Light Dark Matter searches with a next generation Spherical Proportional Counter

Ioannis Manthos

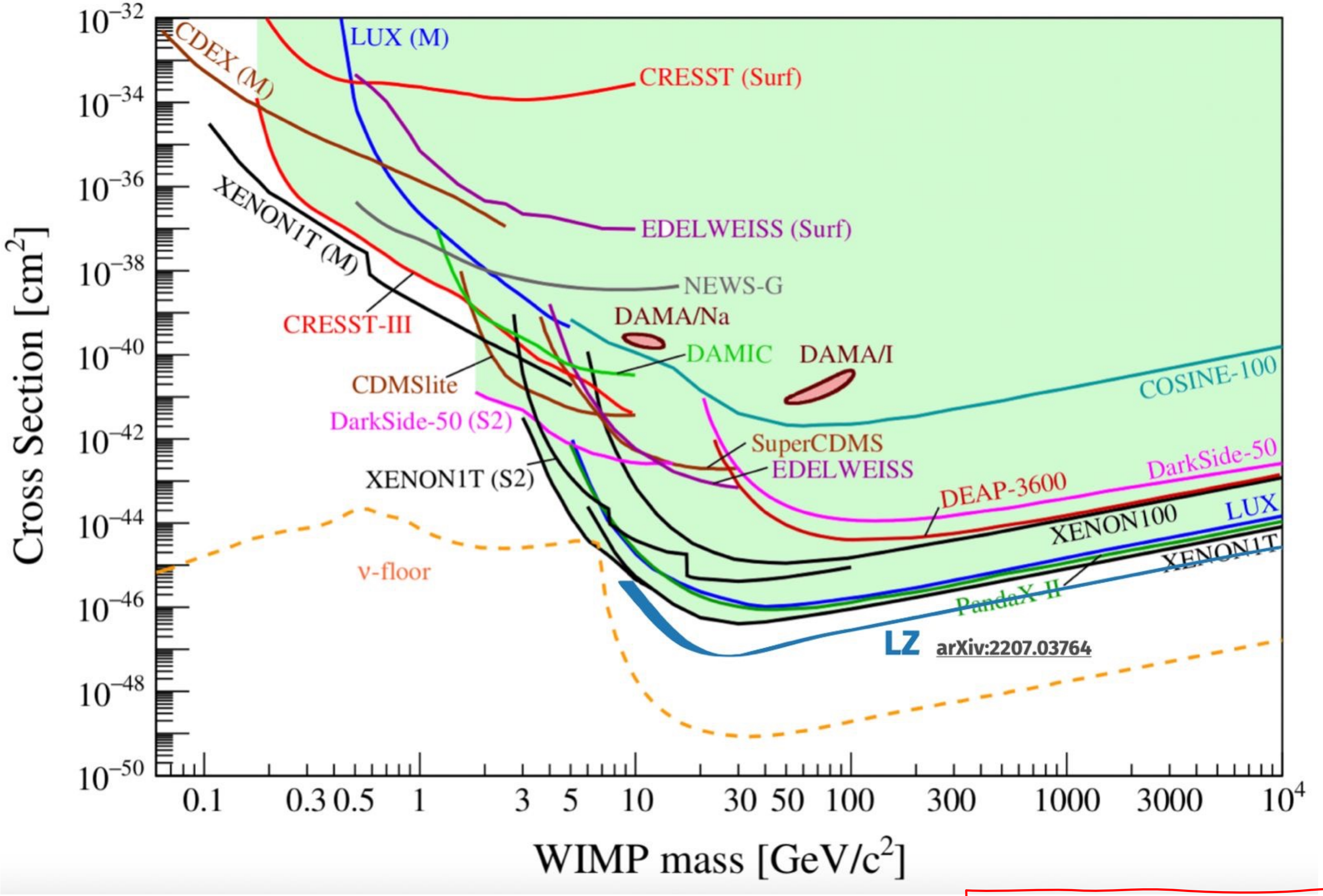
University of Hamburg

on behalf of the NEWS-G collaboration

15th International Workshop on the Identification of Dark Matter 2024

8-12 July 2024, L`Aquila (Italy)

Landscape of Direct Dark Matter searches



Rep. Prog. Phys. 85 (2022) 056201

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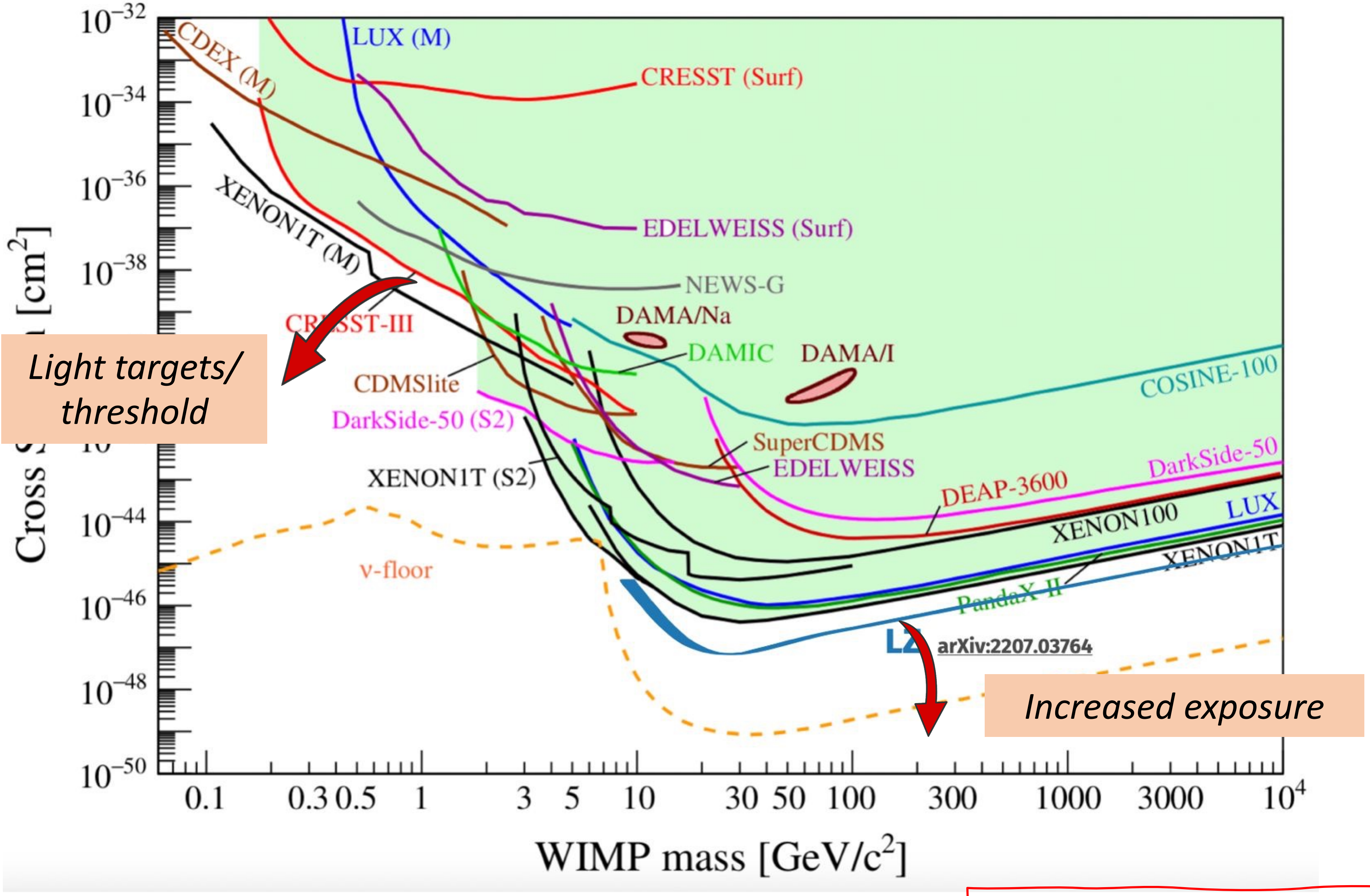

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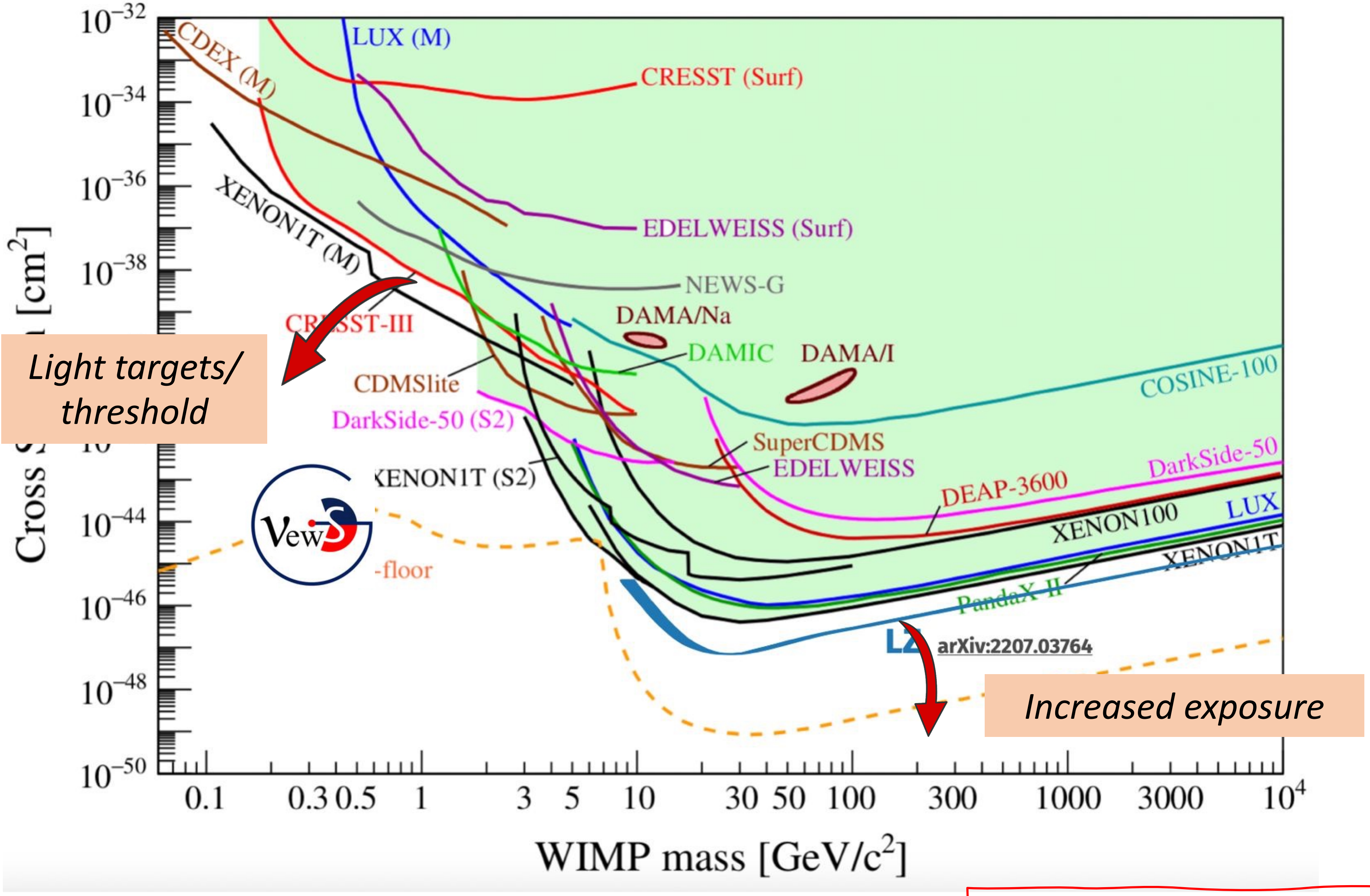

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The NEWS-G collaboration

Light DM searches with a novel gaseous detector, the spherical proportional counter

***N**ew **E**xperiments with **S**pheres - **G**as*

- **11 institutes**
- **~40 collaborators**
- **6 countries**
- **3 underground laboratories**

cea

UNIVERSITY OF BIRMINGHAM

TRIUMF

Subatech

ARISTOTLE UNIVERSITY OF THESSALONIKI

LPSC Grenoble

Queen's UNIVERSITY

UHH Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG

RMC CMR

UNIVERSITY OF ALBERTA

Pacific Northwest NATIONAL LABORATORY

SNOLAB

UKRI Science and Technology Facilities Council

Boulby Underground Laboratory

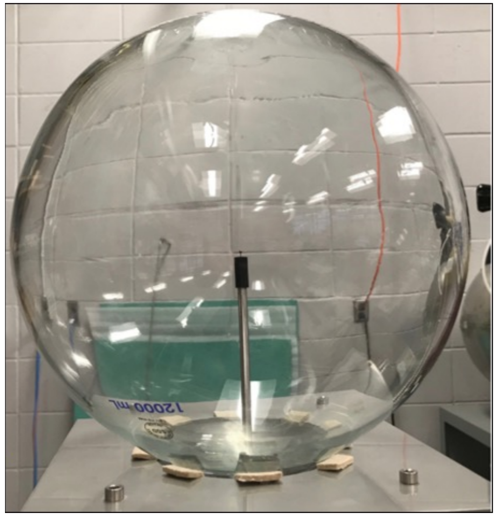
The Spherical Proportional Counter

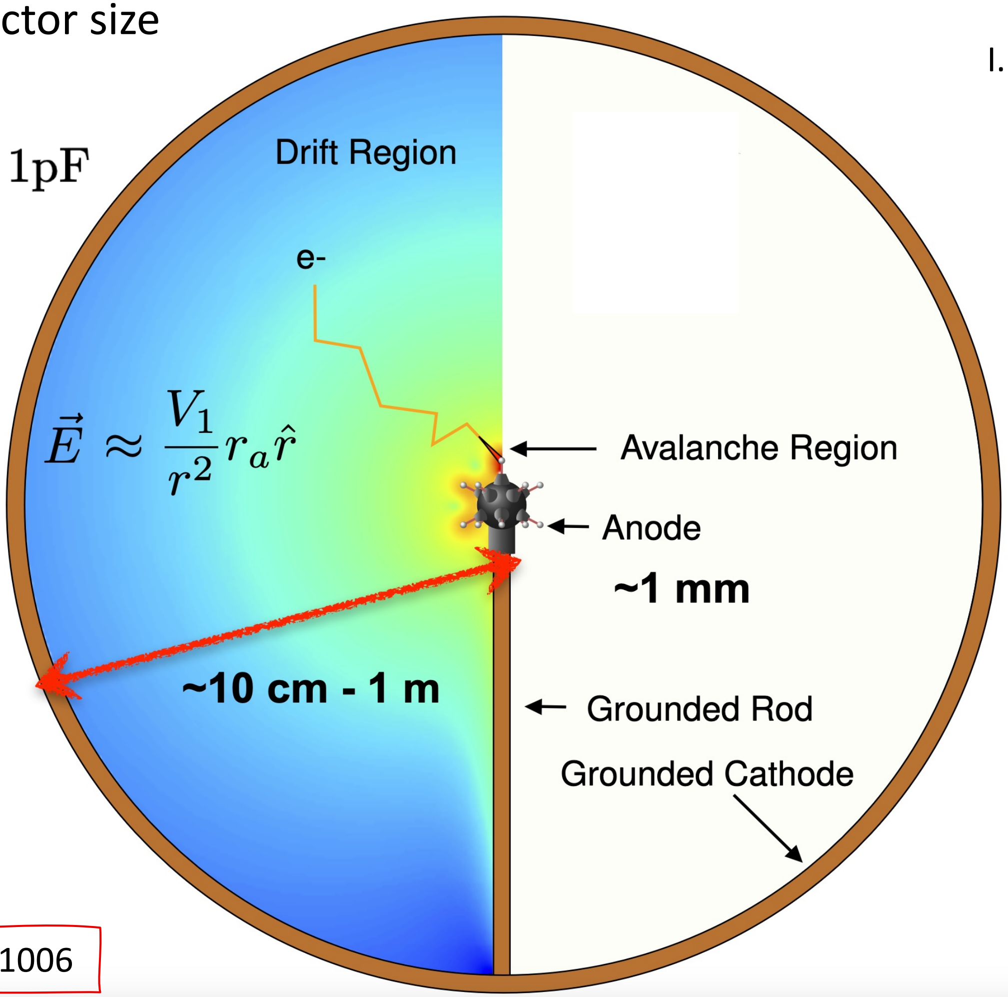
Electric field scales as $1/r^2$
- Divided into "drift" and "amplification" regions

Capacitance independent of detector size
- Low electronic noise

$$C = 4\pi\varepsilon_0 \frac{r_c r_a}{r_c - r_a} \approx 4\pi\varepsilon_0 r_a \sim 1\text{pF}$$

r_c = cathode radius
r_a = anode radius





I. Giomataris and G. Charpak with the SPC prototype

JINST 3 (2008) P09007, JINST 13 (2018) P11006

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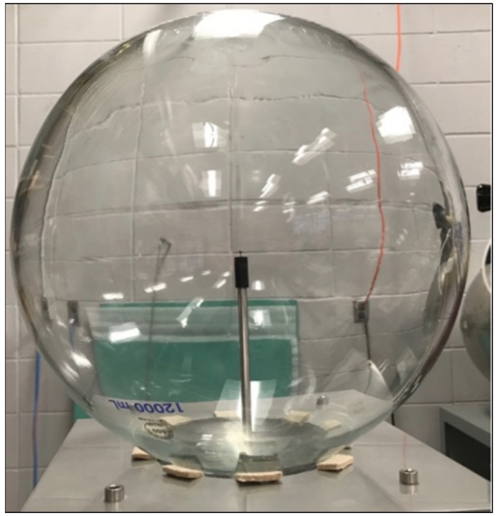
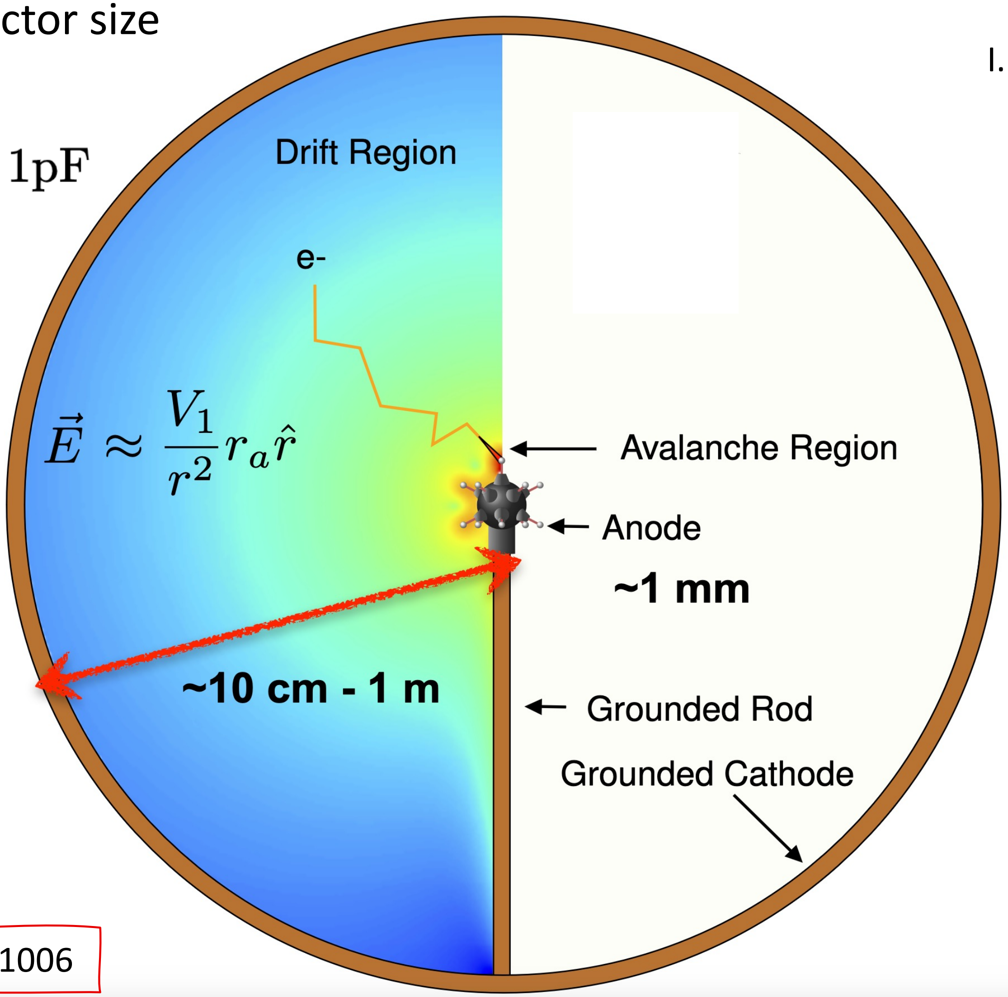


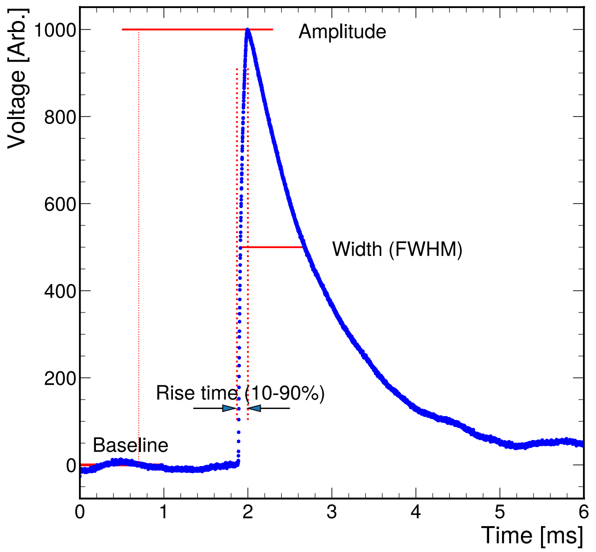


JINST 3 (2008) P09007, JINST 13 (2018) P11006

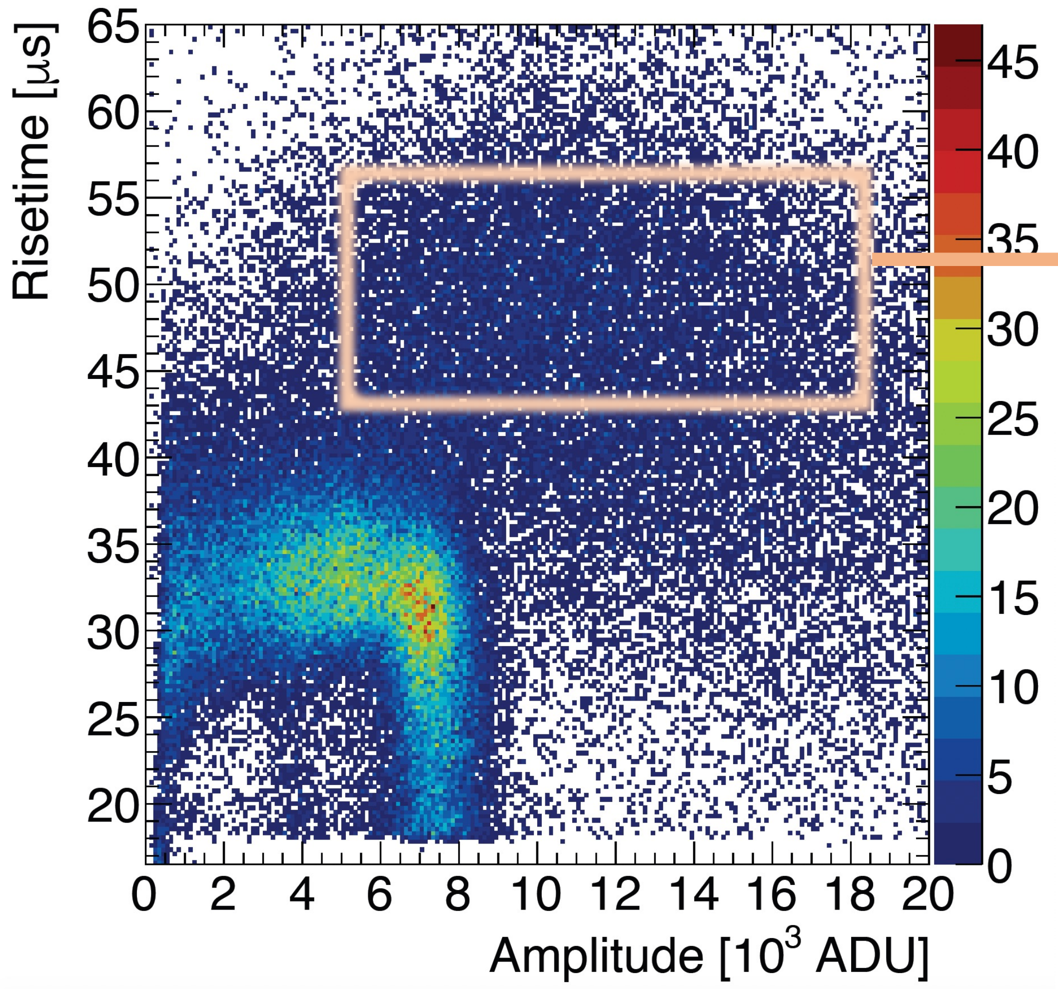
Strengths of SPC

- ✓ Low capacitance - Single e⁻ detection
- ✓ Maximum volume-to-surface ratio
- ✓ Flexibility in target gas and pressures
- ✓ Simple, few-channel read-out
- ✓ Fiducialisation
- ✓ Radiopure construction
- ✓ Bonus: Applications beyond DM (e.g. n-spectroscopy)

