Updates on the Migdal effect and hydrogen doping for dark matter detection

CETUP* Workshop
Institute for Underground Science
at SURF, South Dakota
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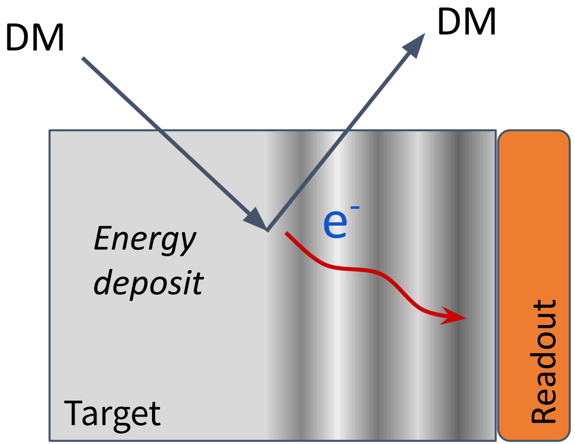
THE UNIVERSITY OF MELBOURNE

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Direct detection fundamentals

- Look for signals of dark matter from the galactic halo scattering off nuclei or electrons in a detector
- Kinetic energy of recoil deposited as:
  - Scintillation
  - Ionization
  - Phonons
- Ths is read out via PMT's, current, TES, imaging…



The Migdal effect allows us to probe lighter dark matter, which would otherwise fall below threshold

Elastic dark matter-nucleus scattering

Differential rate:

Nuclear physics

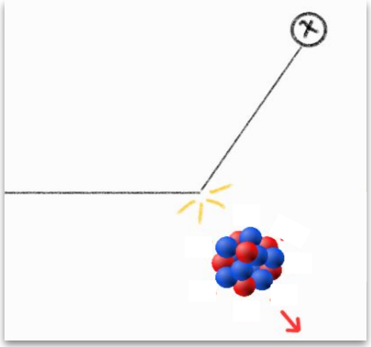
Particle physics

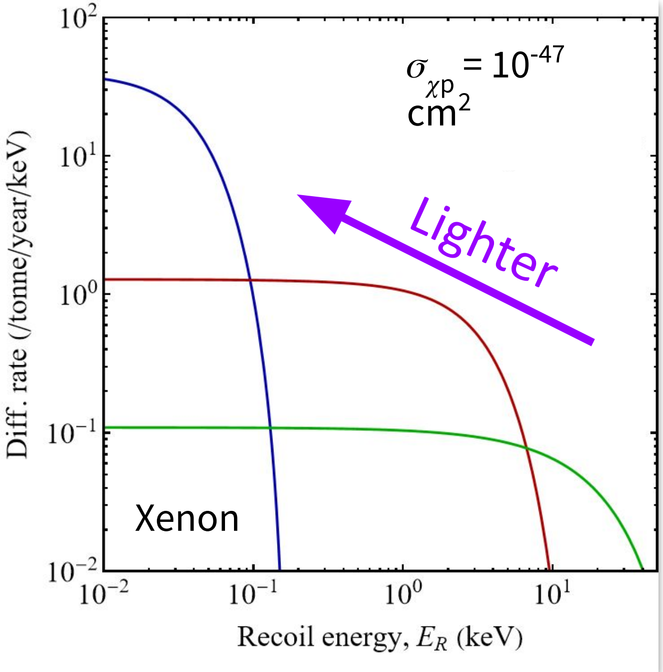
Astrophysics

Where:

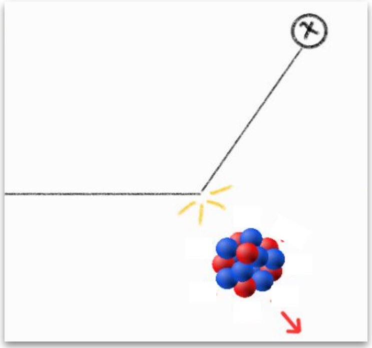
$$v_{\min} = \sqrt{\frac{E_R m_T}{2\mu_{\chi T}^2}}$$

$$E_{R_{\max}} = \frac{2\mu_T^2}{m_T} v_{\max}^2$$



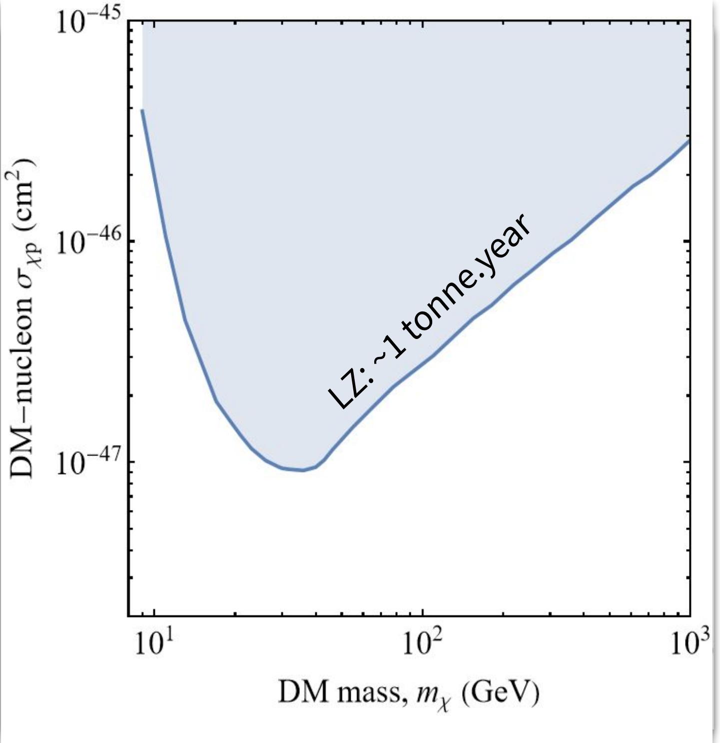


Direct detection's kinematic problem



$$E_{R_{\max}} \approx \frac{m_\chi^2}{m_T} \times 10^{-5}$$

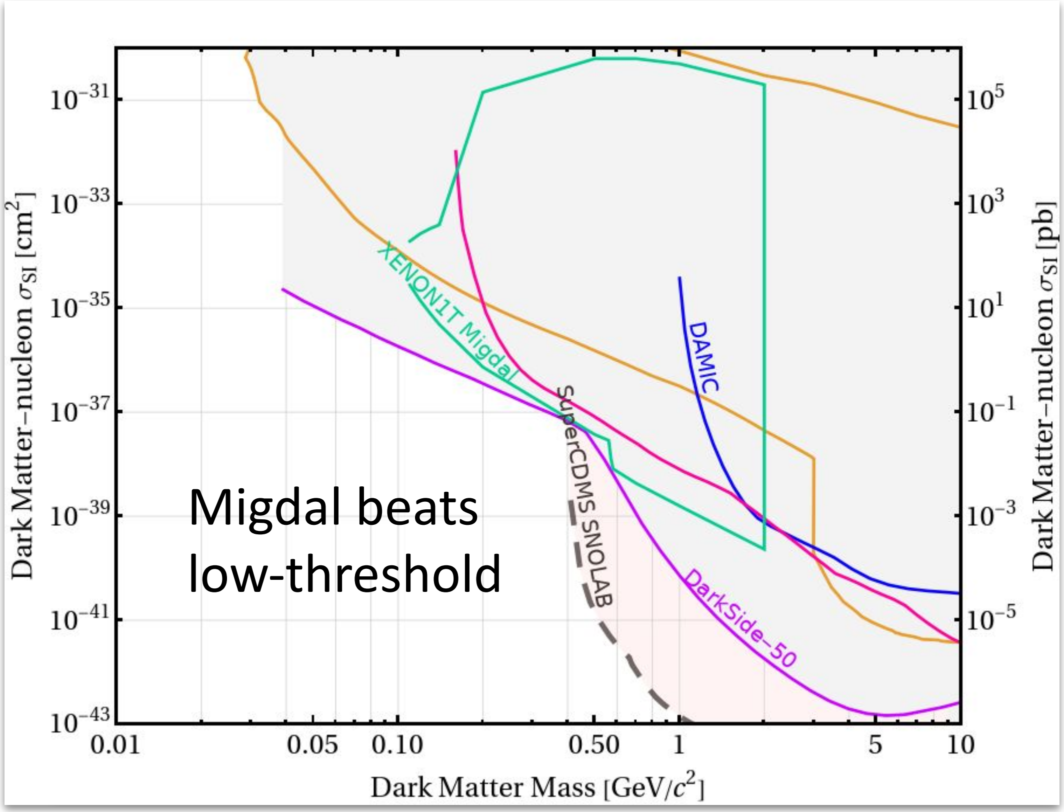
$$E_{EM_{\max}} \approx m_\chi \times 10^{-5}$$



→ Light dark matter does not pack much of a punch

*assuming v_{max}= 800 km/s

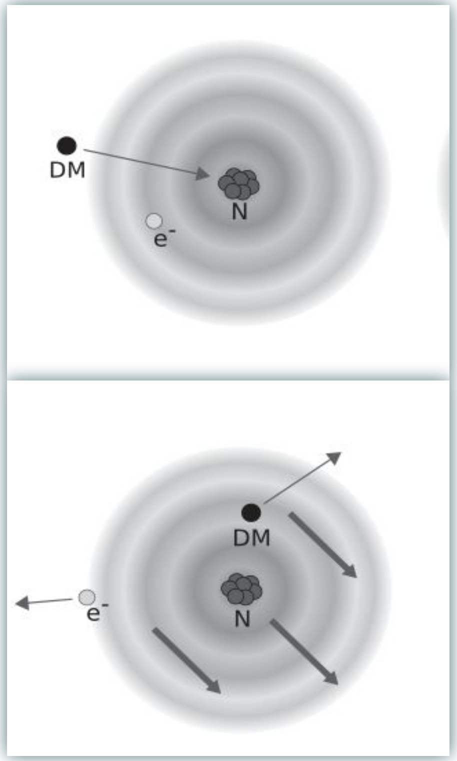
The future of direct detection



The Migdal Effect

- The Migdal effect is atomic ionization or excitation due to a nuclear recoil

- 'Electron shakeoff' has been observed during nuclear decay, but not due to scattering (see for example: *Couratin et al.* *Phys. Rev. Lett.* ***108*** *(2012)*)
  → **Agreement with theory is mixed**

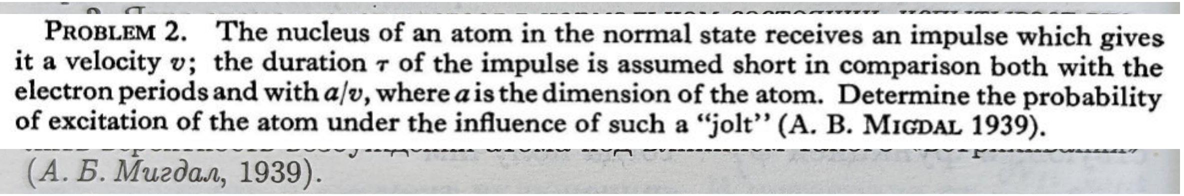


Credit: Dolan et al. PRL 2017

A brief history of the Migdal effect

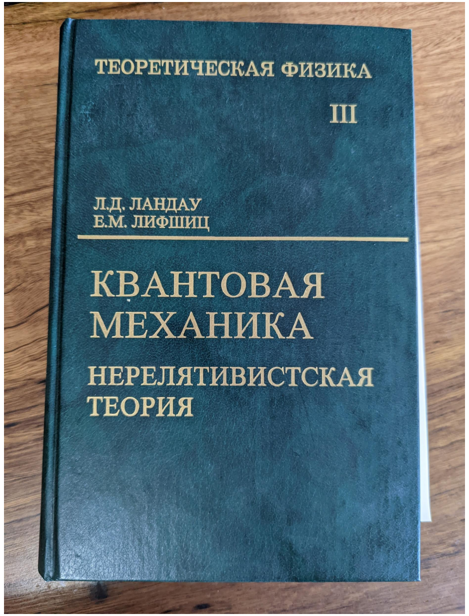
1939: A.B. Migdal, J. Phys. USSR 4 449

1958: Landau and Lifshitz Vol. 3: Quantum Mechanics, sec. 41:



PROBLEM 2. The nucleus of an atom in the normal state receives an impulse which gives it a velocity v; the duration τ of the impulse is assumed short in comparison both with the electron periods and with a/v, where a is the dimension of the atom. Determine the probability of excitation of the atom under the influence of such a "jolt" (A. B. MIGDAL 1939).

