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

Paolo Franchini

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Lancaster University

XX International Workshop on Neutrino Telescopes

Venice, 26 October 2023

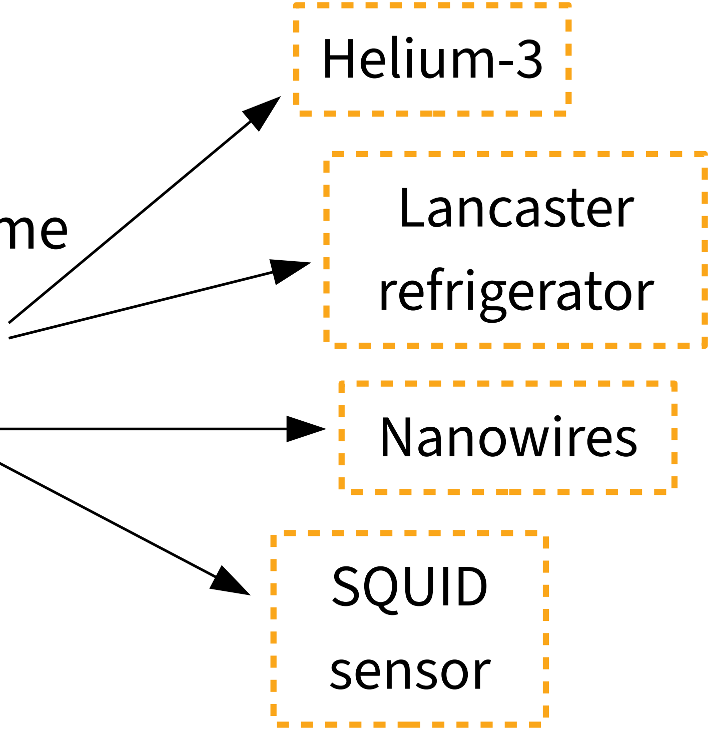
QUEST DMC

Outline

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

Quantum Enhanced Superfluid Technology for Dark Matter and Cosmology

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



"I was conscious that I knew practically nothing..."

