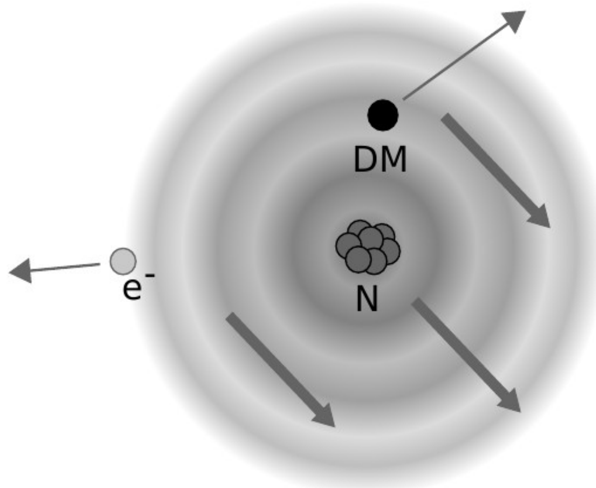
Precise Predictions and New Insights for the Migdal Effect



Matthew Dolan
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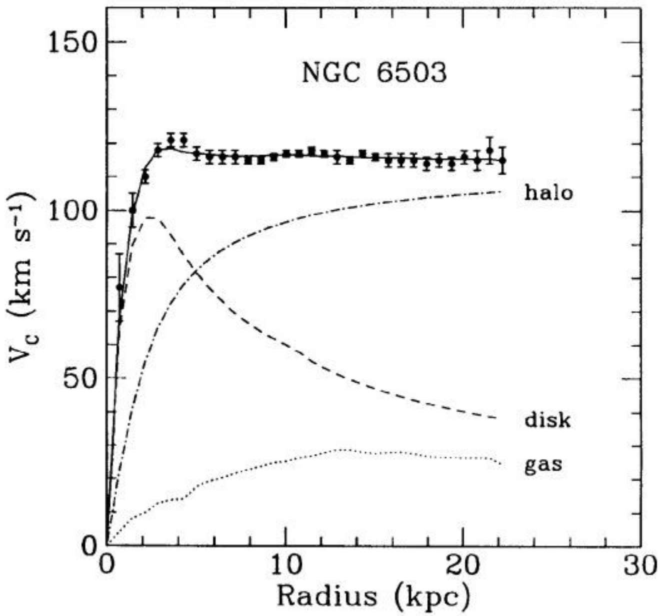
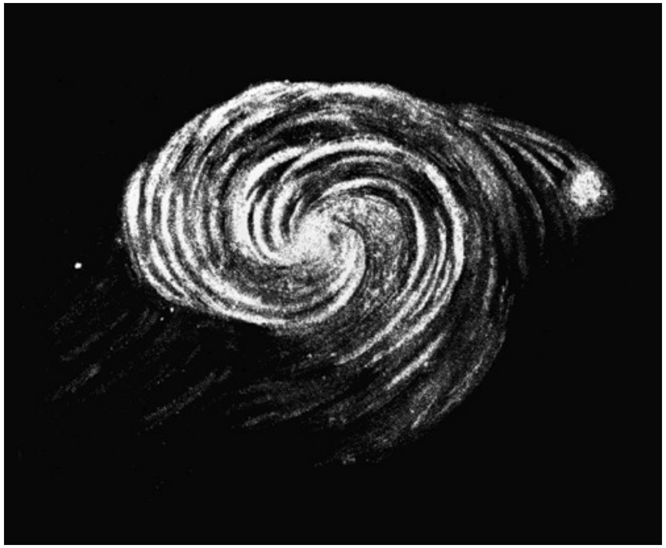
Nicole Bell, Peter Cox, MJD, Jay Newstead, Alex Ritter 2305.04690 (PRD)

