Project 1: Searching for Dark Matter beyond WIMPs with Novel Detector Technologies

RAL/PPD PhD Open Day
27th February 2025

Dr Ashlea Kemp & Prof Jocelyn Monroe
RAL/University of Oxford

UKRI Science and Technology Facilities Council
Particle Physics

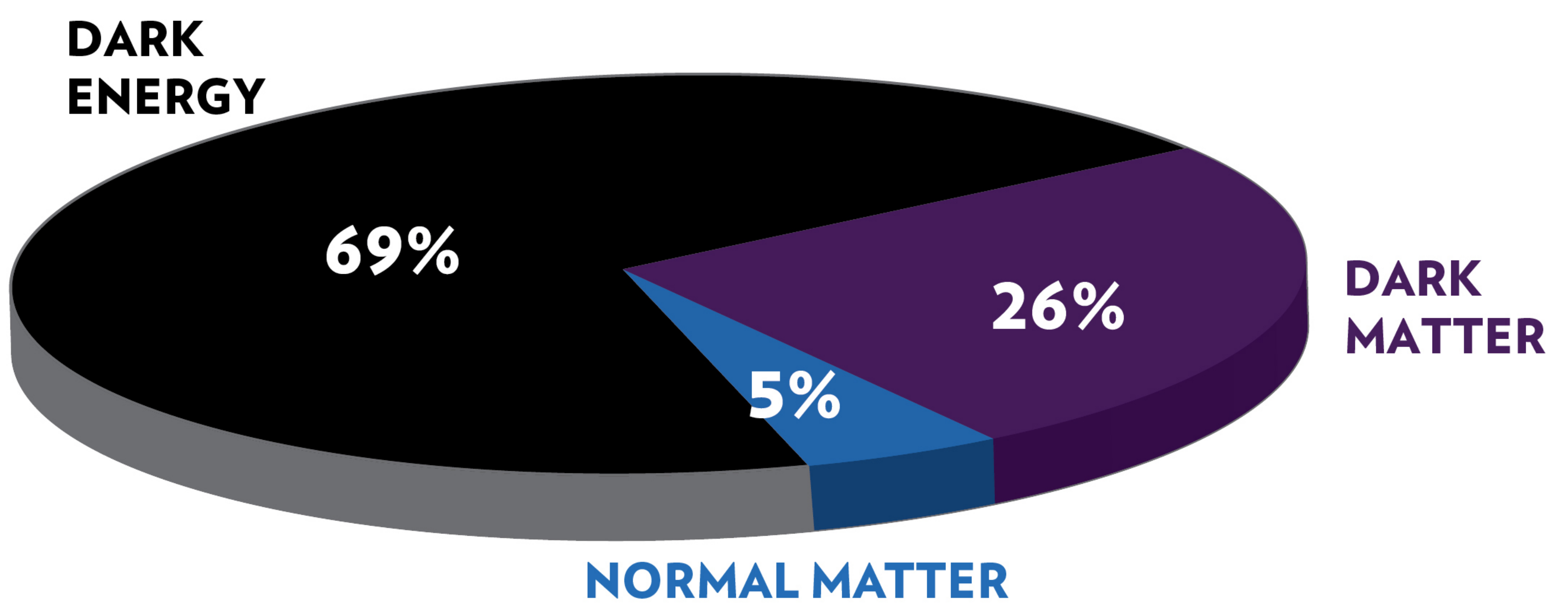
DARKSIDE

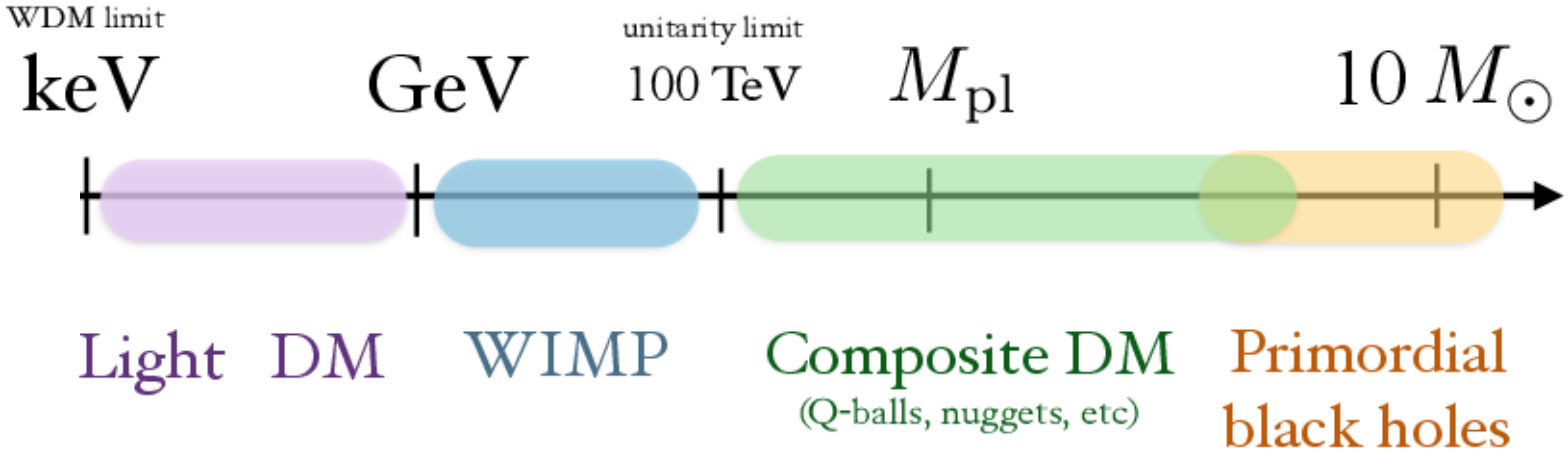
QUEST DMC

UNIVERSITY OF OXFORD

The Challenge (Part 1)

Mass Scale of Dark Matter - Not to Scale

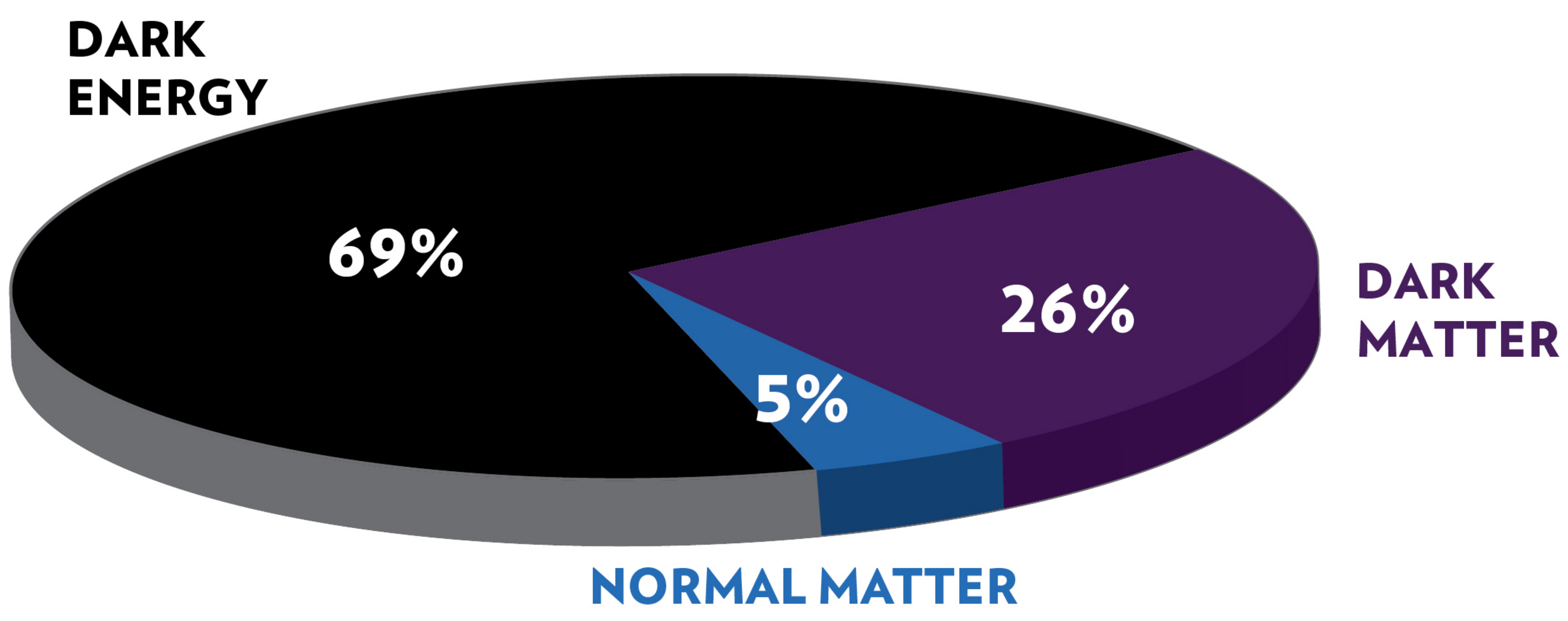


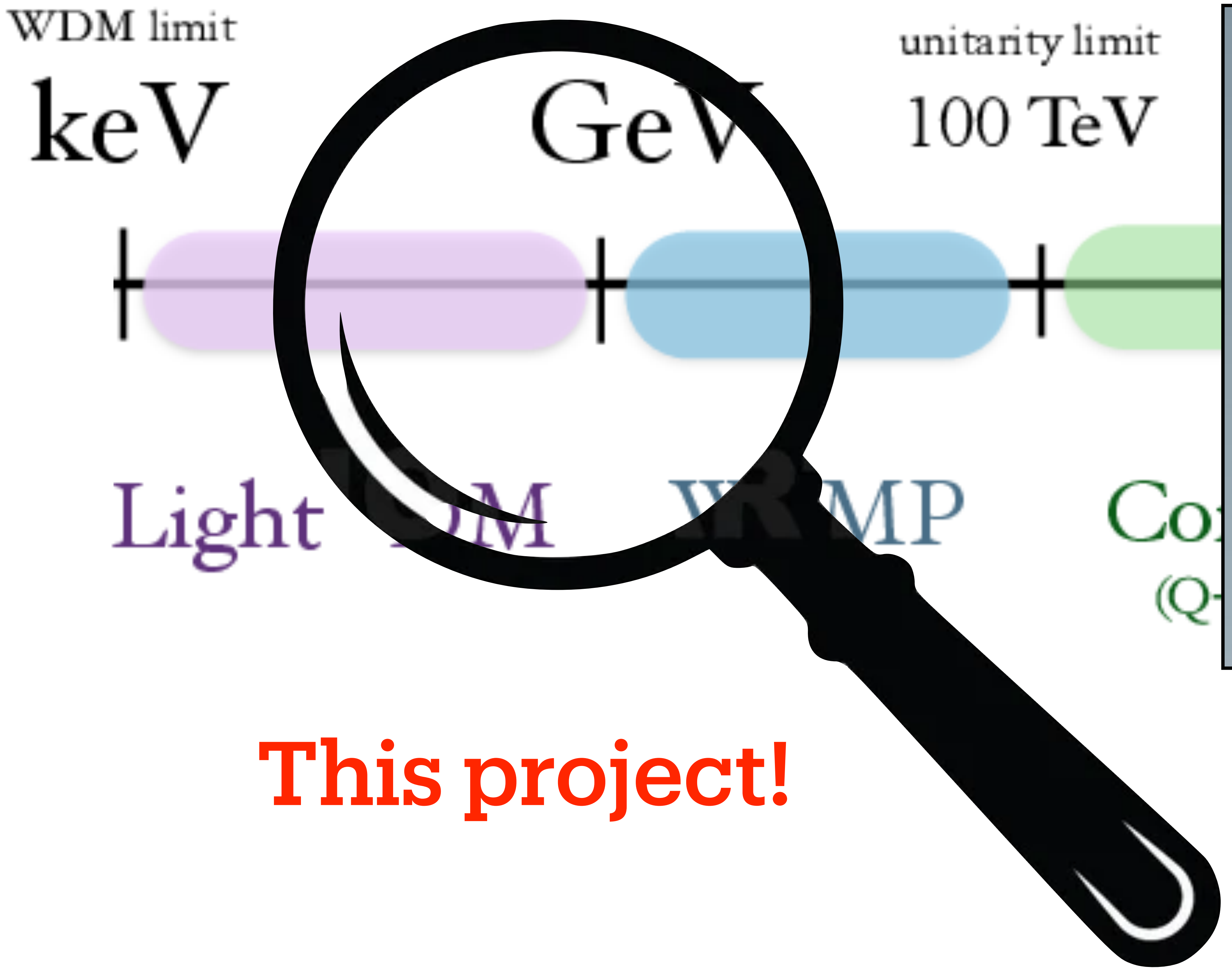


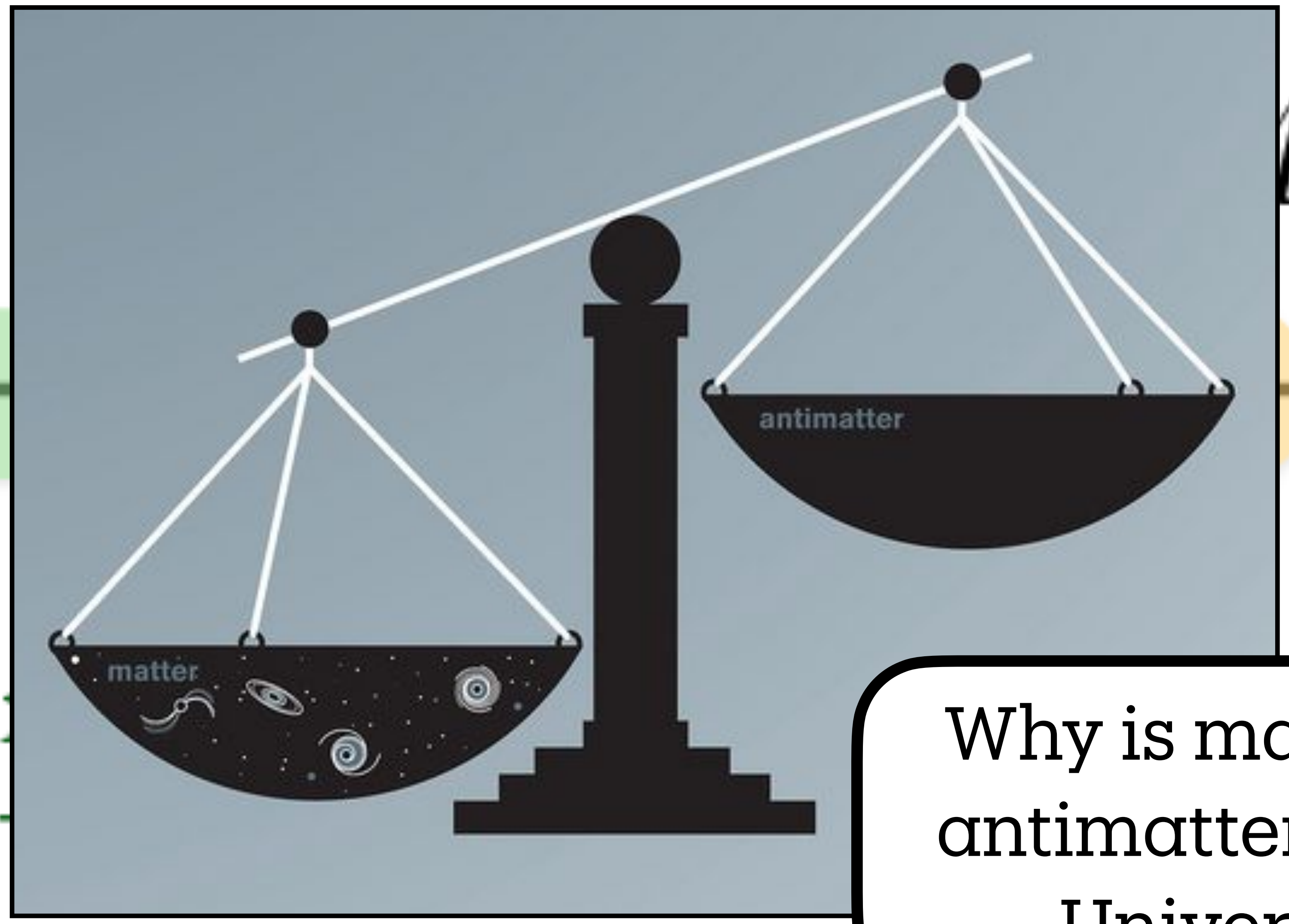
Dark Matter Particles span a vast parameter space!