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

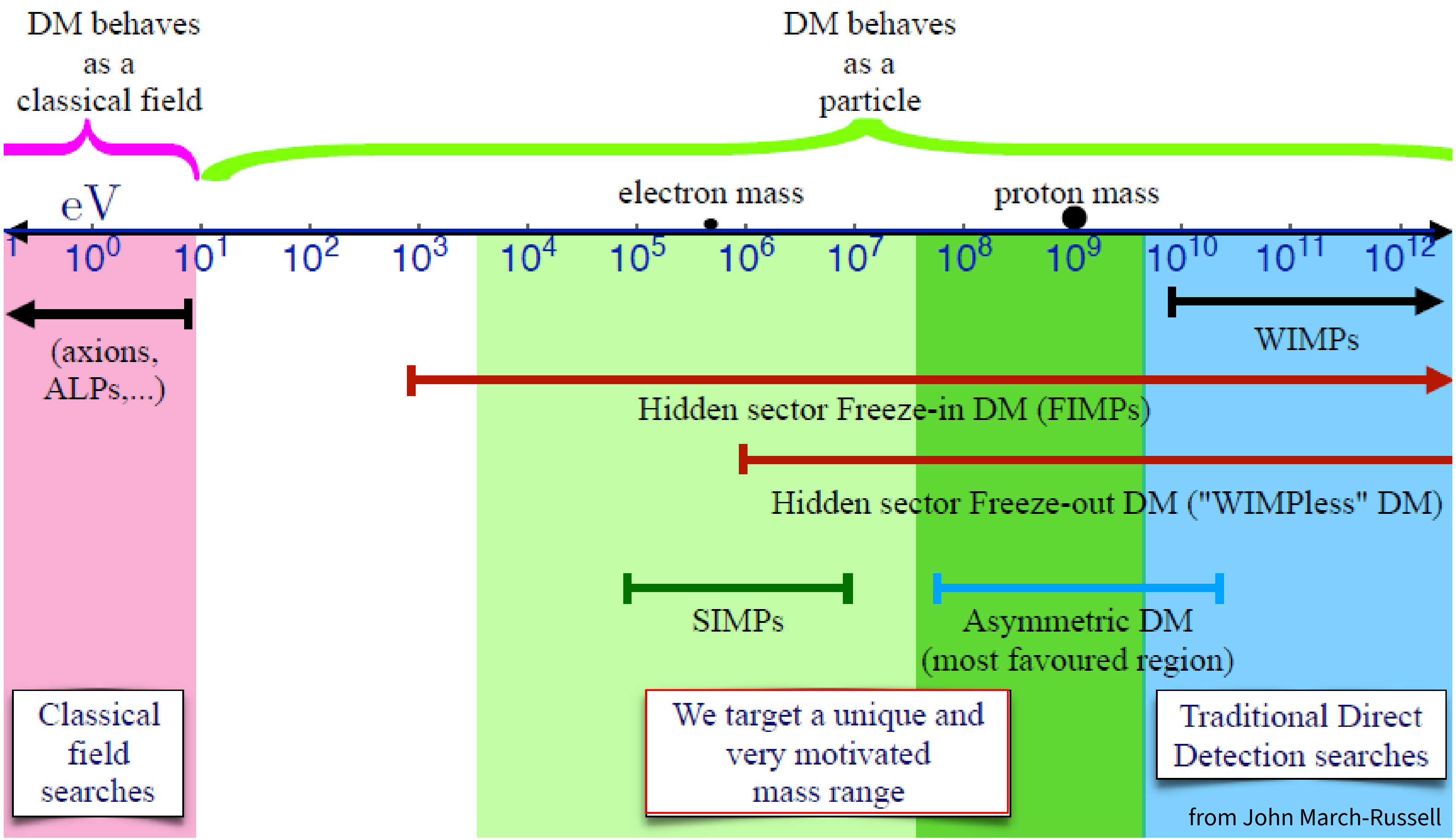
Socrates:
0 books

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

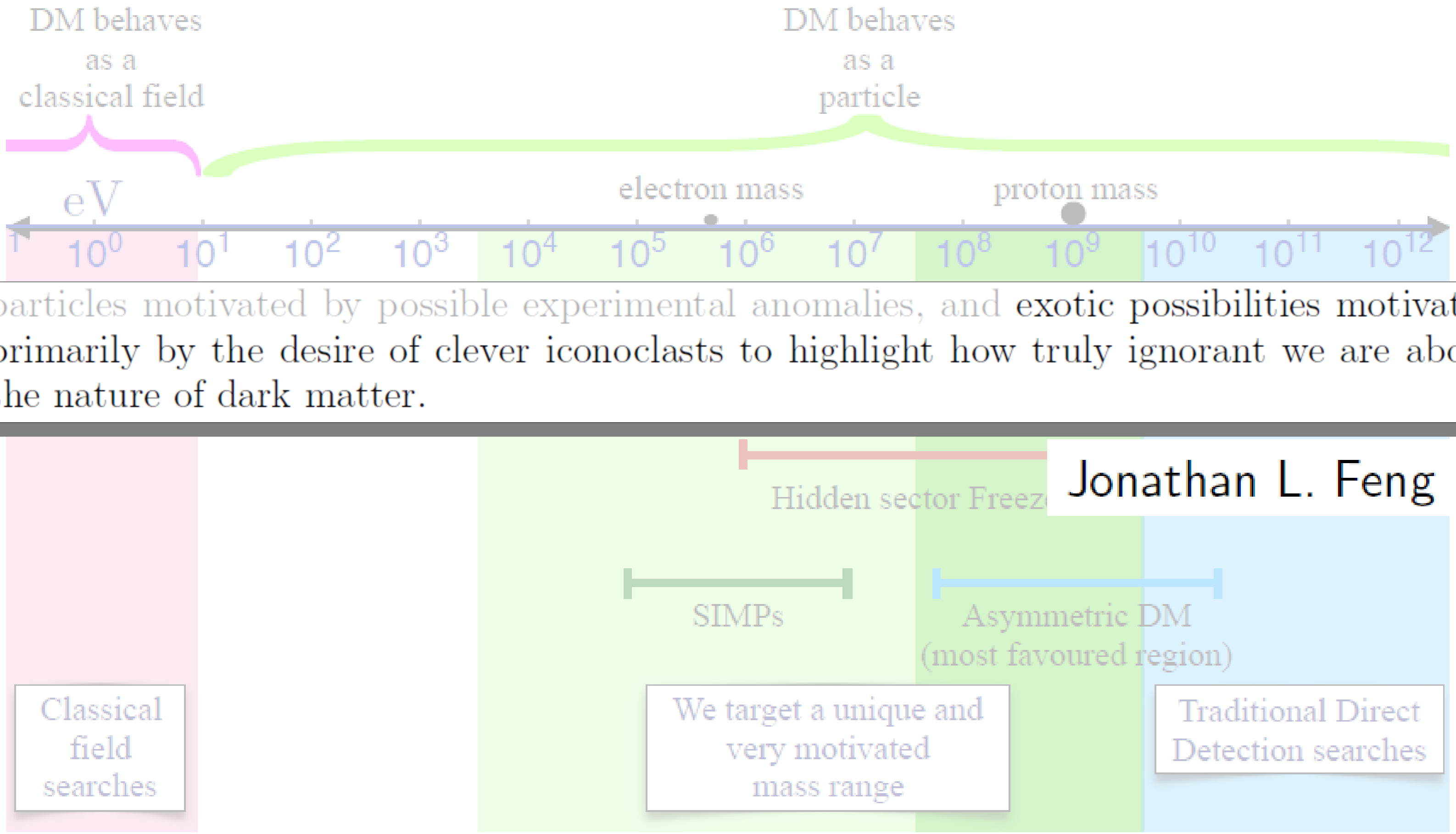
Socrates:
0 books

Dark matter `hep-th`:
1300 papers on arχiv

Direct dark matter detection: candidates



Direct dark matter detection: candidates



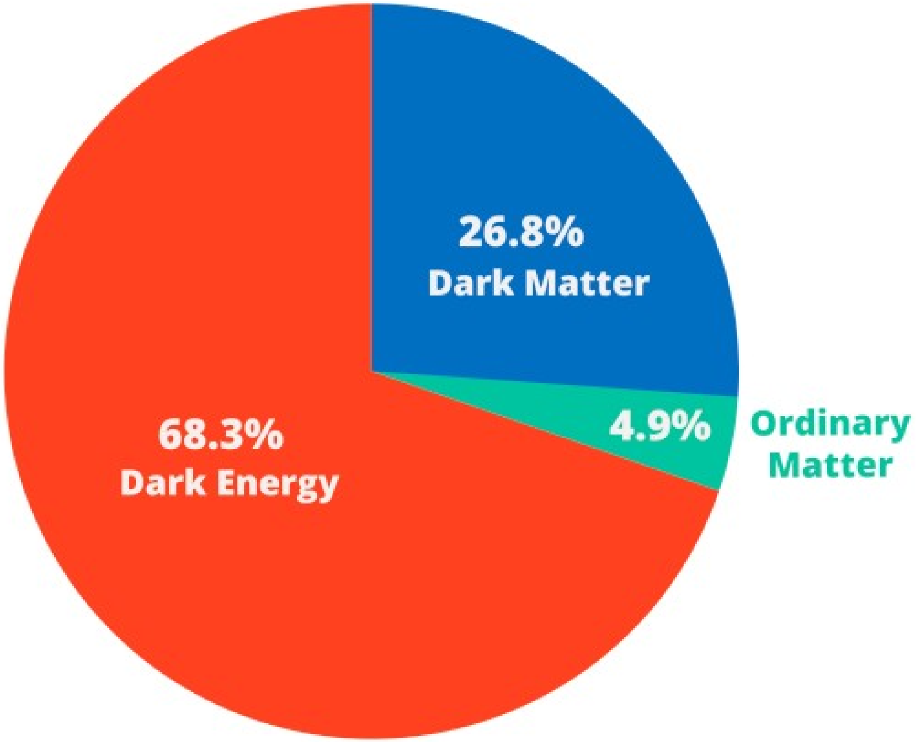
particles motivated by possible experimental anomalies, and exotic possibilities motivated primarily by the desire of clever iconoclasts to highlight how truly ignorant we are about the nature of dark matter.

Jonathan L. Feng

The dark matter hypothesis

- Matter and energy content of the universe

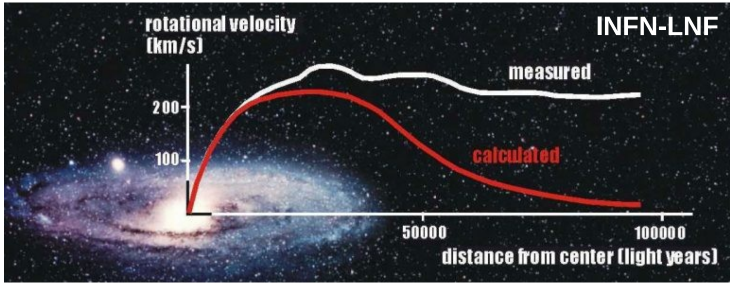
- Dark matter is 85% of mass

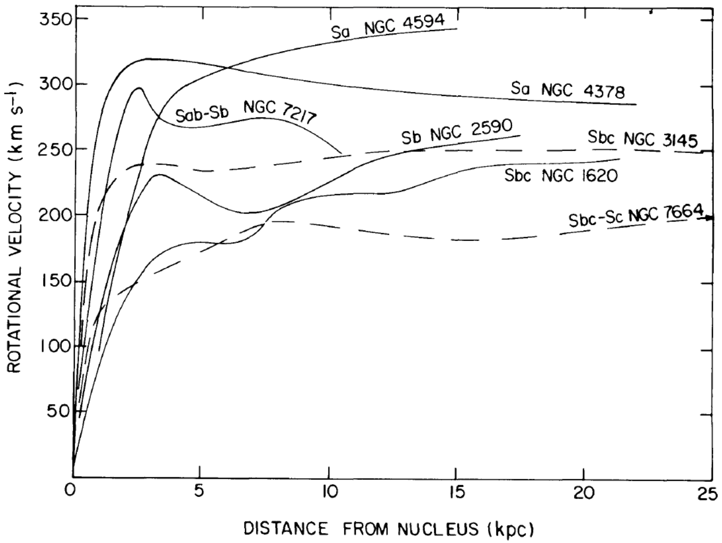


The dark matter hypothesis

- Evidences from gravitational interactions
  - Spiral and elliptical galaxies: rotation curves
  - Galaxy clusters: gravitational lensing
  - Cosmic Microwave Background
  - Colliding galaxy clusters: x-rays

- No electromagnetic interaction ("dark")
- Stable over billion years
- Non-baryonic: an unknown particle?



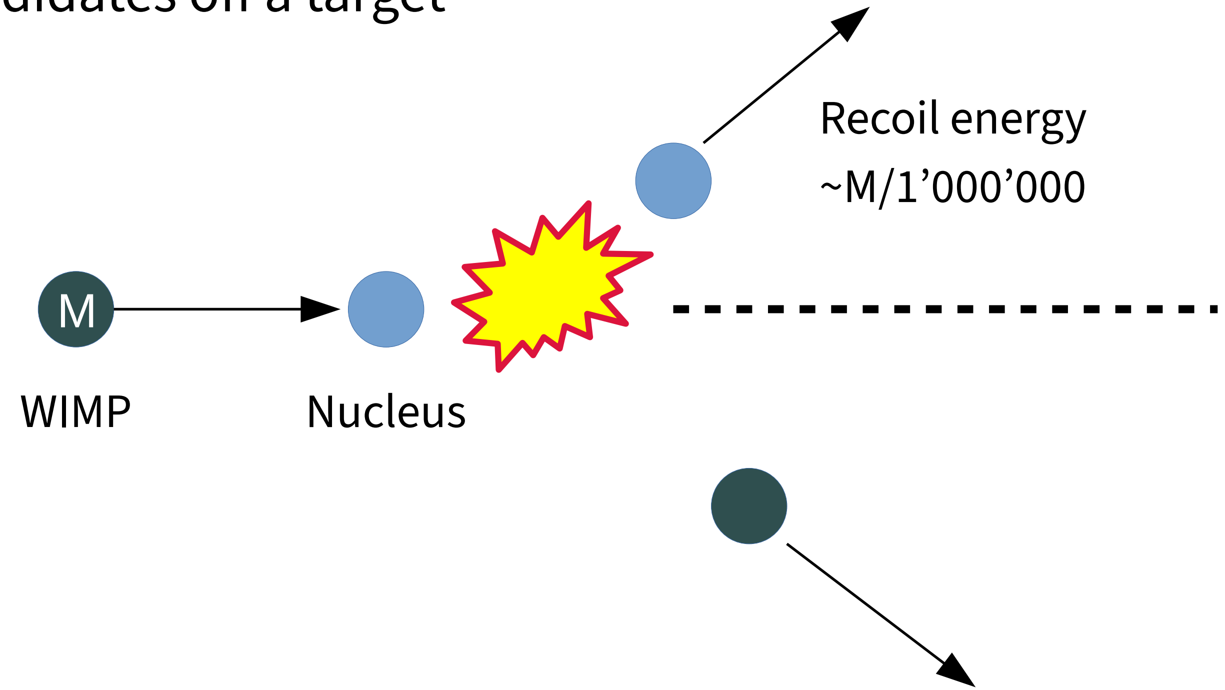


Rubin, V.C.; Thonnard, N.; Ford, W.K. Jr. (1978)

