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

Paolo Franchini

GUINEAPIG 2023
Montreal,
12 July 2023

200 days of French

Write this in French

Duo, where are your arms?

Duo | où | sont | tes | bras

Fill in the blanks

Le cheval est gentil et les vaches sont gentilles .

Write this in English

Ses oreilles sont plus grandes que ses pieds.

His | ears | are | bigger | than | his | feet

Le chef ne va nulle part sans son pingouin.

The | boss | isn't | going | anywhere | without | his | penguin

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

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- Future prospects

Helium-3

Lancaster refrigerator

Nanowires

SQUID sensor

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

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

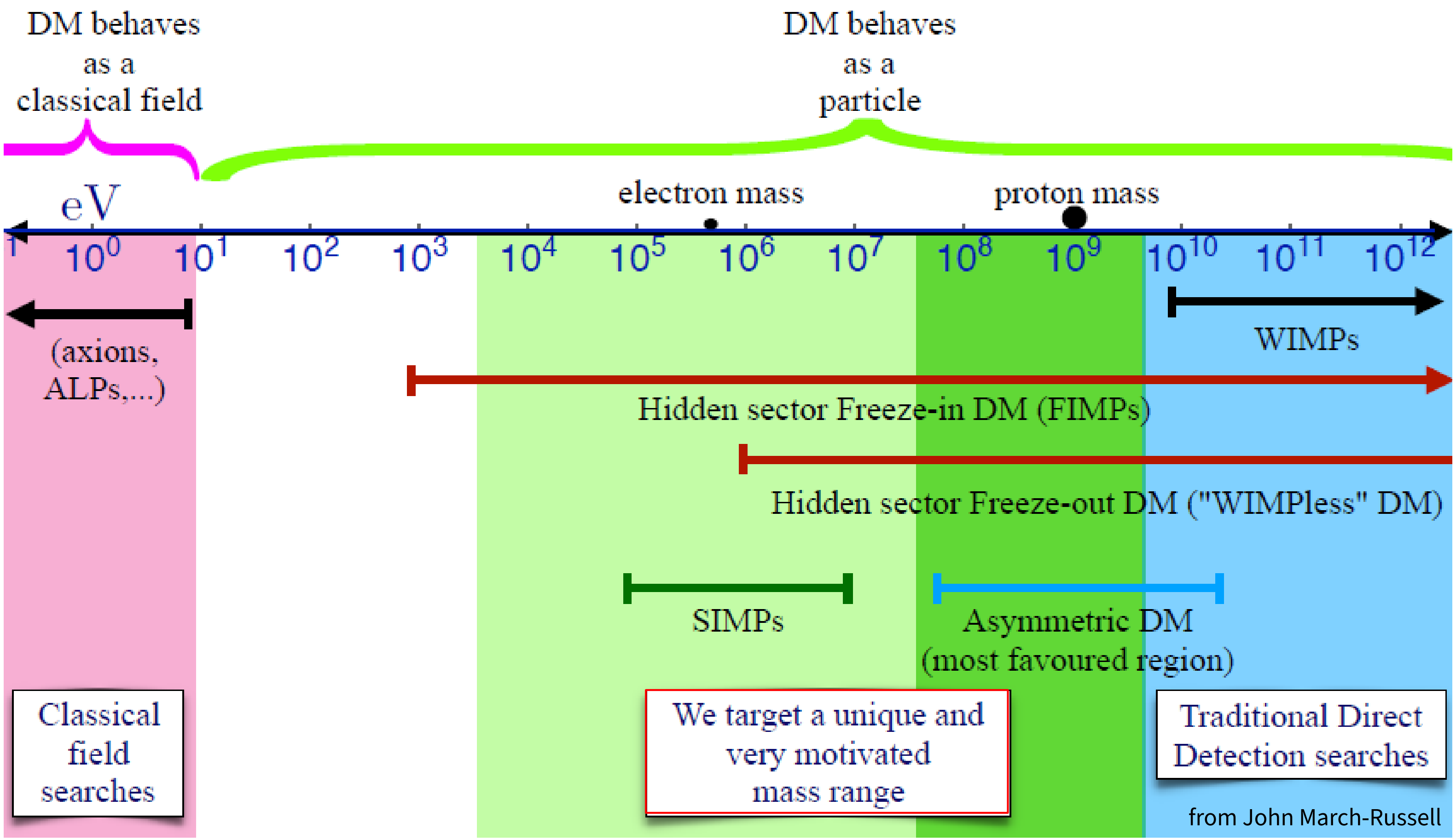
Socrates:
0 books

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

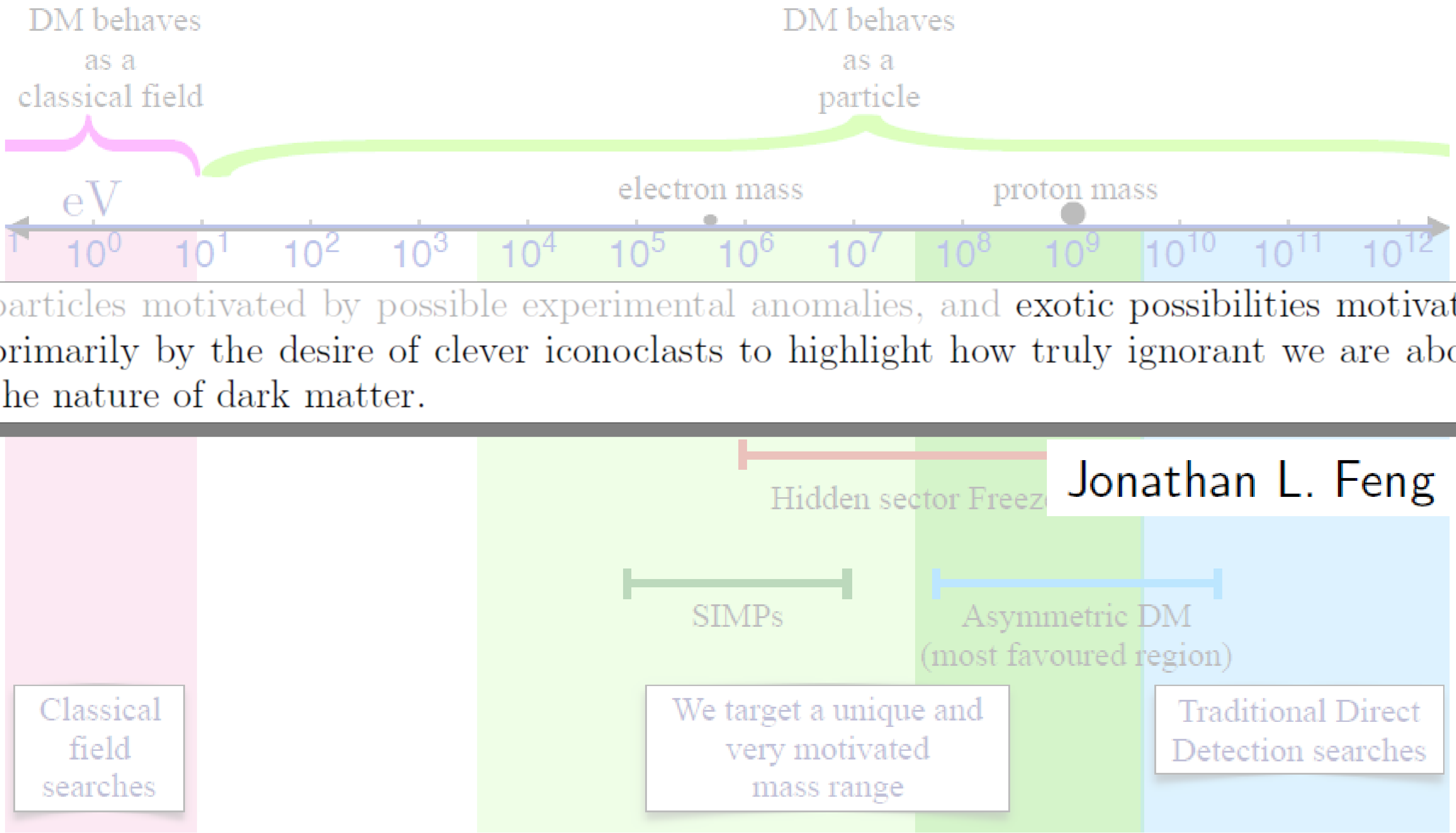
Socrates:
0 books

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

Direct dark matter detection: candidates



Direct dark matter detection: candidates



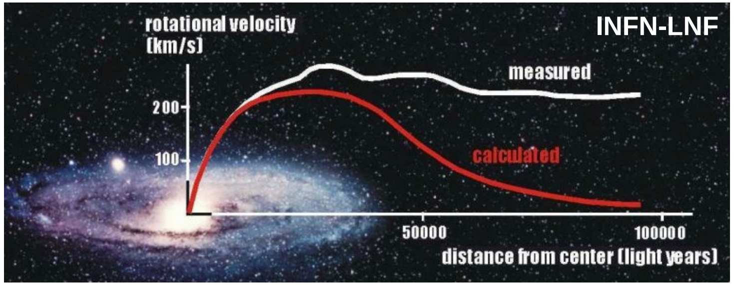
particles motivated by possible experimental anomalies, and exotic possibilities motivated primarily by the desire of clever iconoclasts to highlight how truly ignorant we are about the nature of dark matter.

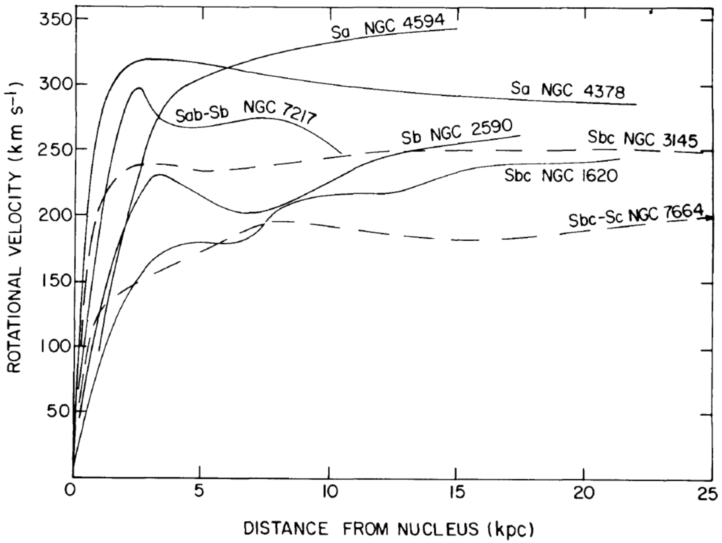
Jonathan L. Feng

The dark matter hypothesis

- 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?

