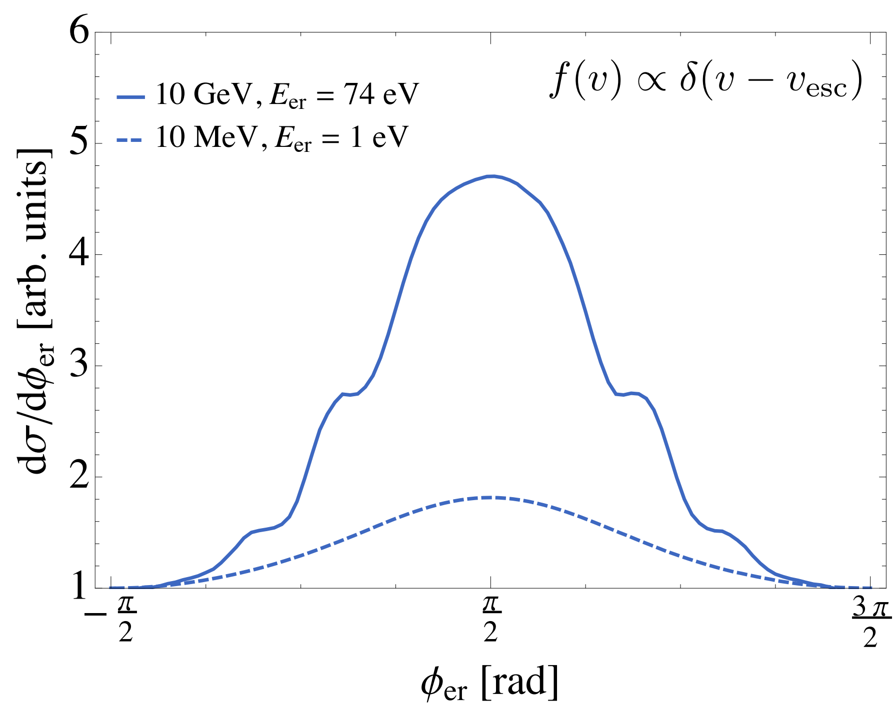
For DM stream parallel to graphene sheet, electrons are preferentially emitted in the plane

Diffraction patterns are visible if the final momentum of the electron satisfies

$$k_f = \frac{2\pi}{\text{lattice spacing}} \simeq 9 \text{ keV}$$

(Diffraction pattern washes out as the velocity dispersion of DM increases)





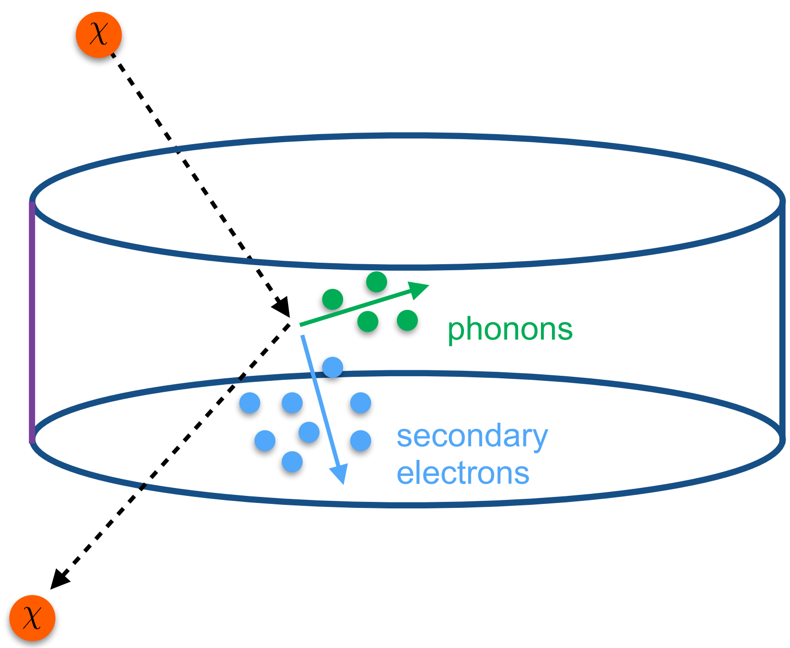
Considerations for Target Choice

Material Property	Why We Care
Band gap	Minimum dark matter mass
Lattice spacing	Localization of scattering
Dimensionality	Directionality