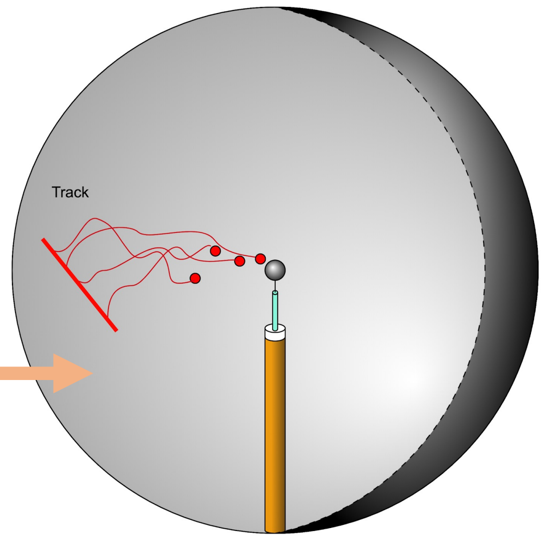
Pulse Shape Discrimination



Use pulse shape parameters to differentiate events



‘muon’-like events



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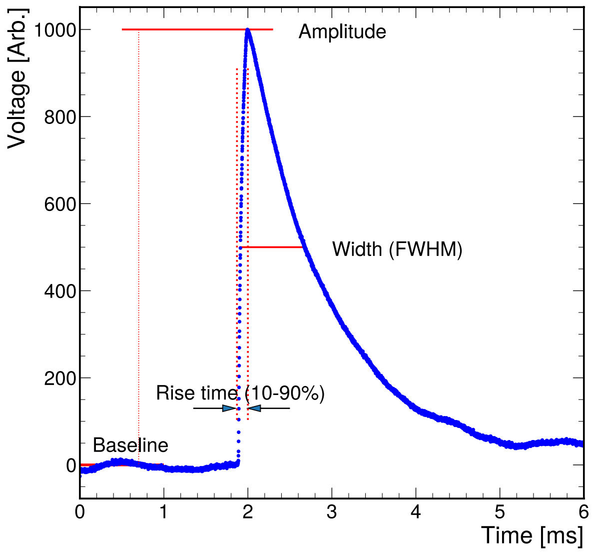

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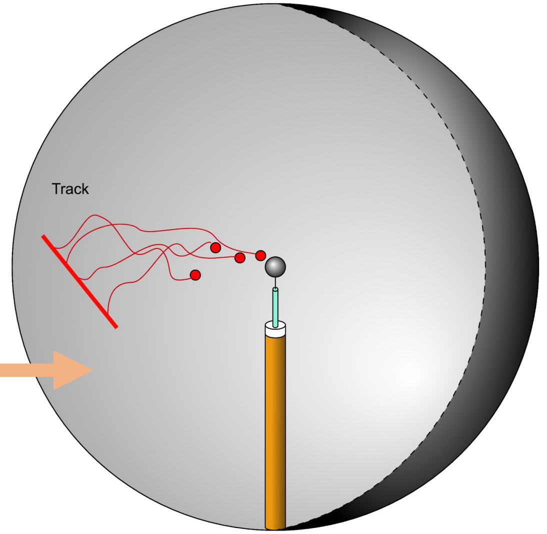

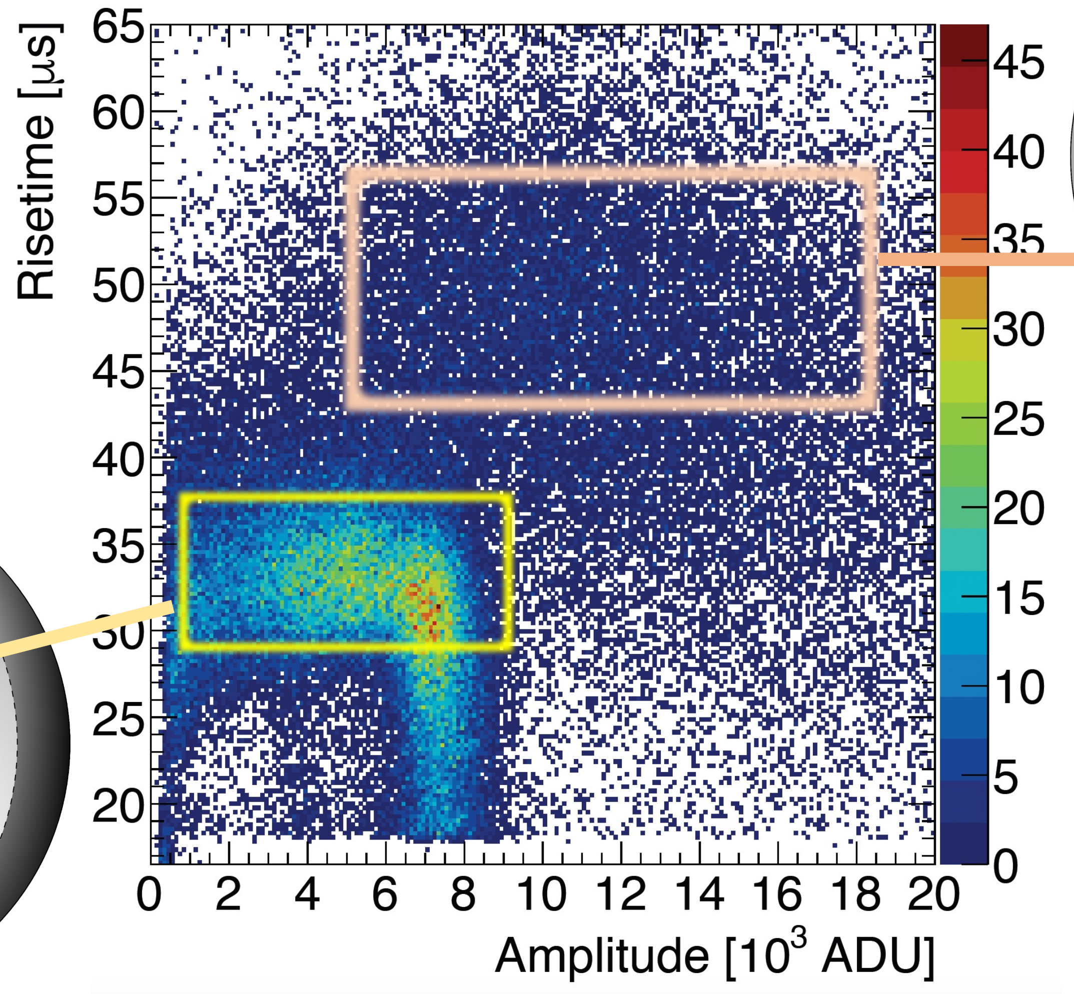

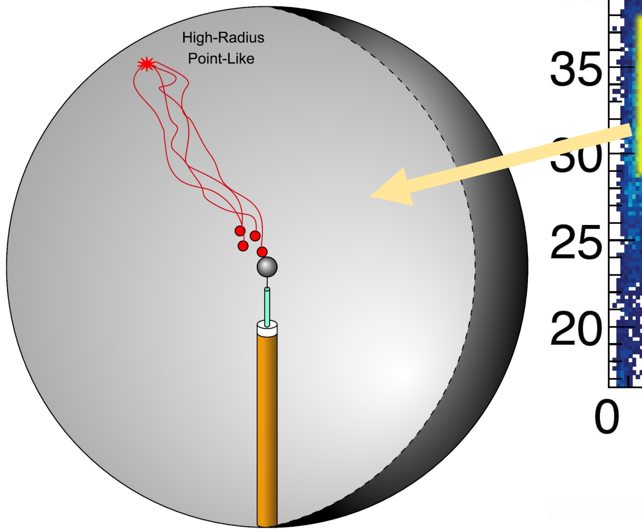

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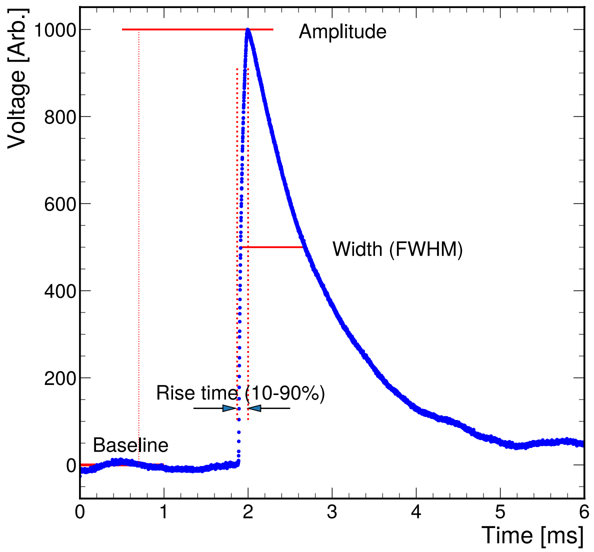

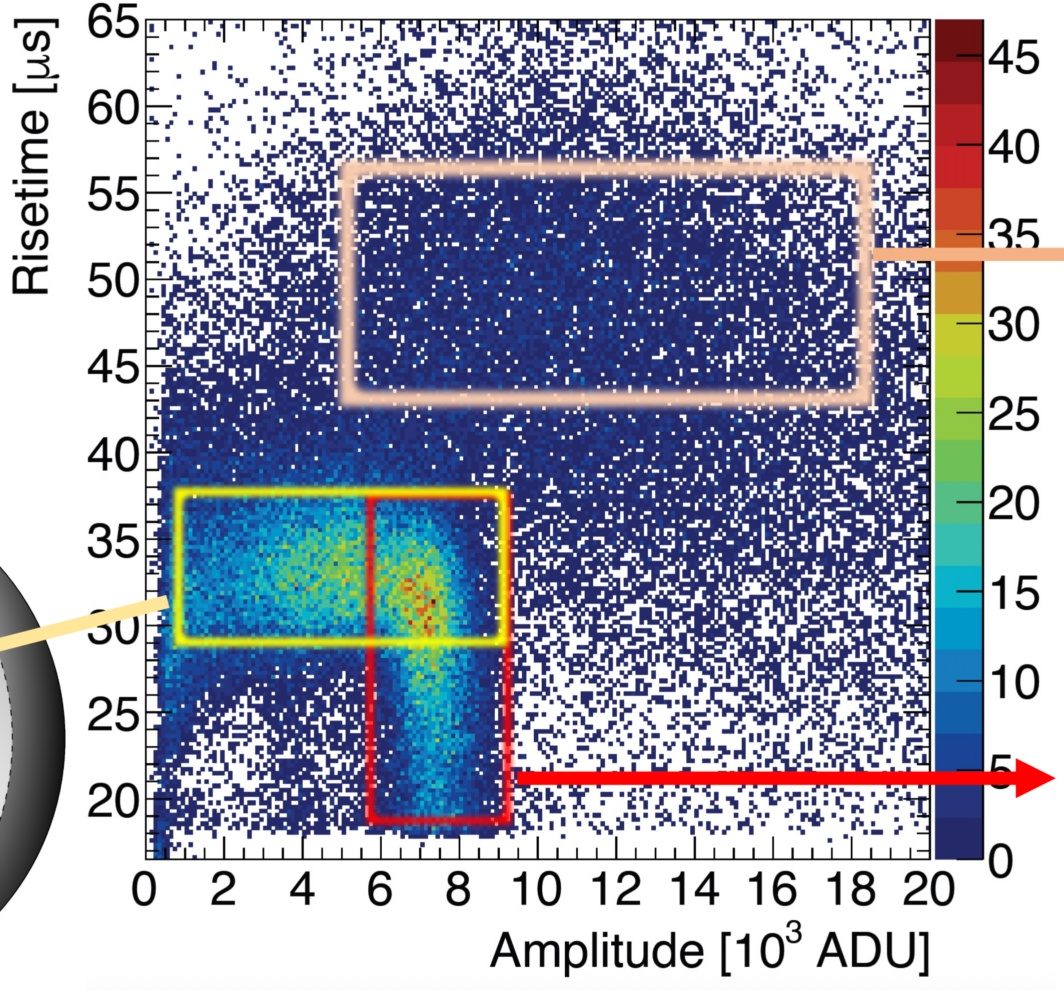

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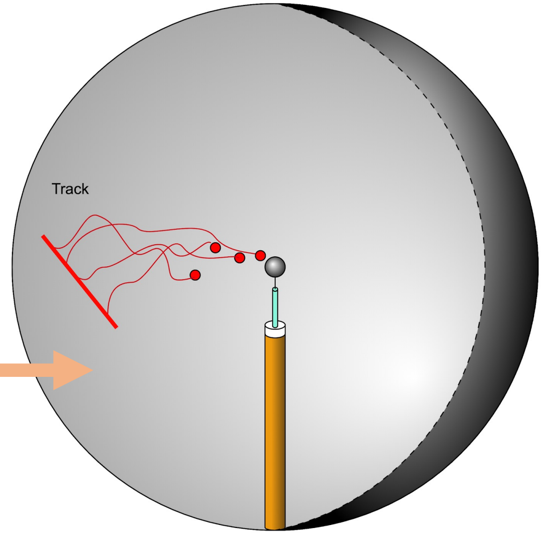
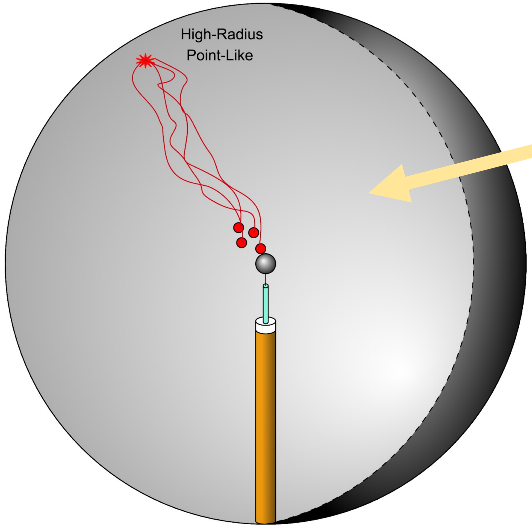
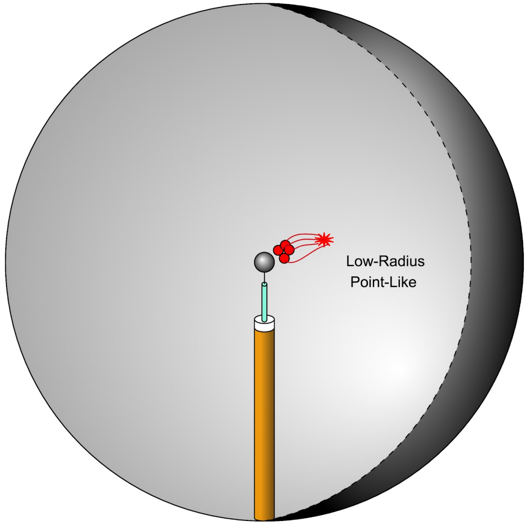
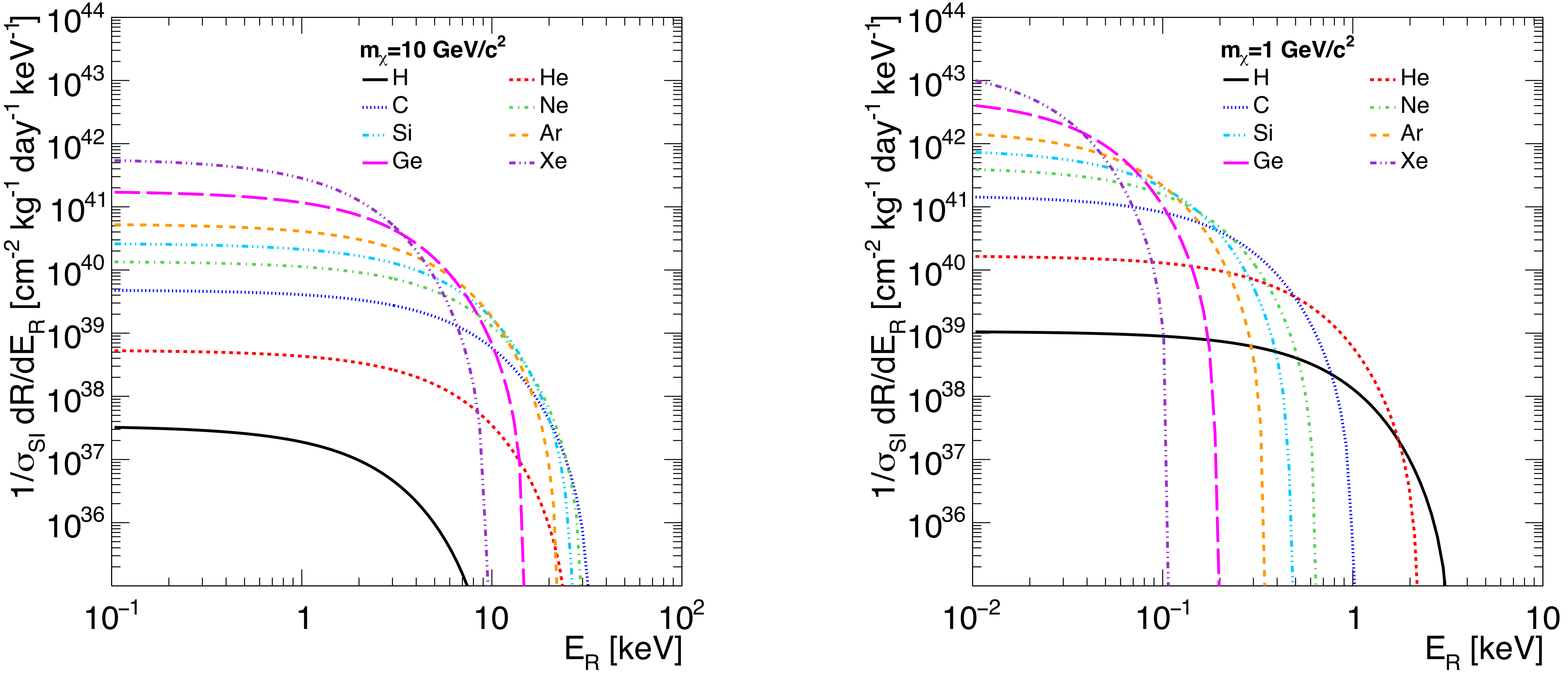






Light Dark Matter Detection - Kinematics

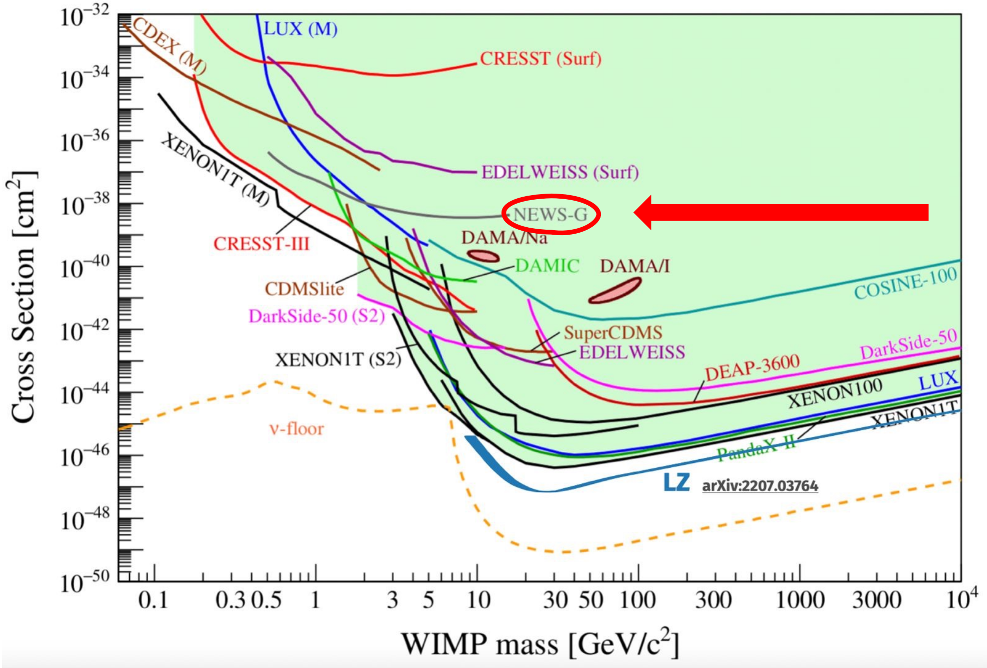


- Low-mass targets are favourable for light-DM detection by nuclear recoils
- Requirement for low energy thresholds to see recoil energy

First NEWS-G Detector - SEDINE

- **First NEWS-G results** in 2018: Ø60 cm prototype in LSM, France
- Ne:CH_4 (99.3%:0.7%) **9.6 kg day exposure**
- **Strongest SI limit at time (2017)** on 0.5 GeV candidate

Astropart.Phys. 97 (2018) 54-62



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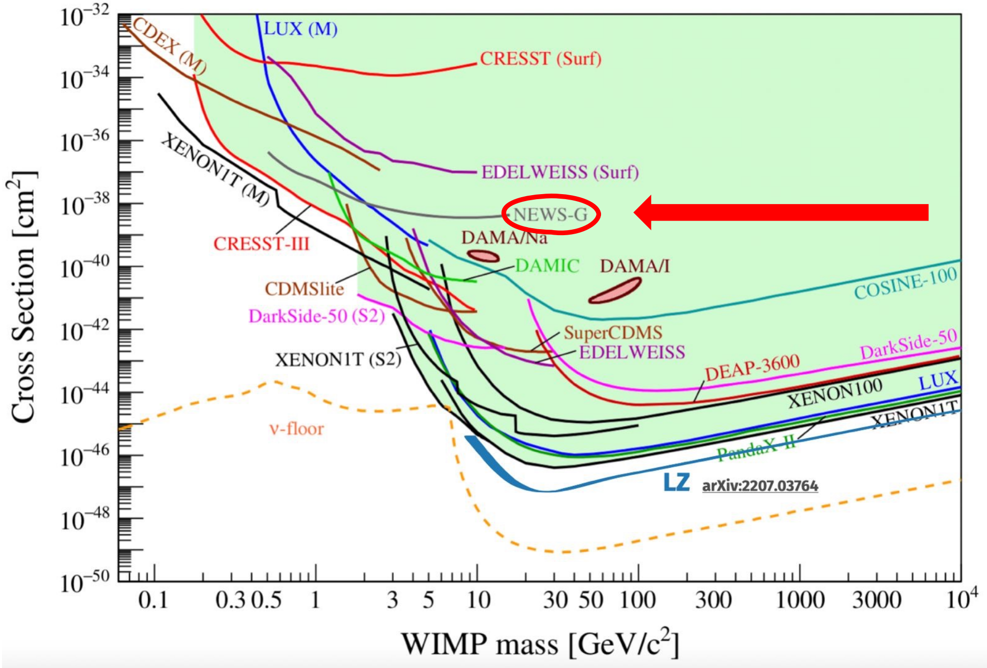


But where next?

