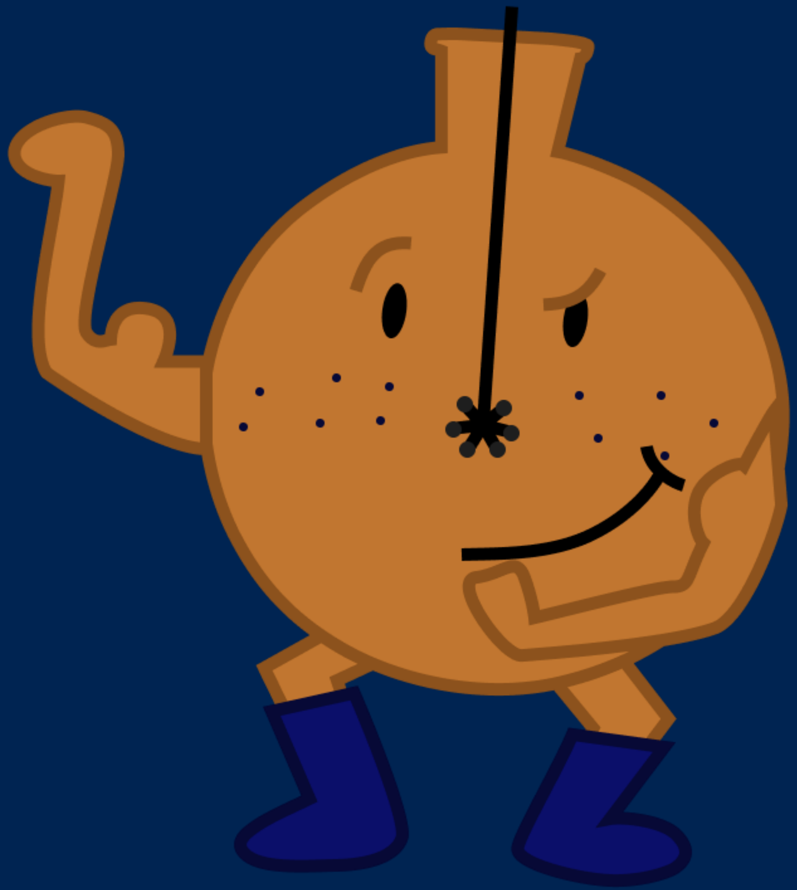
The NEWS-G experiment

Jean-Marie Coquillat

EIEIOO 2024, Kingston

May 13th, 2024

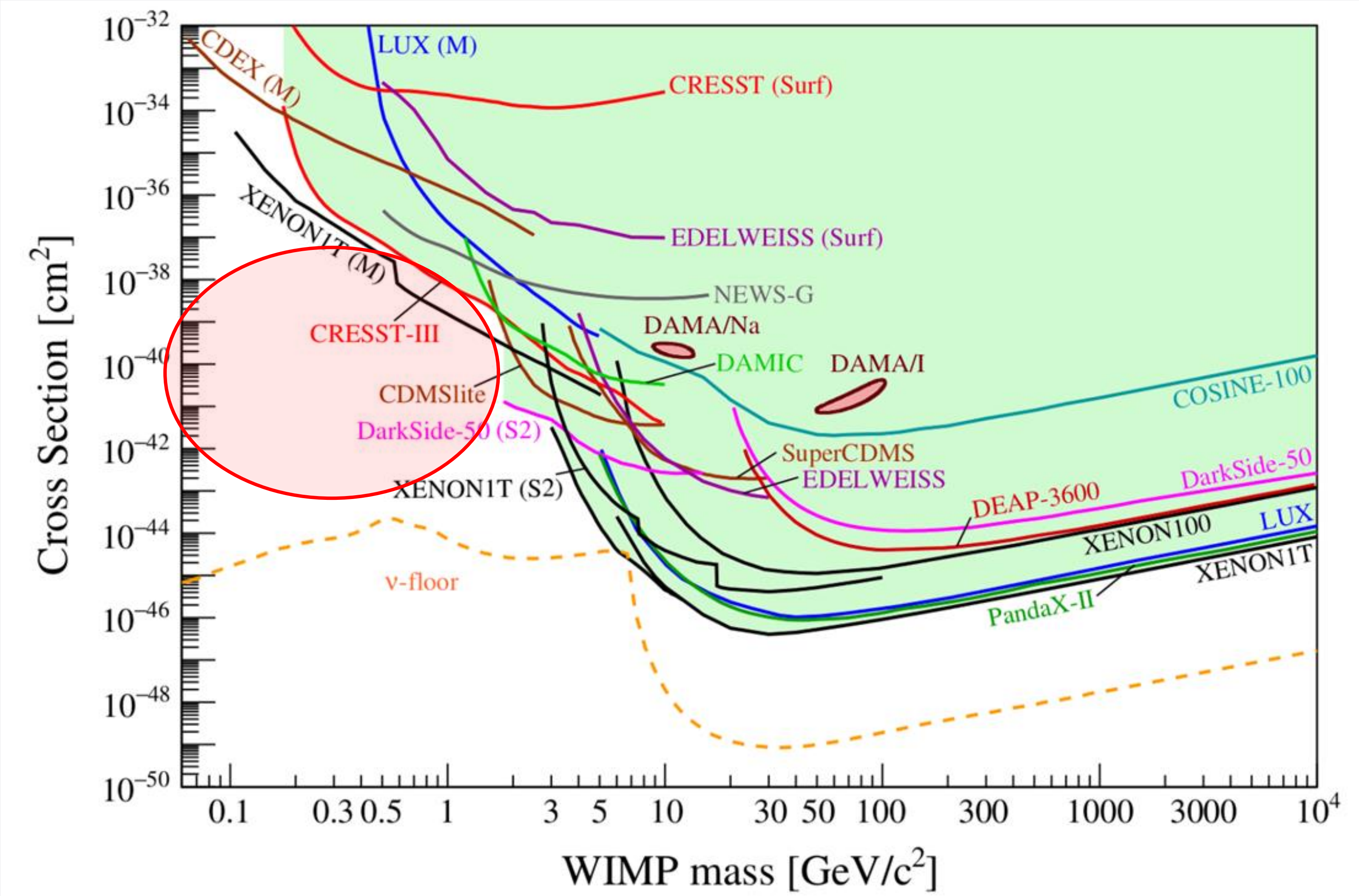


Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Queen's University

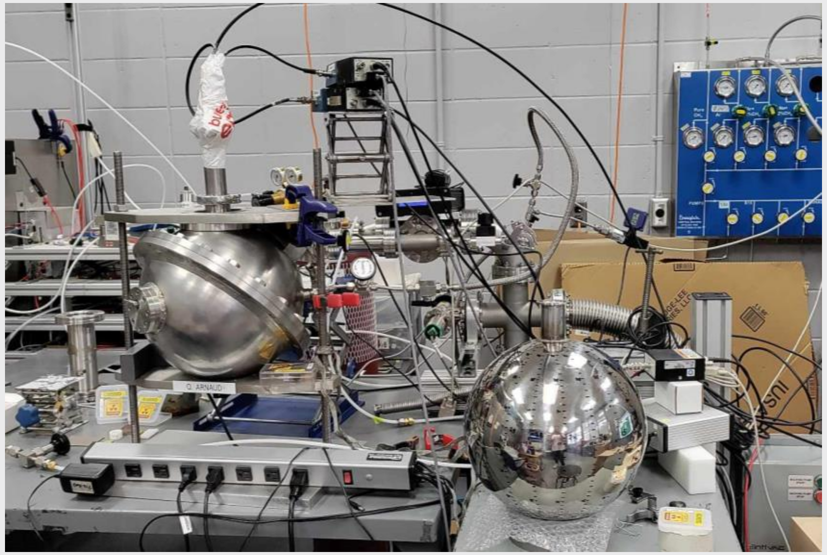
Low mass WIMP search motivation

Given the absence of canonical WIMPs, there is motivation to look at the parameter space left at lower masses (~0.1-1 GeV) for WIMP-like dark matter candidates.

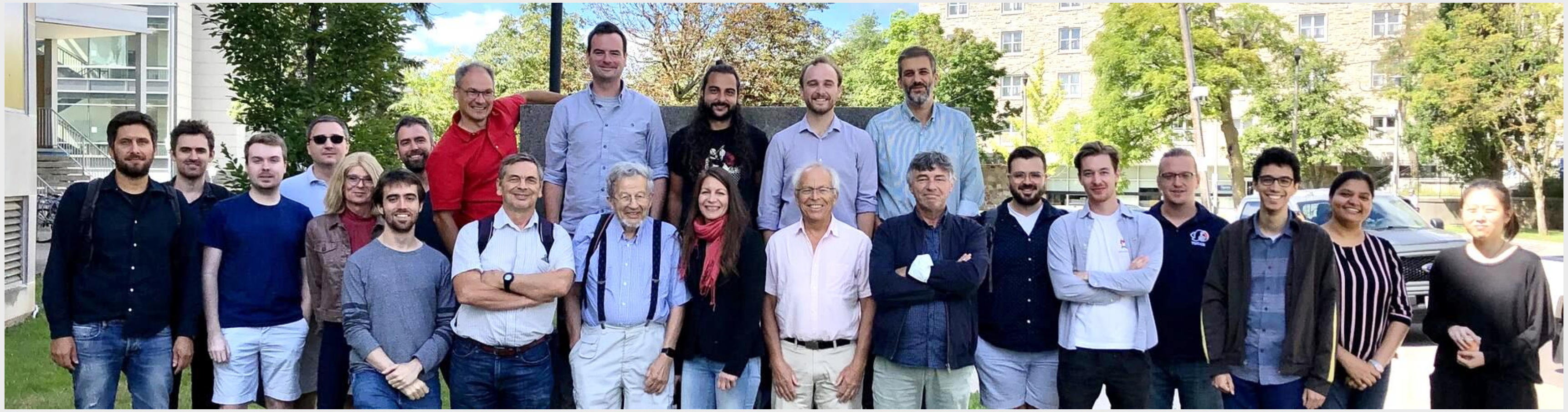


arXiv:2104.07634 [hep-ex]

NEWS-G and SPCs

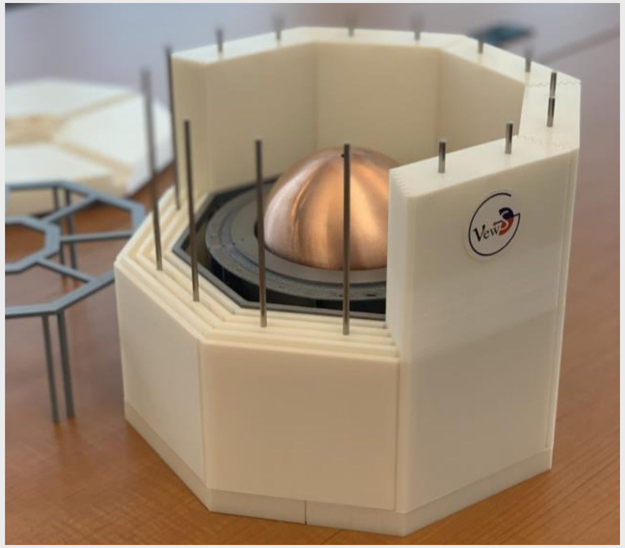


- The NEWS-G experiment uses spherical proportional counters (SPC) to search for low mass dark matter.
- SPCs are metallic spheres filled with gas, with a central anode producing a radial electric field.
- Advantages of SPC:
  - Very low threshold (single-ionization)
  - Can use different gases
  - Sphere provides optimal volume/surface ratio



NEWS-G and SPCs

- The last dark matter limits are from the SEDINE detector (60 cm diameter) at the *Laboratoire Souterrain de Modane* (LSM) in 2017.
- There was 42 days of data with neon + 0.7% of methane at 3.1 bars.
- The latest detector, S140 (or SNOGLOBE), is a 135 cm of diameter copper sphere currently at SNOLAB, after a short commissioning at the LSM in 2019.
- SNOLAB commissioning of S140 started in 2022.



S-140 detector model

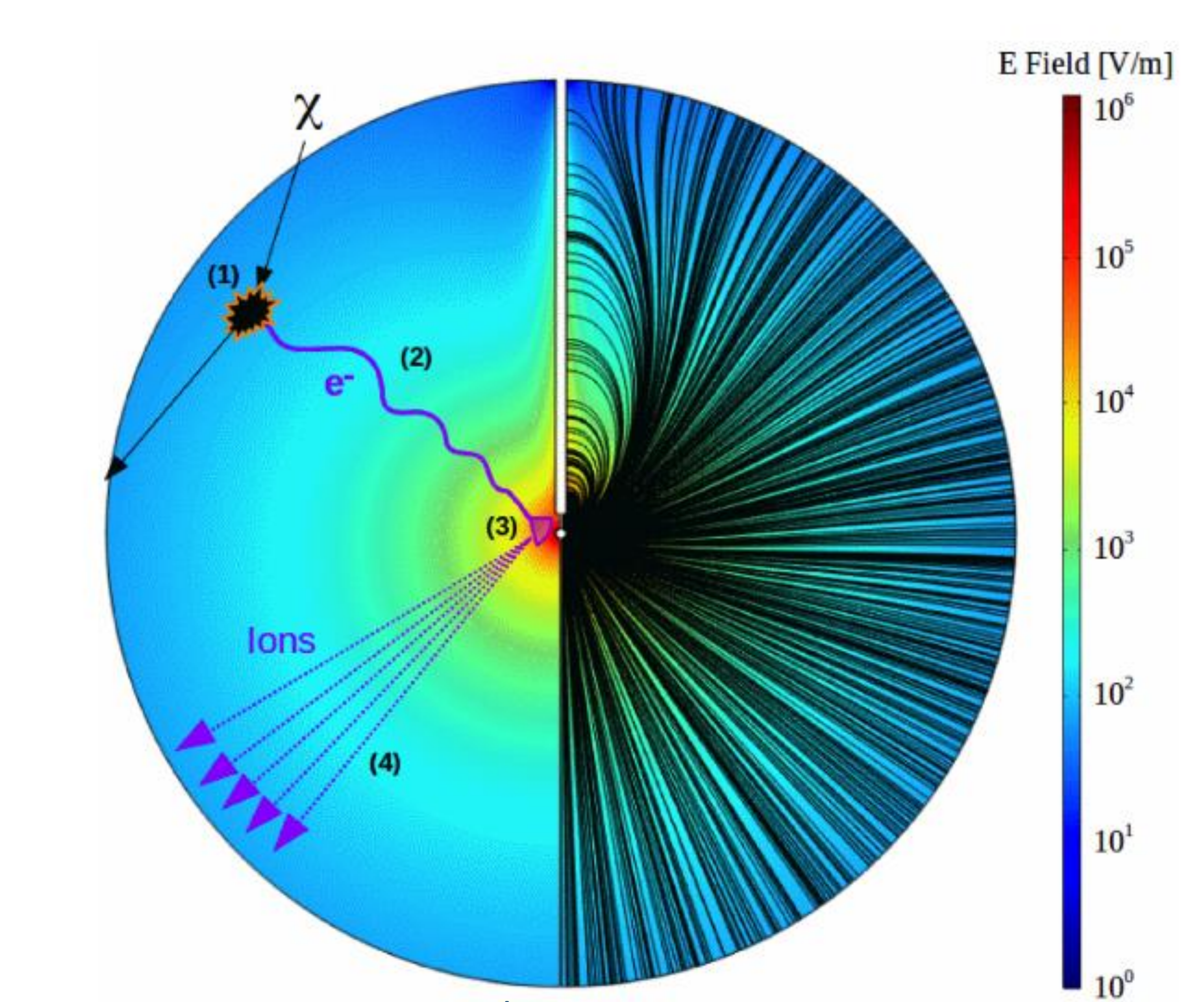
The SEDINE detector

doi: 10.1016/j.astropartphys.2017.10.009

Queen's UNIVERSITY

How an SPC works:

1. Atomic recoil causes ionization of the gas.
2. Primary electrons drift towards the central anode.
3. Townsend avalanche near the anode amplifies the signal.
4. Drifting secondary ions induce a current on the anode.



