Search for Low-Mass Dark Matter with NEWS-G

University of Birmingham, Particle Physics Seminar, 6th November 2019

P. Knights

University of Birmingham, UK and IRFU, CEA Saclay, France

news-g.org

Dark Matter

- Evidence from gravitational observations
  - Rotational velocities
  - Galactic collision
  - Gravitational lensing
- Approximately 85% of mass

480 RUBIN, FORD, AND THONNARD Vol. 238

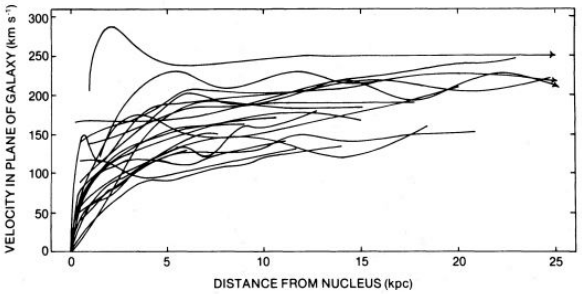
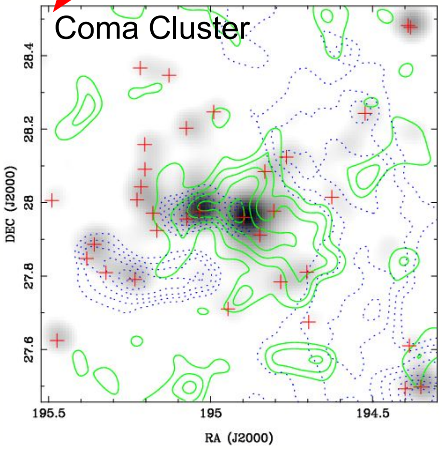
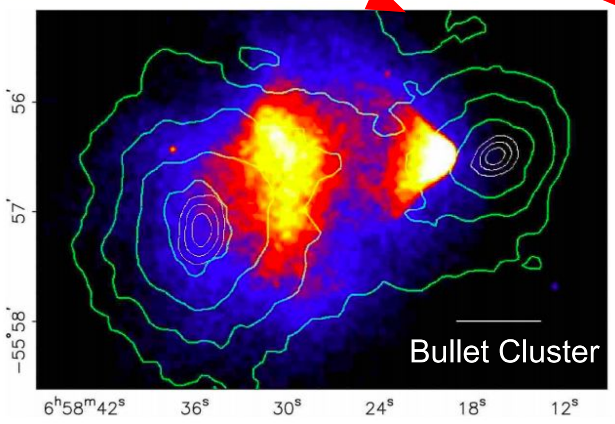
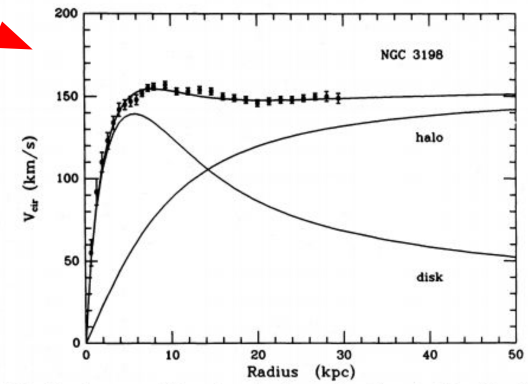


FIG. 6.—Superposition of all 21 Sc rotation curves. General form of rotation curves for small galaxies is similar to initial part of rotation curve for large galaxies, except that small galaxies often have shallower nuclear velocity gradient and tend to cover the low velocity range within the scatter at any R.

Astrophys.J. 238 (1980) 471







—Fit of exponential disk with maximum mass and halo to observed rotation curve (*dots with error bars*). The scale length of the disk has been taken equal the light distribution (60″, corresponding to 2.68 kpc). The halo curve is based on eq. (1), $a = 8.5$ kpc, $\gamma = 2.1$, $\rho(R_0) = 0.0040\ M_\odot\ pc^{-3}$.

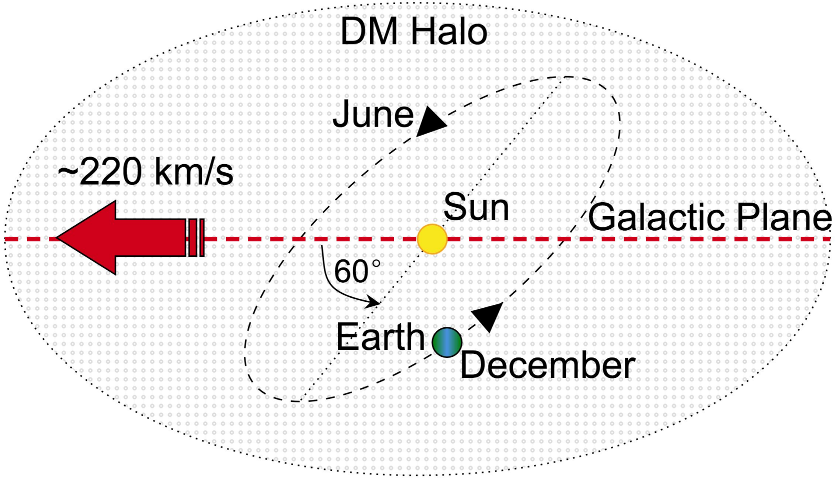
Astron.Astrophys. 498 (2009) L33

Astrophys.J. 648 (2006) L109-L113

Astrophys.J. 295 (1985) 305-313

Local DM Halo

- Local DM density is ρ~0.3-0.4 GeV cm^{-3}
  - Solar system travelling through this
  - 'DM Wind'
- DM modeled as collisionless gas
  - Maxwell-Boltzmann velocity distribution
  - Local flux: $(10^7/m_\chi)$ GeV cm^{-2} s^{-2}
- Motion of Earth → velocity time dependent
  - Expect annual modulations to DM flux
- Directionality

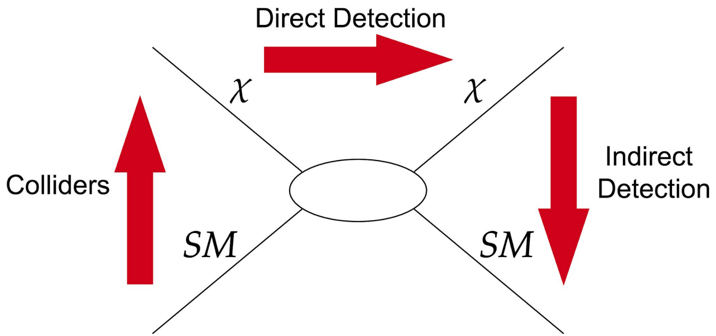


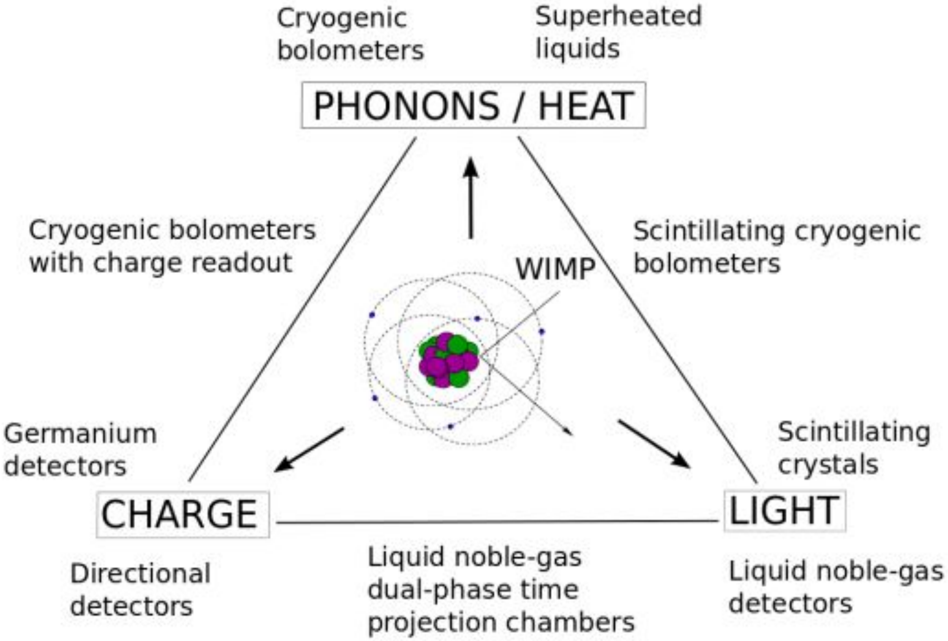
J.Phys. G41 (2014) 063101

JCAP 1008 (2010) 004

Direct Detection

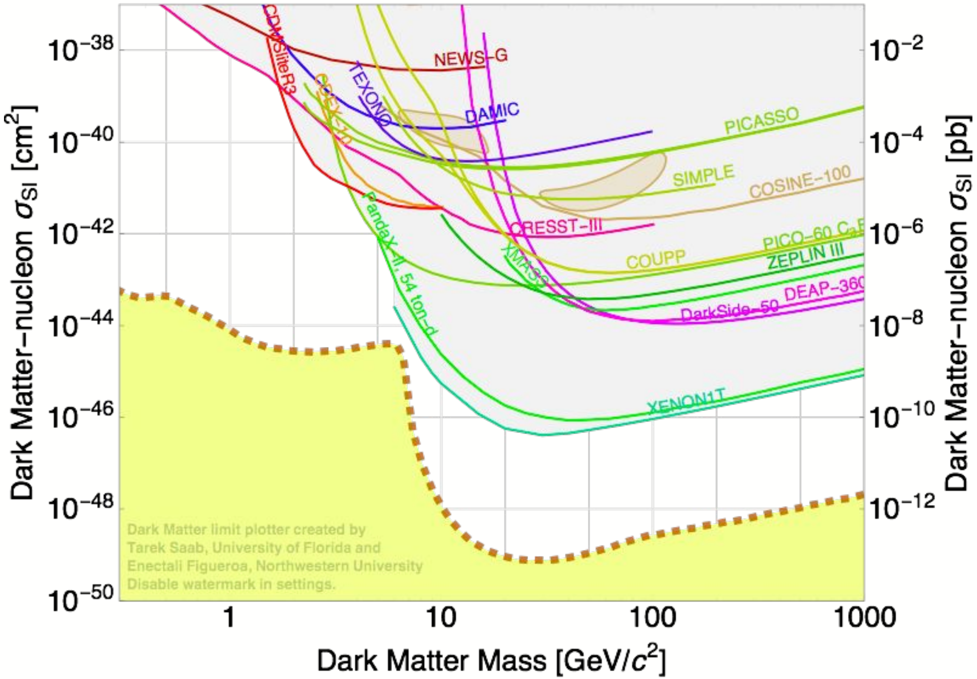
- DM interaction with nucleus
  - Recoiling nucleus deposits energy





J.Phys. G43 (2016) no.1, 013001

Landscape

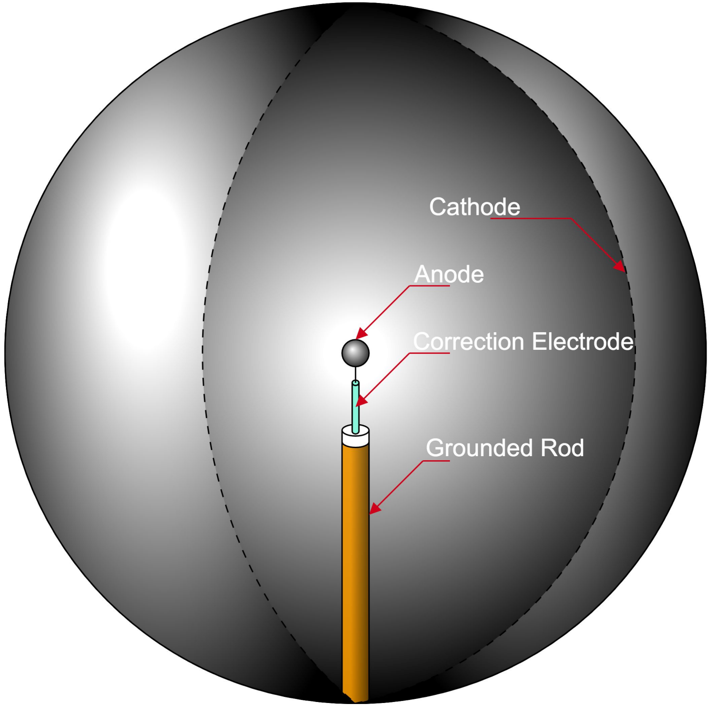


- World-leading sensitivity above ~10 GeV/c^2 for liquid xenon experiments
  - Multi-tonne experiments
- Increasing interest unexplored lower masses