Development in instrumentation, detector physics, and detector simulation were required for next generation of NEWS-G

Multianode read-out with the ACHINOS sensor

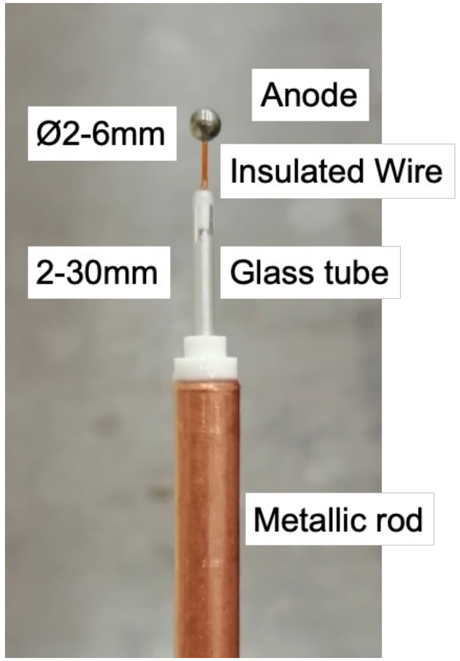
Single anode: Drift and Amplification fields are connected → depends on anode radius

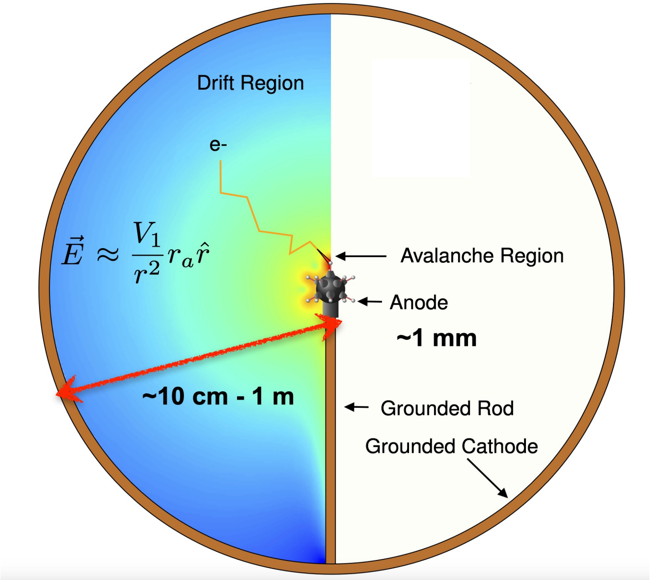
$$\vec{E} = \frac{V_1}{r^2}\frac{r_c r_a}{r_c - r_a}\hat{r} \approx \frac{V_1}{r^2} r_a$$

Challenge:

High voltage→ Discharges (sparking) on avalanche region

Low field → e^- - ion recombination on drift region





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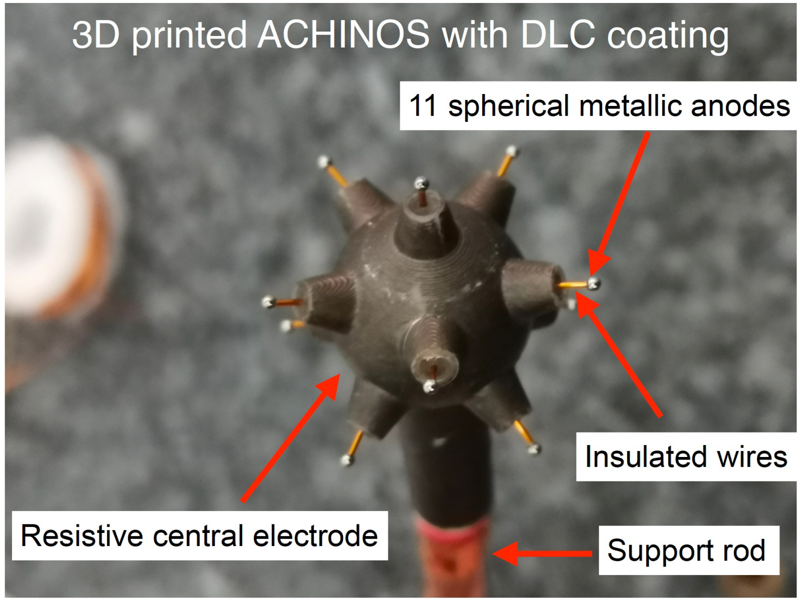

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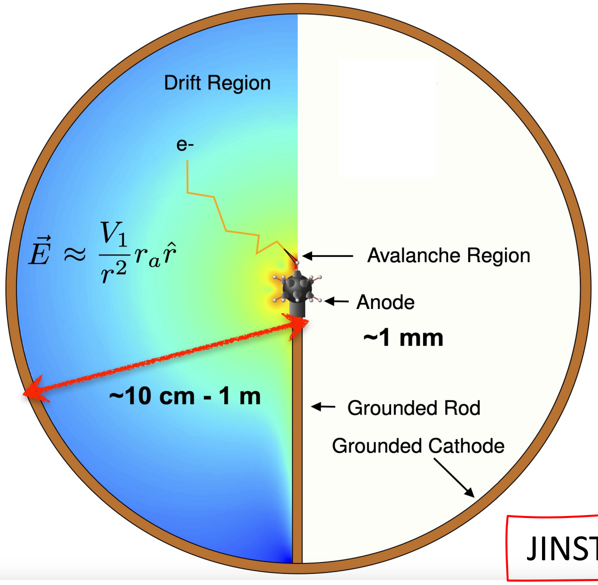
Solution:

ACHINOS multi-anode sensor



ACHINOS multi-anode sensor

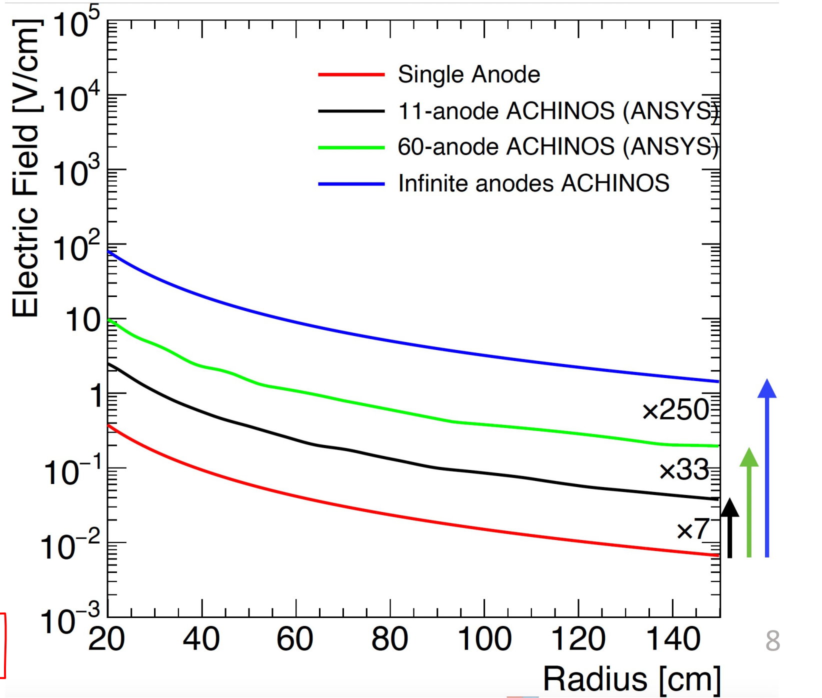
- Multiple anodes placed at equal radii
- Sensors with 5, 11, 33 anodes operated
- Decoupling drift and amplification fields

✓ Allows for increased target mass

✓ Individual anode read-out

✓ TPC-like capabilities

JINST 15 (2020) P11023, JINST 17 (2022) C08025, JINST 19 (2024) P01018



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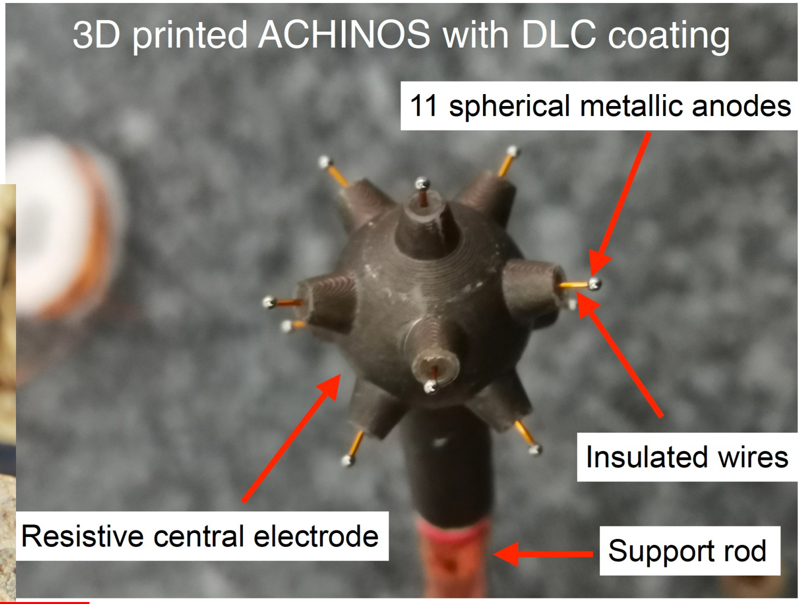

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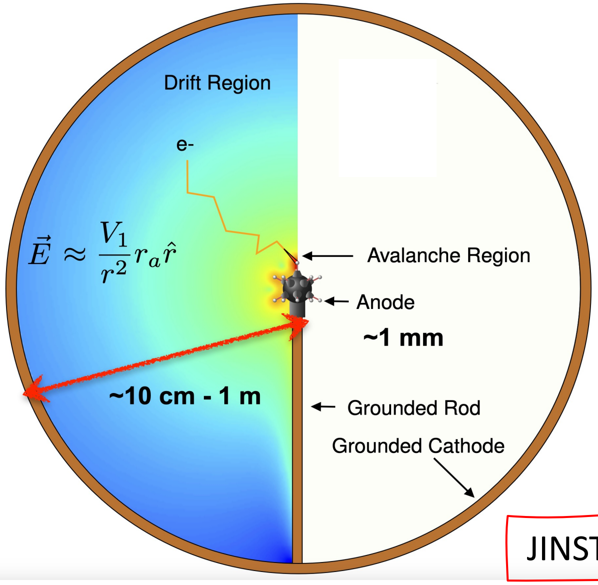
Αχινός (Greek - sea urchin)



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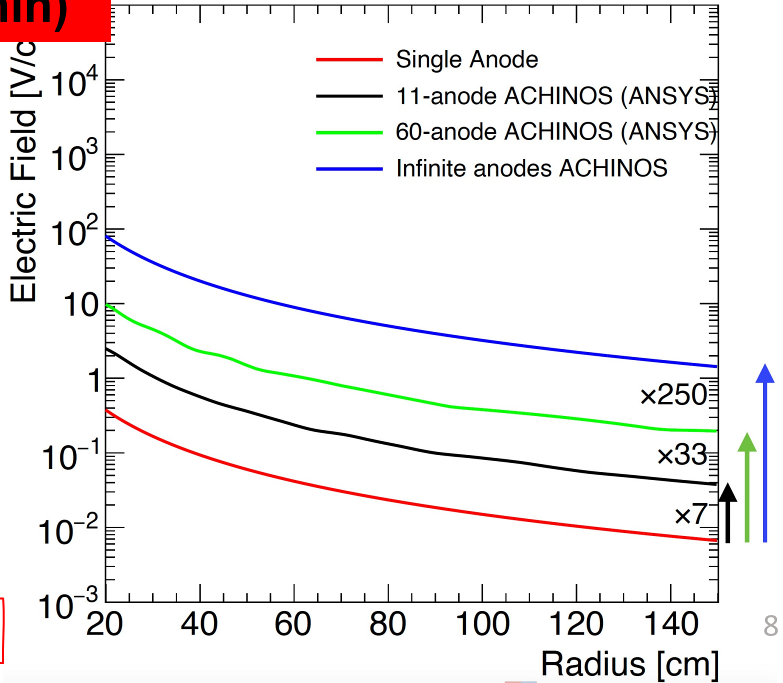


JINST 15 (2020) P11023, JINST 17 (2022) C08025, JINST 19 (2024) P01018

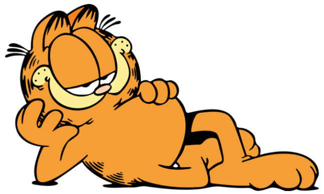
SPC simulation framework

SPC simulation framework for complete simulation of a detection setup

- **GEANT4** for particle transport in a geometry and their interaction with materials

- FEM simulation (**ANSYS, COMSOL**) of electromagnetic fields

- **Garfield++** for the generation, drift and multiplication of primary electrons and signal generation



JINST **15** (2020) C06013

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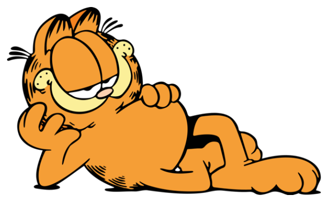
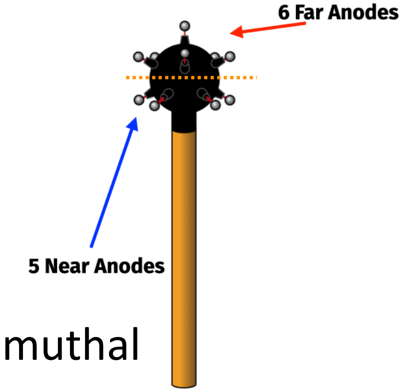
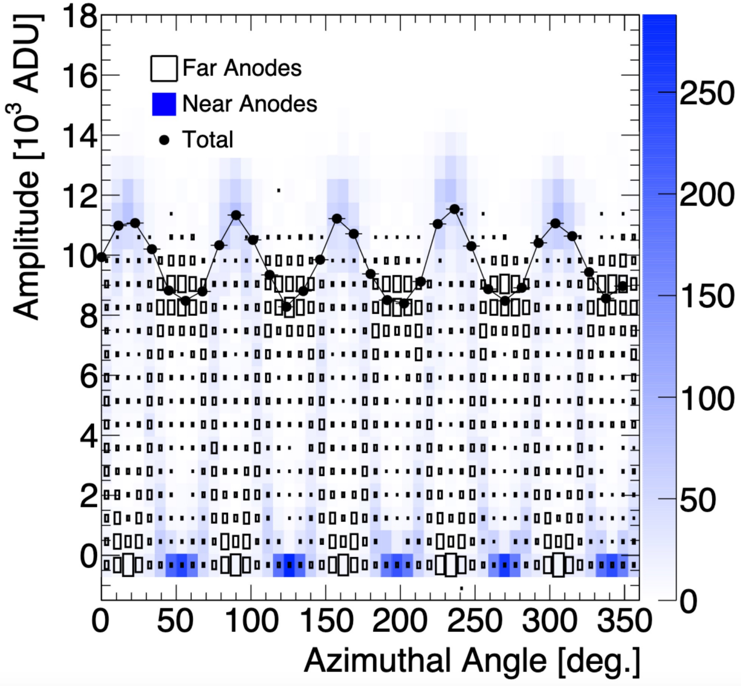


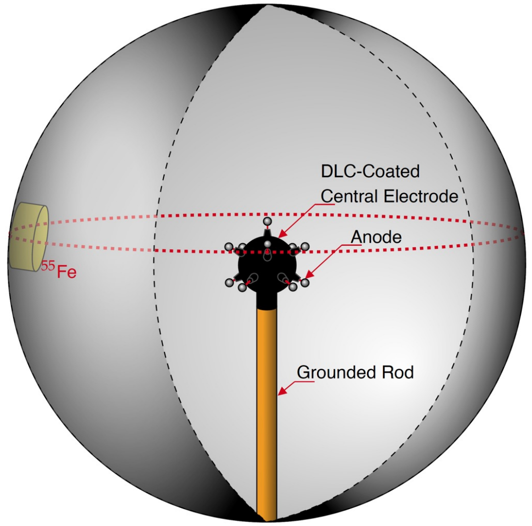
JINST **15** (2020) C06013

<u>Simulation has advanced SPC R&D</u>

- Early ACHINOS read out anodes in 2 groups (6 Far – 5 Near)
- Experimentally observed **amplitude dependence** on source azimuthal position
- Investigated with simulation







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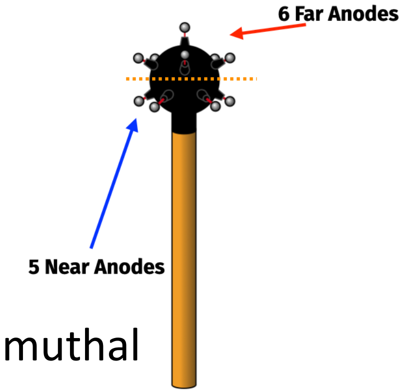

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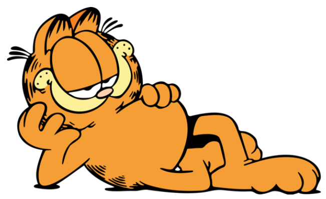

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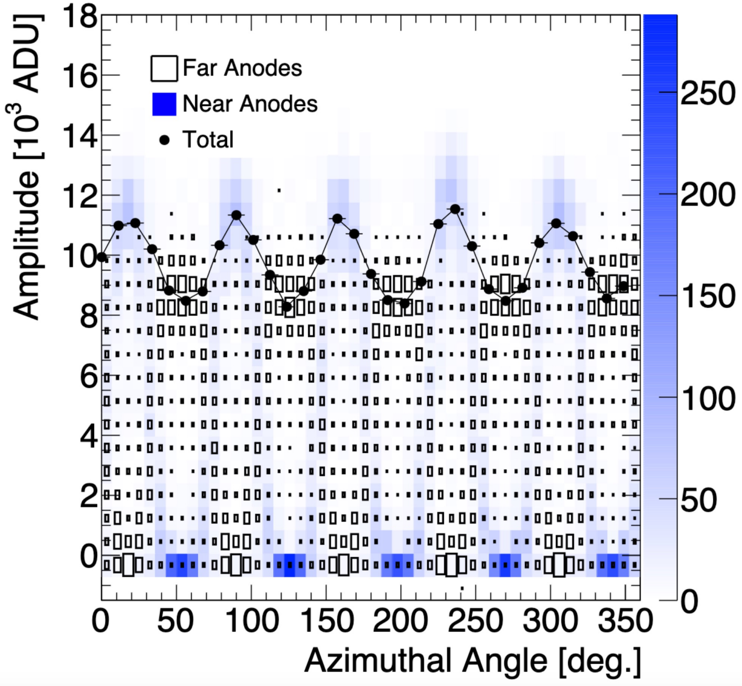
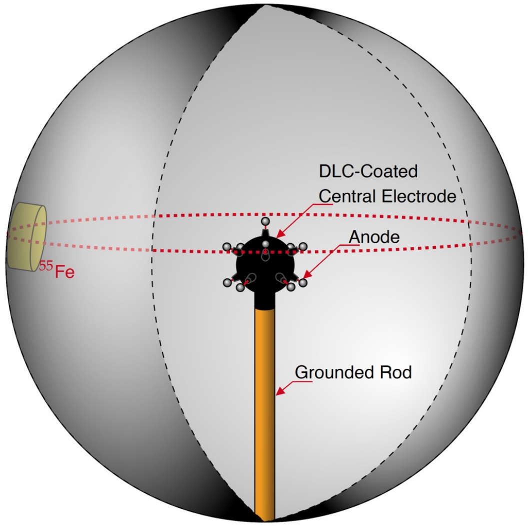
- Signal **higher on Near anode than Far: Electric field higher** due to rod
- Effect corrected by increasing voltage applied on Far anodes
- Now standard practise for bias on 2-channels ACHINOS

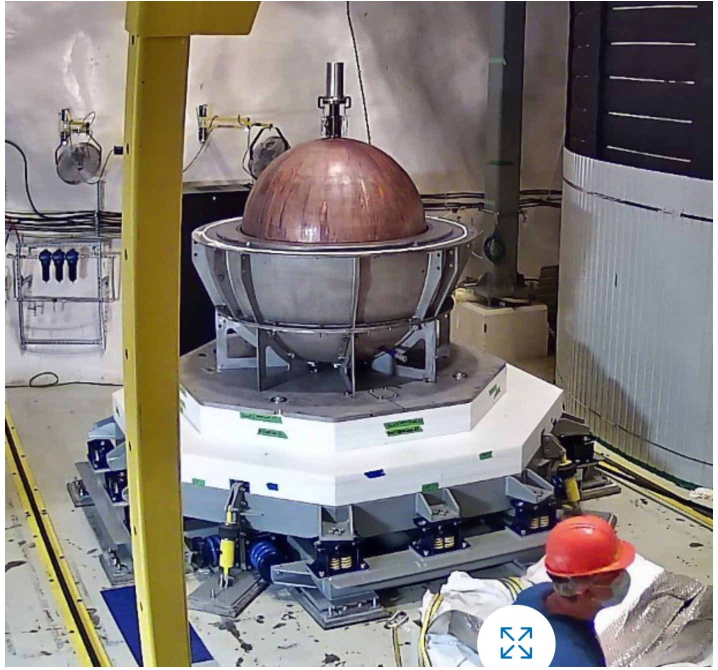


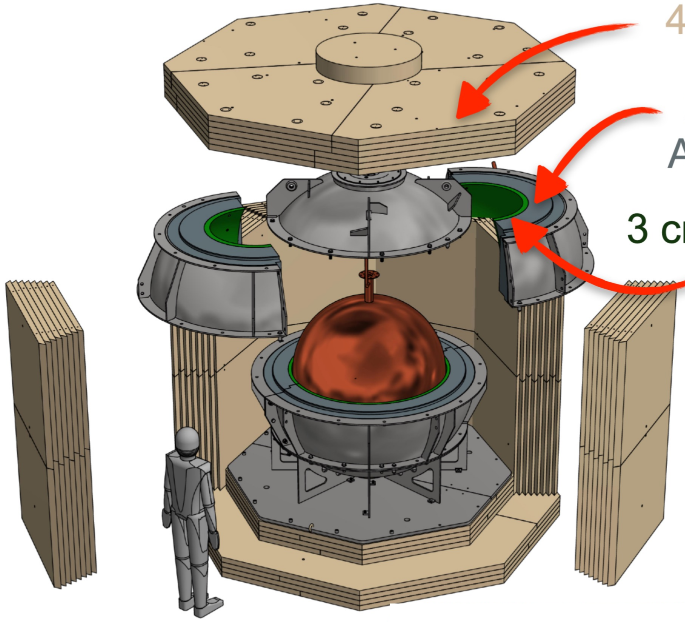


Light Dark Matter Searches with the SPC in SNOLAB

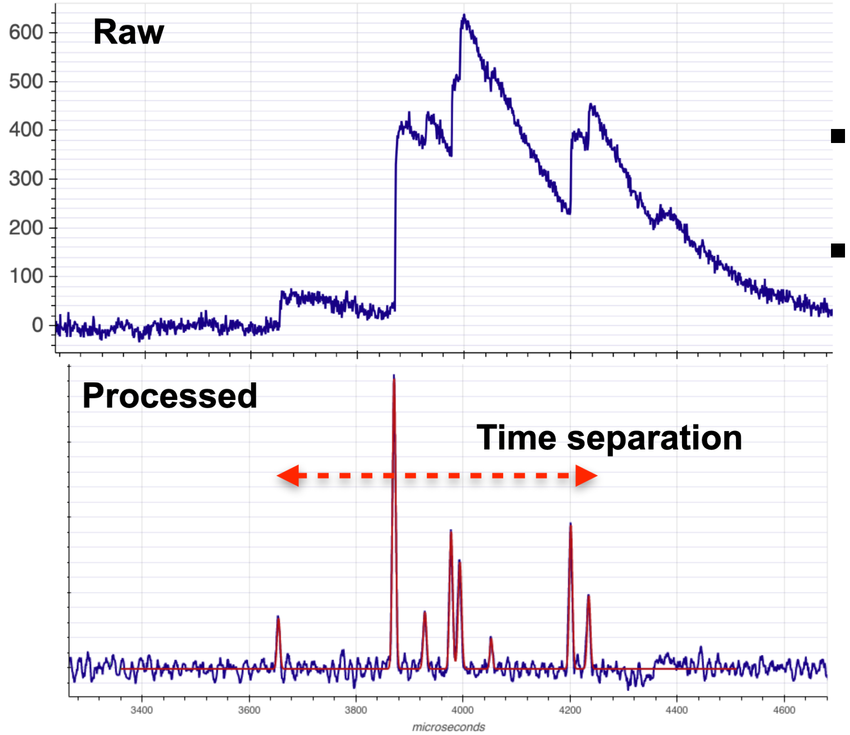
- **⌀140 cm SPC** 4N (99.99% pure) Aurubis copper
    - Electroplated internal layer
    - Low radioactivity shielding material
- Constructed and tested in LSM, France
- Commissioning data analysis finalising
- **First physics run in SNOLAB** in 2023

✓ **~20 kg·days exposure** with Ne:CH_4





JINST 18 (2023) 02, T02005



- Discriminating variable: time separation
- Surface/volume and coincidence discrimination

