QUEST-DMC: Probing Dark Matter with Nanowires, Superfluid Helium-3 and Quantum Sensors

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QUEST DMC

Quantum Enhanced Superfluid Technology for Dark Matter and Cosmology

- QUEST-DMC dark matter search programme
- Bolometry in Helium-3 with nanowires
- Measurement of the deposited energy
- Estimated sensitivity
- Future prospects

Helium-3

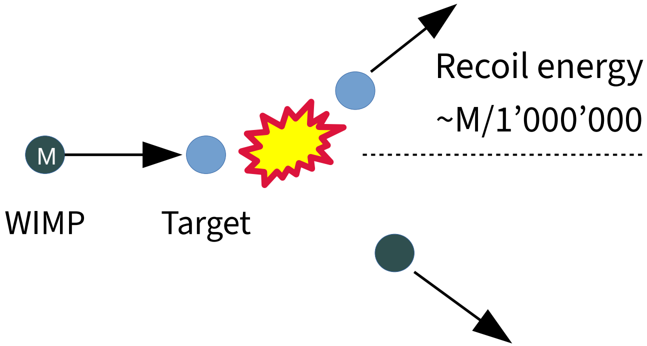
ULT refrigerators

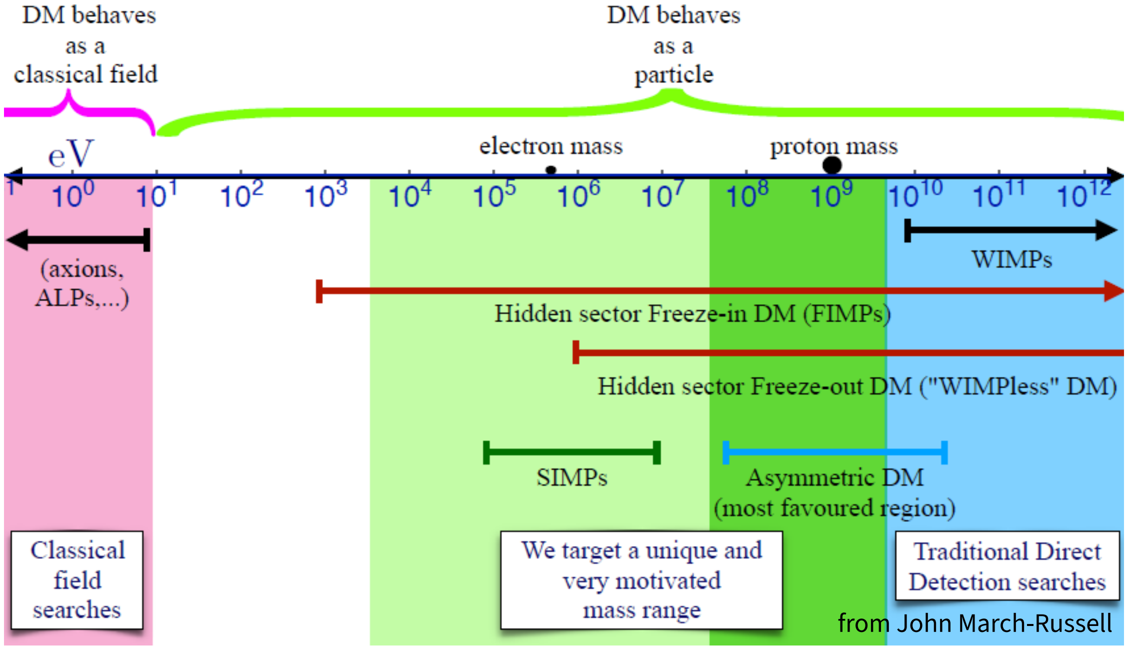
Nanowires

SQUID sensors

Direct dark matter detection

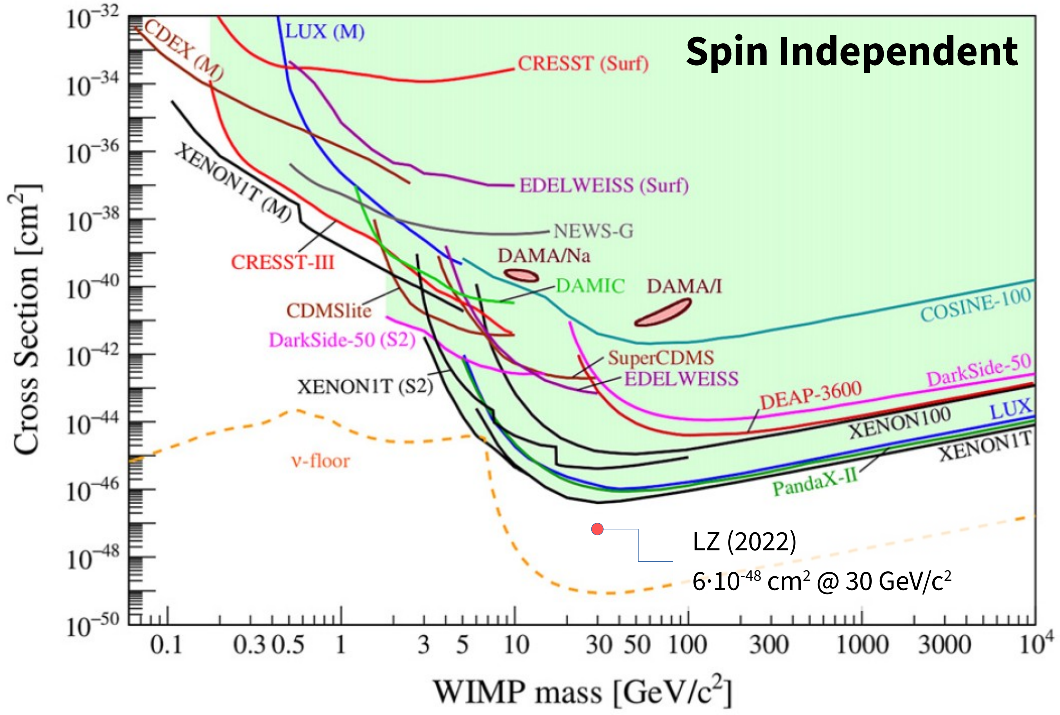
- WIMP candidates
- Theoretical motivation for **sub-GeV** dark matter models
- Reach **sub-eV recoil energy** for low mass investigation