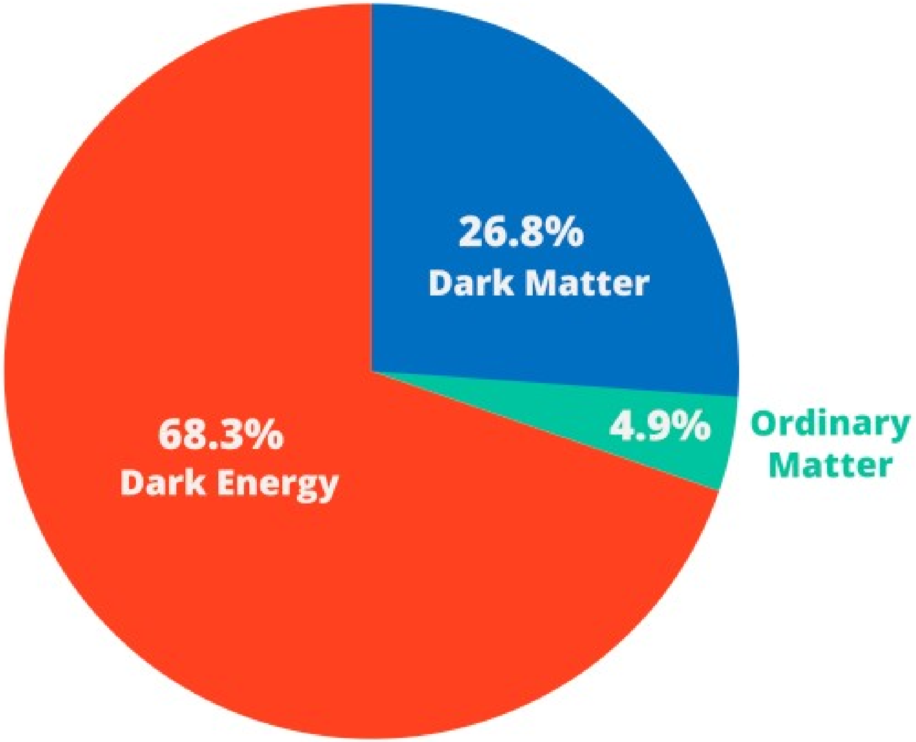




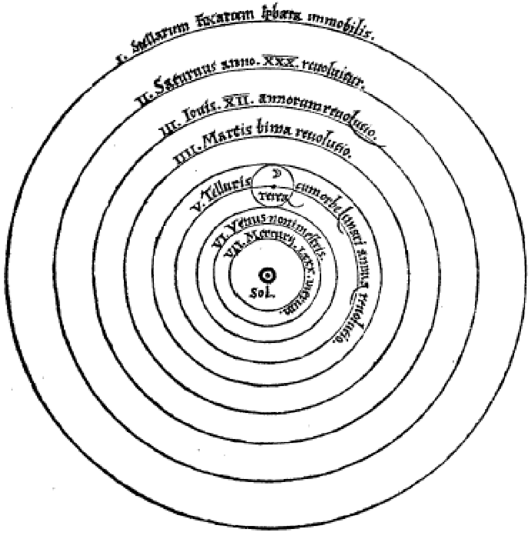
Rubin, V.C.; Thonnard, N.; Ford, W.K. Jr. (1978)

The dark matter hypothesis

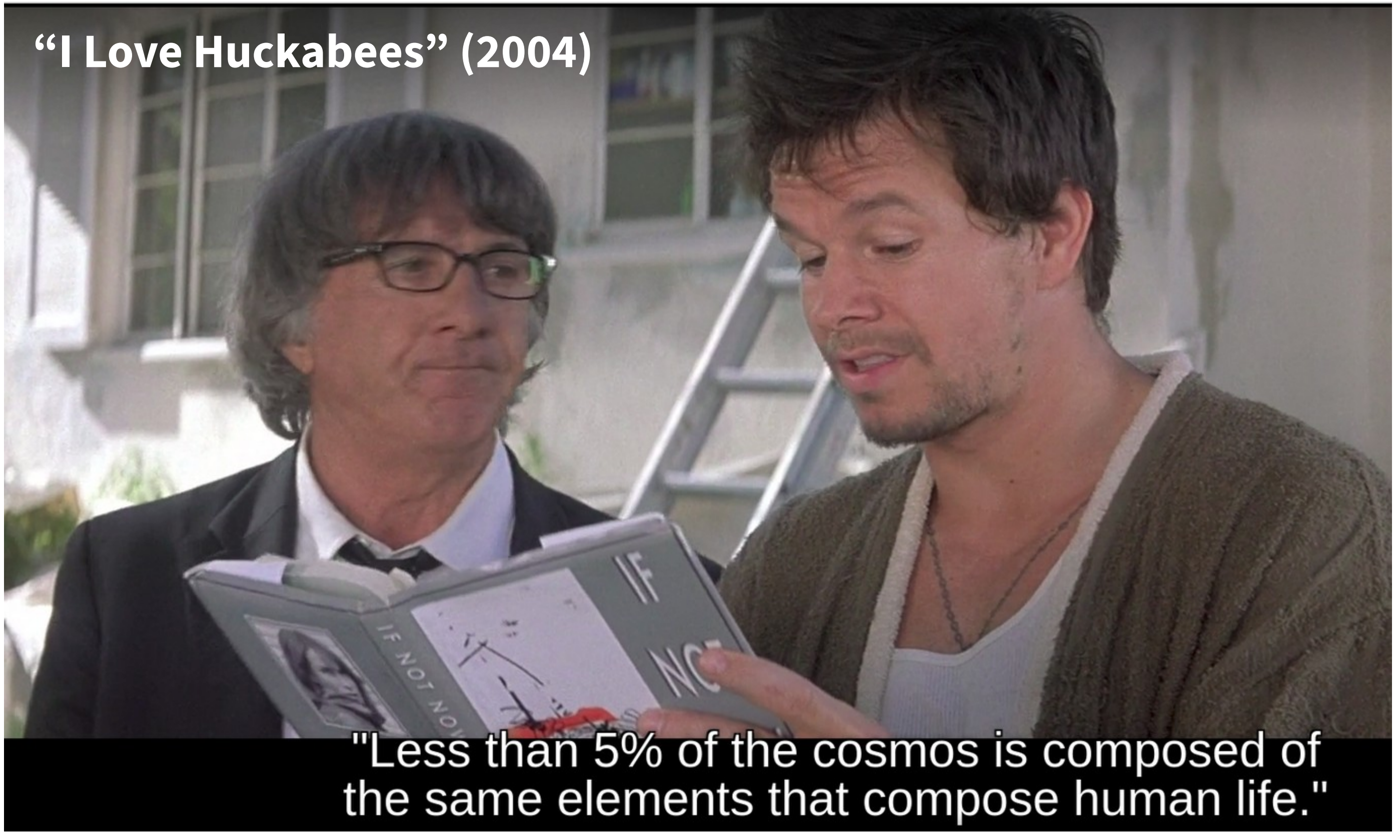
- Matter and energy content of the universe
- Dark matter is 85% of mass
- *Philosophical implications*



Paradigm shift?