(*А. Б. Мигдал*, 1939).



2005: First application to DM detection:
J.D. Vergados and H. Ejiri, Phys. Lett. B 606, 313, arXiv:[*hep-ph/0401151*]

2018: First detailed atomic calculations for DM:
M. Ibe, W. Nakano, Y. Shoji and K. Suzuki, JHEP 1803 (2018) 194 *arXiv:1707.07258*

2018: First experimental constraints:
M. Dolan, F. Kahlhoefer and C. McCabe Phys. Rev. Lett. 121 (2018) *arXiv:1711.09906*

Ionization probabilities

What goes into the rate calculation?

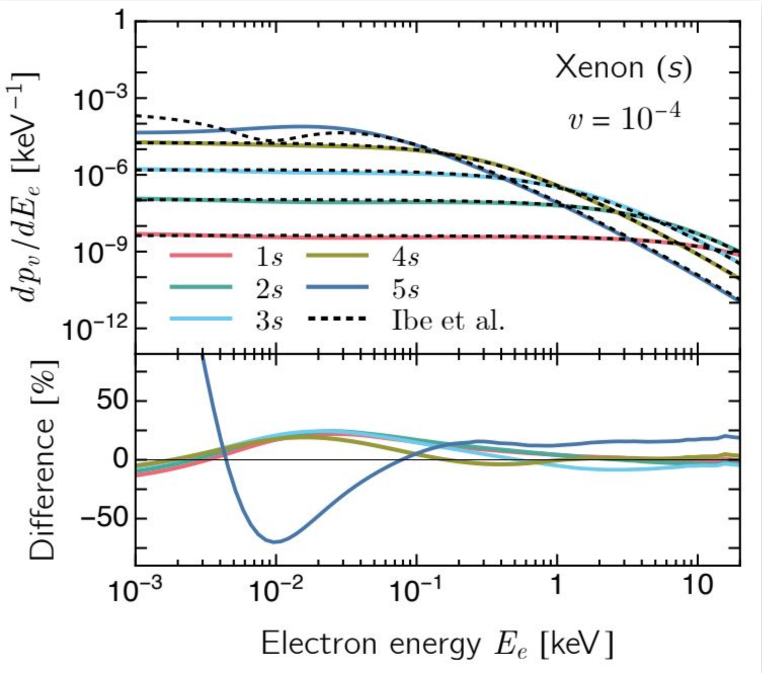
$$\frac{d^2R}{dE_{\rm NR}dE_i} = \frac{d^2R_{iT}}{dE_{\rm NR}dE_i} \times |Z_{\rm ion}|^2$$

$$|Z_{\rm ion}|^2 = \frac{1}{2\pi}\sum_{n,\ell}\int dE_e \frac{d}{dE_e} p^c_{q_e}(n\ell \to (E_e))$$

Ionization prob.

Relevant matrix elements obtained by boosting the electronic wavefunction:

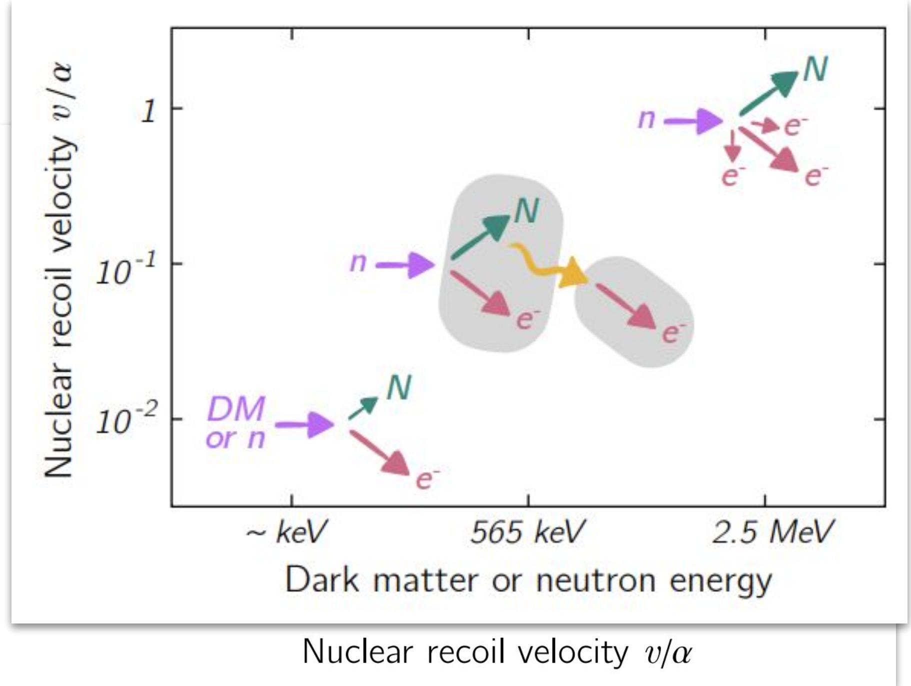
$$\left\langle \Psi_f \middle| \exp\left(im_e\boldsymbol{v}\cdot\sum_{k=1}^{N}\boldsymbol{r}_k\right) \middle| \Psi_i \right\rangle$$



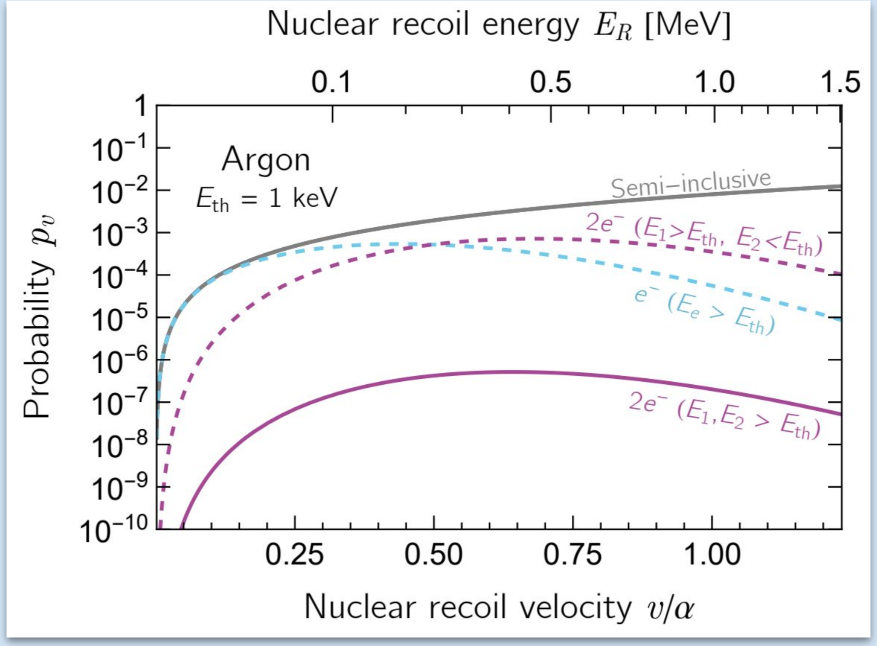
Cox et al. Phys.Rev.D 107 (2023)
[*arXiv:2208.12222*]

Ionization probabilities cont.

i) Dipole approx is fine for DM, but



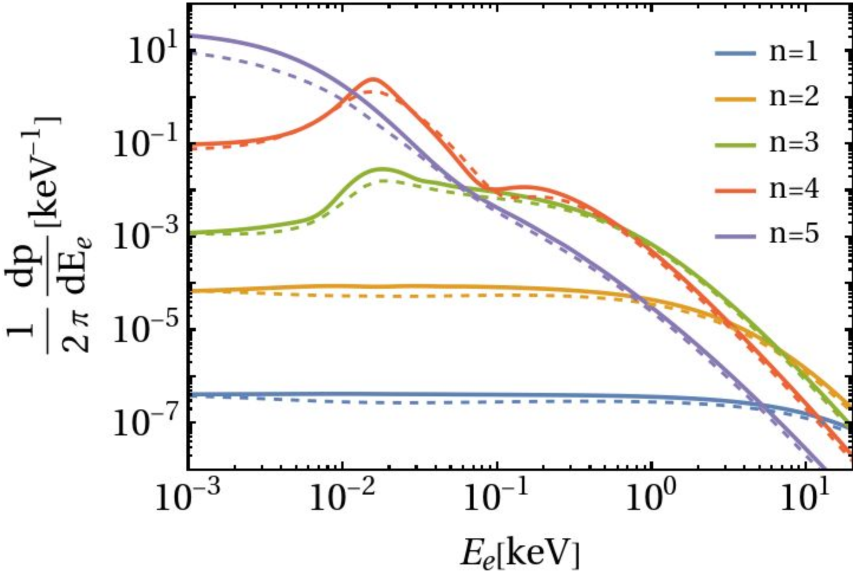
ii) Multi-electron Migdal

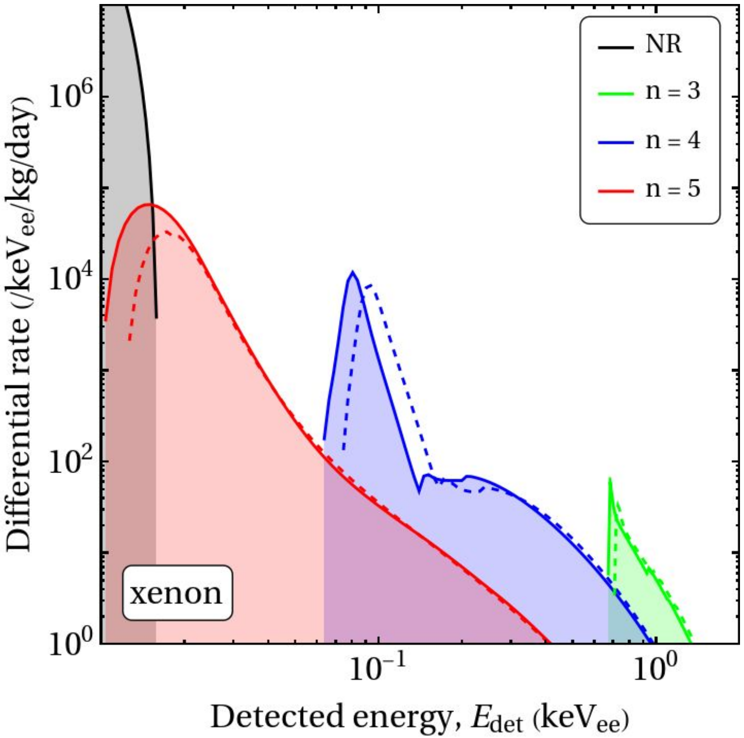


Cox et al. Phys.Rev.D 107 (2023) [*arXiv:2208.12222*]

Ionization probabilities: Cox (dashed) vs. Ibe/dipole (solid)

