nEXO

Long-term performance of VUV-sensitive silicon photomultipliers (SiPM) for large-scale liquid xenon detectors

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Physics at the interface: Energy, Intensity, and Cosmic frontiers
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Outline and Participants

- Large LXe TPCs for neutrinoless double beta decay (nEXO)
- Scintillation light collection with VUV-sensitive SiPMs:
  The UMass LXe optics system
- SiPM long-term characterization
- Case study: recovery of light collection efficiency
- Outlook

Postdocs

- Priyanka Kachru (now at FBK)
- Wesley Gillis (now at Bates)

PhD students

- Edryd van Bruggen
- Hannah Peltz Smalley
- Seth Thibado

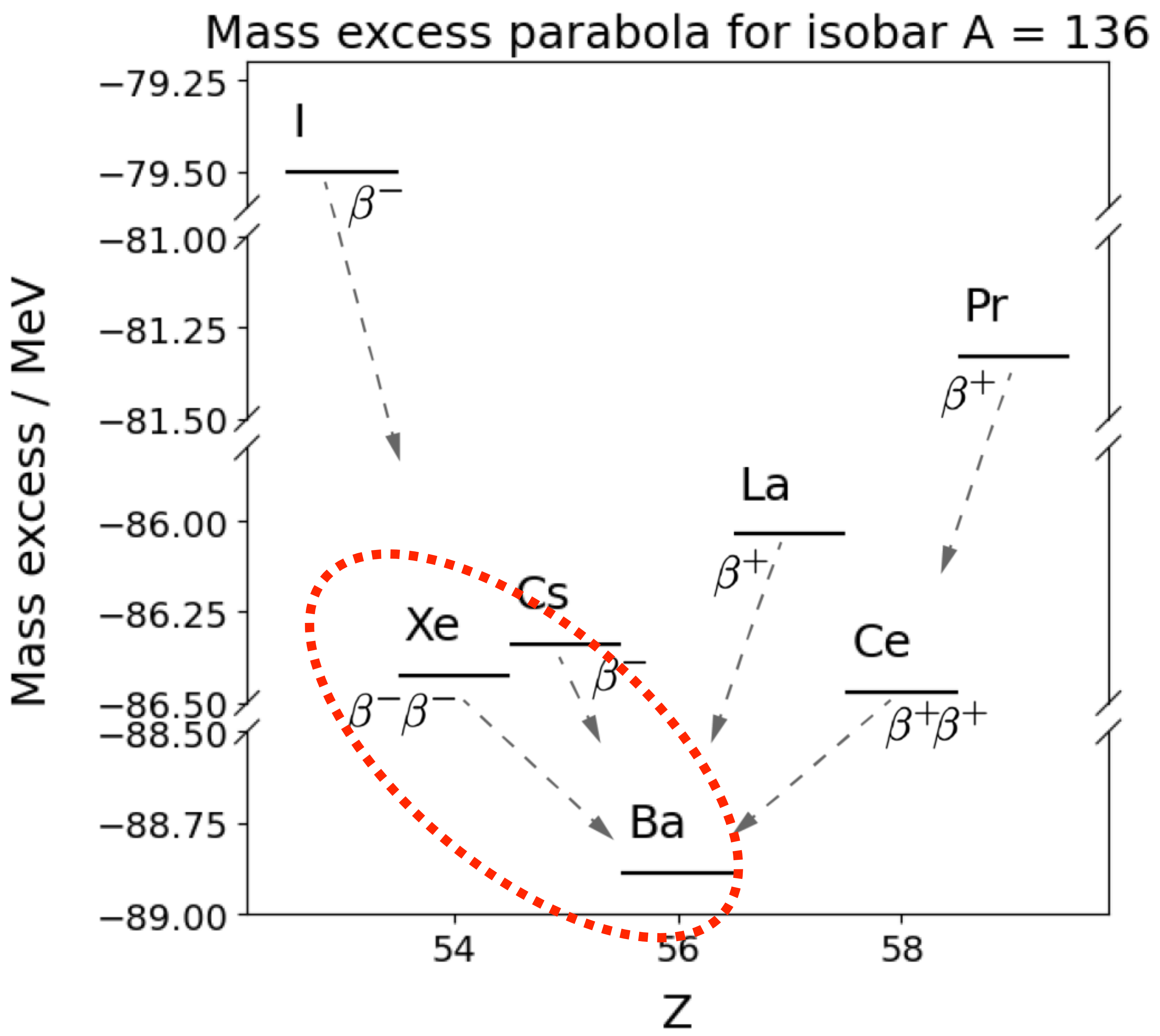
Master's exchange student

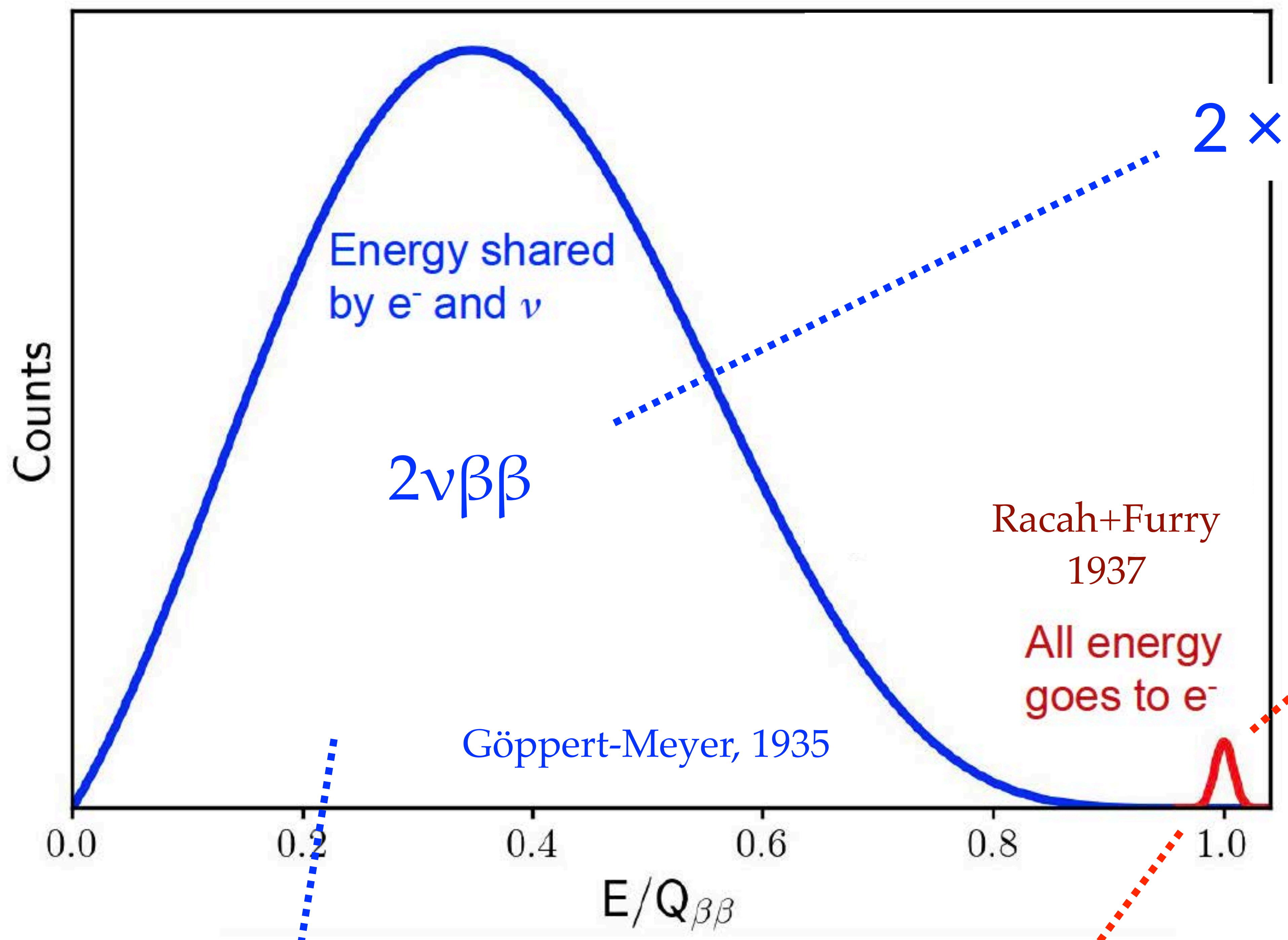
- Thomas Schwartze (Uni. HD)

Undergraduate students

- Marty Tsankov
- Noah Jenkins
- Zihan Rao
- Makayla Bobusia
- Julia Pankowska
- Nick Yazbek
- Loick Marion