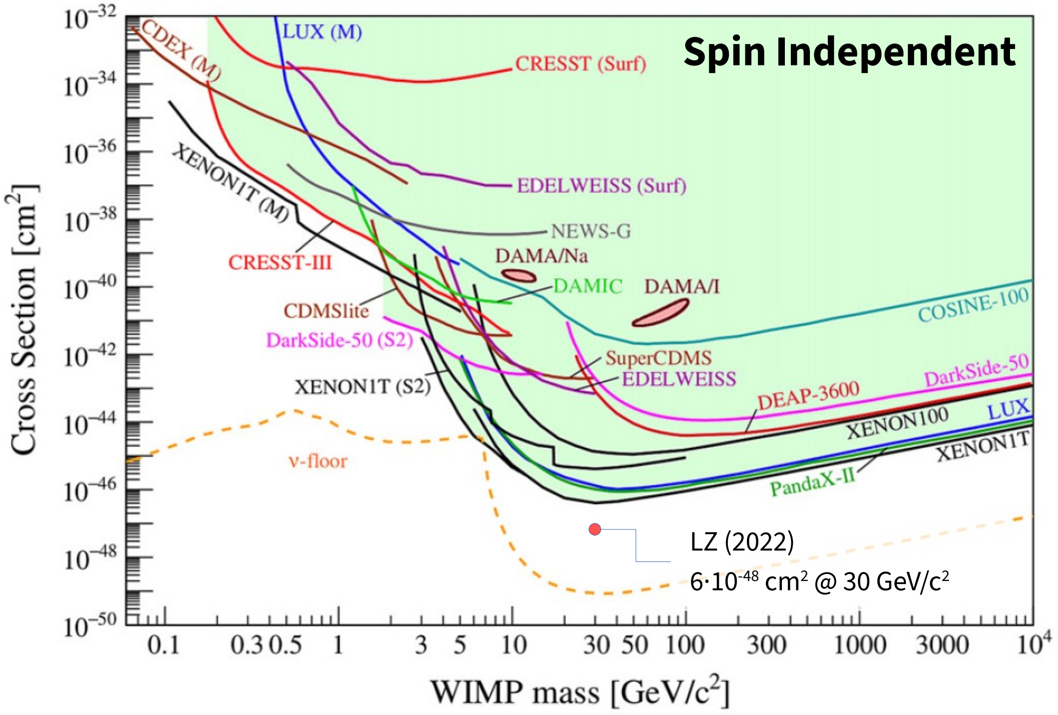
Direct dark matter detection: WIMPs

- **Signal:** scattering of DM candidates off a target
  - rare processes…
  - … but many WIMPs

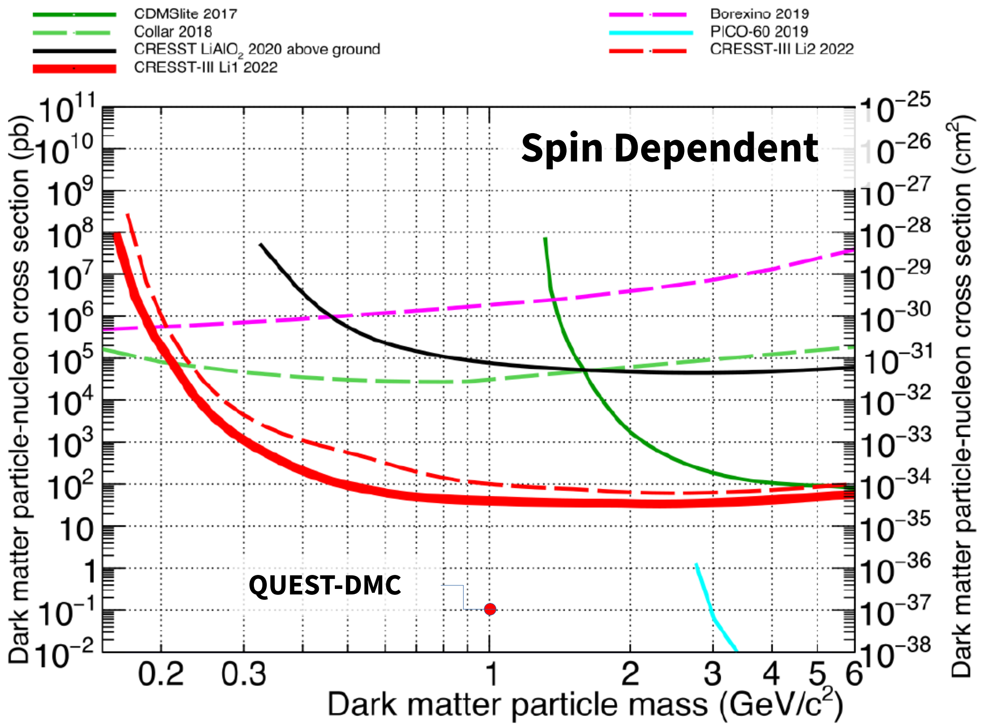
- **Backgrounds:**
  - Cosmic rays
  - Radioactive environment
  - Radioactive contamination
  - Neutrinos



