SiPM Experience and Lessons from TAO

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On behalf of the JUNO collaboration

Institute of High Energy Physics

CEPC Workshop, Shanghai, 2026

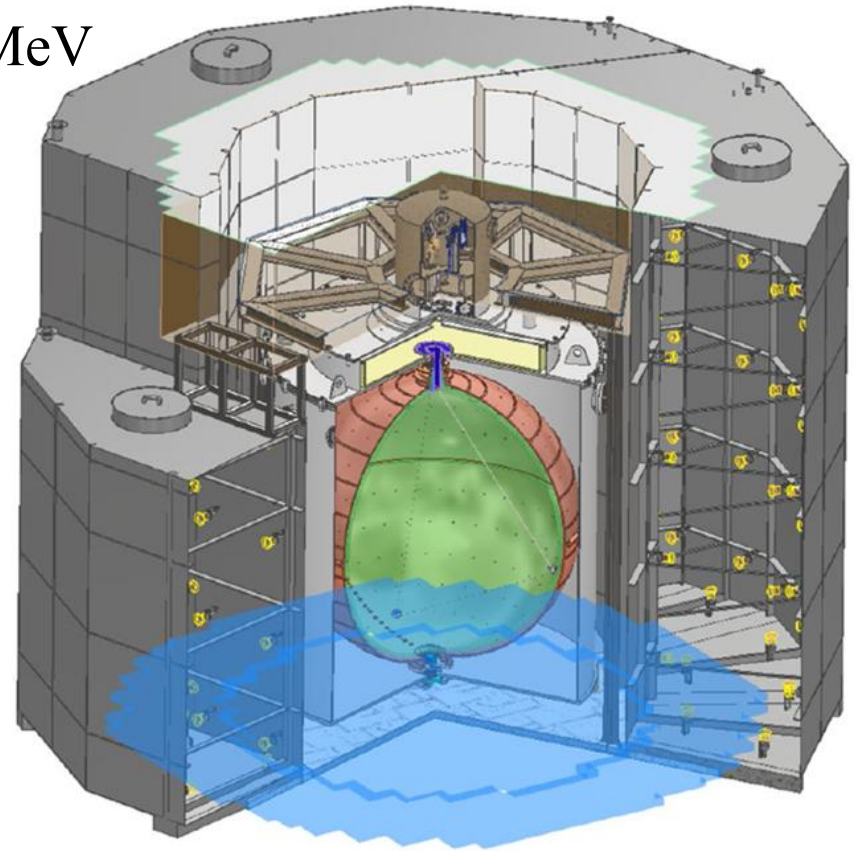
Outline

- TAO and its photodetector system
- SiPM selection and characterization
- Mass production and QA/QC
- Readout, detector installation and performance
- Lessons learned
- Summary

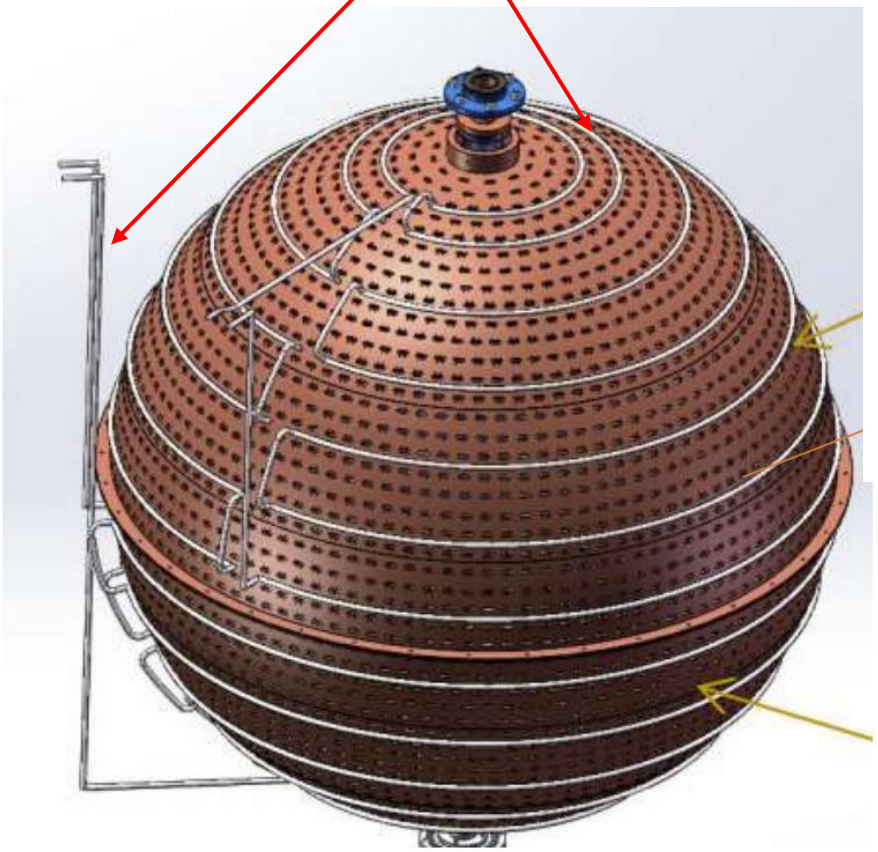
The TAO Experiment

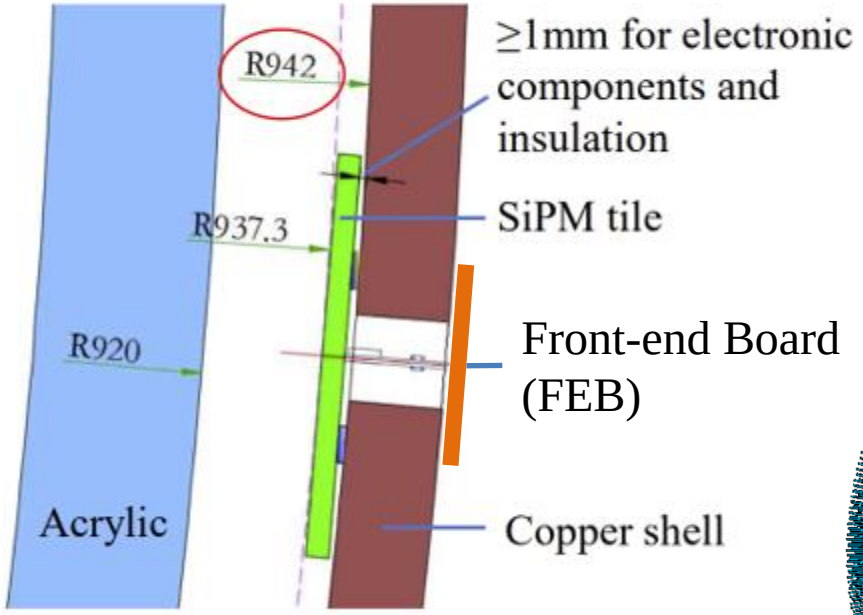
- A satellite experiment of JUNO, 43.2 m from one of reactor cores at Taishan NPP
  - Measure reactor neutrino spectrum w/ unprecedented energy resolution, ~2% @ 1 MeV
  - Provide reference data for JUNO and nuclear database
  - Fine structure observation and reactor anomaly investigation
  - Neutrino spectrum measurement from U/Pu, SNF, and other physics
- 2.8 ton Gd doped Liquid Scintillator (LS) detector, ~4500 p.e./MeV
  - 10 m^2 SiPM w/ high coverage and PDE
  - Operating at -50 ℃ to reduce DCR
  - New LS recipe for low temperature
- From Inner to Outside
  - Gd-LS contained in an acrylic vessel
  - SiPM and support (Copper shell)
  - LAB buffer + SS vessel
  - Two veto detectors, Water tanks + plastic scintillator
- Data taking began on Feb. 10, 2026

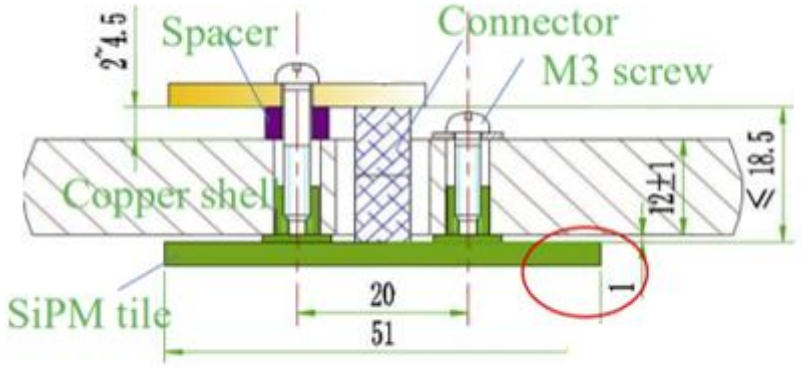
TAO CDR ready in 2020
arXiv:2005.08745



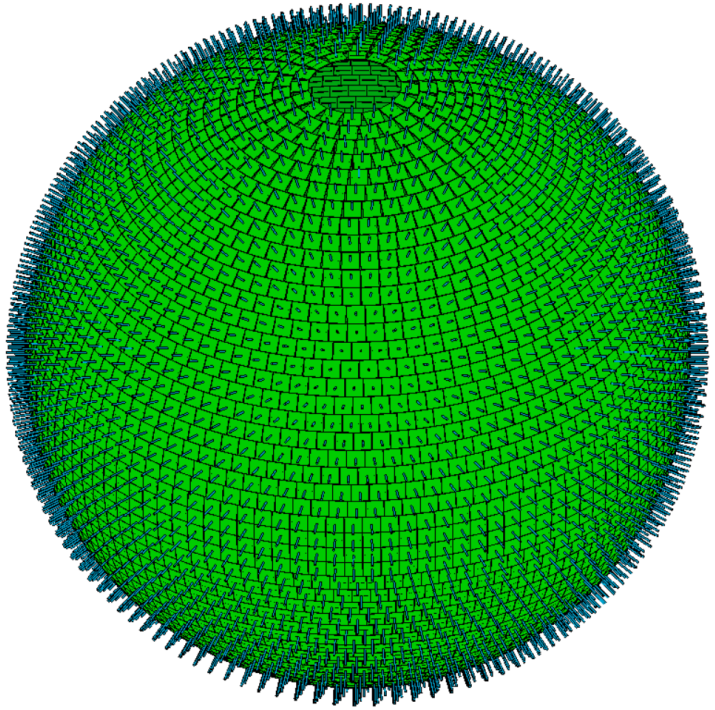
Cooling pipes







4024 SiPM tiles
5 cm × 5 cm each



Key SiPM Parameters

❄ SiPM performance directly propagates to detector-level observables

➢ Light yield, energy resolution, trigger threshold, timing resolution, background rate, dynamic range, and long-term stability

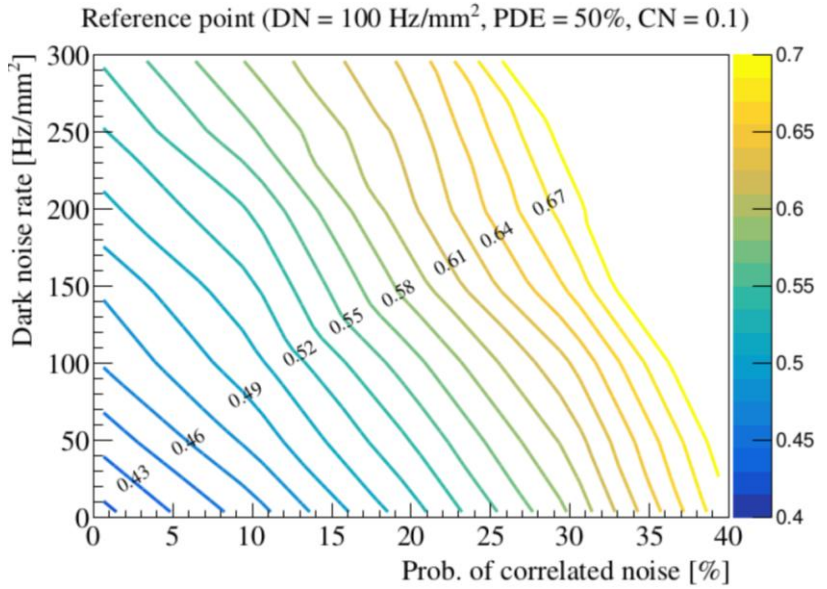
Parameter	Why It Matters
Photon Detection Efficiency, PDE	Sets the detected light yield; drives energy resolution and low-energy threshold
Gain and Gain Uniformity	Determines SPE calibration quality and charge reconstruction precision
Dark Count Rate, DCR	Contributes to energy resolution, accidental backgrounds, low-energy threshold, bandwidth
Optical Cross-talk	Increases apparent photoelectron counts and affects energy linearity
After-pulsing	Distorts waveform and biases charge/timing reconstruction
Single Photon Time Resolution, SPTR	Impacts event timing, vertex reconstruction, and coincidence selection
Microcell Size and Recovery Time	Defines dynamic range, filling factor, saturation behavior, and high-rate capability
Breakdown Voltage and Temperature Dependence	Affects gain/PDE/noise stability; requires monitoring and compensation
Radiation Tolerance and Aging	Determines long-term performance stability and systematic uncertainties

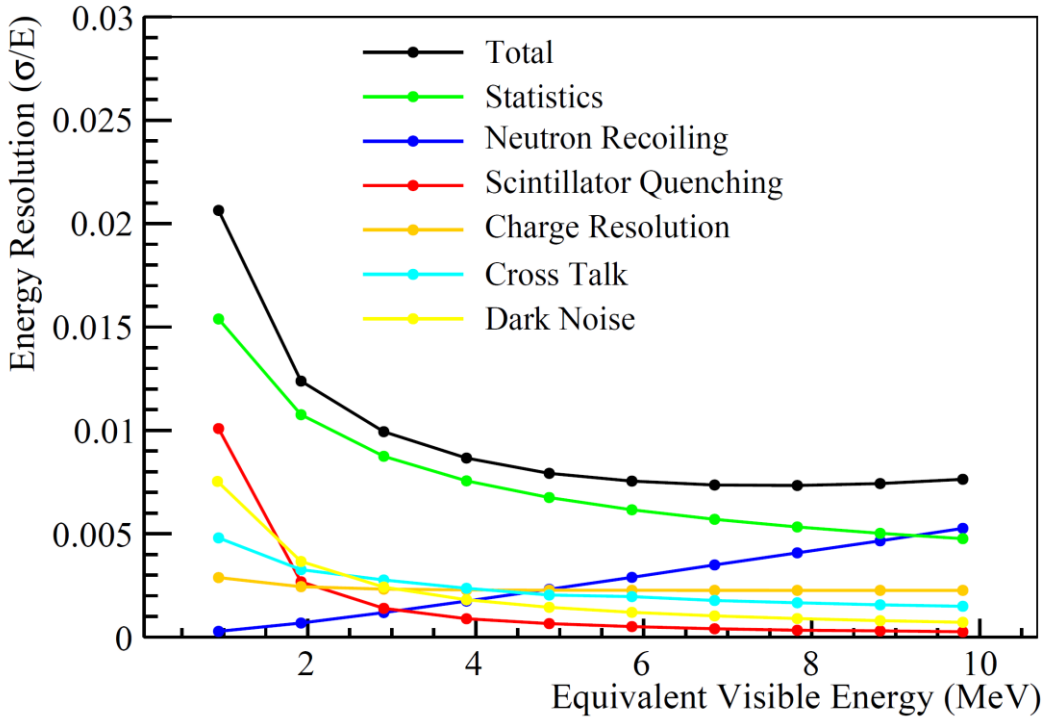
❄ In TAO, we need high PDE, low DCR and correlated noise, and good uniformity of the breakdown voltage

SiPM Requirements in CDR

Table 6-1: Requirements on the SiPM parameters.

Parameters	Specification	Comments
PDE	$\geq 50\%$	at 400 nm, not including correlated noise
Dark count rate	≤ 100 Hz/mm^2	at -50°C
Probability of correlated noise	$\leq 10\%$	including cross talk and afterpulsing
Uniformity of V_{bd}	$\leq 10\%$	to avoid bias voltage tuning
Size of the SiPM device	$\geq 6 \times 6$ mm^2	for easy handling
SiPM coverage within tiles	$\geq 94\%$	not included in SiPM's PDE





PDE, DCR and correlated noise strongly depend on bias voltage applied on SiPMs

For any given SiPMs, the optimal operating voltage should exist

Survey of SiPM Vendors

Several SiPM vendors were investigated, leading to a shortlist of 3 candidate suppliers

Having multiple suppliers is important not only for the cost control, but also for the risk mitigation

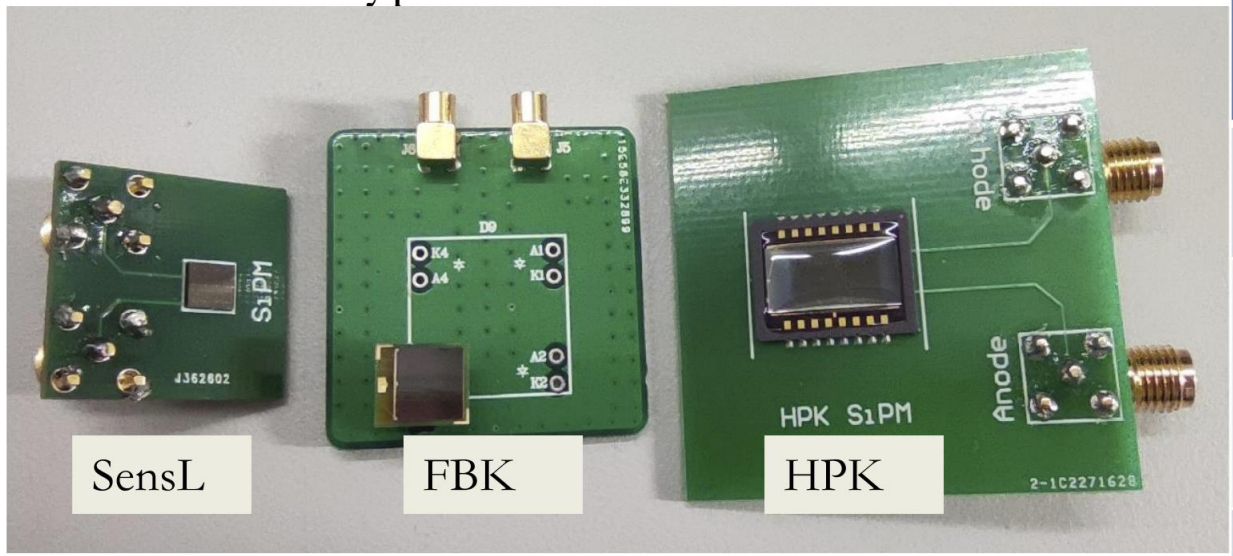
Vendors	SensL	Hamamatsu	FBK
Type	MicroFJ-60035	S14160/S14161	NUV-HD
Cell size (μm)	35	50	40
Cell Fill factor (%)	76	74	81
PDE (%)	**51**	**50**	**56**
Peak wavelength (nm)	420 (250-900)	450 (270-900)	410 (280-700)
Dark count rate (kHz/mm^2)	70	166	150
Gain	6.0 x 10^6	2.5 x 10^6	3.5 x 10^6
Crosstalk probability (%)	20	7	10

