Calibrating the Migdal Effect in Semiconductors

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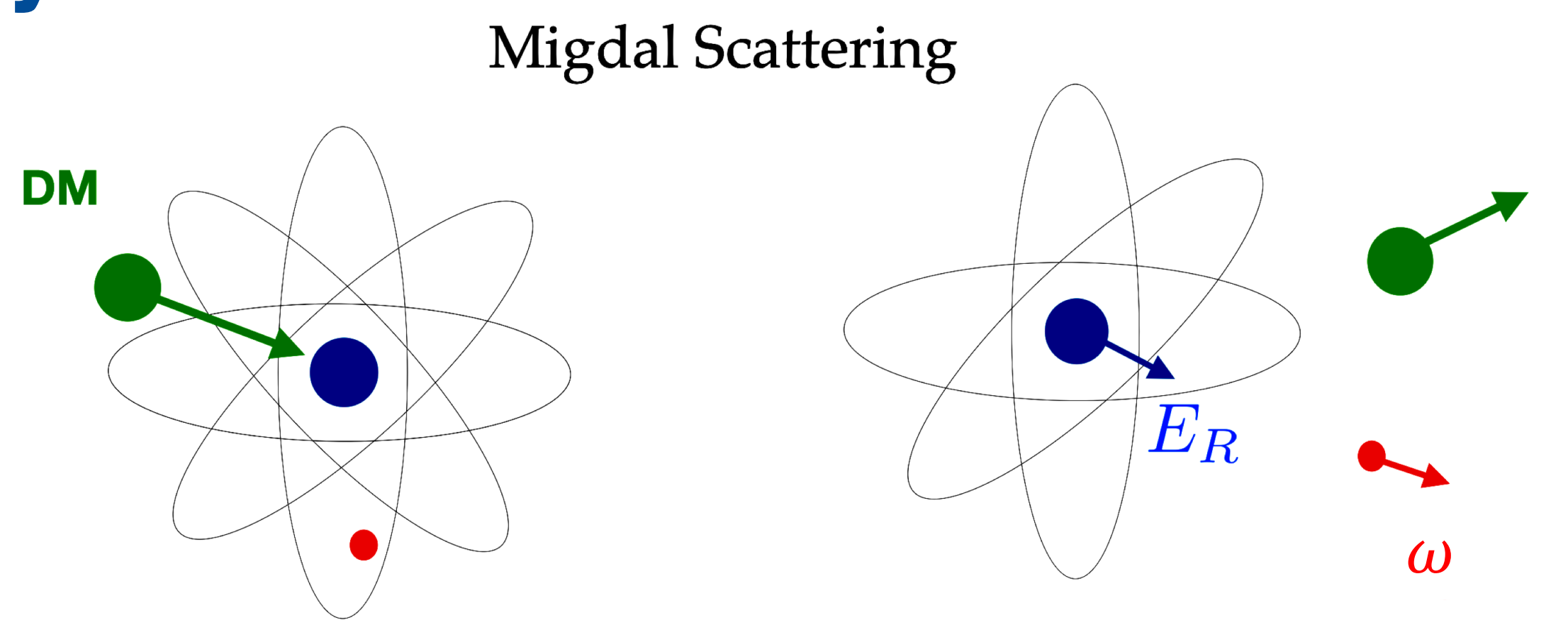
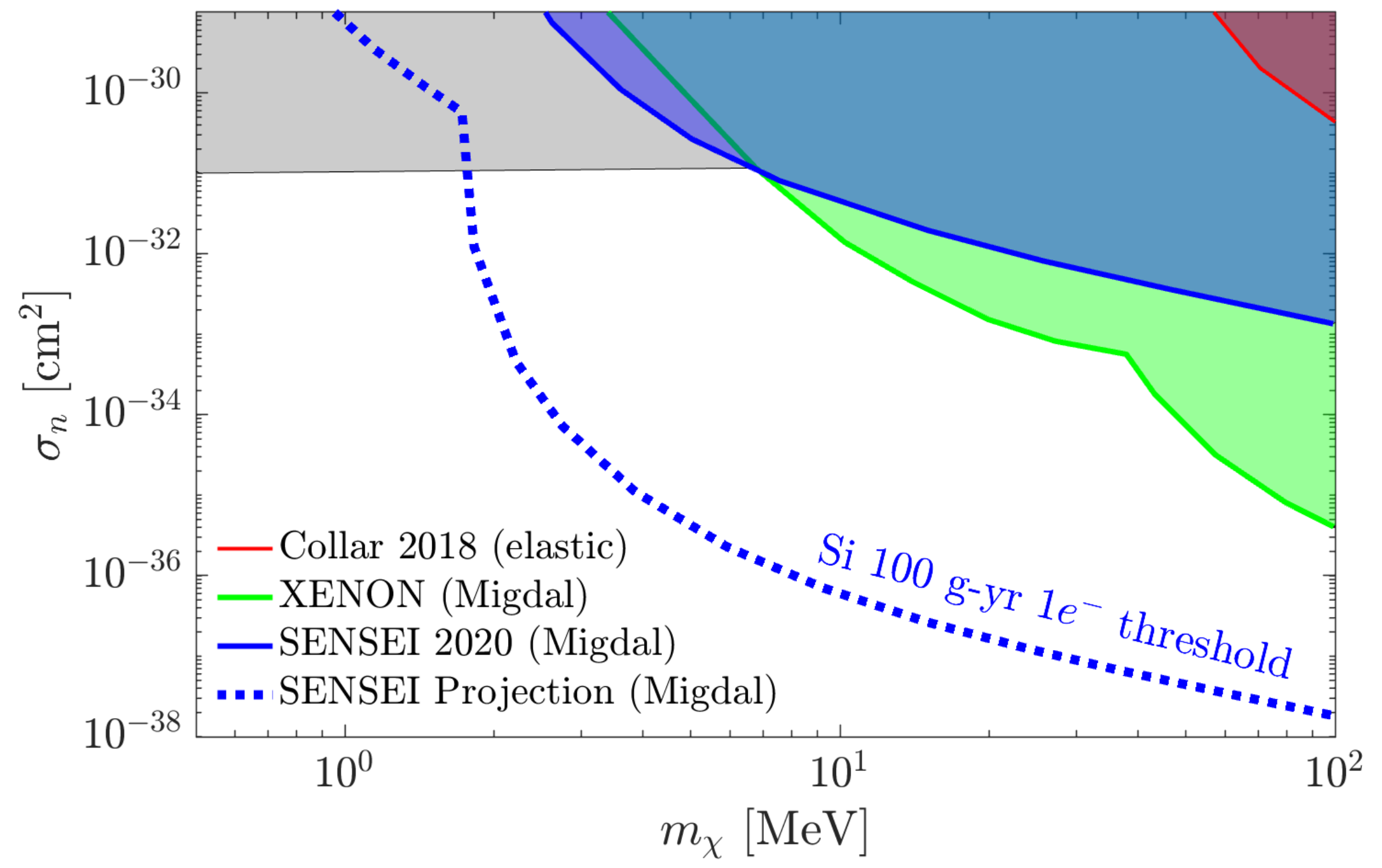
The Migdal Effect – A Brief Summary

