Direct detection from the GeV to the eV scale:

Migdal effect to superfluids

Peter Cox
The University of Melbourne

Dark matter landscape

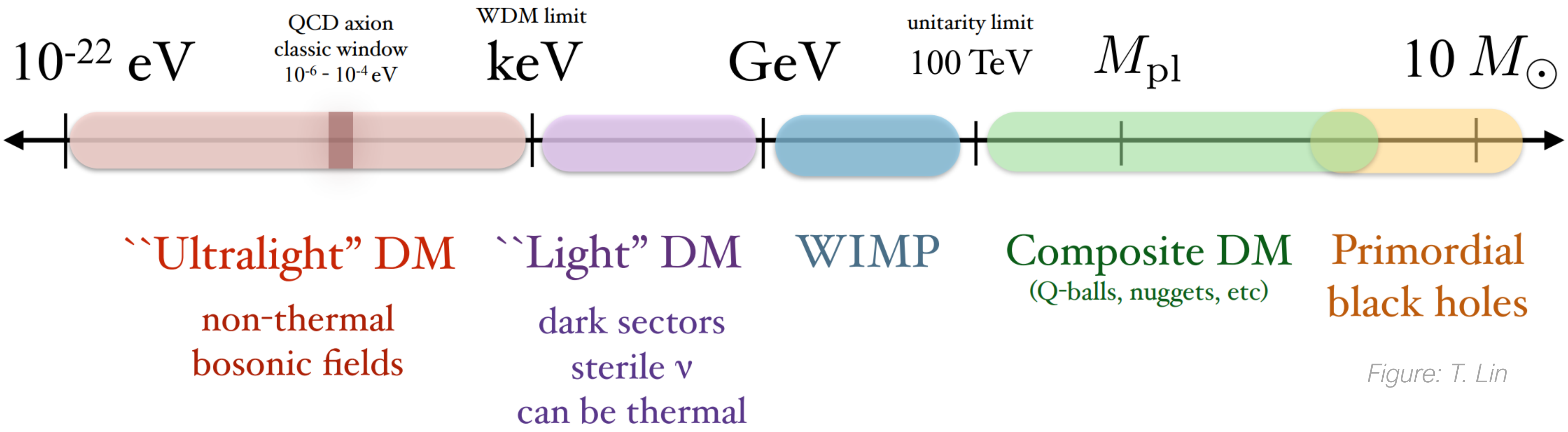
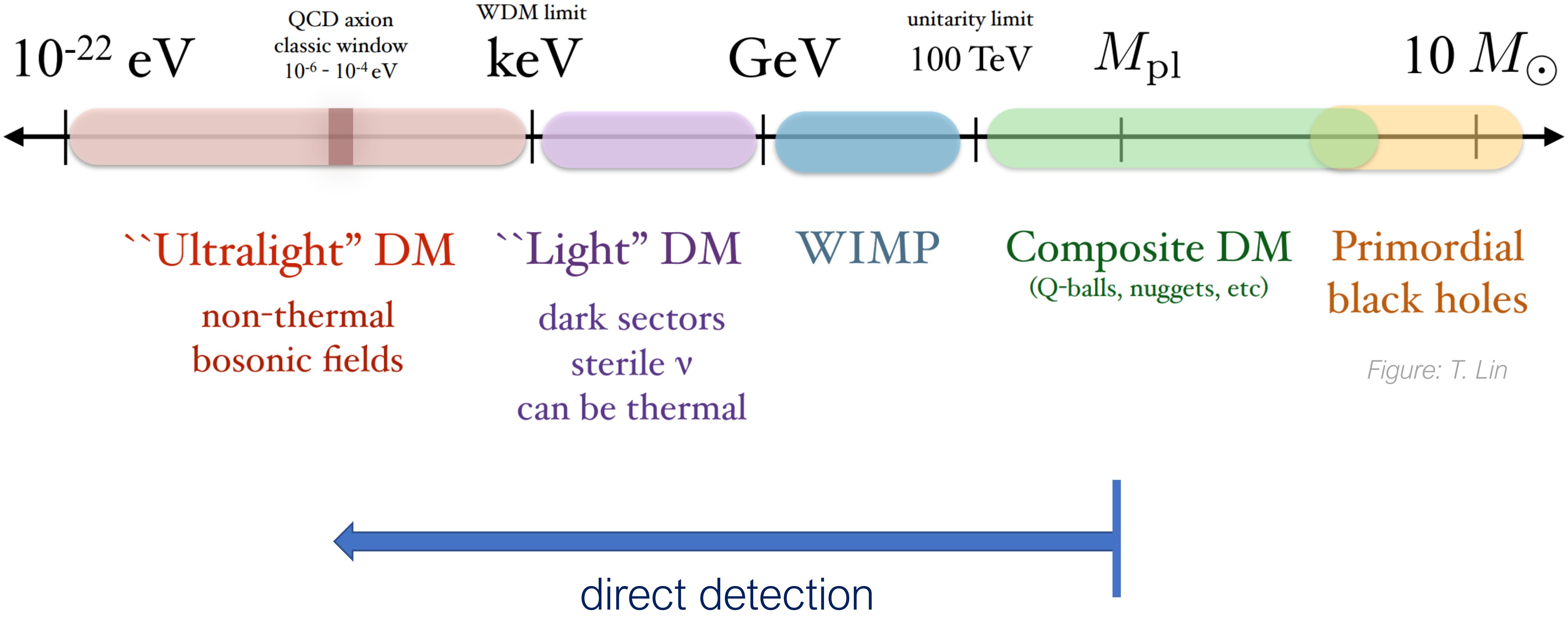


Figure: T. Lin

Dark matter landscape



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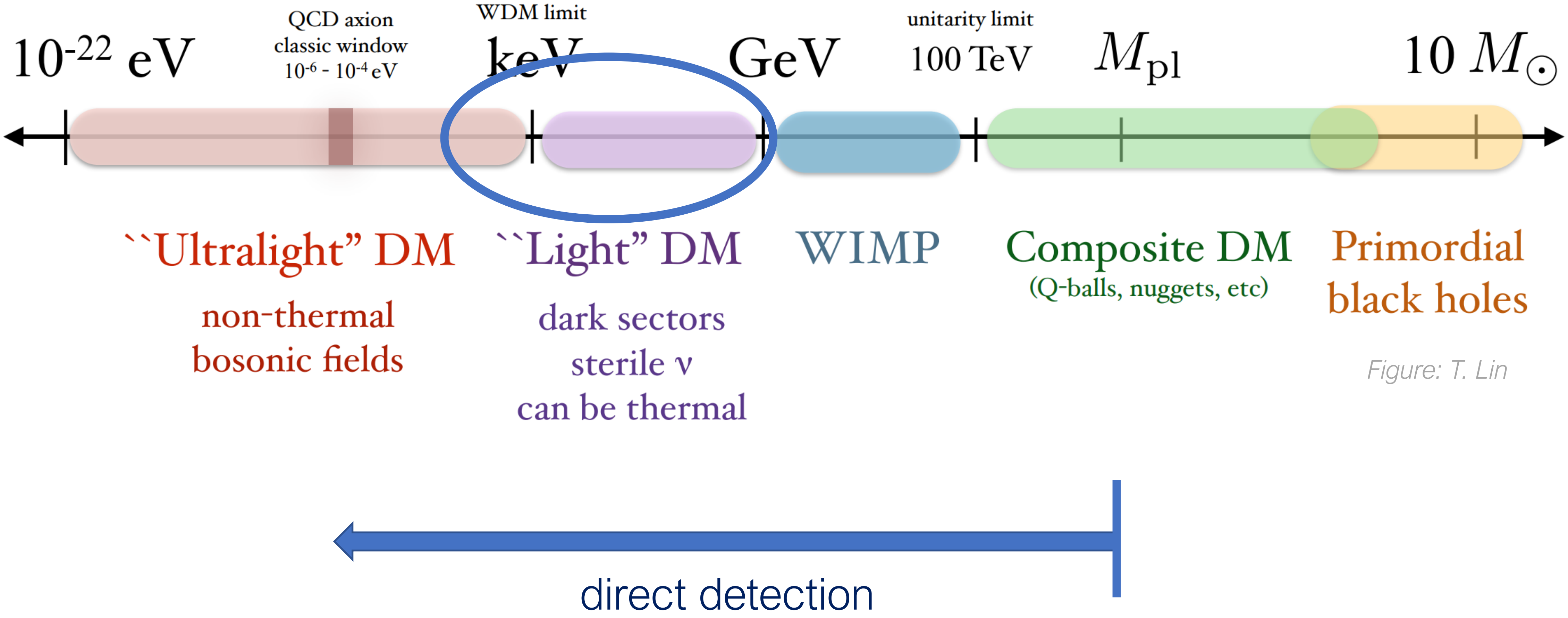
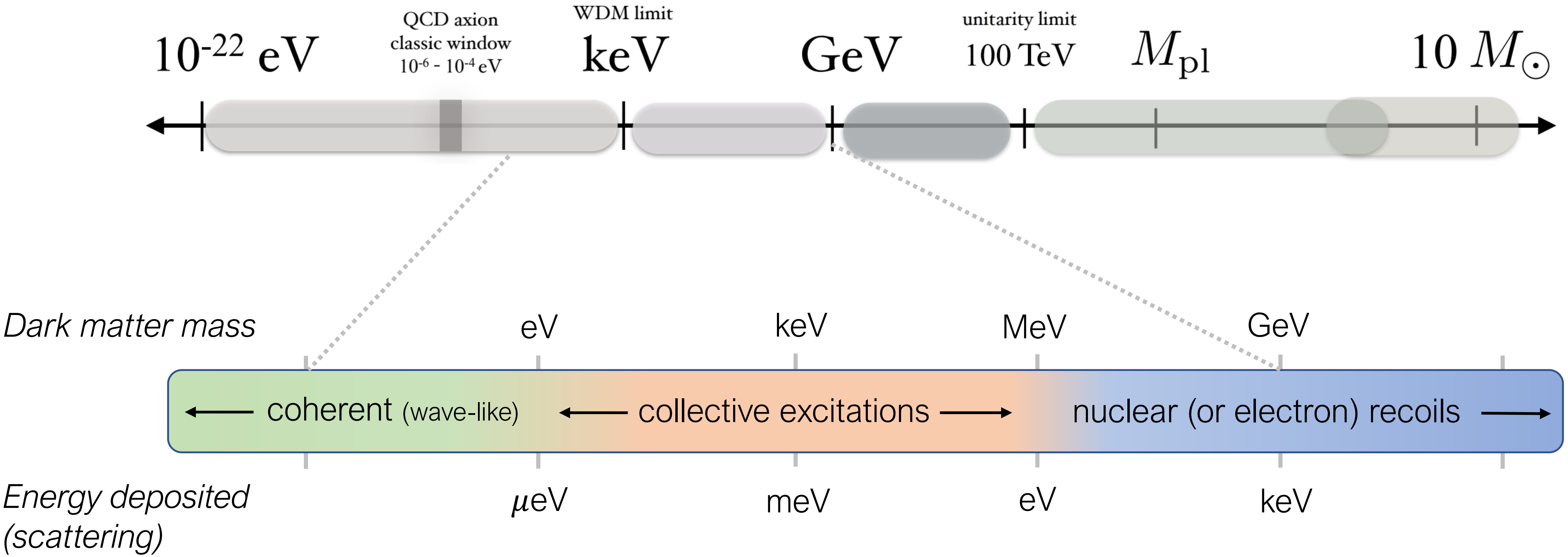


