Exploring light dark matter with the Migdal effect in hydrogen-doped liquid xenon

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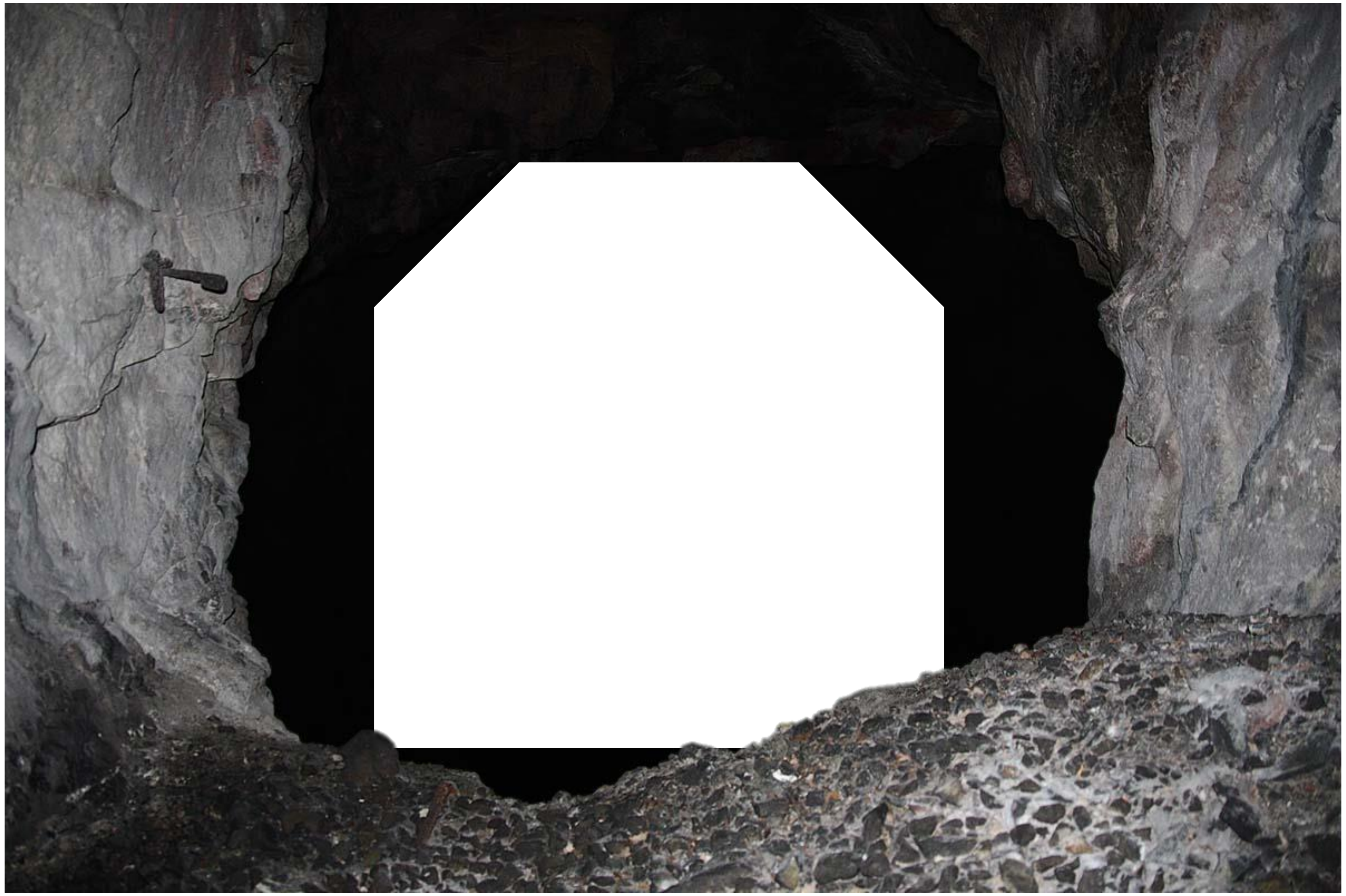
2305.04690

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

THE UNIVERSITY OF MELBOURNE

Dark matter direct detection



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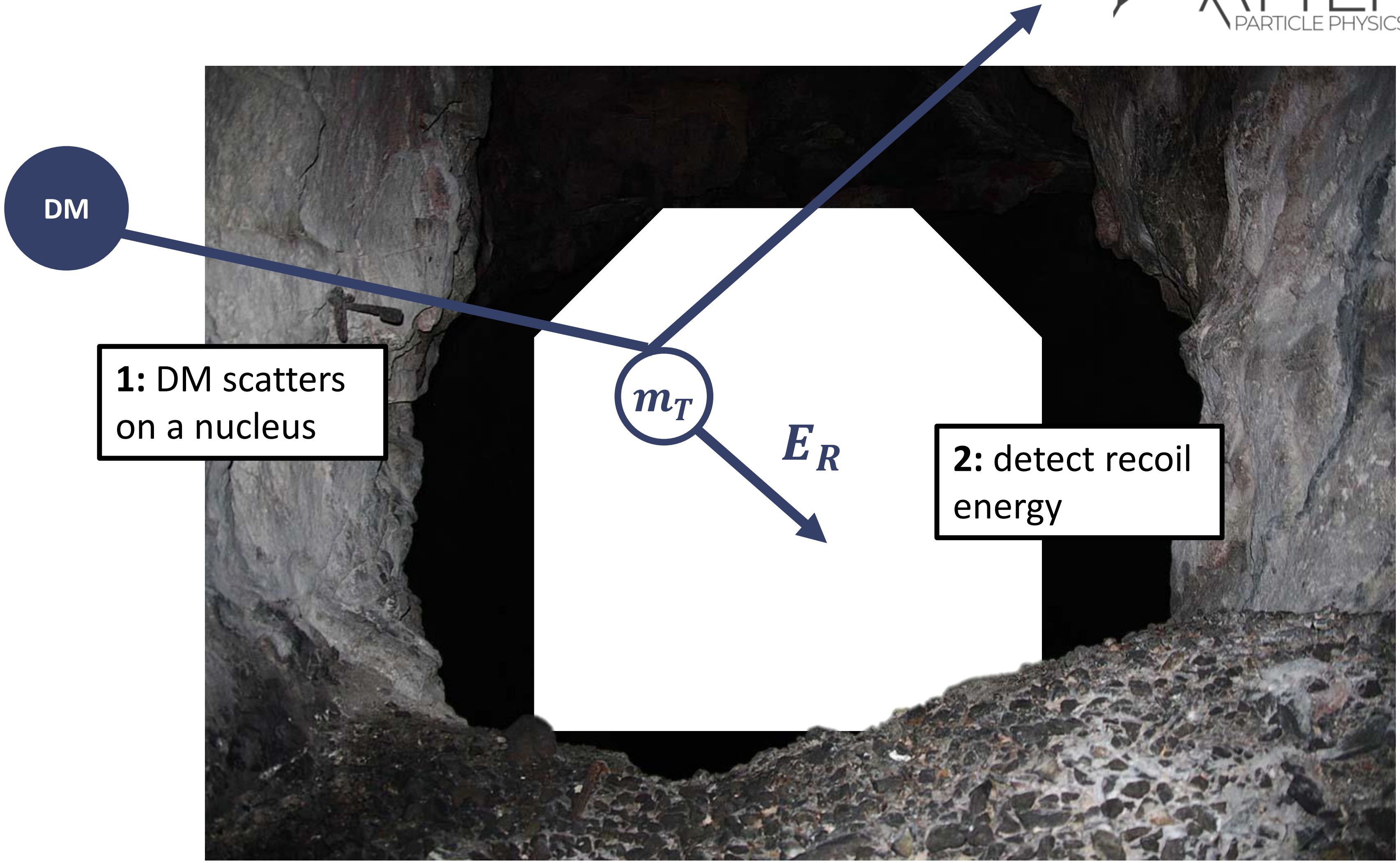
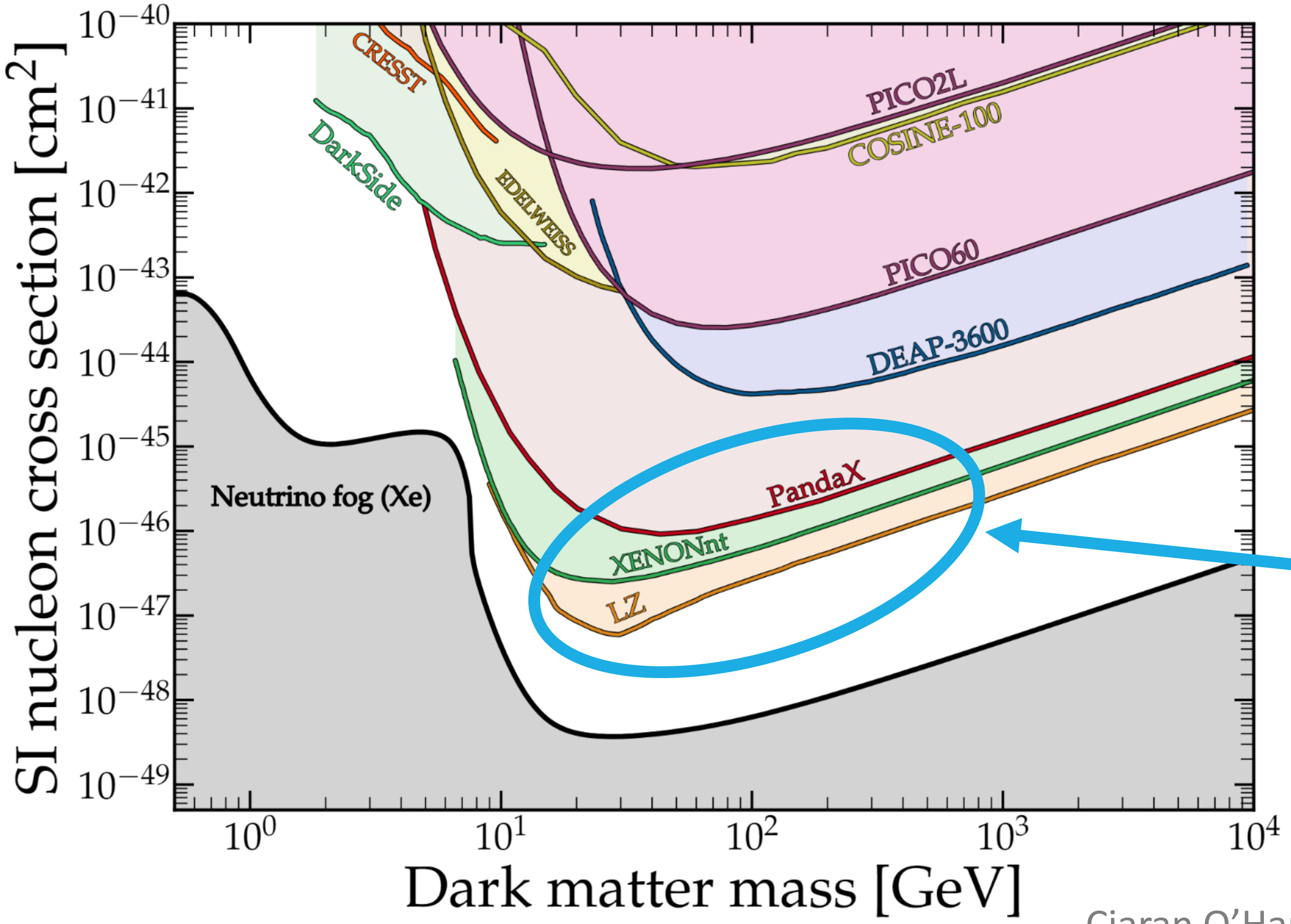


