Data-driven dark matter-electron scattering rates from the dielectric function

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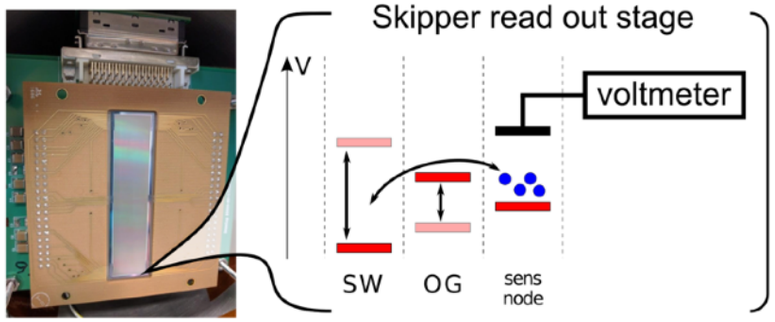
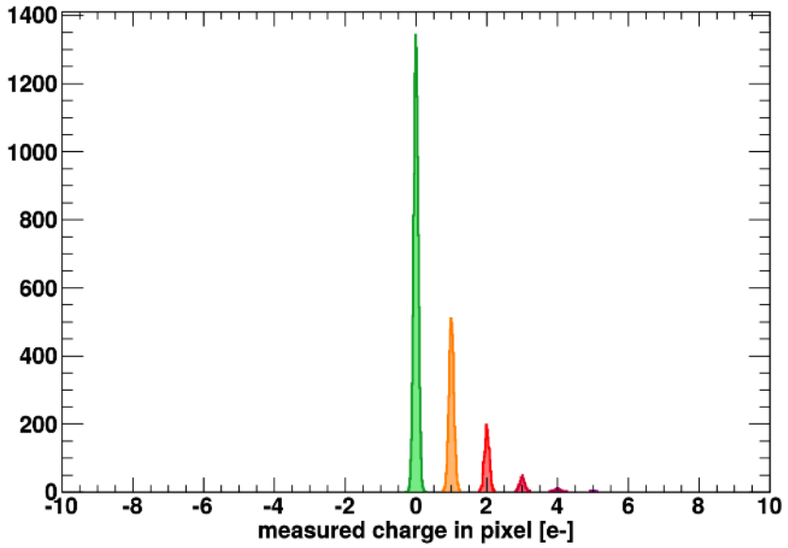
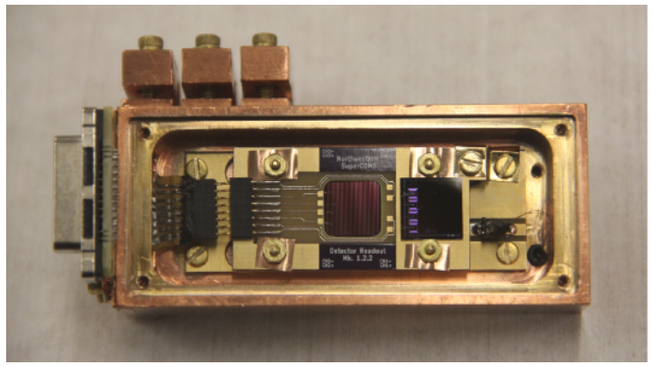
Recent advances in DM-electron scattering

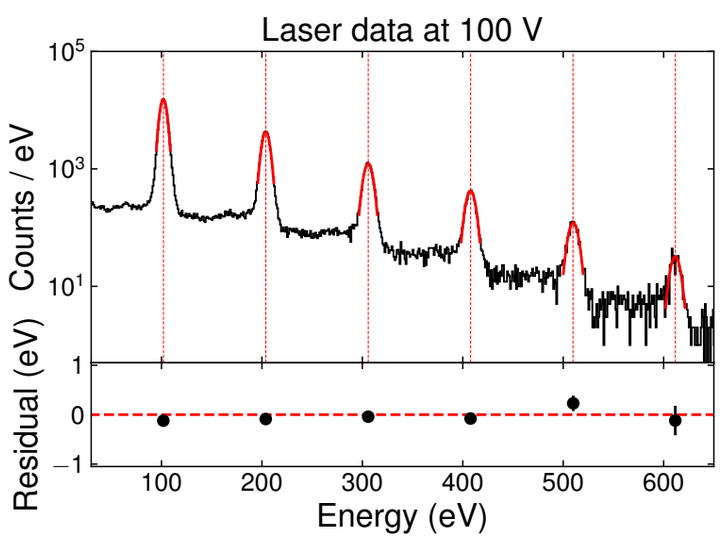
SENSEI:

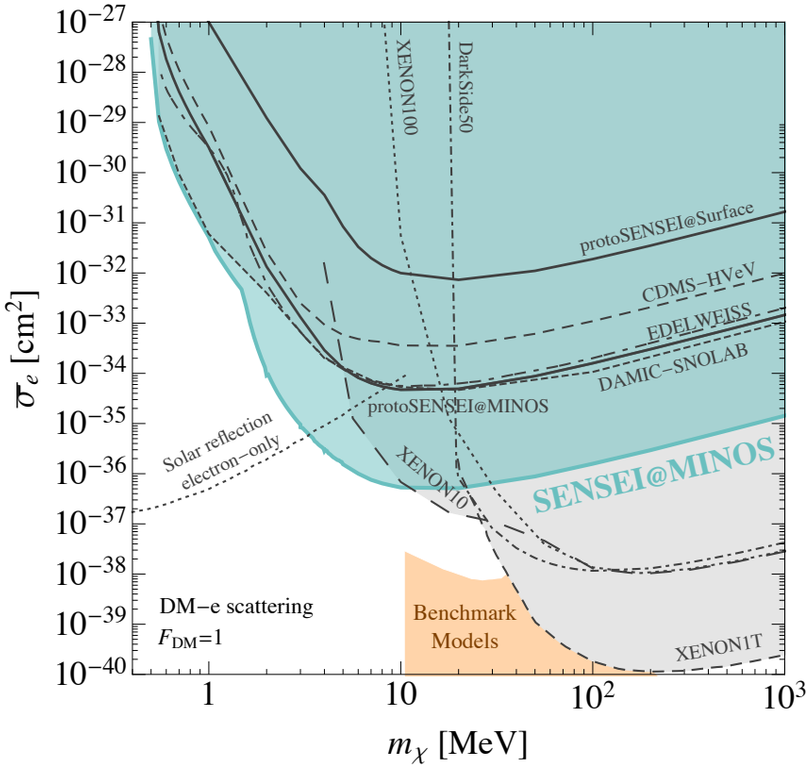




SuperCDMS HVeV:







Well-motivated parameter space is very close!