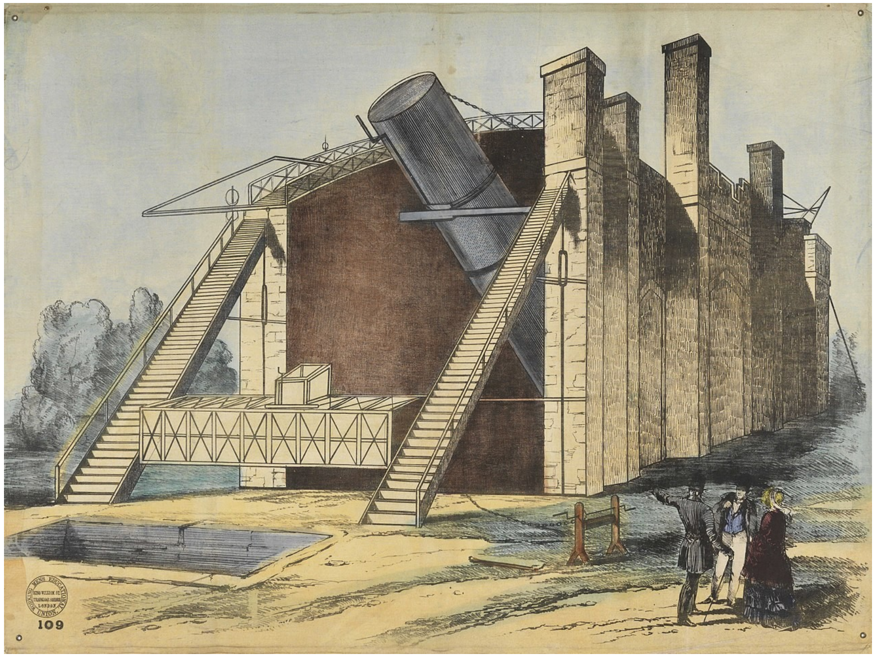
https://petercox.github.io/Migdal/

Dark Matter

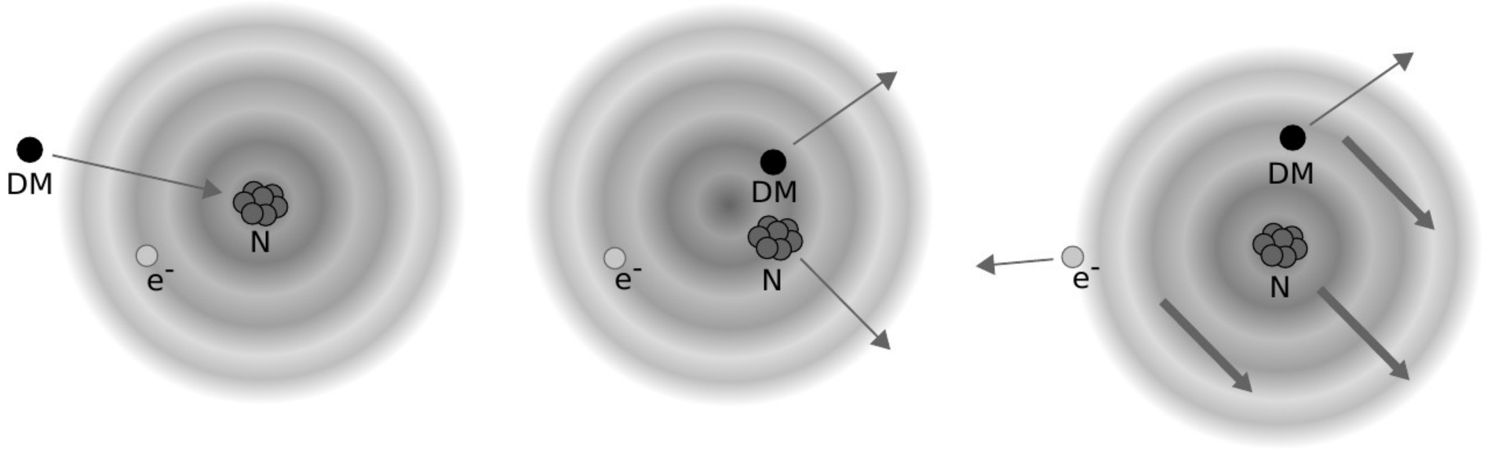


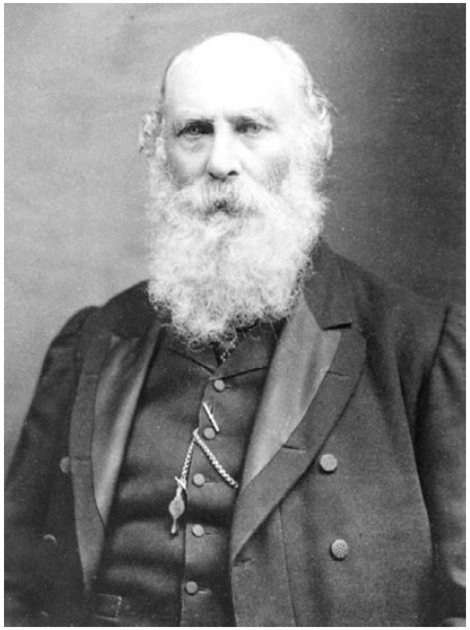
- It’s out there





The Migdal Effect





Atomic ionisation or excitation following nuclear recoil.

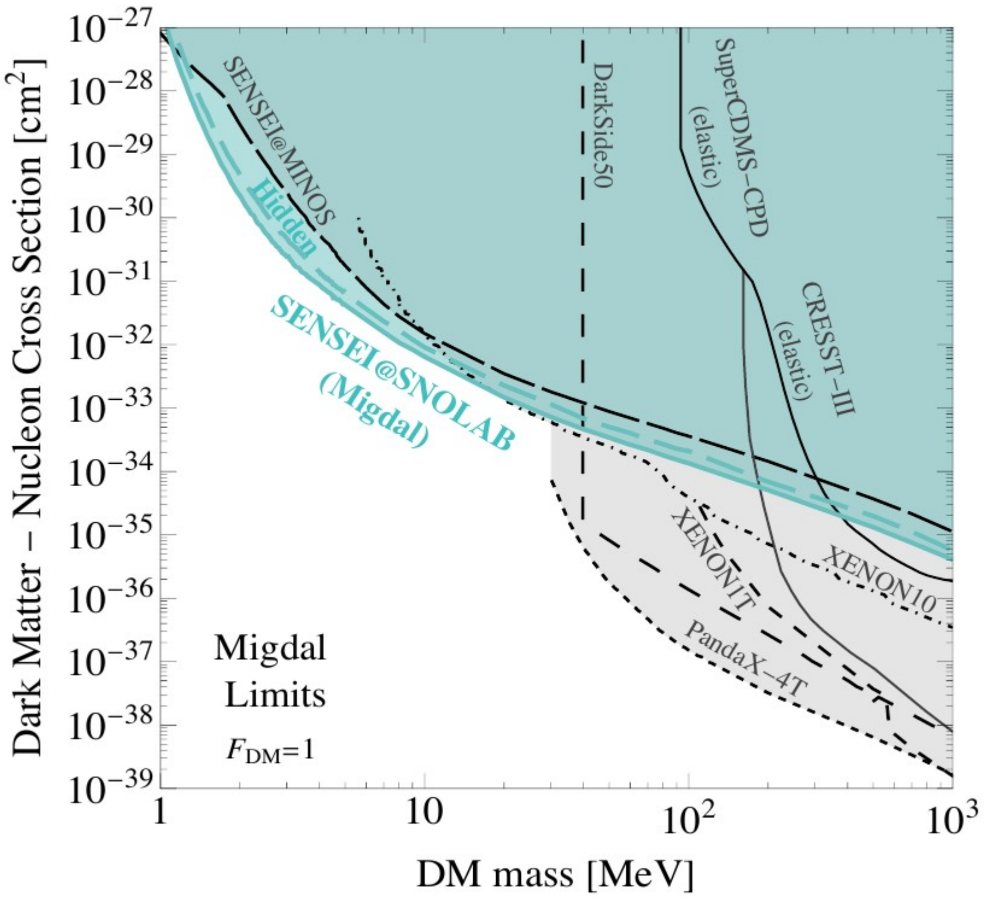
Migdal, 1939

Ibe et al, 1707.07258

Dolan, Kahlhoefer, McCabe, 1711.09906

Low Mass Direct Detection

- Nuclear recoil below threshold
- Migdal electron can be above threshold
- Drives current low mass limits



