Searching for light dark matter with DarkSPHERE

Lachlan Milligan

University of Birmingham

DM Direct Detection Landscape

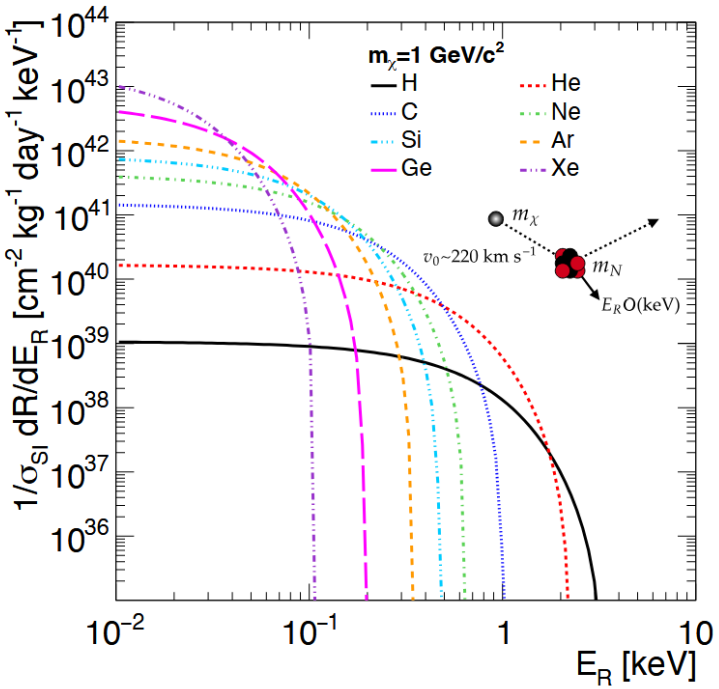
UNIVERSITY OF BIRMINGHAM

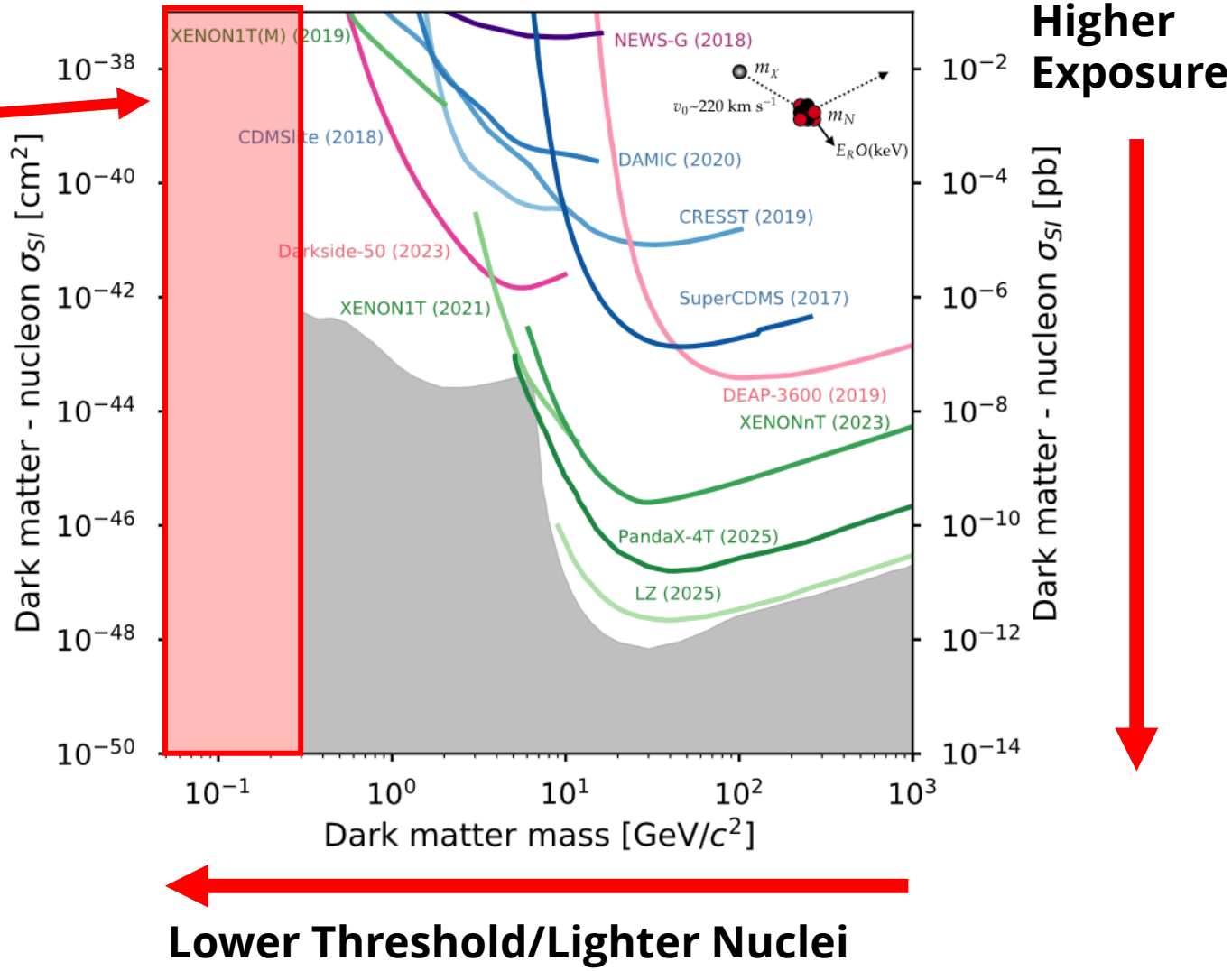
Exploring light dark matter in the low mass region (0.01-10 GeV) requires:

- Low detector thresholds
- Light nuclei

Unexplored low mass region – light dark matter

Combination of requirements necessitates novel detector approaches!

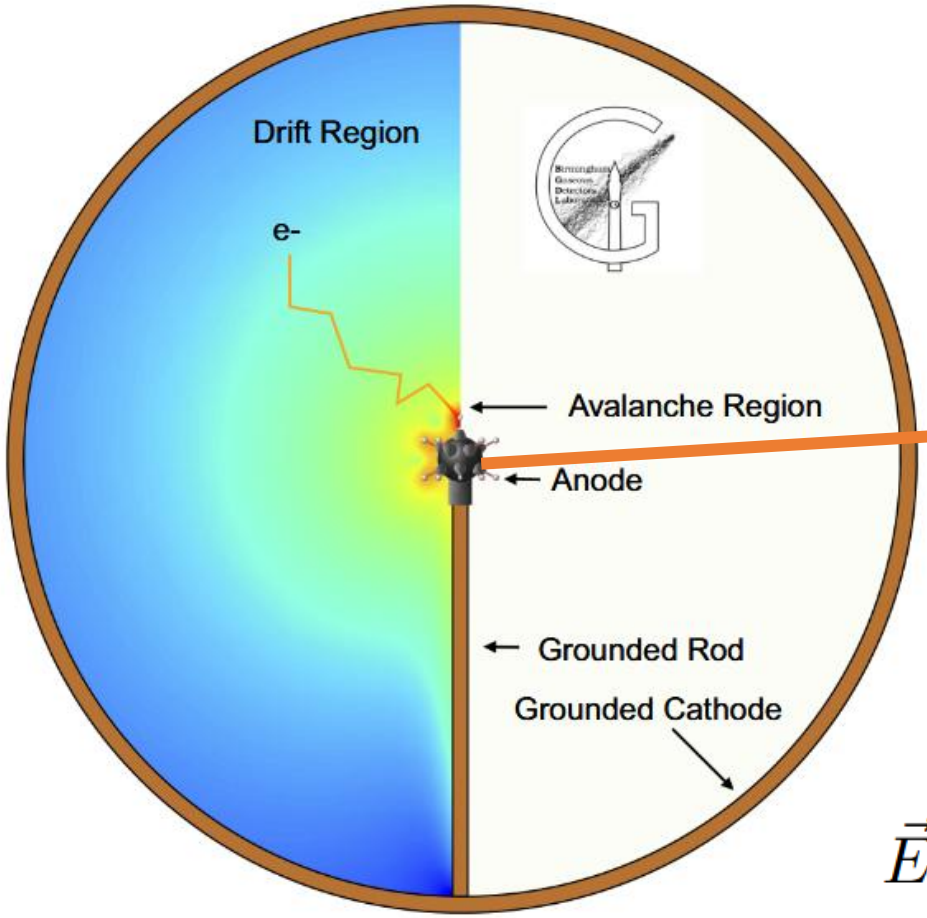




Higher Exposure

Lower Threshold/Lighter Nuclei

The Spherical Proportional Counter



"Achinos" Sensor

$$\vec{E} \approx \frac{V_1}{r^2} r_a \hat{r}$$

$$C \approx 4\pi\varepsilon_0 r_a$$

Key strengths for a light DM search:

- **Choice in gas targets (light nuclei) and pressures**
- **Low capacitance:** low electronic noise, **single electron threshold**
- **Detector fiducialisation**
- Simple design: **entirely radiopure construction**
- Electric **field split between drift and amplification region**
- **Decoupling of regions by Achinos sensor and position reconstruction**

Applications: x-ray/alpha spectroscopy, neutron detection!

