R2D2

MIGDAL

Migdal In Galactic Dark mAtter expLoration

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University of Birmingham

Υποψηφιότητα για τη θέση

Πειραματική Φυσική Υψηλών Ενεργειών - Οργανολογία

Εθνικό Μετσόβιο Πολυτεχνείο

01/11/2021

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SCHOOL OF APPLIED MATHEMATICAL AND PHYSICAL SCIENCES

NATIONAL TECHNICAL UNIVERSITY OF ATHENS

Career Track Record

2009 Ptychion in Physics, Aristotle University of Thessaloniki
Thesis: *A study of the energy resolution of a Micromegas detector*

2011 MSc Computational Physics, Aristotle University of Thessaloniki
Thesis: *Neutrino detection with a spherical proportional counter*

2016 Ph.D. in Particle Physics, Aristotle University of Thessaloniki
Thesis: *Study and detection of low energy neutrinos*

2016 Eurotalents Research Fellow, Université Paris-Saclay, CEA Saclay, France
Subject: *Search for light WIMPs with a gaseous spherical detector*

2019 Marie Skłodowska-Curie Fellow, University of Birmingham, UK.
Project: *DarkSphere*: Search for light Dark Matter with a Spherical Proportional Counter

Motivation for my research - Goals

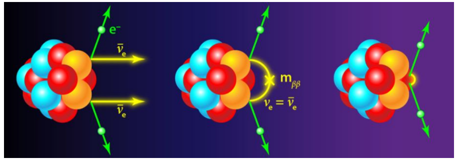
Crossroads in Modern Physics - Unveiling the invisible Universe

What constitutes DM?

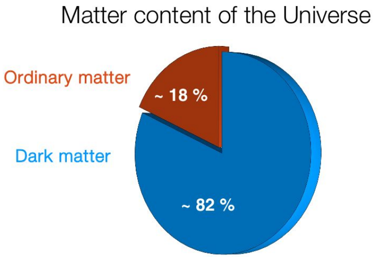
Dark Matter Particle (X^0)

X^0 mass: $m = ?$
X^0 spin: $J = ?$
X^0 parity: $P = ?$
X^0 lifetime: $\tau = ?$
X^0 scattering cross-section on nucleons: ?
X^0 production cross-section in hadron colliders: ?
X^0 self-annihilation cross-section: ?

What in the nature of neutrino?



What is mass?

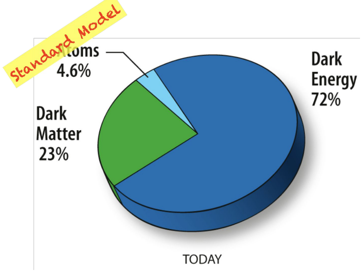


Developing tools for discovery - Novel detector technologies for Rare Event Searches

Large mass	Extreme radiopurity	Good energy resolution

DM searches with novel detectors

Direct Dark matter searches

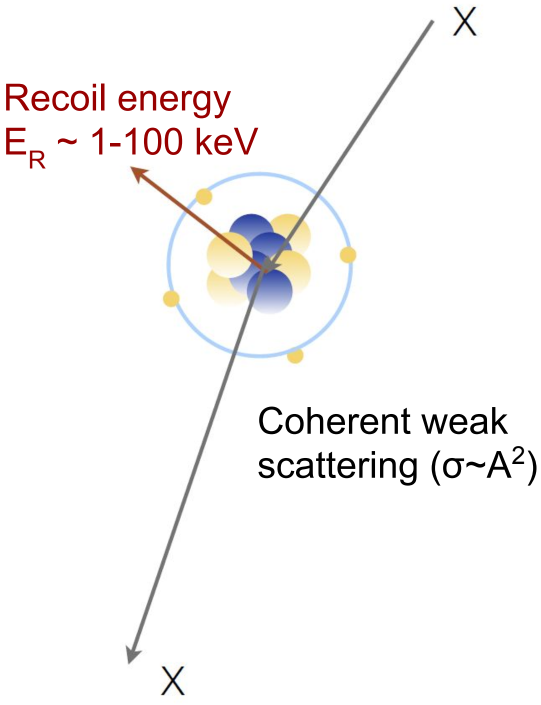


PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

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

WIMP miracle era

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

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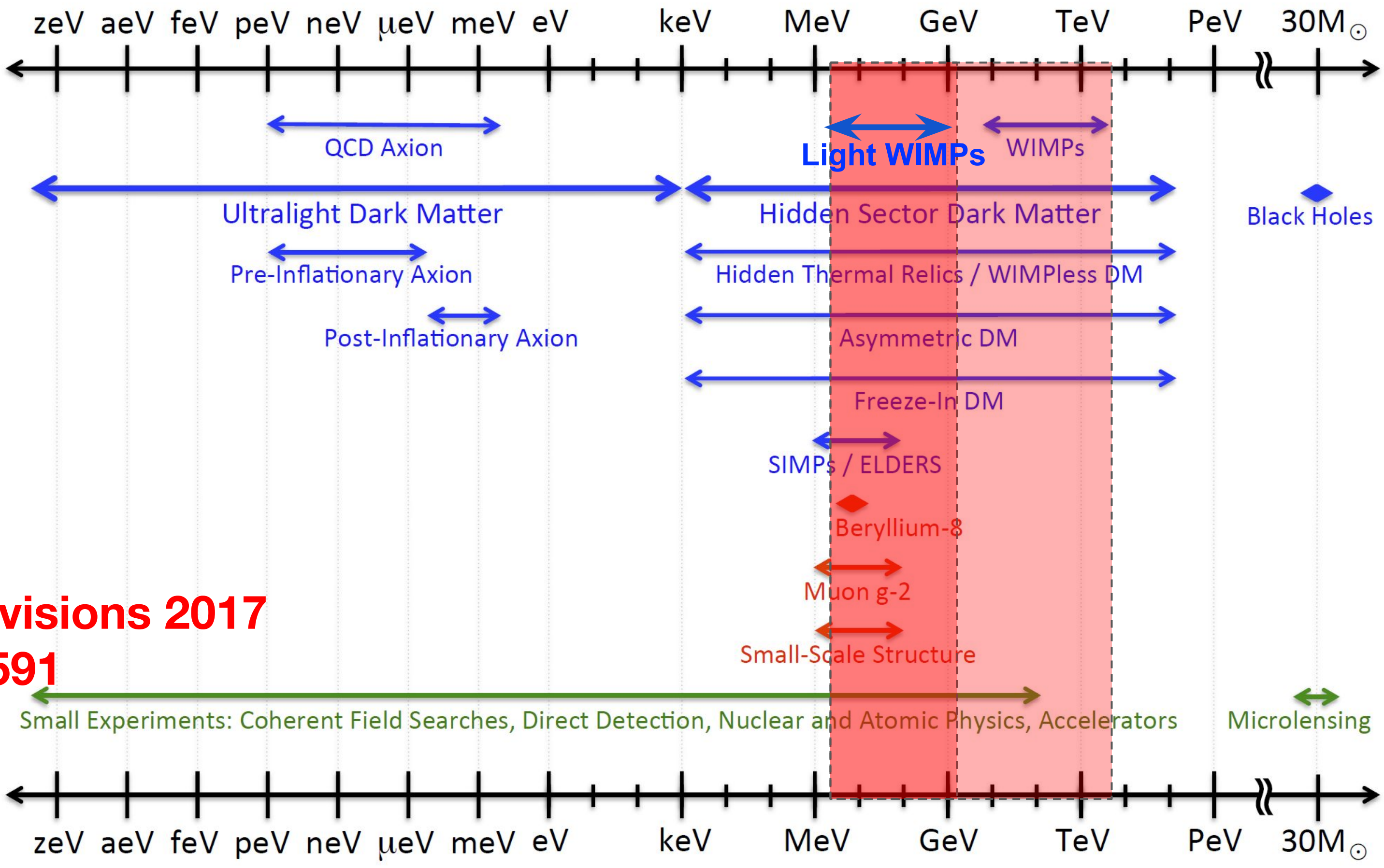
WIMP-less miracle era

PRL **101,** 231301 (2008) PHYSICAL REVIEW LETTERS week ending 5 DECEMBER 2008

Dark-Matter Particles without Weak-Scale Masses or Weak Interactions

Jonathan L. Feng and Jason Kumar
Department of Physics and Astronomy, University of California, Irvine, California 92697, USA
(Received 4 April 2008; published 1 December 2008)

Dark Sector Candidates, Anomalies, and Search Techniques

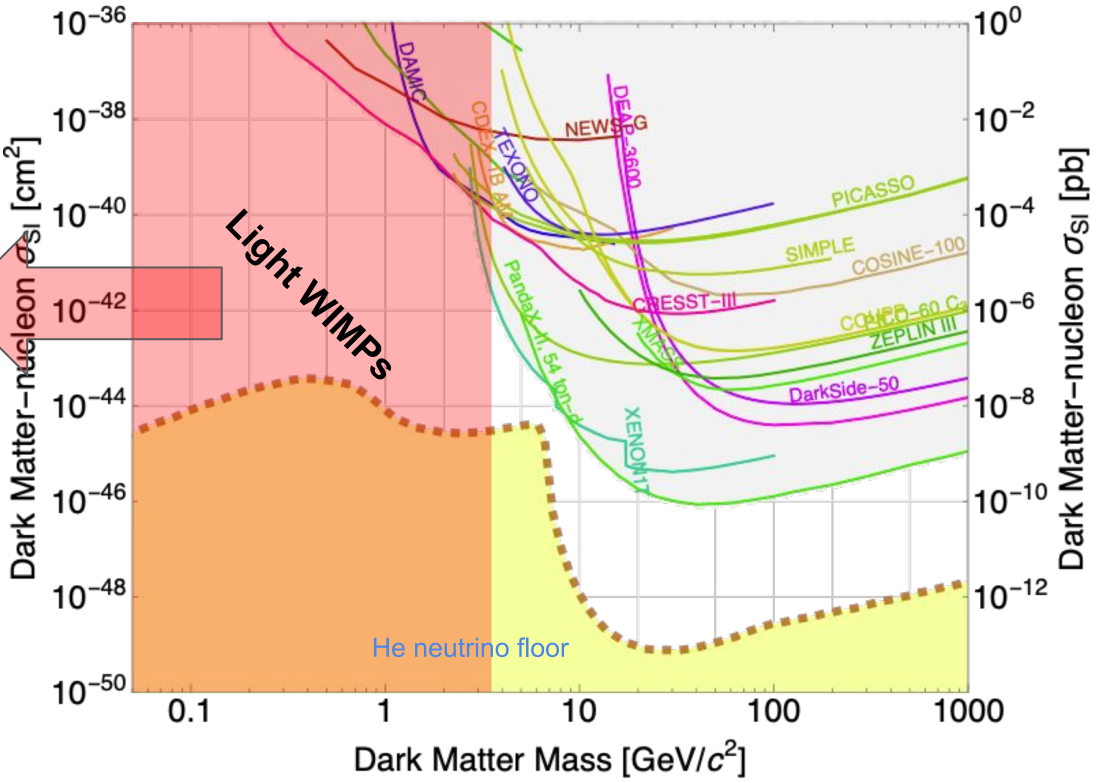


Cosmic visions 2017
1707.04591

Light Dark Matter (LDM) mass region searches

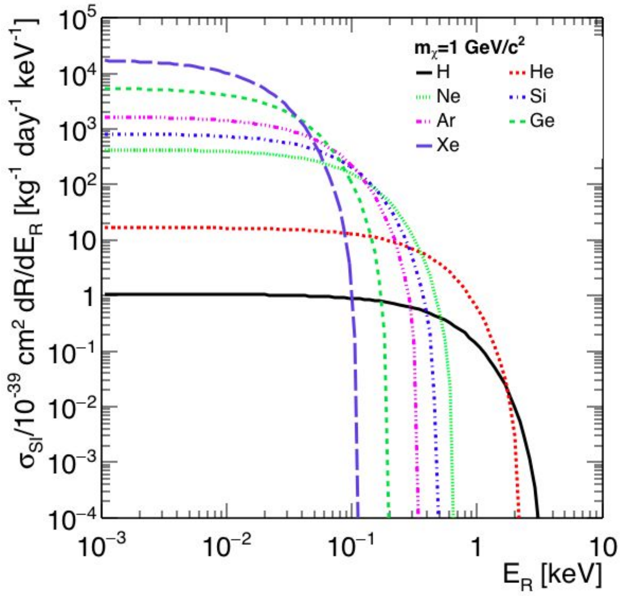
LDM searches require detectors with:

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

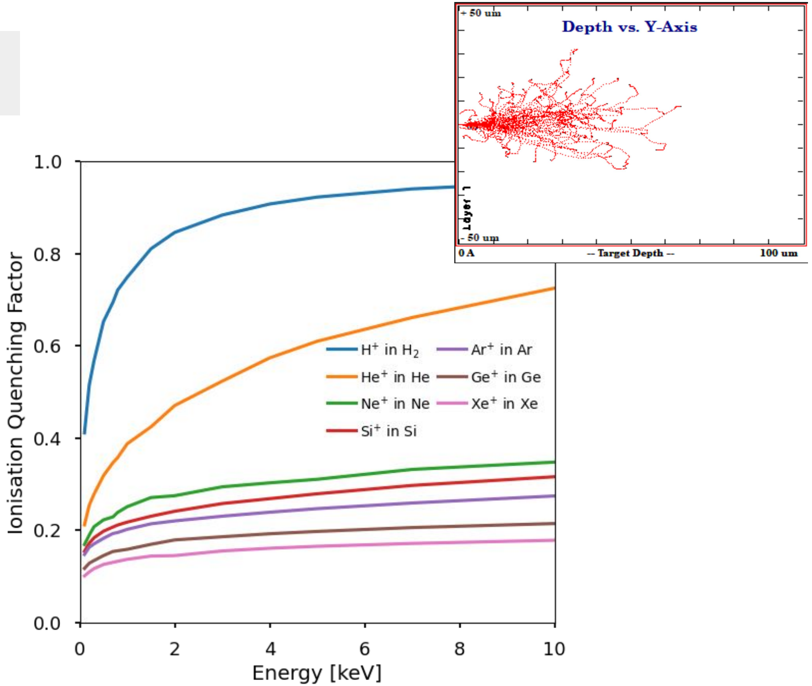


Advantages of light targets for light WIMPs

Favourable recoil energy distribution for lighter targets



Lighter projectile-Lighter target
⇒ Better Match



For lighter elements more of the recoil energy turns into detectable signal

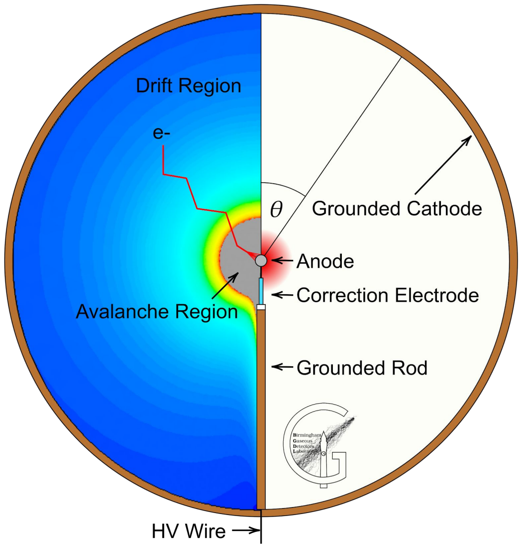
NEWS-G collaboration
UK, France, Greece, Canada, US

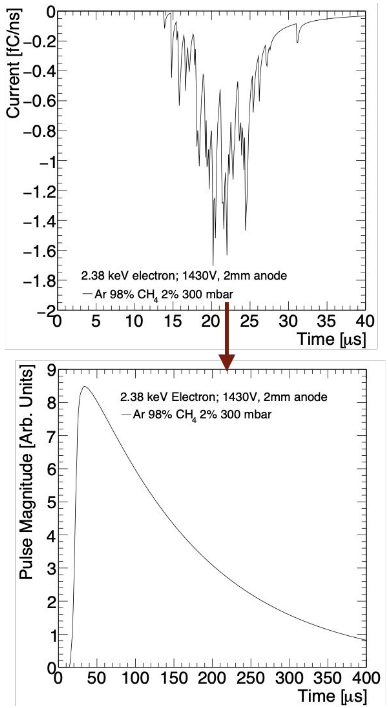
Light Dark Matter searches with an innovative gaseous detector the Spherical Proportional Counter

I.Giomataris et al, JINST, 2008, P09007

I.Katsioulas et al, JINST, 13, 2018, no.11, P11006

The Spherical Proportional Counter





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

$$C = 4\pi\epsilon\frac{r_a r_c}{r_c - r_a} \approx 4\pi\epsilon r_a$$

r_A = anode radius
r_C = cathode radius

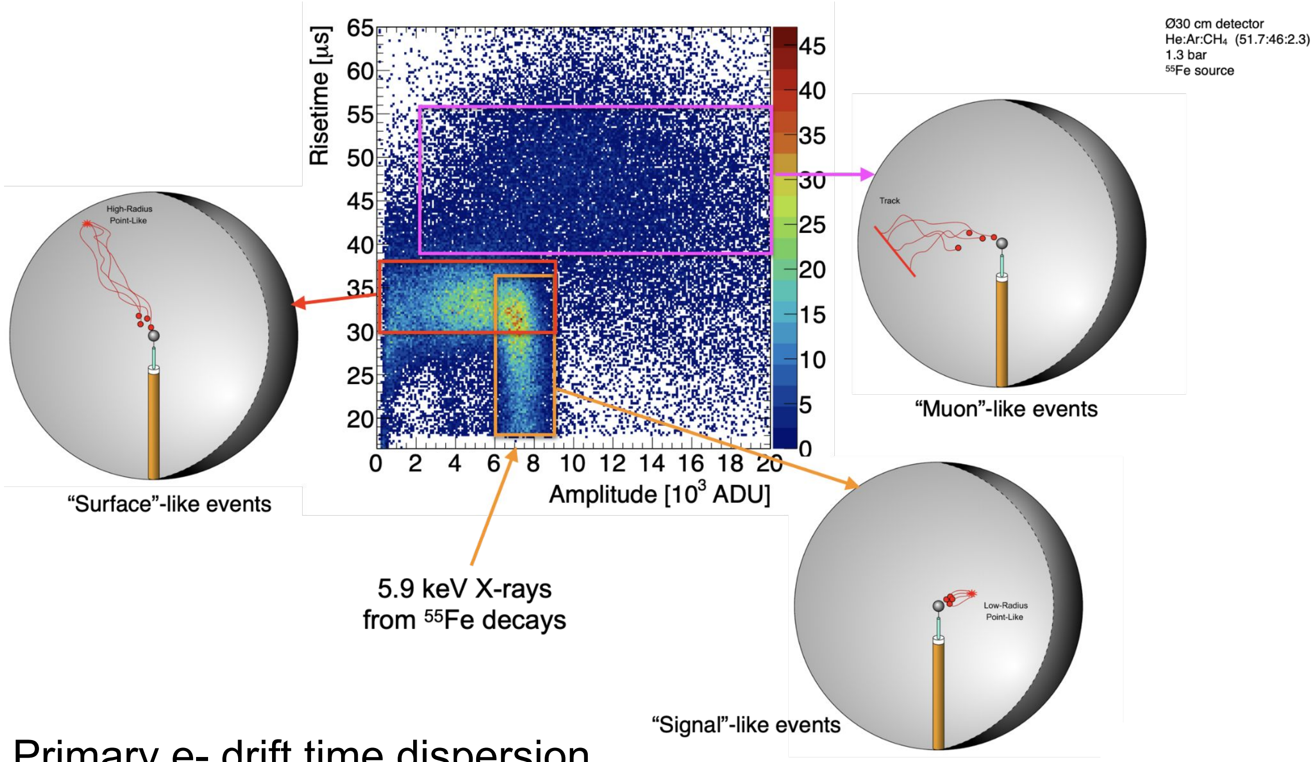
Electric field scales as $1/r^2$, volume divided in: "drift" and "amplification" regions

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**

In the picture: I.Giomataris, G.Charpak Testing the prototype

Pulse shape discrimination

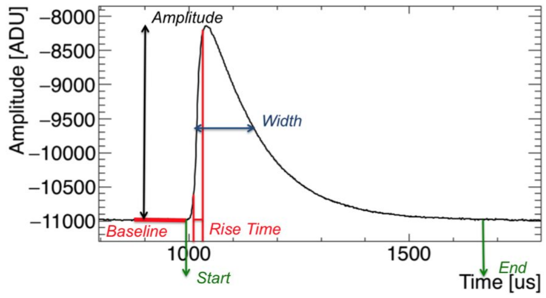


Primary e- drift time dispersion

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

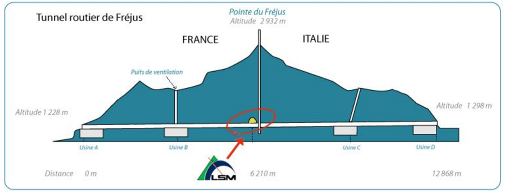
Basic Parameters

- Baseline
- Noise
- Amplitude (Pulse Height)
- Rise time
- Width
- Integral
- Number of peaks