1: DM scatters on a nucleus

2: detect recoil energy

Current direct detection limits

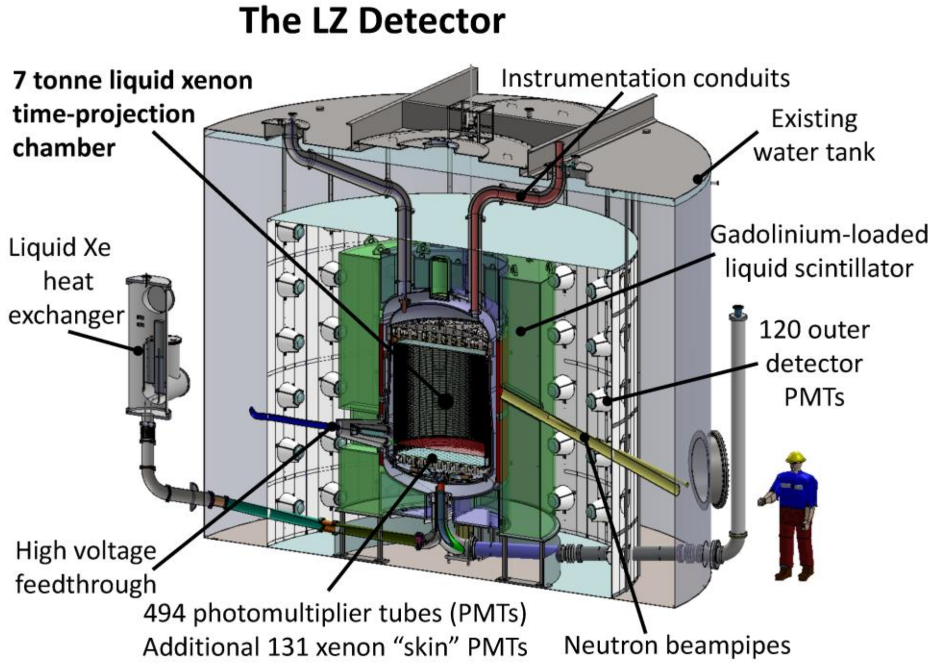


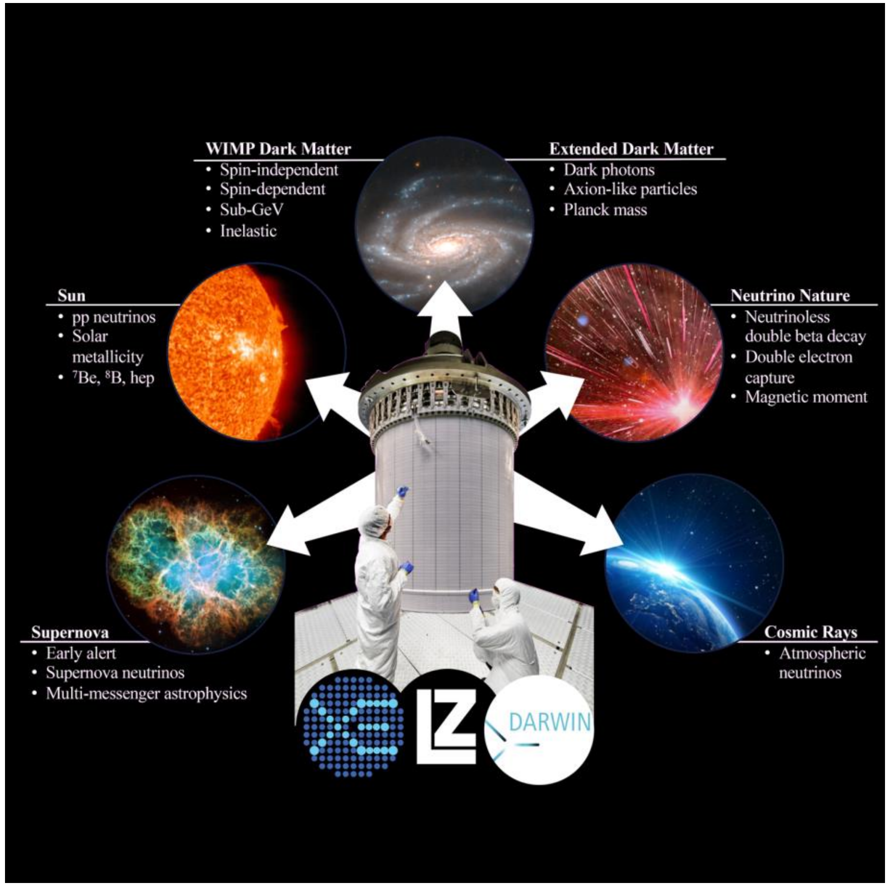
Liquid xenon dual-phase TPCs

Ciaran O'Hare, CDM Annual Workshop 2023

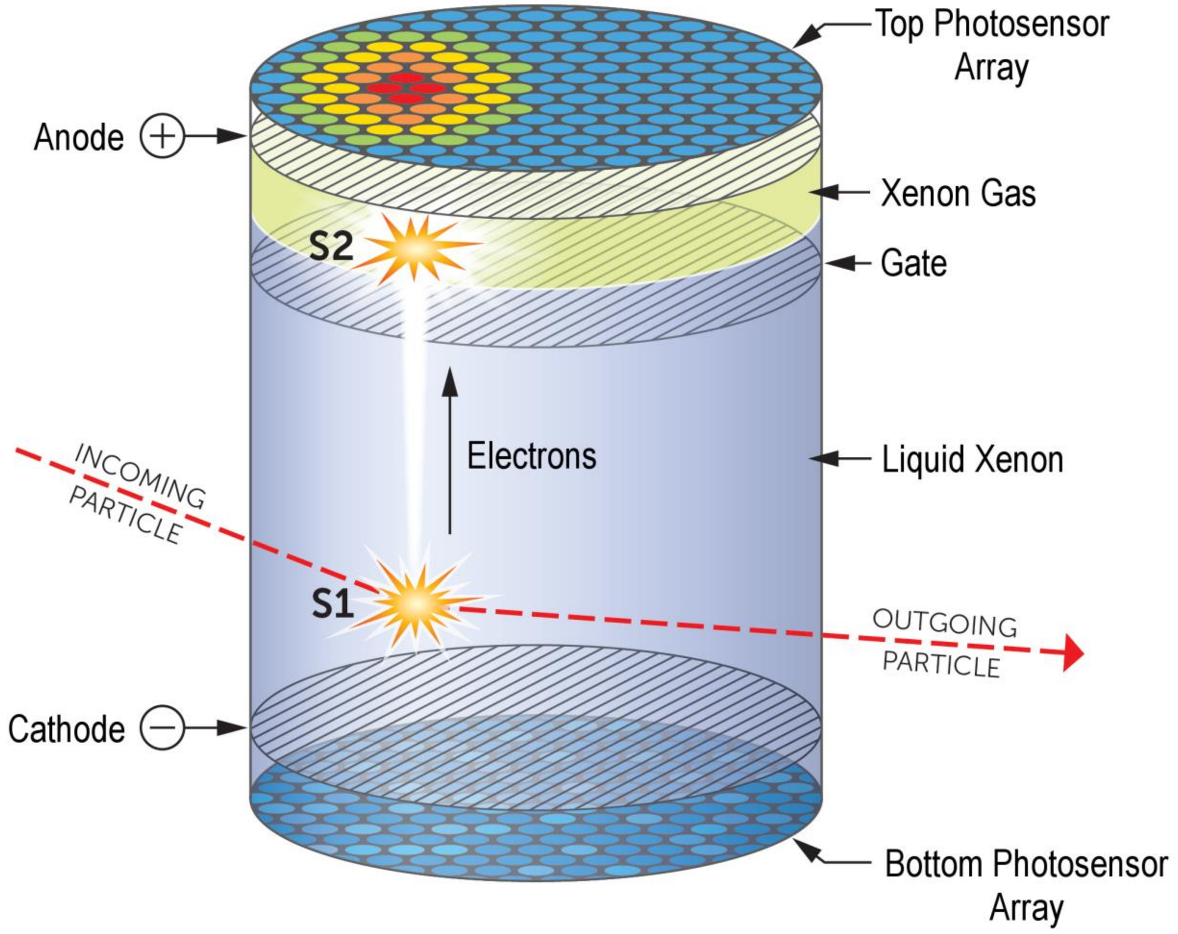
Liquid xenon time-projection chambers

