Discovering the Migdal Effect with Neutrons

Duncan Adams
Rouven Essig
B. Lenardo, J. Lin, R. Mannino, J. Xu (Xe)
D. Baxter, H. Day, Y. Kahn (Si)

The Migdal Effect - Background

- 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!

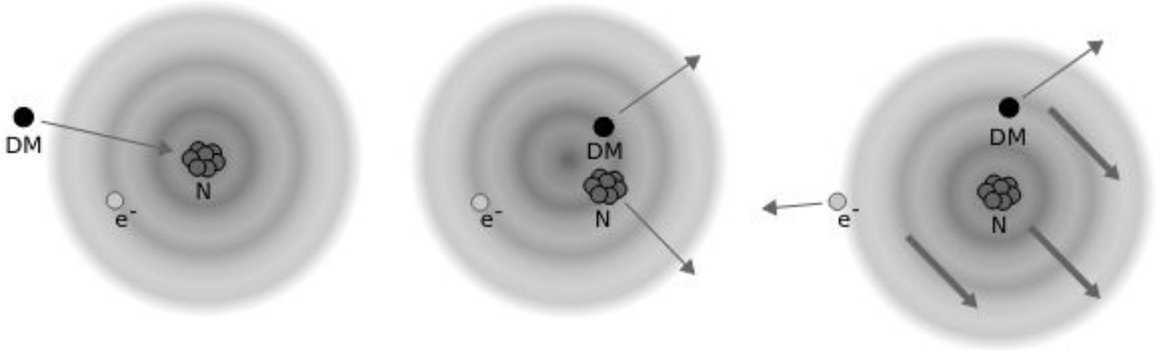


Fig: Incoming DM scatters off nucleus, with electron being ejected from its shell
Dolan, Kahlhoefer, McCabe: 1711.09906

