Searching for light dark matter with DarkSPHERE

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DM Direct Detection Landscape

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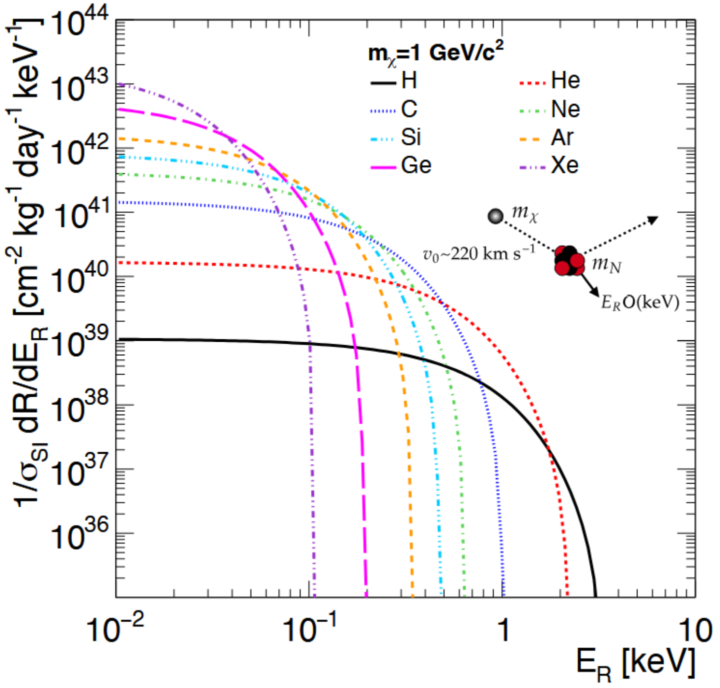
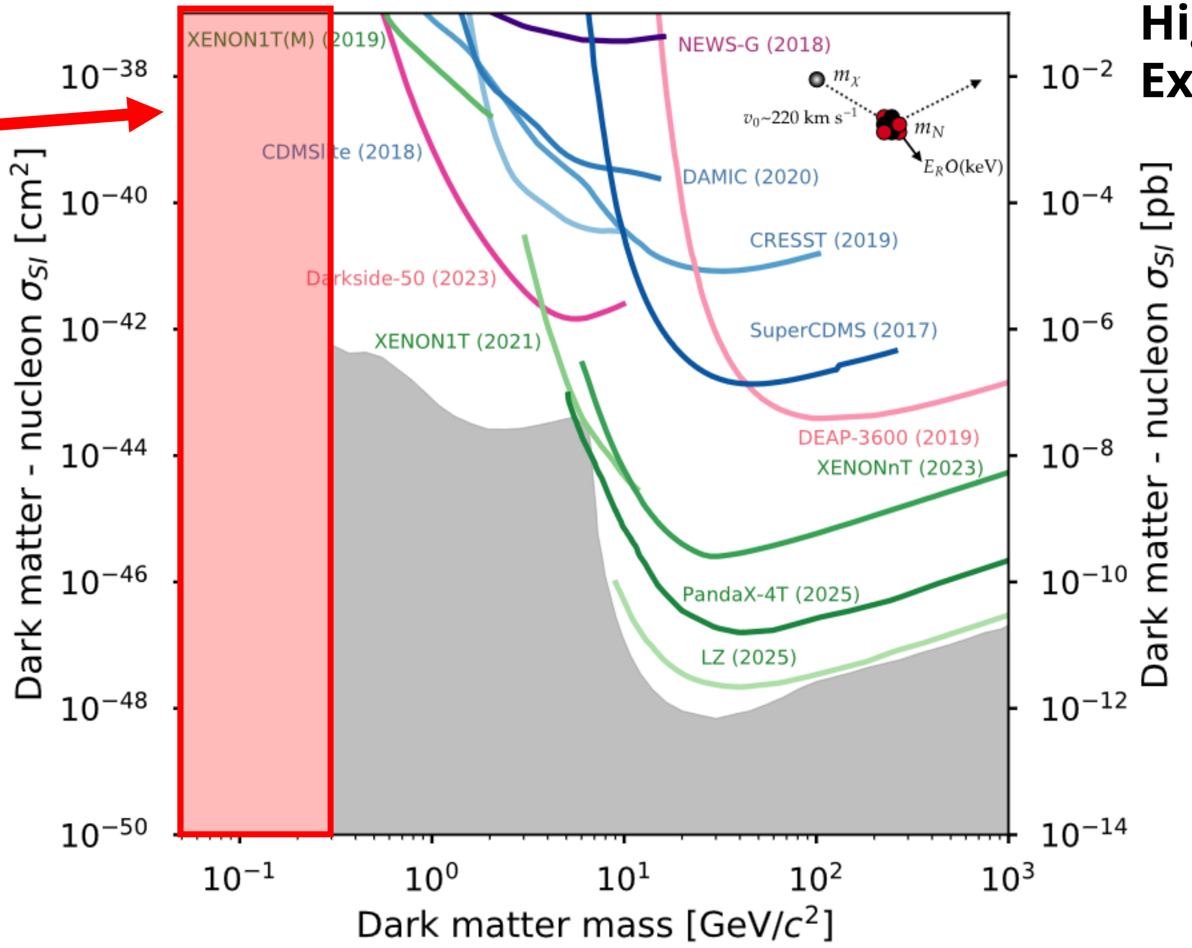
Exploring light dark matter in the low mass region (0.01-10 GeV) requires:
- Low detector thresholds
- Light nuclei
  - Kinematic matching

Unexplored low mass region – light dark matter

Combination of requirements necessitates novel detector approaches!





Higher Exposure

Lower Threshold/Lighter Nuclei

The Spherical Proportional Counter

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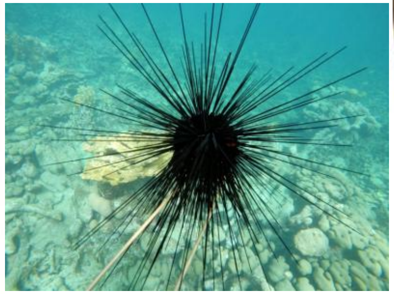
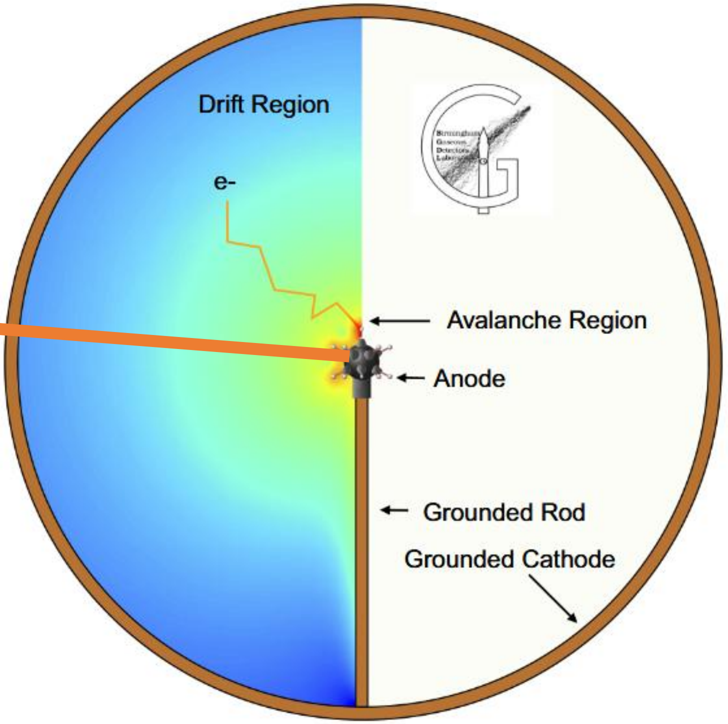
"Achinos" Sensor





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

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

Increased DM sensitivity comes from **increased exposure** via:

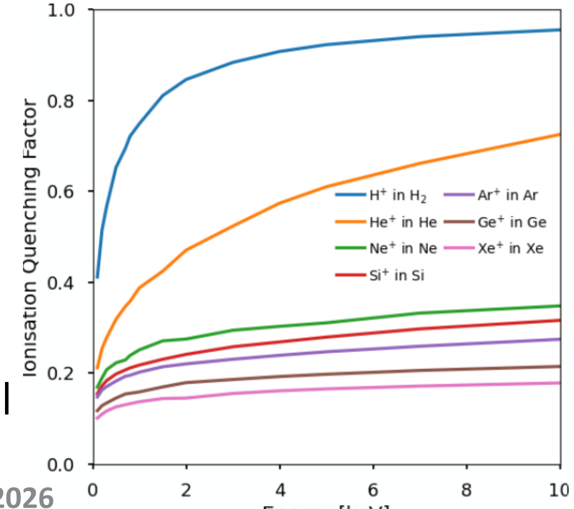
- Increased **pressure**
- Increase **volume**

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

Achieved by Achinos: Avalanche region set by individual anodes, drift by combined field

Key strengths for a light DM search:

- **Choice in gas targets (light nuclei) and pressures**
- **Low capacitance:** low electronic noise, single **electron threshold**
- Simple design: **entirely radiopure construction**
- Electric field **split between drift and amplification region**
- **Position reconstruction**



