Experimental search for the Migdal effect with keV-level xenon nuclear recoils

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Publication and collaborators

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- Thanks to all of our collaborators!

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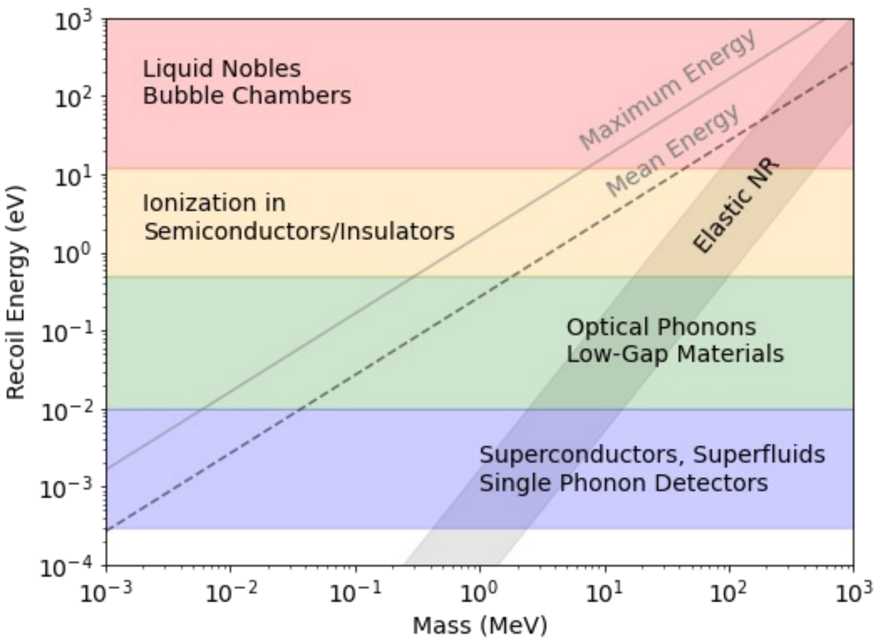
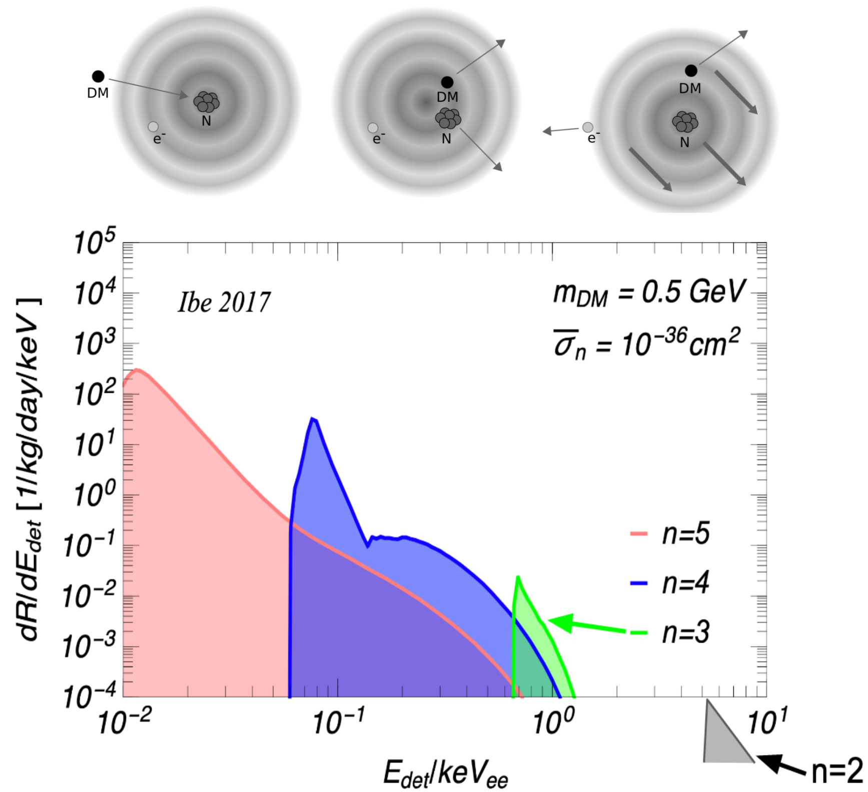
Low-mass dark matter and the Migdal effect

- There is a strong interest in low-mass dark matter searches
- Inelastic interactions have significant advantages
- The Migdal process is a promising avenue



