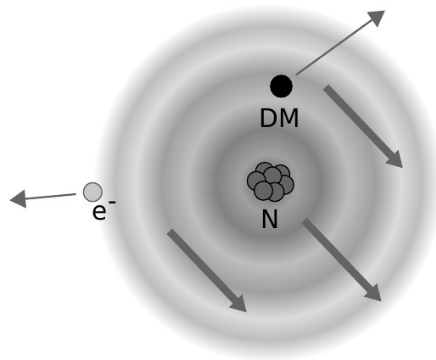
Other Aspects of Low Mass Direct Detection



Matthew J. Dolan
University of Melbourne
Centre of Excellence for Dark Matter Particle Physics

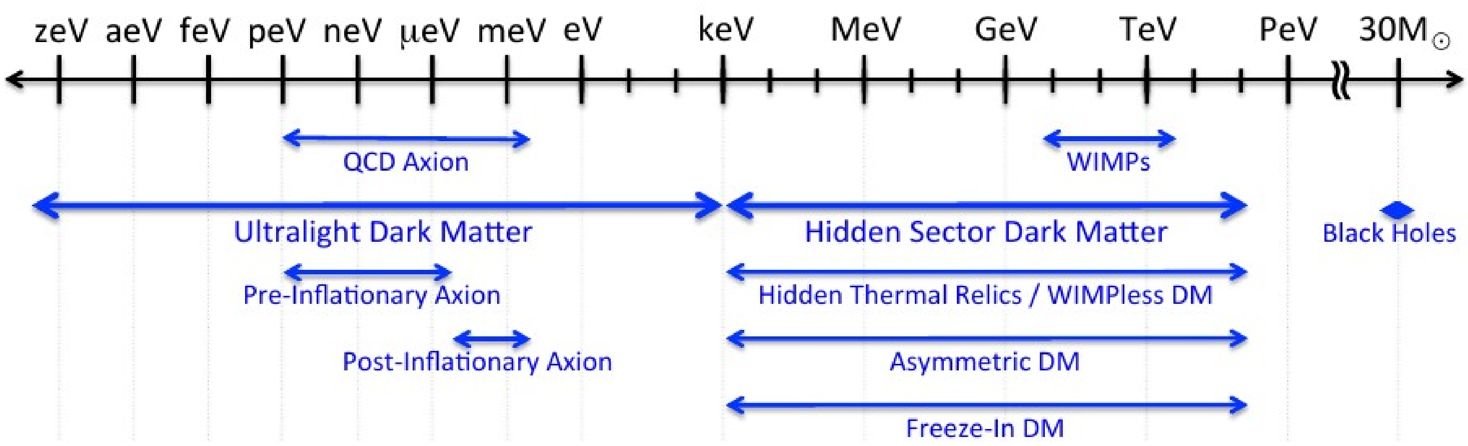
Various papers by various people, mostly not me

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

THE UNIVERSITY OF MELBOURNE

Dark Matter: Theory Perspective

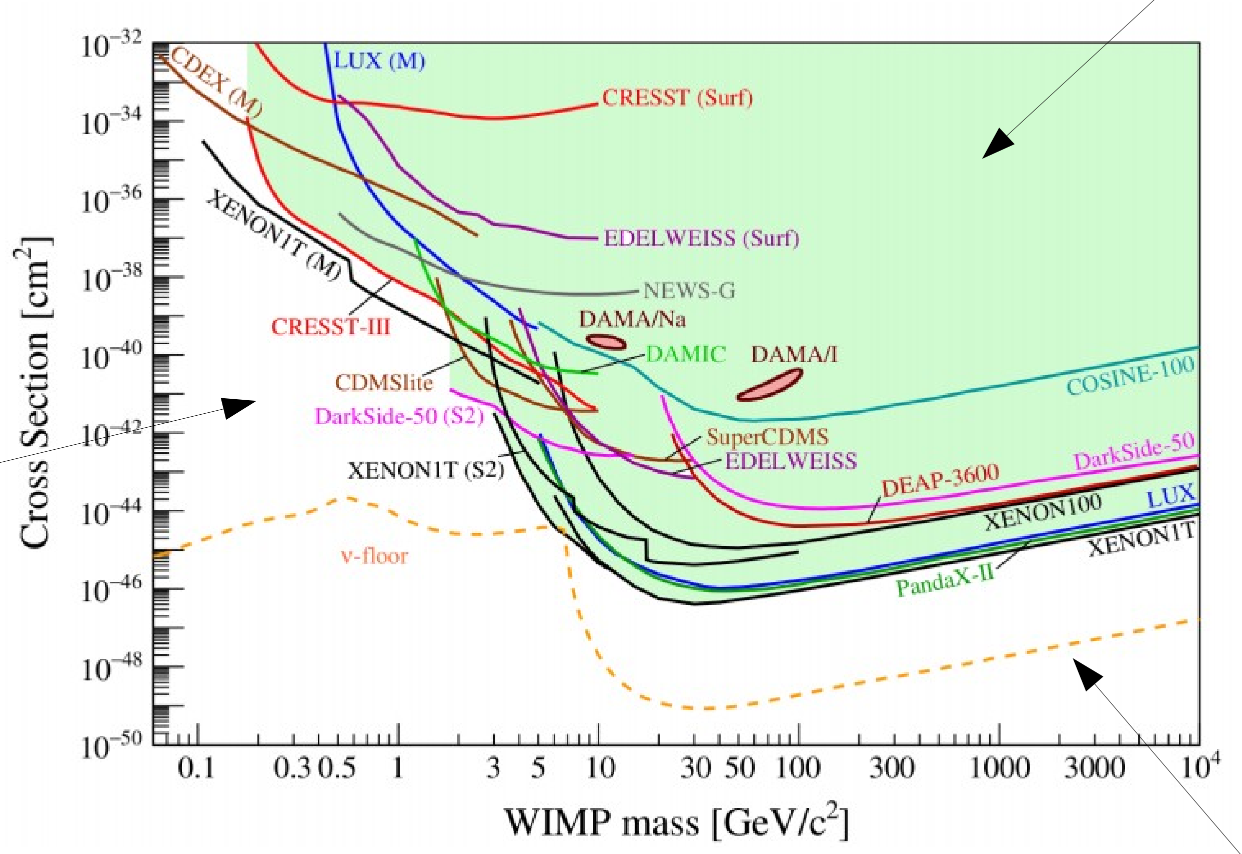
- Previously: Theory and Experiment largely driven by weak-scale issues with Standard Model
- Results from Direct Detection and LHC have driven interest in exploring different mass scales
    - New approach: what can we do now/soon with existing technologies?