SRIM simulation

Lighter gases have good ionisation QF

Based on SRIM simulation

Current SPCs: NEWS-G

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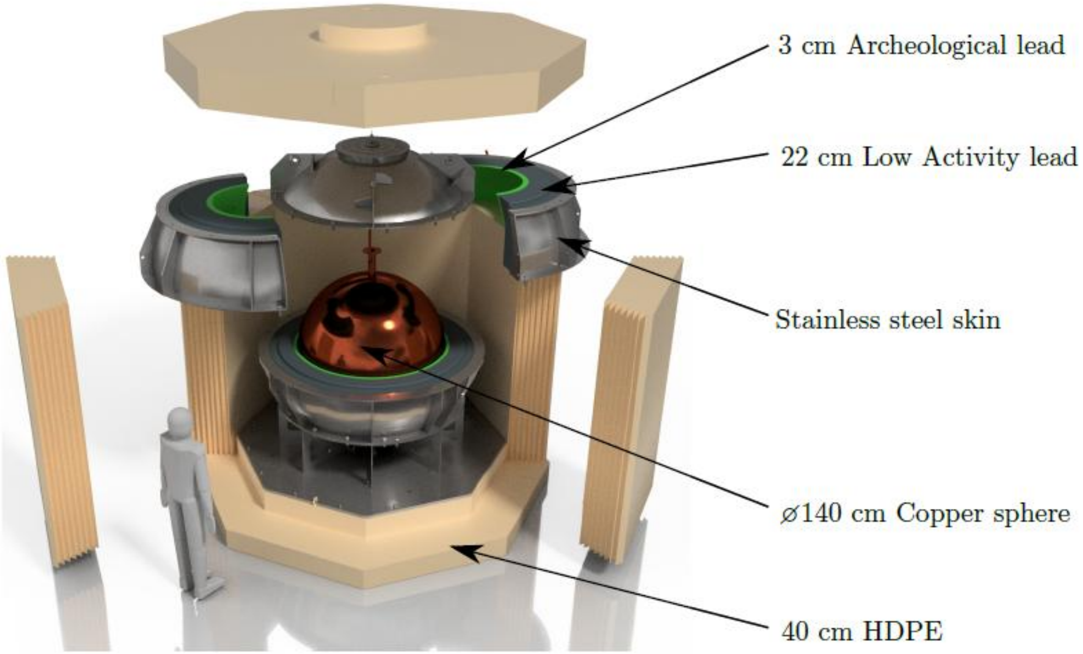
First NEWS-G results obtained by SEDINE (Ø60 cm) at Modane (Astropart. Phys. 97, 54 (2018))

Current: S140 in SNOLAB – Ø140 cm detector of 4N (99.99% pure) copper (electroplated inner layer)

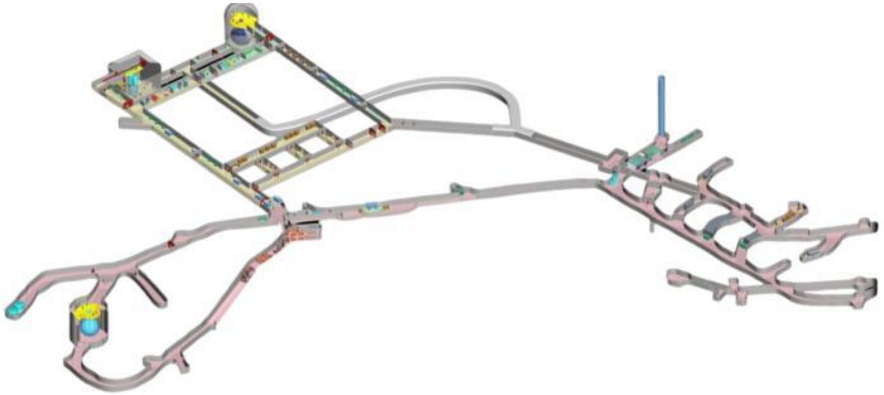
- First physics run finalised 2023, **first results published**
- ~20 kg·days exposure with Ne:CH_4

See next talk from G. Giroux on NEWS-G and S-140!

JINST 18 (2023) 02, T02005



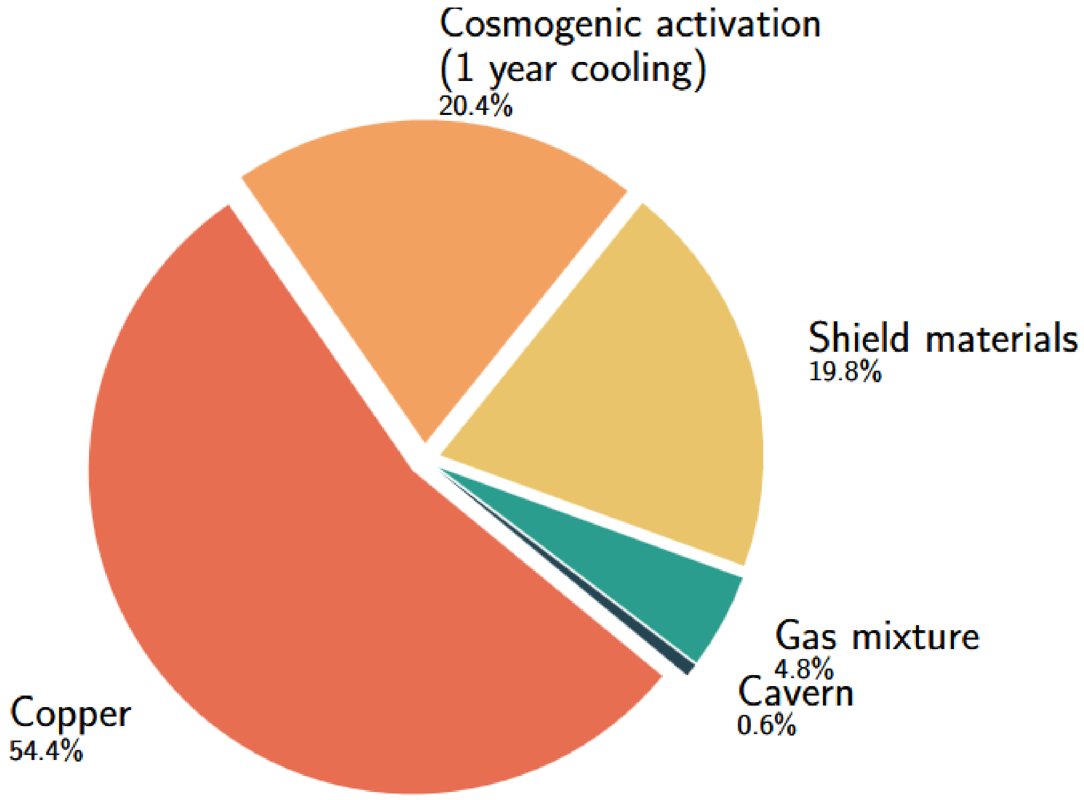
SNOLAB

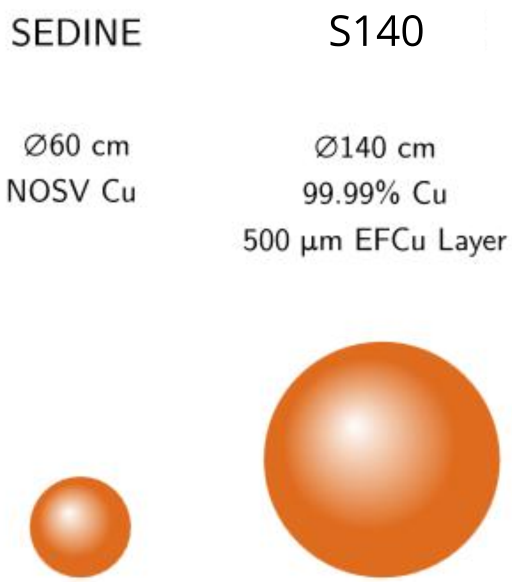


Reducing Backgrounds

Based on simulated backgrounds

[A. Brossard, NEWS-G Thesis](#)





