QUEST-DMC: Simulation studies for the detection of sub-GeV dark matter with a superfluid Helium-3 calorimeter

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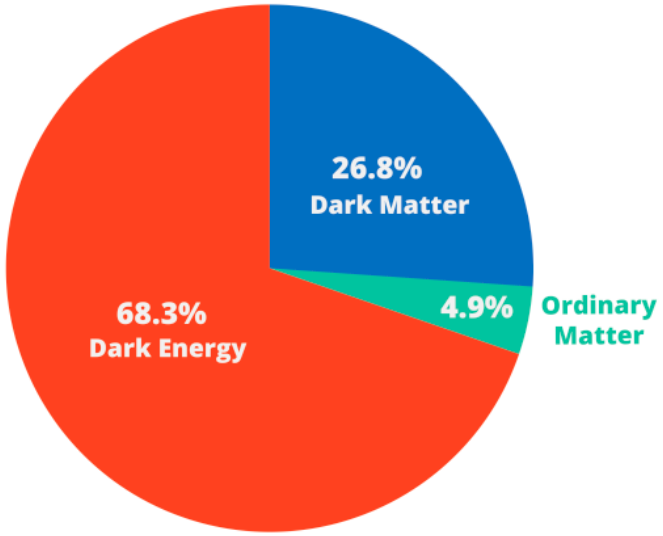
22 September 2022