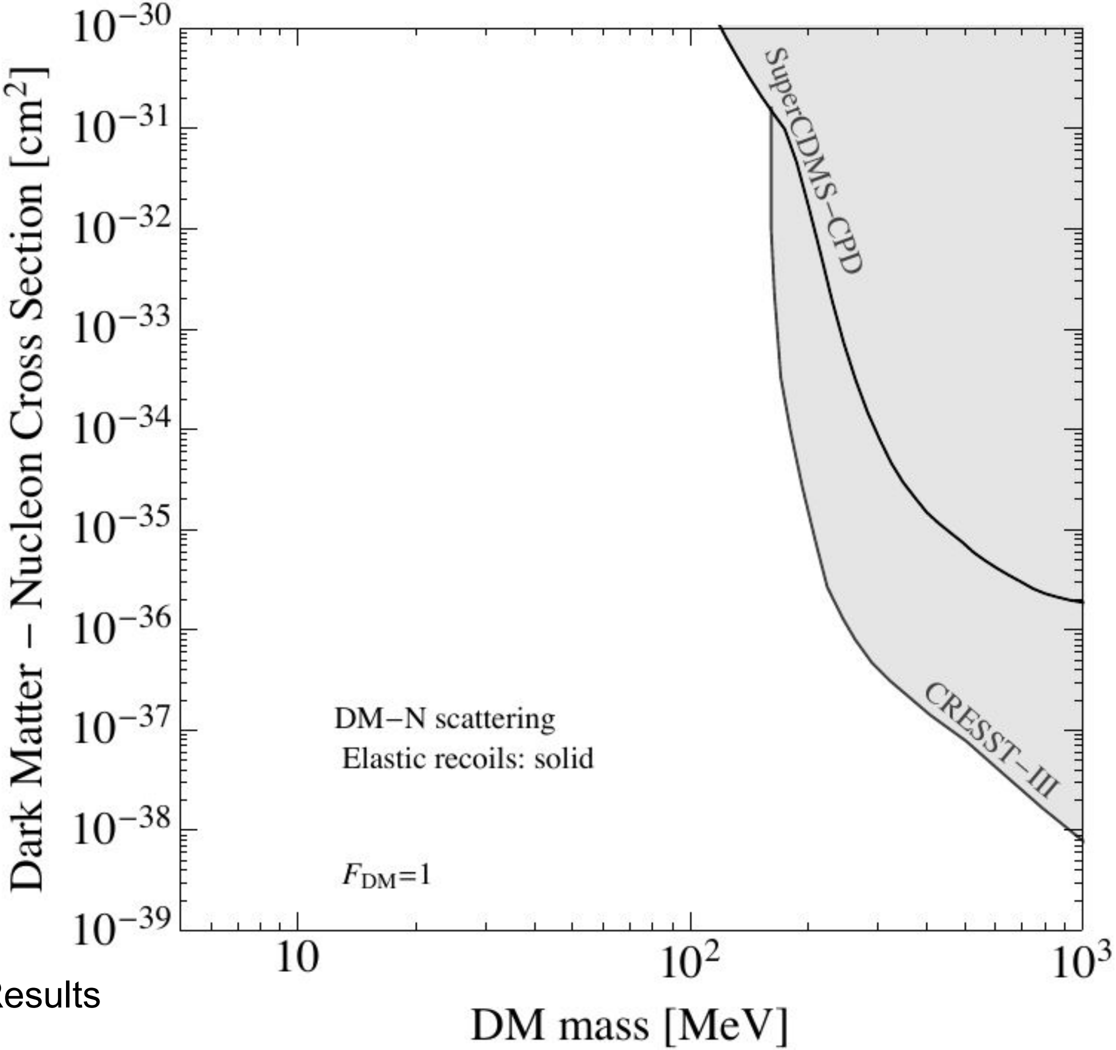
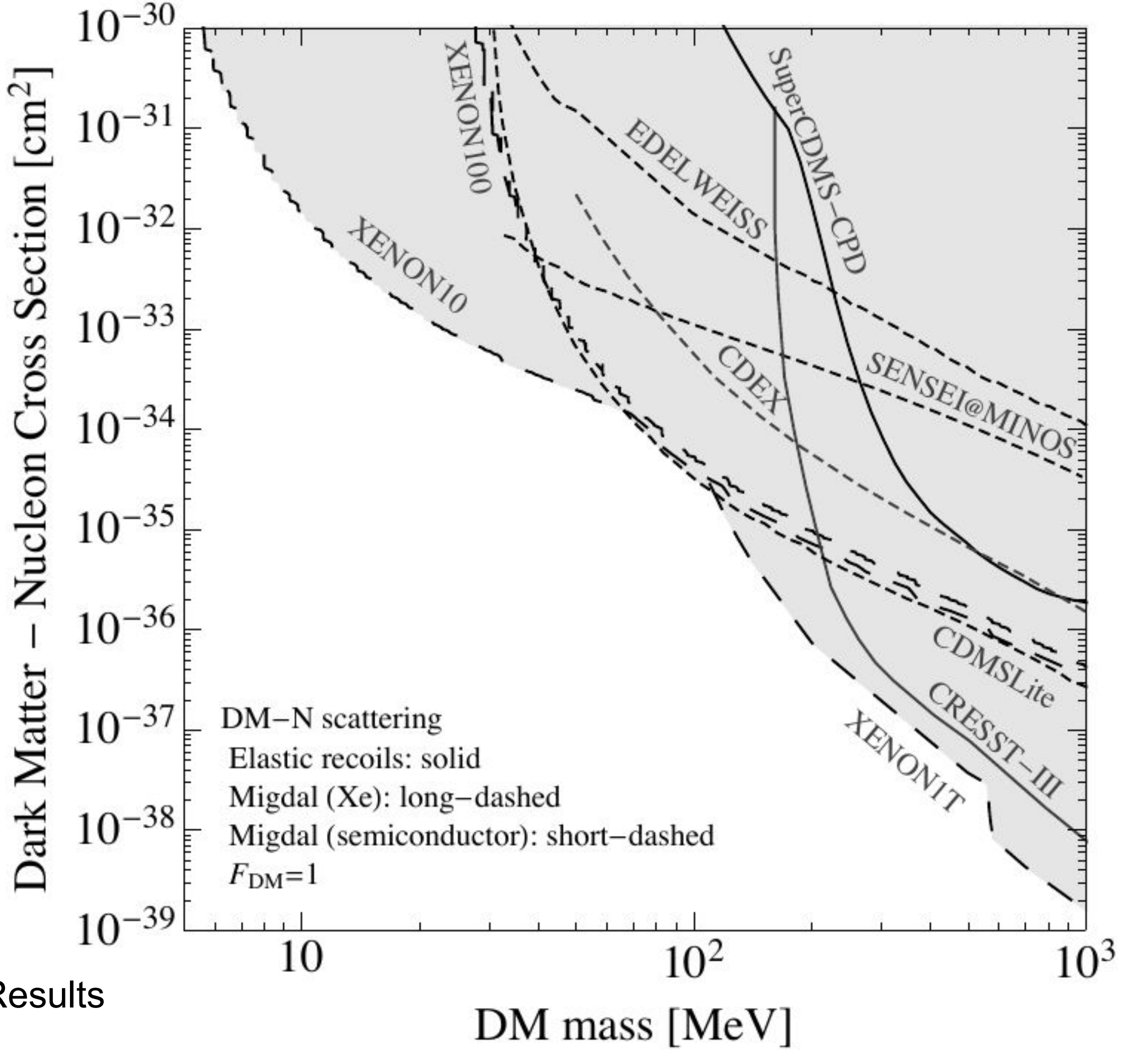


Fig: Compiled Migdal Results
Essig et al: 2203.0829



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Previous Studies

- Papers appear in mid 2000s for WIMPS

  Ejiri, Vergados: 0401151

  Ejiri, Moustakidis,Vergados: 0510042

- Ibe et al publish groundbreaking study in 2017

  Ibe et al: 1707.07258

- Development of theory calculations:

  Bell et al: 1905.00046

  Baxter, Kahn, Krnjaic: 1908.00012

  Essig, Pradler, Sholapurkar, Yu: 1908.10881

  Liu, Wu, Chi, Chen: 2007.10965

  Knapen, Kozaczuk, Lin: 2104.12786

- MIGDAL Collaboration in UK - actively working to get the first results in gas

  https://migdal.pp.rl.ac.uk/

- Feasibility study of Migdal from neutrons and CEνNS in Xe and Ar

  Bell, Dent, Lang, Newstead, Ritter: 2112.08514

This Work

- 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
- Important to measure this effect in a controlled laboratory setting

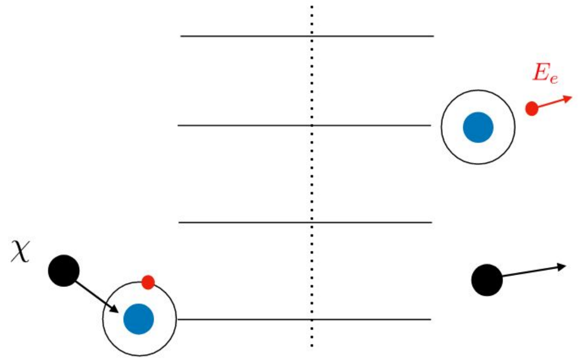


Fig: Cartoon of Migdal Effect in a semiconductor

Kahn, Krnjaic, Mandava: PhysRevLett.127.081804

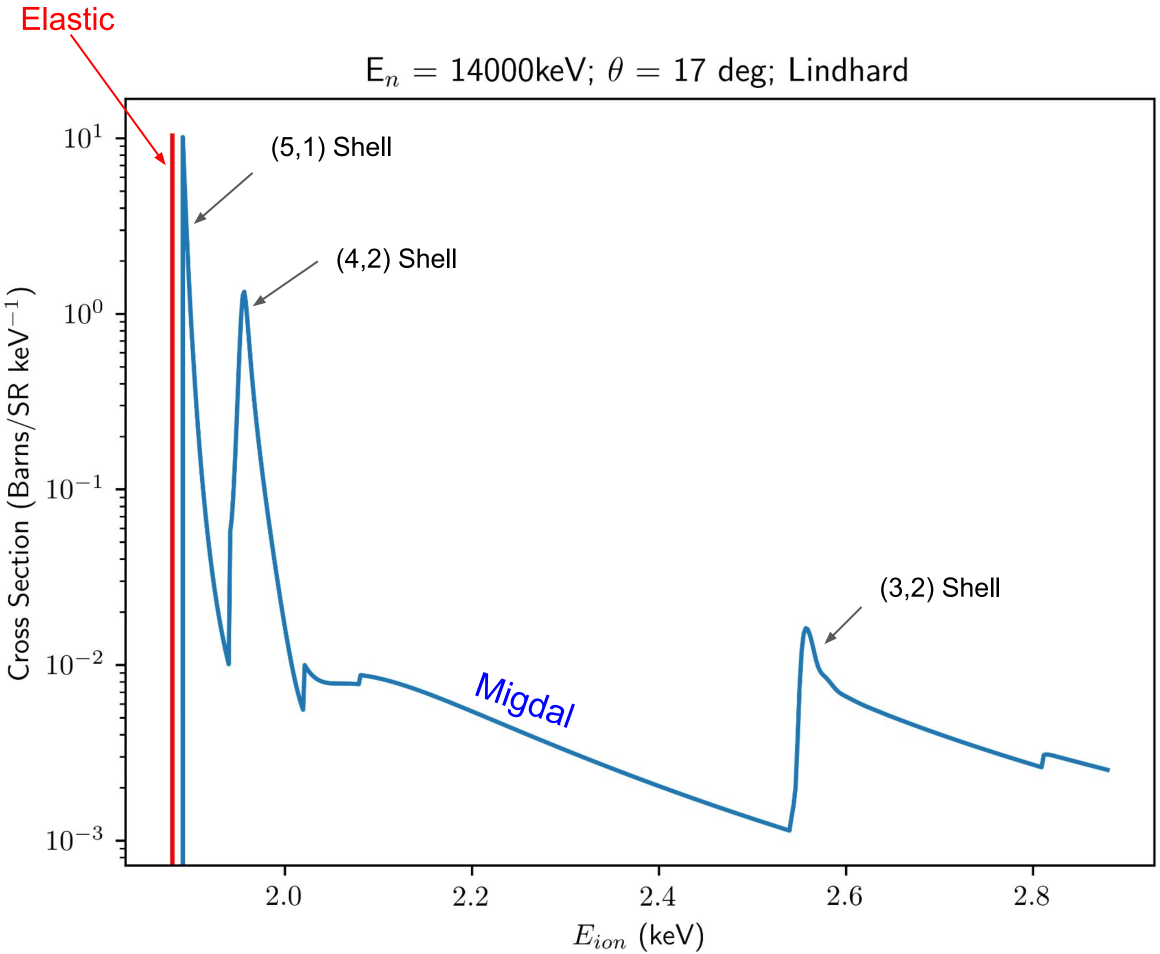
Overview of Calculation

- Migdal factorization: $R_M \sim R_{el} \times P_M$
- Using elastic cross sections taken from nuclear databases
- Ionization spectra from Migdal
- Predict observables in idealised setups
- In Xe, S1/S2 (scintillation/charge)
- In Si, event rate binned in number of electron-hole pairs

Ionization Energy - Migdal vs Elastic

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.