Current Direct Detection limits

- DM-nucleon scattering

Ruled out



“Low-mass”

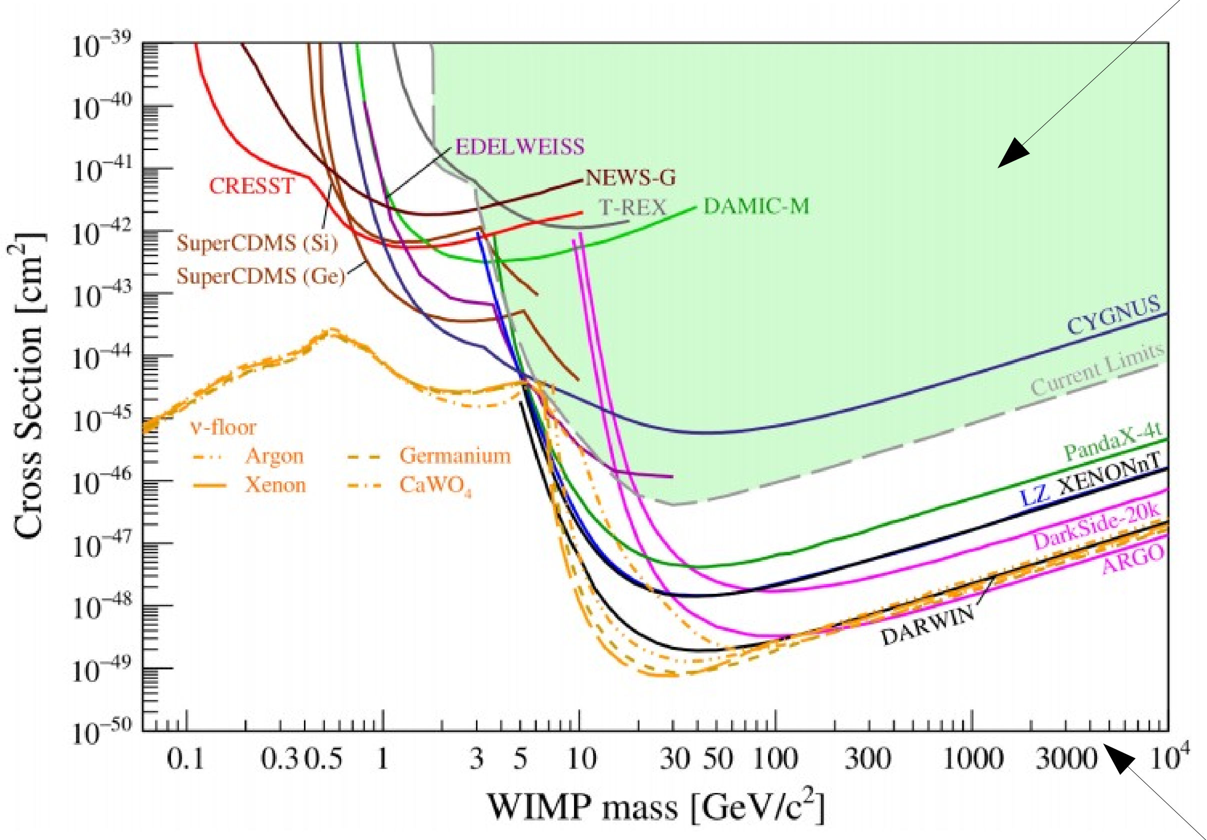
“Neutrino Floor”

APPEC Report

Future Direct Detection limits

- DM-nucleon scattering

Ruled out

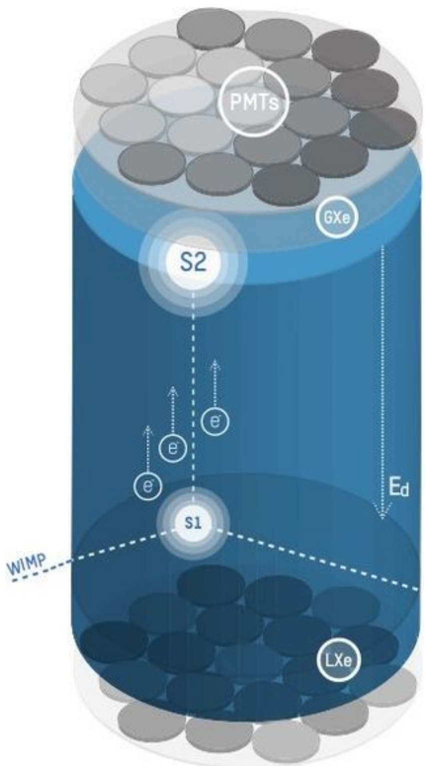


Liquid-Noble Gas Experiments

"Neutrino Floor"

APPEC Report

Direct Detection Kinematics



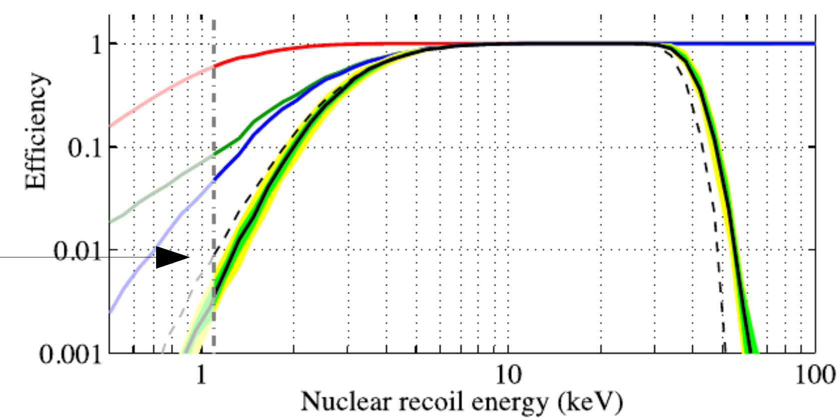
For a momentum transfer q, the nuclear recoil energy is

$$E_{NR} = \frac{q^2}{2m_N} \leq \frac{2\mu_{DM}^2 v_{DM}^2}{m_N}$$

Maximum nuclear recoil energy is

$$E_{NR}^{\max} \sim 0.1\,\mathrm{keV} \times \left(\frac{131}{\mathrm{A}}\right) \times \left(\frac{\mathrm{m_{DM}}}{1\,\mathrm{GeV}}\right)^2$$