Figure: T. Lin

Direct detection regimes



Detection strategy depends on coherence length of dark matter

Current status: nuclear recoils (SI)

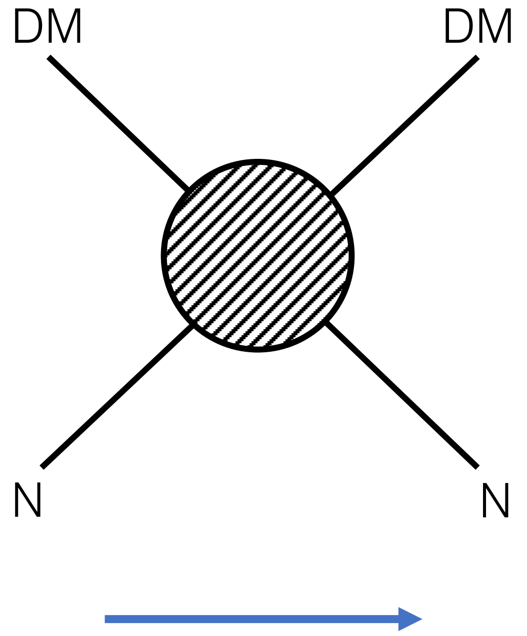


Figure: C. O'Hare

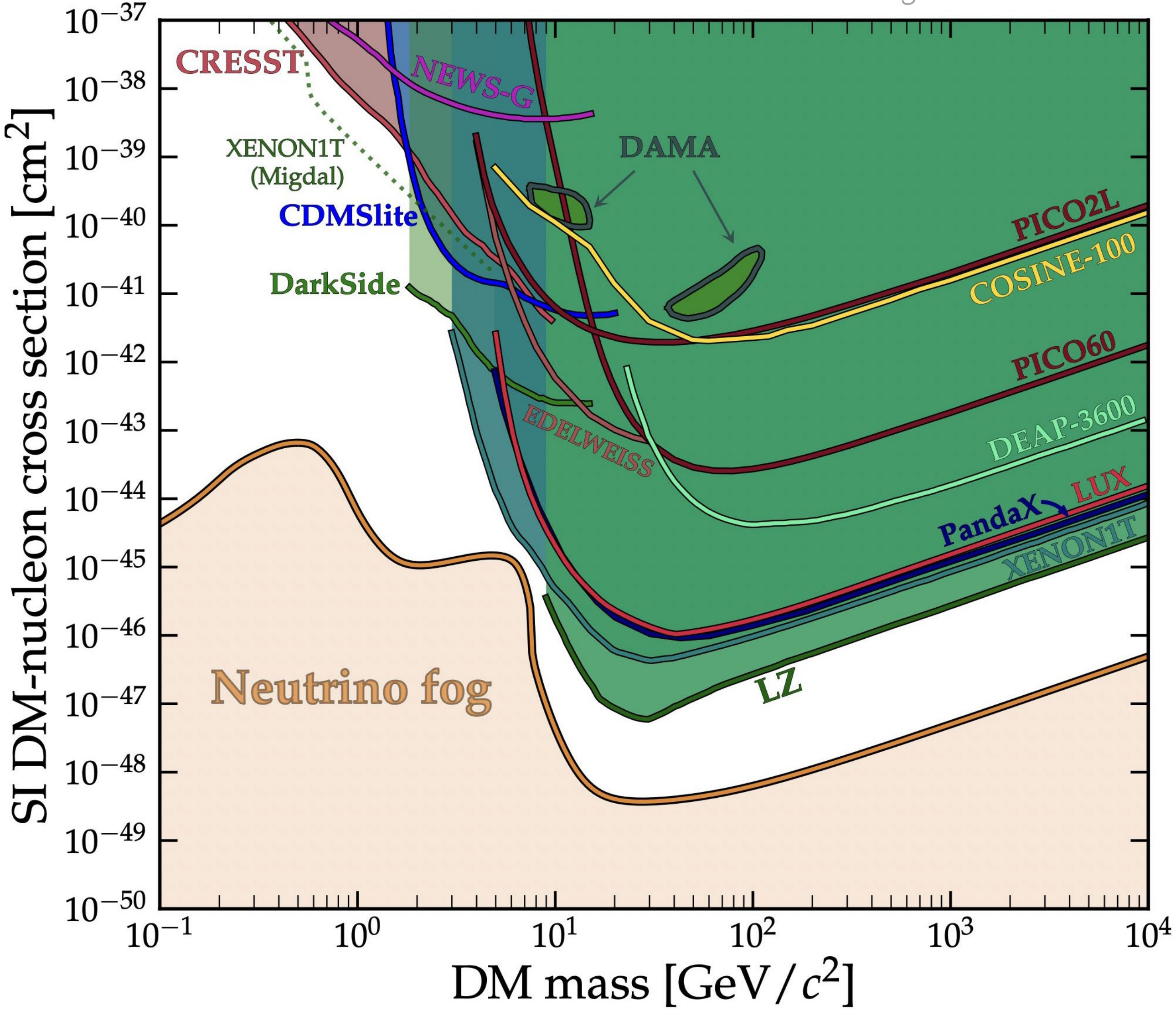


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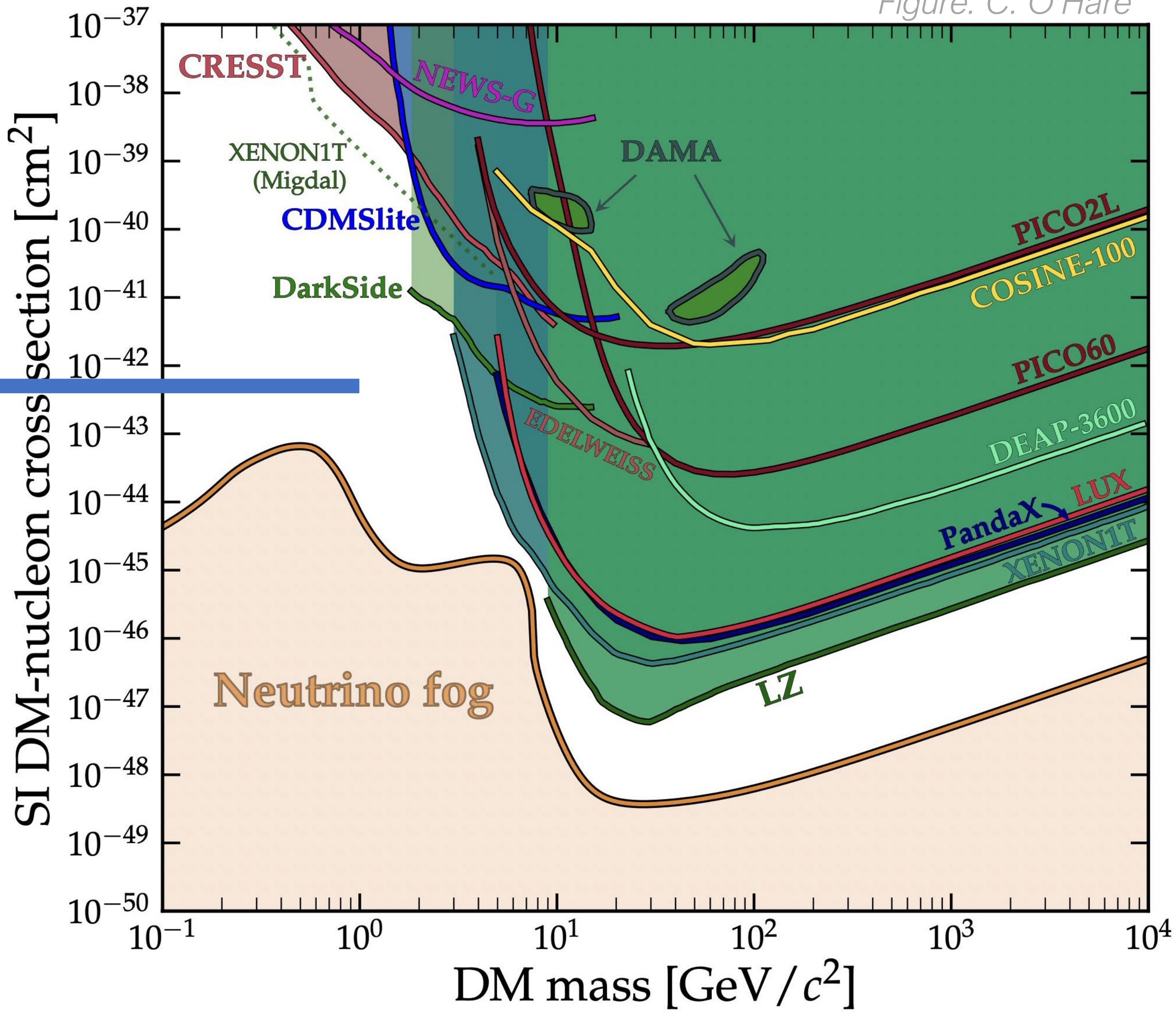
Figure: C. O'Hare