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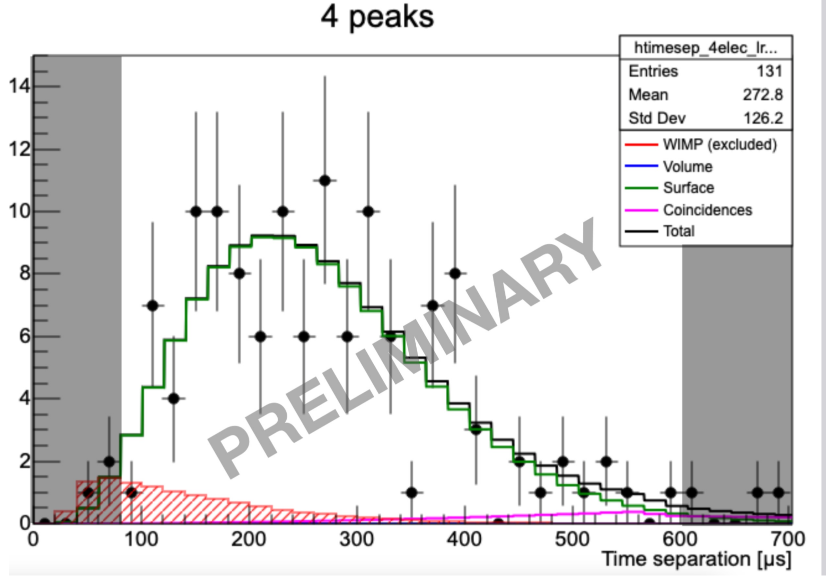
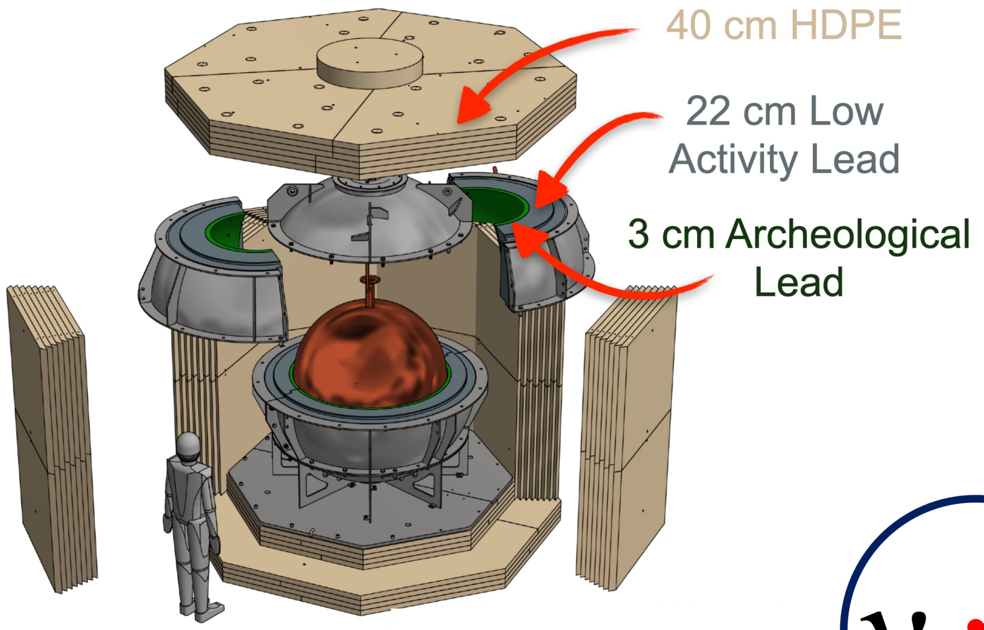
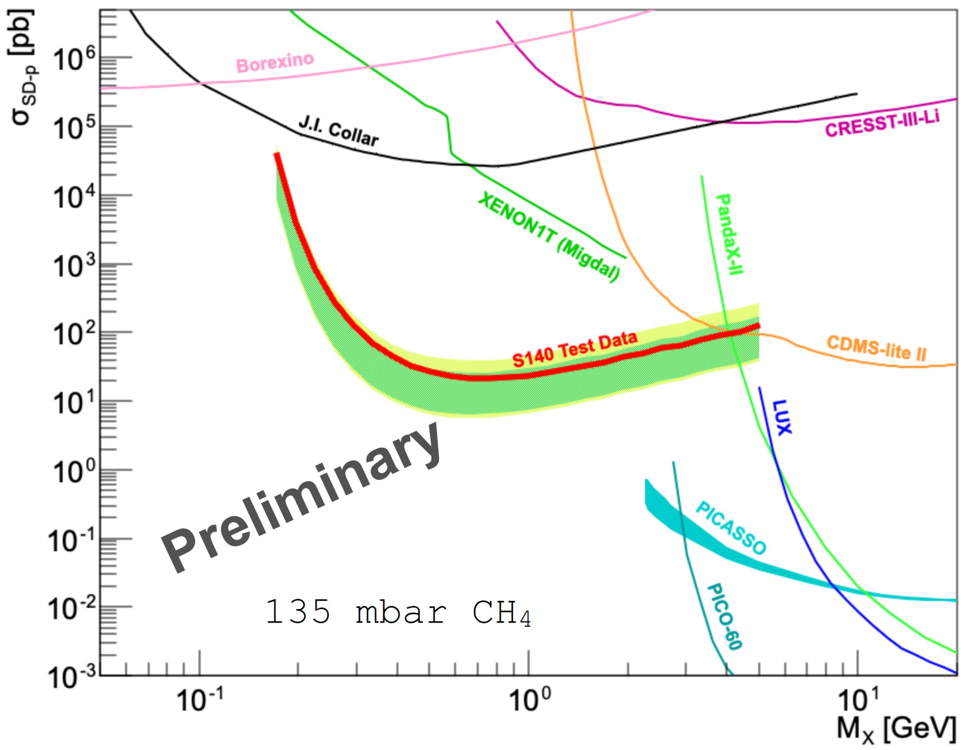




JINST 18 (2023) 02, T02005



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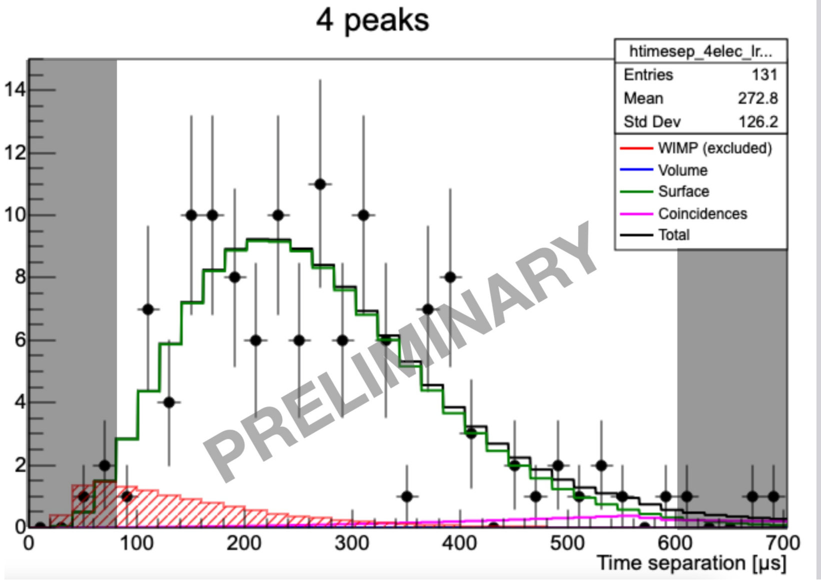

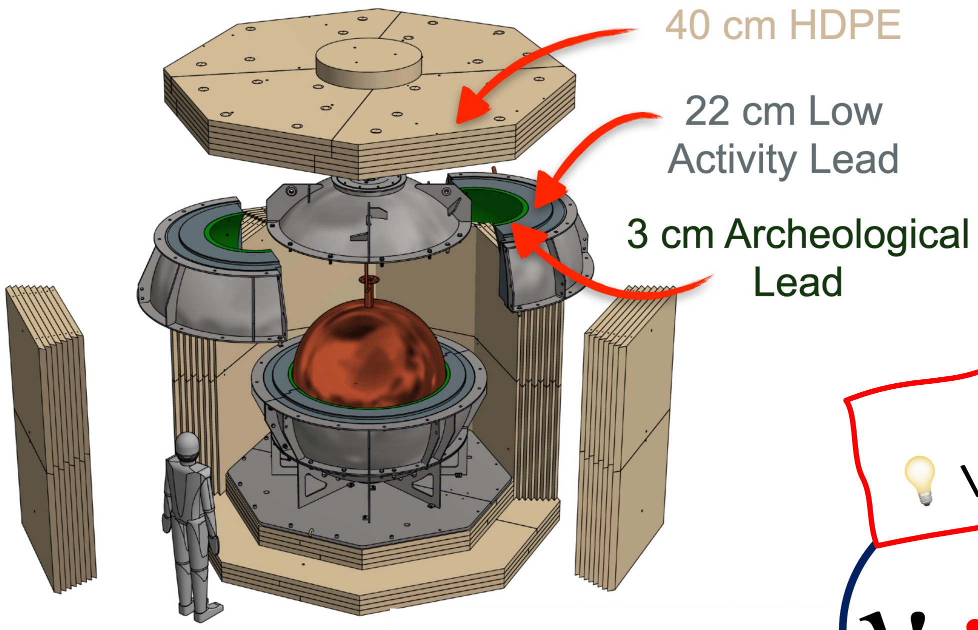

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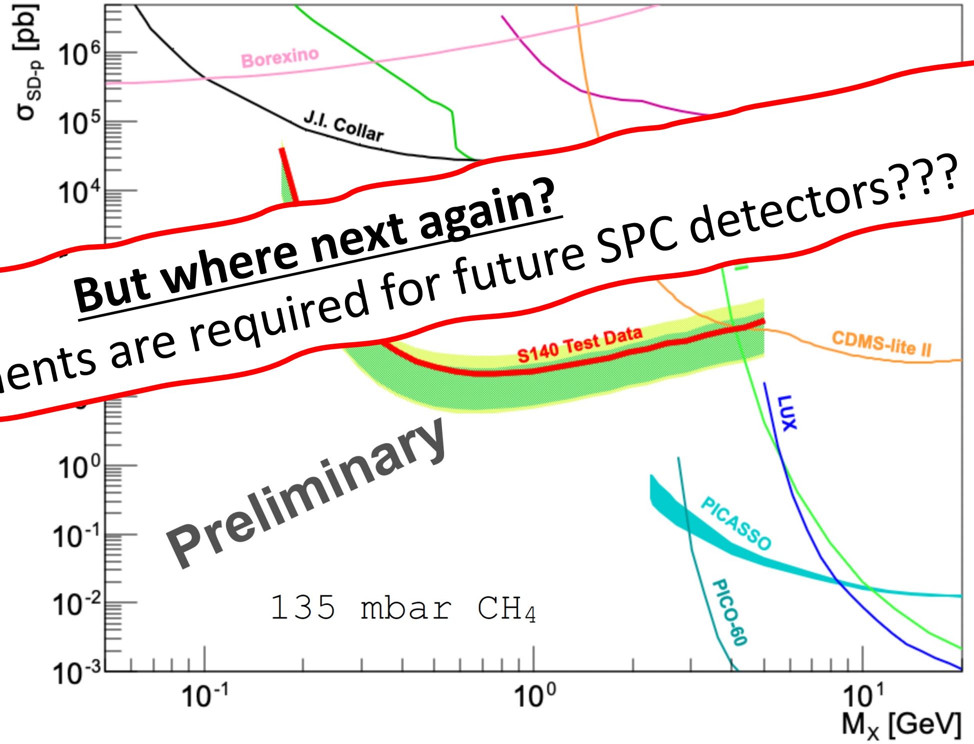


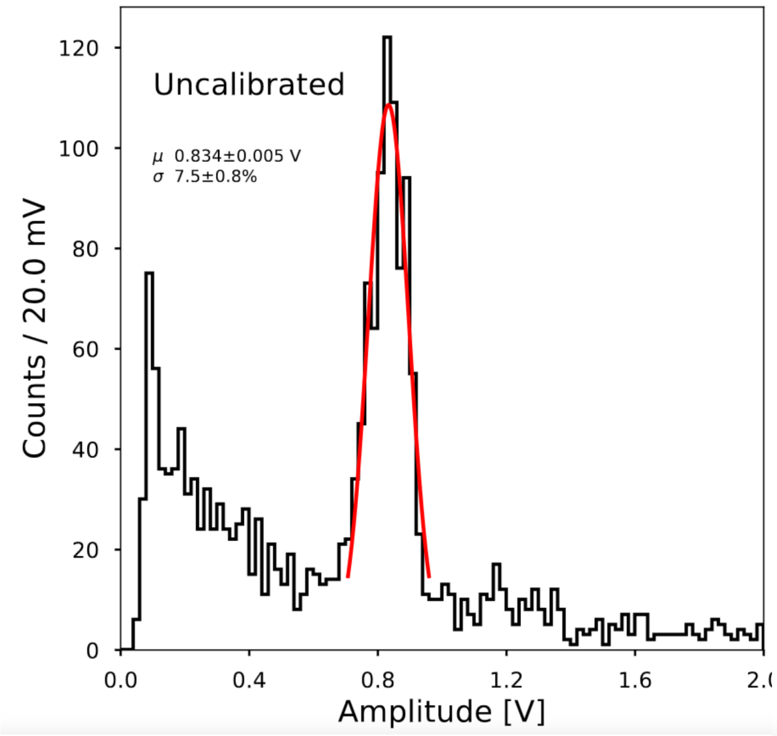
But where next again?

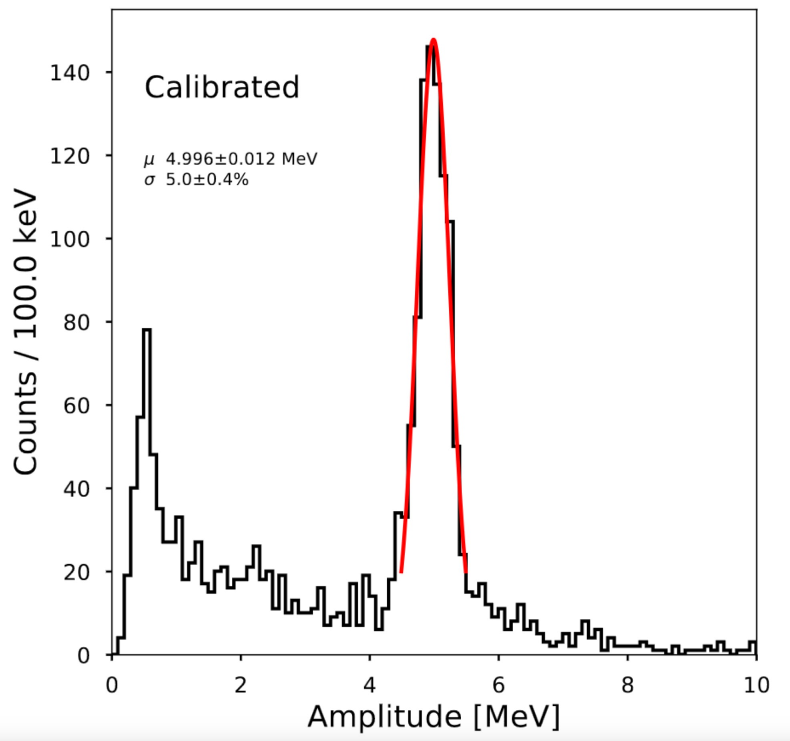
What developments are required for future SPC detectors???

Individual anode Read-out, 11 anodes ACHINOS

- Developed electronics and read-out to instrument all **11 anodes individually**
- **Improved energy resolution**, fiducialisation, track reconstruction, …

Data (500 mbar Ar:CH_4 2%)





JINST 19 (2024) 01, P01018

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- Simulation study of the effect of sensor mechanical deformations

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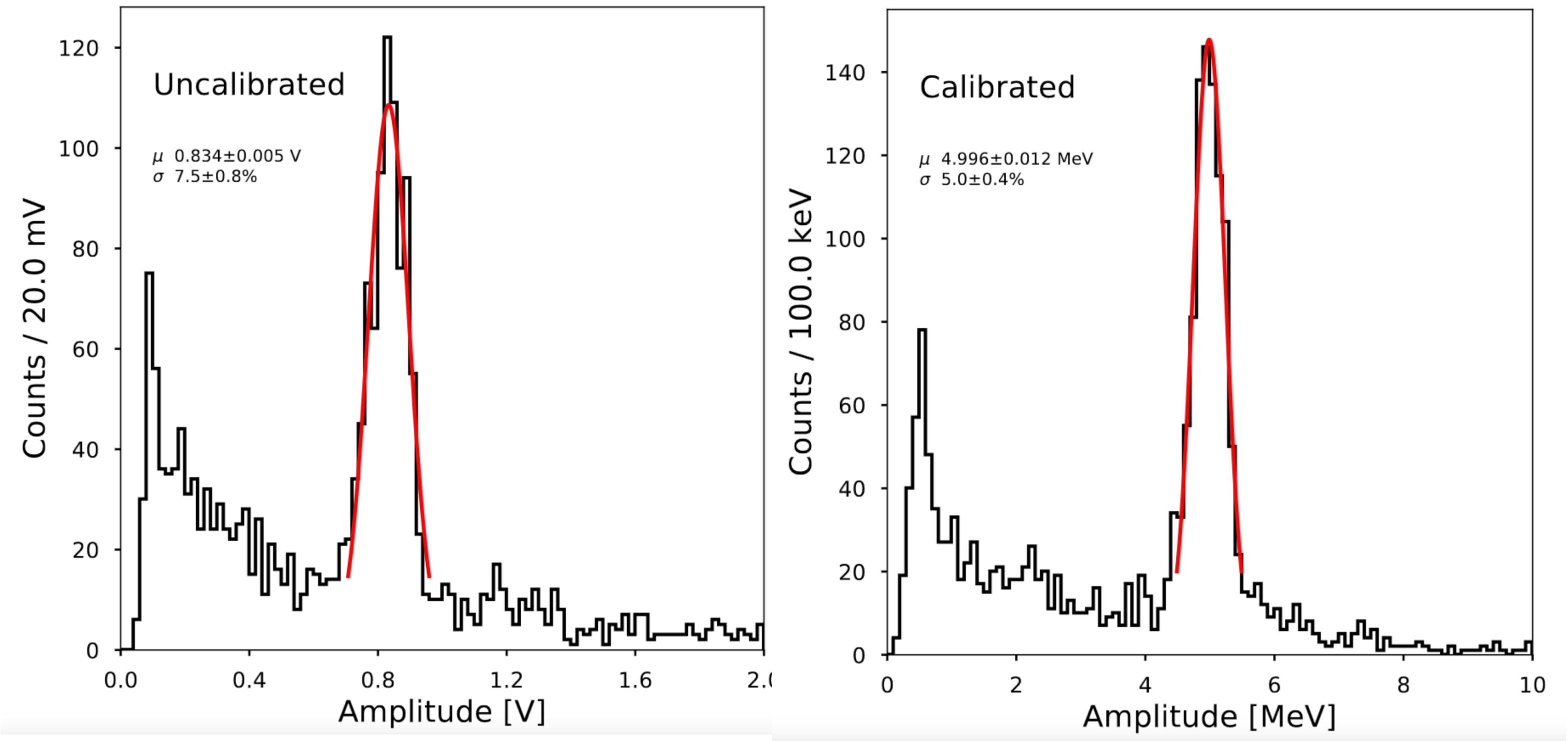
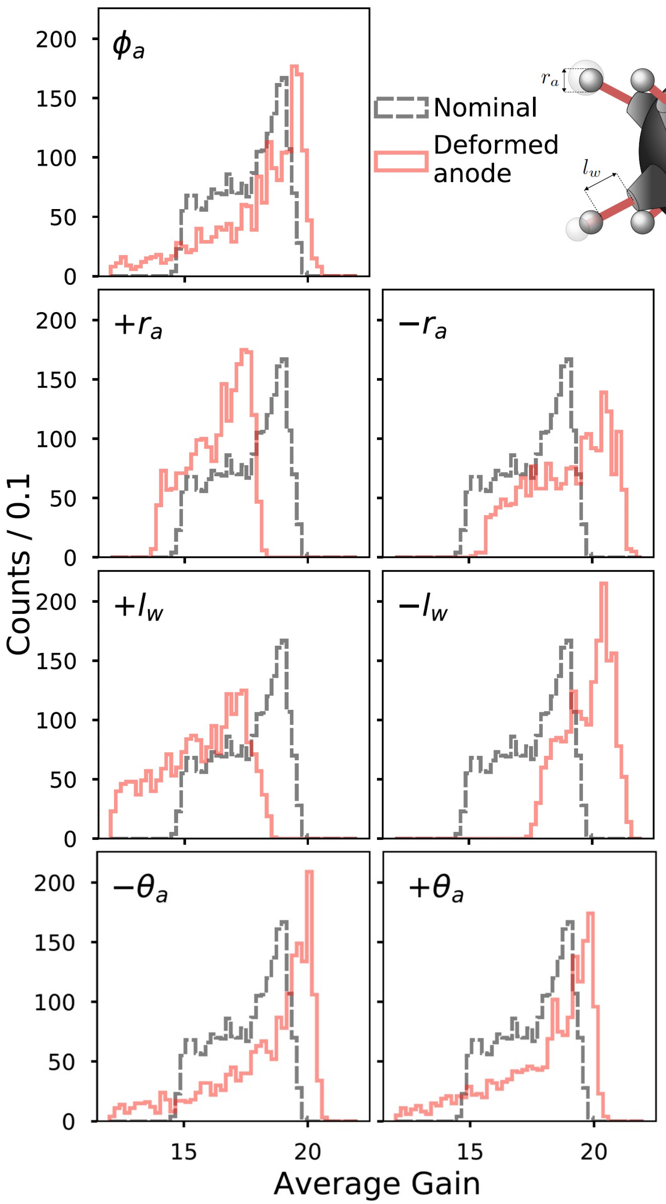
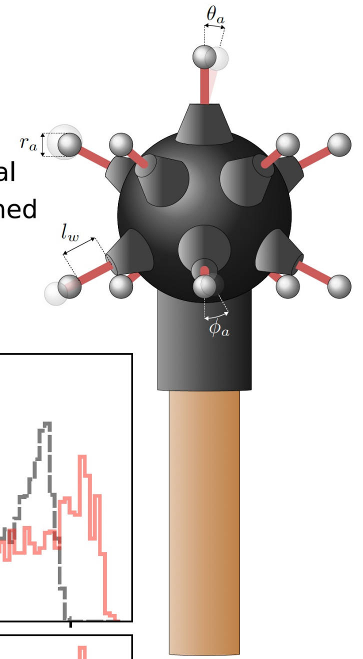


