# Characterization of the Hamamatsu R12699-406-M4 2-inch Photomultipliers

## in MarmotX and XAMS

Maricke Flierman | 27-08-2024 | LIDINE 2024

Nikhef
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# Rare event searches
## Xenon time projection chambers

**WIMP DM**
Spin-dependent
Spin-independent
Light WIMPs
*and more*

**Other DM candidates**
Dark photons
Axion-like particles
*and more*

**Neutrinos**
Atmospheric & solar neutrinos
Neutrino Magnetic Moment
Super Nova (Early Warning System)
B8 CE$\nu$NS

**Weak decays**
Double Electron Capture
Spectral shape measurements
$0\nu\beta\beta$ & $2\nu\beta\beta$

| XENON10 | XENON100 | XENON1T | XENONnT (present) | DARWIN/ XLZD (future) |
|---|---|---|---|---|
| 14kg | 62kg | ~2 t | ~6 t | ~37 t |

# Rare event searches

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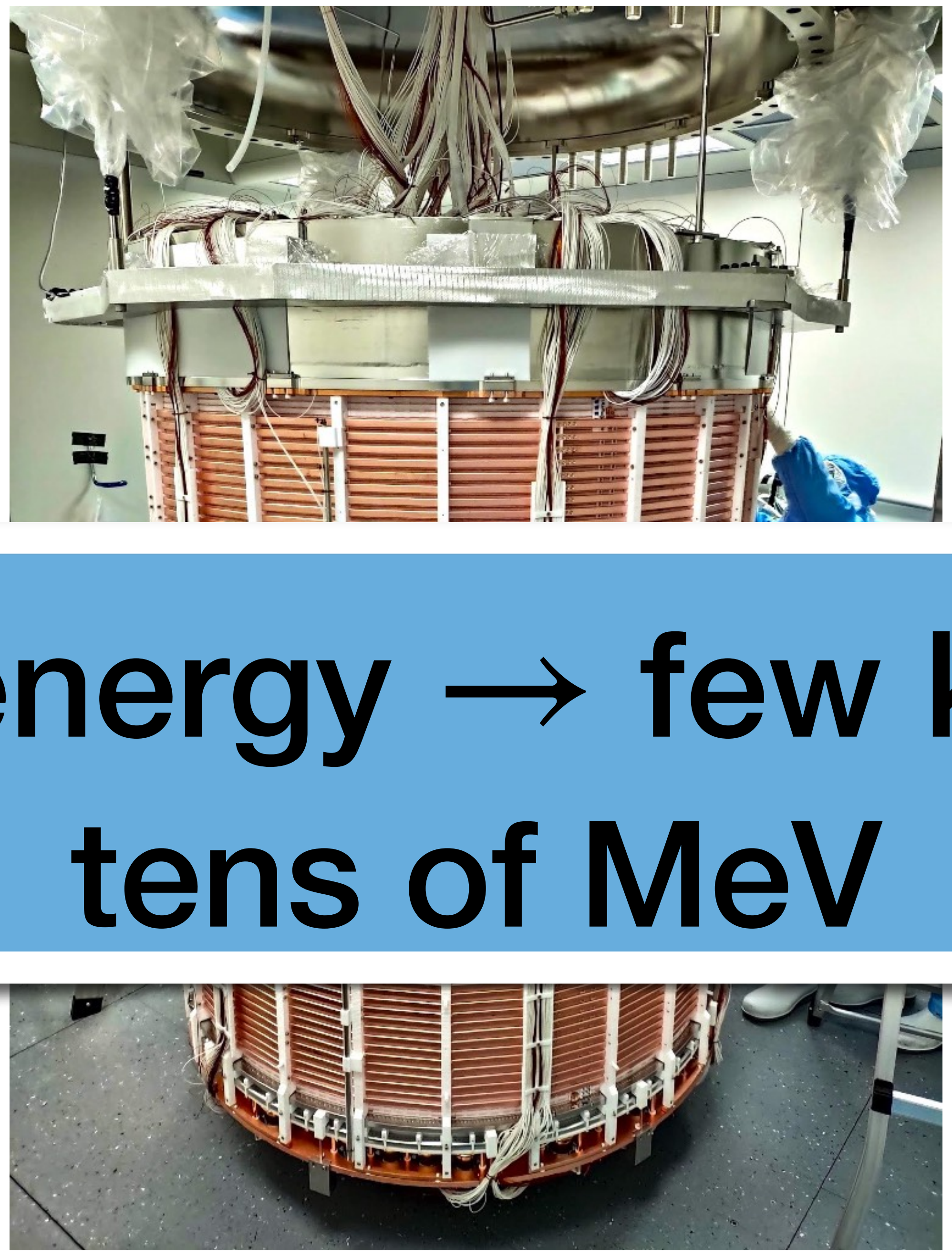

Low energy → few keV to tens of MeV

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|---|---|---|---|---|
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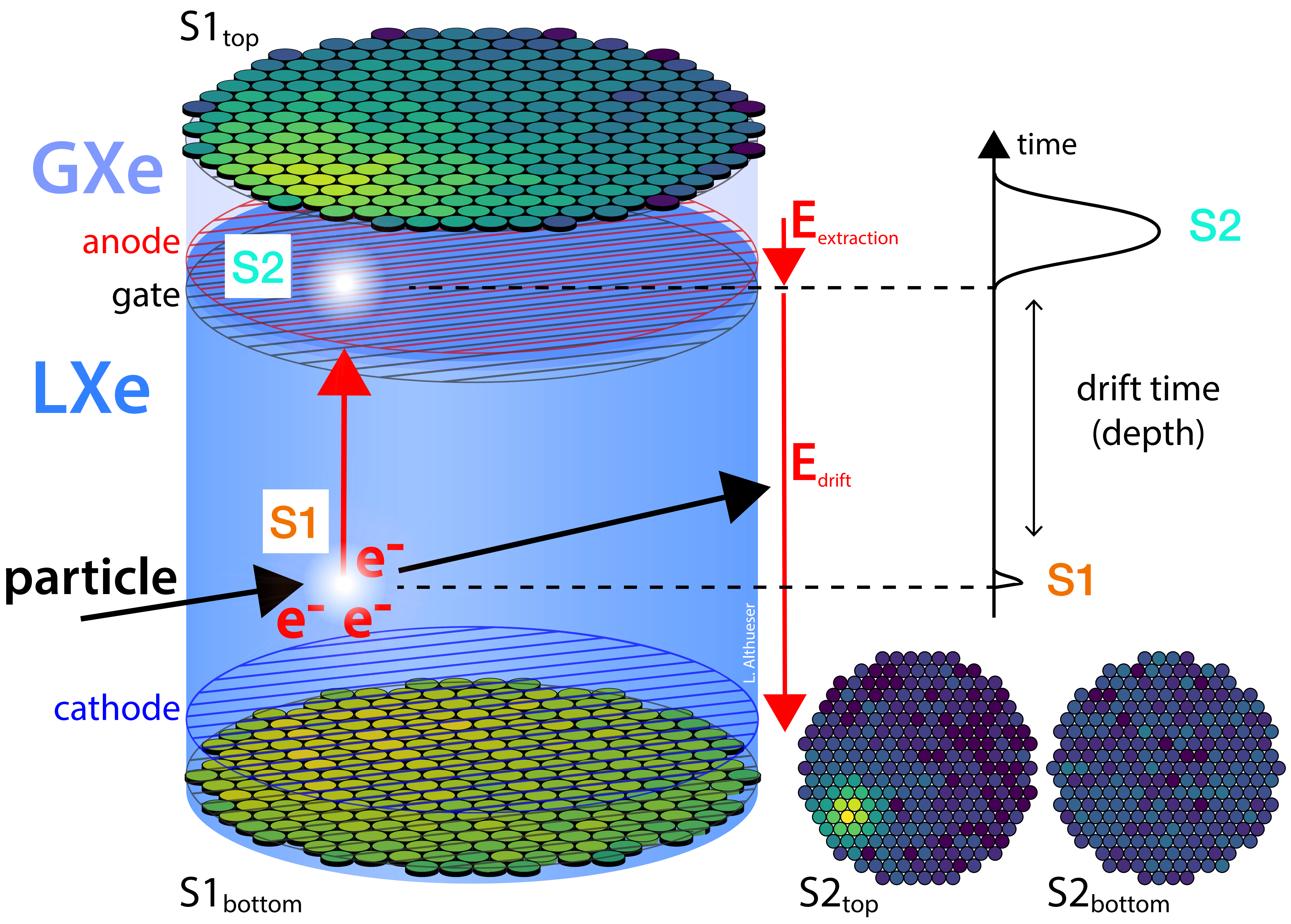
# Dual-phase xenon TPC

## Working principle

- Readout of both scintillation and ionization signals
- Prompt scintillation light: S1
- Secondary (proportional) scintillation light: S2
- Reconstruction of
  - 3D position (**x, y, z**)
  - Energy
  - Interaction type (ER/NR) through S1/S2 ratio
- Self-shielding → fiducial volume



# R12699-406-M4 2-inch PMT

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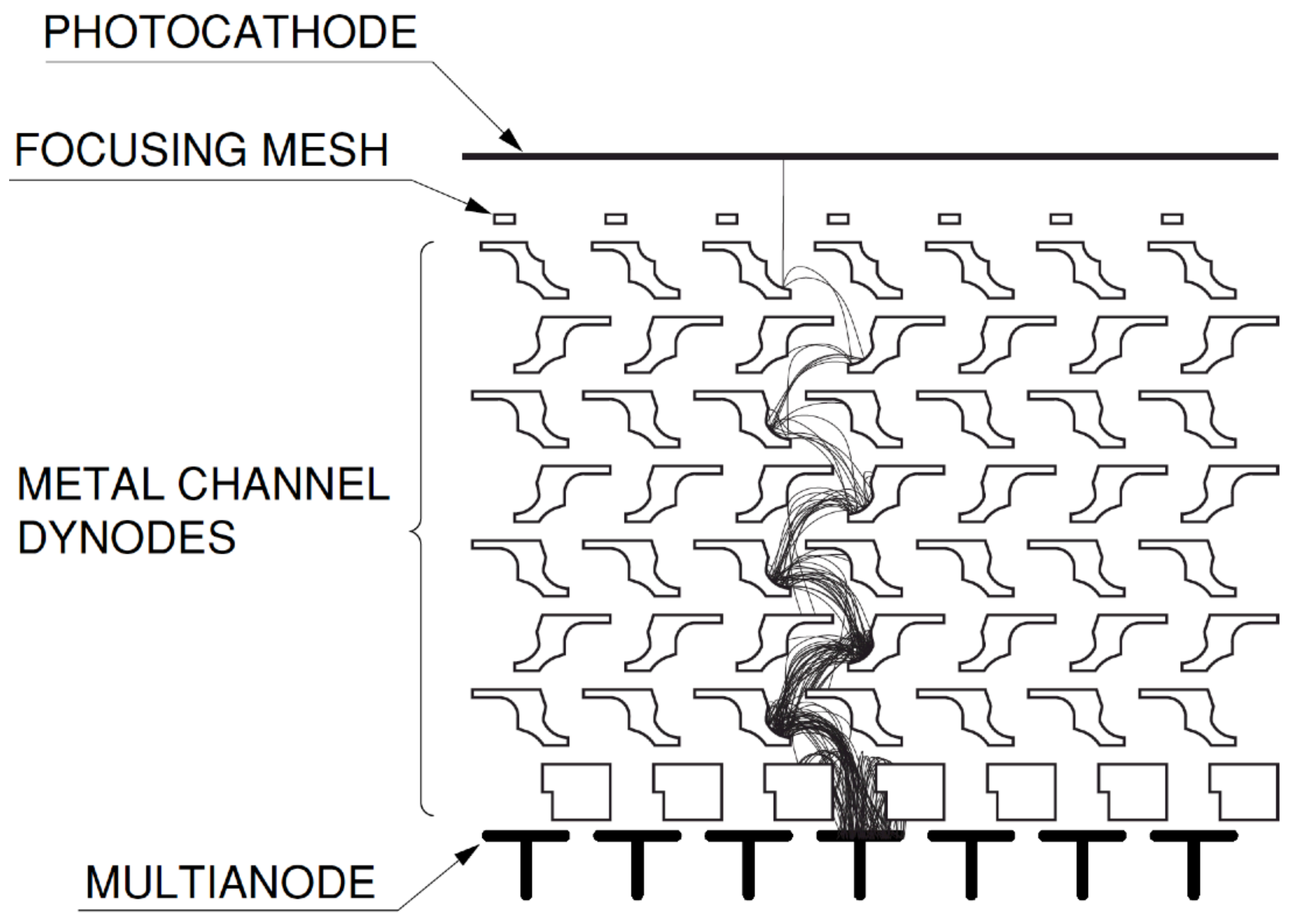
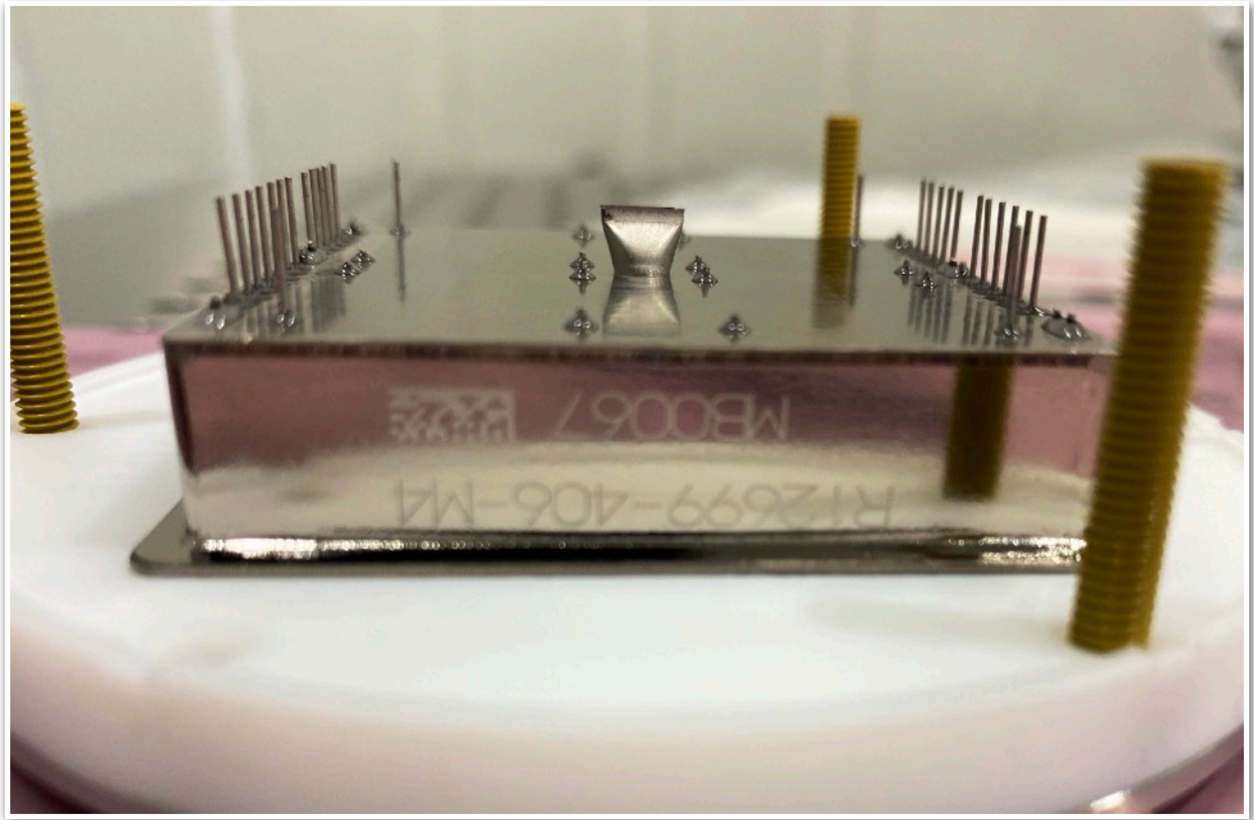
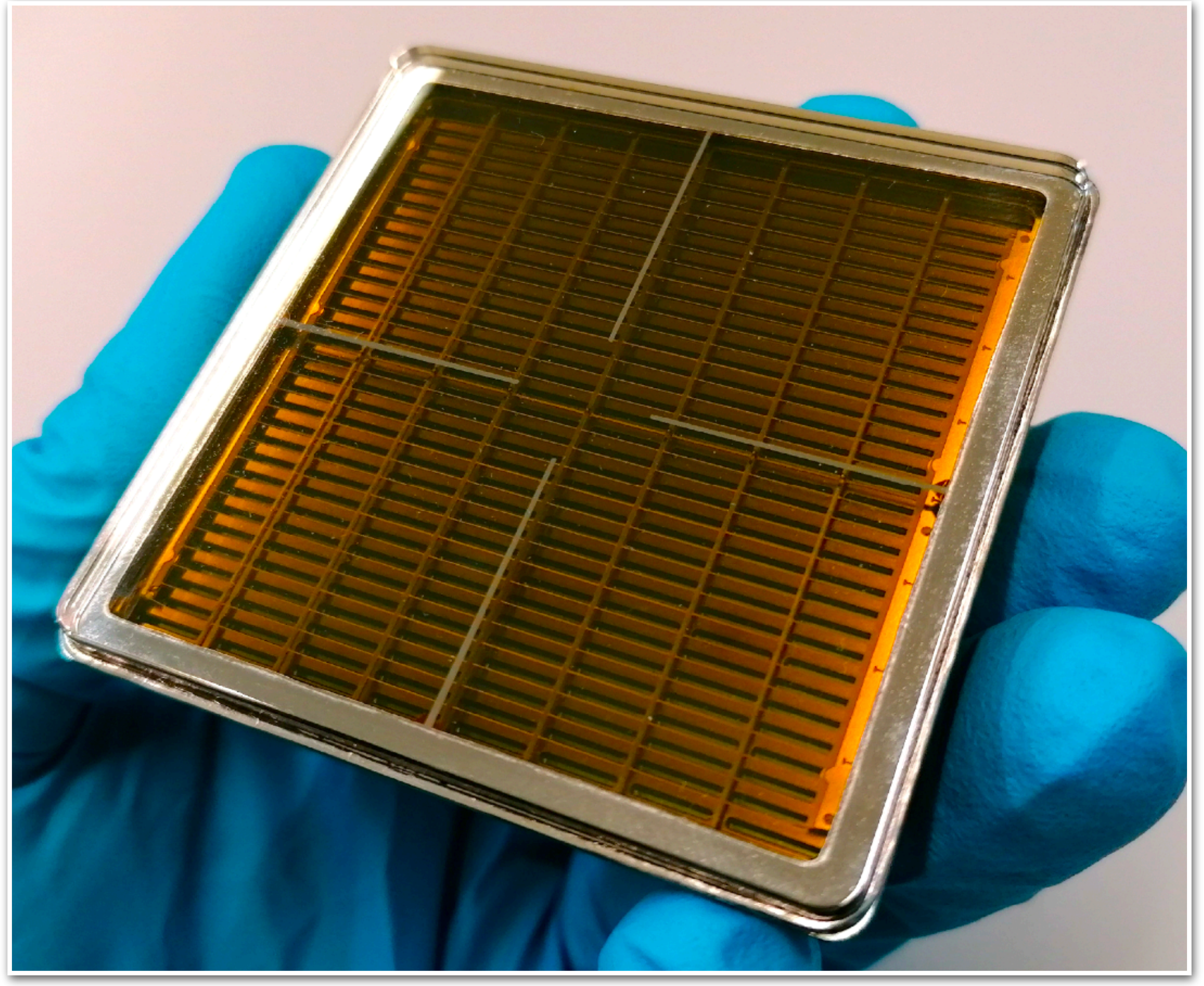


Multianode metal channel dynode principle


Low profile PMT


Hamamatsu R12699 M4 2-inch PMT 52 x 52 x 15 mm

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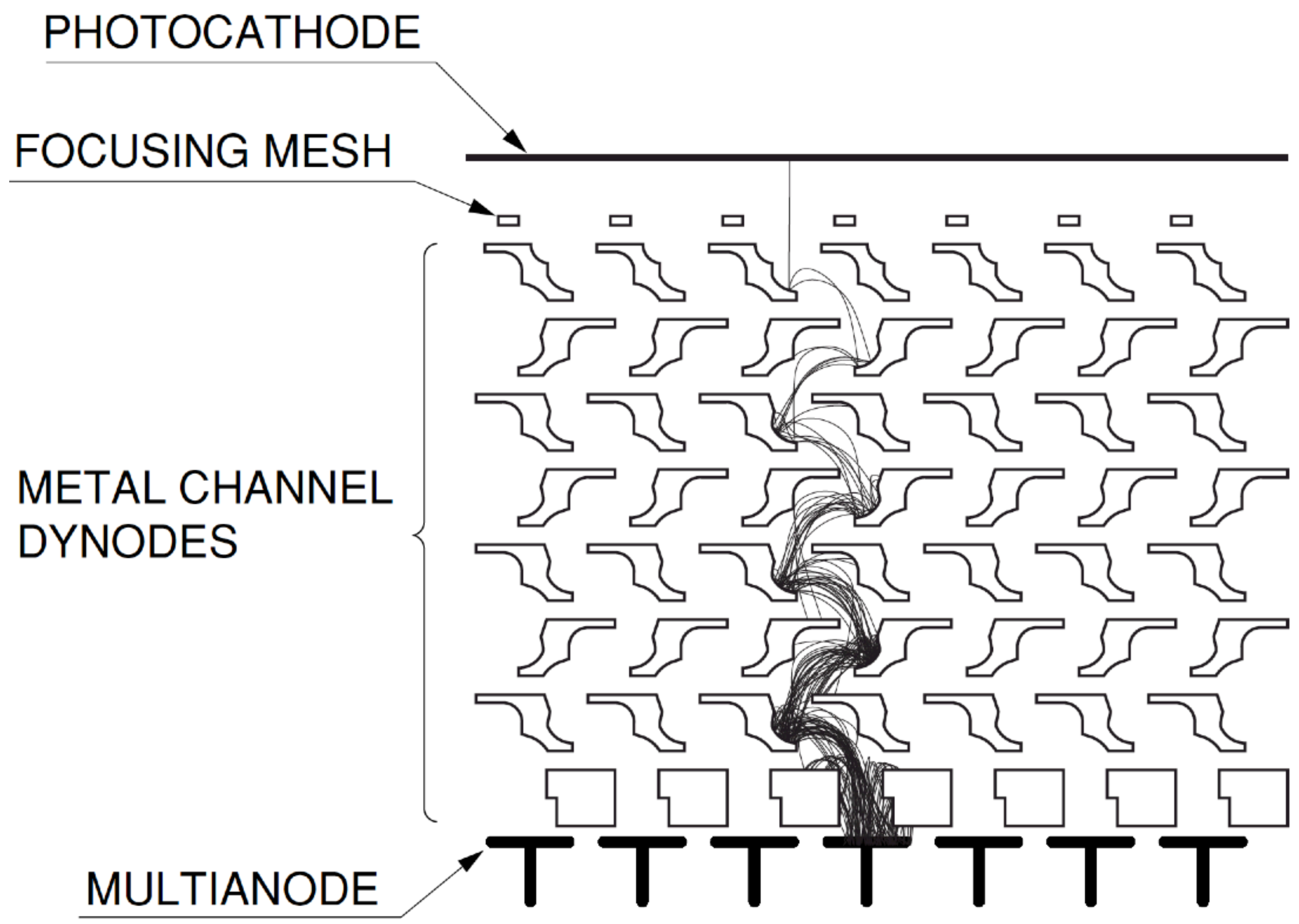
    - Low buoyancy
    - Sub-ns rise-time and transit-time spread (TTS) (i.e. very fast)