Lower energy thresholds

&

inelastic processes



Increased exposure

Ionisation & Bremsstrahlung

Vergados & Ejiri '04
Kouvaris & Pradler '17
Ibe+ '17

(Inelastic) electromagnetic processes can accompany a nuclear recoil

- Ionisation (Migdal effect)
- Bremsstrahlung

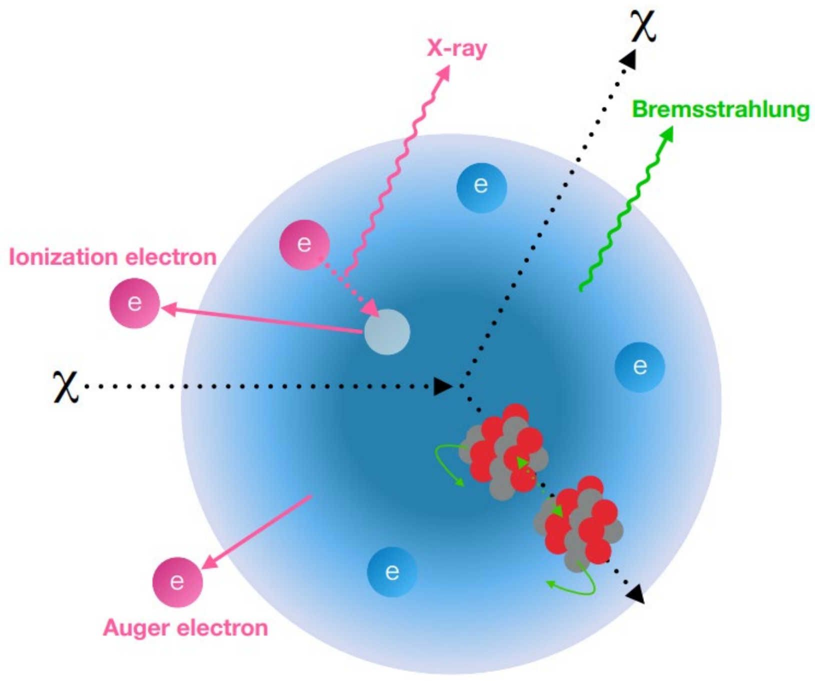


Figure: XENON collaboration

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Elastic nuclear recoil:

$$E_{NR}^{\max} = \underline{0.1\,\mathrm{keV}} \left(\frac{131}{A}\right)\left(\frac{m_\chi}{\mathrm{GeV}}\right)^2$$

Inelastic scattering:

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

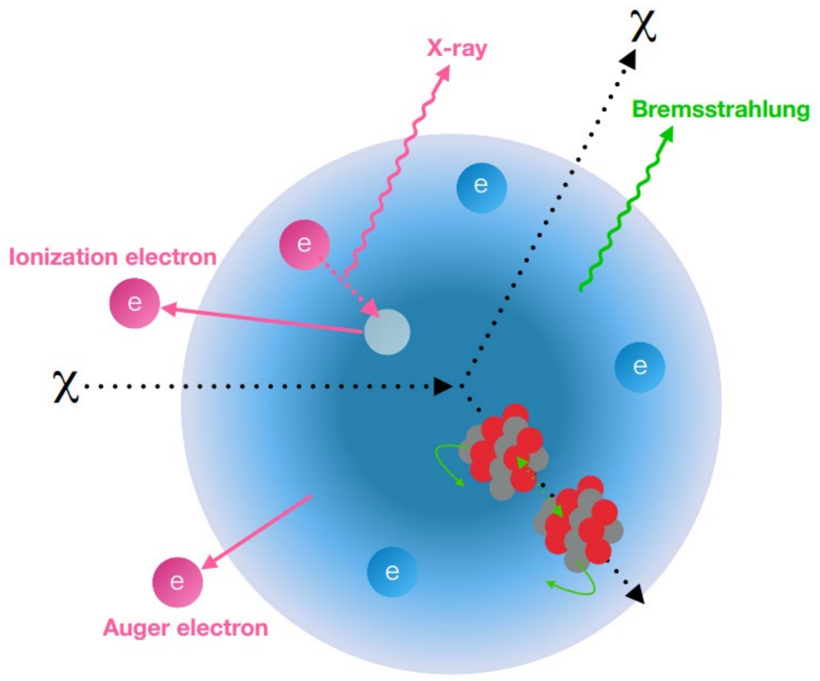
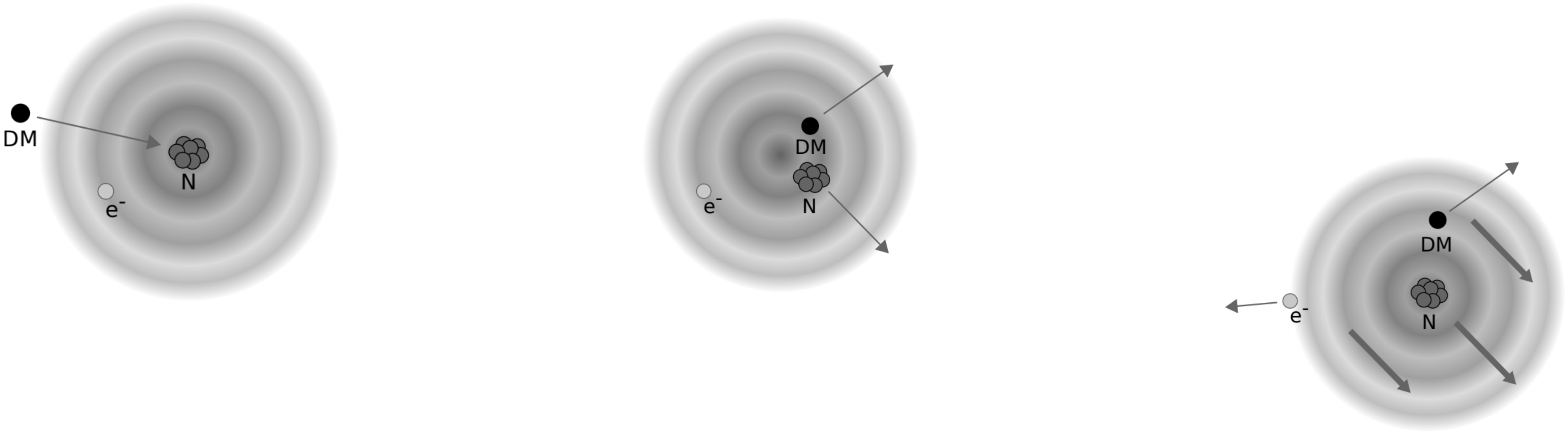


Figure: XENON collaboration

Migdal effect

Migdal 1939

Ionisation/excitation due to displacement of nucleus after nuclear recoil



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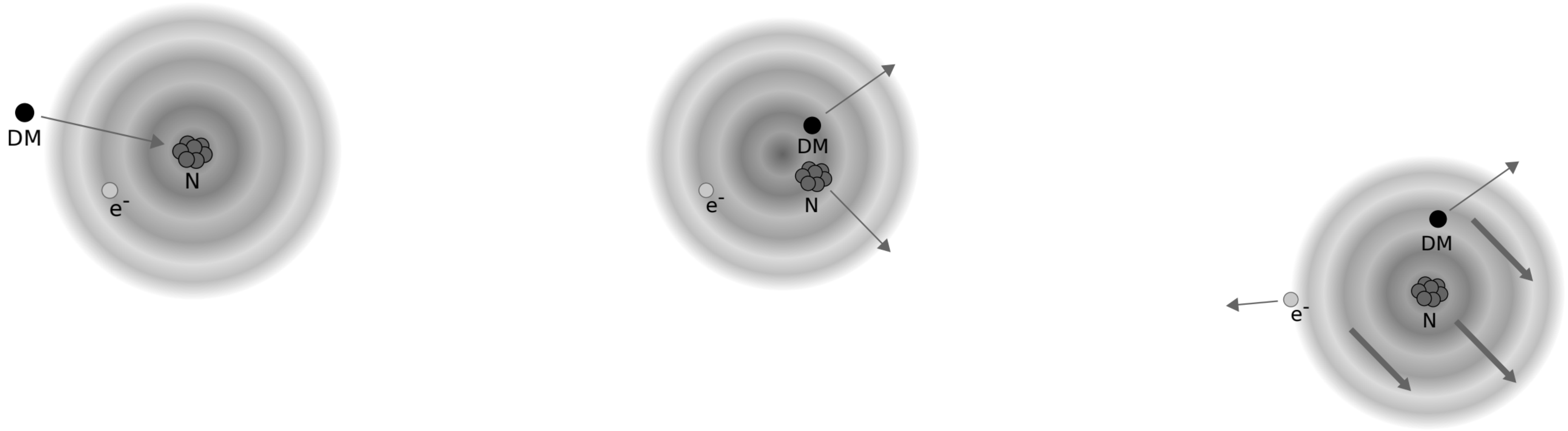
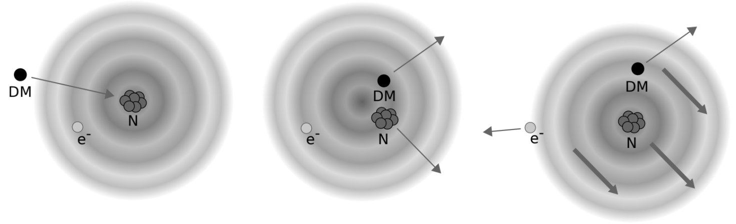


- Observed in $\alpha, \beta^{\pm}$ decays
- Not yet observed in neutron scattering – *important to validate theory for dark matter searches*

Calculating the Migdal rate

Migdal 1939



In rest frame of nucleus, wavefunction of moving electron cloud obtained by Galilean boost:

$$\left|\Psi'\right\rangle = U(\boldsymbol{v})\left|\Psi\right\rangle = e^{-im_e \sum_k \boldsymbol{v}\cdot\boldsymbol{r}_k}\left|\Psi\right\rangle$$

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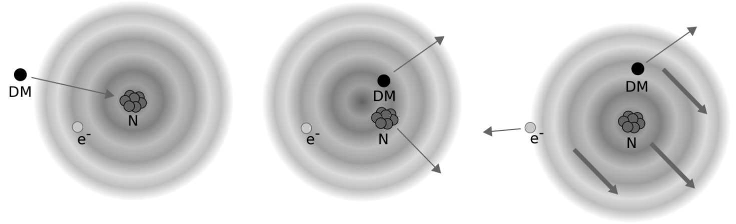

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Transition probability:

$$p_v\left(\Psi_i \to \Psi_f\right) = \left|\left\langle \Psi_f \middle| \exp\left(im_e \boldsymbol{v}\cdot\sum_{k=1}^{N}\boldsymbol{r}_k\right) \middle| \Psi_i \right\rangle\right|^2$$

electronic wavefunctions at $v = 0$

Calculating the Migdal rate

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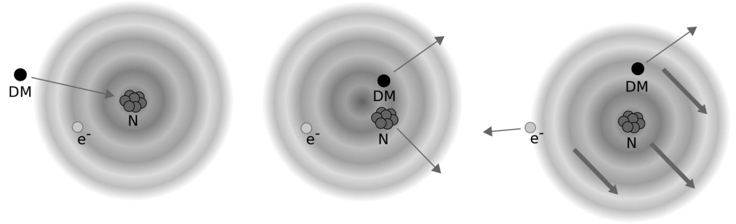

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electronic wavefunctions at $v = 0$