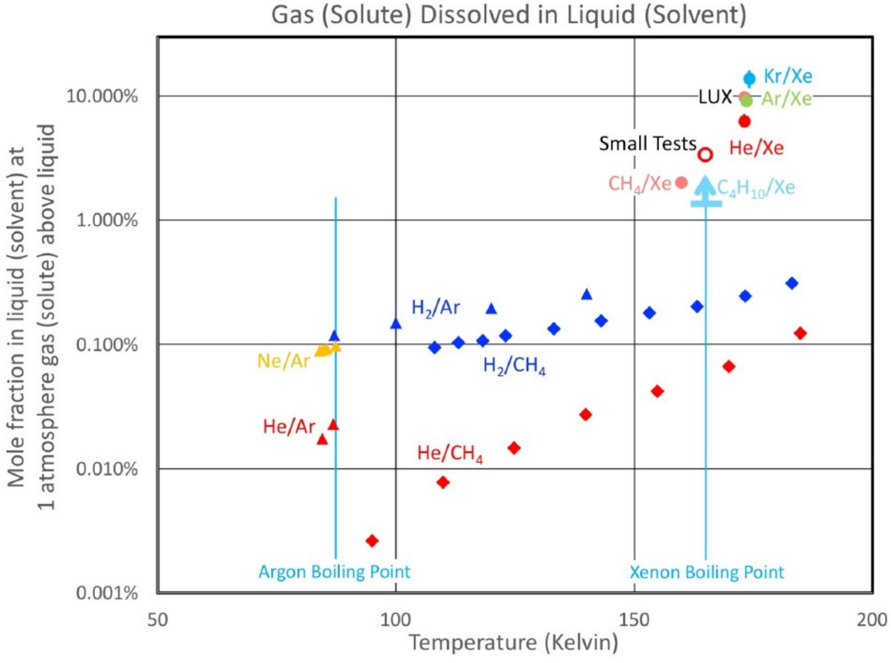
SENSEI, 2312.13342

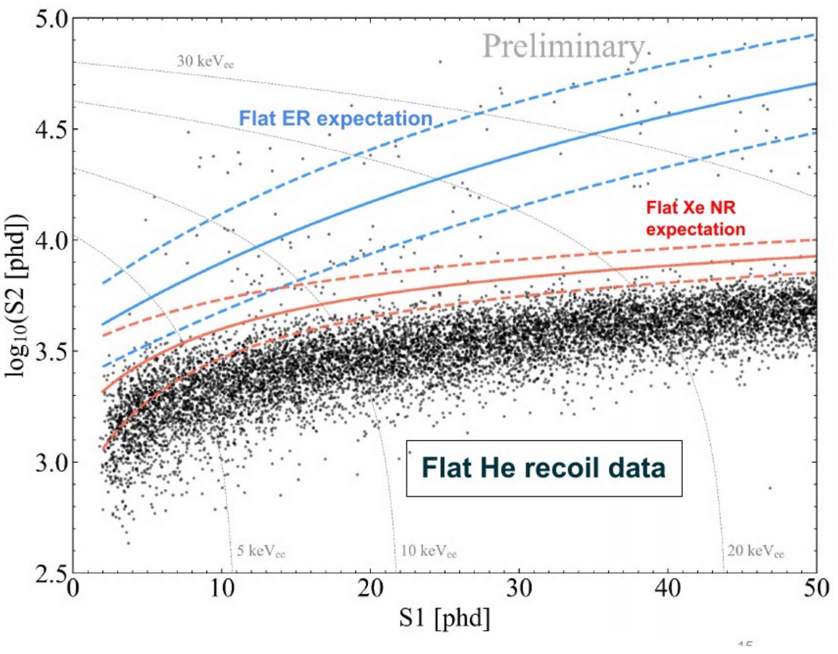
Future Direct Detection: HydroX?

HydroX: Dope LZ with molecular hydrogen

- Larger recoil energies compared to Xe.
- Possible %-level solvency
- H2 recoil vs LXe recoil discrimination?

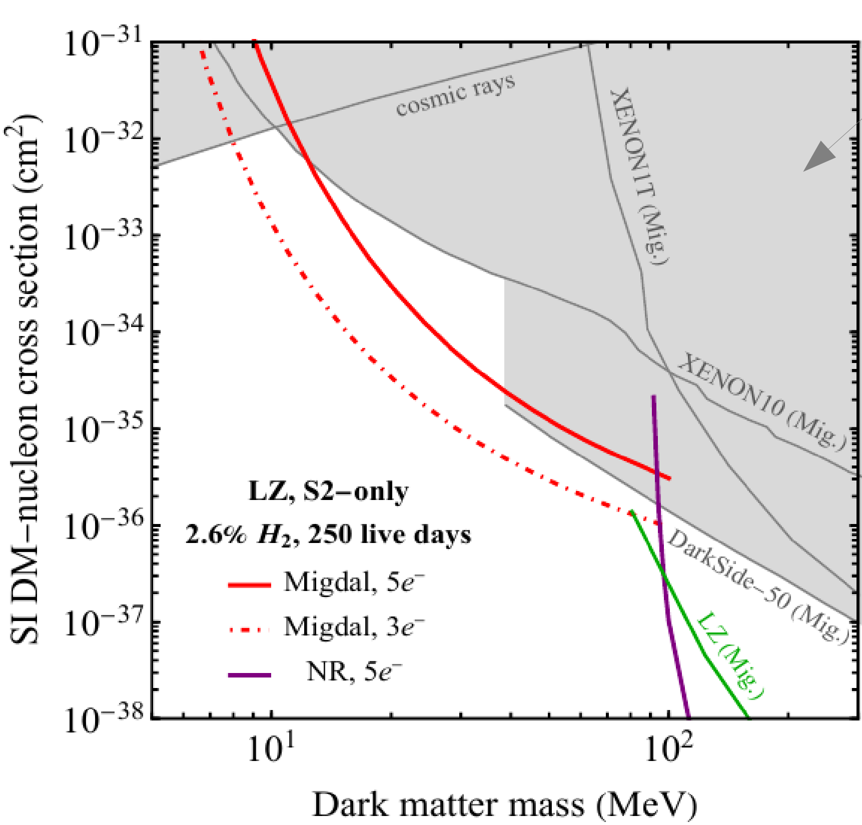
- Signal yields of H2-doped LXe?
- Cryogenics of H2-doped Lxe?
- Tritium contamination?

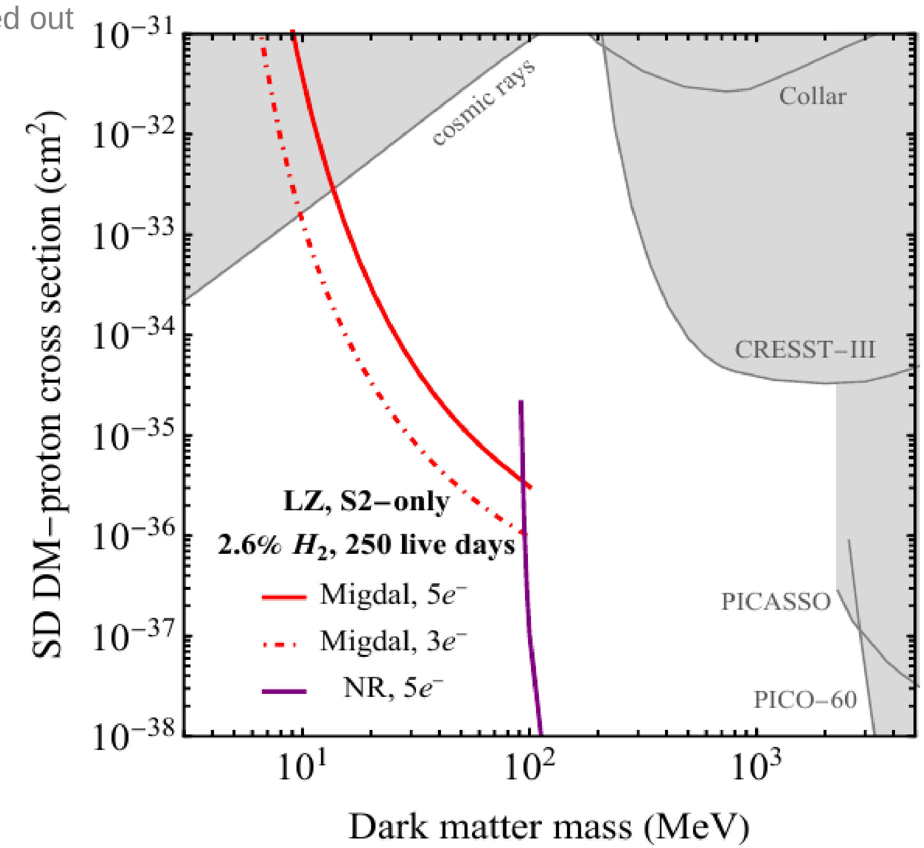




Alissa Monte, DPF 2019 and Scott Haselschwardt, DM UCLA '23

The Migdal Effect and H2-Doped LXe: LZ





- Spin-independent scattering
- Can probe new regions of dark matter mass 5-40 MeV.