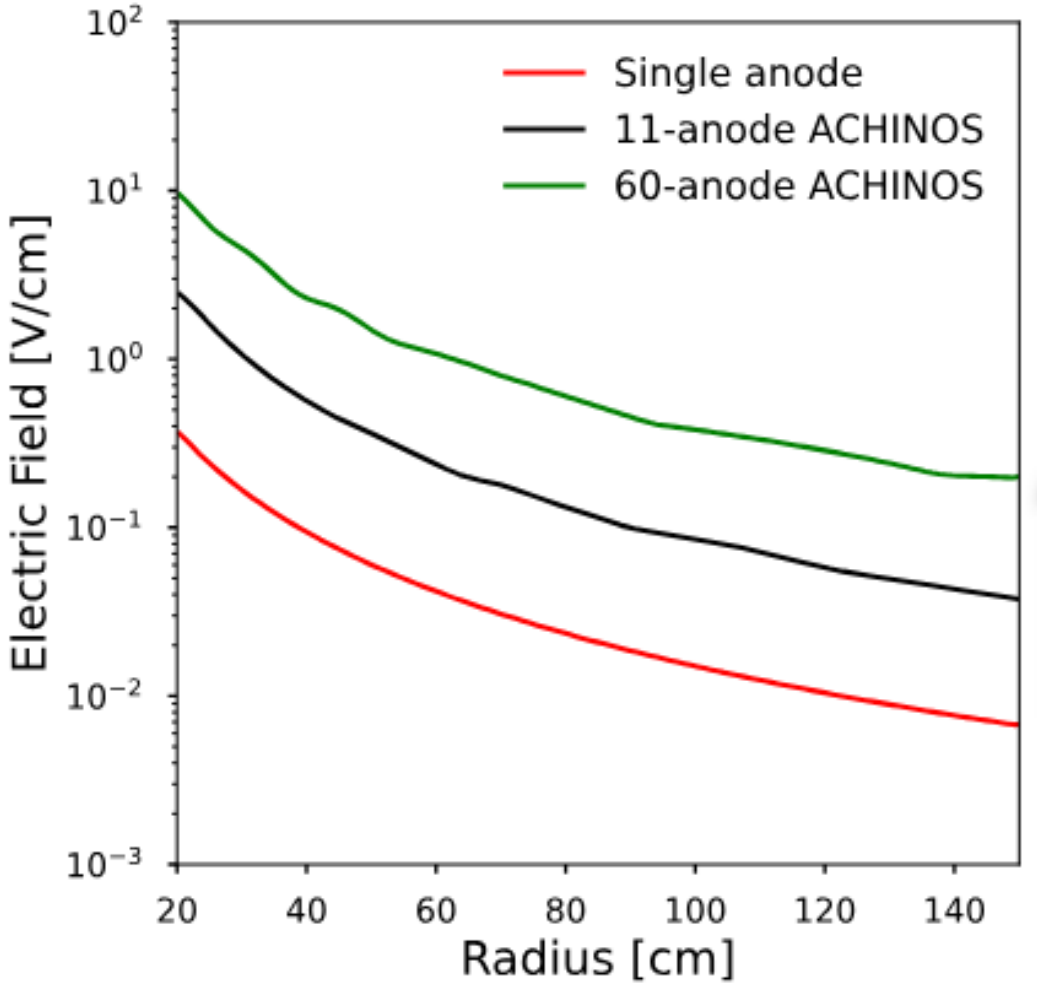
Achinos Sensor

Increased DM sensitivity comes from **increased exposure** via:
- Increased **pressure**
- Increase **volume**

Requires higher gain → Higher E-field **(G~E/P)**

Challenge: hard to scale V with size and pressure ($E \propto V r_a / r^2$)
Solution: "Achinos" sensor

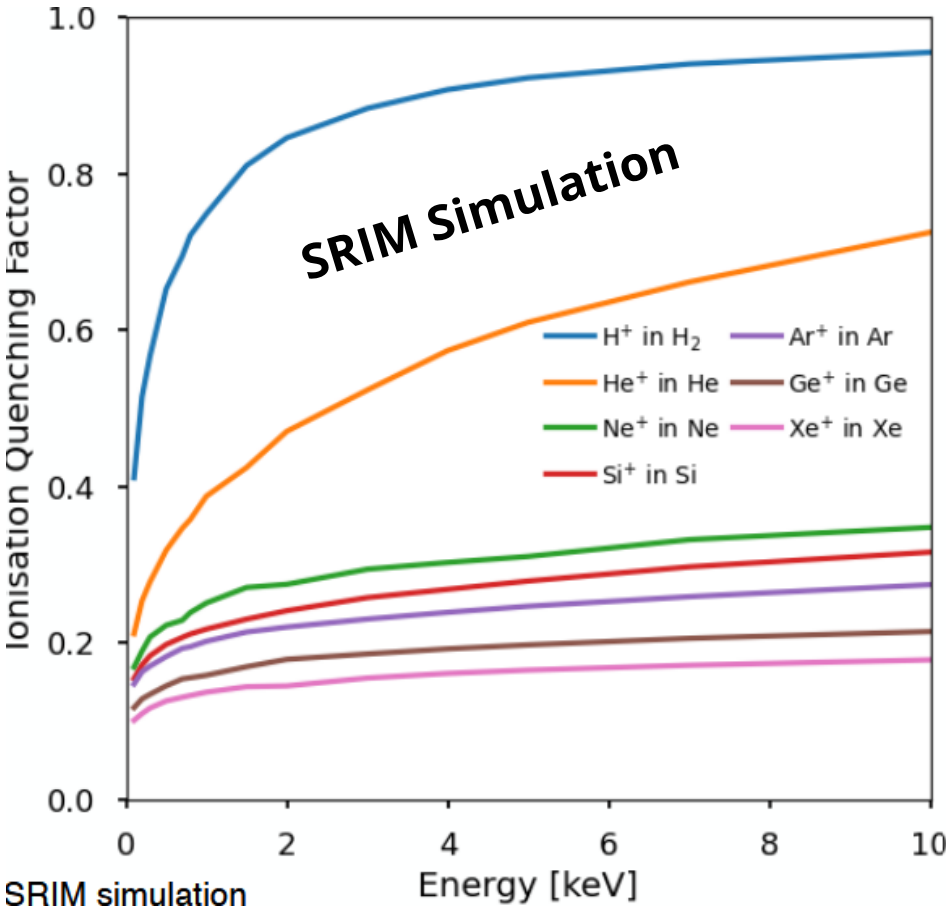
- Avalanche: Individual anode radius + voltage
- Drift: Combined field of all anodes



JINST **15** P11023

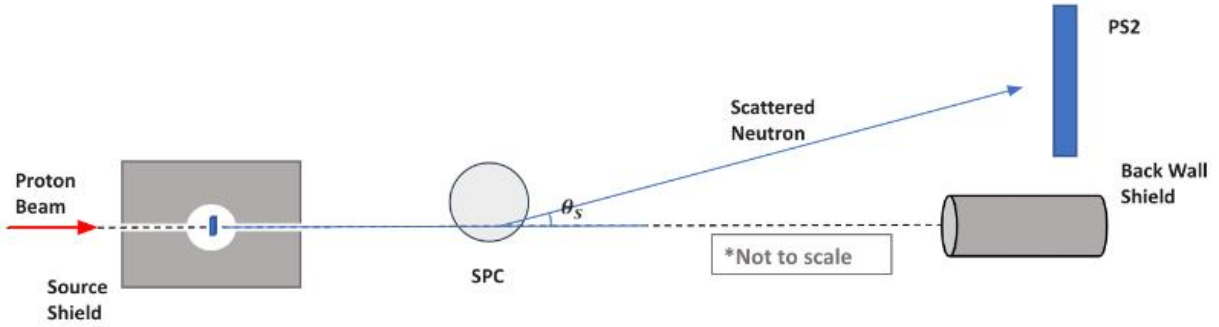
Ionisation Quenching Factors

Fraction of nuclear recoil energy dissipated via ionisation
- **Visible energy in an SPC**



Recoils on **lighter elements** deposit **more visible energy**

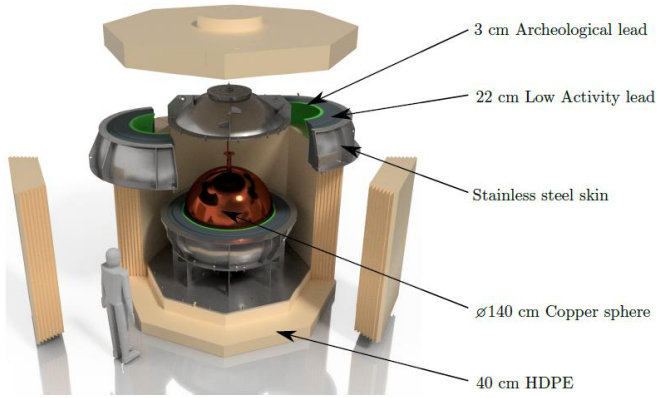
New measurement campaign at NCSR Demokritos, Athens