Reducing Backgrounds

Based on simulated backgrounds

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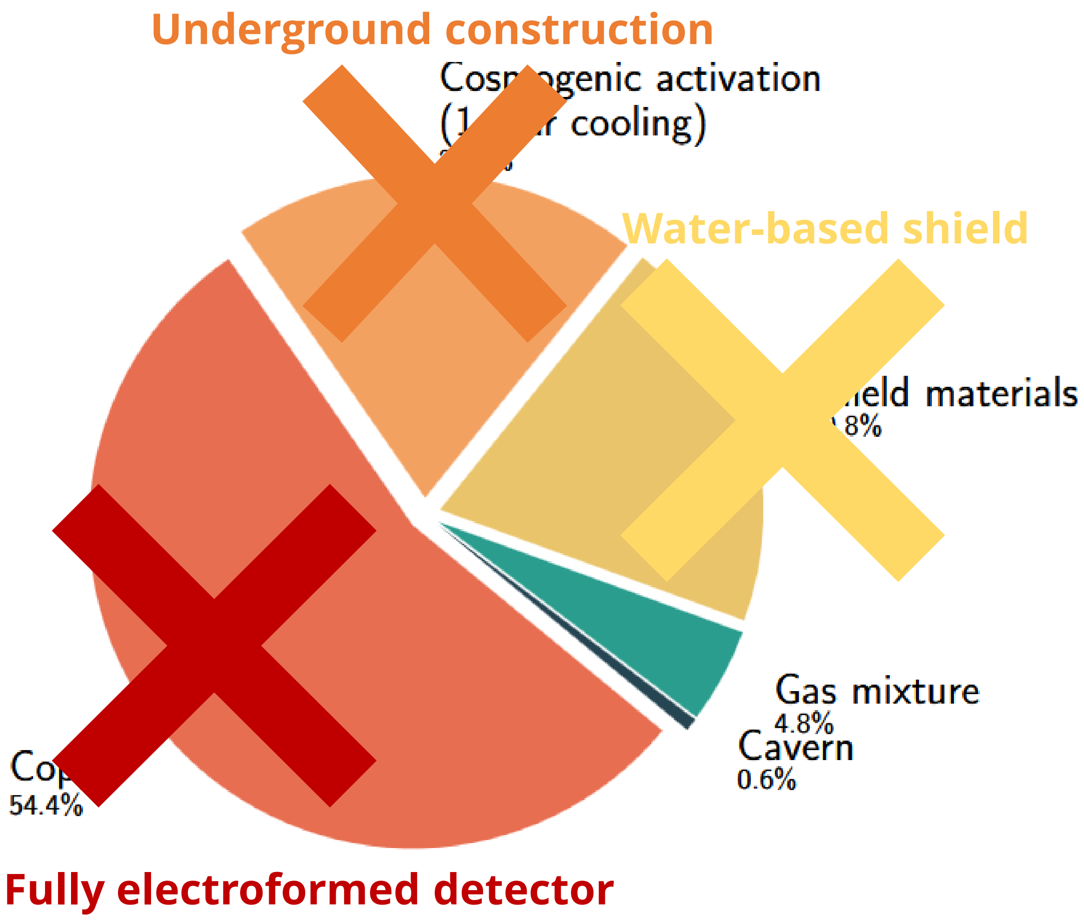
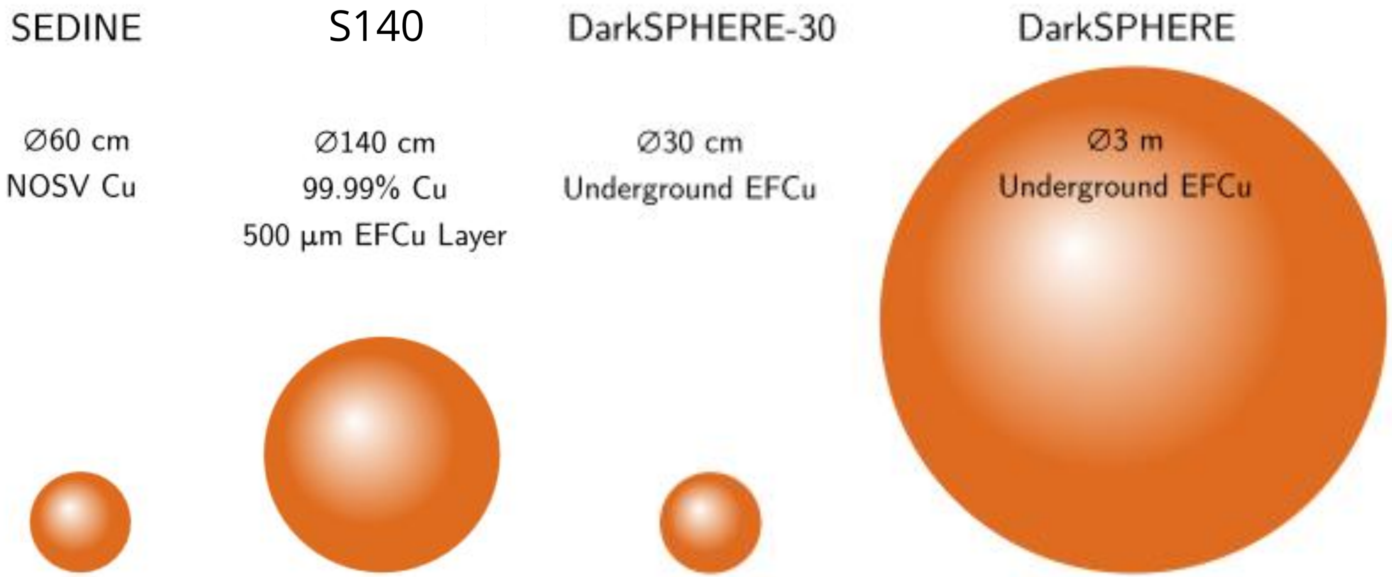


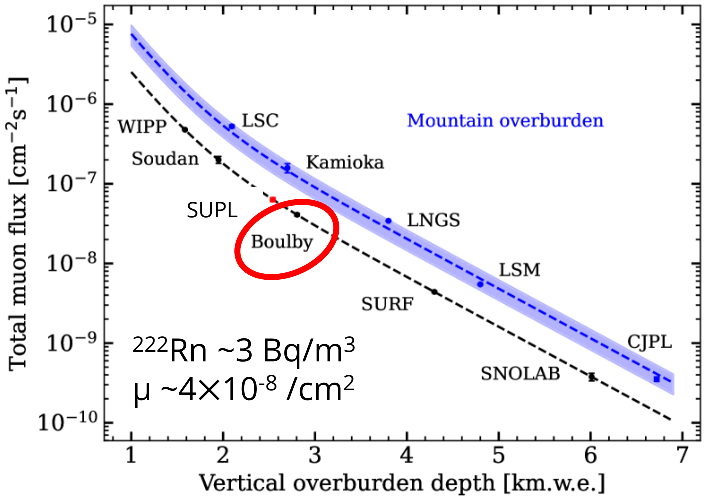


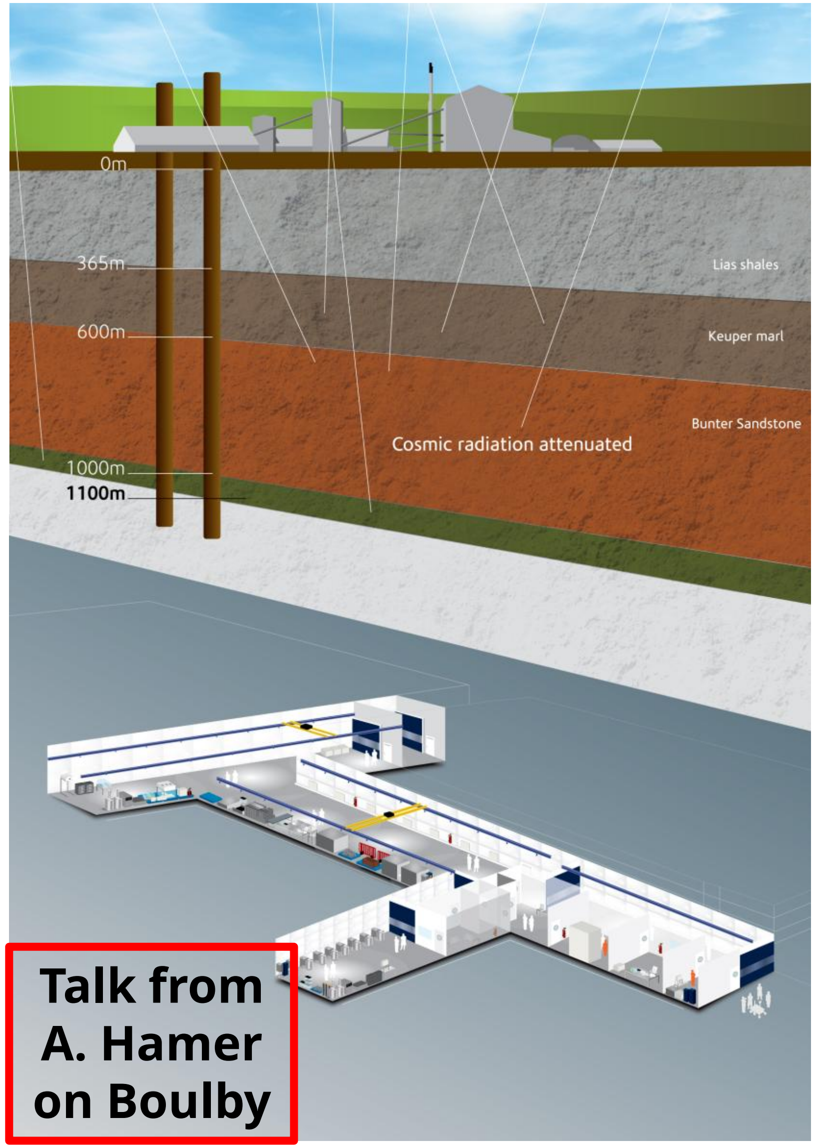
DarkSPHERE Experiment

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

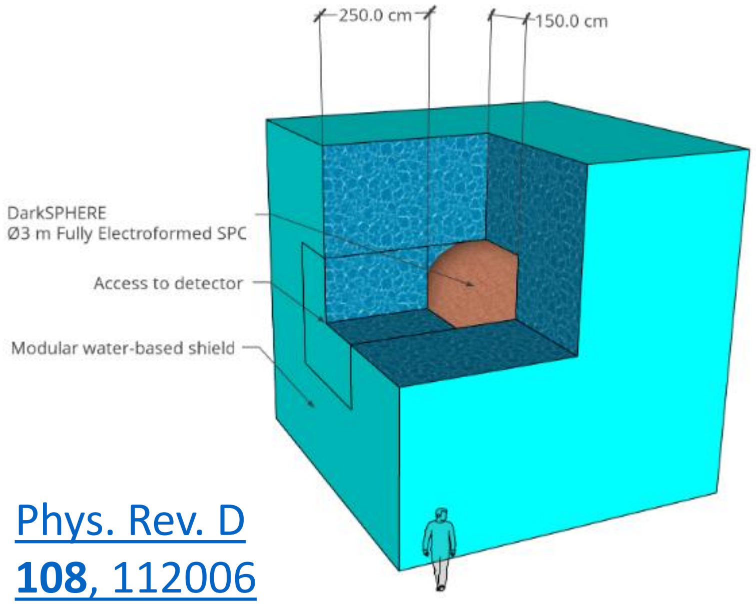
Pure water shield: **0.01 cpd/kg/keV in ROI**

Shielding Configuration	Environmental background rate $\leq 1\,\mathrm{keV}$ [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)



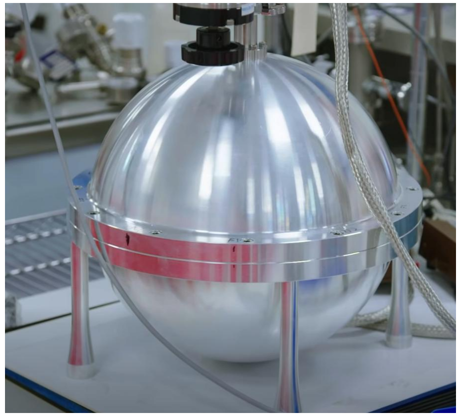


Talk from A. Hamer on Boulby



Shielding design engineering study ongoing!

