

Facilities Overview Session: Boulby Underground Laboratory

RISQ Workshop 2024

Fermilab

Dr Ashlea Kemp & Dr Elizabeth Leason, 31st May 2024



Boulby Underground
Laboratory

Introduction: Boulby

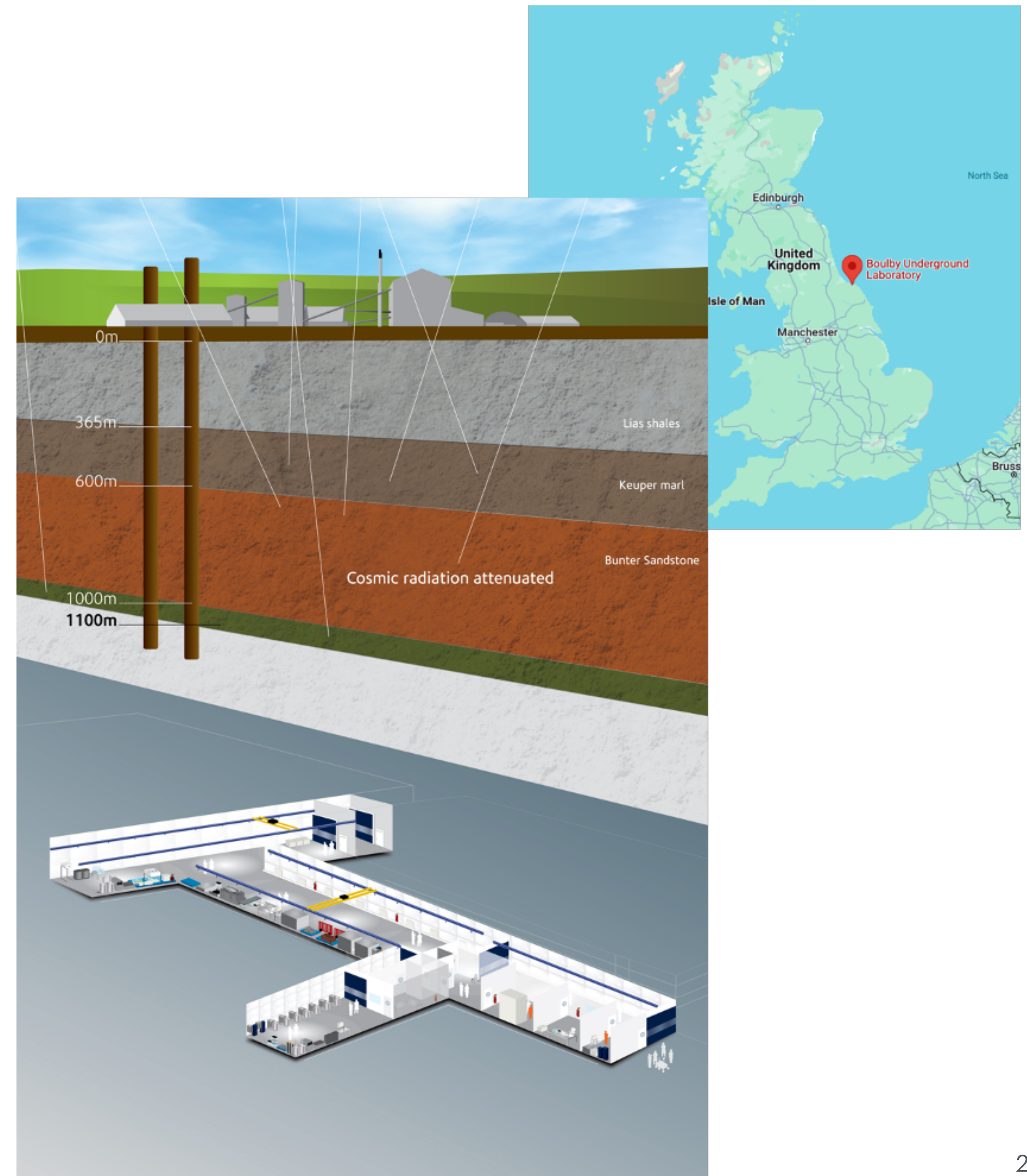
Open since 1968, mining potash (KCl) for fertiliser: now polyhalite.

Deepest mine in the UK @ 1.1 km (2805 m.w.e).

Laboratory operated by STFC in partnership with ICL.

Surface comprised of office and laboratory space.

Underground comprised of 4000 m³ cleanroom laboratory space.



Dark Matter & Neutrinos @ Boulby

1990s: First dark matter experiments at Boulby using NaI crystals
[Phys.Rep.307(1998)275-282].

1990s - 2012: ZEPLIN Xe programme.



→ First ever dual-phase Xe detector for DM searches:
[Astropart.Phys.28(2007)287-302].

2001 - 2012: DRIFT low pressure gas TPC with directional and track-length discrimination. Next gen: CYGNUS.

DarkSphere: R&D for Cu electroforming for 3 m spherical proportional counter detector [arxiv:2301.05183].

Button: Water-based anti-neutrino detector, currently under construction.

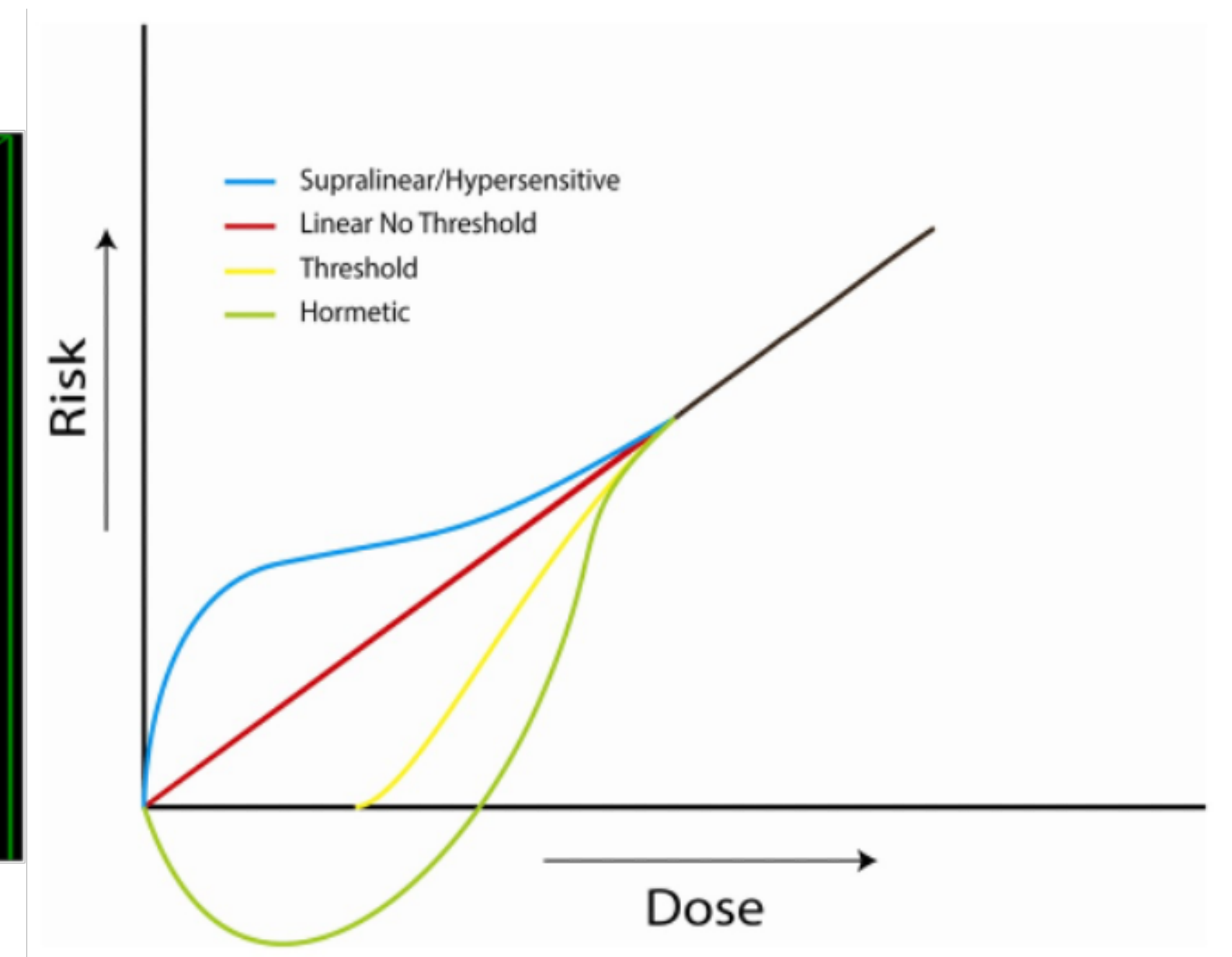
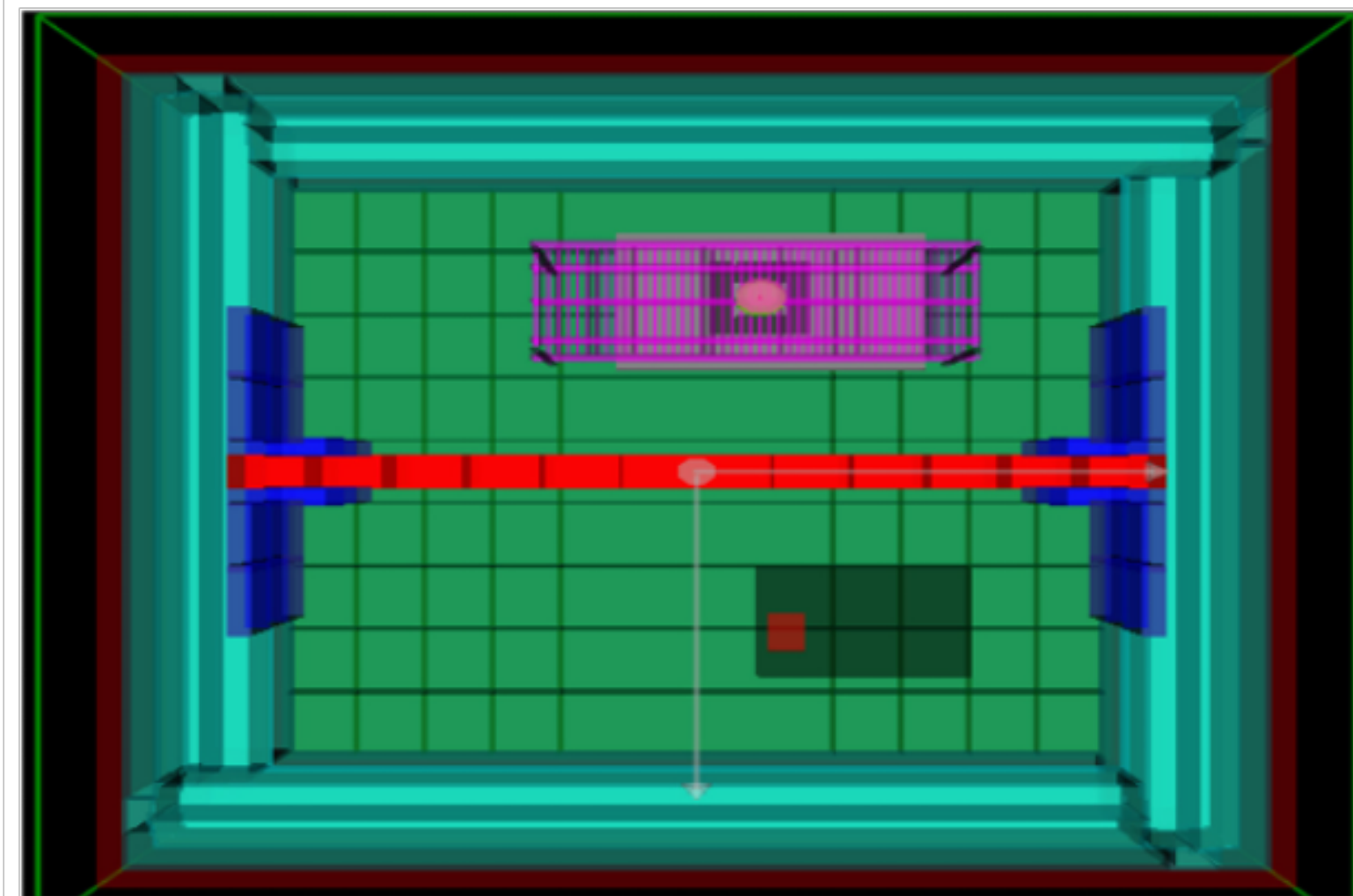


Astrobiology @ Boulby

SELLR: Ultra-low radiation dose astrobiology experiments.

