Spin-Dependent Dark Matter Rates from Neutron Scattering

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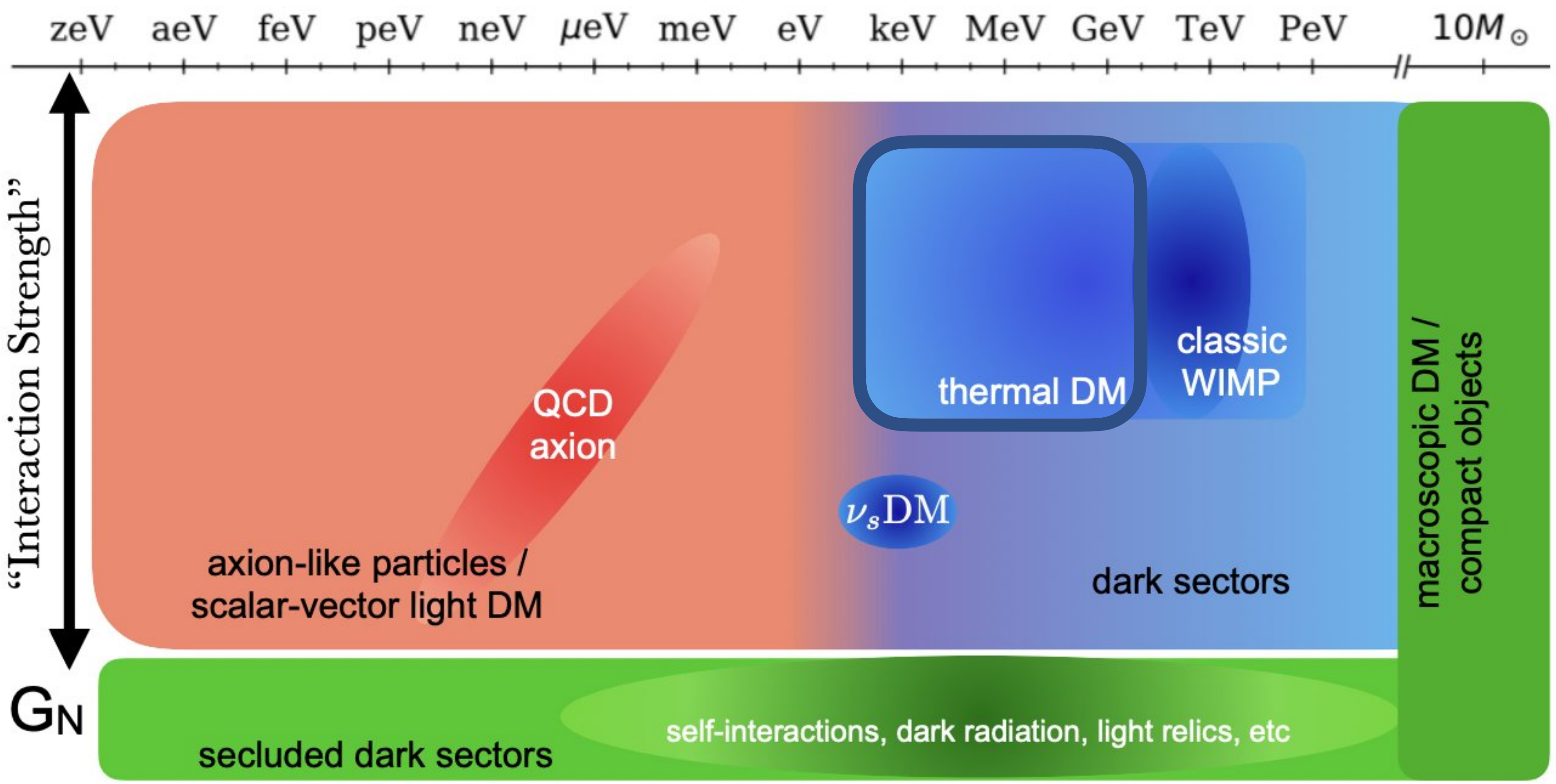
arXiv:2504.02927, with Asher Berlin, Alex Millar, Tanner Trickle