from John March-Russell

Direct dark matter detection: WIMPs



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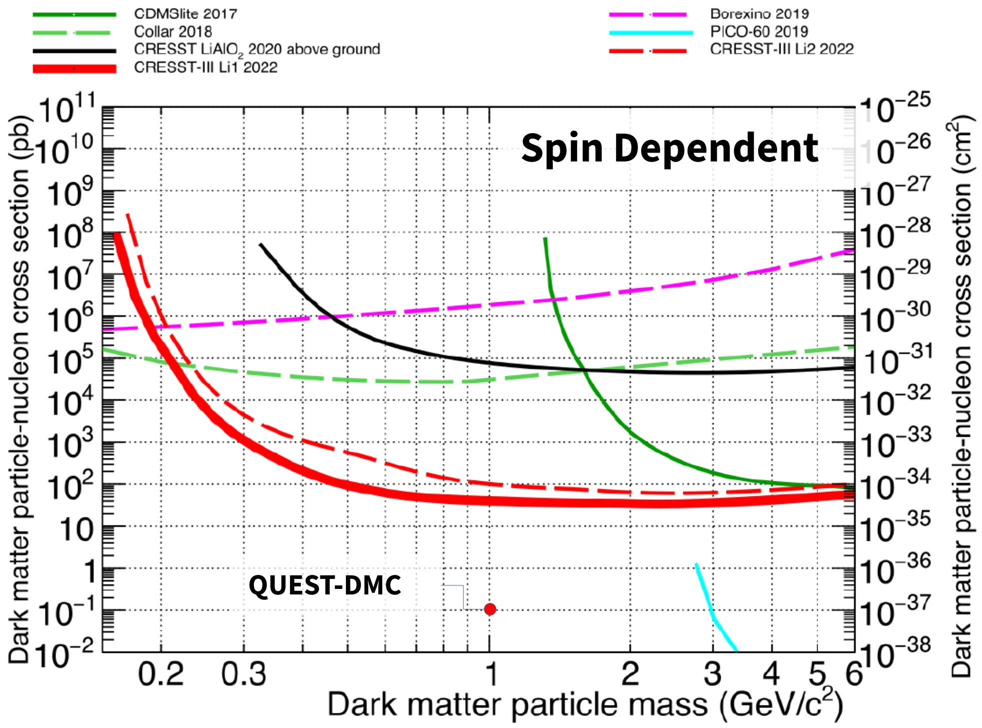

https://arxiv.org/abs/2207.07640

QUEST-DMC programme

- Beyond Standard Model physics investigation
  - Quantum sensors
  - Helium at ultra-low temperatures

1) What is the nature of Dark Matter?
Detection of sub-GeV dark matter with
a quantum-amplified superfluid He3 calorimeter

2) How did the early universe evolve?
Phase transition in extreme matter ↔ early universe

Lancaster University
University of Oxford
Royal Holloway University of London
University of Sussex
University of Liverpool
UKRI Science and Technology Facilities Council
UKRI Engineering and Physical Sciences Research Council

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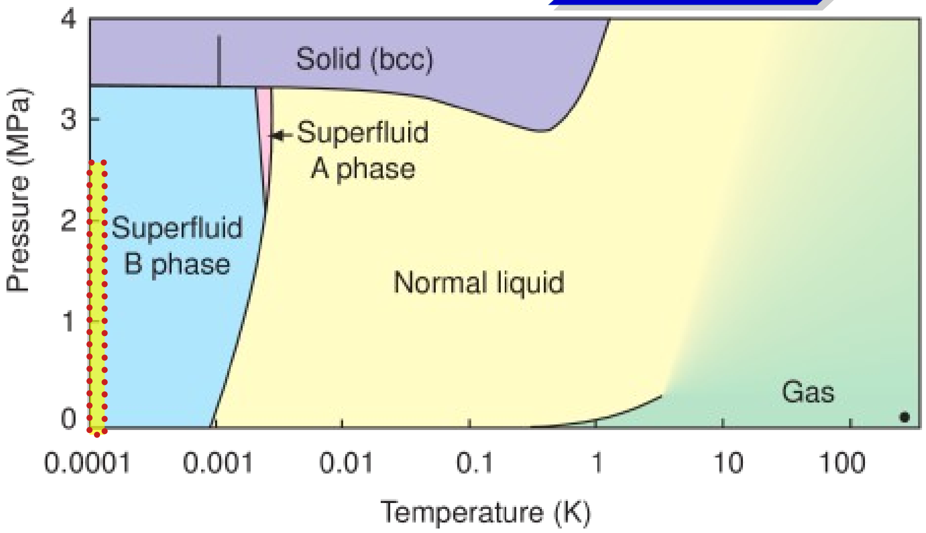
Target → Detector → Readout

Superfluid He3

Helium-3

Target

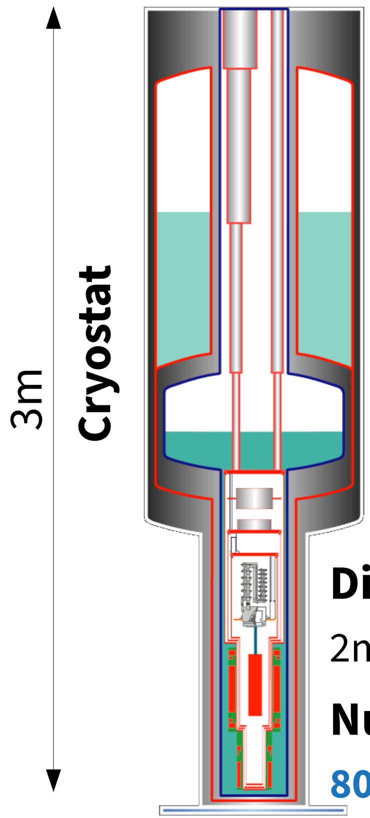
- Superfluid (1972) below 2.5 mK
- Spin ½: spin dependent sensitivity



- ^{3}**He-B**:
  - He3 as a fermionic condensate (similar to BSC theory's Copper pairs)
  - Composite bosons, 100nm size
  - Pair of bound quasiparticles with 10^{-7} eV energy and an effective mass