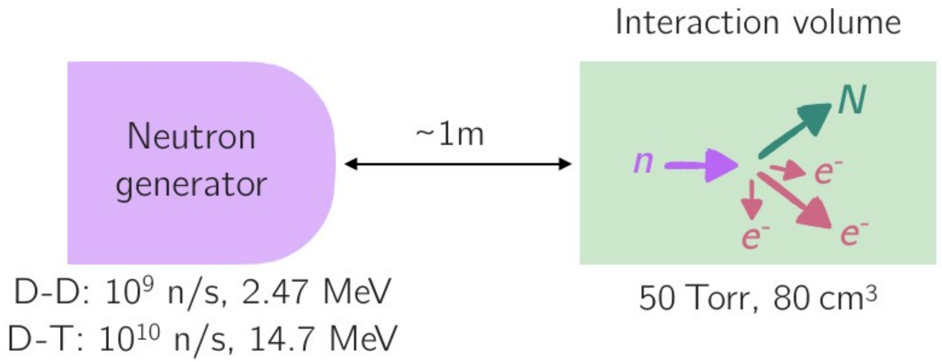
- Spin-dependent scattering
- Vast new regions of parameter space for SD scattering on protons.

Bell, Cox, MJD, Newstead, Ritter 2205.04690

The Migdal Effect: Direct Observation?

- Migdal theory results used for DM limits
- Direct evidence for Migdal: ionisation after neutral particle scattering?
- No!

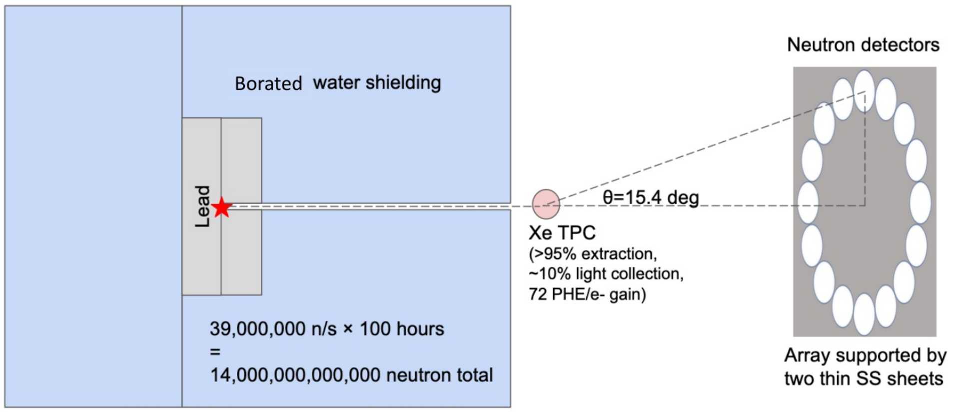
- Evidence from alpha and beta decays (1970s)
- Now: neutron beam proposals for calibration and first direct observation



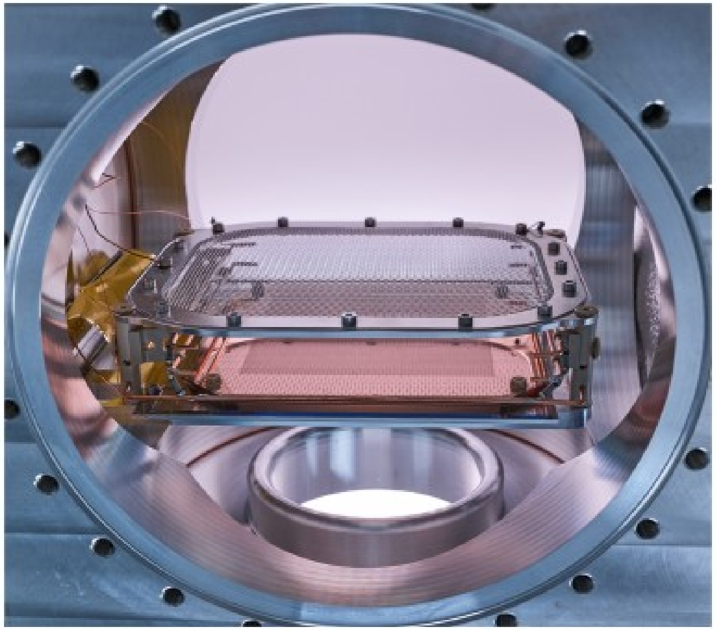
Cox, MJD, McCabe, Quiney 2208.12222

Neutron Beam Experiments

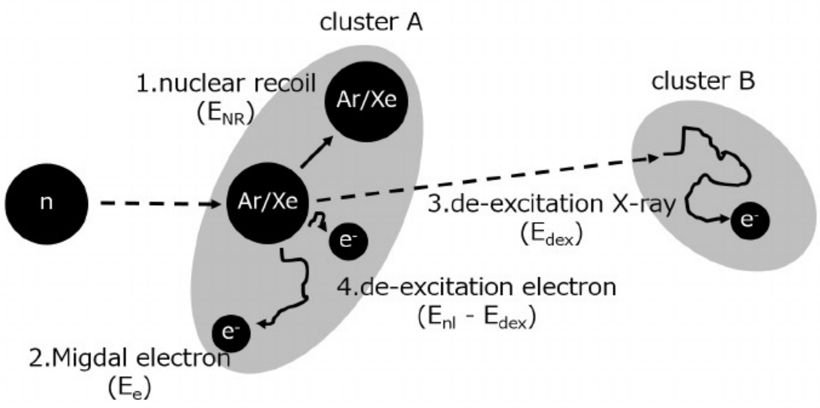
- Neutron beams for discovery and calibration
- Higher recoil velocity than dark matter regime