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

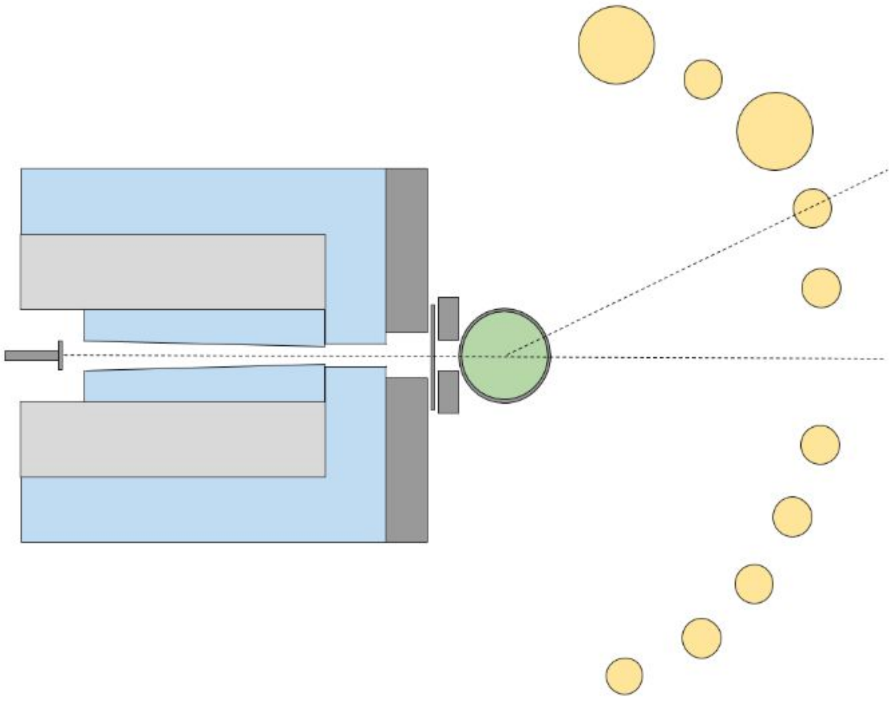
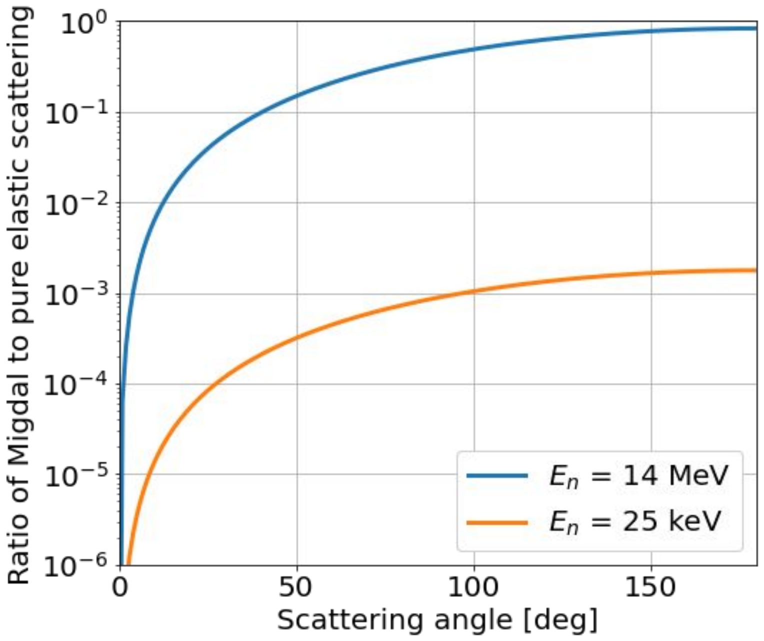


Fig: A cartoon of a backing array setup used in calibration (Lenardo et al: 1908.00518)