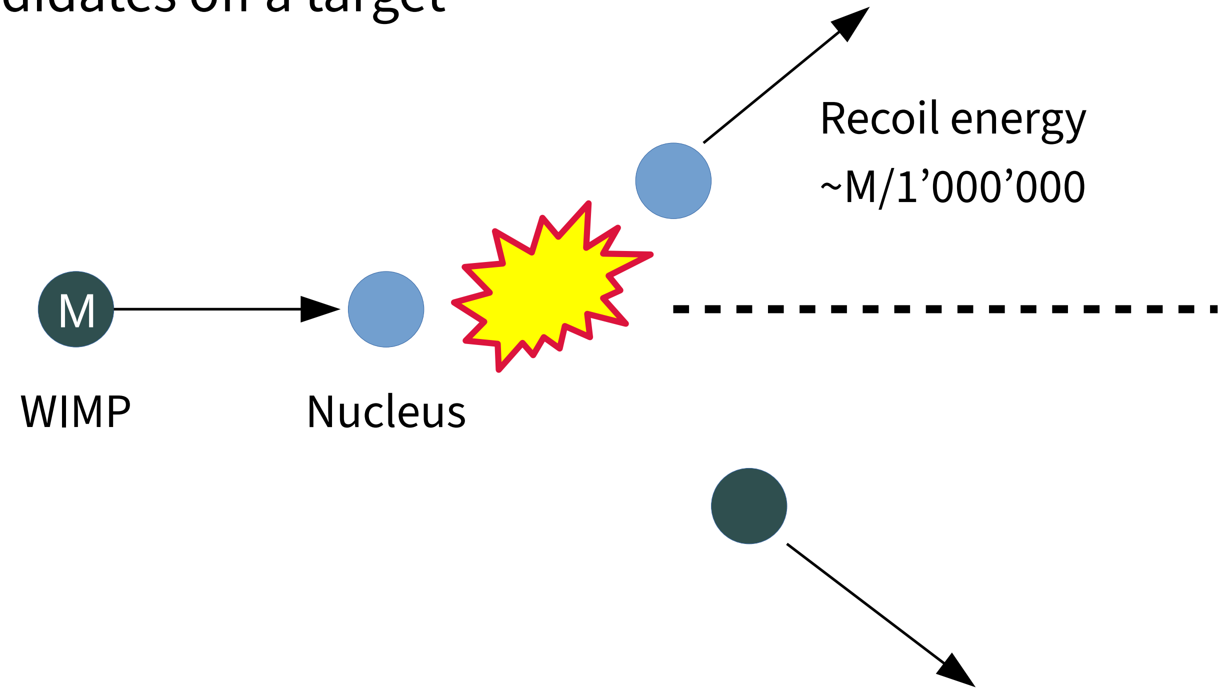


Copernican revolution



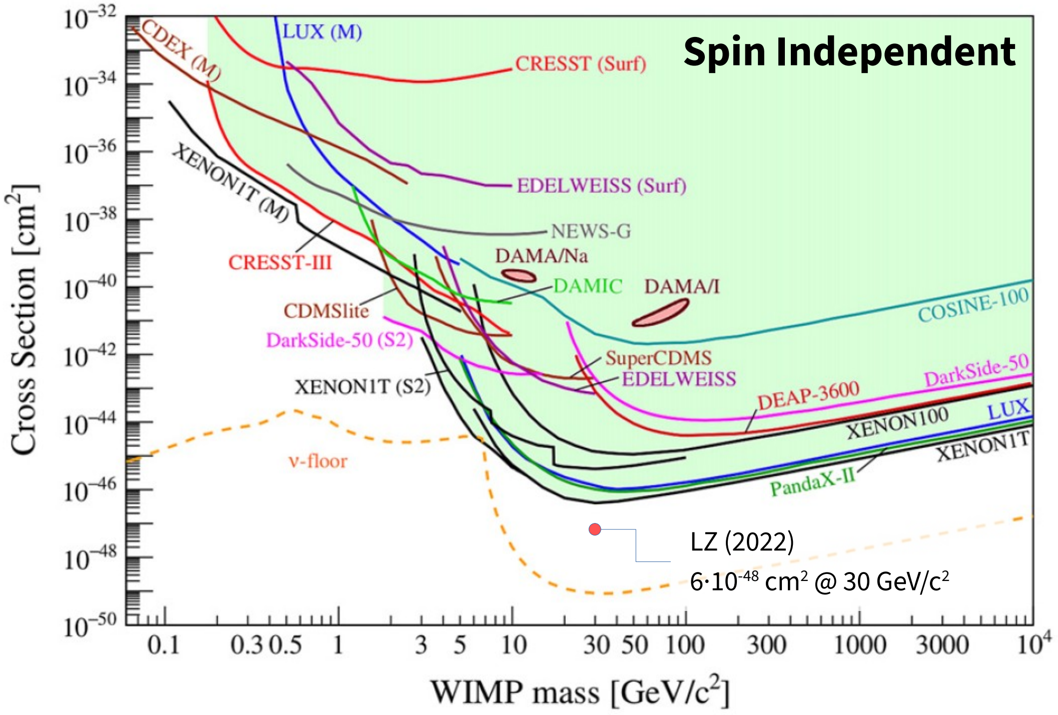
Direct dark matter detection: WIMPs

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

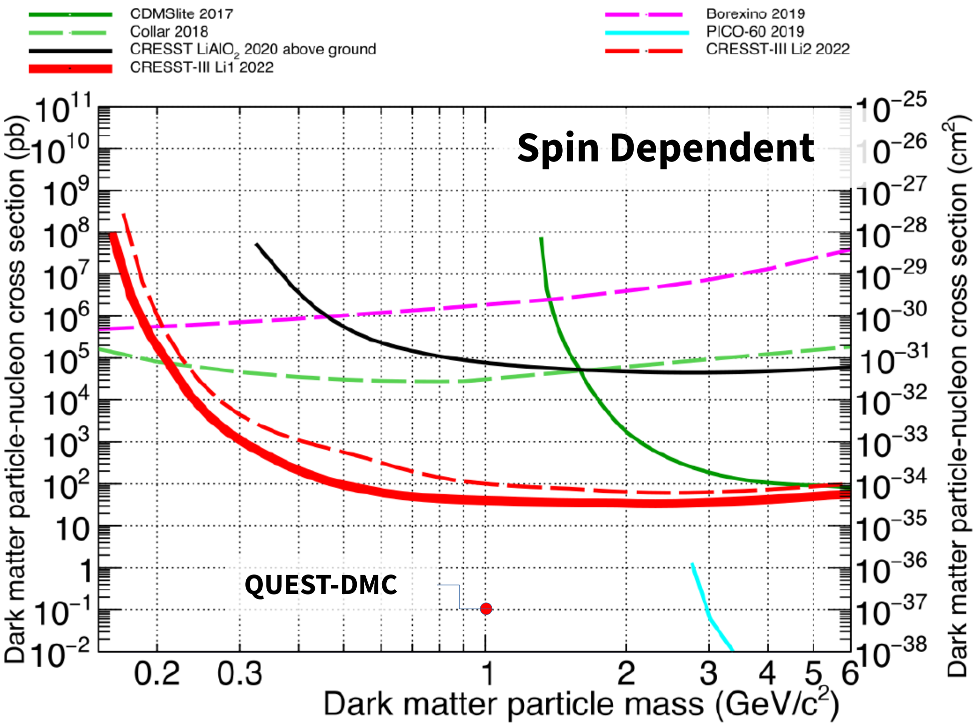


- **Backgrounds:**
  - Cosmic rays
  - Radioactive environment
  - Radioactive contamination
  - Neutrinos

Direct dark matter detection: WIMPs



Rep. Prog. Phys. 85 (2022) 056201



https://arxiv.org/abs/2207.07640

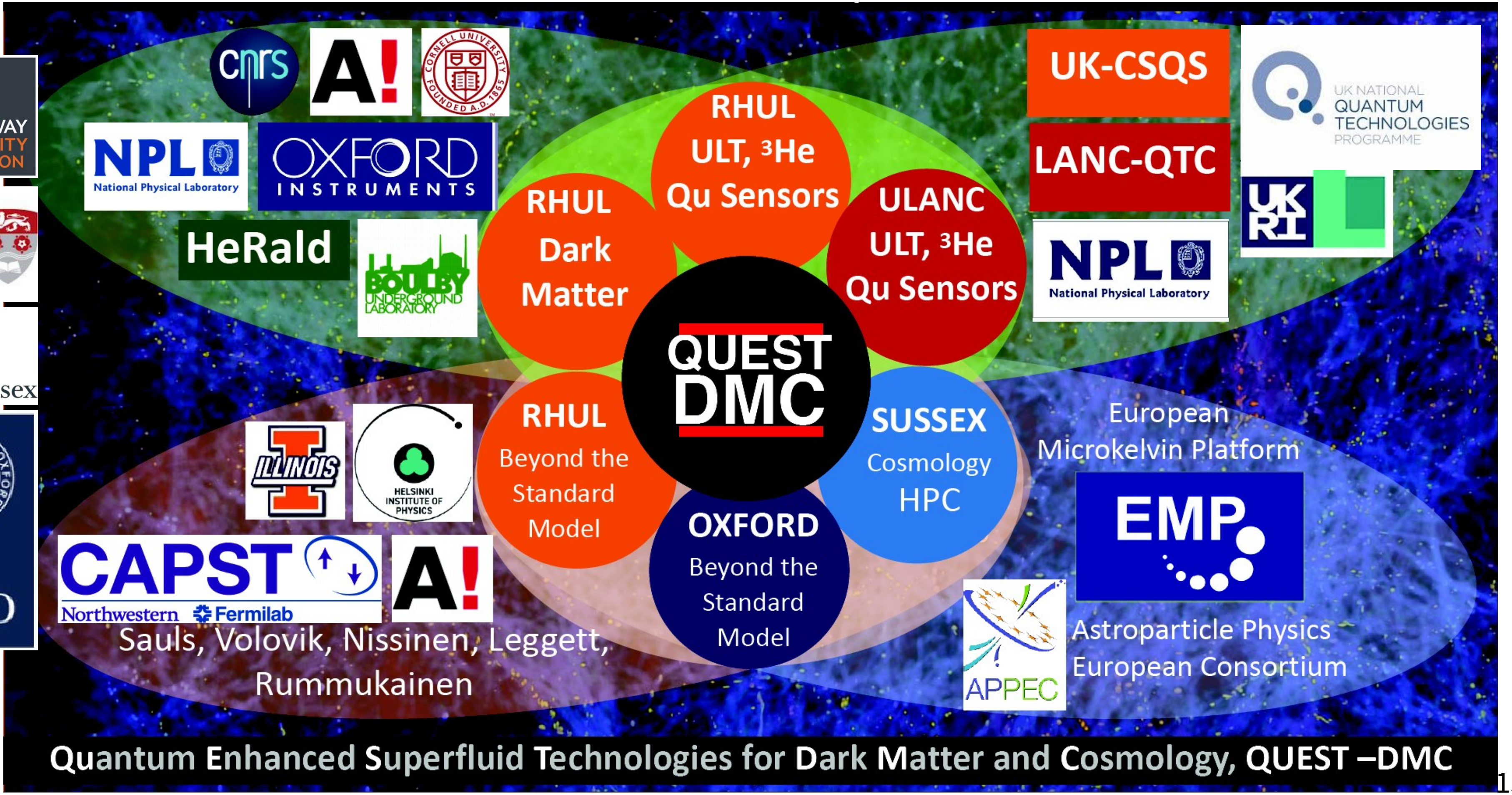
QUEST-DMC collaboration and ecosystem

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

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

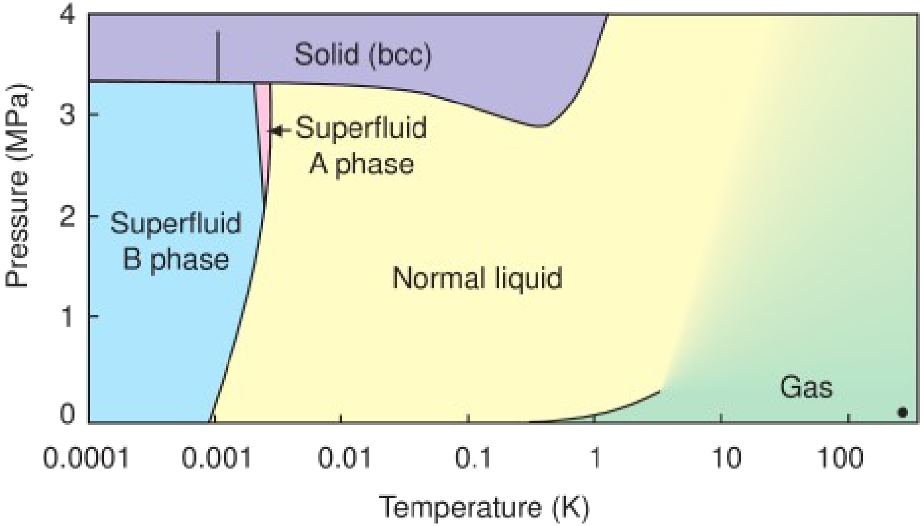
Target → Detector → Readout

Superfluid He3

Helium-3

Target

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

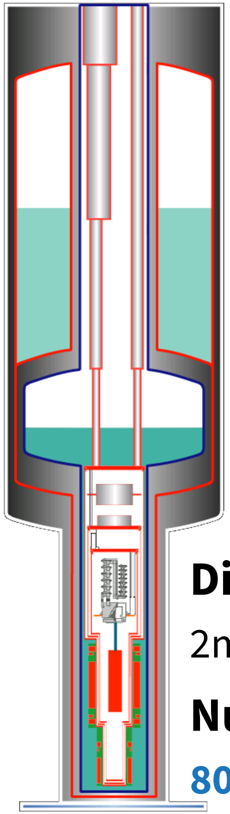


- **^{3}He-B**:
  - He3 as a fermionic condensate (similar to BSC theory)
  - Cooper pairs: composite bosons, 100nm size
  - Pair of bound quasiparticles with 10^{-7} eV energy and an effective mass