Migdal effect also studied in

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

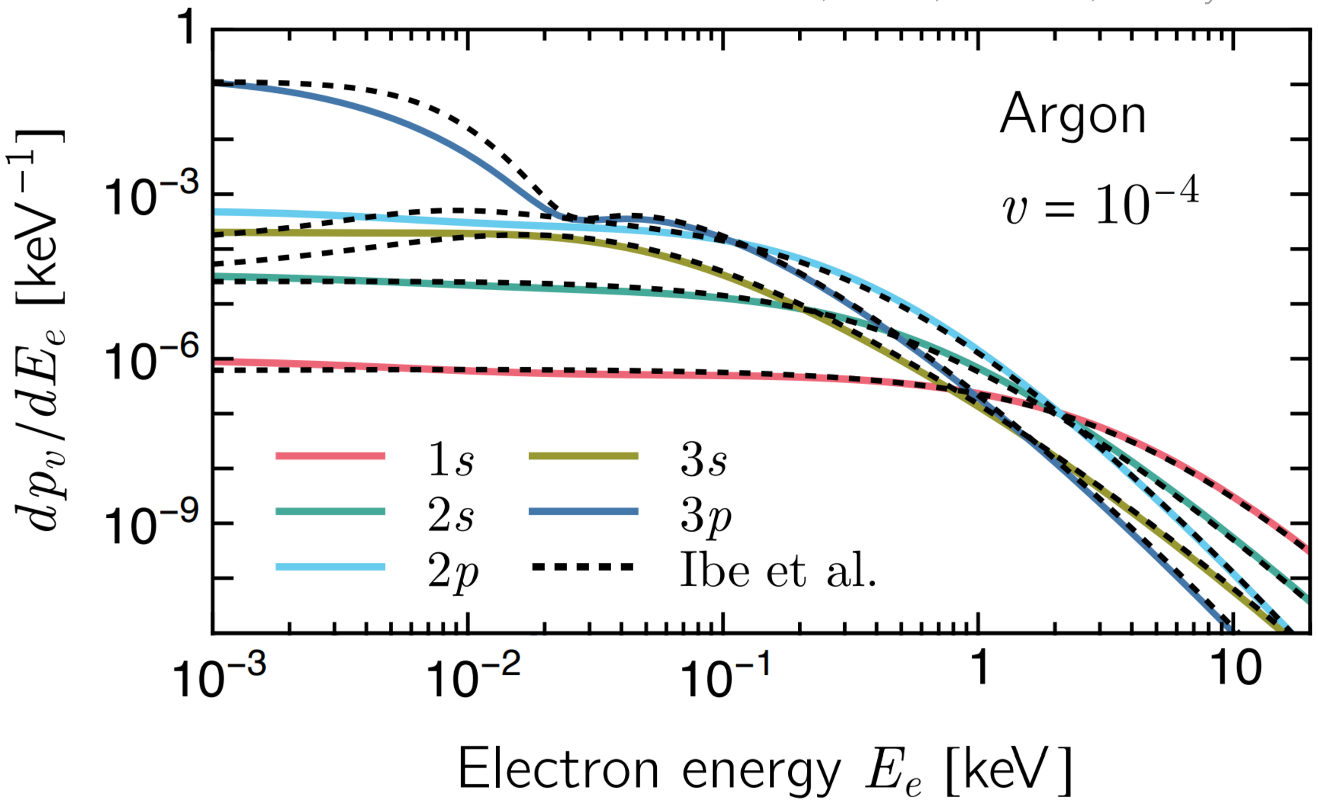
Migdal ionisation probabilities

- Inner shells dominate rate at high e^- energies

  → Additional x-ray / auger electrons from de-excitation

- Valence electrons dominate at very low energies

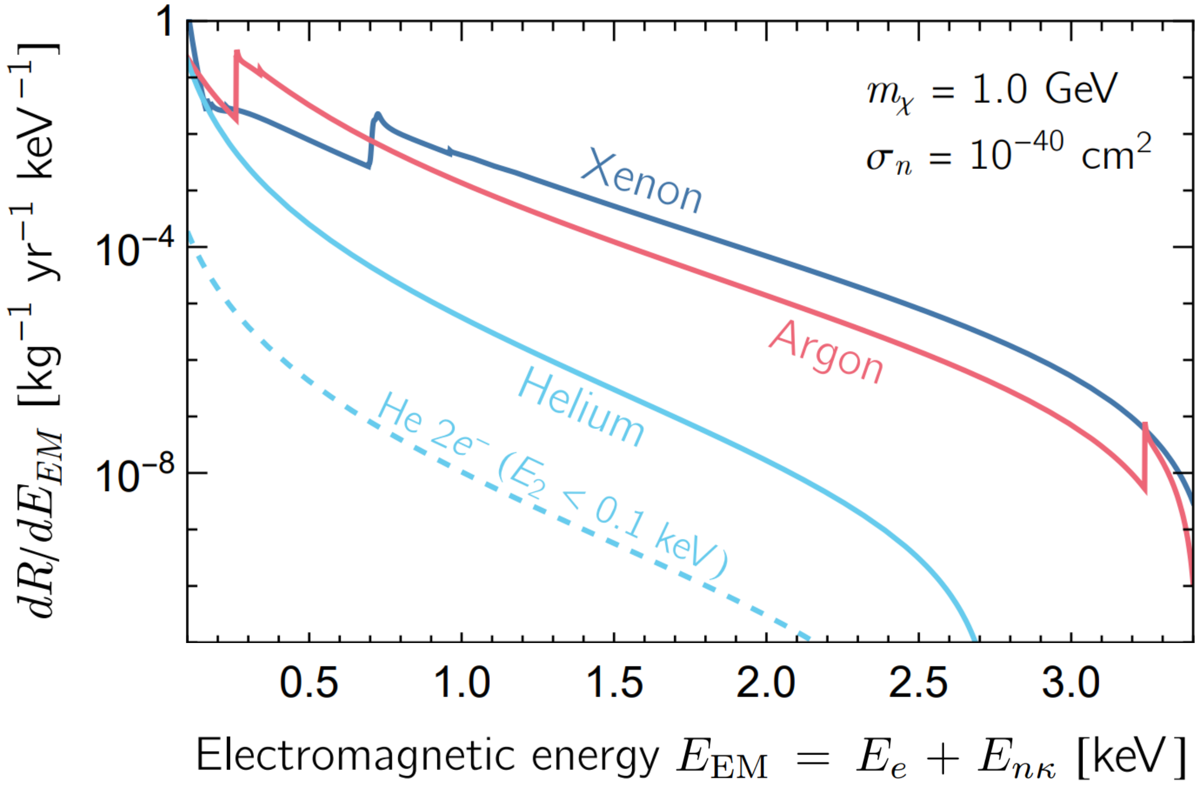
PC, Dolan, McCabe, Quiney '21



Migdal rate in DM scattering

$$\frac{d^2R}{dE_R dE_e} = \underbrace{\frac{A^2\sigma_n|F_N|^2}{2m_\chi\mu_{\chi n}^2}} \underbrace{\sum_{n\kappa}\frac{dp_v(n\kappa\to E_e)}{dE_e}}_{\text{Migdal ionisation probability}} \underbrace{\frac{\rho_\chi}{m_\chi}g_\chi(v_{\min})}$$

PC, Dolan, McCabe, Quiney '21



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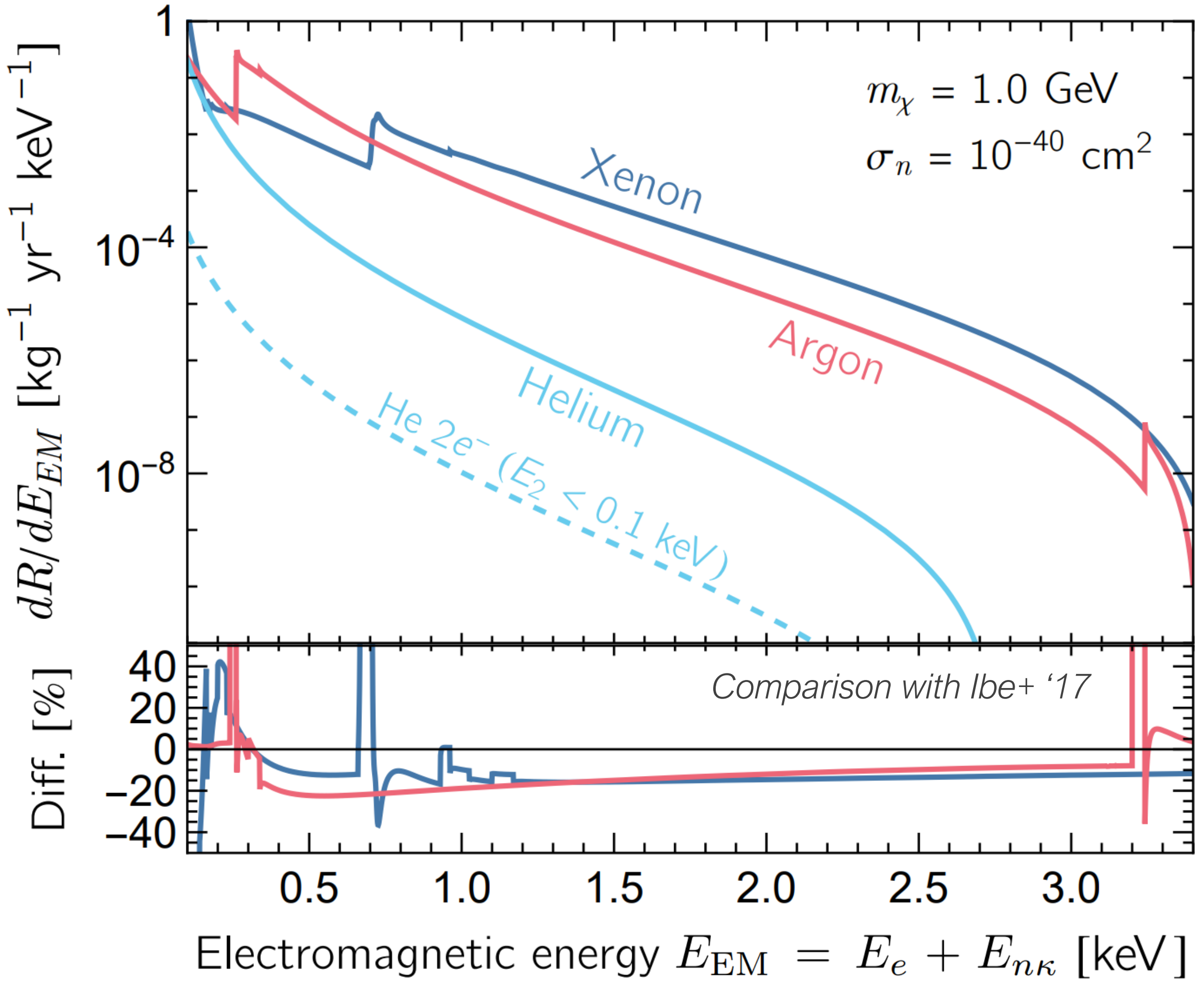
- Good agreement with earlier dipole approximation results *(Ibe+ '17)*
- Differences due to orbital energies & atomic potential