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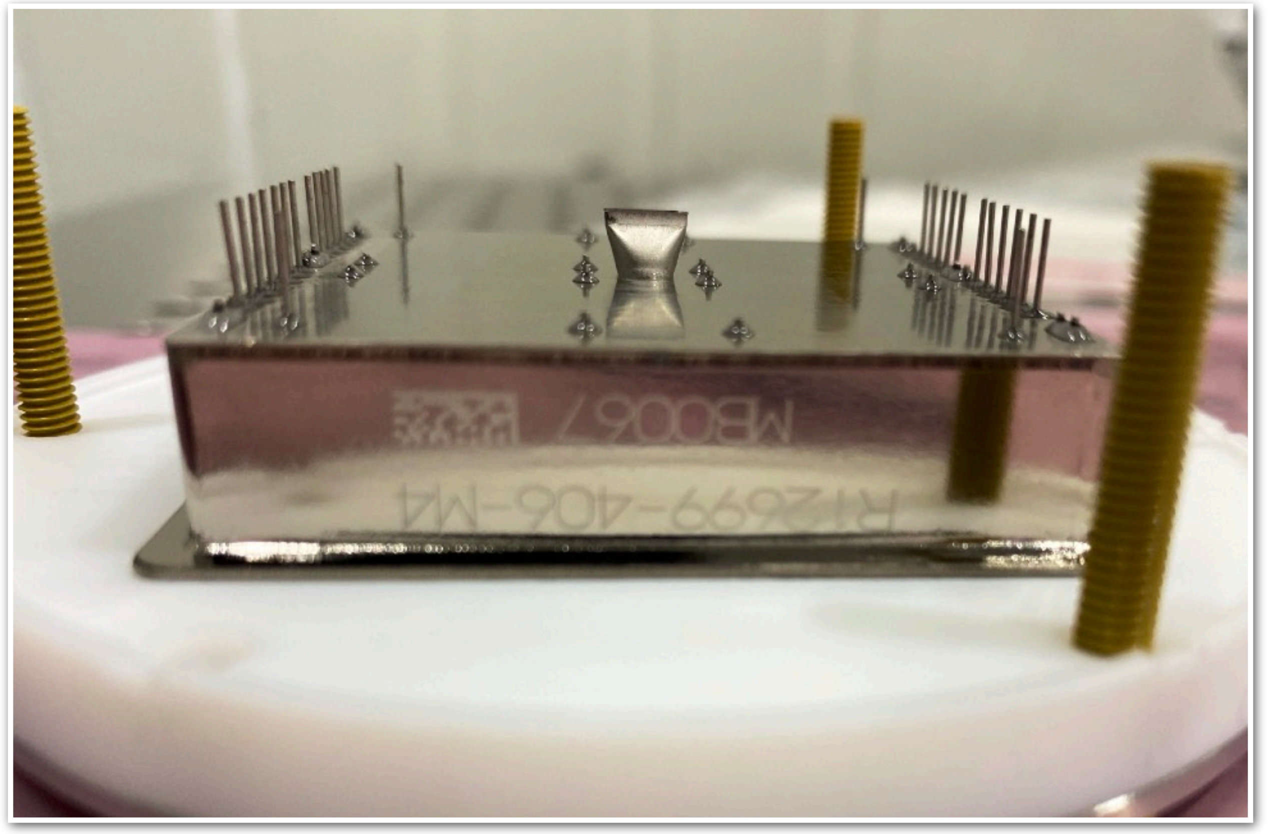

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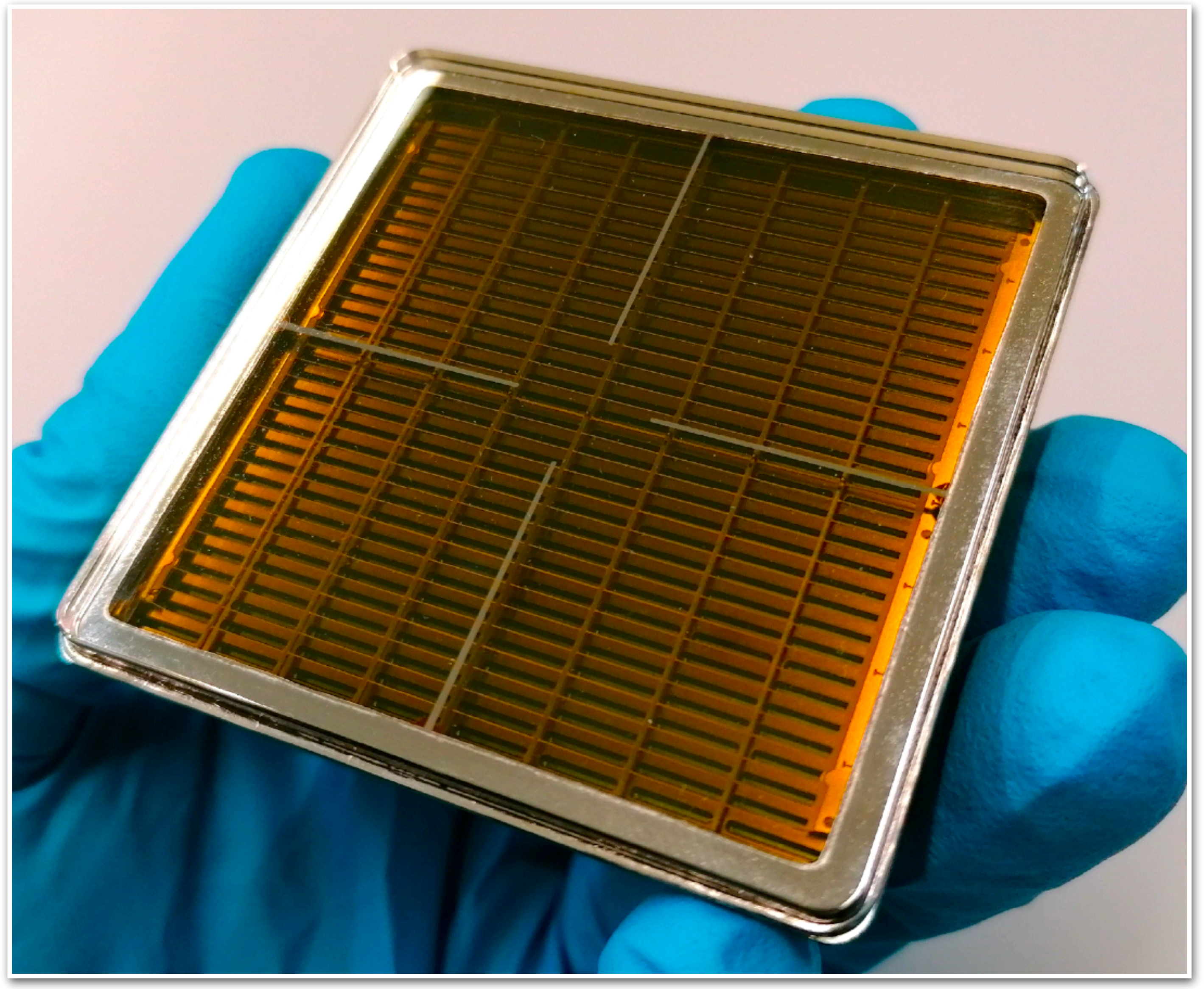

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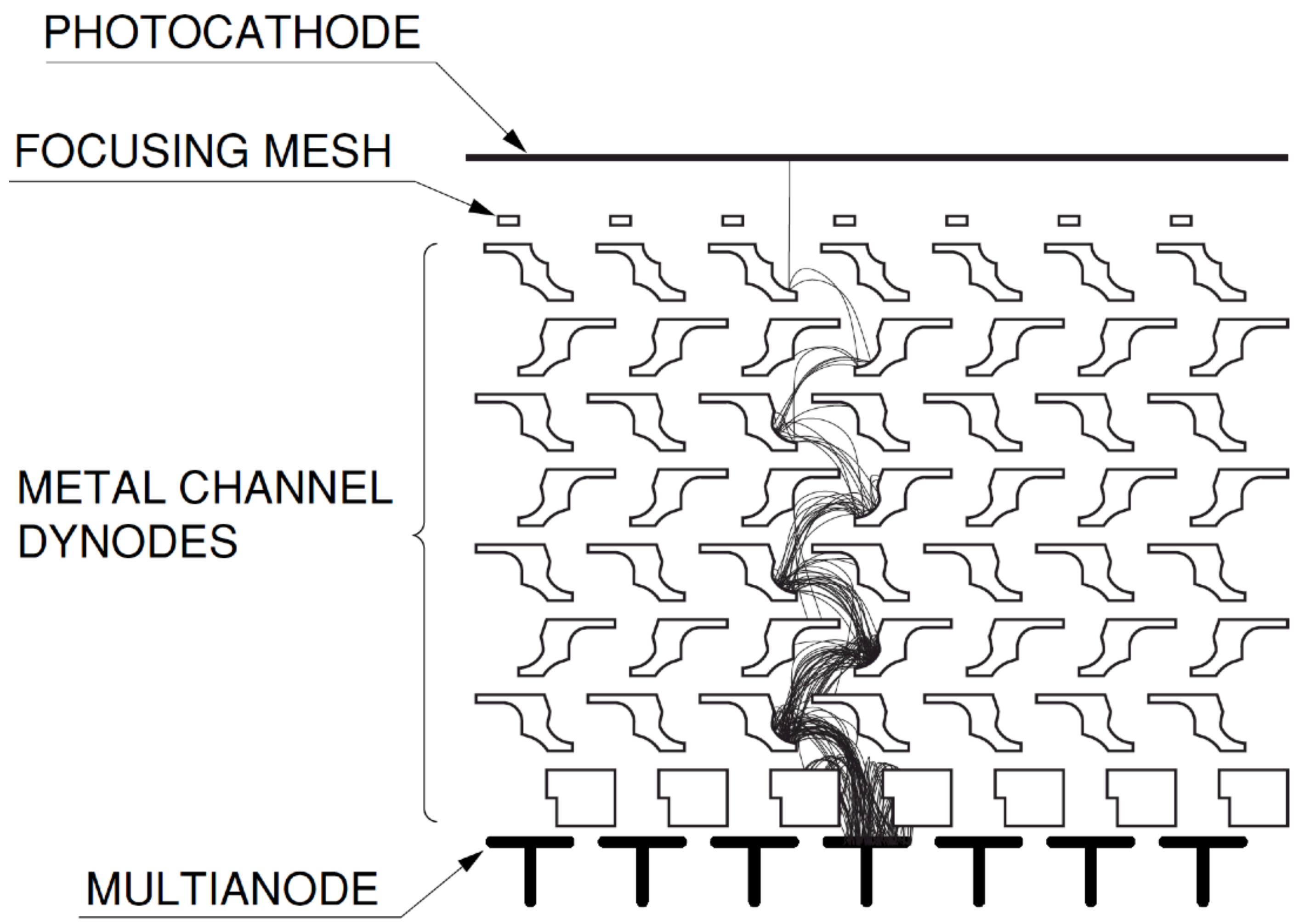
    - Less HV cables per channel
    - Variable granularity

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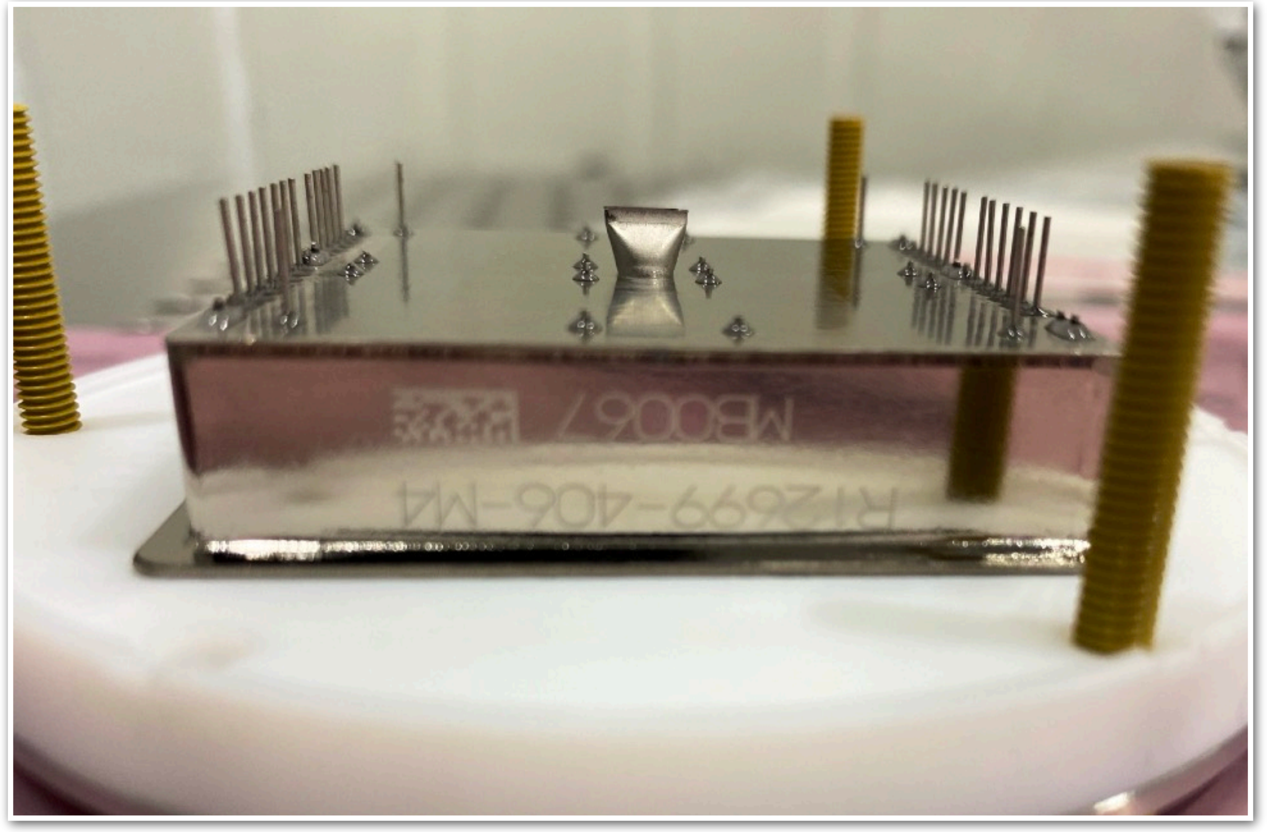

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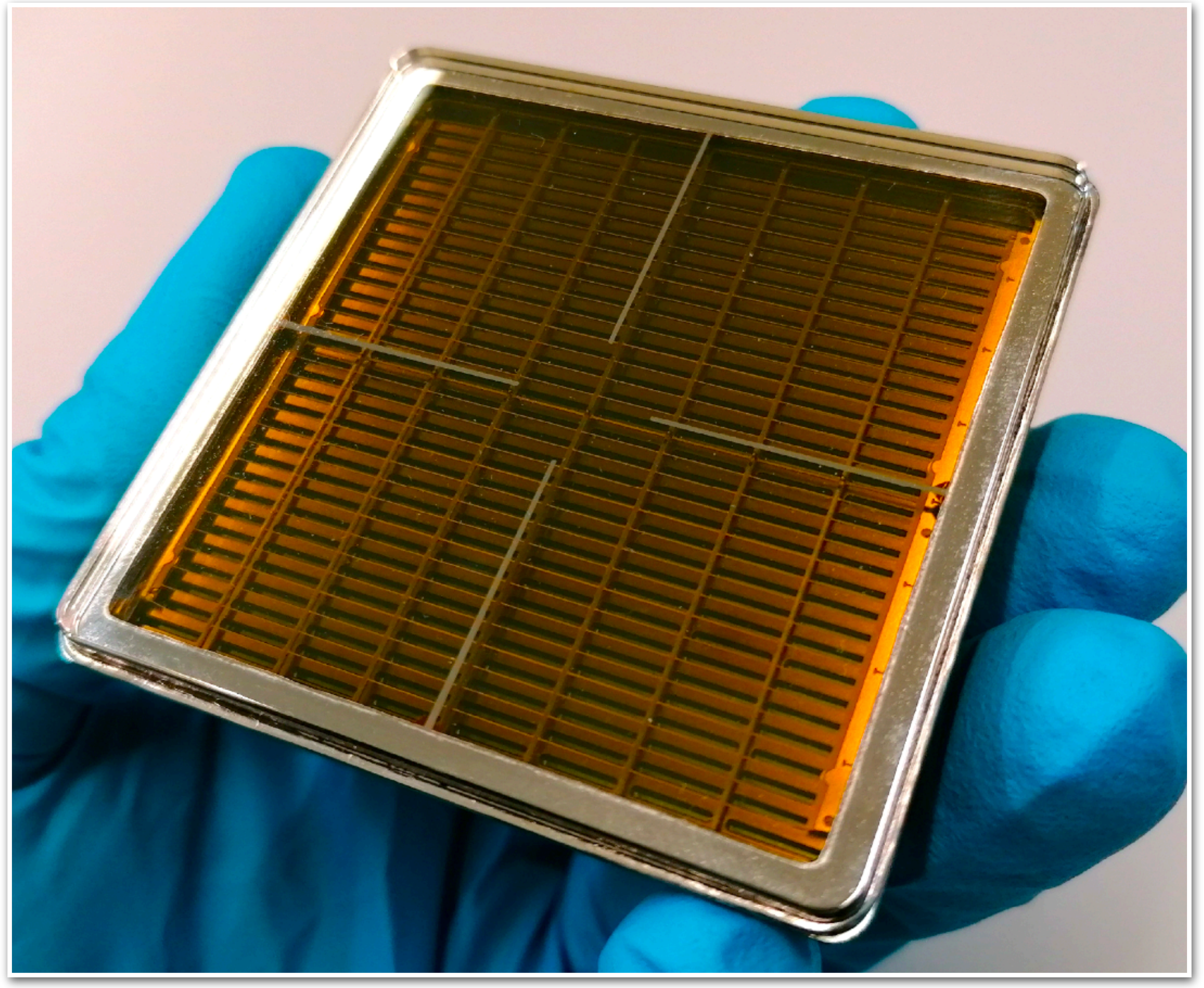

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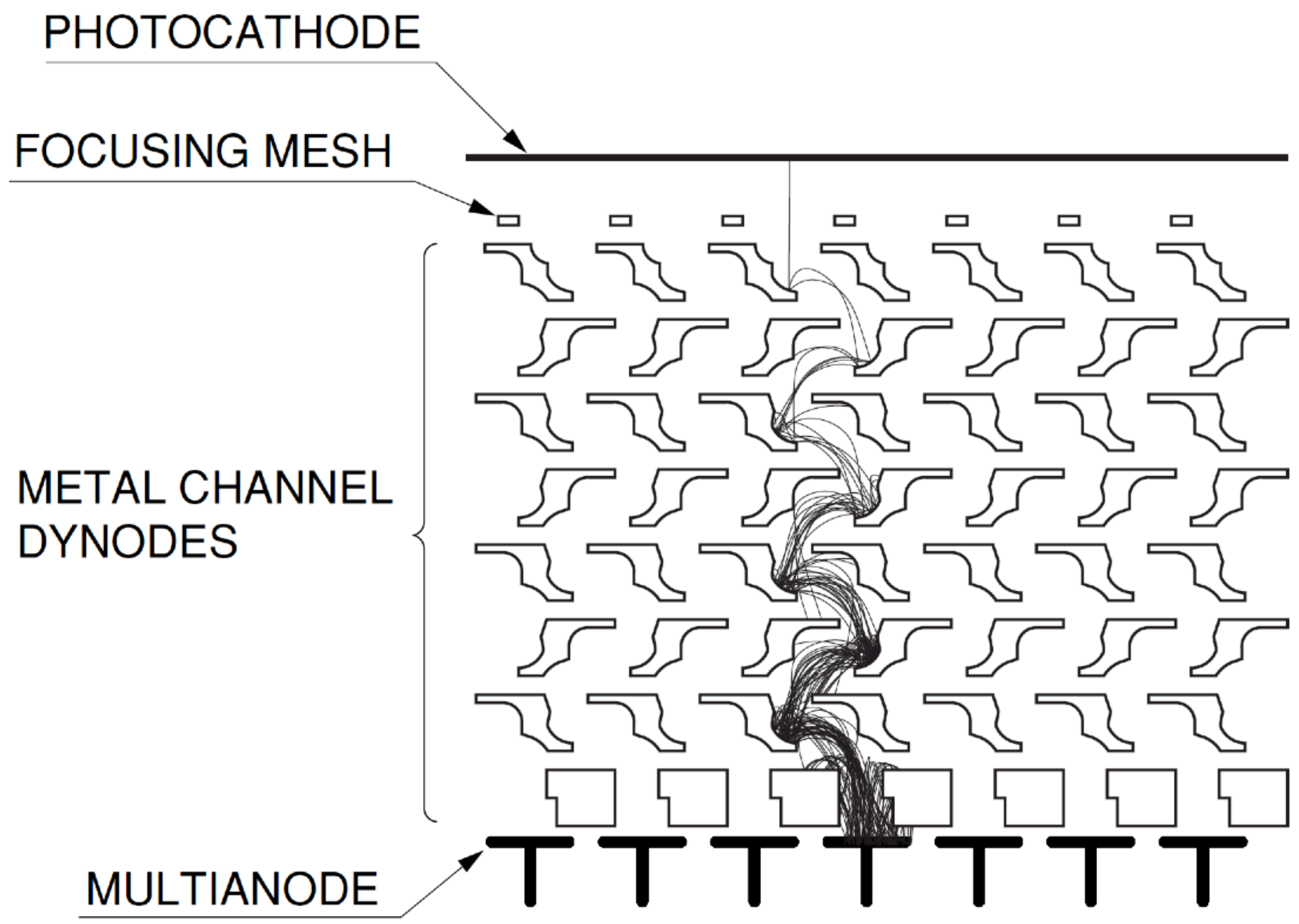
- 75% photocathode coverage
- QE of 33% (similar to 32.5% of R11410-21 XENONnT PMTs)
- Improved radioactivity*



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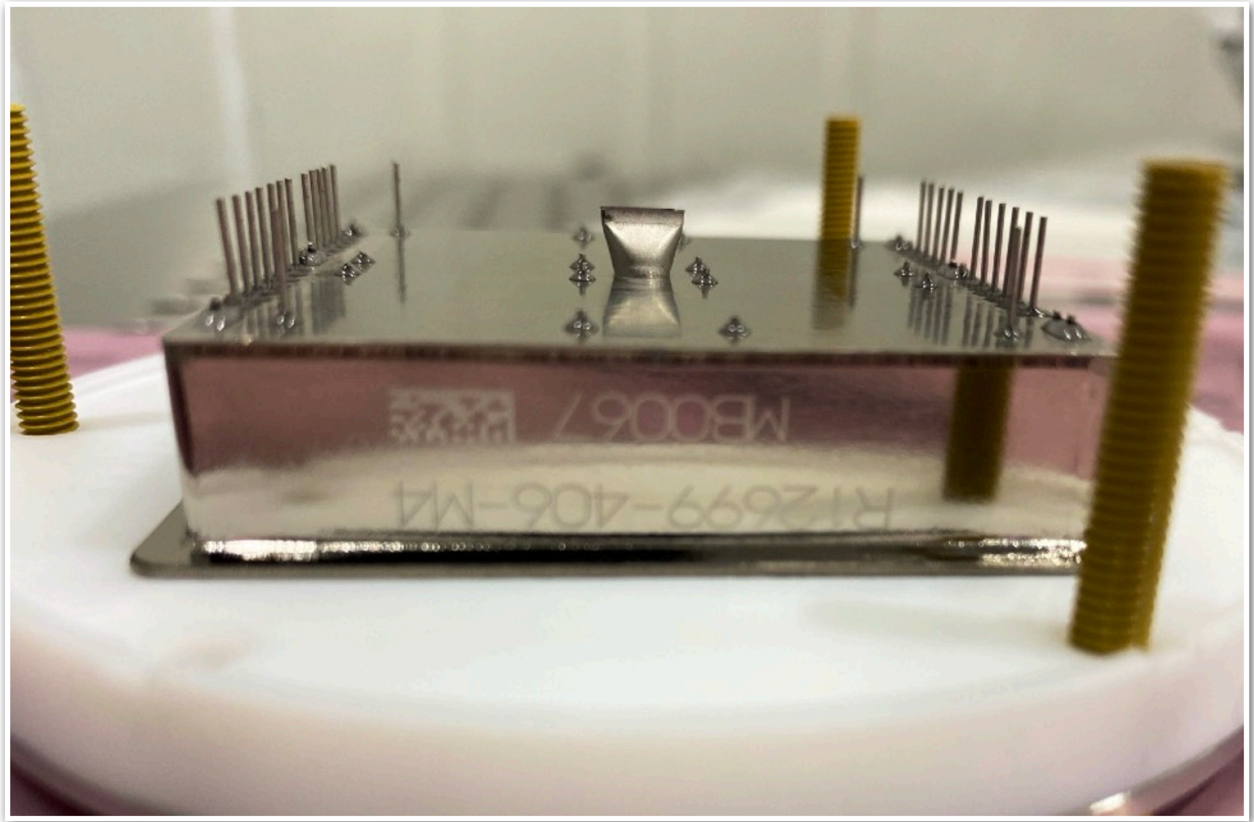
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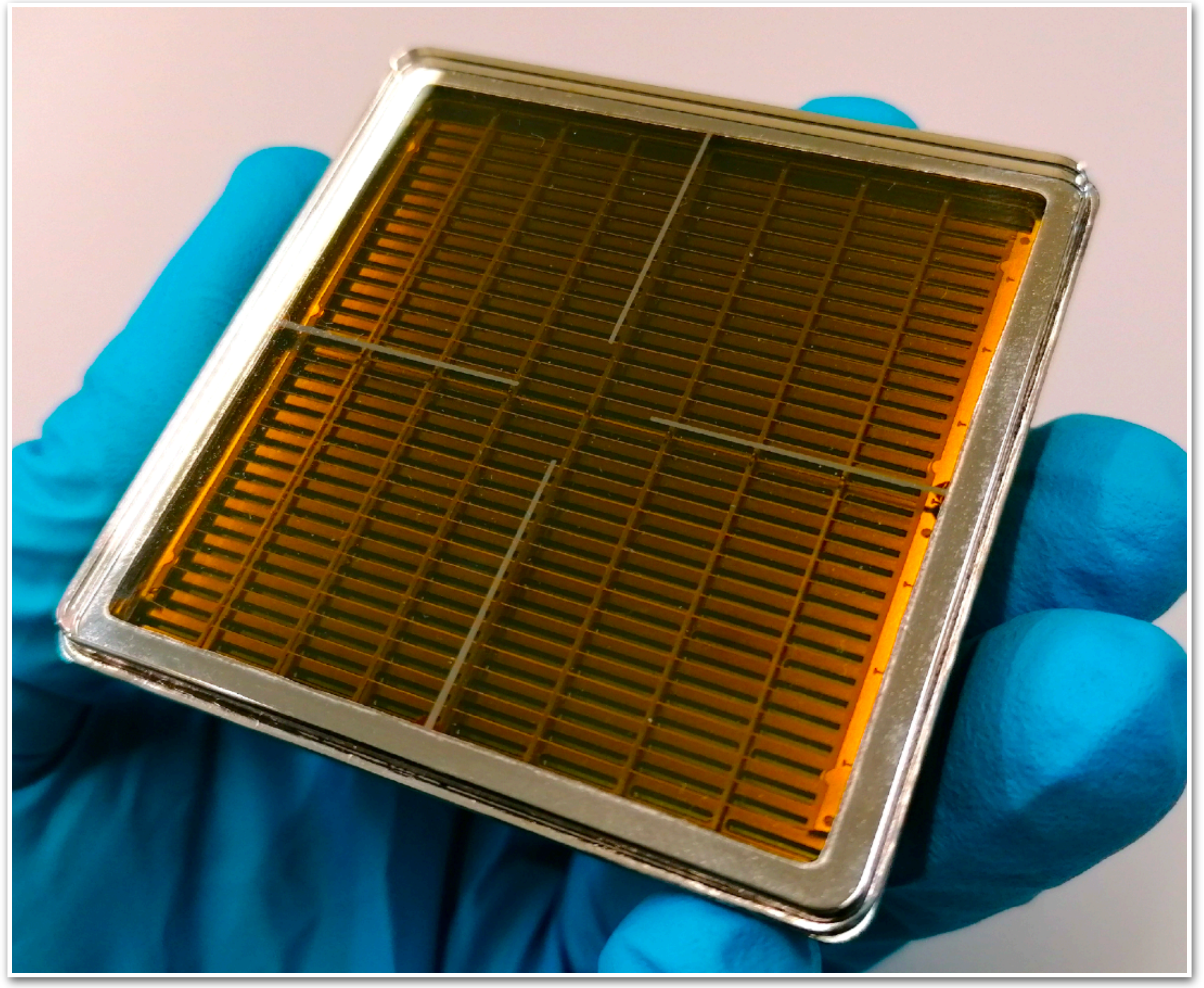
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* See XeSAT2024 presentation by Y. Meng (PandaX)