Lancaster advanced refrigerator

Target

Lancaster University



Wet dilution refrigerator

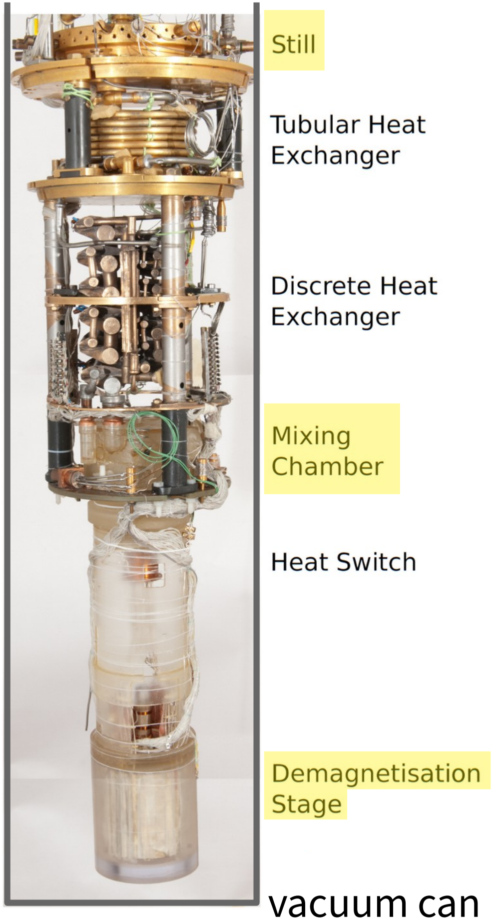
Target

0.5 K

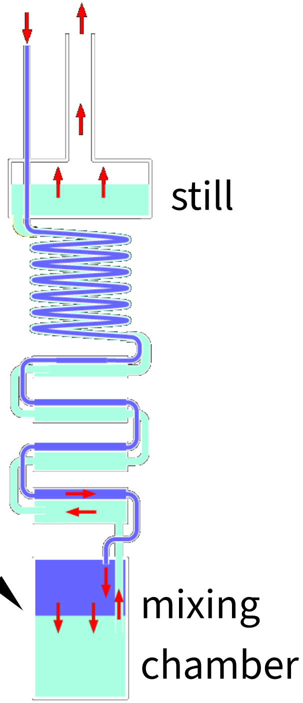
1.6 mK

world record

80 uK

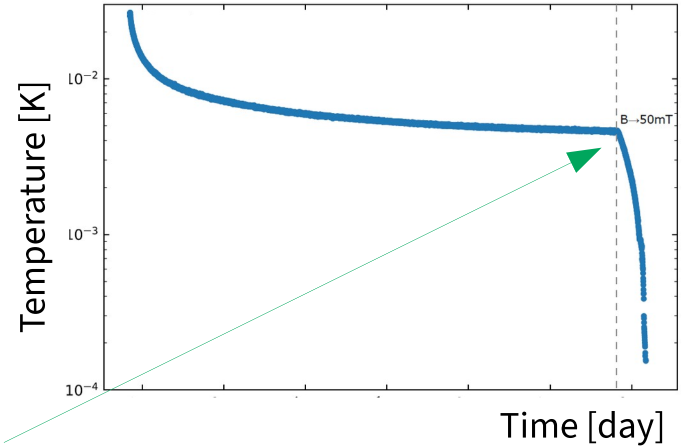


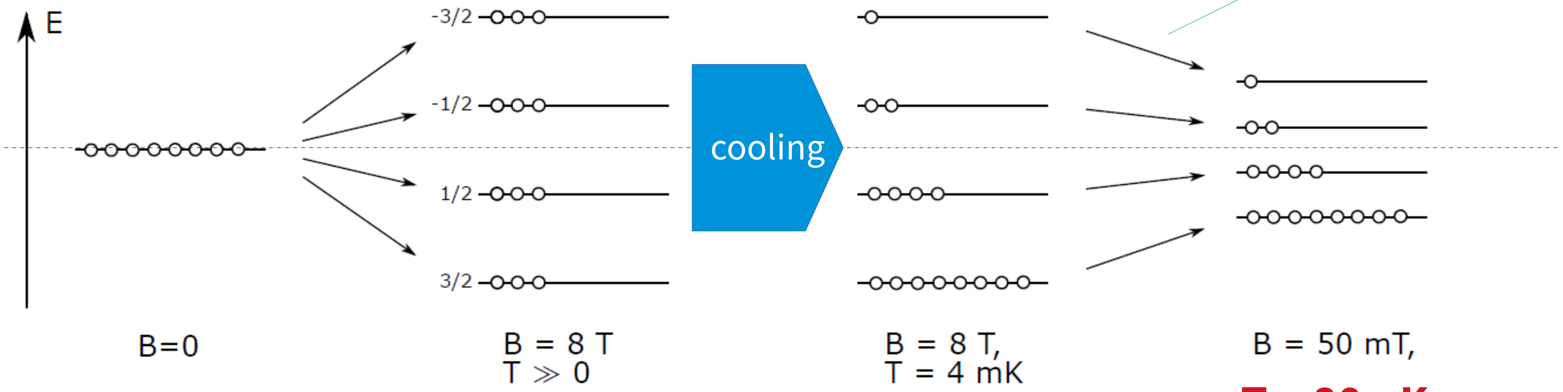
- Still (He4)
- Heat exchangers
- **Mixing chamber**
  - He3 concentrate and diluted phases
  - Dilution process absorbs heat
  - Diluted He3 back up in the still
  - Cooling of concentrated in the way



Nuclear demagnetisation refrigeration

- Copper lattice (spin 3/2)
- Cooling from adiabatic demagnetisation

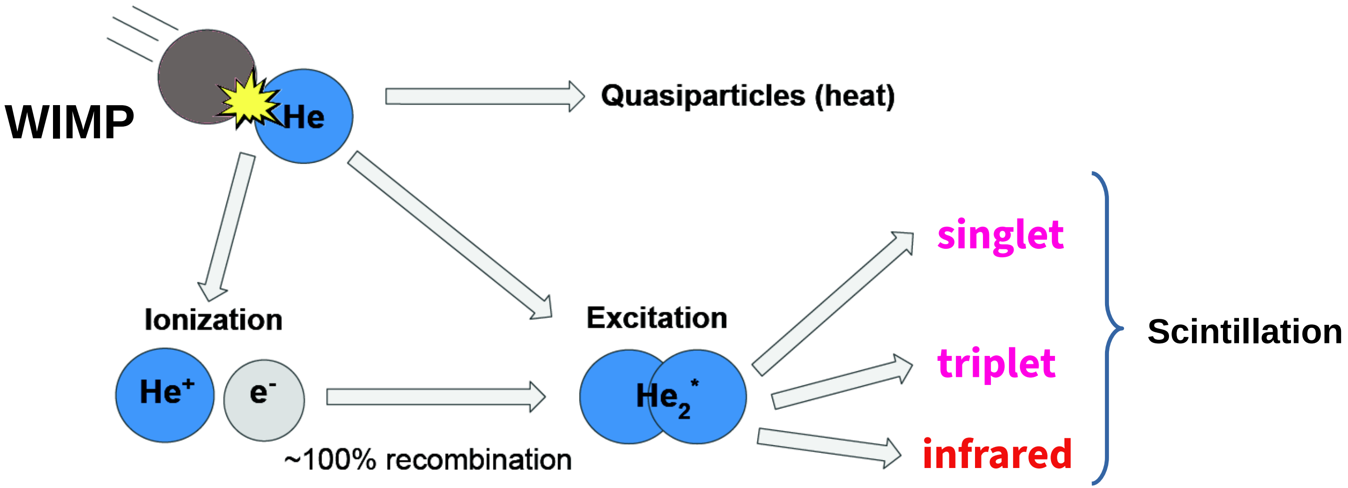


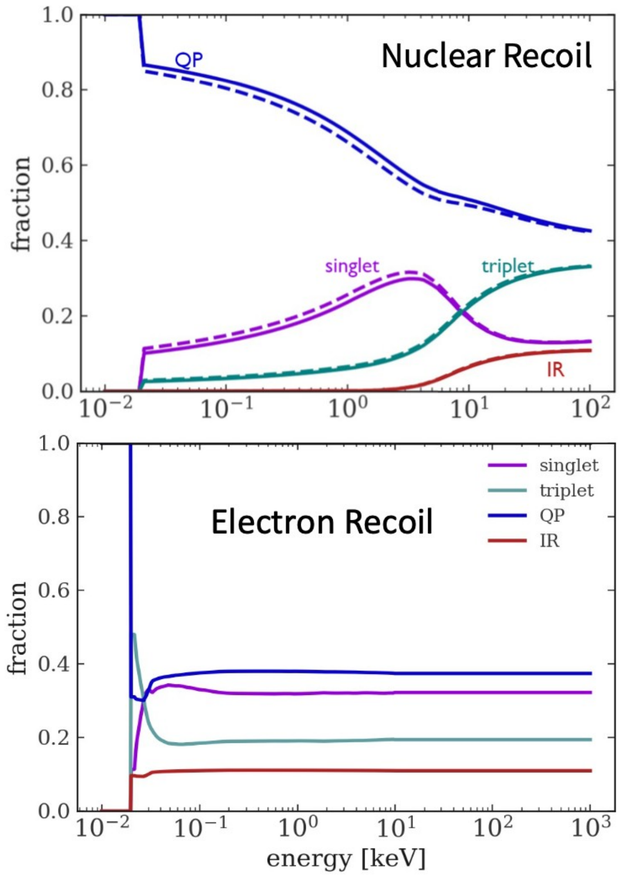


T = 80 uK

Dark Matter events in He3

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





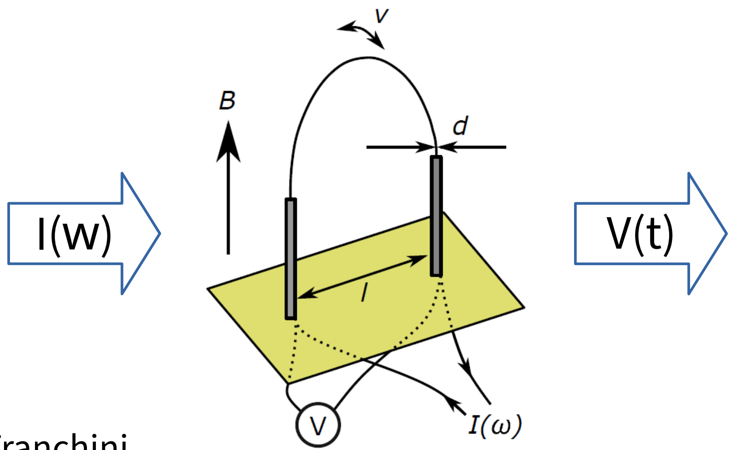
QUEST-DMC

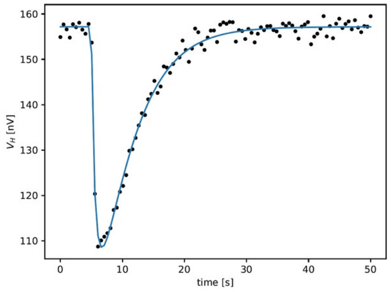
Target → Detector → Readout

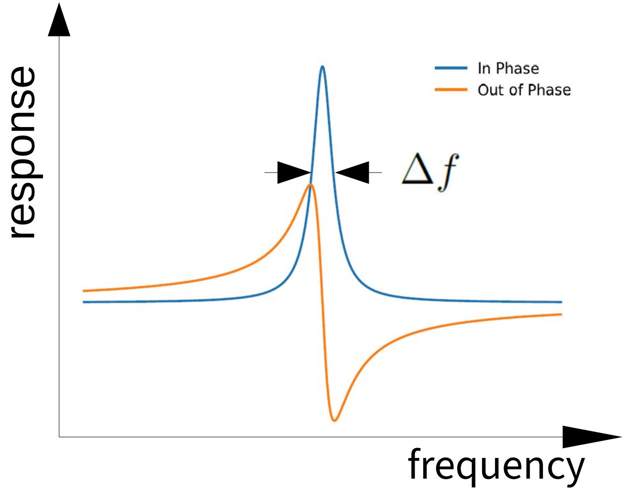
Vibrating nanowire

Bolometer response

- Wire oscillating in magnetic field in a He3 cm^3 box
- Damping force on the oscillator, enhanced by Andreev reflections
- Voltage response
- Measure **energy deposition** as variation of the resonance width Δf