Advanced Parameters

- Deconvoluted amplitude
- Number of electrons
- etc



NEWS-G at Modane

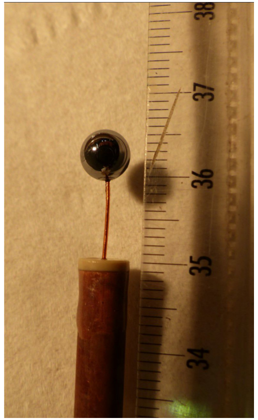
SEDINE detector

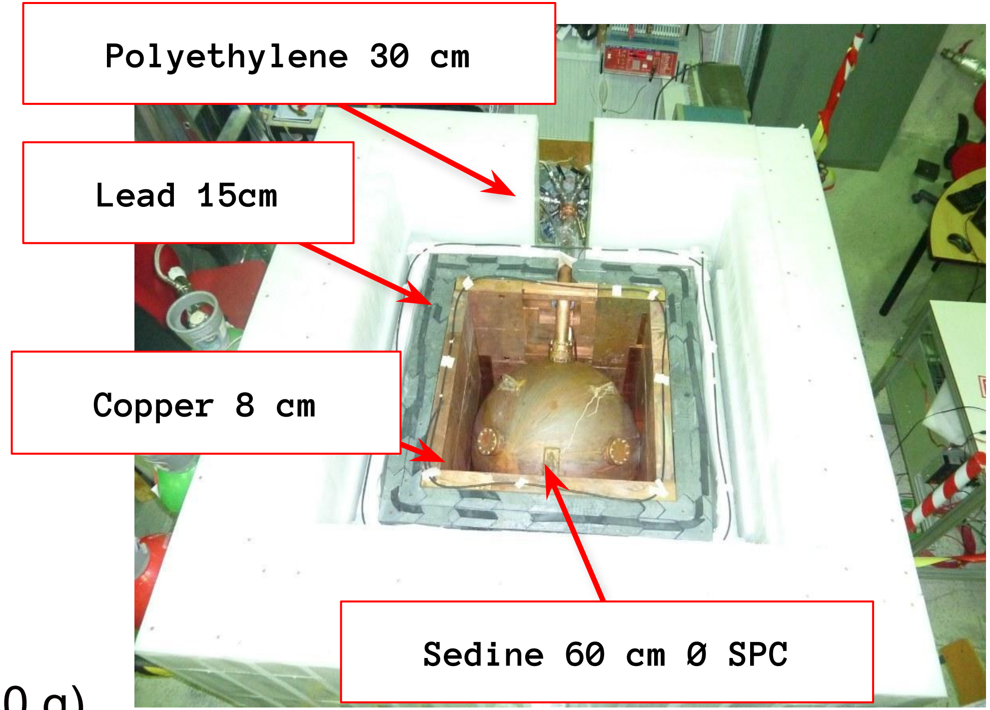
Vessel

Ø 60cm copper

Sensor

Ø 6.3mm Si



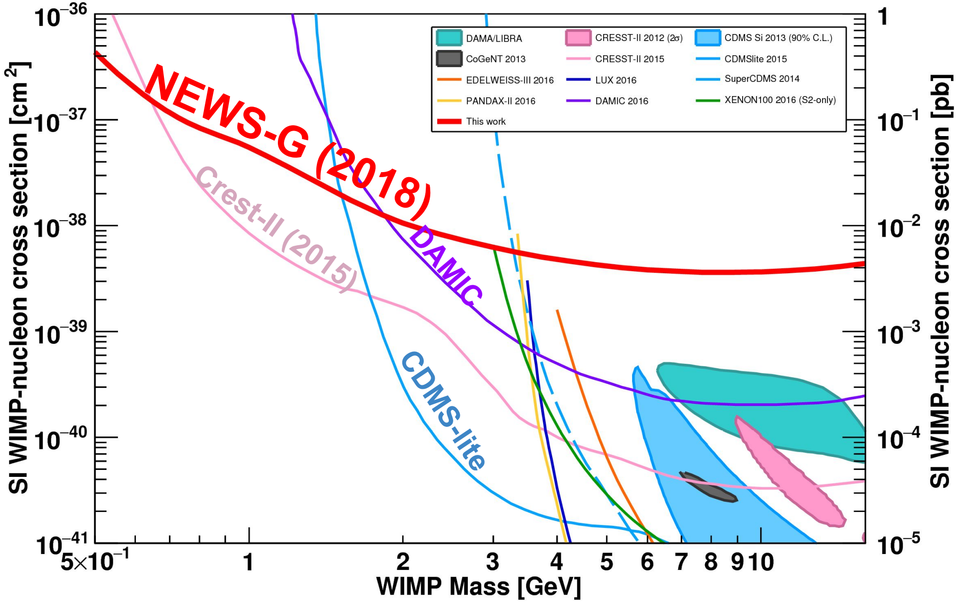


Gas Mixture: Ne+0.7%CH_4 at 3.1 bar (280 g)

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

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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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[d] Chemistry & Chemical Engineering Department, Royal Military College of Canada, Kingston, Ontario K7K 7B4, Canada
[e] Physik Department E12, Technische Universität München, James-Franck-Str. 1, Garching 85748, Germany
[f] LSM, CNRS/IN2P3, Université Grenoble-Alpes, Modane, France
[g] SNOLAB, Lively, Ontario, P3Y 1N2, Canada
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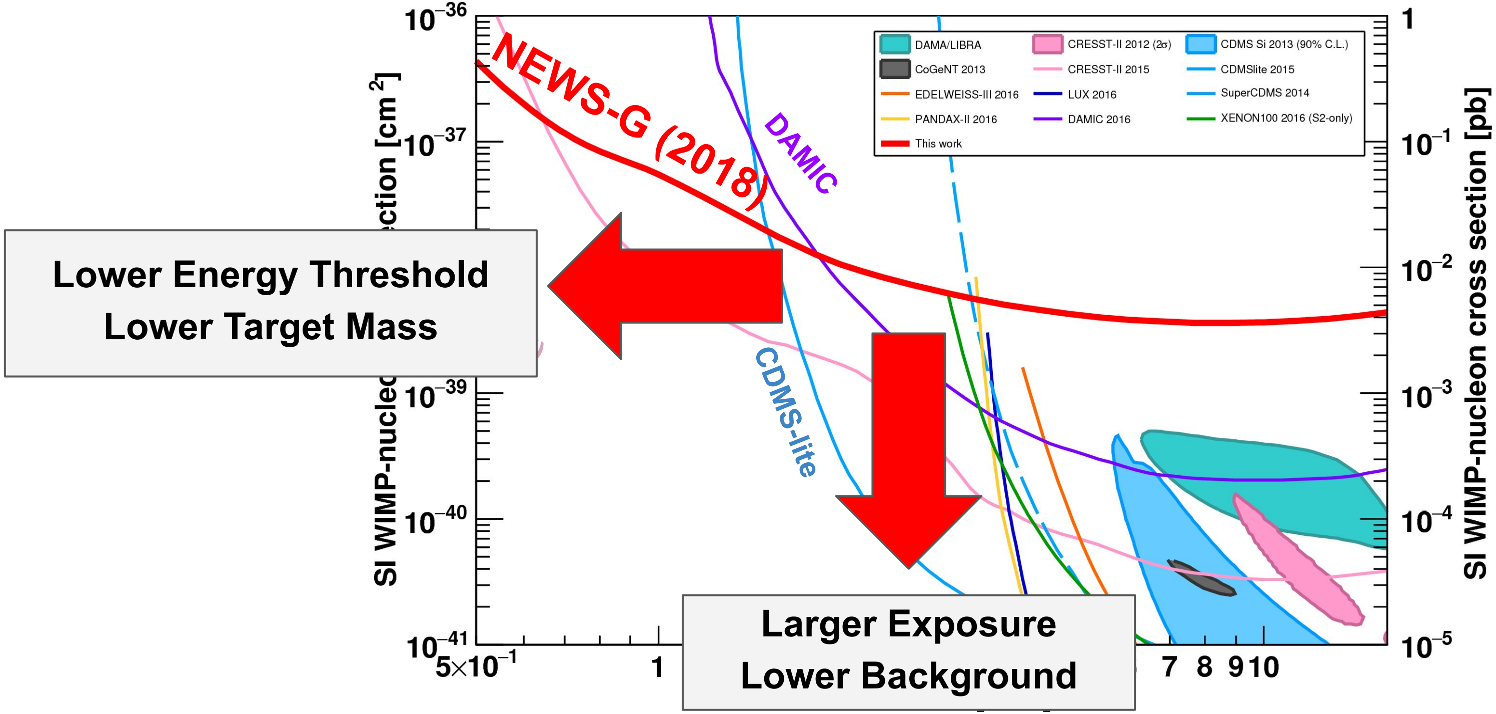
[i] Department of Physics, Aristotle University of Thessaloniki, GR-52124 Thessaloniki, Greece

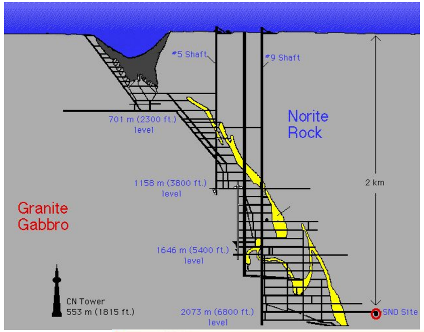
Exclusion at 90% confidence level (C.L.) of cross-sections above $4.4 \cdot 10^{-37}$ cm^2 for a **500 MeV/c^2 WIMP**

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

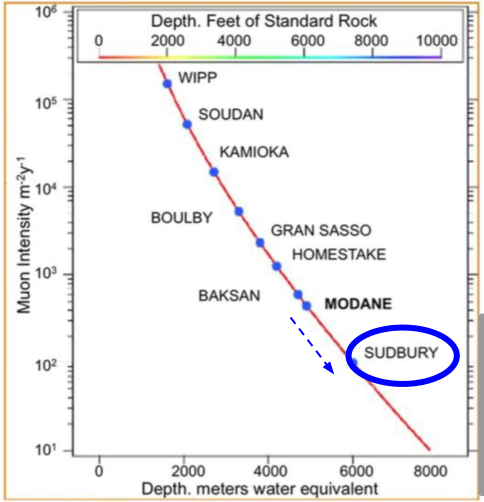
NEWS-G moving forward

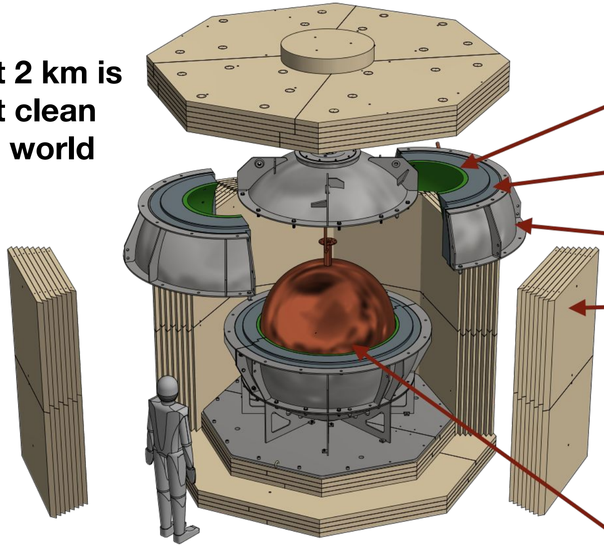


The NEWS-G detector at SNOGLOBE



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





3 cm archaeological lead

22 cm of Very Low Activity lead

Stainless steel skin

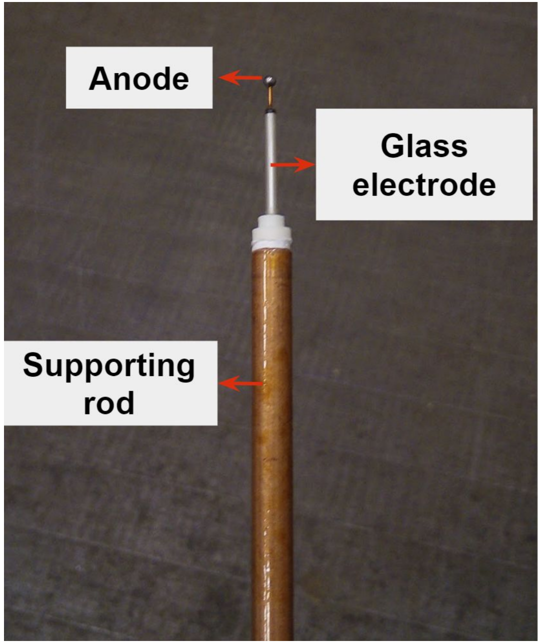
40 cm high density polyethylene

Ø140 cm
4N Copper (99.99% pure)
Assembled at LSM

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

Breakthroughs in SPC instrumentation

Resistive sensors

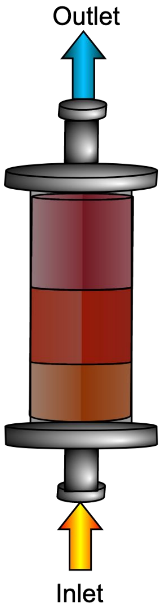


I. Katsioulas et al, JINST, 13, 11, P11006, 2018
10.1088/1748-0221/13/11/P11006

Multi-anode sensors

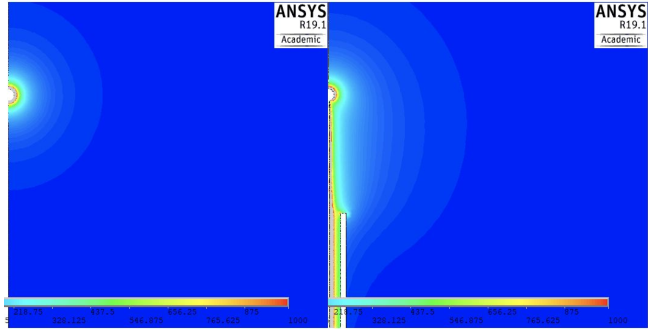
Giganon, A. et al, 2017. "A Multiball Read-out for the Spherical Proportional Counter.", *JINST*

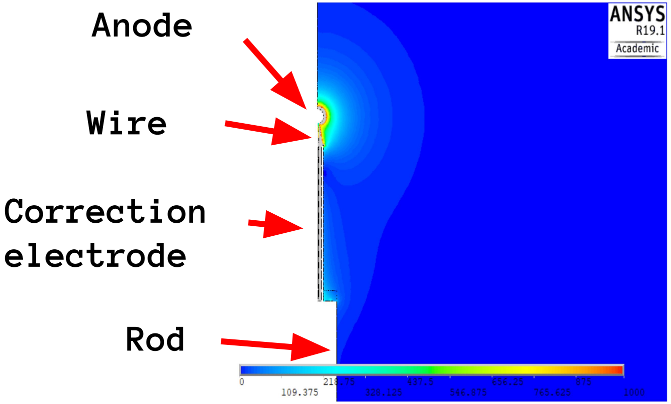
Reducing Backgrounds

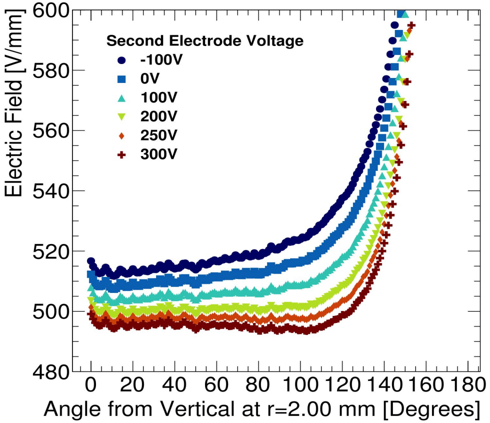


Improving energy resolution and stability

Electric field homogeneity



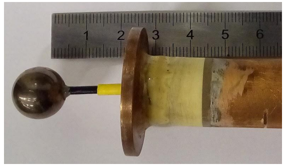
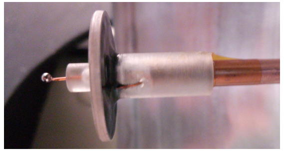
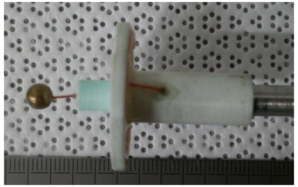
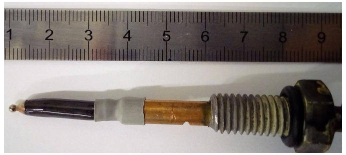
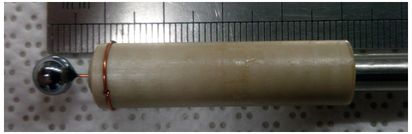
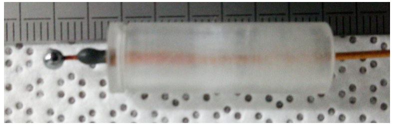


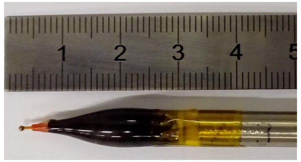


- **Ideally, electric field:**
  - **Purely radial**
  - **Strength $1/r^2$**
- **Reality more complex, as support structure needed for sensor**
  - **$E=E(r,\theta)$**
  - **Non-uniform detector**
  - **Response**
- **Improved field uniformity by adding correction electrode**

Different kind of sensors

Materials used: Copper, Brass, Steel, Iron, PE, PEEK, Teflon, Kapton, Plexiglass, Si, Araldite, Cyanoacrylate, Graffite, Bakelite, Resistive Polymers … and different kind of mixtures of them !

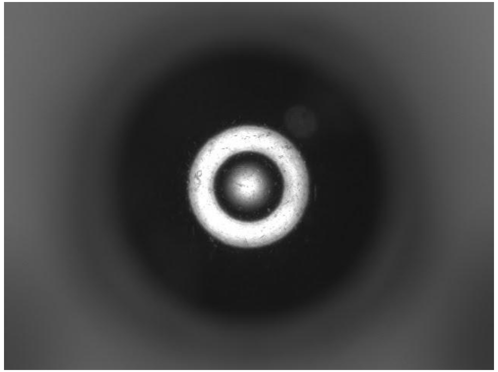









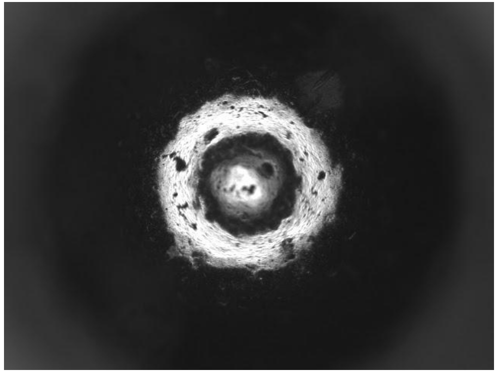
Anode quality and Construction techniques

Controlling diameter and surface smoothness or roughness

2 mm Inox ball



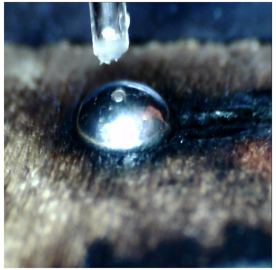
3 mm steel ball

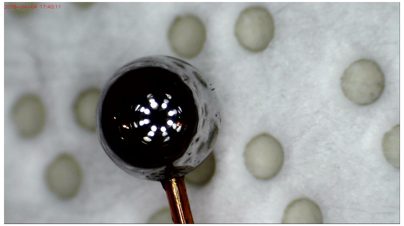


In theory they are of the same grade !

