Heating via nuclear scattering

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Contents

- Sub-threshold scattering
- Heating channels
- Progress: Where are we now?

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Heating via sub-threshold scattering

If our DM is too light to break sufficiently many Cooper pairs, can we detect it?

Perhaps! We have access to time-series temperature data.

Heating via sub-threshold scattering

Suppose we have no *dark* channel for heating:

$$\frac{dT}{dt} \sim P_{\text{bkg}}(t),$$

with P_{bkg} some background heating power (e.g. cosmic rays, surroundings).

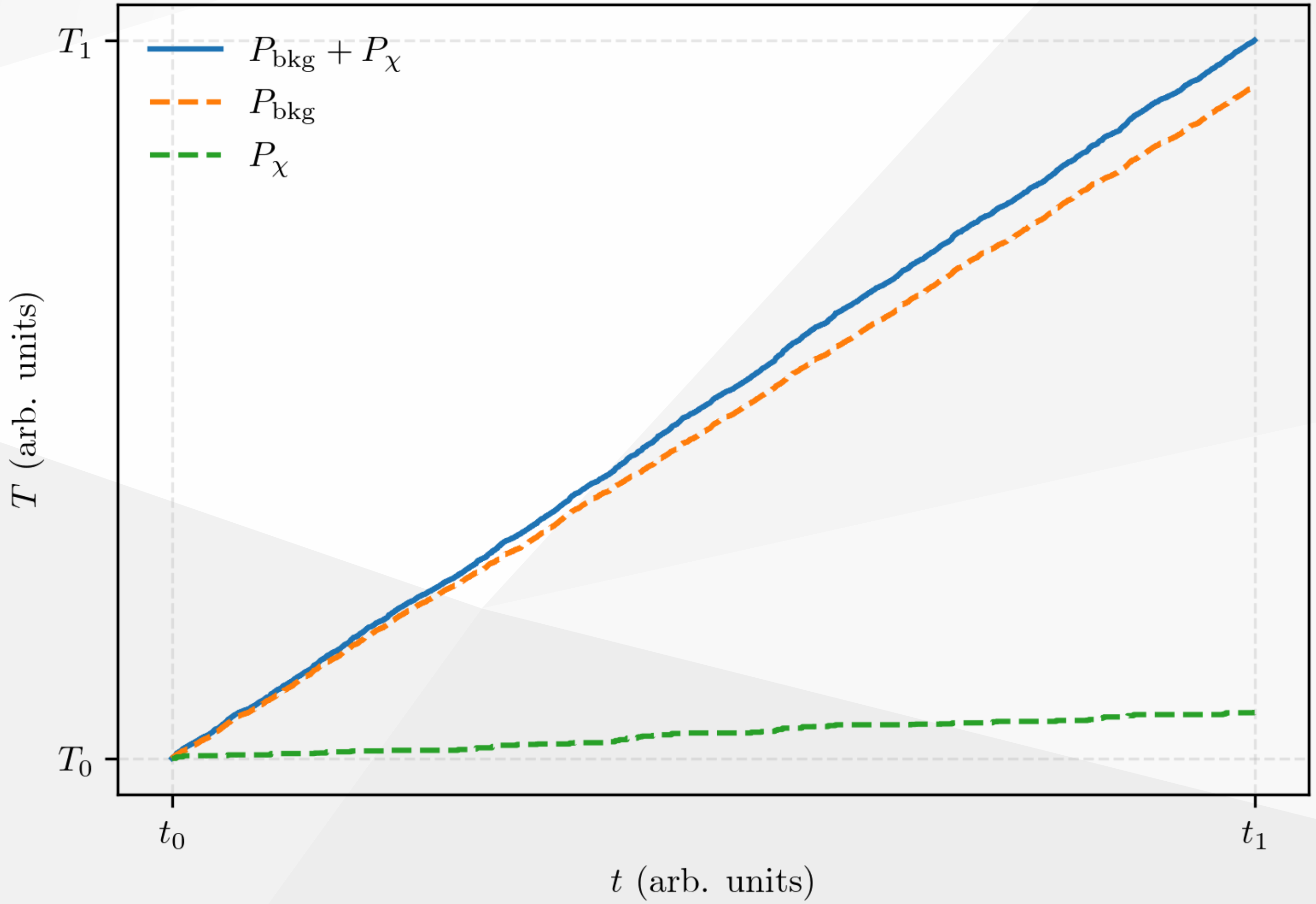
Heating via sub-threshold scattering

The presence of DM scattering adds an additional heating channel:

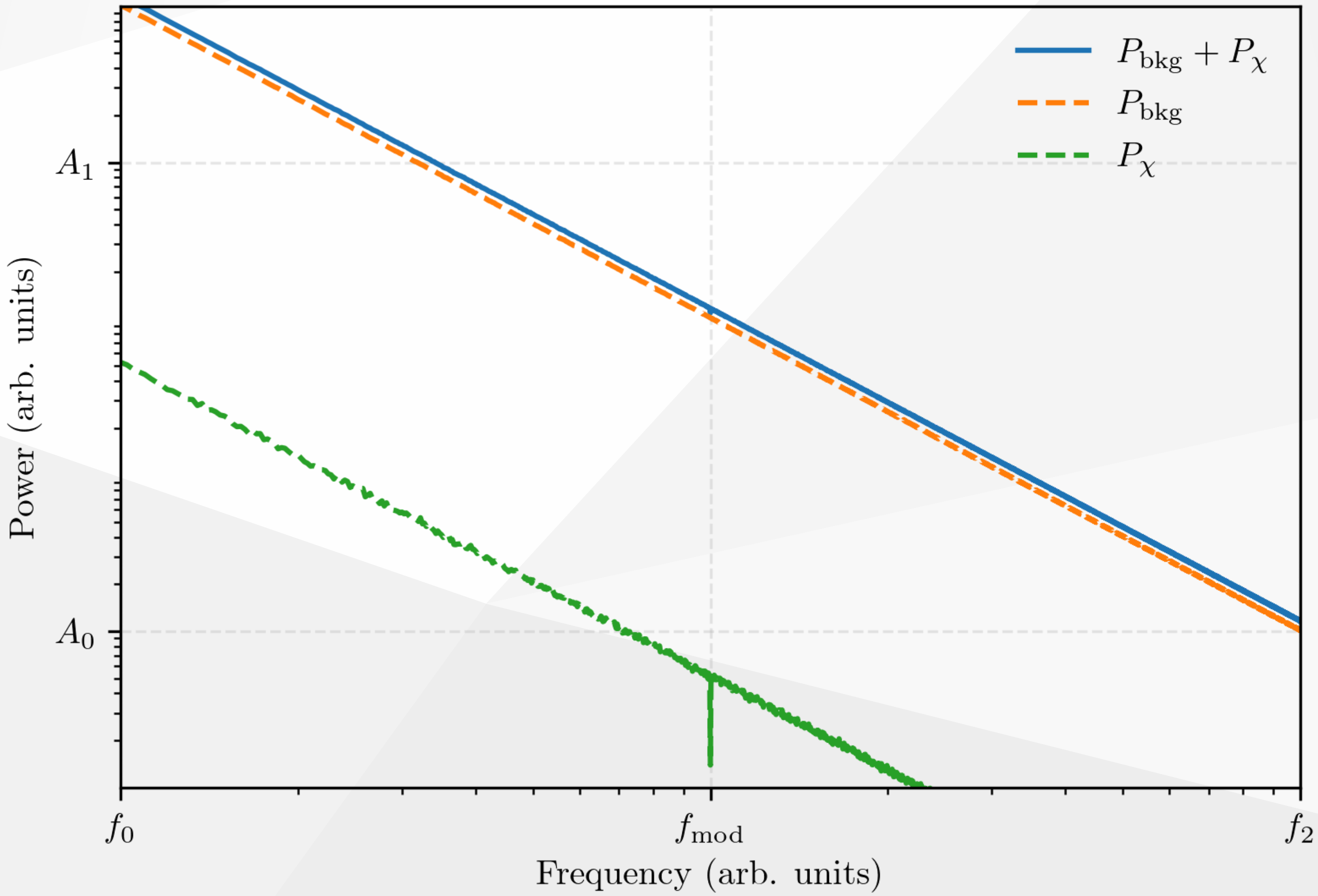
$$\frac{dT}{dt} \sim P_{\mathrm{bkg}}(t) + P_{\chi}(t),$$

