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

Paolo Franchini

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Lancaster University

ICHEP 2024 | PRAGUE

19 July 2024

QUEST DMC

Quantum Enhanced Superfluid Technology for Dark Matter and Cosmology

QUEST DMC

- 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 sensor

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

“I was conscious that I knew practically nothing...”

“I was conscious that I knew practically nothing...”

Socrates:

0 books

“I was conscious that I knew practically nothing...”

Socrates:

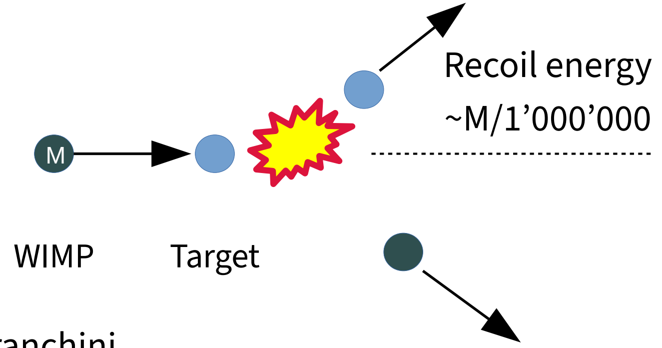
0 books

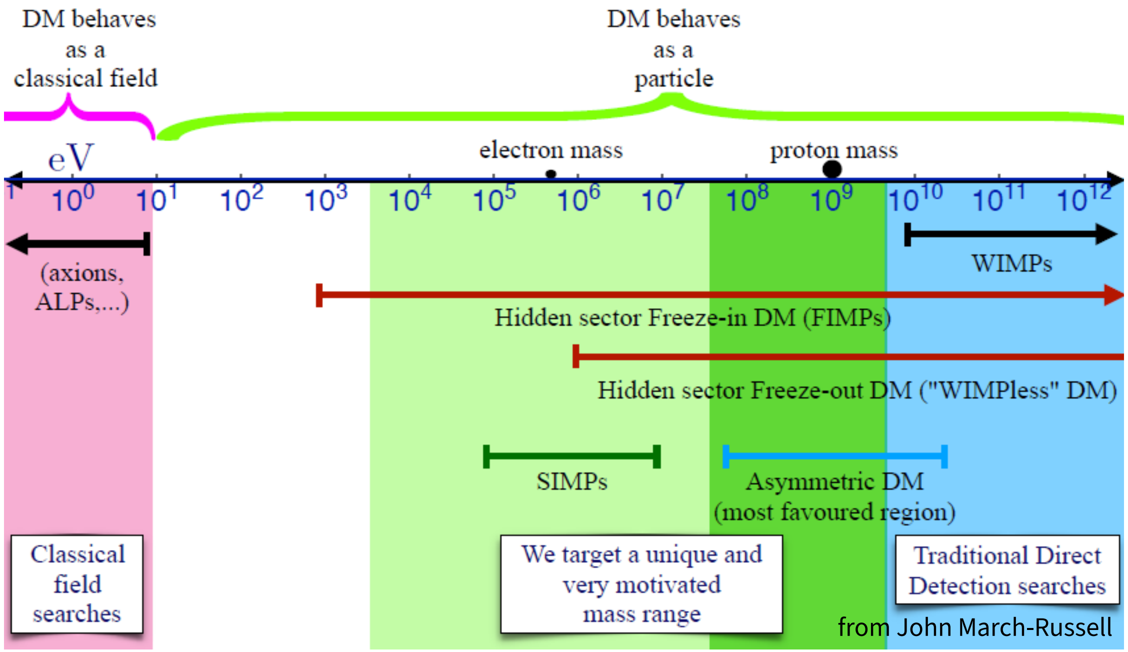
Dark matter hep−th:

1300 papers on arχiv

Direct dark matter detection

- WIMP candidates
- Theoretical motivation for **sub-GeV** dark matter models
- Reach **sub-eV recoil energy** for low mass investigation
- Novel use of superfluid ^{3}He





from John March-Russell

QUEST-DMC

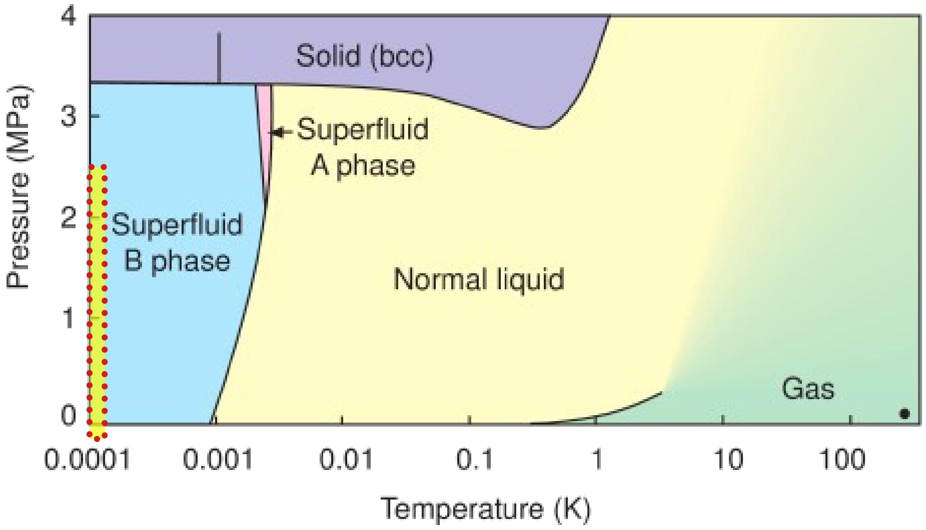
QUEST-DMC

Target → **Detector** → **Readout**

Superfluid He3

Helium-3

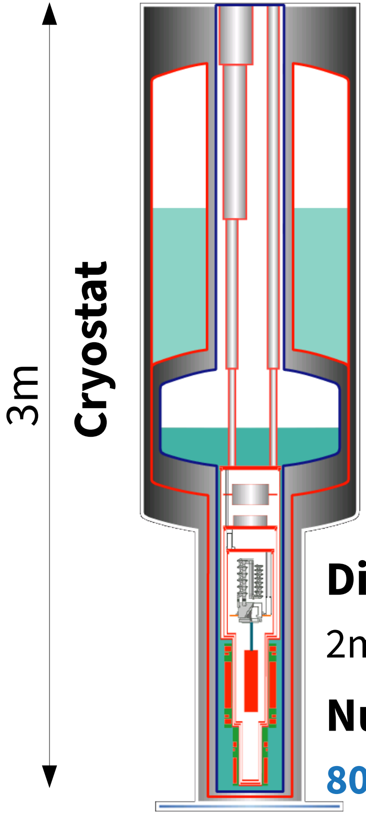
Target



- Superfluid (1972) below 2.5 mK
- Spin ½: spin dependent sensitivity
- **^{3}He-B**:
  - He3 as a fermionic condensate (similar to BSC theory)
  - Cooper pairs: composite bosons, 100nm size
  - Pair of bound quasiparticles with 10^{-7} eV energy and an effective mass