Current SPCs: NEWS-G

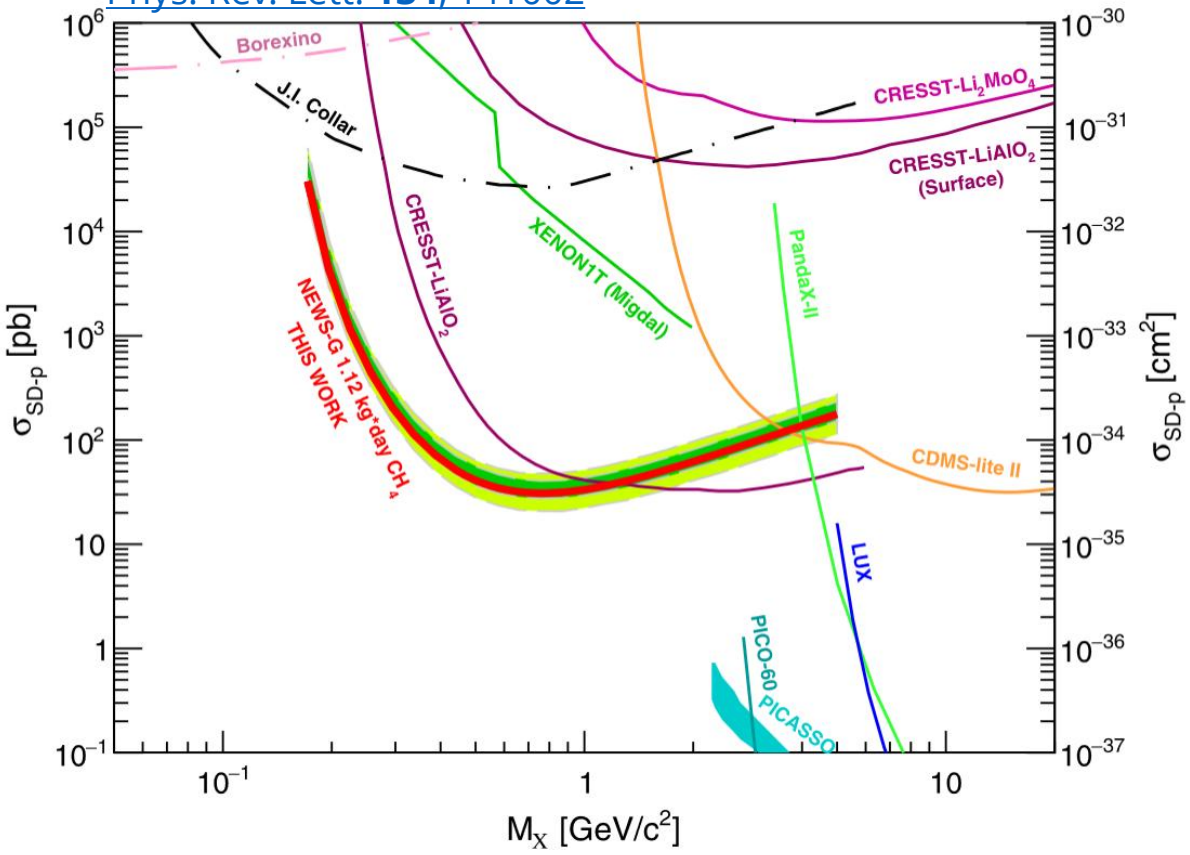
S140 in SNOLAB – ∅140 cm detector of 4N (99.99% pure) copper (electroplated inner layer)

- First physics run finalised 2023, **first results published**
- ~20 kg·days exposure with Ne:CH_4



