DarkSPHERE: Reaching the Neutrino Floor with a Spherical Proportional Counter

HEP 2021

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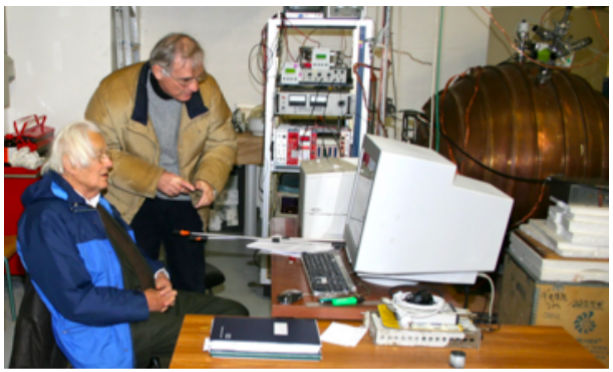
NEWS-G

New **E**xperiments **W**ith **S**pheres - **G**as
Light DM searches with a novel gaseous detector, the spherical proportional counter

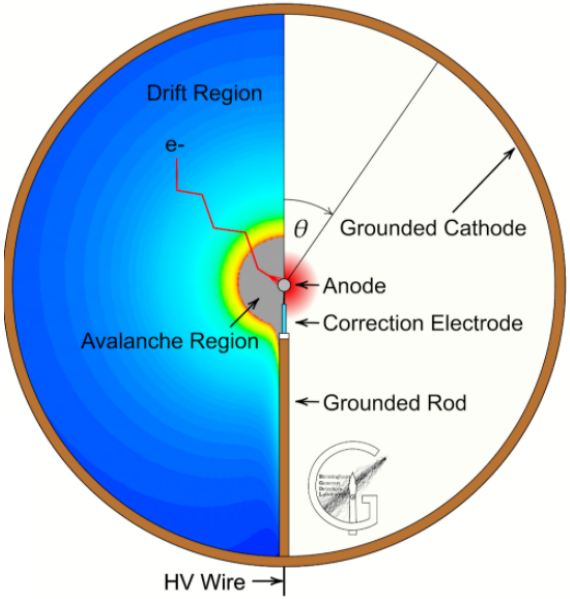
Spherical Proportional Counter

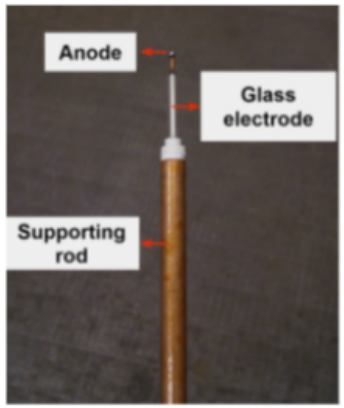
- $\mathcal{O}$**(0.1-1 m) diameter** sphere with $\mathcal{O}$**(1 mm) spherical anode** in centre
- Voltage applied to anode
- **Maximum volume-to-surface**
- Flexibility in gas choice, can operate at high pressures
- Single electron threshold capability



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

JINST,2008,P09007 JINST,13,2018,no.11,P11006





r_c = cathode radius
r_a = anode radius

- **Electric field** scales as $\sim \mathbf{1/r^2}$
  - Divides detector into drift and avalanche regions

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

- **Capacitance independent of detector size**
  - **Large volume** with **low electronic noise**

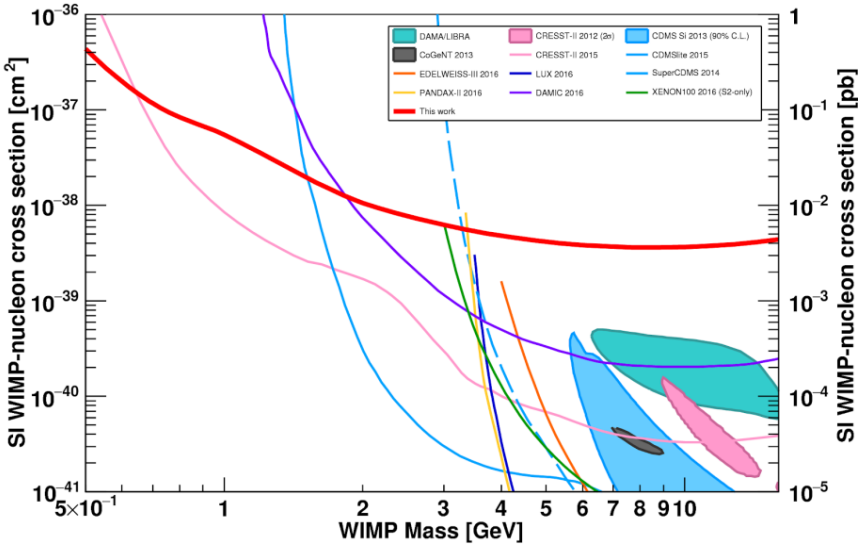
$$C = 4\pi\epsilon_0 \frac{r_c r_a}{r_c - r_a} \approx 4\pi\epsilon_0 r_a$$