Test linear relation between radiation dose & damage to an organism (bacteria).

Ran in ZEPLIN II castle w/ collaboration with DM physicists for background modelling: [Front.Astron.SpaceSci.14(2020)] .



Facilities

Underground:

> 4000 m³ class 1k & 10k (ISO 6 & 7) clean room lab space.

10 Gb internet; AC; air filtration; 5T & 10T lifting; LN generation; fume hood; clean prep space.

Boulby Underground Screening (BUGS):

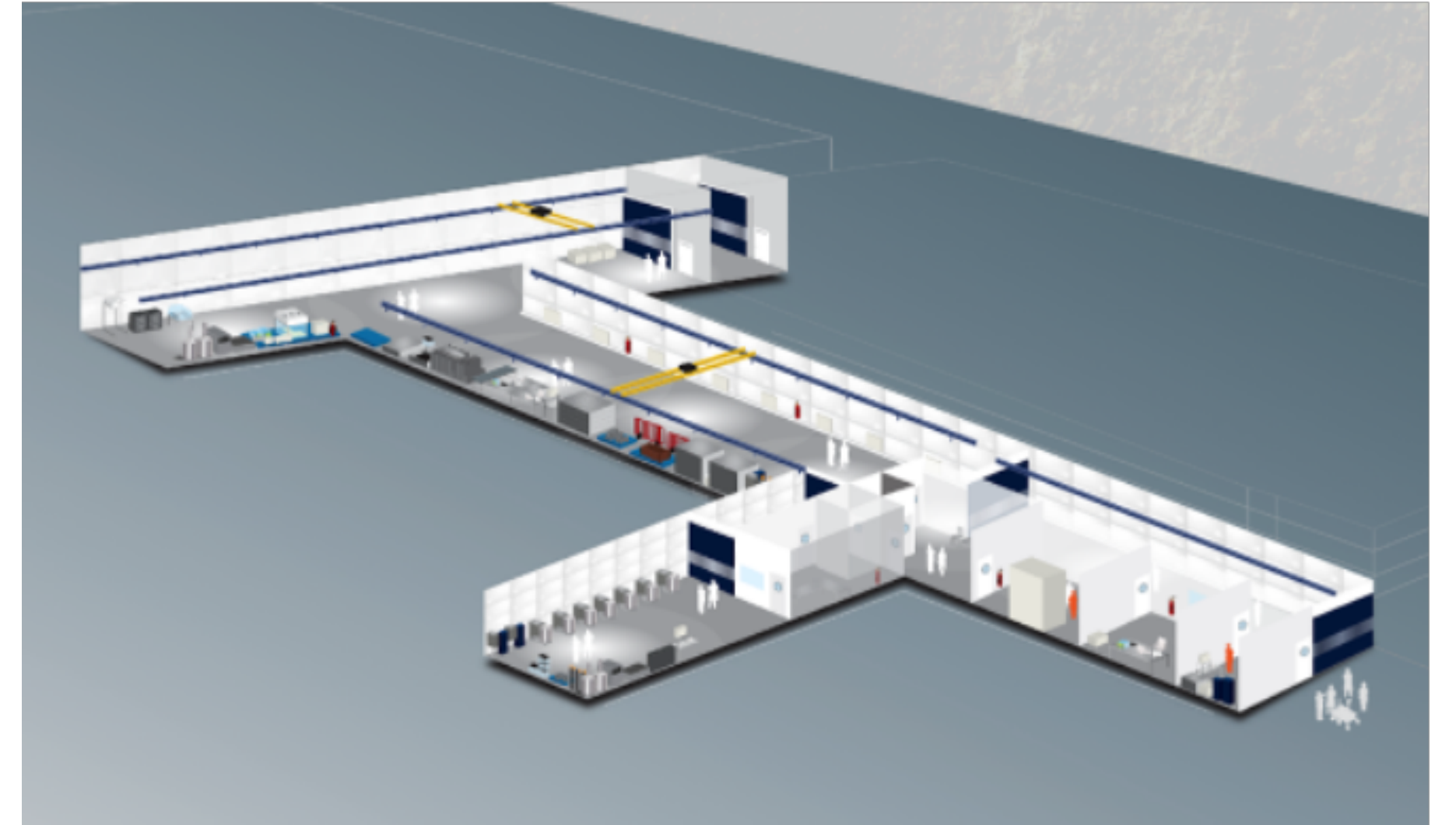
8 ULB Germanium detectors.

2 XIA Surface α detectors.

Currently commissioning Rn emanation & IC-PMS.

Goals? PPT sensitivity for G3 DM & neutrino experiments.

[[j.astropartphys.2017.11.006](https://arxiv.org/abs/2308.03444), [arXiv.2308.03444](https://arxiv.org/abs/2308.03444)].



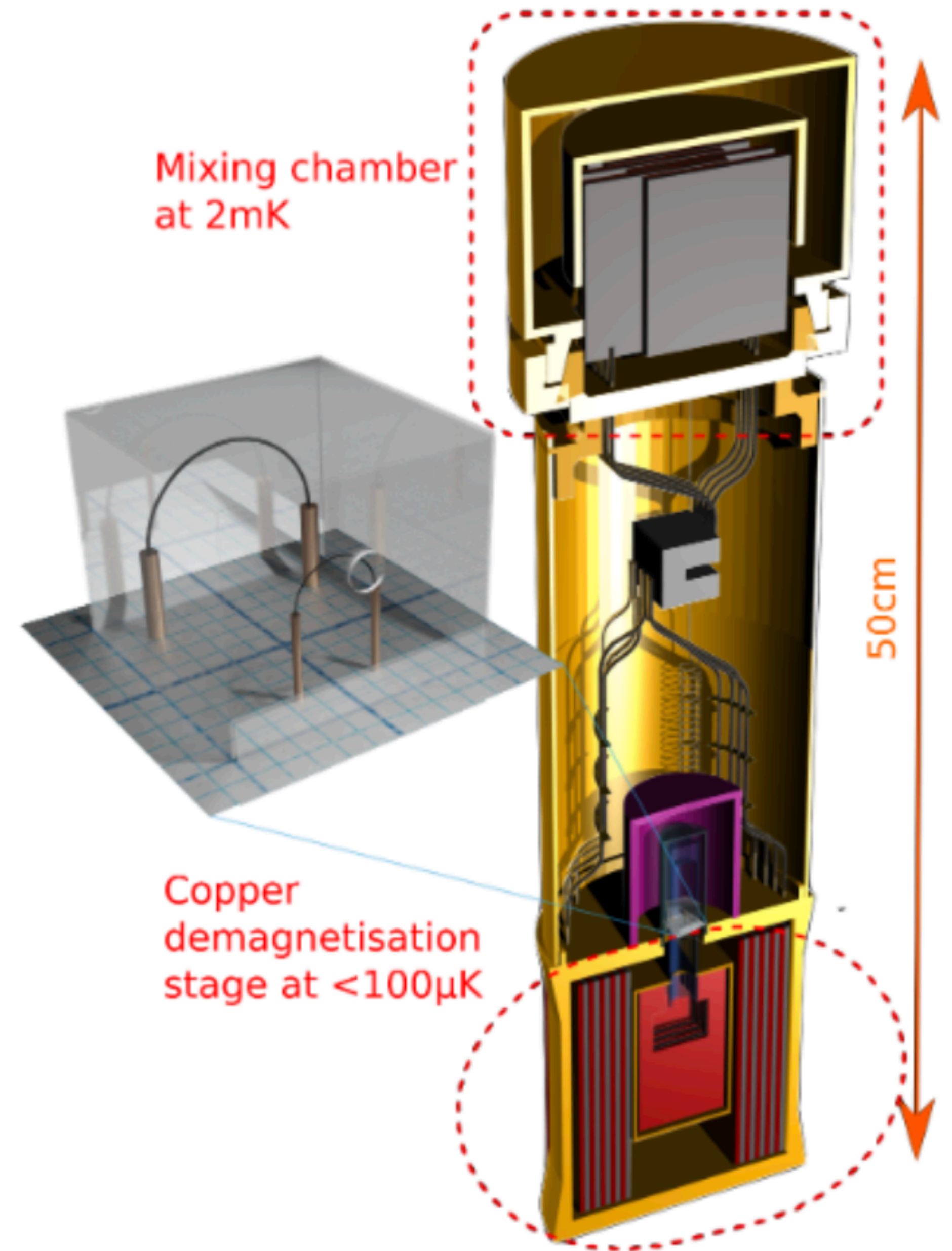
QUEST-DMC: Overview

The **Q**Uantum **E**nhanced **S**uperfluid **T**echnologies-**D**ark **M**atter **C**ollaboration (QUEST-DMC) programme:

1) What is dark matter? (WP1)

2) How did the early Universe evolve? (WP2)

