Towards a Scalable Method for Proportional Electron Multiplication in Liquid Xenon

I. Giomataris[1], K. Kanzawa[2], I. Katsioulas[3], **P. Knights[4]**, K. Nikolopoulos[4,5], H. Sekiya[6], P. Walters[4]

[1]CEA Saclay, [2]Nagoya University, [3]European Spallation Source, [4]University of Birmingham, [5]University of Hamburg, [6]Kamioka Observatory, ICRR, The University of Tokyo

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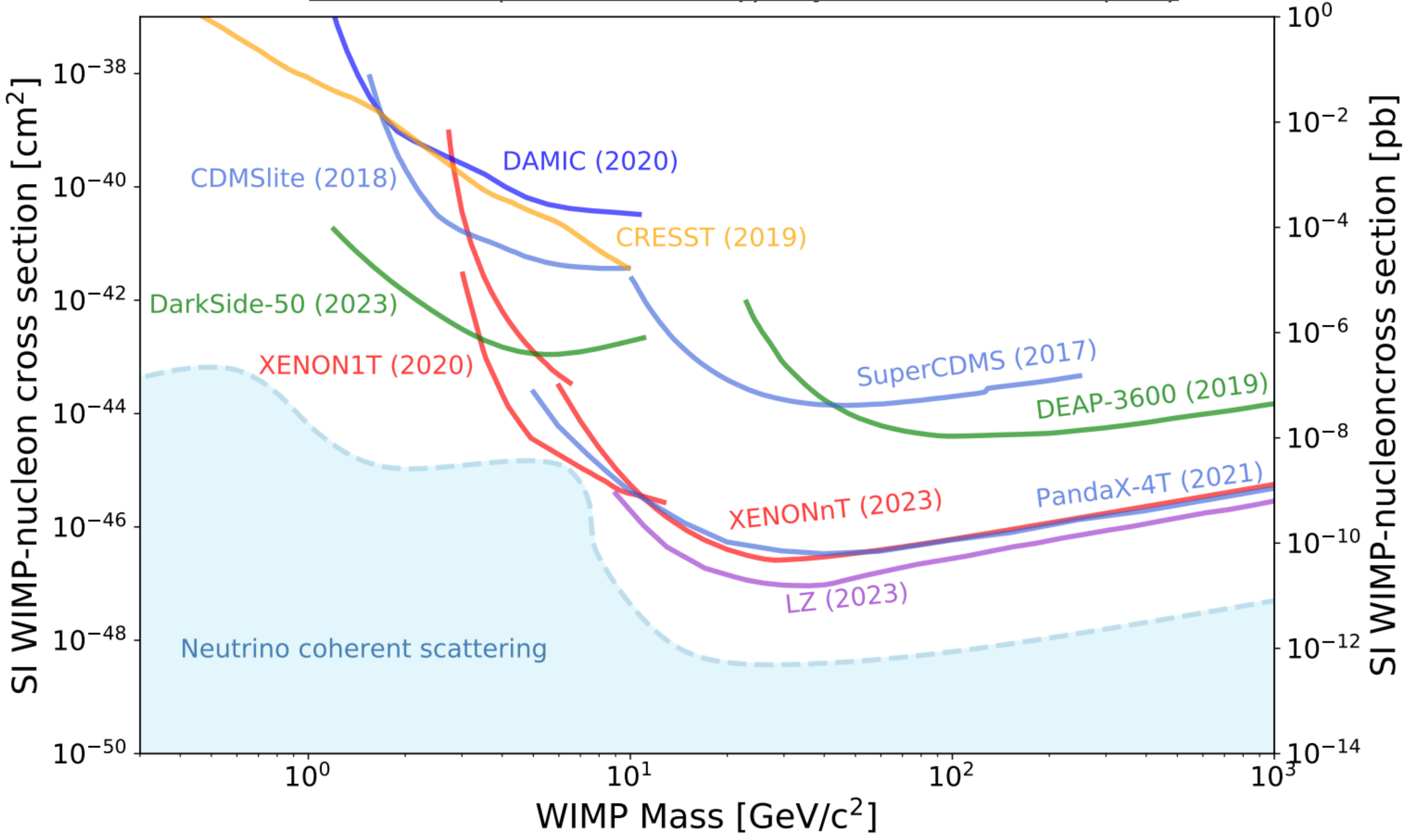
Direct Dark Matter Searches

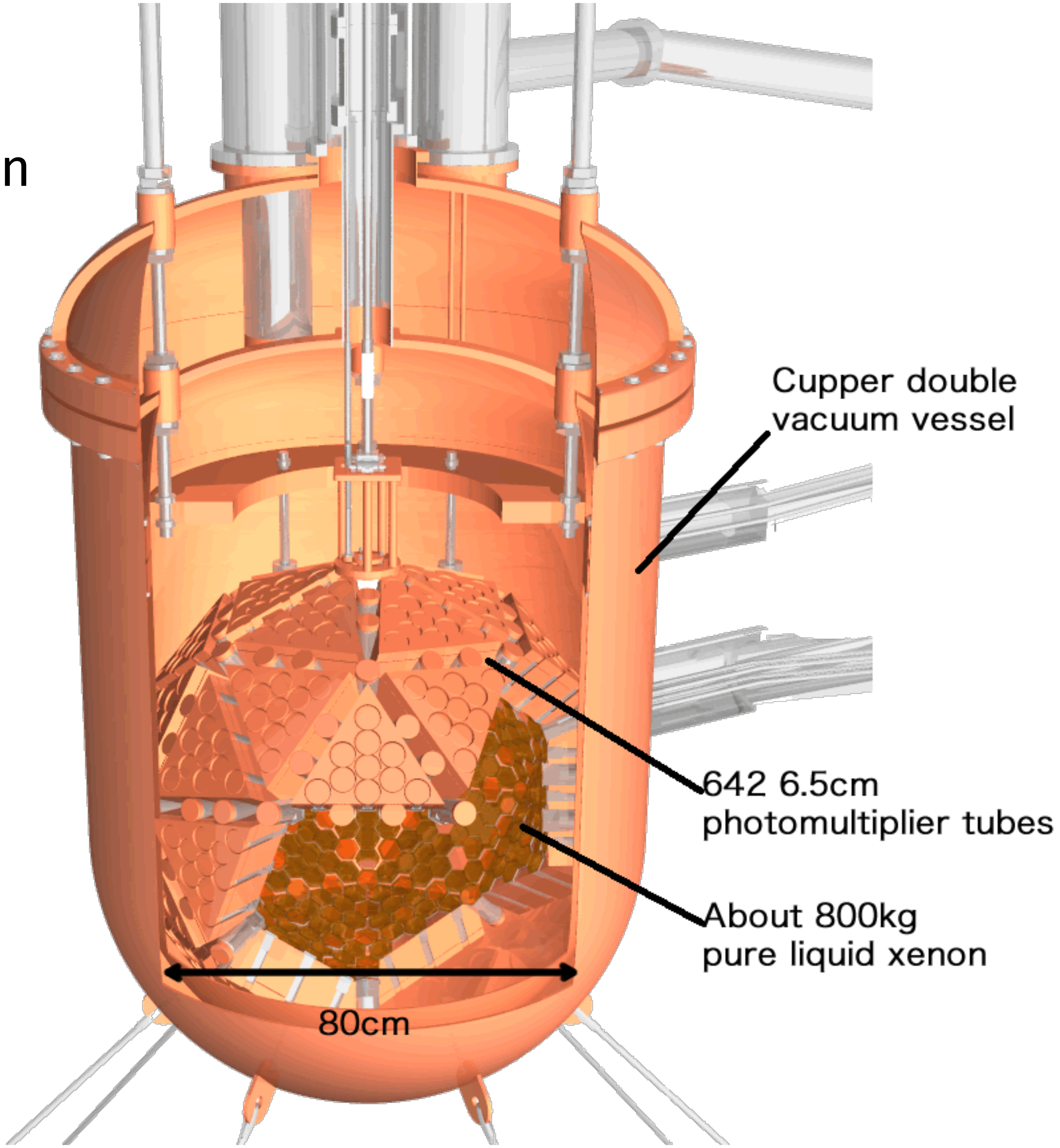
- ❖World-leading sensitivities from Dual-Phase TPCs
  - ➡LZ, Panda-X, Xenon-nT, etc.
- ❖Technology has intrinsic background rejection
  - ➡Difference of S1 and S2 signal allows ER vs NR discrimination
- ❖Requires two-phase operation
  - ➡Gas phase to generate S2
- ❖Designs converge to cylinders or polygonal prisms
  - ➡Geometry limits photo-coverage

S. Navas et al. (Particle Data Group), Phys. Rev. D 110, 030001 (2024)



XMASS Experiment

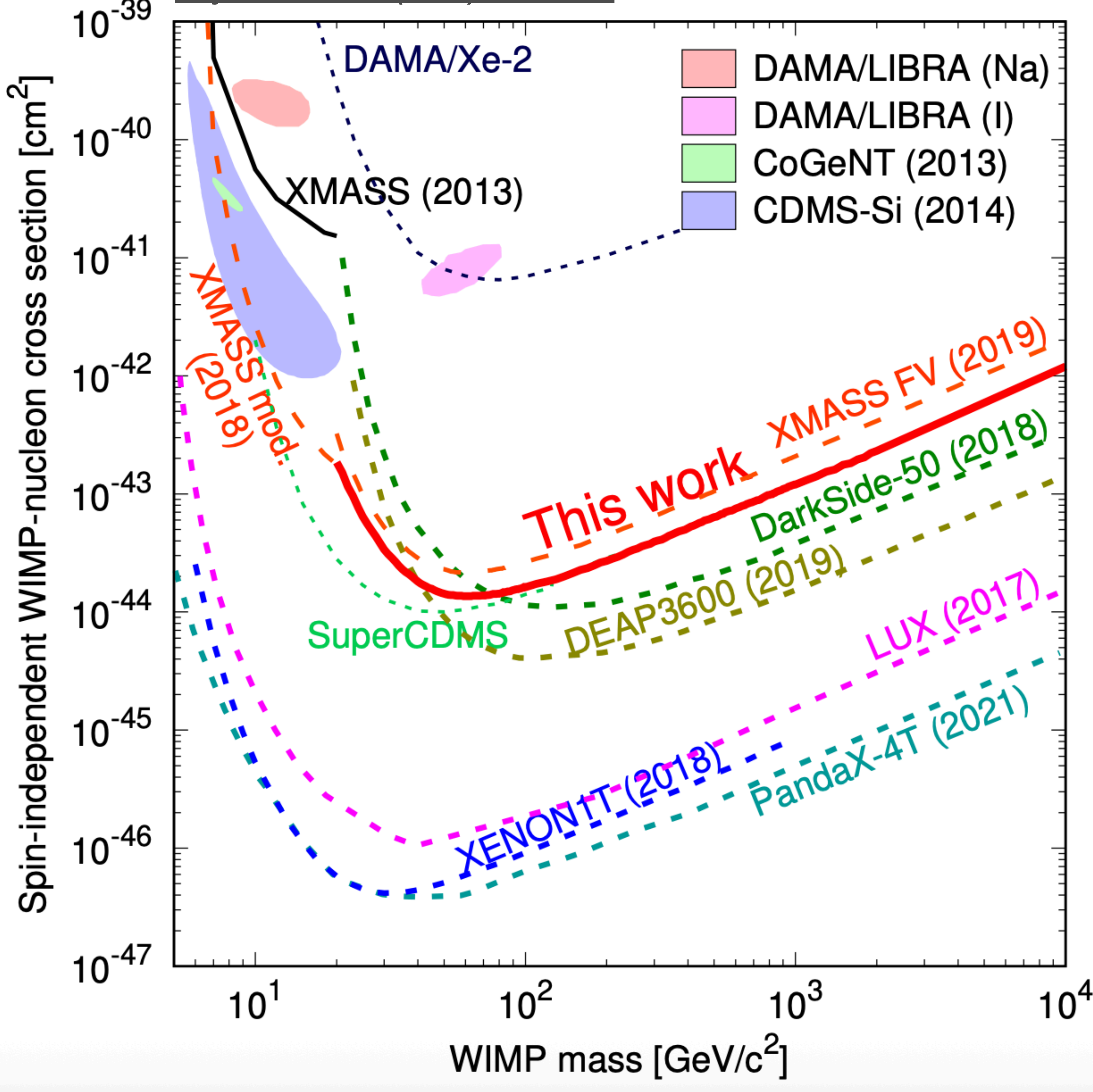
- ❖Single-phase, almost spherical, liquid xenon detector
  - ➡642 PMTs arranged on surface of a pentakis dodecahedron
- ❖~800 kg total Xe; ~100 kg fiducial
- ❖Only observes 'S1' equivalent
  - ➡Does not benefit from same background discrimination



XMASS-I Result

- ❖XMASS-I result from full data with 97 kg fiducial mass and 1590.9 days total live time
  - ➡Strict fiducial cuts required to reduce β-decay backgrounds
- ❖XMASS-I is leading single-phase LXe technology
- ❖Technology would benefit greatly from additional fiducialisation capabilities and ER vs NR discrimination

Phys.Rev.D 108 (2023) 8, 083022



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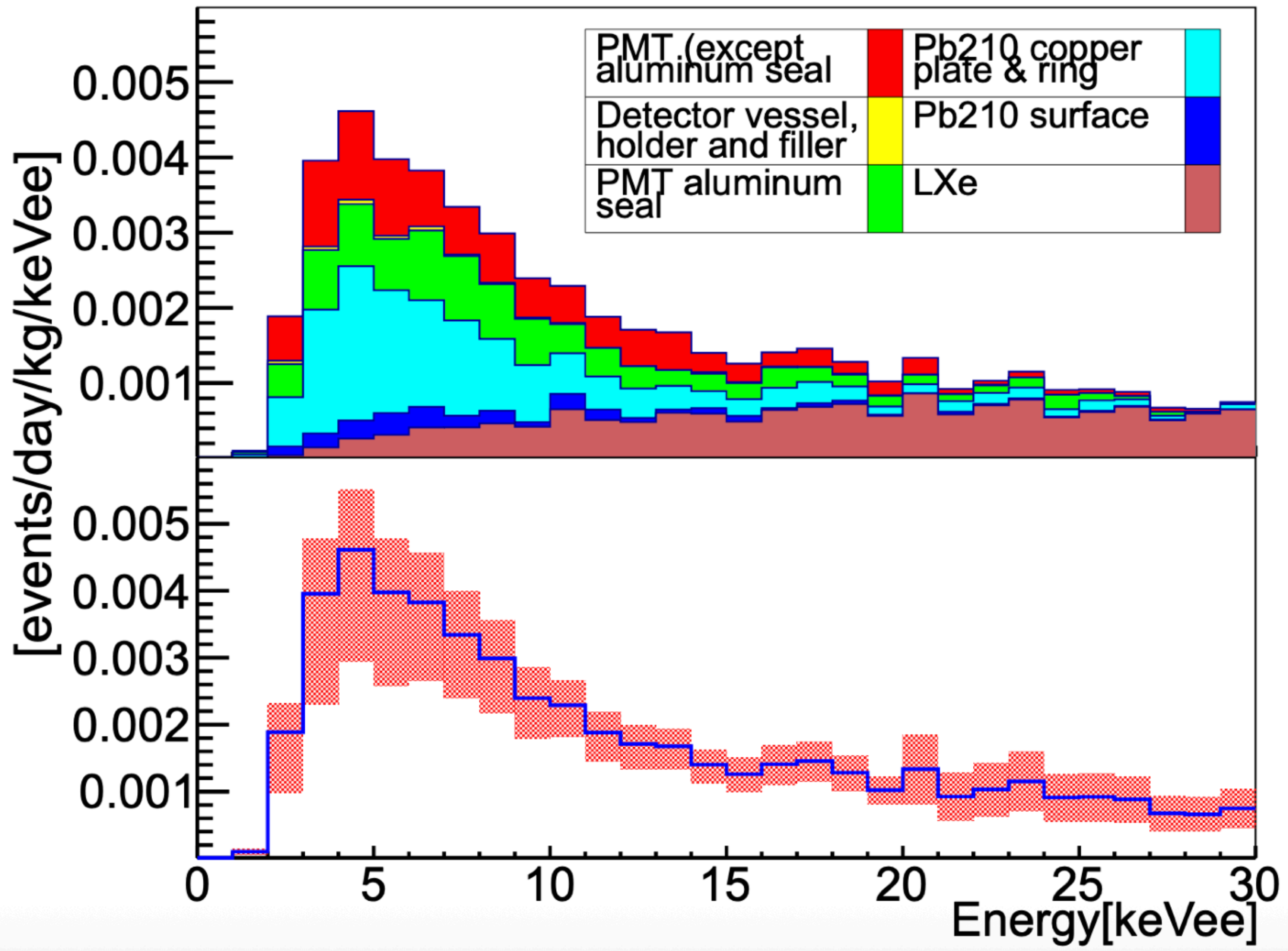

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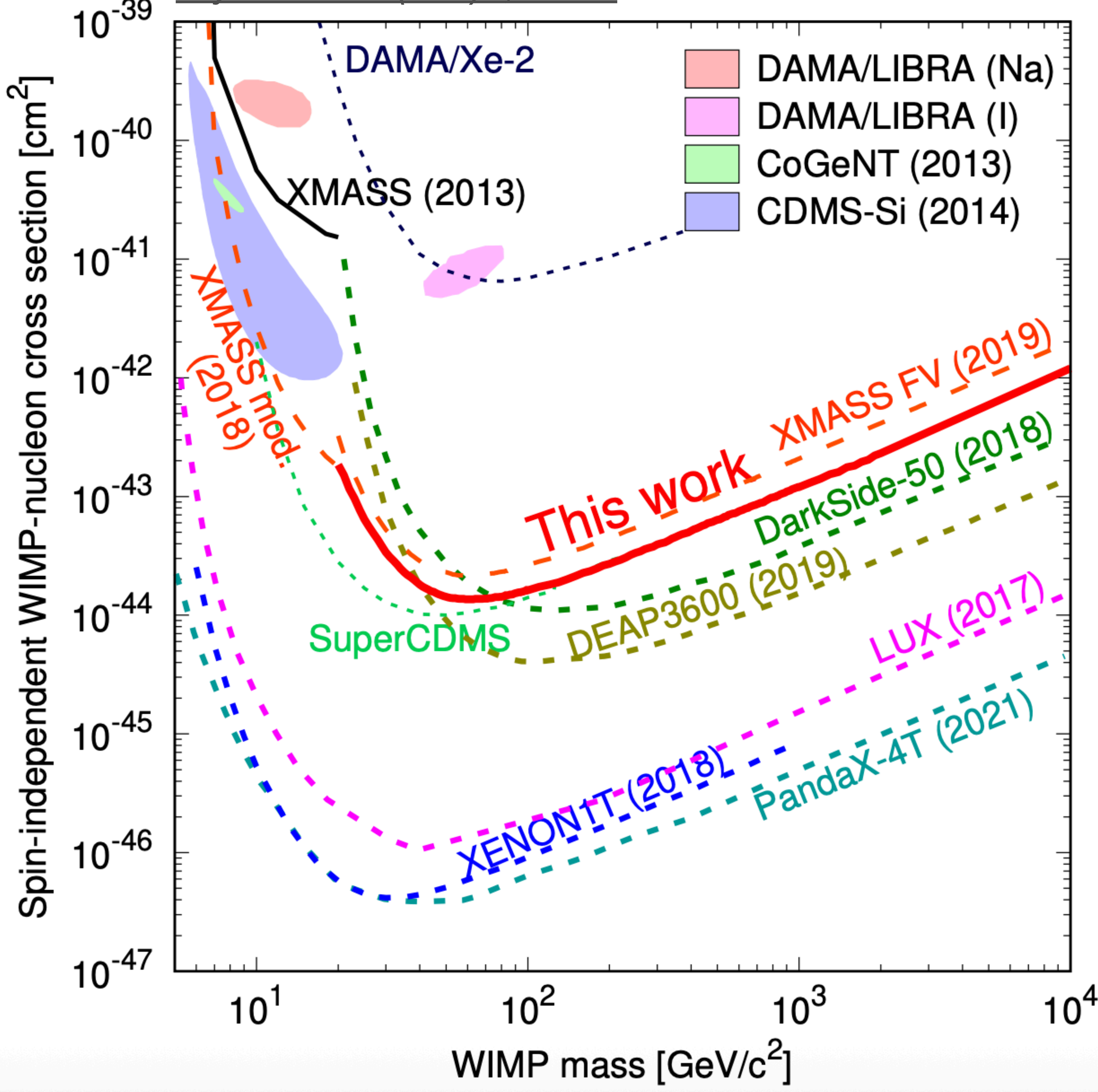

