The Migdal effect for dark matter detection

CYGNUS Workshop,
The University of Sydney
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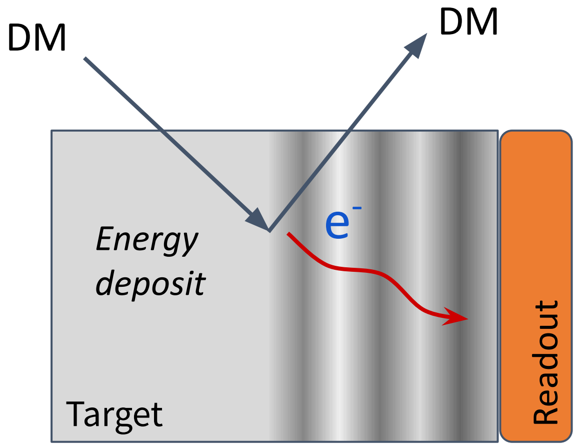
THE UNIVERSITY OF MELBOURNE

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

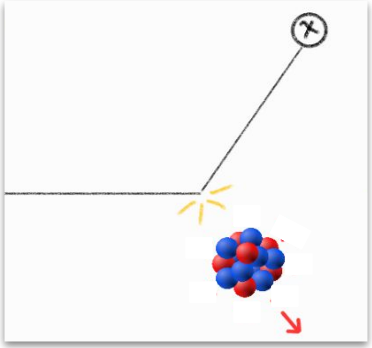
Direct detection fundamentals

- 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

Direct detection's kinematic problem



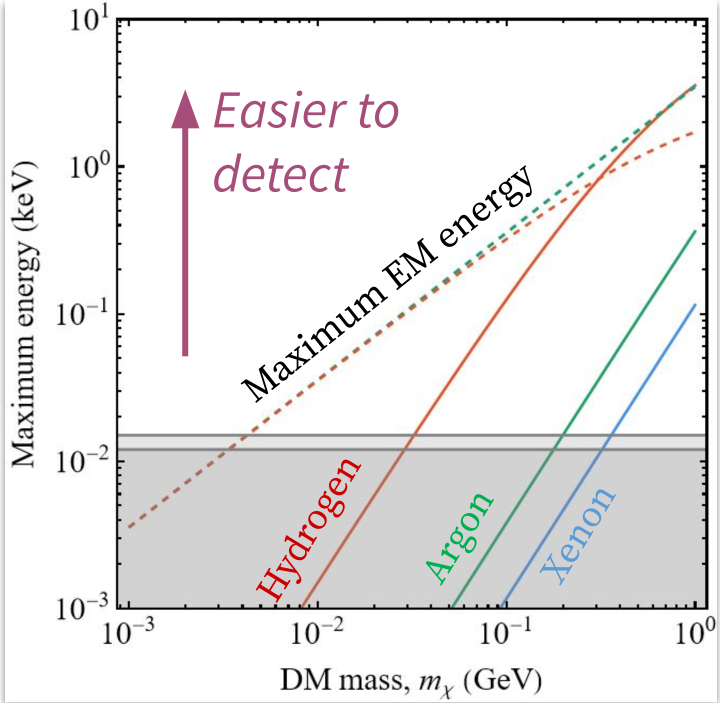
$$E_{R_{\max}} = \frac{2\mu_T^2}{m_T} v_{\max}^2$$

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

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

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

→ Light dark matter does not pack much of a punch



*assuming v_{max} = 800 km/s

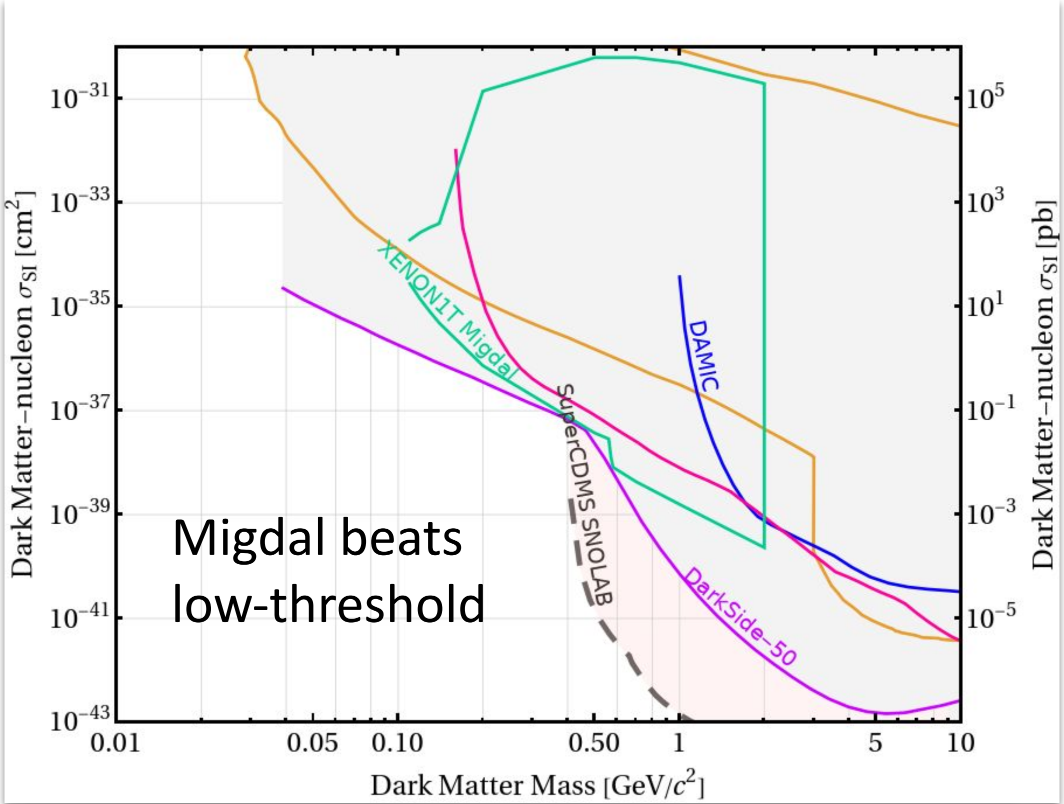
Future of direct detection

Present/near term:

- XENONnT: 5 tonne x 4 years (Xe)
- LZ: 5.5 tonnes x 1000 days (Xe)
- PandaX-4T: 3.7 tonnes x 2 years
- SuperCDMS: 81 (25) kg.years Ge (Si)

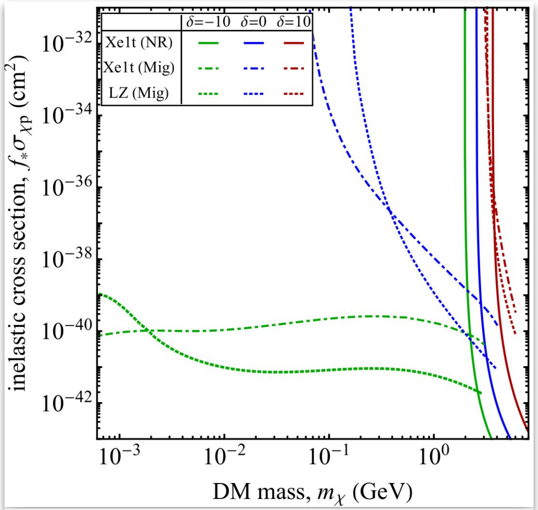
Future:

- DarkSide-20k: 20t x 5 years (Ar), 2026+
- XLZD: 40t x 10 years (Xe), 2027+
- Argo: 300t x 10 years



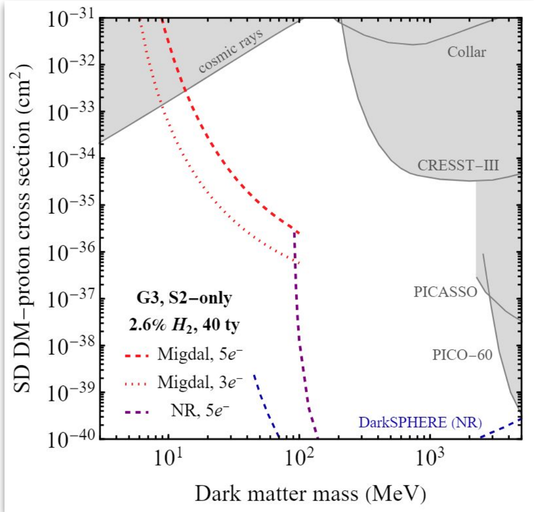
What can we do with the Migdal Effect?