The performance of all SiPMs looks quite promising

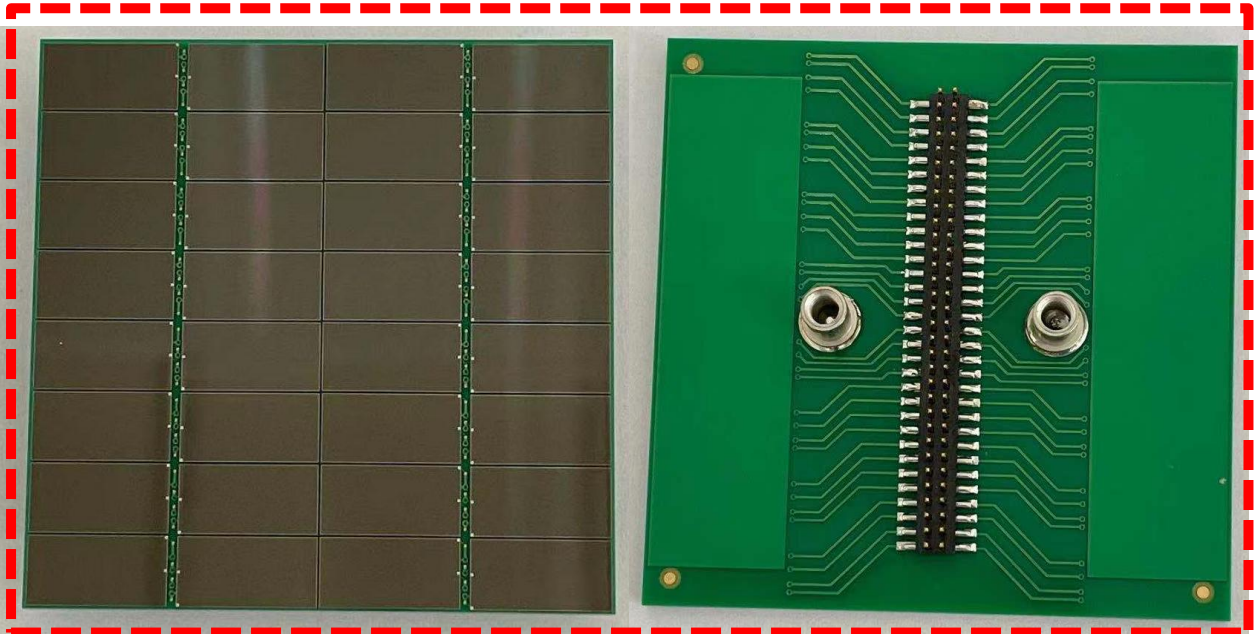
TAO starts R&D work with FBK and HPK in 2020

Samples from Different Vendors

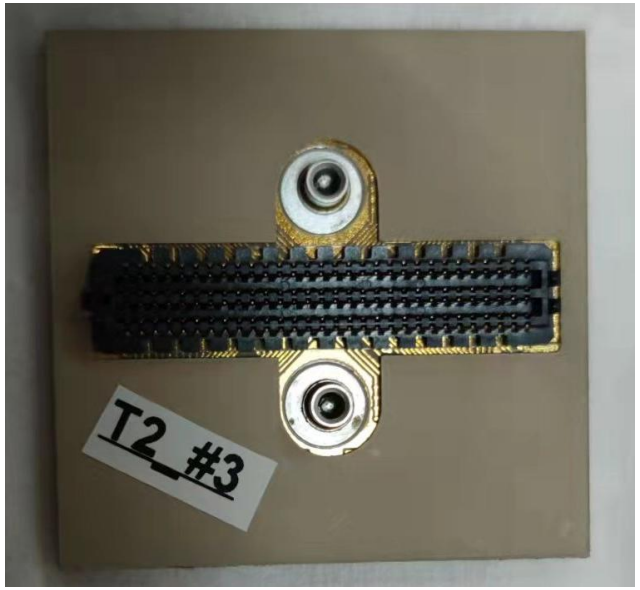
SiPMs: three types from different vendors



Vendor	Type	Pixel size (μm*μm)	Total size (mm*mm)
SensL	MicroK-40035-E715	35*35	4*4
FBK	NUV-HD LowCT_v2 (Double/Triple trenches)	50*50 (75*75)	6*6
HPK	S16080	75*75	6*12







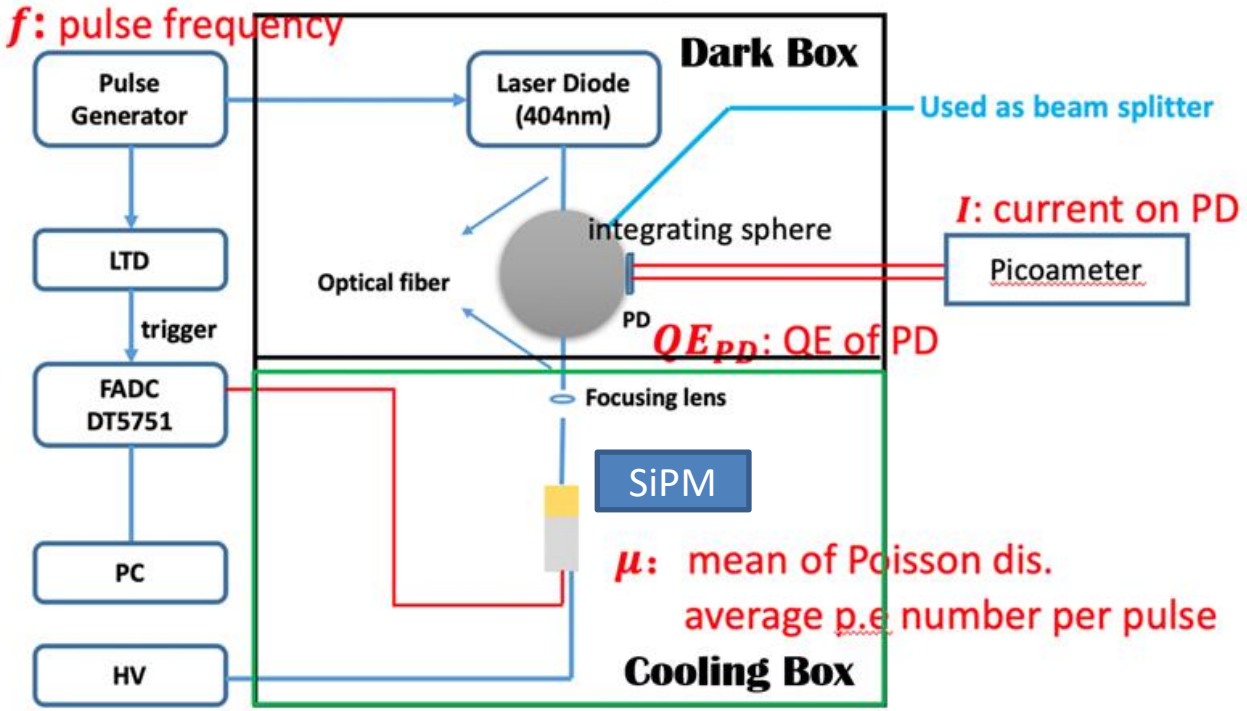
SiPM Characterization

❄ Every parameter interested by TAO has been carefully measured

- ➢ PDE: absolute value, spectral and angular responses
- ➢ Spectral and angular responses of reflectance
- ➢ Noise factors: DCR, crosstalk, after-pulse
- ➢ Gain, breakdown voltage

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Nuclear Inst. and Methods in Physics Research, A 973 (2020) 164171



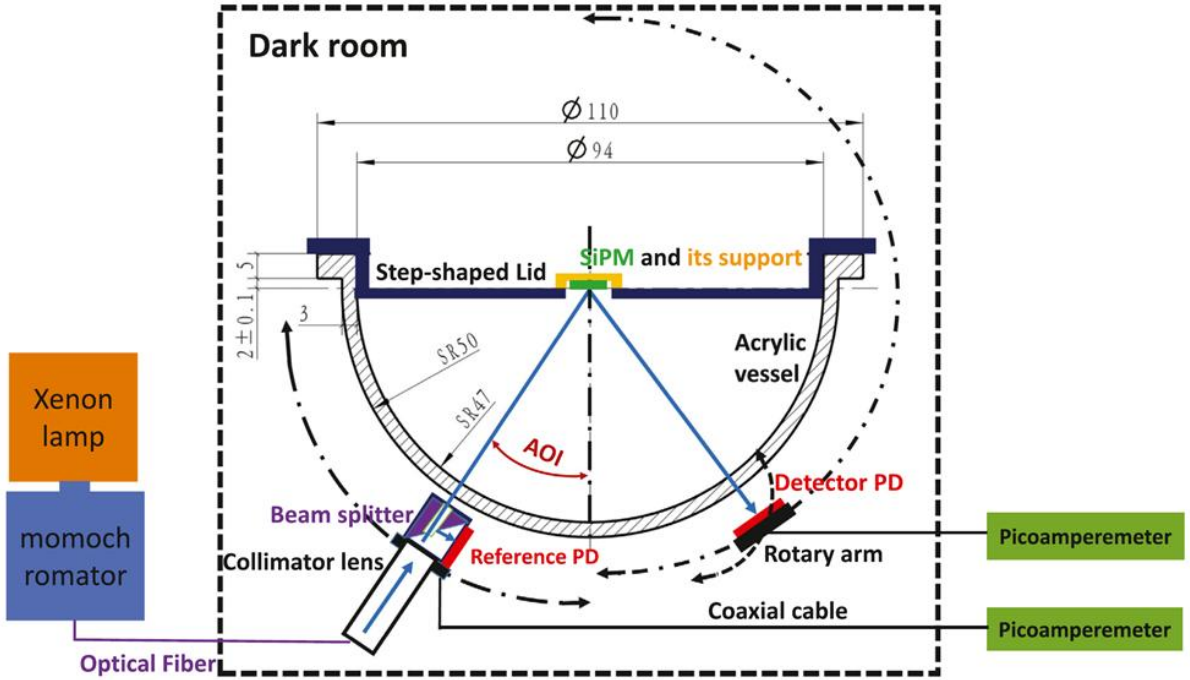
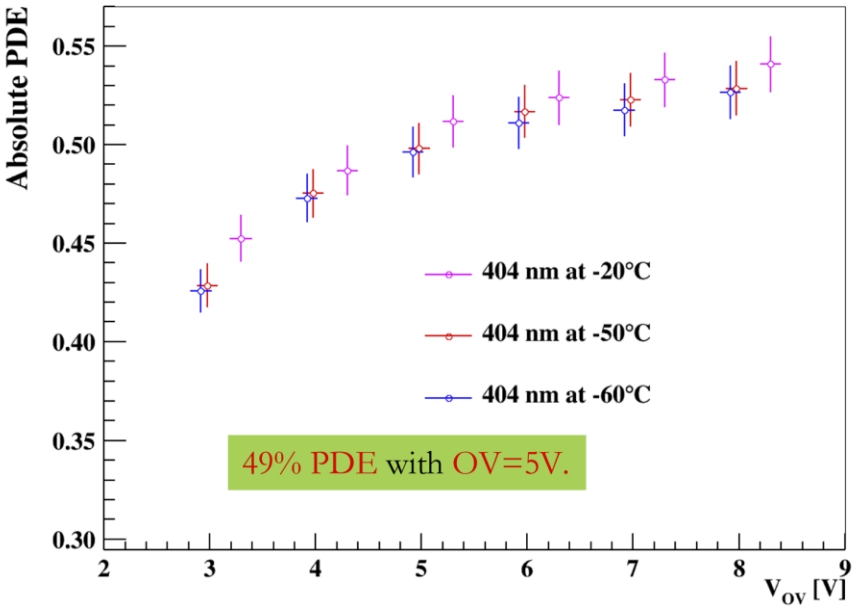
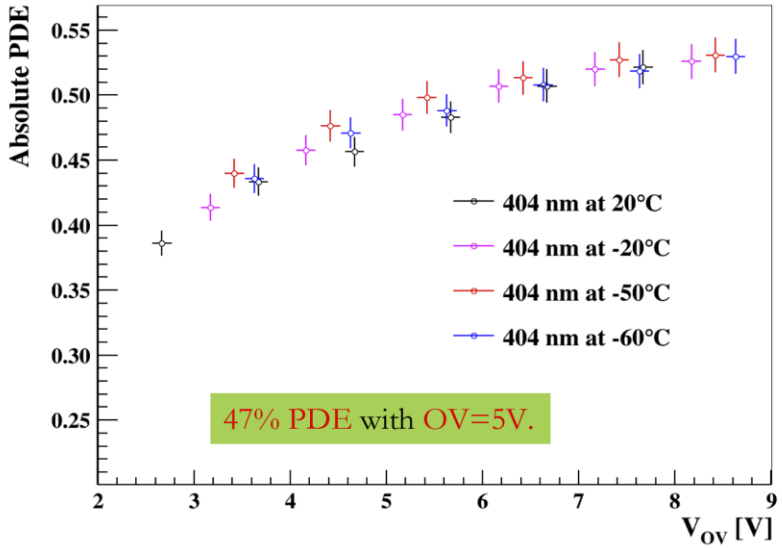


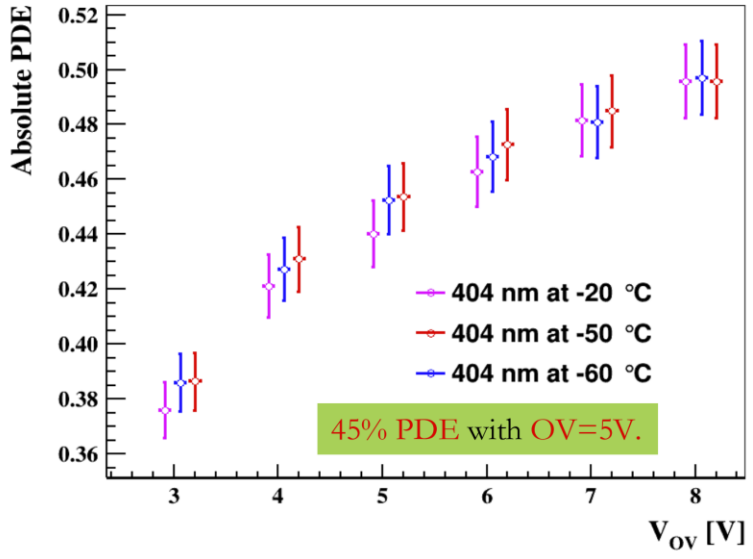
Fig. 1. Schematic diagram of the instrumentation.