NEWS-G Collaboration

Spherical Proportional Counter

- ~1 mm ball in ~0.1-1 m radius spherical shell
- Ideal electric field varies as $1/r^2$
- Primary electrons produced by ionisation in gas
- Drift under E-field towards anode
- Avalanche within ~1 mm of the anode



Advantages:

- **Low capacitance**, independent of detector size
- Lowest **surface area to volume ratio**
- **Fiducialisation** and **PID**
- **Flexible** choice of **gas targets**
- Simple read-out

$$\vec{E} = \frac{V_1}{r^2}\frac{r_c r_a}{r_c - r_a}\hat{r} \quad C \approx 4\pi\varepsilon_0 r_a$$

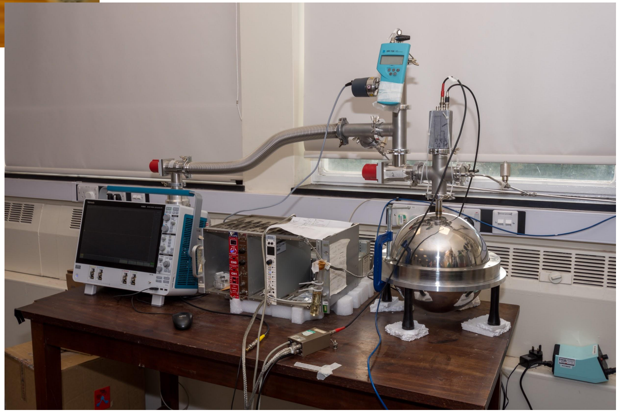
I.Giomataris et al, JINST, 2008, P09007

Spherical Proportional Counter

I. Giomataris and G. Charpak with a spherical proportional counter in CEA Saclay (sphere was previously a LEP RF cavity)

CEA Saclay

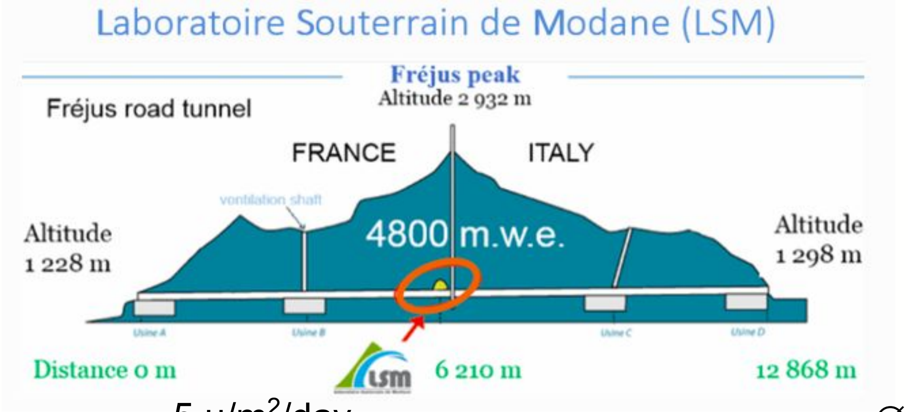
Birmingham



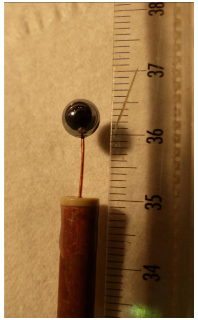
SEDINE, LSM France

SEDINE - First NEWS-G DM Detector

- ∅60 cm spherical proportional counter
- Using Aurubis NOSV Copper
- Several stages of chemical cleaning
- ∅6.3 mm anode
- Located in Modane Underground Lab., France



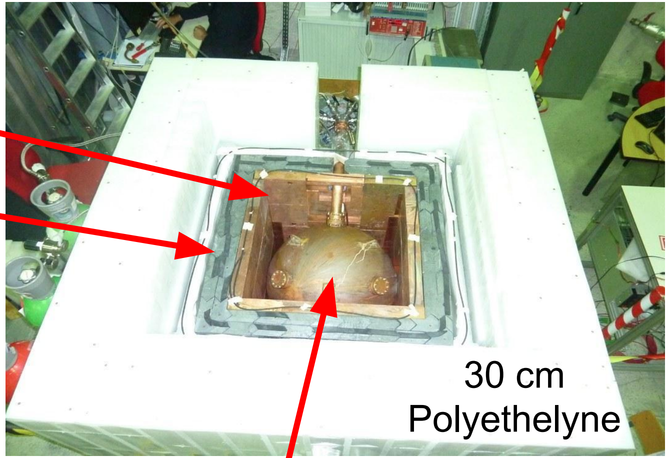
5 μ/m^2/day
(Surface: ~14x10^6 μ/m^2/day)



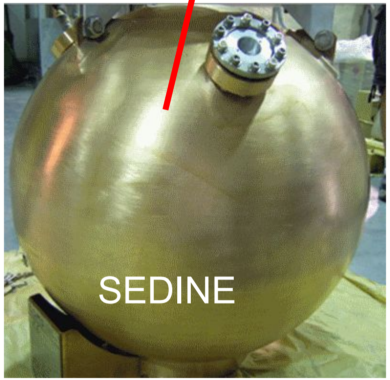
∅6.3 mm Anode

8 cm Cu

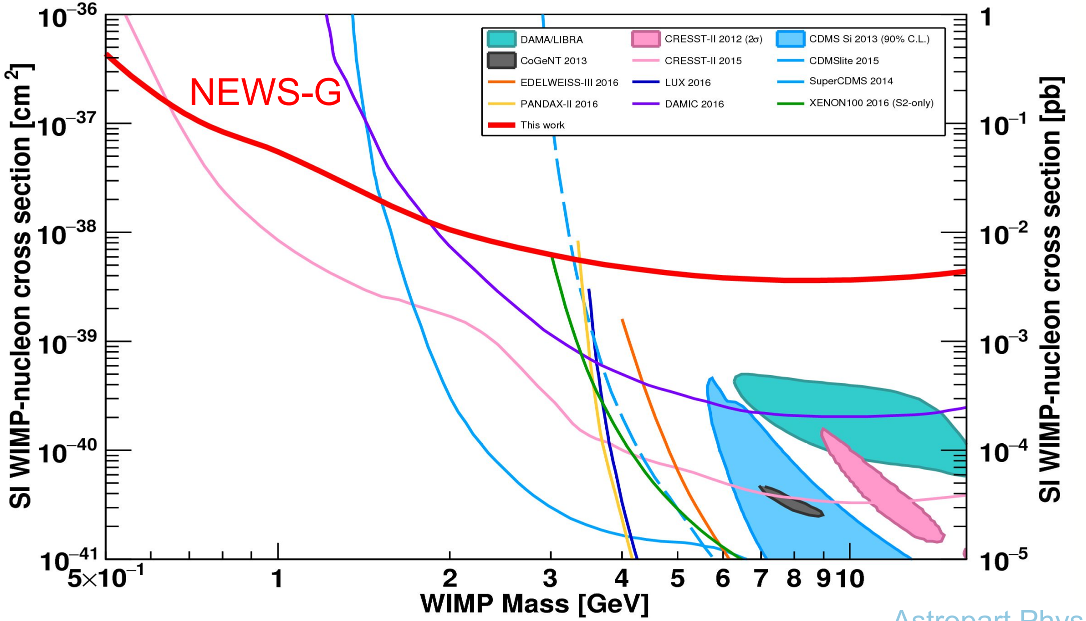
15 cm Lead



30 cm Polyethelyne



First results



Astropart.Phys. 97 (2018) 54-62

- Ne:CH4 (99.3%:0.7%) at 3.1 bar (280 g)
- 9.6 kg*days exposure (34.1 days)
- Cross-sections above 4.4×10^{-37} cm^2 at 90 % confidence level for 0.5 GeV/c^2

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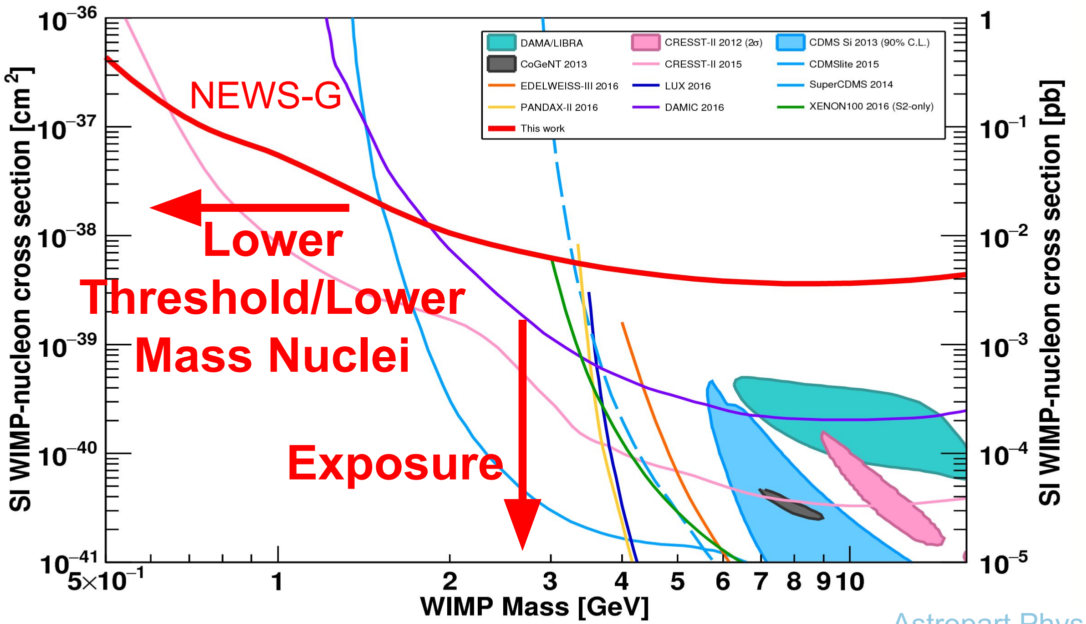