doi: 10.1016/j.nima.2019.162390

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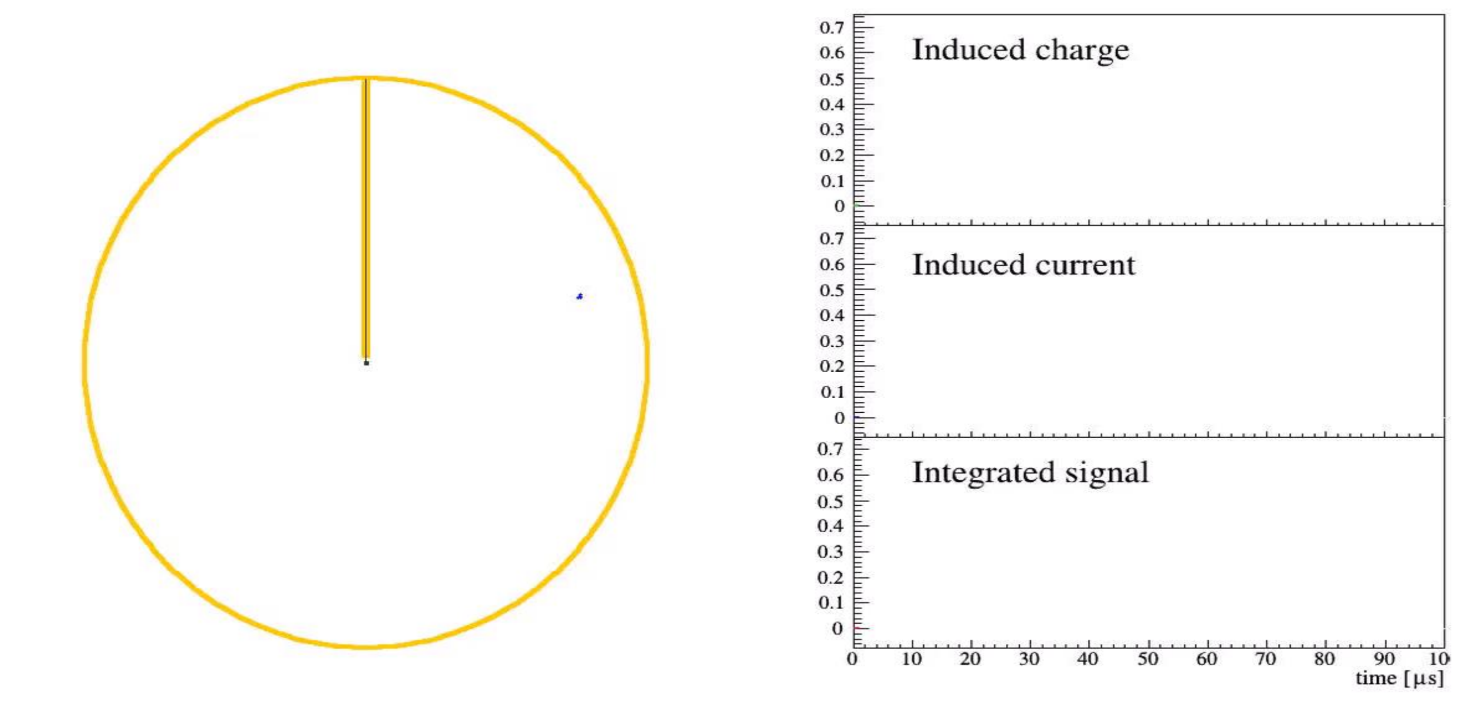
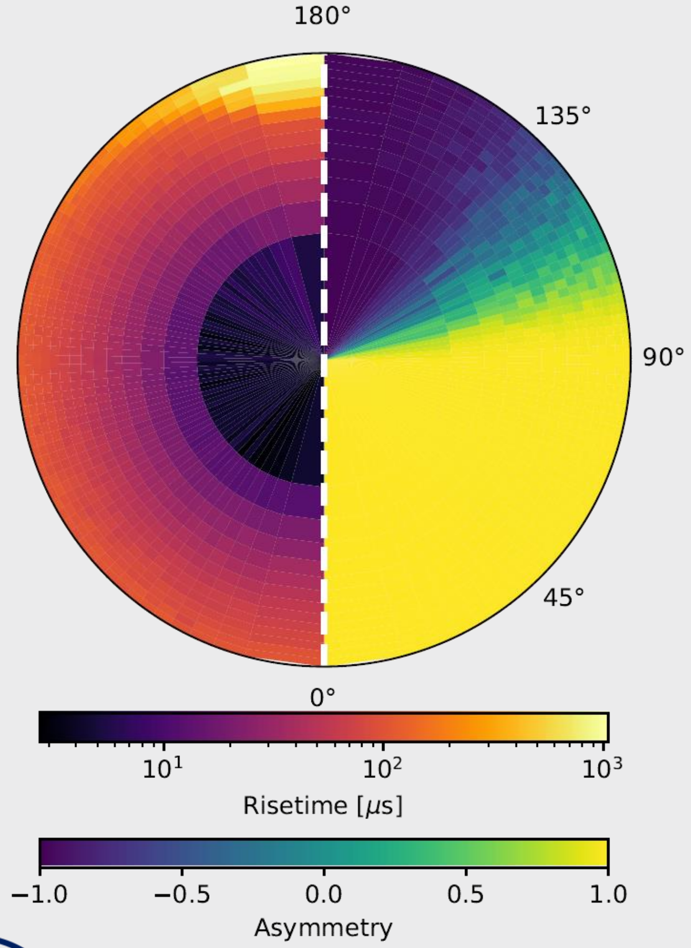


Animation by Philippe Gros

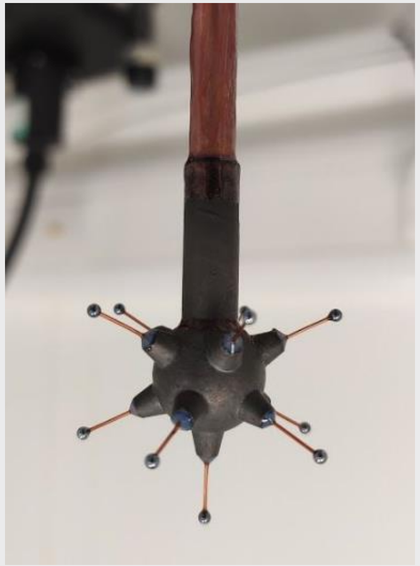
Sensor (achinos)

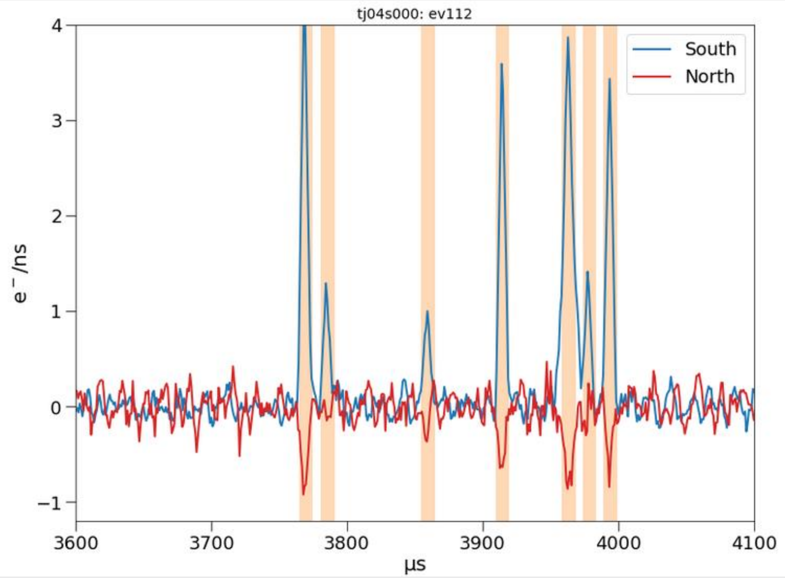
- NEWS-G now uses a multi-anode sensor that can achieve high gain while keeping a strong electric field at a high radius.
- The sensor is divided in two channels connecting the anodes of each hemisphere.
- A signal on one channel induces a negative signal on the other one (Shockley-Ramo effect).
- About 2/3 of the volume leads to the south anodes, due to the effect of the rod on the electric field.

arXiv:2301.05183



doi:10.1088/1742-6596/2156/1/012059





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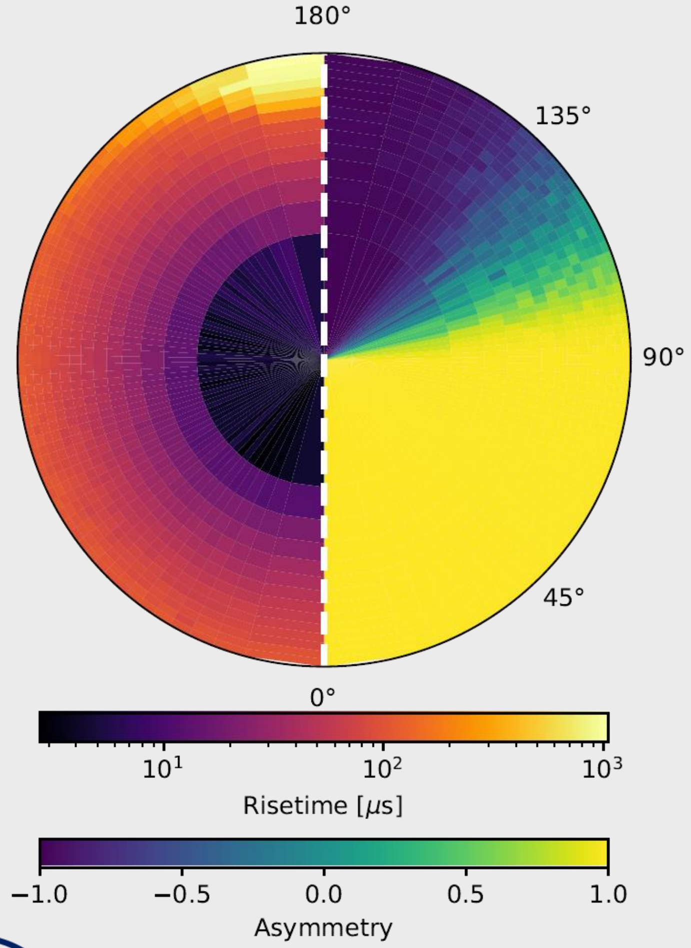

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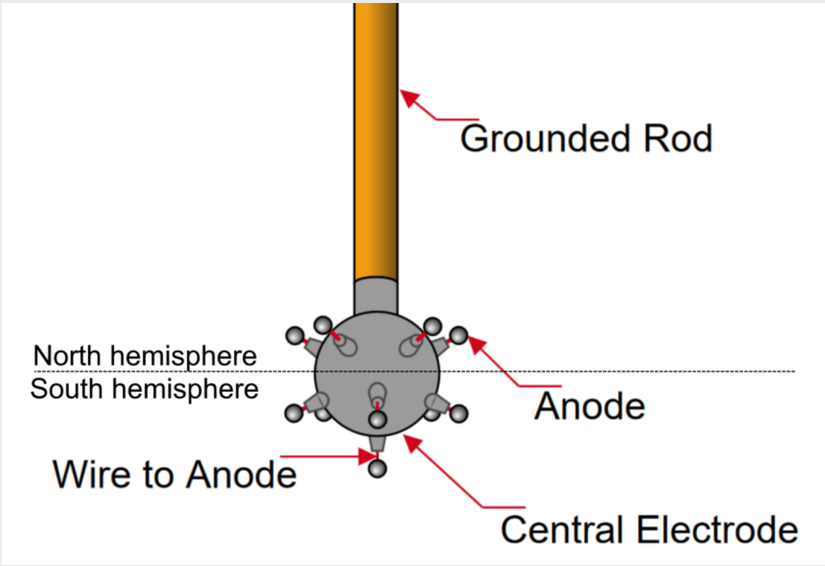

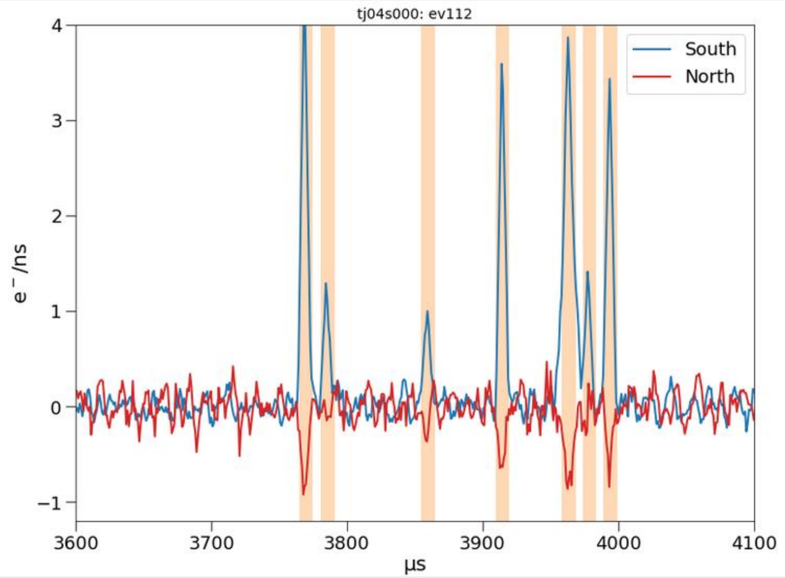

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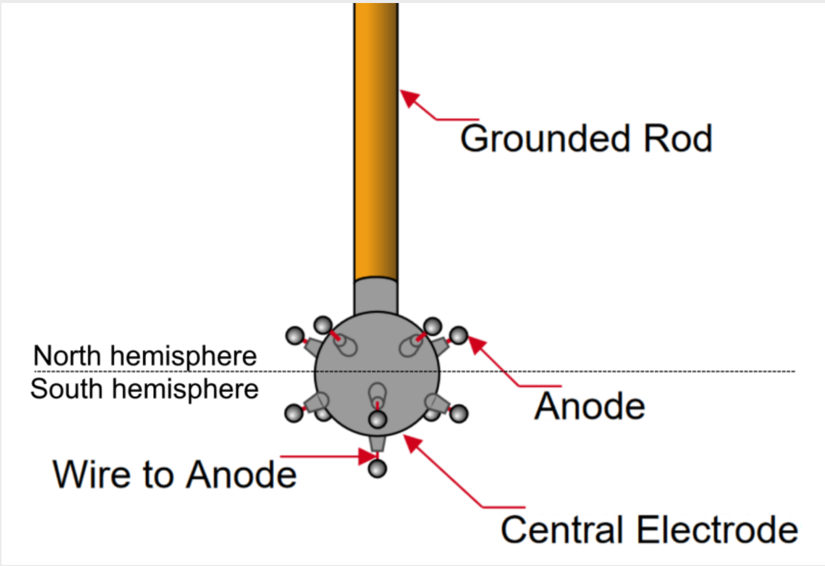

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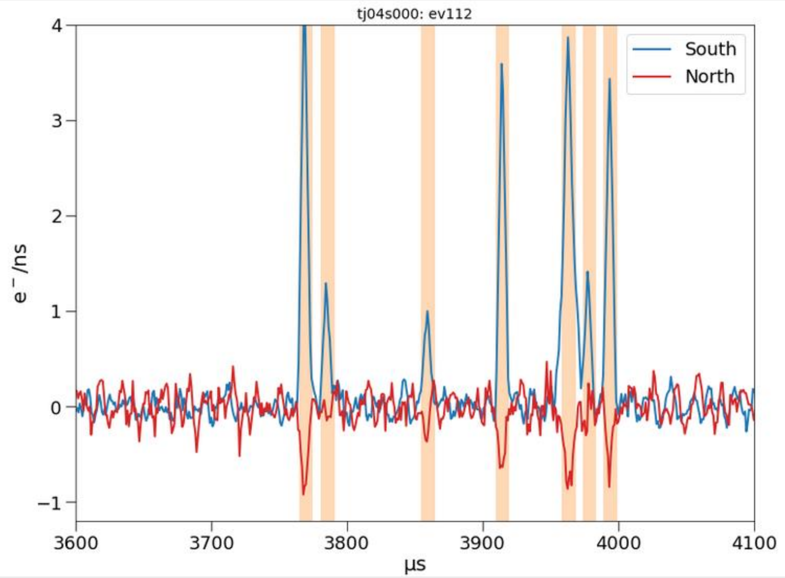
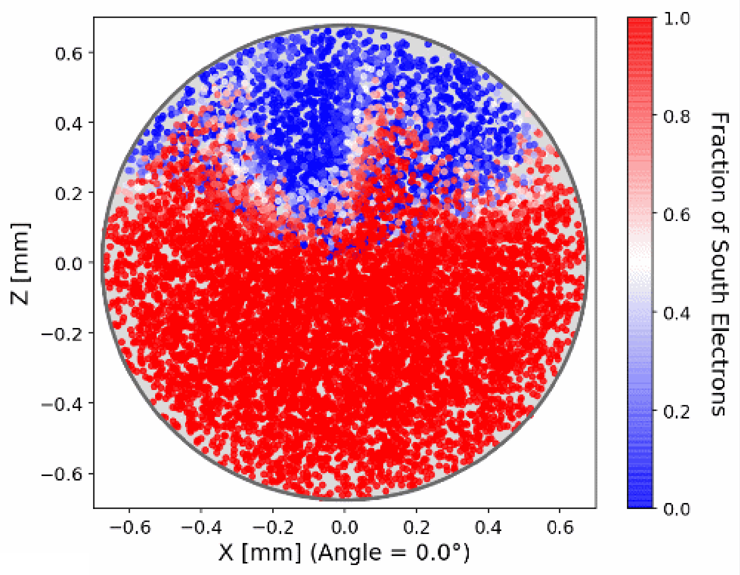
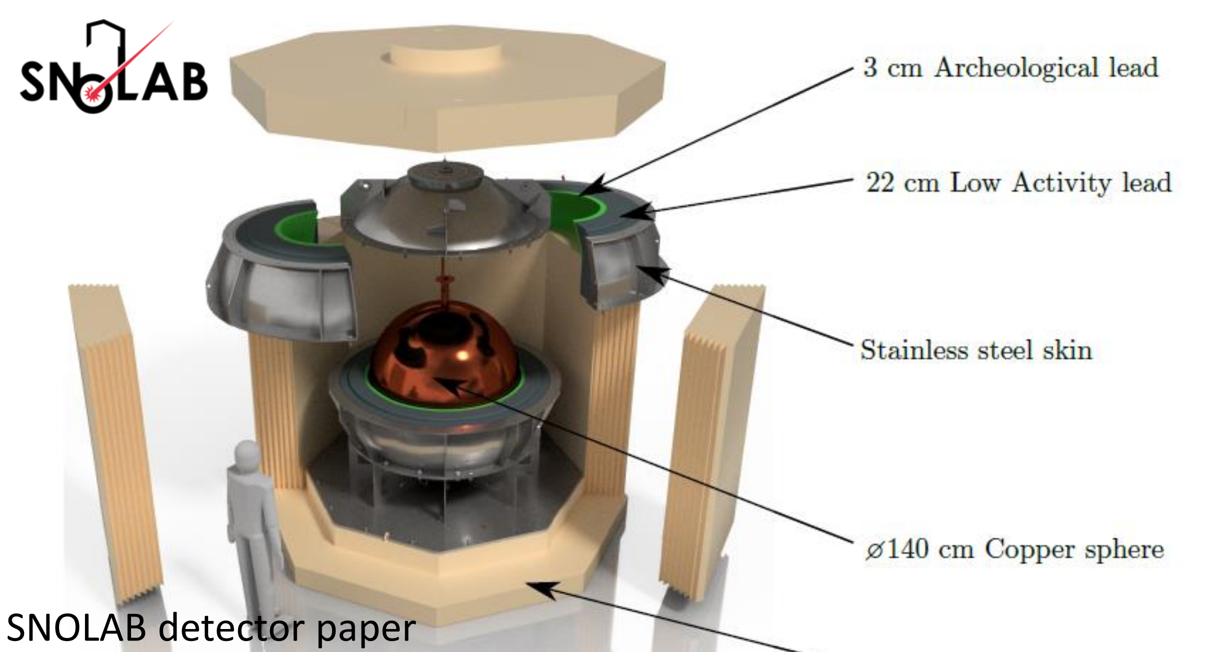




Only pure south events were kept as candidate events.

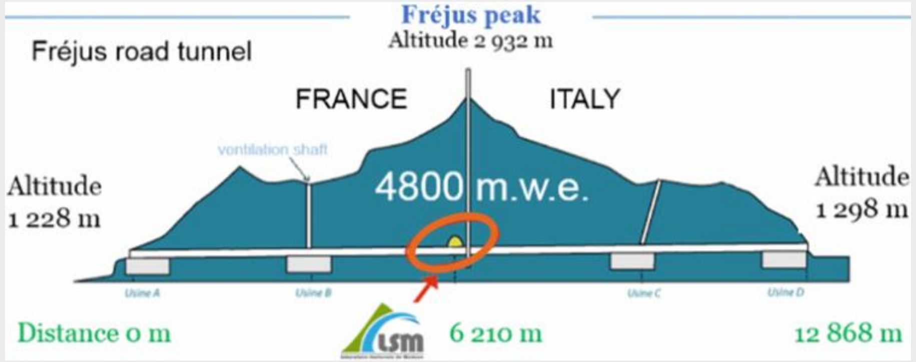
Shielding and data taking with S140

- The sphere is made of C10100 copper, with the inner 0.5 mm being electroformed ultra-pure copper.
- Lead, archeological lead and polyethylene (PE) make the shielding, although water was used at the LSM since the PE shield was unfinished.
- 10 days of physics data taken in 135 mbar of CH_4 at the LSM before the detector was shipped to SNOLAB.



