# Search for Light Dark Matter with Spherical Proportional Counters

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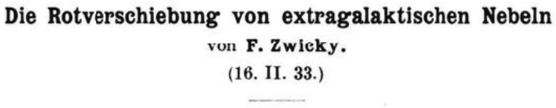
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no 841261 (DarkSphere)

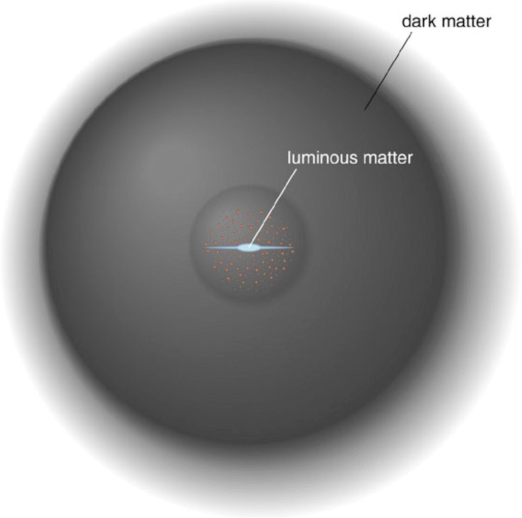
MARIE CURIE ACTIONS

# The dark matter conundrum

## Observations of Zwicky 87 years ago


Die Rotverschiebung von extragalaktischen Nebeln
von F. Zwicky.
(16. II. 33.)

"The Redshift of Extragalactic Nebulae", published in German in Helvetica Physica Acta in 1933

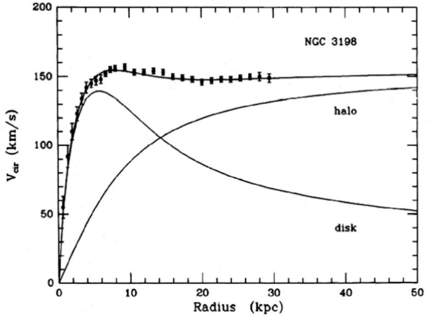



"In a spiral galaxy, the ratio of dark-to-light matter is about a factor of ten. That's probably a good number for the ratio of our ignorance-to-knowledge. We're out of kindergarten, but only in about third grade."
**Vera Rubin**

**What should it be from astrophysical constraints:**

- Mostly "Cold"
- Non-Baryonic
- "Weakly" interacting
- $\Omega_{DM}$= 0.265
- Stable or $\tau_X >> \tau_U$

No Standard Model particle matches the criteria



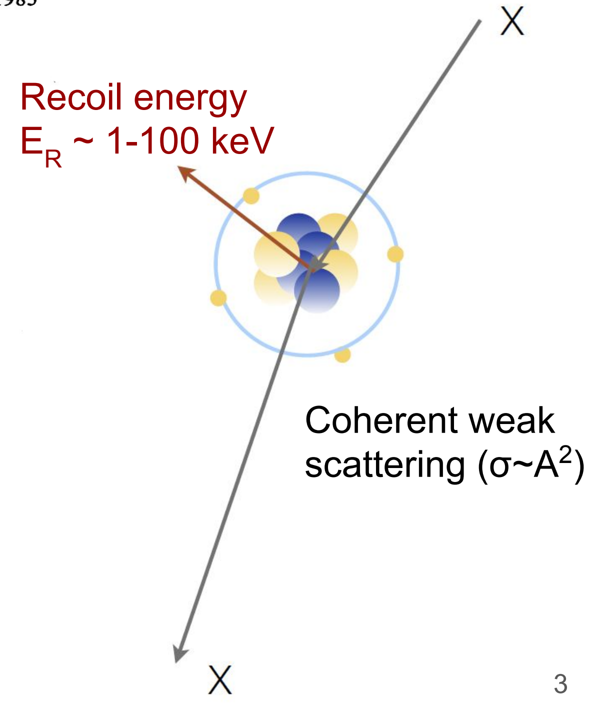
# Dark matter detection

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

**Detectability of certain dark-matter candidates**

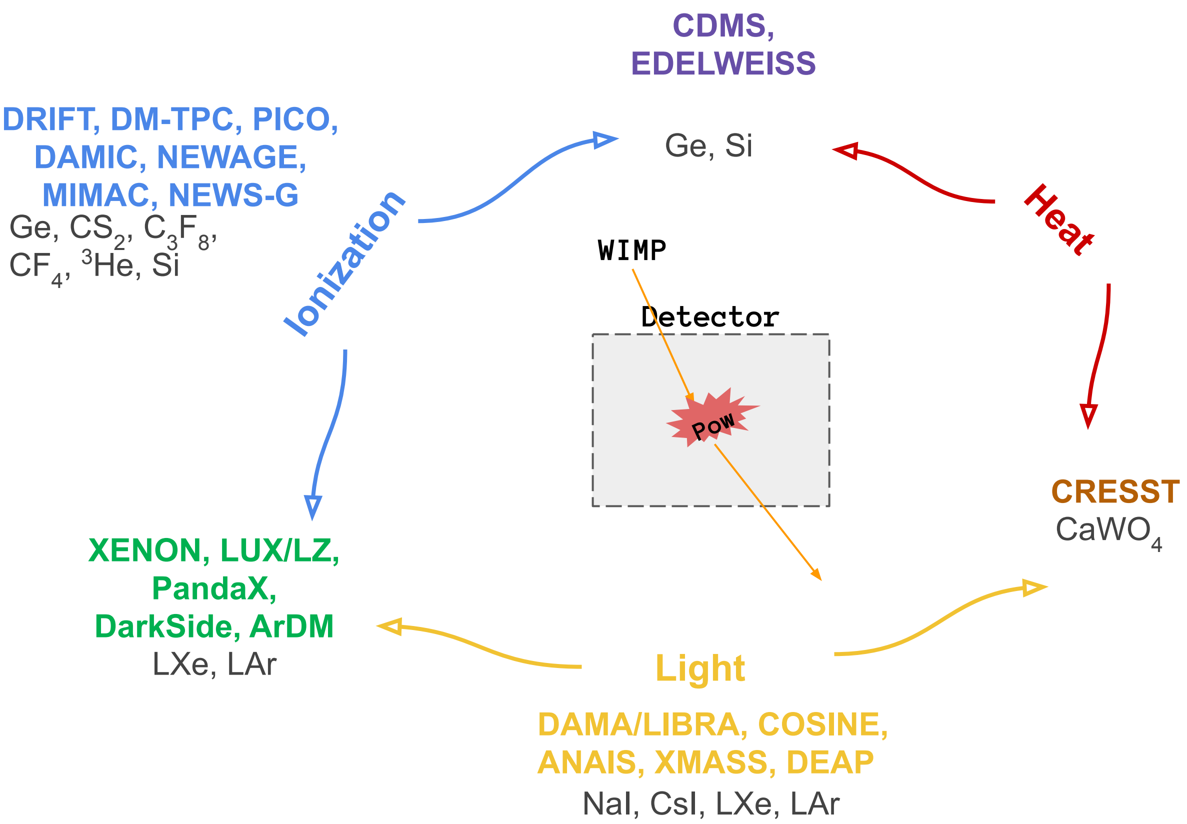
Mark W. Goodman and Edward Witten
*Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544*
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

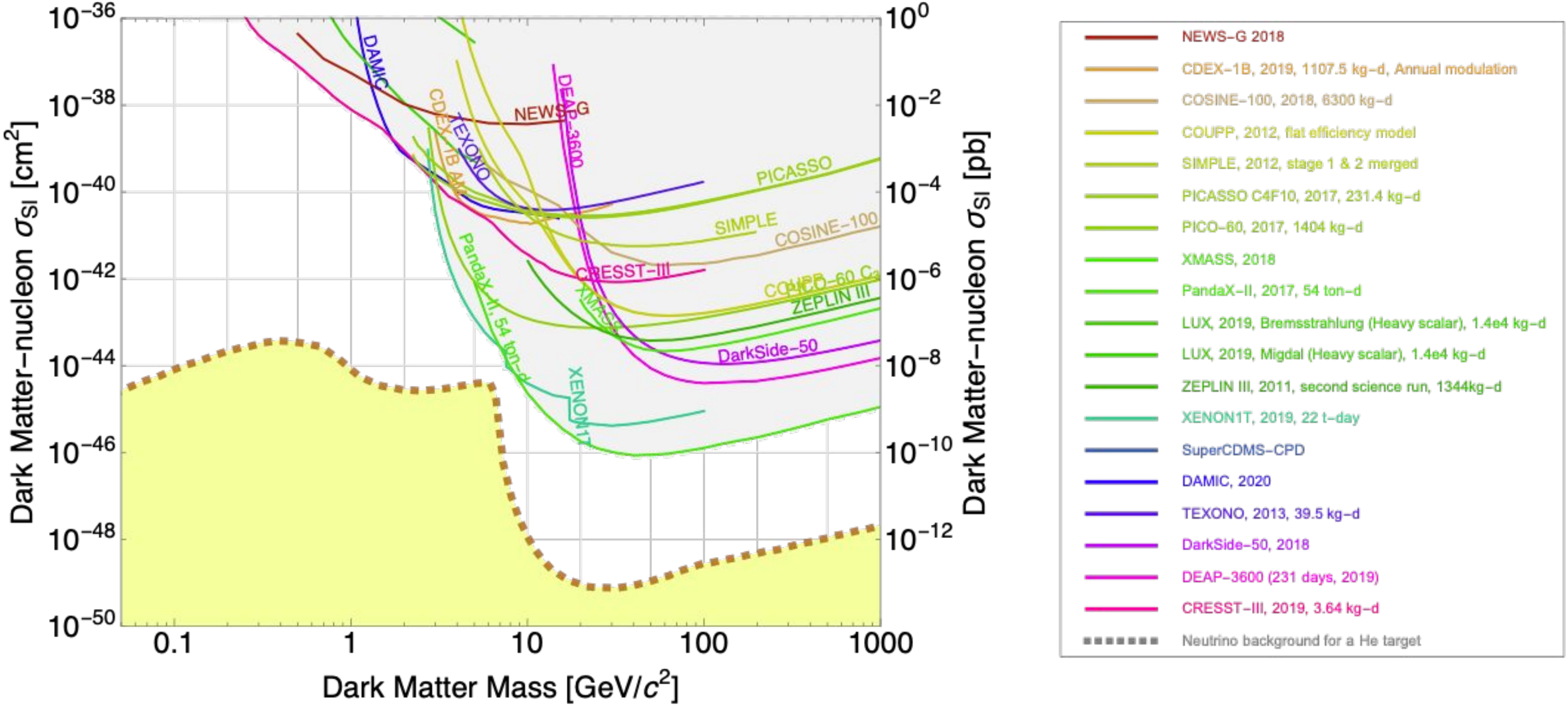



**“WIMP miracle” ⇒ Relic abundance explained by a massive particle (5 GeV/$c^2$ - few TeV/$c^2$ ) interacting through weak scale interaction with baryonic matter**

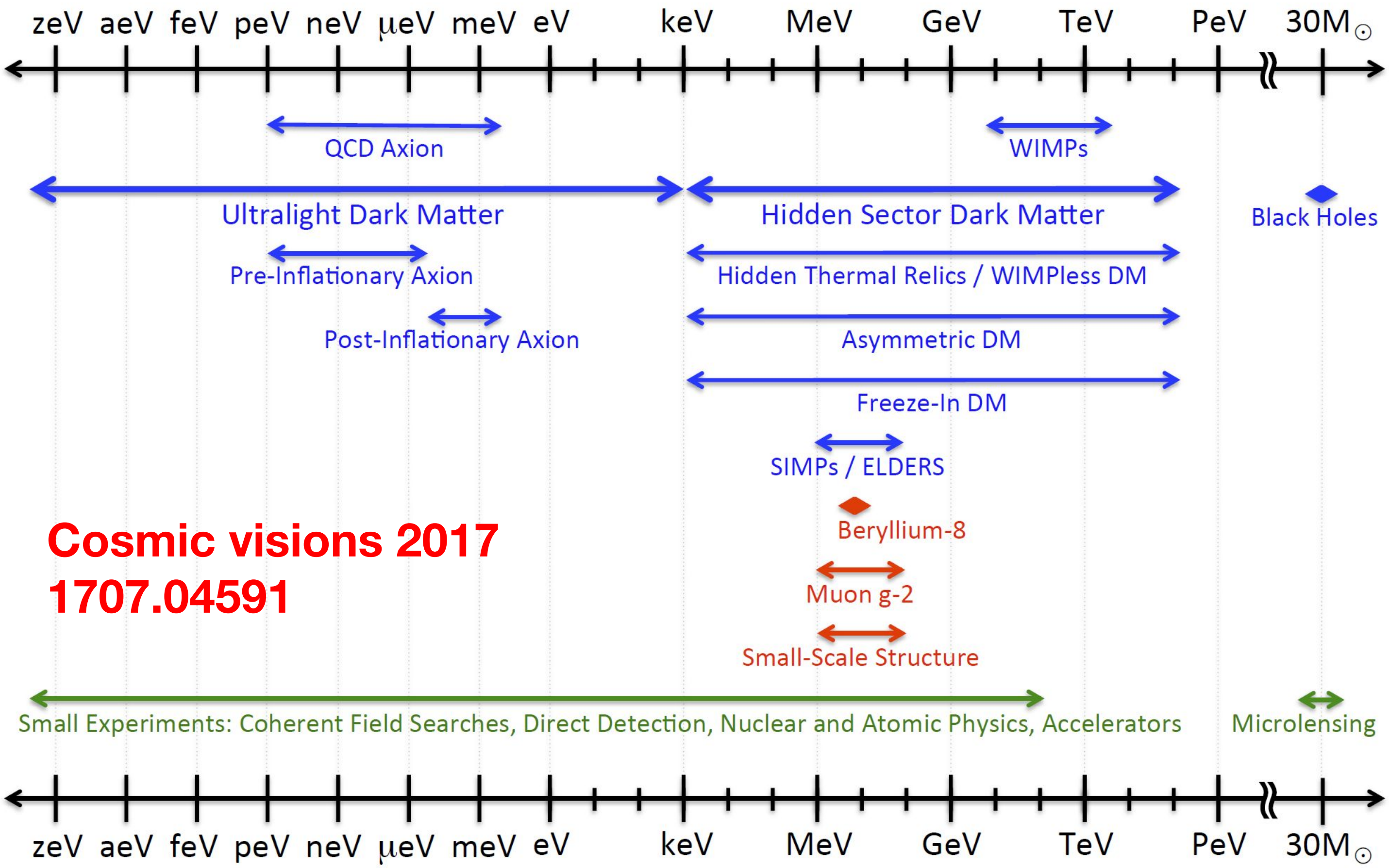
# State of the art for dark matter detectors



# Direct detection landscape

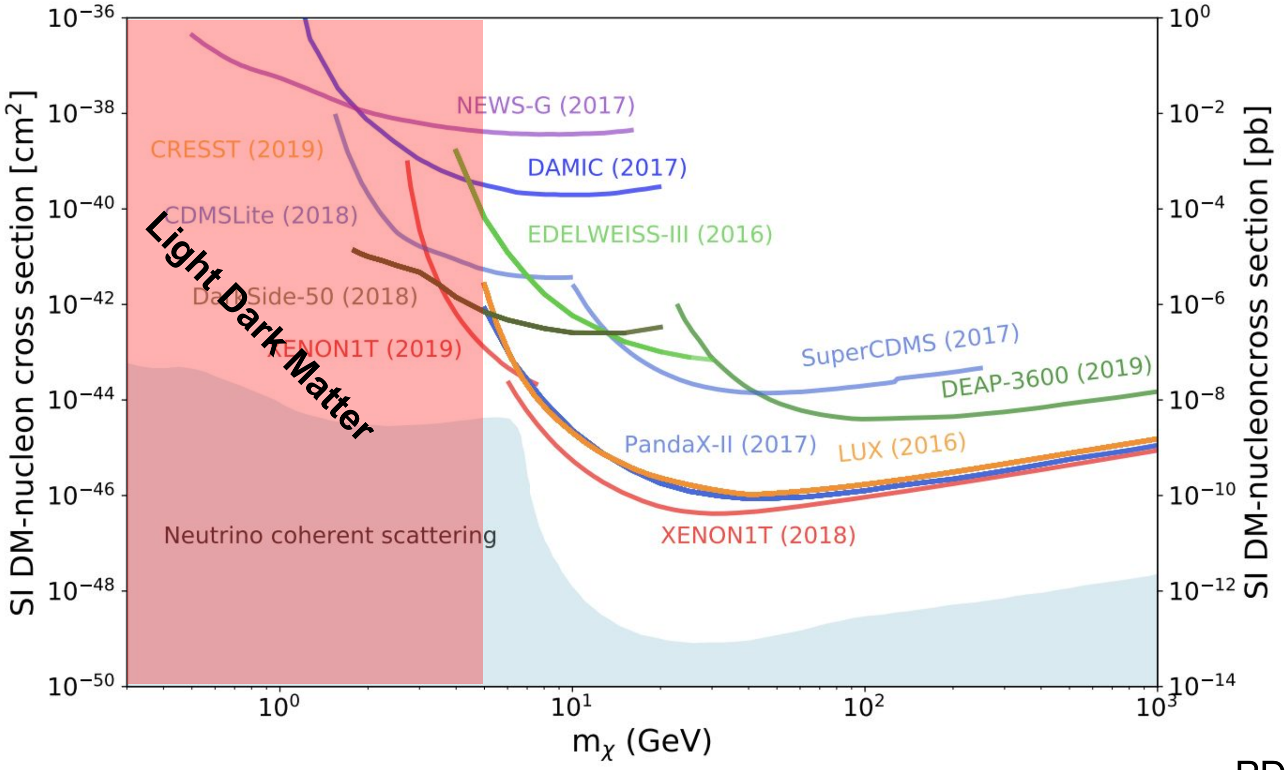


# Dark Sector Candidates, Anomalies, and Search Techniques



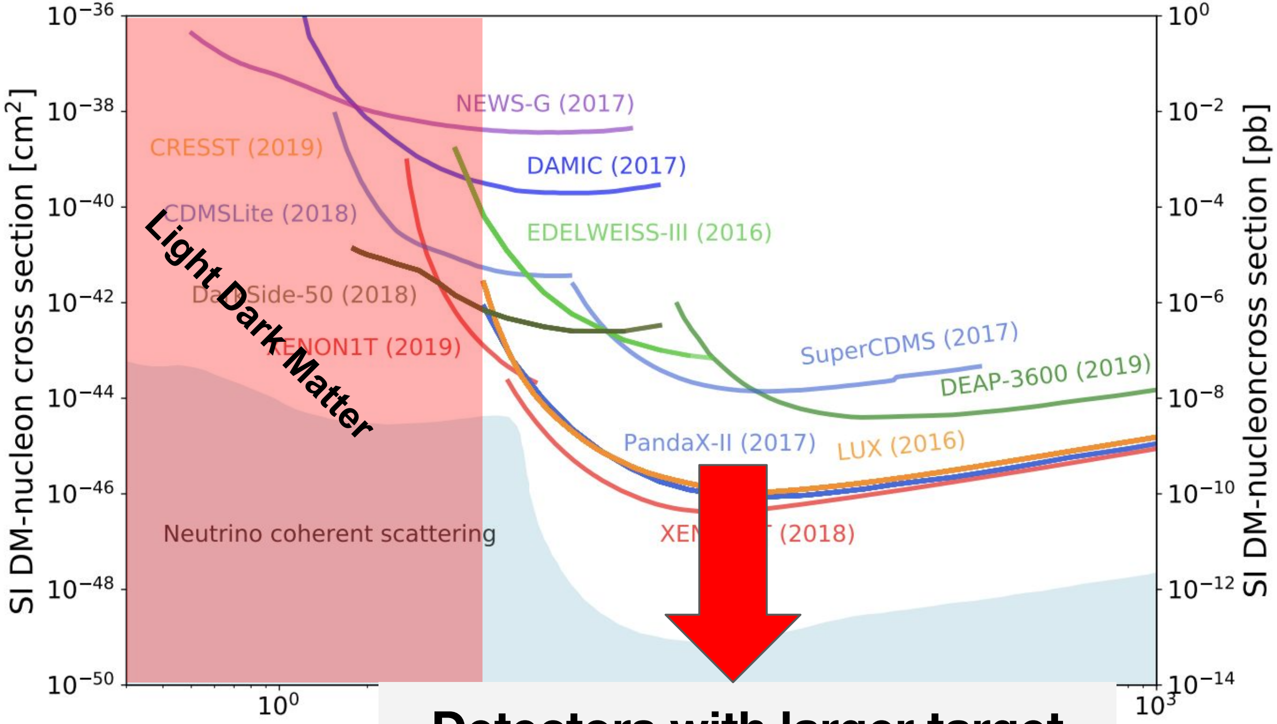

**Cosmic visions 2017**
**1707.04591**

# Light Dark Matter (LDM) mass region




PDG 2019

# How does one search the LDM region?



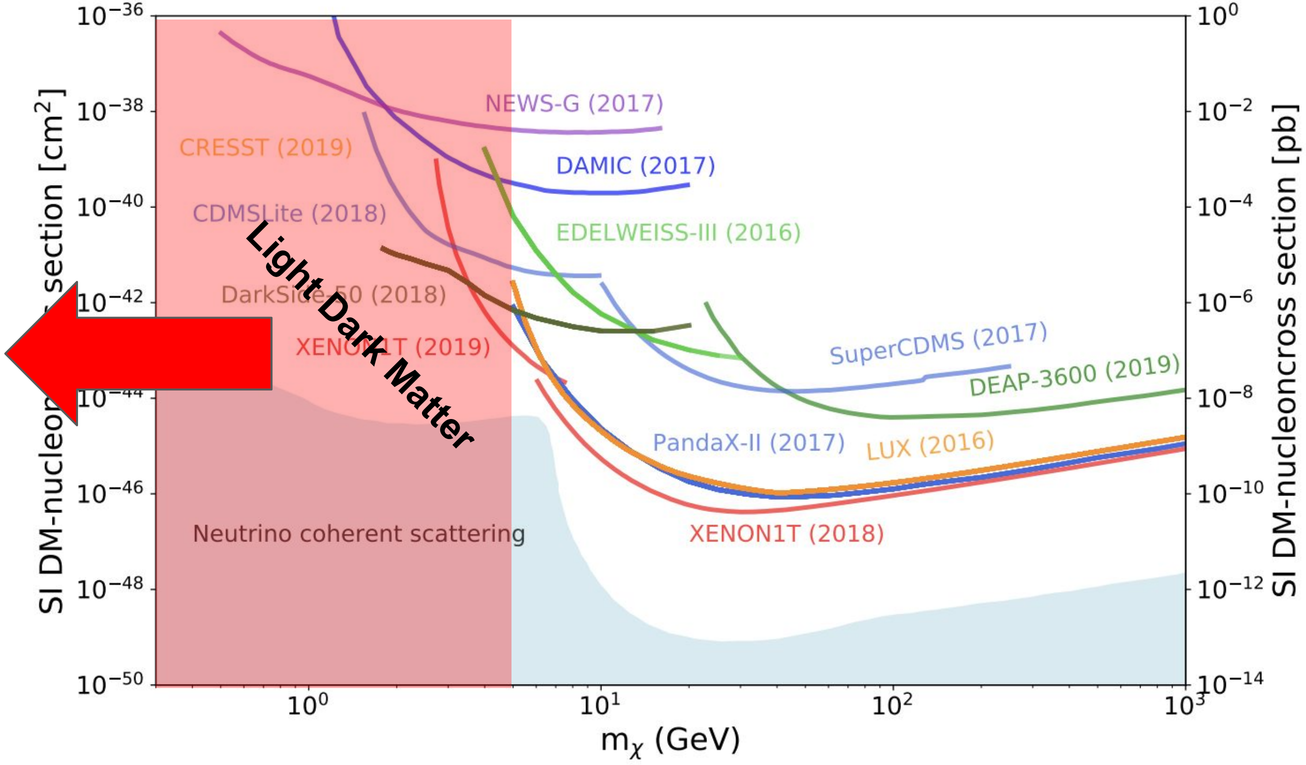

**Detectors with larger target mass - exposure kg·days**

PDG 2019

# Direct detection landscape

**New detector technologies:**

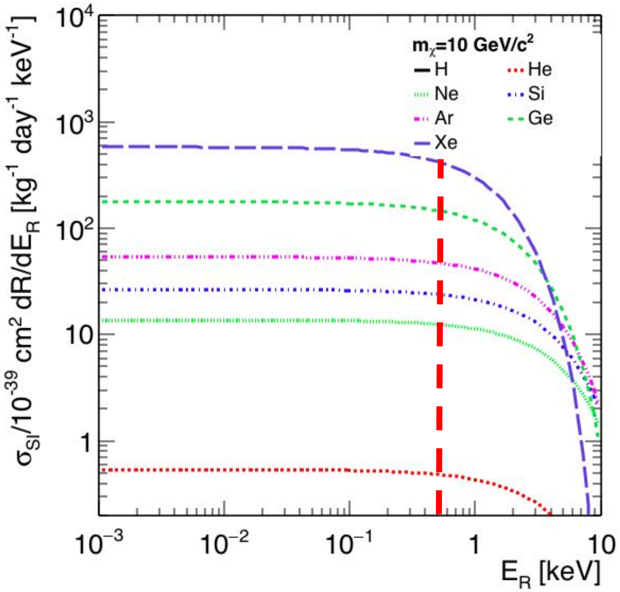
- **Lower threshold**
- **Lighter targets**