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

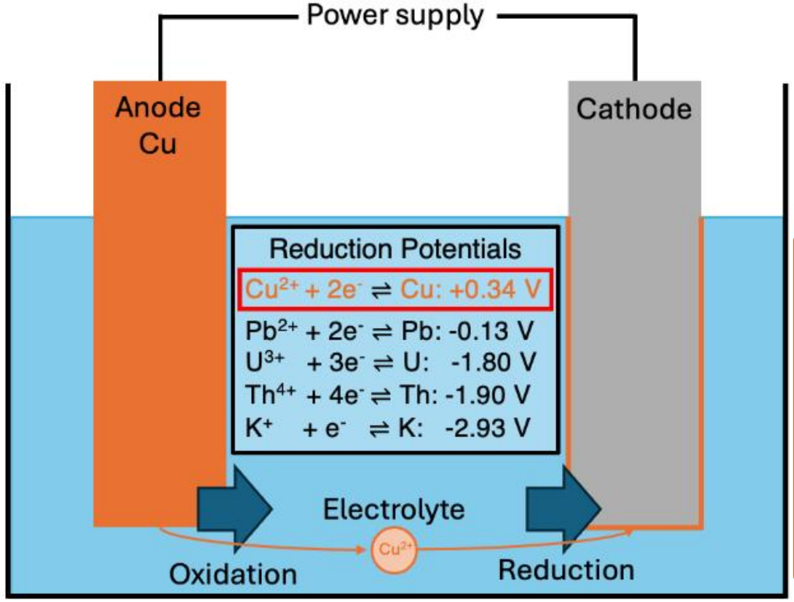


[Phys. Rev. D **108**, 112006]

First Electroforming Underground

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 also pure alloys project ([D. Spathara NIMA (2026) arXiv:2509.07406]()):
- Improving mechanical performance of EFCu w/ CuCr alloys!

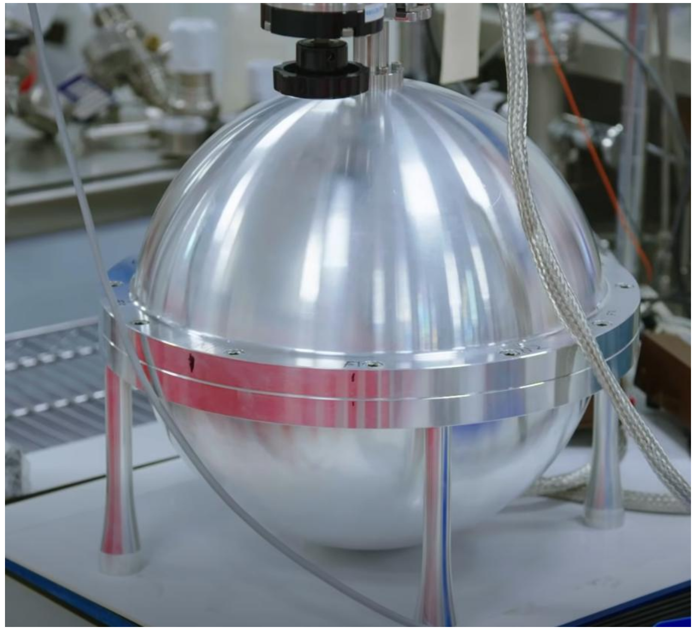
See also: Poster from D. Spathara

UKRI Engineering and Physical Sciences Research Council

Towards DarkSPHERE-30

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

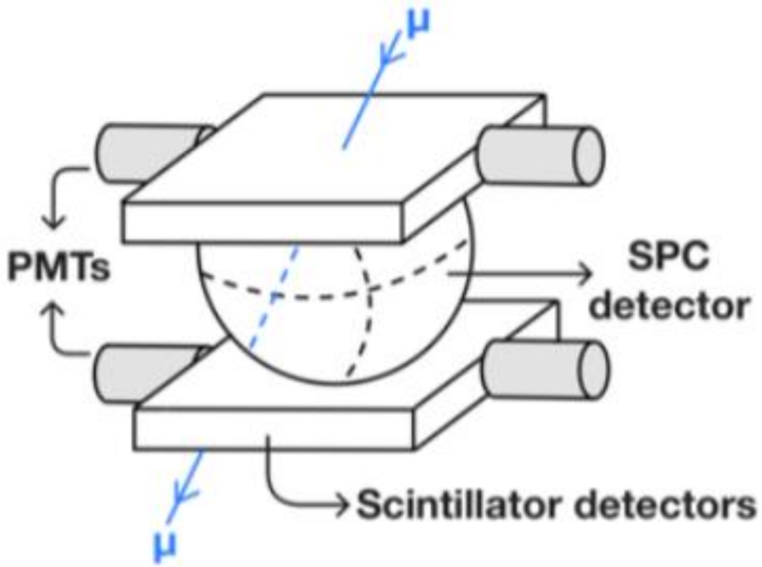
Key requirements being worked towards:
- **Underground electroforming of sphere – to begin this year!**
- Suitable underground performance – in process!
- Water-based shielding: sims in process, decision being made



Proposed location!

Detectors for Spallation Backgrounds

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



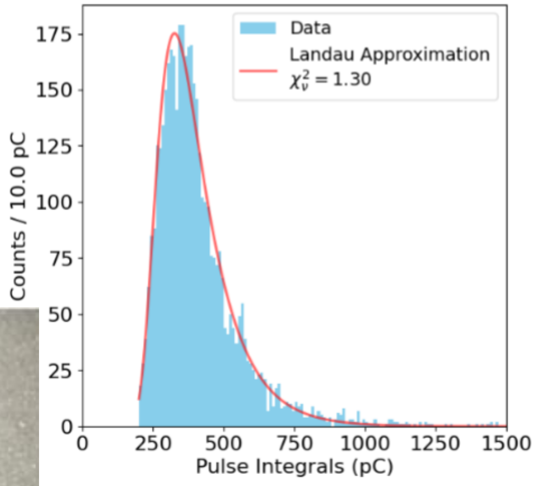
Study **muon-induced neutron backgrounds** with detectors constructed in Birmingham:

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

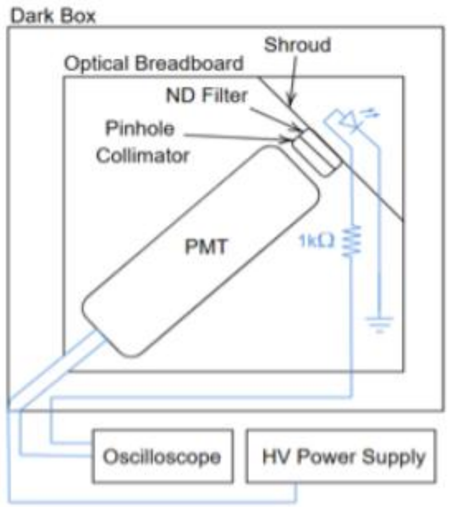
Ability to separate muon-induced neutrons **strengthens neutron background characterisation**

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

Assembled detector (efficiencies >99%)



PMT QA testing setup



Physics Potential

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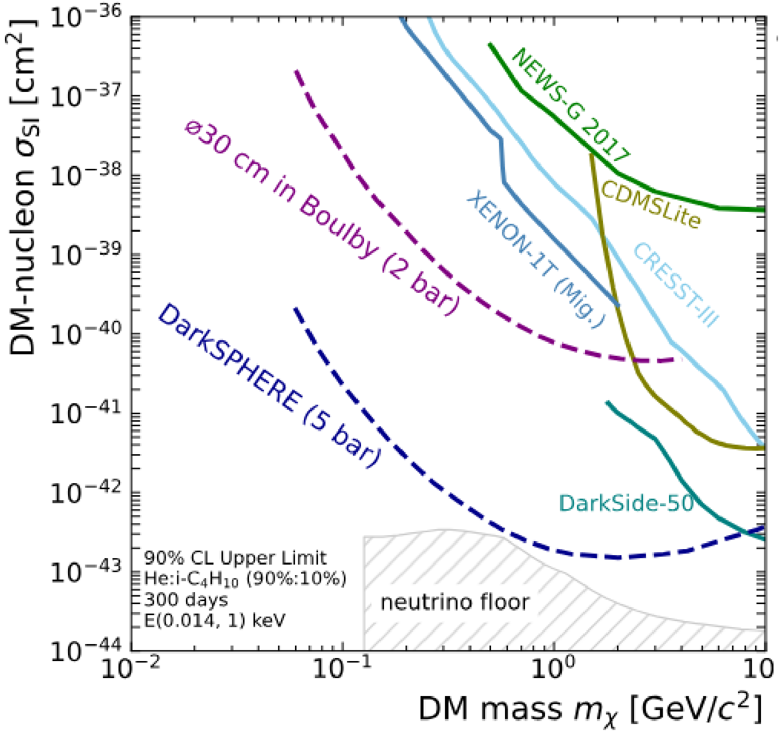
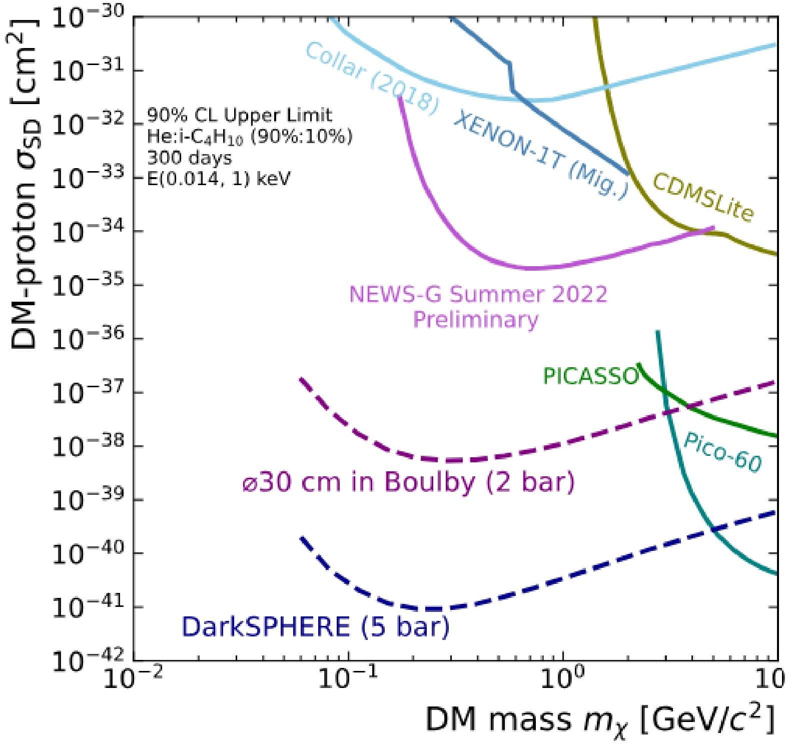
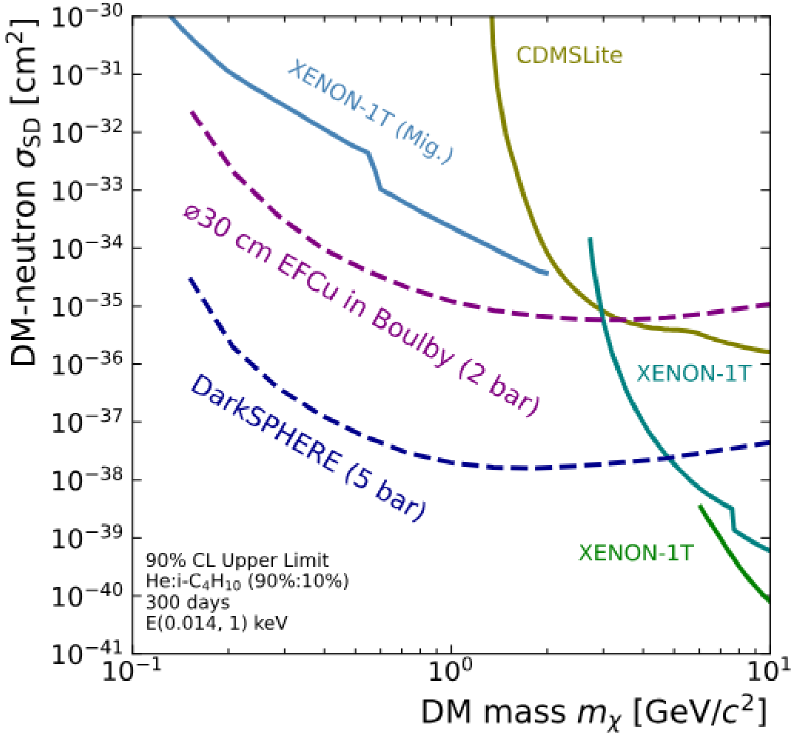
- Sensitivity **up to the neutrino fog** in SI DM-nucleon interactions
- **SD limits for both p/n** interactions are **world-leading** via H and C isotopes
- A **⌀30 cm detector** also capable of **world-leading limits**, actively working towards commissioning