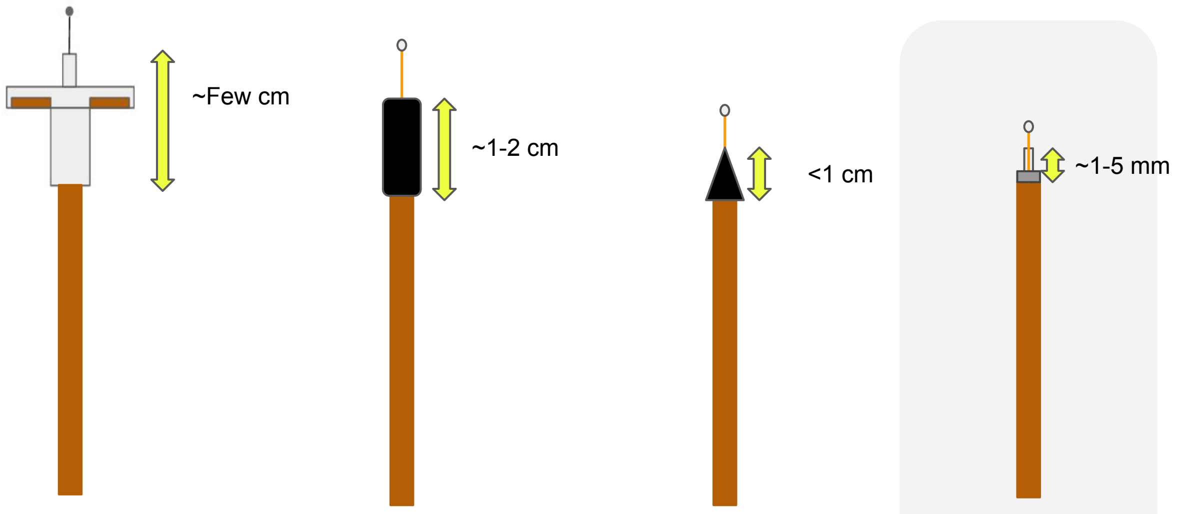
“μ-soldering” anodes

- Better sphericity
- Less anode deformations
- Easy construction





Evolution of the SPC single anode sensor



Classic "umbrella"
< 2016

Bakelite Version 1
2017 first half

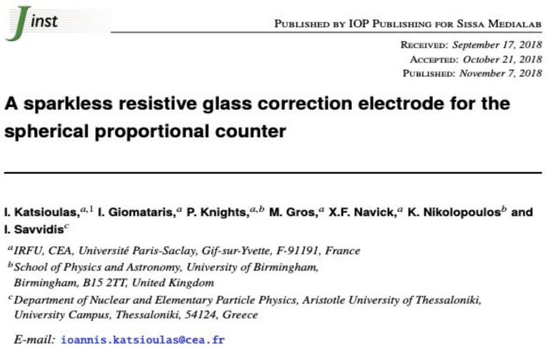
Bakelite Version 2
2017 second half

Glass
2018

Evolution target:

1. Detector stability
2. Homogeneous response
3. Low mass
4. Low radioactivity
5. Precision

The resistive glass electrode



JINST
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A sparkless resistive glass correction electrode for the spherical proportional counter

I. Katsioulas,[a,1] I. Giomataris,[a] P. Knights,[a,b] M. Gros,[a] X.F. Navick,[a] K. Nikolopoulos[b] and I. Savvidis[c]

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[b] School of Physics and Astronomy, University of Birmingham, Birmingham, B15 2TT, United Kingdom
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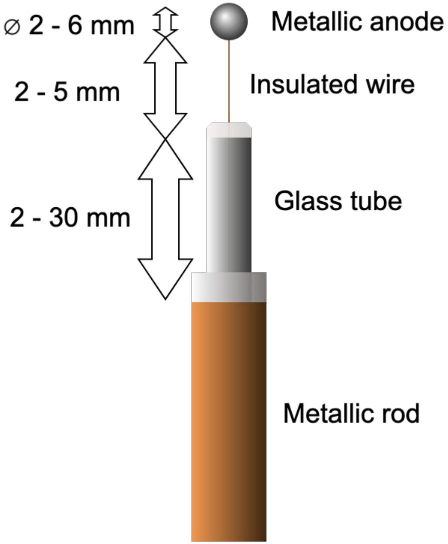
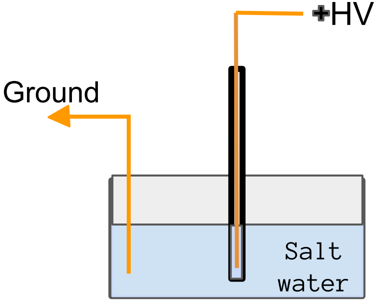
E-mail: ioannis.katsioulas@cea.fr

Design

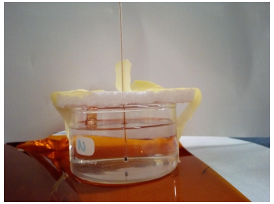


Implementation

Resistivity measurement



Schematic


Real structure

Provides
- Spark quenching
- Charge evacuation

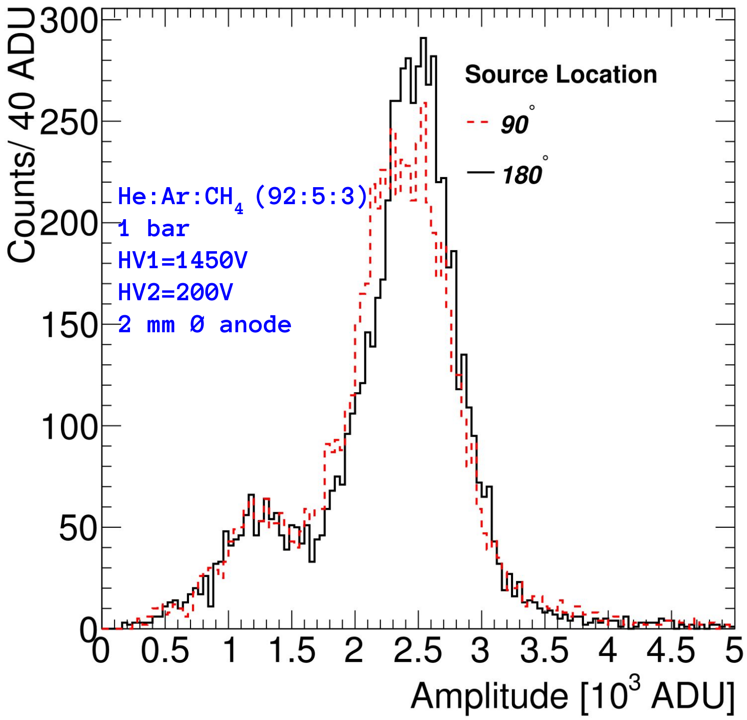
Advantages
- Simple
- Symmetric
- Robust
- Low material budget

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

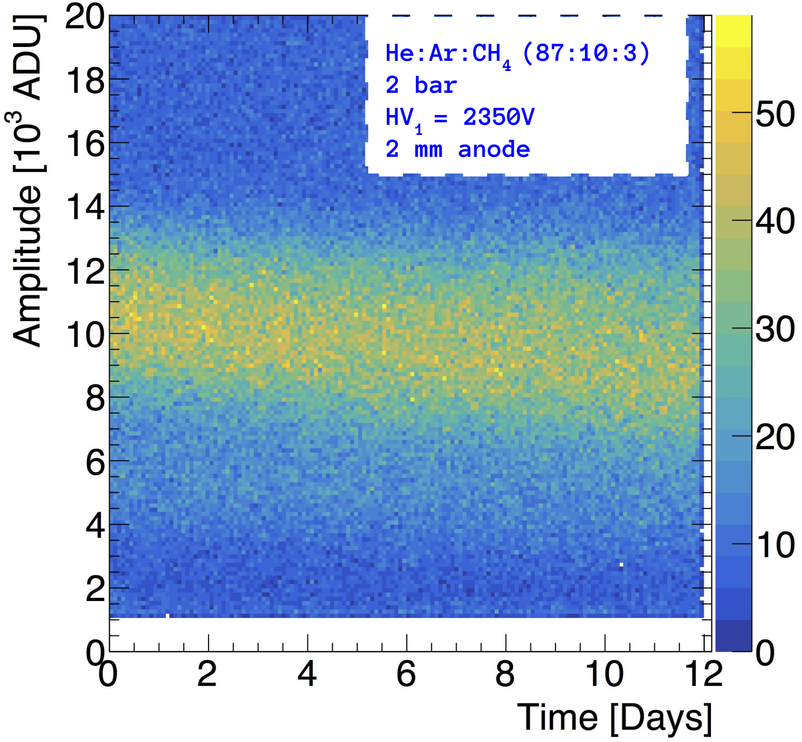
I. Katsioulas et al, JINST, 13, 11, P11006, 2018
10.1088/1748-0221/13/11/P11006

Performance of the glass sensor

Measurements with the SPC in the two positions



Detector stability



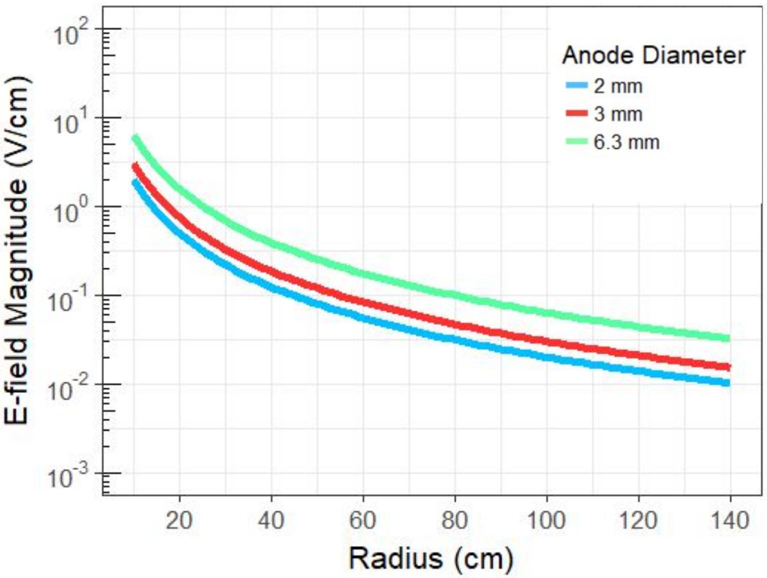
Increasing target mass

Electric field strength in large volume SPCs

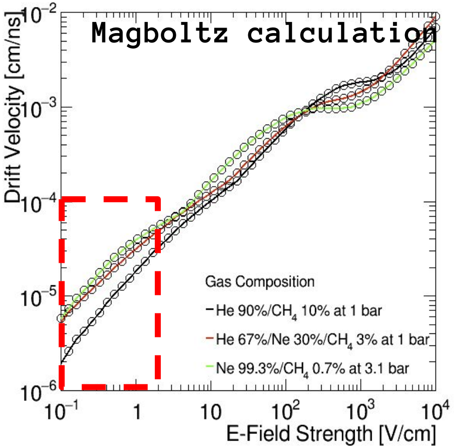
Scaling-up

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

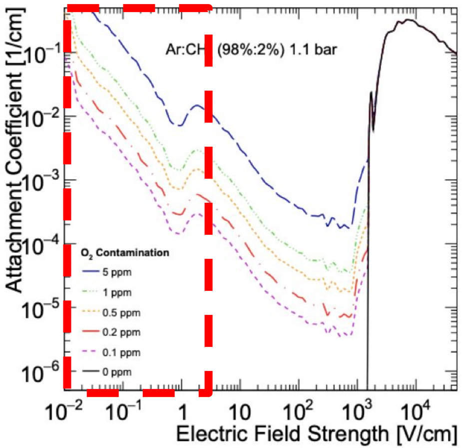
Comparison of E-field magnitude for different anode diameters



Drift velocity of e⁻

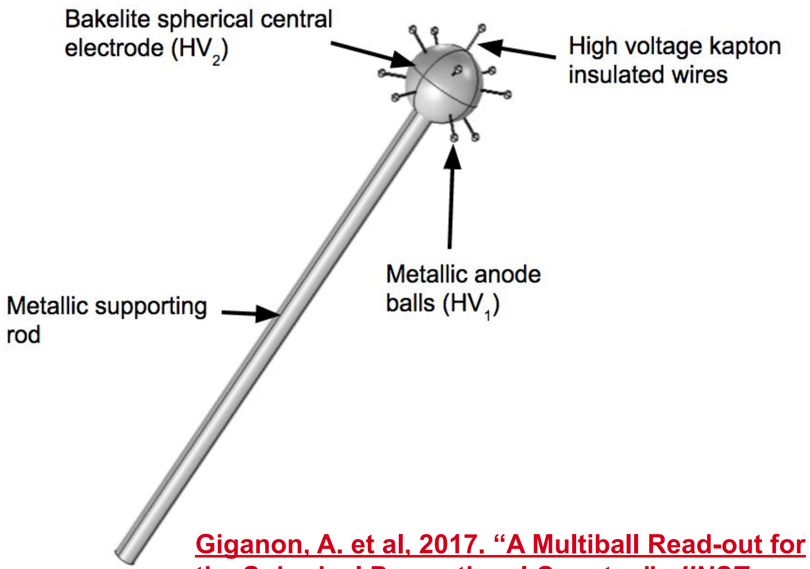


Attachment coefficient vs E-field magnitude

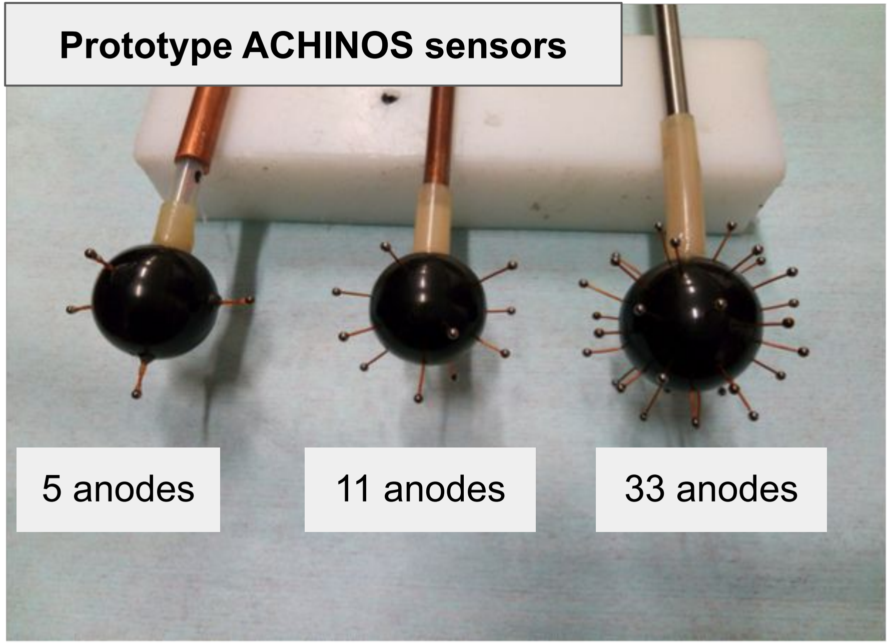


Low E-field region - - -

The multi-anode sensor - ACHINOS



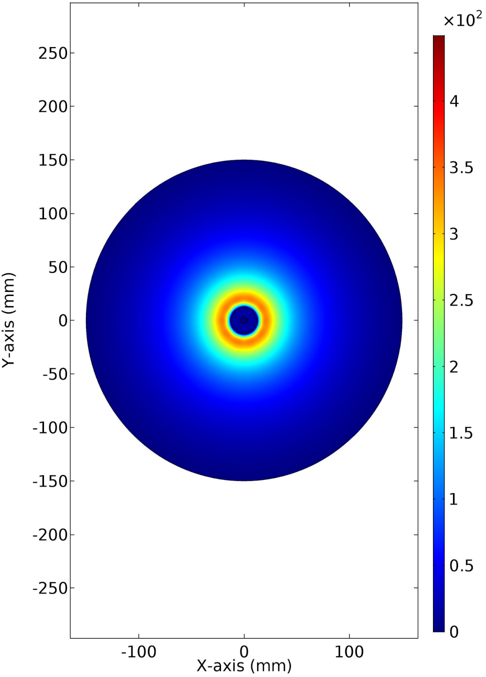
Giganon, A. et al, 2017. "A Multiball Read-out for the Spherical Proportional Counter.", *JINST*



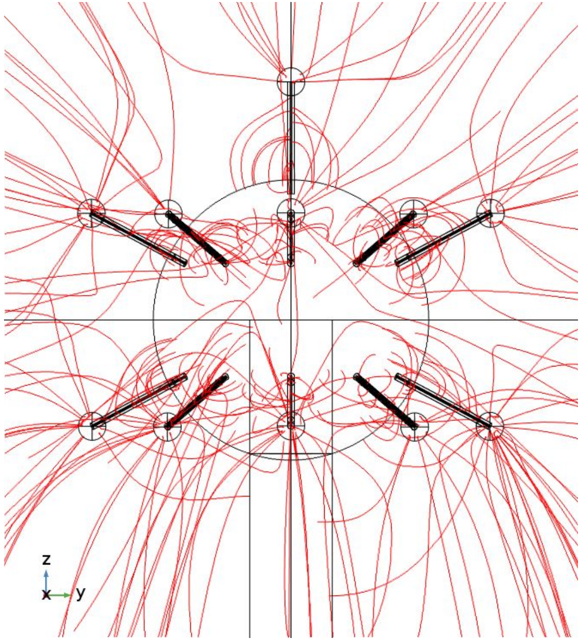
Instead of one ⇒ Use multiple anodes set to the same potential !!!

Electric field configuration with an ACHINOS

Collective iso-potentials



Electric field lines near the anodes

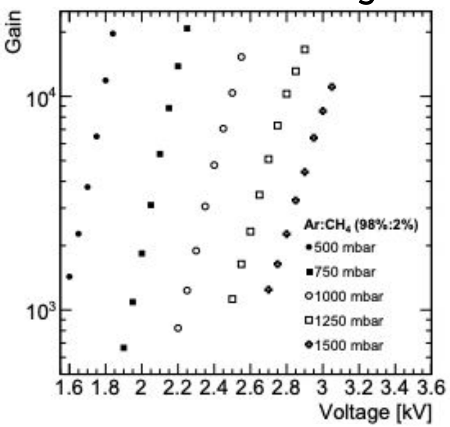


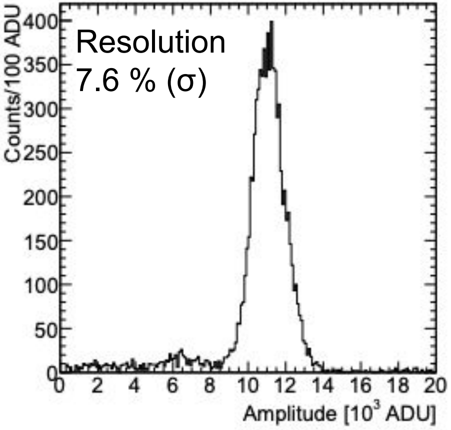
- **Decouples electron drift and multiplication**
  - **Small anode size → high gain**
  - **More anodes → Efficient charge collection**
- **Allows for increased target mass**
  - **Larger volume**
  - **Higher pressure**
- **Individual readout TPC-like capabilities to the SPC**

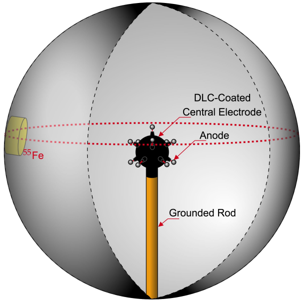
Performance of ACHINOS with resistive coating

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

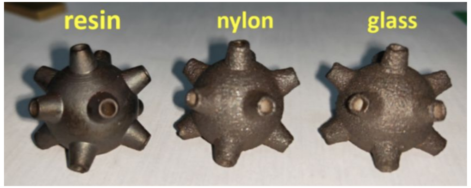
Gain vs Voltage



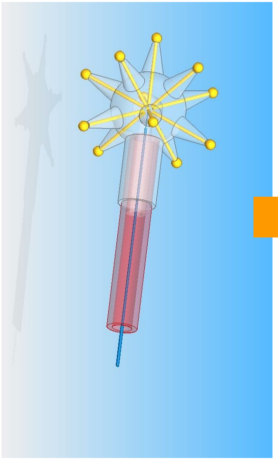




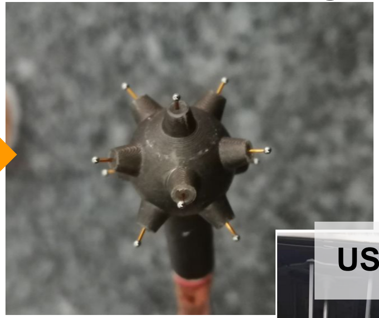
Measurement of the 5.9 keV ^{55}Fe X-ray line

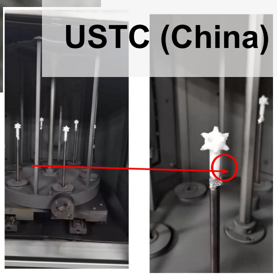


3D design



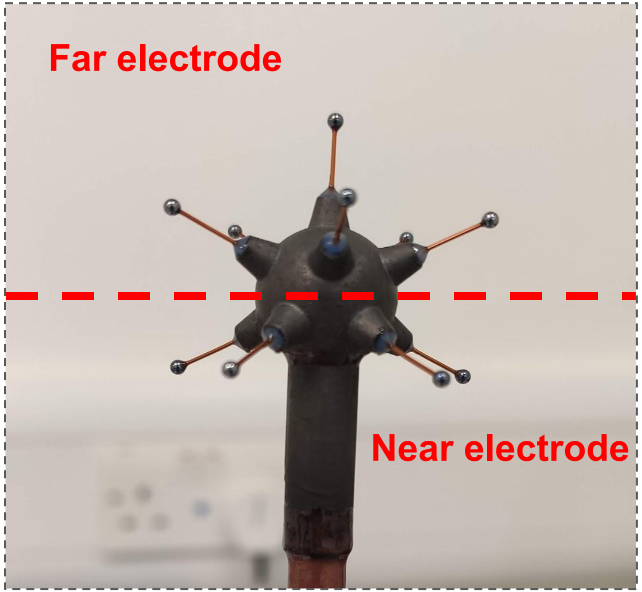
3D printed modules with DLC coating





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

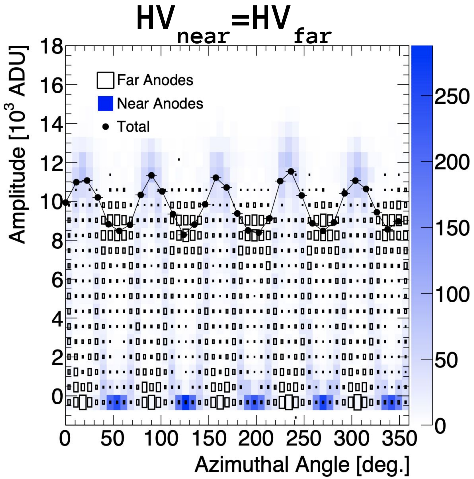
Performance of ACHINOS with resistive coating

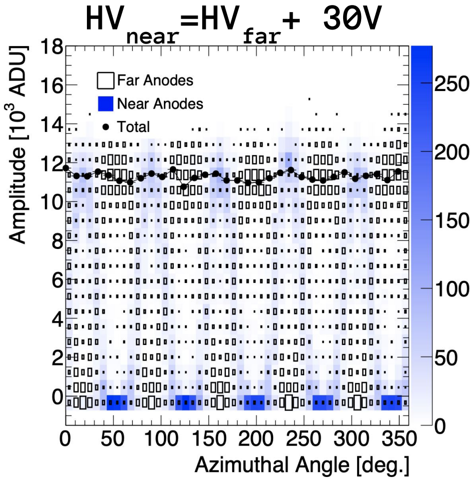


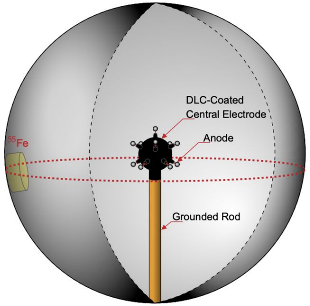
2 channel readout

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

Simulations

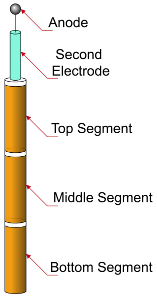






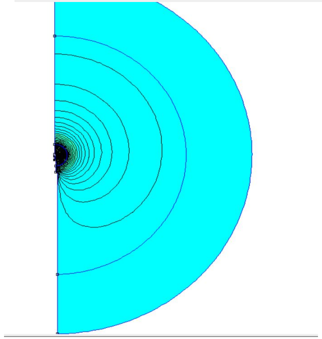
Irradiation with an 55Fe source vs Azimuthal angle