where one or both of these terms may be time-dependent.

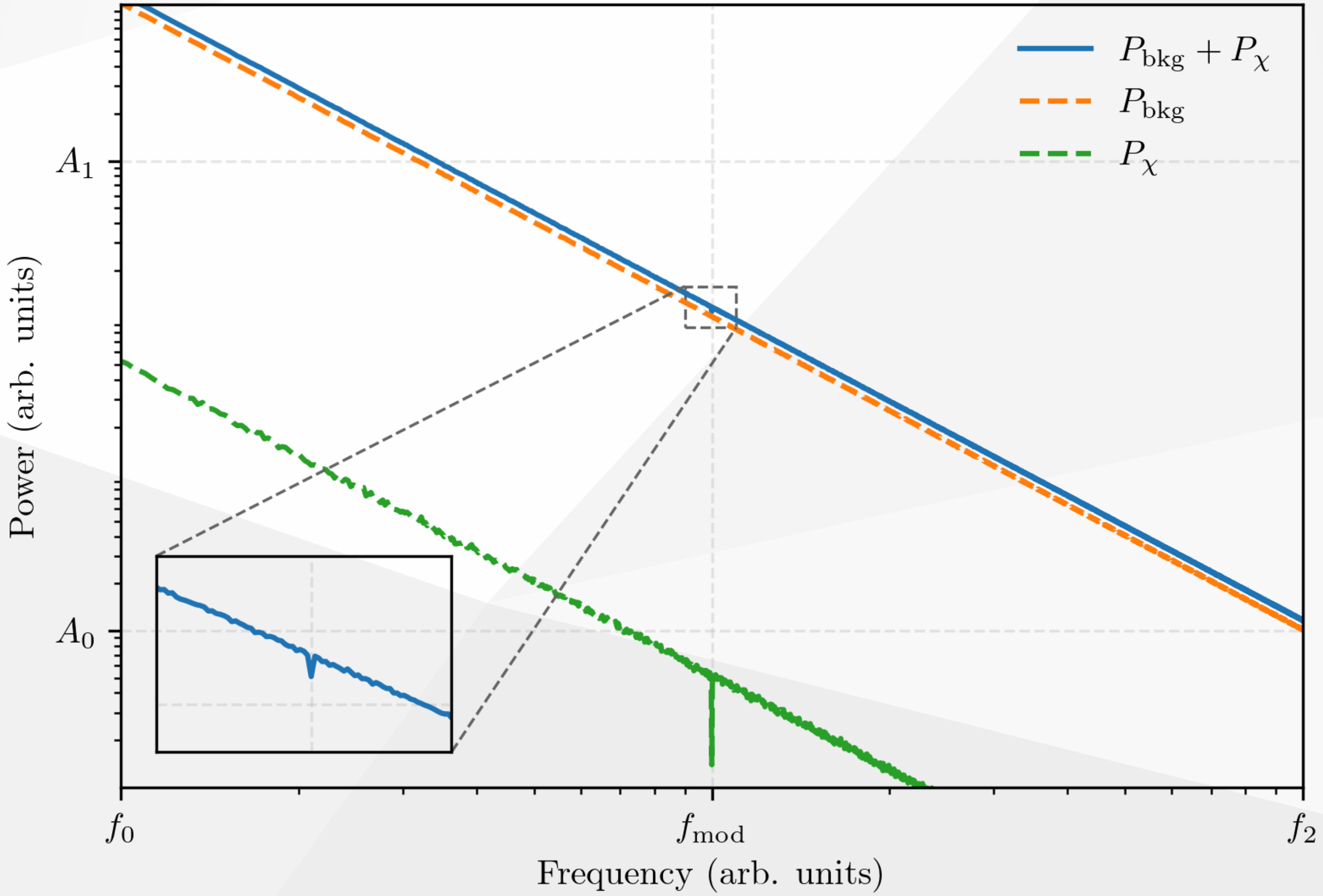
Heating via sub-threshold scattering



Heating via sub-threshold scattering



Heating via sub-threshold scattering



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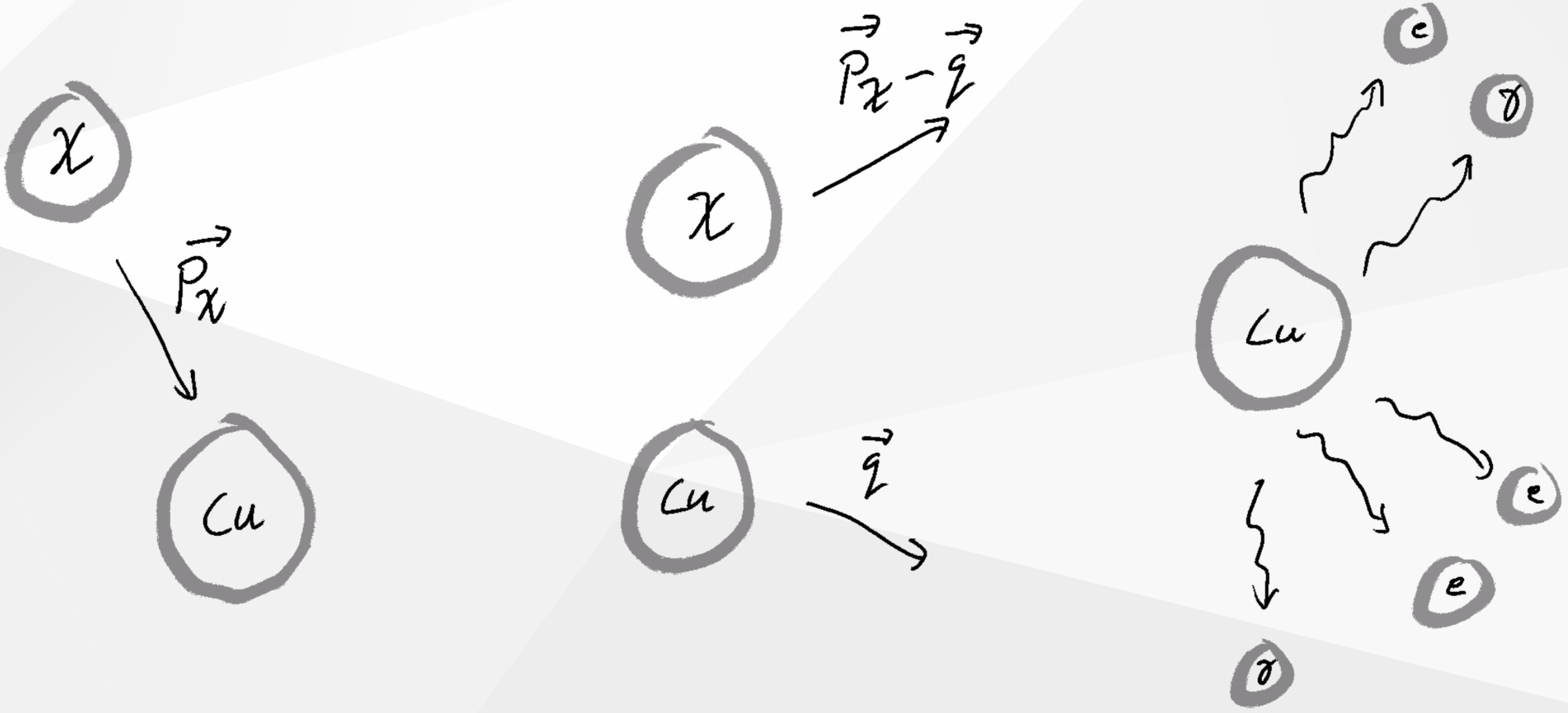
Heating Sources

- Direct scattering on electrons (See Tania's talk)
- Scattering on nuclei:
  - Nuclear recoil
  - The Migdal effect

Heating Sources: Nuclear Recoil