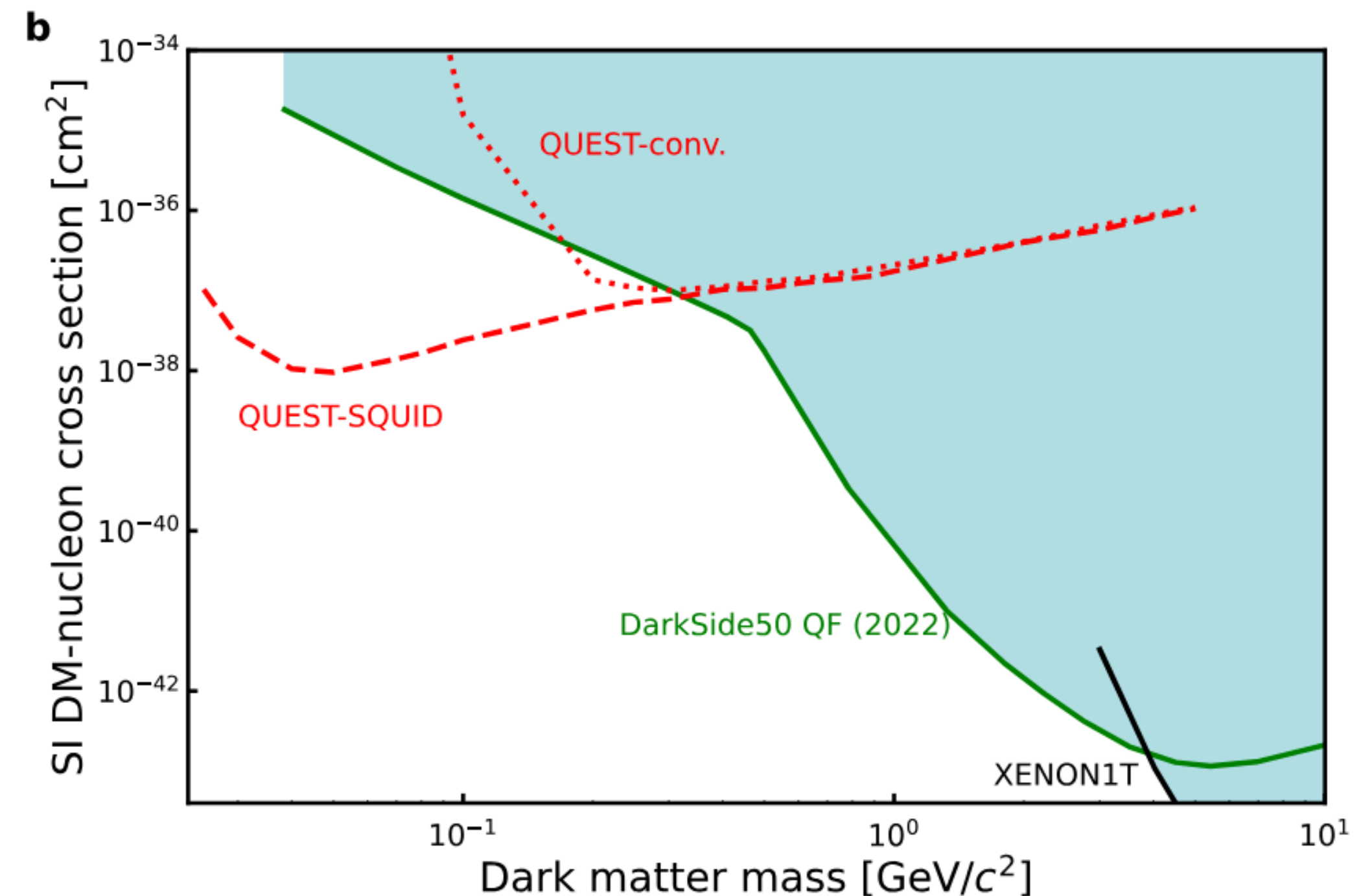
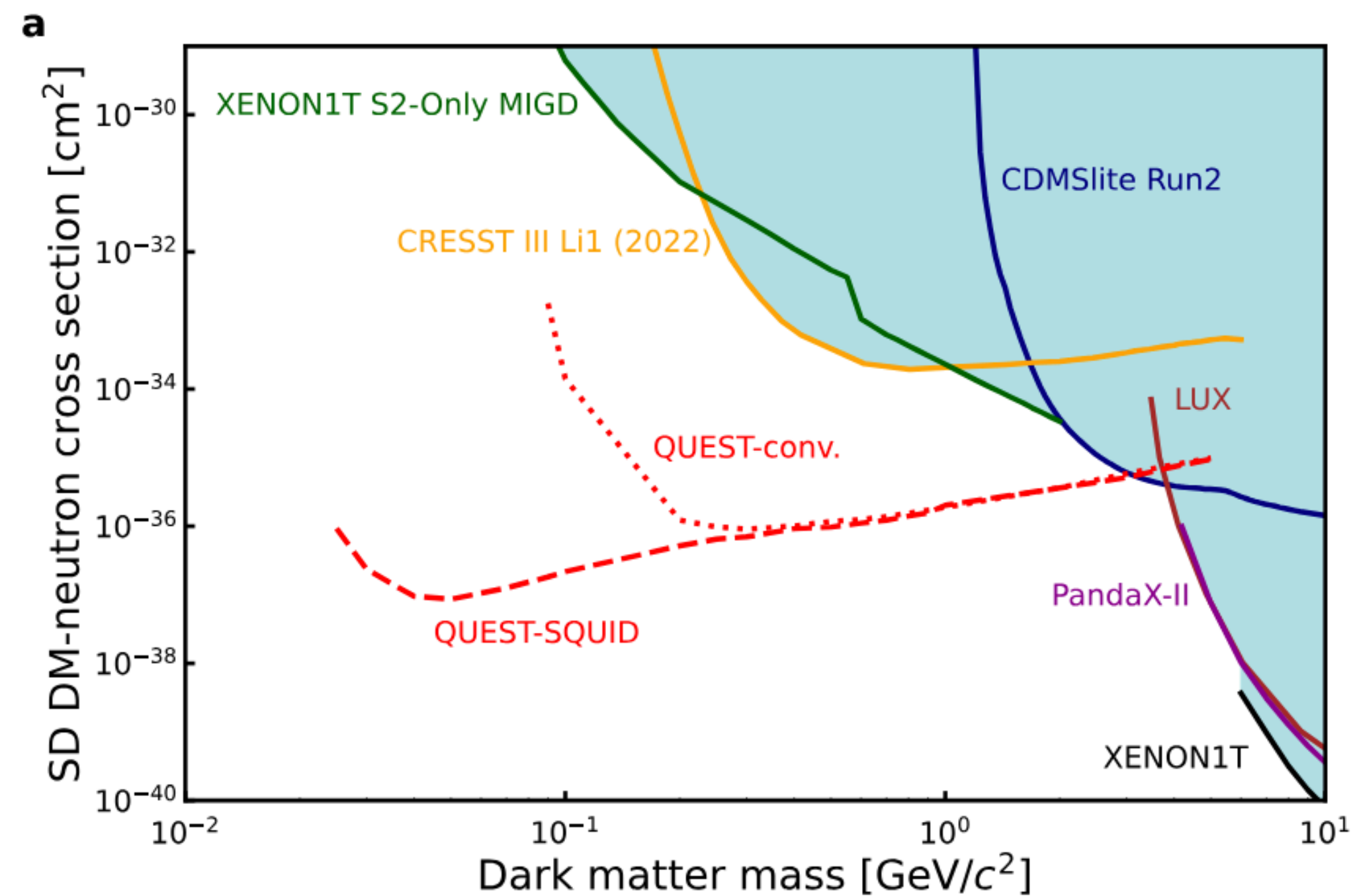
QUEST detector: Search for χ - ^3He atom scattering in superfluid ^3He target enclosed in 1 cm^3 bolometer box, instrumented with a nanowire sensitive to quasiparticles. Readout performed with lock-in amplifier or SQUID.



QUEST-DMC: Overview

Projected sub-eV energy thresholds opens up a new window of parameter space to search for light dark matter particles via spin-independent and spin-dependent interactions.

[Eur. Phys. J. C (2024) 84:248]



QUEST-DMC: Radioassay

“QUEST-DMC: Background Modelling and Resulting Heat Deposit for a Superfluid Helium-3 Bolometer”
[arXiv:2402.00181].

Sample	Mass [g]	Detector	Measured activity [mBq/kg]					
			$^{238}\text{U}_{\text{early}}$	$^{238}\text{U}_{\text{late}}$	^{210}Pb	$^{232}\text{Th}_{\text{early}}$	$^{232}\text{Th}_{\text{late}}$	^{40}K
Stainless steel	544.2	Roseberry	16(8)	2.5(0.9)	82(27)	3.1(1.2)	3.9(0.9)	< 6.2
Al 6061-O	642.6	Lunehead	8330(270)	15.3(3.9)	-	356(12)	334.4(8.2)	56(8)
Painted Al	923.0	Chaloner	25680(230)	16.2(3.2)	60480(540)	259.2(8.3)	342.2(6.2)	21.8(9.6)
Brass	107.0	Roseberry	< 7.6	4(1)	14990(350)	< 1	< 1.1	< 7.3
Silver sinters	37.1	Roseberry	< 90	< 36	430(320)	< 27	< 28	< 385
Vespel	38.3	Chaloner	87 ± 66	90(14)	418 ± 85	111(25)	64(14)	430(240)
Fiberglass	6.02	Chaloner	32580(640)	15154(62)	68600(1400)	11400(100)	12005(62)	23520(440)
Araldite	161.9	Roseberry	< 3.6	< 4.8	14.5(9.7)	< 3.4	< 2.2	< 25.5
Stycast	131.5	Chaloner	< 10.5	< 9.5	< 14.9	< 12.9	< 6.2	< 122.2
GRP	106.9	Lunehead	5700(1000)	7460(120)	-	7840(160)	7350(100)	4900(570)
PEN	35.1	Roseberry	< 4.2	6.4(2.7)	26(13)	< 3.4	< 2.4	< 22.8
Annealed Cu	19.1	Belmont	< 258	23.4(7.4)	-	< 12.2	< 5.7	< 138
Polyester Yarn	16.7	Roseberry	< 448	175(16)	-	< 30.4	< 10.4	746(206)
Macor	42.4	Roseberry	-	955(30)	-	386(60)	504(24)	2333000(4000)
kel-F	97.6	Roseberry	< 6.9	13.6(2.0)	13.7(12.9)	< 4.6	< 7.3	< 44.7
Si Pieces	6.9	Belmont	< 39.2	< 110	39.9(40.1)	< 69.1	< 57.1	< 319

Excluded use for experimental cell – stycast or araldite instead

Assayed 18 materials so far.

Boulby Expansion

“Towards a major new underground science facility in the North East, with the potential to host a major international science infrastructure, such as a next generation dark matter experiment”.

Medium scale expansion in current lab (2025-2030).

New excavation (2030++) for next generation low background particle physics.

Host world-leading next generation science 2030+: fundamental and applied low background science including quantum sensors and quantum computing.

Boulby Expansion

Courtesy of Sean Paling

Boulby Activities Now and Potential Future

Now	
Current Projects	Status
CYGNUS - DM R&D	E/P
News-G - DM R&D	A
BUGS: Ge, XIA, RnEm - Material Screening	A
RECON - Nuclear Security R&D	A
BUTTON – Nuclear security R&D	A
Muon Tomog – CCS & undersea Geoimaging R&D	A
RESOURCE – Energy store R&D	A
Seismology/AION R&D	A
BISAL – Biology/Astrobiology	A
MINAR – Planetary Exploration Tech development	A
Misc. Other. SELLR, C14, Adrok, BIO-SPHERE...	A/P
Outreach/ Education - Misc events, progs, Remote3...	A

Status: A = Active, P = Paused, E = End, I = Interest confirmed

2023-2030

Medium Term (Current Lab + mods)	Status
BUGS: Ge, XIA, RnEm, ICPMS - Material Screening	A/I
BUTTON-30 – Nuclear security R&D	A
RECON+ - Nuclear Security R&D	A/I
DarkSPHERE – DM Search	I
DATUM – Neutrino Tech R&D	I
SoLAR, SOLAIRE – DM/Neutrino R&D	I
AION-100 & 1000 R&D	I
Seismology Array – Geosurvey R&D	I
RESOURCE+ – Energy store R&D	A/I
Muon Tomog – CCS & undersea Geoimaging R&D	A/I
BISAL+ – Biology/Astrobiology	A/I
MINAR+ – Planetary Exploration Tech development	A/I
Misc. Other. Quantum Computing Tech R&D	-
Outreach/ Education: General Public, Schools +	A