SEDINE - First NEWS-G DM Detector

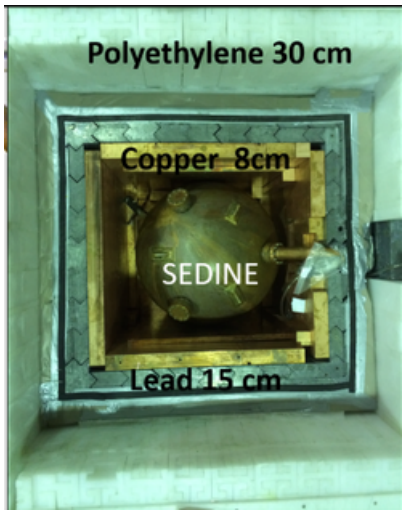
60 cm diameter detector

- Using Aurubis NOSV **copper, chemically cleaned to remove radon**
- Located in Modane Underground Lab., France
- Operated with **3.1 bar Ne:CH_4 (99.3%:0.7%)**
- 34.1 live-days, 9.6 kg/days

Astropart.Phys. 97 (2018) 54-62



SEDINE results exclude at 90% CL cross-sections above 4.40×10^{-37} cm^2 for a 0.5 GeV DM particle

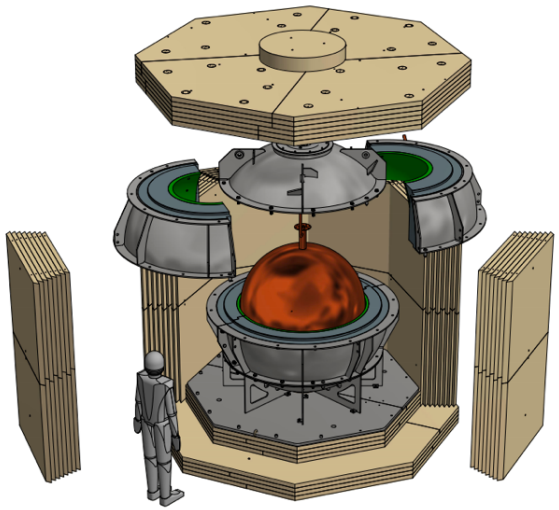


Laboratoire Souterrain de Modane (LSM)

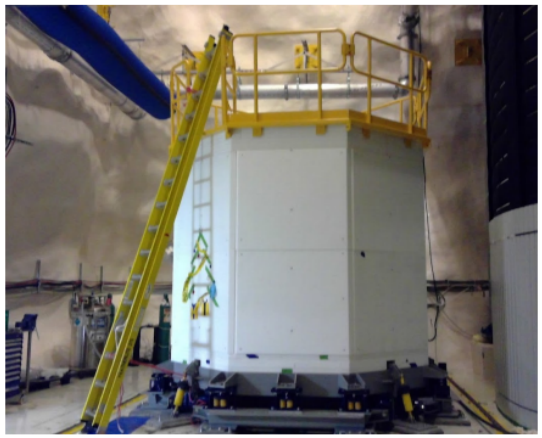
SNOGLOBE

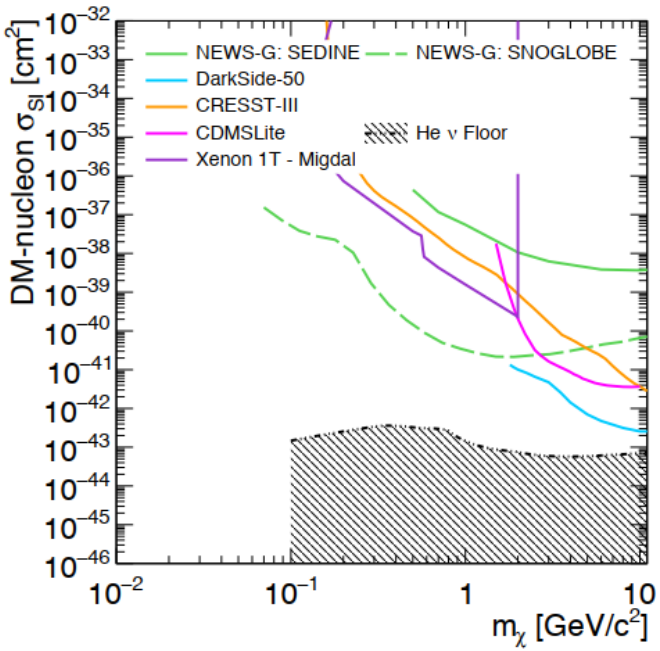
140 cm diameter detector

- Constructed and tested in Modane Underground Lab., France
- Currently under commisionning in SNOLAB, Canada
- **4N (99.99% pure) Aurubis copper**
- **Electroplating** used to apply 500 µm **ultra-pure inner layer, reducing background rate below 1 keV by 70%**