Difference mostly from shifted ionization energies



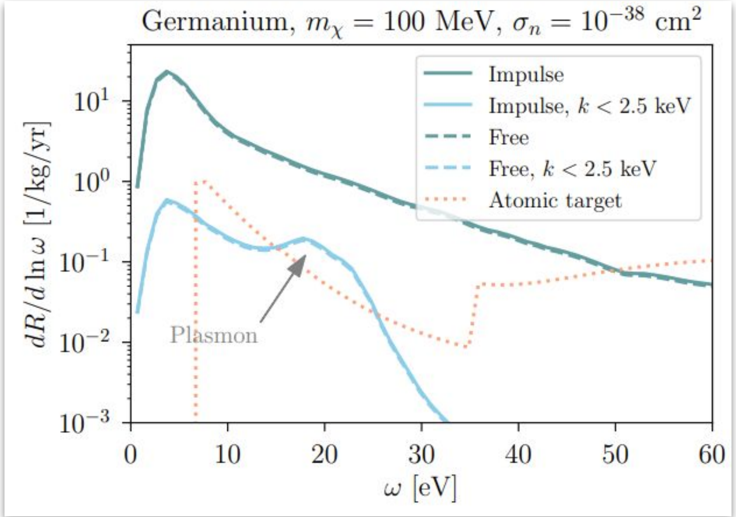


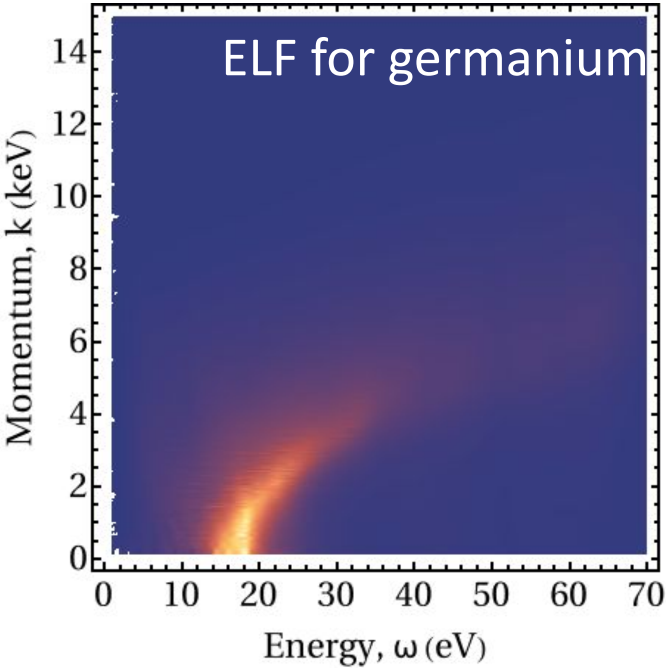
Ionization probabilities in semiconductors

When the atom is not isolated things are more complicated:

Energy loss function

$$\frac{dP}{d\omega} = 4\alpha \int \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{Z_{\rm ion}^2(k)}{k^2} \mathrm{Im}\left[-\epsilon_{00}^{-1}(\mathbf{k},\omega)\right] \frac{|\mathbf{v}_N \cdot \mathbf{k}|^2}{\omega^4}.$$





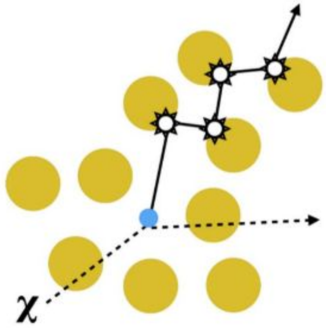
From the DarkELF package, calculated with DFT (GPAW)

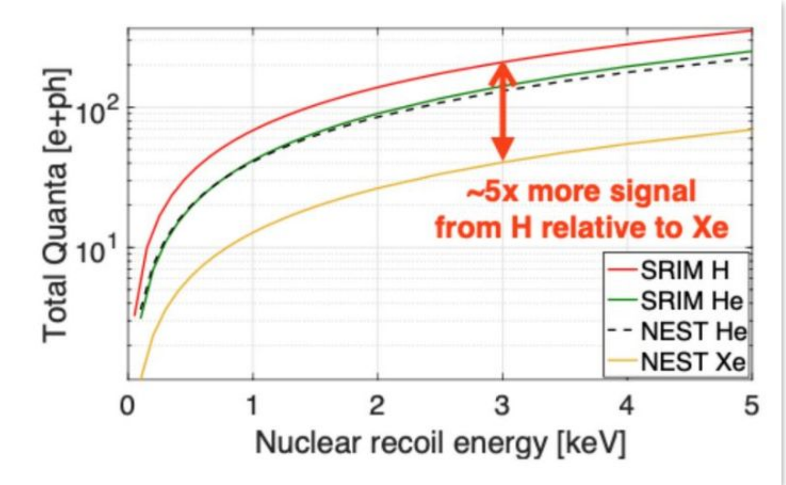
Knapen et al. Phys.Rev.Lett. (2021) arXiv:2011.09496

Hydrogen doping LXe TPCs

$$E_{R_{\max}} = \frac{2\mu_T^2}{m_T} v_{\max}^2$$

- Hydrogen detector not feasible
- Can we add H_2 to LXe?

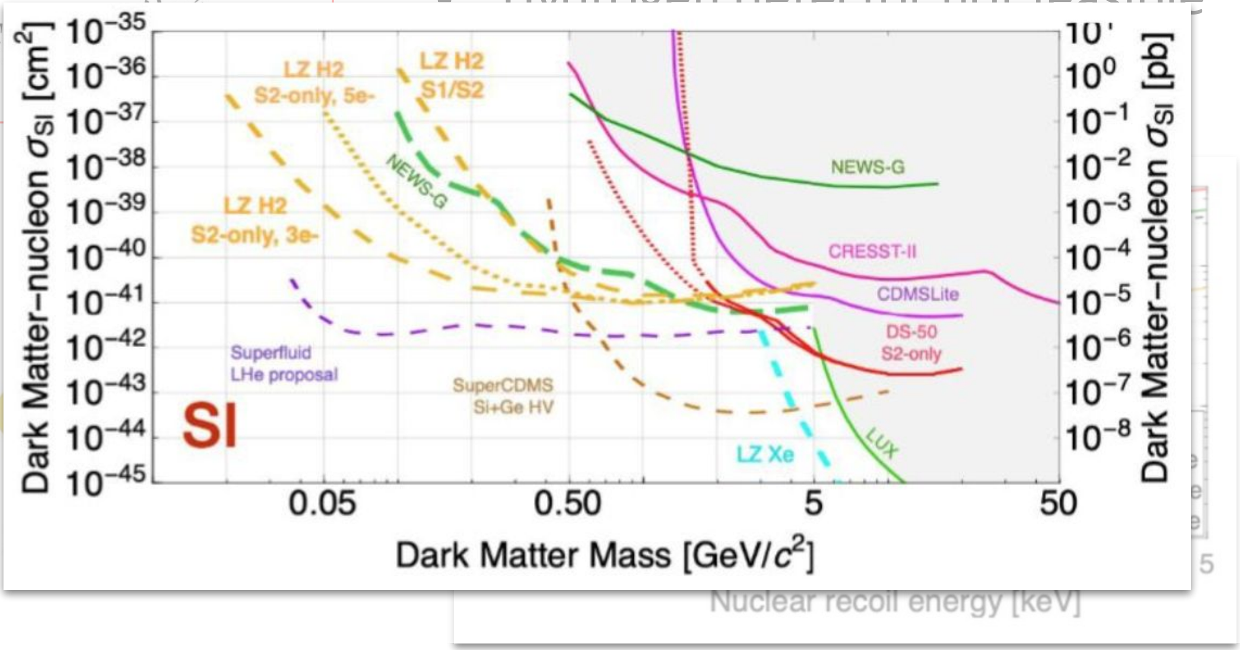




From [*talk by Drew Ames, SLAC, CPAD workshop 2023*]

Hydrogen doping LXe TPCs

- Hydrogen detector not feasible

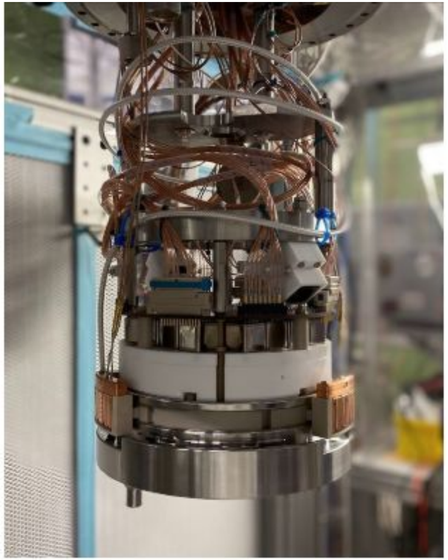


From talk by Drew Ames, SLAC, CPAD workshop 2023

Hydrogen doping LXe TPCs

Hydro-X platform at SLAC will:

- Investigate effect on S2
- Develop gas-handling system
- Test effects of H on PMTs



From talk by Drew Ames, SLAC, CPAD workshop 2023

Combining hydrogen doping with Migdal

- Projections for adding 2.5 kg of H_2 to LZ and doing S2-only search

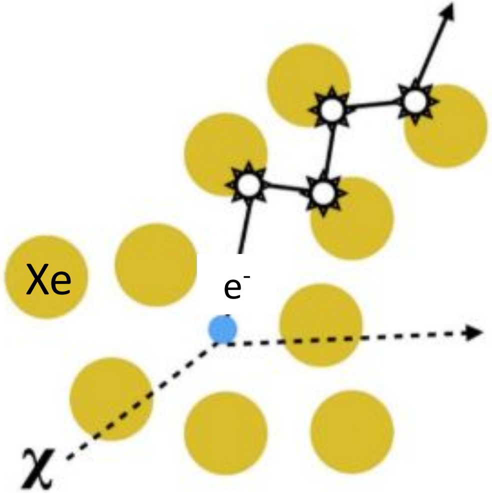
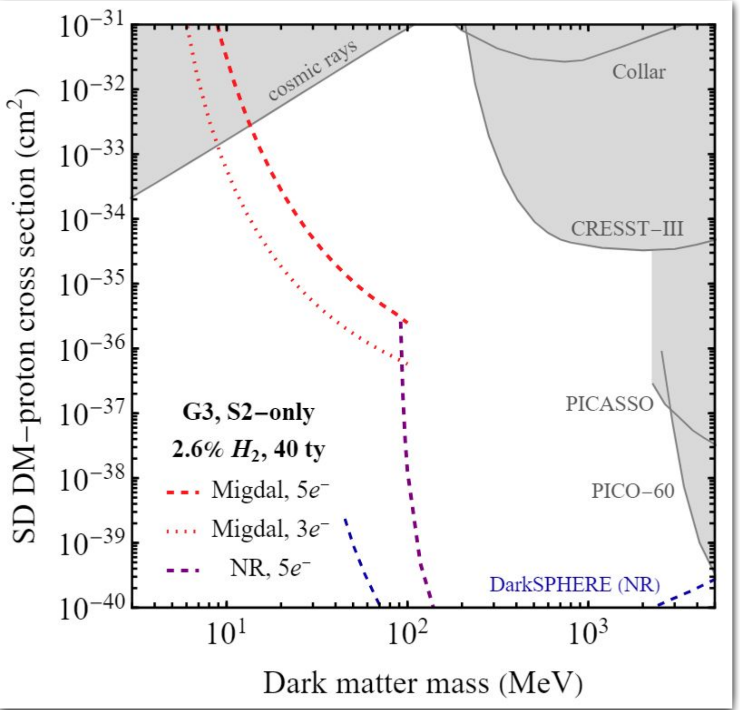
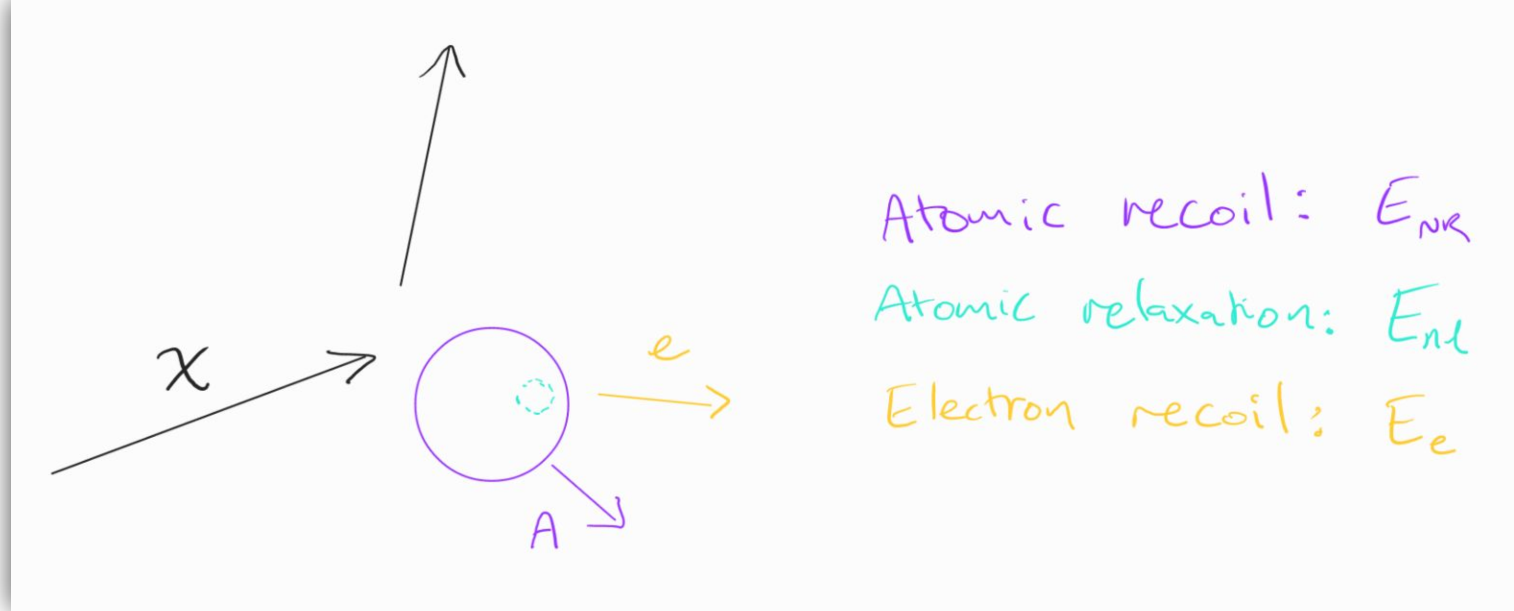


