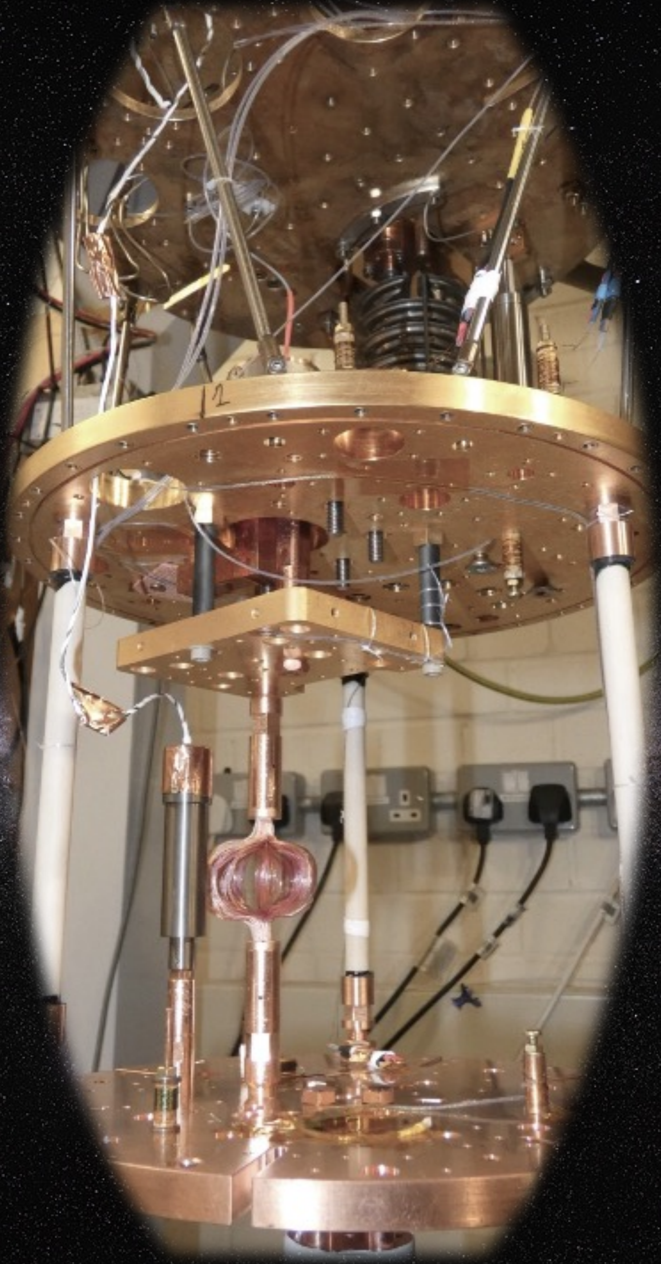
UltraDark: ultralow temperature underground facility for dark matter and quantum systems



Elizabeth Leason
EPSRC Quantum Technology Fellow
University of Oxford

ECFA Durham, 24.09.2024

QUEST DMC

UNIVERSITY OF OXFORD

QUEST-DMC

EXPERIMENTAL	Robert Smith, Lizzie Blooomfield
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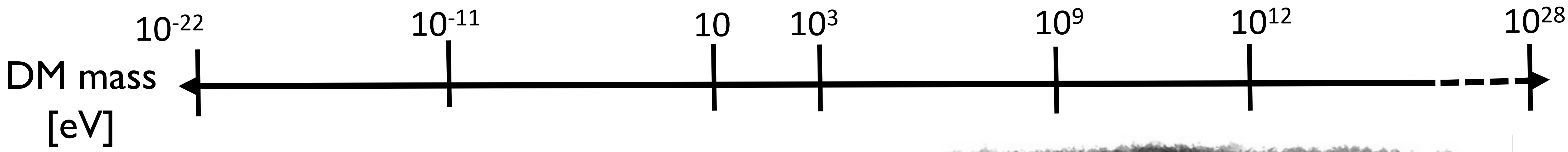
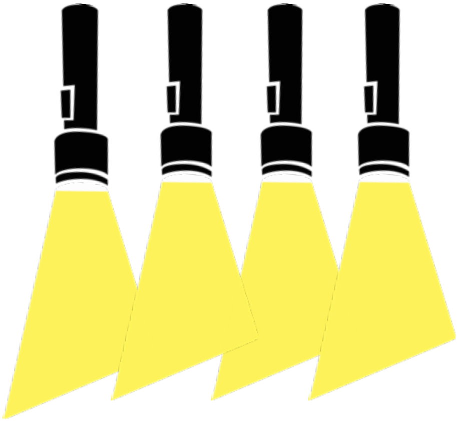
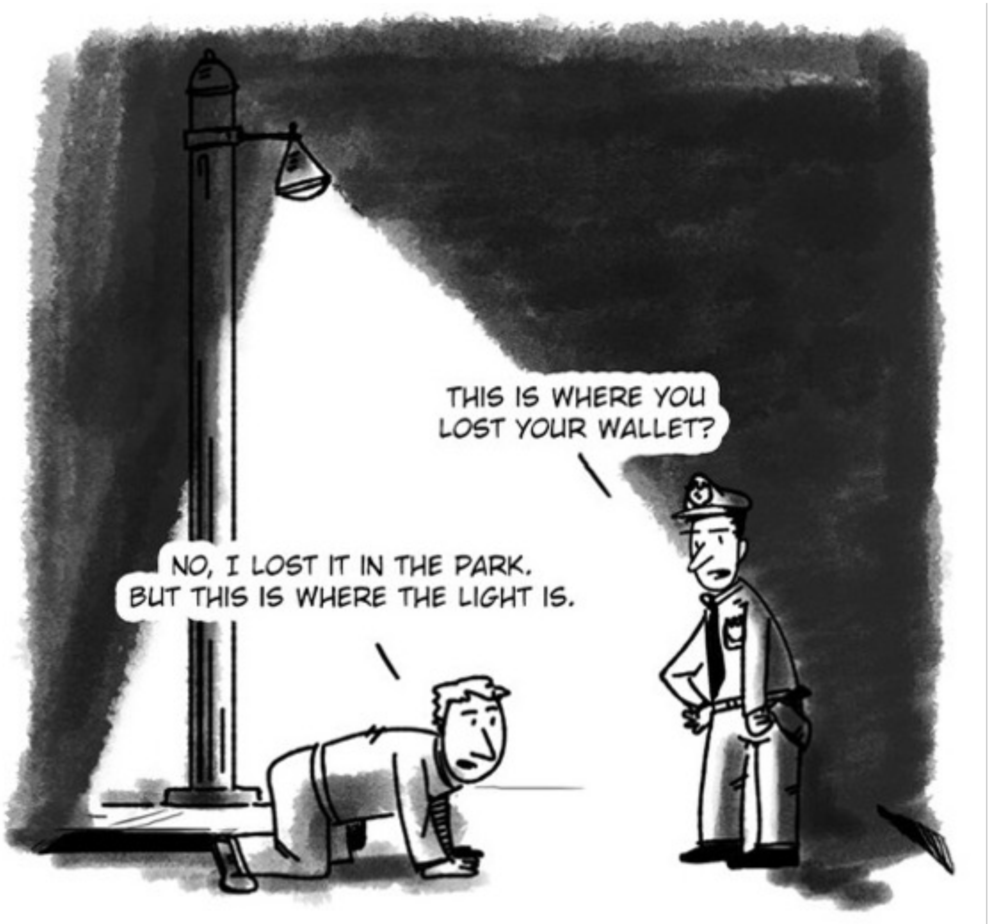
Dr. Paolo Franchini	Dr Dmitry Zmeev
Prof. Richard Haley	Dr Vladislav Zavyalov
Dr. Petri Heikkinen	Tineke Salmon, Luke Whitehead
Dr Sergey Kafanov	**THEORY**
Dr Ashlea Kemp	Dr Neda Darvishi
Dr. Elizabeth Leason	Prof. Mark Hindmarsh
Dr. Lev Levitin	Prof. Stephan Huber
Prof. Jocelyn Monroe	Dr Asier Lopez-Eiguren
Dr Theo Noble	Prof. John March-Russell
Dr Jonathan Prance	Dr Juri Smirnov
Dr Xavier Rojas	Prof. Stephen West
Prof. John Saunders	Dr. Quang Zhang

Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology

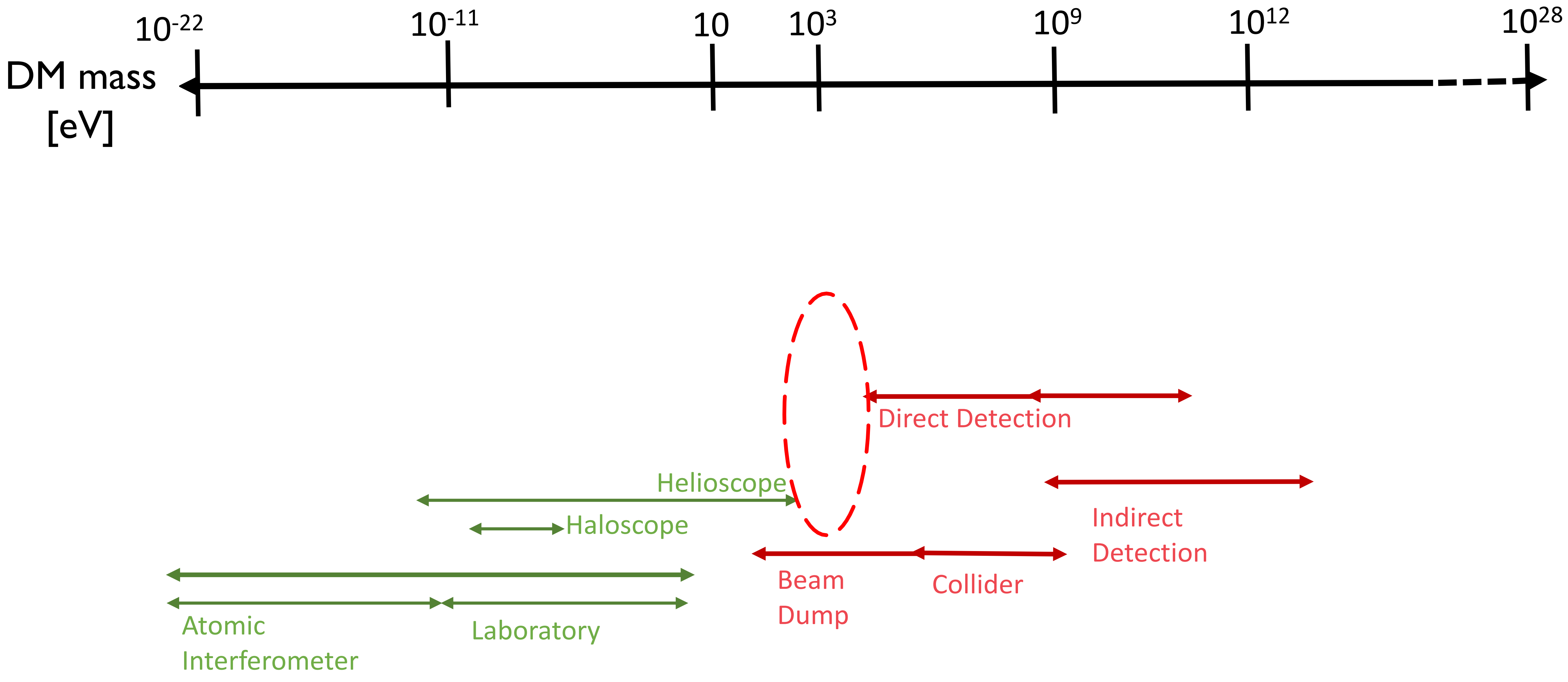
Motivation


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



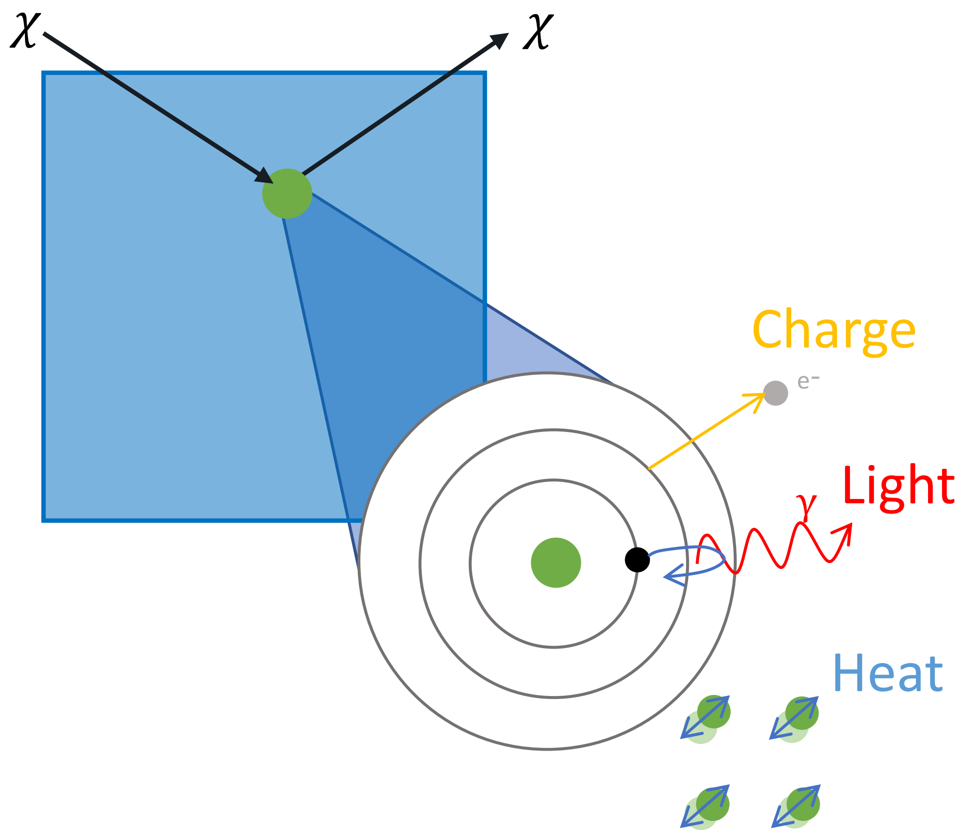

THIS IS WHERE YOU LOST YOUR WALLET?
NO, I LOST IT IN THE PARK. BUT THIS IS WHERE THE LIGHT IS.

Search strategies



Low threshold requirements

- Detector target – kinematic matching and signal generation process with low energy barrier