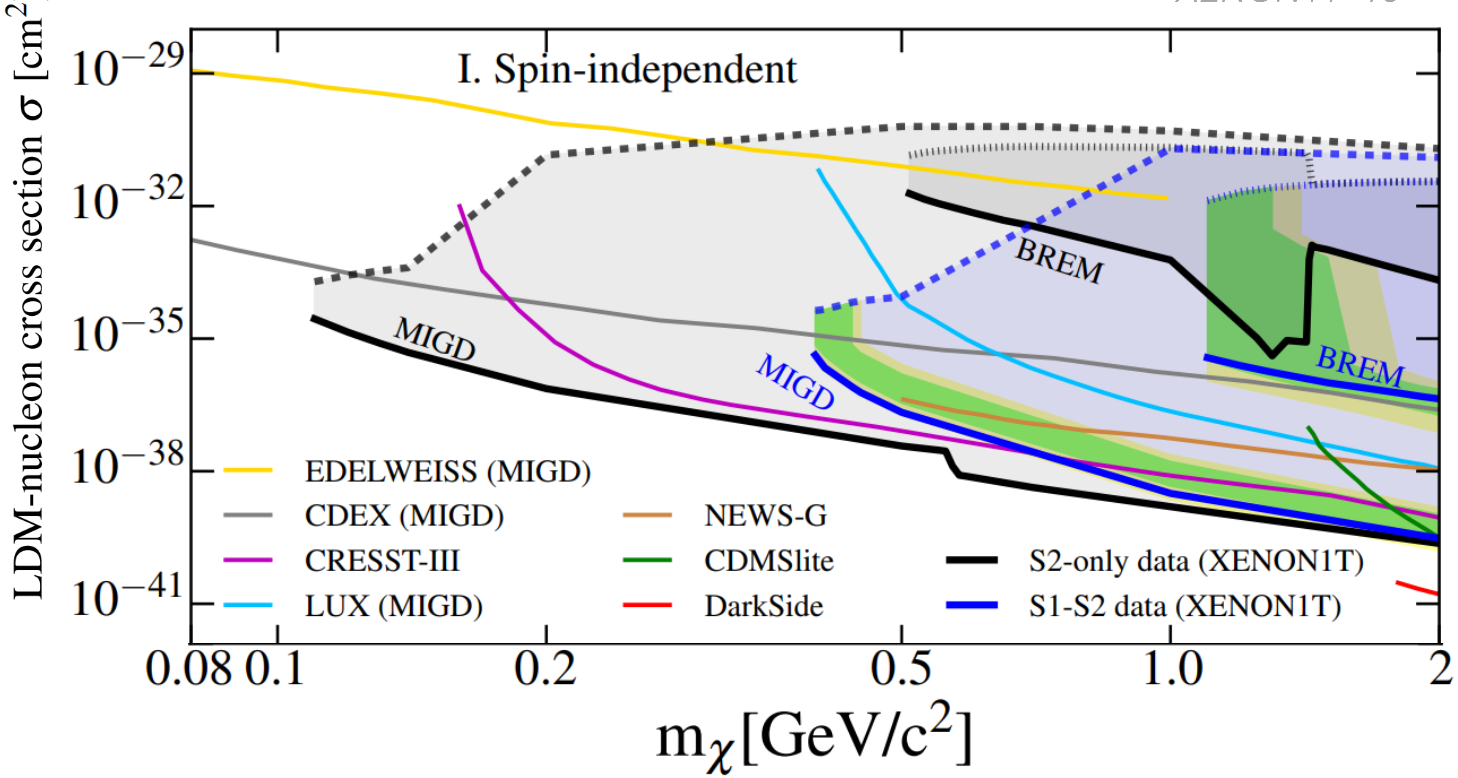
PC, Dolan, McCabe, Quiney '21



Current limits: sub-GeV dark matter

Migdal effect provides world-leading limit for $m_{DM} \lesssim 1\text{GeV}$

XENON1T '19



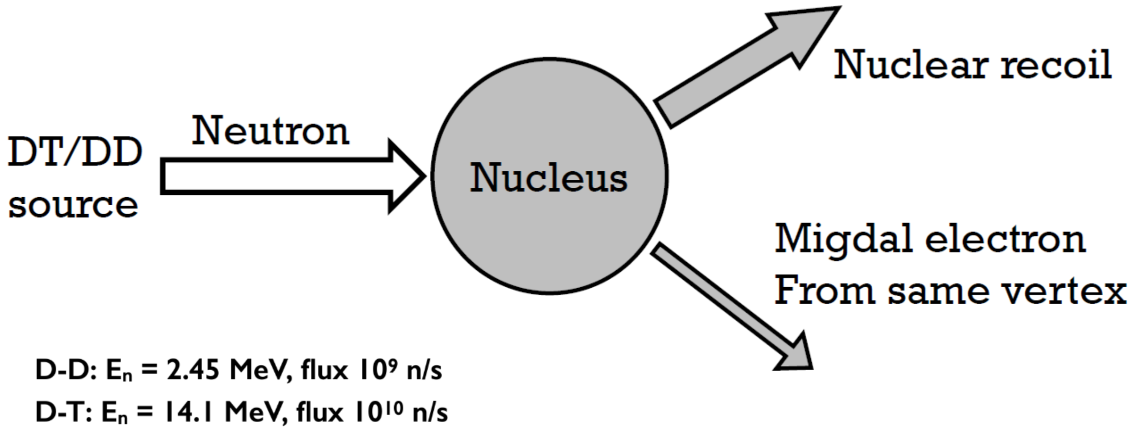
Important to calibrate Migdal effect and validate theory

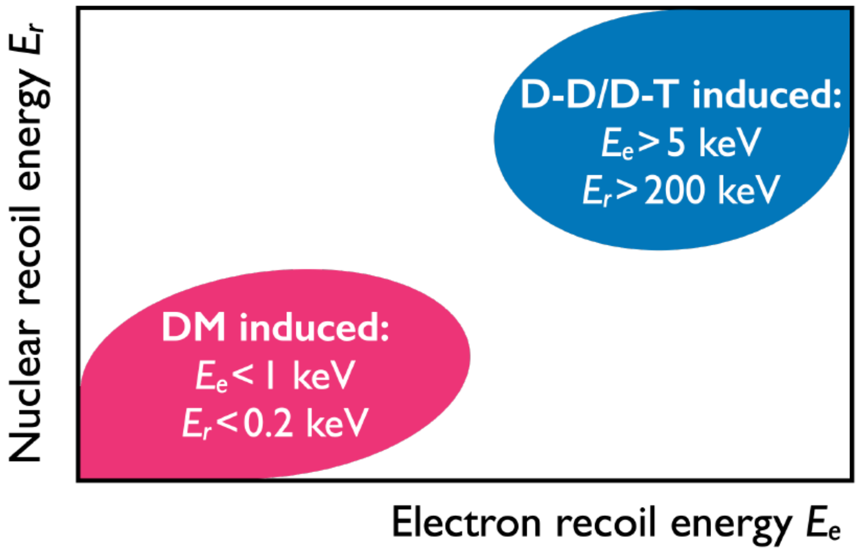
MIGDAL

Migdal In Galactic Dark mAtter expLoration

Araujo+ '22

- Observe Migdal effect in neutron scattering using optical TPC
- Phase 1: CF_4
  Phase 2: CF_4 + noble gases



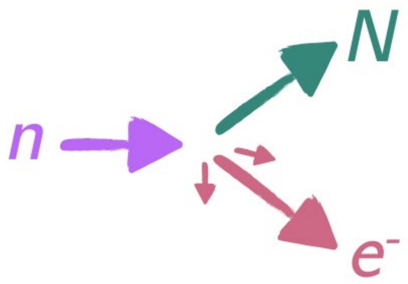


Neutron scattering (MIGDAL experiment)

PC, Dolan, McCabe, Quiney '21

- At high recoil velocities, observable rate dominated by

1 hard (keV) e^- + soft electrons



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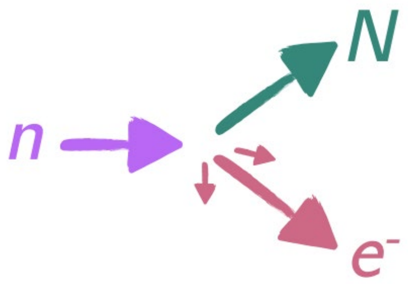
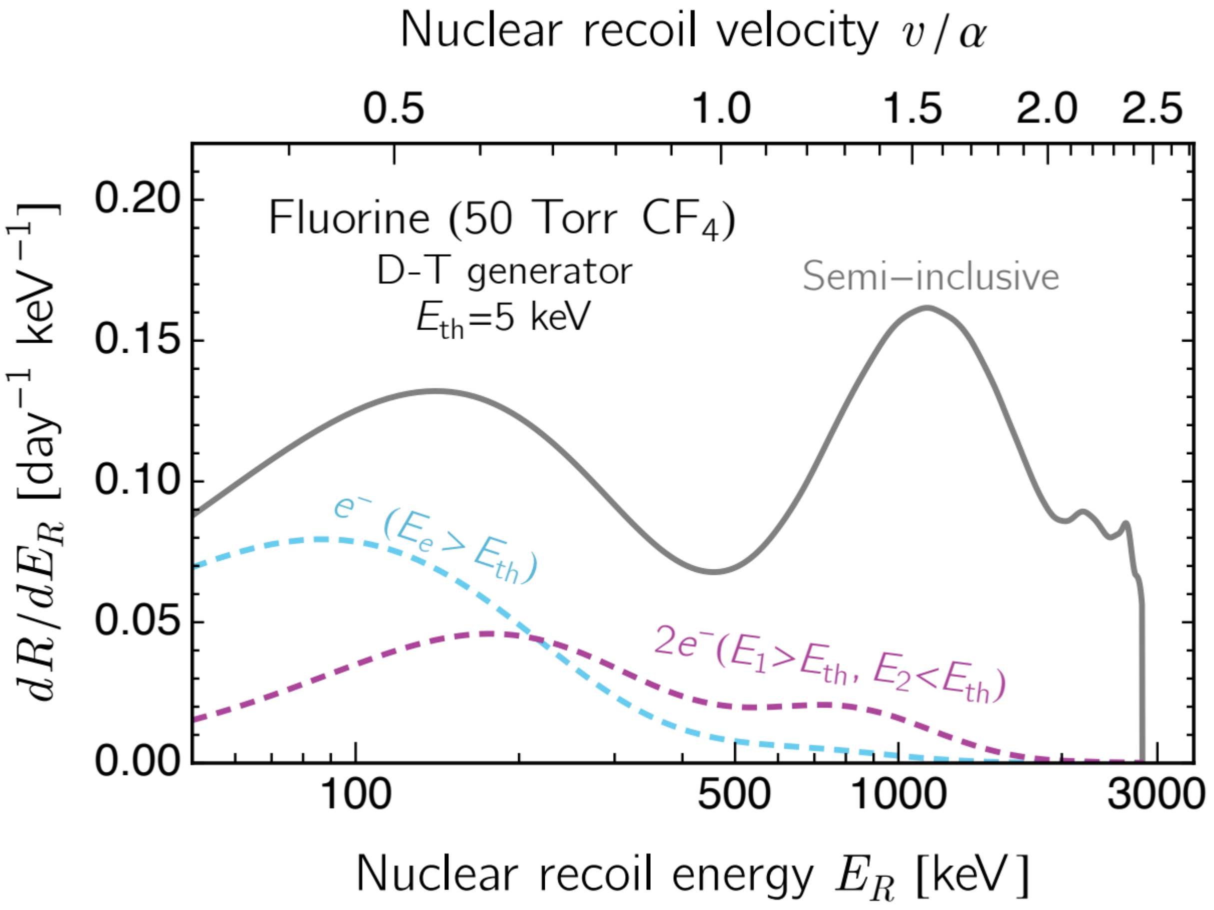


- *Must* include multiple ionisation processes to obtain accurate predictions



Direct detection with superfluid He

Why Helium?