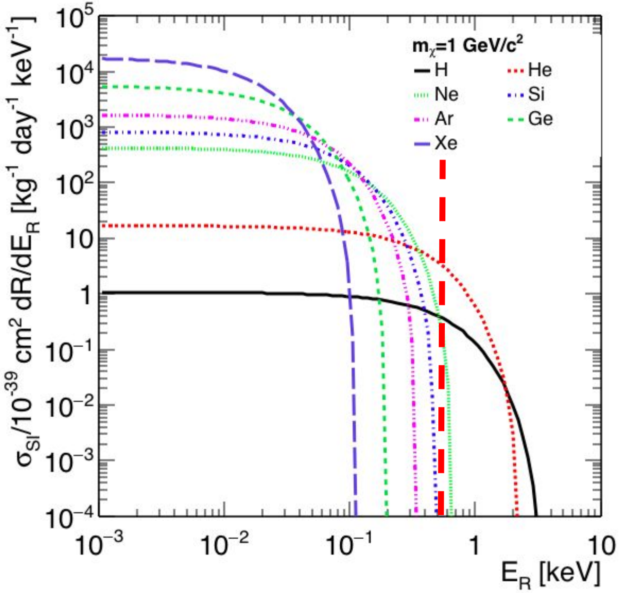



PDG 2019

# Light-DM detection particularities - A

## Target kinematics



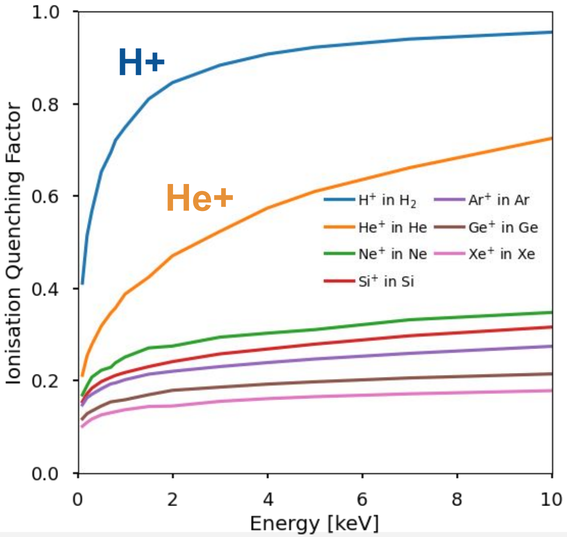

*500 eV*

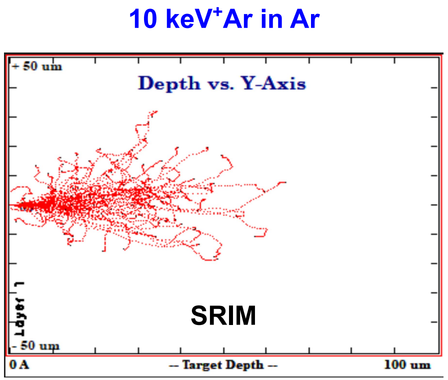
**Light Projectile + Light target ⇒ Better kinematic match**

# Light-DM detection particularities - B

## Ionization quenching

**Quenching factor: fraction of ion kinetic energy dissipated in a medium in the form of ionization electrons and excitation of the atomic and quasi-molecular states.**



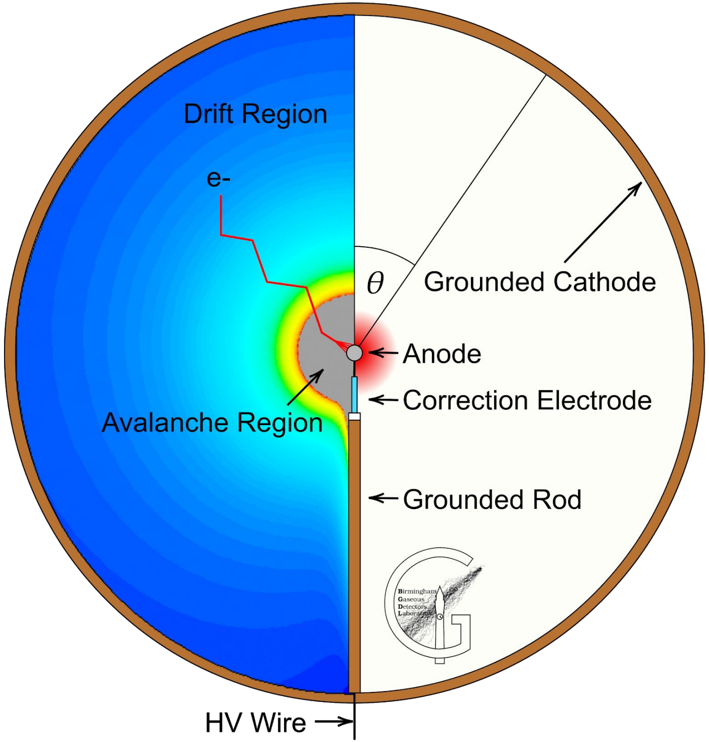

**Light Projectile + Light target ⇒ Less demanding detector threshold**

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


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

# The Spherical Proportional Counter (SPC)

I.Giomataris et al ,JINST,2008, P09007




## Electric field

**Strong radial dependence**

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

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

**Detector volume naturally divided in:**

- **Drift region**
- **Amplification region**

- Simple design
- Single readout

# Spherical Proportional Counter (SPC)

## The "birth" of a detector

**Old LEP RF cavities**

**Spherical gaseous detectors**

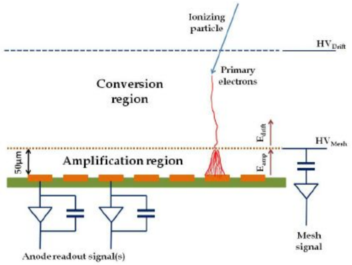
*In the picture:*
*I.Giomataris, G.Charpak*

# Advantage of spherical geometry

## Large detectors - Low threshold

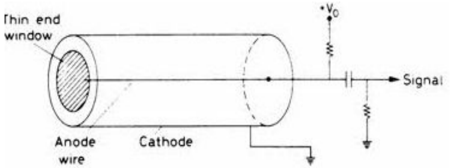
***Capacities for a 1 $m^3$ detector in different geometries***

### Parallel Plate



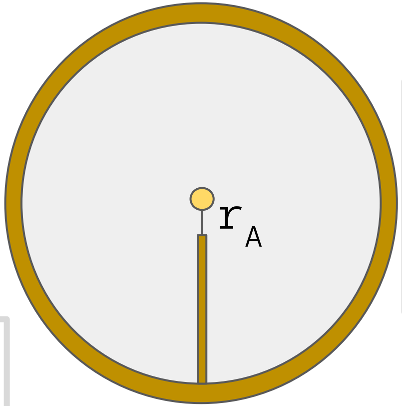

$$C = \varepsilon_0 \frac{S}{d} \approx 3500 \text{ pF}$$

### Cylindrical




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

### Spherical




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

**Lower Capacitance ⇢ Lower Electronic Noise ⇢ Lower Threshold**

# Advantage of spherical geometry

## Construction with radiopure materials

**Advantages of the spherical geometry**

- Lowest surface to volume ratio
- Sustains higher pressure
- Robustness (anode Ø 1 mm - 6.3 mm)

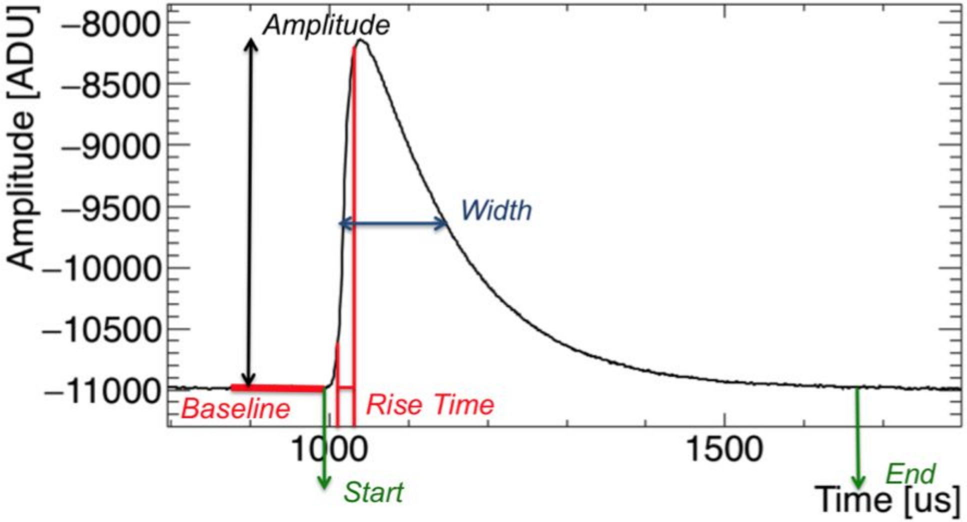
**Built solely by radiopure materials**

- Vessel made of Cu (~tens of kg)
- Rod made of Cu (~hundreds of gr)
- **All the rest less < 1 g**

# Induced Pulses

## Pulse Shape Analysis (PSA) parameters

### Long Tail Pulse




**Rise time & Width ∝ Drift time dispersion**

**<u>Basic Parameters</u>**

- Baseline
- Noise
- <u>Amplitude</u> (Pulse Height)
- <u>Rise time</u>
- <u>Width</u>
- Integral
- Number of peaks

**A lot of information in the pulse shape**

# Pulse-Shape Discrimination

(1) X-rays in volume,

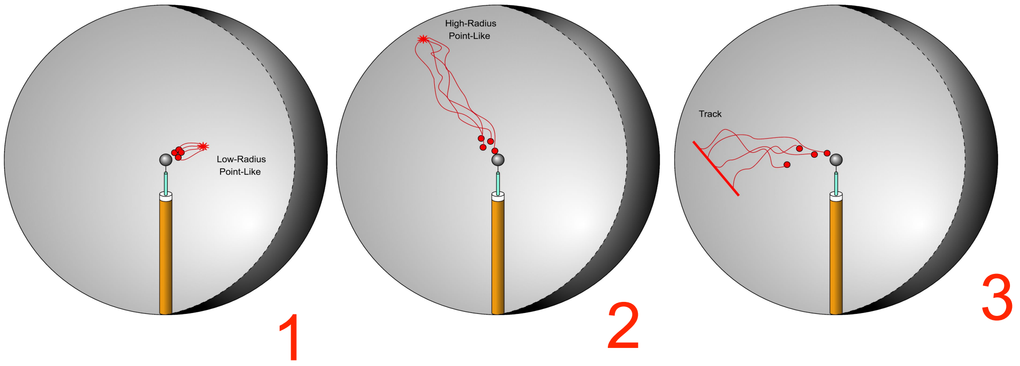
(2) X-rays near cathode

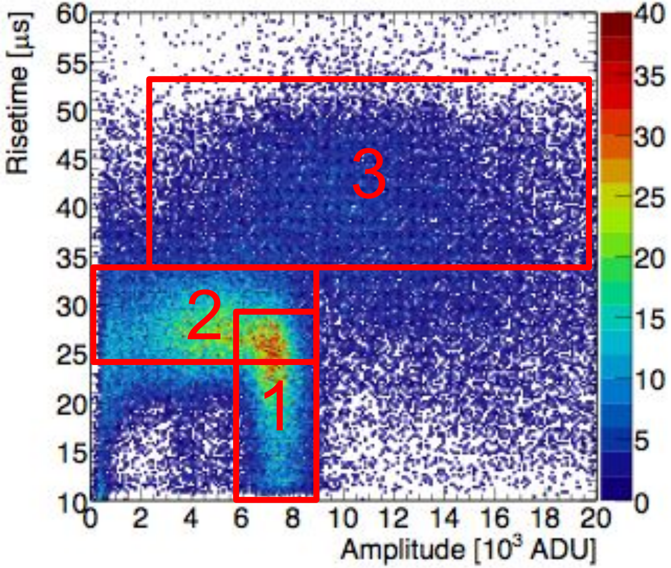
(3) Cosmic Muons

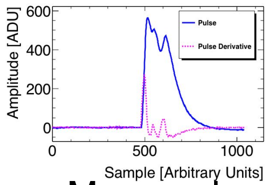
⌀30 cm detector
1.3 bar
He:Ar:CH4
(51.7:46%:2.3%)
Fe-55 Source
Inside

Rise time (~charge collection time) selections to:

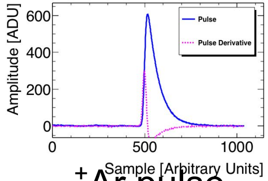
- Distinguish point-like versus extended ionisations
- Fiducialise detector
  - Majority of background from cathode material
  - Can select against near-cathode events
- Reliant on homogeneous electric field and high electric field at large radii (for charge collection)



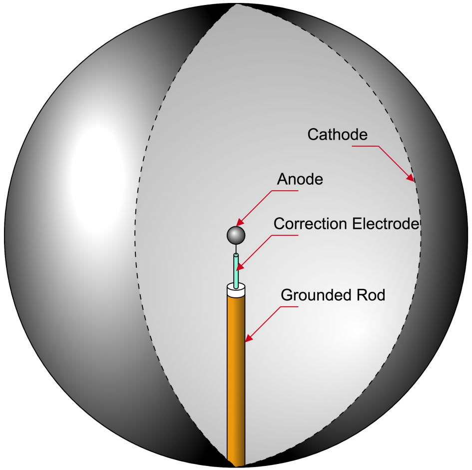

Muon pulse




$^{+}$Ar pulse

# Detector features

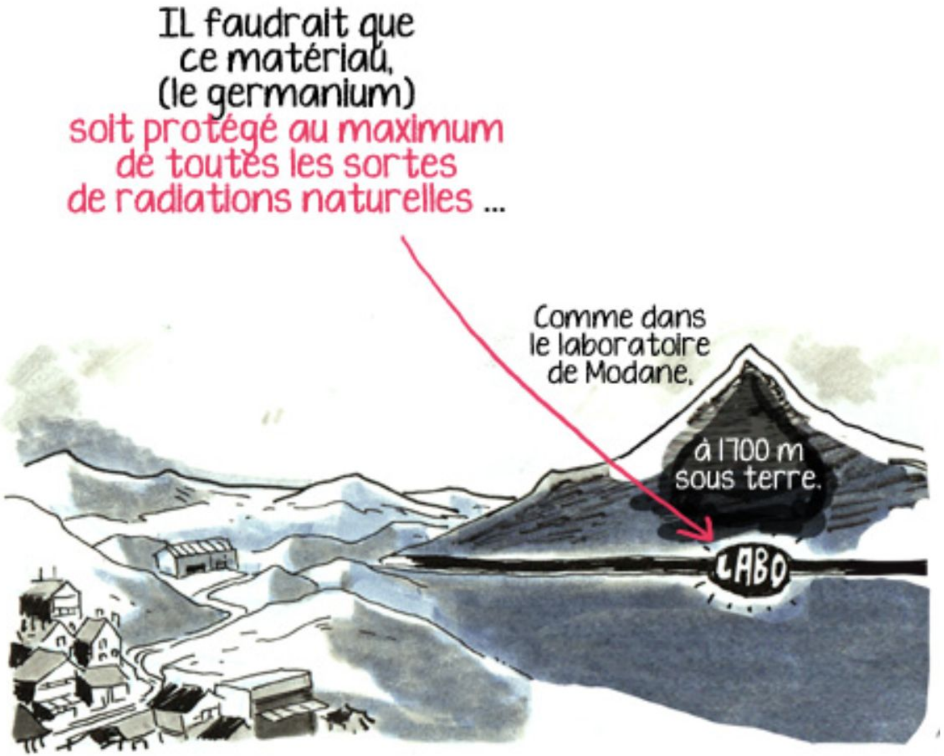
- **Large volume read out with a small number of channels**
- **Single electron threshold due to:**
  - **Low capacitance**
  - **High gain**
- **Radio-pure construction**
- **Background rejection handles**
- **Flexible operation**
  - **Swappable gases-targets**
  - **Variable pressure choice**

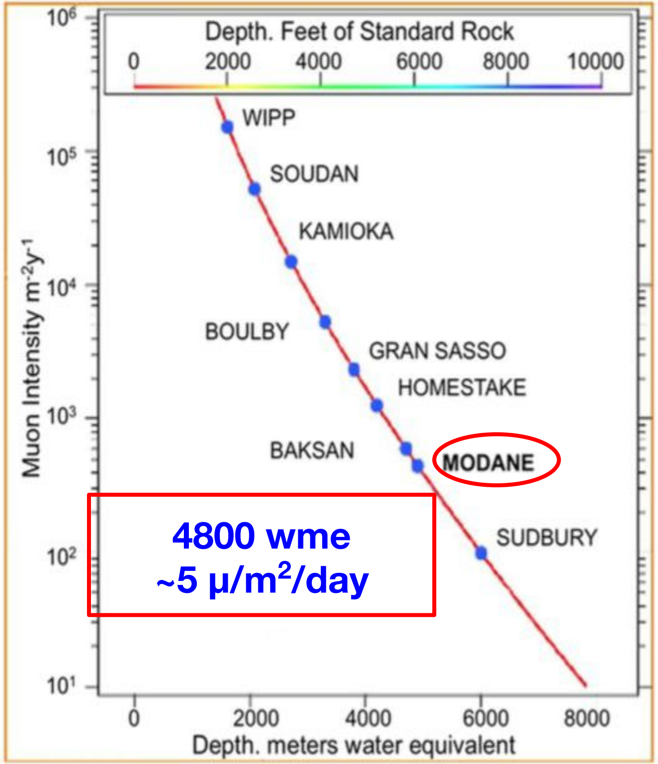



Applications include:

- Dark matter searches
- 2β0ν decay searches
- CEνNS physics
- Neutron spectroscopy (potentially useful for proton therapy)

