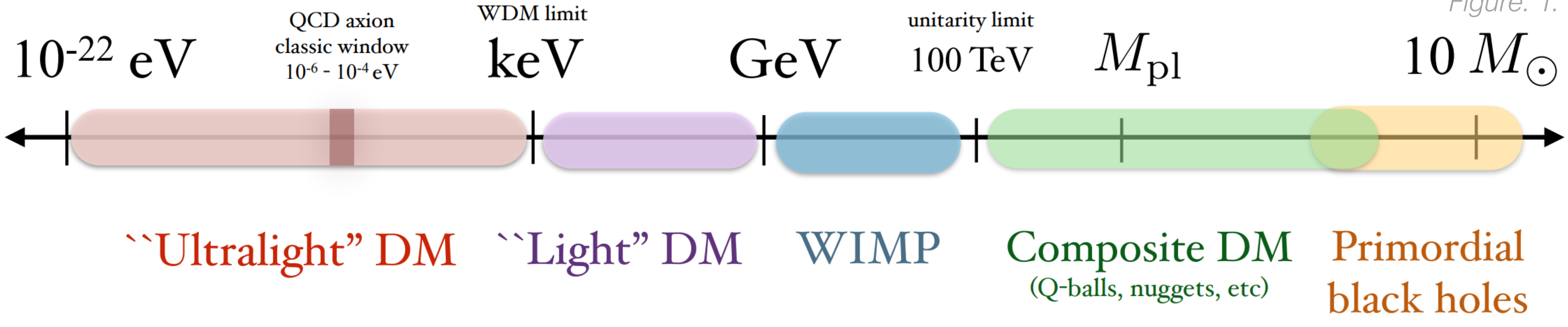
Dark matter detection with the Migdal effect & superfluids

Peter Cox

The University of Melbourne

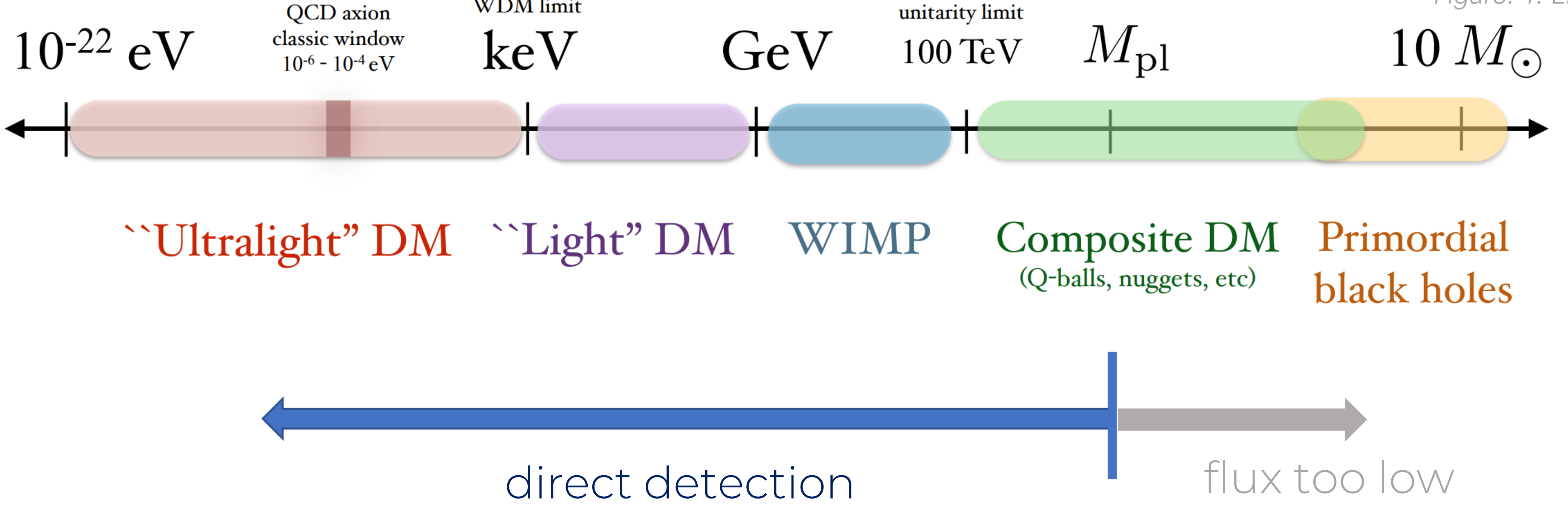
Dark matter landscape

Figure: T. Lin



Dark matter landscape

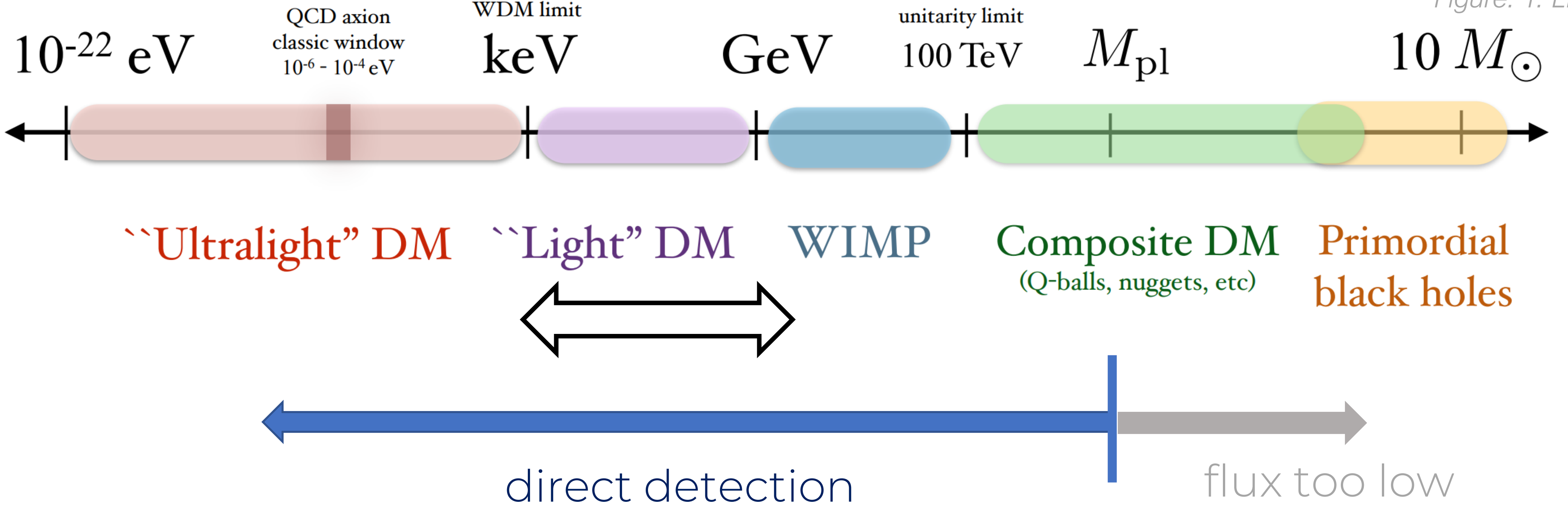
Figure: T. Lin



Direct detection: Search for scattering/absorption of halo dark matter in terrestrial detectors

Dark matter landscape

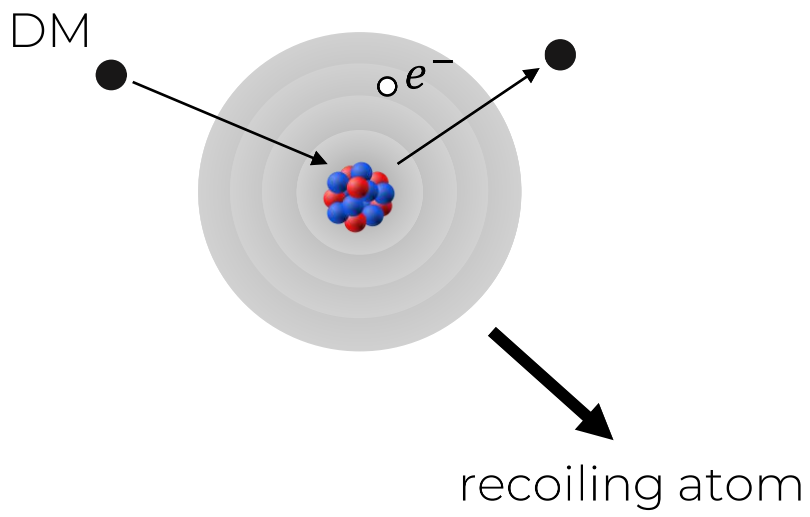
Figure: T. Lin

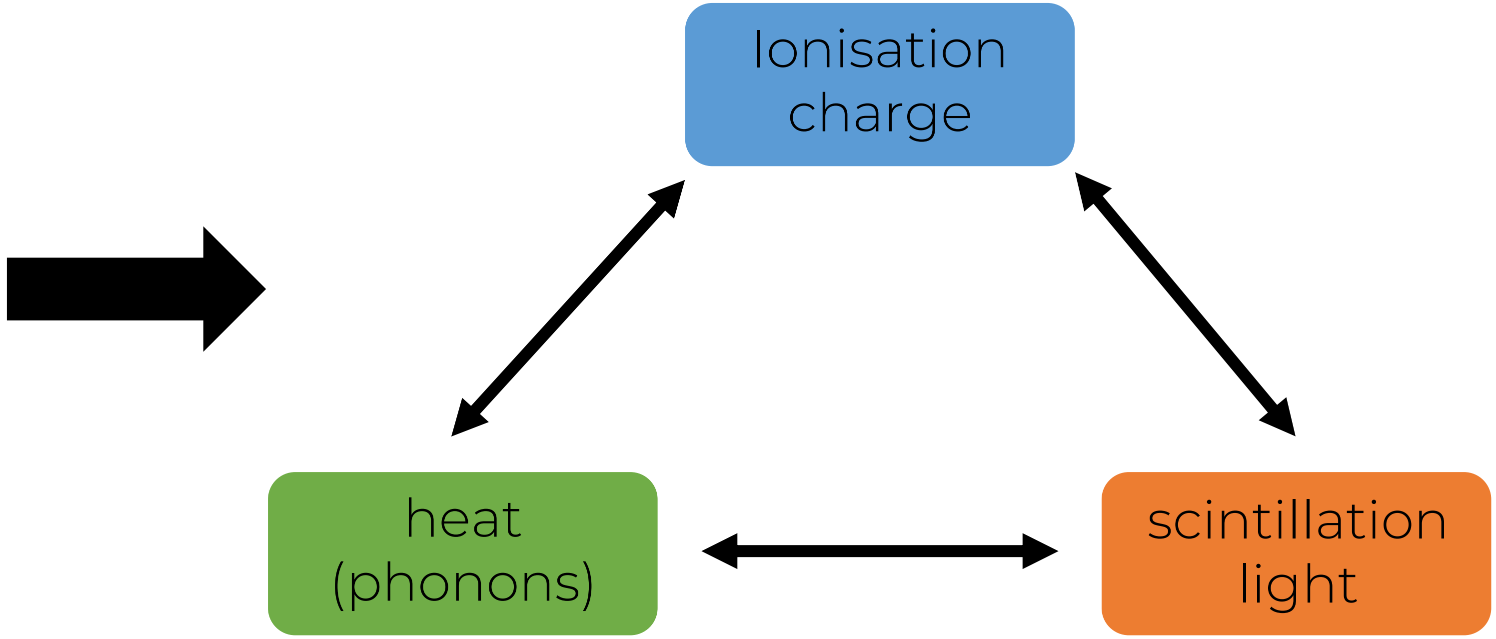


Direct detection: Search for scattering/absorption of halo dark matter in terrestrial detectors