Lancaster advanced refrigerator

Target

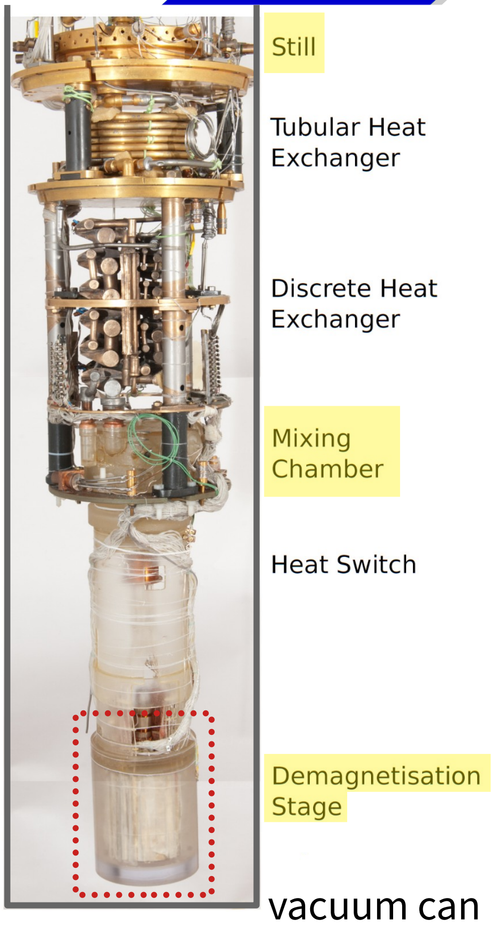


0.5 K

1.6 mK

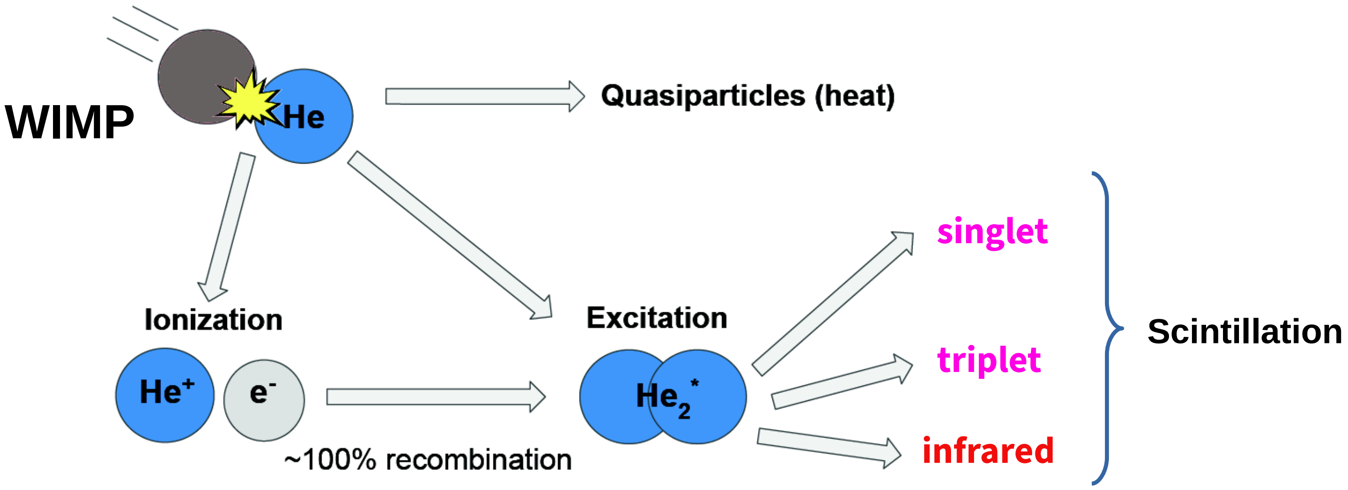
world record

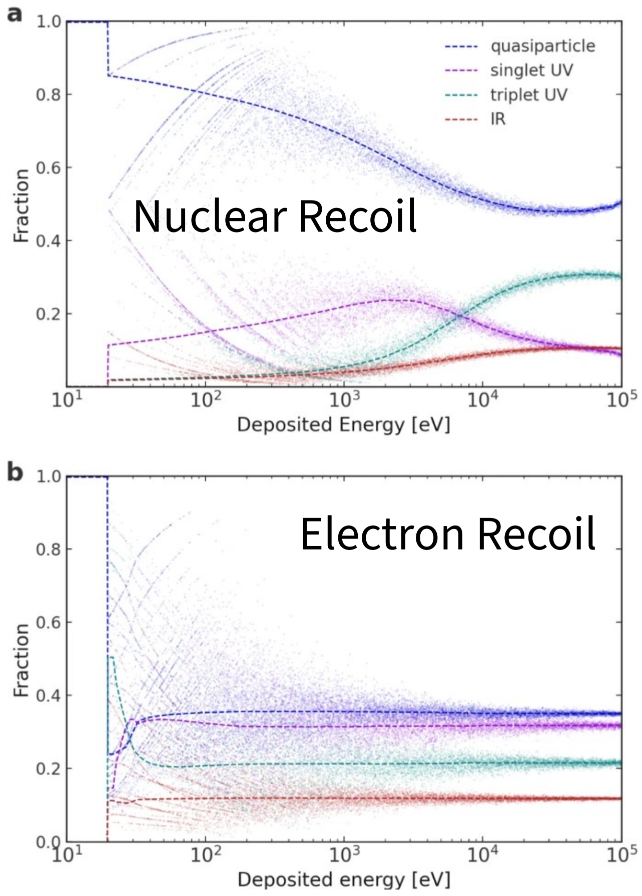
80 uK



Dark Matter events in He3

- Collision WIMP-He3 atom
  - **Heat:** quasiparticle excitations (10^7/eV)
  - **Light:** from de-excitation





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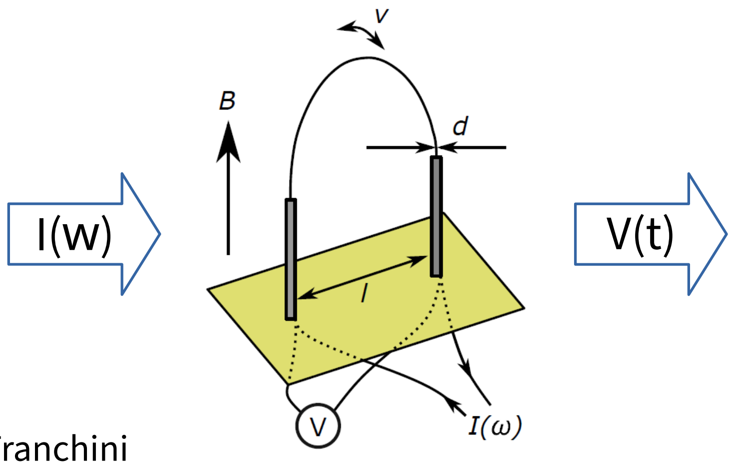
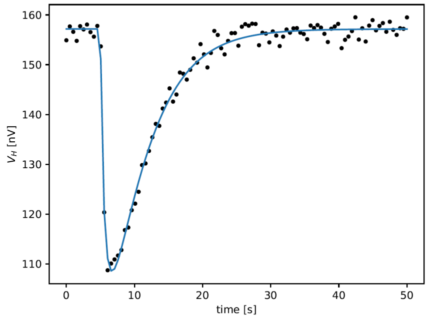
Vibrating nanowire + SiPM