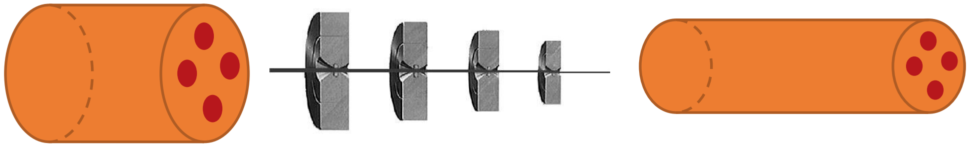


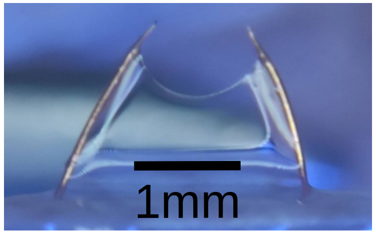


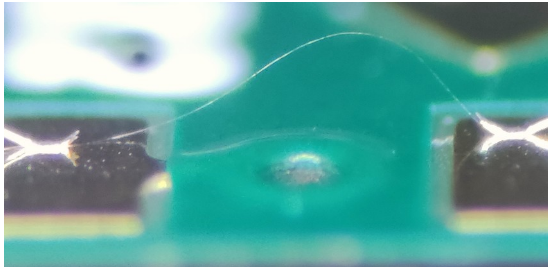


Lancaster nanowires

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







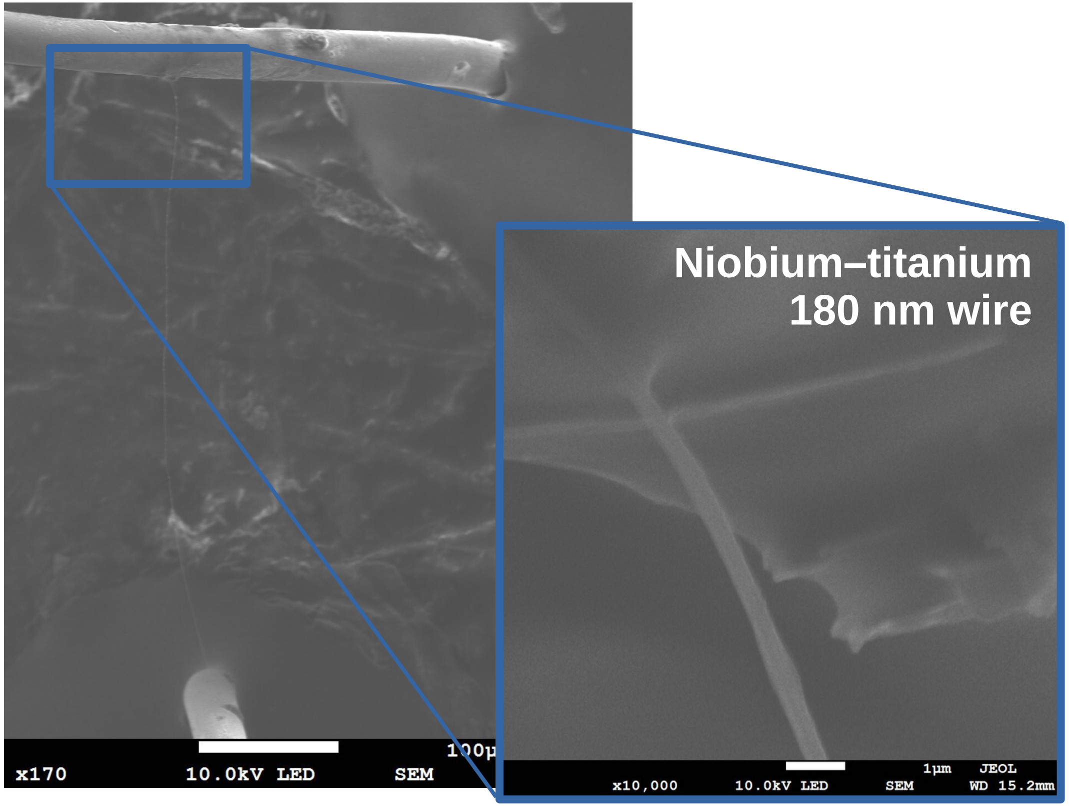
Lancaster nanowires

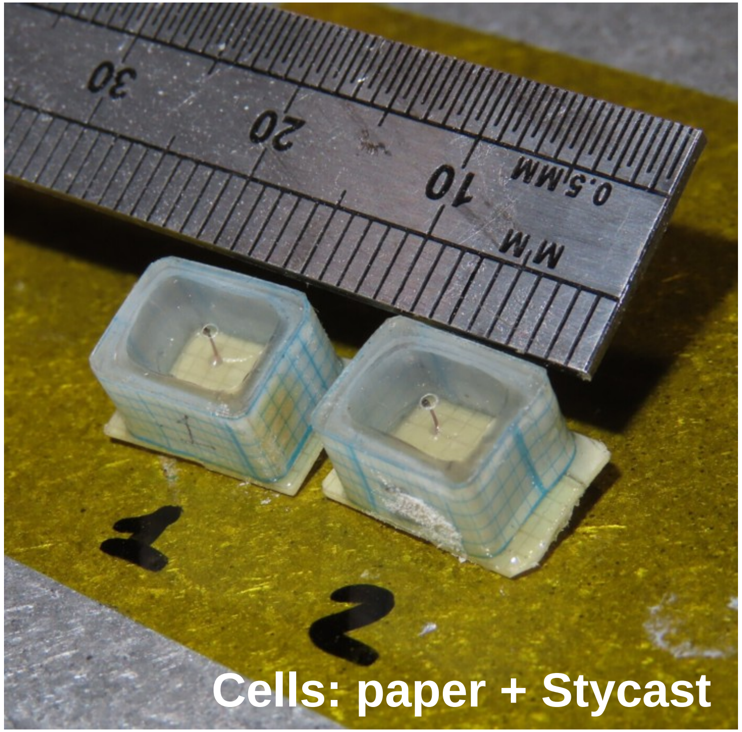
Detector

1/500

of a cat's whisker

Cells with wires





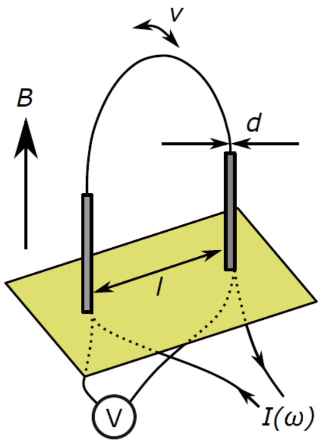
QUEST-DMC

Quantum sensor

Bolometer in He3

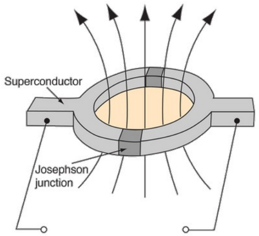
Readout

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



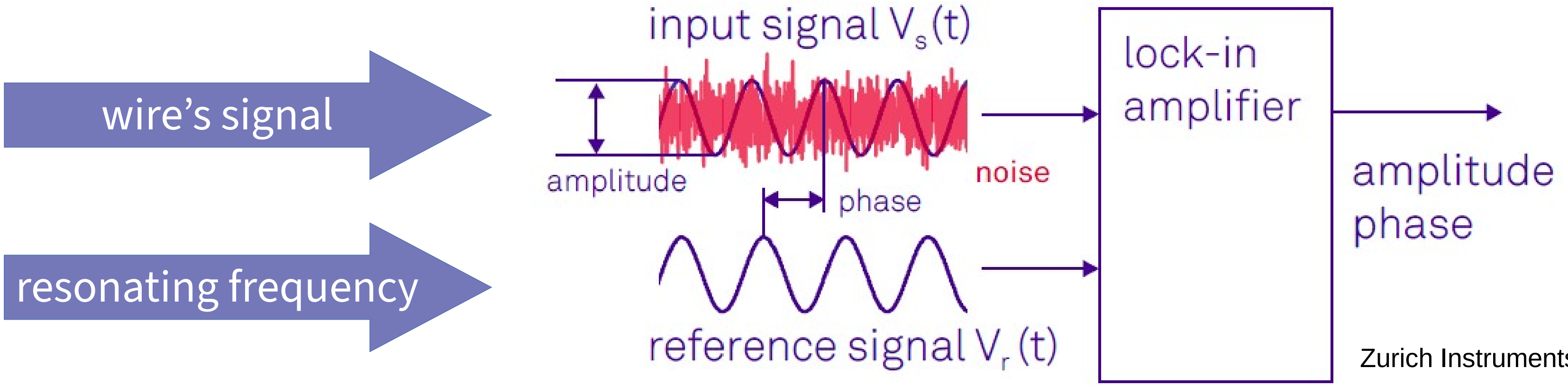
Lock-in amplifier

SQUID readout



Lock-in amplifier

- Extract signal (in a defined frequency band) from a noisy background using a reference signal (RMS noise ~ 10 nV)
  - Amplitude
  - Phase

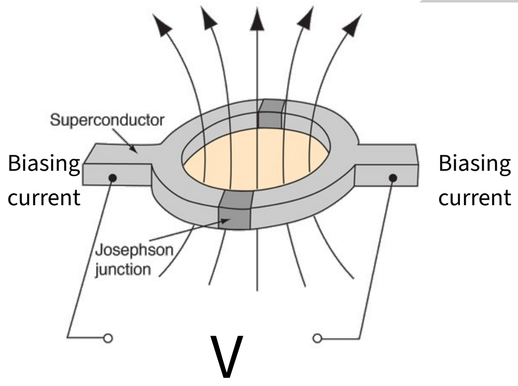


Zurich Instruments

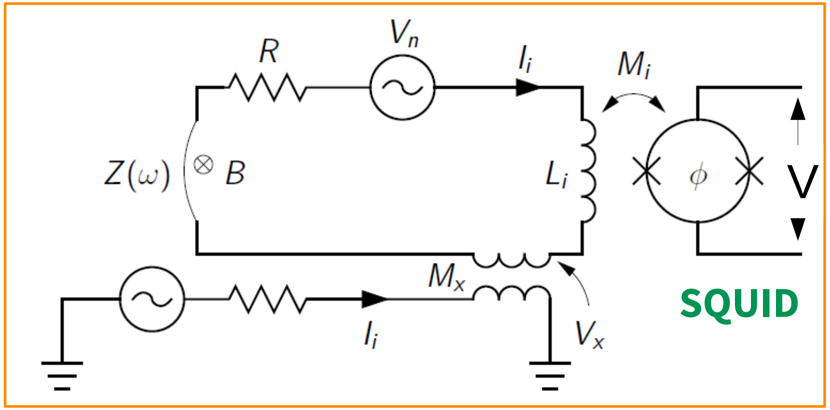
DC SQUID

Readout

- Superconducting QUantum Interference Device
- Magnetometer , 10^{-14} T (brain: 10^{-13}T)
- Magnetic flux into electrical voltage