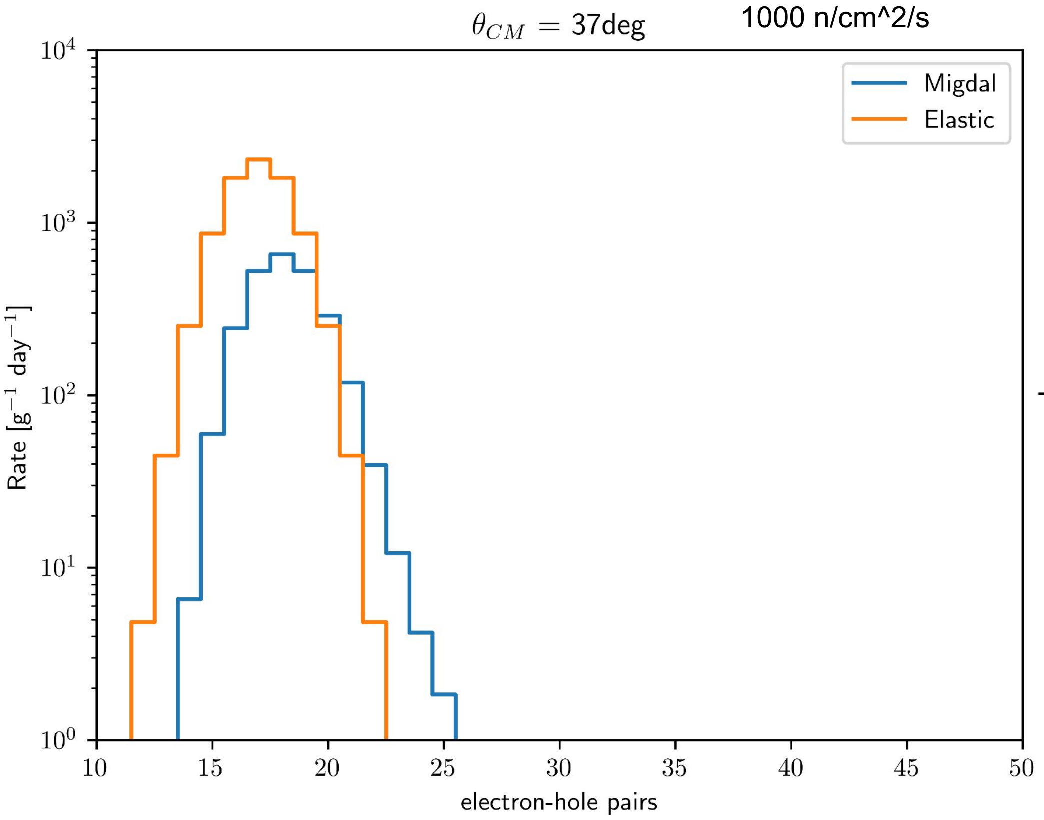
Experimental Strategy - Optimization

- 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

Results - Silicon@54keV



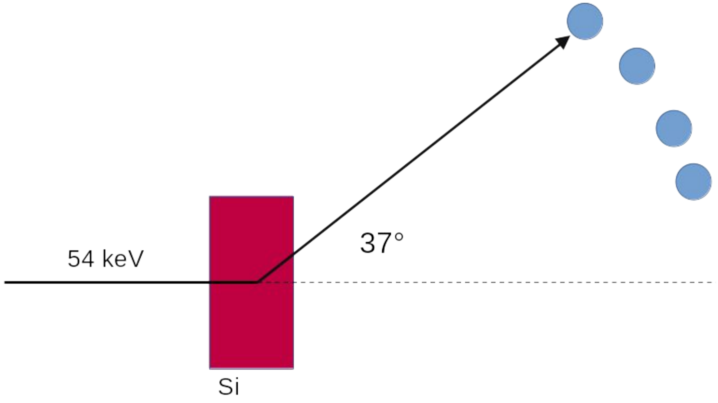


Fig: A schematic of the Si experiment

Ionization Yield: Sarkis, Aguilar-Arevalo, D'Olivo: 2001.06503
Charge Production: Ramanathan, Kurinsky: 2004.10709

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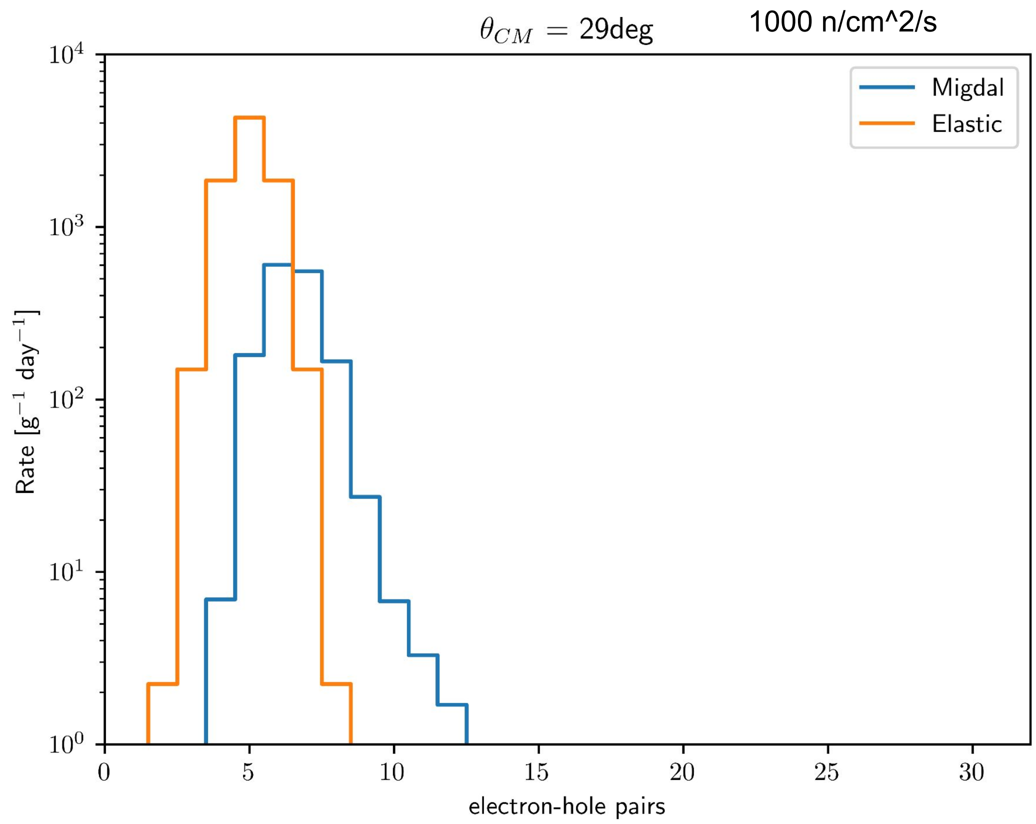