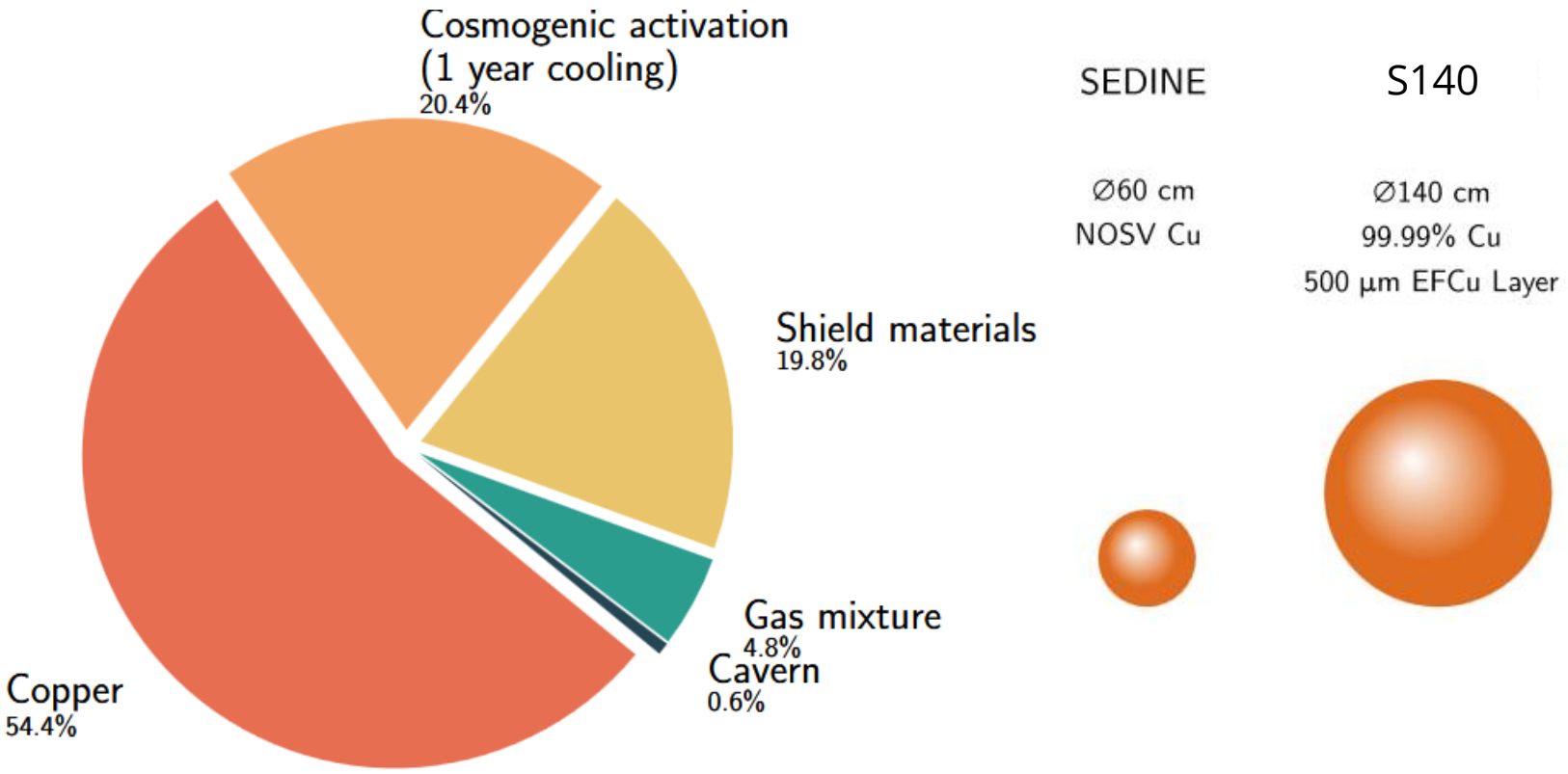
JINST 18 (2023) 02, T02005

Phys. Rev. Lett. **134**, 141002



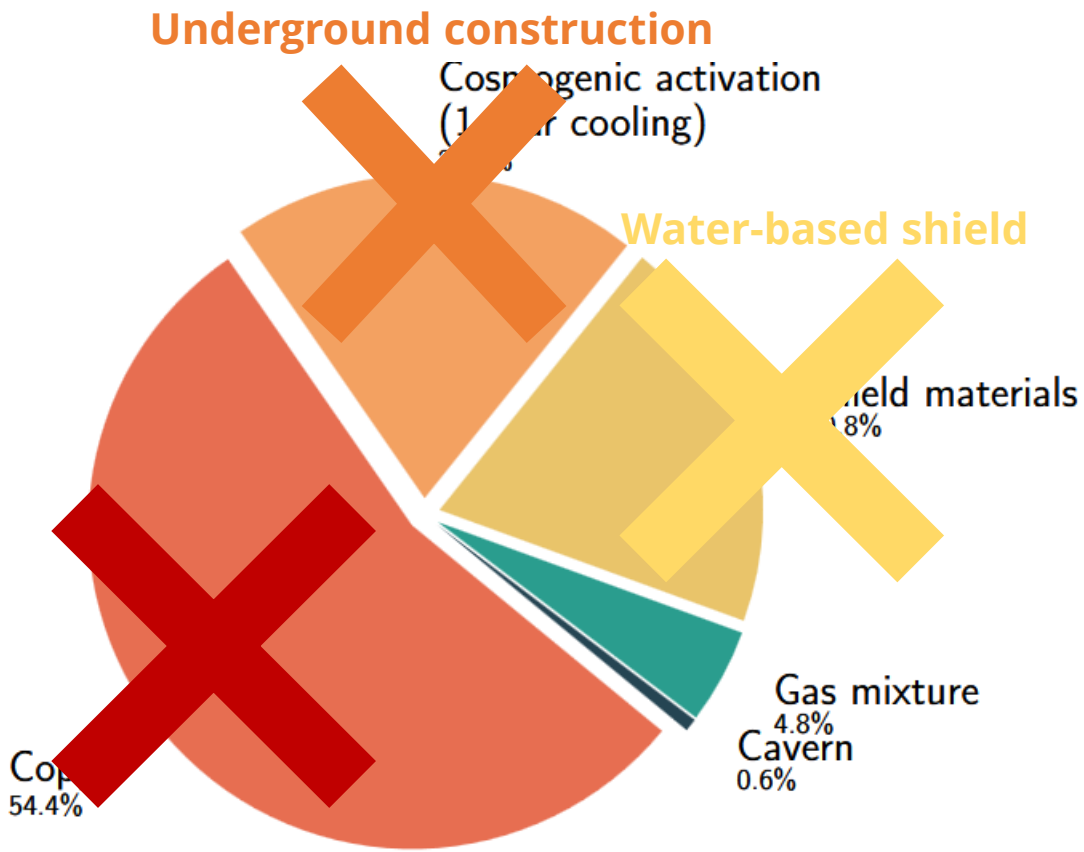
Reducing Backgrounds

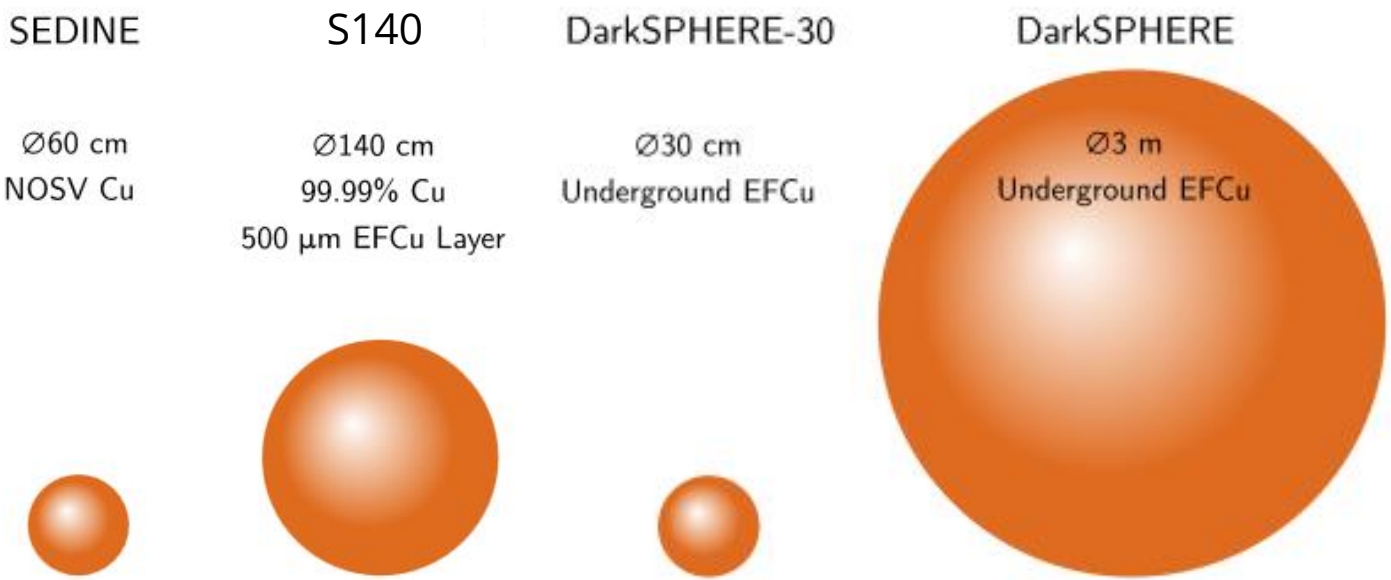
Based on simulated backgrounds



Reducing Backgrounds

Based on simulated backgrounds





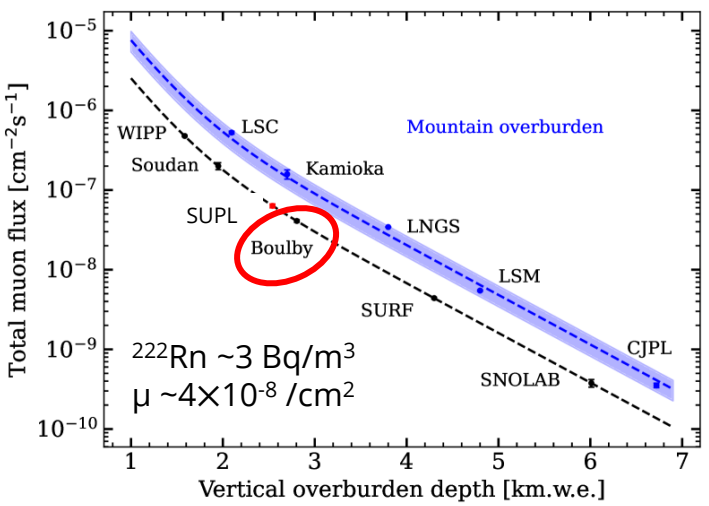
Fully electroformed detector

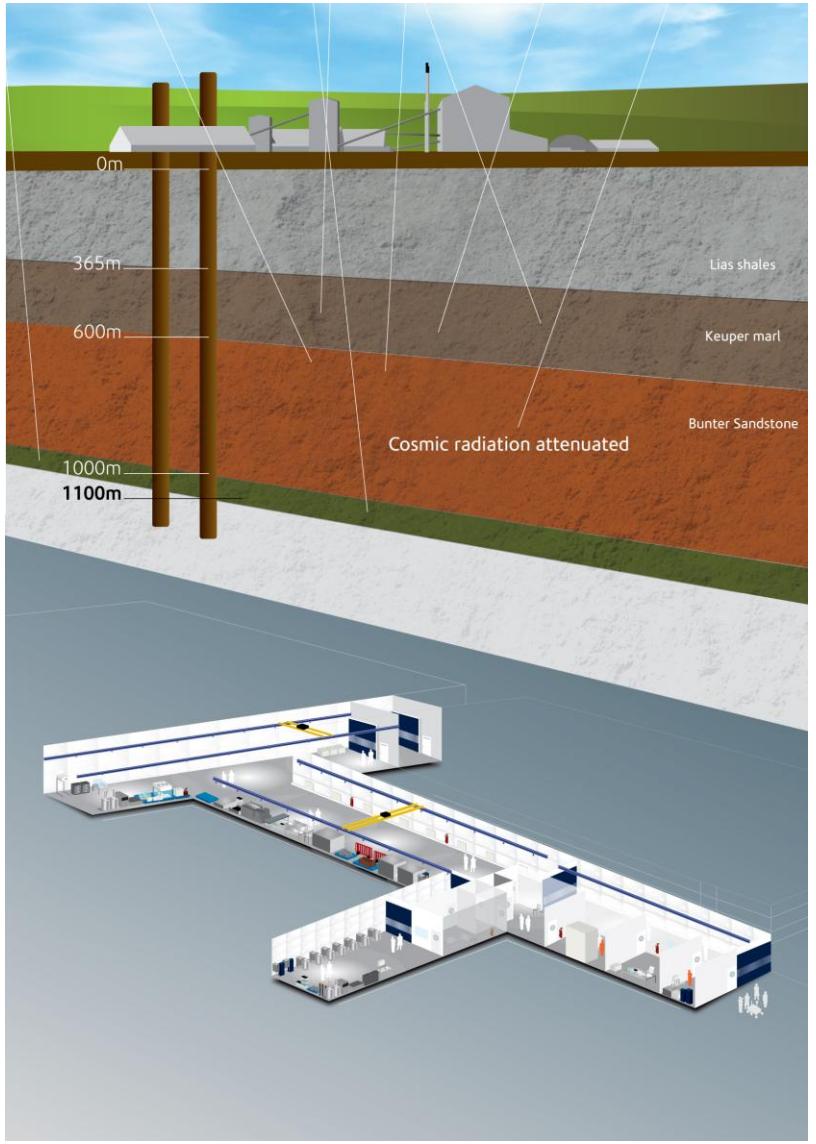
DarkSPHERE Experiment

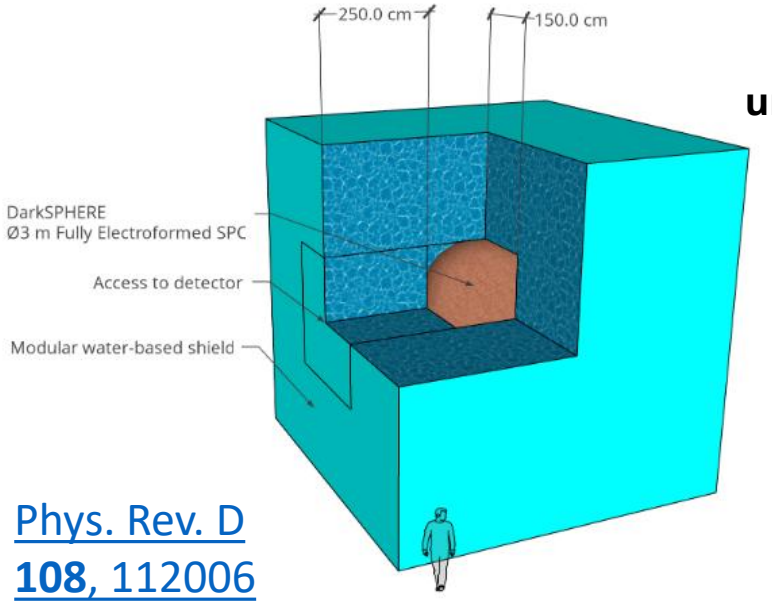
DarkSPHERE: ⌀ 3 m detector constructed underground
- Fully electroformed underground
- Water-based shield
- Boulby as potential host

Pure water shield: **0.01 cpd/kg/keV in ROI**

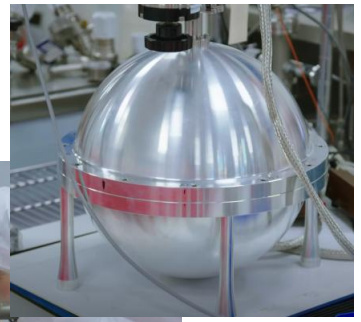
Shielding Configuration	Environmental background rate ≤ 1 keV [dru] Photon-induced Photon	Neutron-induced Neutron	Neutron-induced Photon	Muon-induced
2.5 m water	4.2×10^{-3} (0.3)	9×10^{-5} (5)	1.3×10^{-4} (0.4)	5×10^{-3} (4)