Direct dark matter detection: WIMPs

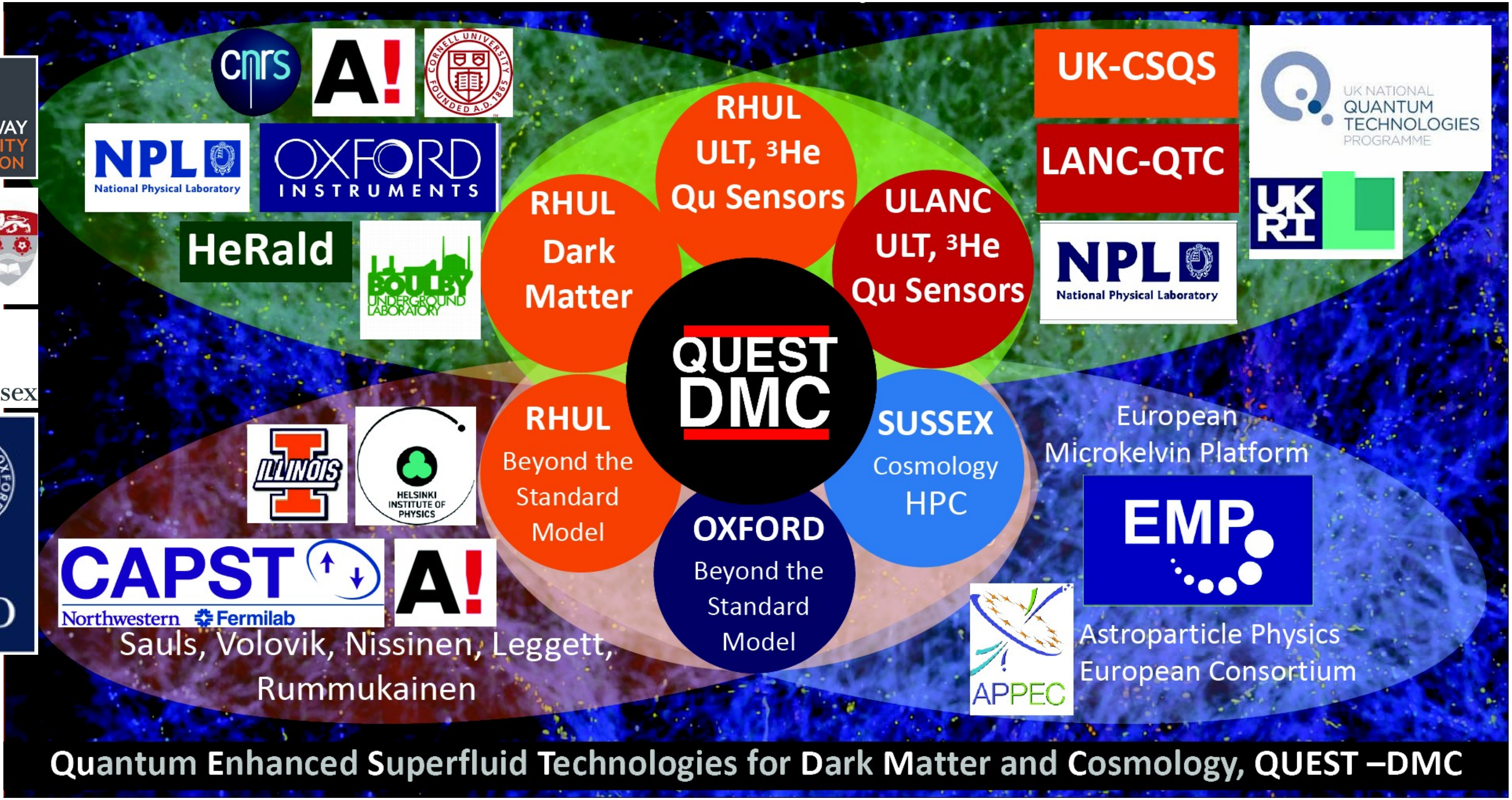


Rep. Prog. Phys. 85 (2022) 056201



https://arxiv.org/abs/2207.07640

QUEST-DMC collaboration and ecosystem



ROYAL HOLLOWAY UNIVERSITY OF LONDON

Lancaster University

University of Sussex

UNIVERSITY OF OXFORD

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

QUEST-DMC

Target

Detector

Readout

QUEST-DMC

Target | **Detector** | **Readout**

Superfluid He3

Vibrating nanowire

Quantum sensor

QUEST-DMC

Analysis

Spin dipendent WIMP-nucleon cross section: 10^{-37} cm^2 @ 1 GeV/c^2

eV recoil energy threshold

background < 1 event/kg/day/keV$_{DEP}$

QUEST-DMC

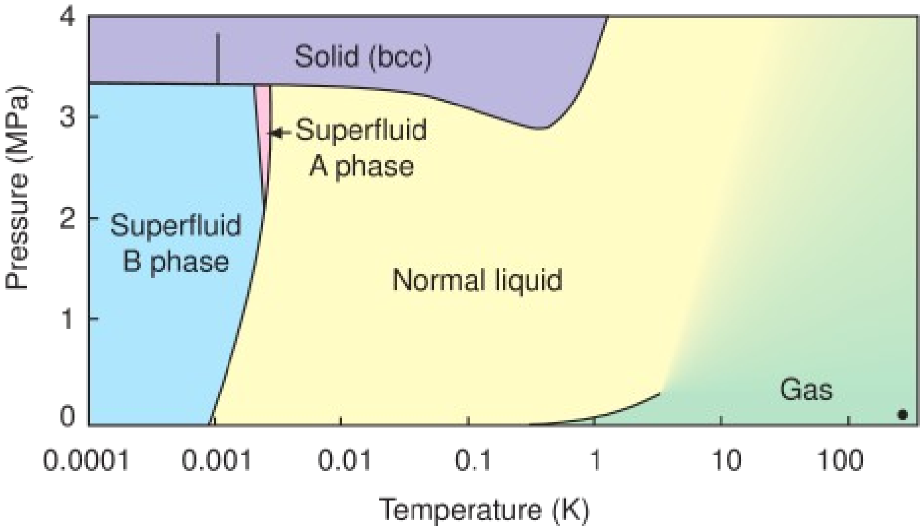
Target → **Detector** → **Readout**

Superfluid He3

Helium-3

Target

- Spin ½ (!)
- Superfluid (1972) below 2.5 mK
- P-wave pairing and multiple superfluid states
- **^{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