The Challenge (Part 1)

Mass Scale of Dark Matter - Not to Scale







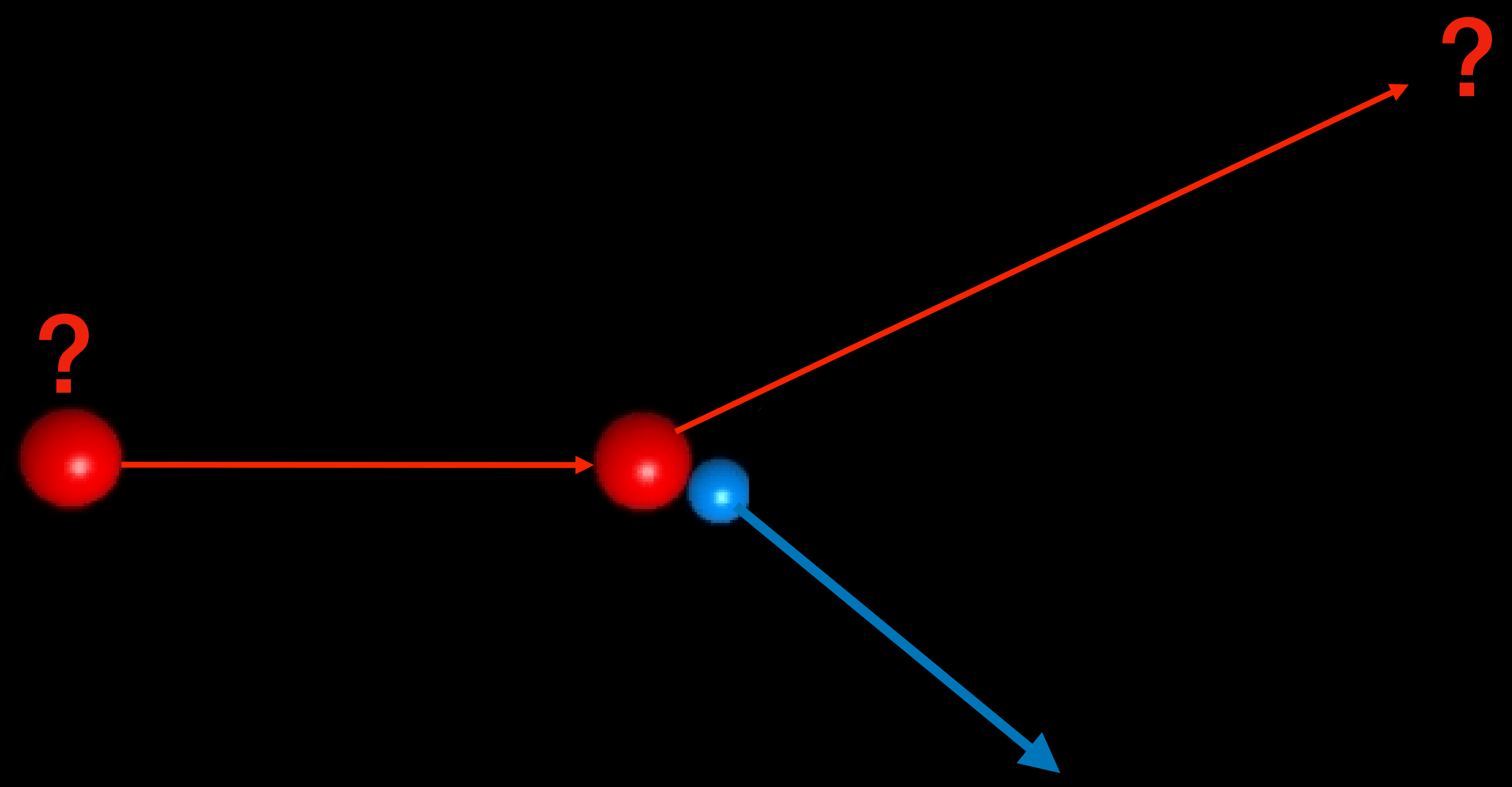
Why is matter >> antimatter in the Universe?

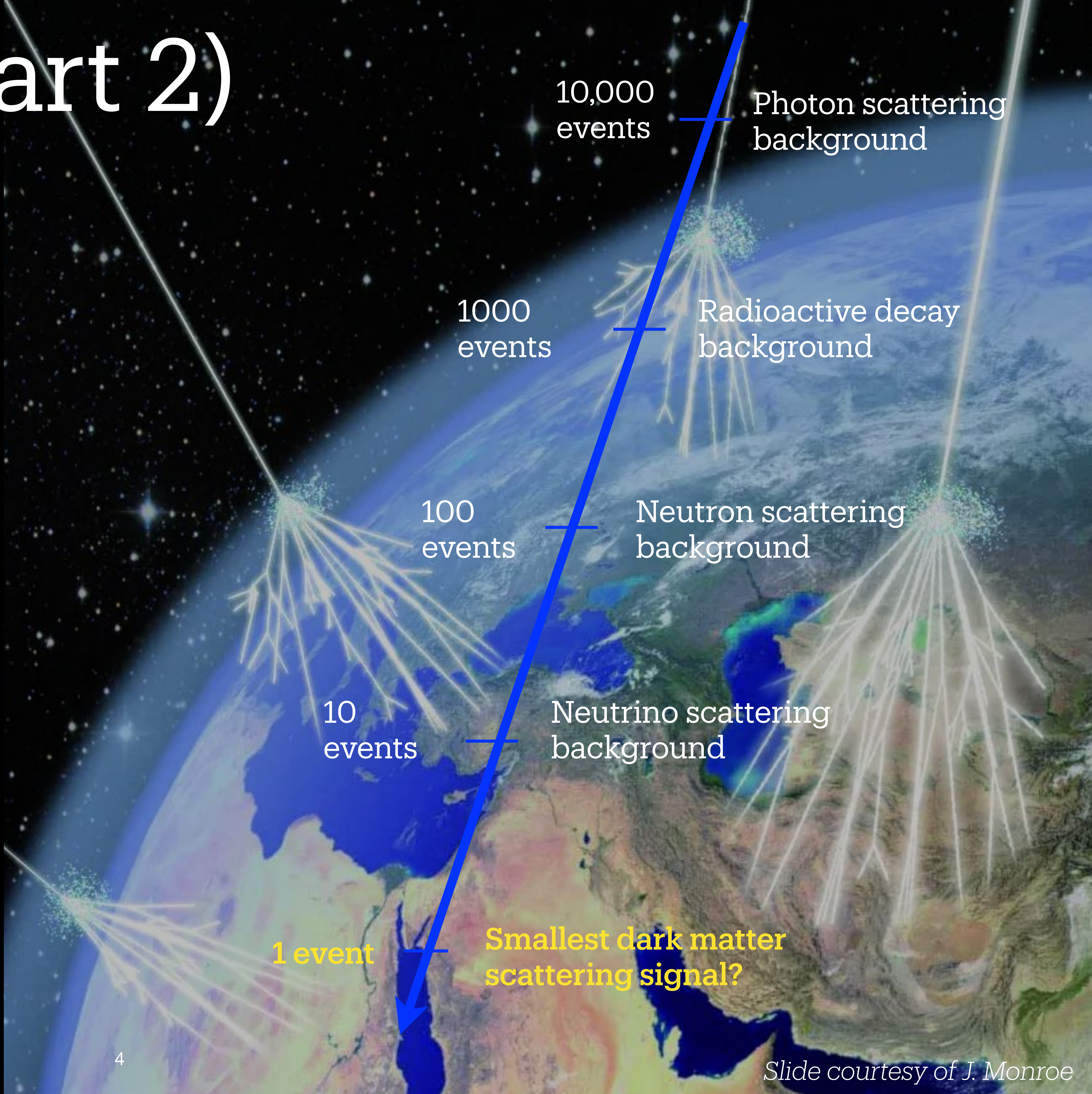
This project!

Rich set of new DM-SM interactions predict candidates in "sub-GeV" mass region.

The Challenge (Part 2)

There are other particles that can mimic a dark matter signal, which interact much more frequently than dark matter particles!





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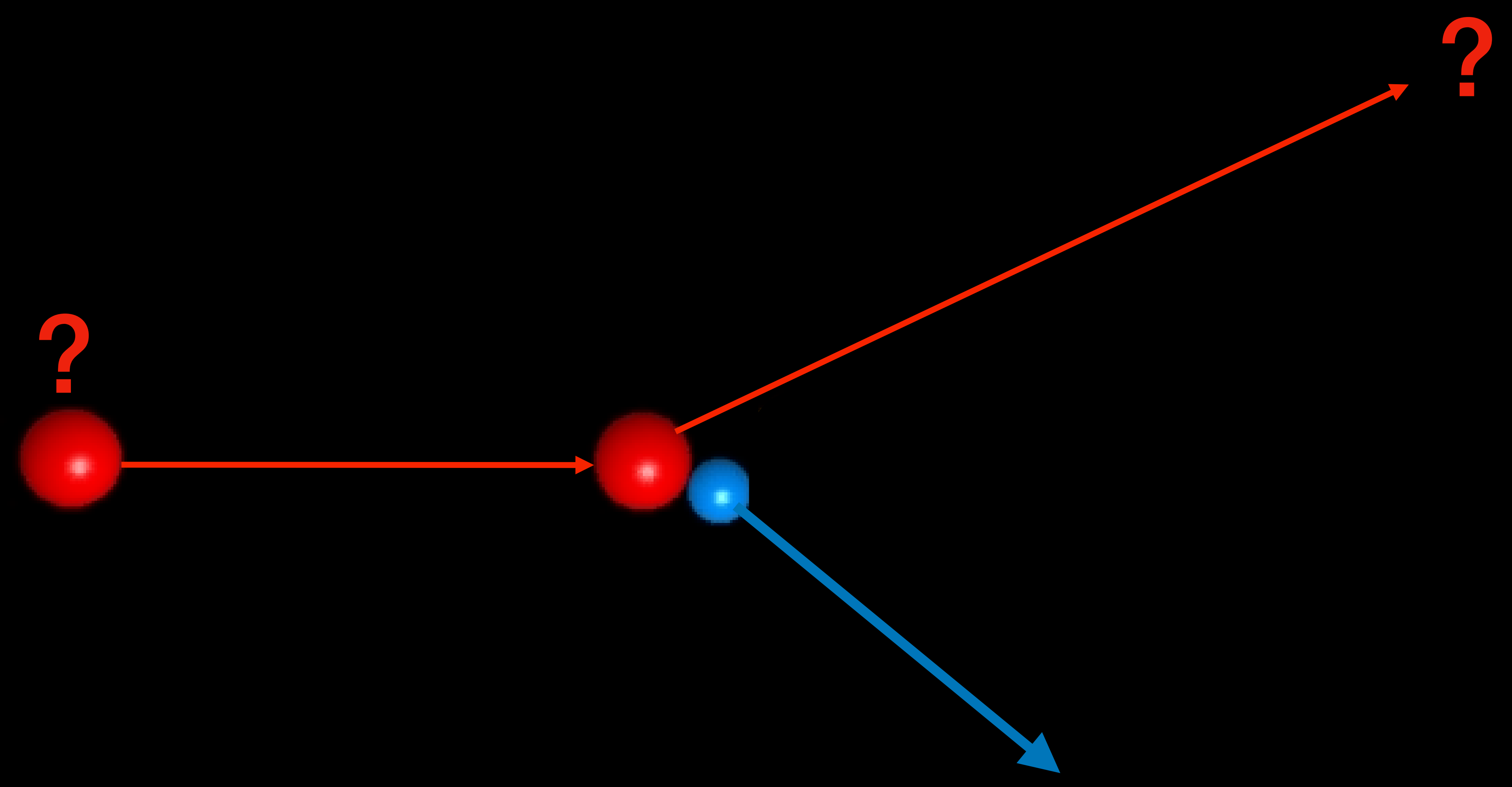
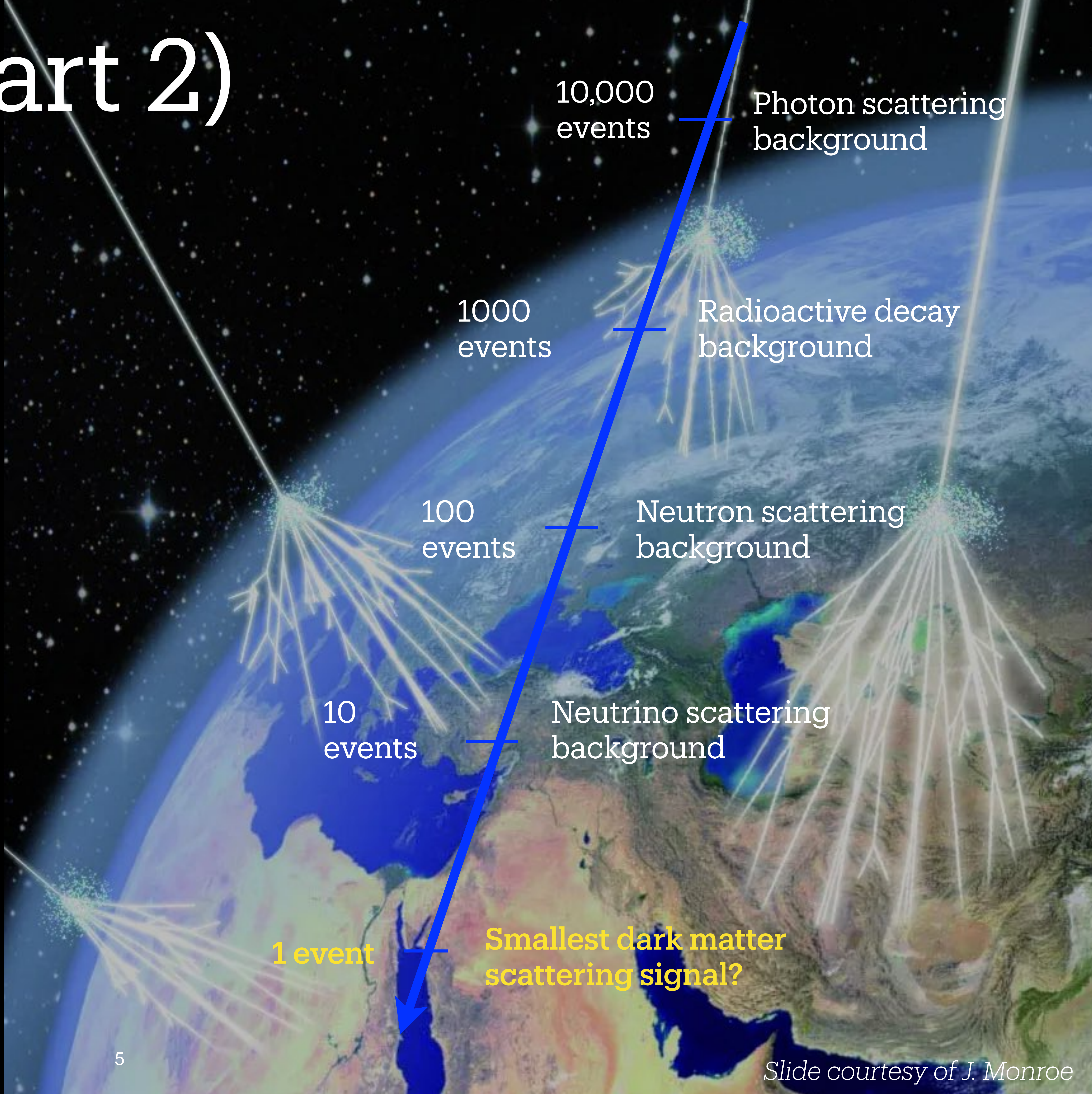


Naturally occurring radioactivity and cosmic rays are particularly problematic!

←This project!



DarkSide-20k: Overview

Global Argon Dark Matter Collaboration (GADMC) comprised of 400+ people across 14 countries.

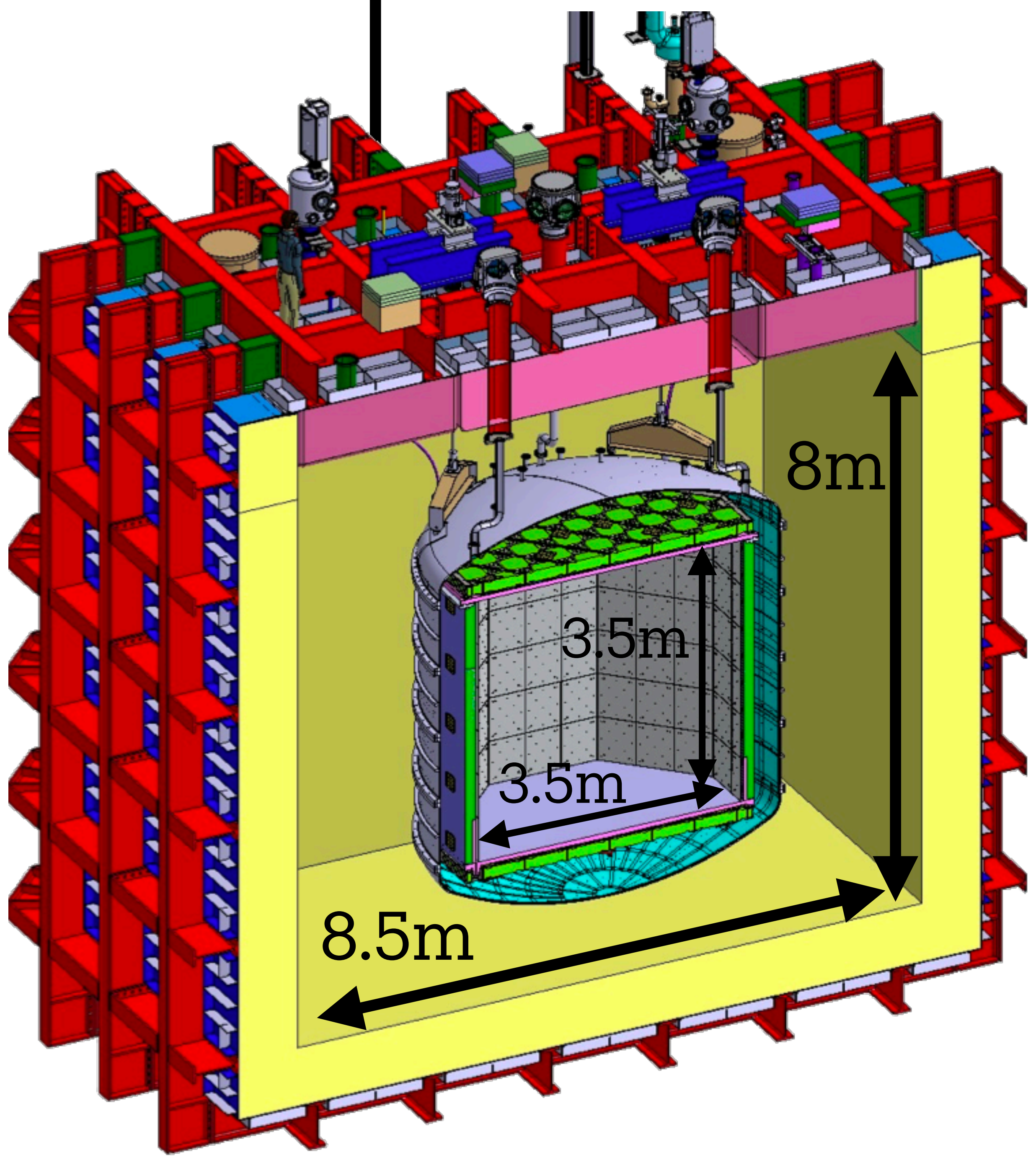
Goal of DarkSide-20k: directly observe spin-independent WIMP interactions, with projected sensitivity down to neutrino fog.