If you transfer some amount of energy or momentum to a nucleus, there is a non-zero probability that the final state of that atom will be directly ionized as a result of the coupling between the nuclear and electronic systems





Above – Projected limits for the Migdal effect in SENSEI for a 100 g-yr exposure compared against existing constraints

The Migdal effect allows for coherent nuclear scattering in the sub-GeV mass regime where dark matter has enough kinetic energy to ionize an electron, but the required momentum transfer to the nucleus is elastically forbidden.

$$\frac{d^2R_M}{dE_r\,d\omega} = \frac{dR_{el}}{dE_r} \times q^2 \frac{d\widetilde{P}_e}{d\omega}$$

$$\frac{d^2P_M}{d\cos\theta_n\,d\omega} = \frac{d\widetilde{P}}{d\cos\theta_n}(E_n, \omega, \cos\theta_n)\,\frac{d\widetilde{P}_e}{d\omega}(\omega)$$

Determining the Angular Dependence

$$\left(\frac{d\widetilde{P}_e}{d\omega}\right)_{\text{sol.}} = \frac{4\alpha}{\omega^4 m_N^2}\int \frac{d^3\vec{k}}{(2\pi)^3} Z_{\text{ion}}^2(k)(\hat{q}\cdot\hat{k})^2\,\mathcal{W}(\vec{k},\omega)$$

This process has never been measured in neutron scattering, but should be present as a background to elastic scattering at the level of ~1:1000.

$$\frac{d\widetilde{P}}{d\cos\theta_n} = \frac{N_0\rho_T L\sigma_{el}}{A_N}\frac{\mu^2 m_N E_n}{\beta m_n^2}\left(\frac{m_n}{m_N}\cos\theta_n + \beta\right)^2 \times \left\{1 - \frac{\mu^2}{m_n^2}\left(\frac{m_n}{m_N}\cos\theta_n + \beta\right)^2 - \frac{\omega}{E_n}\right\},$$

$$\beta \equiv \sqrt{1 - \frac{m_n^2}{m_N^2}(1-\cos^2\theta_n) - \frac{m_n\omega}{\mu E_n}}.$$

The wavefunctions probed are the same as used to calculate dark matter electron scattering, for which there is no direct Standard Model calibration.