# NEWS-G at Modane



# NEWS-G at Modane

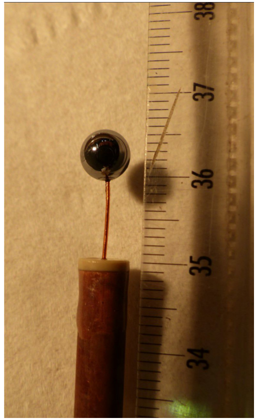
## SEDINE detector

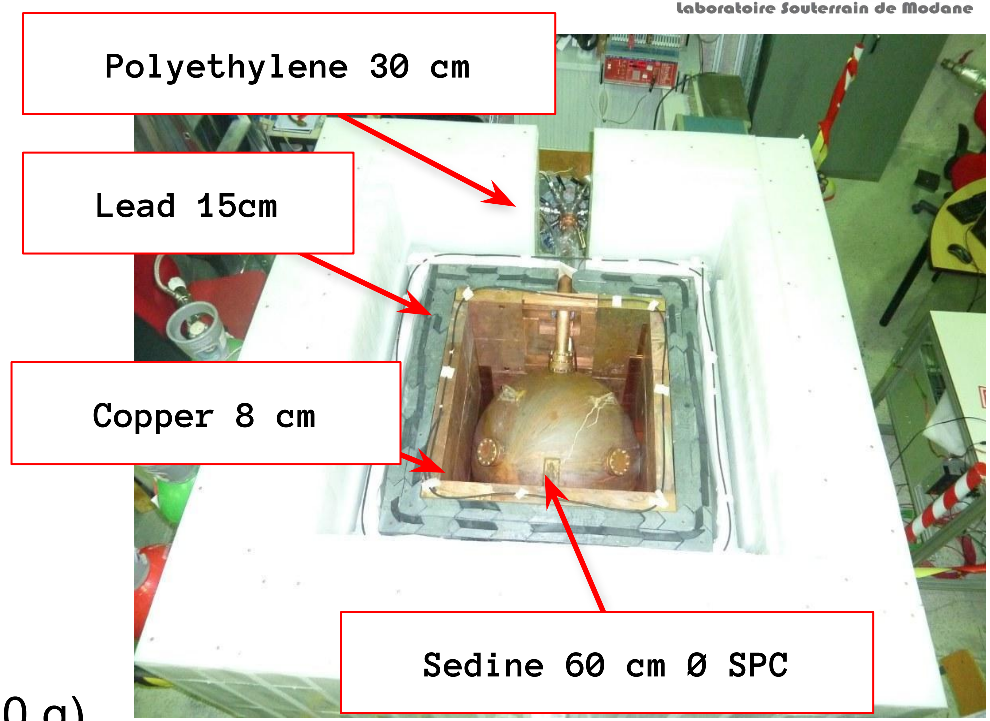
**Vessel**

Ø 60cm copper

**Sensor**

Ø 6.3mm Si



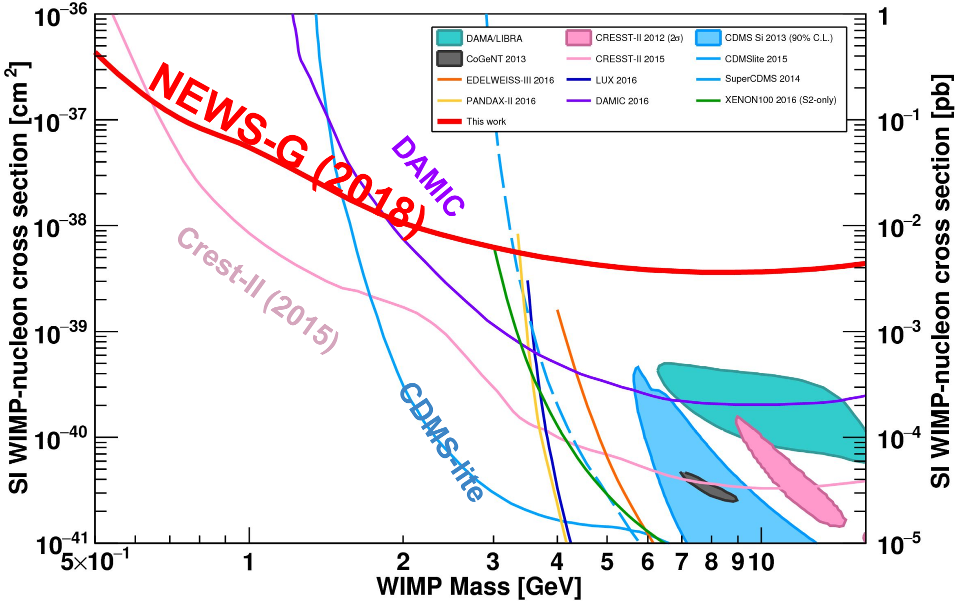



**Gas Mixture:** Ne+0.7%$CH_4$ at 3.1 bar (280 g)

**Exposure:** 9.6 kg*days (34.1 live-days x 0.28 kg)

# First results of NEWS-G with SEDINE (2018)

[NEWS-G collaboration, Astropart. Phys. 97, 54 (2018), doi: 10.1016/j.astropartphys.2017.10.009]





Astroparticle Physics 97 (2018) 54–62

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/astropartphys


First results from the NEWS-G direct dark matter search experiment at the LSM


Q. Arnaud[a,*], D. Asner[b], J.-P. Bard[c], A. Brossard[a,c], B. Cai[a], M. Chapellier[a], M. Clark[a], E.C. Corcoran[d], T. Dandl[e], A. Dastgheibi-Fard[f], K. Dering[a], P. Di Stefano[a], D. Durnford[a], G. Gerbier[a], I. Giomataris[c], P. Gorel[g], M. Gros[c], O. Guillaudin[h], E.W. Hoppe[b], A. Kamaha[a], I. Katsioulas[c], D.G. Kelly[d], R.D. Martin[a], J. McDonald[a], J.-F. Muraz[h], J.-P. Mols[c], X.-F. Navick[c], T. Papaevangelou[c], F. Piquemal[f], S. Roth[a,1], D. Santos[h], I. Savvidis[i], A. Ulrich[e], F. Vazquez de Sola Fernandez[a], M. Zampaolo[f]

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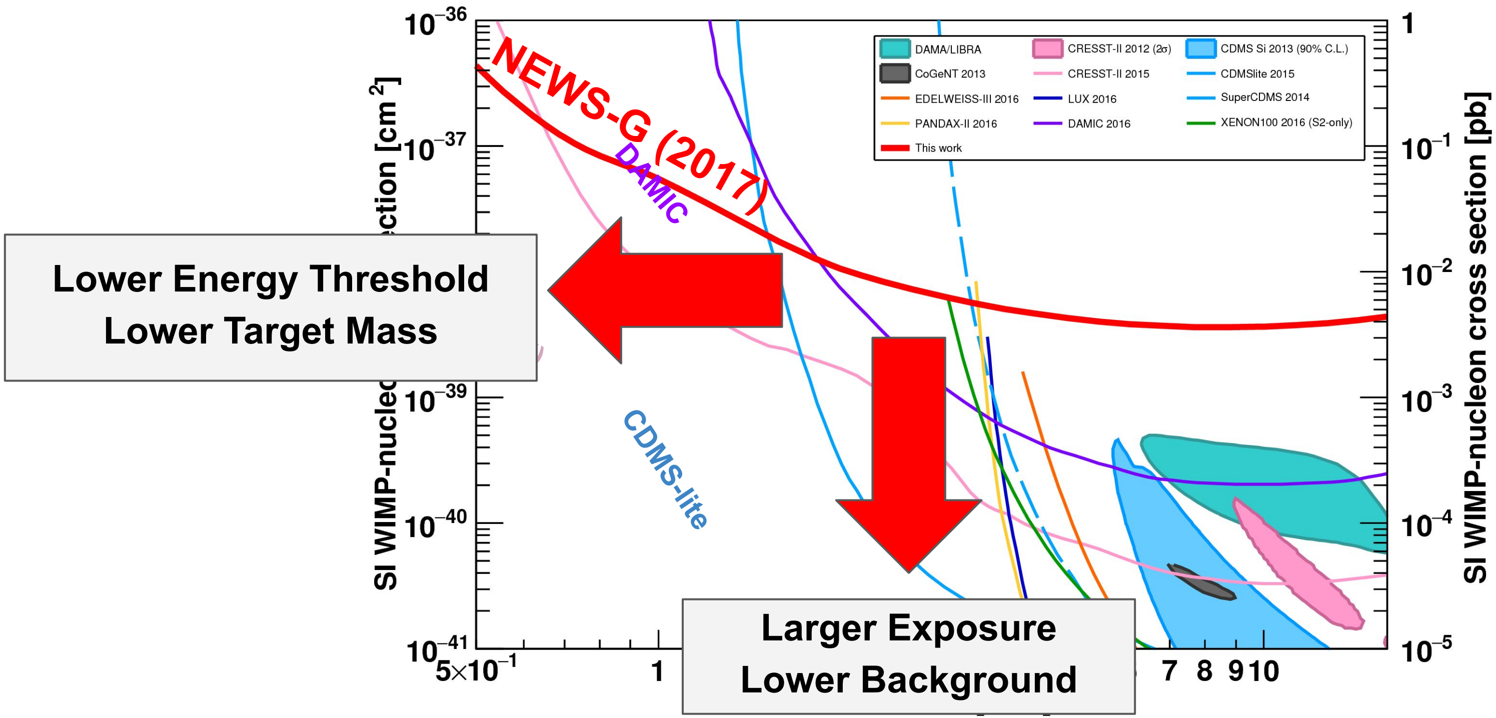
[i] Department of Physics, Aristotle University of Thessaloniki, GR-52124 Thessaloniki, Greece

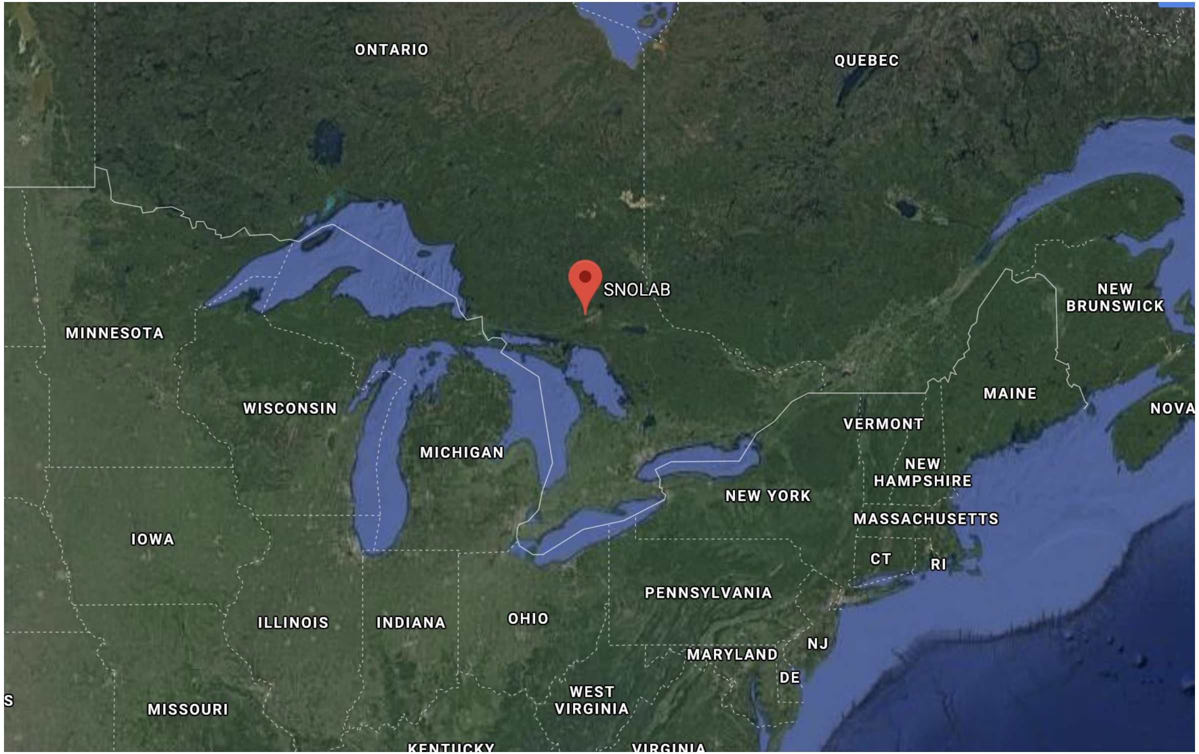

Exclusion at 90% confidence level (C.L.) of cross-sections above $4.4 \cdot 10^{-37}$ cm$^2$ for a **0.5 GeV/c$^2$ WIMP**

*Limit set on spin independent WIMP coupling with standard assumptions on WIMP velocities, escape velocity and with quenching factor of Neon nuclear recoils in Neon calculated from SRIM*

# NEWS-G moving forward



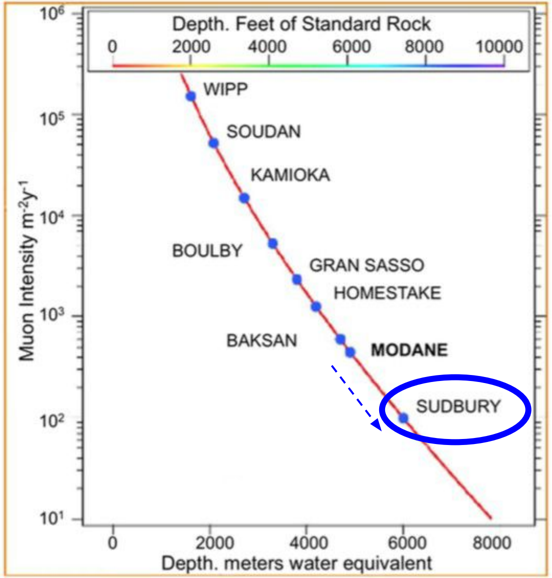
# NEWS-G at SNOLAB



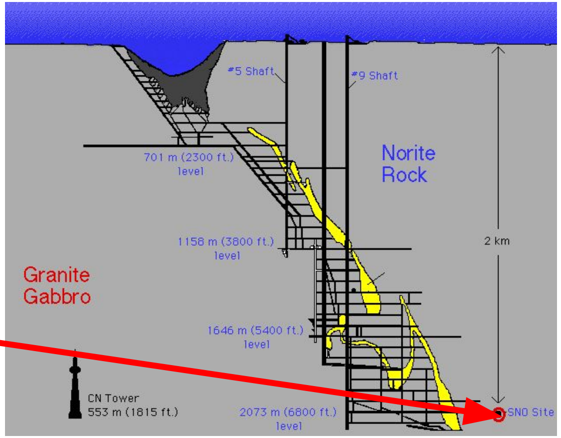
# NEWS-G at SNOLAB

## The underground laboratory in the Sudbury, Canada

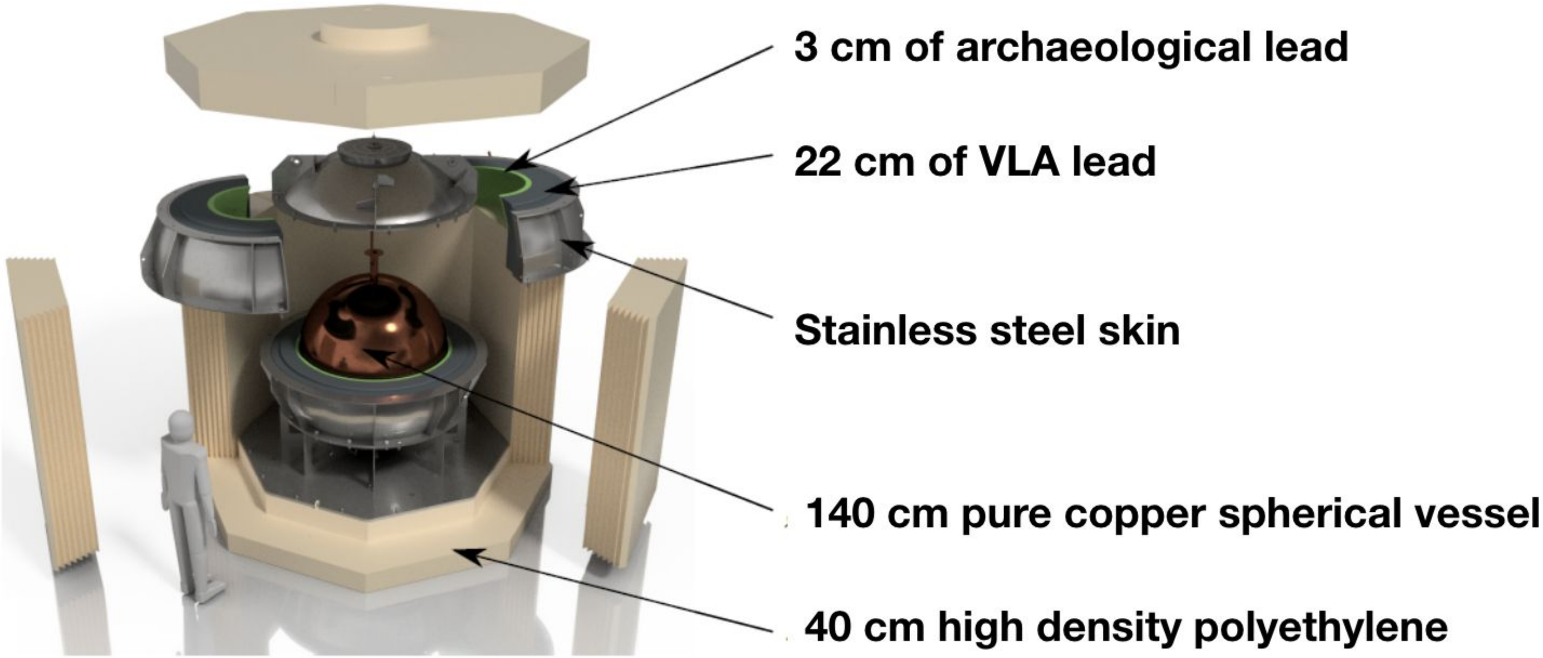
**Deeper underground**
**0.25 μ/m$^2$/day**
**~8x lower μ flux than LSM**




**Practically, at 2 km is the deepest clean room in the world**

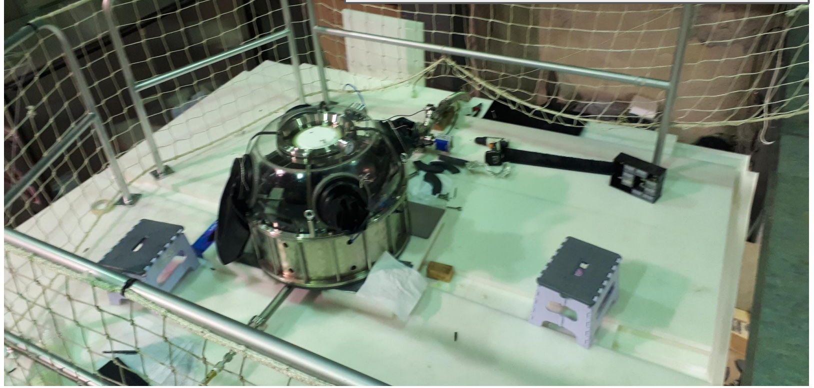



# The NEWS-G detector - SNOGLOBE



# SNOGlobe at LSM

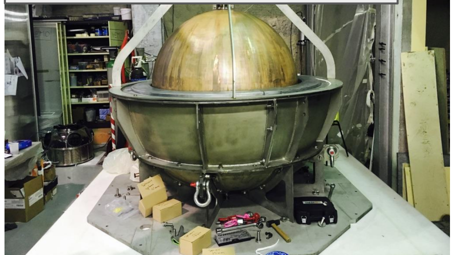
- Detector already commissioned at LSM
  - Assembled and operated for a month
  - Gases used Ne/$CH_4$ (1 bar), $CH_4$ (135 mbar)
  - Sensor and electronics performance tested
  - Backgrounds under study