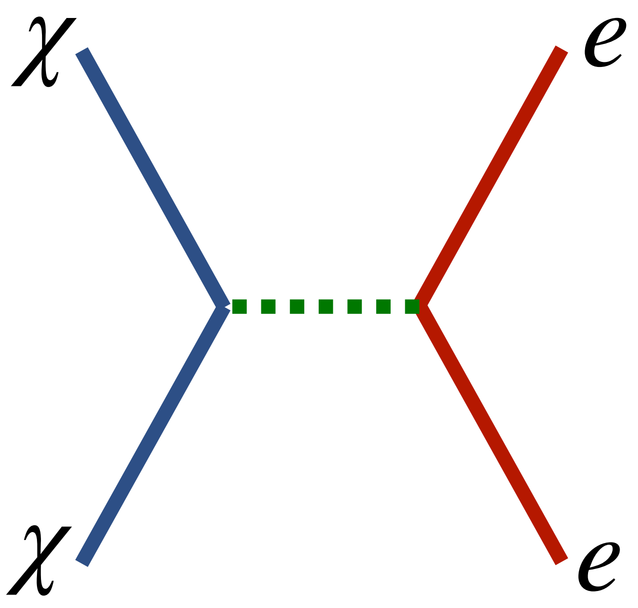


Light particle dark matter is an interesting experimental target:

- Can be produced through relatively simple production mechanisms
- Requires dedicated experiments, but not very large detector scales
- Complementary to new technology for low threshold, low background detectors
- Rate depends in detail on material properties, motivating new calculations

Couplings to Electron Density and Spin

Dark matter couplings to nonrelativistic electrons can have several forms:



$H \sim O_\chi n_e$ coupling to density: like electric potential ϕ

$H \sim \mathbf{O}_\chi \cdot \mathbf{s}_e$ coupling to spin: like magnetic field $\mathbf{B}$

$H \sim \mathbf{O}_\chi \cdot \mathbf{p}_e$ coupling to momentum: like vector potential $\mathbf{A}$

$H \sim \mathbf{O}_\chi \cdot (\mathbf{s}_e \times \mathbf{p}_e)$

$H \sim O_\chi (\mathbf{s}_e \cdot \mathbf{p}_e)$

(these possibilities are same order, but have no simple Standard Model analogue)

The DM scattering rate in medium depends on response functions for these quantities

When similar SM interaction exists, response function can be measured with SM probes

Responses to Dark Matter-Electron Couplings

The simplest case: coupling to density

$$H \sim O_\chi n_e$$

DM acts like electric field

Scattering makes electronic excitations

Material response determined by

$$\chi_e = -\frac{\partial \rho_{\text{ind}}}{\partial \rho_{\text{ext}}} = 1 - \frac{1}{\epsilon}$$

Susceptibility χ_e measured by charged probes, like electrons

Next simplest case: coupling to spin

$$H \sim \mathbf{O}_\chi \cdot \mathbf{s}_e$$

DM acts like magnetoquasistatic field

Scattering makes magnetic excitations

Material response determined by

$$\chi_m = \frac{\partial \mathbf{M}}{\partial \mathbf{B}_{\text{ext}}}$$

(spin response only)

(χ_m is a tensor)

Susceptibility χ_m measured by uncharged magnetic probes, like neutrons

The Scattering Rate Per DM Particle

$$\Gamma(\mathbf{v}) = \int_{\mathbf{q}} \mathscr{F}^{ij}(\mathbf{q}, \omega_{\mathbf{q}})\, \chi''_{m,ij}(\mathbf{q}, \omega_{\mathbf{q}})$$