Neutrinoless Double Beta (0νββ) decay in LXe

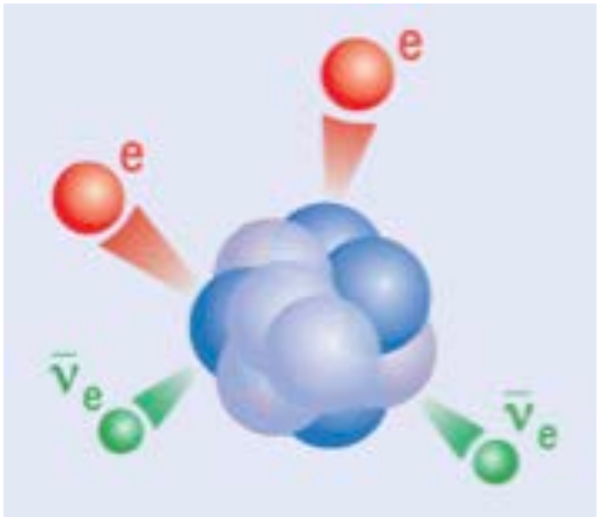


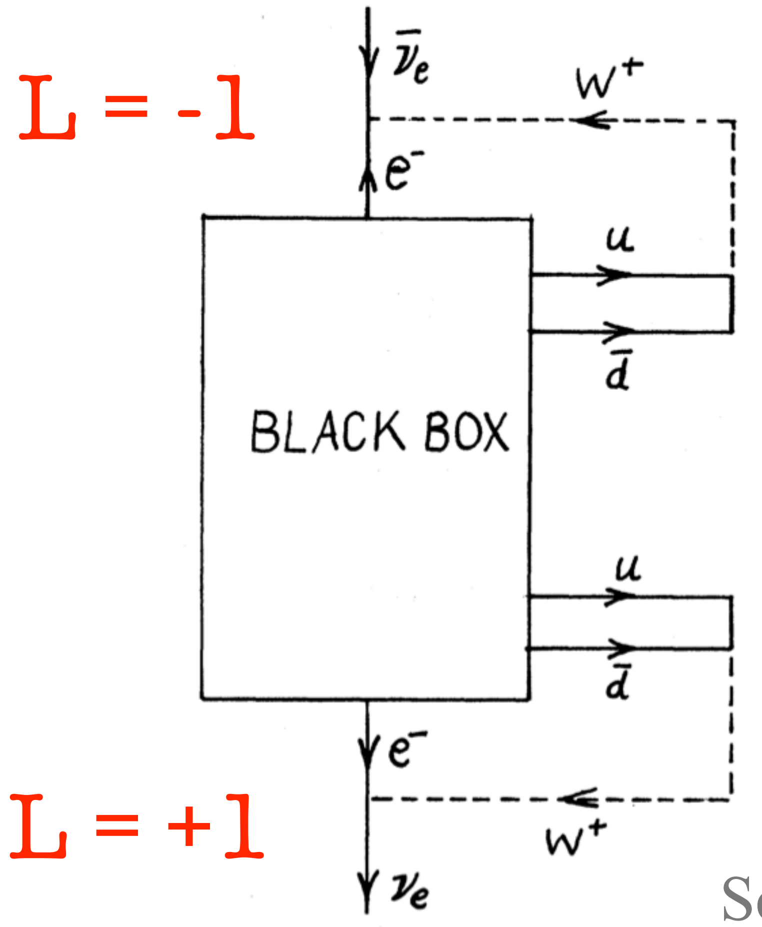


2×10^{21} y

$> 4 \times 10^{26}$ y

✦ Search for event excess at the endpoint

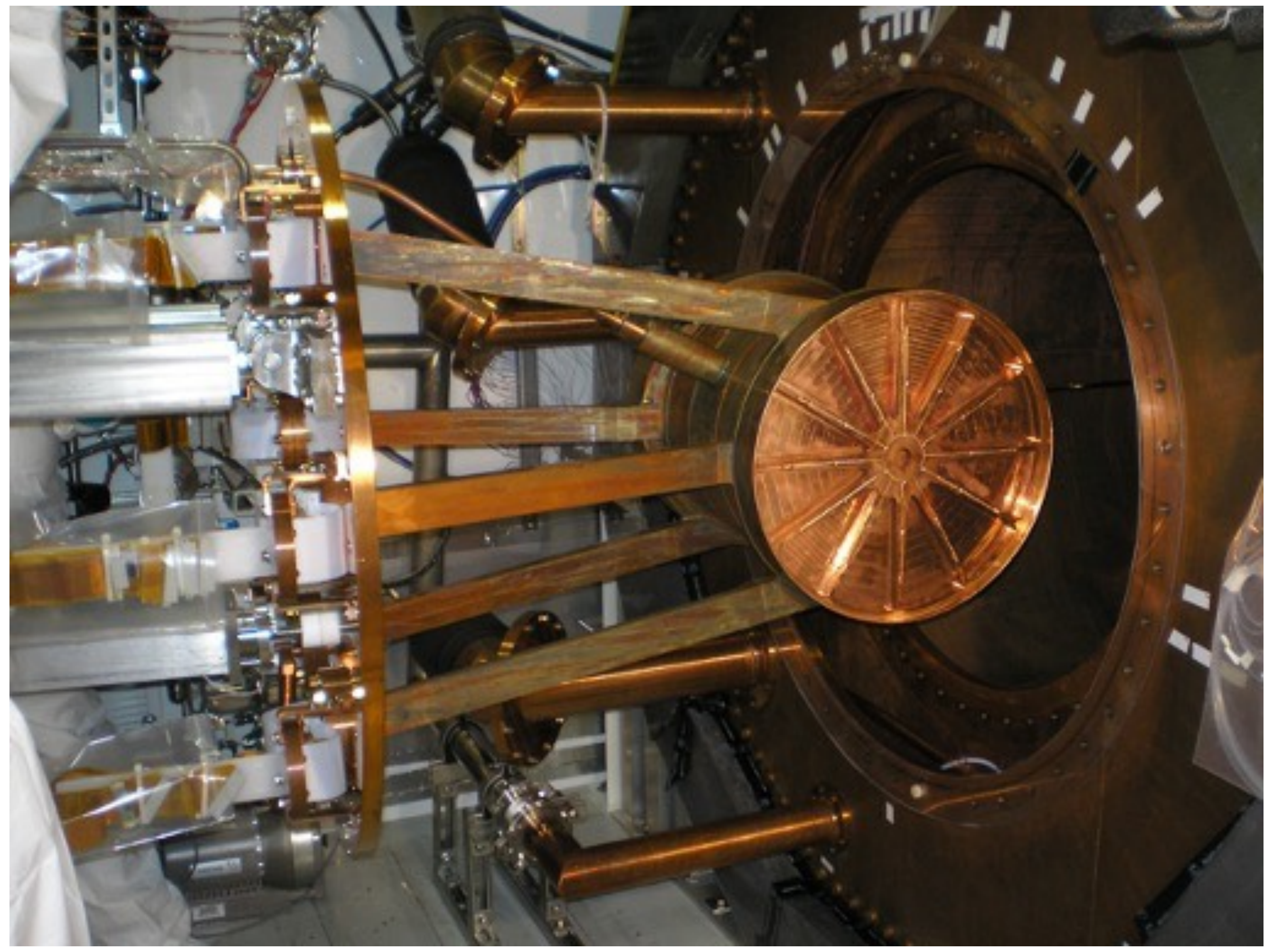


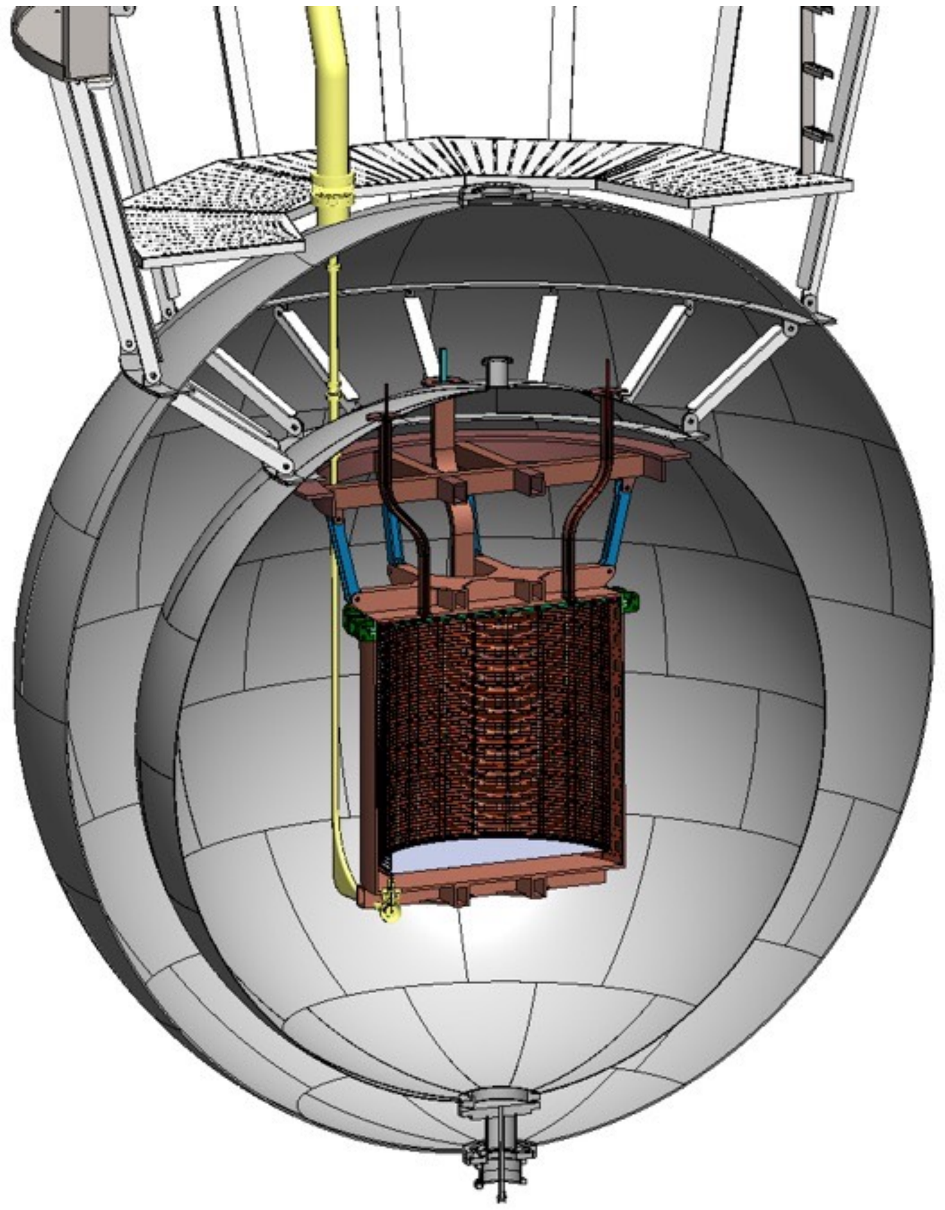


Schechter + Valle 1982

✦ Double beta decay is possible in even-even nuclei for which single beta decay is forbidden (pairing binding energy)

The EXO program (2001-): R&D -> EXO-200 -> nEXO

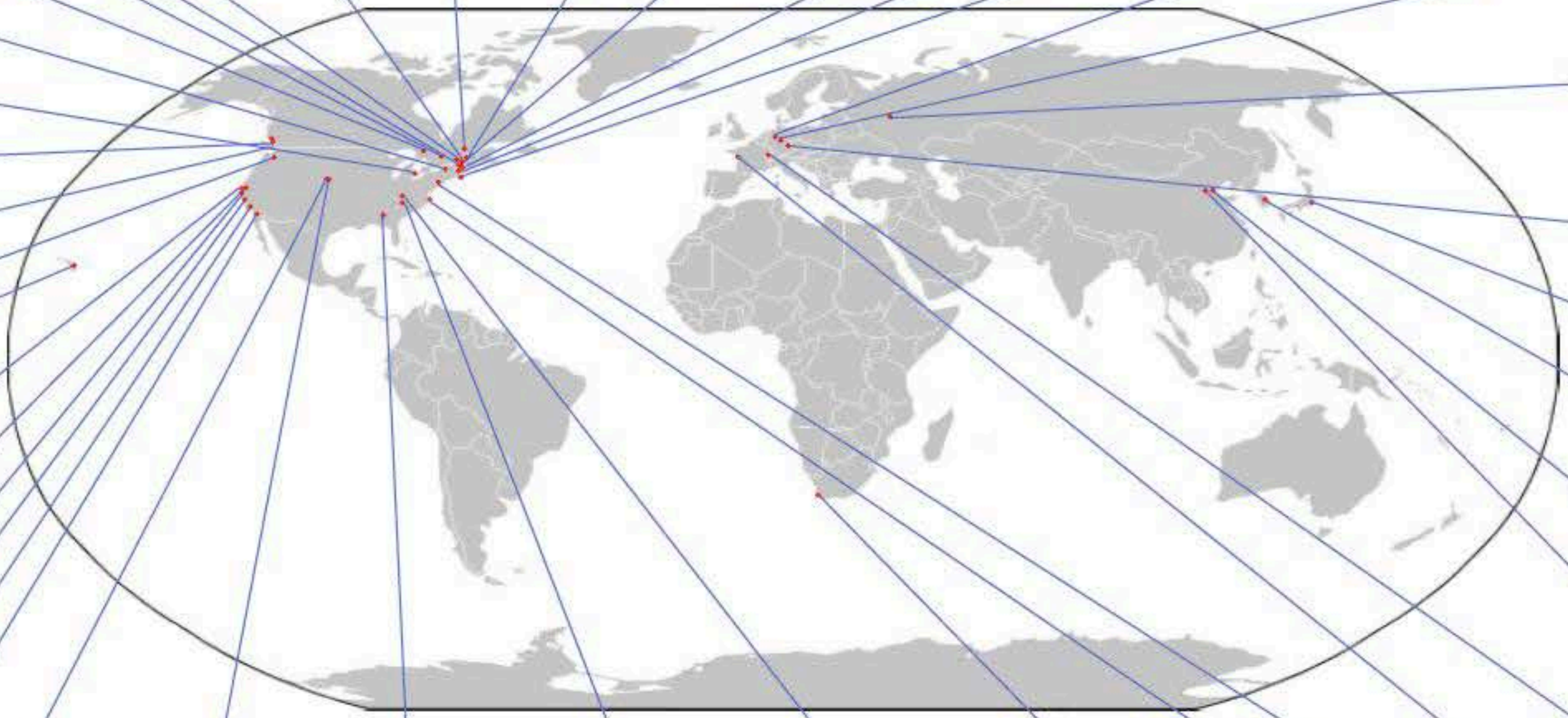




- Liquid xenon TPC is a powerful detector technology to search for $0\nu\beta\beta$ decay
- EXO-200 ran 2011-2018 at WIPP
  - 200 kg enriched LXe (80% ^{136}Xe) TPC
  - Light readout with **VUV-sensitive LAAPDs**
  - Ultra-low background design with HFE heat transfer fluid
  - First measurement of ^{136}Xe $2\nu\beta\beta$ decay
  - Best bounds on ^{136}Xe $0\nu\beta\beta$ decay in 2012 and one of the strongest to date ($T_{1/2} > 3.5 \times 10^{25}$ y)
- nEXO designed to explore $T_{1/2}$ beyond 10^{28} years
  - 5000 kg enriched LXe (90% ^{136}Xe) TPC + light readout
  - Rooted in EXO-200 design, some novel solutions
  - Light readout with **VUV-sensitive SiPMs**
  - Mature conceptual design —> SNOLAB

nEXO

A world wide effort involving 10 countries, 40 institutions, ~200 collaborators



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SNOLAB
Queen's University
Université de Sherbrooke
McGill
University of Massachusetts Amherst
Yale University
Montclair State University
Brookhaven National Laboratory
Carleton University
Laurentian University Université Laurentienne
Rensselaer
University of Windsor
The University of British Columbia
TRIUMF
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University of Hawai'i
Skyline College Achieve.
Lawrence Livermore National Laboratory
SLAC National Accelerator Laboratory
Stanford University
Caltech
UC San Diego
Colorado School of Mines
Colorado State University
The University of Alabama 1831
Oak Ridge National Laboratory
University of Kentucky
University of the Western Cape
UNCW University of North Carolina Wilmington
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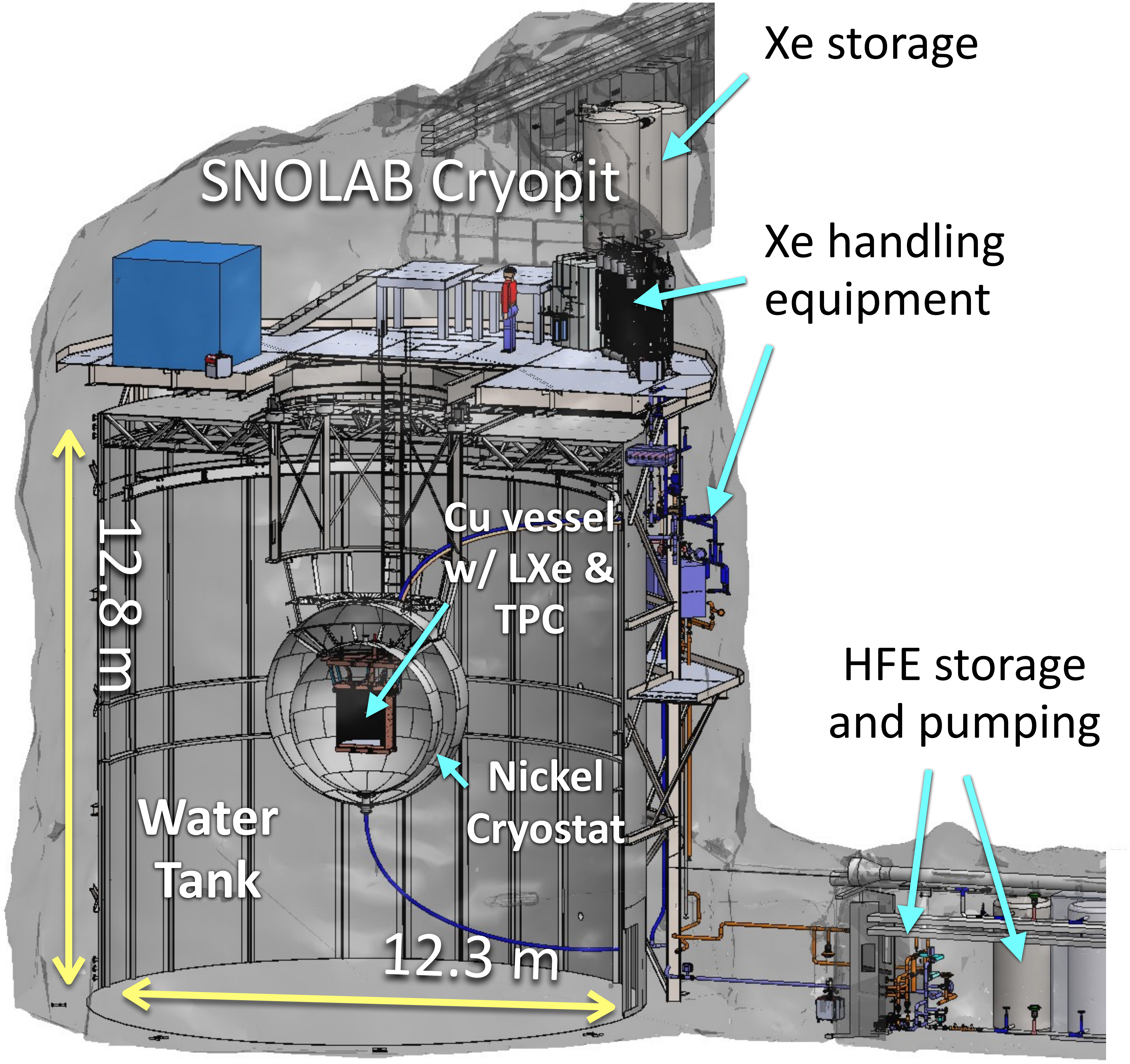
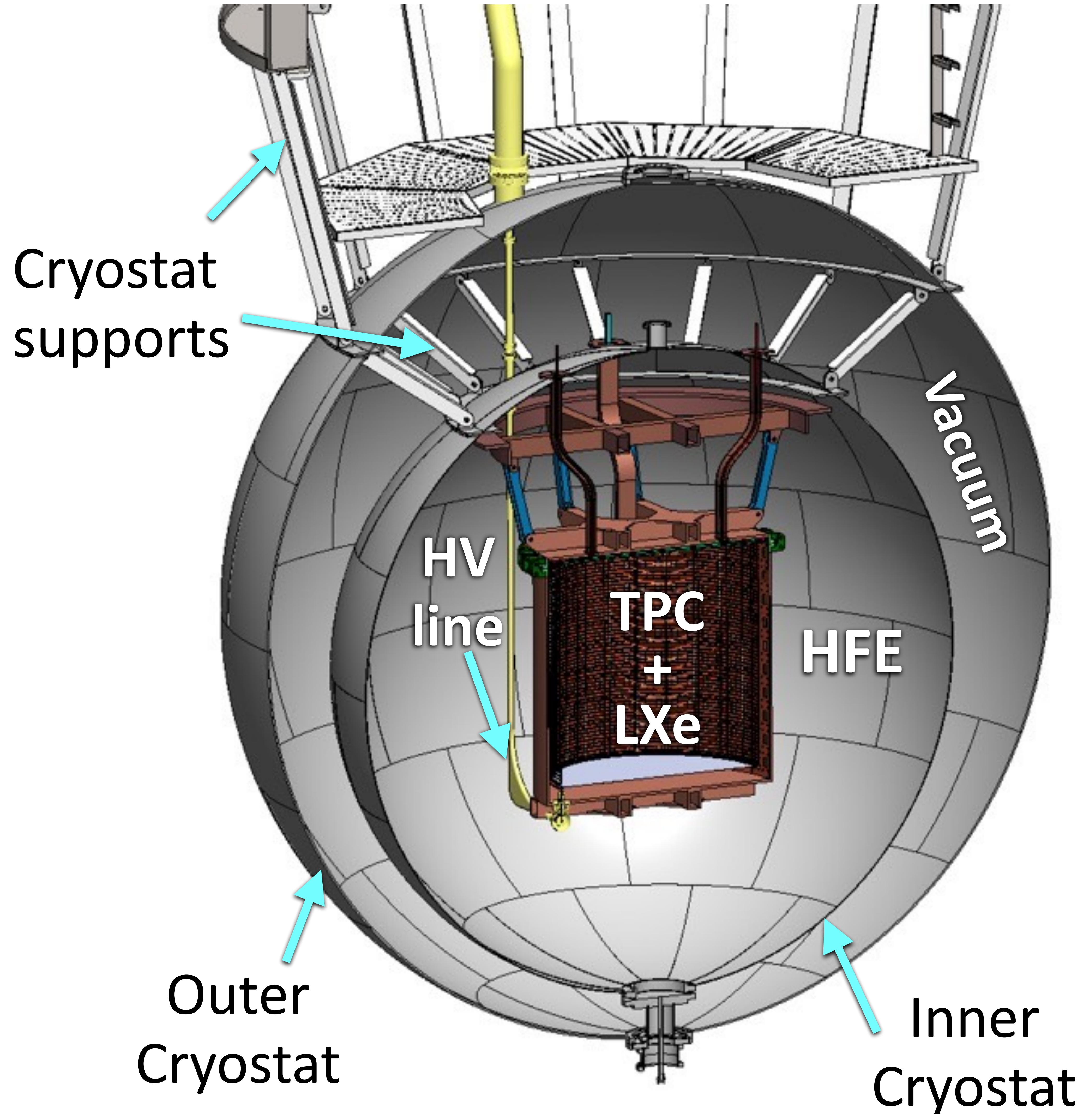
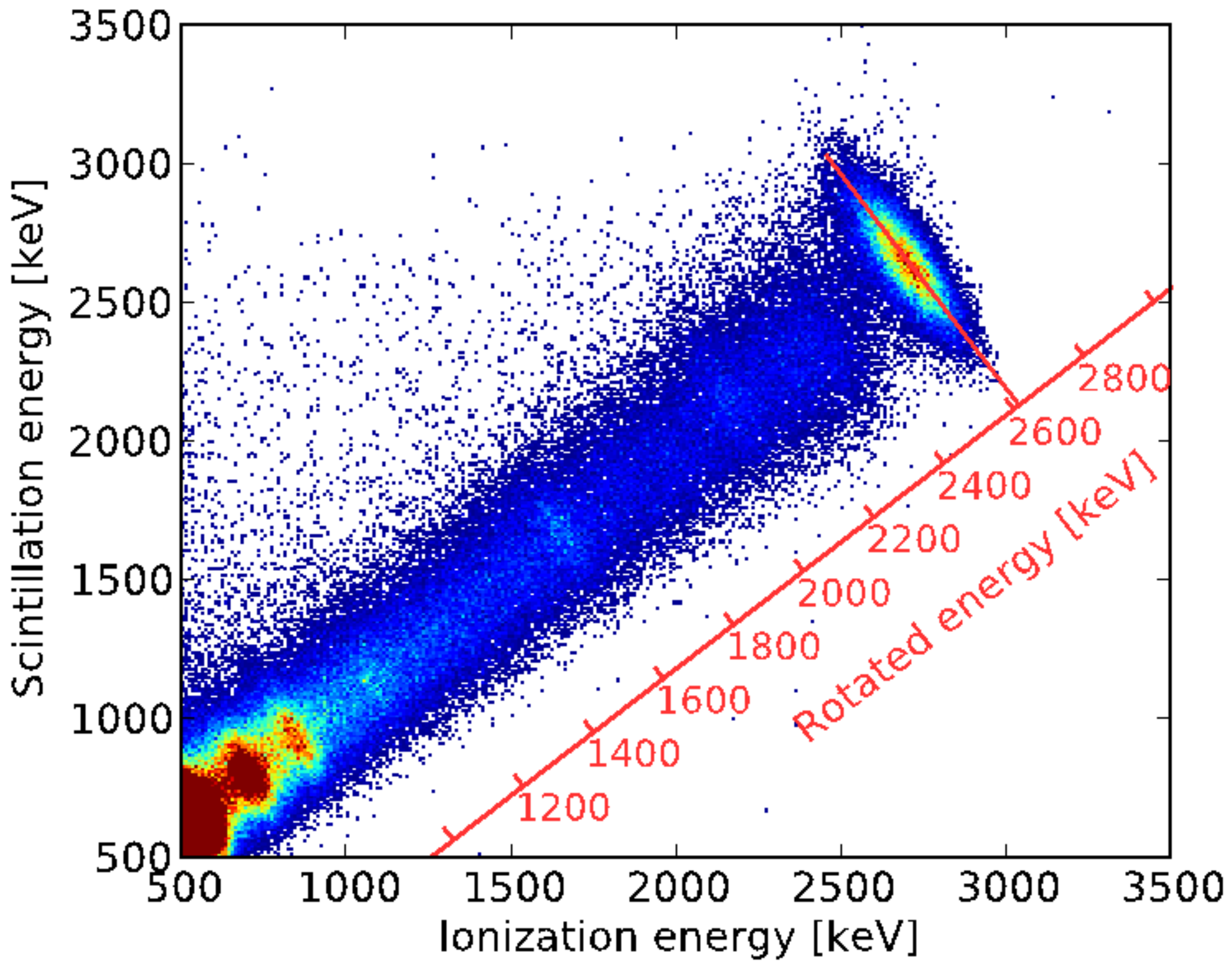
WWU Münster