Heating Sources: Nuclear Recoil

In the free nucleus picture:

$$Q \simeq E_N \simeq \frac{q^2}{2m_N}$$

For DM of mass m_χ:

$$q \simeq m_\chi v_{\mathrm{DM}}$$

Heating Sources: Nuclear Recoil

In the free nucleus picture:

$$Q \simeq \frac{m_\chi^2 v_{\mathrm{DM}}^2}{2m_N}$$

For a copper nucleus:

$$Q(m_\chi = 10\,\mathrm{MeV}) \simeq 0.8\,\mathrm{meV}$$

Heating Sources: Nuclear Recoil

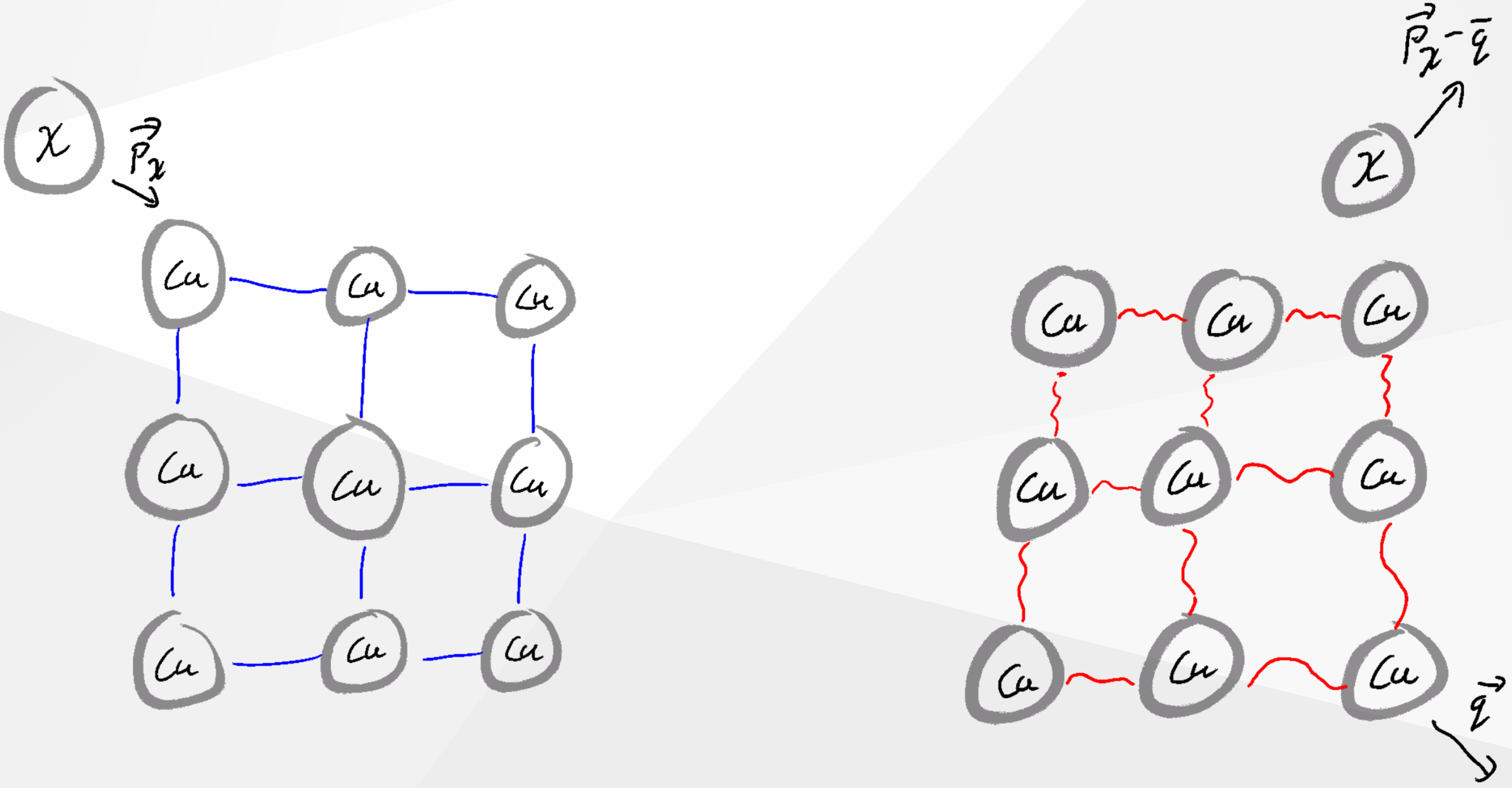
The heating rate is found via:

$$P_{\rm nuc} = \int dE_N \, \frac{dR_{\rm nuc}}{dE_N} E_N$$

In this free nucleus picture:

$$\frac{dR_{\rm nuc}}{dE_N} \sim \int d^3q \, d^3p_f \, \delta(\vec{p}_i - \vec{p}_f - \vec{q}) \ldots$$

Heating Sources: Nuclear Recoil



Heating Sources: Nuclear Recoil

Taking into account collective effects:

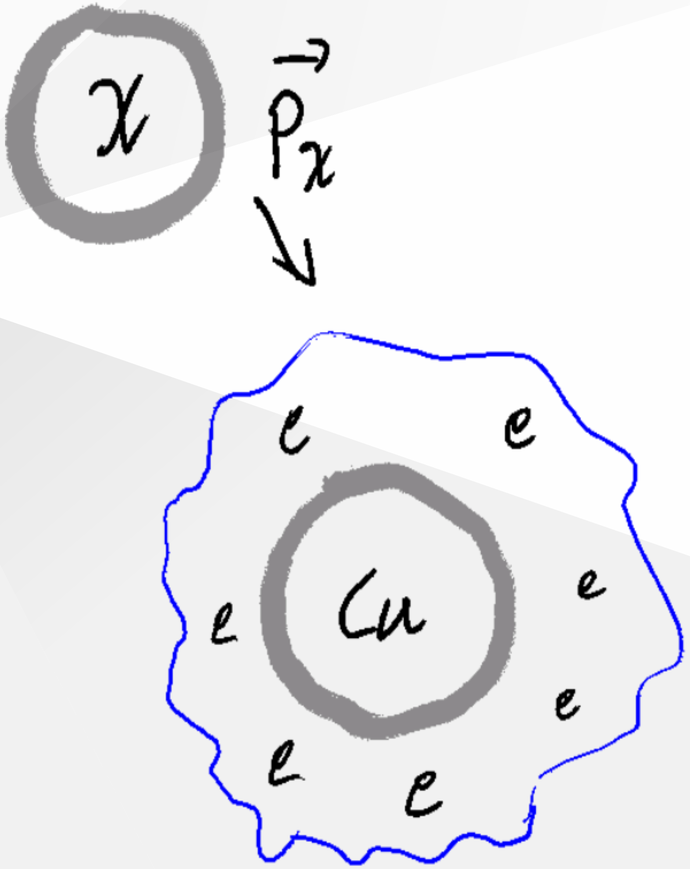
$$\delta(\vec{p}_i - \vec{p}_f - \vec{q}) \to F(|\vec{p}_i - \vec{p}_f - \vec{q}|),$$

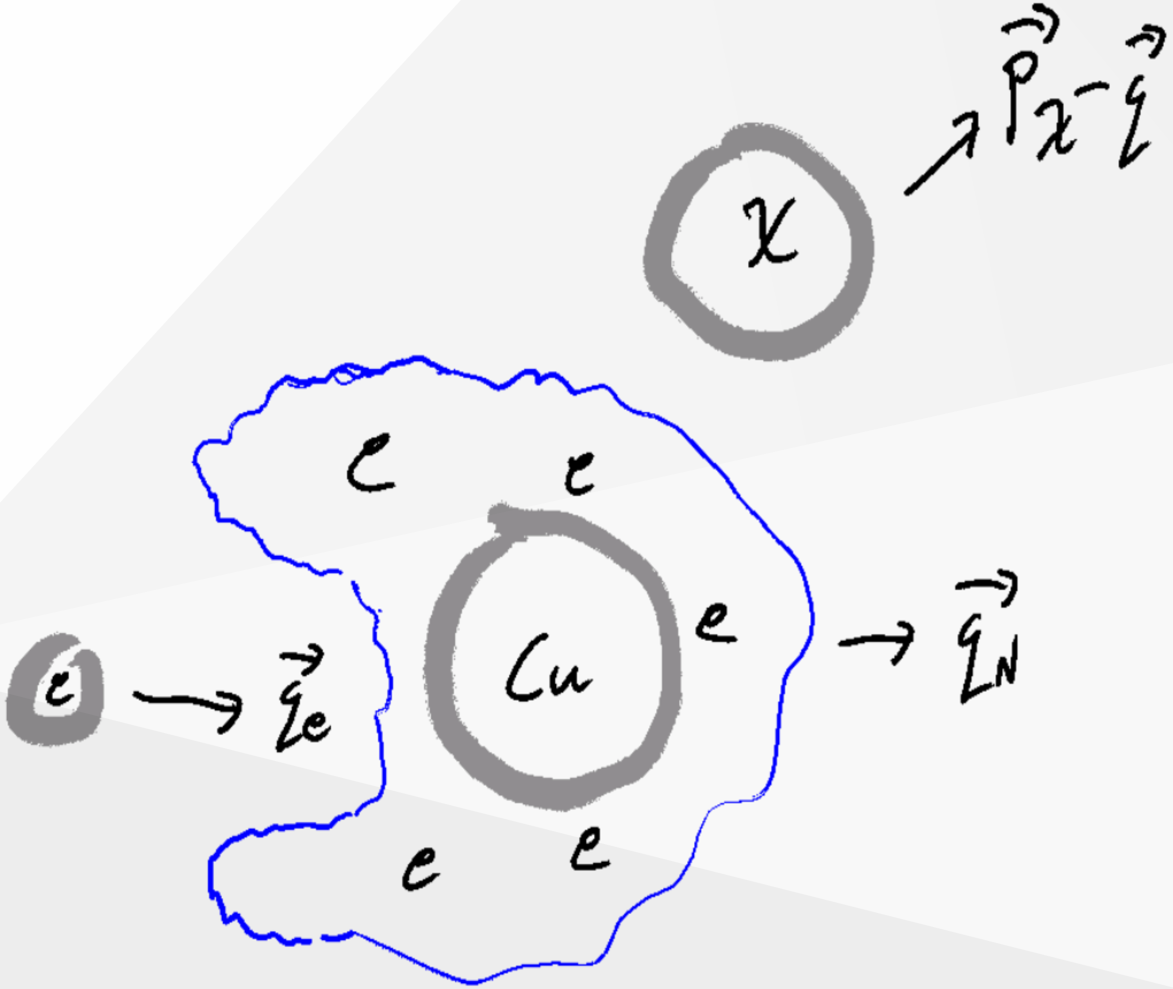
With a simple crystal form factor:

$$F(q) \sim \exp\left(-\frac{q^2}{2m_N\bar{\omega}_{\mathrm{ph}}}\right),$$

with $\bar{\omega}_{\mathrm{ph}} \sim \mathcal{O}(30\,\mathrm{meV})$.

