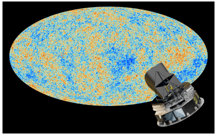
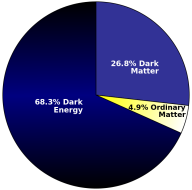
Rare event searches with gaseous detectors

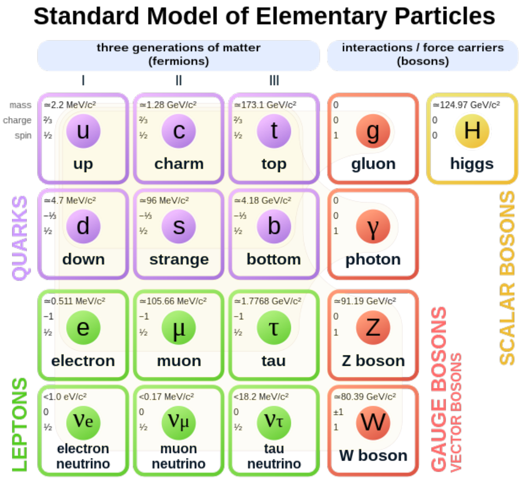
Tom Neep, on behalf of the Birmingham Gaseous Detectors Laboratory (and many others)
Birmingham
April 27, 2020

The Standard Model (& beyond)

- The Standard Model of particle physics is "complete"
- It does an annoyingly good job of describing the data from the LHC (with a few notable exceptions)
- Lots of observations suggest that dark matter exists
    - Galactic rotation curves
    - Cosmic microwave background
    - Small scale structure
    - 'Bullet' cluster

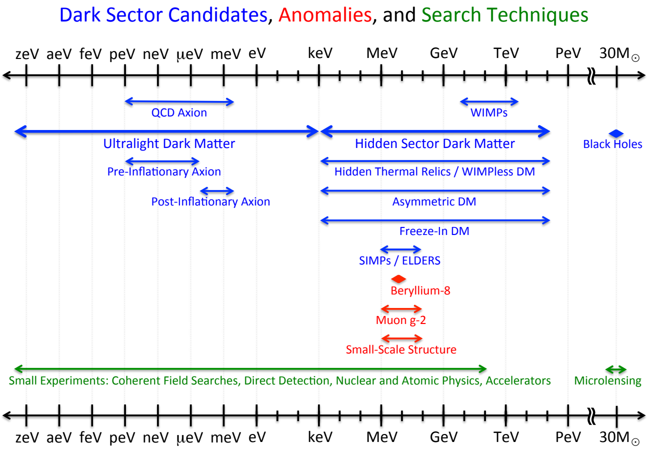




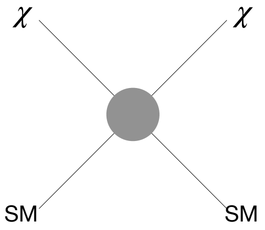


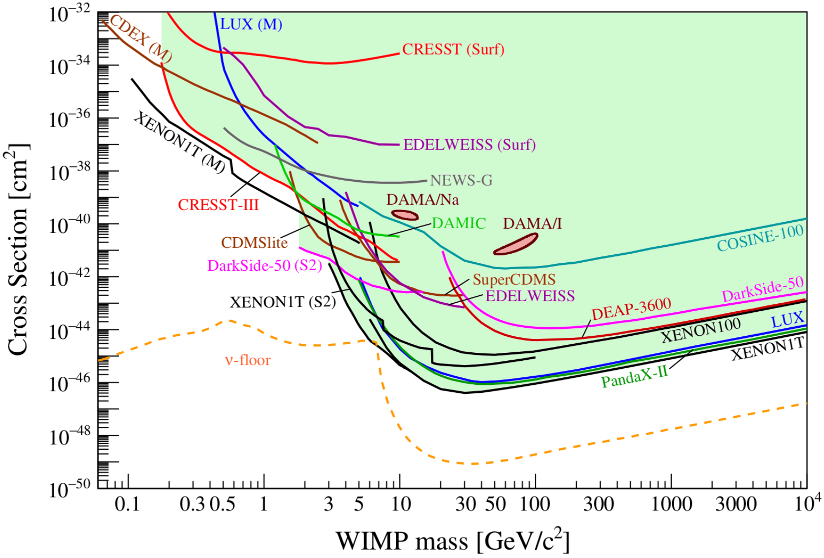
Dark matter

- What do we know about dark matter? Not much!



Dark matter





- Direct dark matter searches have made great strides in excluding WIMP-like dark matter
- Increasing interest in pushing towards lower masses, $\mathcal{O}(100\ \mathrm{MeV})$

The Migdal effect

- Direct dark matter experiments search for dark matter scattering off a nucleus
- The nucleus ionises the detector medium
- However, when the nucleus recoils it can “leave behind” the electron cloud
- This can lead to the emission of an electron (we’ll call this the Migdal electron)
- Thresholds for detecting electrons are lower – we would see these events
- The Migdal effect first predicted in 1939, recent renaissance due to applicability to DM

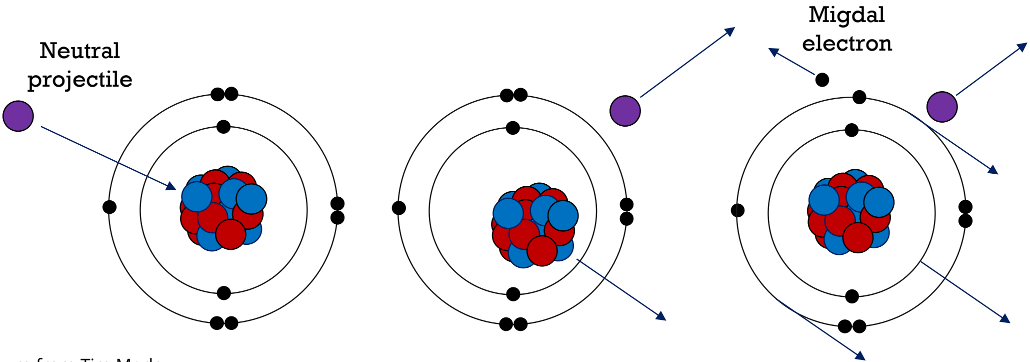


Figure from Tim Marley

Exploring lower dark matter masses

To explore dark matter masses of $\mathcal{O}(100\ \mathrm{MeV})$ we need detectors with a lower threshold

Option A: Exploit the Migdal effect

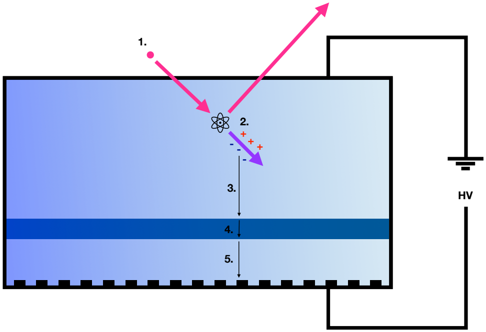
- No need to build a new detector?
- Can reinterpret existing results?
- **Problem: The Migdal effect has not yet been observed in nuclear scattering!**
- **Solution:** Build a detector to observe the Migdal effect in nuclear scattering

Option B: Build detectors with light targets

- If DM is light then a light target is a better match
- Need a low background detector – low material budget
- Need low electronic noise – aim for single electron threshold
- **Solution:** Build a detector which can be filled with a light target

A generic gaseous detector

1. Particle enters the detector and scatters off a nucleus
2. Nucleus ionizes the gas, creating electron–ion pairs
3. In the presence of an electric field, electrons drift towards the anode
4. Electrons avalanche in a region with high E-field magnitude. Electrons given enough energy to ionize more electrons–ion pairs, which in turn can ionize more and so on. . .
5. Electrons (or ions) induce current on electrodes (Shockley-Ramo)



- Can build large detectors at a reasonable cost
- The gas and pressure can be changed to suit the requirements of the experiment

