Recent advancements in the SPC instrumentation for the NEWS-G experiment

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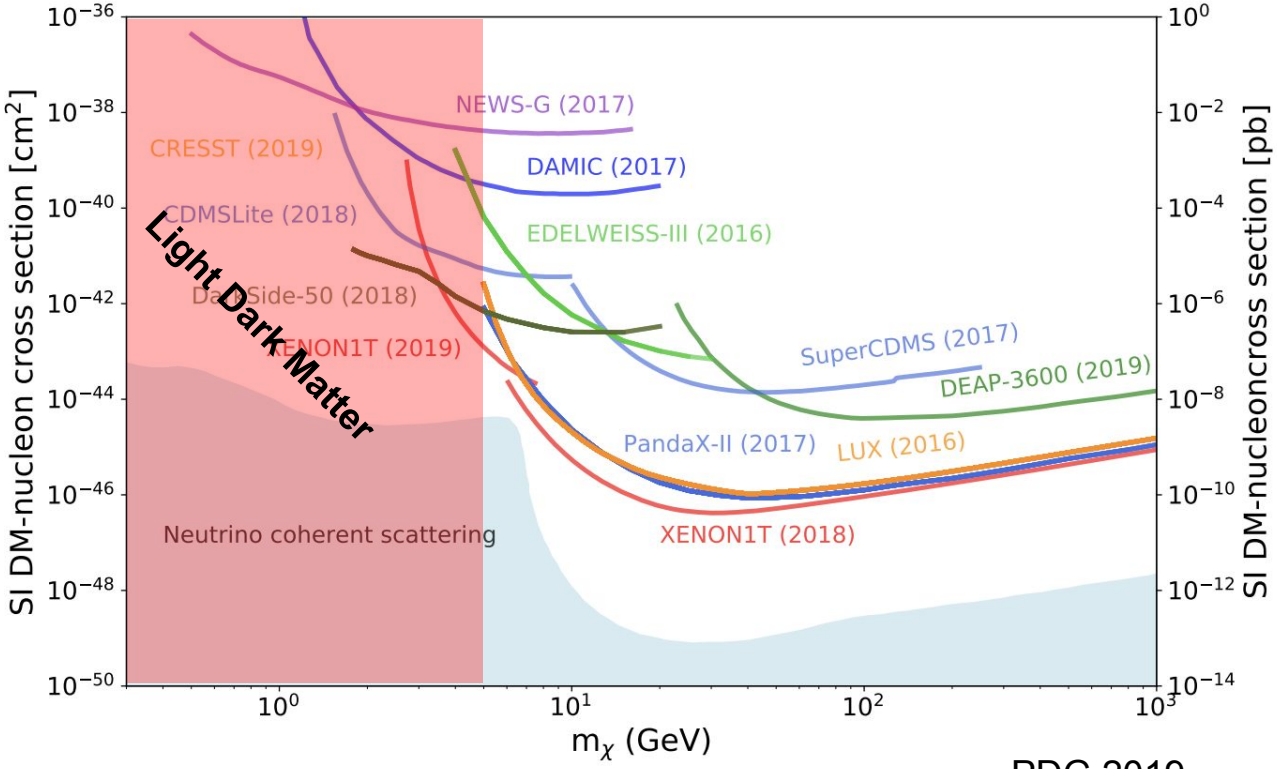
Light Dark Matter searches with an innovative gaseous detector the Spherical Proportional Counter

HHeNe

news-g.org

NEWS-G collaboration
UK, France, Greece, Canada, US

Light Dark Matter (LDM) mass region



PDG 2019

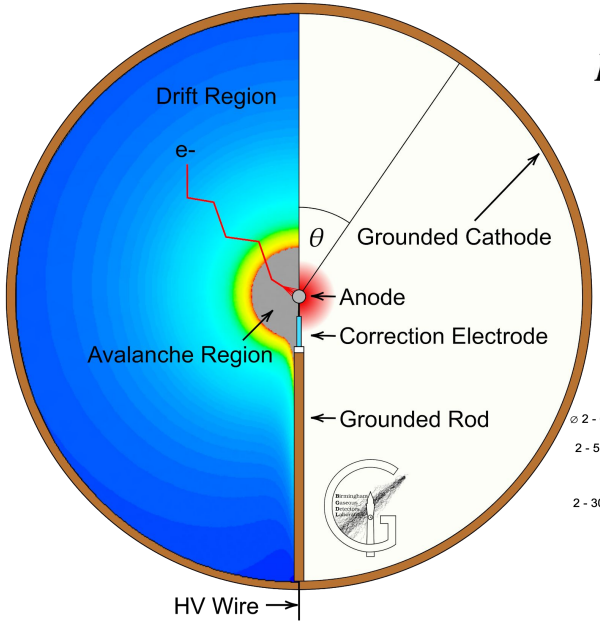
LDM searches require detectors with:

- **Lower thresholds**
- **Lighter targets**

For projectile-target kinematic match and increased ionisation by nuclear recoils

See K.Nikolopoulos' talk
See M.Vidal's talk

The Spherical Proportional Counter

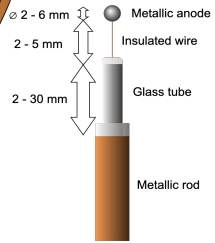


Electric field

$$E(r) = \frac{V_0}{r^2}\frac{r_A r_C}{r_C - r_A} \approx \frac{V_0}{r^2} r_A$$

r_A = *anode radius*
r_C = *cathode radius*

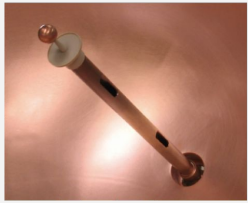
Design



Implementation

Basic advantages

- **Large volume/ few read-out channels**
- **Single electron threshold:**
  - **Low capacitance**
  - **High gain**
- **Radio-pure construction**
- **Background rejection handles**
- **Flexible operation**
  - **Swappable gases-targets**
  - **Variable pressure choice**

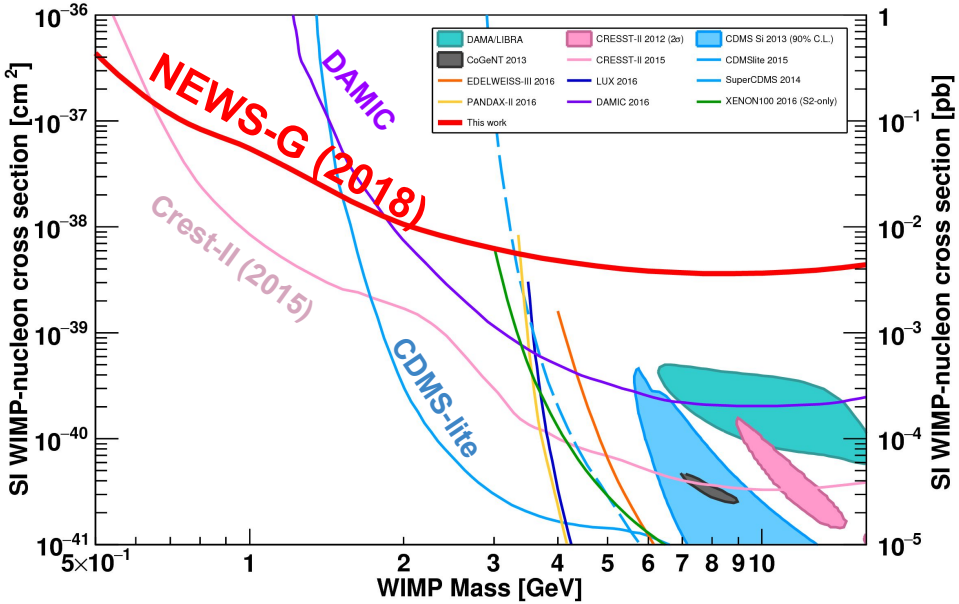


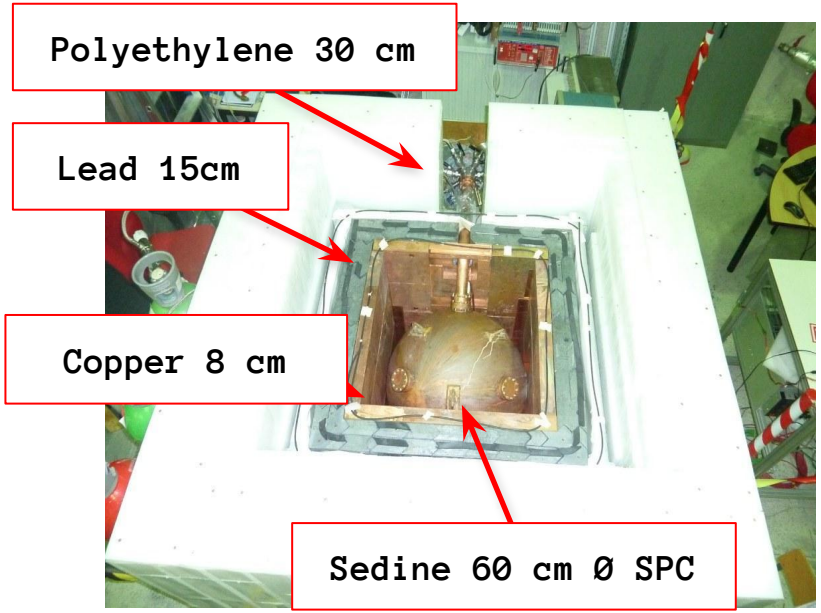
I.Giomataris et al ,JINST,2008, P09007

I. Katsioulas et al, JINST, 13, 11, P11006, 2018
10.1088/1748-0221/13/11/P11006

First NEWS-G results at LSM

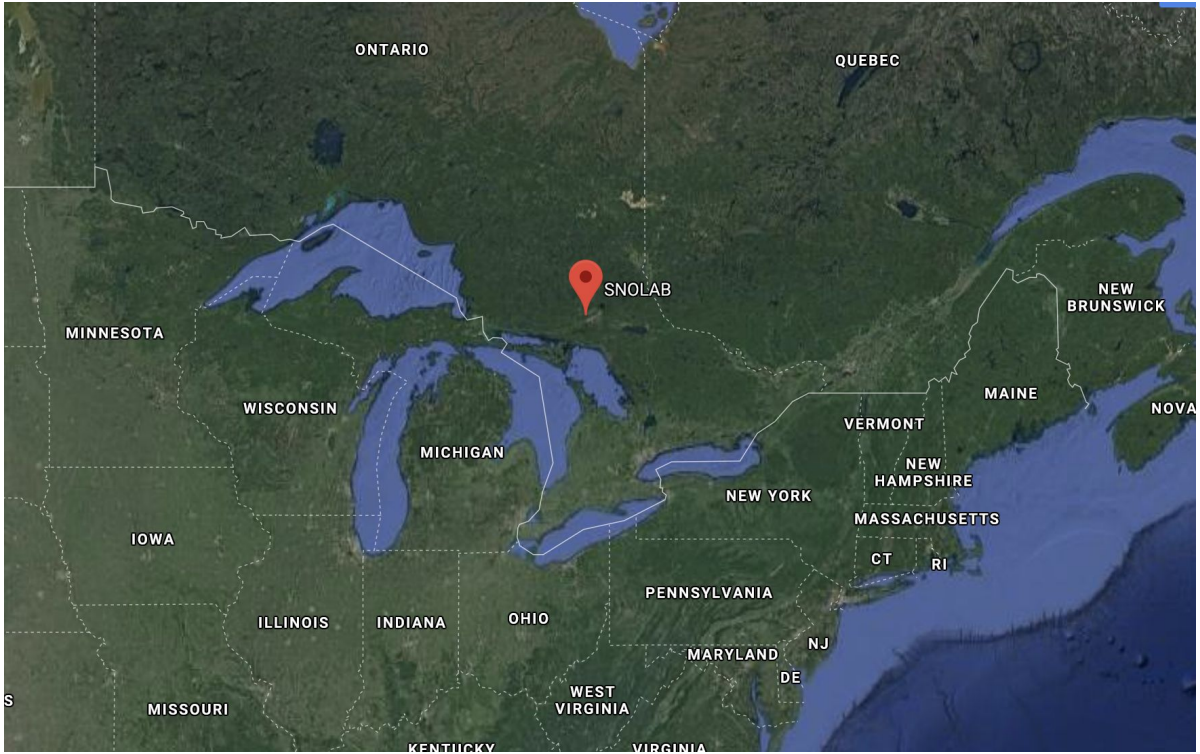
[NEWS-G collaboration, Astropart. Phys. 97, 54 (2018)](#)





Ne+0.7%CH_4 at 3.1 bar (280 g)
9.6 kg*days (34.1 live-days x 0.28 kg)