Directional Electrons

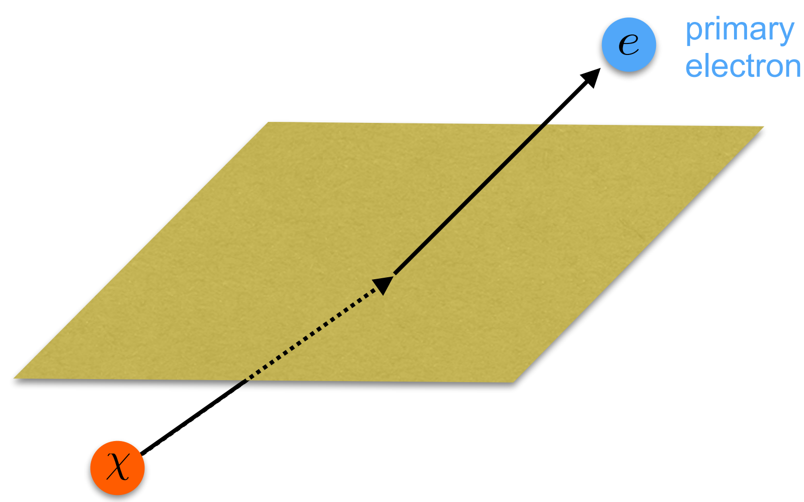
Can we retain directional information of scattered electron?

Directional information is lost if secondaries of the interaction are being detected



ex: SuperCDMS

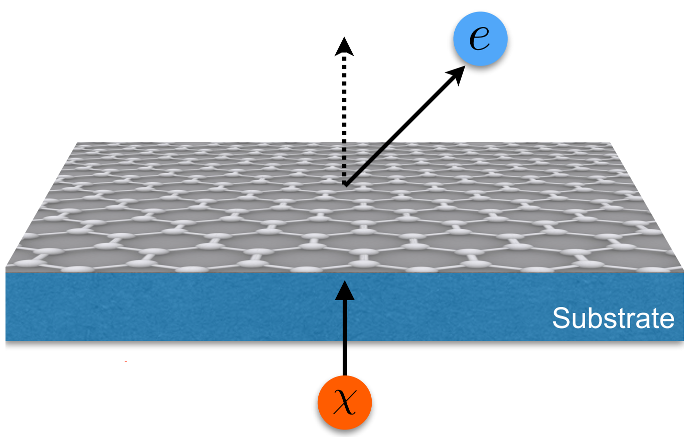
To directly measure the electron's direction, it must be ejected from the target



Requires 2D target

Count Rate

Forward scattering is still preferred even when dark matter is incident normal to graphene sheet

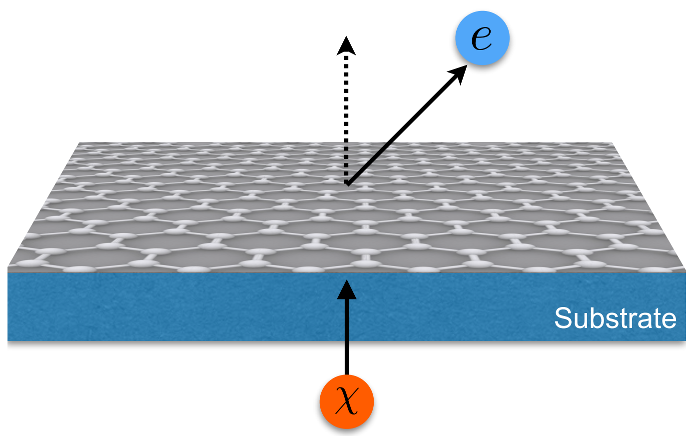


Most electrons are ejected into vacuum and detected

Count Rate

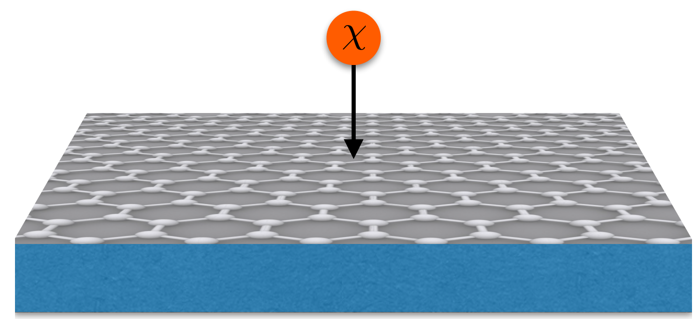
Forward scattering is still preferred even when dark matter is incident normal to graphene sheet