Simulation





JINST 19 (2024) 01, P01018

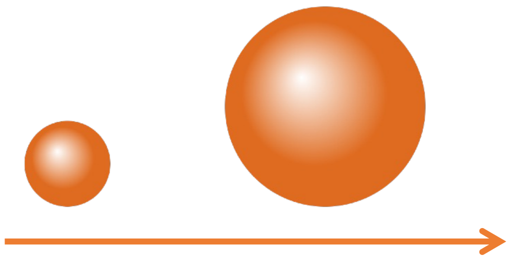
Towards the Neutrino Fog with NEWS-G

SEDINE

⌀60 cm
NOSV Cu

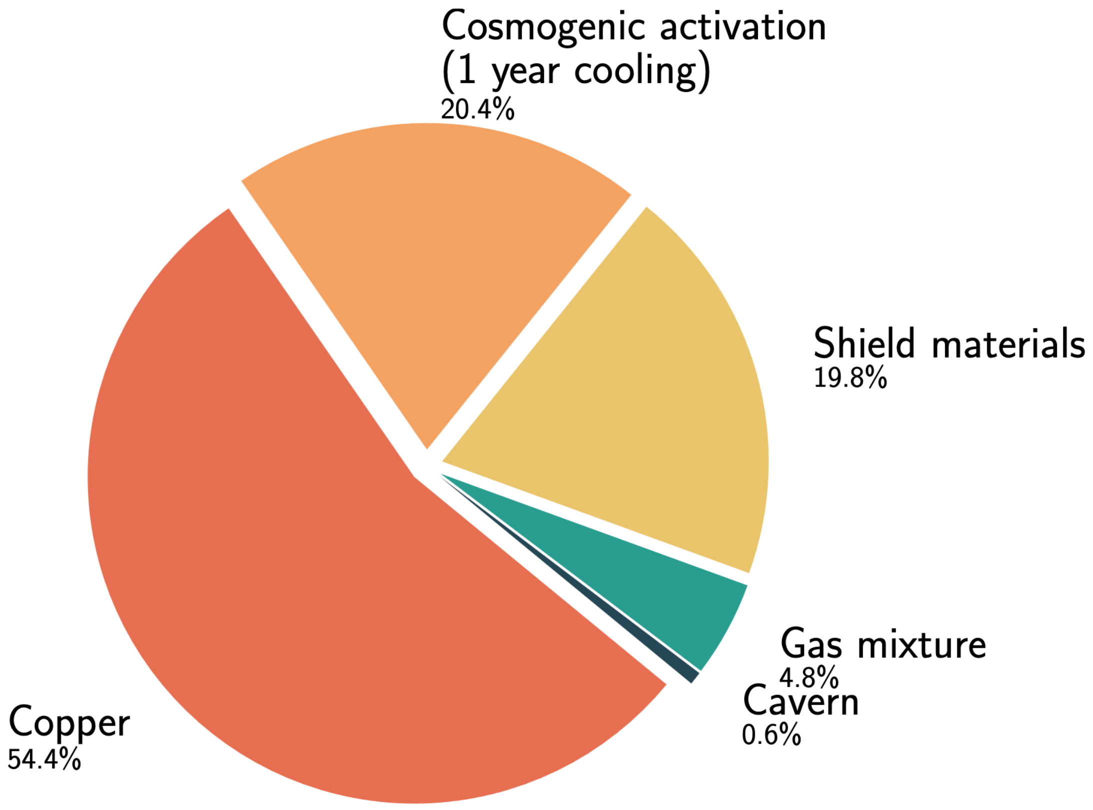
SNOGLOBE

⌀140 cm
99.99% Cu
500 µm EFCu Layer



Existing detectors

Simulated background for SNOLAB SPC



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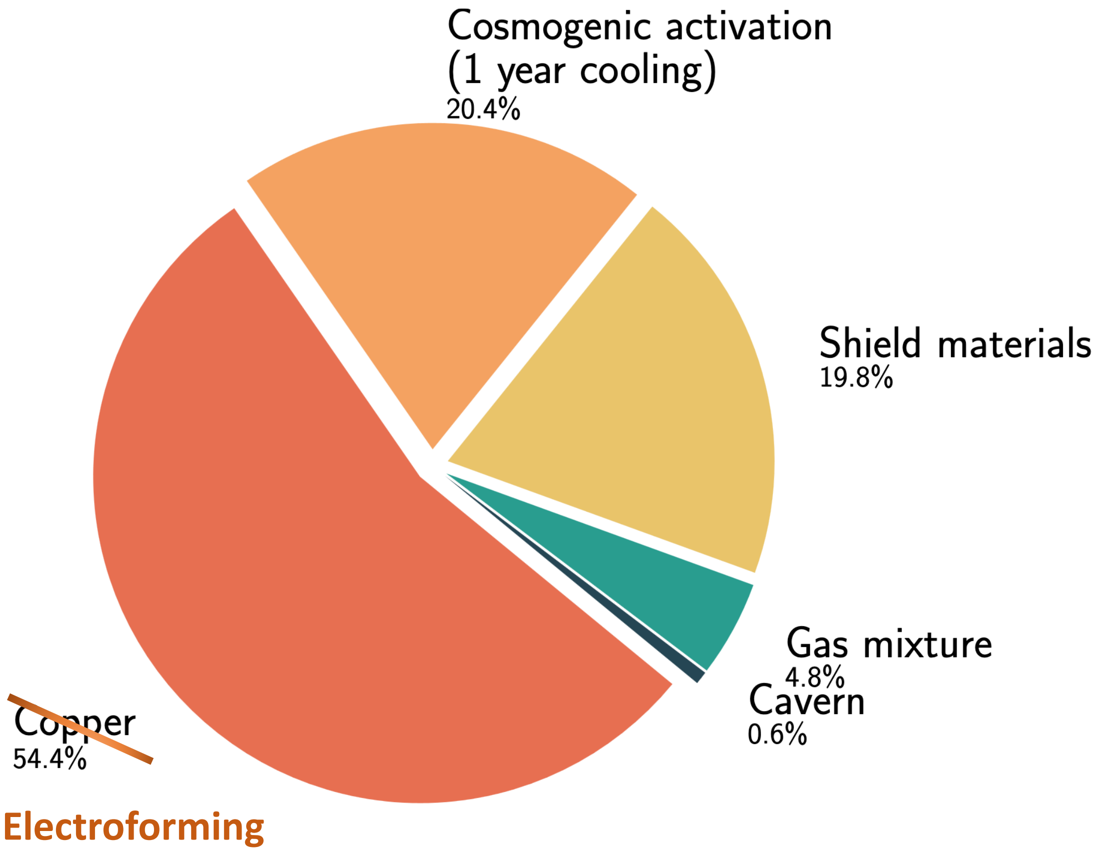

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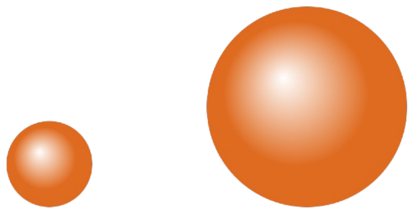

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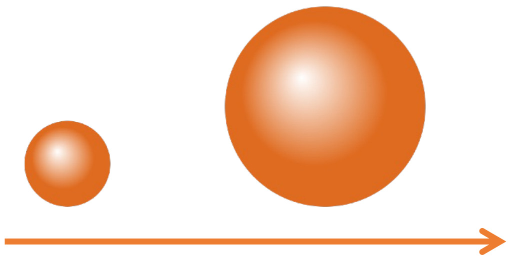

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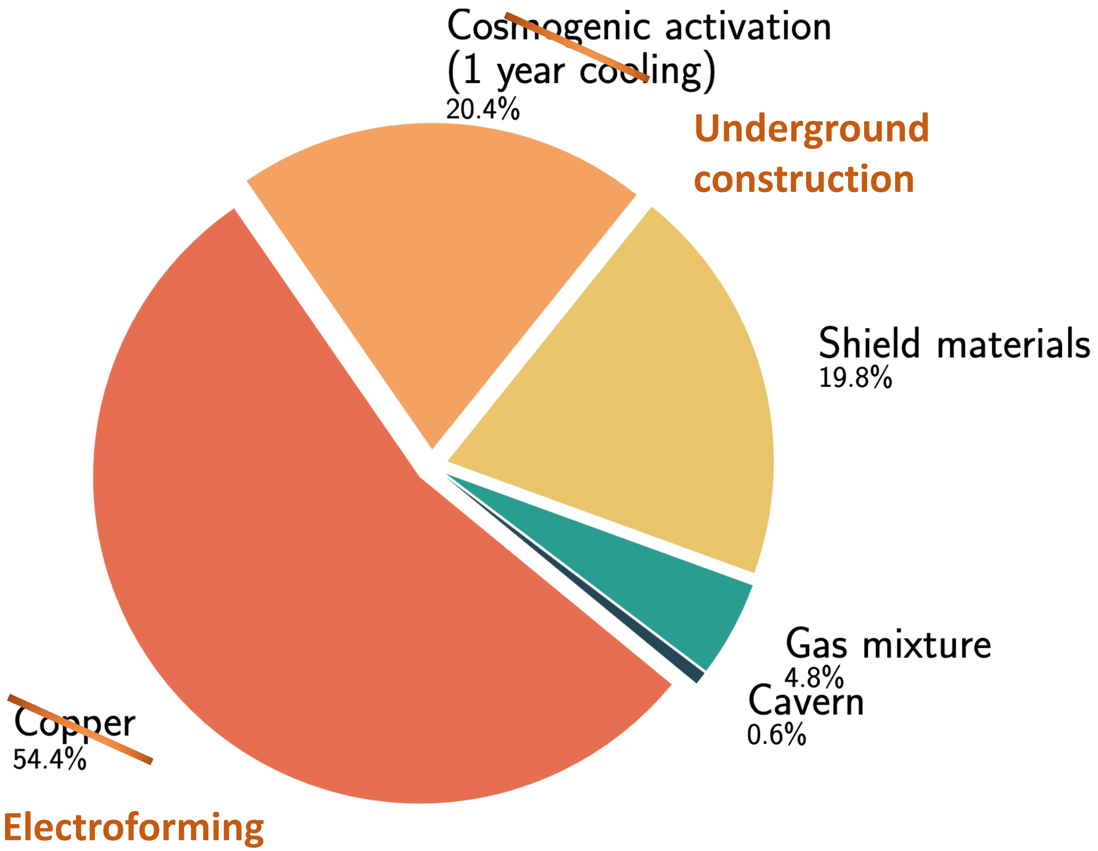

Towards the Neutrino Fog with NEWS-G

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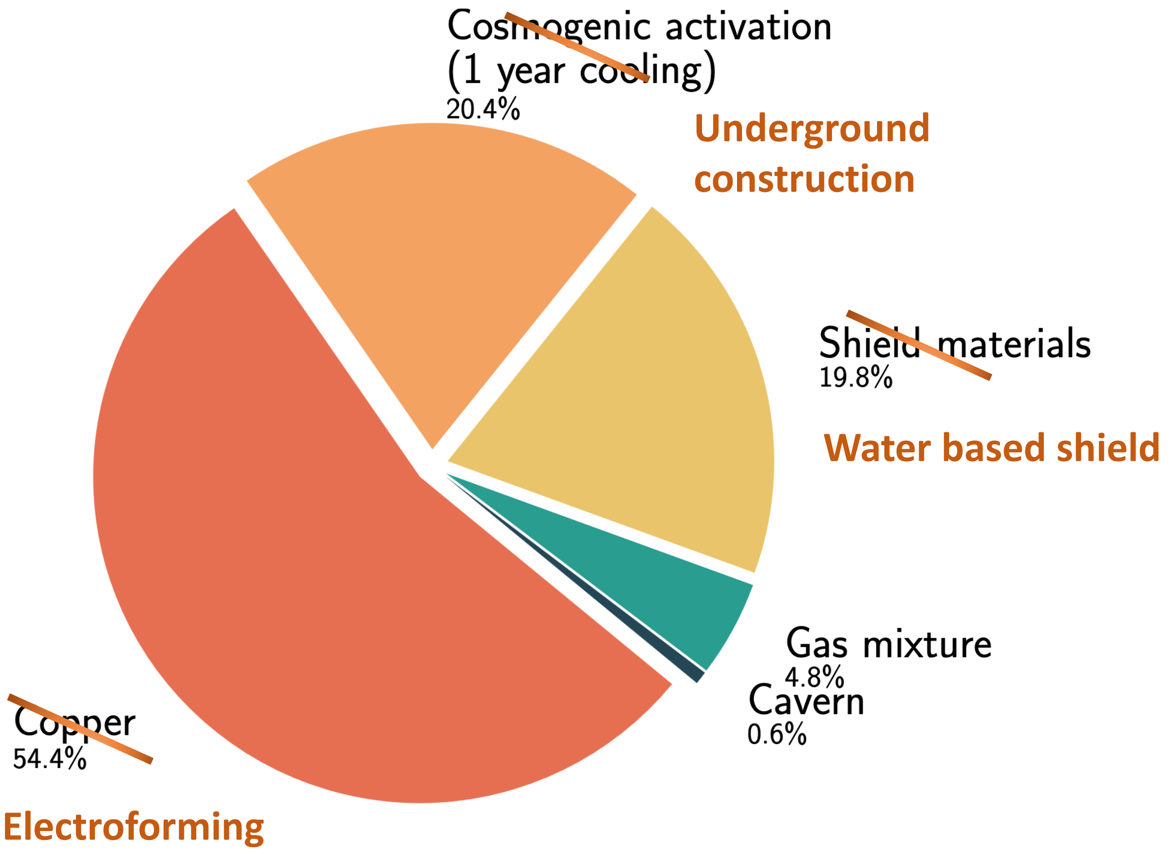

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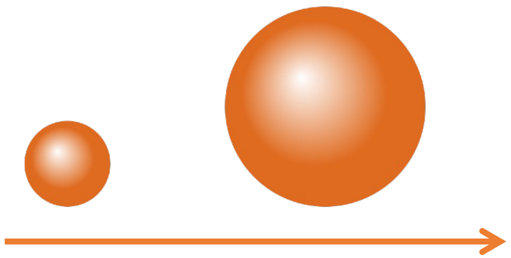

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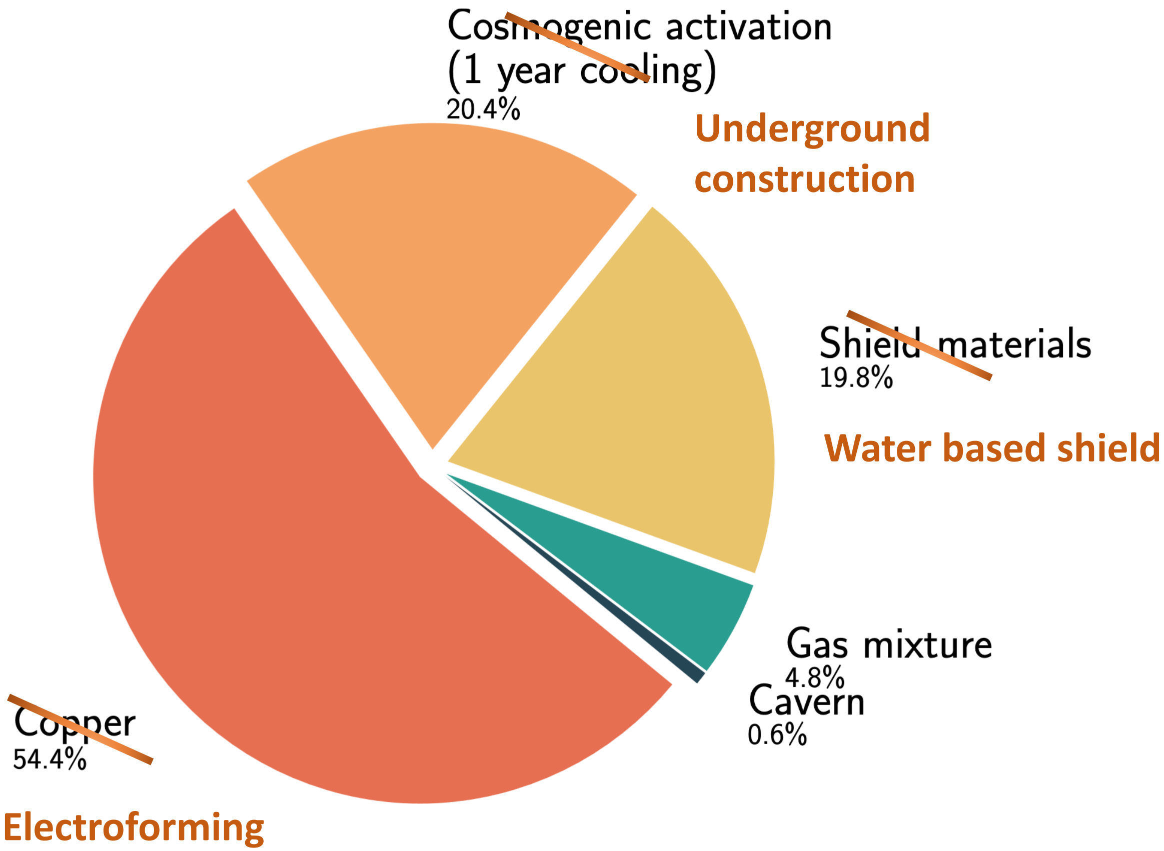

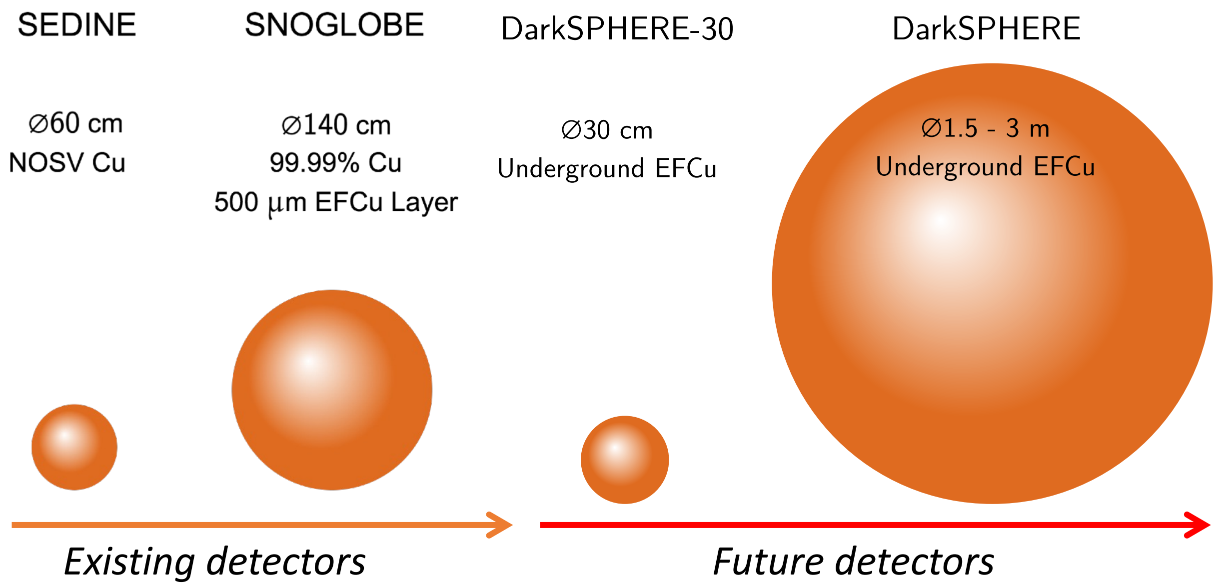

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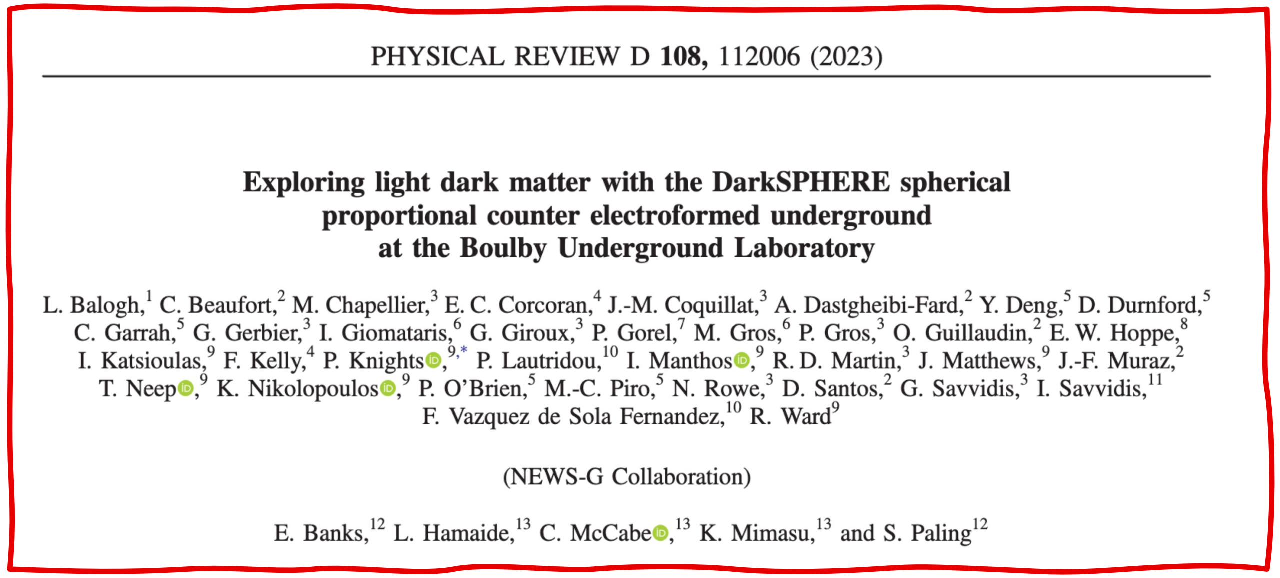
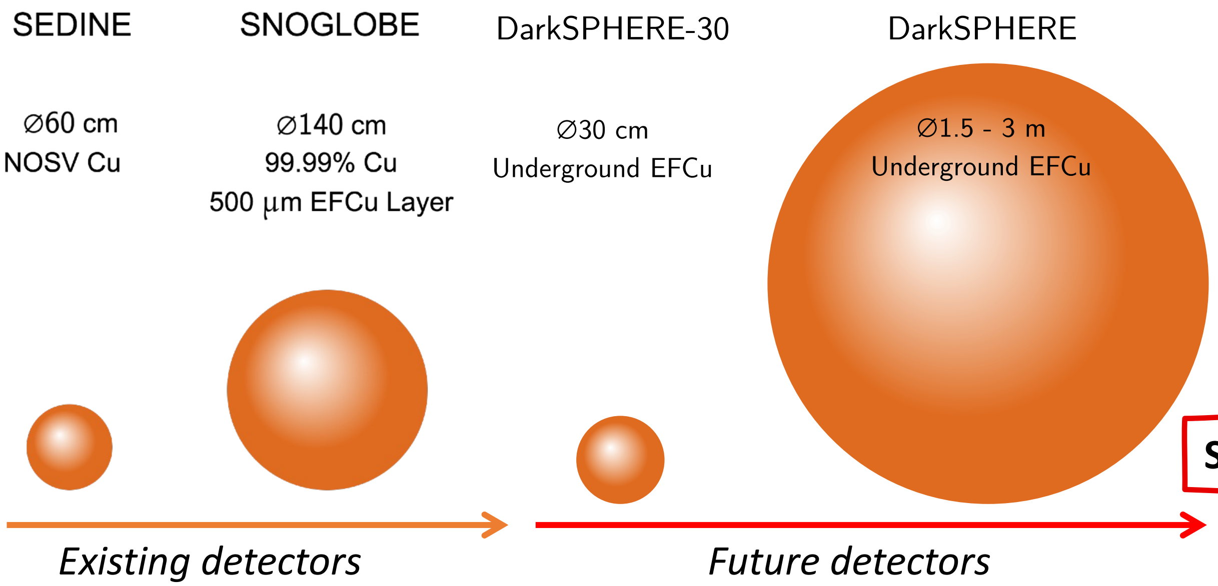

PHYSICAL REVIEW D **108**, 112006 (2023)

Exploring light dark matter with the DarkSPHERE spherical proportional counter electroformed underground at the Boulby Underground Laboratory

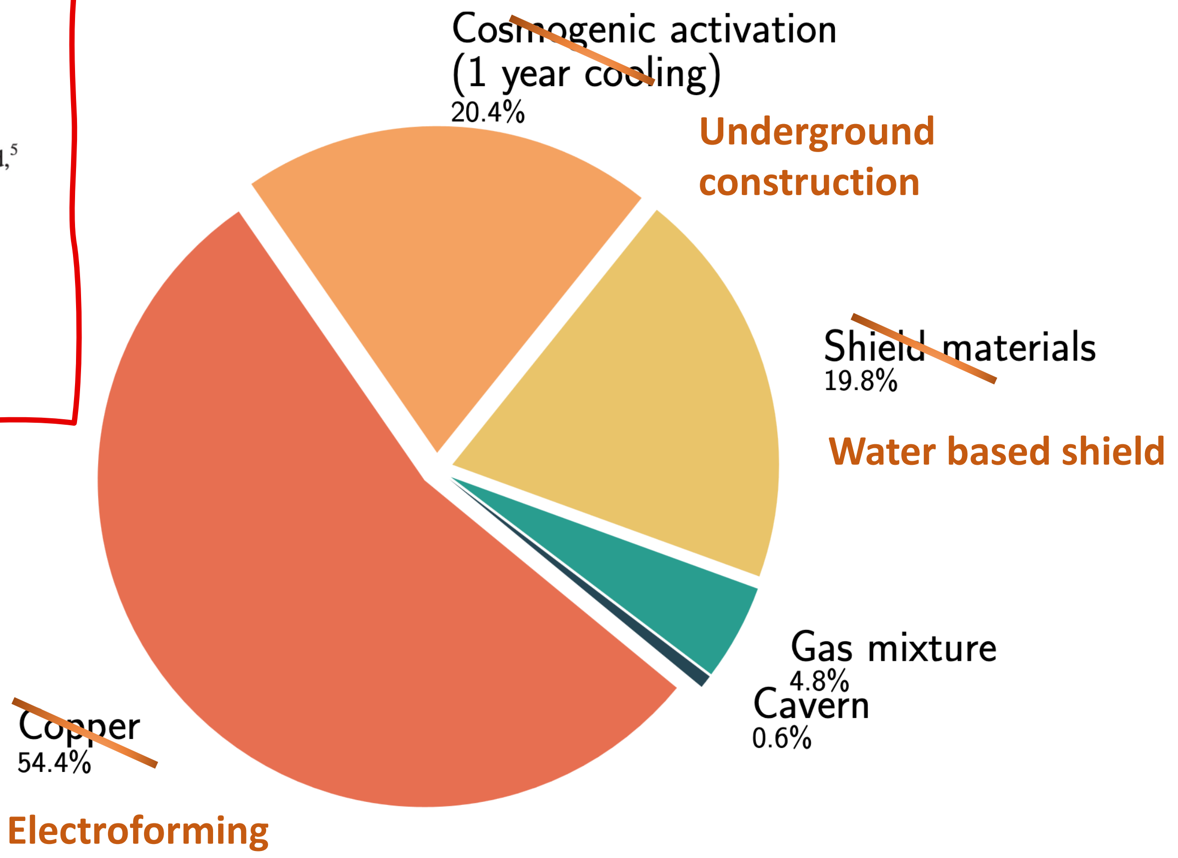
L. Balogh,[1] C. Beaufort,[2] M. Chapellier,[3] E. C. Corcoran,[4] J.-M. Coquillat,[3] A. Dastgheibi-Fard,[2] Y. Deng,[5] D. Durnford,[5] C. Garrah,[5] G. Gerbier,[3] I. Giomataris,[6] G. Giroux,[3] P. Gorel,[7] M. Gros,[6] P. Gros,[3] O. Guillaudin,[2] E. W. Hoppe,[8] I. Katsioulas,[9] F. Kelly,[4] P. Knights,[9,*] P. Lautridou,[10] I. Manthos,[9] R. D. Martin,[3] J. Matthews,[9] J.-F. Muraz,[2] T. Neep,[9] K. Nikolopoulos,[9] P. O'Brien,[5] M.-C. Piro,[5] N. Rowe,[3] D. Santos,[2] G. Savvidis,[3] I. Savvidis,[11] F. Vazquez de Sola Fernandez,[10] R. Ward[9]

