The Migdal effect in semi-conductors

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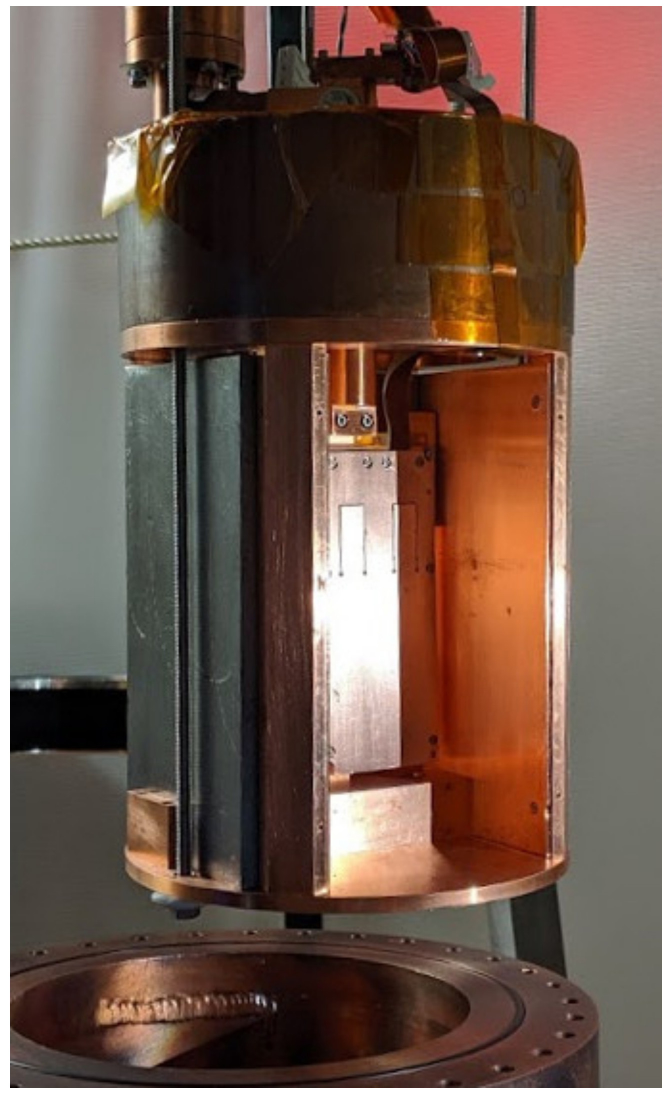
Introduction

Direct detection with semi-conductors

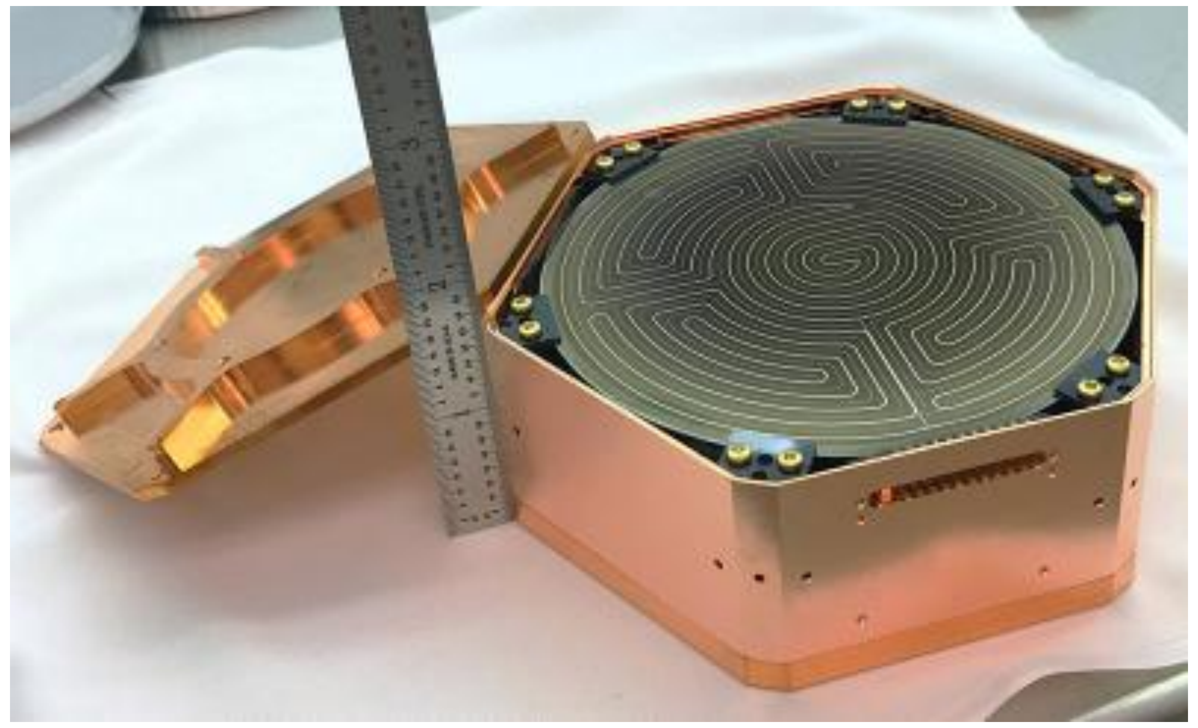
low energy thresholds (~2 electrons)