Heating Sources: Migdal Effect





Heating Sources: Migdal Effect

In Migdal events, energy is efficiently transferred to the electrons:

$$\omega_e \simeq E_{\text{bind}} \sim \mathcal{O}(\text{eV}),$$

assuming this ends up as heat

$$Q \simeq E_{\text{bind}}.$$

Much larger than nuclear recoil!

Heating Sources: Migdal Effect

But there's an issue:

$$P_{\text{Migdal}} = \int d\omega_e \, \frac{dR_{\text{Migdal}}}{d\omega_e} \, \omega_e ,$$

where now:

$$\frac{dR_{\text{Migdal}}}{d\omega_e} = \int dE_N \, \frac{dR_{\text{nuc}}}{dE_N} \mathcal{P}_{\text{Migdal}}(\omega_e | E_N),$$

and $\mathcal{P}_{\text{Migdal}} \sim 10^{-4} - 10^{-2}$.

Heating Sources

As a rough estimate, $P_{\mathrm{Migdal}} \simeq P_{\mathrm{nuc}}$ around $m_\chi = 10\,\mathrm{MeV}$.

Need to consider both effects.

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Progress: Overview

- Theory: Done!
  - We have the rates, Migdal probability.

- Computation: On its way.
  - Nuclear recoil channel, not yet programmed.
  - ...but, get it for free from Migdal.
  - Migdal computation is tough.

Progress: Migdal Effect

The Migdal probability scales like:

$$\mathcal{P}_{\mathrm{Migdal}} \sim \frac{1}{\omega_e^4} \mathrm{Im}\left[-\frac{1}{\epsilon(q,\omega_e)}\right],$$

which is susceptible to divergences as $\omega_e \to 0$.

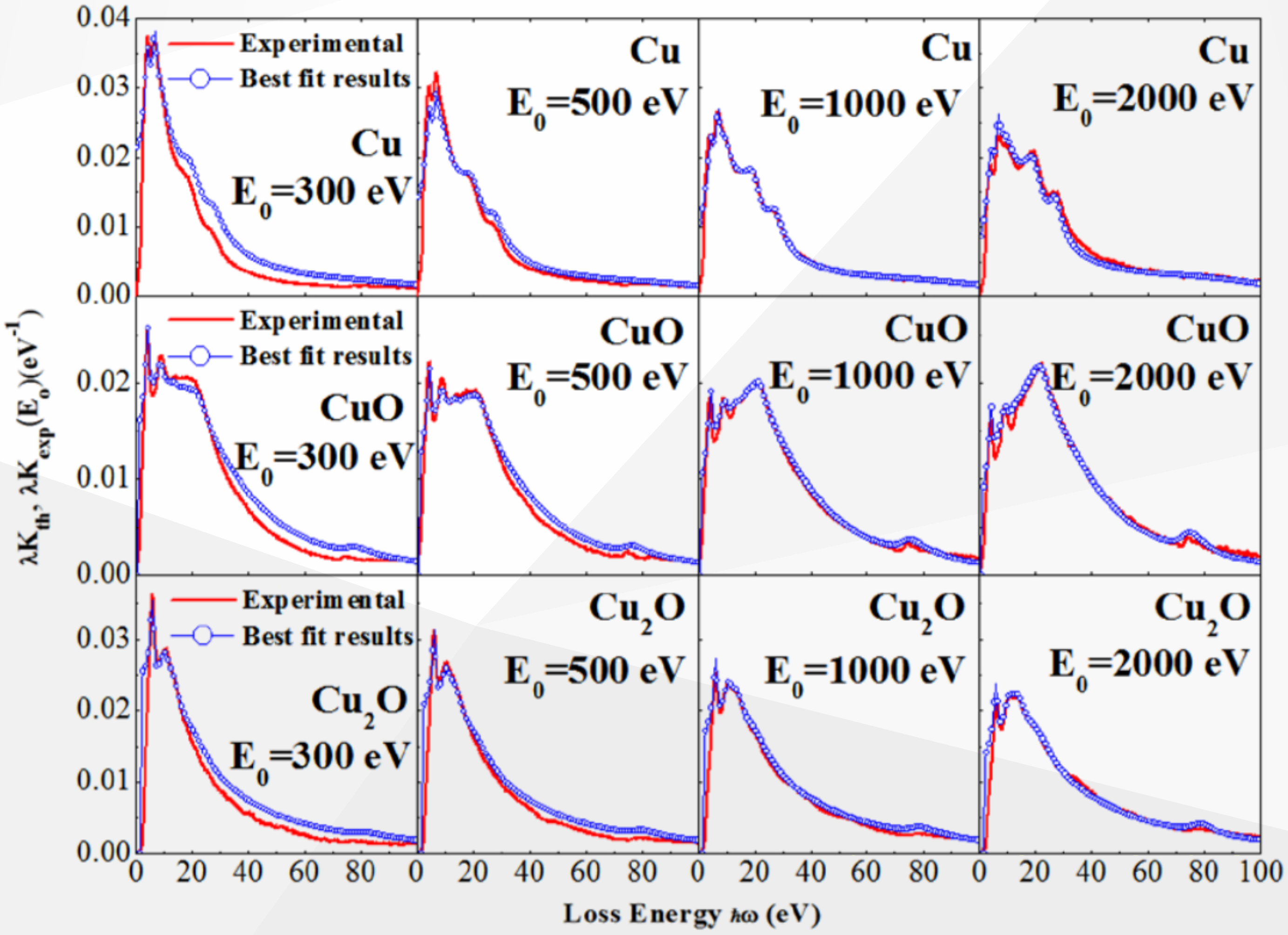
Progress: Migdal Effect

We need an ELF that properly captures the low ω_e behaviour.

The Lindhard method is oversimplified, treating the electron gas as a non-interacting system.