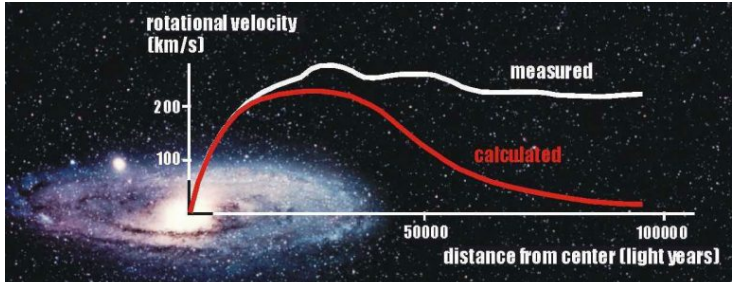
The dark matter hypothesis

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

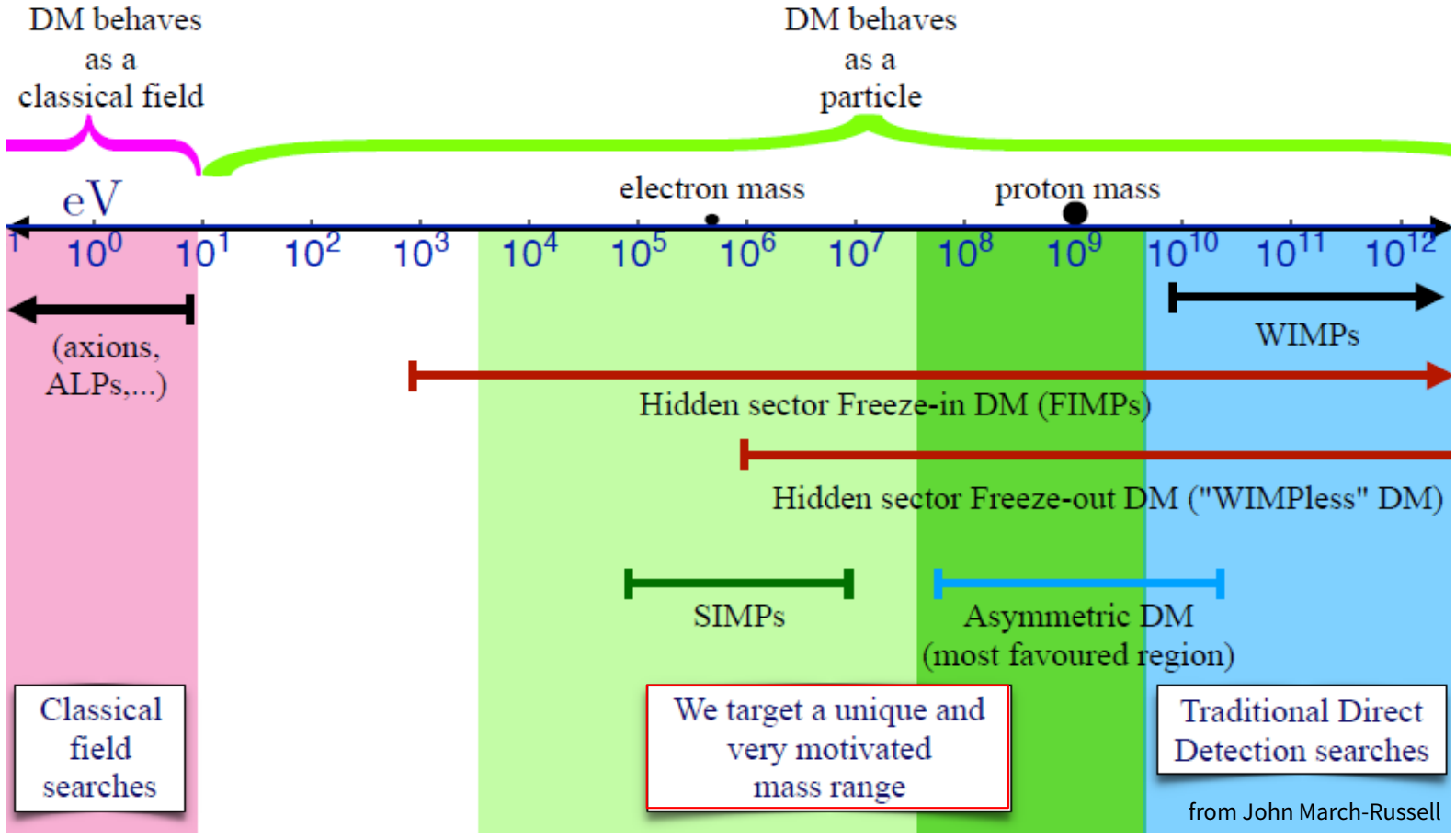


- Evidences from gravitational interactions

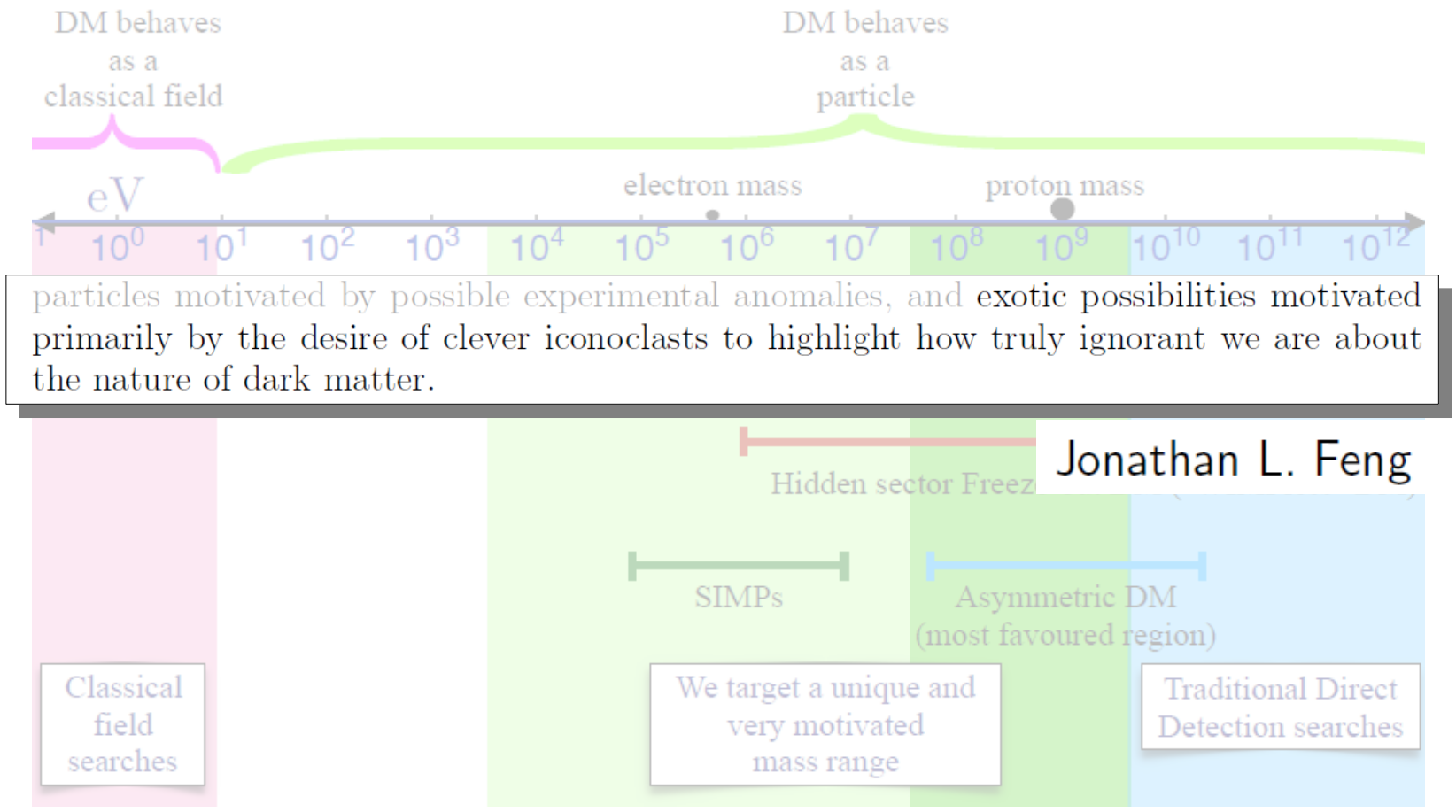
- No electromagnetic interaction (“dark”)
- Stable over billion years
- Non-baryonic: **an unknown particle?**



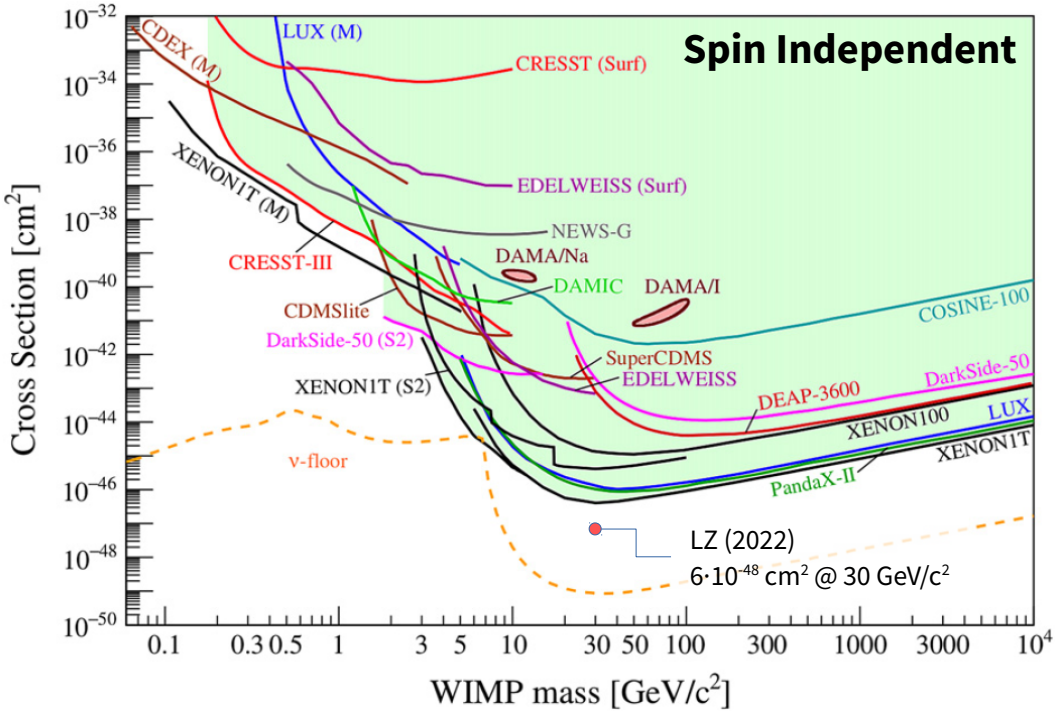
Direct dark matter detection: candidates