SENSEI (Si)



ionization

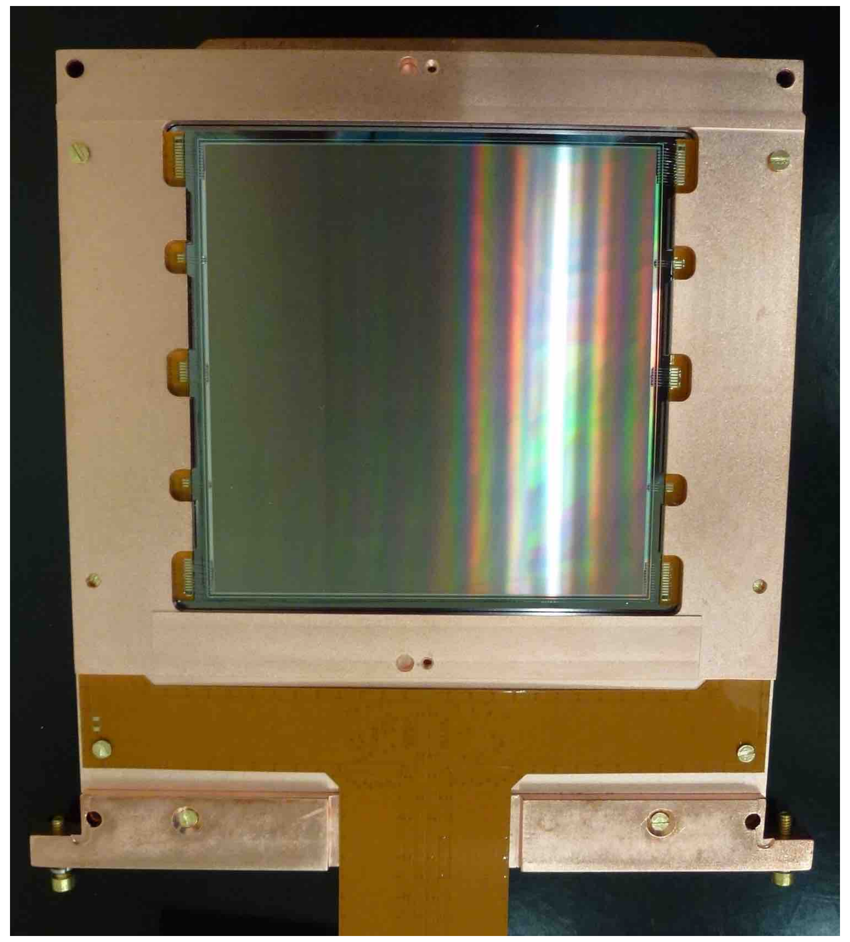
SuperCDMS (Ge, Si)