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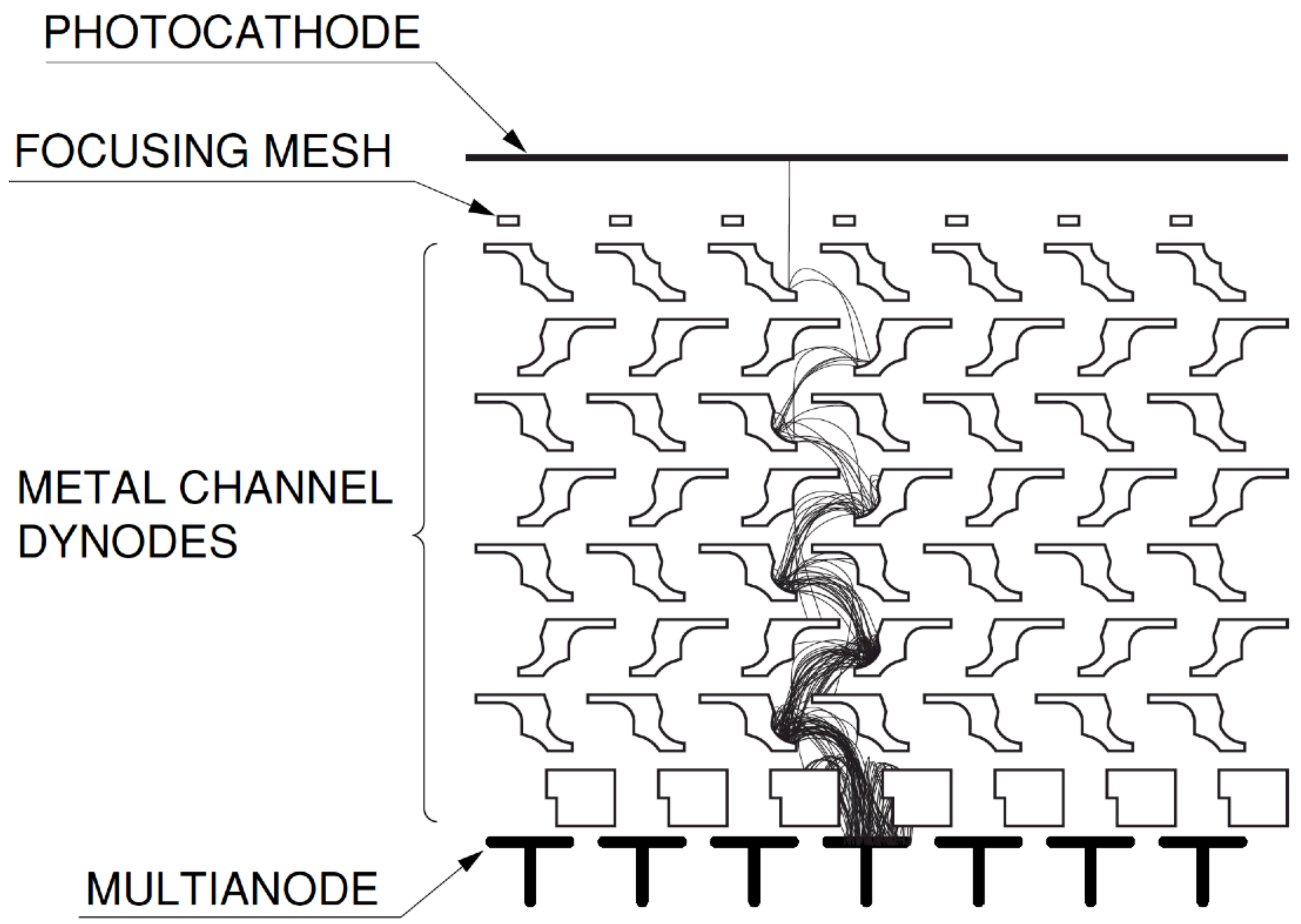
From now on “2-inch PMTs”

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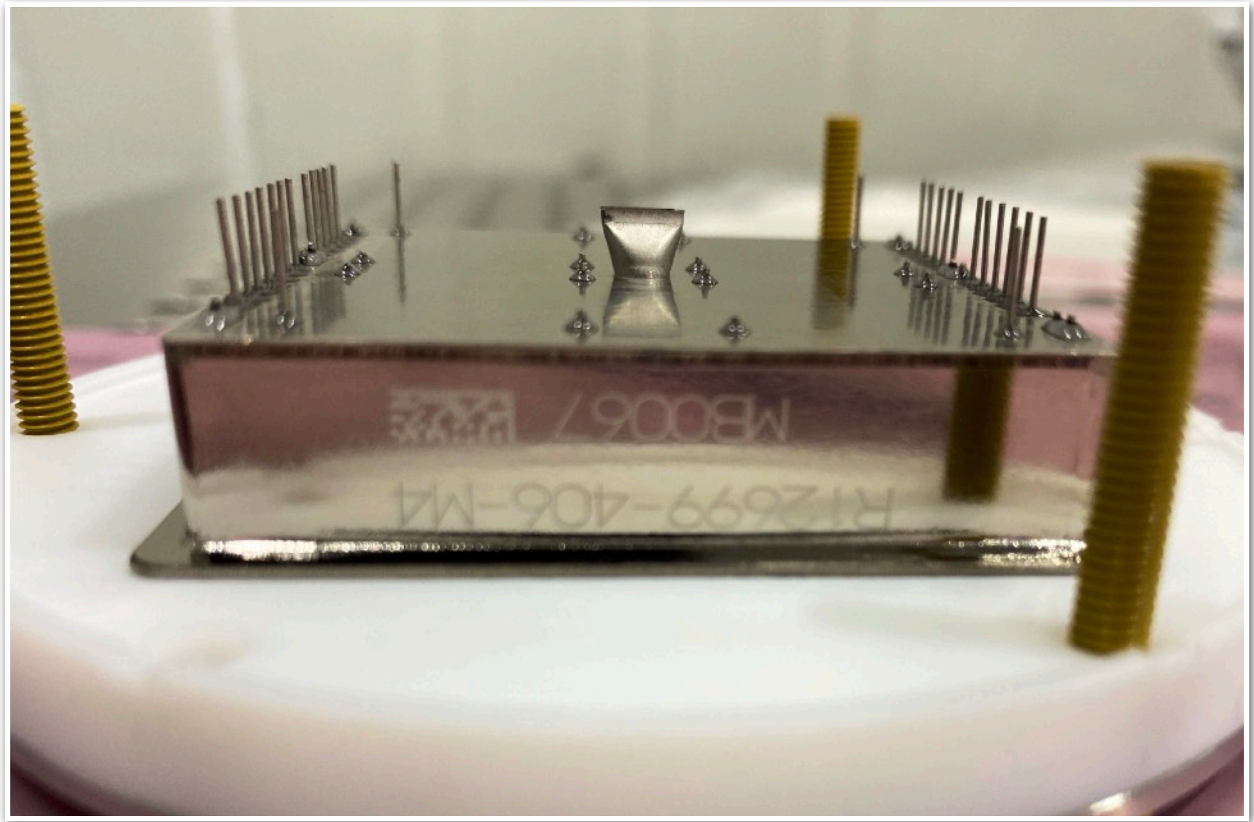

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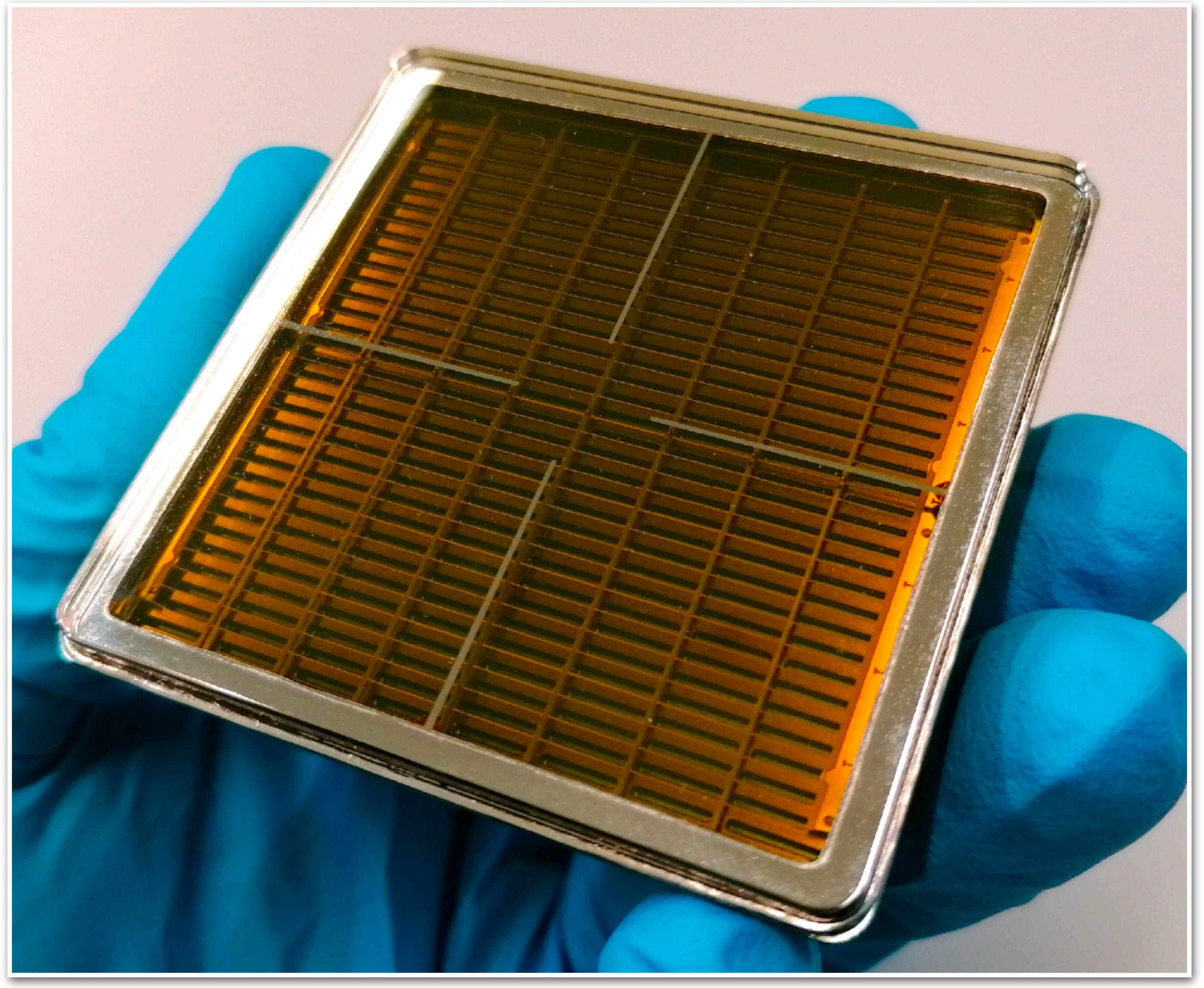

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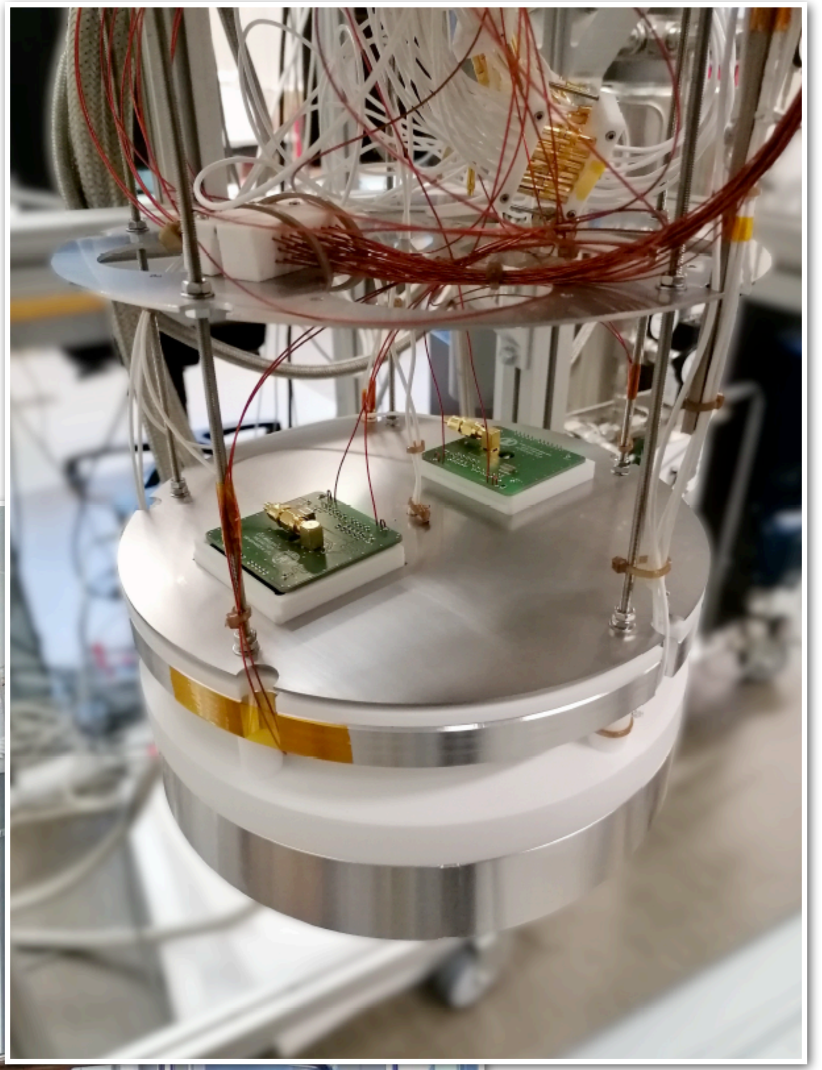
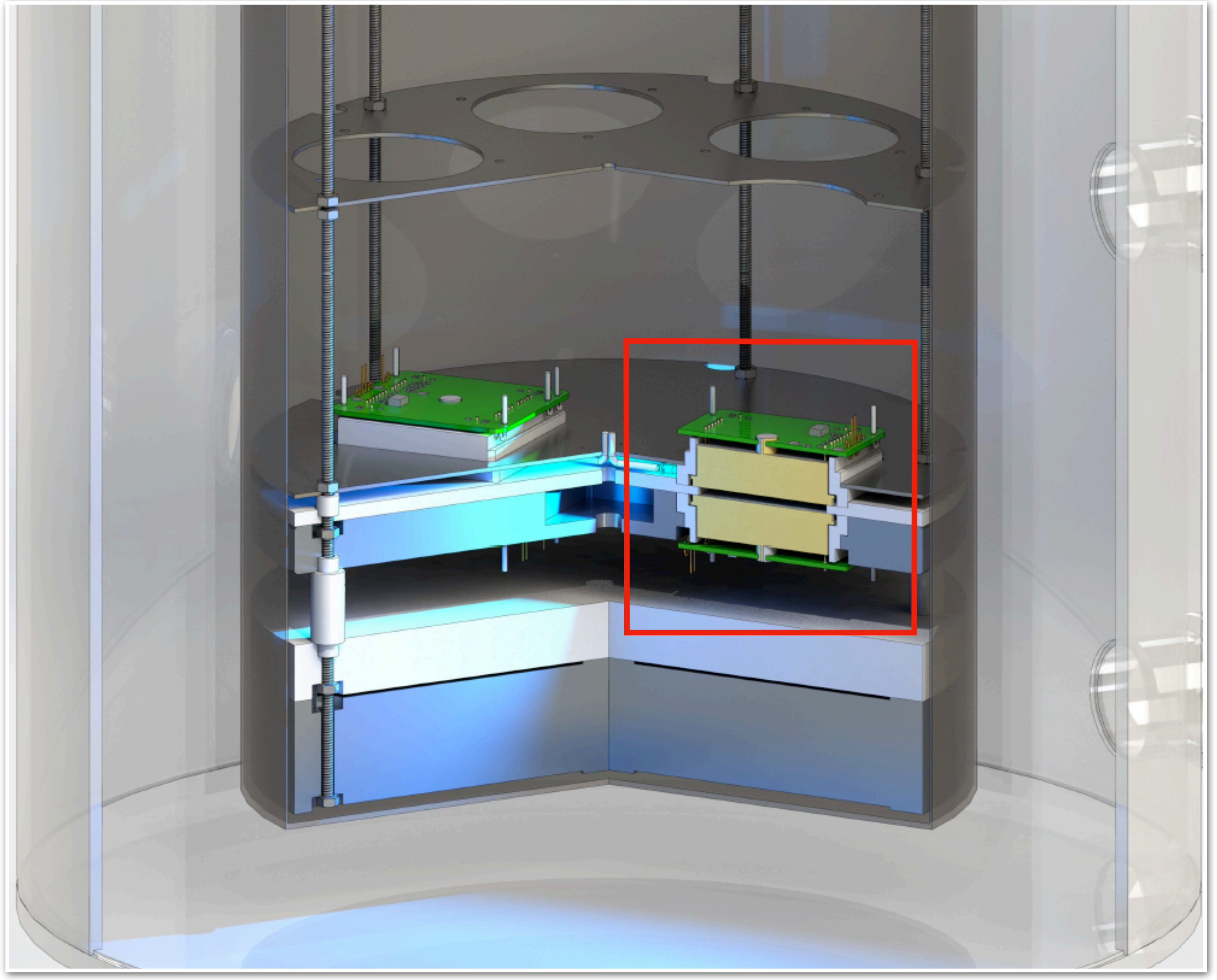
# MarmotX

Universität Zürich[UZH]

## Photosensor R&D



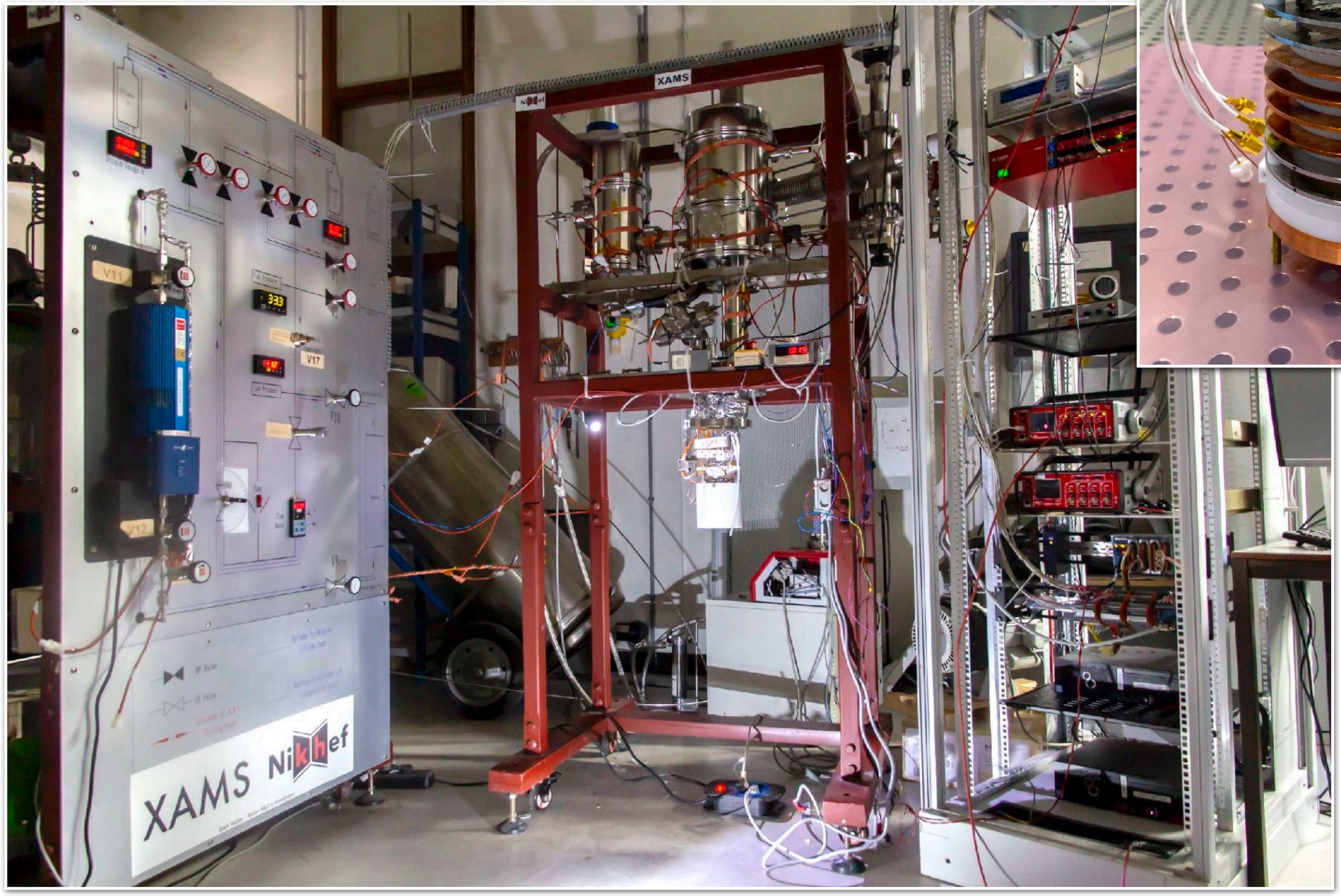

Full MarmotX setup



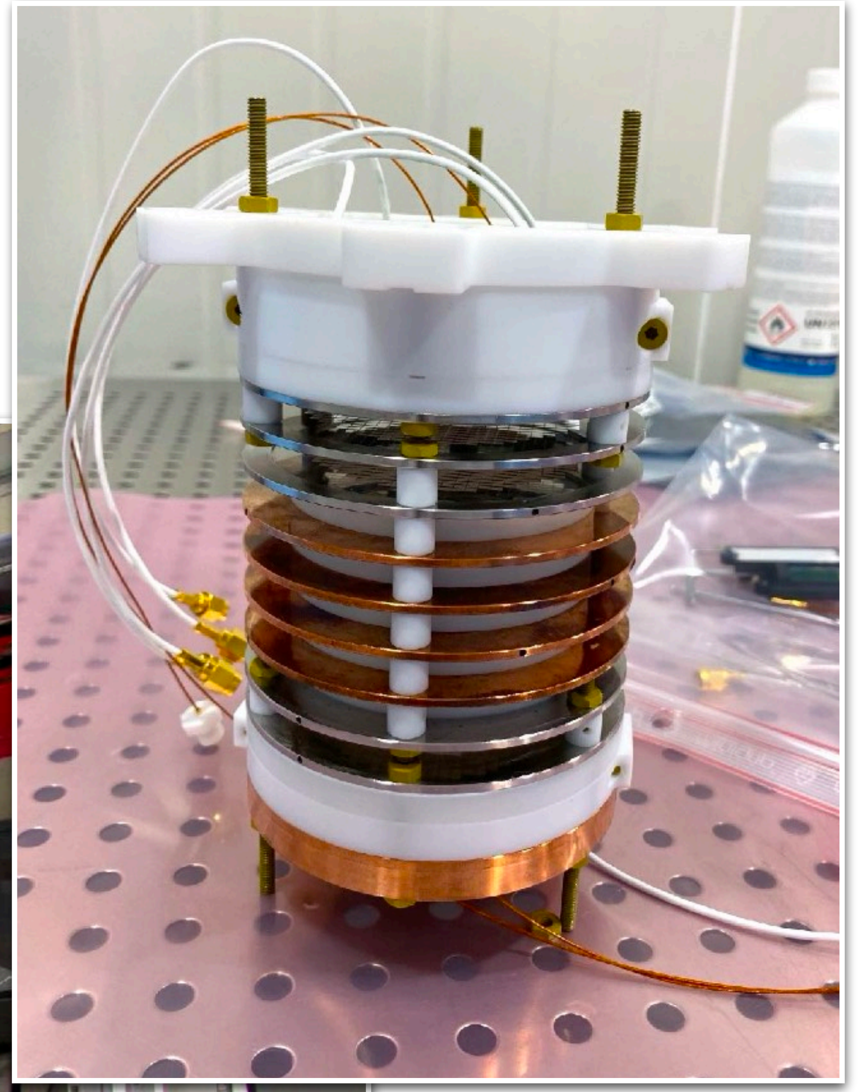
MarmotX cryostat with two pairs of face-to-face 2-inch PMTs