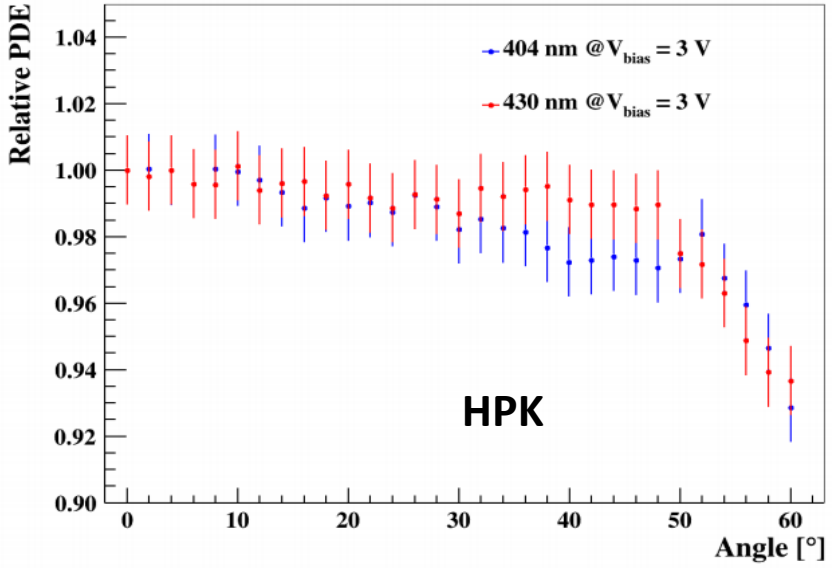
Absolute PDE of HPK SiPM at 404nm

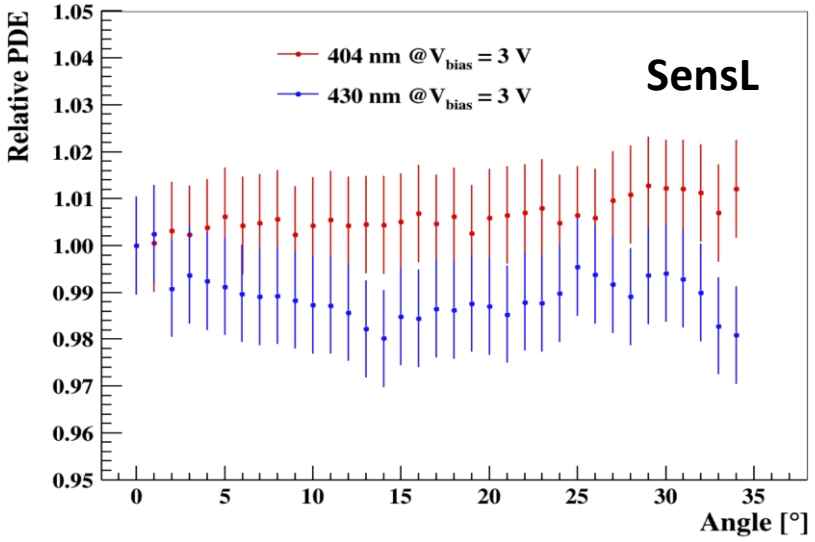


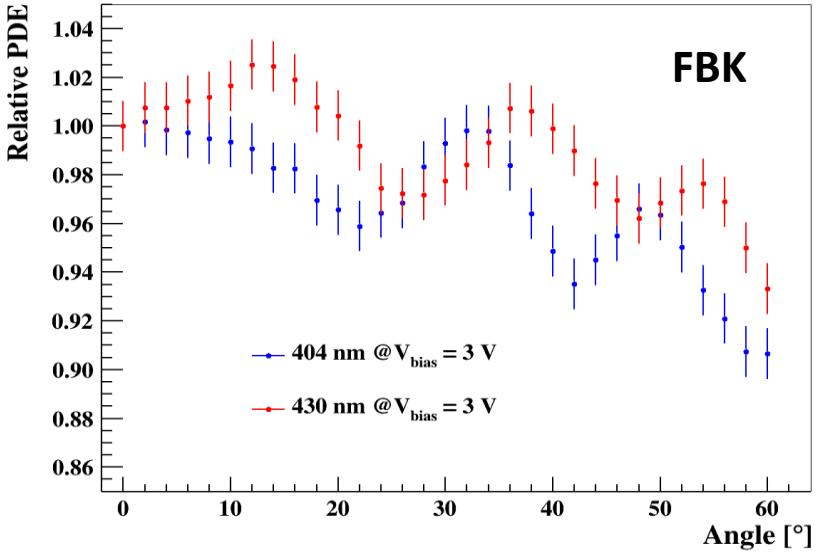
Absolute PDE of SensL SiPM at 404nm



Absolute PDE of FBK SiPM at 404nm

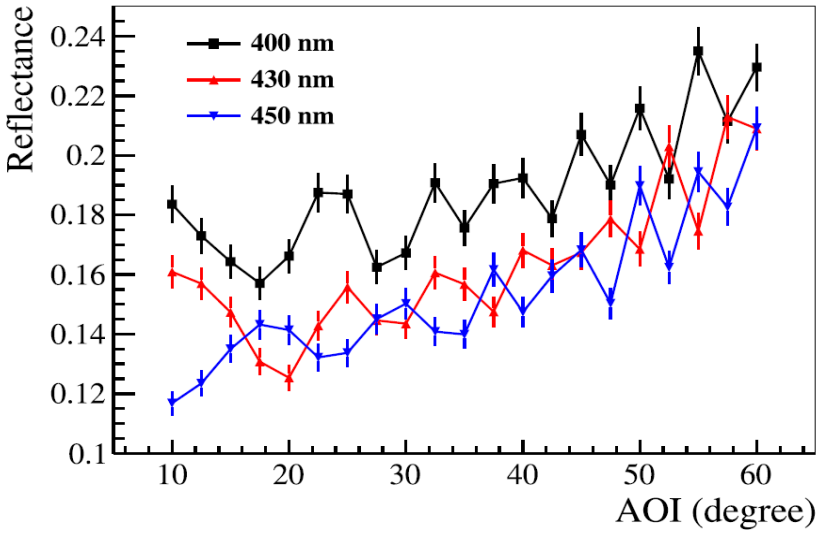




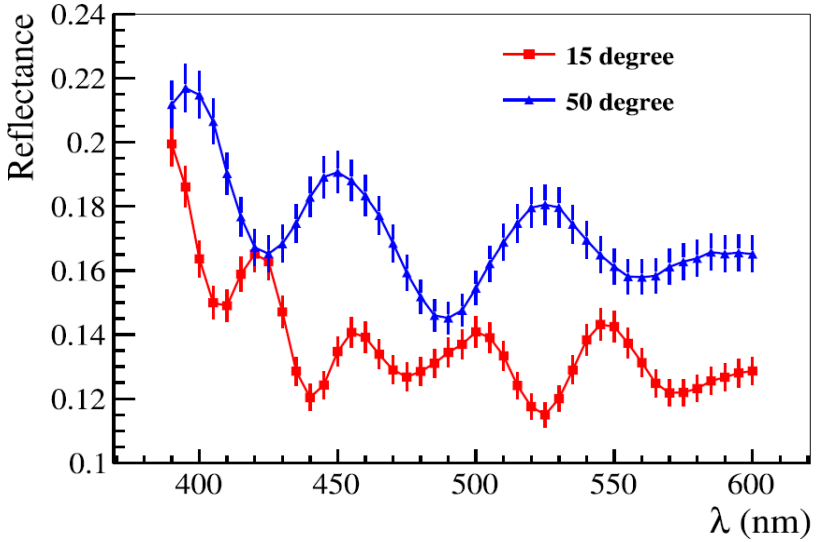


Reflectance

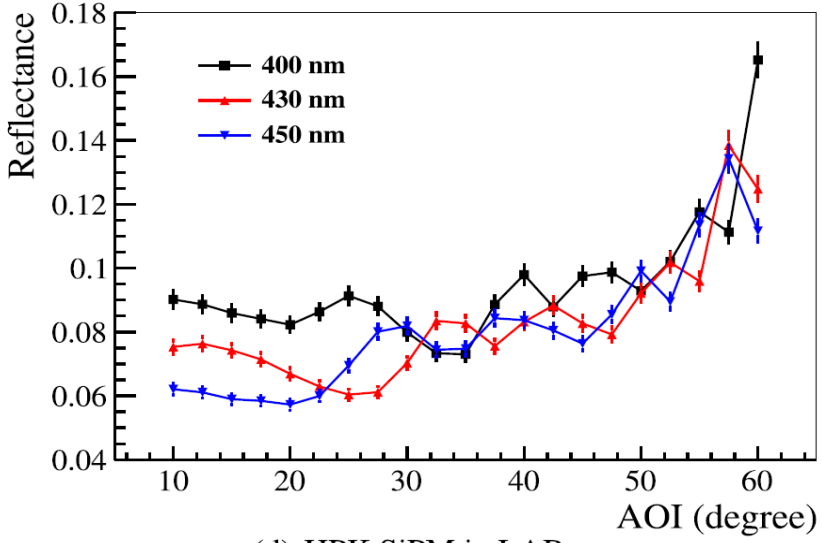
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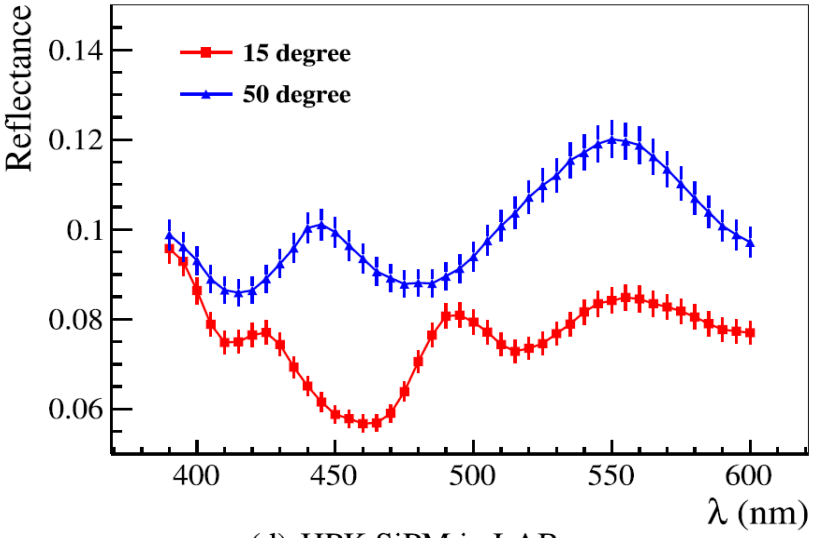
(b) FBK SiPM in LAB



(b) FBK SiPM in LAB



(d) HPK SiPM in LAB

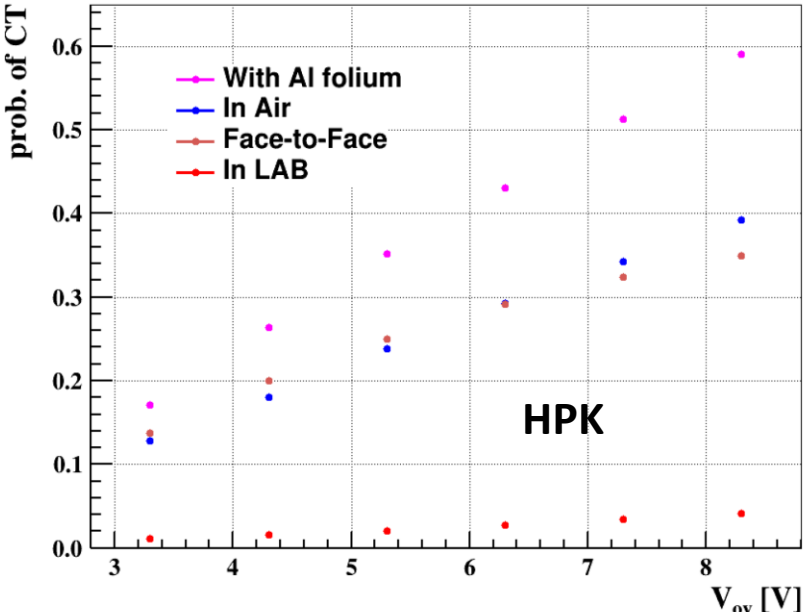


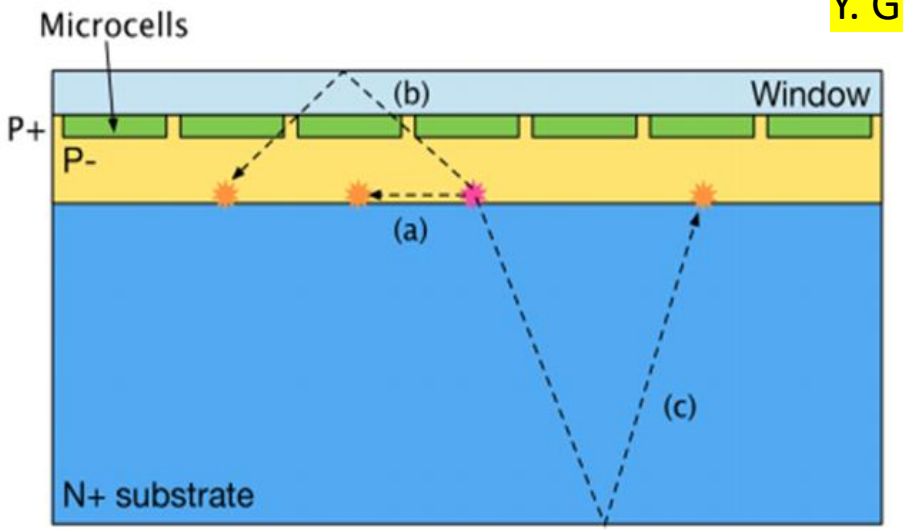
(d) HPK SiPM in LAB

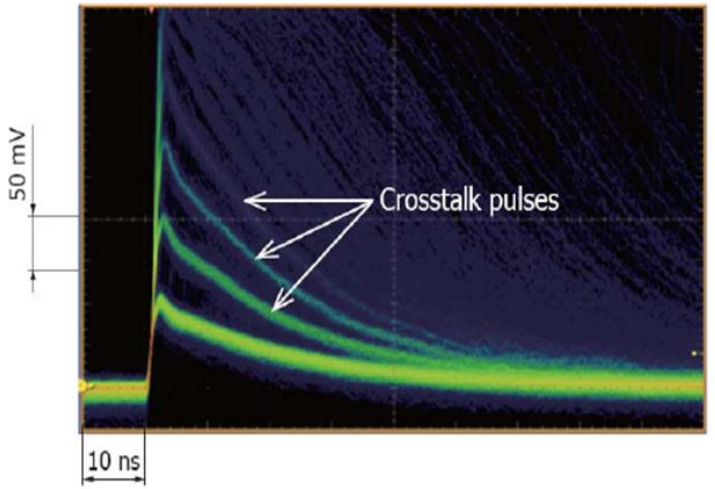
- The reflectance of SiPMs is important for TAO, due to its spherical arrangement
- The fine structure is mainly caused by the anti-reflective coating layer on silicon
- Reflectance increases with angle of incidence

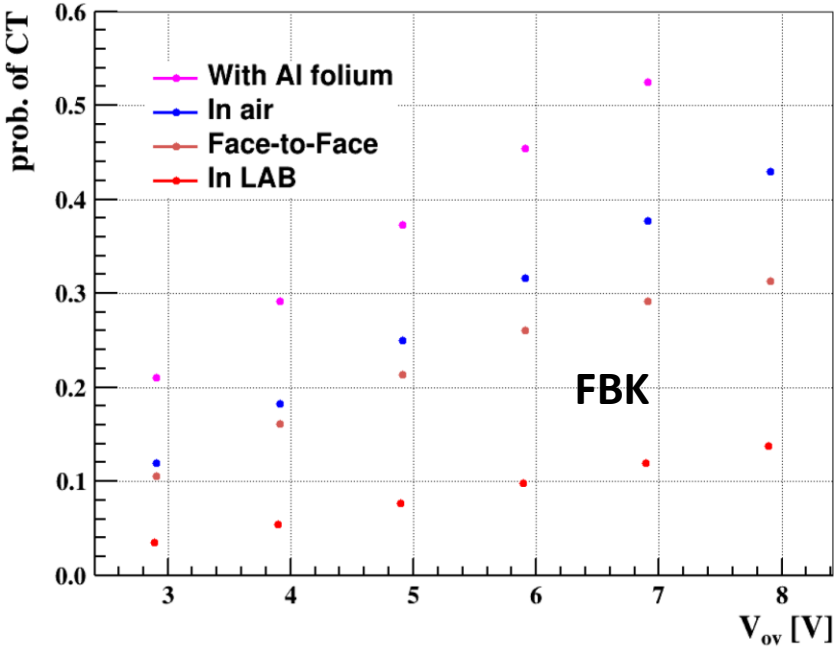
Optical Crosstalk (Internal & external)

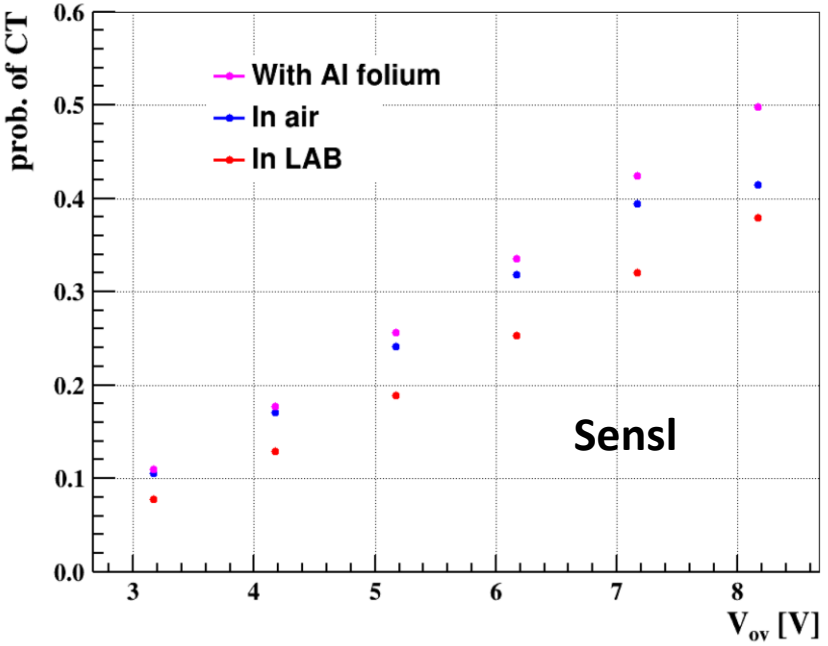
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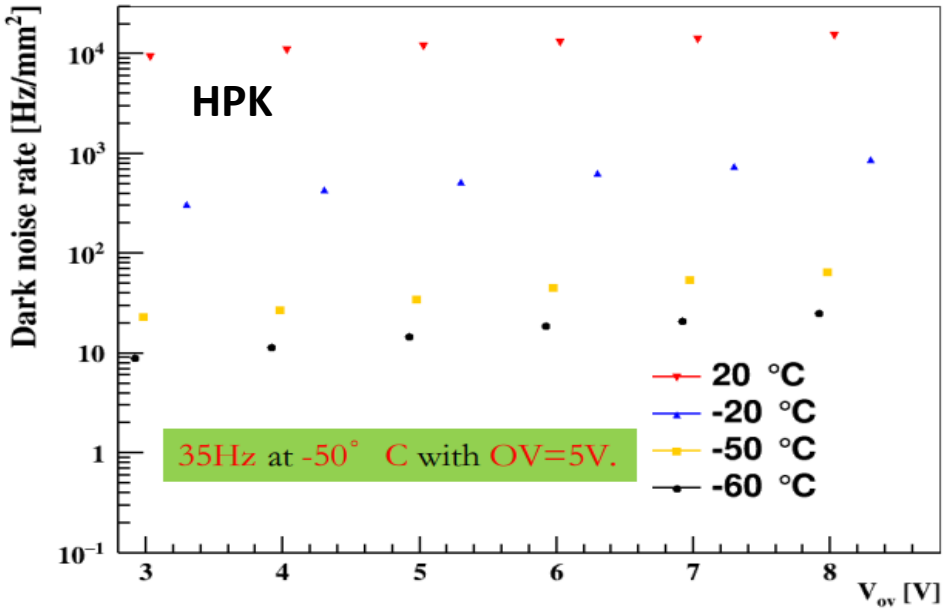


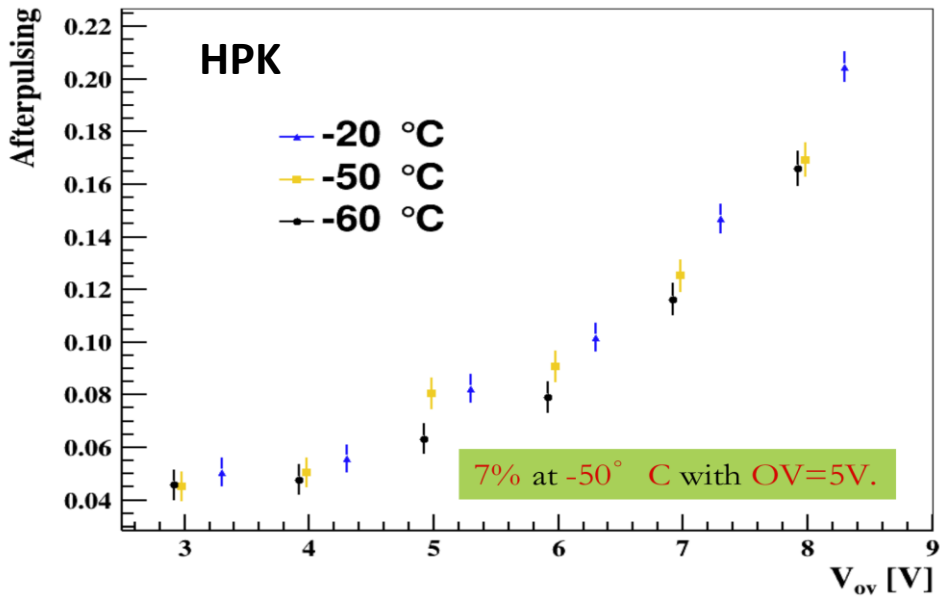
TAO is sensitive to both internal and external CT

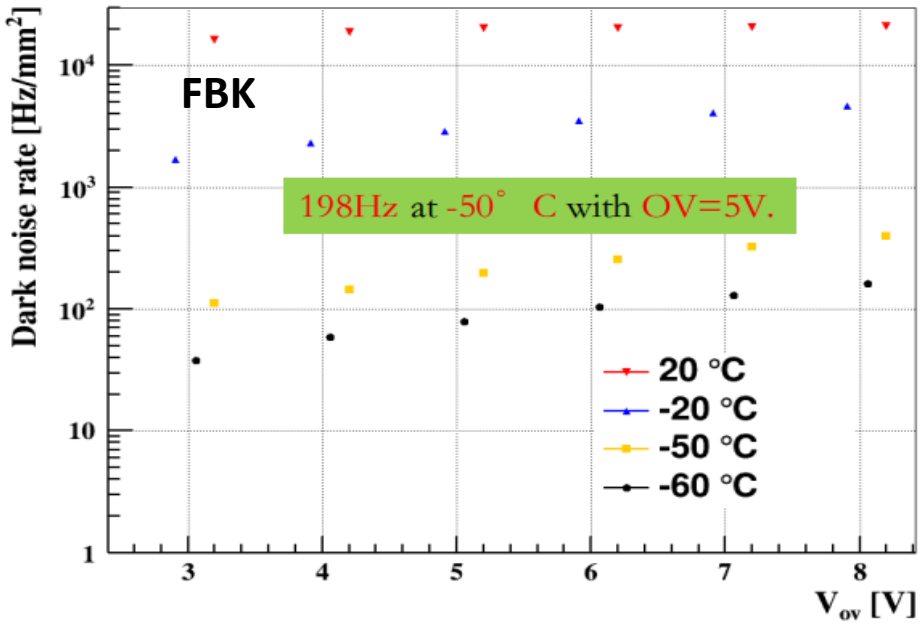
Optical trenches can effectively reduce internal CT

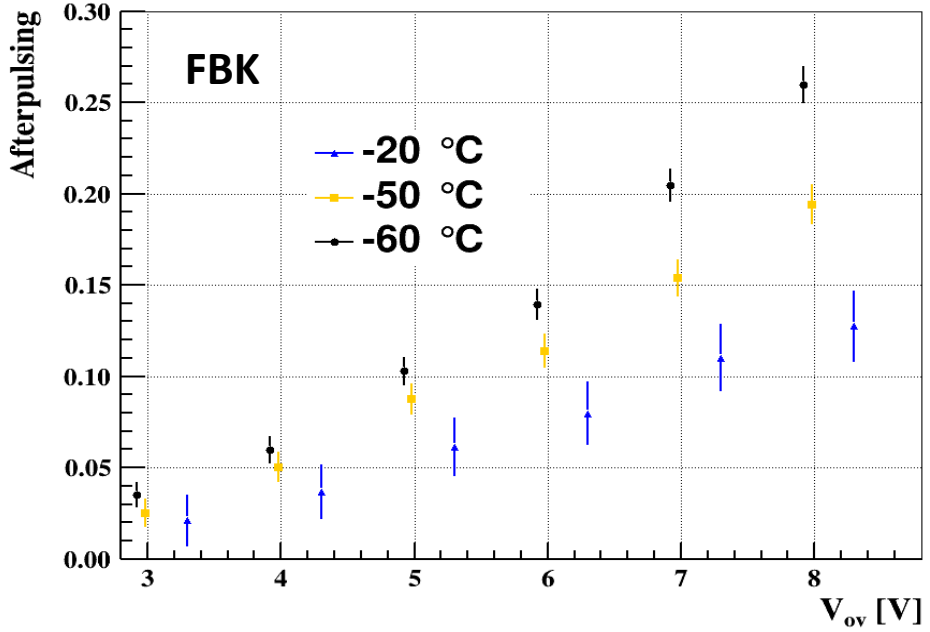
External CT is dominated in TAO, due to the good refractive index match between LAB and epoxy resin