Xu et al, 2307.12952

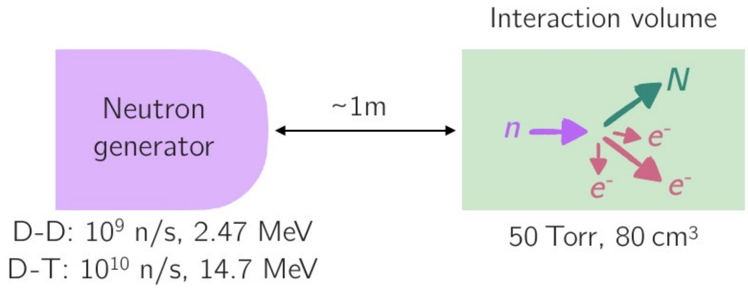


MIGDAL Collaboration, 2207.08284



Nakamura et al, 2009.05939

Also Bell et al, 2112.08514



The Migdal Effect

- Electronic wave-function from Galilean boost of initial state
- Transition probability:

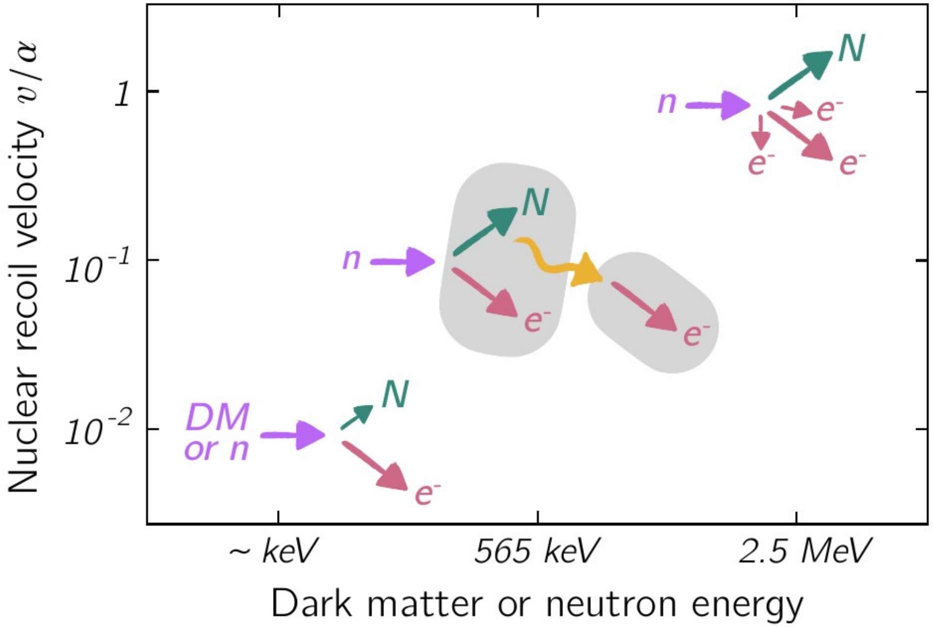
$$p_v\left(\Psi_i \to \Psi_f\right) = \left|\left\langle \Psi_f \middle| \exp\left(i m_e v \cdot \sum_{k=1}^{N} r_k\right) \middle| \Psi_i \right\rangle\right|^2$$

- Dipole approximation
- Small recoil velocities
- Single electron ionisation/excitation

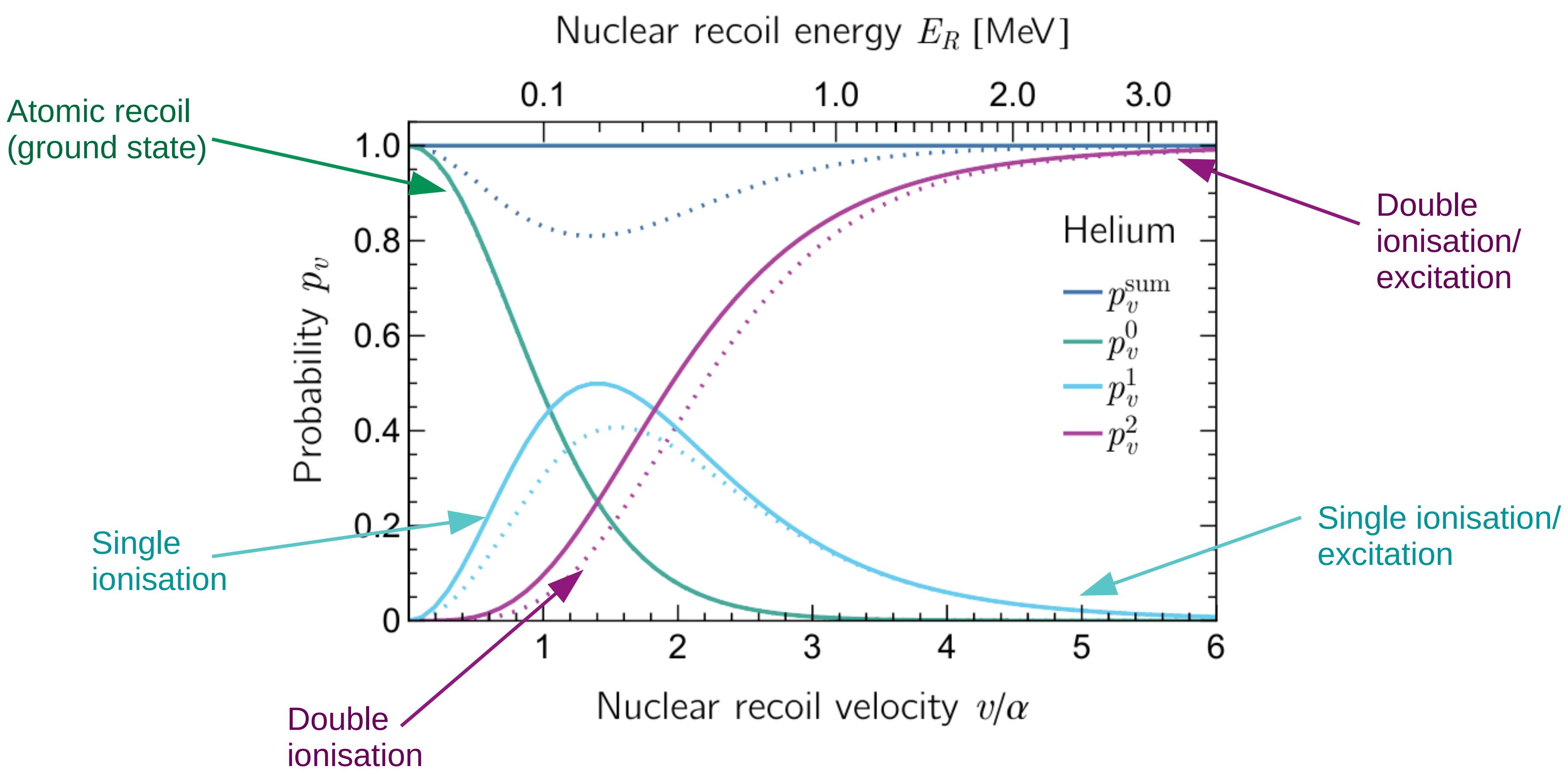
$$\exp\left(i m_e \mathbf{v} \cdot \sum_{k=1}^{N} \mathbf{r}_k\right) \approx 1 + i m_e \mathbf{v} \cdot \sum_{k=1}^{N} \mathbf{r}_k$$