Lancaster advanced refrigerator

Lancaster University



Liquid nitrogen

70K

He4 bath

4.2K

Dilution refrigerator

2mK

Nuclear stage

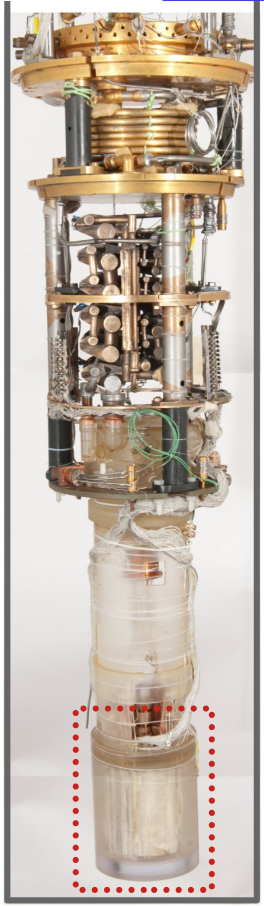
80uK

0.5 K

1.6 mK

world record

80 uK



Still

Tubular Heat Exchanger

Discrete Heat Exchanger

Mixing Chamber

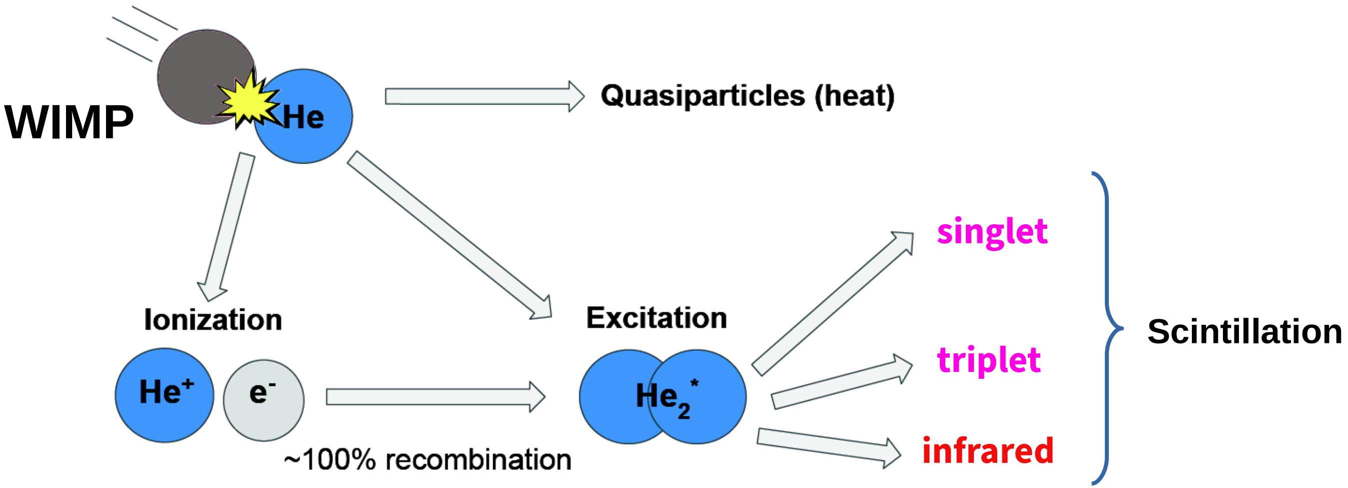
Heat Switch

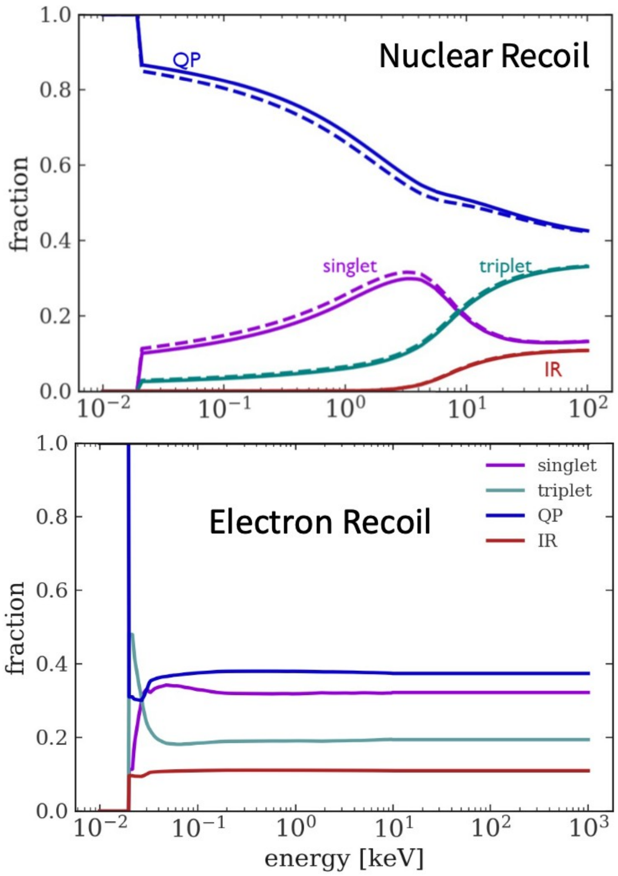
Demagnetisation Stage

vacuum can

Dark Matter events in He3

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