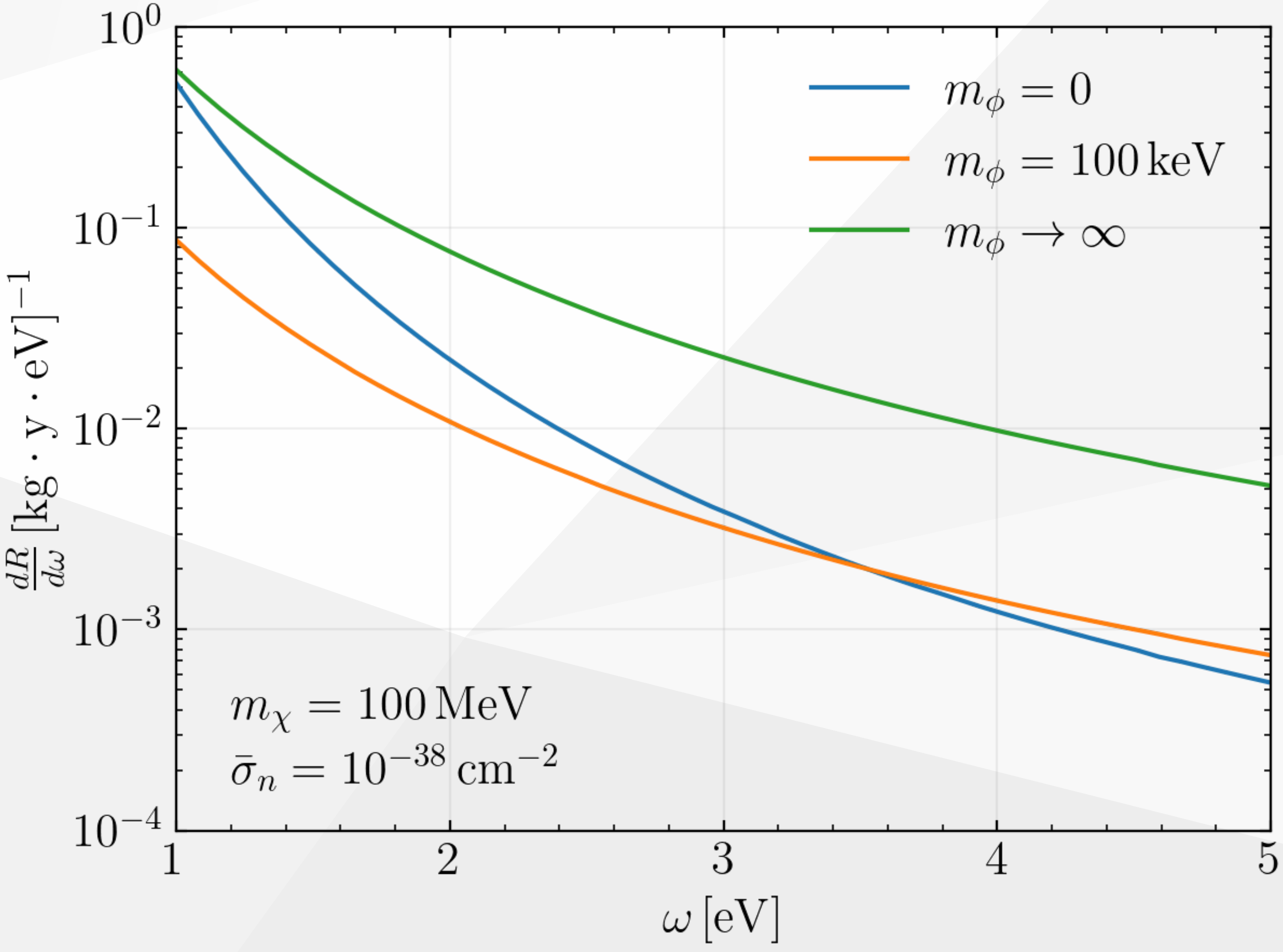
Fits to experimental data fail at properly capturing the low ω_e behaviour.