WIMP dark matter direct detection

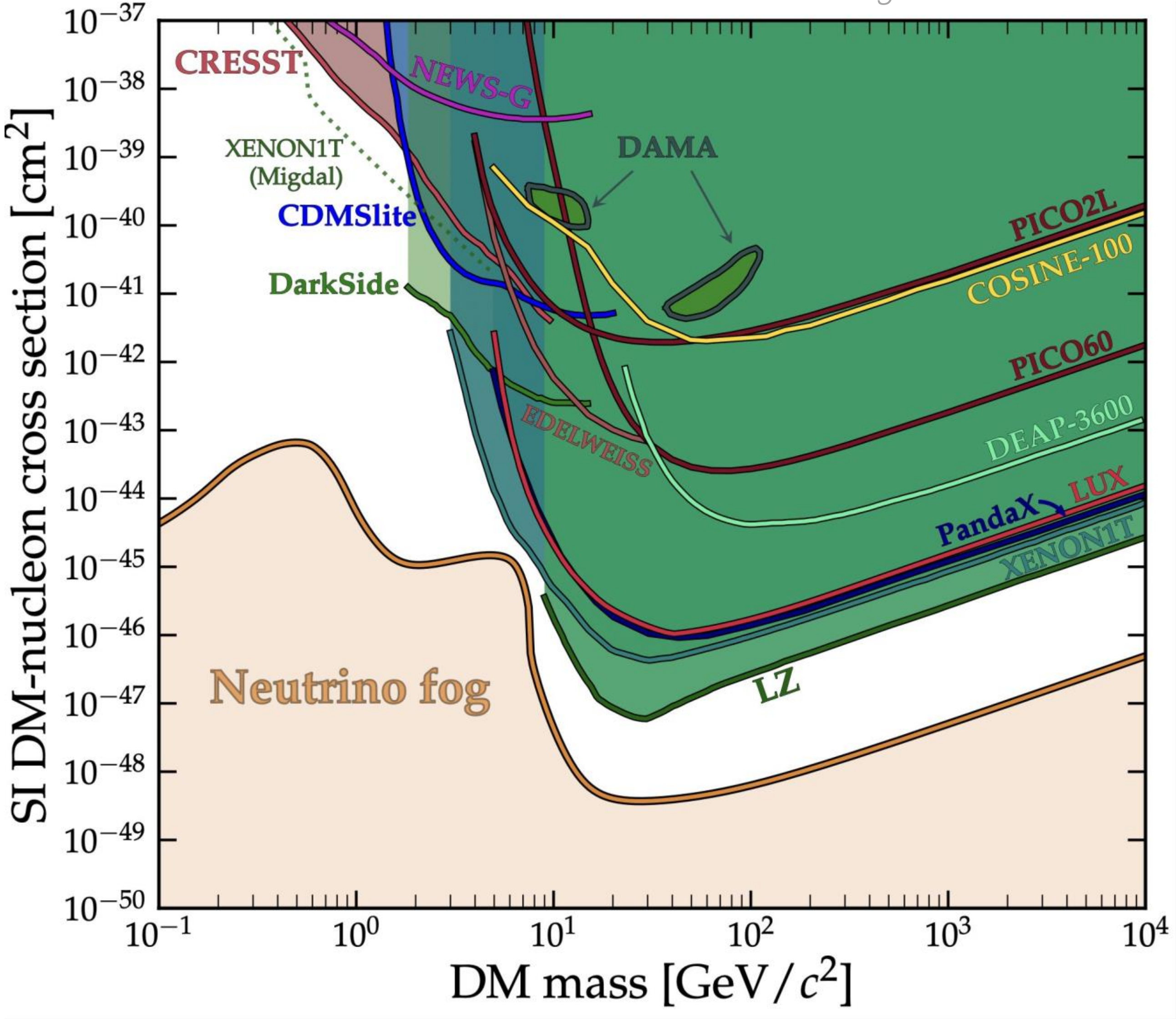
Elastic scattering of dark matter on nuclei (or electrons)





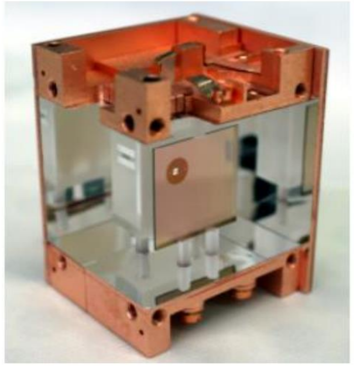
Direct detection: current status

Figure: C. O'Hare



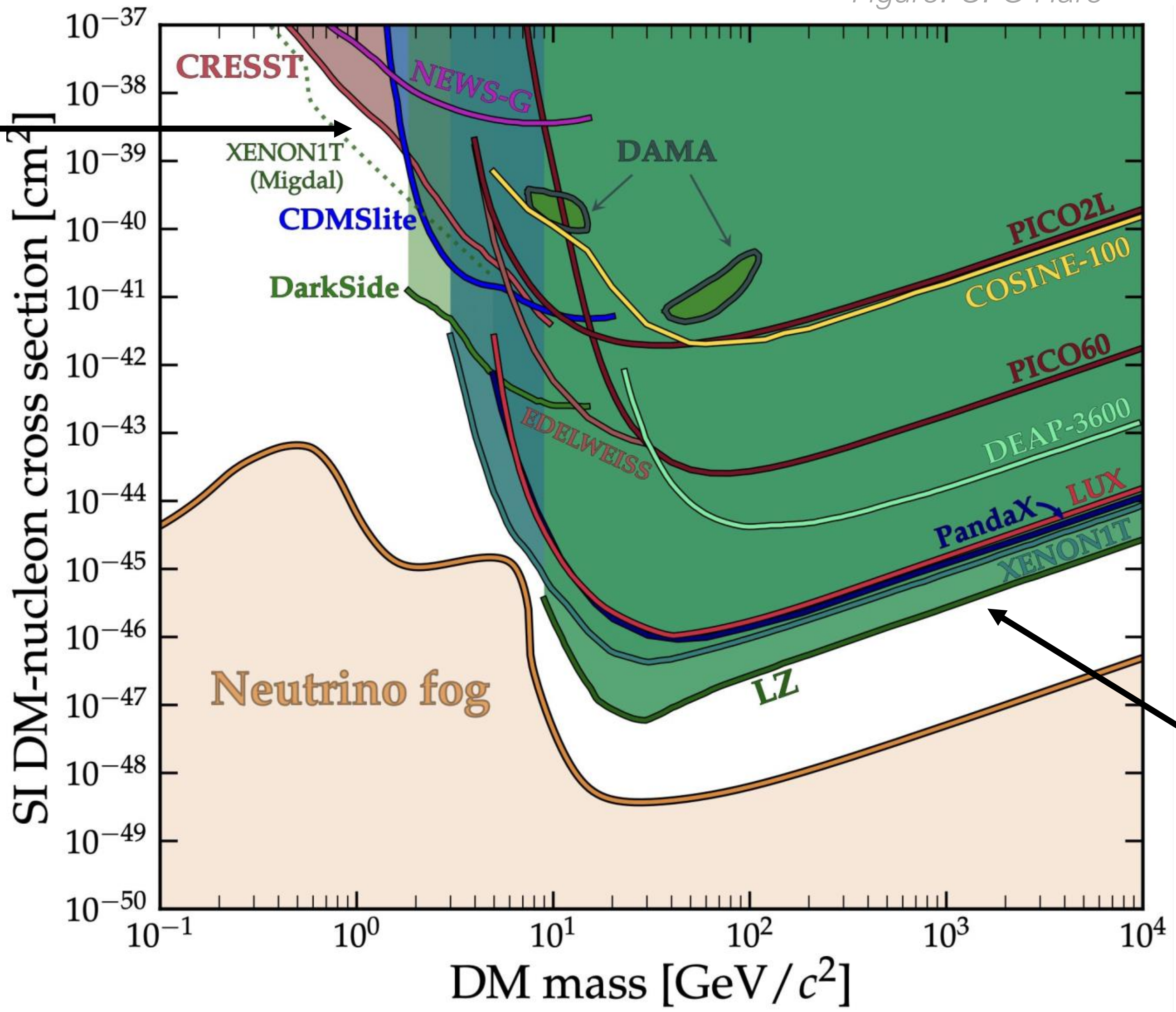
Direct detection: current status

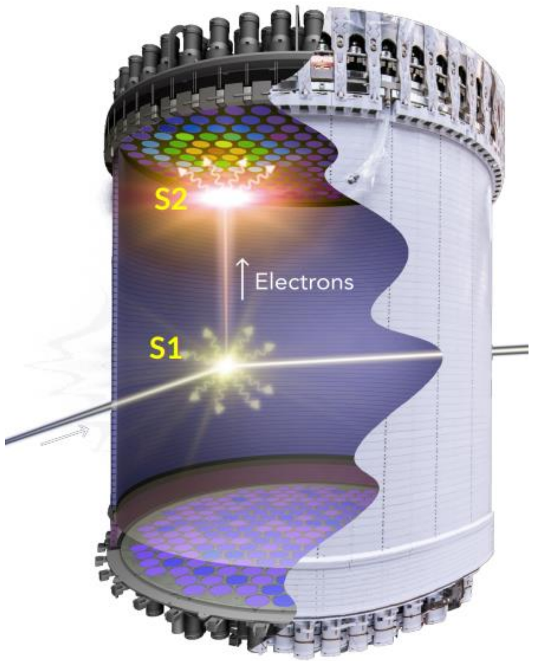
cryogenic experiments



CRESST

Figure: C. O'Hare





LUX-ZEPPLIN (LZ)

tonne-scale liquid Ar/Xe experiments

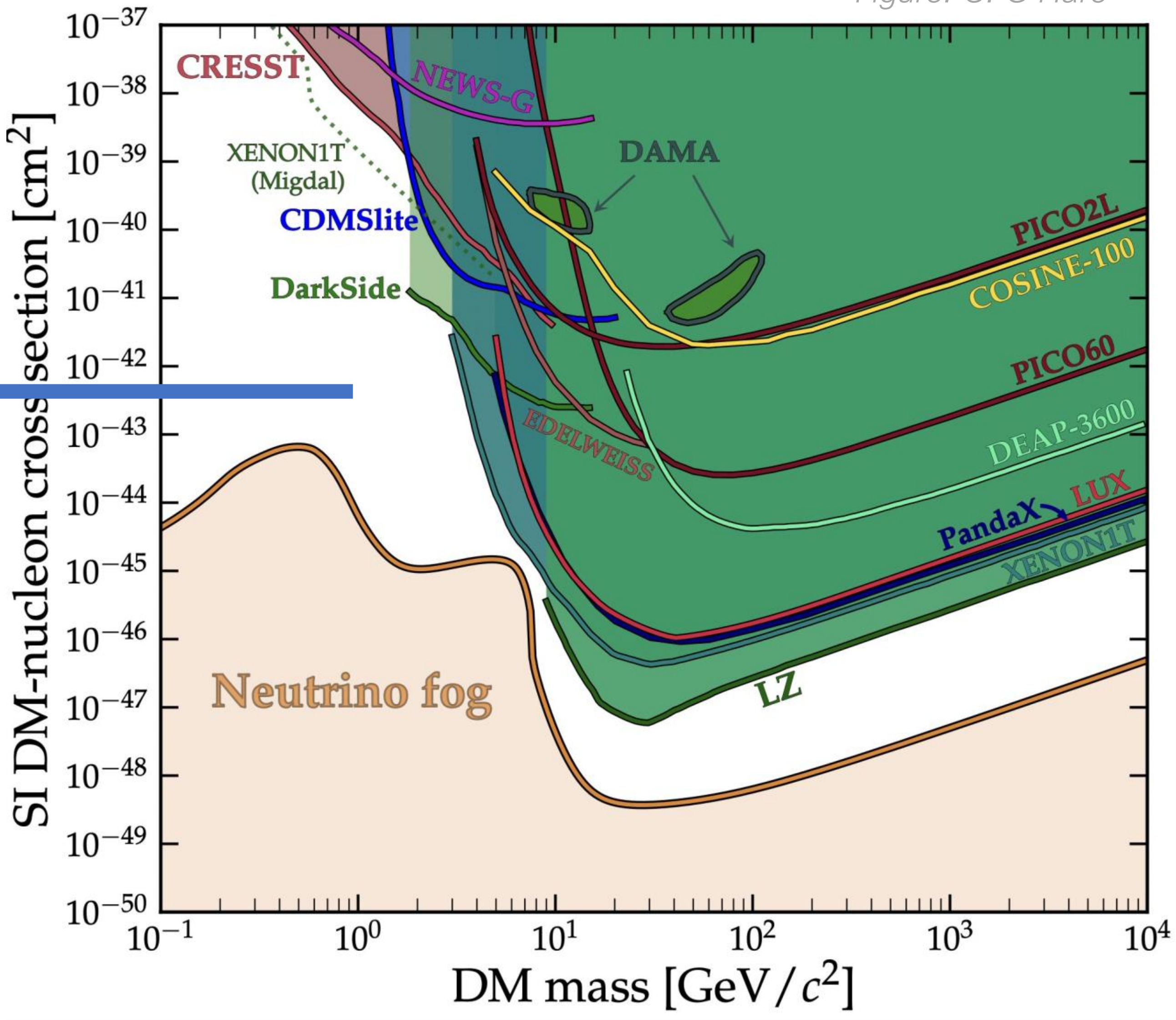
Direct detection: current status

Figure: C. O'Hare

New detectors with lower energy thresholds

or

Inelastic scattering processes



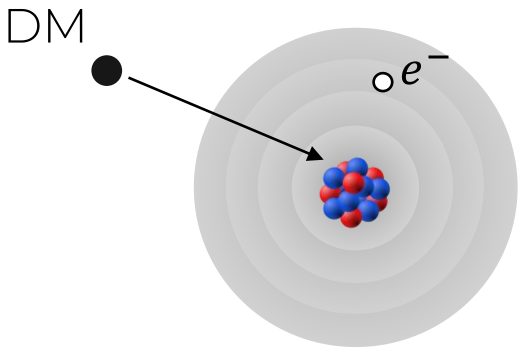
Increased exposure

(bigger detectors)