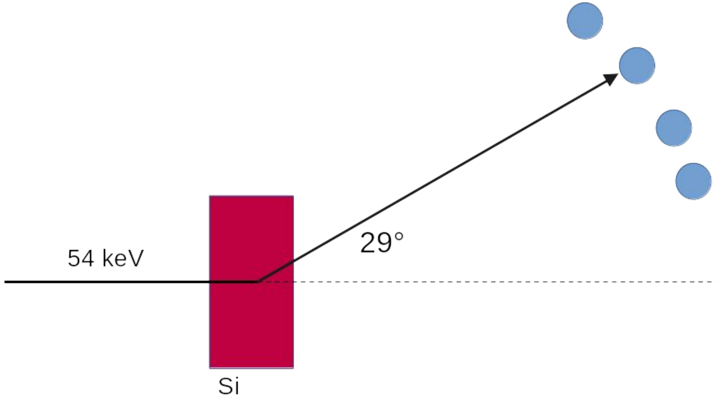

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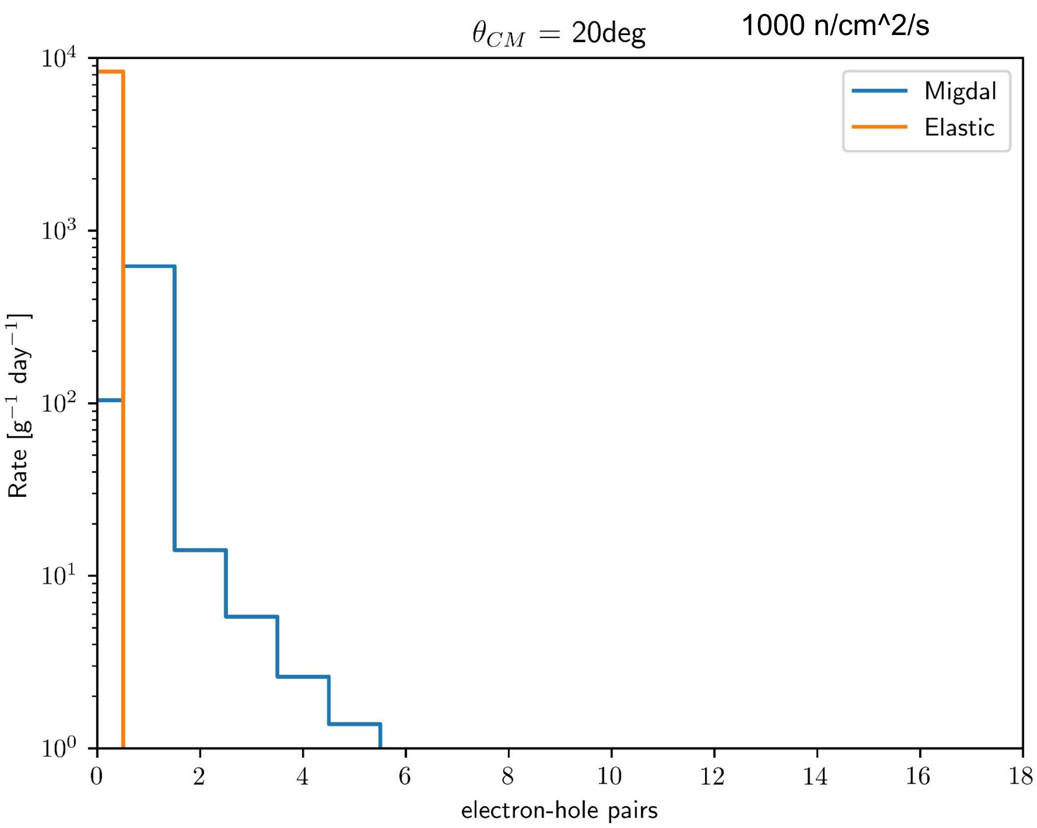