(NEWS-G Collaboration)

E. Banks,[12] L. Hamaide,[13] C. McCabe,[13] K. Mimasu,[13] and S. Paling[12]



Simulated background for SNOLAB SPC



Study used Boulby underground laboratory (UK) as target host laboratory

DarkSPHERE in Boulby

Science and Technology Facilities Council

Boulby Underground Laboratory

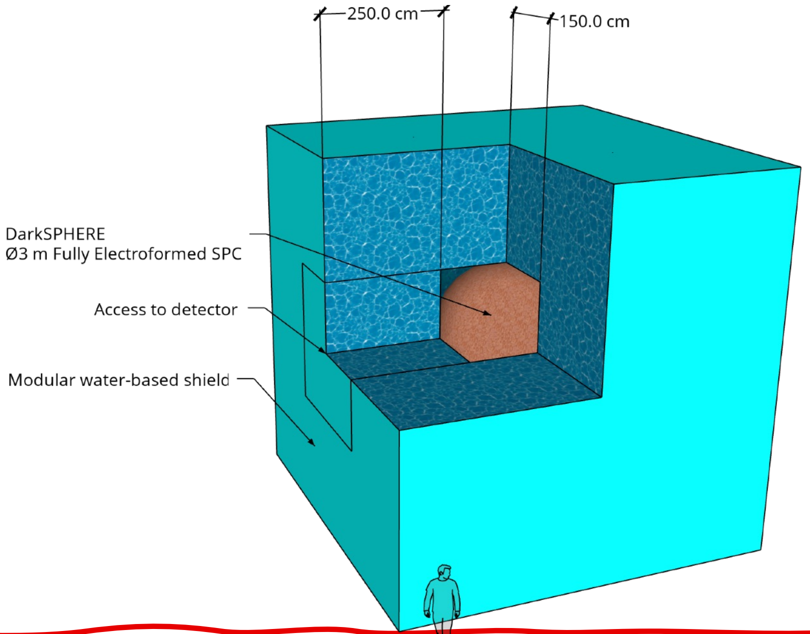
^{222}Rn ~3 Bq/m^3 *P. Scovell, DMUK 2019*

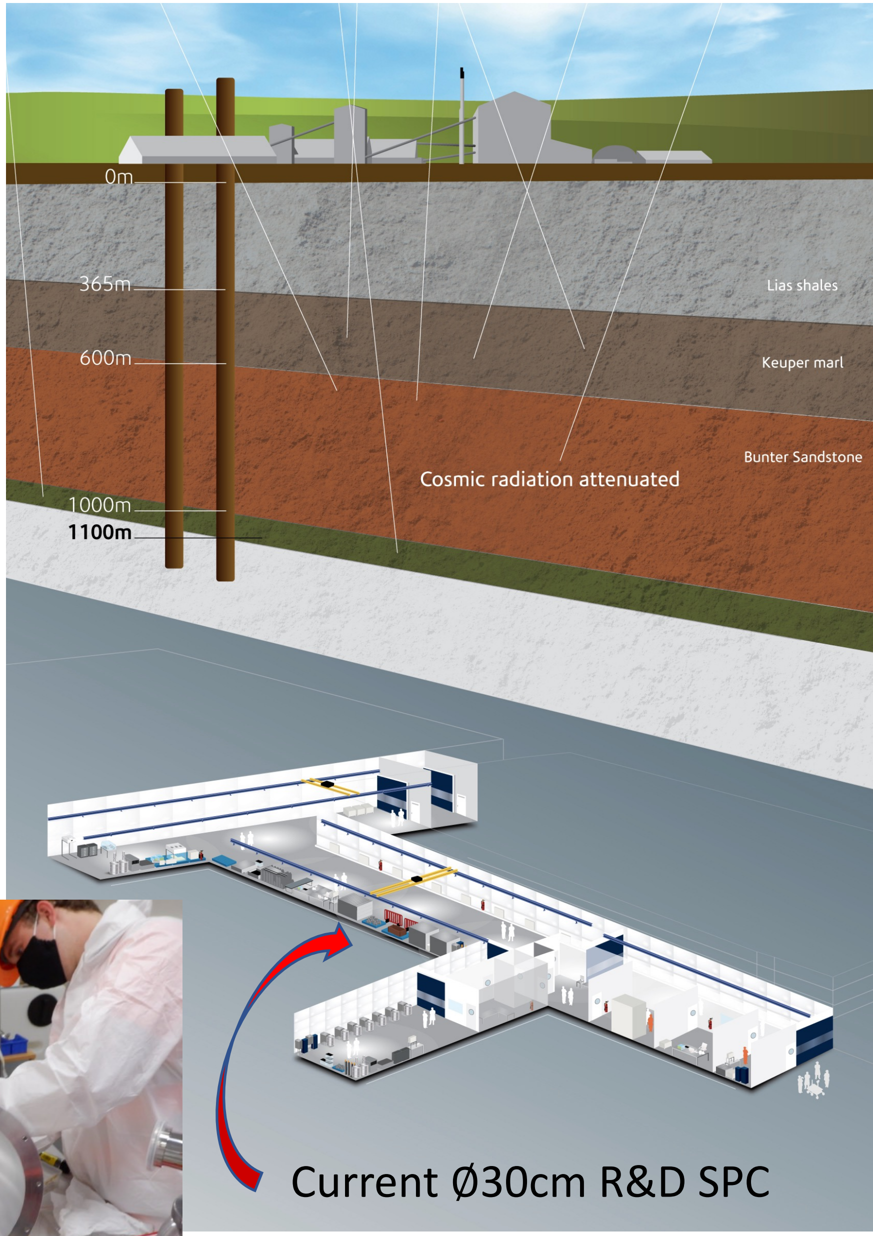
μ ~4×10^{-8} /cm^2/s *NIMA 511 (2003) 347-353*

Proposed future 1.4 - 3m in diameter NEWS-G detector

- **Fully electroformed** detector
- **EF deep-underground**, in host laboratory
- Contained in low-radioactivity **water-based shielding**, sufficient for background goal **0.01 event/keV/kg/day** in ROI
- Using **light-nuclei gases** for low-mass DM search (He:i-C_4H_{10})

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





Boulby Underground Laboratory, North Yorkshire, UK

DarkSPHERE in Boulby

Science and Technology Facilities Council
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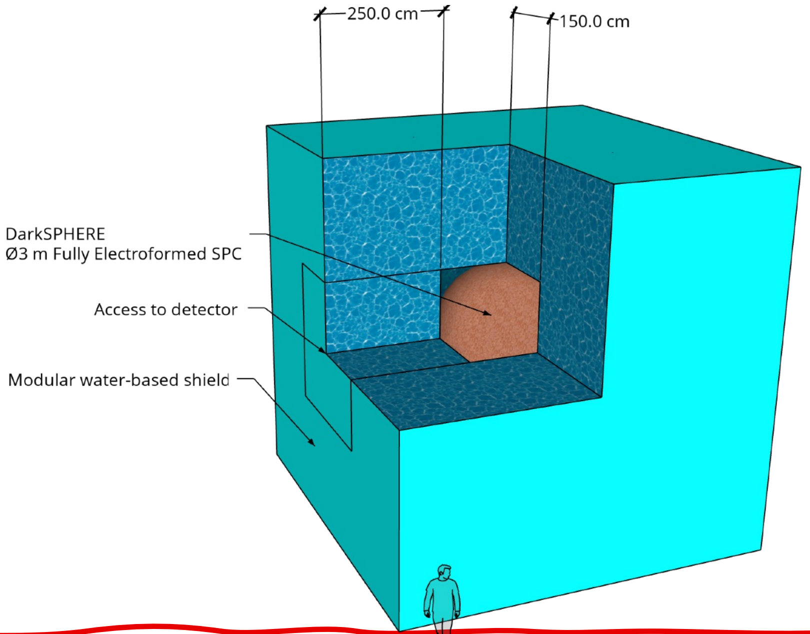
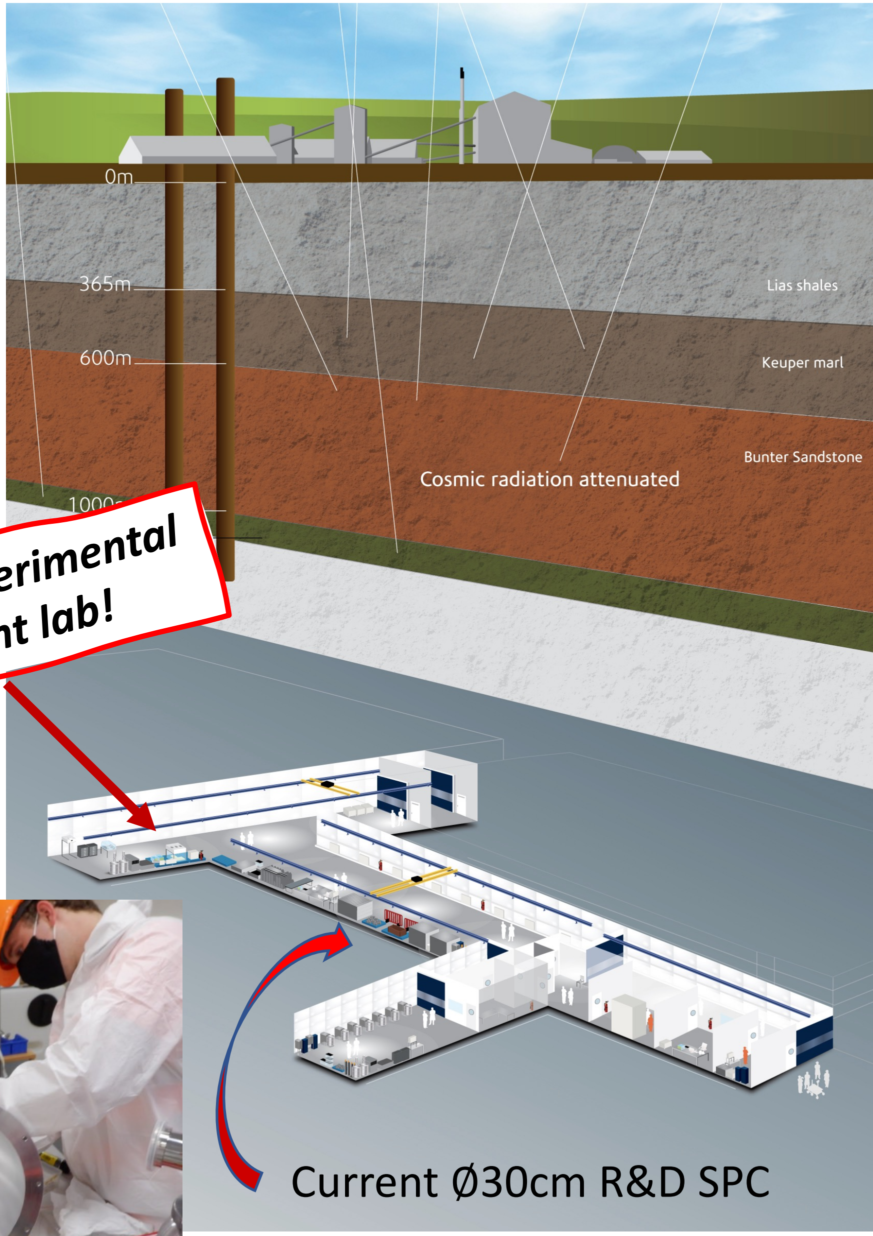
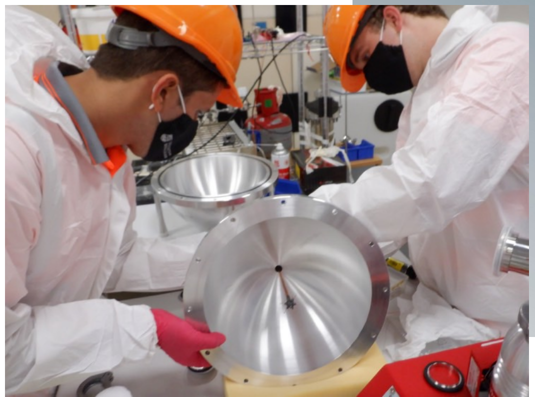




Fits in Large Experimental Cavern of current lab!

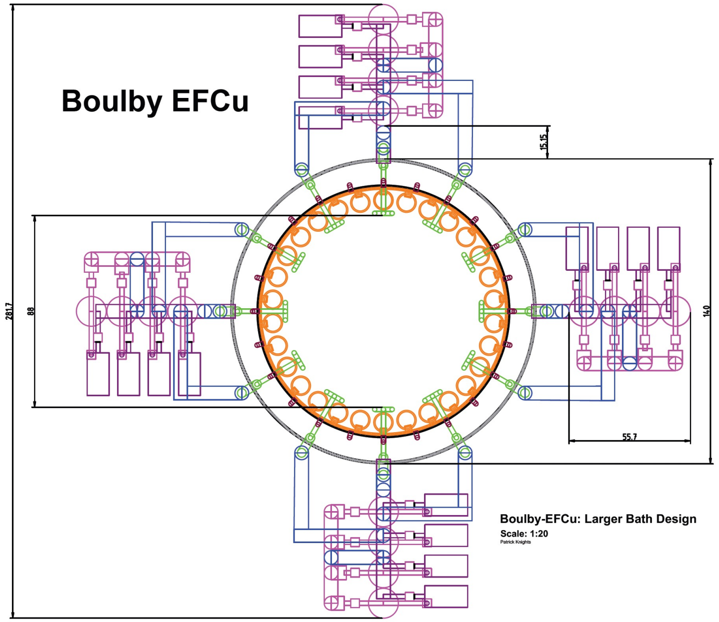


Current Ø30cm R&D SPC

Boulby Underground Laboratory, North Yorkshire, UK

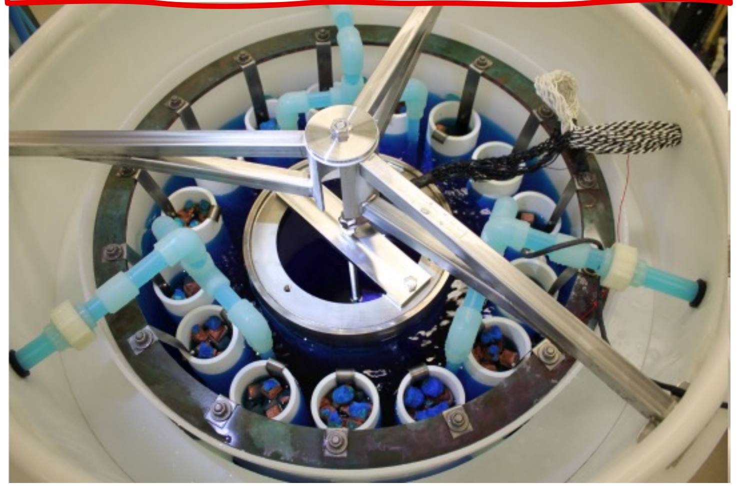
EFCu in Boulby

- ECuME project, SNOLAB, of ⌀140cm detector + scale model in PNNL
- STFC (UK funding agency) funding for an ultra-pure EFCu facility underground in Boulby
  - ➢ Currently under construction



Construction of bath underway

Example electroforming bath at Pacific Northwest National Laboratory

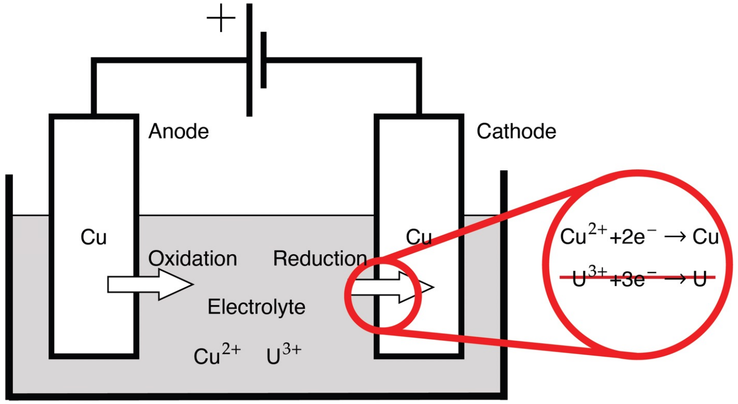


Credit: E W Hoppe, PNNL

First EFCu test in Boulby

Potentiostatic electroforming Cu: suppresses contaminants (e.g. U, Th, K) through electrochemical properties

- Result: **highly-pure copper**
- Used to apply internal shield to S140 detector



NIMA 988 (2021) 164844

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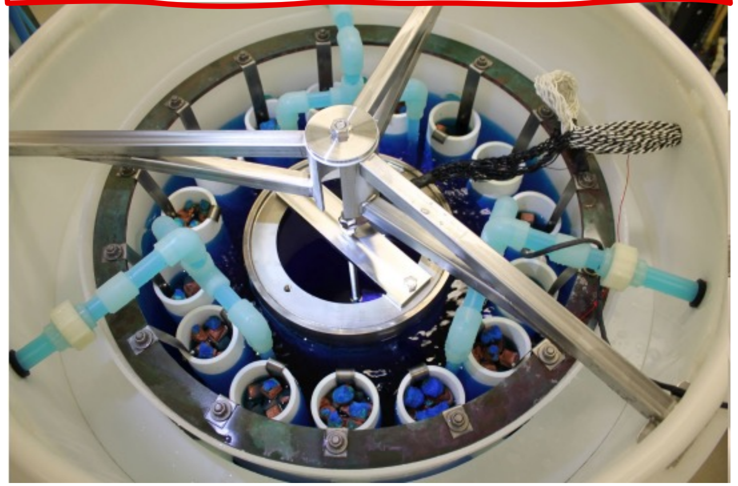

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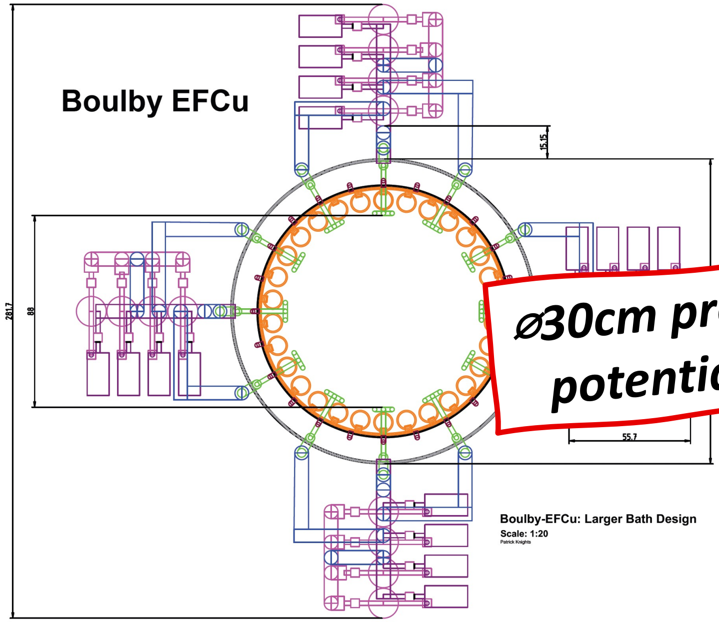

⌀30cm prototype with world-leading physics potential to begin construction this year!

First EFCu test in Boulby

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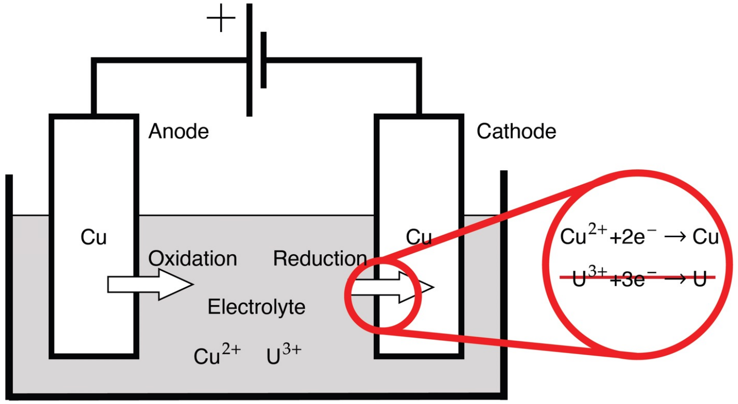
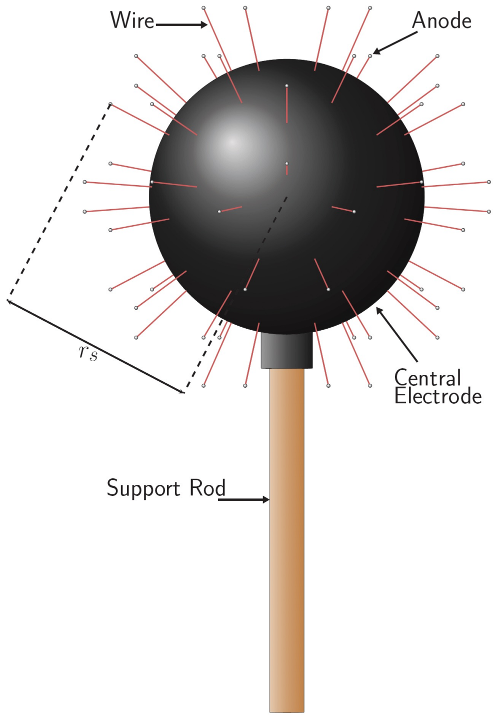
- Result: **highly-pure copper**
- Used to apply internal shield to S140 detector

