Arxiv: 2210.04917

Discovering the Migdal Effect with Neutrons

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Why do we care?

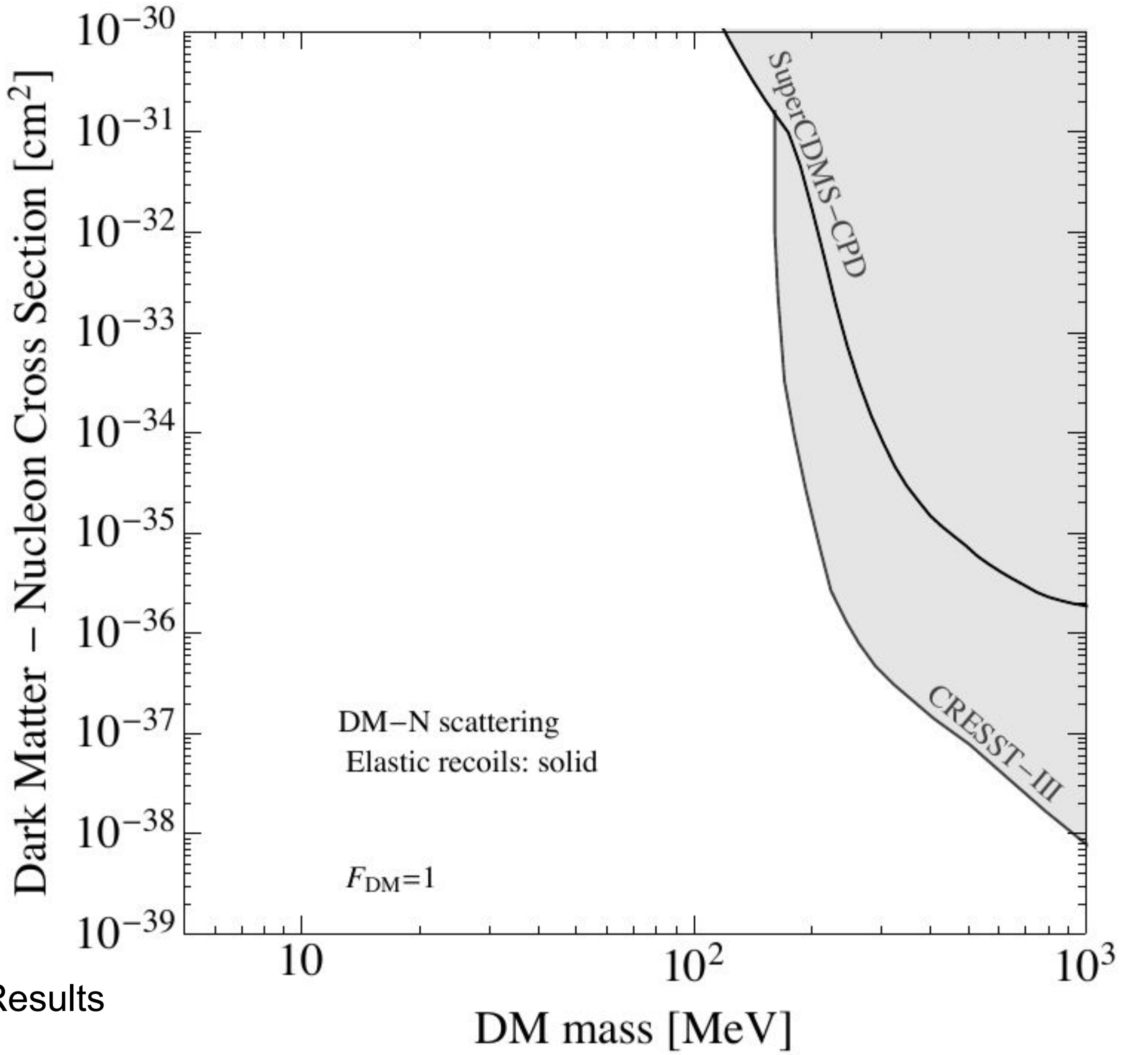

Fig: Compiled Migdal Results

Essig et al: 2203.0829

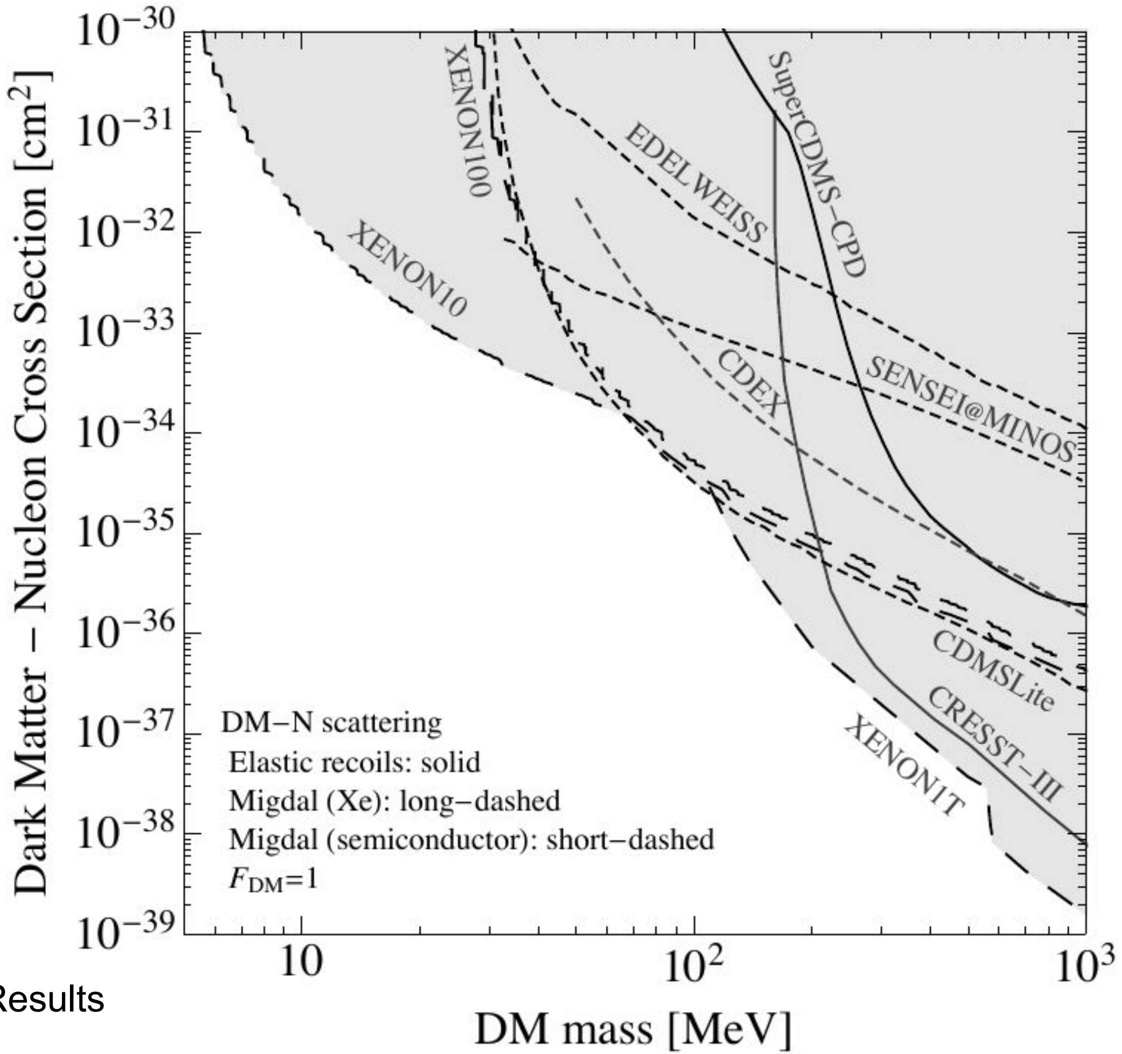

Fig: Compiled Migdal Results
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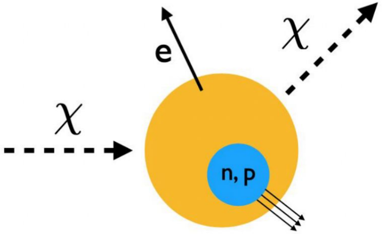
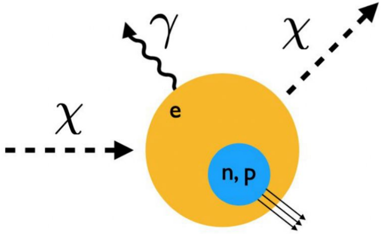
The Migdal Effect - Basics

- Ionization signal from nuclear recoils, theorized by A. Migdal in the 30s