Image credit Drew Ames, SLAC



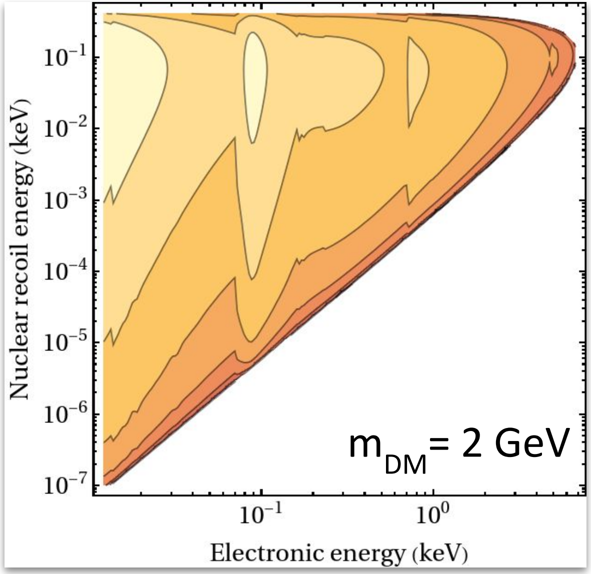
*N. Bell, P.Cox, M.Dolan, **JLN,** A.Ritter*
arXiv:2305.04690

Let's rewind:
What does a Migdal event look like?



What does a Migdal event look like?

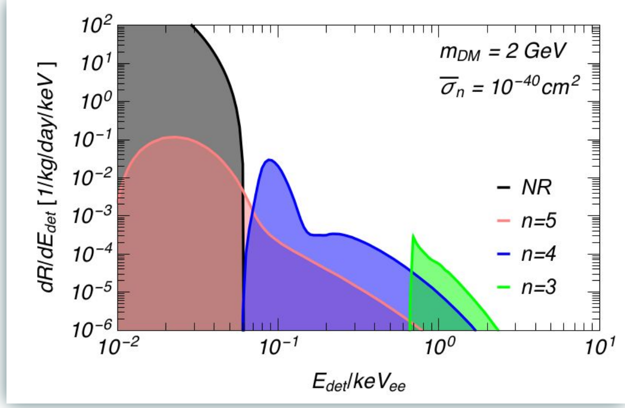
Double differential rate:



Simple:

Energy deposited w quenching:

$$E_{\text{det}} = \mathcal{L}E_R + E_e + E_{nl}$$



Hard:

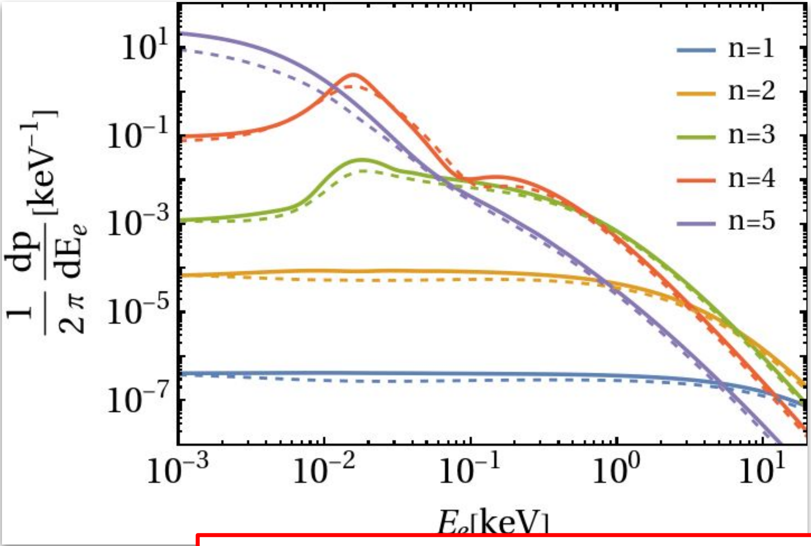
Detector modelling/calibration:

?

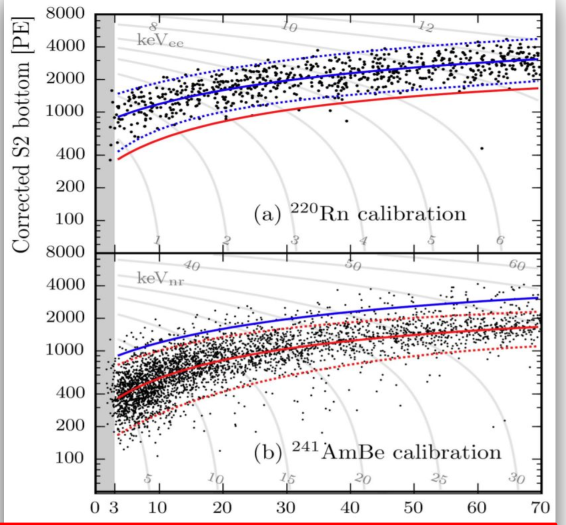
Calibrating the Migdal effect

Two distinct tasks:

1. Verify theoretical predictions of the ionization probabilities

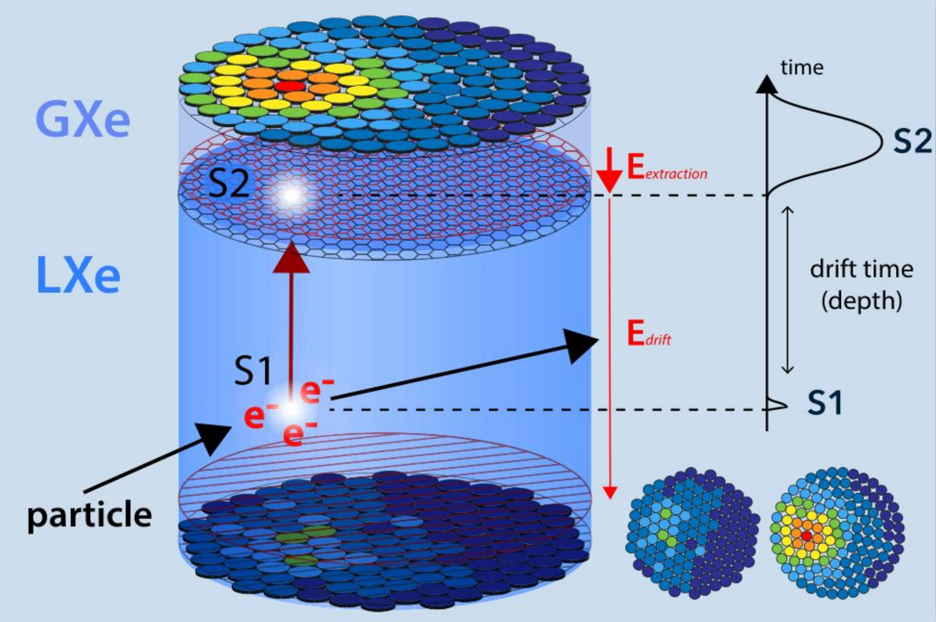


2. Calibrate the detector response to the energy depositions

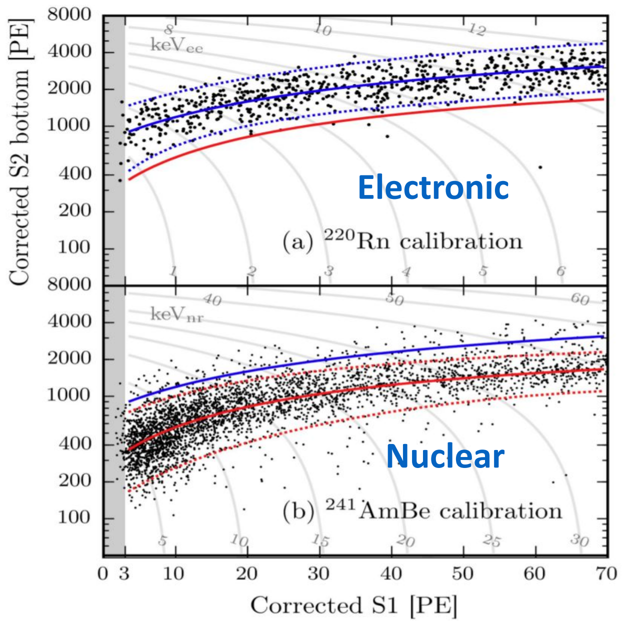


Both tasks most easily performed with neutron scattering

Experiment: Anatomy of a liquid xenon detector

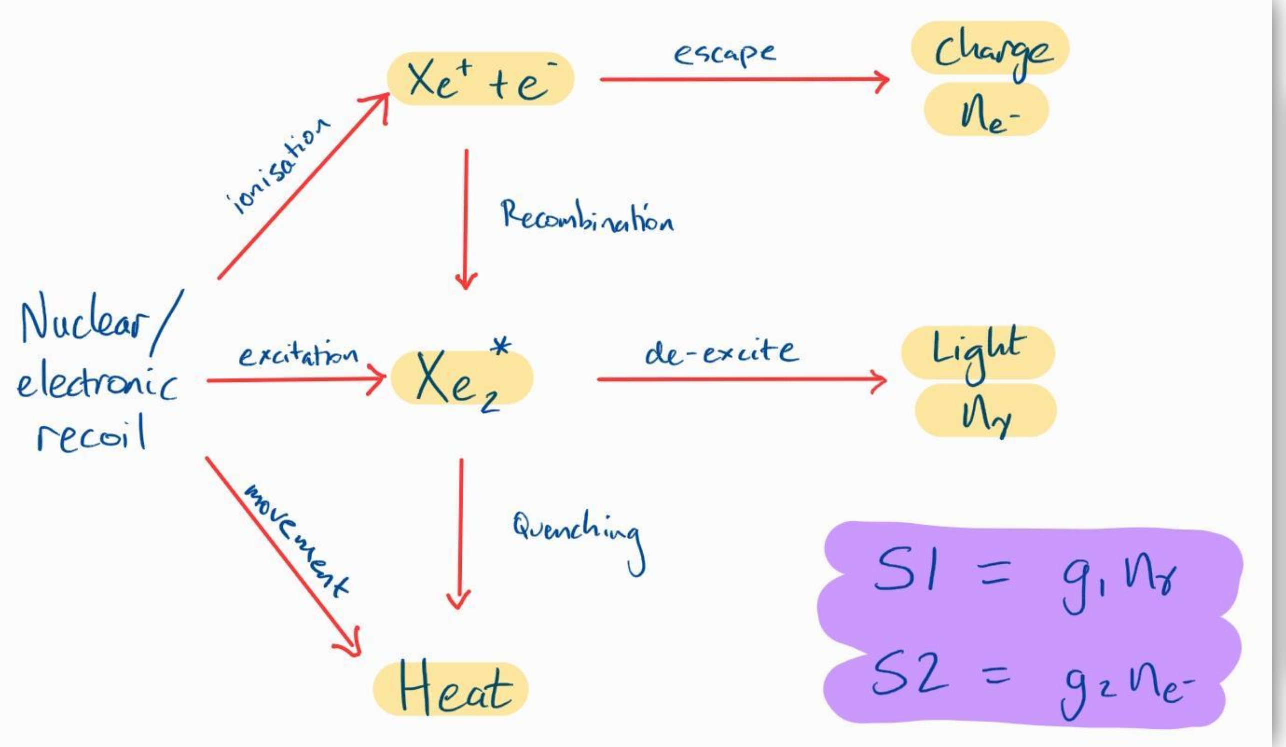


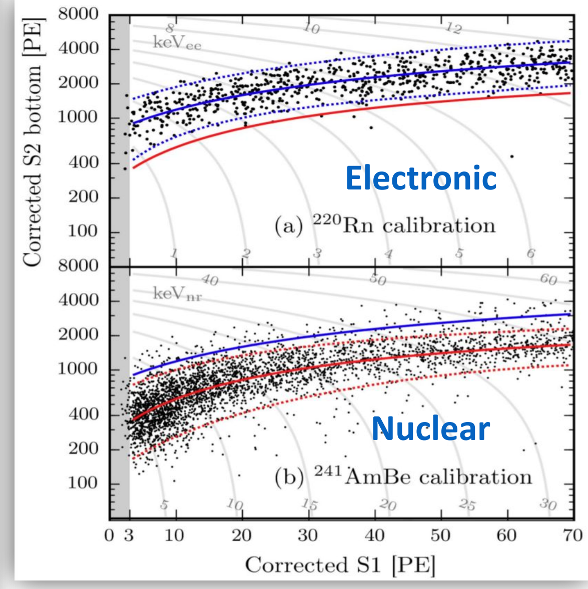
Credit: XENON1T collaboration



XENON1T Phys.Rev.Lett. 119 (2017)

Experiment: signal production

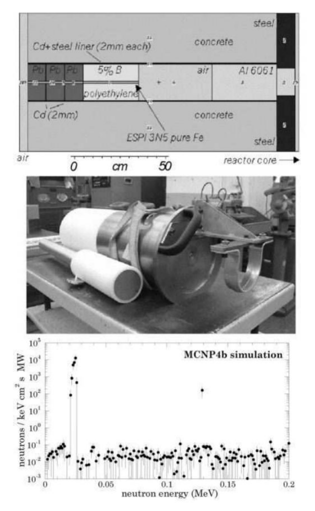




XENON1T Phys.Rev.Lett. 119 (2017)

Potential low-energy neutron sources

Nuclear reactor + filter

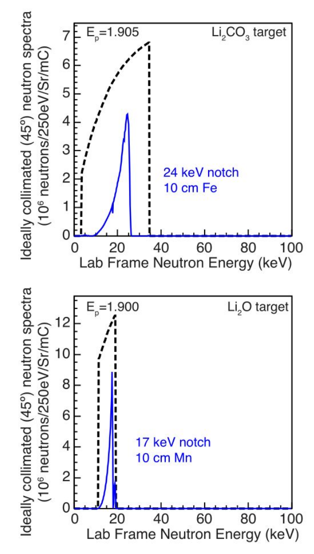


Pros:
-Large flux
-Continuous operation

Cons:
-Gamma backgrounds
-Location

Barbeau et al. arXiv:nucl-ex/0701011

Li + p near threshold + filter

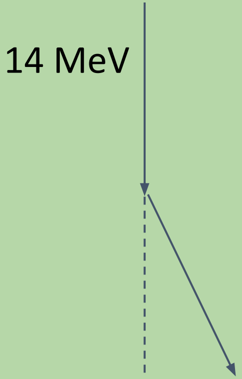


Pros:
-Pulsed beam

Cons:
-May require large/cooled targets
-Location

Joshi et al. arXiv:1403.1285

DT/DD-generator + measure recoil angle

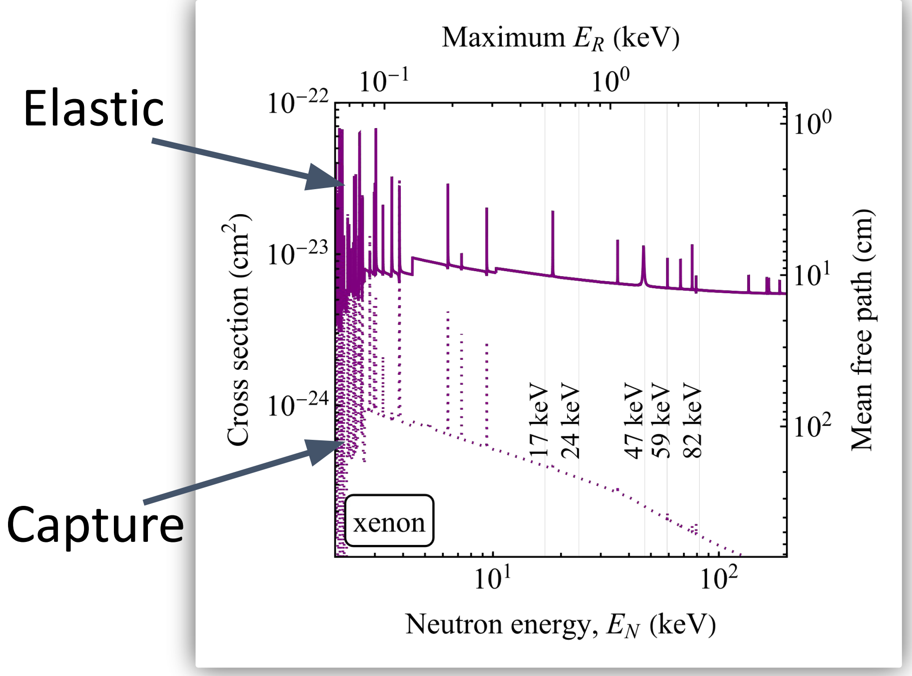


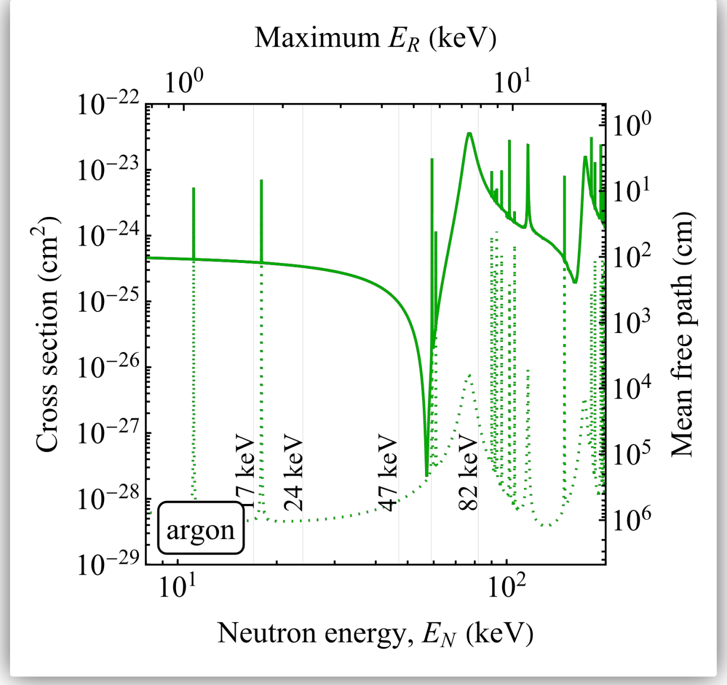
Pros:
-Potential for in situ

Cons:
-Small flux

Xu et al. arXiv:2307.12952

Low-energy neutron cross sections

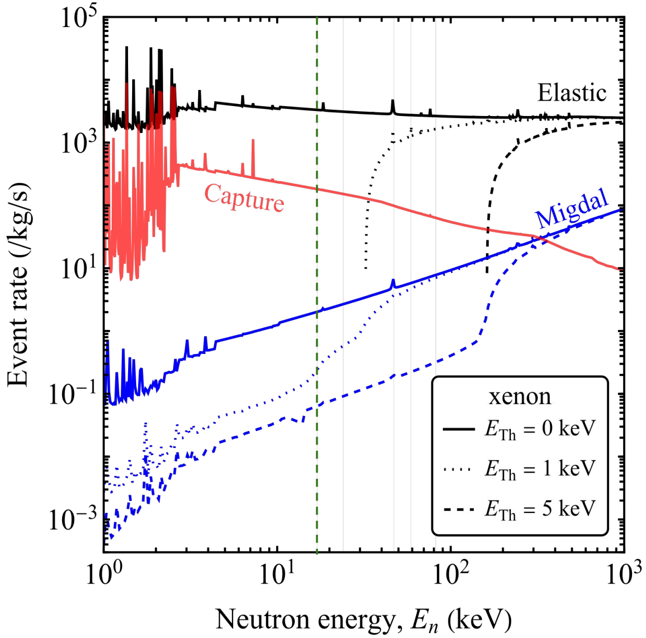




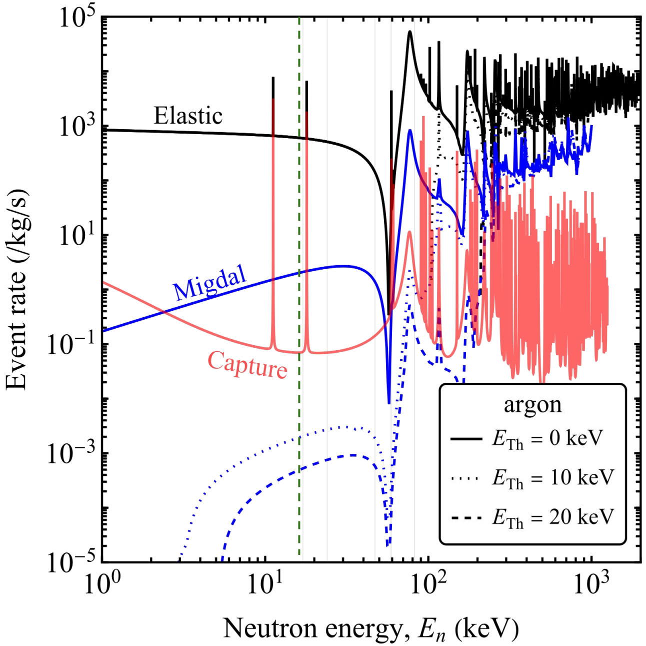
- Radiative capture of neutrons will be a significant background
- Inelastic scattering is >100 keV threshold for all but xenon-129