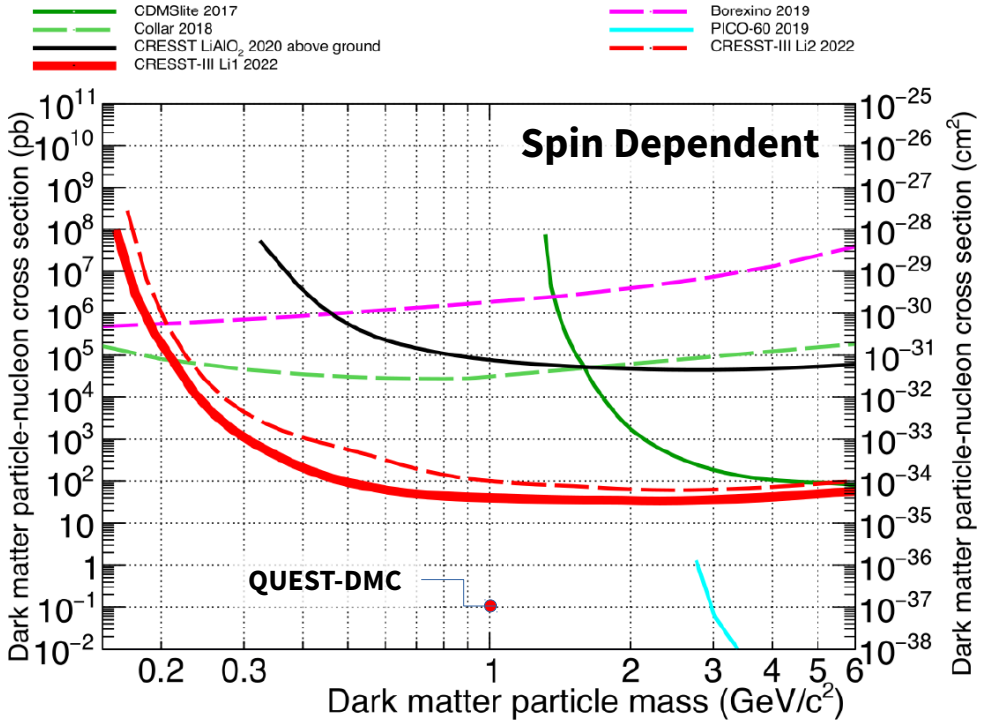


Direct dark matter detection: candidates



Direct dark matter detection: WIMPs



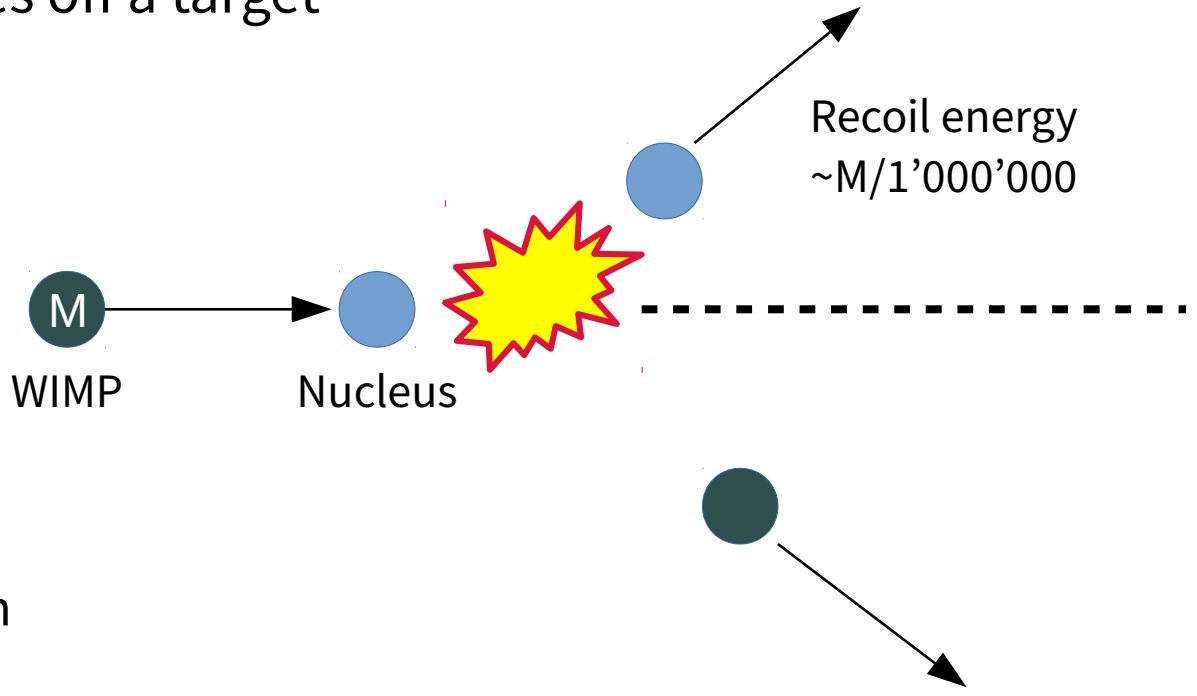


Rep. Prog. Phys. 85 (2022) 056201

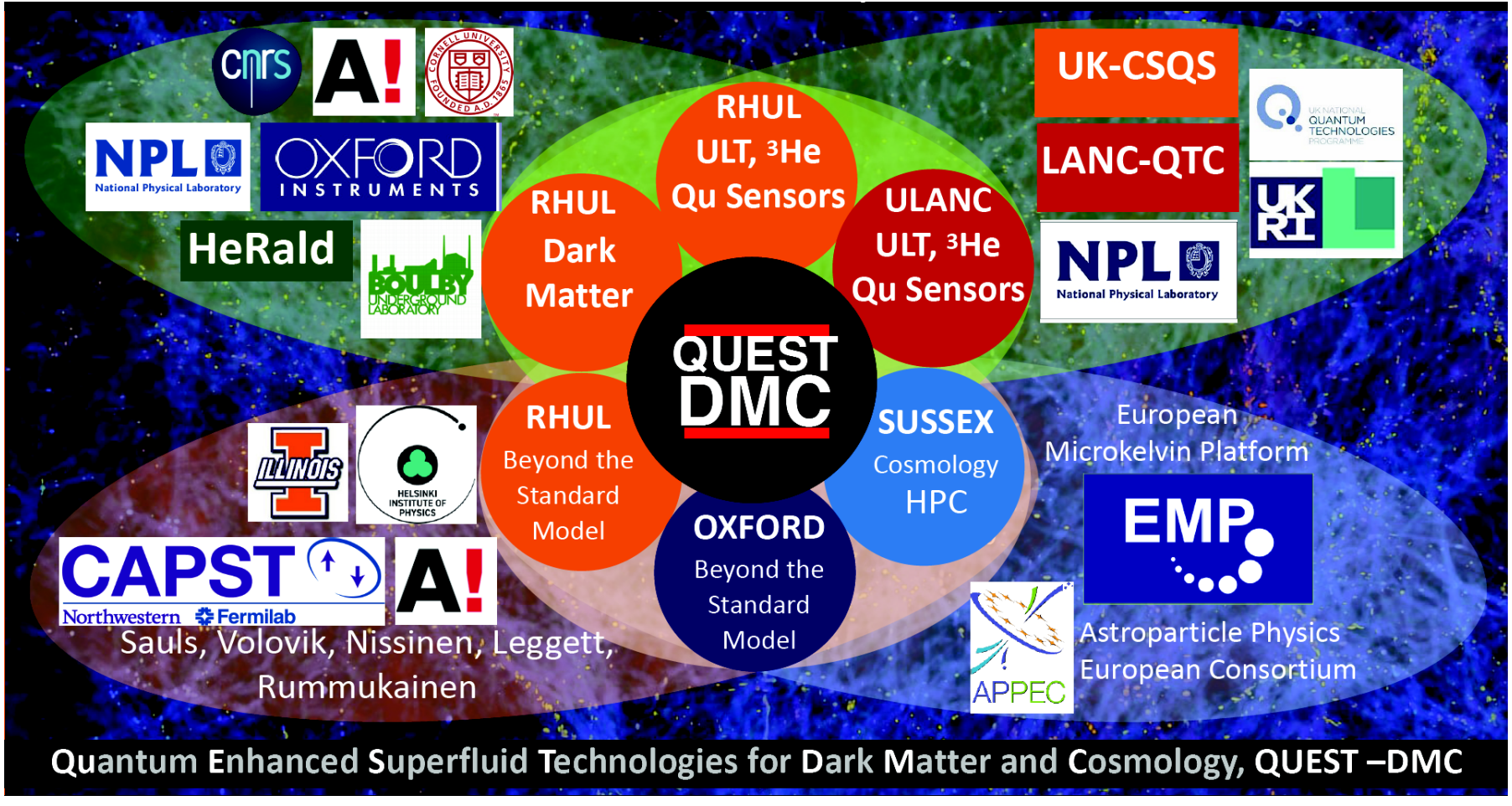
https://arxiv.org/abs/2207.07640

Direct dark matter detection: WIMPs

- Scattering of DM candidates off a target
  - rare processes…
  - … but many WIMPs
- Backgrounds
  - Cosmic rays
  - Radioactive environment
  - Radioactive contamination
  - Neutrinos



QUEST-DMC collaboration and ecosystem



QUEST-DMC programme

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

- **What is the nature of Dark Matter?**

  Detection of sub-GeV dark matter with a quantum-amplified superfluid He3 calorimeter

- **How did the early universe evolve?**