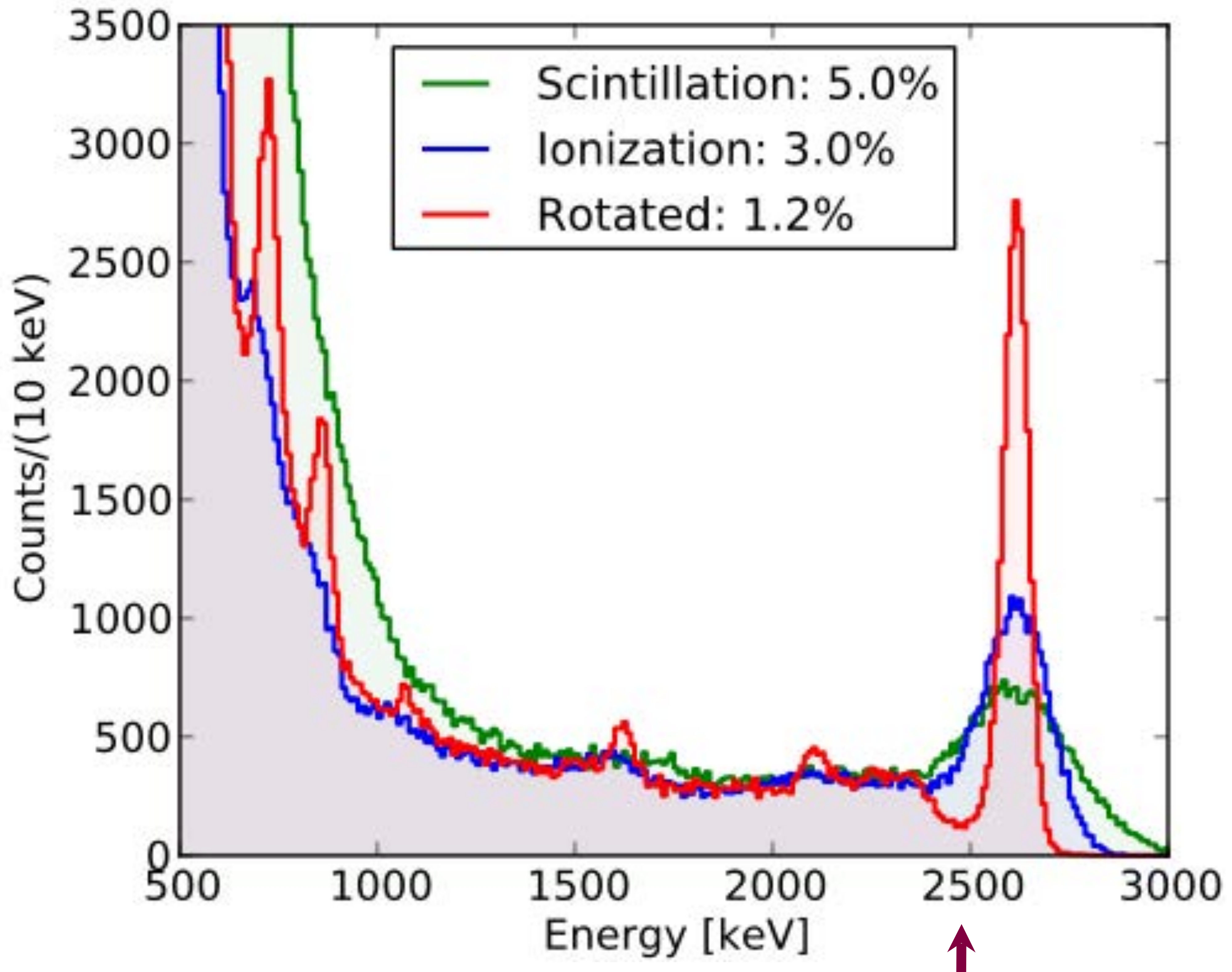
The nEXO detector at SNOLAB





Light + Charge for optimal energy resolution in LXe



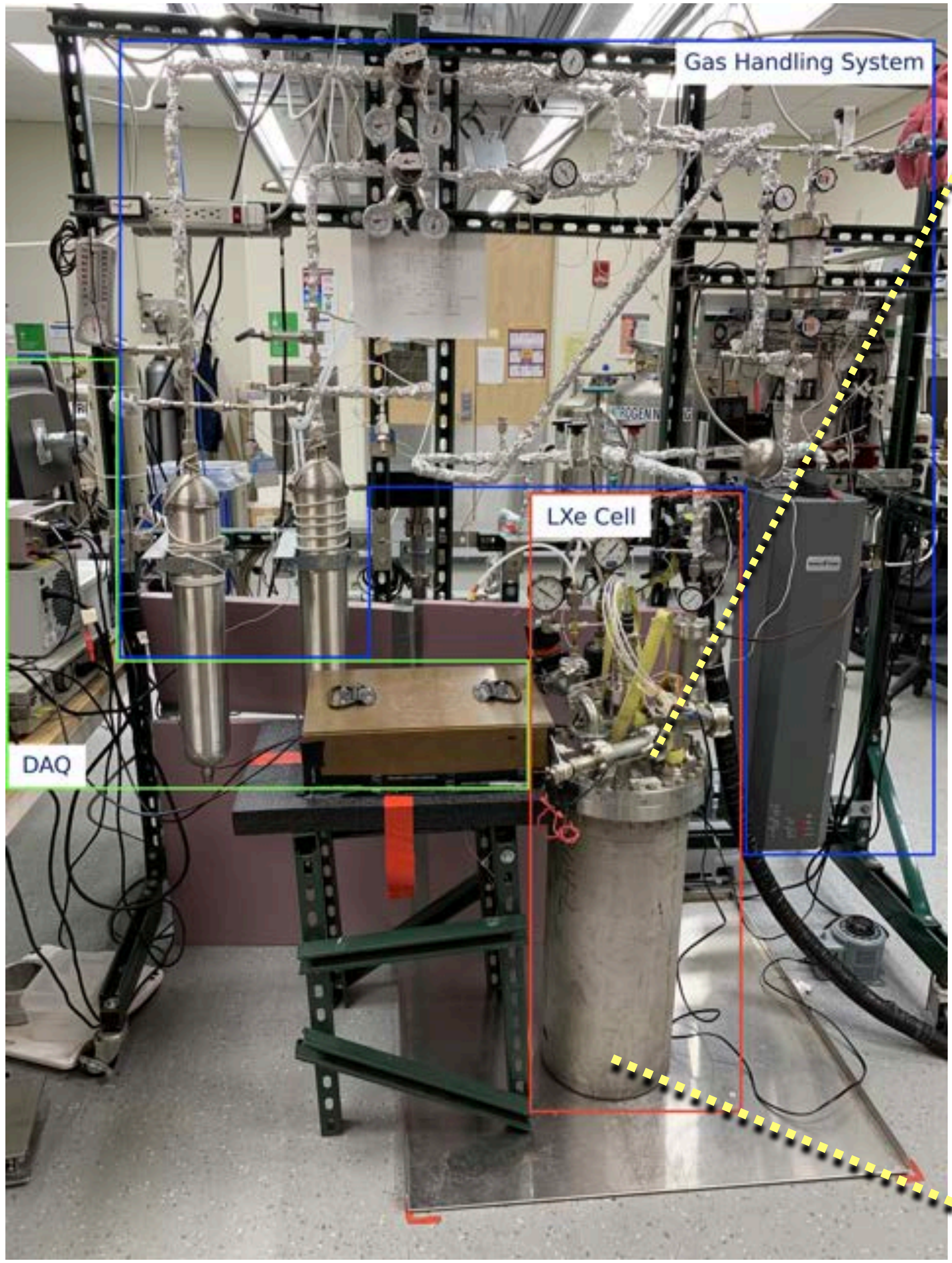


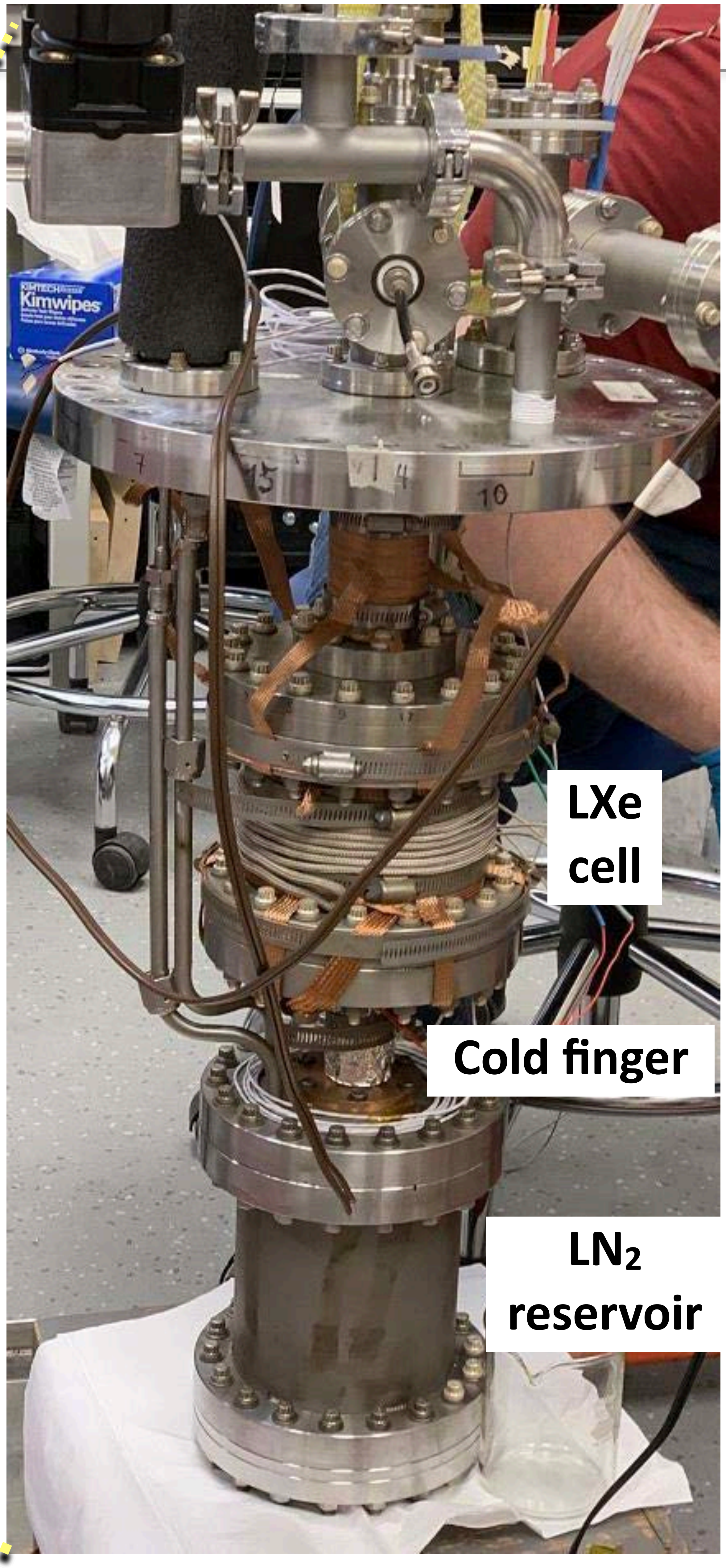
^{136}Xe

$Q_{\beta\beta}$

Efficient light collection is important !