Fully installed shielding

Temporary neutron shielding

Glove-box

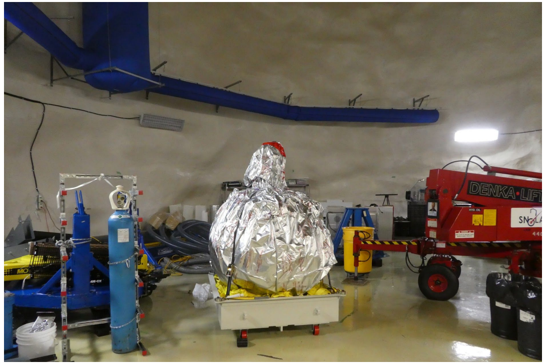


Half installed lead shielding

# Status of installation at SNOLAB

Shipment December 2019

Moving underground




Placement

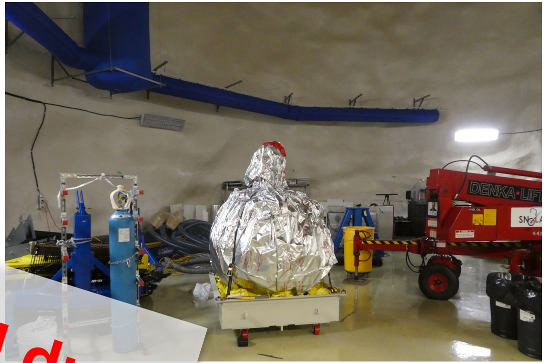
Flushed with $N_2$

# Status of installation at SNOLAB

**Installation work halted due to COVID-19 lockdown**
**Restarted in Sep 2020**

Shipment December 2019

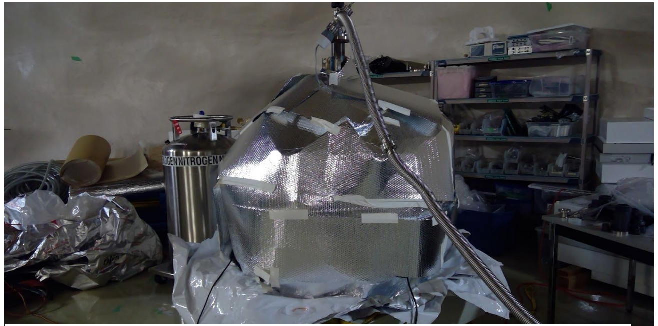
Moving underground

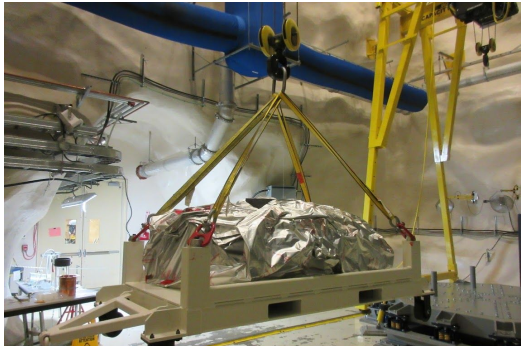


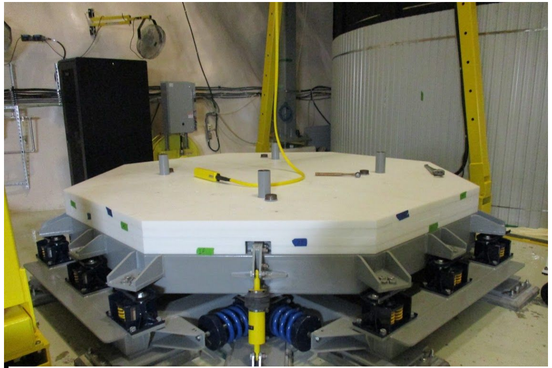
Placement

Flushing with $N_2$

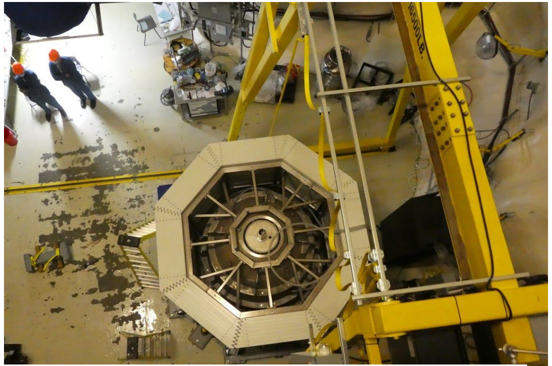
# Status of installation at SNOLAB

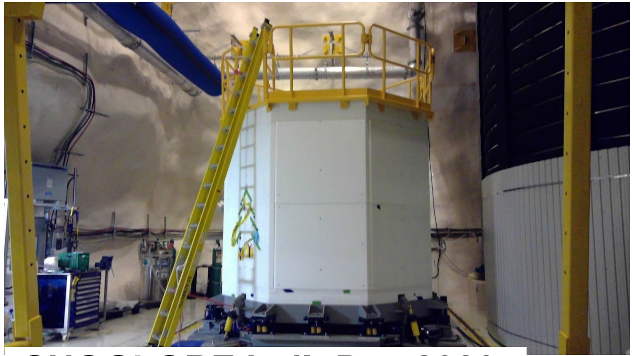

Unwrapped and baked Sep 2020


Lead pieces arrival


Seismic platform installation

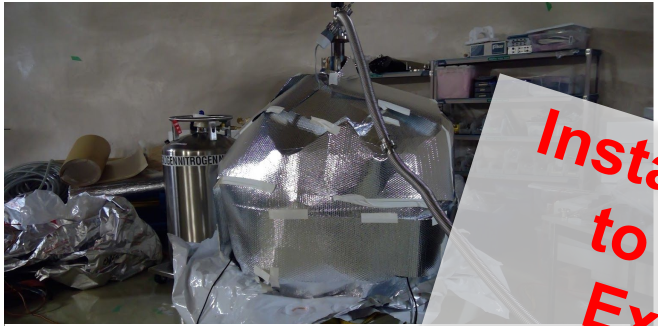

SPC inserted in Lead shield


PE shielding installation

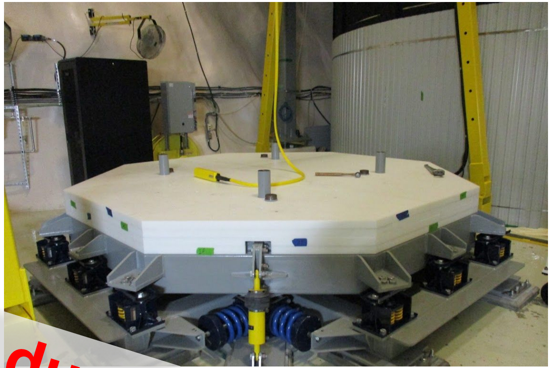

SNOGLOBE built Dec 2020

https://www.youtube.com/watch?v=NMjhzkLJP6M

# Status of installation at SNOLAB



Unwrapped and baked Sep 2020

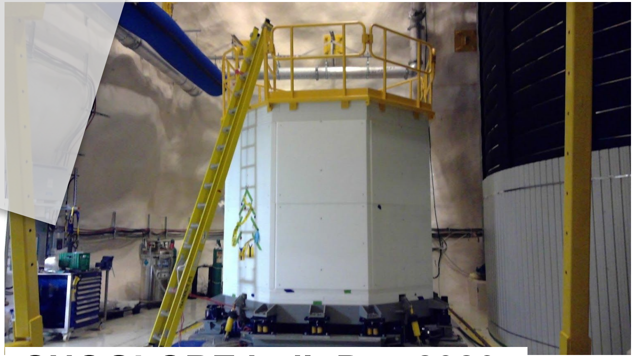


platform installation

**Installation work halted due to COVID-19 lockdown**
**Expected to restart in February 2021**

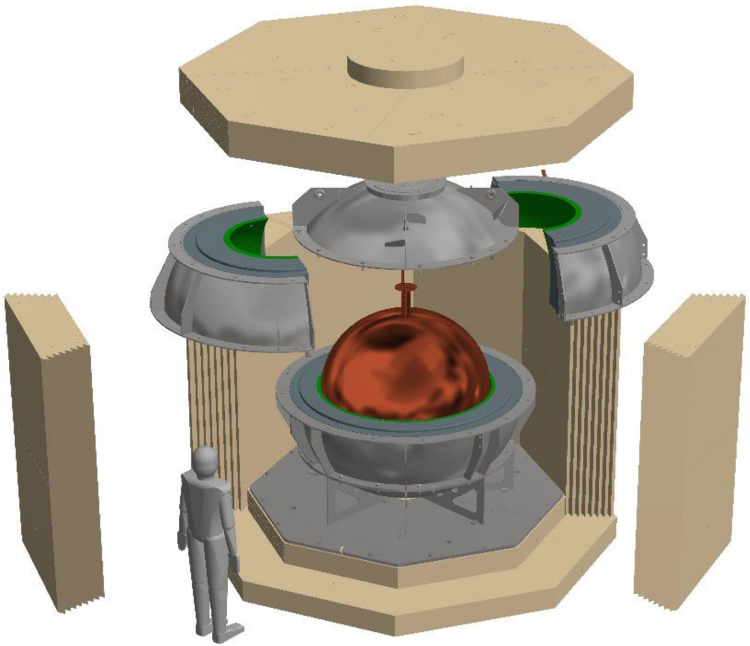
SPC inserted in Lead shield

PE shielding installation



SNOGLOBE built Dec 2020

# Challenges with the NEWS-G detector



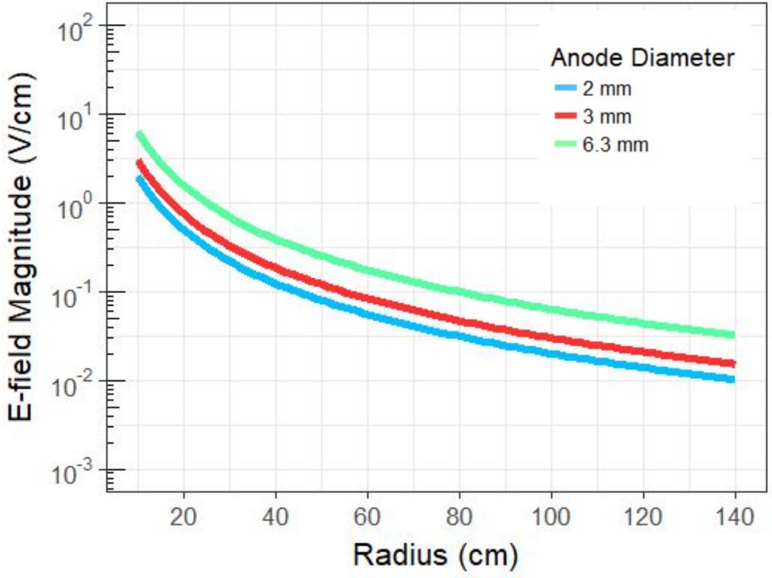
- Charge collection at large radii and high pressure operation
  - Electric field strength
  - Contaminants
- Detector response uniformity
- Background
  - Material purity
- Monitoring and calibration
- Detector simulation/response

# Electric field strength in large volume SPCs

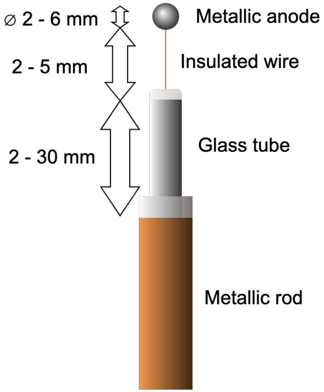
## Scaling-up

$$v(r), E(r) \sim r_A/r^2$$

**Comparison of E-field magnitude for different anode diameters**



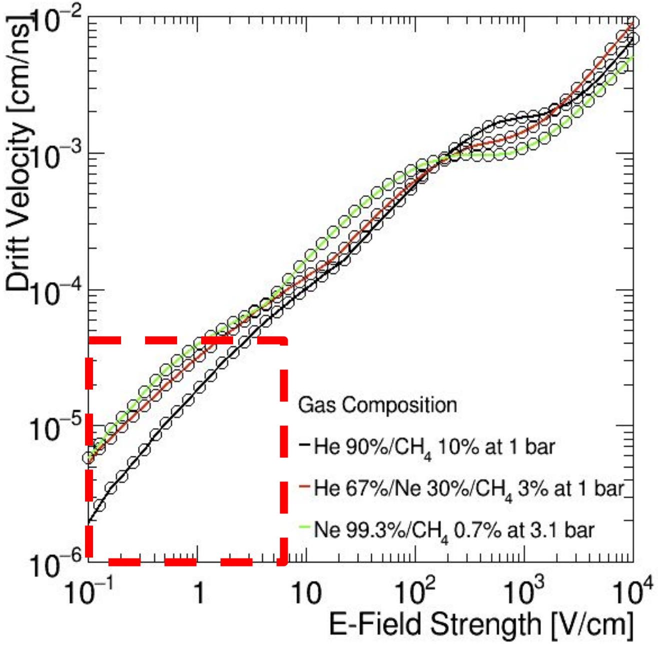

Single anode glass sensors

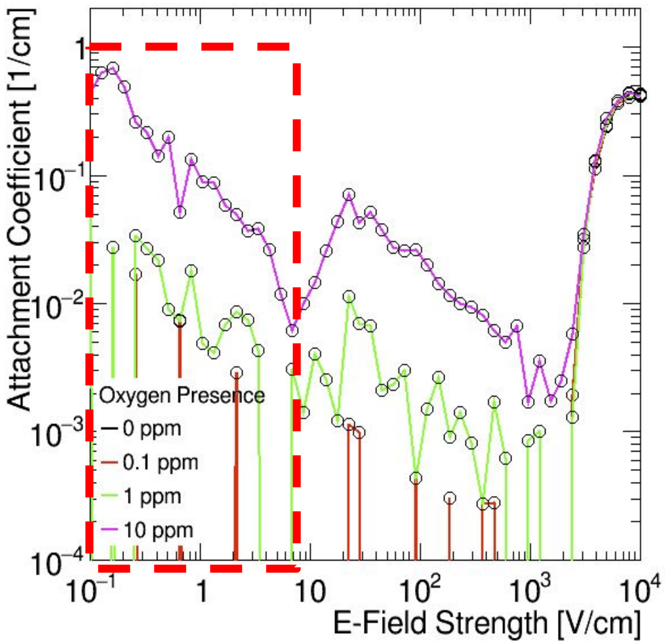



I. Katsioulas et al, JINST, 13, 11, P11006, 2018
10.1088/1748-0221/13/11/P11006

# Charge collection in low electric field

## Magboltz study on the sensitivity to contaminants

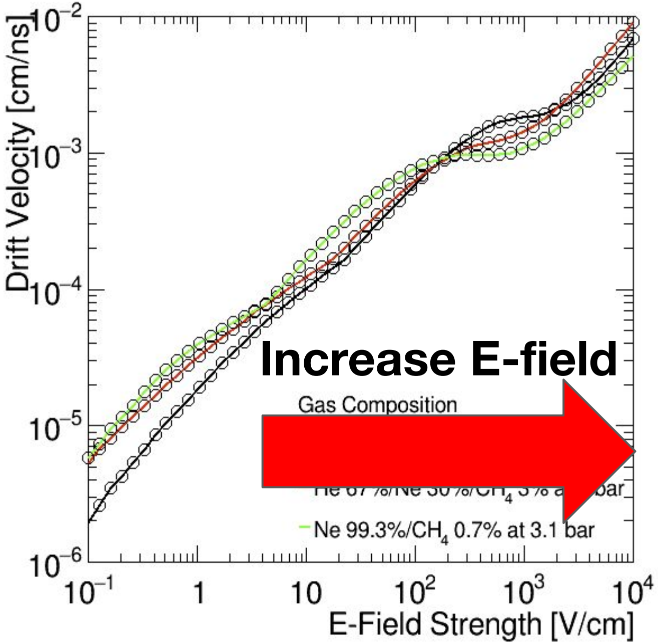


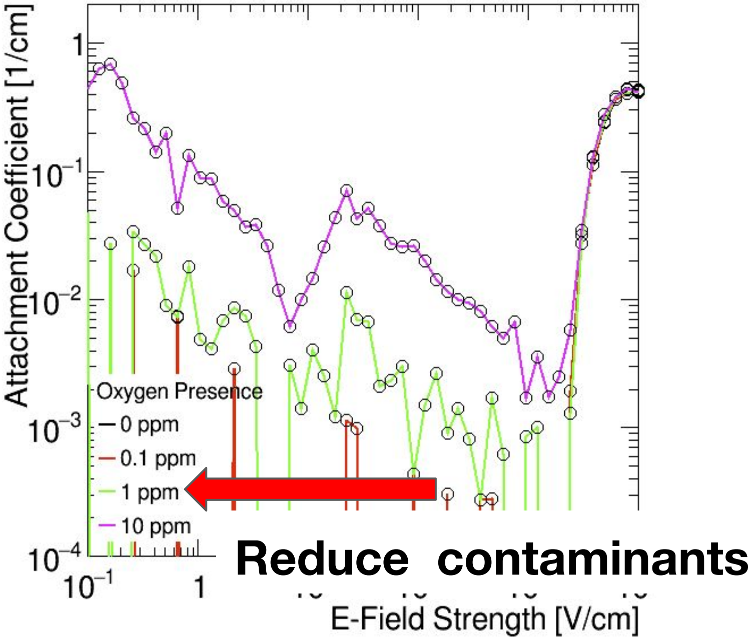




*Low E-field region*

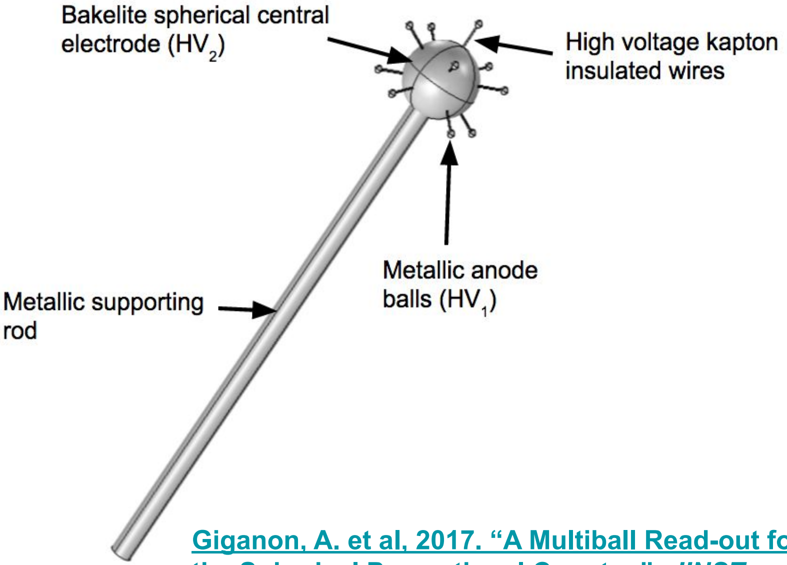
# Charge collection in low electric field

## Magboltz study on the sensitivity to contaminants

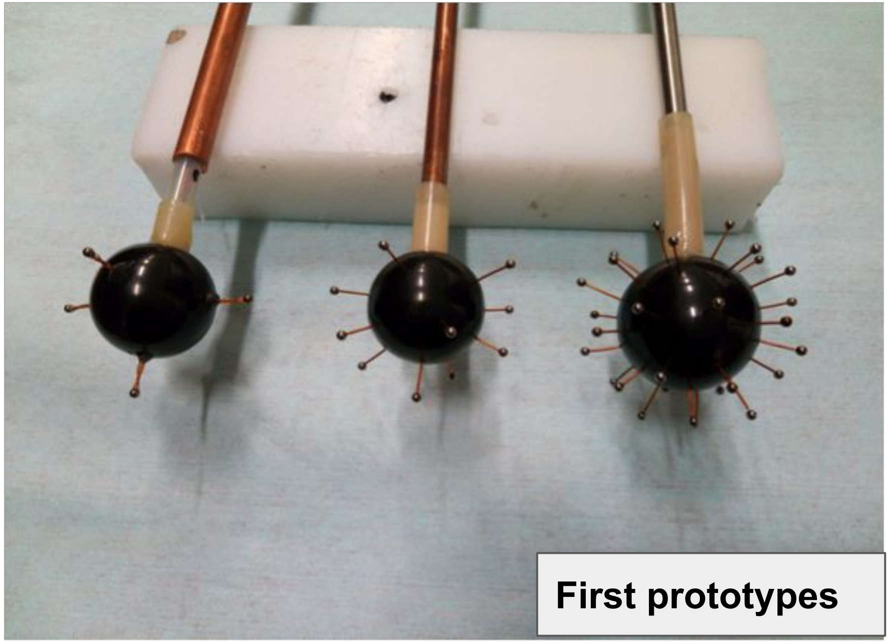


# The multi-anode sensor - ACHINOS

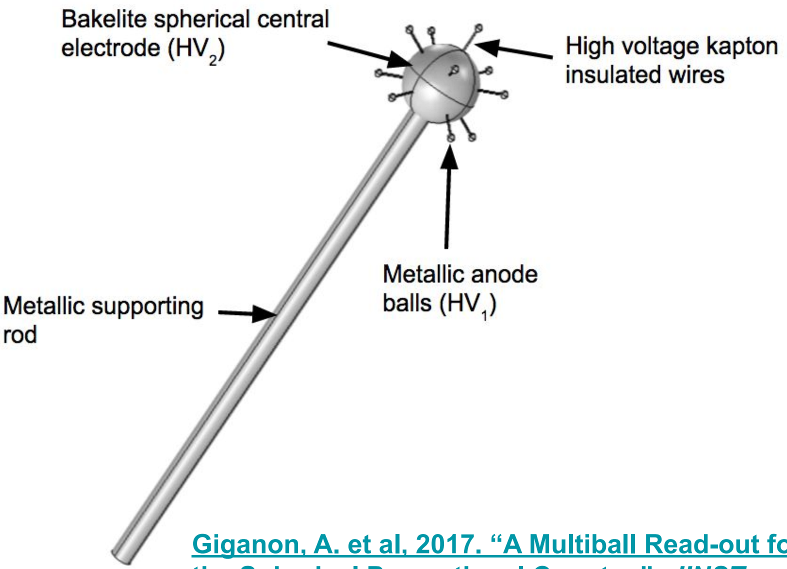



[Giganon, A. et al, 2017. "A Multiball Read-out for the Spherical Proportional Counter.", *JINST*]




**Instead of one => Use multiple anodes set to the same potential !!!**

# The multi-anode sensor - ACHINOS

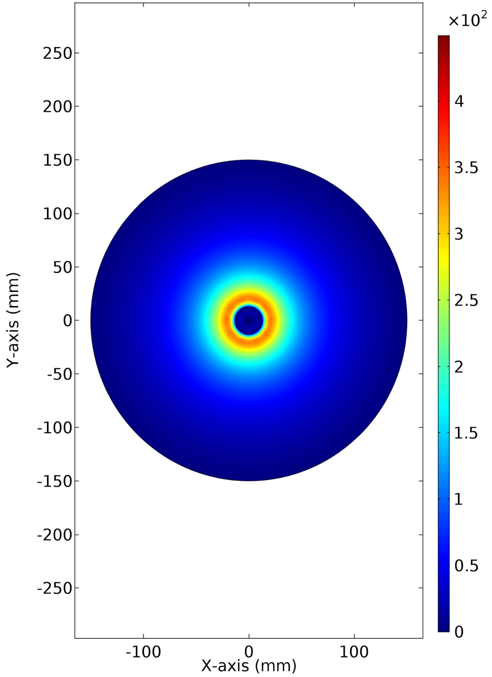



Giganon, A. et al, 2017. “A Multiball Read-out for the Spherical Proportional Counter.”, *JINST*

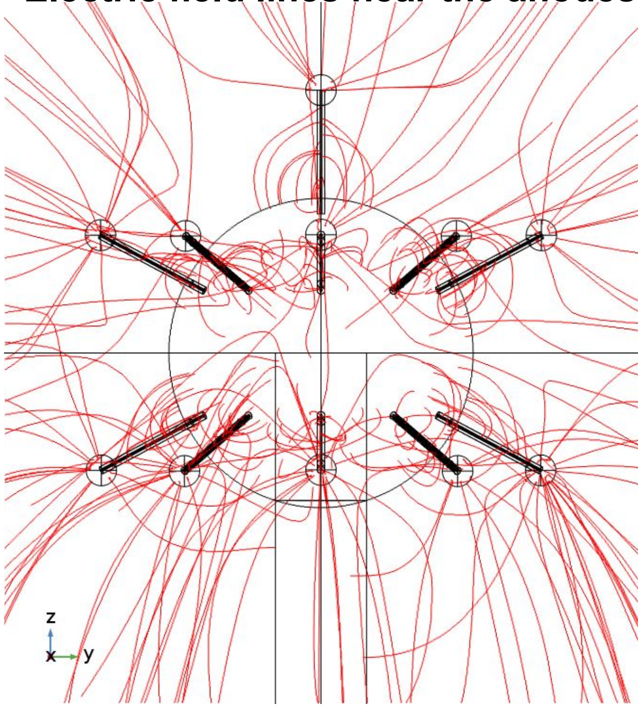
**Instead of one => Use multiple anodes set to the same potential !!!**

# Electric field configuration with an ACHINOS

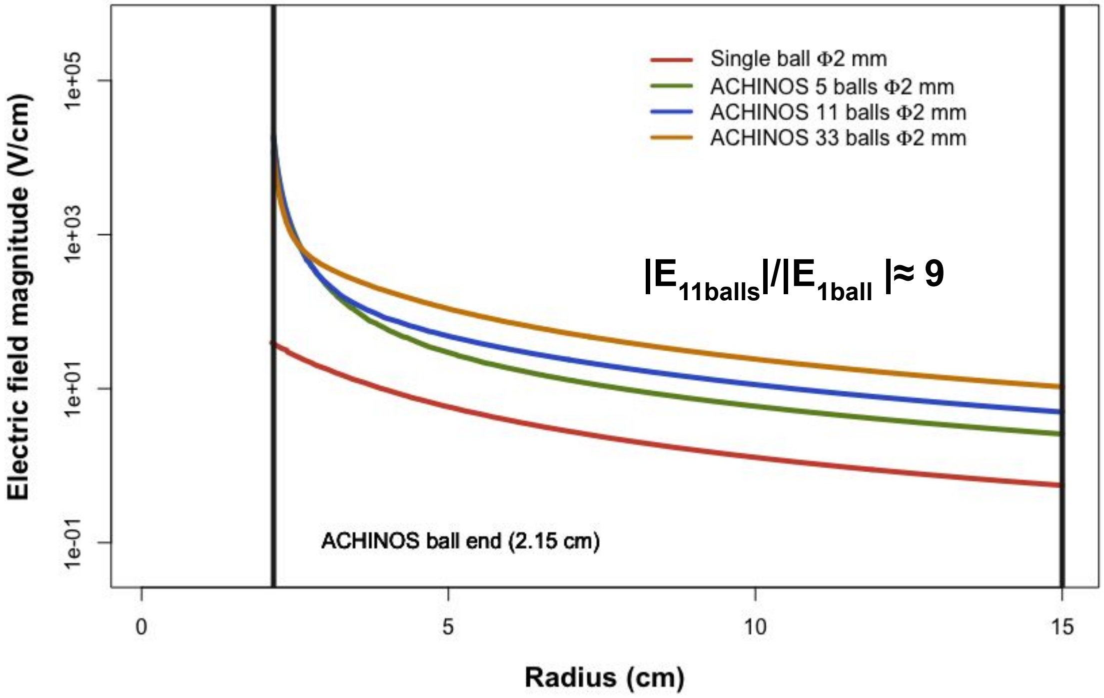
## Collective iso-potentials




## Electric field lines near the anodes



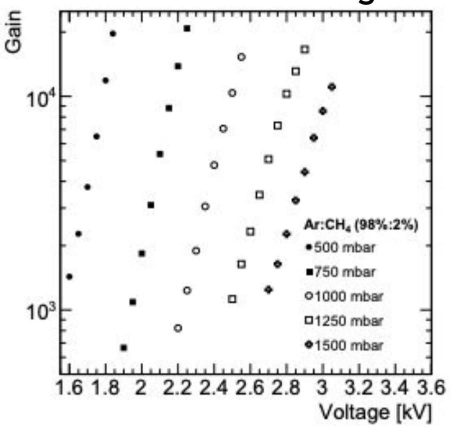
# Advantages of the ACHINOS sensor

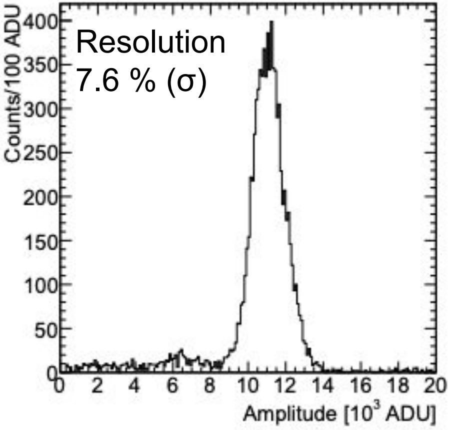



- Decouples electron drift and multiplication
  - Small anode size → high gain
  - More anodes → Efficient charge collection
- Allows for increased target mass
  - Larger volume
  - Higher pressure
- Individual readout TPC-like capabilities to the SPC