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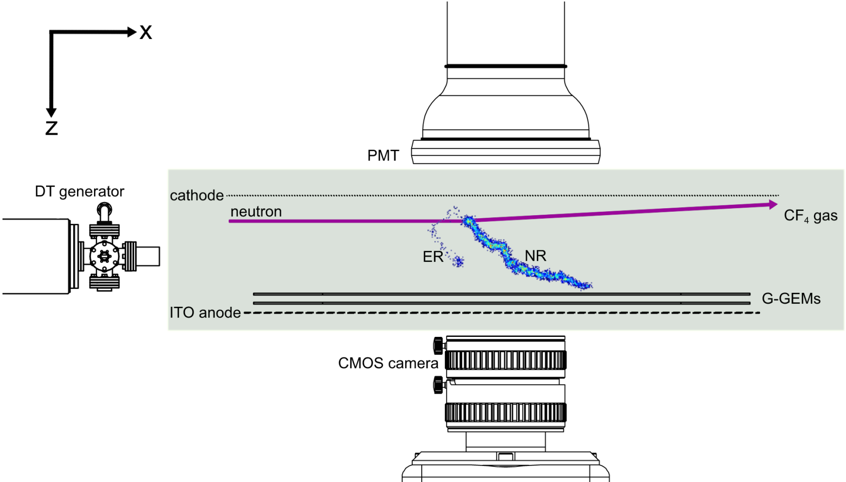
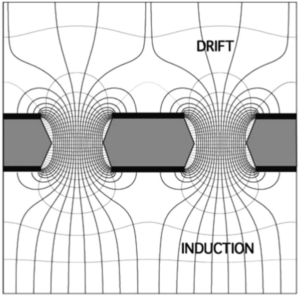
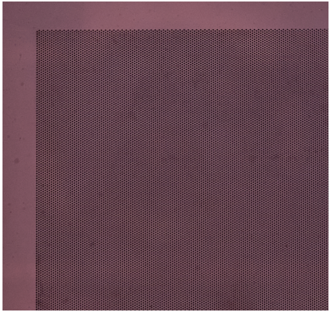
The MIGDAL Experiment

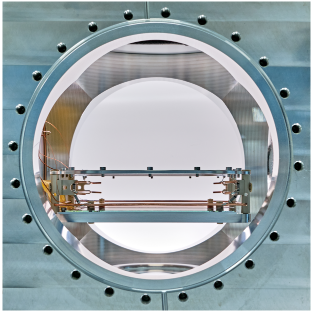
- The **M**igdal **I**n **G**alactic **D**ark M**A**tter Exp**L**oration experiment aims to make an unambiguous observation of the Migdal effect in nuclear scattering using an optical time projection chamber
- Similar concept to the diagram on the previous slide



MIGDAL: Avalanche region – Gas Electron Multipliers





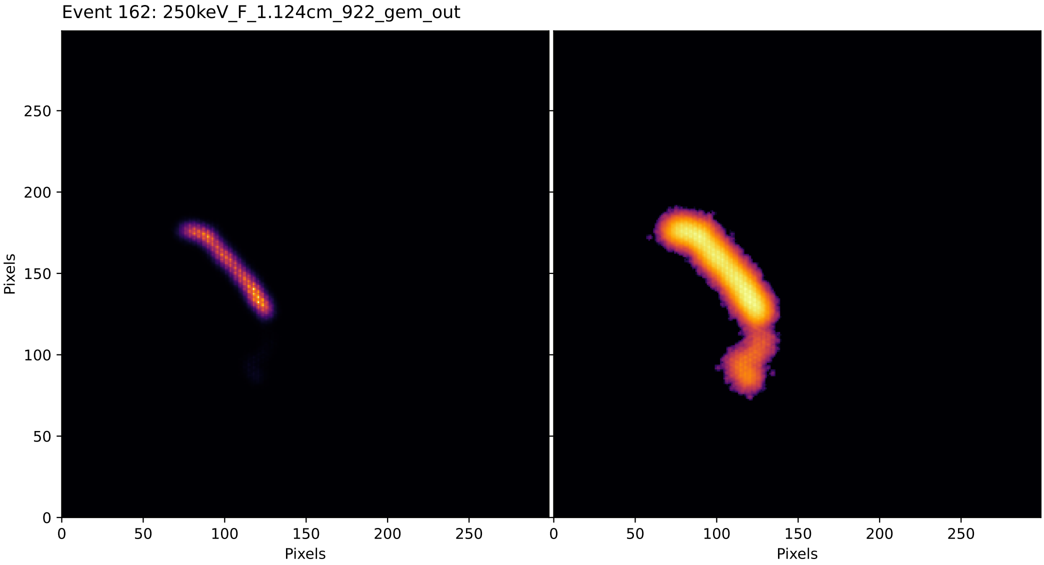


- Electron avalanche performed using two GEMs
- GEMs are micropattern gas detectors, in the same family of gaseous detectors as Micromegas
- Very small holes in a dielectric sheet
- Electrons are directed through the holes and avalanche inside of them
- GEM parameters: 170 μm diameter holes, 280 μm pitch

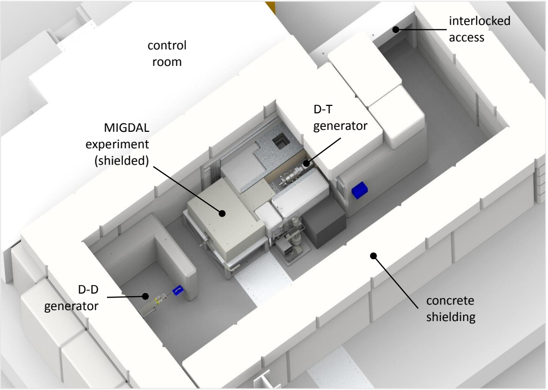
MIGDAL: Readout

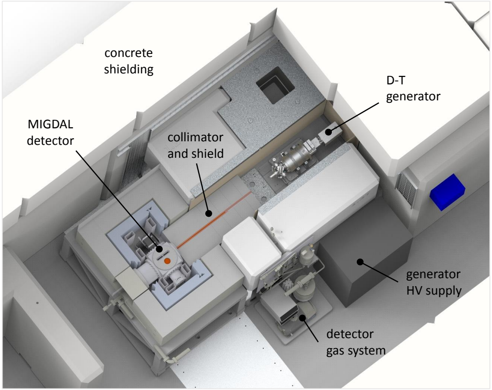
- The experiment is equipped with multiple readouts
- A PMT is used to collect light produced in both the initial ionization and in the avalanche. This gives us information about the absolute z-position of the initial interaction
- An Indium Tin Oxide (ITO) strip anode is used to readout the charge produced. This gives us information about the tracks produce in the x and z (time) directions
- A CMOS camera records the light leaving the GEMS, giving us a picture of the tracks in the x–y plane
- We are involved in simulating all of this, I am the simulation coordinator for the experiment

Example simulated Migdal-like event: CMOS image



The NILE facility at ISIS, RAL





- Experiment will be based at RAL
- We will first use a 2.45 MeV DD neutron source and later a 14.1 MeV DT neutron source
- Expect to start data taking **very** soon. **Stay tuned!**

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The NEWS-G Collaboration

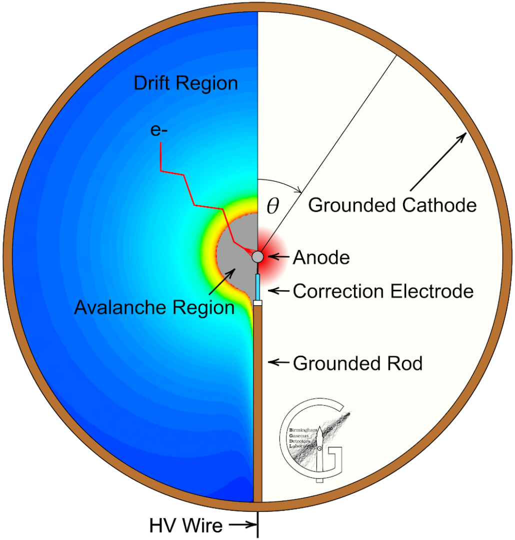
Spherical Proportional Counters (SPCs)

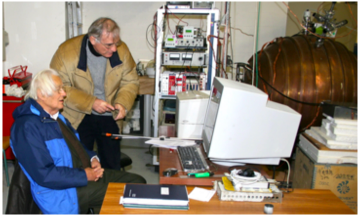
Overview

- SPCs consist of a grounded metalic shell, which acts as a cathode, a gas volume and a central anode sensor
- The anode is kept at a high voltage and supported by a grounded metallic rod