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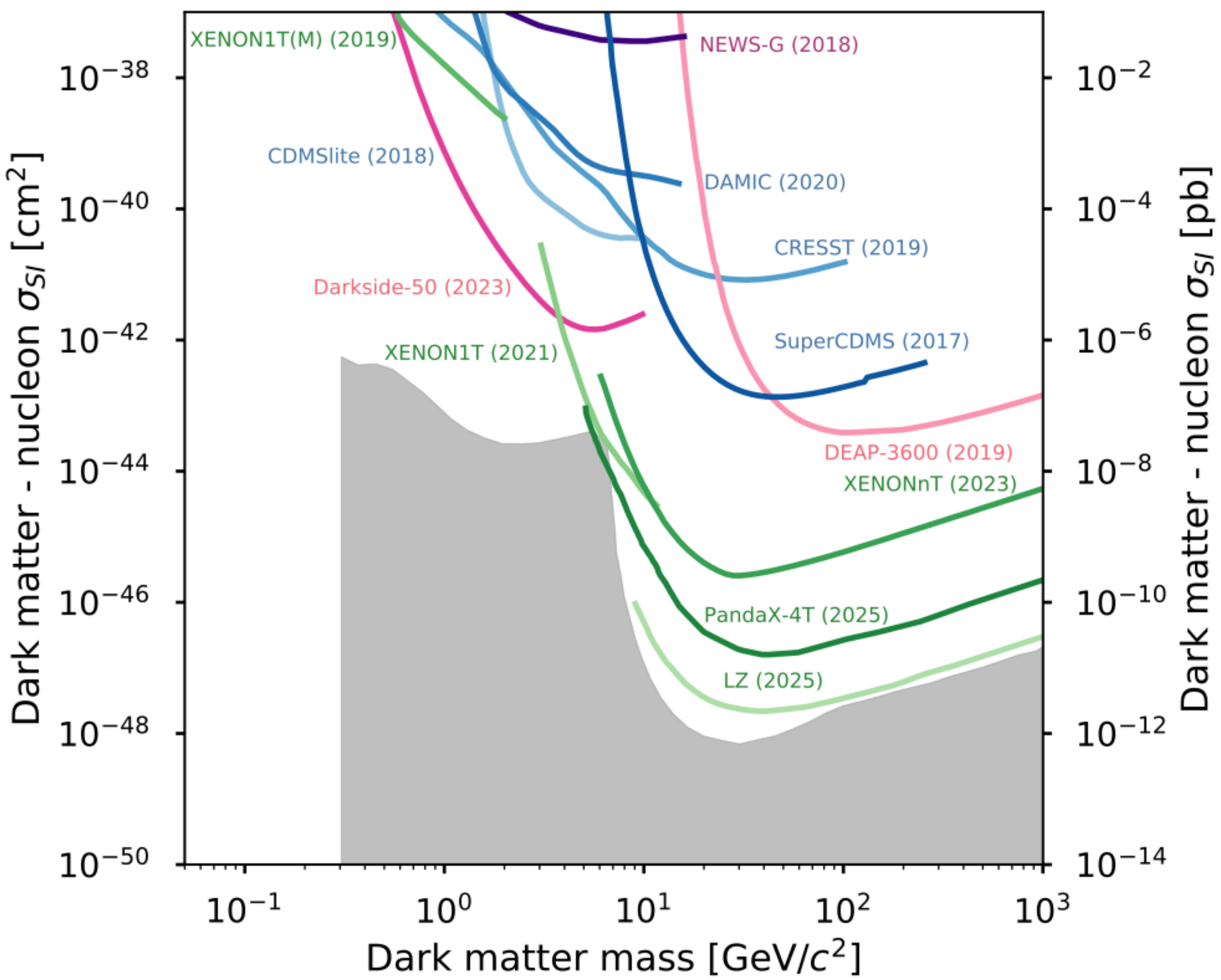
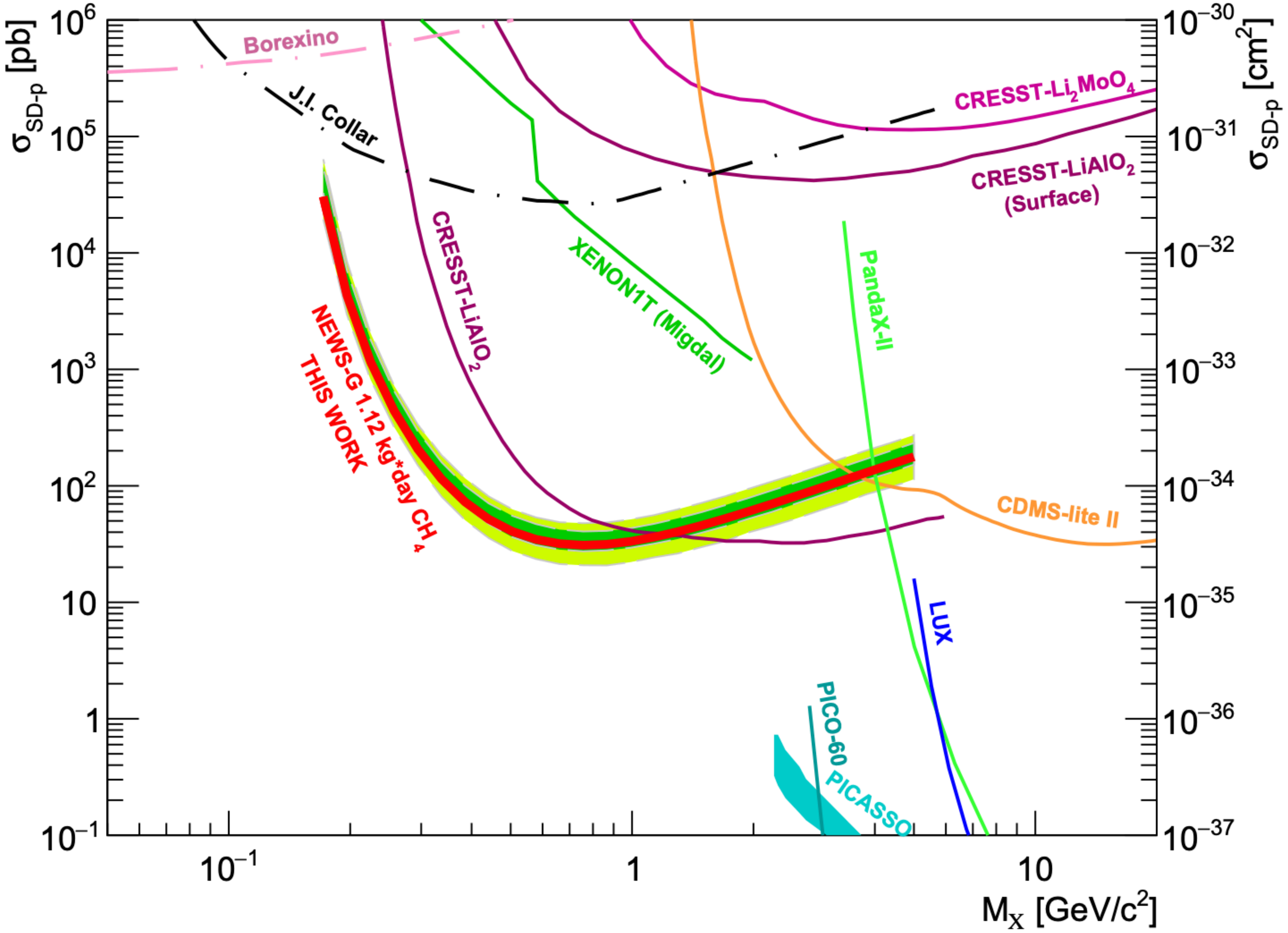
Plot by L. Millins

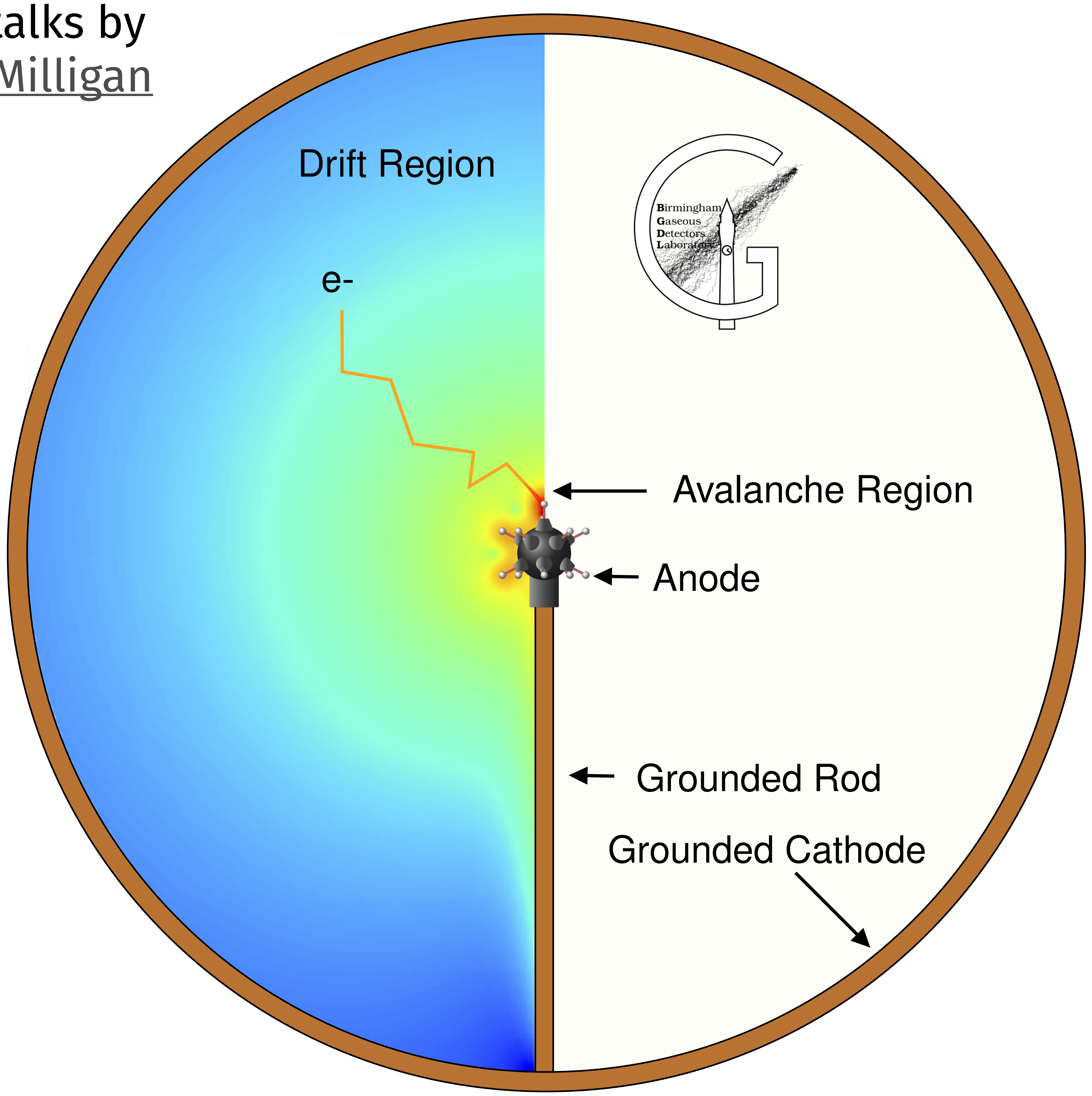


Phys.Rev.Lett. 134 (2025) 14, 141002



Spherical Proportional Counters

More on this in talks by
G. Giroux and L. Milligan



- ❖Low capacitance, single-e detection
- ❖Smallest surface area to volume ratio
- ❖Low-mass target nuclei
- ❖H and C (in CH_4, i-C_4H_{10}), He, Ne, etc.
- ❖Simple, radiopure construction
- ❖Currently used for direct DM searches by NEWS-G
  - ➡S140 in SNOLAB *Phys.Rev.Lett. 134 (2025) 14, 141002*
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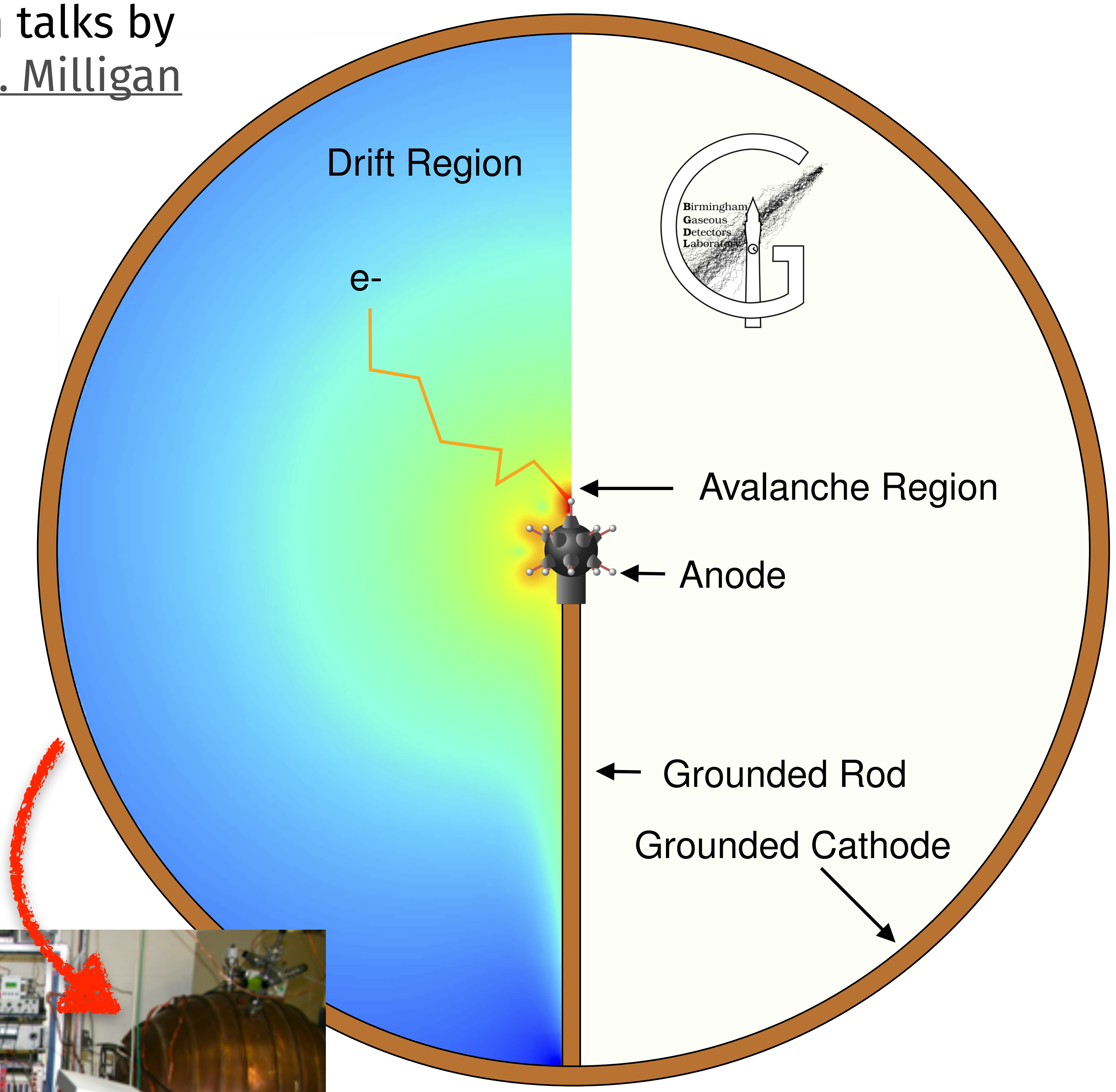

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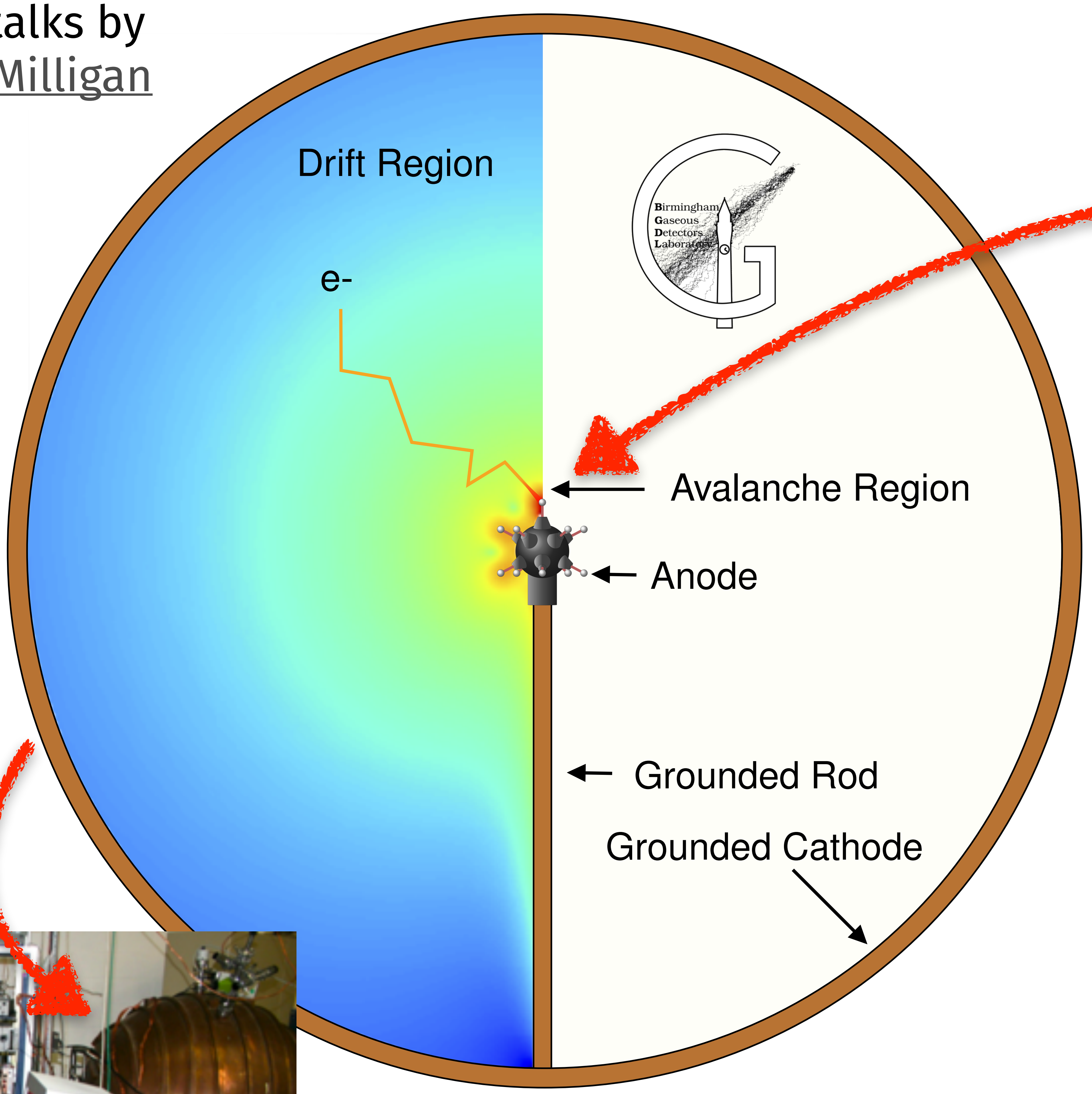