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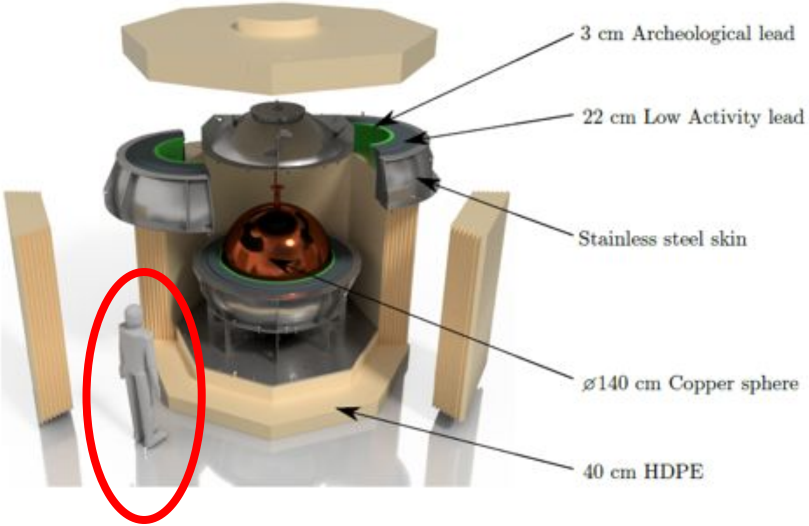
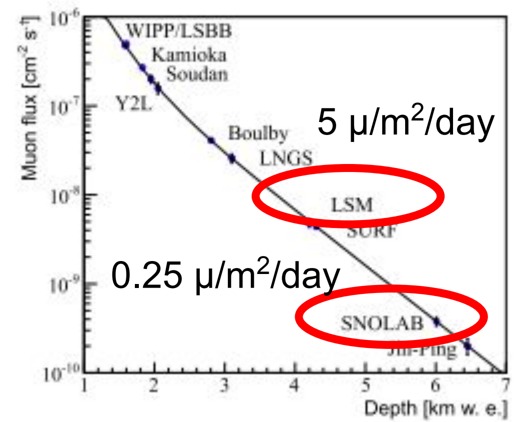
SNOGLOBE

- ∅130 cm detector
- 4N (99.99% pure) Aurubis copper
- Completed first operation in LSM
- Being shipped to SNOLAB, Canada

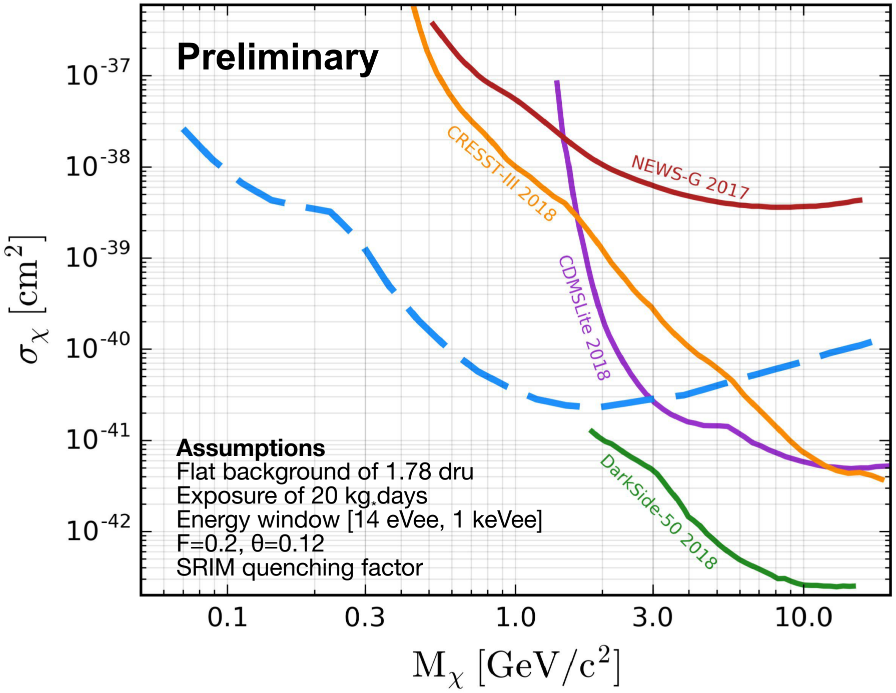


J.Phys. G43 (2016) no.1, 013001



Pushing the Boundaries

- To increase low-mass sensitivity:
  - Target mass
    - Larger detector
    - Higher Pressure
  - Background suppression
    - PID and Fiducialisation
    - Purity of Materials
  - Low mass target nuclei
    - e.g. H from CH_4



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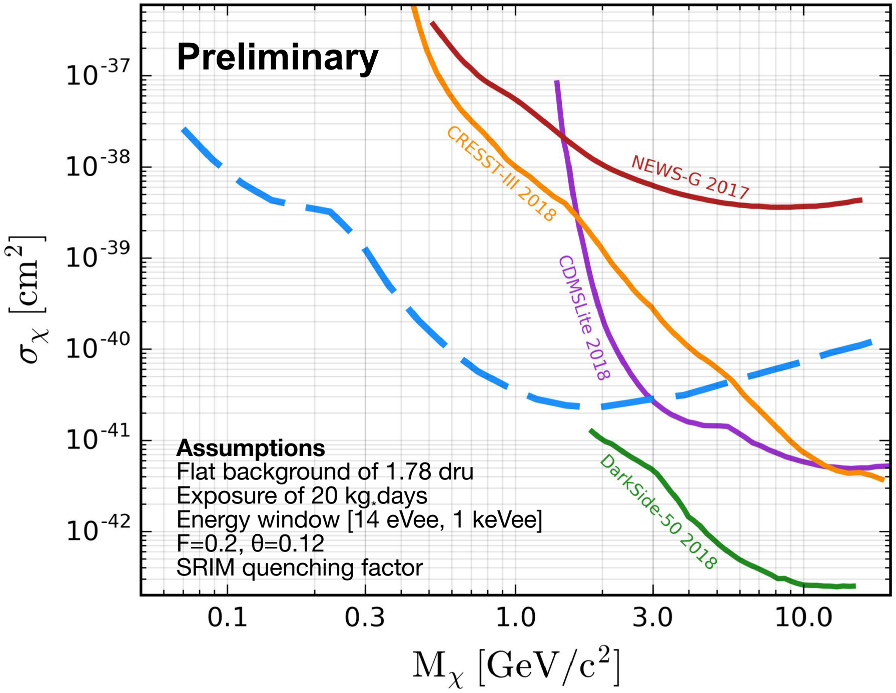
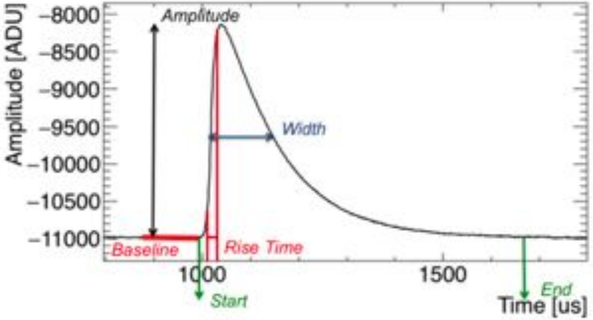
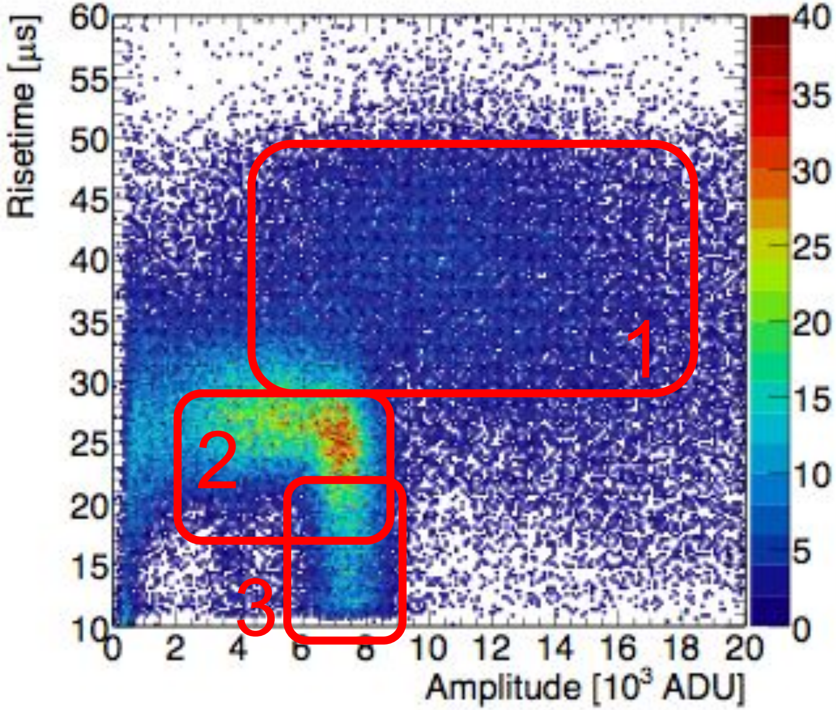


Instrumentation Development

Fiducialisation and Particle Identification

- **Ideal case:** $1/r^2$ electric field in detector
  - Electrons from larger radii diffuse more
  - **Larger spread in electron arrival** at the anode → Larger **pulse rise time**/width
  - Spatially **extended primary ionisation** results in higher pulse rise times/widths
- **Particle ID** by pulse-shape analysis
  - e.g. cosmic muons and X-rays





(1) Cosmic Muons, (2) X-rays near shell, (3) X-rays in volume

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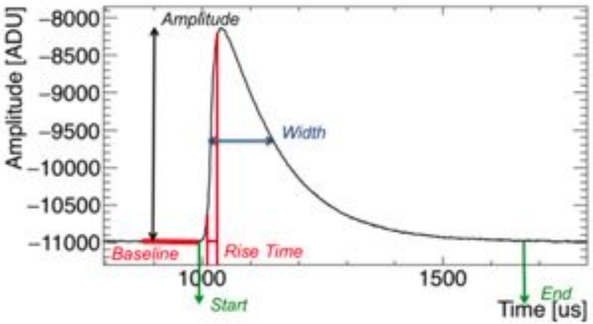