QUEST-DMC

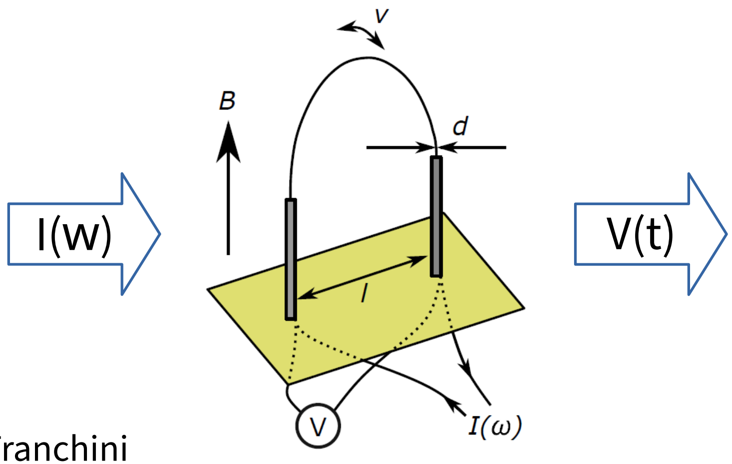
Target → Detector → Readout

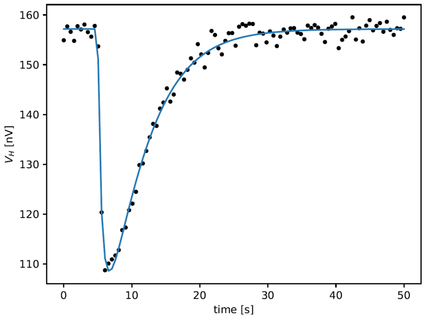
Vibrating nanowire

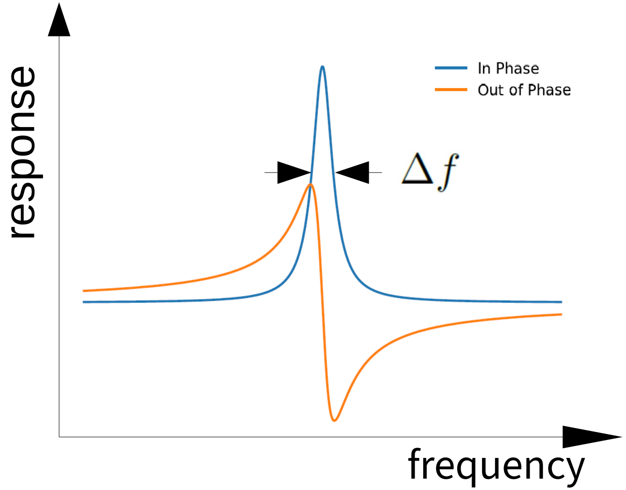
Bolometer response

Detector

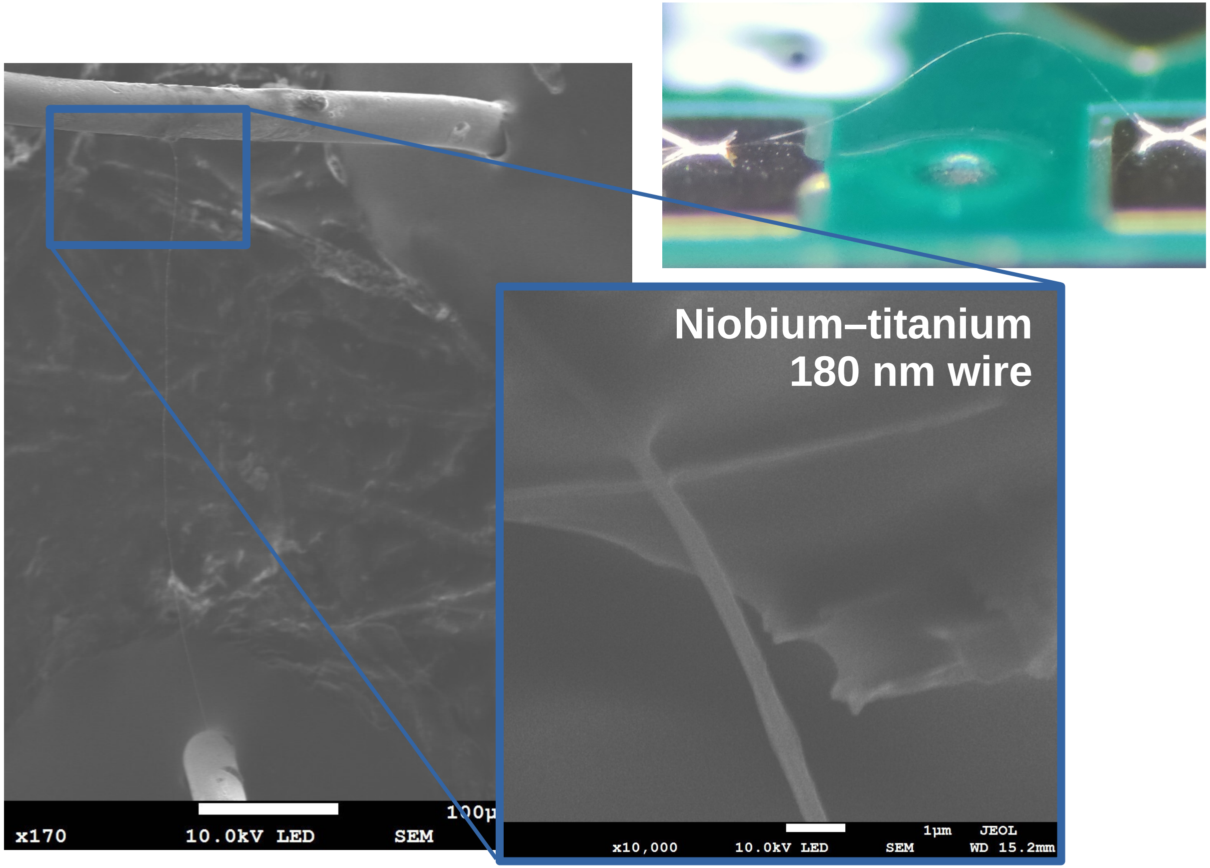
- Wire oscillating in magnetic field in a **He3 cm³ box**
- Damping force on the oscillator due to QP interactions
- Voltage response
- Measure **energy deposition** as variation of the resonance width Δf