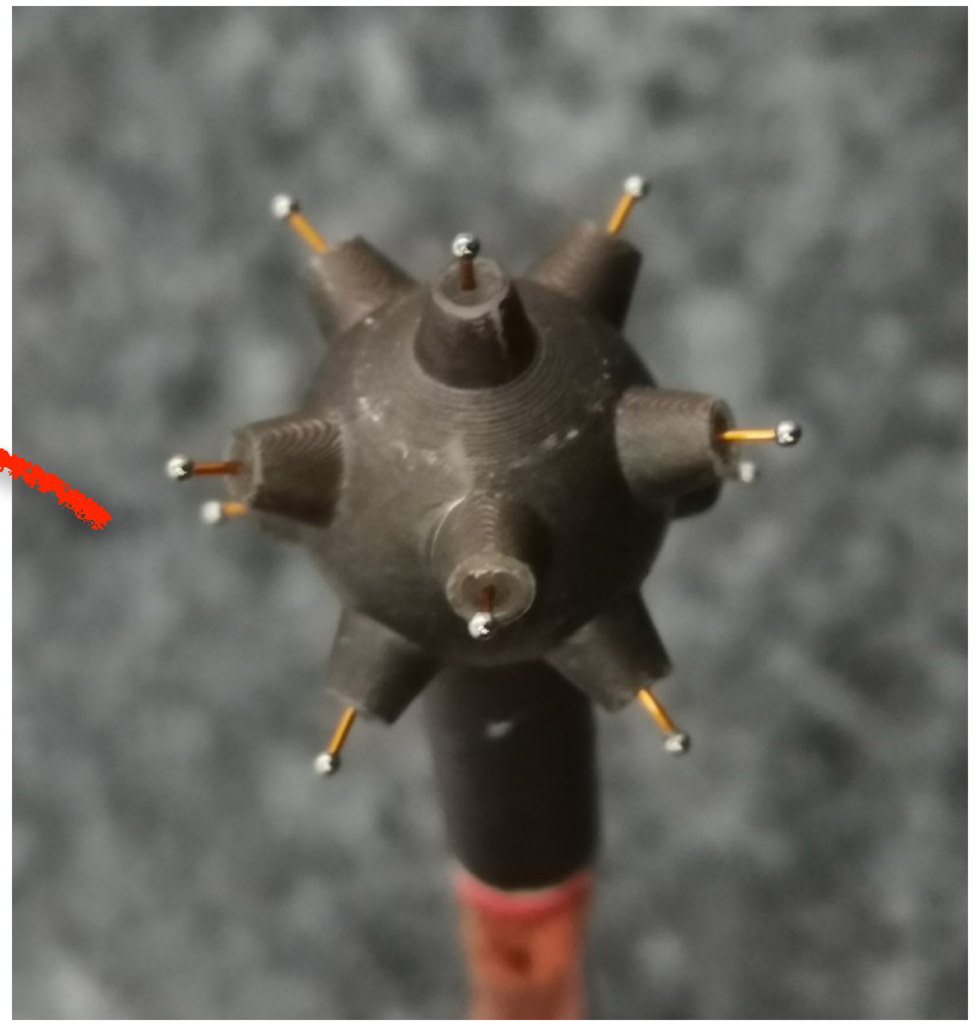

JINST 15 (2020) 11. 11
JINST 19 (2024) 01, P01018

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- ❖Single anode: drift and avalanche fields coupled
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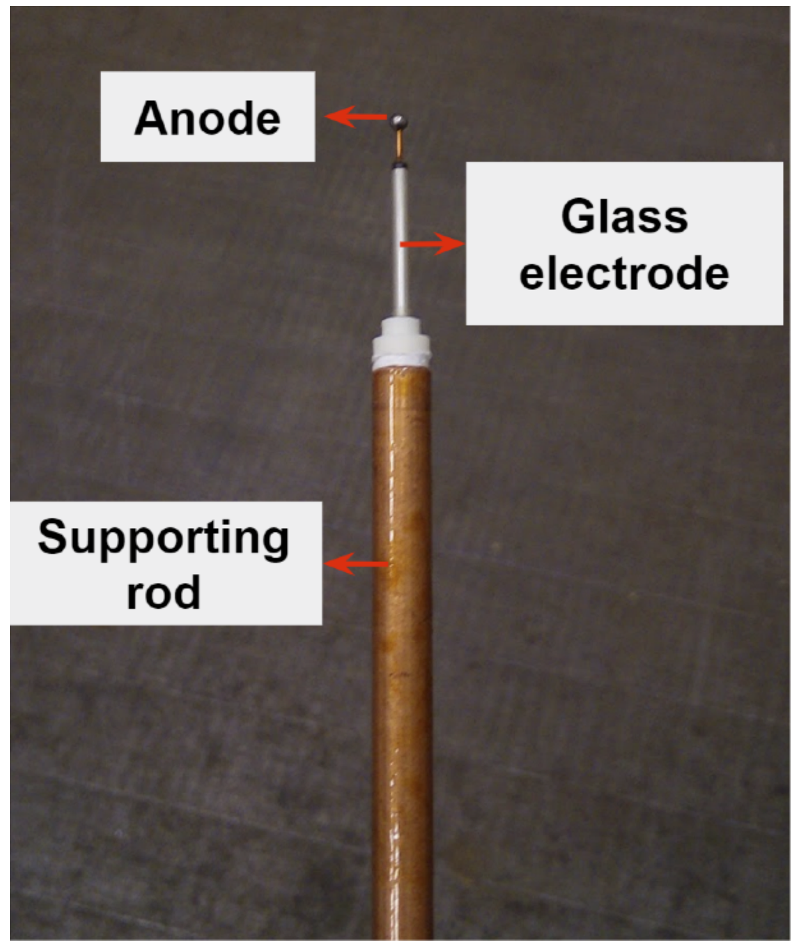
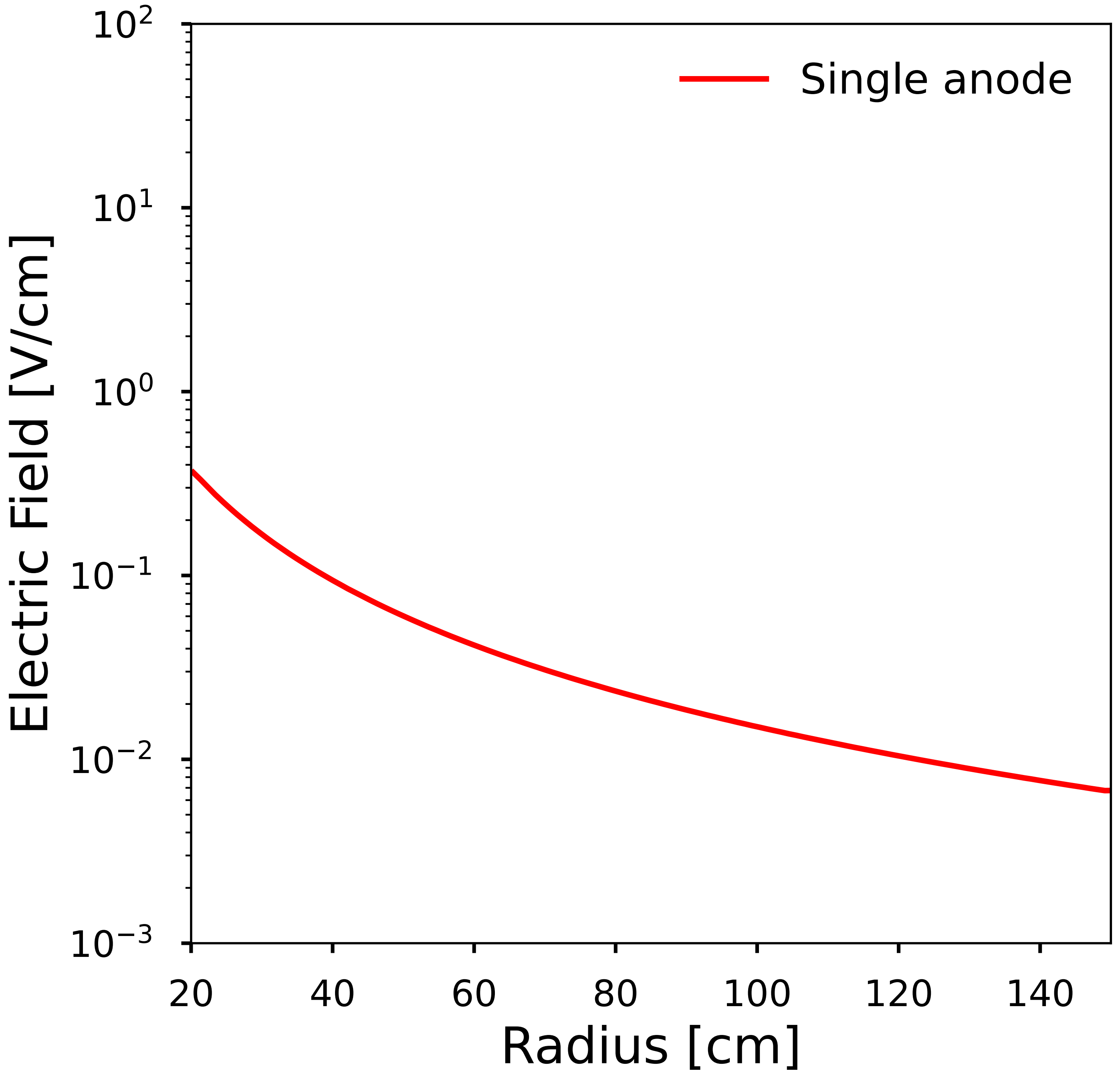
  - ➡Challenge to scale detector size or pressure





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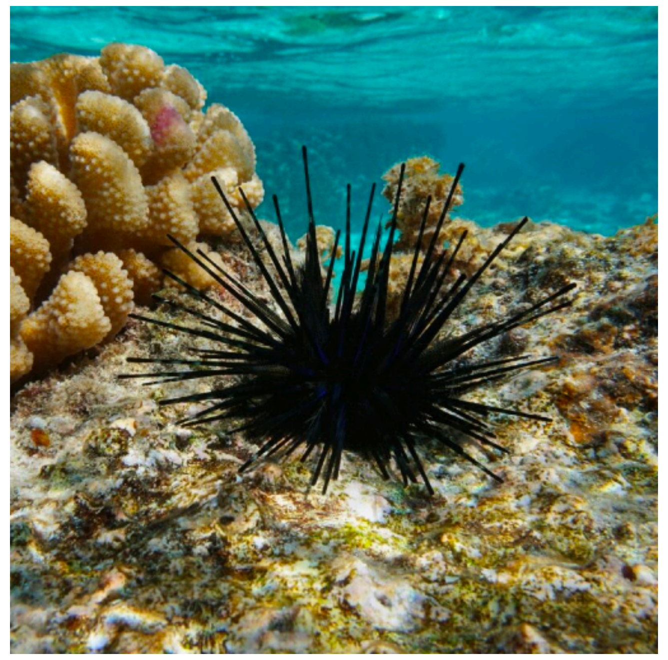

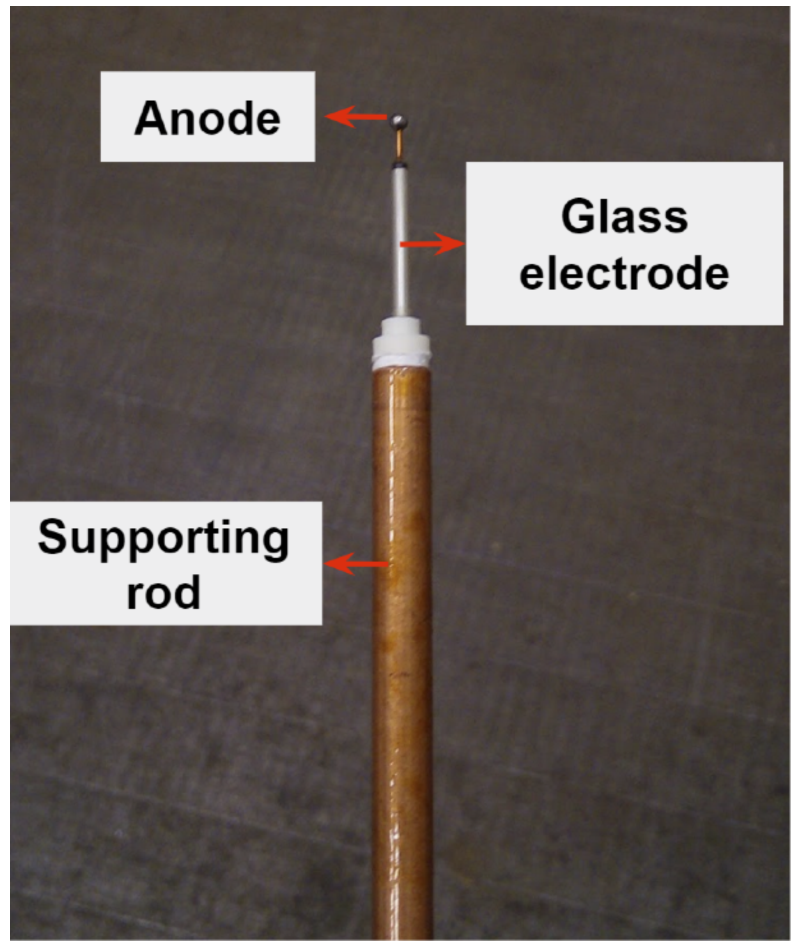

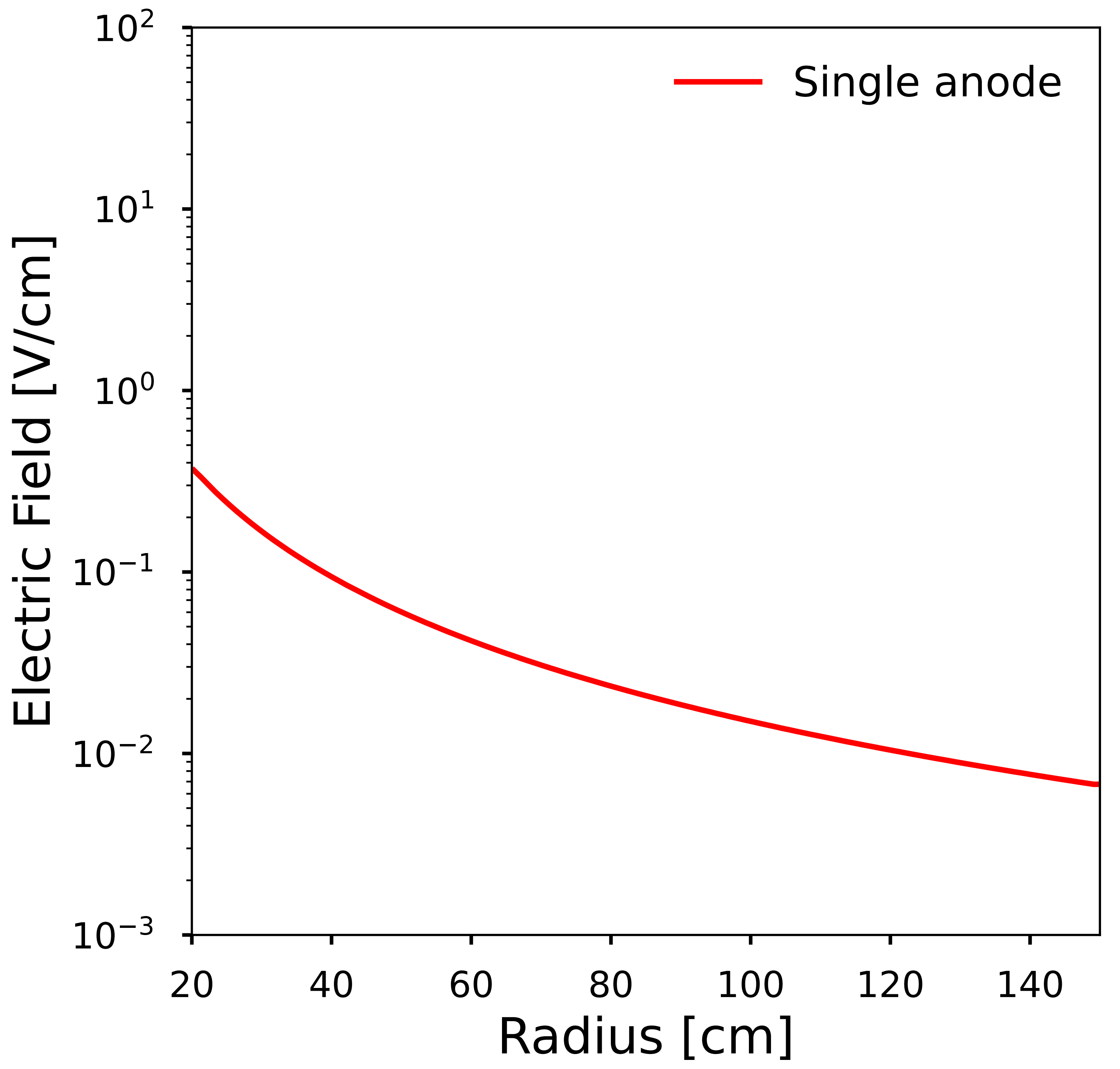

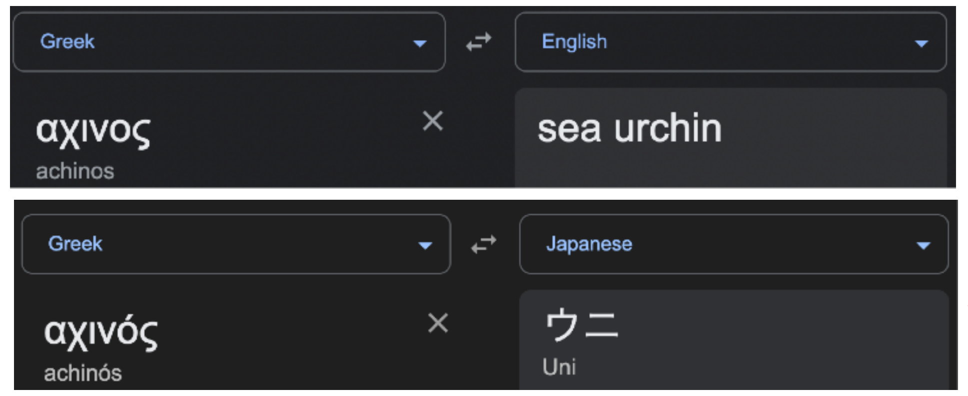

Single anode: *JINST 13 (2018) 11, P11006*
Simulation framework: *JINST 15 (2020) 06, C06013*
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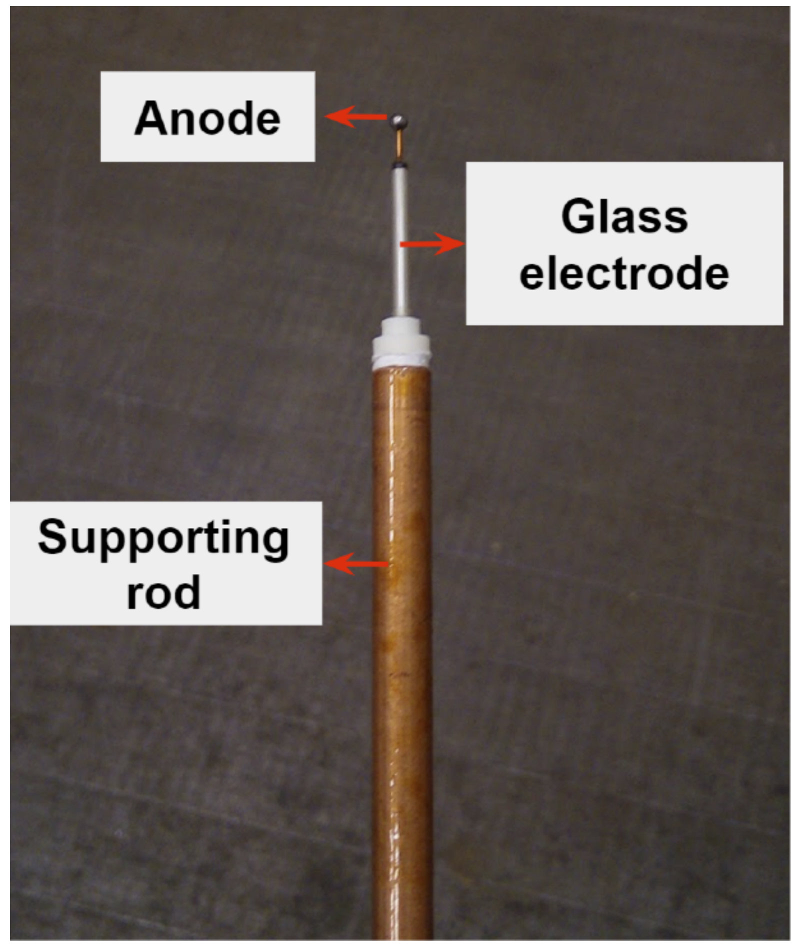

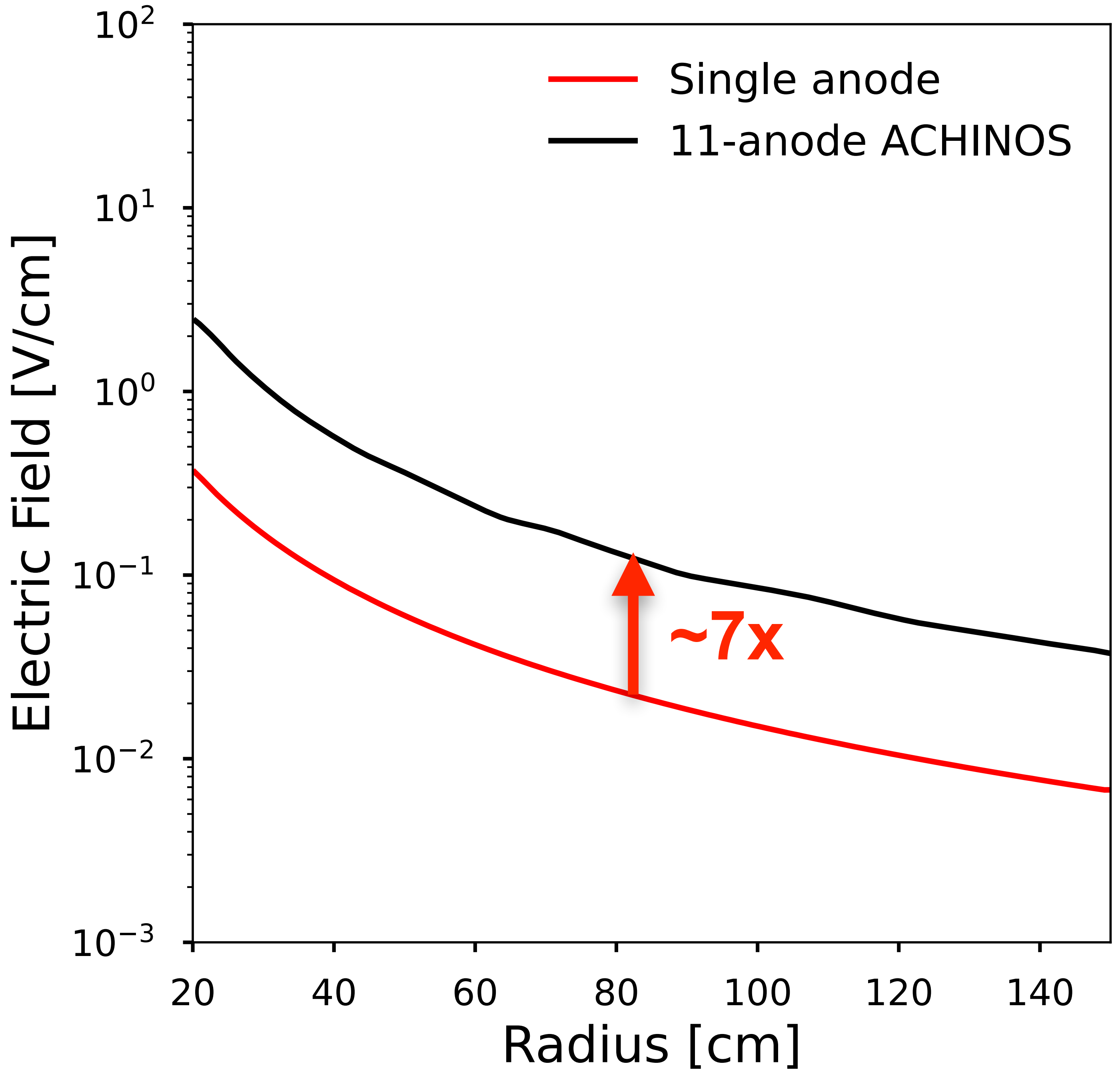

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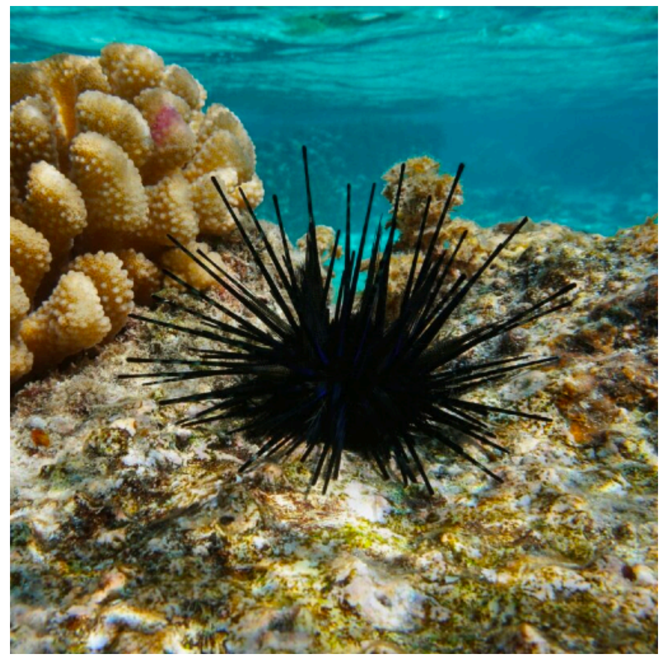