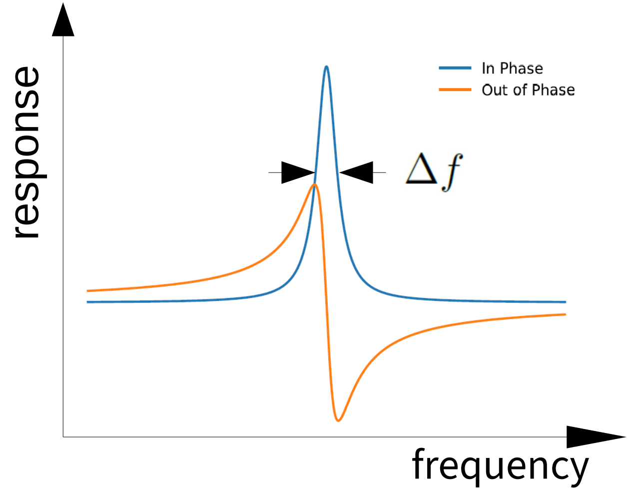
Bolometer response

Detector

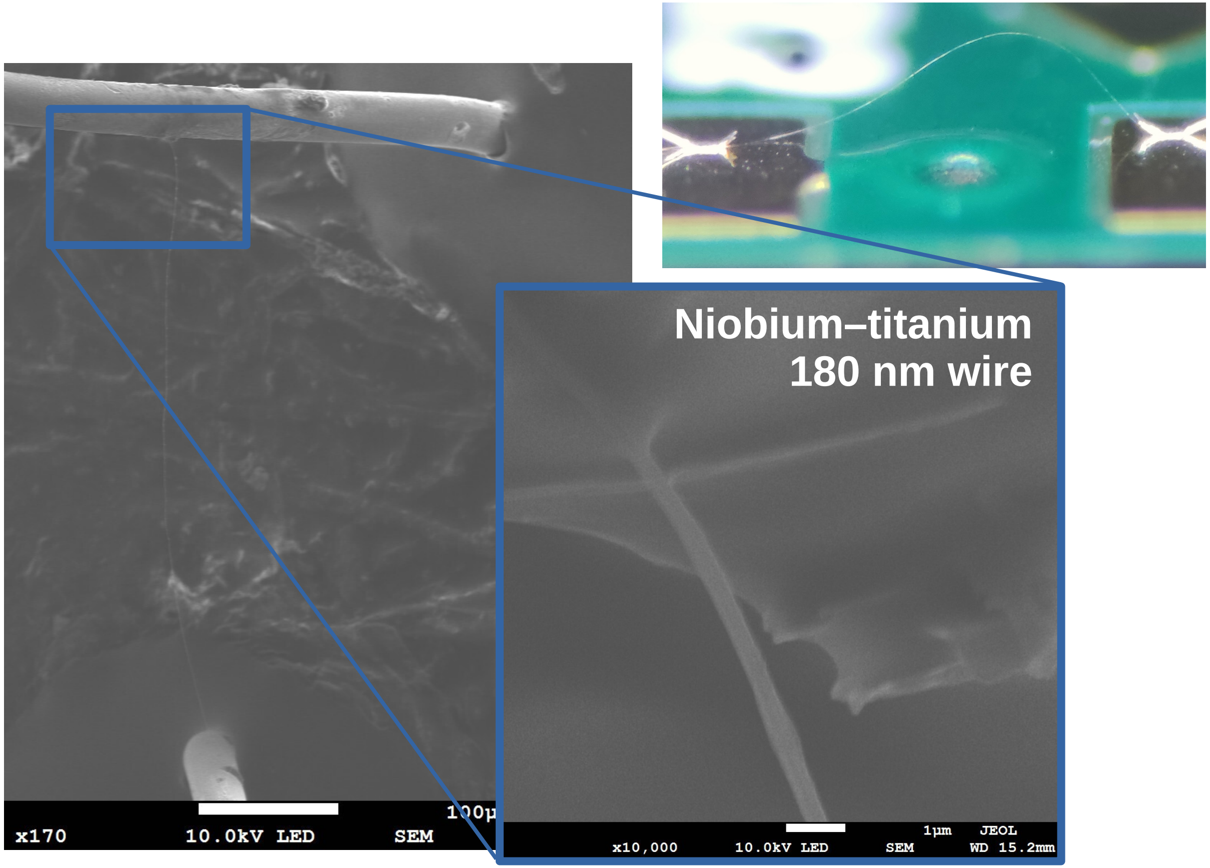
- Wire oscillating in magnetic field in a **He3 cm³ box**
- Damping force on the oscillator due to QP interactions
- Voltage response
- Measure **energy deposition** as variation of the resonance width Δf

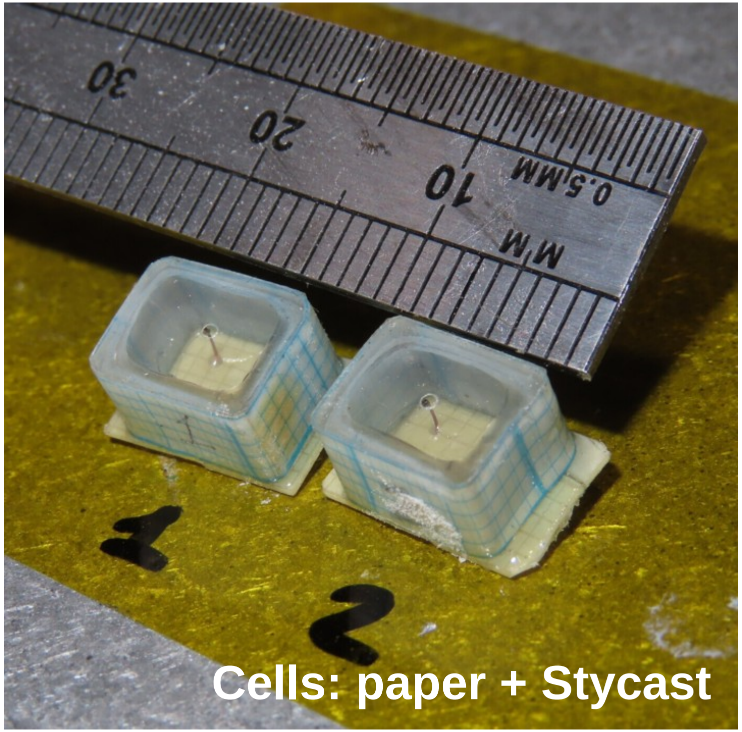






First prototype: cells with wires

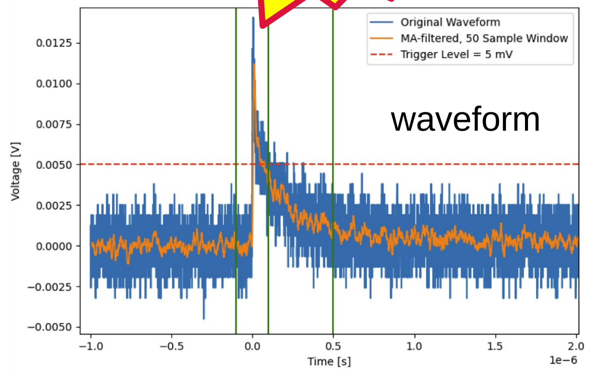


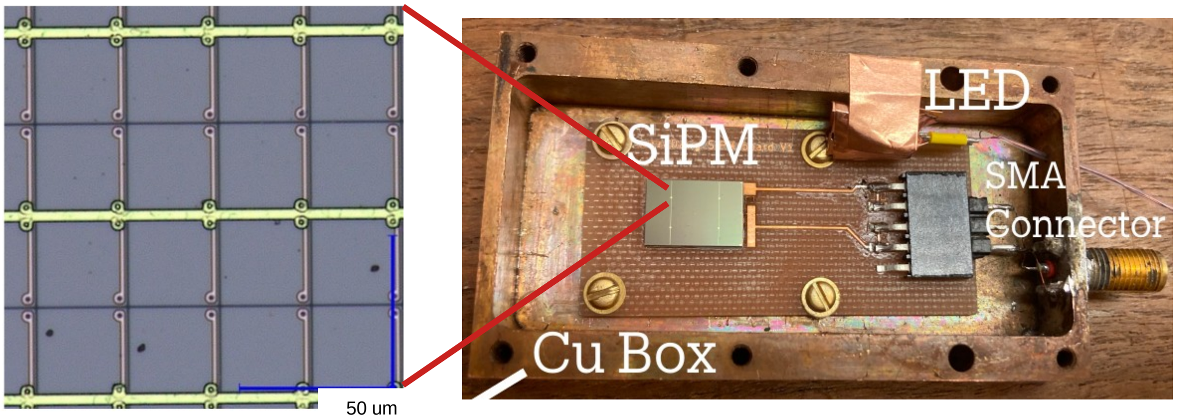


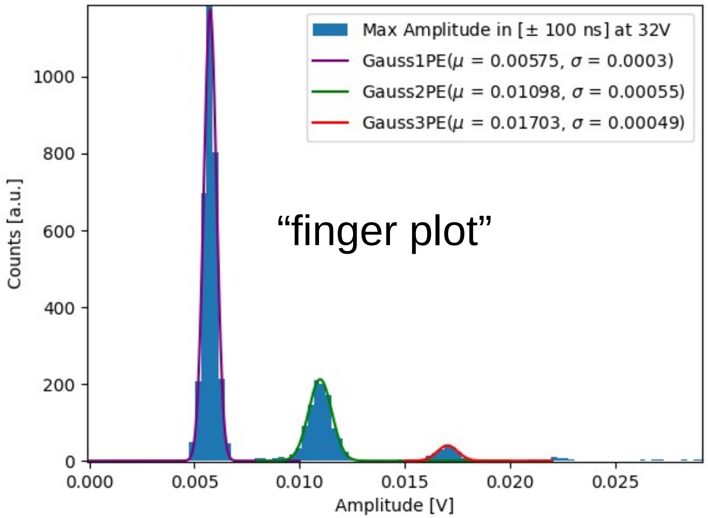
Light sensing with SiPMs

DATA!

