# Charge Amplification in Liquid Xenon with a Needle Electrode and Development of a Spherical Detector

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Nagoya Workshop on Technology and Instrumentation in Future Liquid Noble Gas Detectors
Nagoya University
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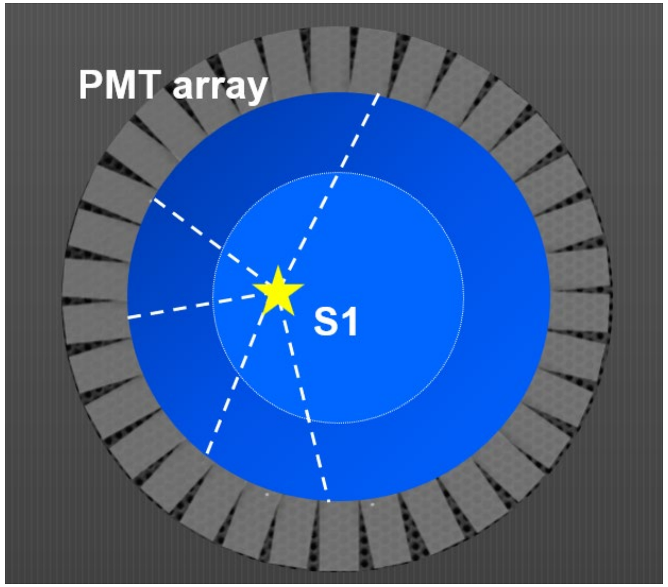
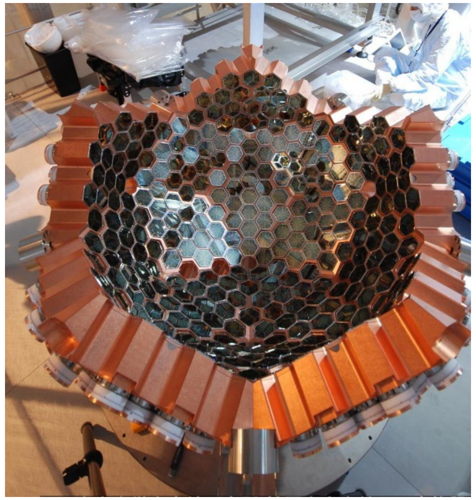
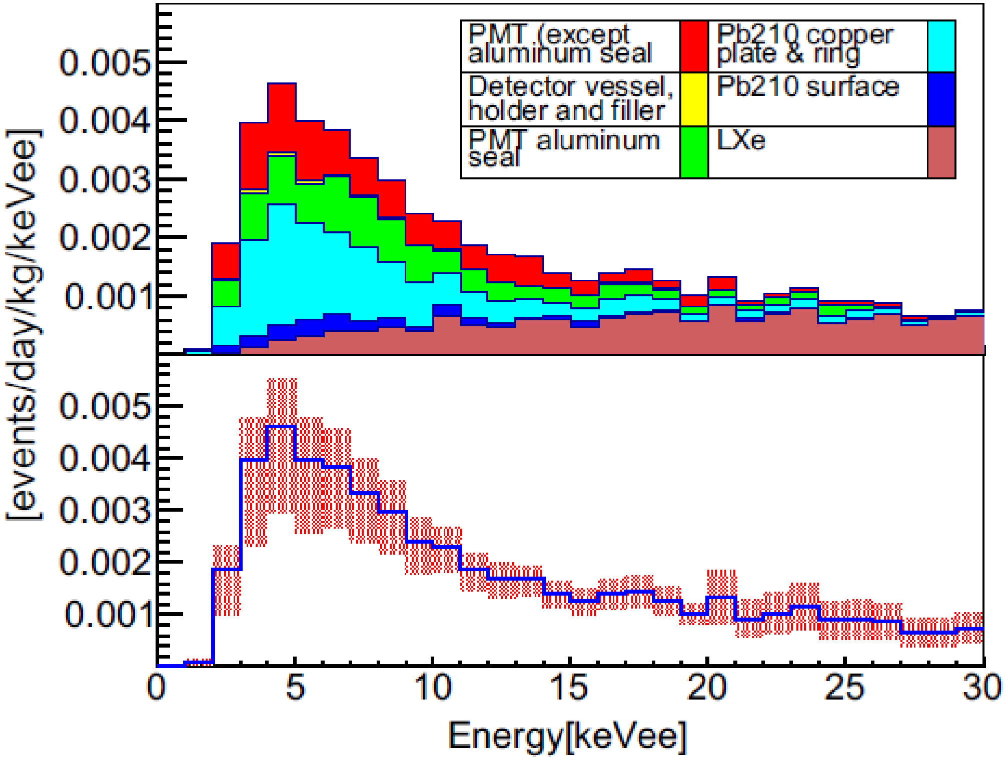
# Motivation

- The Spherical LXe scintillator; XMASS
  - Event reconstruction with 642 PMTs
  - XMASS recently published results of full data set
- The two weak points.
  - Surface BG due to mis-reconstruction
  - No PID capability



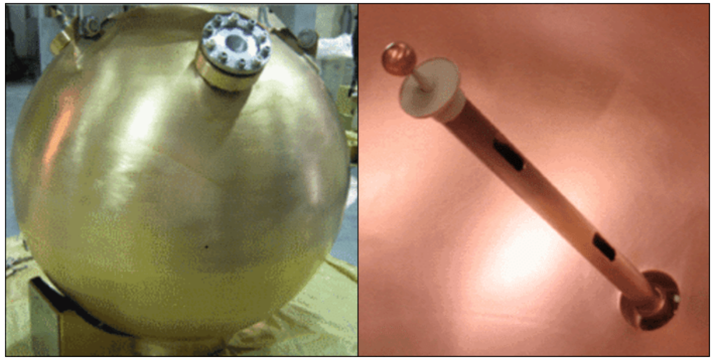



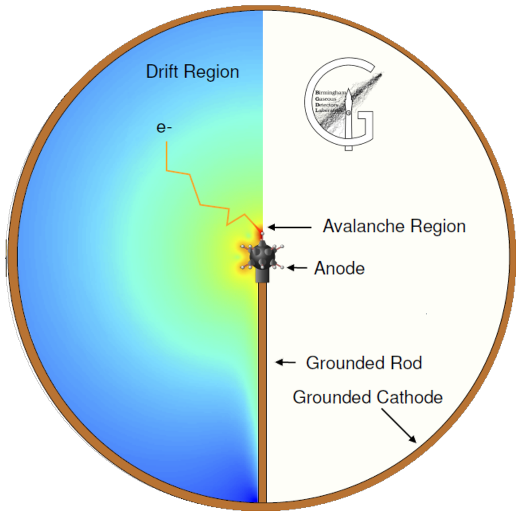
XMASS results
PHYSICAL REVIEW D 108, 083022 (2023)

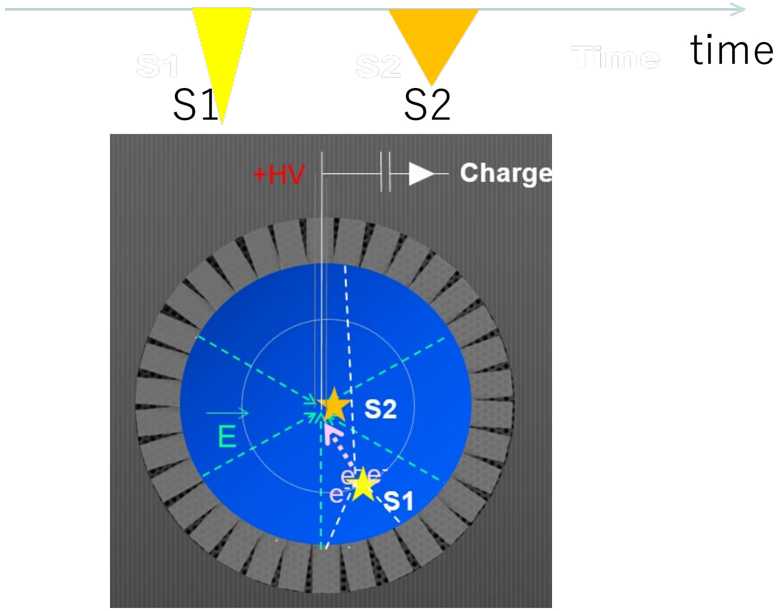


# Motivation

- Sensitivity can be further improved if fiducialization/background rejection is improved.
  - Can this be done by adding charge-amplification like NEWS-G, a spherical gas TPC, to get S2 signal?
  - If so, the scalability of the spherical detector will be a great advantage for future large detectors.
- NEWS-G: Charge-only, gas XMASS: Light-only, liquid

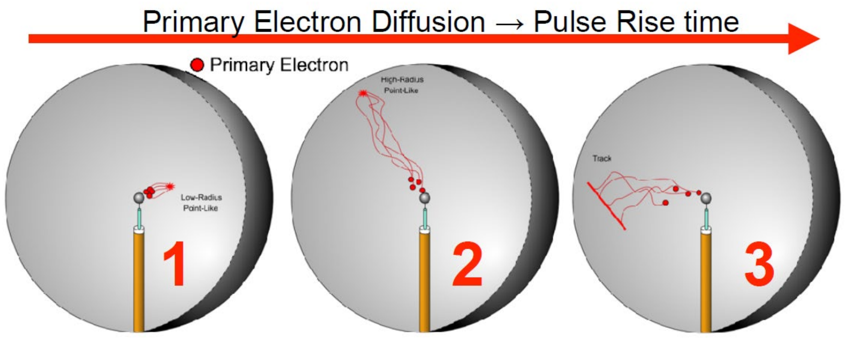




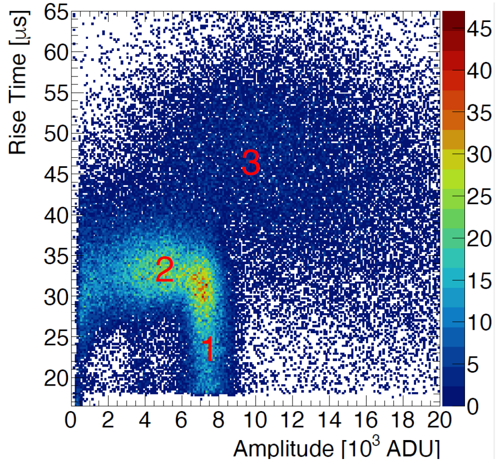



# Motivation

- NEWS-G
  - Even only with Charge-information, fiducialization and PID capable via PS
    - Electron from larger radii diffuse more → Larger spread in arrival → higher pulse rise time/width



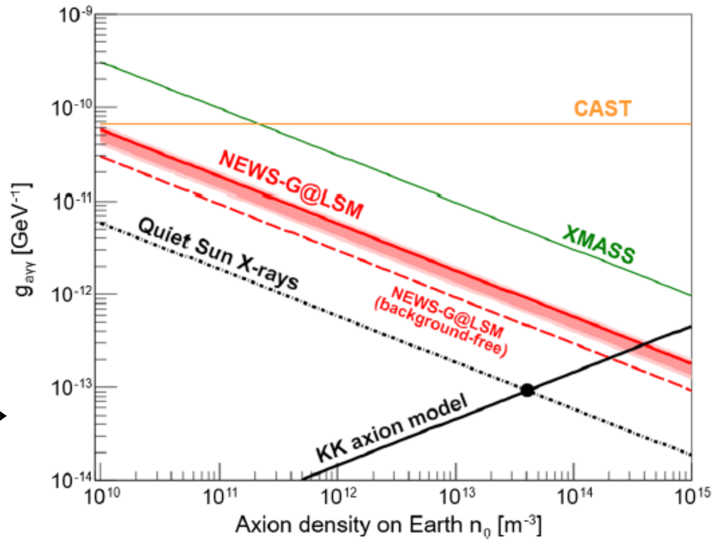

(1) $\gamma$ in volume, (2) $\gamma$ near shell, (3) cosmic $\mu$




Ø30 cm detector, 1.3 bar
He:Ar:CH4 (51.7:46%:2.3%)

Phys. Rev. D 105, 012002 (2022)

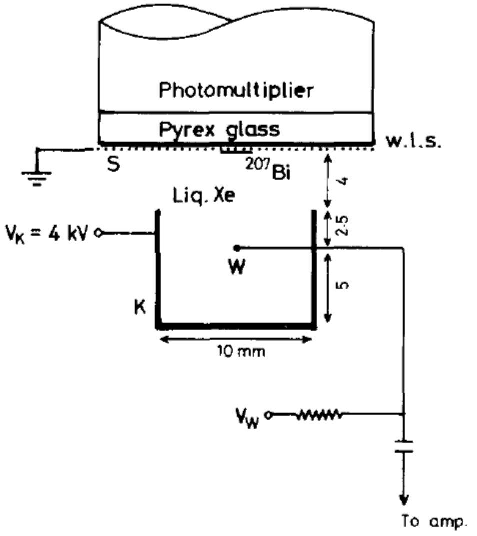
Solar Kaluza-Klein axion search results with $\phi$ 60cm →

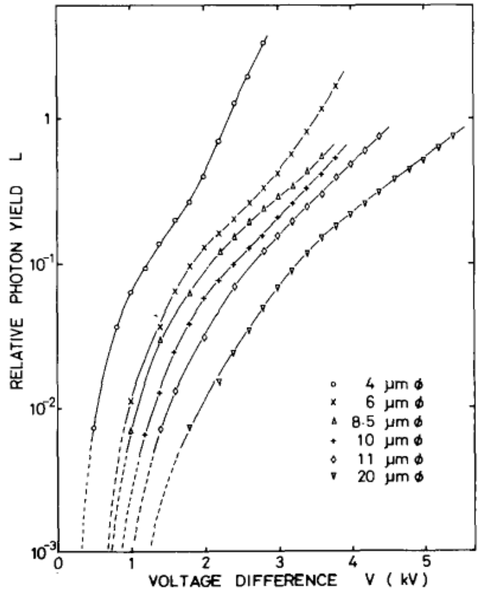


# Historical backgrounds

- The first idea in MPGD2011 with I.Giomataris
- S2 in LXe itself has been demonstrated with wires since 1970's