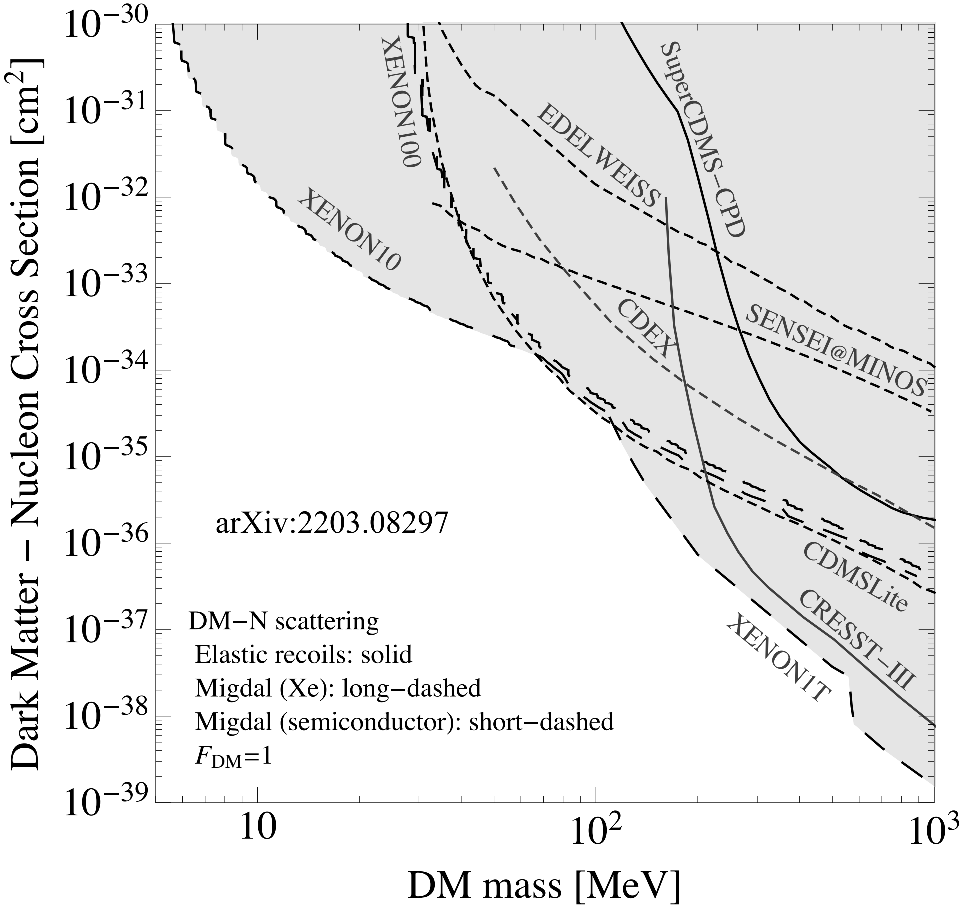
Snowmass2021 Cosmic Frontier: The landscape of low-threshold dark matter direct detection in the next decade, arXiv:2203.08297



Observable energy for Migdal interactions induced by 0.5 GeV dark matter in liquid xenon, *Ibe, et al, JHEP, 03 (2018), 194*