Installed in SNOLAB
Dec 2020

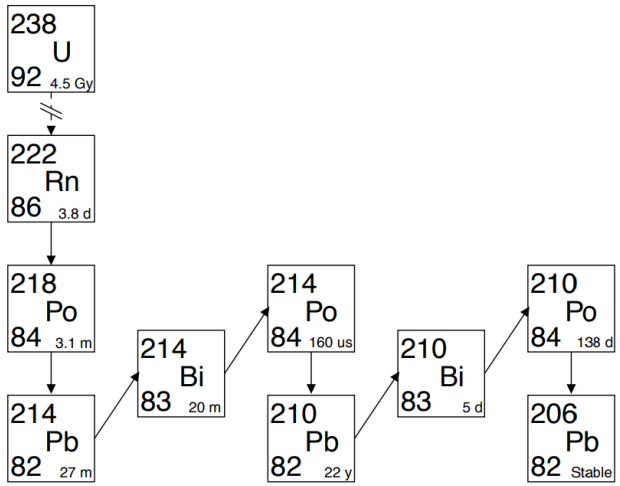


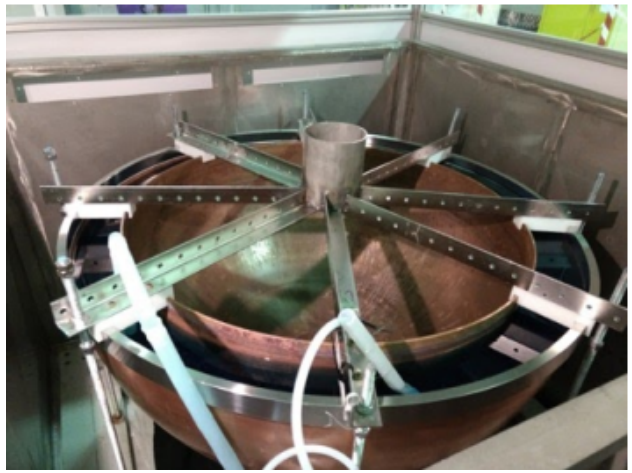


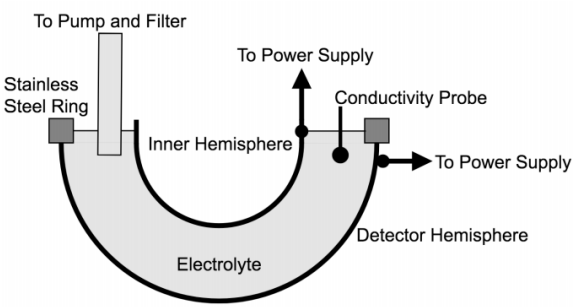
Preliminary sensitivity projection for SNOGLOBE

Electroplating

- **Contaminants** from ^{238}U and ^{232}Th decay chain, **naturally deposited by ^{222}Rn**
- **Copper has a high reduction potential**, contaminants do not
  - **Preferentially deposited**
  - Creates **ultra-pure layer of copper**
- ICP-MS assay of sample comparable to other electroformed copper
- ^{210}Po in electroformed copper is below XIA UltraLo-1800 sensitivity < 3 mBq/kg