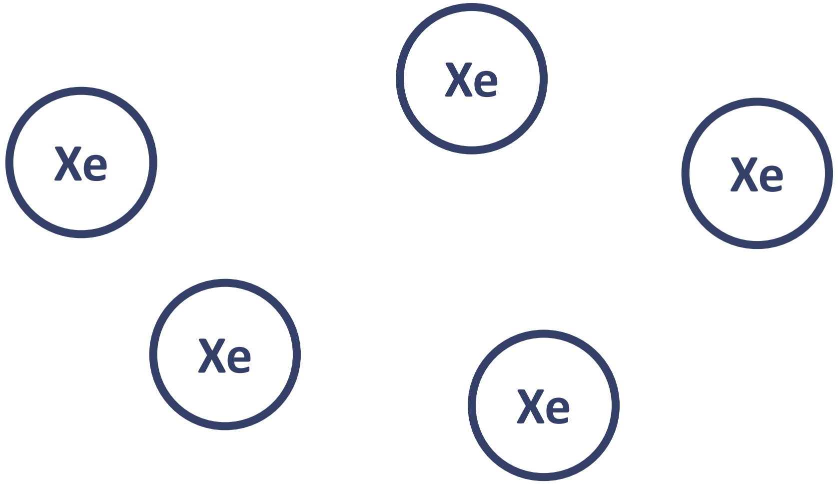
Currently the most sensitive detectors for GeV-TeV scale DM (e.g. WIMPs)





Dual phase time-projection chamber





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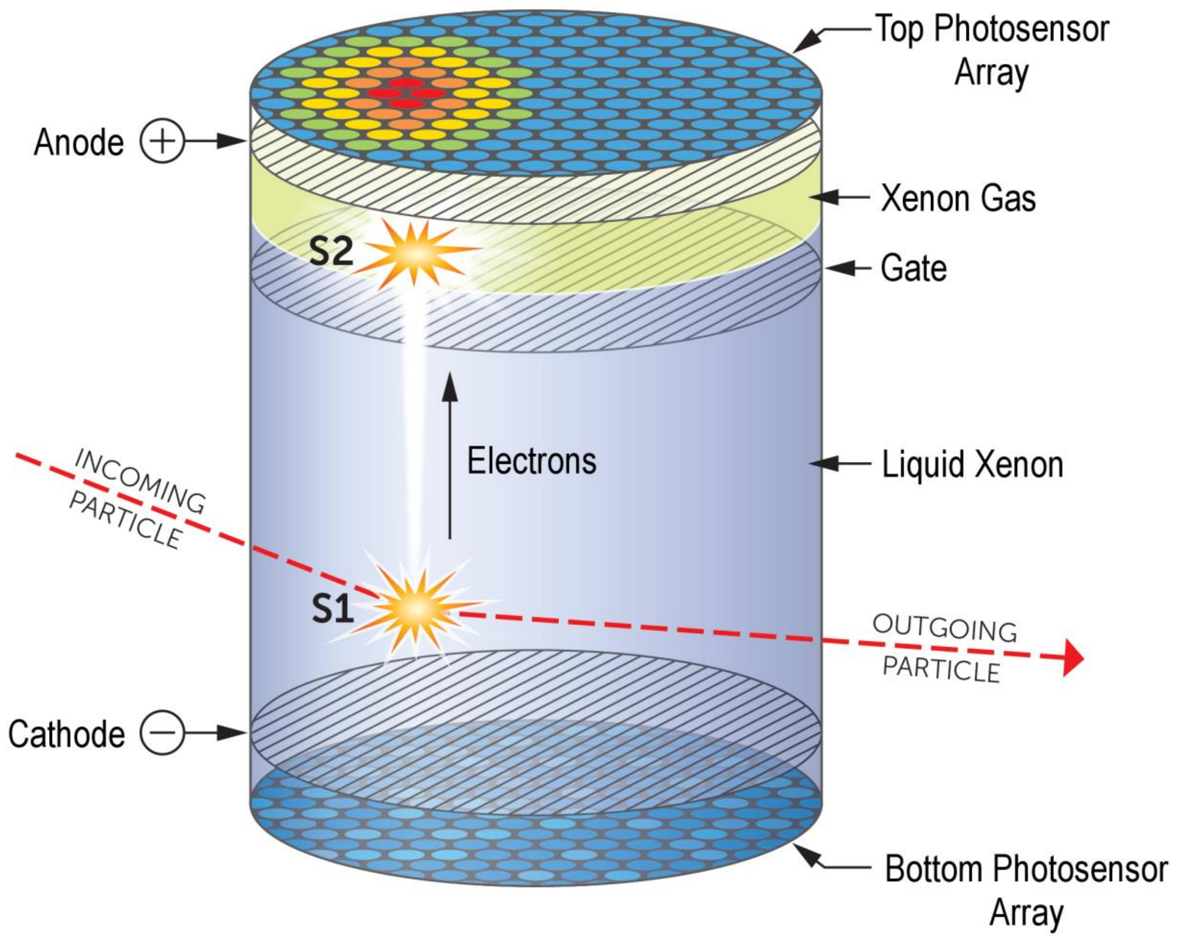
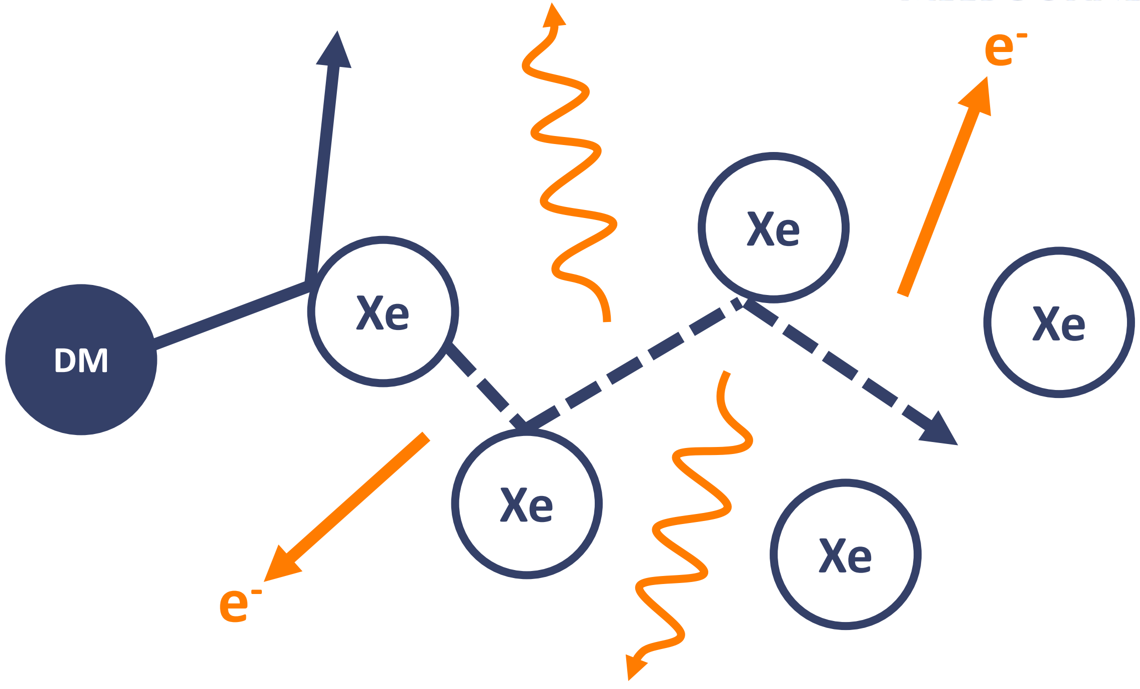