integral over DM momentum transfer $\mathbf{q}$

DM energy transfer

$$\omega_{\mathbf{q}} = \mathbf{q} \cdot \mathbf{v} - \frac{q^2}{2m_\chi}$$

DM form factor, depends on model

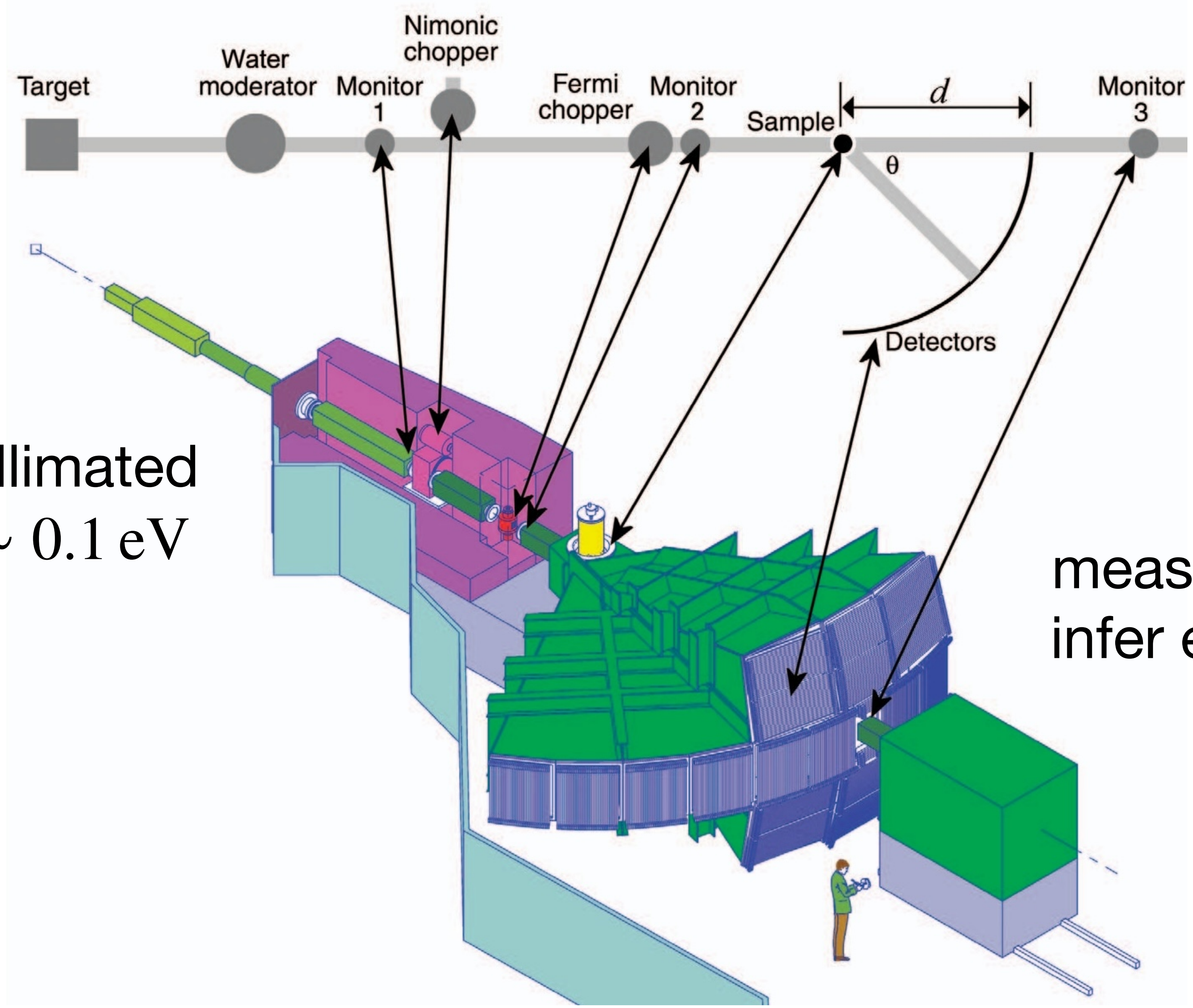
if DM sources only divergence: $\mathscr{F}_{ij} \propto \hat{\mathbf{q}}_i \hat{\mathbf{q}}_j$

if DM sources only curl: $\mathscr{F}_{ij} \propto \delta_{ij} - \hat{\mathbf{q}}_i \hat{\mathbf{q}}_j$

(anti-Hermitian part of) material's dynamical magnetic susceptibility **(automatically strongly isotropic!)**

simple ferromagnet example: $\chi''_m(\mathbf{q}, \omega) \sim n_s\, \delta(\omega - \omega_m(\mathbf{q})) \begin{pmatrix} 1 & i & 0 \\ -i & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$