K. Masuda, NIM 1979




Basic S2 properties were already reported

S. Suzuki, JPS membership Journal 1998

日本物理学会誌 Vol. 53, No. 3, 1998

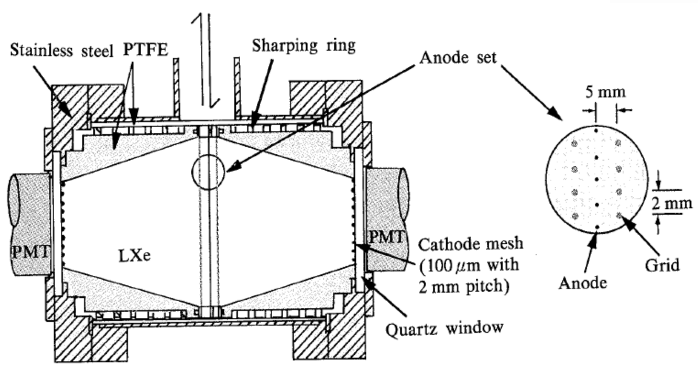
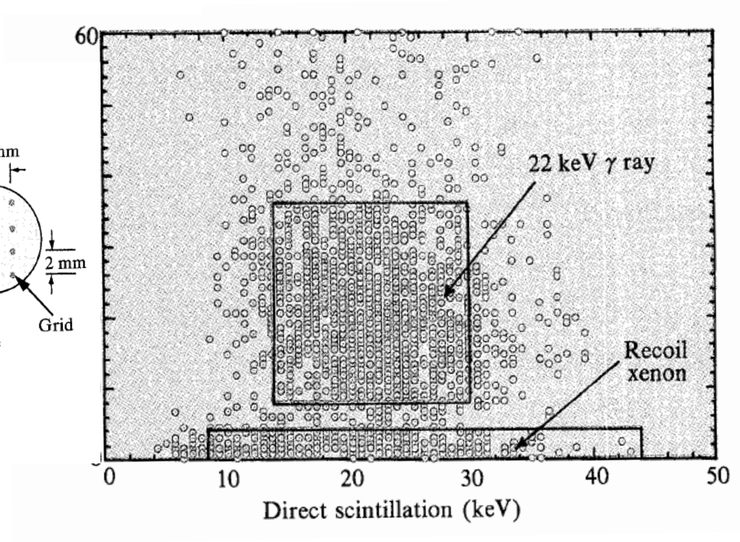


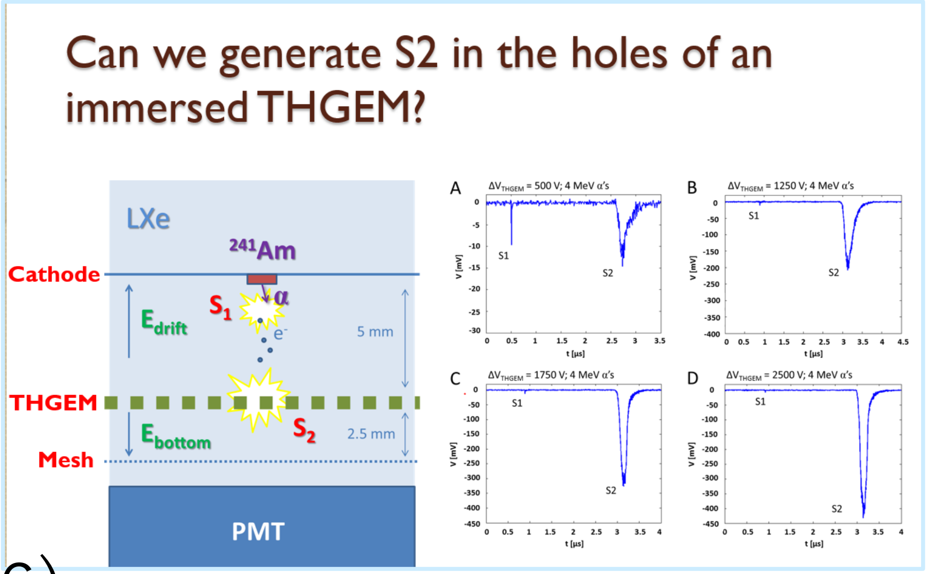

図2 プロトタイプチェンバーの断面図.

3.5μm wire !




The lowest energy record, $^{109}$Cd 22keV
PID performance is shown

# Historical backgrounds

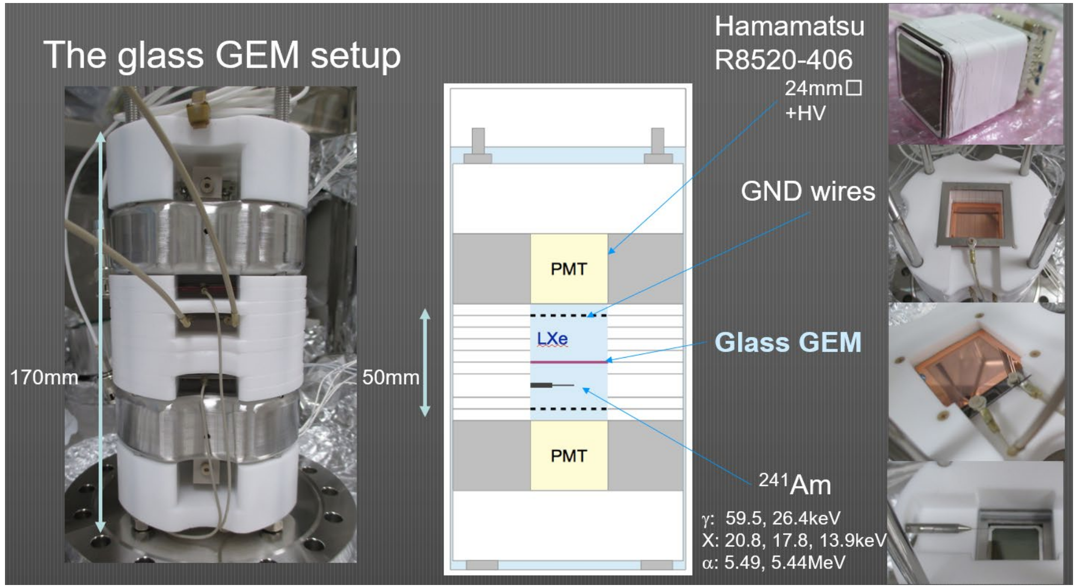


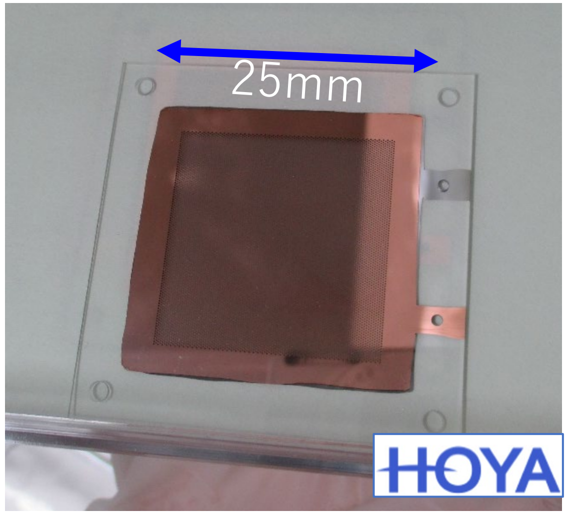

- S2 with GEM? L. Arazi JINST 8 C12004 (2013)

  Later, Lior said it was occurred in the bubble beneath the GEM…

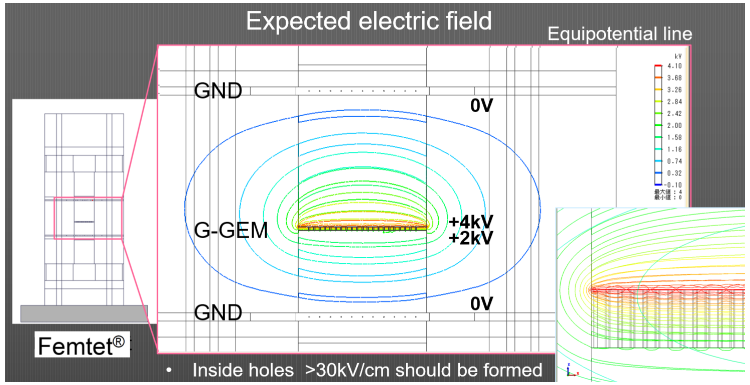
- Started the actual R&D to see S2 (2016)
  - Test bench and development of Glass-GEM with HOYA (→MIGDAL)

No S2 was observed….



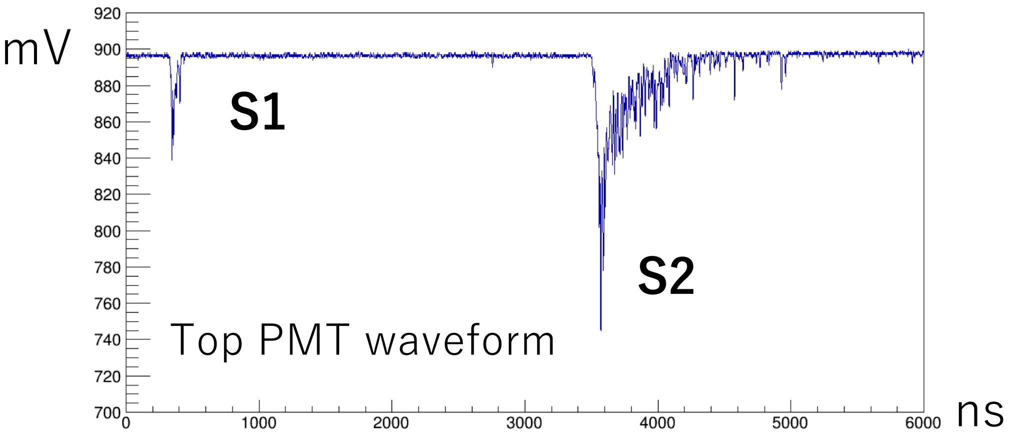




$\Delta V_{G\text{-}GEM}$=2.5kV
( drift:0.4kV/cm, G-GEM:38kV/cm)

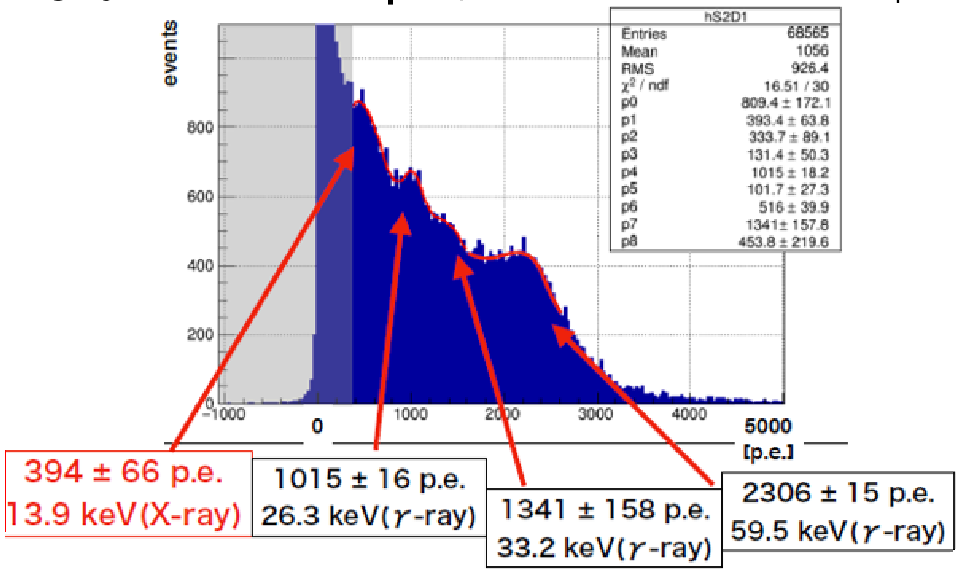


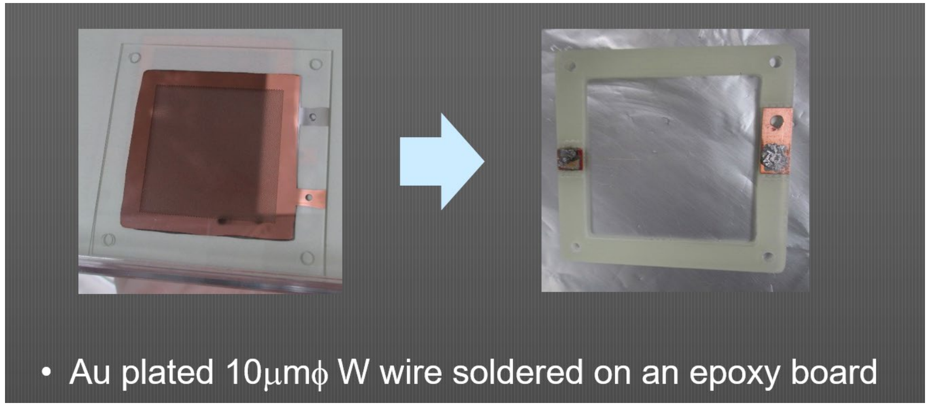
# Historical backgrounds

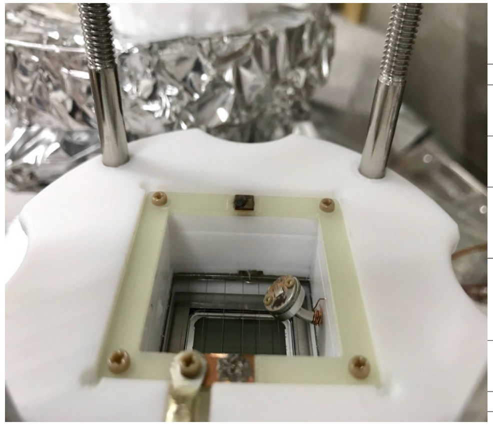
- 10μm wire with $^{241}$Am: Clear S2 (2018)