DCR and After Pulse









DCR is sensitive to temperatures, ~3 orders reduction at -50 ℃, compared with that room temperature

HPK and FBK SiPMs show a different temperature dependence of after-pulse

SiPM Procurement Strategy for TAO

❄ A solid understanding of SiPM performance was the foundation of the procurement process

❄ SiPM parameters are highly correlated and depend strongly on over-voltage

- ➢ The over-voltage dependence can vary significantly among vendors
- ➢ Different parameters affect TAO energy resolution in different ways

❄ To enable a fair and physics-driven comparison, an effective PDE was defined based on MC studies

- ➢ It includes the benefit of PDE
- ➢ It also incorporates the degradation from noise-related effects

An example: $\boldsymbol{PDE_{Eff} = PDE - 0.51 + 0.35 \times P_{cn} + 0.84 \times P_{cn}^2 + (4.2 \times 10^{-4} + 2 \times 10^{-4} \times P_{cn}) \times DCR}$

❄ This approach reduced multiple correlated SiPM parameters to a single detector-relevant figure of merit

❄ The technical score in the tender evaluation was then linked to this effective PDE

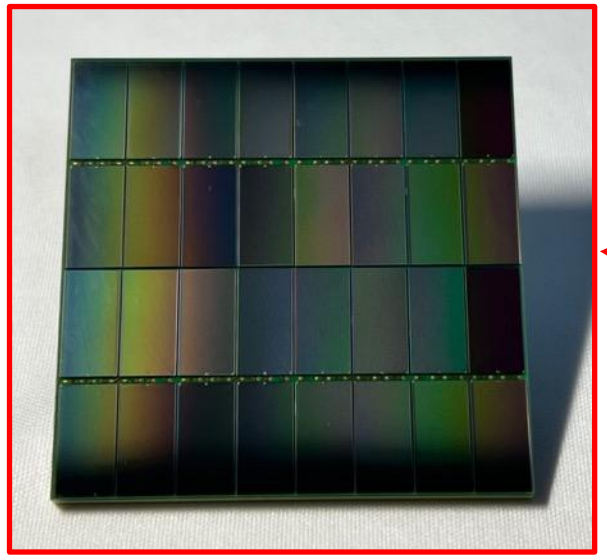
❄ 10 m² of SiPMs were eventually procured from Hamamatsu

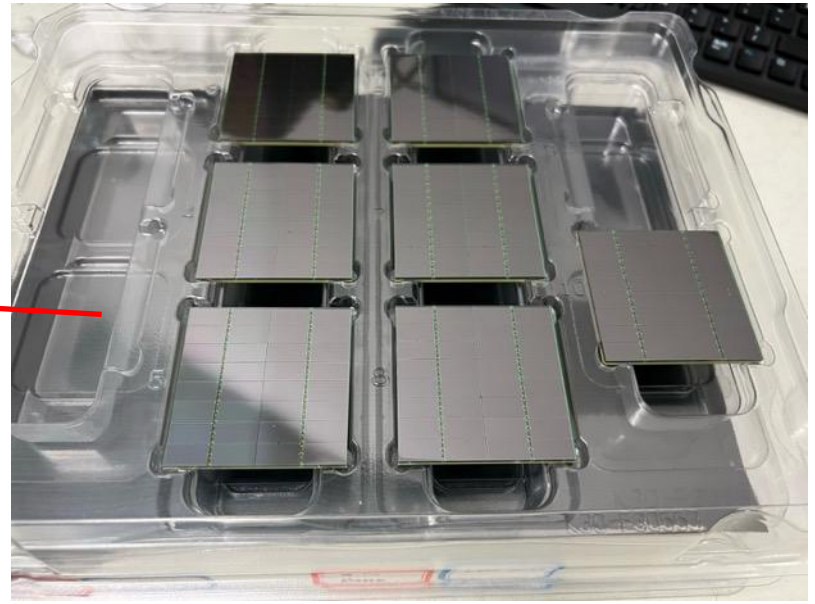
SiPM Production for TAO

- A customized type S16088 from Hamamatsu, similar to S13360-6075PE
  - Pixel size: 75 μm
  - SiPM chip size: 12 mm × 6 mm
  - Each SiPM tile holds 32 chips, with 2 chips connected in parallel per channel
- Coverage of photo-sensitive area: 89.6%
- Channel capacitance: 5,100 pF



- Received 4,100 SiPM tiles from Hamamatsu
  - 4024 tiles mounted on the detector
  - Total area: 4024 tiles × 32 chips × 12 mm × 6 mm ≈ 9.27 m^2
- Number of Channels for QA/QC: 4100 × 16 = 65,600





SiPM QA/QC Program for TAO

❄All SiPMs underwent a dedicated QA/QC procedure before installation, including:

① Microscopic visual inspection

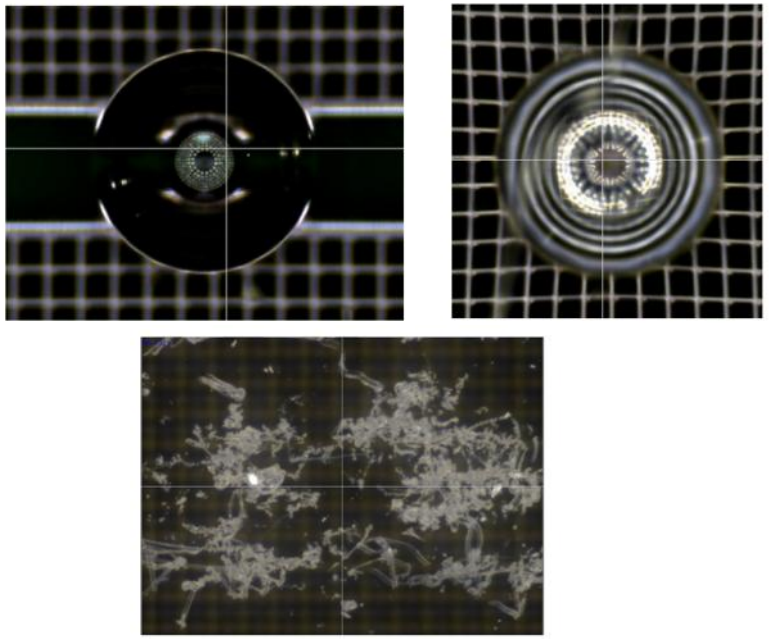
- Surface defects, contamination, package quality

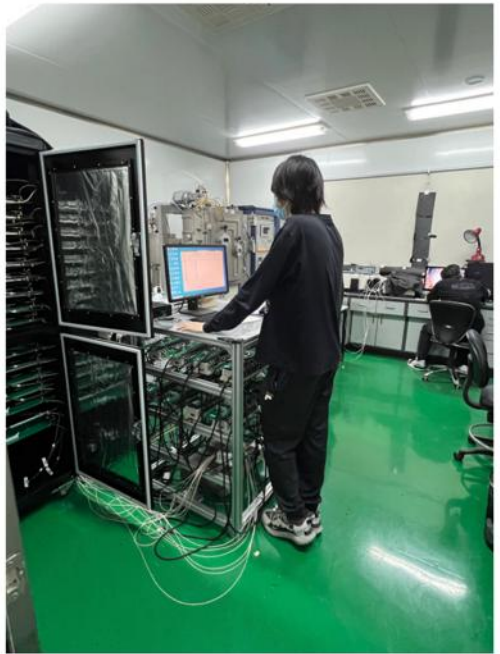
② Burn-in test at room temperature, 2 weeks running at ~3 V OV

- Screen for early failures and unstable devices

③ Mass testing at -50 ℃

- Measure key performance parameters, including gain, PDE, dark noise, cross-talk, after-pulsing and channel uniformity



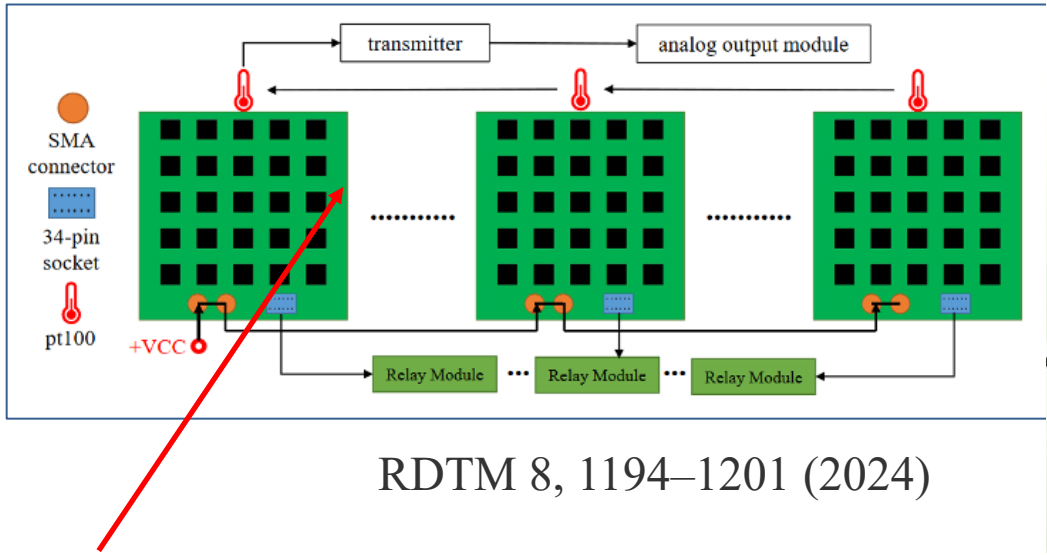






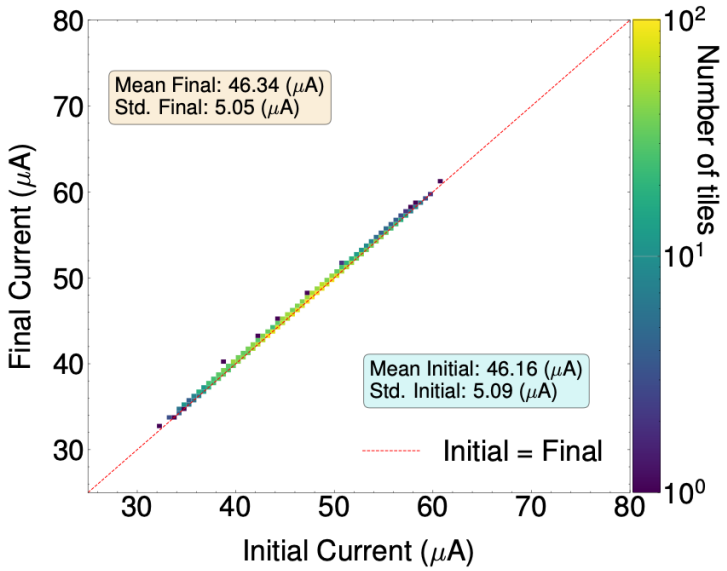
Burn-in Test

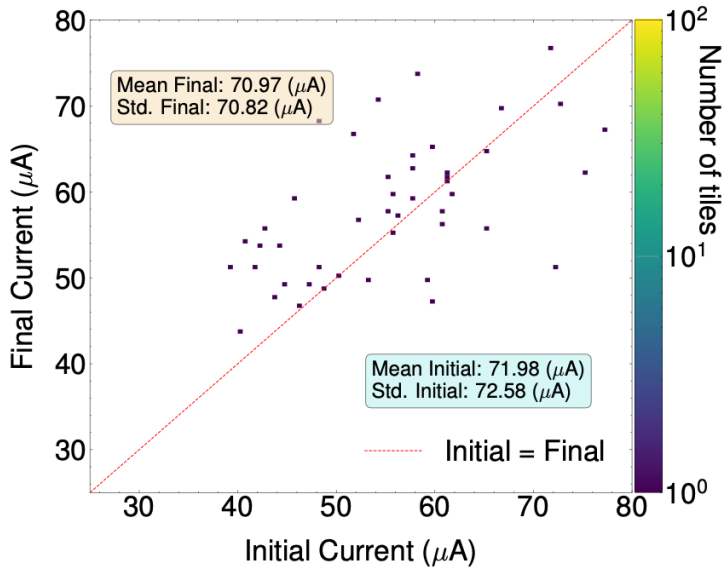
- SiPM tiles operated in the dark at room temperature
  - Fixed voltage: ~55V, ~3 V over-voltage
- 400 SiPM tiles per run, with each run lasting two weeks
- **Dark current** and **ambient temperature** periodically recorded
- Burn-in campaign completed by the end of 2023
- A few tiles were tagged as "bad"



RDTM 8, 1194–1201 (2024)



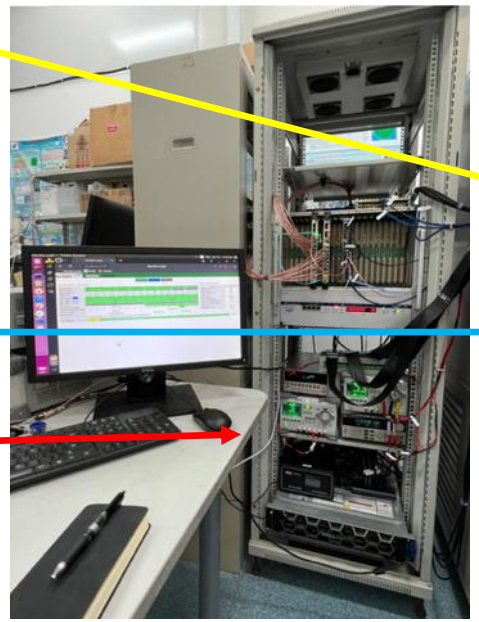


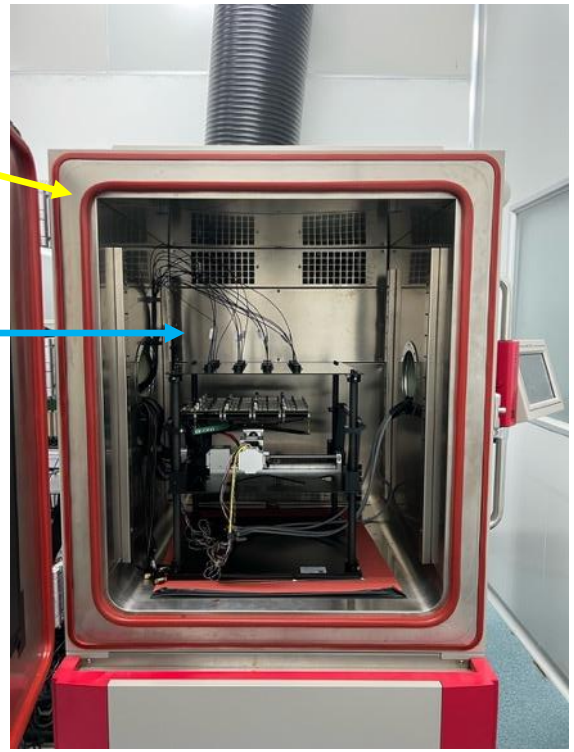


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SiPM Mass Testing Setup

- Climate chamber (dark, -50°C)
- Reference SiPMs closed to tiles provide the absolute PDE anchor, and measure the light field
- 420 nm LED in pulsed mode, guide light to chamber via optical fibers and diffusers
- Waveforms recorded by DAQ
- 16 tiles/run, and 3 runs/day
- Designed by JINR and IHEP

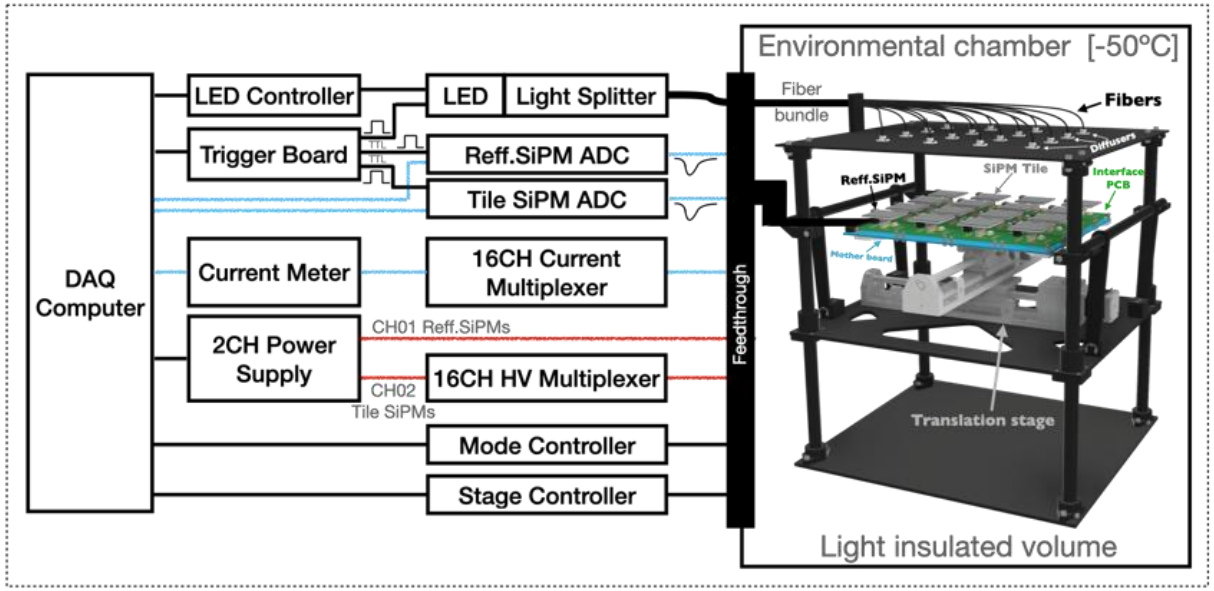




Cryogenic chamber, providing dark and low temperature (-50℃) environment



Platform with movement control for light field calibration



A. Rybnikov *et al* 2024 *JINST* **19** P05035

Charge Spectrum

- Analyze waveforms to obtain charge spectra
- Initial detected photons + prompt crosstalk
  - Gaussian-smeared Generalized Poisson (G.P.)
- After-pulse:
  - Gaussian-smeared geometric distribution

$$\frac{\mathrm{d}p}{\mathrm{d}Q} = GP_{0,\mu,\lambda} \cdot N\left(Q;0,\sigma_0\right) + \sum_{n=1}^{n_{\max}} GP_{n,\mu,\lambda} \cdot \sum_{i=0}^{i_{\max}} G(i;n,\alpha) \cdot N\left(Q;n,i,\sigma_n\right)$$

$$N\left(Q;n,i,\sigma_n\right) = \frac{1}{\sqrt{2\pi}\sigma_n} e^{-\frac{(Q-(\mathrm{Ped.}+n\cdot\mathrm{Gain}+i\cdot Q_{\mathrm{ap}}))^2}{2\sigma_n^2}}$$