Advantages

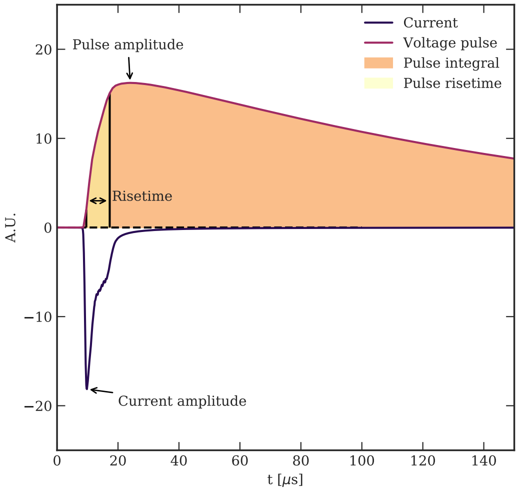
- Low capacitance, independent of cathode radius – low noise, single electron threshold
- High-pressure operation – can reach large target masses
- Optimal volume-to-surface ratio – low background
- Single readout in its simplest form
- Easy to switch target gas



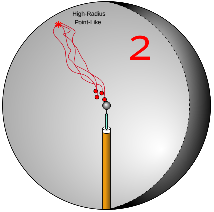


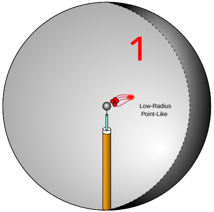
Pulse analysis

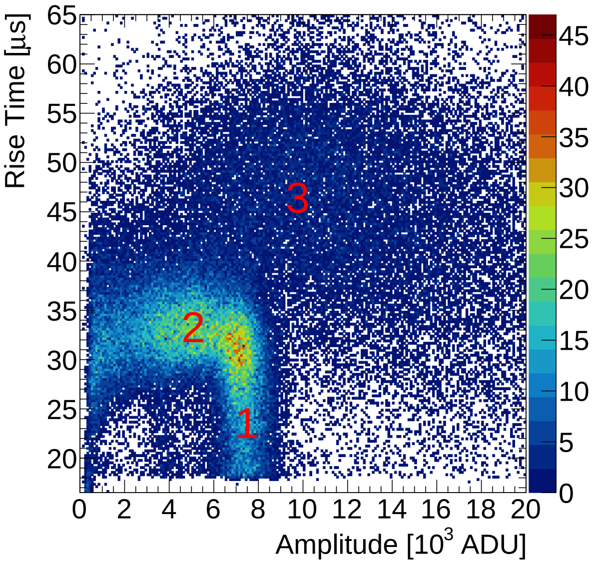
- The signal of an ”event” is a voltage pulse, which can be deconvolved to get a current pulse.
- Each pulse contains information that can be used to distinguish different features of observed events, potentially allowing signal/background discrimination

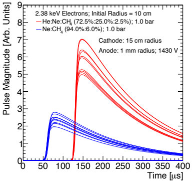


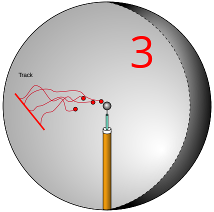
Pulse shape discrimination









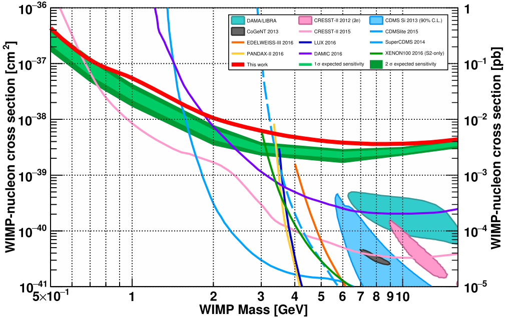


Astropart. Phys. 97, 54 (2018)

- The first NEWS-G detector was called SEDINE and operated at LSM for 43 days in Spring 2015
- 60 cm diameter copper SPC filled with Ne+CH4 (0.7%) at 3.1 bar [9.6 kg · days]
- Set world leading limits on "WIMP-like" dark matter with $m_{\chi^0} < 650$ MeV
- Limits have since been surpassed
- Main background from decays in the copper sphere

How to improve?

- Larger target mass (bigger detector)
- Lower backgrounds
- Better signal/background discrimination



Larger target mass – bigger detector?

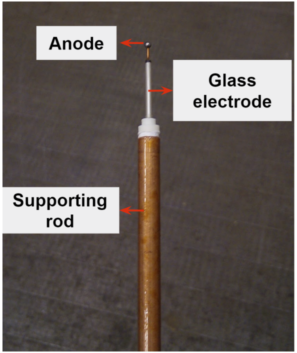
- To increase the target mass we ideally want a larger detector
- Not as simple as it might sound

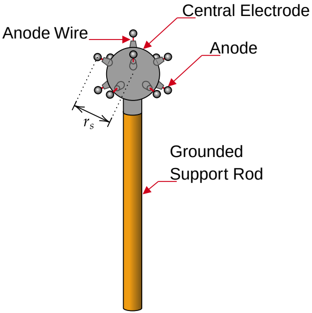
$$E(r) = \frac{V_0}{r^2} \frac{r_a r_c}{r_c - r_a} \approx \frac{V_0}{r^2} r_a \qquad E(r_a) \approx \frac{V_0}{r_a}$$

- Electric field drops with r^2
- To collect the charge at the edge of the detector efficiently we need a large drift field
- Can increase the drift field by increasing the anode radius
- But increasing the anode radius reduces the electric field in the avalanche region (lower gain)
- So need to increase the voltage, but this can lead to instabilities
- Ideally we need a way to decouple the fields in the avalanche and drift regions...

Solution: ACHINOS

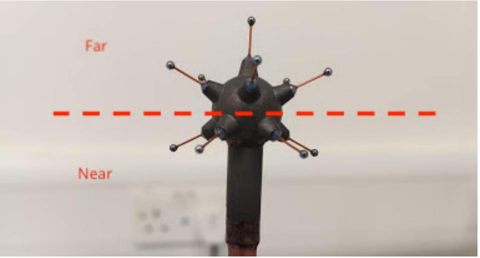
- The solution is to use a multiple anode sensor, known as ACHINOS sensors ▸ ACHINOS
- The drift field and avalanche fields can be decoupled

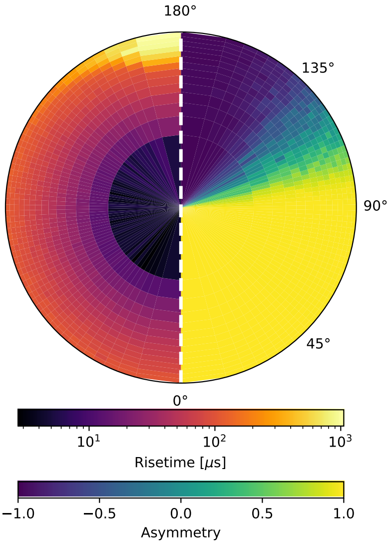




Solution: ACHINOS

- An additional advantage is that we can perform multi-channel readout, allowing the position of the primary interaction to be determined and help particle identification (distinguish signal from certain backgrounds)
- Plot shows the amplitude asymmetry formed from the rod-side and far-side anodes from simulation

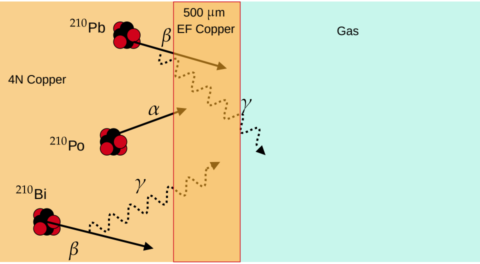


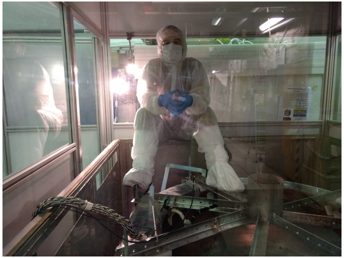


Electroplating

NIM A 988 (2021) 164844

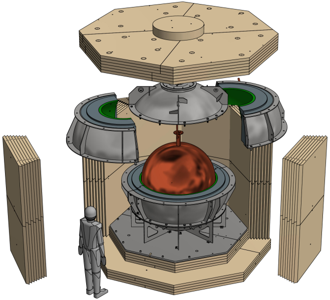
- The largest background in the previous iteration of the analysis was from ^{210}Pb decays in the copper sphere
- In addition to using 99.99% pure copper, the inner surface of the sphere has been **electroplated**
- A 500 μm layer of pure copper has been plated on the inner surface of SNOGLOBE
- Rate of copper $\approx$ 36 μm per day
- Expect to reduce background rate by more than a factor of 2 in the ROI