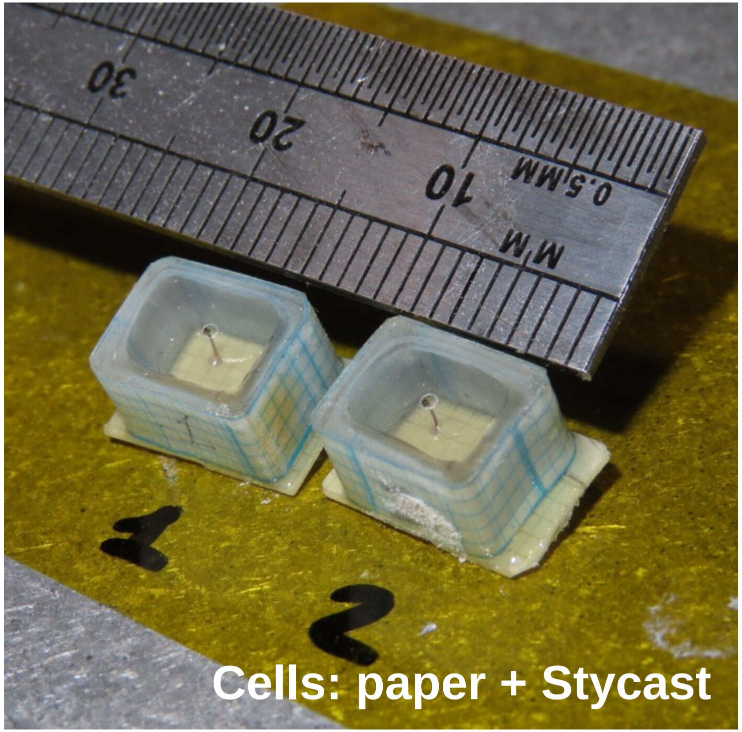






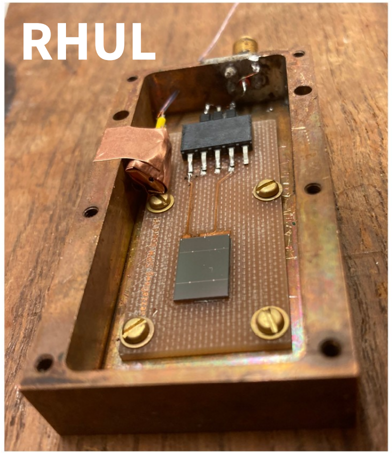
First prototype: cells with wires

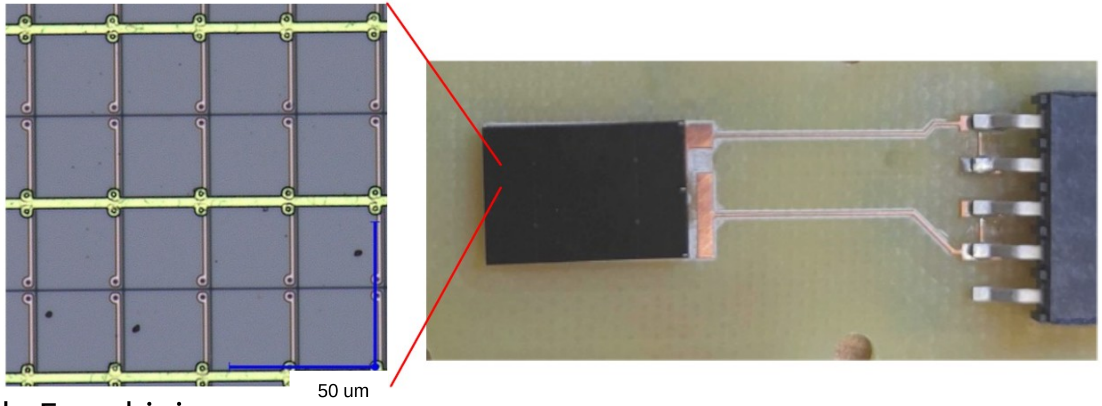


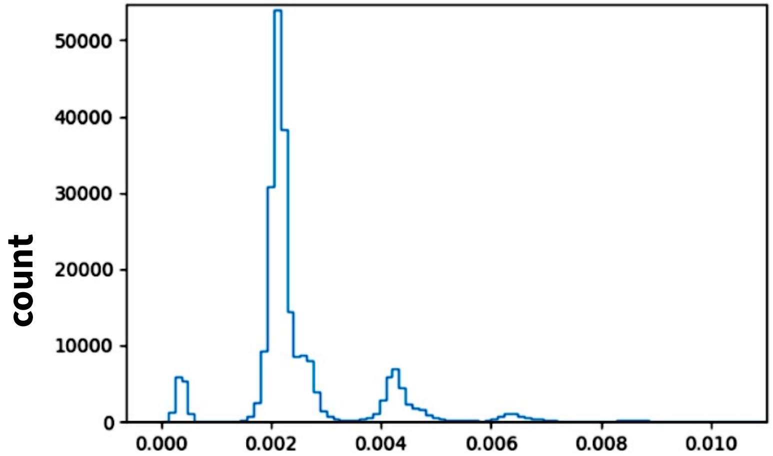


Photon sensing

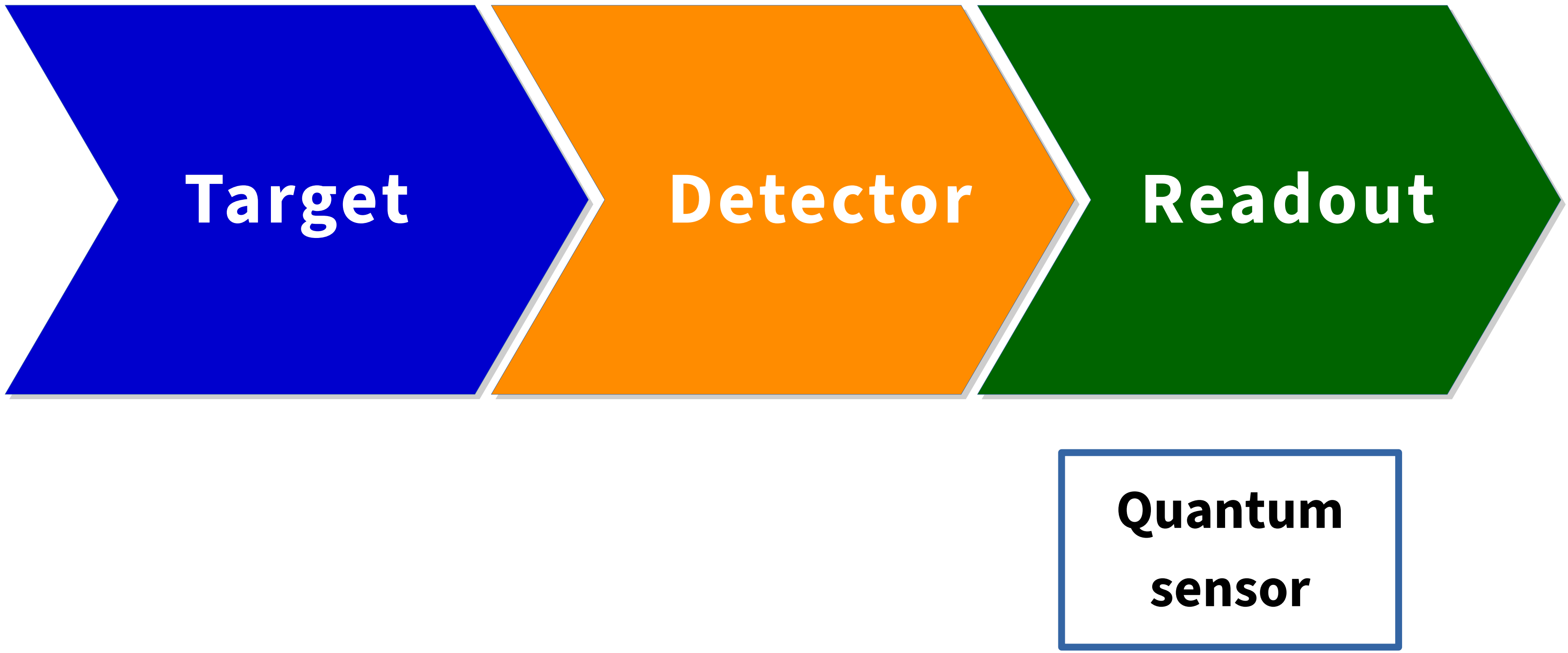
- Silicon PhotoMultipliers explored technology
- SIPMs have high-gain and single photon resolution
- Successfully tested at 25mK
  (1K in literature A. Ferri et al, 2016 JINST 11 P03023)
- To be coupled with a scintillator