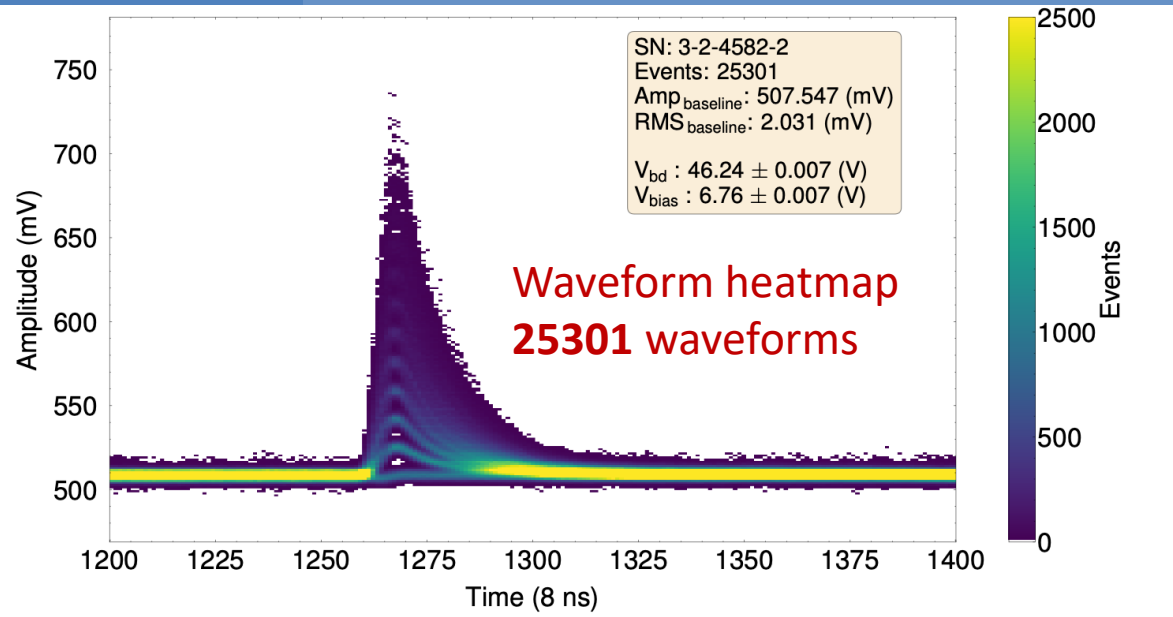
$$GP_{n,\mu,\lambda} = \frac{\mu(\mu+n\lambda)^{n-1}e^{-\mu-n\lambda}}{n!}$$

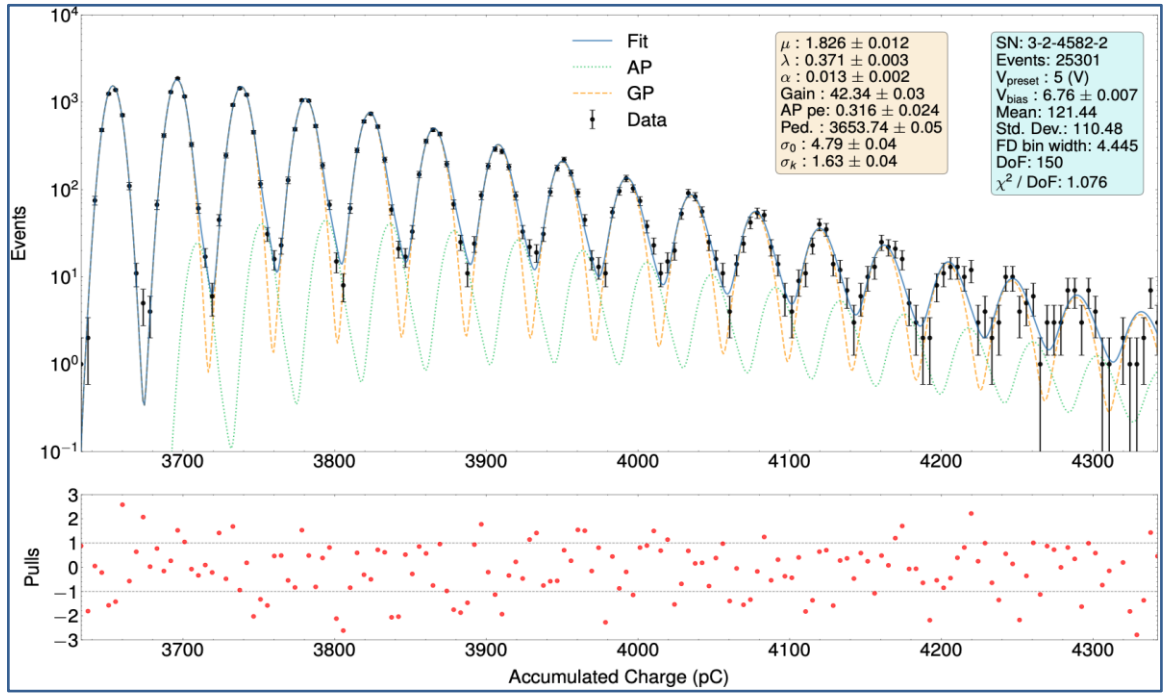
$$G(i;n,\alpha) = (1-n\alpha)(n\alpha)^i, n\alpha < 1$$

$$\sigma_n^2 = n\cdot\sigma_k^2 + \sigma_0^2,$$

Free parameters:

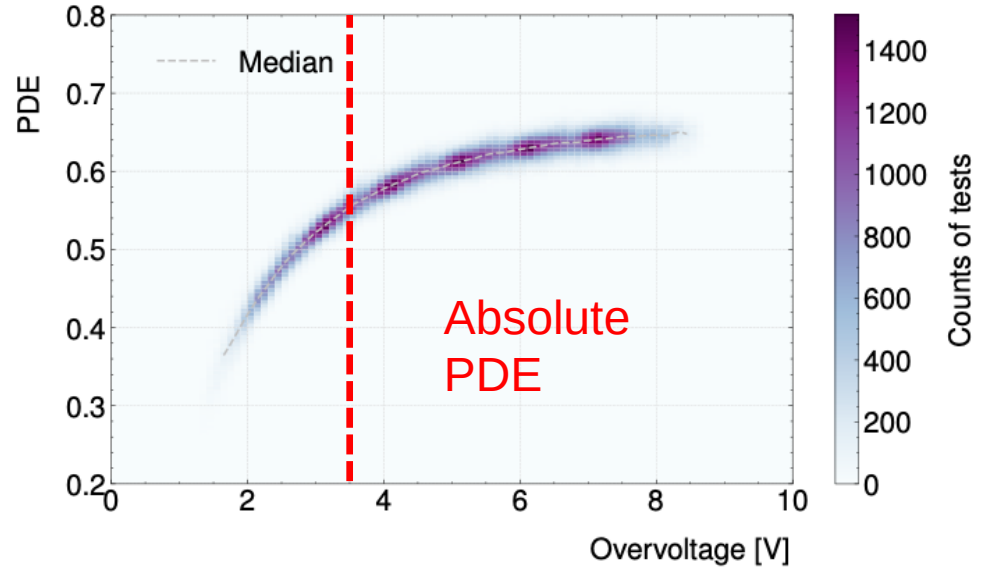
- μ, λ from G.P.
- Single p.e. gain
- After-pulse charge
- After pulse prob. α
- Baseline noise σ_0
- σ_k from SiPM pixels
- pedestal

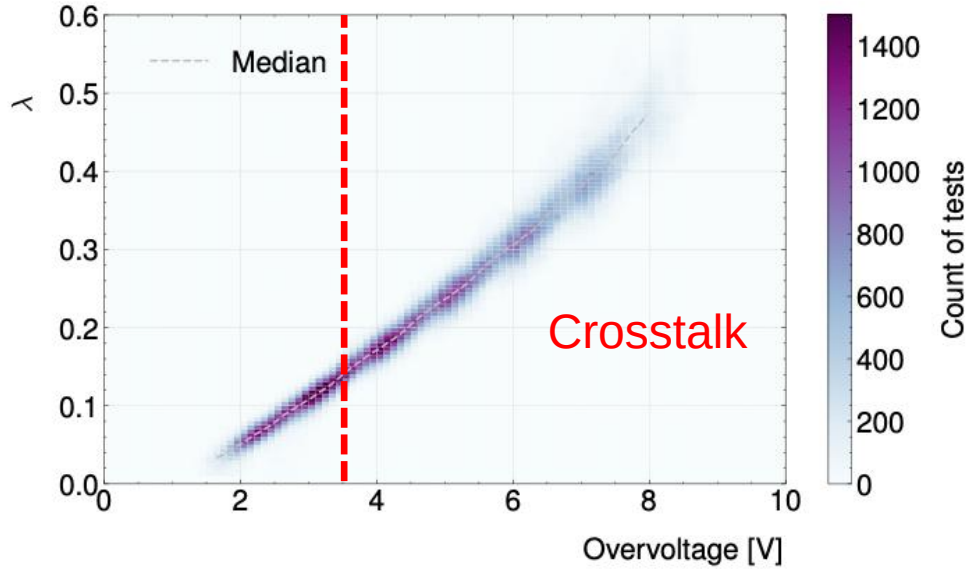


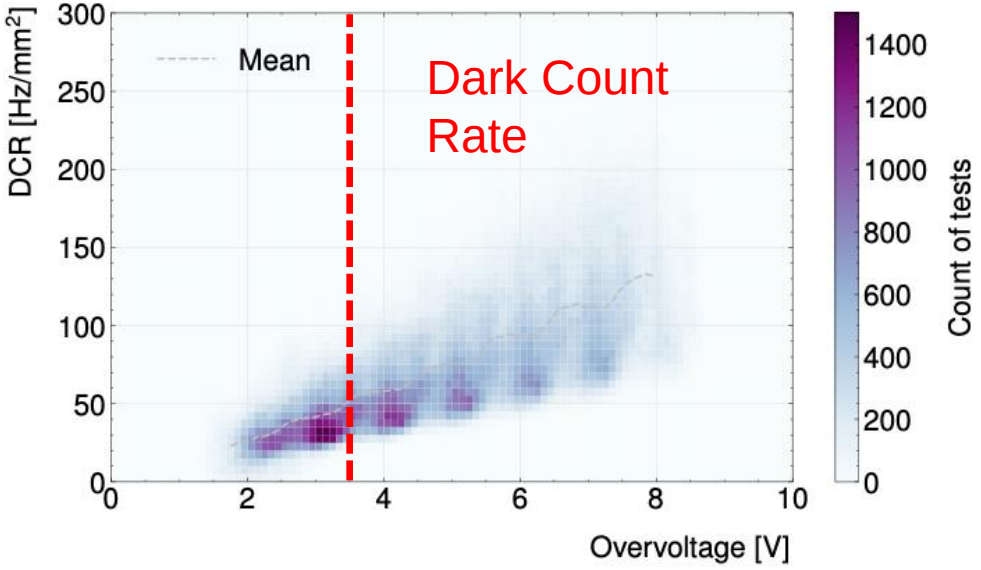


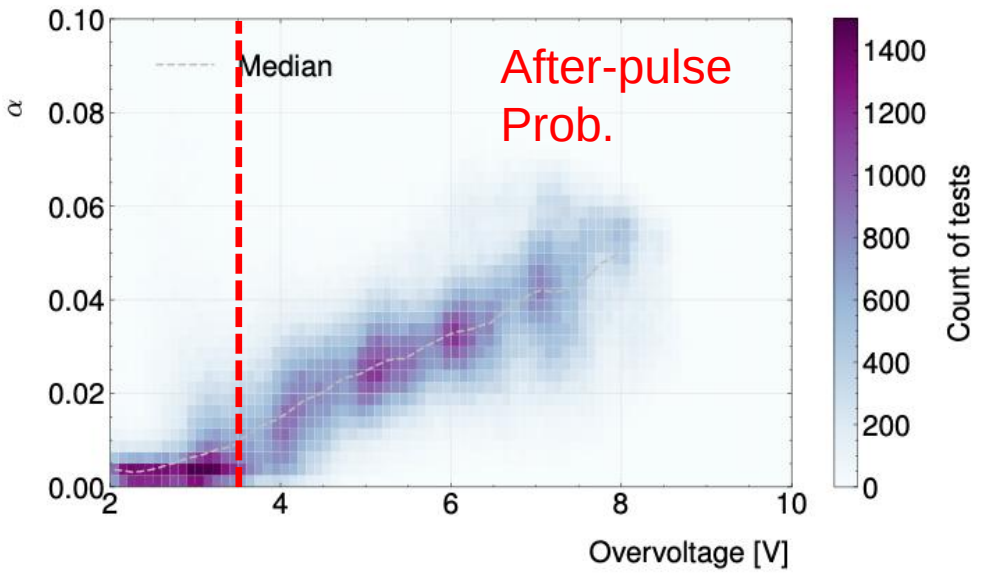
Results Interpretation

1 entry =
1 charge
spectrum fit

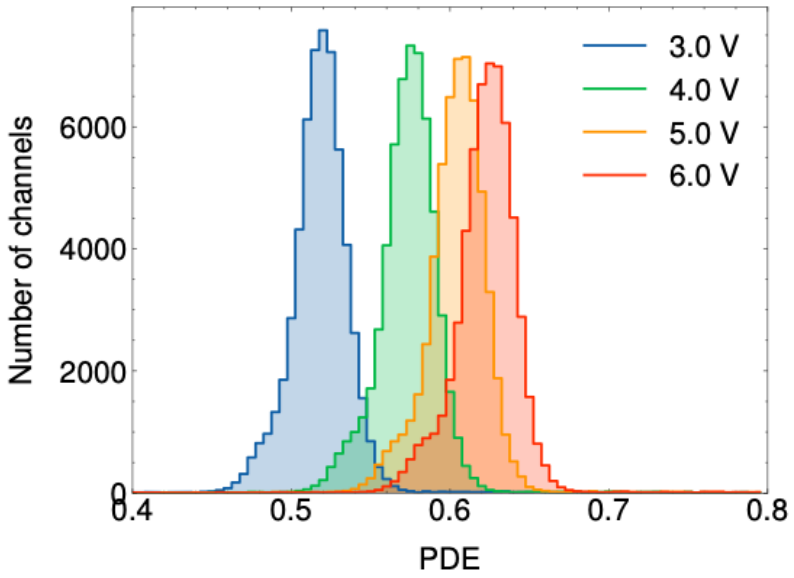


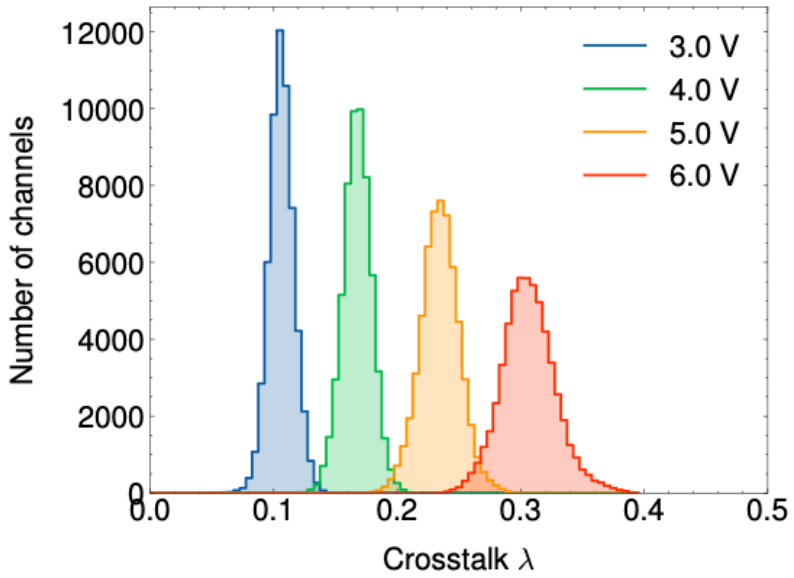


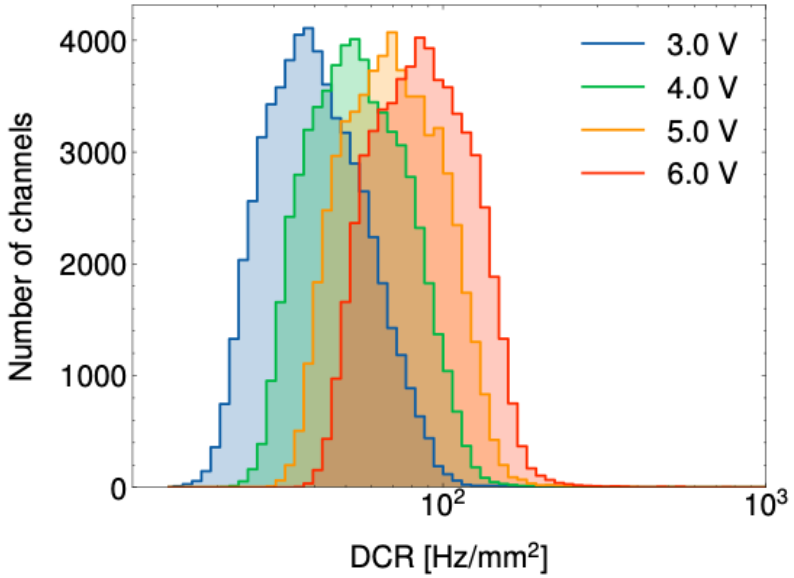


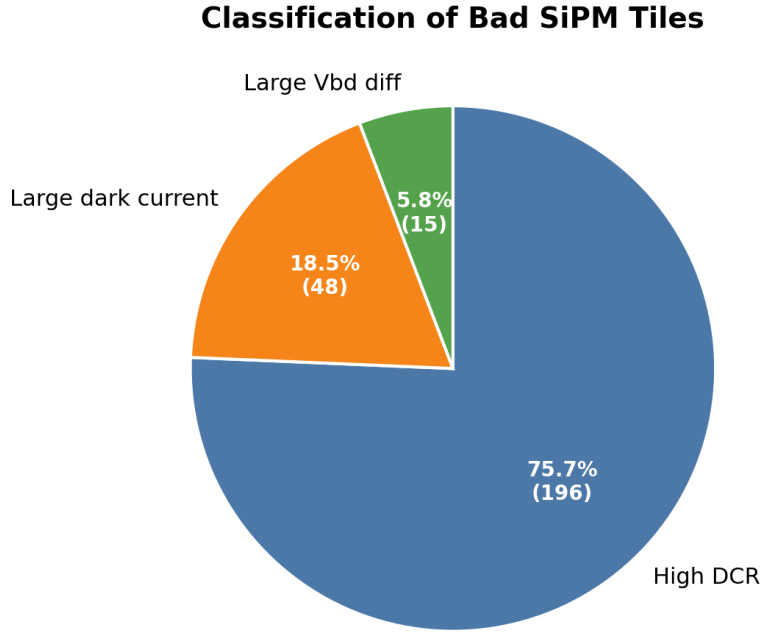


Results Interpretation









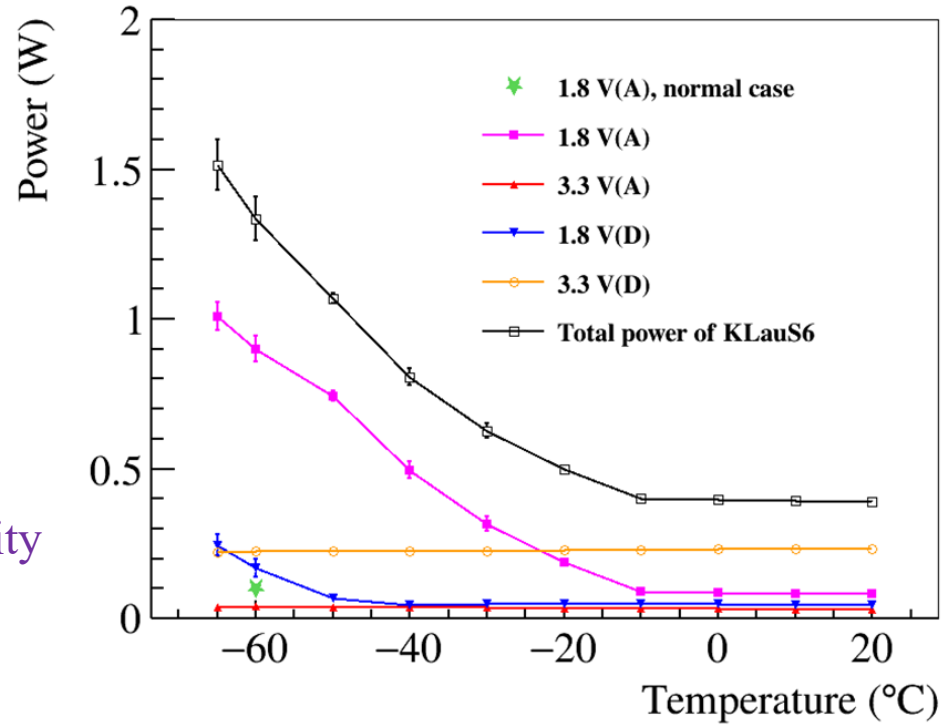
259 Tiles returned to HPK

❄ Two approaches were studied during the early R&D phase

❄ Discrete scheme, finally selected by TAO

❄ ASIC scheme

- ➢ Based on the KLauS chip developed by Heidelberg University
  - Was interested by ECAL
  - High channel density and good granularity, 64,384 channels
- ➢ A 1/500-scale mockup block demonstrated:
  - good SNR, SPE resolution, linearity, dynamic range
  - Performance met TAO design requirements
    - ✓ W. Wang et al., NIMA 996 (2021) 165110
  - Some plots are available in the backup
- ➢ Reason not selected
  - An unexplained increase in power dissipation at low temperatures
  - No impacts on performance, but concerns about long-term reliability
- ➢ A possible readout option for the future upgrade of TAO