  Phase transition in extreme matter ↔ early universe

Direct dark matter detection

Direct dark matter detection

QUEST-DMC dark matter search programme

Detection of dark matter with a quantum-amplified superfluid He3 calorimeter

- spin dependent WIMP-nucleon interaction and ALP electron scattering
- eV – GeV scale

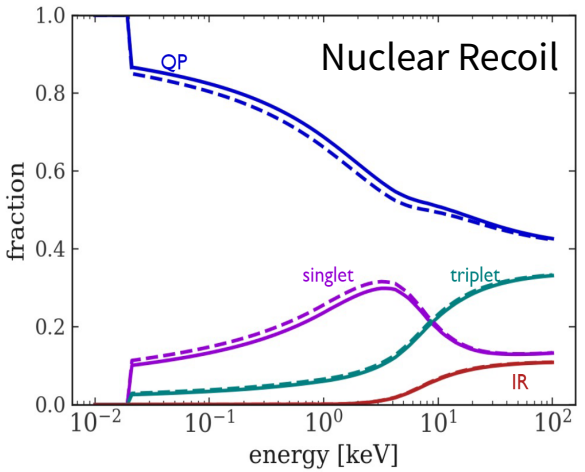
<u>Aiming for</u>:

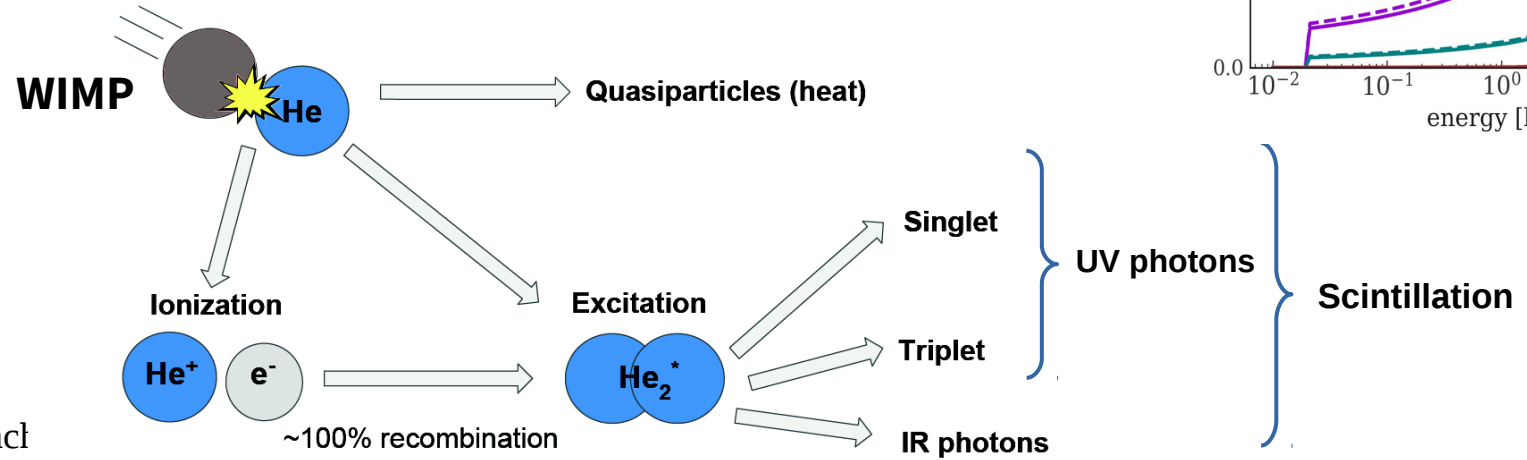
- WIMP-nucleon cross section: 10^{-37} cm^2 @ 1 GeV/c^2
- 10 eV recoil energy threshold
- background < 1 event/kg/day/keV_{DEP}

Dark Matter events in He3

Target

- Ultra-cold liquid He^3 in the $O(100\ \mu K)$ range
- Quantum superfluid condensate of He^3 atoms
- Collision WIMP-He^3 atom
  - Heat as **quasiparticle** excitations
  - **Light** from de-excitation