NEWS-G at SNOLAB

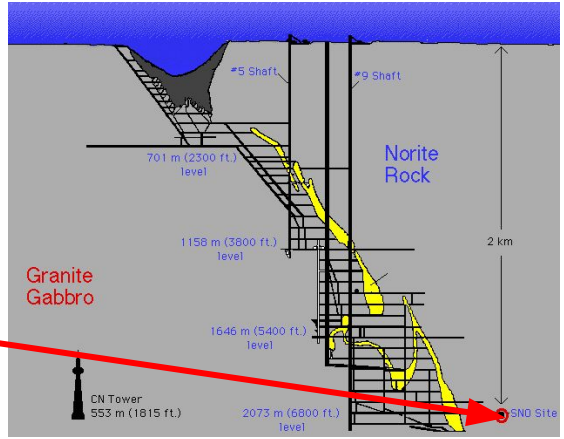


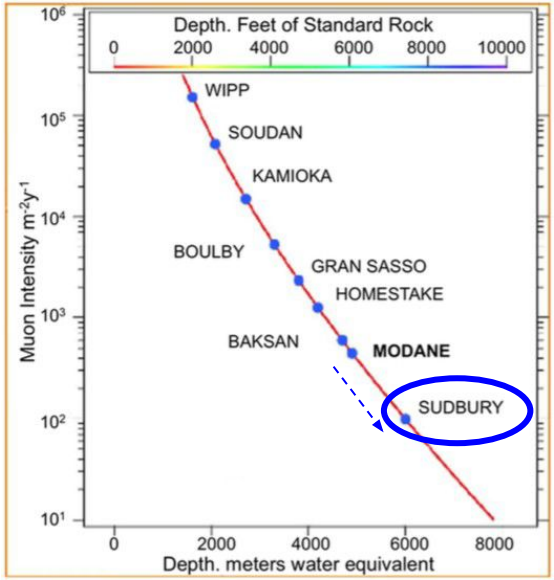
NEWS-G at SNOLAB

The underground laboratory in the Sudbury, Canada

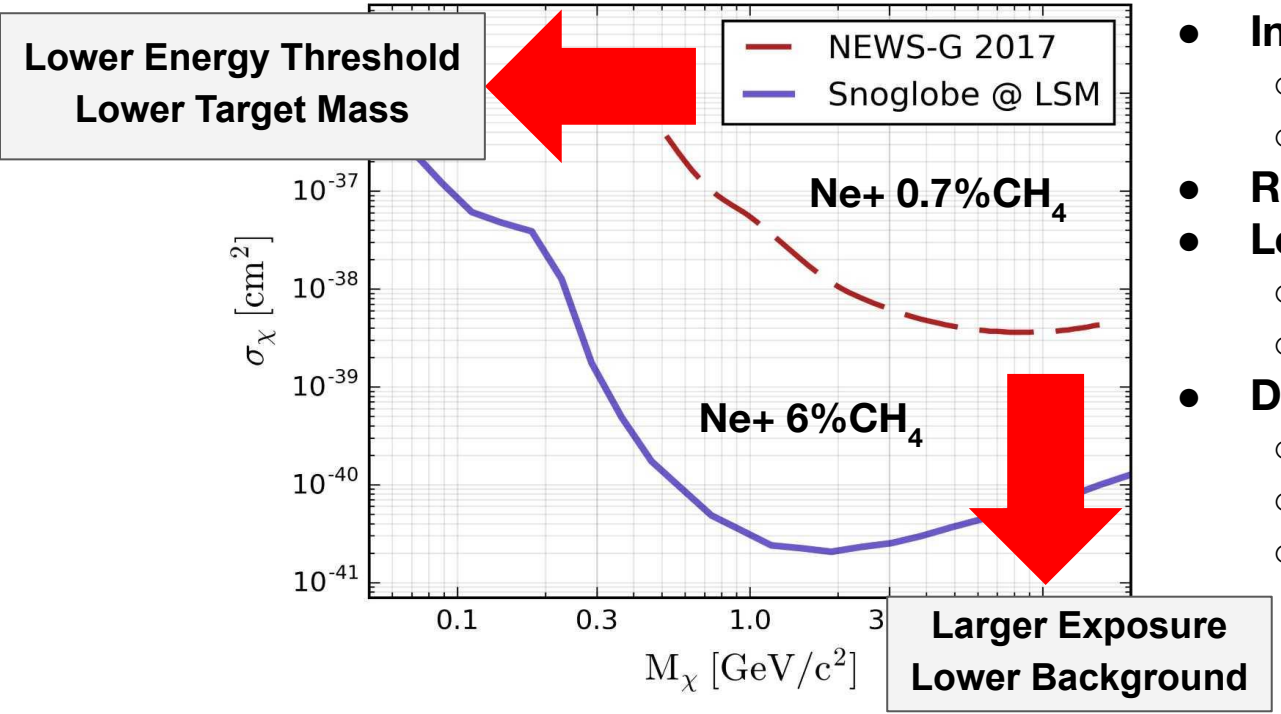
Deeper underground
0.25 μ/m²/day
~8x lower μ flux than LSM

At 2 km: the world's deepest clean room



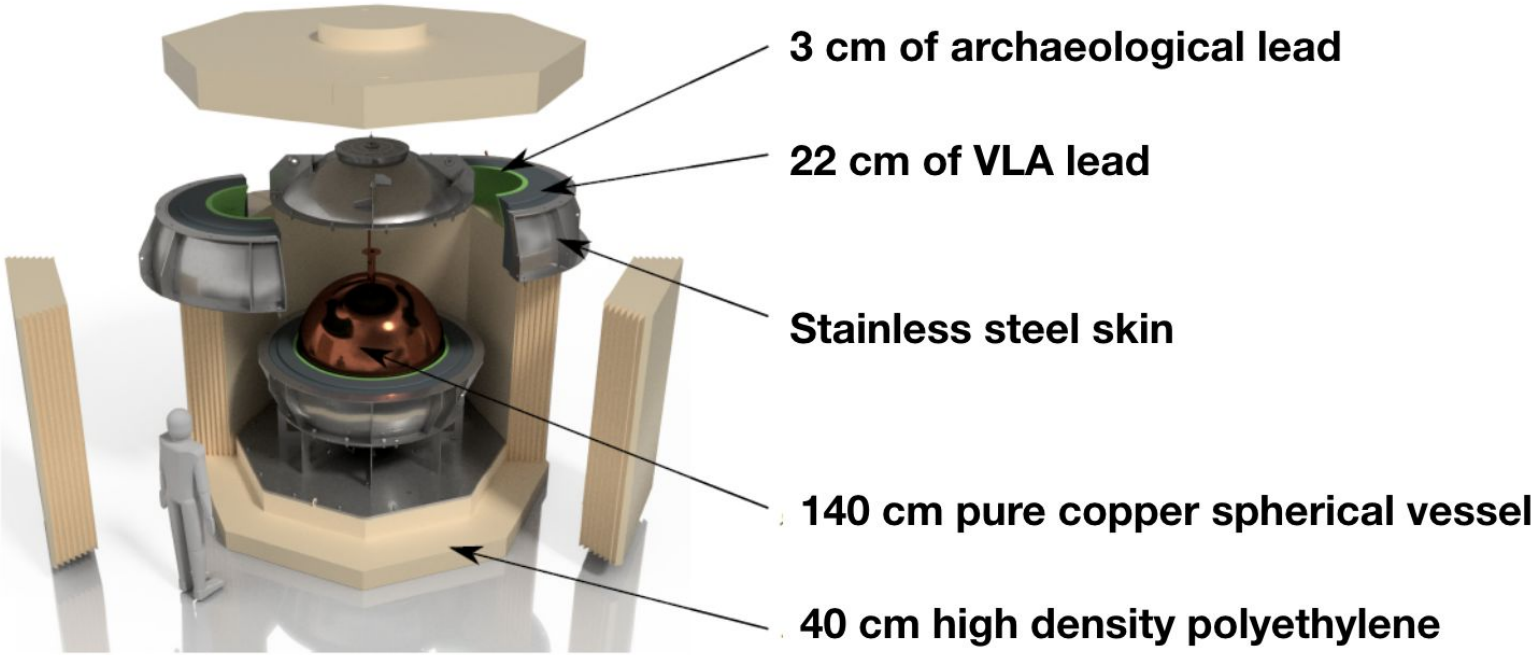


NEWS-G aims for the future

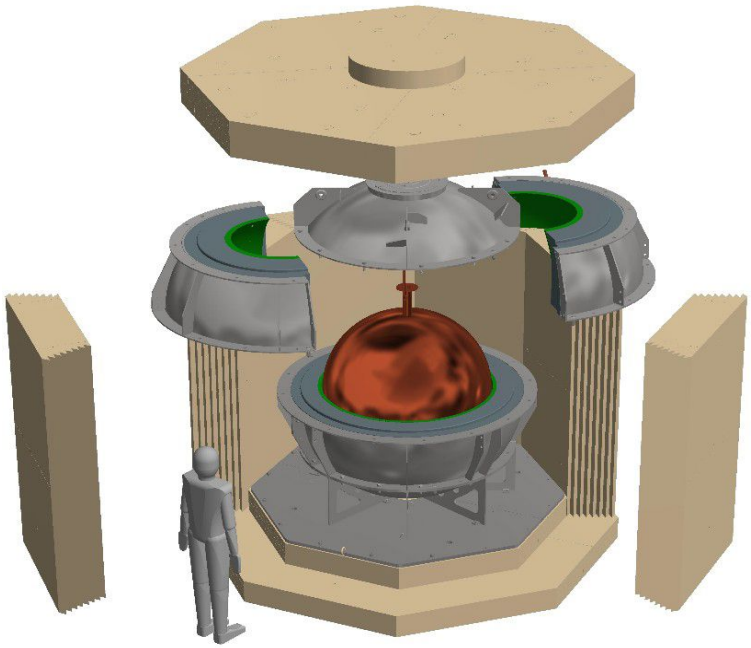


- Increase exposure
  - Mass
  - Duration
- Reduce backgrounds
- Low energy threshold (1e-)
  - High gain
  - Hydrogen reach targets
- Data quality monitoring
  - Control Pressure
  - Gain
  - Gas quality

The SNOGLOBE detector - Configuration



The SNOGLOBE detector - Challenges



- Uniform charge collection and high pressure operation
  - Electric field strength
  - Contaminants reduction
- Material purity
- Monitoring and calibration