Neutron Scattering Experiments



make beam of collimated neutrons with $E \sim 0.1\,\mathrm{eV}$

measure angle of scattering, infer energy from arrival time

Well-developed technique with dozens of dedicated facilities

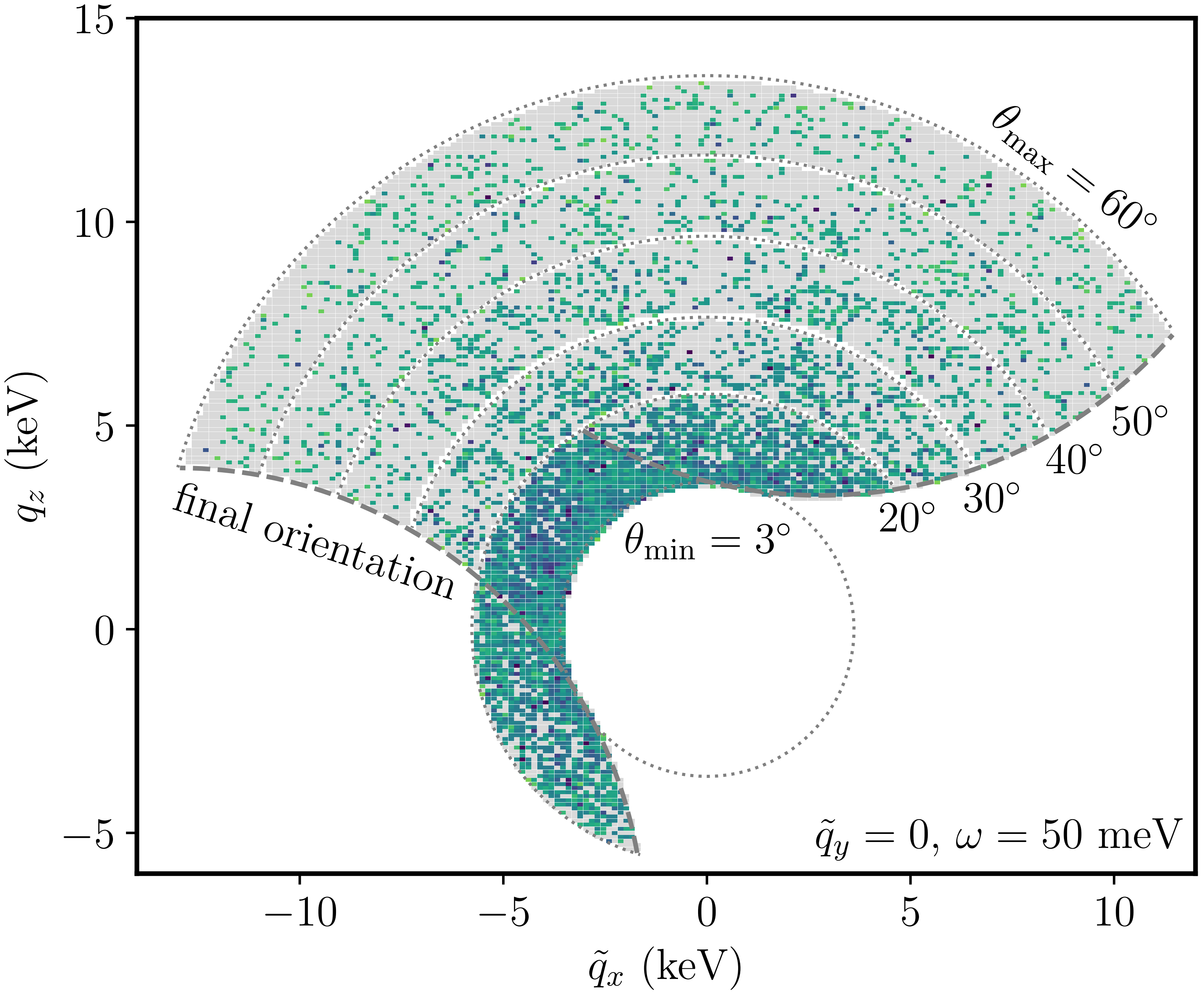
A Slice of a Real Neutron Scattering Dataset