2030-2040+

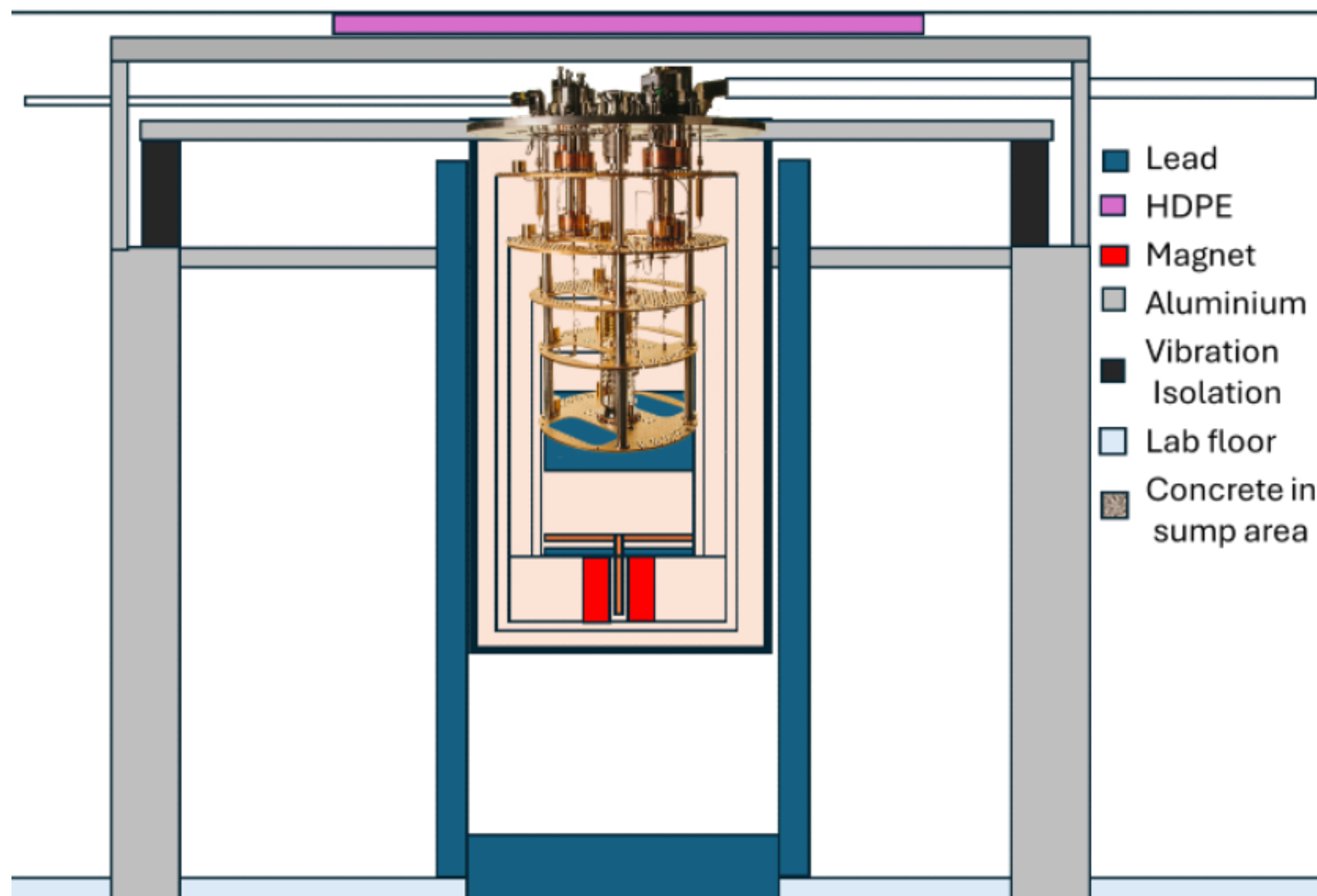
Long Term (Current lab plus major new lab)
<p>Particle Physics and Low Background Science:</p> <p>Dark Matter: Major Next Gen Experiments:</p> <ul style="list-style-type: none"> Xenon (XLZD) Argon (DarkSideLM+) Gas (DarkSPHERE+) <p>Neutrinos:</p> <ul style="list-style-type: none"> BUTTON-100+ DATUM (LEGEND Support), SoLAR / SOLAIRE+ <p>Mat screening & LB Techniques: A world's best facility:</p> <ul style="list-style-type: none"> Ge, XIA, RnEm, ICPMS, Cleanliness & Engineering R&D <p>Misc Other:</p> <ul style="list-style-type: none"> AION-100 AION 1000 Nuclear Security Gamma spec Quantum Computing Tech R&D & Operation
<p>Earth & Environmental Science:</p> <ul style="list-style-type: none"> Sustainable Energy R&D Seismology Observatory Geological Repositories R&D Misc geology / Geophysics R&D
<p>Astrobiology & Planetary Exploration:</p> <ul style="list-style-type: none"> Extremophile R&D Astrobiology / life beyond Earth R&D Human habitation R&D Planetary exploration technology development Robotics and AI Mining and industry application development.
<p>Outreach and Education:</p> <ul style="list-style-type: none"> A National Centre for Science and technology outreach and education.

Target projects for a major new UK underground facility / campus

Proposal: UltraDark

STFC Call: £10 million for medium term, world leading dark matter experiment.

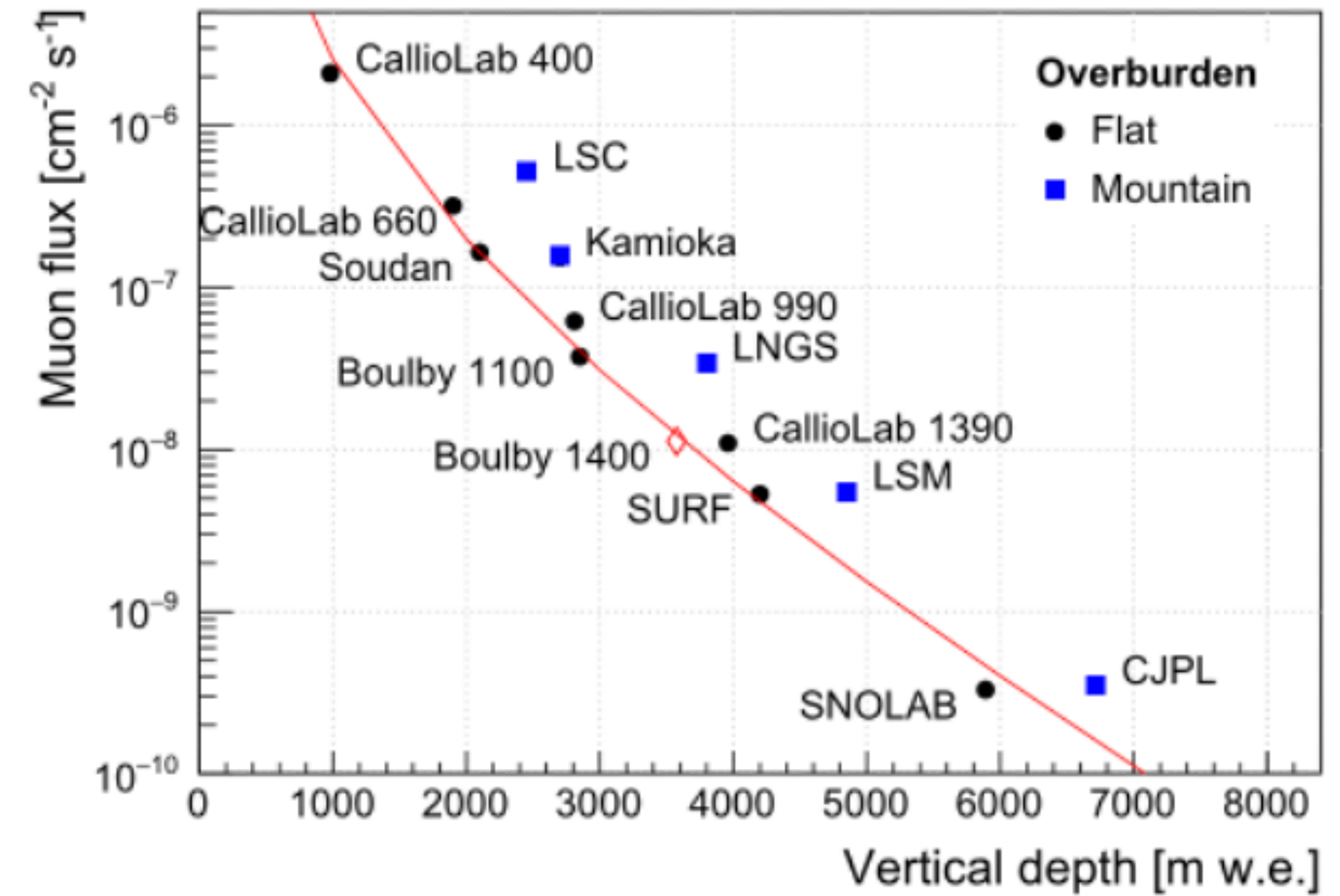
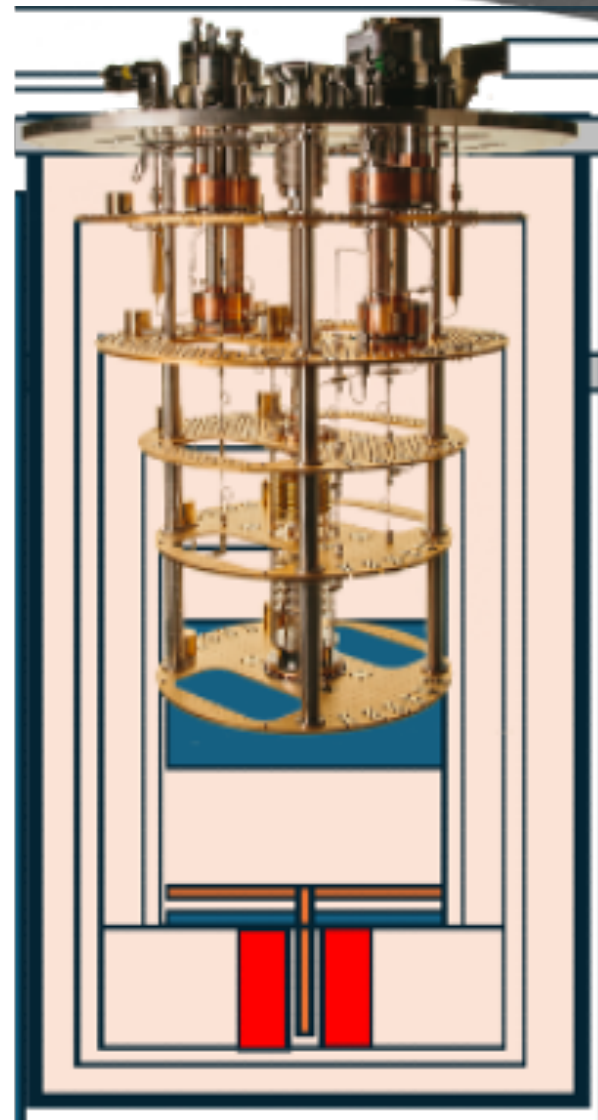
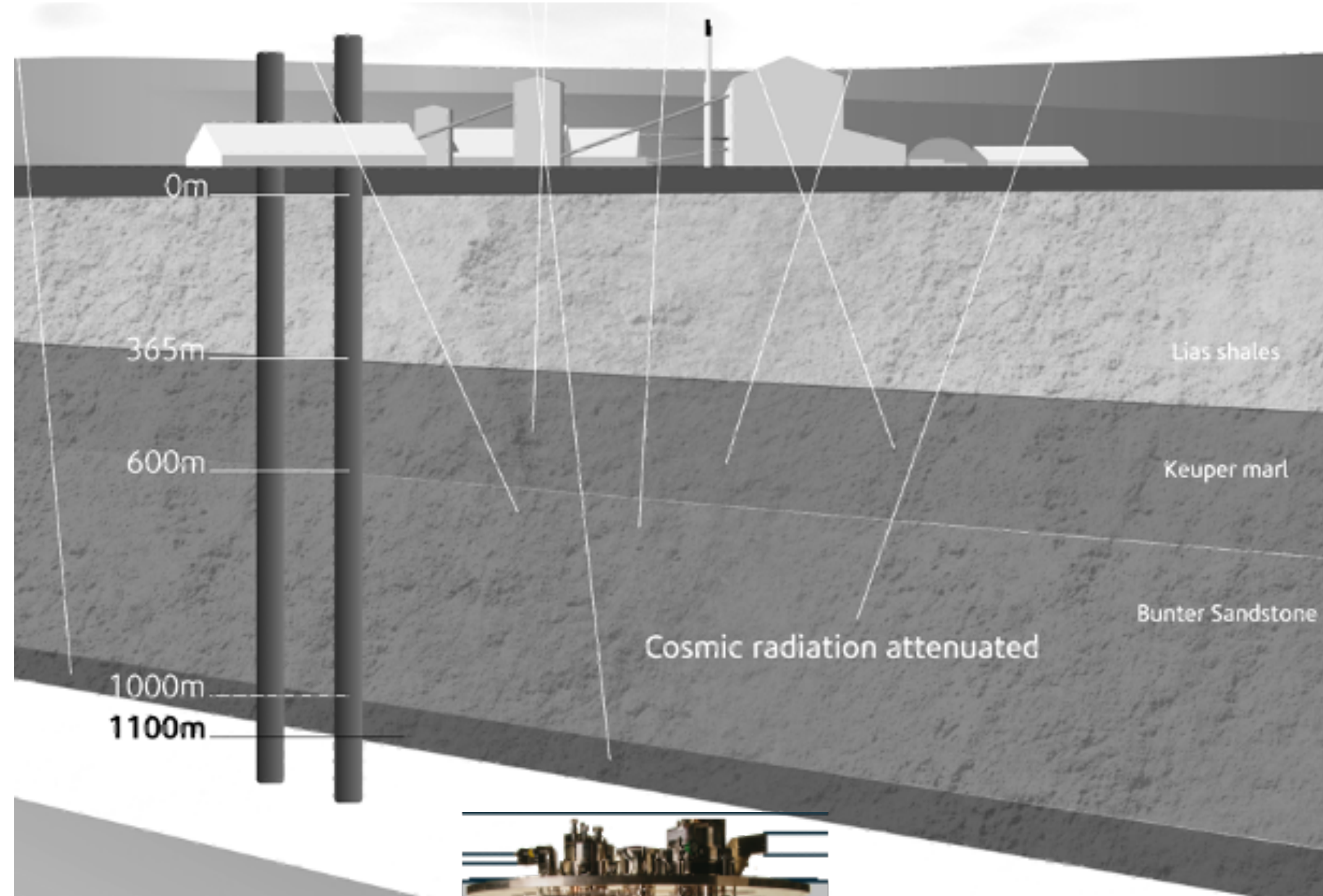
Proposal: Construct low background, ultra-low temperature platform with international access for dark matter and isolated quantum system experiments.