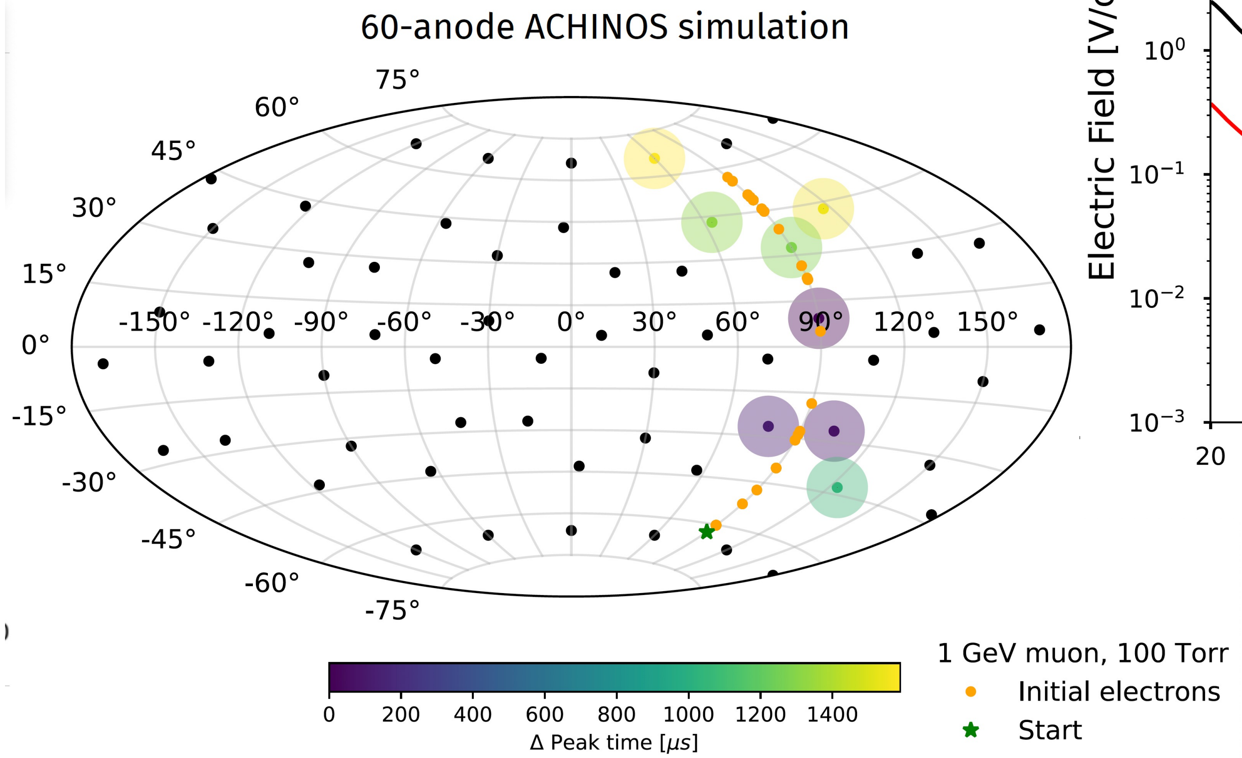


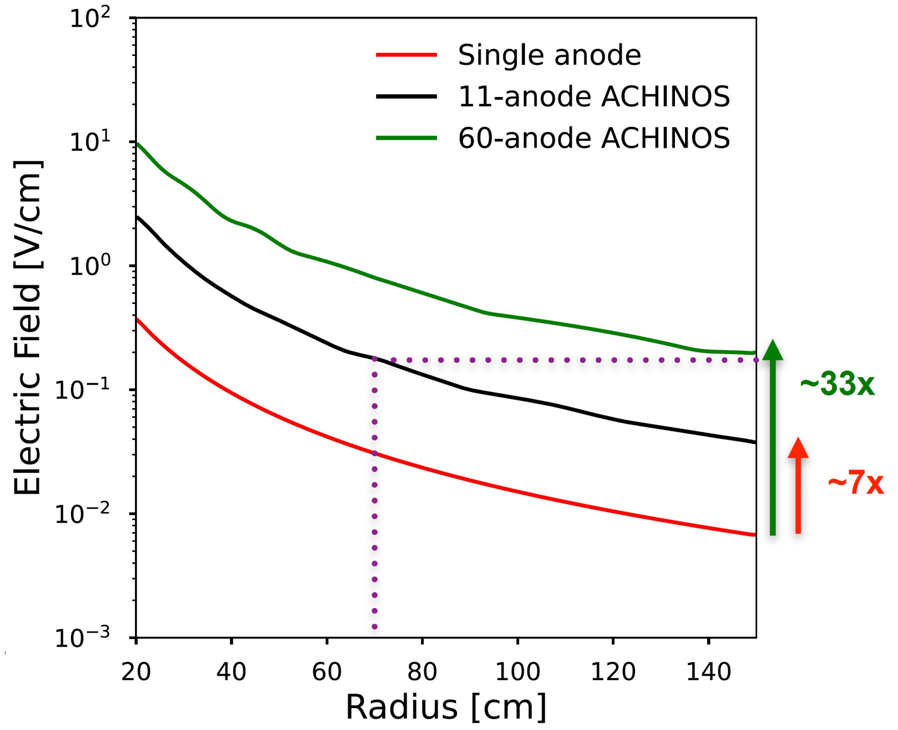
NIMA 988 (2021) 164844

Further R&D on SPC instrumentation

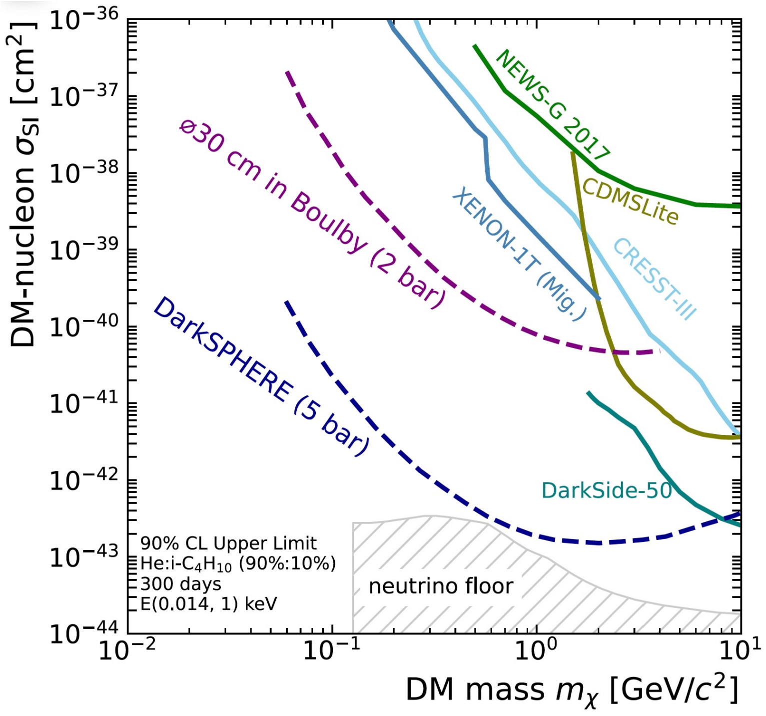
- Current ACHINOS thought to be sufficient for S140
- To maintain same drift field in ⌀3m **DarkSPHERE**, need larger ACHINOS moving towards a **60-anode ACHINOS** with 1mm (or smaller) anodes
- Improved position resolution, TPC-like capabilities





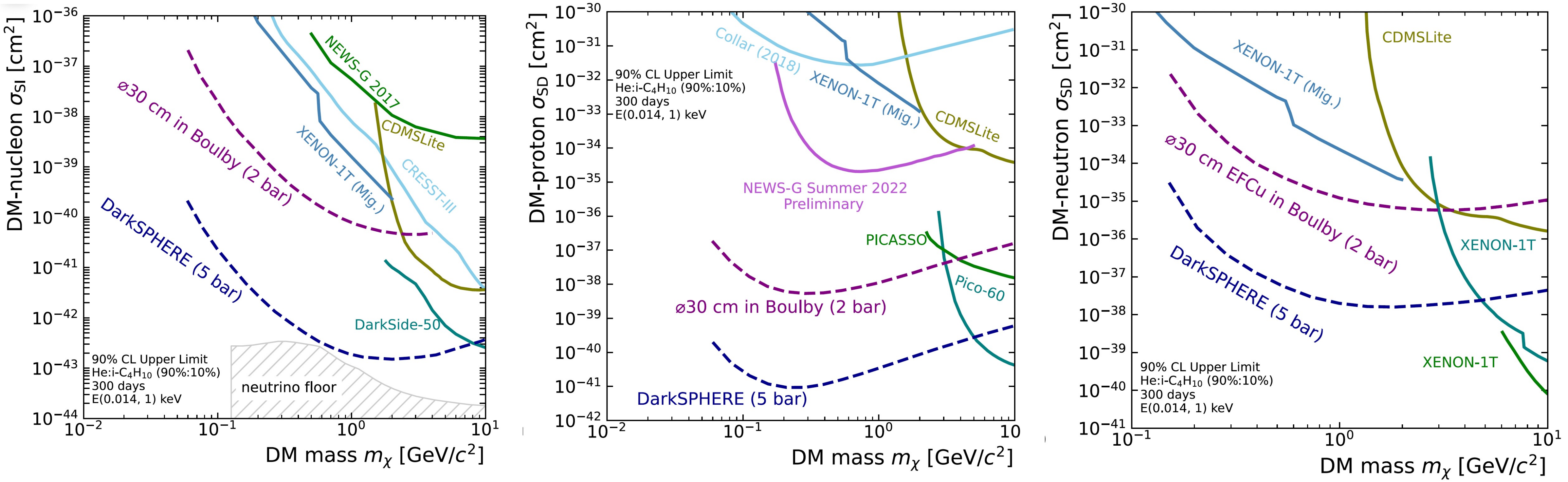


DarkSPHERE: Physics potential



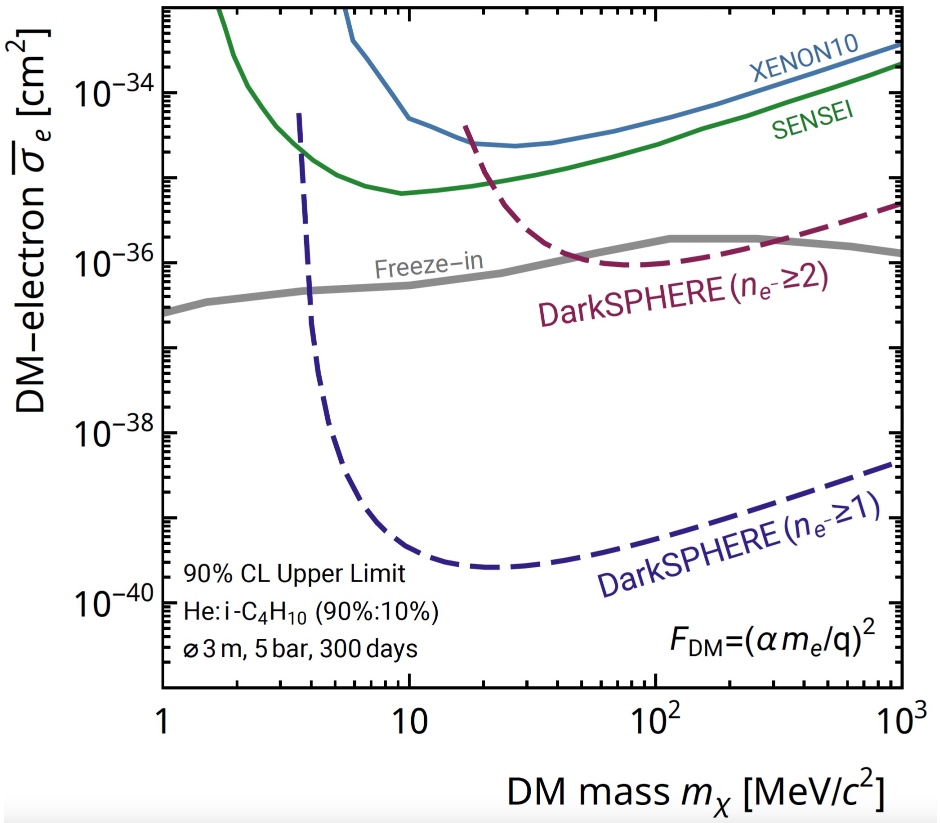
- '**Neutrino-floor**' reaching potential in DM-nucleon SI interactions
- ⌀30cm prototype in Boulby in a DarkSPHERE-like shield will have world-leading sensitivity

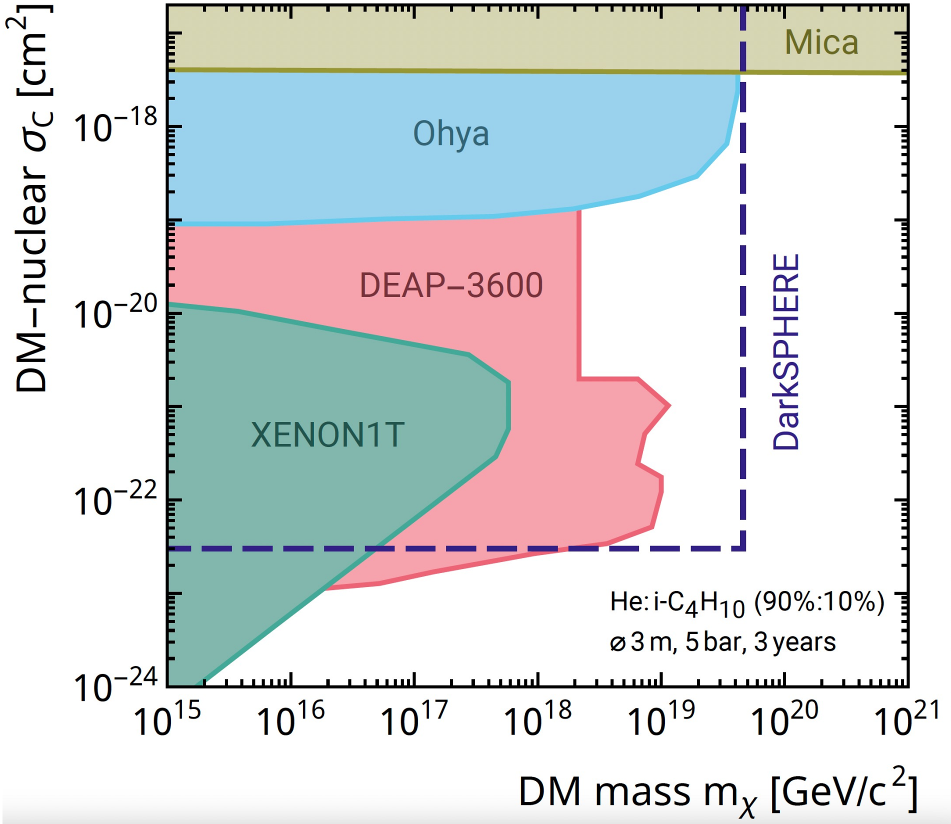
DarkSPHERE: Physics potential



- ‘**Neutrino-floor**’ reaching potential in DM-nucleon SI interactions
- ⌀30cm prototype in Boulby in a DarkSPHERE-like shield will have world-leading sensitivity
- **World-leading** potential in SD interactions through natural-abundance H and C isotopes

DarkSPHERE: Physics potential





- Sensitivity to **DM - electron** scattering through low threshold
- A 3m SPC has capability to test heavy **exotic candidates**

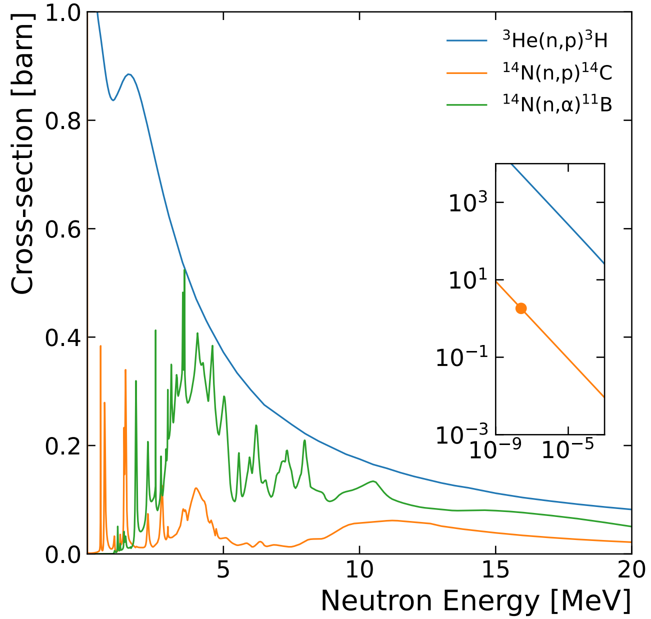
Neutron Spectroscopy with SPC

SPC as neutron spectrometer with N_2 gas

- **Background measurements** for rare-event searches
- Medical and industrial applications

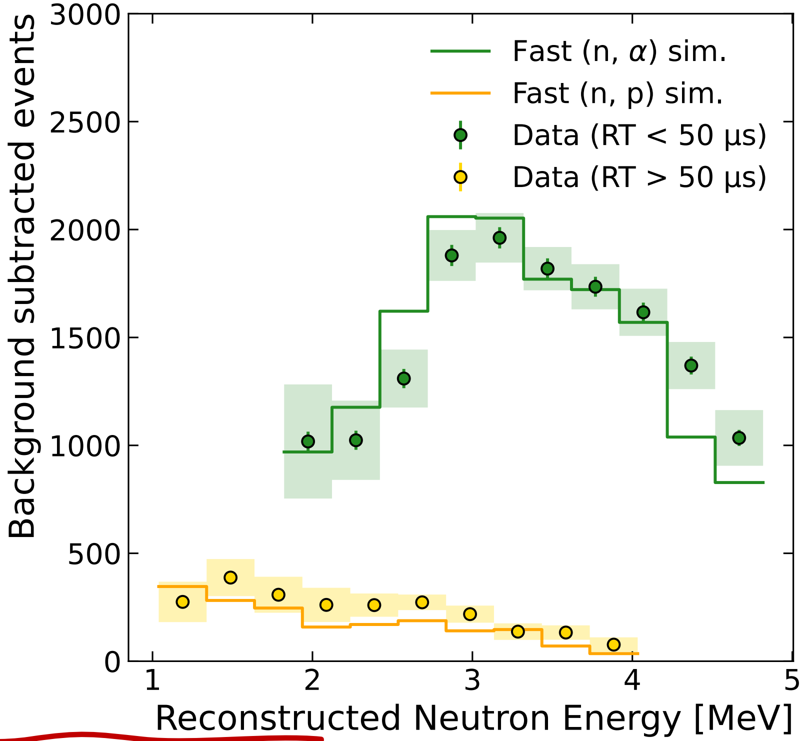
NIMA 1049 (2023) 168124

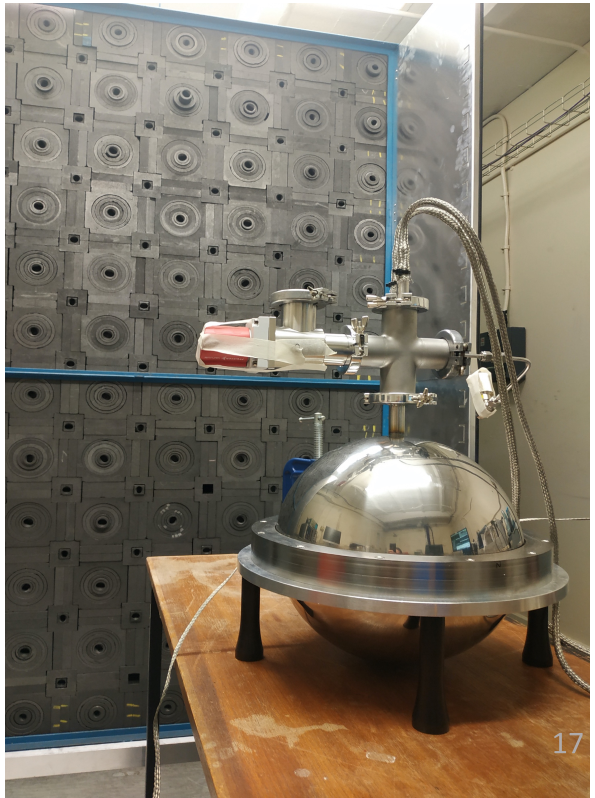
$^{14}N + n \rightarrow {}^{14}C + p$ + 625 keV
$^{14}N + n \rightarrow {}^{11}B + \alpha$ - 159 keV



Neutron energy reconstruction

- Risetime → (n,α) - (n,p) event separation
- Correcting for the energy of the interactions

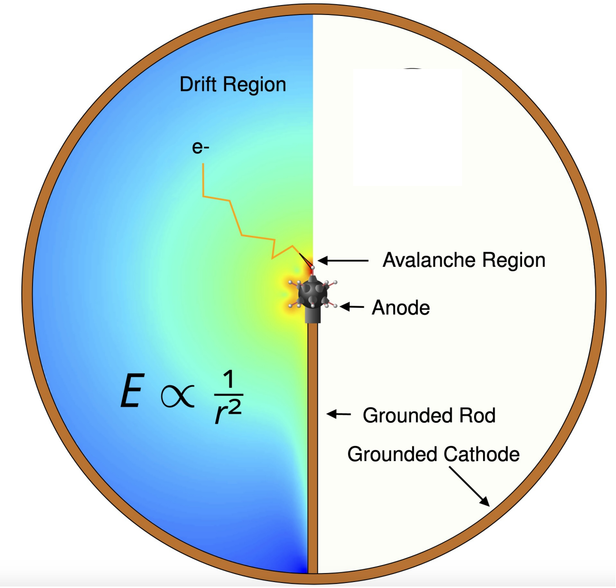


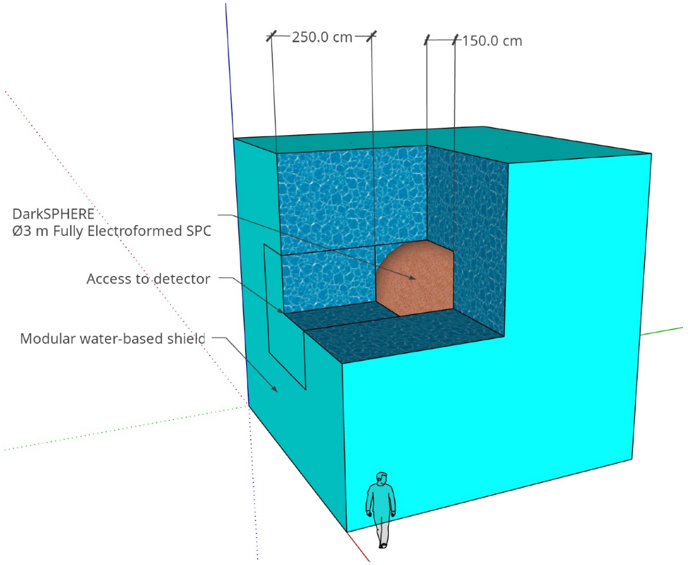


Method will benefit for SPC instrumentation advancements

Direct light Dark Matter searches with Spherical Proportional Counters

- Novel gaseous detector technology
- Unique probe to light Dark Matter detection uncharted phase-space territories
- Ongoing intense R&D on sensor development, radiopure detector construction
- DarkSPHERE project aims to detect (or exclude) light Dark Matter in the 0.05-10 GeV mass range, touching the neutrino fog!