- Enhanced sensitivity to $\sigma_{\chi n}$ for sub-GeV DM
- Migdal scattering has never been measured
- Need to measure and calibrate in a controlled environment!



The atom emits an electron (Migdal effect).

[Ibe, Nakano, Shoji, Suzuki - arXiv:1707.07258, Dolan, Kalhoefer, McCabe - arXiv:1711.09906]



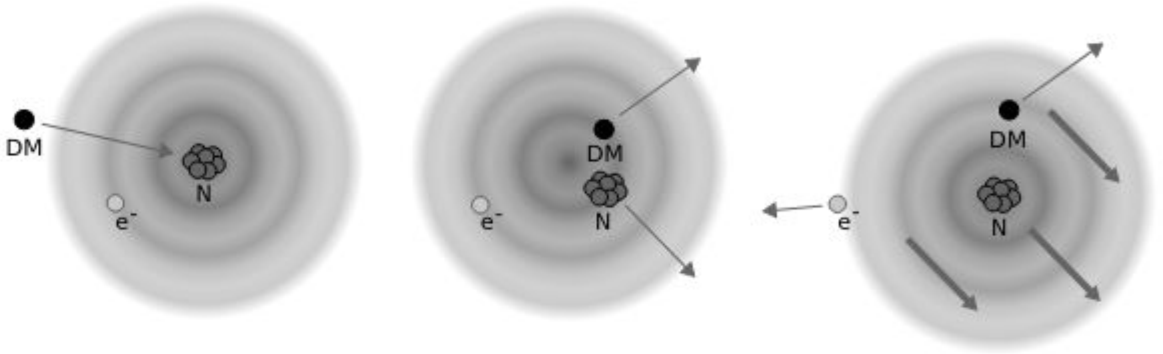
The polarised atom emits a photon.

[Kouvaris, Pradler - arXiv:1607.01789]

Image Credit: Cortona et al.

Atomic Migdal Effect

- Nuclear recoil leads to sudden displacement of nucleus
- Ionization cloud must “catch up” to nucleus
- Probability that electron(s) are ionized instead



Incoming DM scatters off nucleus, with electron being ejected from its shell
Dolan, Kahlhoefer, McCabe: 1711.09906

Semiconductor Migdal Effect

- Nucleus can be excited to higher energy levels in its potential, leading to excitations of phonons
- Phonons can kick electrons up to conduction band
- Inner shell electrons can be directly liberated from parent nucleus
- LOTS of assumptions in the standard calculations (what we want to test!)