S1 (light signal): primary scintillation photons

S2 (charge signal): electrons drifted through detector and accelerated through a gas phase

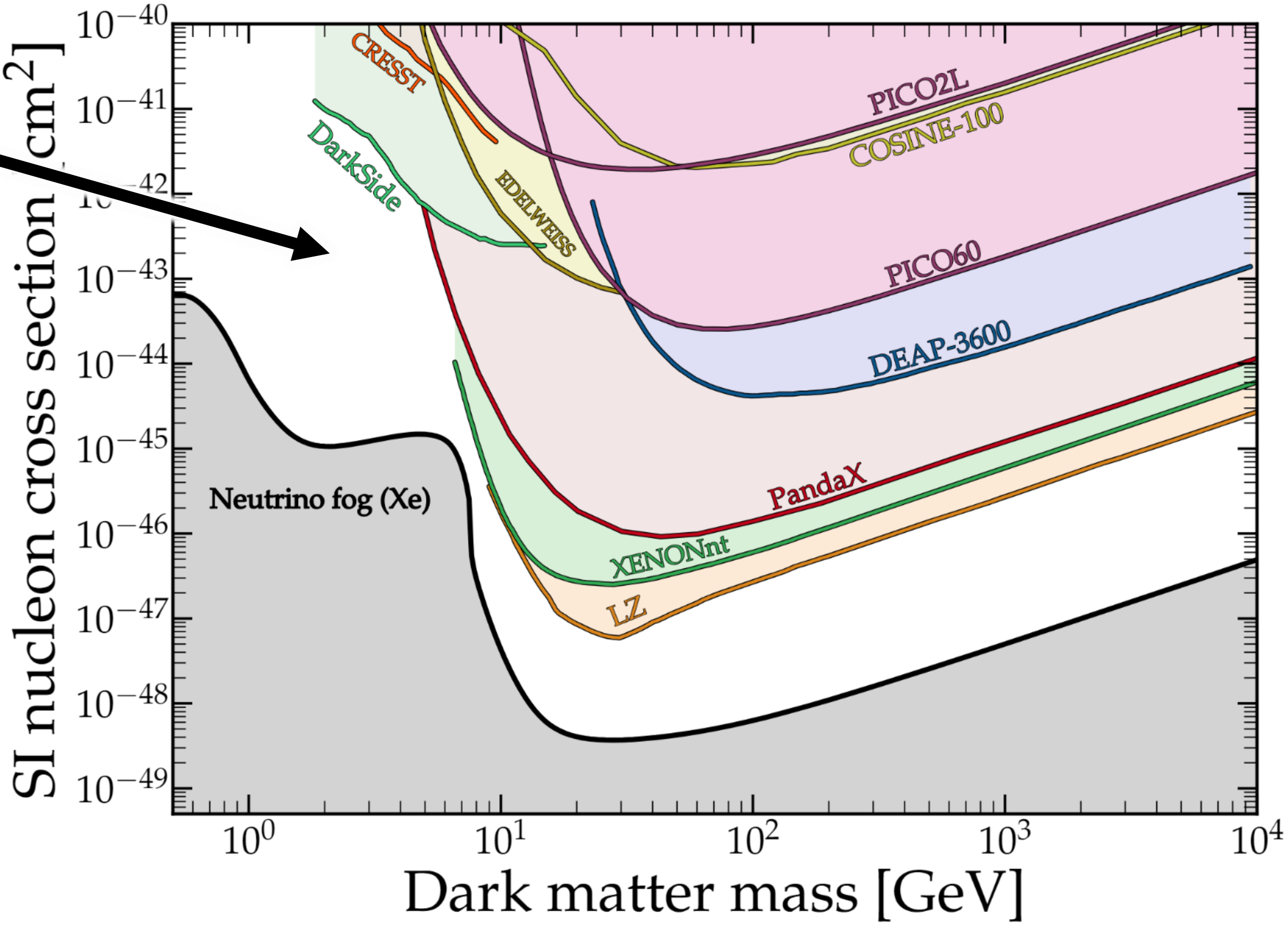
Direct detection for light* DM

Lose sensitivity to "light" dark matter (< a few GeV)