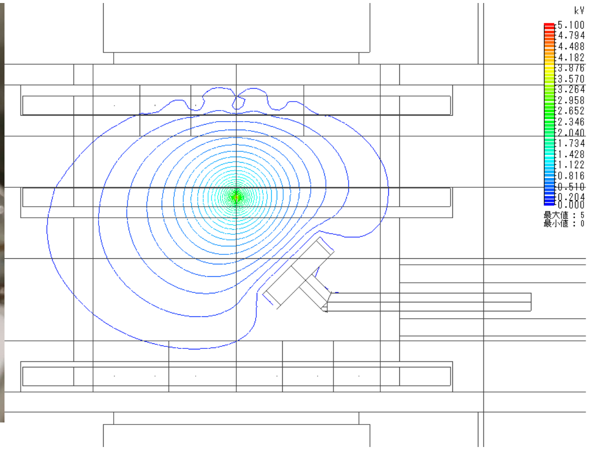



**S2@ 5kV** **L.Y. 30p.e./keV** Clear 13.9keV peak



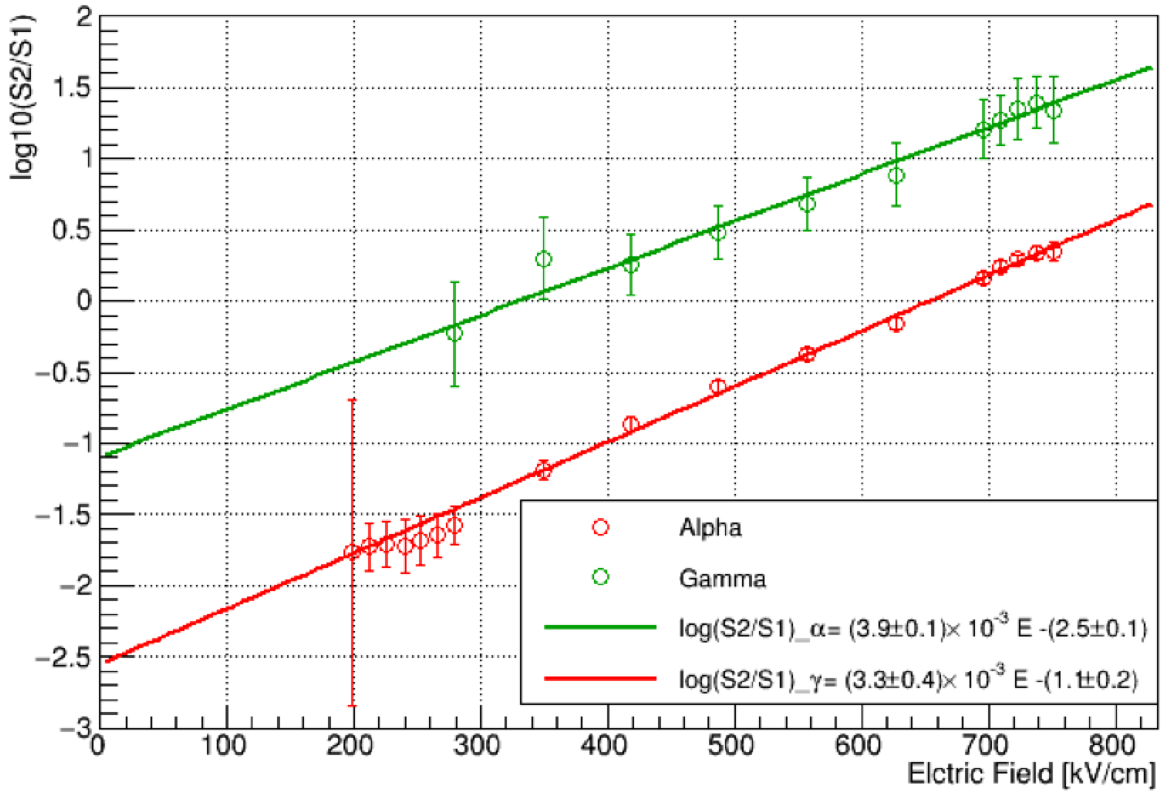



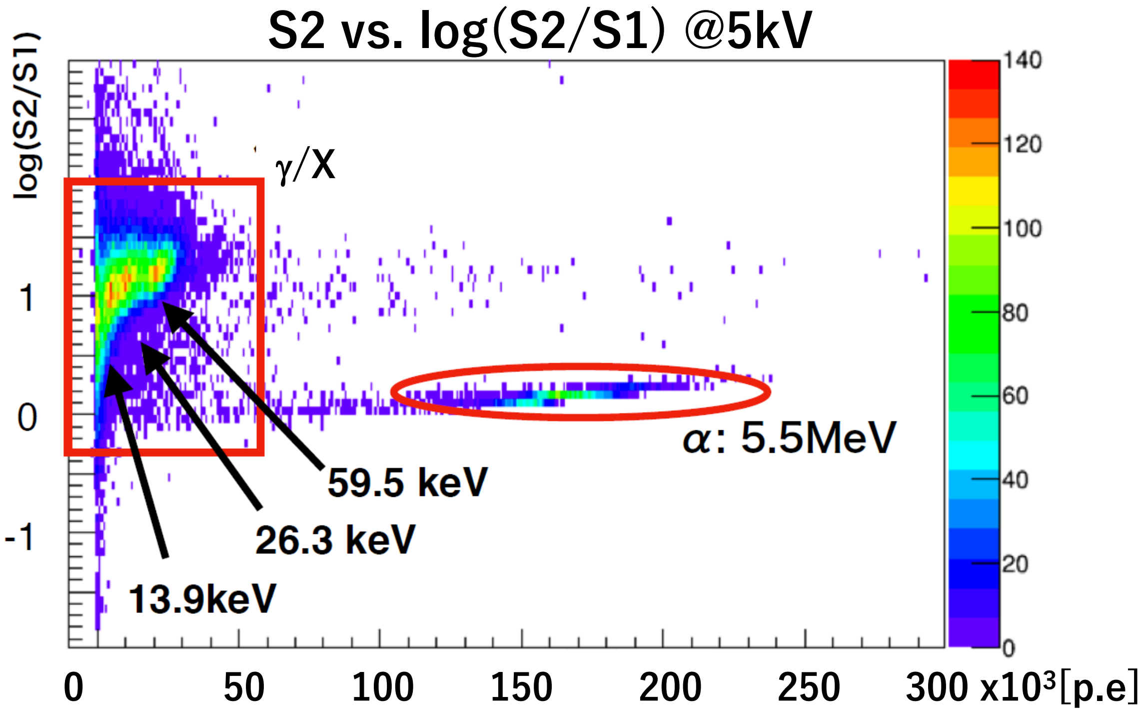


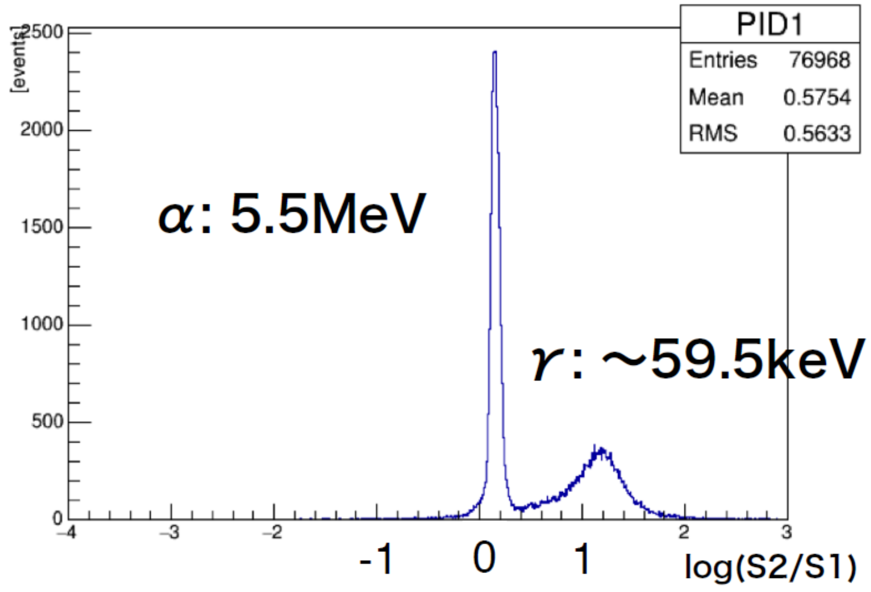
| half life | α [MeV] | B.R. [%] | γ/X [keV] | B.R. [%] |
|---|---|---|---|---|
| 432.2 y | 5.388 | 1.4 | 26.3 | 2.4 |
| | 5.443 | 13.0 | 33.2 | 0.13 |
| | 5.486 | 84.5 | 59.5 | 35.9 |
| | | | 13.9 | 42.0 (Np-L) |

# Historical backgrounds

- 10μm wire with $^{241}$Am: PID (2018)