June 2023 DarkSide-20k Collaboration Meeting at LNGS

DarkSide-20k: Detector

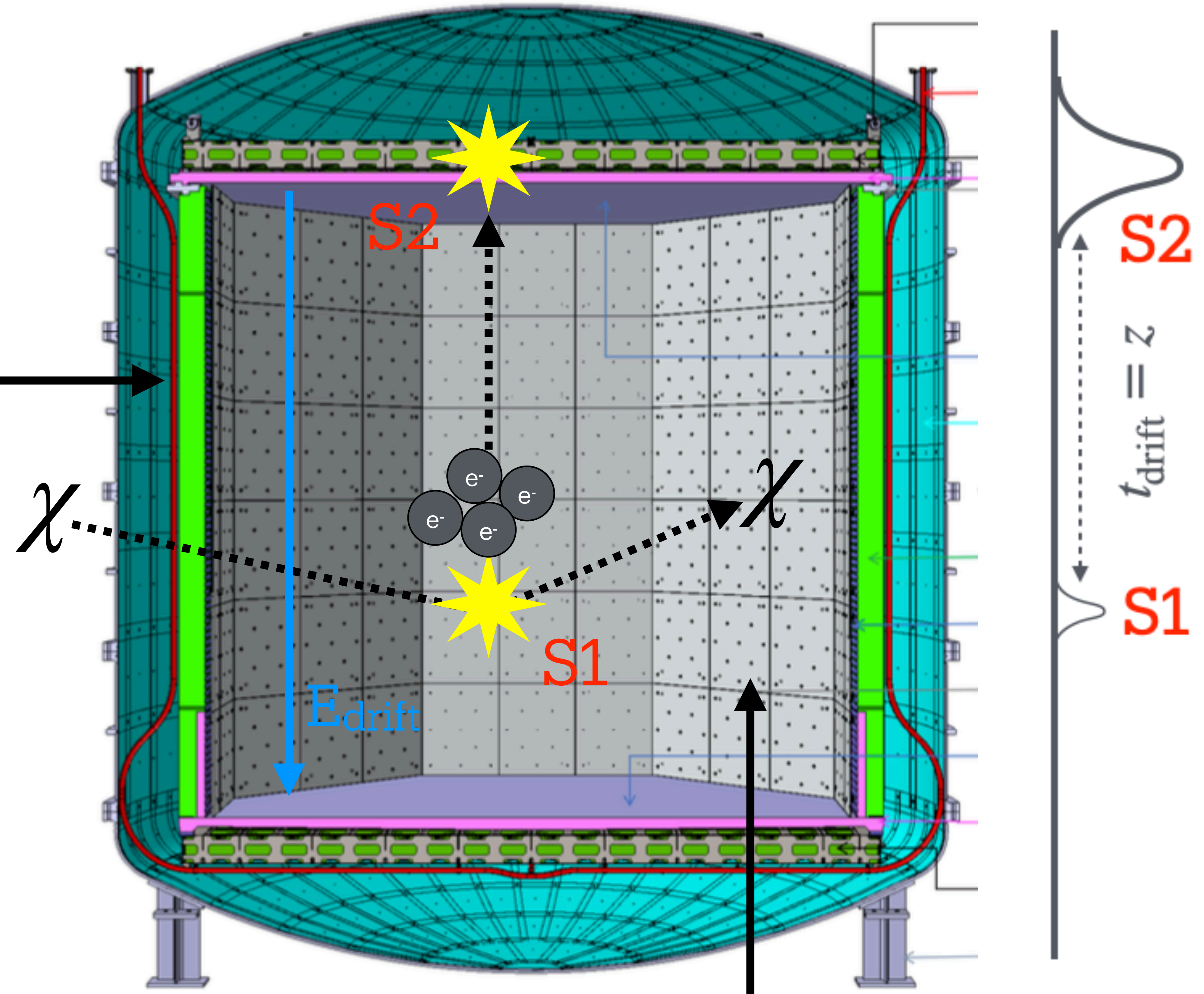
Cosmogenic (Outer) Veto:

- 650t Atmospheric Argon.
- Instrumented with Silicon Photomultipliers (SiPMs) with sparse coverage.



Neutron (Inner) Veto:

- Enclosed in Stainless Steel (SS) vessel. Plastic neutron shield surrounding SS.
- 35t Underground Argon.
- PMMA (acrylic) barrel.
- Instrumented with SiPMs; UK building 7 m^2.



Dual-Phase TPC:

- 50t Underground Argon. Instrumented with 2x Optical Plates of SiPM arrays with 21 m^2 coverage.

DarkSide-20k: Status

Construction at LNGS well underway:

- ✓ Cryostat and infrastructures in LNGS Hall C complete.
- ✓ Cryogenics system operating in Hall C.
- ✓ TPC components in production.
- ✓ Installation of UK photodetectors starting late 2026.
- ✓ Construction complete 2027: data-taking from 2028.

UK groups have built 7m² of Silicon Detector Readout, Production, and Installation, including here at RAL!

Do go and see the Cleanroom tour today if you can!

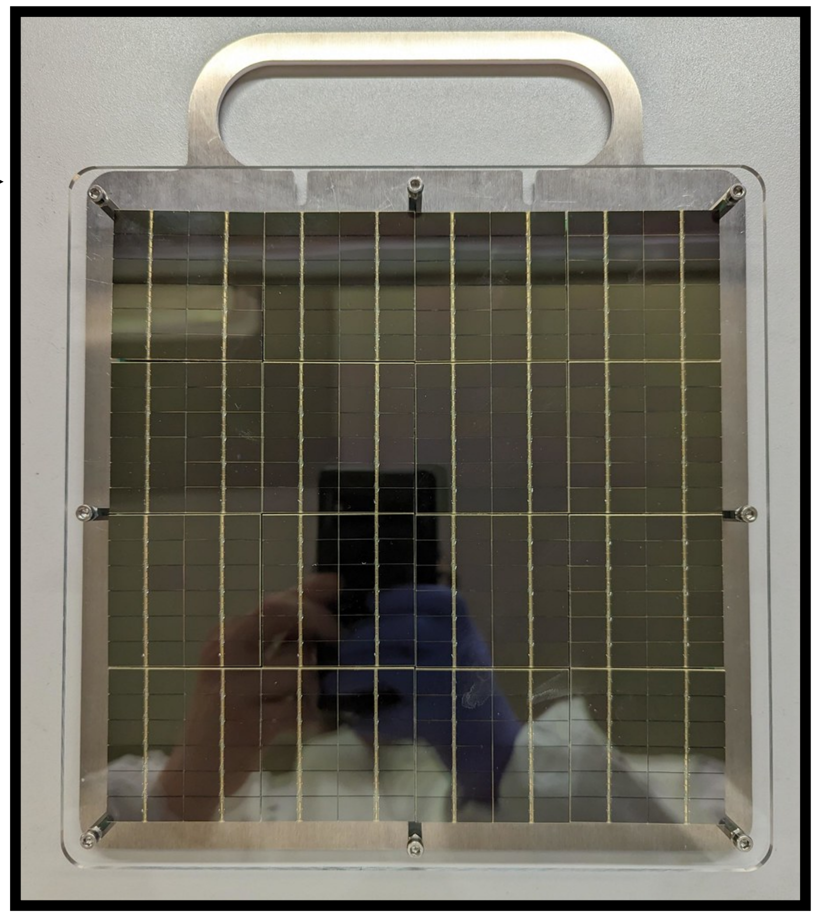
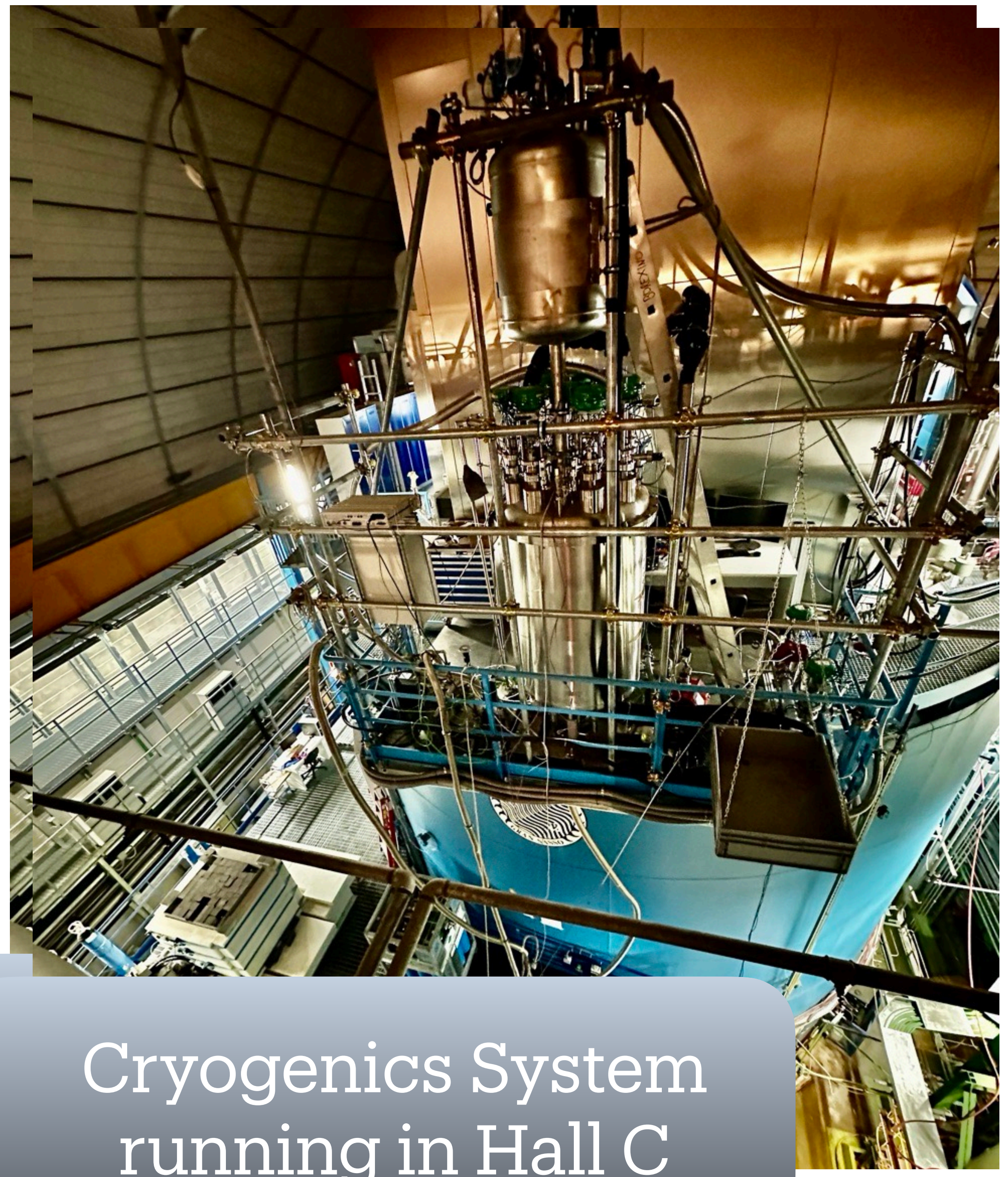


Image courtesy of P. Franchini

DarkSide-20k located in Hall C at LNGS, Italy (3400 m.w.e)

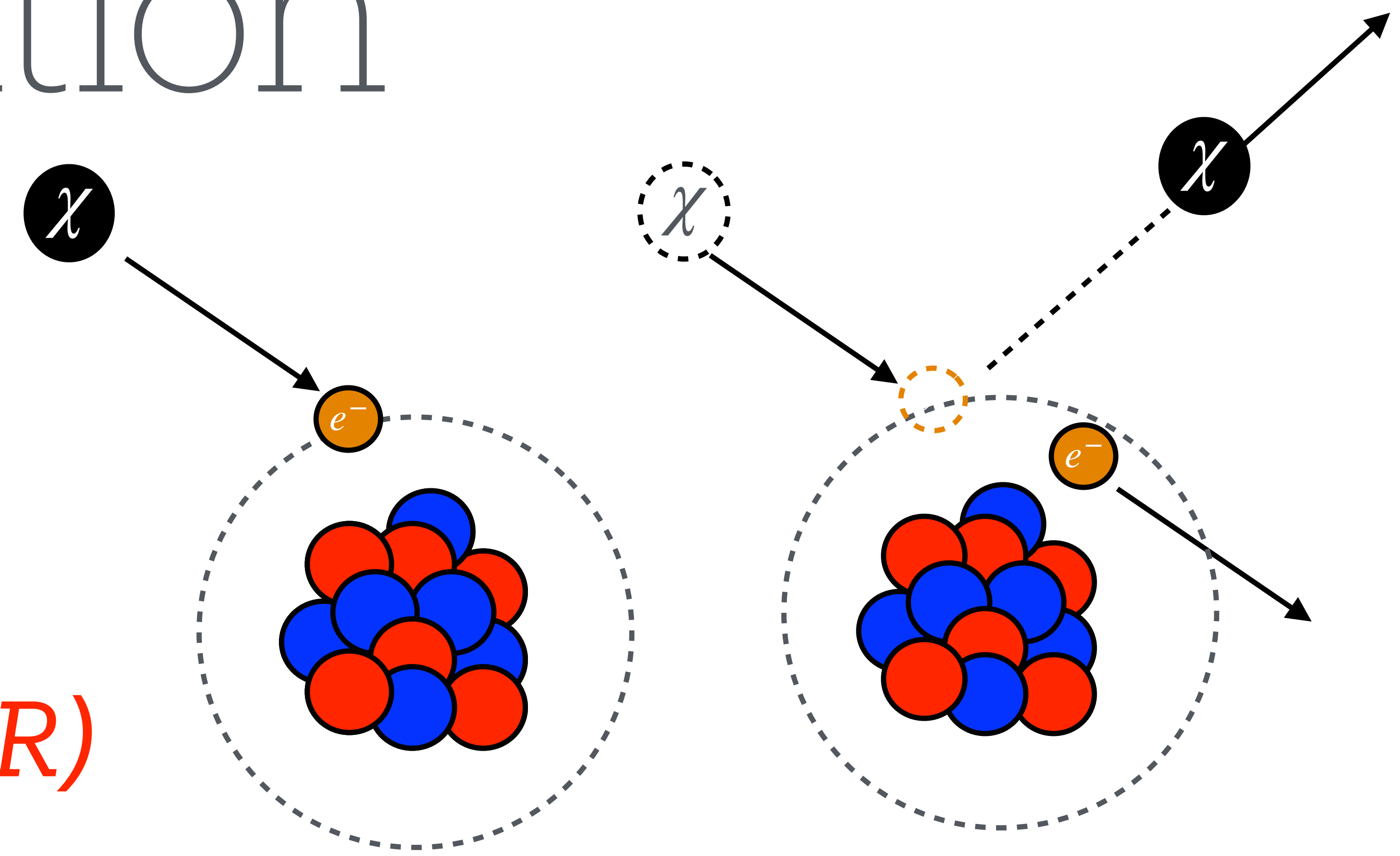
Cryostat complete in Hall C (LNGS)