R&D sphere to **assess underground performance!**



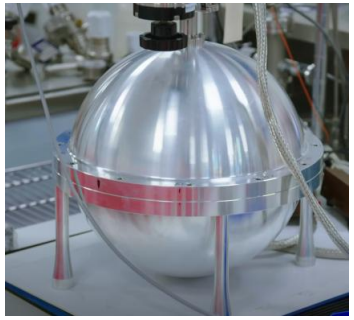
[Phys. Rev. D **108**, 112006]

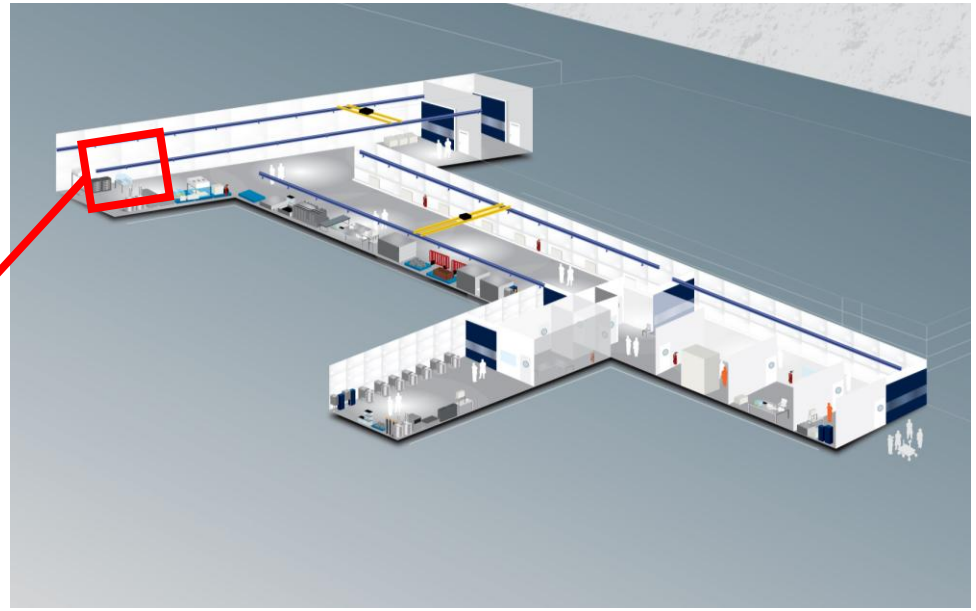
Towards DarkSPHERE-30

UNIVERSITY OF BIRMINGHAM

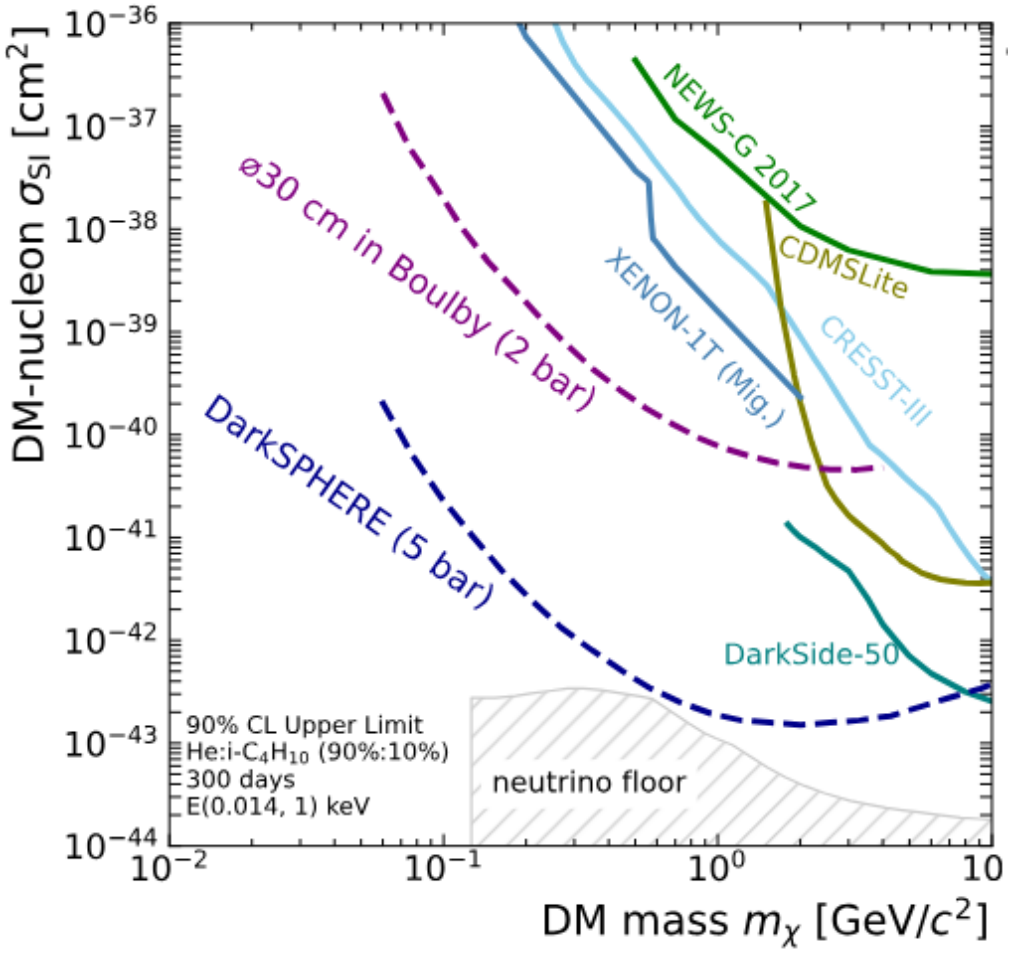
Working towards commissioning of ∅30 cm SPC in Boulby:
- Fully electroformed
- Also capable of **world-leading limits**

Key requirements being worked towards:
- Underground electroforming of sphere – to begin this year!
- Suitable underground performance – in process!
- Water-based shielding: sims in process, decision being made





Proposed location!



Towards DarkSPHERE-30

UNIVERSITY OF BIRMINGHAM

Underground Electroforming

Produces **ultra-pure copper**:
- Underground: no cosmogenic activation
- Process preferences copper deposition over radio-impurities
- Effective removal of radio-impurities

First ultra-pure copper electro-plated in Boulby
- Moving towards 30 cm sphere

See talk from G. Rogers on Thursday!

Assessing Underground Performance at Boulby

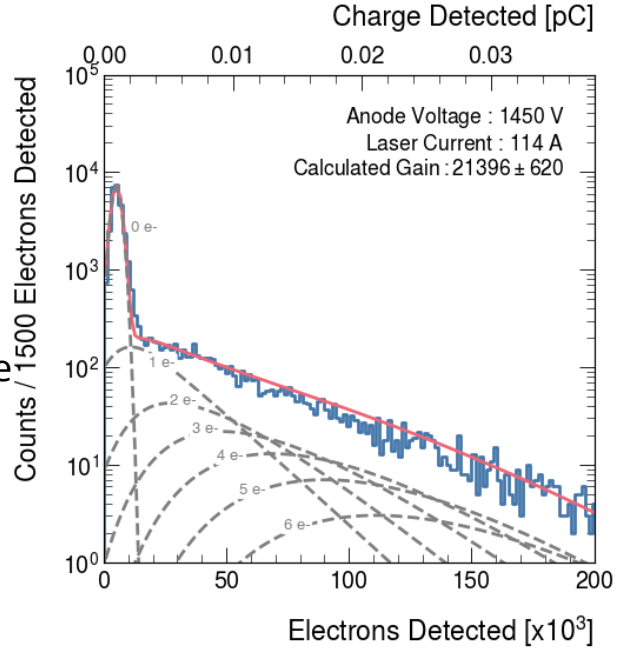
R&D SPC currently underground in Boulby
- **Aim:** Achieve single electron sensitivity underground

Plan: Utilise 213 nm UV laser system currently used for gas property studies

Demonstration for future use as in-situ monitoring

See talk from P. Walters on Thursday!

UV laser, 213 nm, 1-10 Hz pulse rate



Pure Alloys Project

UNIVERSITY OF BIRMINGHAM

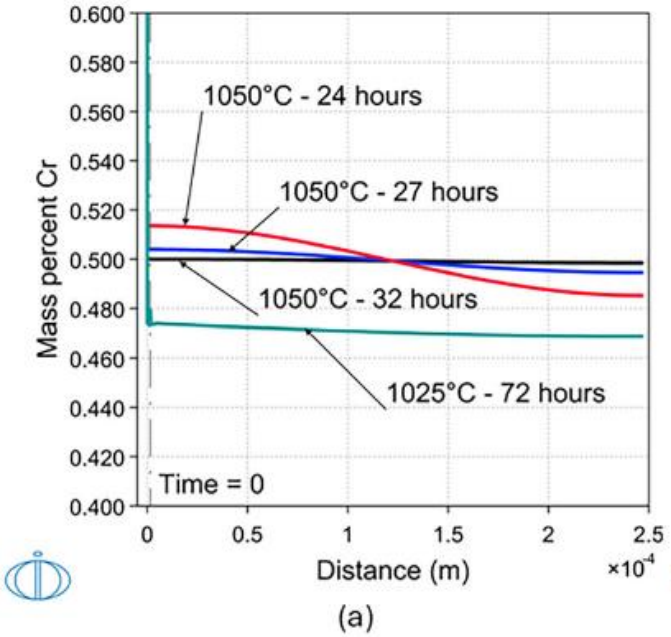
See also **pure alloys project:** Improving **mechanical performance** of EFCu w/ **CuCr alloys**!