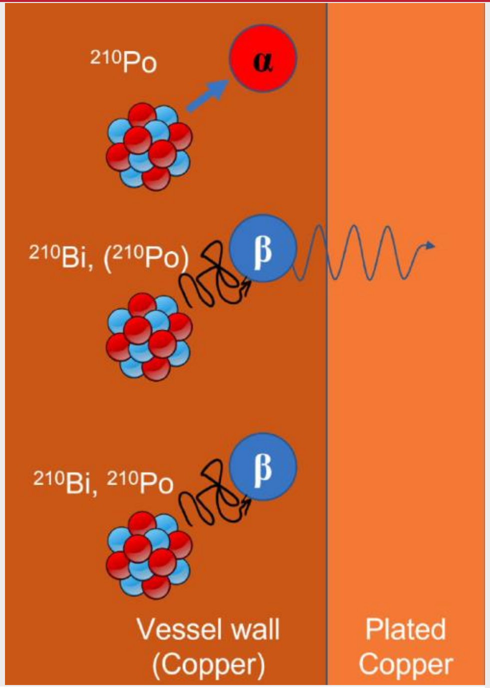
SNOLAB detector paper
doi:10.1088/1748-0221/18/02/T02005

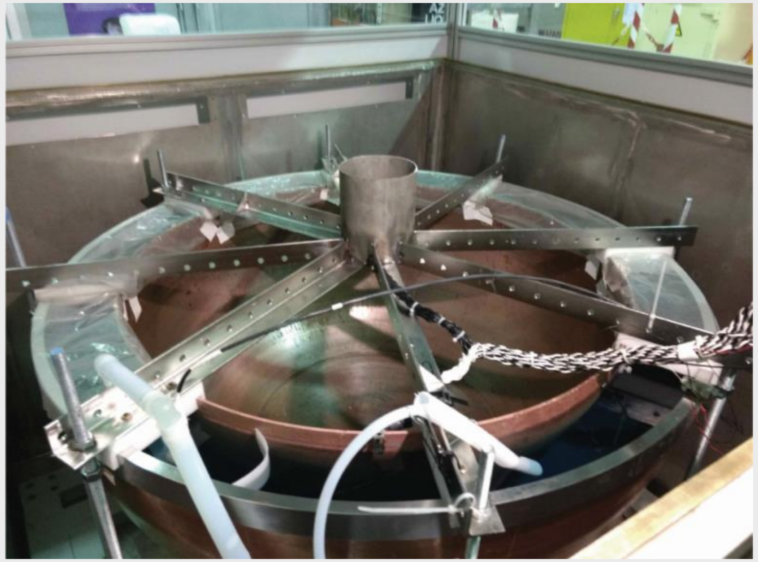
Laboratoire Souterrain de Modane (LSM)

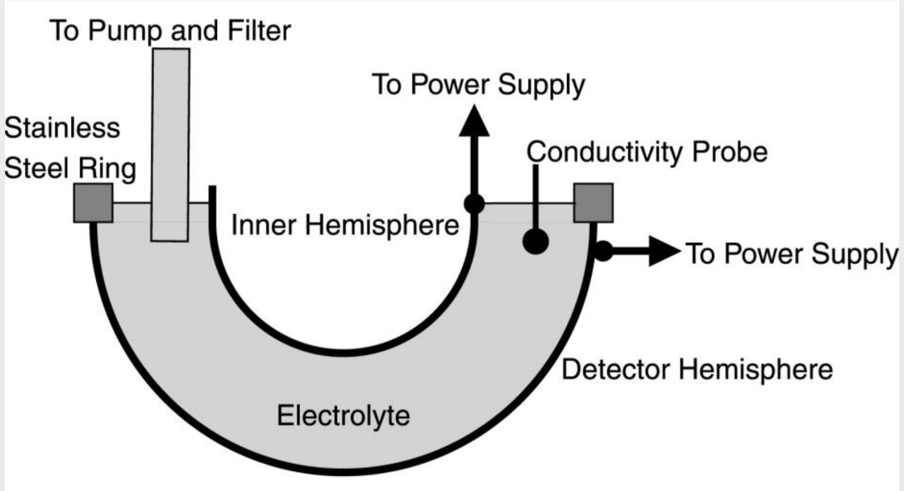


Copper electroforming

- Even the C10100 copper bulk contains traces of ^{210}Pb, which emits bremsstrahlung X-rays through their beta decay.
- The electroforming of the 0.5mm inner copper surface was done in collaboration with the Pacific Northwest National Lab at the LSM.
- This reduces the overall background by 98%, and the sub-keV background by 70%.

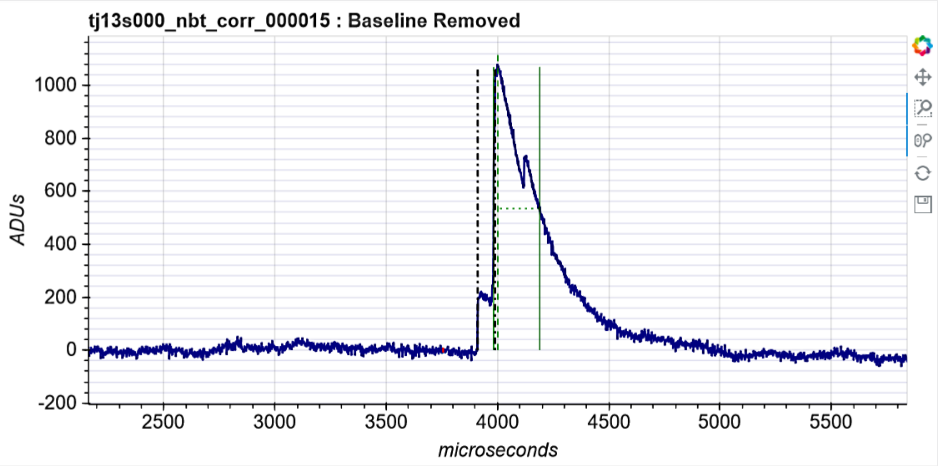






Double deconvolution

- Ionization equations: $\langle PE \rangle = \frac{E}{W(E)}$; $W_{nr} = \frac{W_\gamma}{QF(E)}$
- Primary ionization follows a COM-Poisson distribution, and the avalanche follows a Polya distribution.
- The exponential decay of the preamplifier and the ion response are deconvolved from the raw signal.
- The integrated double-deconvolved amplitude is proportional to the energy, while the rise time is a measure of the diffusion which relates to the event radial position.



DOUBLE-DECONVOLUTION

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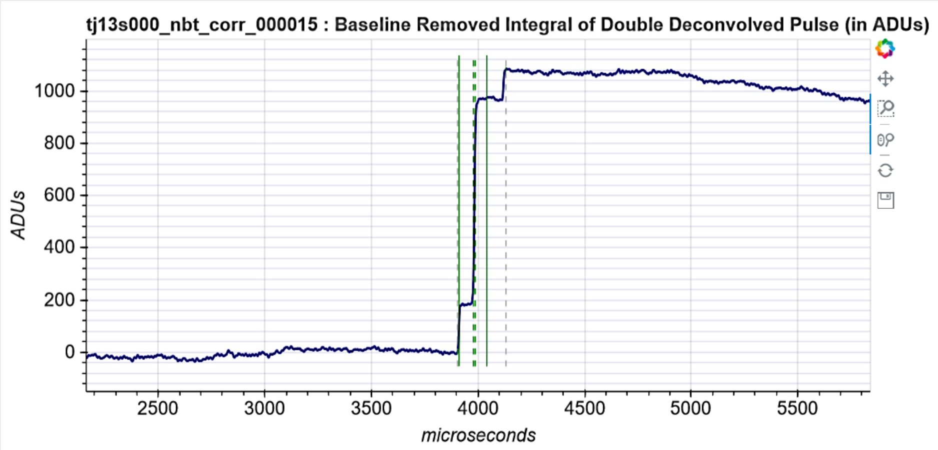
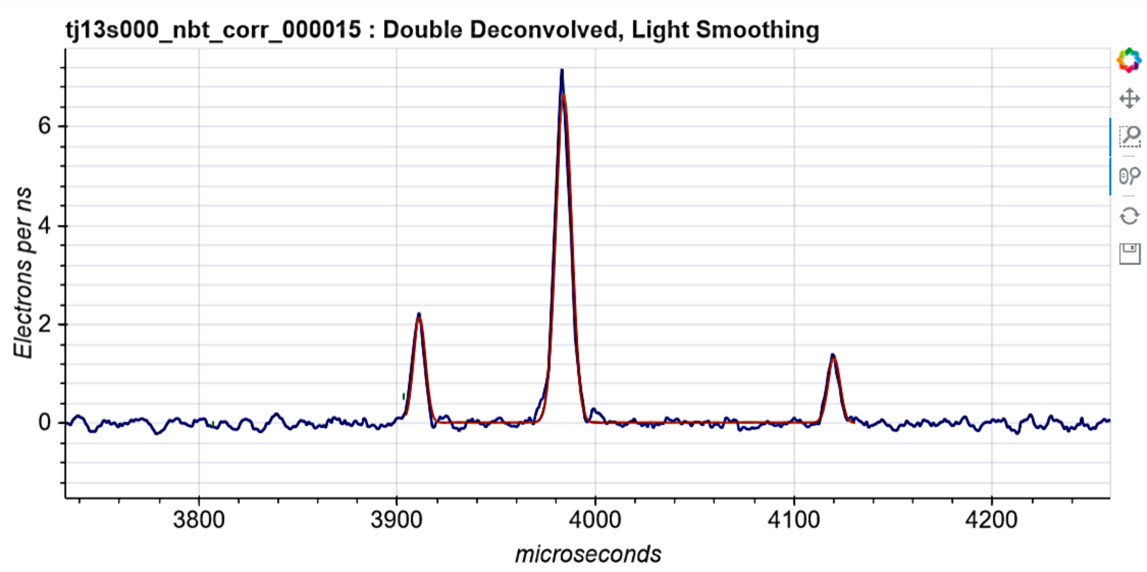
INTEGRATION

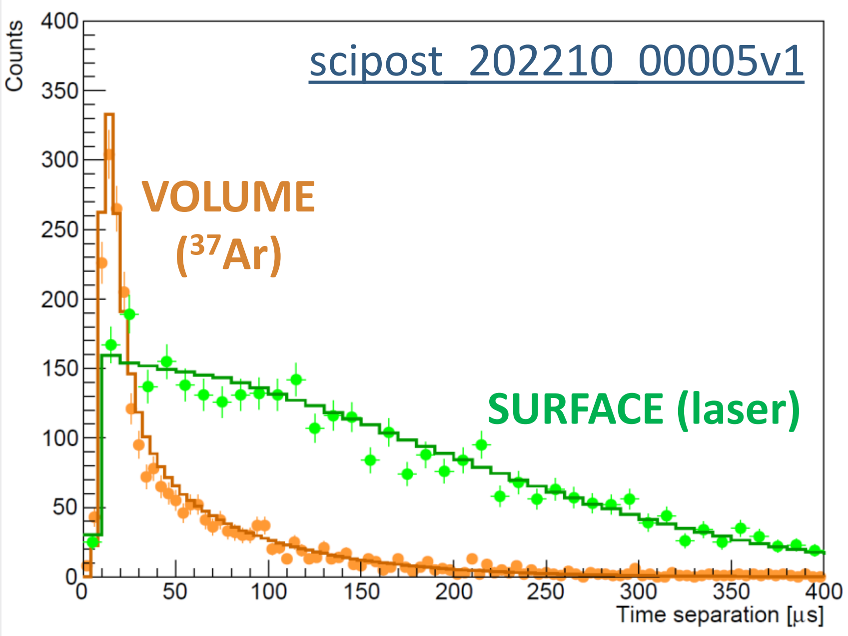
There is work on improving this using machine learning.



Peak counting and time separation

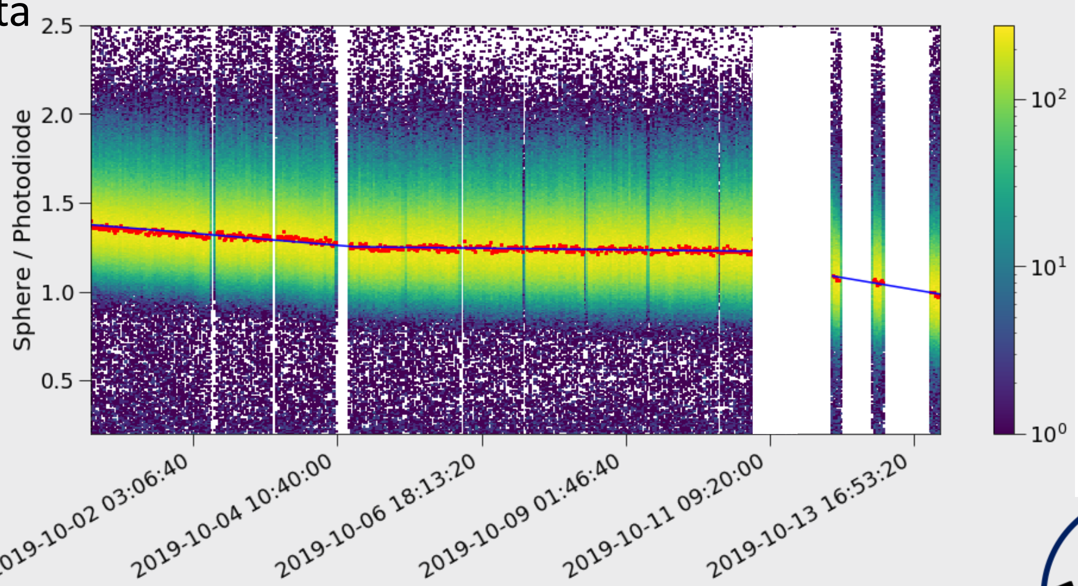
- With the large sphere of S140, it is possible to count individual primary electrons using ROOT TSpectrum.
- The single-electron trigger efficiency is 60%, with a noise trigger proportion around 10^{-4}.
- Surface events experience more diffusion than volume events, which causes the time separation between the first and last peak to be larger.
- The number of electrons is a measure of the energy.

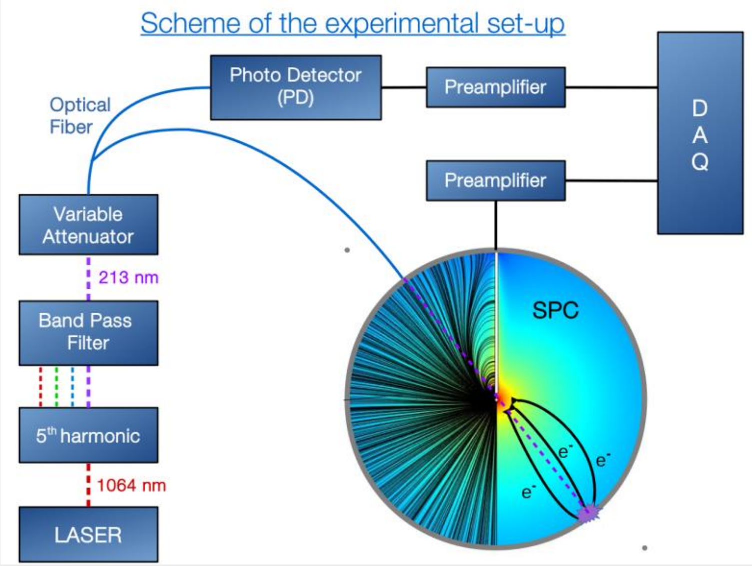


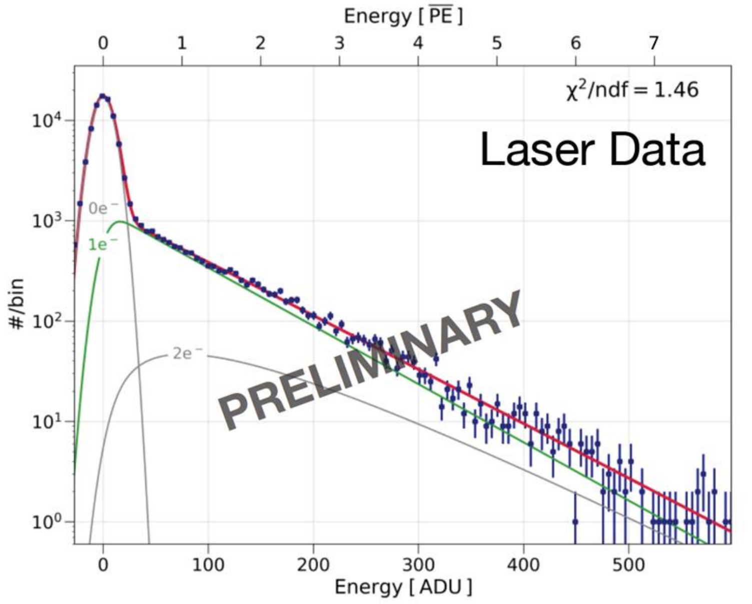


Laser calibration

- A 213nm UV laser is directed at the inner copper surface of the sphere and releases electrons though the photoelectric effect.
- The UV light also goes to a photodetector so the laser events can be tagged.
- Low-intensity laser data enables measurements of the single electron detector response (gain, avalanche statistics, trigger efficiency, peak detection threshold).
- High intensity laser data is used in all runs to enable constant monitoring of the detector.
- Gas degradation inducing a decrease in gain can be seen through laser events.