LUX NR Sensitivity

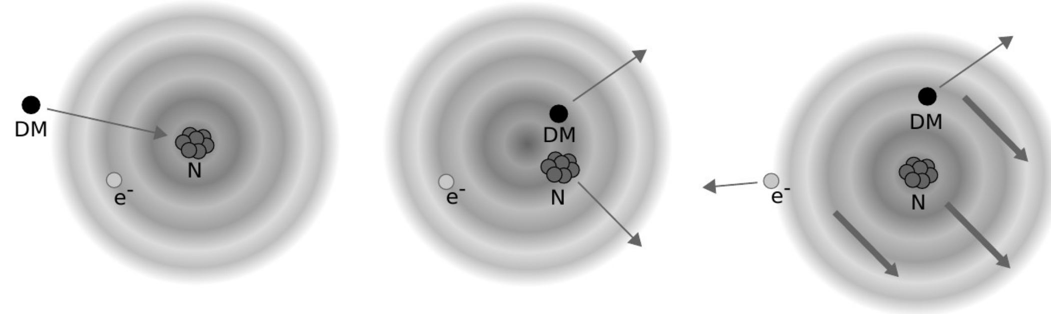


Loss of efficiency for keV nuclear recoils

Lore: Difficult to set nuclear recoil-based limits below GeV scale

Akerib et al, 1512.03506 (PRL)

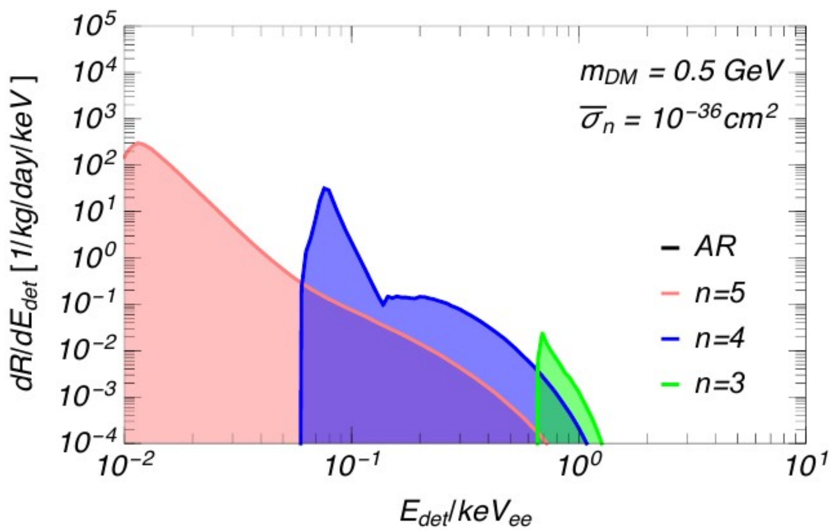
The Migdal Effect

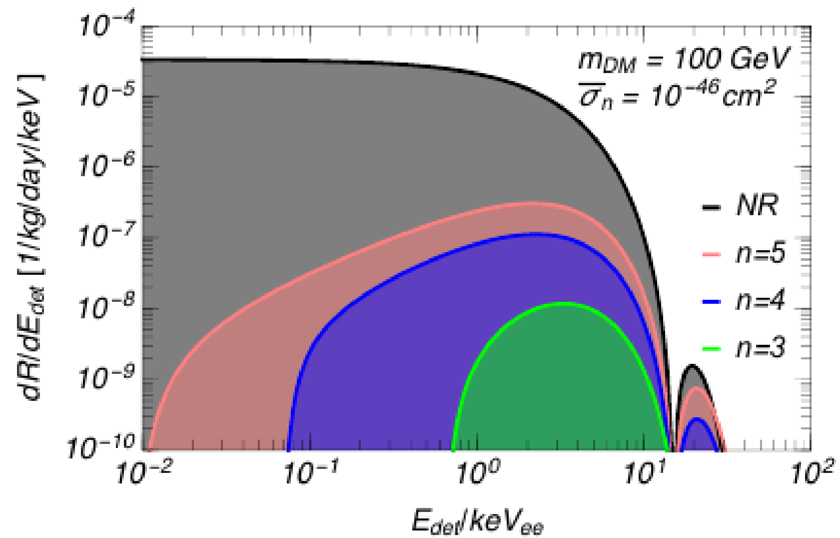


Electron cloud after recoil $$|\Phi'_{ec}\rangle = e^{-im_e \sum_i \mathbf{v}\cdot\hat{\mathbf{x}}_i}|\Phi_{ec}\rangle$$

Probability of ionisation $$\mathcal{P} = |\langle\Phi^*_{ec}|\Phi'_{ec}\rangle|^2$$

Used central potential, dipole approximation + atomic physics code (FAC)