But can we do more?







Physics Potential: Exotic

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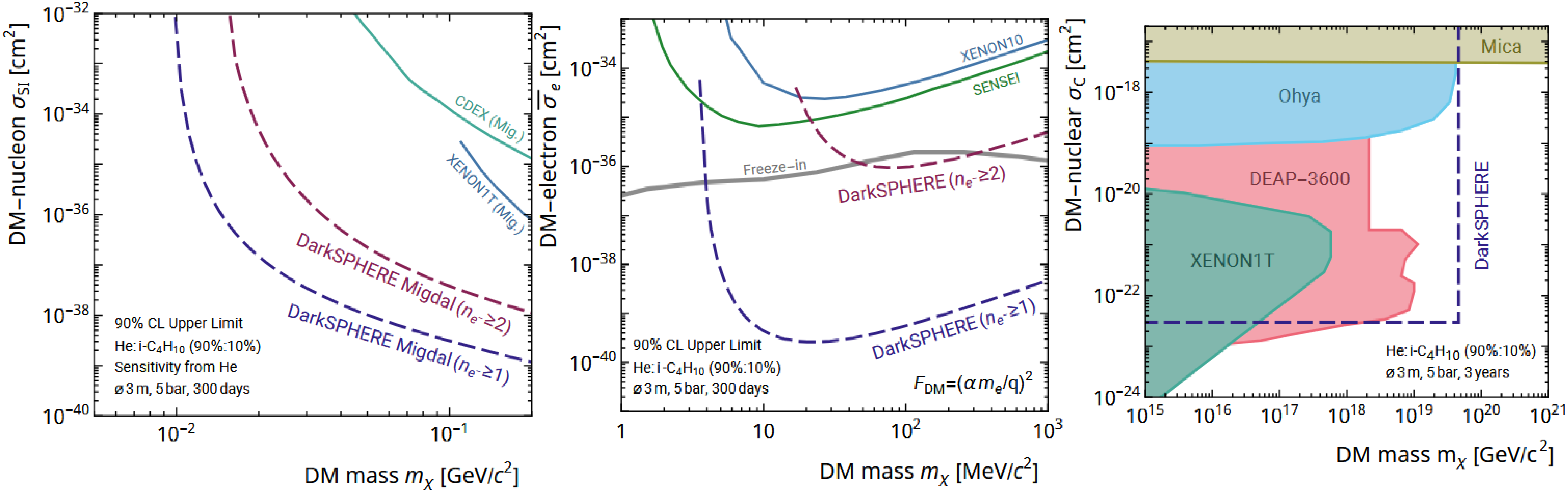
- Sensitivity is enhanced via the Migdal effect
- DM-electron scattering limits possible via low threshold
- Other exotic candidates can also be studied

Can we even go on-wards from this?



Physics Potential: EFT Operators

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$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_\chi} * \int_{v>v_{min}} v f(\vec{v} + \vec{v_E}) \frac{d\sigma_T(v, E_R)}{dE_R} d^3v$$

Assess the potential of DarkSPHERE assuming different EFT operators

16 linearly independent operators, containing:
- q: momentum transfer
- $v^{\perp}$: transverse relative velocity
- $s_{\chi,N}$: dark matter/nucleon spin

Some intuition:
- **O1 and O4 are typical SI/SD interactions**
- Extra q: weighting towards harder recoils
- $s_{\chi,N}$ and q: non-standard responses beyond SI/SD

$$\boxed{\mathcal{O}_1^N \equiv \mathbb{1}}$$

$$\mathcal{O}_3^N \equiv i\, \boldsymbol{s}_N \cdot (\boldsymbol{q} \times \boldsymbol{v}_N^{\perp}) , \qquad \boxed{\mathcal{O}_4^N \equiv \boldsymbol{s}_\chi \cdot \boldsymbol{s}_N ,}$$

$$\mathcal{O}_5^N \equiv i\, \boldsymbol{s}_\chi \cdot (\boldsymbol{q} \times \boldsymbol{v}_N^{\perp}) , \qquad \mathcal{O}_6^N \equiv (\boldsymbol{s}_\chi \cdot \boldsymbol{q})(\boldsymbol{s}_N \cdot \boldsymbol{q}) ,$$

$$\mathcal{O}_7^N \equiv \boldsymbol{s}_N \cdot \boldsymbol{v}_N^{\perp} , \qquad \mathcal{O}_8^N \equiv \boldsymbol{s}_\chi \cdot \boldsymbol{v}_N^{\perp} ,$$

$$\mathcal{O}_9^N \equiv i\, \boldsymbol{s}_\chi \cdot (\boldsymbol{s}_N \times \boldsymbol{q}) , \qquad \mathcal{O}_{10}^N \equiv i\, \boldsymbol{s}_N \cdot \boldsymbol{q} ,$$

$$\mathcal{O}_{11}^N \equiv i\, \boldsymbol{s}_\chi \cdot \boldsymbol{q} , \qquad \mathcal{O}_{12}^N \equiv \boldsymbol{v}_N^{\perp} \cdot (\boldsymbol{s}_\chi \times \boldsymbol{s}_N) ,$$

$$\mathcal{O}_{13}^N \equiv i(\boldsymbol{s}_\chi \cdot \boldsymbol{v}_N^{\perp})(\boldsymbol{s}_N \cdot \boldsymbol{q}) , \qquad \mathcal{O}_{14}^N \equiv i(\boldsymbol{s}_\chi \cdot \boldsymbol{q})(\boldsymbol{s}_N \cdot \boldsymbol{v}_N^{\perp}) ,$$

$$\mathcal{O}_{15}^N \equiv (\boldsymbol{s}_\chi \cdot \boldsymbol{q})[\boldsymbol{s}_N \cdot (\boldsymbol{q} \times \boldsymbol{v}_N^{\perp})] , \qquad \mathcal{O}_{16}^N \equiv (\boldsymbol{s}_\chi \cdot \boldsymbol{v}_N^{\perp})(\boldsymbol{s}_N \cdot \boldsymbol{v}_N^{\perp}) ,$$

$$\mathcal{O}_{17}^N \equiv i[\boldsymbol{s}_\chi \cdot (\boldsymbol{q} \times \boldsymbol{v}_N^{\perp})](\boldsymbol{s}_N \cdot \boldsymbol{v}_N^{\perp}) .$$