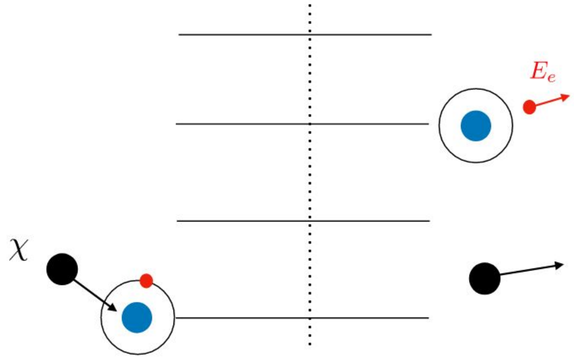
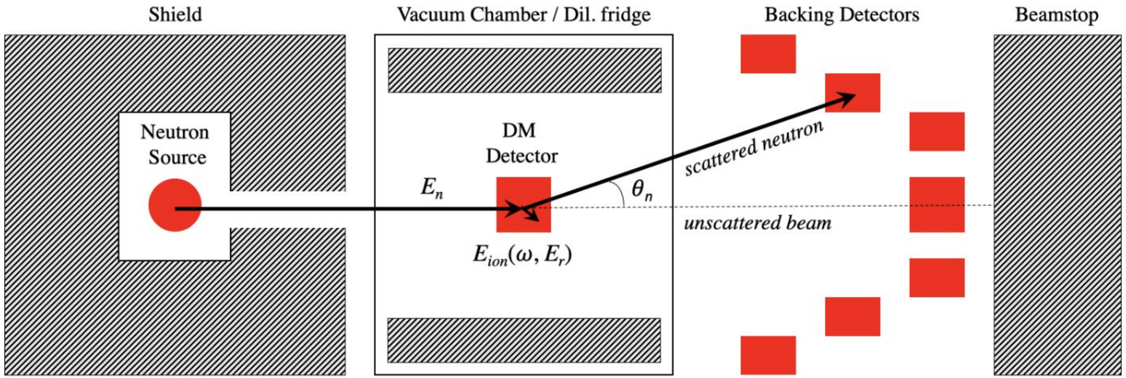


Fig: Cartoon of Migdal Effect in a semiconductor

Kahn, Krnjaic, Mandava: PhysRevLett.127.081804

My Contribution

- Propose a novel detection strategy using a neutron beam with backing detector array
- Calculations of Migdal spectra at fixed scattering angle
- Smoking gun signal: tail of events that produce more ionization than a pure elastic nuclear recoil