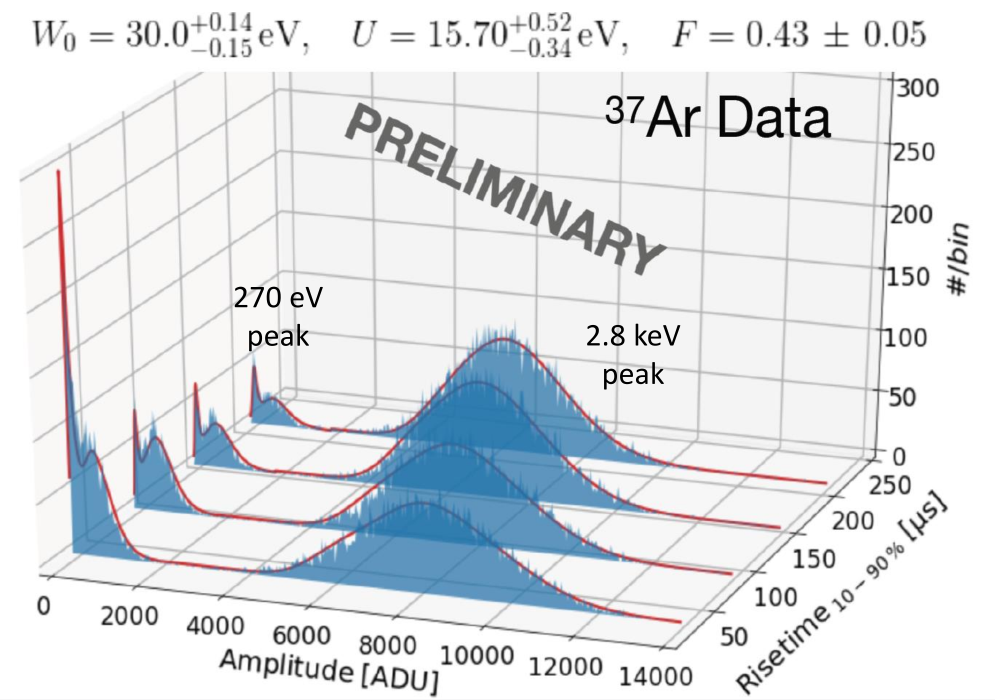






^{37}Ar Calibration

- Some argon-37 is released inside the sphere, and the gas diffuses in the whole volume. ^{37}Ar is produced at the Royal Military College in Kingston, in their SLOWPOKE-II reactor from CaO irradiation.
- This isotope is radioactive and has two main X-ray peaks (270 eV and 2.8 keV). It decays with a half-life of 35 days through electron capture.
- Argon-37 enables:
  - Energy calibration
  - Electron attachment parametrization
  - W-value and Fano factor measurements
  - South-channel anodes gain measurements



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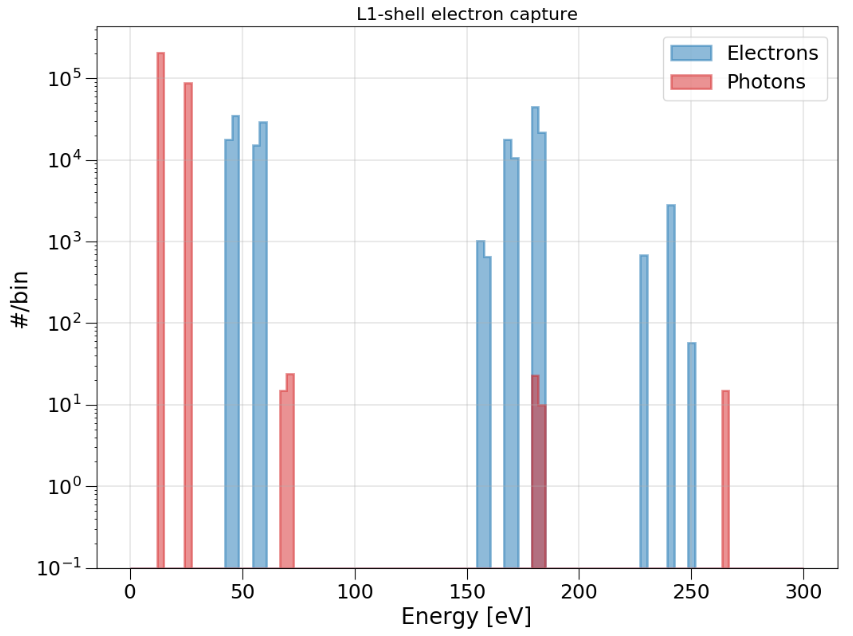
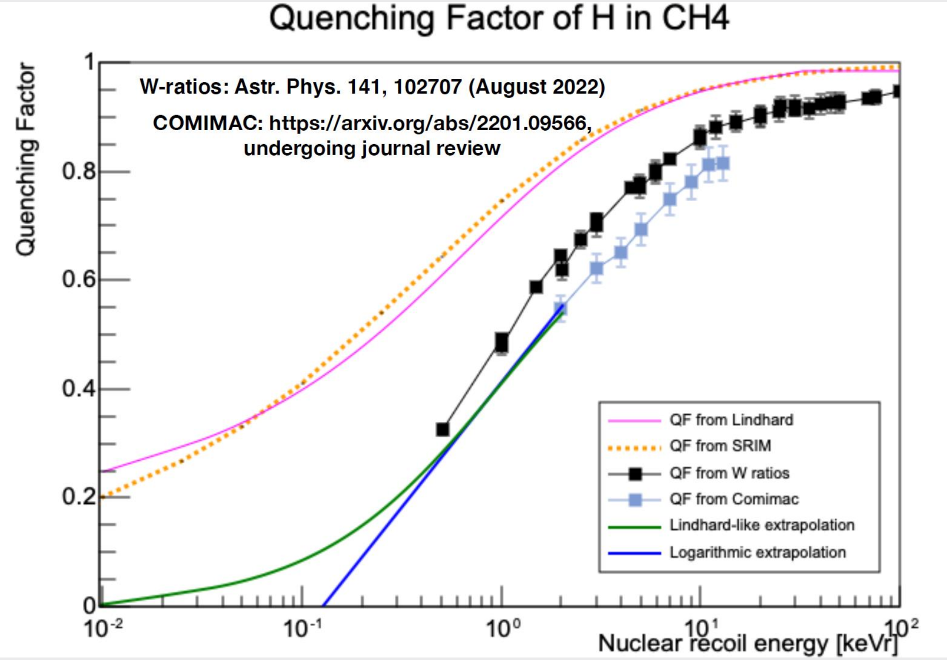
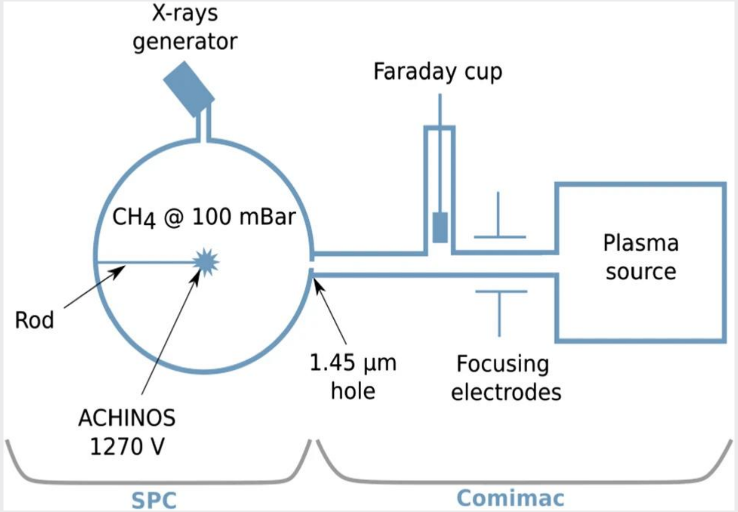


Quenching factor

- The quenching factor is the ratio between electronic (no E loss) and nuclear (some E loss) recoil energies.
- The quenching factor was measured at COMIMAC as well as obtained from literature W-values.
- Lower energy quenching factor were extrapolated logarithmically (more conservative).
- Future quenching factor measurements for lower energies and other gas mixtures in preparation.

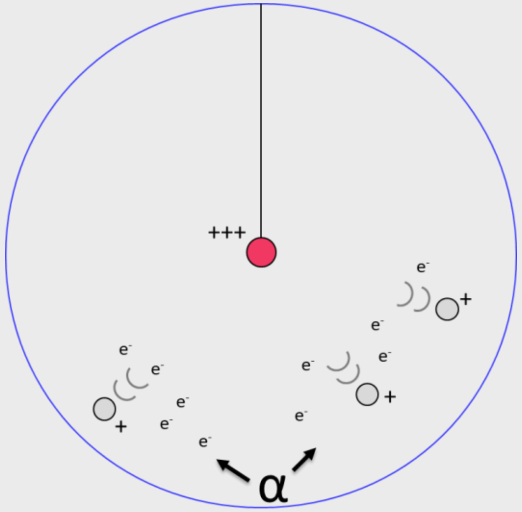


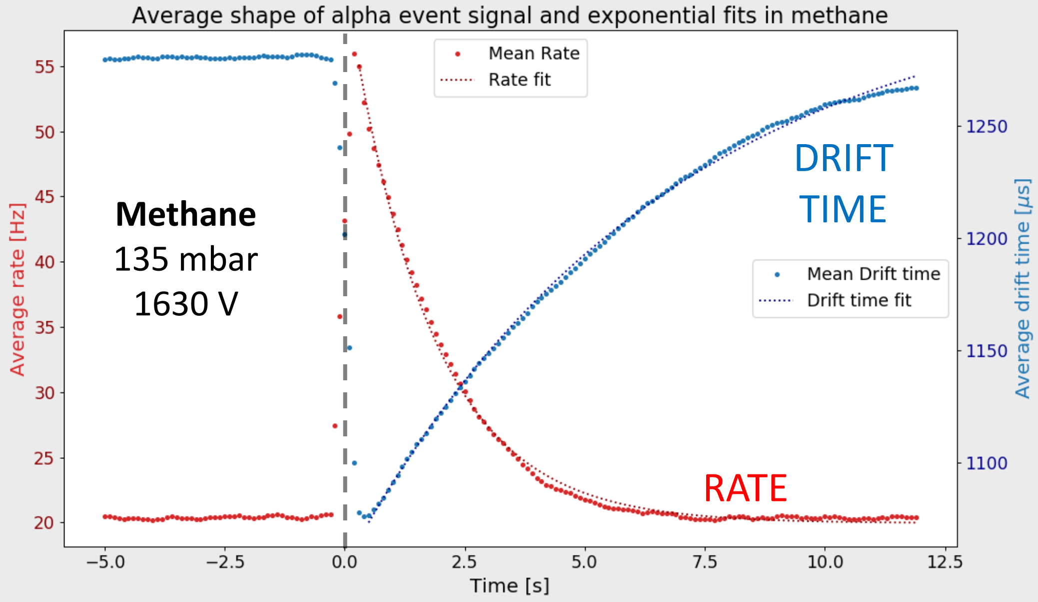


doi:10.1140/epjc/s10052-022-11063-9

Alpha contamination

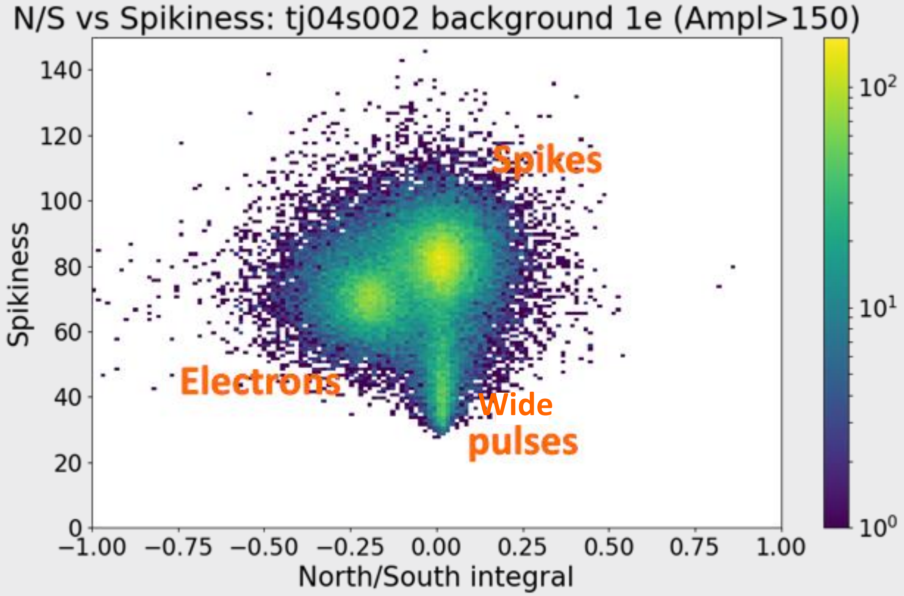
- There is ~25 mHz of alphas from ^{210}Po contamination in the copper surface.
- Alphas ionize a lot of gas and create a space charge that disturbs the electric field, and changes the electron drift time.
- Probably due to attachment, a high rate of low energy events keep happening for around 5s after each alpha.
- We remove 70% of the low-energy background with a 5s cut after each detected alpha, keeping 88% of the total time.

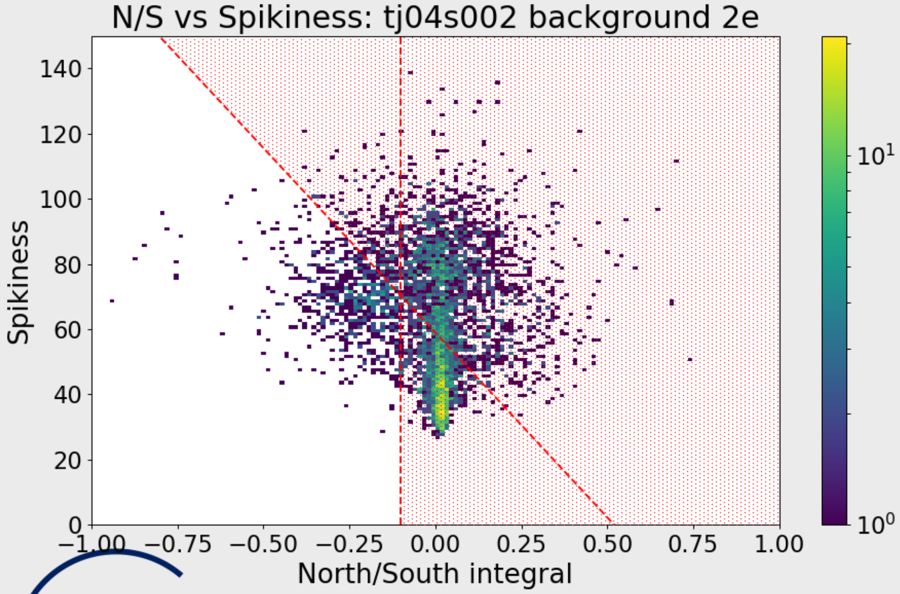




Pulse shape discrimination

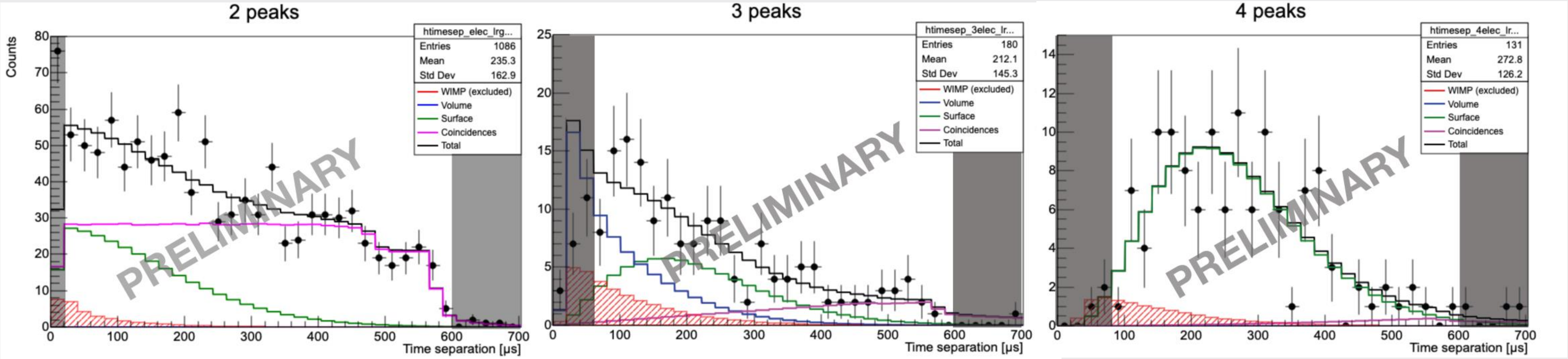
- There are spurious pulses caused by electronic discharges in the data.
- Those can be discriminated from physical events with two different methods:
  - Spurious pulses are either measurably spikier or wider than physical events.
  - Spurious pulses do not cause a negative induced pulse on the opposite channel.
- Around 95% of the spurious pulses are removed with cuts usings theses discriminants, while still keeping 77% of the physical events.





Physics data fits

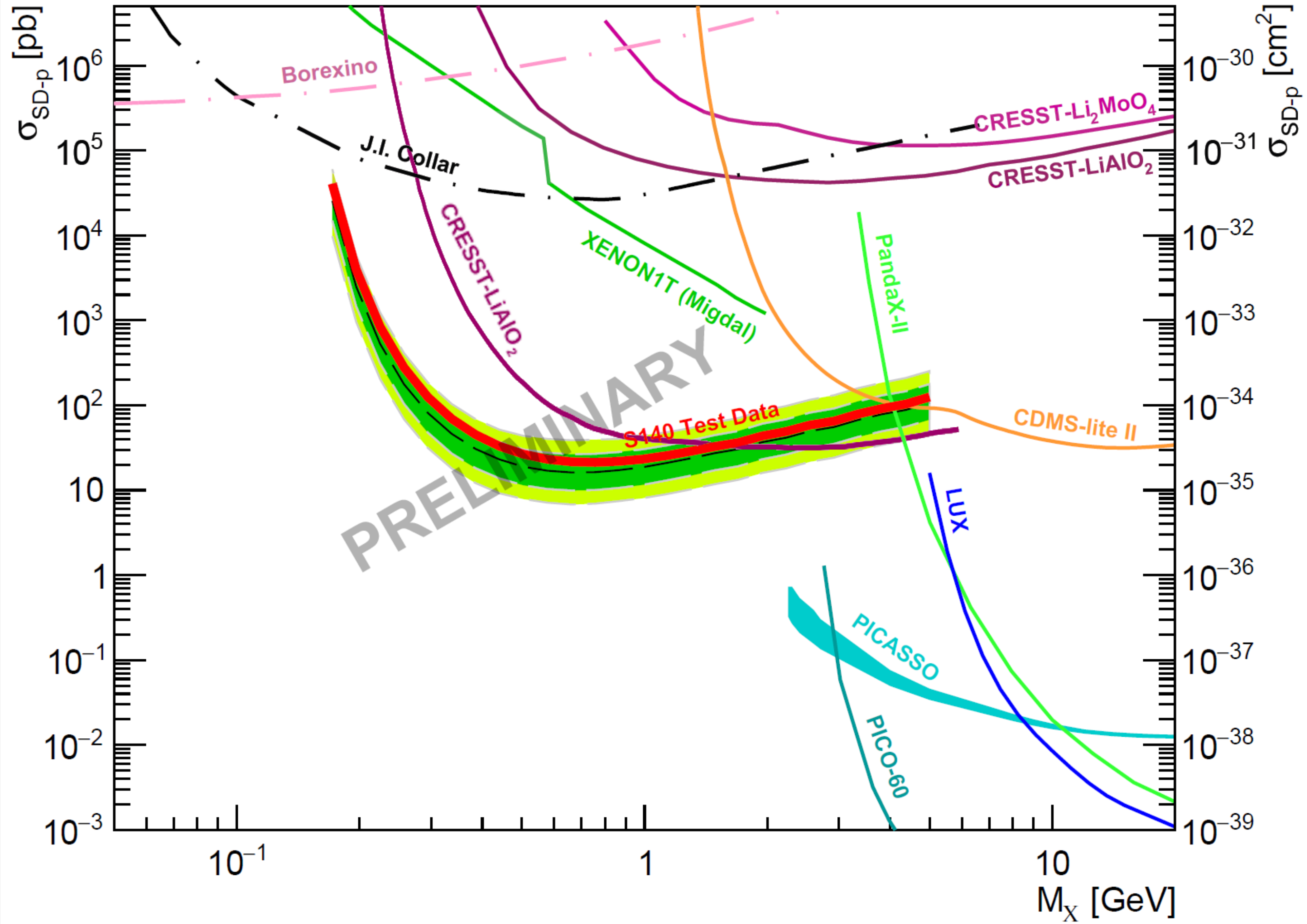
- 30% of the full data was set aside as a test data before the rest is unblinded.
- Profile likelihood fits of the test data were made for 2-3-4 peak data.
- Fits with contributions from surface background, coincidences and WIMP signal.
- No significant WIMP signal was detected.



scipost_202210_00005v1

Preliminary limits

- WIMP exclusions limits with ~0.12 kg·days of data
- Strongest constraints for the proton spin-dependent interaction in the 0.2 - 1.5 GeV range.
- Final blind data results to come in a few weeks.