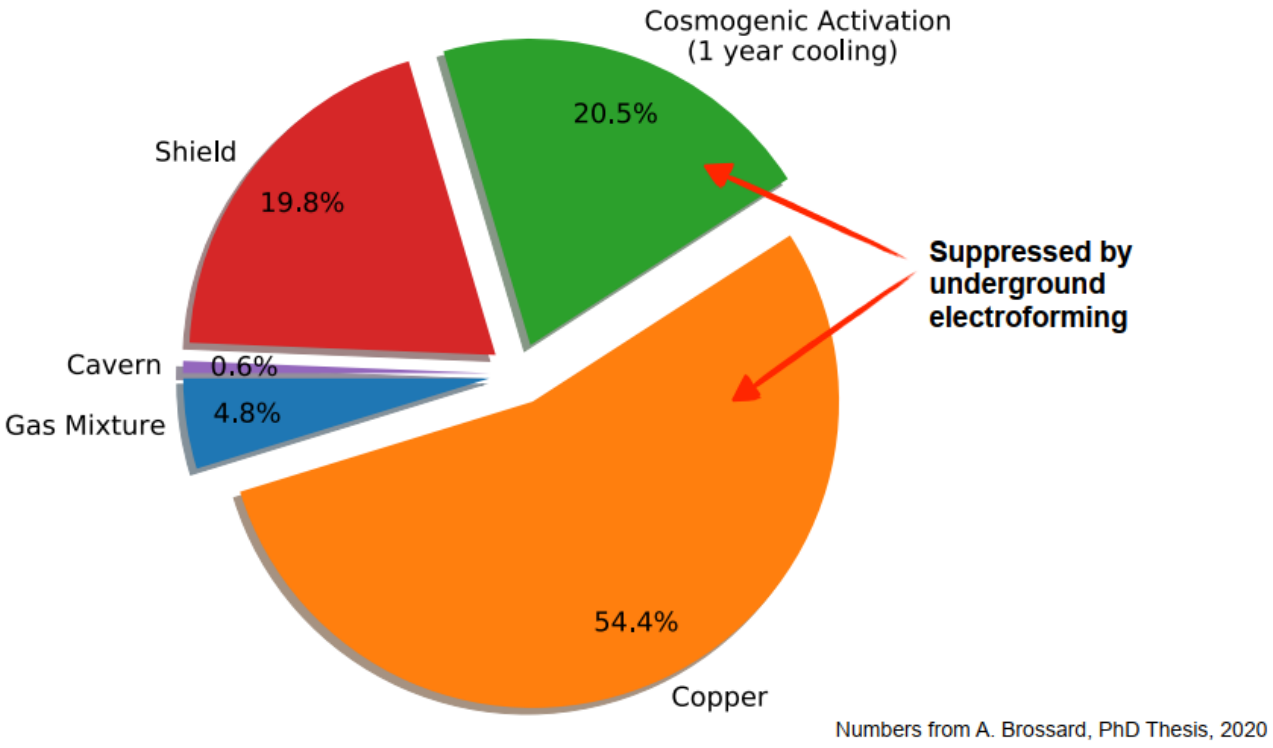
NIMA 988 (2021) 164844

ICP-MS Assay

Sample	Weight [g]	^{232}Th [μBq kg^{-1}]	^{238}U [μBq kg^{-1}]
C10100 Cu (Machined)	-	8.7 ± 1.6	27.9 ± 1.9
Cu Electroformed	-	<0.119	<0.099
Hemisphere 1	0.256	<0.58	<0.26
Hemisphere 2	0.614	<0.24	<0.11

SNOGLOBE Background Contributions

- **Detector made from 4N copper** with **only inner layer electroformed**, so **^{210}Pb contamination** is still a **dominant background**
- **Cosmogenic activation** will still occur and **contribute to background**
- **Next step** to suppress these further is **underground electroforming**

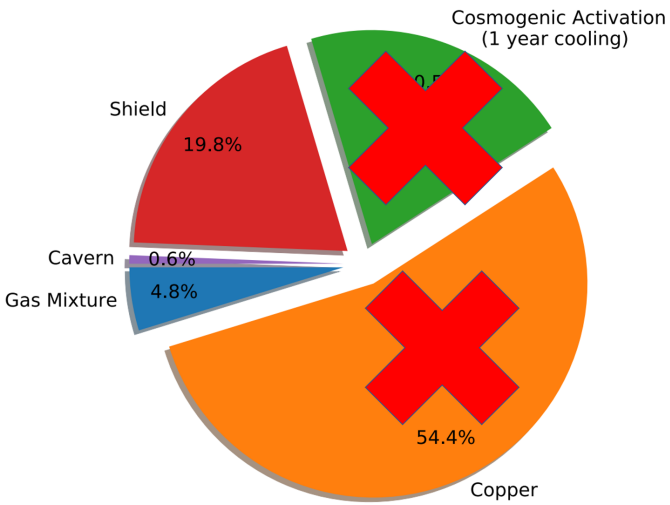


Numbers from A. Brossard, PhD Thesis, 2020

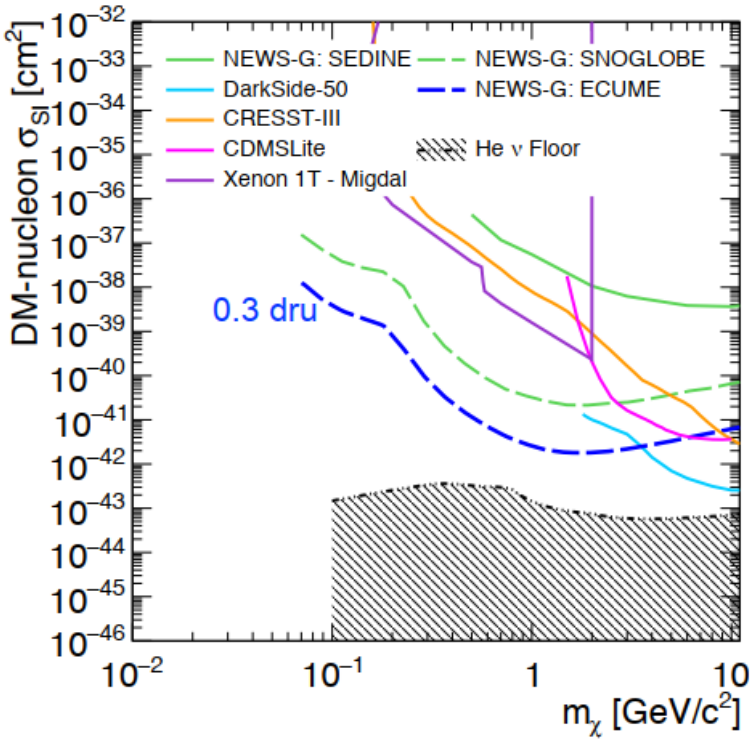
ECuME

140 cm diameter detector

- **Fully electroformed copper**
- **Electroformed underground** at SNOLAB, **suppressing cosmogenic activation**
- Production rate $\sim$ 1 mm/month
- 30 cm prototype this summer
  - Full detector construction late this year
- **Using SNOGLOBE shielding**