Progress: Experimental Fits

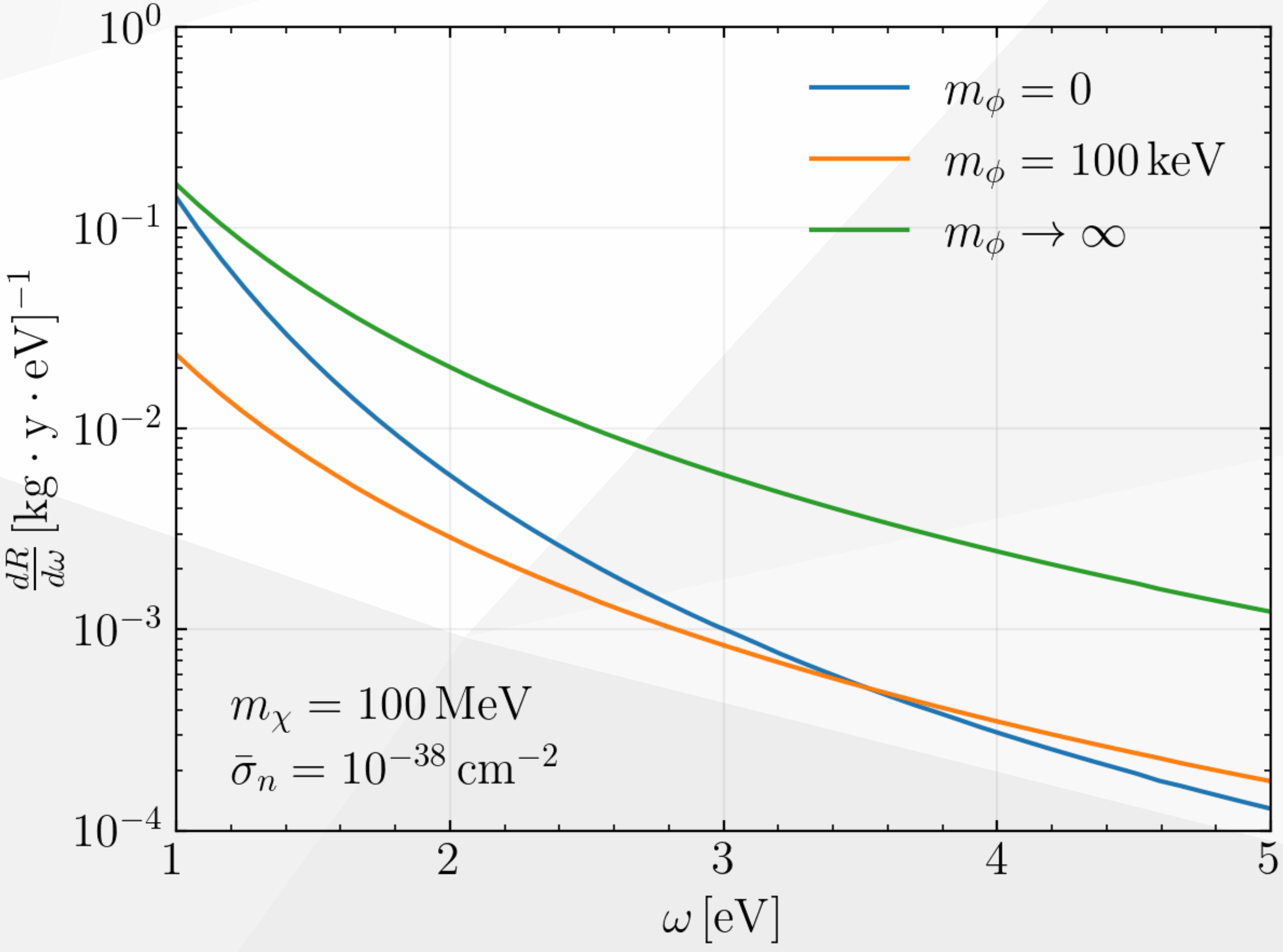


J. Phys.: Condens. Matter 24 (2012) 175002 (8pp).

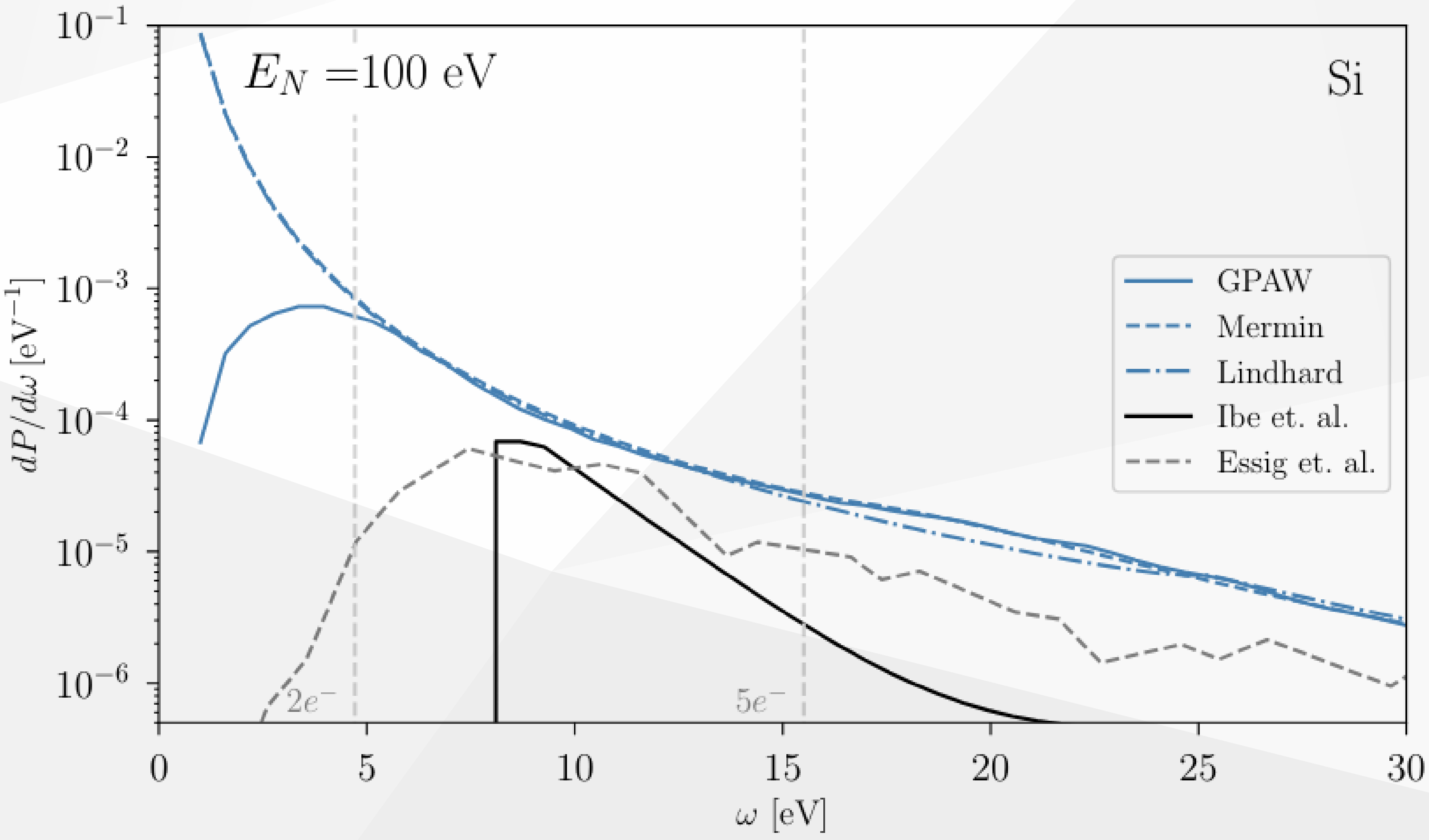
Progress: Experimental ELF



Progress: Lindhard ELF

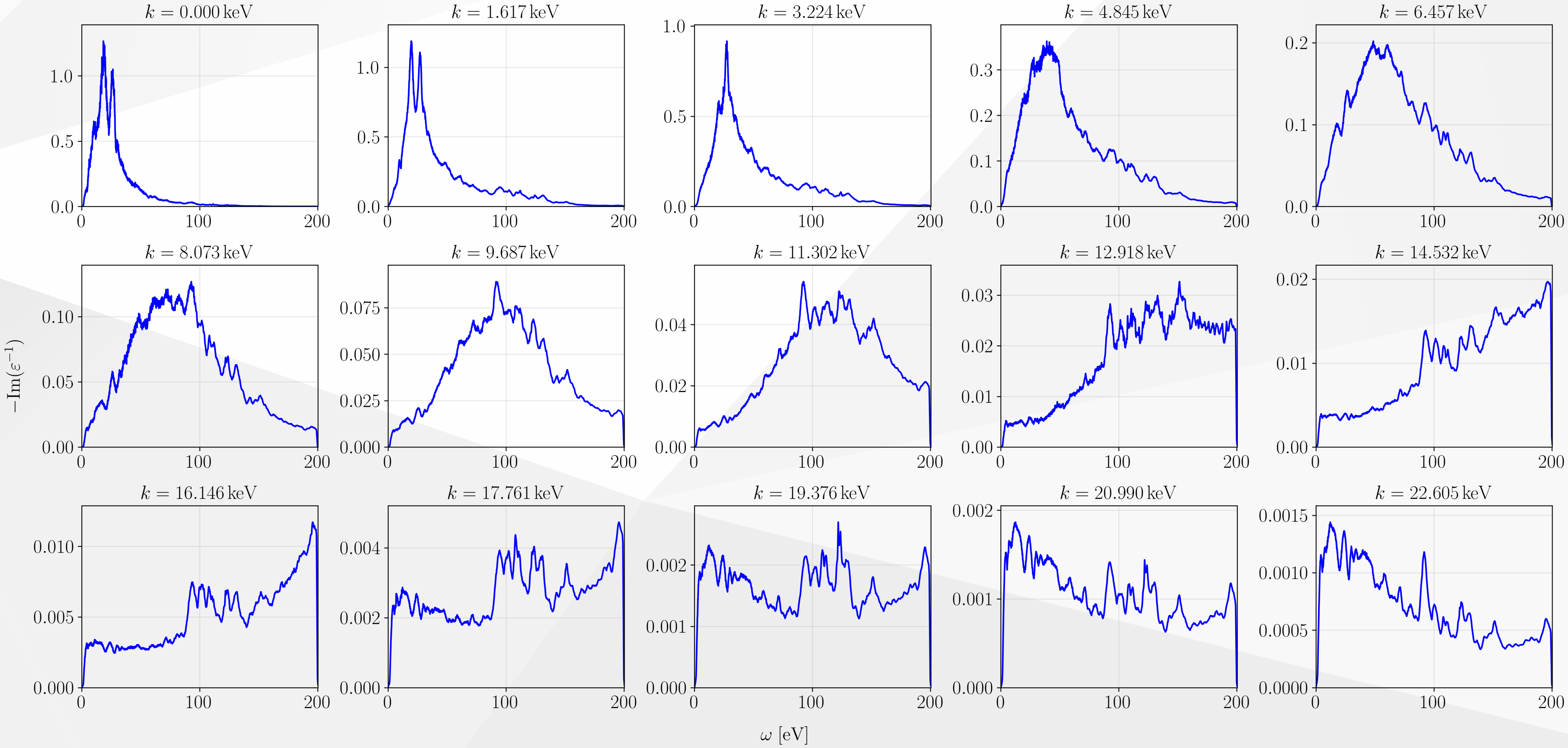


Progress: Solution?

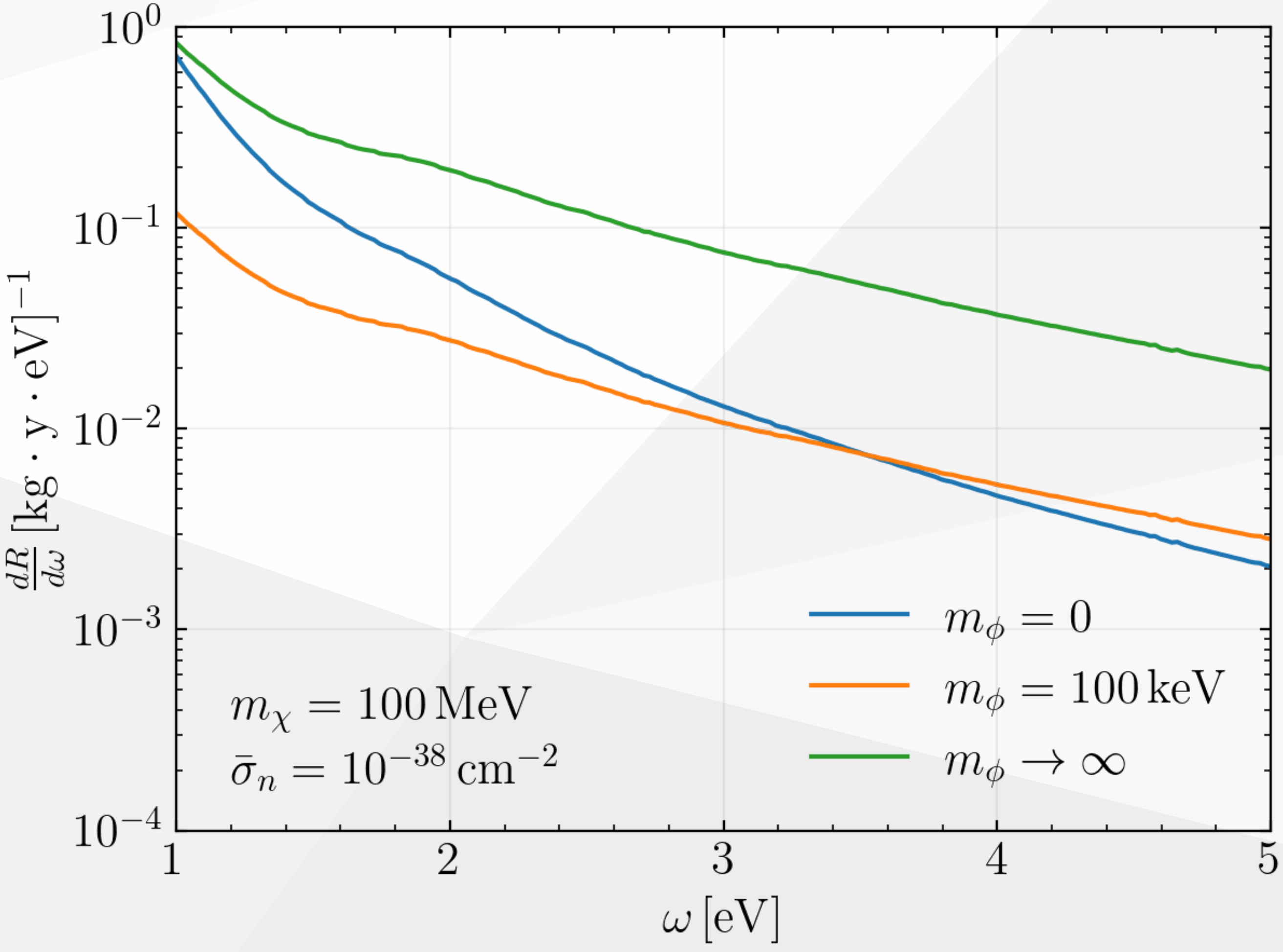


Phys. Rev. D 105, 015014 (2022).

Progress: GPAW ELF



Progress: DFT ELF



Progress: What's next?

This took around half a day to run.

What's next? We need to:

- Push to higher q, ideally up to $q \sim 30\,\mathrm{keV}$. This is expensive, $t \sim q_{\mathrm{max}}^{4.76}$. Push to denser $\vec{k}$ grids too, $t \sim N_k^{4.08}$.
- Try different xc functionals. More precision, more expensive. However, the GS computation is cheap compared to the ELF currently ($\sim 10\,\mathrm{m}$ vs $12\,\mathrm{h}$).

Thank you!

Questions?