Recoil energy below detector threshold

$$E_R < E_{\text{th}}$$

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



Ciaran O'Hare, CDM Annual Workshop 2023

Extending the reach to light DM

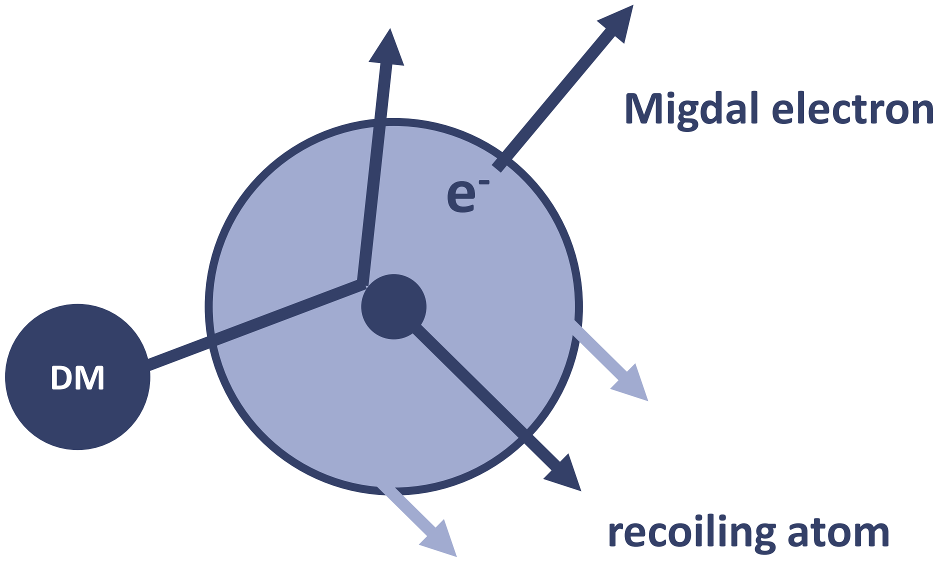
The Migdal effect

The recoiling nucleus is momentarily displaced from the electron cloud

→ electron ionisation

Rare process: ~1 in 10,000 recoils

The energy of the recoiling electron can be above the detector threshold

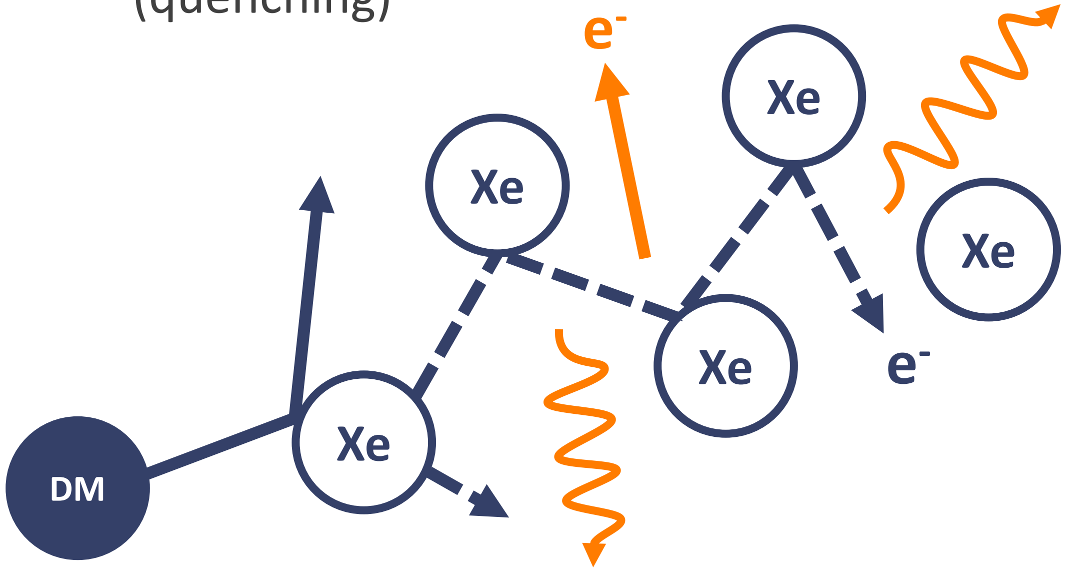


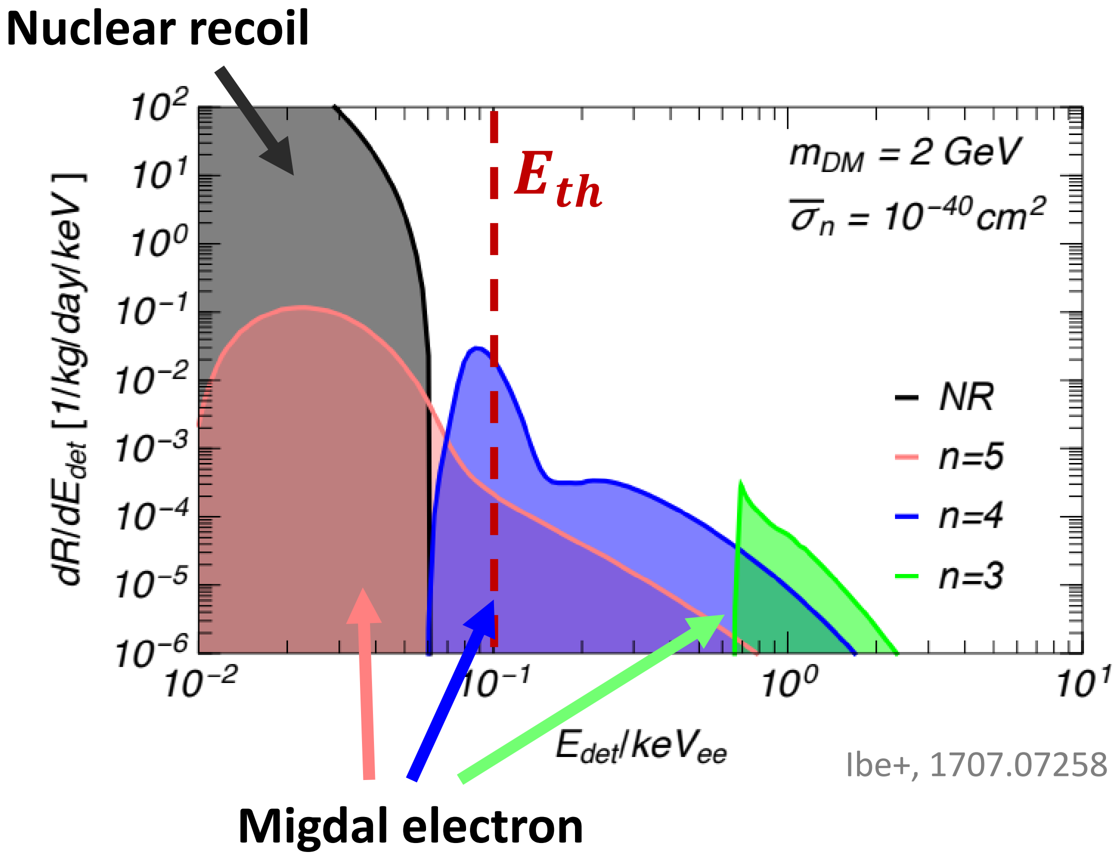
$$E_{EM_{\max}} = \frac{\mu_T}{2} v_{\max}^2 \quad \textbf{vs} \quad E_{R_{\max}} = \frac{2\mu_T^2}{m_T} v_{\max}^2$$

Migdal searches

When the nuclear recoil energy is below threshold, look for the **S1/S2** signal from the Migdal electron

- can also perform an **S2-only** search to lower the threshold
- Recoiling electron loses less energy to heat (quenching)





Ibe+, 1707.07258

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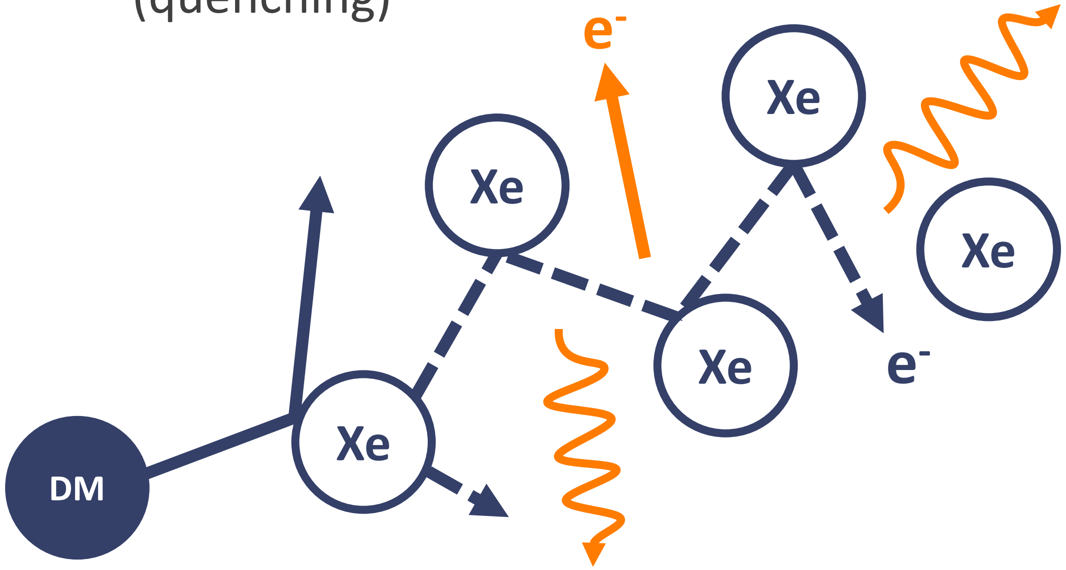
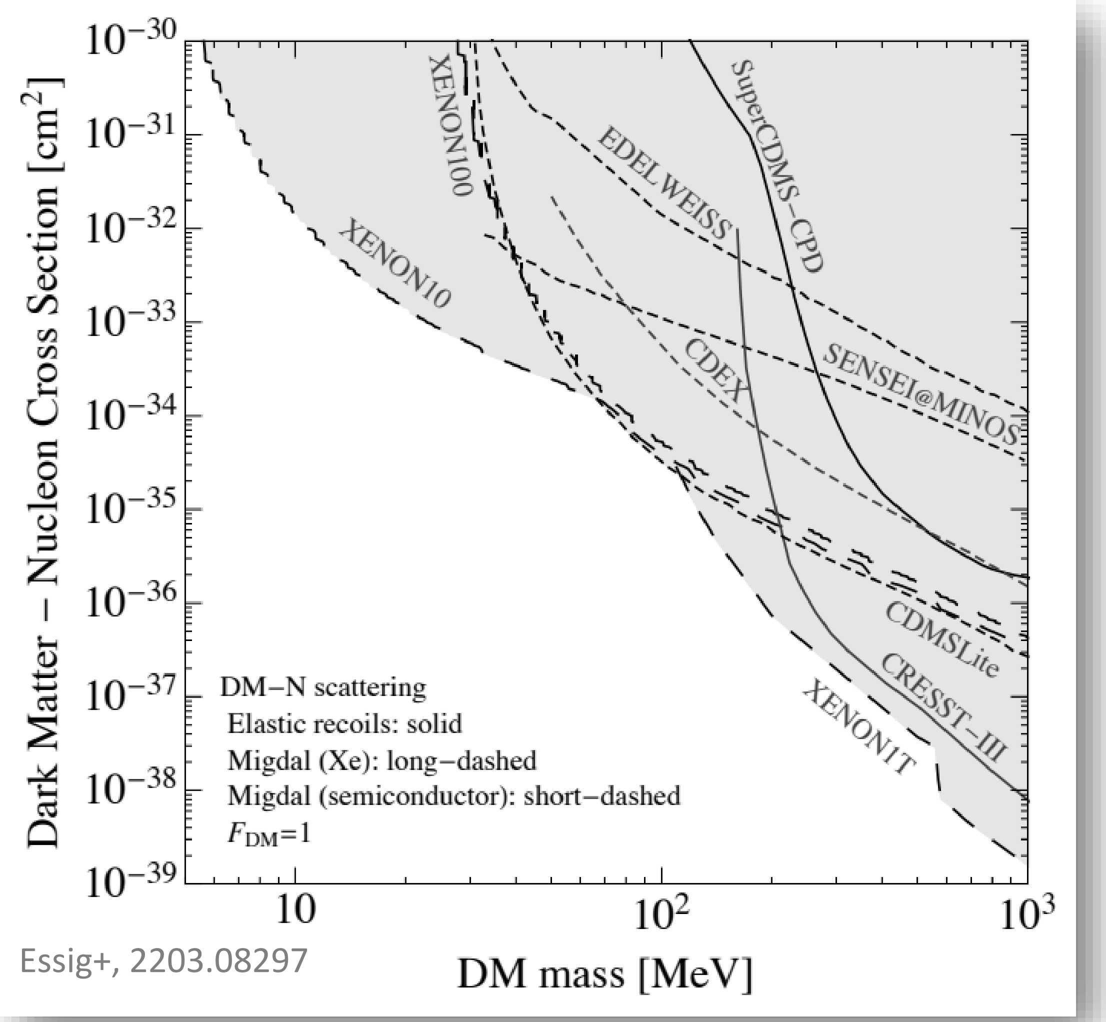
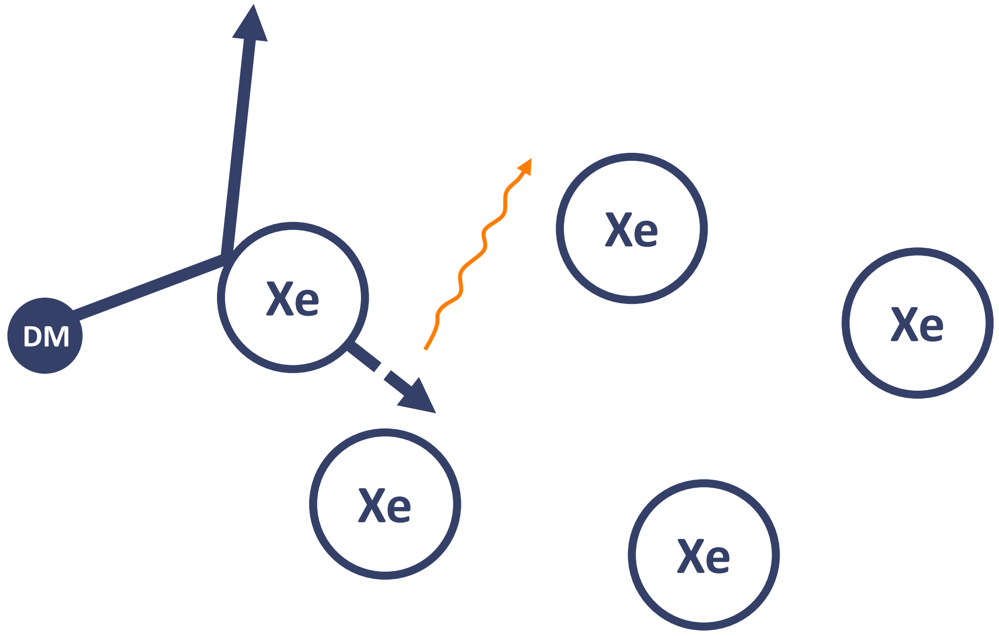