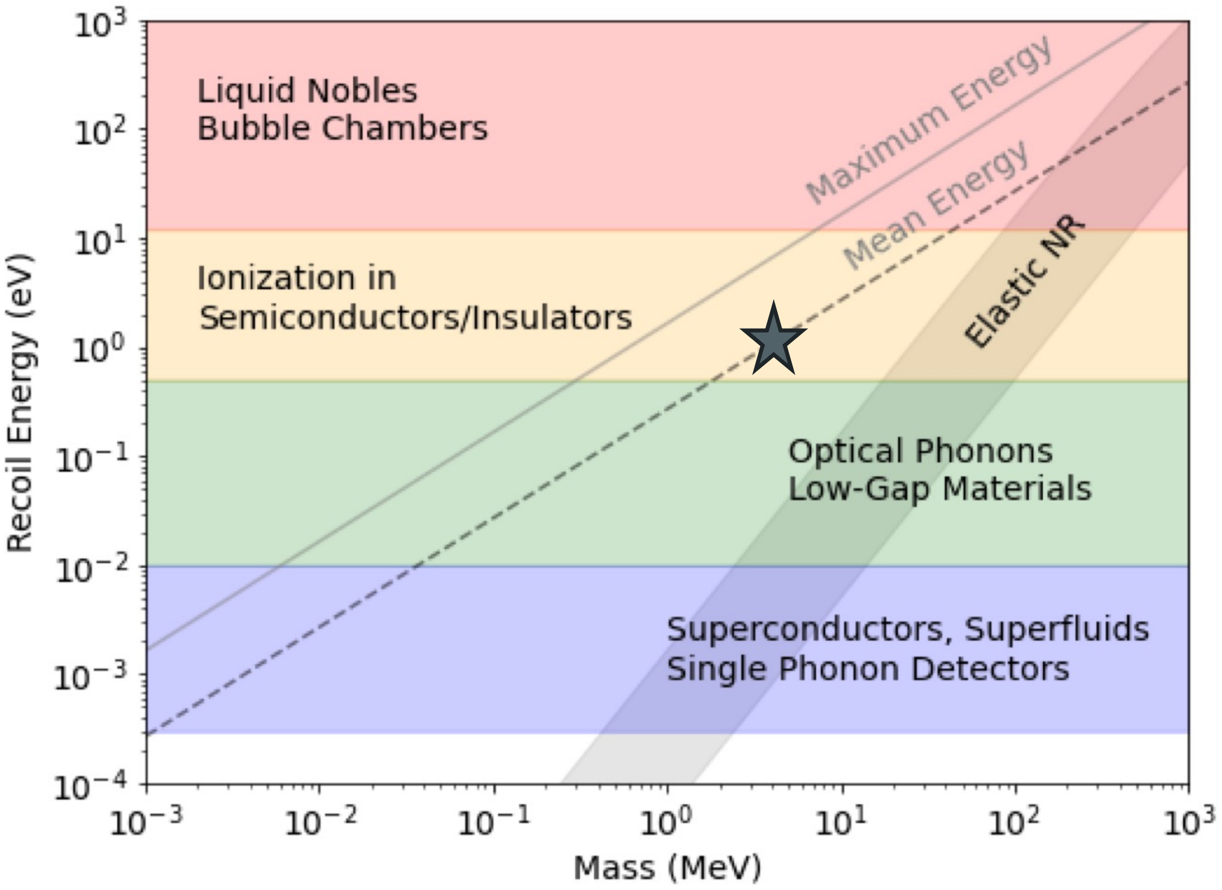
- Low noise readout

Why superfluid? Going even lower

Threshold limit from quanta production:

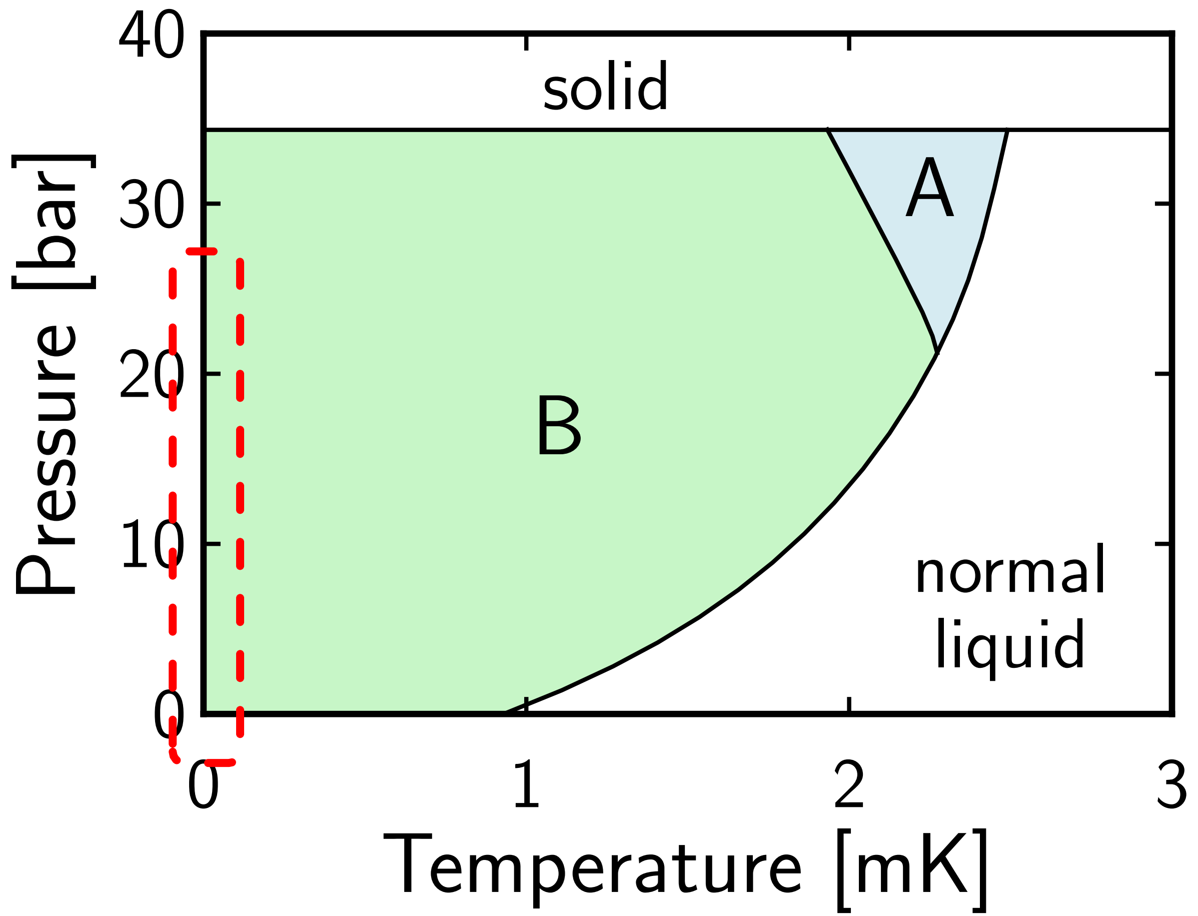
- ~10eV Xe, Ar ionisation
- ~1eV semiconductor gap Ge, Si
- μeV – meV excitations in low gap materials
- **< μeV – superfluids**

★ SuperCDMS: **9.2 eV threshold**
CDMS Phys. Rev. D 104, 032010 (2021)



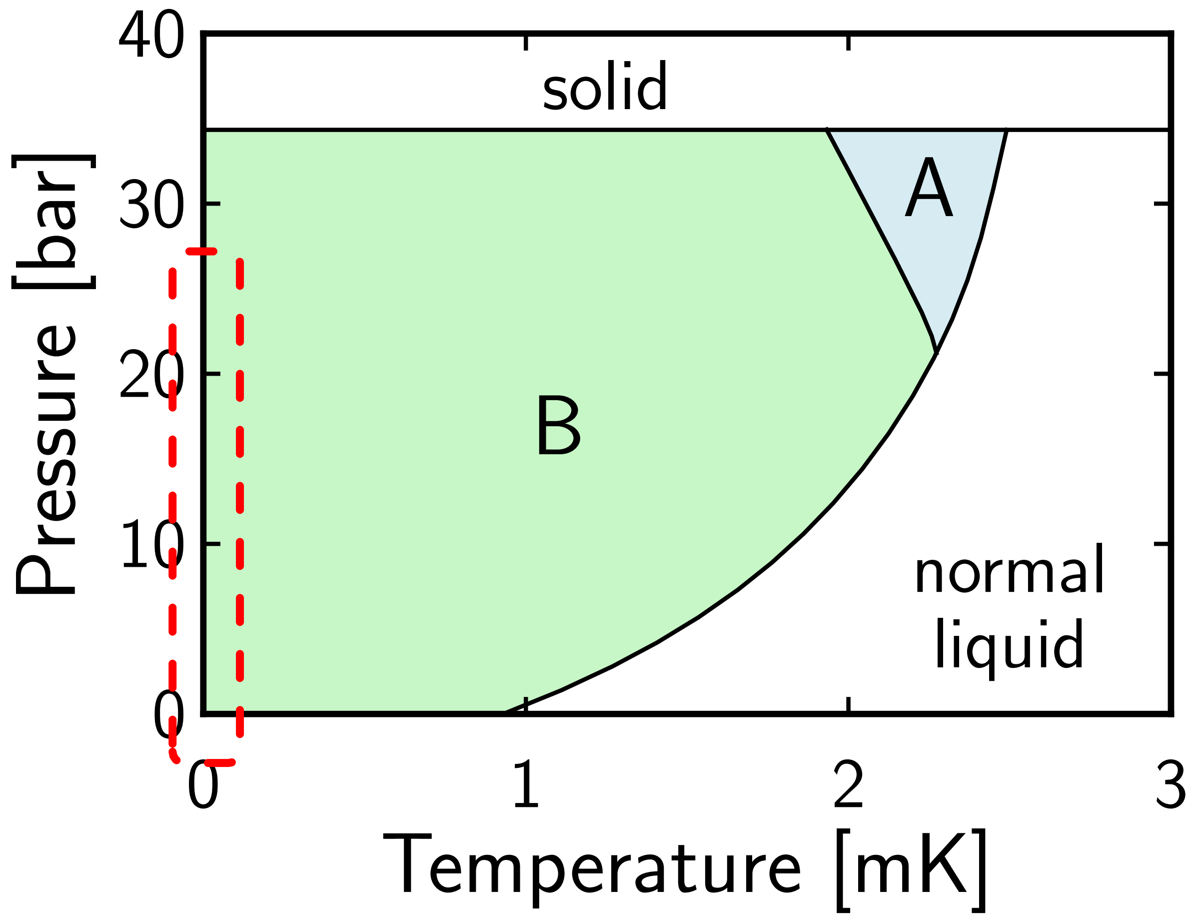
Snowmass report 2022

Globally unique: superfluid helium 3



- Cooper pairing of He atoms - superfluid <2mK
- Two superfluid phases: A and B
- Isotropic B-phase at $\sim 100\mu K$
- Energy $\Delta \sim 10^{-7} eV$ required to break Cooper pairs and give single **quasiparticles (QPs)**