# Performance of ACHINOS with DLC coating

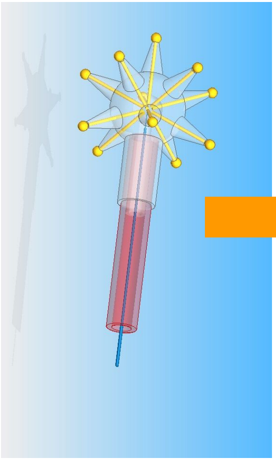
Gain vs Voltage



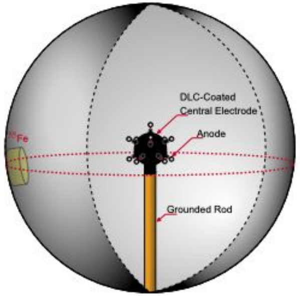




Measurement of the 5.9 keV
$^{55}$Fe X-ray line

3D design



Modules using 3D printing



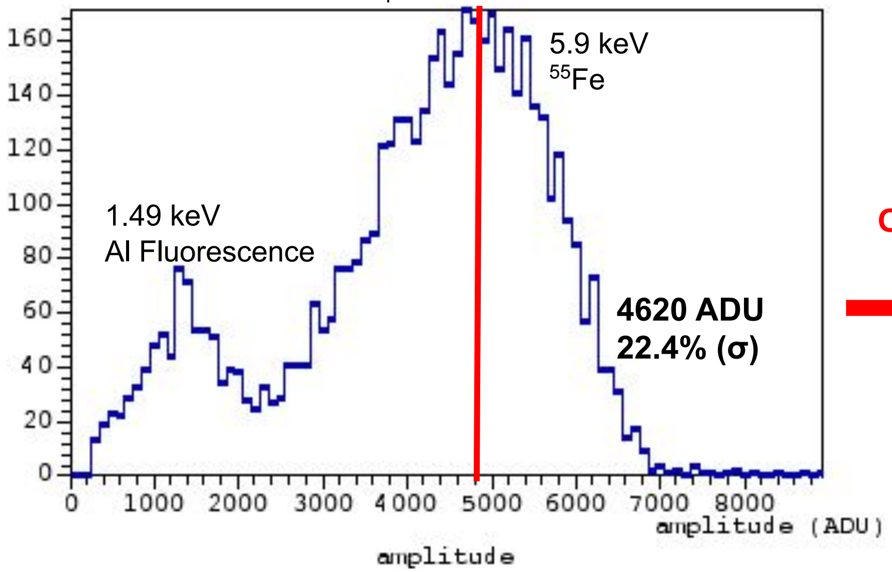

- Good energy resolution
- High pressure operation (> 2 bar)
- High gain
- Stability
- 2 channel readout

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

# 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

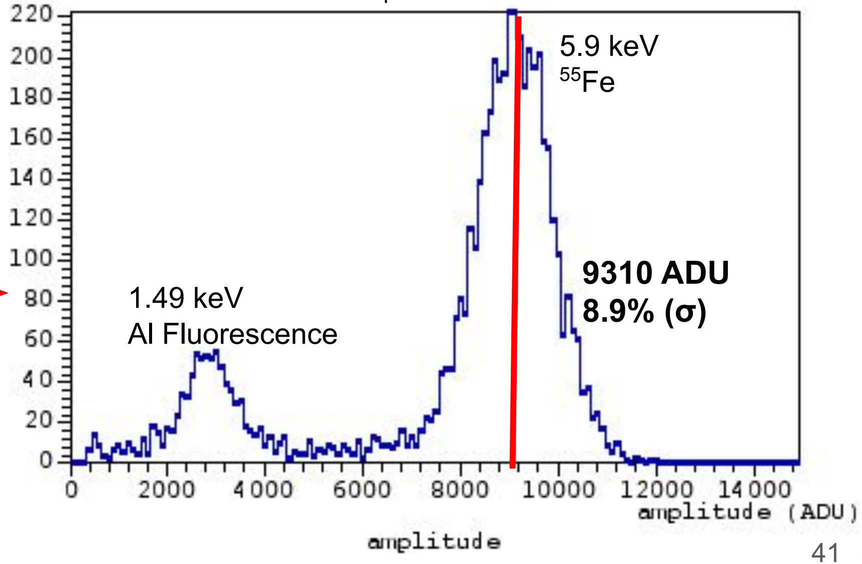
600 mbar He+10% $CH_4$ **without contaminant filtering**




**Using**

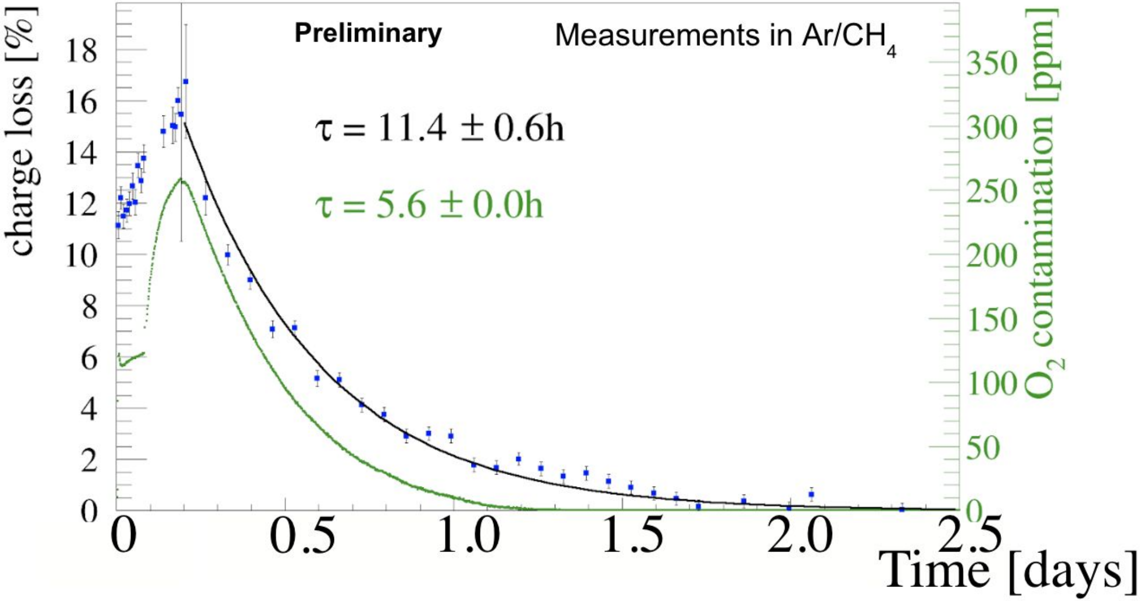
**Oxisorb**

600 mbar He+10% $CH_4$ **with contaminant filtering**



# Filtering within a recirculation system

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



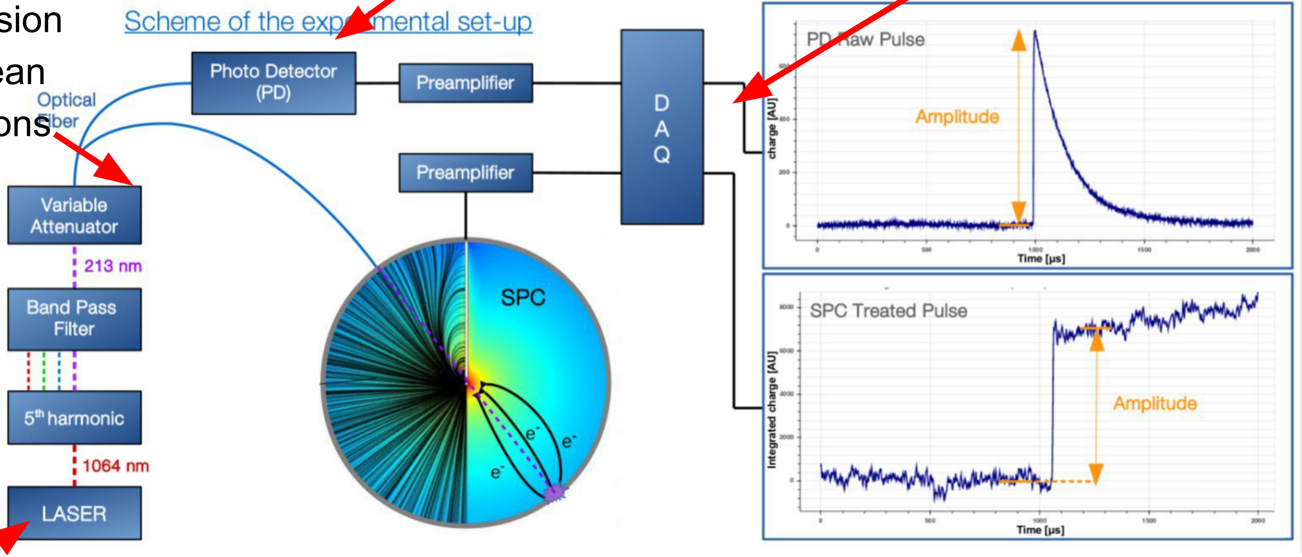
*NEWS-G Collaboration, Phys. Rev. D 99, 102003 (2019)*

# Laser calibrations

Parallel photodetector to tag laser events

Common DAQ for timing analysis between two channels

Tunable transmission to control the mean number of electrons



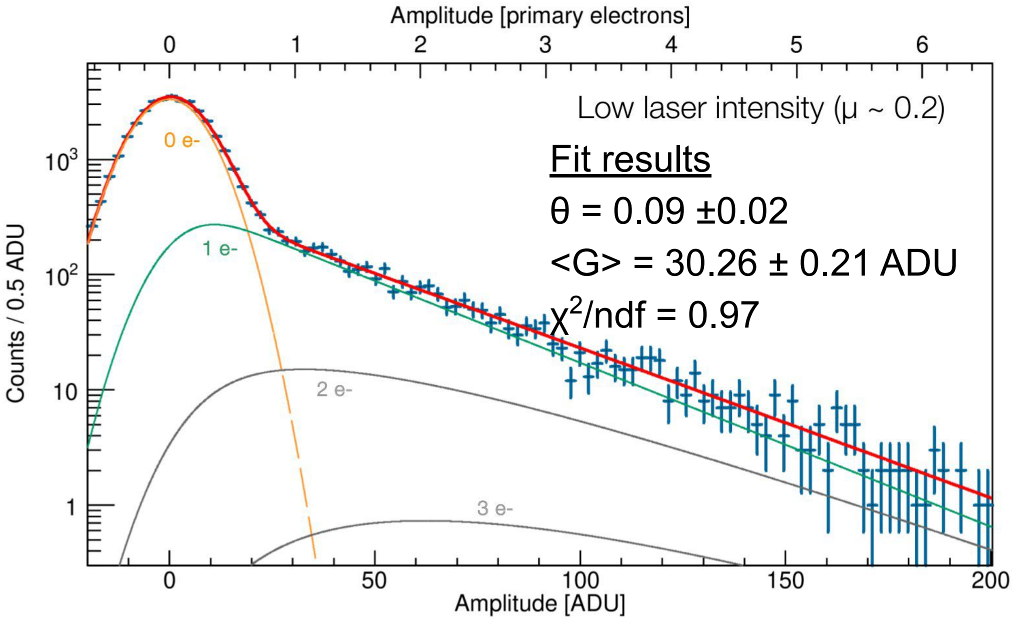

A powerful UV laser capable of extracting 100s of electrons

- **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**

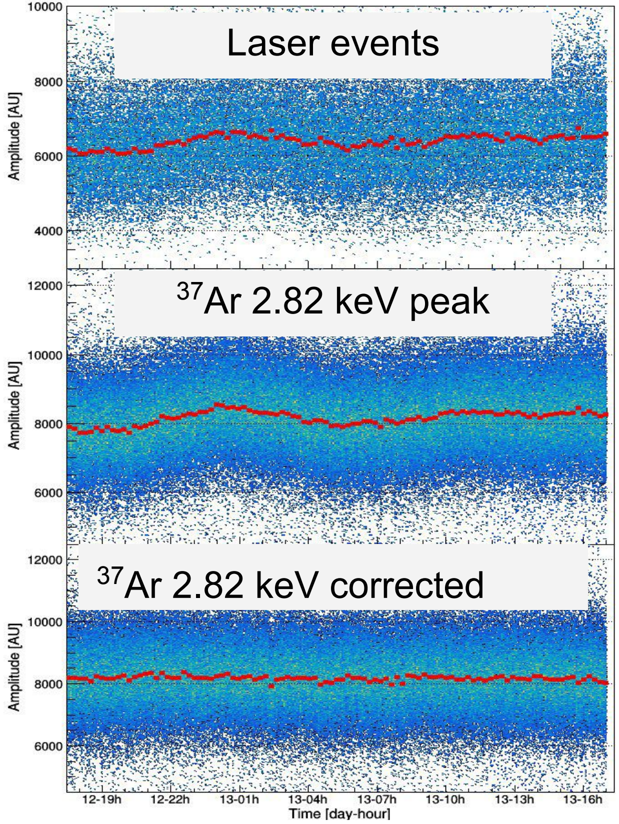
*NEWS-G Collaboration, Phys. Rev. D 99, 102003 (2019)*

# Laser calibrations

## Single electron response modeling

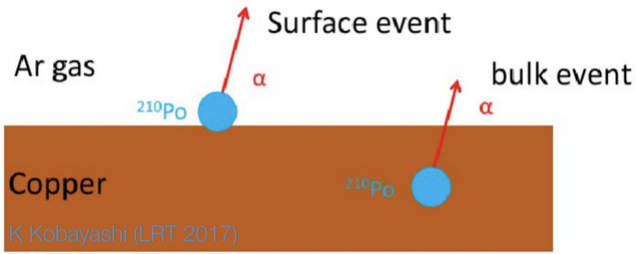


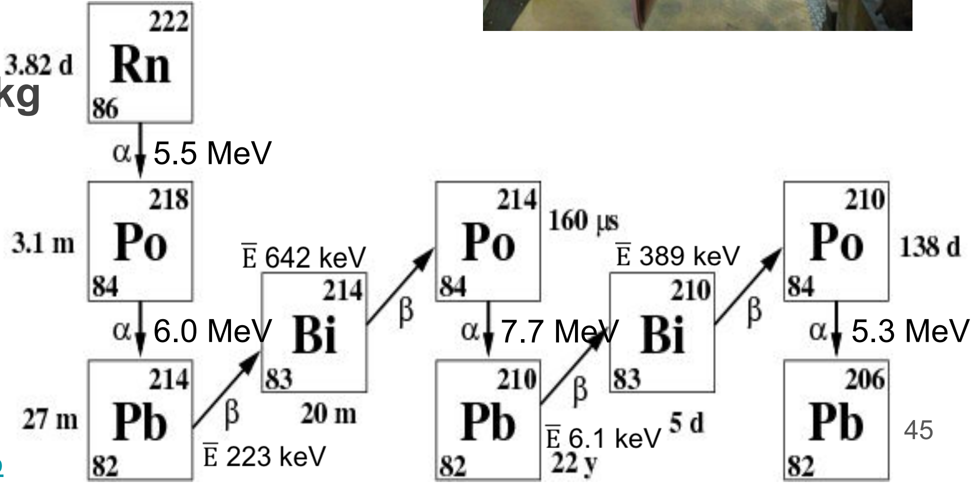

## Detector monitoring



# Background in NEWS-G copper

- **4N Aurubis Oxygen Free Copper C10100 (99.99% pure)**
  - Spun into two hemispheres
- **Copper has no long-lived isotopes**
- **$^{63}Cu(n,\alpha)^{60}Co$ from fast neutrons – mostly cosmic muon spallation**
- **Contaminants : U and Th decay chain traces**
  - Measured for NEWS-G ~10 µBq/kg
  - $^{210}Pb$ out of equilibrium - 28.5 mBq/kg



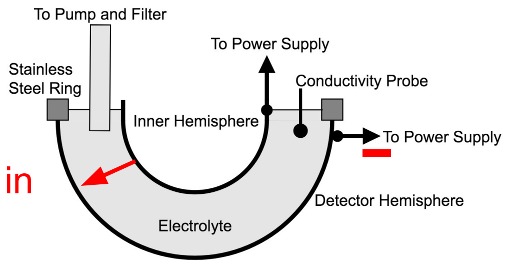
# Electroplating Copper

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]

### The setup during electroplating at LSM

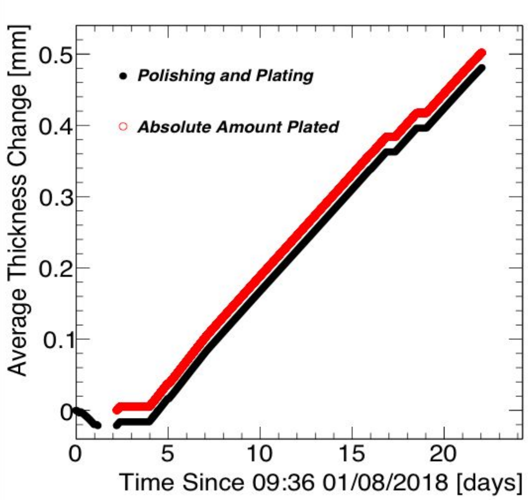


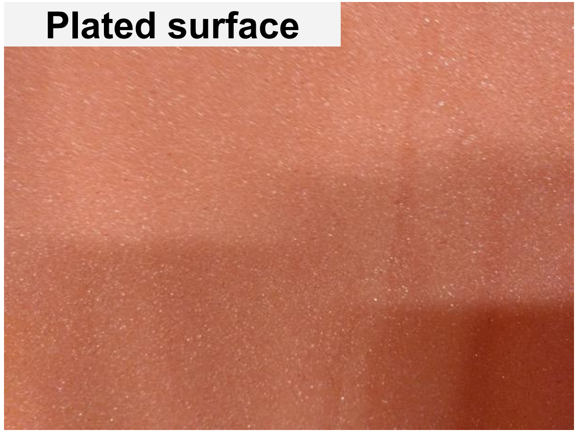

Cu Movement in Electroplating

- Using PNNL expertise - Strong participation from UoB in electroforming copper
- The inner surface of the detector was electroplated to stop Bremsstrahlung X-rays from $^{210}$Pb and $^{210}$Bi β-decays in copper
- 0.5 mm pure copper plated on inner surface at LSM: expected background from $^{210}$Pb and $^{210}$Bi under 1 keV reduced by a factor 2.6
- Total background in the experiment expected to be 1.96 dru

**P.Knights**
**UoB - Paris-Saclay**

# Result after plating

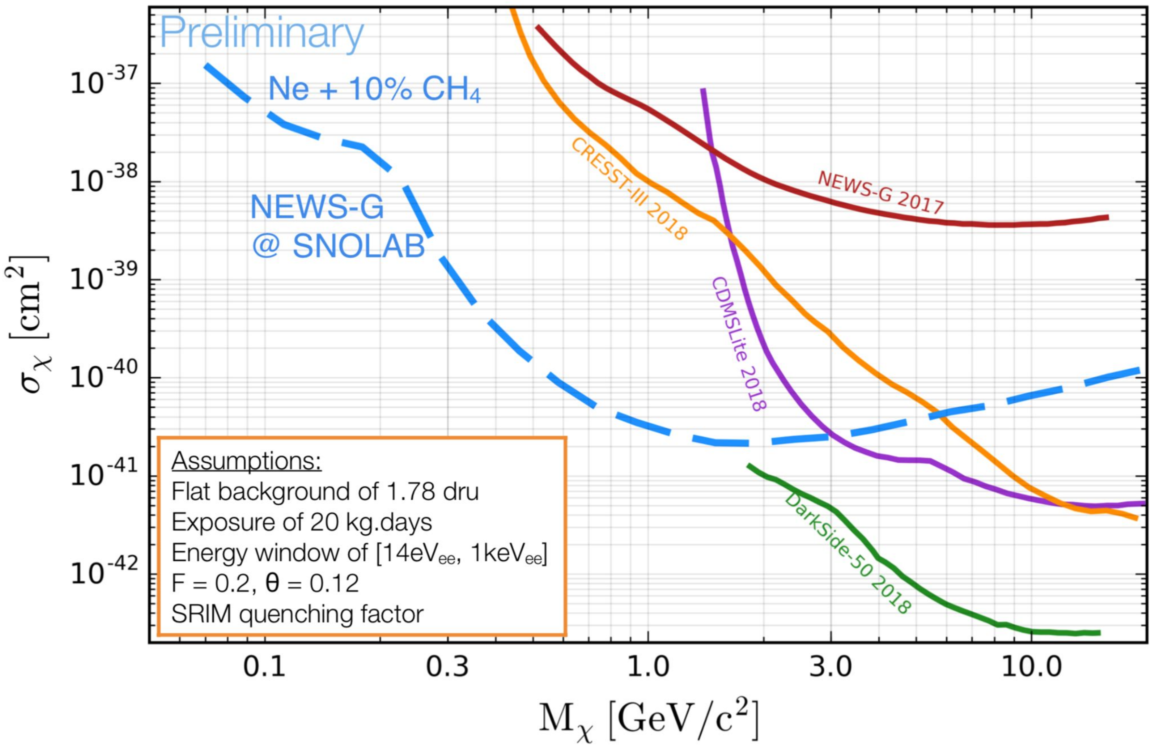




- **Good surface quality achieved**
- **Hemispheres electron-beam welded together**
- **Detector already operating at LSM**
- **Copper was deposited at a rate of ~36 µm/day**
  - **Result is promising for possibly a whole detector electroformed underground**

# Projected sensitivity for SNOGLOBE

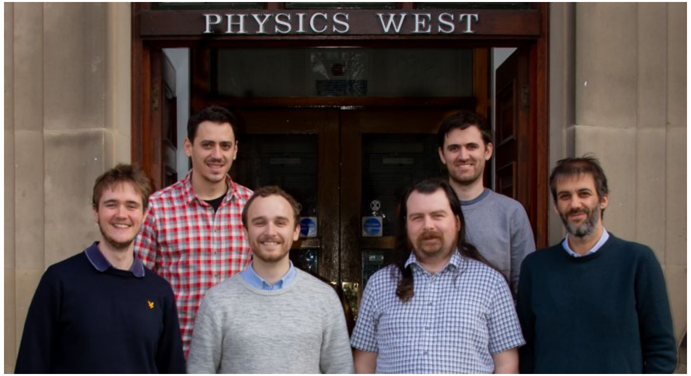



- **Low threshold**
- **Strong background rejection handles**
- **Hydrogen-rich mixtures**
- **Lower backgrounds**

# NEWS-G @ Birmingham

I. Katsioulas, P. Knights, J. Mathews I. Manthos, T. Neep, K. Nikolopoulos, R. Ward

- Co-spokesperson (April 2021)
- Physics Run coordination
- Radiopurity-Background suppression techniques
- Detector physics simulations
- Multivariate analysis techniques
- Ionisation quenching studies
- Neutron background studies



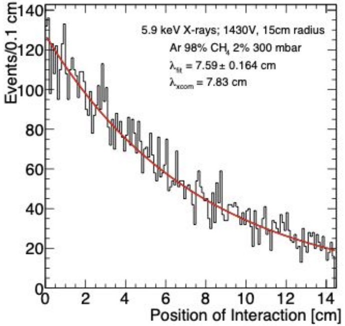

Newest additions!