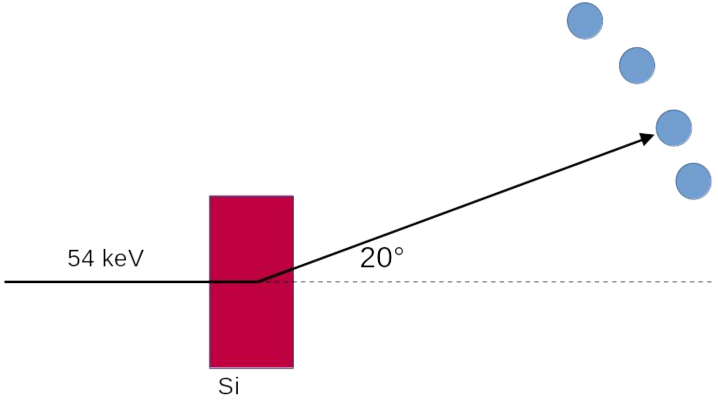

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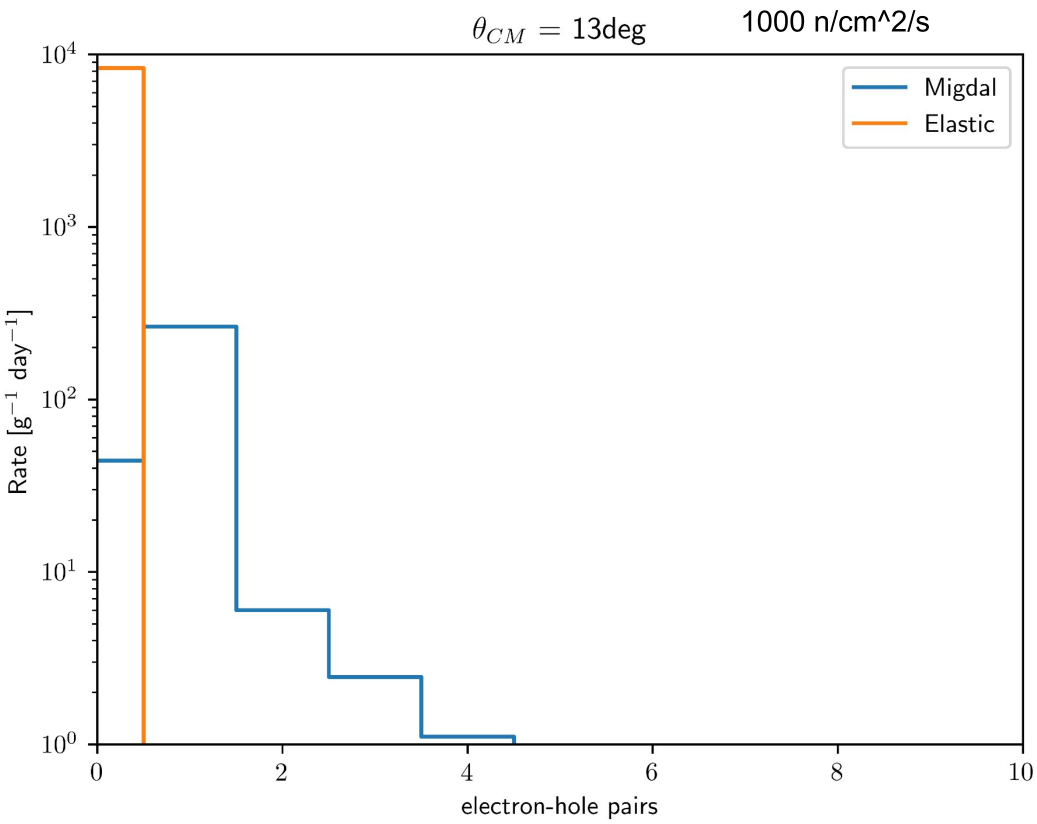