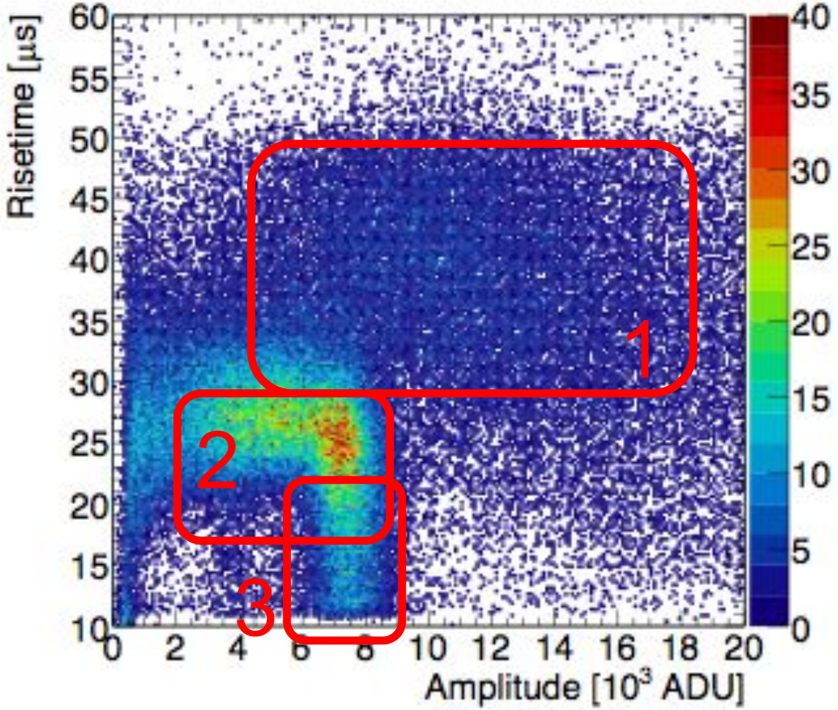

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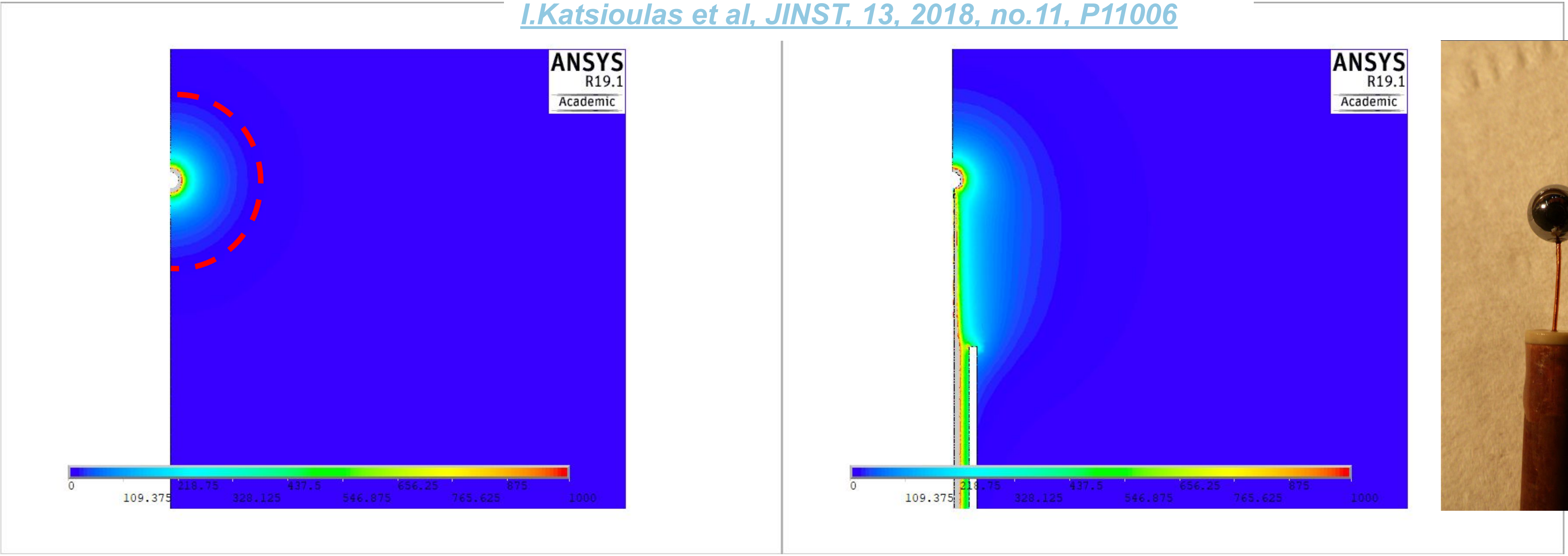
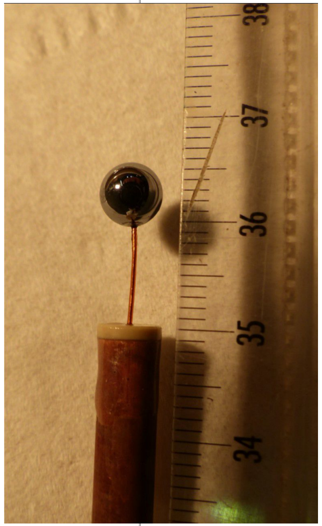
Distortion of Electric Field

[I.Katsioulas et al, JINST, 13, 2018, no.11, P11006](https://doi.org/)

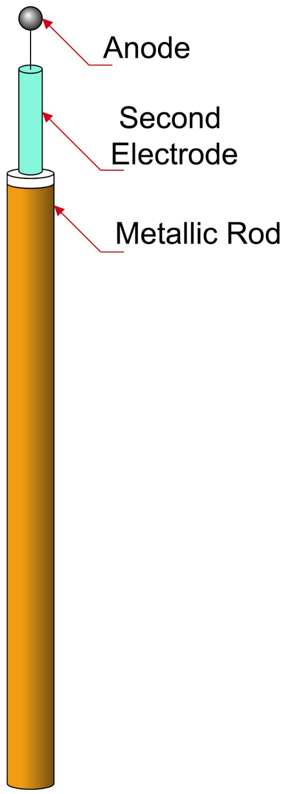




- Support rod and wire to anode distort the electric field
- Deteriorated energy resolution and particle discrimination capability
- Reduced fiducial volume of the detector

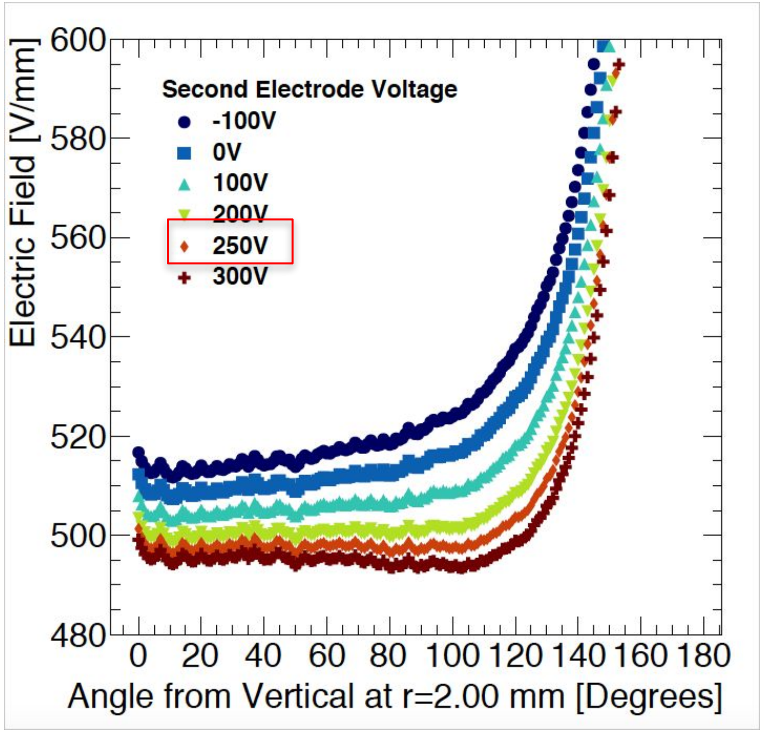
Correction Electrode

- Idea: incorporate correction electrode at top of support rod
- Voltage on correction electrode used to adjust electric field around the anode to improve uniformity
- Geometry and voltages for second electrode studied using ANSYS Finite Element Method (FEM) software



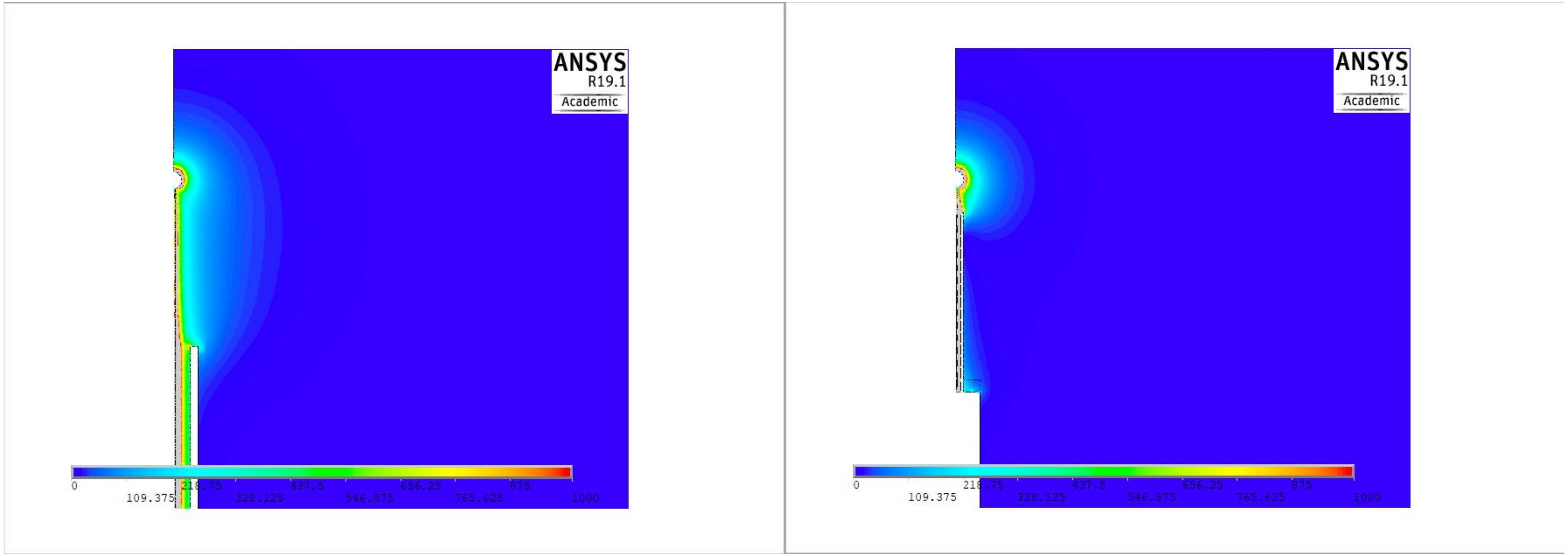
Study of Correction Electrode Design

- Several parameters were explored:
  - Anode size
  - Anode-correction electrode distance
  - Correction electrode length
  - Correction electrode voltage
- Figure of merit: electric field homogeneity near the anode



For r_c =15 cm, r_a = 1 mm, d = 3 mm, l = 20 mm, V_1 = 2000 V

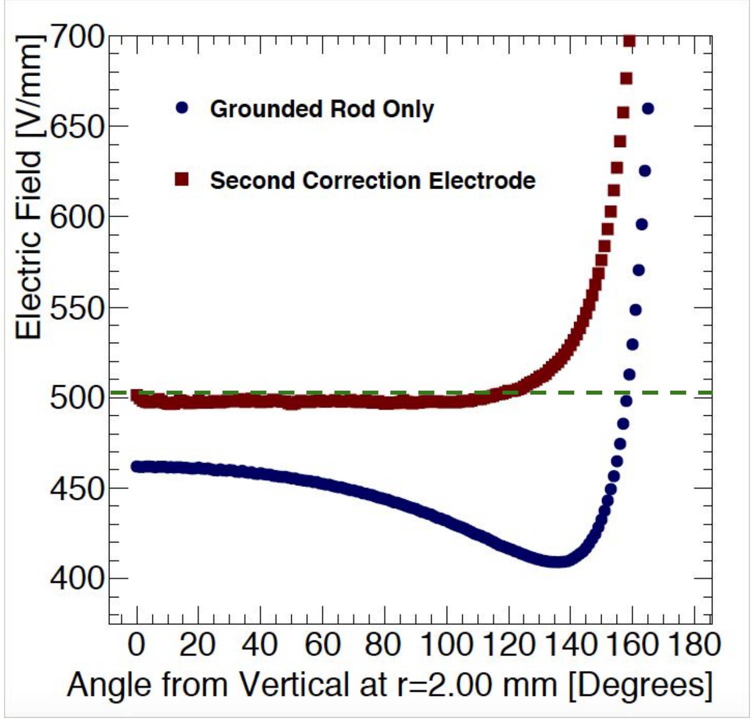
Comparison to Rod-Only Design



- Distortion to electric field near the anode greatly reduced

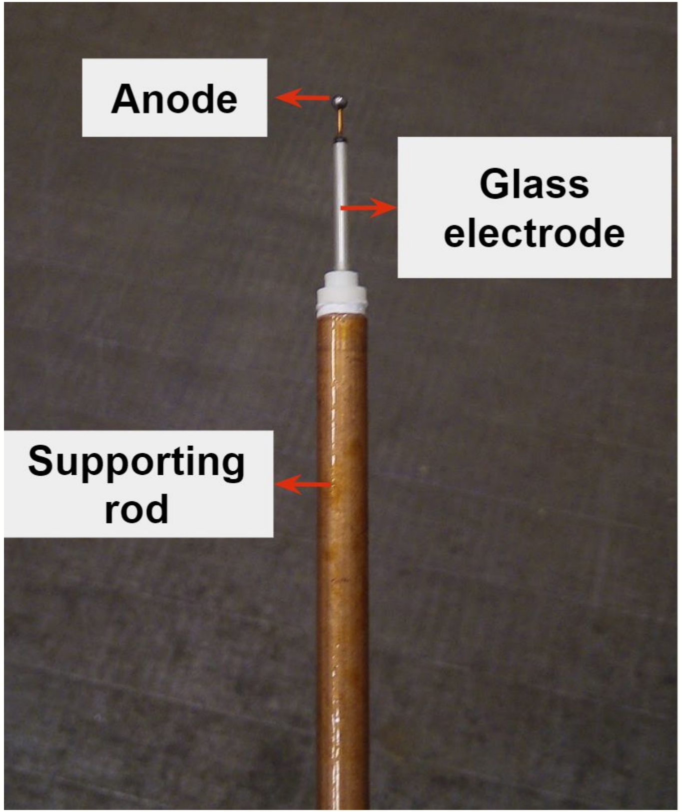
Comparison to Rod-Only Design

- Electric field magnitude near anode
- Correction electrode increases field magnitude and homogeneity
  - Note: In ideal case, E = 503 V/mm