Migdal effect

Migdal 1939
Ibe et. al. 2017

Electronic ionisation due to a nuclear recoil



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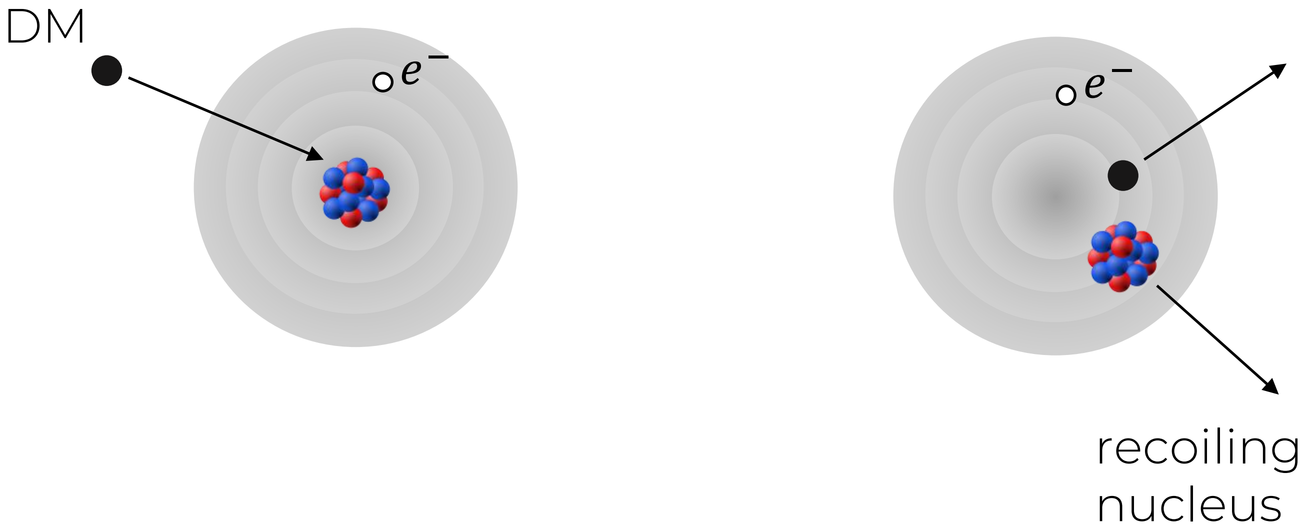

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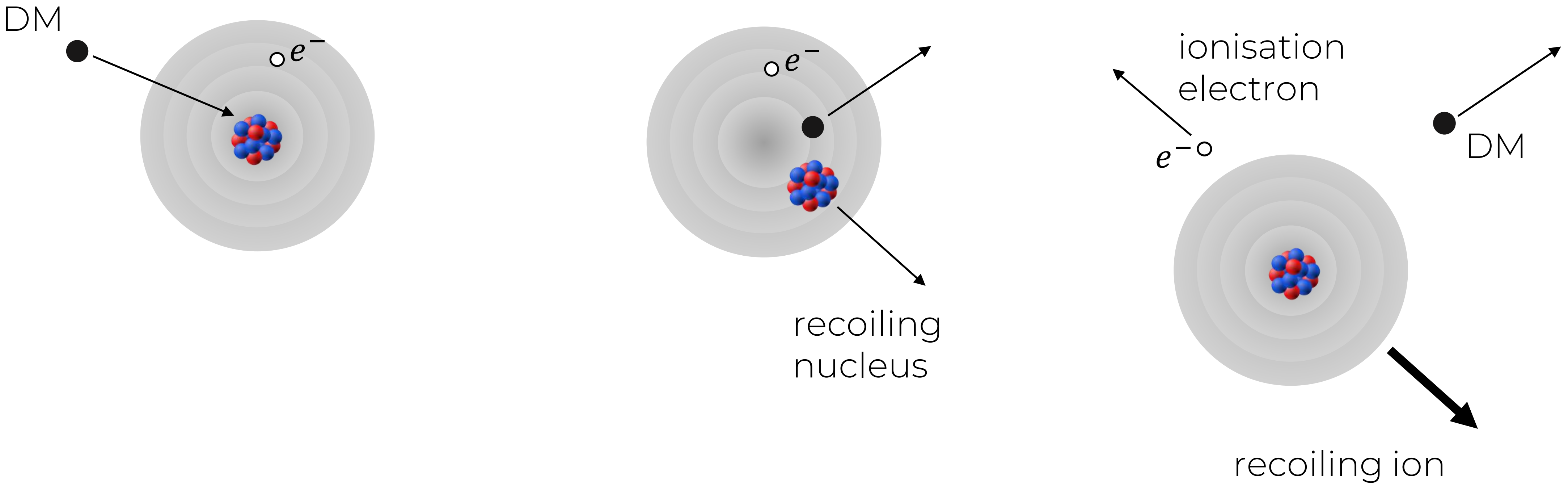

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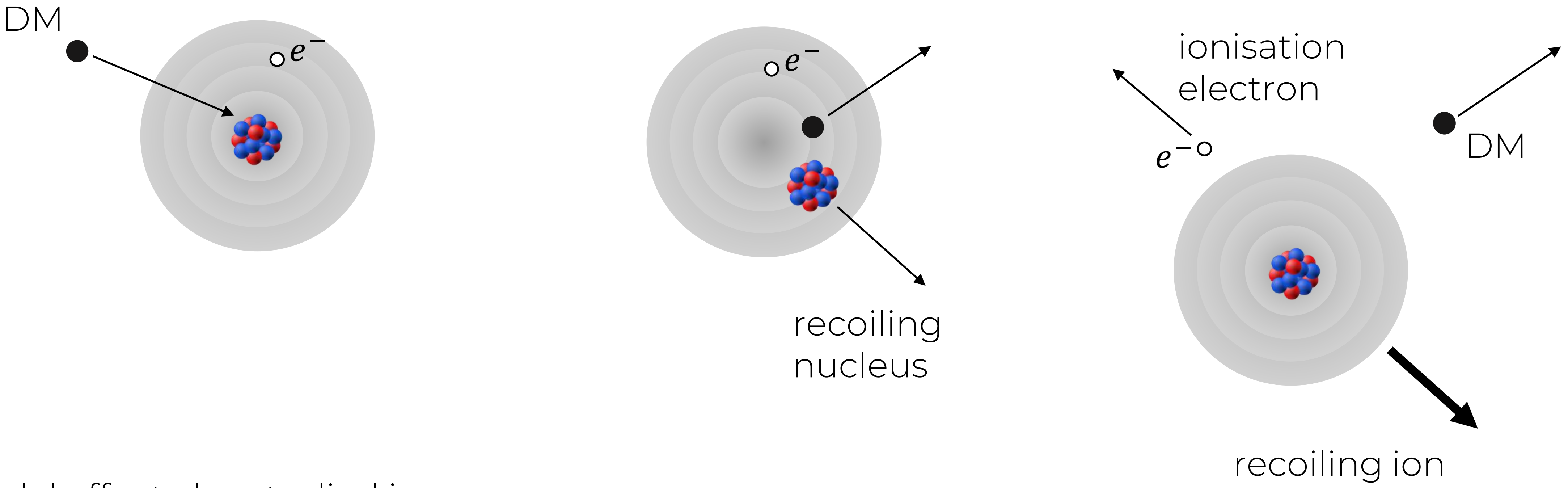
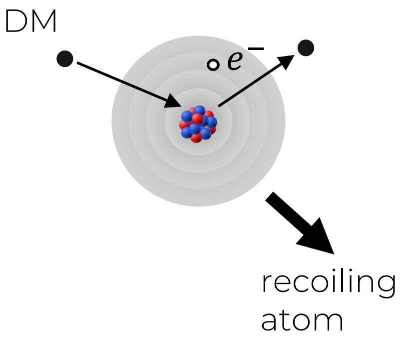


Migdal effect also studied in

- Molecules (Blanco+ ‘22)
- Semiconductors (e.g. Knapen+ ’20; Liang+ ‘22)

Migdal effect

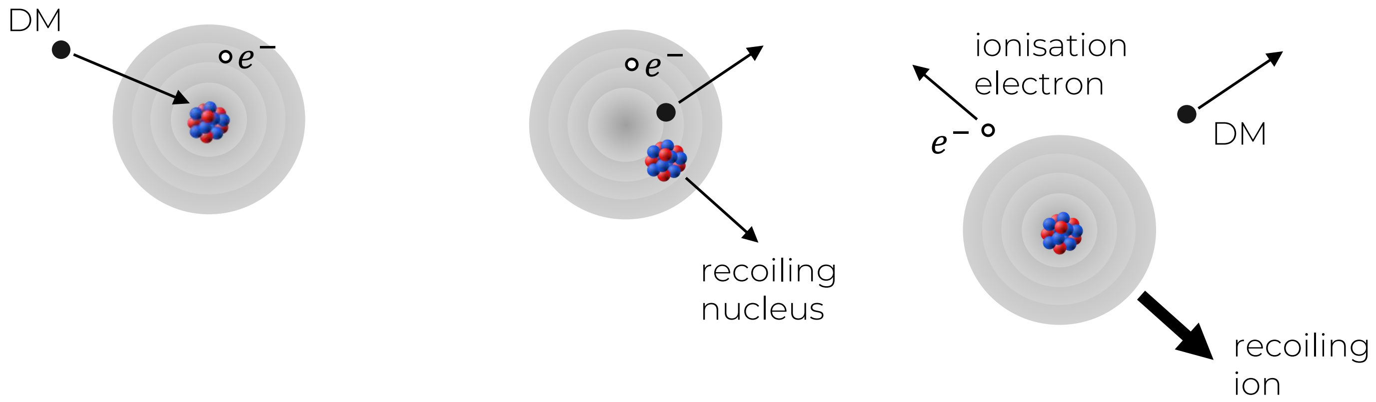
Elastic scattering



$$E_{NR}^{\max} = 0.1\,\mathrm{keV}\left(\frac{m_\chi}{\mathrm{GeV}}\right)^2$$

Low-energy recoil
(sub-threshold)

Migdal (inelastic)