Hydrogen doping

Another way to improve the sensitivity to light DM



Hydrogen doping

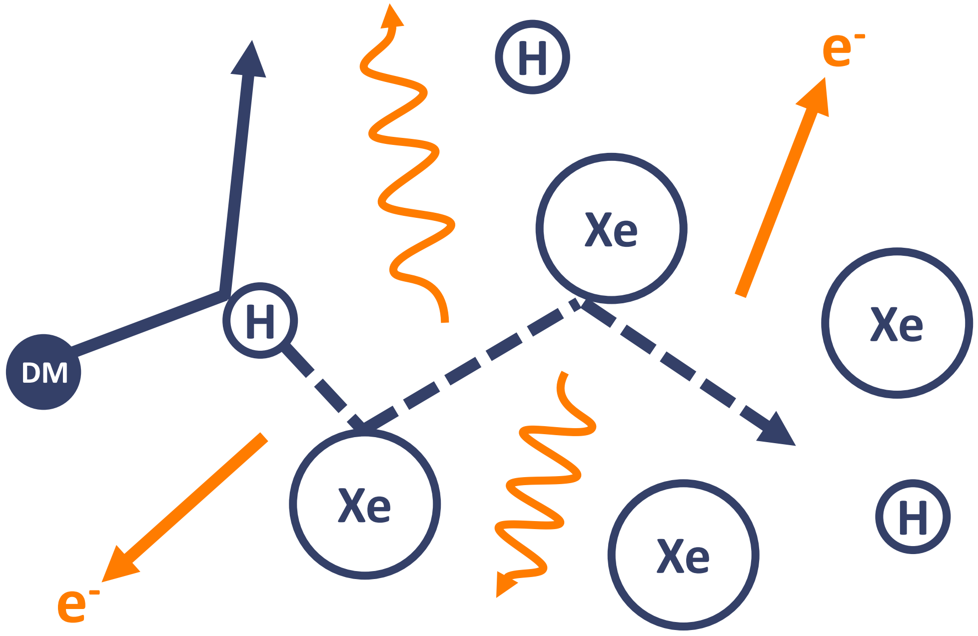
Another way to improve the sensitivity to light DM

- A light target provides better kinematic matching to light DM

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

decrease m_T

- Recoiling hydrogen also loses less energy to heat than a recoiling xenon atom



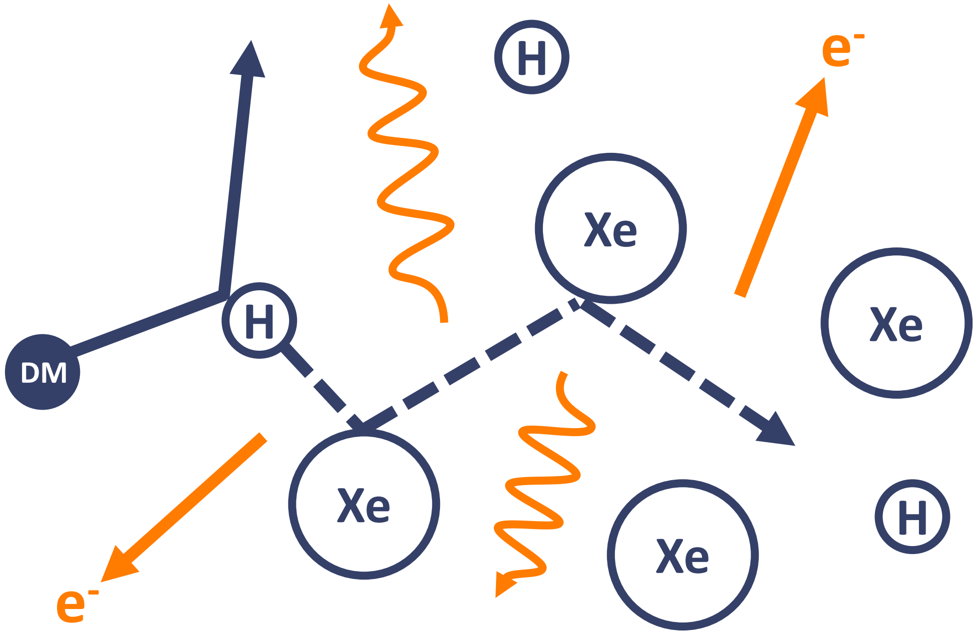
Why doping?

Why not build a new detector entirely of a light target?

Exploit the sensitivity of a light target + the excellent sensor properties of LXe

- Hydrogen is the **target**
- Xenon is the **sensor**

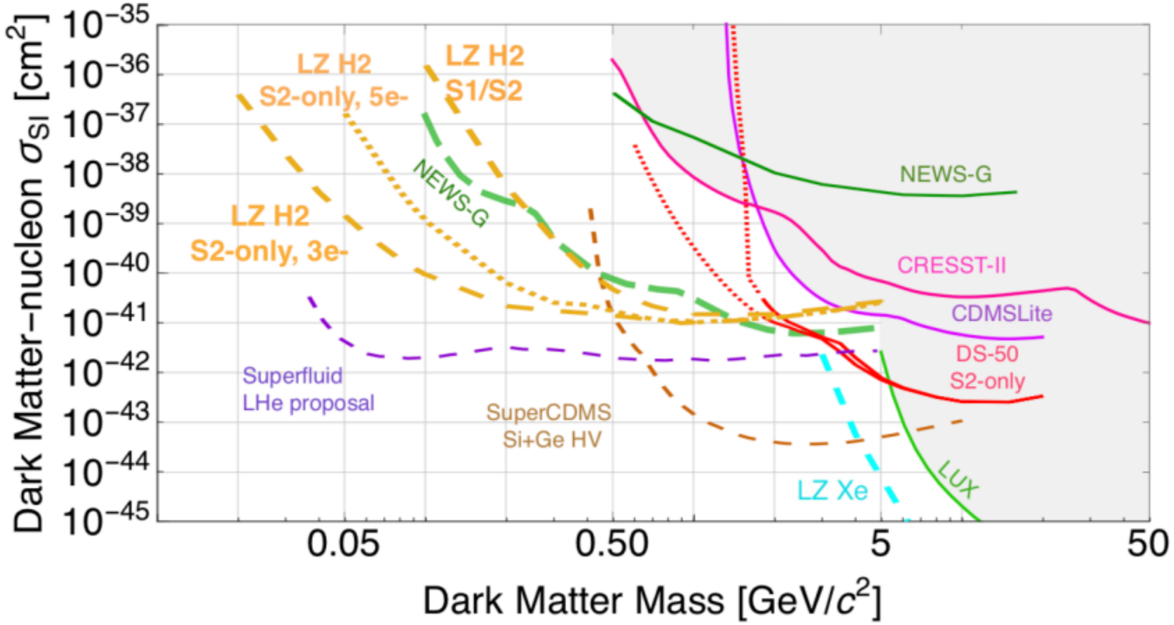
Utilise existing detector technology & calibration