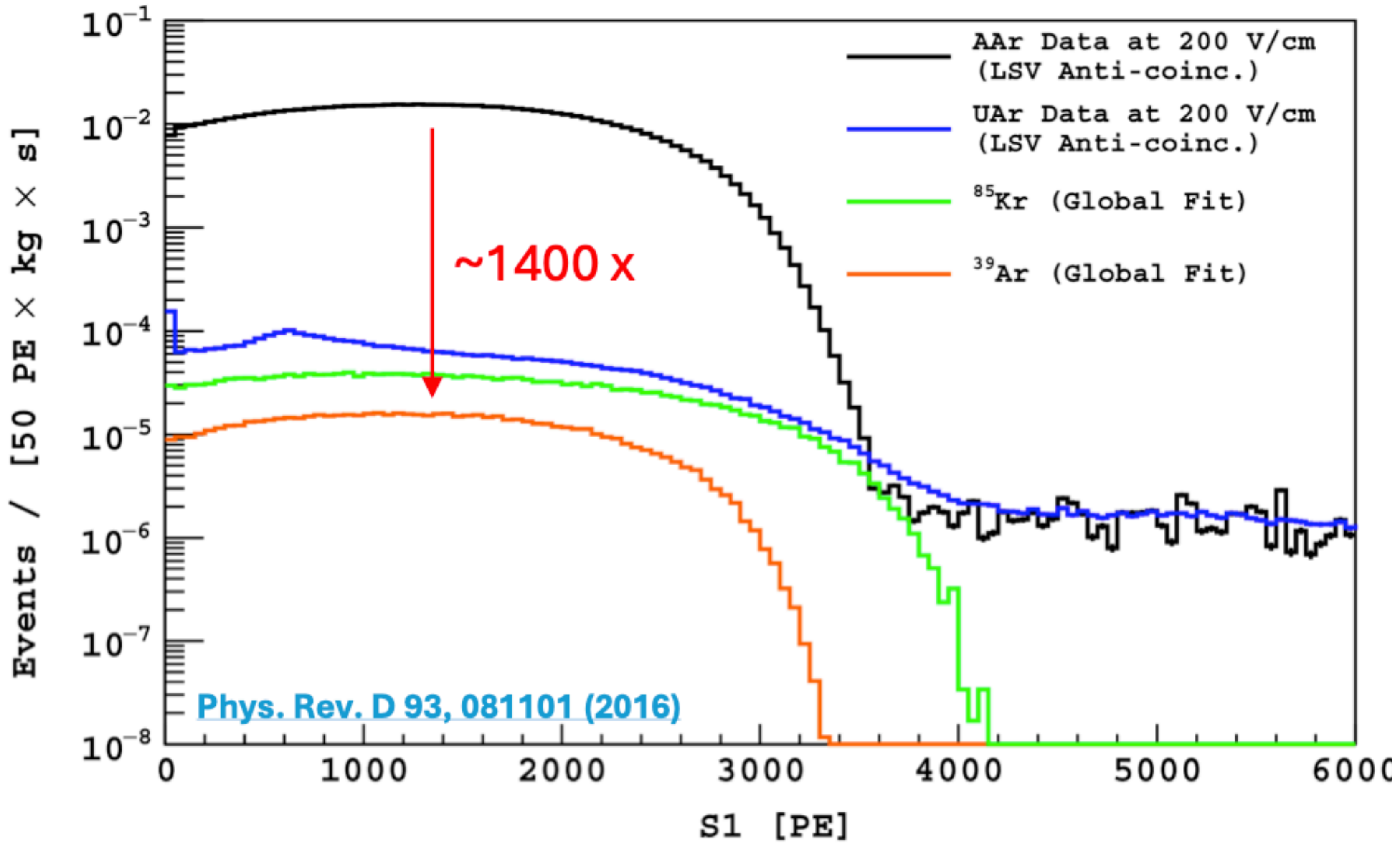
Cryogenics System running in Hall C

DarkSide-20k: Background Mitigation

The only way to be confident we have found dark matter is to **minimise our backgrounds.**



Electron Recoil (ER)

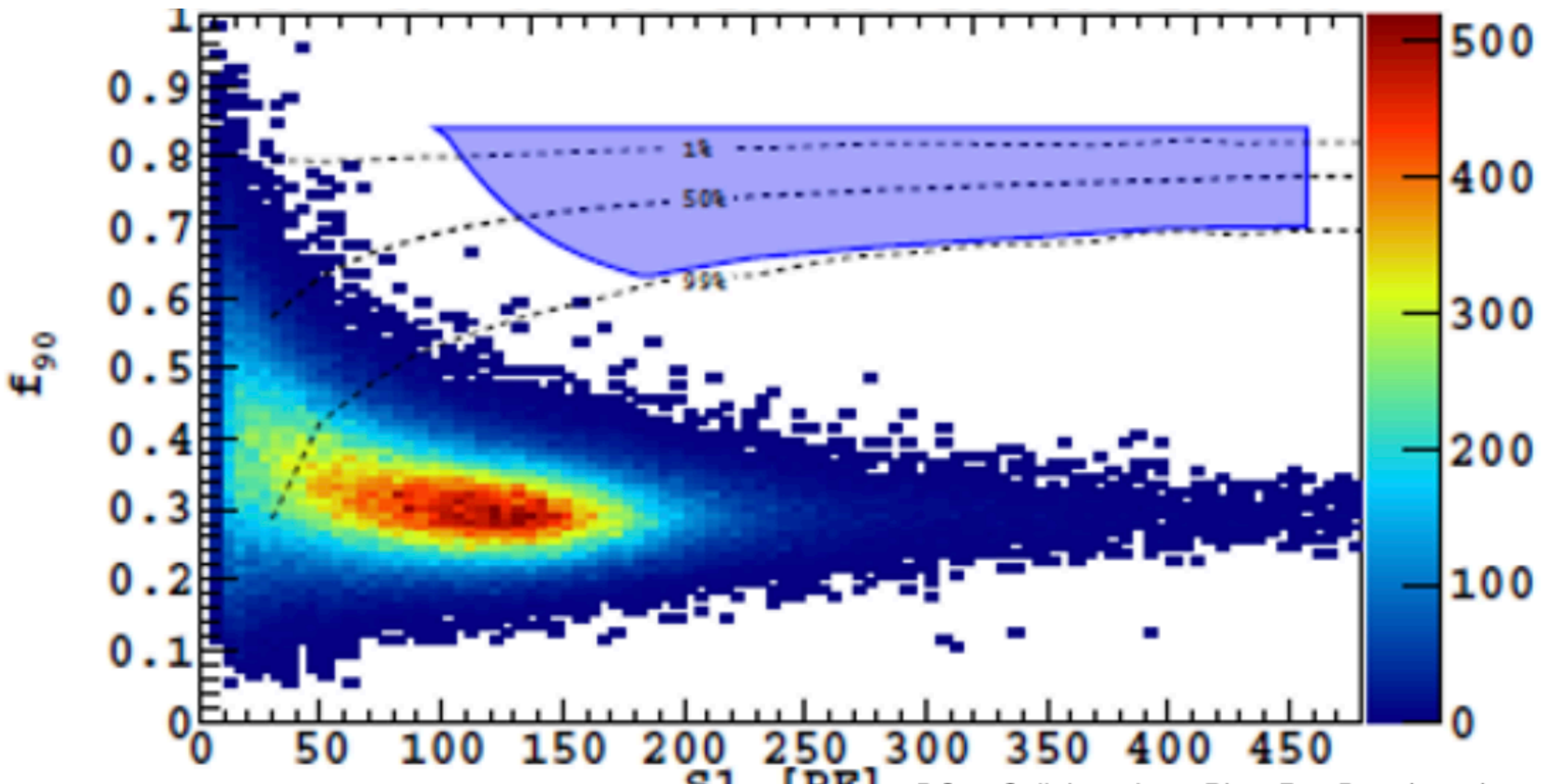


Major Argon advantage: Strong ER background discrimination.

Electron recoils (background) and nuclear recoils (signal) produce very different pulse shapes. Can use pulse shapes to discriminate between them.

Atmospheric Argon has ^{39}Ar radioactive isotope with high activity of 1 Bq/kg: high electron recoil background rate.

^{39}Ar Depletion factor ~1400!



DS50 Collaboration., *Phys.Rev.D* 98 (2018) 1020(

World-leading PSD demonstrated ~10^{10} electron recoil rejection power.

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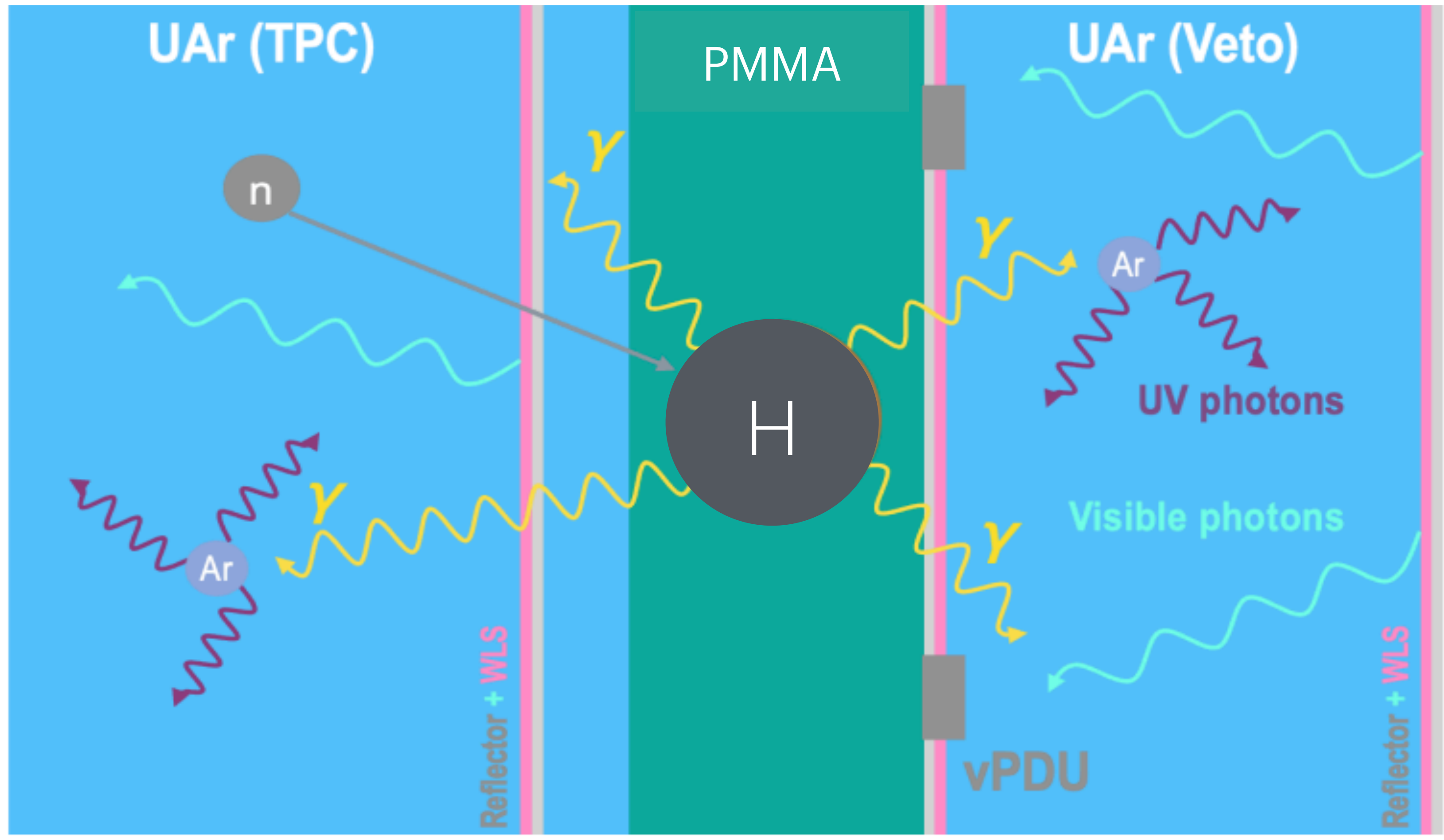
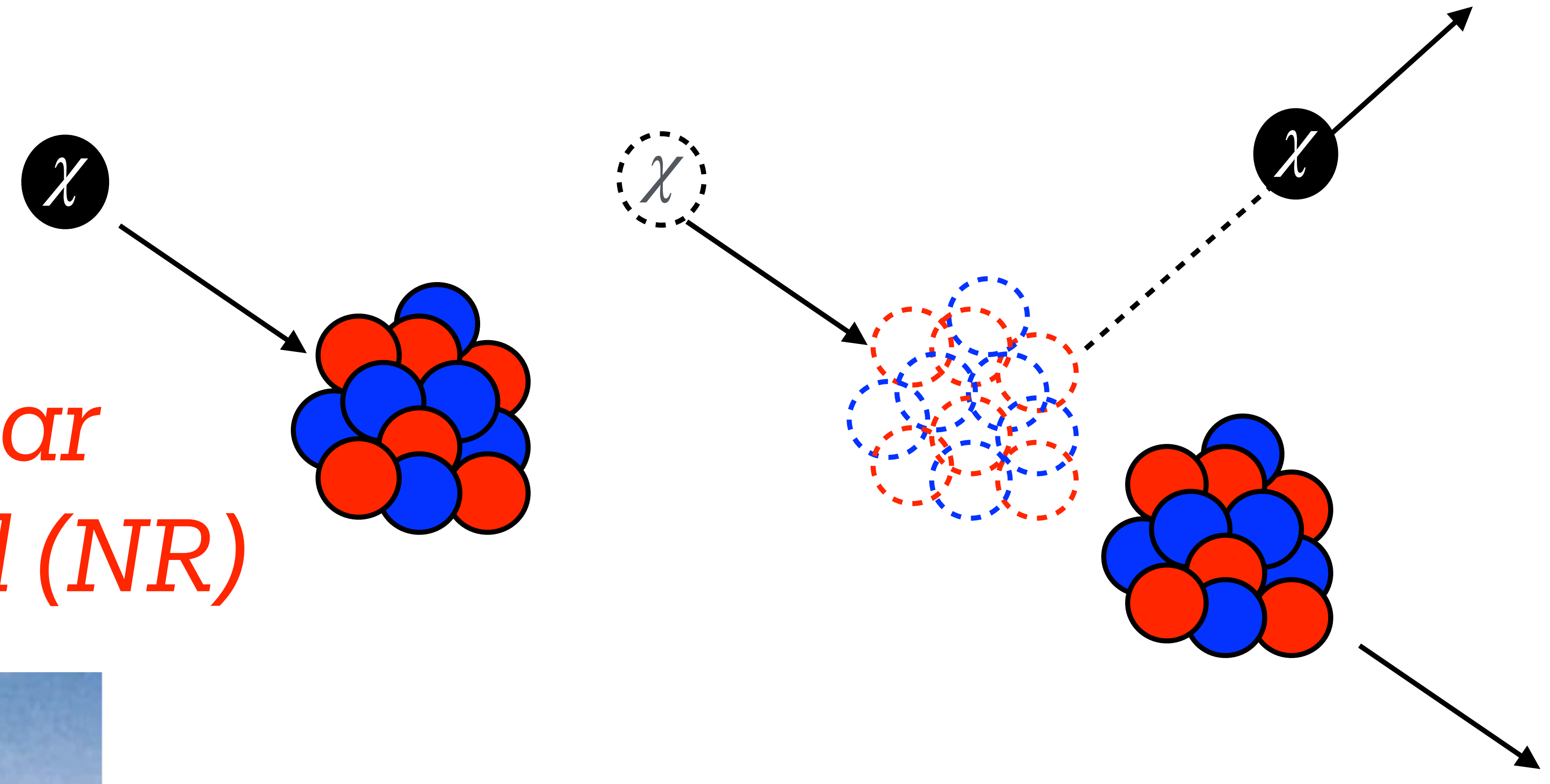


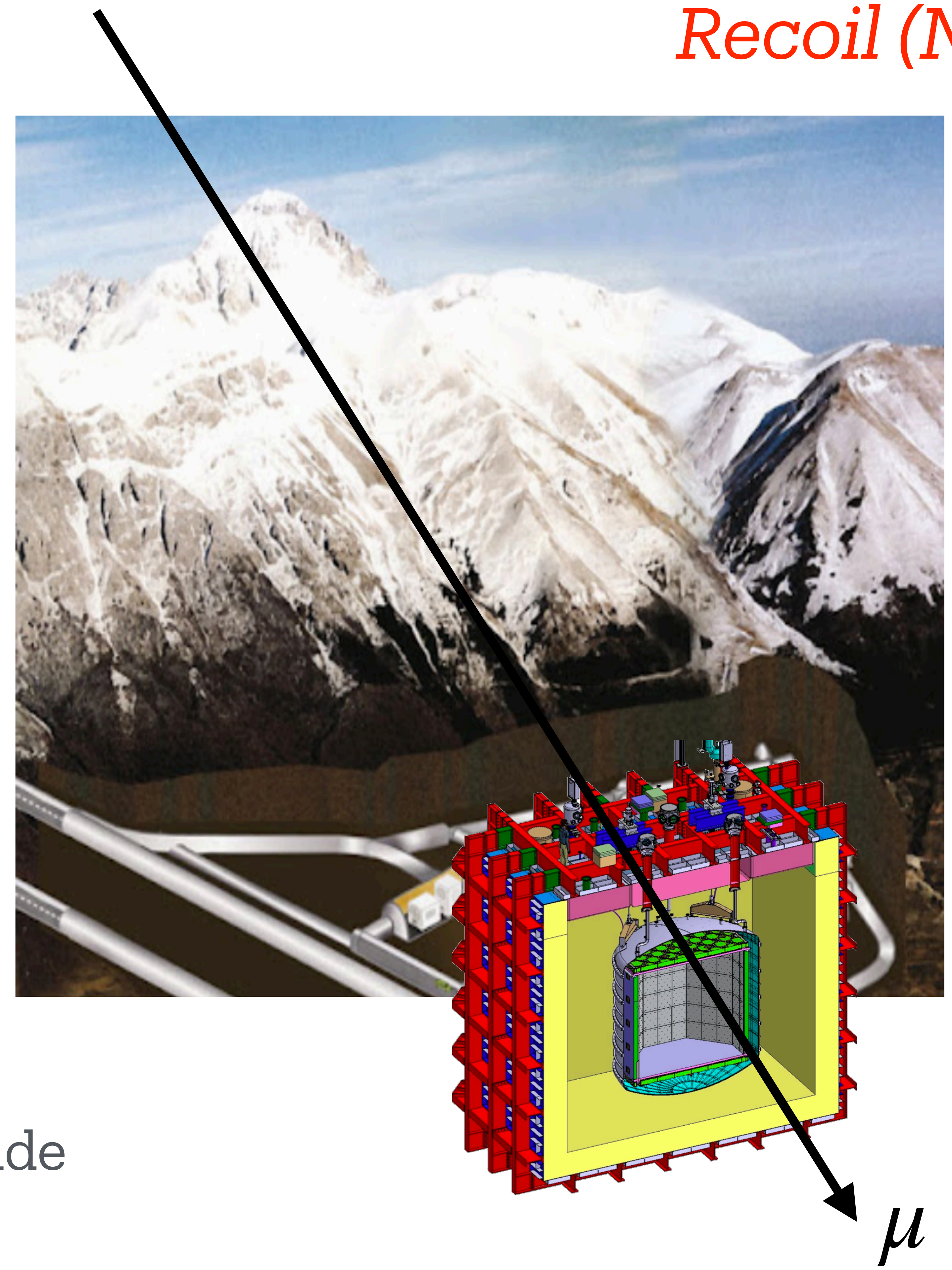
Neutrons most dangerous background for WIMP search.