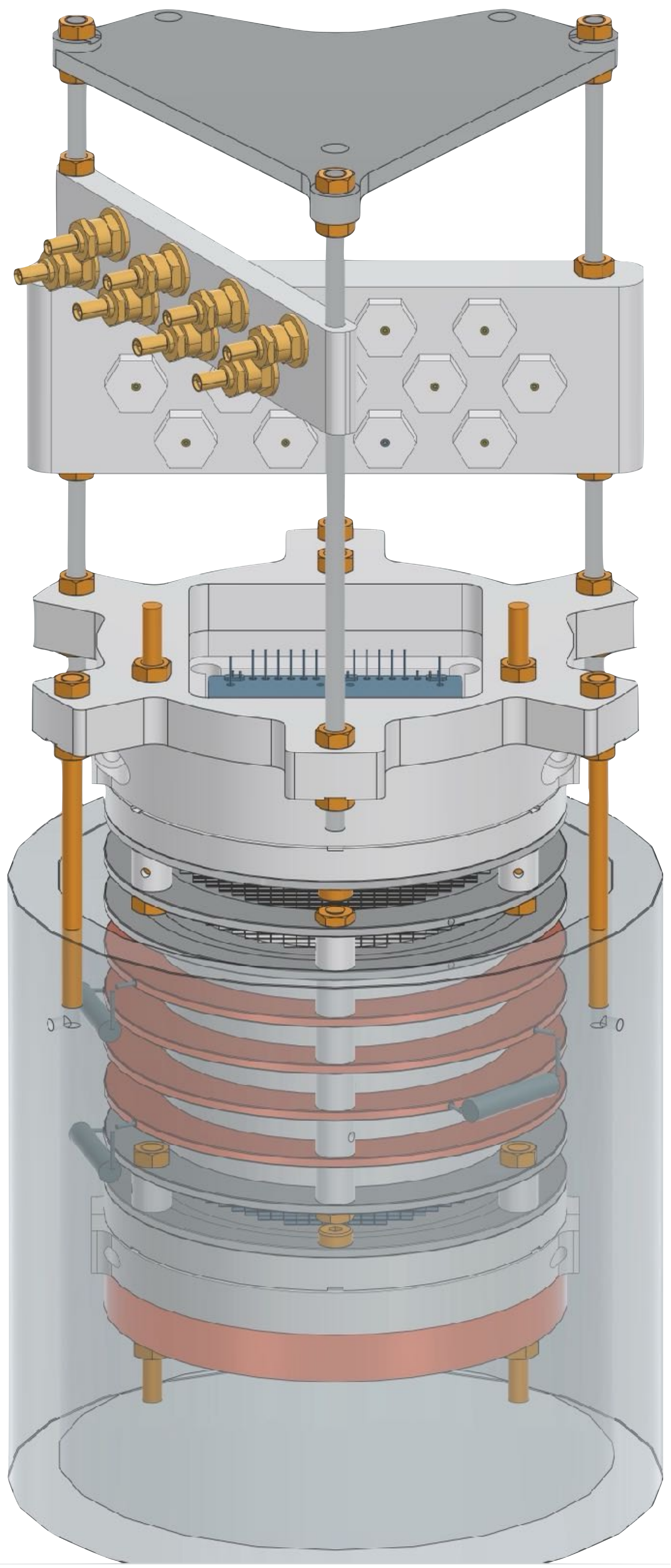
# XAMS

## Dual-phase xenon TPC




Full XAMS setup





XAMS dual-phase xenon TPC with two 2-inch PMTs installed

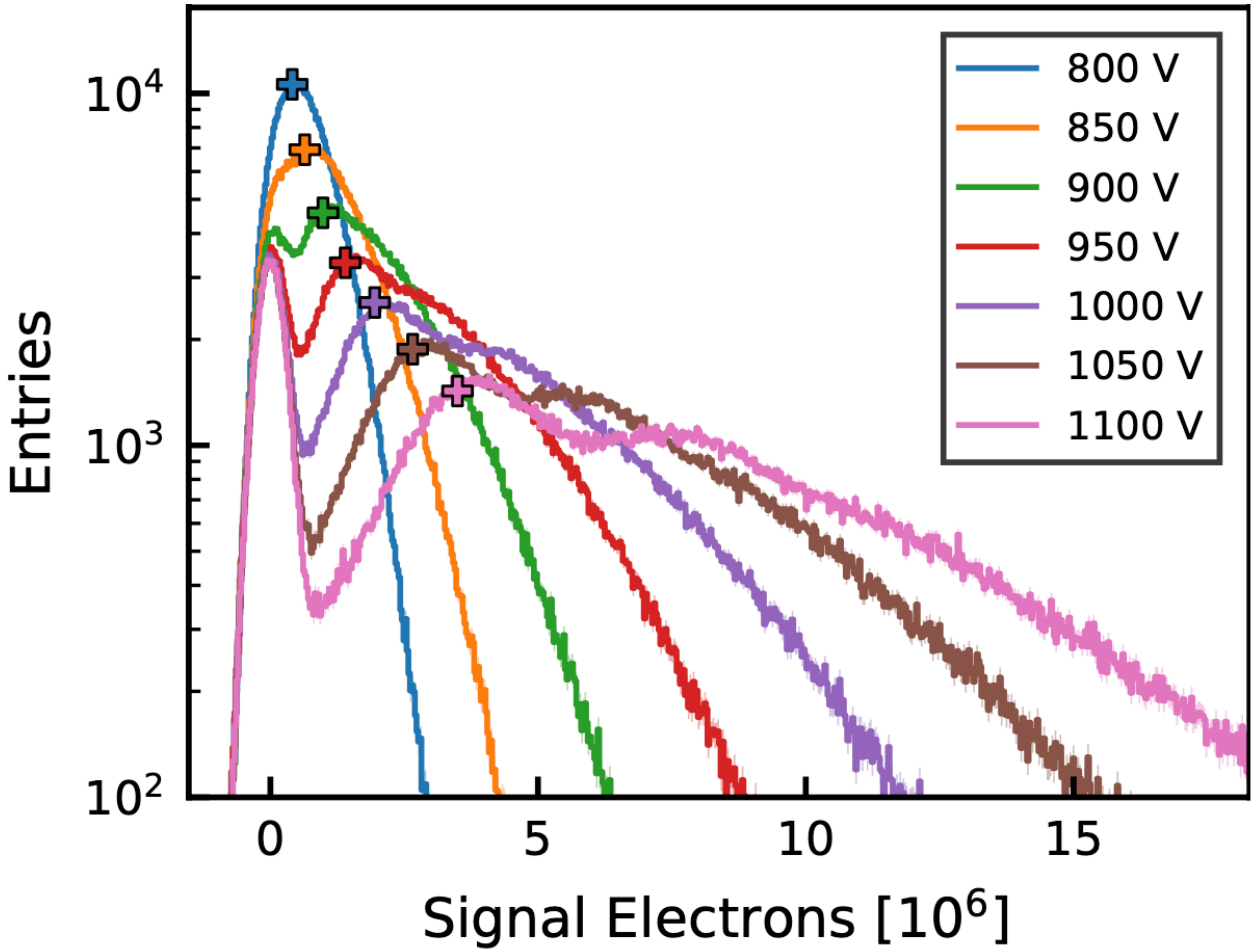
# Results

SPE response | Dark counts | Afterpulsing | Position reconstruction

# Characterization results

## Single photoelectron response

- Model independent approach as proposed by Saldanha et al. (2016)[1]
- SPE resolution $\sigma_{1PE}/\mu_{1PE}$ factor 1.23±0.14 higher than R11410-21 PMTs
- Typical gain of $2 \cdot 10^6$ exceeded for each PMT at nominal voltage (~1000V)
- Long term gain stability tests ongoing



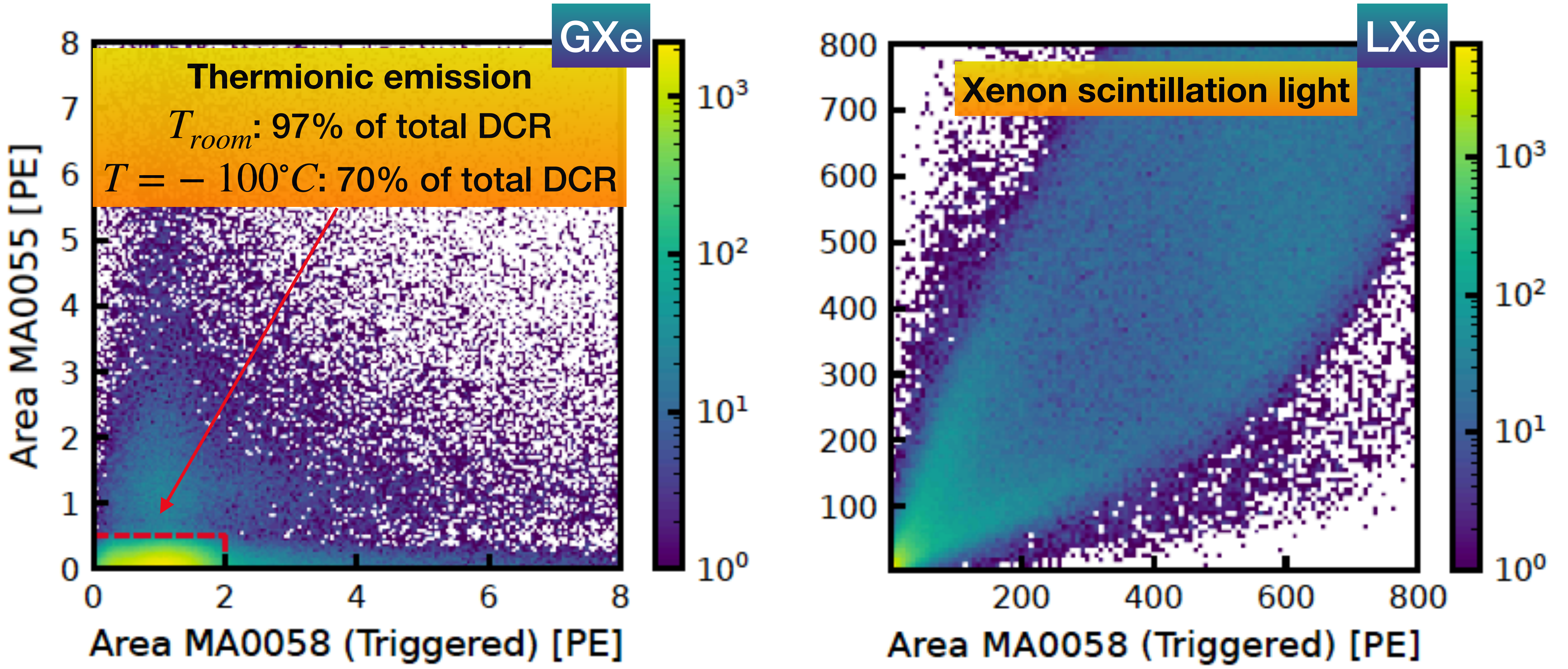

[1]Saldanha, R., Grandi, L., Guardincerri, Y., & Wester, T. (2017). Model independent approach to the single photoelectron calibration of photomultiplier tubes. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *863*, 35-46.

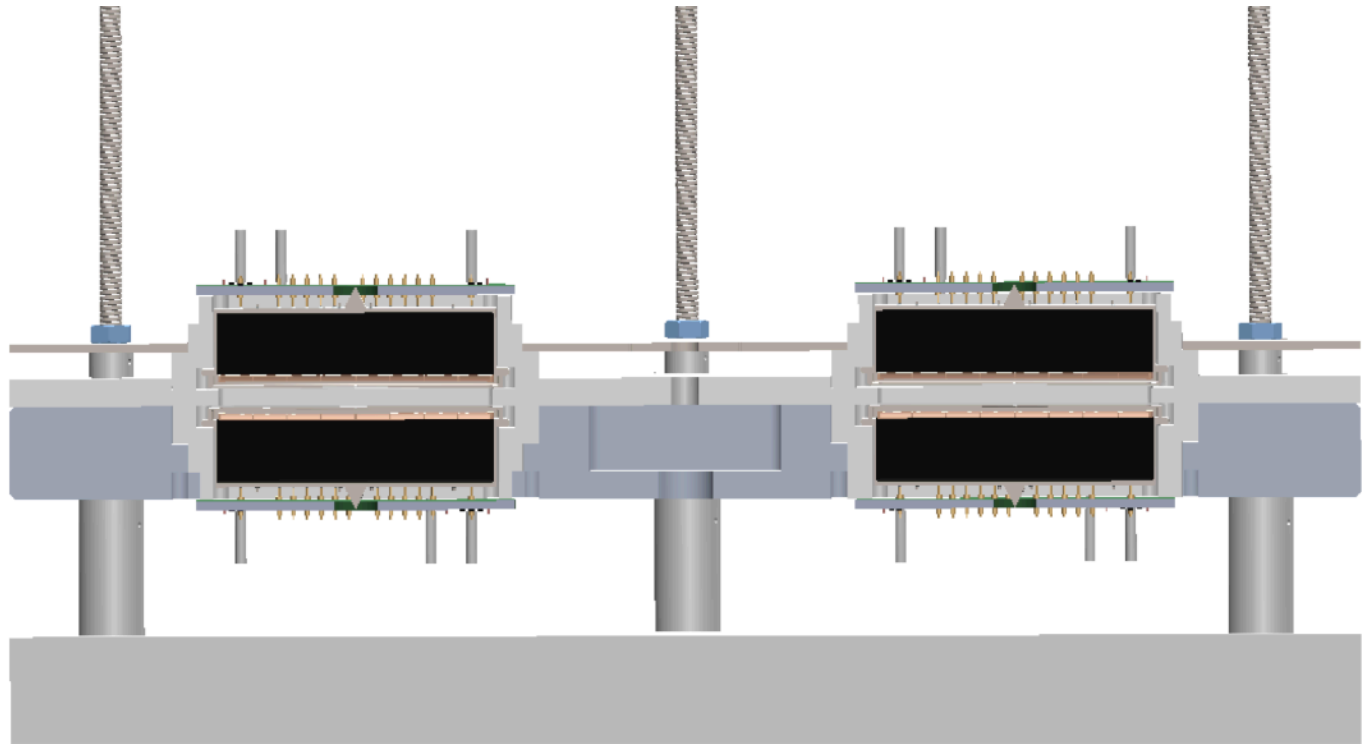
# Characterization results

## Dark counts

- Dark counts (DC) dangerous for accidental coincidences (ACs)
- Important background for WIMP and LowER searches in DARWIN

| | DC rate at LXe temperature [Hz/cm²] |
|---|---|
| **R12699-406-M4** | 0.4 ± 0.2 |
| **R11410-21** | 1.4 ± 0.7 |



Two facing 2-inch PMTs in MarmotX

# Characterization results

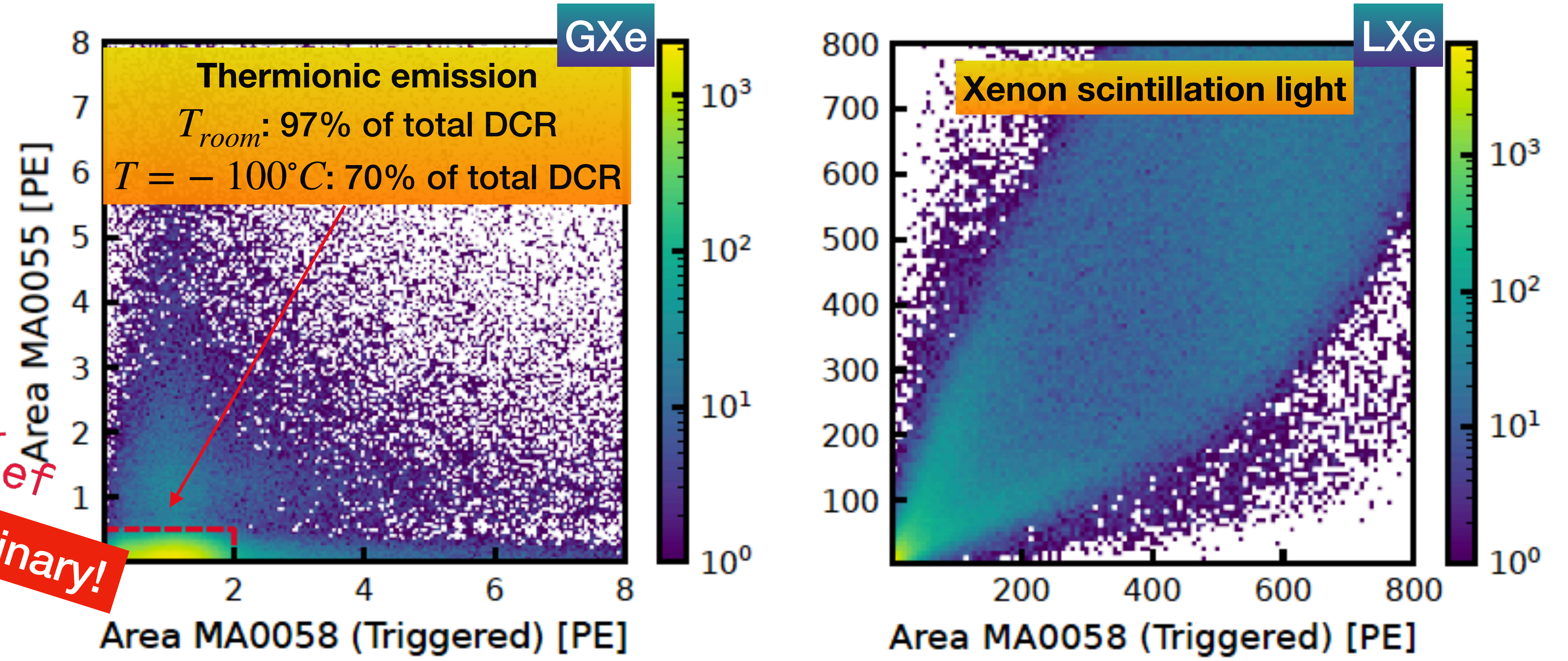
## Dark counts

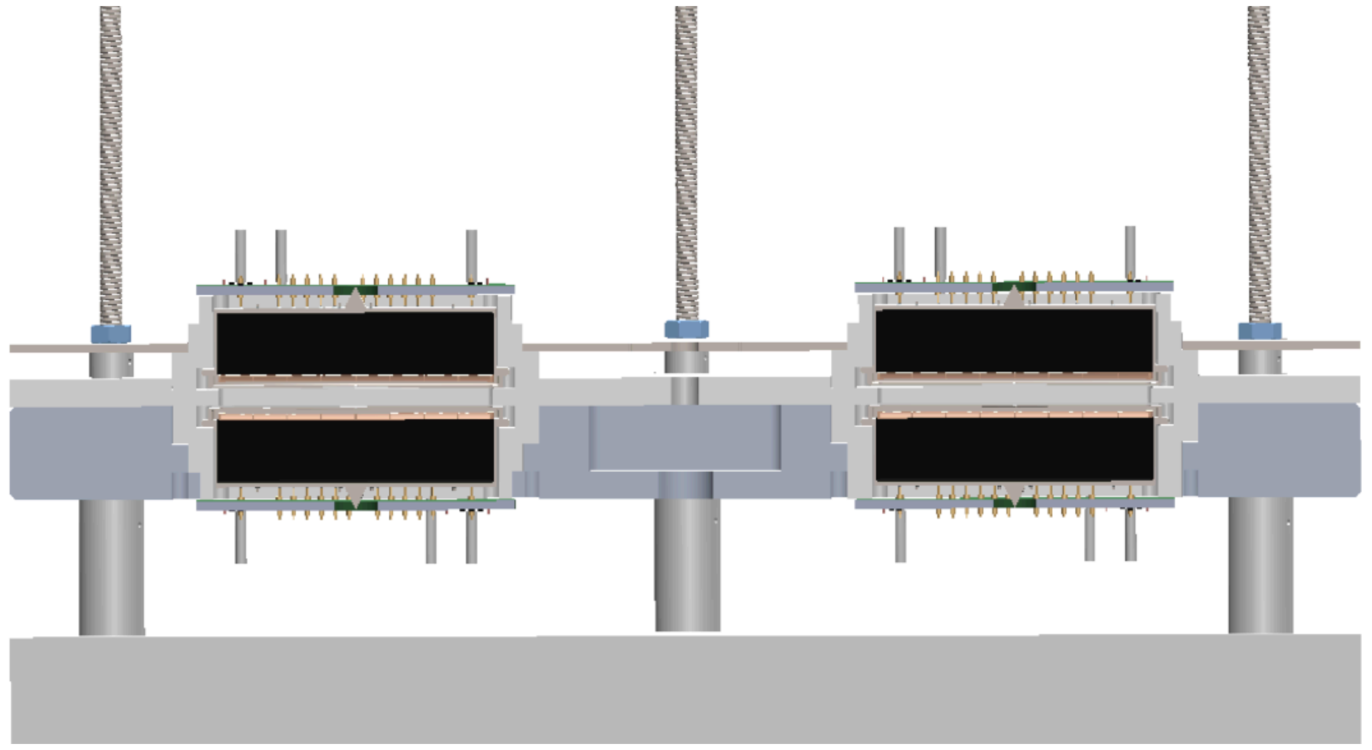
- Dark counts (DC) dangerous for accidental coincidences (ACs)
- Important background for WIMP and LowER searches in DARWIN

Very preliminary!

| | DC rate at LXe temperature [Hz/cm²] | AC rate estimation for DARWIN in WIMP ROI* [events/year] |
|---|---|---|
| **R12699-406-M4** | 0.4 ± 0.2 | $4 \cdot 10^4$ |
| **R11410-21** | 1.4 ± 0.7 | $3 \cdot 10^5$ |

*4-fold coincidence, S1 ROI (4,20) PE and S2 ROI (100,1000) PE
AC rate same order of magnitude for XENONnT sized detector