Taken at the MAPS spectrometer on sample of yttrium iron garnet

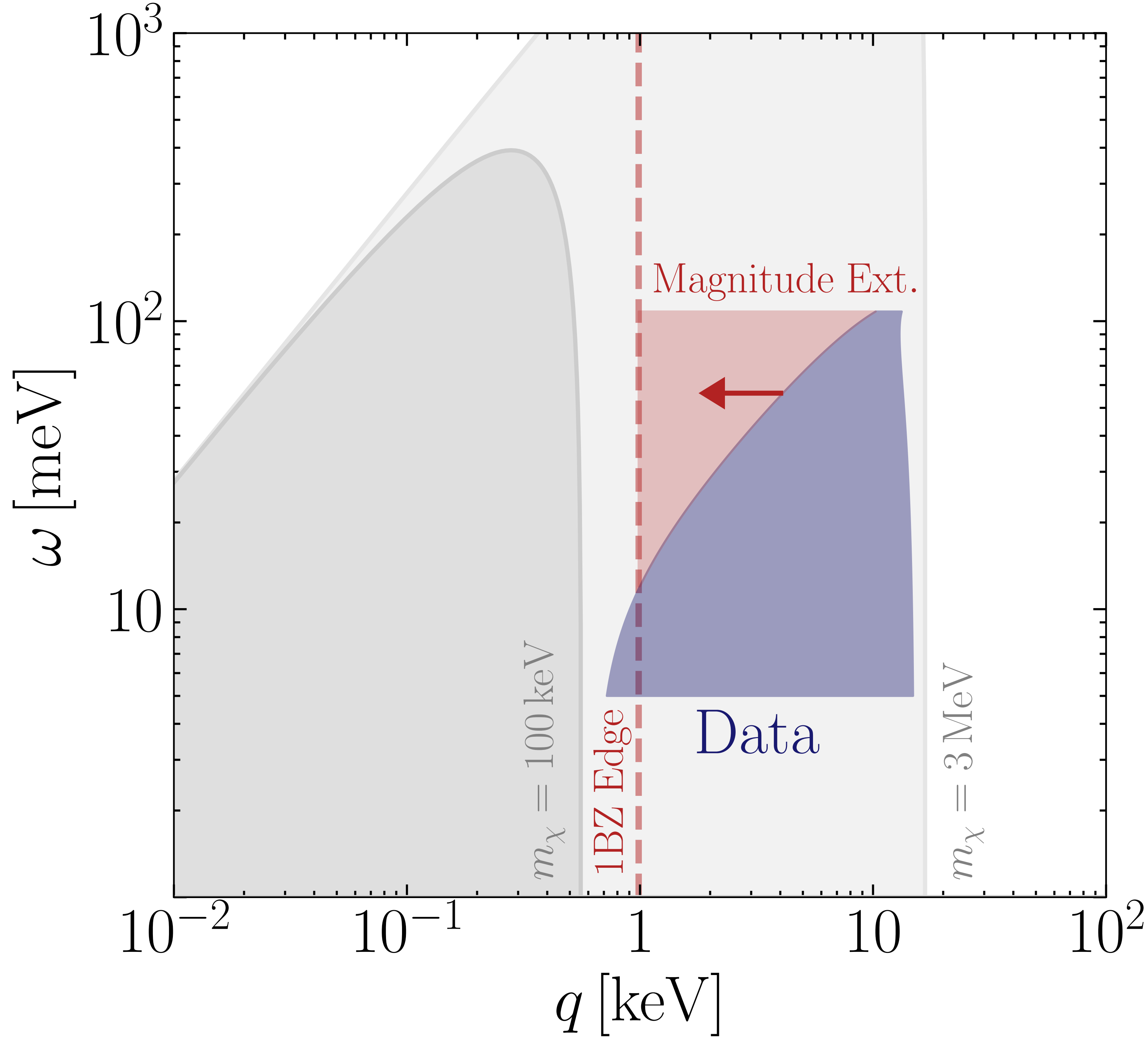
Each crystal orientation probes an arc in this plane

Limits of arc determined by detector coverage

Arc rotated by rotating the crystal in the lab frame



Kinematics of Neutron Scattering



Existing neutron scattering data already probes q of MeV dark matter scattering, as $m_n v_n \sim m_\chi v_\chi$

Highest possible ω aren't probed, as $v_n \sim 10^{-5} \ll v_\chi$, but all ω relevant for magnetic scattering are probed

Some lower q not probed, as $m_n \sim \mathrm{GeV} \gg m_\chi$, but filled by constant extrapolation downward

Dark Matter Scattering Rates From Neutron Scattering

Find χ''_m with neutron scattering, infer DM rate and sensitivity

Works very well for MeV mass DM in yttrium iron garnet, closely matching theory

Generalizes to any material, and reduces theory uncertainty

Potential to find promising materials for direct detection experiments