Radiogenic neutrons originate from intrinsic radioactivity in surrounding detector materials.

Thermal neutron capture produces high energy gamma: **reject WIMP-like events in TPC that coincide with gamma capture event in neutron veto.**

Nuclear Recoil (NR)



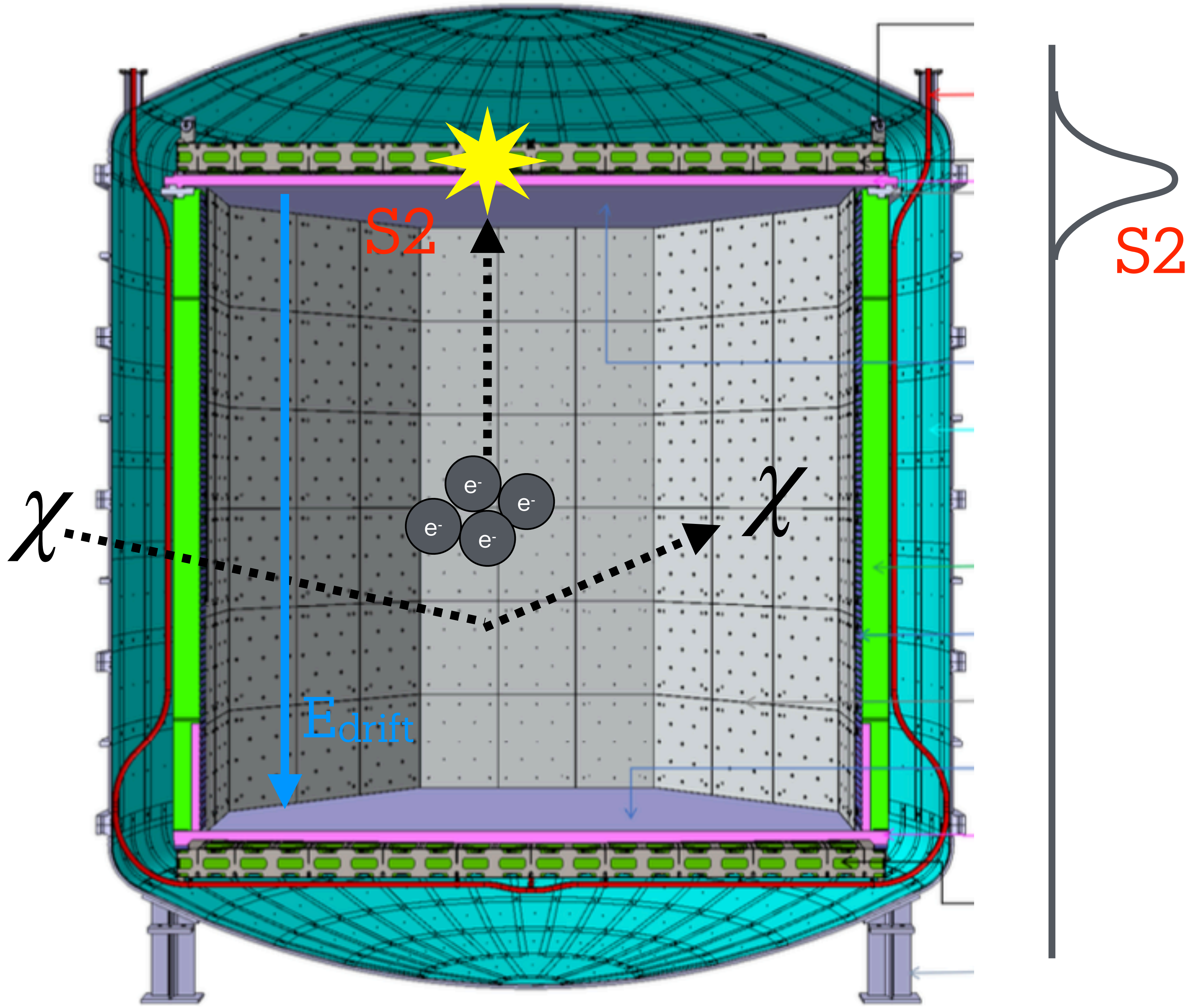


High energy cosmic-ray muons can produce neutrons from interactions with surrounding rock or detector materials.

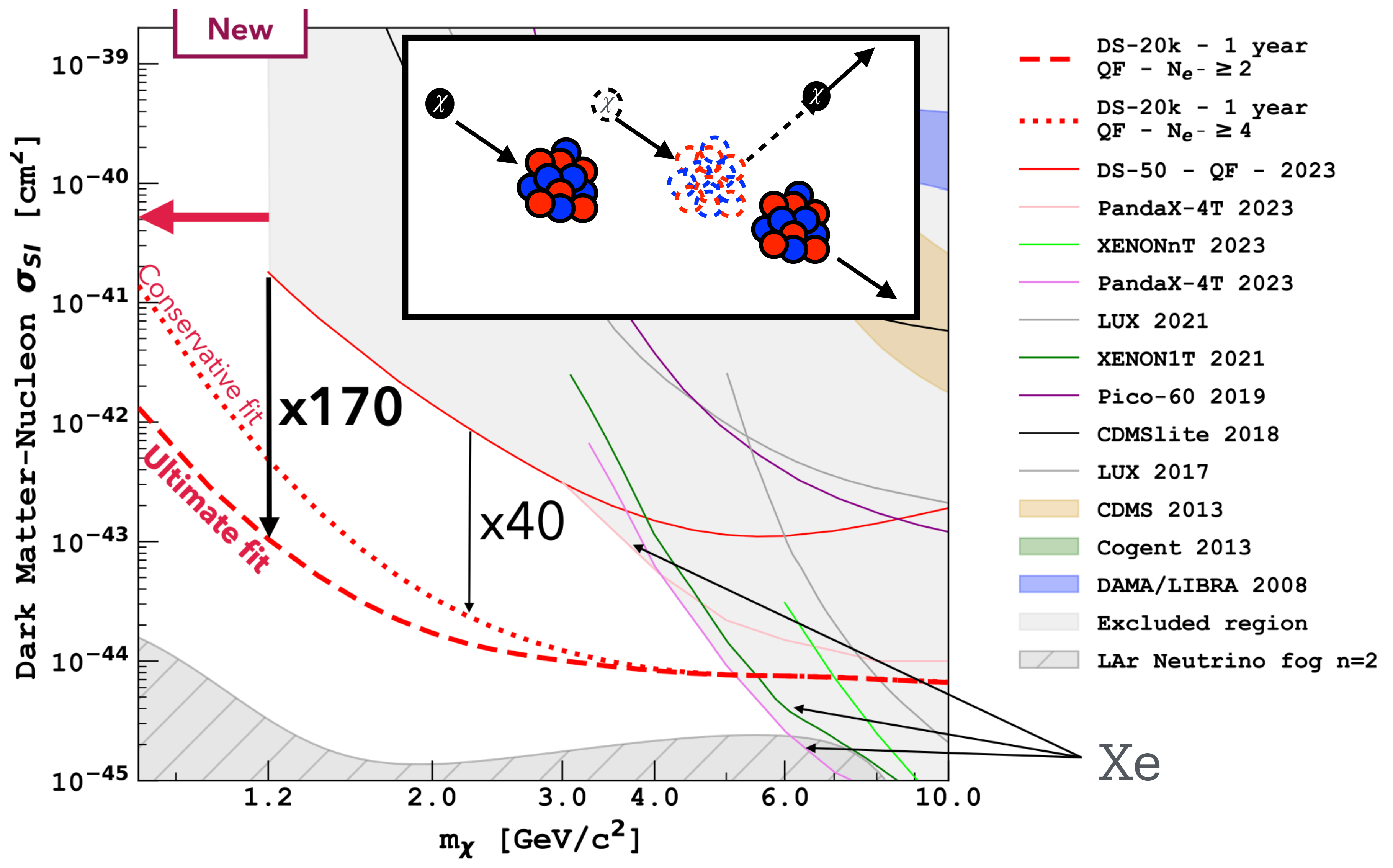
Muons deposit energy in AAr volume via ionisation: **reject WIMP-like events in TPC that coincide with muon tag in cosmogenic veto.**

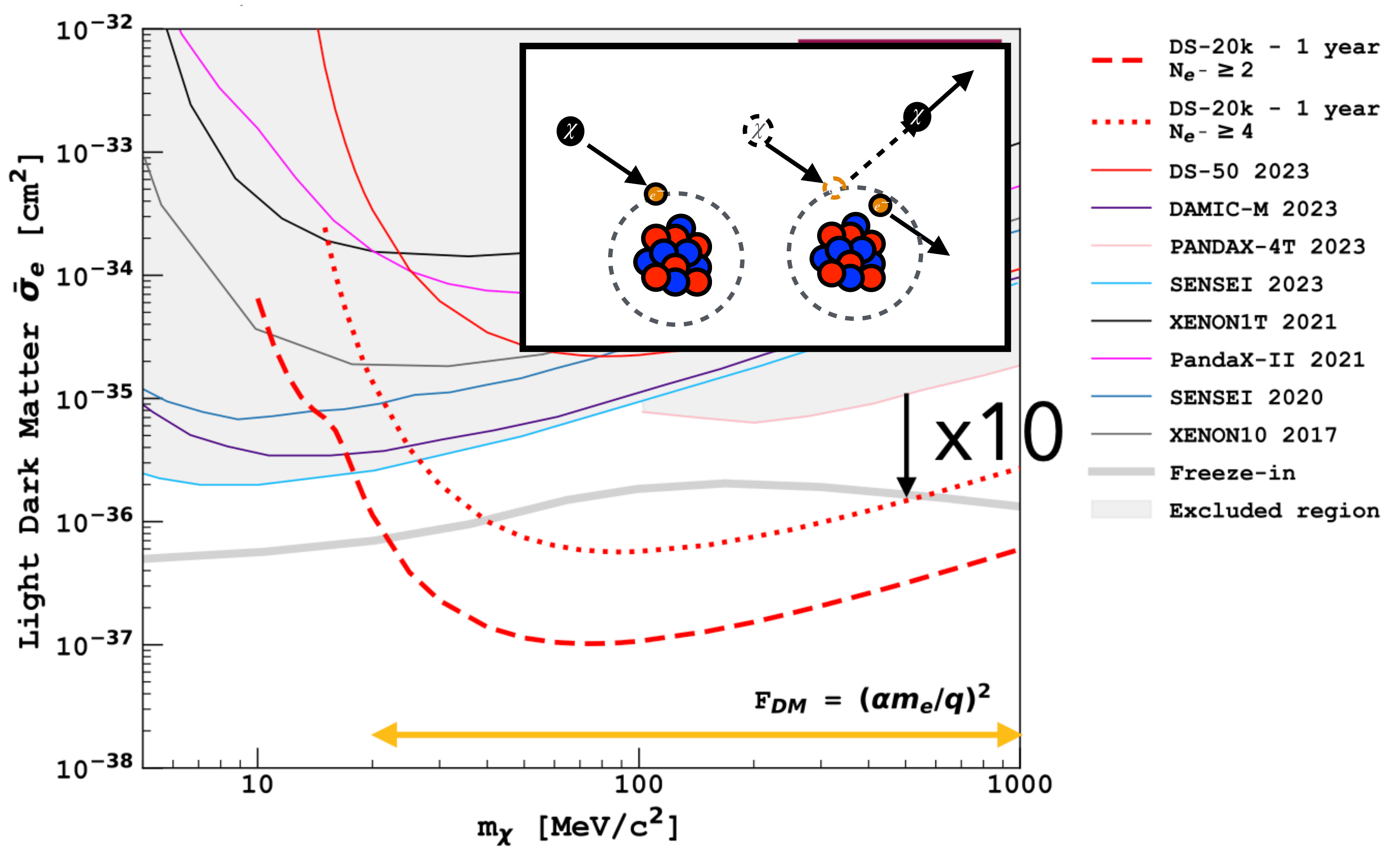
DarkSide-20k: Low-Mass Sensitivity

Dual-phase TPC design drifts and extracts single ionisation electrons in gas with near-100% efficiency— signal amplified a further x20 exploiting electroluminescence in the gas phase.



By exploiting ionisation signal (S2) only, DarkSide-20k can reach sub-keV recoil energy thresholds: opens the door to sub-GeV dark matter candidates beyond vanilla WIMP paradigm!





"DarkSide-20k sensitivity to light dark matter particles." Communications Physics 7, no. 1 (2024): 422.

QUEST-DMC: Overview

QUEST-DMC is 1/7 flagship experiments funded by UKRI Quantum Technologies for Fundamental Physics programme.

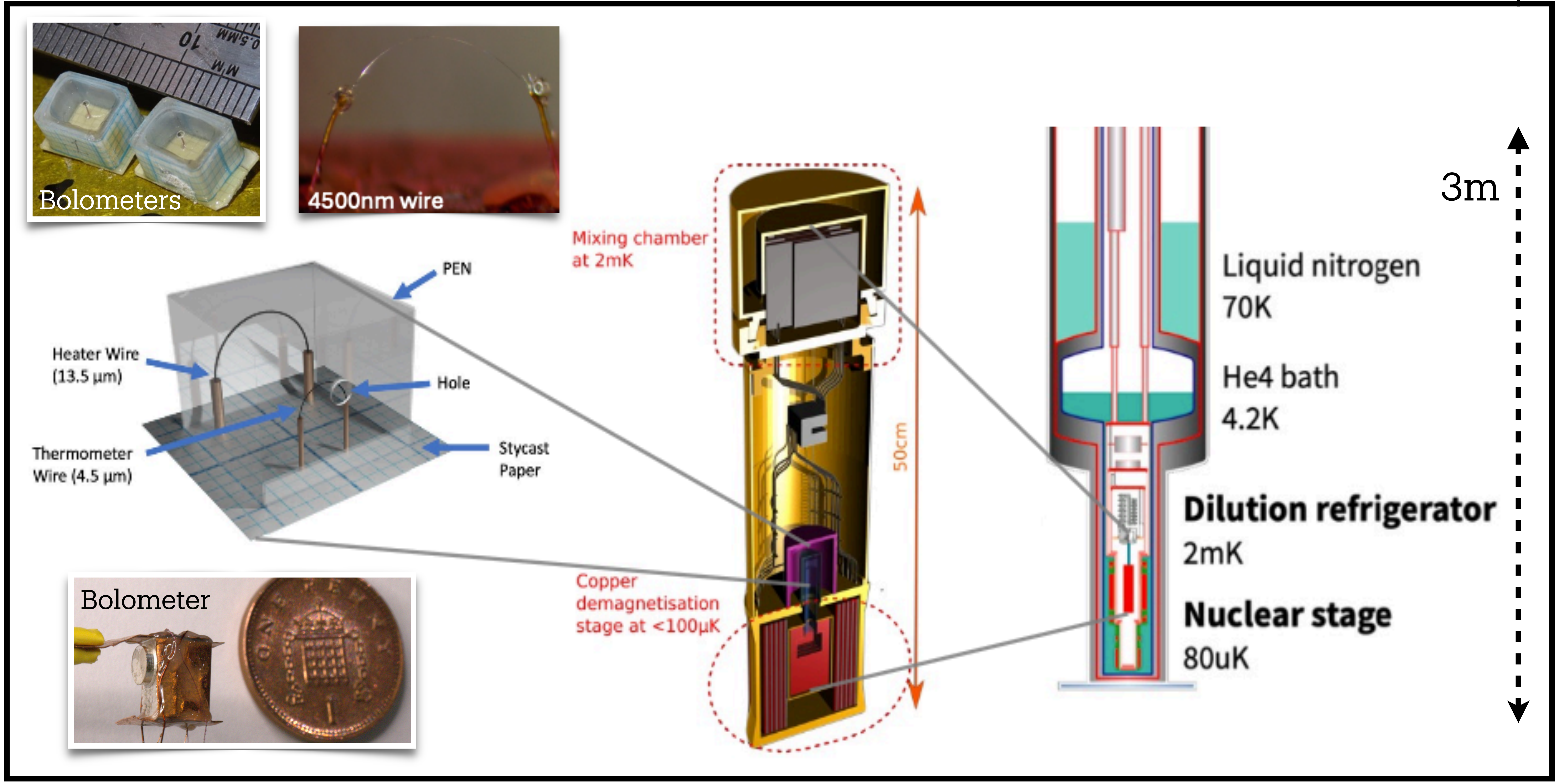
Goal of QUEST-DMC: directly observe spin-*dependent* sub-GeV dark matter interactions.