How do we make sure our signal rates are calibrated?

Rate predictions from QEDark

electron recoil spectrum

$$\frac{dR_{\rm crystal}}{d\ln E_e} = \frac{\rho_\chi}{m_\chi} N_{\rm cell}\, \overline{\sigma}_e\, \alpha \times \frac{m_e^2}{\mu_{\chi e}^2} \int d\ln q \left(\frac{E_e}{q}\eta\big(v_{\rm min}(q,E_e)\big)\right) F_{\rm DM}(q)^2 \left|f_{\rm crystal}(q,E_e)\right|^2$$

crystal form factor

$$\left|f_{\rm crystal}(q,E_e)\right|^2 = \frac{2\pi^2(\alpha m_e^2 V_{\rm cell})^{-1}}{E_e} \sum_{i\,i'} \int_{\rm BZ} \frac{V_{\rm cell}\, d^3k}{(2\pi)^3} \frac{V_{\rm cell}\, d^3k'}{(2\pi)^3} \times E_e\, \delta(E_e - E_{i'\vec{k}'} + E_{i\vec{k}}) \sum_{\vec{G}'} q\, \delta(q - |\vec{k}' - \vec{k} + \vec{G}'|) \left|f_{[i\vec{k},i'\vec{k}',\vec{G}']}\right|^2$$

wavefunction overlap

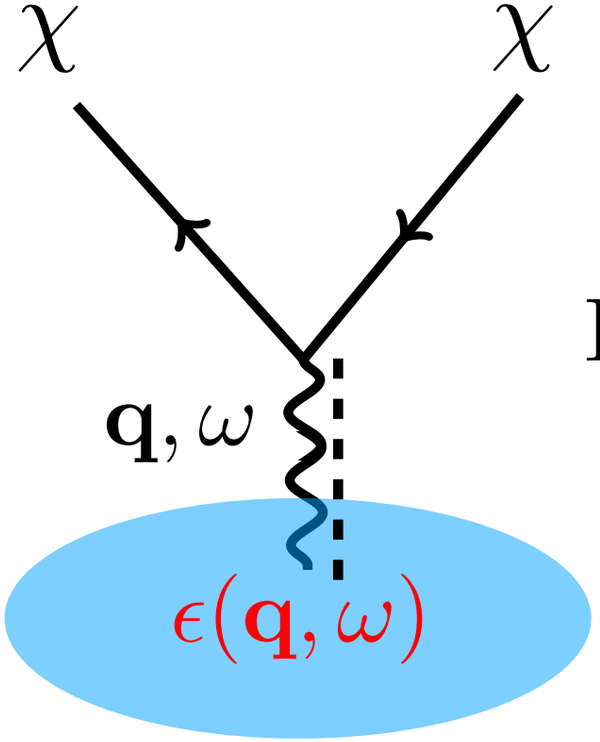
$$f_{[i\vec{k},i'\vec{k}',\vec{G}']} = \sum_{\vec{G}} u^*_{i'}(\vec{k}' + \vec{G} + \vec{G}') u_i(\vec{k} + \vec{G})$$

This is pure theory: how well does it compare with data?
How do we calibrate charge yield from recoil spectrum?

Rate predictions from dielectric

$$\mathrm{Im}\left(-\frac{1}{\epsilon(\mathbf{q},\omega)}\right) = \frac{\pi e^2}{q^2}\sum_f \left|\langle f|\hat{\rho}(\mathbf{q})|0\rangle\right|^2 \delta(\omega_f - \omega)$$

many-body electron density



DM-electron interaction (assumed spin-independent)

Dielectric function

$$\Gamma(\mathbf{v}) = \int \frac{d^3\mathbf{q}}{(2\pi)^3}\,|V(\mathbf{q})|^2\,\left[\frac{q^2}{e^2}\,2\,\mathrm{Im}\left(-\frac{1}{\epsilon(\mathbf{q},\omega)}\right)\right]$$

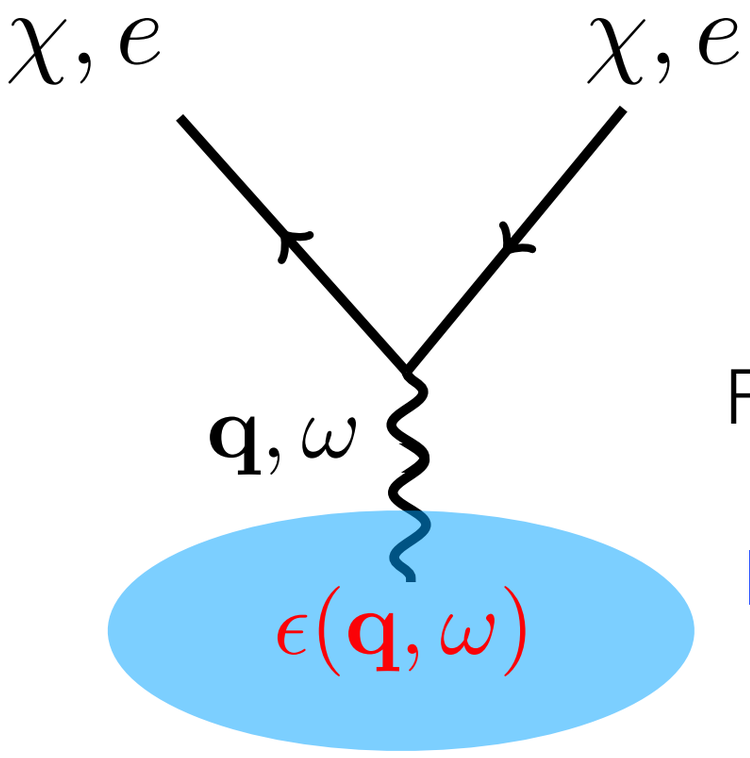
That's the answer, for any material.