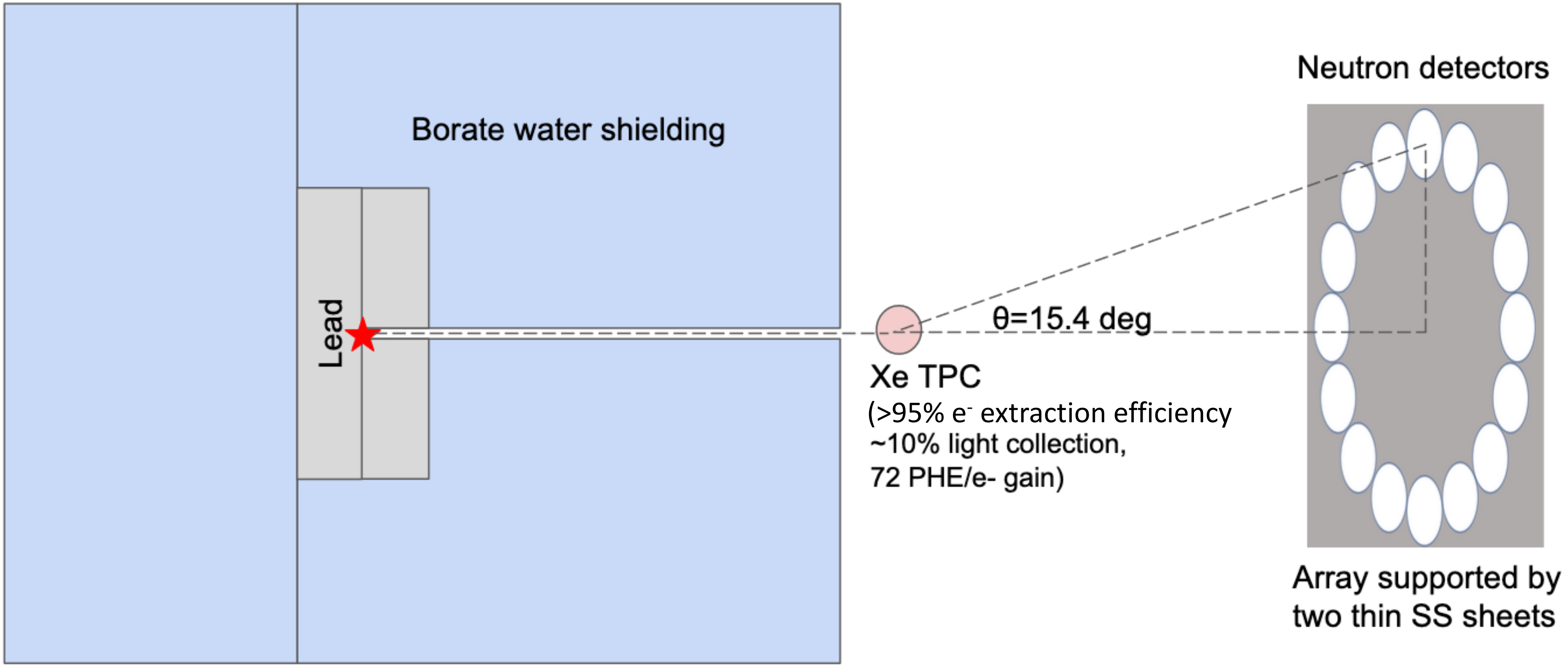
Newfound sensitivity in existing experiments

- Potential enhancement of low-mass dark matter sensitivity has been explored
  - *LUX, PRL 122 131301 (2019)*
  - *XENON1T, PRL 123, 241803 (2019), PRD.106.022001 (2022)*
  - *DarkSide50, PRL 130, 101001 (2023)*
  - *EDELWEISS, PRD 106, 062004 (2022)*
  - *CDEX-1B, PRL 123.161301 (2019)*
  - *SuperCDMS, PRD 107, 112013 (2023)*
  - and more …
- The Migdal effect has not been experimentally verified