HydroX

HydroX is a proposal to dope LZ

- Dope it after its first science run with H_2
- Currently in the R&D stage



Haselschwardt, UCLA DM ’23 (HydroX)

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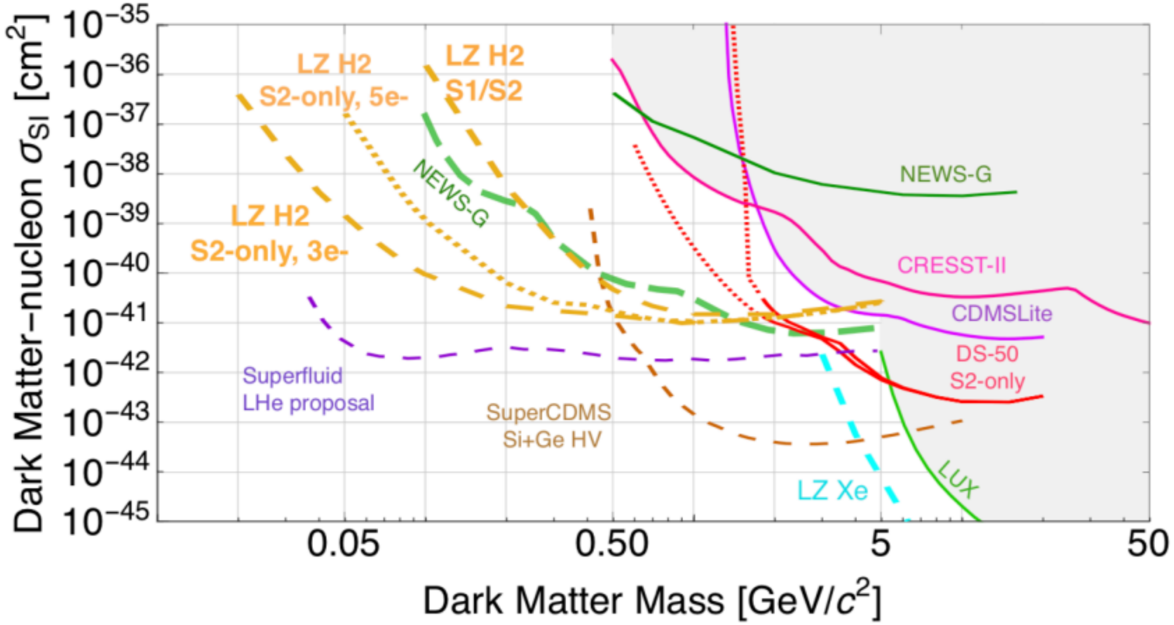


Haselschwardt, UCLA DM '23 (HydroX)

Questions

- What S1/S2 yields do you have for a recoiling proton?
  - Initial simulations
  - Calibration
- Do your xenon yields change?
- How much H_2 can you dissolve in xenon?
  - Probably up to ~5%
- Do you mess with the cryogenics?

Hydrogen doping + Migdal

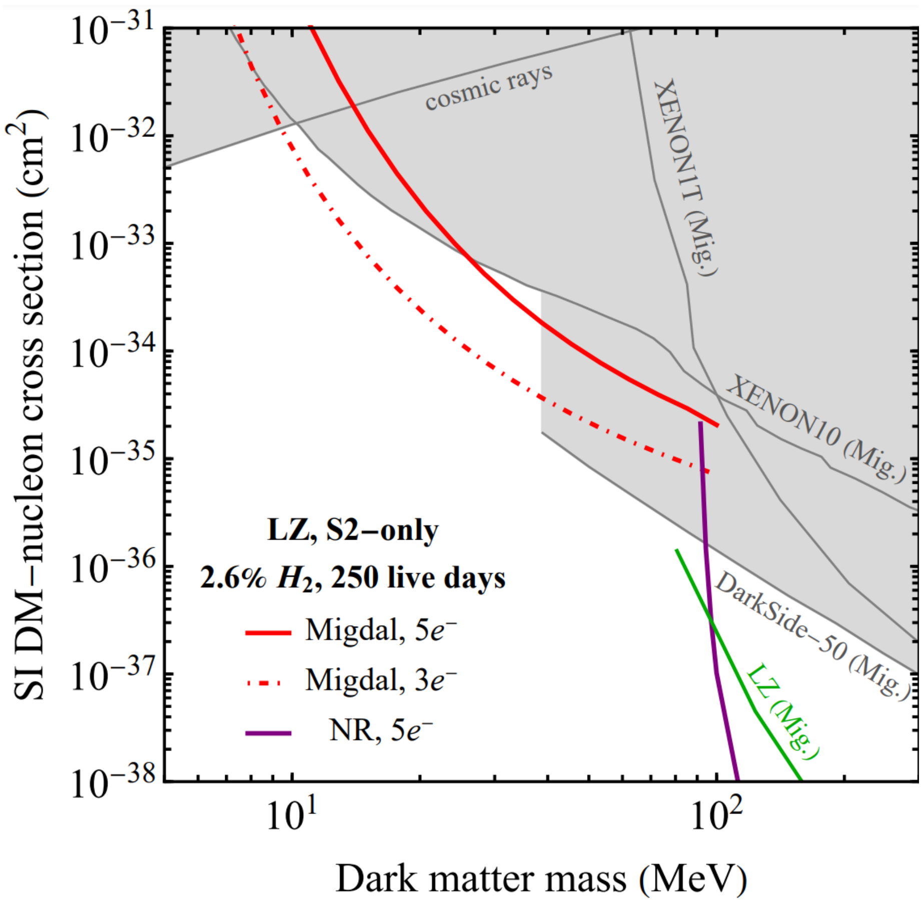
Hydrogen doping + Migdal

Assumed

- 2.6% H_2 dissolved (~2.5 kg in 6.2t of xenon)
- Running for 250 live days

S2-only analysis

- Lowers the threshold
  - 5 detected electrons should be doable
  - 3 detected electrons is maybe optimistic
- Large background from electrons created at the anode and cathode
  - Assume anode BG can be removed via pulse-shape discrimination