[Berggren, Hochberg, **YK**, Kurinsky, Lehmann, Yu, arXiv:2101.08263; Knapen, Kozaczuk, Lin, arXiv:2101.08275]

Directly measurable!

Electrons probe electron density just like DM.
(In CM, known as "loss function")

Assume Coulomb probe is perturbative:



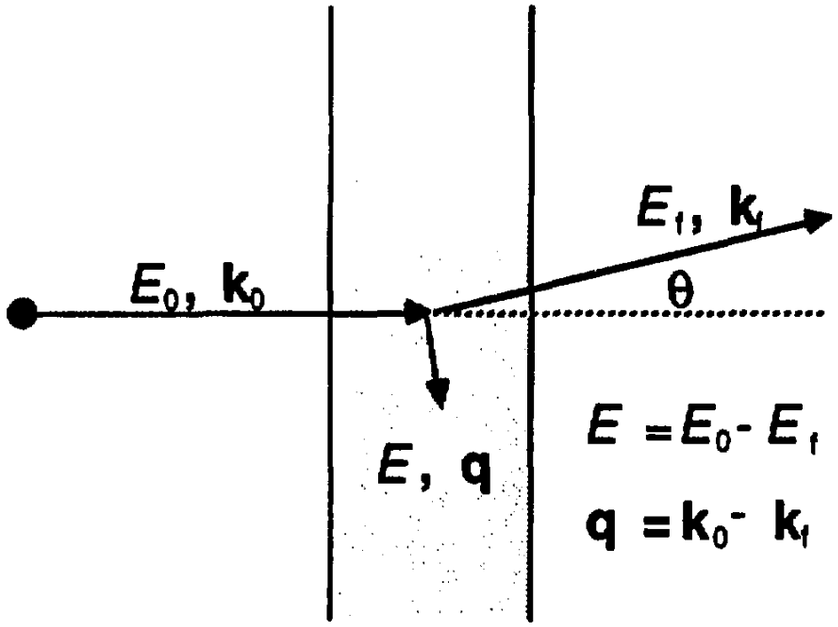
$$\mathrm{Im}\left(-\frac{1}{\epsilon(\mathbf{q},\omega)}\right) = \frac{\pi e^2}{q^2}\sum_f |\langle f|\hat{\rho}(\mathbf{q})|0\rangle|^2 \delta(\omega_f - \omega)$$

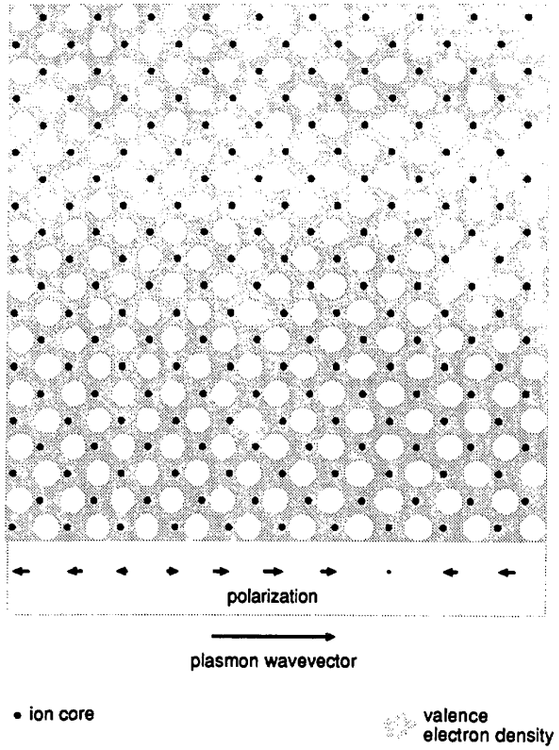
For electron scattering, where $\hat{\rho}(\mathbf{q})$ is the electron density operator, $\mathcal{S}$ **is** the dielectric function: linear response to electron density perturbations

Just like deep inelastic scattering: fire a known probe at an unknown target to learn about its constituents

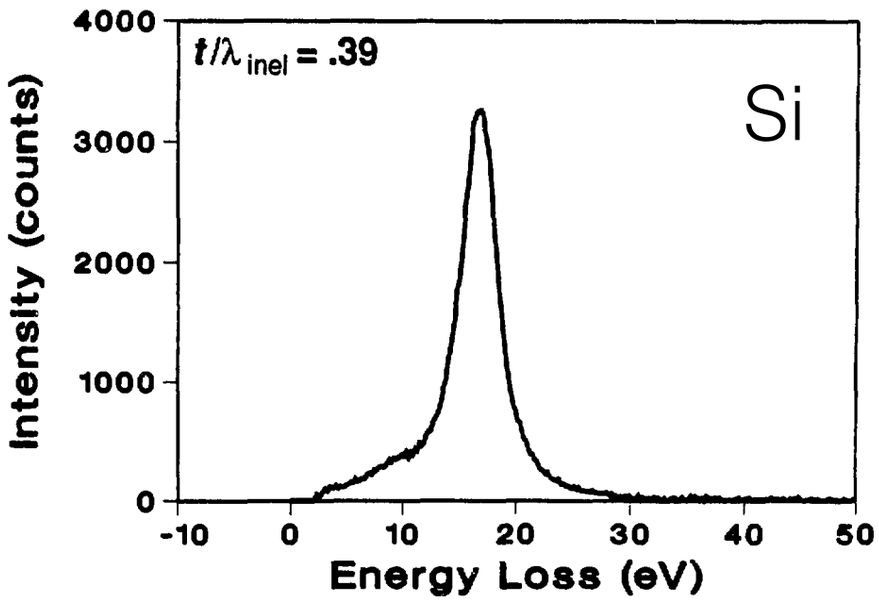
[Pines and Nozieres Phys. Rev. 1959;
Berggren, Hochberg, **YK**, Kurinsky, Lehmann, Yu, arXiv:2101.08263]