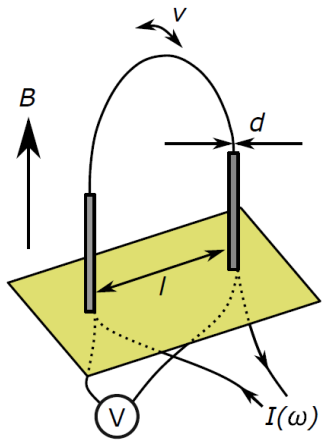


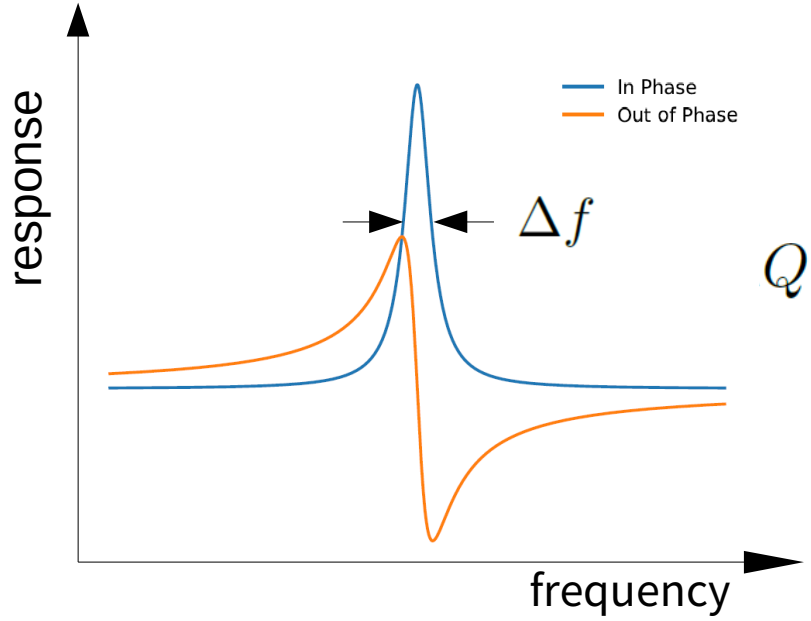


Bolometer in He3

Detector

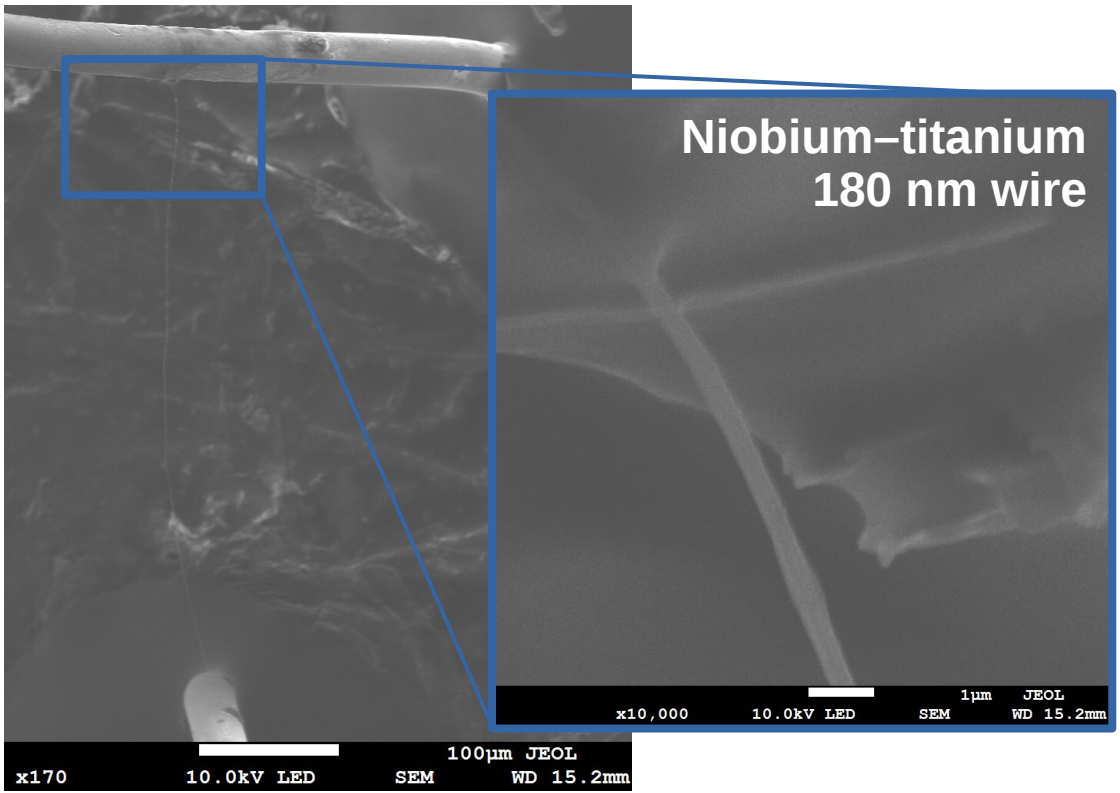
- Deposited energy as variation of the damping force on the resonator
- Measure **energy deposition** as variation of the resonance width