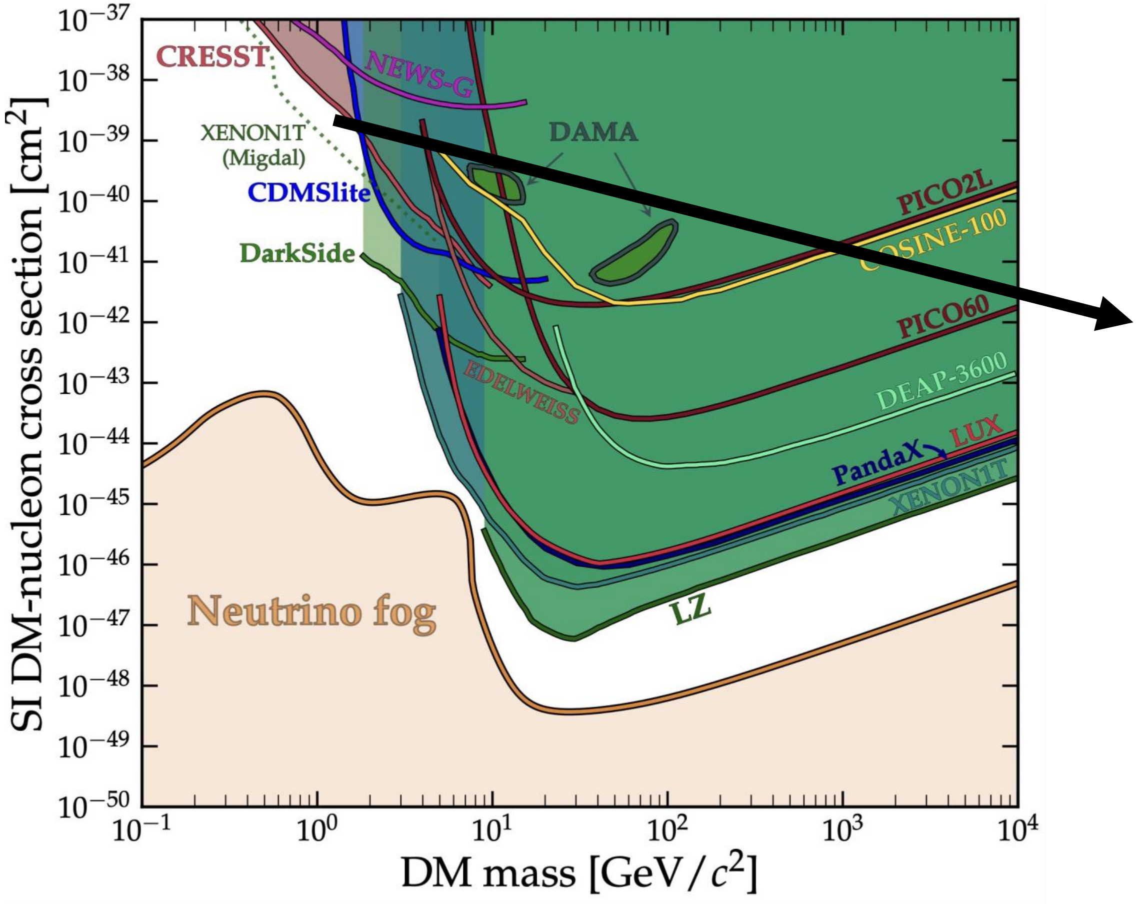


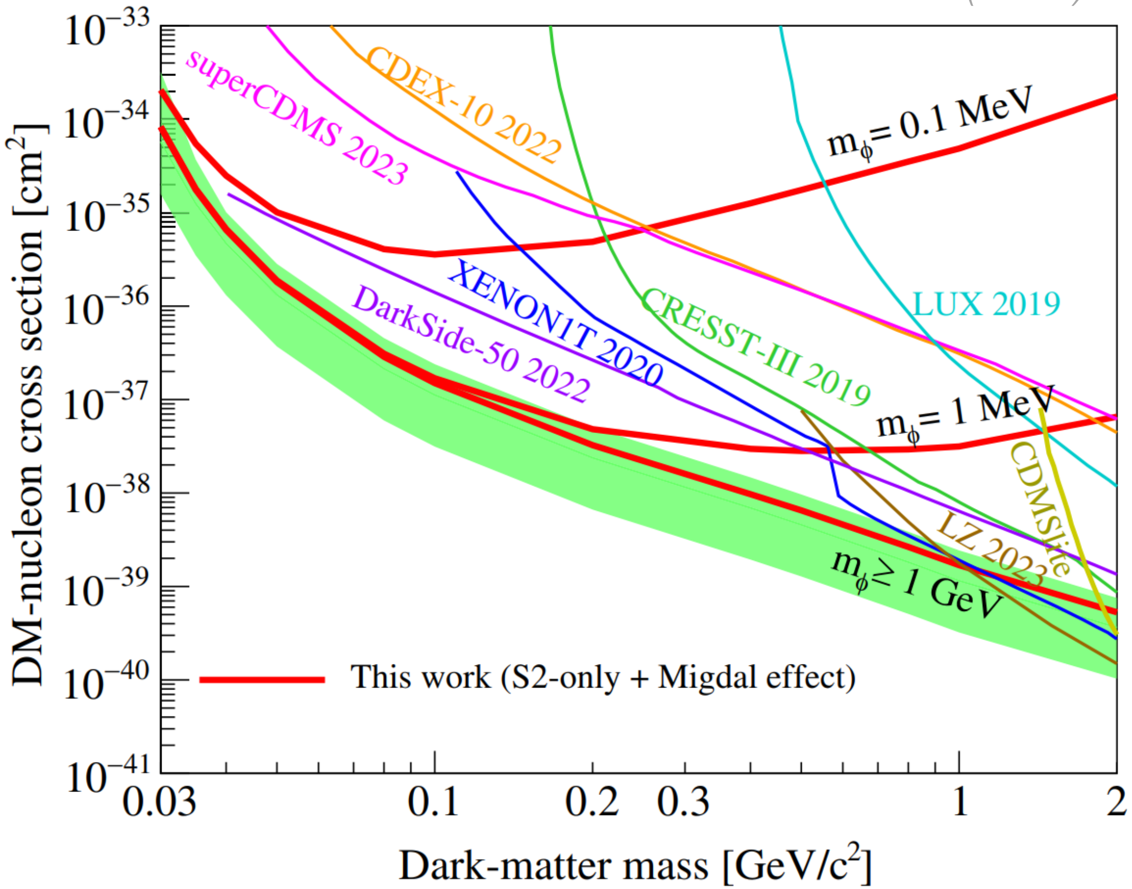
$$\omega_{\max} = \frac{1}{2} m_\chi v_\chi^2 \sim 3\,\mathrm{keV}\left(\frac{m_\chi}{\mathrm{GeV}}\right)$$

Higher energy
electronic signal

Migdal effect

Provides world-leading direct detection limit for masses below 1 GeV



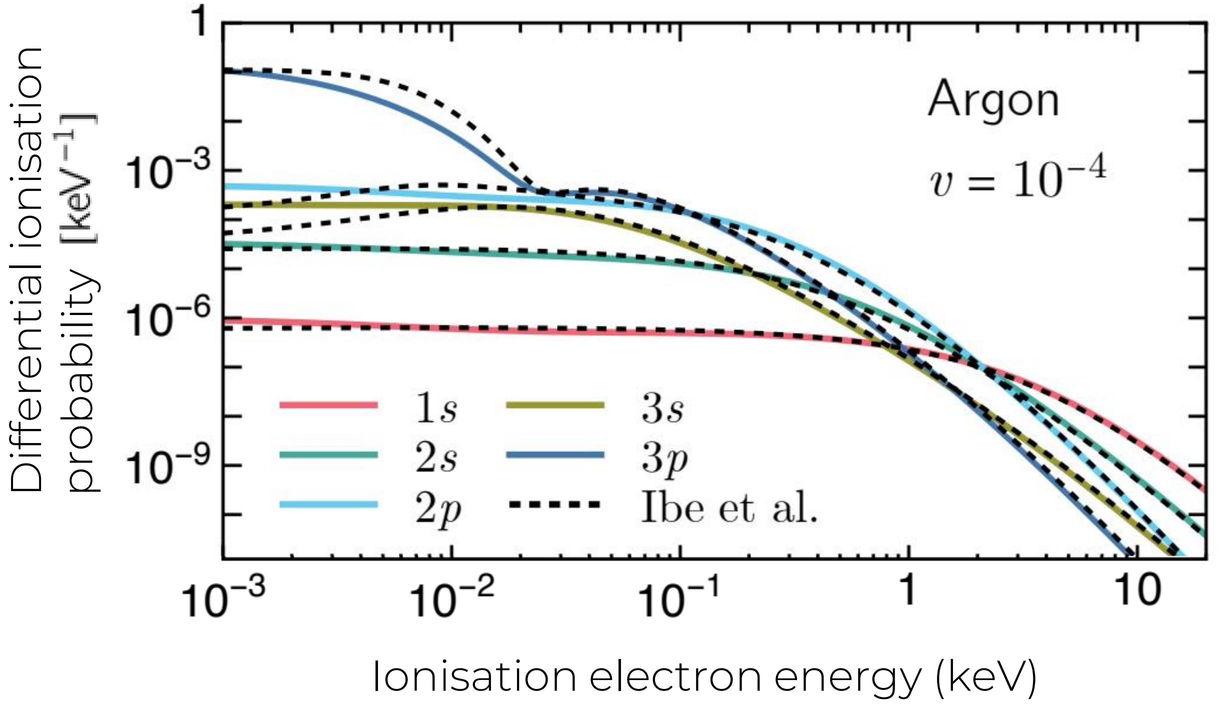


Migdal ionisation probability

PC, Dolan, McCabe, Quiney
Phys. Rev. D 2023

New precision theory valid across all recoil energies

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



Low recoil energy
(dark matter searches)

Migdal ionisation probability

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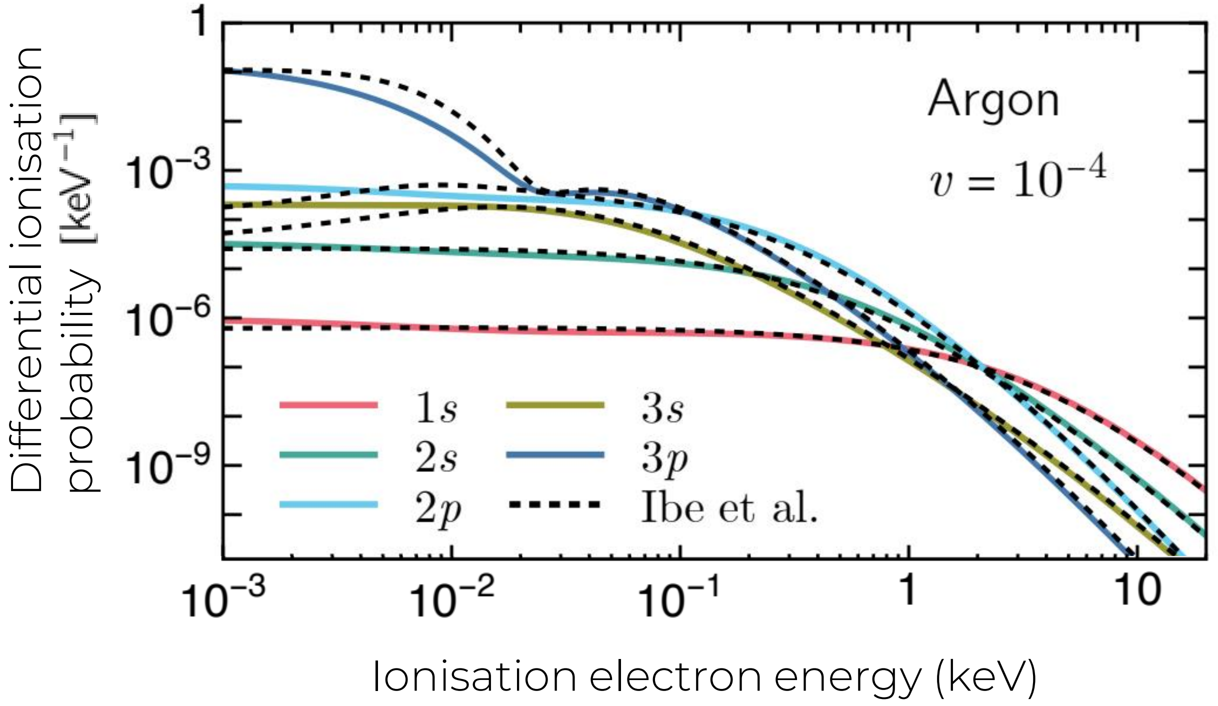