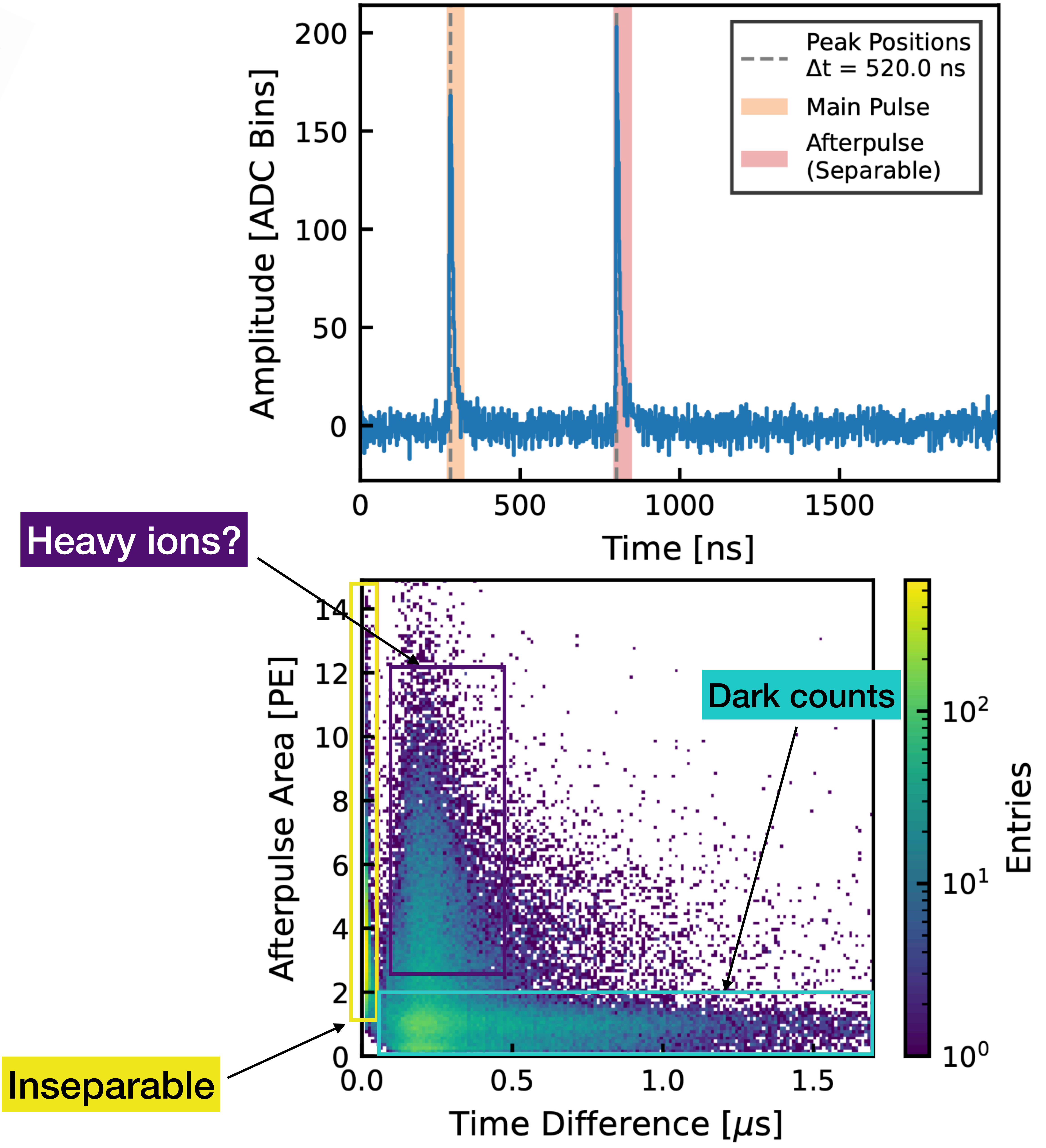



Two facing 2-inch PMTs in MarmotX

# Characterization results

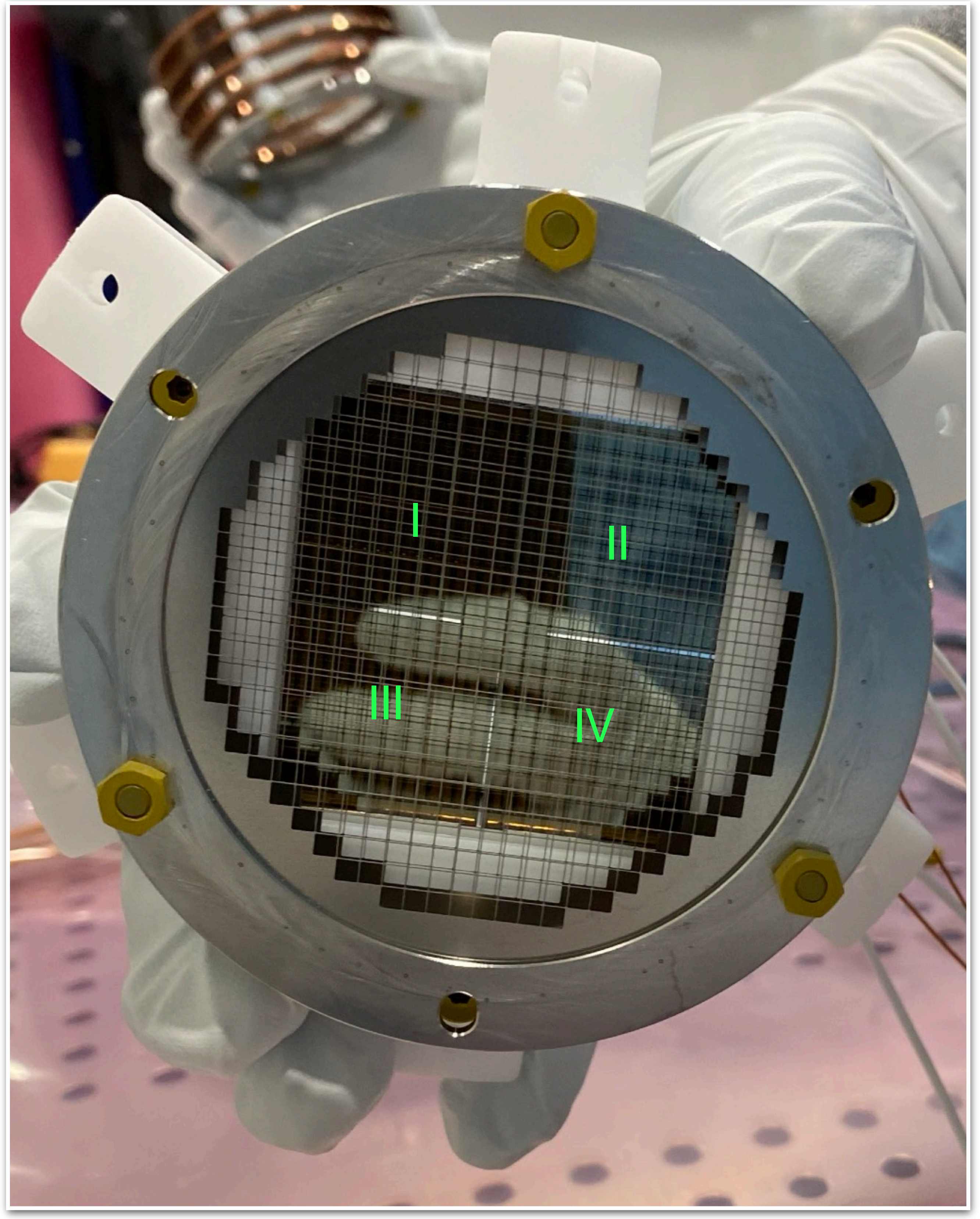
## Afterpulsing

- Timing: ion drift path and mass-to-charge ratio
- Expected timing order of magnitude faster than R11410-21 PMTs
- Different AP treatment needed
- For 8PE/trigger occupancy, separable AP rate: (0.90±0.2)%/PE → hard to compare



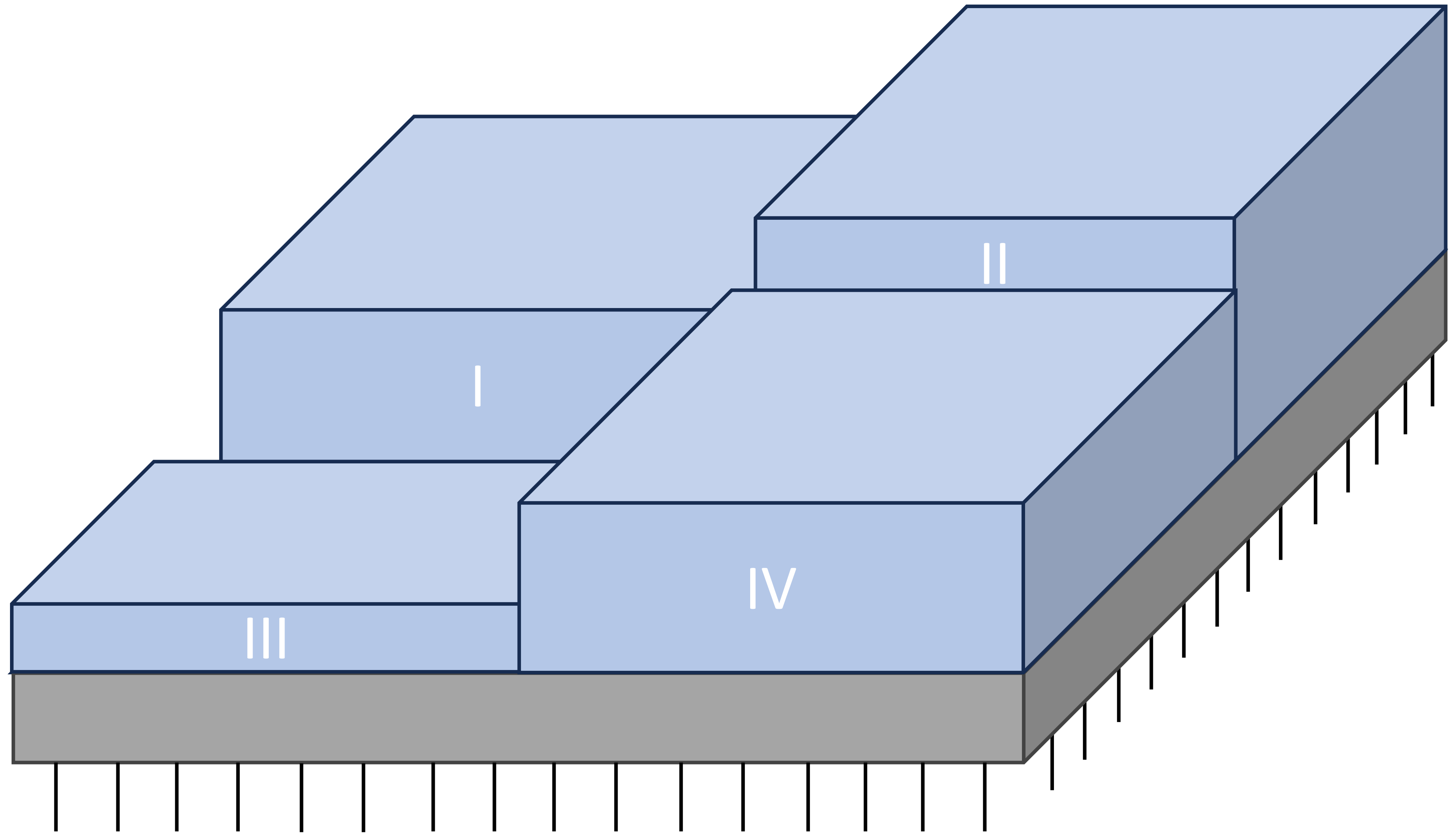
# Characterization results

## Position reconstruction




XAMS Top PMT holder including anode and top screening meshes

$$X = \sum_{i=1}^{4} \frac{x_i I_i}{I_{total}}$$




Center of gravity method

# Characterization results

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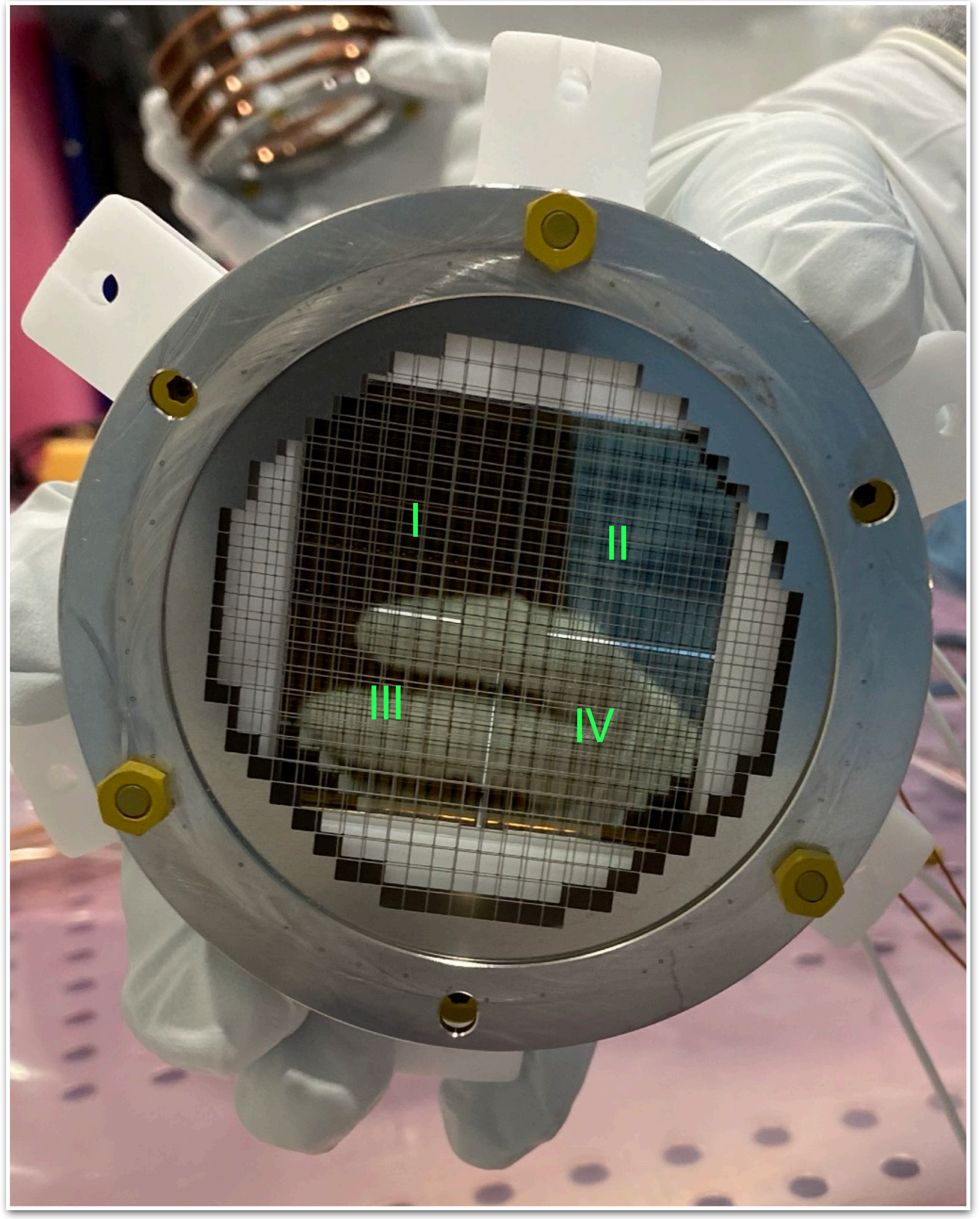


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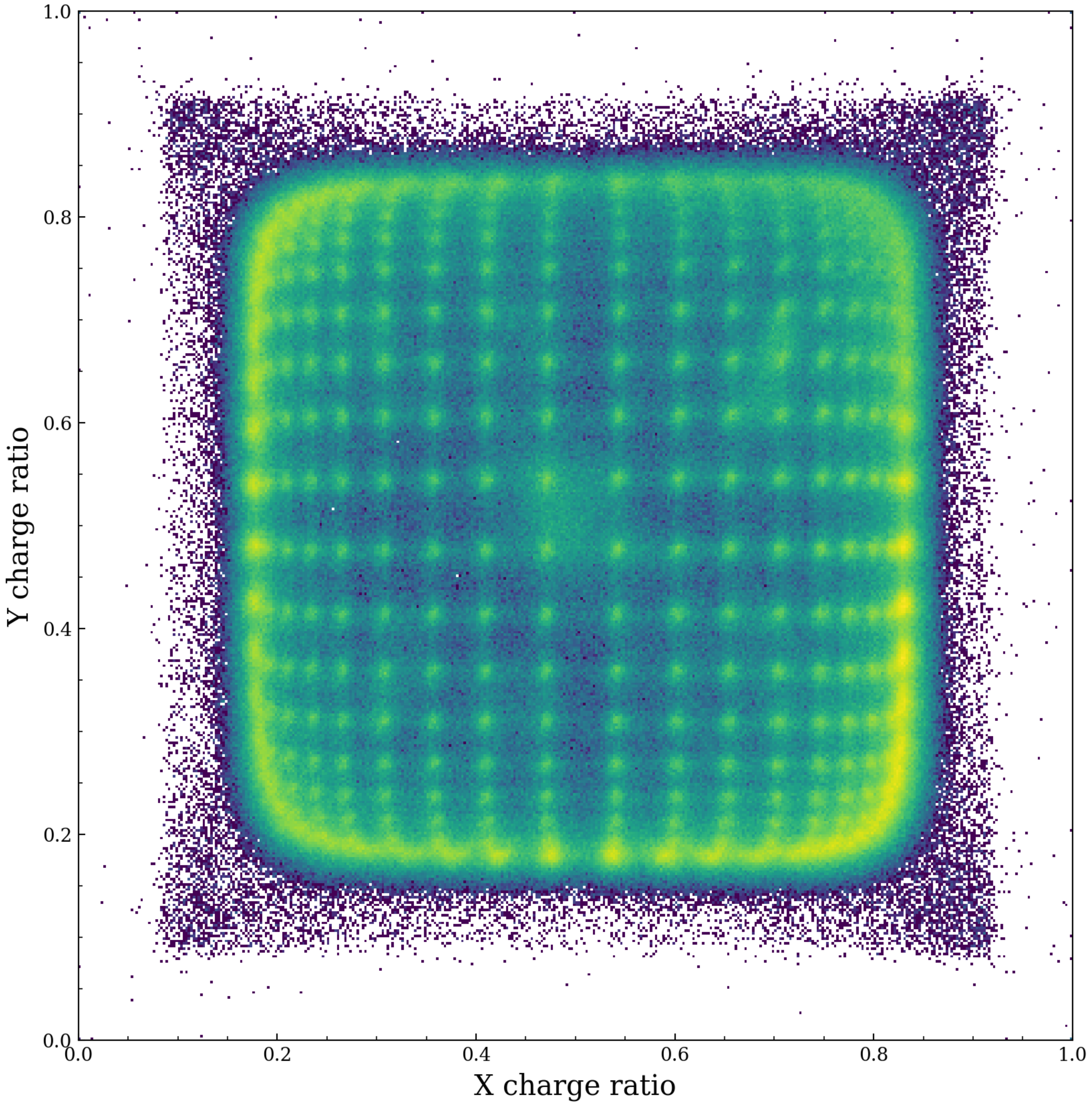

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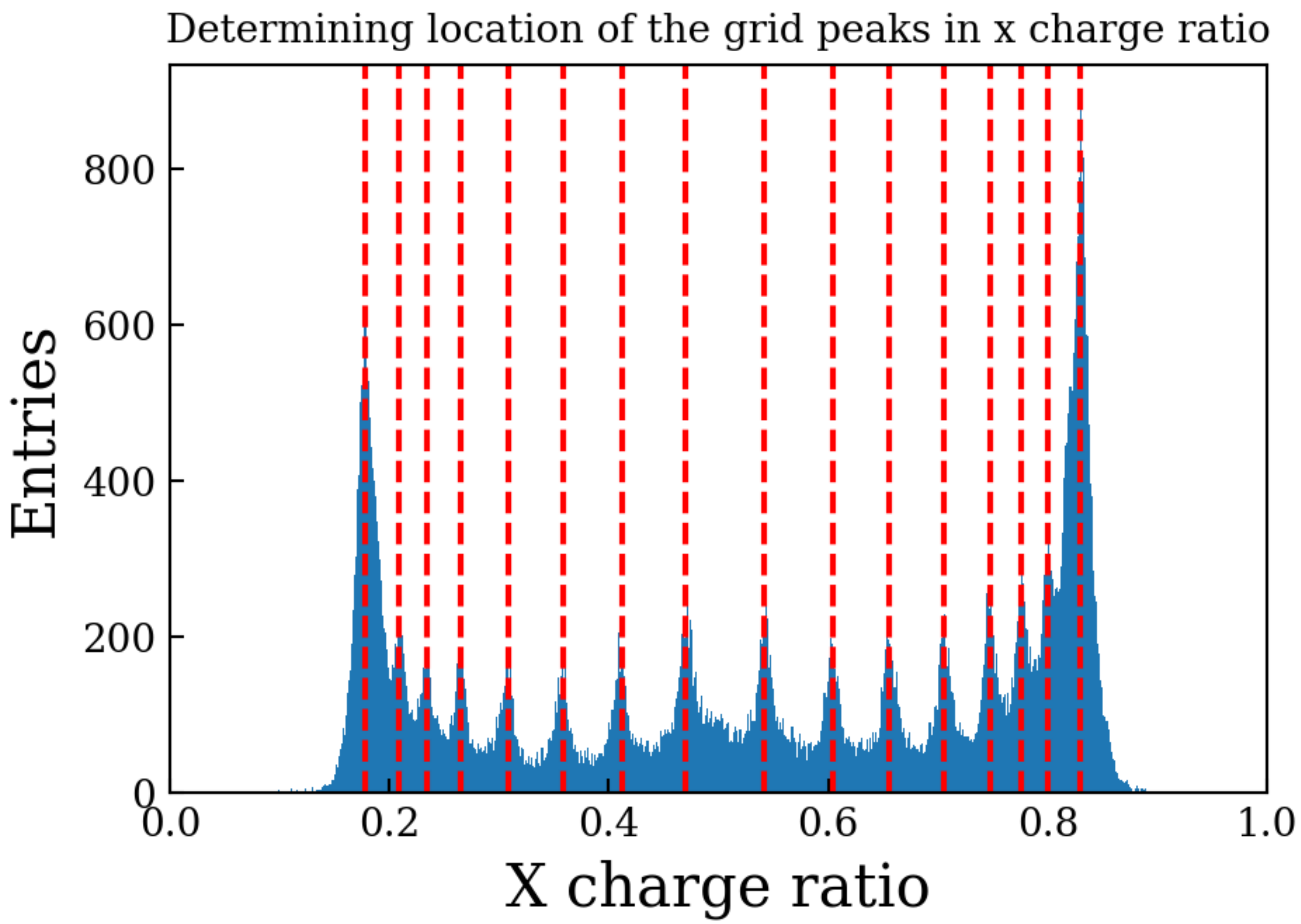