The UMass optical LXe system

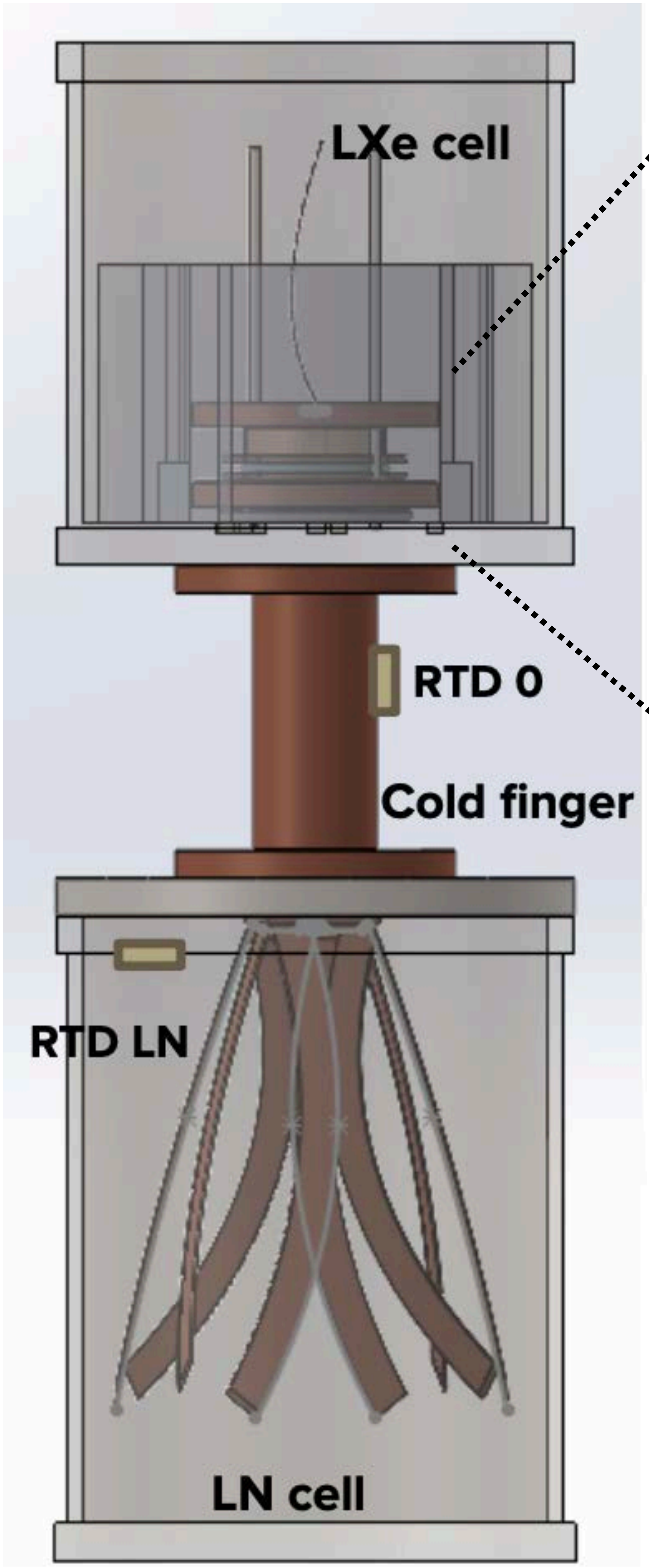


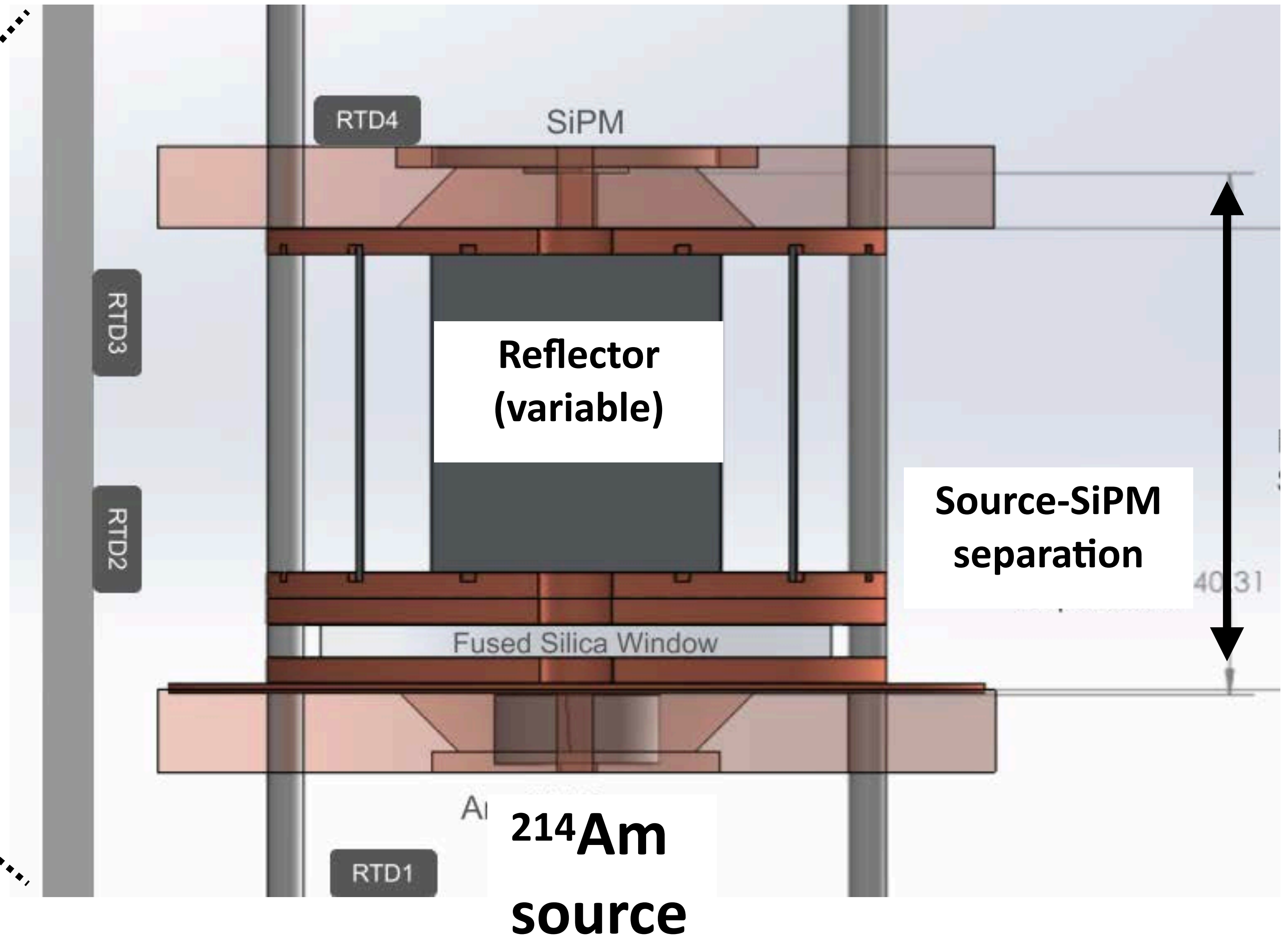


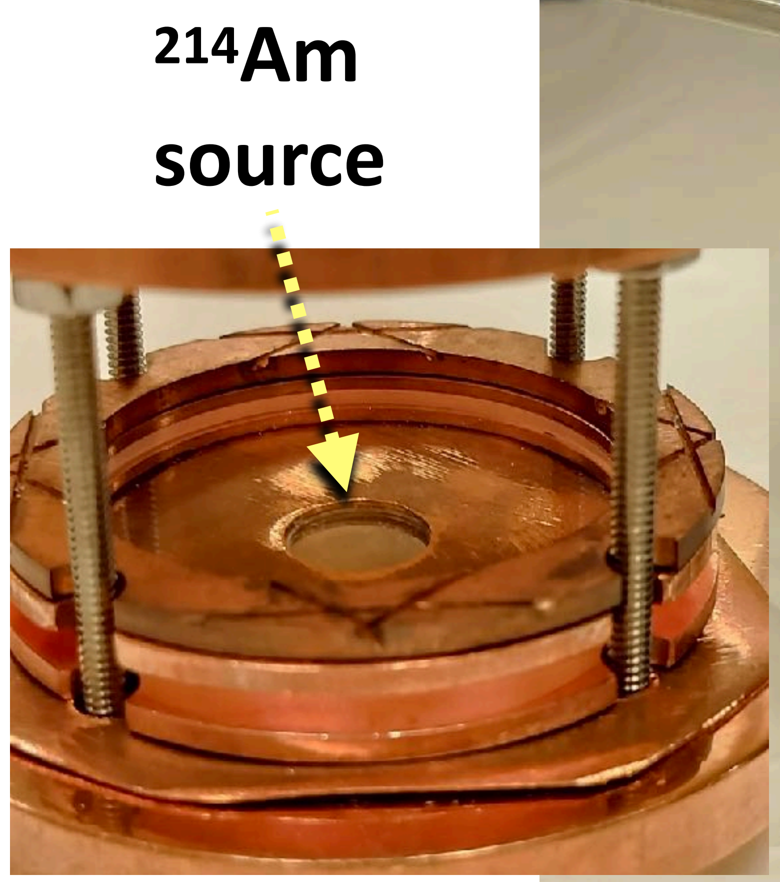
System designed to study VUV optics at material interfaces and testing of SiPMs

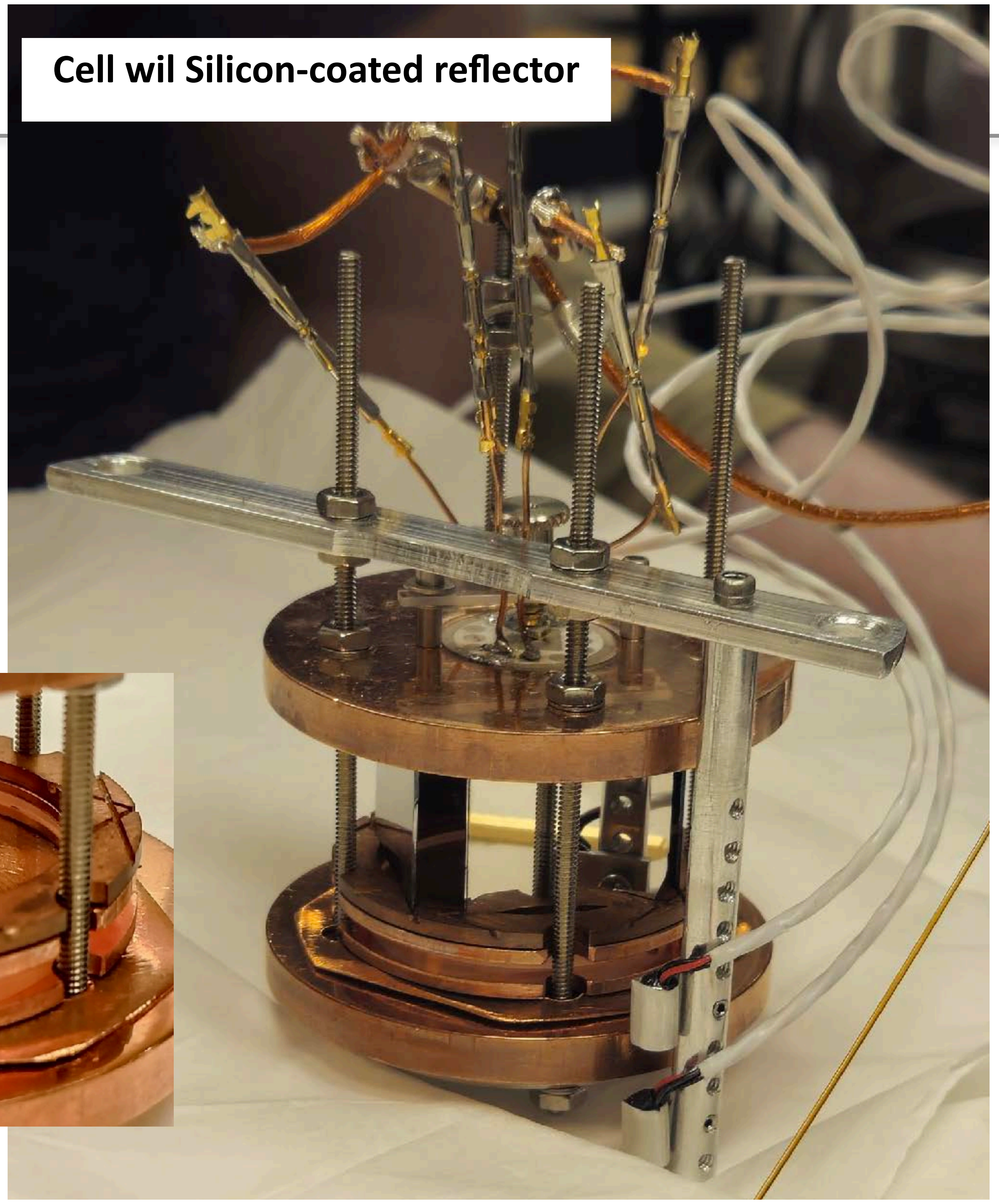
- Cell volume: 1.5 L
- LN_2 + cold finger cryogenics
- Typical amount of liquid xenon (LXe): 1.5 kg
- No xenon recirculation
- One SiPM readout with:
  - Cremat CR-Z-SiPM Q-sensitive pre-amplifier
  - Cremat CR-S-1μs shaping amplifier
  - Z-TEC ZT4421 digitizer
- LED illumination (via fiber)