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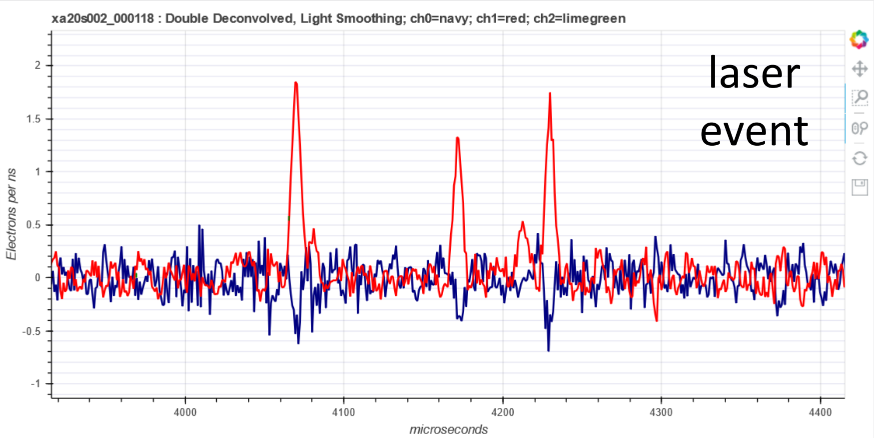
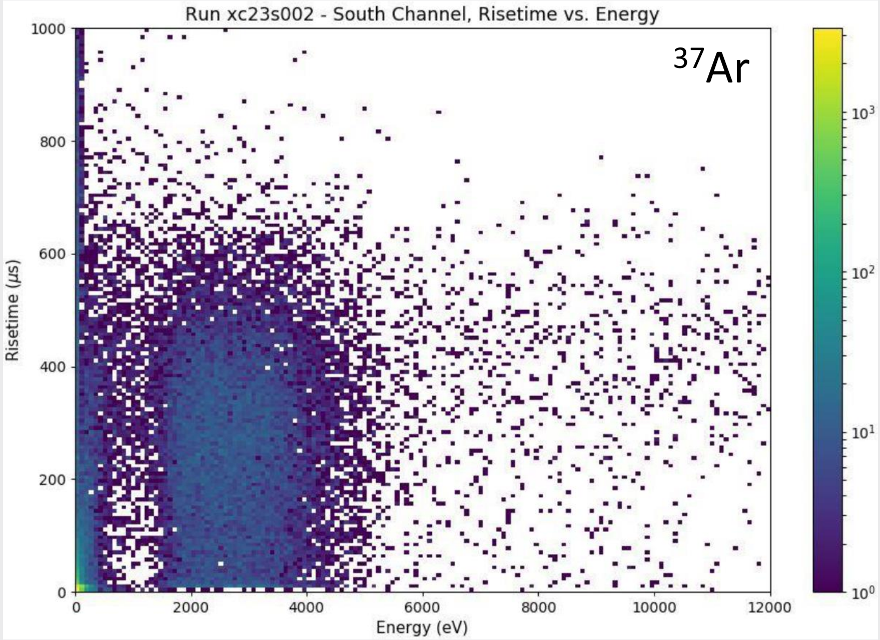
Data taking in SNOLAB

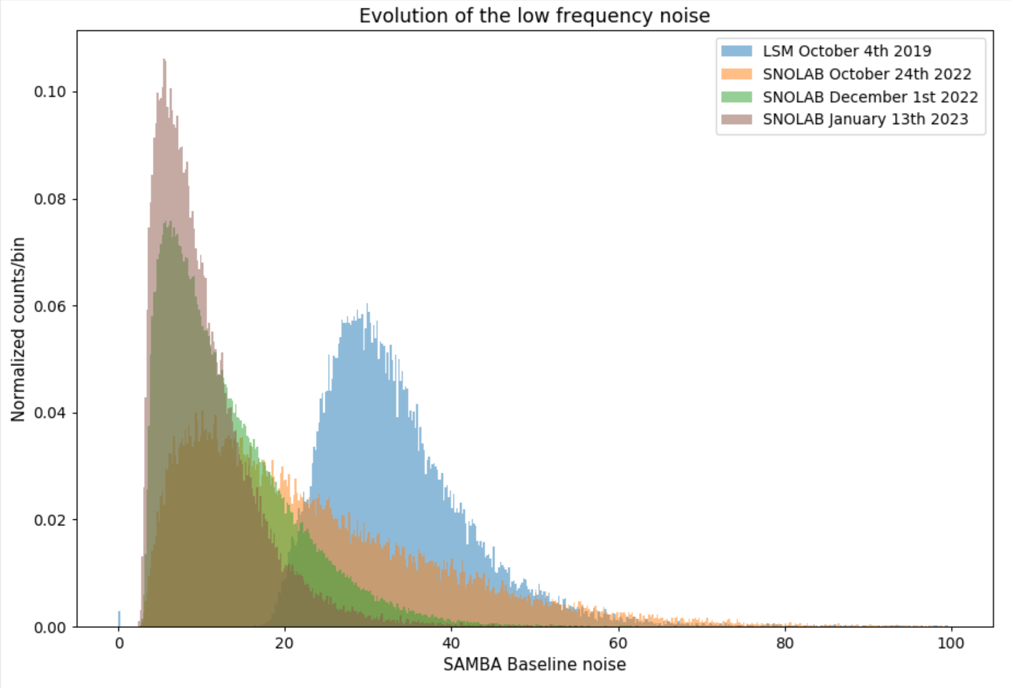
- One physics data campaign taken, preparing the next one
- Still countable electrons
- Improvements from LSM:
  - Trigger on three channels (North, South, PD)
  - Reduced noise
  - No spurious pulses
  - Better gas purity
  - Neon+2%CH_4, CH_4, Ar+CH_4, He+CH_4 etc.

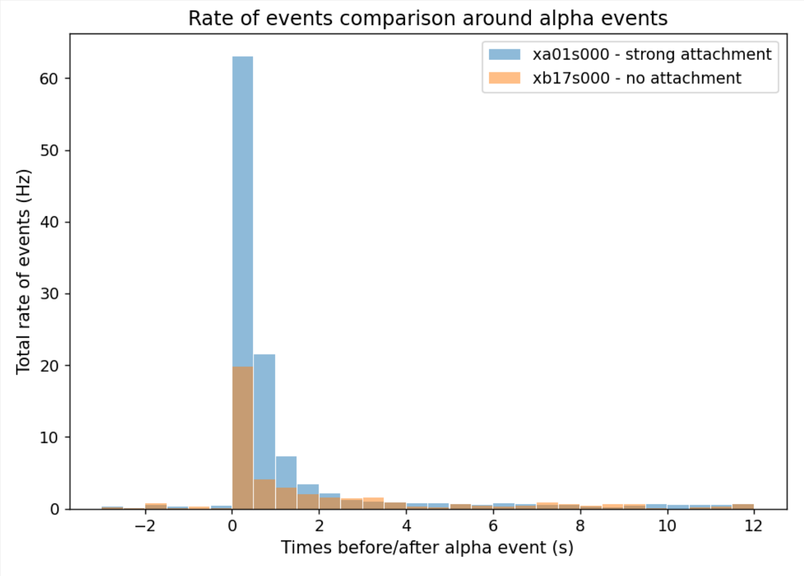




SNOLAB noise

- Multiple improvements (dampening vibrations, better electronic isolation) across months slowly reduced the background noise.
- Better gas quality was shown to reduce the alpha induced background.
- Expected improvements for the rest of the year:
  - Additional etching
  - New gas purifier
  - New radon trap
  - New sensors





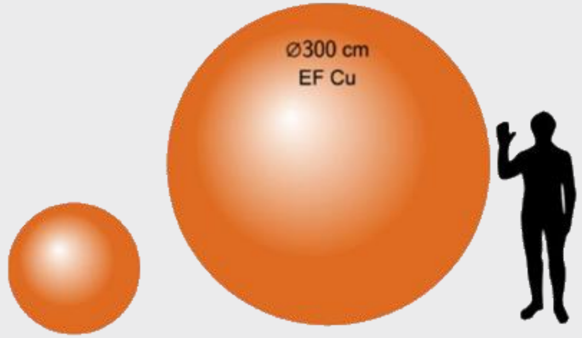
Future DM projects

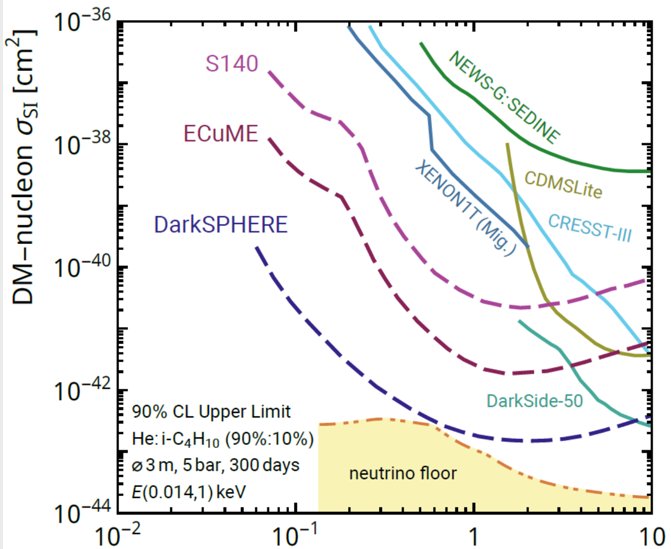
ECuME

- Fully underground electroformed 140 cm of diameter copper sphere to be made inside SNOLAB.
- Mini-ECUME prototype with 30 cm of diameter built at PNNL.

DarkSPHERE

- Fully electroformed 3m of diameter sphere in a water shield for the Boulby Underground Laboratory, in England (under consideration).



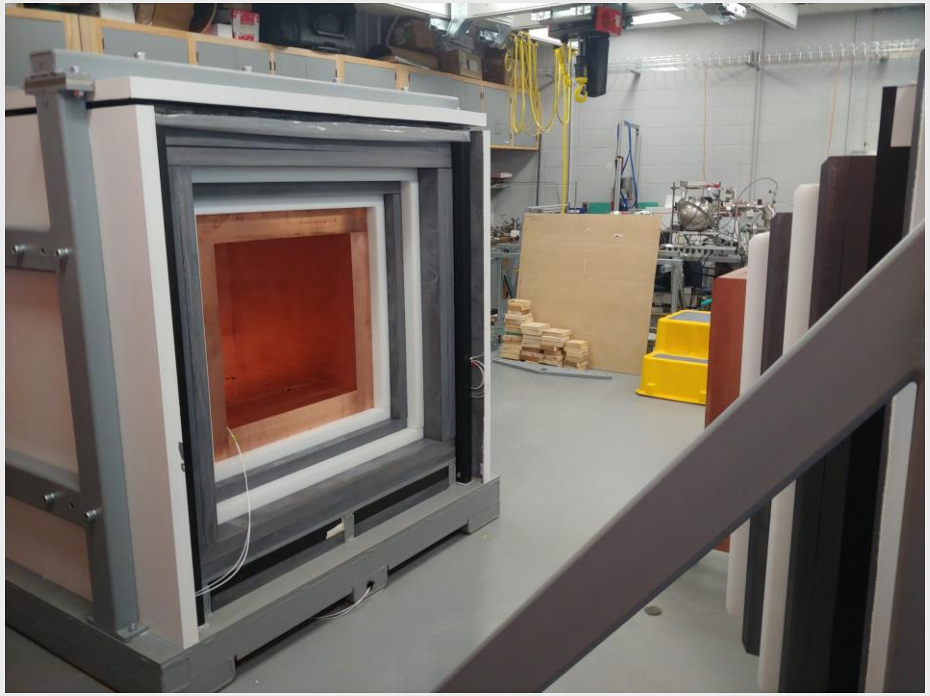


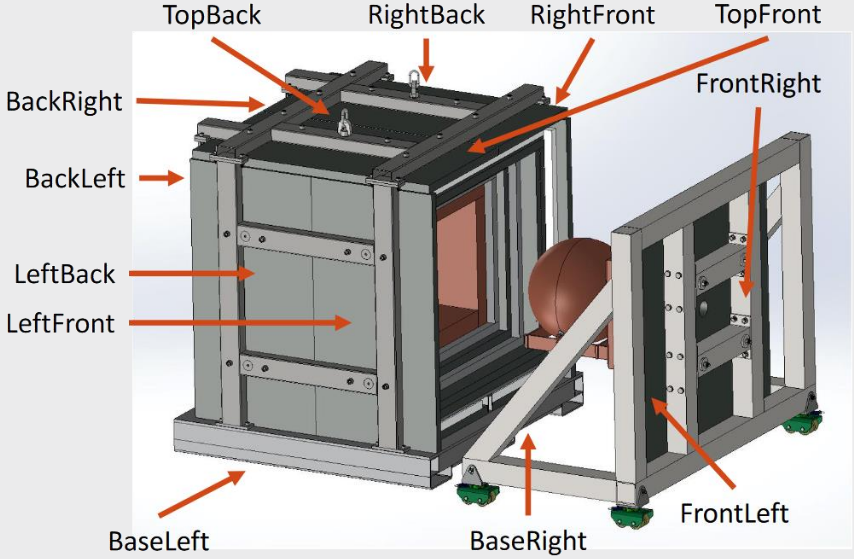
arXiv:2301.05183

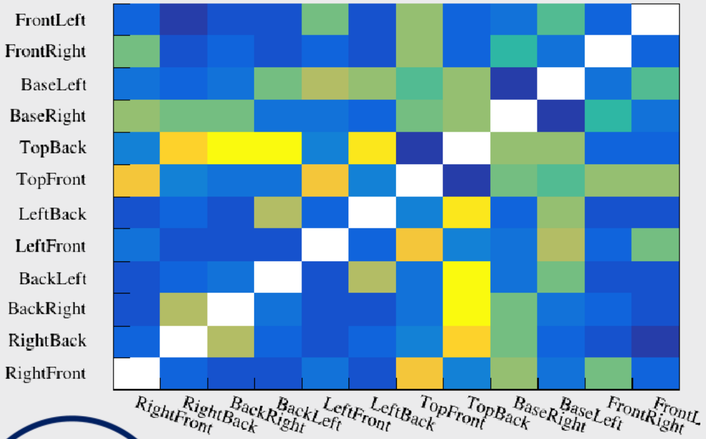
Neutrino research

NEWS-G³ (or G3)

- Shield at Queen's University intended for CEvNS detection at nuclear reactors.
- The shield is comprised of multiple layers of lead, polyethylene, scintillators (muon veto) and copper. It was completed last summer.
- Tests, simulations and calibrations are currently being done at Queen's.







Team at Queen's (and within M.I.)