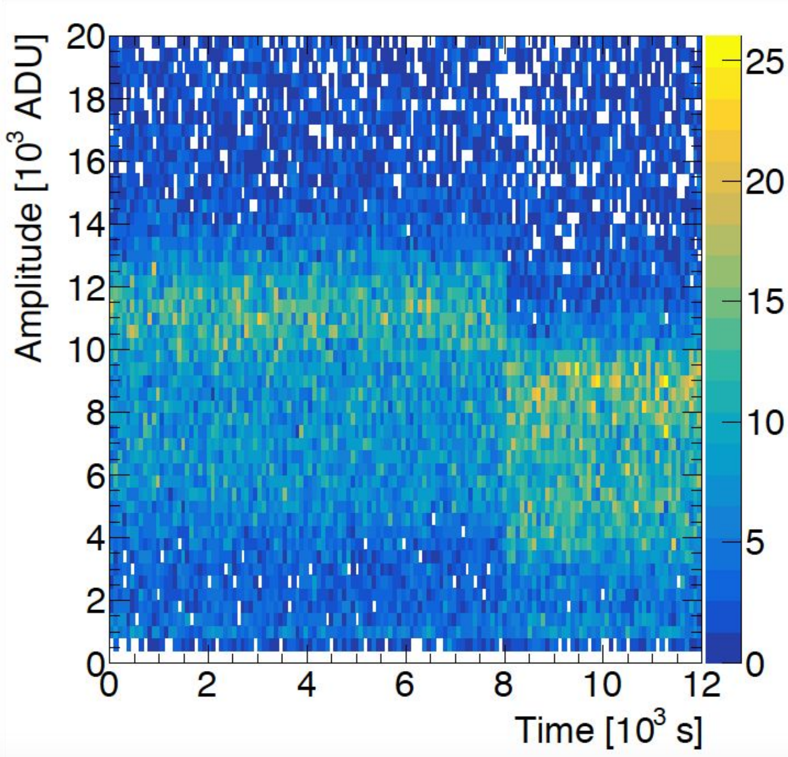
Resistive Material and Implementation

- In practice, correction electrode material must be chosen to reduce spark probability and increase detector stability
  - Can't use metal → Sparking
  - Materials with resistivities of O(10^{10} Ω□cm)
    - e.g: Soda-lime glass
- Prototypes tested in detector in CEA Saclay



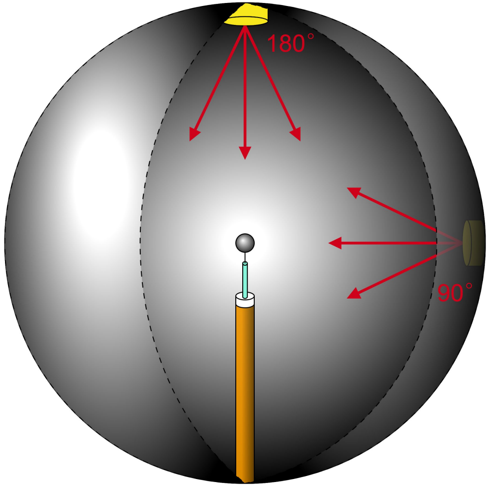
Response of Correction Electrode

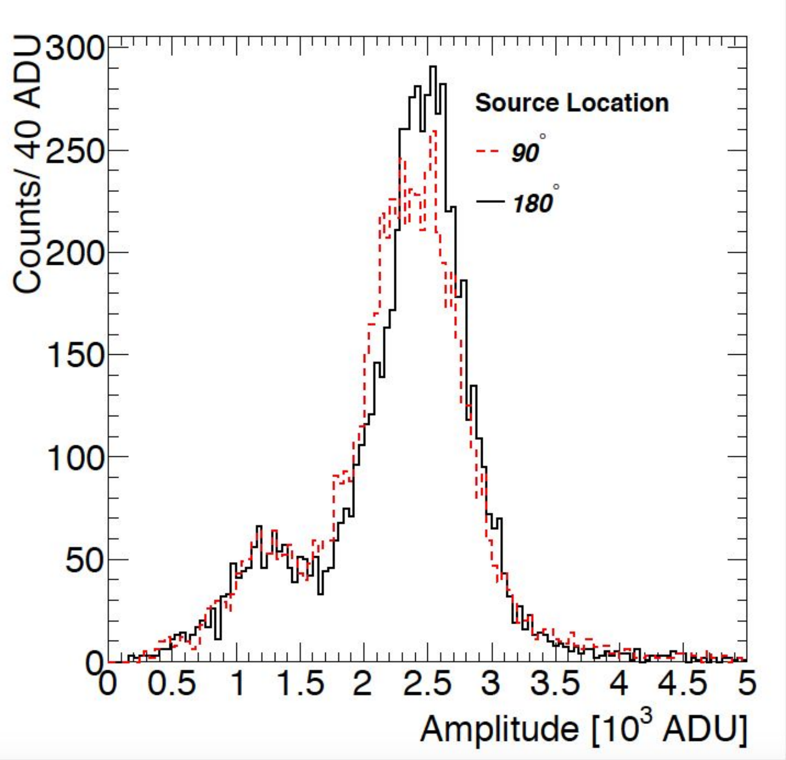
- ^{55}Fe source placed inside detector
  - Mainly 5.9 keV X-rays
- Detector filled with 1 bar of He:Ar:CH4 (87%:10%:3%)
- Amplitude stable
  - At 8000 s, correction electrode voltage changed: 100 V to 200 V
  - See response in amplitude



Homogeneity of Response

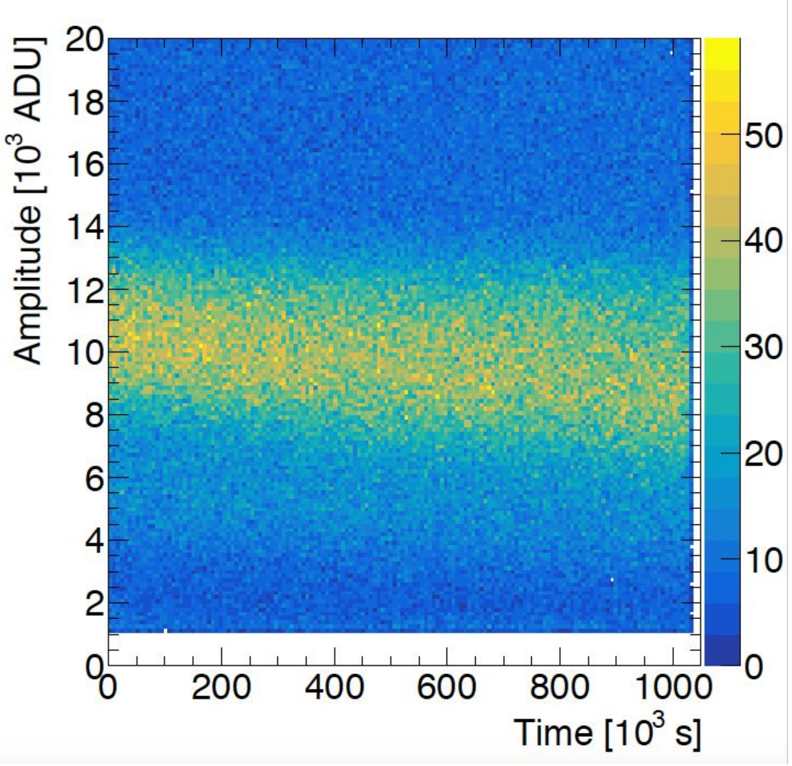
- Detector filled with 1 bar of He:Ar:CH_4 (92%:5%:3%)
- ^{55}Fe Source placed in two locations
- Similar response → High uniformity





Detector Stability

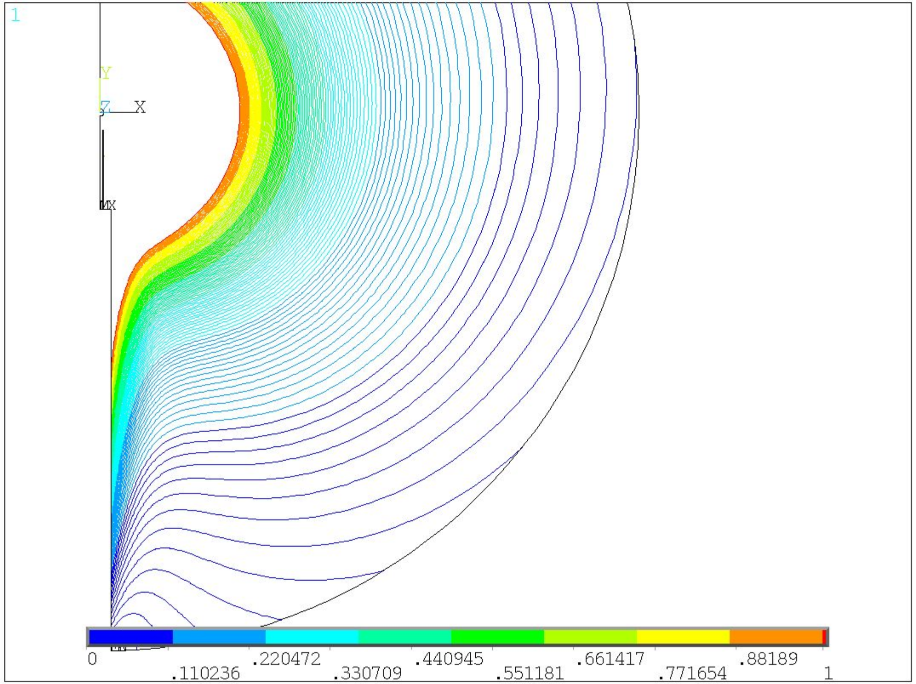
- Detector filled with 2 bar of $He:Ar:CH_4$ (87%:10%:3%)
- Over ~12 days, gain stable, no sparks
  - Small decrease in gain over time due to contaminant gases (e.g. O_2) leaking into the detector



Electric Field at Large Radii

- Correction electrode ensures uniform gain
- At large radii, electric field distorted by the grounded rod

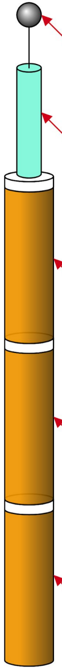
Electric Field Contour Map [V/mm]