Globally unique: superfluid helium 3



- Cooper pairing of He atoms - superfluid <2mK
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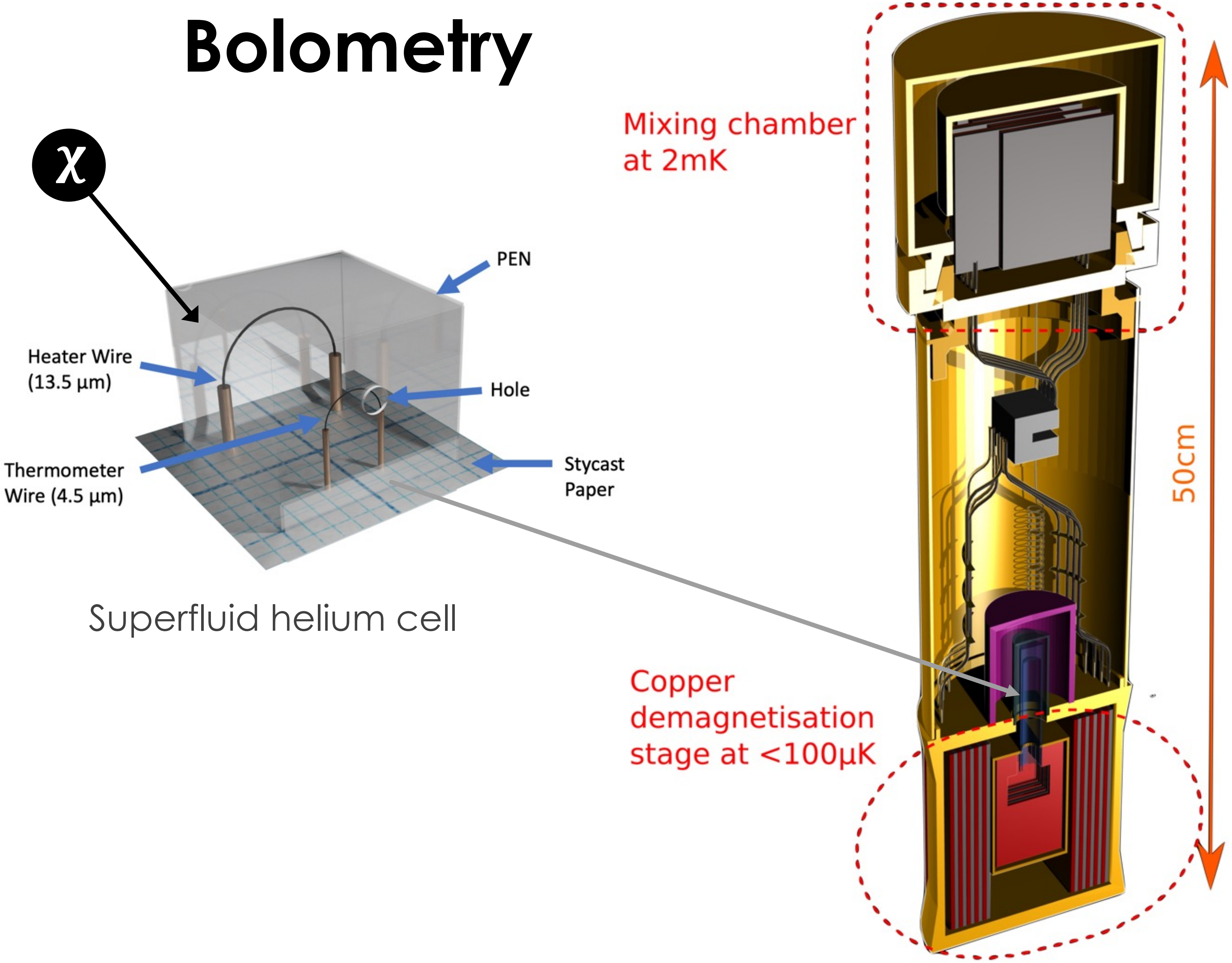
- Energy $\Delta \sim 10^{-7}$**eV** required to break Cooper pairs and give single **quasiparticles (QPs)**

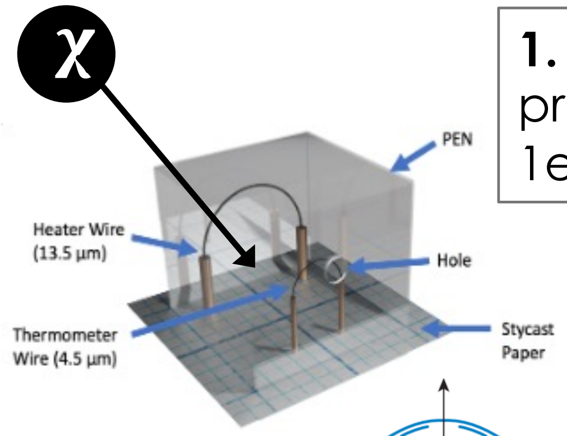
Unpaired nucleon:

➢Spin dependent dark matter – nucleon interaction

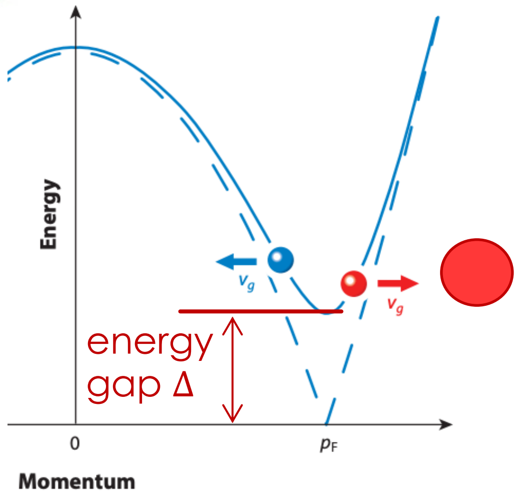
Bolometry



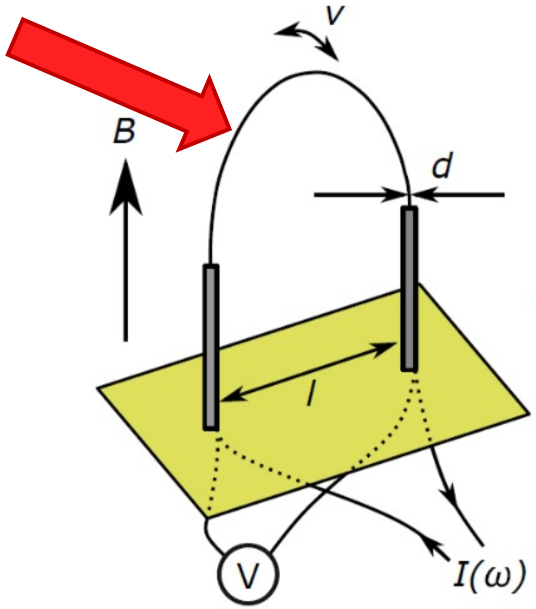
Superfluid helium cell

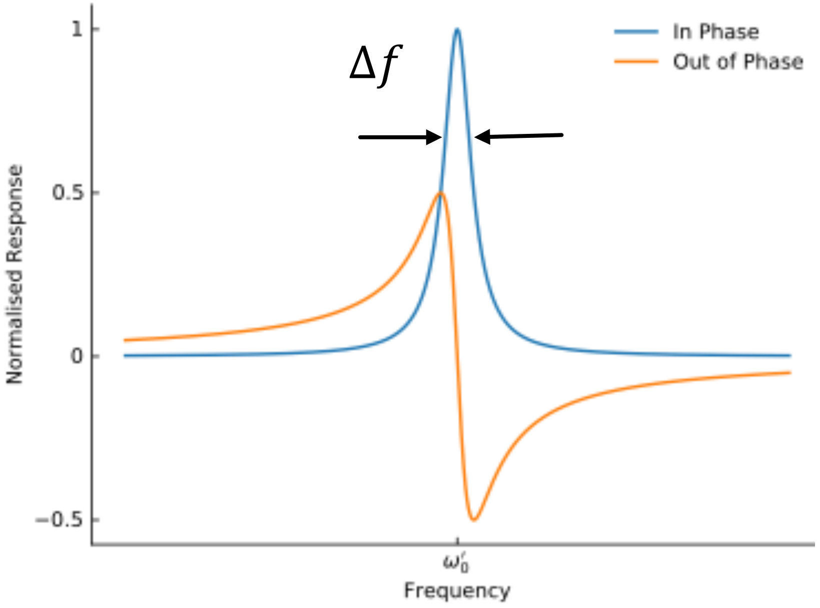


1. Energy deposit
produces quasiparticles
1eV → 10^7 quanta



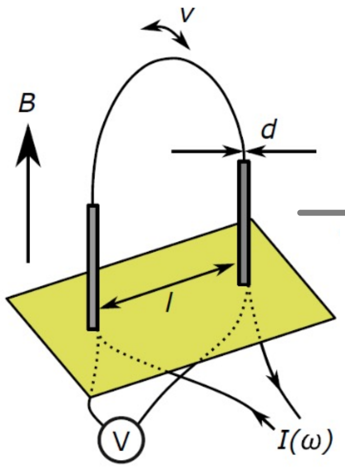
2. Ballistic propagation
QP collisions with nanowire
exert damping force





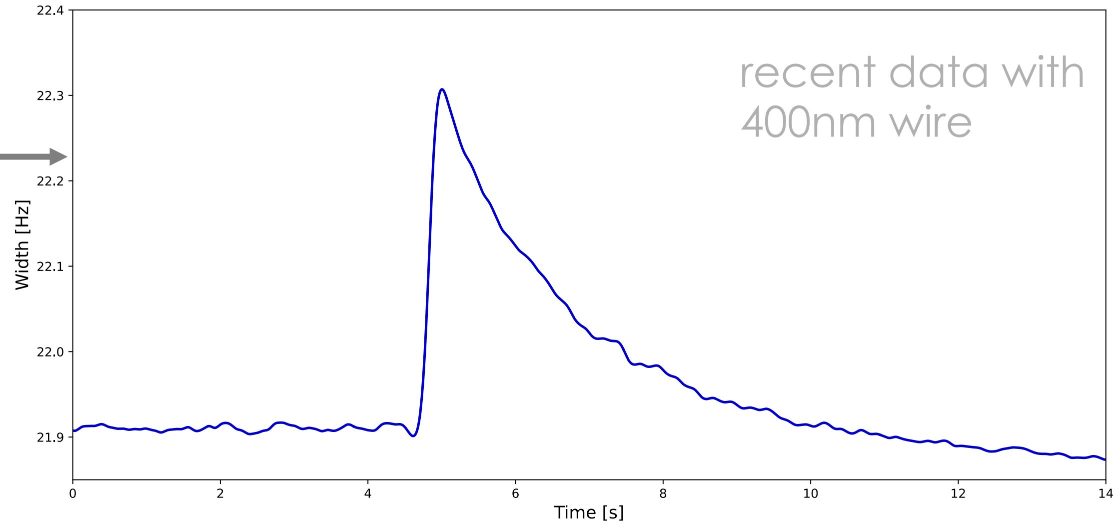
3. Measure nanowire
resonator width change
< 0.1 Hz width changes

Quantum sensing



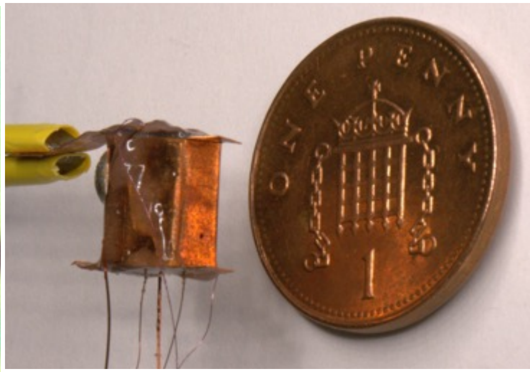
Cold preamplifier:
- Transformer
- SQUID circuit
- …

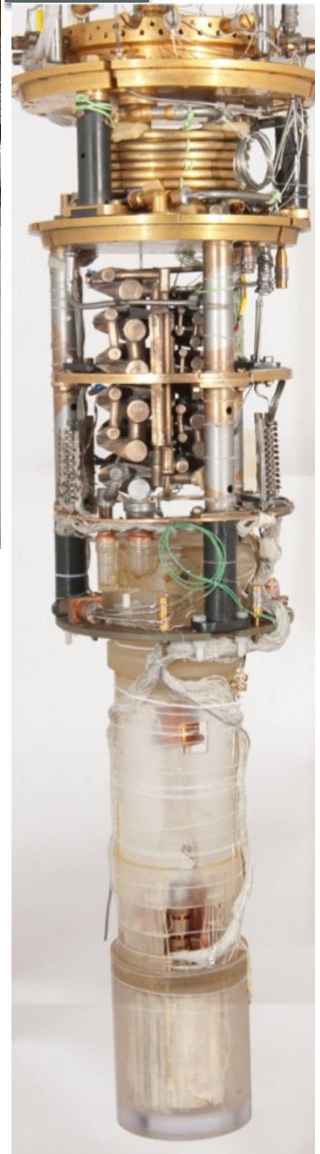
Lockin amplifier

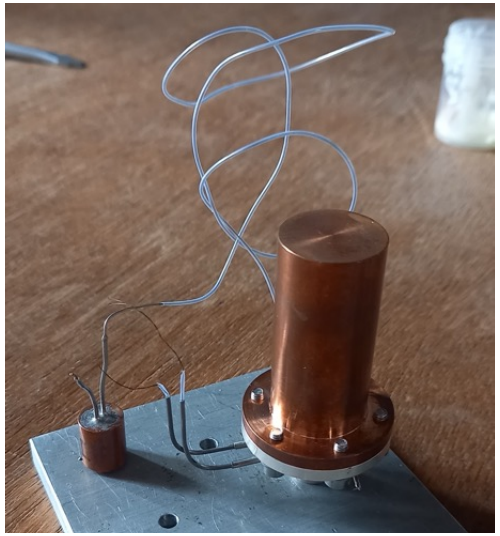


SQUID readout:
- 2-stage PTB SQUID amplifier
- *[IEEE Trans. Appl. Supercond. 17 (2007)]*
- potential to achieve **sub eV energy threshold** *[E.P.J.C 84, 248 (2024)]*
- other options in future – hyQUIDs, quibits etc

QUEST DMC

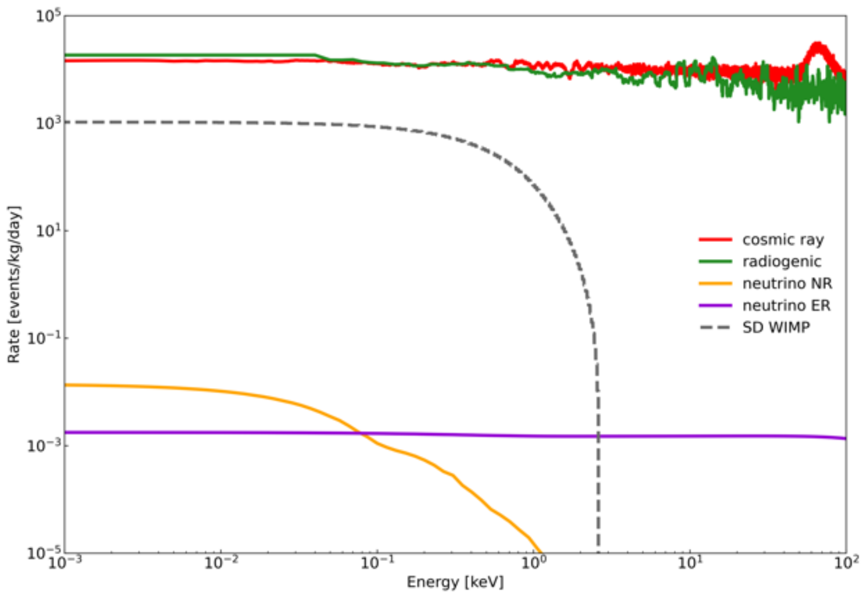






- bolometer operation (coldest: 150 μK)
- nanowire fabrication (smallest: 180 nm)
- SQUID readout of nanowires
- calibration techniques