- Low atomic mass – good kinematics for light DM
- Superfluid at cryogenic temperatures
- Readily obtainable and naturally radiopure
- Multiple detectable signals

Nuclear recoils in superfluid He

Nuclear recoils in liquid Helium can produce a variety of signals:

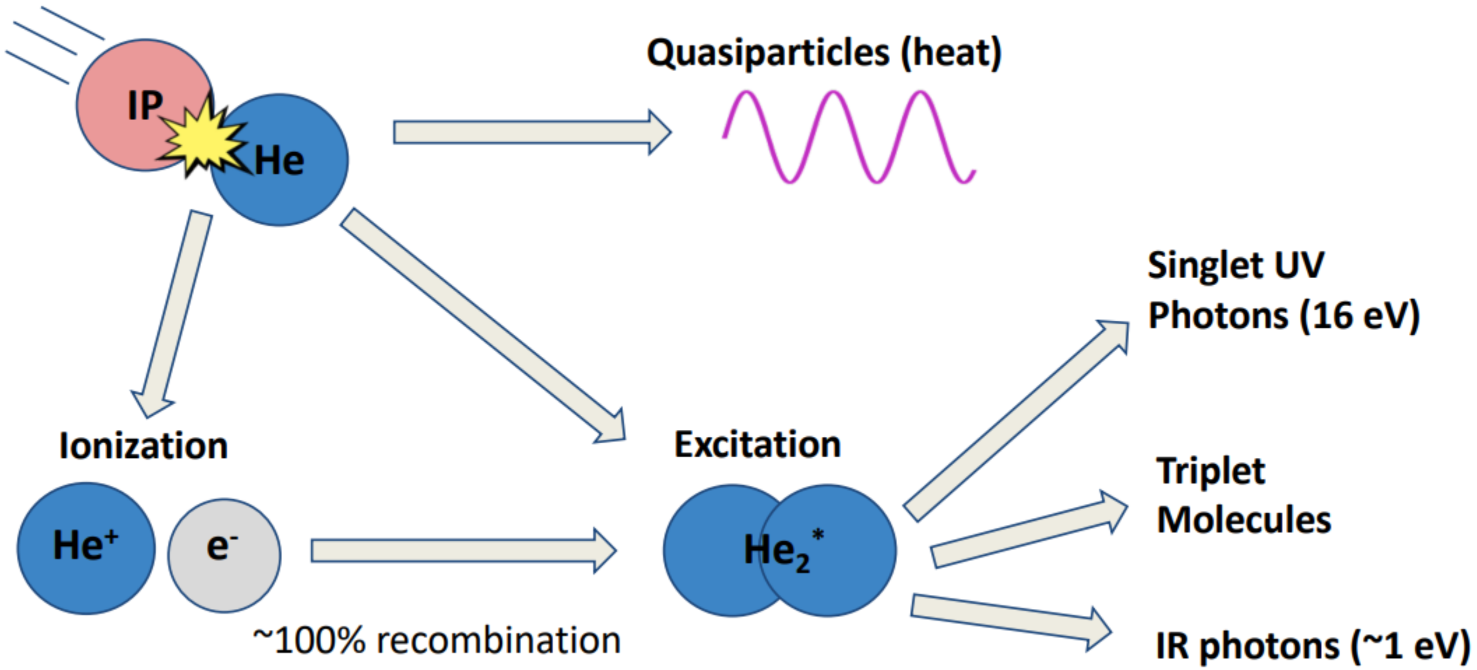


Figure: D. McKinsey

Bulk superfluid He detector

Lanou, Maris & Seidel '87
Guo & McKinsey '13
Ito & Seidel '13
Hertel+ '18

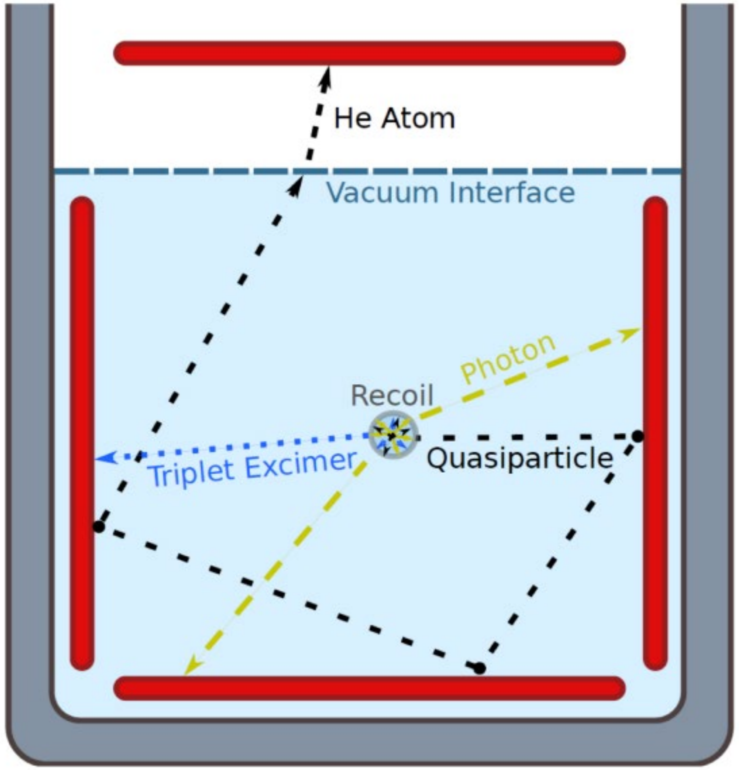


Figure: Hertel+ '18

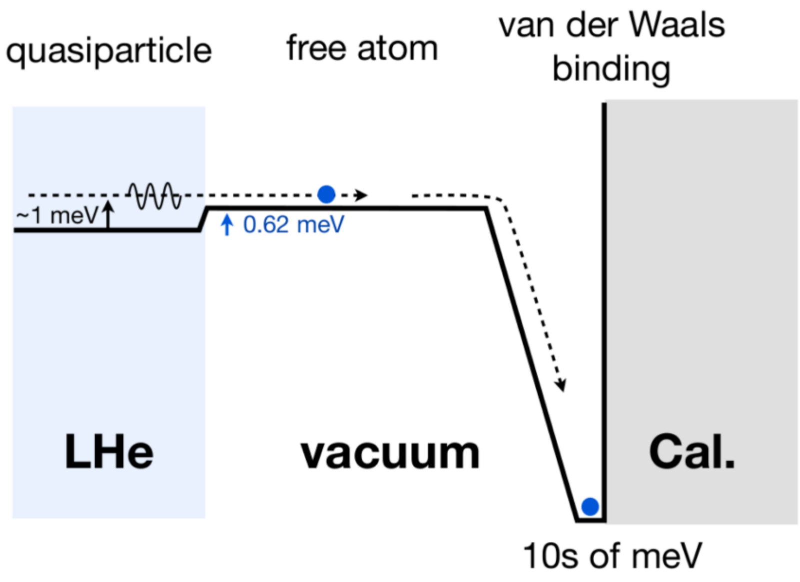


Figure: D. McKinsey

Adsorption onto surface amplifies signal

Bulk superfluid He detector

Hertel+ '18

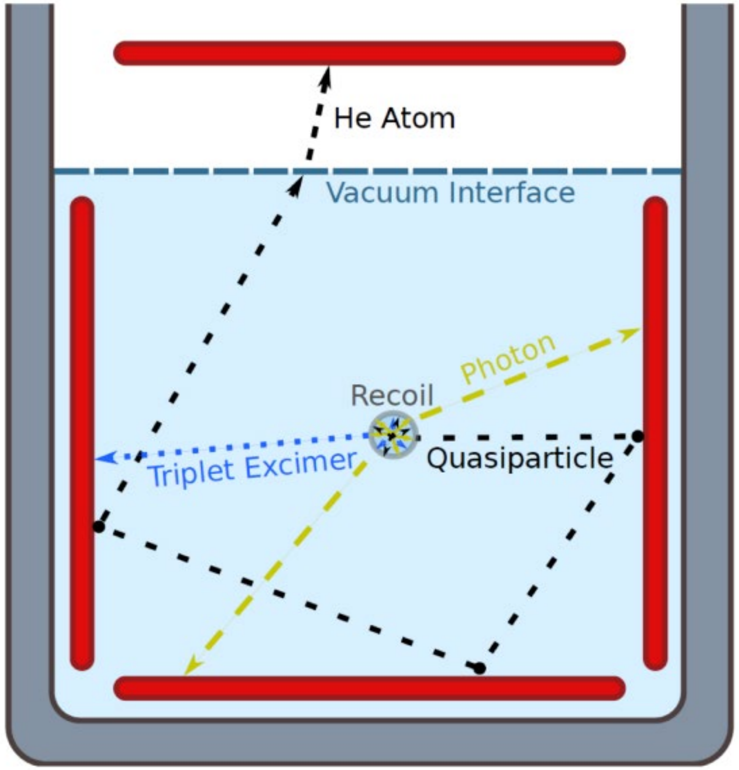
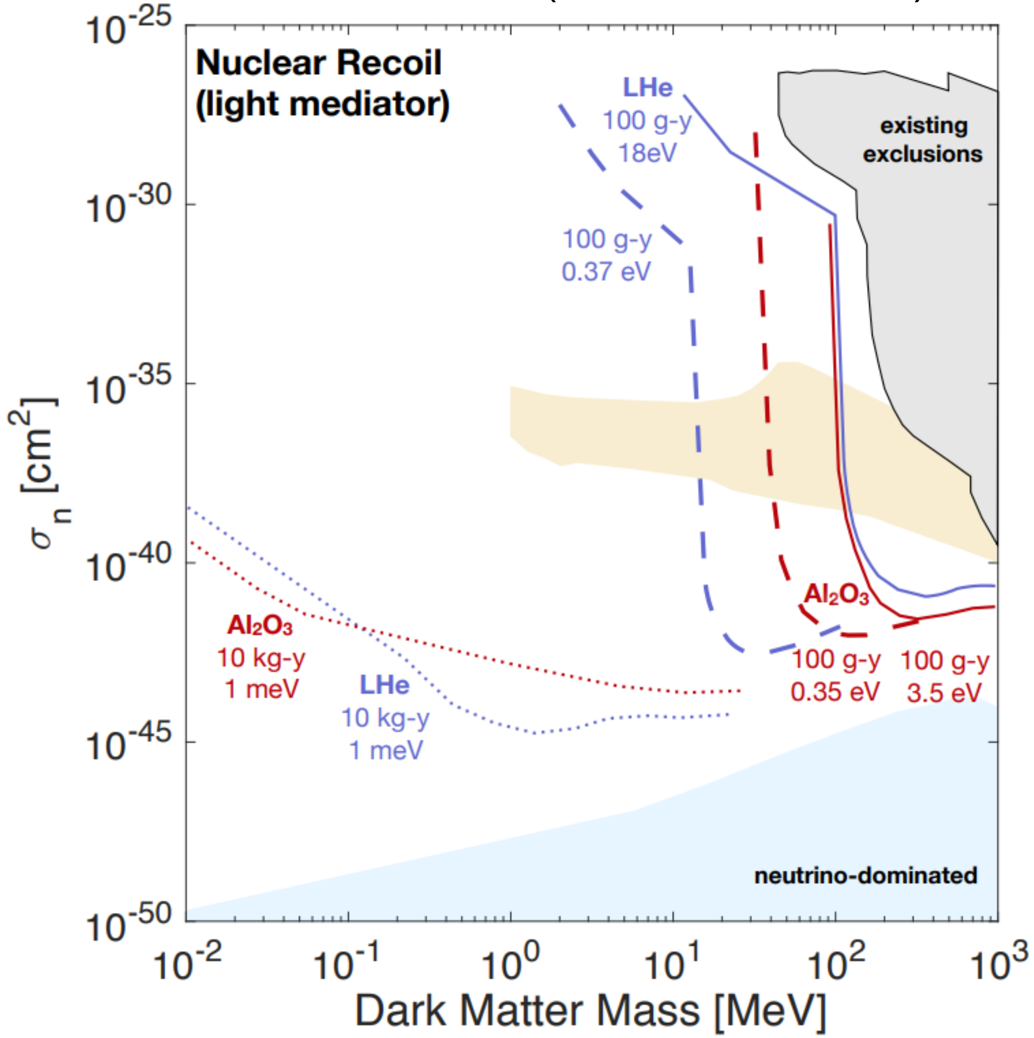


Figure: Hertel+ '18