- Silicon PhotoMultipliers explored technology
- SIPMs have high-gain and single photon resolution
- Successfully tested at 25mK, coupled with a scintillator (1K in literature A. Ferri et al, 2016 JINST 11 P03023)
- Next test for temperatures < 25mK







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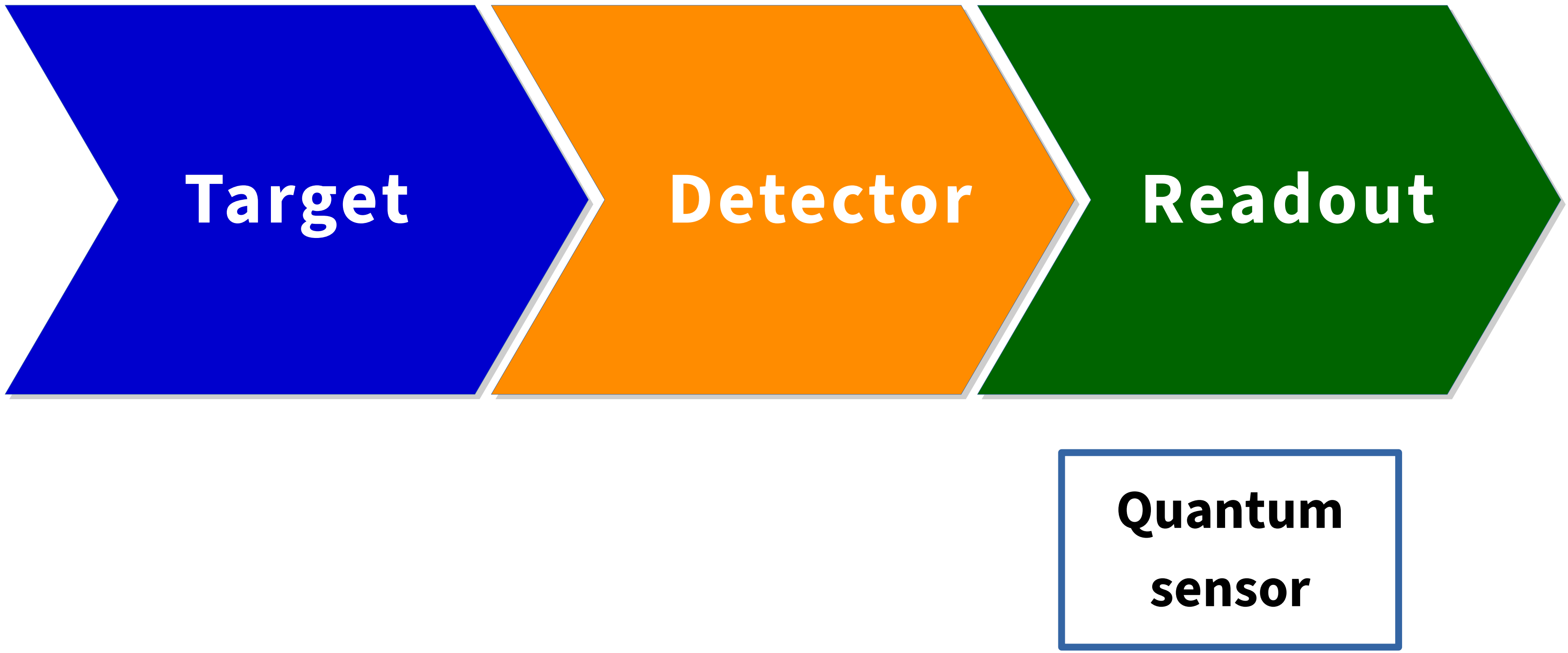
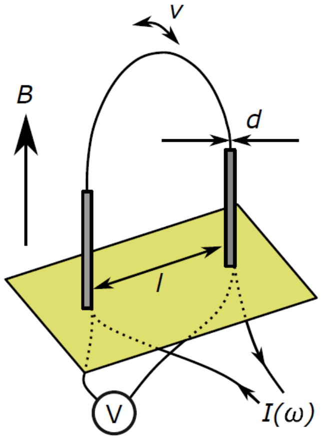


Bolometer in He3

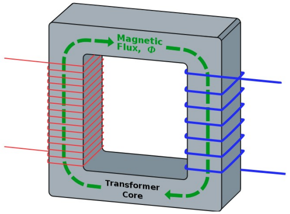
Readout

- Deposited energy as variation of the damping force on the resonator

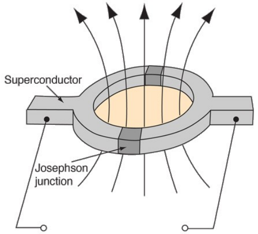


Cold transformer

SQUID readout



Conventional: 31 eV



SQUID: 0.51 eV

Superconducting **QU**antum **I**nterference **D**evice

Magnetometer, 10^{-14} T (brain: 10^{-13}T)

Magnetic flux into electrical voltage

Analysis

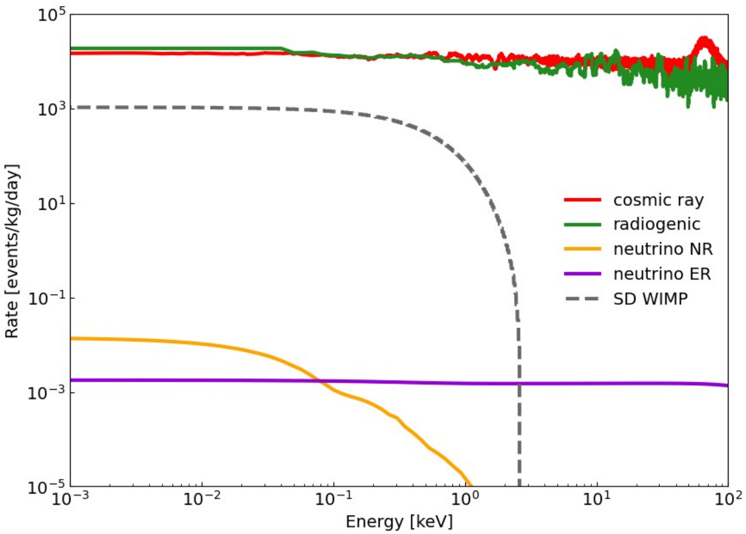
Background

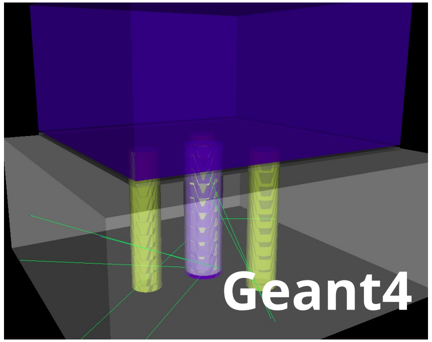
Analysis

- Radiogenic
- Cosmic rays
- Neutrinos

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	$< 1.60 \times 10^5$	1.50×10^4	1.00×10^7	7.57×10^3	7.57×10^3	$< 7.20\times10^3$	800	4.20×10^4	< 700	0.00
Aluminium	8.33×10^3	15.3	70.7	356	334	60.5	< 0.940	< 3.12	< 1.10	0.00
Superinsulation	679	< 200	$< 3.90\times10^3$	200	200	4.93	0.00	3.50×10^3	400	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	1.20×10^4	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