Ibe et al, 1707.07258

- We keep exponential factor
- Understand multiple ionisation
- Improve treatment of atomic physics

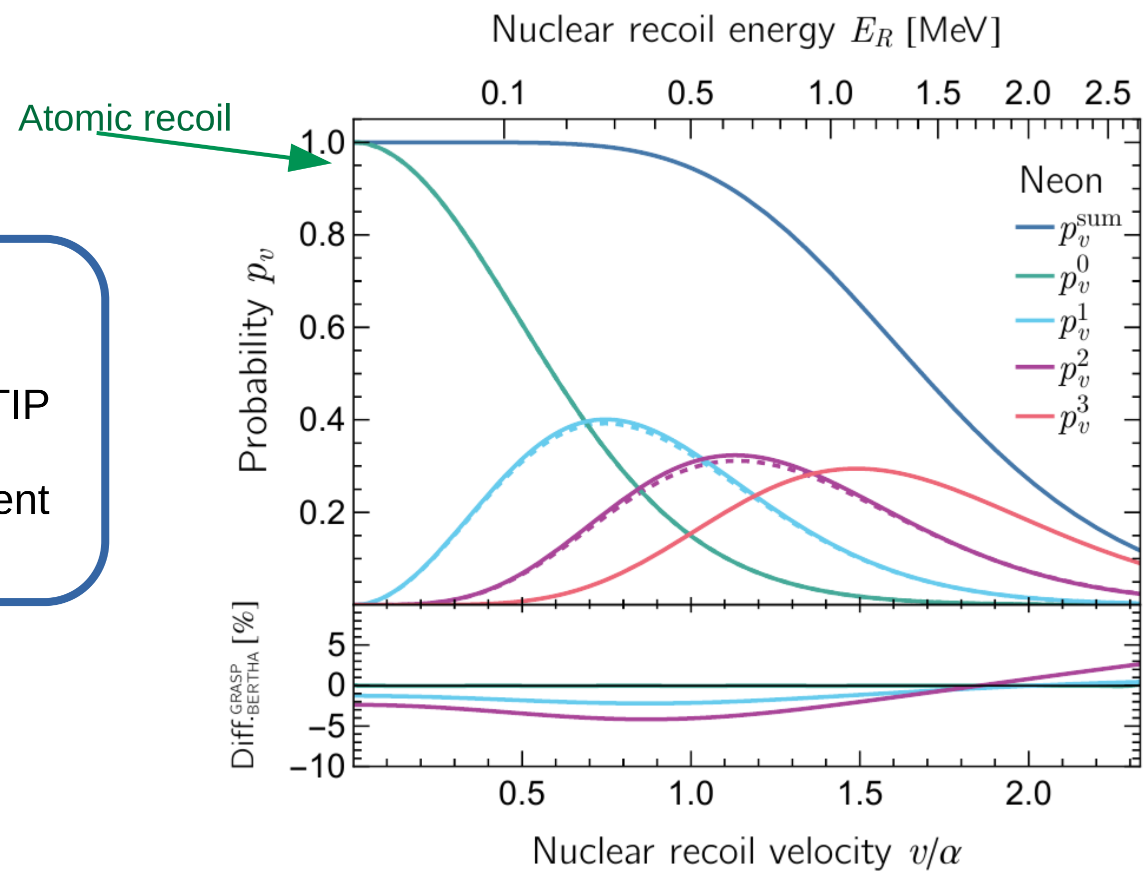


Integrated Transition Probabilities: Helium



Consistency of Different Calculations

- Solid: BERTHA
- Dashed: GRASP+RATIP
- Percent-level agreement



- We calculate up to triple transitions
- Ignoring quad-transitions and above: loss of unitarity at high velocity
- Is this a major problem?

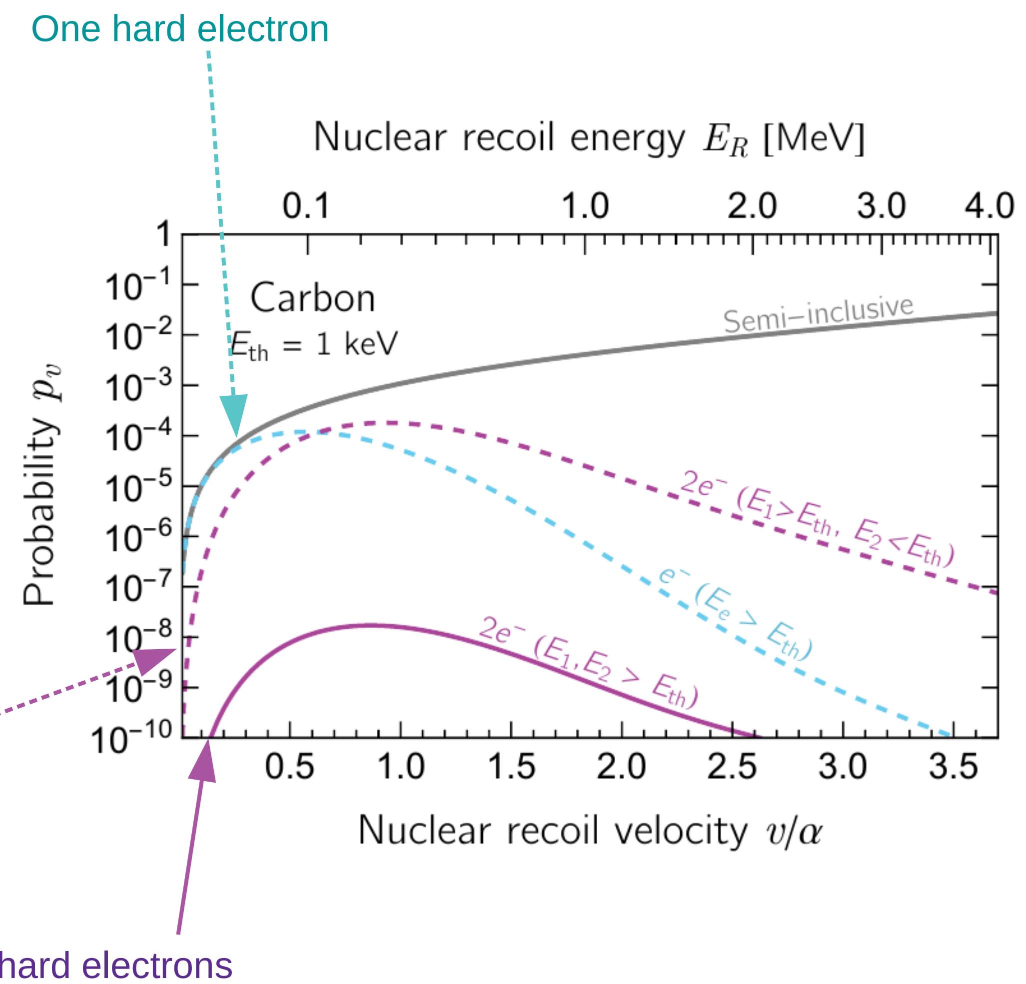
Thresholds matter!