Twin facilities – underground at Boulby and above ground at RHUL for commissioning and pilot runs.

Cryogen-free dilution refrigerators with nuclear demagnetisation stage capable of reaching <0.5 mK [arxiv:2209.07903].

Proposal: UltraDark

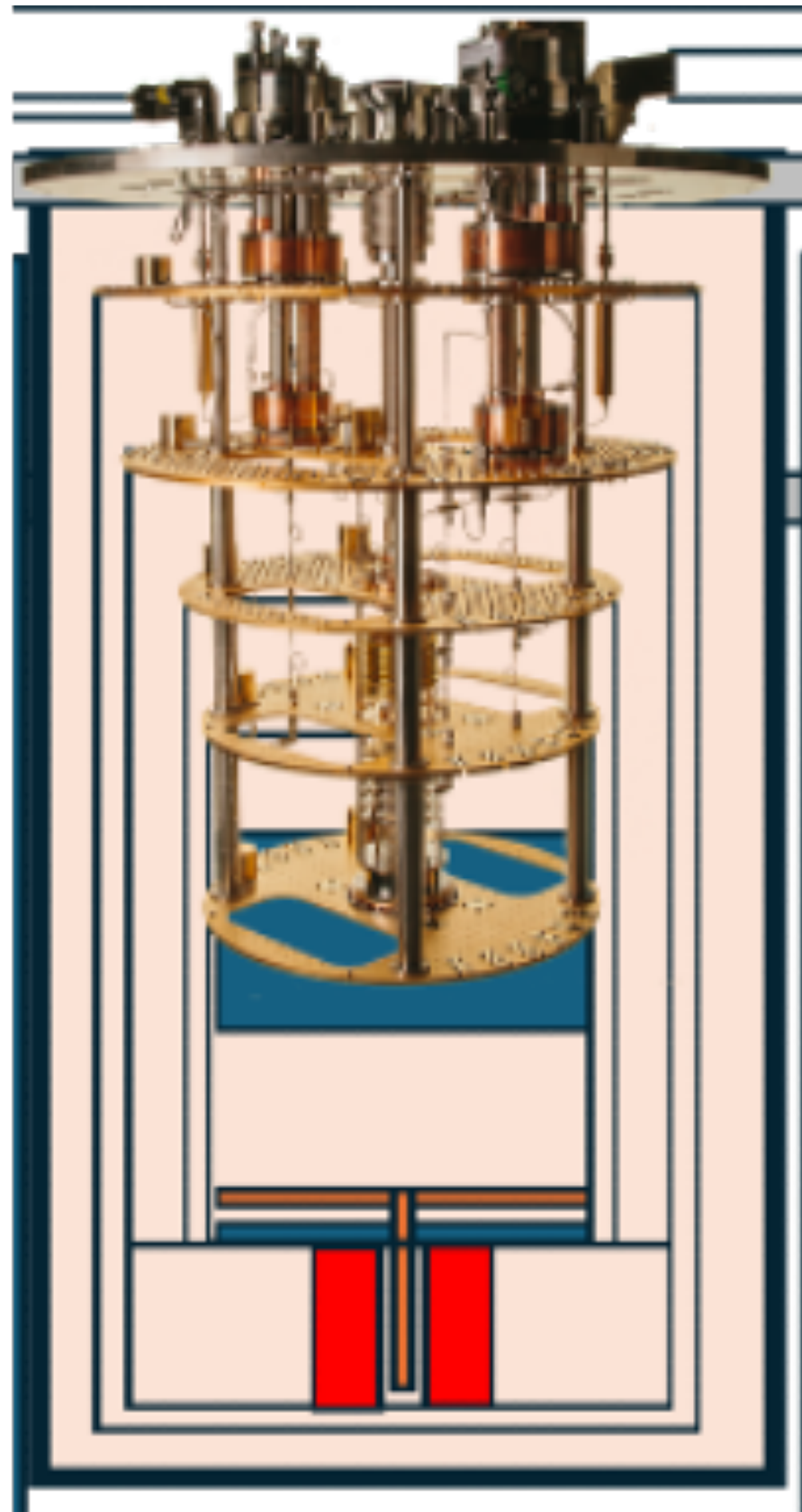


Muon flux @ 2805 m.w.e: $(4.09 \pm 0.15) \times 10^{-8} \text{ cm}^2/\text{s}$.

Measured using ZEPLIN liquid scintillator muon veto: [Nucl.Instrum.Meth.A511(2003)347-353].

Proposal: UltraDark

Laboratory Gamma Activity



Low activity rock: mainly halite (NaCl) with minor sylvite and mudstone impurities.

HPGe assay [Bq/kg]:

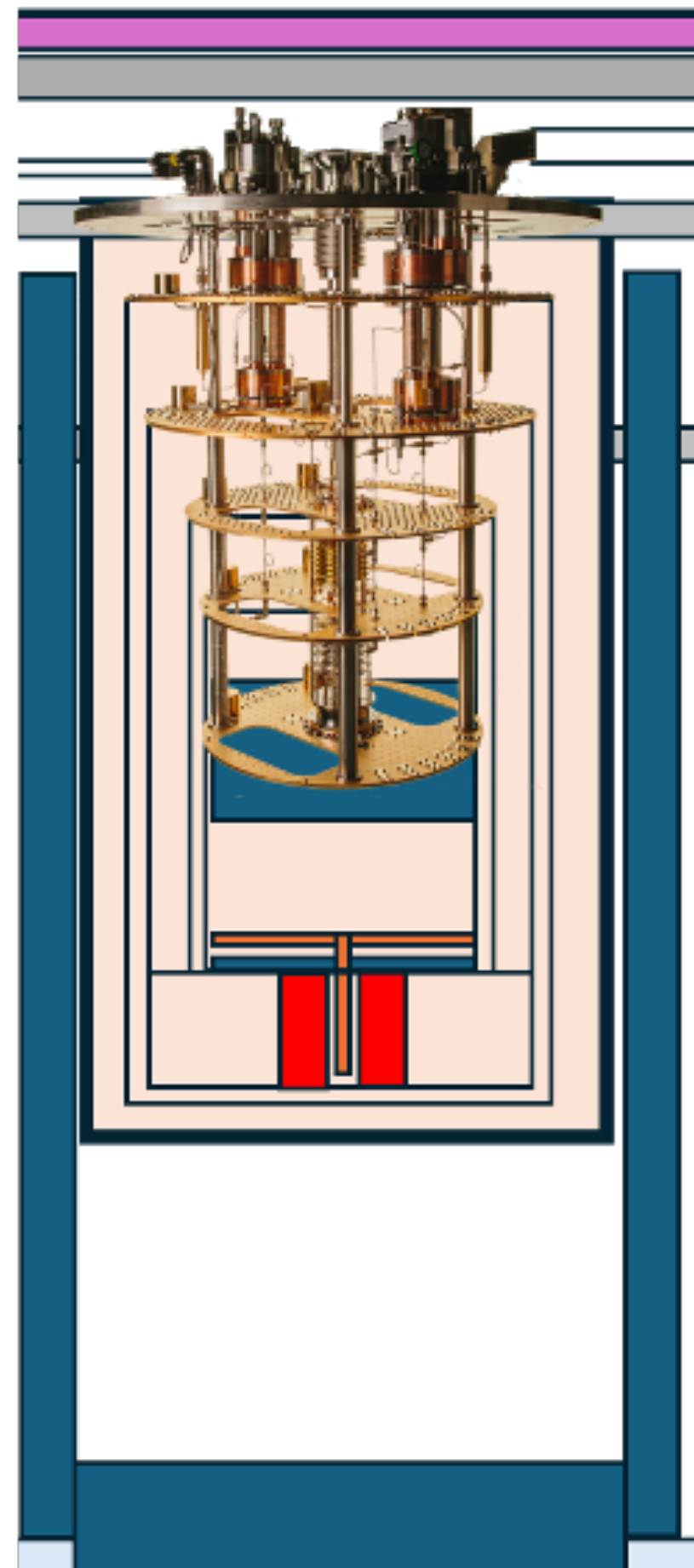
238U	232Th	40K
0.40 ± 0.09	0.6 ± 0.1	11 ± 1

Low Radon air: 2.23 ± 0.03 Bq/m³ (main lab) [arxiv:2308.03444].

Lab gamma flux measurement using Ge detectors: **0.128 /cm²/s** [J.Radioanal.Nucl.Chem.298(2019)1483-1489].

Proposal: UltraDark

Shielding



HDPE lead: 30 cm on wheels.

Lead shield:

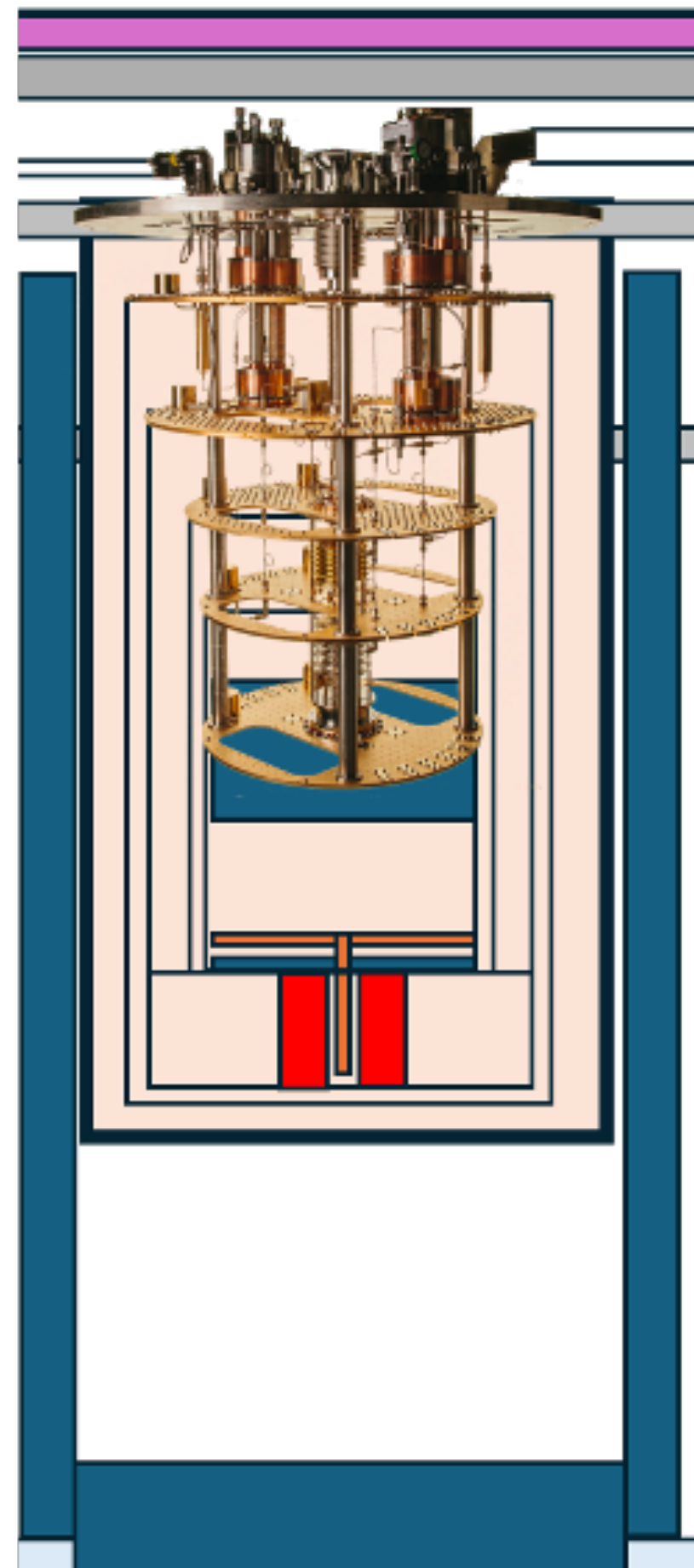
- External 10 cm.
- Internal 3 cm.