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

November 2024 QUEST-DMC Collaboration Meeting at University of Liverpool

QUEST-DMC: Detector

~ 1 cm^3 superfluid helium-3 bolometer instrumented with vibrating nanowire resonators, operated inside nuclear demagnetisation cryostat below 1 mK.



The QUEST-DMC detector is ~1.3 million times colder than your freezer at home 🥶

Slide courtesy of E. Leason

QUEST-DMC: Detector

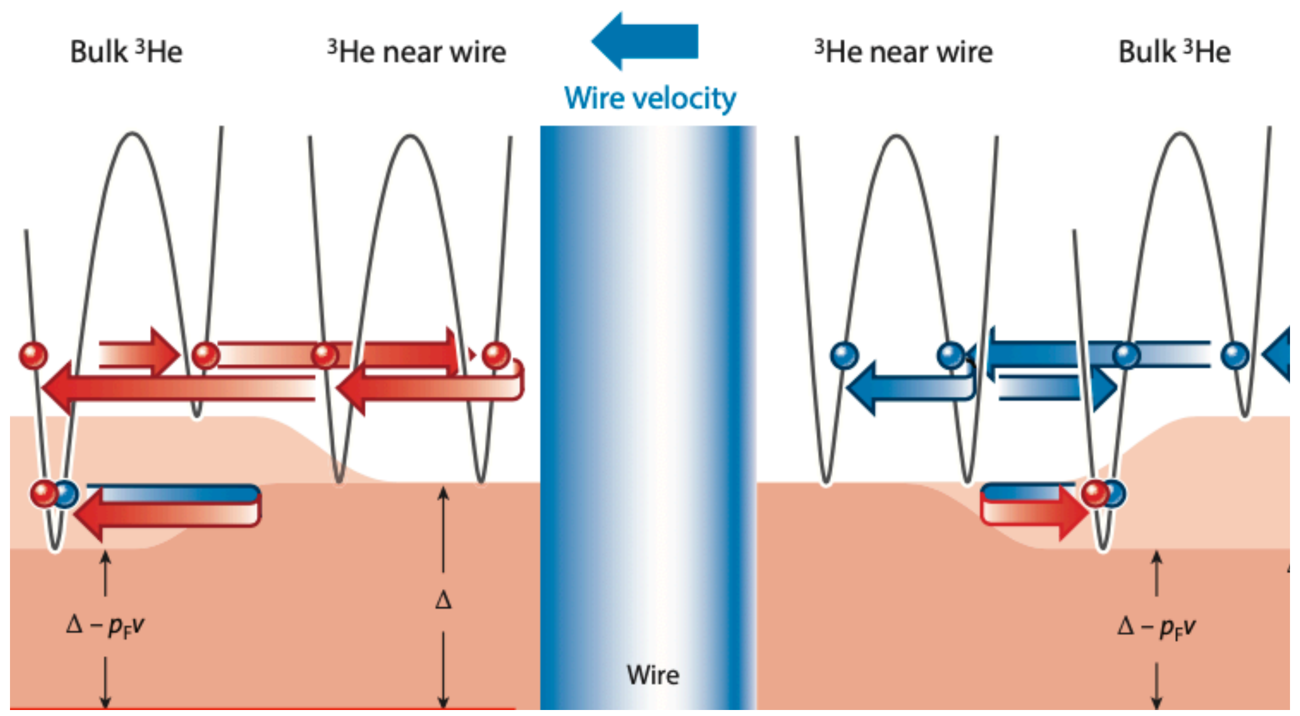
~ 1 cm^3 superfluid helium-3 bolometer instrumented with vibrating nanowire resonators, operated inside nuclear demagnetisation cryostat below 1 mK.

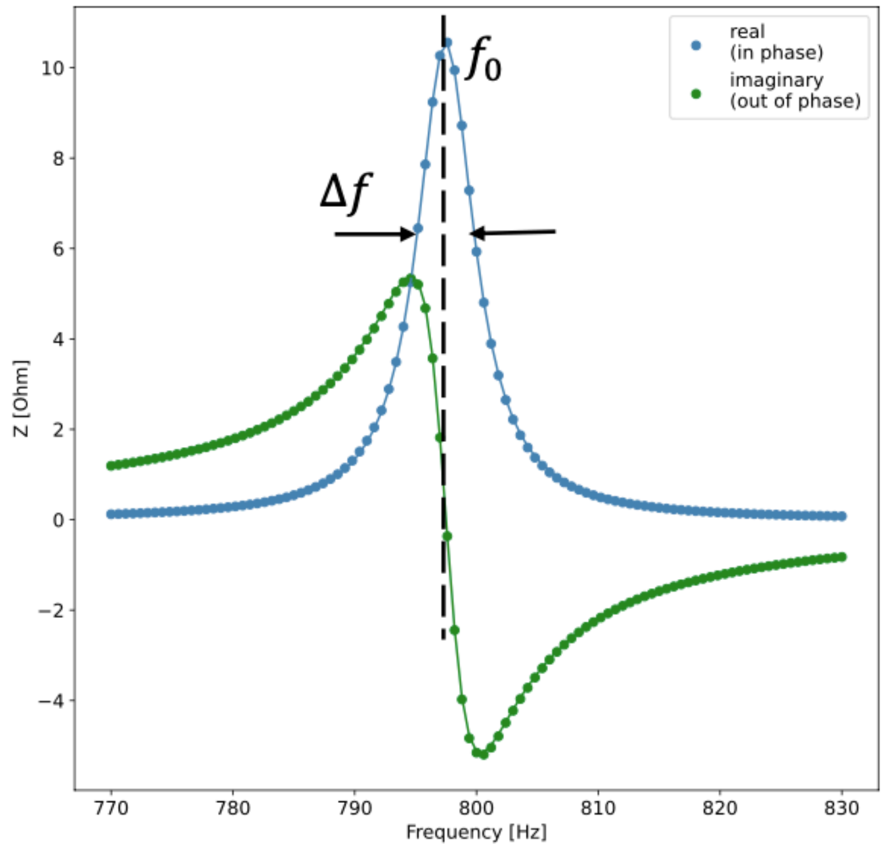
DM-He interactions produce heat in form of quasiparticles (QPs): 1 eV → 10^7 quanta!

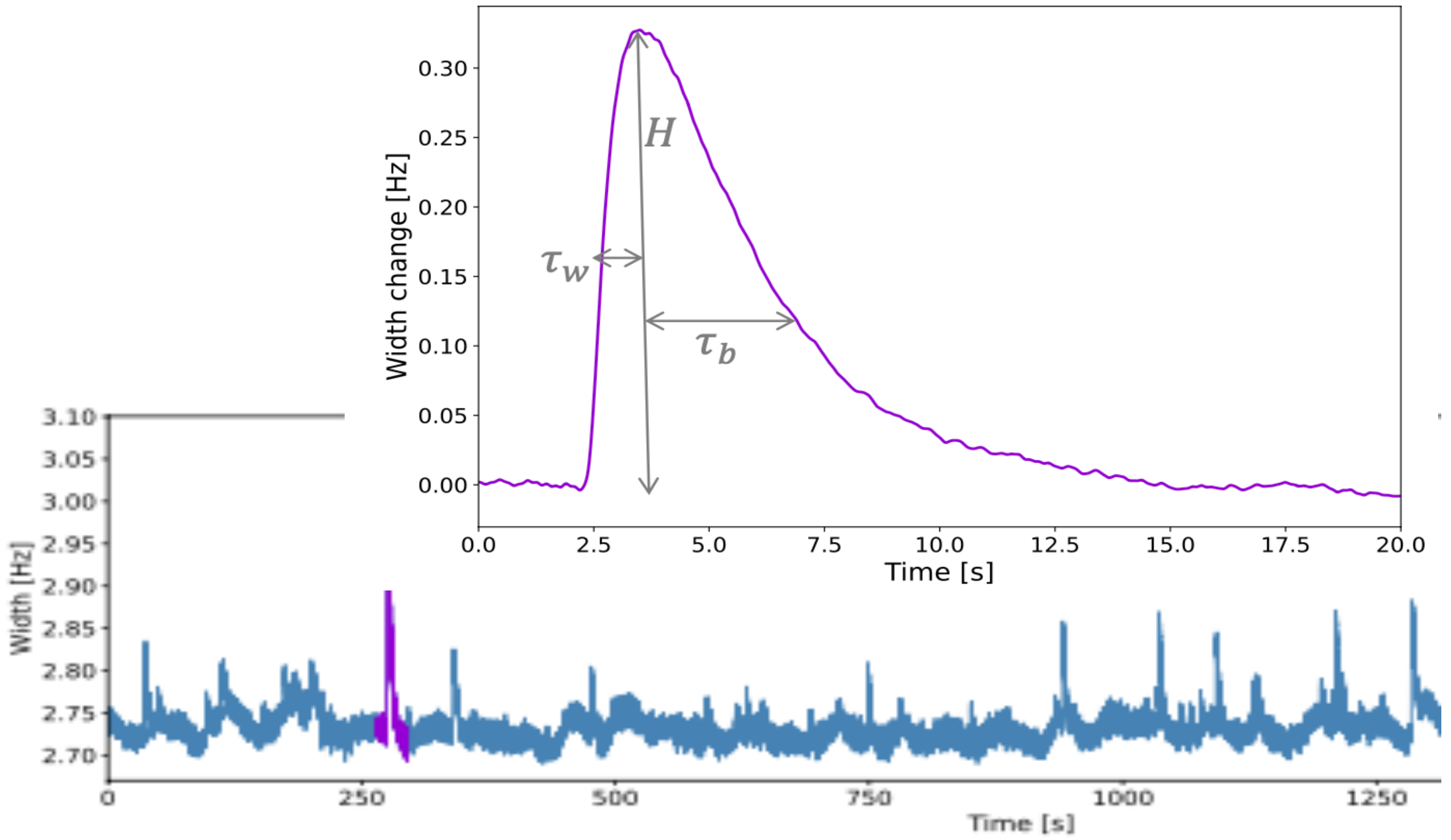
QPs collisions with nanowire exerts damping force.

Nanowire driven by AC current in vertical B field: measure increase in resonance width from damping.

Inducted voltage readout by Superconducting Quantum Interference Device (SQUID).







Plots courtesy of E. Leason

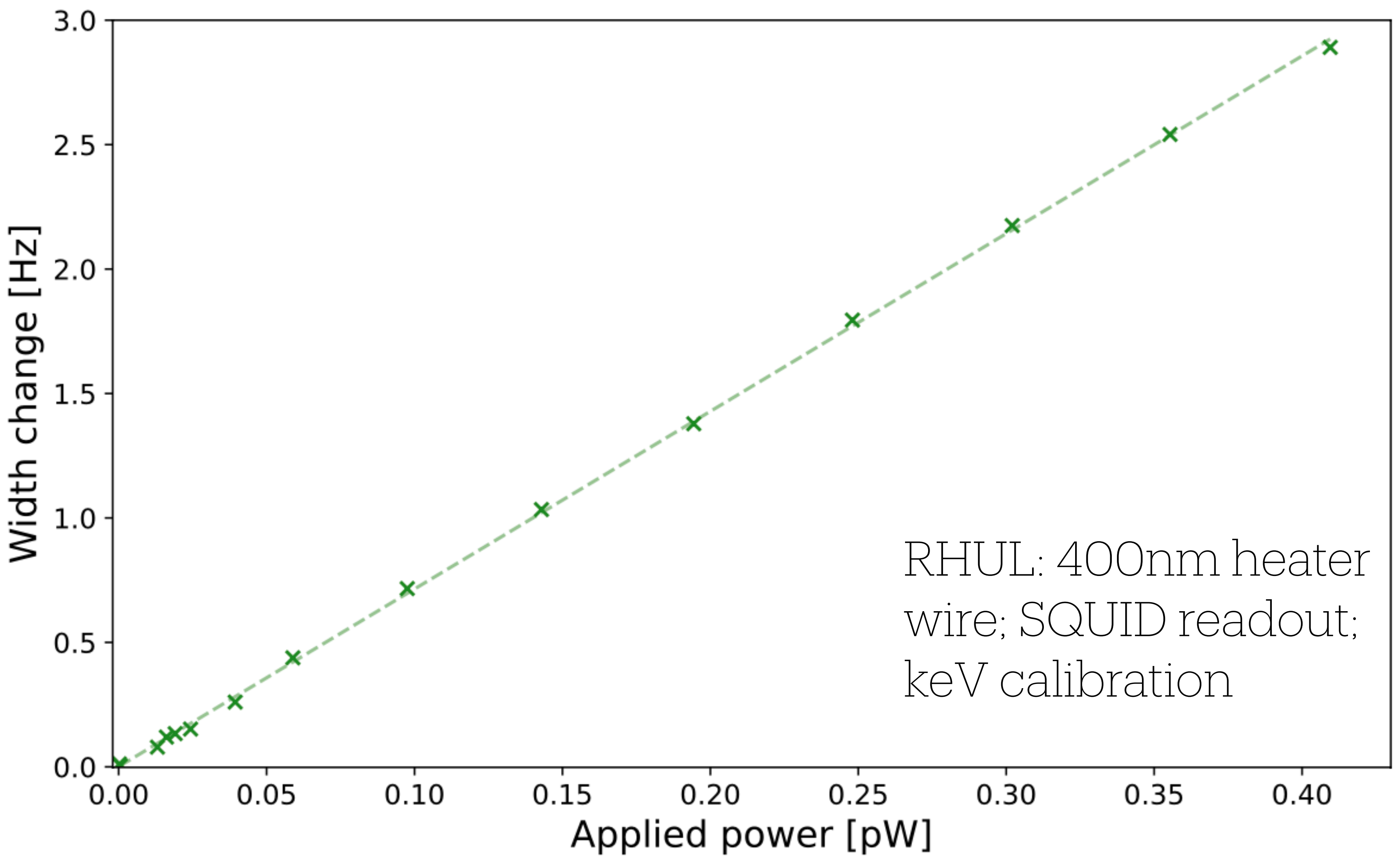
The QUEST-DMC detector is ~1.3 million times colder than your freezer at home 🥶

QUEST-DMC: Status

Operated up to 4 bolometers at <300 μK with smallest nanowires ever made at two sites (RHUL/ Lancs)

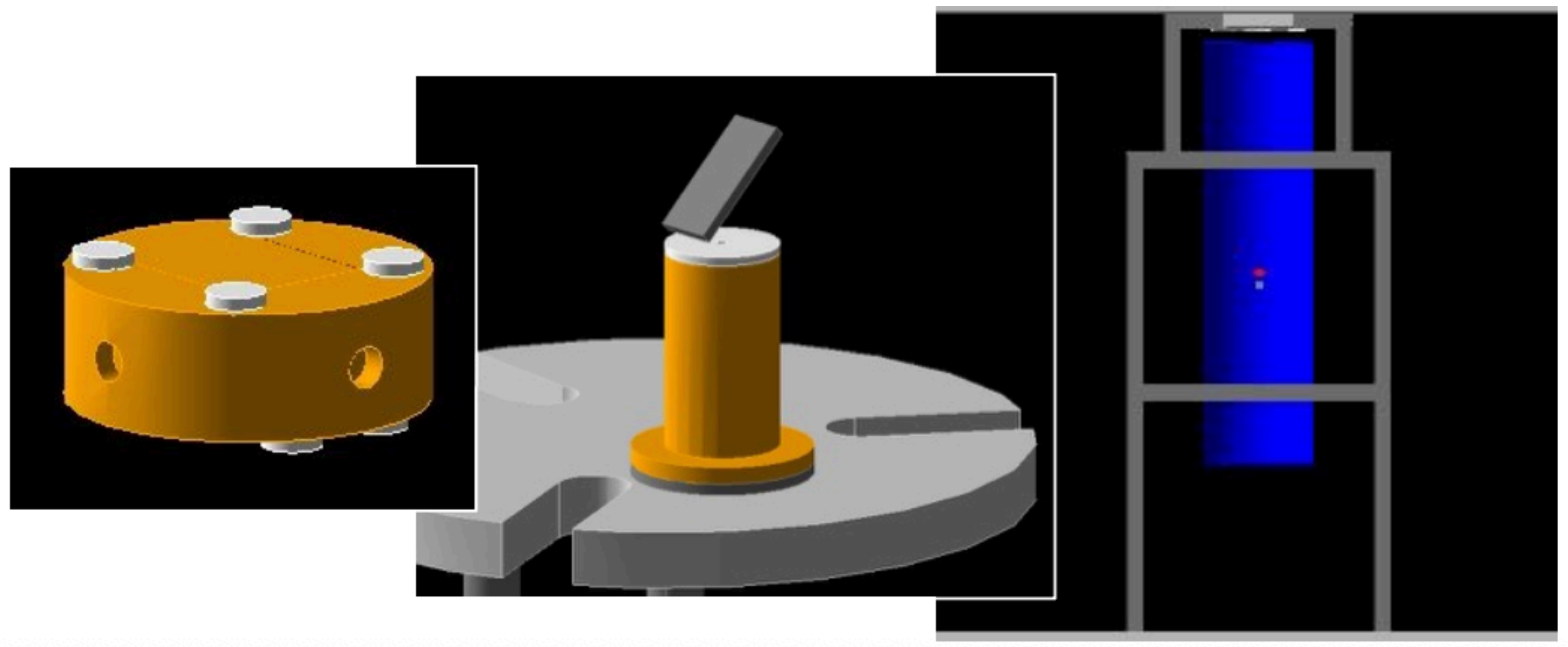
Demonstrated superfluid helium-3 bolometer with nanomechanical resonators using SQUID readout (arxiv:2508.10602)

