QUEST-DMC: LOW MASS DARK MATTER SEARCH WITH HELIUM-3

ELIZABETH LEASON

OXFORD AND RHUL

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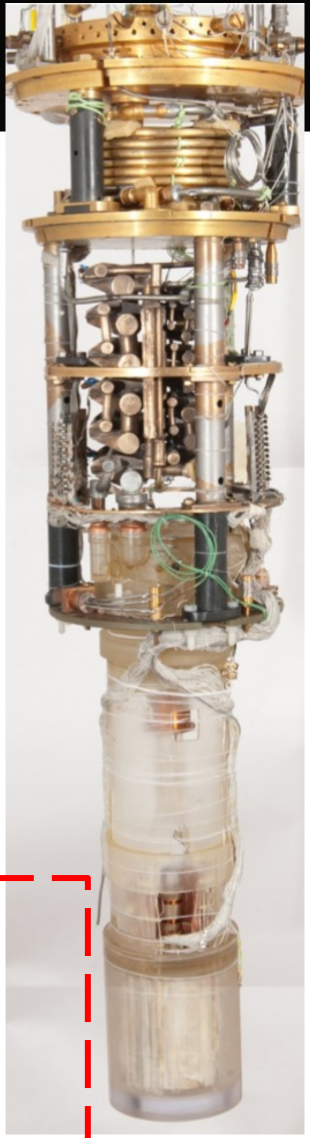
OUTLINE

1. What does the direct detection landscape look like?
   Current limits and challenges
2. Why use a ^{3}He target?
3. How can we use ^{3}He for a dark matter search? *QUEST-DMC detector*
4. What have we done so far?
   Recent progress
5. Where are we heading?

OUTLINE



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QUEST-DMC:

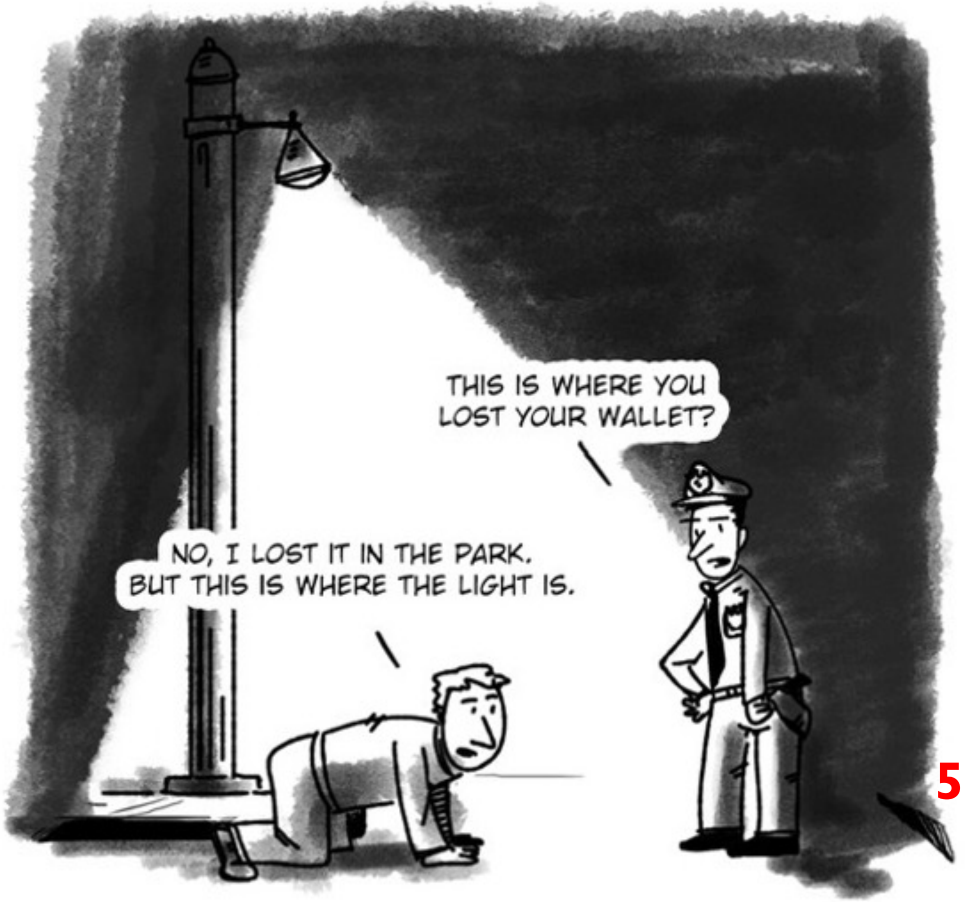
- Ultra low temperature physics
- Ultra low noise readout
- Ultra low threshold DM search

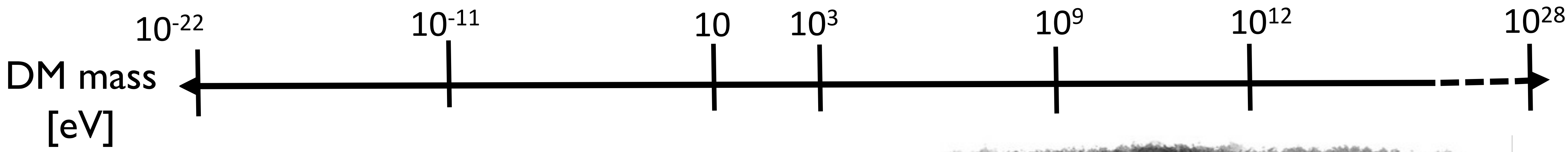
1. WHAT DOES THE DIRECT DETECTION LANDSCAPE LOOK LIKE?

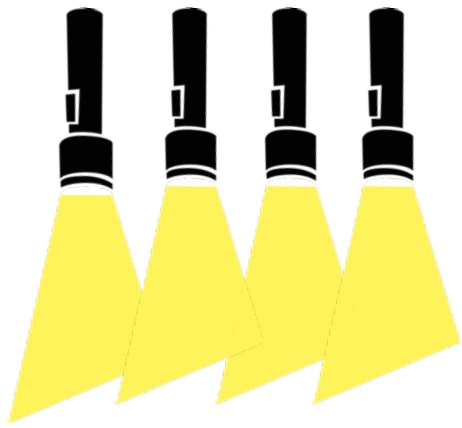
CURRENT LIMITS AND CHALLENGES OF LOW MASS DARK MATTER SEARCHES

DM mass [eV]

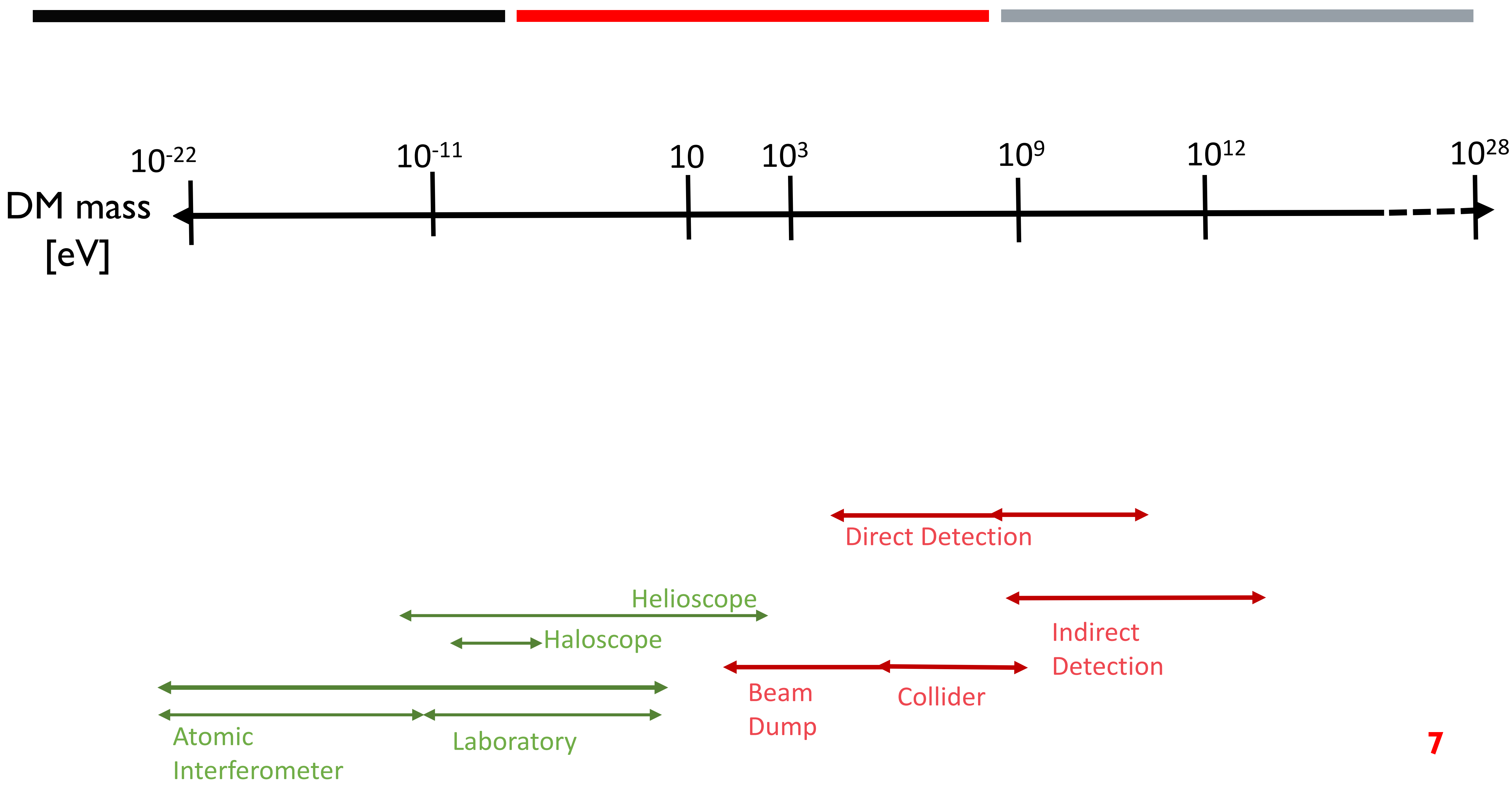
10^{-22} 10^{-11} 10 10^{3} 10^{9} 10^{12} 10^{28}



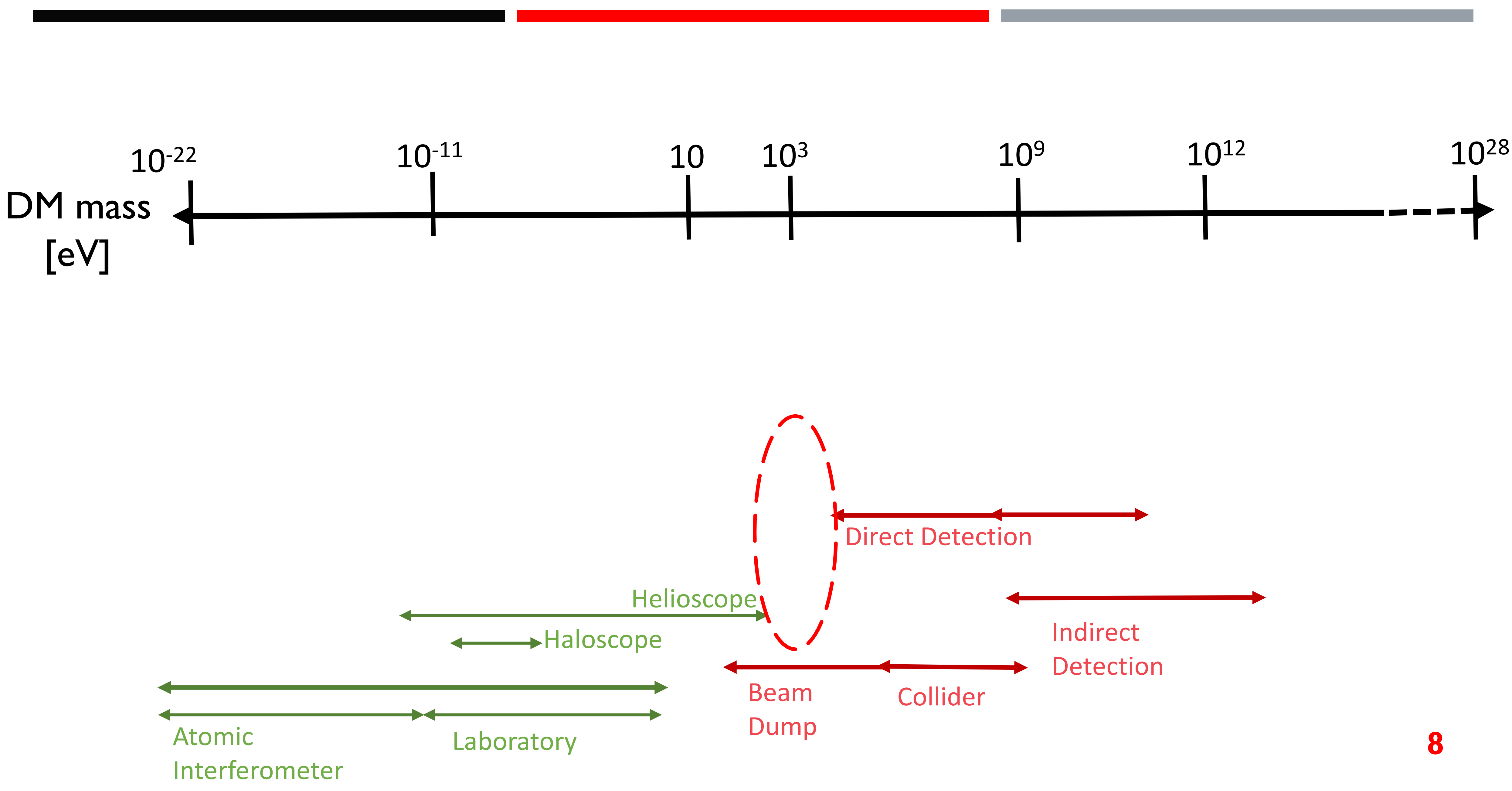

DM mass [eV]
10^{-22}
10^{-11}
10
10^{3}
10^{9}
10^{12}
10^{28}




THIS IS WHERE YOU LOST YOUR WALLET?
NO, I LOST IT IN THE PARK. BUT THIS IS WHERE THE LIGHT IS.



DM mass [eV]
10-22
10-11
10
103
109
1012
1028
Direct Detection
Helioscope
Haloscope
Indirect Detection
Beam Dump
Collider
Atomic Interferometer
Laboratory



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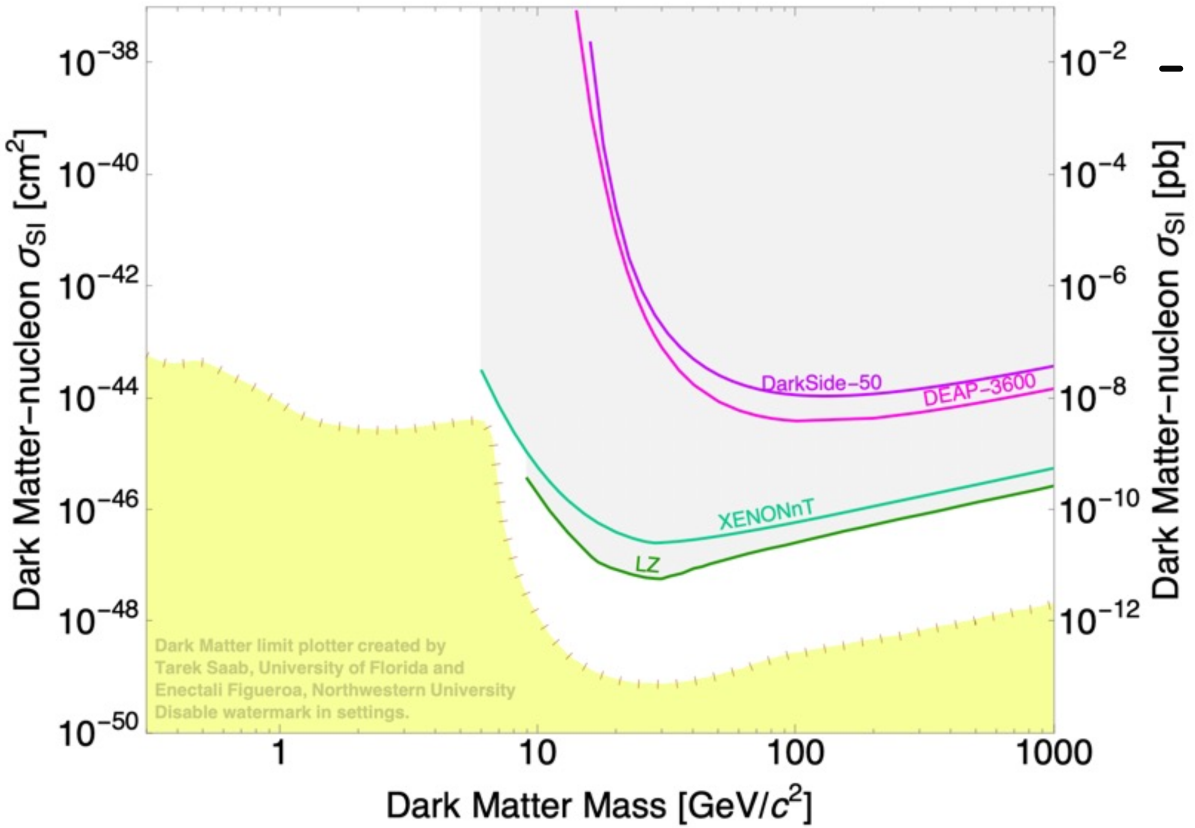
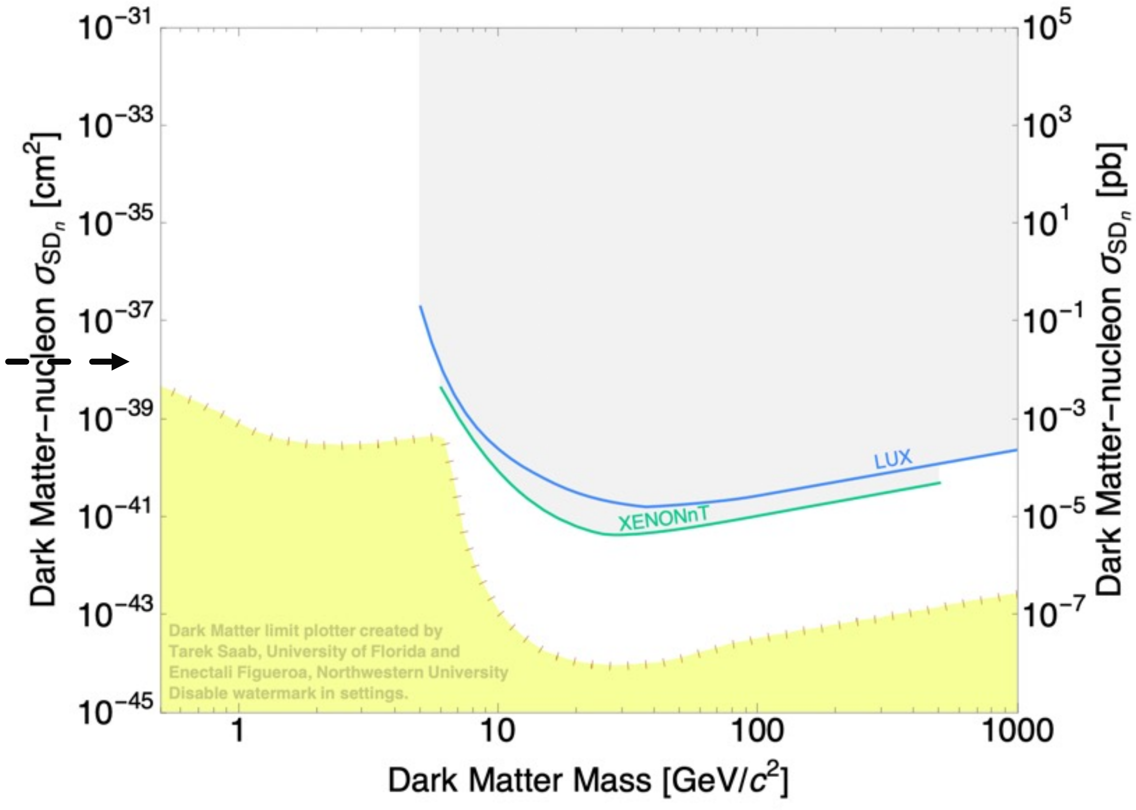
DIRECT DETECTION