Inspired by: Pfeifer, D. et al, Nucl. Instrum. Methods Phys. Res., A 935 (2019) 121-134

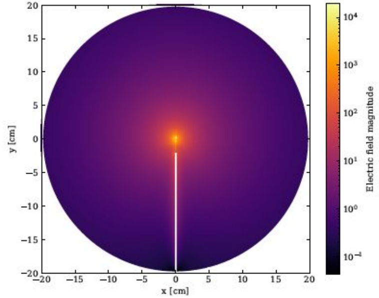
# Simulating the detector response

1. Detector is initialised and initial particle is generated
2. Geant4 tracks particles and interactions
3. Electrons with energy <2 keV are passed to Garfield++
4. Heed calculates further ionisation and $\delta$-electrons produced
5. Using the gas transport parameters, ionisation electrons are transported up to the avalanche region
6. Electron avalanche is simulated
7. Ions and electrons produced in avalanche drift in electric field, and induced electric current is calculated
8. Signal is processed through electronics module to form pulse

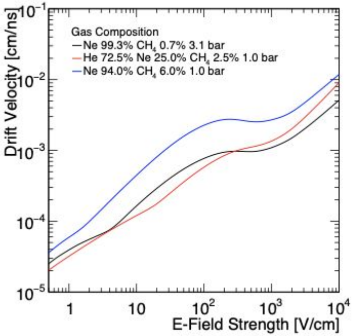
Primary interaction



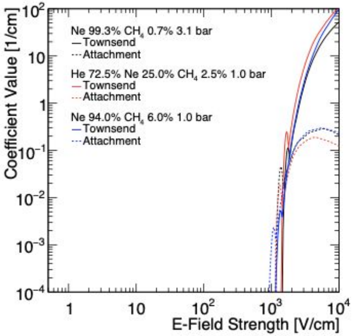

Electric field




Electron Drift




Electron Multiplication



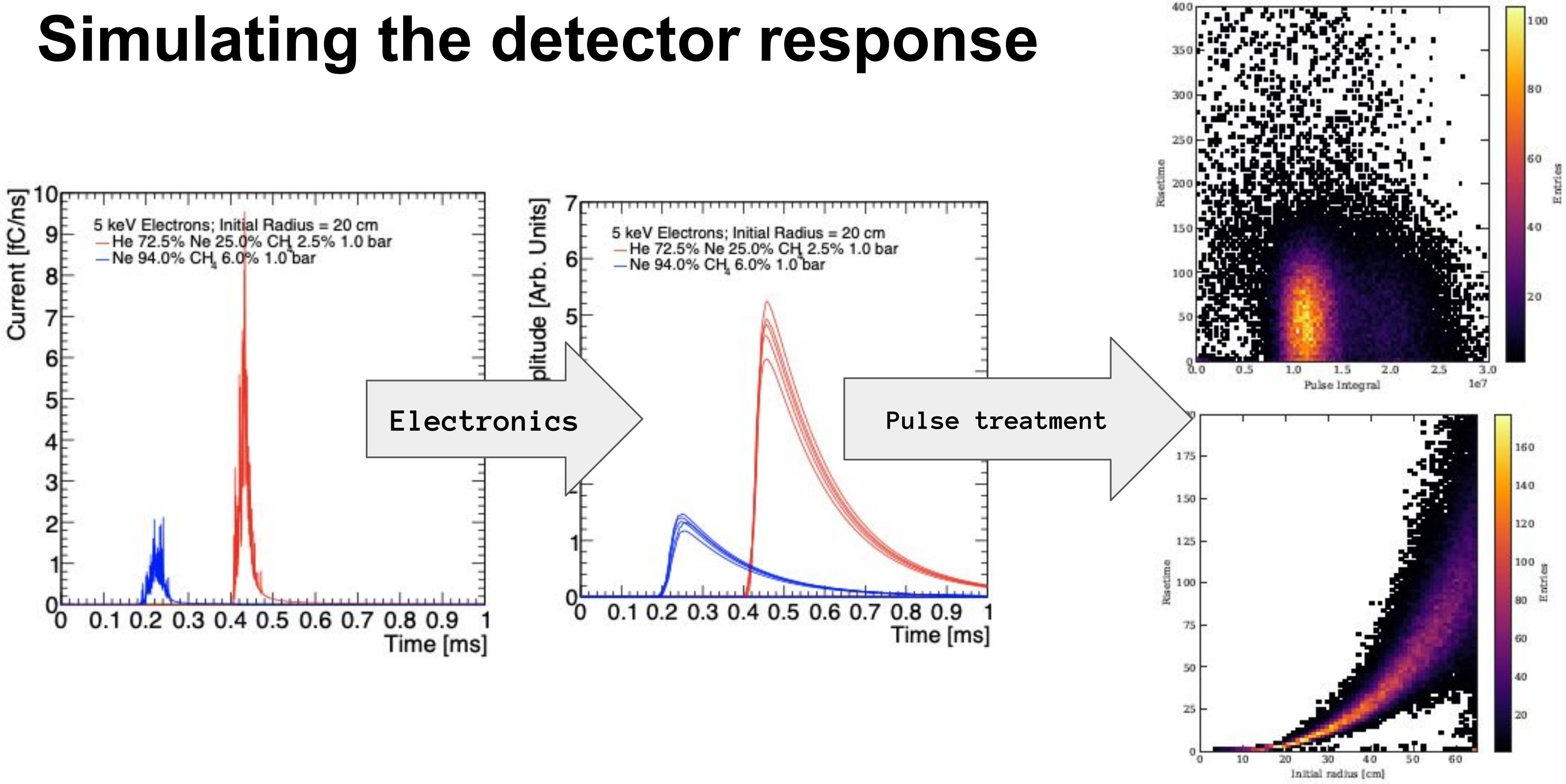

Geant4

Garfield++

Katsioulas, I. et al, 2017. "Development of a Simulation Framework for Spherical Proportional Counters",arXiv:2002.02718

Katsioulas, I. et al, 2017. “Development of a Simulation Framework for Spherical Proportional Counters”,arXiv:2002.02718

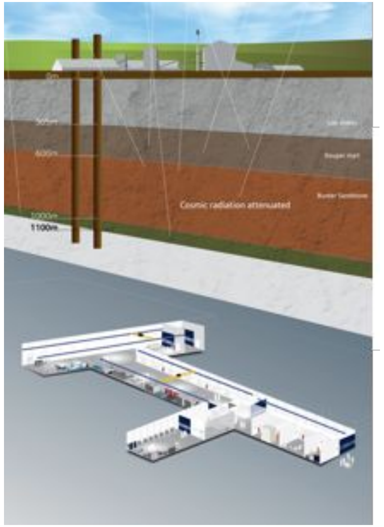
# Simulating the detector response





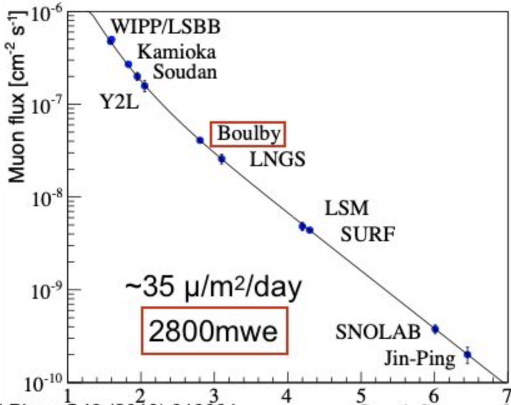

Ioannis Katsioulas | i.katsioulas@bham.ac.uk | EDIN seminar

# Collaboration with Boulby underground laboratory

Lowest Radon Levels 3 Bq/m$^3$

BOULBY UNDERGROUND LABORATORY

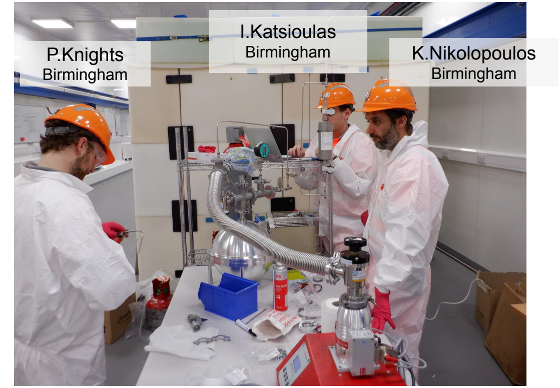


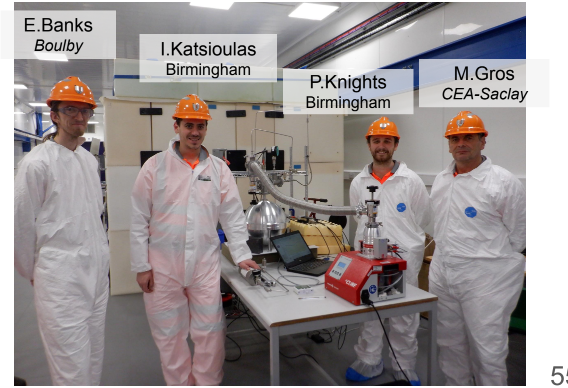

J.Phys. G43 (2016) 013001

# Background measurements at Boulby

- Instrumentation R&D at controlled environment
- Neutron flux measurement
  - Thermal neutron
  - Fast neutron
- Including energy information
- Method applicable to all other underground laboratories

**Aluminium S30**



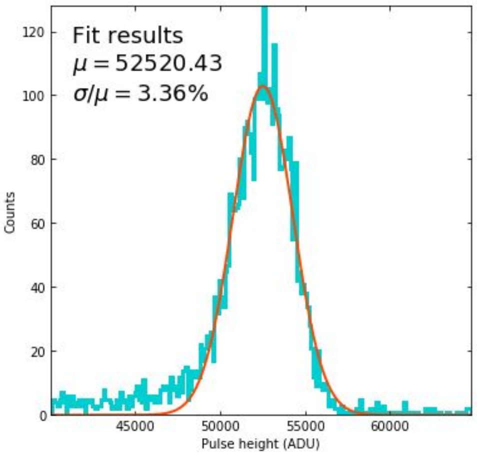
# Neutron detection with SPCs

- Neutron spectroscopy with Spherical Proportional Counter
  - Using Nitrogen as gas
  - $^{14}N+n \rightarrow ^{14}C+p$ + 625 keV
  - $^{14}N+n \rightarrow ^{11}B+\alpha$ - 159 keV
- Initially demonstrated: *Bougamont, E et al (2017). NIM A, 847, 10–1*
  - $^{252}$Cf, $^{241}$Am$^{9}$Be, ambient fast neutrons
  - Thermal neutrons
  - Operation at 0.2-0.5 bar
  - HV reached 6 kV

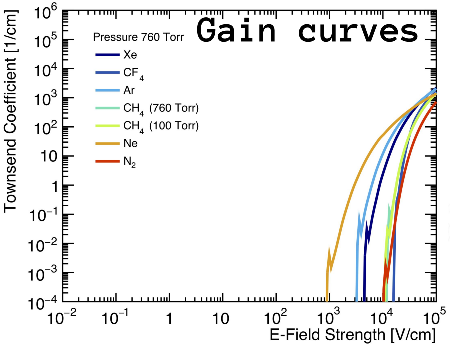
**Goals:**

- Operation in high pressure (~5 bar)
  - Minimisation of wall effect
  - Larger target mass - Sensitivity
- Calibration with mono-energetic neutrons
- Measurements with thermal and fast neutrons

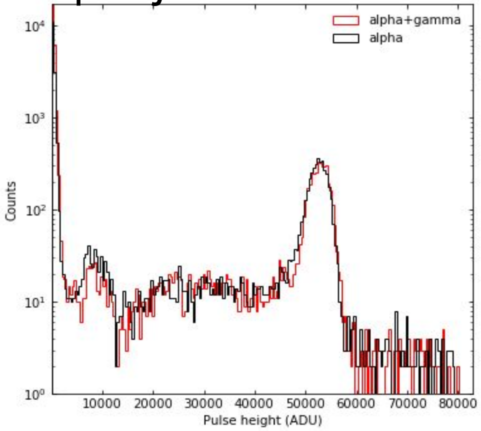
Resolution



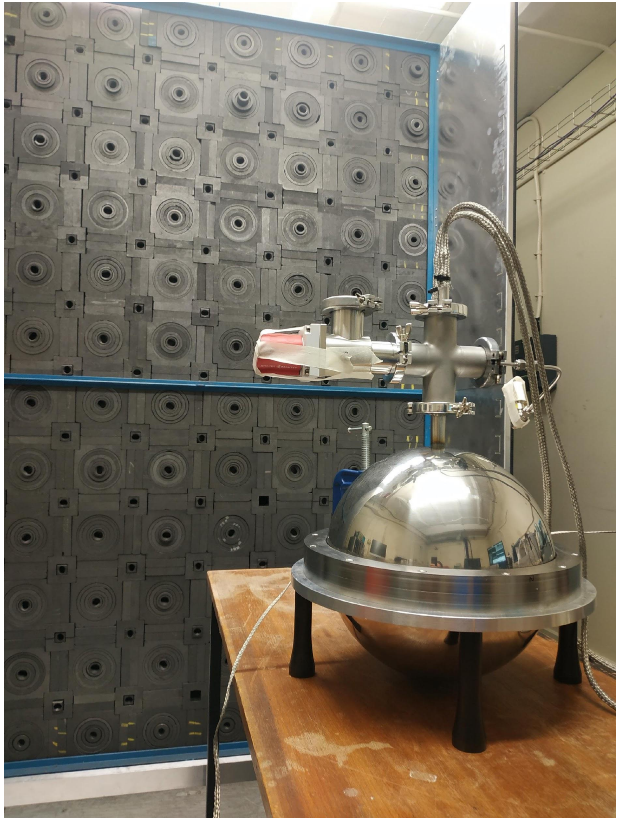

Gain curves



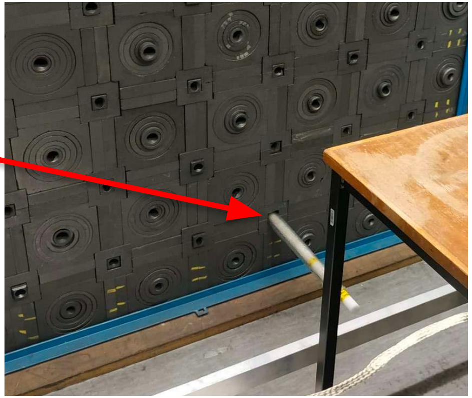

γ-ray discrimination



# Neutrons measurements at UoB



$^{241}Am^{9}Be$ **neutron source**
A = ~$10^{10}$ Bq



**SPC**
- 30 cm ∅
- $N_2$ gas filling

**Multi-anode sensor**
- 11 anodes
- 1mm ∅
- Reading in 2 channels

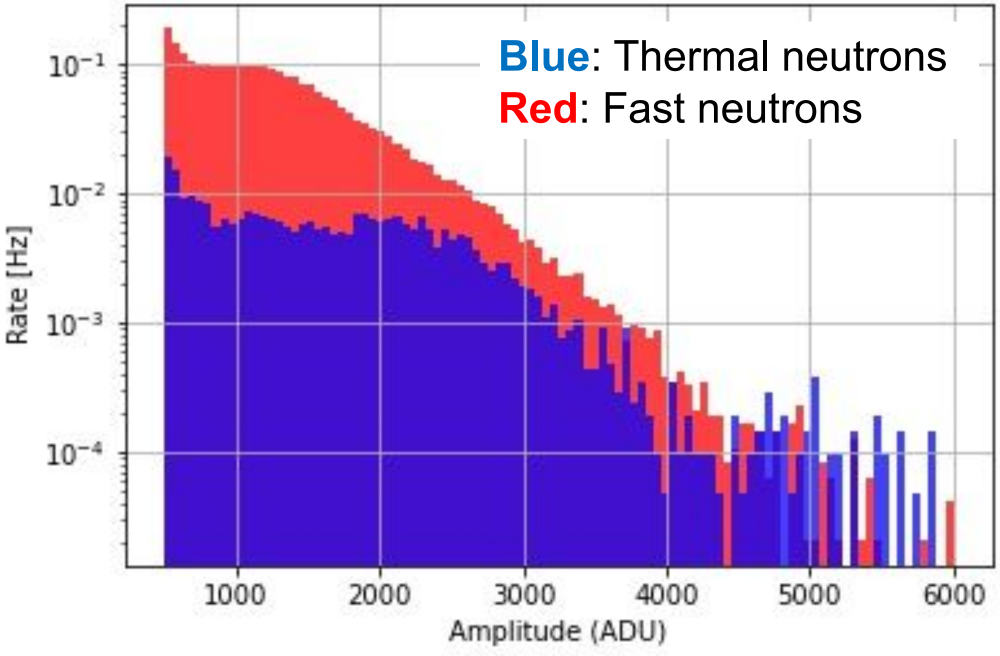
Investigate the capability of the SPC to detect fast neutrons and neutrons thermalized by the graphite.

# Neutron measurements with the SPC

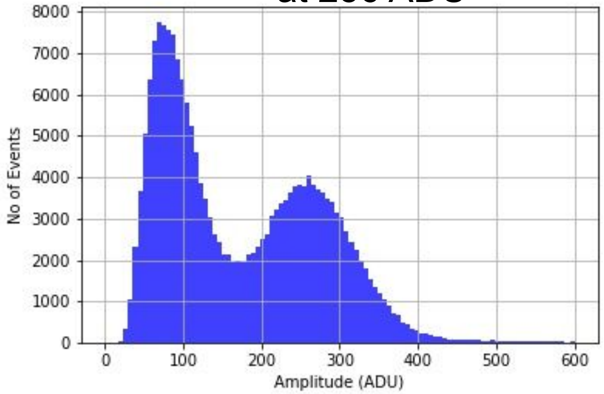
**$^{241}Am^{9}Be$ neutron source**

1 bar $N_2$, 3.8 kV

**Preliminary results (ongoing analysis)**

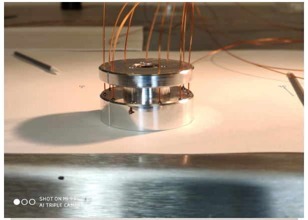



**Thermal neutrons**
at 256 ADU

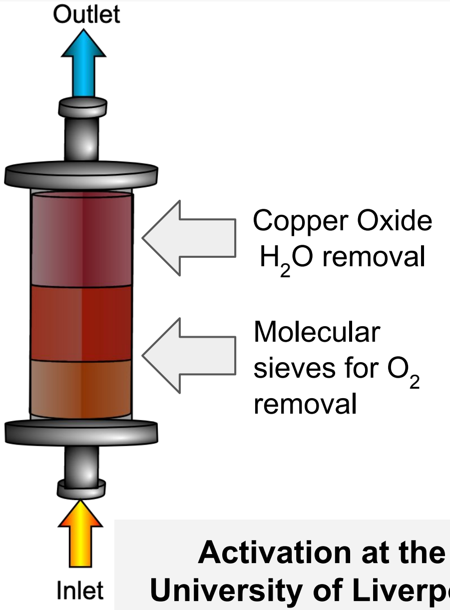


# Instrumentation developments at UoB

**ACHINOS - Achievements**
- **Fully coated with DLC**
- **Improved accuracy on anode placement**
- **Improved spacing**

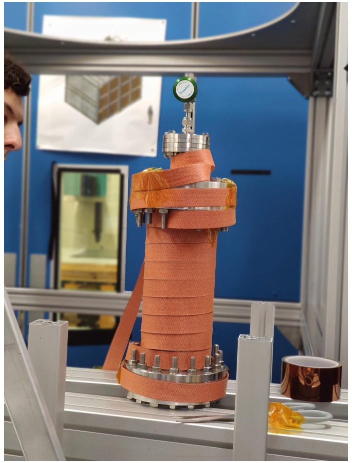


Gas Filter - Aims
- Replace commercial filters
- Reduce Rn emanation
- Maintain efficiency
- Known ingredients
- Cost effective




**Activation at the University of Liverpool**

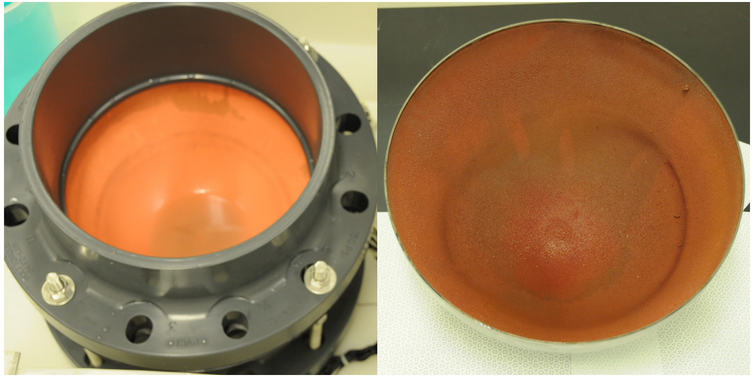
***Collaboration with Dr. K.Mavrokoridis Team***