E-field correction - Voltage degrader

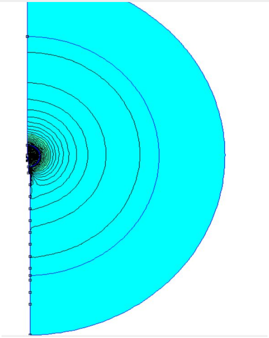


- **Grounded rod distorts electric field**
- **Voltage gradient along rod, as in ideal geometry, would restore ideal field.**
- **Voltage applied to each segment is the average ideal voltage over the segment.**

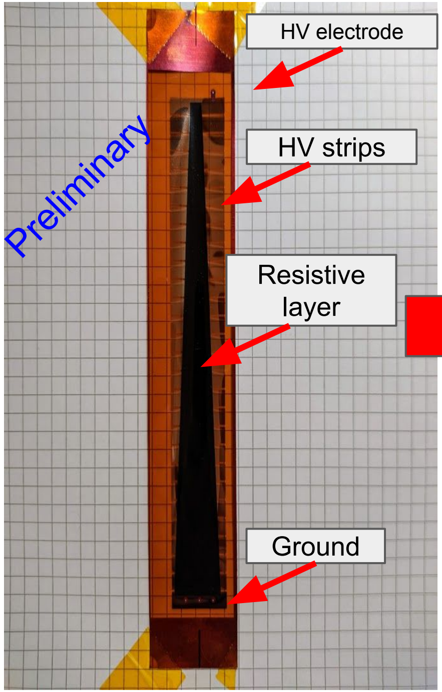
No correction



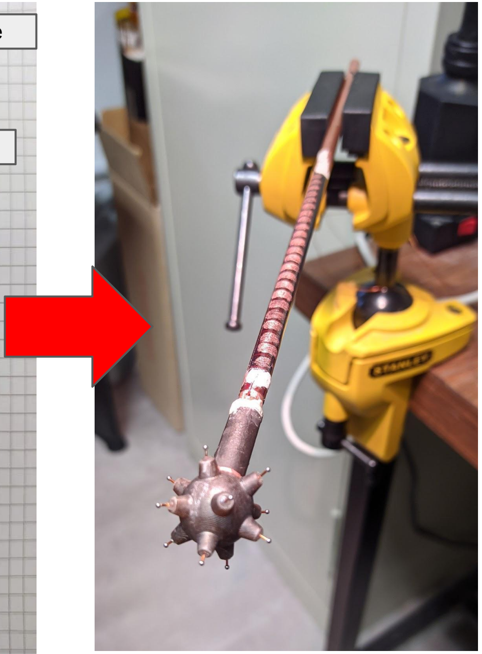
Voltage degrader



Resistive strip degrader

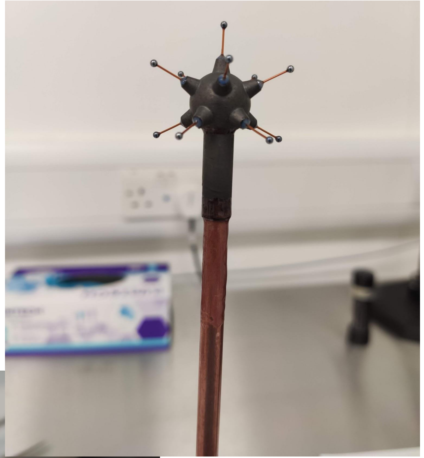


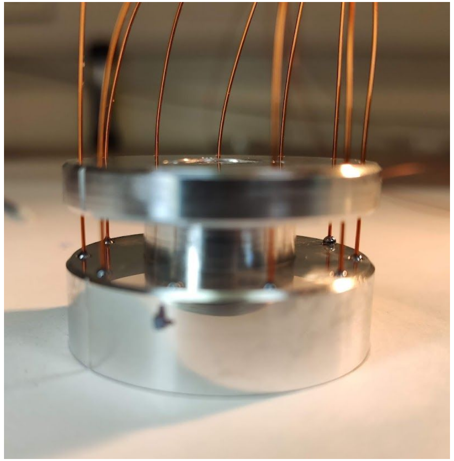
ACHINOS with Degrader

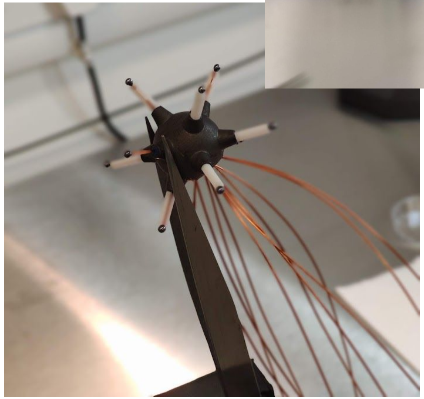


Tools developed for ACHINOS construction

Assembly tools developed:
- **Simultaneously bonding several wires and anodes**
- **Custom-made spacers to position and align the anodes.**







Kamioka (Japan)-Birmingham

- **New collaboration** for the development of an **ACHINOS-like sensor for LXe TPC**
- **Goal:** XMASS background reduction through the S2-signal (electroluminescence)
- **Funded by**:
  - **ICRR-University of Tokyo,** Inter-University Research Program (Co-I), 5M ¥
  - **Royal Society** International Exchanges (Co-I), 12 k£

Reducing Backgrounds

Custom made purifications systems

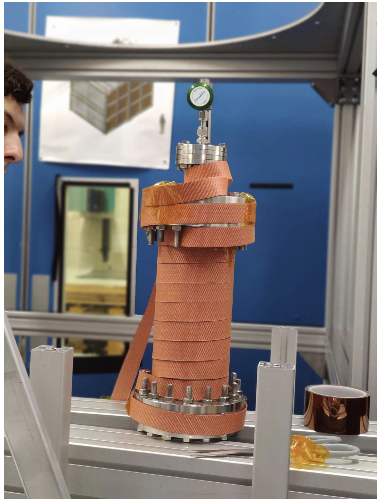
Aims:
- Few and known components
- Assay emanation of each component individually

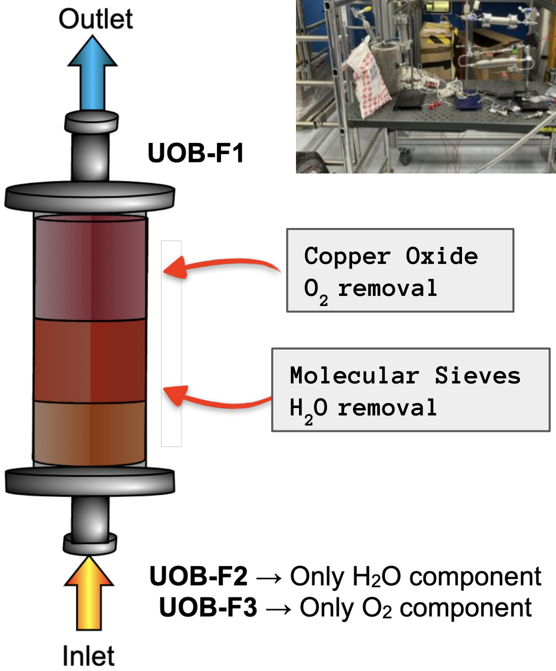
Birmingham-Liverpool-Zaragoza collaboration

Dark Matter - Neutrinos - Axions

- **Commercial O_2/H_2O purifiers efficient**
- **Problem: ^{222}Rn emanation**

⇒Major BG in Rare Event Searches

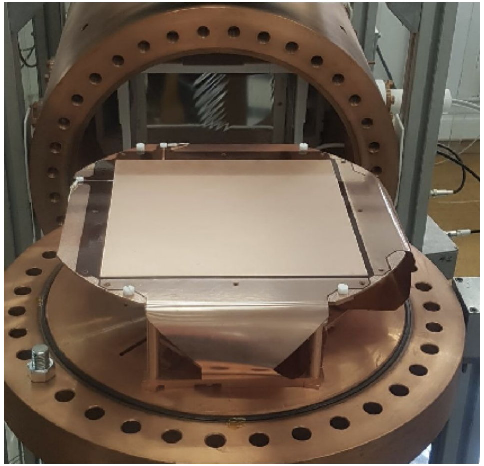




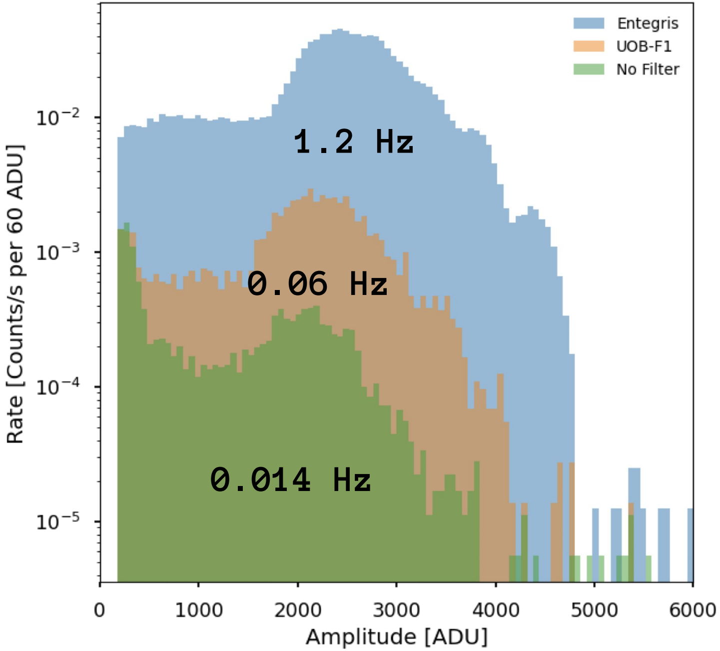
UOB-F2 → Only H_2O component
UOB-F3 → Only O_2 component

Rn emanation results

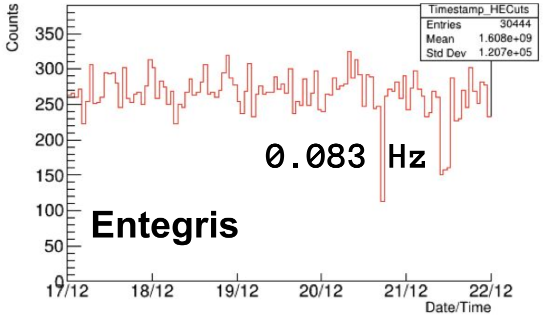
Low-background MicroMegas-based TPC at Carfranc

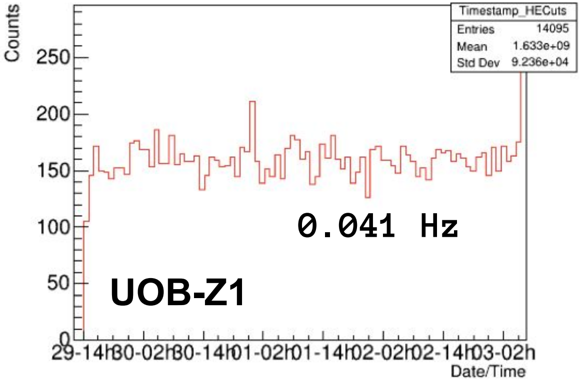


SPC at UOB



Circulation with TREX at LSC

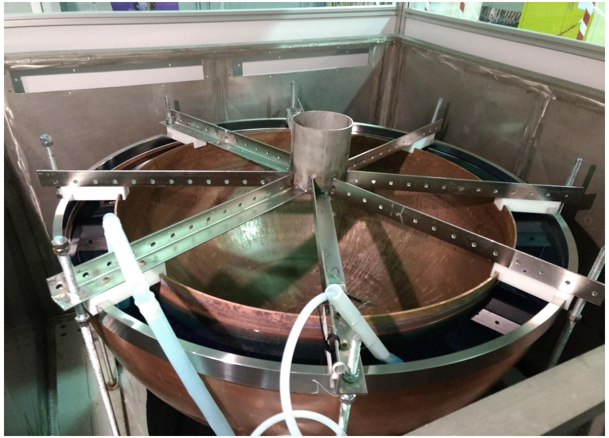




UOB-Z1 under test

Reducing Background - Electroforming Copper

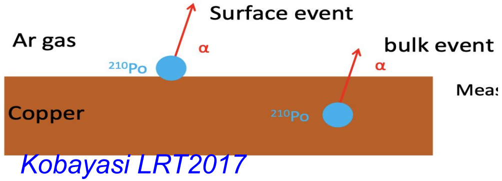
The setup during electroplating at LSM

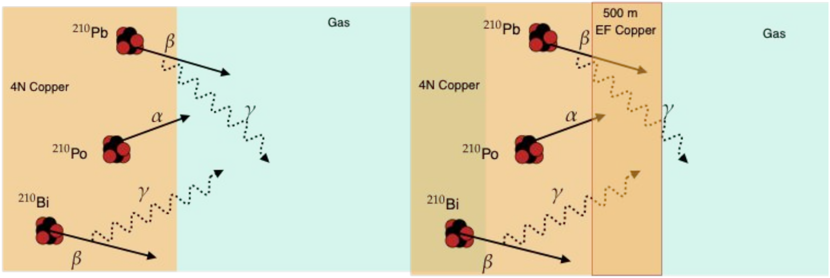


Contaminants : U and Th decay chain traces

- Measured for NEWS-G ~10 µBq/kg

- ^{210}Pb out of equilibrium - 28.5 mBq/kg

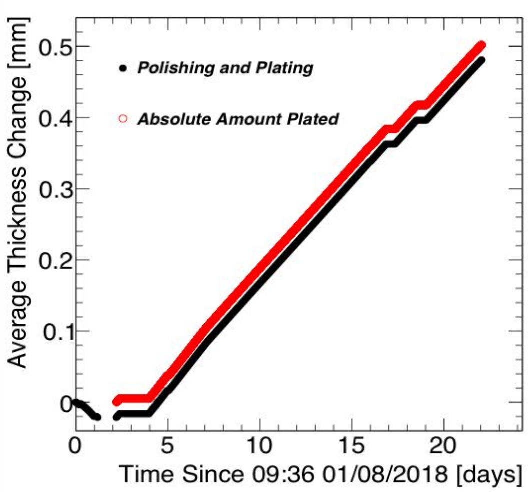




- **Background**: Bremsstrahlung X-rays from ^{210}Pb and ^{210}Bi β-decays in Cu
- **Layer of ultra-pure Cu on the inner surface** of the detector.
  Suppresses ^{210}Pb and ^{210}Bi backgrounds by factor 2.6 (<1keV)
- Using PNNL expertise and strong UoB contribution a 500 um electroplated copper was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

Result after plating

NEWS-G, NIM A 988 (2021) 164844



- **Good surface quality achieved**
- **Hemispheres electron-beam welded together**
- **Copper was deposited at a rate: ~36 μm/day → ~ 1mm/month**

Result is promising for possibly a whole detector electroformed underground

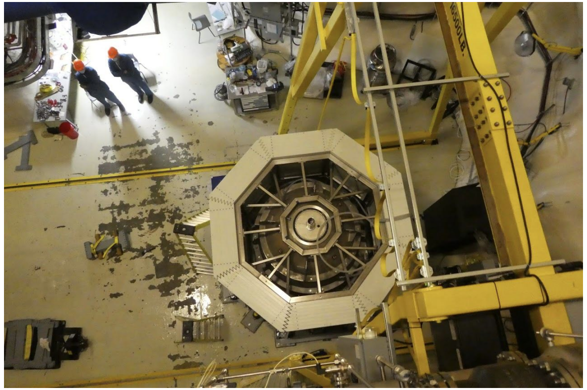
First large-scale underground radio-pure electroformation

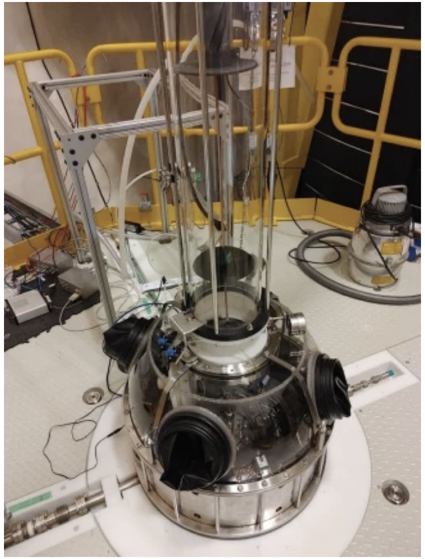
Relevant for all next generation rare event experiments!

(e.g. LEGEND, DARWIN, ARGO)

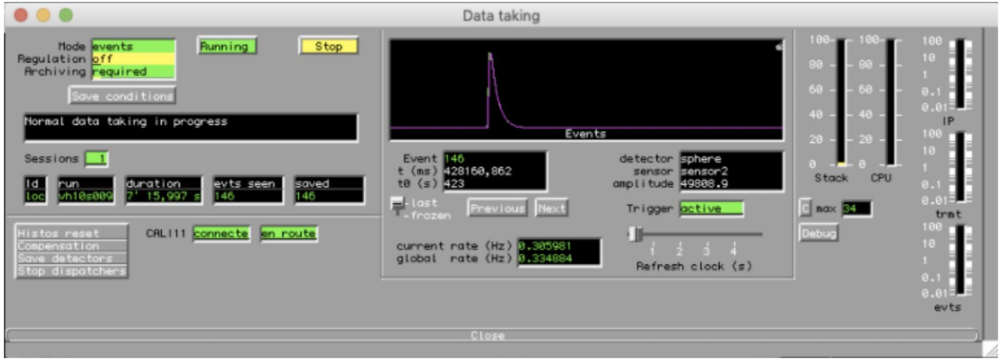
SNOGLOBE: NEWS-G at SNOLAB

Currently under commissioning:
Electronics, Calibration, Detector response





First operation in SNOLAB, 10th Aug. 2021

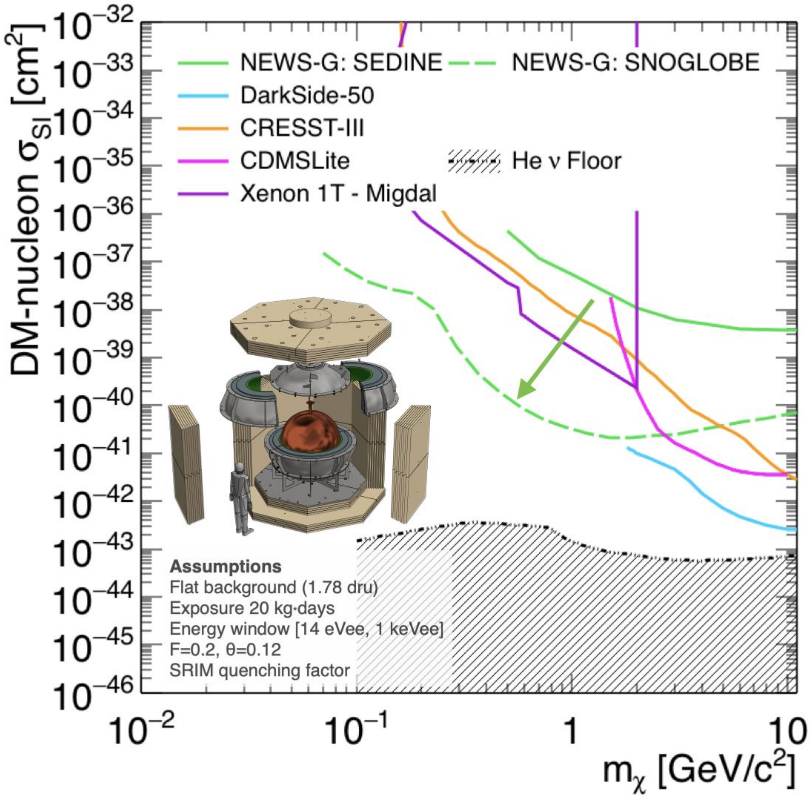


Strategy overview

- Exposure: 20 kg.d exposure Ne/CH4 94/7
  - ~22 days at 1 bar, ~ 30 days taking into account 25%-30% possible dead time
- **Laser operation for calibration and gas properties study**
- Fiducialisation/Event discrimination through rise time - **Electron counting**
- Maximum percentage of CH4

Next Steps

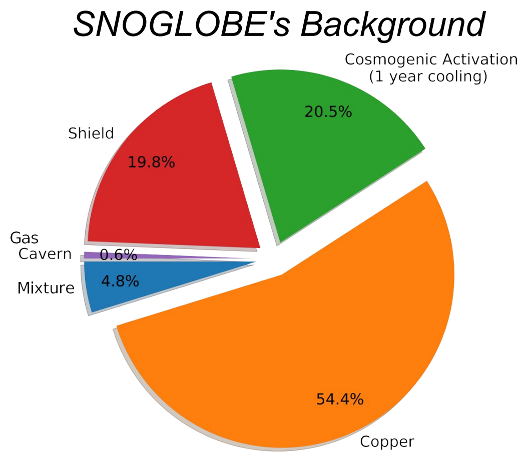
- Operation with Ne:CH4 2% and 7%
- Isobutane use instead of CH_4
- Addition of non-flammable quenchers as N_2
- Use CF_4, ^3He in the gas mixture
- ^{19}F odd-neutron Spin-dependent-DM searches