Estimated gamma flux:
 $(1.28) \times 10^{-3} / \text{cm}^2/\text{s}.$

Internal lead shield made
from 500 year old
Hampton Court lead
supplied by NPL.

Proposal: UltraDark

Secondaries



Cosmic muon induced neutrons in rock: $1.72 \times 10^{-6} / \text{cm}^2/\text{s}$.

- Measured using liquid scintillator: [Astropart. Phys. 27(2007)326-338].

After HDPE shielding: $1.42 \times 10^{-8} / \text{cm}^2/\text{s}$.

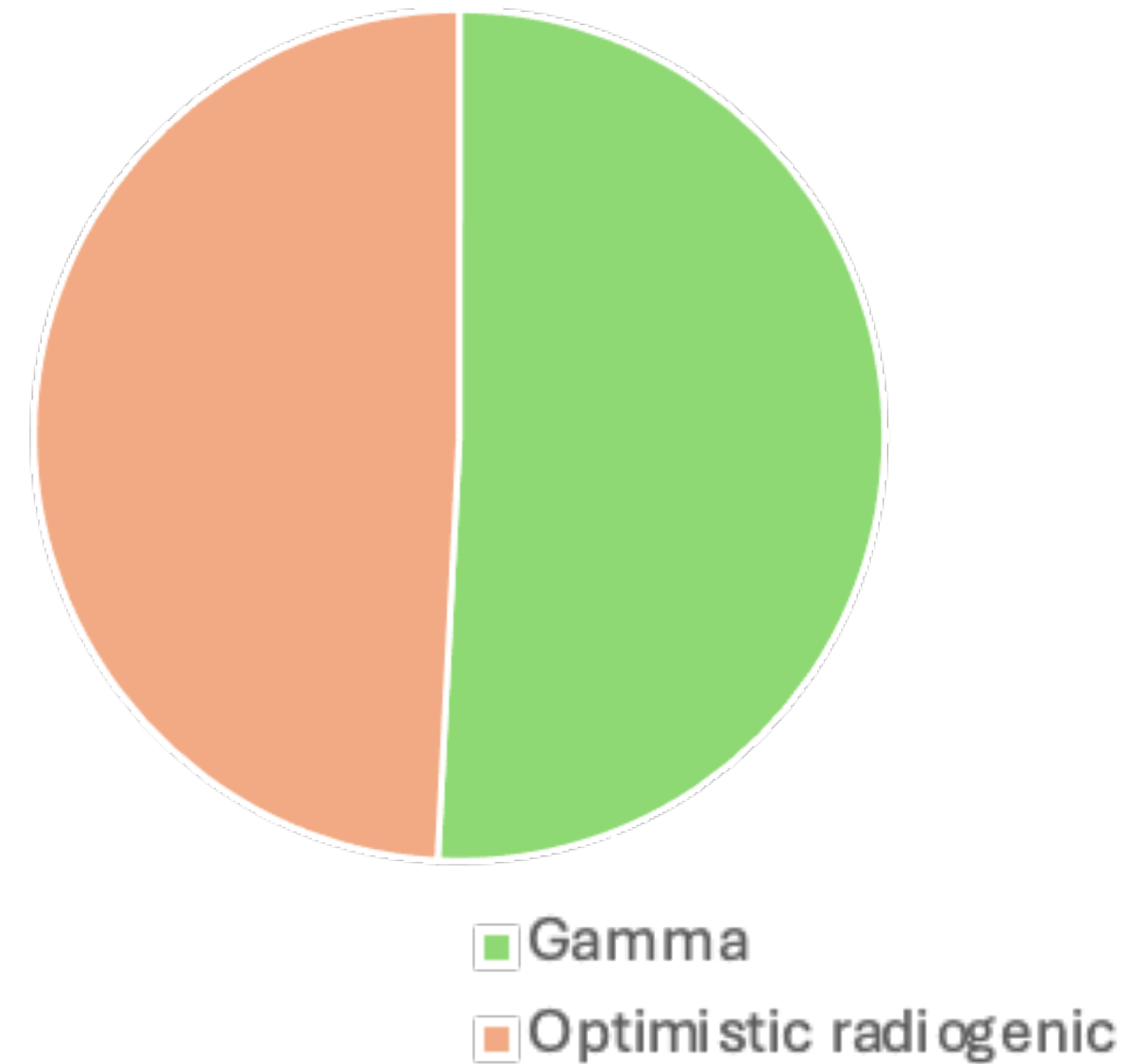
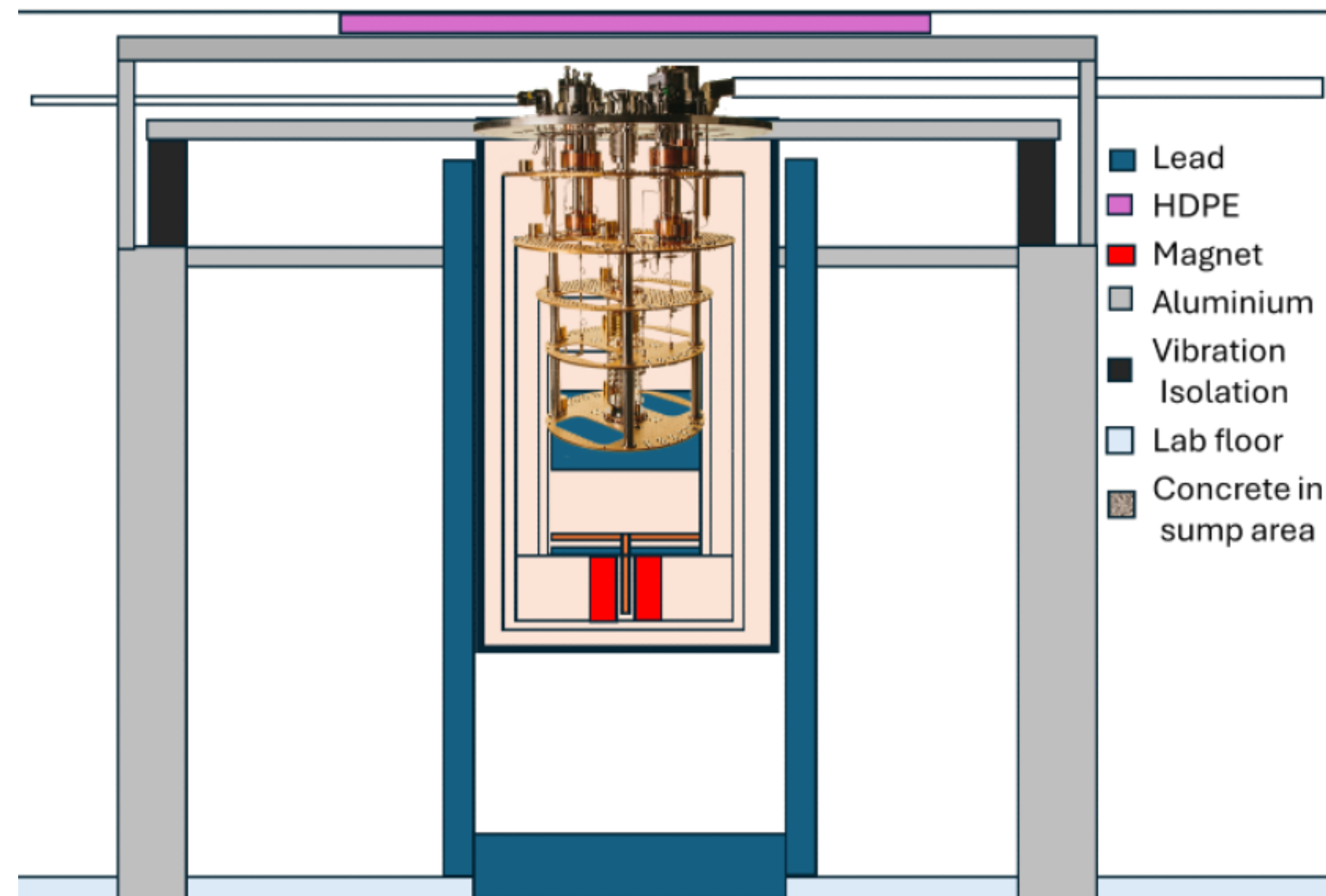
Induced in lead: $1.75 \times 10^{-9} / \text{cm}^2/\text{s}$.

Gammas from neutron capture in HDPE: $1.71 \times 10^{-6} / \text{cm}^2/\text{s}$.

Shielded by lead at mixing chamber: $8.53 \times 10^{-7} / \text{cm}^2/\text{s}$.

Proposal: UltraDark

Underground Estimate



Radiogenic background from detector components: [Eur.Phys.J.C (2024)84:248].

Current model: $3.09 \times 10^{-2} / \text{cm}^2/\text{s}$.

Optimistic case: $1.24 \times 10^{-3} / \text{cm}^2/\text{s}$.

(Improved material choices and internal shielding).

Similar level to gamma flux: $(1.28) \times 10^{-3} / \text{cm}^2/\text{s}$.