Physics Potential: EFT Operators

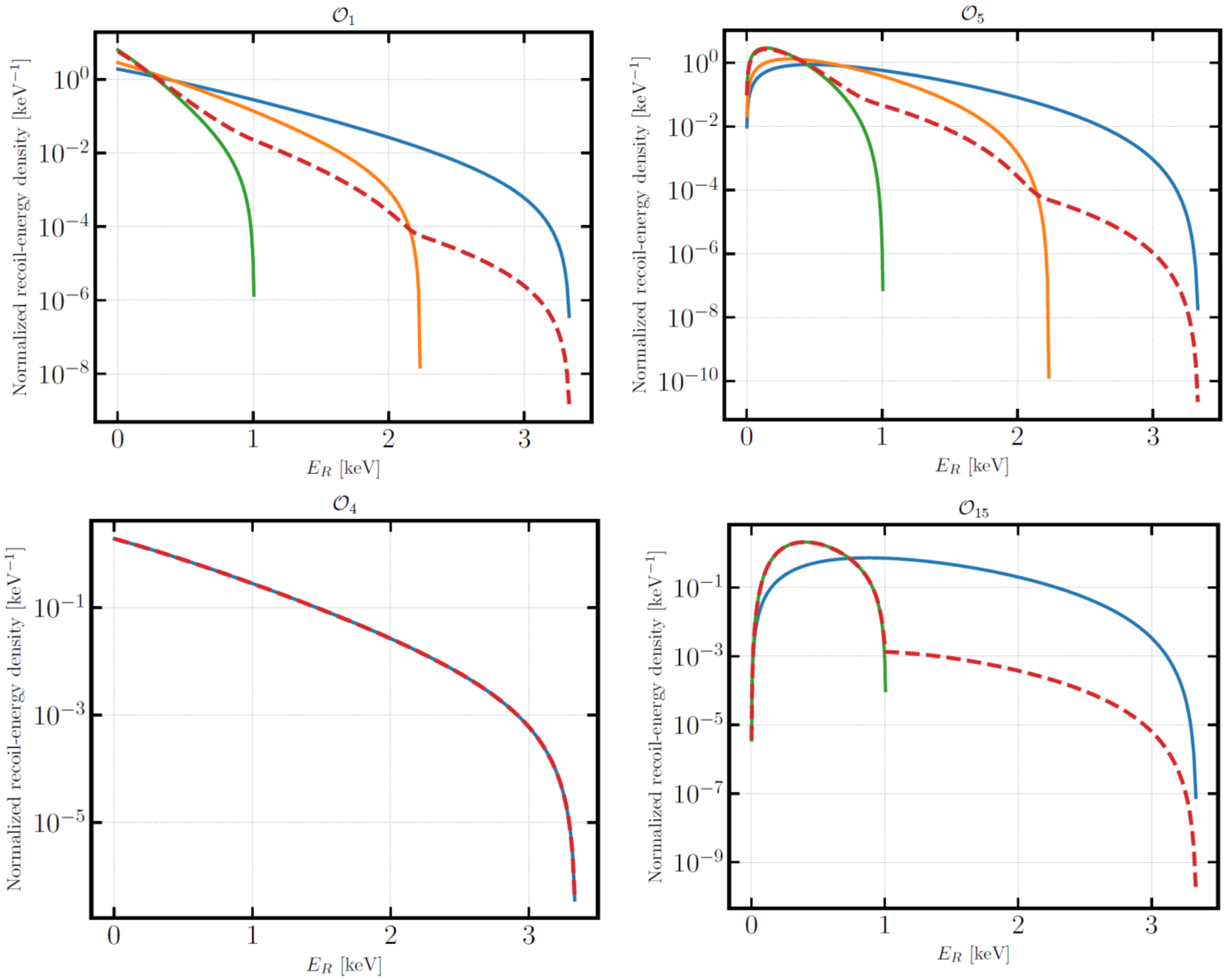
Operators can **strongly modify recoil distributions** from typical provided by O1 and O4
- Enhancement of intermediate energy region
- Enhancement at lower energies in some cases
- Components can drop out depending on $s_{\chi,N}$ dependence

$$\mathcal{O}_1^N \equiv \mathbb{1} \ ,$$

$$\mathcal{O}_4^N \equiv \boldsymbol{s}_\chi \cdot \boldsymbol{s}_N \ ,$$

$$\mathcal{O}_5^N \equiv i\, \boldsymbol{s}_\chi \cdot (\boldsymbol{q} \times \boldsymbol{v}_N^\perp) \ ,$$

$$\mathcal{O}_{15}^N \equiv (\boldsymbol{s}_\chi \cdot \boldsymbol{q})[\boldsymbol{s}_N \cdot (\boldsymbol{q} \times \boldsymbol{v}_N^\perp)] \ ,$$



Physics Potential: EFT Operators

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Physics potential **(projected limits) compared to DEAP-3600:**

- **Approx. equivalent sensitivity, but in lighter unexplored regime**
- Broadly constrained by O1 sensitivity
- Sensitivity **order of some operators are changed/reversed**
- Sensitivities on par

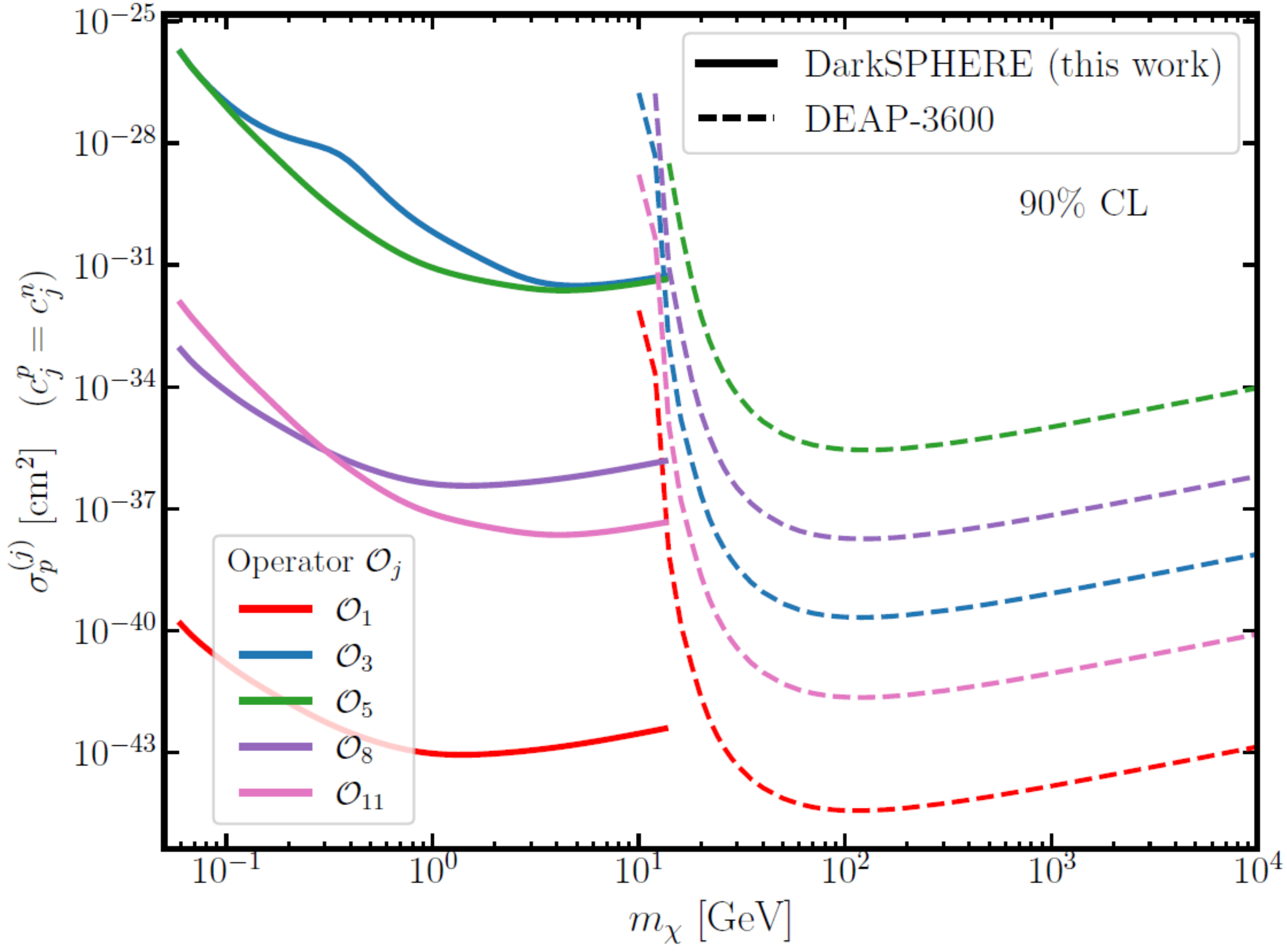
$$\mathcal{O}_1^N \equiv \mathbb{1} \ ,$$

$$\mathcal{O}_3^N \equiv i\, \boldsymbol{s}_N \cdot (\boldsymbol{q} \times \boldsymbol{v}_N^\perp) \ ,$$

$$\mathcal{O}_5^N \equiv i\, \boldsymbol{s}_\chi \cdot (\boldsymbol{q} \times \boldsymbol{v}_N^\perp) \ ,$$

$$\mathcal{O}_8^N \equiv \boldsymbol{s}_\chi \cdot \boldsymbol{v}_N^\perp \ ,$$

$$\mathcal{O}_{11}^N \equiv i\, \boldsymbol{s}_\chi \cdot \boldsymbol{q} \ ,$$



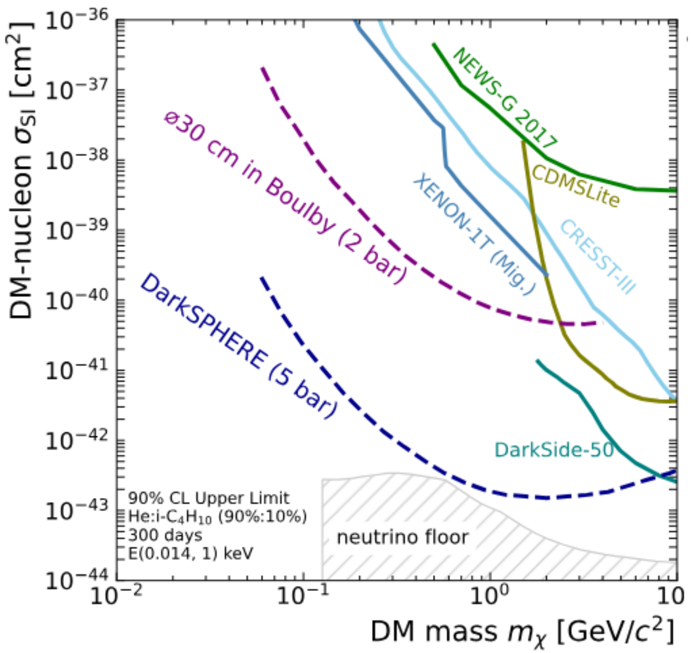
Summary

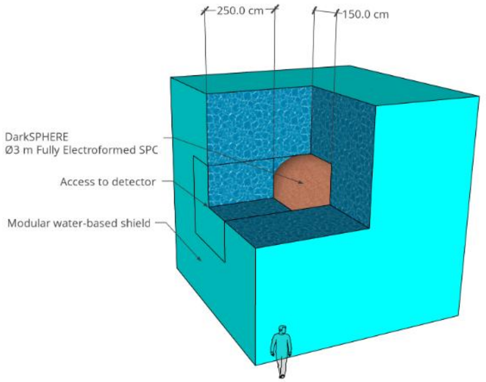
Light DM mass range largely unexplored – spherical proportional counters well-suited to explore this region