phonon

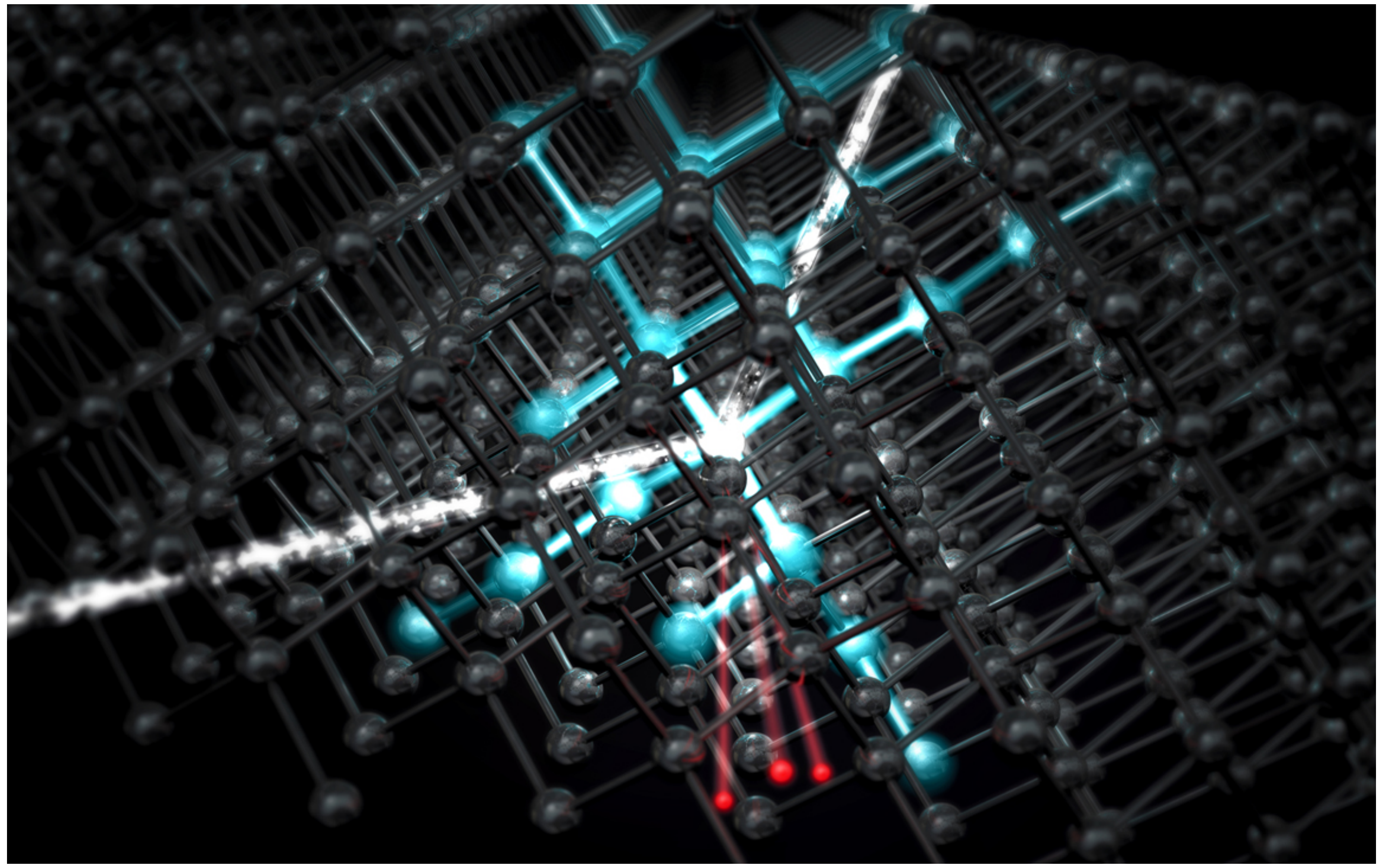
ionization

DAMIC (Si)



ionization

What happens in the detector



(superCDMS)

Electron recoil

The recoil electron is freed (Ge: 0.74eV, Si: 1.18eV)

It looses its kinetic energy by freeing other electrons

Finally, the freed charges dissipate as phonons

Nucleus recoil

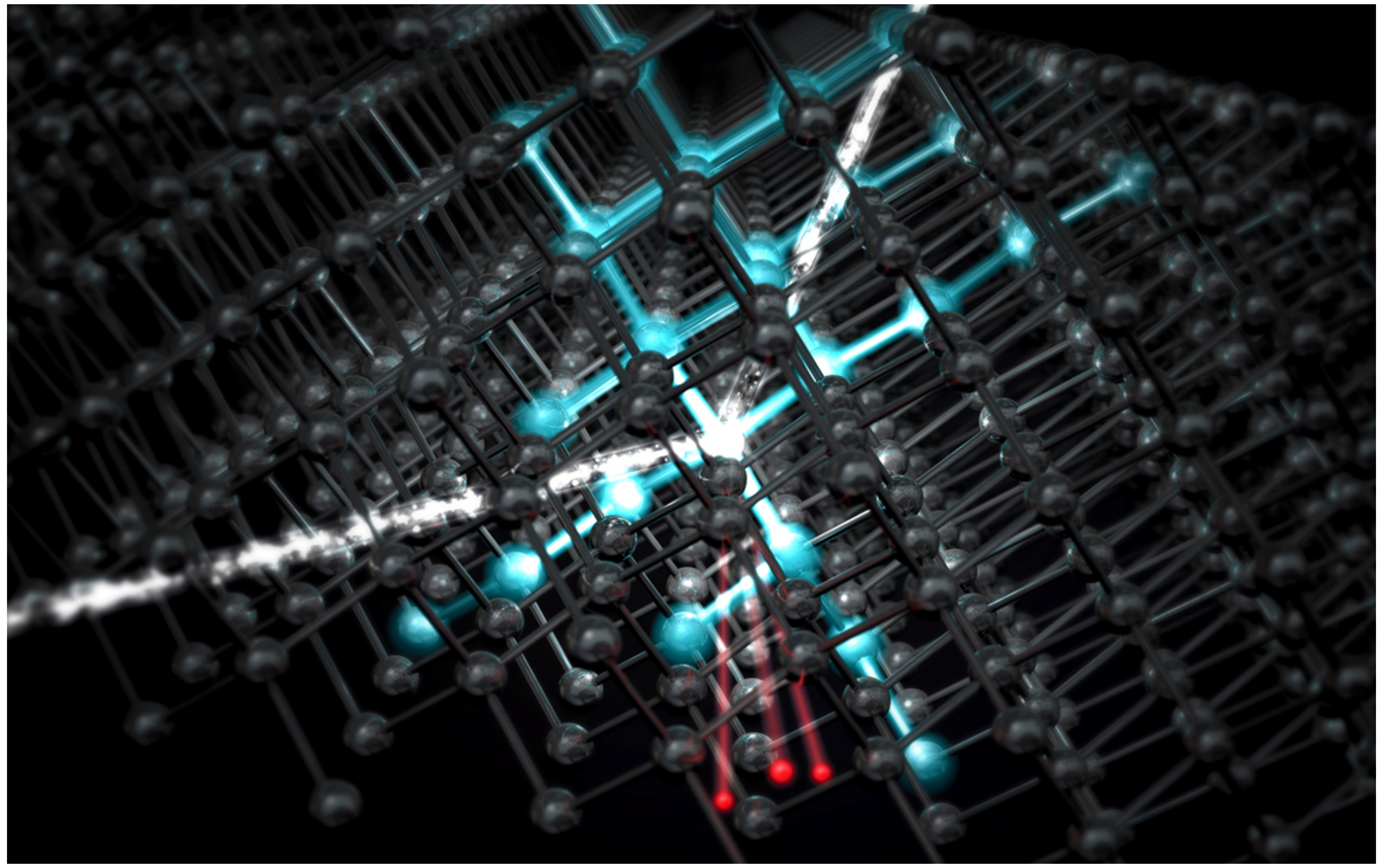
The recoil nucleon starts to move and some valence electrons are freed