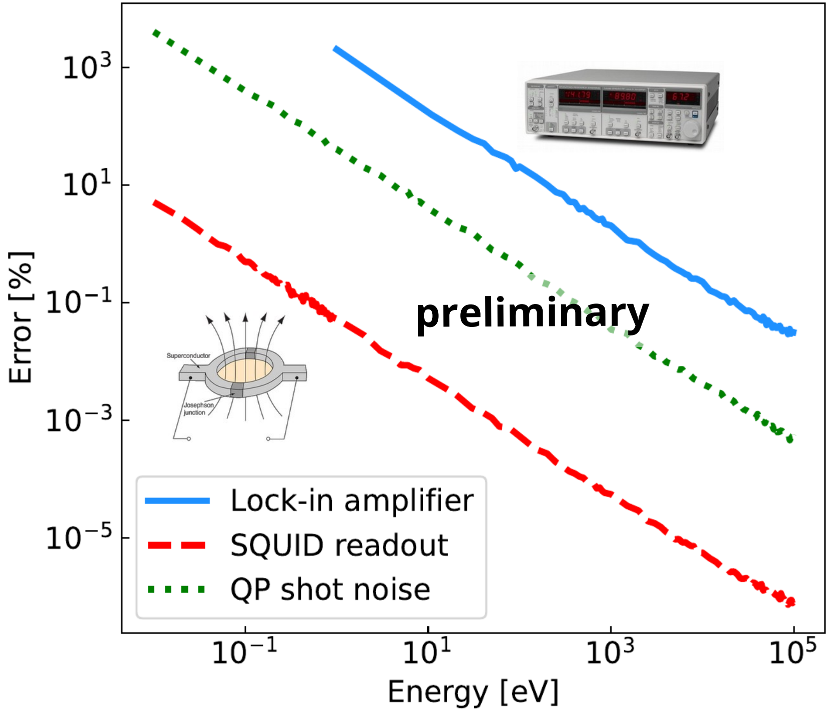
- Voltage drive applied inductively
- Wire has Z(w) impedance
- Output current I_i
- Resulting flux read by SQUID
- Output voltage **V**



Readout sensitivity

Readout

- Error on the energy measurement ↔ DM energy threshold



Conventional: 39 eV

SQUID: 0.71 eV

QUEST-DMC

Analysis

Background

Analysis

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

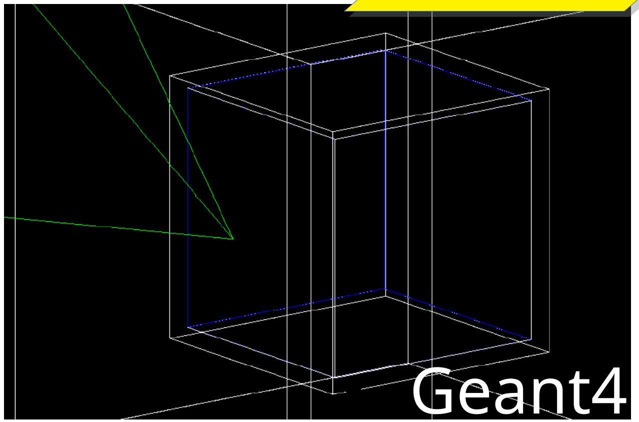
Alphas
Betas
Gammas
Neutrons
Muons

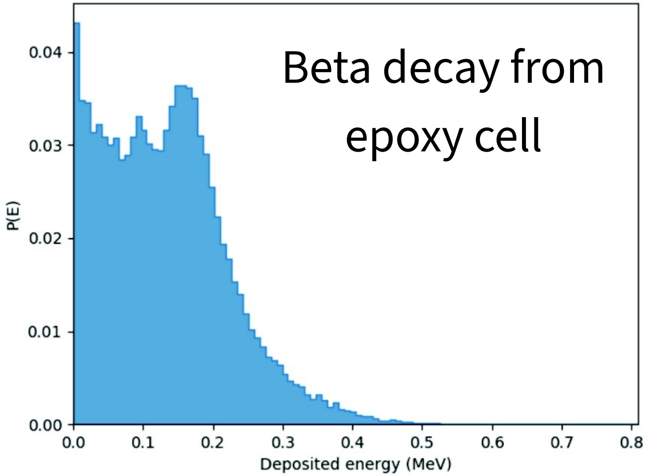
→ **Goal**: 1 background event/kg/day

Background: radiogenic

Analysis

- Simulation of the decays
  - Energy deposited in the cm^3 He^3 cell
- Estimated activity
  - Radiopurity database
  - Screening of the materials
- Probability density functions

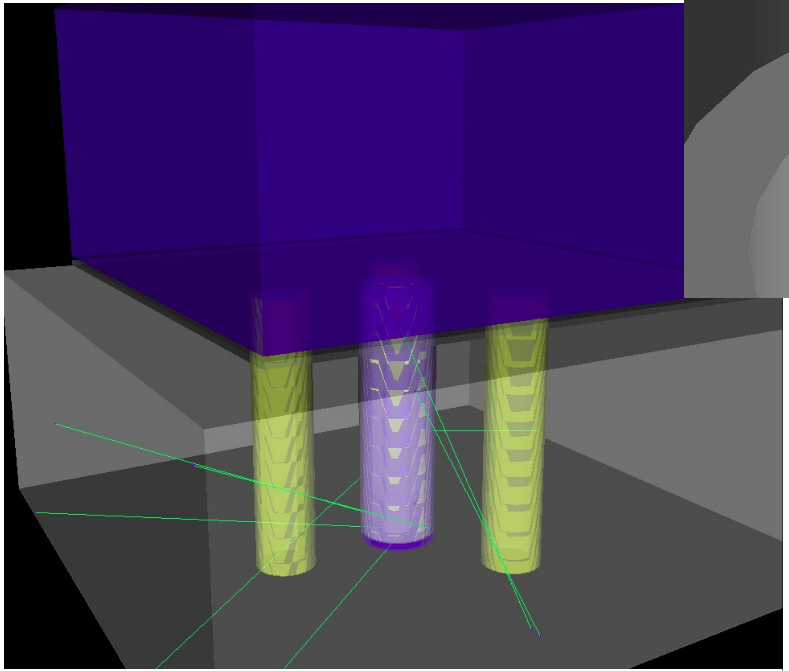


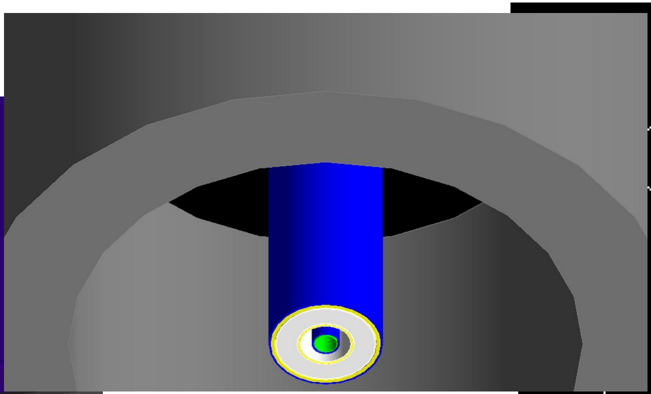


Background: simulation

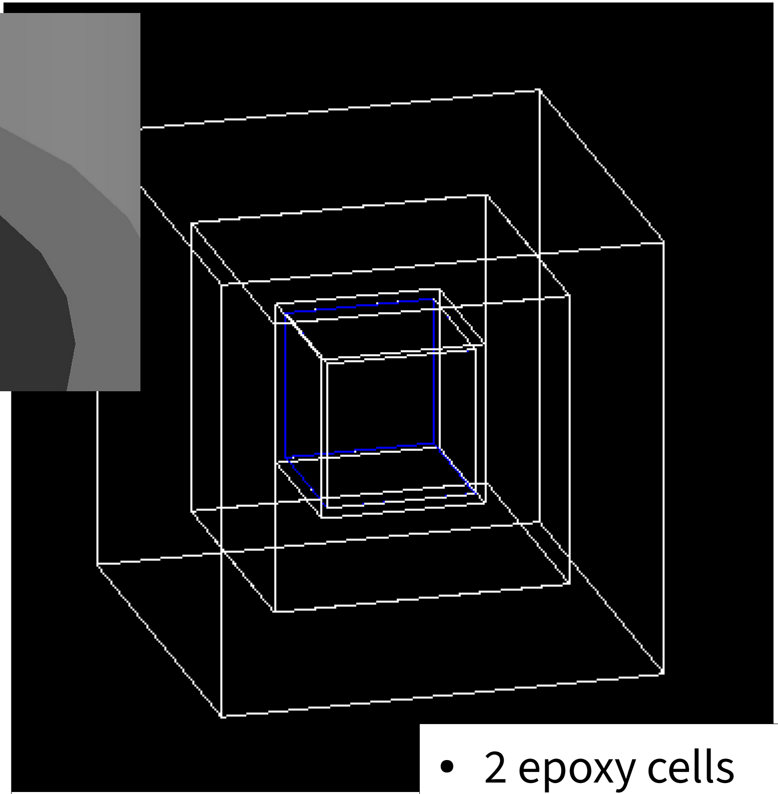
Analysis

Geant4 simulation





- Dewar
- Insulation
- Nitrogen
- Insulation
- Liquid He^4
- Vacuum can
- Radiation shield



- 2 epoxy cells
- **Liquid He^3 cm^3**

Background: screening

Analysis

- Boulby Undeground Laboratory (UK) screening measurements:

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

- Current setup, estimated radiogenic activities:

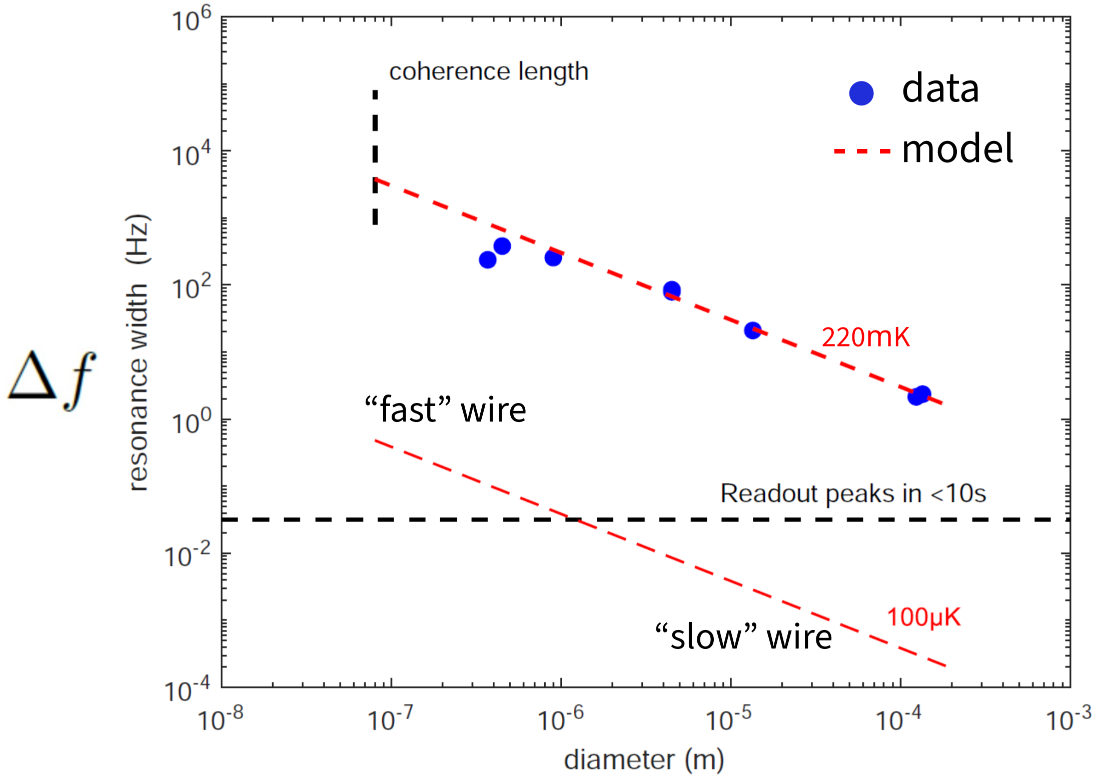
Component	Expected counts [0-10 keV] /kg/day	/cell/day	Uncertainty
Cosmic ray	1.05×10^5	3.31	11 %
Radiogenic ER	8.31×10^4	2.61	14 %
Solar ν ER	1.51×10^{-2}	4.76×10^{-7}	2 %
Solar ν NR	6.37×10^{-4}	2.01×10^{-9}	2 %
TOTAL	1.88×10^5	5.92	