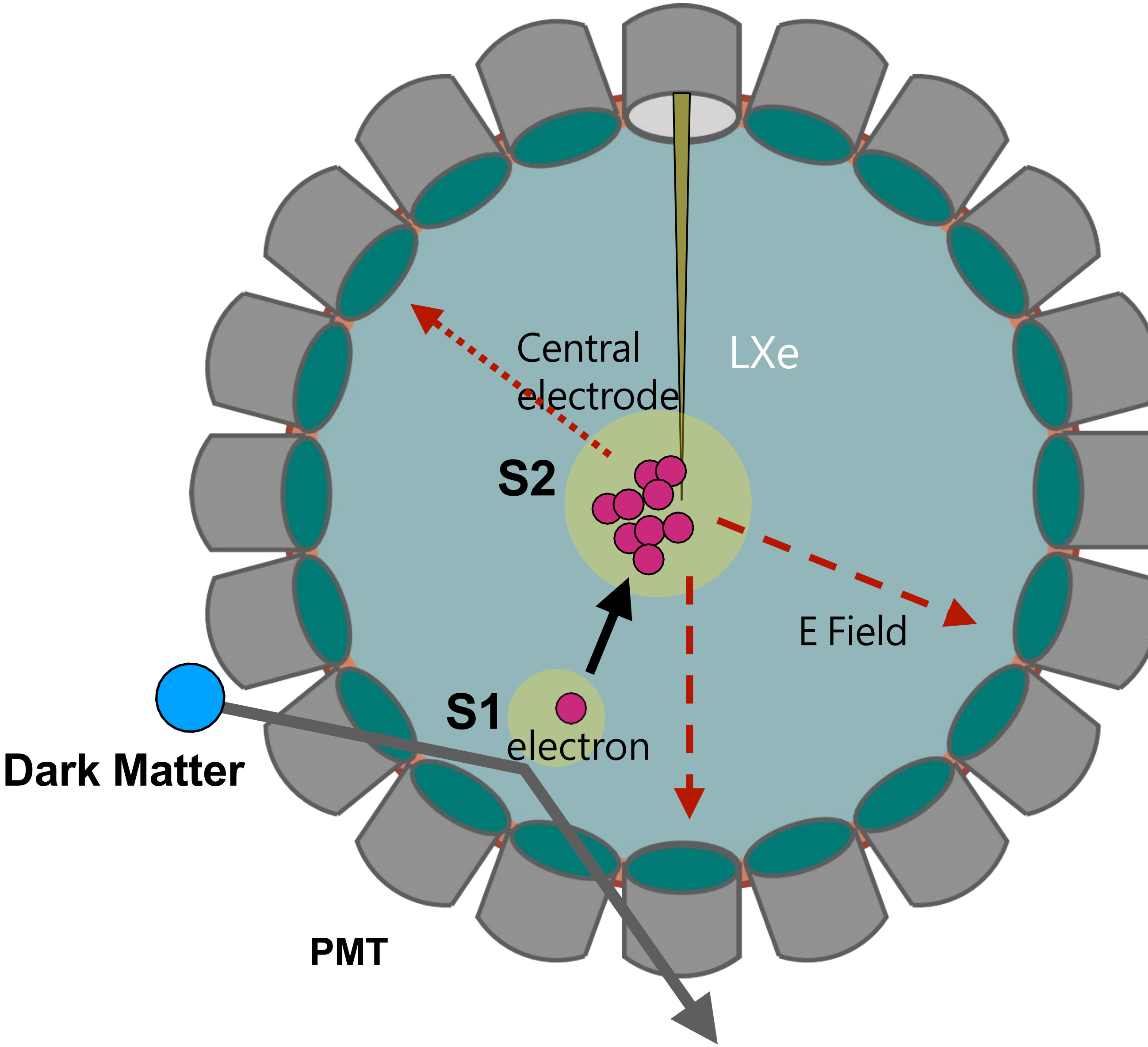


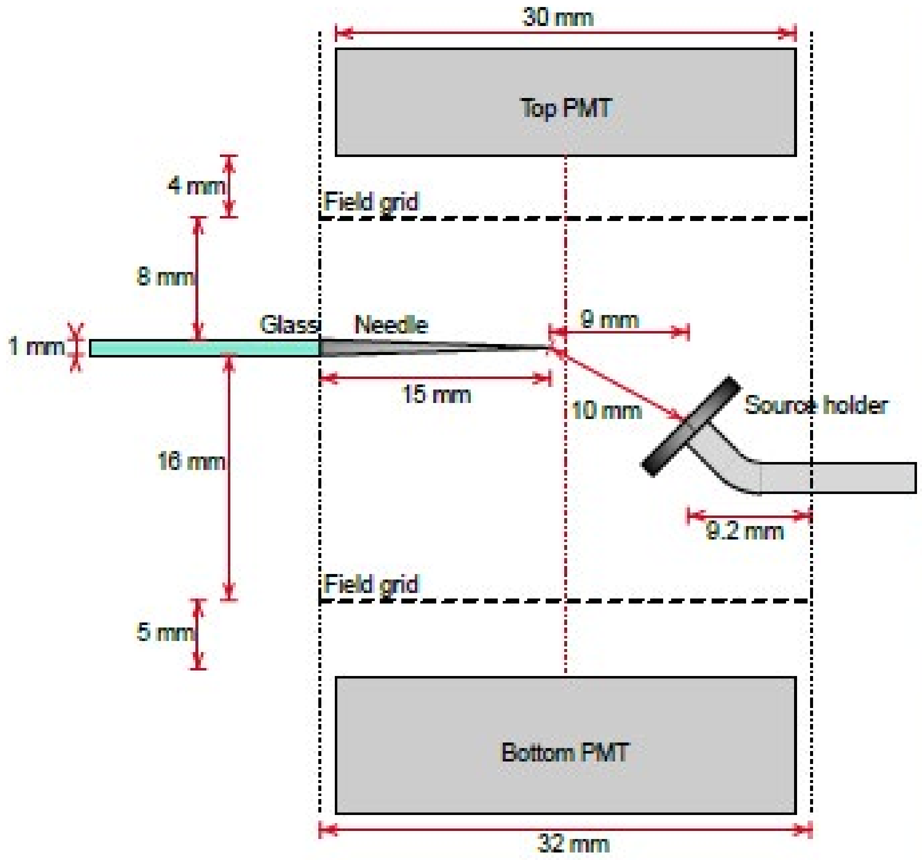
arXiv:2401.02327

To achieve this →

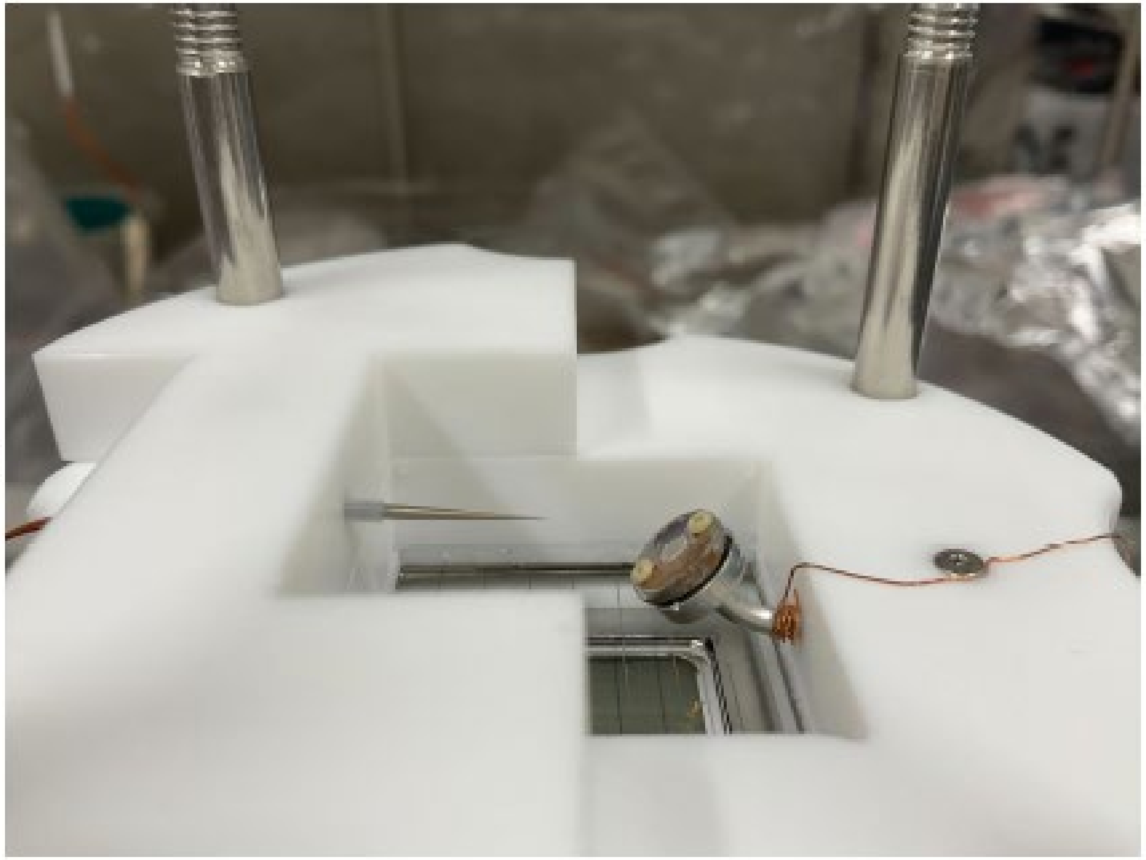


# The test setup

- ϕ 10μm wire → SUS303 ϕ 50μm needle



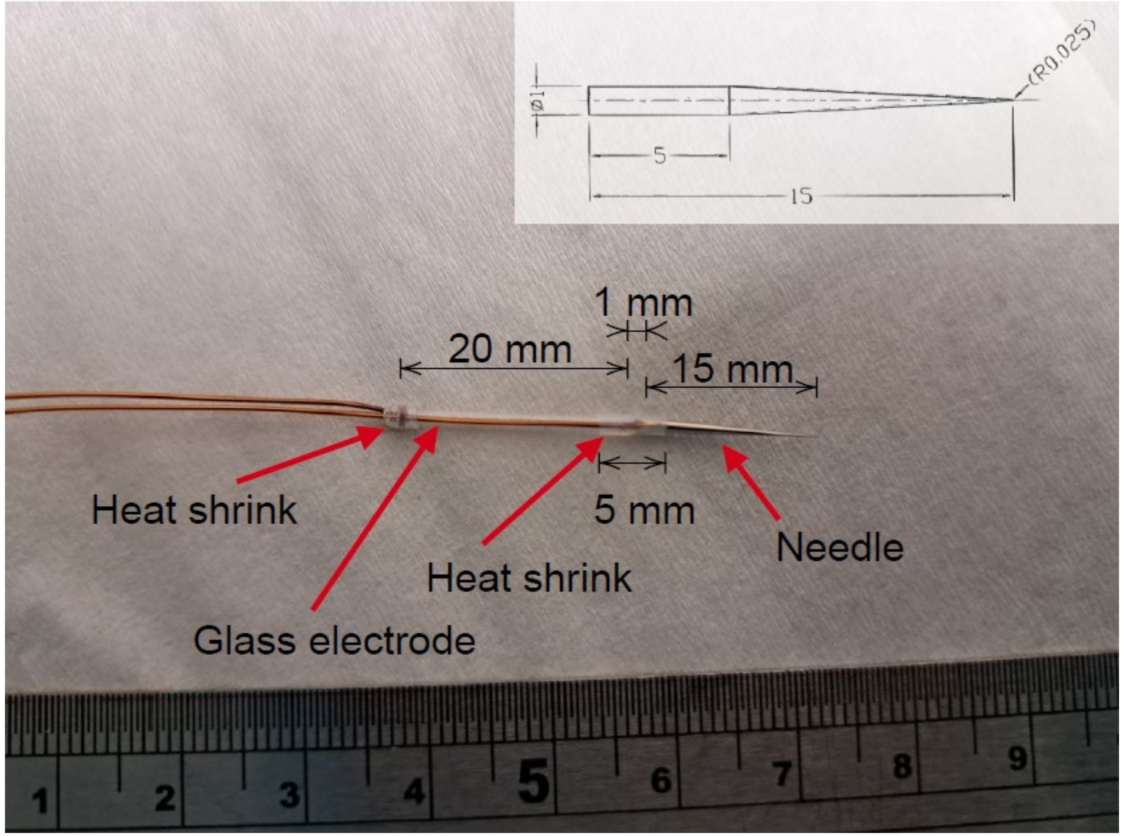

(a)



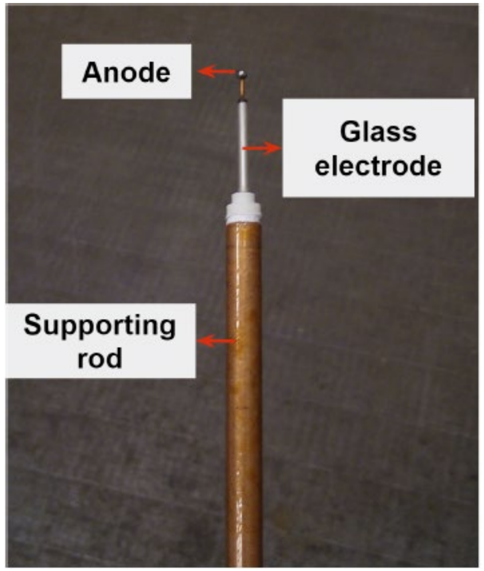
(b)

# Needle protected by resistive glass

- A grounded resistive electrode made of a soda-lime glass tube
  - The use of a resistive material to support the needle reduced the potential for discharge or charging up, compared to a conductive or insulator, respectively.