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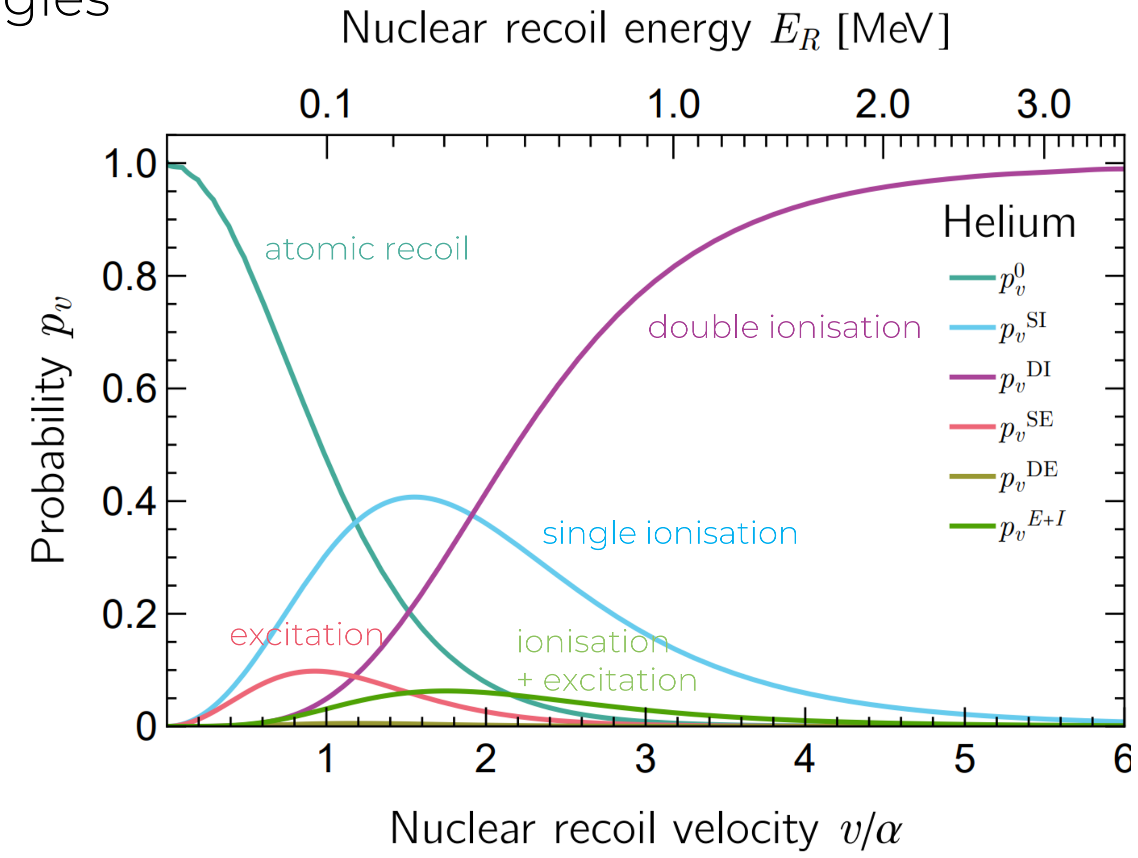
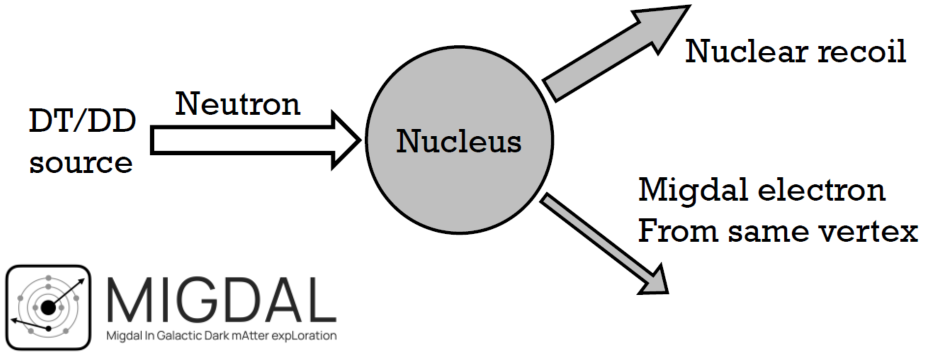


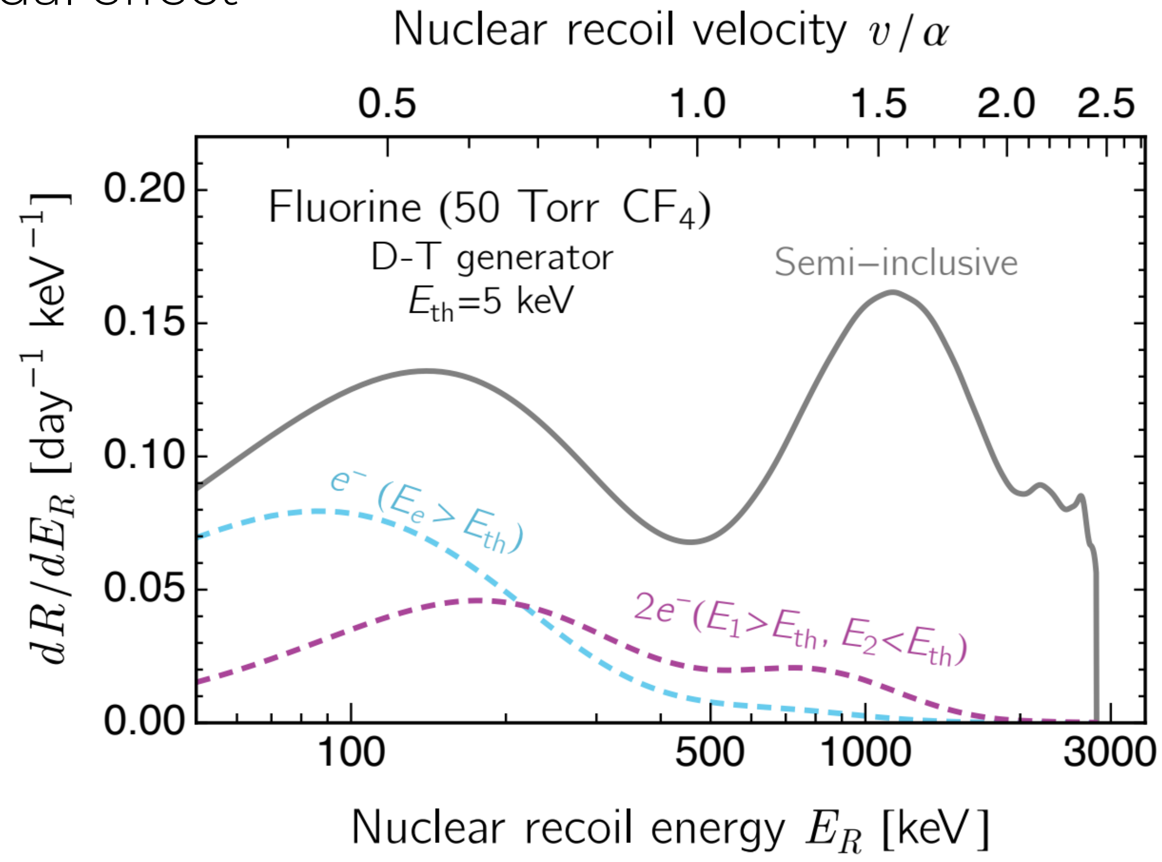
High recoil energies

Calibrating the Migdal effect – neutron scattering

- Important to calibrate Migdal effect for DM searches
- Several experiments underway to observe Migdal effect in neutron scattering *(MIGDAL, LZ, LLNL)*



PC, Dolan, McCabe, Quiney '23



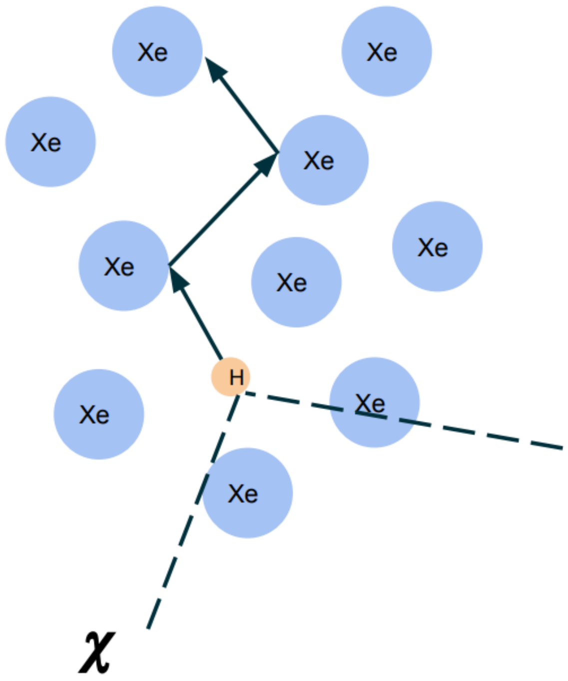
Hydrogen doping

HydroX: proposal to dope liquid Xe experiments with hydrogen

Better kinematics for light DM scattering

$$E_{NR} = \frac{q^2}{2m_N}$$

Target : *hydrogen (few %)*
"Sensor": *liquid xenon*



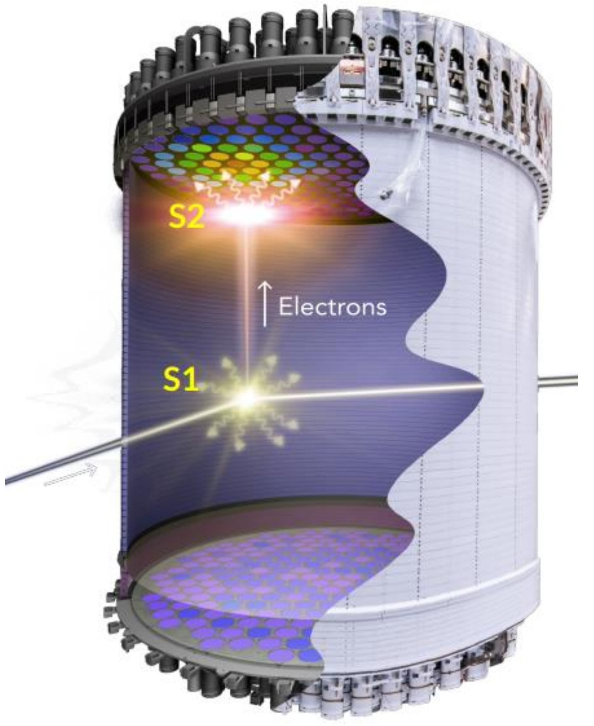


Figure: HydroX / LZ collaboration

Hydrogen doping

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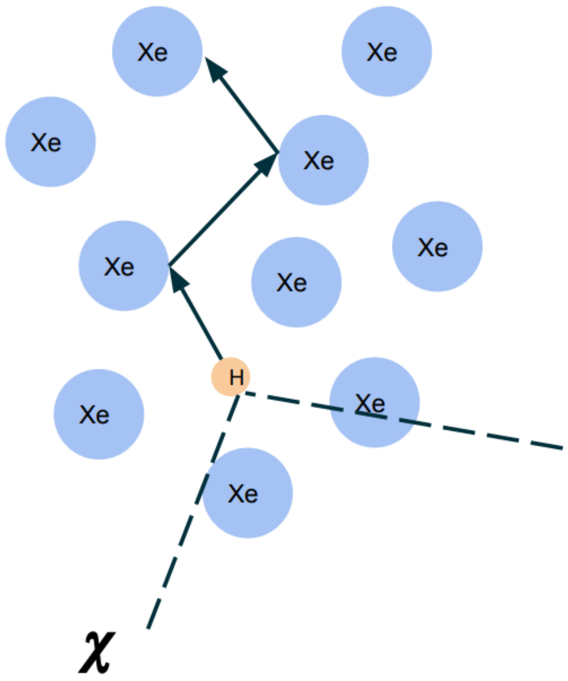


Target : *hydrogen (few %)*
"Sensor": *liquid xenon*

R&D with small-scale TPCs ongoing
(HydroX collaboration)