HeRALD (TESSERACT)



*see also *DELight* proposal (magnetic readout)

Superfluids for sub-MeV dark matter

Sub-MeV dark matter can only excite collective modes

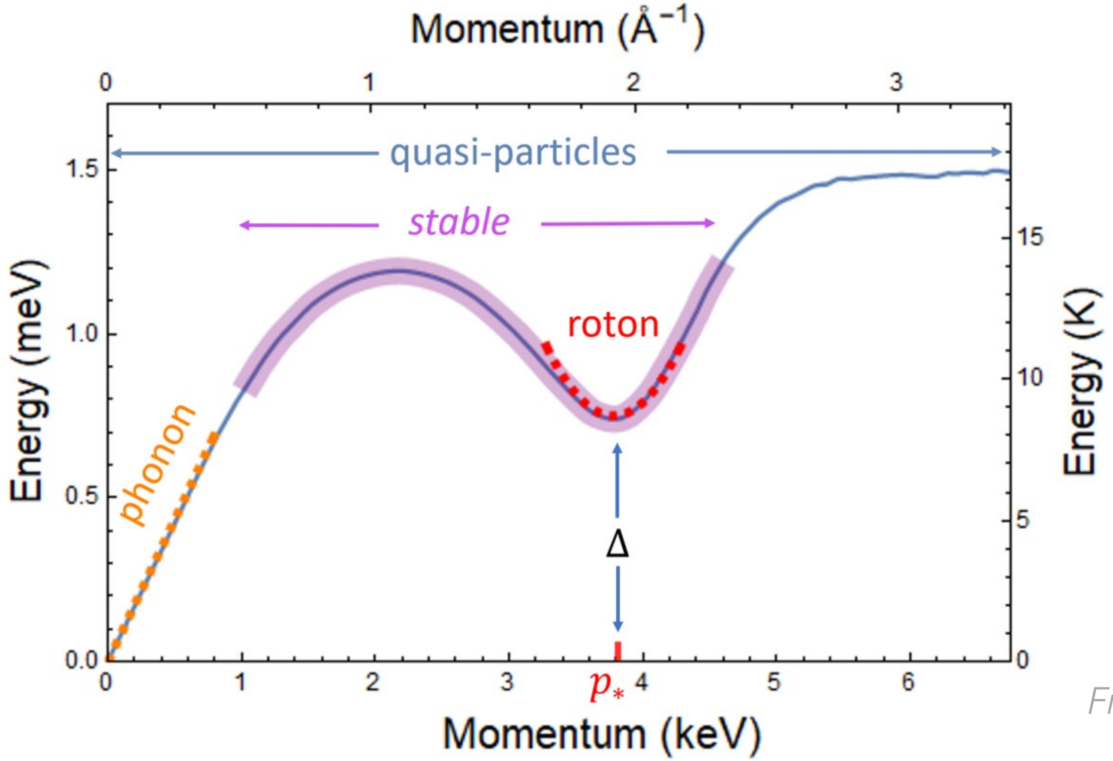


Figure: arXiv:2108.07275

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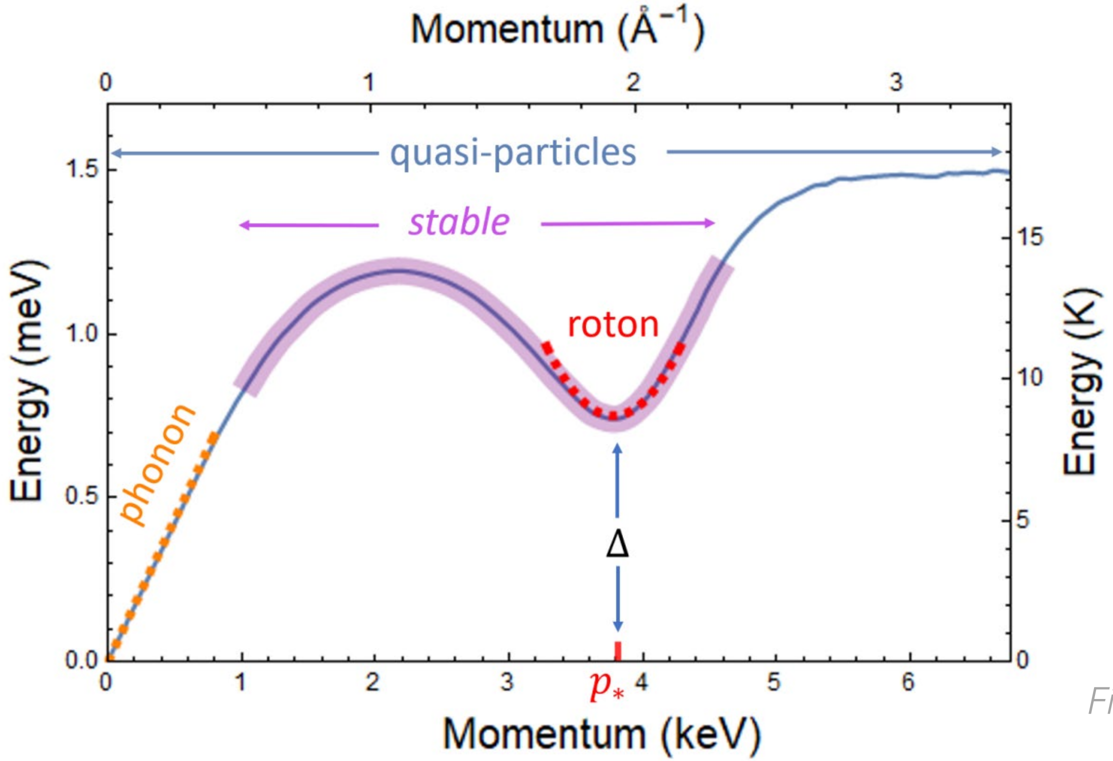


Figure: arXiv:2108.07275

How to detect phonons with energies $\lesssim$ meV ?

Superfluid optomechanics

superfluid filled optical cavity

Sound waves in superfluid modify refractive index

➡ coupling between optical and phonon modes

Superfluid optomechanics

superfluid filled optical cavity

photons phonon

$$H_{\text{OM}} = -g(a_{\gamma_1} a^\dagger_{\gamma_2} b_m + a^\dagger_{\gamma_1} a_{\gamma_2} b^\dagger_m)$$