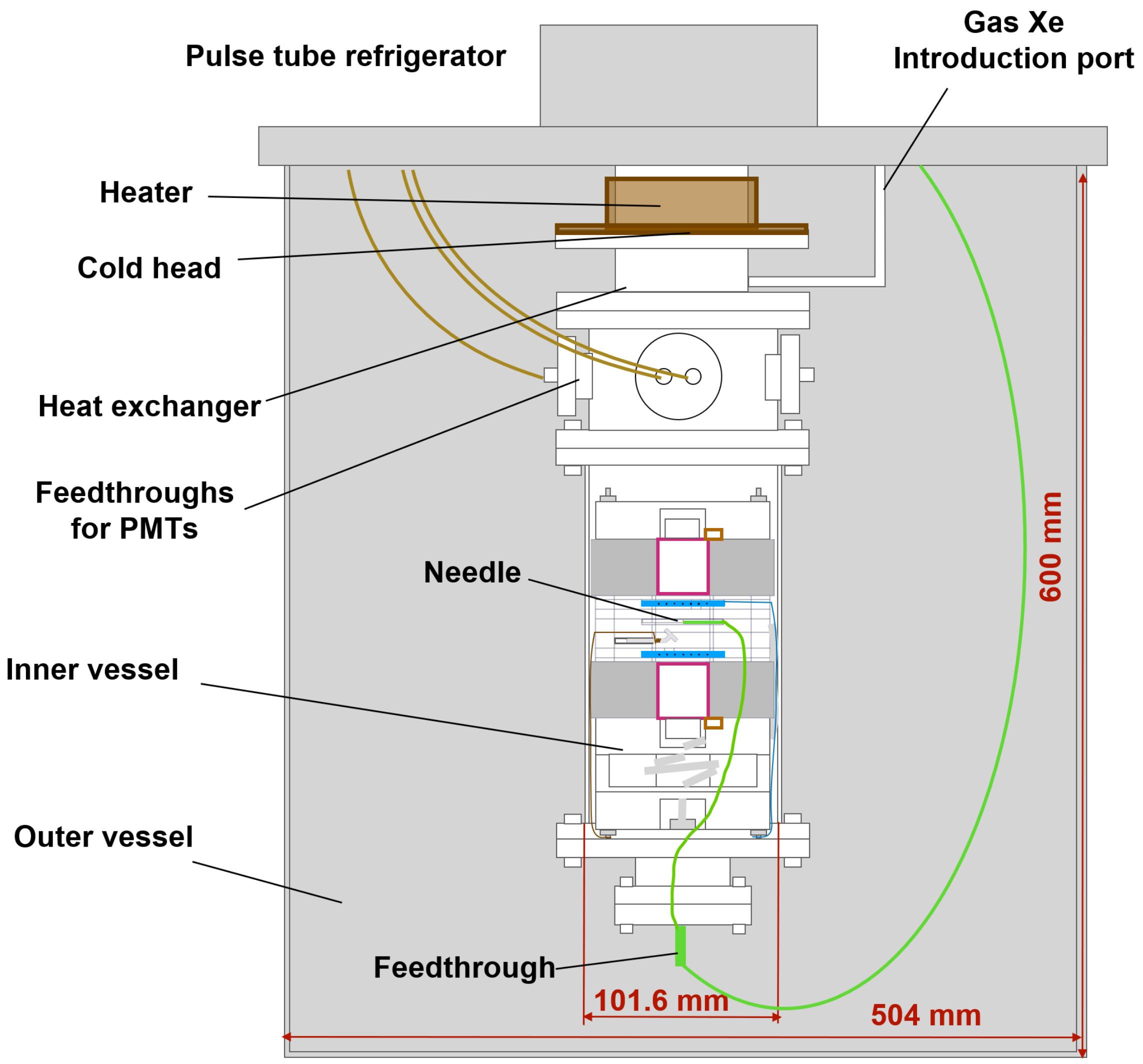


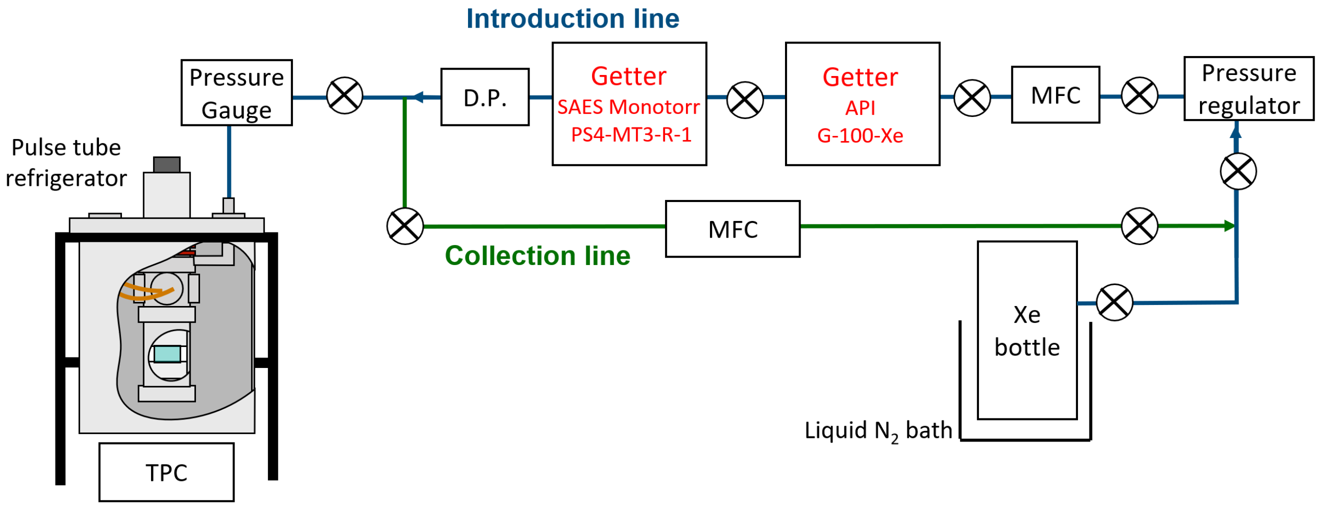

Ref: NEWS-G's electrode
JINST 13 P11006 (2018)

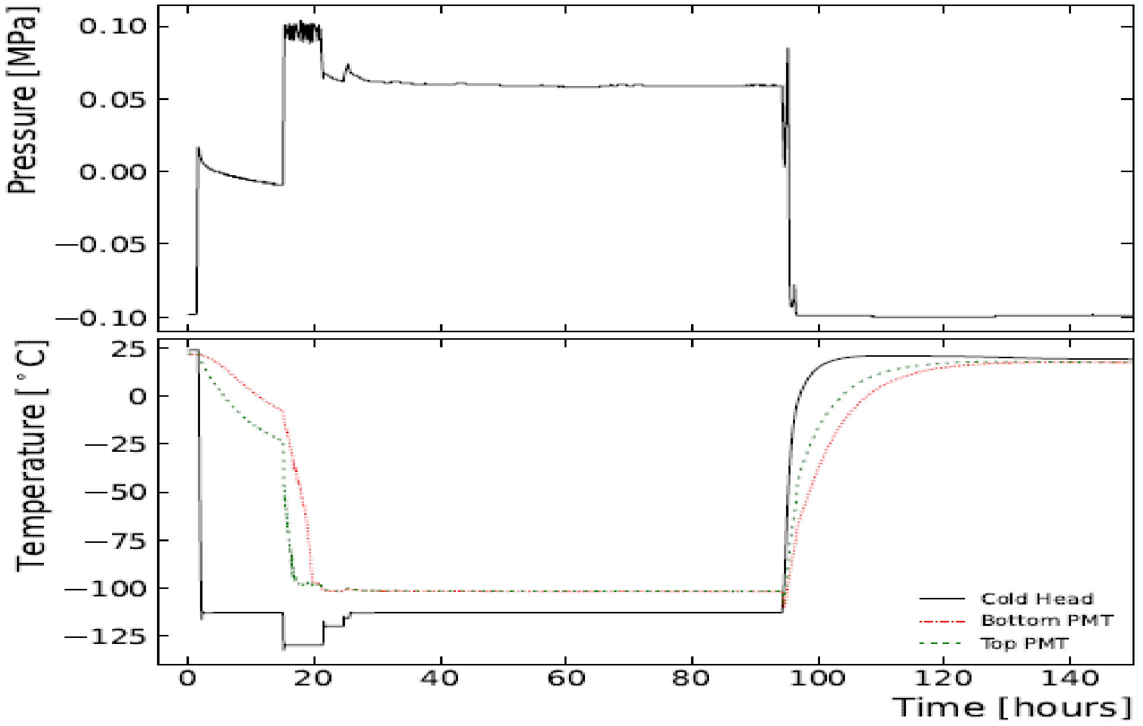


# Cryostat

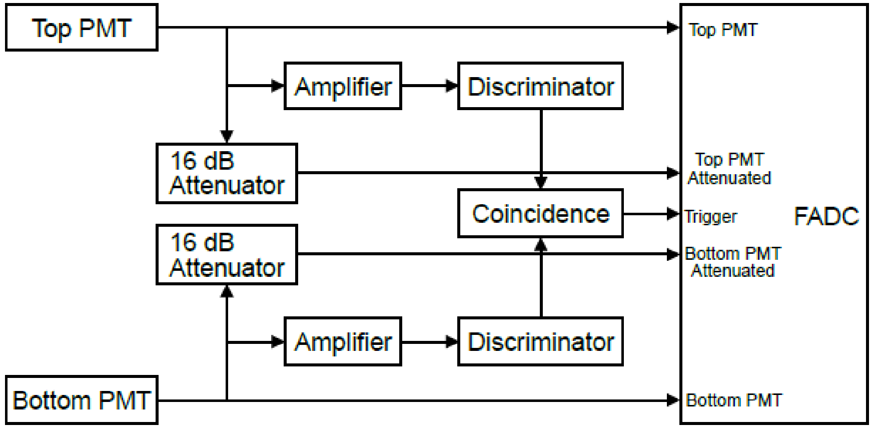
- Nov. 6 to Nov. 10, 2023



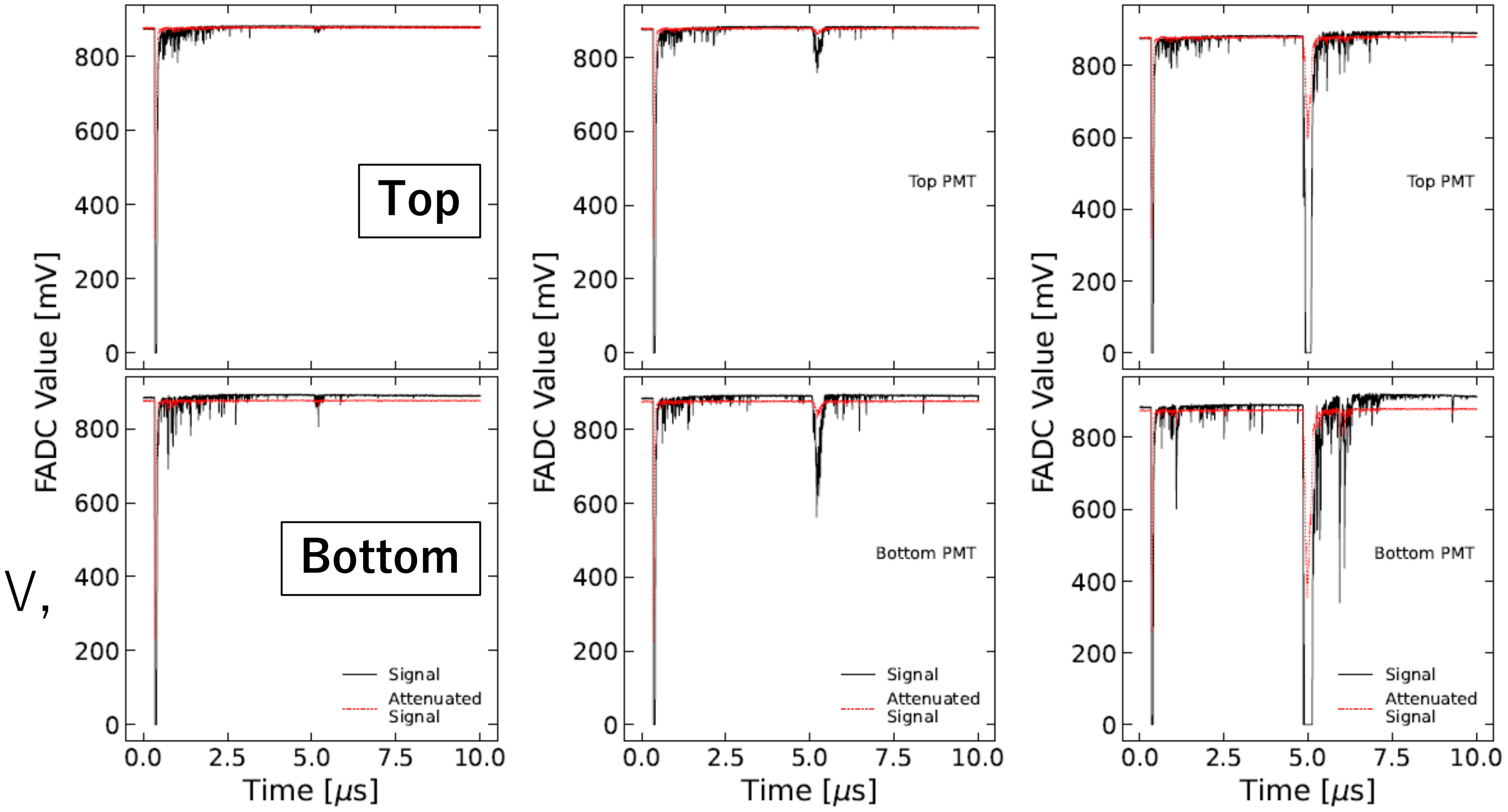



# The results: S1 and S2 waveforms



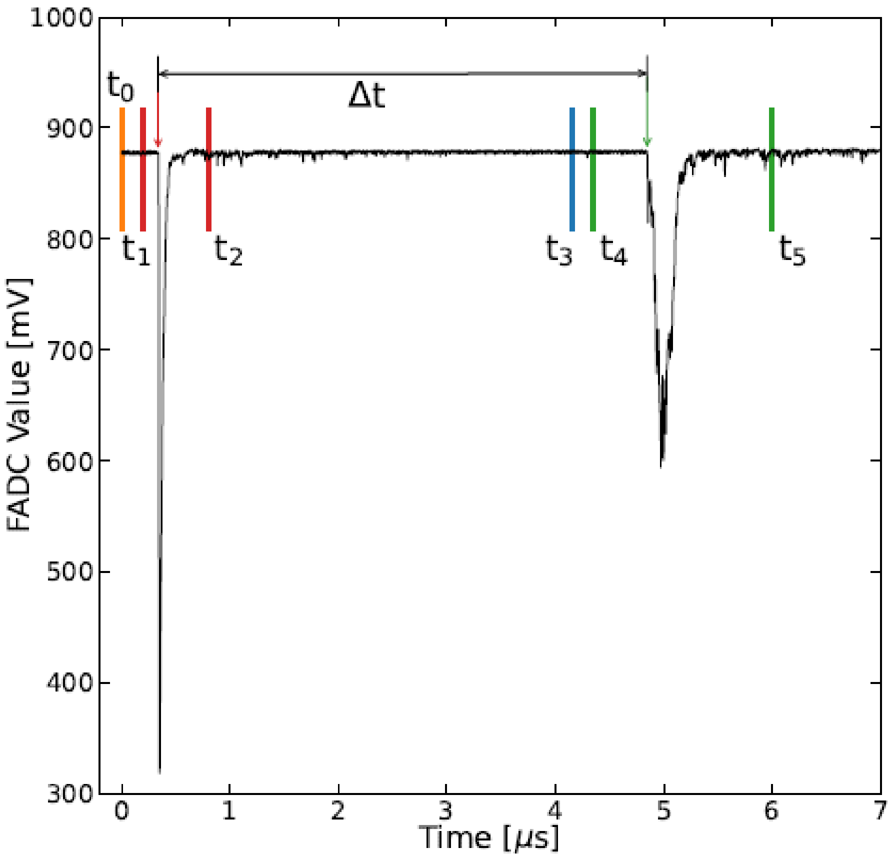

- PMTs biased to 792 V and 892 V, adjusting gains to $7 \times 10^6$
  - Direct PMT outputs
  - 16dB attenuated PMT outputs




**Needle 2500V** **4500V** **6000V**

For voltages above 2000V, an S2 signal was observed in the PMT signals.

# The results: S1 and S2 waveforms




- The baseline for S1: the average FADC value 200 ns before the S1 trigger ($t_0$~$t_1$)
- The area of the S1 signal: integrating between 200ns and 800ns($t_1$~$t_2$)
- The baseline for S2: the average between 4.05 $\mu$ s and 4.25 $\mu$ s ($t_3$~$t_4$)
- The area of the S2 signal: integrating between 4.25 $\mu$ s and 6.0 $\mu$ s ($t_4$~$t_5$)
- The time between the S1 and S2 signals $\Delta t$ is defined as the difference between the two onset times.