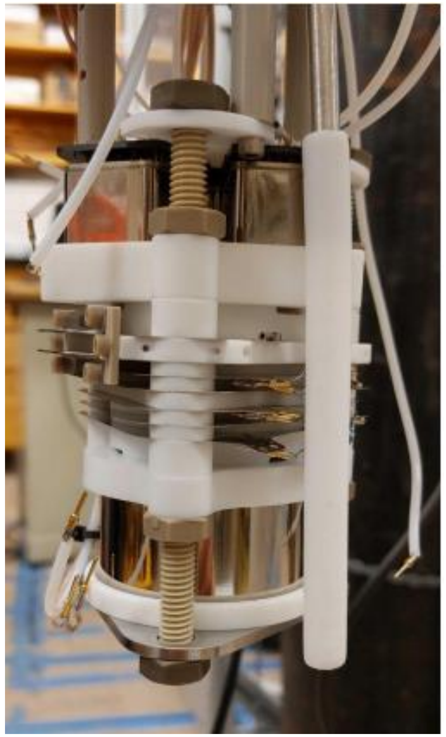


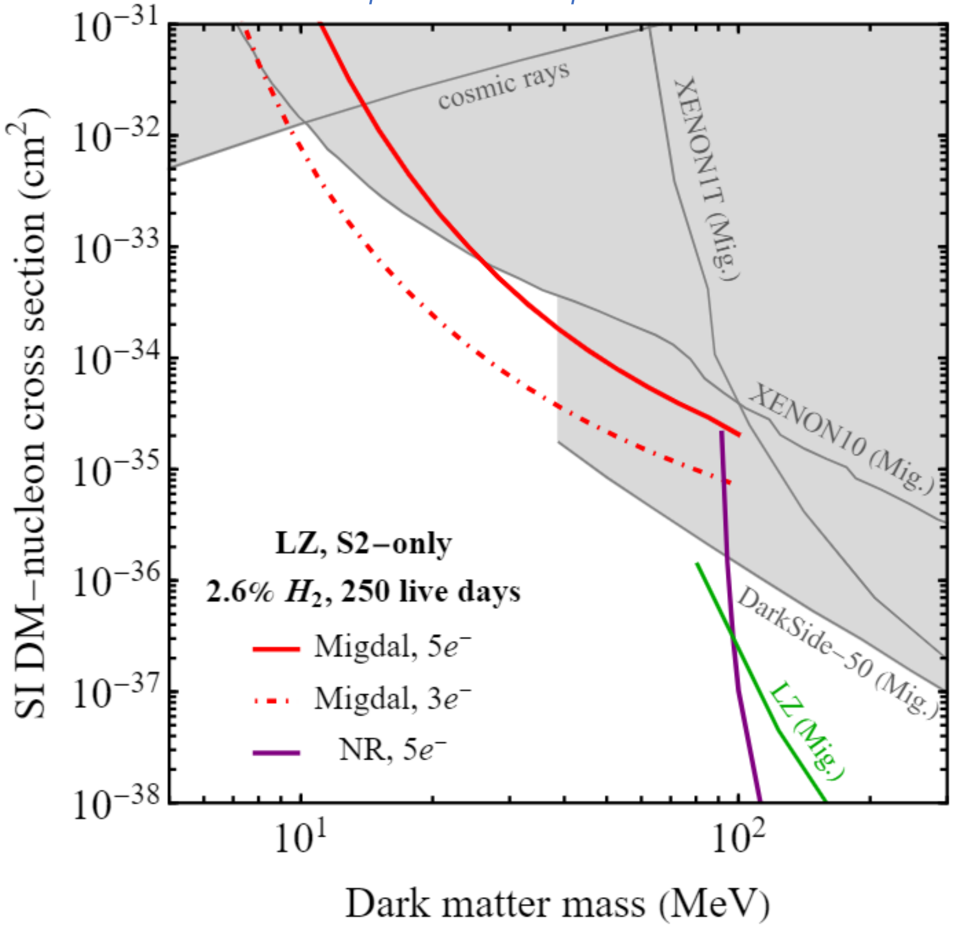
Figure: HydroX collaboration

H_2-doping & Migdal effect

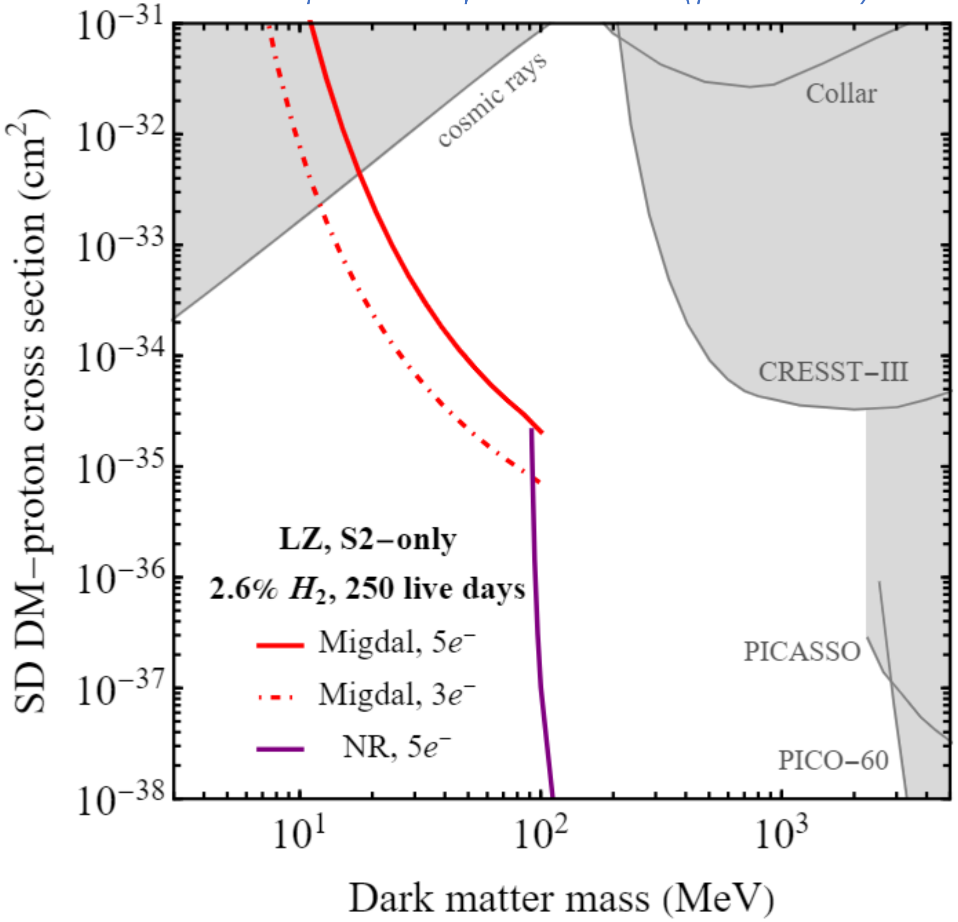
Bell, PC, Dolan, Newstead, Ritter (2023)

Maximise low mass reach of Xe experiments – *especially for SD scattering*

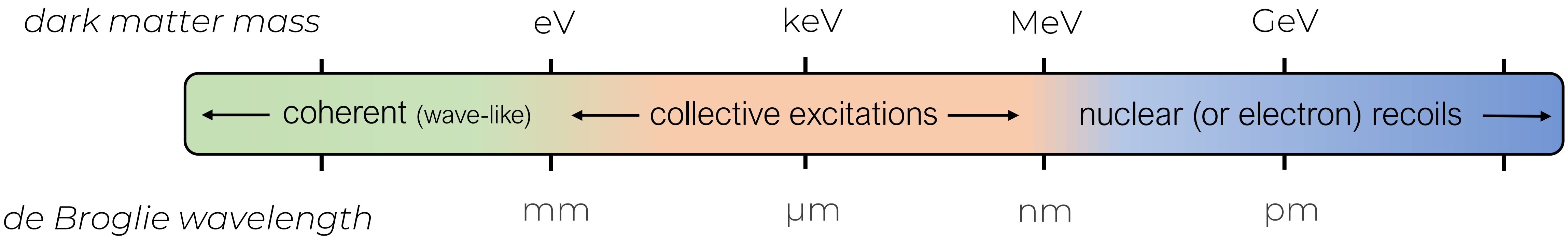
Spin-independent



Spin-dependent (proton)



Sub-MeV direct detection: collective excitations



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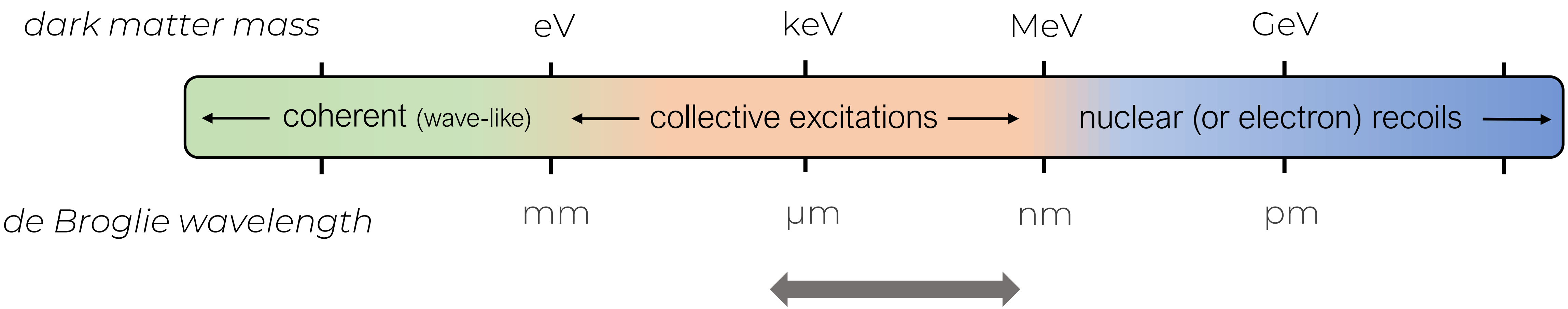
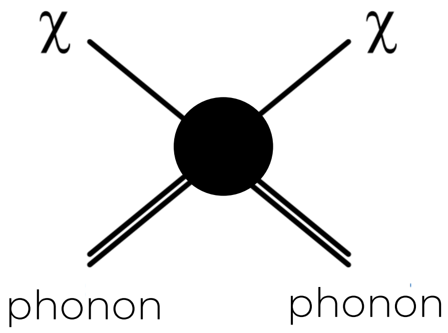


Sub-MeV mass DM interacts directly with collective excitations (*e.g. phonons*)

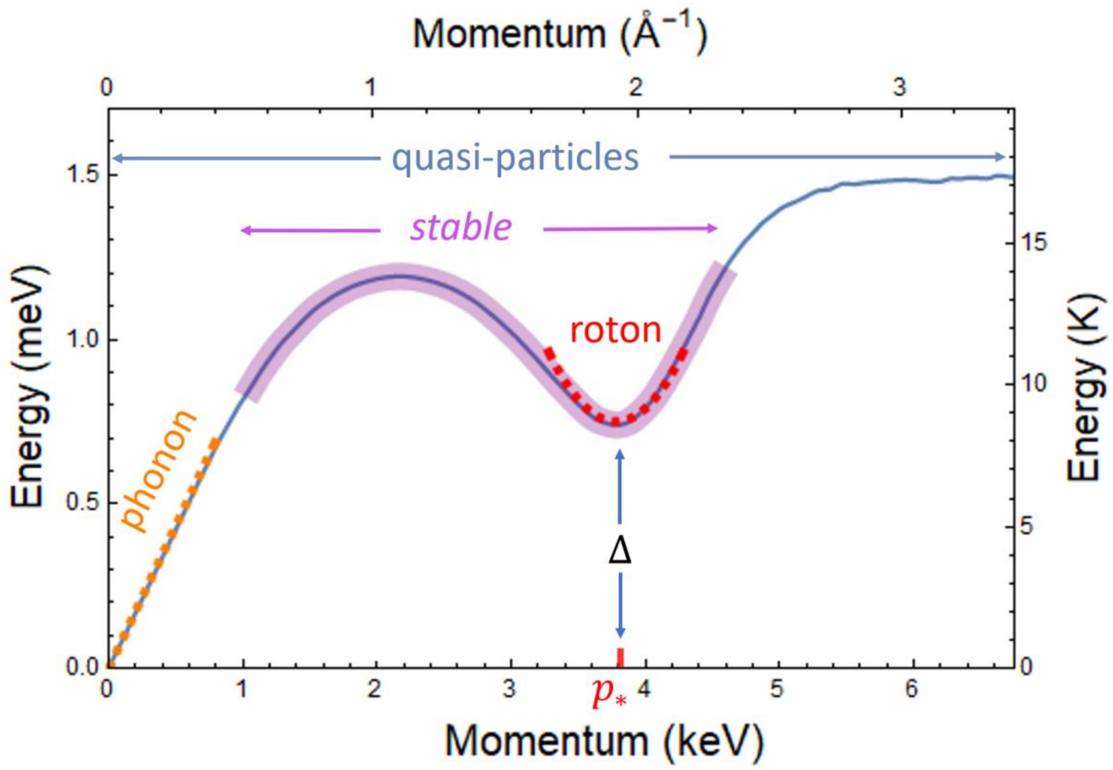


How to detect low energy phonons?