Proposal: UltraDark

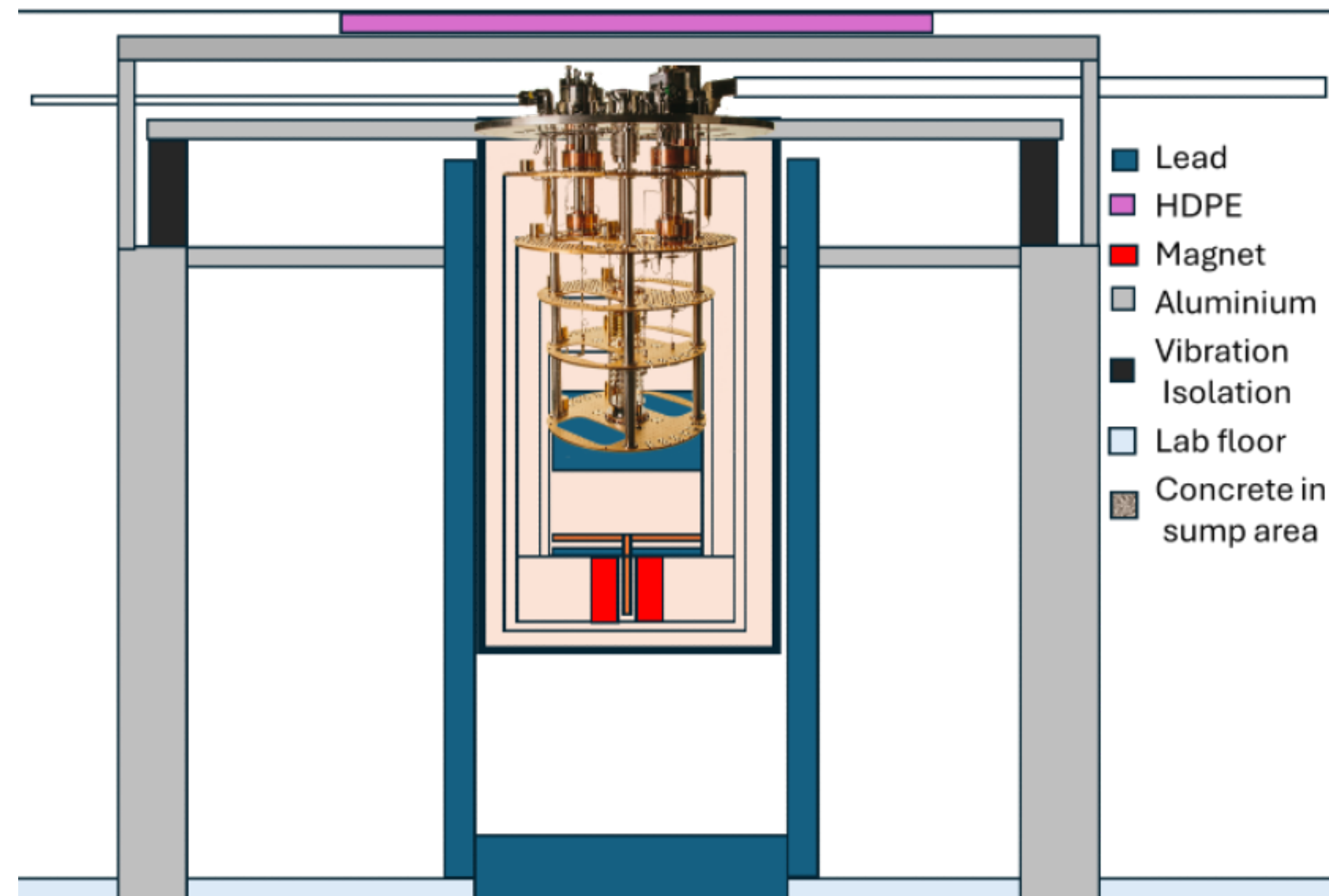
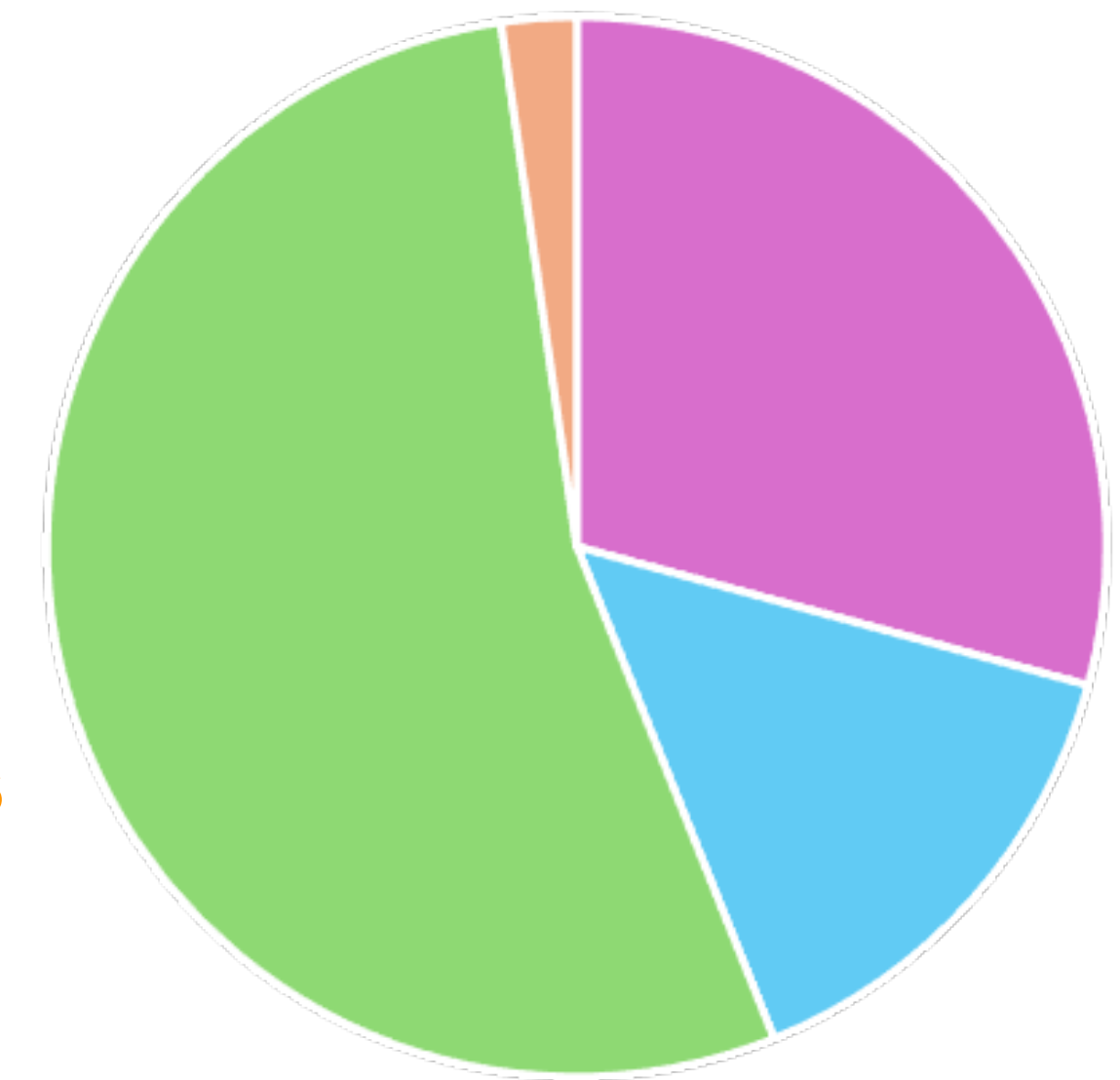
Surface Comparison

Same shielding and secondary production considerations.

Starting from much higher cosmic muons & neutron fluxes:

Muon: $1.67 \times 10^{-2} / \text{cm}^2/\text{s}$; Neutron: $1.63 \times 10^{-2} / \text{cm}^2/\text{s}$

Muon: $1.58 \times 10^{-2} / \text{cm}^2/\text{s}$
Neutron: $7.96 \times 10^{-3} / \text{cm}^2/\text{s}$
Gamma: $2.91 \times 10^{-2} / \text{cm}^2/\text{s}$
(Optimistic) detector
radiogenic: $1.24 \times 10^{-3} / \text{cm}^2/\text{s}$

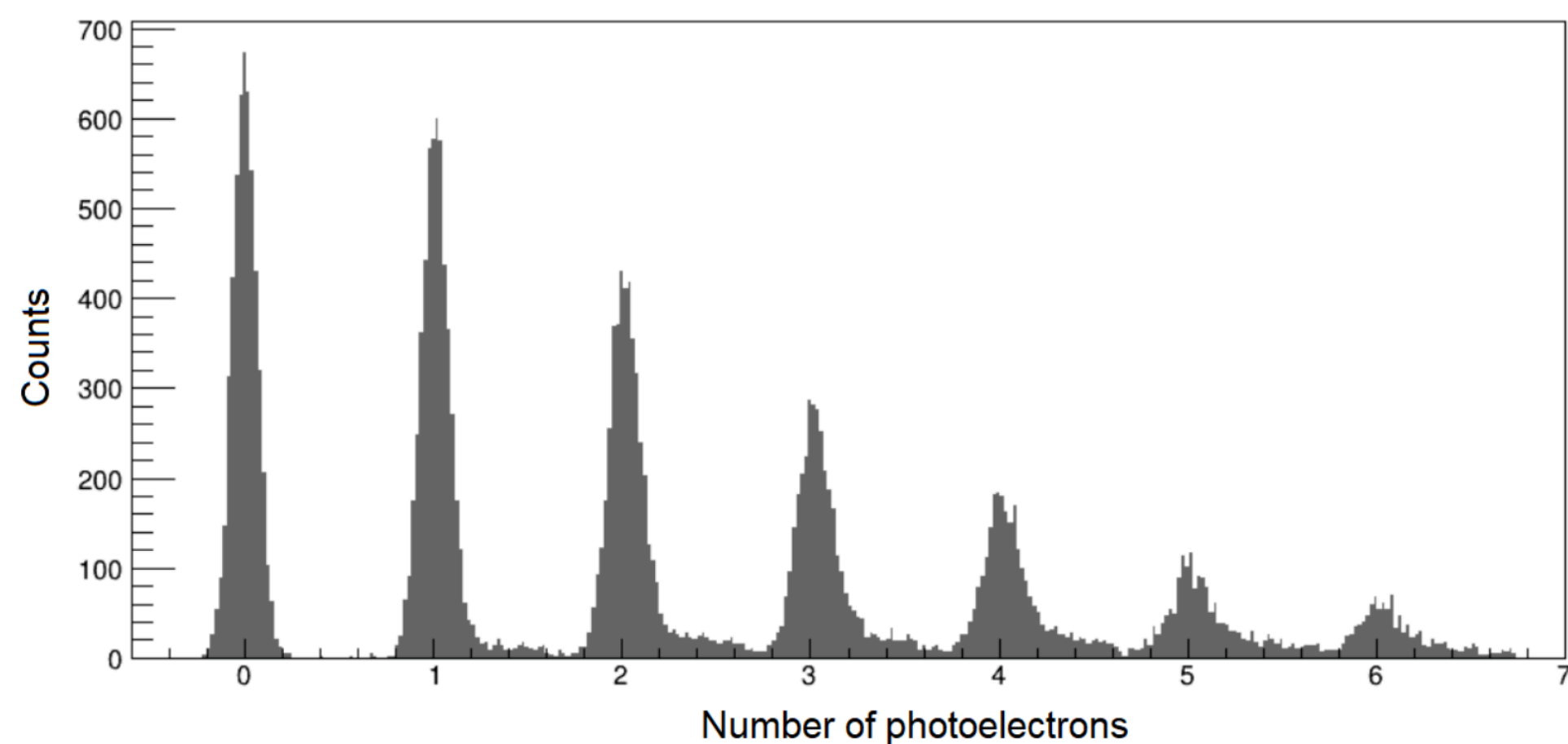


Proposal: UltraDark Photon Detection

Exploring Silicon Photomultipliers (SiPMs) as candidate photon sensors for QUEST-DMC.

SiPMs: solid-state photodetectors with single-photon sensitivity ($\sim 10^6$ gain factor).