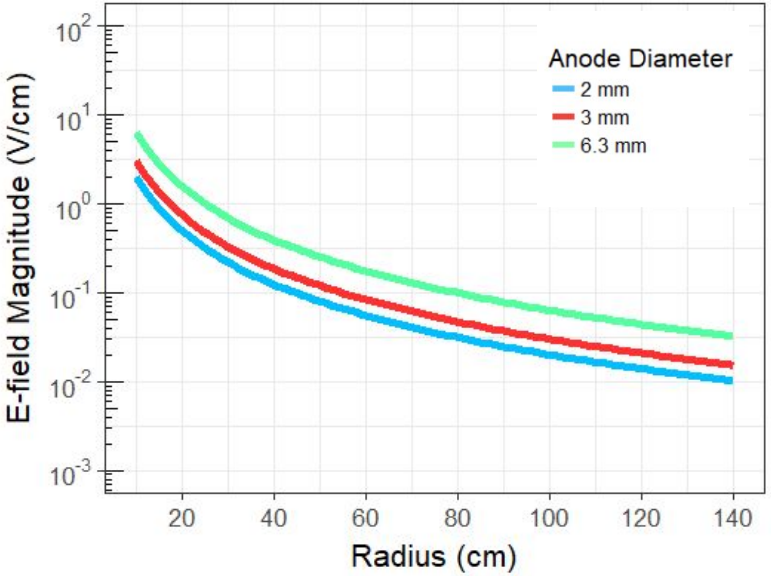
Sensor

Electric field strength in large volume SPCs

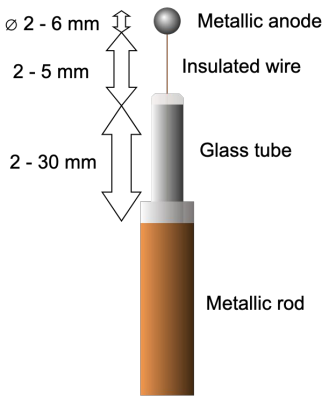
Scaling-up

$$v_{drift}(E/P), G(E/P) \sim E \approx r_A \frac{V}{r^2}$$

Comparison of E-field magnitude for different anode diameters



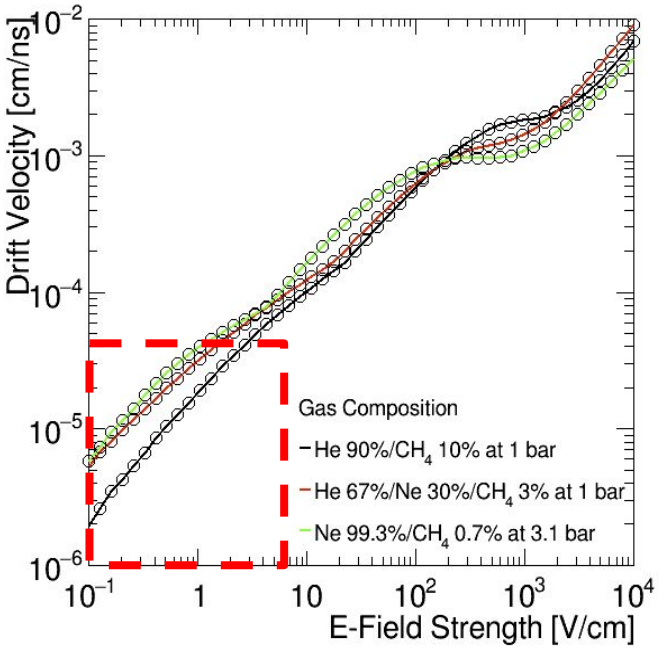
Single anode glass sensors

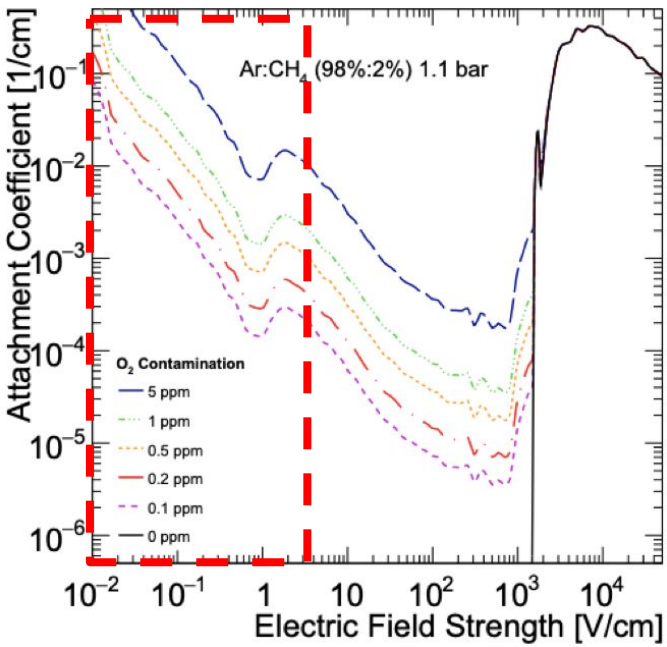


I. Katsioulas et al, JINST, 13, 11, P11006, 2018
10.1088/1748-0221/13/11/P11006

Charge collection in low electric field

Magboltz study on the sensitivity to contaminants





Low E-field region

Charge collection in low electric field

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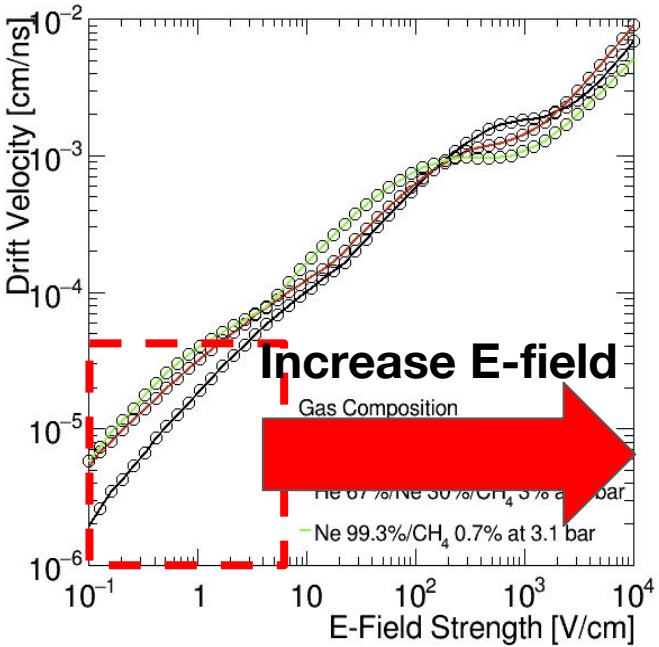
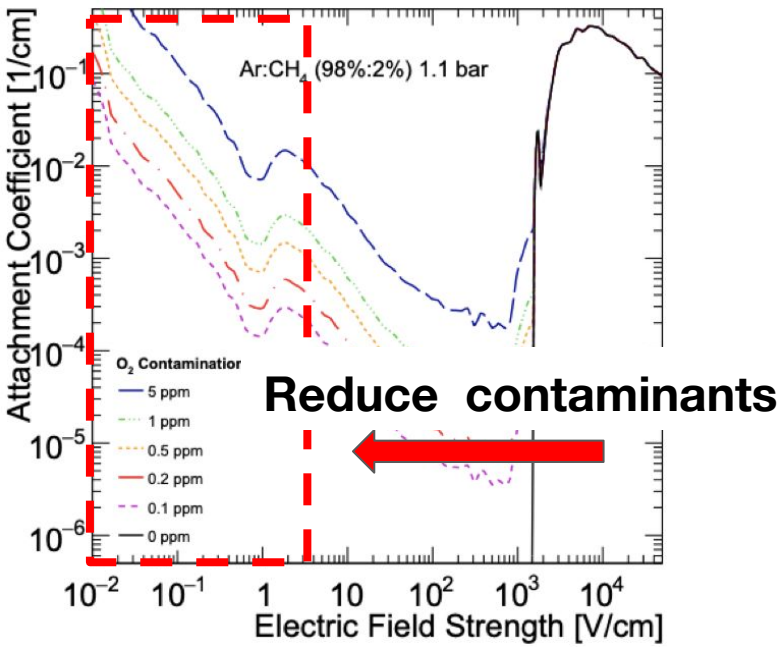
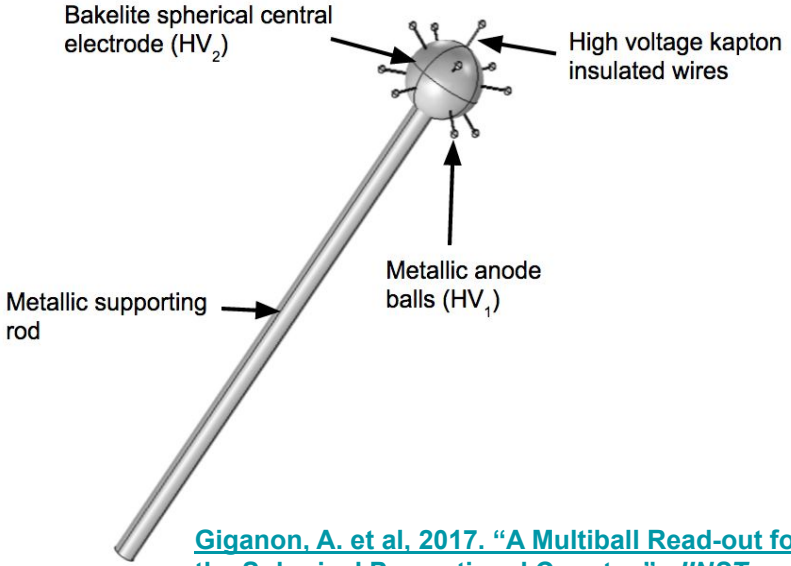




Low E-field region

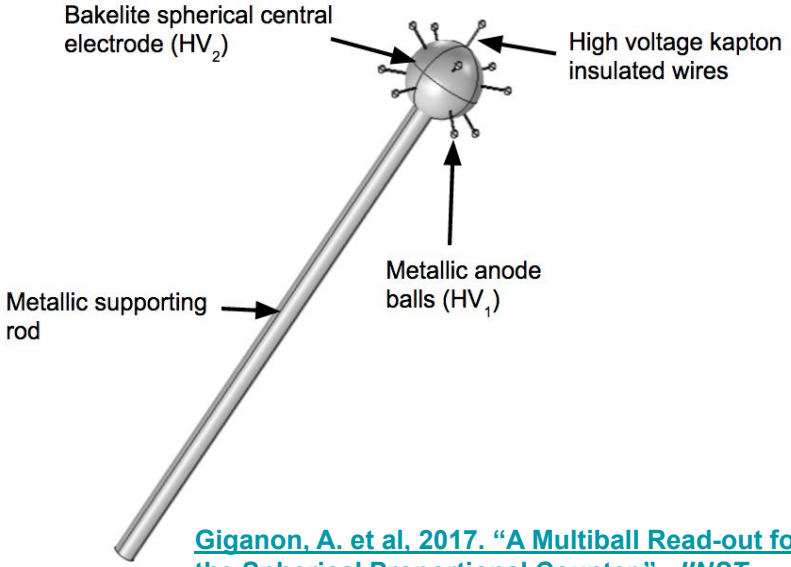
The multi-anode sensor - ACHINOS



Giganon, A. et al, 2017. "A Multiball Read-out for the Spherical Proportional Counter.", *JINST*

Instead of one ⇒ Use multiple anodes set to the same potential !!!

The multi-anode sensor - ACHINOS



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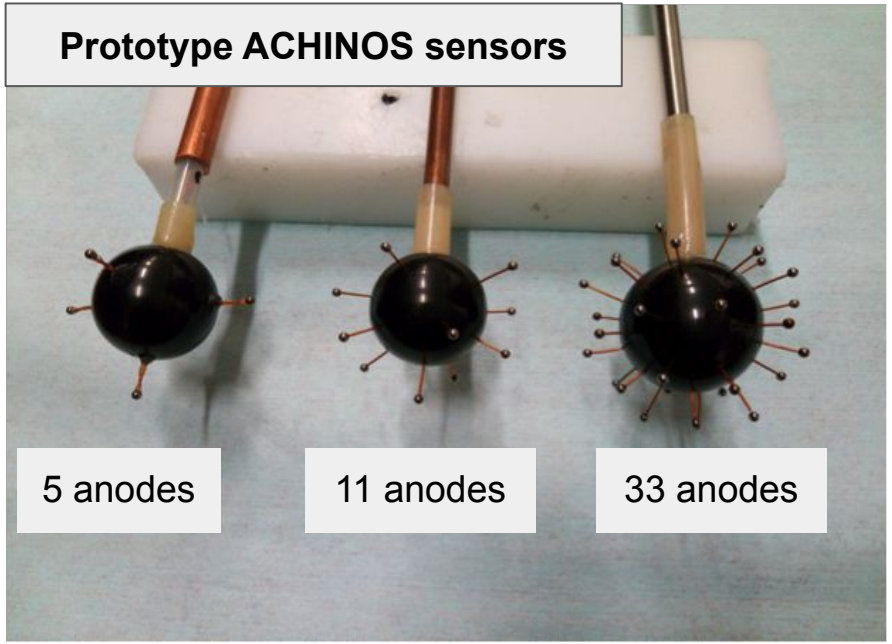
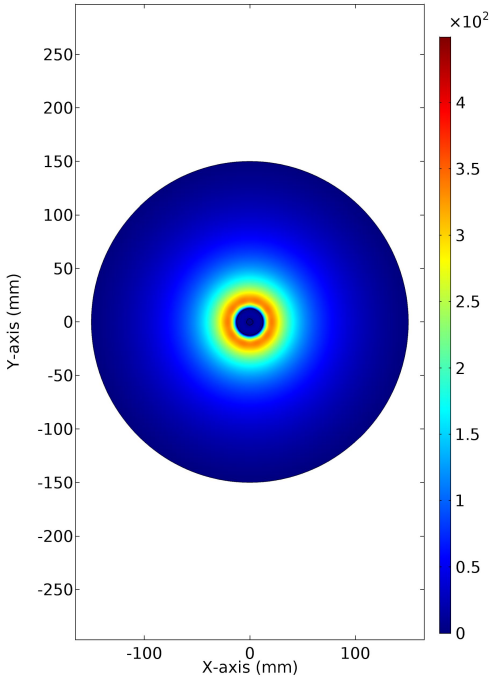


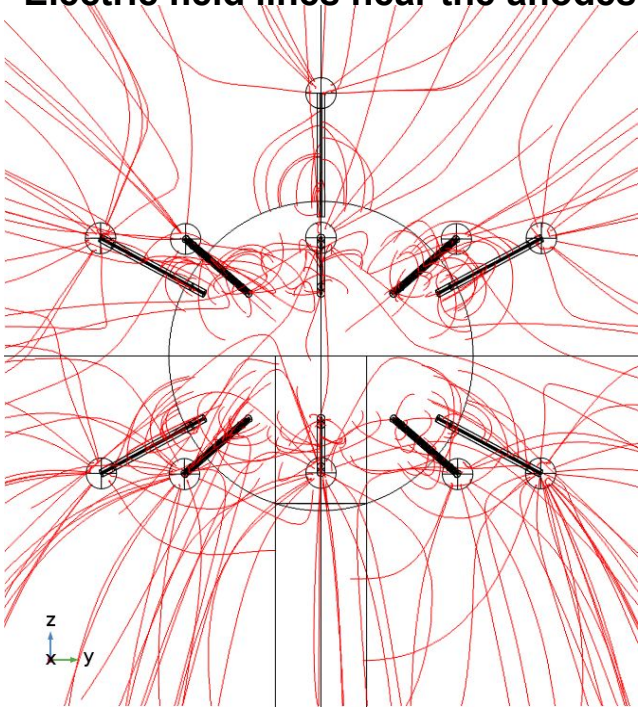
Instead of one ⇒ Use multiple anodes set to the same potential !!!

Electric field configuration with an ACHINOS

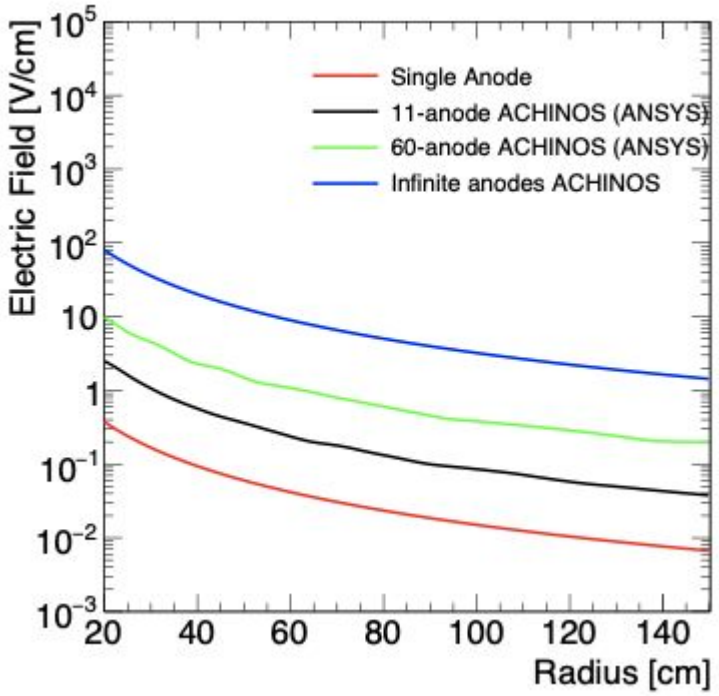
Collective iso-potentials



Electric field lines near the anodes



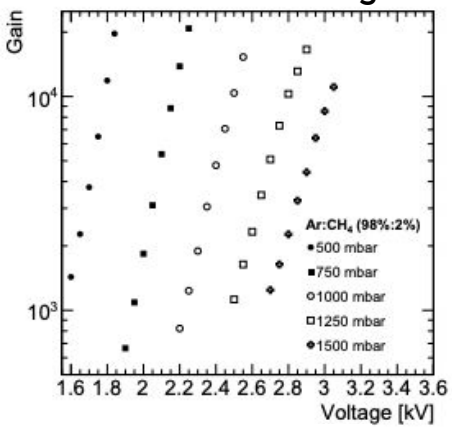
Advantages of the ACHINOS sensor

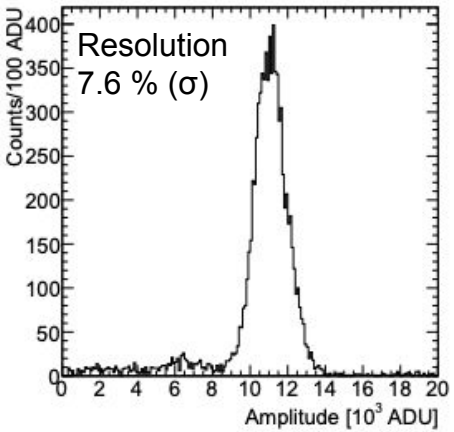


- Decouples electron drift and multiplication
  - Small anode size → high gain
  - More anodes → Efficient charge collection
- Allows for increased target mass
  - Larger volume
  - Higher pressure
- Individual readout TPC-like capabilities to the SPC