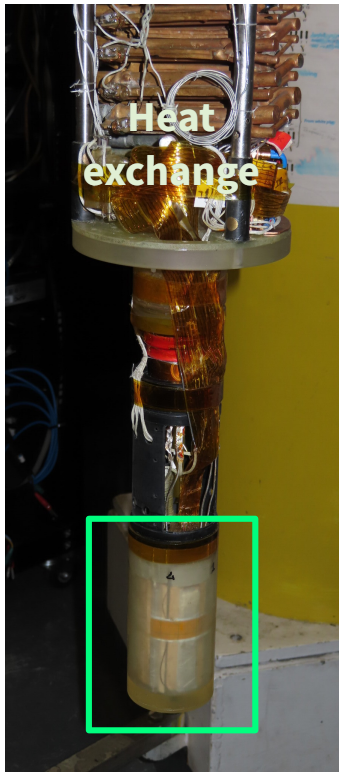


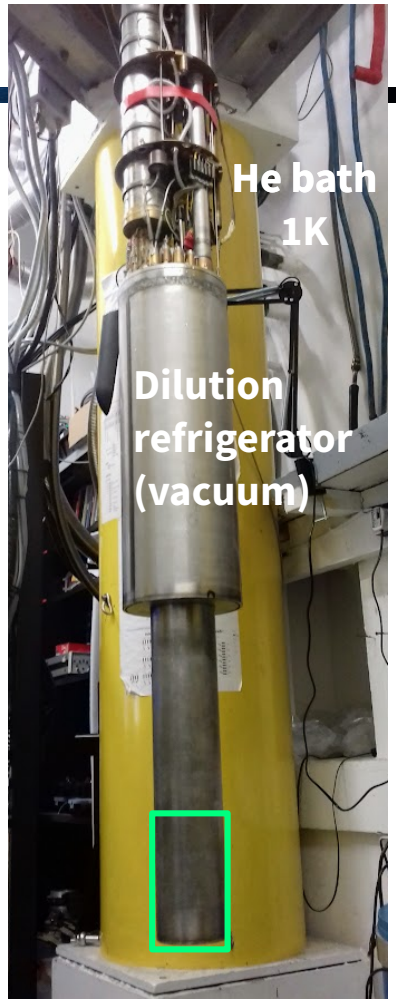


$$Q = \alpha(T_0, P)\Delta(\Delta f)$$

Bolometer in He3



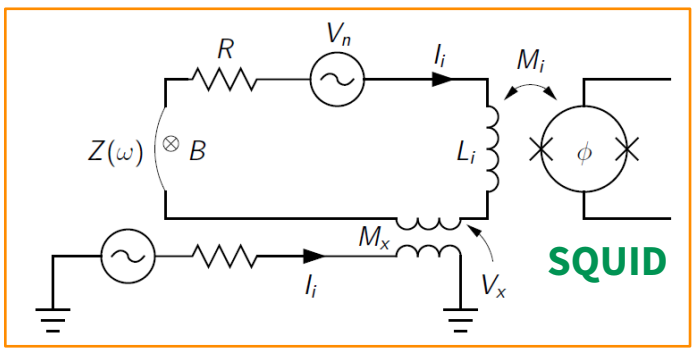




Bolometer response: SQUID

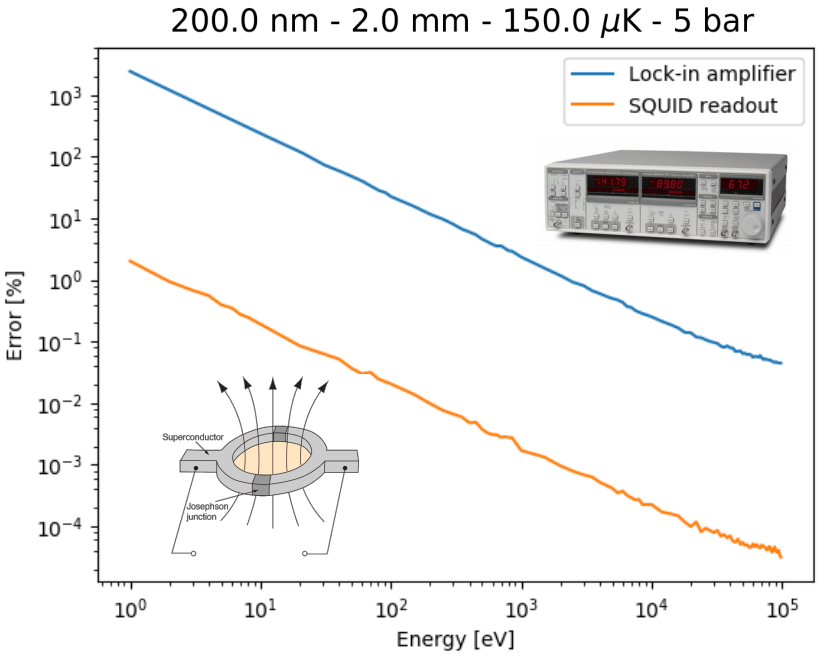
Readout

- Error on the energy measurement ↔ DM energy threshold
- Quantum sensors



$$V_{RMS} = \sqrt{\left|Z(\omega_0) + R + i\omega_0 L_i\right|^2 S_\phi \Delta f / M_i^2 + 4k_B T R \Delta f + k_B T l B^2 / m}$$

Current and thermal noise



Background

Analysis

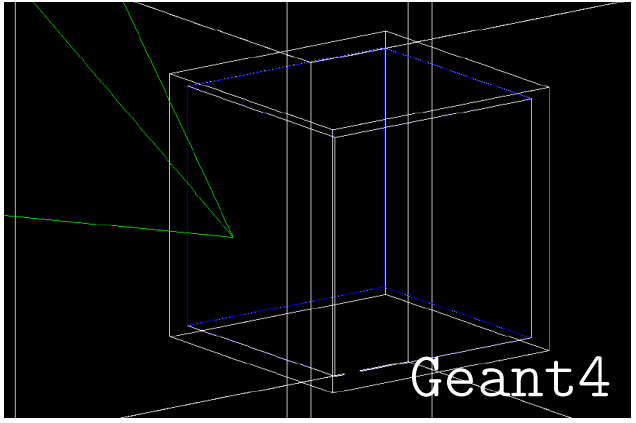
- Cosmic rays
- Cosmic rays induced
- Radioactive decays
  - Environment
  - Contamination
  - Materials
- Neutrinos (irreducible)

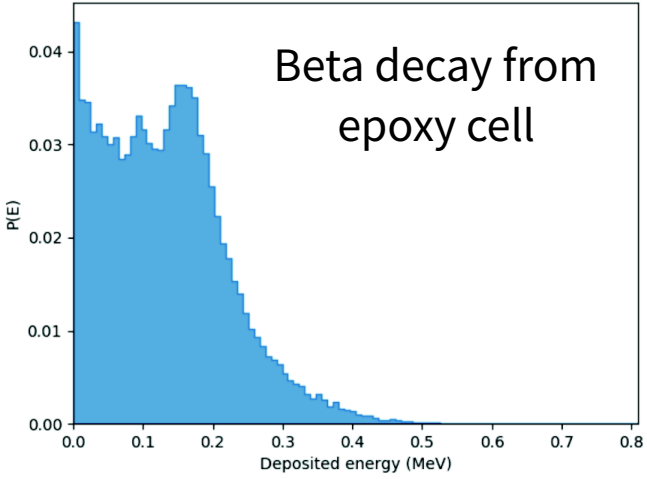
- Alphas
- Betas
- Gammas
- Neutrons
- Muons

→ **Goal**: 1 background event/kg/day

Background

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





Background: screening

- Boulby screening measurements:

	Stycast [mBq/kg]	Araldite [mBq/kg]	GRP [mBq/kg]
238UE	<10.5	<3.6	5684.2 ± 1029.8
238UL	<9.5	<4.8	7464 ± 115.6
210Pb	<14.9	14.5	
232ThE	<12.8	<3.4	7844.5 ± 155.9
232ThL	<6.2	<2.2	7353.6 ± 100.8
40K	<122.2	<25.5	46904.7 ± 565.3