Dark matter detection with superfluid ^{4}He

Promising target material is superfluid helium-4

Figure: Matchev et. al '21



Long-lived collective excitations (phonons/rotons)

Dark matter detection with superfluid ^{4}He

Upcoming experiments using superfluid helium-4 target: *HeRALD, DELight*

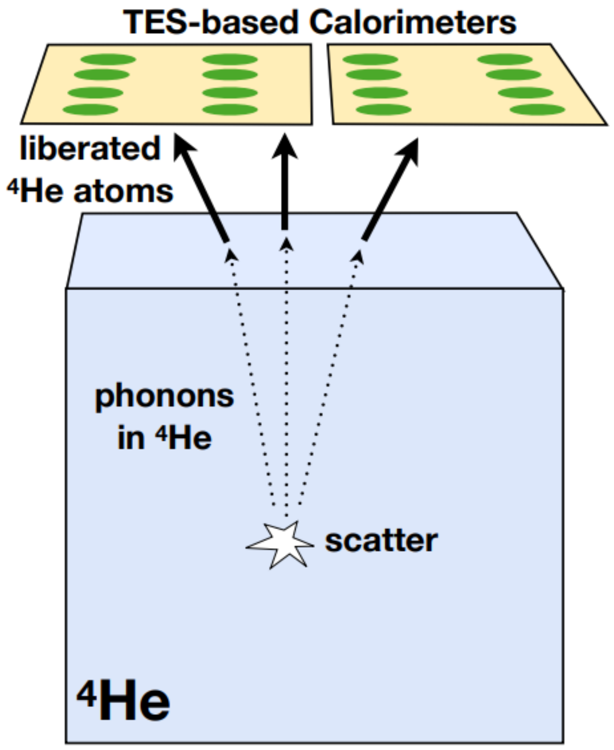
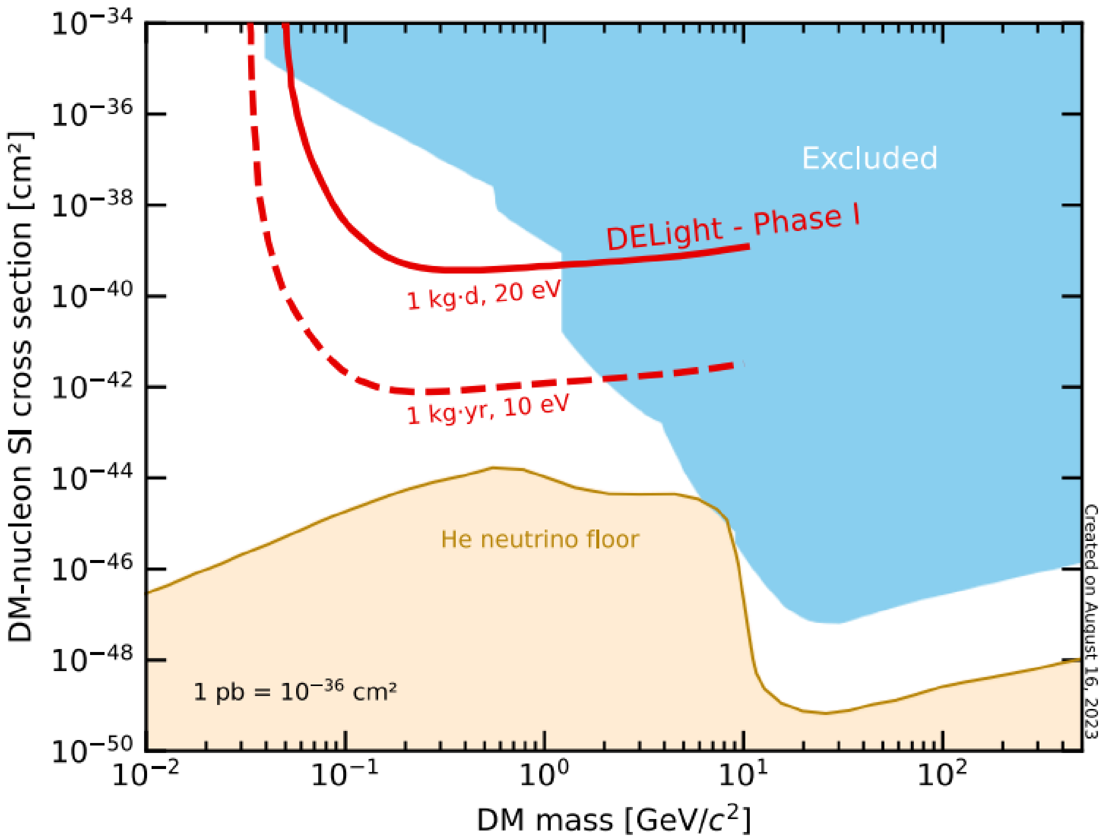


Figure: Herald Collaboration

DELight Collaboration

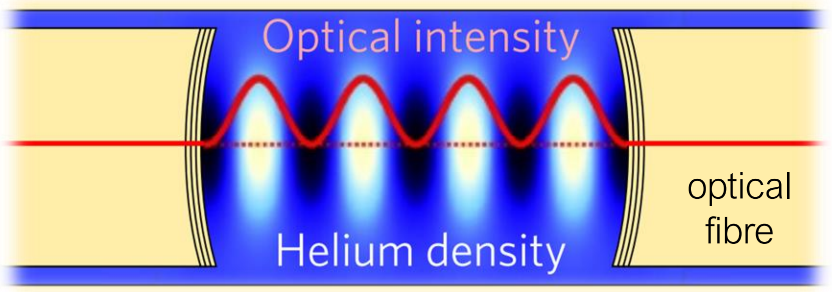


Superfluid optomechanics for dark matter

Baker, Bowen, PC, Dolan, Goryachev, Harris
arXiv:2306.09726

Superfluid optomechanical cavities as *single phonon detectors*

Figure: Kashkanova+ '16



superfluid ^{4}He filled optical cavity

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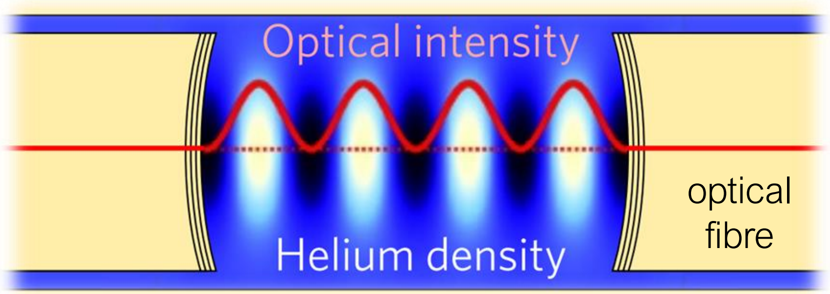

superfluid ^{4}He filled optical cavity

Interaction between acoustic (density) and optical modes

$$H_{\mathrm{OM}} = -g_0(a^\dagger_{\gamma_1} a_{\gamma_2} b^\dagger_m + \mathrm{h.c.})$$

photons phonon

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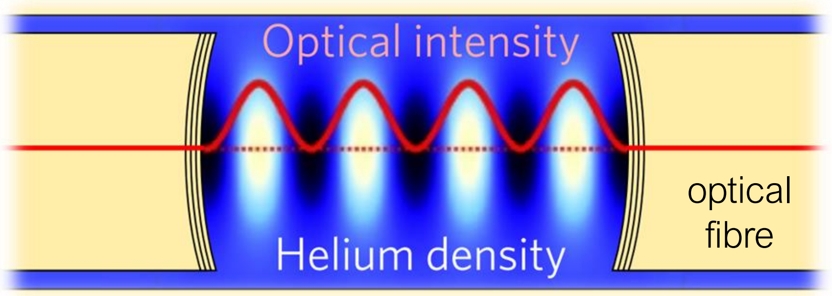

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$$\rightarrow -g_0\sqrt{N_1}(a_{\gamma_2} b^\dagger_m + \text{h.c.})$$

pump
laser

Optomechanical interaction converts
~μeV phonons into detectable ~eV photons

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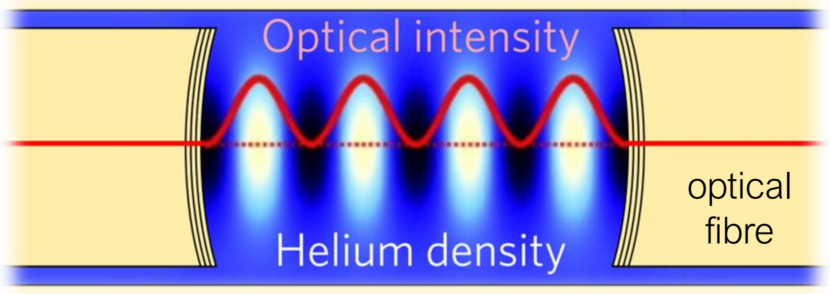

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pump laser

Optomechanical interaction converts
~μeV phonons into detectable ~eV photons

Optomechanical systems have demonstrated μeV phonon counting (e.g. Patil et. al. '22)

Narrow-band detection

Superfluid optomechanical systems as dark matter detectors:

- ✓ exceptional low-energy sensitivity (~μeV)
- × narrow-band detector (single phonon energy)

➡ Very low dark matter scattering rate due to restricted phase space

Narrow-band detection & phonon lasing

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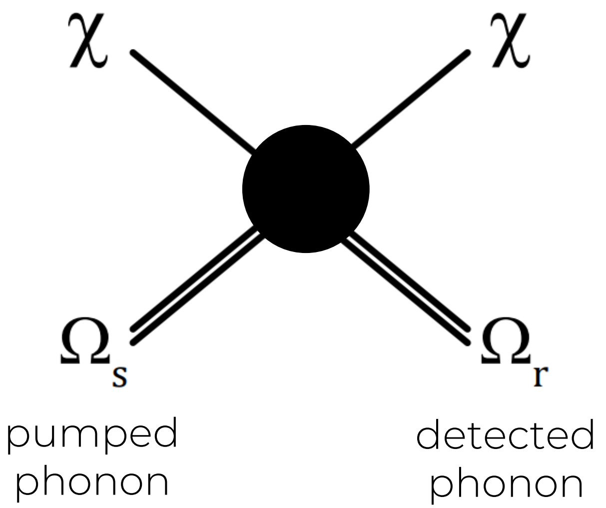


Solution: *Phonon lasing*

- *Stimulated* scattering rate
  (proportional to phonon occupation number)

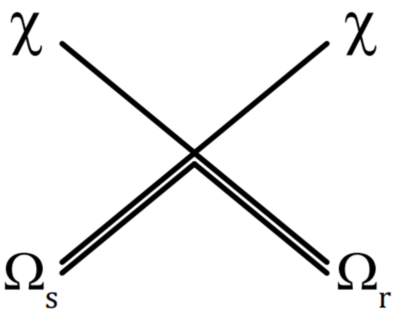
- Achieved via optomechanical interaction

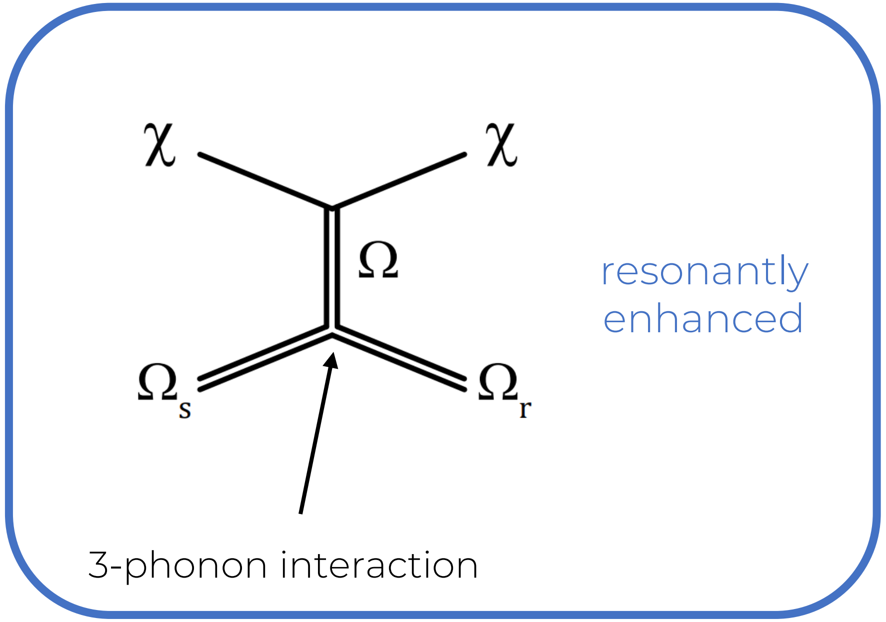
Dark matter – phonon scattering

Low-energy phonons in superfluid described by effective field theory (EFT)

- Phonons are Nambu-Goldstone bosons of U(1) symmetry breaking

Two contributions to stimulated scattering process:



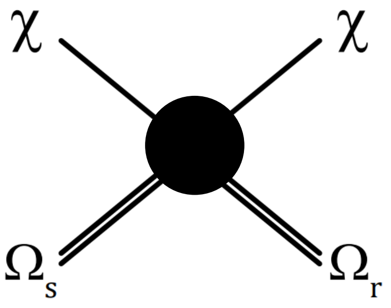


Superfluid optomechanics for dark matter

1 *Scattering*

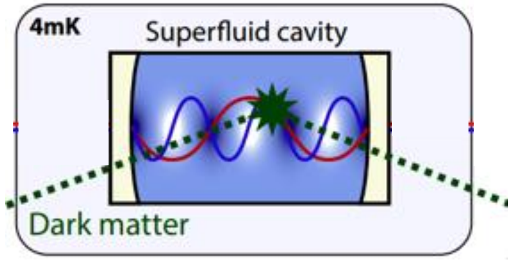
DM excites ~μeV phonon in superfluid

(stimulated scattering process with phonon lasing)



pumped phonon *(lower-energy, high occupation)*

excited phonon *(higher energy)*



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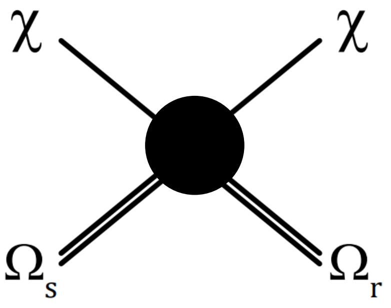

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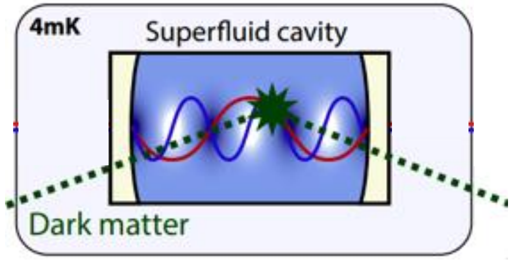
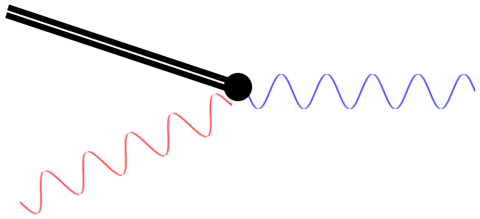


2 *Conversion & amplification*

phonon interacts with pump laser, producing higher energy photon



phonon

pump laser

Superfluid optomechanics for dark matter

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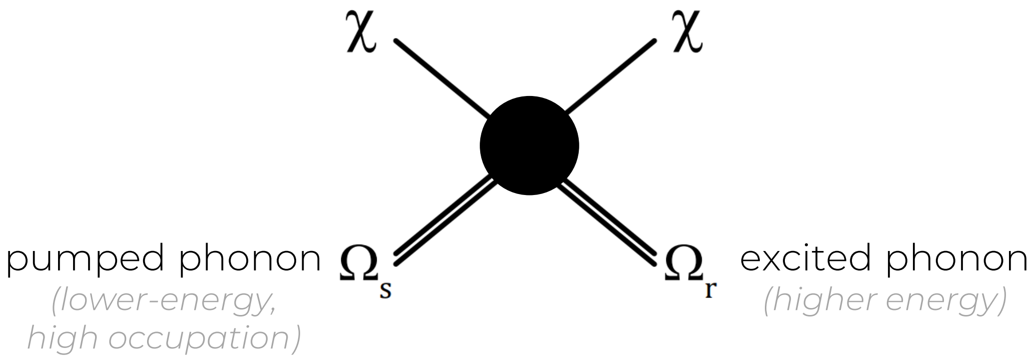

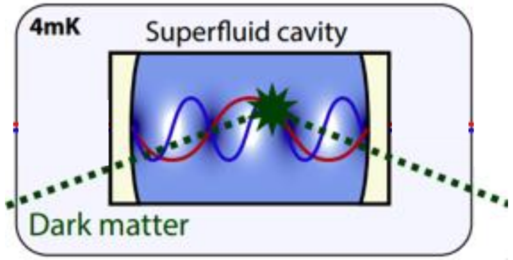

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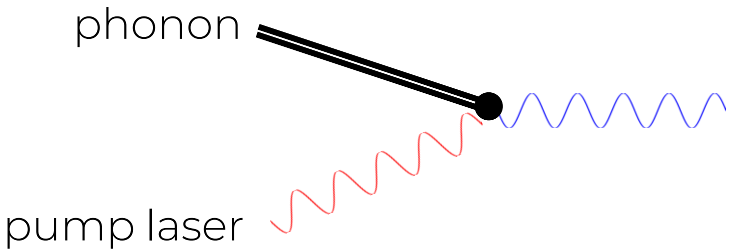
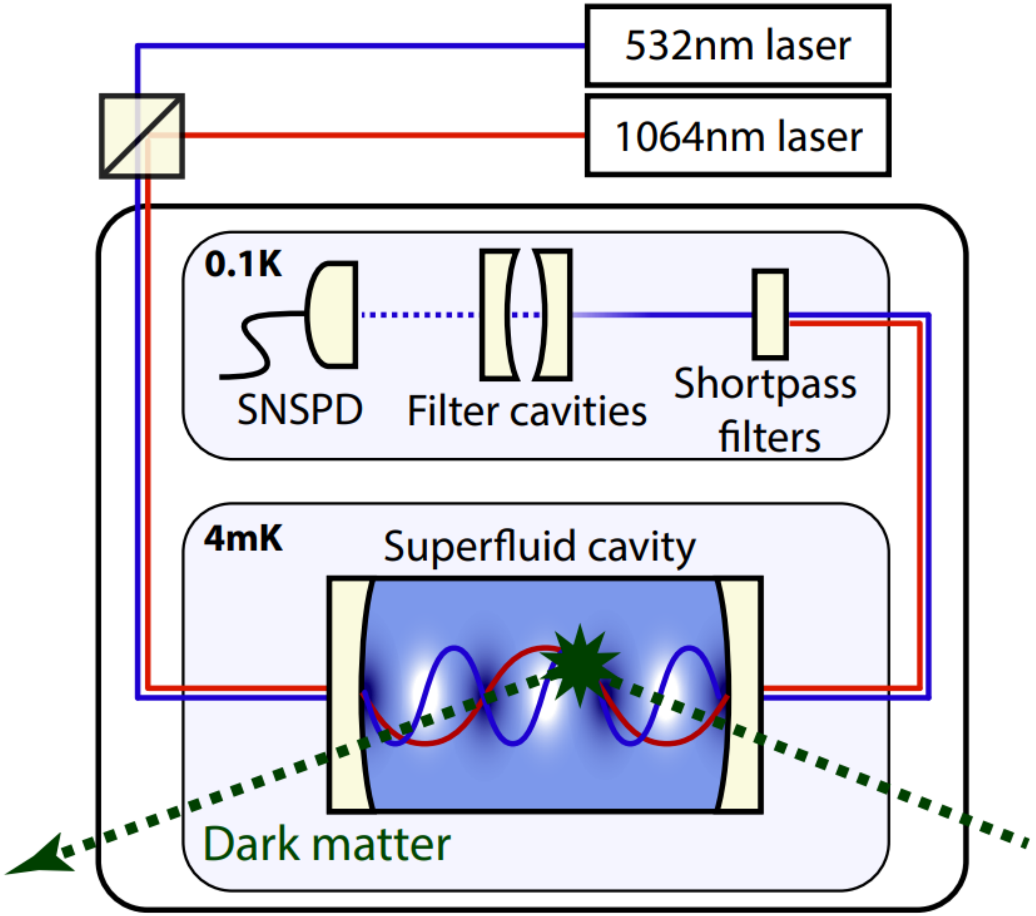


3 *Detection*
photon detected by single photon detector (SNSPD)

ODIN: Optomechanical Dark-matter INstrument



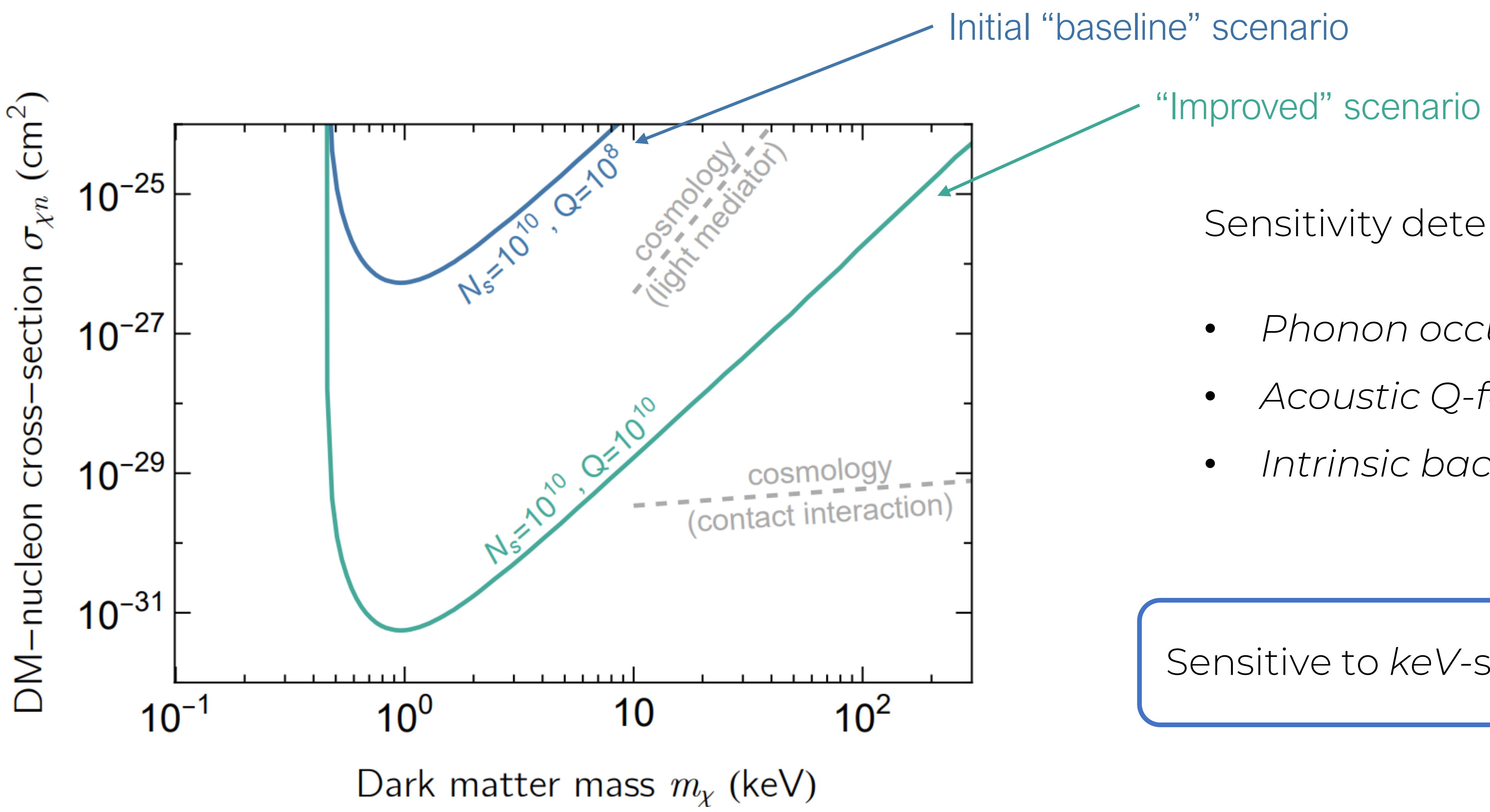
cavity dimensions ~ 30cm x 0.7mm

Main detector backgrounds:

- *Thermal phonons*
  (10^{-5} Hz at T = 4mK and Q = 10^{10})
- *SNSPD dark counts*
  (~6×10^{-6} Hz)
- *Incomplete filtering of pump lasers*
  (especially 532nm, supressed with filter cavities)

Expected background rate ~1 event/day

ODIN: Projected Sensitivity



Sensitivity determined by:

- *Phonon occupation*
- *Acoustic Q-factor*
- *Intrinsic background rate*

Sensitive to *keV*-scale dark matter

Summary

Direct detection is moving into the sub-GeV regime

Migdal effect

- Extending reach of existing experiments into sub-GeV regime
- Ongoing effort to calibrate in neutron scattering

Superfluid He

- Promising target for sub-MeV searches
- Optomechanical single phonon detectors: convert ~μeV phonons to ~eV photons
- ODIN will be sensitive to keV mass dark matter