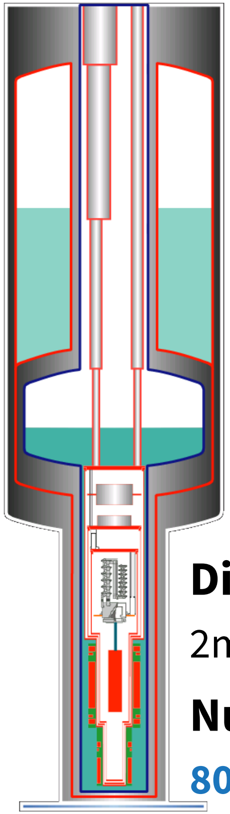
Lancaster advanced refrigerator

Target

Lancaster University

3m

Cryostat



Liquid nitrogen

70K

He4 bath

4.2K

Dilution refrigerator

2mK

Nuclear stage

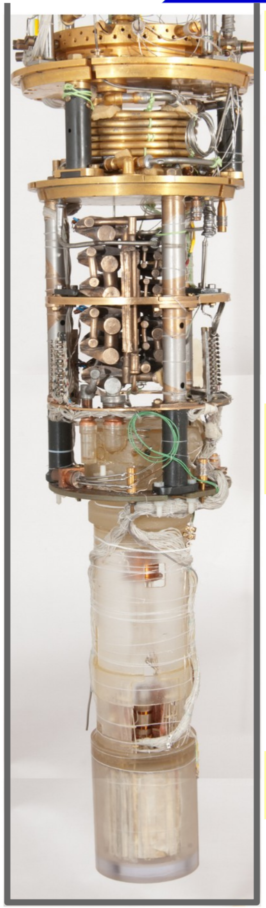
80uK

0.5 K

1.6 mK

world record

80 uK



Still

Tubular Heat Exchanger

Discrete Heat Exchanger

Mixing Chamber

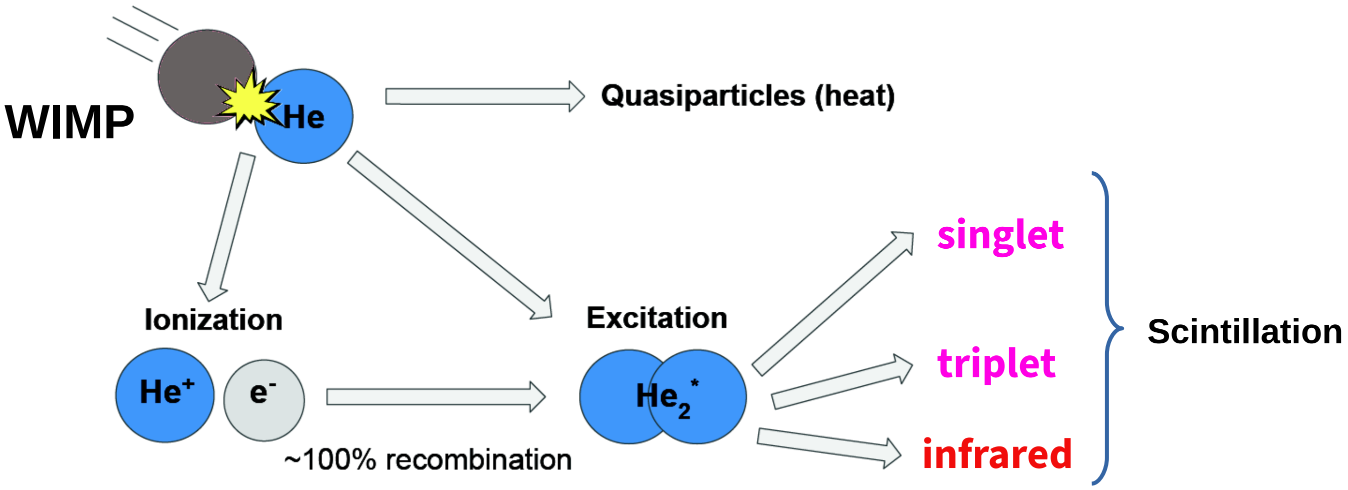
Heat Switch

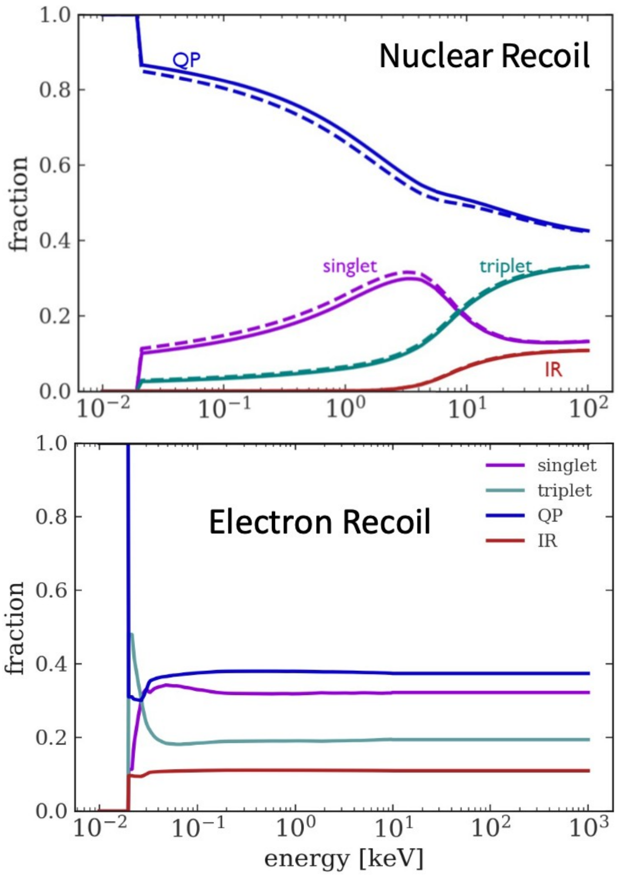
Demagnetisation Stage

vacuum can

Dark Matter events in He3

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





QUEST-DMC

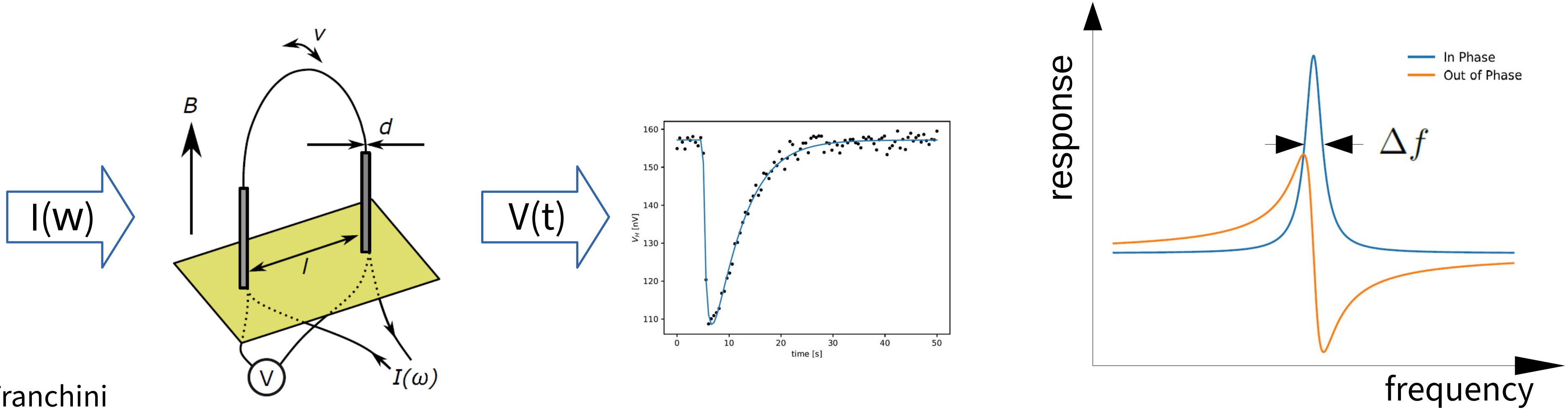
Target → Detector → Readout

Vibrating nanowire

Bolometer response

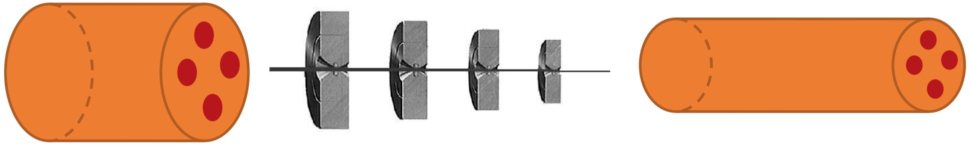
Detector

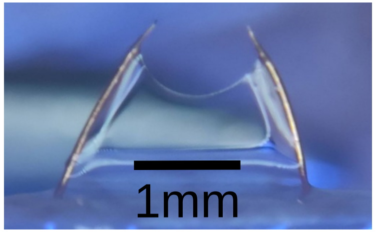
- Wire oscillating in magnetic field in a **He3 cm³ box**
- Damping force on the oscillator, enhanced by Andreev reflections
- Voltage response
- Measure **energy deposition** as variation of the resonance width Δf

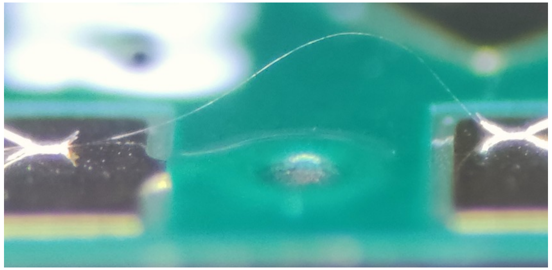


Lancaster nanowires

1. 200 um copper matrix with 1 um Nb-Ti wires
2. Draw the cable in multiple dies
3. Etch the copper and replace with water
4. Microscope + tweezers
5. Replace water with IPA
6. Let dry
7. Mount on a PCB







Autti S. et al, “Long nanomechanical resonators fabricated with wire drawing technology” - submitted to “*Nature nanotechnology*”

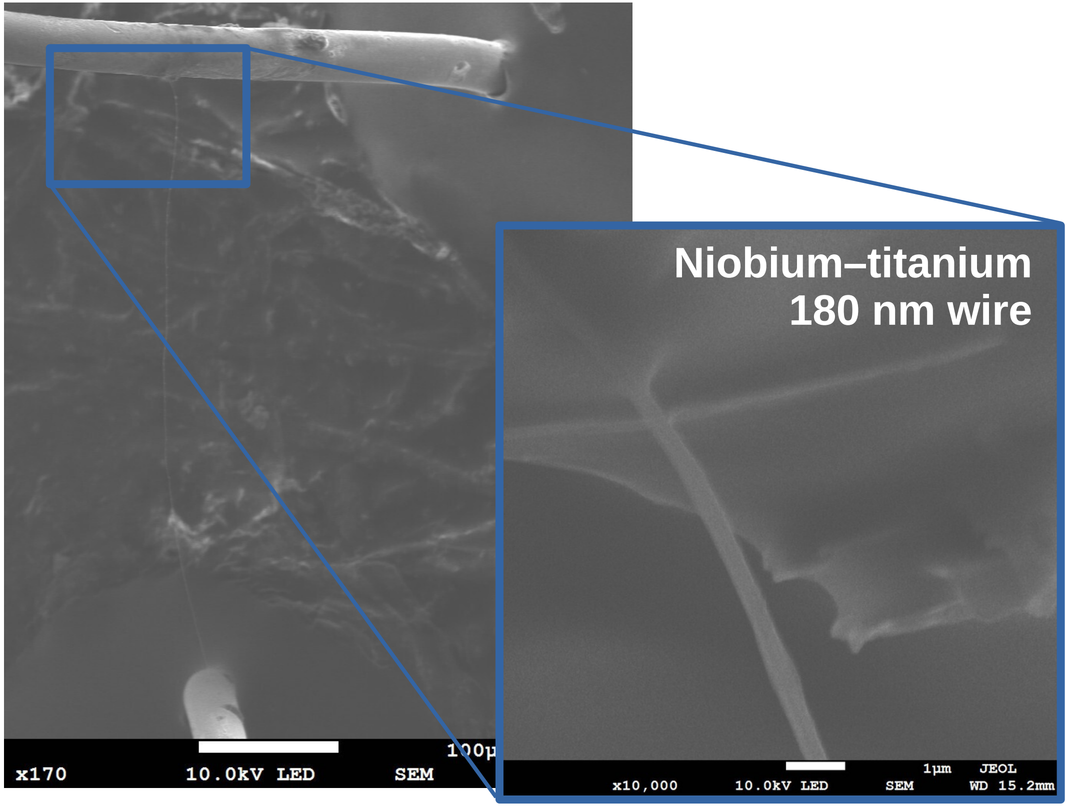
Lancaster nanowires

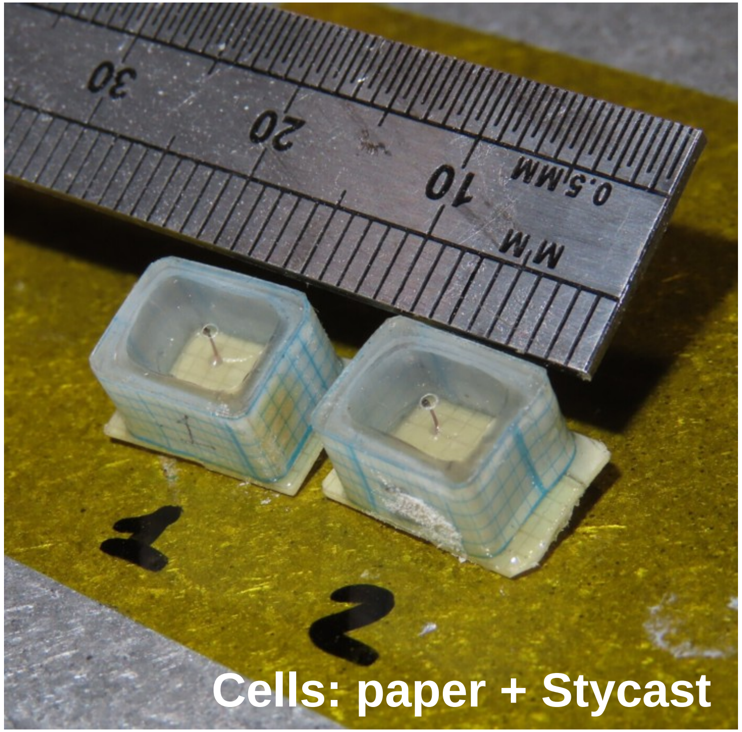
Detector

Trivia:

~500 nanowires to make a cat’s whisker

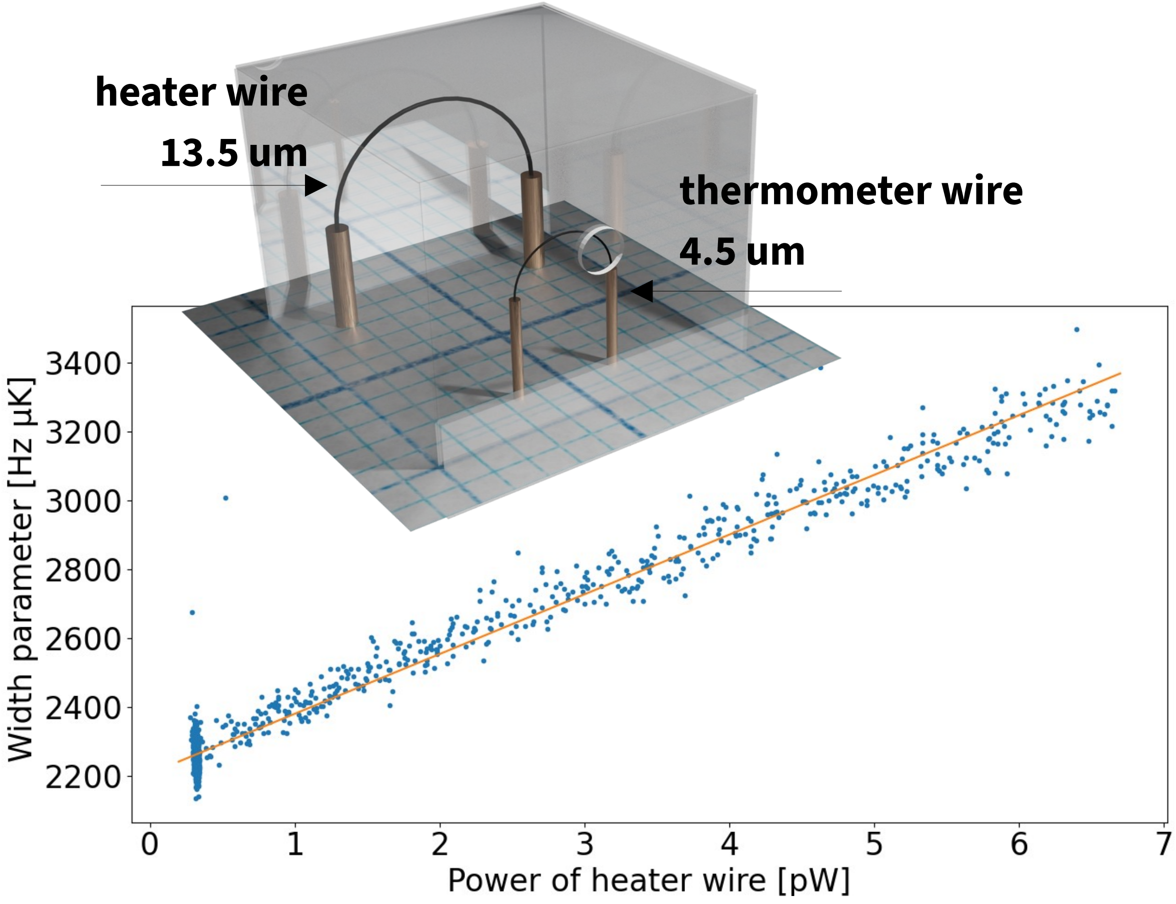
Cells with wires

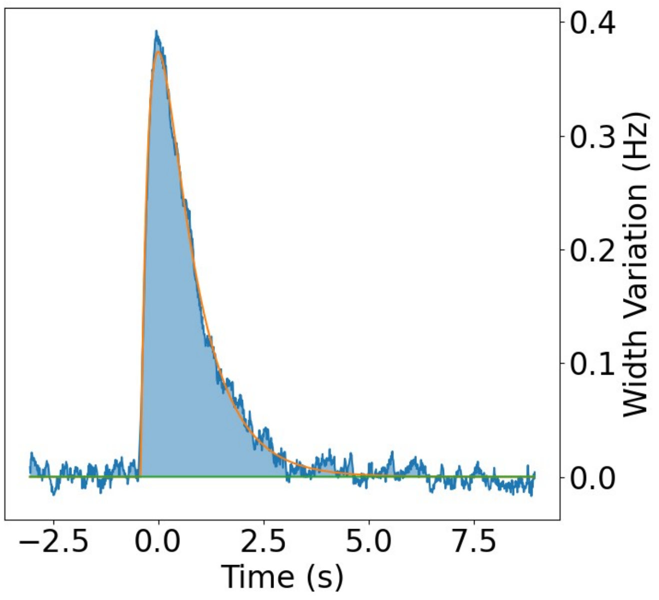




Bolometer in He3: calibration

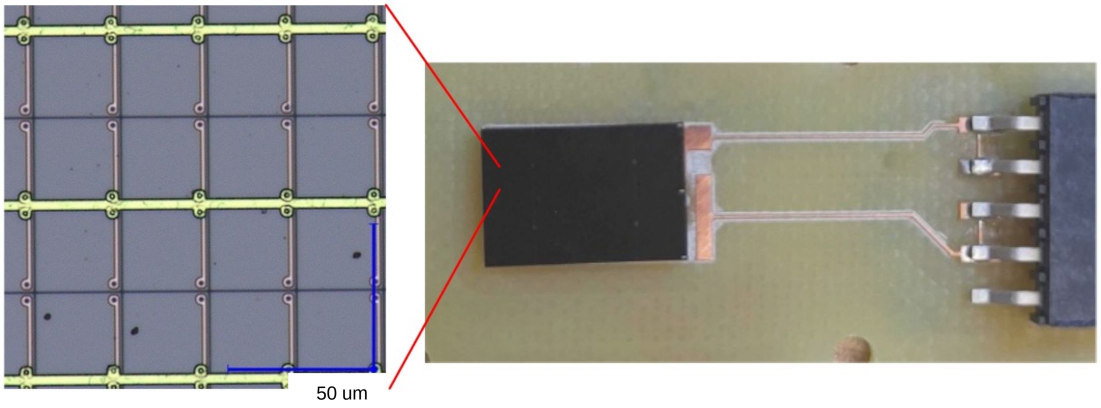
DATA!

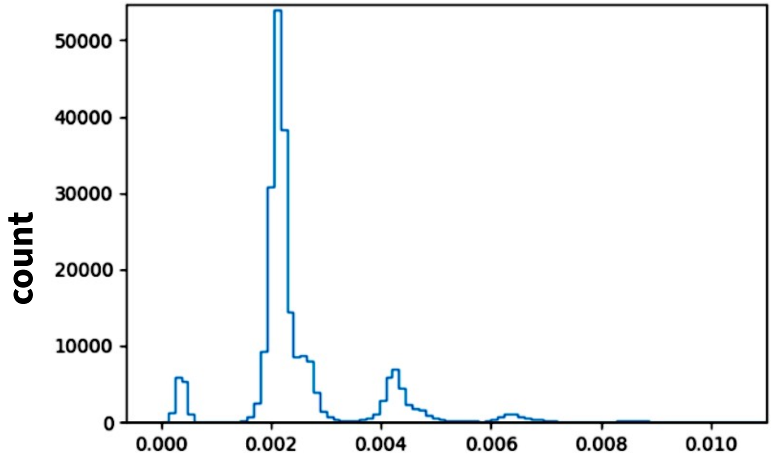




Photon sensing

- Silicon PhotoMultipliers explored for photon sensing
- SIPMs have high-gain and single photon resolution
- Wave length shift to near-UV
- Successfully tested at 4K `[A. Ferri et al, 2016 JINST 11 P03023]`





QUEST-DMC

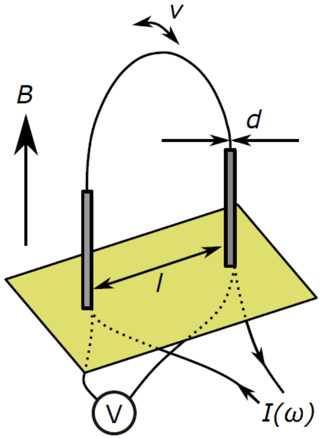
Target → Detector → Readout

Quantum sensor

Bolometer in He3

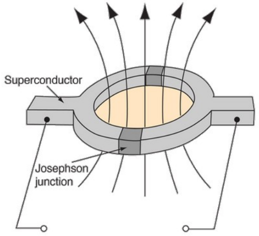
Readout

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



Lock-in amplifier

SQUID readout



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

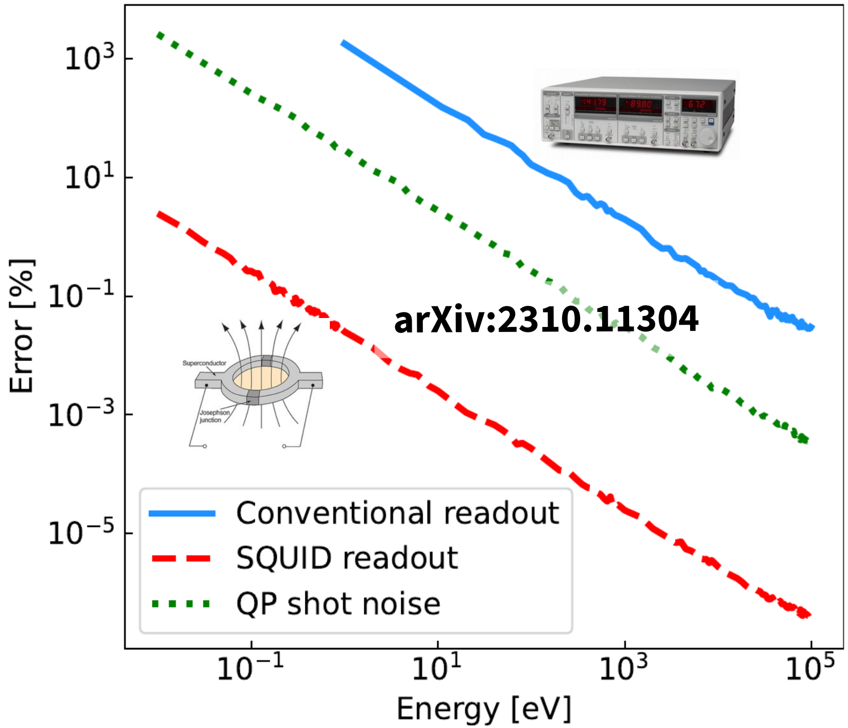
Magnetometer, 10^{-14} T (brain: 10^{-13}T)