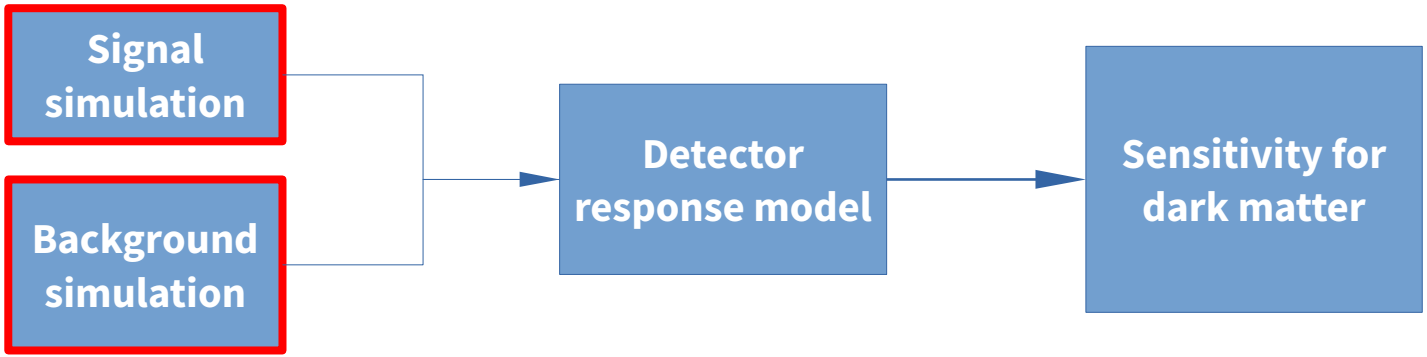
- Current setup estimated activities, per cell per day:

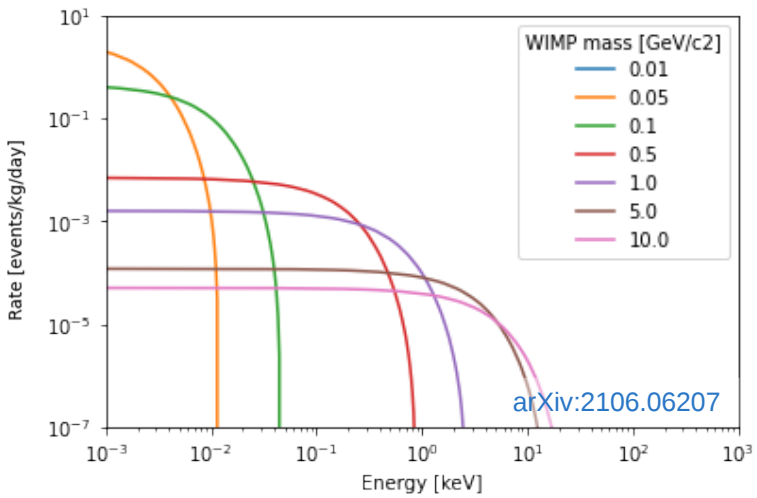
Particle	Events/0.1g/day in 0-10 keV
Beta	2.73e-3
Gamma	5.47e-4
PP neutrino	7.56e-7
CNO neutrino	3.33e-8

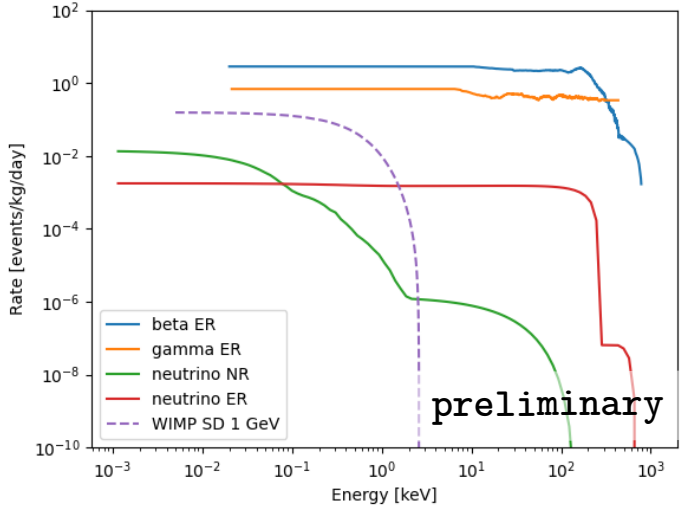
~3 event/kg/day/keV

Sensitivity projection

preliminary







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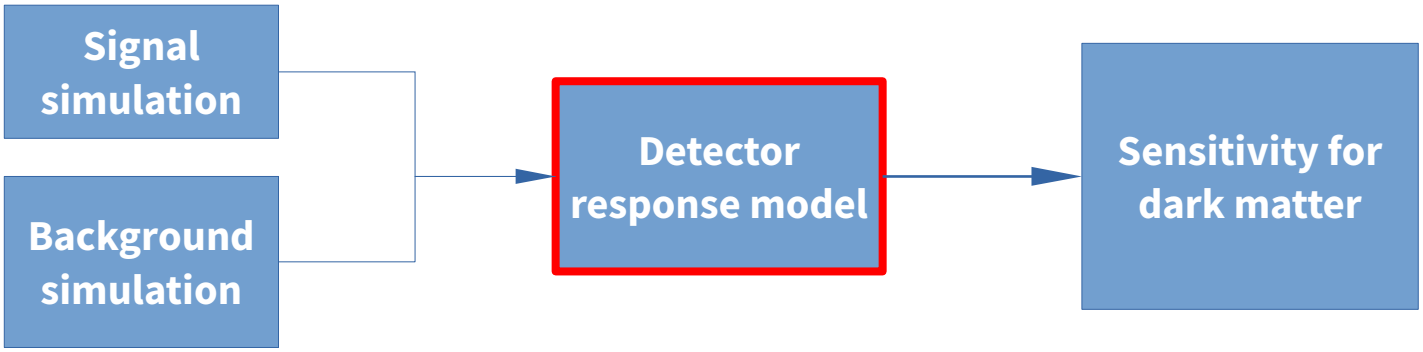