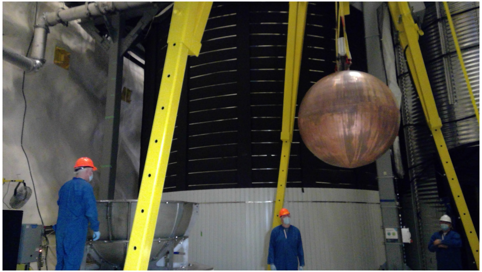




SNOGLOBE @ SNOLAB

- The current NEWS-G SPC is called SNOGLOBE. This will operate at SNOLAB in Canada having previously operated at LSM.
- Several improvements over SEDINE
- 140 cm diameter $\rightarrow$ **Possible thanks to the ACHINOS**
- 4N Aurubius Copper (99.99% pure) **with 500μm electroplated copper** inner surface
- Two readouts (possible fiducialisation)

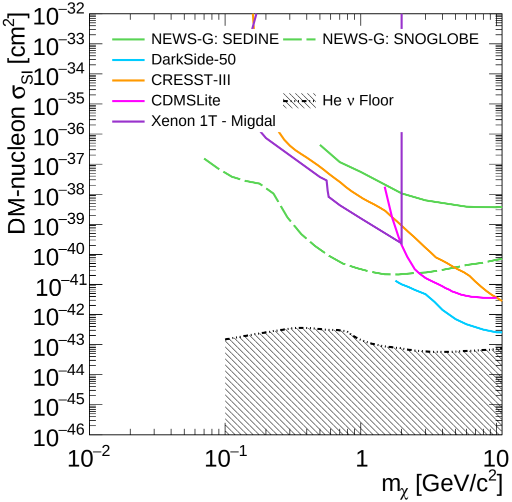




SNOGLOBE projection

SNOGLOBE

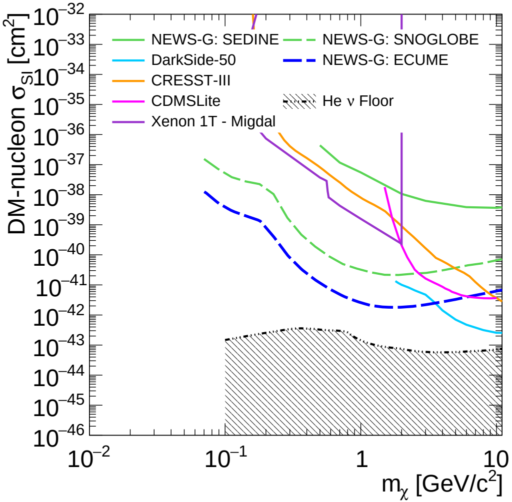
- Expect to improve sensitivity by several orders of magnitude and set limits down to 100 MeV
- The detector is now in position at SNOLAB
- Commissioning is underway and data taking to start this year (delayed due to COVID)



The Future: ECUME & DarkSPHERE

ECUME

- Despite the electroplating, we still expect the largest background with SNOGLOBE to come from decays in the copper sphere
- The ECUME project aims to build a fully electroformed detector underground



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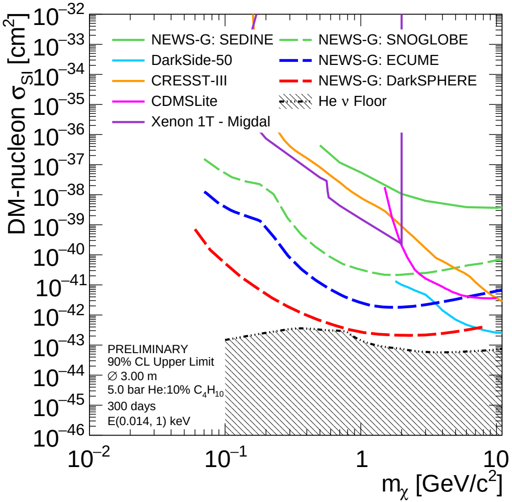
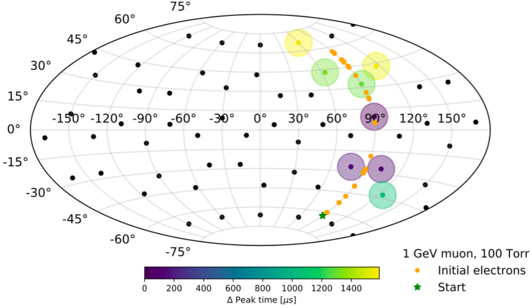
DarkSPHERE

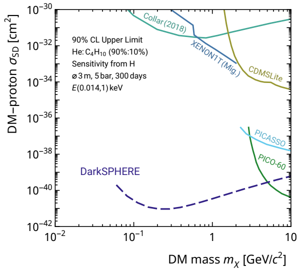
- Proposal to build a 3m diameter fully-electroformed detector
- Will operate with He and isobutane
- We hope to build and operate this detector at Boulby Underground Lab.
- An opportunity for world leading dark-matter experiment in the UK!!

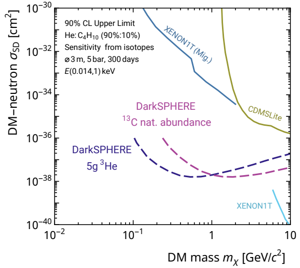


DarkSPHERE

- Simulations of a 60 anode (!) ACHINOS for DarkSPHERE
- Will potentially allow some level of tracking
- DarkSPHERE will set world leading spin-dependent dark matter limits
- Interest from UK theory community: **arXiv:2110.02985**







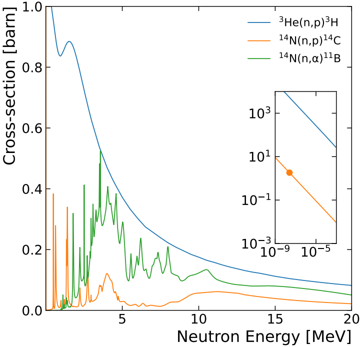
Backgrounds from neutrons in the cavern may become problematic. Can we measure these in-situ?

Neutron detectors

- Detecting neutrons is difficult
- Current neutron detectors have several disadvantages
- Helium-3 based proportional counters are efficient for thermal and fast neutrons, but need to be operated at high pressure.
- Helium-3 is extremely expensive

- **Proposal:** use an SPC filled with N_2 to detect neutrons
- Nitrogen is non-toxic, non-flammable and cheap

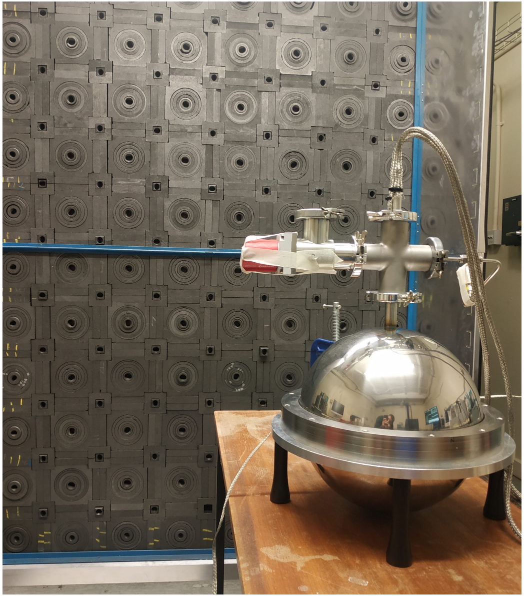
$$^{14}\mathrm{N} + n \rightarrow {}^{14}\mathrm{C} + \mathrm{p} + 625\,\mathrm{keV}$$
$$^{14}\mathrm{N} + n \rightarrow {}^{11}\mathrm{B} + \alpha - 159\,\mathrm{keV}$$



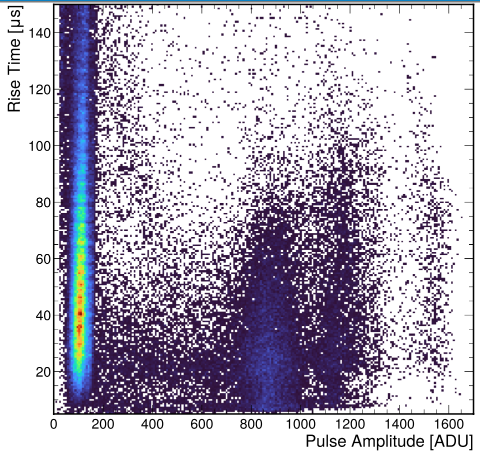
We have been measuring neutrons with a nitrogen–filled SPC in Birmingham!