Magnetic flux into electrical voltage

Readout sensitivity

Readout

- Error on the energy measurement ↔ dark matter energy threshold



Conventional: 31 eV

SQUID: 0.51 eV

Analysis

Background

Analysis

- Cosmic rays
- Radioactive decays
  - Environment
  - Contamination
  - Materials
- Neutrinos (irreducible)

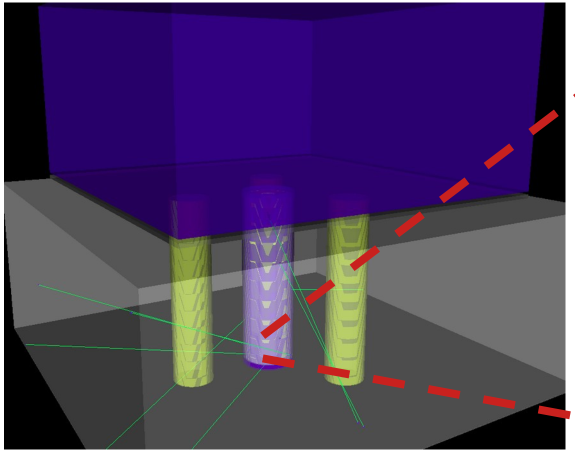
Alphas
Betas
Gammas
Neutrons
Muons

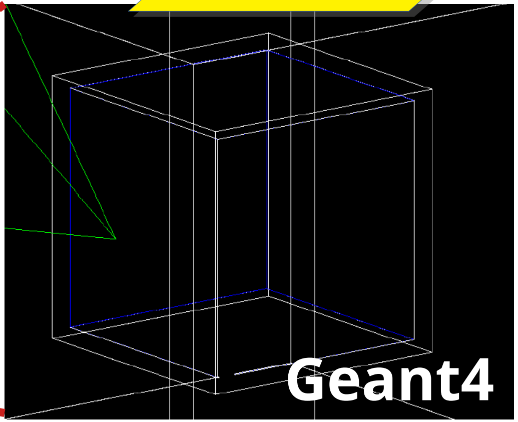
→ **Goal**: 1 background event/kg/day

Background: radiogenic

Analysis

- Geant4 simulation
  - Energy deposited in the cm^3 He^3 cell
- Estimated activity
  - Radiopurity database
  - Screening of the materials





Beta decay from epoxy cell

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

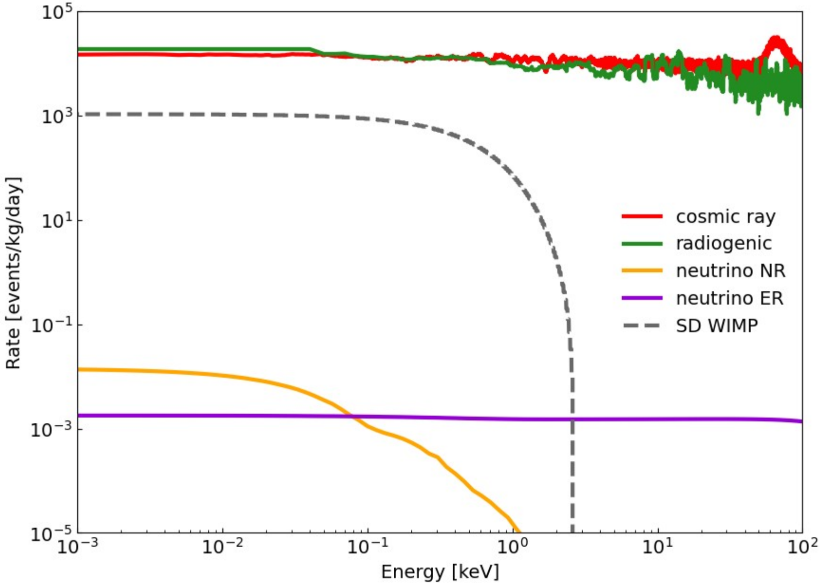
BOULBY UNDERGROUND LABORATORY

Background: neutrino and cosmics

Analysis

- **Neutrinos** from nuclear processes in the Sun:
  - proton-proton chain: 99% of solar energy
  - CNO chain: 1%
  - Experimental values + solar models
  - Nuclear and Electron recoils

- **Cosmics**
  - CRY generator + GEANT4
  - Assumed 90% vetoing efficiency

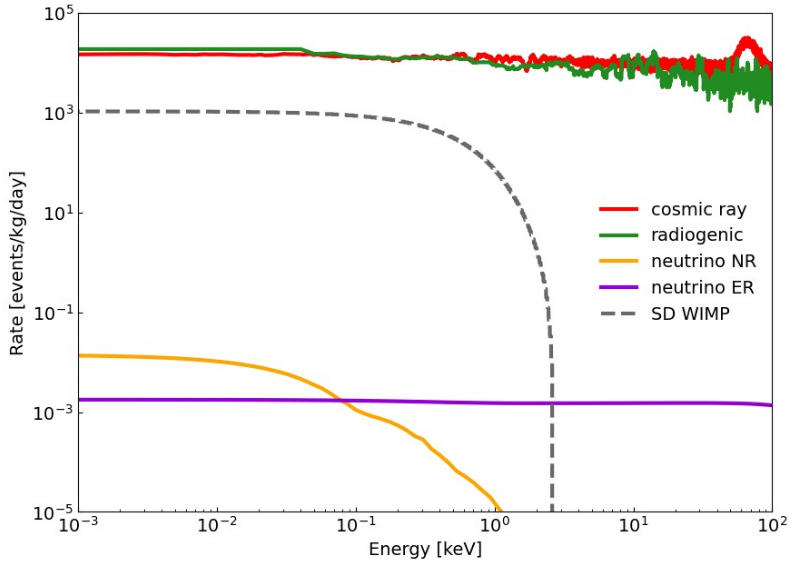


Background

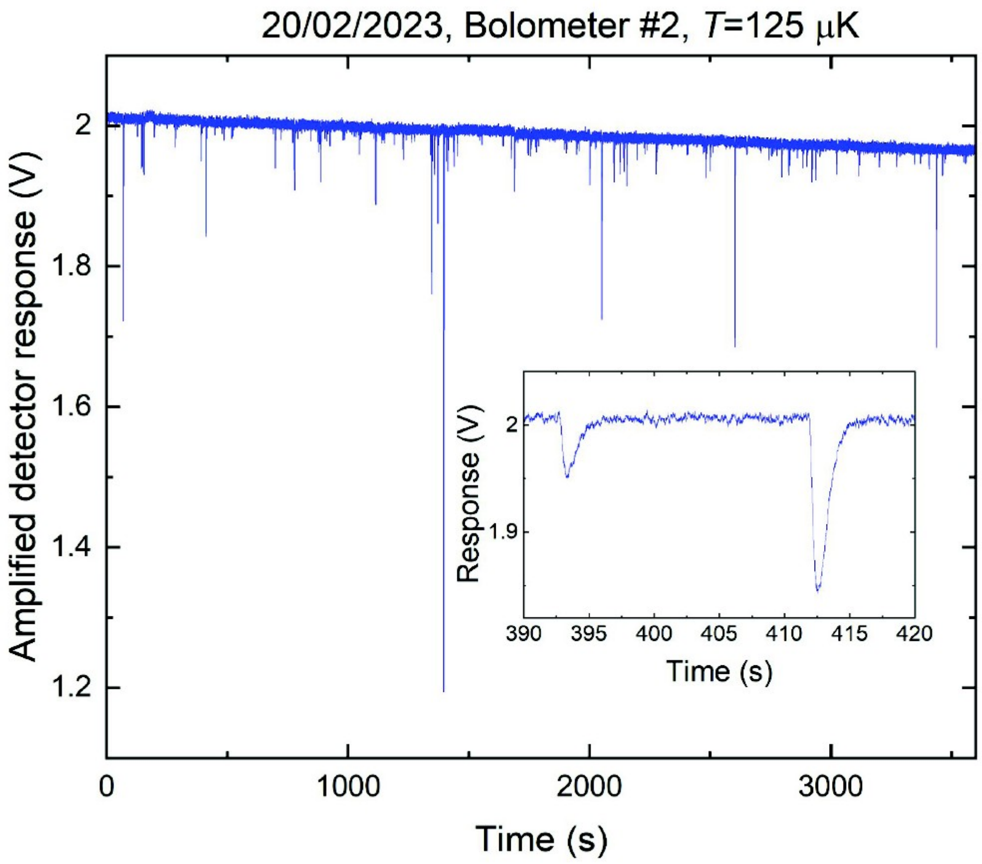
Analysis

- Current setup, estimated event rates in the ROI

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	



Bolometer in He3: events



Extract:

- Rate of background events
- Energy spectrum
- Energy threshold

Sensitivity projection

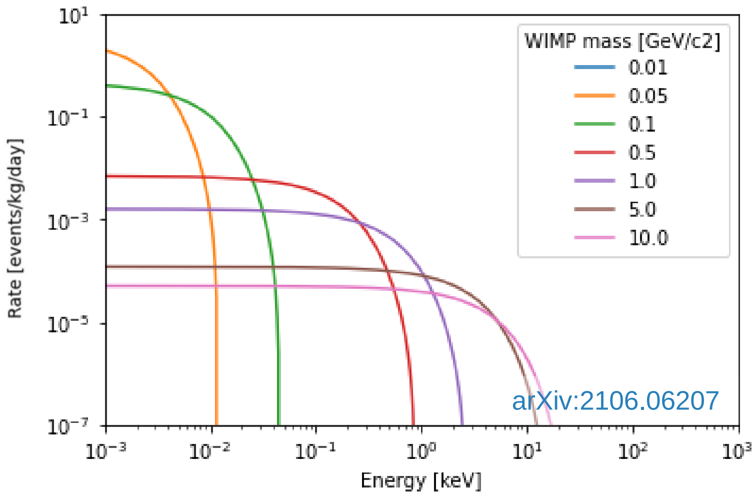
submitted

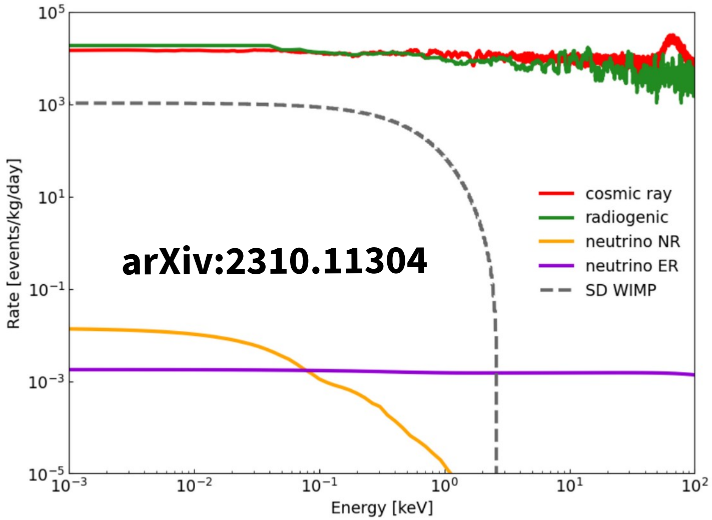
Signal simulation

Background simulation

Detector response model

Sensitivity for dark matter





Sensitivity projection

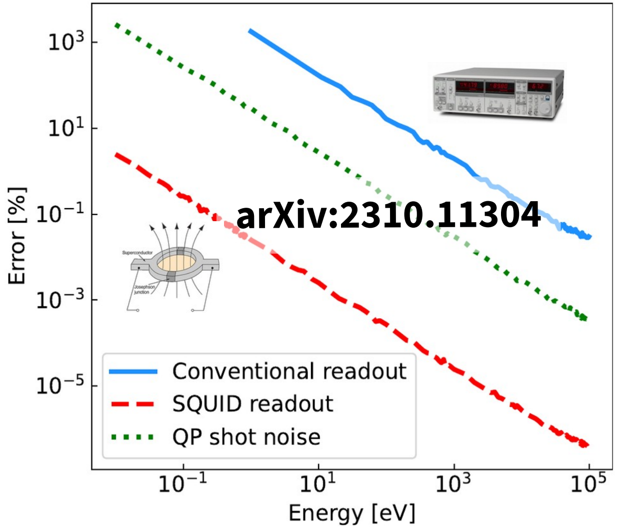
submitted

Signal simulation

Background simulation

Detector response model

Sensitivity for dark matter



Sensitivity projection

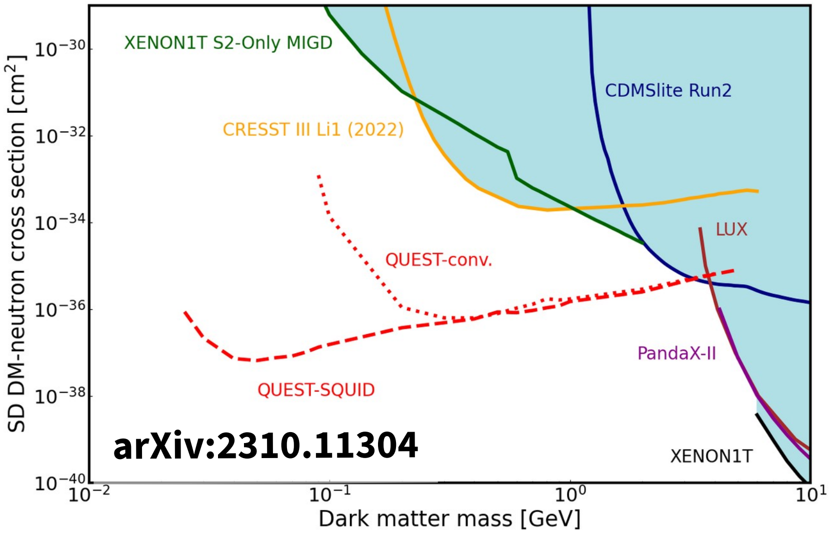
submitted

Signal simulation

Background simulation

→ Detector response model → Sensitivity for dark matter

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

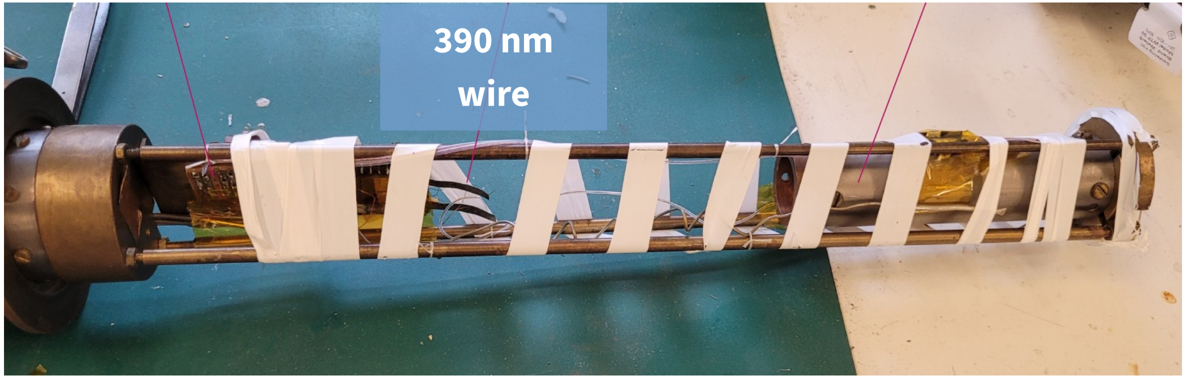


Conclusion and outlook

- **Simulation** and **analysis** tools in place
- Produced a **first sensitivity limit**, based on actual constructed detector cells and modelled energy reconstruction validated on data (submitted to EPJ-c)

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

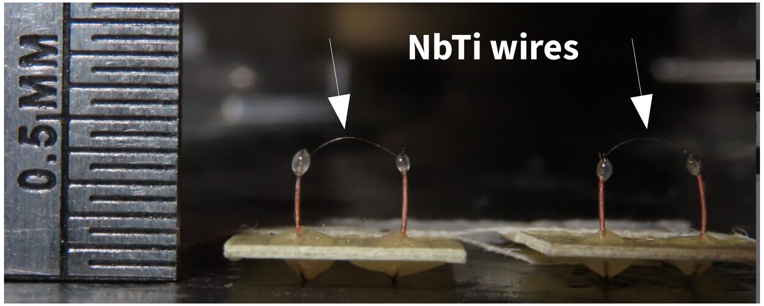
Conclusion and outlook

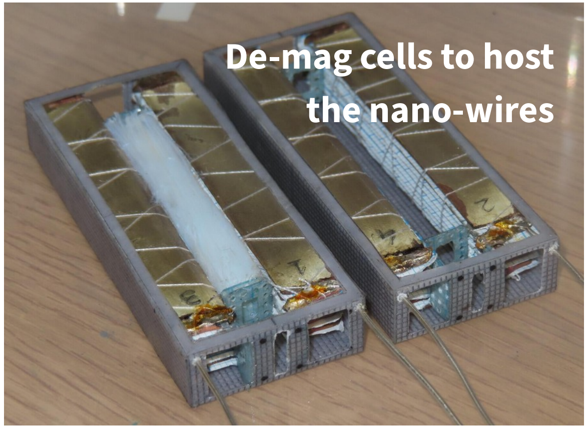


- SQUID being operated at RHUL
- To be operated at uK tempeatures in Lancaster

Conclusion and outlook

- Work towards SQUID readout of nanowires
- Start operating ^{3}He cells with nanowires





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" - submitted to EPC-J
https://arxiv.org/abs/2310.11304