- Noble liquids dominate searches down to ~6GeV, best sensitivity at ~30GeV

DarkSide50 –Phys.Rev. D.**98**, 102006(2018) **DEAP-3600** – Phys. Rev. D100, 022004 (2019)

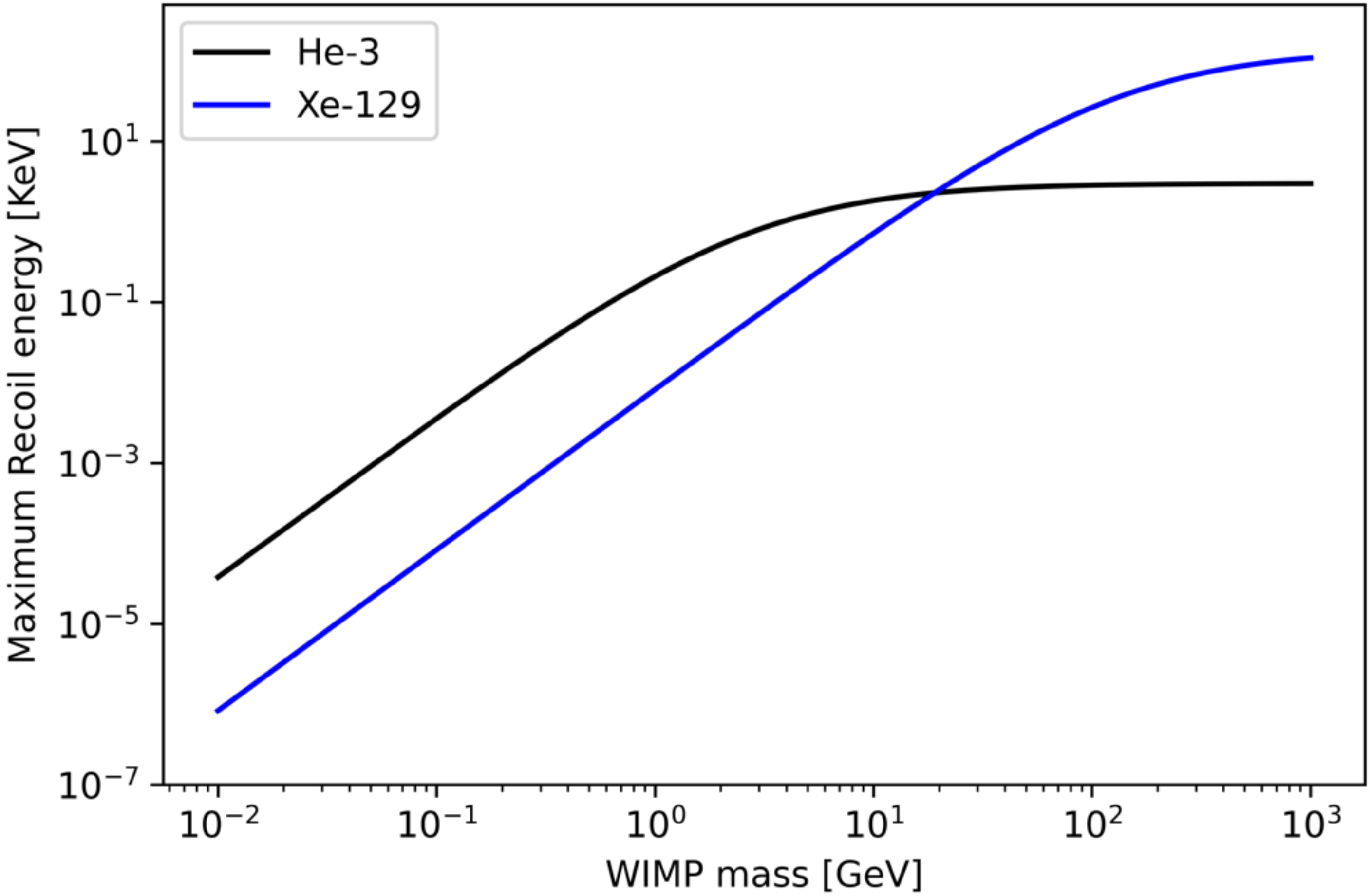




LZ – Phys.Rev.Lett. **131**.041002(2023
XENONnT – Phys.Rev.Lett. 131,041003(2023)

LUX - Phys.Rev.Lett.118,251302(2017)

GOING TO LOWER MASSES



Kinematic matching: lighter target – smaller atomic mass $E_R \propto \frac{M_X}{M_N+M_X}$.

Light nuclei can probe lower masses

If the detector threshold is low enough!

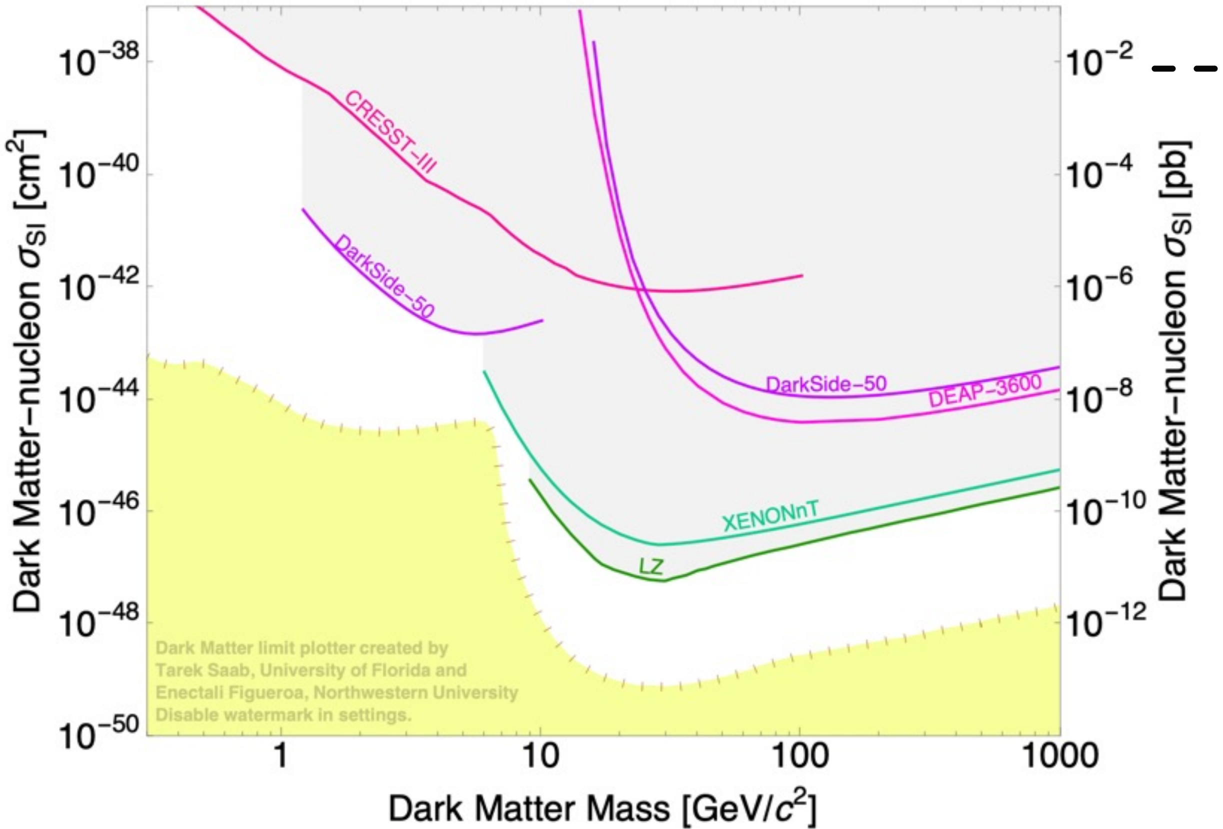
LOWER THRESHOLD

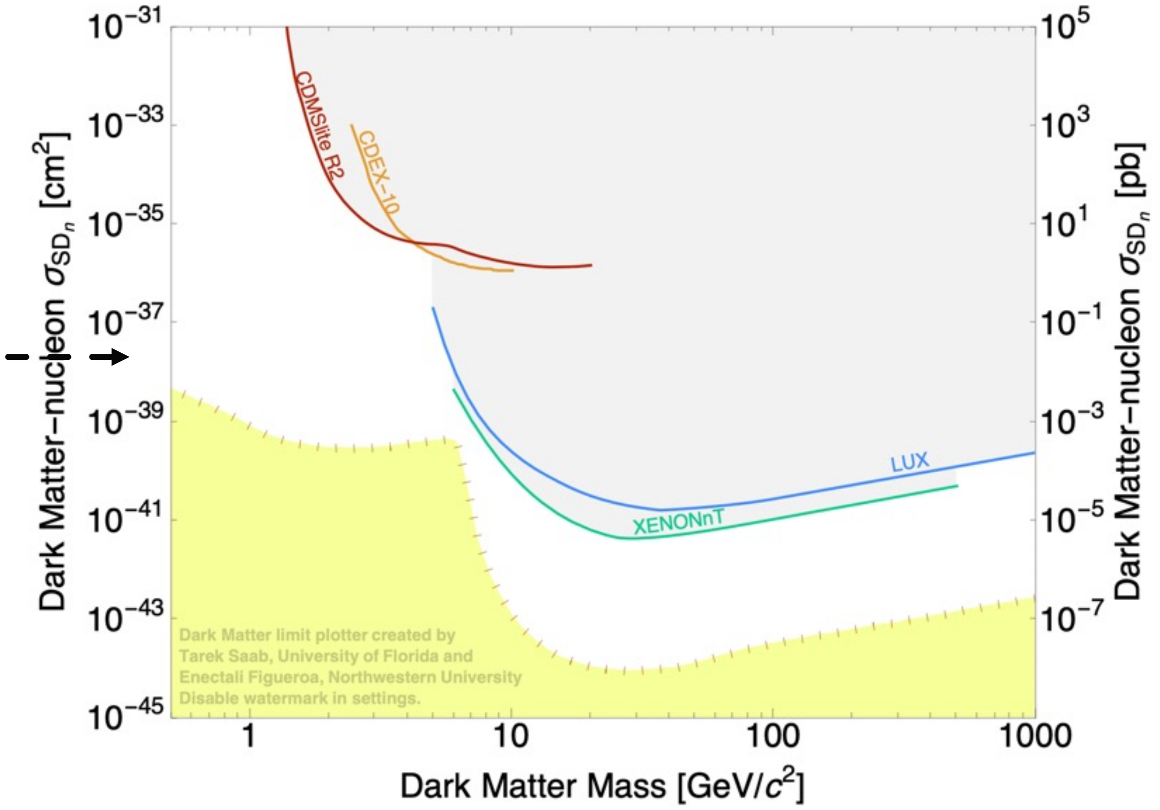
New analysis techniques and technologies:

- Ionisation only searches
- Electron scattering

LOWER MASS SEARCHES

- S2 only: DarkSide-50 Phys. Rev. D **107**, 063001(2023)





Ge Targets:

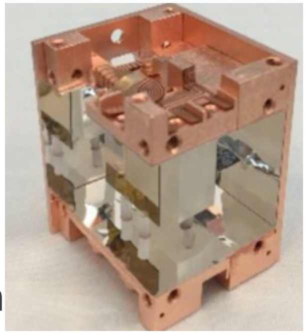
- CDMSLite R2 – Phys. Rev. D 97, 022002 (2018)
- CDEX-10 Phys. Rev. Lett. **120**, 241301(2018)

LOWER THRESHOLD

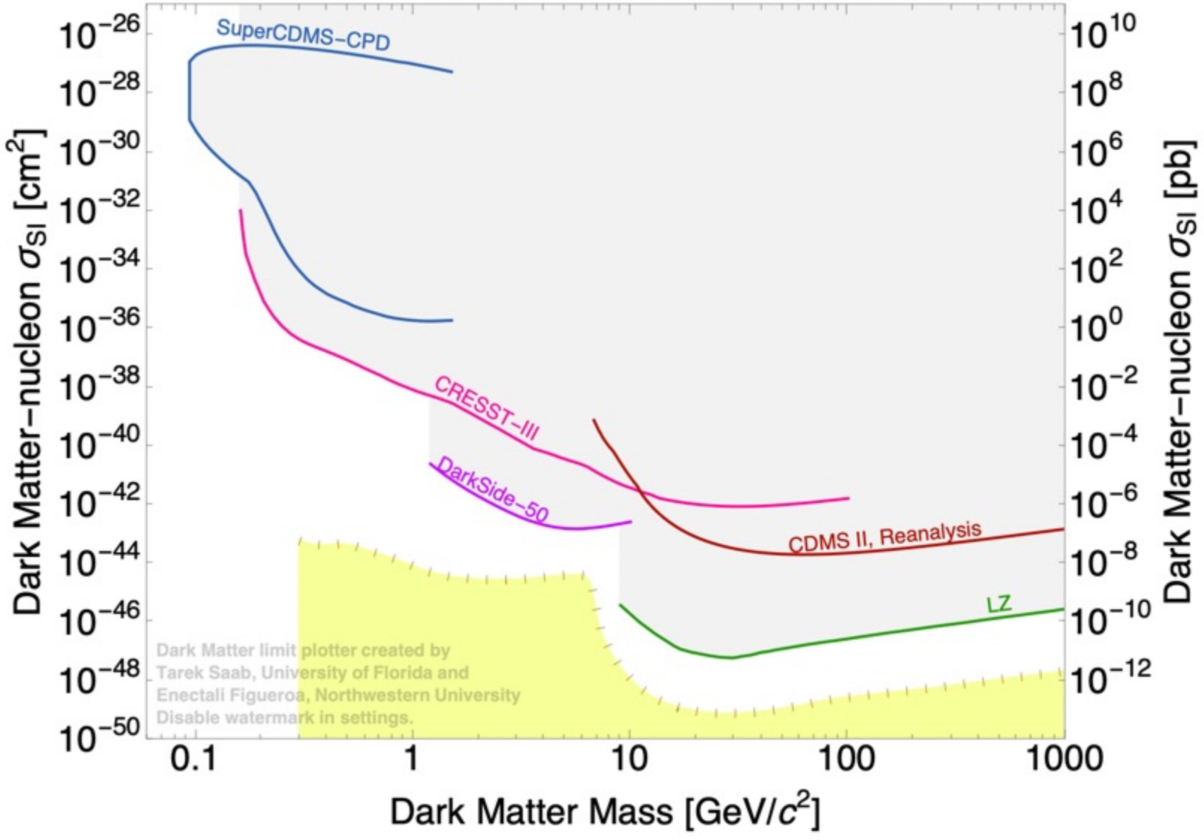
New analysis techniques and technologies:

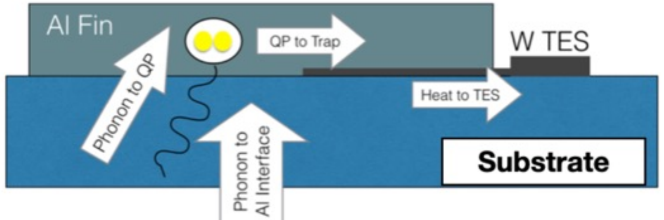
- Ionisation only searches
- Electron scattering
- New detector materials – use processes with low energy barrier
- Low noise readout – improve energy resolution

CURRENT TECHNOLOGY



- CRESSTIII Phys. Rev. D 100, 102002 (2019)
  - CaWo4 scintillating bolometer - 30 eV thresh
- CDMSII Phys.Rev.Lett. 116 (2016) 071301
- Ge and Si crystals - 5 keV threshold
- SuperCDMS Phys. Rev. Lett. 127, 061801 (2021)
  - Si crystal with QETs (Quasiparticle trap and TES) -16.2 eV threshold
- Recent developments: CDMS Phys. Rev. D 104, 032010 (2021)
  - **9.2 eV threshold** ***Lowest achieved for a macroscopic detector***

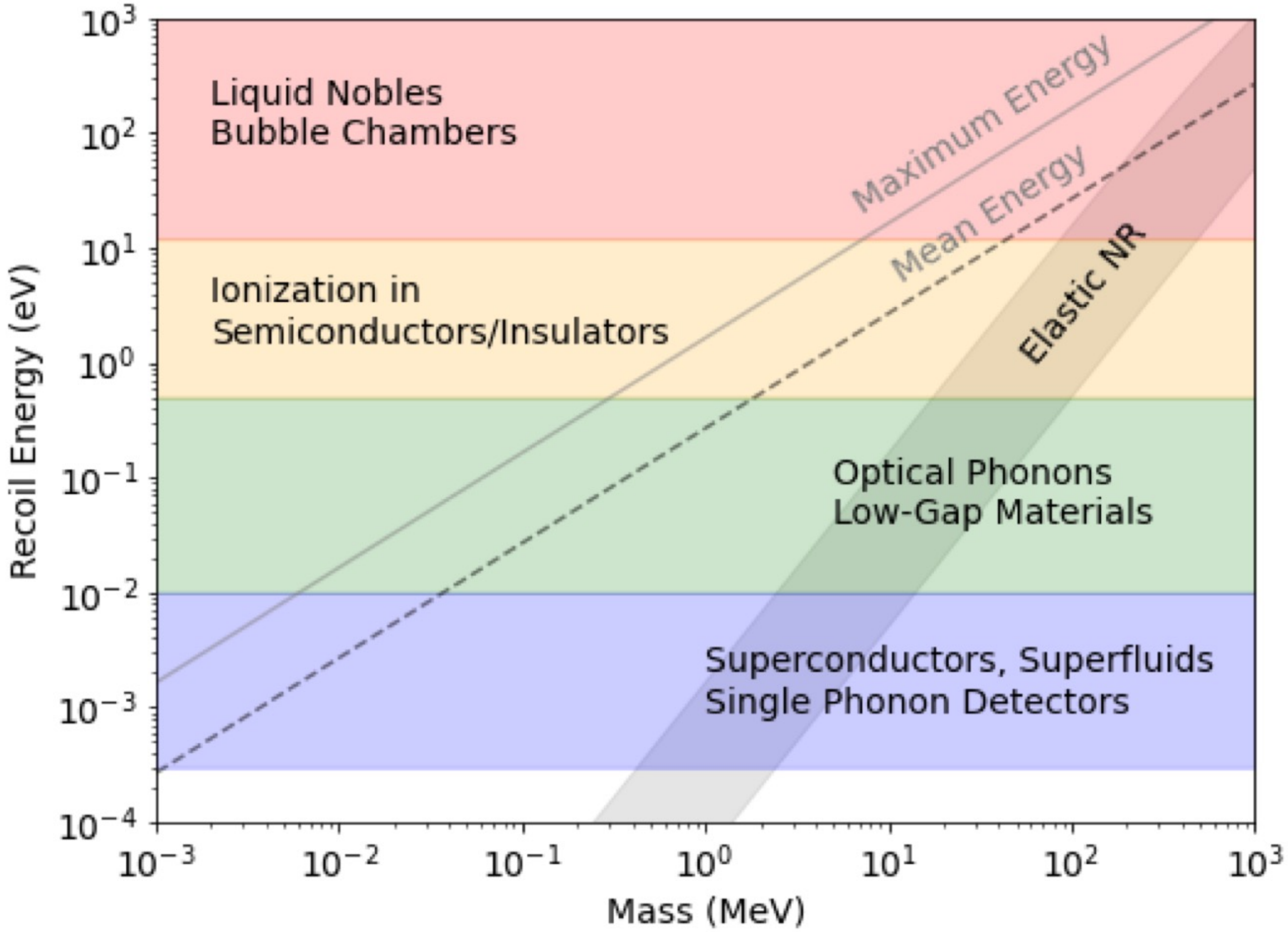




GOING EVEN LOWER

Fundamental threshold limit from process for quanta production:

- ~10eV Xe, Ar ionisation
- ~1eV semiconductor gap Ge, Si
- μeV – meV collective excitations doped semiconductors, superconductors, Dirac materials
- < μeV - superfluids



Snowmass report 2022

2. WHY USE A SUPERFLUID 3HE TARGET?

HELIUM

- Second most abundant element
- Two stable isotopes ^{4}He(99.9998%) and ^{3}He(0.0002%)
- Can be liquid down to absolute zero!