Migdal from inelastic DM:



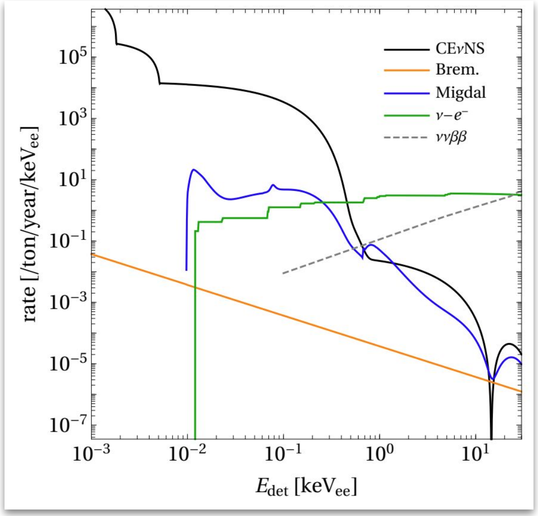
Bell, Dent, Dutta, Kumar, **JLN**
arXiv:2103.05890

Migdal + Hydrogen-doping:



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

Migdal from neutrinos

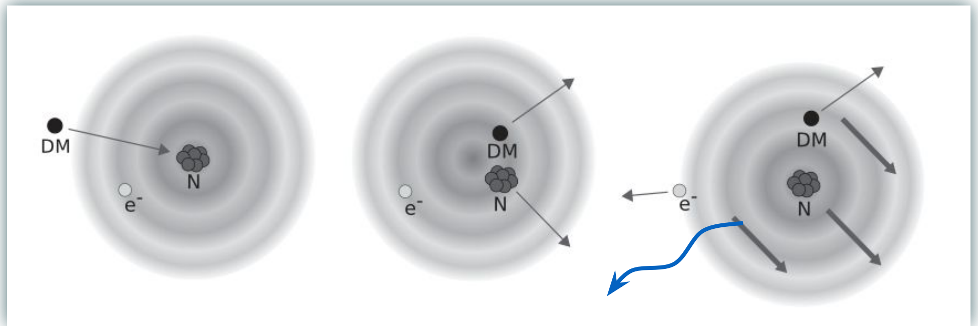


N. Bell, Dent, **JLN,** Sabharwal, Weiler
arXiv:1905.00046

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**

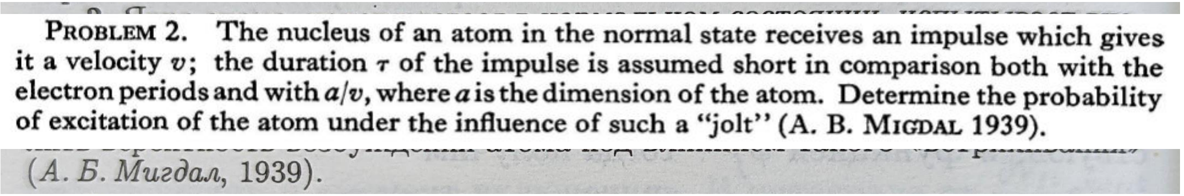


Credit: Dolan et al. PRL 2017

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:



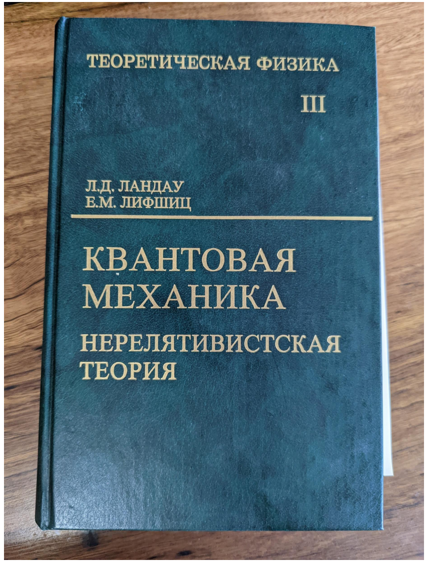
PROBLEM 2. The nucleus of an atom in the normal state receives an impulse which gives it a velocity v; the duration τ of the impulse is assumed short in comparison both with the electron periods and with a/v, where a is the dimension of the atom. Determine the probability of excitation of the atom under 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?

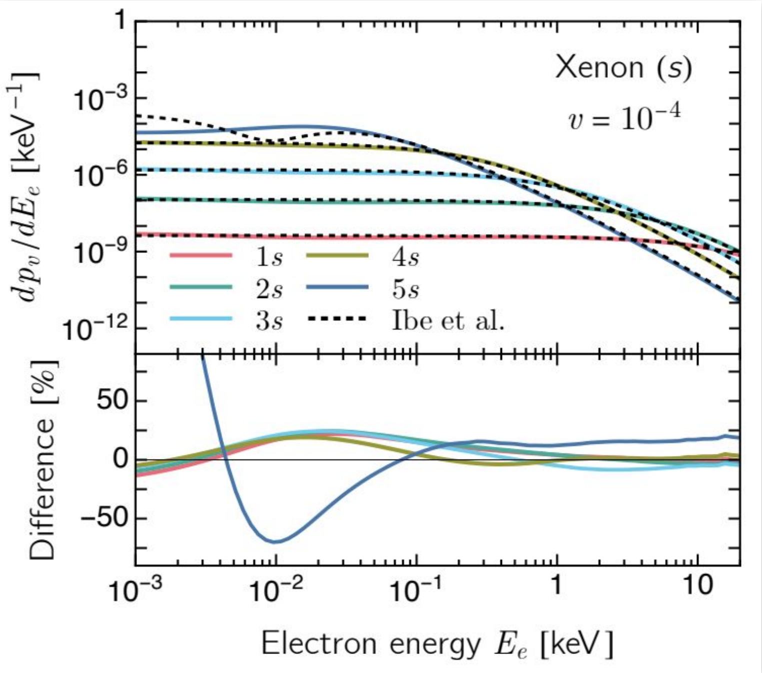
$$\frac{d^2R}{dE_{\rm NR}dE_i} = \frac{d^2R_{iT}}{dE_{\rm NR}dE_i} \times |Z_{\rm ion}|^2$$

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

Ionization prob.