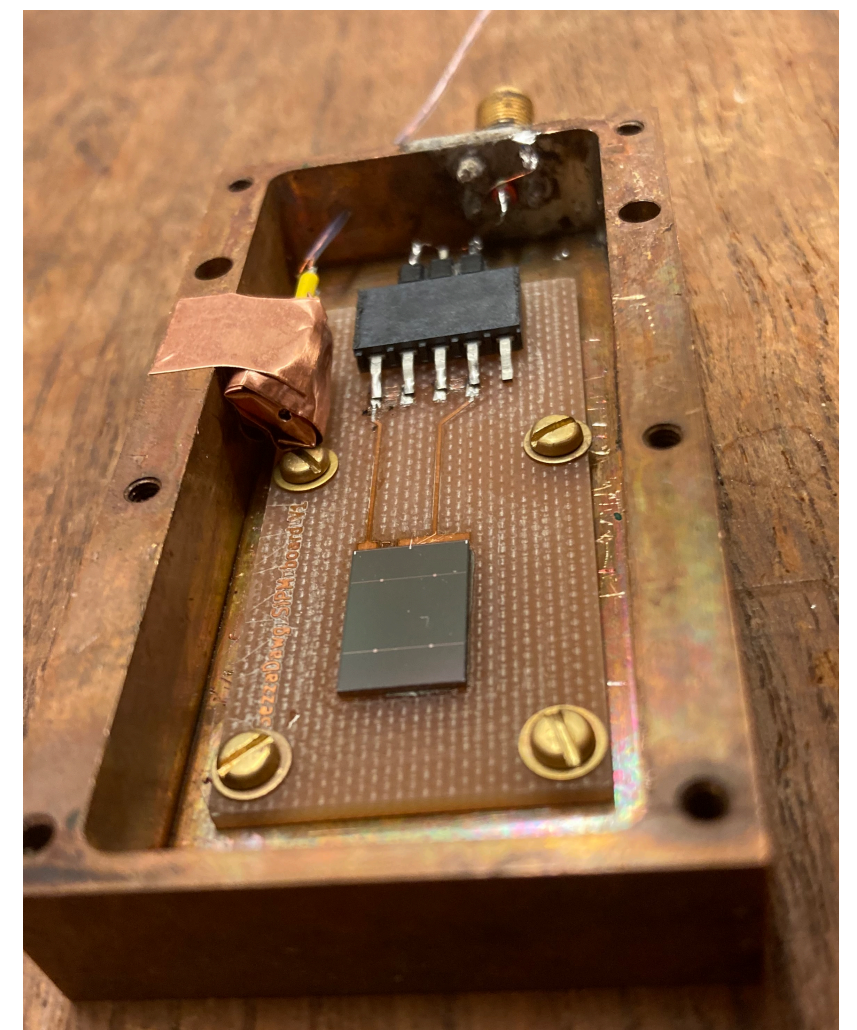
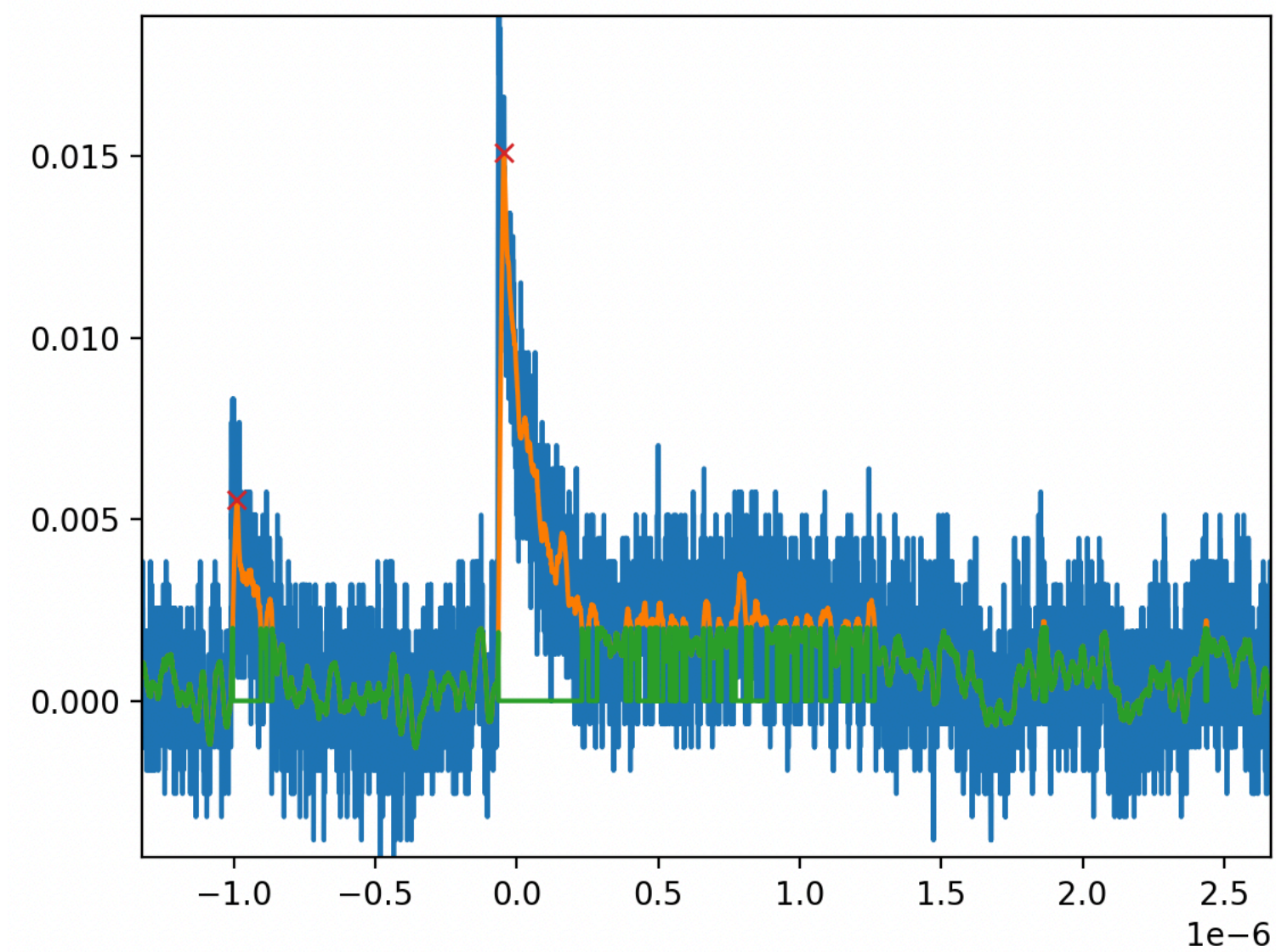
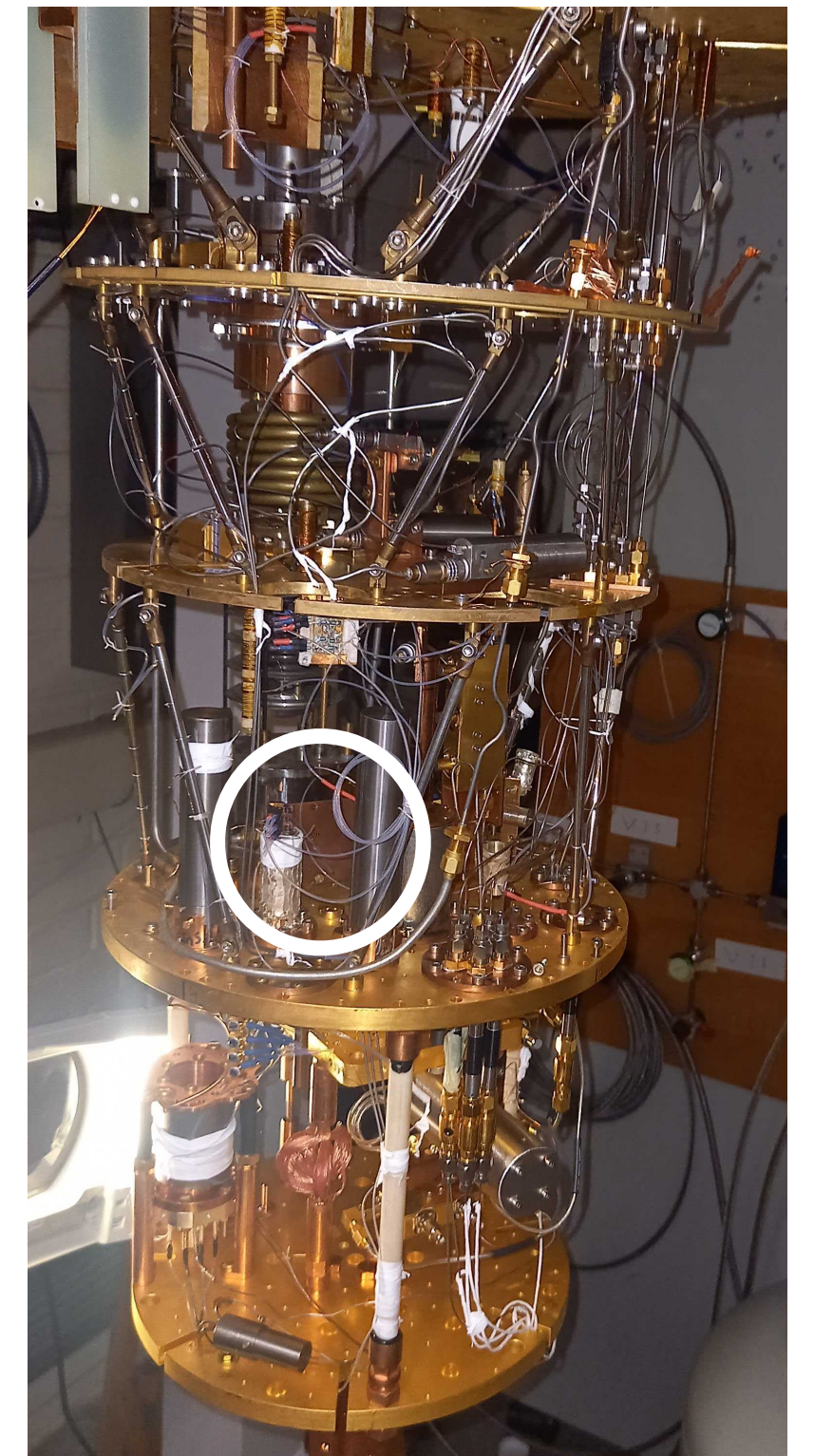
At cryogenic temperatures (~ 80 K), SiPMs boast excellent single-photon resolution and extremely low dark-noise - very important for dark matter experiments.



Currently operating SiPM at ~ 10 mK...

...it works! (Never been shown to operate < 1 K before).

Work is ongoing to characterise the device at 10 mK and optimise the readout noise.



Summary & Outlook

Boulby is the world's only polyhalite mine.

Naturally low activity rock and low radon air compared to other underground facilities.

Boulby has a long history in dark matter searches & low background science.

Substantial development & expansion planned.

UltraDark: unique proposal to reach $< \text{mK}$ temperatures.

Follow Boulby on X: <https://x.com/boulbylab>

Backup

Interdisciplinary Science

Earth and Environmental:

- RECON: CTBT Atmospheric radionuclide monitoring for nuclear security
- Muon Tomography - developing techniques for deep 3D geological surveying for applications including carbon capture and storage [Phil.Trans.R.SocA377(2018)0059]

Astrobiology and planetary exploration technology development:

- MINAR (Mine Analogue Research) and BISAL (Boulby International Subsurface Astrobiology Lab) ([webpage](#))



Germanium Screening

Nondestructive HPGe for U, Th chain measurements at keV-MeV energies.

Different detector types and configurations for range of different sample geometries and γ -ray energies.

Detectors inside 10 cm lead + 10 cm high purity copper castles and constructed using low radioactivity materials.

Castle purged with N₂ gas to remove airborne Rn, residual Rn in the N₂ removed using charcoal traps.

Extensively used by LZ and DarkSide projects during commissioning.

18 samples assayed so far for QUEST-DMC project.



Boulby Development Project

Boulby Development Project (2022-2025): expand current lab and infrastructure to host low background particle physics and multi-disciplinary underground science experiments.

Beyond this (2025-2030): looking to host world leading medium scale dark matter detector: **£10 million fund.**

Continued expansion in a staged approach (2030++):

1. Current salt strata (1.1km) - house medium scale experiment and expand for long term multi-disciplinary lab.
2. Deeper polyhalite (1.3km) - large experimental cavern targeting next generation low background particle physics.

Prepare to host world-leading next generation science 2030+: fundamental and applied low background science including quantum sensors and quantum computing.