Naturally leads to daily modulation in total count rate



Most electrons are ejected into vacuum and detected

12 hours later…



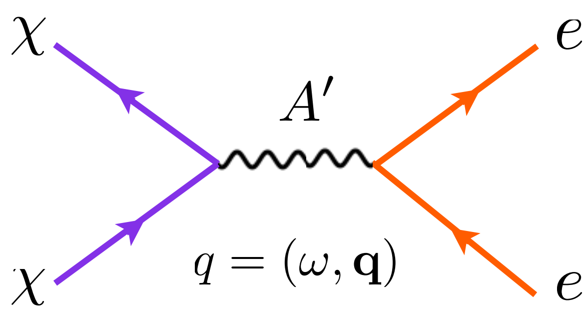
Most electrons are scattered into substrate and not detected

Considerations for Target Choice

Material Property	Why We Care
Band gap	Minimum dark matter mass
Lattice spacing	Localization of scattering
Dimensionality	Directionality
Optical Response	Suppression of scattering rate
Quasiparticle Lifetime	Detectability of scattered electron

Optical Response

Dark photon propagator is modified in the target medium



$$\langle |\mathcal{M}|^2 \rangle \propto \frac{1}{\left(q^2 - m_{A'}^2\right)^2 \left(1 + \sigma^2/\omega^2\right)}$$

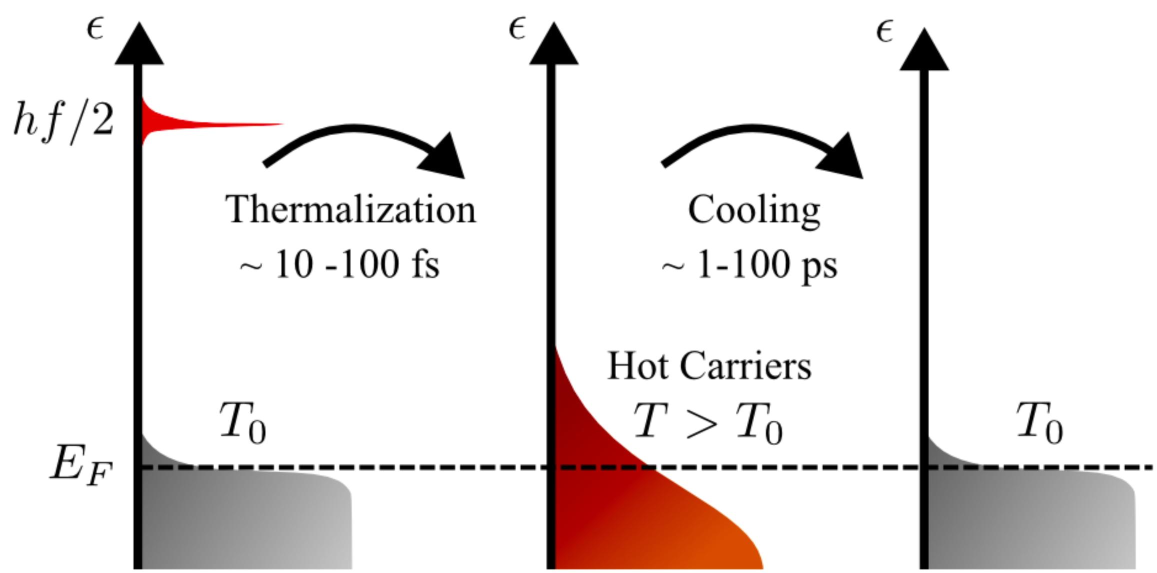
Effective mass of dark photon is larger in materials with higher conductivity

Insulating targets with small band gaps are important in the push to lighter dark matter masses

Hochberg, Pyle, Zhao, and Zurek [1512.04533]

Quasiparticle Lifetime

Quasiparticles can lose energy by scattering off of other electrons, phonons, or impurities in the lattice



Song and Levitov [1410.5426]

To detect excited quasiparticles, energy loss should not be too rapid relative to the time it takes to probe the signal

Considerations for Target Choice

Material Property	Why We Care
Band gap	Minimum dark matter mass
Lattice spacing	Localization of scattering
Dimensionality	Directionality
Optical Response	Suppression of scattering rate
Quasiparticle Lifetime	Detectability of scattered electron
Topological Properties	???