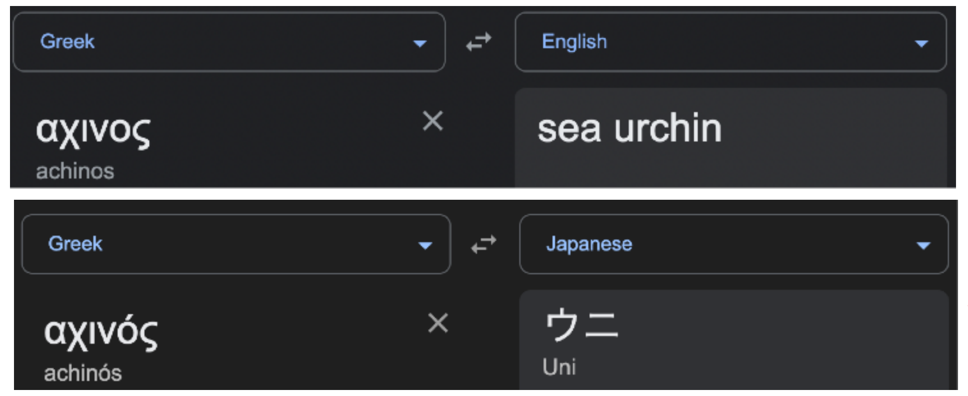

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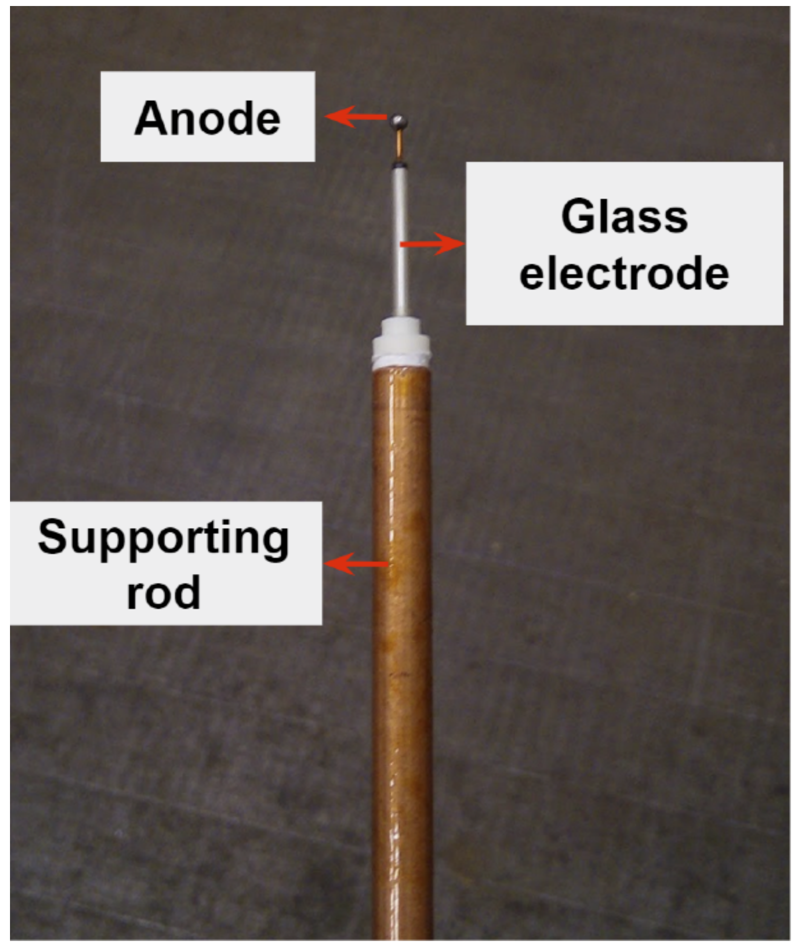

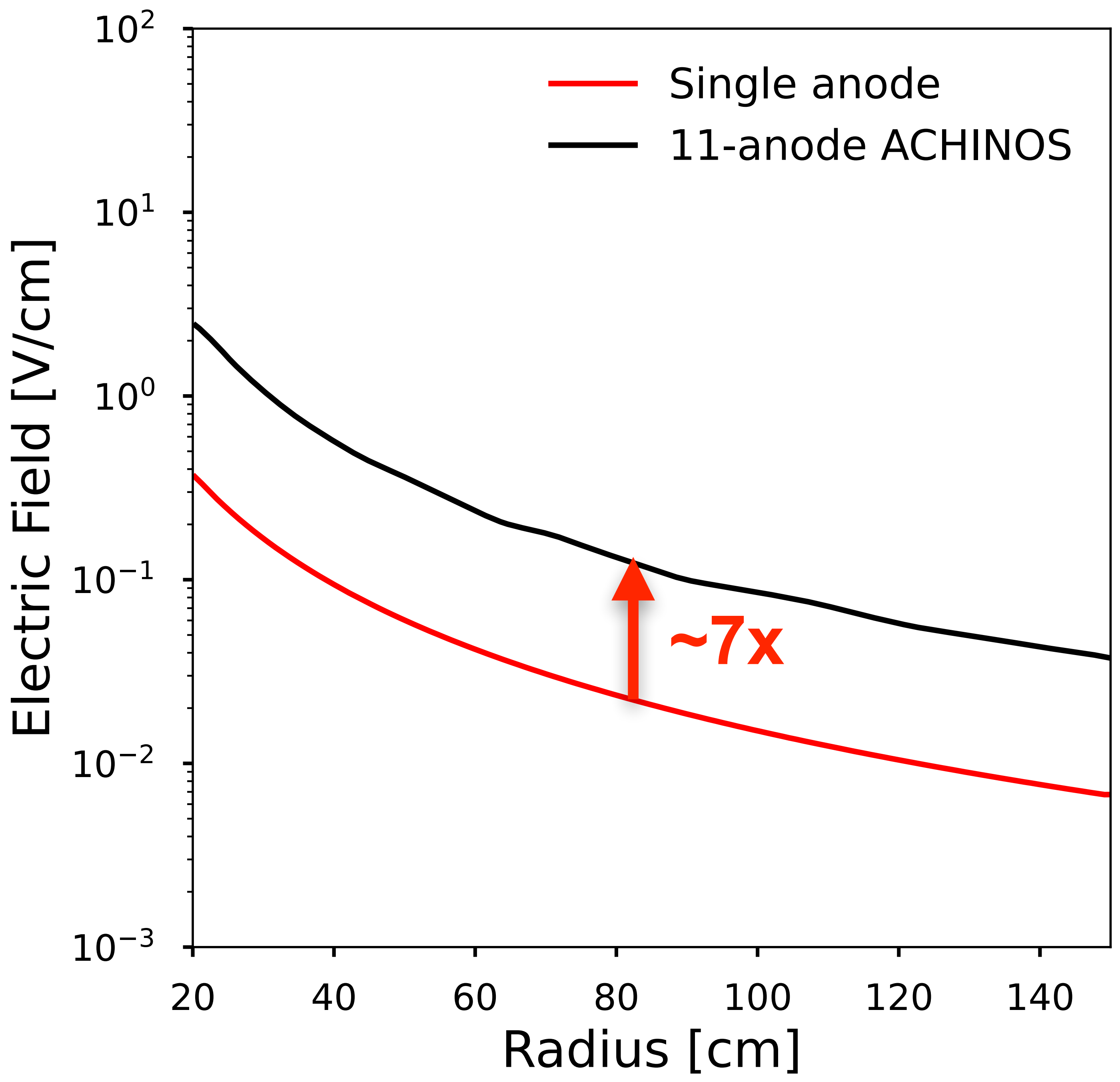

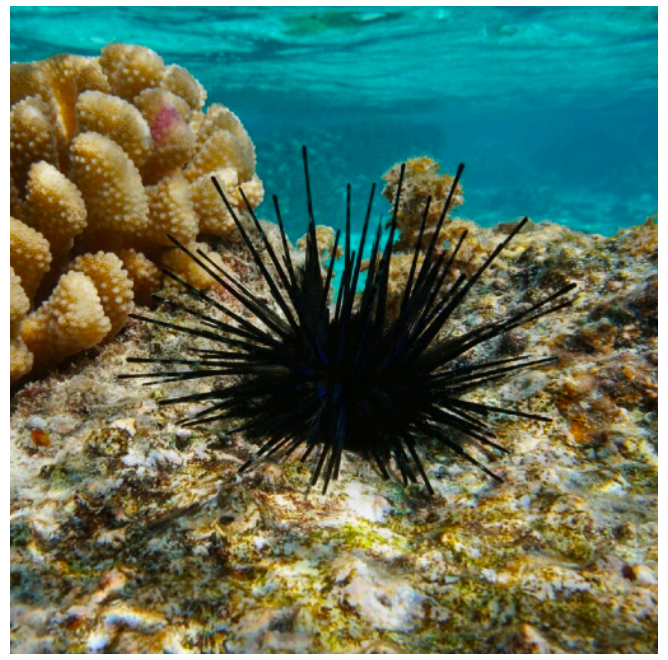

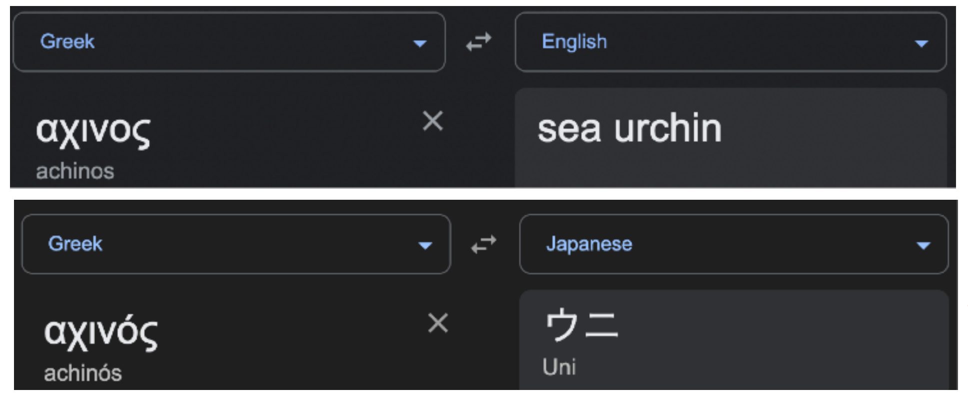

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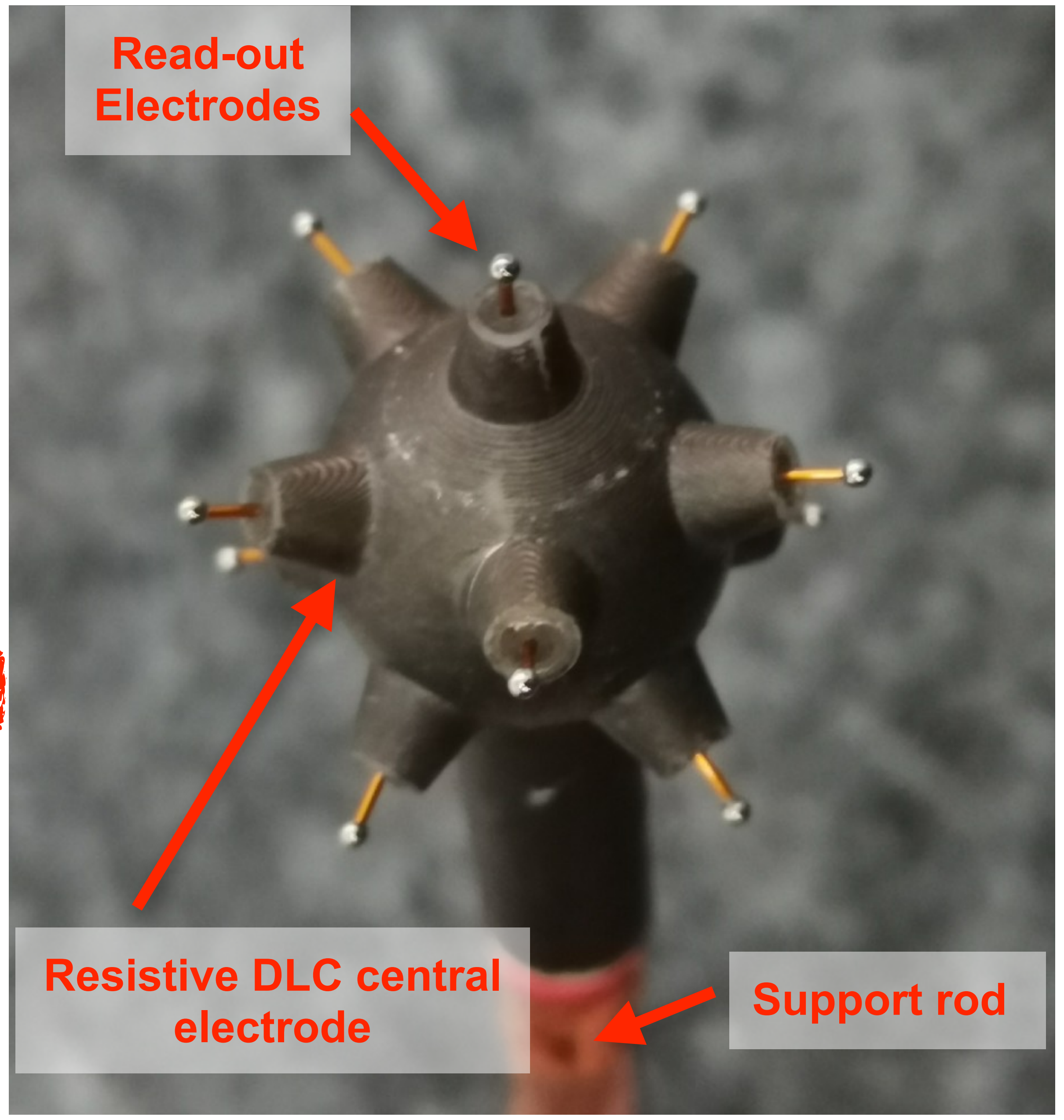

Combining Two Spherical Detectors

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Measurement of scintillation from proportional electron multiplication in liquid xenon using a needle

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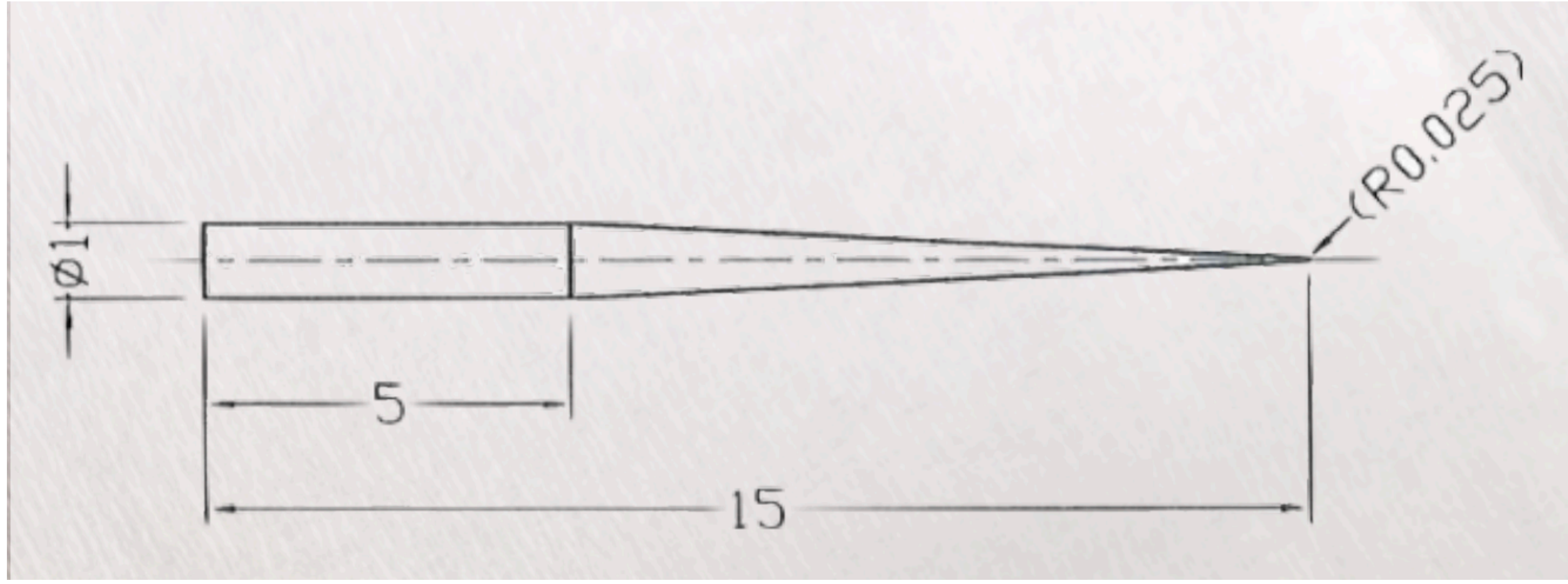
Proportional Signal Amplification in LXe



❖ACHINOS currently uses ⌀1 mm anodes
➡Fields ~<40 kV/cm near anode surface at ~2 kV

❖Approximately x10 increase required in LXe
➡Previous studies indicate ~400 kV/cm threshold for electroluminescence in LXe (~700 kV/cm for electron multiplication)

❖Motivates the use of spherical-tipped needles
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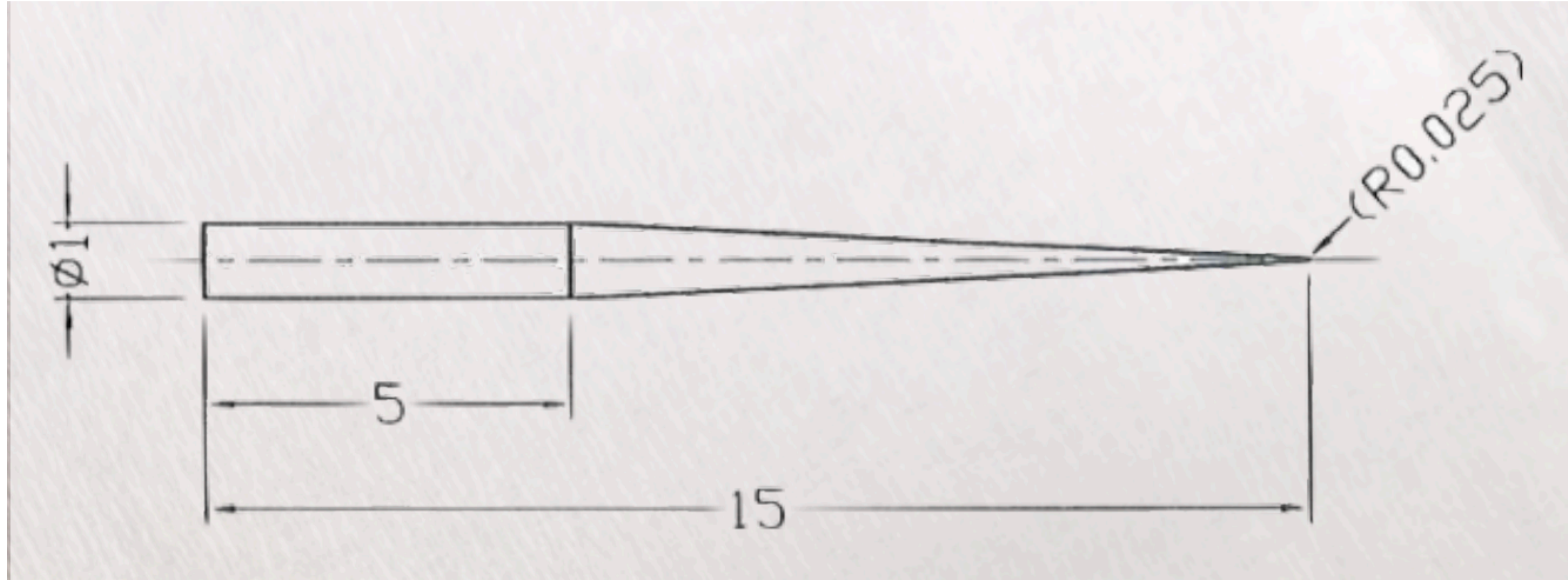
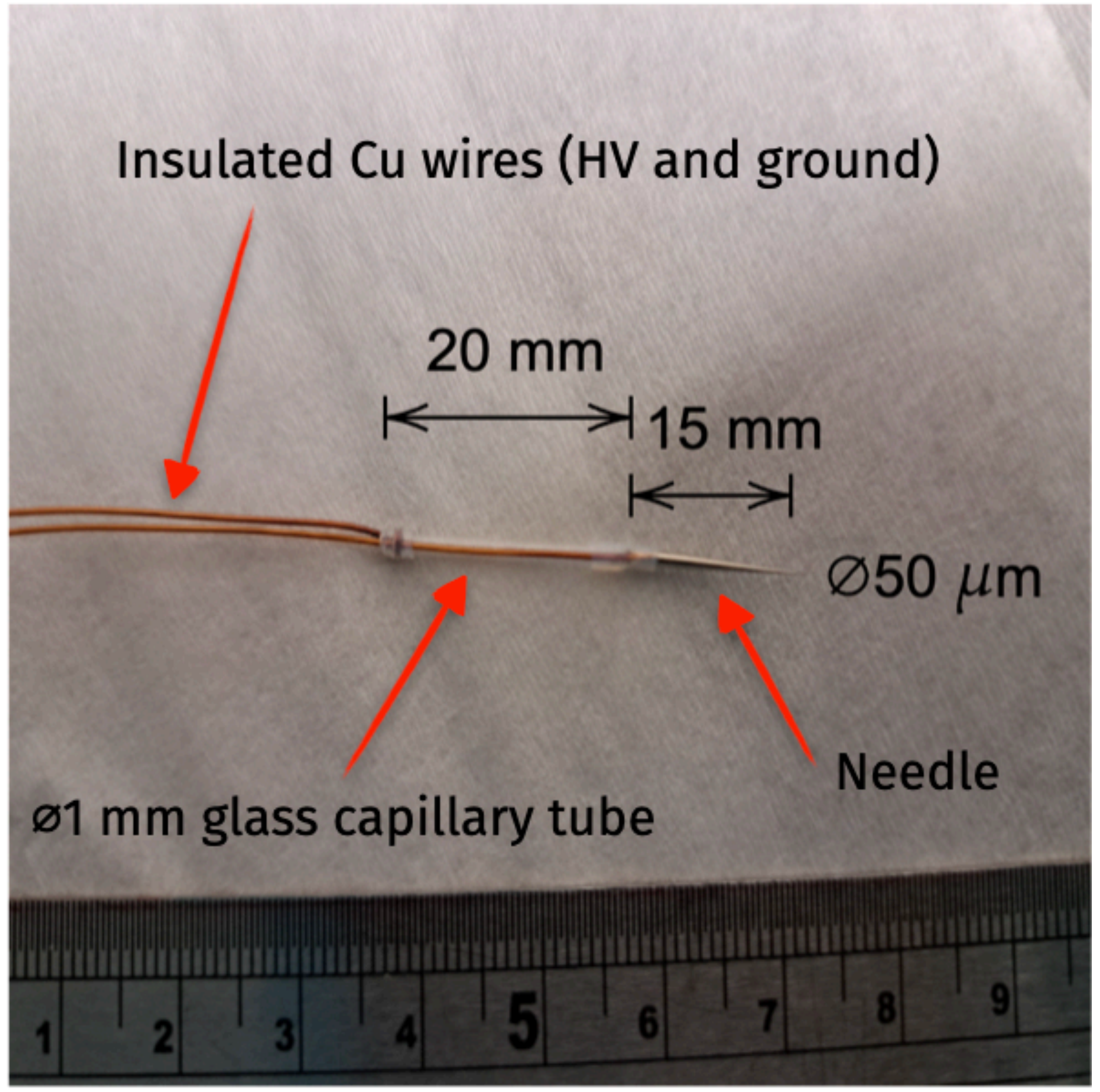
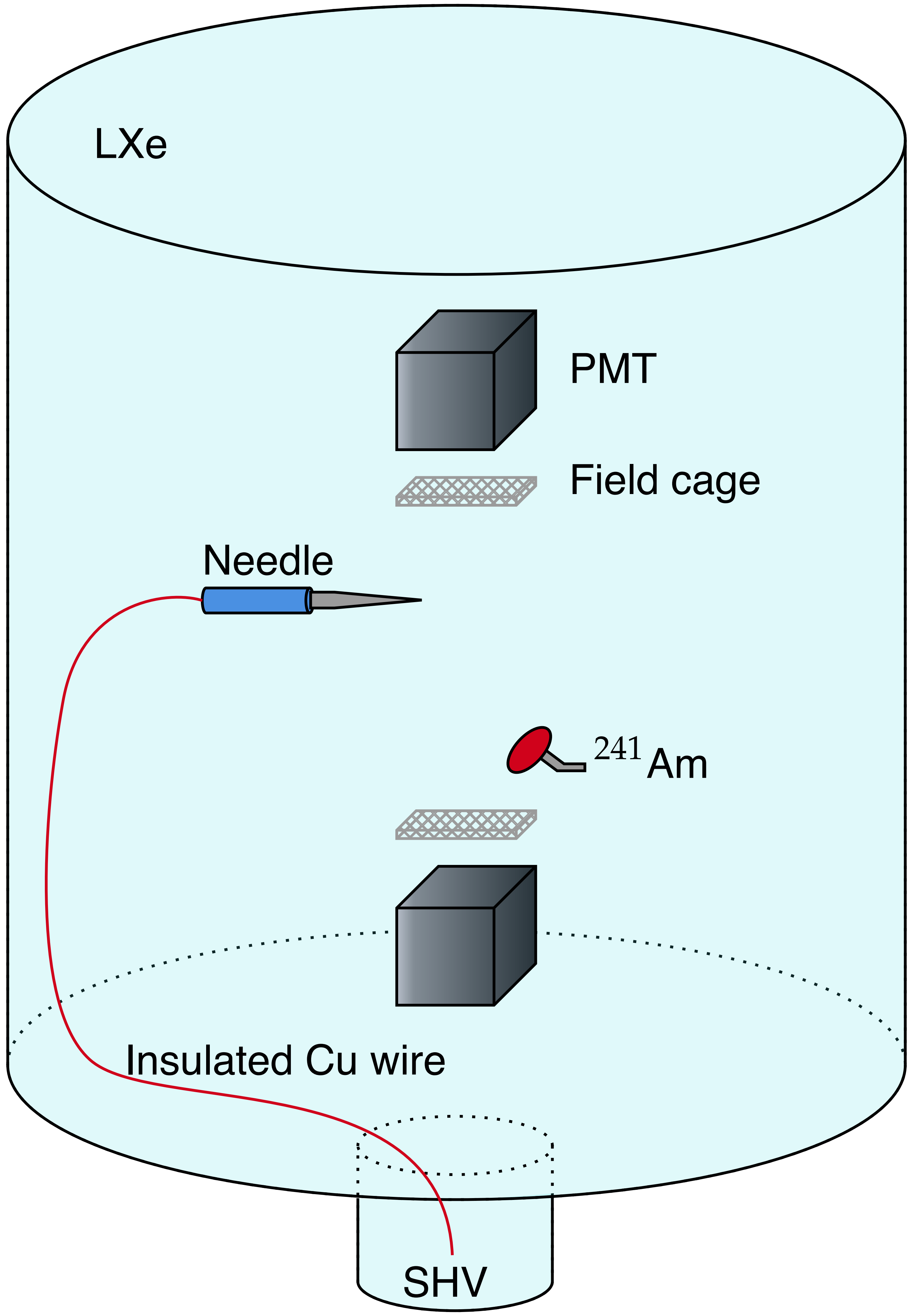