Component	Expected counts [0-10 keV] /kg/day	/cell/day	Uncertainty
Cosmic ray	1.05×10^5	3.31	11 %
Radiogenic ER	8.31×10^4	2.61	14 %
Solar ν ER	1.51×10^{-2}	4.76×10^{-7}	2 %
Solar ν NR	6.37×10^{-4}	2.01×10^{-9}	2 %
TOTAL	1.88×10^5	5.92	





Sensitivity projection

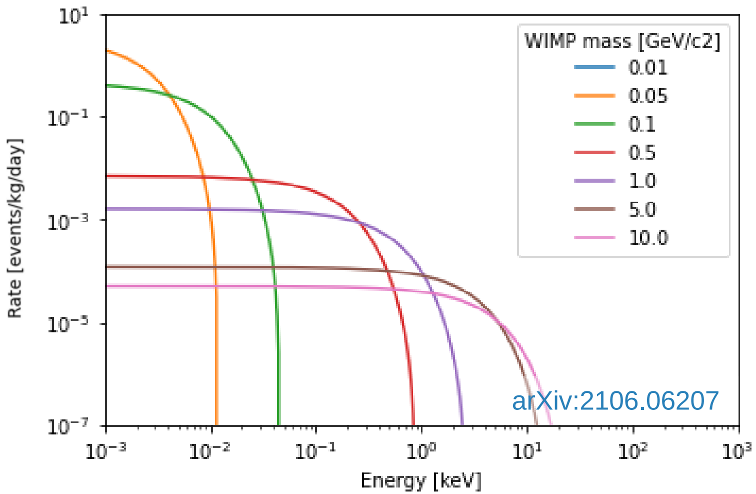
published

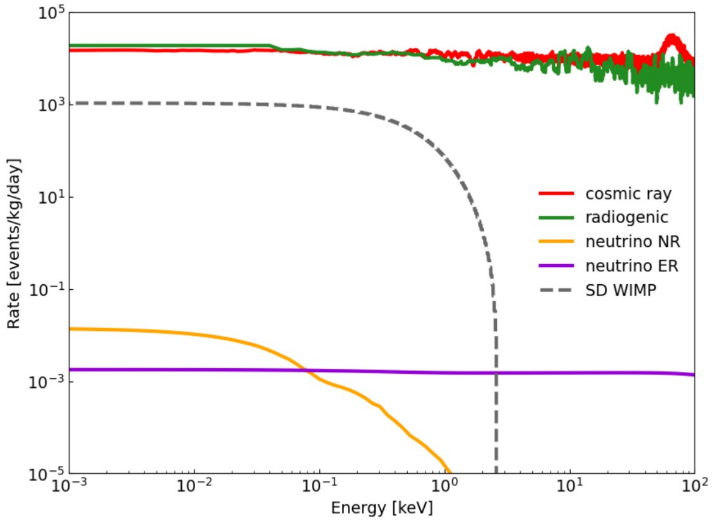
Signal simulation

Background simulation

Detector response model

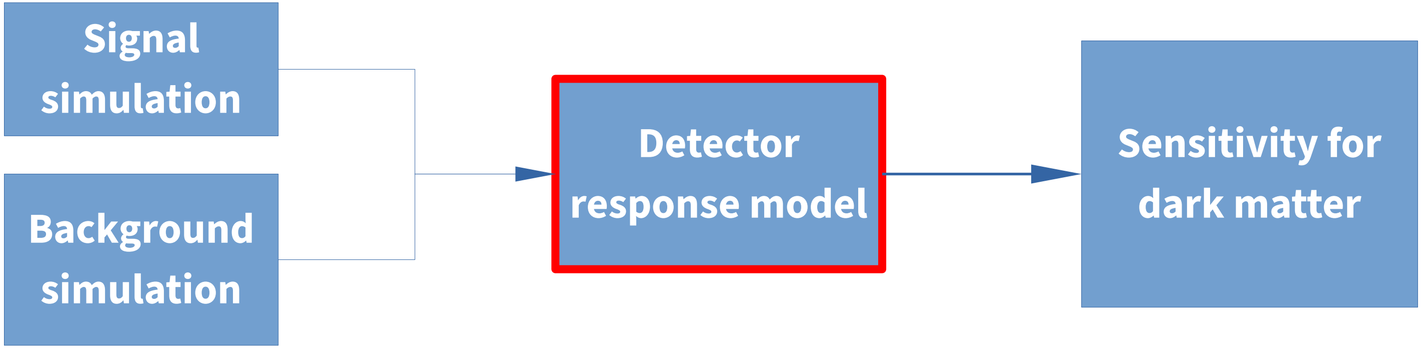
Sensitivity for dark matter

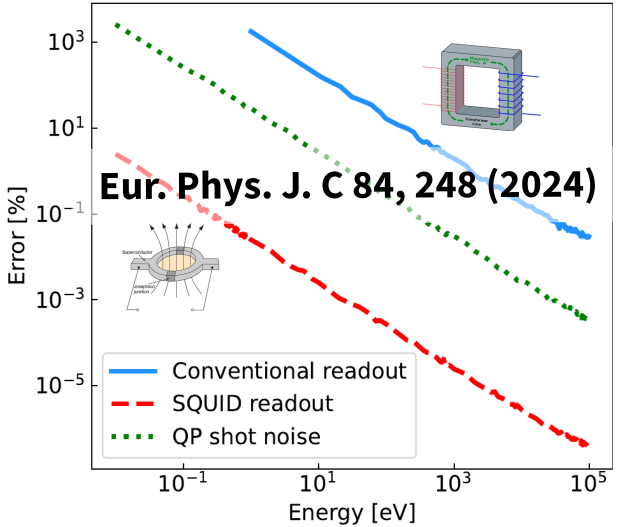