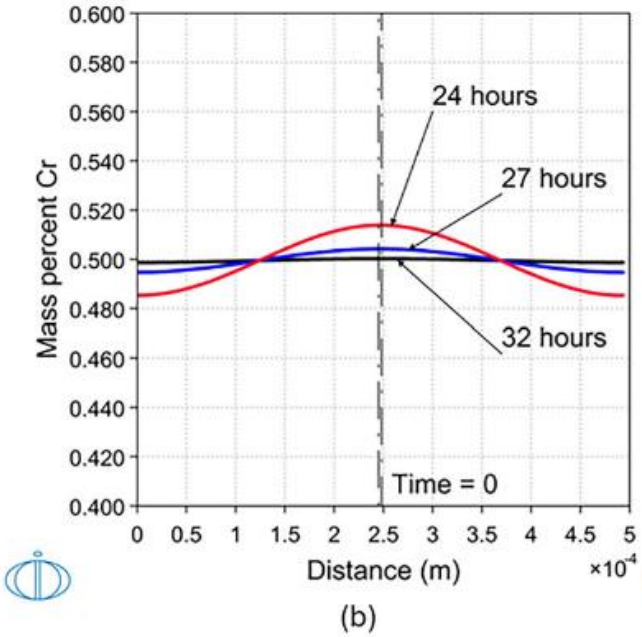
- D. Spathara NIMA (2026)
- D. Spathara arXiv:2509.07406

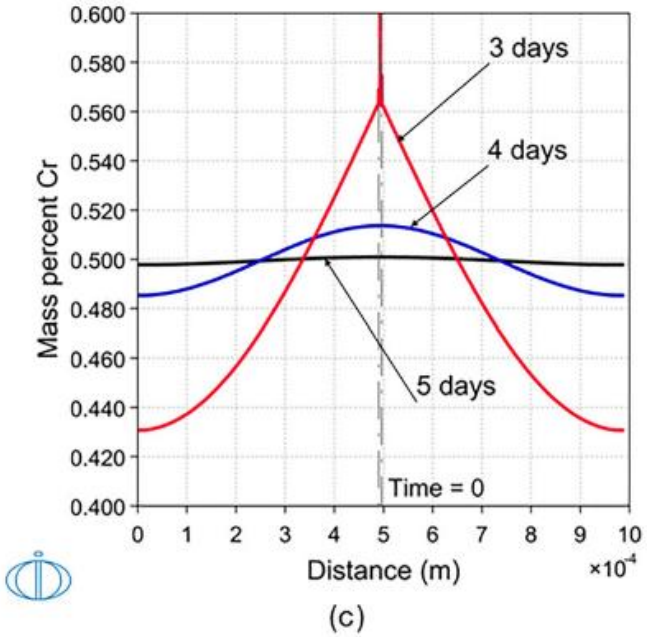
Layer Configuration	Thickness			Time
	Cr layer (μm)	Cu layer (μm)	Alloy (μm)	
Single-sided	1.5	245	246.5	32 h
Double-sided	3	245	493	32 h
Double-sided	6	490	986	5 d

Requires novel materials design to optimize alloy composition

- e.g. Alloy profile impacts material properties
- Layer thickness and specifics of heat treatment impacts alloy profile







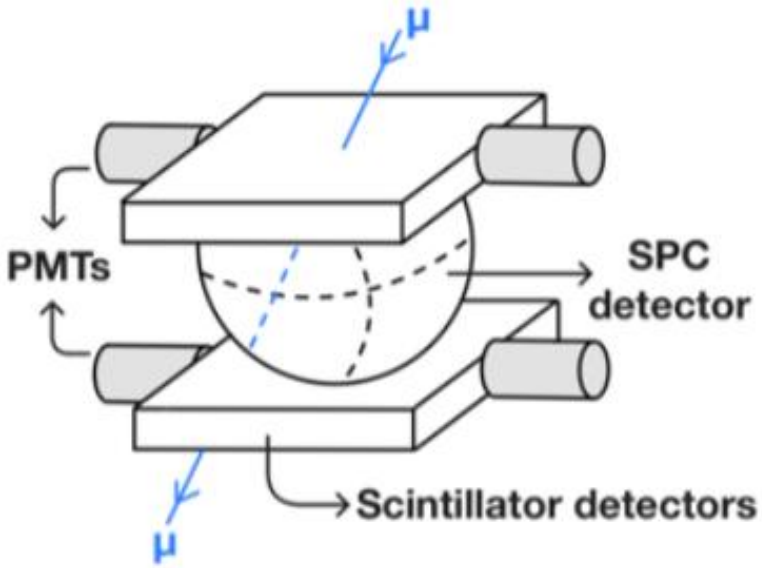
See: D. Spathara *Communications Physics* **vol 8**, 464 (2025)

Note: from simulations

Detectors for Spallation Backgrounds

UNIVERSITY OF BIRMINGHAM

Co-authors: H-M. Huckvale, A. Mattison



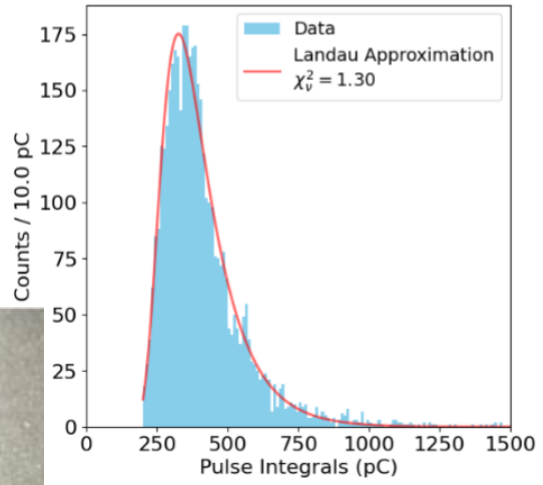
Assembled detector (efficiencies >99%)

Study **muon-induced neutron backgrounds** with detectors constructed in Birmingham:

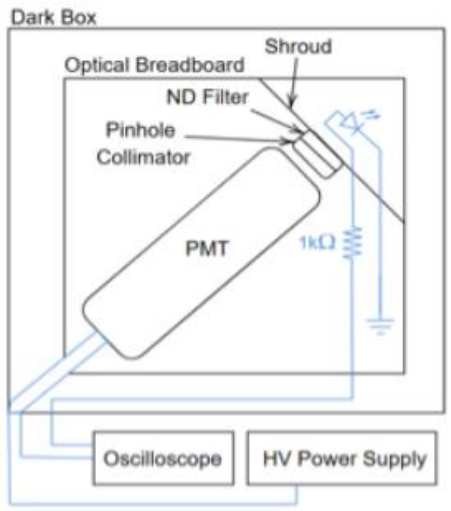
- Constituent PMTs characterised for quality assessment
- Final detectors characterised for muon tagging

Ability to separate muon-induced neutrons **strengthens neutron background characterisation**

- **SPC capable of neutron measurements with N_2 gas** (NIMA, vol 1049, 168124 (2023))