- At large recoil velocities *observable* rate is dominated by

  1 hard + multiple soft electrons

- Production of multiple hard electrons suppresed

Hard: energy above experimental threshold
Soft: energy below experimental threshold



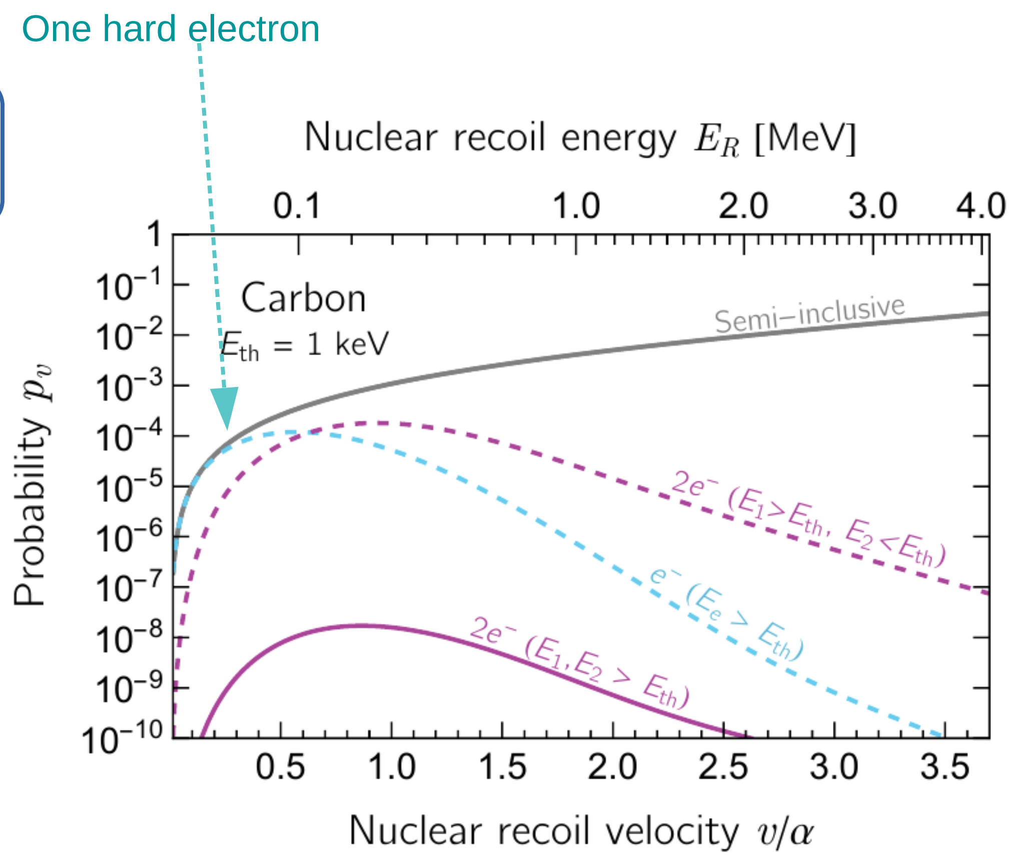
Semi-inclusive ionisation probabilities

Semi-inclusive probability: probability for a single ionisation electron above threshold, all others soft.

$$p_v(|\Psi_i\rangle \to |\chi_{b_1} X_{\text{soft}}\rangle) = \frac{1}{(N-1)!} \sum_{b_2,\ldots,b_N}^{(E<E_{\text{th}})} \left| \left\langle \chi_{b_1} \ldots \chi_{b_N} \middle| e^{i m_e \boldsymbol{v} \cdot \sum_k \boldsymbol{r}_k} \middle| \Psi_i \right\rangle \right|^2$$

- Sum over states where (N-1) electrons have energies less than threshold
  - Can approximate this as

$$\sum_{\alpha=1}^{N} \left| \left\langle \chi_{b_1} \middle| e^{i m_e \boldsymbol{v} \cdot \boldsymbol{r}} \middle| \psi_{a_\alpha} \right\rangle \right|^2$$



Breaks down when $v/\alpha \gtrsim 8.6\sqrt{(E_{\text{th}}/1\ \text{keV})}$,

The MIGDAL Experiment: Neutron Cross-sections

- Neutron-induced Migdal rate

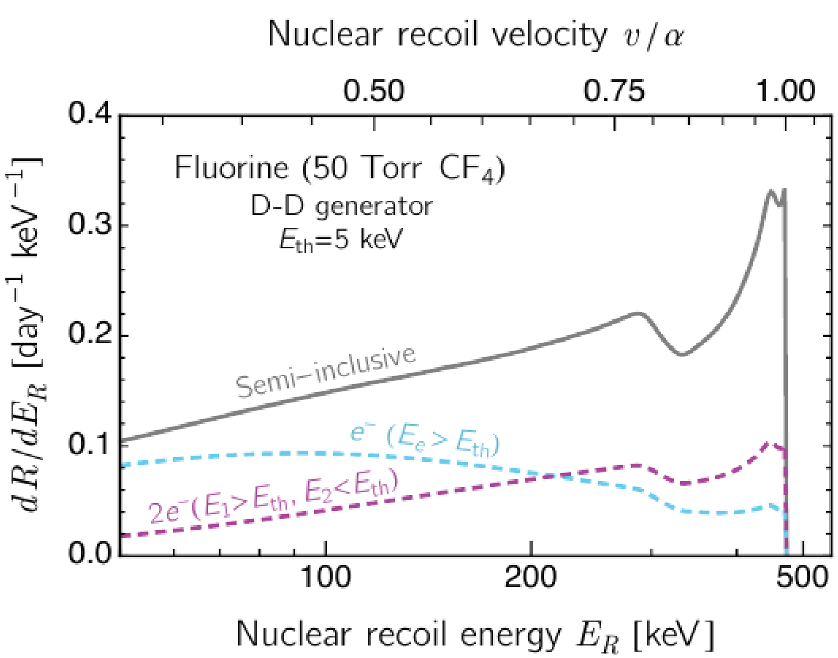
$$\frac{d^2R}{dE_R dE_e} = \phi_n \sum_i N_T^i \frac{d\sigma_s^i}{dE_R} \sum_{n\kappa} \frac{dp_v^i(n\kappa \rightarrow E_e)}{dE_e} \,,$$