Relevant matrix elements obtained by boosting the electronic wavefunction:

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

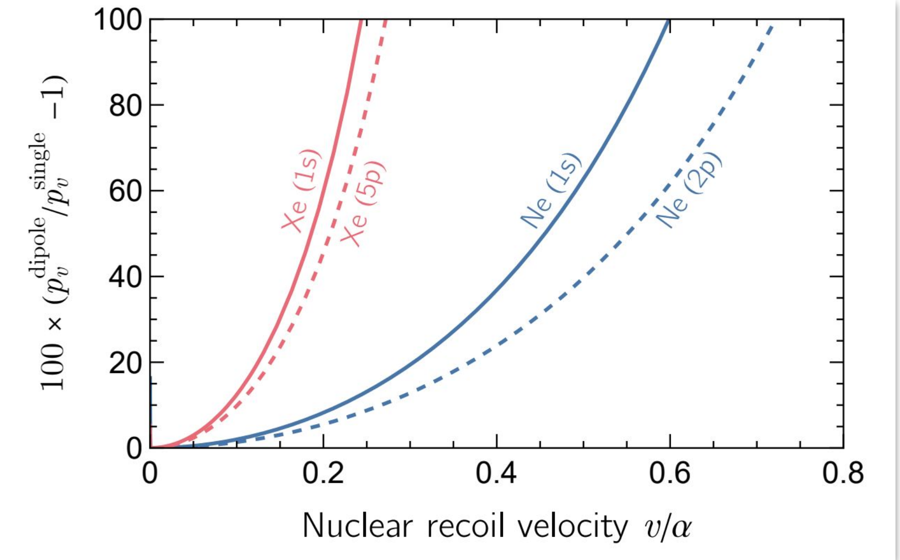


Cox et al. Phys.Rev.D 107 (2023)
[*arXiv:2208.12222*]

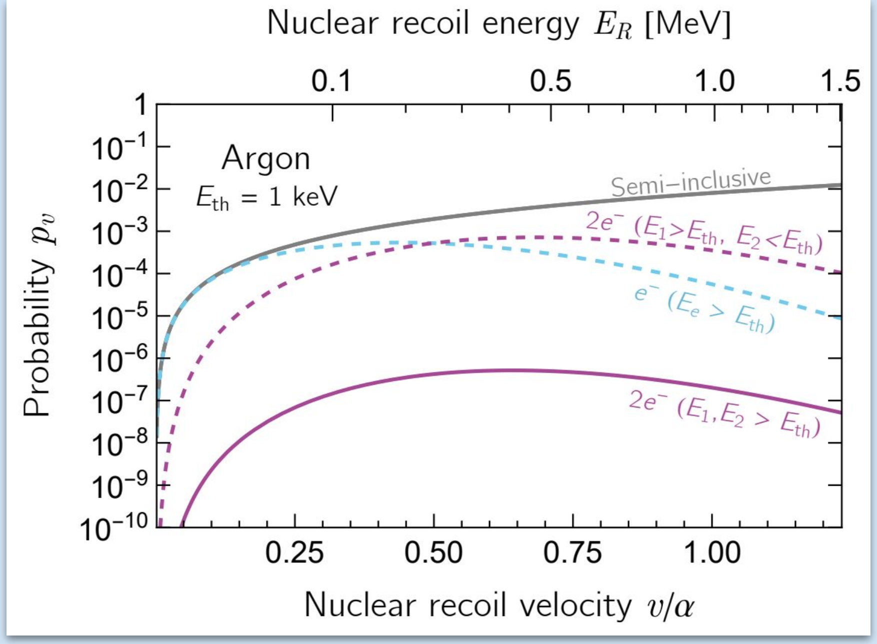
Ionization probabilities cont.