Depending on the recoil energy, the nucleon is freed or oscillates in the potential (~ 20eV)

The electrons dissipate as electron recoil

The nucleon is stopped by other nucleons and electrons (phonons & ionizations)

What happens in the detector



(superCDMS)

Electron recoil

The recoil electron is freed (Ge: 0.74eV, Si: 1.18eV)

It looses its kinetic energy by freeing other electrons

Finally, the freed charges dissipate as phonons

Nucleus recoil

consider the Migdal effect here

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Depending on the recoil energy, the nucleon is freed or oscillates in the potential (~ 20eV)

The electrons dissipate as electron recoil

The nucleon is stopped by other nucleons and electrons (phonons & ionizations)

Previous works

R. Essig, J. Pradler, M. Sholapurkar, and T.-T. Yu, Phys. Rev. Lett. 124, 021801 (2020), arXiv:1908.10881 [hep-ph].

Crystal form factor

Z.-L. Liang, L. Zhang, F. Zheng, and P. Zhang, Phys. Rev. D 102, 043007 (2020), arXiv:1912.13484 [cond- mat.mes-hall].

Tight binding, Wannier function

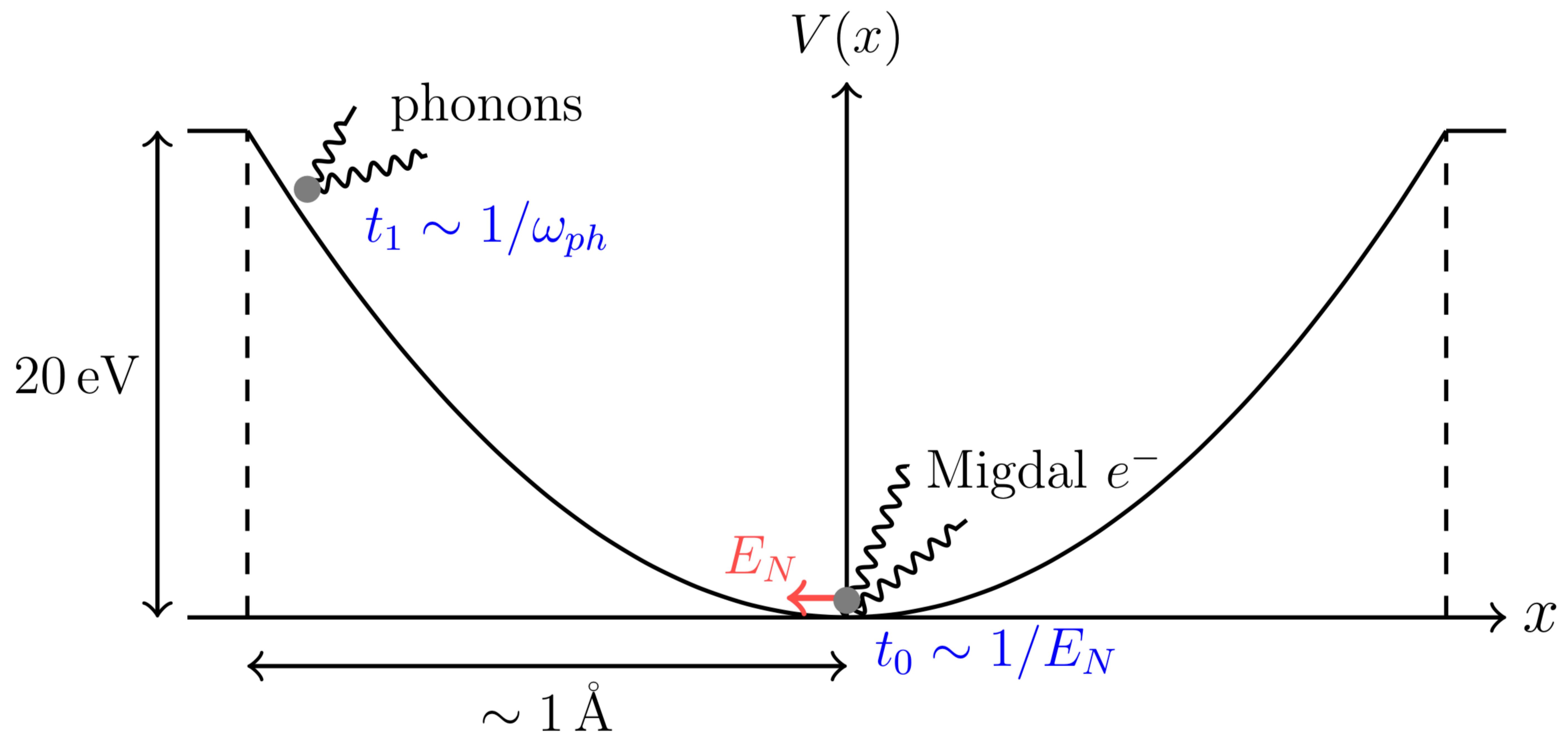
C.-P. Liu, C.-P. Wu, H.-C. Chi, and J.-W. Chen, (2020), arXiv:2007.10965 [hep-ph].