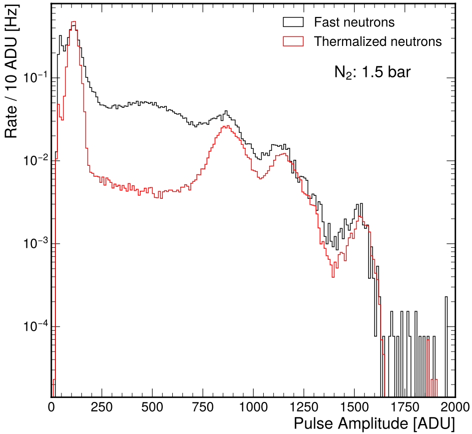
The Graphite Stack

- To test the detection of neutrons we use an $^{241}Am^{9}Be$ source
- Use the 30 cm diameter SPC, filled with N_2 and instrumented with a two-channel achinos
- A graphite stack is used to thermalise neutrons. We can move the source in/out of the stack to get thermal/fast neutrons.



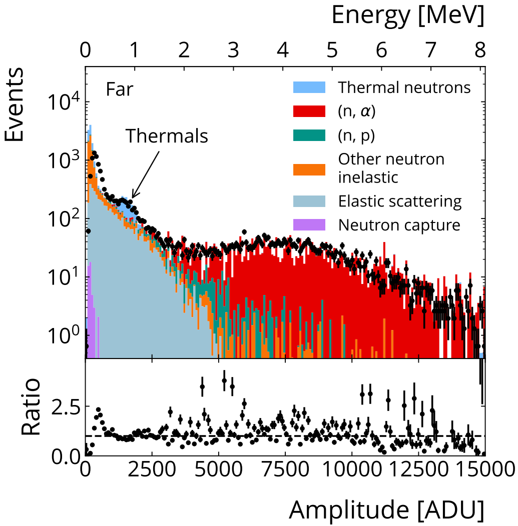
Graphite stack - 1.5 bar, 4500V





- Impurities in the gas emitted by filter (Radon) actually quite useful to calibrate the detector!
- Paper very soon!

- We can also produce neutrons at the MC40 cyclotron
- Deuteron beam on a Beryllium target to produce fast neutrons with energies up to 10 MeV
- Can place various moderators in the beam (paraffin, boron doped polyethylene, lead)
- Make comparisons with our simulation framework (preliminary results)!



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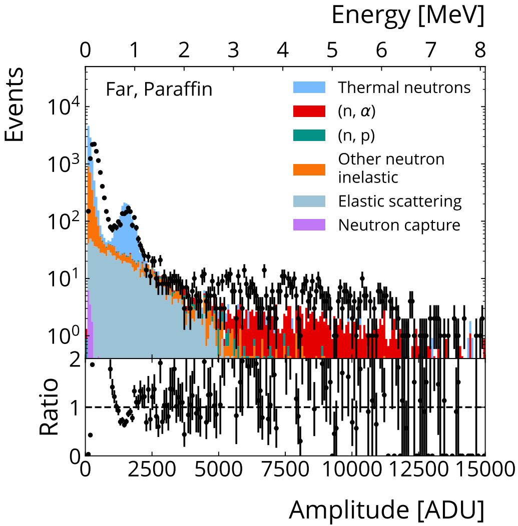


What else?

- Many experiments are searching for $0\nu\beta\beta$ decay

Requirements for a $0\nu\beta\beta$ experiment

1. **Low background** Low rate of signal events requires as small a background as possible
2. **Large isotope mass** Limits on $0\nu\beta\beta$ half-life require large isotope masses
3. **Good energy resolution** Essential to discriminate the $0\nu\beta\beta$ signal from the $2\nu\beta\beta$ background

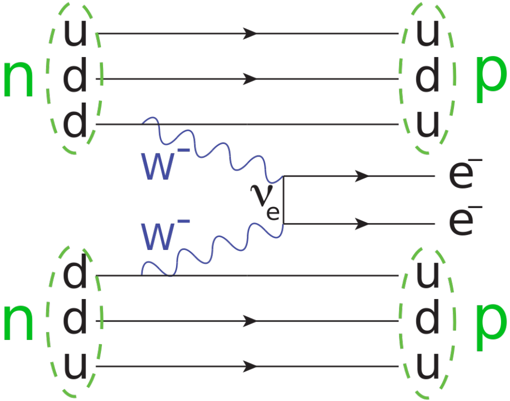
Properties of Spherical Proportional Counters

1. **Low background** a) Spherical shape has the optimal surface-to-volume ratio, b) Very low material budget c) Radial discrimination through pulse analysis
2. **Large isotope mass** Large masses of extremely pure gaseous isotopes can be achieved through high pressure operation
3. **Good energy resolution ???**

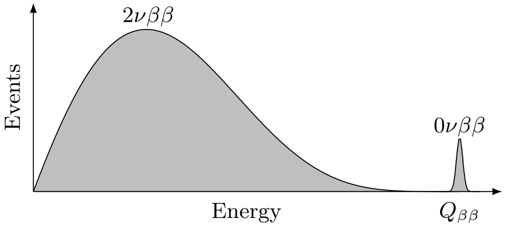
- SPCs good $0\nu\beta\beta$ detectors? Conceptual design investigated in detail in JINST 13 (2018) 01, P01009

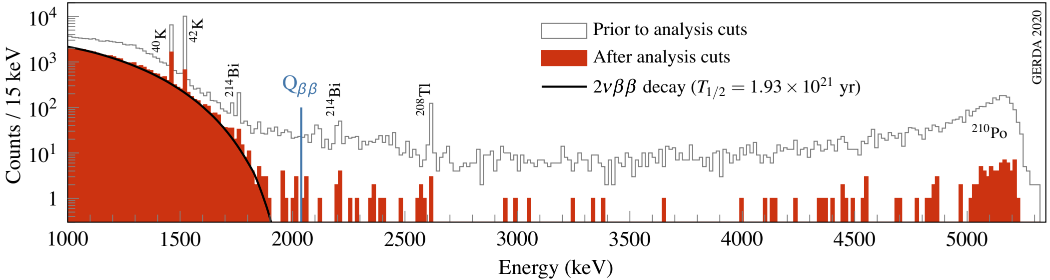
Neutrinoless double beta decay

- Neutrinos have mass and oscillate between flavours! Right-handed neutrinos?
- Majorana proposed that neutral particles can be their own anti-particles
- If this is the case then we can introduce neutrinoless double-beta decay
- Such a process would violate lepton number and may help to shed light on the matter–anti-matter asymmetry of the universe



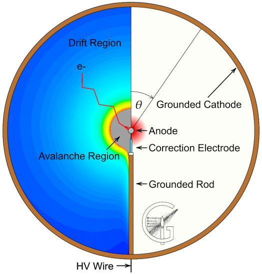
- Measure the energy of two electrons
- If there is $0\nu\beta\beta$ then we expect a peak at the *Q*-value of the process, compared with a continuous spectrum from $2\nu\beta\beta$
- Example below from the GERDA experiment