Experimental Strategy - Backing Detectors

- Tag scattering angle of the outgoing neutron
- Comparison with predicted migdal signal at fixed angle
- Ionization from both the nuclear recoil (quenching), and the Migdal electron
- Tried and true methods for ionization calibration, need to optimize for Migdal

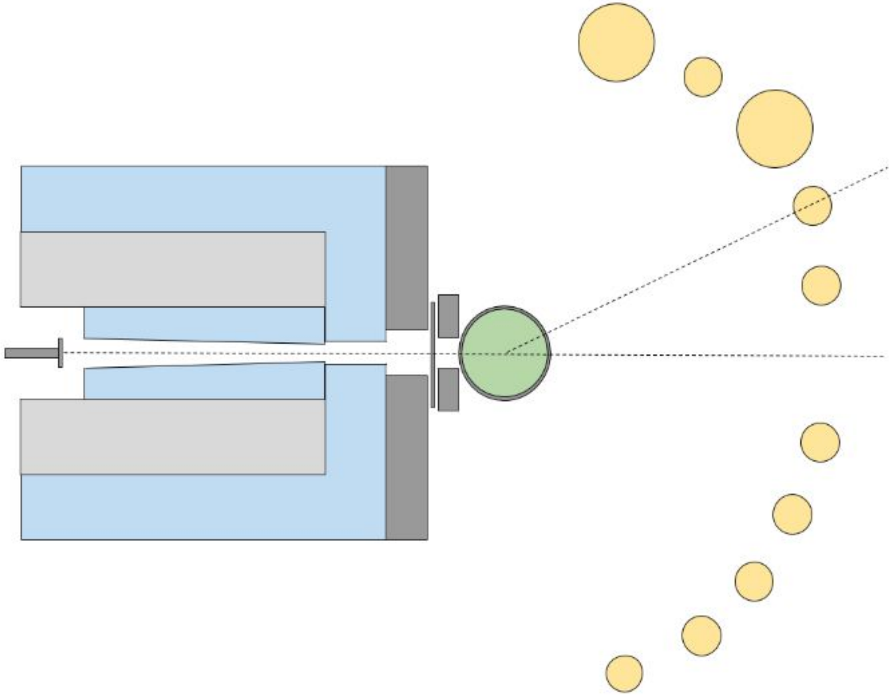
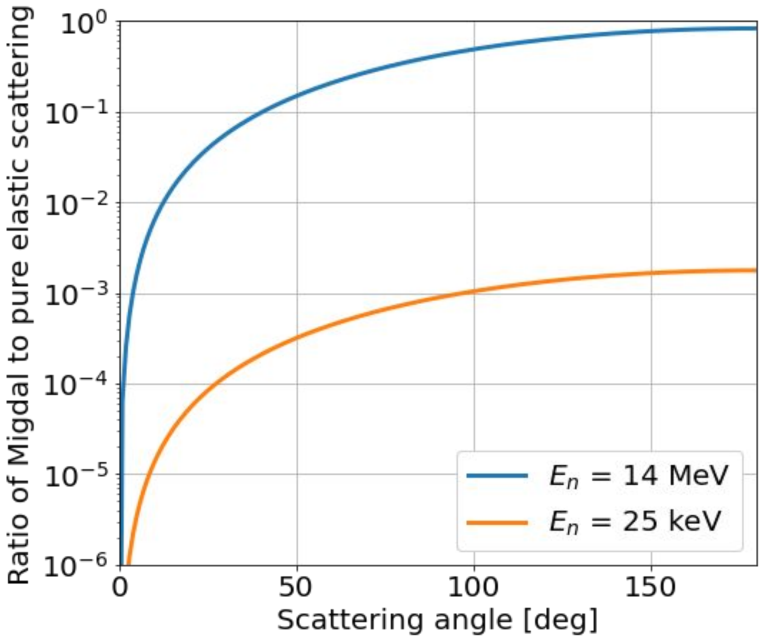