Photoabsorption

Contents

Derivation

Timescales



DM-nucleus interaction

$$E_N \sim \frac{m_\chi^2 v_\chi^2}{m_N} \sim 35\text{eV}\left(\frac{m_\chi}{\text{GeV}}\right)^2$$

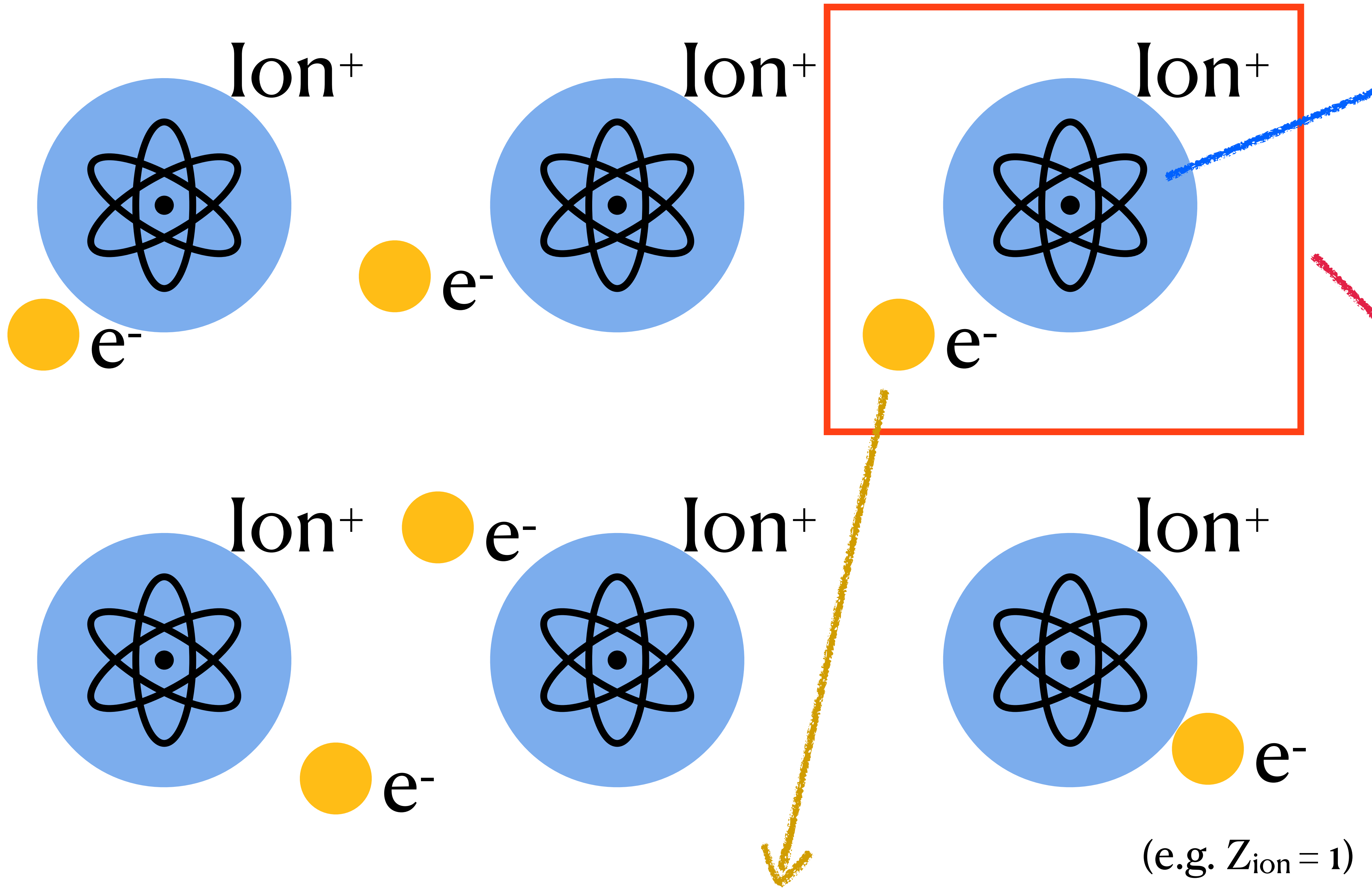
Nucleus motion

$$\omega_{ph} \sim 30 - 50\text{meV}$$

The impulse approximation is good enough for $m_\chi \gtrsim 70\text{MeV}$

Model

consider only Z_{ion} valence electrons



Bloch wave function

DM-nucleon interaction

$$H_\chi = \frac{2\pi b_\chi}{m_\chi}\delta(\mathbf{r}_\chi - \mathbf{r}_N)$$

Nucleon in the lattice

$$\langle \mathbf{r}_N | \psi_0 \rangle = \frac{(m_N^3 \bar{\omega}^3)^{1/4}}{\pi^{3/4}} e^{-\frac{1}{2} r_N^2 m_N \bar{\omega}}$$