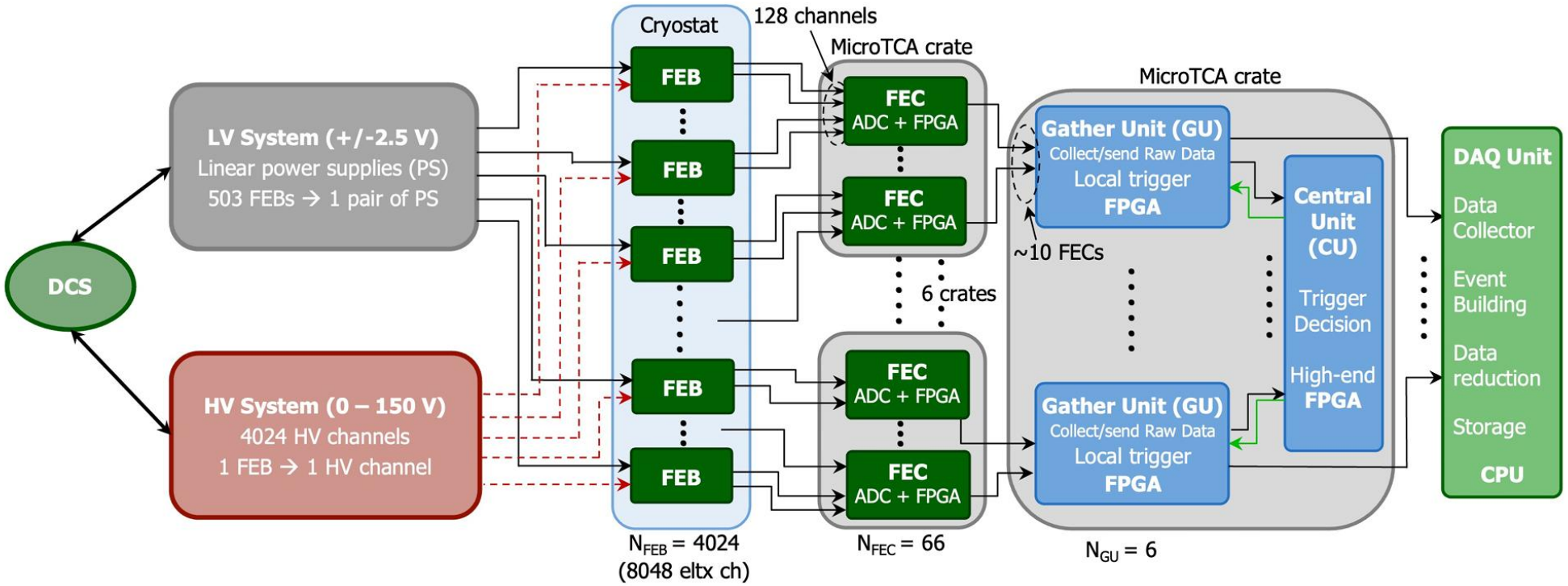


❄ FEB

- 2 channel/tile, 8,048 channels in total
  - SiPM ganging in one channel: 2s2p×4
- FEBs operated in the cold
- Analog FEB signals transmitted to FECs via ~14 m differential-pair cables

❄ FEC

- 16-bit ADC, 125 MHz digitization of analog signals
- FPGA boards integrated in μTCA.4 crates
- Online Q/T extraction performed in FPGA via waveform analysis
- White Rabbit used for precise clock synchronization



❄ The required radioactivity background rate in TAO: **< 100 Hz in fiducial volume**

- ➢ The achieved rate is **47 Hz**, and this is a non-trivial task

❄ An extensive radioassay campaign for material control and selection

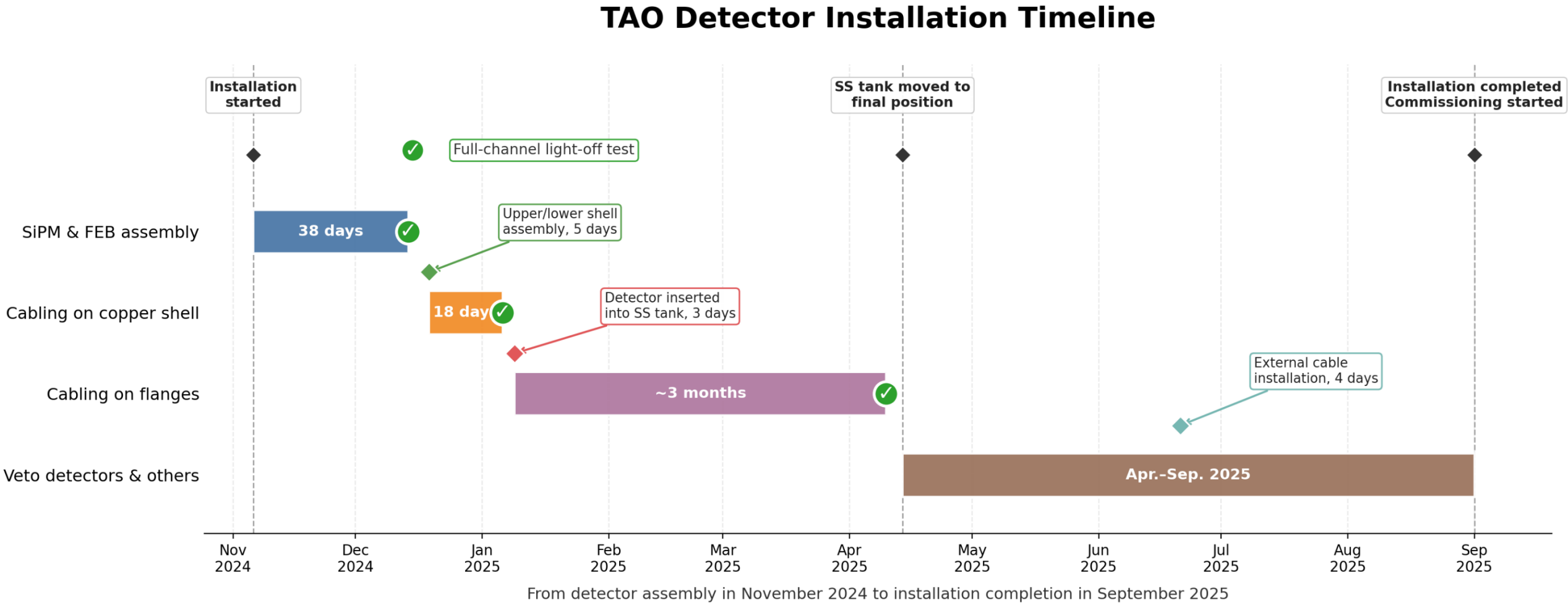
- ➢ Aramid PCB used for SiPM tiles and FEBs, U: < 1.19 Bq/kg; Th: < 1.17 Bq/kg; K: < 3.09 Bq/kg
  - Standard FR4 PCB was rejected due to high radioactivity
- ➢ RC components on FEBs, mainly capacitors, were screened
  - FEB radiopurity improved by about a factor of 2
- ➢ Low-radioactivity connector
  - Commercial Samtec ERM8/ERF8 (Bq/kg): ^{238}U = 8.75; ^{232}Th = 14.2; ^{40}K = 16.4
  - Custom connectors (Bq/kg): ^{238}U < 0.72; ^{232}Th < 0.92; ^{40}K < 2.58



❄ Cleanliness control

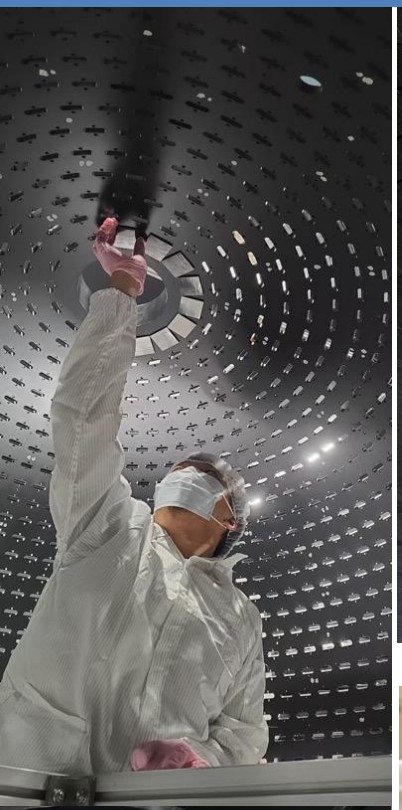
- ➢ EVERY in-tank component carefully cleaned
- ➢ Installation performed in a clean room

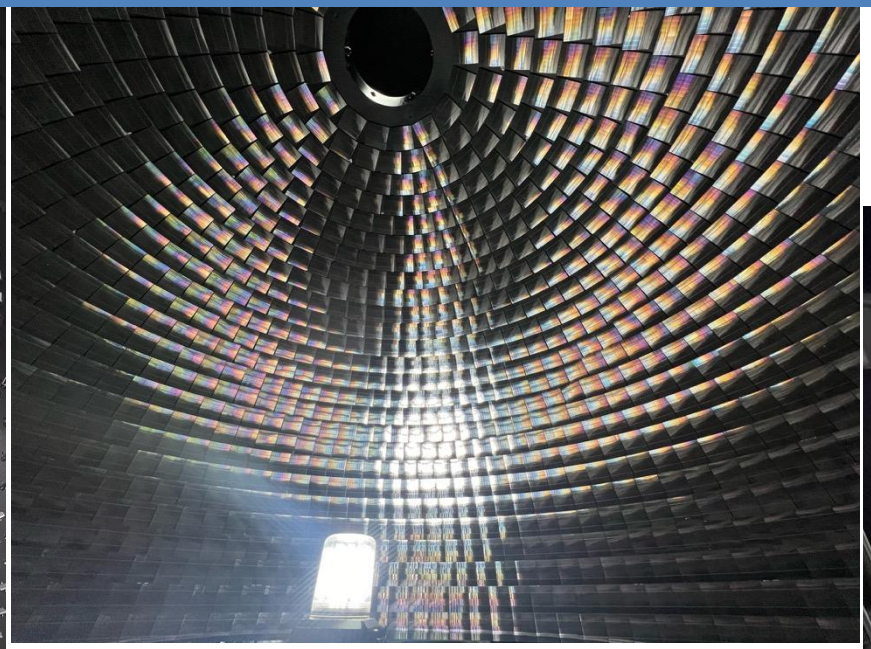
Detector Installation Timeline



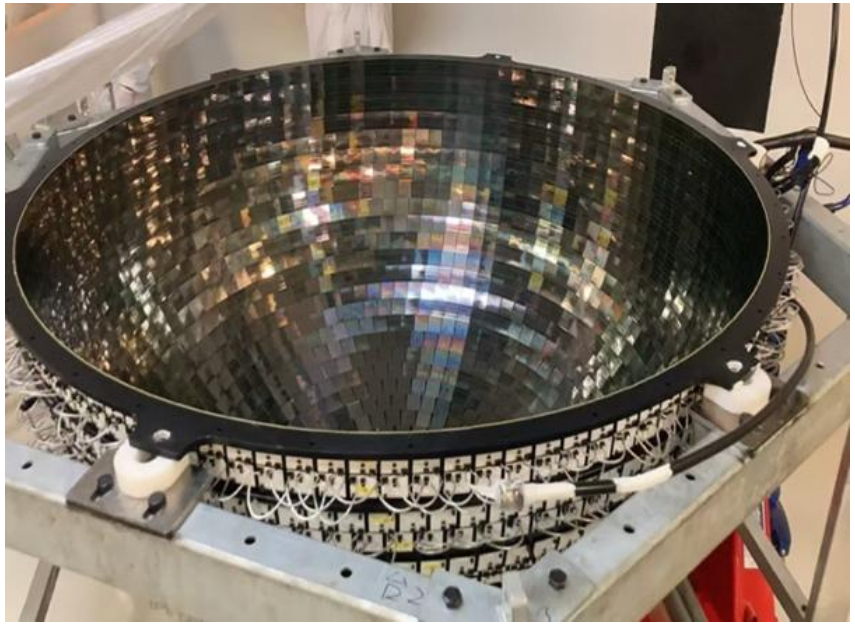
- To ensure cleanliness and quality control, all in-tank installation work was performed by our team members, with no external workers involved
- **3 light-off tests performed** after key milestones to ensure full-channel connectivity and readout integrity during installation