Understanding single e- event rate

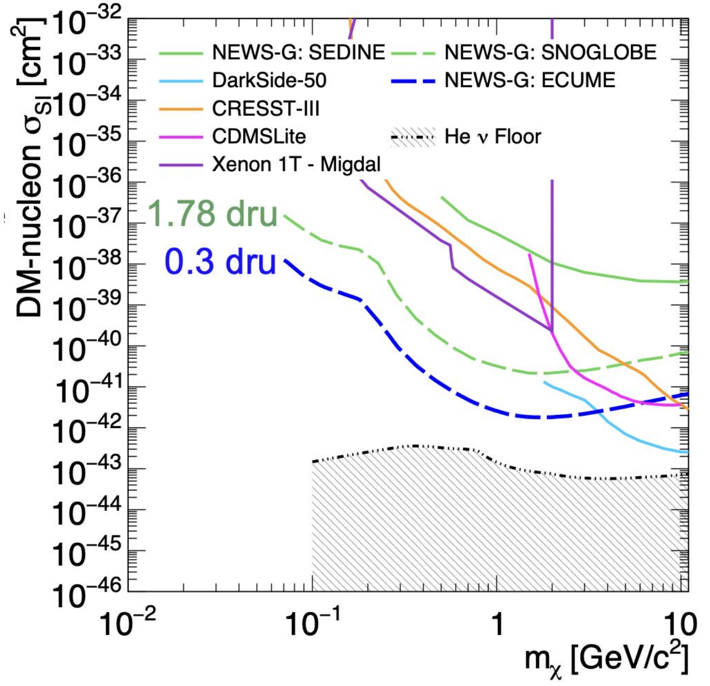
ECuME

- **Fully underground-electroformed** ∅140 cm sphere
  - Electroformed in SNOLAB - **Suppress Cu contamination**
  - No machining or welding - grow sphere directly
- **Builds on achievements of NEWS-G** electroplating
- Using shielding of SNOGLOBE in SNOLAB



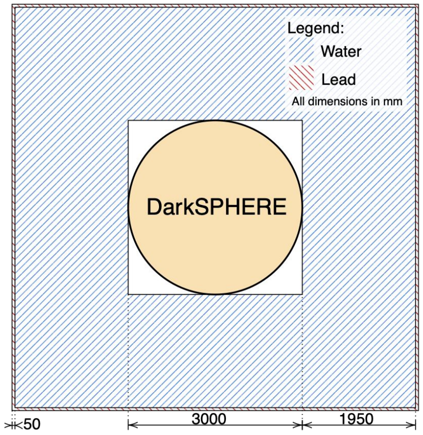
Status:

- R&D for ∅30 cm scale prototype
- Operation beginning soon
- Full-scale in 2022
- Physic exploitation will follow
- ECuME is initially dedicated to NEWS-G, but after it will be an **electroplating facility available in SNOLAB**



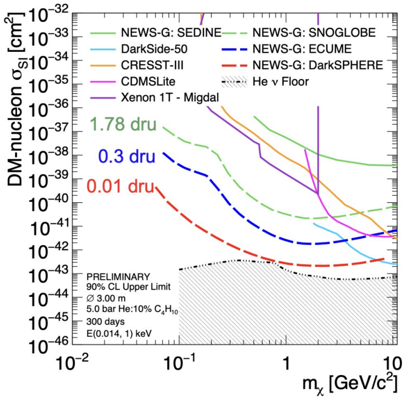
Reaching the neutrino floor with NEWS-G: DarkSphere

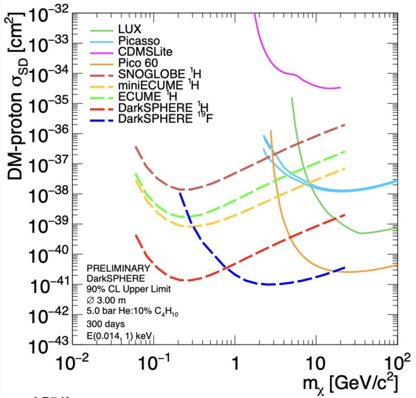
Development led by Birmingham, with NEWS-G and UK-DM contributions (Boulby, KCL, UCL, UoL)



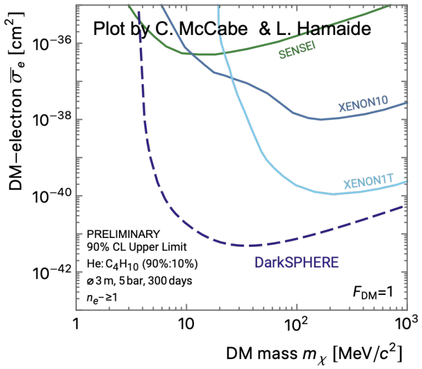
Conceptual parameters:

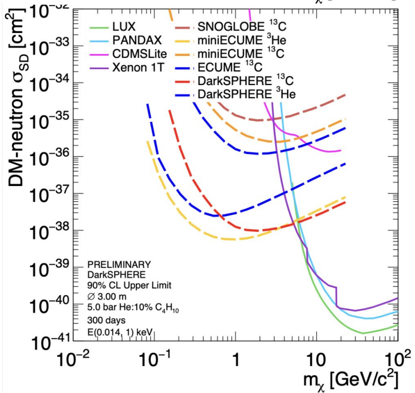
- **Installation at Boubly**
- **3 m ⌀ SPC**
- **Fully electroformed underground**
- **Pressure up to 5 bar**
- **Target mass *O(100kg)***





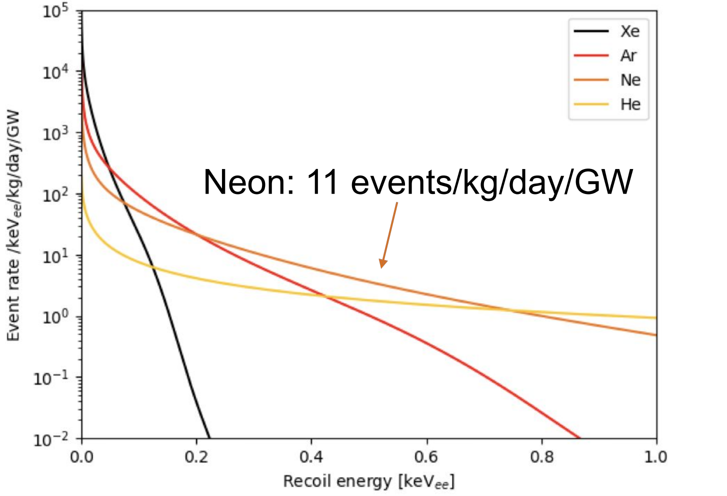
- **Discovery potential** in SI, SD nucleon-DM interactions, and in DM-electron interactions
- **Multi-physics platform**: 0νββ searches, neutrino physics, supernova detection, …

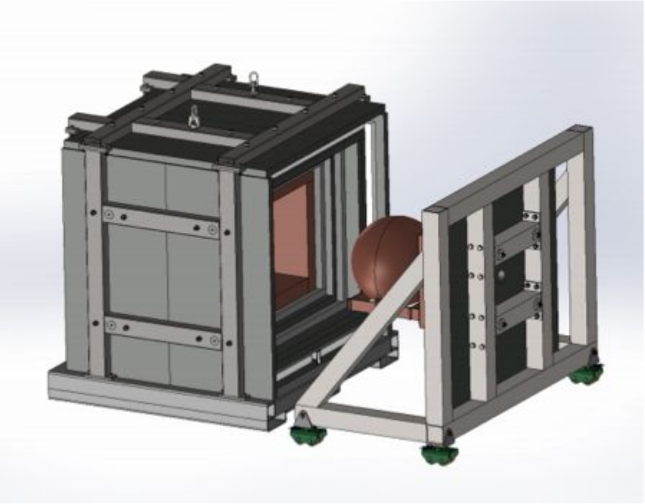




NEWS-G3: Neutrino coherent scattering searches (CEvNS)

- **CEvNS opens a window to investigation non-standard neutrino interactions**
  - First observations by COHERENT in NaI (2017) and Ar (2020)
  - Unique complementarity with DM searches as sensitivity reaches the neutrino floor
- **NEWS-G3: A low-threshold low-background sea-level facility**
  - Environmental and cosmogenic background studies towards **reactor** CEvNS studies
  - Shielding: Layers of pure copper, polyethylene, and lead, with active muon veto
- Commissioning in 2022





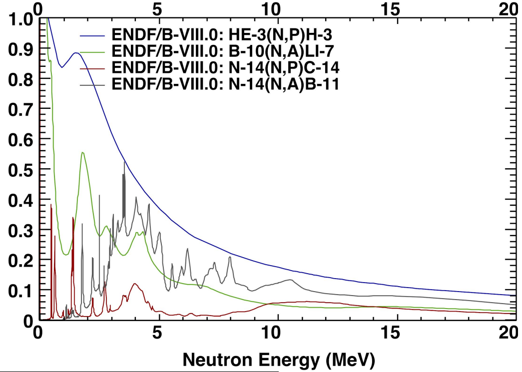
- **Participated in the Letter of Interest submitted to SNOWMASS**
- **Participation of the CEvNS community white paper**

Fast neutron detection with an SPC

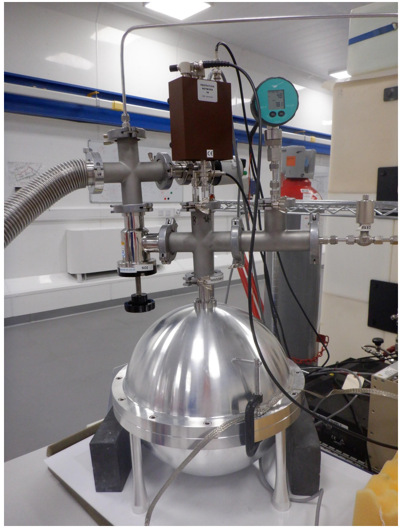
A N_2-filled spherical detector

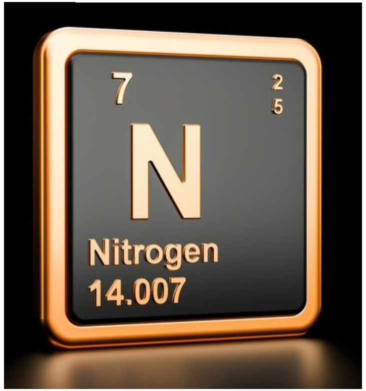
A novel detector for neutron detection

Nitrogen as target:
$^{14}N + n \rightarrow {}^{14}C + p + 625\ keV,\ \sigma_{th} = 1.83\ b$
$^{14}N + n \rightarrow {}^{11}B + \alpha - 159\ keV,\ thres = 1.7\ MeV$



- Large volume (0.1 m^3 - 1 m^3)
- Inert gas - safe - not toxic
- High stopping power
- Operation without moderation
- Measurement of neutron energy
- Operation in sensitive environments
- Low γ-ray efficiency
- Cost efficient
- Possible alternative to ^3He

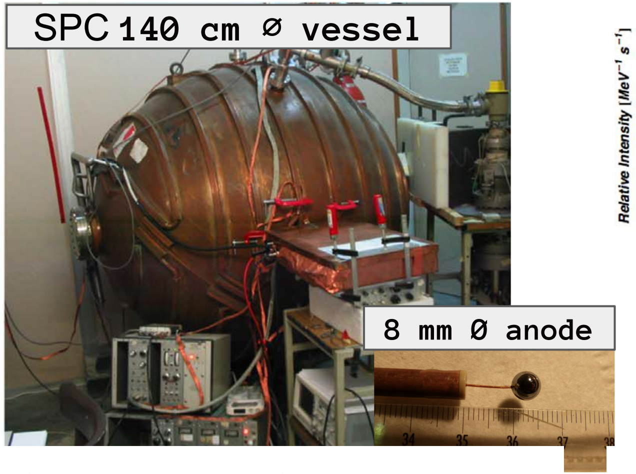




Neutron detection with SPC

Proof of principle

Bougamont, E et al (2017). NIM A, 847, 10–1

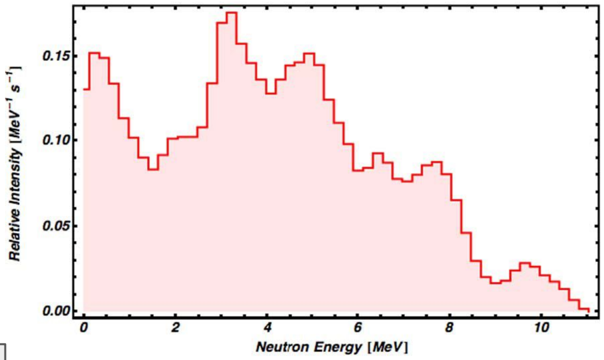


First measurements:

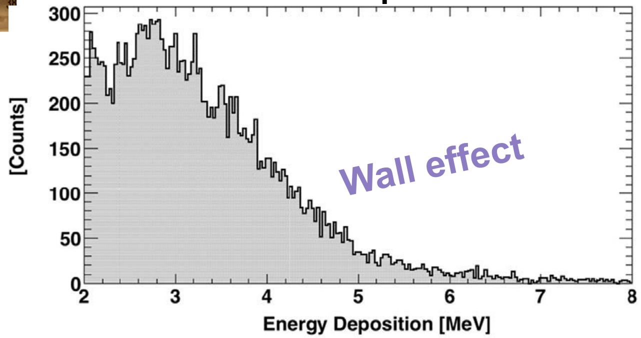
- ^{252}Cf, ^{241}Am^{9}Be and ambient fast neutrons
- Thermal neutrons

```
N₂ at 0.1–0.3 bar
HV ~ 6 kV
```

AmBe spectrum

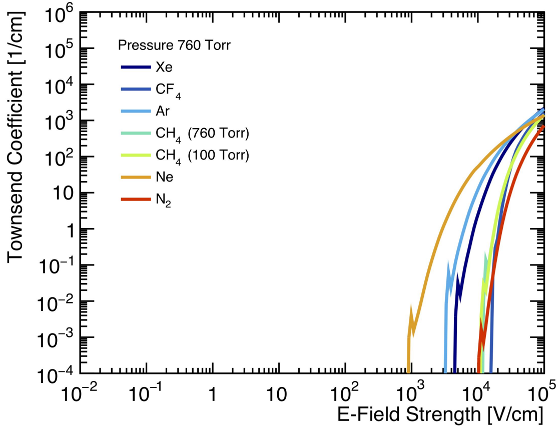


Measured spectrum

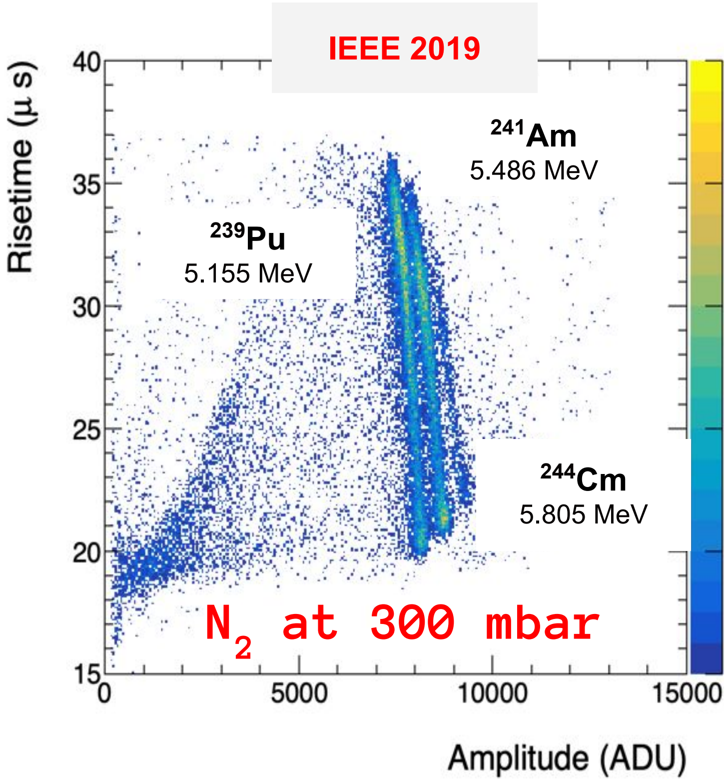


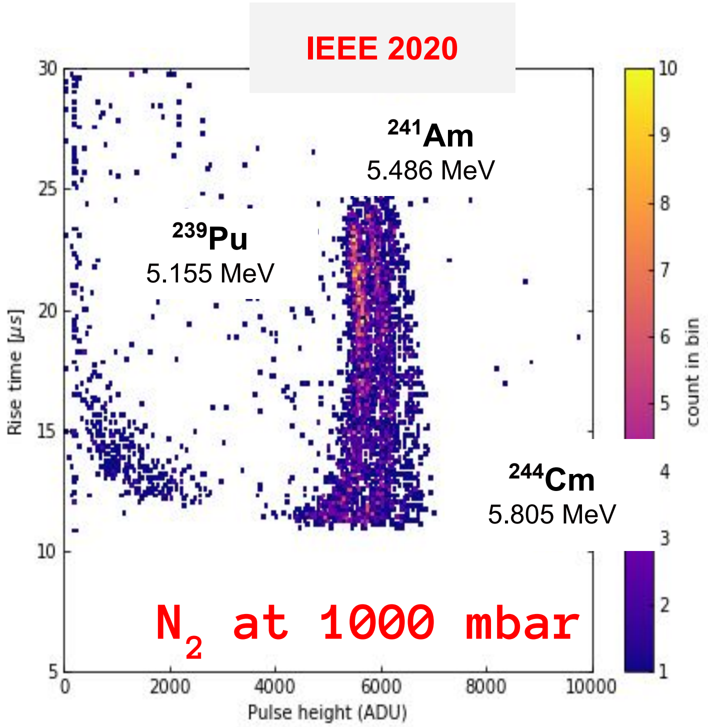
Limiting factors then:

- ➔ Wall effect
- ➔ Low pressure
- ➔ Sparking - Instability
- ➔ Impurities
- ➔ Charge collection losses



Latest results with N_2-filled SPCs

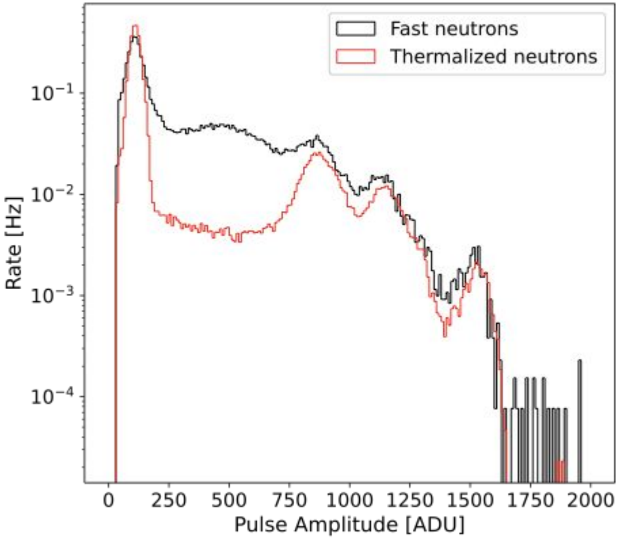




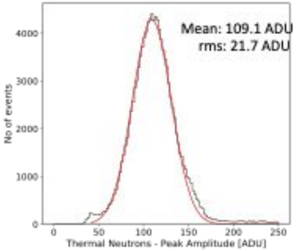
Measurements at UoB's graphite stack

$^{241}Am^{9}Be$ neutron source
A = 2.6 x 10^6 Bq

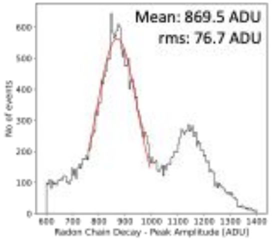
- Calibration measurements
- Thermal and fast neutrons at **1 bar** (4.2 kV)
- Thermal and fast neutrons at **1.5 bar** (4.5 kV)
- Thermal neutrons at **2 bar** (5 kV)



Thermal Peak 625 keV

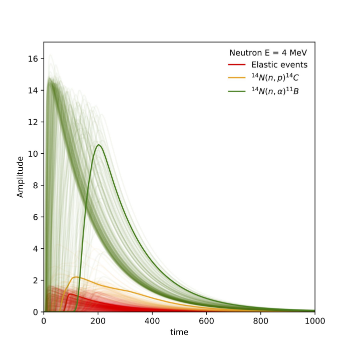


^{222}Rn Peak 5.5MeV

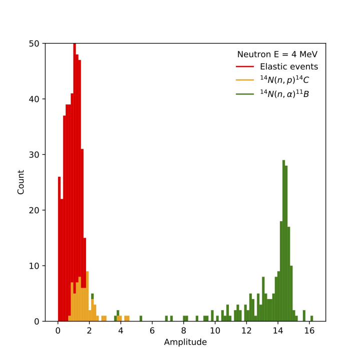


Using the UoB simulation framework

Simulated pulses



Simulated amplitude distribution

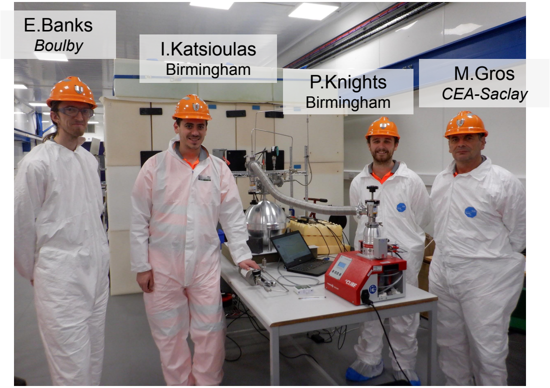


Future plans and activities

Next steps:

1. Simulation of the detector response
2. Validation of simulations using measurements of calibration sources and monoenergetic neutrons beams
3. Unfolding of incident neutron spectra
4. Software toolkit for automation neutron spectra estimation

Aluminium S30



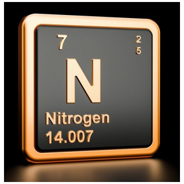
Installation of the SPC in Boulby in 2019

- R&D in controlled environment:
  - Rate effects
  - Space charge effects
- **Fast neutron spectra measurements**
- Method is applicable to **all other underground laboratories**

Aimed applications:

-Medical e.g. neutron flux in hadron therapy environments

- Industry and security e.g. Oil search industry



Neutron backgrounds studies in SNOLAB

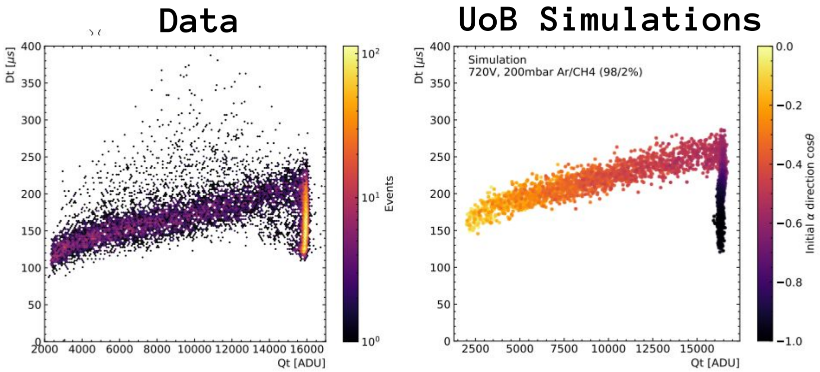
R2D2: 0ν2β decay searches with a gaseous spherical TPC

➡ **0νββ decay is the most sensitive way to demonstrate the Majorana nature of neutrino!**

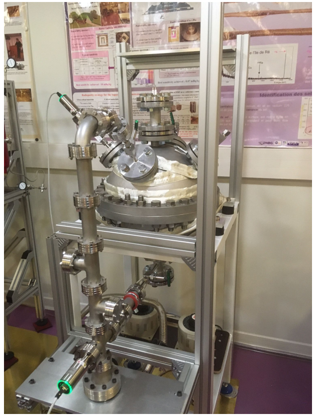
R2D2 collaboration

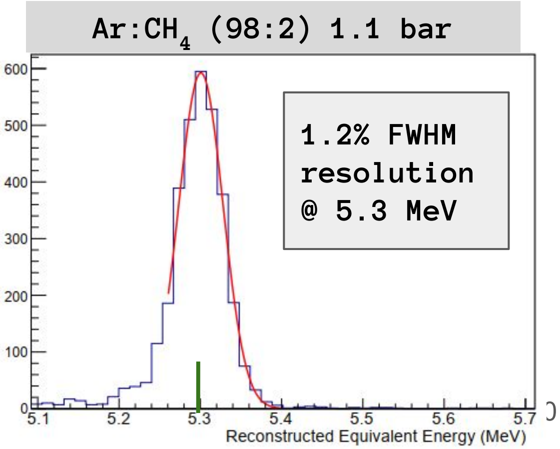
R2D2 R&D Goal: Demonstrate the use of a high pressure ^{136}Xe spherical TPC being use for *0νββ* searches with “zero” background and tonne scale

- UoB has close collaboration with the University of Bordeaux to exchange knowledge on
  - Sensor development
  - Electronics
  - Simulations
- **Funded by CRNS France, International Emerging Action (Co-I)**, *eAchinos*, 2020-2022, (€20,000)



SPC at Bordeaux

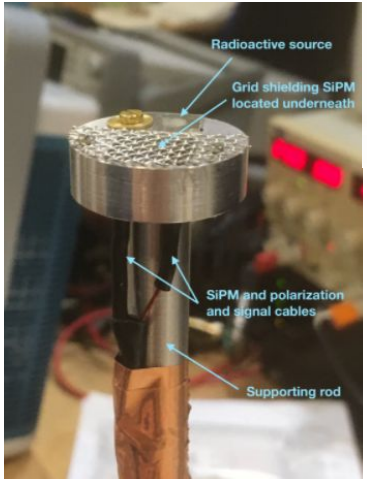




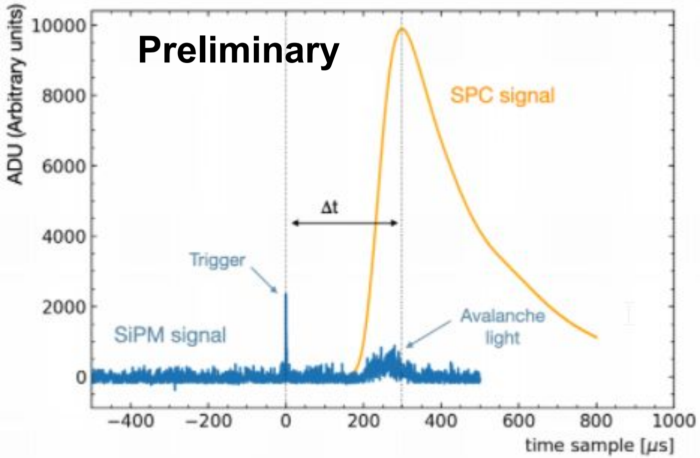
Glass sensor

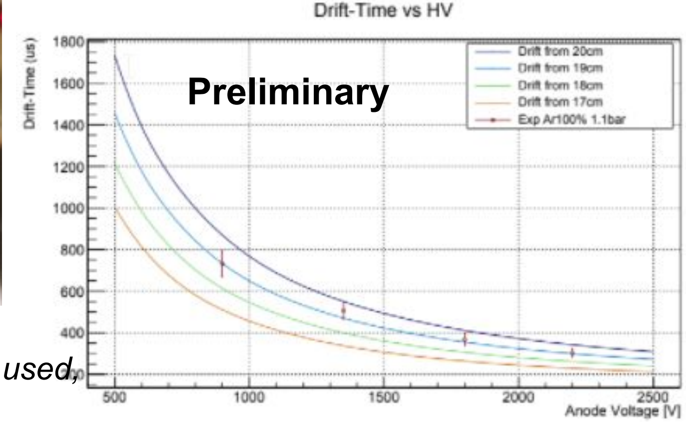
Reading out scintillation

- **SPC operated in pure argon** to observe the scintillation light and use it as trigger
- Two signals observed with the SiPM:
  - **Primary scintillation light (S1) used as trigger**
  - **Electroluminescence during avalanche (S2)**
- The time between S1 and S2 is the electron drift time
  - Garfield++ simulation validated with this info
  - Excellent agreement found for alphas emitted at ~19 cm from the anode



6x6 mm^2 Hamamatsu SiPM used, 15% QE at 128 nm



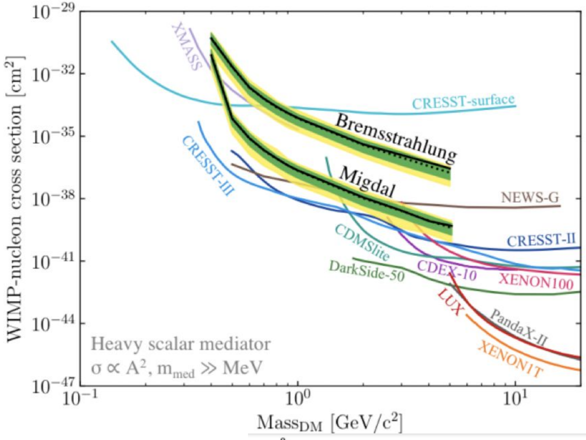


MIGDAL experiment

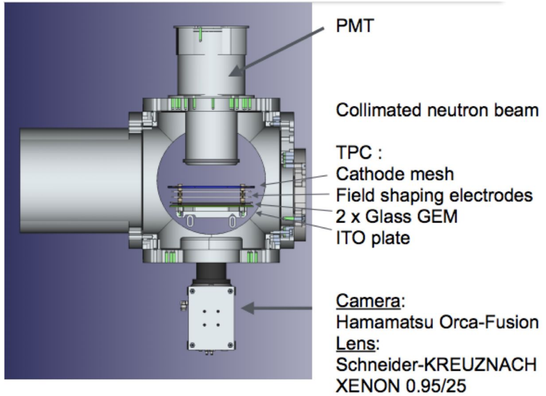
Unambiguous Migdal effect observation and measurement

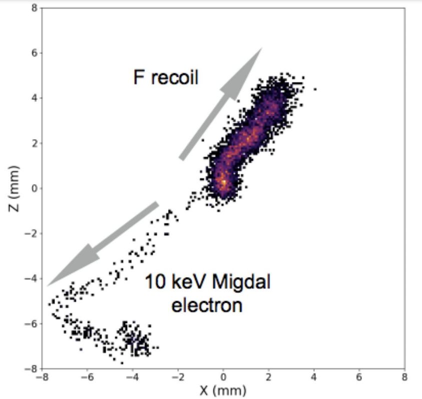
Migdal effect: Light DM with heavy targets

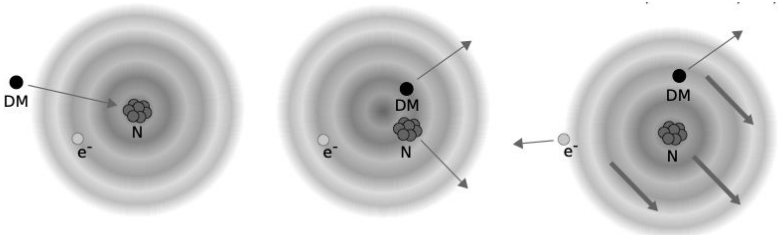
LUX: PRL 122 (2019) 13, 131301
Also Xenon1T: PRL 123 (2019) 24, 241803



- Analysed theoretically by Arkady Migdal
    - Nuclear scattering (1939)
    - α and β± decays (1941)
- Relevance for DM searches
    - Ibe et al. JHEP03(2018)194
- Theoretical calculations for DM available
- Effect observed in α and β± decays
    - **Not observed in nuclear scattering**



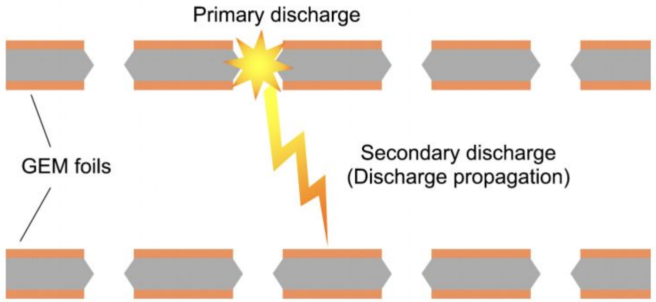




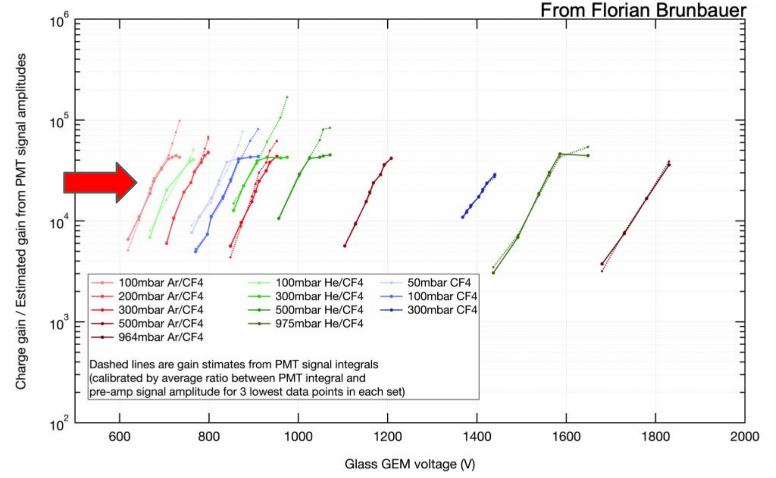
The challenge in MIGDAL

Study case:

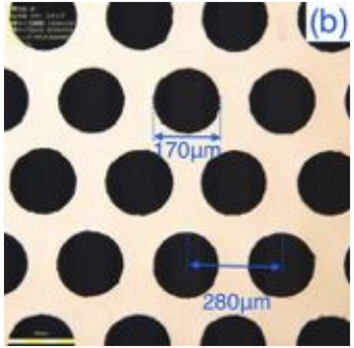
- E_{dep} = 144.4 keV by 5 MeV C^+ in CF_4
- n_0 = 4370 primary electrons (W=34eV)
- $G \cdot n_0$ = ~ $2 \cdot 10^8$ → 34.88 pC



1. Appearance of heavy ions can release a large number of electrons with high ionisation density
2. The dense cloud can be funneled through one or few GEM holes
3. $G \cdot n_0 \gtrsim 10^8$ (Raether limit) is reached, causing a breakdown.



Glass GEM electrode

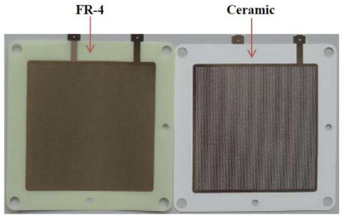


Destroyed GEM electrode

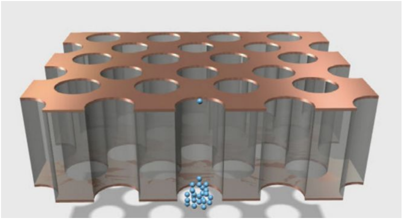
Possible solutions

RD51 common project goal submitted (Co-I)
Comprehensive studies of the glass, ceramic- and kapton-THGEMs in high- and low-pressure TPCs.

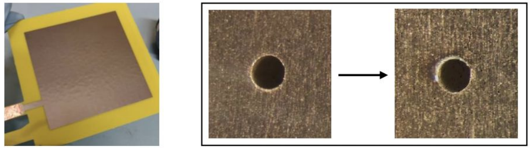
Ceramic THGEMs



Glass GEMs

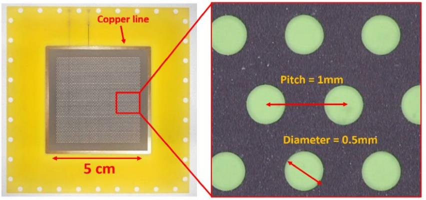


Alternative Coating THGEMS
(Higher Fusion Point)



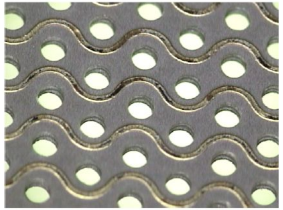
Replacing copper layer by a metal with higher fusion point.

- **Cu → 1085 ºC**
- **Ni → 1455 ºC**
- **ITO→ 1926 ºC**
- **W → 3422 ºC**



DLC coated THGEMs

Self quenching mechanism naturally protects against discharges

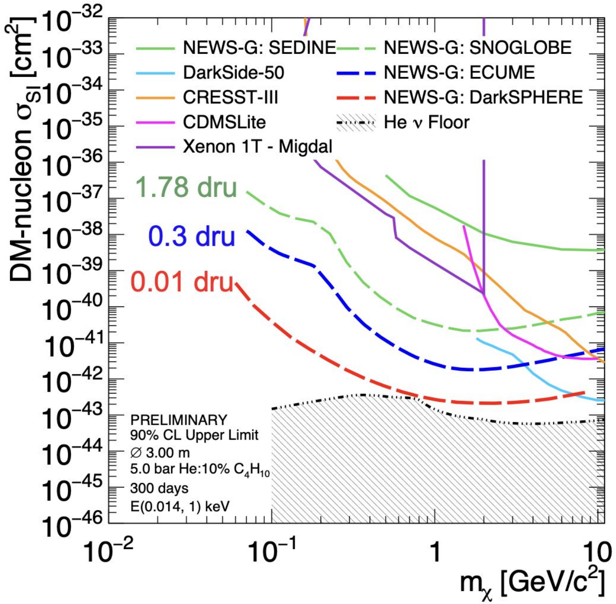


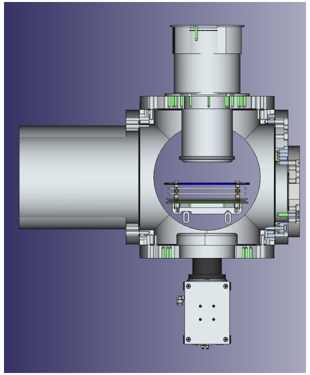
Stripped GEMS
Or Combination of Resistive/Alternative coating GEMS

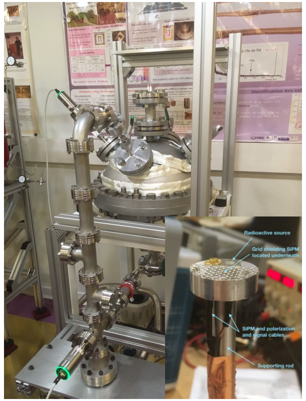
Lower capacitance of the strips reduces energy released in a spark

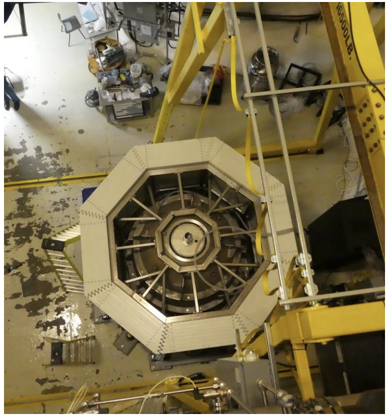
Summary

- ❑ Investigated key questions in Physics!
  - ❑ Searching unexplored light DM region
- ❑ Explored novel methods for light DM and a next generation of experiments
  - ❑ Technologies relevant for future projects
  - ❑ Industrial applications
- ❑ Ideally positioned to lead such developments







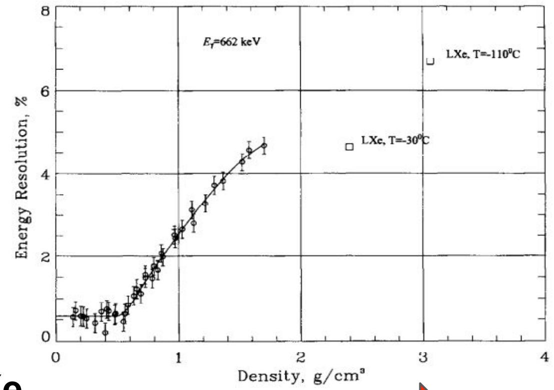


Extra slides

The high pressure Xe spherical TPC for 0νββ

Combine SPC traits such as:

- Simple design
- Low material budget
- Robustness
- High gain
- Large volume
- Pressure variation



With advantages of gaseous ^{136}Xe

- Safe and easy to enrich (^{136}Xe is ~ 8%)
- Good scintillation properties
- Event containment in high pressure
- Moderate density for BG rejection
  - Tracking of ~MeV e, p, α
  - Ionisation vs scintillation yields per species for particle discrimination
- Energy resolution is good up to < 0.55 g/cm^3!

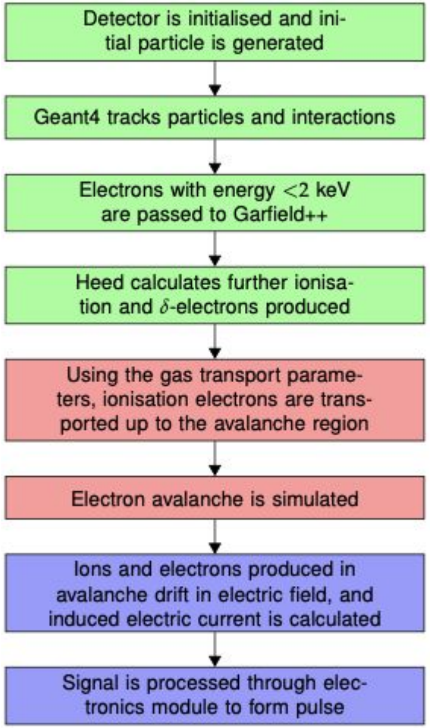
10.1016/S0168-9002(97)00784-5

To get:

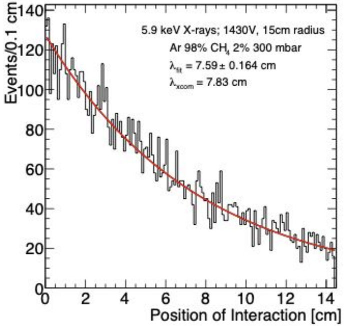
- Good energy resolution
- Extremely low (*zero?*) background
- Scalability to large isotope mass
  - 1 tonne ~ ∅ 2m at 40 bar
- High detection efficiency