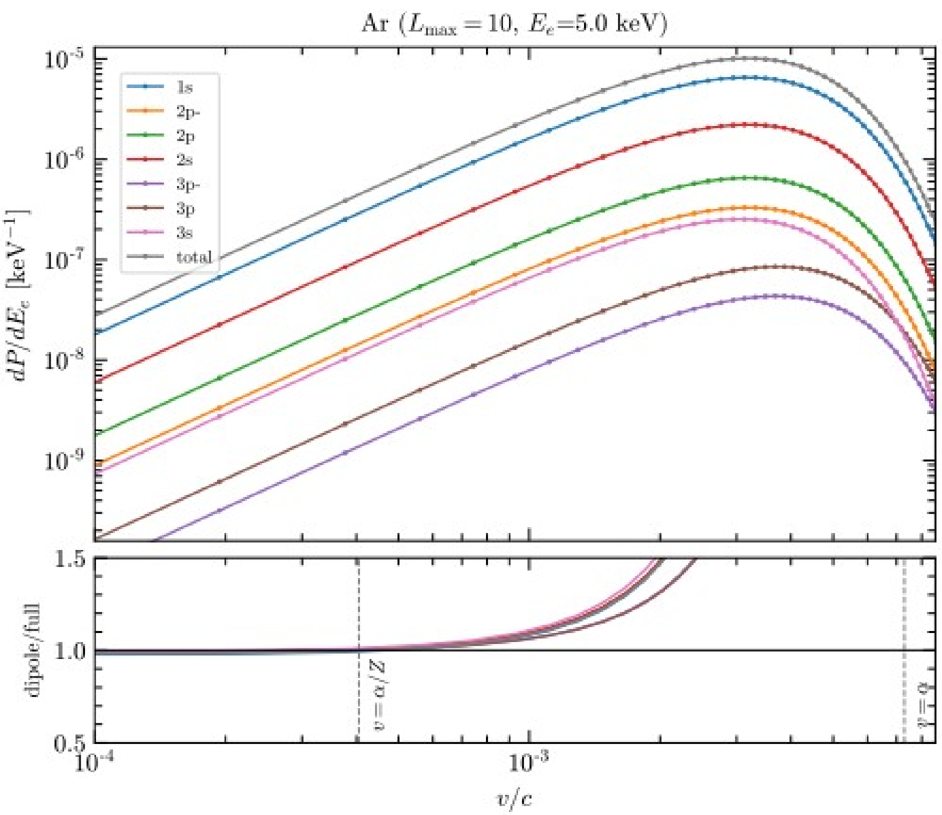
A. Migdal, 1939, 1941

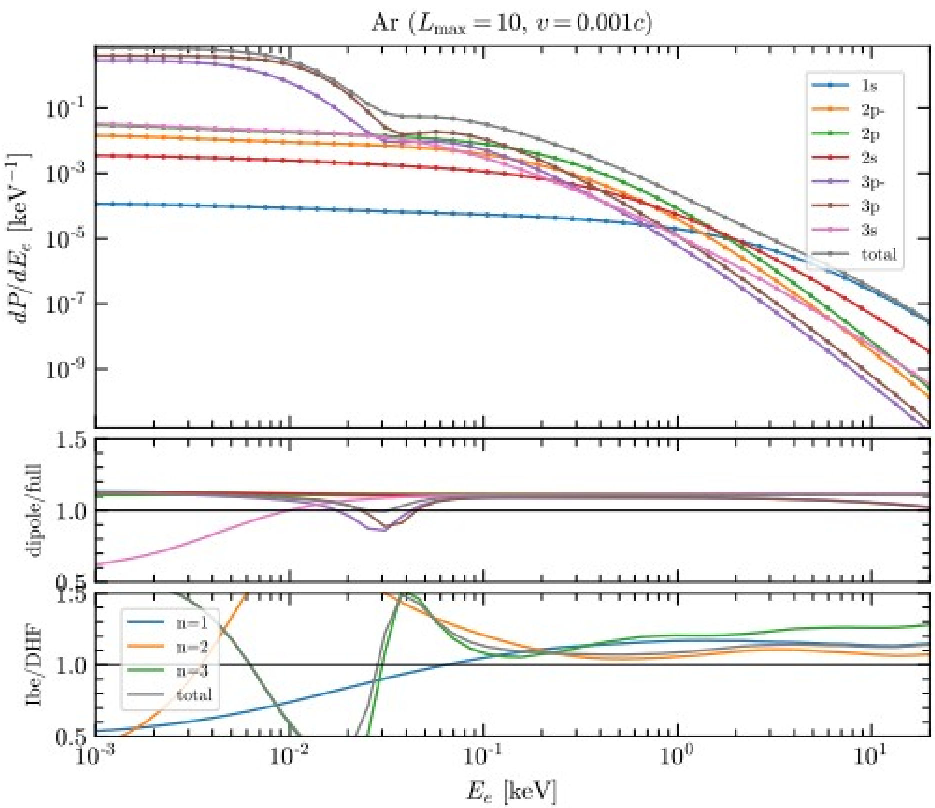
Ibe et al, 1707.07258

MJD et al, 1711.09906

The Migdal Effect

- Expect dipole approximation to get worse for increasing Z
- Robust predictions for future DD and calibration experiments
- MIGDAL (RAL): 2.5/14 MeV neutrons from DD/DT generators
- Possibility of multiple ionisations



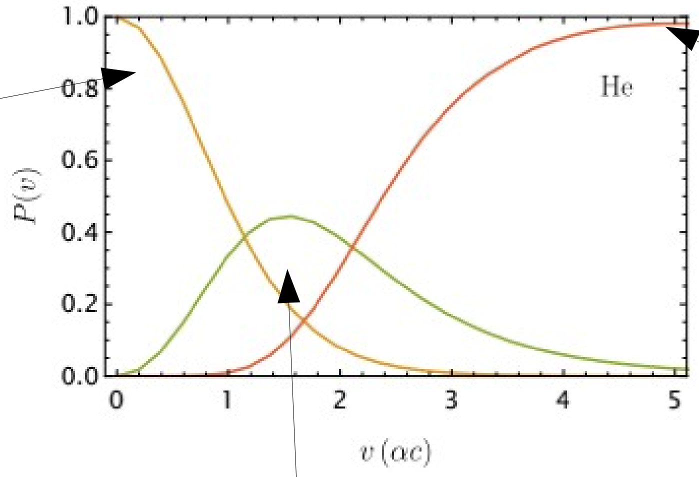


Cox, Dolan, McCabe, Quiney, in progress

The Migdal Effect

- Expect dipole approximation to get worse for increasing Z
- Robust predictions for future DD and calibration experiments
- MIGDAL (RAL): 2.5/14 MeV neutrons from DD/DT generators
- Multiple ionisations