i) Dipole approx is fine for DM, but breaks down rapidly

130 keV 187 keV

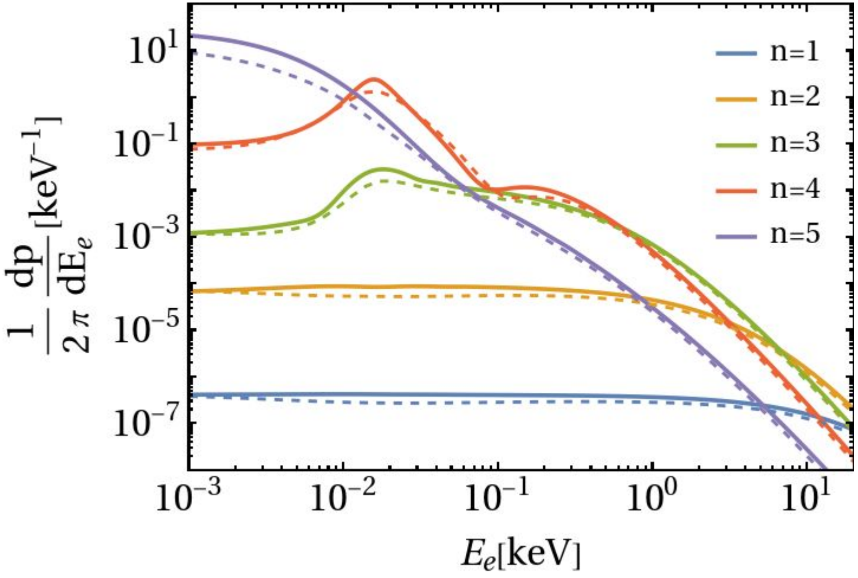


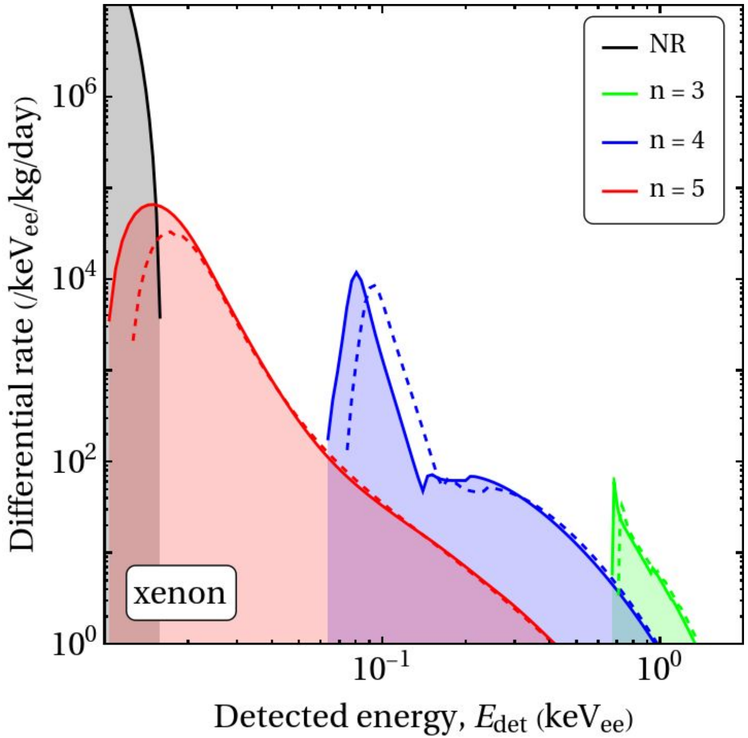
ii) Single electron is fine for DM



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

Difference mostly from shifted ionization energies



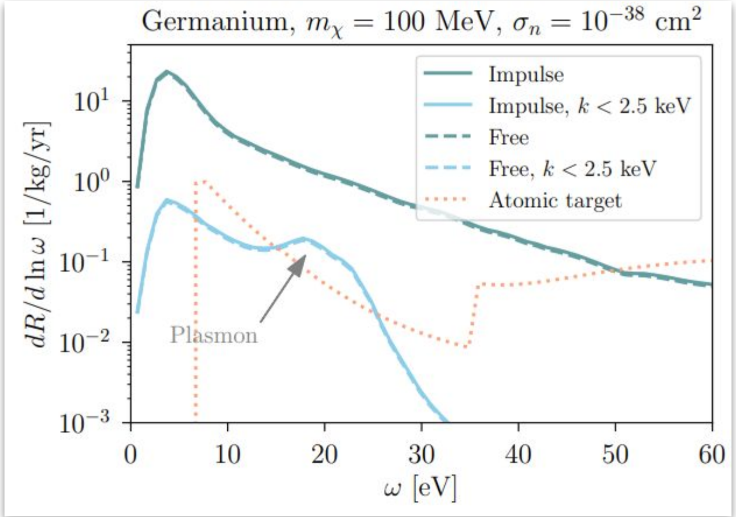


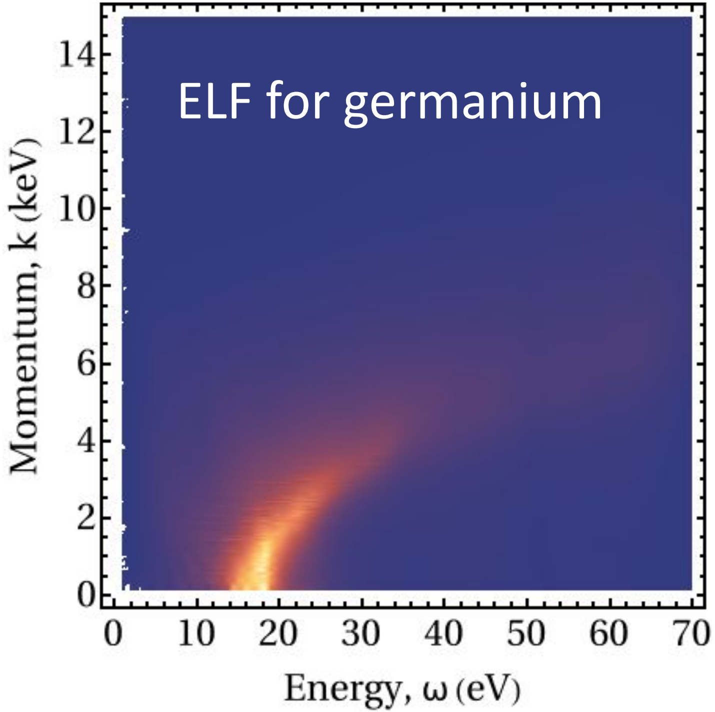
Ionization probabilities in semiconductors

When the atom is not isolated things are more complicated

Energy loss function

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

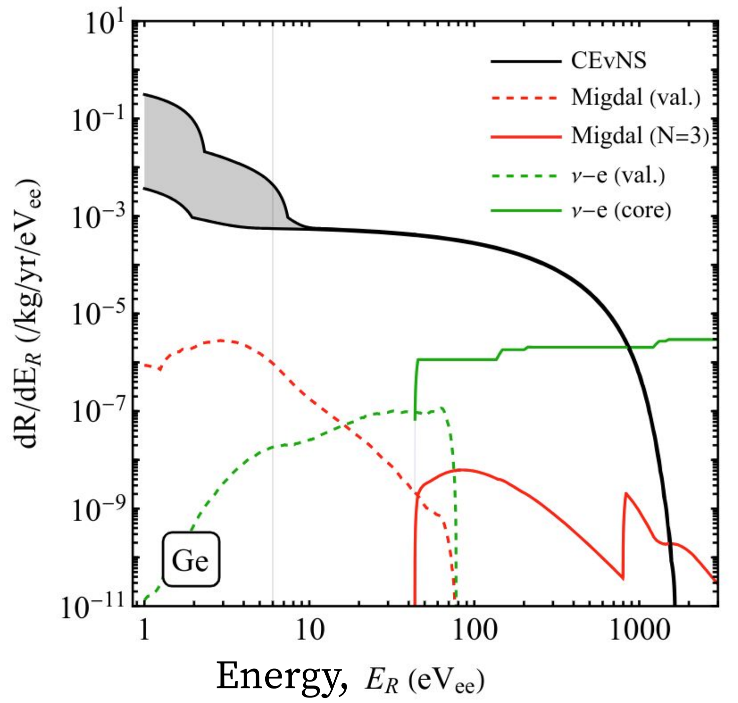


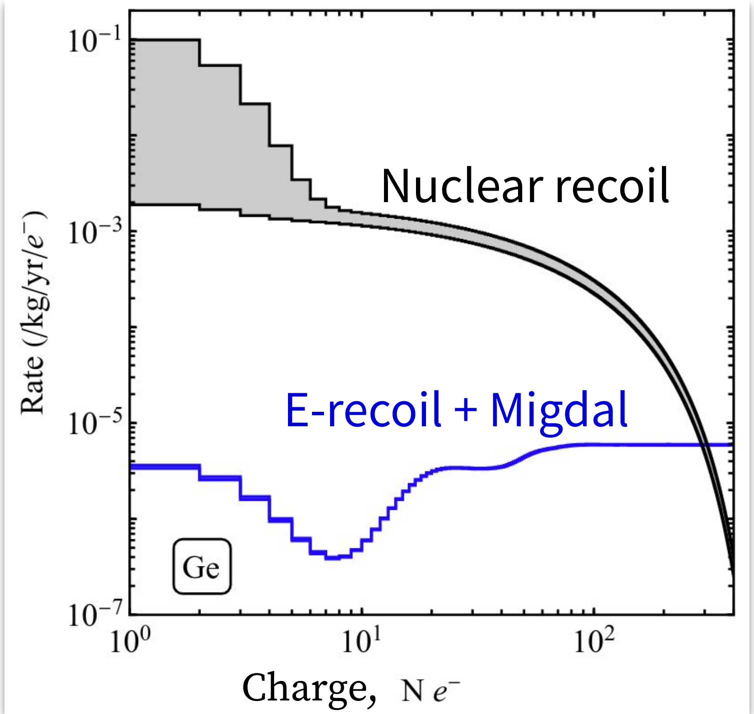


From the DarkELF package, calculated with DFT (GPAW)

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

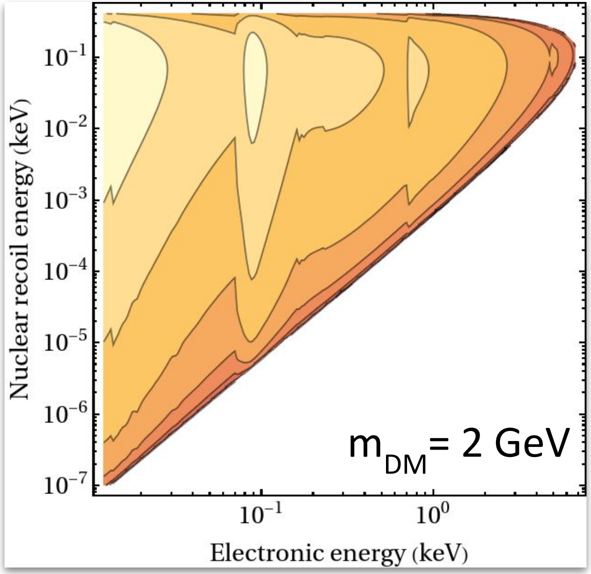
Neutrino rates in semiconductors



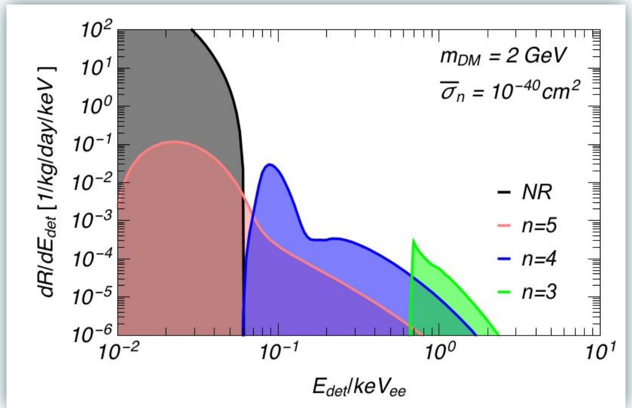


What does a Migdal event look like?