For incoherent scattering

$$m_\chi \gg 10\text{MeV}$$

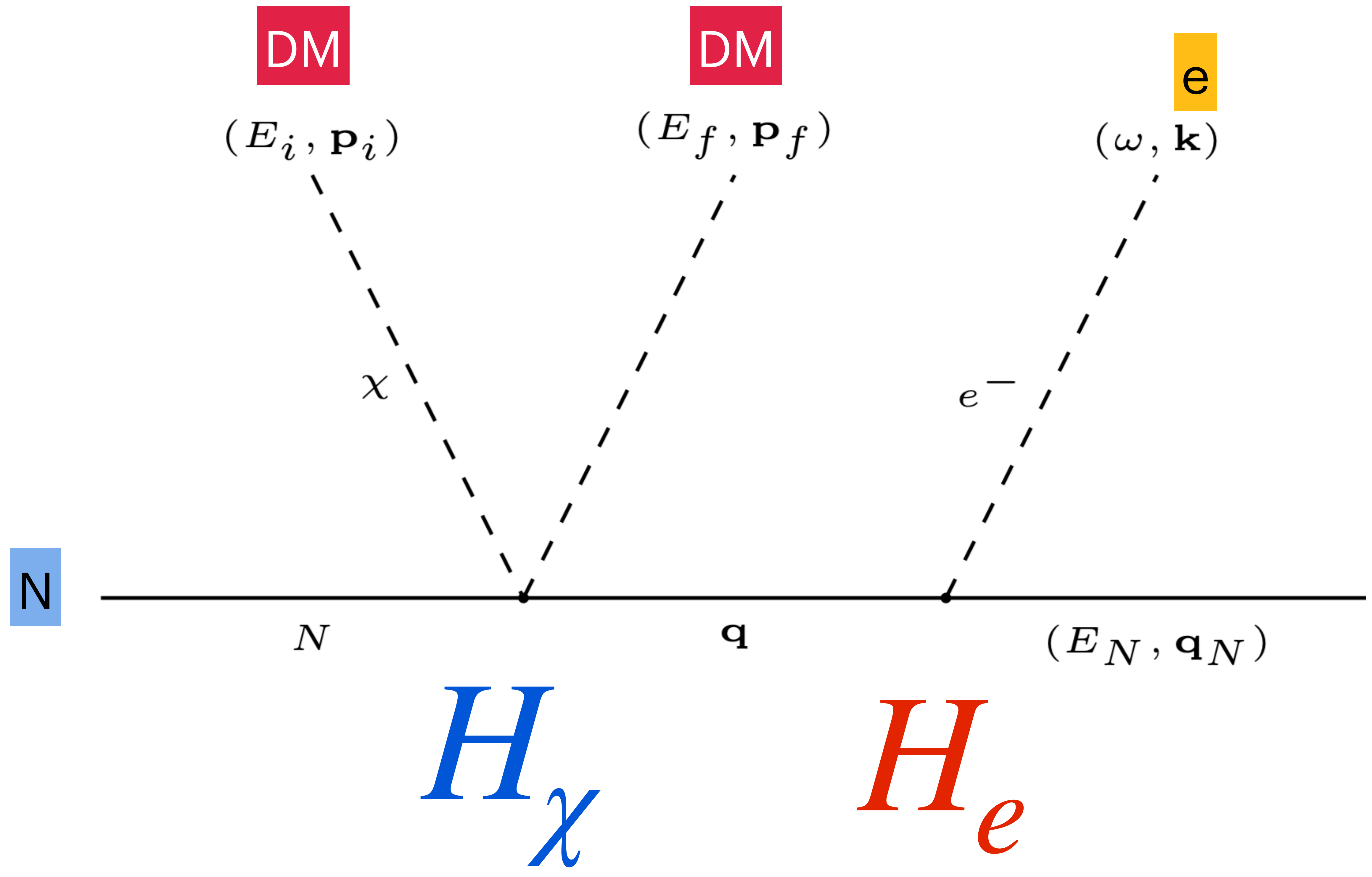
Ion-electron interaction

$$H_e = -\int d^3\mathbf{r}' \frac{Z_{\text{ion}}\alpha}{\epsilon(\mathbf{r}, \mathbf{r}', \omega)} \frac{1}{|\mathbf{r}' - \mathbf{r}_N|}$$

ε: Dielectric function

$$\mathbf{E}(\mathbf{r}, \omega) = \int d^3\mathbf{r}'\ \epsilon^{-1}(\mathbf{r}, \mathbf{r}', \omega)\mathbf{E}_{\text{ext}}(\mathbf{r}', \omega)$$

2->3 scattering



$$\mathcal{M}_a = \sum_{\mathbf{q}} \frac{\langle \mathbf{q}_N, \mathbf{p}_e + \mathbf{k} | H_e | \mathbf{q}, \mathbf{p}_e \rangle \langle \mathbf{p}_f, \mathbf{q} | H_\chi | \mathbf{p}_i, \psi_0 \rangle}{\omega + \frac{q_N^2}{2m_N} - \frac{q^2}{2m_N}} \tag{A8}$$

$$\mathcal{M}_b = -\sum_{\mathbf{q}} \frac{\langle \mathbf{p}_f, \mathbf{q}_N | H_\chi | \mathbf{q}, \mathbf{p}_i \rangle \langle \mathbf{q}, \mathbf{p}_e + \mathbf{k} | H_e | \mathbf{p}_e, \psi_0 \rangle}{\omega + \frac{q^2}{2m_N}} \tag{A9}$$