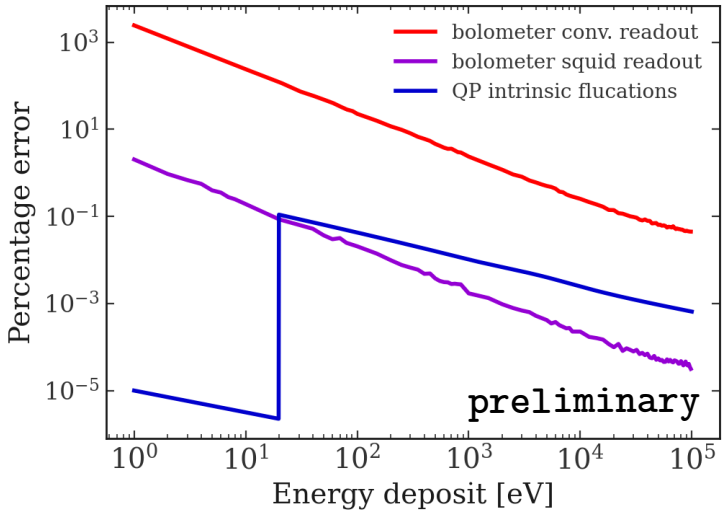

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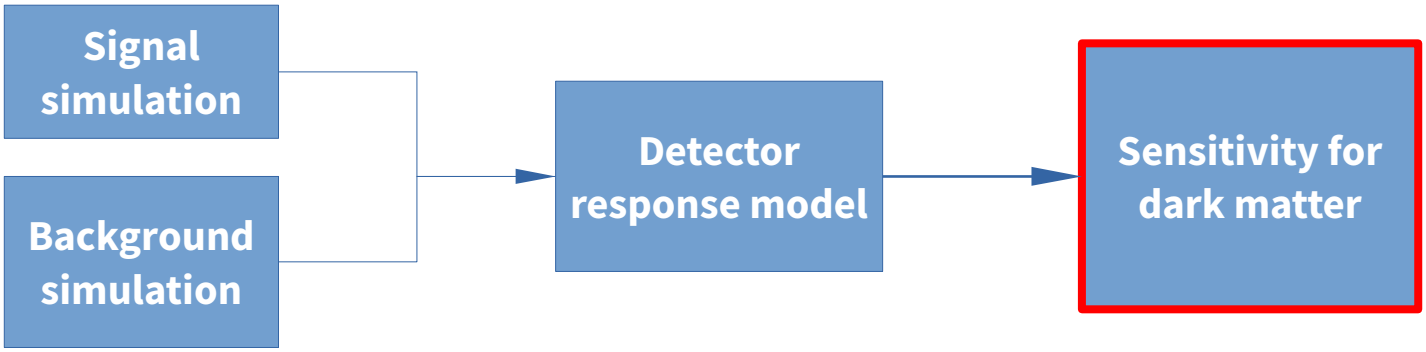
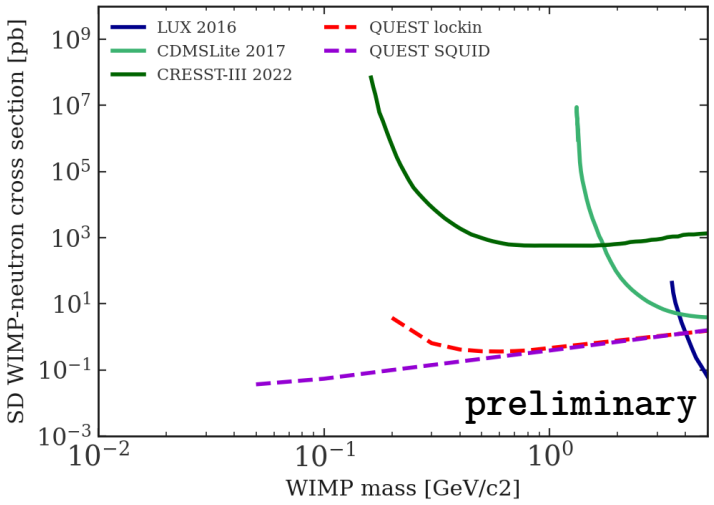


- 5 cells: 1 cm^3, 0.1 mg of He^3 each
- 50% duty cycle
- Exposure: 6 months



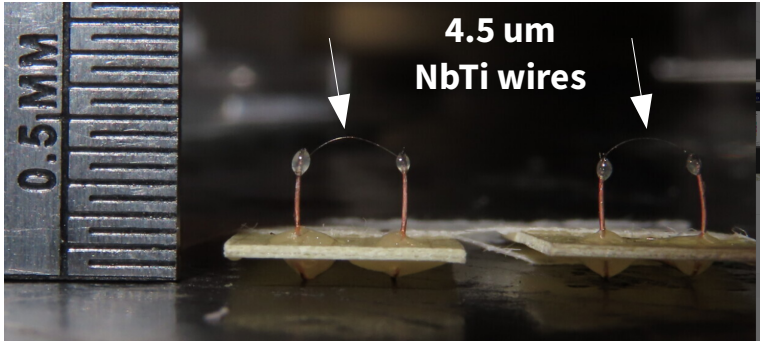
Conclusion and outlook (1/2)

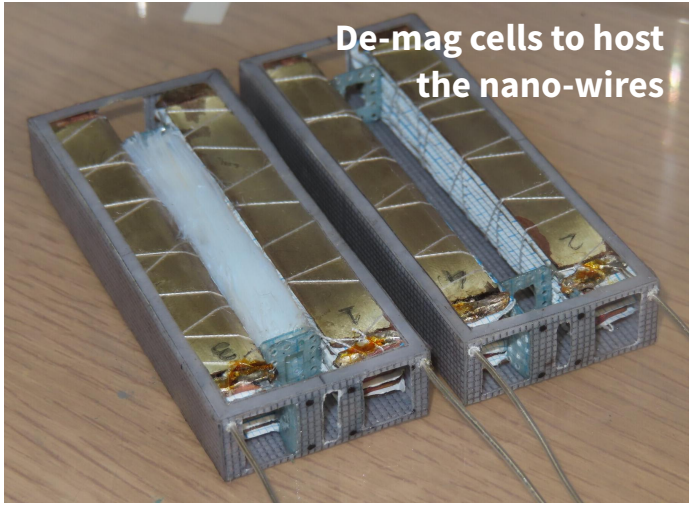
- Simulation and analysis machinery in place
- Produce a first sensitivity limit, based on actual constructed detector cells and modelled energy reconstruction validated on data

- Next:
  - Include background from cosmic rays
  - Include other Dark Matter sources and models

Conclusion and outlook (2/2)

- Work towards SQUID readout of a nanowire
- Start operating He^3 cells with nanowires
- Calibration of the bolometer





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