The UMass optical LXe system





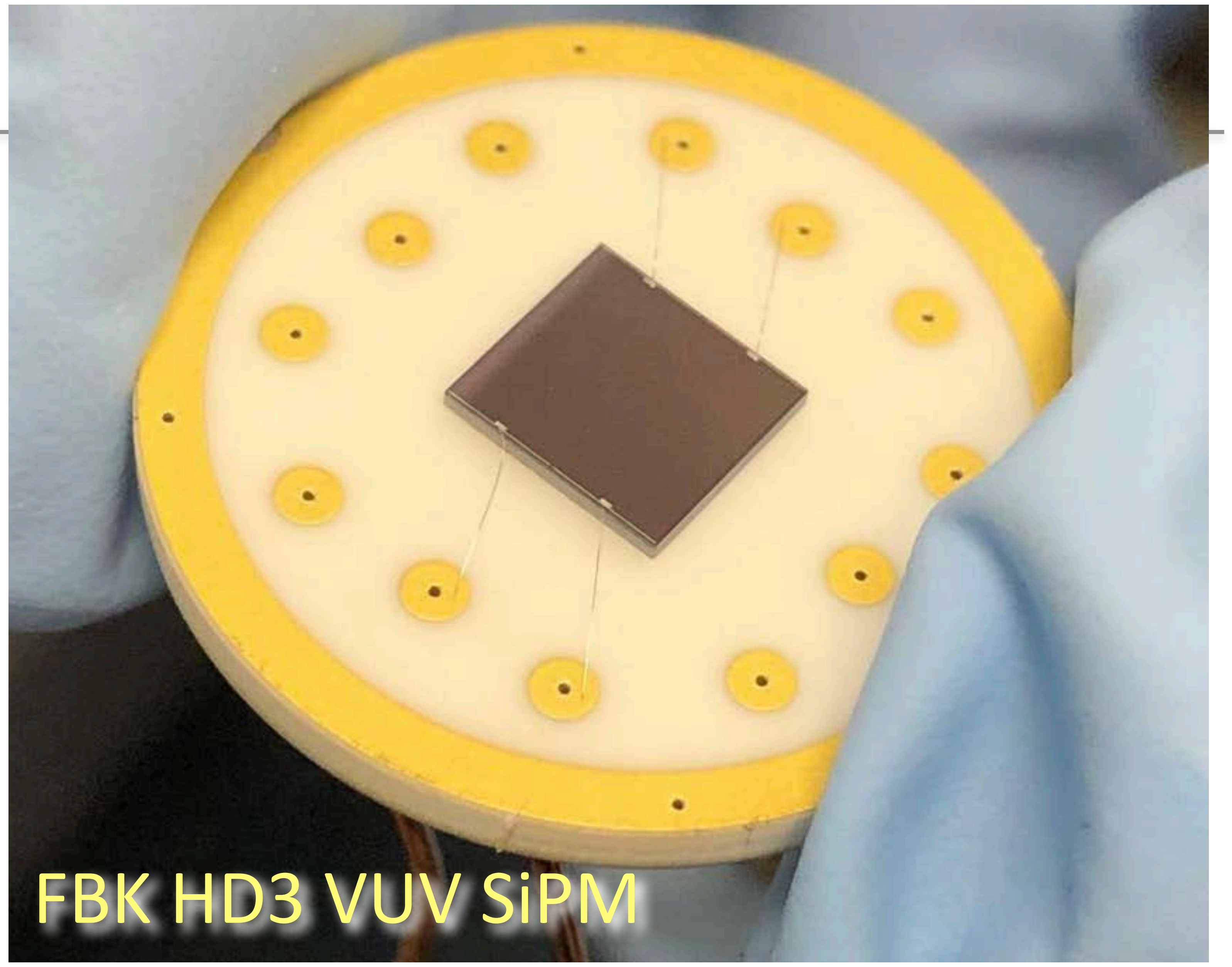


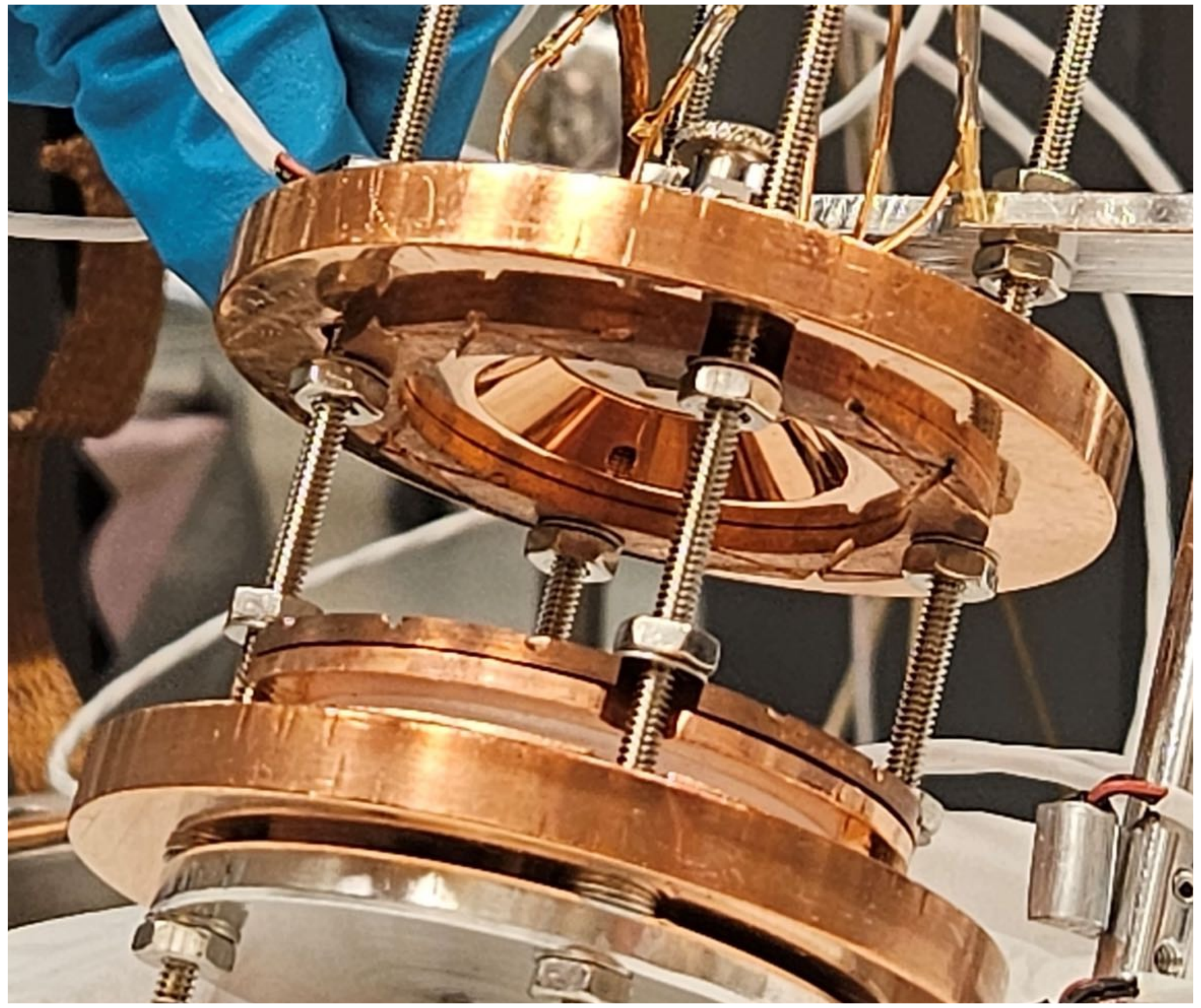


- 3.1 kBq ^{241}Am alpha source, 20-40 mm away (variable distance)
  - Mean alpha energy of 5.49 MeV
  - Used to produce point-like xenon scintillation
- RTD sensors inside cell report temperature

Sillicon Photomultipliers (SiPMs)

- Pixelated photon counting devices
    - array of 100-10,000 Single Photon Avalanche Diodes (SPADs)
- Electrons produced by photoelectric effect from incident photons are accelerated by electric field
    - Above a **Breakdown Voltage**, the electric field at the junction is large enough to produce electron gain via impact ionization (avalanche —> SPADs operated in Geiger mode)
    - **Over-voltage (OV)**: Bias applied above the breakdown voltage
    - **Gain**: Charge carriers produced per initial photoelectron (10^5-10^7)
    - **Correlated avalanches (CA)**: SPADs triggered by a primary avalanche
- The nEXO collaboration operates cryogenic, VUV-sensitive SiPMs from Hamamatsu and Fondazione Bruno Kessler (FBK)





Sillicon Photomultipliers (SiPMs)

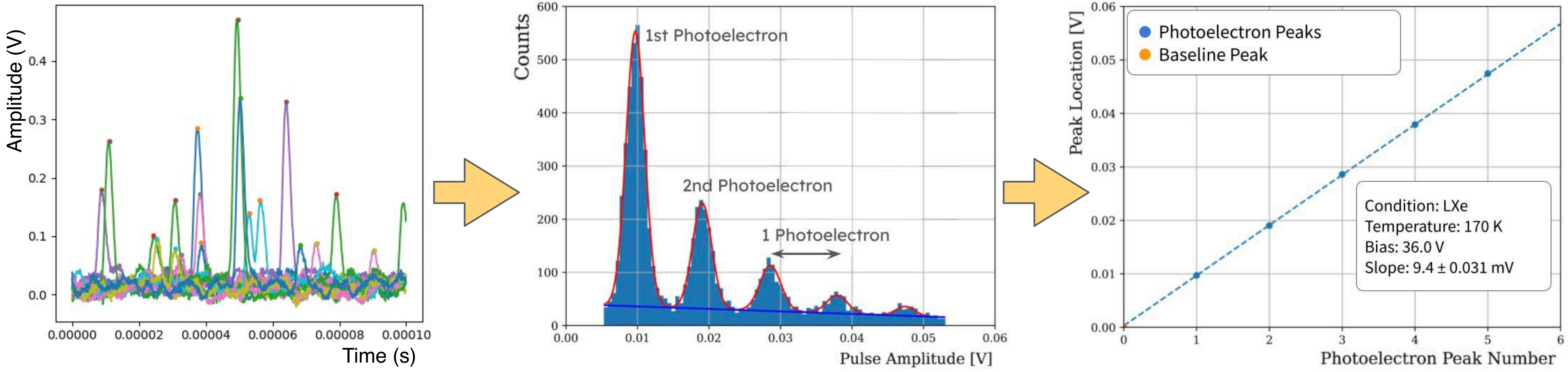
Over the past four years, our group operated a single, windowless FBK HD3 VUV SiPM (SN: VUVHD LF LOW-AP W13)

The LXe cell was repeatedly:

- Exposed to air
- Opened to reconfigure its layout
- Filled with LXe
- Cooled down under vacuum and gas (nitrogen, xenon)
- Baked out

November 2021	SiPM installed, first IV curves performed
March – November 2022	Characterization in Gaseous Nitrogen (GN)
March – August 2023	7 Runs in Liquid Xenon (LXe)
June 2024	Bakeout Incident
July 2024	SiPM readout wire redesigned
March – October 2024	10 Runs in Liquid Xenon (LXe)
May – September 2025	Characterization in Gaseous Nitrogen (GN)

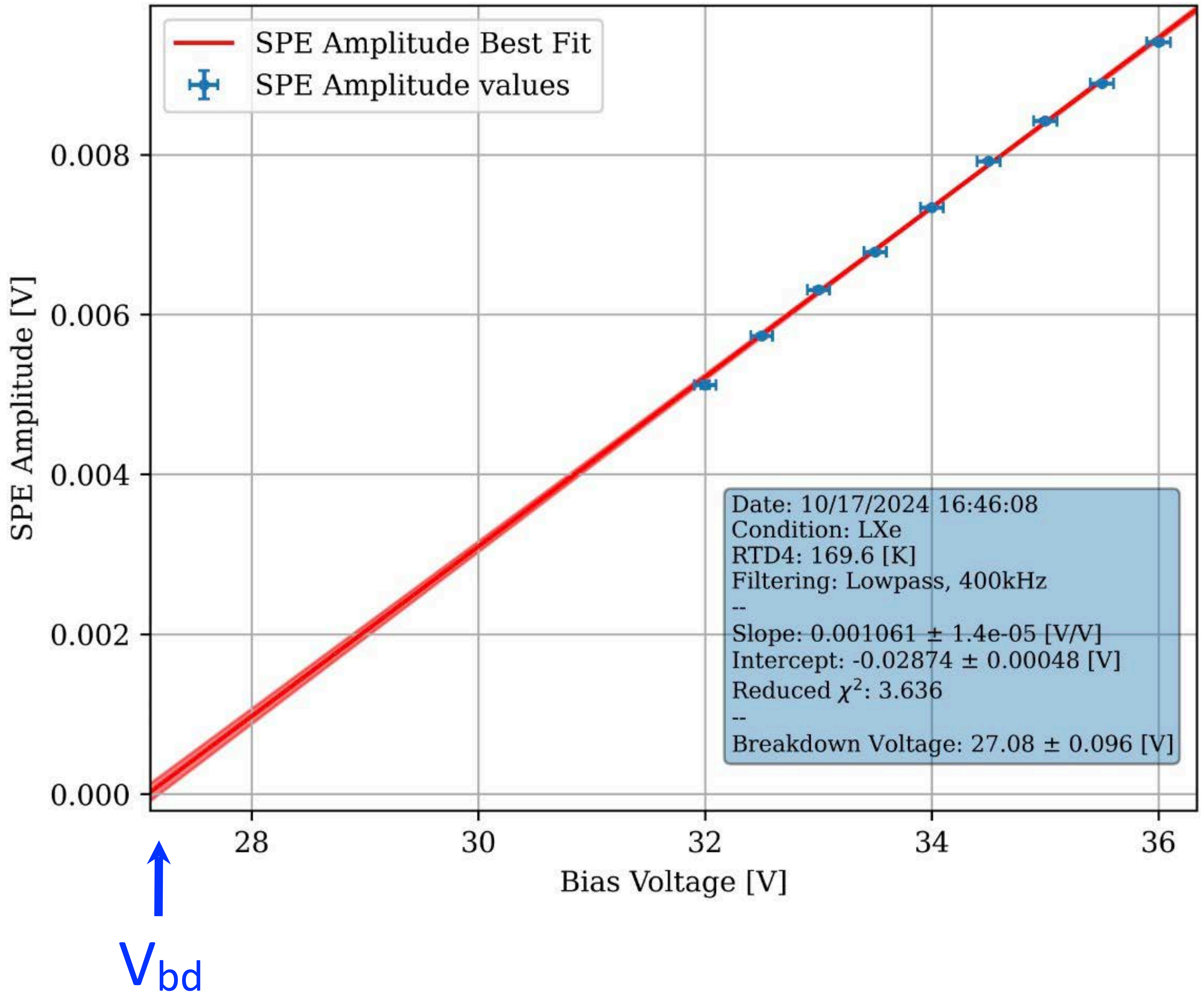
Single Photo Electron (SPE): Gain



Single PhotoElectron (SPE) Amplitude: Voltage of single photoelectron signal (A_{SPE})