Nothing happens



Double ionisation

Single ionisation

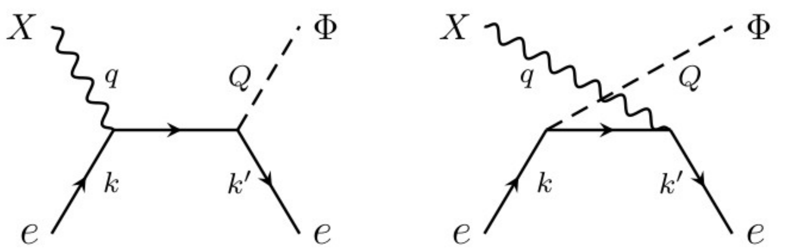
Cox, Dolan, McCabe, Quiney, in progress

Many Other Ideas

Dror et al, 2011.1940
Josh Wood, MSc Thesis

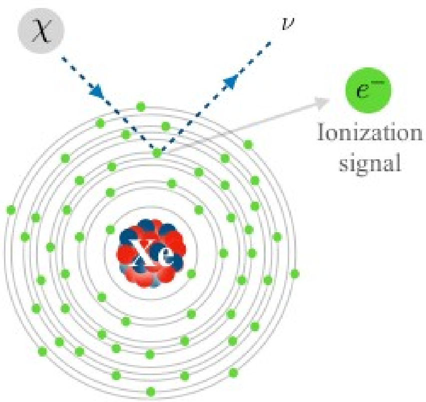
Kahn, Lin, 2108.03239

- DM electron scattering → Kurinsky talk
- Dark matter absorption: Final state phonons

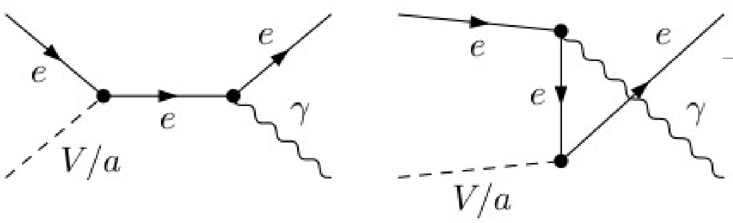


Hochberg et al, 1604.06800

Final state neutrinos



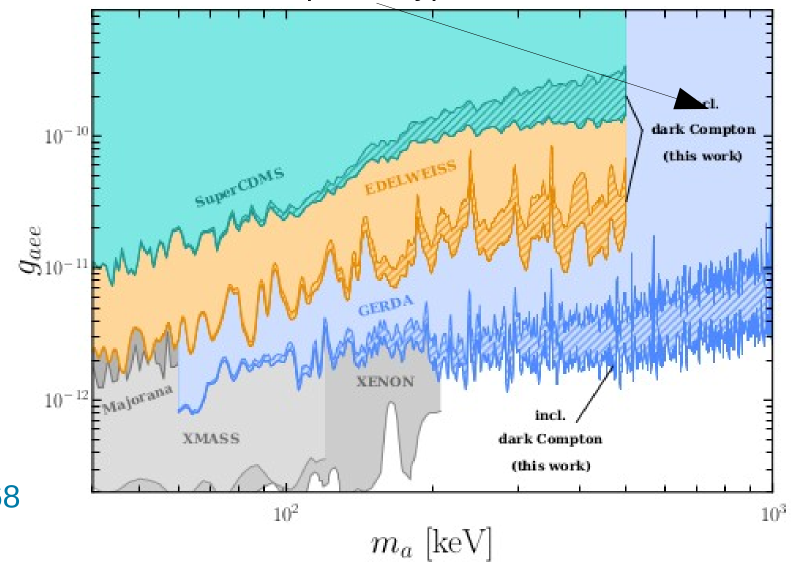
Final state photons: Dark Compton Scattering



Hochberg et al, 2109.08168

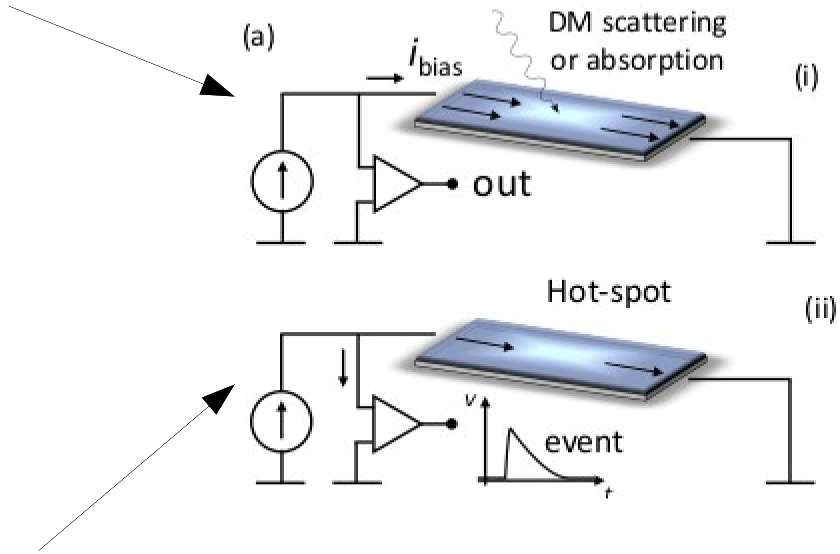
See also
Bell, MJD, Robles, 2005.12950

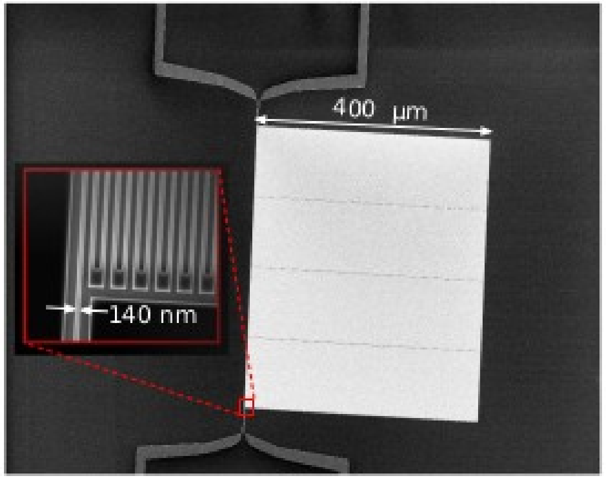
Limits from neutrino experiments.
Also: DUNE, SuperK, HyperK