Final result

$$\frac{d\sigma}{d\omega} = \frac{2\pi^2 A^2 \sigma_n}{m_\chi^2 v_\chi} \int \frac{d^3\mathbf{q}_N}{(2\pi)^3} \int \frac{d^3\mathbf{p}_f}{(2\pi)^3} \delta(E_i - E_f - \omega - E_N) \times 4\alpha Z_{\rm ion}^2 \sum_{\mathbf{K}} \int \frac{d^3\mathbf{k}}{(2\pi)^3} \left[\frac{1}{\omega - \mathbf{q}_N \cdot (\mathbf{k}+\mathbf{K})/m_N} - \frac{1}{\omega} \right]^2$$

$$\times \frac{F(\mathbf{p}_i - \mathbf{p}_f - \mathbf{q}_N - \mathbf{k} - \mathbf{K})^2}{|\epsilon_{\mathbf{K}\mathbf{K}}(\mathbf{k},\omega)|^2} \times \frac{4\pi^2\alpha}{V} \sum_{\mathbf{p}_e} \frac{|[\mathbf{p}_e + \mathbf{k}|e^{i\mathbf{r}\cdot\mathbf{K}}|\mathbf{p}_e]_\Omega|^2}{|\mathbf{k}+\mathbf{K}|^2} \left(f(\mathbf{p}_e) - f(\mathbf{p}_e + \mathbf{k})\right) \delta(\omega_{\mathbf{p}_e+\mathbf{k}} - \omega_{\mathbf{p}_e} - \omega)$$

$\sim \omega^{-4}$

Nucleus in the lattice

Screening

Migdal factor

Occupation number

Final result

$\sim \omega^{-4}$

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

$$\times \frac{F(\mathbf{p}_i - \mathbf{p}_f - \mathbf{q}_N - \mathbf{k} - \mathbf{K})^2}{|\epsilon_{\mathbf{KK}}(\mathbf{k}, \omega)|^2} \times \frac{4\pi^2\alpha}{V} \sum_{\mathbf{p}_e} \frac{|[\mathbf{p}_e + \mathbf{k}|e^{i\mathbf{r}\cdot\mathbf{K}}|\mathbf{p}_e]_\Omega|^2}{|\mathbf{k} + \mathbf{K}|^2} \left(f(\mathbf{p}_e) - f(\mathbf{p}_e + \mathbf{k})\right) \delta(\omega_{\mathbf{p}_e + \mathbf{k}} - \omega_{\mathbf{p}_e} - \omega)$$