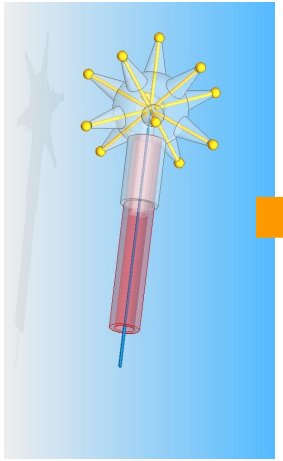
Performance of ACHINOS with resistive coating

Gain vs Voltage

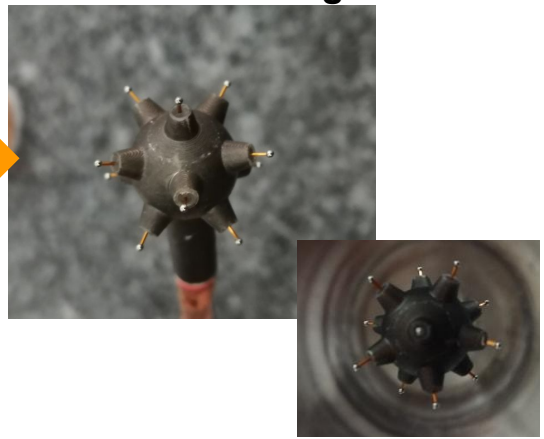


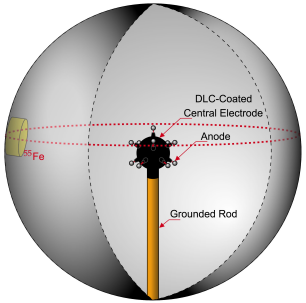


3D design



3D printed modules with DLC coating



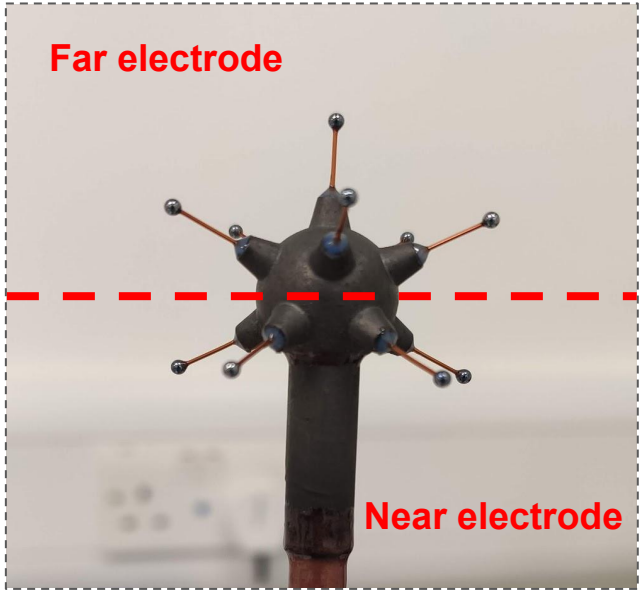


Measurement of the 5.9 keV ^{55}Fe X-ray line

I. Giomataris *et al* 2020 *JINST* 15 P11023

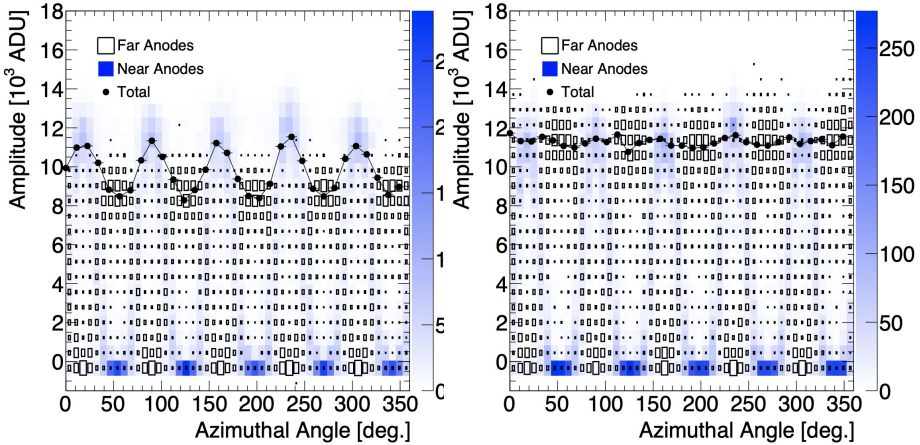
- Good energy resolution
- High pressure operation (> 2 bar)
- High gain
- Stability
- Multi-anode readout

Performance of ACHINOS with resistive coating



I. Giomataris *et al* 2020 *JINST* 15 P11023

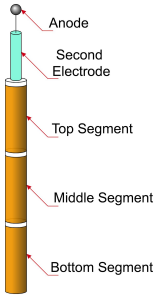
Simulations



- Good energy resolution
- High pressure operation (> 2 bar)
- High gain
- Stability
- **2 channel readout**

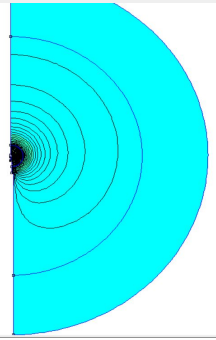
Results expected soon!

E-field correction - Voltage degrader

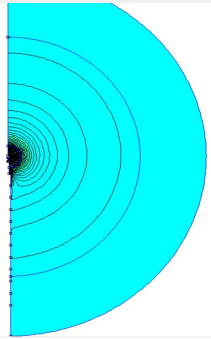


- **Grounded rod distorts electric field**
- **Voltage gradient along rod, as in ideal geometry, would restore ideal field.**
- **Voltage applied to each segment is the average ideal voltage over the segment.**

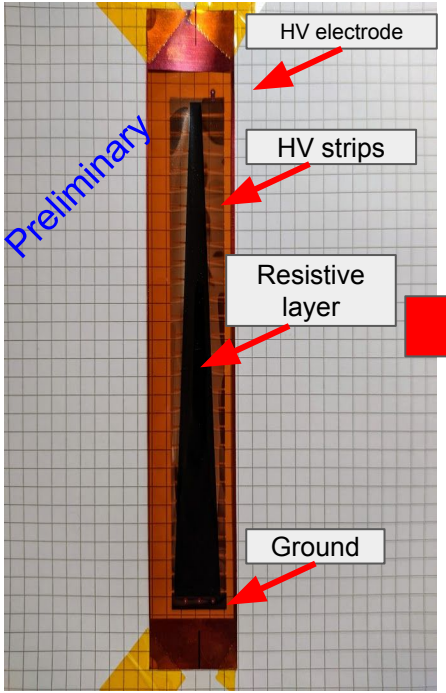
No correction



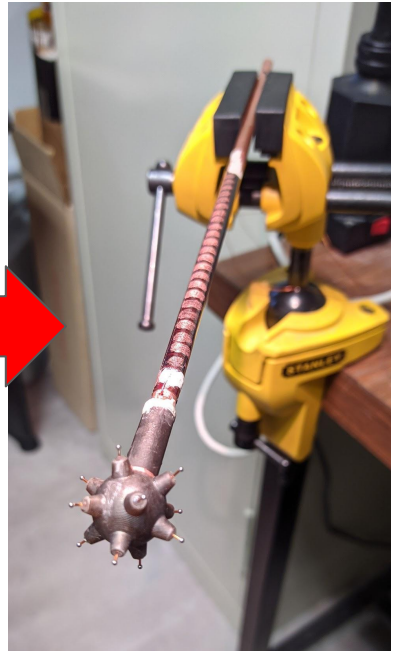
Voltage degrader



Resistive strip degrader



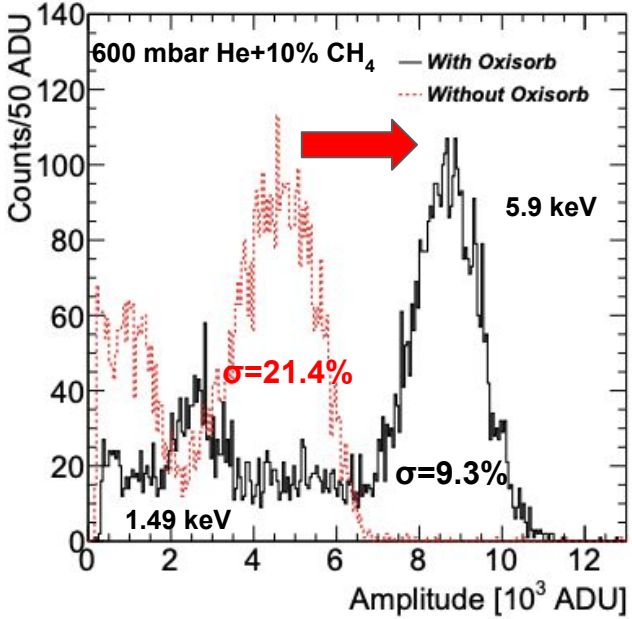
ACHINOS with Degrader

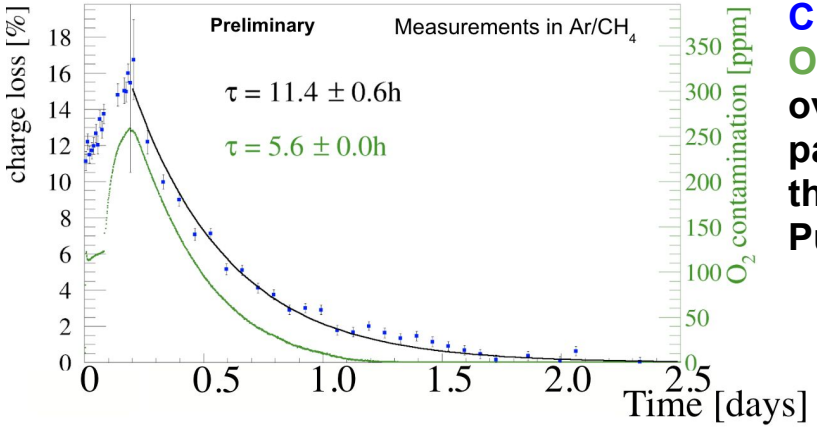


Purification

Gas Purification

- Contaminants: O_2, H_2O, electronegative gases
- Filtering with: Getter, Oxysorb, Custom filter
- Filtering in a gas recirculation system
  - SAES MicroTorr Purifier (MC700 902-F)
  - Incorporated with Residual Gas Analyser
- Improved filtering efficiency in large sphere





Charge Loss and **Oxygen Concentration** over Time while gas passes circulated through MicroTorr Purifier

Laser

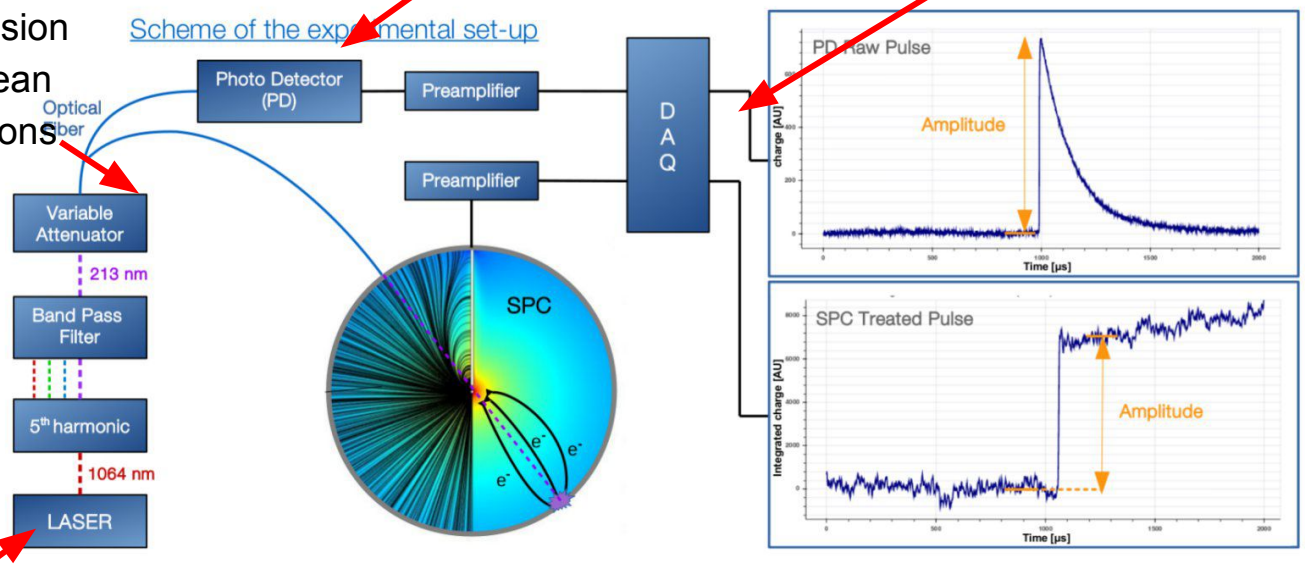
Q. Arnaud et al. (NEWS-G Collaboration), Phys. Rev. D 99, 102003 (2019)