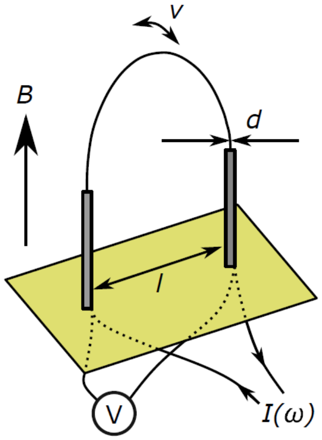
QUEST-DMC



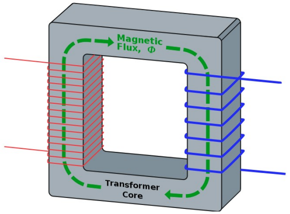
Bolometer in He3

Readout

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

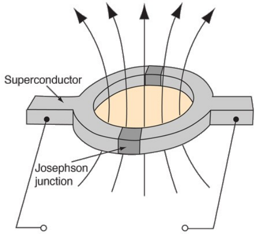


Cold transformer



Conventional: 31 eV

SQUID readout



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

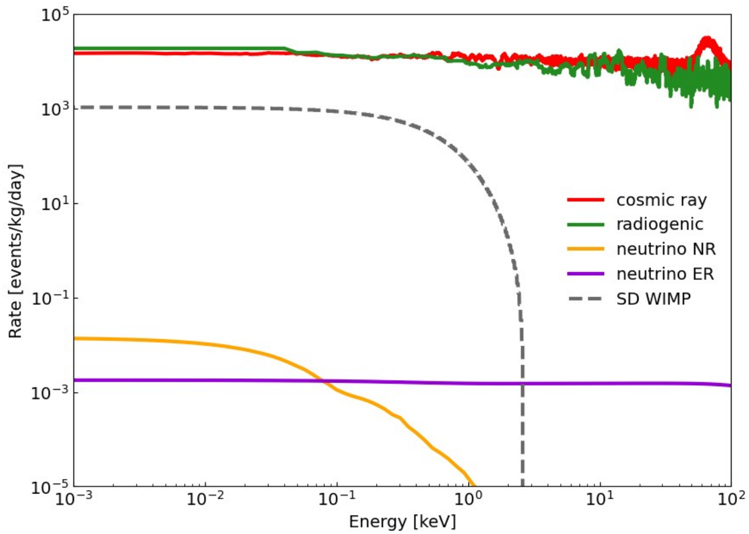
Background

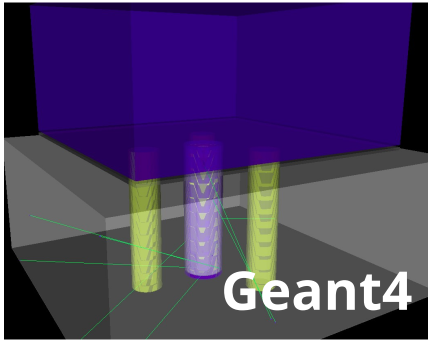
Analysis

- 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	$< 7.20 \times 10^3$	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	$< 3.90 \times 10^3$	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

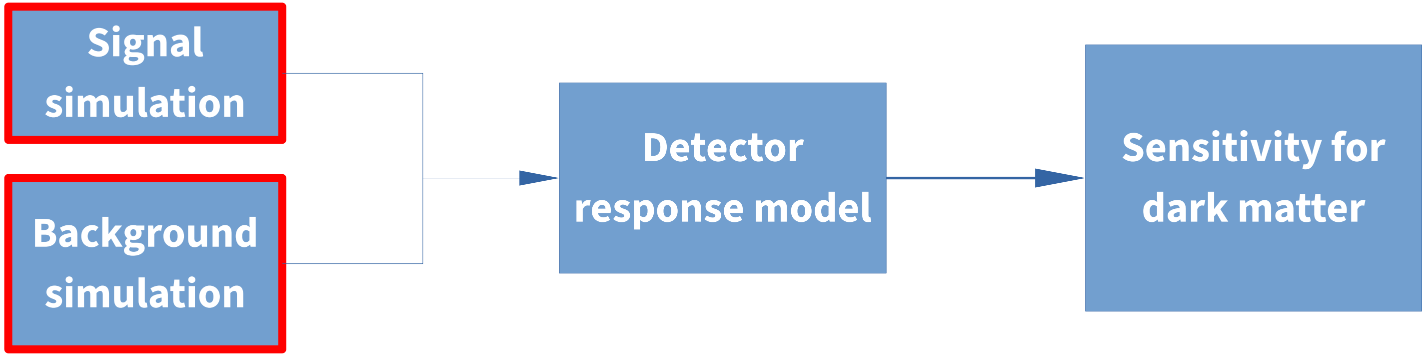
Component	Expected counts [0-10 keV] /kg/day	Expected counts [0-10 keV] /cell/day	Uncertainty
Cosmic ray	1.05×10^5	3.31	11 %
Radiogenic ER	8.31×10^4	2.61	14 %
Solar ν ER	1.51×10^{-2}	4.76×10^{-7}	2 %
Solar ν NR	6.37×10^{-4}	2.01×10^{-9}	2 %
TOTAL	1.88×10^5	5.92	