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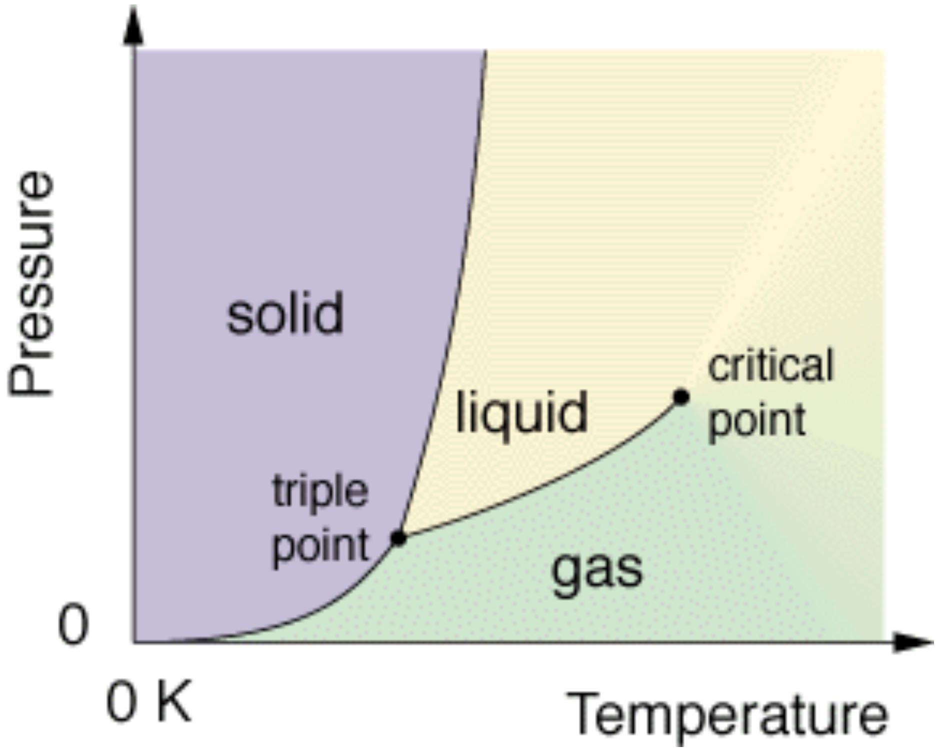

Typical phase diagram

Image: http://ltl.tkk.fi/research/theory/helium.html

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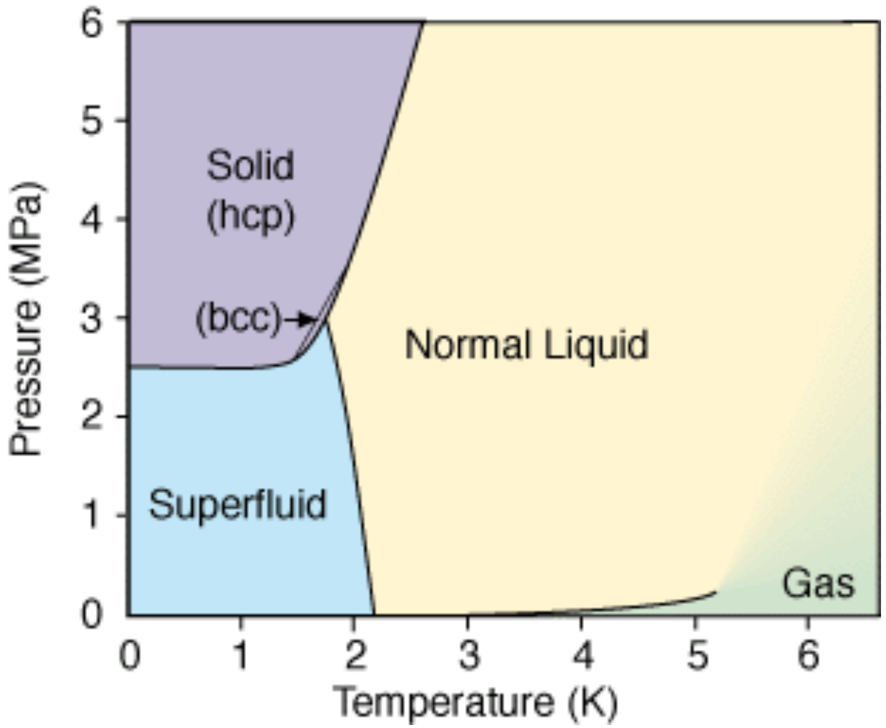

^{4}He phase diagram
- Remains liquid at low pressures
- Superfluid below 2.17K (discovered 1937)

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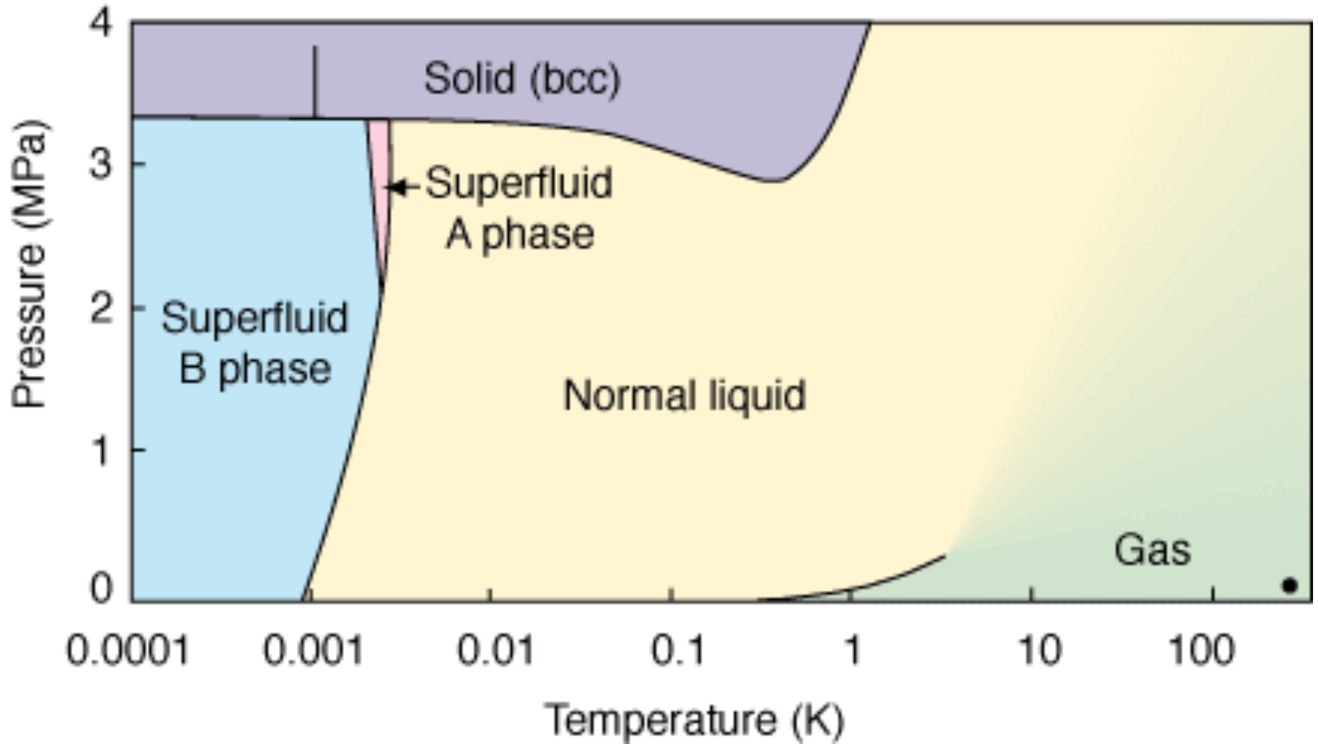
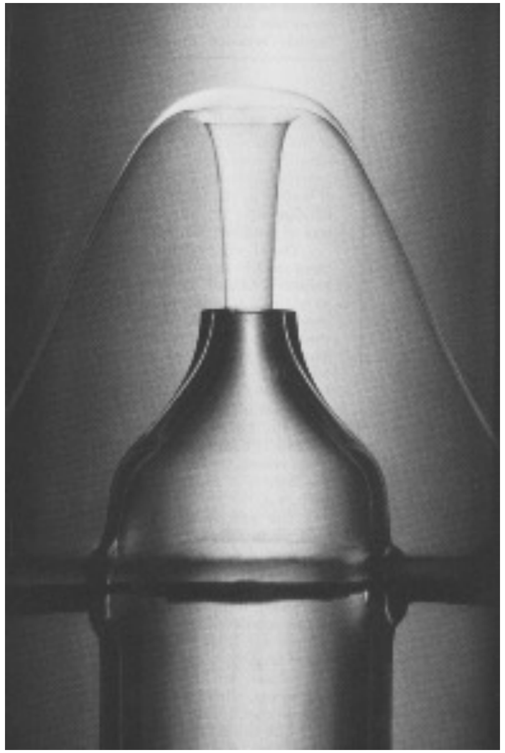


^3He phase diagram

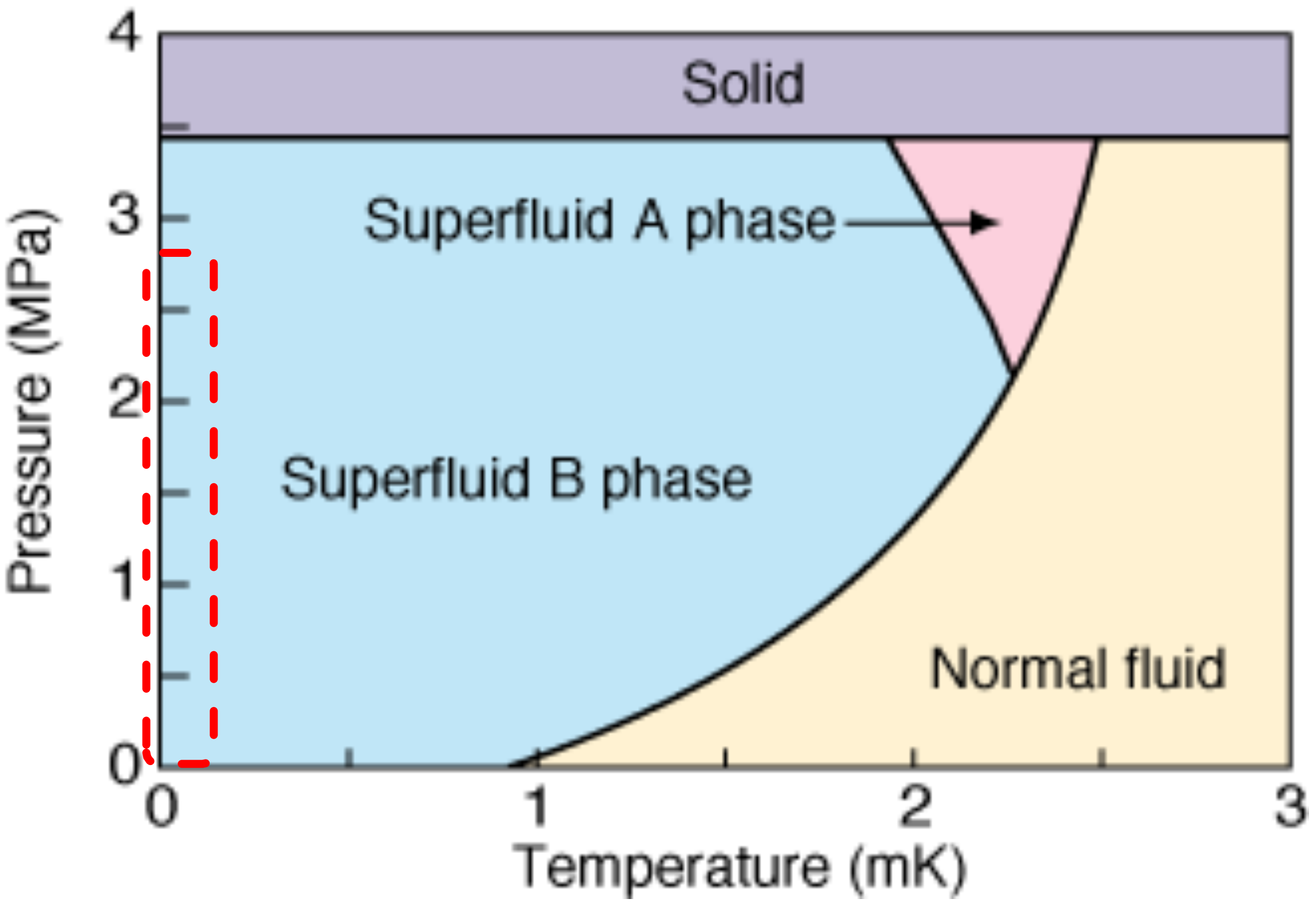
- Superfluid below 2.5mK (discovered in 1972)

SUPERFLUIDS

- Dissipation-less flow, zero viscosity
- Requires single coherent ground state and energy gap to excitations above this
- Spin 0 (boson) ^{4}He – related to Bose Einstein condensation
- Spin ½ (fermion) ^{3}He – cannot condense to ground single state
  - Cooper pairing into weakly bound integer spin pairs
  - Similar to superconductor, but magnetic (not phonon) interactions and p-wave (not s-wave) pairing
  - Pairs of atoms behave as bosons and condense to single ground state



HELIUM-3

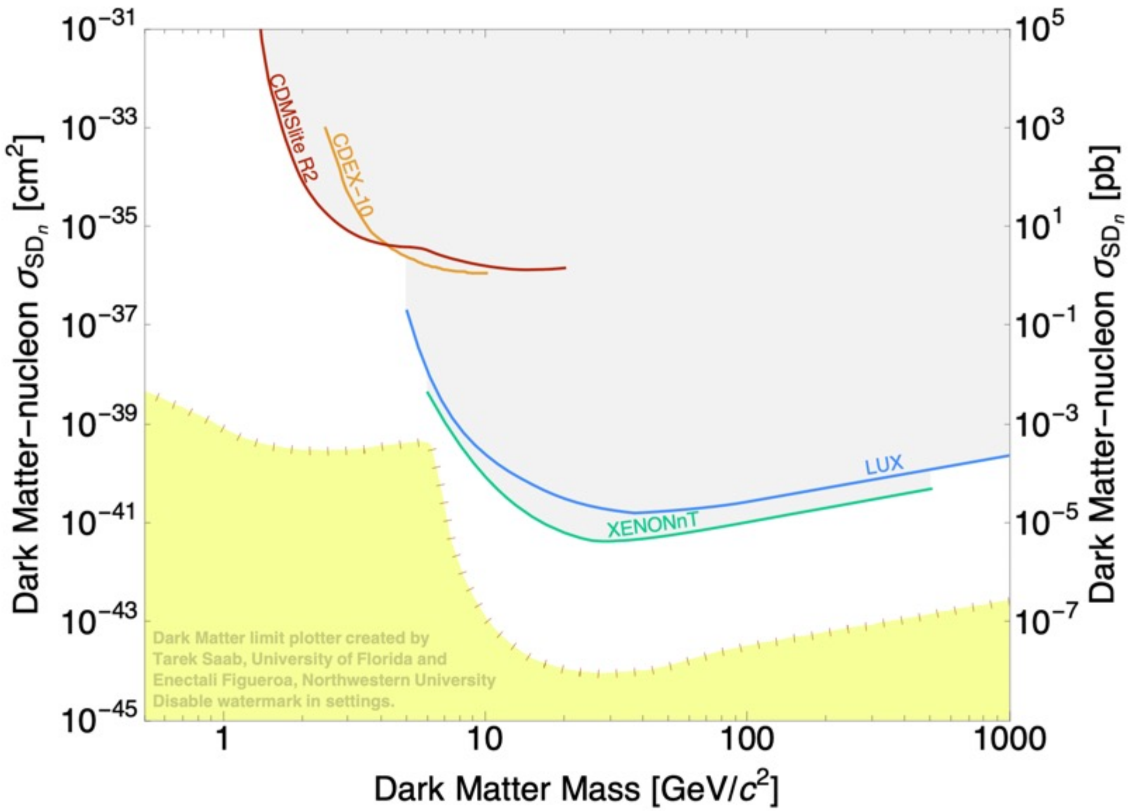


- Two superfluid phases due to spin pairing
- Isotropic B-phase at $\sim 100 \mu K$
- Small superfluid gap $\Delta \sim 10^{-7} eV$ between Cooper pair and single quasiparticles (QPs)

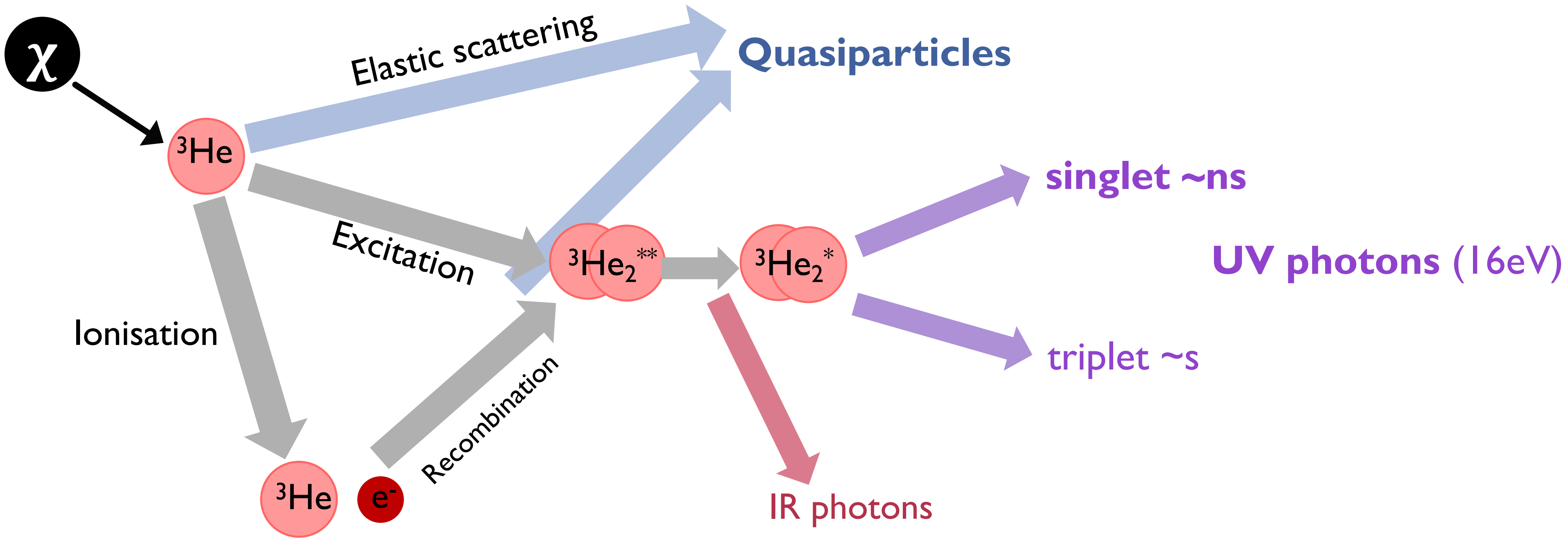
SPIN DEPENDENT INTERACTIONS

1. **Spin independent** - coherent scattering with all nucleons, vector or scalar couplings, cross section scales with atomic mass number
2. **Spin dependent** – axial vector interaction couples to nuclear spin, requires uneven total angular momentum (unpaired nucleon)