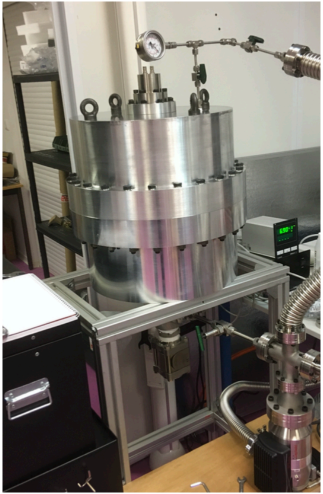




The R2D2 project

- R2D2 (Rare decays with a radial detector) is an R&D project to investigate using a Xenon filled SPC to search for $0\nu\beta\beta$





The initial goal of the project is to demonstrate the required energy resolution to search for $0\nu\beta\beta$ can be achieved (1% FWHW at $Q_{\beta\beta}$ of 2.458 MeV)

Experimental setup

R2D2 spherical TPC: first energy resolution results

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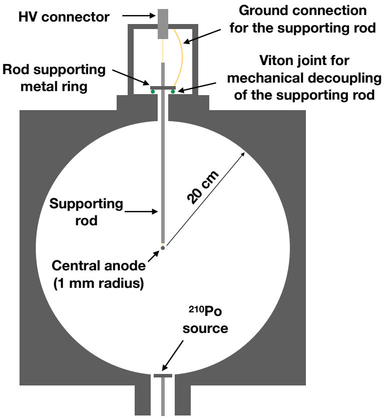
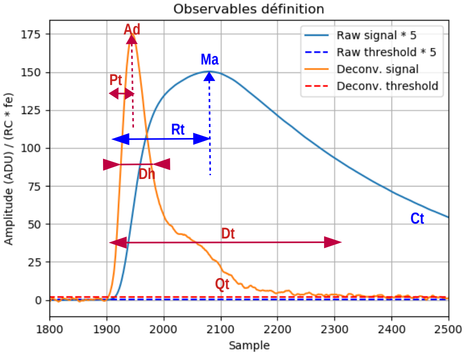
[f] *SUBATECH, IMT-Atlantique, Université de Nantes, CNRS-IN2P3, France*

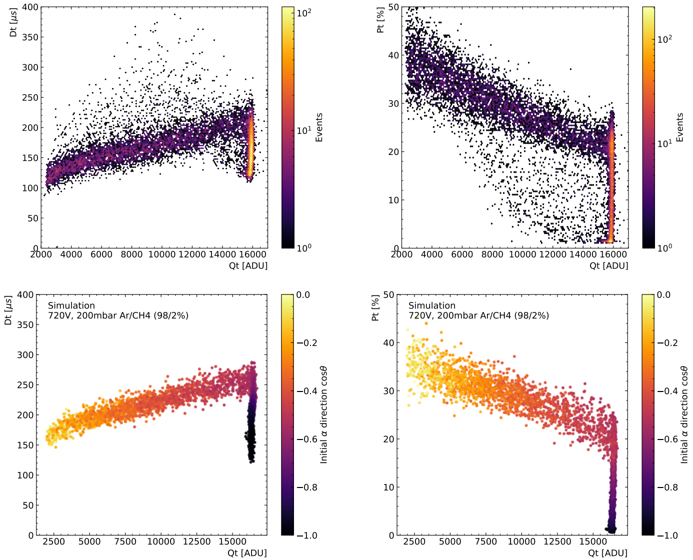
- To investigate whether the desired energy resolution can be achieved a 20 cm radius aluminium SPC has been produced and operated at CENBG in Bordeaux
- The detector was filled with a mix of Argon/CH_4 (98/2%)
- An α particle source (^{210}Po) was used, producing α particles with $E = 5.3$ MeV



Results (i)

- Measured data are compared with simulation results using ▸ JINST 15 (2020) 06, C06013
- Good agreement
- Pulse properties can be used to select specific events

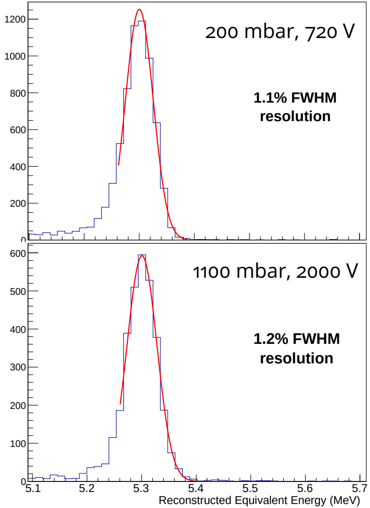




Results (ii)

Resolution measurement

- The energy resolution is measured to be $\approx 1.1\%$ FWHM at 5.3 MeV
- Scaling to the $Q_{\beta\beta}$ of ^{136}Xe gives a resolution of 1.6%
- W-value and Fano factor of Xenon more favourable than Argon
- Tested at two different pressures (track lengths varying from a few to 20 cm). Results independent of track length.
- Promising first results!

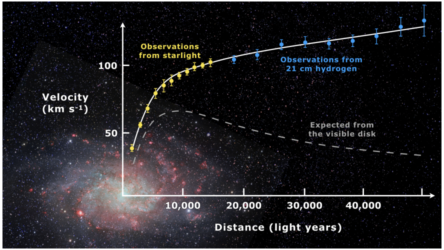


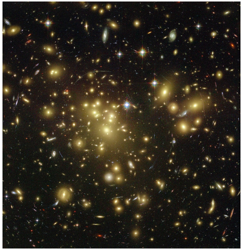
Summary

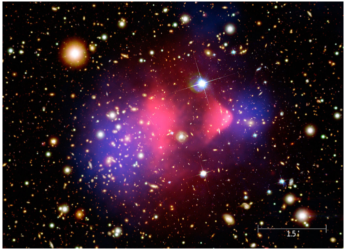
- The Birmingham gas lab is involved in a wide range of activities. **Not just Dark Matter!**
- **MIGDAL** experiment will start taking data very soon!
- **NEWS-G** experiment in place in SNOLAB, calibration underway and physics runs expected shortly!
- The **ECUME** project will result in a fully electroformed detector
- We hope that **DarkSPHERE** will bring a world-leading dark matter experiment to the UK!
- **Neutron measurements** have been performed here in Birmingham – expect papers on the graphite stack and cyclotron measurements in the coming weeks/months!
- The **R2D2** project is continuing to study the suitability of an SPC for $0\nu\beta\beta$ decay searches. Recently demonstrated adding light readout to an SPC