Heat injection calibration down to femtowatt scales (~few keV)

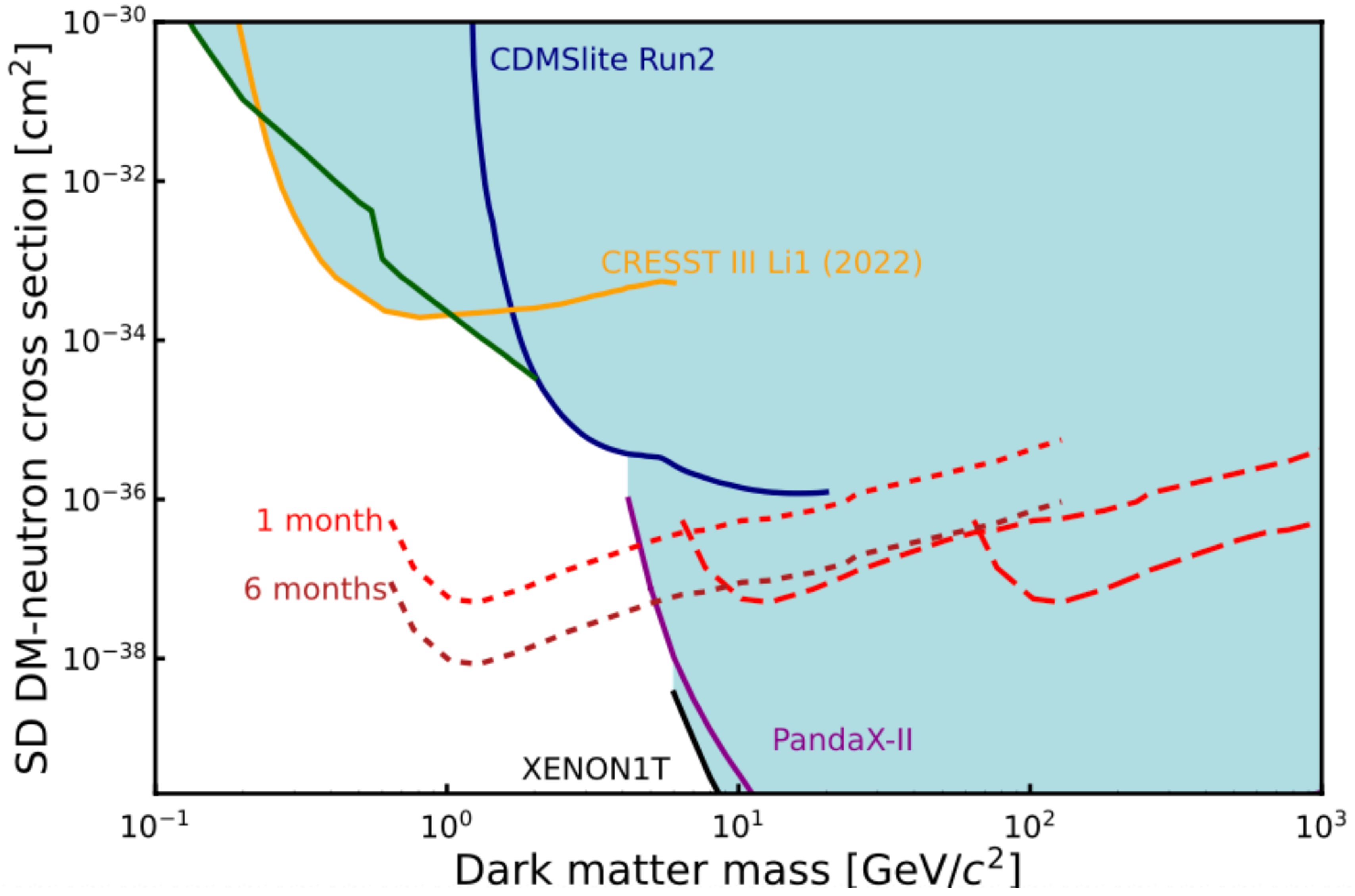


Full GEANT4 background model (cosmic rays, gammas, detector radiogenics), based on Boulby material screening: JLTP(QFS2023)

Baseline-modelling and pulse finder/fitter using CNN currently in development.



Goal: <100 eV energy threshold to access <GeV/c² dark matter



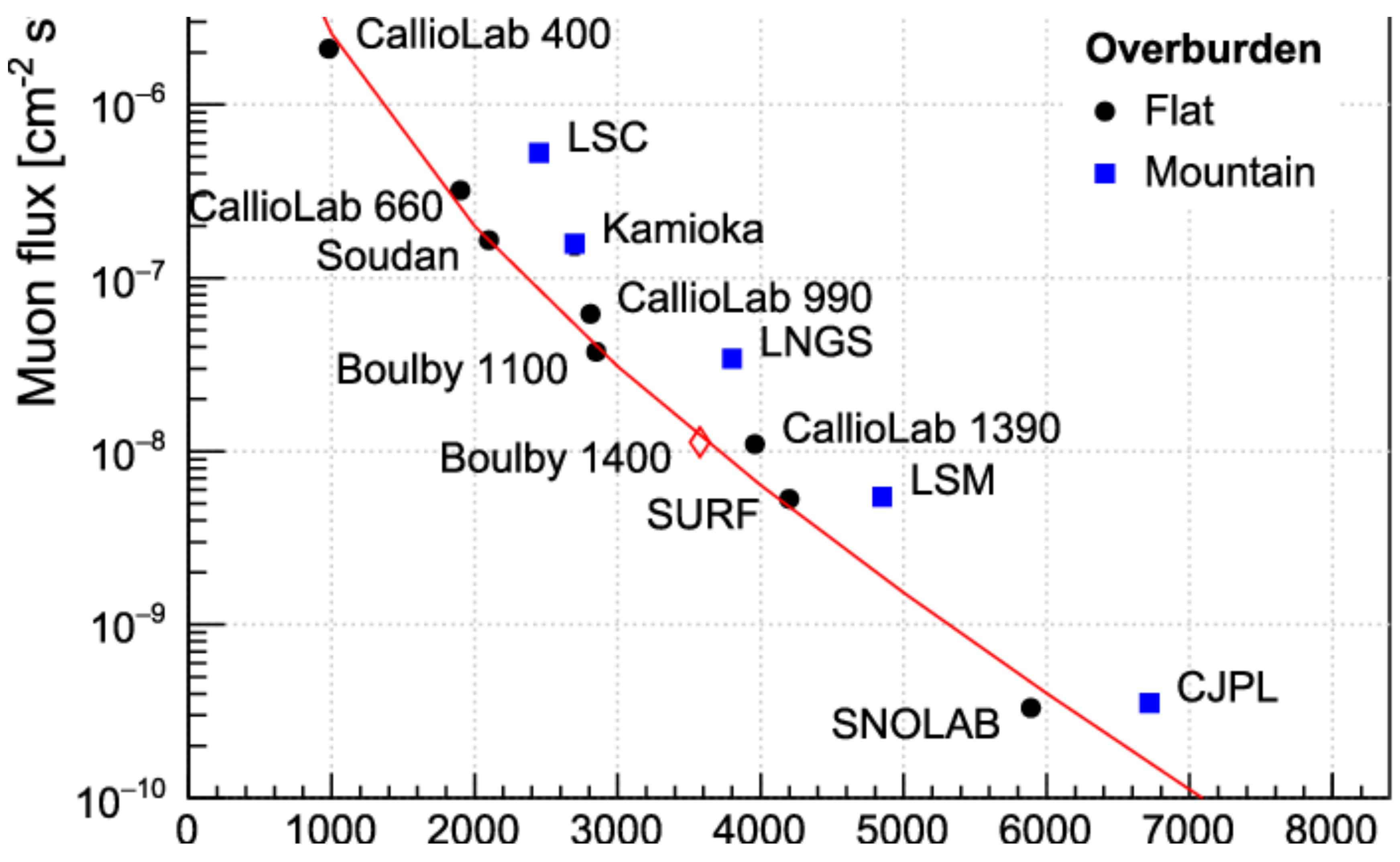
Earth shadowing effects: JCAP04(2025)017

Non-relativistic EFT operators: JCAP10(2025)044

QUEST-DMC: Background Mitigation

The only way to be confident we have found dark matter is to **minimise our backgrounds.**

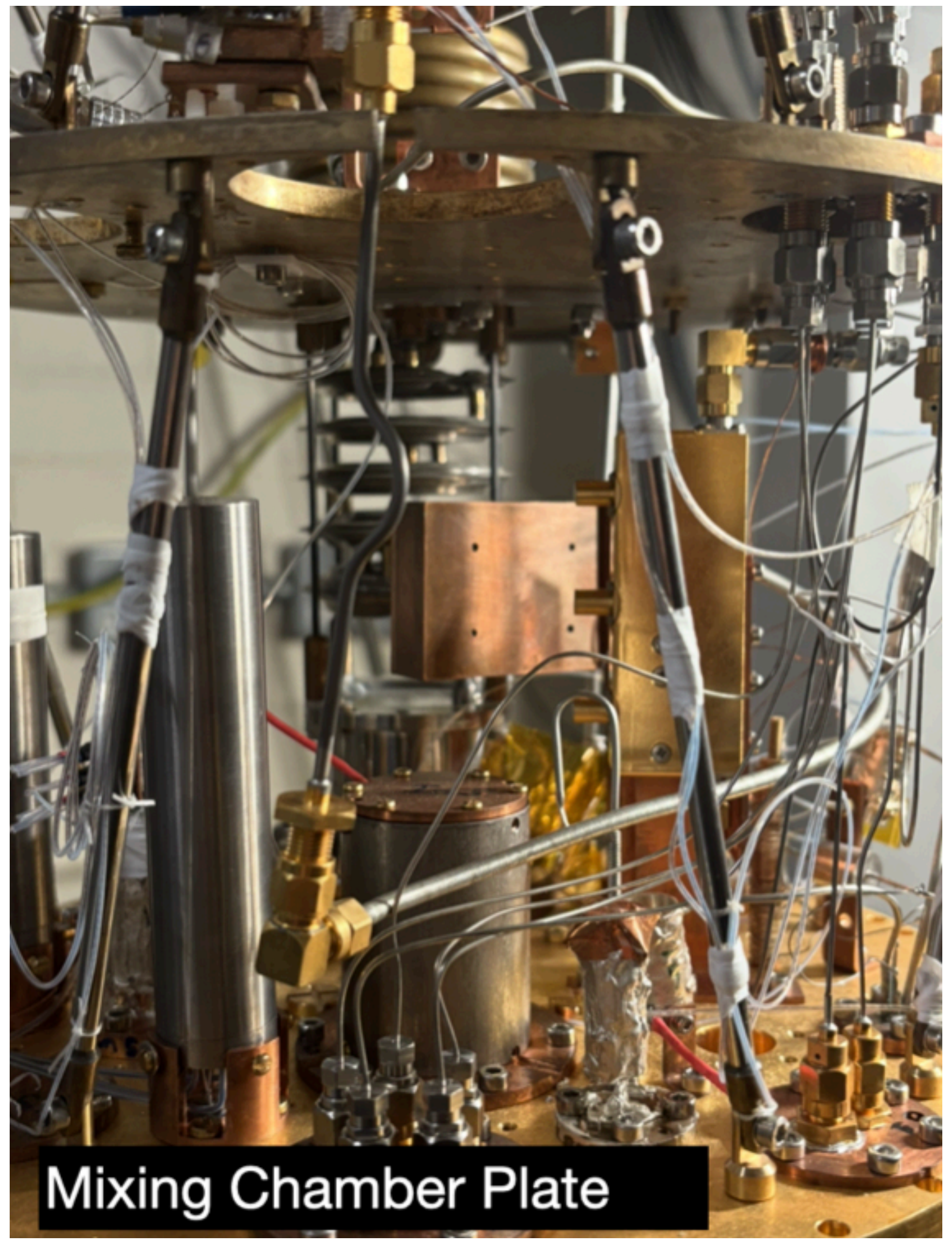
- Unlike DarkSide-20k, QUEST-DMC is operated at surface level: no shield from cosmogenic backgrounds!



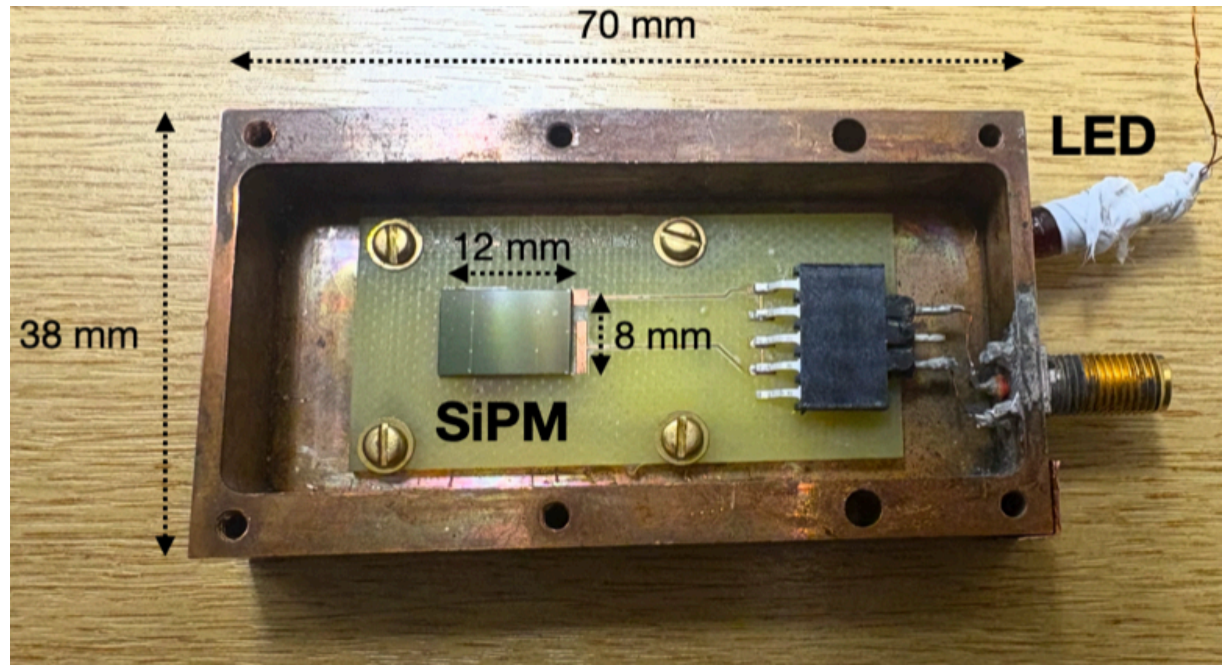
QUEST-DMC needs a cosmic-ray muon veto system!