✓ ^{3}He can test spin-dependent WIMP-neutron interaction

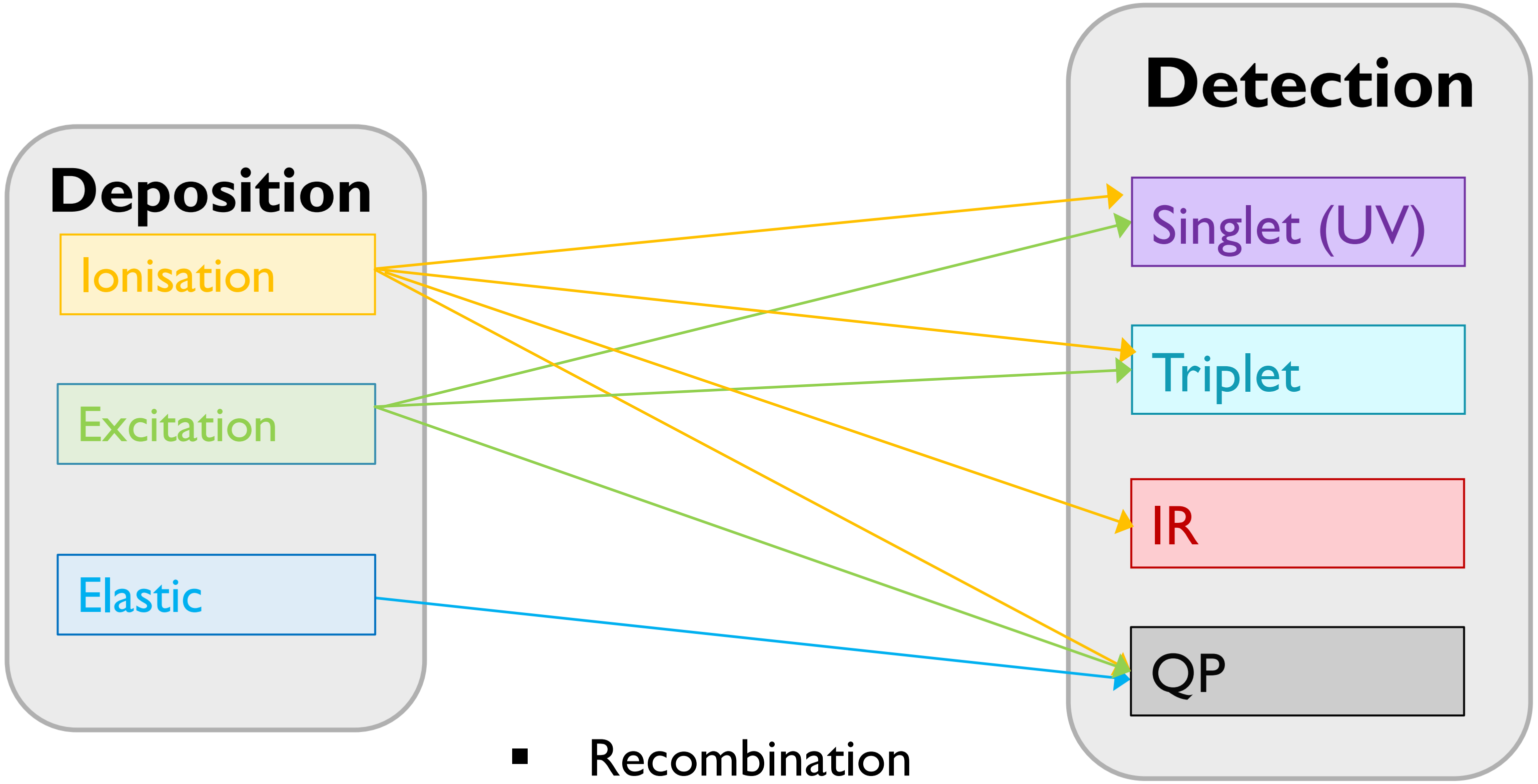


SIGNAL CHANNELS



ENERGY PARTITIONING

- Nuclear quenching
- Ionisation and excitation cross sections



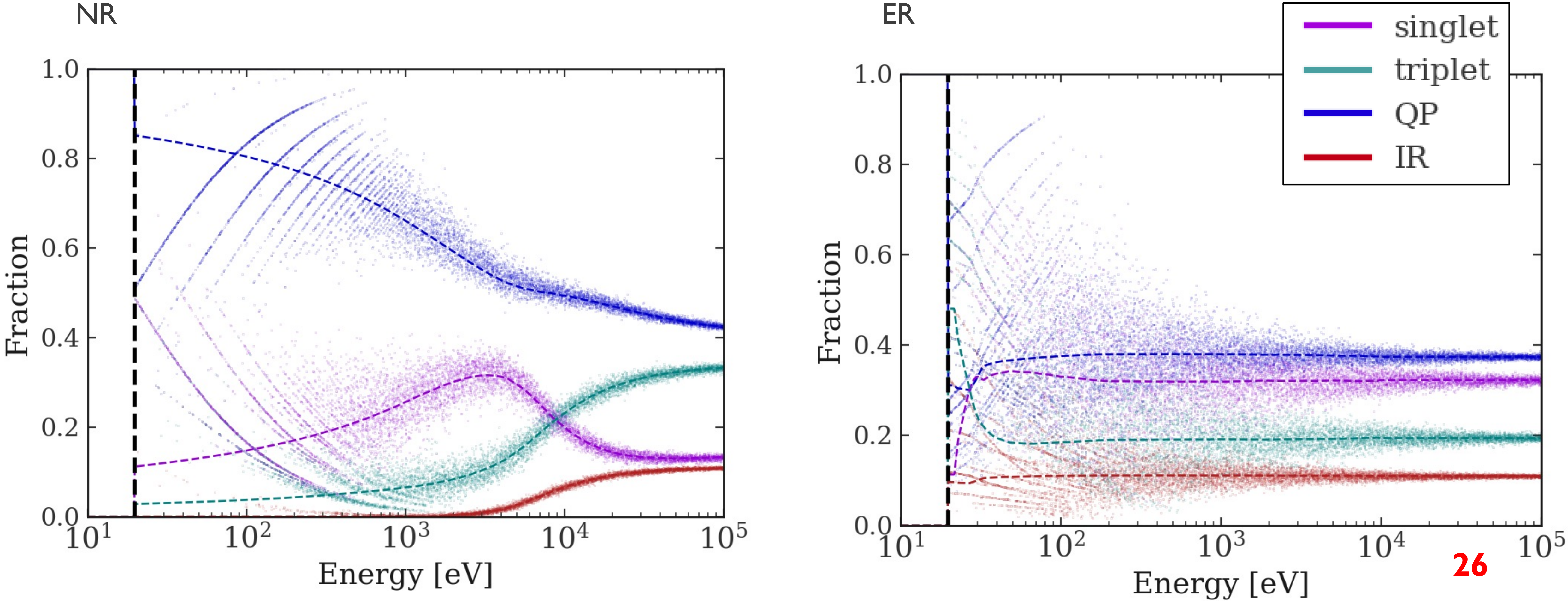
- Recombination
- Decay cascade

Calculations follow Phys.Rev.C.88.025805(2013)

SIGNAL CHANNELS

- Partition for nuclear recoil (NR) and electron recoil (ER) interactions

NR ER



3. QUEST-DMC DETECTOR SCHEME

THE COOLEST DIRECT DETECTION EXPERIMENT

QUANTUM ENHANCED SUPERFLUID TECHNOLOGIES FOR DARK MATTER AND COSMOLOGY, QUEST–DMC

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Lancaster University

University of Sussex

UNIVERSITY OF OXFORD

UNIVERSITY OF LIVERPOOL

1. Detection of sub-GeV dark matter with a quantum-amplified superfluid ^{3}He calorimeter

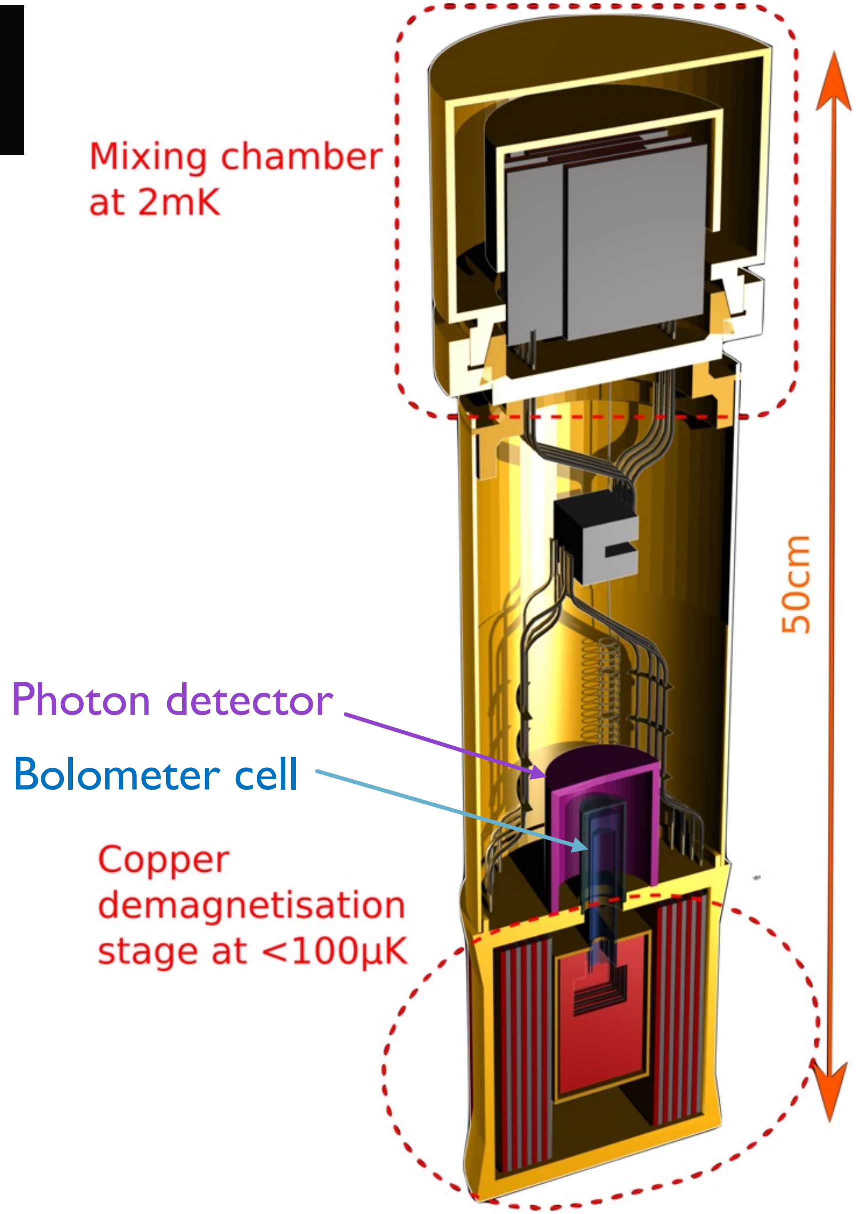
2. Phase transitions in extreme matter, relevant to cosmology and gravitational wave production

UKRI Engineering and Physical Sciences Research Council

UKRI Science and Technology Facilities Council

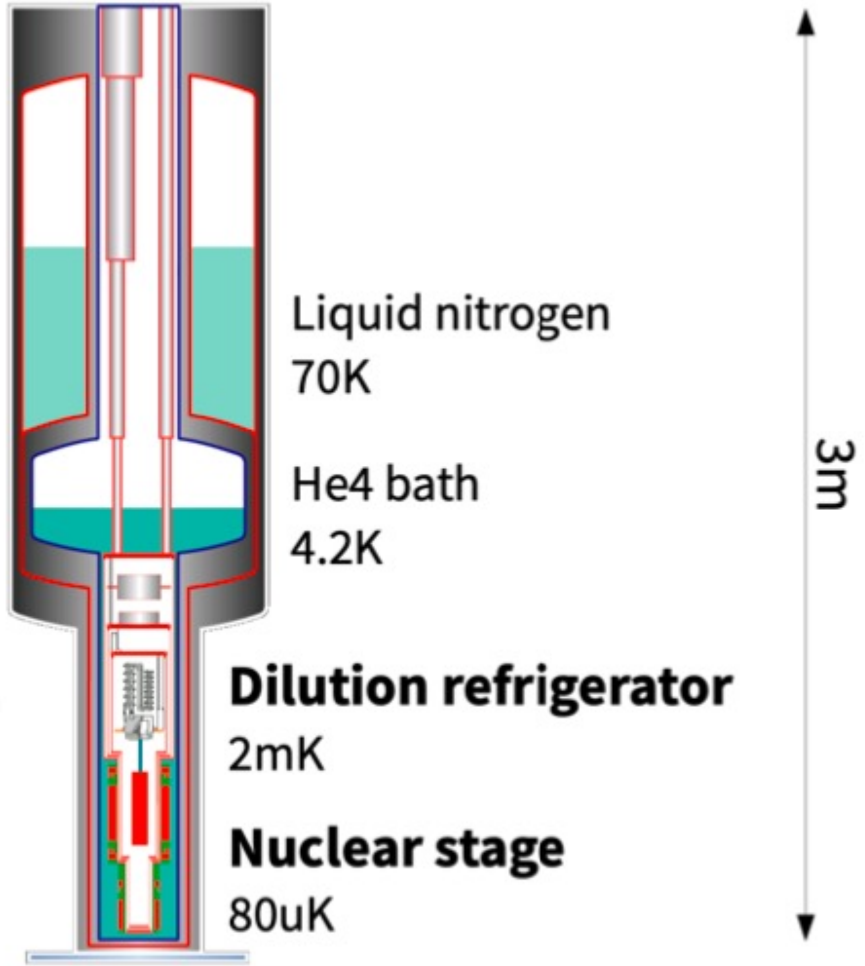
QUEST-DMC EXPERIMENT

1. Quasiparticles (heat) – bolometry using vibrating nanowires immersed in superfluid ^3He cell
2. Scintillation photons (light) – photon detectors above the ^3He target



CRYOSTAT OPERATION

- Concentric nitrogen and helium baths cool to 4.2K
- ^{4}He pot cools to 1.2K
- Dilution of ^{4}He – ^{3}He mix gives 2.3mK base temperature
- Adiabatic demagnetisation for single shot cooling to ~100uK



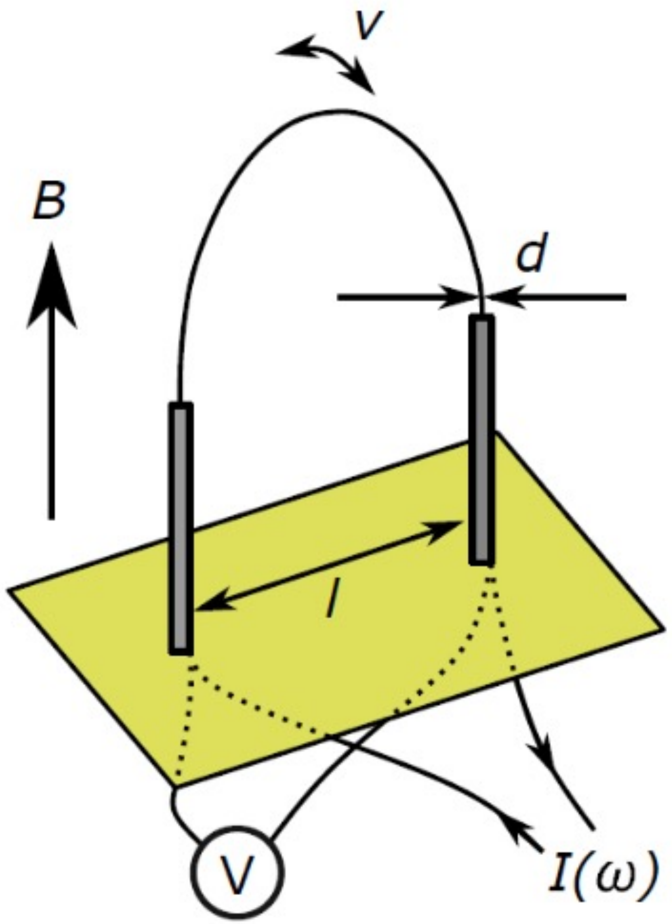
BOLOMETRY

- Vibrating nanowire resonator in a vertical magnetic field
- Damping force from QP collisions:

$$F = \frac{\pi}{4} v d p_F^2 v_F N_0 exp\left(\frac{-\Delta}{k_B T}\right)$$

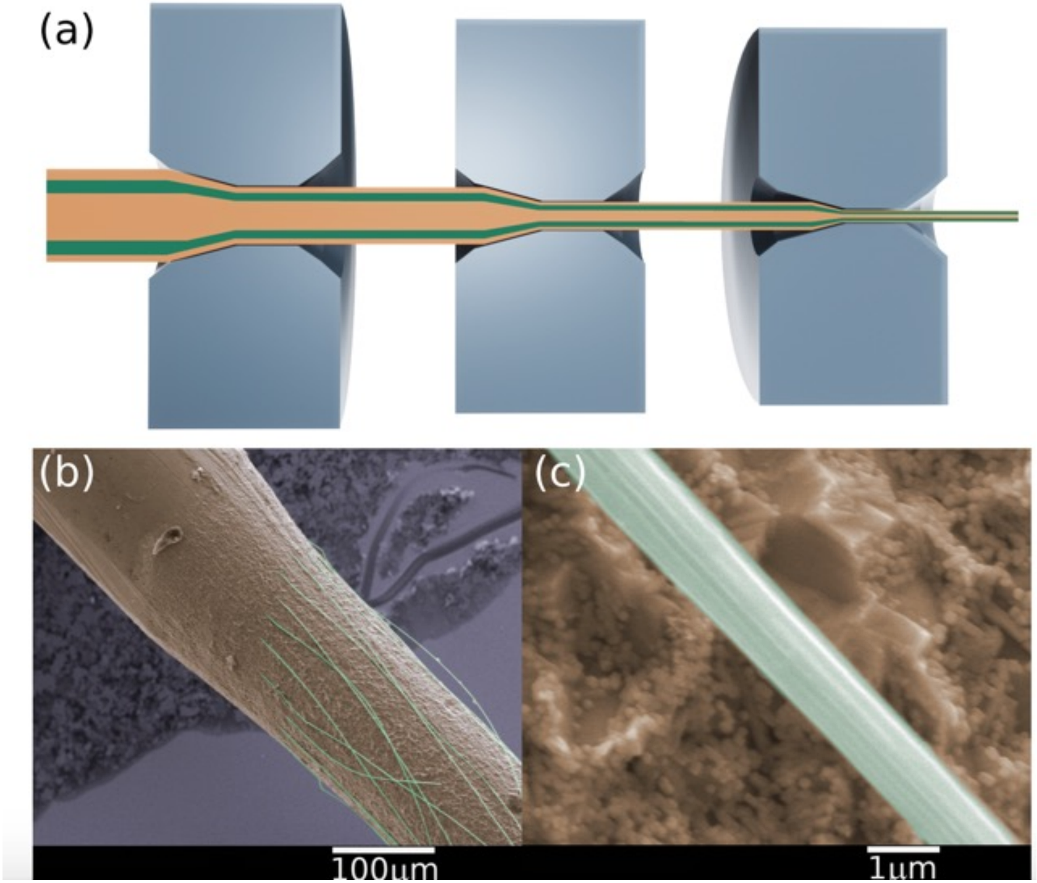
wire 3He

- Andreev scattering amplifies force



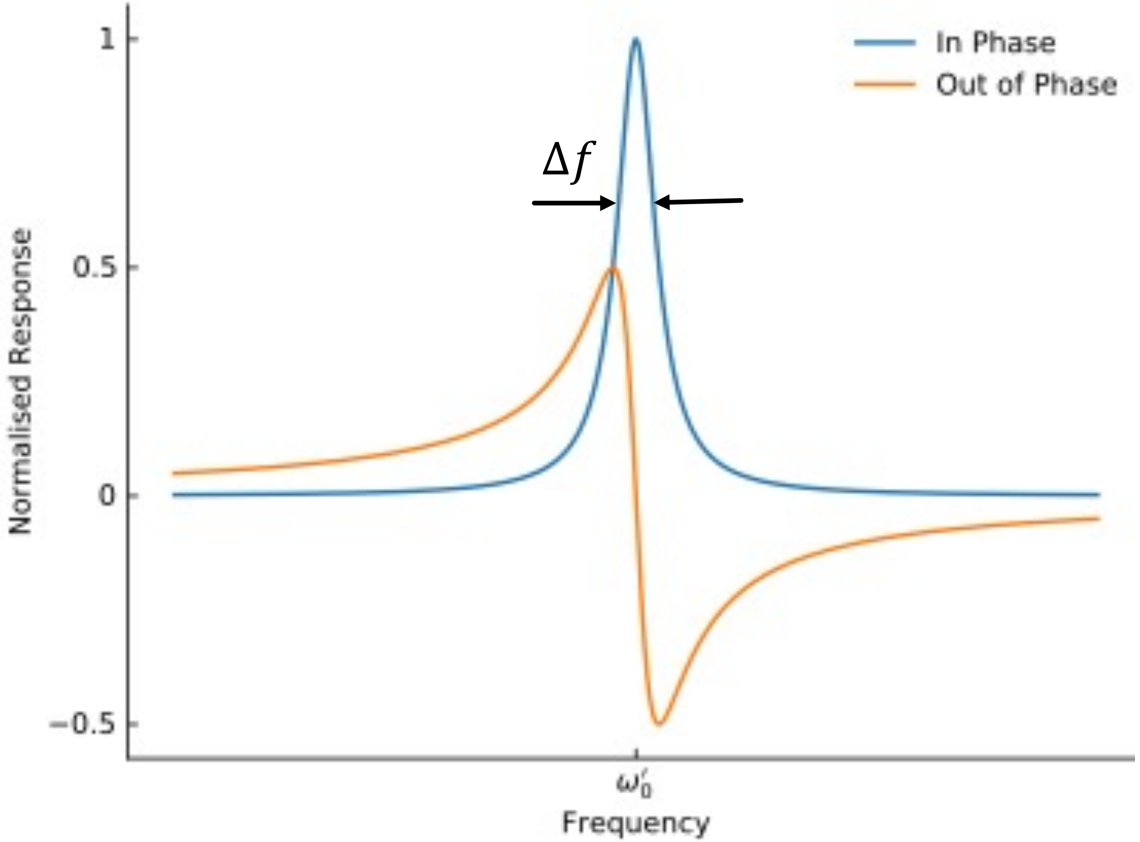
NANOWIRES

- Small wire diameter - fast response time
- NbTi nanowires - few mm length and O(100nm) diameter
- Fabrication using wire drawing, cable etching and plucking single filament
- QUEST-DMC paper: arxiv:2311.02452