Test TPC

- ❖Structure tested at Kamioka Observatory in test TPC
  - ➡^{241}Am source used as α-source
  - ➡TPC read-out by two Hamamatsu R8520-406 PMTs



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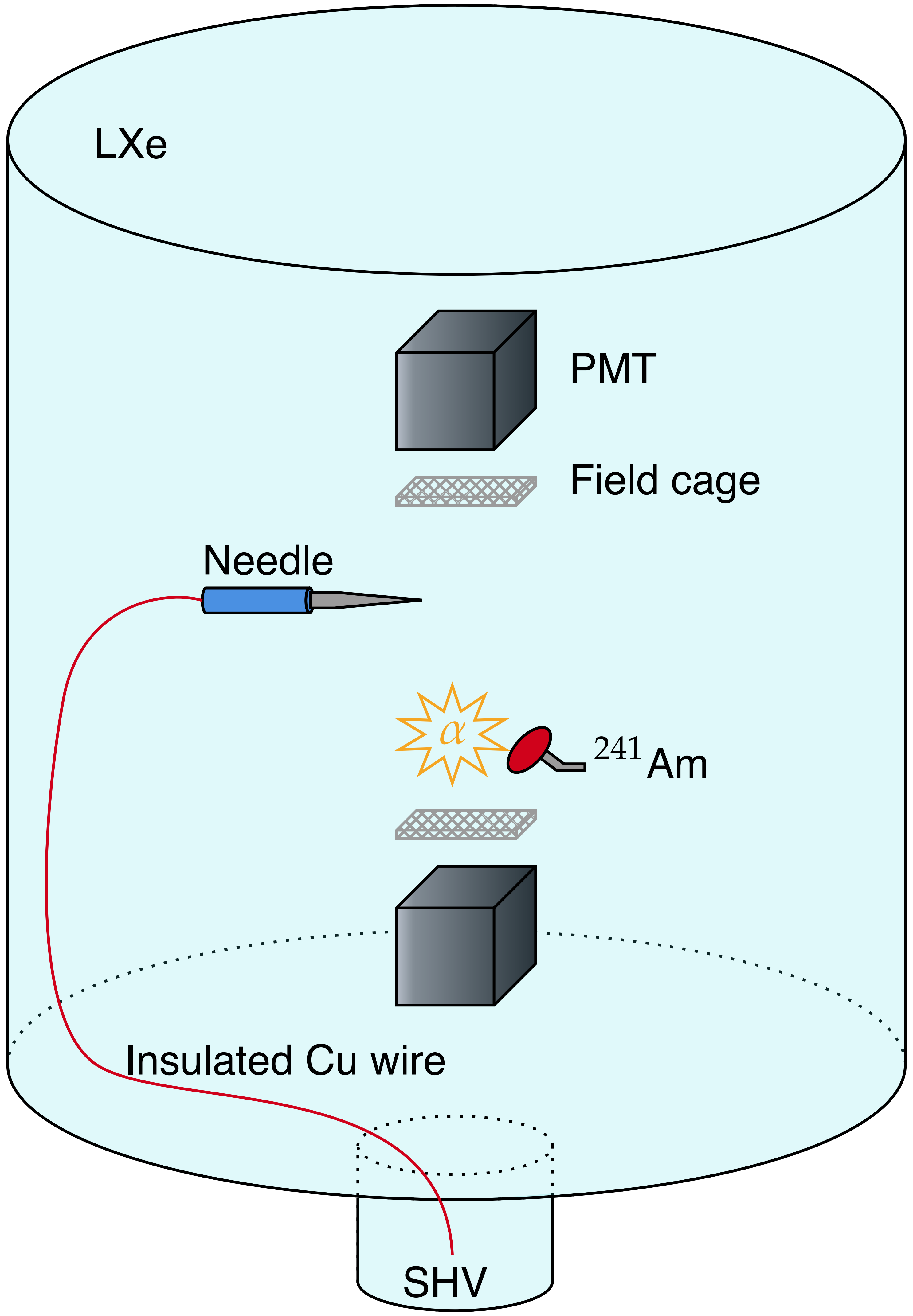

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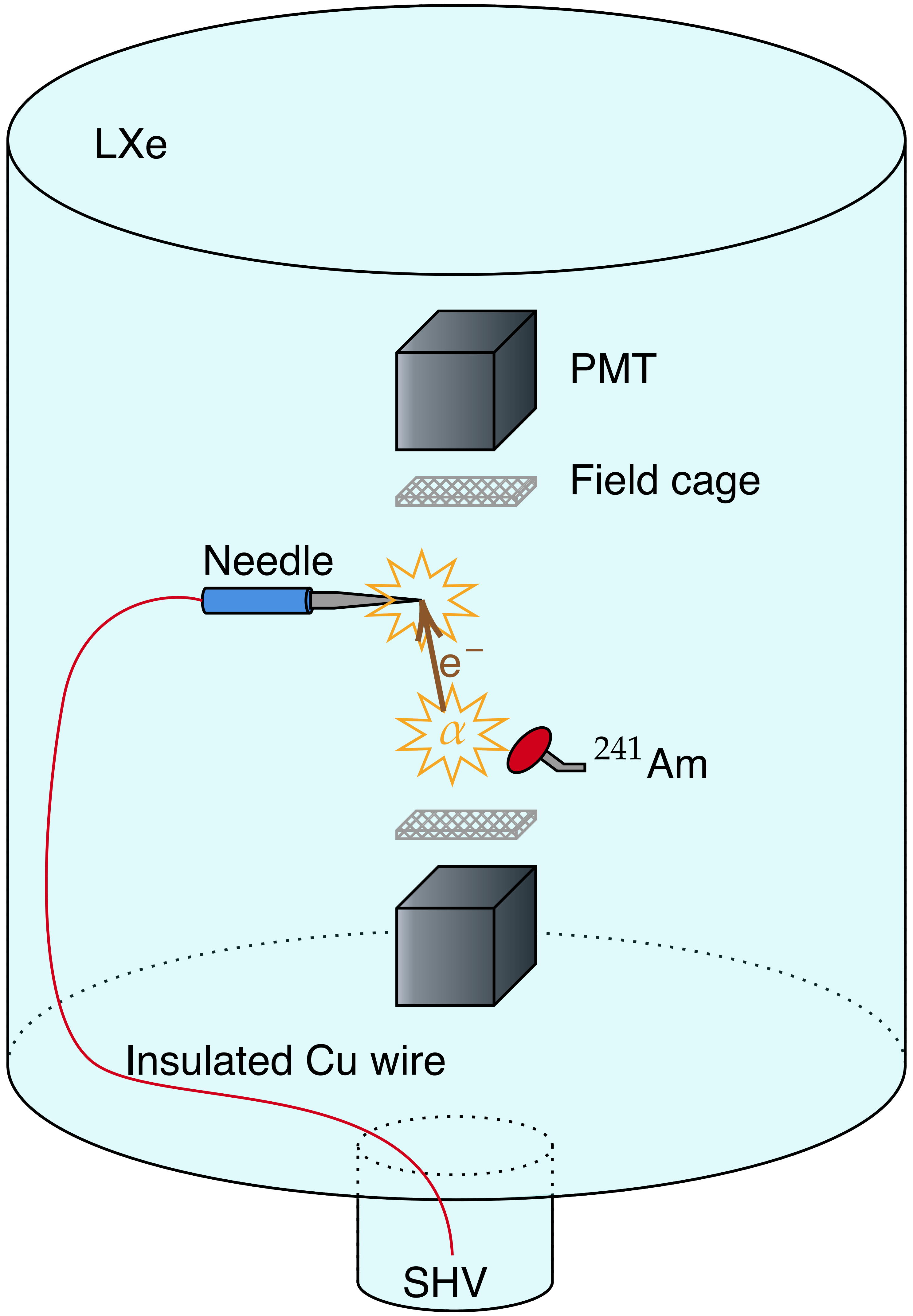

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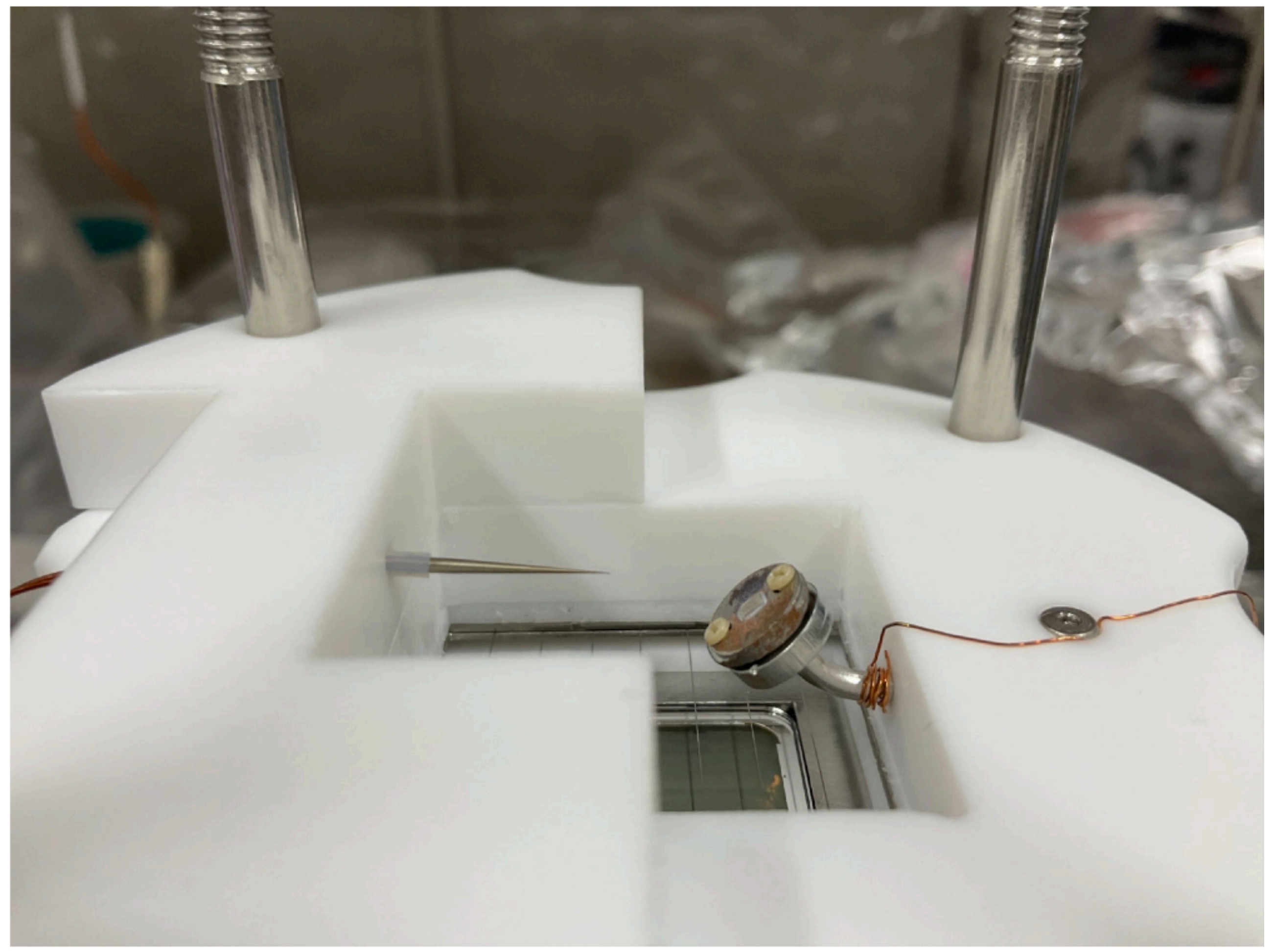