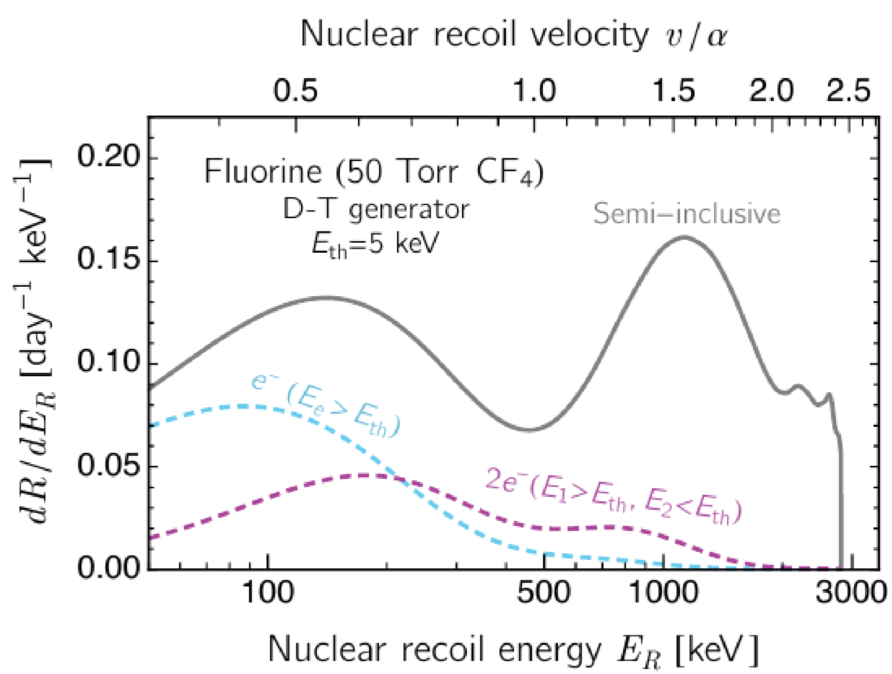
Neutron flux

Number of target atoms

Neutron-nucleus cross-section

- Need semi-inclusive cross-section for multiple soft ionisations
- Treat molecule as discrete set of atoms.

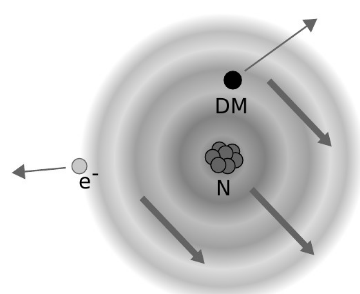




Cox, MJD, McCabe, Quiney, 2208.12222

Conclusions

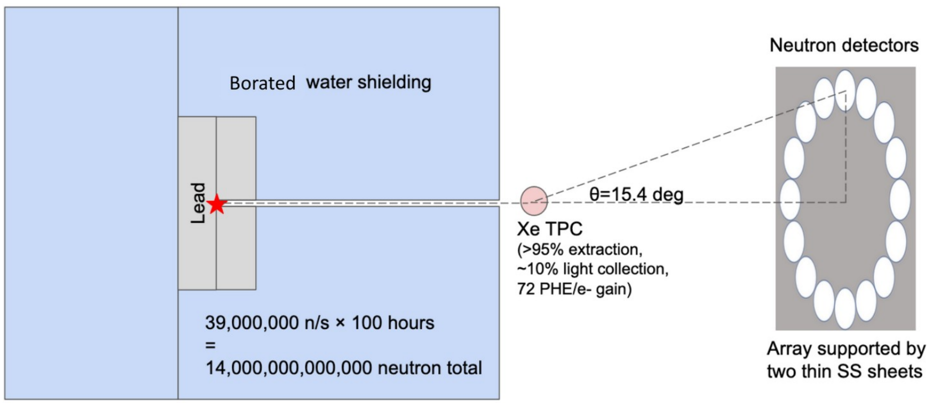
- Revisited and improved calculations of the Migdal effect
- Beyond dipole approximation, multiple ionisations, high recoil velocities
- Applications in direct detection and neutron experiments
- Migdal extends sensitivity of hydrogen-doped LXe experiments
- Major enhancement in SD proton scattering limits possible.

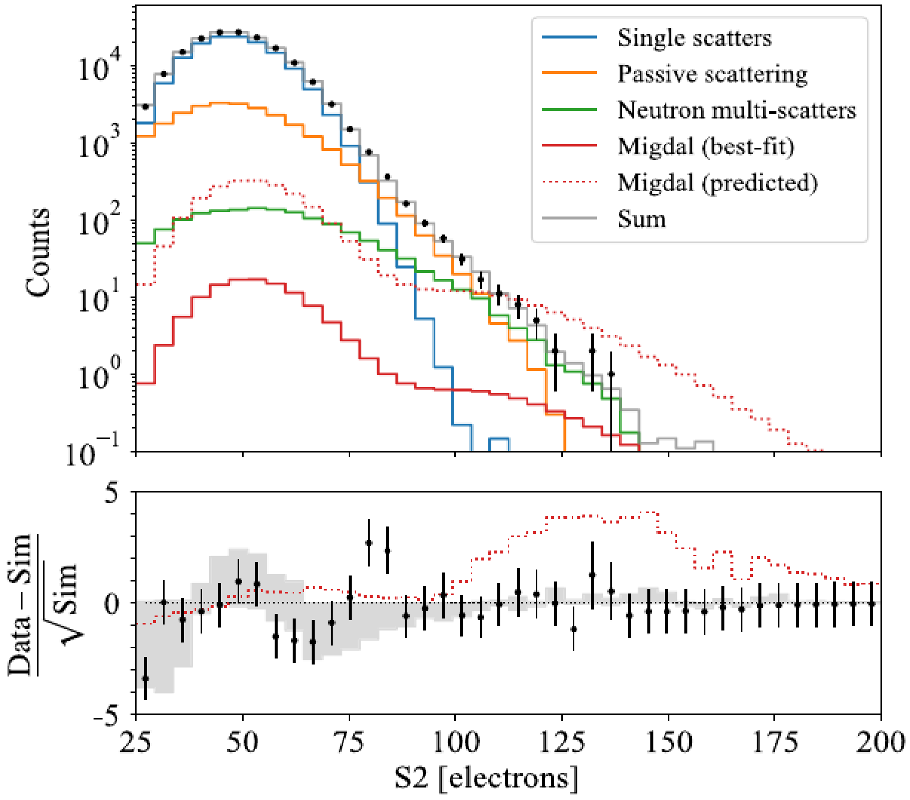


https://petercox.github.io/Migdal/

Extra Material: Neutron Scattering at LLNL

- LLNL: DT source (14.1MeV) incident on Xe TPC with neutron detector array





- Predicted Migdal: 148.2 ± 16.3
- Observed Migdal: $16.3^{+21.7}_{-16.3}$

- Calculations wrong: unlikely
- Enhanced electron-ion recombination in liquid xenon?
- Make S2 signal more S1-like
- Might not be such an issue for DM searches...

Xu et al, 2307.12952