Guillaume Giroux:
Co-P.I. of the experiment


Philippe Gros:
Makes everything in the lab work


Jean-Marie Coquillat:
Coordinates the data analysis and makes fits


Pierre Gorel:
SNOLAB man


Jon Clarke:
Looks at the single-electron background


Annabelle Makowski:
Does machine learning and works on gain fluctuations

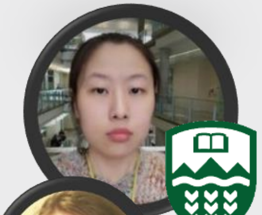

Hayden Meadows:
Works on CEvNS detection with G3


Neha Panchal:
Works on quenching factor measurements


Georges Savvidis:
Builds cool new sensors, works on G3


Mischa Kapp:
Characterizes sensors with various pressure configurations


Mayank Arora:
Building a neutron beam at RMTL for calibrations



Yuqi Deng:
Does space charge simulations & alpha monitoring
-Supervised by Marie-Cécile Piro


Mackenzie Moring:
Working on backing detector assembly

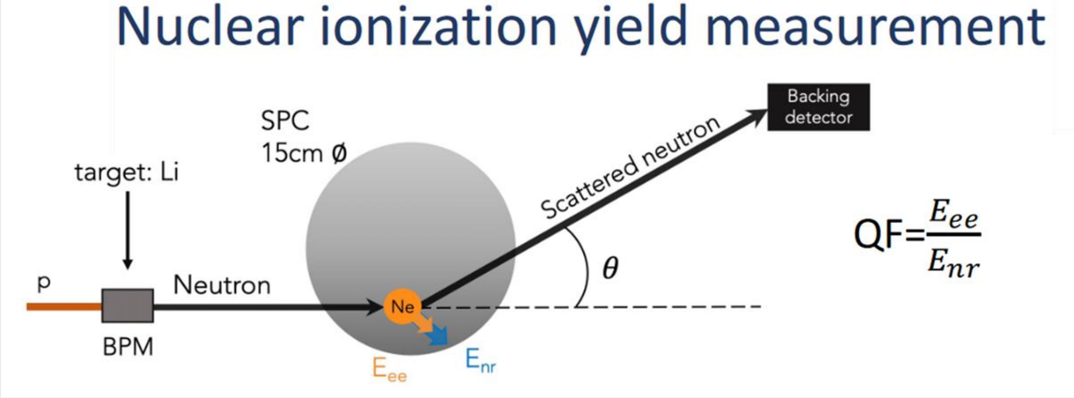
Conclusion

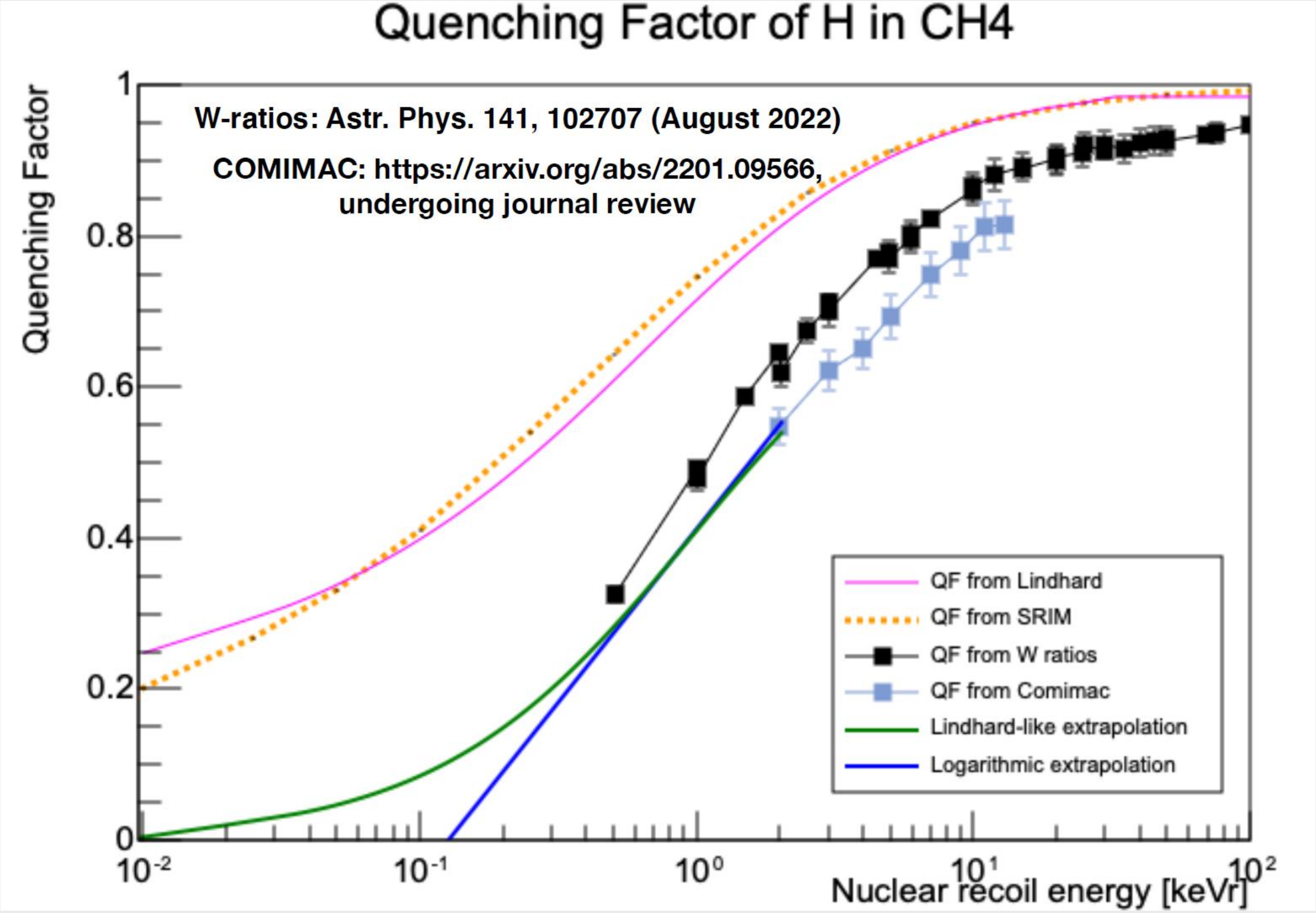
- NEWS-G and SPCs well suited for low mass dark matter search.
- LSM data able to set new SD-p WIMP constraints with CH_4.
- Currently taking and analyzing physics improved data from SNOLAB.
- Promising future projects in the works.

Thank you!

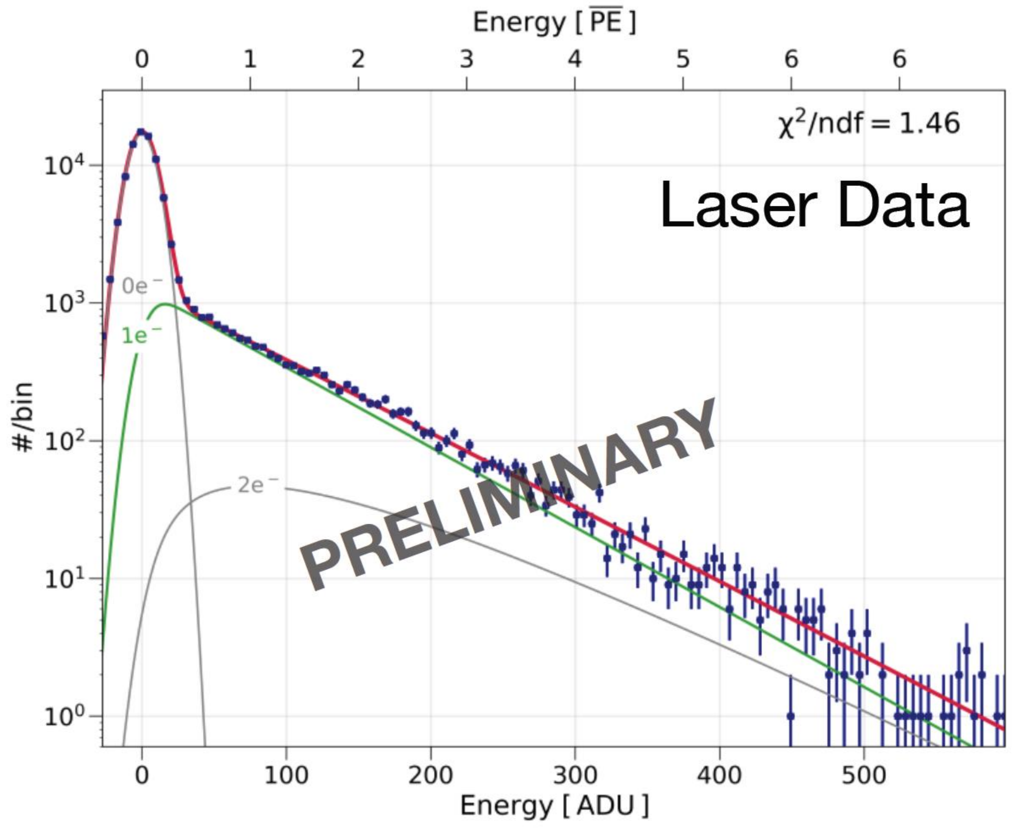
Extra slides

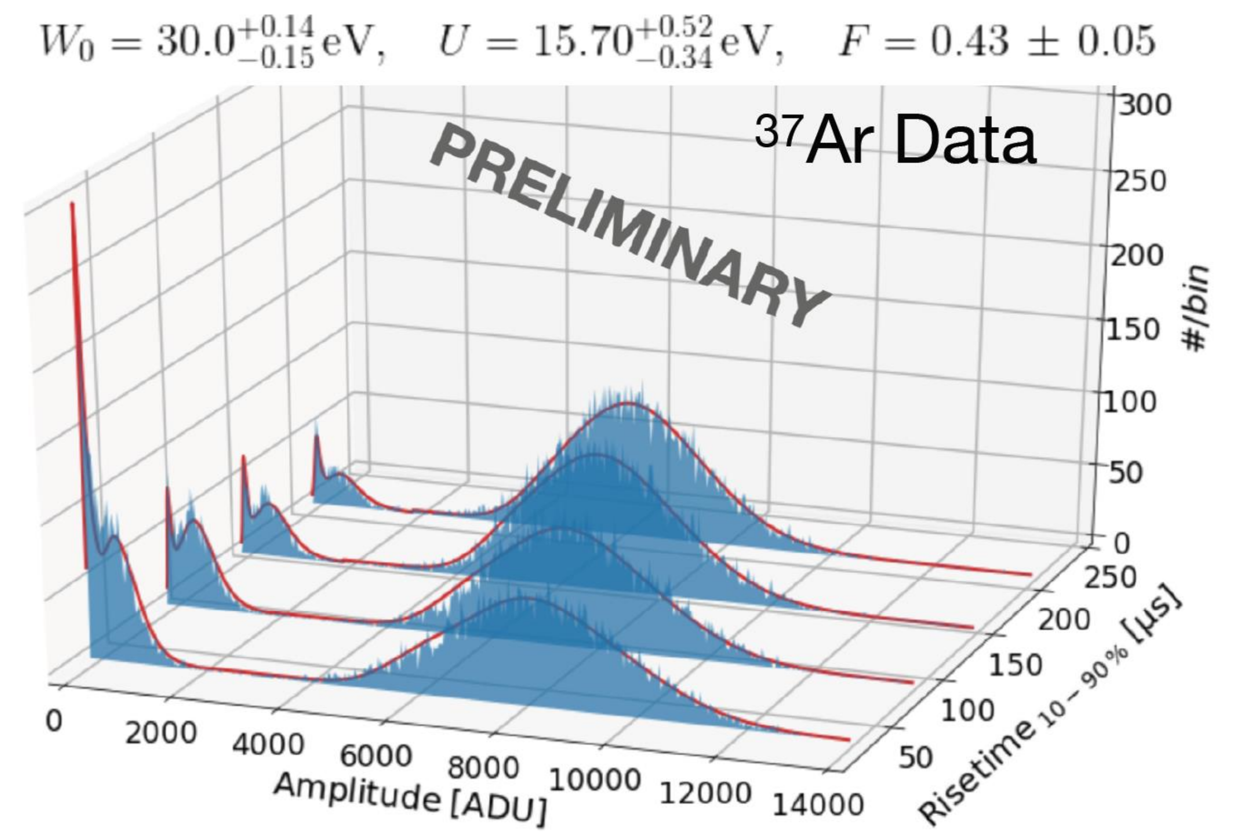
Quenching factor





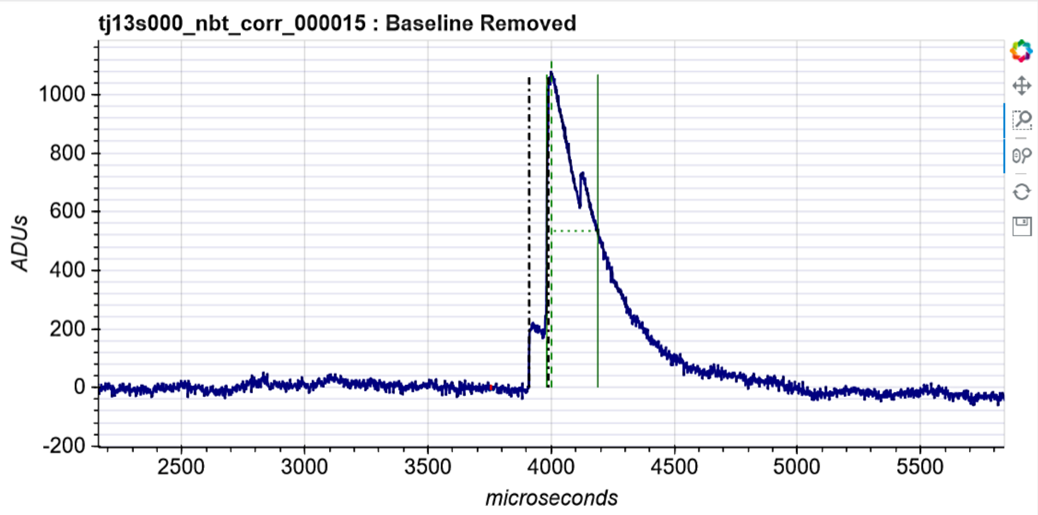
Gas mixture and calibration (laser and ^{37}Ar)



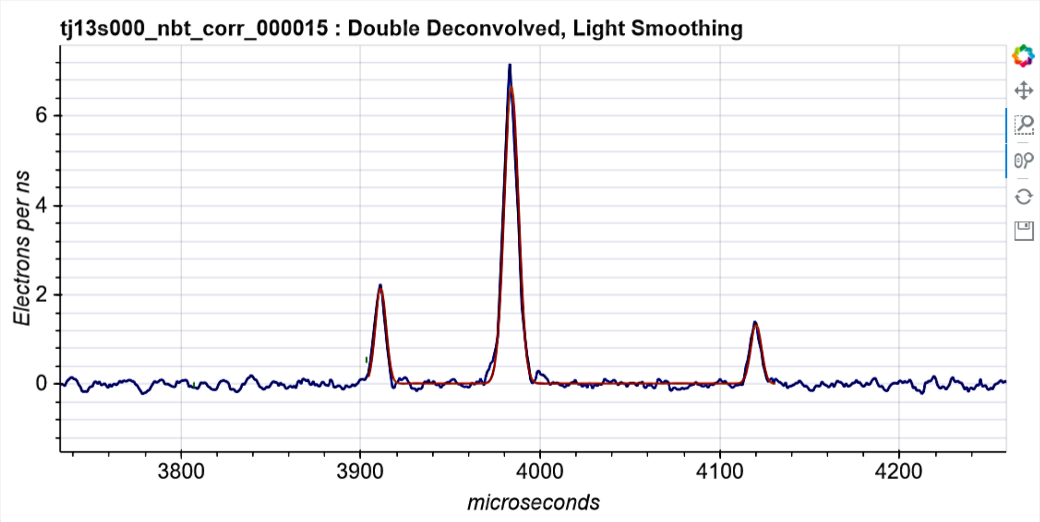


doi:10.1088/1742-6596/2156/1/012059

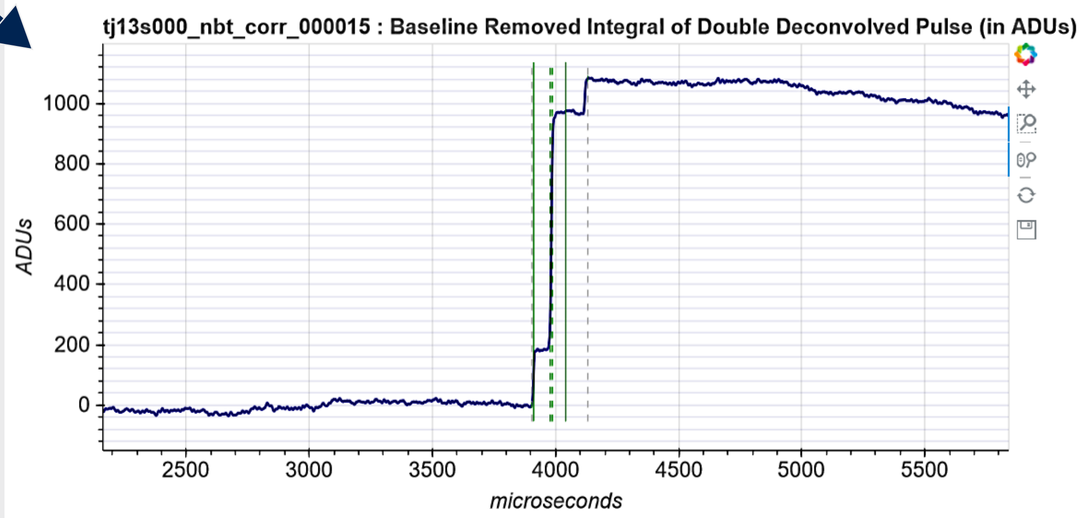
Double deconvolution



Double deconvolution

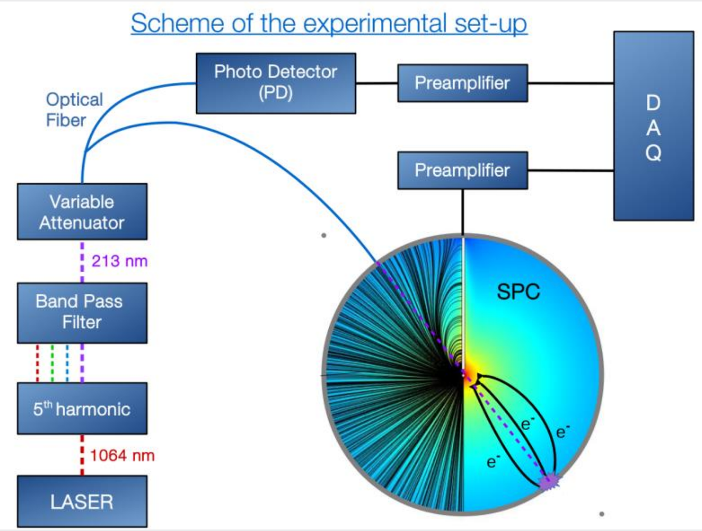


Integration

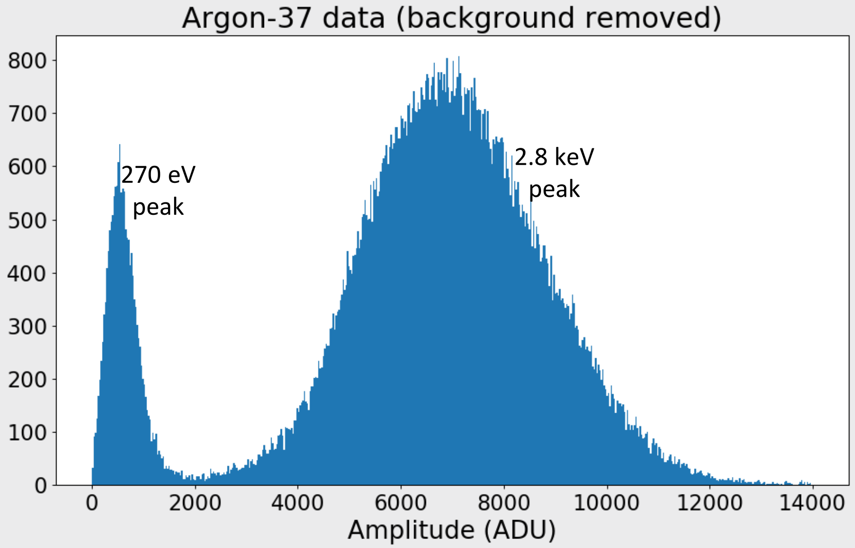


The ballistic deficit is the signal amplitude that gets underestimated due to the exponential decay of the preamplifier.
The full amplitude (energy) is retrieved by doing a double deconvolution of the raw signal, and then integrating the pulses.