Superfluid optomechanics

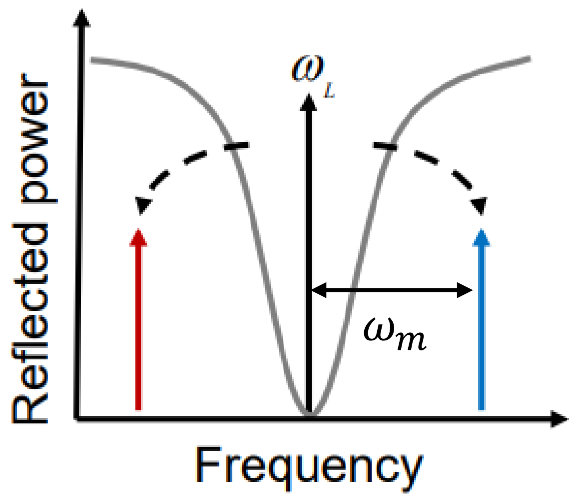
superfluid filled optical cavity

photons phonon

$$H_{\mathrm{OM}} = -g(a_{\gamma_1} a^\dagger_{\gamma_2} b_m + a^\dagger_{\gamma_1} a_{\gamma_2} b^\dagger_m)$$
$$\to -g\sqrt{N_1}(a^\dagger_{\gamma_2} b_m + a_{\gamma_2} b^\dagger_m)$$

pump laser

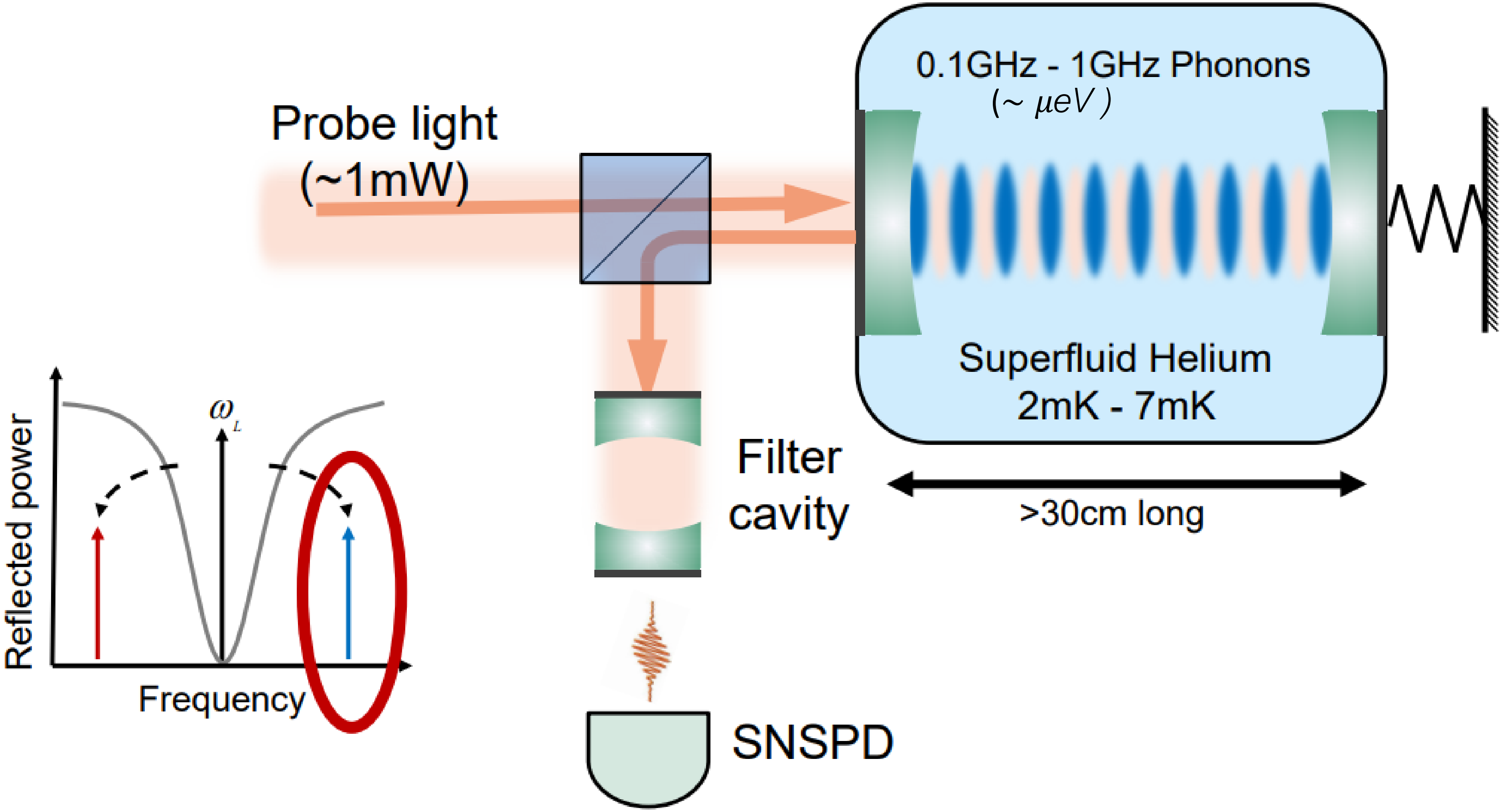
$$\omega_m = \omega_{\gamma_1} \pm \omega_{\gamma_2}$$



Single phonon detector for μeV phonons!

Superfluid optomechanics for DM

Baker, Bowen, PC, Dolan, Goryachev, Harris (work in progress)



Superfluid optomechanics for DM

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(work in progress)

- Can achieve extremely low energy thresholds

- *BUT*: narrow-band detectors (single phonon energy)

  $\Longrightarrow$ Small scattering rate due to restricted phase space

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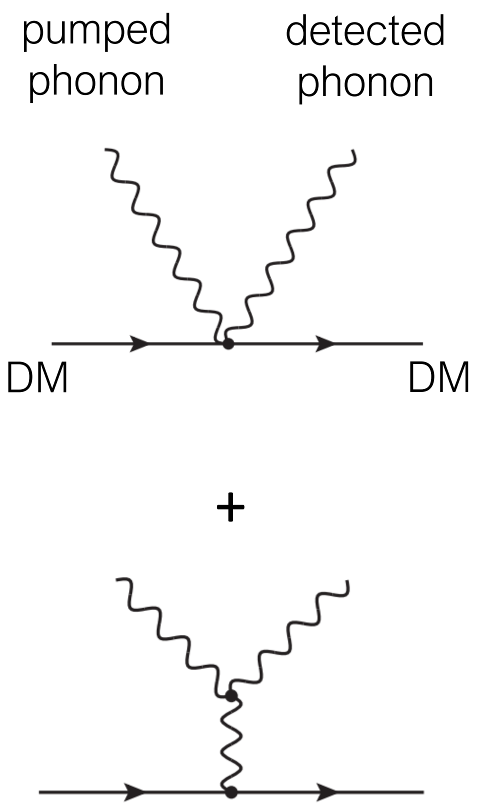
- Can achieve extremely low energy thresholds
- *BUT*: narrow-band detectors (single phonon energy)

  ➡ Small scattering rate due to restricted phase space

- *Solution*: two phonon processes with phonon lasing

  ➡ rate proportional to phonon occupation number



Also optomechanical axion detection *Murgui, Wang, Zurek '22*

Superfluid optomechanics for DM

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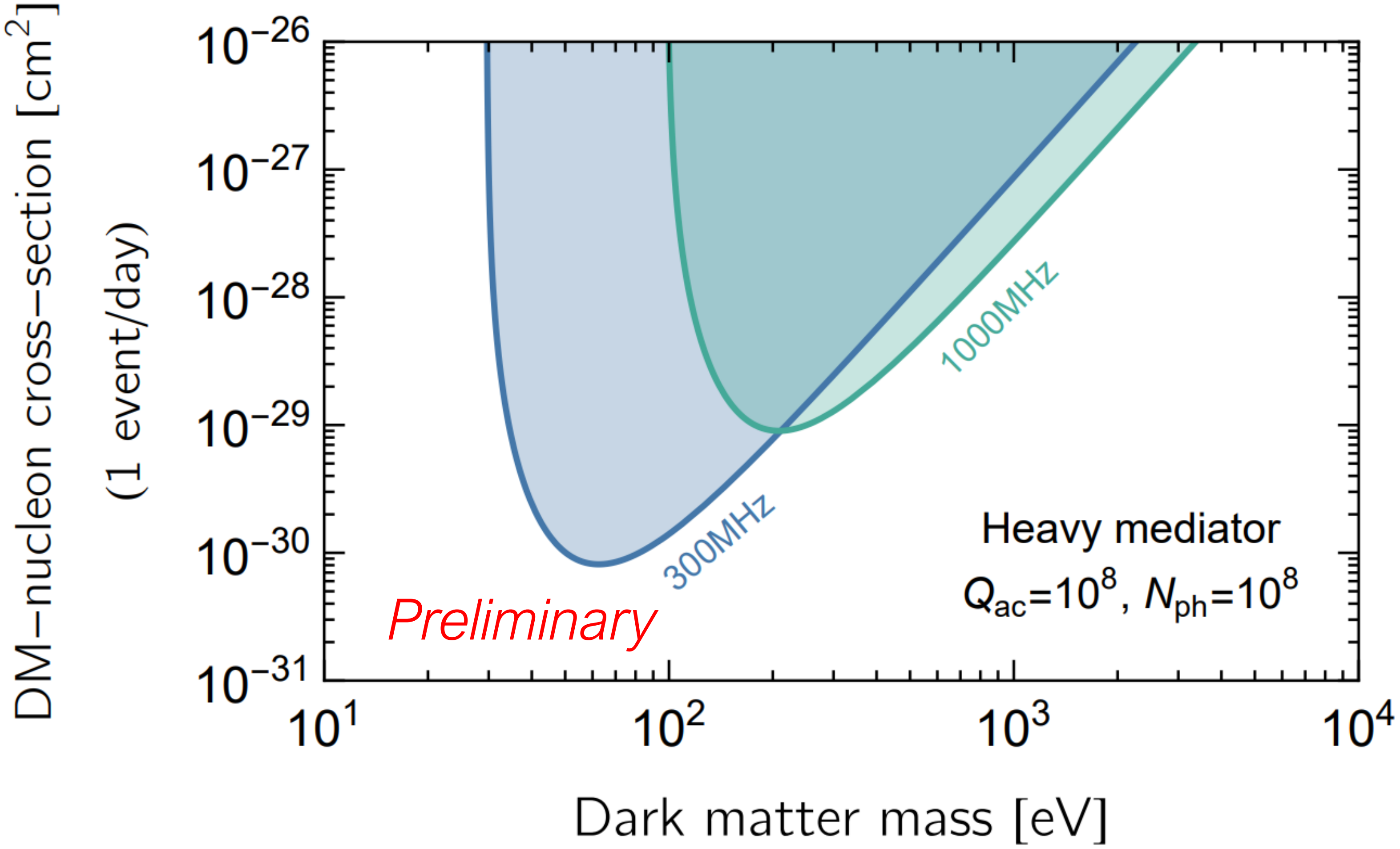
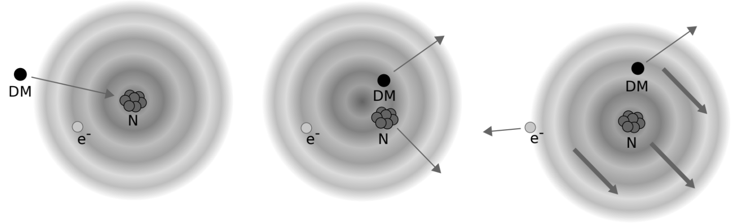
(work in progress)



Outlook

- Direct detection can probe a wide-range of dark matter masses, including outside traditional WIMP window



- Migdal effect extends reach of existing experiments to lower masses
- Superfluid He is a promising detector material for sub-GeV dark matter
- Optomechanical systems can probe sub-keV masses (ongoing R&D and design work)