Plasmons





Semi-relativistic electron scattering **not** described by single-particle electron-electron scattering, but by a collective long-range charge wave (plasmon). Electron preferentially deposits ~15 eV of energy, **regardless of initial kinetic energy**



[M. Kundmann, PhD. thesis, 1988]

Avatars of the dielectric

Polarizability: measures linear response to E-fields

$$\epsilon(\mathbf{q}) = \frac{\mathbf{D}(\mathbf{q})}{\mathbf{E}(\mathbf{q})} = \frac{V_{\rm Coulomb}(\mathbf{q})}{V_{\rm eff}(\mathbf{q})}$$

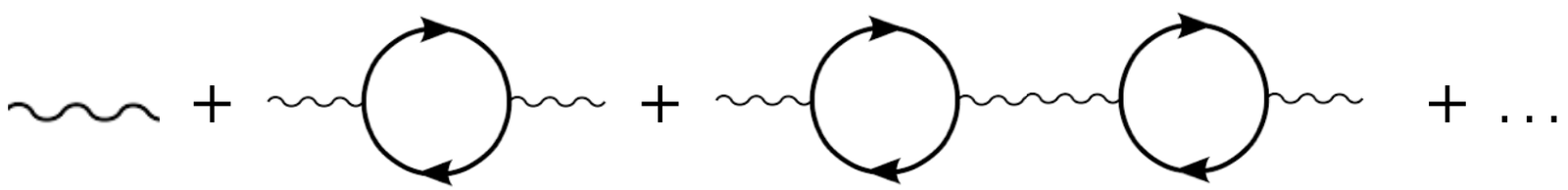
Real-time correlator for electron density

$$\epsilon^{-1}(\mathbf{q},\omega) = 1 - \frac{e^2}{q^2}\frac{1}{V}\int d\tau e^{i\omega\tau}\langle \hat{\rho}_e(\mathbf{q},\tau)\hat{\rho}_e(-\mathbf{q},0)\rangle\Big|_{i\omega\to\omega}$$

Many-body density operator: generalizes single-particle picture

Can compute with random phase approximation (RPA):

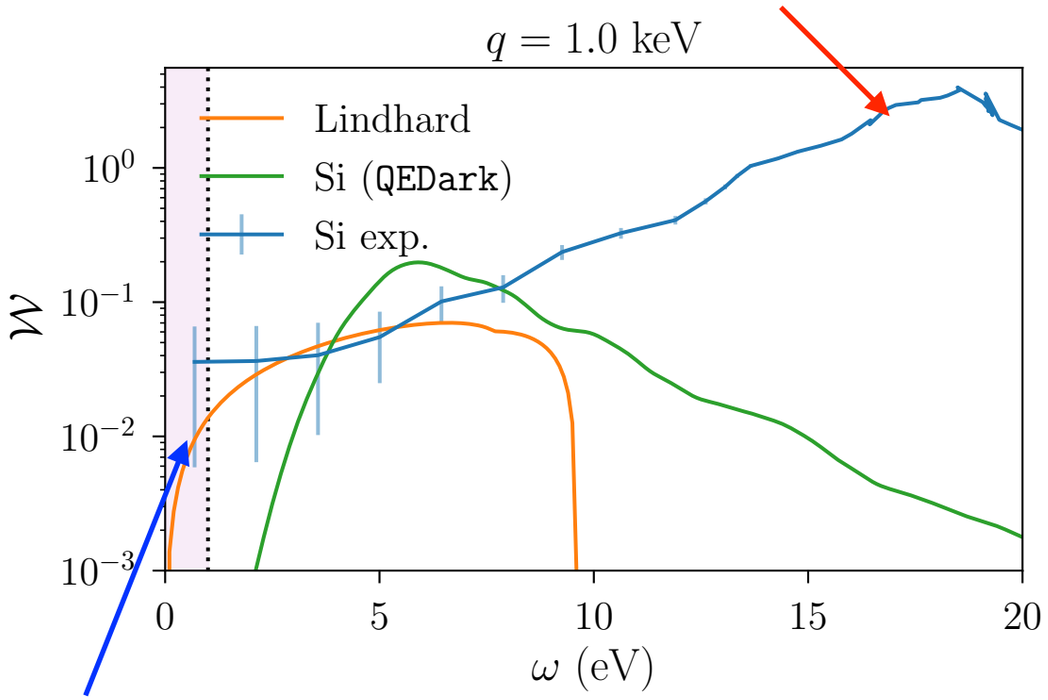
$$\epsilon(\mathbf{q}) = 1 - \frac{e^2}{q^2}\Pi_q$$



Exact dielectric function contains **all** screening and many-body effects: required to move beyond single-particle formalism