Sensitivity projection

published





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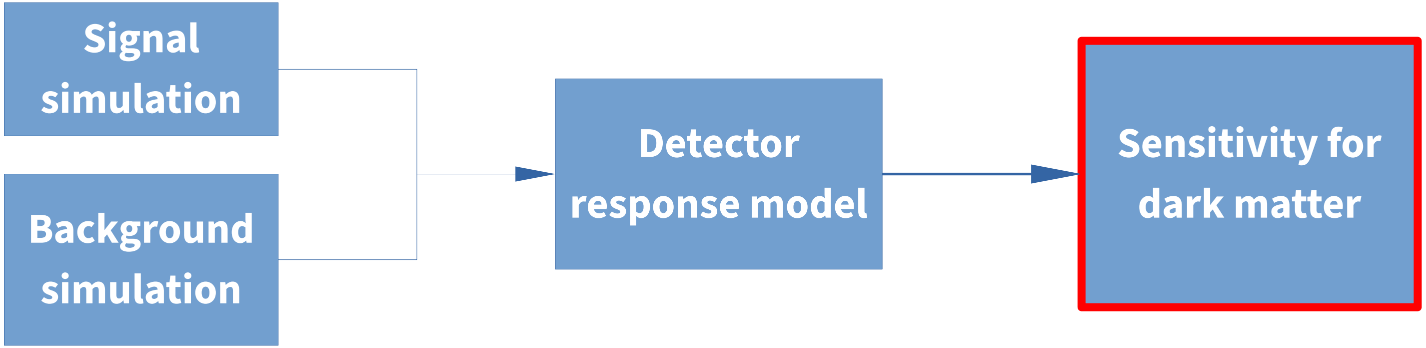
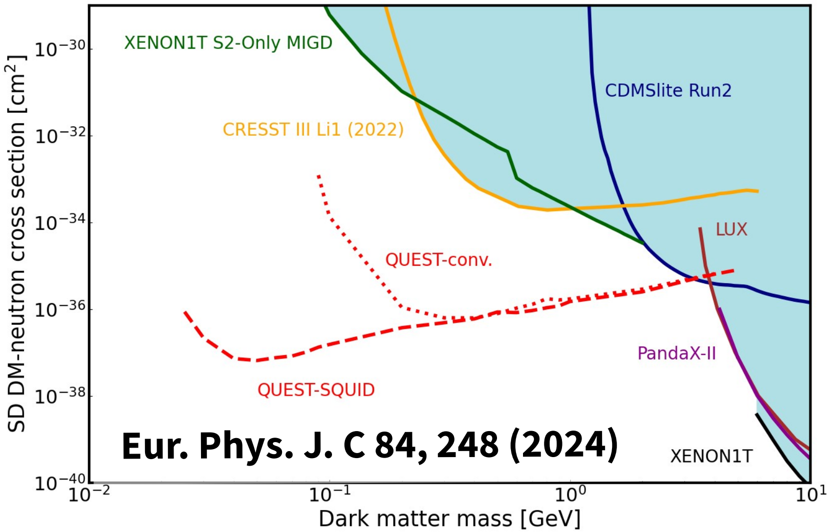
Sensitivity projection

published



- 5 cells
- Exposure: 0.0135 g/years of ^{3}He
- 1 year with 50% duty cycle



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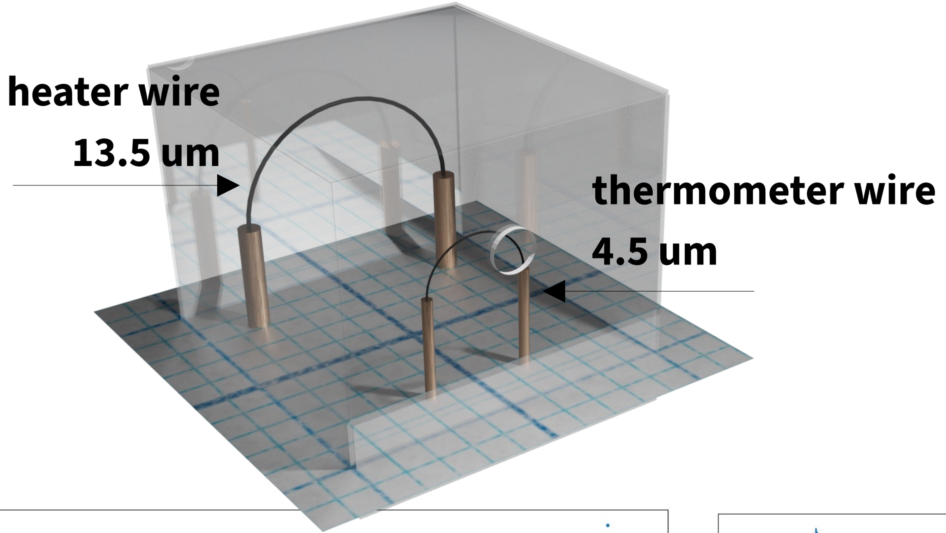
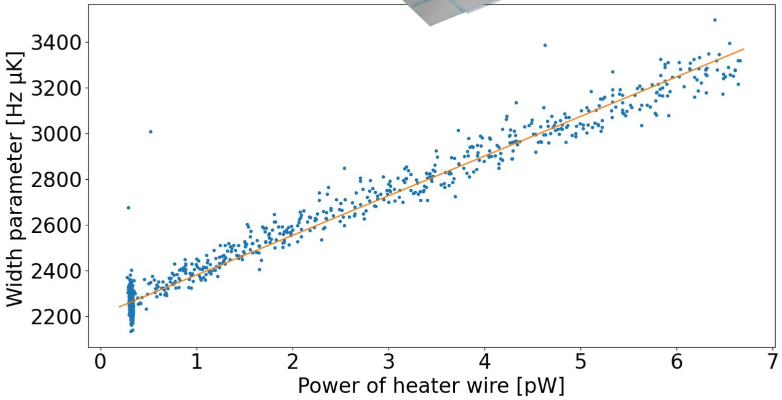
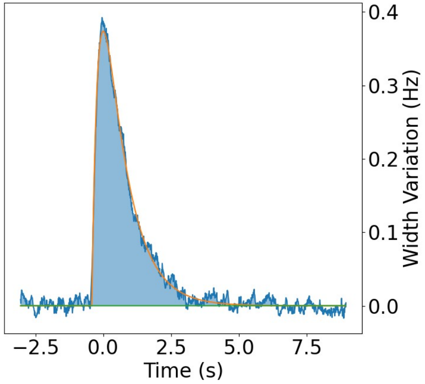
First prototype of bolometer

DATA!