# The results: S1 for 5.5MeV α

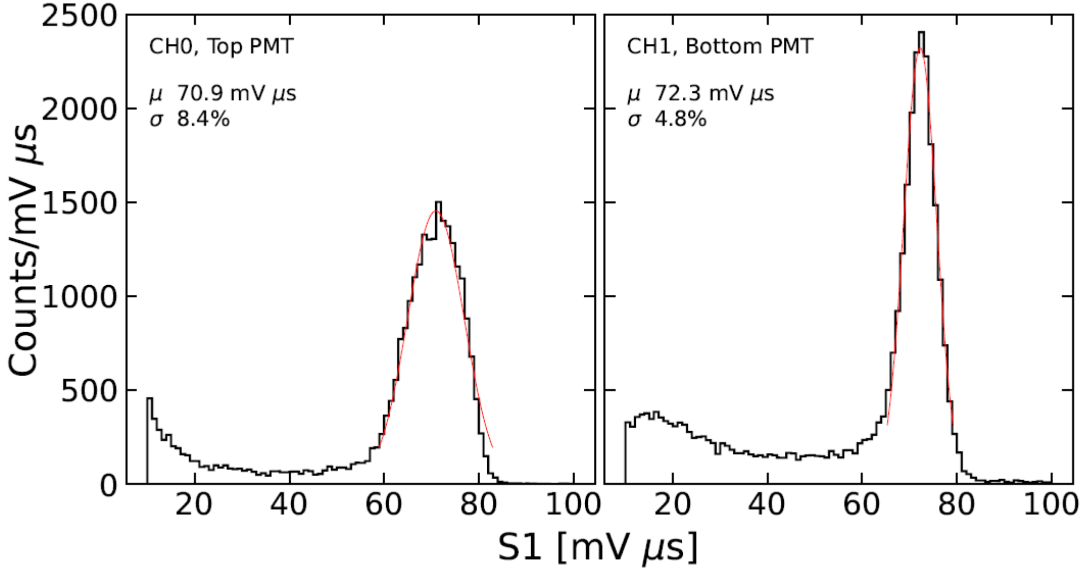



**Figure 6.** Example S1 distribution for the Top and Bottom PMTs. The peak corresponds to the $^{241}$Am $\alpha$-particle, and is fit with a Gaussian function to extract the mean value.

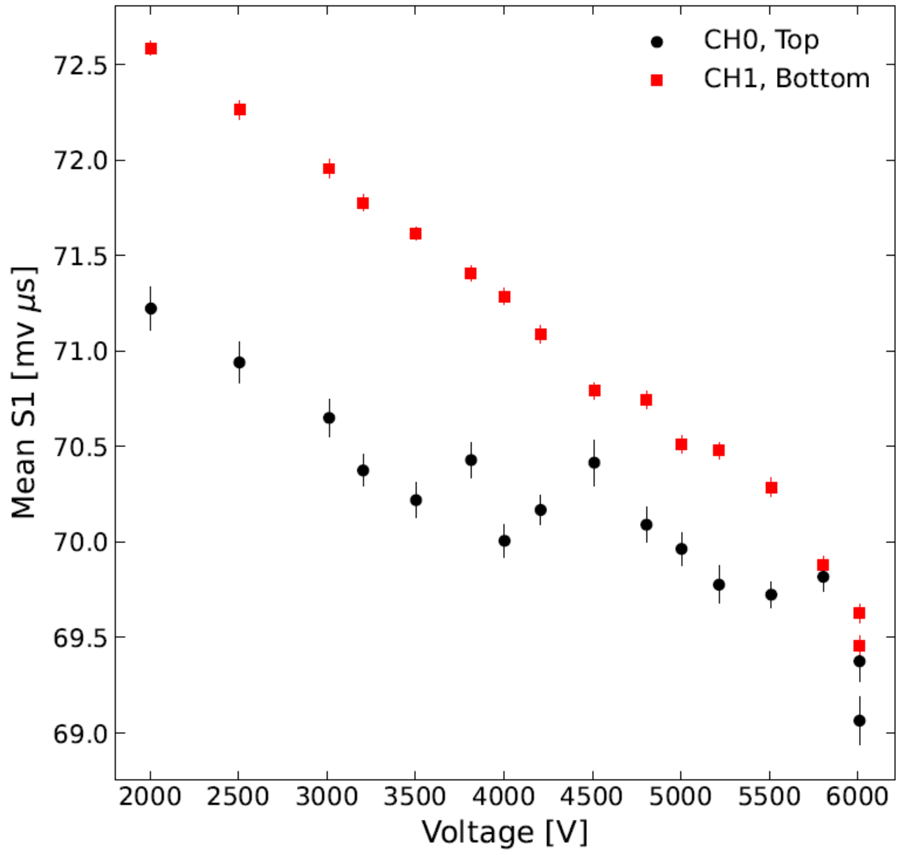
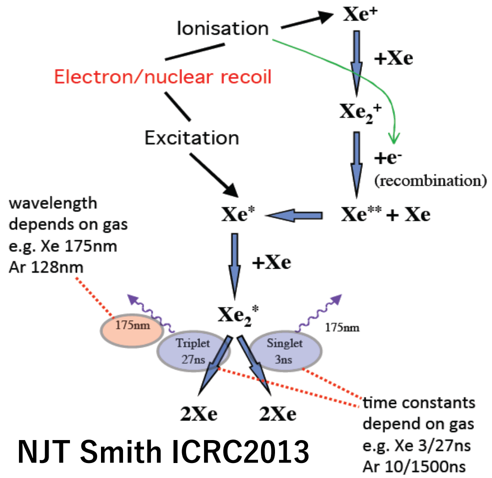


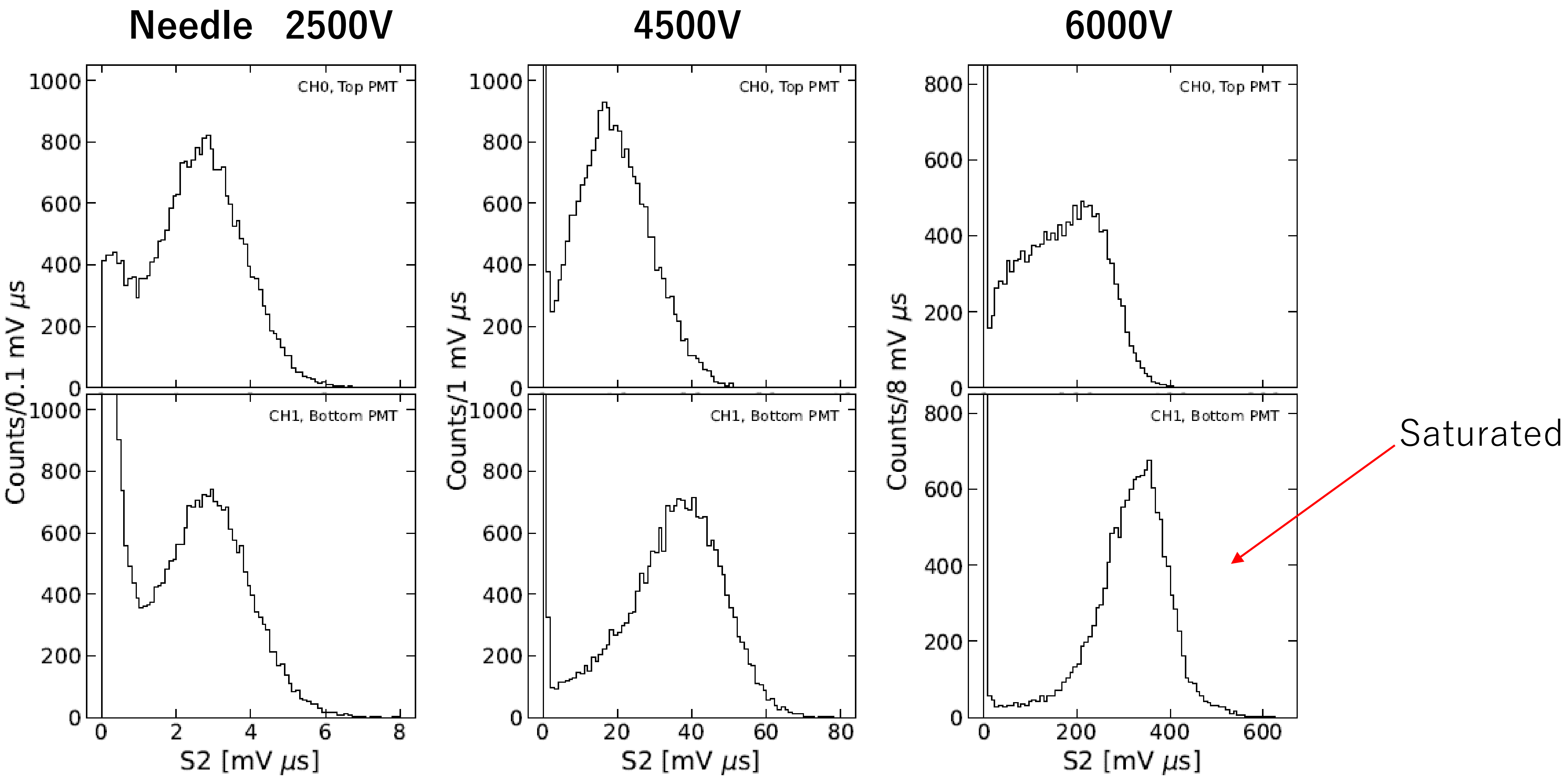

**Figure 7.** Mean S1 as a function of voltage applied to the needle.




NJT Smith ICRC2013

- S1 decreases as higher voltage applied.

# The results: S2 for 5.5MeV a




- S2 increases as higher voltage applied.

# The results: S2 for 5.5MeV a

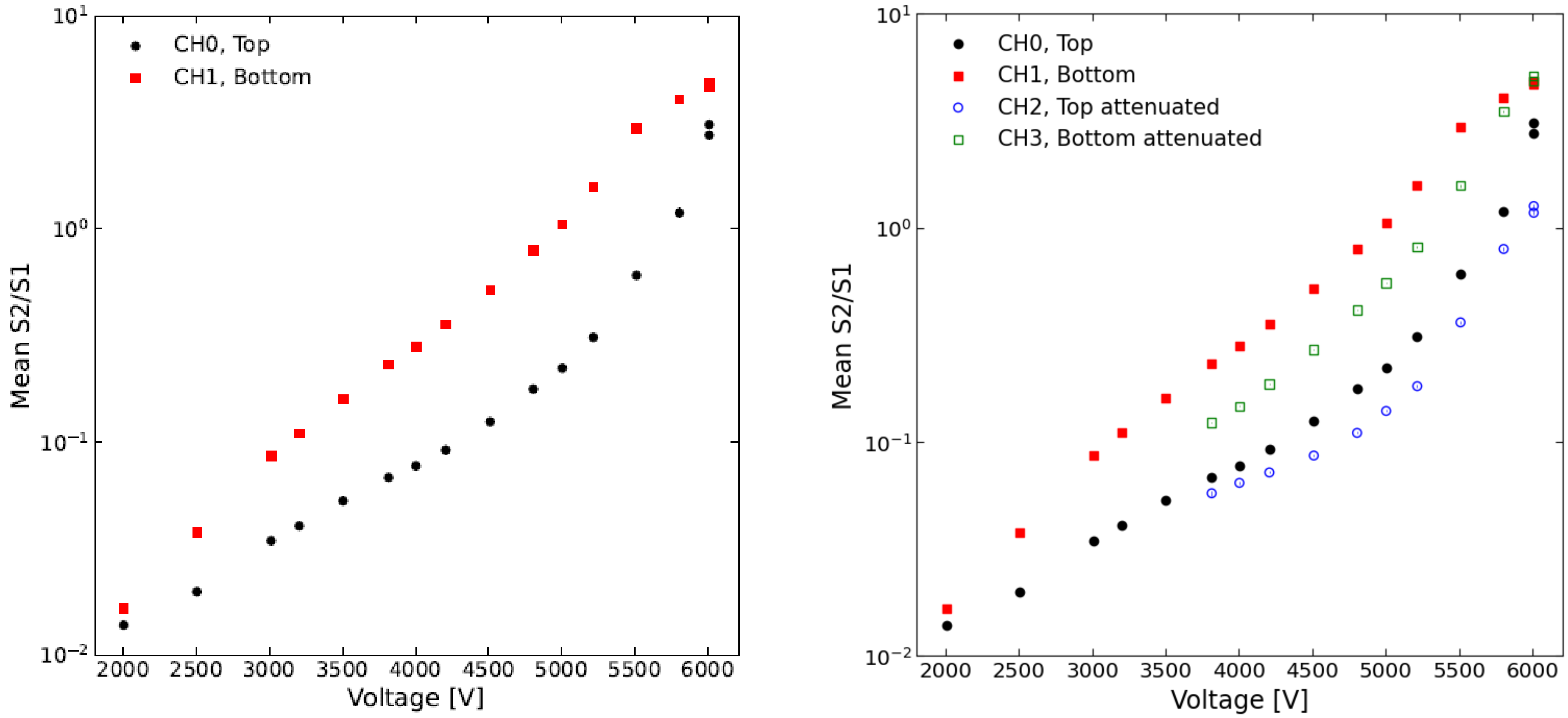
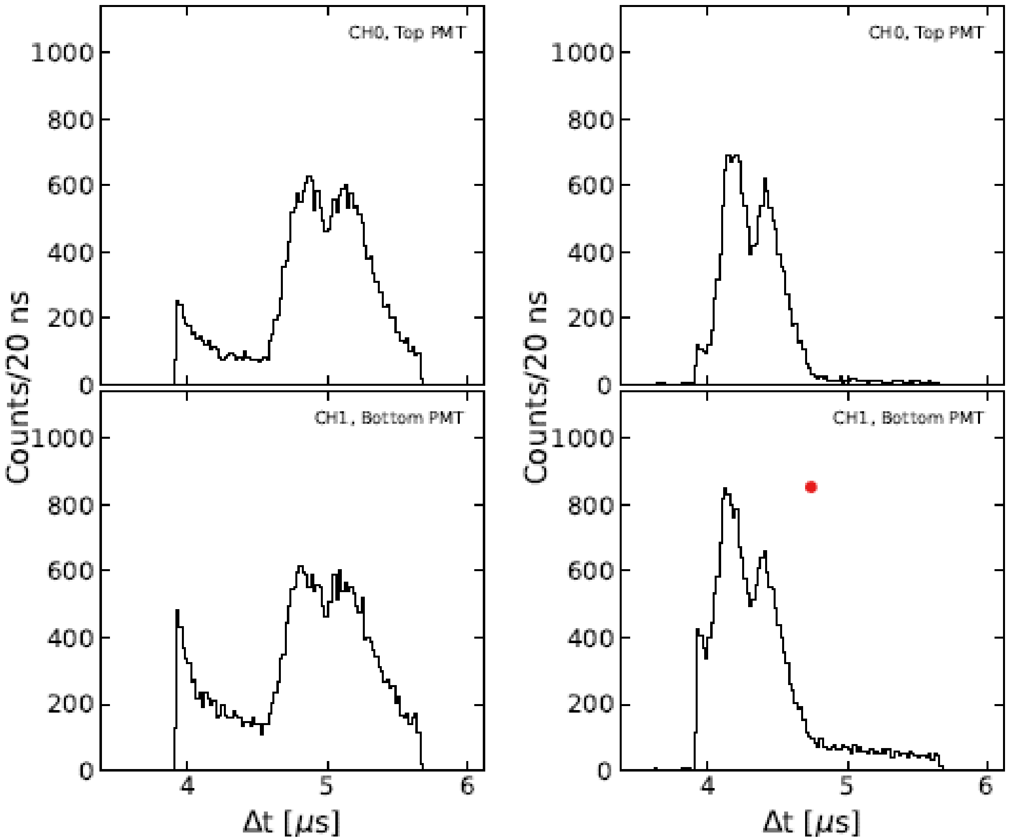