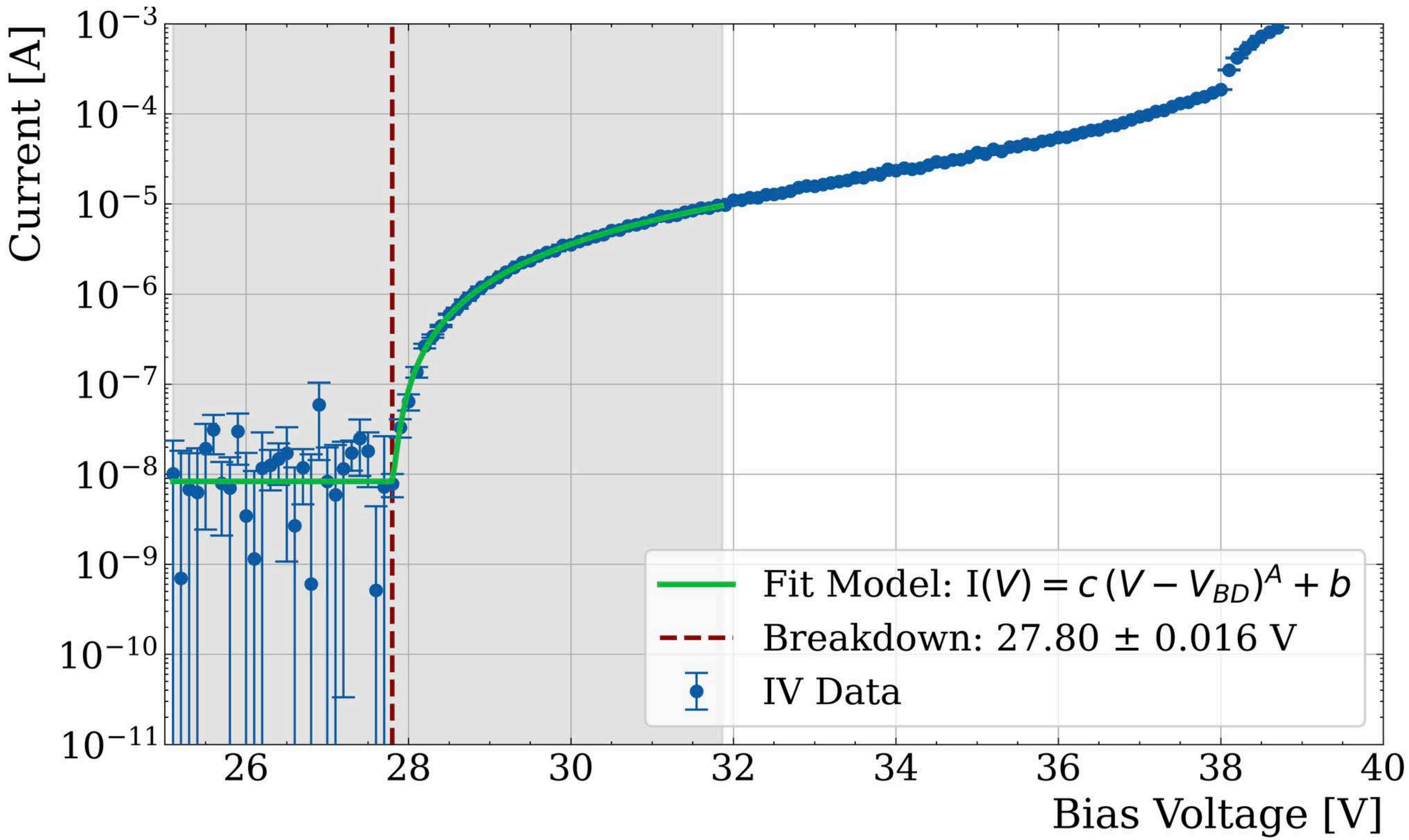
- Calculated by finding the average distance between photoelectron peaks
- Convert SiPM signal (A_i) to number of SPAD avalanches —> quantized finger plot
- Repeat for different Over-voltages (8-10) —> Gain is the slope of A_i vs. peak number

Single Photo Electron (SPE): Breakdown Voltage (V_{bd})



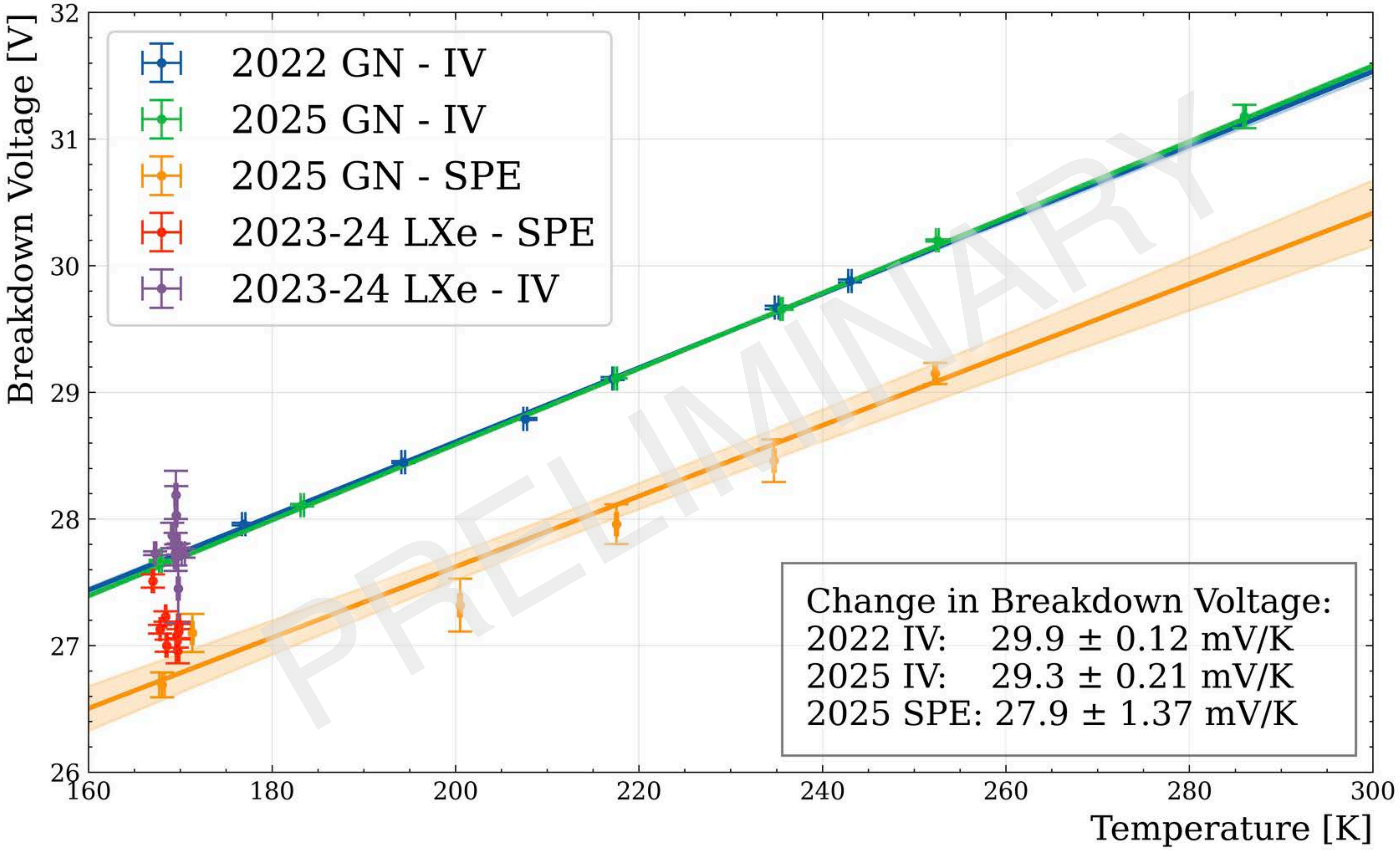
- Gain is linear with Over-voltage
- **Breakdown Voltage (V_{bd}):**
  bias voltage at which Gain = 0

I-V Curves



Current [A]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
26
28
30
32
34
36
38
40
Bias Voltage [V]
Fit Model: $I(V) = c\,(V - V_{BD})^A + b$
Breakdown: 27.80 ± 0.016 V
IV Data

Stability of the Breakdown Voltage

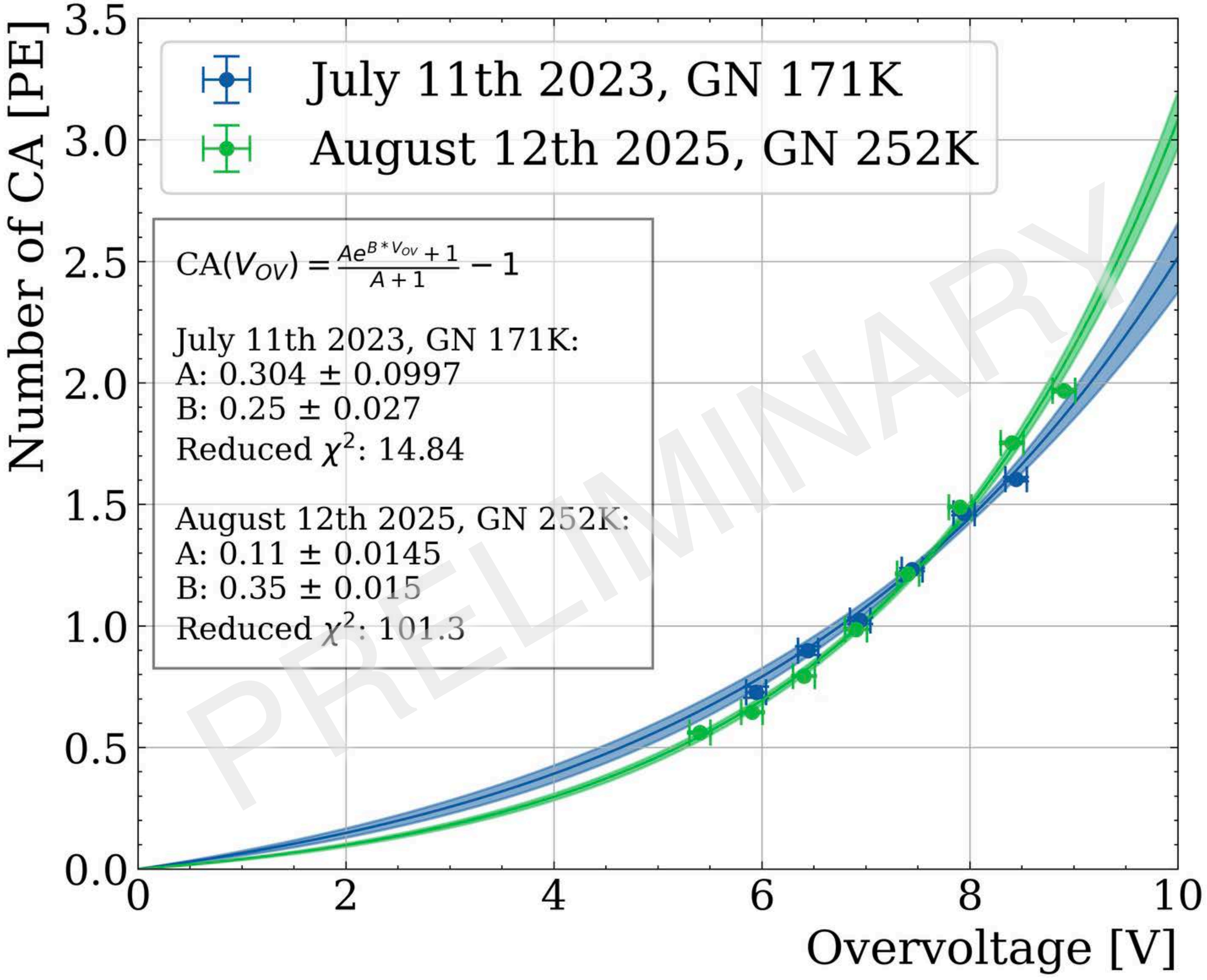


- Breakdown measurement in gaseous nitrogen and liquid xenon.
  - Collected from SPE and IV data in 2022 and 2025 at temperatures of 170K-290K.
- **IV Breakdown voltages are consistent over a 3 year span.**

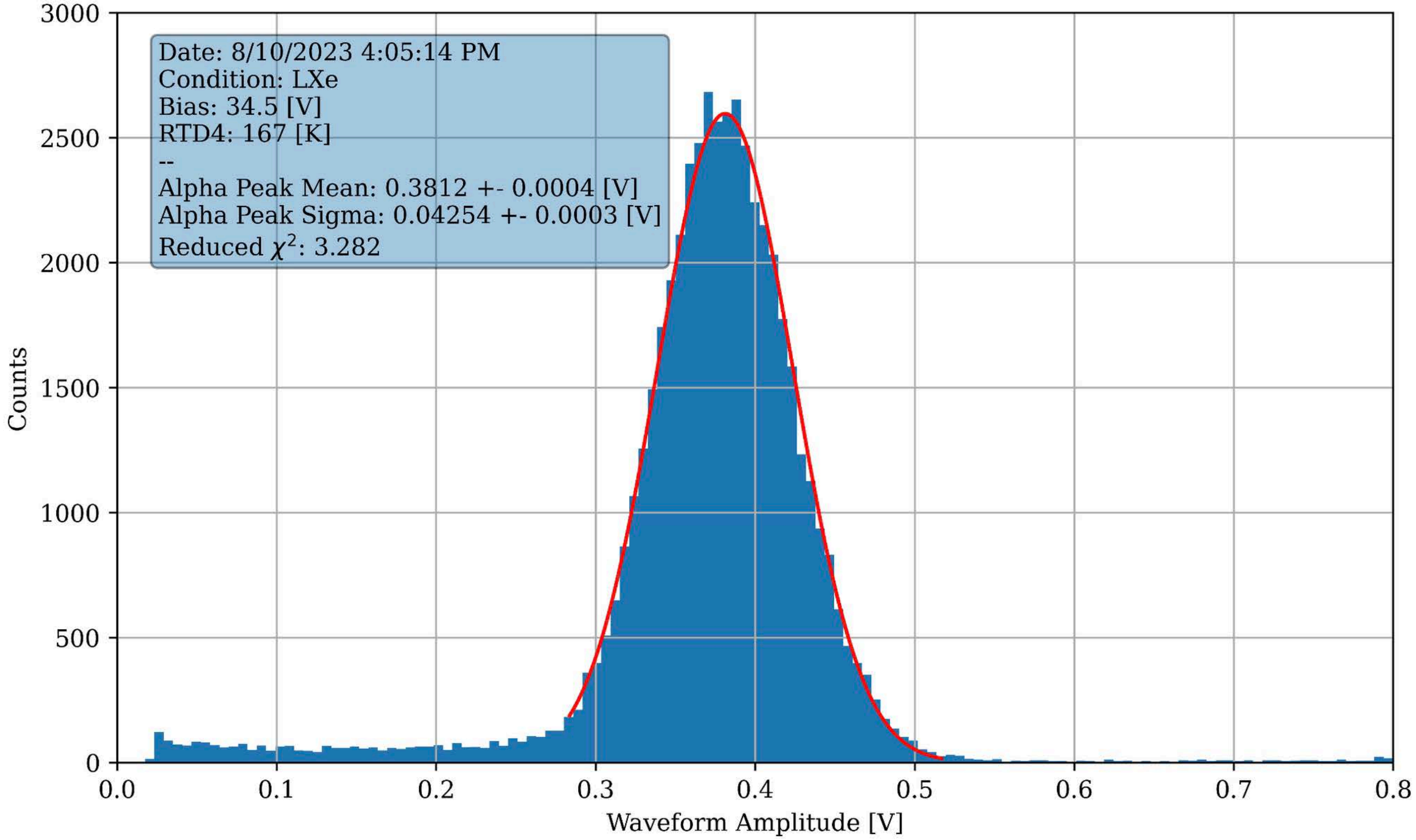
Stability of the Correlated Avalanche Rate