Energy deposited:

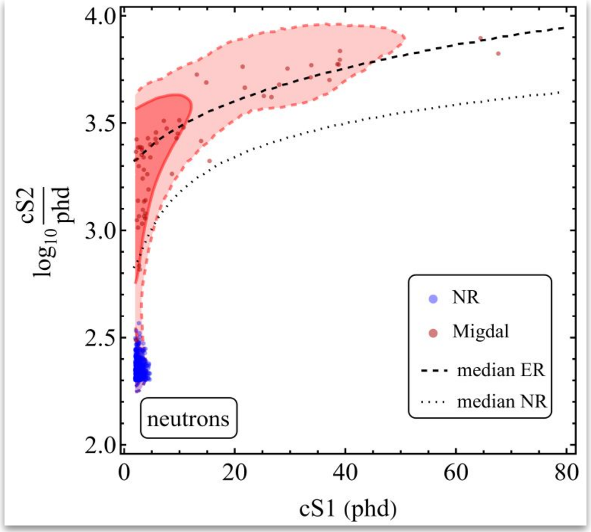


Energy deposited w quenching:



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

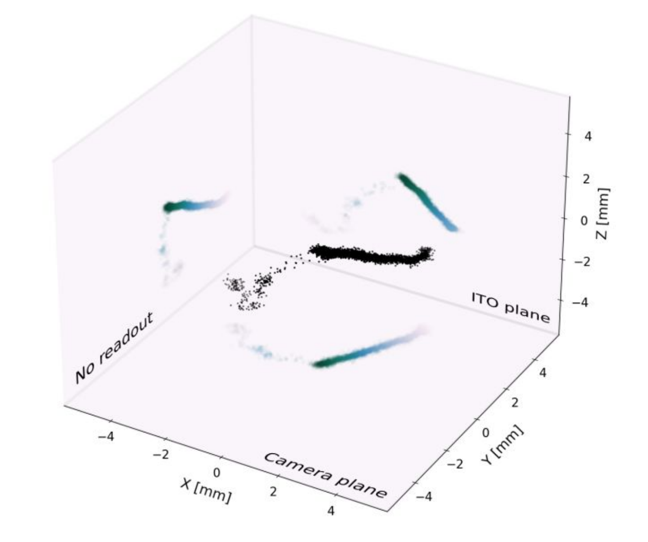
Detector modelling, e.g.:



Calibrating the Migdal effect (in LXe TPCs)

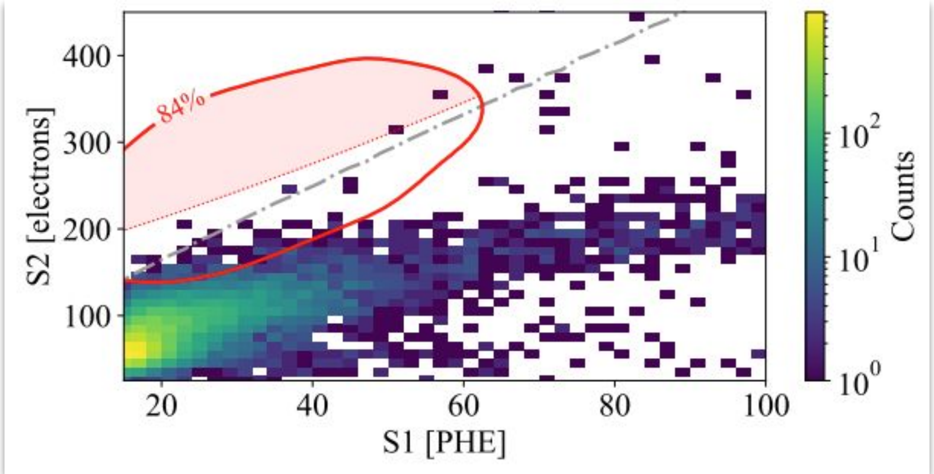
Two experimental goals:

1. Verify theoretical predictions:
   The MIGDAL experiment (see next talk)



Araújo *et al. Astropart. Phys.* (2023) [arXiv:2207.08284](https://arxiv.org/abs/2207.08284)

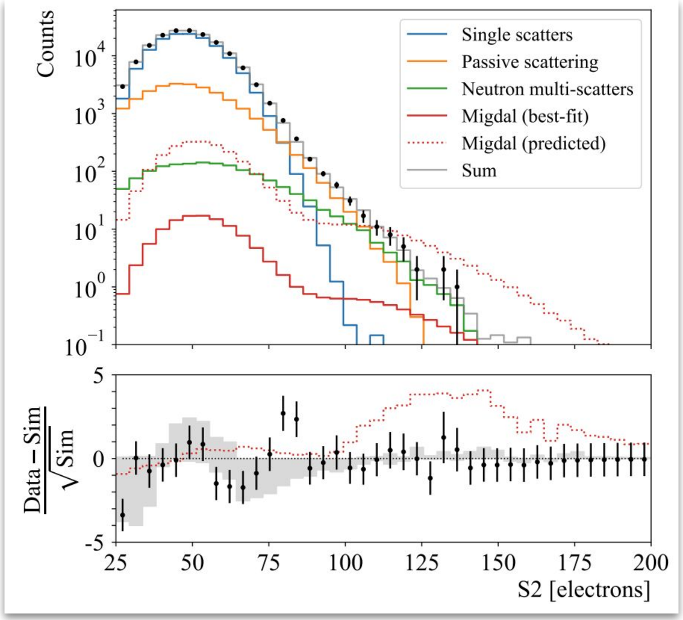
2. Calibrate detector response



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

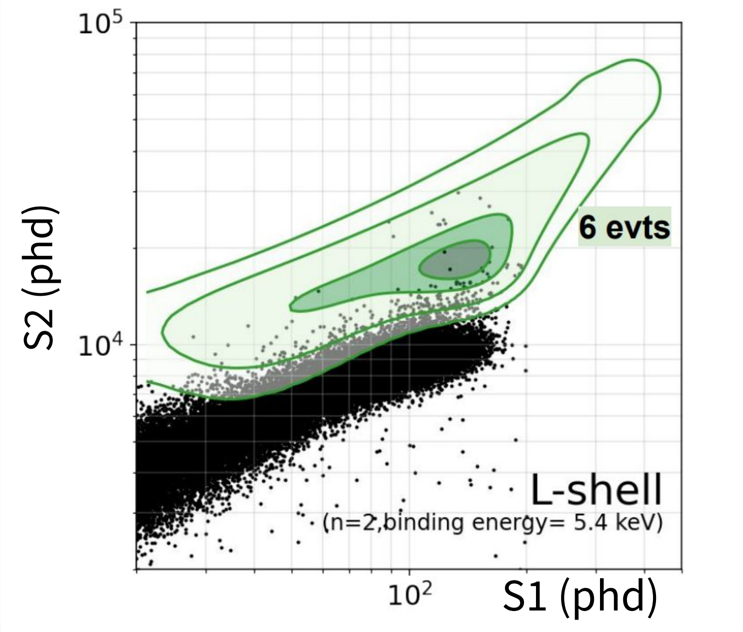
Calibrating the detector response to the Migdal effect

Livermore group dedicated measurement (DT generator 14 MeV neutrons, 7 keV NR):