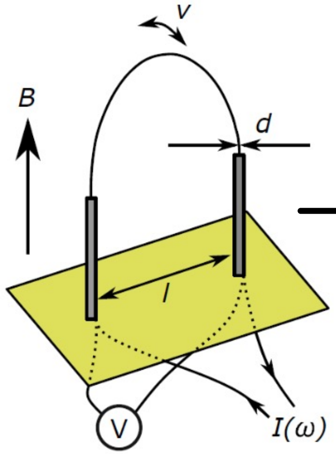
BOLOMETRY

1. Frequency sweep – find resonant frequency and base width from Lorentzian fit



2. Response tracking – drive on resonance
   - Drag force changes oscillation amplitude: $\Delta f = \dfrac{2F}{\pi^2 \rho d^2 v}$
   - Calculate change in resonance width from voltage change
   - Energy proportional to variation of resonance width

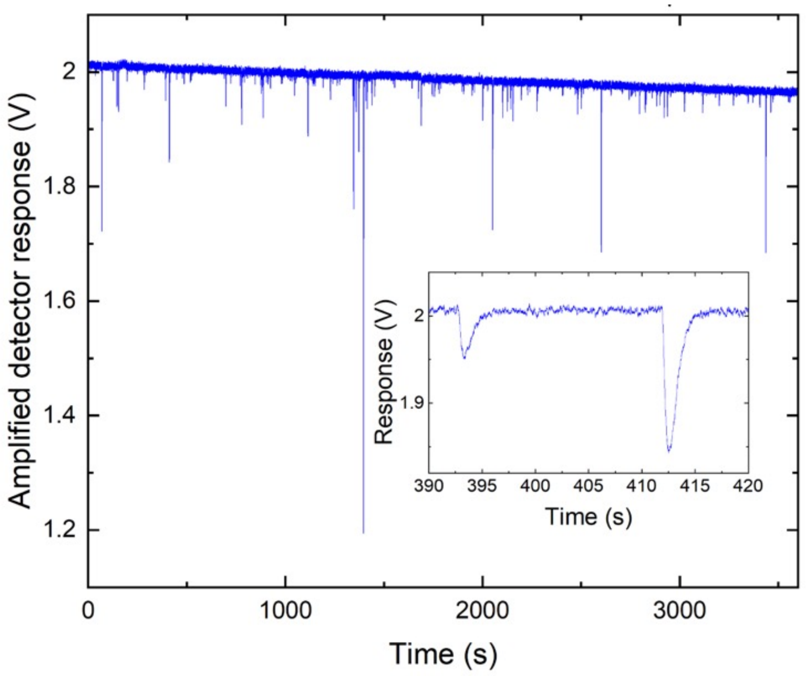
BOLOMETER READOUT



Cold preamplifier:

- Transformer
- SQUID circuit

Lockin amplifier



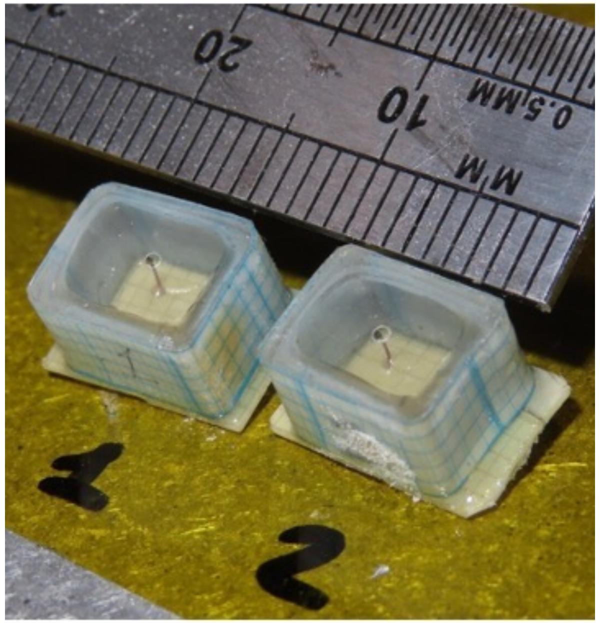
Data from 4.5μm wire, T=125μK

Readout induced voltage on nanowire:

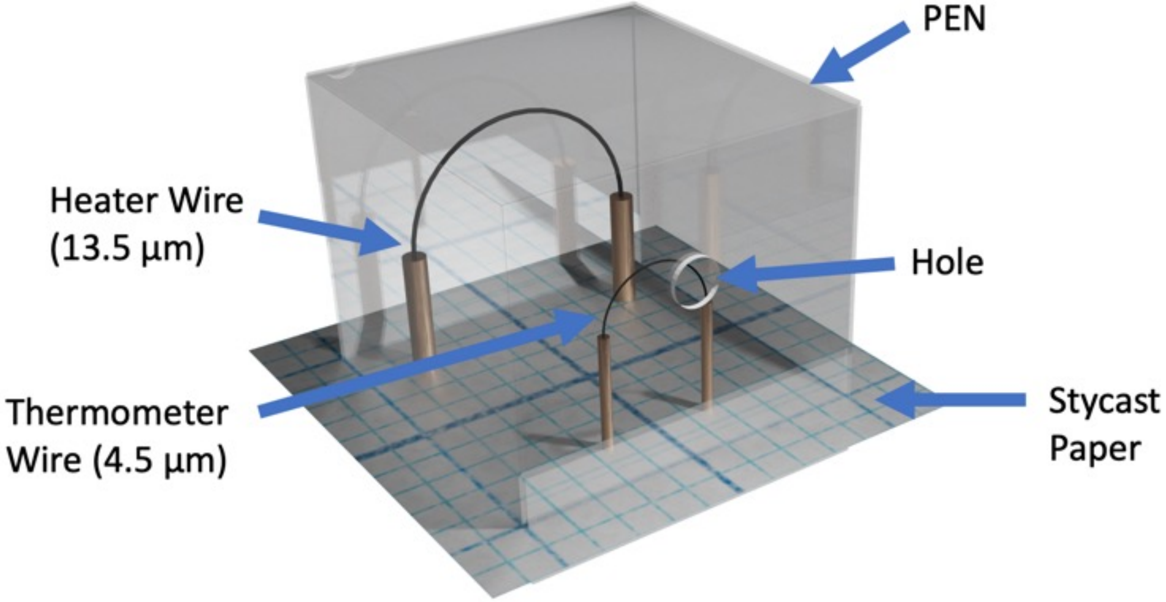
- Conventional method – cold transformer plus lockin
- Reduce noise – SQUID readout, low noise high-gain preamplifier

4. RECENT PROGRESS AND ONGOING TESTS

BOLOMETER CALIBRATION

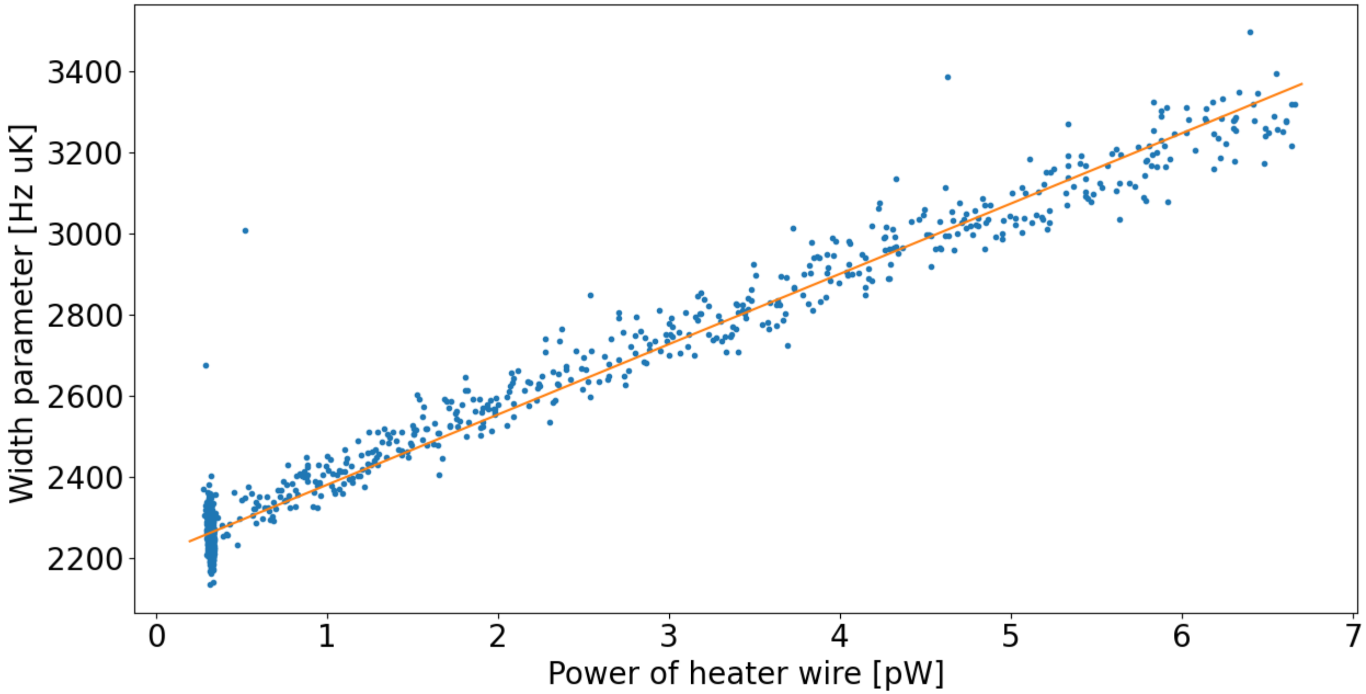


- Bolometer calibration campaign – two bolometers with (4.5 um) thermometer wire and (13.5 um) heater wire
- Heater wire driven above QP pairing breaking velocity generates QPs detected by thermometer wire



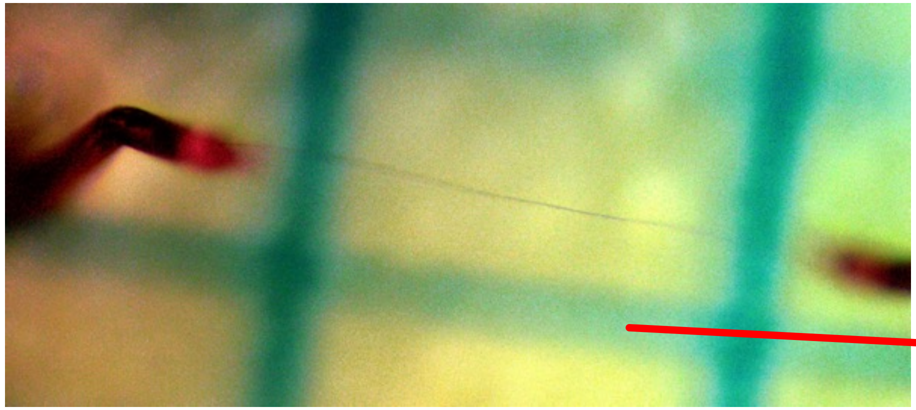
ENERGY MEASUREMENT

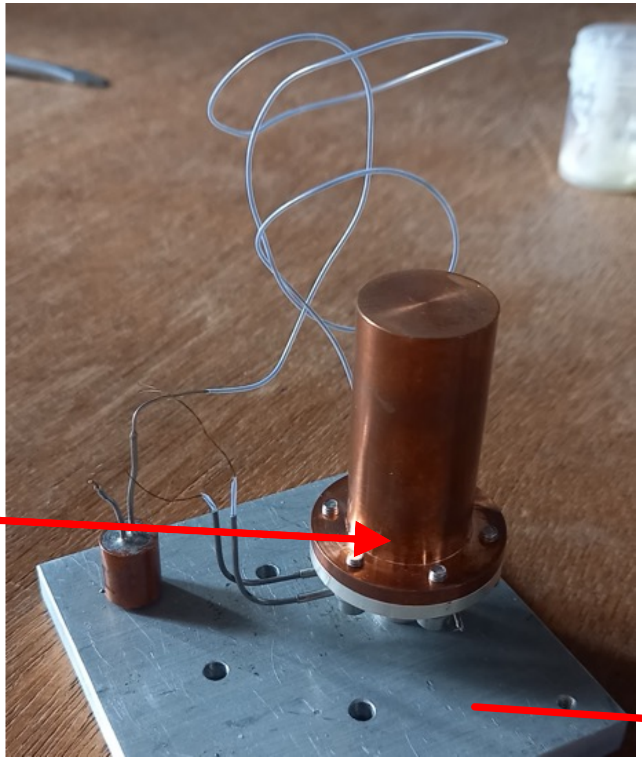
- Change in width of thermometer wire vs (known) injected heater power to find calibration coefficient: $P = K(\Delta f - \Delta f_0)T$
- Use to determine power from tracking data Δf measurements



SQUID READOUT TEST

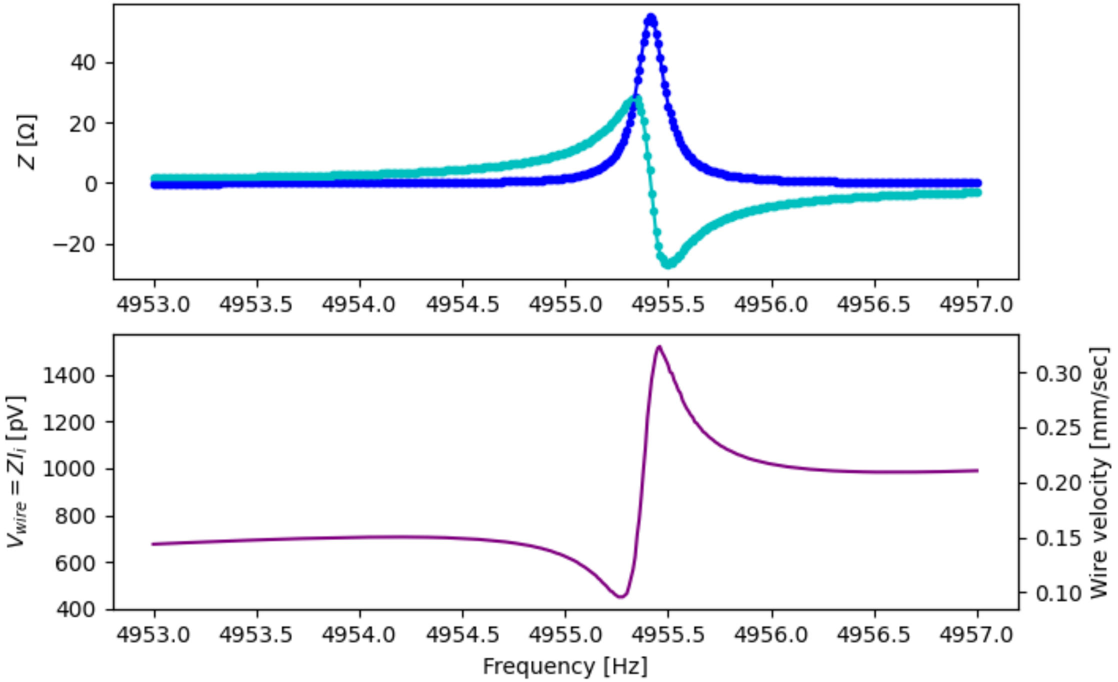
400nm wires down to 0.2mK





SQUID READOUT TEST

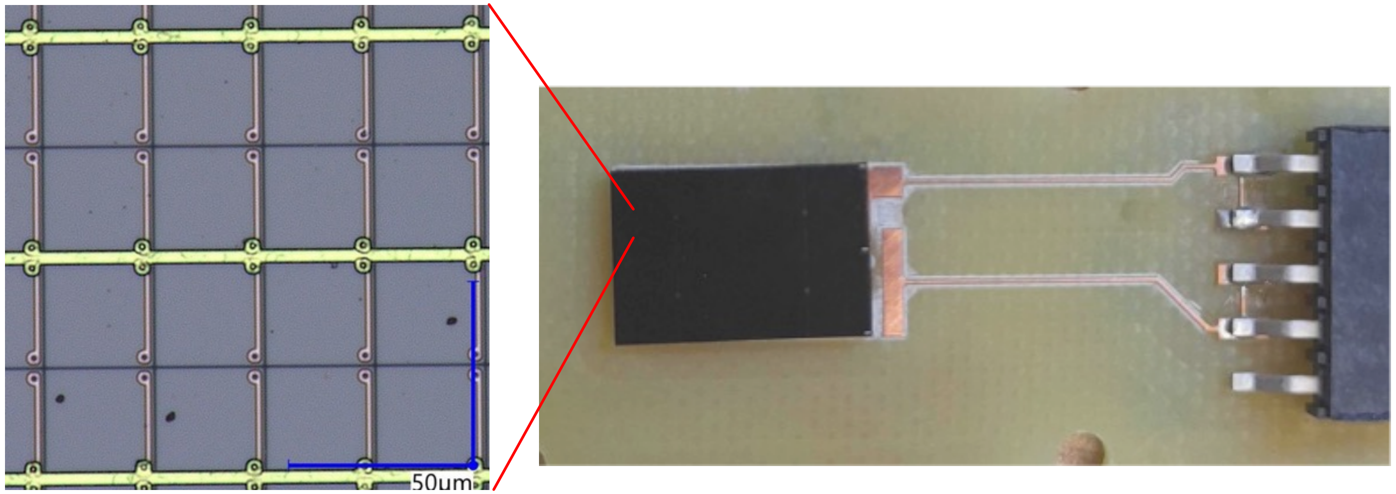
- Successful readout of two nanowires on vacuum and liquid helium3
- Promising noise improvement
- Plan to measure the shot noise and response to fixed energy calibration source

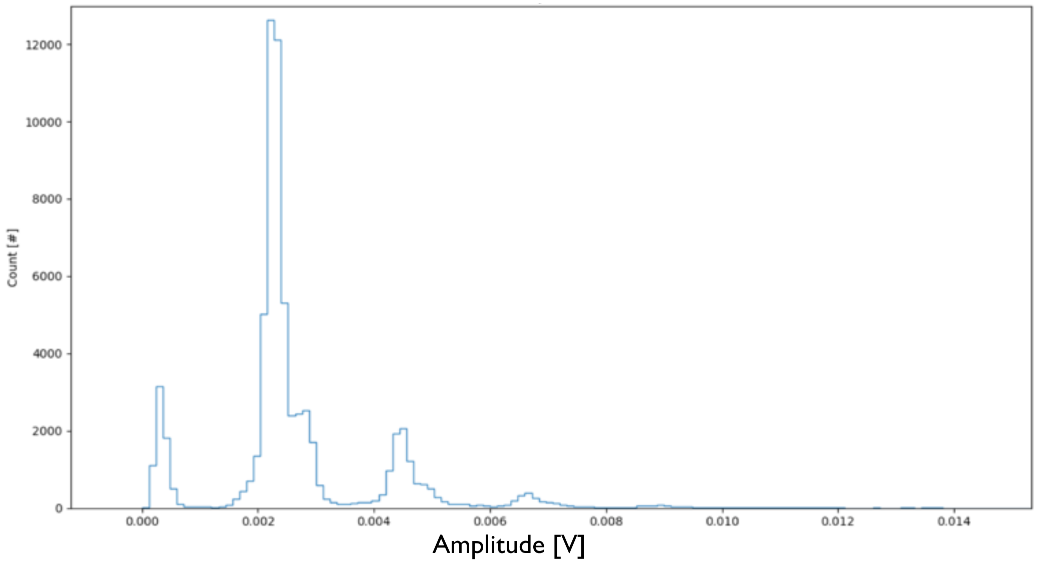


$$Z = \frac{2\pi f A}{(2\pi f_0)^2 - (2\pi f)^2 + 4i\pi^2 f \Delta f} + R + 2i\pi f L_i$$