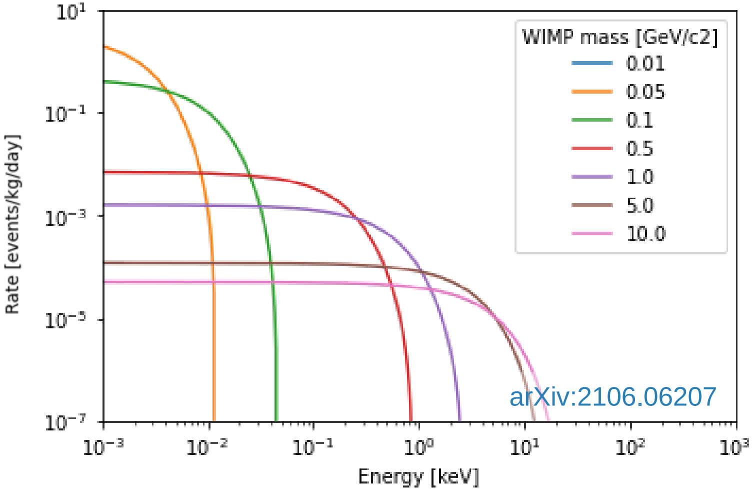


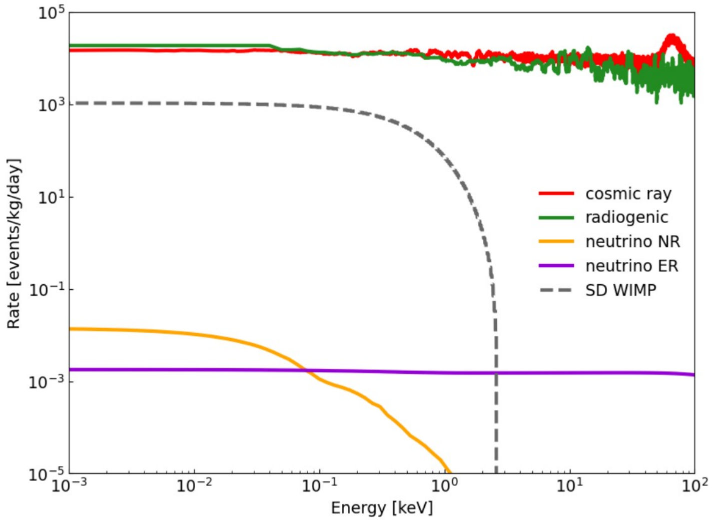


Sensitivity projection

published

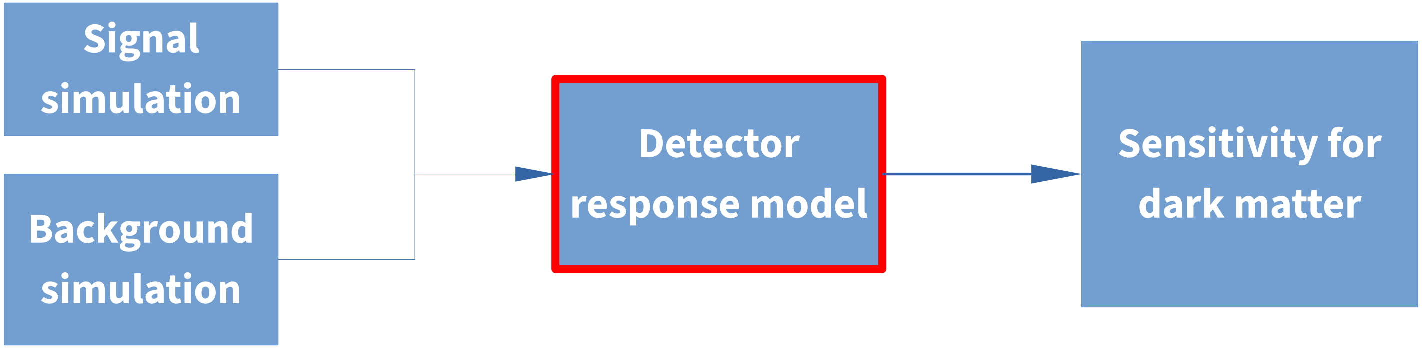


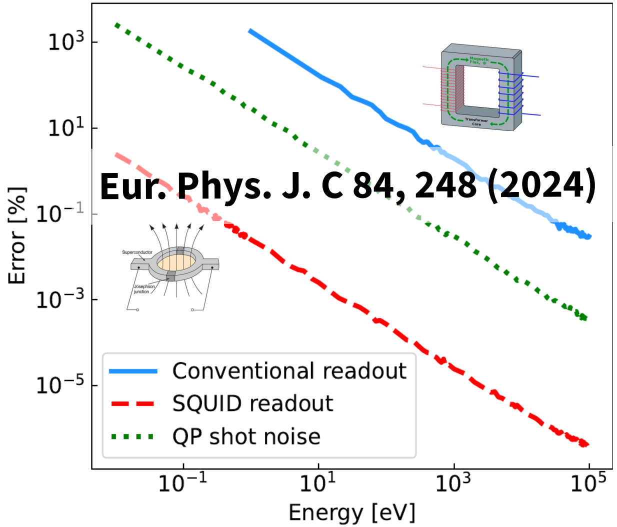




Sensitivity projection

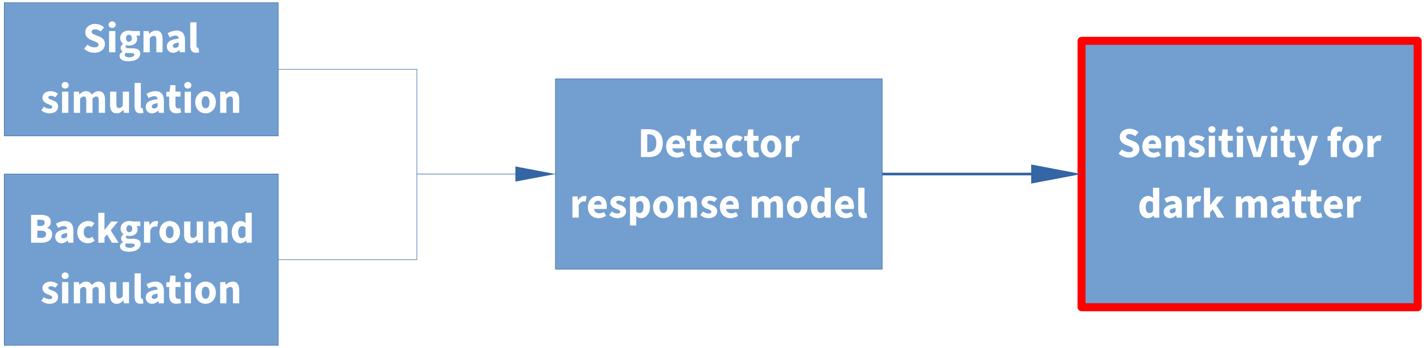
published



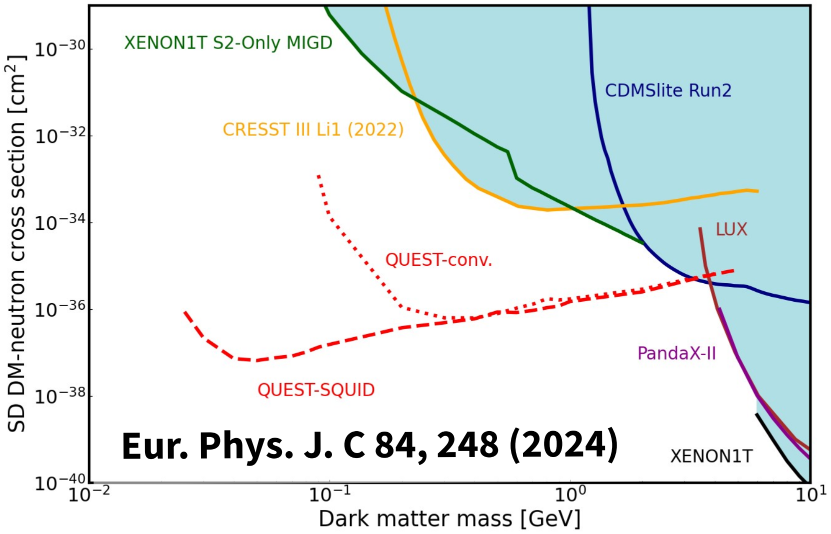