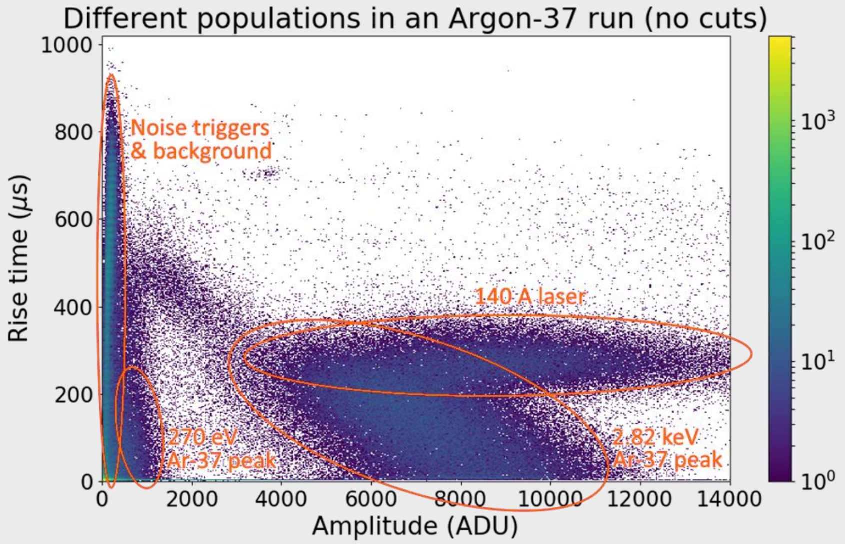
Calibration and background



Laser calibration [10]



^{37}Ar calibration



Selection of different kinds of events

Two troublesome kinds of background:

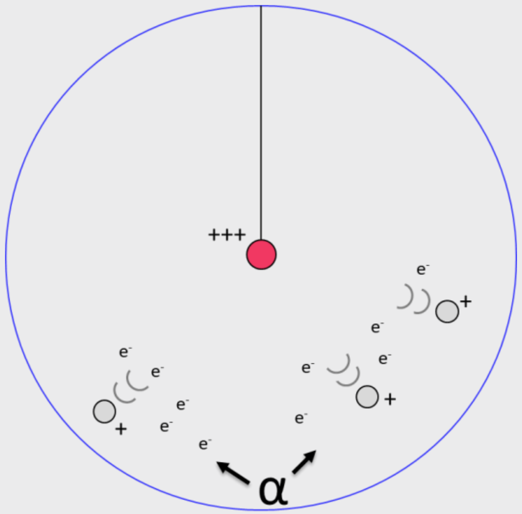
Alphas

- There is ~25 mHz of alpha contamination in the detector.
- Alpha events are easy to remove due to their high energies.
- However, they cause a significant number of low energy events, similar to WIMP signal.

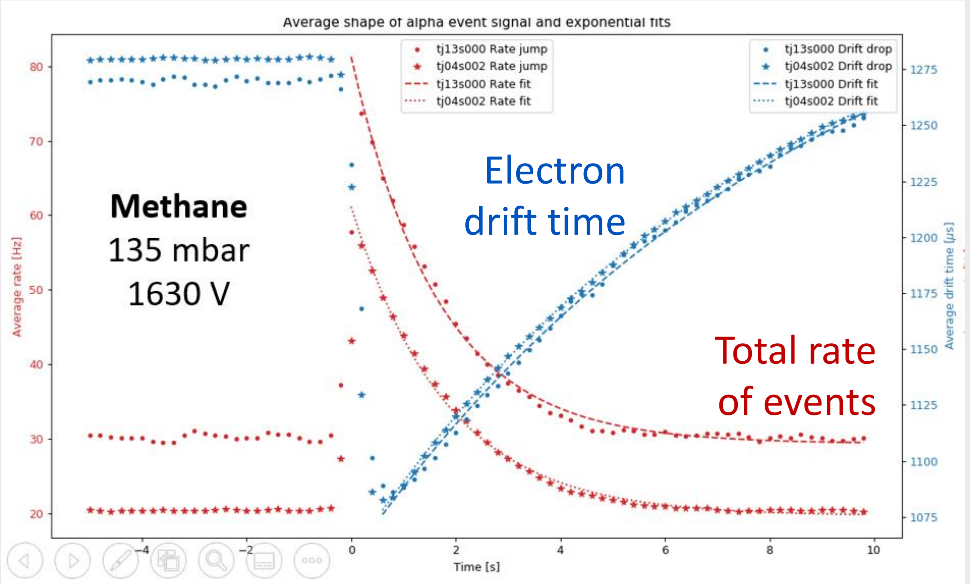
Spikes

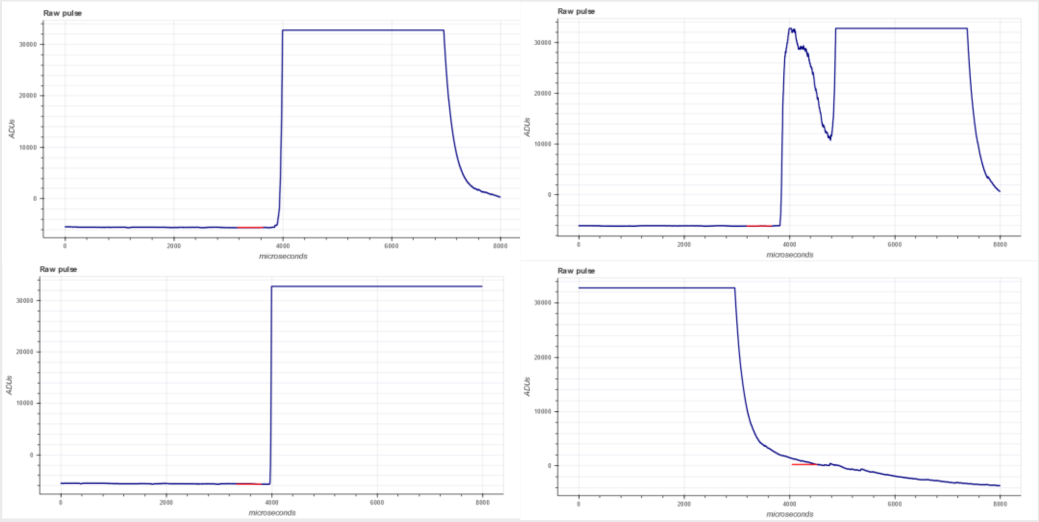
- They are non-physical sudden rises of the signal.
- They do not come from any primary electron, do not create a Townsend avalanche.
- They can be caused by irregularities in the voltage supply or internal discharges.

Alpha background

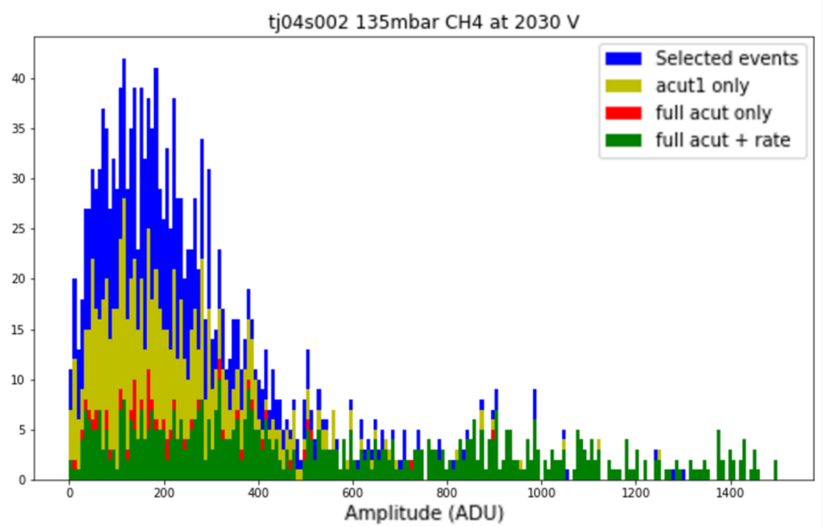


There is ^{210}Po contamination in the copper surface, which causes alphas that ionize a lot of gas. All the ions create a space charge that disturbs the electric field, and changes the electron drift time. For some still unknown reason, a high rate of low energy events keep happening for around 5s after each alpha.





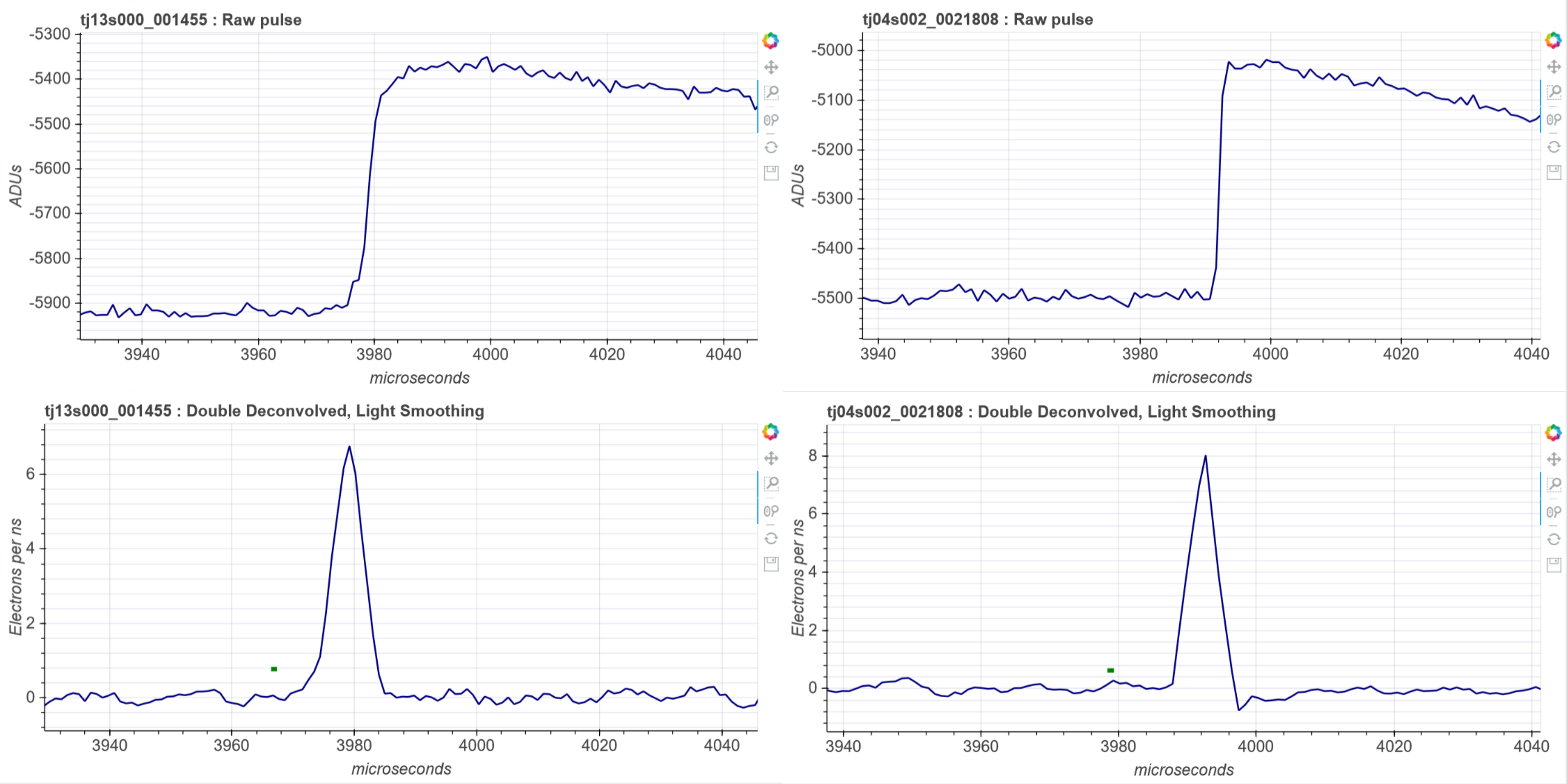
The saturated alpha signals can be broken up and difficult to detect, but using the drift time, rate of events and decreasing baselines, we can identify alphas and remove most of the low-energy background due to them with a 5s cut after each alpha, keeping 85-90% of the total time.