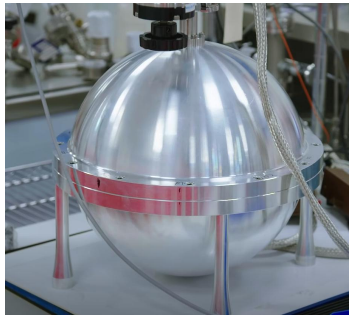
DarkSPHERE is proposed as a future detector that will reduce key backgrounds dominant in current SPCs
- Fully electroformed
- Constructed underground
- Pure water-based shielding

Converging towards a **ø30 cm fully electroformed detector (DarkSPHERE-30)**
- Electroforming of sphere planned for this year
- Underground performance of SPC in Boulby being studied

Potential of DarkSPHERE assessed **assuming different EFT operators**
- **Potential on par with that seen in DEAP-3600** but for lighter unexplored regime







Backups

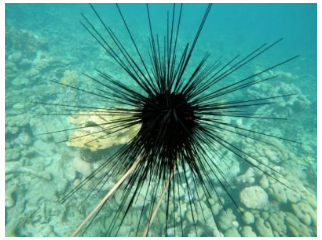
Achinos Sensor

Increased DM sensitivity comes from **increased exposure** via:

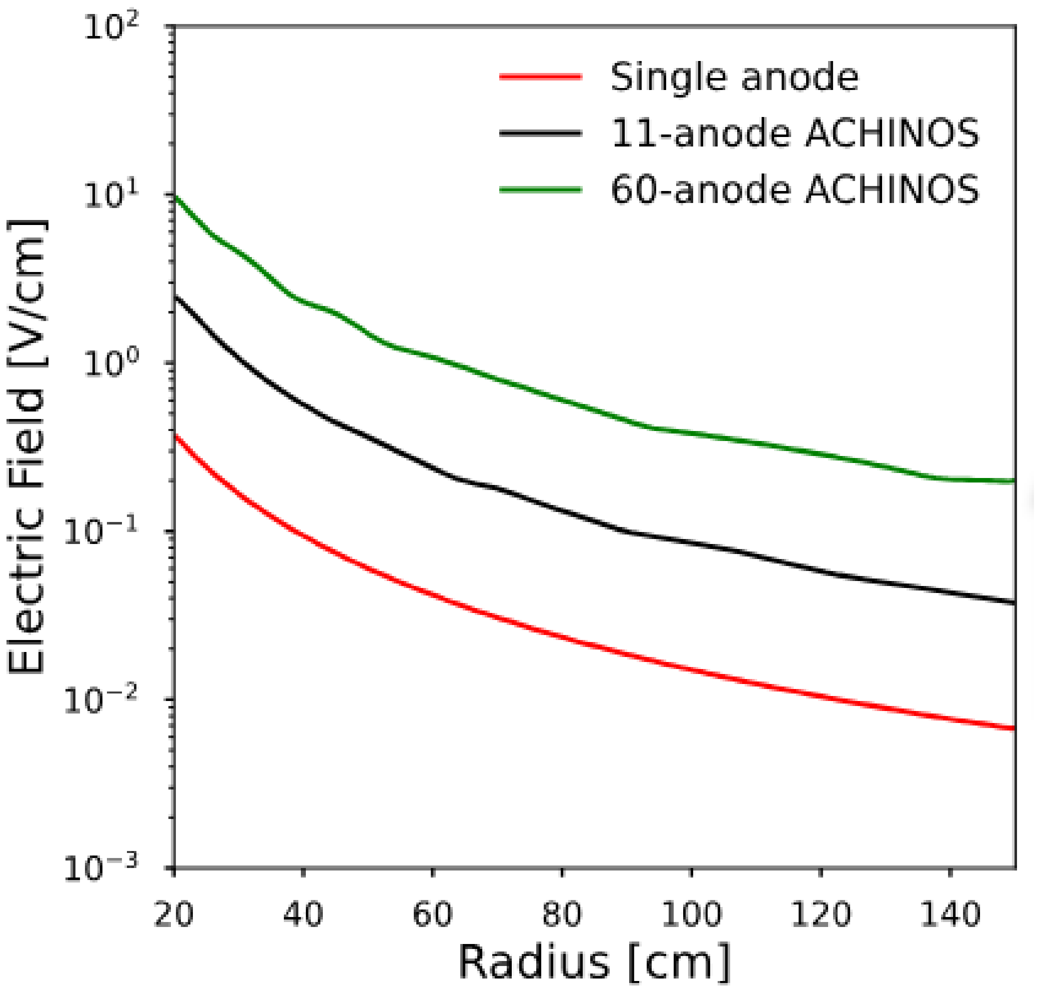
- Increased **pressure**
- Increase **volume**

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



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Pure Alloys Project

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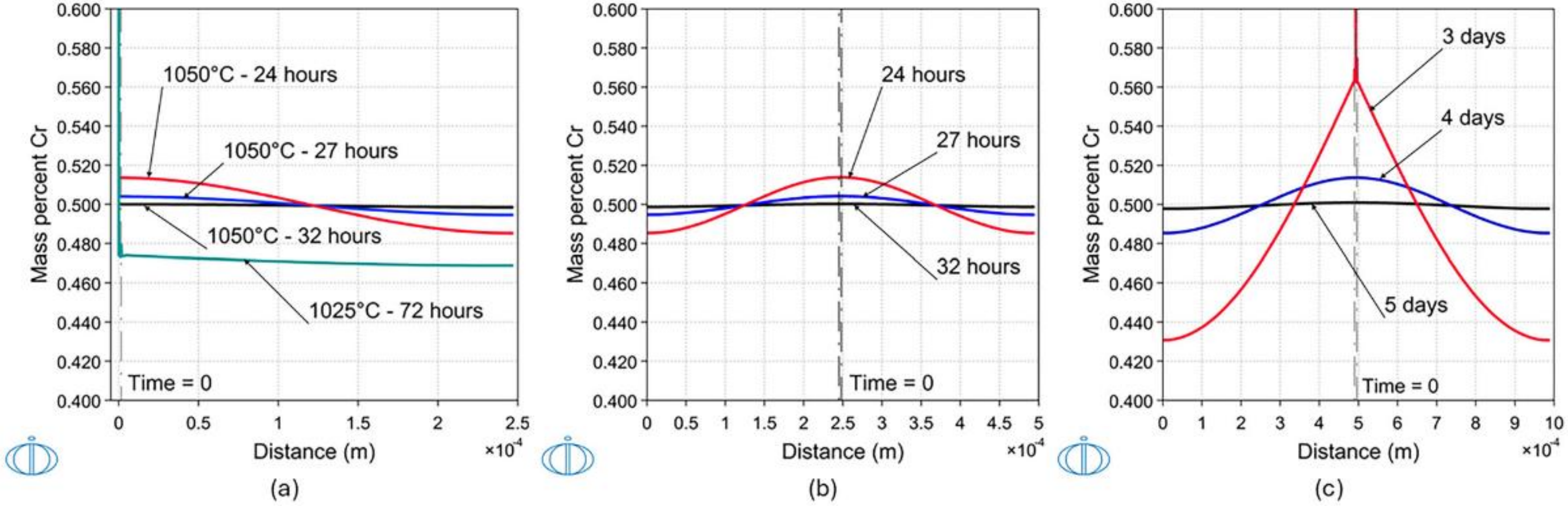
See also **pure alloys project:** Improving **mechanical performance** of EFCu w/ **CuCr alloys**!
- D. Spathara NIMA (2026)
- D. Spathara arXiv:2509.07406

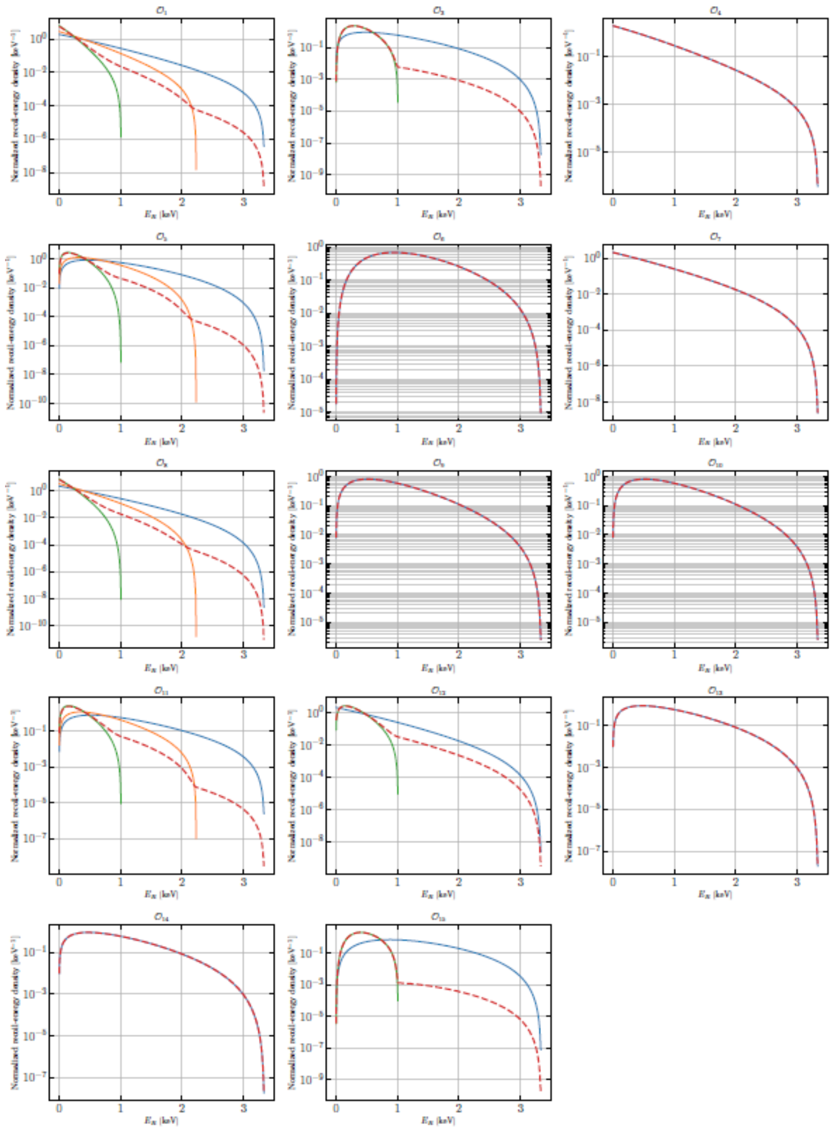
Layer	Thickness			
Configuration	Cr layer (μm)	Cu layer (μm)	Alloy (μm)	Time
Single-sided	1.5	245	246.5	32 h
Double-sided	3	245	493	32 h
Double-sided	6	490	986	5 d