- **Correlated Avalanches (CA)**: PulseS caused by photons generated internally to the SiPM from a primary electron avalanche.
  - Total number of avalanches overestimates incident photons (>1 /photon)
  - Need to use CA to convert number of avalanches to detected photons.
- Calculated by finding the average amplitude of all the pulse peaks used in SPE analysis.
- Property of the internal structure of the SiPM, should not change with temperature or over time.
- **The number of correlated avalanche per primary avalanche calculated from SPE data is consistent over a two-year span.**

$$\mathrm{CA} = \frac{1}{N}\sum_{i=1}^{N}\frac{A_i}{A_{SPE}} - 1$$



Alpha Pulses as standard candles



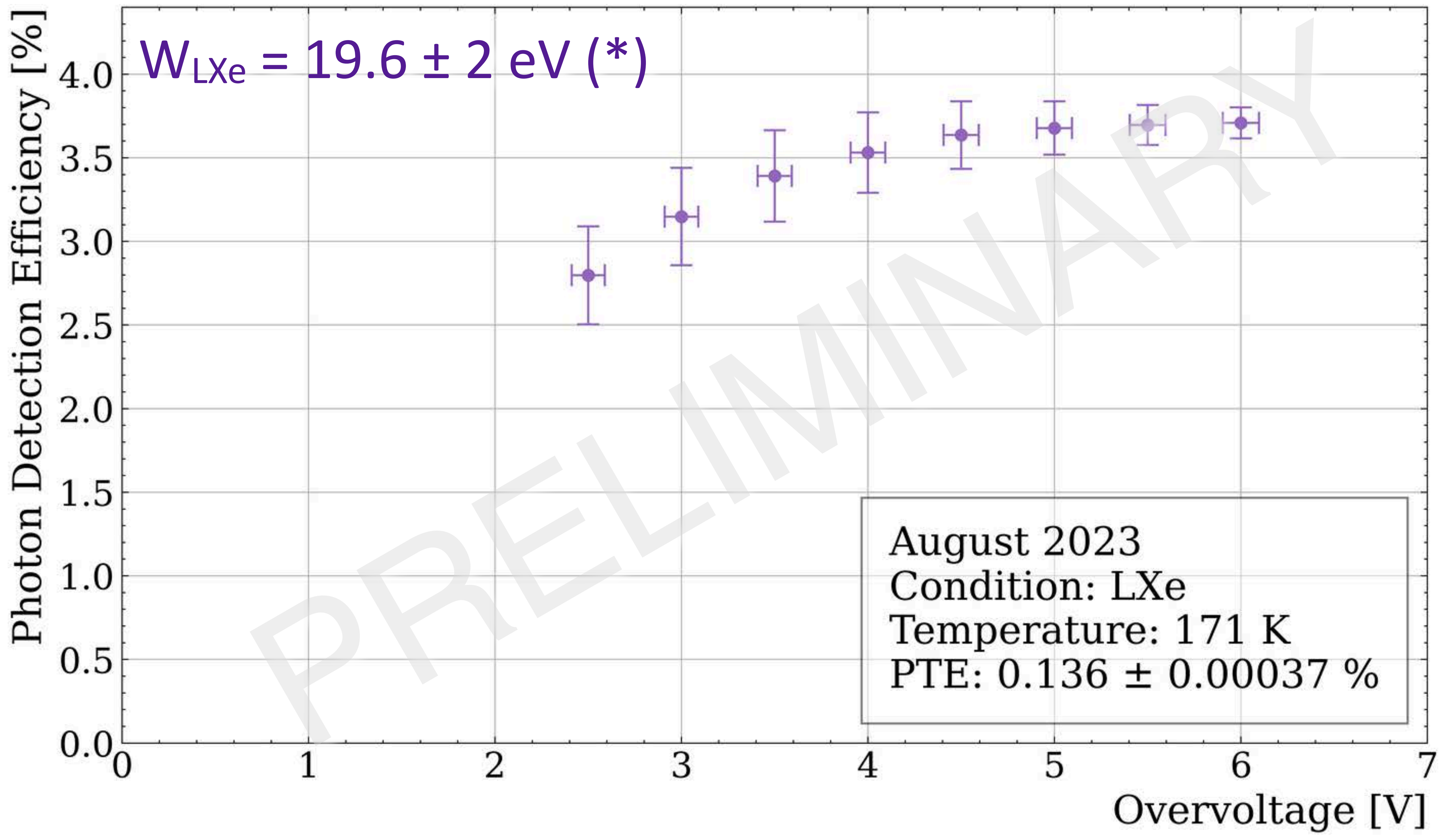
- We perform optical measurements using the bright α pulses
- For every OV, amplitude and width of the α pulse are converted into the number of SPAD firings
- Correcting for CA, we obtain the number of detected photons

Photon Detection Efficiency (PDE)

$$N_0 = E_\alpha / W^{\alpha}_{\mathrm{LXe}}$$

$$\mathrm{PDE}(\mathrm{V_{OV}}) = \frac{Q_{\mathrm{LXe}}/(Q_{\mathrm{SPE}}(\mathrm{CA}+1))}{N_0 \cdot \mathrm{PTE}}$$

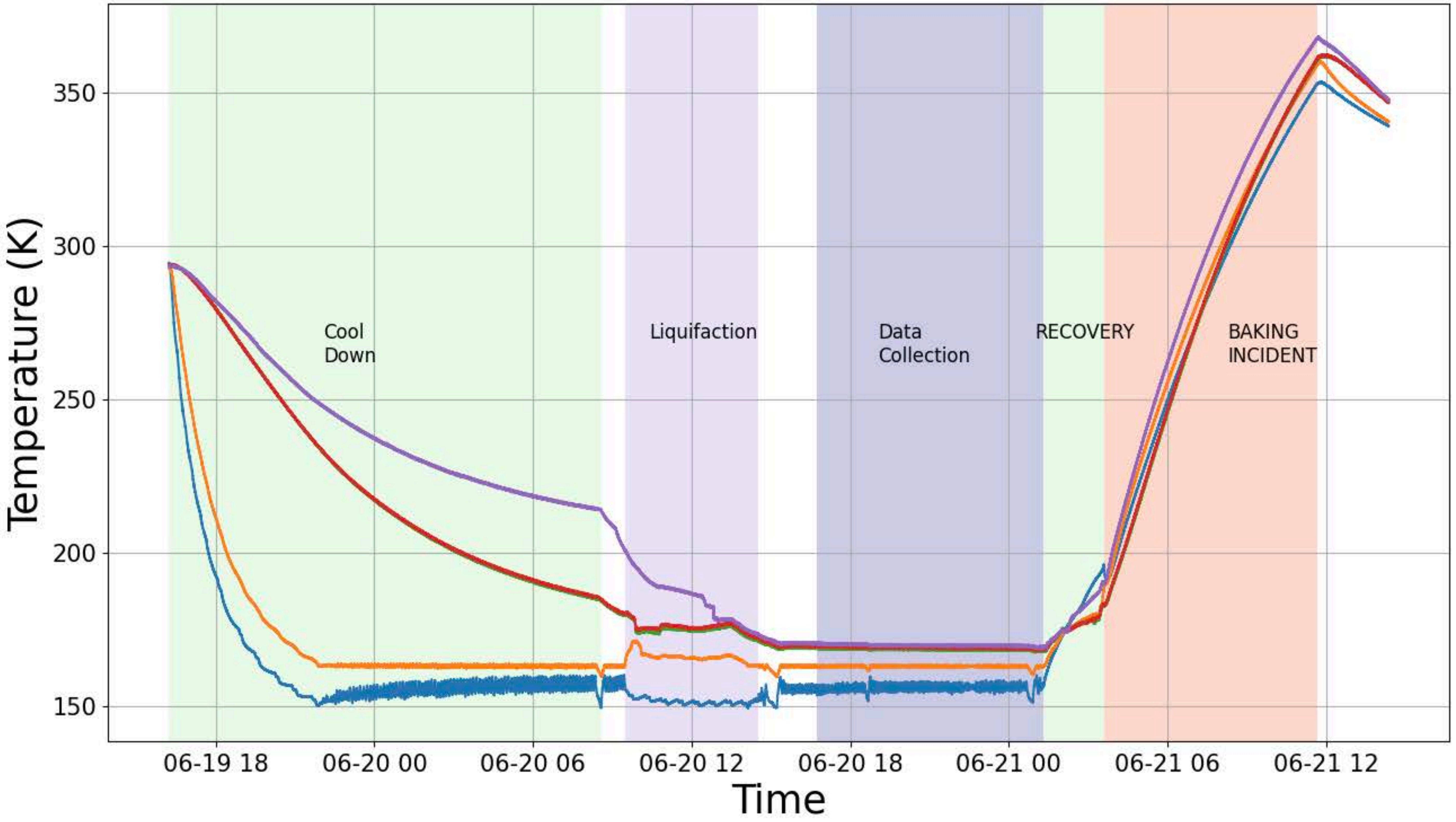
- **Percentage of incident photons which produce an electron avalanche.**
- Use SPE amplitude and number of correlated avalanches to convert the SiPM signal pulses (e.g., the alpha pulses) into number of detected photons.
- # of incident photons ~ # of photons generated by alpha source x **Photon Transmission Efficiency (PTE)**:
  - Percentage of photons which travel and terminate at the SiPM.
  - Found through the Monte Carlo ray tracing light simulation framework Chroma.



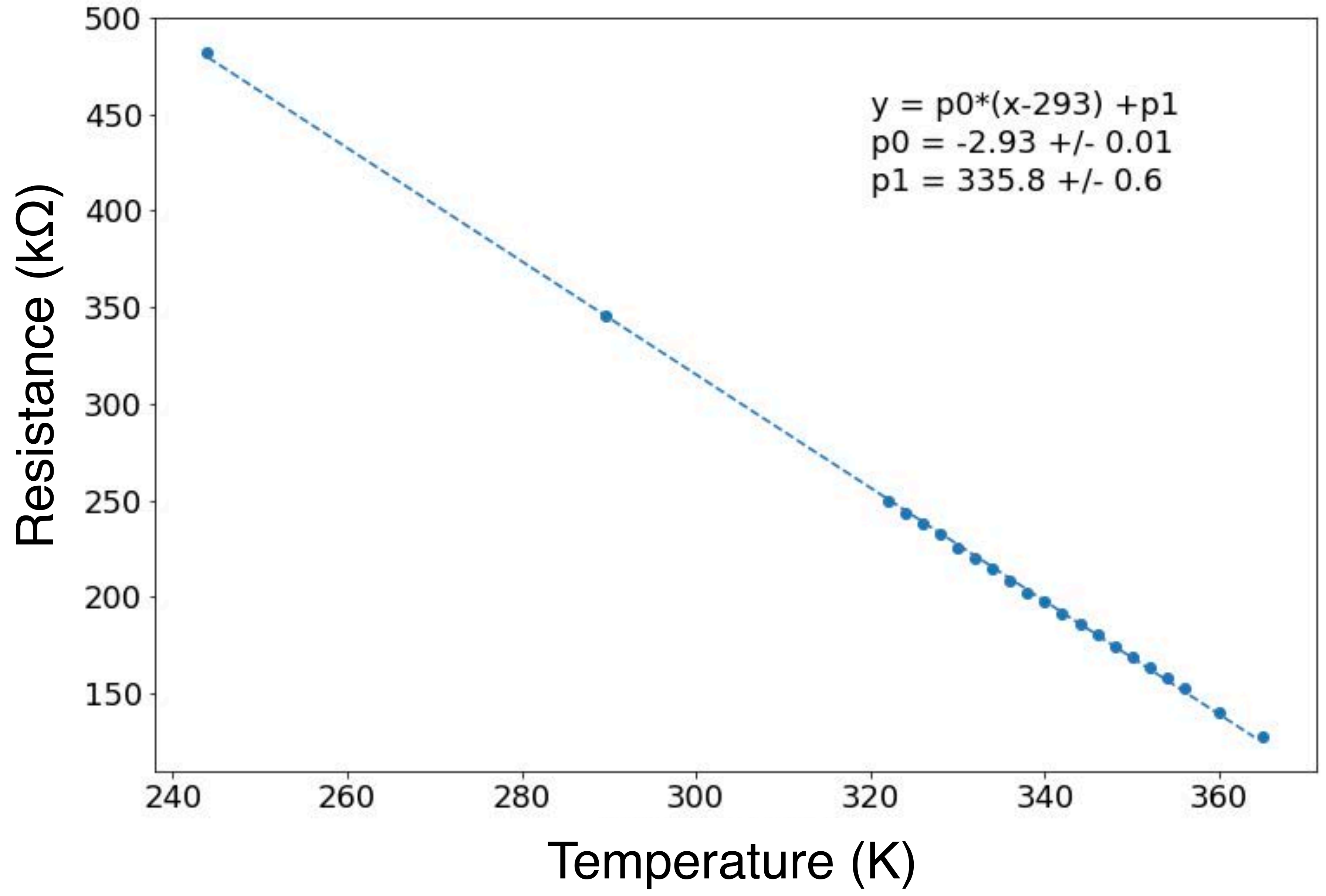
(*) A. Baldini, C. Bemporad, F. Cei, et al. IEEE Trans. Dielectrics and Electrical Insulation, 13, 547-555 (2003)