Spikiness

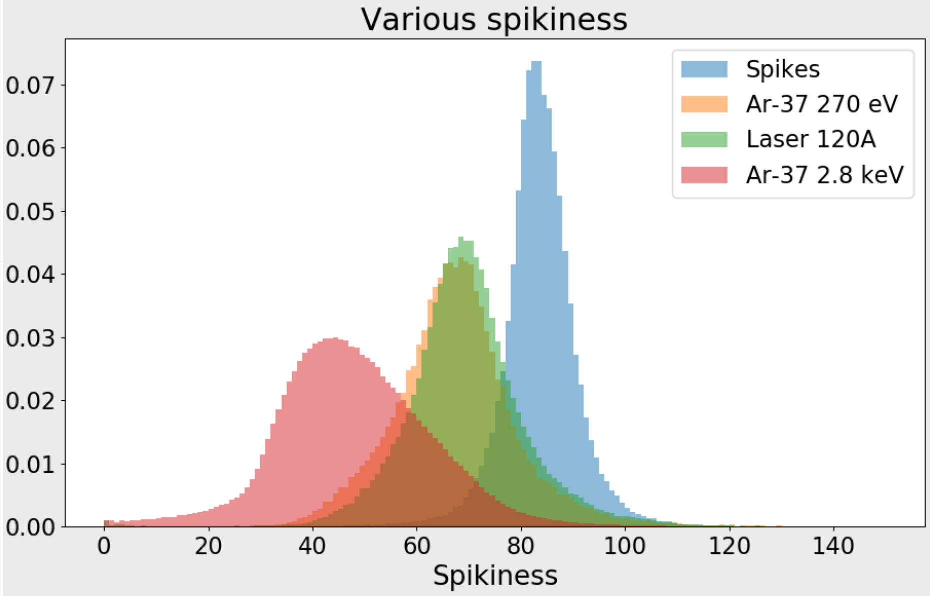
1st comparison method
Spikiness

$$\text{Spk} = \frac{\text{Max signal derivative}}{\text{Peak height}}$$



Probable electron event

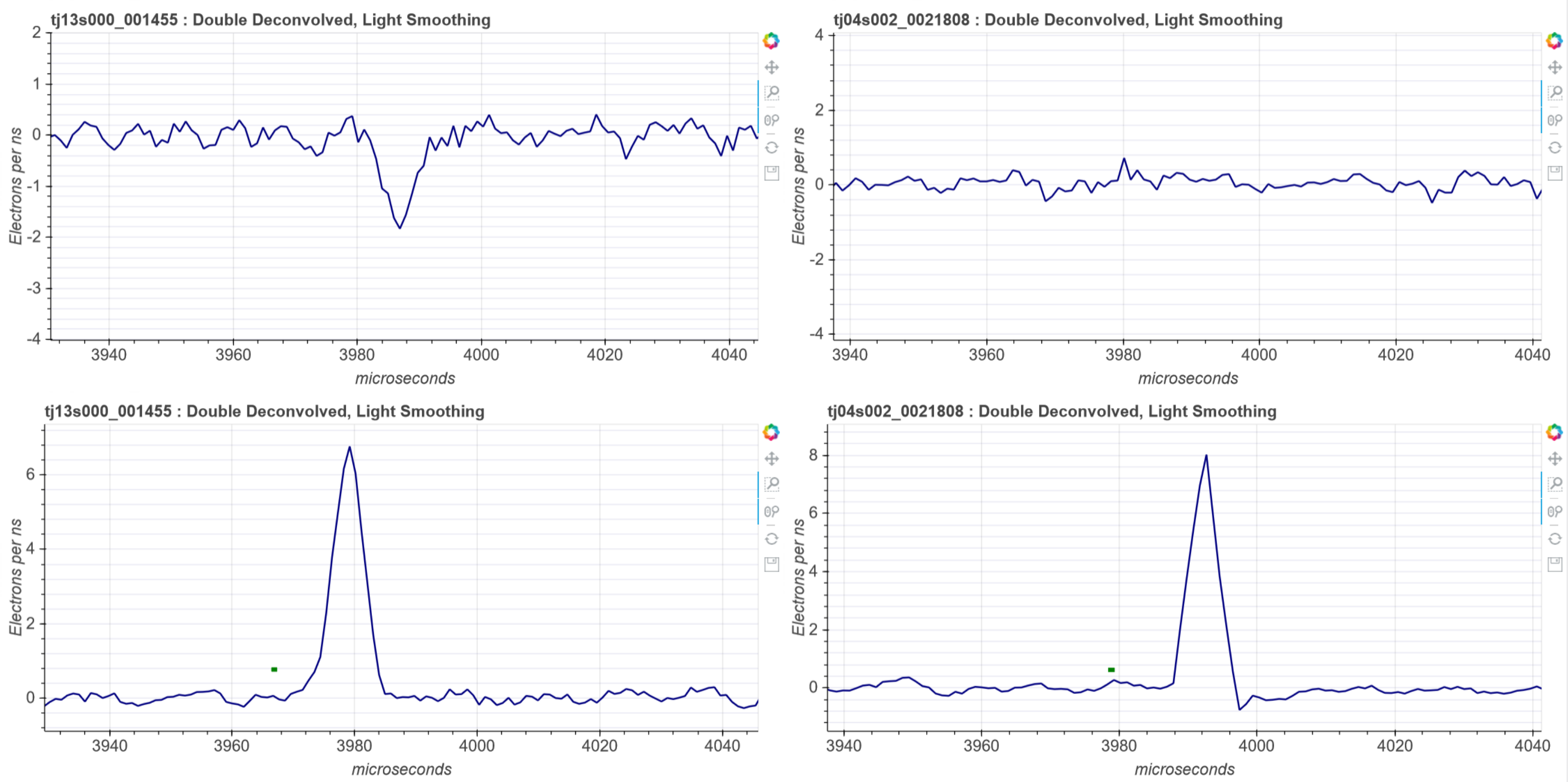
Probable spike event

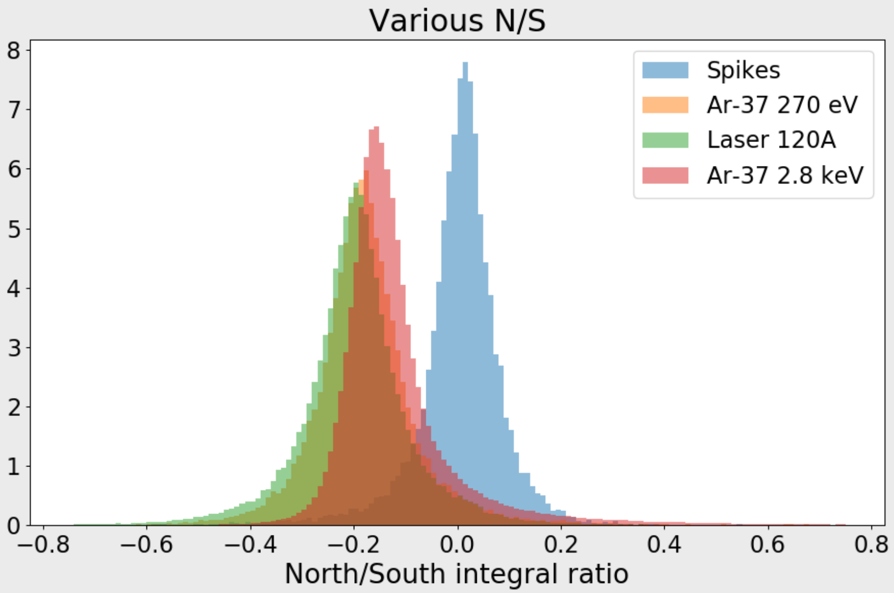


North/South integral ratio

2^{nd} comparison method
N/S ratio

$$N/S = \frac{\text{North DD2 integral}}{\text{South DD2 integral}}$$



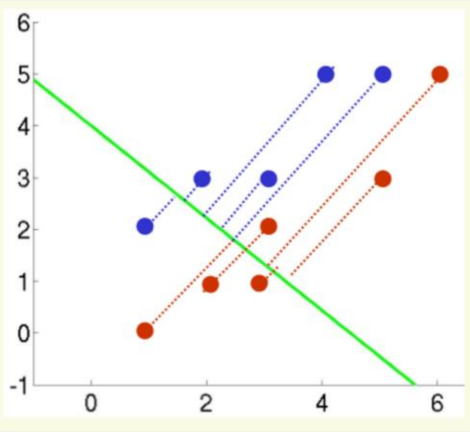


Probable electron event

Probable spike event

Linear Fisher discriminant

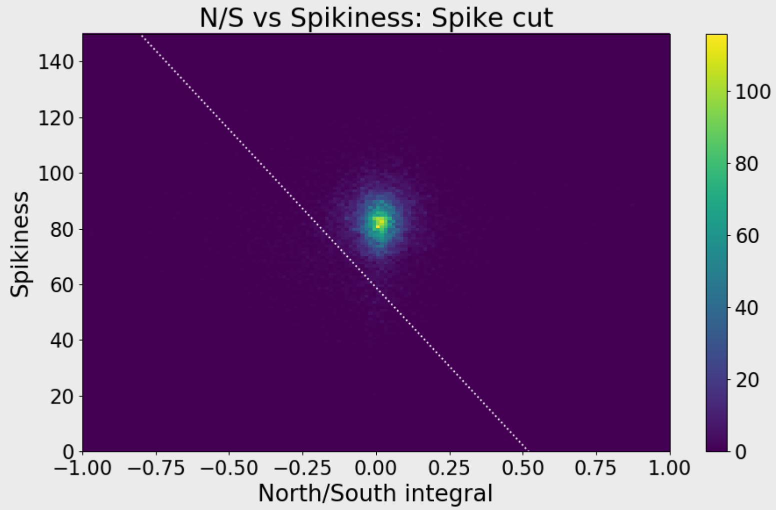
Optimal comparison:
Combining both methods

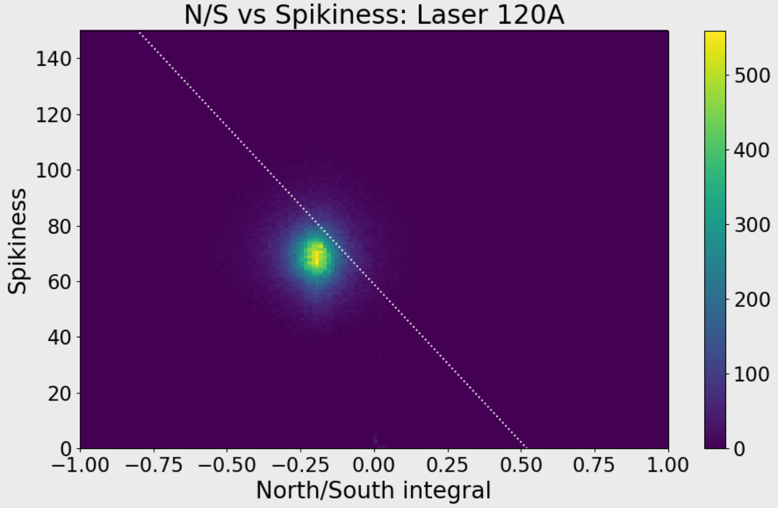


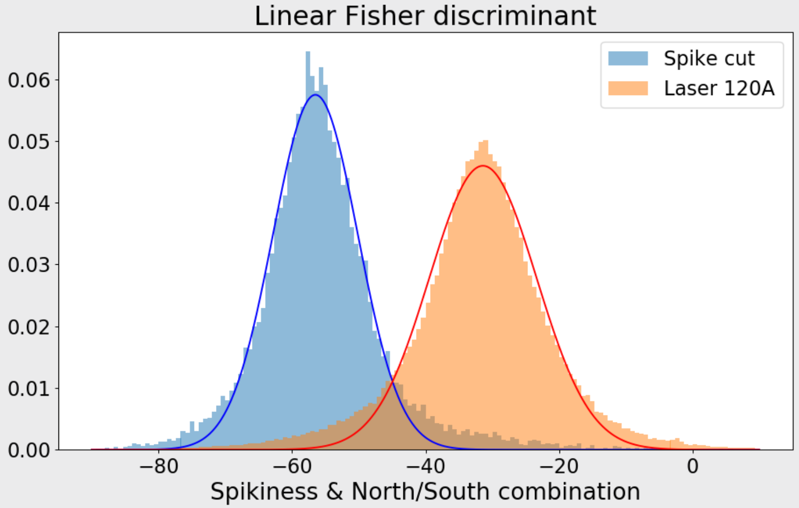
Separation $J(\omega) = \frac{(\mu_1 - \mu_2)^2}{N_1(\sigma_1)^2 + N_2(\sigma_2)^2}$

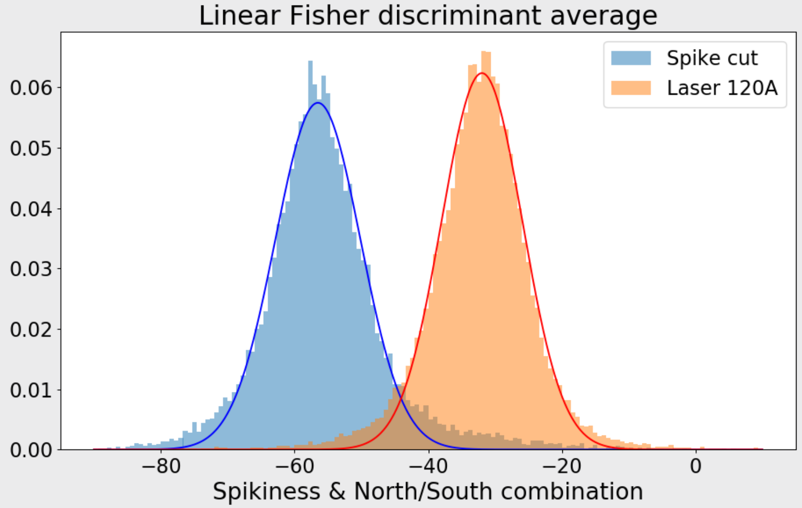
New axis $\tau_i = \omega^t x_i^t$

ω=[−0.678619815,−76.8674863]
Spk NS

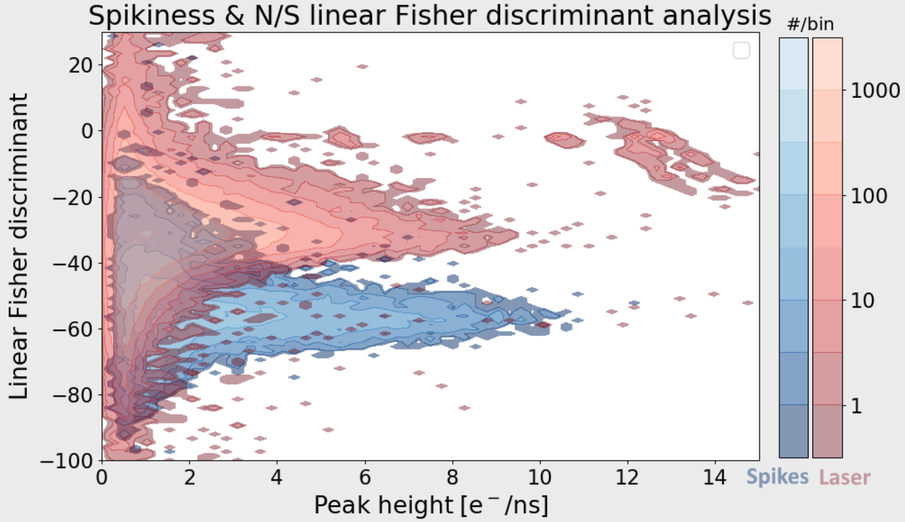




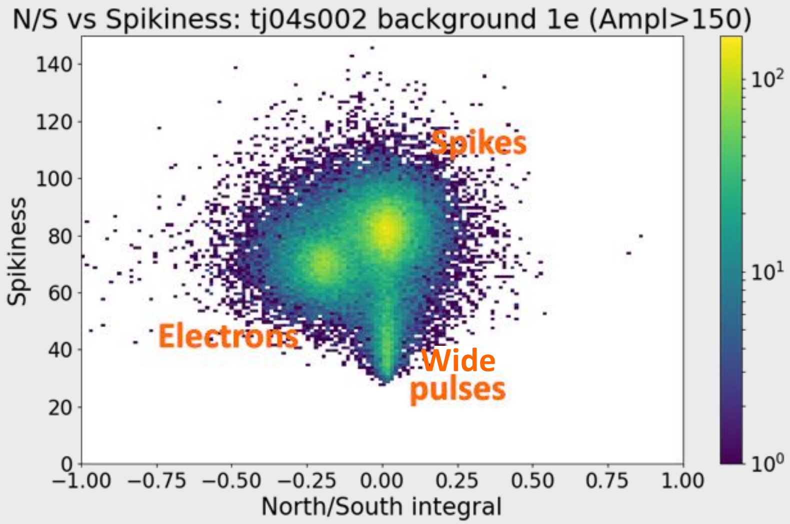




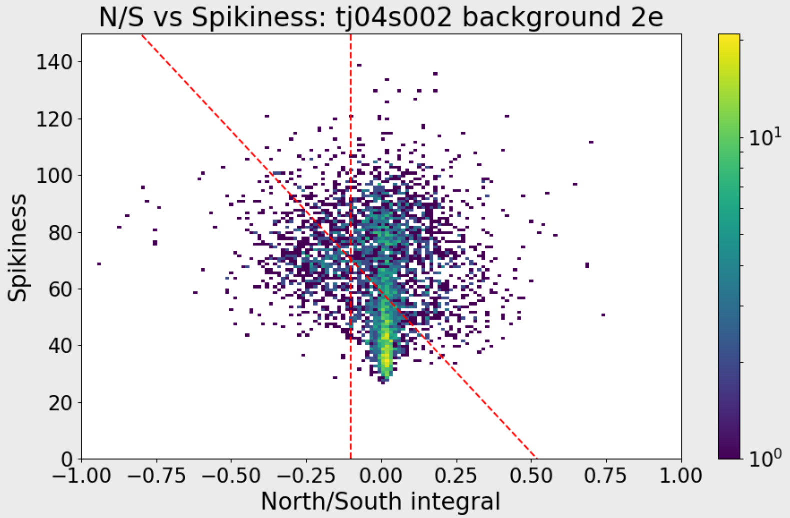
Fits to the physics data



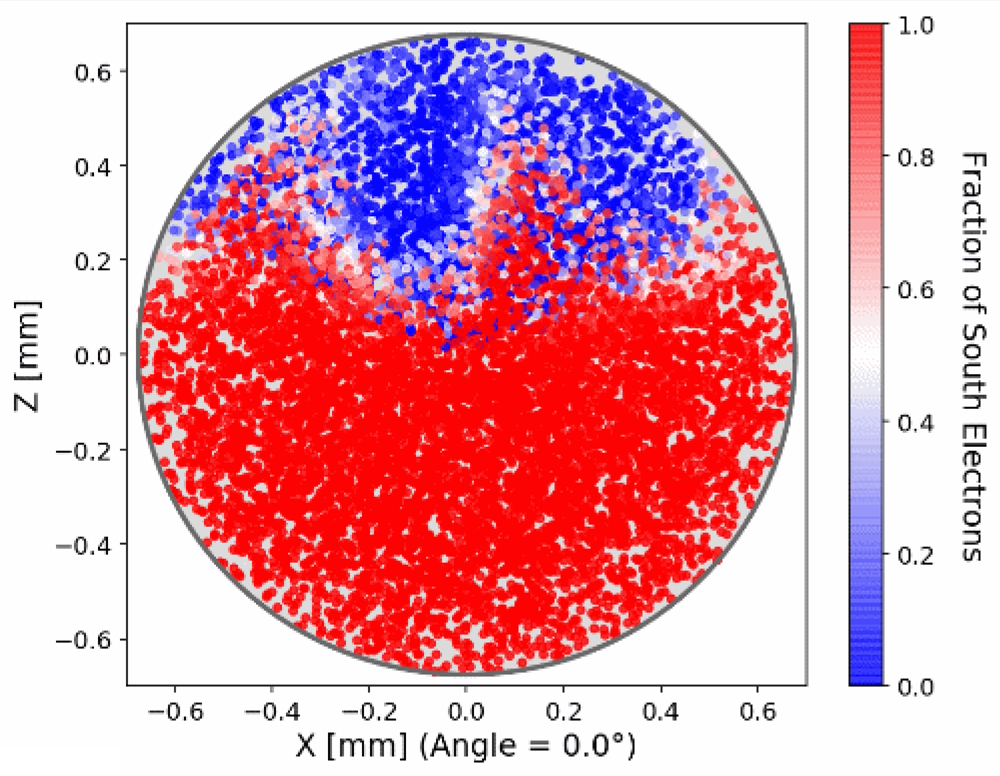
The separation between electron and spike events is weaker at lower energies.

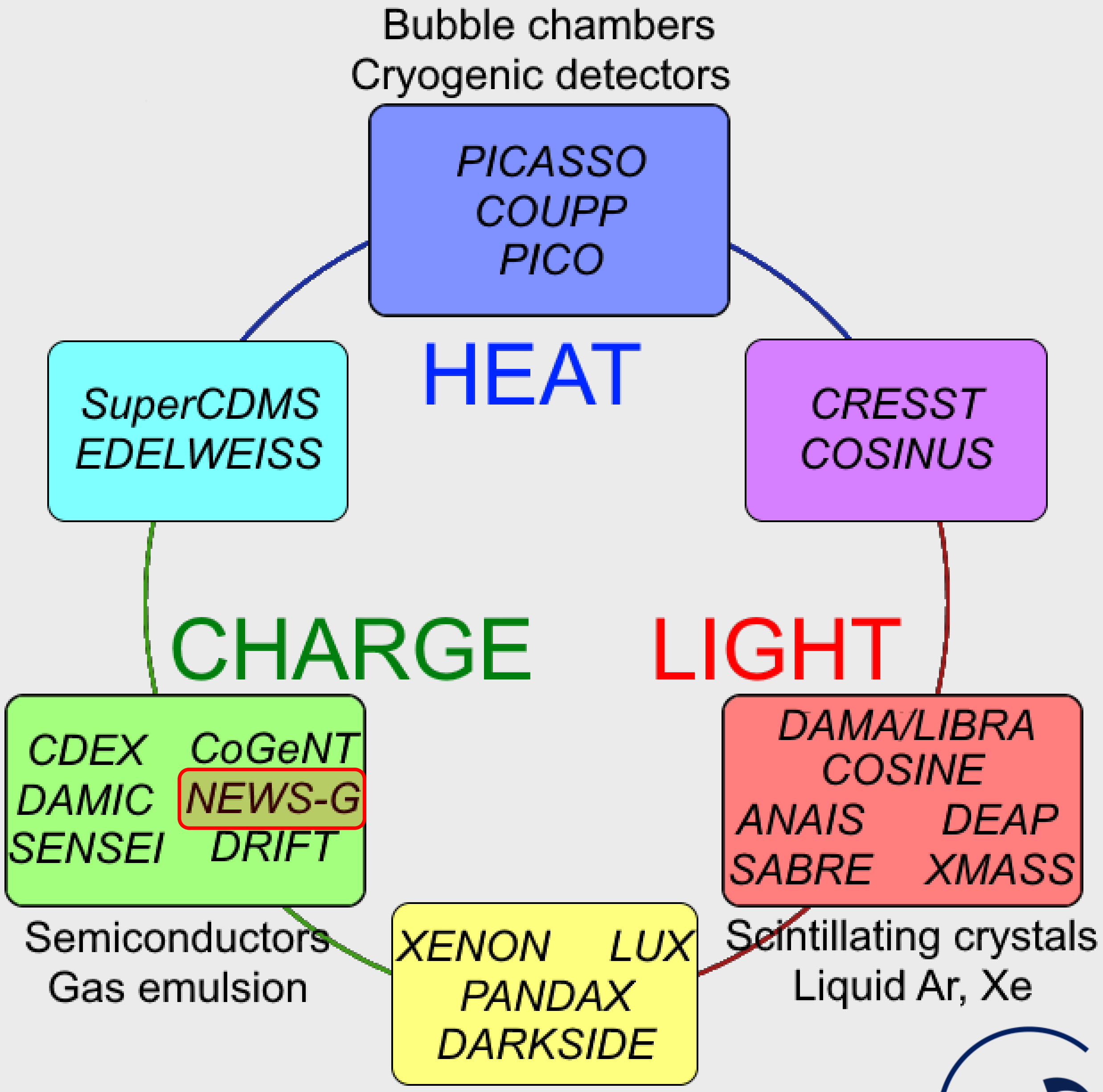


Wide pulses are another dominant background of unknown origin in the data.



A cut on N/S removes fat pulses (dominant in 2-peak data) and a Fisher discrim. cut removes spikes.


0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
Z [mm]
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
X [mm] (Angle = 0.0°)
1.0
0.8
0.6
0.4
0.2
0.0
Fraction of South Electrons


Bubble chambers
Cryogenic detectors
PICASSO
COUPP
PICO
HEAT
SuperCDMS
EDELWEISS
CRESST
COSINUS
CHARGE
LIGHT
CDEX CoGeNT
DAMIC NEWS-G
SENSEI DRIFT
DAMA/LIBRA
COSINE
ANAIS DEAP
SABRE XMASS
Semiconductors
Gas emulsion
XENON LUX
PANDAX
DARKSIDE
Scintillating crystals
Liquid Ar, Xe

Queen's
UNIVERSITY