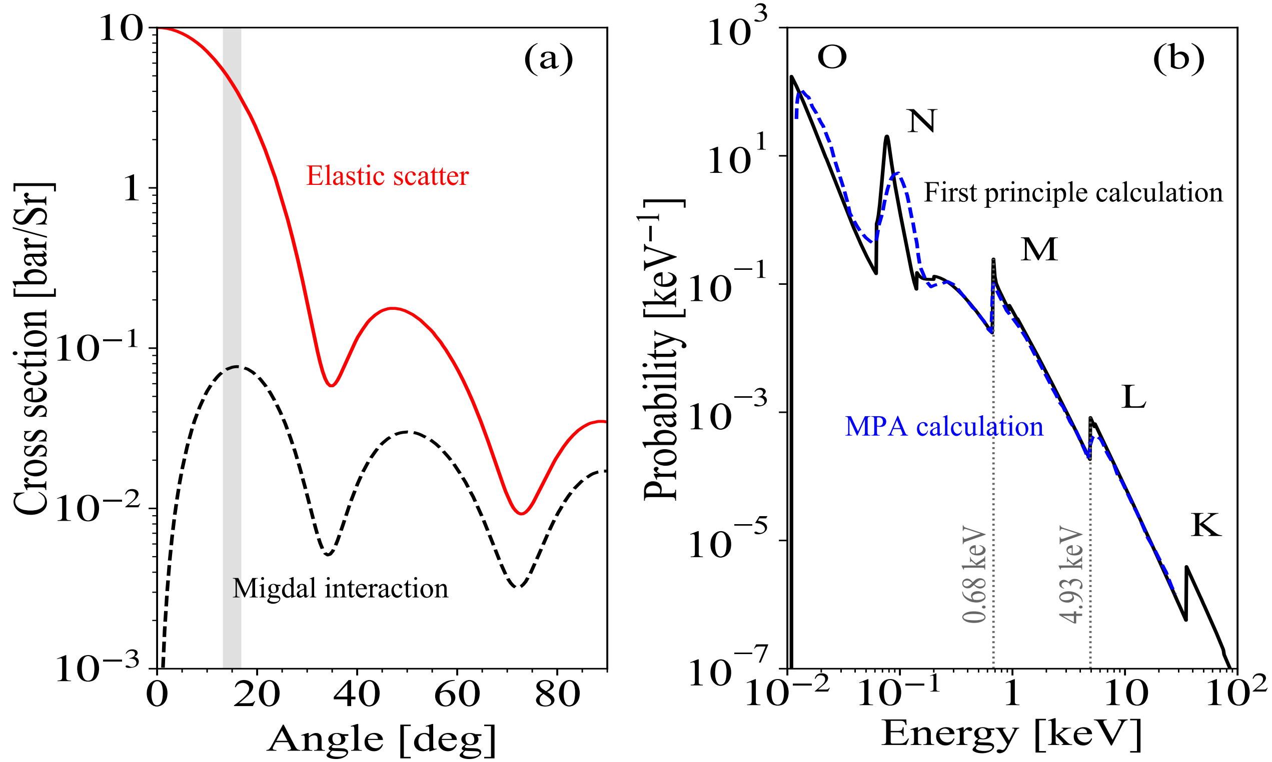
Measuring Migdal with 14.1MeV neutrons

- **High energy neutrons (14.1 MeV):** enhance Migdal cross section, reduce neutron multi-scatter (NMS)
- **Tag scattered neutrons:** obtain interaction time, reduce background with neutron time of flight (TOF)
- **Quasi-mono-energetic NR:** reduce signal rate uncertainties from nuclear cross section and efficiency
- **Low scatter angle:** reduce NR energy, separate Migdal events from pure NRs



Neutron-induced Migdal interactions in xenon

- Migdal cross section follows that of elastic scatters with an additional $E_n(1\text{-}\cos\boldsymbol{\theta})$ dependence
- Migdal signals accompanying low-energy NRs will appear different from pure NRs