Numbers from A. Brossard, PhD Thesis, 2020

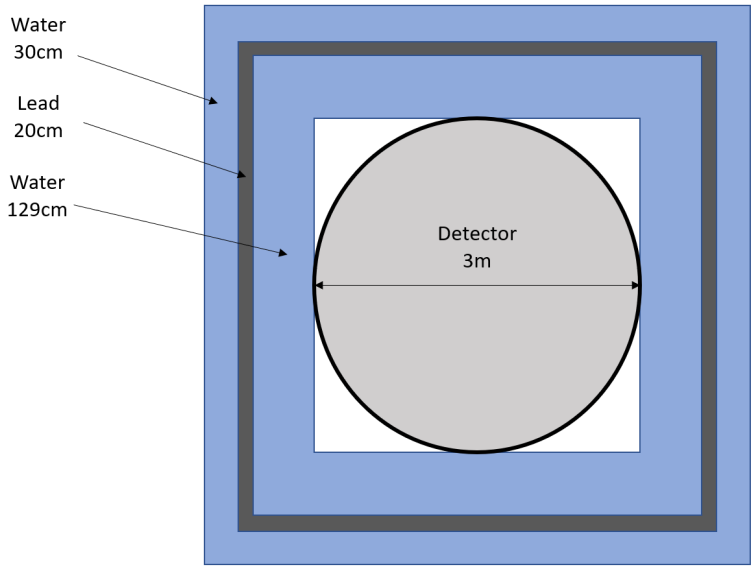


- Idea: **Improve shielding configuration**

DarkSPHERE - Aspiring to Reach the Neutrino Floor

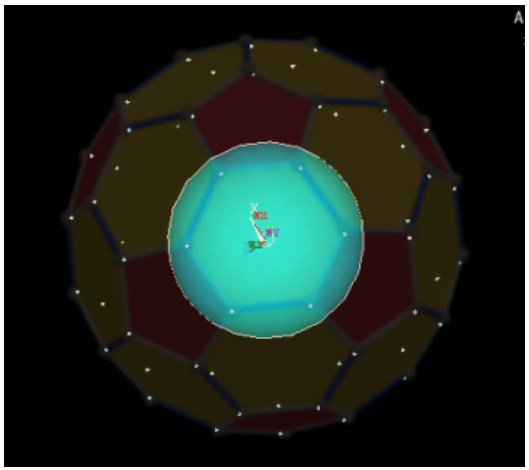
3m diameter detector

- **Fully electroformed underground**
- **Improved shielding design**
- **Improved readout sensor** to support larger detector
- Operate with **5 bar He:C_4H_{10} (90%:10%)**
- **Targeting to be hosted in Boulby Underground Laboratory**, UK, in the Large Experimental Cavern (LEC)
  - Underground science facility located 1.1 km below ground in Boulby mine
  - Experience hosting gaseous detector experiments (e.g. DRIFT)



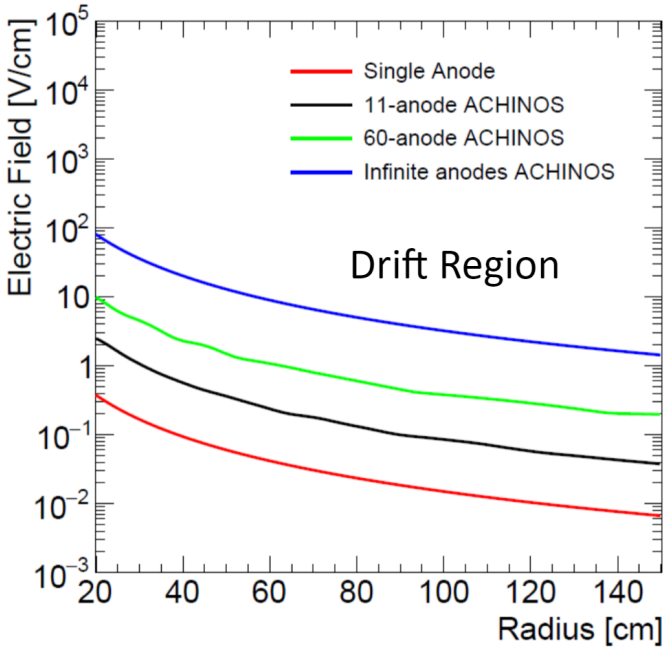
DarkSPHERE Readout Sensor

- **11-anode ACHINOS sensors** used **in current SPCs**
- Anodes at equal radii from centre
- **60-anode sensors being investigated**
- **Higher electric field magnitude** at higher radii with more anodes - supports **larger detectors and higher pressures**



60-anode ACHINOS simulated with ANSYS - anodes are white points at the vertices of a truncated icosahedron

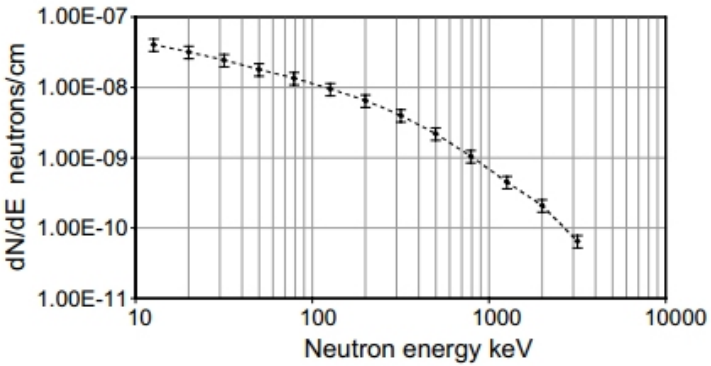
JINST 12 (2017) 12, P12031
JINST 15 (2020) 15, P11023