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

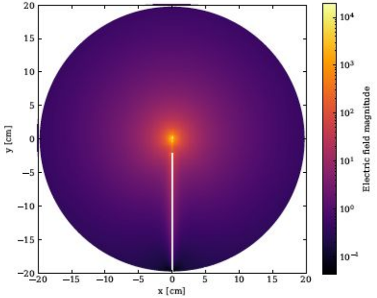
Simulating the detector response



Primary interaction

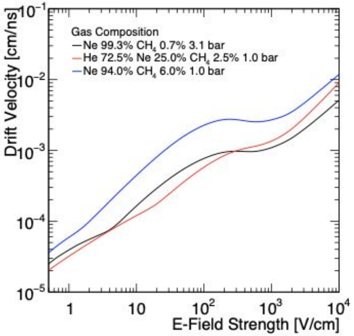


Electric field

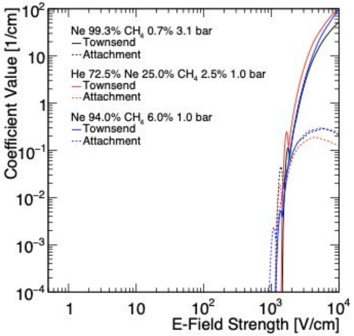


Garfield++

Electron Drift

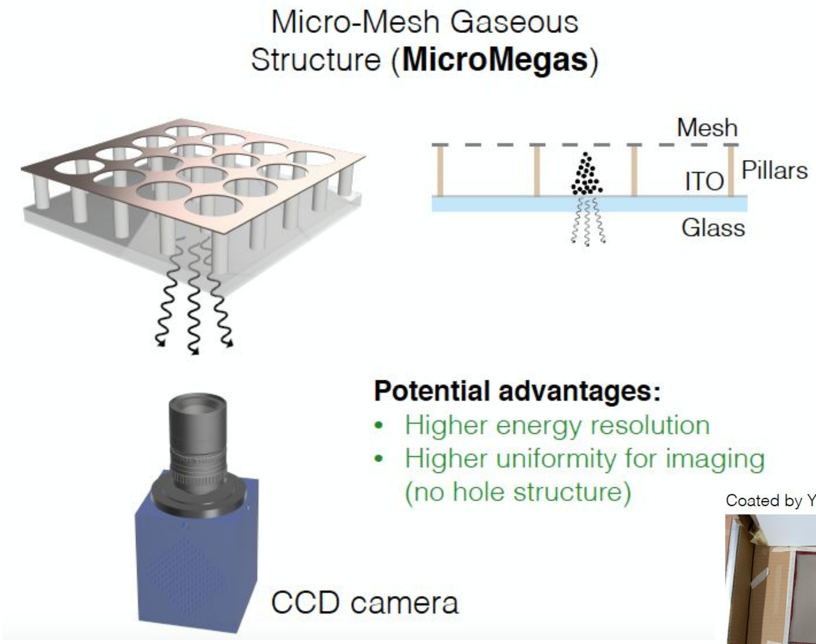


Electron Multiplication

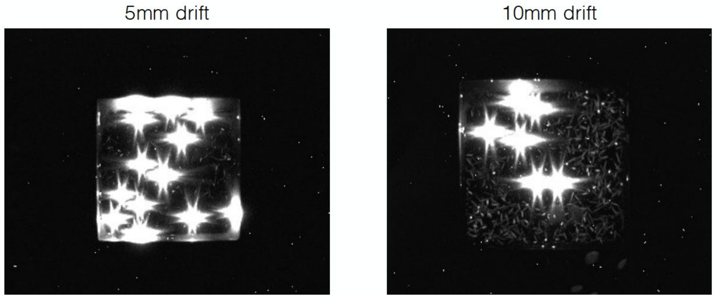


Katsioulas, I. et al “Development of a Simulation Framework for Spherical Proportional Counters”,arXiv:2002.02718

Glass MicroMegas and DLC coated mesh



From T.Papaevangelou and F. Brunbauer

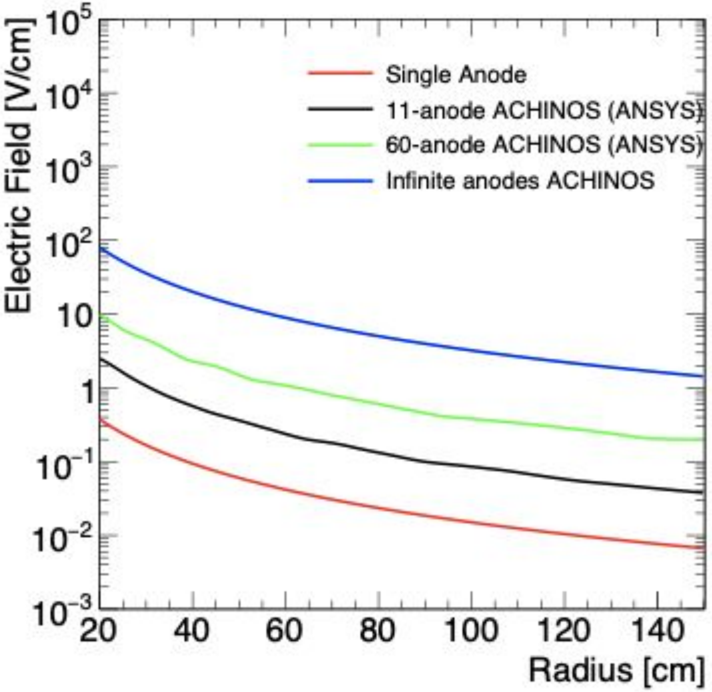


Coated by Yi (USTC)

- **Spark resistant**
- **Superior spatial resolution compared to triple-GEM-based detector**
- **Not optimised yet for 50 torr CF_4**
- **Is 10^4 gain achievable in CF_4?**

https://doi.org/10.1016/j.nima.2019.163320

Advantages of the ACHINOS sensor

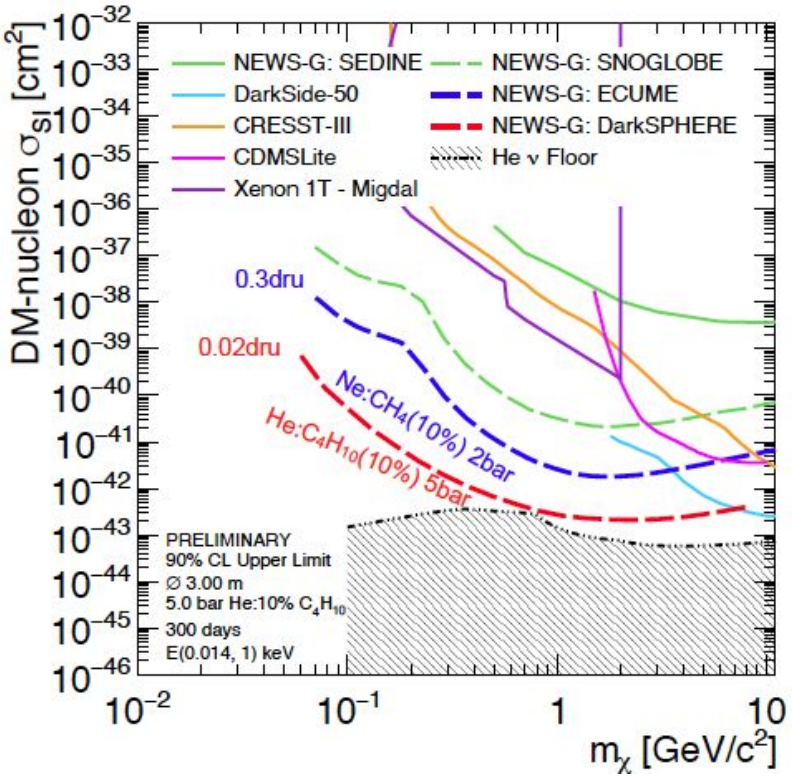


- **Decouples electron drift and multiplication**
  - **Small anode size → high gain**
  - **More anodes → Efficient charge collection**
- **Allows for increased target mass**
  - **Larger volume**
  - **Higher pressure**
- **Individual readout TPC-like capabilities to the SPC**

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

Conceptual parameters:

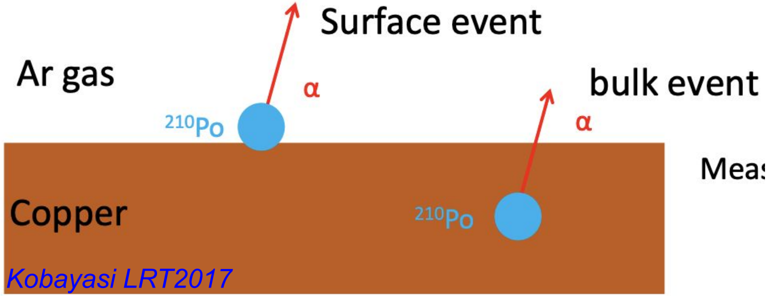
- **Installation at Boubly**
- **3 m ⌀ SPC**
- **Fully electroformed underground**
- **Operation with He/iC_4H_{12} and possibly Xe**
- **Pressure up to 5 bar**
- **Large target mass *O(100kg)***
- **Sensitivity down to the *v*-floor**
- **Multiphysics platform**

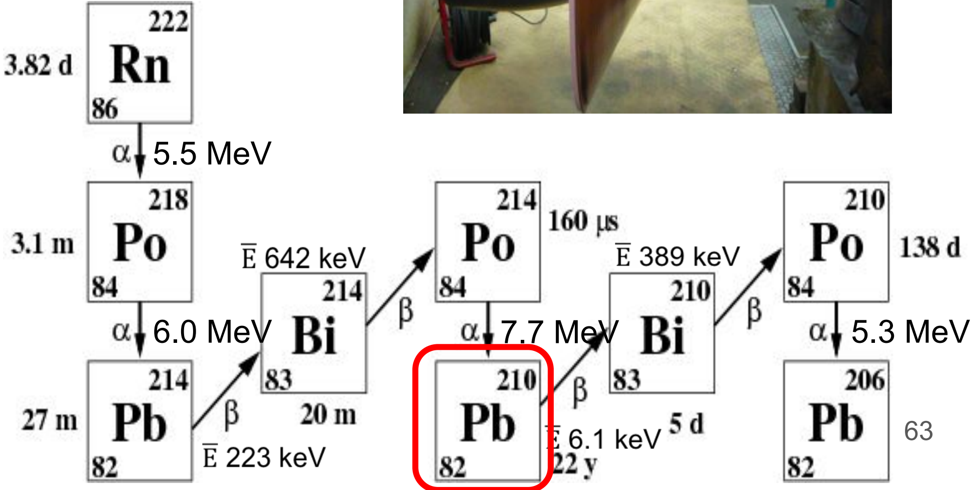


Dimensions in mm

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





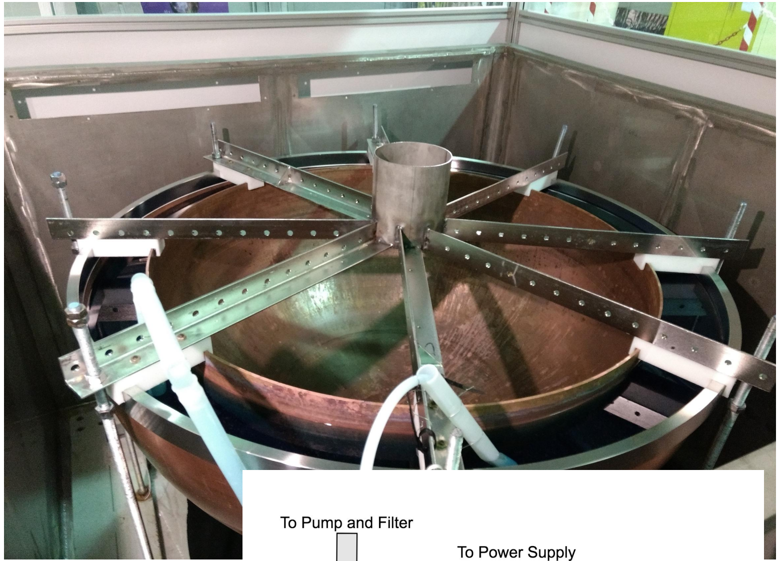
Electroplating Copper

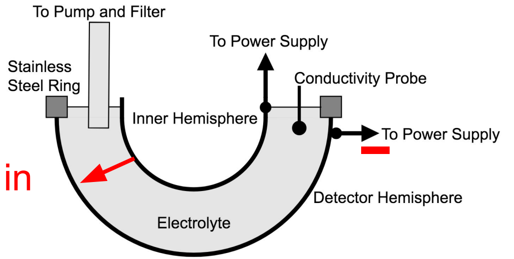
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 988, 1 February 2021, 164844

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]

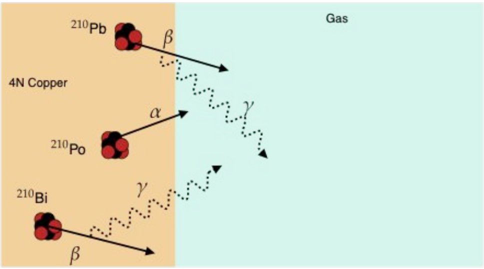
The setup during electroplating at LSM

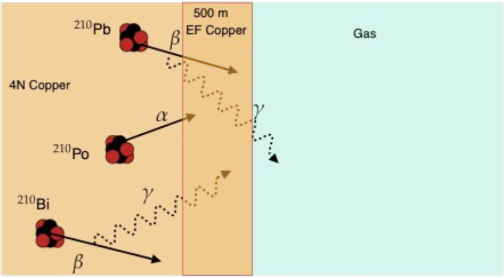




Cu Movement in Electroplating

- **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 (<1keV)
- Using **PNNL expertise** and strong UoB contribution a **500 um electroplated copper was deposited on the inner surface** at LSM.





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	μBq/kg	0.05	0.06	0.005
	^{222}Rn	111	μBq/kg	0.05	0.04	0.2
Copper sphere 500 μm electrolyte	~~^{210}Pb~~	~~28.5~~	~~mBq/kg~~	~~1.04~~	~~1.01~~	~~0.86~~
	~~^{238}U~~	~~3~~	~~μBq/kg~~	~~0.0117~~	~~0.115~~	~~0.028~~
	~~^{232}Th~~	~~12~~	~~μBq/kg~~	~~0.0754~~	~~0.0602~~	~~0.162~~
	~~^{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	μBq/kg	0.142	0.094	0.277
	^{232}Th	9.1	μBq/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	μBq/kg	0.17	0.132	0.5
	^{232}Th	9	μBq/kg	0.0251	0.0201	0.075
	^{40}K	<1.46	mBq/kg	<0.35	0.26	0.67
Cavern	Gamma	4.87×10^{-8}	γ/cm^2/s	0.0084	0.0095	0.00464
	Neutron	4000	neutron/m^2/day	0.0044	0.0004	3.54×10^{-11}
	Muon	0.27	muon/m^2/day	0.00062	0.00044	5.04×10^{-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

WIMP search run data

Target: Ne+0.7%CH_4 at 3.1 bar → 280 gr target mass

Duration: 42 days in sealed mode

Dead time: 20.1%

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

Trigger threshold: 35 eVee (~100% efficient at 150 eVee)

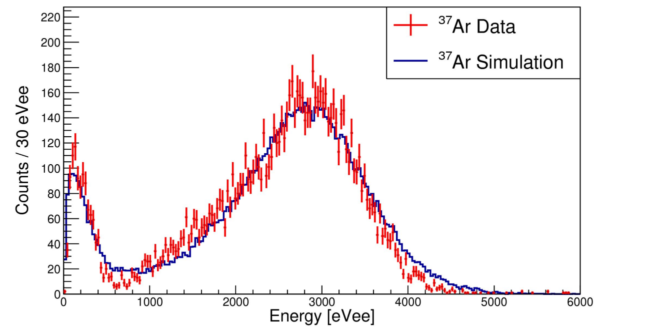
Analysis threshold: 150 eVee (~720 eVnr)

Calibration: ^{37}Ar gaseous source, 8 keV Cu fluorescence, AmBe neutron source

Calibrations

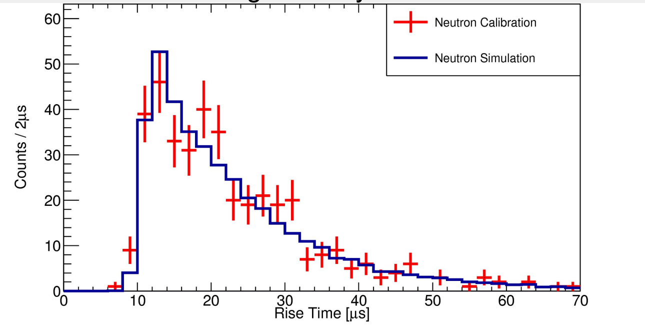
^{37}Ar gaseous source

2.82 keV and 270 eV X-rays (K and L shells)



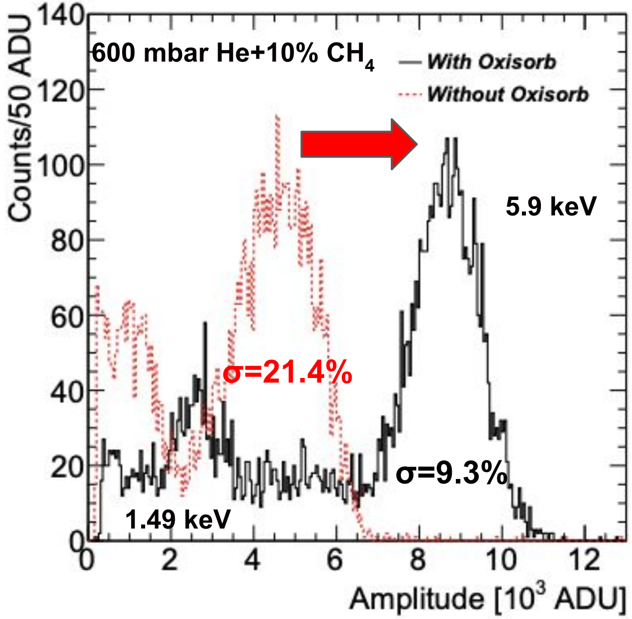
^{241}Am-^{9}Be neutron source

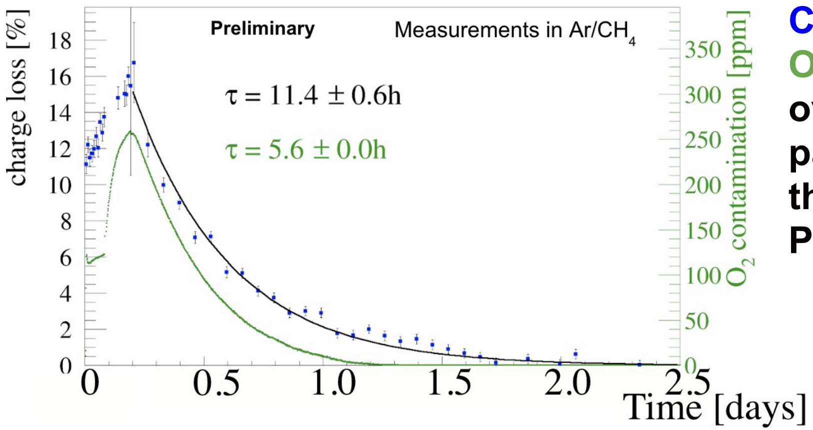
Nuclear recoils homogeneously distributed in the volume



Gas Purification

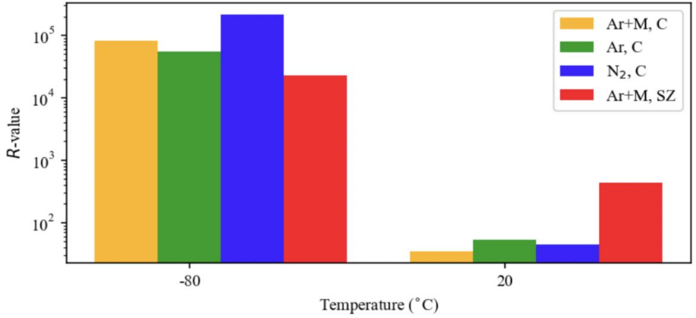
- Contaminants: O_2, H_2O, electronegative gases
- Filtering with: Getter, Oxysorb, Custom filter
- Filtering in a gas recirculation system
  - SAES MicroTorr Purifier (MC700 902-F)
  - Incorporated with Residual Gas Analyser
- Improved filtering efficiency in large sphere





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

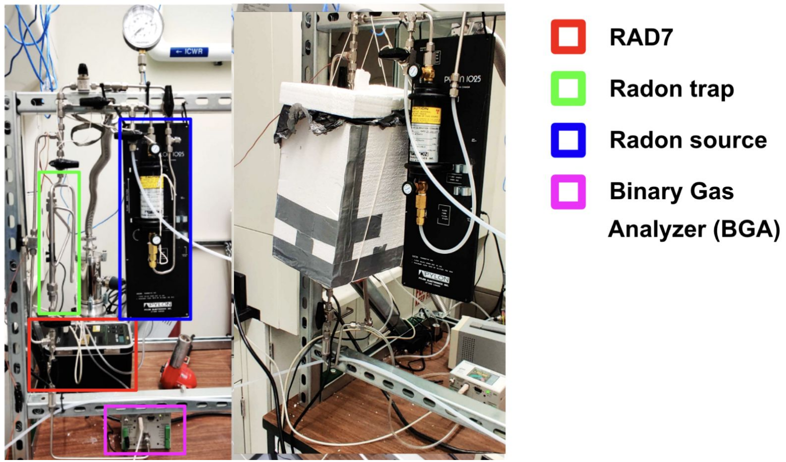
Rn trap development status



- ❑ Much more efficient at low temperature.
- ❑ Silver zeolite can be a good alternative but more measurements are needed.
- ❑ CH4 adsorption still a problem.