$\mathrm{Im}[\epsilon_{KK}(k, \omega)]$

Nucleus in the lattice

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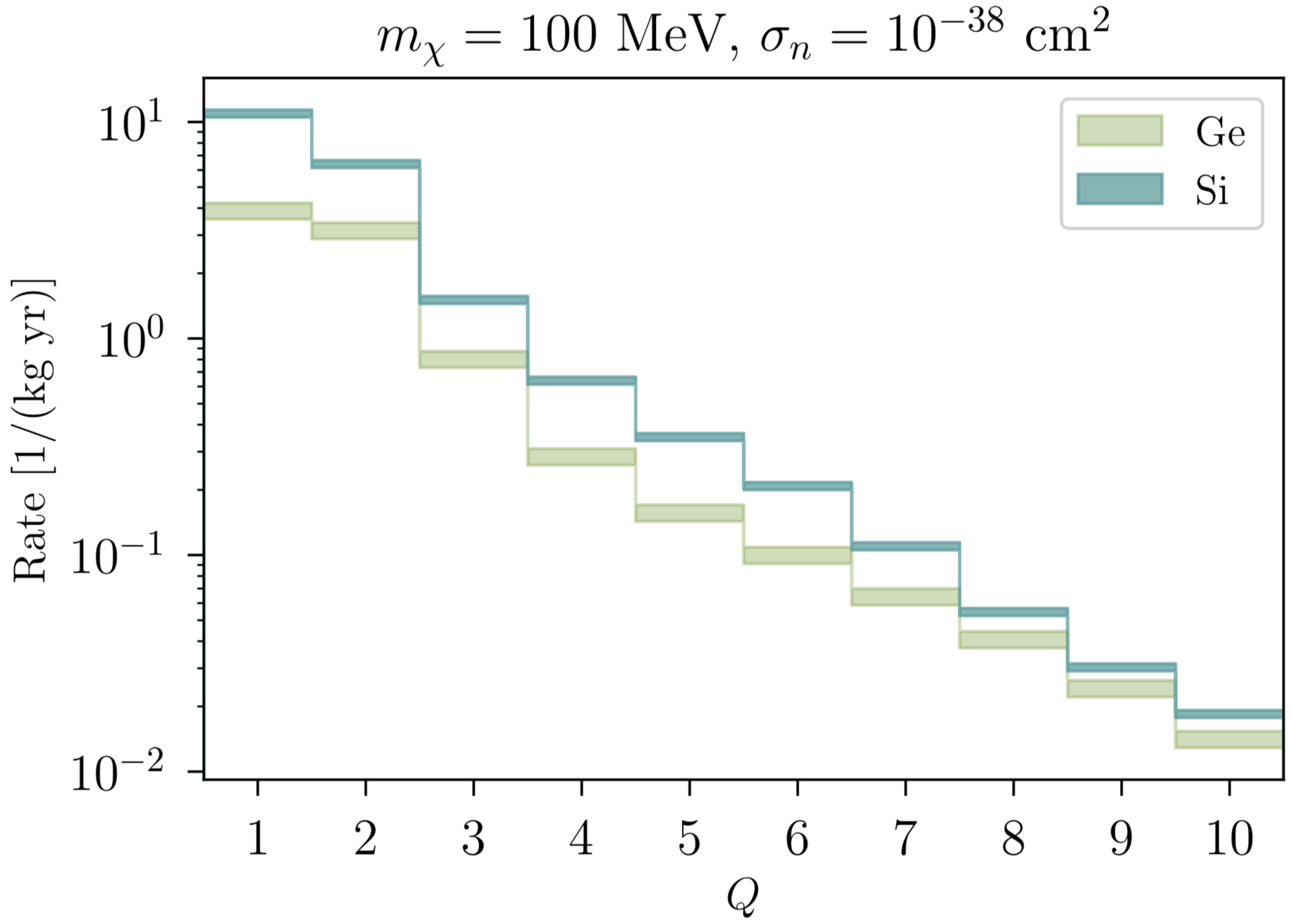
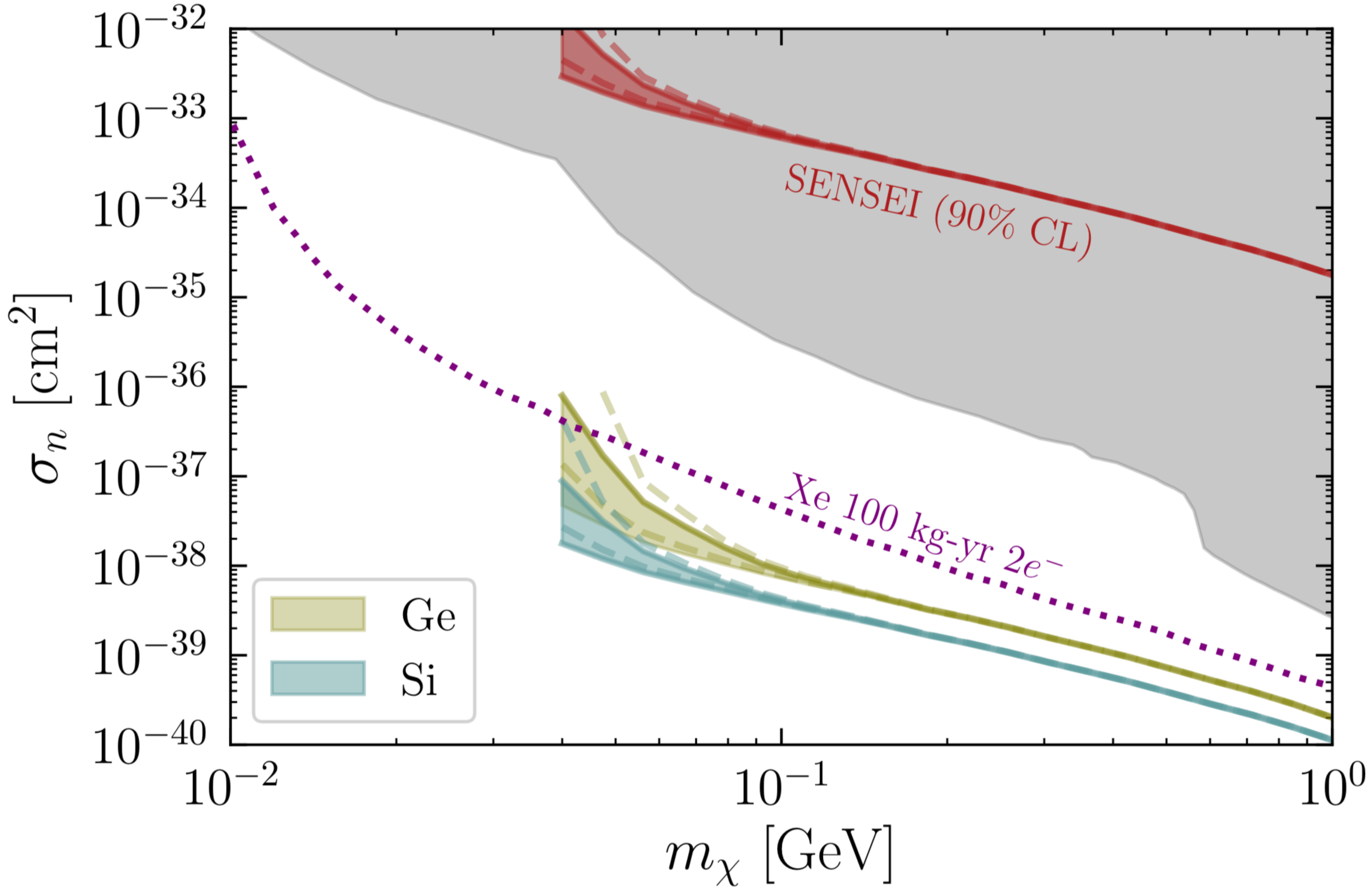
Numerical Results

Event rate



$m_\chi = 100$ MeV, $\sigma_n = 10^{-38}$ cm^2
Ge
Si
Rate [1/(kg yr)]
10^1
10^0
10^{-1}
10^{-2}
1
2
3
4
5
6
7
8
9
10
Q

Constraints



$Q \geq 2$

Band: uncertainty from impulse approx

Dashed: without form factor, F

Summary

- Recent experiments with semi-conductors can observe 1~2-electron signals
- With only elastic scattering with nucleus, the energy deposit is limited. However, the Migdal effect boosts the energy deposit and make the signal visible
- They calculated the response of the valence electrons just after the nuclear recoil
- We can search DM mass down to ~40MeV with experiments like SENSEI, SuperCDMS and DAMIC.