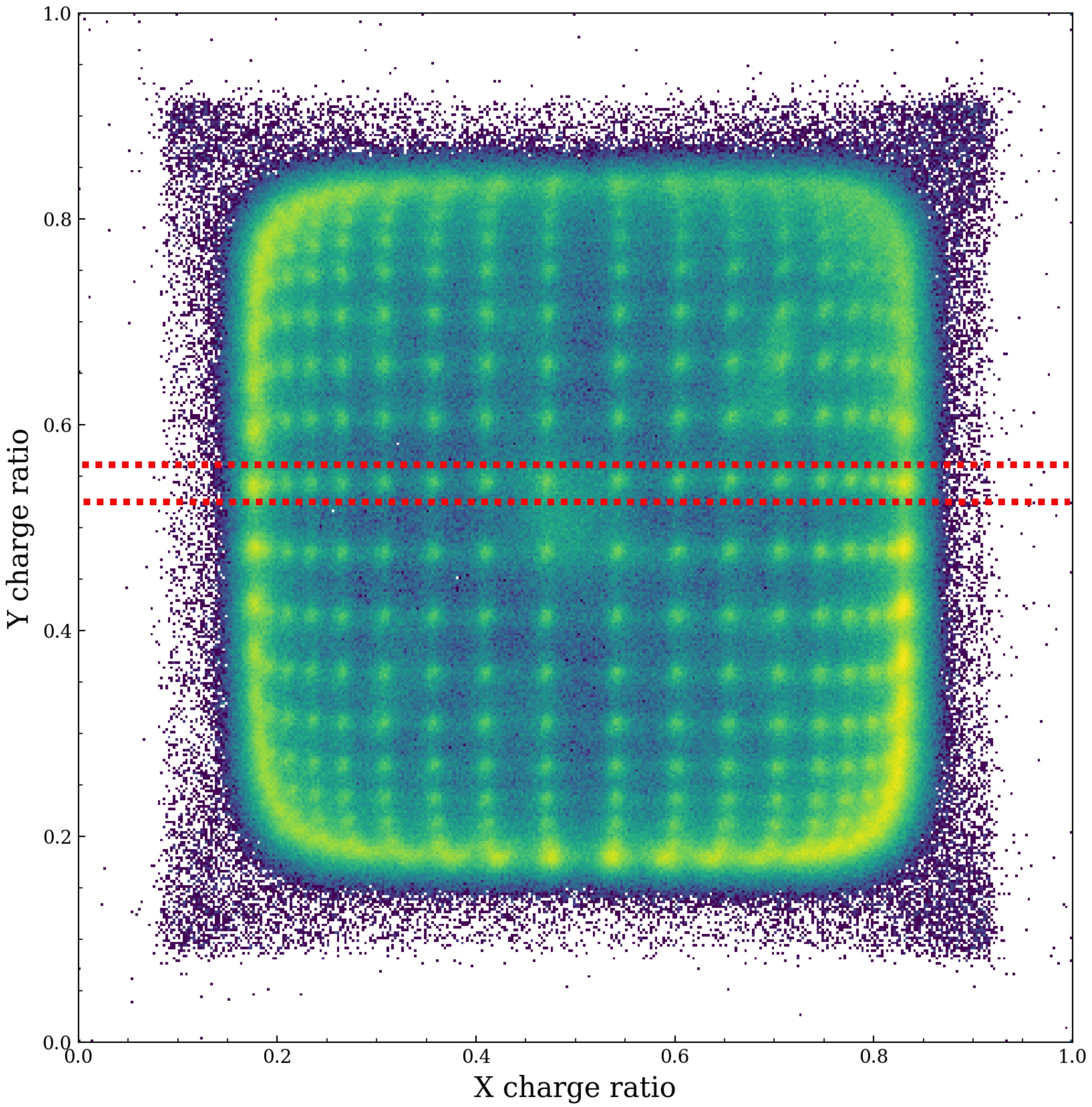

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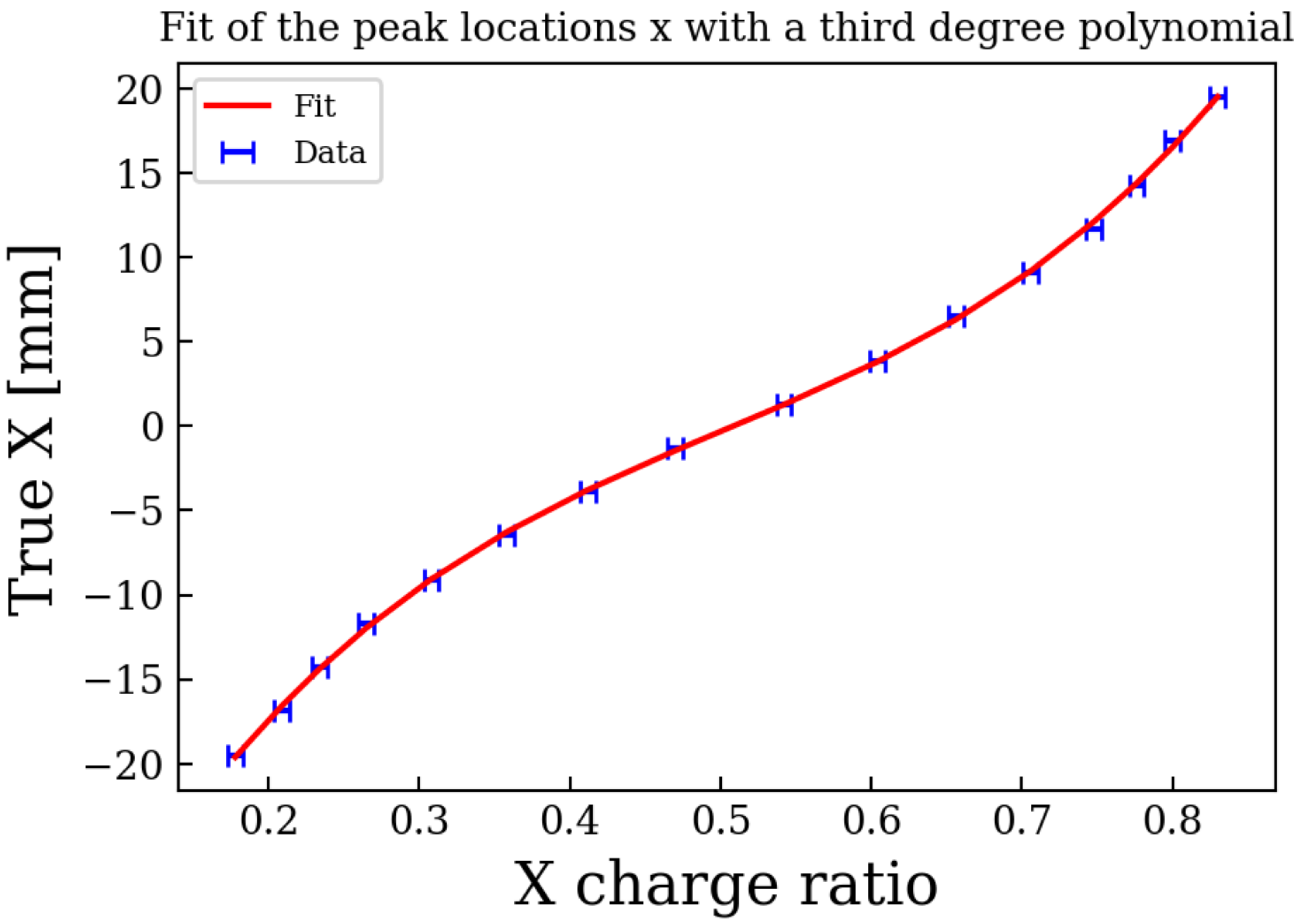


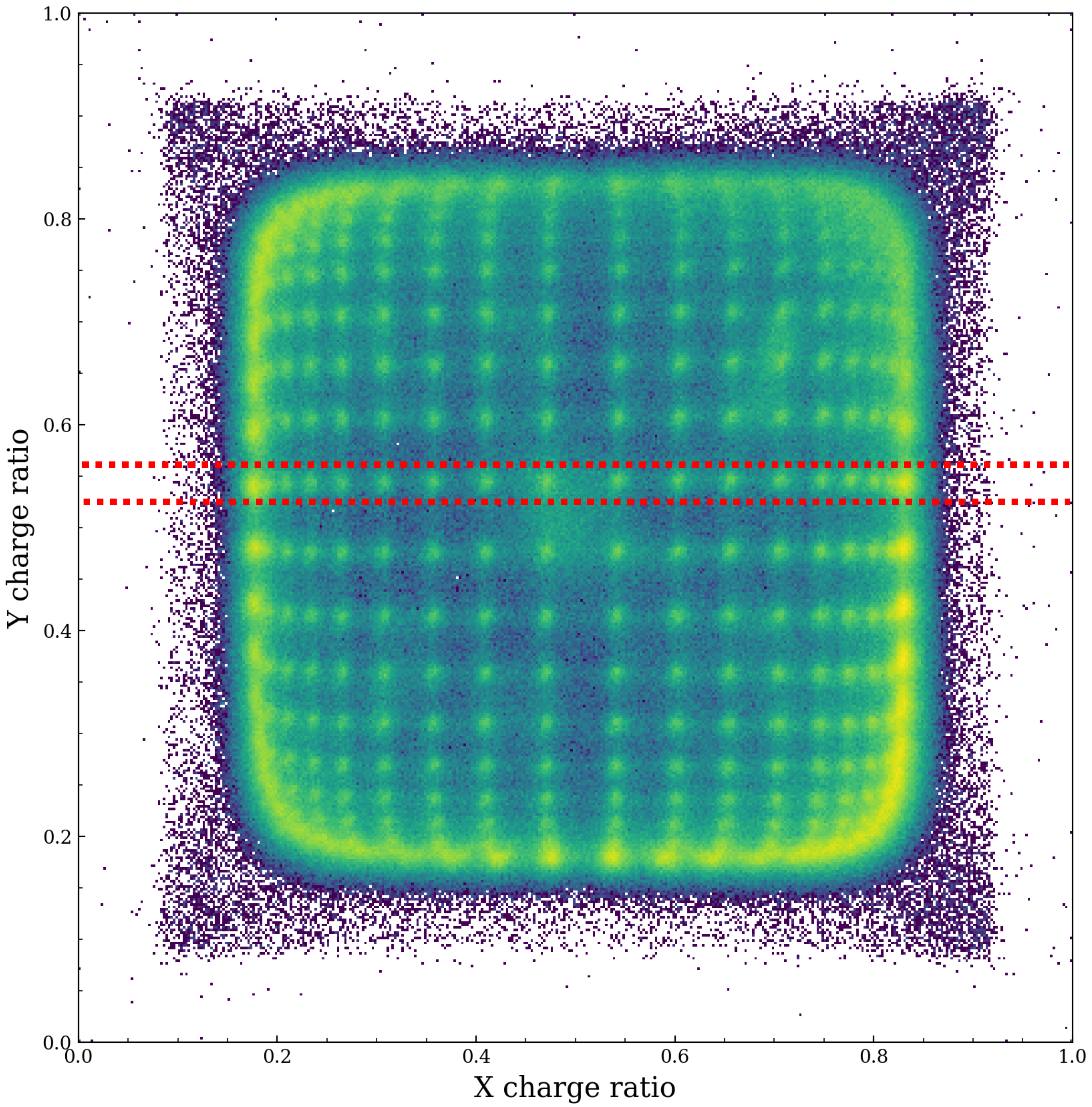

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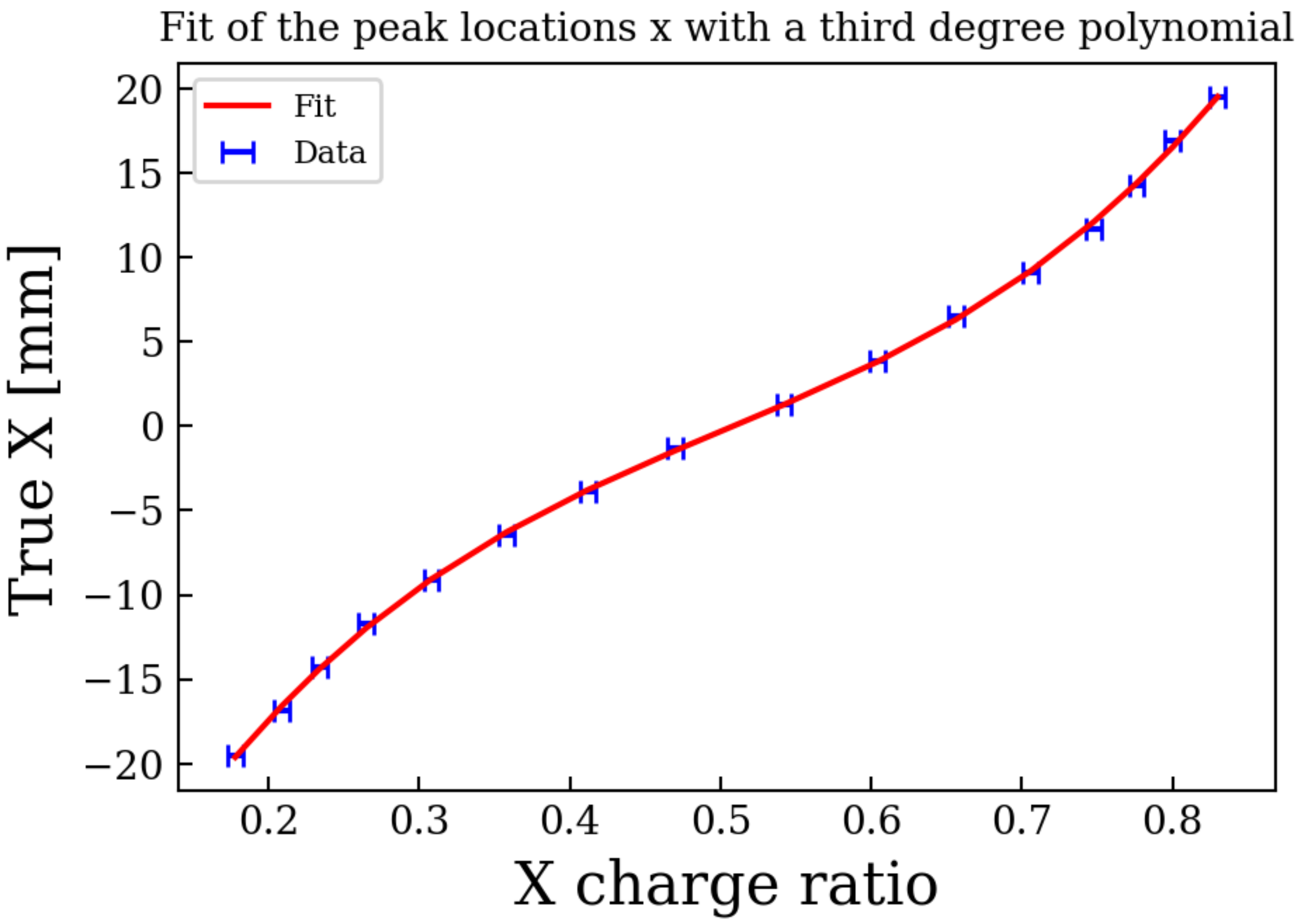


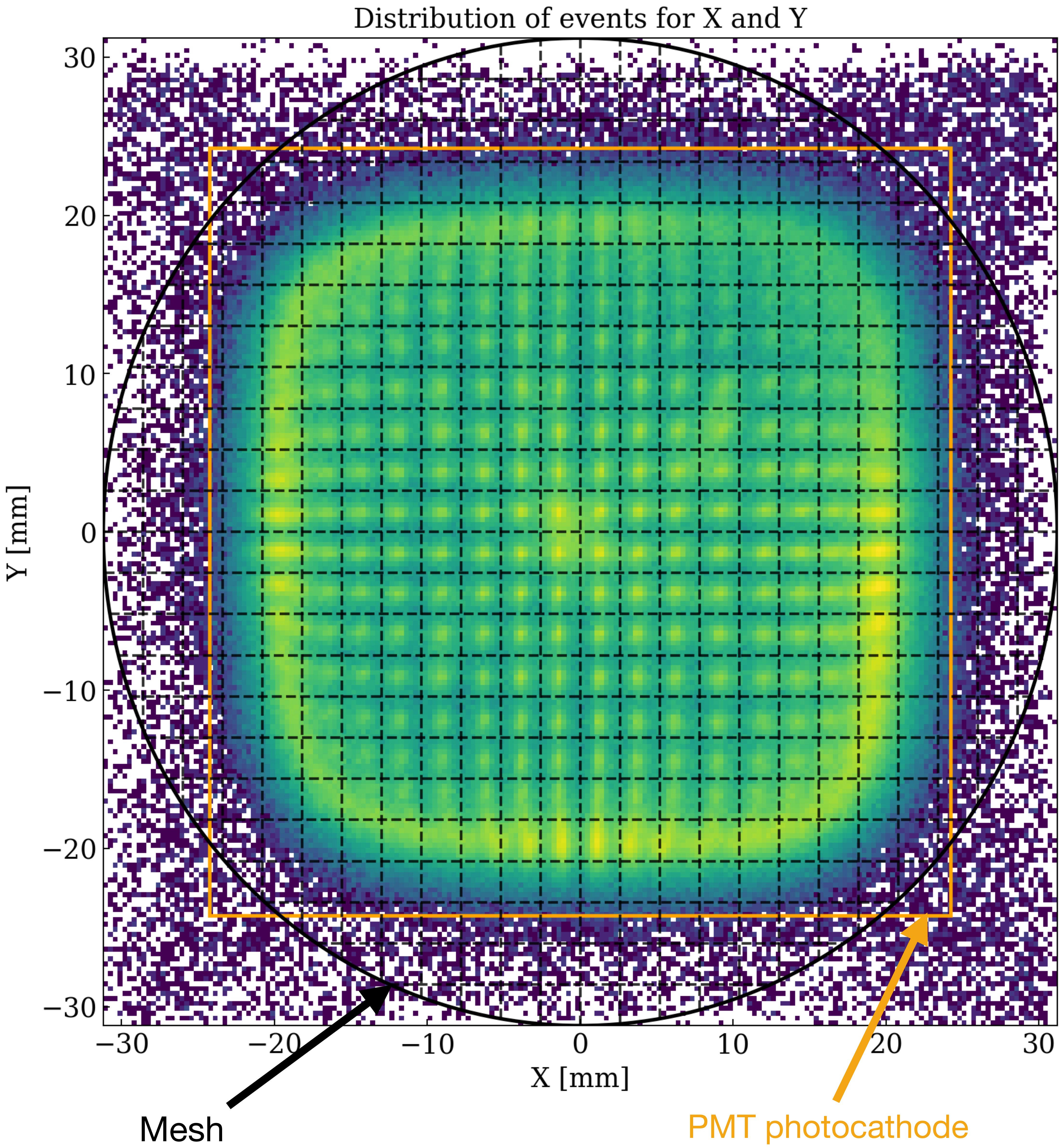

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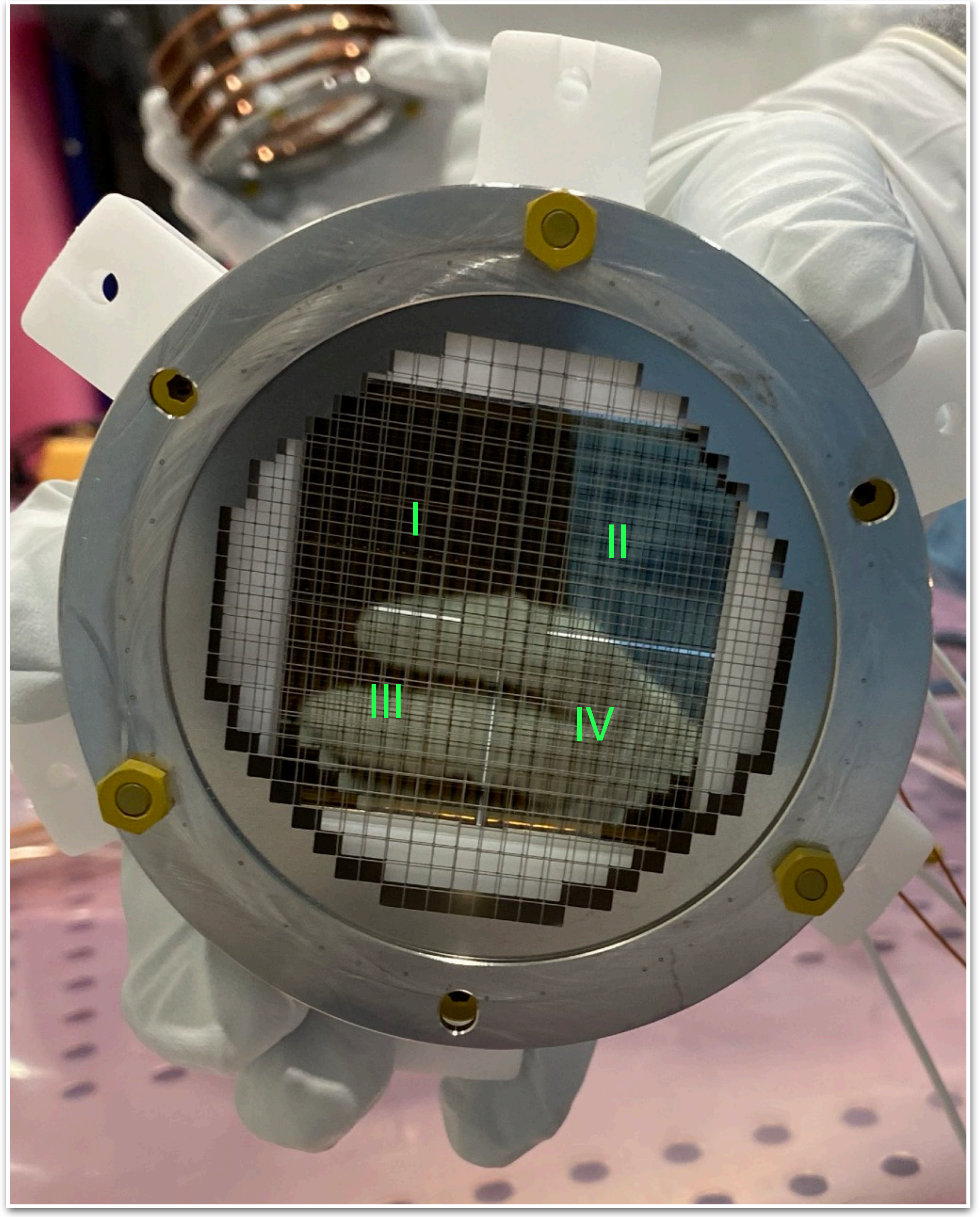


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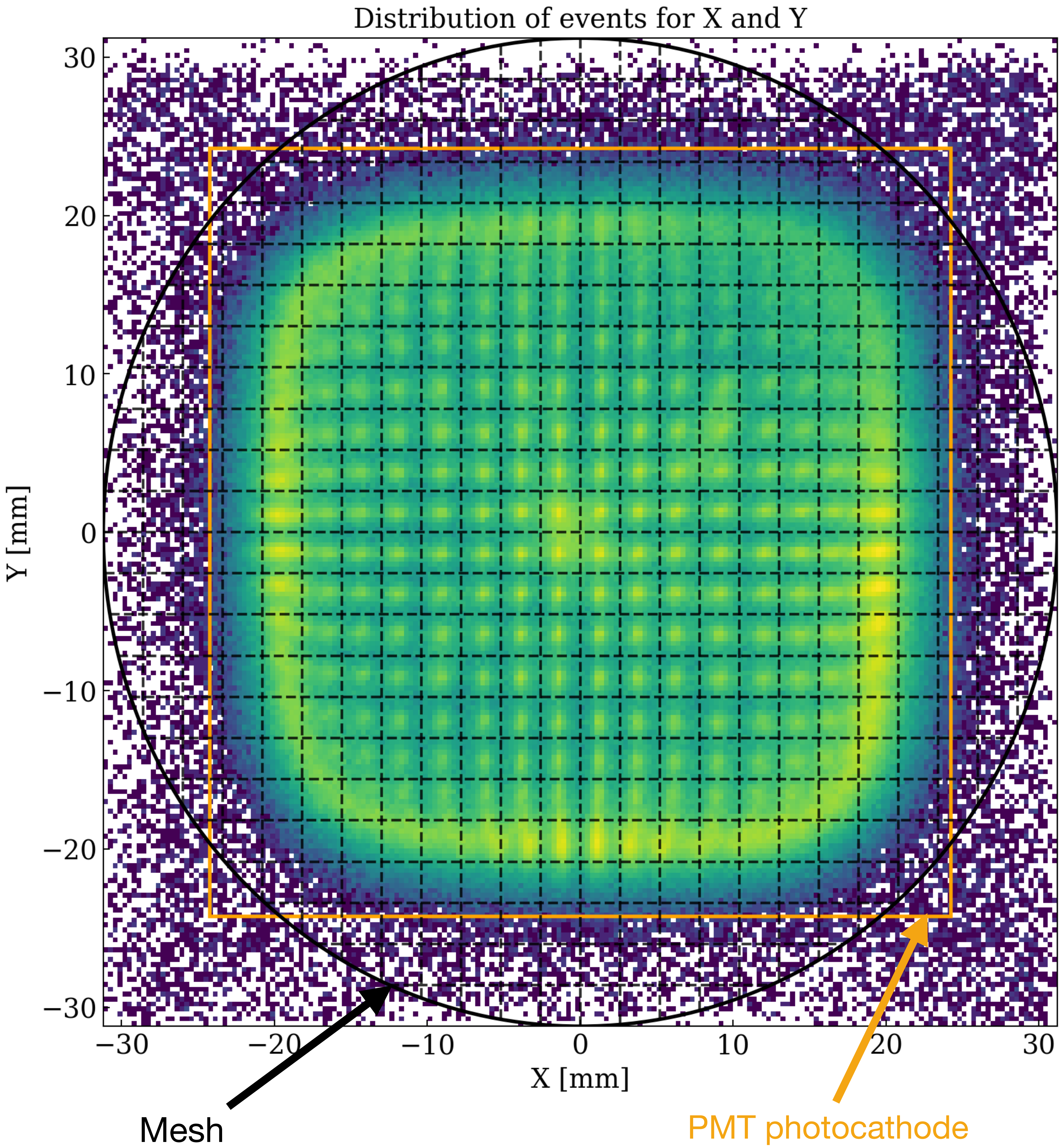
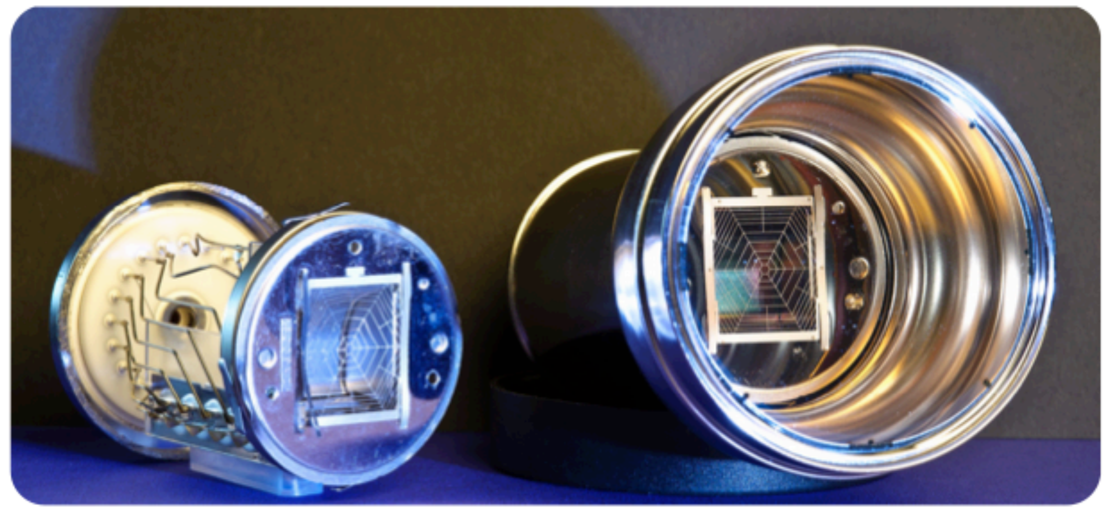


# Summary and comparison

## R12699 & R11410-21

+ position reconstruction!