UNIVERSITY OF LIVERPOOL

# ECUME - Electroformed CUprum Manufacturing Experiment

- 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



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

## Current Status:

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

# ECUME - Electroformed CUprum Manufacturing Experiment

| | Source | Contamination / flux | Unit | Events rate <1 keV [dru] | Events rate in [1;5] keV [dru] | Total rate [mHz] |
|---|---|---|---|---|---|---|
| Gas mixture | $^{3}H$ | 13 | $\mu$Bq/kg | 0.05 | 0.06 | 0.005 |
| | $^{222}Rn$ | 111 | $\mu$Bq/kg | 0.05 | 0.04 | 0.2 |
| Copper sphere 500 $\mu m$ electrolyte | ~~$^{210}Pb$~~ | ~~28.5~~ | ~~mBq/kg~~ | ~~1.04~~ | ~~1.01~~ | ~~0.86~~ |
| | ~~$^{238}U$~~ | ~~3~~ | ~~$\mu$Bq/kg~~ | ~~0.0117~~ | ~~0.115~~ | ~~0.028~~ |
| | ~~$^{232}Th$~~ | ~~12~~ | ~~$\mu$Bq/kg~~ | ~~0.0754~~ | ~~0.0602~~ | ~~0.163~~ |
| | ~~$^{40}K$~~ | ~~0.1~~ | ~~mBq/kg~~ | ~~0.0157~~ | ~~0.0186~~ | ~~0.0622~~ |
| Roman lead | $^{210}Pb$ | <25 | mBq/kg | <0.14 | <0.12 | 0.057 |
| | $^{238}U$ | 44.5 | $\mu$Bq/kg | 0.142 | 0.094 | 0.277 |
| | $^{232}Th$ | 9.1 | $\mu$Bq/kg | 0.0256 | 0.0161 | 0.0577 |
| | $^{40}K$ | <1.3 | mBq/kg | <0.28 | 0.23 | 0.65 |
| Low activity lead | $^{210}Pb$ | 4.6 | Bq/kg | 0.053 | 0.055 | 0.17 |
| | $^{238}U$ | 79 | $\mu$Bq/kg | 0.17 | 0.132 | 0.5 |
| | $^{232}Th$ | 9 | $\mu$Bq/kg | 0.0251 | 0.0201 | 0.075 |
| | $^{40}K$ | <1.46 | mBq/kg | <0.35 | 0.26 | 0.67 |
| Cavern | Gamma | $4.87 \times 10^{-8}$ | $\gamma/cm^2/s$ | 0.0084 | 0.0095 | 0.00464 |
| | Neutron | 4000 | neutron/$m^2$/day | 0.0044 | 0.0004 | $3.54 \times 10^{-11}$ |
| | Muon | 0.27 | muon/$m^2$/day | 0.00062 | 0.00044 | $5.04 \times 10^{-8}$ |
| Total | | | | 1.67 | 1.54 | 2.4 |
| ~~Total + cosmogenic activation of the copper sphere~~ | | | | ~~5.20~~ | ~~5.20~~ | ~~5.4~~ |
| ~~Total + cosmogenic activation of the copper sphere and 6 months of cooling~~ | | | | ~~2.8~~ | ~~2.5~~ | ~~3.4~~ |
| ~~Total + cosmogenic activation of the copper sphere and 1 years of cooling~~ | | | | ~~2.1~~ | ~~1.9~~ | ~~3.0~~ |
| ~~Total + cosmogenic activation of the copper sphere and 2 years of cooling~~ | | | | ~~1.9~~ | ~~1.7~~ | ~~2.9~~ |

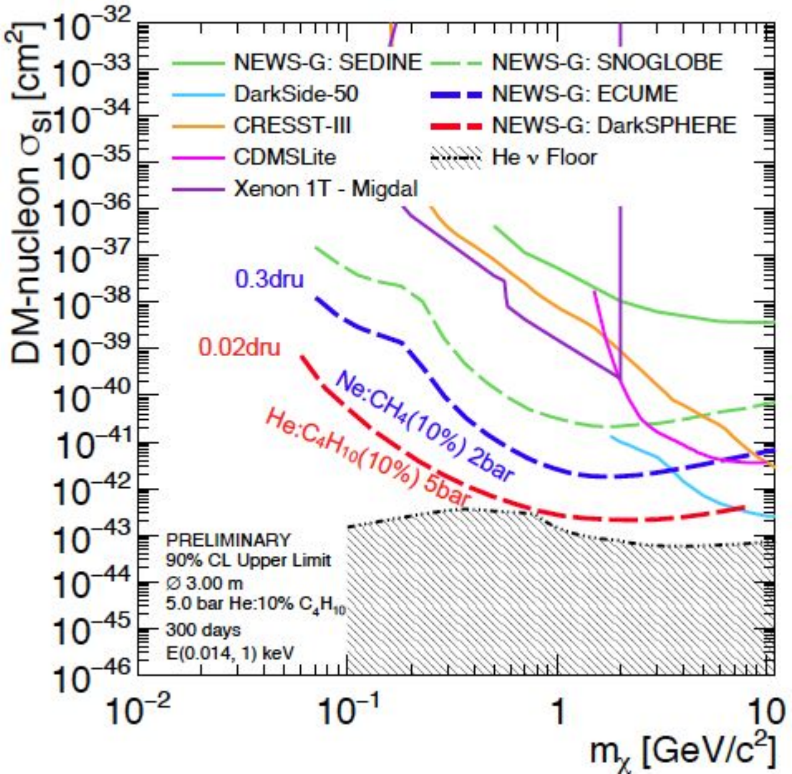
Removing contributions from copper, lead shielding becomes dominant background

*PhD Thesis, Alexis Brossard, 2020*

# DarkSPHERE: Exploring light Dark Matter with Spherical Proportional Counters electroformed underground

## Conceptual parameters:

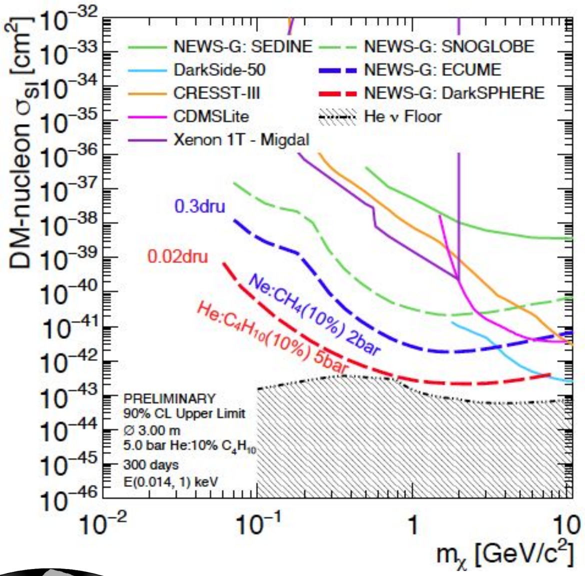
- Installation at Boubly
- 3 m ⌀ SPC
- Fully electroformed underground
- Operation with He/i$C_4H_{12}$ and possibly Xe
- Pressure up to 5 bar
- Large target mass *O(100kg)*
- Sensitivity down to the *ν*-floor
- Multiphysics platform

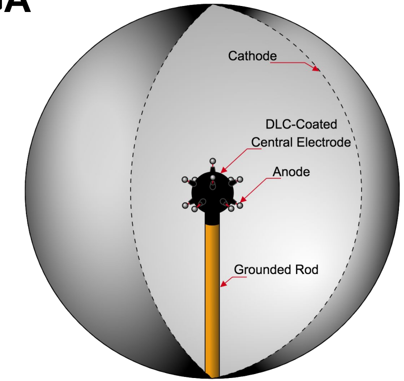



Dimensions in mm

# Summary

- **NEWS-G searches for light DM candidates**
  - **Lighter targets**
  - **Improved shielding/materials/procedure**
  - **Lower energy threshold**
- **Sensor Development**
  - **Improved electric field uniformity**
  - **ACHINOS: electric field in large detectors**
- **Improved gas quality: Filtering, Recirculation,**
- **Improved calibration/monitoring: $^{37}$Ar, Laser, RGA**
- **Simulation framework development**
- **On going work at Boulby!**
- **Paving the way for future NEWS-G!**
- **Many physics opportunities!**

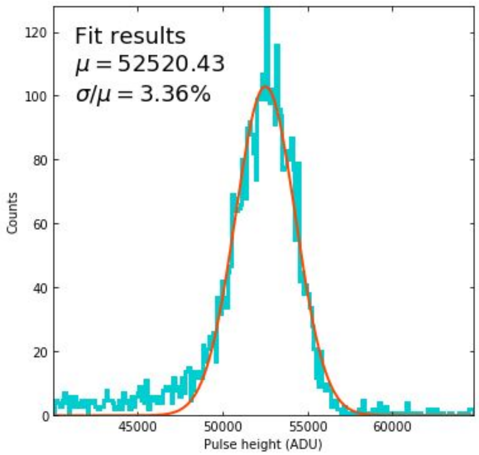


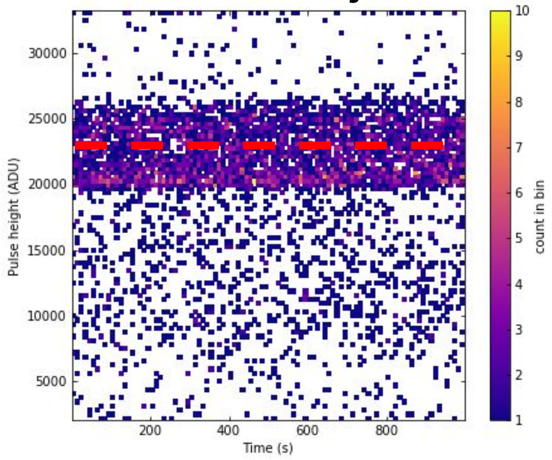

# BACKUP SLIDES

# Detector characterisation - In progress

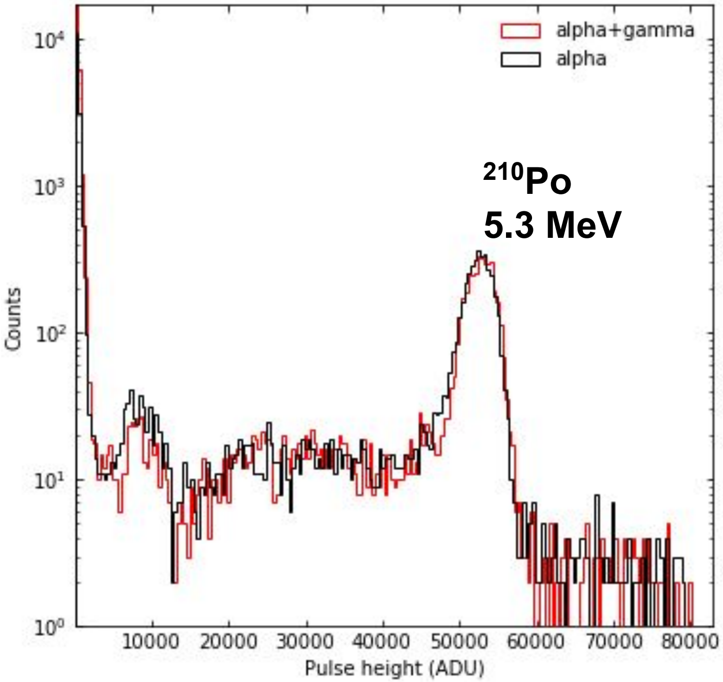
Resolution




Stability




γ-ray discrimination




**Planning:**

- **Operation at up to 2 bar**
  - **Minimisation of wall effect**
  - **Larger target mass - Sensitivity**
- **Calibration with mono-energetic neutrons**
- **Measurements with thermal and fast neutrons**

# BG budget

| | Source | Contamination / flux | Unit | Events rate <1 keV [dru] | Events rate in [1;5] keV [dru] | Total rate [mHz] |
|---|---|---|---|---|---|---|
| Gas mixture | $^{3}H$ | 13 | $\mu$Bq/kg | 0.05 | 0.06 | 0.005 |
| | $^{222}Rn$ | 111 | $\mu$Bq/kg | 0.05 | 0.04 | 0.2 |
| Copper sphere 500 $\mu m$ electrolyte | $^{210}Pb$ | 28.5 | mBq/kg | 1.04 | 1.01 | 0.86 |
| | $^{238}U$ | 3 | $\mu$Bq/kg | 0.0117 | 0.115 | 0.028 |
| | $^{232}Th$ | 13 | $\mu$Bq/kg | 0.0754 | 0.0692 | 0.163 |
| | $^{40}K$ | 0.1 | mBq/kg | 0.0157 | 0.0186 | 0.0622 |
| Roman lead | $^{210}Pb$ | <25 | mBq/kg | <0.14 | <0.12 | 0.057 |
| | $^{238}U$ | 44.5 | $\mu$Bq/kg | 0.142 | 0.094 | 0.277 |
| | $^{232}Th$ | 9.1 | $\mu$Bq/kg | 0.0256 | 0.0161 | 0.0577 |
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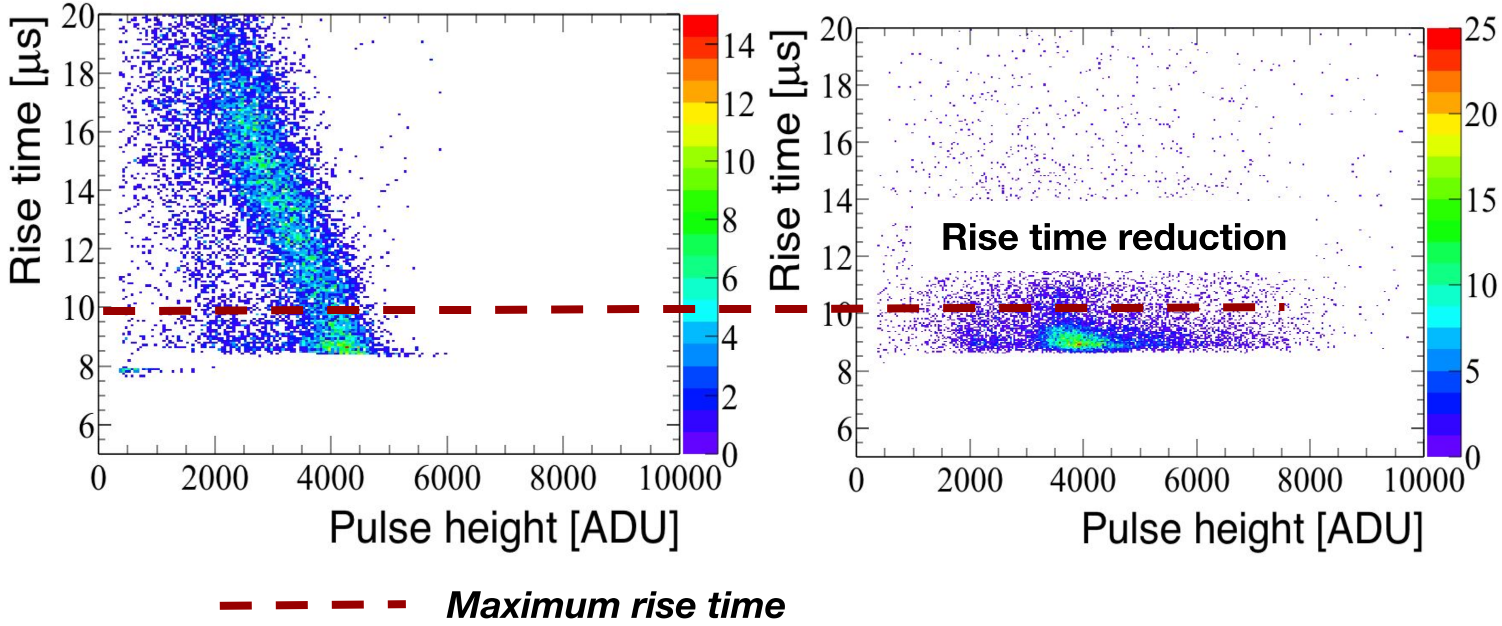
| | Muon | 0.27 | muon/m$^2$/day | 0.00062 | 0.00044 | $5.04 \times 10^{-8}$ |
| Total | | | | 1.67 | 1.54 | 2.4 |
| Total + cosmogenic activation of the copper sphere | | | | 5.20 | 5.20 | 5.4 |
| Total + cosmogenic activation of the copper sphere and 6 months of cooling | | | | 2.8 | 2.5 | 3.4 |
| Total + cosmogenic activation of the copper sphere and 1 years of cooling | | | | 2.1 | 1.9 | 3.0 |
| Total + cosmogenic activation of the copper sphere and 2 years of cooling | | | | 1.9 | 1.7 | 2.9 |

# Results with the prototypes

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

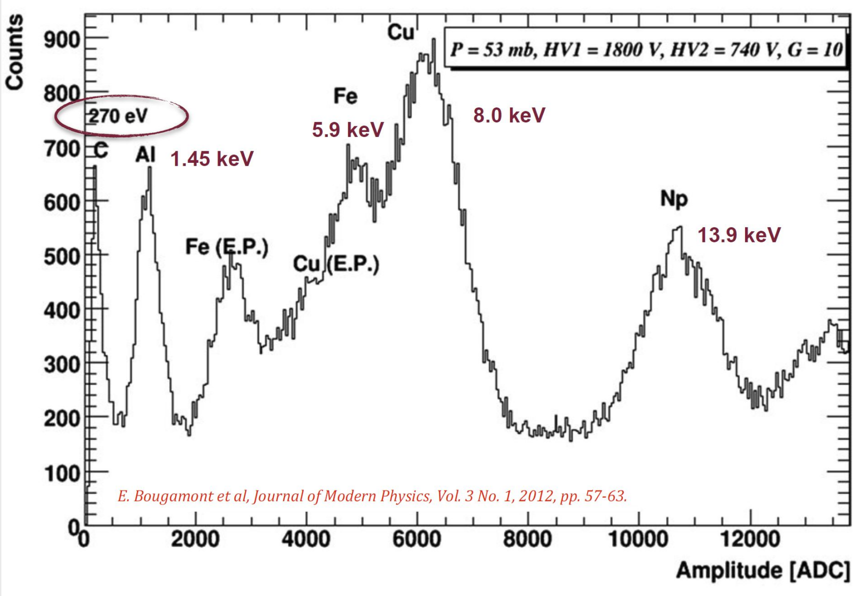
## Rise time reduction

**Single anode** | **11-anode ACHINOS**




$He:Ar:CH_4$(80:11:9)
640 mbar
$HV_1$ = 2015 V
$HV_2$ = −200 V
2 mm Ø anodes

# Low energy detection capabilities of a large volume SPC




**SPC Ø 130 cm**

**Gas: Ar+2%$CH_4$**

**Detection of fluorescence X-rays**

$^{241}$Am -> $^{237}$Np+$^{4}$He+ 5.6 MeV

**Lines**

Al -> 1.45 keV

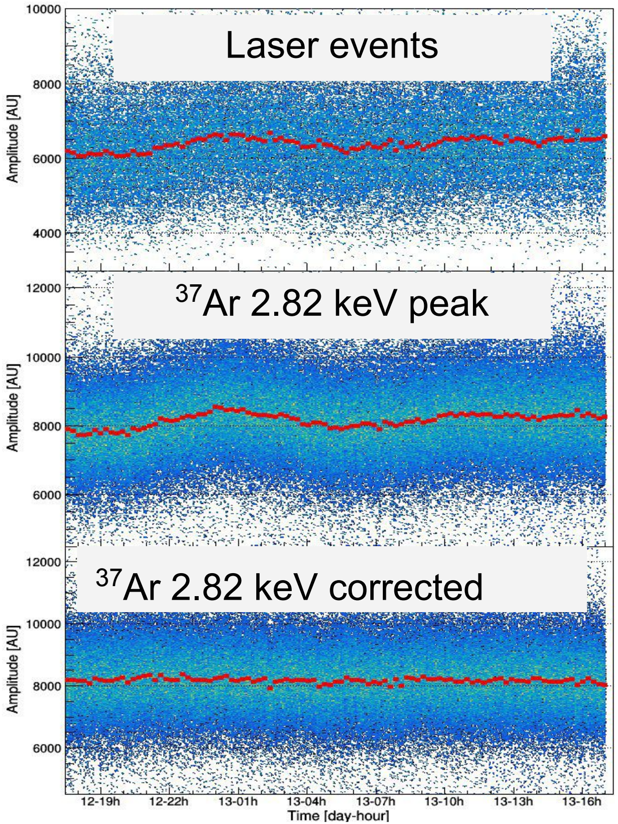
Cu -> 13.93 keV

$^{237}$Np -> 13.93 keV($L_\alpha$ 17.60 keV($L_\beta$)

**-Energy threshold at the single electron level**

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

# 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...**

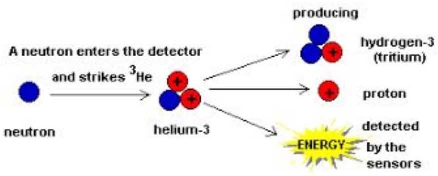
**Laser monitoring data could even be used to correct for long-term fluctuations**