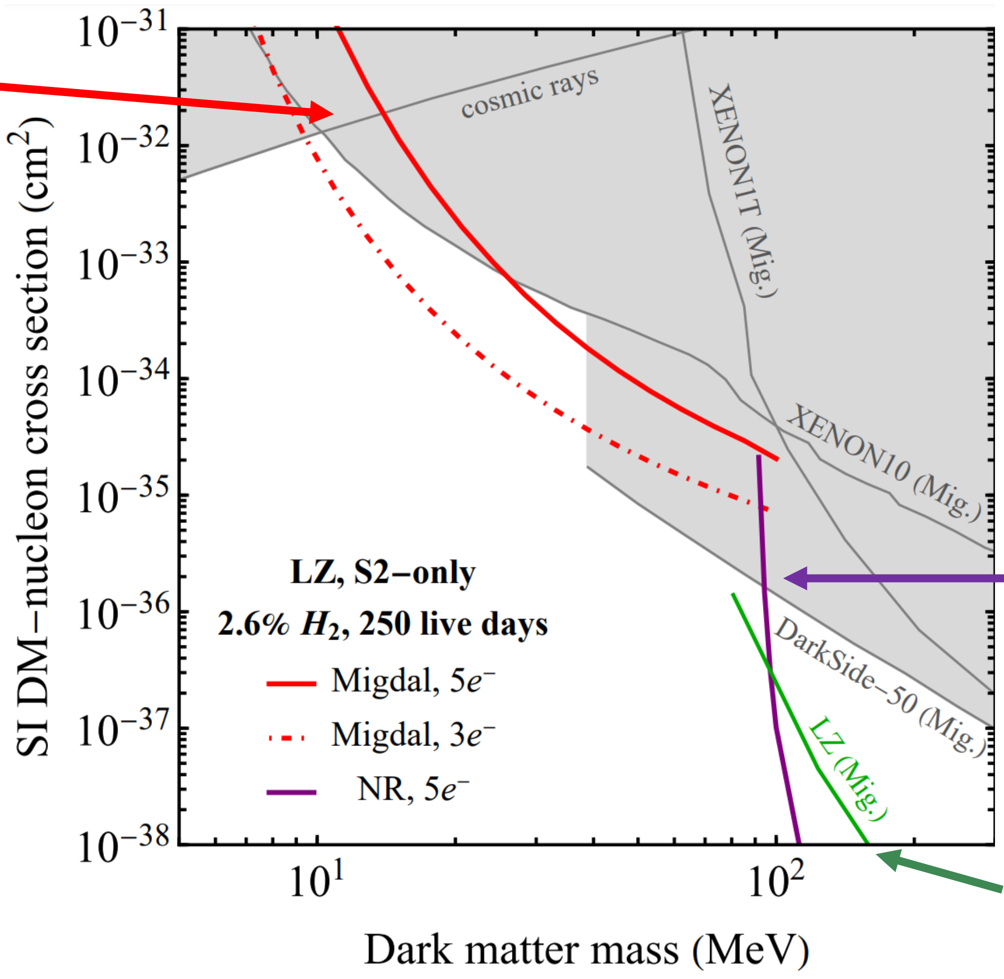
Spin-independent scattering

Migdal + H-doping

5e⁻ only just beats limits from XENON10

- Much older detector, but the analysis was done with a 1 electron threshold

3e⁻ can constrain DM down to masses below 10 MeV



recoiling hydrogen
same as HydroX

LZ projected Mig. sensitivity
w/o H-doping

Spin-dependent proton scattering

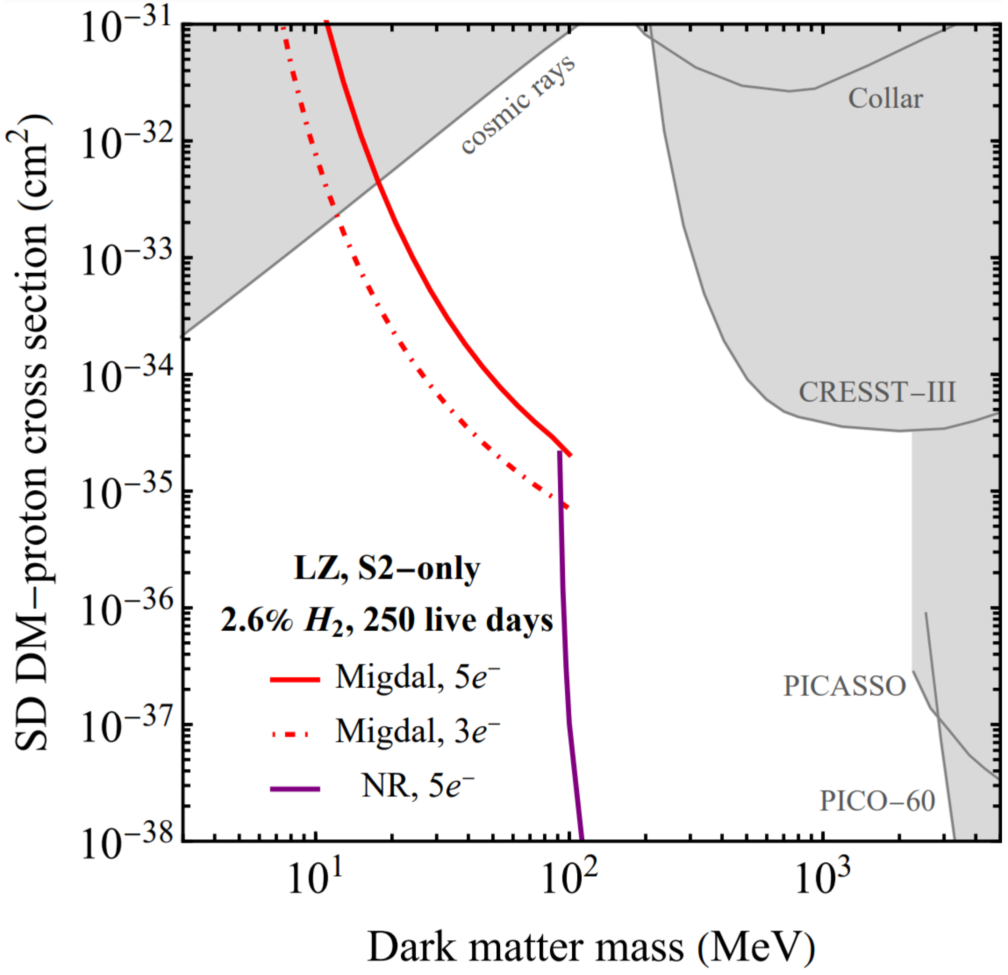
Spin-dependent **proton** sensitivity is much stronger than any current experiments!

- Xenon has an even number of protons

Current best constraints:

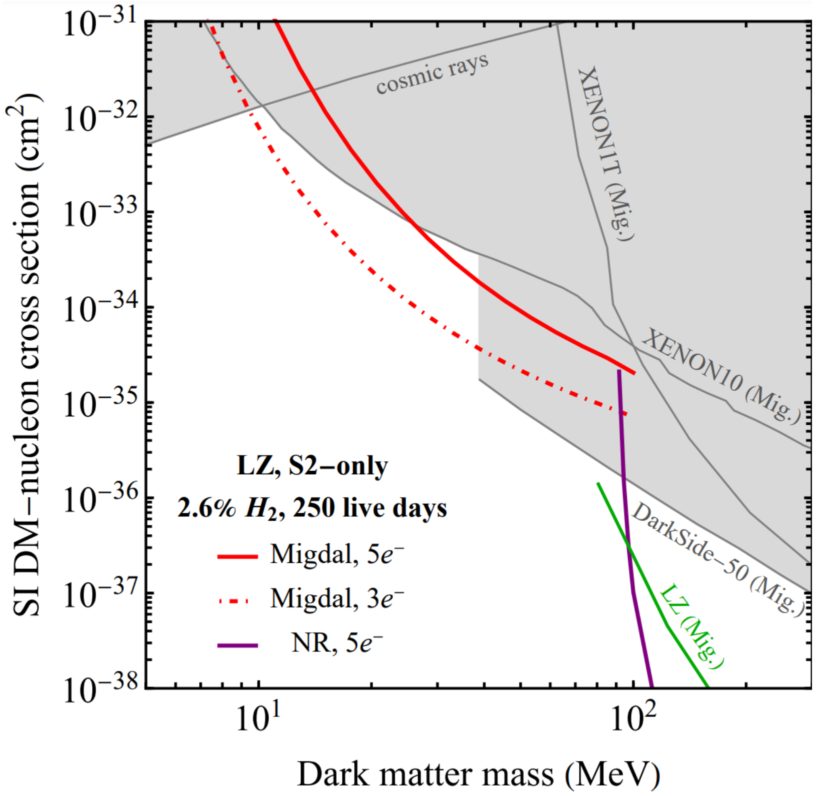
- **fluorine**-based (PICO-60, PICASSO)
- **lithium**-based (CRESST-III)

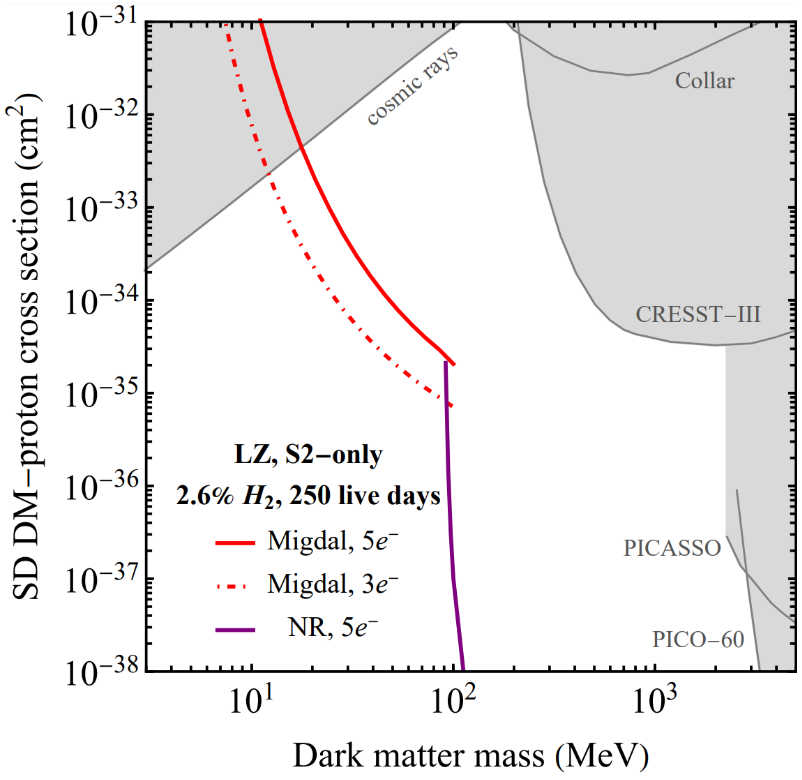
H-doped LZ could probe DM masses an order of magnitude below current constraints



Thank you!

Can set limits on dark matter below 10 MeV with Migdal searches in hydrogen-doped liquid xenon experiments





Backup slides

Helium

Helium could also be used as the light target, **however**

- Lose sensitivity to spin-dependent proton scattering
- It leaks through the PMT glass and spoils the vacuum
  - Not a problem with (molecular) hydrogen