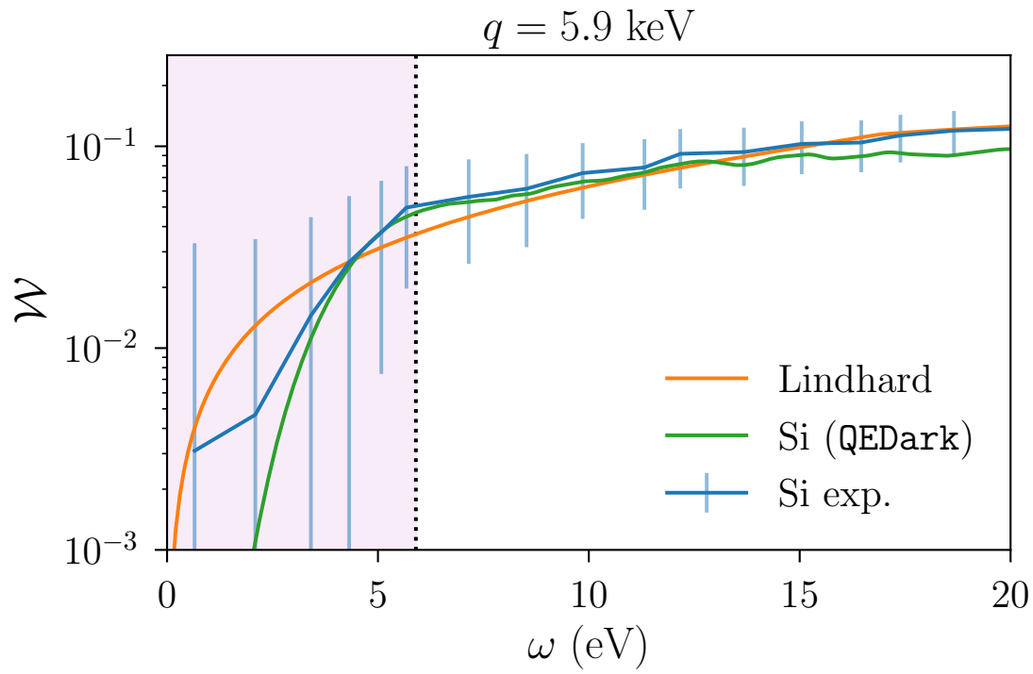
QEDark vs. data

Low momentum: plasmon



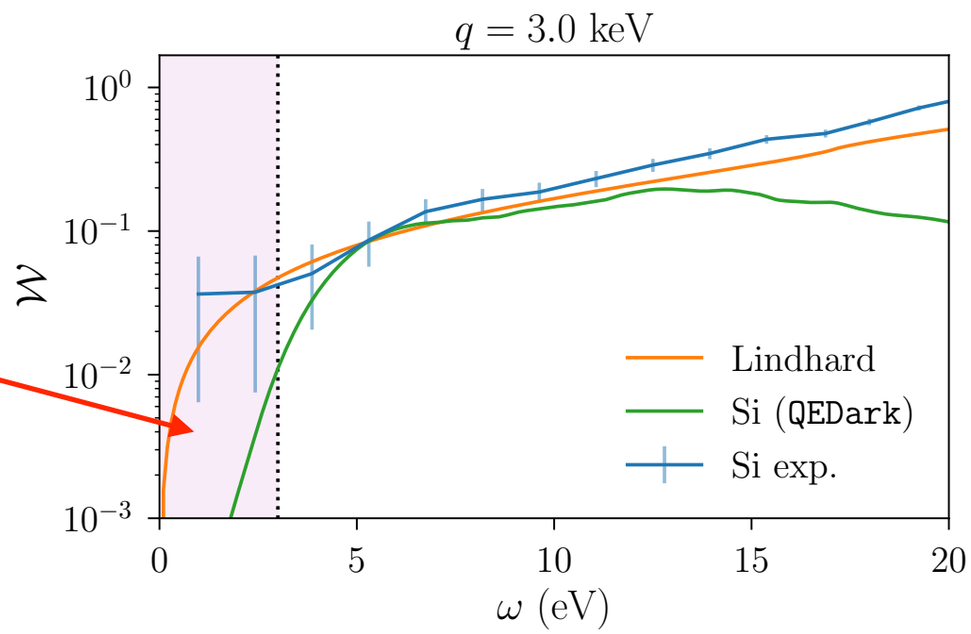
(but no above-gap excitations accessible)