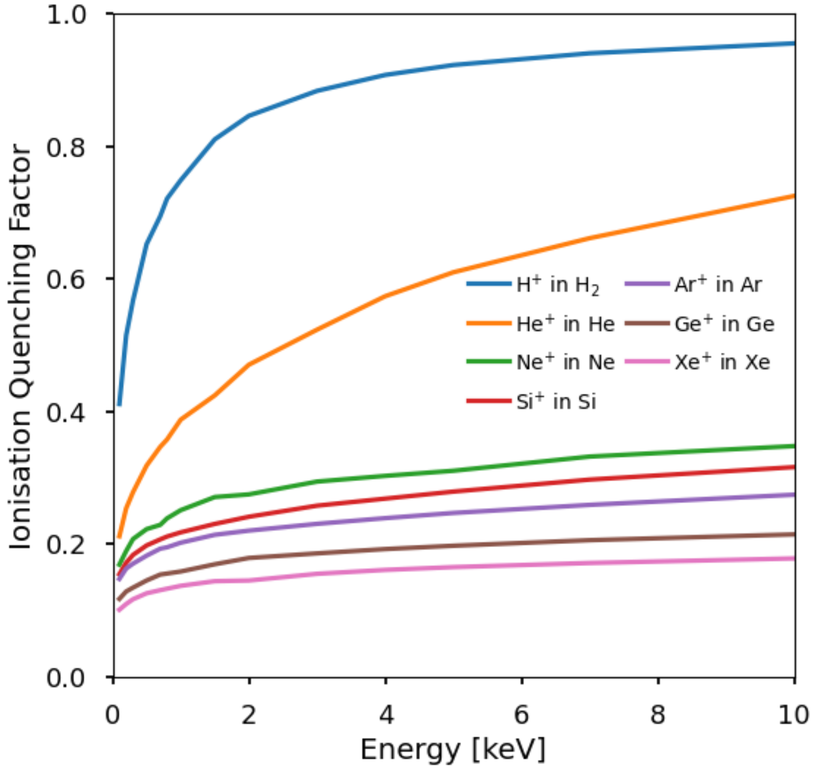
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Science and Technology Facilities Council
Boulby Underground Laboratory

- **Back up slides**

Ionisation Quenching Factor

low-mass targets are **favourable for light-DM searches**
QF values in literature not precisely determined



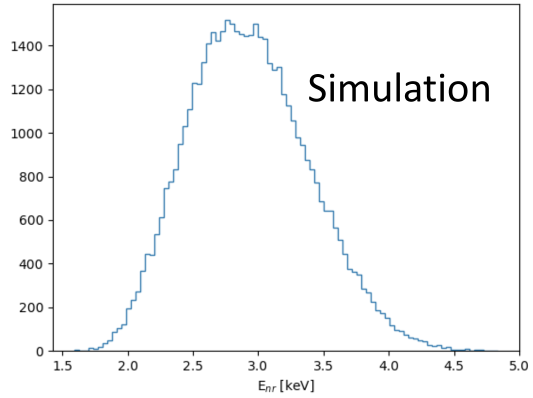
2 measurement approaches in NEWS-G

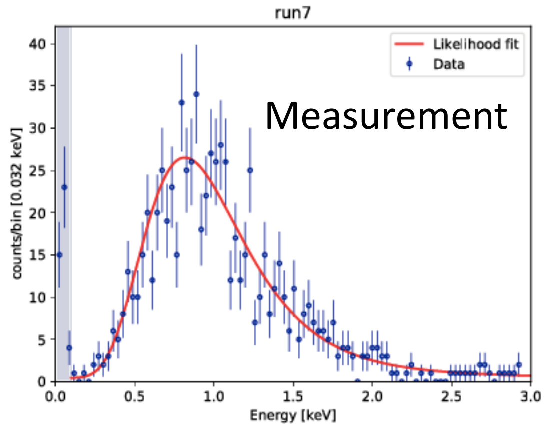
- Neutron scattering at TUNL — Phys.Rev.D 105 (2022) 5 052004
- Electron/Ion beam, COMIMAC, Grenoble — Eur.Phys.J.C 82 (2022) 12 1114

Innovative approach using literature measurements

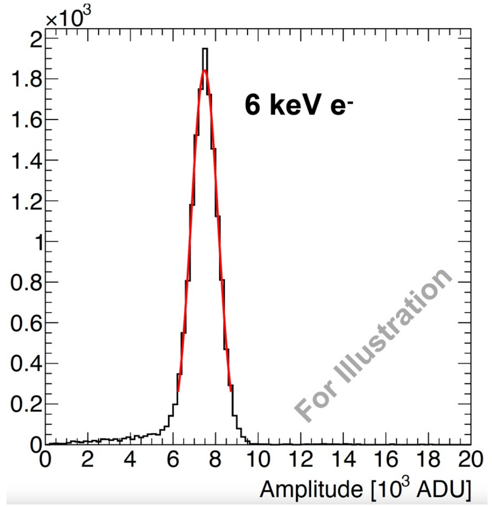
Astropart.Phys. 141 (2022) 102707

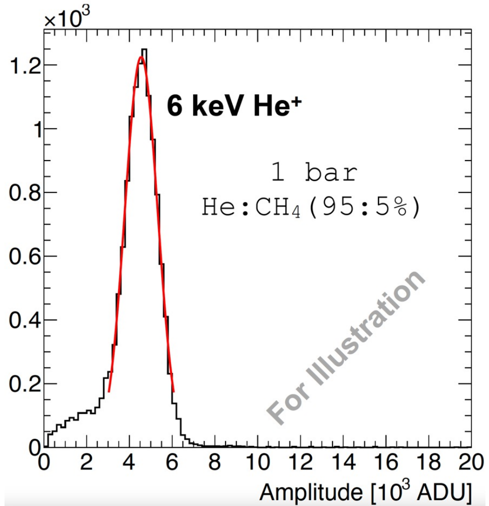
TUNL:





Grenoble:





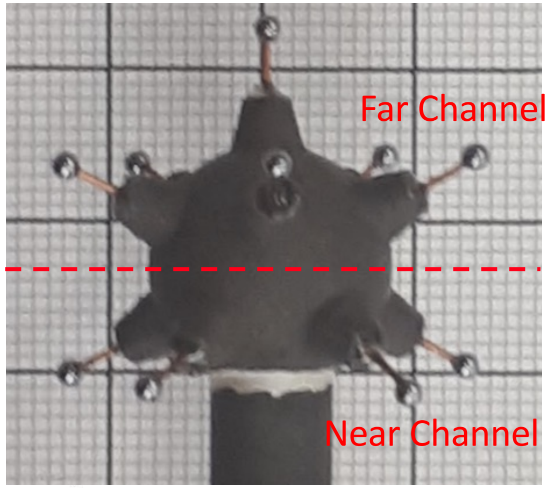
11-anode ACHINOS sensor – Two channels readout

Shockley–Ramo theorem

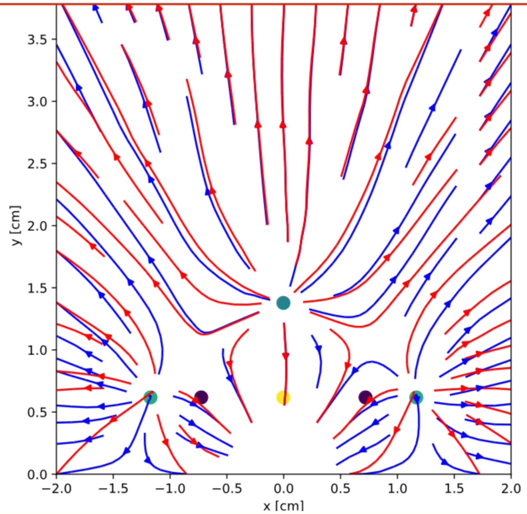
- instantaneous electric current induced by a charge moving in the vicinity of an electrode

$$i = -q\frac{\vec{E}_w \cdot \vec{v}}{V_w}$$

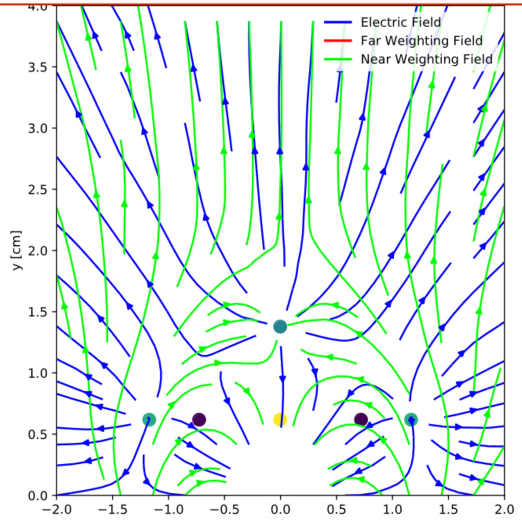
- Weighting fields produce negative pulses to the off-trigger channel

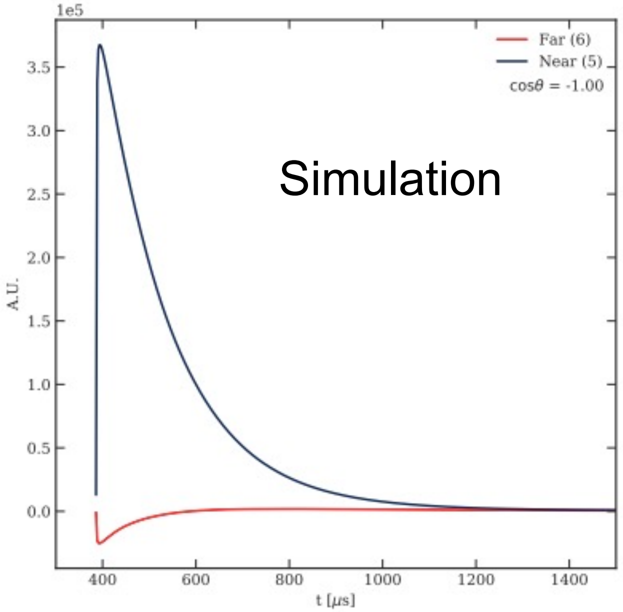


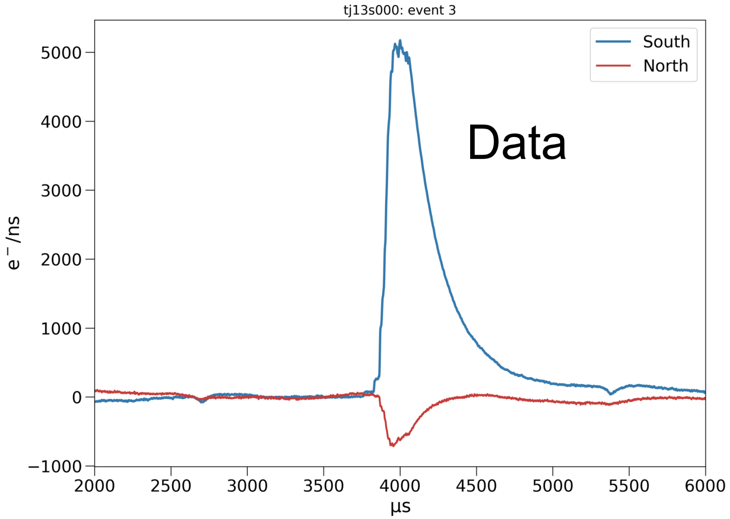
Far electrode weighting field on Far Side



Near electrode weighting field on Far Side



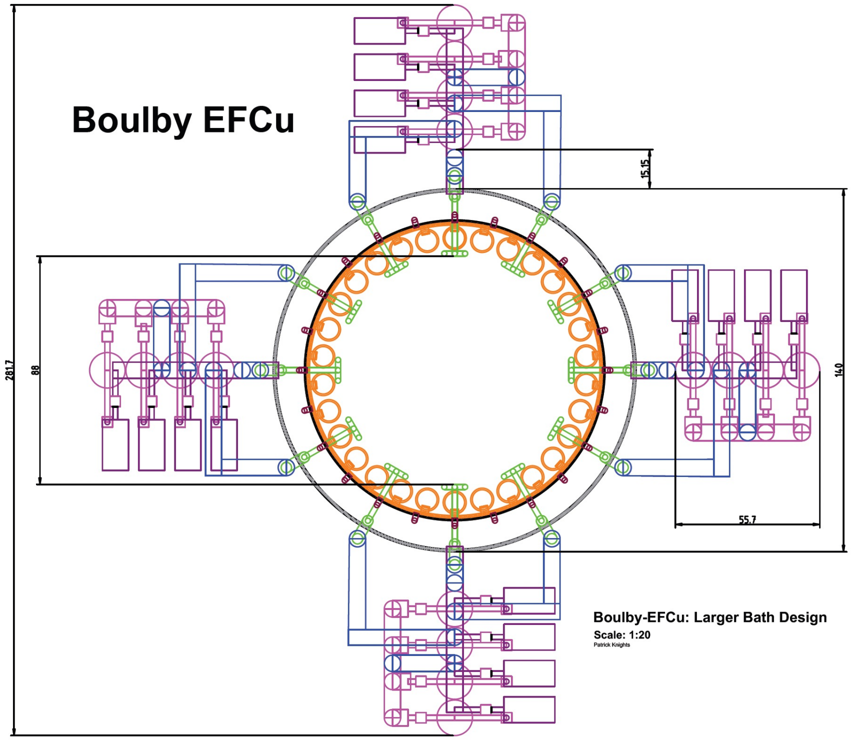


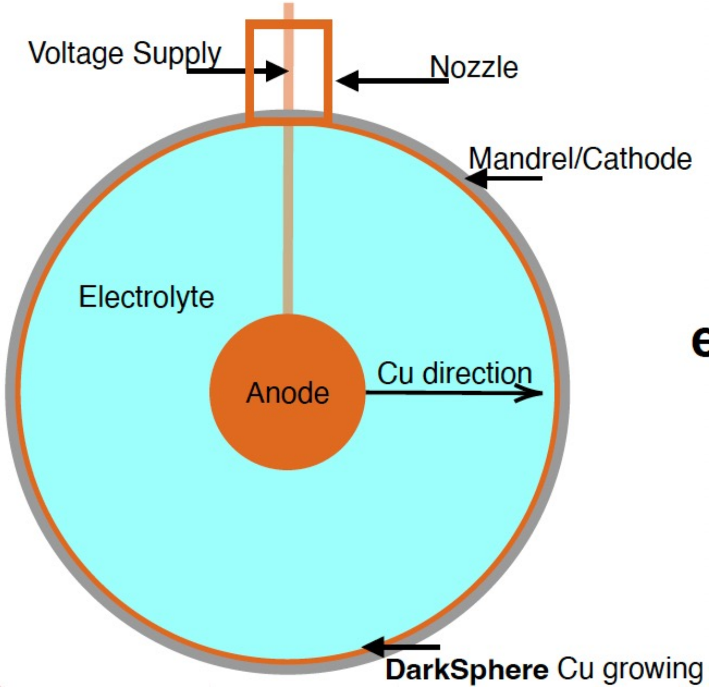


JINST 17 (2022) C08025

DarkSPHERE will be fully electroformed underground in Boulby

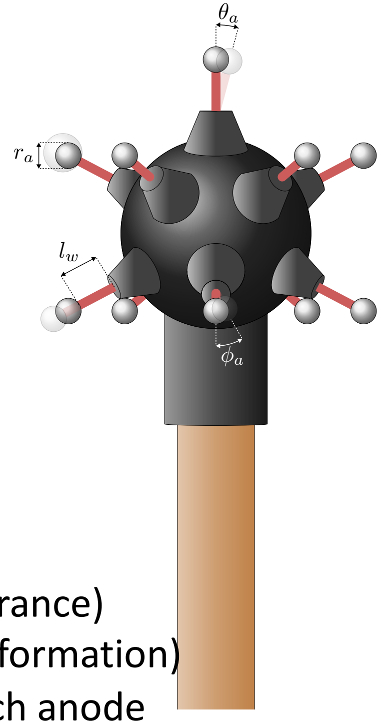
ECuME project, SNOLAB, of ⌀140cm detector + scale model in PNNL
STFC (UK funding agency) funding for an ultra-pure EFCu facility underground in Boulby
➡️Currently under construction





Individual ACHINOS channels readout

Two channels readout limitations

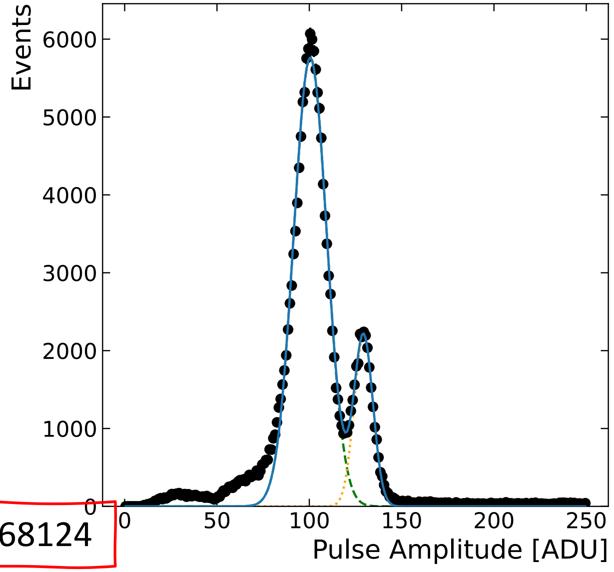


Two channel readout cannot exploit detector potential

- Construction non-uniformities effect on
  - Field non-homogeneities
  - Limited resolution

Example: Thermal neutron peak detection on 5-anode channel

- 4-anodes present energy resolution ~20%
- 1-anode has different gain, with energy resolution ~7%

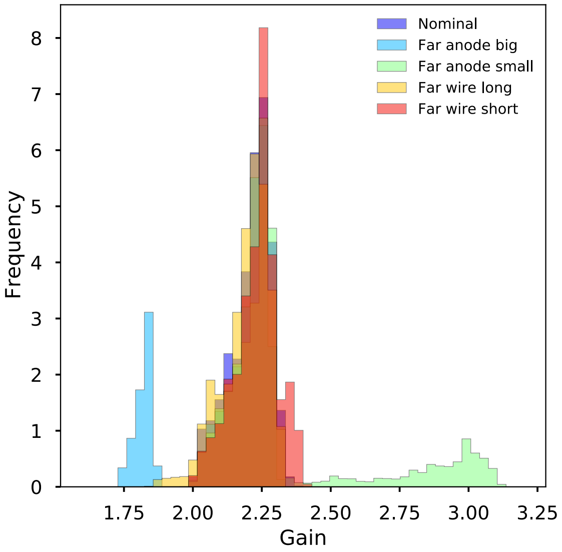


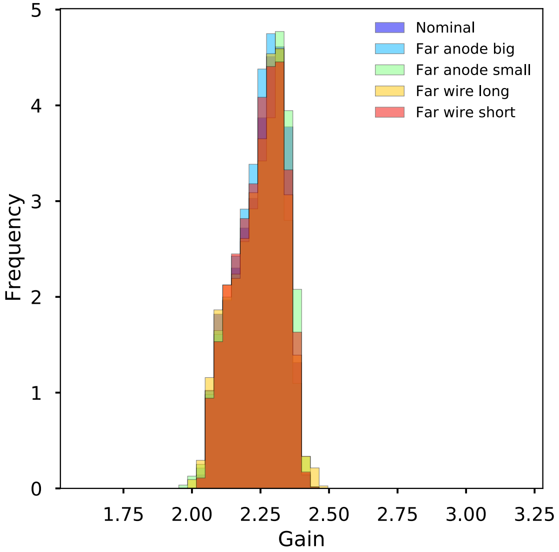
NIMA 1049 (2023) 168124

Evaluating sensor deformations

__Simulation study__

- Gmsh and Elmer to reproduce ACHINOS sensor
- Deformations considered
  - Radius (r_α) $\pm$0.075mm (manufacturer tolerance)
  - Wire length (l_w) $\pm$0.05mm (perceptible deformation)
- Correction by applying a different voltage to each anode

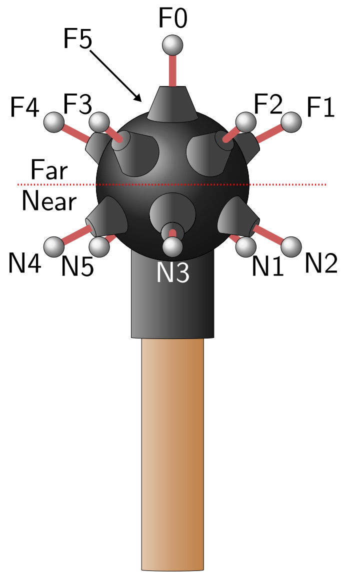




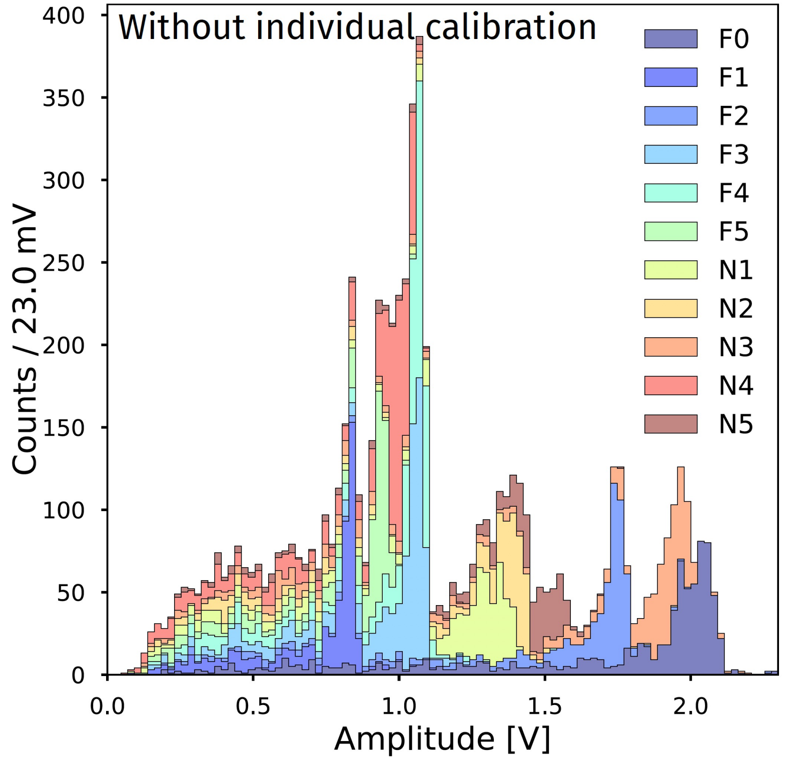
Performance of ACHINOS sensor – Individual readout

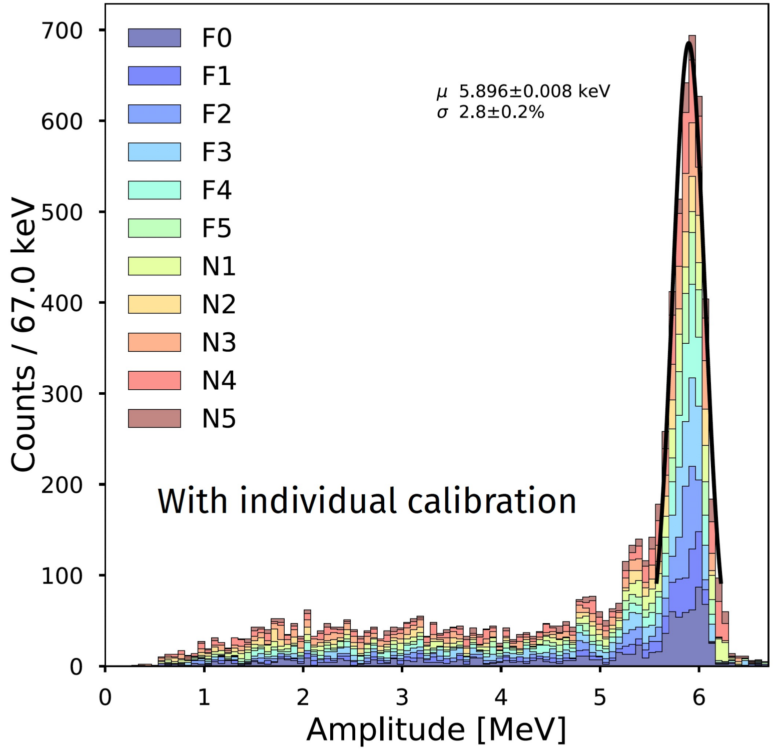
Response of the SPC to shared events on multiple anodes

- ^{210}Po α source, pointing each individual anode
- Individual anode normalisation, using calibration data



Data (500 mbar Ar:CH4 2%)





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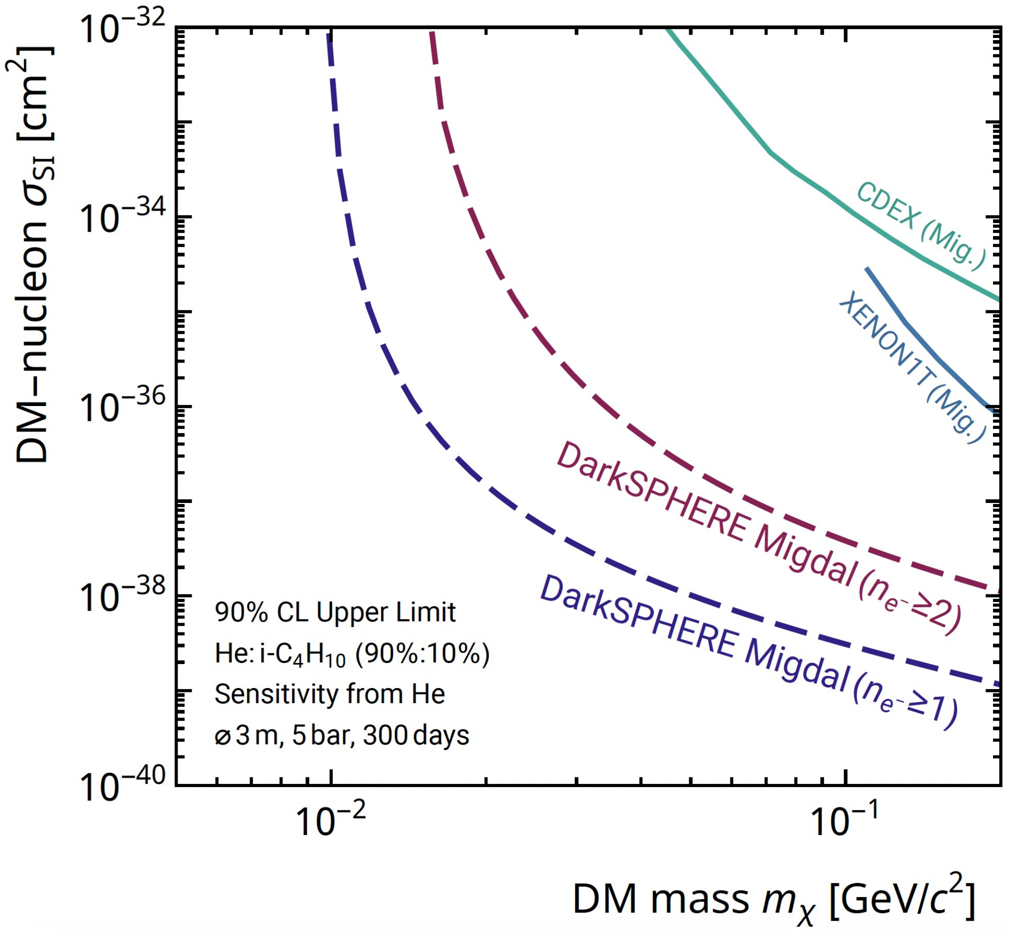
DarkSPHERE: Physics potential



- Enhanced sensitivity through **MIGDAL effect** in nuclear scattering