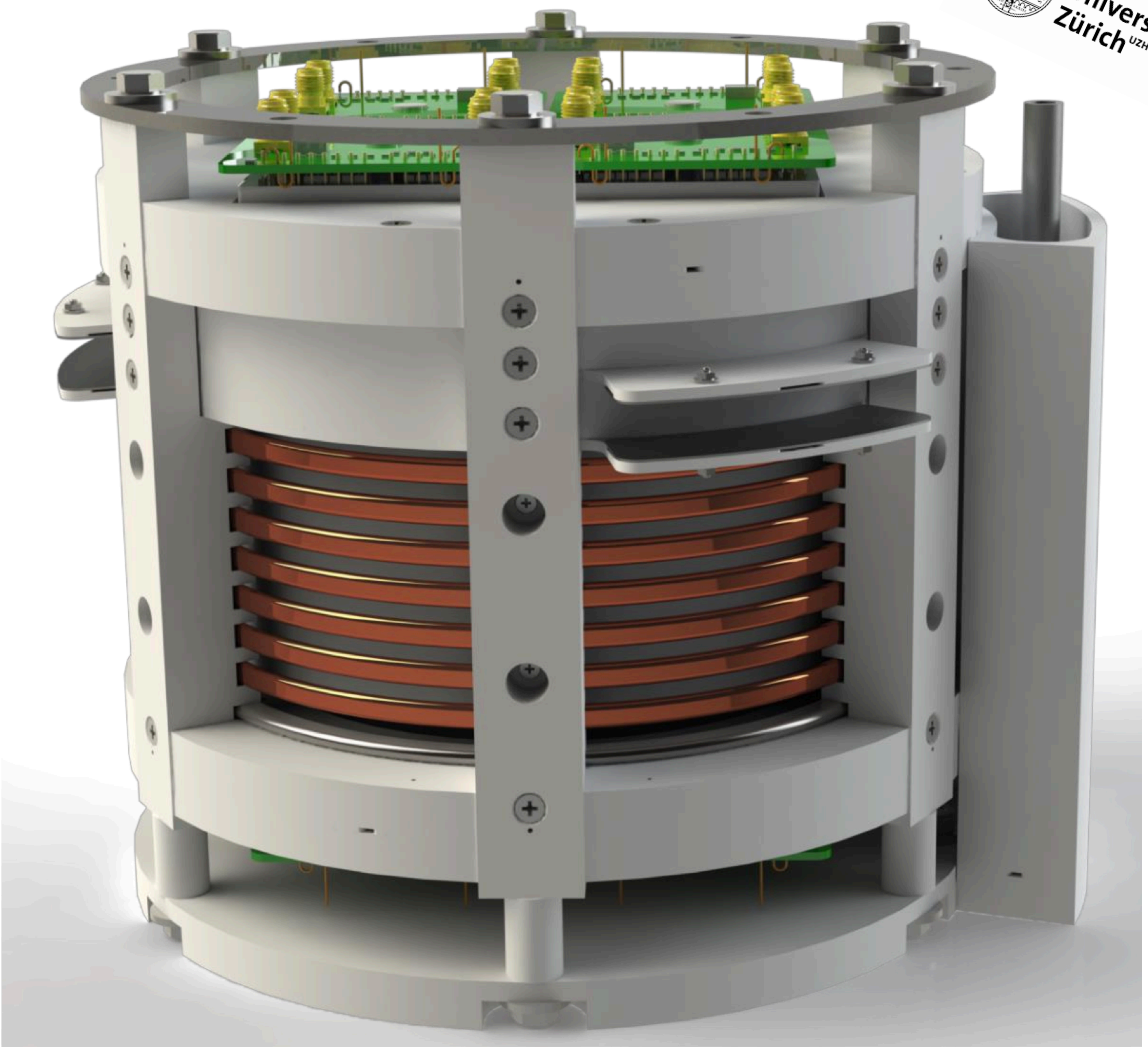
| | | | |
|---|---|---|---|
| Dimensions | ↕ 114 mm ⌀ 77.5 mm | ↕ 14.8 mm ↔ 56 mm | + |
| Packing density | 61.8 % | 75.0 % | + |
| Dynodes (structure / number of stages) | Box & linear-focused / 12 | Metal channel / 10 | |
| Operation voltage (nominal / maximum) | 1500 V / 1750 V | 1000 V / 1100 V | + |
| Quantum efficiency at 175 nm (data sheet / effective) | 32.5 % / (34.5±2.8) % | 33 % / *tbd* | + |
| Gain (data sheet / effective) | $3.5 \cdot 10^6$ / $(5.4 \pm 2.1) \cdot 10^6$ | $1.5 \cdot 10^6$ / $(3.0 \pm 0.8) \cdot 10^6$ | |
| Time response (Rise time / Transit time / Transit time spread) | 5.5 / 46 / 9 ns | 1.2 / 5.9 / 0.41 ns | + |
| Expected $He^+$ afterpulse delay | 0.5 µs | 0.03-0.06 µs | − |
| Dark count rate (-100°C, >¼ PE) | (1.4±0.7) $Hz/cm^2$ | (0.5±0.2) $Hz/cm^2$ | + |

See https://agenda.ciemat.es/event/4282/contributions/5135/attachments/3439/5445/Lidine_Bismark_2023.pdf

# Outlook

## Ongoing studies

- Long term stability tests
  - Gain/SPE response
  - Afterpulse rate
- Extend characterization to more PMTs
- Assembly of 2x4 TPC setup at UZH
- Improving position reconstruction resolution by building simulation of XAMS



Design of 2x4 setup at UZH

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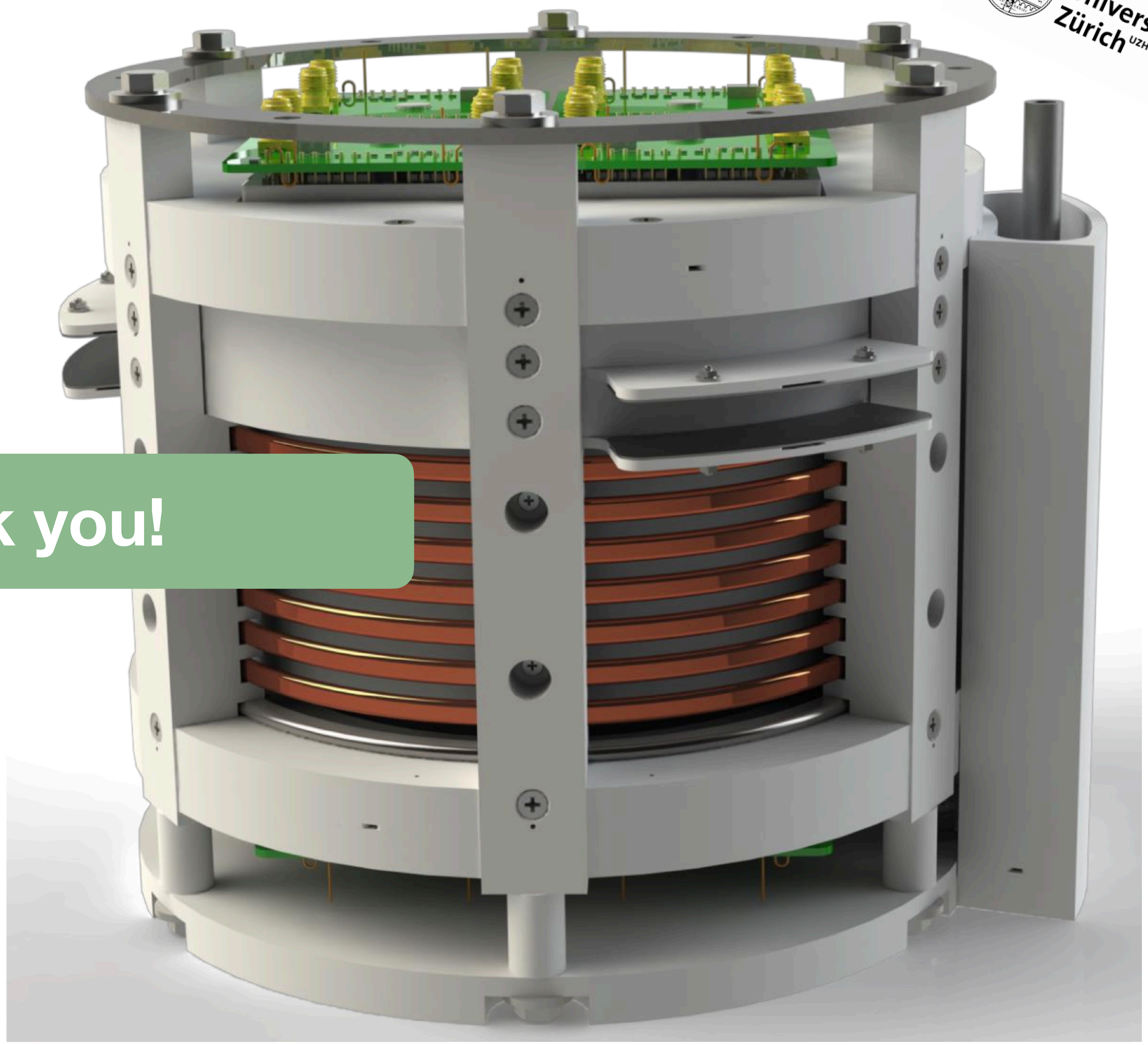
**Thank you!**

Universität Zürich UZH



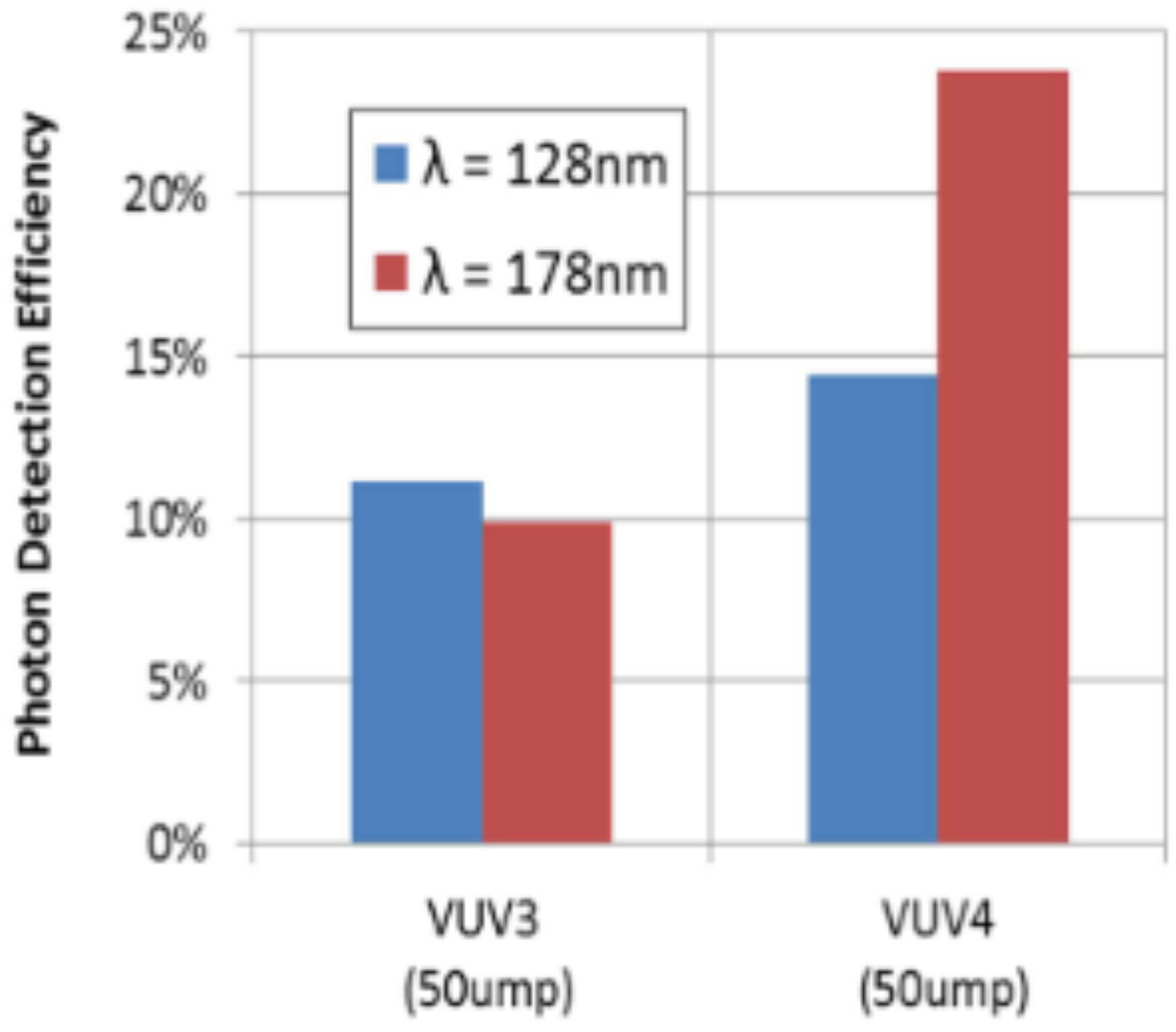
Design of 2x4 setup at UZH

# Backup slides

# SiPMs

## Pros and cons

- Pros:
  - No high voltage needed
  - Cheap
  - Low radioactivity
- Cons:
  - We need a large photosensitive surface → high channel count (high DCR, lots of cables, high data stream, etc)
  - Lower QE ~20% for UV sensitive SiPMs



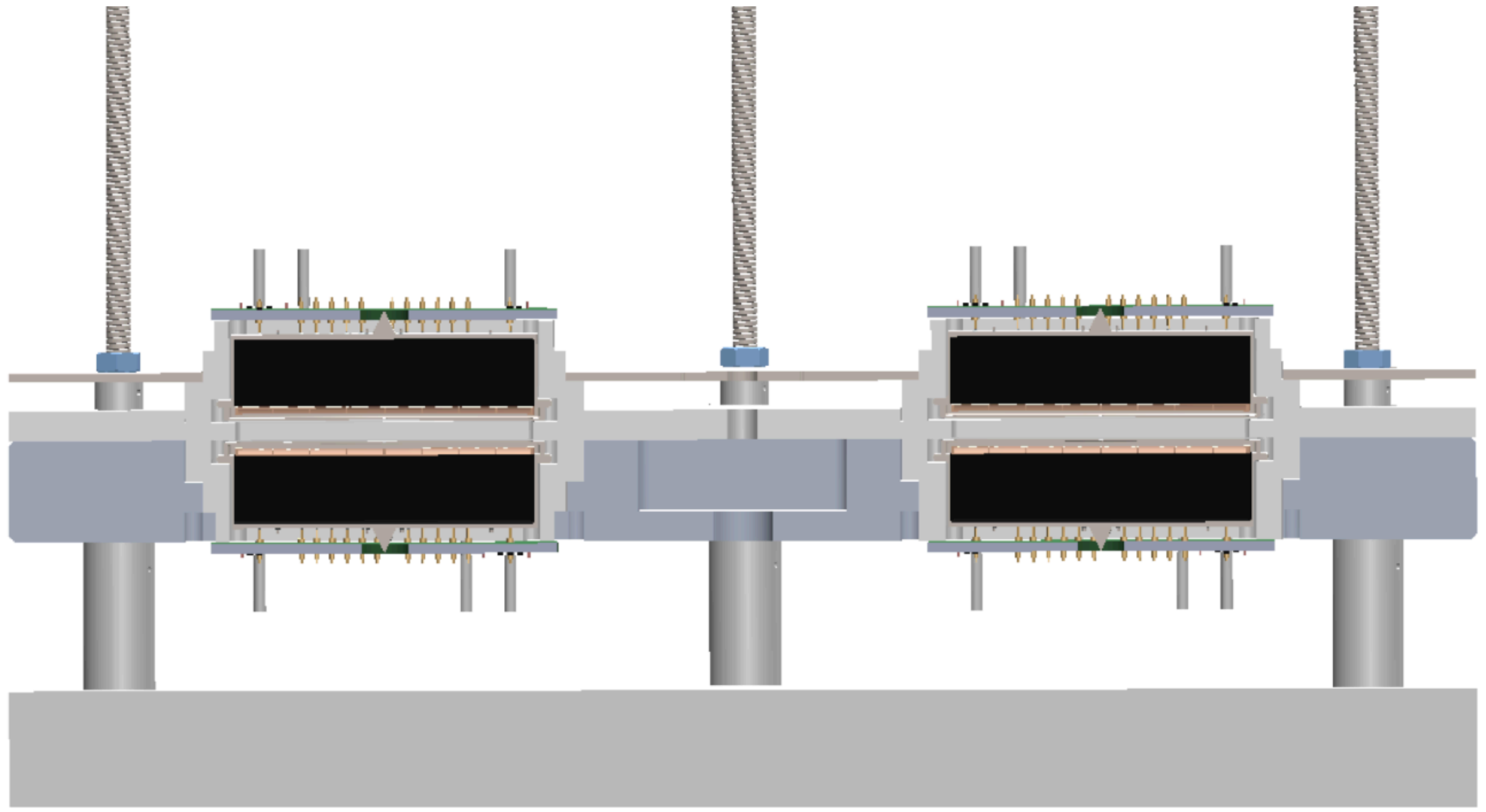

From Hamamatsu datasheet

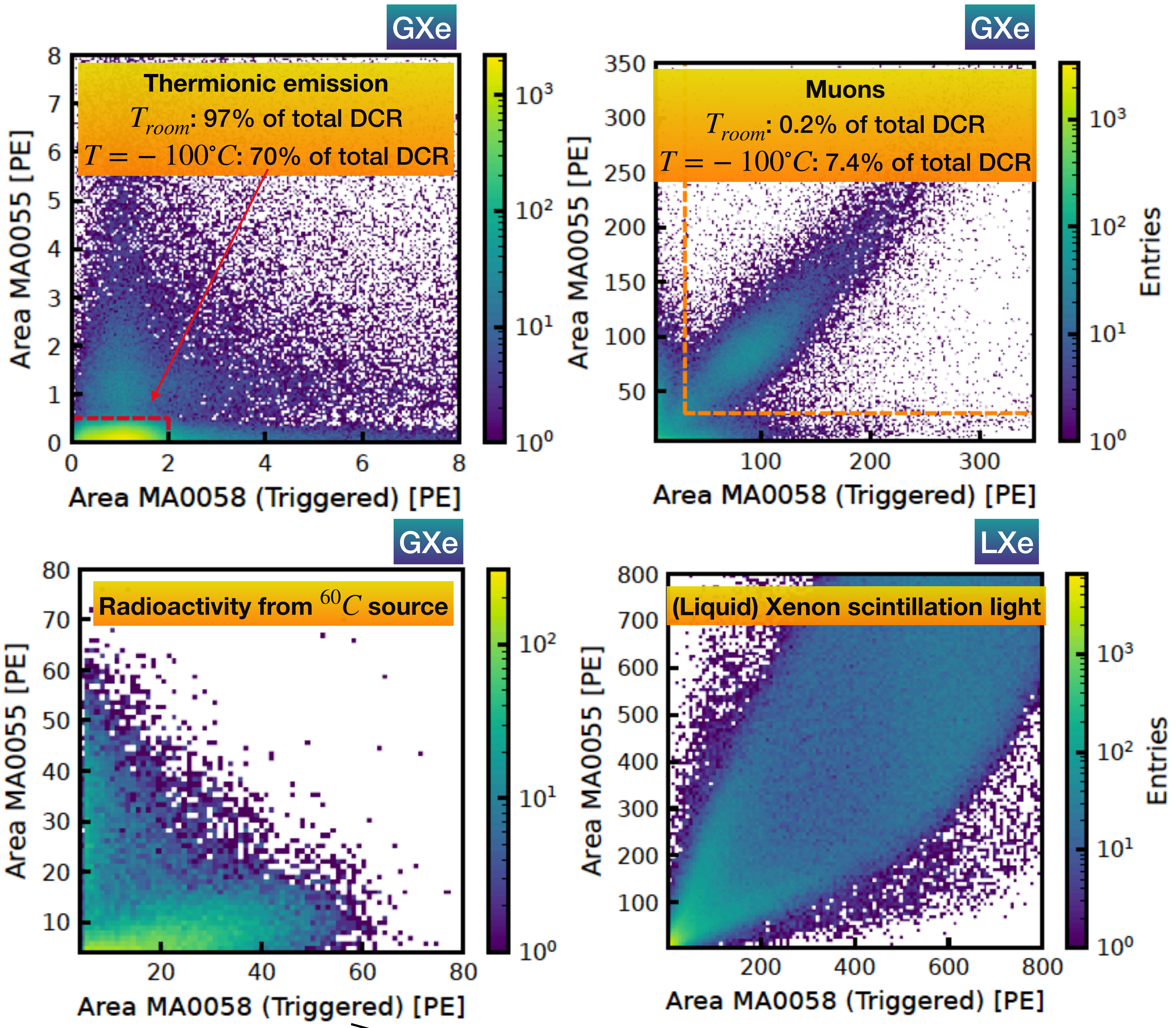
# DCR to AC estimation

## Very preliminary

- Semi-analytical (partially simulation, partially theory) model to predict AC rate as a function of:
  - Dark Count Rate
  - Detector parameters (g1, g2, SEG, electric fields, etc)
  - Detector geometry (size, number of PMTs, etc)
- Matched to XENON1T data
- Extrapolated to DARWIN-sized detector

# DCR and LE






1/4 PE threshold

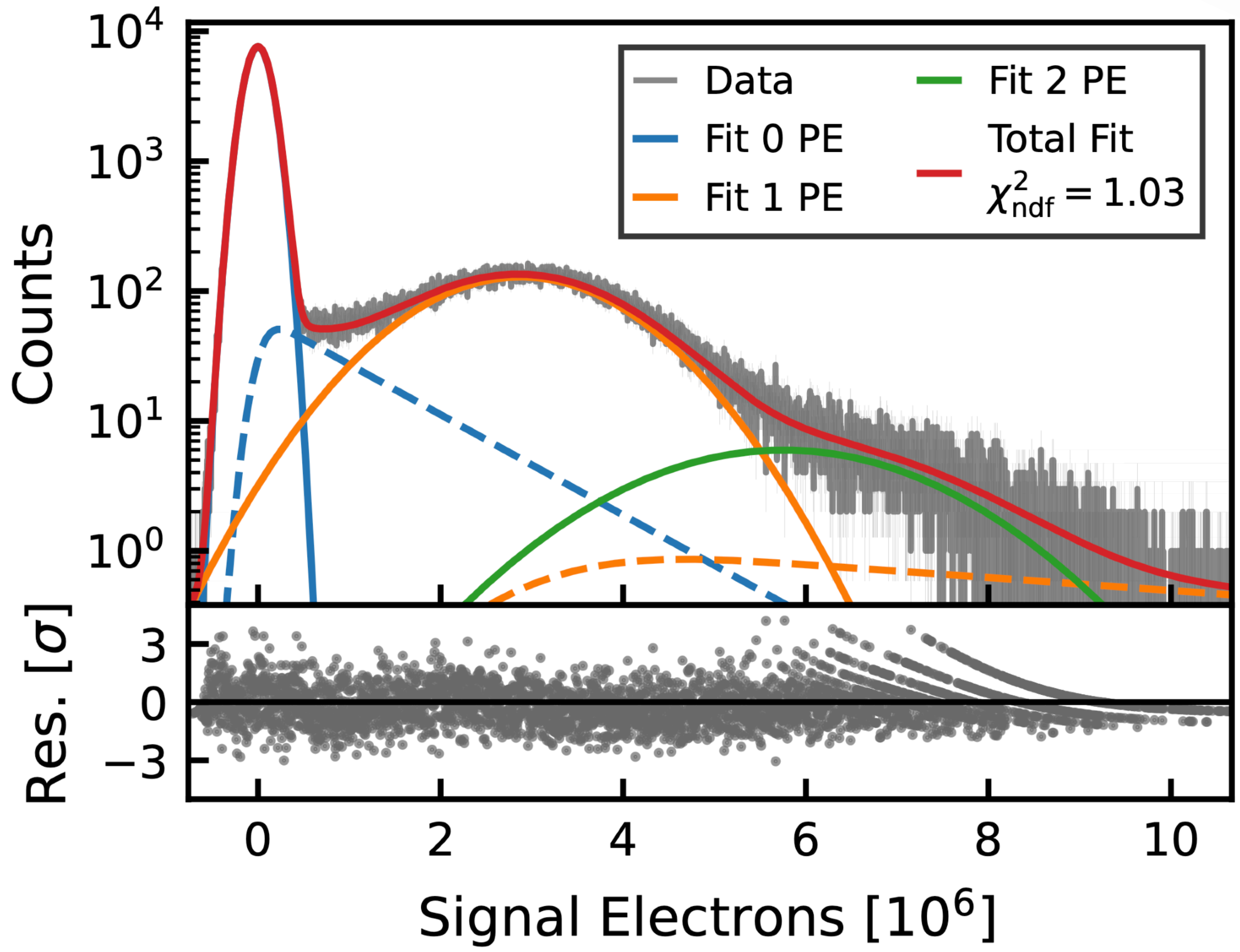
# Model independent approach[1]