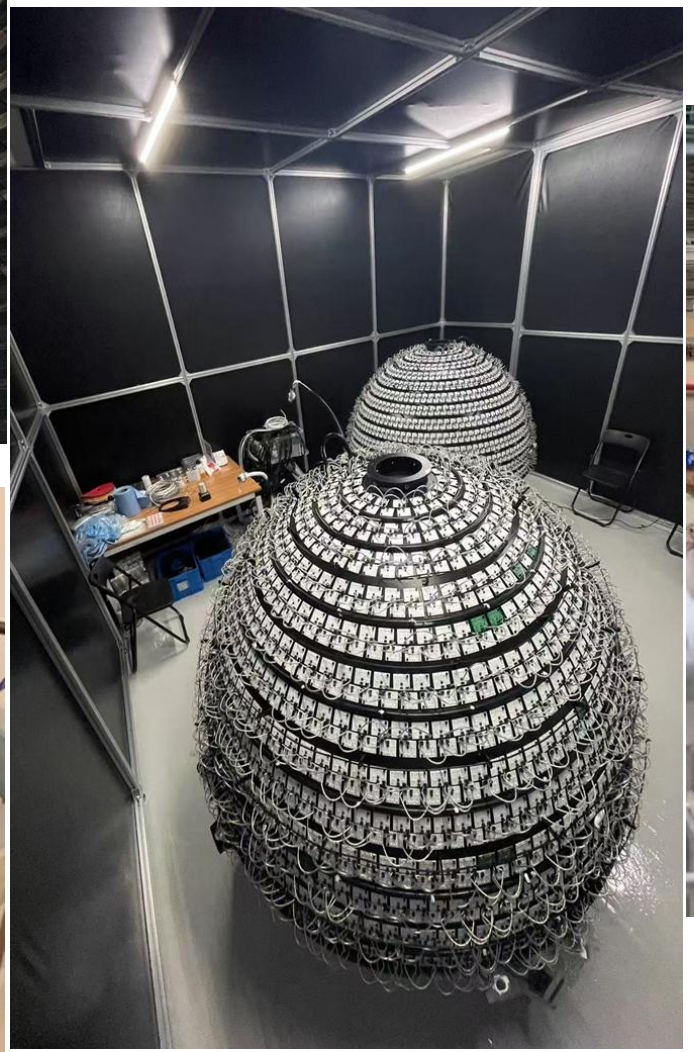
SiPM Installation











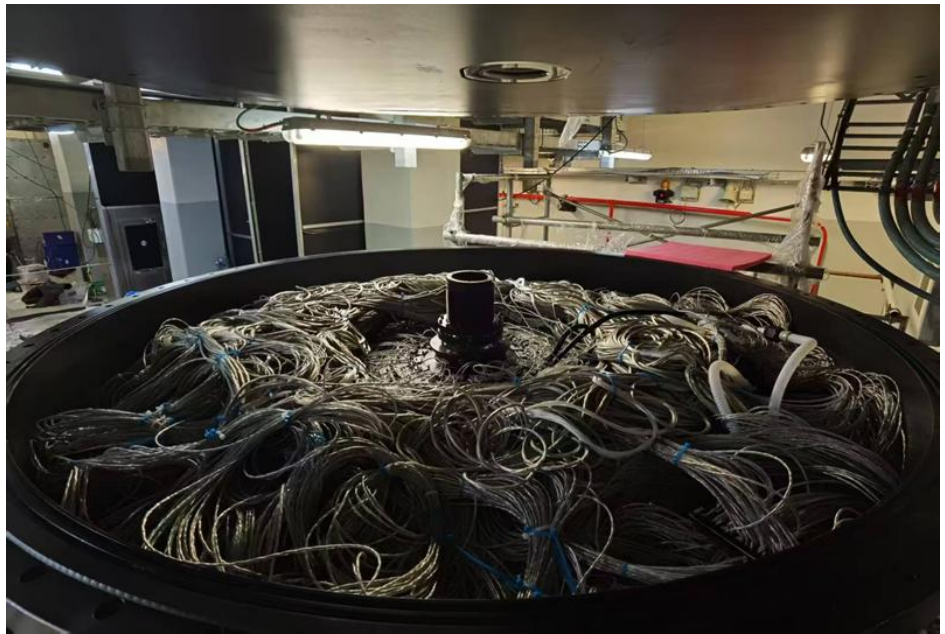


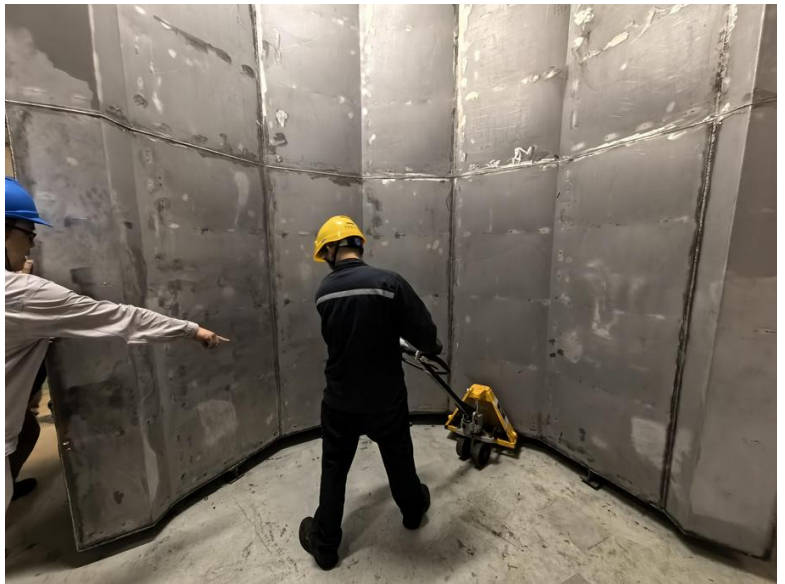
SiPM Installation





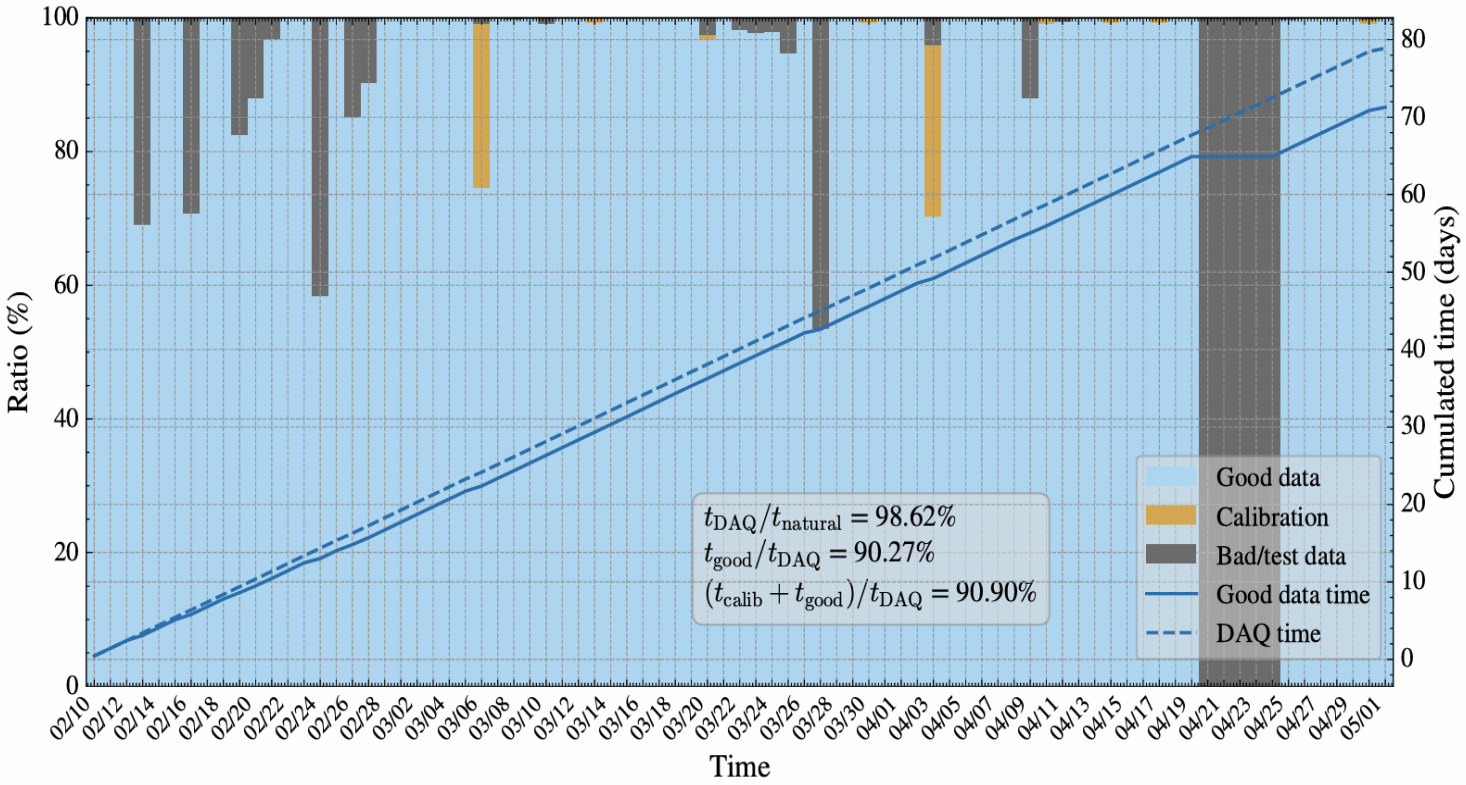






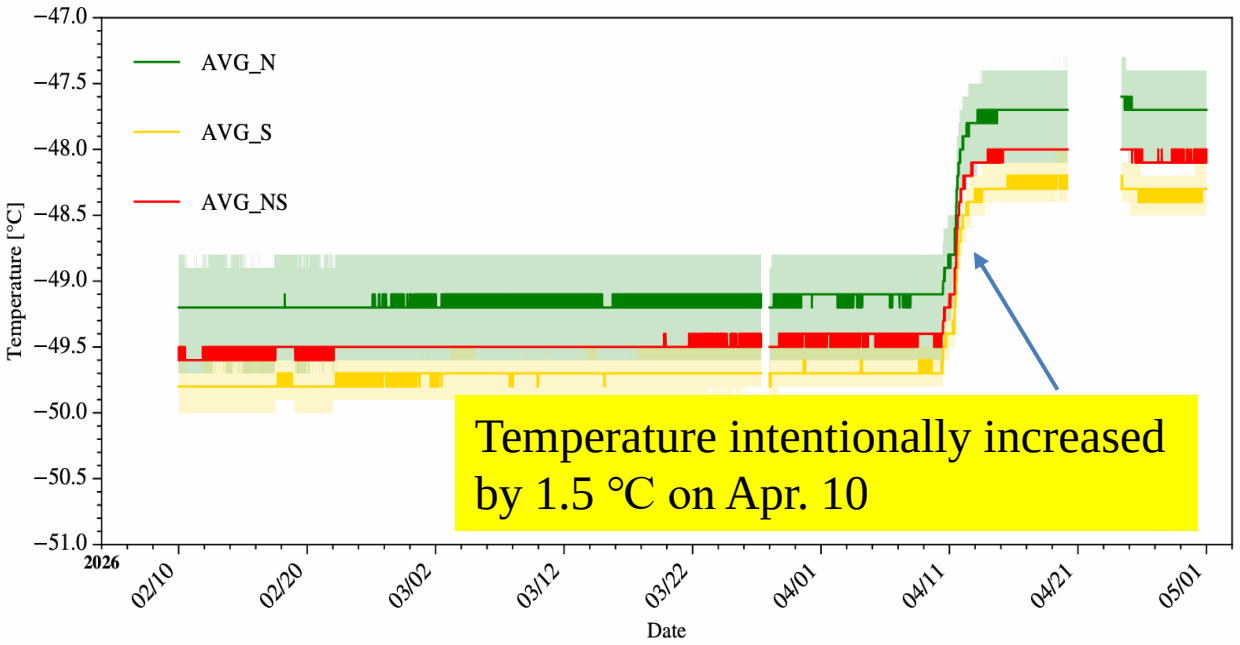
TAO Detector starts running

- The TAO detector installation was completed in September last year
- The detector commissioning was completed at the beginning of this year
- TAO started physics data taking on Feb. 10, 2026

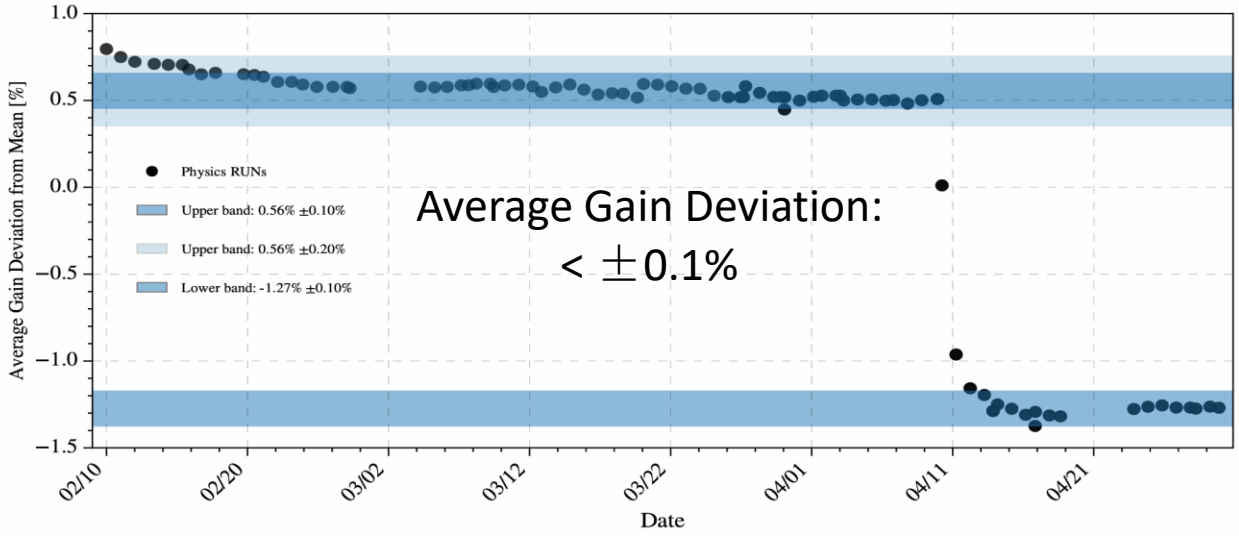


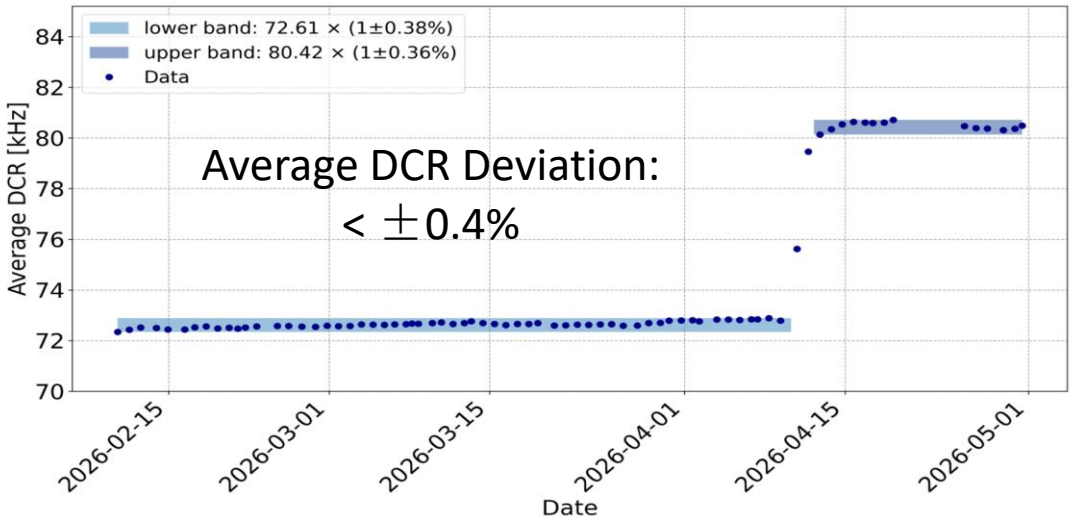


Detector Temperature



- TAO operates at -49 °C with good temperature control:
  - Uniformity: < ±0.5 °C, stability: < 0.2 °C, meet requirements
- Key challenges and solutions
  - New low-temperature LS recipe, NIM A 1009 (2021) 165459
  - Copper shell adopted for thermal uniformity
    - Tricky for 2-meter-scale copper shell fabrication
  - Strict control of FEB power dissipation
  - Optimized feedthroughs, calibration, cabling, and insulation
- A 1:1 prototype detector was built to validate and improve the whole cryogenic design
- Further cryogenic-system optimization is ongoing





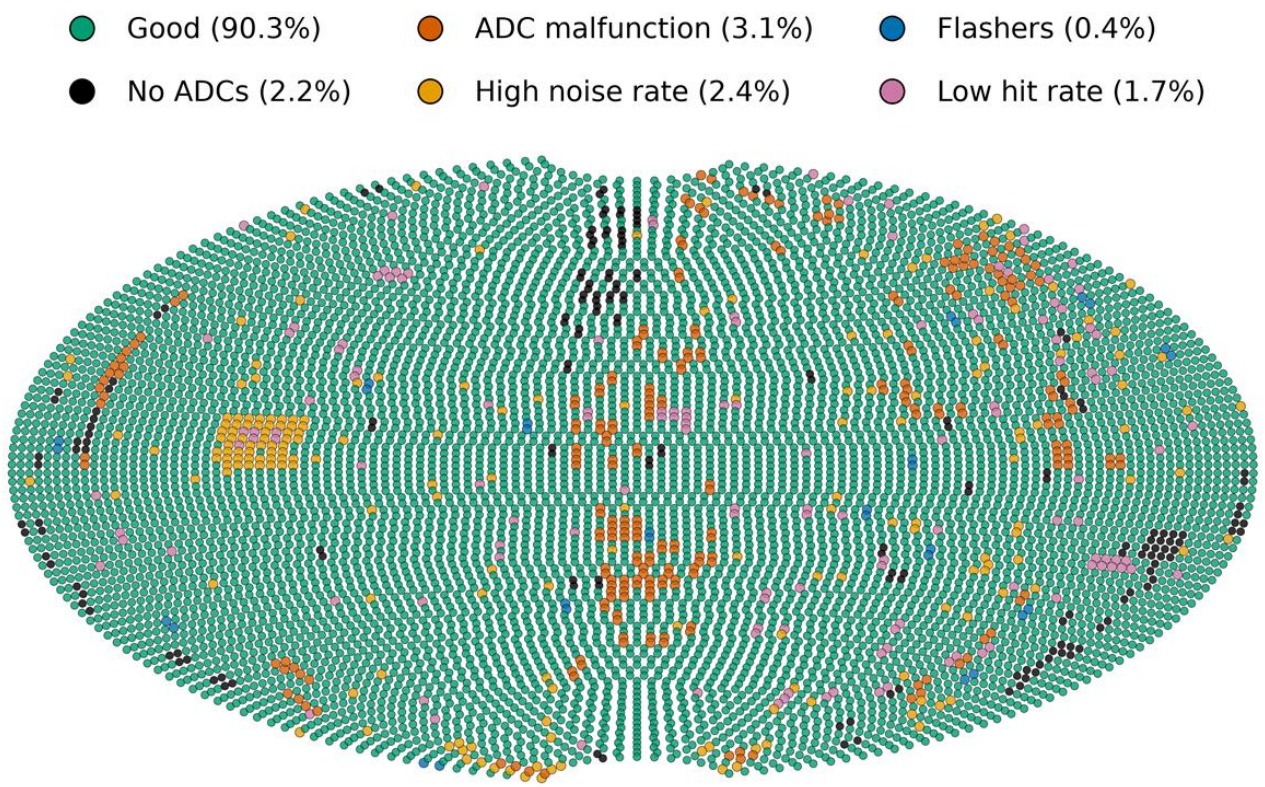
Detector Performance – Good Channel Map

❄ ~90% good channels

- ➢ Total channel number: 8,048

❄ For the rest ~10%

- ➢ 5.3% ADC missing/broken
  → will be completed/replaced
- ➢ 2.4% noisy channels
  → addressing noise issue
- ➢ Low hit rate: 1.7%
- ➢ Flasher: 0.4%
  → Most likely caused by FEBs

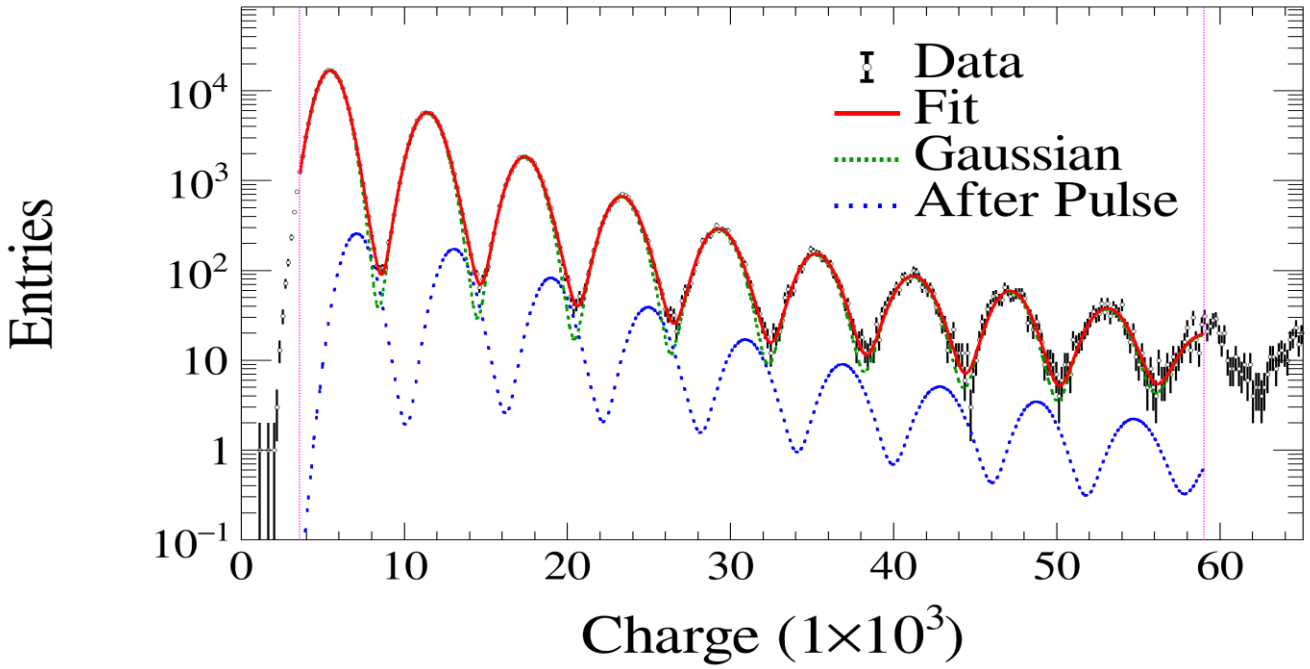


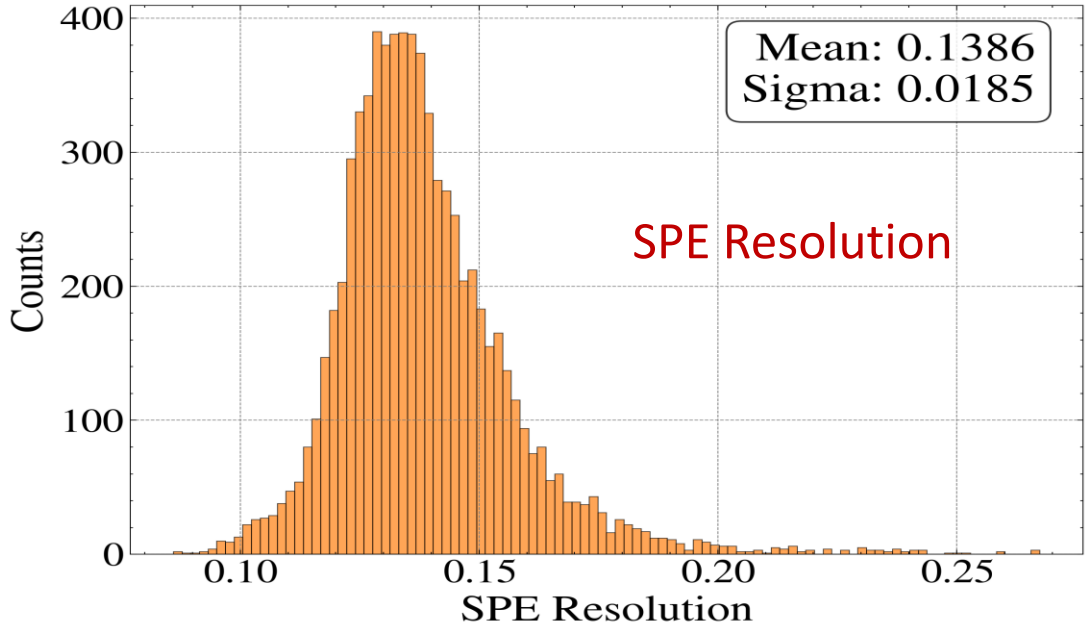
"Reactor Antineutrino Detection with JUNO-TAO: Commissioning Performance and First Results", arXiv:2610.23331

Detector Performance – SiPMs

- SiPM over voltage: **3.5 V** (Ge-68 energy resolution scan)
- Gain: 6000 ± 130 LSB, **uniformity ~2%, stability: ~0.1%**
- Single photo-electron (SPE) resolution: **~14%** (15% in CDR)
- DCR: **~50 Hz/mm^2** (100 Hz/mm^2 in CDR)
- PDE: **> 50%** (SiPM QA/QC), uniformity ~5%
- Cross-talk: **~25%** (preliminary)
- After-pulse: **< 5%** (SiPM QA/QC)

"Reactor Antineutrino Detection with JUNO-TAO: Commissioning Performance and First Results", arXiv:2610.23331