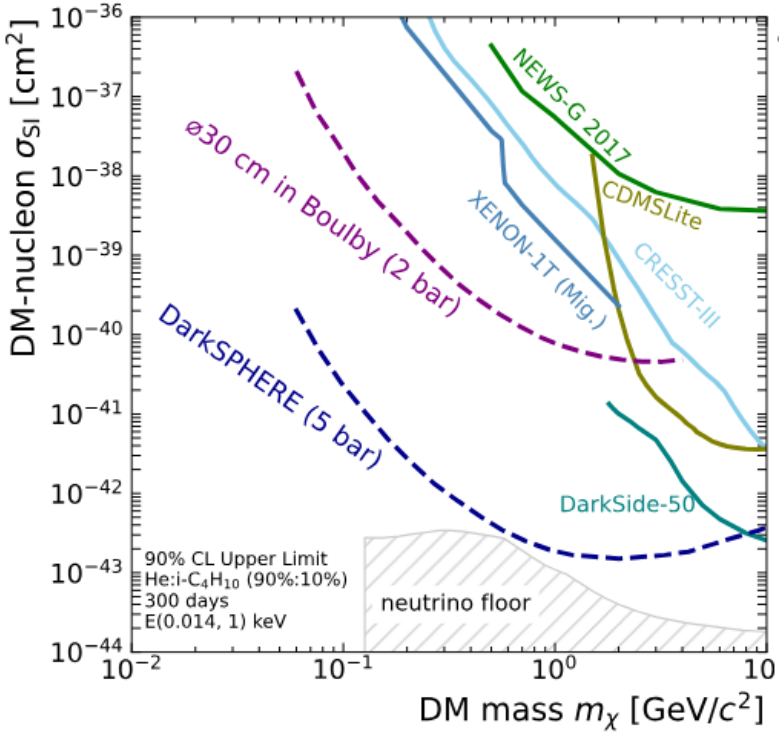
PMT QA testing setup

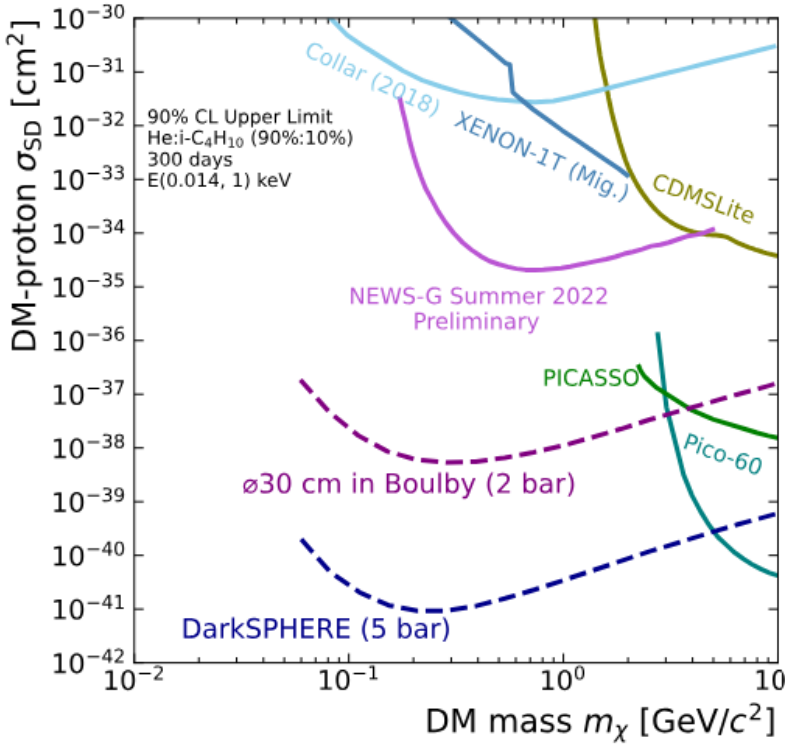


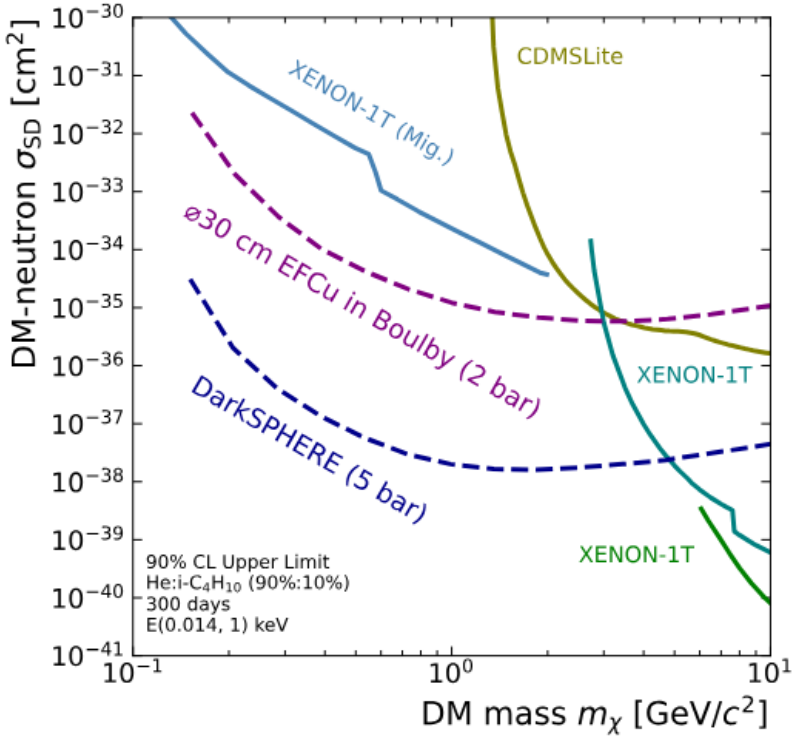
Physics Potential

UNIVERSITY OF BIRMINGHAM

- Sensitivity **up to the neutrino floor** in SI DM-nucleon interactions
- **SD limits for both p/n** interactions are **world-leading** via H and C isotopes
- A ⌀**30 cm detector** also capable of **world-leading limits**, actively working towards commissioning

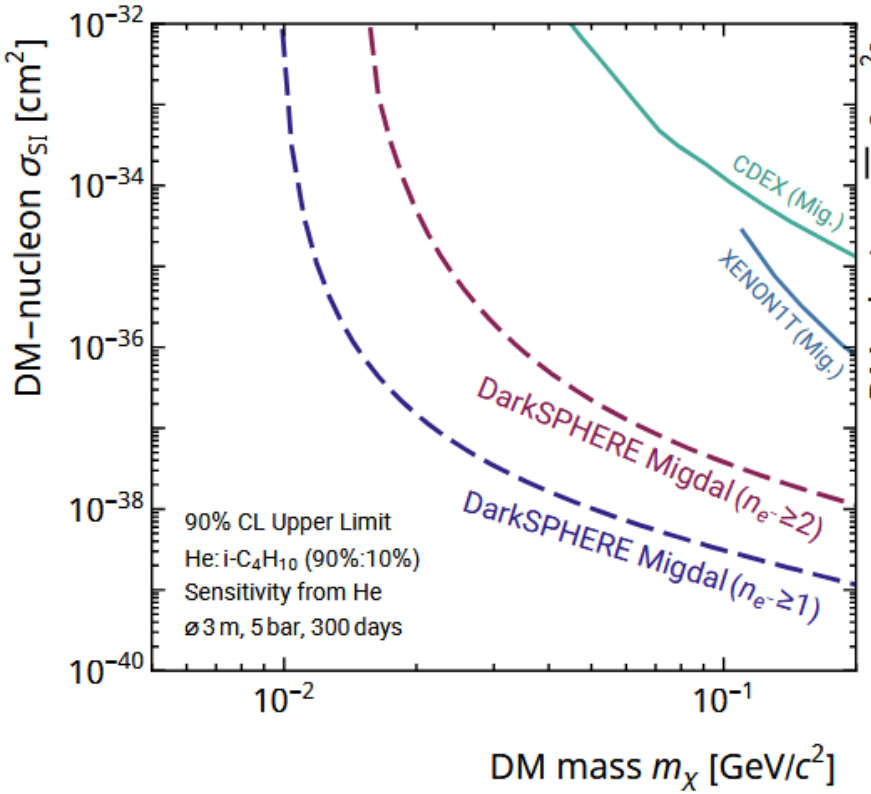


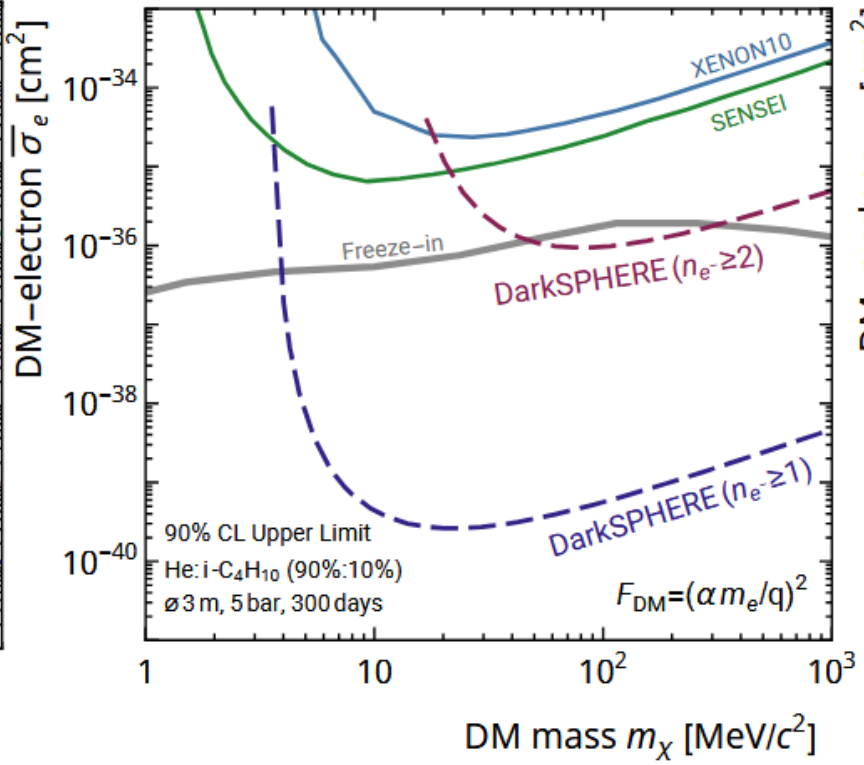


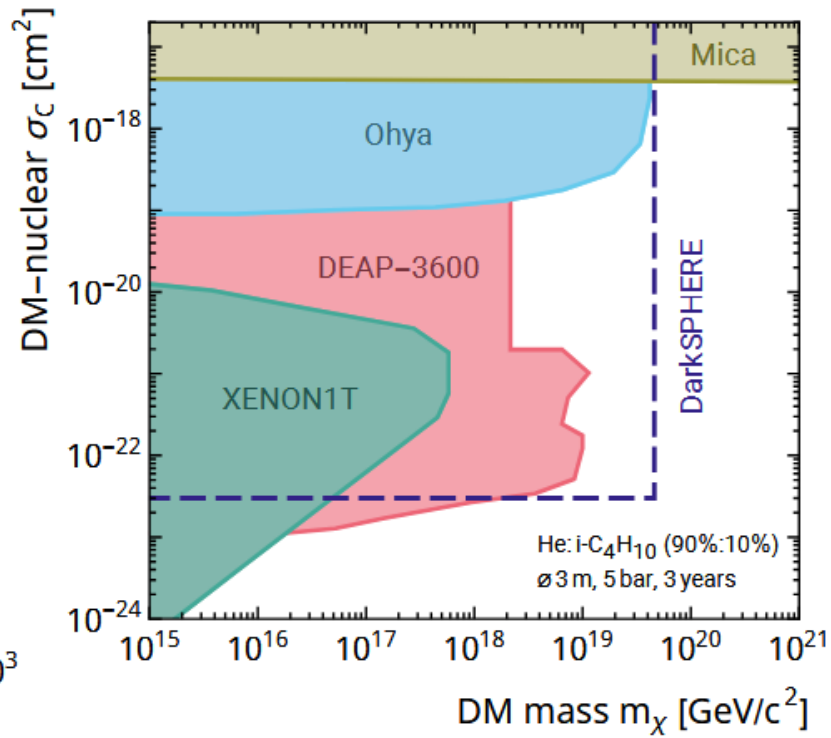


Physics Potential

- Sensitivity is enhanced via the Migdal effect
- DM-electron scattering limits possible via low threshold
- Other exotic candidates can also be studied