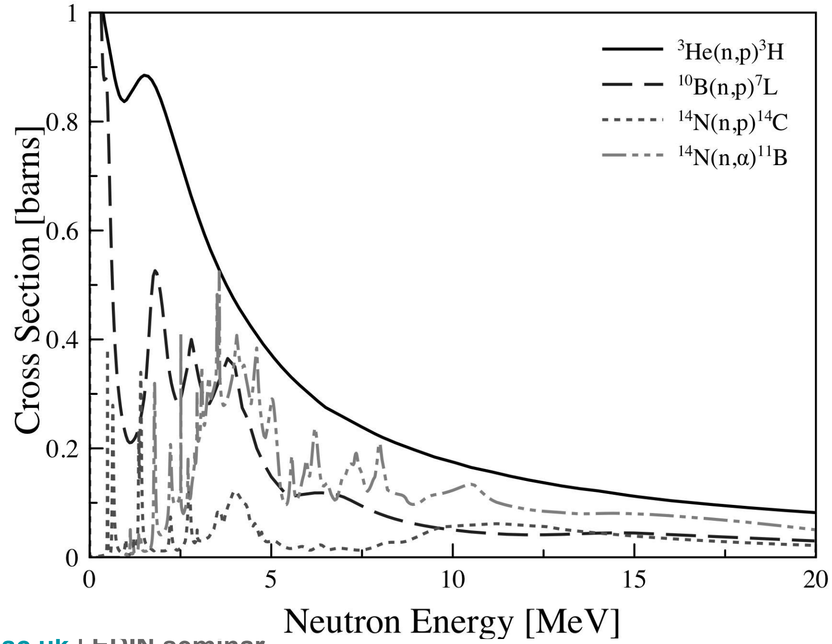
# Neutron spectroscopy

**Common targets:**
**$^{3}He + n \rightarrow {}^{3}H + p + 765\ keV,\ \sigma_{th} = 5330\ b$**

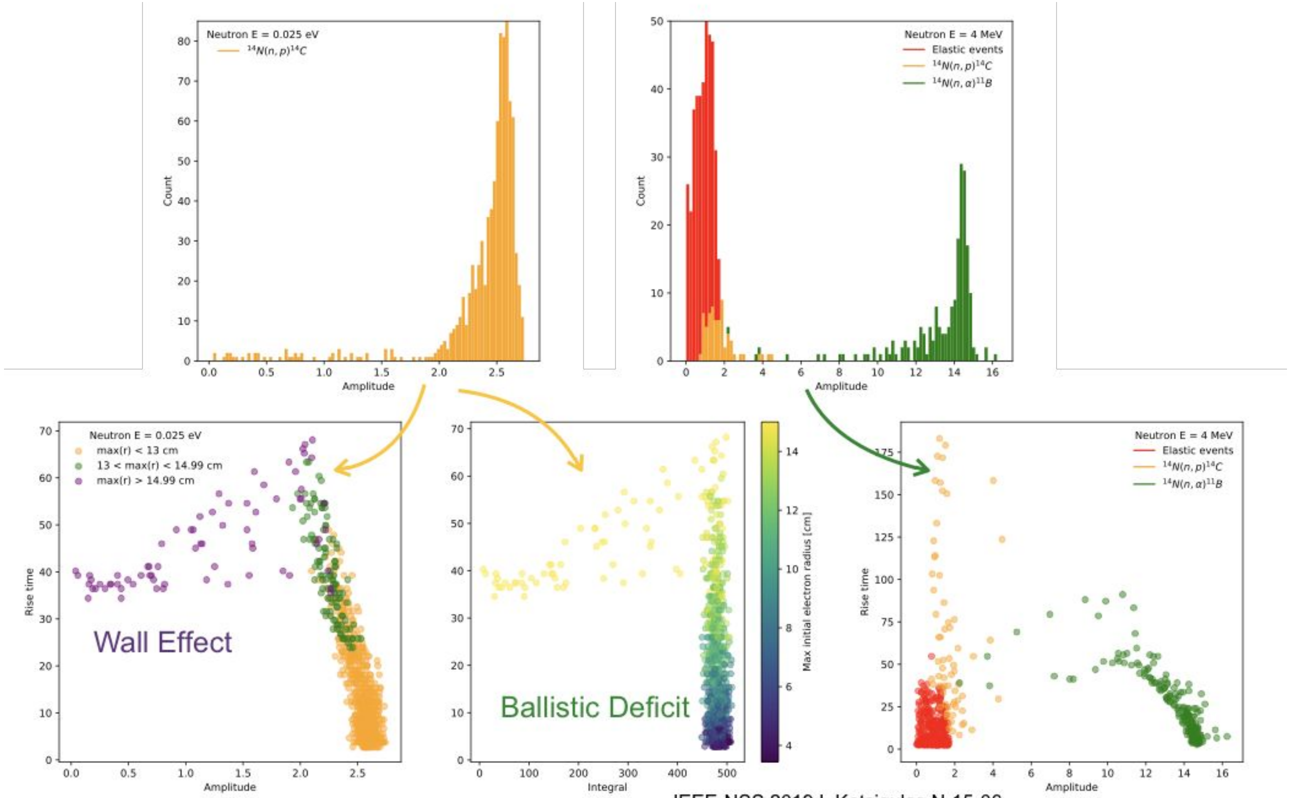
**$^{10}B + n \rightarrow {}^{7}Li^{*} + {}^{4}He + 2310\ keV,\ \sigma_{th} = 3840\ b$**
**$({}^{7}Li^{*} \rightarrow {}^{7}Li + 480\ keV)$**

- **Neutrons: important background in DM searches**
  - Identical signature to signal events
  - Stored material activation
- **Few measurements at underground laboratories**
  - $^{3}$He-based detectors extremely expensive



# Simulation of neutron transport



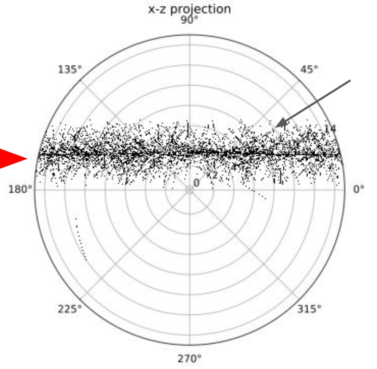

IEEE-NSS 2019 I. Katsioulas N-15-06

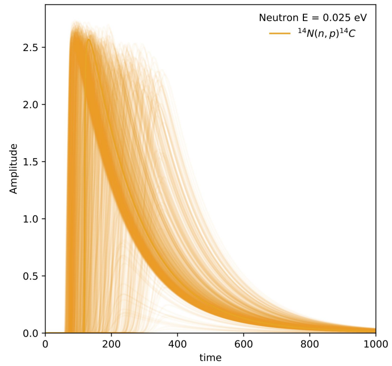
# Simulation of neutron transport

**Simulation Parameters:**
Ø vessel 30 cm
Nitrogen at 300 mbar
Anode Ø 2 mm

Neutron Beam

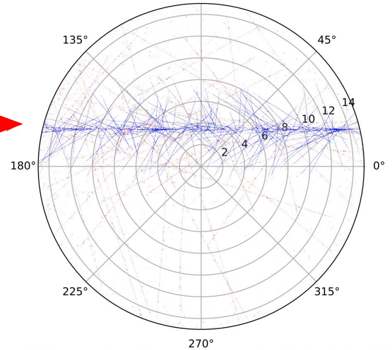
0.025 eV

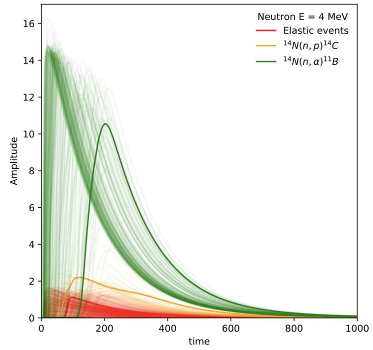



Neutron Beam

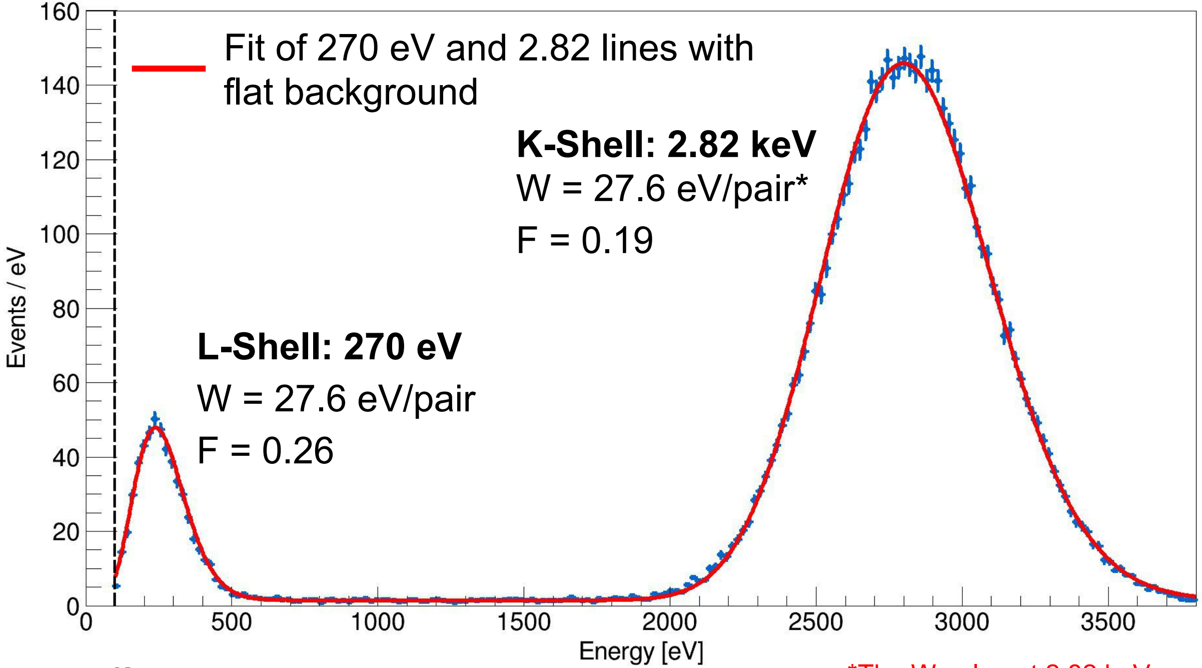
4 MeV



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

# Ar37 calibrations and gas fundamentals properties measurement




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

*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)**

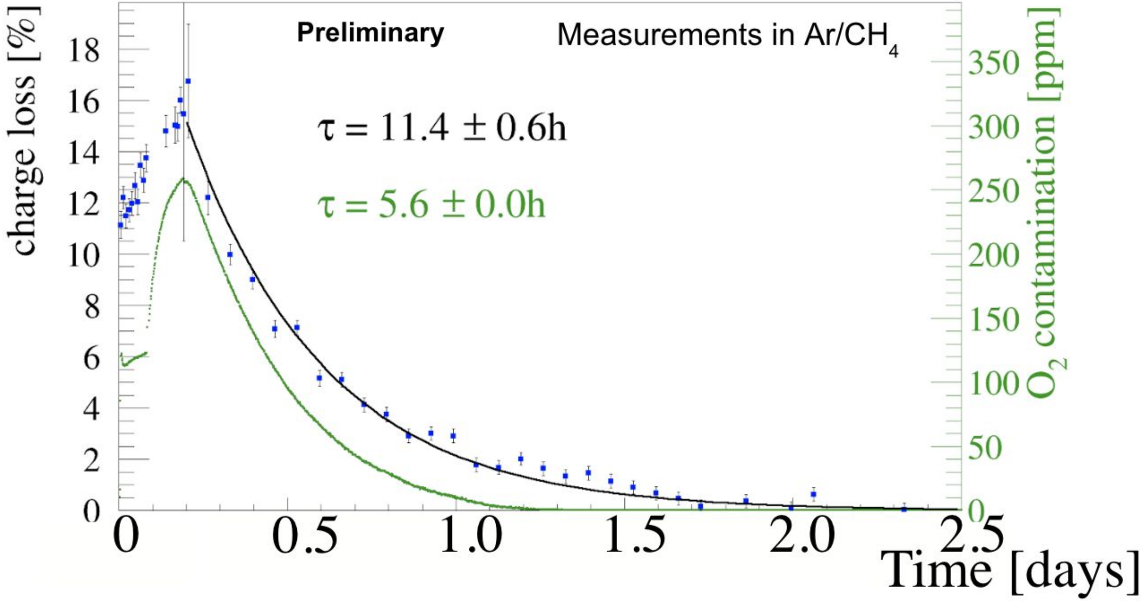
D. Durnford et al, Phys. Rev. D 98, 103013 (2018)

- **Avalanche (Polya)**

# Filtering within a recirculation system

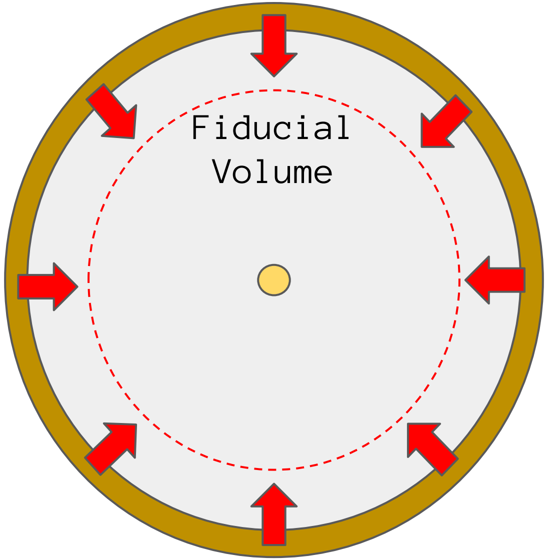
- **SAES MicroTorr Purifier (MC700 902-F) then used**
- **Improved filtering efficiency in large sphere – attachment problem 'solved'**
- **Incorporated into recirculation system with RGA**

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

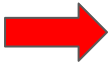


# Background rejection capabilities-A

## Fiducialisation



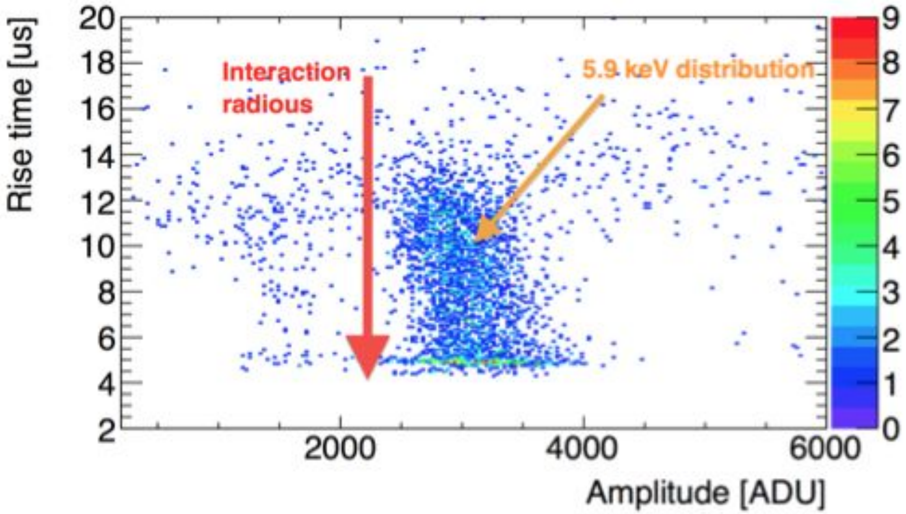

Background comes from the materials of the vessel


**Surface**

Primary e- drift time dispersion

$$\sigma(r) \propto (r/r_{sphere})^3$$

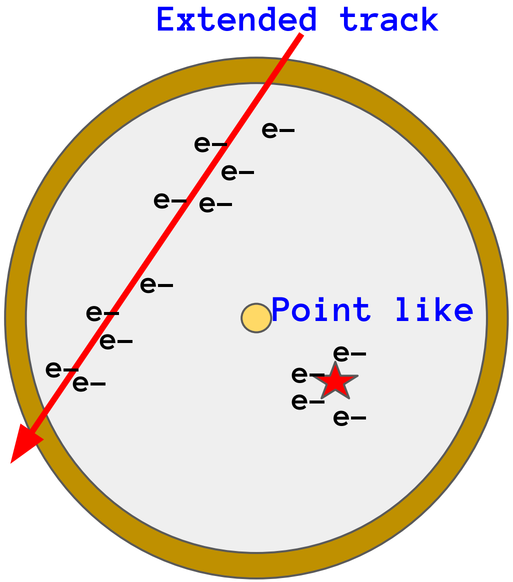
5.9 keV X-rays line

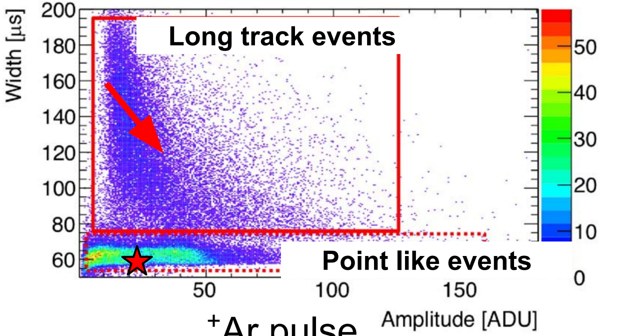



**Rise time → Δt between 90% - 10% of pulse height**

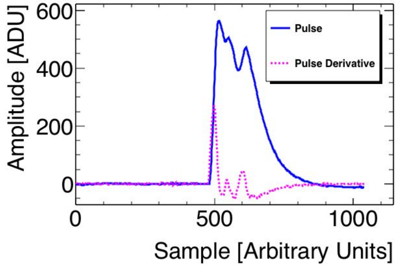
# Background rejection capabilities-B

## Event discrimination



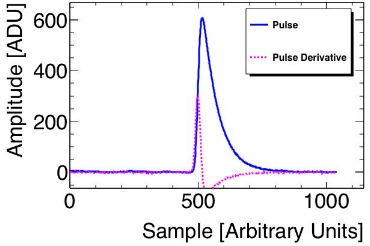




Muon pulse



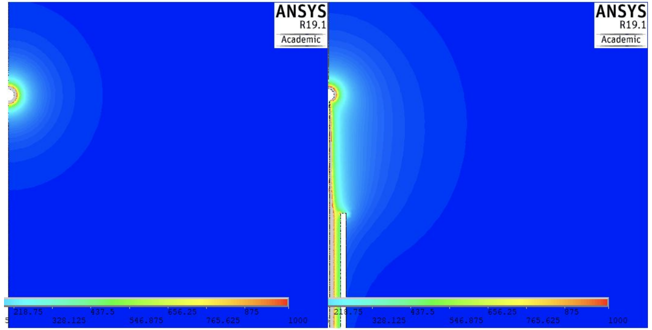

```
Amplitude     = 575 ADU
Width (FWHM) = 155.5 µs
Rise time     = 18.2 µs
```

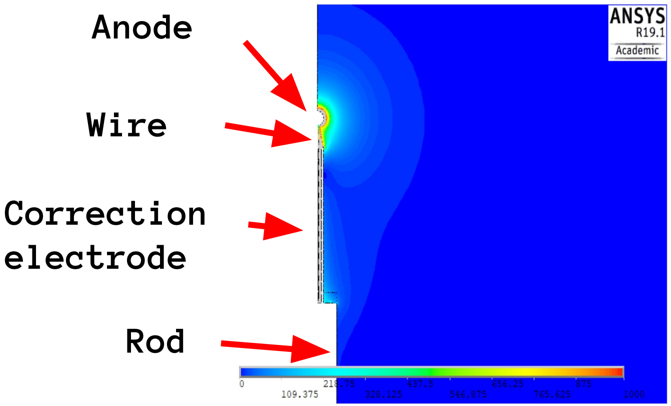
$^{+}$Ar pulse

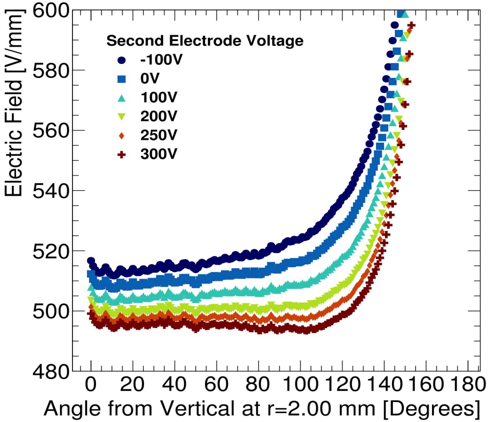



```
Amplitude     = 606 ADU
Width (FWHM) = 63.4 µs
Rise time     = 16.3 µs
```

# Electric field homogeneity



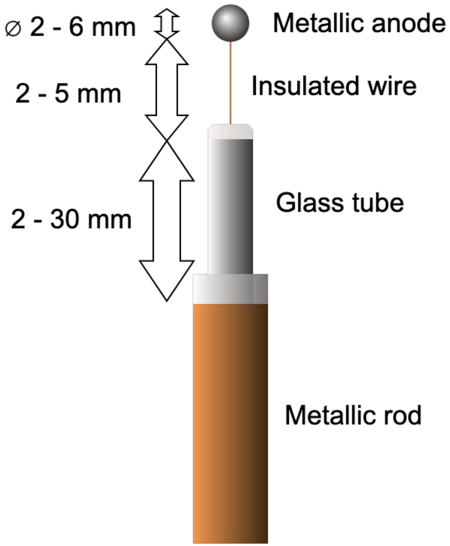




- Ideally, electric field:
  - Purely radial
  - Strength $1/r^2$
- Reality more complex, as support structure needed for sensor
  - $E=E(r,\theta)$
  - Non-uniform detector
  - Response
- Improved field uniformity by adding correction electrode

# The resistive glass electrode

**Design**




**Implementation**

## Provides

- Spark quenching
- Charge evacuation

## Advantages

- Simple
- Symmetric
- Robust
- Low material budget

## Material properties

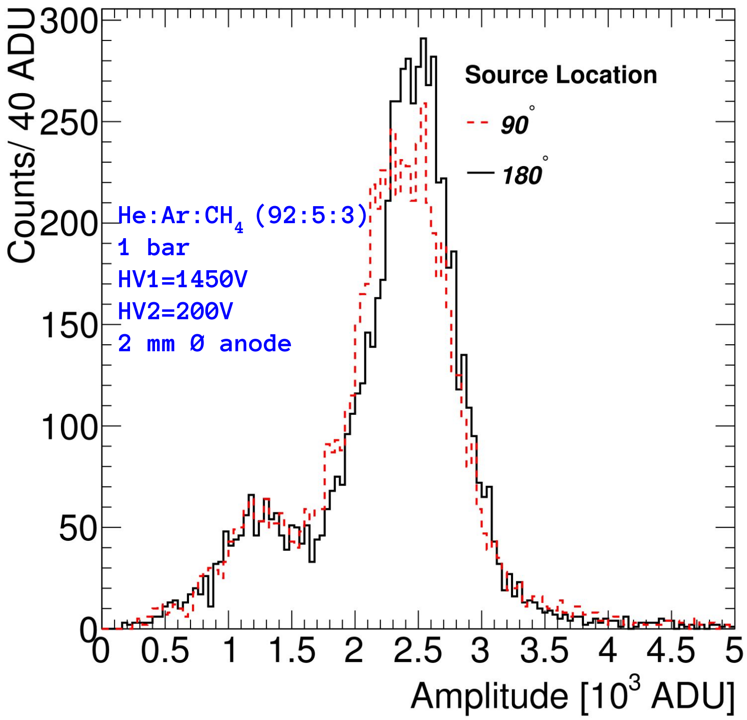
- Soda-lime glass
- $\rho = 5.05\times10^{10}\ \Omega\cdot\mathrm{cm}$
- d = 2.1-2.25 g/cm3
- A = 14.48 mBq/g

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

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

# Performance

**Measurements with the SPC in the two positions**




**Detector stability**