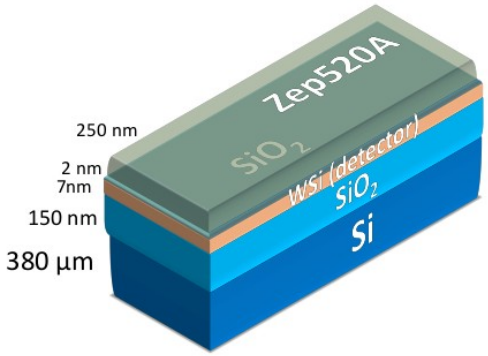
Superconducting Nanowire Single-Photon Detectors (SNSPD)

- Quantum communication/crypto, space communication. Commercially available.
- Wire under some current bias





- Scattering causes departure from equilibrium, causes voltage spike
- Wire returns to superconducting state
- Reset time $\mathcal{O}(10)$ ns

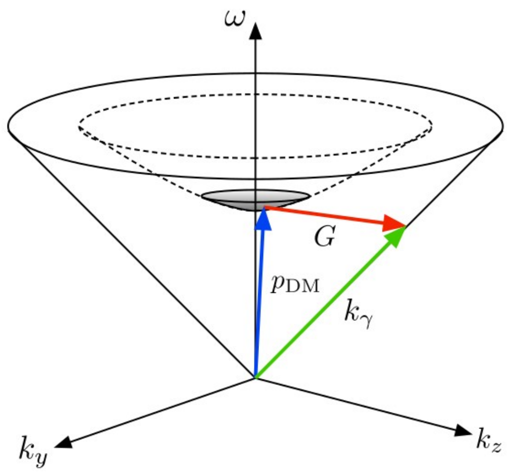


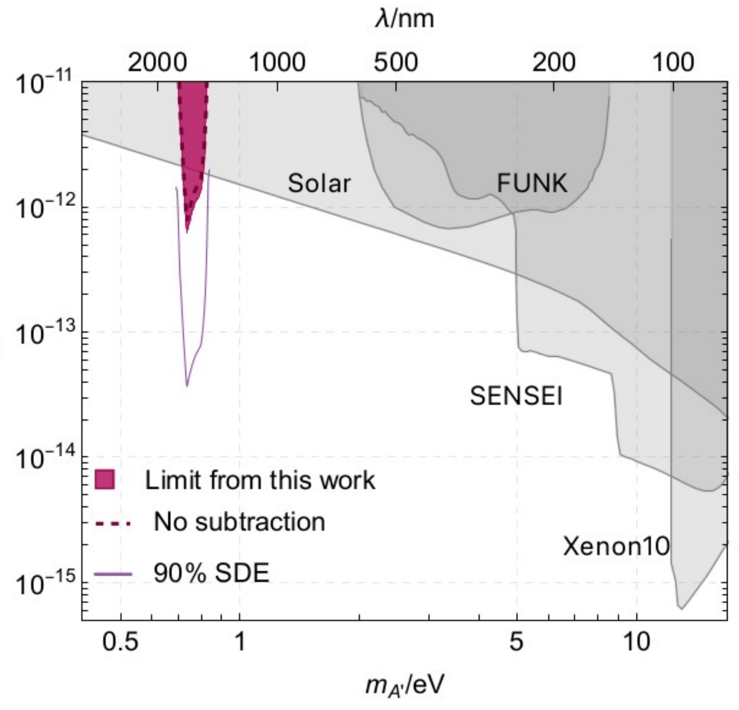
- ~90% detection efficiency at optical/IR wavelengths
- $\mathcal{O}(10^{-4})$ cpd dark count rate

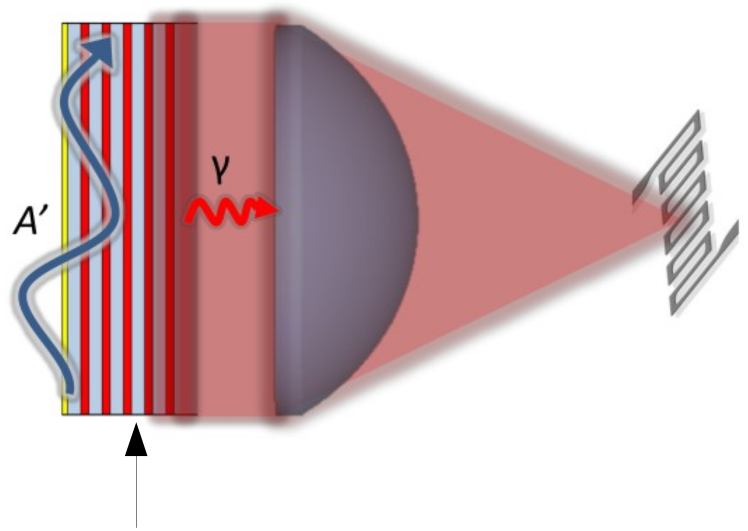
Gol'tsman et al, 2001 | Hochberg et al, 1903.05101 | Hochberg et al, 2110.01586 | Holzman, Ivry (review)

LAMPOST: SNSPDs as detector

- Use as sensor: optical haloscope for dark photon searches
- Add B-field → axion haloscope (also MADMAX)
- eV dark matter → optical/IR photons
- 180 hour data taking
- Achieved ~ 2% detection efficiency