Xu et al. arXiv:2307.12952

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

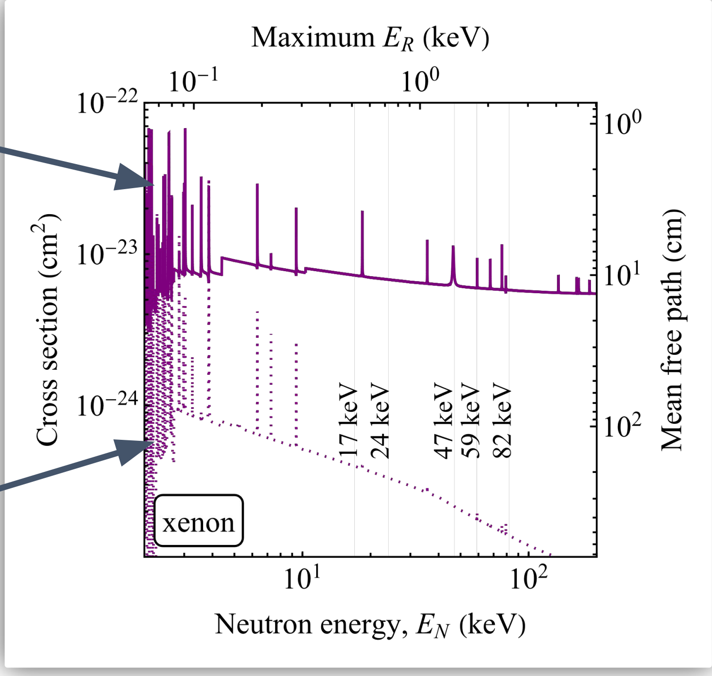


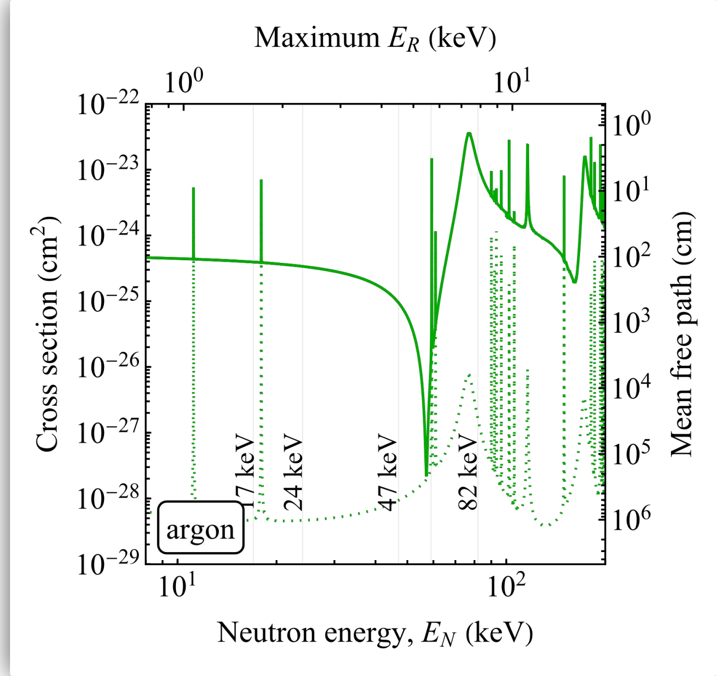
Bang (LZ Collaboration) UCLADM2023 talk

Low-energy neutron cross sections

Elastic

Capture

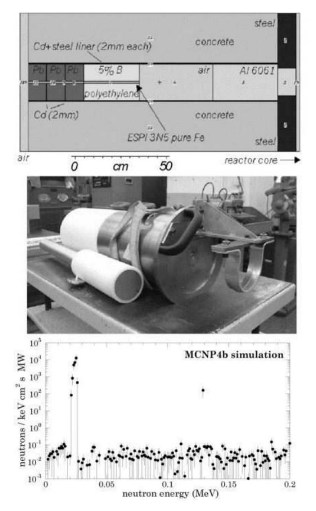




- Radiative capture of neutrons will be a significant background
- Inelastic scattering is >100 keV threshold for all but xenon-129