## Determination of the SPE response

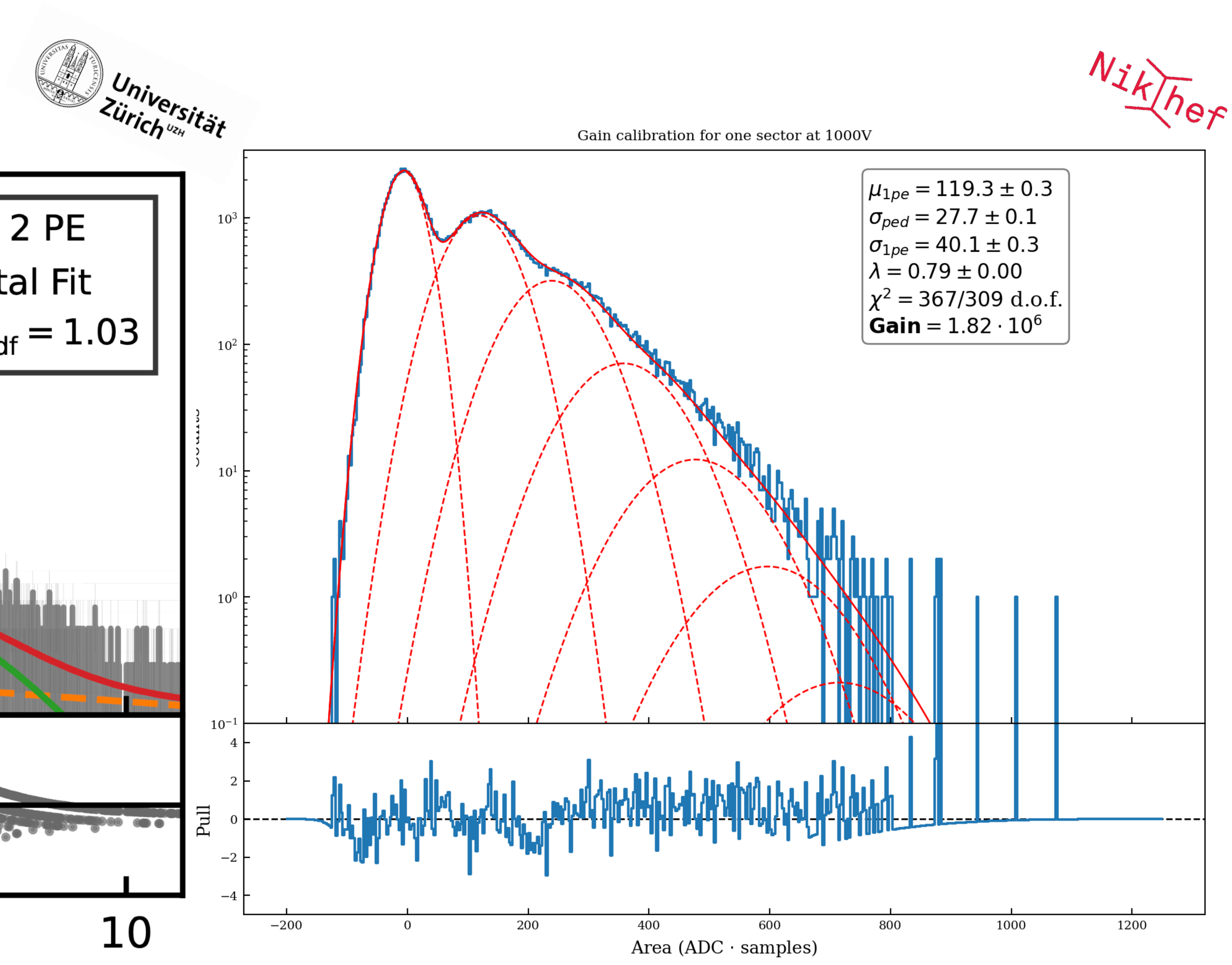
- Fitting
  - Shape of PMT charge spectrum of **fully amplified** PE not known
  - SPE response under amplified due to sub-optimal trajectories through the dynode chain
  - Noise spectrum not known a priori
- Model independent approach
  - Full spectral shape of SPE response not needed
  - Only mean and variance of the SPE distribution + occupancy

[1] Saldanha, R., Grandi, L., Guardincerri, Y., & Wester, T. (2017). Model independent approach to the single photoelectron calibration of photomultiplier tubes. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *863*, 35-46.

# SPE fitting

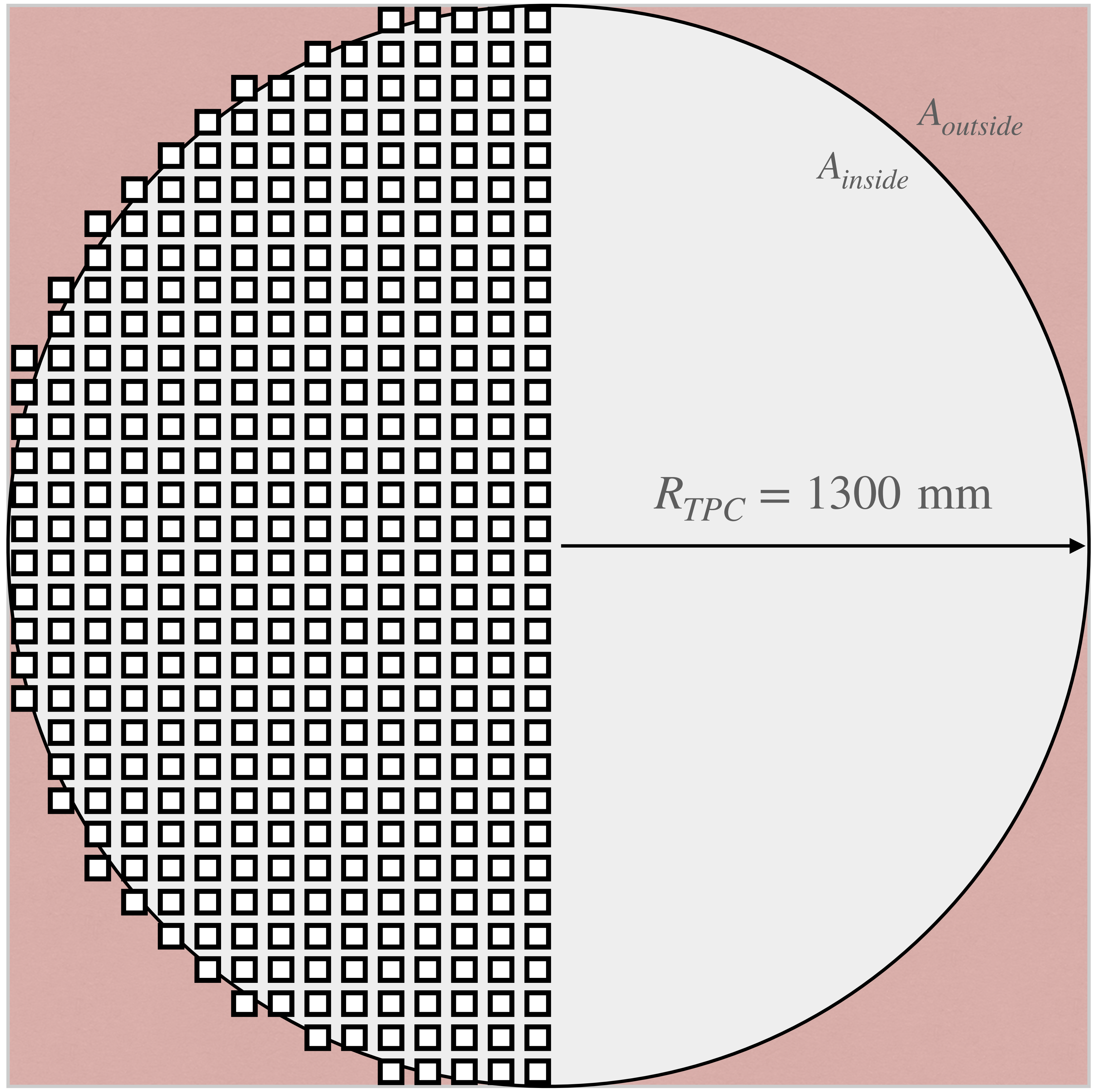


Counts
Data
Fit 0 PE
Fit 1 PE
Fit 2 PE
Total Fit
$\chi^2_{ndf} = 1.03$
Res. [$\sigma$]
Signal Electrons [$10^6$]

Universität Zürich UZH
Nikhef
Gain calibration for one sector at 1000V
$\mu_{1pe} = 119.3 \pm 0.3$
$\sigma_{ped} = 27.7 \pm 0.1$
$\sigma_{1pe} = 40.1 \pm 0.3$
$\lambda = 0.79 \pm 0.00$
$\chi^2 = 367/309$ d.o.f.
**Gain** $= 1.82 \cdot 10^6$
Pull
Area (ADC · samples)

# Number of 2-inch PMTs in DARWIN




$$A_{outside} = (2 \cdot R_{TPC})^2 - A_{inside} = 1.45 \cdot 10^6 \text{ mm}^2$$

$$A_{inside} = \pi \cdot R_{TPC}^2 = 5.31 \cdot 10^6 \text{ mm}^2$$

$$A_{PMT} = (56 + 10)^2 \text{ mm}^2$$

*Margin*

$$N_{PMT} = \frac{A_{inside} + \left\lfloor \frac{A_{outside} - A_{inside}}{A_{PMT}} \right\rfloor}{A_{PMT}} \cdot 2 \approx 2440$$

# Direct detection

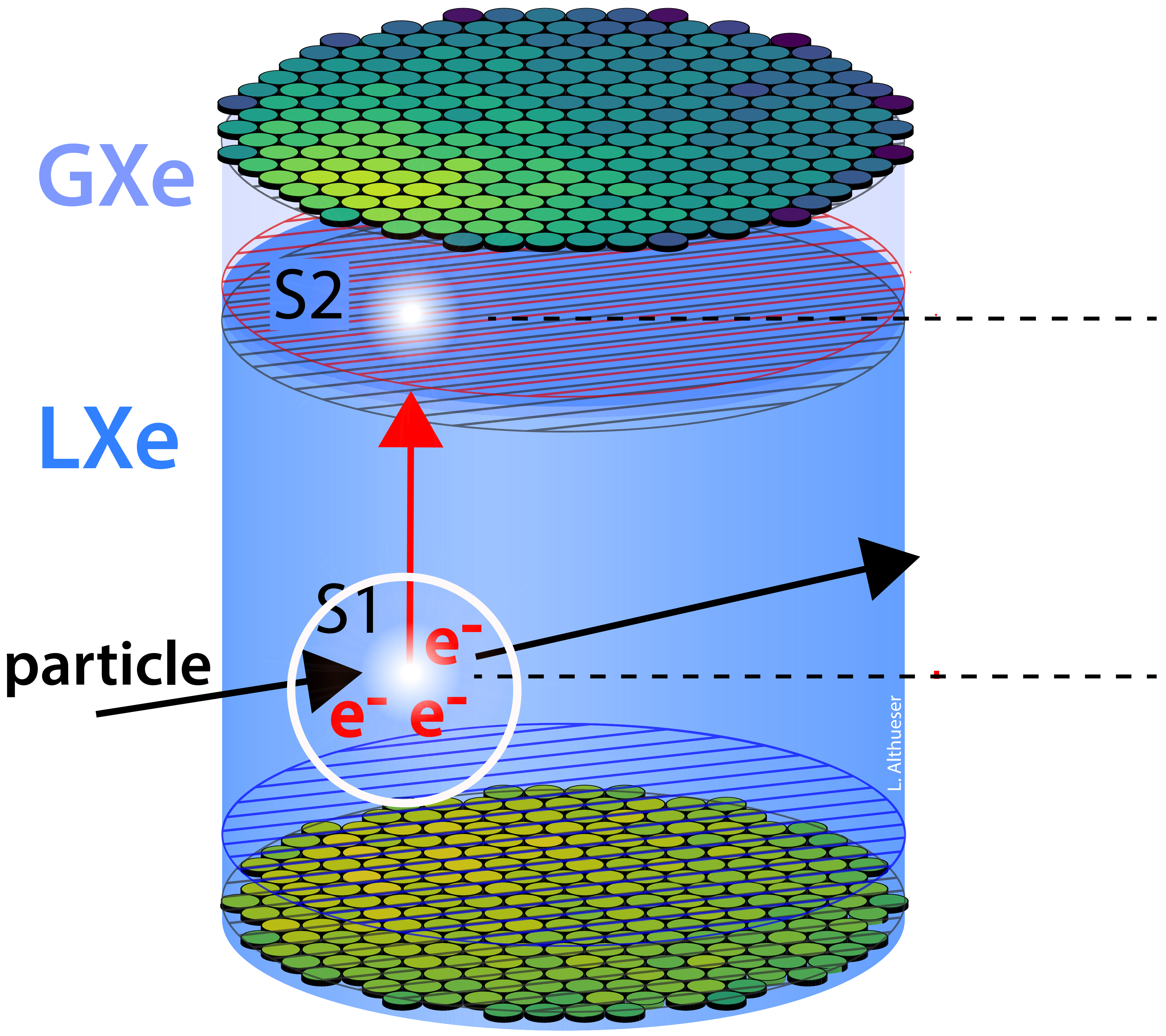
## Dual-phase xenon TPC working principle

1. Particle interacts with the xenon atom, which ionizes and excites the xenon

2. Excited and ionized xenon forms dimer states and de-excite: S1 (mostly bottom PMT array)

3. Freed electrons drift up due to electric field

4. Between the gate and the anode, extraction field causes proportional scintillation of the xenon: S2 (mostly top PMT array).



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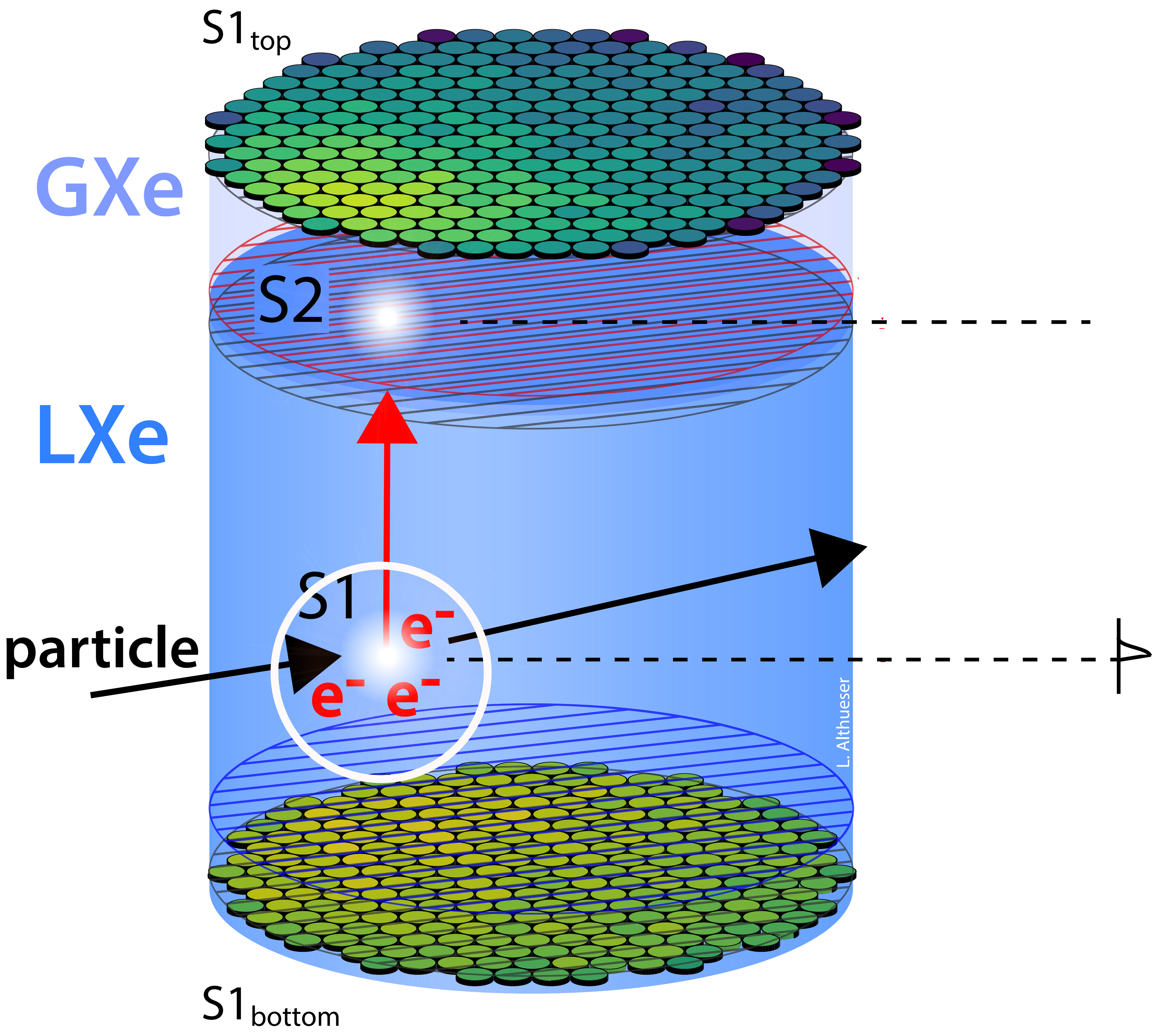

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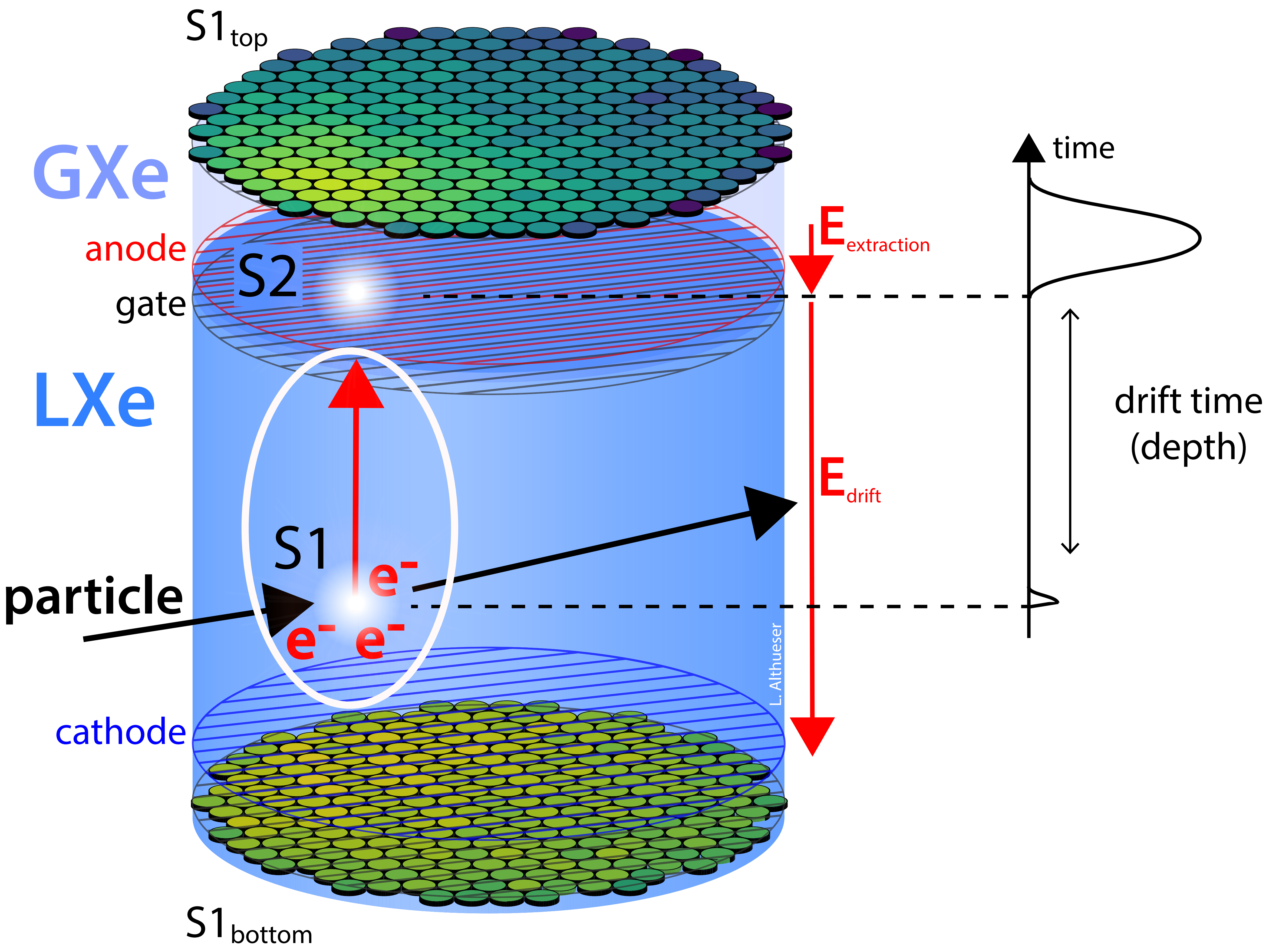

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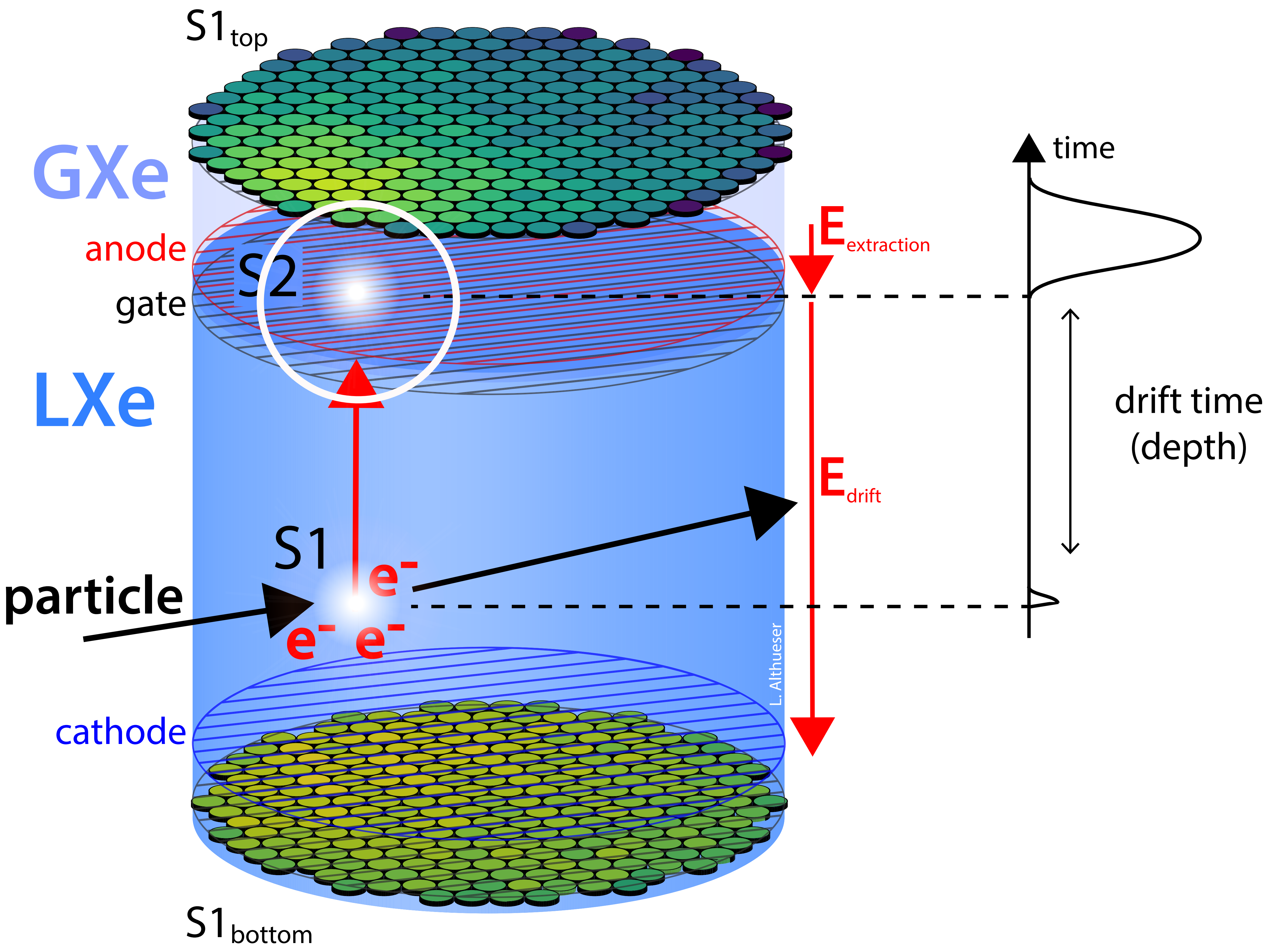

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