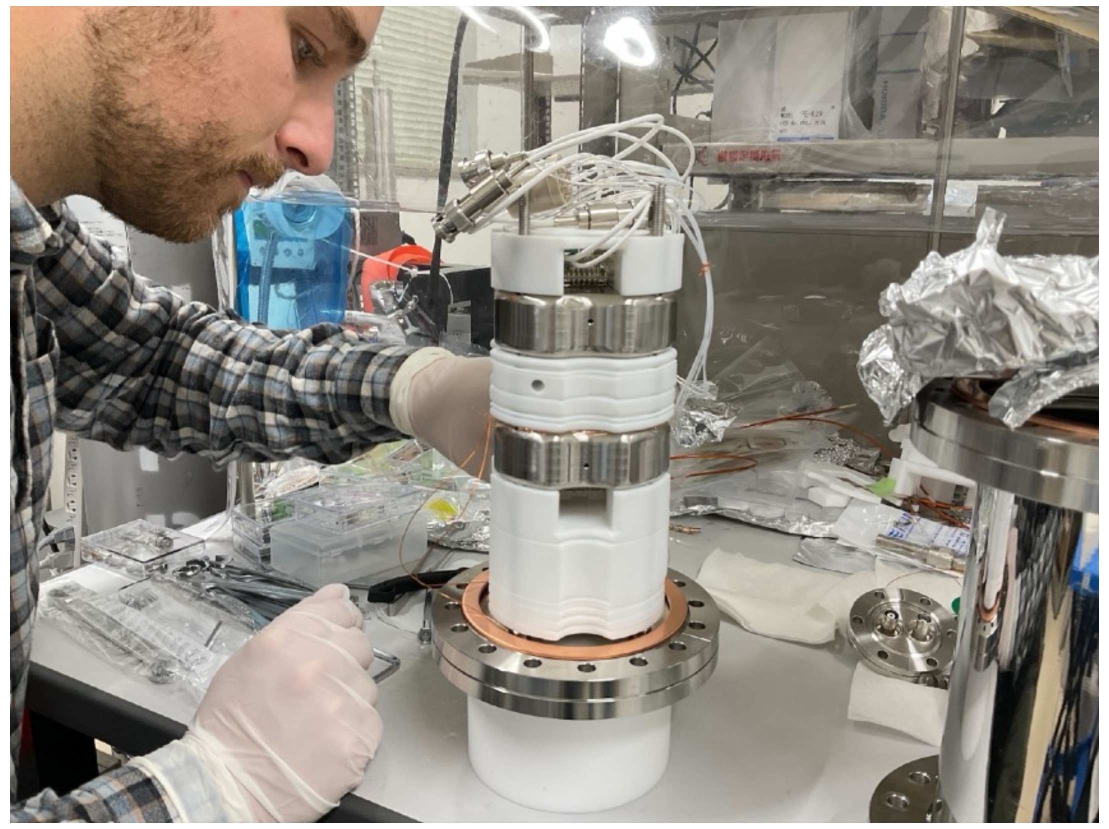

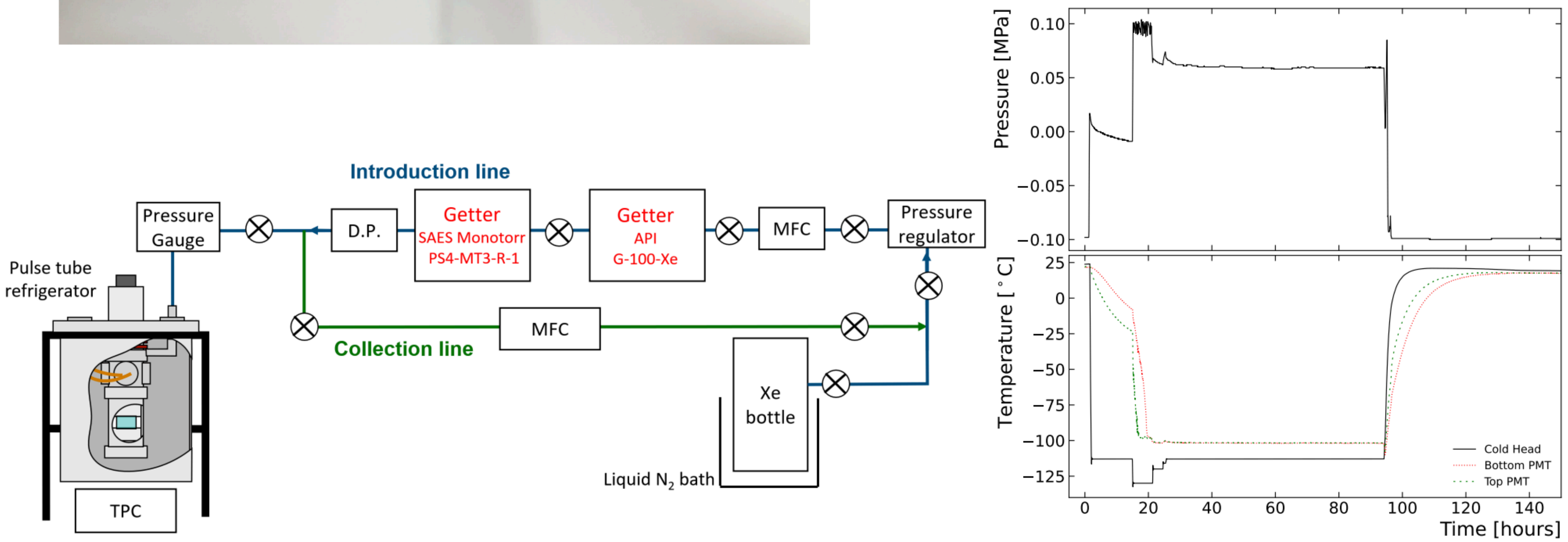

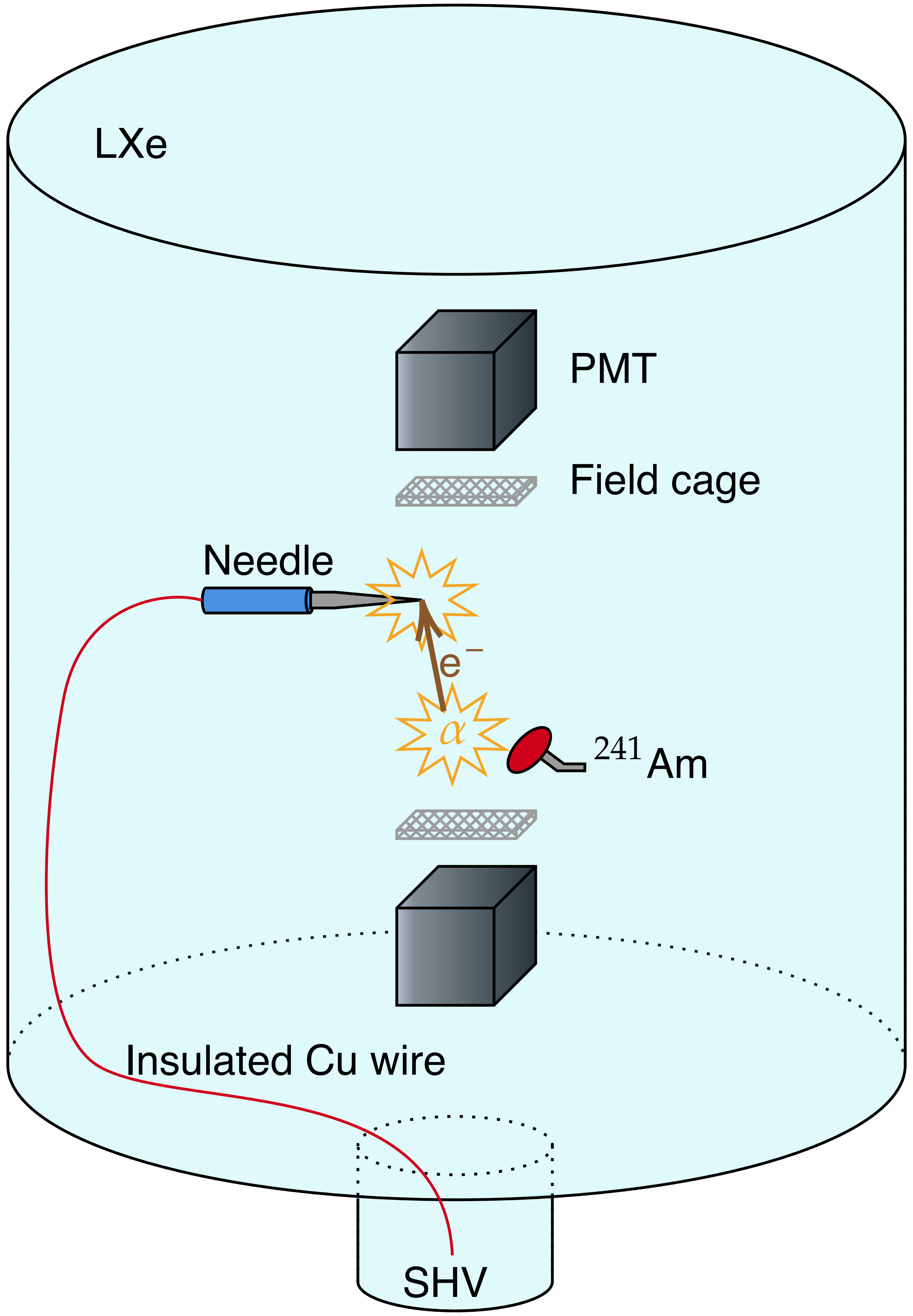

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- S1 is induced by the interaction of the α-particle in the LXe
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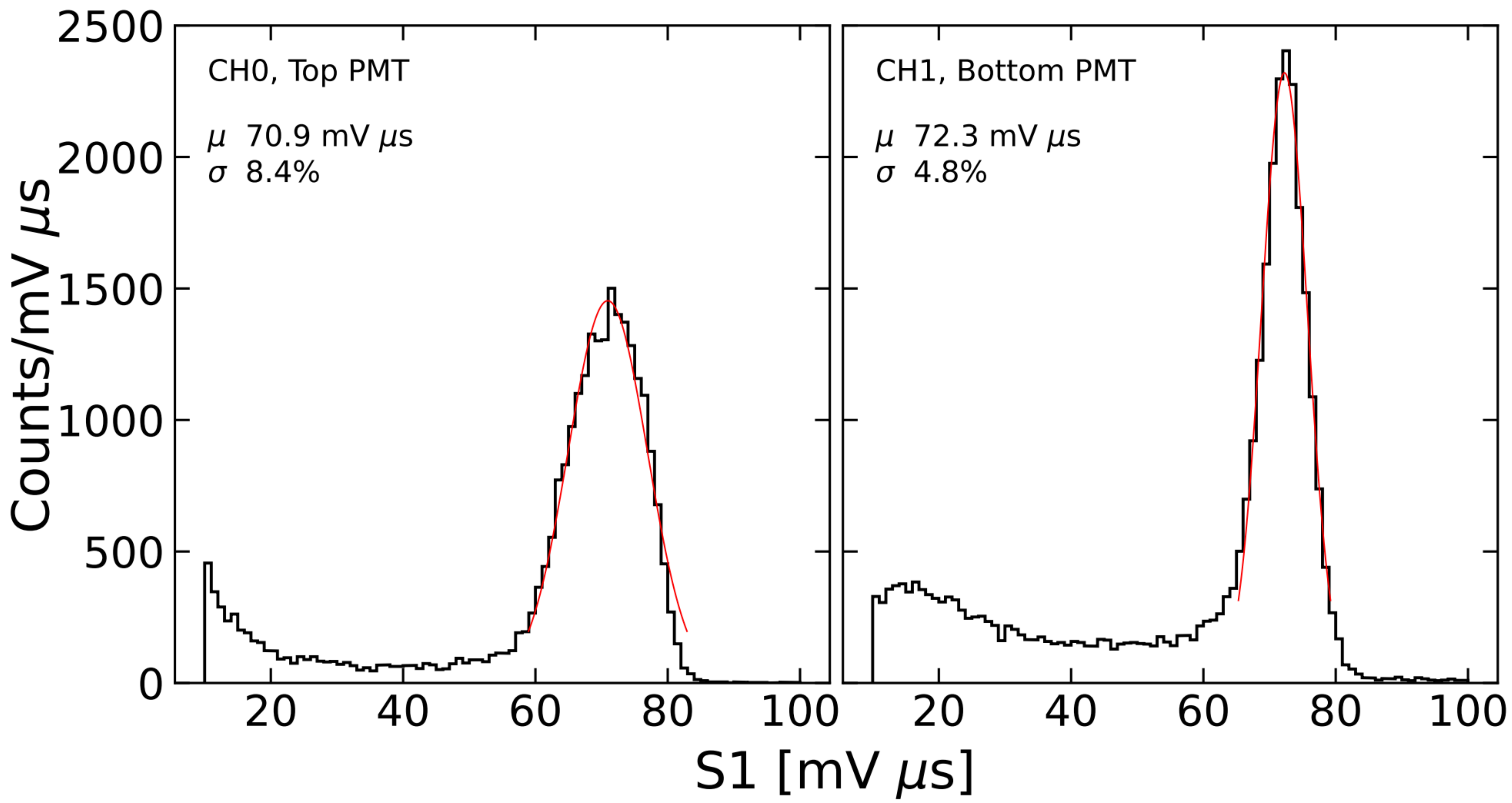
  - ➡S2/S1 used as a metric to look for signal amplification



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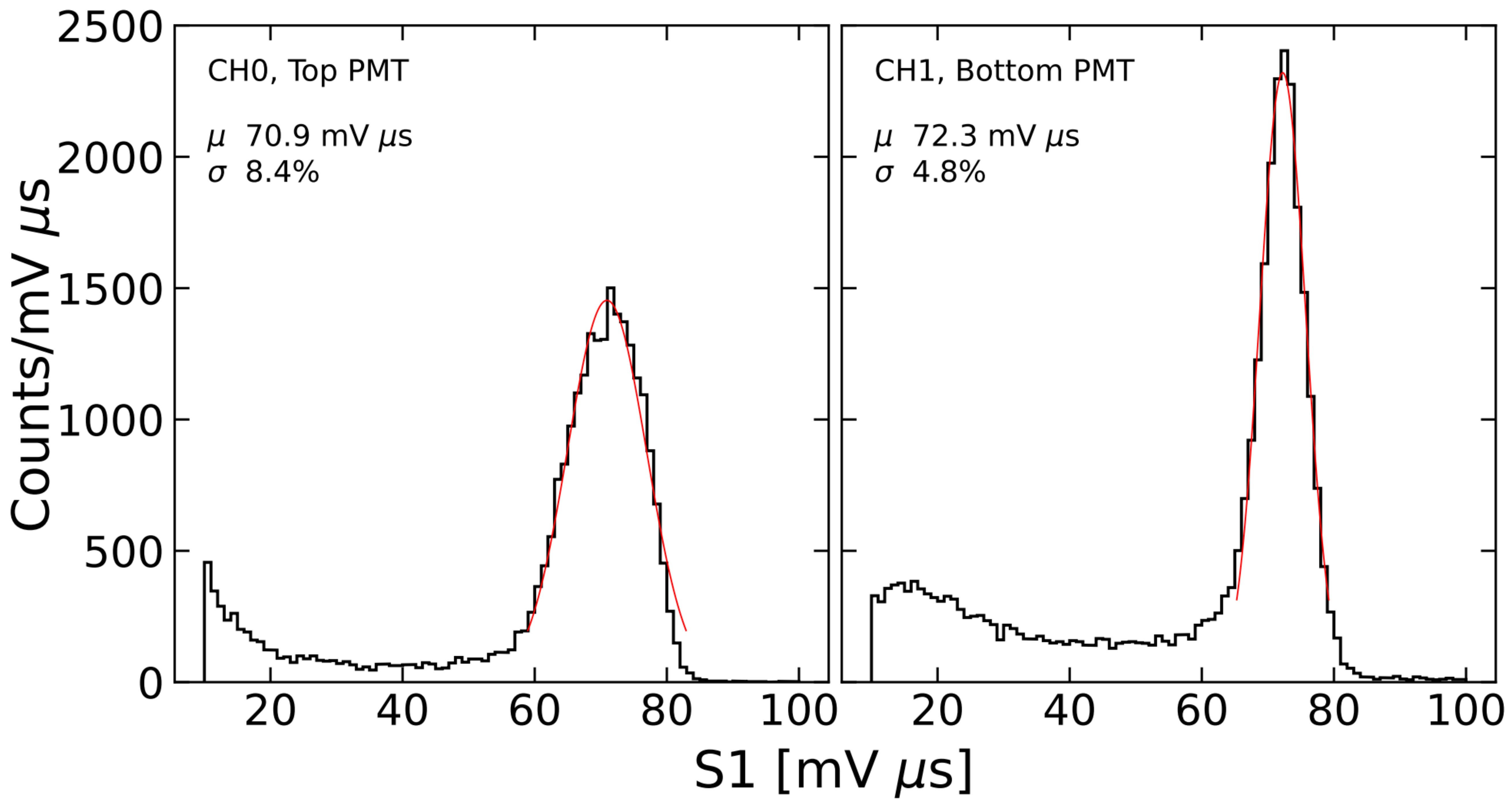

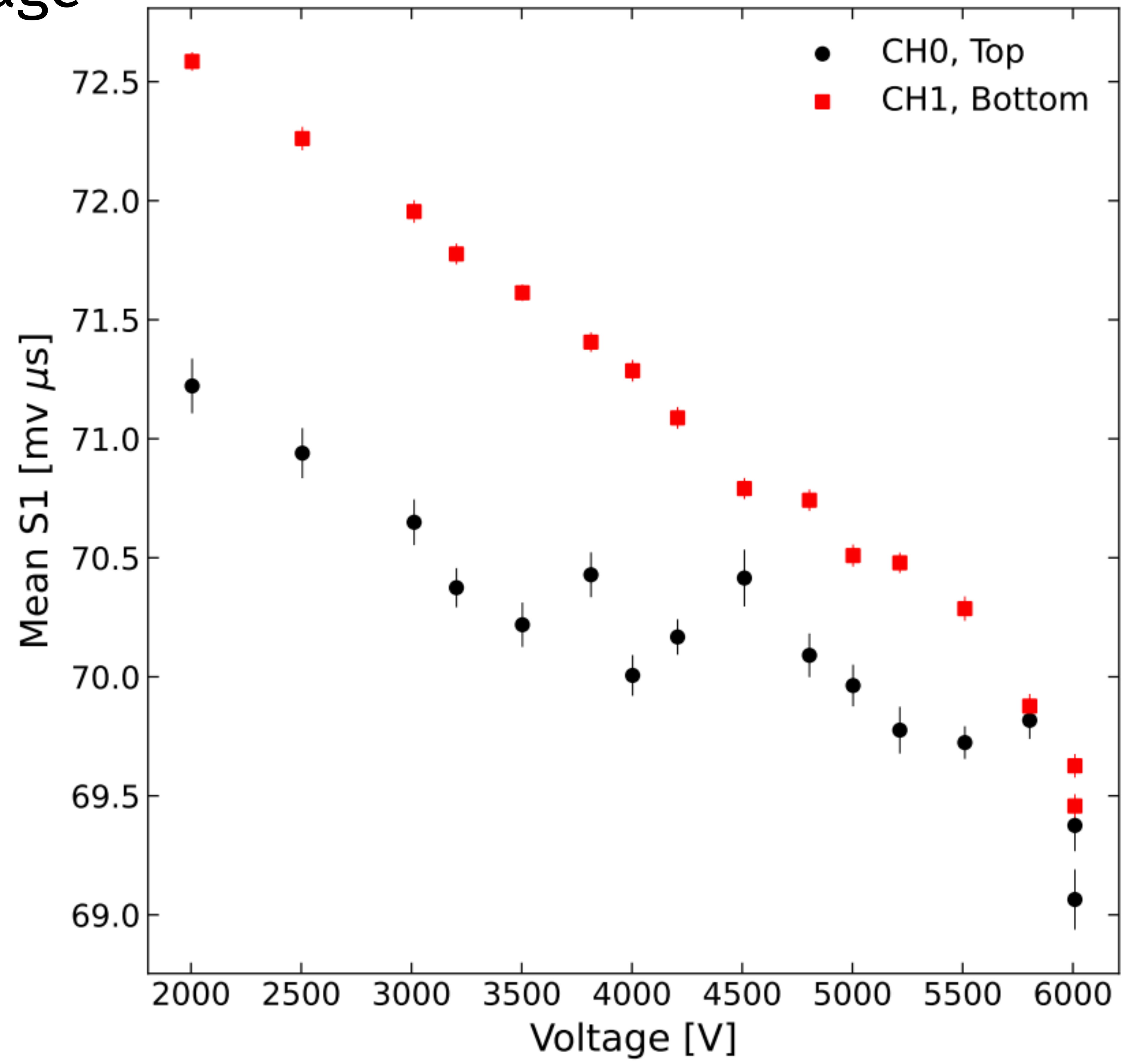

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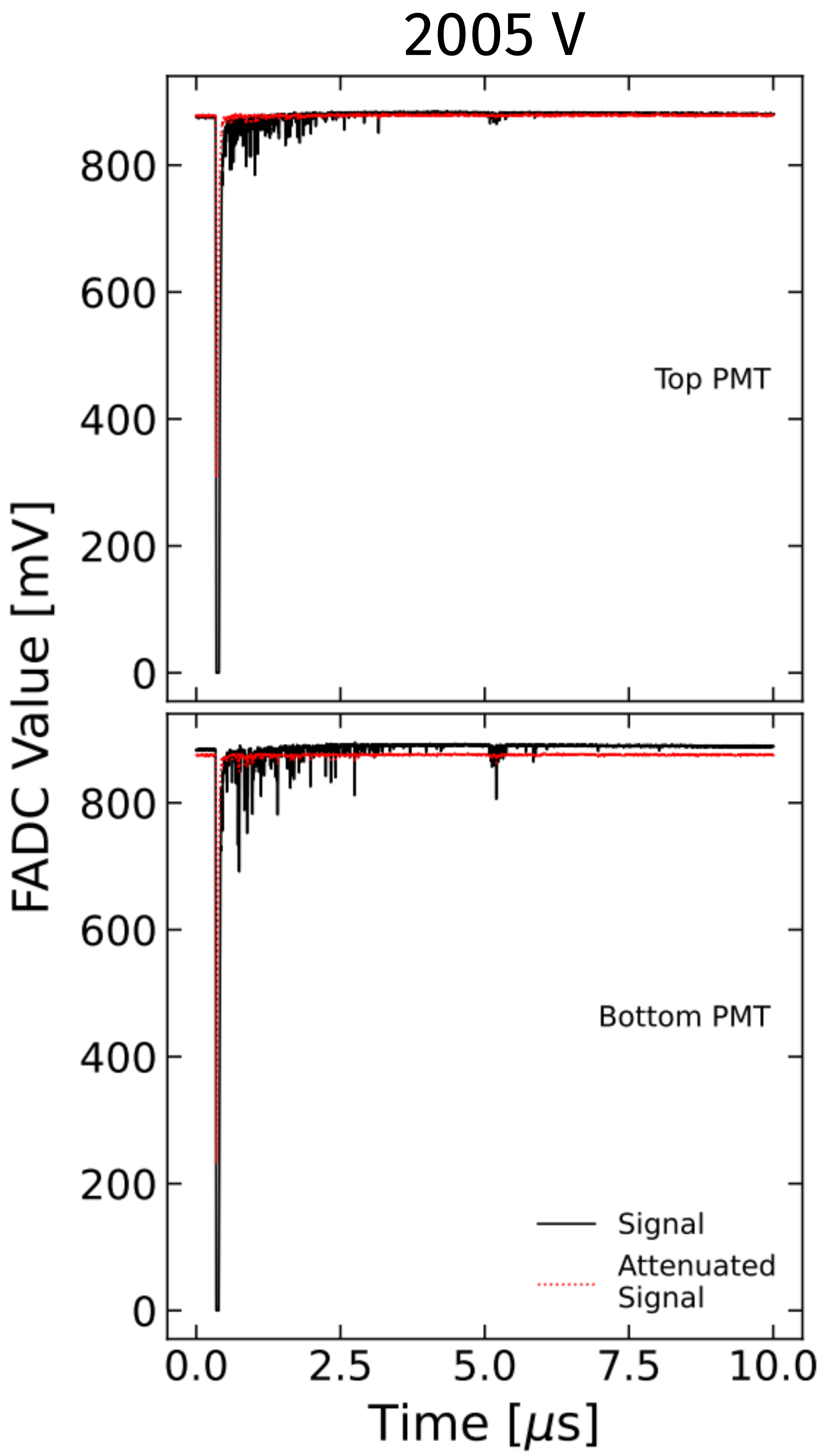

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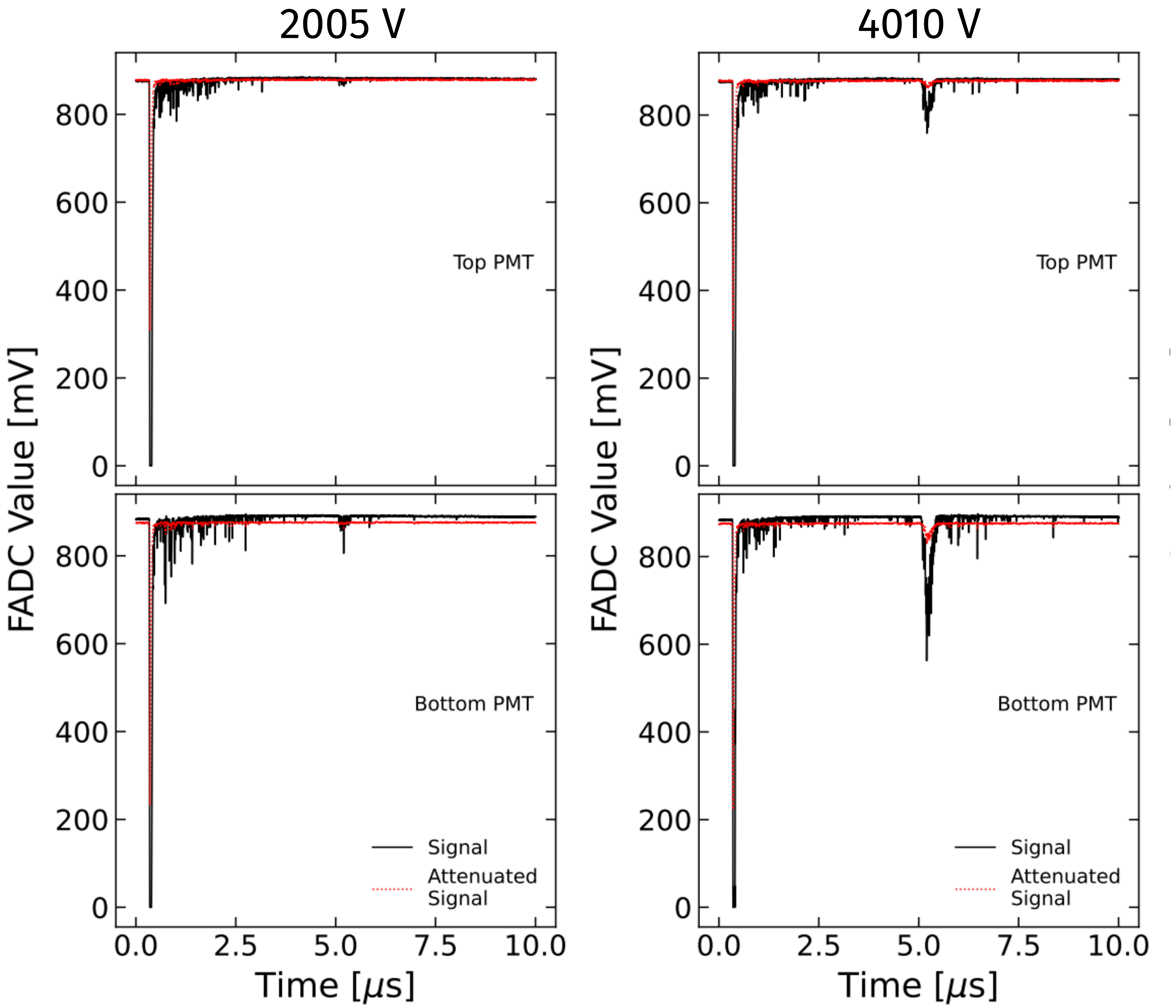

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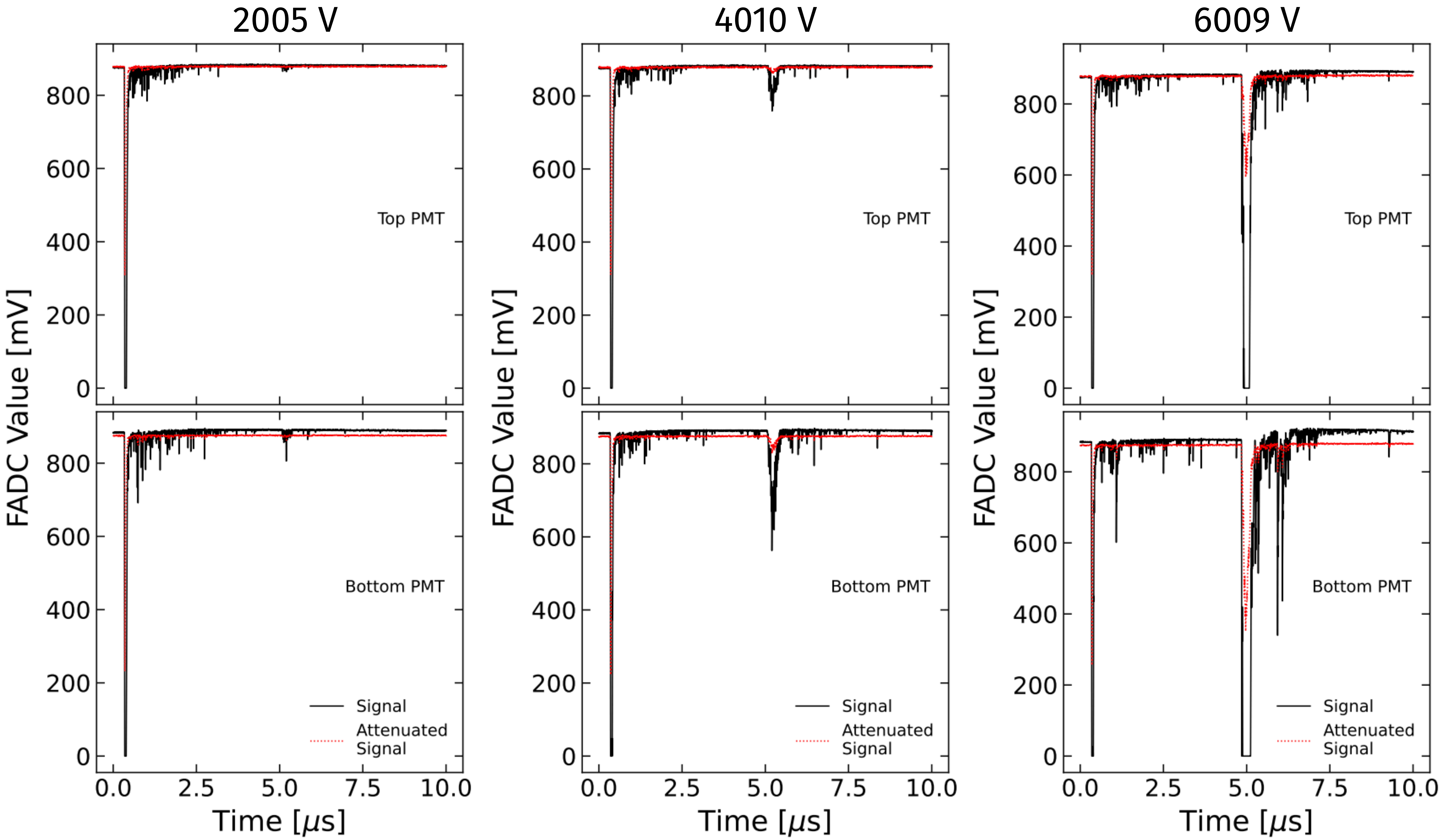