Potential low-energy neutron sources

Nuclear reactor + filter

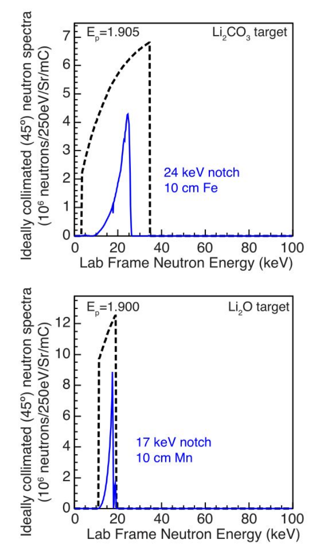


Pros:
- Large flux
- Continuous operation

Cons:
- Gamma backgrounds
- Location

Barbeau et al. arXiv:nucl-ex/0701011

Li + p near threshold + filter

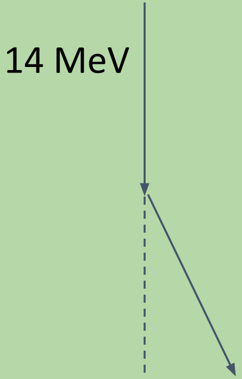


Pros:
- Pulsed beam

Cons:
- May require large/cooled targets
- Location

Joshi et al. arXiv:1403.1285

DT/DD-generator + measure recoil angle



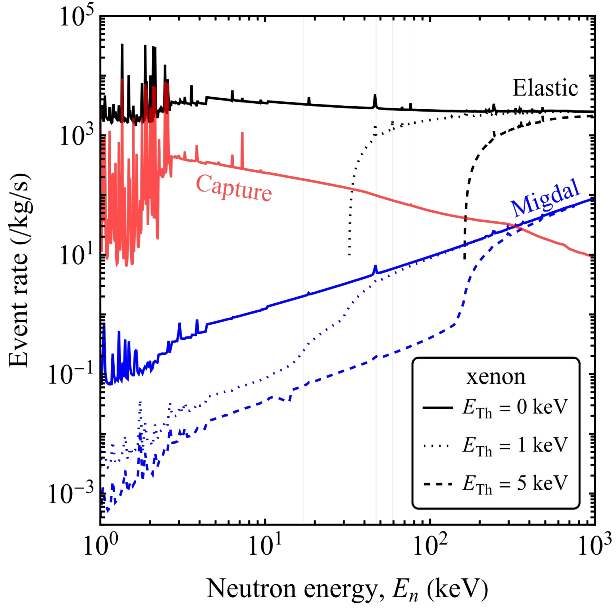
Pros:
- Potential for in situ

Cons:
- Small flux

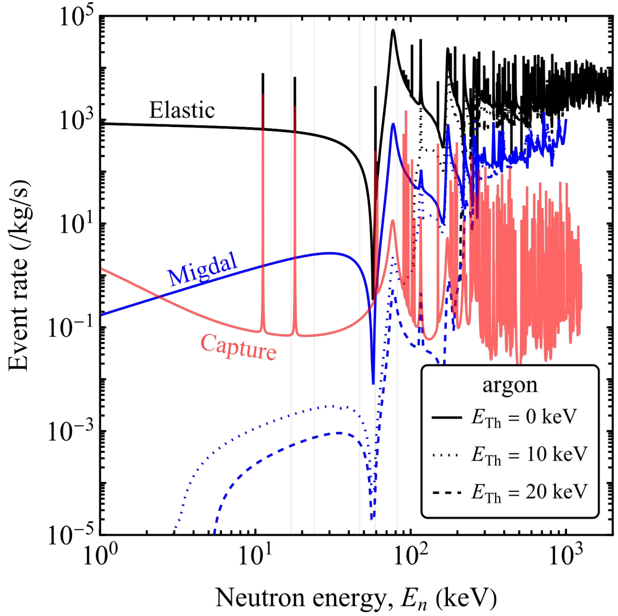
Xu et al. arXiv:2307.12952

Low-energy neutron scattering rates

Xenon



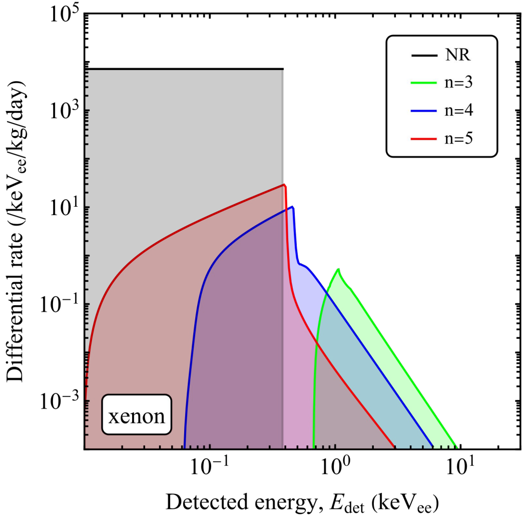
Argon

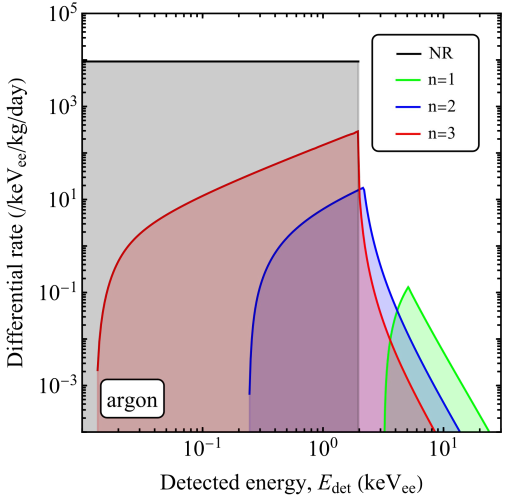


N. Bell, R.Lang, ***JLN***, A.Ritter Phys.Rev.D 105 (2022)

Low-energy neutron Migdal rates

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





Total rates:

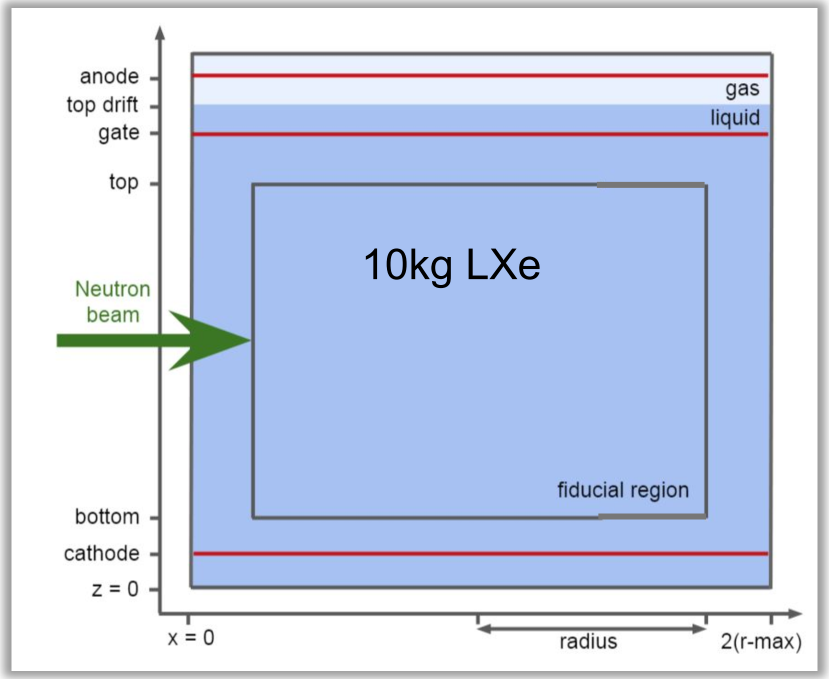
	Xenon	Argon
Nuclear:	2,700 events/kg/s	12,300 events/kg/s
Migdal:	8 events/kg/s	320 events/kg/s

Simulation of LXe detector and neutron beam

Gaussian neutron beam:

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

Modelled on Barbeau et al.



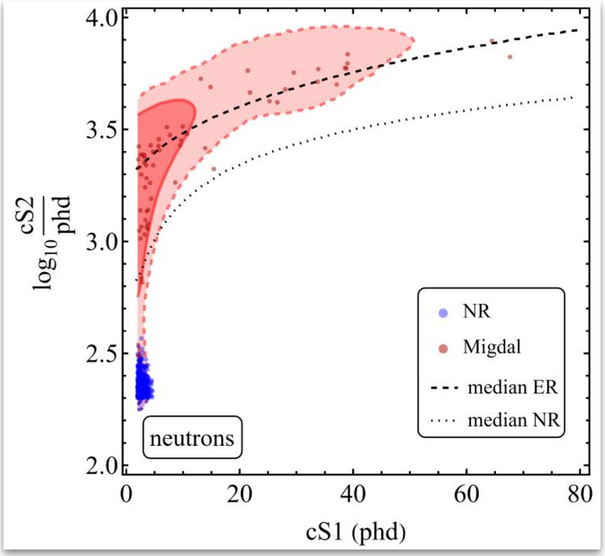
dimension	position (mm)
r_{max}	120.
radius	100.
cathode	20.0
bottom	40.0
top	160.
gate	190.
top drift	195.
anode	200.

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

Simulation with NEST (xenon)

Monte Carlo procedure:

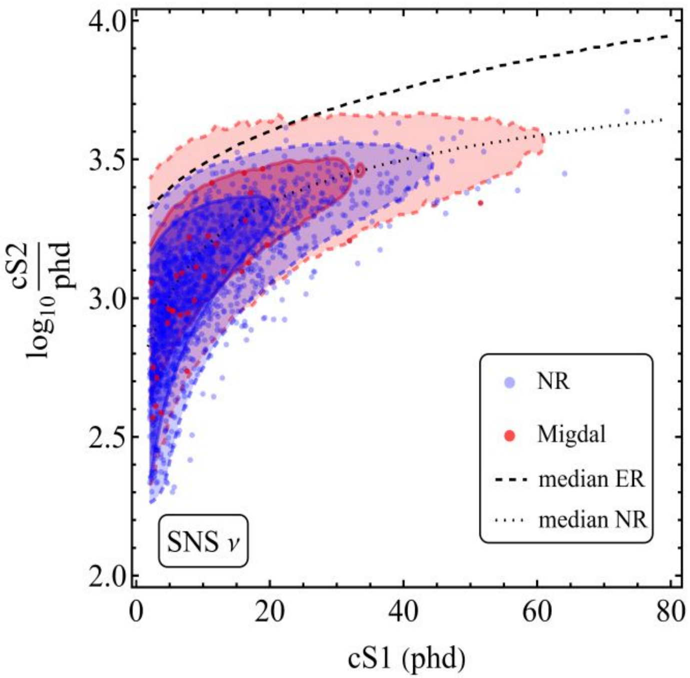
1. Random NR energy from E_R distribution, calculate max. allowed E_{EM}
2. Loop over atomic shells, E_{nl}, and randomly ionize an electron with E_e
3. Calculate the yields of ions and excitons produced by E_R, E_e and E_{nl} using models for NR, β and β respectively
4. Calculate the quanta from the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