Fig: A cartoon of a backing array setup used in calibration (Lenardo et al: 1908.00518)

Experimental Strategy - Optimization

- Theoretical and experimental Constraints
- Theory: $$\frac{R_M}{R_{el}} \propto E_n(1-\cos\theta)$$
- Experiment:
  - Very shallow and very wide angles difficult
  - Difficult to make neutrons of arbitrary energy
  - High energy smearing effects wash out the signal
- The Game: Find angles/energies that give a decent migdal rate but don't make the experiment needlessly difficult or expensive

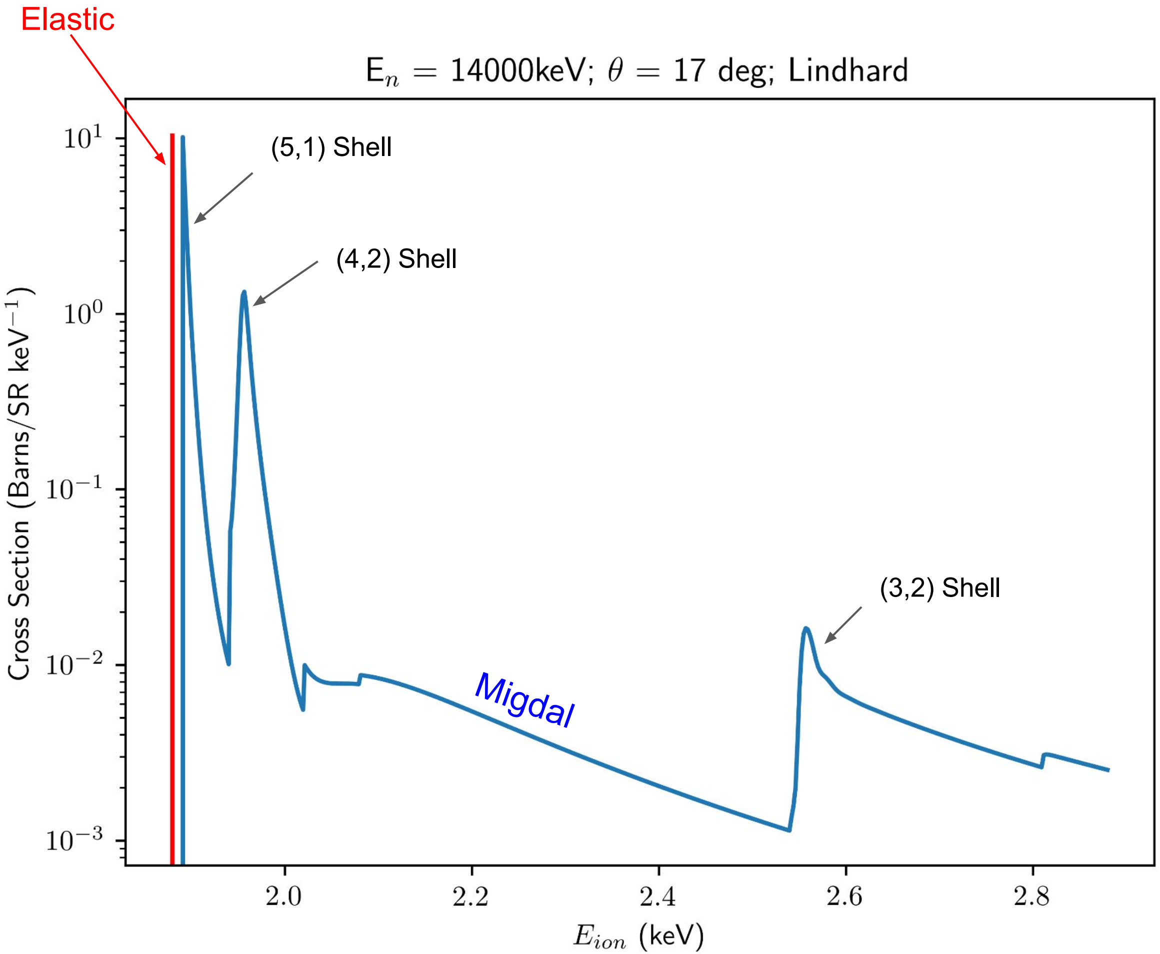


Ratio of migdal/elastic rates in Xe as a function of angle shown for two beam energies

Ionization Spectrum - Theorist's View

Idealised ionization spectrum in Xe. The fixed angle nicely separates the Migdal from the elastic.

In practice, this picture is complicated by energy smearing, multiple scatters, beam spread, etc.