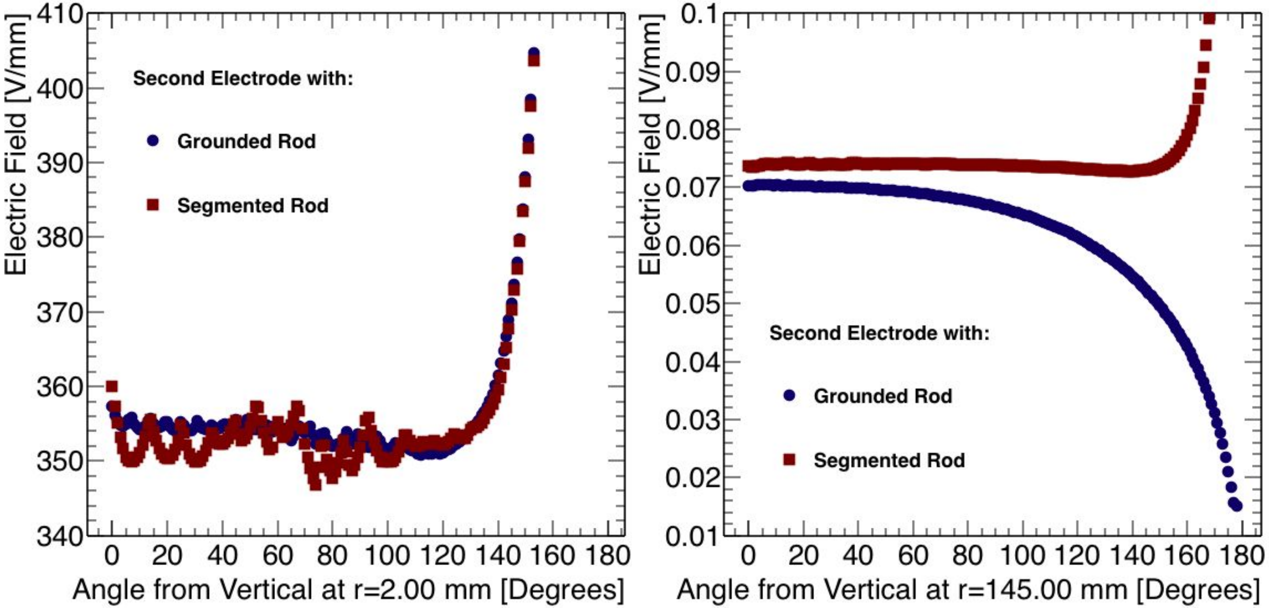
Voltage Degrader with Segmented Rod

- Voltage gradient along rod, as in ideal geometry, would restore ideal solution
- Approximation: segmented rod; voltage at each compartment corresponding to ideal case
- First implementation: Three segments
- Segment lengths/voltages studied using ANSYS

$$V_i = V_0 \frac{r_i - r_a}{r_c - r_a} \frac{r_c}{r_i}$$



Comparison to Grounded Rod Case

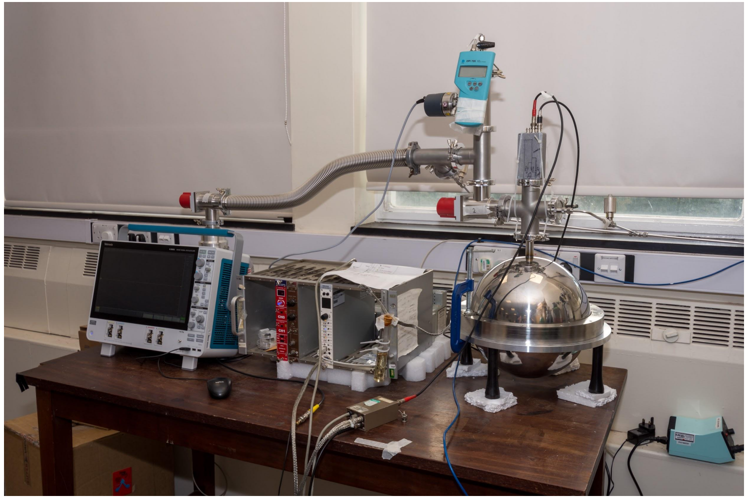


Correction Electrode: 106.2 V
Top segment: 30 mm at 27.7 V
Middle segment: 90 mm at 6.2 V
Bottom segment: grounded

- Electric field near anode remains unaffected
  - Defined by correction electrode
- Improvement in electric field magnitude at larger radii

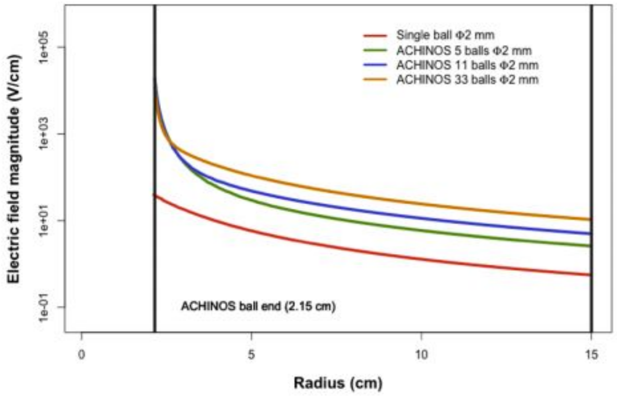
Prototype of Voltage Degrader

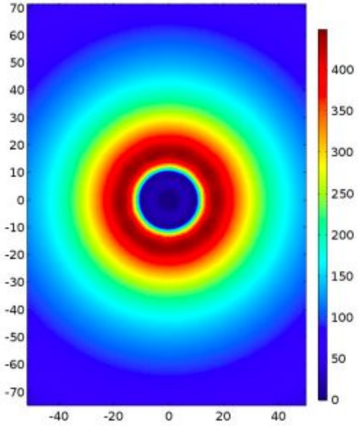
- Electric field studies using ANSYS and simulation of the detector response using Geant4 and Garfield++ ongoing
- Prototype under test here in Birmingham

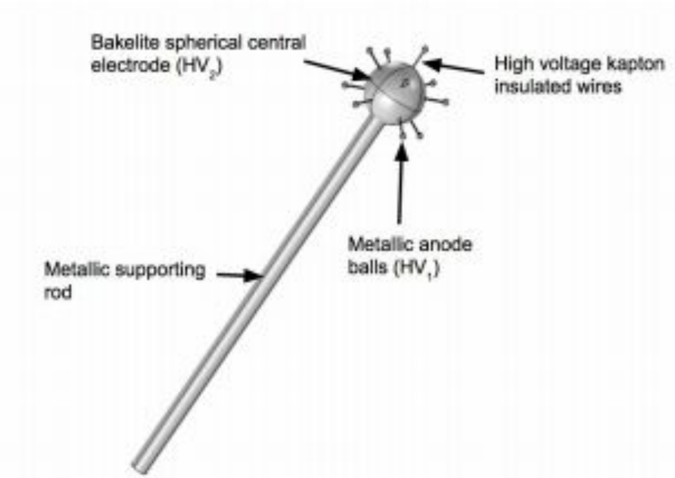


Multi-Anode Structure: ACHINOS

- Multiple anodes, placed at equal distances
  - Gain defined by individual anode sizes
  - Electric field at large radii determined by collective field of all anodes
- Drift and gain are decoupled
  - Allows high pressure operation and/or larger volume detectors



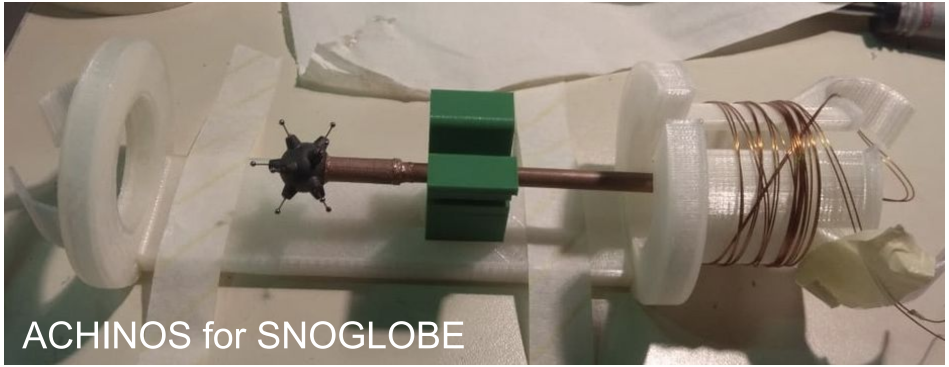




A. Giganon *et al* 2017 *JINST* 12 P12031

Multi-Anode Structure: ACHINOS

- Produced using 3D printed materials
  - Coated with high-resistivity layer
    - Cu-Epoxy Mixtures
    - Diamond-Like Carbon
- Potential for individual anode read-out
  - Possibility of knowing interaction θ and ϕ



ACHINOS for SNOGLOBE

Pushing the Boundaries

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    - Higher Pressure
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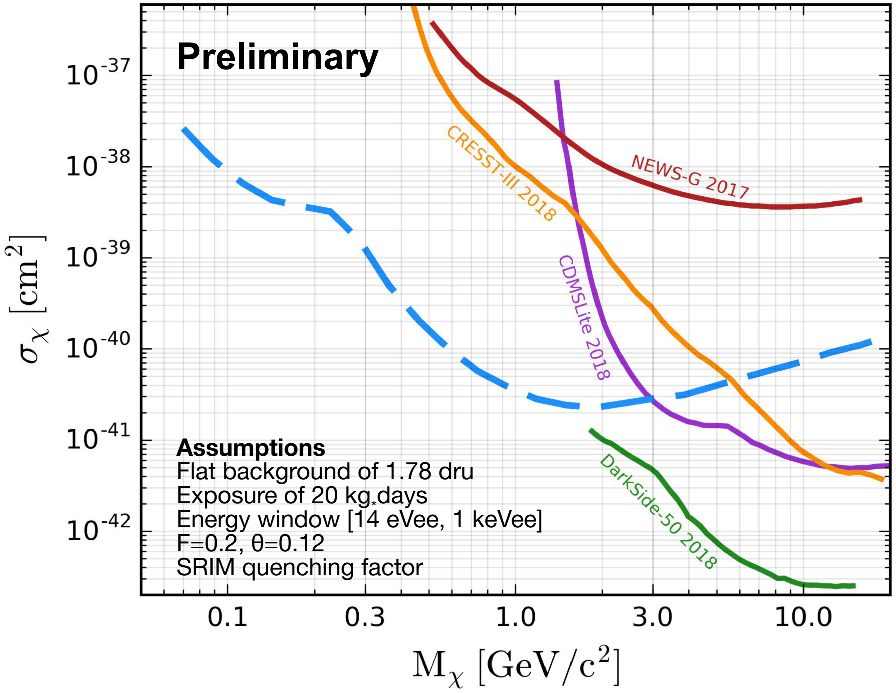
    - PID and Fiducialisation
    - **Purity of Materials**
  - Low mass target nuclei
    - e.g. H from CH_4



Copper Purity

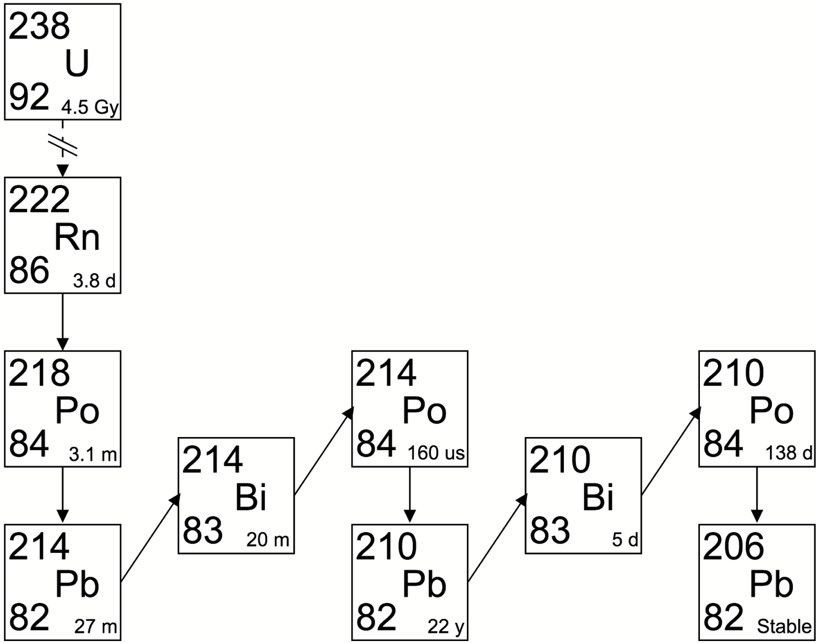
Copper as a Construction Material

Copper is a common construction material for rare event experiments:

- Strong enough to build gas vessels
- Commercially available at high purity
- Low cost
- No long-lived radio-isotopes
  - Longest ^{67}Cu $t_{1/2}$ = 62 hours
- Possibility to electrochemically purify
  - **‘electrowinning’**

Background Contributions in Copper

- $^{63}Cu(n,\alpha)^{60}Co$ by fast neutrons from cosmic muon spallation
- ^{238}U and ^{232}Th decay chain – naturally found and **deposited by ^{222}Rn**
- ^{238}U and ^{232}Th measured directly by mass spectroscopy
  - Infer daughter quantities



*Pacific Northwest National Laboratory, USA

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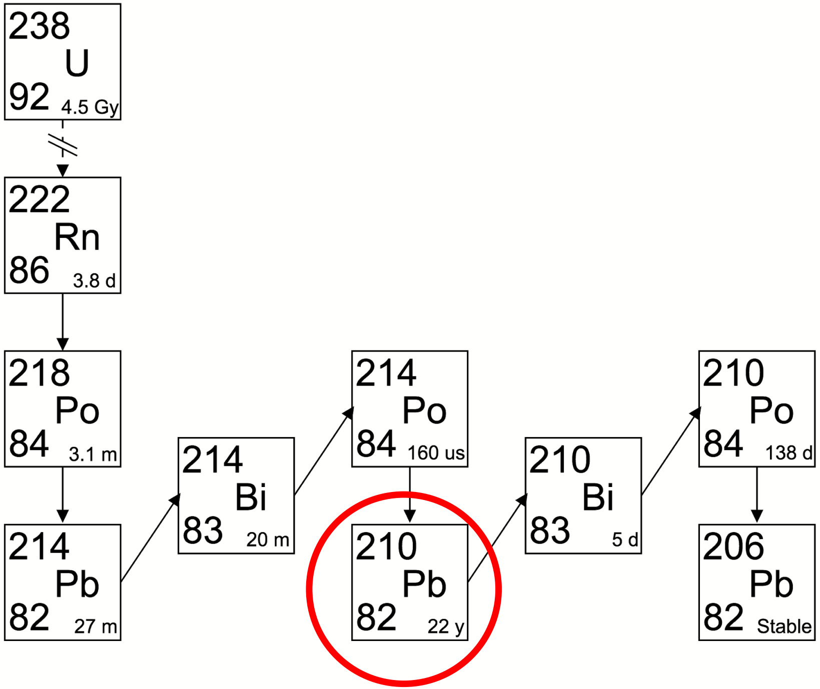


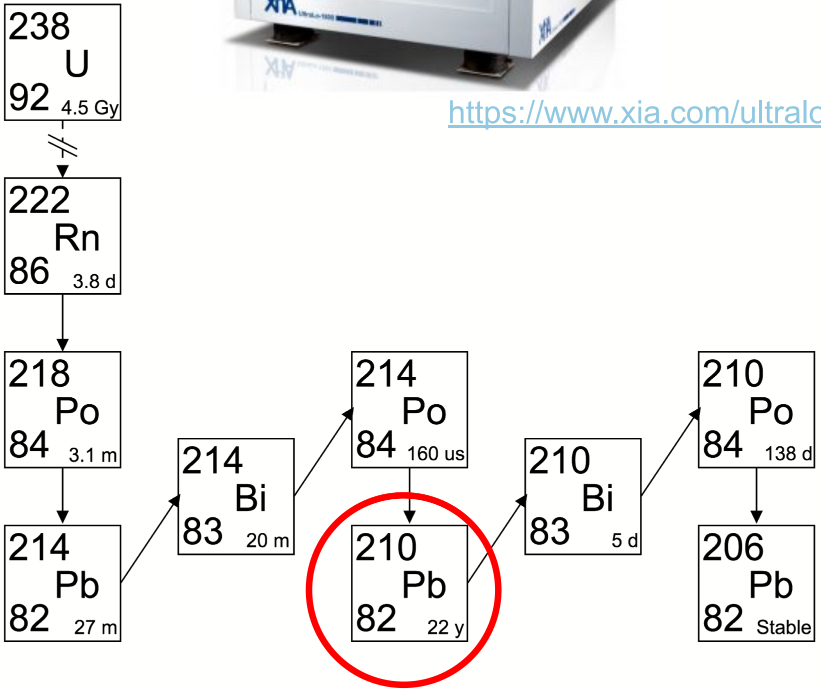
*Pacific Northwest National Laboratory, USA

^{210}Pb in Copper

XIA UltraLo-1800

https://www.xia.com/ultralo-theory.html

- Recent development: **measure α-particle from ^{210}Po decay**
  - ^{210}Pb activity inferred from ^{210}Po
- Confirmed ^{210}Pb contamination by ^{222}Rn during production



Nucl.Instrum.Meth. A884 (2018) 157-161

^{210}Pb in our 4N copper: 28.5±8 mBq/kg

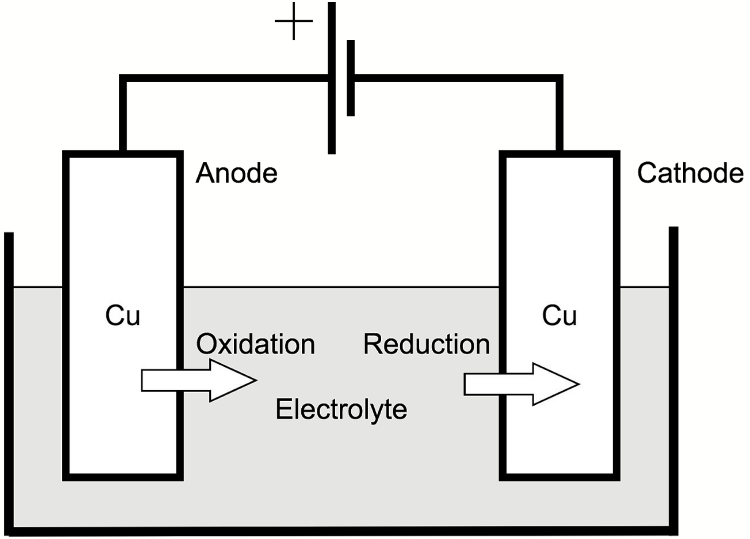
Ultra-Pure Copper Electroplating

- Electrolysis: **oxidation** and **reduction** reactions
- **Ions reduced at cathode** building up material
  - **Current** supplied to drive reactions
  - **Mass deposited** proportional to current supplied:

$$M(t) = \frac{m_r \int I(t)dt}{zF}$$

- Copper benefits from **'electrowinning'** - higher reduction potential than Uranium, Thorium, Lead...
- **Copper refined during electroplating**

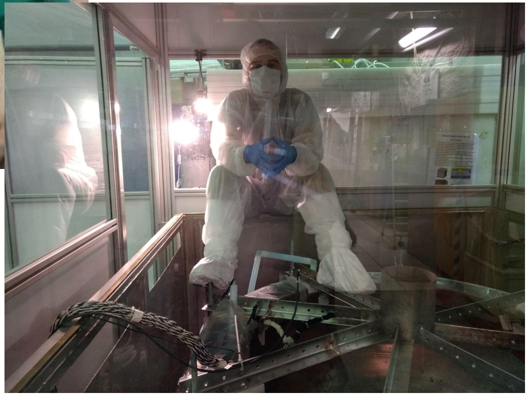
$\boldsymbol{M}$ – mass
$\boldsymbol{m_r}$– molar mass
$\boldsymbol{I(t)}$– current as function of time
$\boldsymbol{z}$– number of electrons transferred in reduction reaction
$\boldsymbol{F}$ – Faraday Constant ($= e\ N_A$)



Adv.High Energy Phys. 2014 (2014) 365432

Preparation of Surface

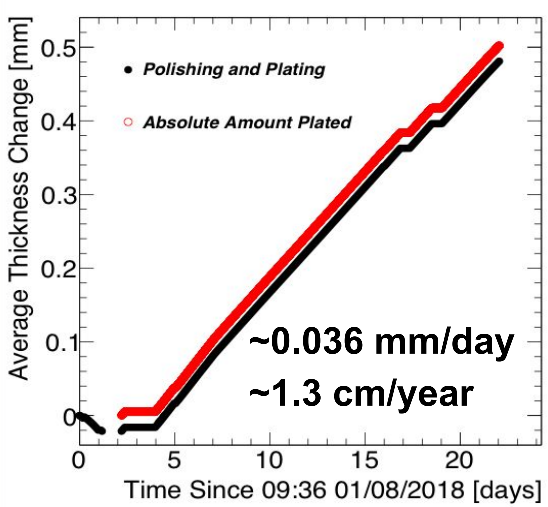
- Operation performed in **LSM**
- Surface sanded and cleaned
- **Chemically etched** using 3% H_2O_2, 2% H_2SO_4 in deionised water
  - Same treatments for **copper anode**
- Installed in clean area
- Electrolyte of H_2SO_4, H_2O and $CuSO_4$

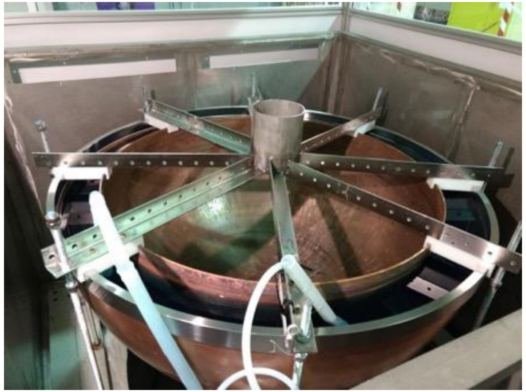


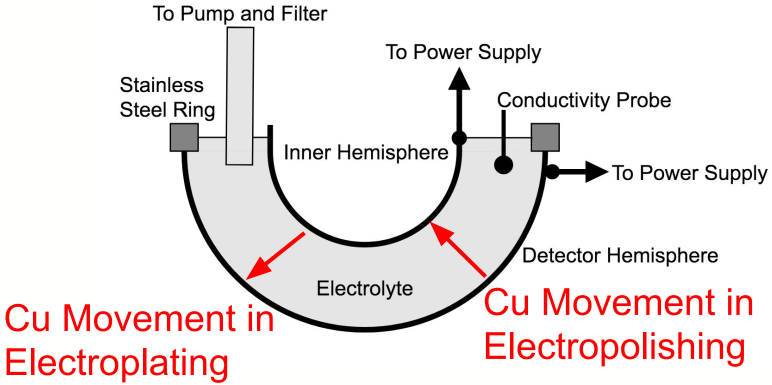
More on surface preparation: https://doi.org/10.1016/j.nima.2007.04.101

Electropolishing and Electroplating

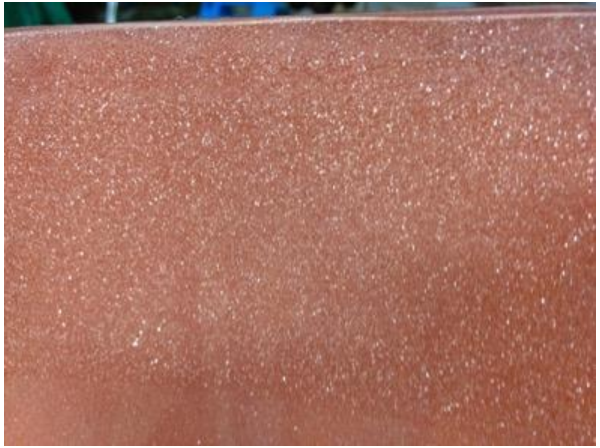
- **Electropolishing**:
  - Preferentially removes raised areas on surface
  - **Increases** $CuSO_4$ concentration
- Plating continued for ~15 days
- In total estimate ~ **500 µm** plated