**Figure 10**. Mean of S2/S1 for each run as a function of needle voltage. The exponential trend expected for proportional amplification is observed. Above 5000 V, signal saturation results in loss of proportionality, which is not observed in the attenuated channels.

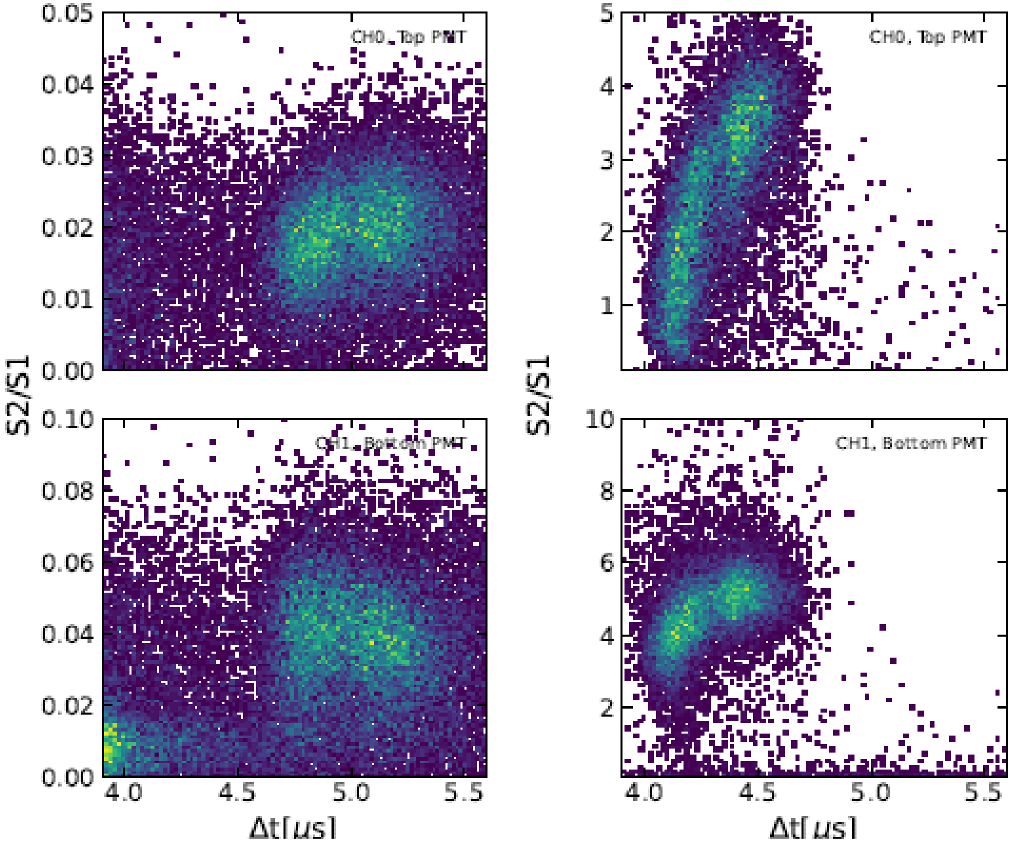
# The results: ΔT

## Δt distribution




Needle 2500V  6000V

## S2/S1 vs Δt




Needle 2500V  6000V

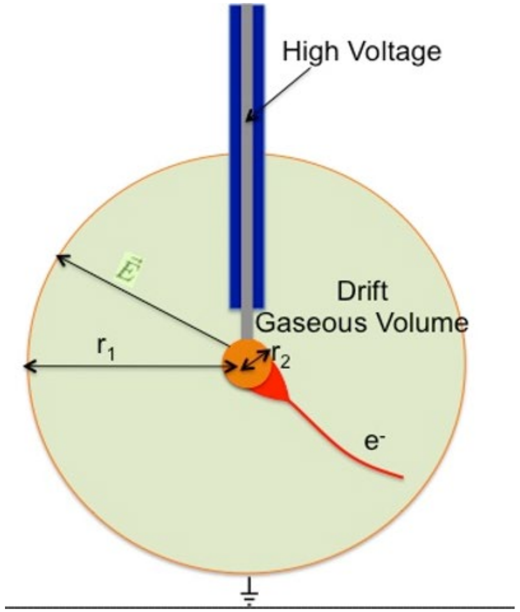
- The drift time of ionization electrons decreases as higher voltage applied.
- There seems two regions of electric field around the needle that are above the threshold where charge amplification occurs with different gains.

# Next: Multi-anode readout “Achinos”

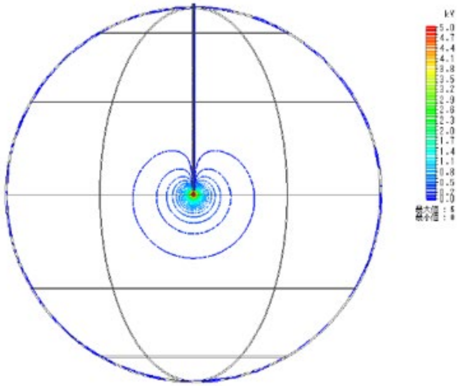
- Single anode: drift and avalanche fields coupled

→ higher voltage for same field at high r

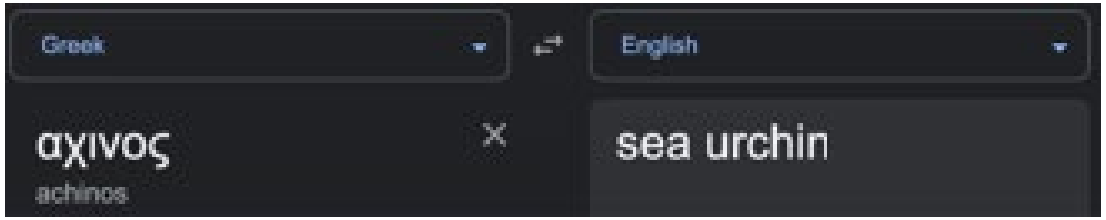
➡Challenge to scale detector size

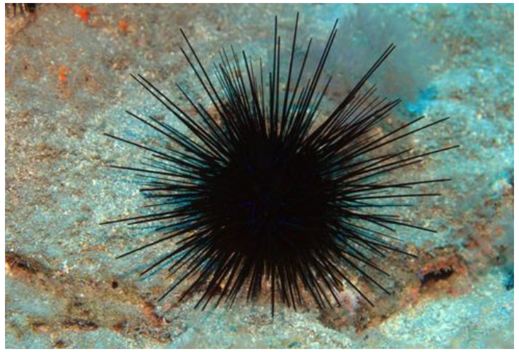



$$E(r) = \frac{V_0}{r^2}\frac{r_1 r_2}{r_1 - r_2} \propto \frac{r_2}{r^2}$$



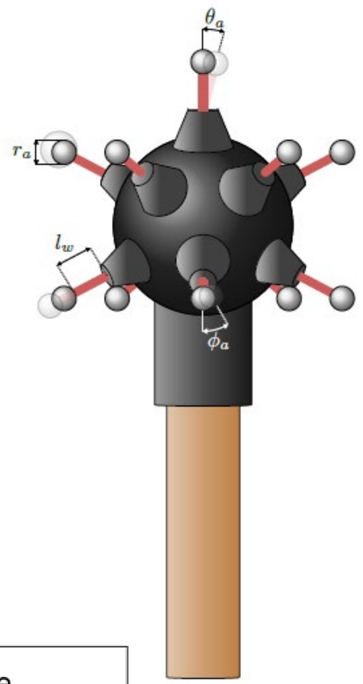
**Idea:** multiple anodes at fixed radius - ACHINOS



# Next: Multi-anode readout "Achinos"

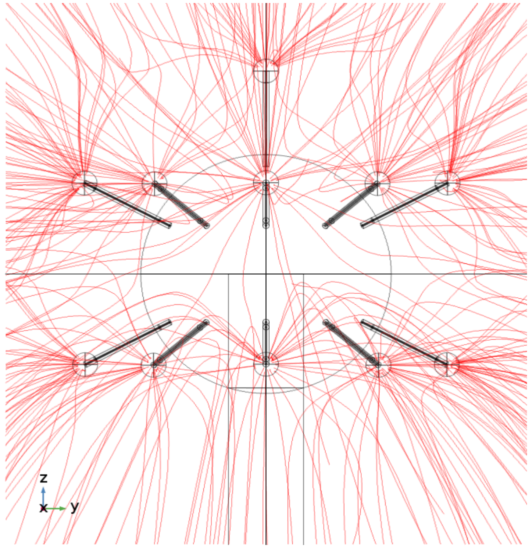
- Multiple ball anodes at fixed radius
  → **Avalanche field:** anode radius + voltage
  **Drift field:** collective field of anodes