- material assay
- background simulation
- data acquisition and analysis tools

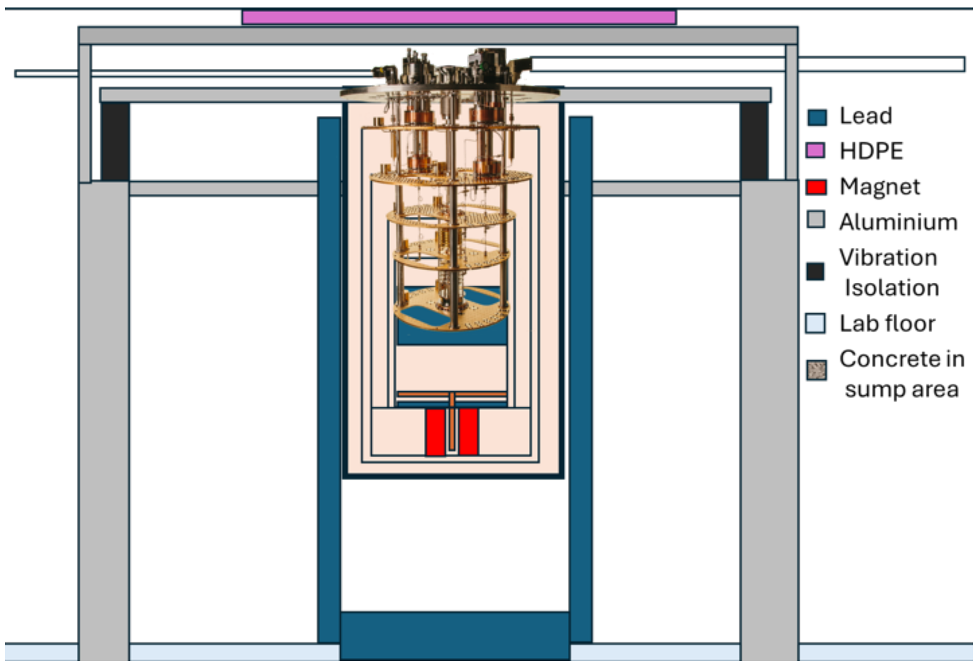


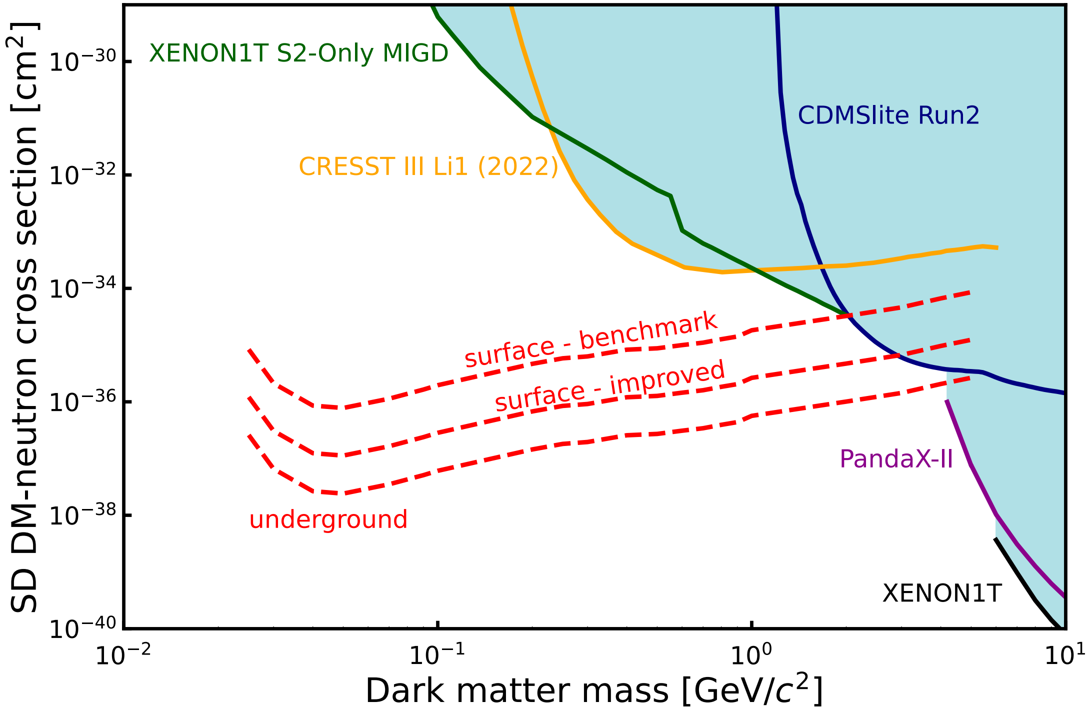
Sensitivity:
*E.P.J.C **84**, 248 (2024)*

Nanowire :
arxiv:2311.02452

Backgrounds:
J Low Temp Phys 215, 465–476 (2024)

UltraDark: underground operation





World's first cryogen-free, dedicated low background nuclear demagnetisation cryostat [Phys. Rev. Applied 18, L041002 (2022)]

- low background material selection
- internal muon veto - *UK Canada quantum proposal*
- shielding HDPE and lead - NPL partnership

Quantum platform

- Backgrounds can limit preparation and manipulation of **macroscopic quantum states** – e.g. qubits [*Eur. Phys. J. C* 83, 94 (2023)]
- Operate superconducting quantum technology in an underground low background environment

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

- RISQ workshop (Fermilab 2024): indico.fnal.gov/event/63132/
- SQMS Quantum for Science (London 2024): indico.cern.ch/event/1379776/