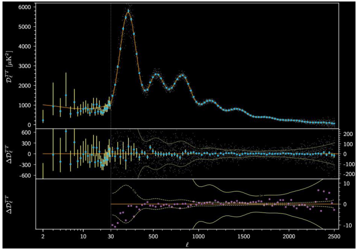
Back-up

Evidence for Dark matter



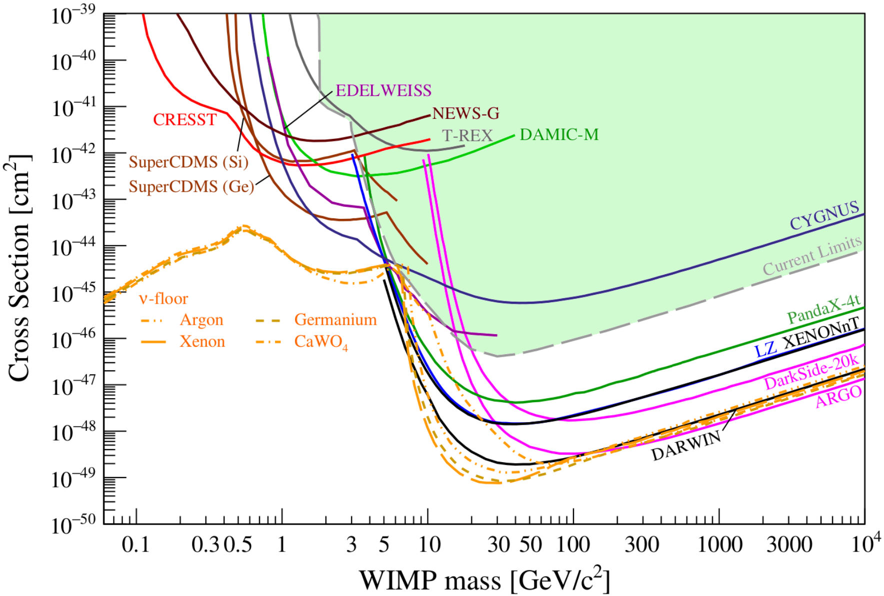




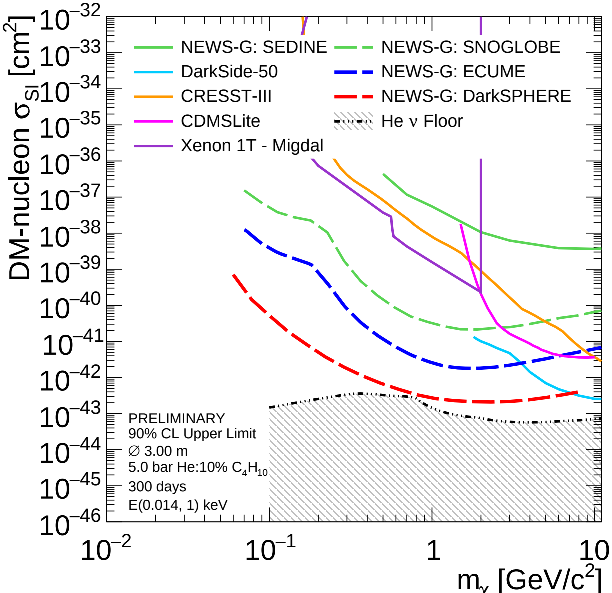


- Galactic rotation curves
- Lensing
- Bullet cluster
- ΛCDM

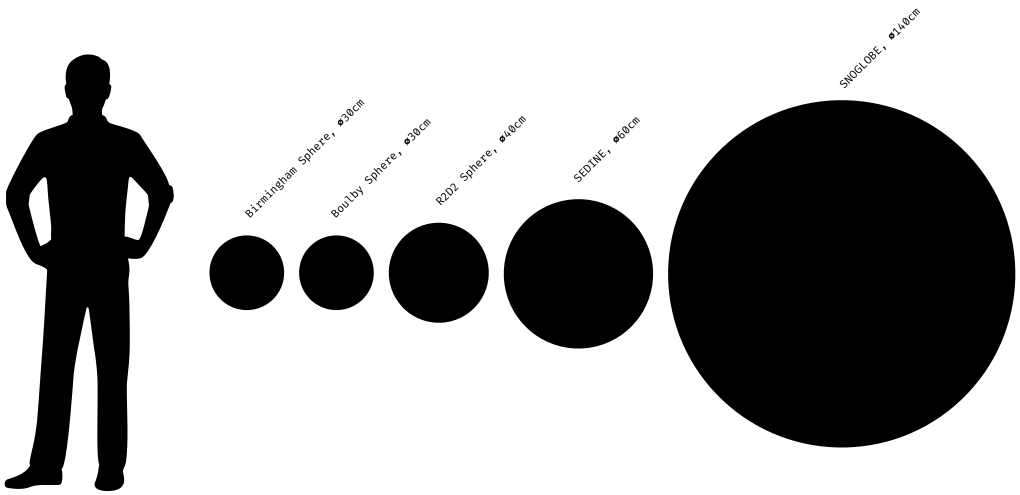
Future DM detectors



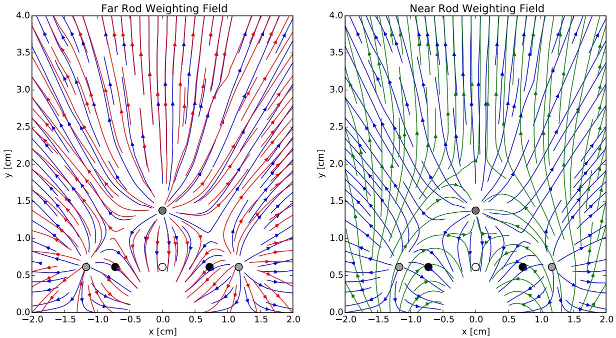
DarkSPHERE projection



The SPC landscape



Achinos weighting fields

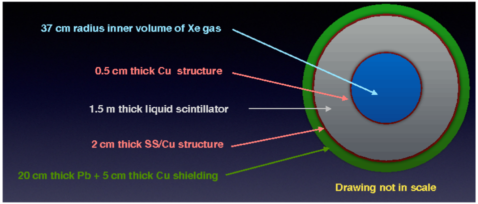


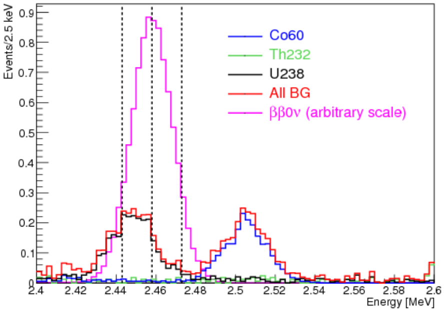
Current on electrode from Ramo-Shockley theorem

$$i_n = -q \frac{\vec{E}_w^n \cdot \vec{v}}{V_w^n} \tag{1}$$

Direction of $\vec{v}$ is the same as the electric field of the detector. Focus on top anode, $\vec{E}$ and $\vec{E}_w^{\mathrm{far}}$ are in same direction. $\vec{E}$ and $\vec{E}_w^{\mathrm{near}}$ are in opposite directions $\therefore$ opposite currents

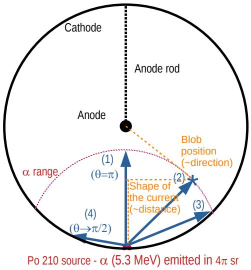
Proposed detector

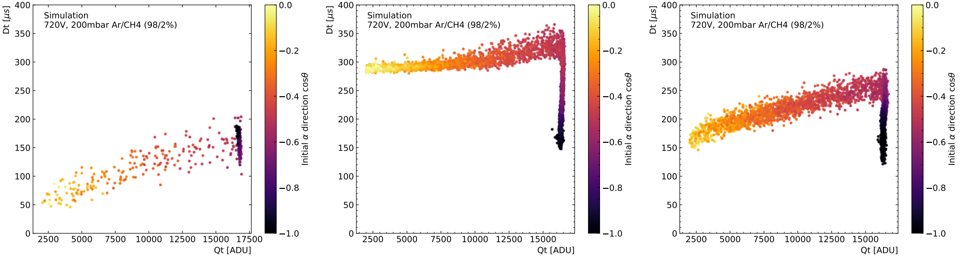




The setup of the detector studied and the most relevant expected backgrounds for one year of data taking

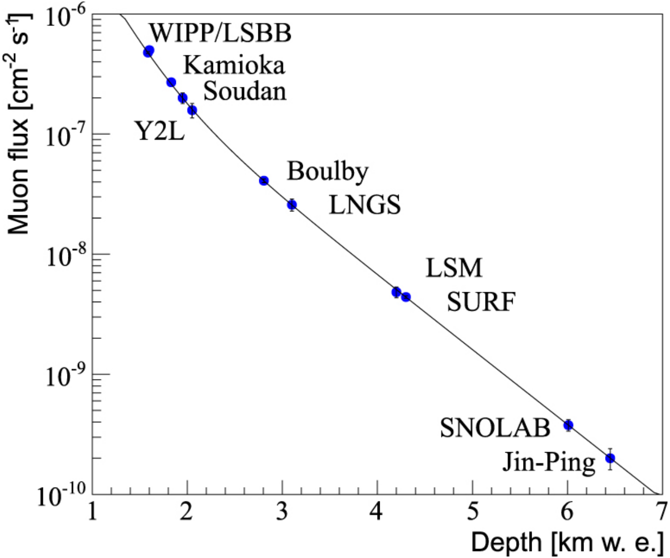
- Interesting lessons learnt during the process of producing the “final” comparison seen on the previous slide
- Diffusion and noise have large impacts on the Dt distribution