Laser calibrations

Parallel photo-detector to tag laser events

Common DAQ for timing analysis between two channels

Tunable transmission to control the mean number of electrons

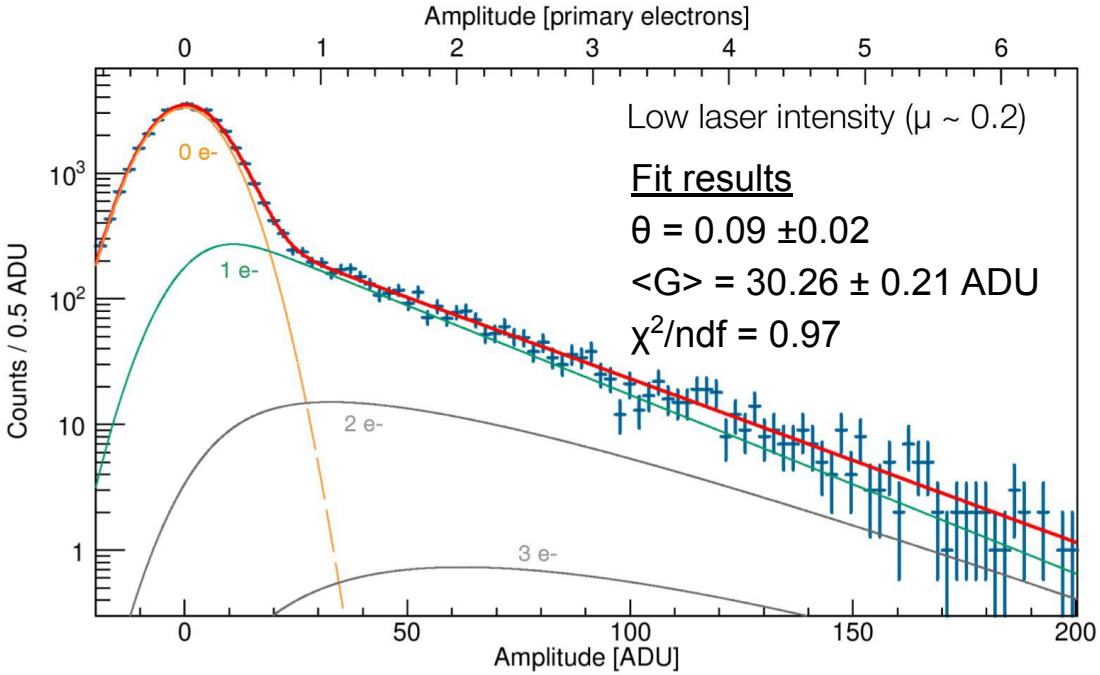


A powerful UV laser capable of extracting 100s of electrons

- **213 nm laser used to extract primary electrons from wall of SPC**
- **Photo detector in parallel tags events and monitors laser power**
- **Laser intensity can be tuned to extract 1 to 100 photo electrons**

Modeling the Single Electron Response

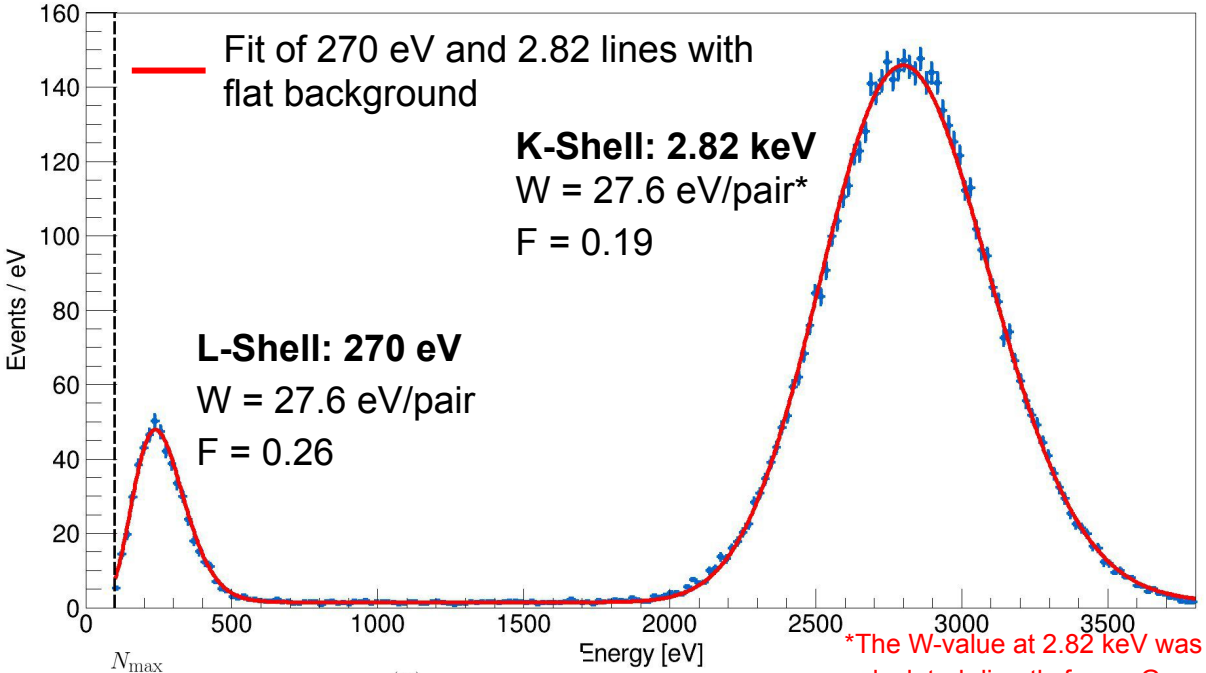
Q. Arnaud et al. (NEWS-G Collaboration), Phys. Rev. D 99, 102003 (2019)



- N photo-electrons are extracted from the surface of the sphere: Poisson
- Each photo-electron creates S avalanche pairs: N^{th} convolution of Polya
- Sum the contributions of all N photo-electrons
- The overall response is convolved with a Gaussian to model baseline noise

Q. Arnaud et al. (NEWS-G Collaboration), Phys. Rev. D 99, 102003 (2019)

Ar37 calibrations and gas fundamentals properties measurement



$$f(E') = \sum_{N=1}^{N_{\max}} P_{\mathrm{CMP}}(N|\mu, F) \times P_{\mathrm{Polya}}^{(\mathrm{N})}(E'|\langle G\rangle, \theta)$$

*The W-value at 2.82 keV was calculated directly from <G> and fixed for this fit

- Ar37 produced by irradiating Ca power with a high flux of fast neutrons
- Together with laser calibrations, can find W (mean Ionization energy) with 1% precision for target gas, and set upper limits on F (Fano factor)

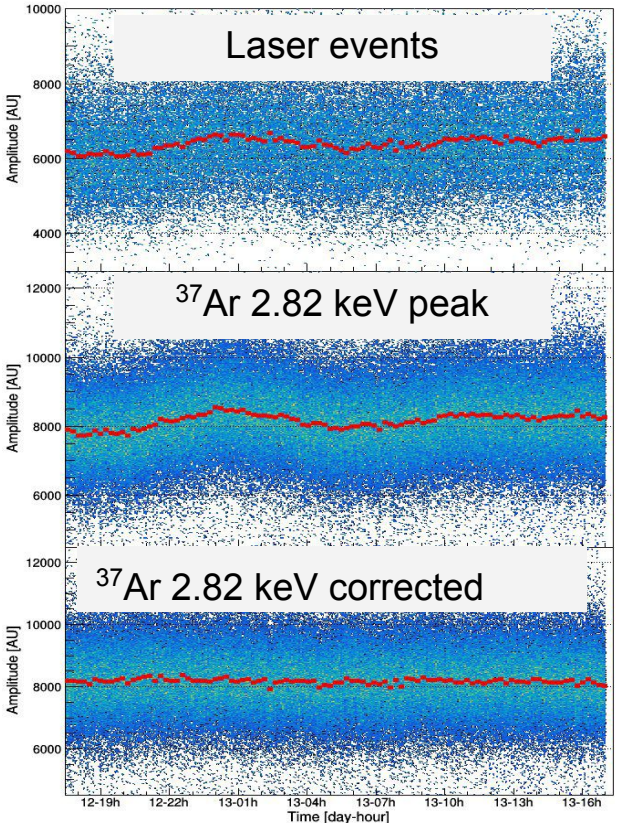
Detector response modeled:

- Primary ionisation (COM-Poisson)

D. Durnford et al, Phys. Rev. D 98, 103013 (2018)

- Avalanche (Polya)

Detector monitoring



The laser can be used to monitor the detector response during physics runs

Long-term fluctuations in gain can be caused by temperature changes, O_2 contamination, sensor damage...

Laser monitoring data could even be used to correct for long-term fluctuations *Q. Arnaud et al. (NEWS-G Collaboration), Phys. Rev. D 99, 102003 (2019)*

Material radiopurity

Background in NEWS-G copper

Copper as a construction material

An excellent construction material for Rare Event experiments:

- **Strong enough to build gas vessels**
- **Commercially available at high purity**
- **Low cost**
- **No long-lived radioisotopes**
- **Longest ^{67}Cu $t_{1/2}$ = 62 h**

Spinning of SNOGLOBE

4N Aurubis Oxygen Free Copper C10100 (99.99%)

Spun into two hemispheres

Background in NEWS-G copper

Radioactive contaminants:

- **U and Th decay chain traces.**
- **$^{63}Cu(n,\alpha)^{60}Co$ produced by fast neutrons – mostly cosmic muon spallation.**

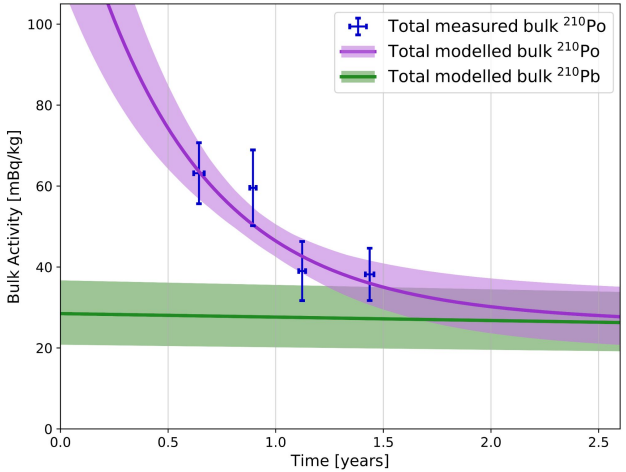
Radioassay for NEWS-G showed:

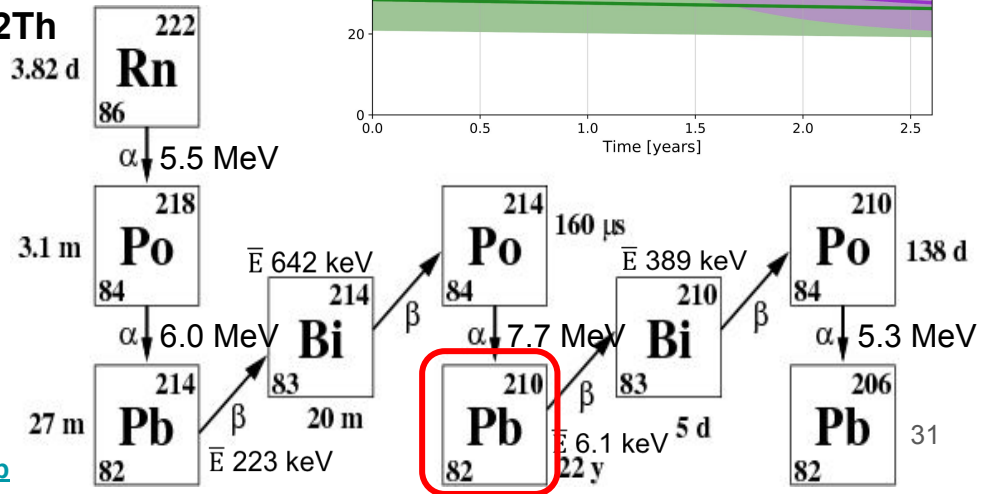
- **~10 μBq/kg using ICP-MS from 238U and 232Th**
- **~28.5 mBq/kg from out of equilibrium 210Pb using XIA UltraLo by inferring progeny activitie**

XIA UltraLo-1800

[NIM A884 (2018) 157-161]

Assay results of NEWS-G copper in collaboration with Kamioka lab





Background in NEWS-G copper

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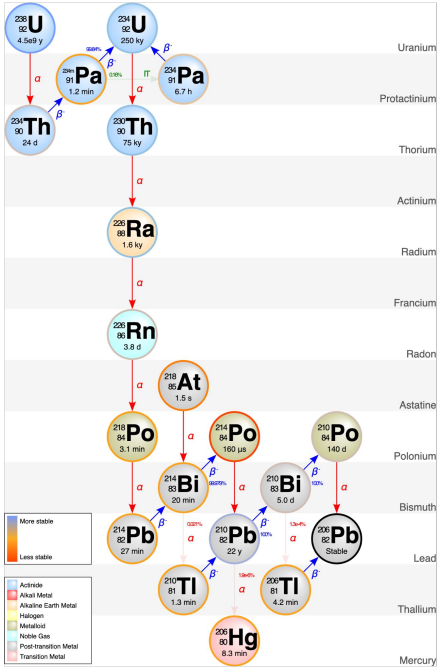
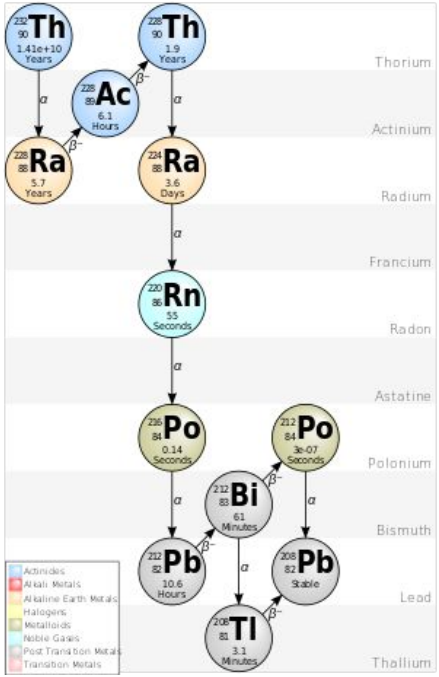
- **U and Th decay chain traces.**
- **$^{63}Cu(n,\alpha)^{60}Co$ produced by fast neutrons – mostly cosmic muon spallation.**