Sensitivity projection

published



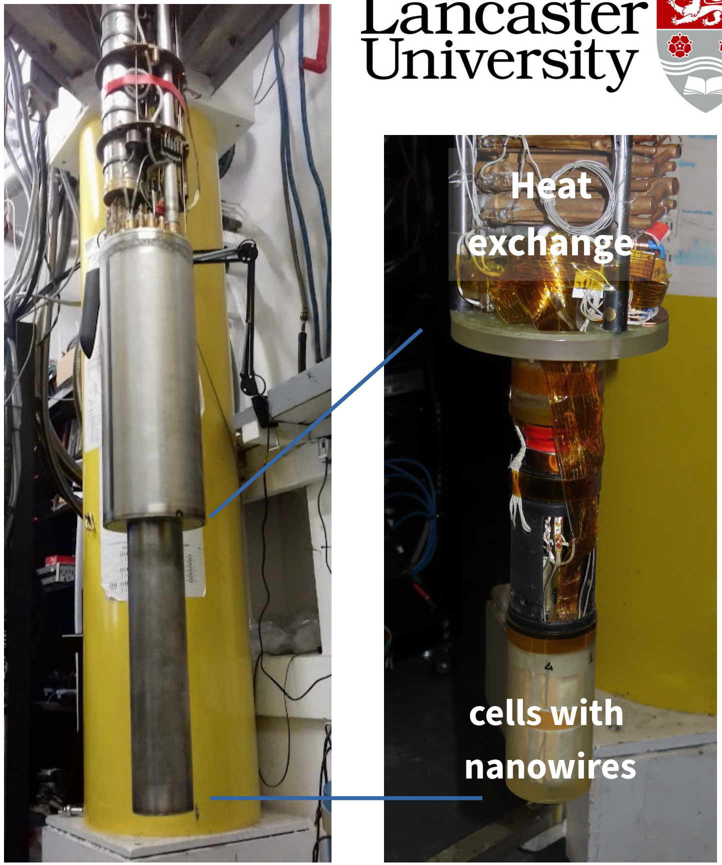
- 5 cells
- Exposure: 0.0135 g/years of ^{3}He
- 1 year with 50% duty cycle

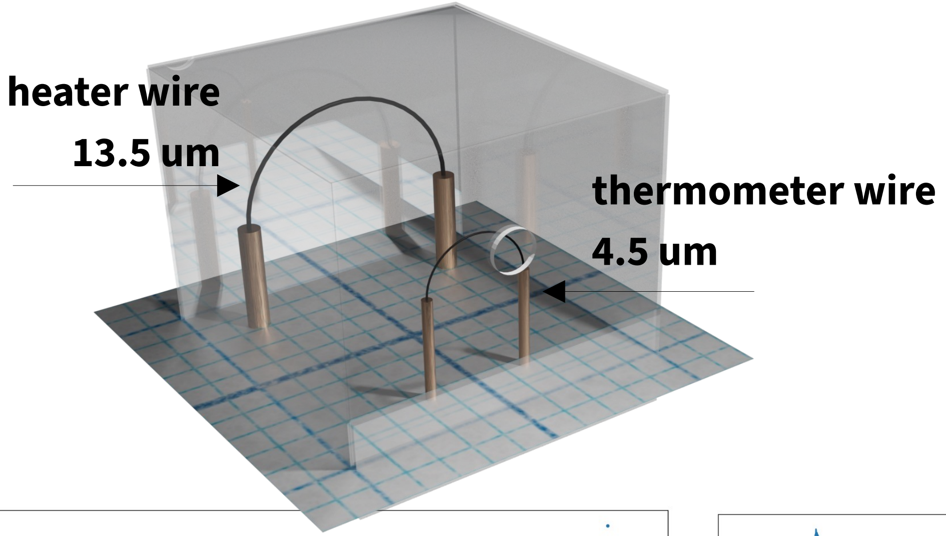


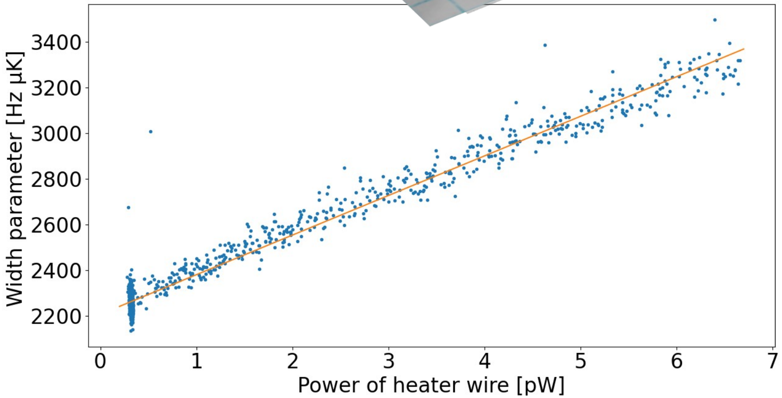
Eur. Phys. J. C 84, 248 (2024)

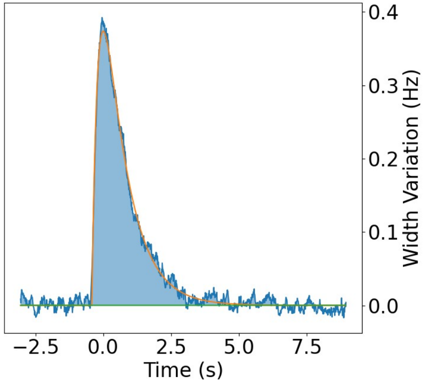
First prototype of bolometer

DATA!