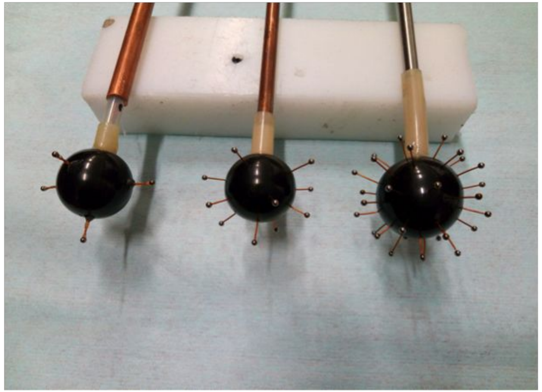
Gas	Temp.	A_0 (Bq)	$A_{f,avg}$ (Bq)	R	f_{Rn} (m^3/min)
N_2	RT	17.12	0.38 ± 0.01	45 ± 1	NA
Ar	RT	38.04	0.72 ± 0.02	53 ± 2	$(1.17 \pm 3.8) \times 10^{-6}$
Ar+M	RT	23.90	0.68 ± 0.02	35 ± 1	$(1.08 \pm 3.8) \times 10^{-6}$
N_2	DI	39.00	$(1.8 \pm 1.2) \times 10^{-4}$	$(2.13 \pm 0.87) \times 10^5$	NA
Ar	DI	20.22	$(3.6 \pm 1.2) \times 10^{-4}$	$(5.55 \pm 4.24) \times 10^4$	NA
Ar+M	DI	31.34	$(3.9 \pm 4.3) \times 10^{-4}$	$(8.14 \pm 4.31) \times 10^4$	NA
Ar+M (SZ)	RT	7.56	$(1.7 \pm 0.4) \times 10^{-2}$	$(4.41 \pm 0.90) \times 10^2$	$(2.85 \pm 0.01) \times 10^{-7}$
Ar+M (SZ)	DI	17.69	$(7.8 \pm 6.3) \times 10^{-4}$	$(2.27 \pm 1.02) \times 10^4$	NA

M.C. Piro (link)



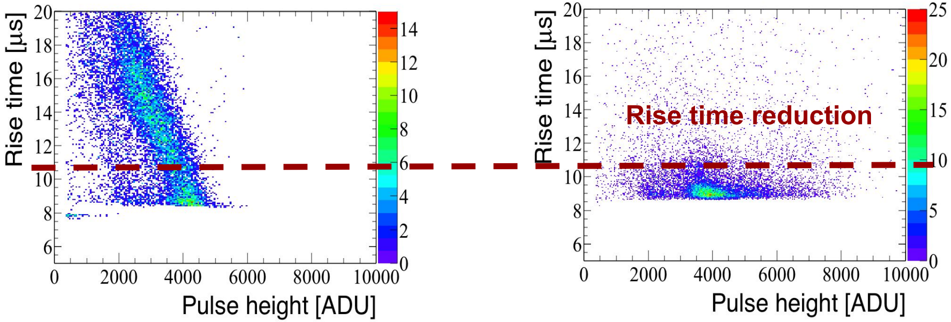
- Compared Carboxen and Silver Zeolite traps in room and dry ice temperature
- Gas tested: Ar, N2, Ar/CH4
- Rn levels can me reduced efficiently especially in dry ice temperature
- Perioding re-emission and trapping of CH4 and Rn observed
- RAD7 to be replaced by the sphere to increase Rn level measurement sensitivity

Results with the first prototypes

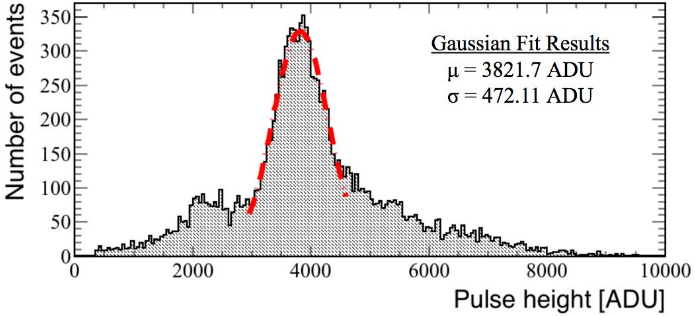


Rise time vs Pulse height
Single ball

Rise time vs Pulse height
11-balls



Measurement of the Fe^{55} 5.9 keV line



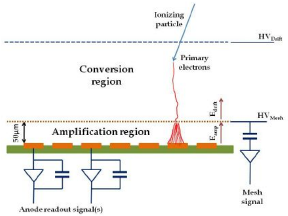
Conditions:

- Gas Mixture: $He:Ar:CH_4$ (80:11:9)
- Pressure: 640 mbar
- HV_1 = 2015 V, HV_2 = -200 V

Advantage of spherical geometry - A

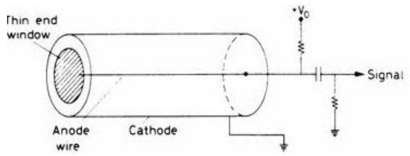
Large volume detector with low threshold

Parallel Plate



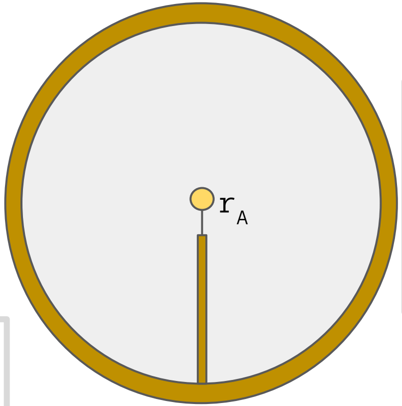
$$C = \varepsilon_0 \frac{S}{d} \approx 3500 \text{ pF}$$

Cylindrical



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

Spherical

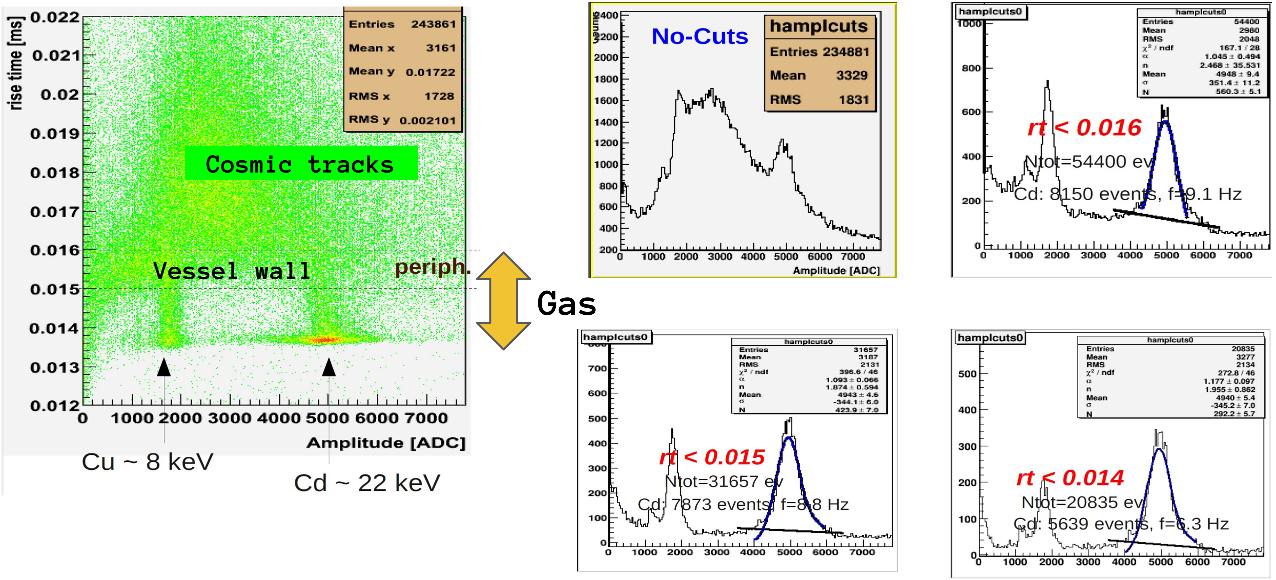


$$C \approx 4\pi\varepsilon r_A \approx 1.5 \text{ pF}$$

Capacitance ~ Electronic noise ~ Threshold

Illustration of particle identification – Background rejection

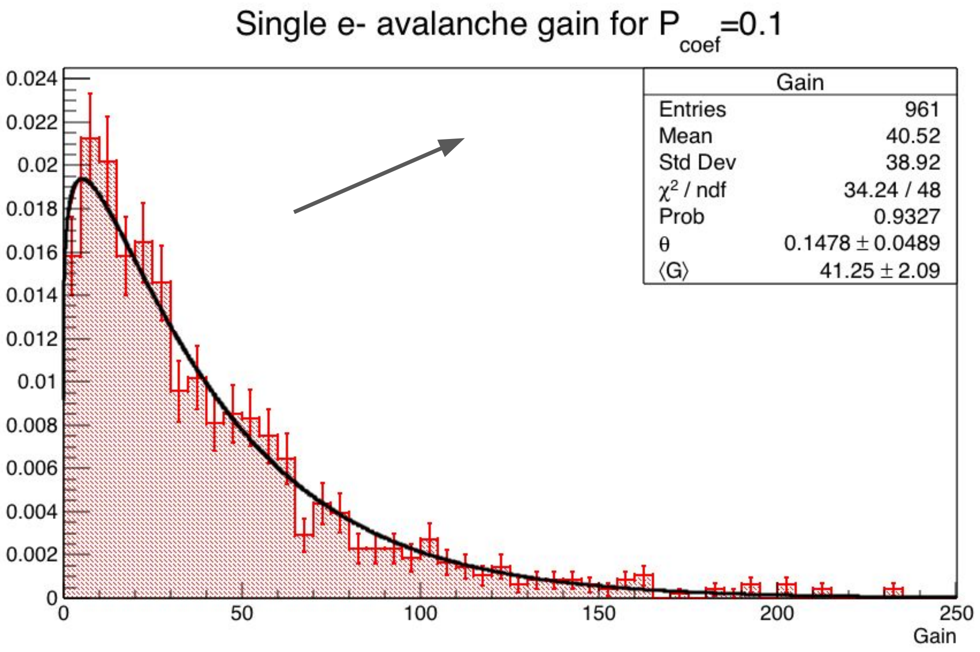
^{109}Cd source
Irradiation through 200µm Al window
P = 100 mb, Ar-CH4 (2%)



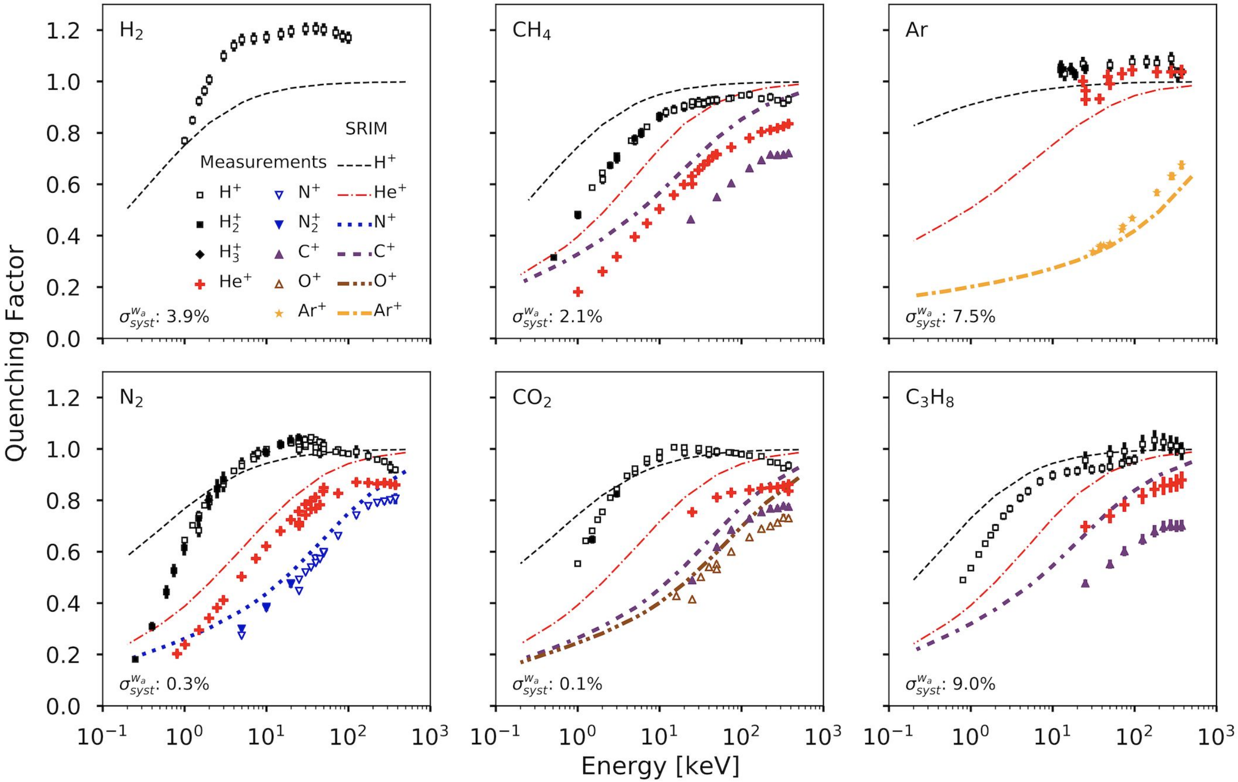
Efficiency of the cut in rt → ~ 70% signal (Cd line)
Significant background reduction

Single e- gain distribution

<u>Conditions:</u>
Ne+0.7% CH_4
3.1 bar
HV=2520 V
Anode Φ 6.3 mm



Ionisation qf vs ion energy vs SRIM



- Agreement with SRIM varies and depends on type, energy range, gas
- Reasonable agreement with N^+ in N_2^+, C^+ and O^+ in CO_2 over 10 keV.
- Comparable to the results for He+ in N_2, CO_2, Ar, and Ar+ in Ar over 10 keV.
- Below 10 keV SRIM predictions are higher than estimations

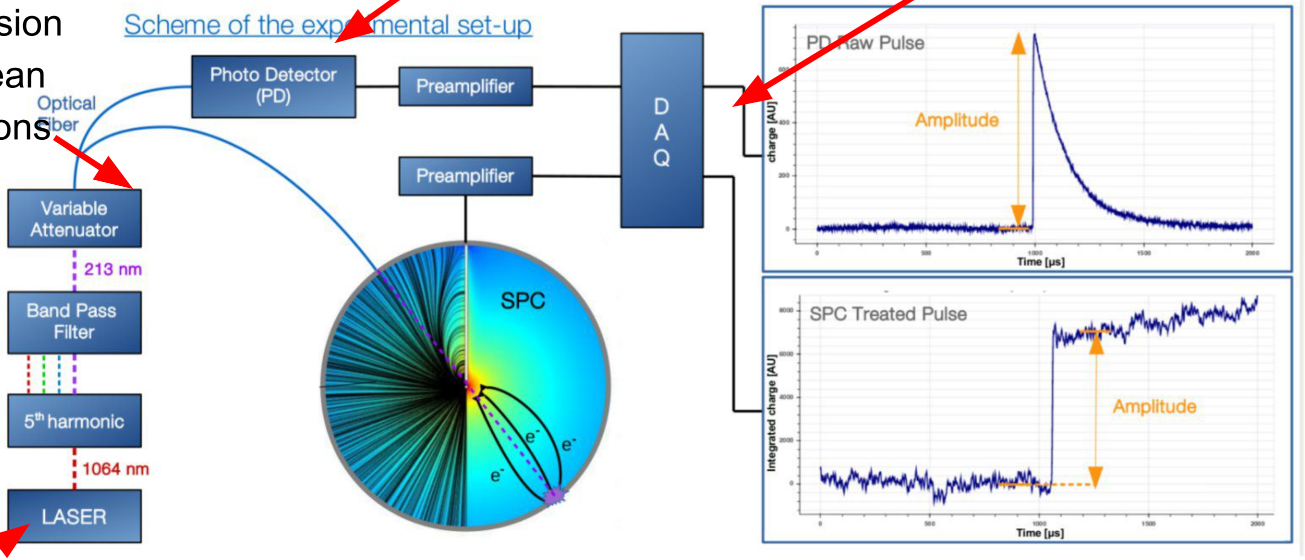
Q. Arnaud et al. (NEWS-G Collaboration), Phys. Rev. D 99, 102003 (2019)

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

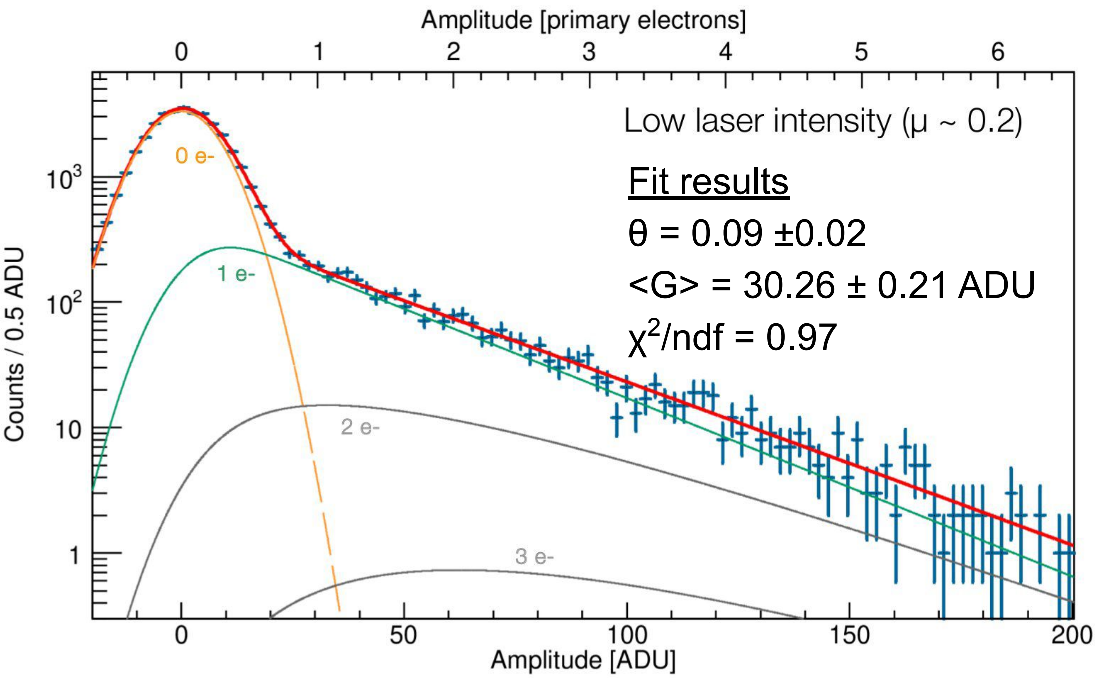


A powerful UV laser capable of extracting 100s of electrons

- **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

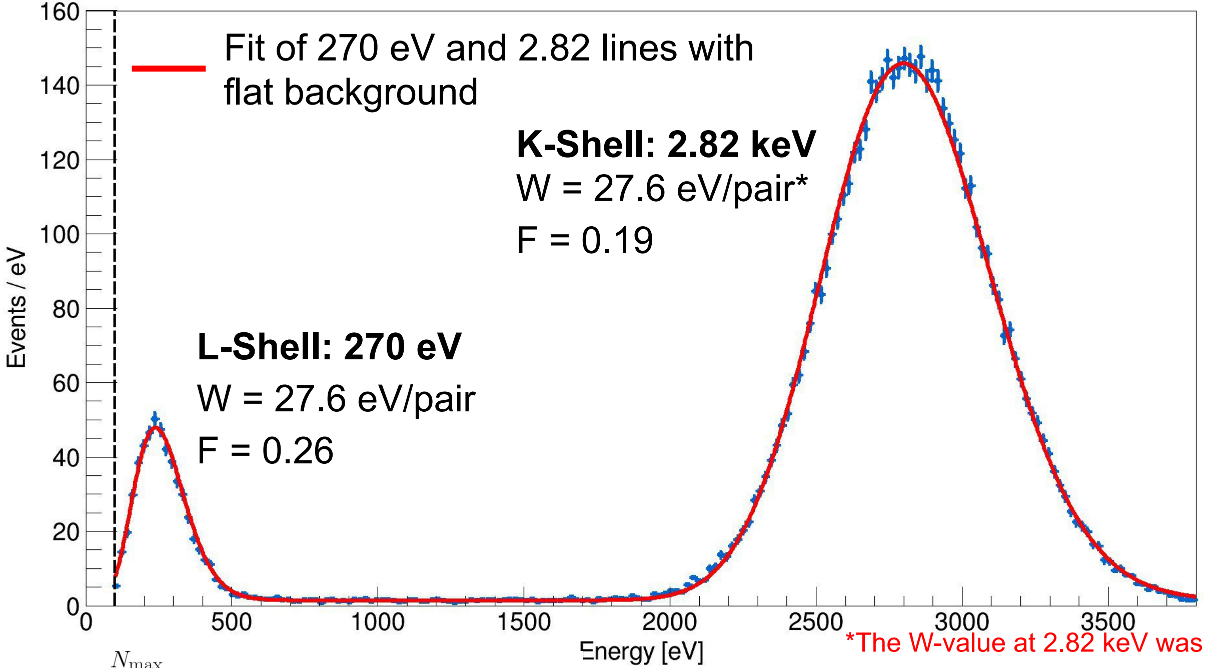
Q. Arnaud et al. (NEWS-G Collaboration), Phys. Rev. D 99, 102003 (2019)



- **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



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

*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)

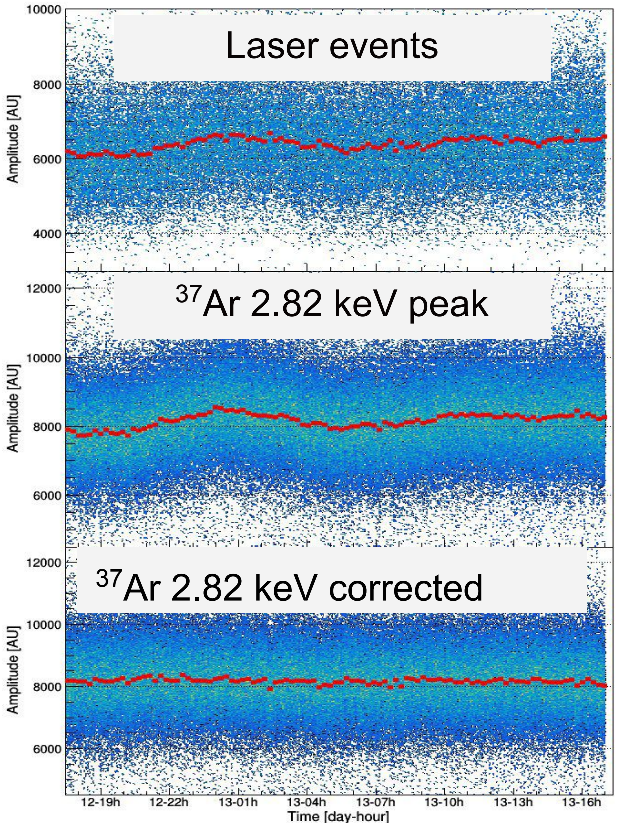
Detector response modeled:

- Primary ionisation (COM-Poisson)

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

- Avalanche (Polya)

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)*