This process is well-measured in beta and alpha decay – it's just based on quantum mechanics.

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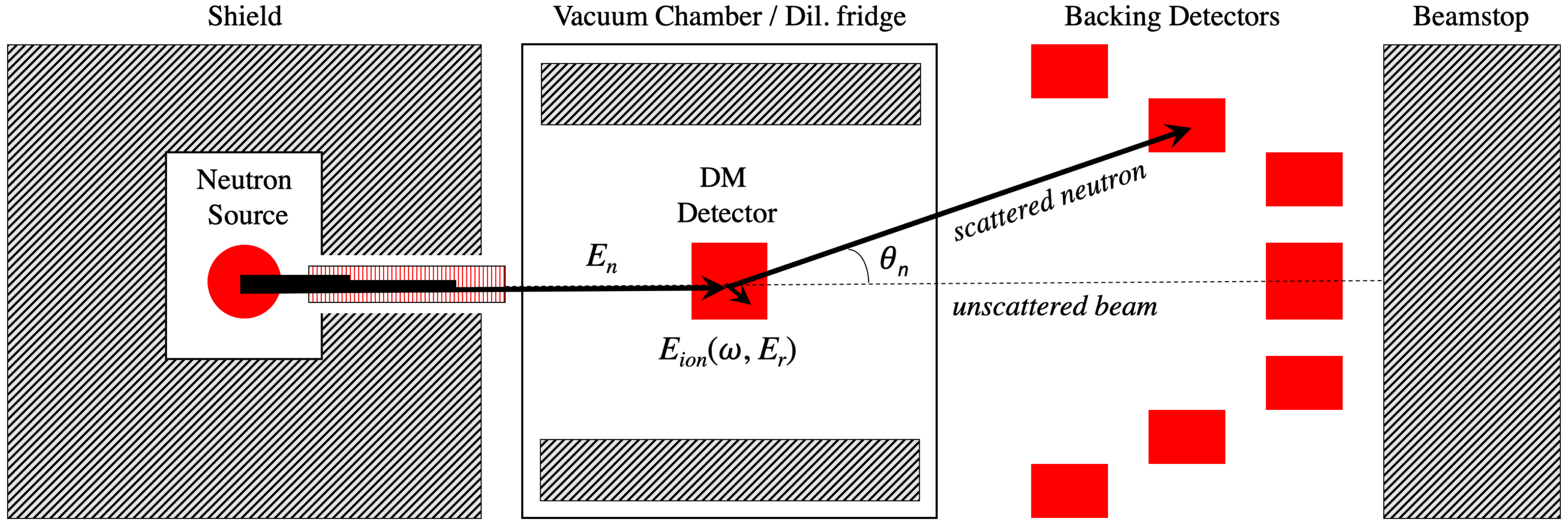
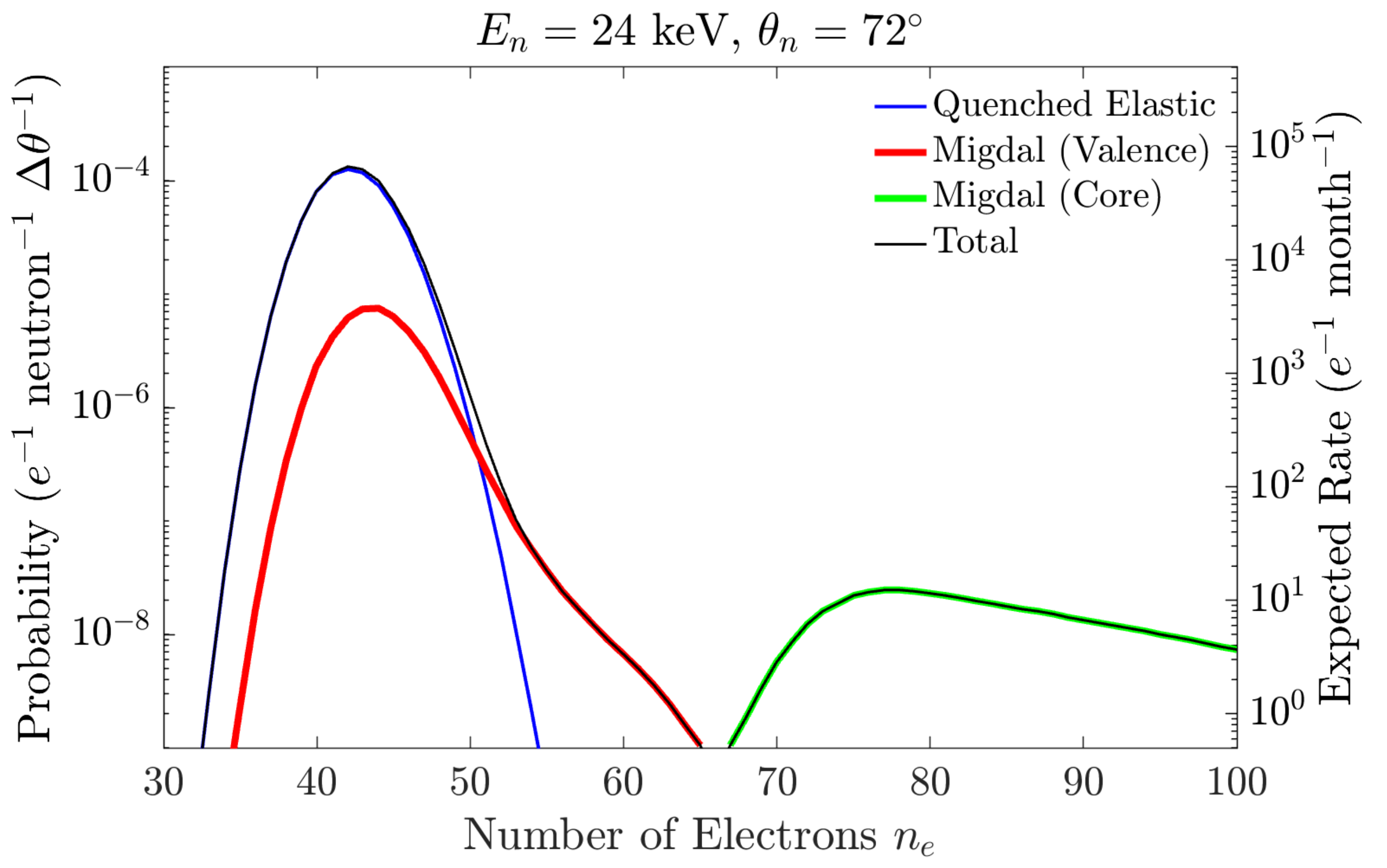
Designing an Neutron Calibration with a Backing Array