Background Contributions

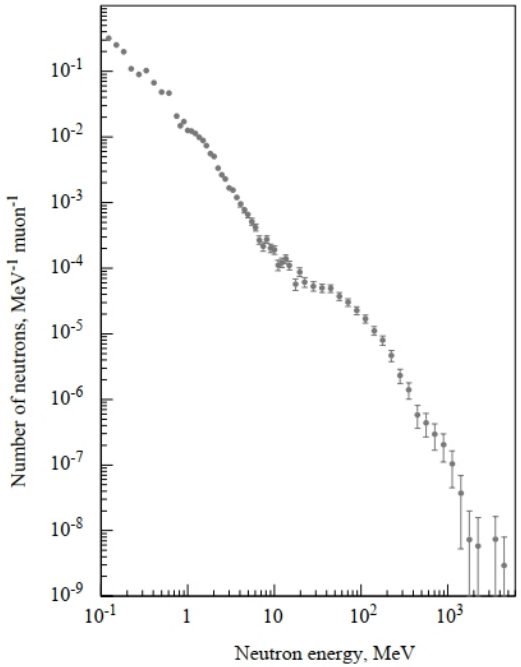
- **Environmental neutrons**
  - From natural radioactivity in cavern rock
  - From cosmic ray interactions
- **Environmental photons**, from natural radioactivity in cavern rock
- **Radioactive contaminants in the detector shielding**

Astroparticle Physics 22 (2005) 409



Natural radioactivity neutron spectrum

NIMA 505 (2003) 688



Cosmic muon-induced neutron spectrum

J.Radioanal.Nucl.Chem. 298 (2013) 3, 1483

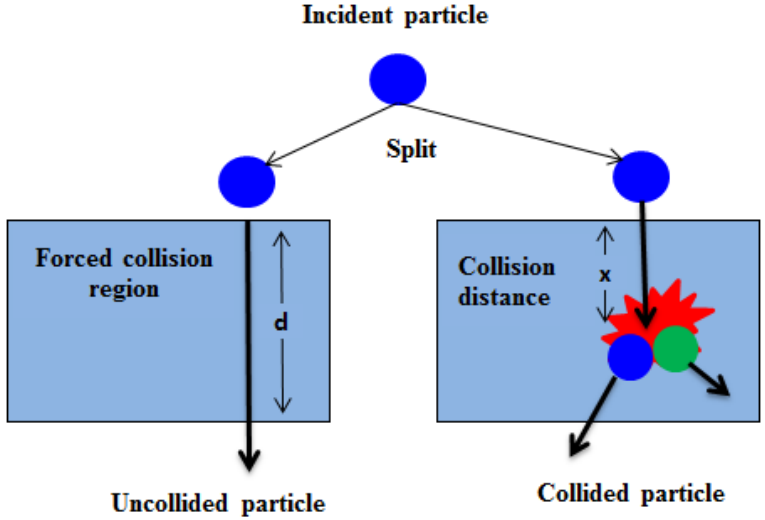
Location	7.4–2734.2 keV	7.4–249.8 keV	250.2–500.4 keV	500.8–1005.2 keV	1005.6–1555.8 keV	1556.2–2055.8 keV	2056.2–2734.2 keV
8	0.128	7.82×10^{-2}	2.15×10^{-2}	1.63×10^{-2}	1.10×10^{-2}	7.14×10^{-4}	5.83×10^{-4}

Photon flux from cavern rock

Estimating Backgrounds with Simulation

- Geant4: **Investigate shielding configurations and background**
- Obtain **interaction probability** in gas for different particle species
- **Interaction probability** together with **background flux measurements** gives **background rate**
- **Forced collision scheme for Monte-Carlo variance reduction**

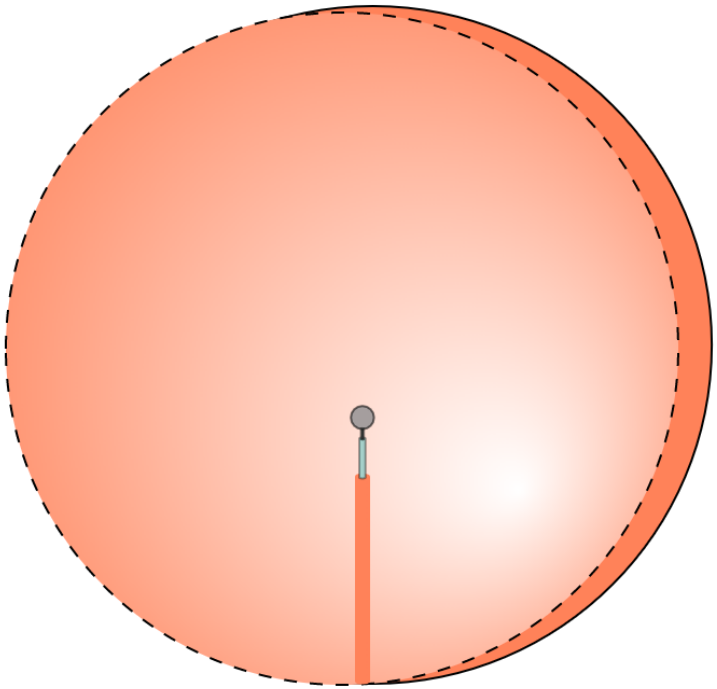
Forced collision biasing method:



doi: 10.5772/53384

Estimated Background from Electroformed Copper Sphere

- **^{210}Pb contamination in the electroformed copper** should be the **dominant background contribution**, as it cannot be reduced
- Estimated to be $< 0.12\ \mu\text{Bq}\,\text{kg}^{-1}$
- Simulated decays within the 1cm detector shell
- **Expected rate is 2.43×10^{-3} /kg/day/keV (dru)**



Water Shielding

- **Target** for shielding is to **reduce all other backgrounds** to the **expected electroformed copper background**
- A **pure water shielding** setup was considered
- Fitting within the 7m cubic area available in the LEC
- **Contamination from ^{40}K** in pure water expected to be **negligible**

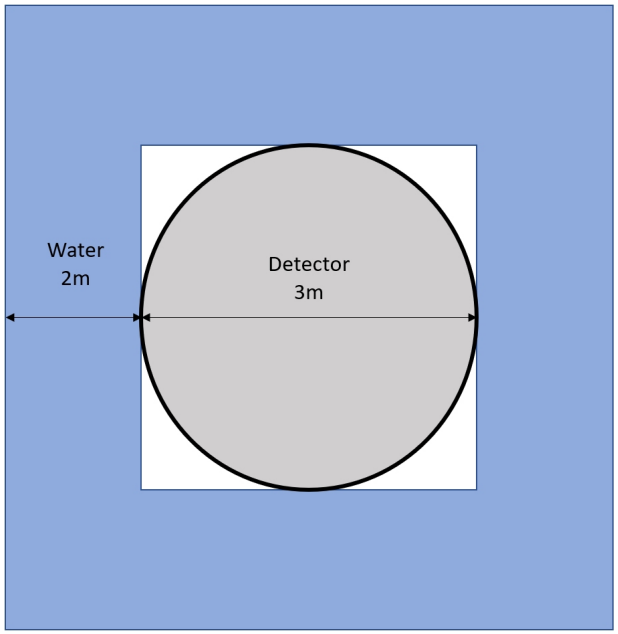


Diagram of a pure water shielding setup with 2m thick water on each side

- **2m thick water suppresses neutron background, but not photons**

Table: Environmental background rates

Rate [dru]	Neutrons	Photons
Total	1.97×10^{-3}	8.11
Neutrons	1.26×10^{-3}	-
Photons	6.35×10^{-4}	7.67
Electrons	6.67×10^{-5}	4.34×10^{-1}
Positrons	5.85×10^{-6}	4.48×10^{-3}

Water Shielding

- Tested increasing water thicknesses beyond what fits in the 7m space
- **3.5m thick water is required to suppress the photon background**

Table: Environmental photon rates

Rate [dru]	Photons
Total	1.90×10^{-3}
Photons	1.52×10^{-3}
Electrons	3.75×10^{-4}
Positrons	4.61×10^{-6}

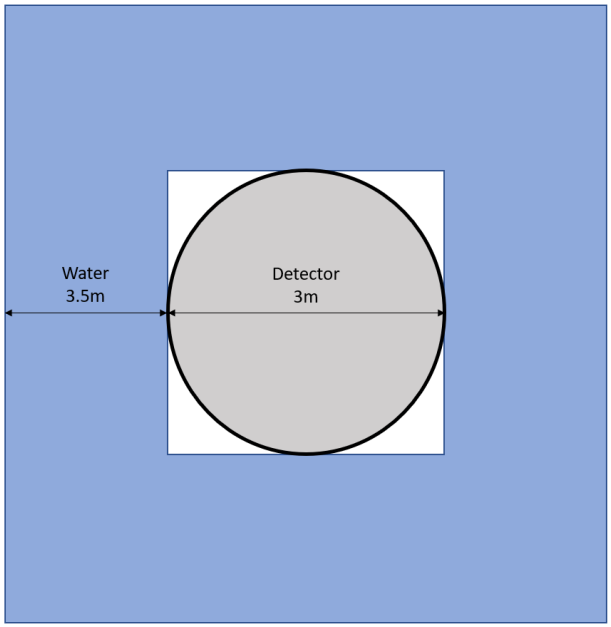


Diagram of a pure water shielding setup with 3.5m thick water on each side

Hybrid Shielding

- Switched to using **water and lead shielding**, fitting in the 7m cubic area available
- **Suppresses both photons and neutrons**