Background in NEWS-G copper

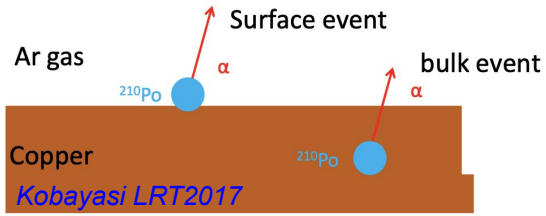
Copper used in SNOGLOBE

Radioassay for NEWS-G showed:

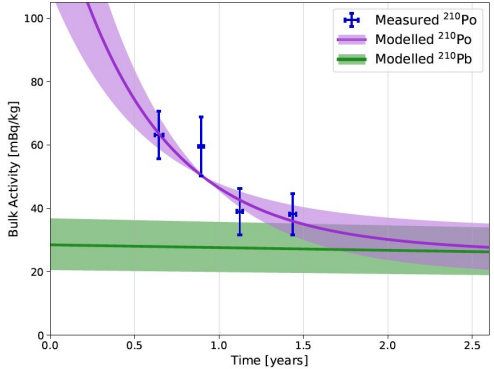
- **~10 μBq/kg using ICP-MS from naturally occurring ^{238}U and ^{232}Th**
- **~28.5 mBq/kg from out of equilibrium ^{210}Pb using XIA UltraLo (*Abe et al)* by inferring progeny activities**

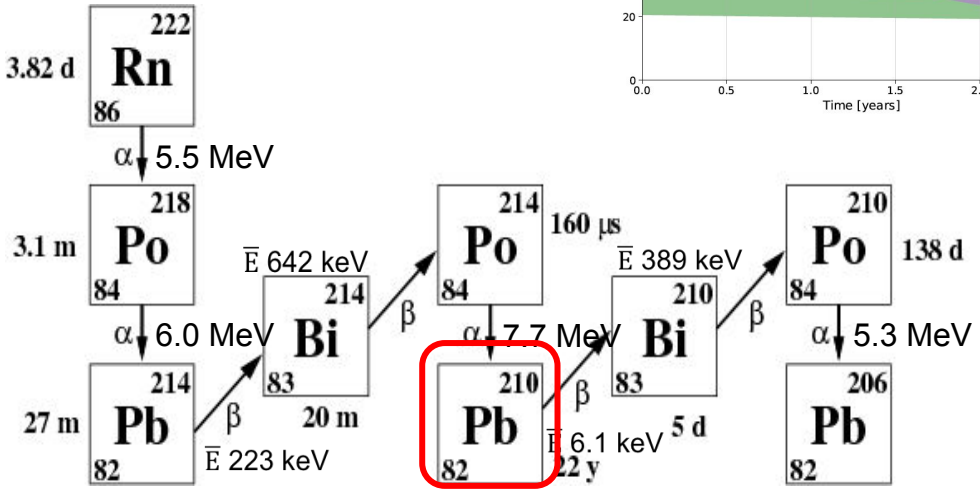
XIA UltraLo-1800

[NIM A884 (2018) 157-161]

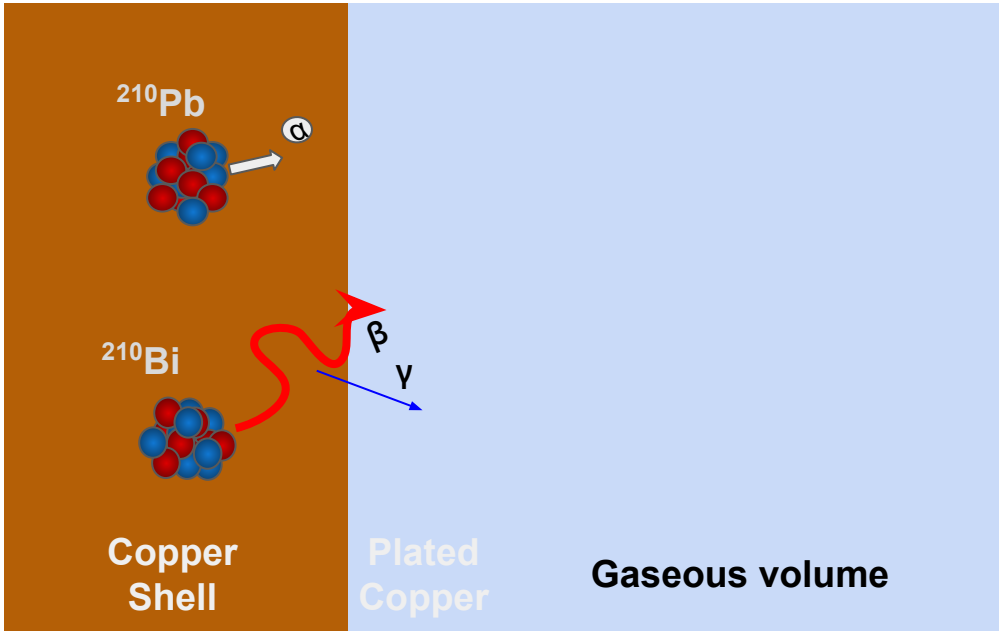


Assay in Kamioka using XIA



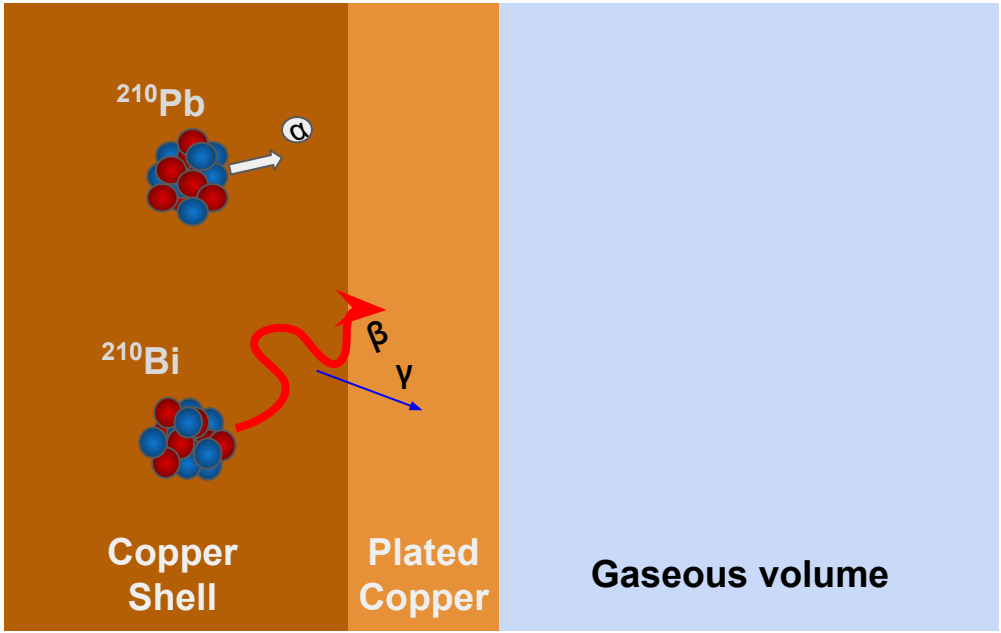


Electroplating Copper - Background mitigation



- **Background: Bremsstrahlung X-rays from ^{210}Pb and ^{210}Bi β-decays in Cu**

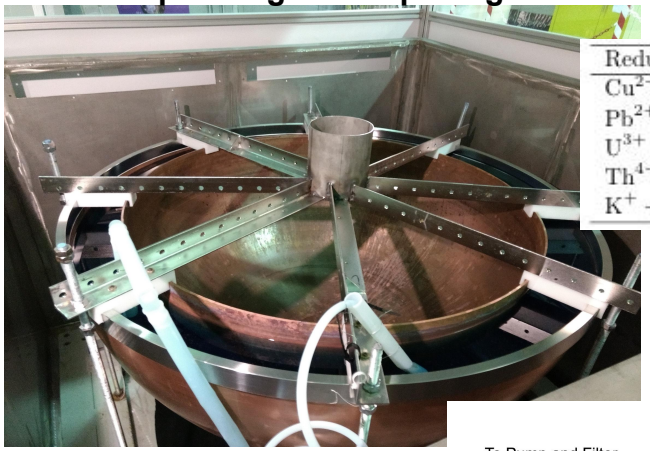
Electroplating Copper - Background mitigation



- Background: Bremsstrahlung X-rays from ^{210}Pb and ^{210}Bi β-decays in Cu
- Layer of ultra-pure Cu on the inner surface of the detector. Suppresses ^{210}Pb and ^{210}Bi backgrounds by factor 2.6 (under 1 keV)

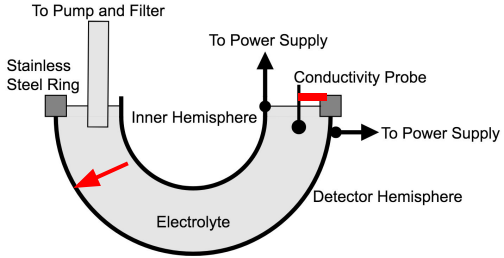
Electroplating Copper - Background mitigation

The setup during electroplating at LSM



Reductants		Oxidants	E^0 (V)
$Cu^{2+} + 2e^-$	$\leftrightharpoons$	Cu	+0.34
$Pb^{2+} + 2e^-$	$\leftrightharpoons$	Pb	−0.13
$U^{3+} + 3e^-$	$\leftrightharpoons$	U	−1.80
$Th^{4+} + 4e^-$	$\leftrightharpoons$	Th	−1.90
$K^+ + e^-$	$\leftrightharpoons$	K	−2.93

Cu Movement in Electroplating



- **Background: Bremsstrahlung X-rays from ^{210}Pb and ^{210}Bi β-decays in Cu**
- **Layer of ultra-pure Cu on the inner surface of the detector. Suppresses ^{210}Pb and ^{210}Bi backgrounds by factor 2.6 (under 1 keV)**
- **Using PNNL expertise a 500 um electroplated copper was deposited on the inner surface at LSM.**

Electroplating Copper - Background mitigation

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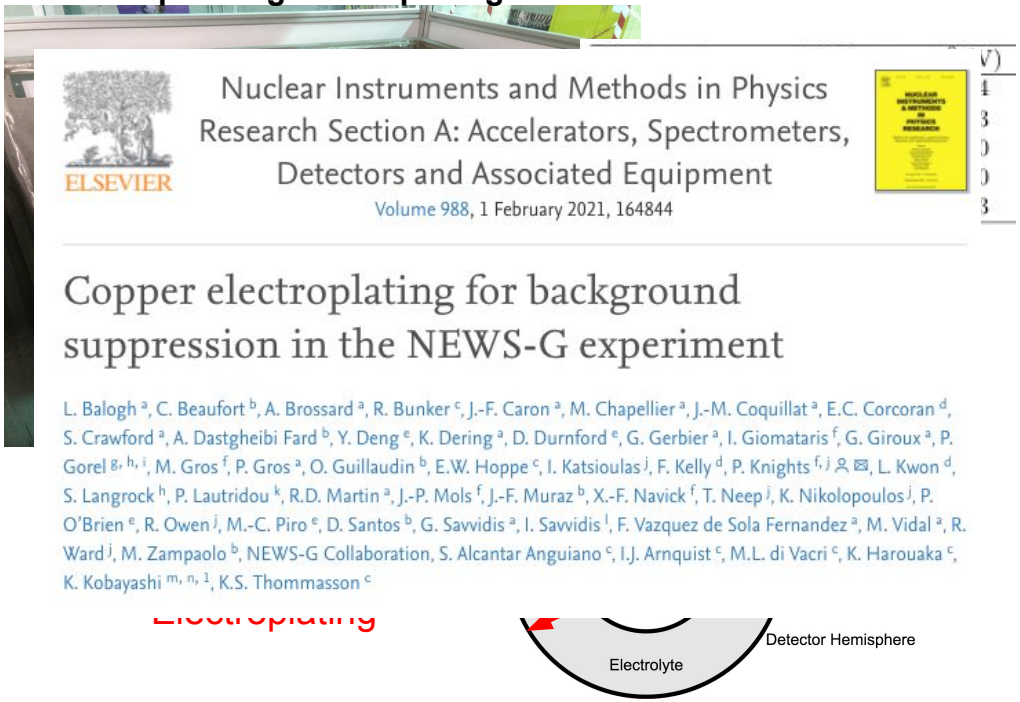
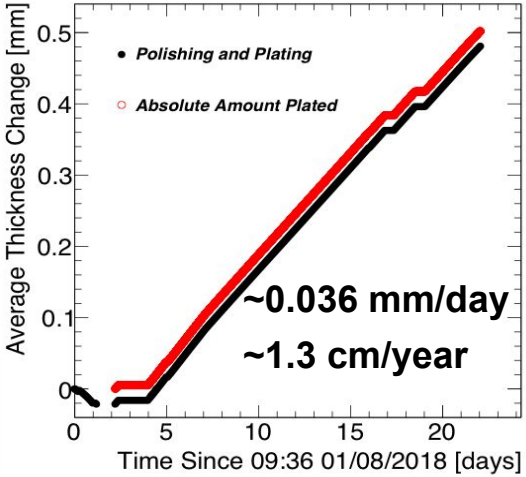

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 988, 1 February 2021, 164844