Labs

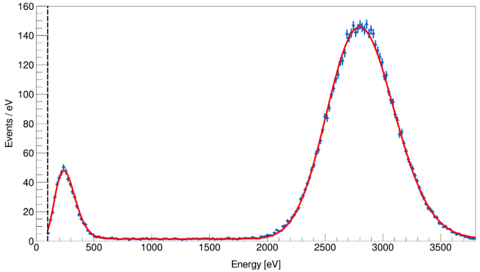
J.Phys. G43 (2016) 013001

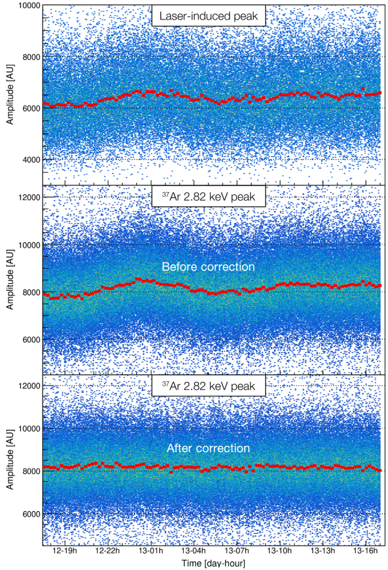


Monitoring & Calibration

Phys. Rev. D 99, 102003

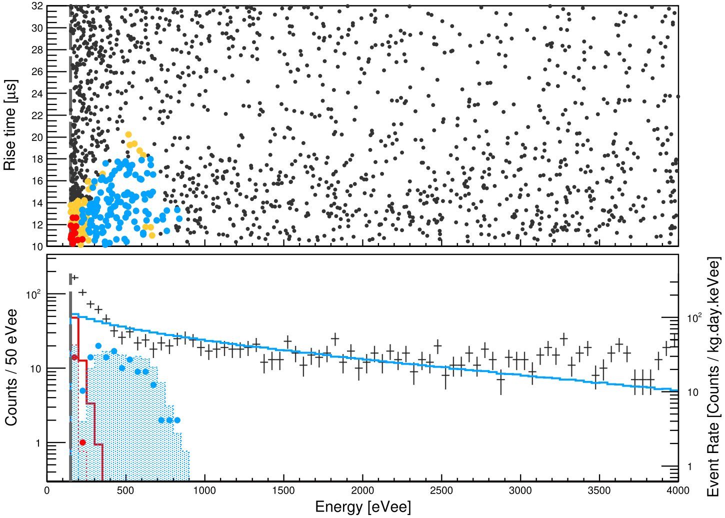
- Detector stability is monitored using a laser system
- Can be used to calibrate the detector
- ^{37}Ar calibrations are performed at the end of runs

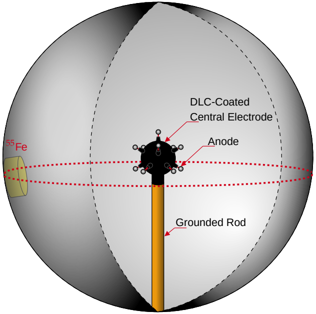




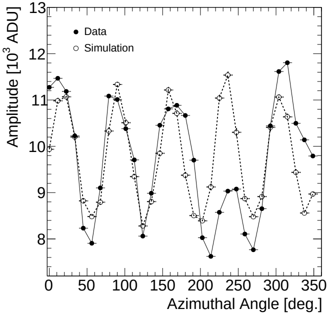
SEDINE analysis

Astropart. Phys. 97, 54 (2018)





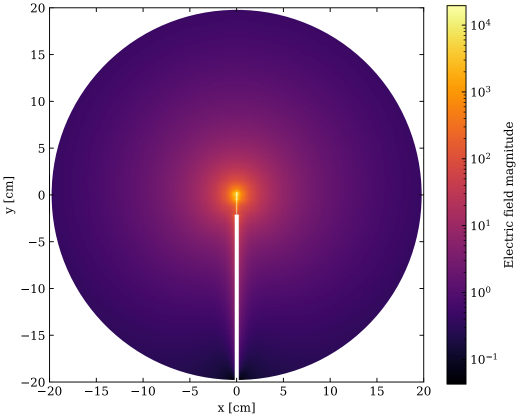
- Studied achinos ϕ dependence for **JINST 15 (2020) 11, P11023**
- 3D printed DLC sensor, 11 1mm diameter anodes in 30cm diameter SPC
- Here an ^{55}Fe source has been moved around the detector (at the same latitude)



- Gain changes versus ϕ
- Lines up with which anode the source is closest too
- Gain variation is well reproduced by the simulation!
- We can show with simulation this can be corrected by applying different voltages to each side of the achinos

Simulation outline

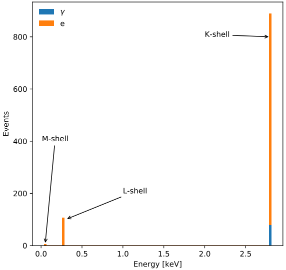
- Our simulation framework combines
  - ▸ Geant4, for simulating the interactions of particles/radiation with matter
  - ▸ Garfield++, for simulating the electron-ion drift and signal calculation (interfaces to Heed, SRIM and Magboltz)
  - ▸ ANSYS, finite-element software, for electric field calculations
- Our framework uses these toolkits, along with custom calculations, to produce a complete simulation

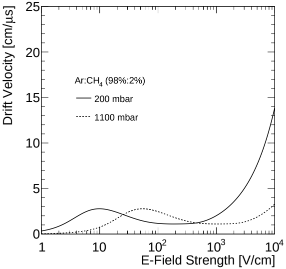


▸ JINST 15 (2020) 06 C06013

Simulation: Initial particle tracking, ionisation and drift

- We use Geant4 to create and track our initial particles we want to study
- Geant4 tracks these through the detector until it produces electrons with $E < 2$ keV
- At this point Garfield++ takes over
- δ-electrons are produced (HEED), and then all the electrons are drifted in the detector using ANSYS and Magboltz





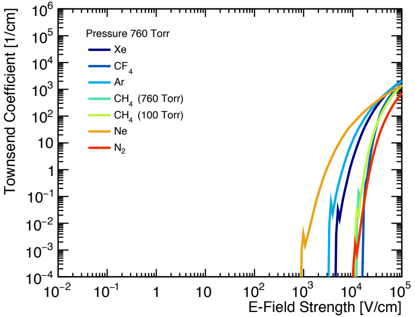
Simulation: Avalanche

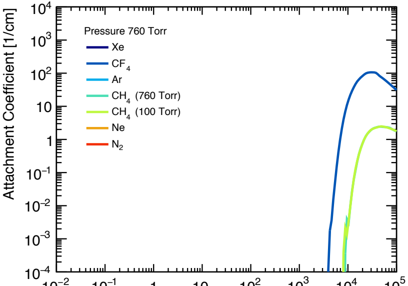
Ansys

- Close to the anode, where the electric field is strongest, the electrons avalanche, producing electron-ion pairs
- Depending on the properties of the detector, this process can produce 10,000s of electrons
- Tracking each one of these becomes extremely computationally expensive
- Instead we parameterise the gain by numerically integrating the townsend coefficient (minus attachment) along the path of each primary electron

$$\overline{G} = \exp\left(\int_{\vec{r}} \alpha(\vec{r}) - \eta(\vec{r})\mathrm{d}\vec{r}\right)$$

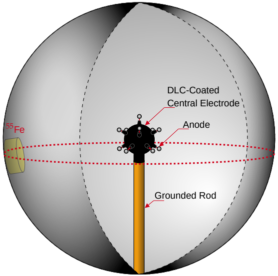
- Electron multiplication then follows a Polya distribution



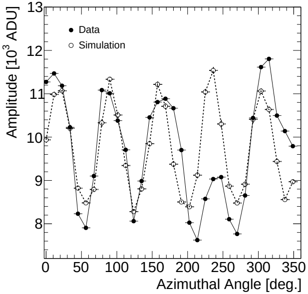


ACHINOS

arXiv 2003.01068



- Studied achinos phi dependence in the context of arXiv 2003.01068
- 3D printed DLC sensor, 11 1mm diameter anodes in 30cm diameter SPC
- Here an ^{55}Fe source has been moved around the detector (at the same latitude)



- Gain changes versus ϕ
- Lines up with which anode the source is closest too
- Gain variation is well reproduced by the simulation!
- Gain is higher when source inline with rod-side anode

arXiv 2003.01068

- We investigated what happens when different voltages are applied to either side of the achinos
- Able to flatten out the gain fluctuations to a large extent with a rough tuning
- Can expect a fine-tuning can lead to uniform gain in near and far sides of the detector
- Could potentially even calibrate each anode individually