PHOTON SENSING WITH SIPMS

- High gain and single photo-electron resolution
- *Successful test of device at 4K - FBK NUV SIPMs [A.Ferri et al. JINST **11** P03023(2016)]*
- Currently testing at mK temperatures
- Use for cosmic muon veto and ER/NR discrimination

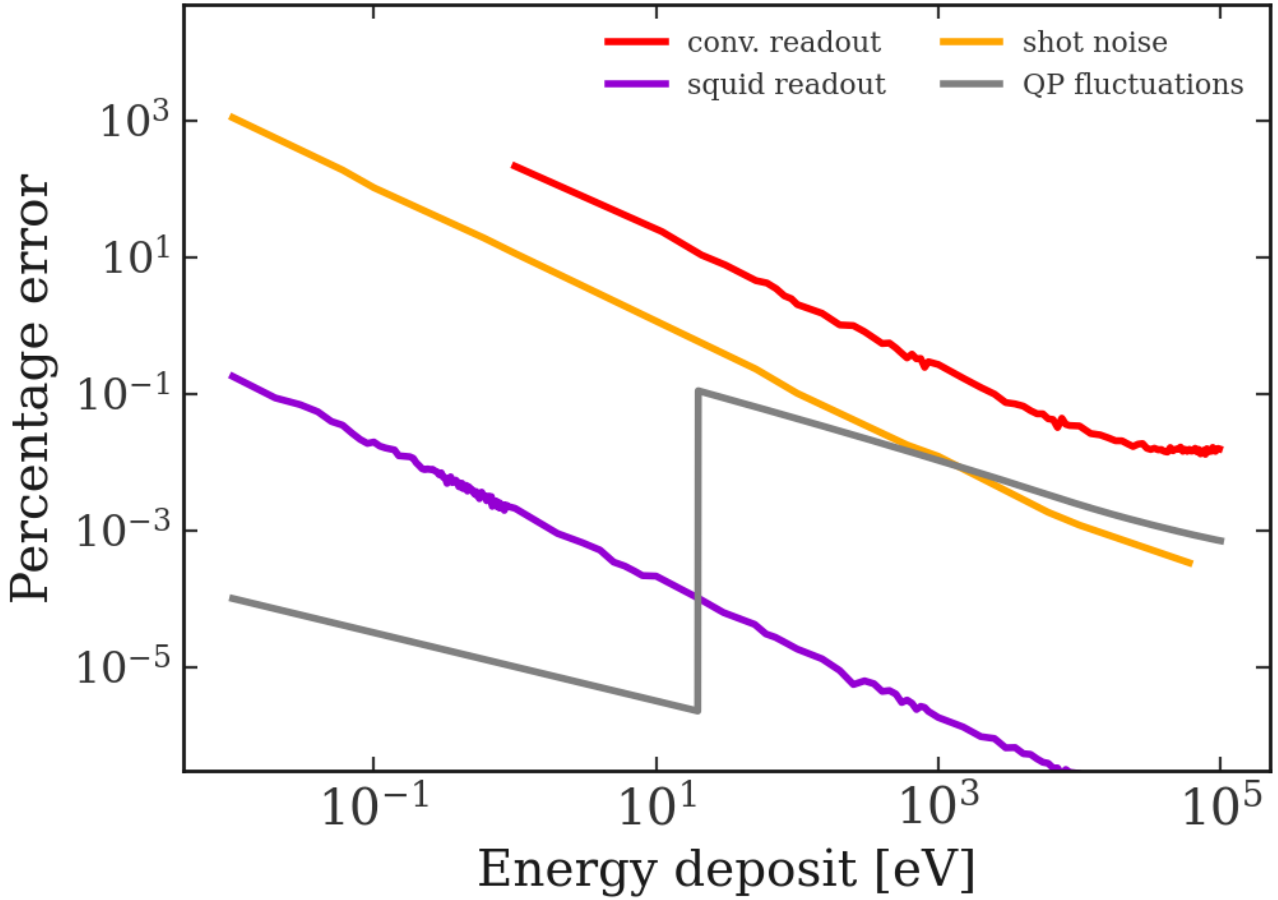




5. WHERE ARE WE HEADING?

FUTURE PHYSICS POTENTIAL

ENERGY MEASUREMENT UNCERTAINTY



- Quasiparticle (QP) production fluctuations
- Readout noise – conventional vs SQUID
- Shot noise – fluctuations on incident QPs

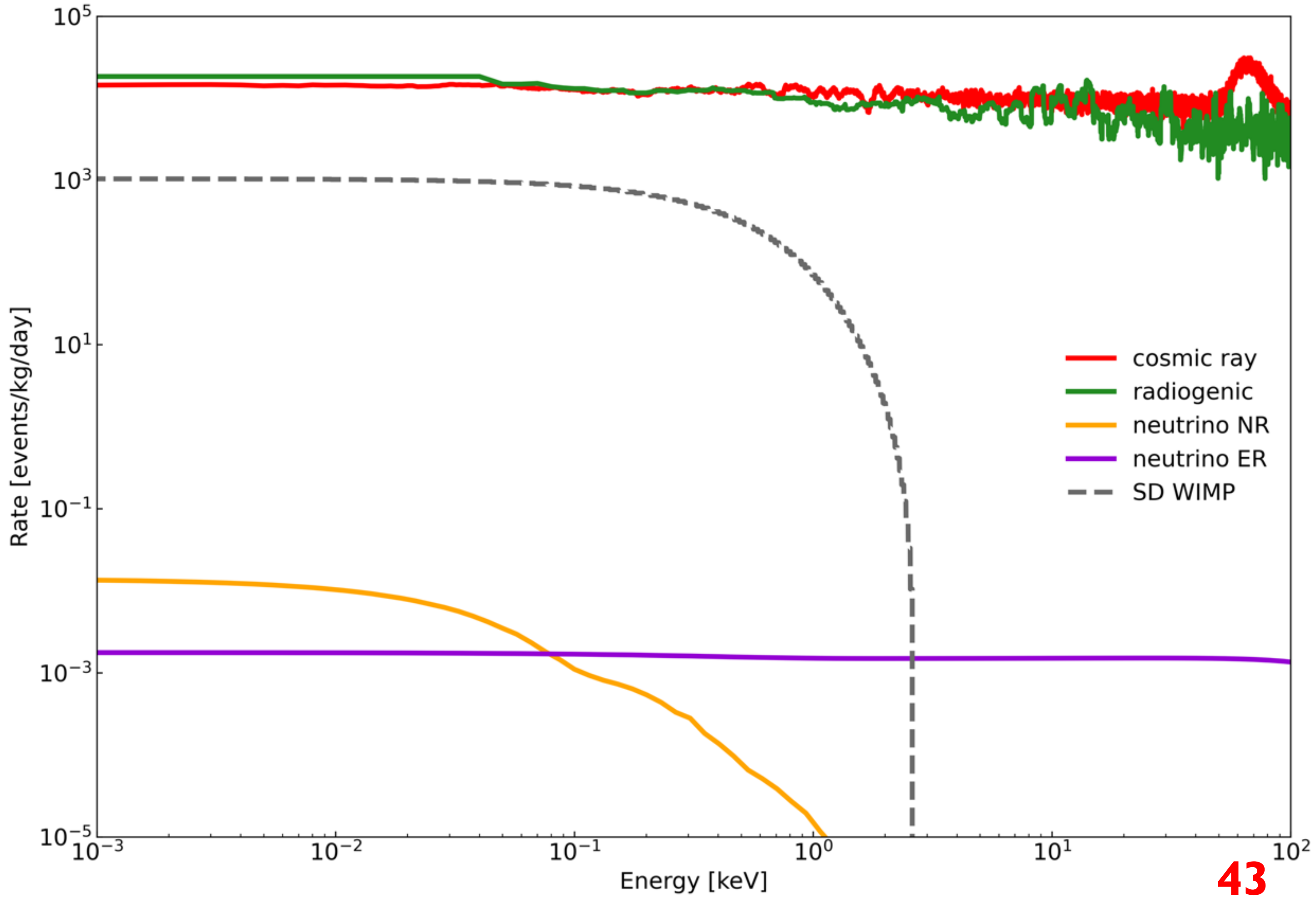
For 400nm wire, 0 bar pressure at 0.12 T/Tc nuclear recoil energy thresholds:

- Conventional readout: 39 eV
- SQUID readout: 0.71 eV

EXPECTED BACKGROUNDS

Background	Events/cell/day [0-10keV]
Cosmic rays	3.31
Radiogenic	2.61
PP neutrino	4.76e-7
CN neutrino	2.01e-9

- Cosmic rays – CRY + Geant4, no shielding and 90% veto efficiency
- Radiogenic - material screening and Geant4



STATISTICAL ANALYSIS

Frequentist hypothesis test using **profile likelihood** test statistic

- Dark matter statistic white paper: EPJC,81, 907(2021)
- Limit setting: null hypothesis = signal + background
- *Parameter of interest*: number of signal events

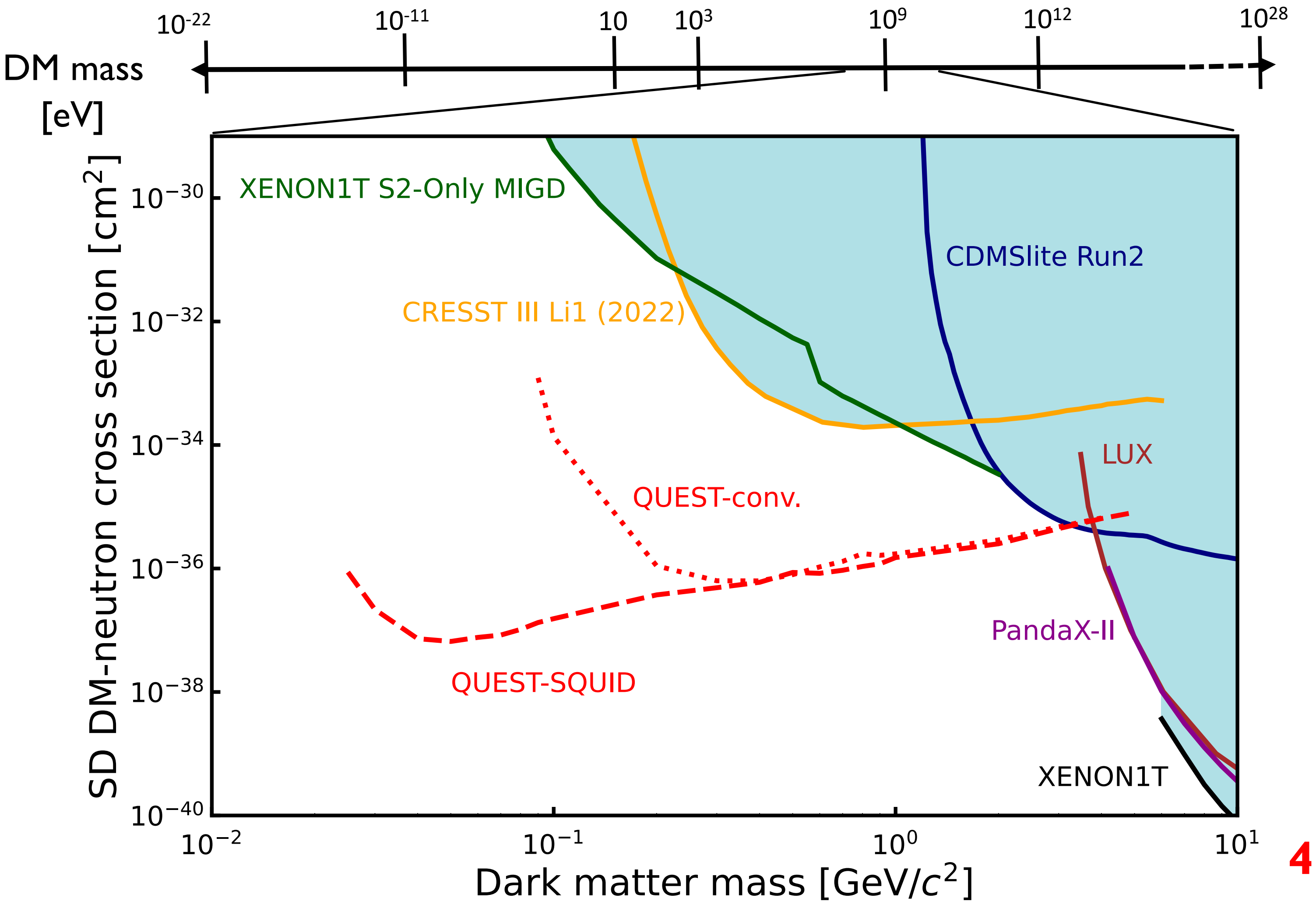
Systematics as *nuisance parameters*:

- Backgrounds – gaussian constraint centred on mean value
- Energy scale - normalisation term, 10% uncertainty from calibration Phys. Rev. Lett. **69**, 1073
- Escape velocity – normalisation as a function of v_{esc} width 67 km/s from M.N.R.A.S.379:755-772(2007)

DARK MATTER SENSITIVITY

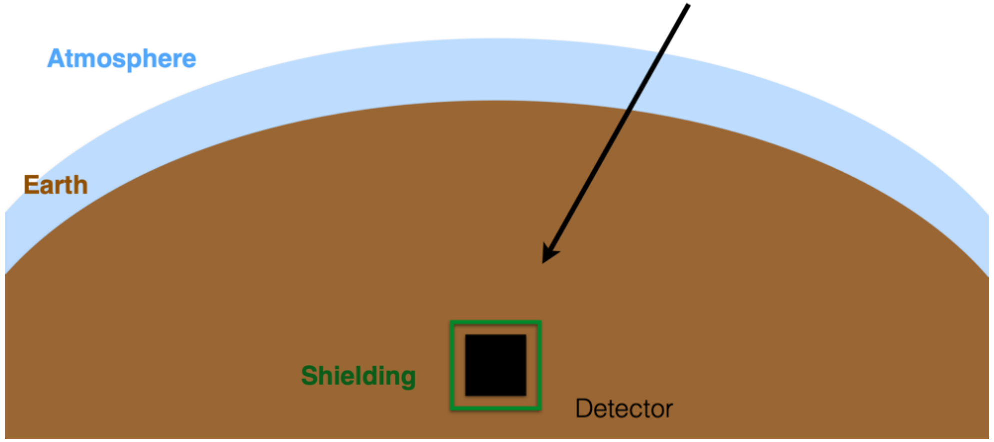
Spin dependent sensitivity projection for:

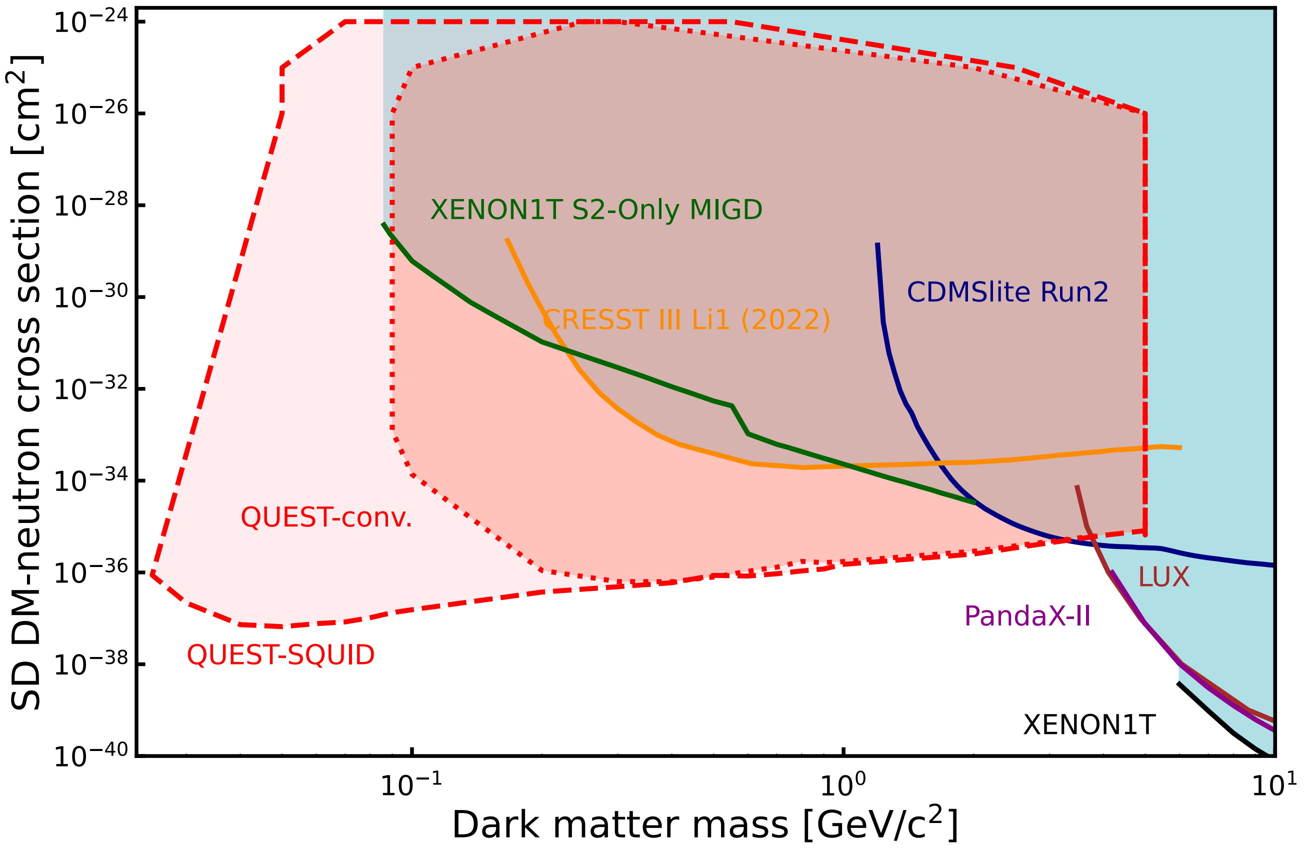
- 5 x 0.3 cm^3 cells
- 6 month run with 50% duty cycle



EARTH SHADOWING

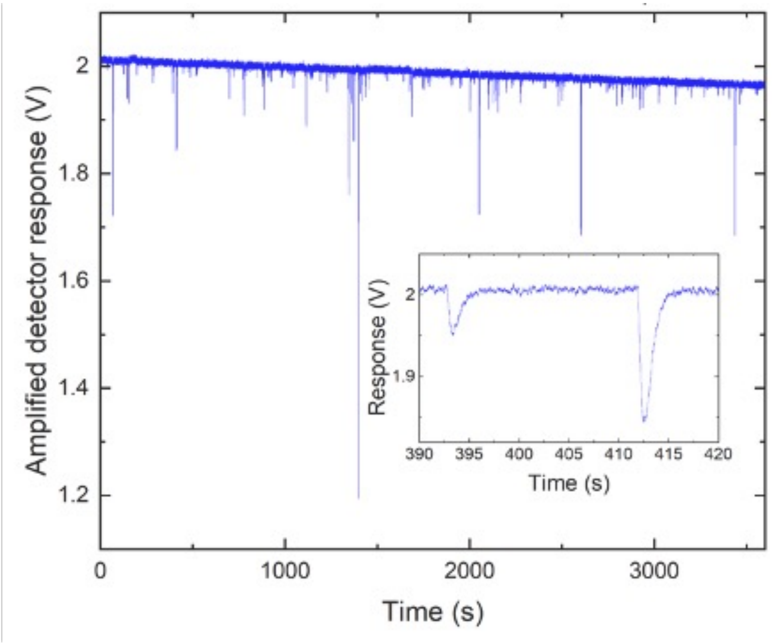
- DM scattering in atmosphere/Earth/shielding can alter path and reduce energy of incoming DM
- Flux and energy reduced until no events exceed threshold
- No sensitivity at highest cross sections