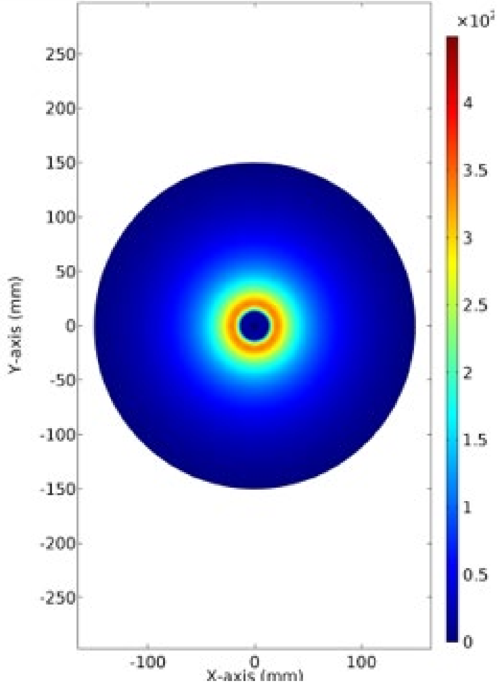


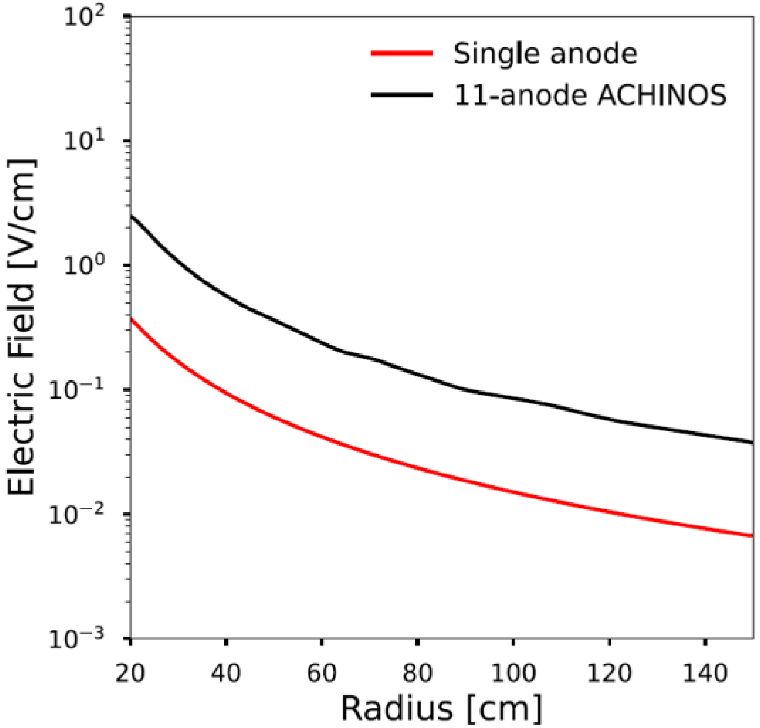

**Collective uniform potentials created**

2018 *JINST* **13** P11006

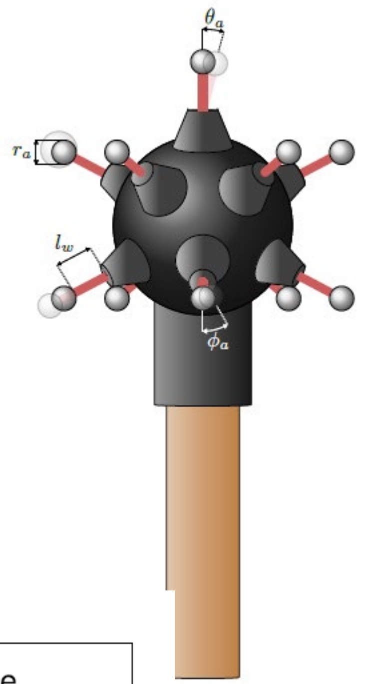
2020 *JINST* **15** C06013



# Next: Multi-anode readout “Achinos”

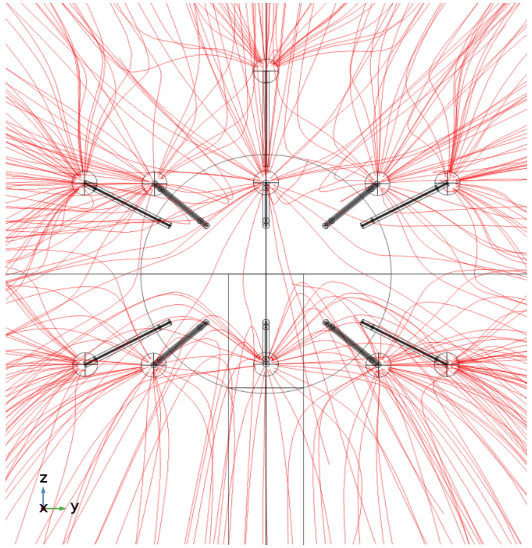


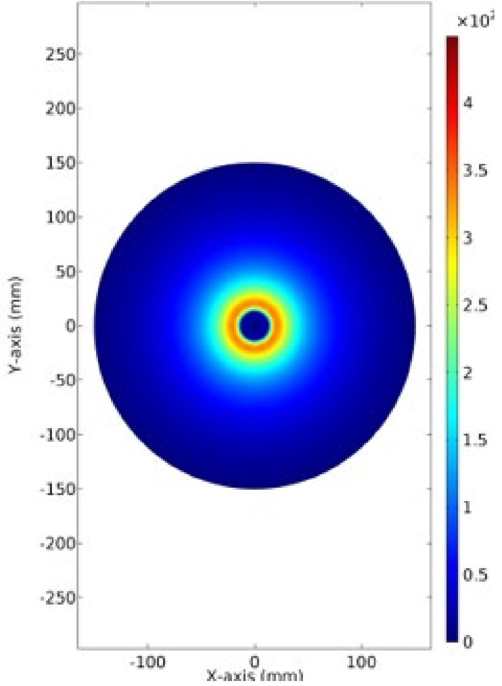

- Multiple ball anodes at fixed radius
  → **Avalanche field:** anode radius + voltage
  **Drift field:** collective field of anodes

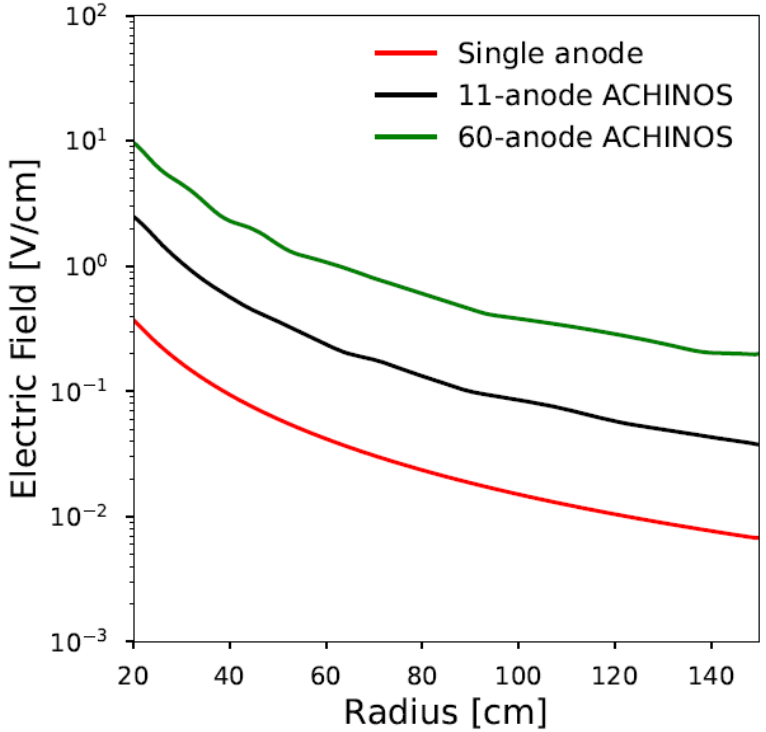
**Collective uniform potentials created**

*JINST* **13** (2018)P11006

*JINST* **15** (2020)C06013





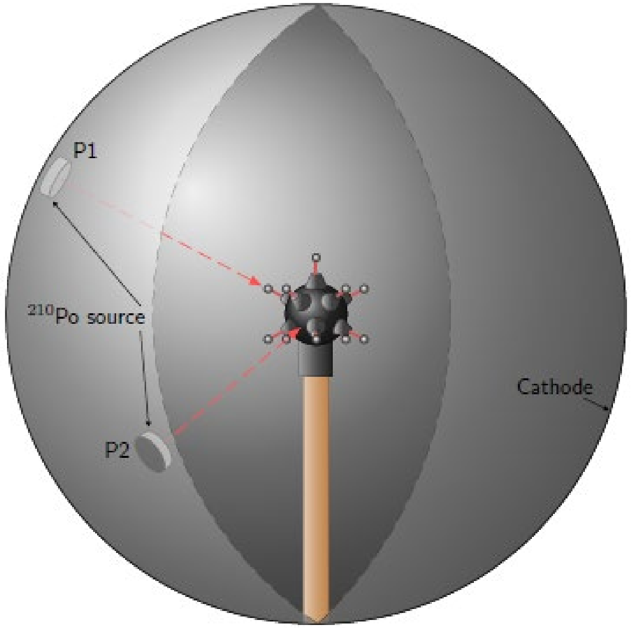



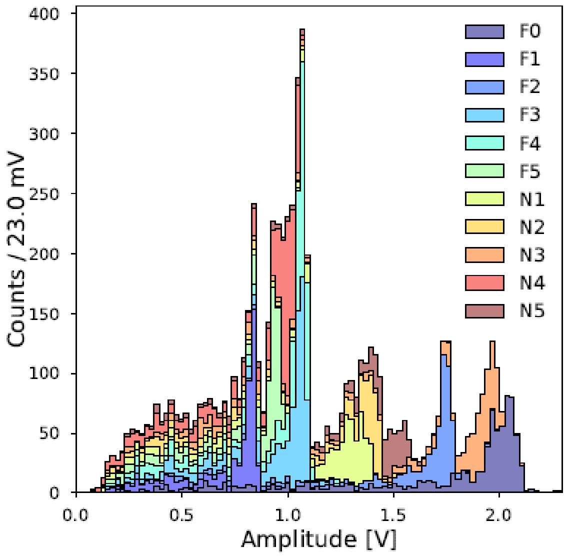
# Next: Multi-anode readout "Achinos" *JINST* **19** (2024) P01018

- High energy resolution demonstrated **by Individual readout**

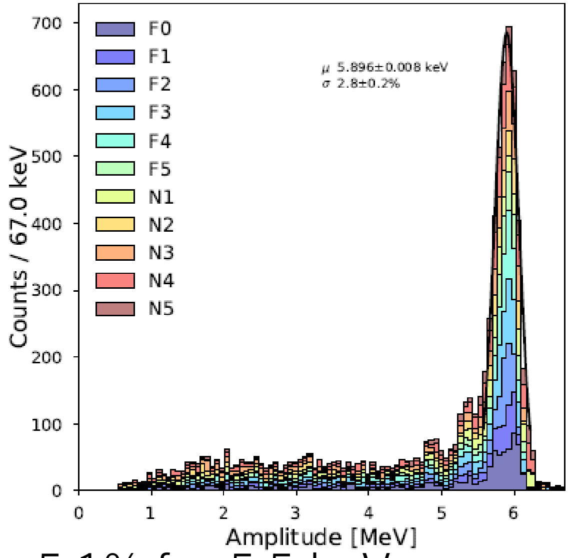
500 mbar Ar:$CH_4$ 2%

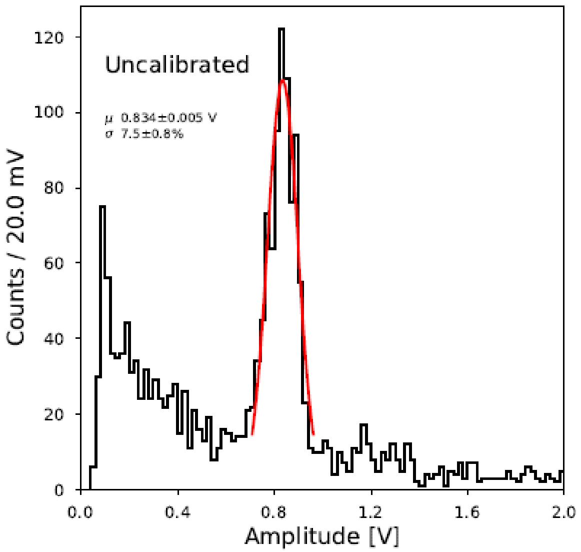
**$^{210}$Po and $^{55}$Fe**



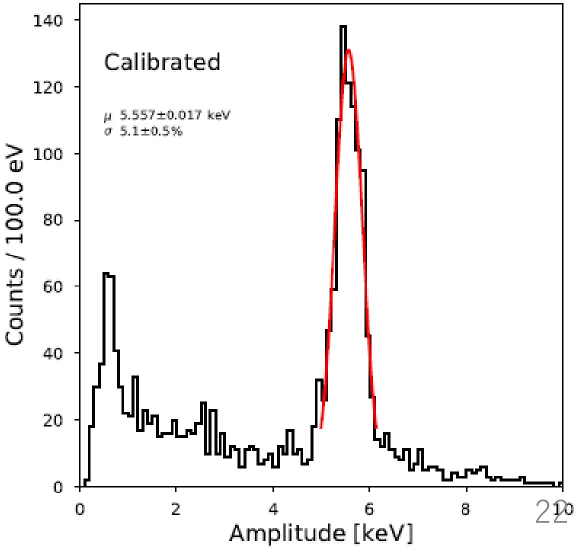




2.8% for 5.9MeV



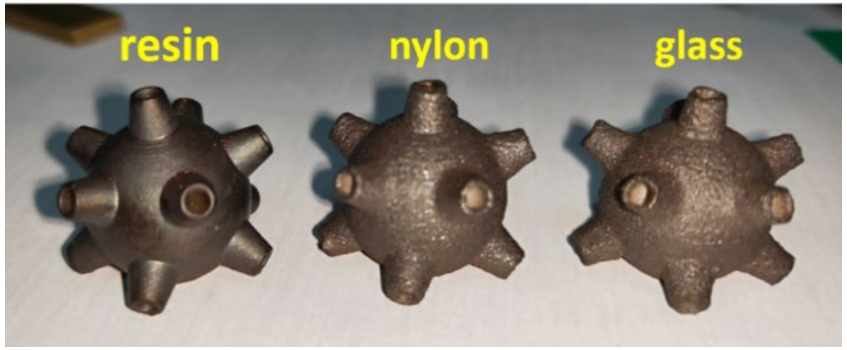

5.1% for 5.5 keV

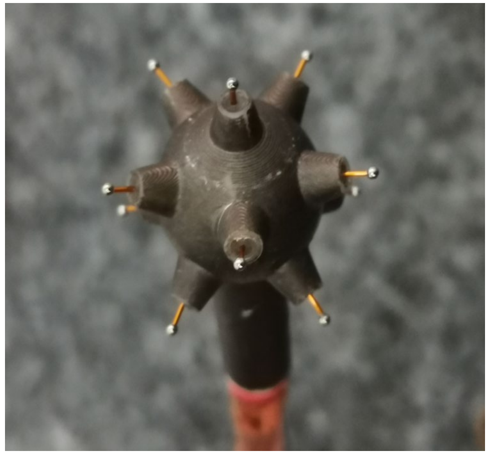


# Resistive Achinos in LXe

*JINST* **15**(2020) P11023

- Current process: DLC coating on the central 3D printed resin structure
  - DLC: a form of amorphous carbon containing both the diamond and the graphite crystalline phase. The measured resistance between two anti-diametric points on the surface, ranged from 0.3 to 10GΩ
  - Other central materials are under testing



- Contacting resistive glass company to try the entire resistive glass Achinos electrode

# Conclusion

- Single-phase TPCs (utilizing charge amplification structures directly in liquid noble elements) present a viable alternative for expanding the capabilities of liquid-phase TPCs in the pursuit of direct DM detection.
- However, achieving this requires innovative approaches in designing charge amplification structures, given the high electric fields required.
- This study presents a novel approach by employing thin, needle-shaped (ϕ50 @edge) structures to produce a secondary signal (S2) in a single-phase liquid xenon TPC test bench.
- Initial results indicate that this approach is viable, as evidenced by the successful detection of S2 signals at voltages ranging from 2kV to 6kV .
- Further investigations are necessary to improve and optimize the charge amplification structure, explore alternative materials and designs, and expand the application of the technique to larger detectors.