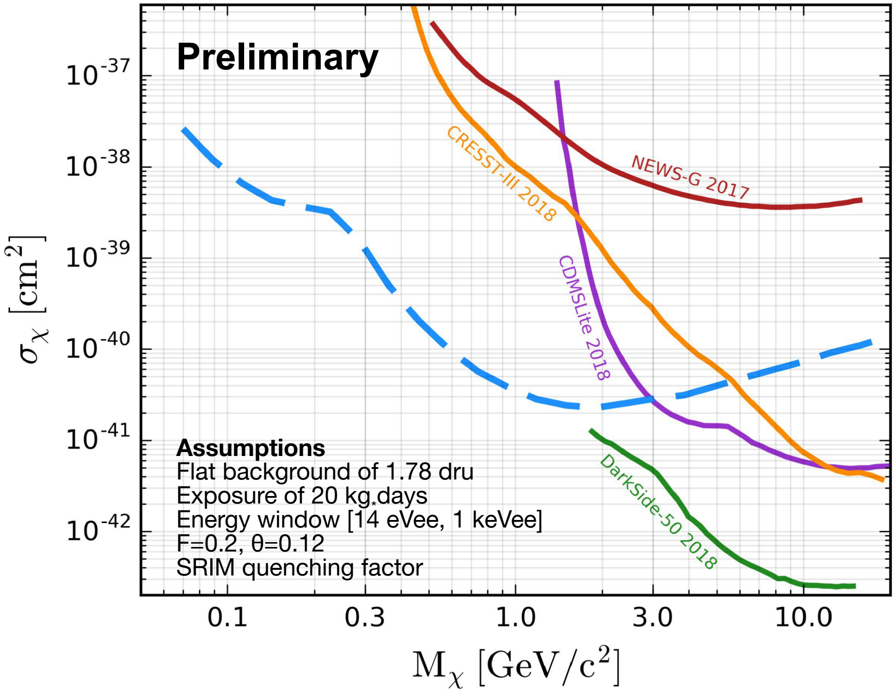
Result



- Layer of Cu deposited on surface
  - Awaiting results of analysis of copper and electrolyte to verify purity
- Geant4 simulation shows decrease in background from 4.58 count/keV/kg/day (dru) < 1 keV to 1.96 dru
- Promising plating rate for electroformed sphere in the future

Pushing the Boundaries

- To increase low-mass sensitivity:
  - Target mass
    - Larger detector
    - Higher Pressure
  - **Background suppression**
    - PID and Fiducialisation
    - Purity of Materials
  - Low mass target nuclei
    - e.g. H from CH_4



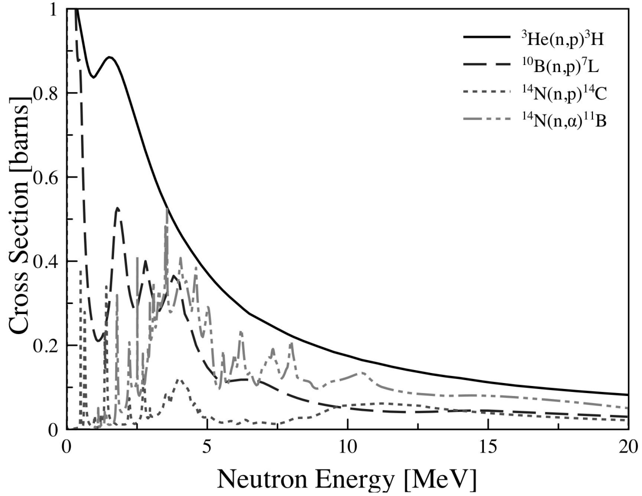
Neutron Measurements

Neutron Detection

- Neutrons are background in DM experiments
- Feasibility spherical proportional counter as neutron detector, using nitrogen gas
- Tests ongoing in Birmingham

$^{14}N + n \rightarrow {}^{14}C + p + 625$ keV, $\sigma_{th} = 1.83$ b

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



Previous Limiting factors:

➔ **Wall effect**
➔ **Sparking - Instability**
➔ **Low pressure**
➔ **Impurities**
➔ **Charge collection efficien**

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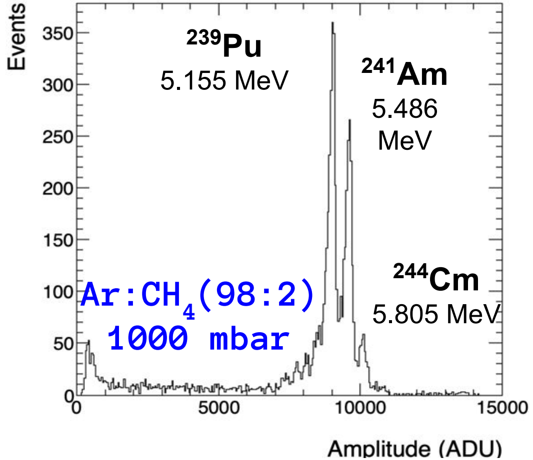
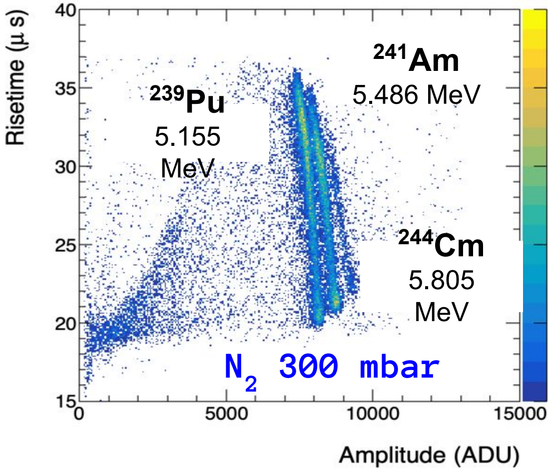


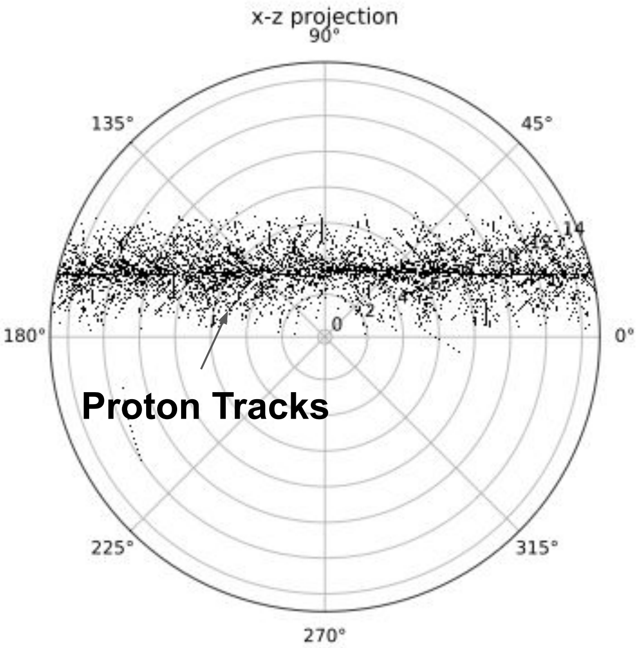


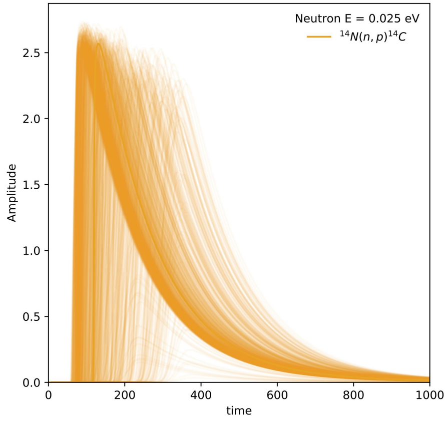
Simulation of neutron transport

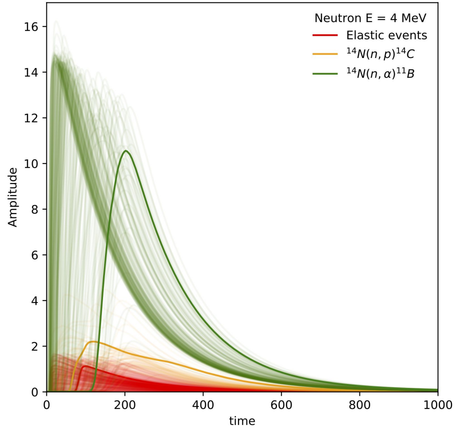
Neutron Beam

0.025 eV/ 4 MeV

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

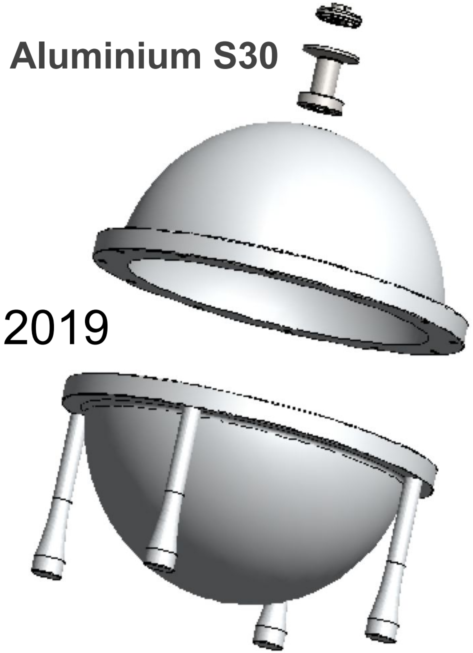






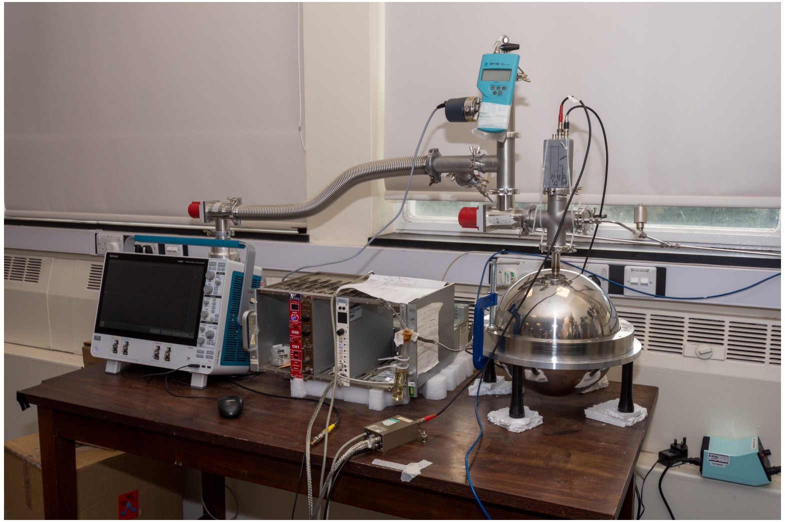
Activities at Boulby

- Aim to measure neutron flux in Boulby Underground Laboratory
  - Space allocated in lab
  - Installation of detector beginning Dec. 2019
- Possibility for further collaboration



Birmingham Gaseous Detector Laboratory

I. Katsioulas, P. Knights, T. Neep,
K. Nikolopoulos, R. Owen, R. Ward
+ MSci and Summer Students



Additional Material