Table: Environmental background rates

Rate [dru]	Neutrons	Photons
Total	1.86×10^{-3}	1.24×10^{-3}
Neutrons	6.57×10^{-4}	-
Photons	1.05×10^{-3}	1.18×10^{-3}
Electrons	1.07×10^{-4}	5.81×10^{-5}
Positrons	4.26×10^{-5}	9.81×10^{-7}

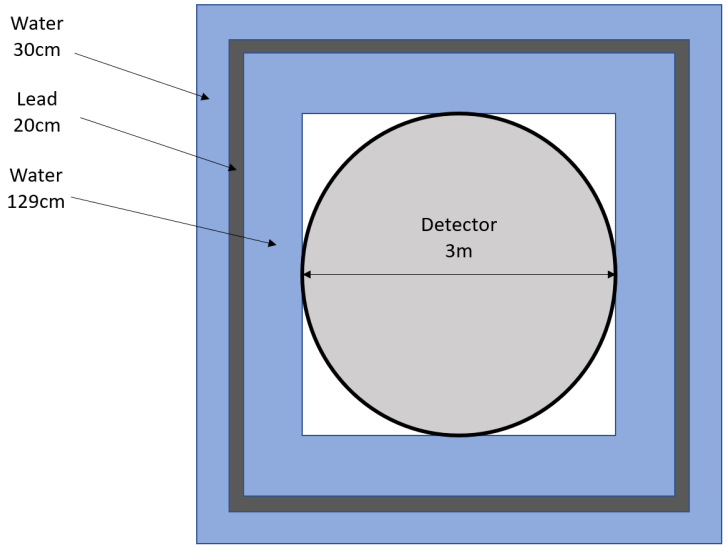


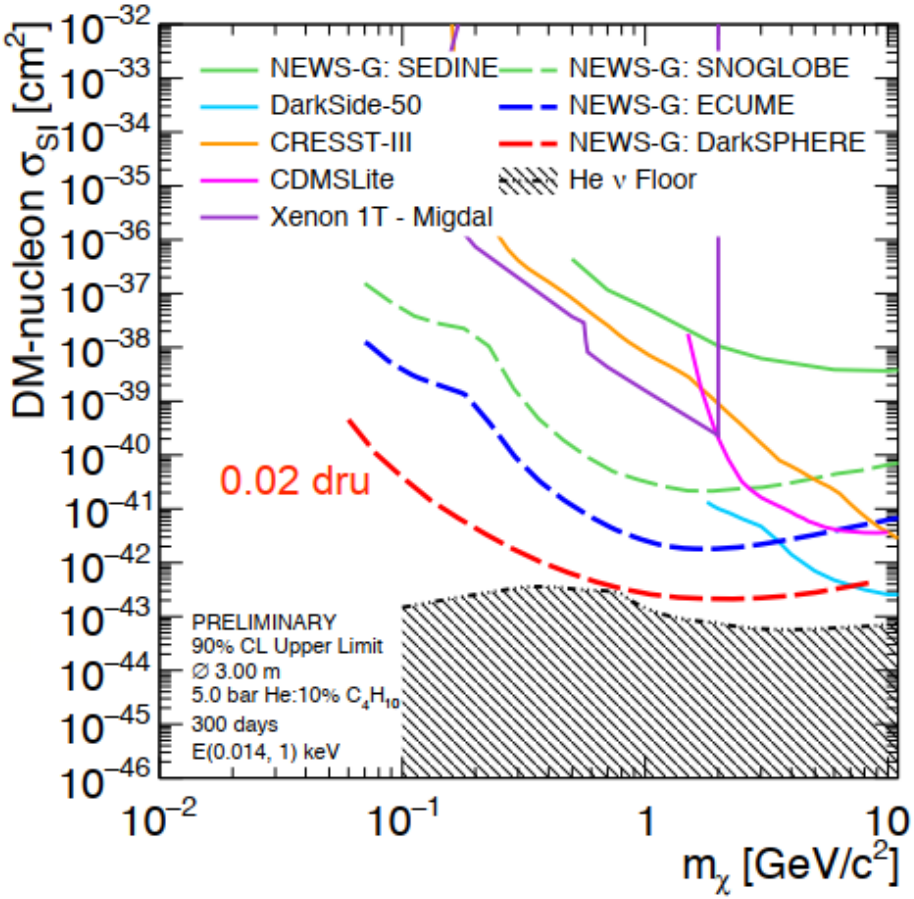
Diagram of a 7m cube water and lead shielding setup

- **High ^{210}Pb contamination** in lead may require additional shielding
  - May need layer of archaeological lead or copper
  - **Currently being investigated**

Physics Potential of DarkSPHERE

Sensitivity reaches the neutrino floor!

- Estimate of a **0.02(dru) flat background** used for this projection
- **Shielding design** aims to **suppress background below this estimate**
- Total running time of 300 days assumed



90% CL upper-limit sensitivity projection

Summary

- Electroformed copper maximises radiopurity
- Electroforming underground also suppresses cosmogenic activation
- DarkSPHERE shielding is being designed
- DarkSPHERE sensitivity projections indicate potential to reach the neutrino floor