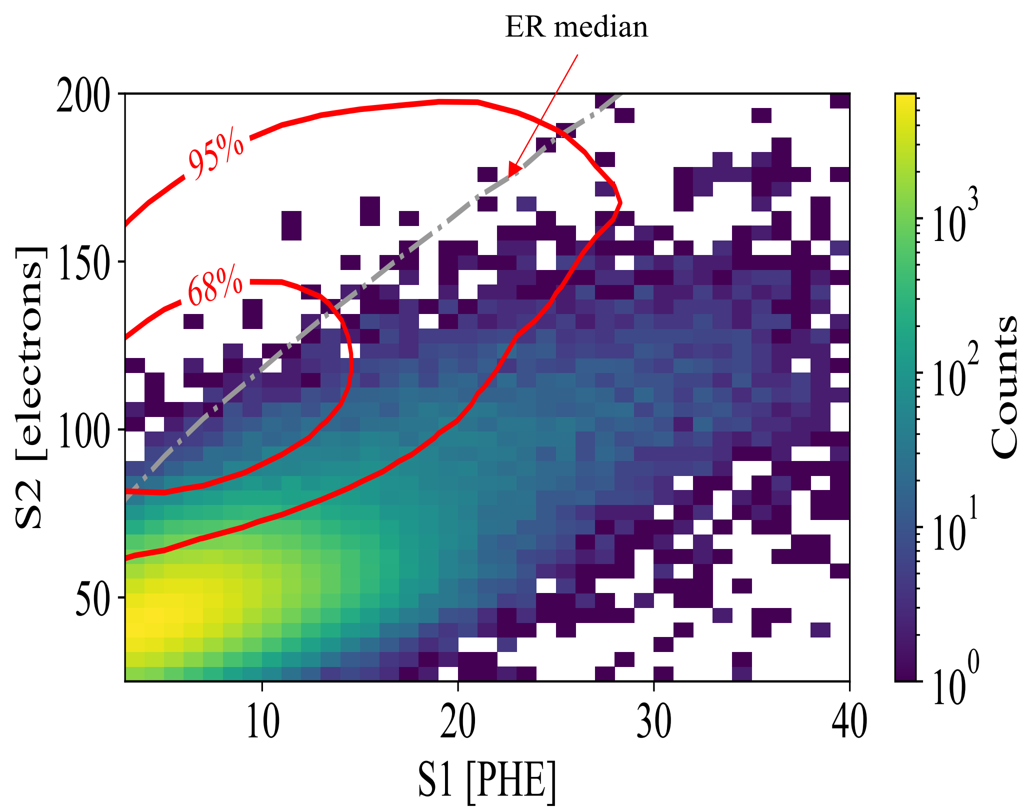


Calculated cross section (left) and energy spectrum (right, two methods tested) for Migdal interactions of 14MeV neutron with xenon

Experimental setup at LLNL

M-shell (0.5—3keV) Migdal search

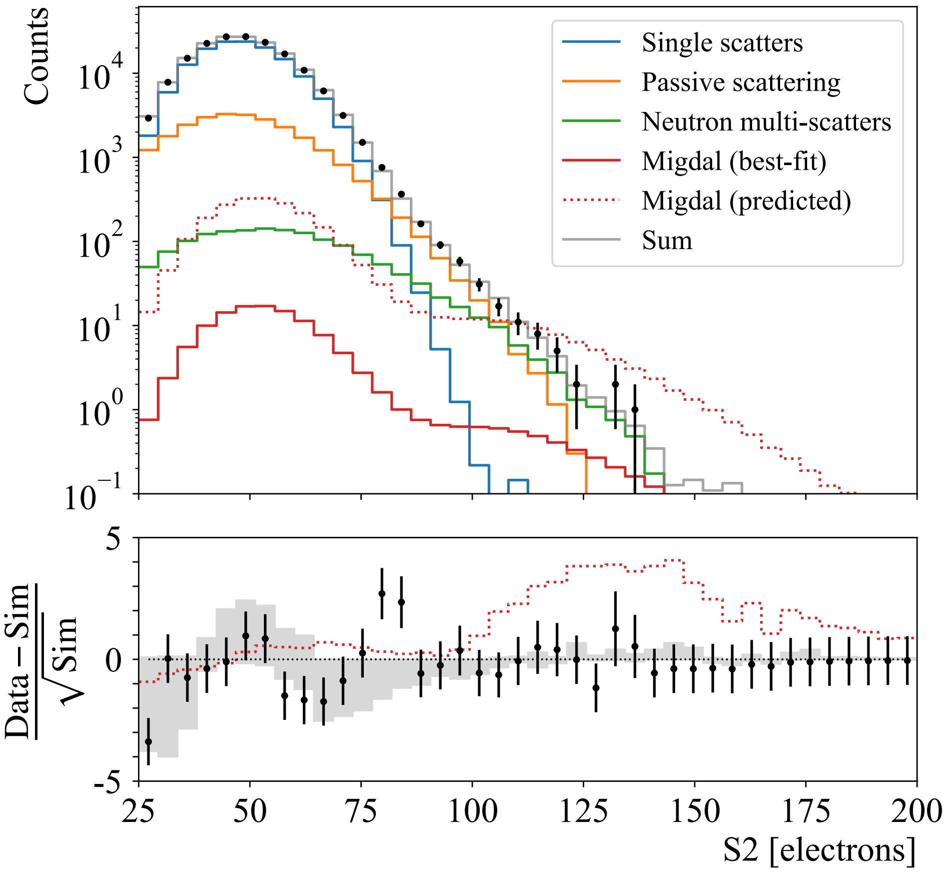
- ~300,000 NRs at 7+/-1.5keV
  - ~5 PHE for S1
  - ~45 e- for S2
- ~4000 Migdal events expected
  - ~200 M-shell interactions
  - 0—20 additional photons, or up to 2 extra PHE
  - ~50 additional electrons
- Electron recoil background is relatively small
- Backgrounds from NMS at high S1-S2 values