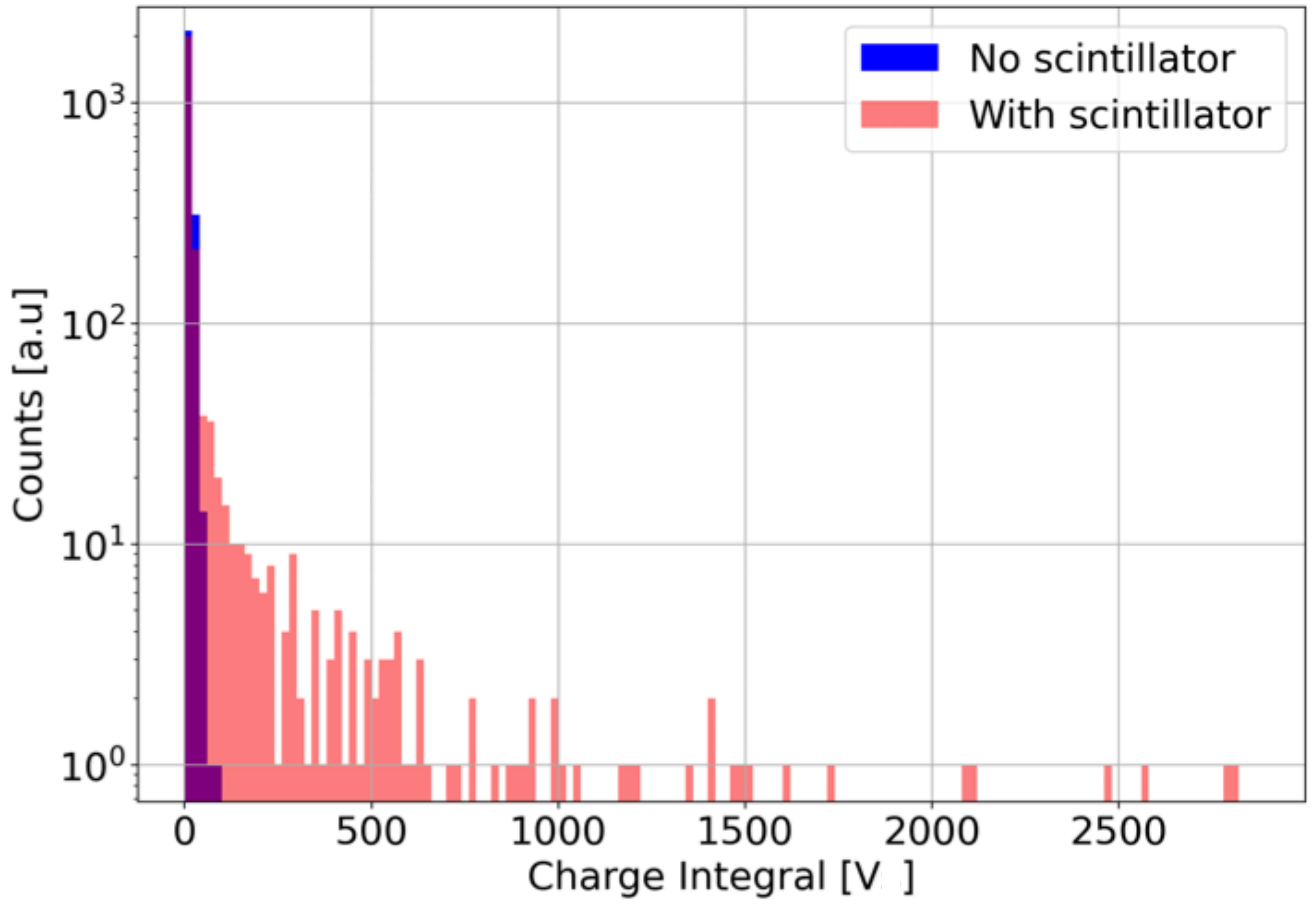
Veto concept: scintillator volume surrounding bolometer detectors, coupled to photon sensor

- Detect ionisation produced by high-energy muon passing through scintillator: **reject candidate DM events in bolometer that coincide with muon tag in veto.**



First proof-of-concept demonstration of operating silicon photomultiplier sensor at ~10 mK inside a dilution fridge, coupled to scintillator block *(arxiv:2512.16769)*



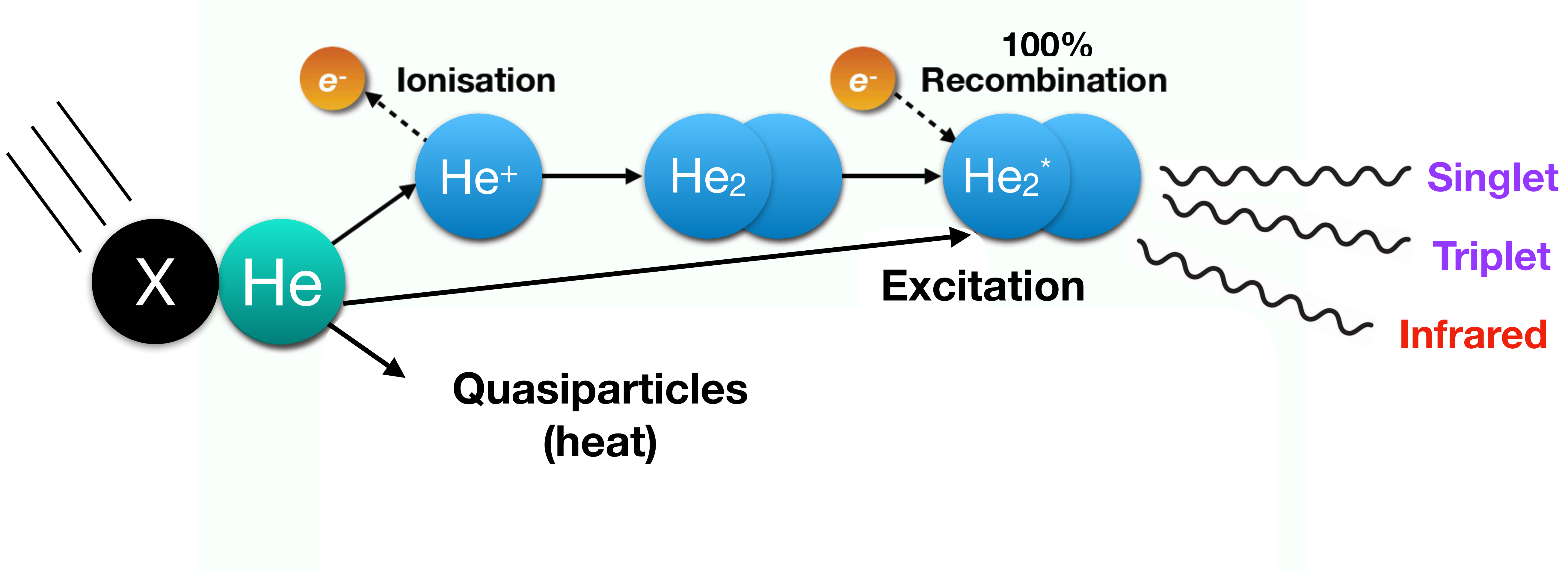


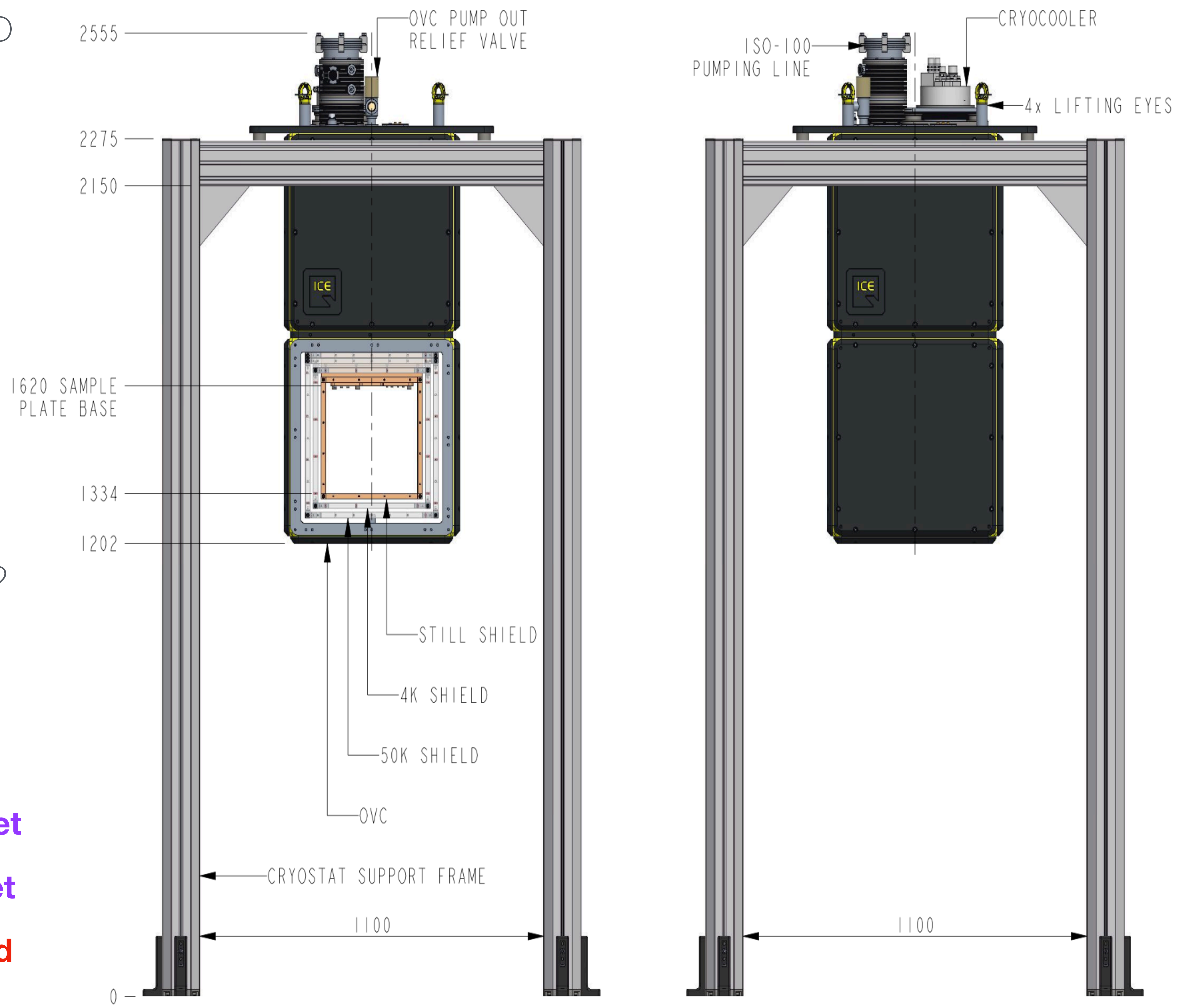
QUEST-DMC: Background Mitigation

Cryogenic characterisation and commissioning of veto detector system will take place on-site at RAL within custom-designed dilution refrigerator (20 mK base temperature): **hardware experience.**

Additional work:

- Adapt veto system to reject ambient gamma background.
- Ultra-low temperature photon detection for He scintillation: further background mitigation strategy?





Summary

In this project, you will...

Gain experience of a **large, international project** through commissioning and calibration of the large-scale neutron and cosmogenic veto systems in DarkSide-20k, on-site at LNGS during your long-term attachment,

Gain first-hand experience with **cryogenic photodetection and operating dilution refrigerators** here at RAL,

Develop essential analysis software to **reject external backgrounds**, combining dark matter target volume and veto sub-detector system information, and,

Directly contribute to low-mass dark matter searches, testing a range of new physics models **beyond the traditional WIMP paradigm**, with the prospect of a combined analysis across QUEST-DMC and DarkSide-20k datasets.

The Supervisors

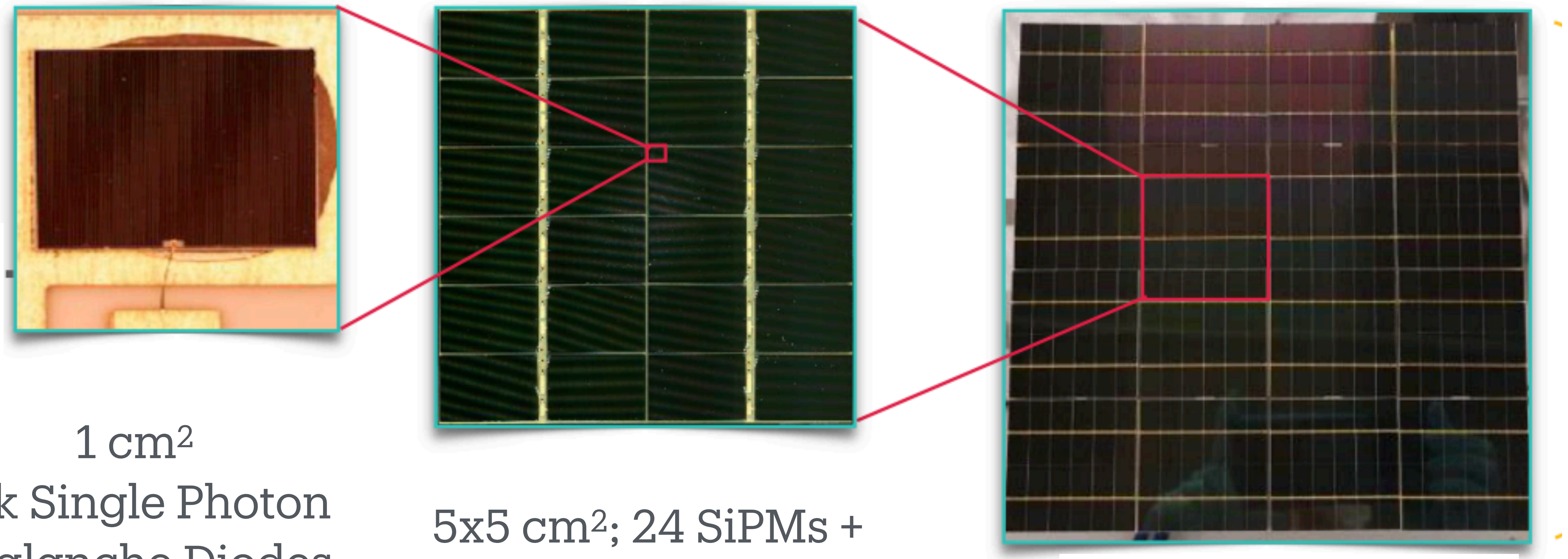
Jocelyn Monroe is a Professor of Particle Physics at the University of Oxford and is seconded to RAL. She plays a leading role in DarkSide-20k, currently serving as deputy spokesperson. Monroe earned her PhD from Columbia University and has held academic positions at MIT, where she was also a Pappalardo Fellow. In 2016, she shared the Breakthrough Prize in Fundamental Physics for her contributions to the Sudbury Neutrino Observatory. Monroe founded the Dark Matter & Neutrino research group at Royal Holloway, University of London before moving to Oxford.

Ashlea Kemp is an experimental particle physicist at RAL. She earned her PhD from Royal Holloway, University of London, during which she was awarded a Leverhulme Study Abroad scholarship. As a postdoctoral researcher, she worked under Prof Art McDonald (2015 Nobel Laureate recipient) at Queen's University in Canada, and Prof Jocelyn Monroe at Royal Holloway/Oxford. In 2024, she was awarded a UKRI Future Leaders Fellowship to establish her own team to pursue research in experimental searches for dark matter.

Back Up

DarkSide-20k: Light Readout with SiPMs

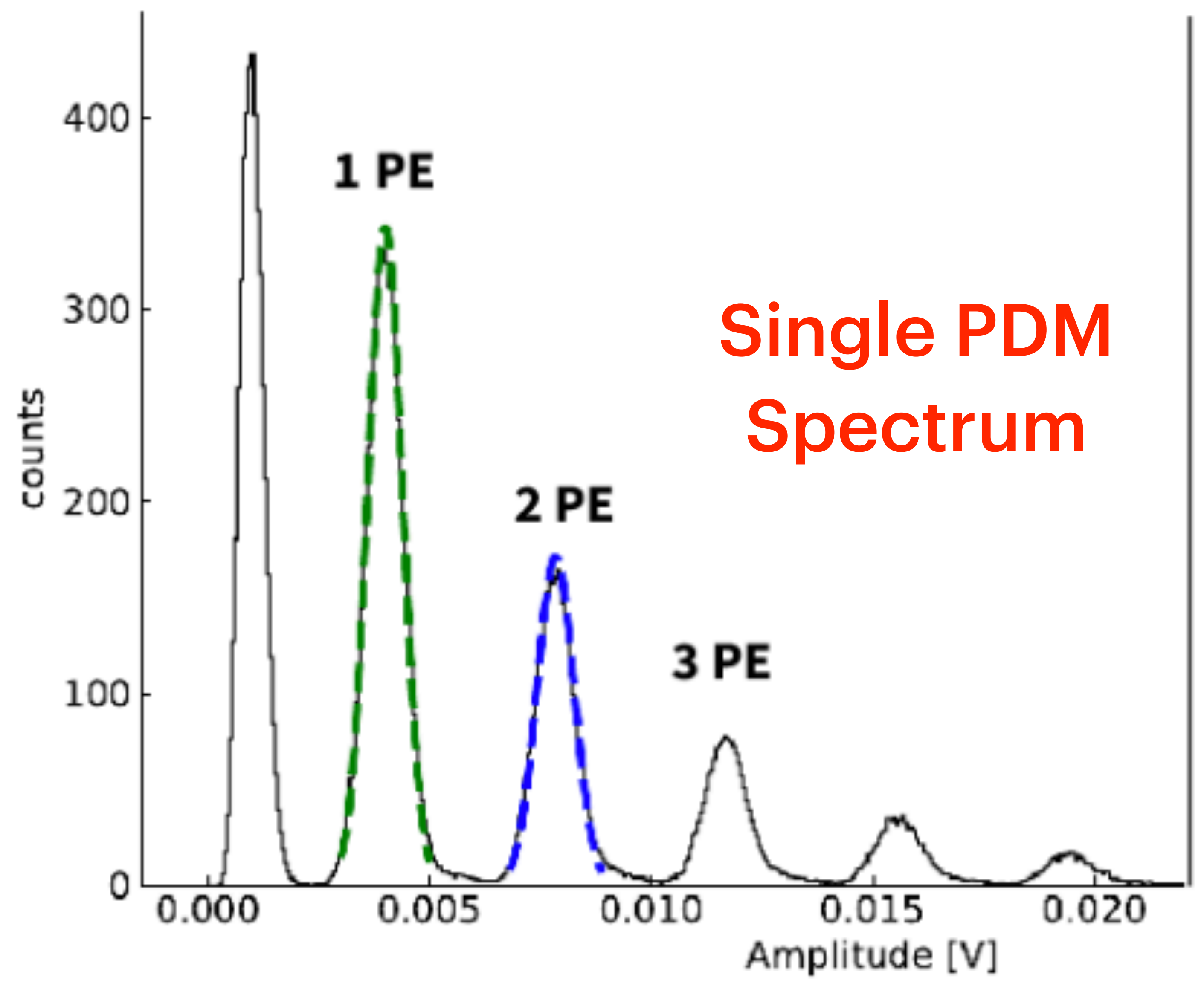
Silicon Photomultiplier (SiPM) | Photodetector Module (PDM) | Photodetector Unit (PDU)



1 cm²
95k Single Photon Avalanche Diodes

5x5 cm²; 24 SiPMs + Front-End Electronics

20 x 20 cm²; 16 PDMs + Motherboard



First dark matter experiment to be fully instrumented with SiPMs!

Why SiPMs? Lower noise; lower radioactivity; higher photon detection efficiency; and excellent single photon resolution compared to traditional photomultiplier tubes (PMTs).