UltraDark: world’s first low background, underground ULT facility

Unique UK capability

Underground opportunities

Quantum device development

World leading dark matter search

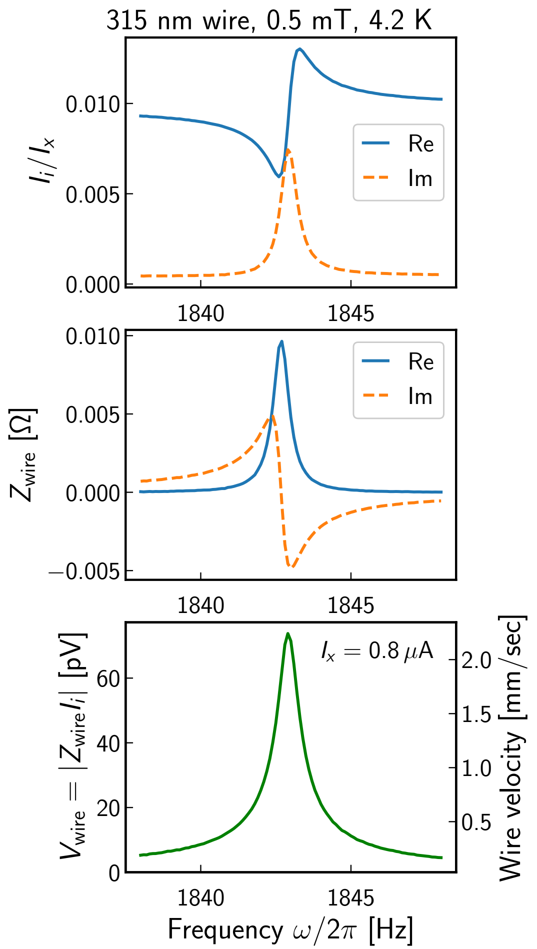
Attract talent across disciplines

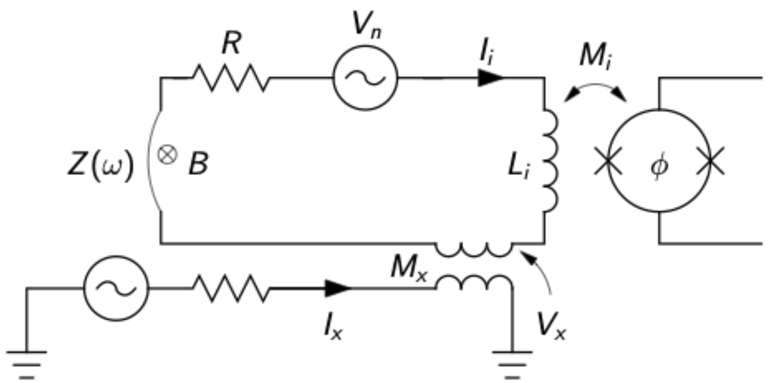
Backup

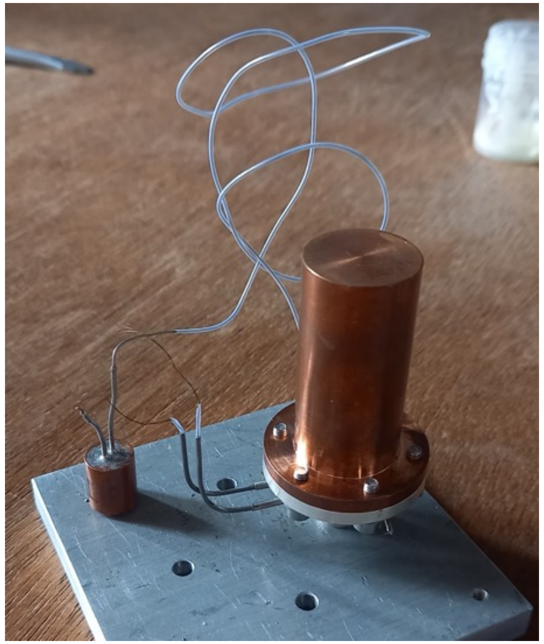
UltraDark Project Timeline

Work Package	Y1: 01/04/2025				Y2: 01/04/202 6				Y3: 01/04/2027				Y4: 01/04/2028				Y5: 01/04/2029			
Task	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Work Package 1: Site Survey, Material Selection, Design																				
WP1.1: Survey of the Boulby LEC site to establish cryostat requirements	■	■	■	■																
WP1.2: Selection of materials for the UltraDark cryostats	■	■	■	■	■	■	■	■												
WP1.3: Design of the UltraDark cryostats	■	■	■	■					■	■	■	■								
WP 1.4: Design of the measurement chain of the UltraDark Cryostats	■	■	■	■	■	■					■	■								
Work Package 2: Construction, Site preparation, Commissioning and Validation aboveground (RHUL)																				
WP 2.1: Construction of the aboveground twin cryostat, UltraDark -A, for validation on the surface					■	■	■	■												
WP 2.2: Construction of the SuperQuest bolometer array and associated readout							■	■	■	■										
WP 2.3: Commissioning of the UltraDark -A cryostat and SuperQuest detector on the surface							■	■	■	■	■	■				■	■	■		
WP 2.4: Final Specification and procurement of the UltraDark -U Cryostat										■	■	■	■	■						
Work Package 3 : Commissioning, Operations and Dark Matter Search																				
WP 3.1: Preparation of site infrastrucutre at Boulby for UltraDark -U						■	■	■	■	■	■	■								
WP 3.2: Installation and Commissioning of the underground cryostat, UltraDark -U											■	■	■	■	■					
WP 3.3: Operations and Calibration of SuperQuest underground															■	■	■	■	■	■
WP3.4 Dark Matter search analysis																		■	■	■

SQUID READOUT scheme

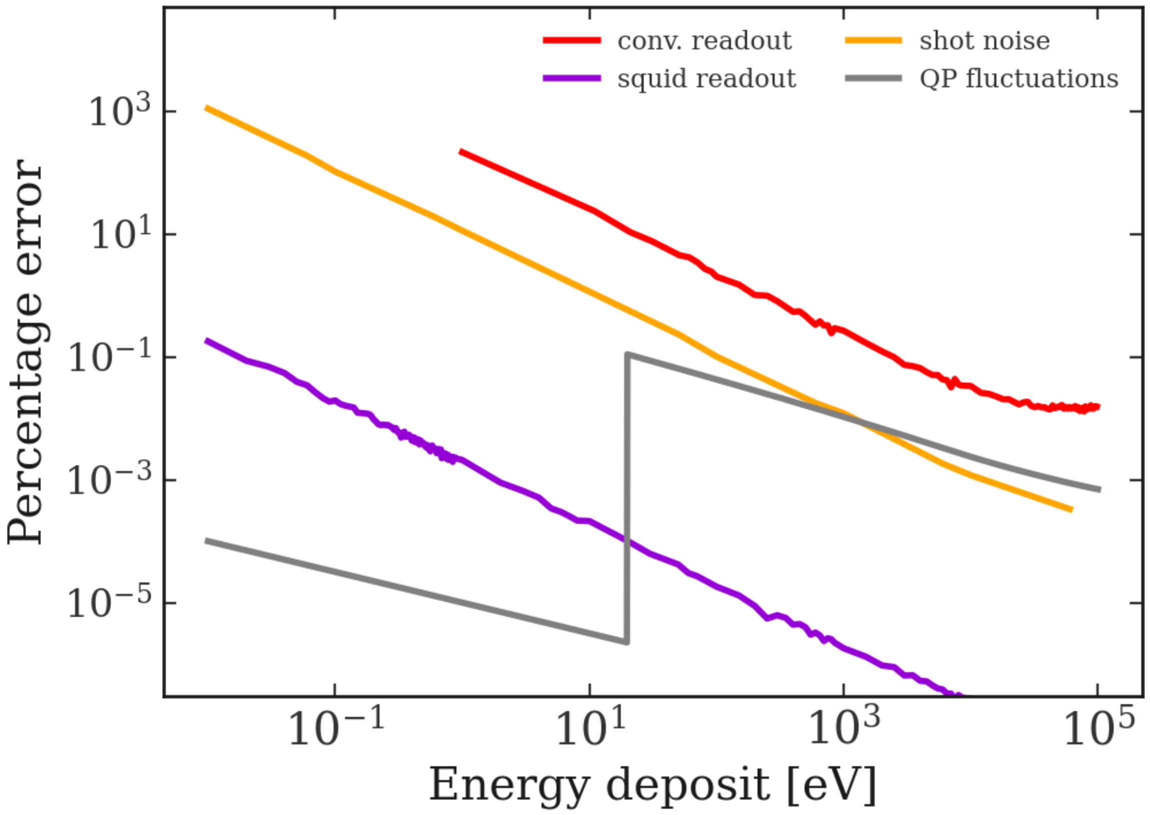






Voltage excitation is applied via a transformer with mutual inductance Mx. SQUID current sensor detects current Ii flowing through the wire with impedance Z(f), contact resistance R, and SQUID input coil Li.