Copper electroplating for background suppression in the NEWS-G experiment

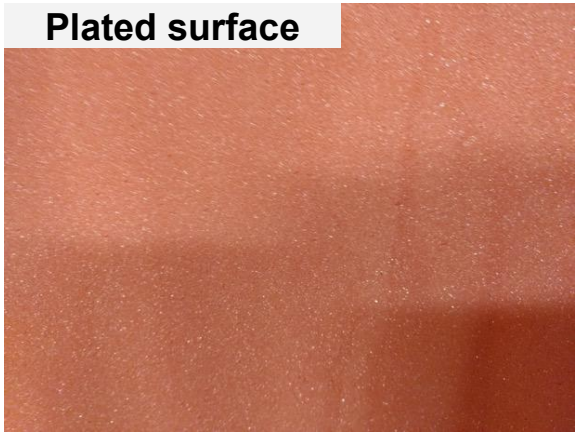
L. Balogh [a], C. Beaufort [b], A. Brossard [a], R. Bunker [c], J.-F. Caron [a], M. Chapellier [a], J.-M. Coquillat [a], E.C. Corcoran [d], S. Crawford [a], A. Dastgheibi Fard [b], Y. Deng [e], K. Dering [a], D. Durnford [e], G. Gerbier [a], I. Giomataris [f], G. Giroux [a], P. Gorel [g, h, i], M. Gros [f], P. Gros [a], O. Guillaudin [b], E.W. Hoppe [c], I. Katsioulas [j], F. Kelly [d], P. Knights [f, j], L. Kwon [d], S. Langrock [h], P. Lautridou [k], R.D. Martin [a], J.-P. Mols [f], J.-F. Muraz [b], X.-F. Navick [f], T. Neep [j], K. Nikolopoulos [j], P. O'Brien [e], R. Owen [j], M.-C. Piro [e], D. Santos [b], G. Savvidis [a], I. Savvidis [l], F. Vazquez de Sola Fernandez [a], M. Vidal [a], R. Ward [j], M. Zampaolo [b], NEWS-G Collaboration, S. Alcantar Anguiano [c], I.J. Arnquist [c], M.L. di Vacri [c], K. Harouaka [c], K. Kobayashi [m, n, 1], K.S. Thommasson [c]

- **Background: Bremsstrahlung X-rays from ^{210}Pb and ^{210}Bi β-decays in Cu**
- **Layer of ultra-pure Cu on the inner surface of the detector. Suppresses ^{210}Pb and ^{210}Bi backgrounds by factor 2.6 (under 1 keV)**
- **Using PNNL expertise a 500 um electroplated copper was deposited on the inner surface at LSM.**

Result after plating



Plated surface

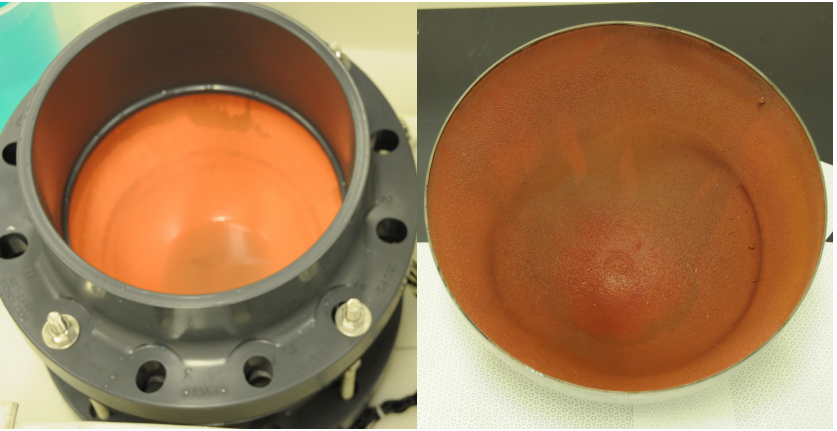


Hemisphere after plating

- Good surface quality achieved
- Hemispheres electron-beam welded together
- Detector already operating at LSM
- Copper was deposited at a rate of ~36 μm/day
  - Result promising for future fully underground electroformed detector

ECuME - Electroformed CUprum Manufacturing Experiment

The largest underground electroforming facility



Scale hemi-spherical model (PNNL) used for previous electroplating of detector

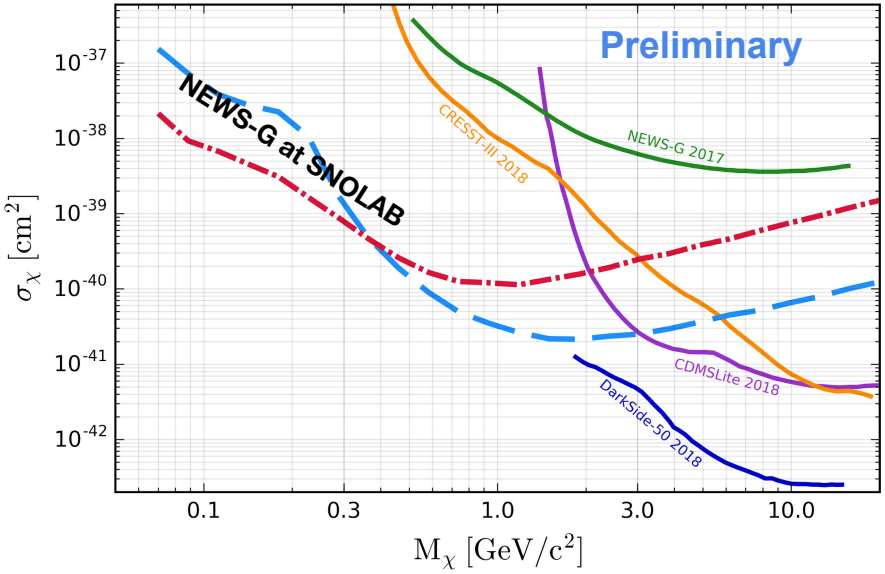
- **Underground electroformed ∅140 cm sphere**
  - **Minimised cosmogenic activation - Electroformed in SNOLAB**
  - **No machining or welding - grow sphere directly**
- **Based on what was achieved for current NEWS-G sphere**
  - **36 μm/day → ~1 mm/month**

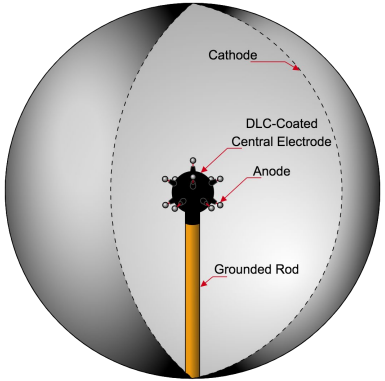
Current Status:

- R&D bath for prototype at PNNL - underway
- ∅30 cm prototype will then be produced
- Full-scale scheduled for late 2021

Summary

- Sensor development
  - Better E-field uniformity
  - High E-field in large detectors
- Improved sensitivity to low-mass WIMPs
  - Lighter targets (H,He)
  - Lower background
  - Lower threshold
- Improved gas quality and monitoring
  - Recirculation
  - Getter
  - RGA
- Improved calibration and monitoring
  - Laser
  - 37Ar





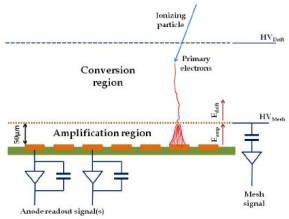
Additional material

Advantage of spherical geometry - A

C~Electronic noise
↑Electronic noise ↑Threshold

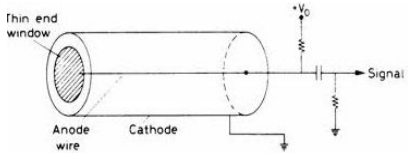
Capacities for a 1 m^3 detector in different geometries

Parallel Plate



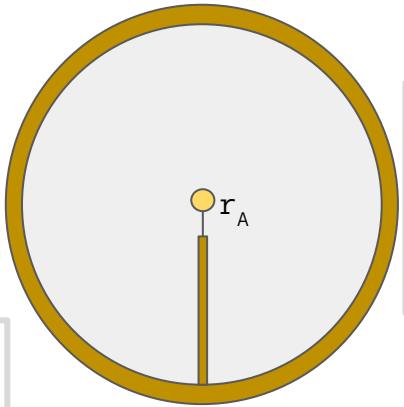
$$C = \varepsilon_0 \frac{S}{d} \approx 3500 \text{ pF}$$

Cylindrical



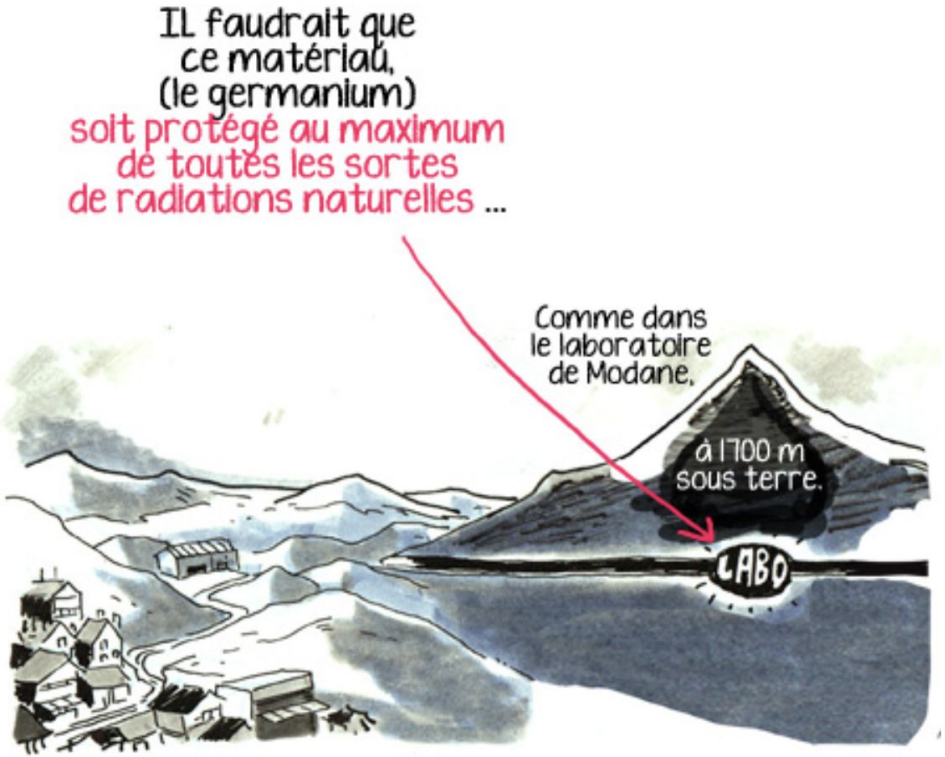
$$C = 2\pi\varepsilon_0 \frac{L}{ln(b/a)} \approx 115 \text{ pF}$$