Large momentum

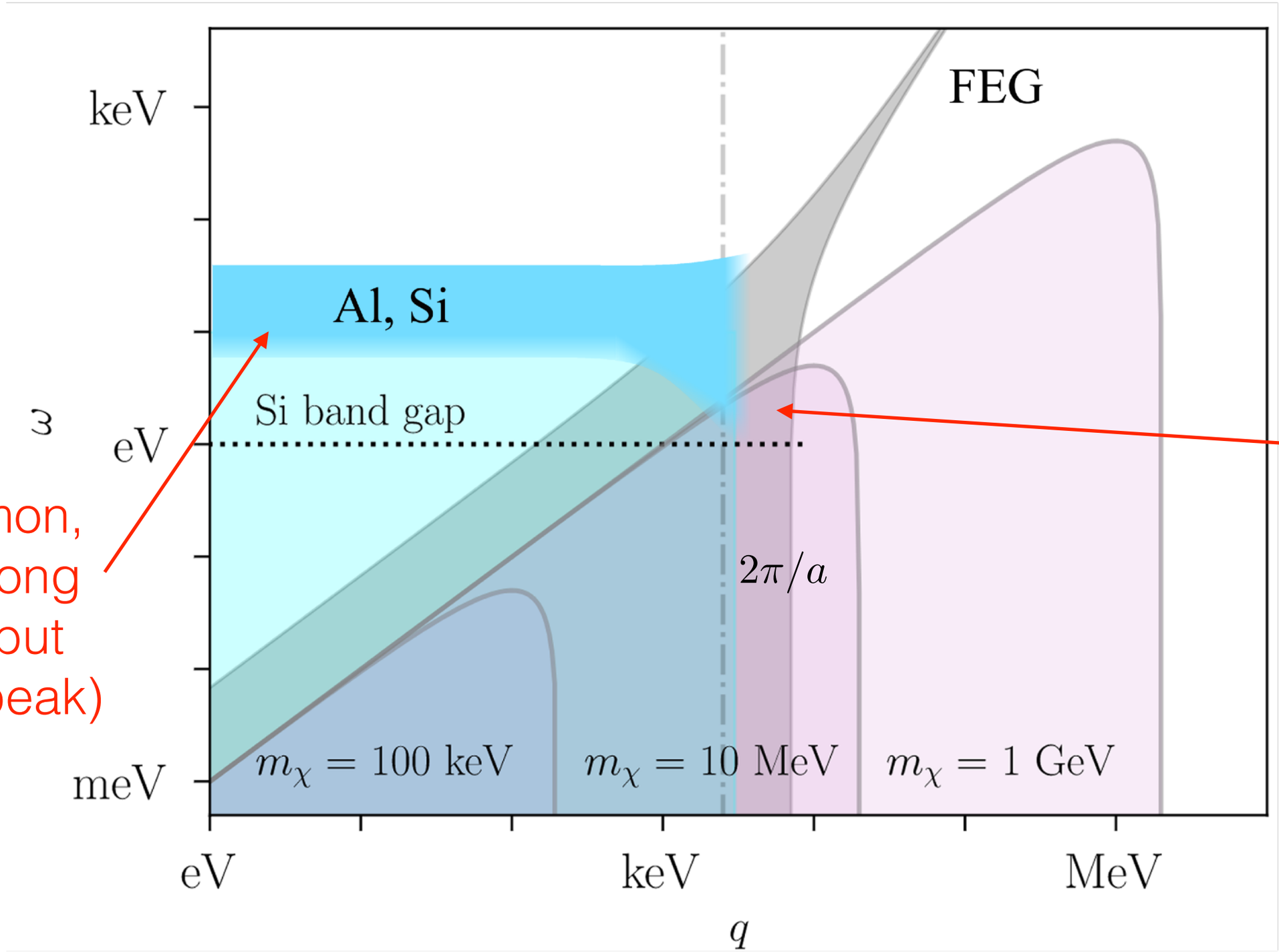


free-electron gas is a decent model

Need measurements: this range of q determines 1-electron rate!



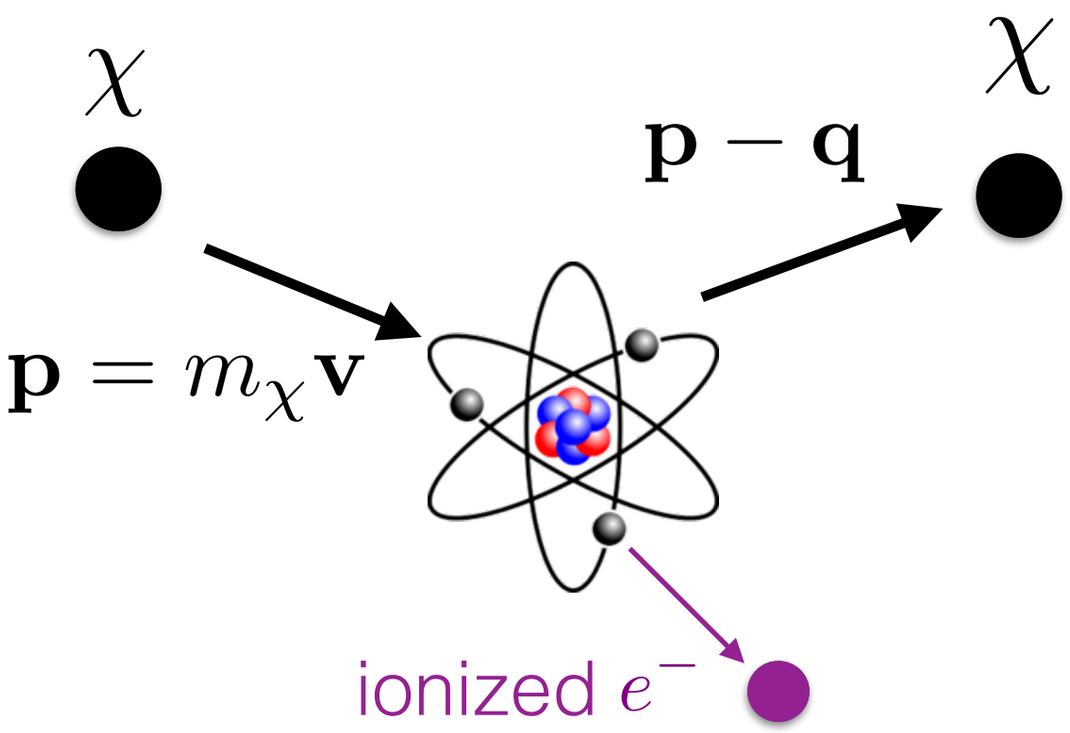
Many-body response function



plasmon, with long tail (but miss peak)

electrons in Si behave kind of like free fermions

Works for atoms/molecules too!



Old formalism:

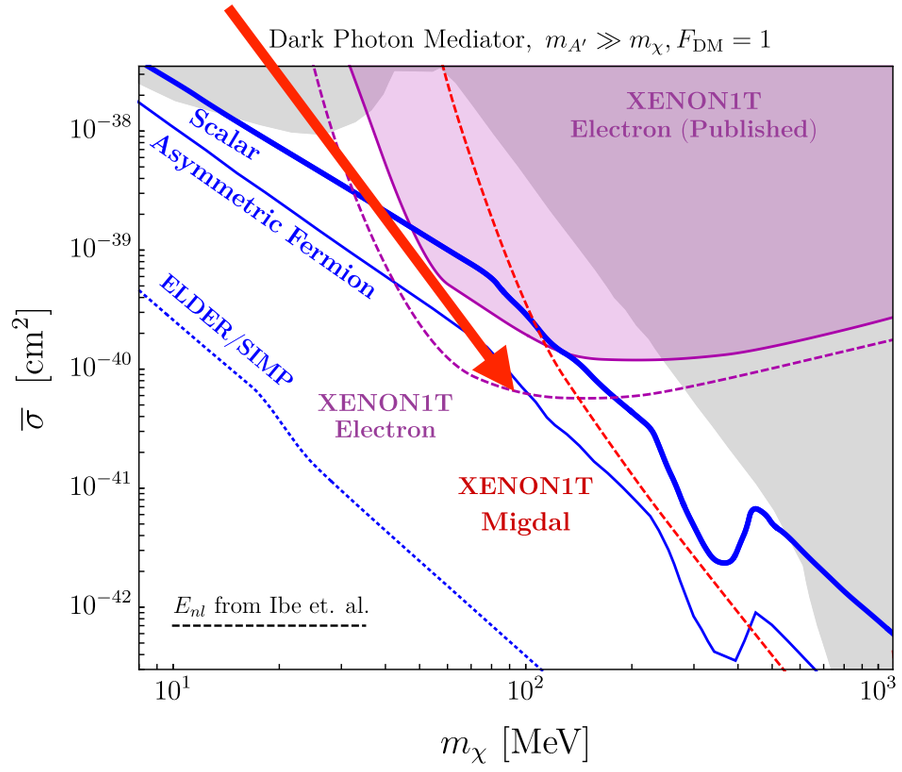
$$|f_{\rm ion}^{nl}(k',q)|^2 = \sum_m \left| \int d^3x\, \psi_{k'}^*(\vec{x})\, \psi_{nlm}(\vec{x})\, e^{i\vec{q}\cdot\vec{x}} \right|^2$$

But which wavefunctions?
What about "Sommerfeld enhancement"?
What about electron correlation or relativistic effects?

New formalism:

$$\mathrm{Im}(\epsilon)(\mathbf{q},\omega) \propto \sum_f |\langle \psi_f | e^{i\mathbf{q}\cdot\mathbf{x}} | \psi_i \rangle|^2 \delta(E_f - E_i - \omega)$$

Just measure the dielectric function!
(e.g. EELS, X-ray scattering)

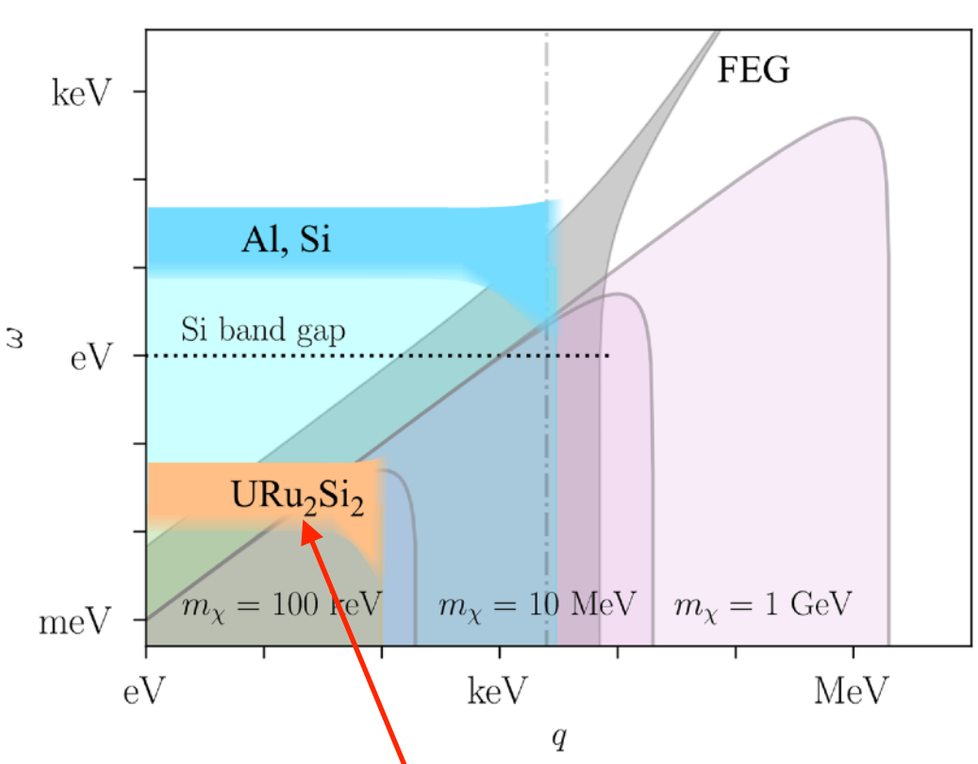


[DarkSide collab. (incl. **YK**), PRL 2018; Baxter, **YK**, Krnjaic, PRD 2020; Berggren, Hochberg, **YK**, Kurinsky, Lehmann, Yu, arXiv:2101.08263]

Optimizing direct detection

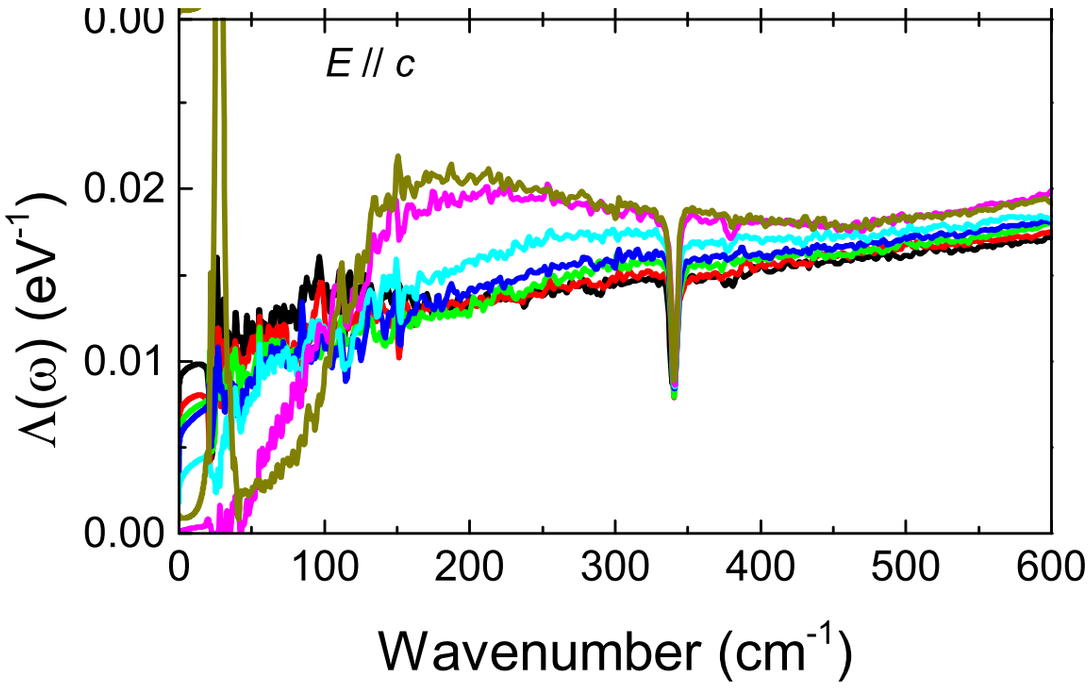
Best option: move to a heavier galaxy where DM is faster.
Next best option: find a material with slow electrons