Spectra in Si

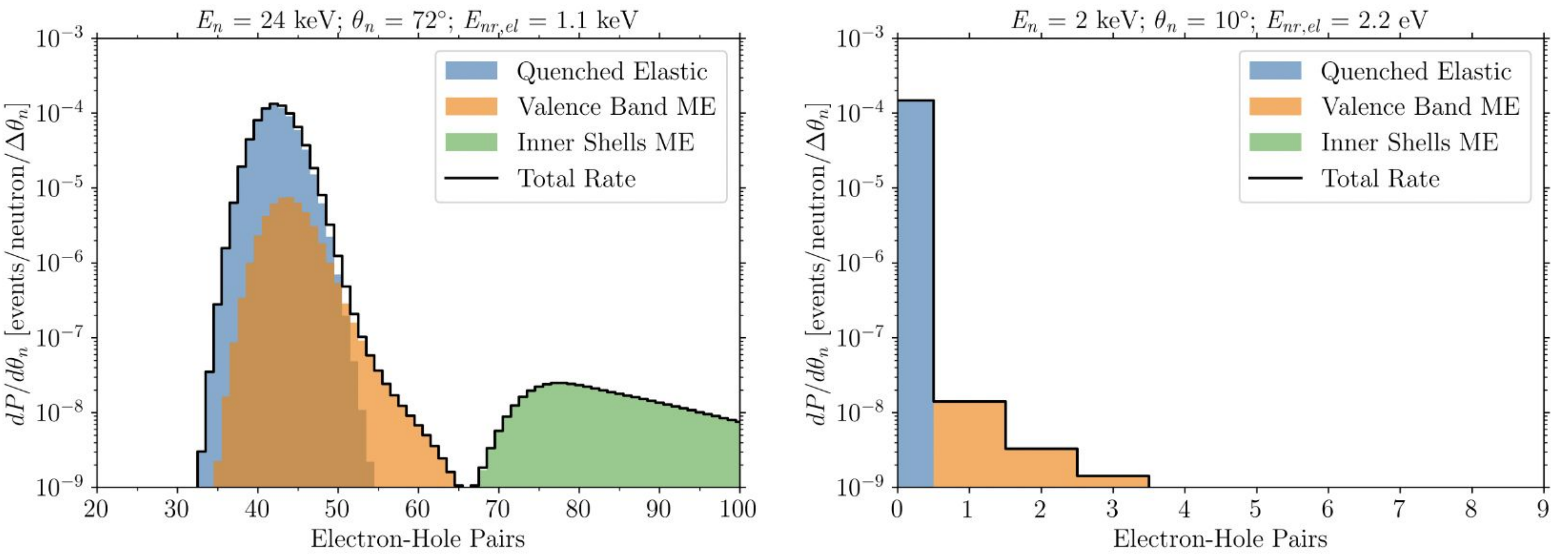
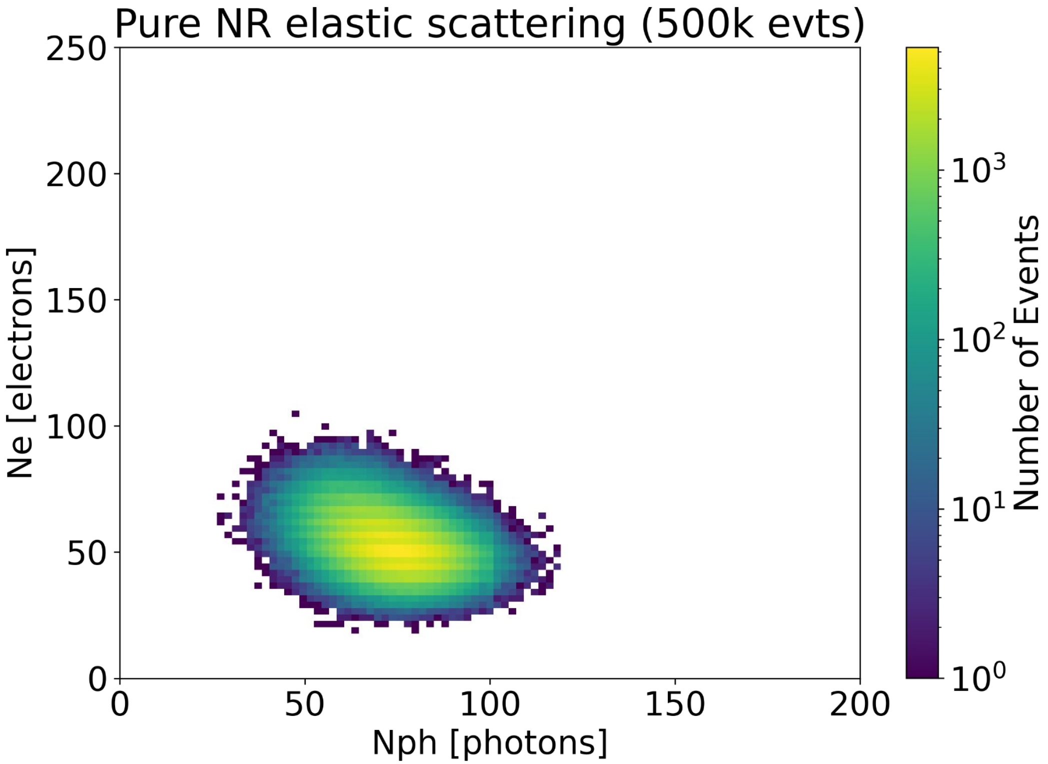