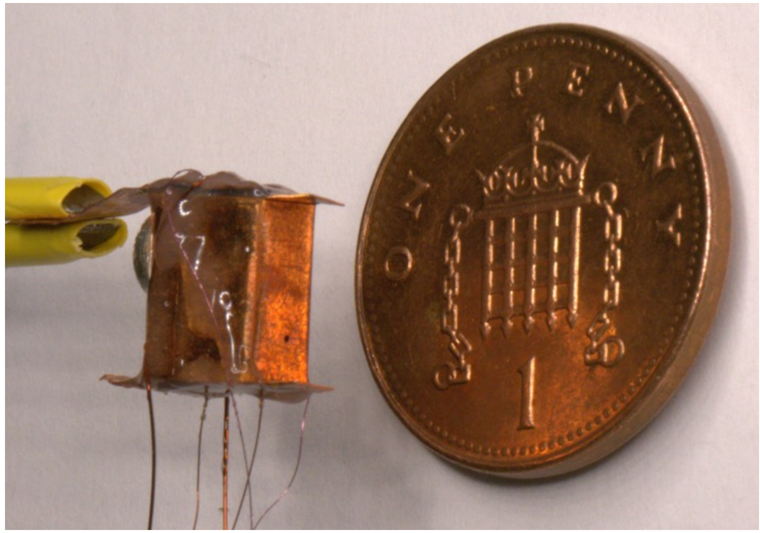
Proof of concept:

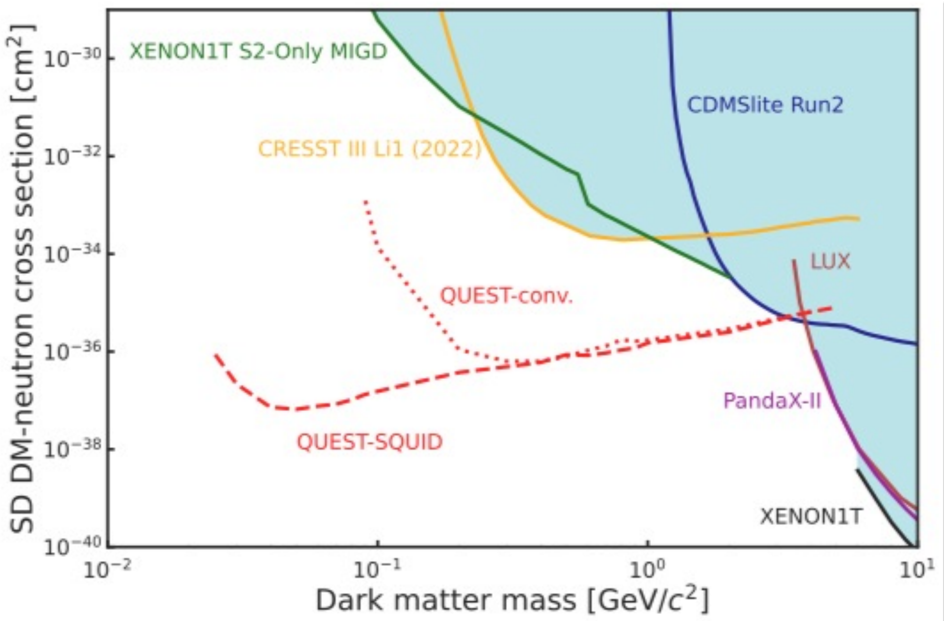
- simulation and analysis *software*
- *bolometer* operation and energy calibration



Ongoing:

- SQUID readout of nanowires
- photon sensors
- new bolometer installation





Aim: 6 month data taking run (**test new dark matter parameter space**)

Sensitivity paper:
E. P. J. C ***84****, 248 (2024)*

Nanowire paper:
arxiv:2311.02452

Background paper:
arxiv:2402.00181

QUEST DMC

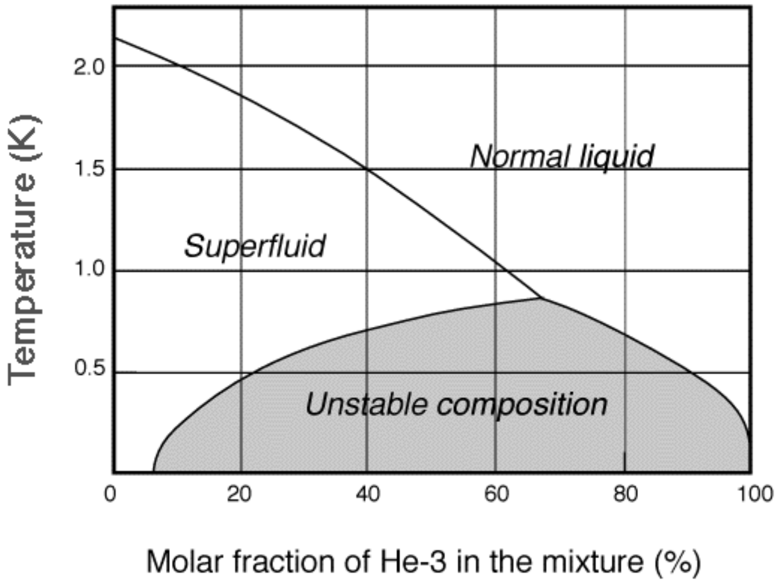
BACKUP

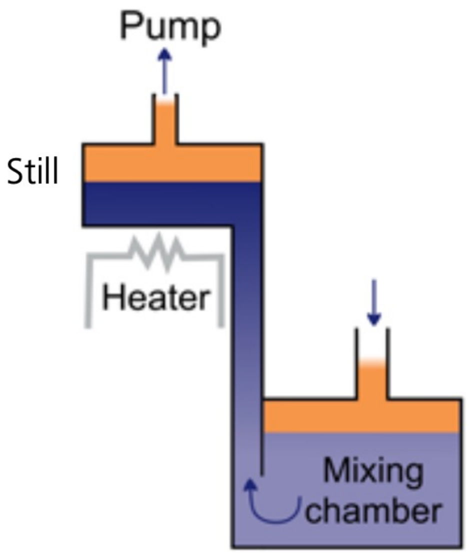
DILUTION REFRIGERATION

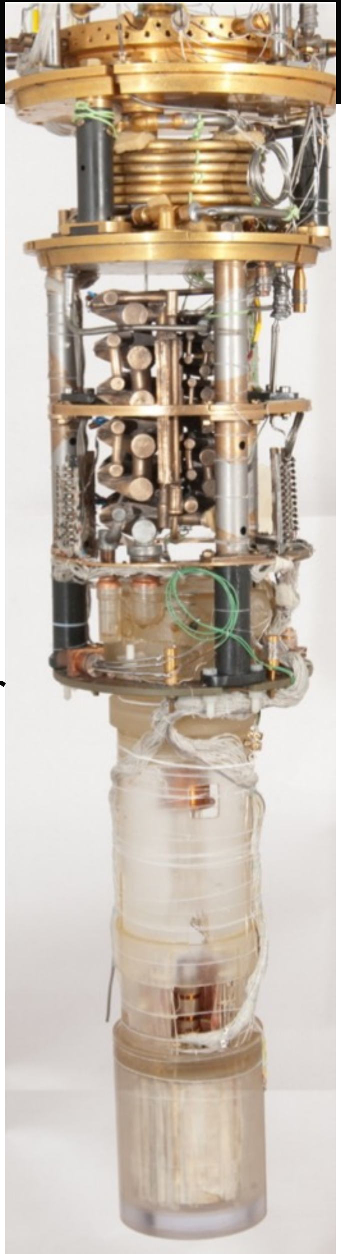
4He – 3He dilution gives 2.3mK base temperature

- Phase separation in 3He – 4He mix at low temperatures, higher entropy in dilute phase
- 3He atoms removed from dilute phase replaced from concentrated phase – increase in entropy removes heat from surroundings:

  $\dot{Q} = 84\dot{n}_3 T^2$ [$\dot{n}_3$ = 3He flow rate across phase boundary]

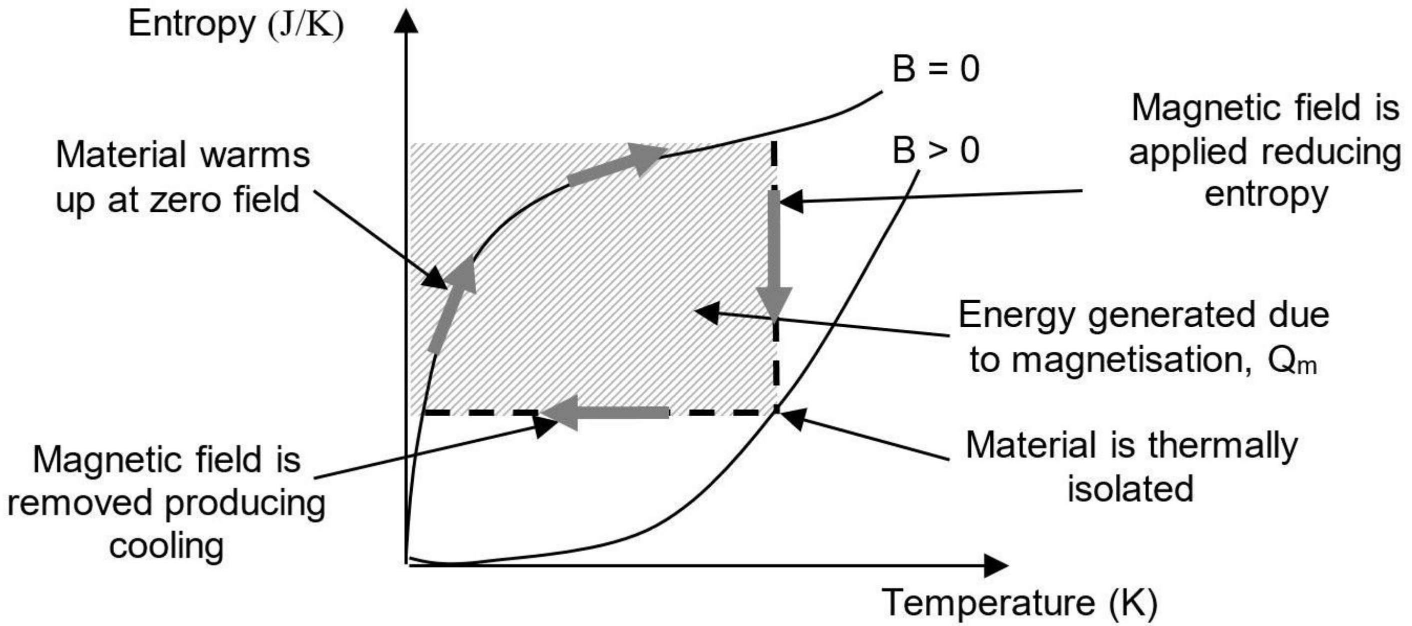


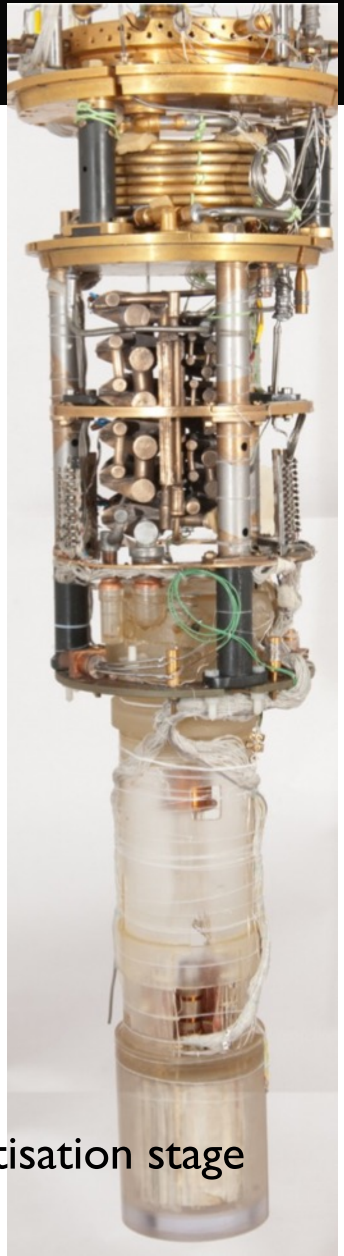




ADIABATIC DEMAGNETISATION

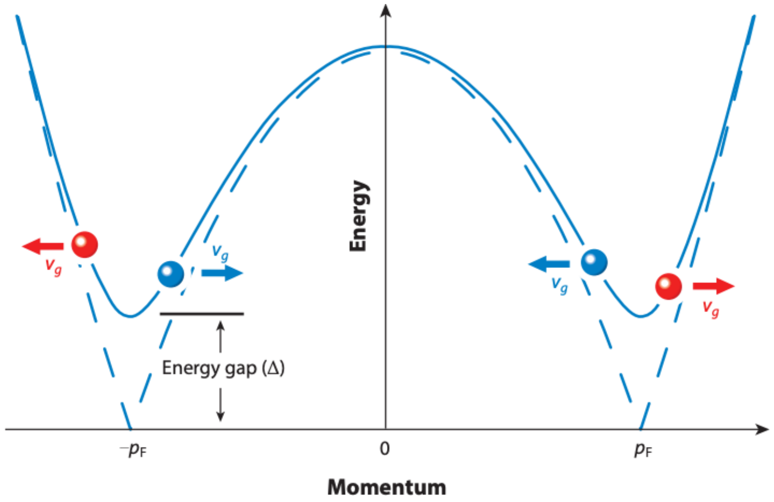
- Following pre-cool to ~mK
- Adiabatic demagnetisation for single shot cooling to ~100uK
- Copper – spins more ordered at high B field, entropy increases when field decreases





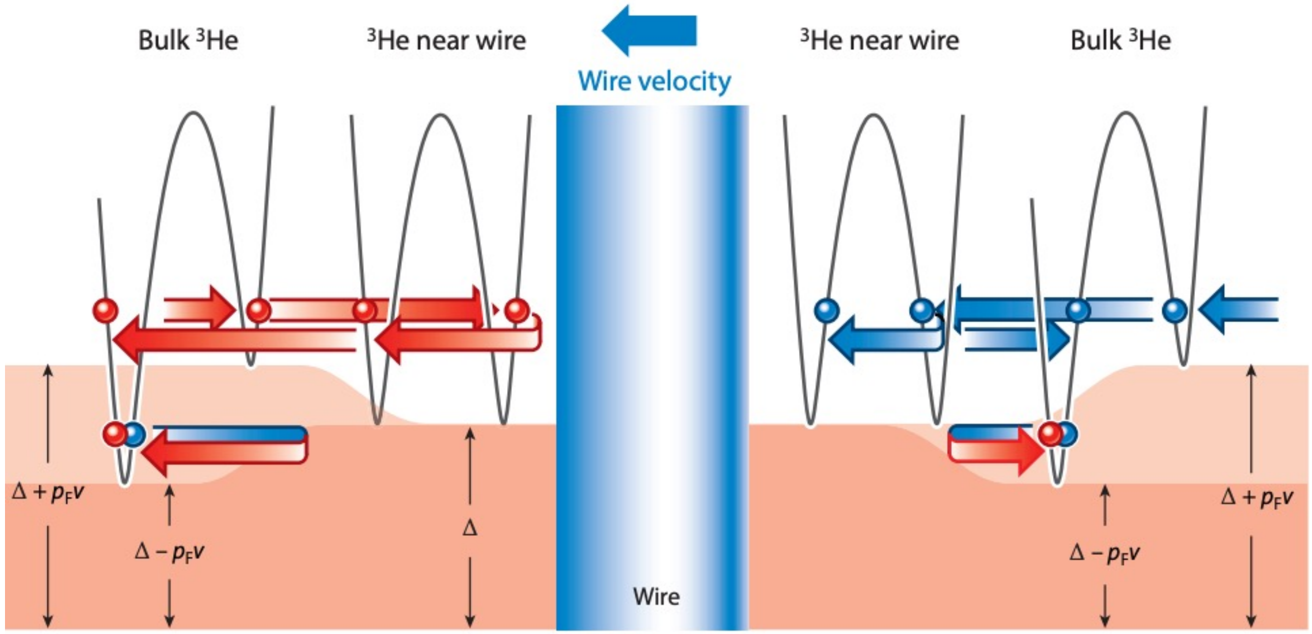
Nuclear demagnetisation stage

ANDREEV SCATTERING



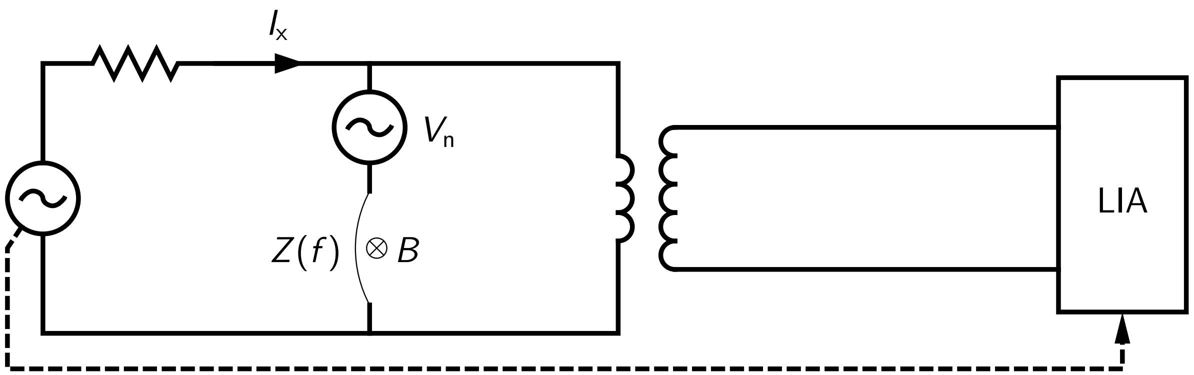
- Quasiparticle dispersion curve , with energy minima at the Fermi momentum.
- Scattering particle drops to min then moves up other side of curve as a hole, with velocity reversed but momentum same.

- Fluid flow and relative motion of wire can increase/decrease the gap.
- Only quasiparticles from in front and quasiholes from behind can transfer momentum |2pF|, increasing the damping.