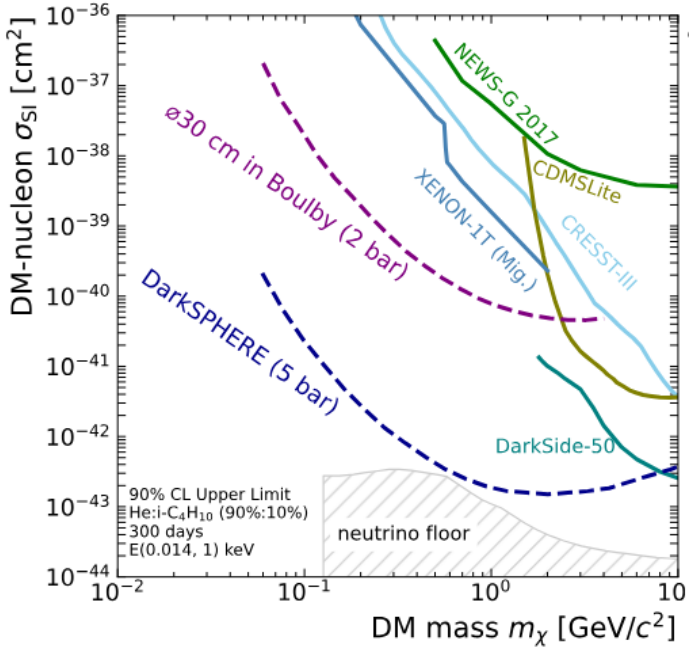
Summary

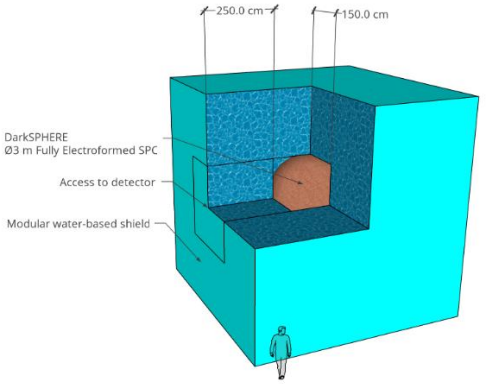
Light DM mass range largely unexplored – spherical proportional counters well-suited to explore this region

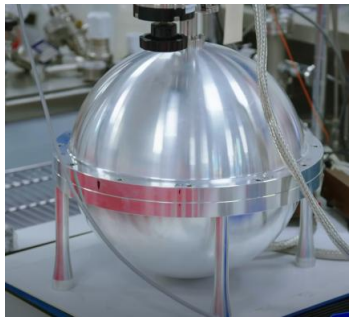
First results from S140 detector at SNOLAB published, world-leading in DM-p interactions

DarkSPHERE is proposed as a future detector that will reduce key backgrounds dominant in current SPCs
- Fully electroformed
- Constructed underground
- Pure water-based shielding

Converging towards a **⌀30 cm fully electroformed detector (DarkSPHERE-30)**
- Electroforming of sphere planned for this year
- Underground performance of SPC in Boulby being studied







Backups

First Electroforming Underground

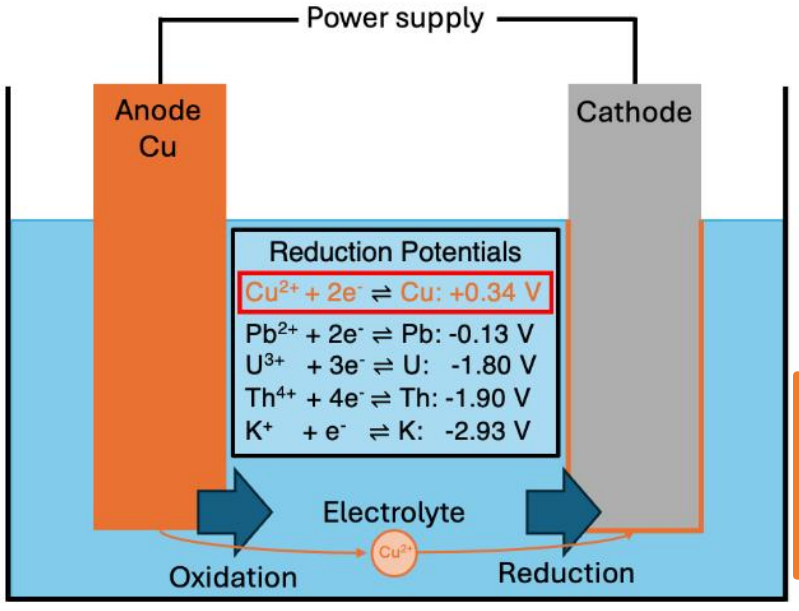
UNIVERSITY OF BIRMINGHAM

Electroforming underground produces **ultra-pure copper**:

- Underground: no cosmogenic activation
- Electroformation process preferences copper deposition over radio-impurities
- Effective removal of radio-impurities

First ultra-pure copper electro-plated in Boulby

- Moving towards 30 cm sphere



See talk from G. Rogers on Thursday!

See also pure alloys project (D. Spathara NIMA (2026) arXiv:2509.07406):

- Improving mechanical performance of EFCu w/ CuCr alloys!

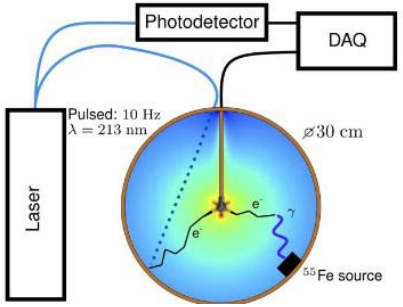
Assessing Underground Performance

UNIVERSITY OF BIRMINGHAM

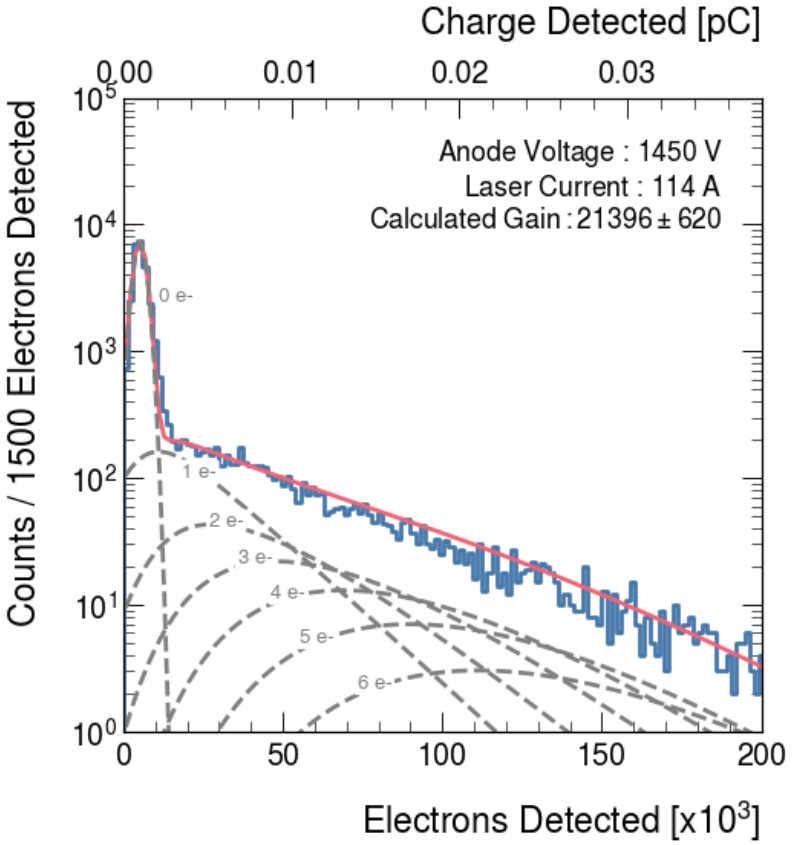
R&D SPC currently underground in Boulby
- **Goal:** assess performance of SPC in underground environment
- **Aim:** Achieve single electron sensitivity underground

Plan: Utilise 213 nm UV laser system currently used for gas property studies

Demonstration for future use as in-situ monitoring



See talk from P. Walters on Thursday!



UV laser, 213 nm, 10 Hz pulse rate