Can access full plasmon peak in heavy-fermion materials:



DM is faster
than Fermi velocity

URu_2Si_2 measured
loss function at q = 0

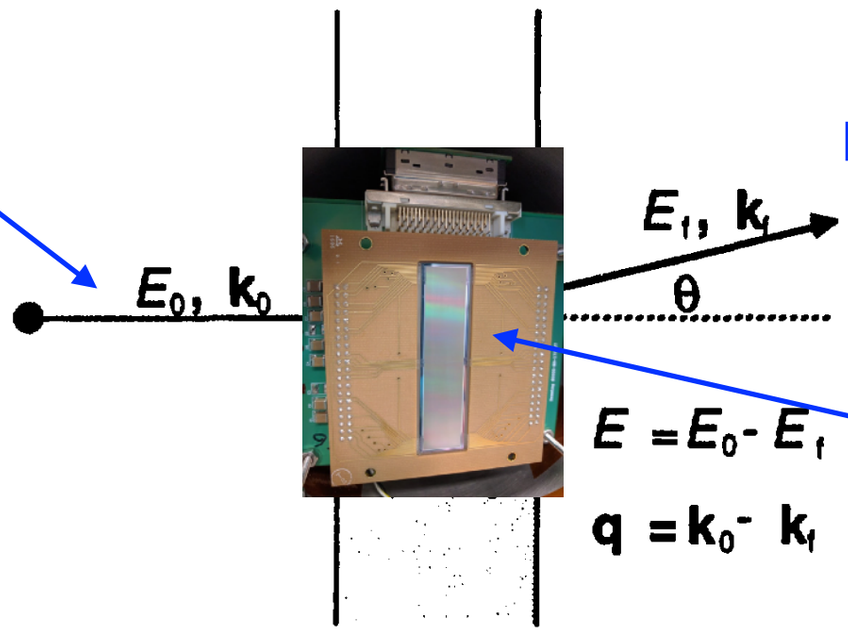


[Berggren, Hochberg, **YK**, Kurinsky, Lehmann, Yu, arXiv:2101.08263;
Abbamonte, **YK**, Kurinsky, Wagner, in progress]

Charge yield calibration

Basic idea: EELS with a CCD

low-current
~20 keV
electron beam

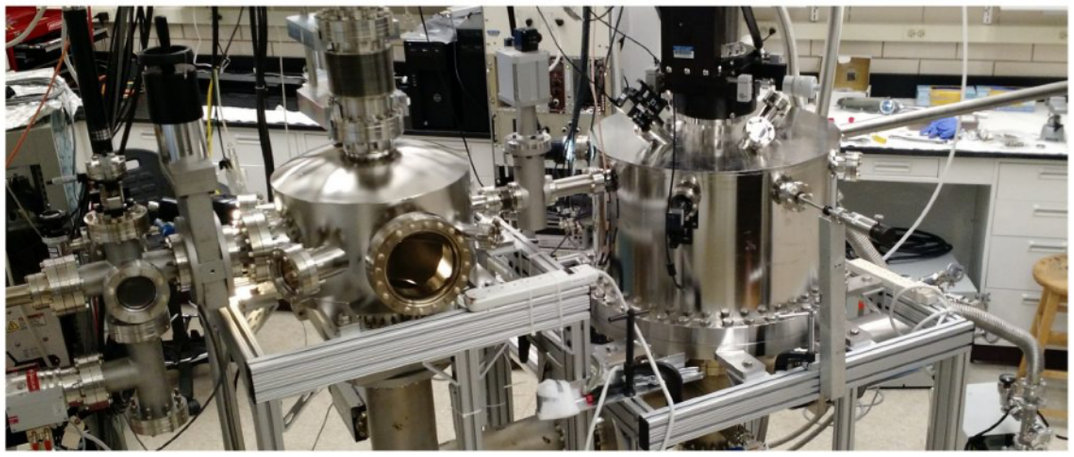


scattered electron
measures loss function

event-by-event
per-pixel charge
measurement

Can directly correlate energy loss with charge yield.
Yes, this is a theorist's cartoon, but this is a
necessary calibration for precise signal predictions!

EELS + CCD needs



[P. Abbamonte lab, UIUC]

- Thin substrate (electron mean free path ~0.2 um in Si)
- Barrier layer at CCD surface
- Low beam current (1 electron per bunch)
- Spot size smaller than 1 pixel (~15 um in SENSEI/Oscura)
- Time-of-flight for coincidence
- Momentum resolution to ~0.5 keV
- Energy resolution to ~0.5 eV
- Magnetically shielded environment (< 3 mG)
- Ultrahigh vacuum (1e-10 torr)
- Not-too-low temp (90-110 K)