Low-energy neutron scattering rates

Xenon



Argon



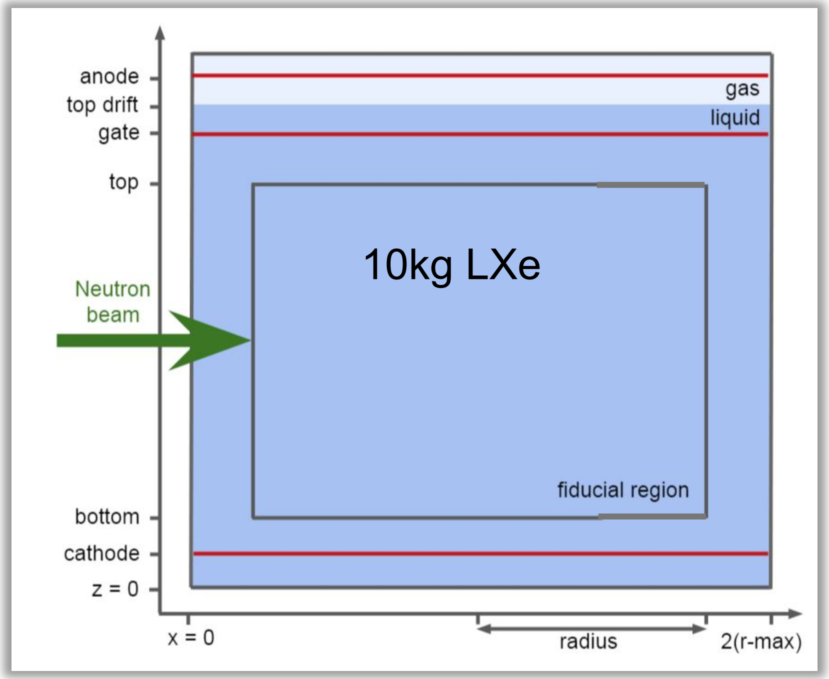
N. Bell, J. Dent, R.Lang, ***JLN***, A.Ritter [Phys.Rev.D 105 (2022)]

Simulation of LXe detector and neutron beam

Gaussian neutron beam:

FWHM = 6cm
Peak flux = 10^8 n/hr
(avg 100n/cm^2/s)

Modelled on Barbeau et al.



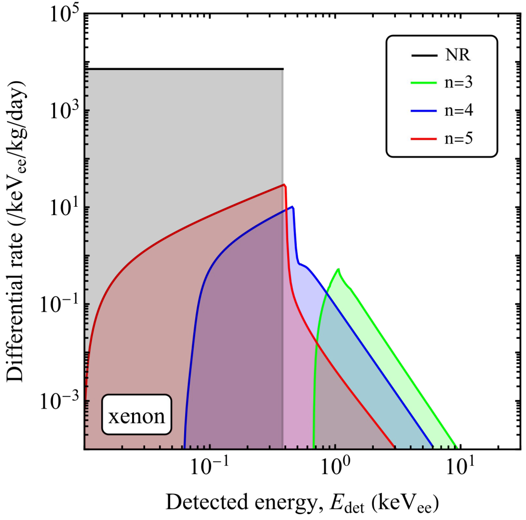
dimension	position (mm)
r_{max}	120.
radius	100.
cathode	20.0
bottom	40.0
top	160.
gate	190.
top drift	195.
anode	200.

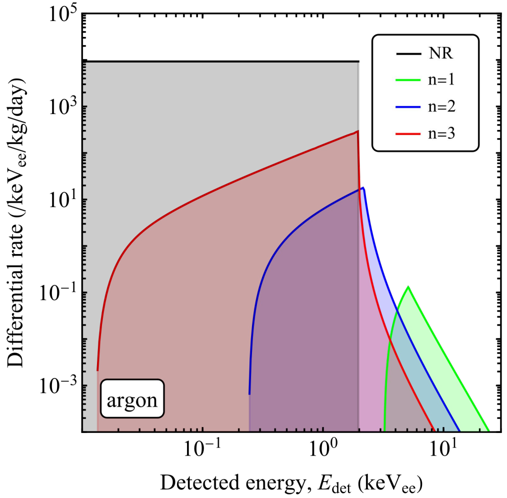
parameter	value
g_1	0.15 PE/γ
g_2	24 PE/e^-
field	300 V/cm
e^- lifetime	350.μs
min S1	2 phd
min S2	250 phd
no. PMTs	60

*N. Bell, J. Dent, R.Lang, **JLN**, A.Ritter [Phys.Rev.D 105 (2022)]*

Low-energy neutron Migdal rates

E = 82 keV neutrons, flux = 100 n/cm^2/s





Total rates:

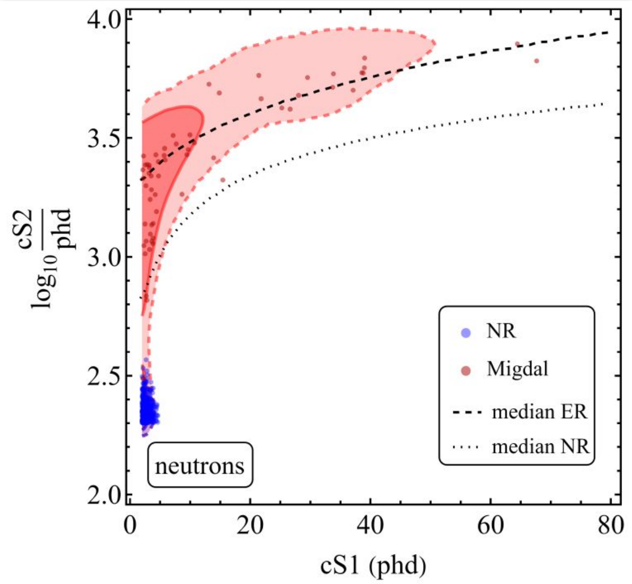
	Xenon	Argon
Nuclear:	2,700 events/kg/s	12,300 events/kg/s
Migdal:	8 events/kg/s	320 events/kg/s

N. Bell, J. Dent, R.Lang, ***JLN***, A.Ritter [Phys.Rev.D 105 (2022)]

Simulation with NEST (xenon)

Monte Carlo procedure:

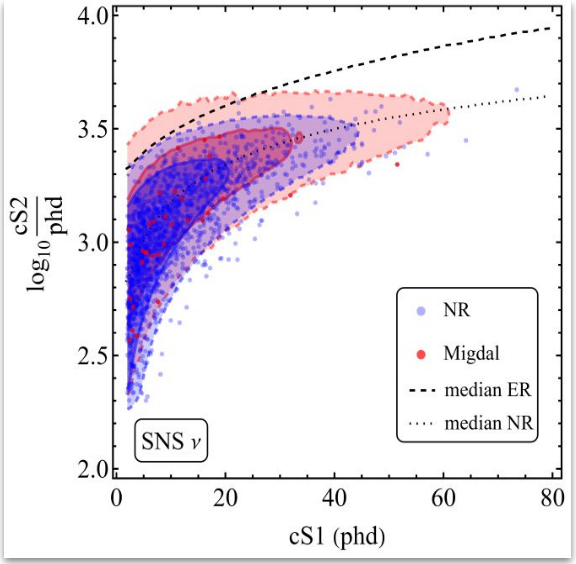
1. Random NR energy from E_R distribution, calculate max. allowed E_{EM}
2. Loop over atomic shells, E_{nl}, and randomly ionize an electron with E_e
3. Calculate the yields of ions and excitons produced by E_R, E_e and E_{nl} using models for NR, β and β respectively
4. Calculate the quanta from the summed yields and then the subsequent S1 & S2



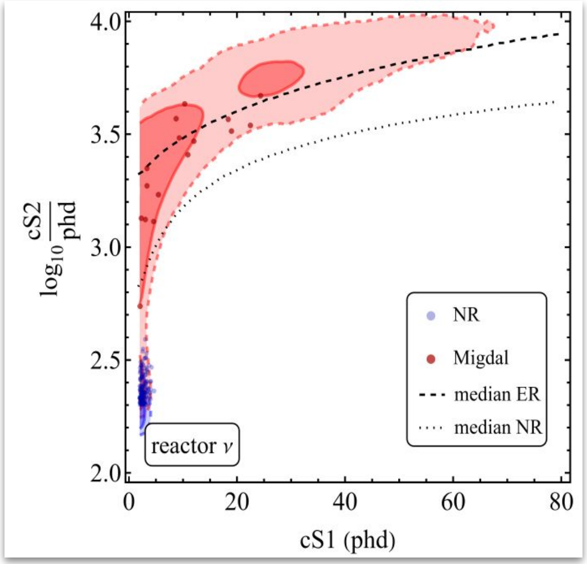
Source	Calc. ratio	Sim. ratio	Sim. rate/kg/day
neutron (17 keV)	6.0×10^{-4}	0.1	600

Brief aside: what about neutrino sources?

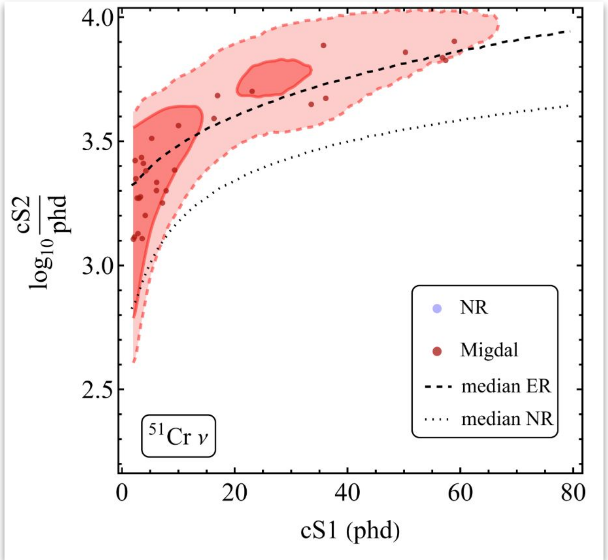
piDAR neutrinos:



Reactor neutrinos:



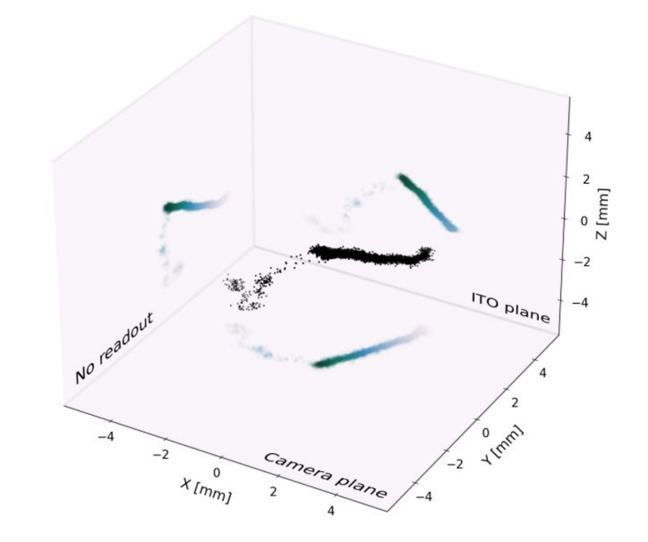
Radio-isotope:



- Poor separation
- Require large exposures

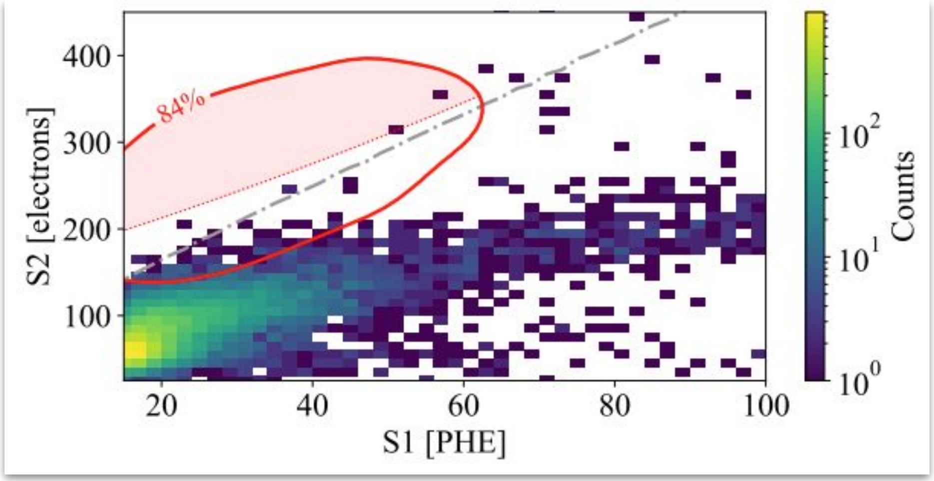
Current experimental calibration efforts

1. Verify theoretical predictions:
   The MIGDAL experiment



Araújo et al. Astropart. Phys. (2023) [arXiv:2207.08284]

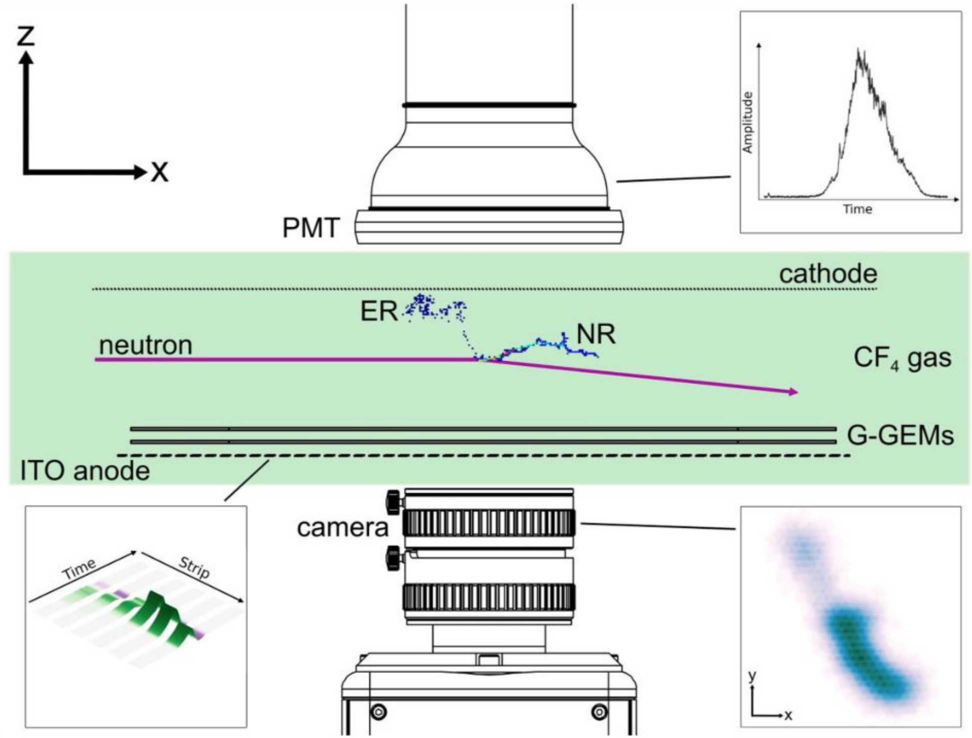
2. Detector response



Xu et al. [arXiv:2307.12952]

1. Verify theoretical predictions: The MIGDAL experiment

- 'High' energy neutron recoils (DD, DT)
- Low-pressure CF_4 gas
- Aim to observe a Migdal event topology
- Setup is operational at RAL

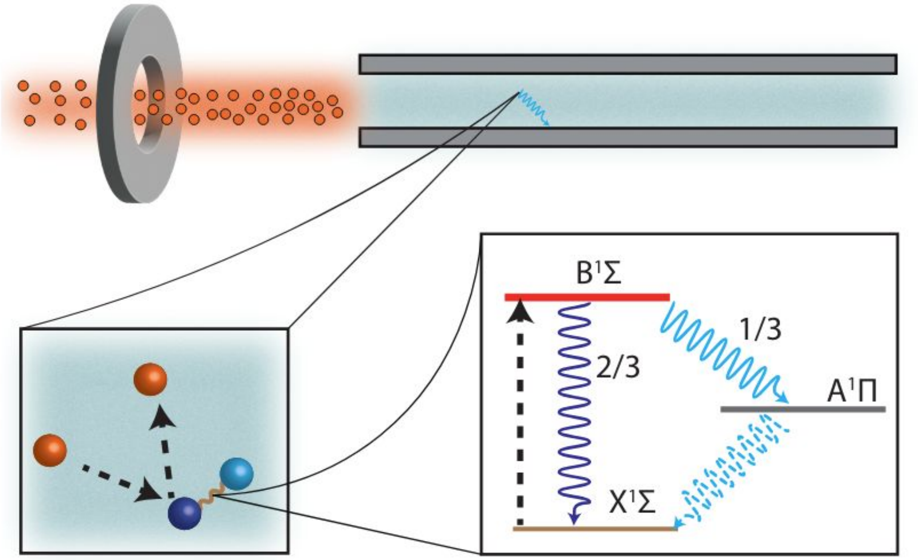


Xu et al. [arXiv:2307.12952](https://arxiv.org/abs/2307.12952)

1. Verify theoretical predictions: Molecular Migdal

- Spallation neutron source (flux~$10^8/cm^2/s$)
- Low-pressure CO gas
- Aim to observe a Migdal excitation
- Can have 5 sigma within hours

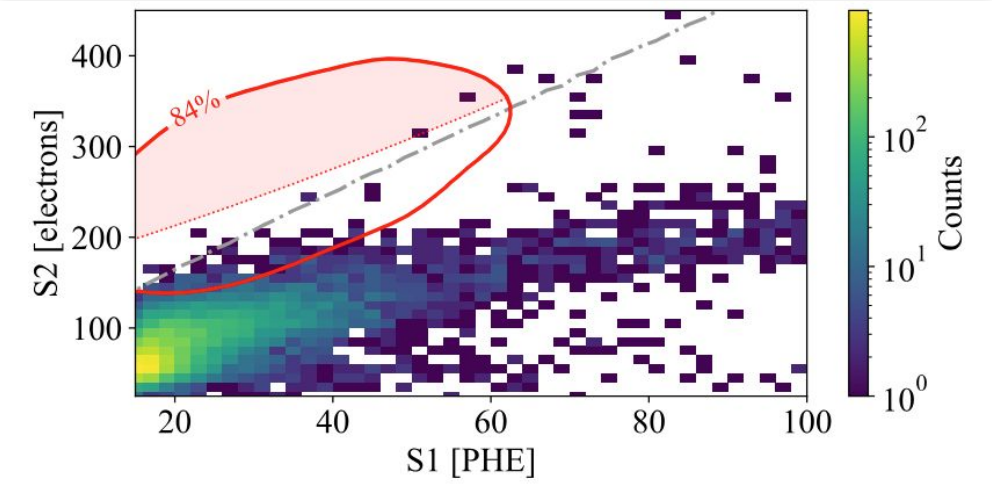
Proposed setup:

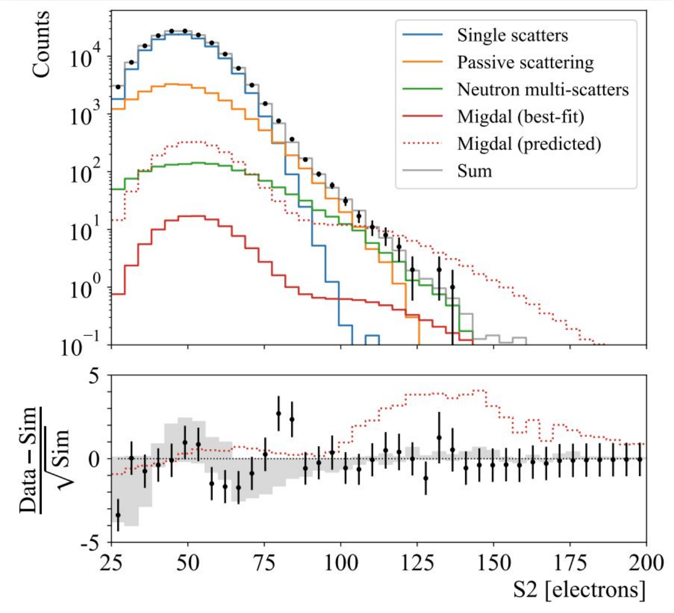


Y. Kahn et al. arXiv:2403.08866

2. Calibrating the detector response to the Migdal effect

Livermore group dedicated measurement (DT generator 14 MeV neutrons, pick out 7 keV NR based on angle):



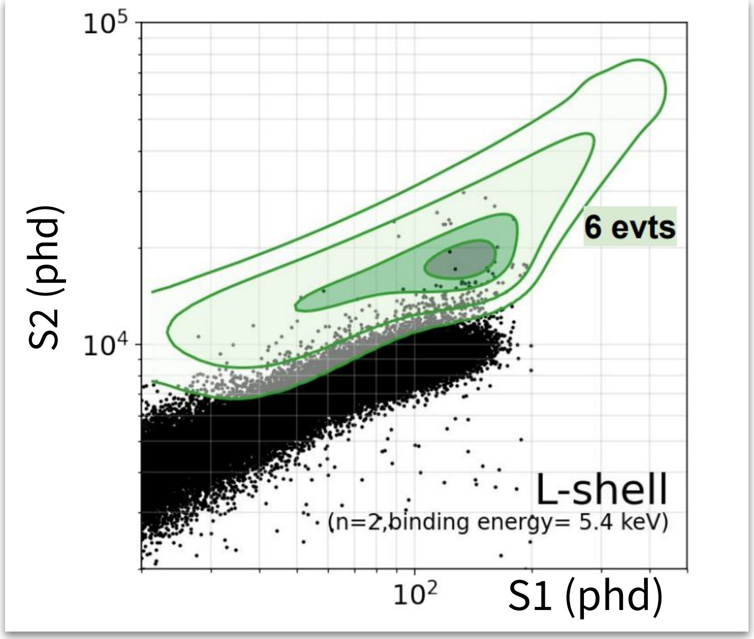


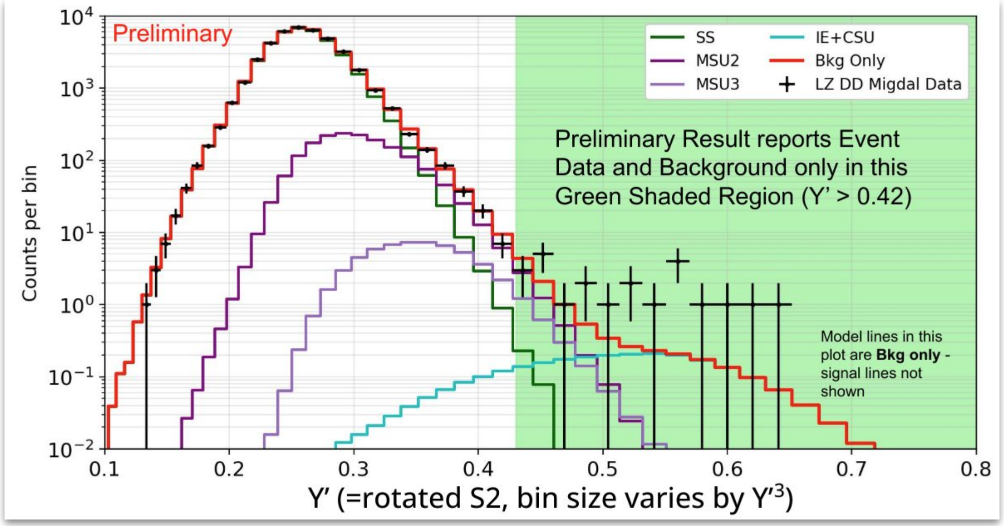
Xu et al. [arXiv:2307.12952]()