Above – In this diagram, neutrons are produced on the left from a source inside of a polyethylene shield, before passing through a custom-designed filter that collimates the beam, moderates the neutron energy to E_n, and filters the neutron energy to be monochromatic. These neutrons then travel directly into a detector housed in a radiation-shielded cryostat, where they deposit ($E_r + \omega$) of energy and scatter at angle θ_n into an array of low-threshold backing detectors.

Right – A panorama of the setup in NEXUS for reference and comparison

The NEXUS underground facility at Fermilab offers the perfect opportunity to calibrate the Migdal effect given it's D-D generator (2.5 MeV neutrons on target at kHz/cm^2) incident on a 10 mK detector space inside of a 200 dru background environment created by a mobile lead shield (~1 event/month ionizing bkg in the energy region of interest)



Left – The left axis gives the differential probability spectra in units of events/neutron/degree of angular coverage for neutron scattering in a 1 cm thick silicon detector located in a mono-energetic 24 keV neutron beam from an iron-filtered D-D generator neutron source in the case of wide-angle scattering at 72°. The right axis maps this calculation onto an expected rate for an experiment consisting of a 1 Hz/cm^2 neutron beam with a radius of 3 cm incident on a fully-efficient SuperCDMS-HVeV NTL-amplification detector array and scattering into a series of 20% efficient backing detectors encompassing 40° of angular coverage. The integrated rates for both valence (red) and core (green) Migdal scatters consist of hundreds of events per month each.