Lancaster University







First prototype of bolometer

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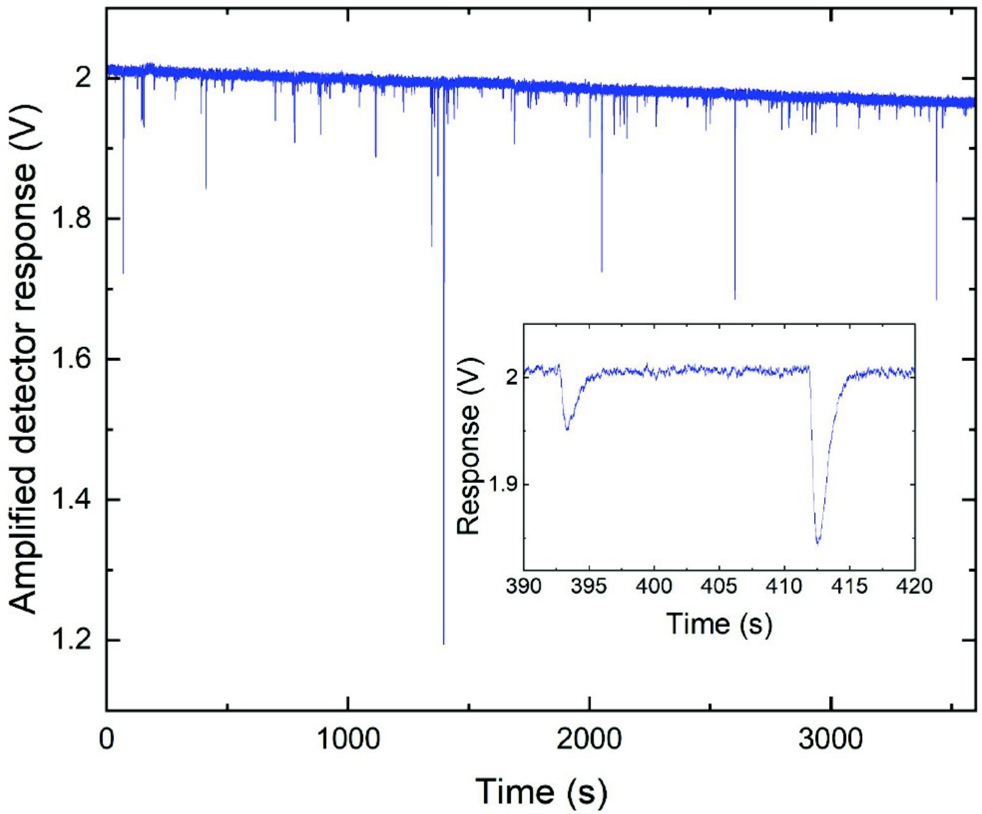
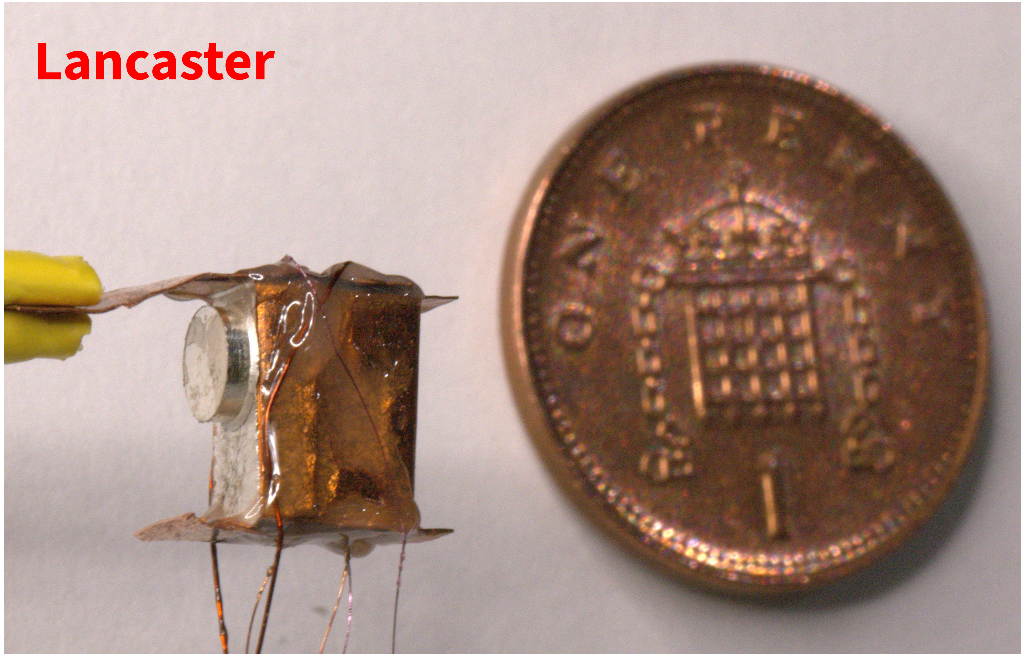


Extract:

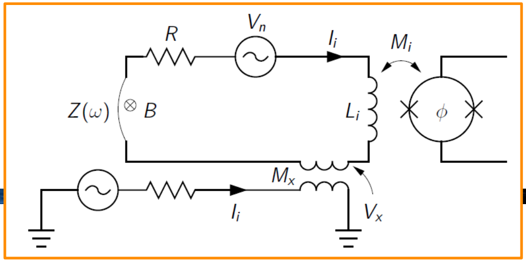
- Rate of background events
- Energy spectrum
- Energy threshold

Improved bolometers

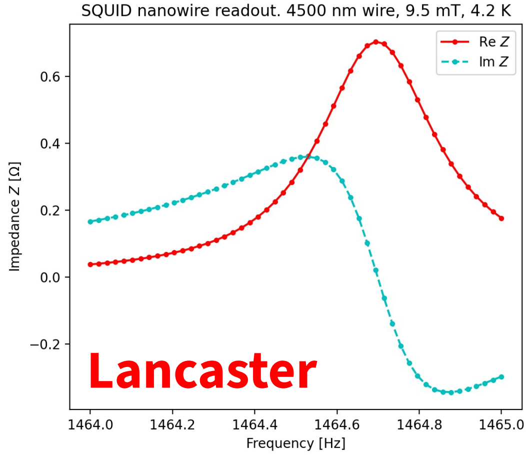
- Copper bolometer currently being operated with SQUID readout

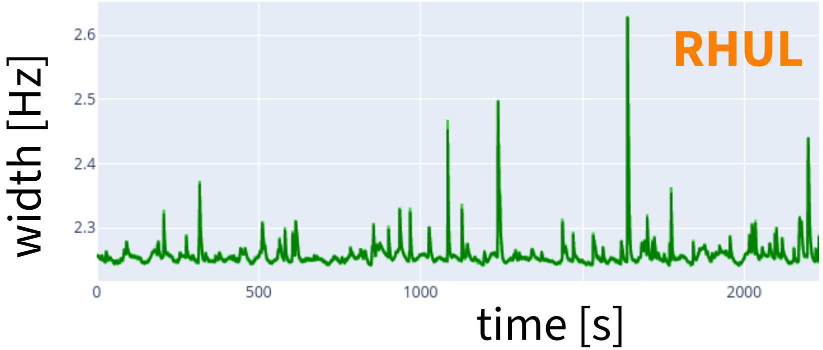


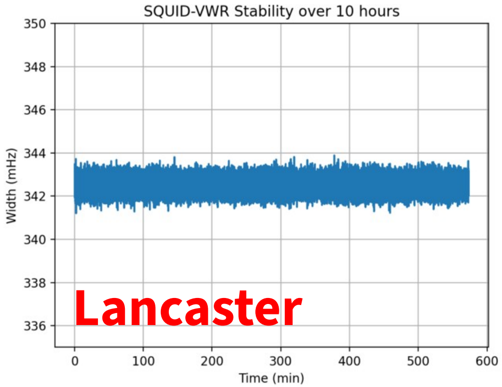
SQUID readout



- Readout of nanowires with the SQUID
- Validating the noise model
- Optimise the data taking conditions
- Reach the predicted resolution
  - Calibration with Fe-55 source (6 keV X-rays)





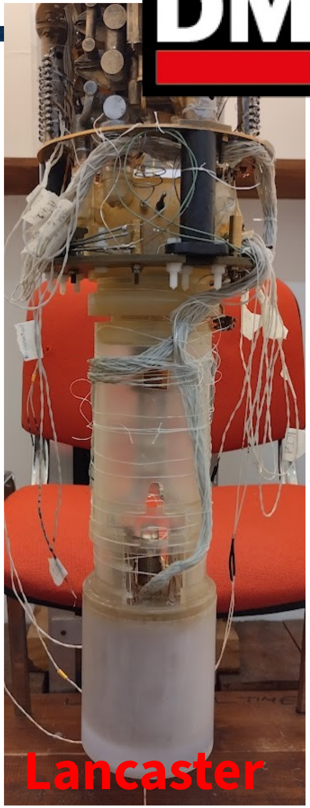


Conclusion and outlook

- Produced a **first sensitivity limit**, based on actual constructed detector cells and modelled energy reconstruction validated on data (Eur Phys J C 84: 248 (2024))
- **Simulation and analysis pipeline in place**
- **First prototype** run in 2023
- Demonstrated **SQUID** readout at μK temperatures
- **Work in progress**:
  - Develop the energy calibration of the bolometer with external Fe-55 **source**
  - Implement **light detection** in the cell
  - Add **cosmic rays tagging**

Conclusion and outlook

- Started operating ^{3}He cells with **nanowires**, with
- **SQUID** readout, and
- Calibration **sources**



Great potential for quantum technologies to open up a new window on the dark matter universe

Eur Phys J C 84: 248 (2024)
J Low Temp Phys 215, 465-476 (2024)