Number of Migdal events consistent with zero

2. Calibrating the detector response to the Migdal effect

LZ *in situ* measurement (DD generator 2.45 MeV neutrons, >20 keV NR):

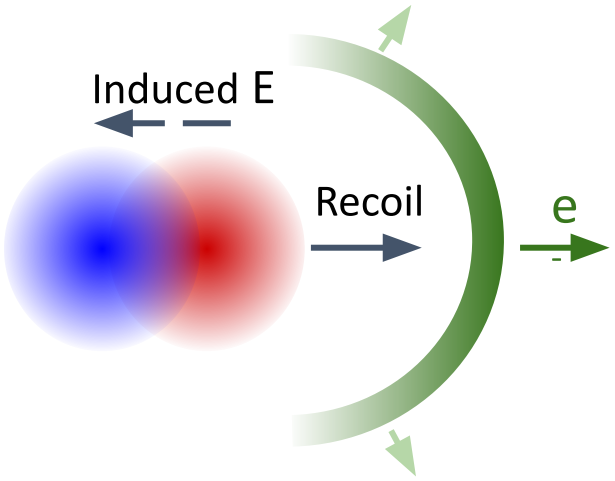


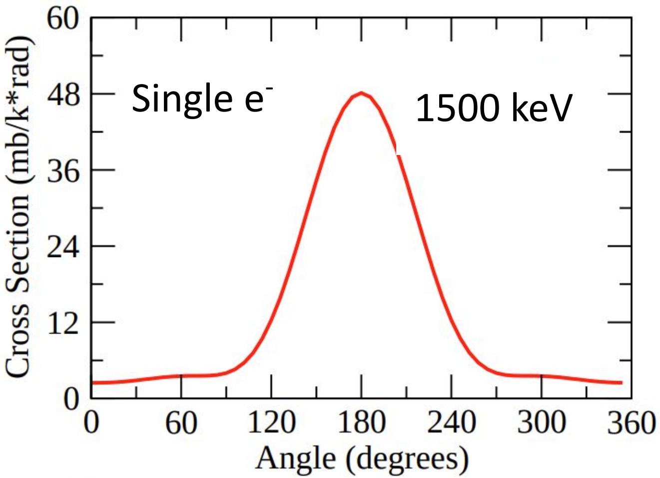


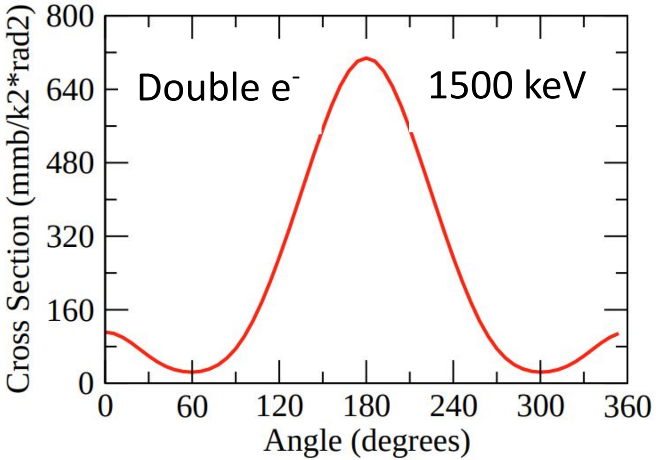
Bang (LZ Collaboration) UCLADM2023 talk

Directional Migdal Effect?

- **Predictions for neutron scattering on He**
  Single ionization has forward-only e
  Double ionization has slight backward e



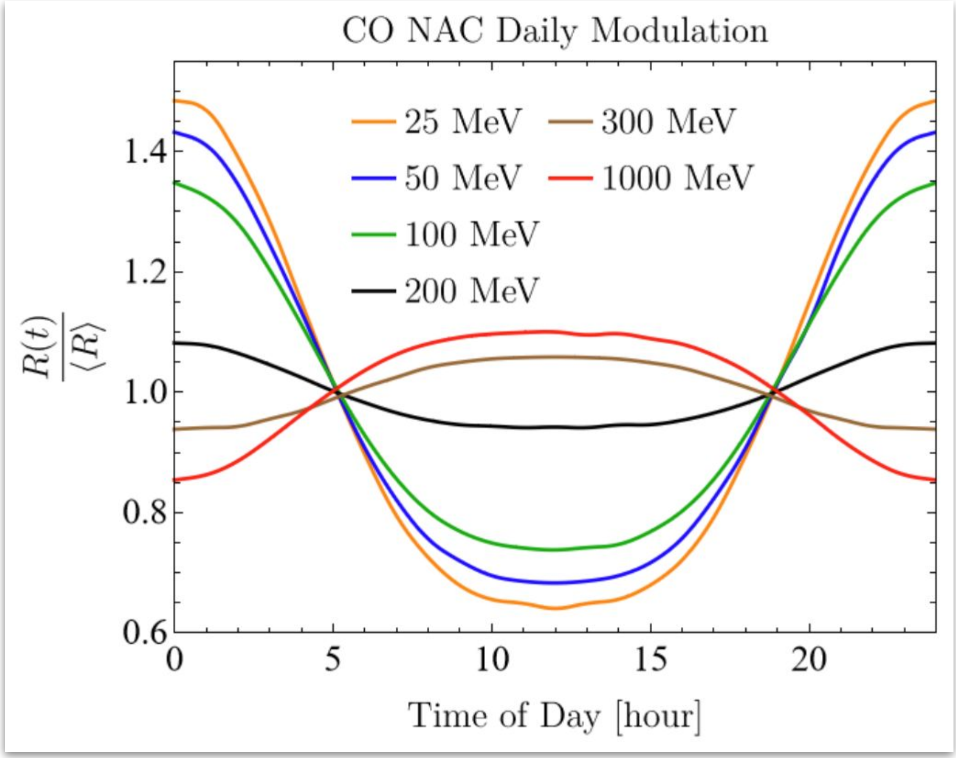




Pindzola et al. [*J. Phys. B 53 (2020)*]

Migdal in molecules

- **Hard,** only computed for simple molecules
- The probability depends on the molecular axis → indirect/statistical directional information
- Non-adiabatic coupling of ground states to excited states provide another (much larger) contribution to Migdal excitation



Blanco et al. arXiv:2208.09002

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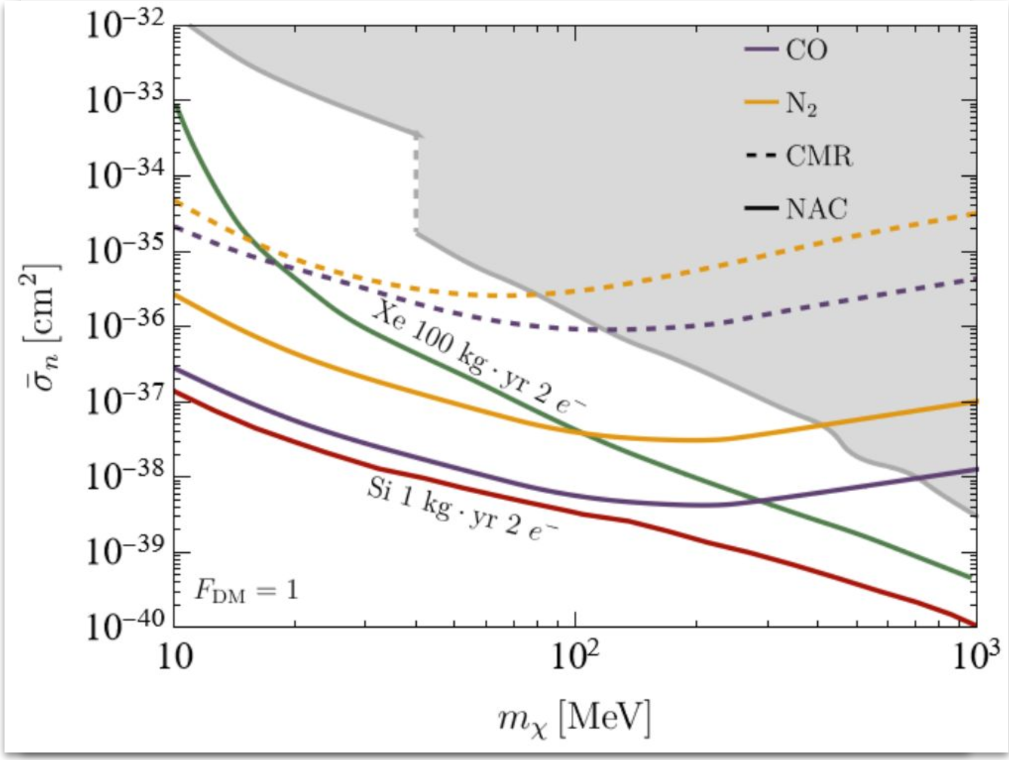
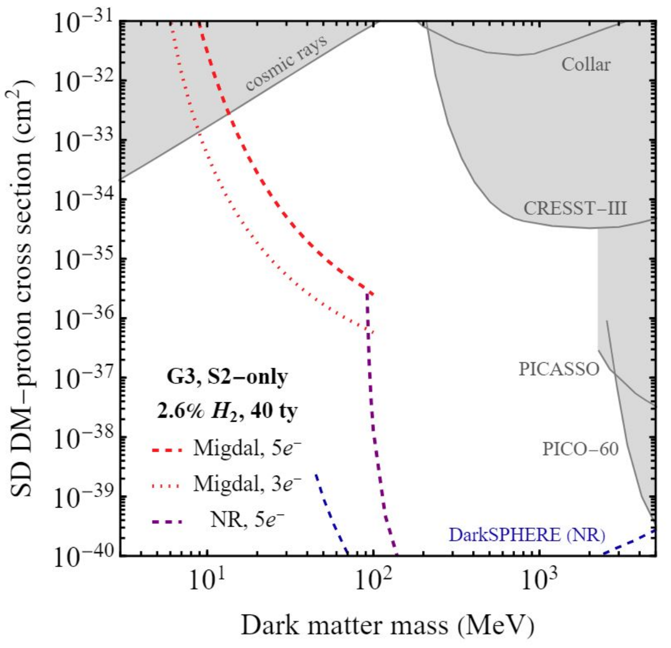


Blanco et al. arXiv:2208.09002

Summary

- The Migdal effect allows access to lighter DM, especially when used in concert with H_2 doping
- It's important to both verify experimental predictions *and* calibrate detector responses → experimental determinations of both are underway
- Directional nature of the Migdal effect, especially in molecules, is interesting → more investigation needed



Collaborators:
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James Dent (Sam Houston)
Rafael Lang (Purdue)

~/code$

https://github.com/jaydenn/nuMigdalCalc
https://github.com/jaydenn/thinNEST
https://github.com/jaydenn/MigdalMC