Data set used for the M-shell Migdal interaction (E_{ER}>0.5keV) search

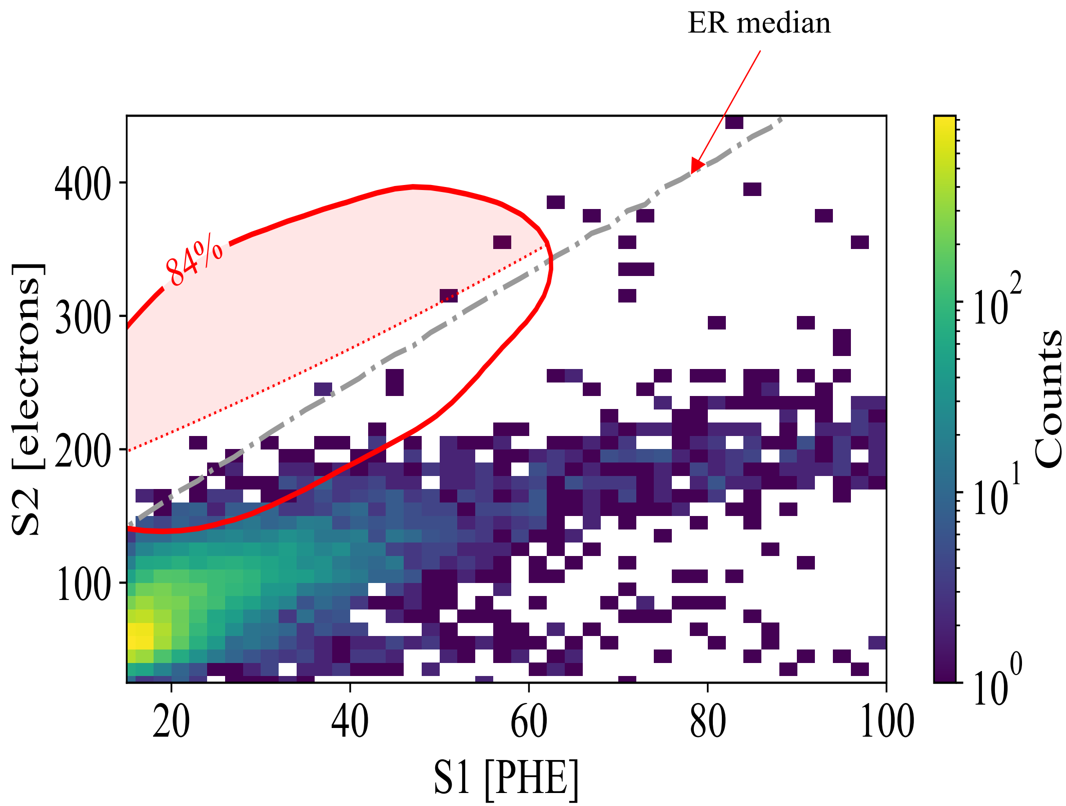
M-shell search result

- 2D (S1-S2) likelihood fit w/ constructed signal and background models
- NMS background rates are constrained by high-S1 data (few Migdal events expected)
- ~10 times fewer Migdal events estimated by fit than prediction, statistically consistent with 0 signals
- Result is robust against fit range choice (including main NR peak or excluding it)
  - Analysis is relatively insensitive to slight mismodeling of NR shape
  - Mostly from large expected separation of Migdal parameter space from NRs



L-shell (>3keV) Migdal search

- ~410k NRs for L-shell search
  - Larger S1 signals → less stringent S1 cleanliness cut → increased event statistics
- Signal ROI defined as within 84% contour (E_{ER}>3keV) and above signal median
  - Well separated from NR population
- 5.7+/-1.2 signals expected
- 2 events observed
- 2.1+/0.9 backgrounds expected



Data set used for the L-shell Migdal interaction (E_{ER}>0.5keV) search

Re-examine the Migdal rate calculation

Measures have been taken to mitigate theoretical uncertainties in this measurement

Nuclear physics term, mostly canceled out by evaluating Migdal rate as a ratio to that of NR