The Bakeout Incident

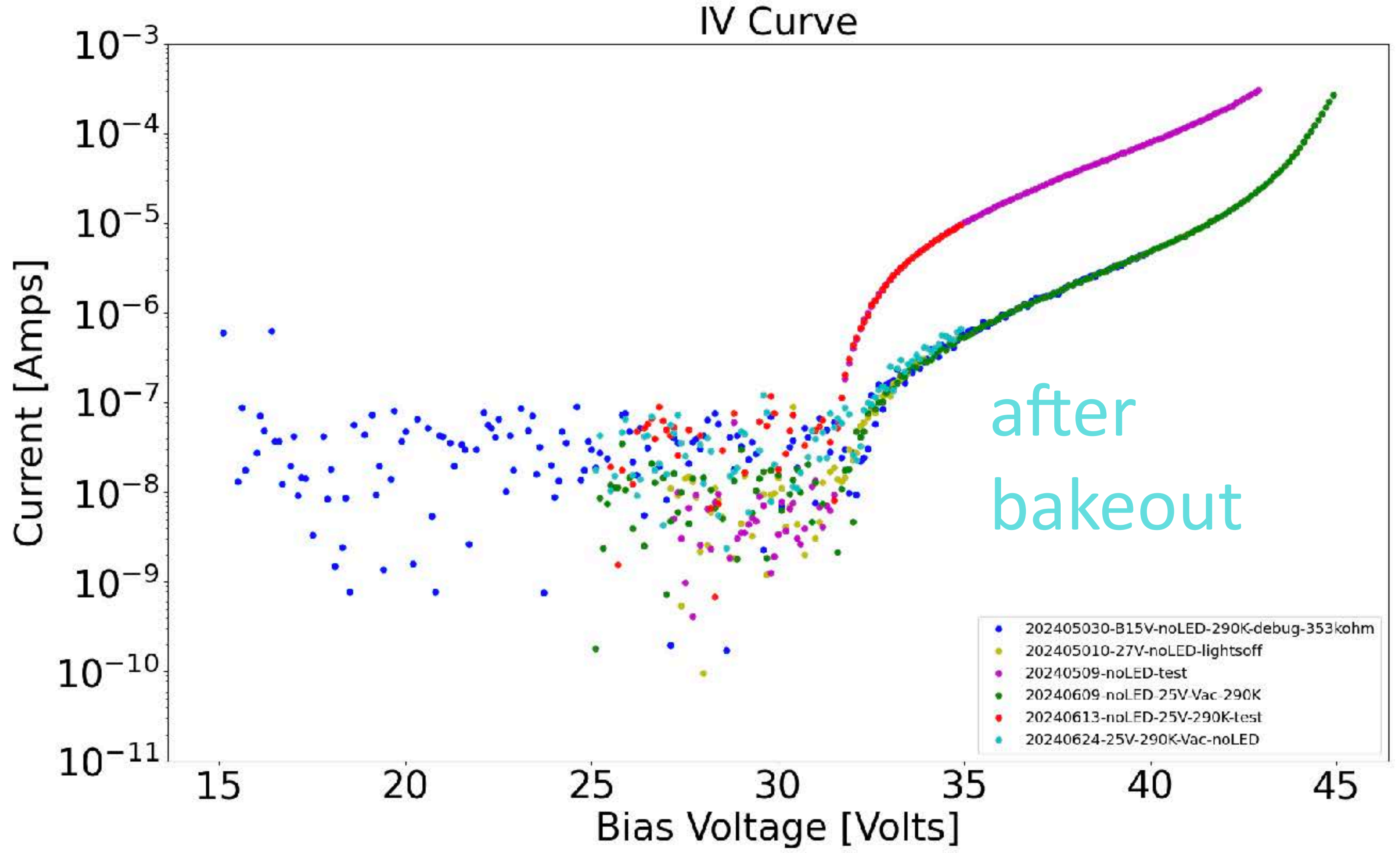
- After a liquefaction and xenon recovery, a bakeout heater was inadvertently left on
- Cell heated up to 367 K over 8 hours, then was let to cool off



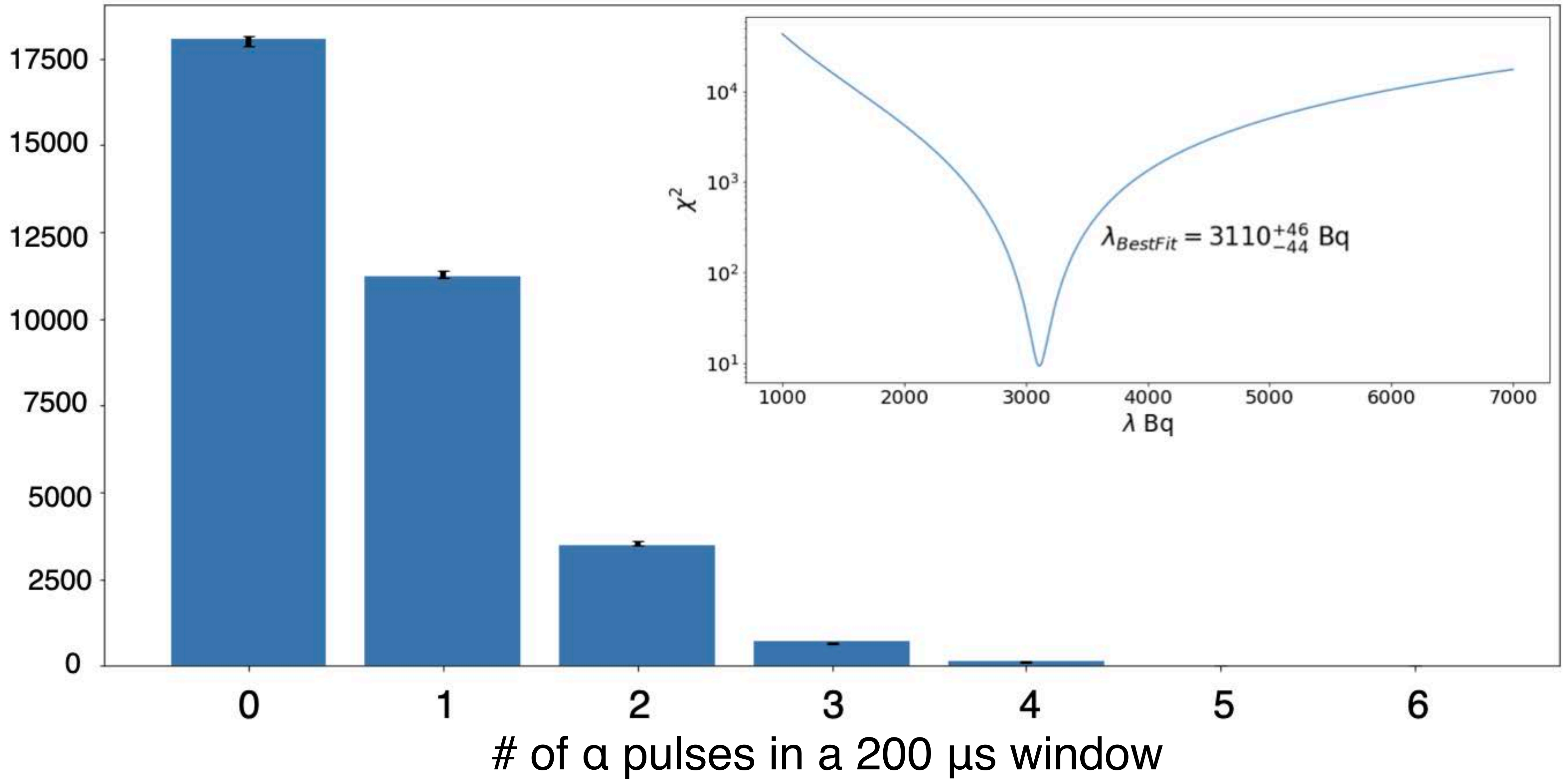
The baby is still kicking !



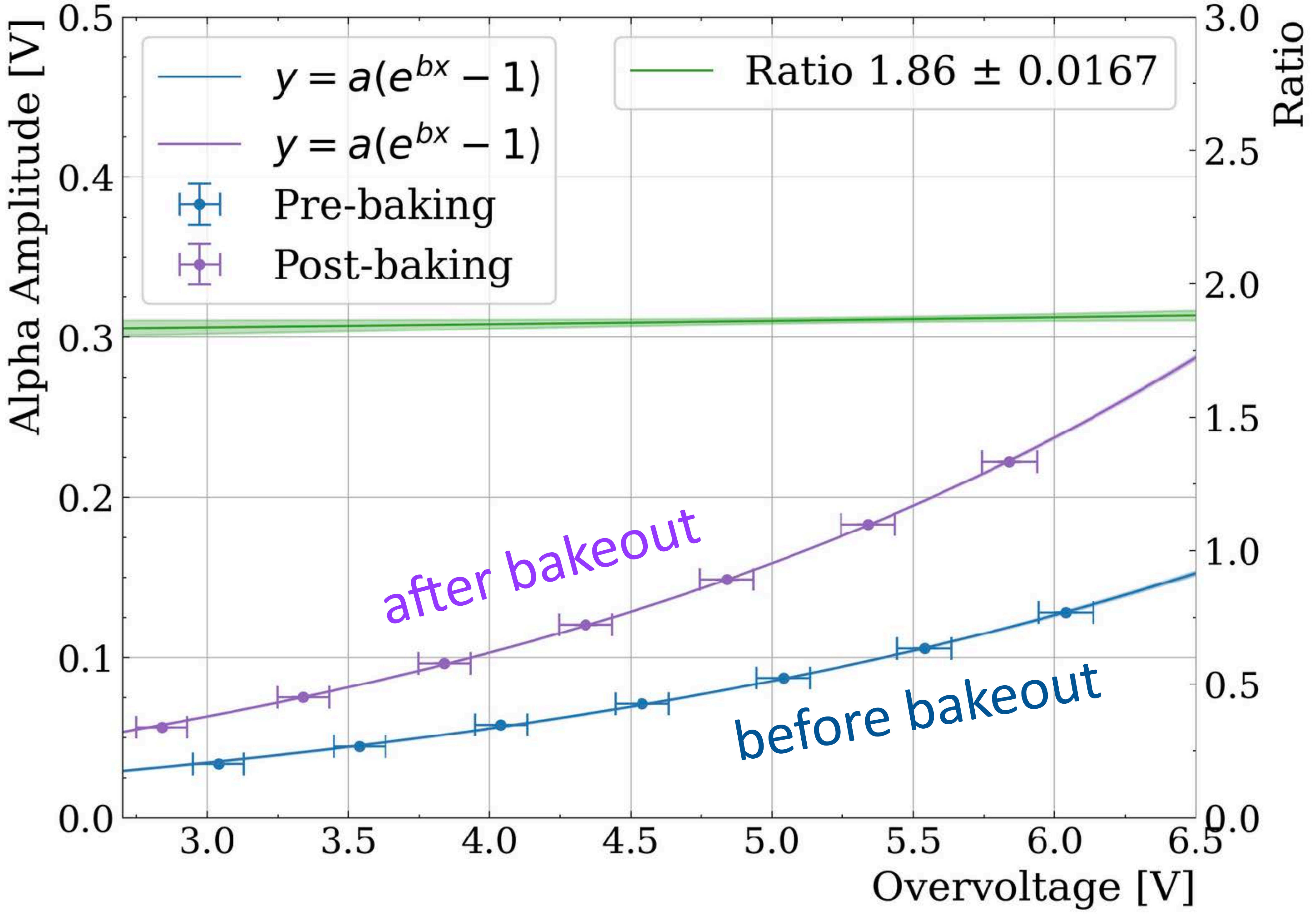
- The SiPM was electrically sound
  - Resistance changed linearly as it cooled off
  - IV curved traced older ones



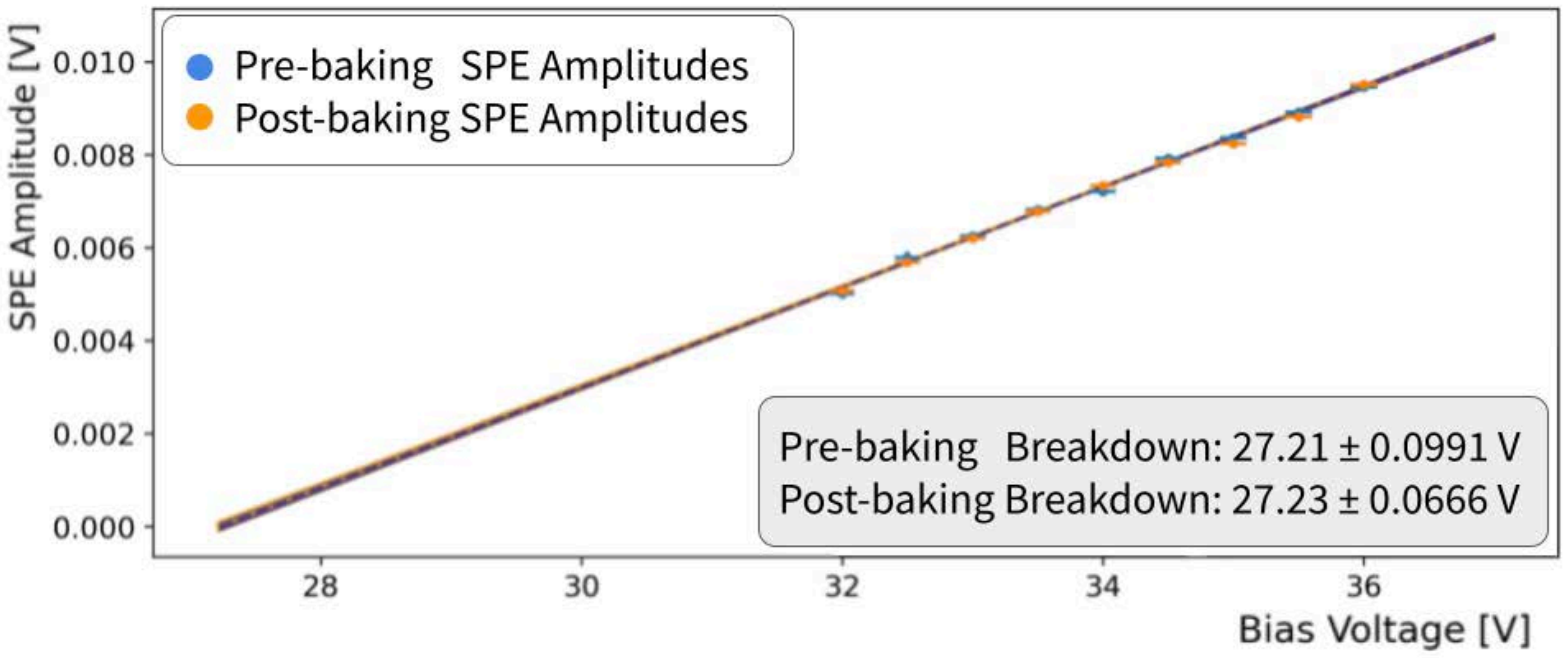
- The surface-plated ^{241}Am is still there !



Significant light yield recovery following bakeout



- A follow-up liquefaction was performed without opening the xenon cell to test the change in light yield from extensive baking, SPE data and xenon scintillation light was collected before and after baking.
- After breakout:
  - **No change in gain or breakdown voltage**.
  - **Observed a 86% increase in light collection**



Conclusions

- At UMass Amherst we study VUV (175 nm) optics for large LXe experiments
- We run a scintillation-only LXe cell, now entirely student operated
- We tested a bare FBK HD3 VUV SiPM for more than three years, subjecting it to repeated cryogenic cycles
  - Breakdown and CA proven stable
- Demonstrated that high-T baking substantially improves light yield
- Parallel work is ongoing on characterizing the reflectivity of various surfaces of interest to nEXO and other LXe TPCs