Energy measurement uncertainty

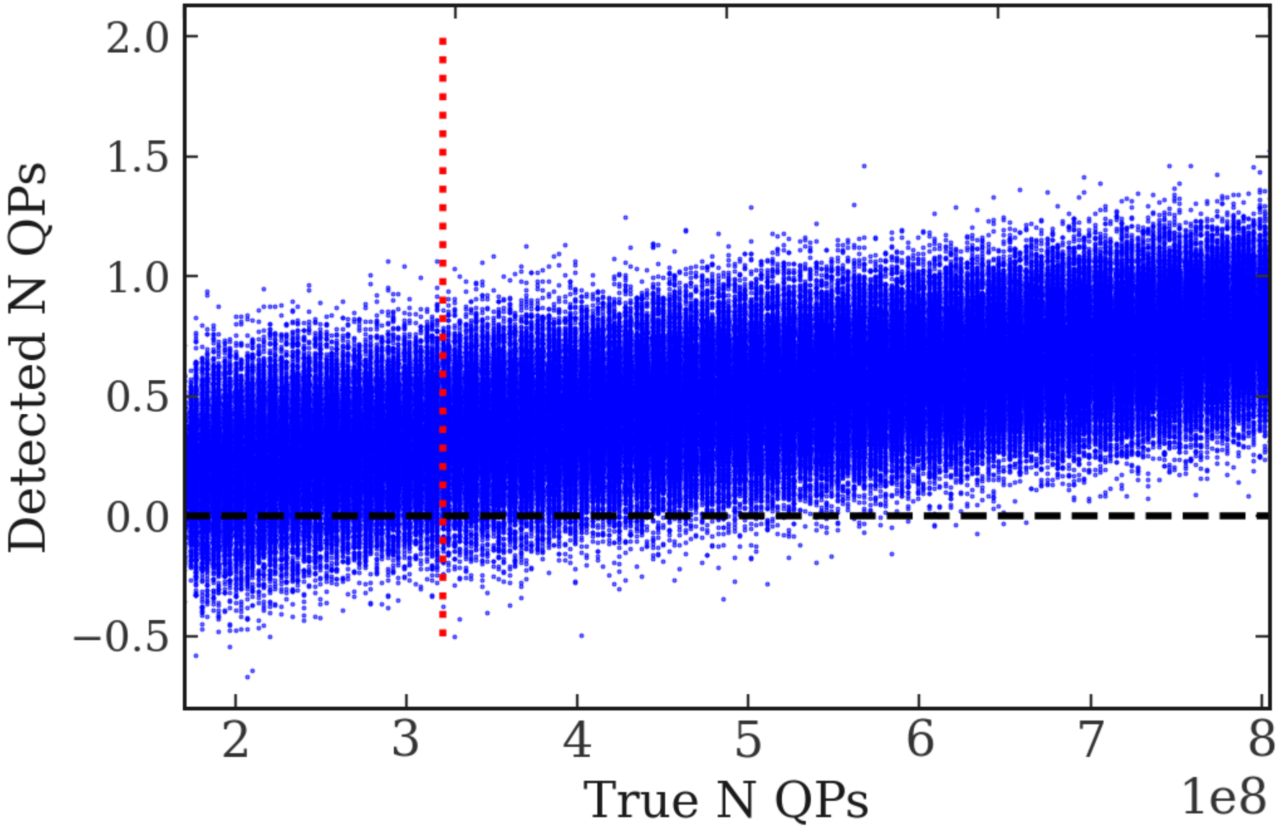


- Quasiparticle (QP) production fluctuations
- Readout noise – conventional vs SQUID
- Shot noise – fluctuations on incident QPs

Nuclear recoil energy thresholds:
[400nm diameter wire at 0.12 T/Tc]

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

Expected energy threshold



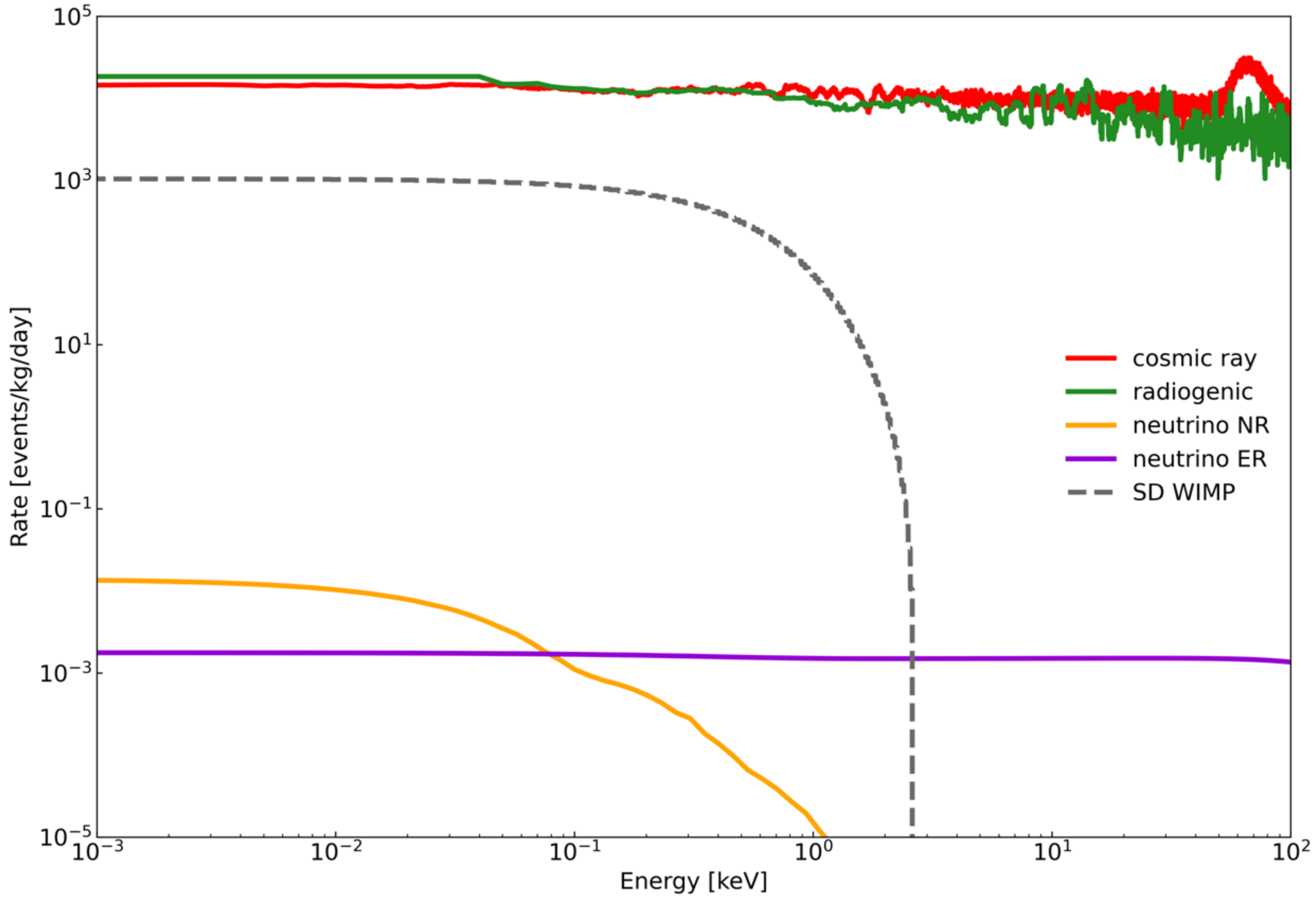
Resolution at threshold – 95% confidence energy > zero.

- Conventional readout: 39 eV
- SQUID readout reduces noise, so resolution is dominated by shot noise.
- 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



QUEST-DMC assays

Sample	Mass [g]	Detector	Measured activity [mBq/kg]					
			$^{238}U_{early}$	$^{238}U_{late}$	^{210}Pb	$^{232}Th_{early}$	$^{232}Th_{late}$	^{40}K
Stainless steel	544.2	Roseberry	16(8)	2.5(0.9)	82(27)	3.1(1.2)	3.9(0.9)	< 6.2
Al 6061-O	642.6	Lunehead	8330(270)	15.3(3.9)	-	356(12)	334.4(8.2)	56(8)
Painted Al	923.0	Chaloner	25680(230)	16.2(3.2)	60480(540)	259.2(8.3)	342.2(6.2)	21.8(9.6)
Brass	107.0	Roseberry	< 7.6	4(1)	14990(350)	< 1	< 1.1	< 7.3
Silver sinters	37.1	Roseberry	< 90	< 36	430(320)	< 27	< 28	< 385
Vespel	38.3	Chaloner	87 ± 66	90(14)	418 ± 85	111(25)	64(14)	430(240)
Fiberglass	6.02	Chaloner	32580(640)	15154(62)	68600(1400)	11400(100)	12005(62)	23520(440)
Araldite	161.9	Roseberry	< 3.6	< 4.8	14.5(9.7)	< 3.4	< 2.2	< 25.5
Stycast	131.5	Chaloner	< 10.5	< 9.5	< 14.9	< 12.9	< 6.2	< 122.2
GRP	106.9	Lunehead	5700(1000)	7460(120)	-	7840(160)	7350(100)	4900(570)
PEN	35.1	Roseberry	< 4.2	6.4(2.7)	26(13)	< 3.4	< 2.4	< 22.8
Annealed Cu	19.1	Belmont	< 258	23.4(7.4)	-	< 12.2	< 5.7	< 138
Polyester Yarn	16.7	Roseberry	< 448	175(16)	-	< 30.4	< 10.4	746(206)
Macor	42.4	Roseberry	-	955(30)	-	386(60)	504(24)	2333000(4000)
kel-F	97.6	Roseberry	< 6.9	13.6(2.0)	13.7(12.9)	< 4.6	< 7.3	< 44.7
Si Pieces	6.9	Belmont	< 39.2	< 110	39.9(40.1)	< 69.1	< 57.1	< 319

Material selection and normalisation of background model.