Quasi-monoenergetic NRs used, E_r~const

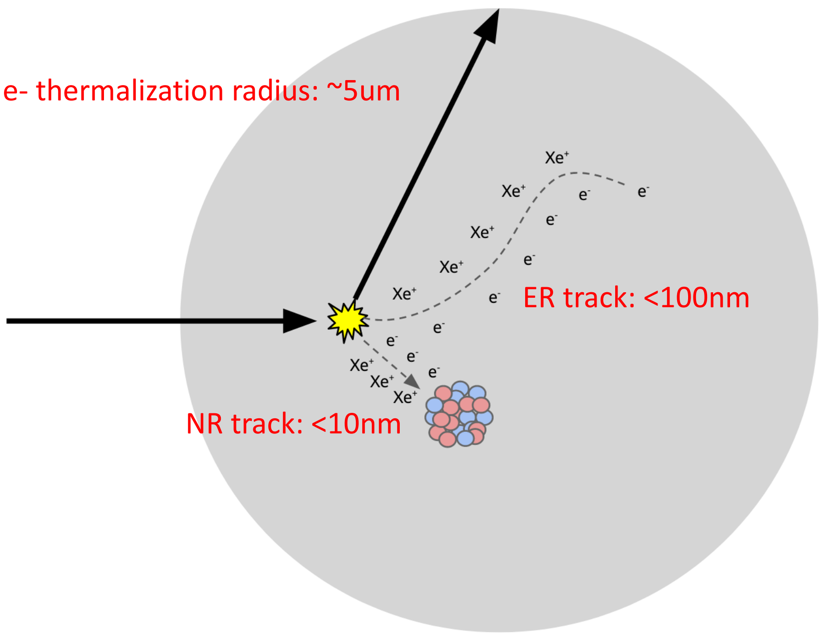
$$\frac{d^2R_M}{dE_r d\omega} = \frac{dR_{el}}{dE_r} \times q^2 \frac{d\tilde{P}_e}{d\omega}$$

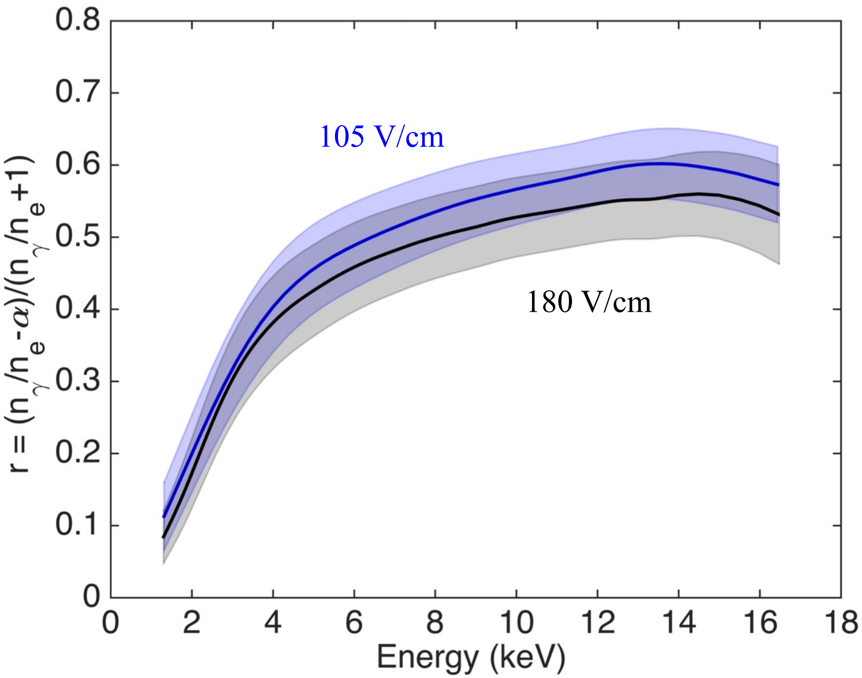
High neutron energy, low Migdal energy, soft limit condition met

Atomic physics term, good agreement between 1st principle calculation and photo-absorption data

What about the experiment: enhanced recombination?

- Electrons and ions produced by the NR track and ER track overlap in space
- Recombination can be enhanced relative to that of NR or ER





Recombination probability for low-energy 3H decay events in liquid xenon measured by LUX, PRD 93, 072009 (2016)

Summary

- The Migdal effect can substantially improve the sensitivity of existing experiments to low-mass dark matter interactions
- Tagged scatters of neutrons with liquid xenon is a promising approach to search for the Migdal effect directly
- We carried out a direct search for the Migdal effect in liquid xenon and achieved a lower background rate than the expected signal rate
- Analysis of experimental data suggests that we do not observe events at the predicted rate in our expected signal region
- Xenon recombination physics may explain the null result
- If enhance recombination is the correct explanation, low-mass dark matter searches could still benefit from the Migdal effect (negligible NR component)
- Additional experimental efforts are being planned to more definitively test the Migdal effect predictions

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