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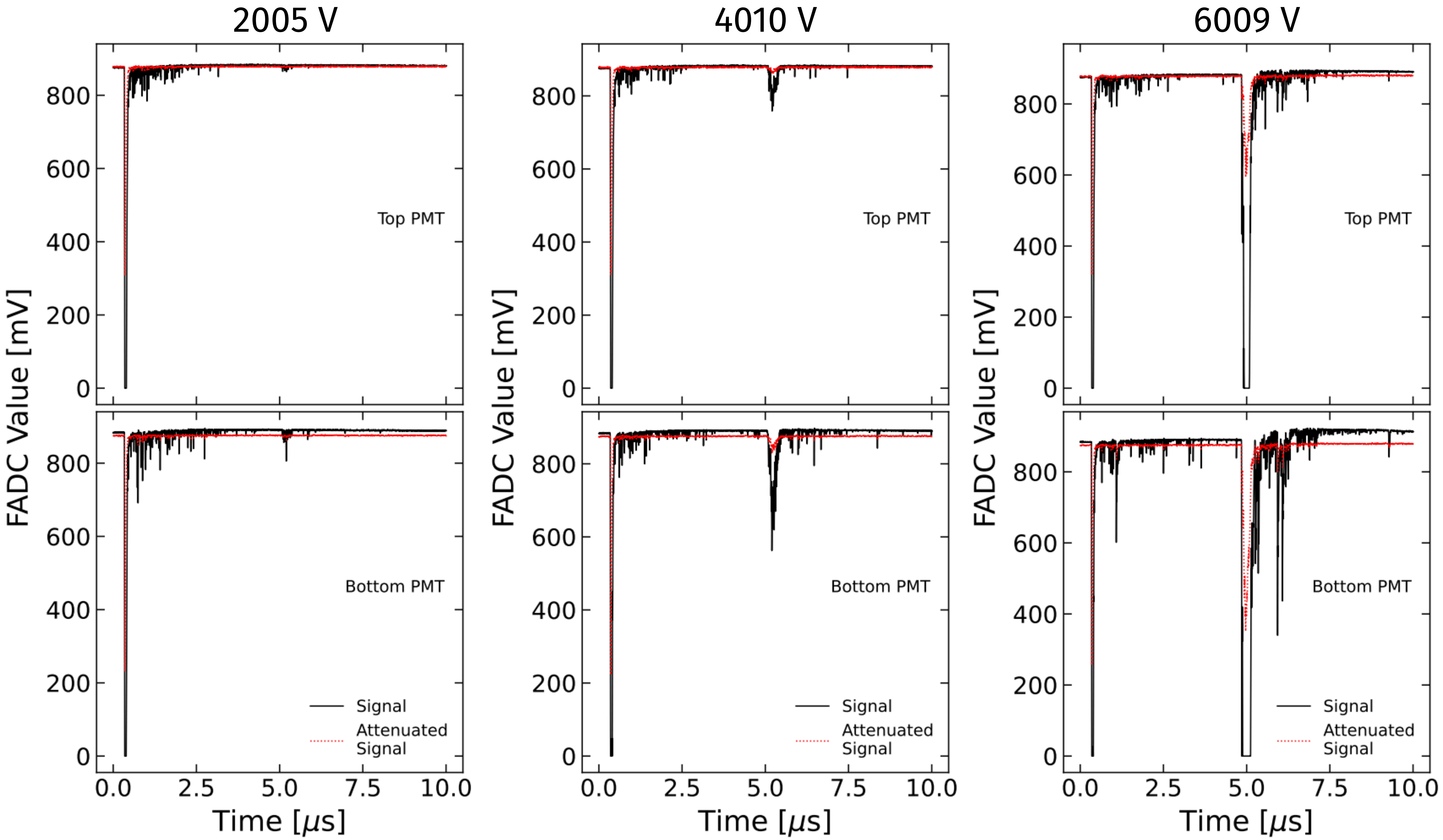

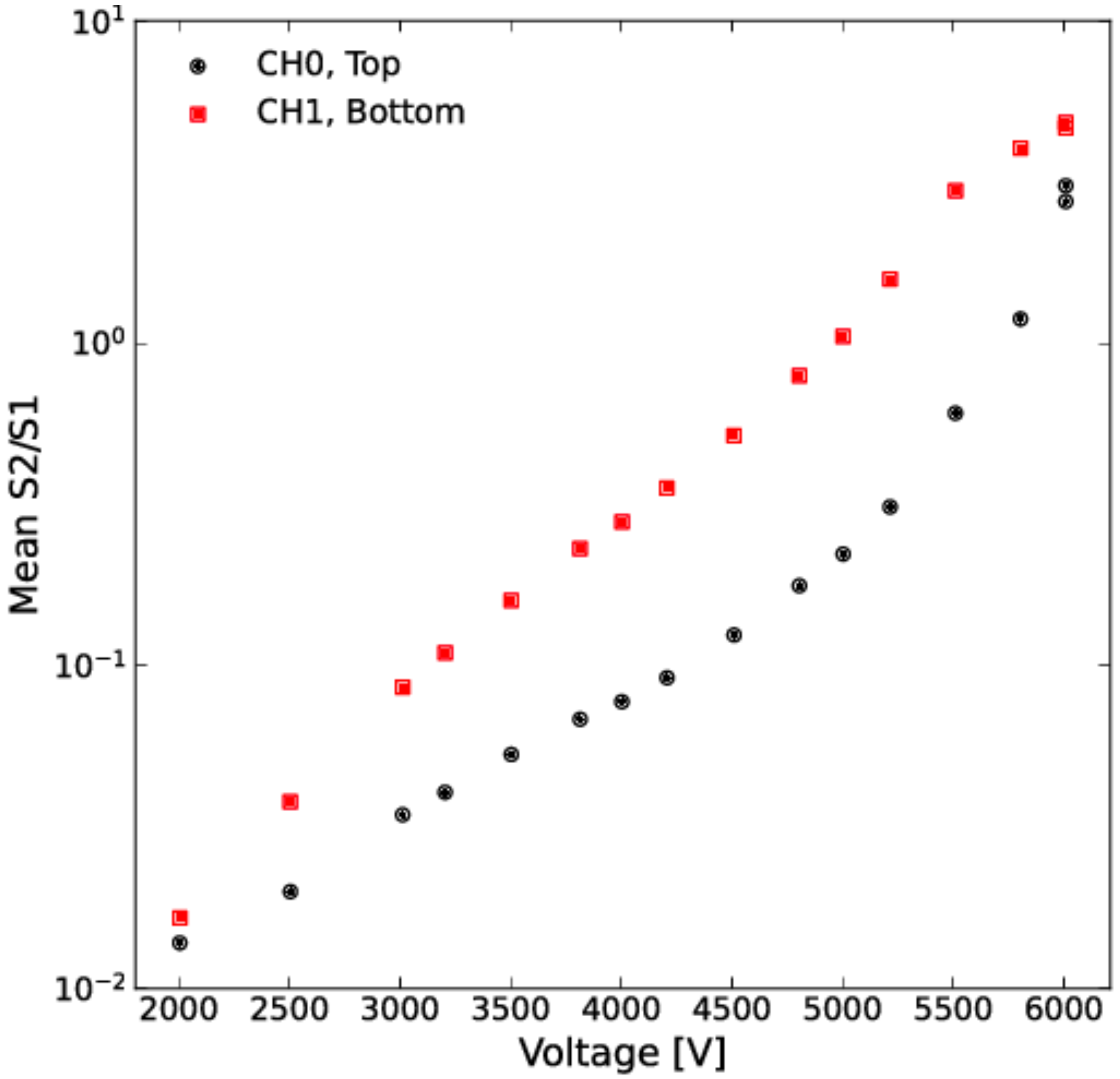

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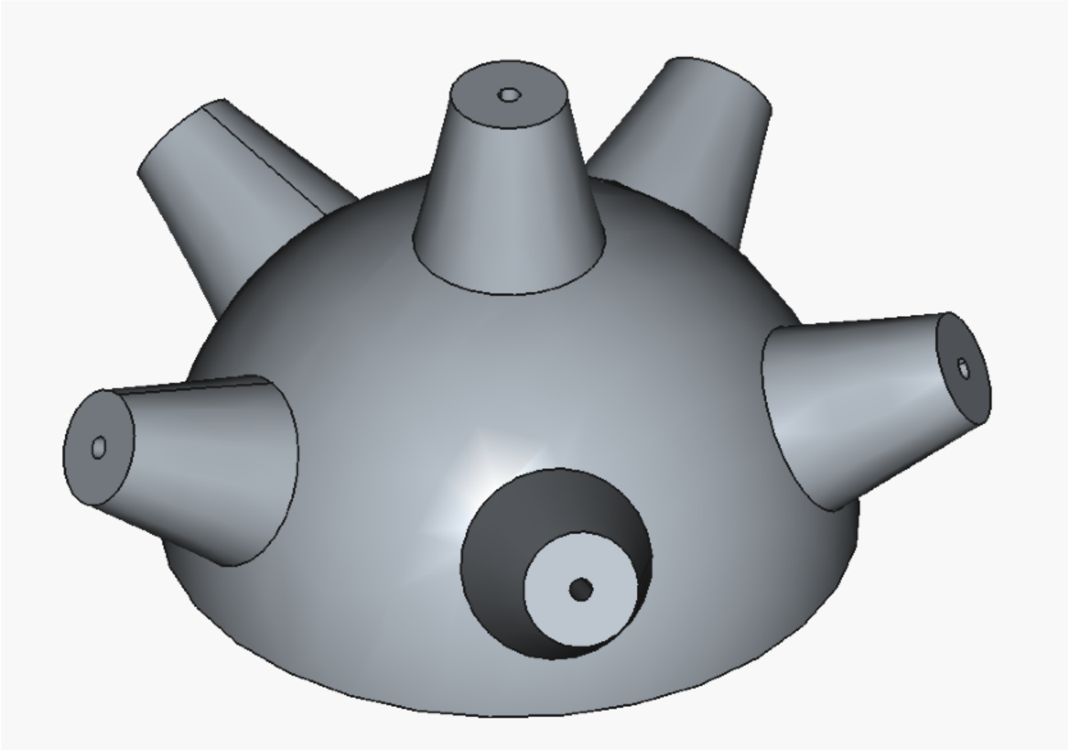

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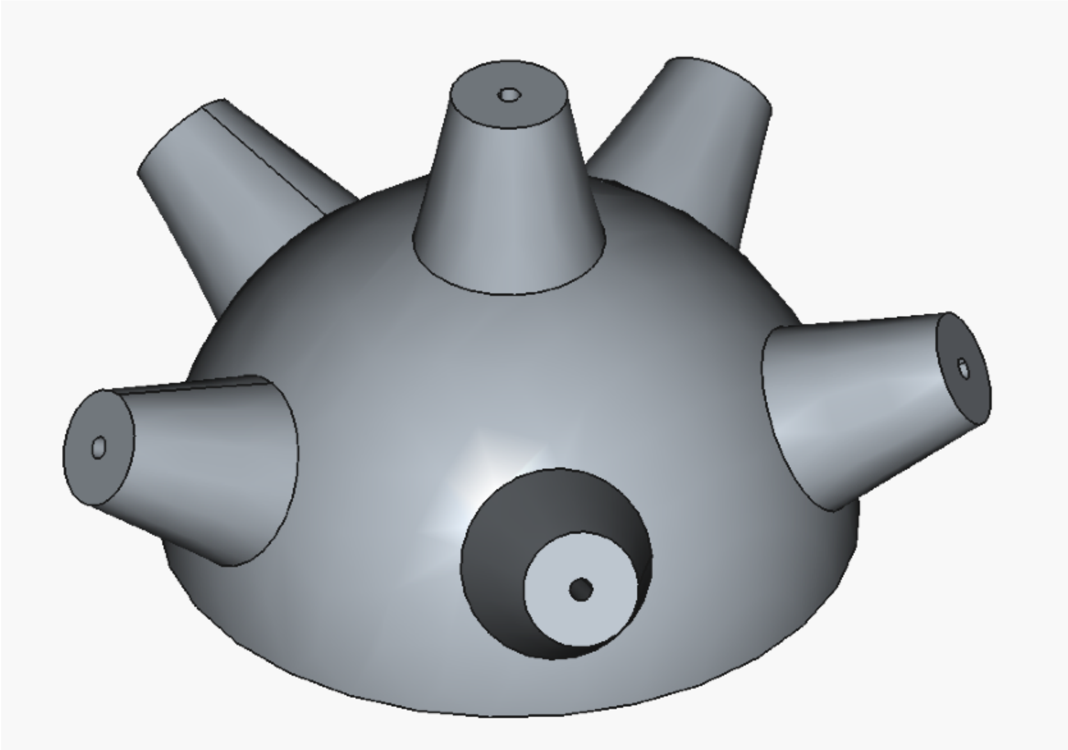
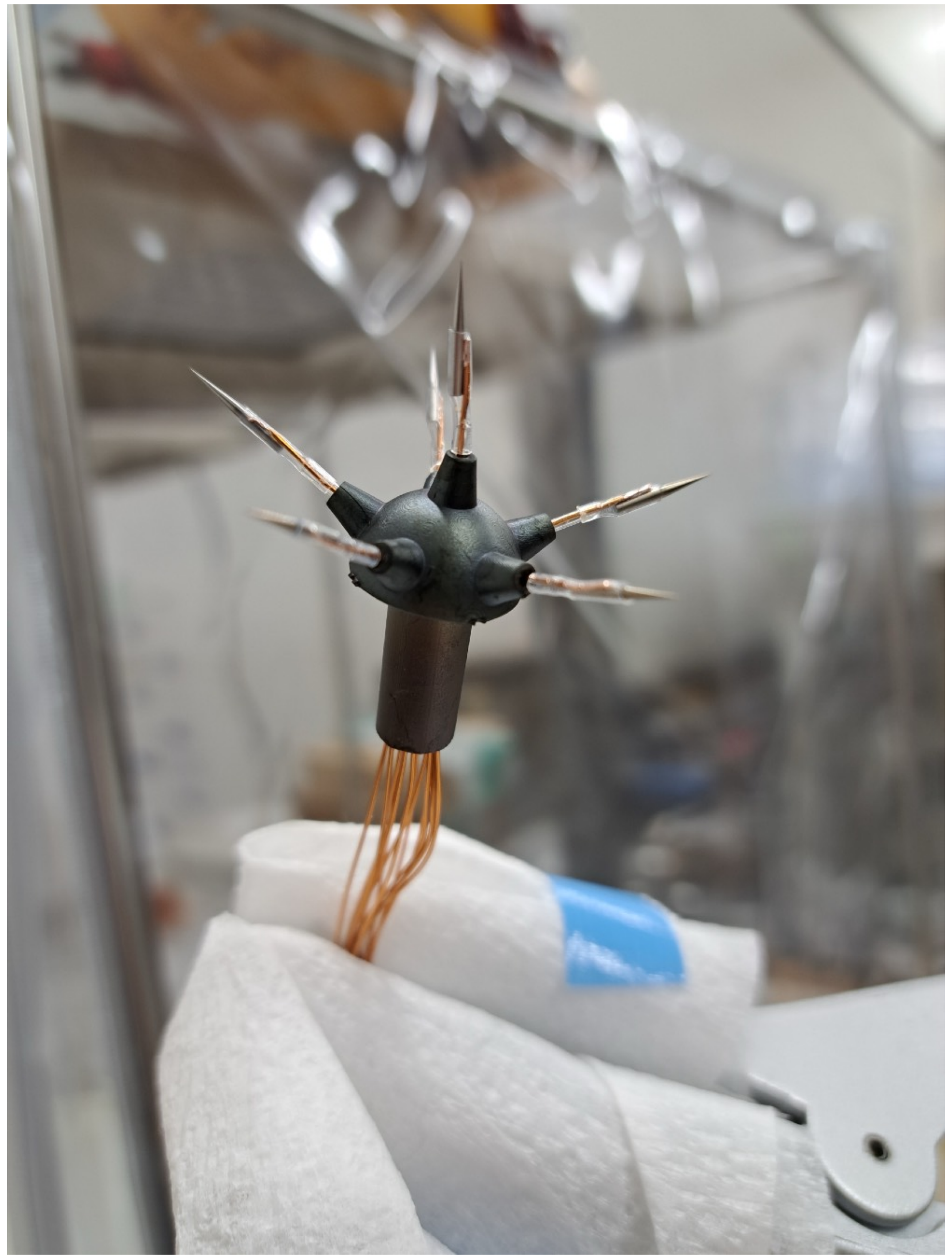
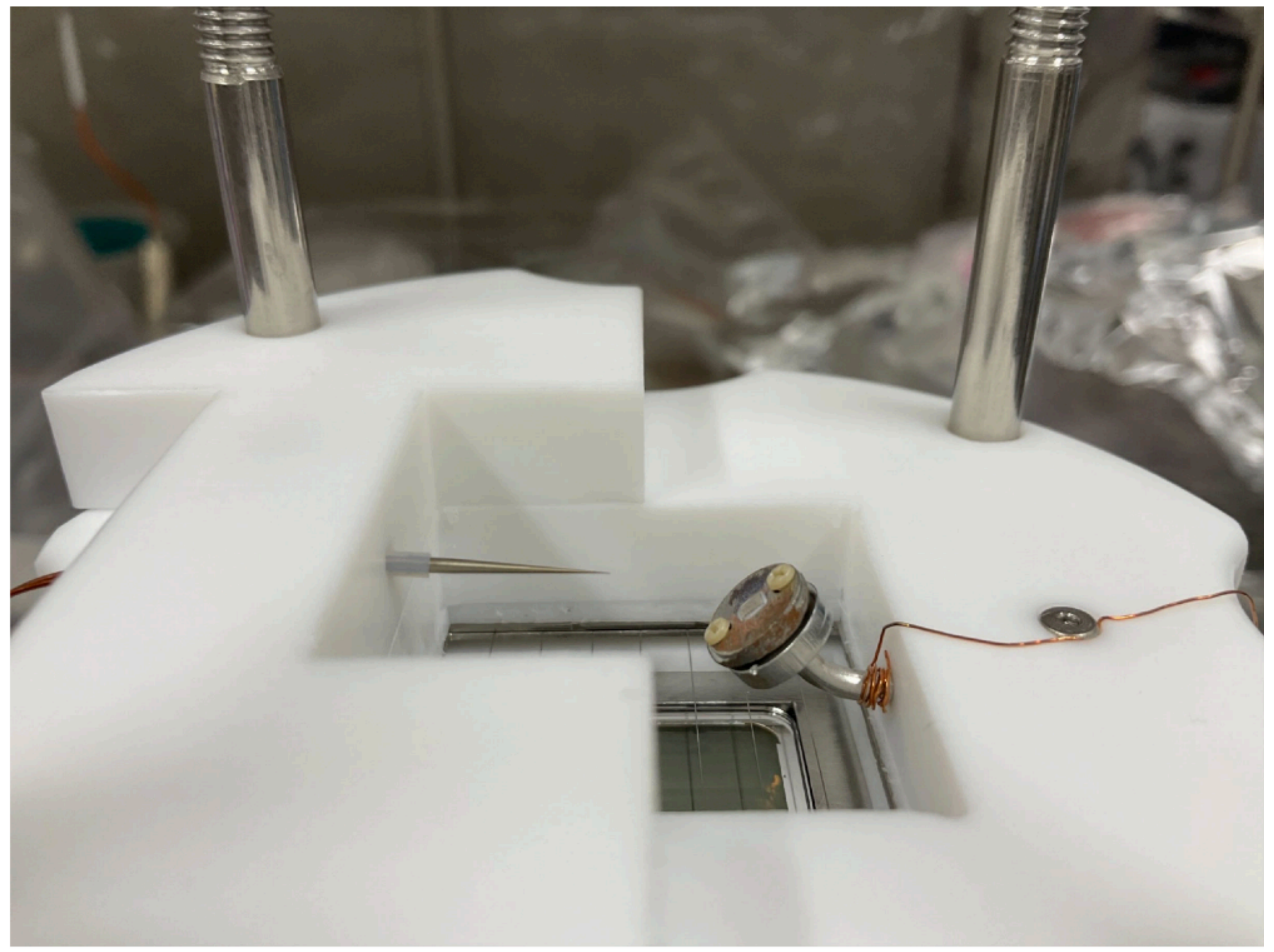
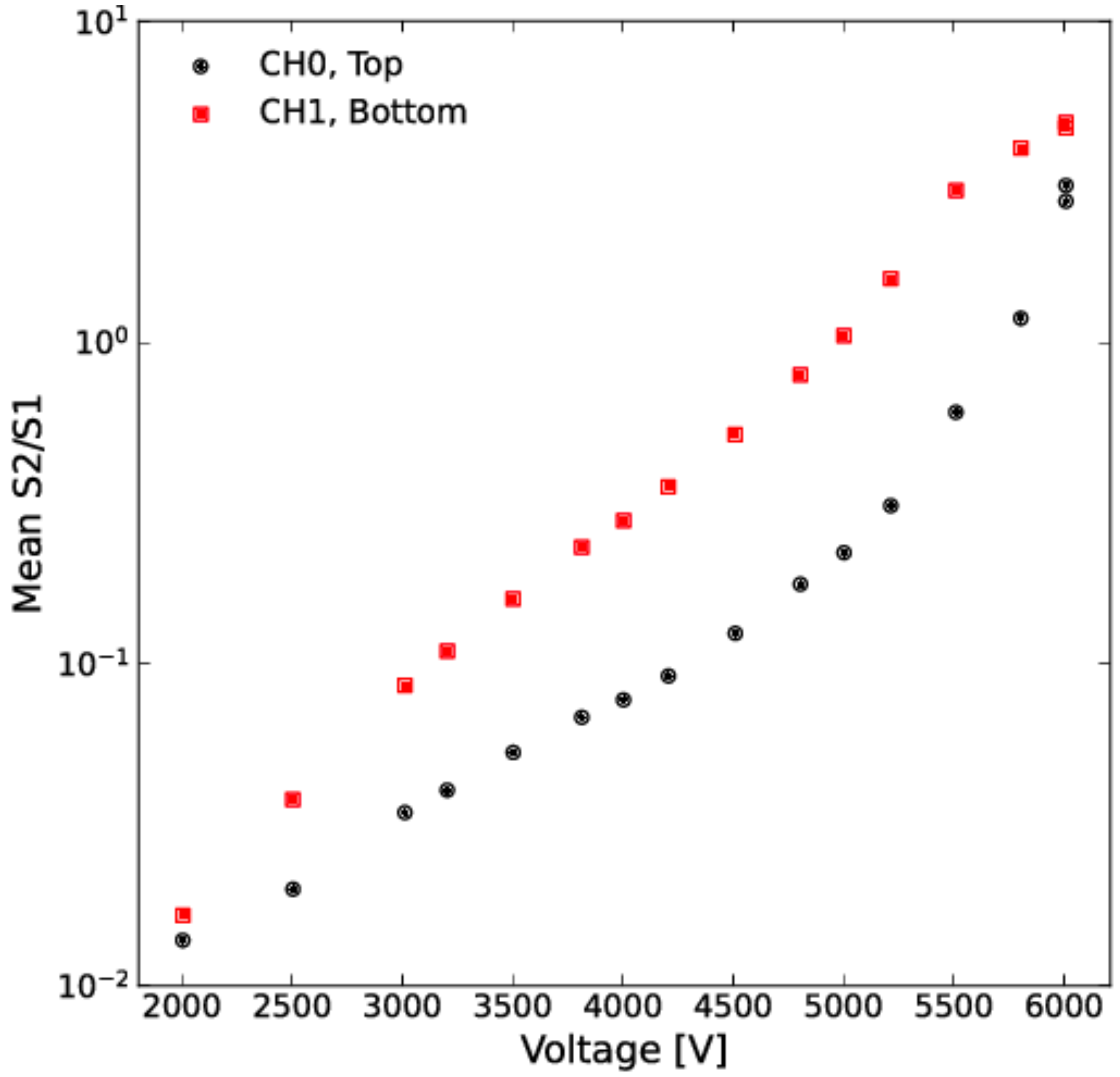