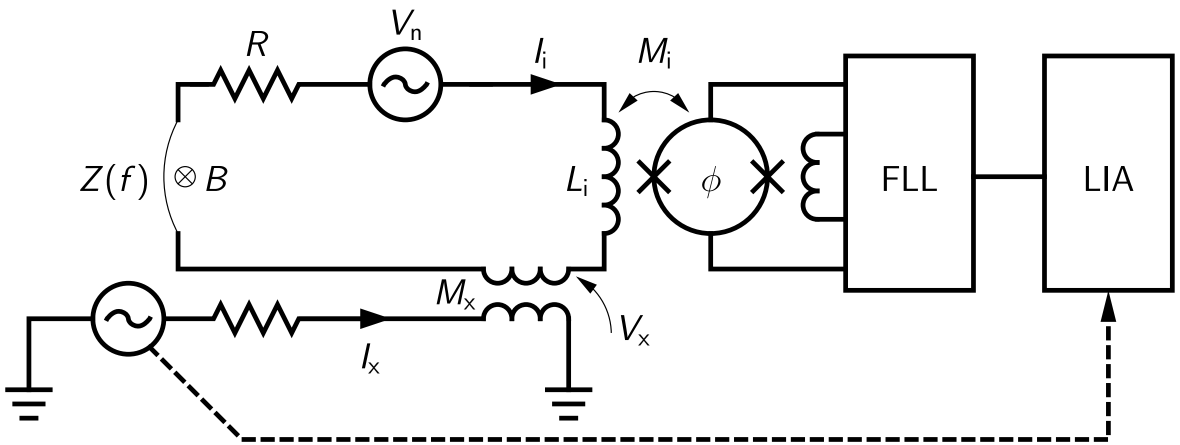


Ref https://www.annualreviews.org/doi/pdf/10.1146/annurev-conmatphys-031016-025411

READOUT SCHEMES

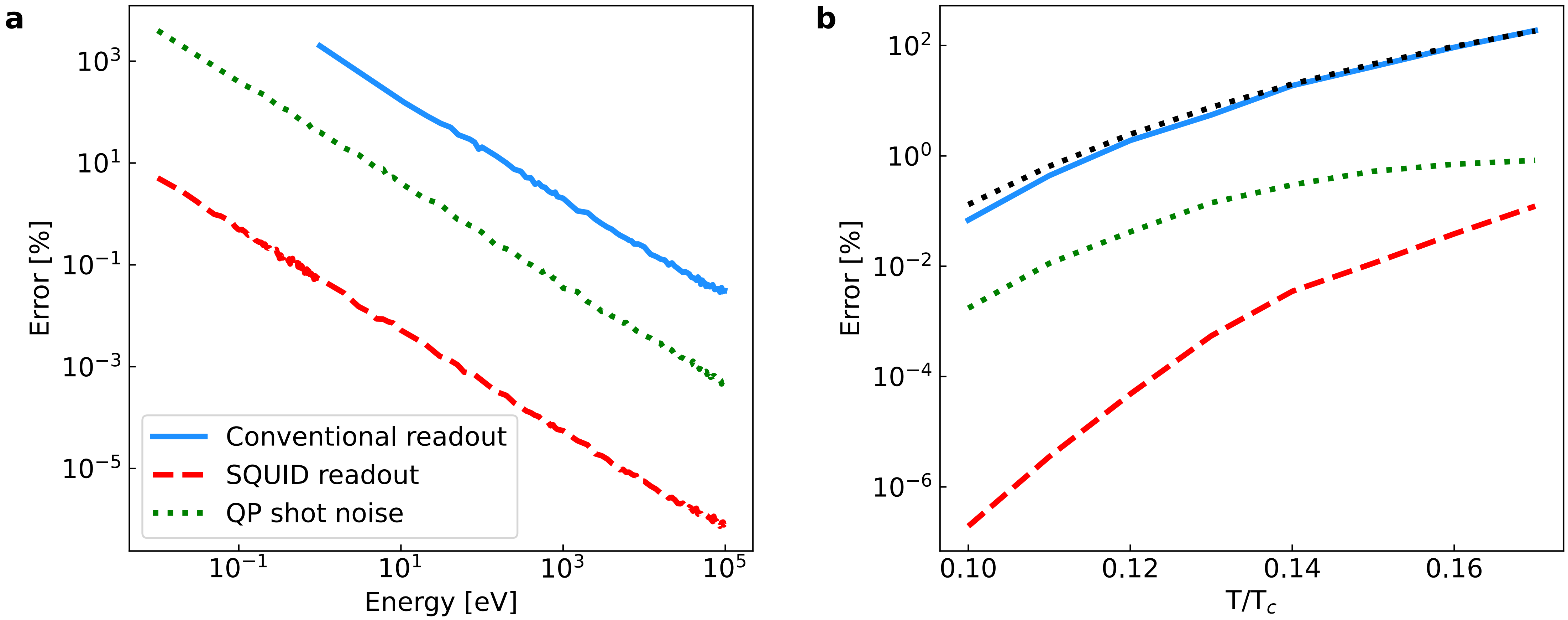


- Conventional – cold transformed plus lockin amplifier

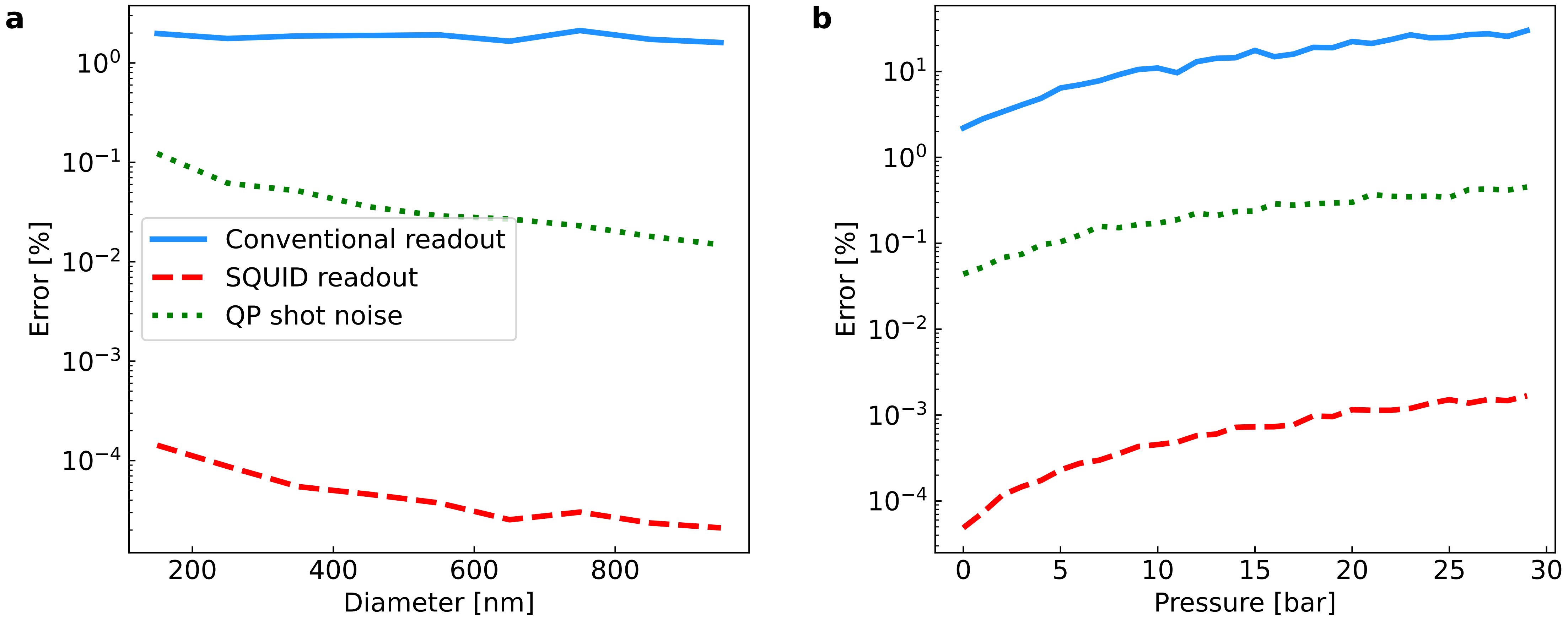


- SQUID readout scheme:
  - Voltage excitation applied inductively through Mx
  - SQUID current sensor detects current Ii flowing through the wire with impedance Z(f), contact resistance R, and SQUID input coil Li.
  - SQUID is connected to lockin via room temperature flux-locked-loop electronics.

READOUT NOISE VS ENERGY AND TEMPERATURE



READOUT NOISE VS DIAMETER AND PRESSURE



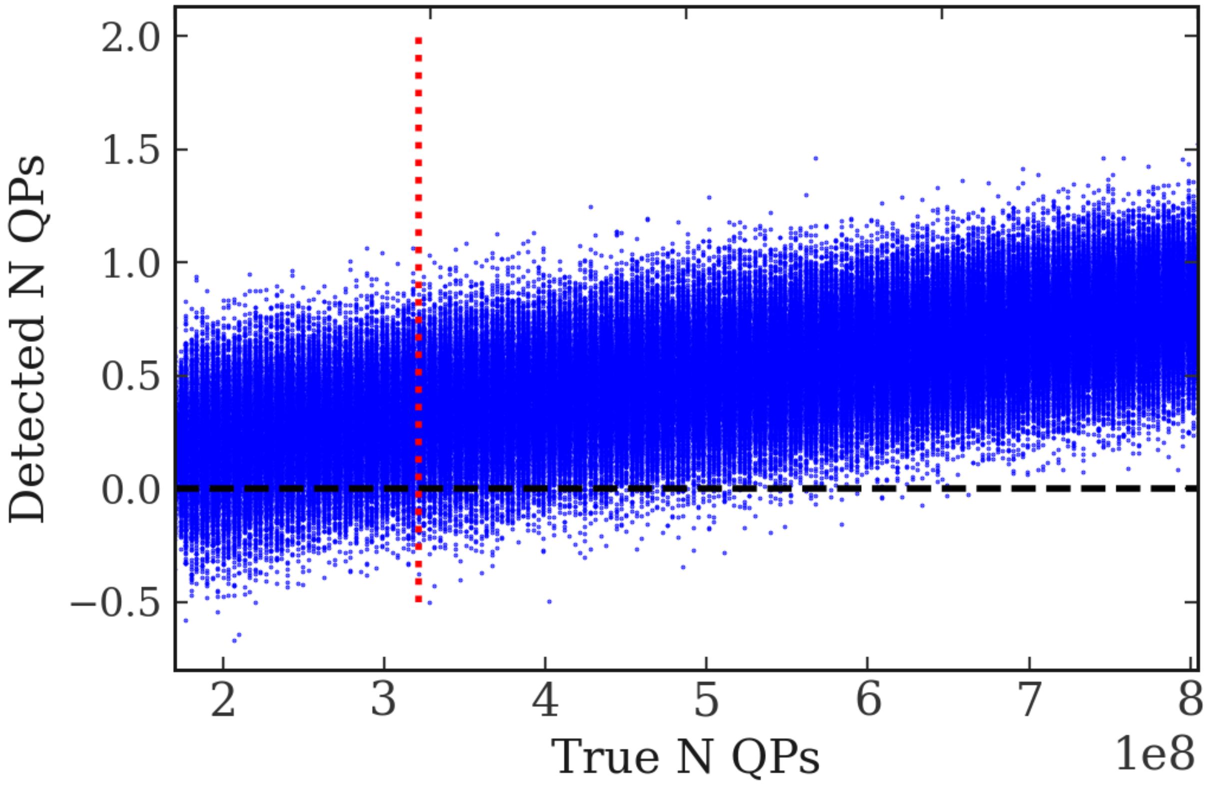
ENERGY THRESHOLD CALCULATION

Threshold determined by resolution at threshold.

Find energy where we have 95% confidence in detecting energy > zero.

For 400nm wire, 0 bar pressure at 0.12 T/Tc nuclear recoil energy thresholds:

- Conventional readout: 39 eV
- SQUID readout: 0.71 eV



RADIOASSAY

- Radioactivity of materials comprising the detector, cryostat and surroundings has been measured using BUGS (Boulby Underground Germanium Suite) gamma ray spectrometry facility & (for concrete) estimated from SNOLab Radiopurity database

TABLE S1. Assay values in mBq kg^{-1} for materials comprising the target cell and cryostat separated into relevant isotopes.

Material	Up ^{238}U	Lower ^{238}U	^{210}Pb	Upper ^{232}Th	Lower ^{232}Th	^{235}U	^{137}Cs	^{40}K	^{60}Co	^{54}Mn
Concrete	$< 1.60 \times 10^5$	15000	1.00×10^7	7570	7570	< 7200	800	42000	< 700	0.0
Aluminium	8330	15.3	70.7	356	334	60.5	< 0.940	< 3.12	< 1.10	0.00
Superinsulation	679	< 200	< 3900	200	200	4.93	0.0	3500	400	0.0
Stainless Steel	16	2.5	82.2	3.1	3.90	0.120	2.00	< 6.20	< 5.20	1.70
Steel	< 12.4	12	12000	4.88	4.88	3.00	2.00	34.1	30.0	1.00
Araldite	< 3.60	< 4.80	14.5	< 3.40	< 2.20	0.0260	2.00	25.5	8.00	0.00
Stycast	< 10.5	< 9.50	< 14.9	< 12.8	< 6.20	0.0762	2.00	122	10.0	0.00

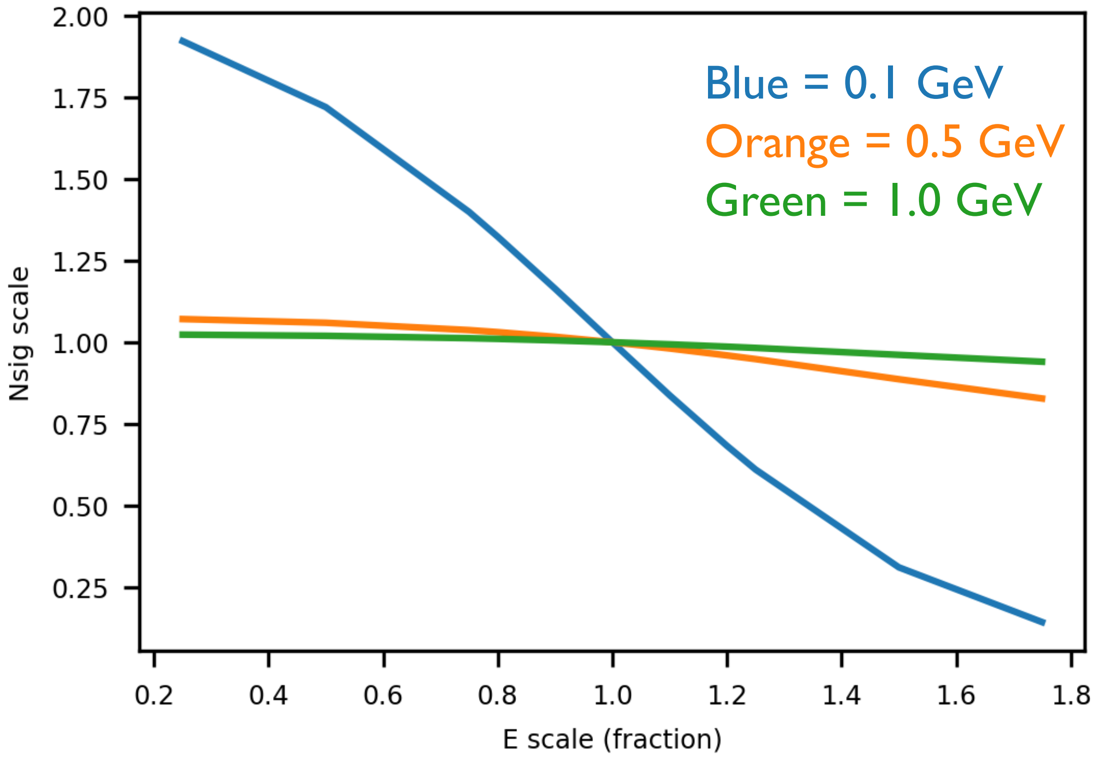
ENERGY SCALE UNCERTAINTY

Contributions:

A. Transfer of deposited energy to measured QP (partition uncertainty, energy transport)

B. Energy calibration and measurement – dominant at 10% level Phys. Rev. Lett. **69**, 1073

- Signal events depend strongly on energy scale for O(meV) WIMP masses (end point near threshold)
- Extra normalisation term in likelihood
- Gaussian constraint with width 0.1

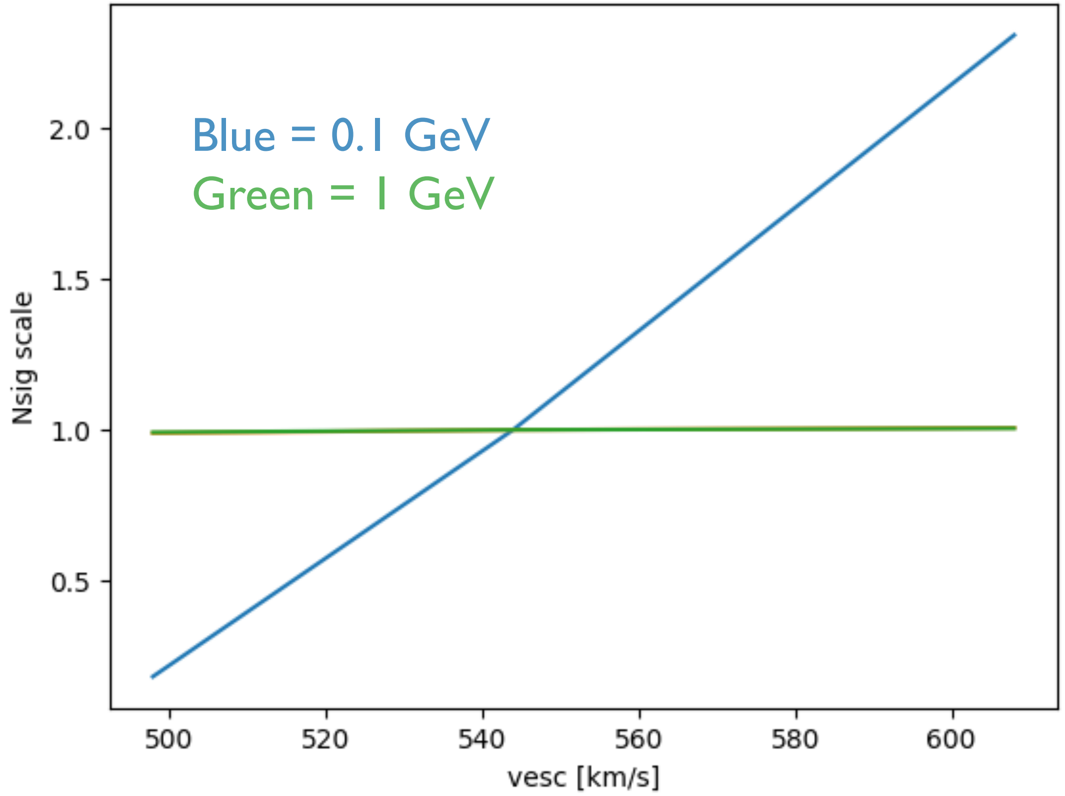


ASTROPHYSICAL UNCERTAINTY

Standard Halo Model assumed.

Escape velocity shifts end point and number of events:

- 0.1 GeV and 1GeV WIMP scaling with range of measured values in EPJ.C,81,907(2021)
- Extra normalisation term in the likelihood
- Gaussian constraint with width 67 km/s from distribution measured by the RAVE survey + cosmological simulations M.N.R.A.S.379:755-772(2007)



STANDARD HALO MODEL

$f(\bar{v}, \bar{v}_E) = N exp(-(\bar{v} + \bar{v}_E)^2)/\bar{v}_0^2 \Theta(v_{esc} - |\bar{v} + \bar{v}_E|)$

Where…

$\bar{v}$ = dark matter velocity on target

$\bar{v}_E$ = velocity of Earth w.r.t dark matter halo

$\bar{v}_E = \bar{v}_0 + \bar{v}_{pec} + \bar{v}_{orb}(t)$

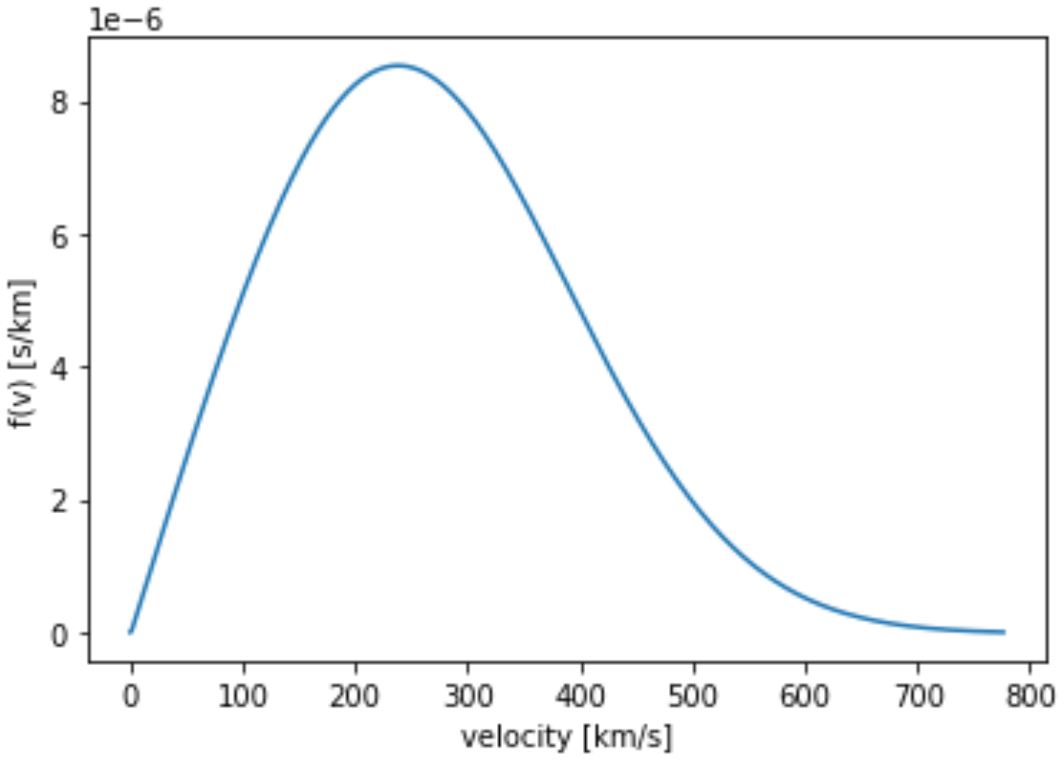
$\bar{v}_0$ = galactic rotation velocity

$\bar{v}_{pec}$ = Sun peculiar velocity

$\bar{v}_{orb}(t)$ = Earth orbital velocity

N = normalisation

Parameter	Value	Reference
Escape velocity, v_{esc}	544 km/s	PRD.101.023006
Galactic rotation velocity, $\bar{v}_0$	(0, 238, 0) km/s	ARAA.081915-023441
Solar peculiar velocity, $\bar{v}_{pec}$	(11.1, 12.2, 7.3) km/s	MNRAS.403.042010
Dark matter density	0.3 GeV/c^2/cm^3	Astropart.Phys.10.1016



WORLDWIDE HELIUM SEARCHES