AND NOW FOR SOMETHING COMPLETELY DIFFERENT

Bolometers in He3

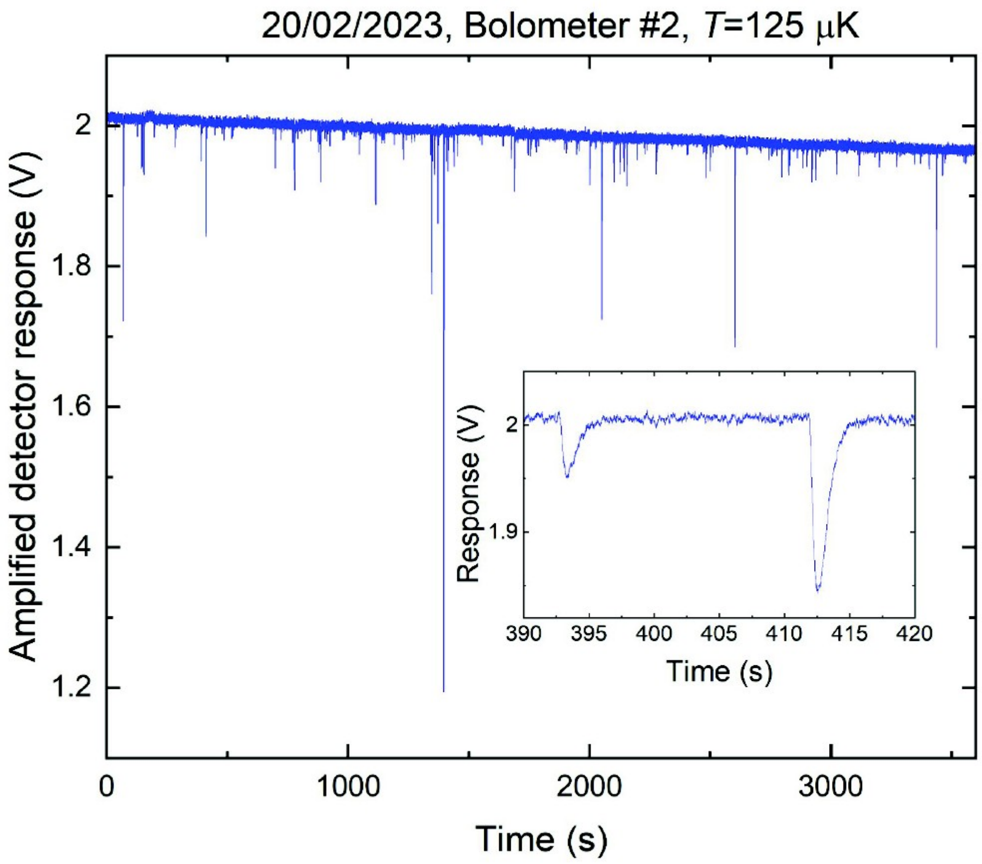
DATA!

- Bolometer operation limitation



Bolometer in He3: events

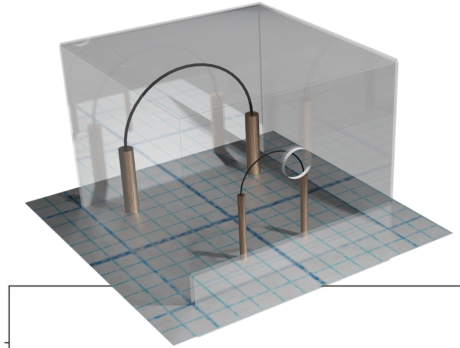
DATA!

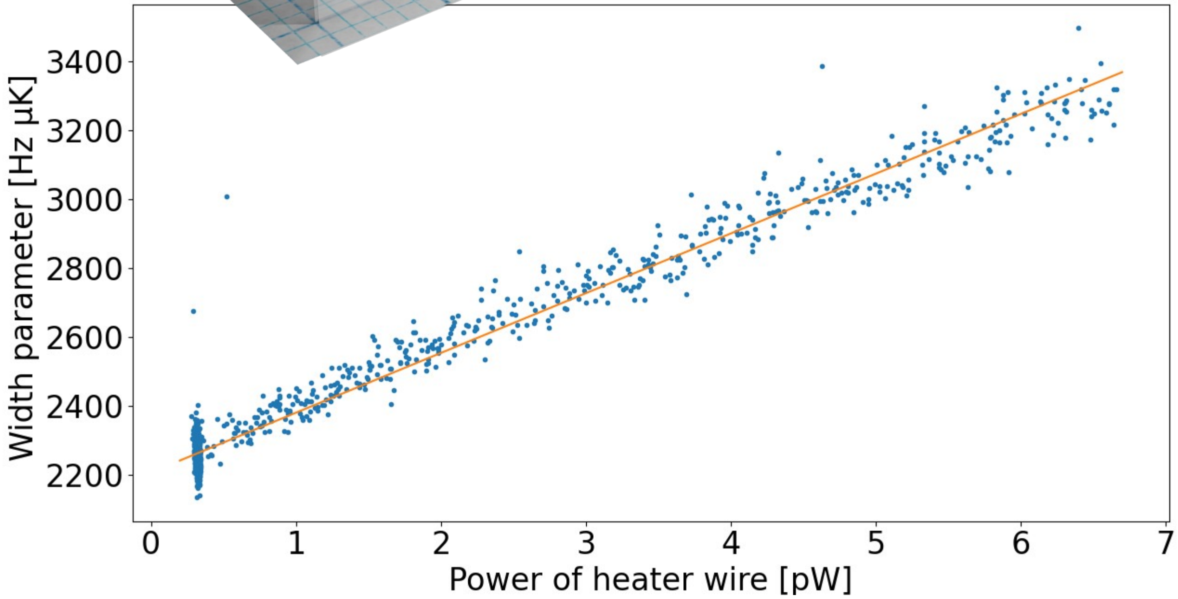


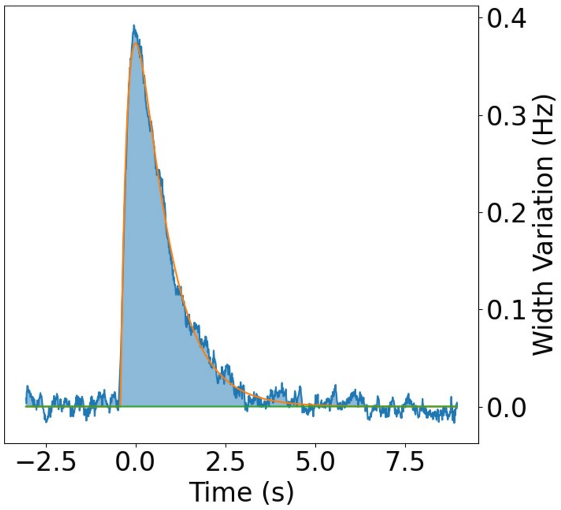
Extract:

- Rate of background events
- Energy spectrum
- Energy threshold

Bolometer in He3: calibration

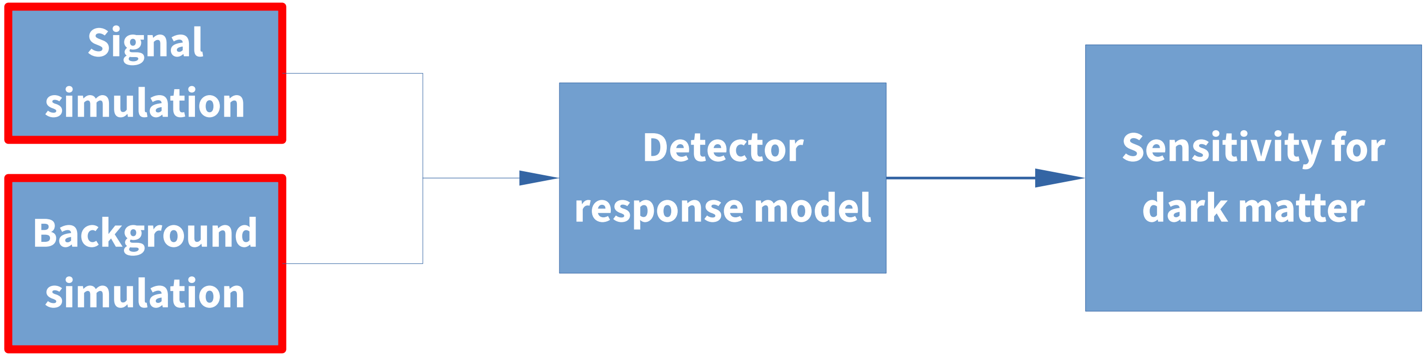


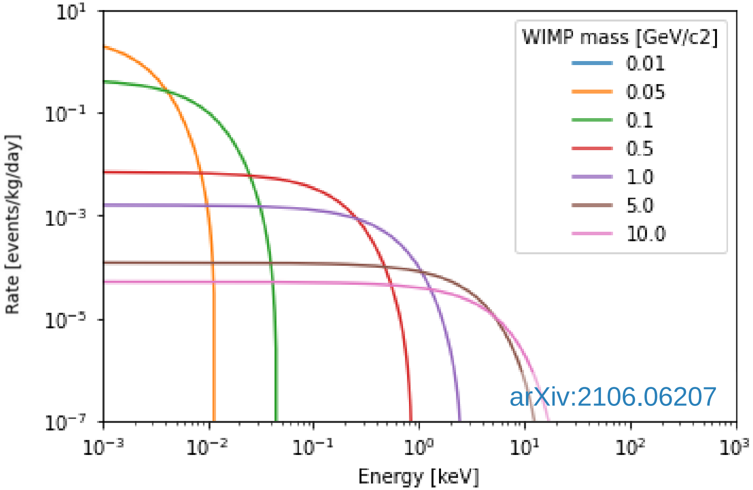


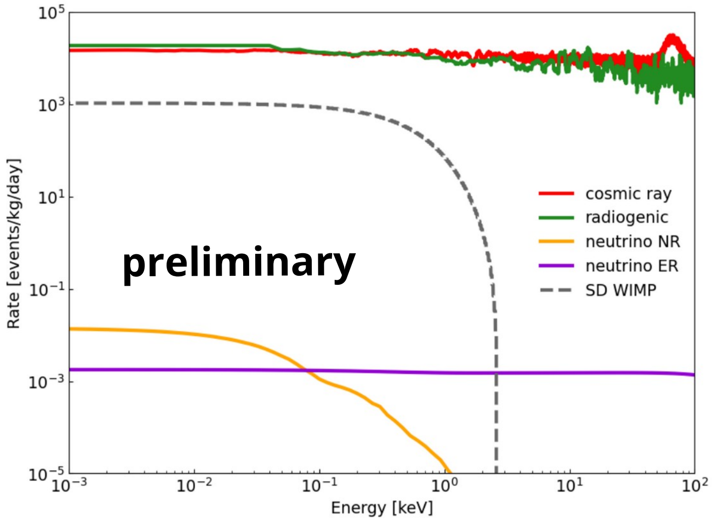


Sensitivity projection

preliminary







Sensitivity projection

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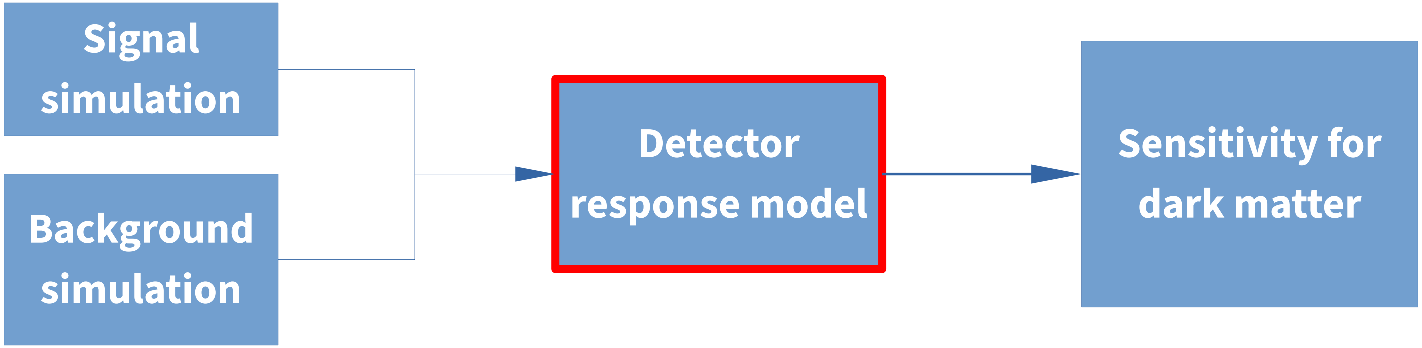
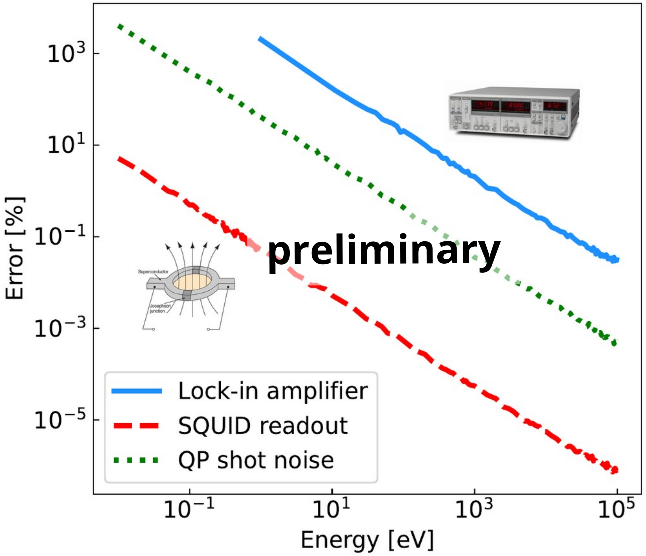
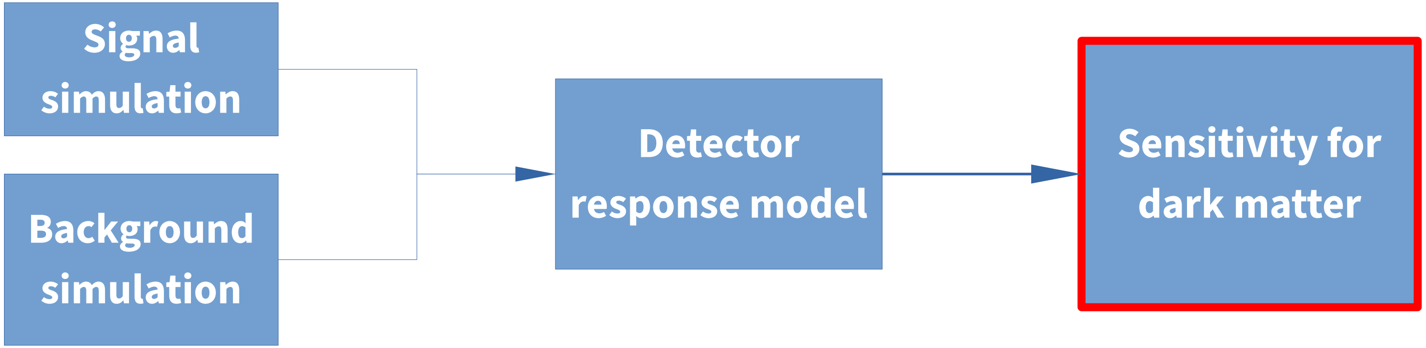


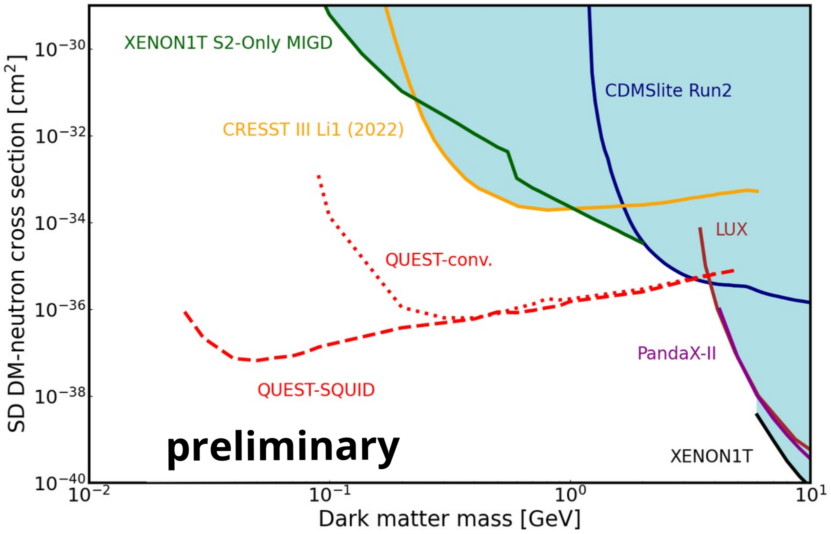


Sensitivity projection

preliminary



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

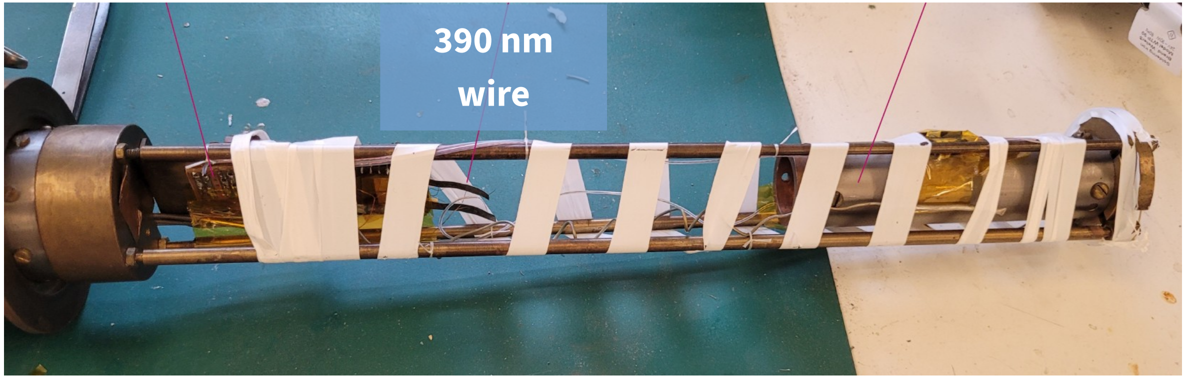


Conclusion and outlook

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

- Next:
  - Compare the model with first round of data
  - Implement light detection in the cell
  - Add cosmic rays tagging

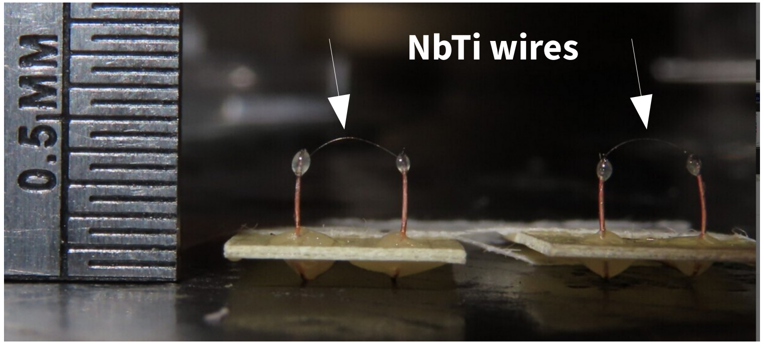
Conclusion and outlook

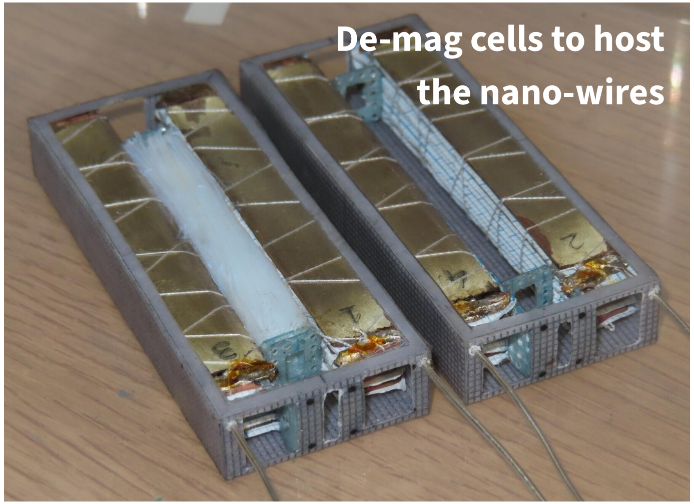


- SQUID operated at RHUL at LN temperatures
- To be operated at uK tempeatures in Lancaster

Conclusion and outlook

- Work towards SQUID readout of a nanowire
- Start operating He3 cells with nanowires





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