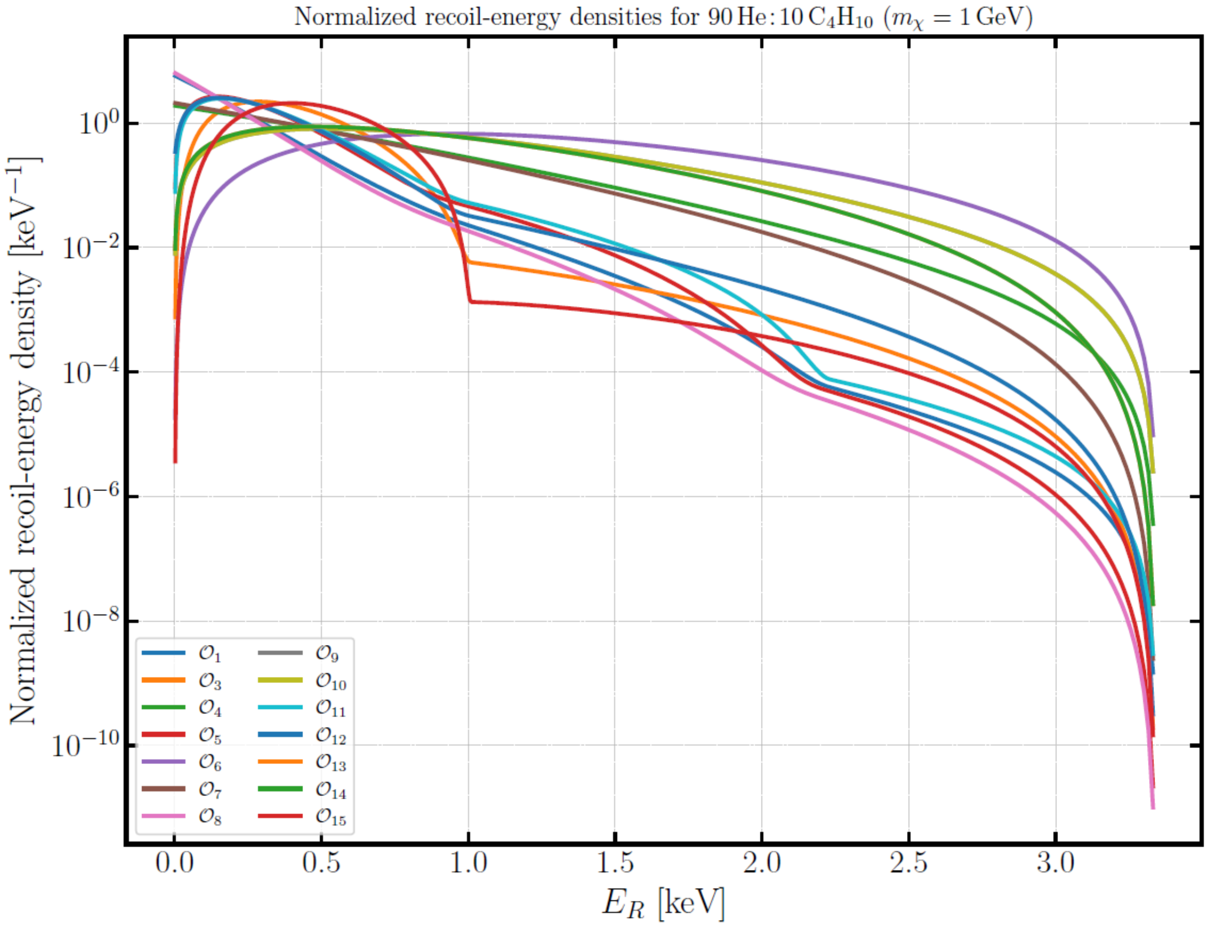
Requires novel materials design to optimize alloy composition
- e.g. Alloy profile impacts material properties
- Layer thickness and specifics of heat treatment impacts alloy profile



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

Note: from simulations





$$\sigma_{\mathrm{SD}}^{N} = \frac{3\mu_N^2}{16\pi}\left(c_4^N\right)^2$$

$$\sigma_{\mathrm{SI}}^{N} = \frac{\mu_N^2}{\pi}\left(c_1^N\right)^2$$

Underground Performance

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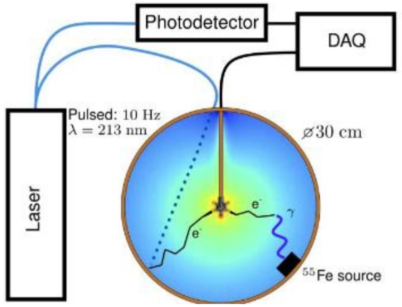
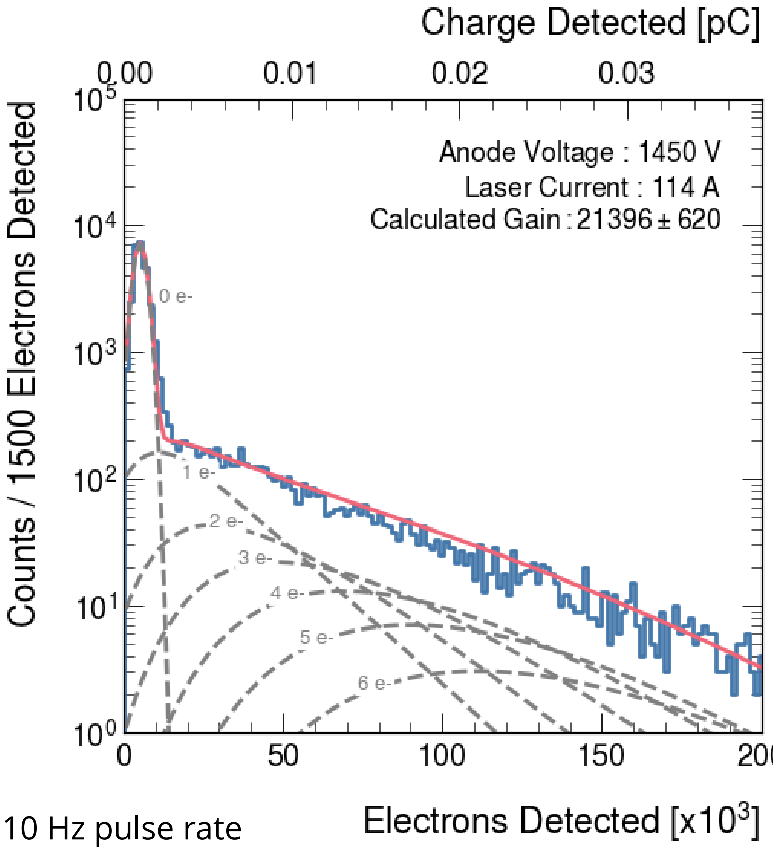
R&D SPC currently underground in Boulby
- **Goal:** assess performance of SPC in underground environment
- **Aim:** Achieve single electron sensitivity underground

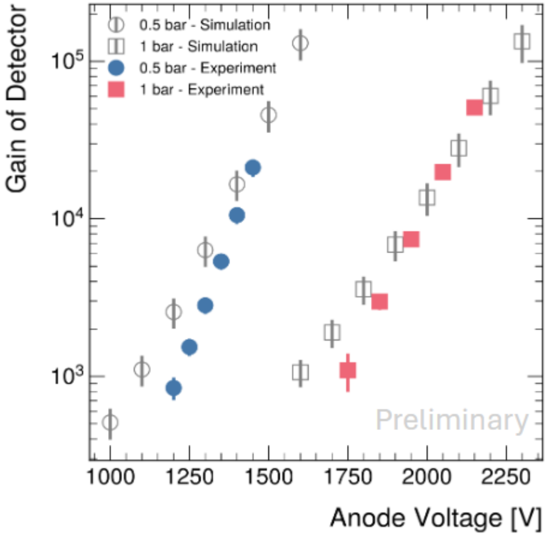
Plan: Utilise 213 nm UV laser system currently used for gas property studies

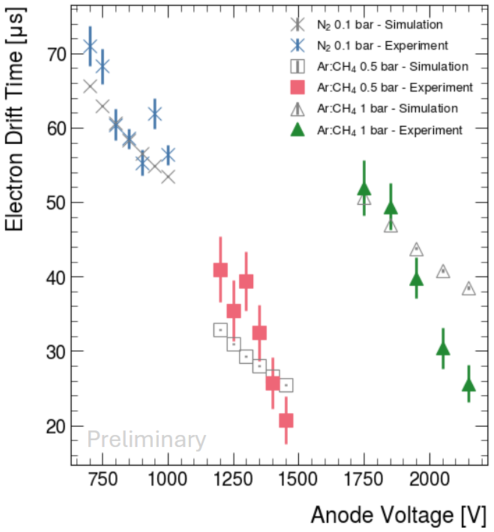
Demonstration for future use as in-situ monitoring of gas properties



Performed using methods outlined in: [NEWS-G, Phys. Rev. D 99, 102003]







UV laser, 213 nm, 10 Hz pulse rate