FIG. 2. Differential probability spectra $dP_{n_e}/d\theta_n$ (in units of events/neutron/degree of angular coverage) are shown per detectable charge quanta n_e in the left (right) plot for an ideal 1 cm thick silicon detector in a $E_n = 24$ (2) keV mono-energetic neutron beam at a fixed scattering angle of $\theta_n = 72$ (10) degrees, assuming the Sarkis ionization efficiency (quenching) model [50] and Ramanathan charge production model [52]. In both cases, we assume perfect backing detector with full azimuthal coverage. **Left:** For higher neutron energies and wide angles, the contribution from the inner shell [12] is distinct above the elastic peak. **Right:** For low neutron energies and shallow angles, the contribution from the valence band [49] separates from the elastic peak.

Results in Xe @ 14MeV, 17°



* NEST: a comprehensive model for scintillation yield in liquid xenon, http://iopscience.iop.org/article/10.1088/1748-0221/6/10/P10002/meta

* Noble Element Simulation Technique, https://zenodo.org/badge/latestdoi/96344242

Plots courtesy of Brian Lenardo

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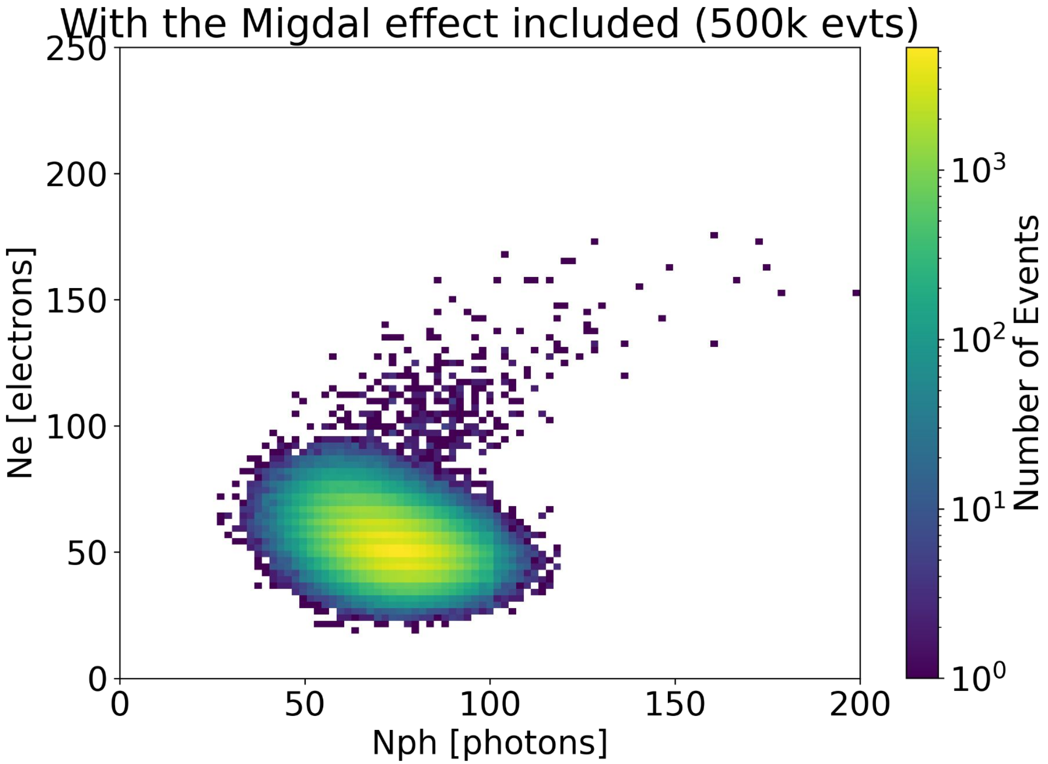

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Cool Photo

Conclusions

- Utilize backing arrays to get a handle on the inelastic kinematics
- “Smoking Gun” is a tail in the ionization rate above the elastic component
- Measurements are difficult and require optimization with Migdal in Mind!
- Xe experiment at LLNL well under way!
- Measurement essential to validate DM limits!
- Migdal will become a standard part of the dark matter toolkit!