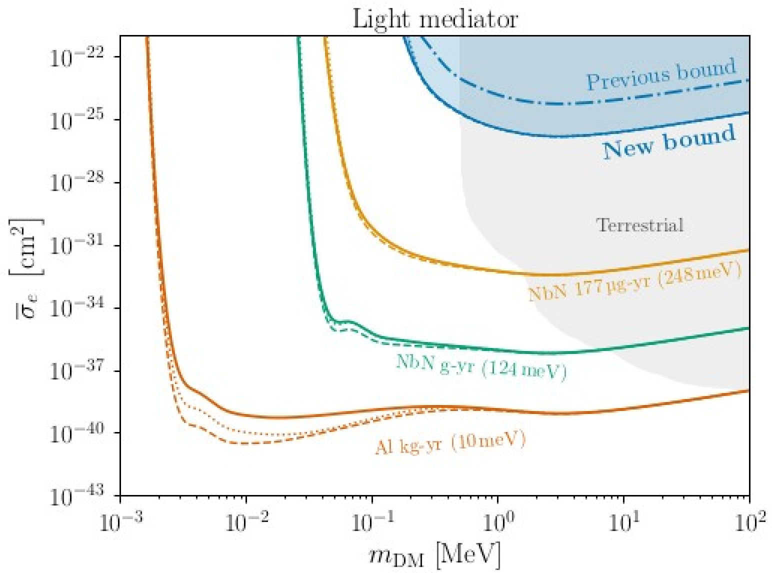
Baryakhtar et al, 1803.11455

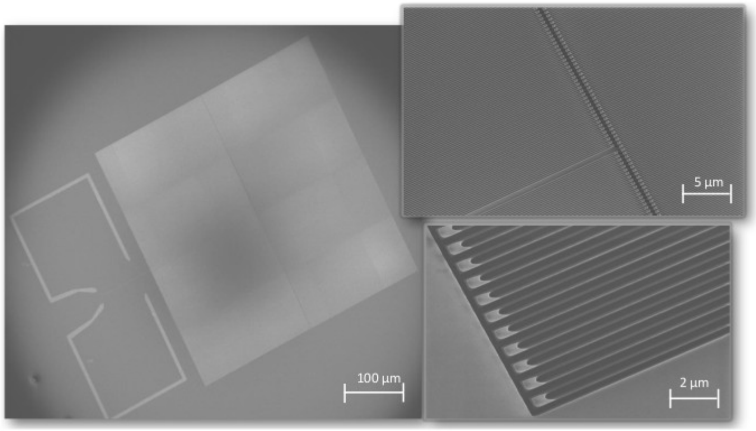
Chiles et al, 2110.01582

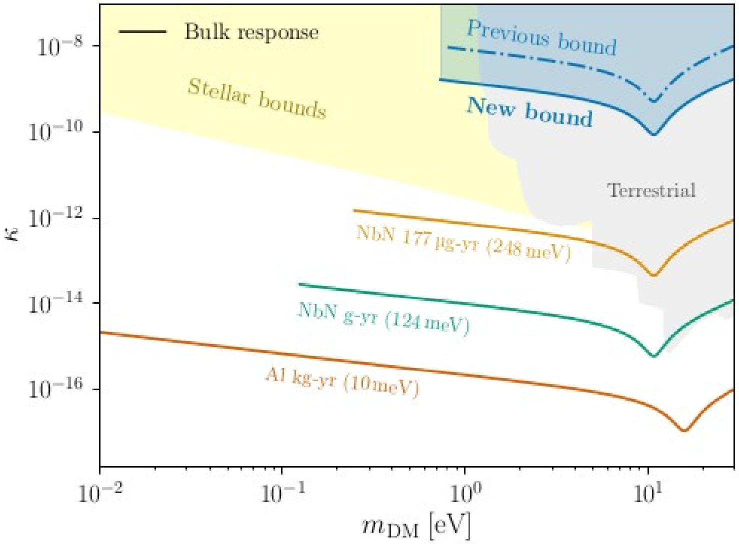
Manenti et al (MUDHI), 2110.10497

SNSPDs as target

- Use as target: DM-e scattering/absorption on SNSPD
- Scattering from thin films: layer small relative to momentum transfer, changes layer response.
- Enhancement of cross-section!
- Scalability? Stacks → Directional info?





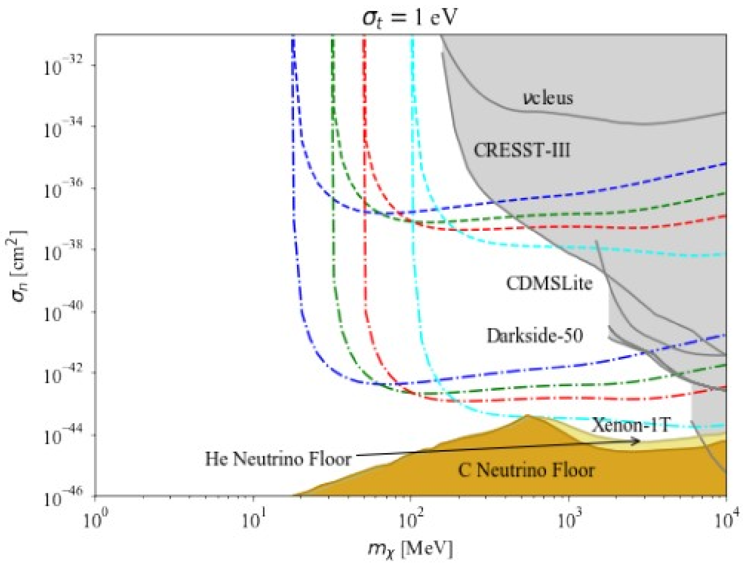


Lasenby et al, 2110.01587

Hochberg et al, 2110.01586

Diamonds are for Direct Detection

- Atomic number 12 (compare Si=32, Ge=75, Na=23, I=127)
- Semiconductors: both phonon and charge readout possible
- High velocity, long-lived phonons with long mean-free paths.
- Radiation hardness and high isotopic purity
- OTOH: C14 backgrounds and large band-gap
- Use in quantum sensing, accelerator physics → industrial availability