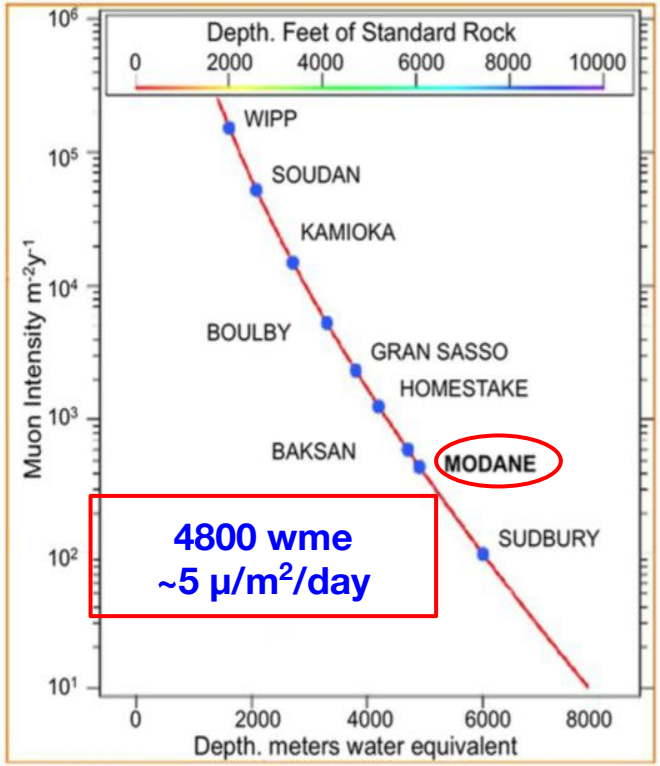
Spherical



$$C \approx 4\pi\varepsilon r_A \approx 1.5 \text{ pF}$$

NEWS-G at Modane



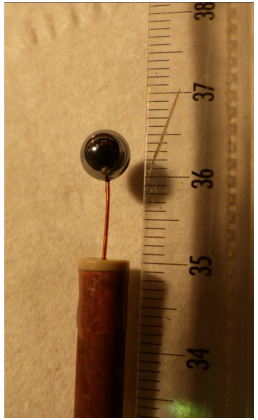


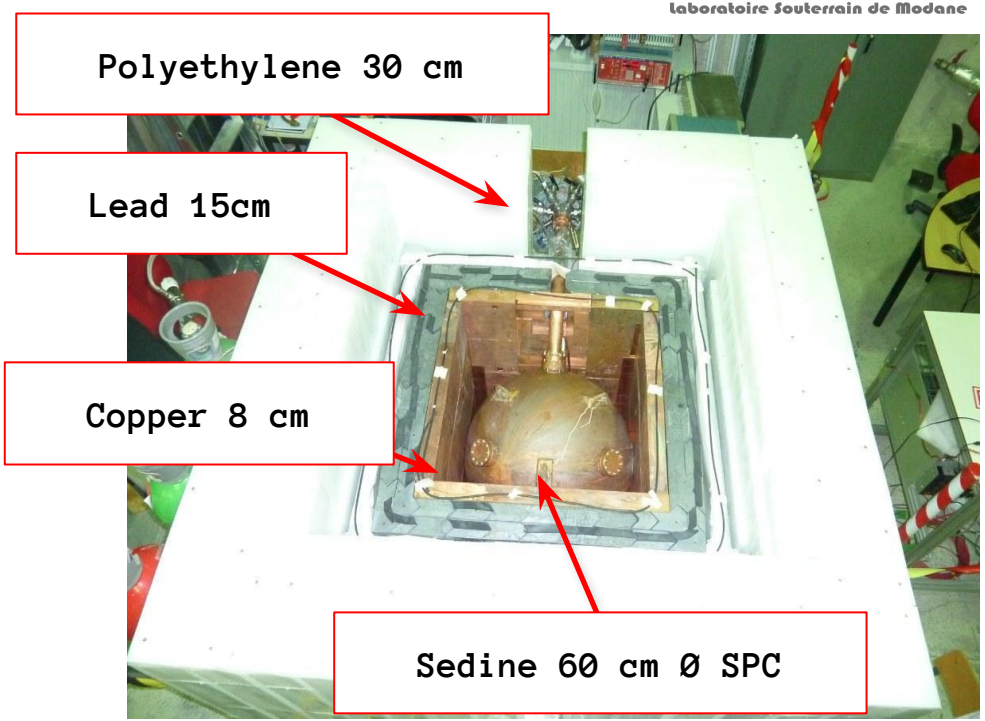
NEWS-G at Modane

SEDINE the prototype

Vessel
Ø 60cm copper

Sensor
Ø 6.3mm Si

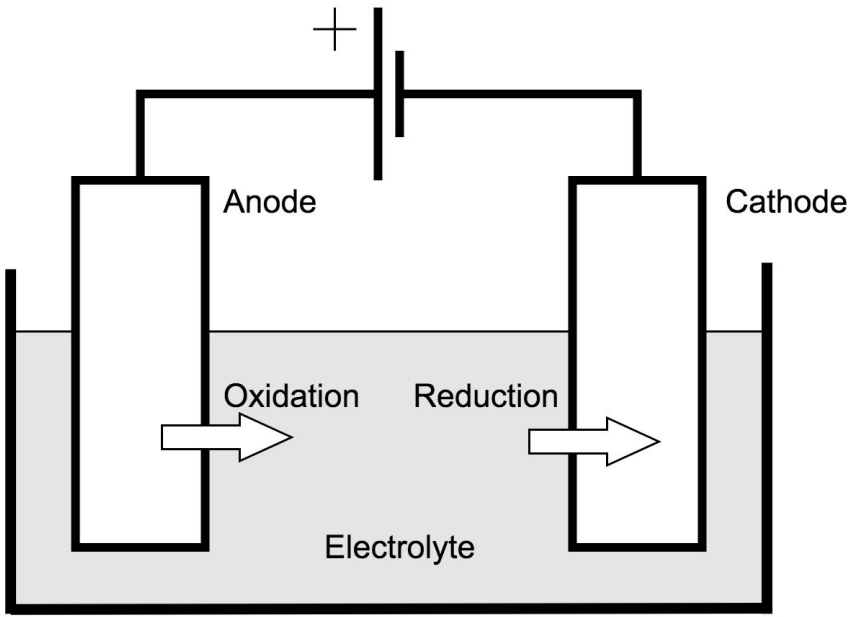




- **NOSV Copper vessel (Ø 60 cm)**
- **Equipped with a 6.3 mm Ø sensor**
- **Chemically cleaned several times for Radon deposit removal**

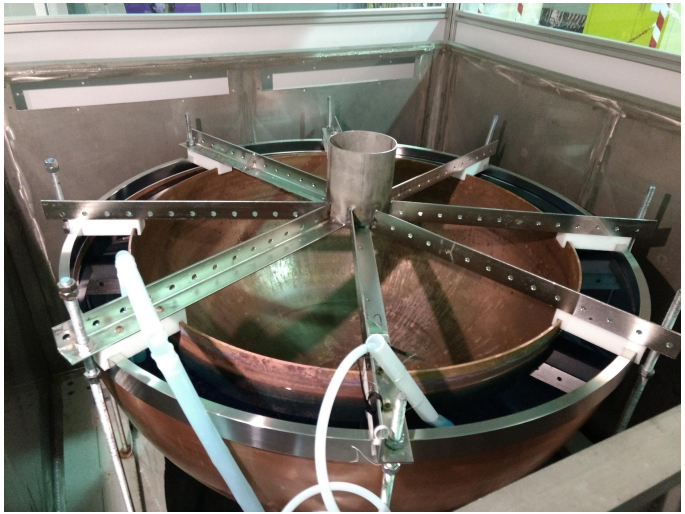
Electroplating Copper

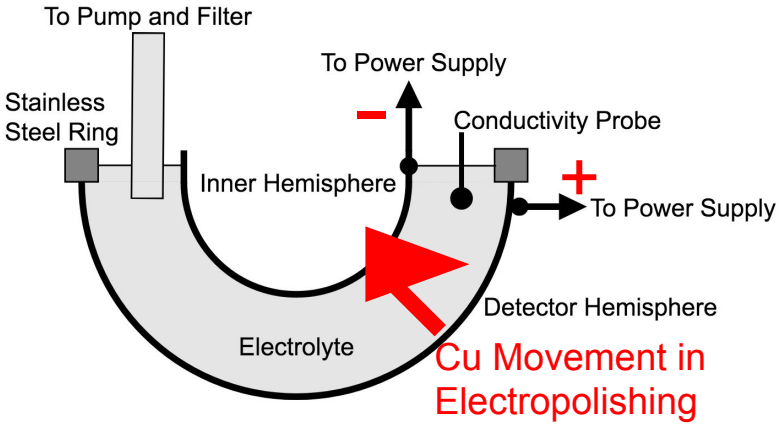
- Some ions reduce more readily than others – **reduction potentials**
- Copper benefits from '**electrowinning**' – high reduction potential +0.34 V
- Reduction potential of:
  - Uranium: -1.80 V
  - Thorium: -1.90 V
  - Lead: -0.44 V
  - **All lower than copper → refined during electroplating**
- Using PNNL expertise, already electroformed Cu for Majorana Experiment



Electropolishing

- Electropolishing serves several purposes
  - Removes layer from hemisphere without chemical or mechanical attack
  - Preferentially **removes high spots** from surface
  - **Increases concentration** of $CuSO_4$ in electrolyte
- First (second) hemisphere 21.2±0.1 μm (28.2±0.1 μm) polished





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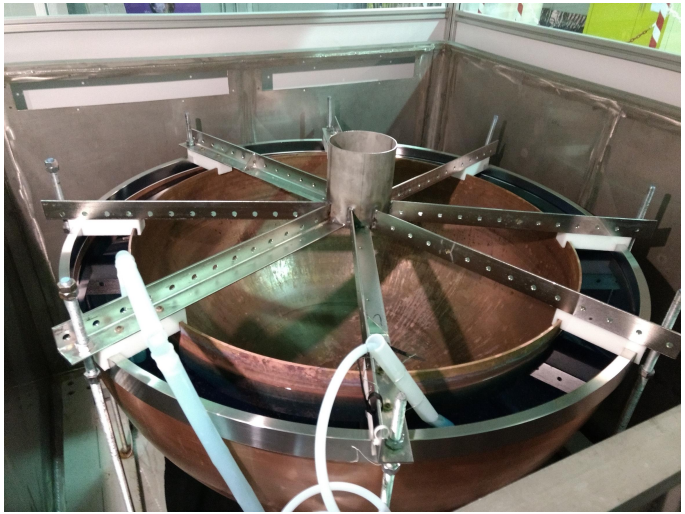
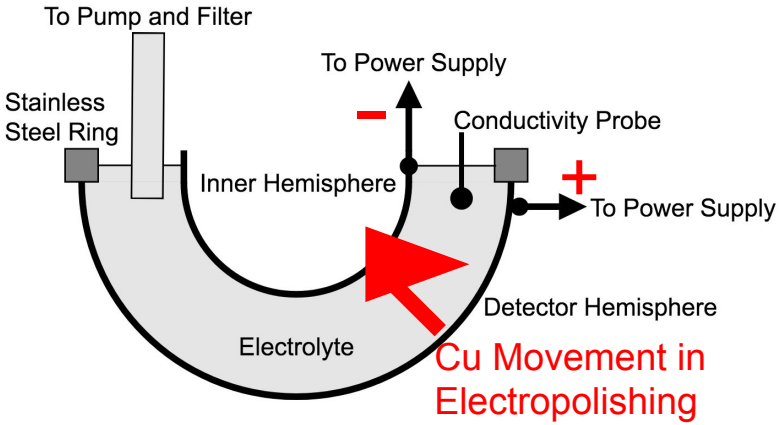
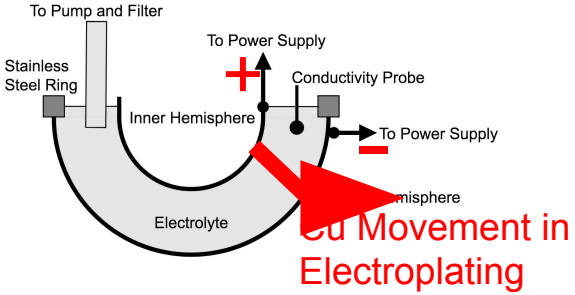
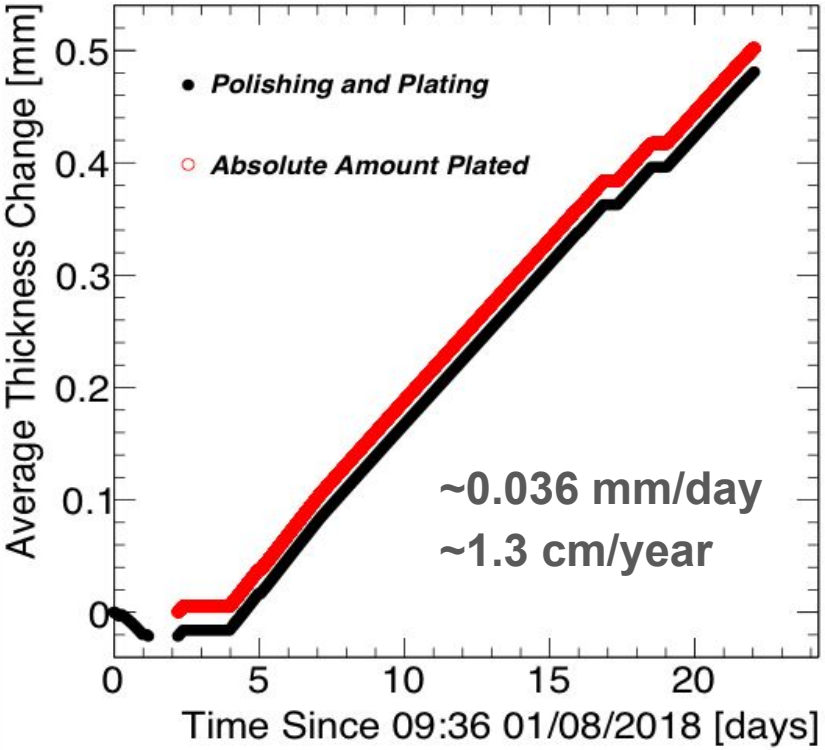




Electroplating

- Electroplating performed with pulsed current
- 0.27 to 0.3 V amplitude in forward and reverse directions of plating
  - Established value for copper plating
- Plating continued for ~**15 days**
- In total first (second) hemisphere plated **502.1±0.2 μm (539.5±0.2 μm)**
- Passivation with Citric Acid



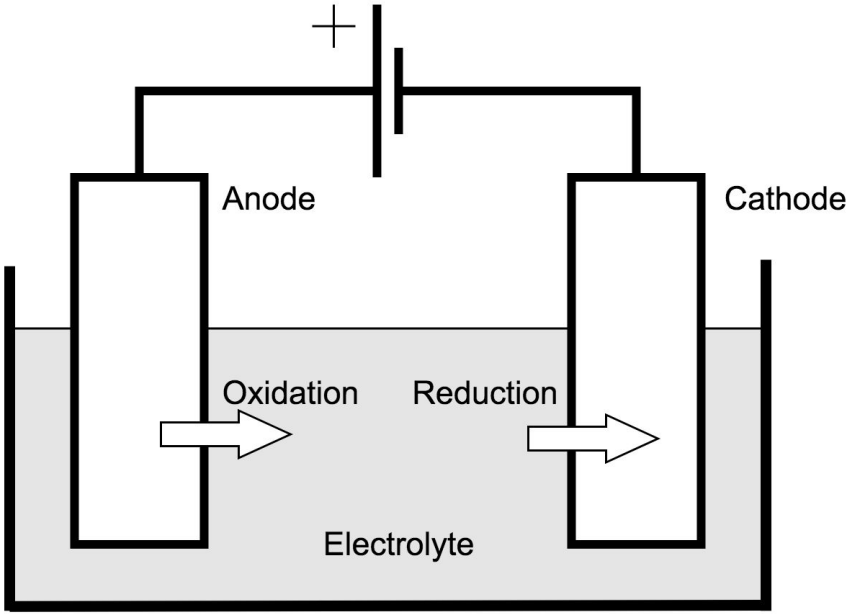


Future NEWS-G Detectors

- Next generation of detector will require even **lower background material**
- Two options:
  - **6N copper sphere**
  - **Electroformed** intact sphere
- 6N more currently favoured; **less pure than electroformed** but **commercially available** and potentially **lower cost**
  - Electroformed copper could be the generation after – demonstrated **growth ~ 1.3 cm/year**
  - 10 bar, ∅ 60 cm sphere requires 4 mm walls - ~ **4 months**
- Currently planned to be ∅ 60 cm, installed in NEWS-G@LSM shielding

Sample	^{210}Pb contamination (mBq/kg)	^{210}Po contamination (mBq/kg)
OFC#1 (C1020) (MMC)	40±8	47±21
OFC#2 (C1020) (MMC)	20±6	33±14
OFC#3 (C1020) (MMC)	27±7	$(1.6\pm0.3)\times10^2$
OFC#4 (C1020) (MMC)	23±8	$(2.2\pm0.4)\times10^2$
OFC#5 (C1020) (SH copper products)	17±6	44±18
OFC#6 (C1020) (SH copper products)	27±8	24±17
OFC (class1) (SH copper products)	36±13	38±3
Coarse copper (MMC)	$(57\pm1)\times10^3$	$(16\pm2)\times10^3$
Bare copper (MMC)	8.4±4.0	$(1.1\pm0.2)\times10^2$
OFC (MMC)	23±8	$(1.3\pm0.3)\times10^2$
6N copper (MMC)	<4.1	<4.8
Electroformed copper (Asahi-Kinzoku)	<5.3	<18

Electroformed copper (PNNL) ~<100 nBq/kg ^{238}U & ^{232}Th

Electroplating Copper

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