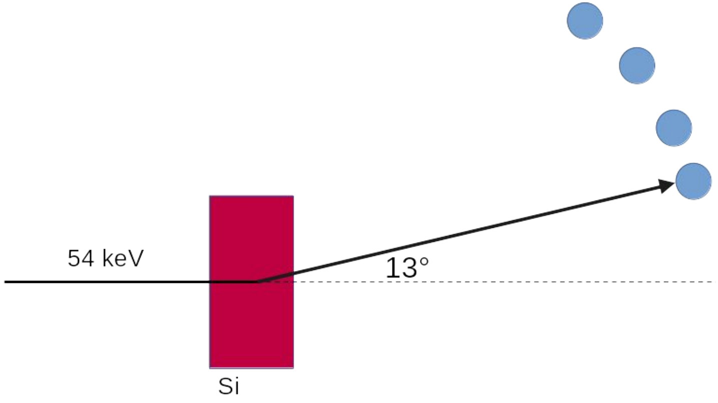

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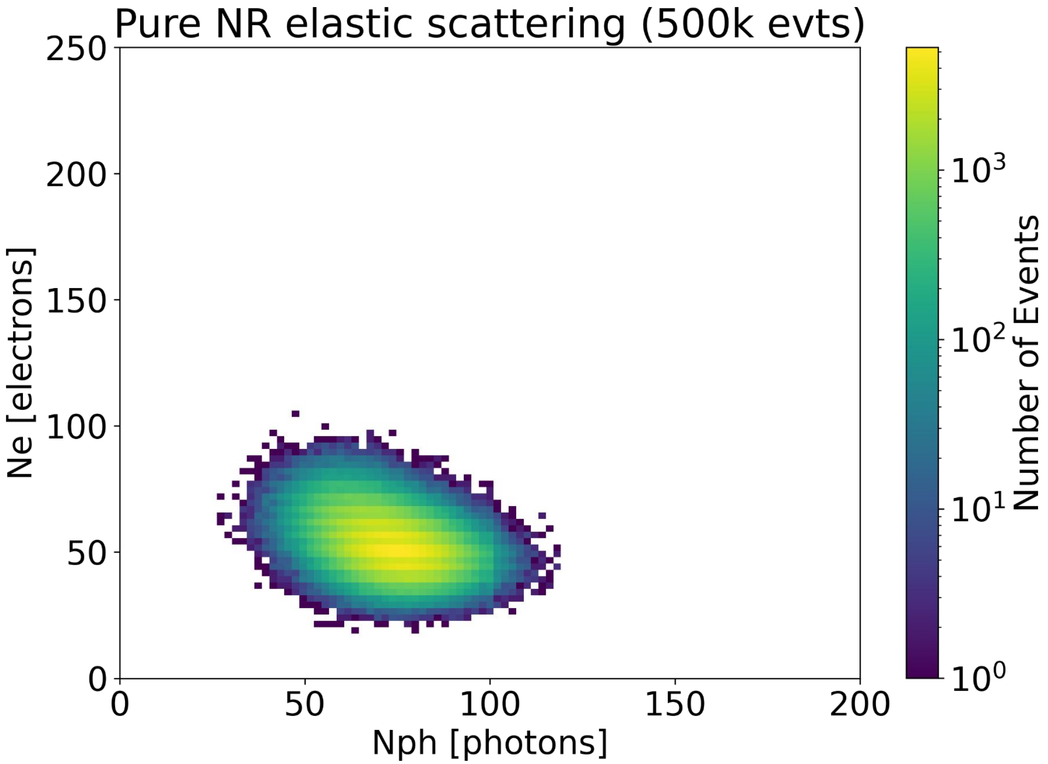
Results - Xenon@14MeV, 17°



* 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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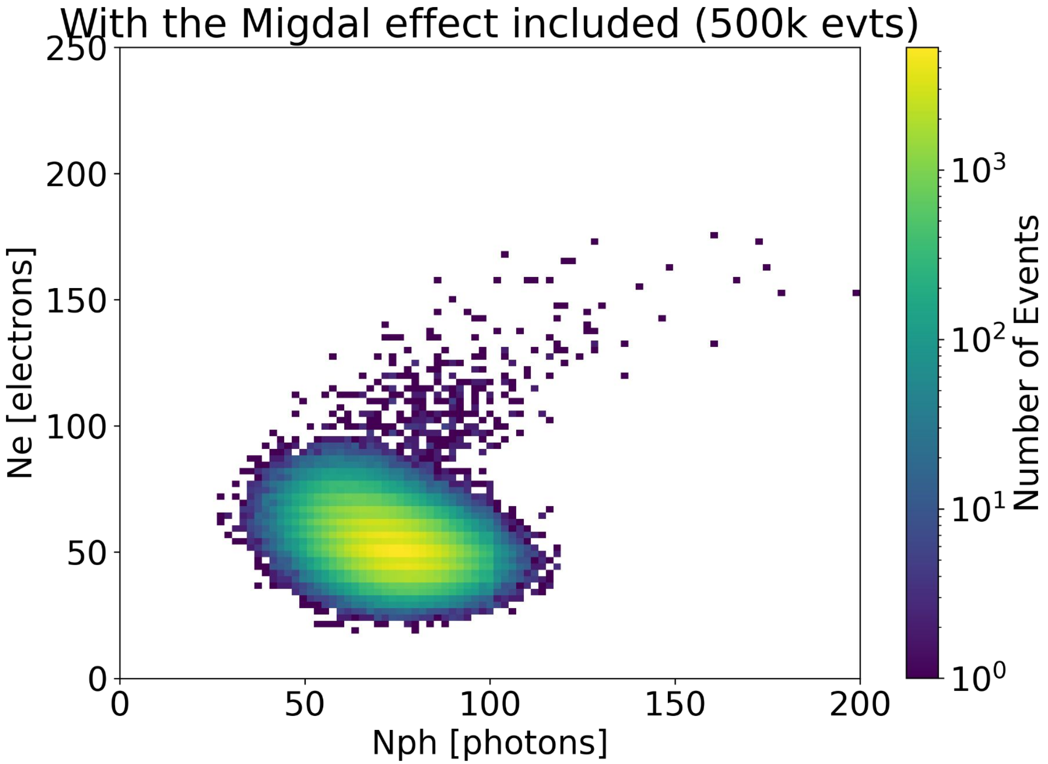

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Next Steps

- Measurements being developed in Xe and Si!

Conclusions

- Measurements at a fixed scattering angle give a high discovery potential of the Migdal effect

- "Smoking Gun" is a tail in the ionization rate above the elastic component

- Measurement essential to validate DM limits!