Helium
Diamond
Silicon
Xenon

Nuclear scattering limit projections
Dashed: g-day
Dot-dashed: kg-year

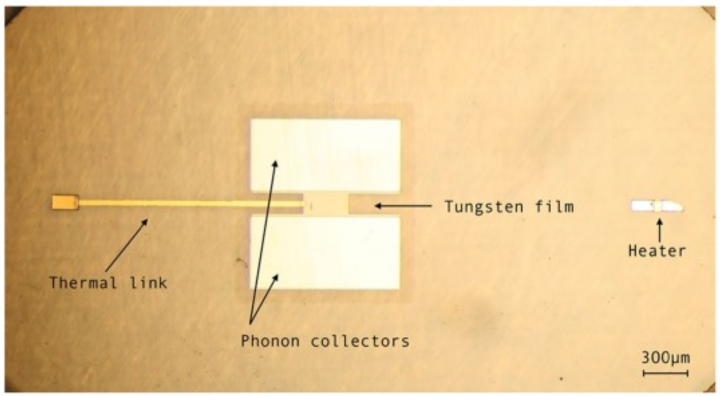
Kurinsky et al, 1901.07569

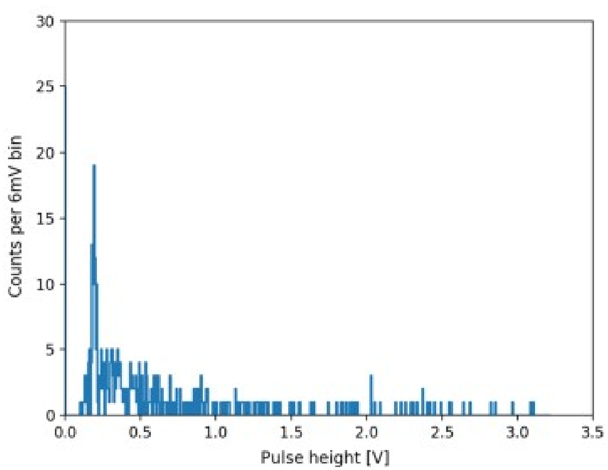
Griffin et al, 1910.10716

Also: SiC Griffin et al, 2008.08560

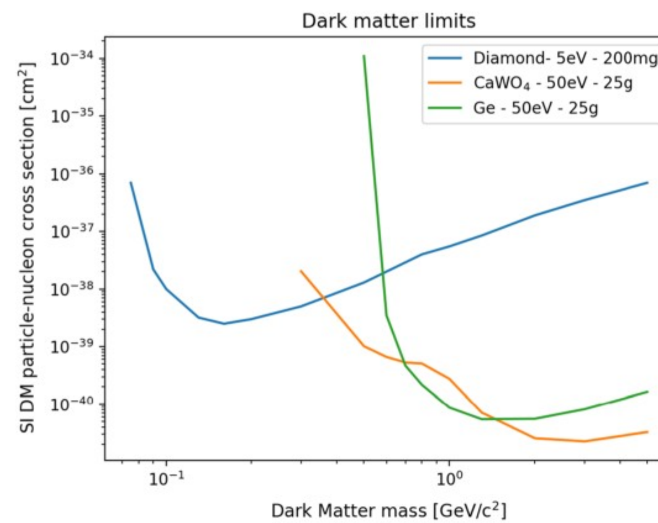
Diamonds are for Direct Detection

- C13: Possibility of spin-dependent sensitivity
- Diamond CCDs?
- Ideas on directional detection: futuristic Marshall et al, 2009.01028
- First cryogenic diamond detector with TES with sample $5 \times 5 \times 2\,\mathrm{mm}^3$





With (uncalibrated) Fe55 source



Projected limits
Assumes 1 yr exposure

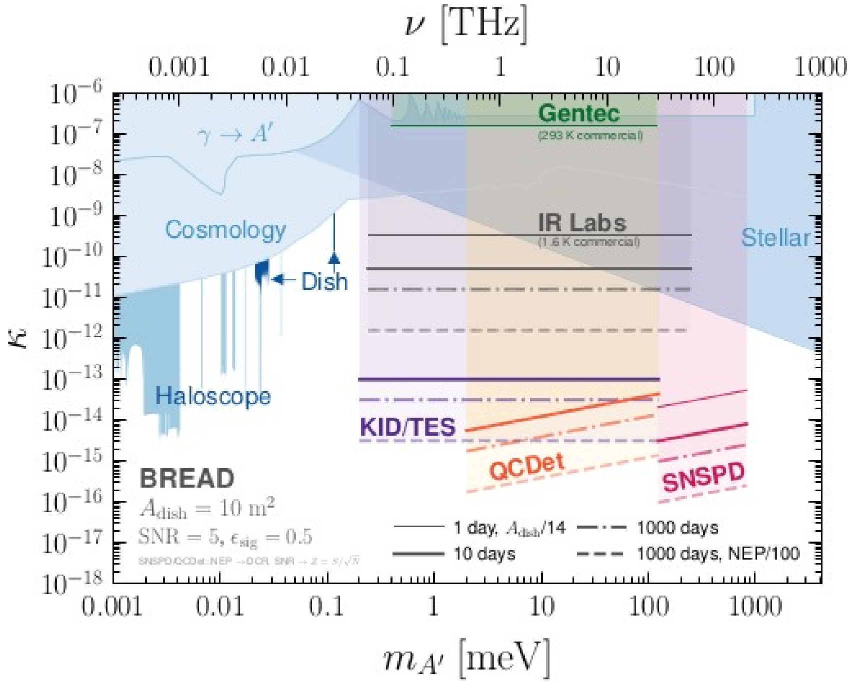
Canonica et al, JLTP (2020)

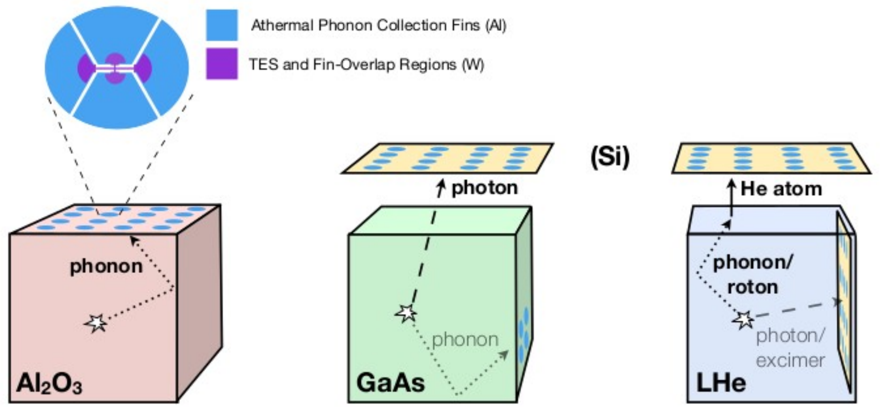
Outlook

- Push towards low-mass dark matter in direct detection
- New calculations to extend and understand capabilities of current and future detectors
- New models extending theory-space
- Application of quantum technologies to achieve lower thresholds

Quantum Something

- TESSERACT: build the meta-collaboration around the read-out technology for different detector materials
- Quantum devices becoming an integral part of low-mass dark matter searches.





TESSERACT

Liu et al (BREAD), 2111.12103