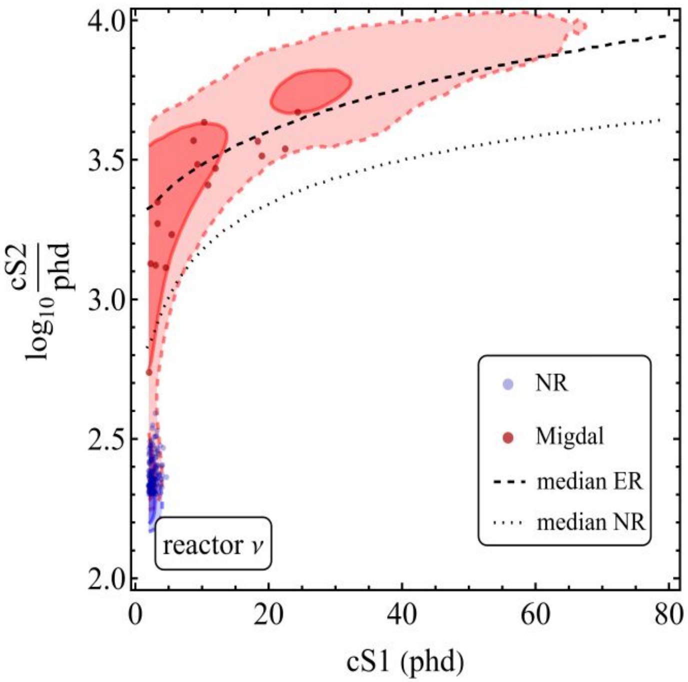


Source	Calc. ratio	Sim. ratio	Sim. rate/kg/day
neutron (17 keV)	6.0×10^{-4}	0.1	600
reactor neutrinos	1.7×10^{-4}	0.1	4.3×10^{-4}
SNS neutrinos	1.5×10^{-2}	0.02	8.8×10^{-3}
^{51}Cr neutrinos	5.4×10^{-6}	∞	8.2×10^{-6}

→ Neutrons are the only viable candidate

Migdal from low-energy neutrino sources





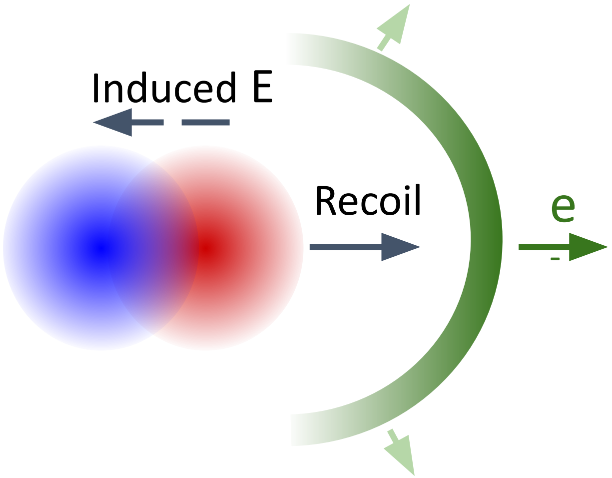
N. Bell, R.Lang, ***JLN****, A.Ritter* [Phys.Rev.D 105 (2022)]

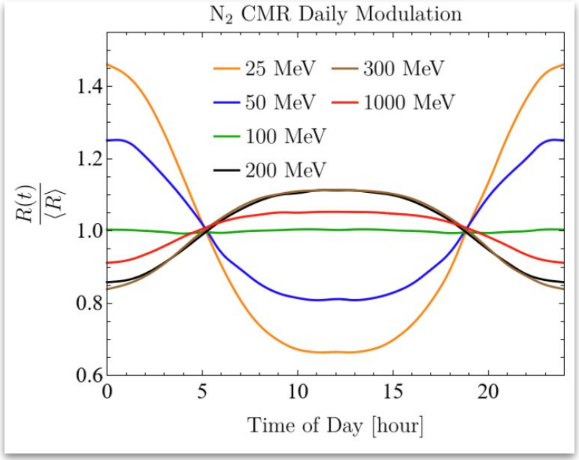
Directional Migdal Effect?

- **Isolated atoms:**
  The nuclear recoil creates a dipole - the electron is preferentially emitted in direction of recoil (see e.g. from alpha decay)

- **Molecular:**
  Ionization prob. depends on molecular axis → indirect/statistical directional information (see Blanco et al.)

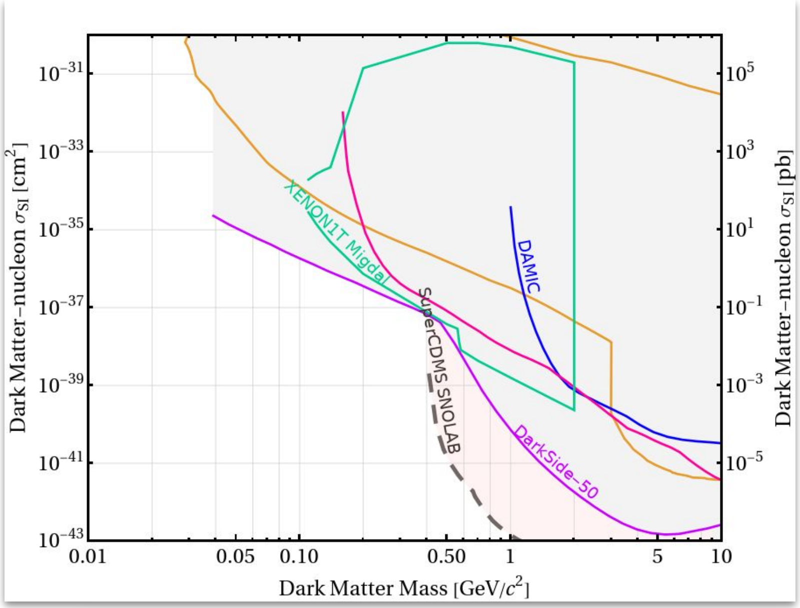
- **Condensed matter:**
  The dielectric function has angular dependence → indirect/statistical directional information





Summary

- The Migdal effect allows access the lighter DM
- It's important to both verify experimental predictions *and* calibrate detector responses
- Directional nature of the Migdal effect is likely weak, but it should be investigated further

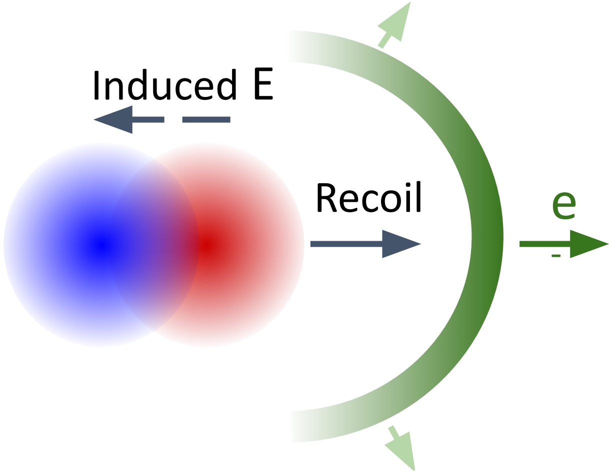


Collaborators:
Nicole Bell, Alex Ritter, Peter Cox, Matt Dolan (UniMelb)
James Dent (Sam Houston)
Bhaskar Dutta (TAMU)
Rafael Lang (Purdue)
Jason Kumar (Hawaii)

~/code$

https://zenodo.org/record/5587760
https://github.com/jaydenn/nuMigdalCalc
https://github.com/jaydenn/thinNEST
https://github.com/jaydenn/MigdalMC

Directional Migdal Effect?



- **Predictions for neutron scattering on He**
  Single ionization has forward-only e
  Double ionization has slight backward e
  From: *Pindzola et al J. Phys. B 53 (2020)*