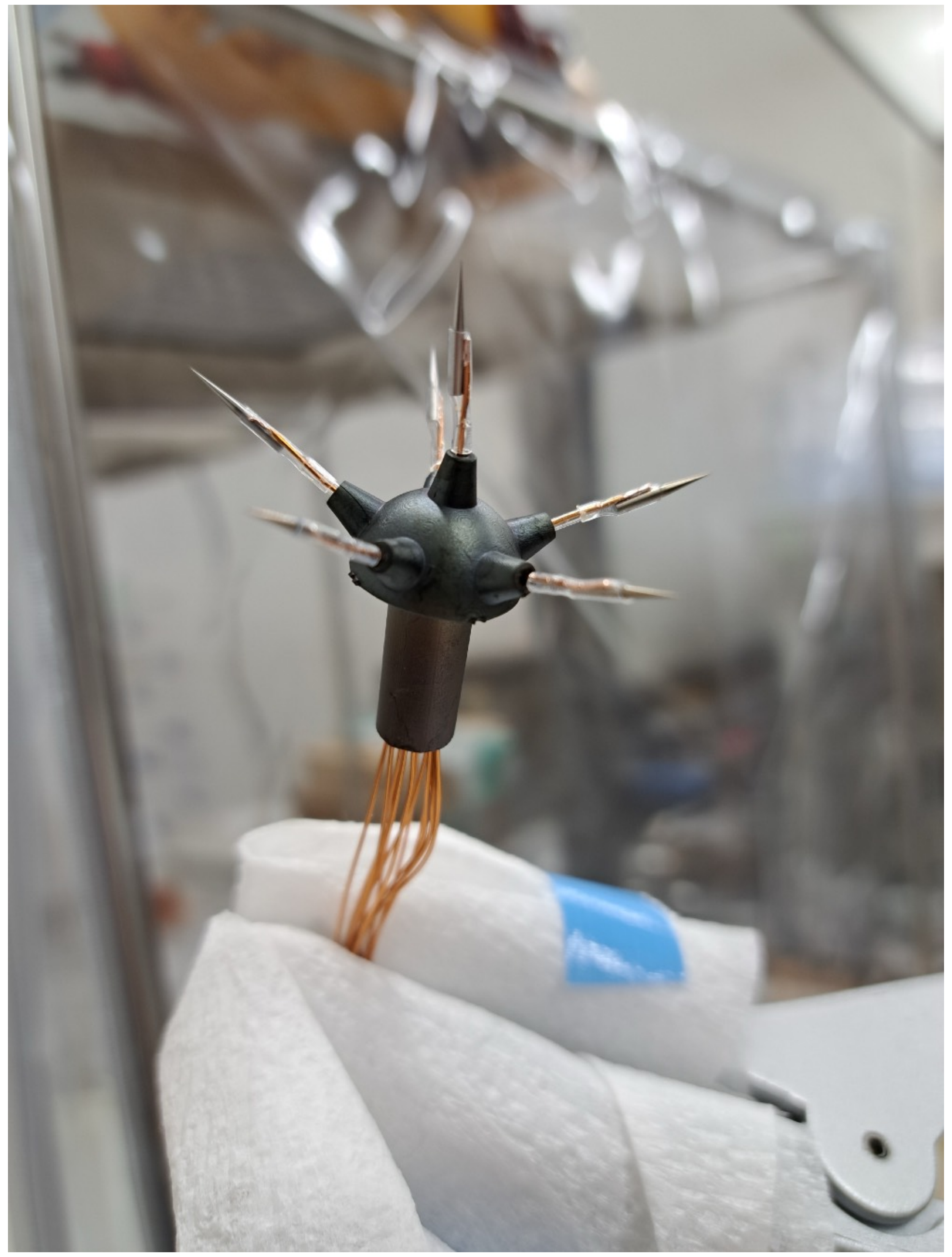


Summary

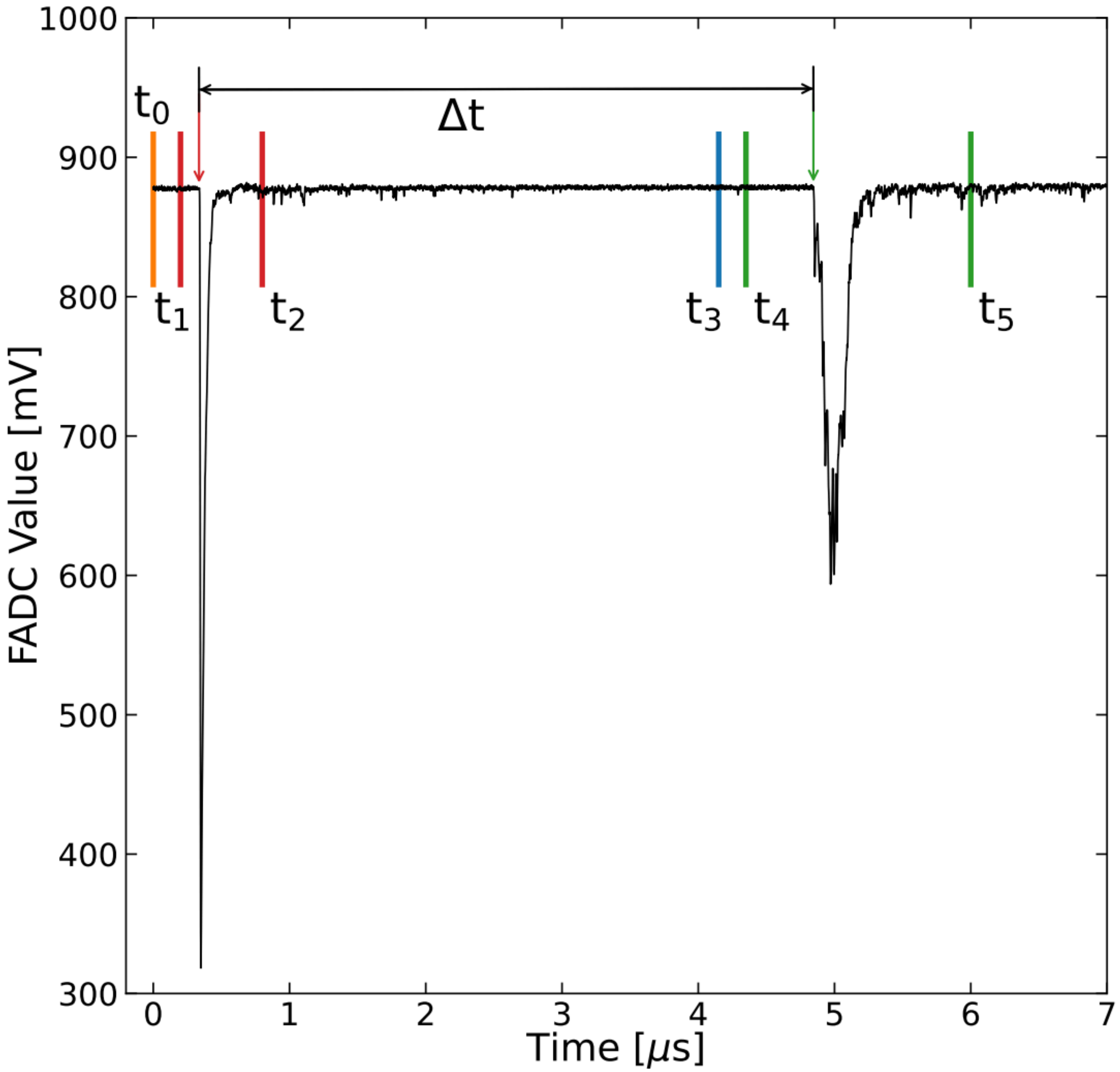
- ❖XMASS-I design has high photo-coverage, but its performance would be enhanced from improved background rejection
- ❖Demonstration of a scalable charge-amplification structure in a LXe TPC, inspired by spherical proportional counter
- ❖Moving towards a multi-electrode design which would be suitable for installation in a spherical LXe detector



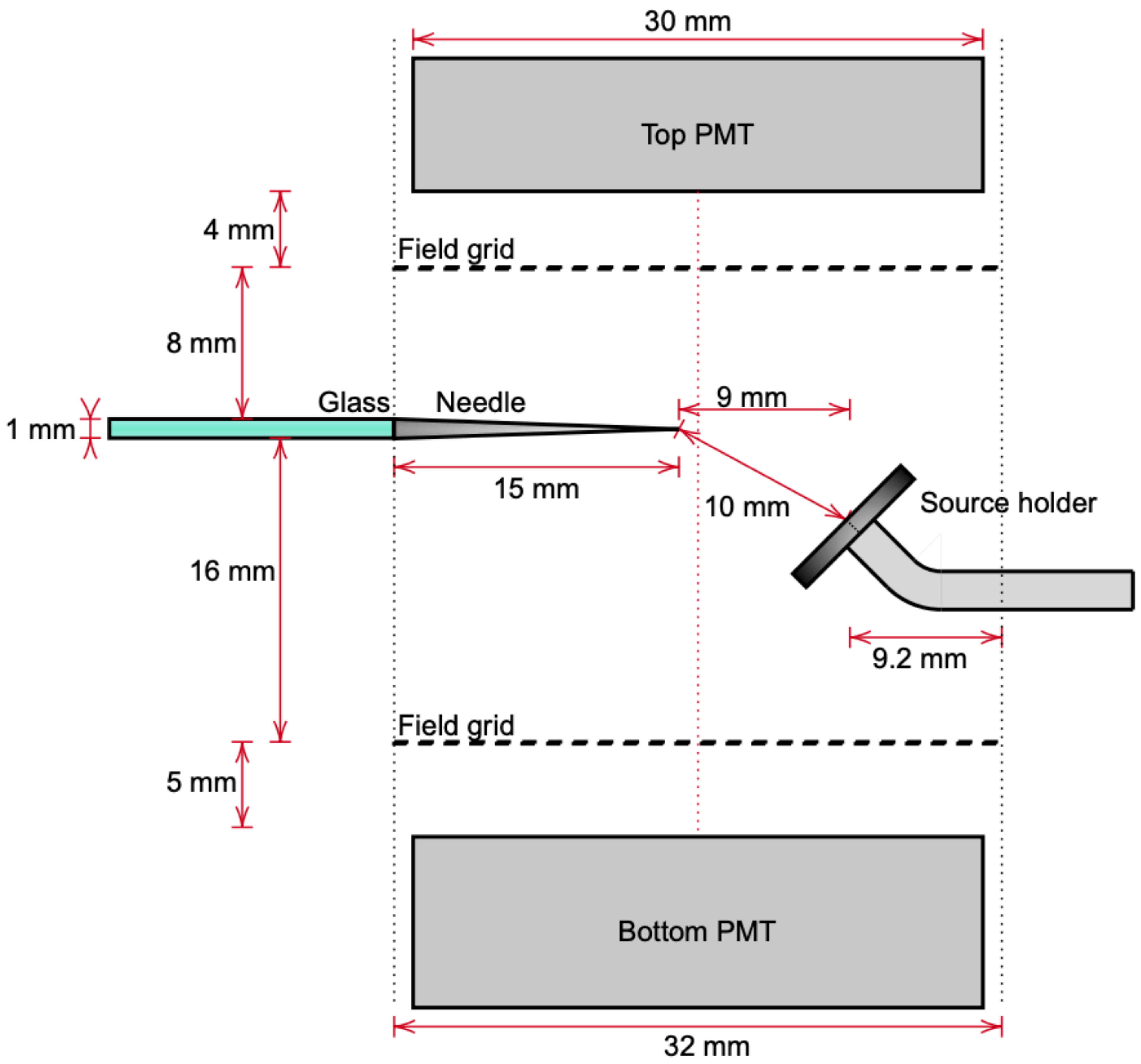


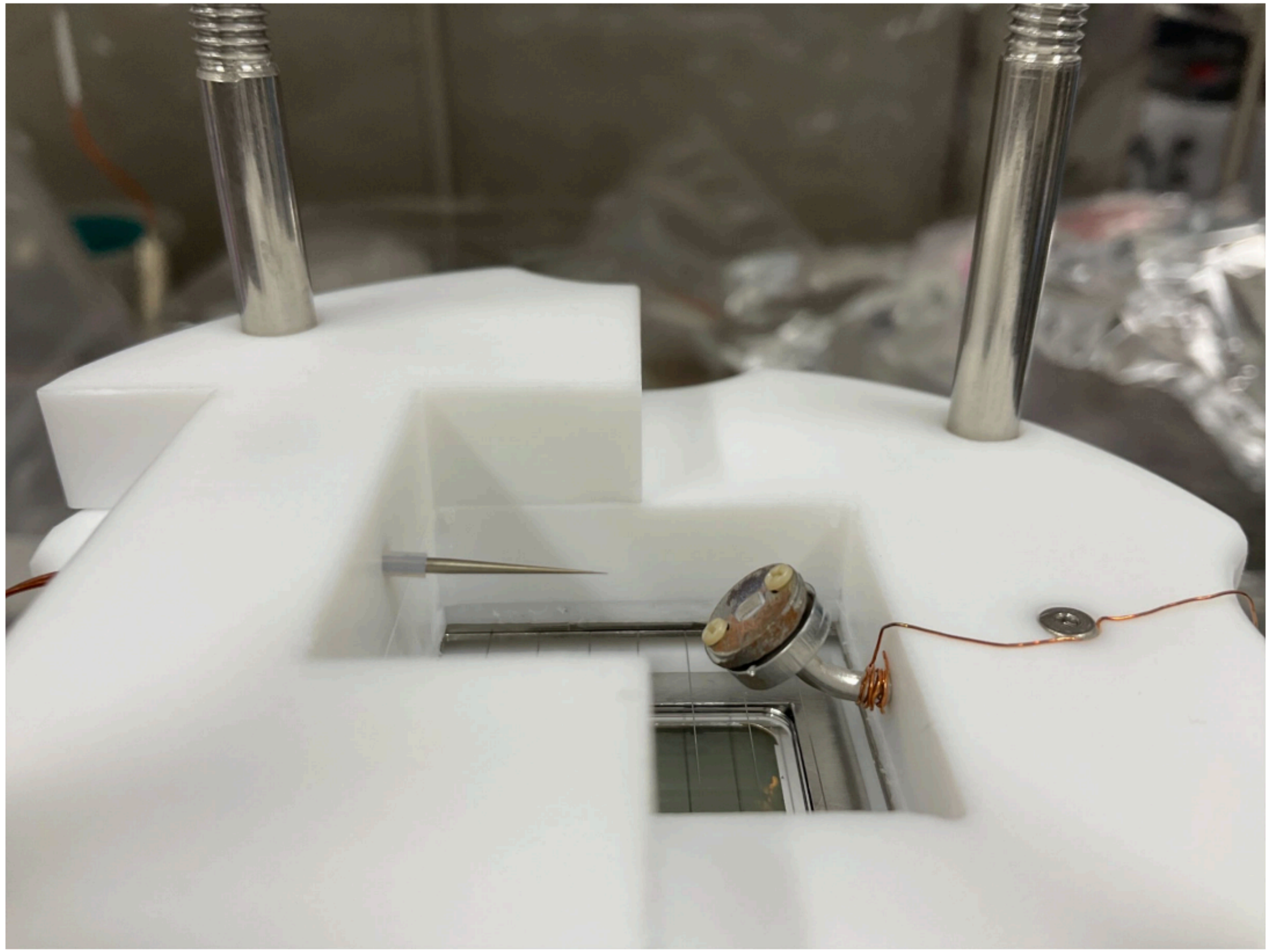


Pulse Shape Processing

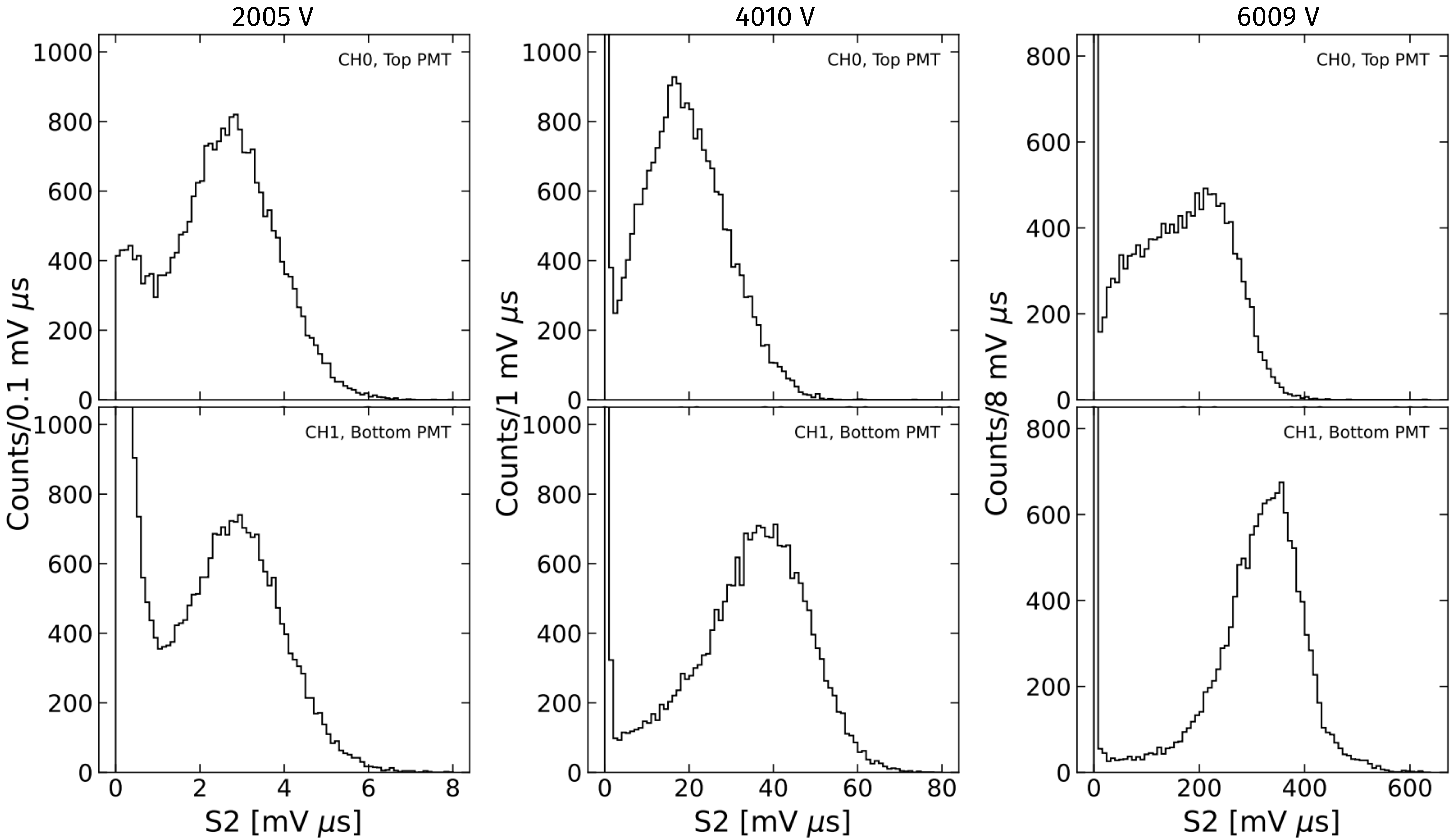


Experimental Configuration





S2 Integral


2005 V
4010 V
6009 V
CH0, Top PMT
CH1, Bottom PMT
Counts/0.1 mV μs
Counts/1 mV μs
Counts/8 mV μs
S2 [mV μs]
0
200
400
600
800
1000
0
2
4
6
8
20
40
60
80
600

Data Acquisition