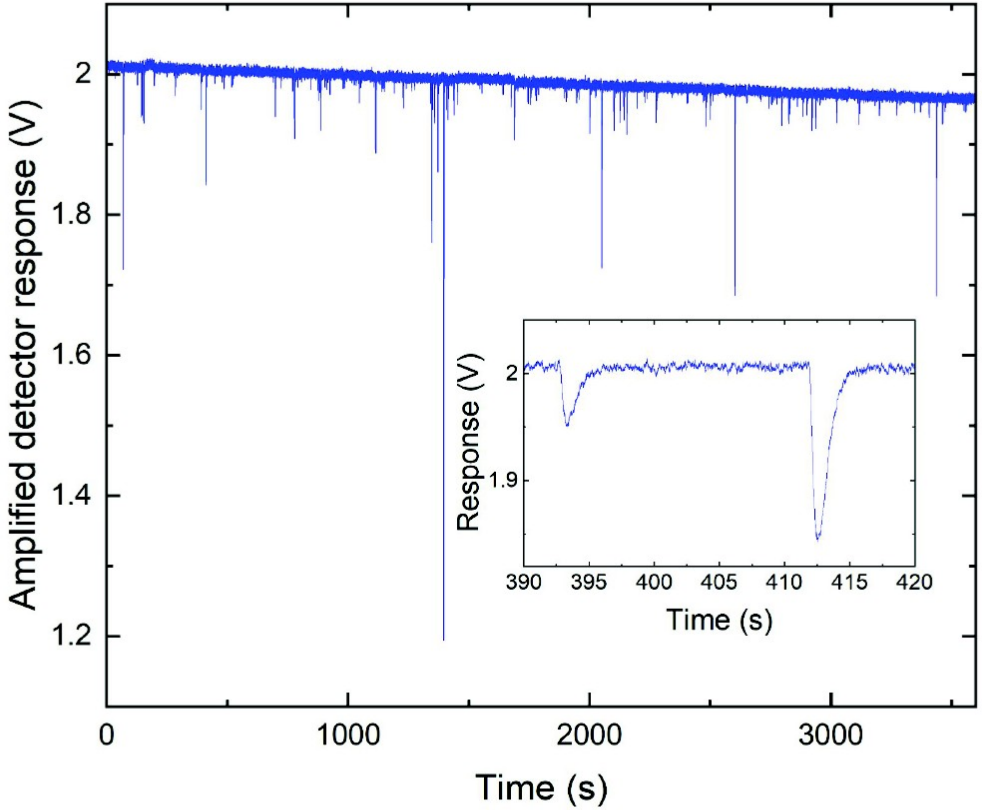






First prototype of bolometer

DATA!



Extract:

- Rate of background events
- Energy spectrum
- Energy threshold

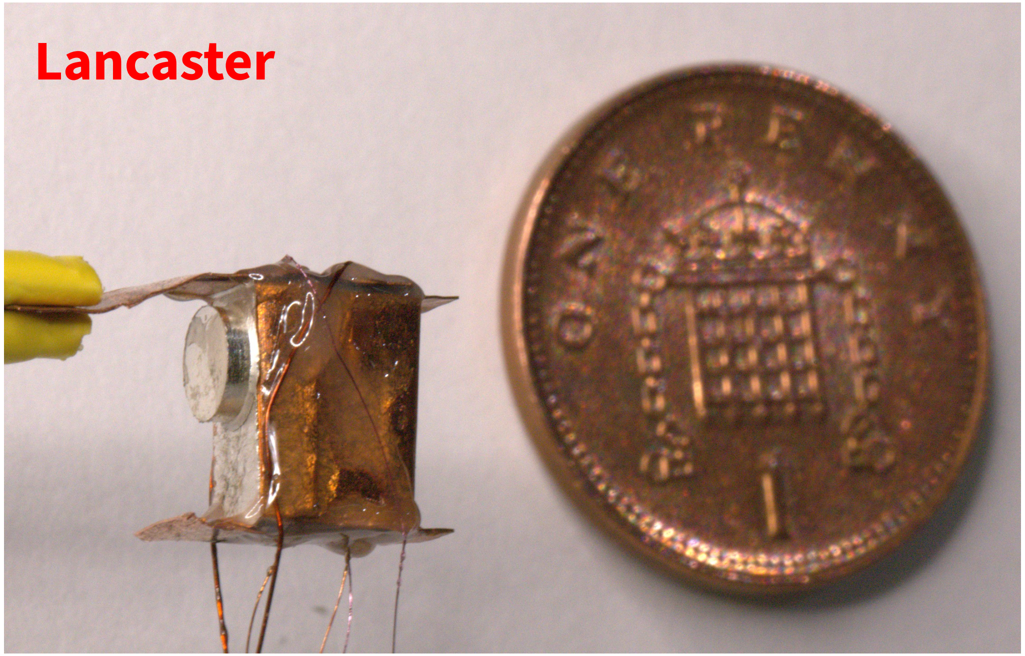
Conclusion and outlook

- Produced a **first sensitivity limit**, based on actual constructed detector cells and modelled energy reconstruction validated on data (published in EPJ-C)
- **Simulation and analysis pipeline in place**
- **First prototype** run in 2023

- **Work in progress**:
  - Develop the energy calibration of the bolometer with external Fe55 **source**
  - Demonstrate **SQUID** readout at μK temperatures
  - Implement **light detection** in the cell
  - Add **cosmic rays tagging**

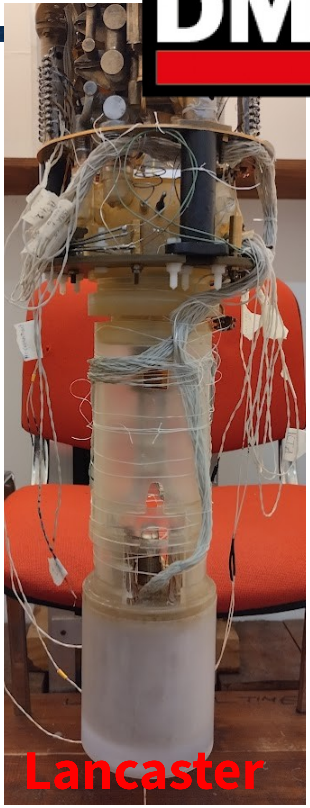
Conclusion and outlook

- New copper bolometers



Conclusion and outlook

- Start 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

"QUEST-DMC superfluid 3He detector for sub-GeV dark matter"
https://link.springer.com/article/10.1140/epjc/s10052-024-12410-8