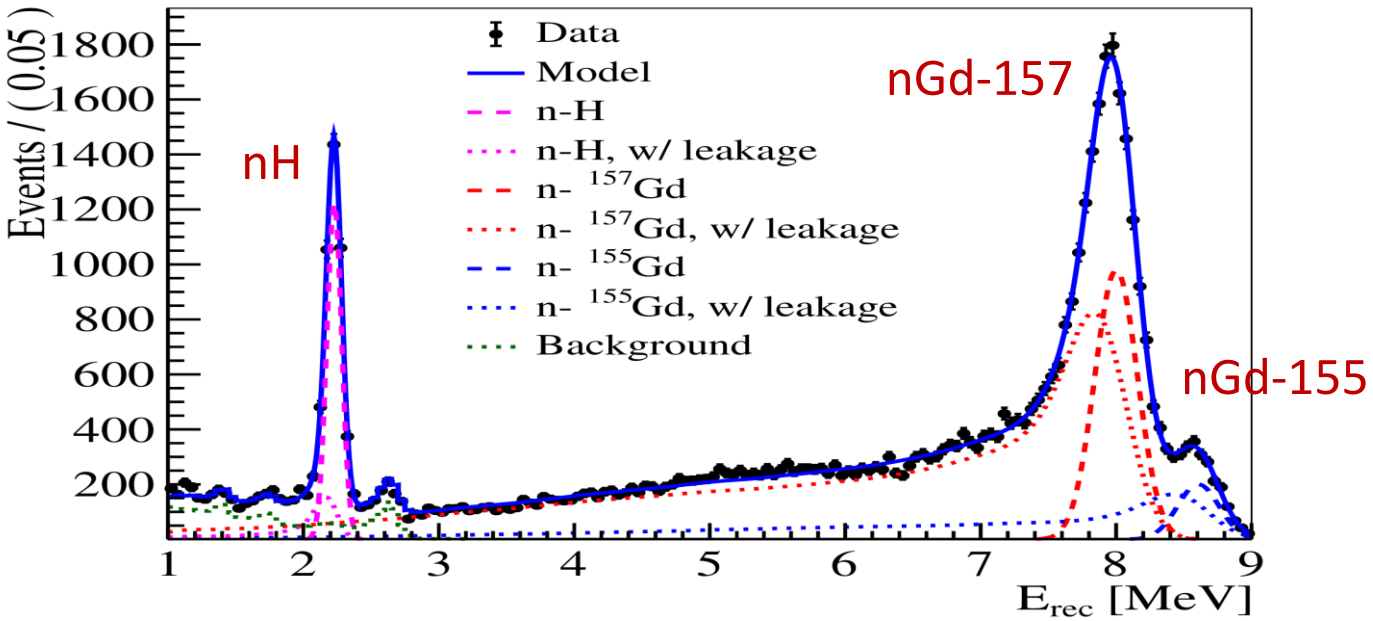


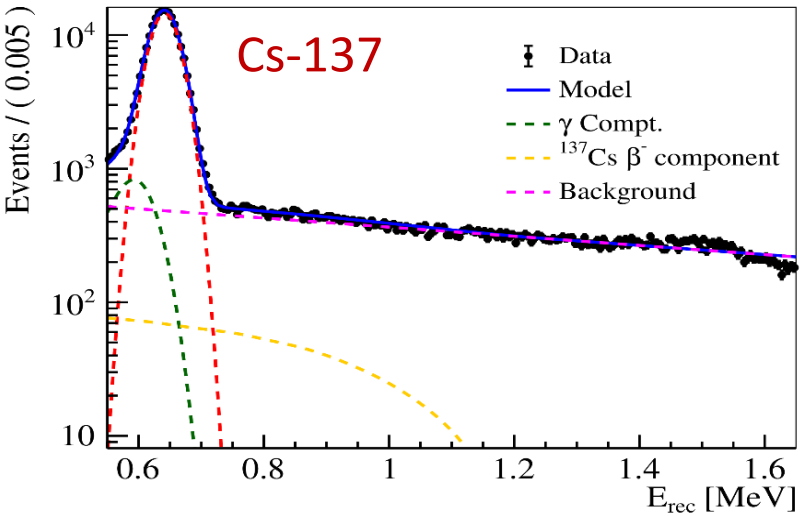


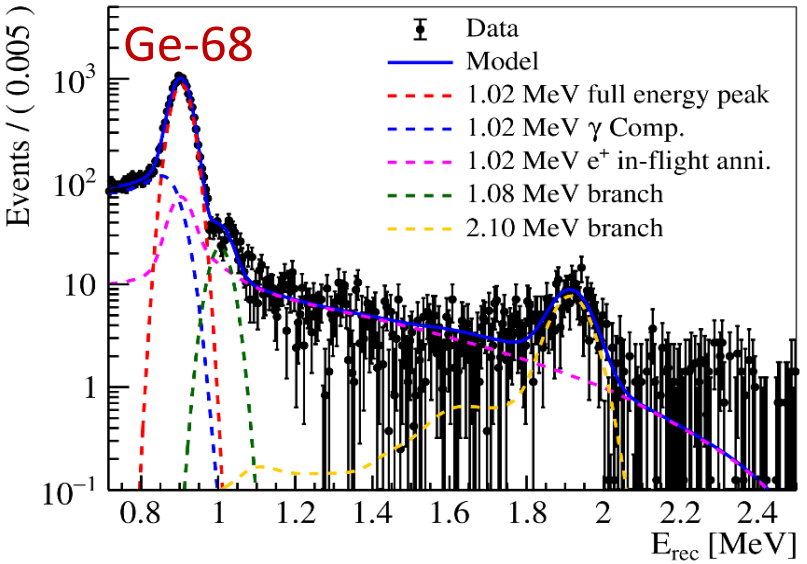
Detector Performance – Energy Resolution

- Light Yield: **~4,000 PE/MeV (1,785 PE/MeV from JUNO)**
- Cs-137 @R = 200 mm: **3.65%**
  - 0.662 MeV peak + beta component + energy leakage
- Ge-68 @R = 0: **2.82% @~1MeV**
  - 1.022 MeV peak + e+ annihilation in-flight + 1.08 de-excitation + energy leakage
- nH/nGd (R<400mm): **2.24% / 1.91%**
  - 2.223 / 7.9 / 8.5 MeV peak + energy leakage tail
- World-leading energy resolution among LS detectors

"Reactor Antineutrino Detection with JUNO-TAO: Commissioning Performance and First Results", arXiv:2610.23331



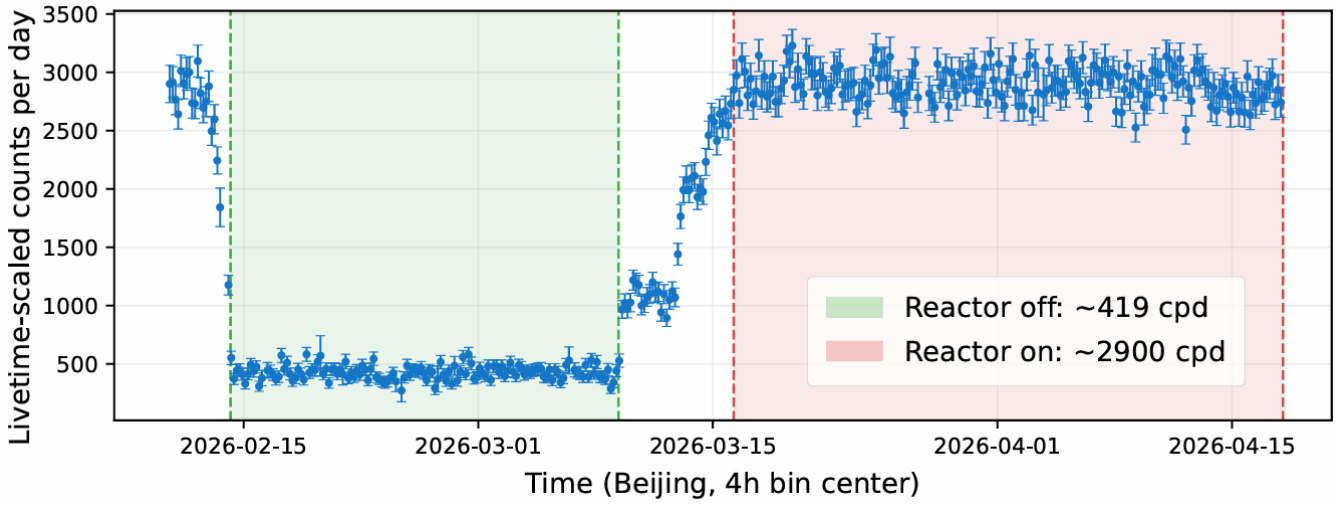


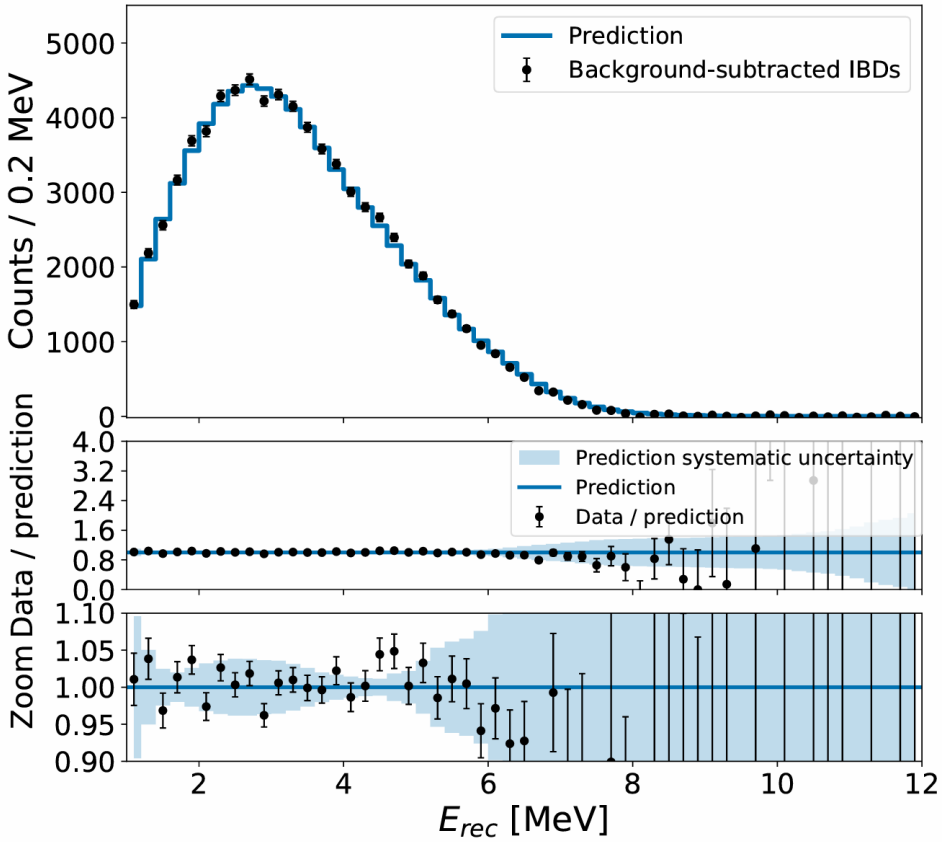


First Reactor Neutrino Spectrum from TAO

- Using **31.3 days of reactor-on data** and **29.4 days of reactor-off data**
- Observed candidate rates:
  - Reactor-on: ~2900 events/day
  - Reactor-off: ~419 events/day
- Prediction based on the Huber-Mueller model, convoluted with TAO detector response
- Good agreement observed between data and prediction

"Reactor Antineutrino Detection with JUNO-TAO: Commissioning Performance and First Results", arXiv:2610.23331





Key Lessons Learned

- Some of these points may sound obvious, but they are extremely useful to keep in mind during real installation work
- **A detector is only as robust as its weakest step**
  - Even one procedure performed below standard can lead to channel loss, no matter how well the other steps are done
- **SiPM QA/QC is necessary, but not sufficient**
  - Even if every SiPM channel passes testing, a loose connector or a missing flange cable can still result in the loss of signal from an entire SiPM tile
- **Careful preparation pays off**
  - It may take extra time upfront, but it often saves much more time later — although not always
- **Laboratory success does not guarantee site success**
  - A procedure that works perfectly in the lab may fail under real installation constraints, such as limited space, awkward access angles, humidity, schedule pressure, or nuclear power plant safety rules
- **Never ignore small issues**
  - There are no small problems in detector construction, as every unresolved detail can become a major issue later

Summary

❄ The TAO detector has been constructed and the data taking began on Feb. 10, 2026

❄ 10 m^2 of SiPMs have been deployed for precision reactor antineutrino spectrum measurement

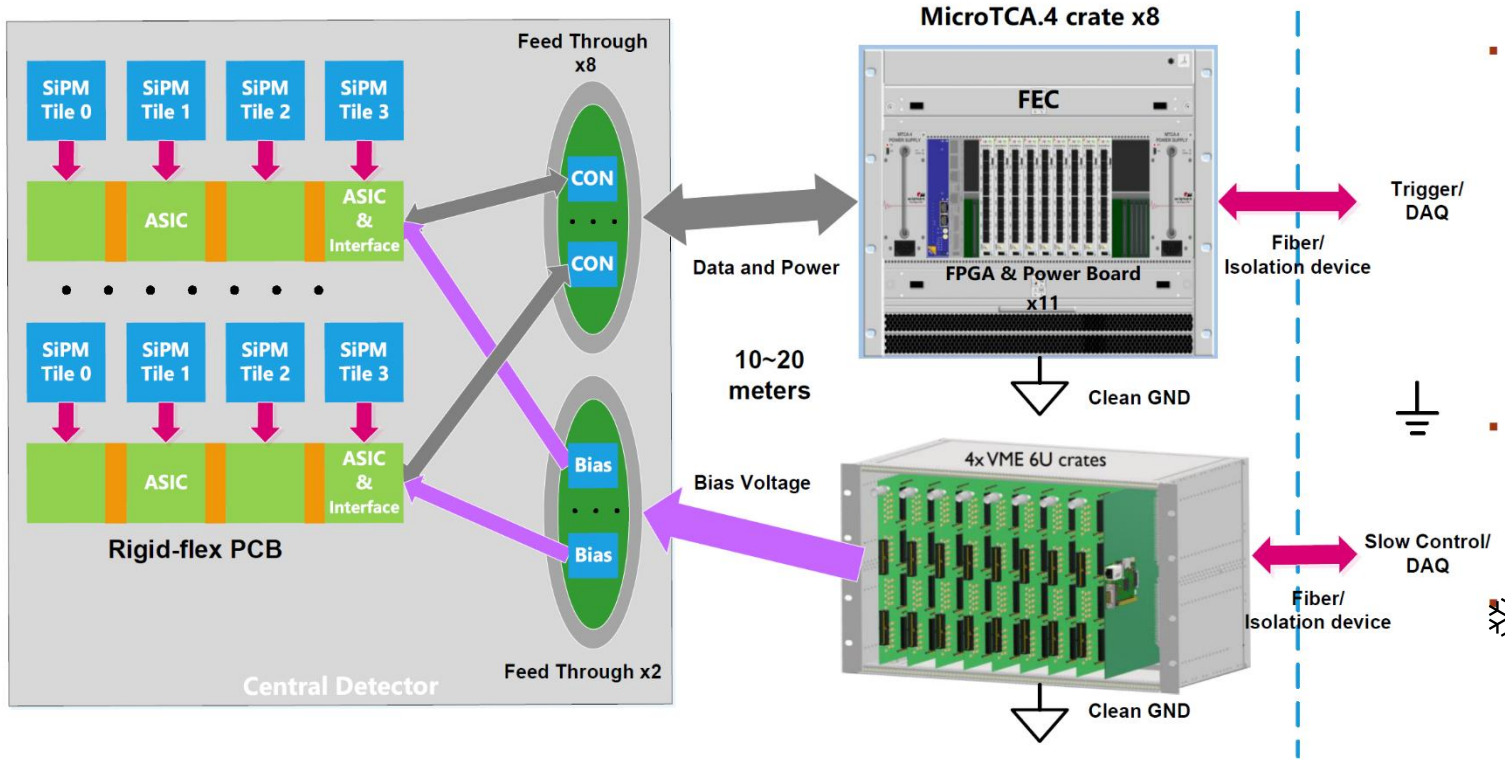
❄ Achieved world-leading energy resolution: 2.8% @Ge-68

❄ The first IBD analysis with one month of data shows good data/prediction agreement

- ➢ Provide inputs for JUNO neutrino mass ordering analysis

❄ Detector maintenance and optimization are ongoing, aiming to further improve the energy resolution

Thank you



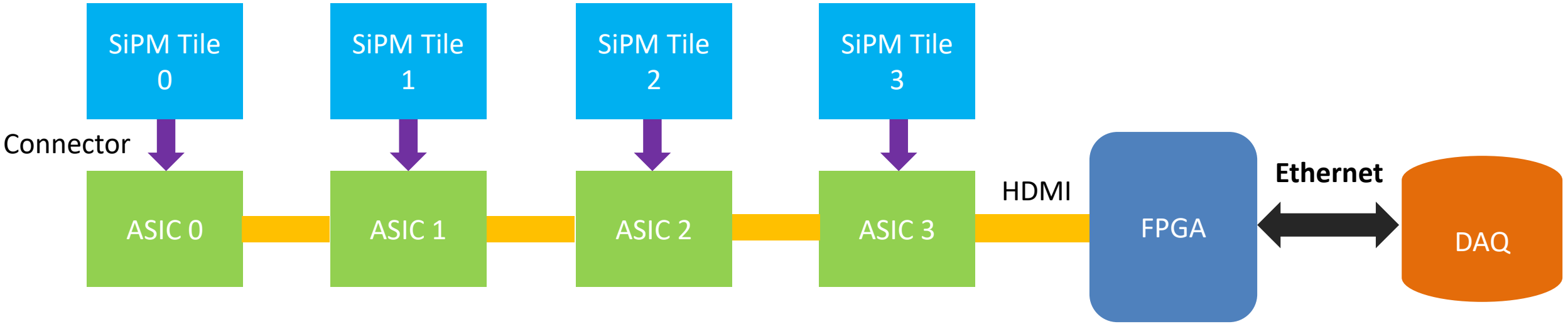
❄ FEB

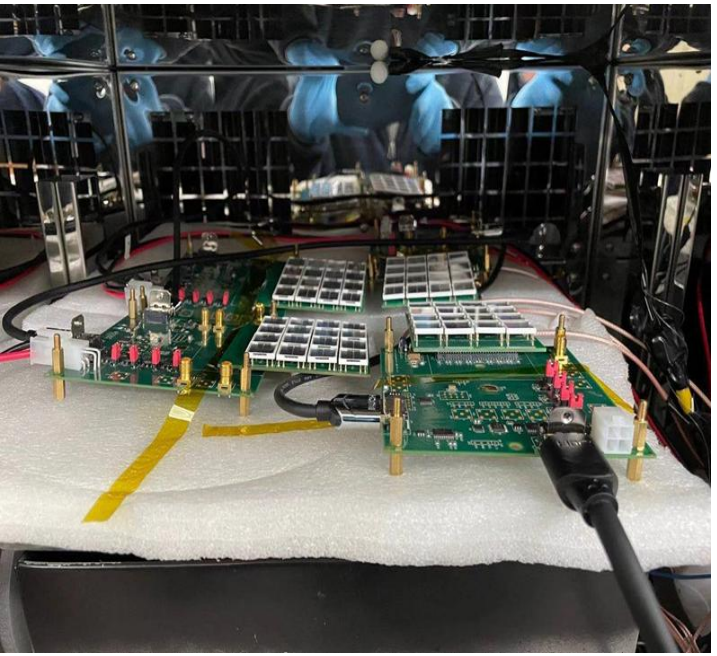
- 1 chip readout 2 tiles, 16 ch/tile
- Total 64,384 channels, 2012 chips
- Rigid-flex PCB, 4 tiles in 1 group
- Tile and FEB are connected with connectors
- Digital signals from FEB will be transferred to FEC via HDMI cables, 3-4 m inside the SS tank, ~10 m outside the tank

❄ FEC

- FPGA & Power boards in MicroTCA.4 crate
- Slow control, timestamp, sending data to TDAQ

A mockup block with 1/1000 TAO readout channels







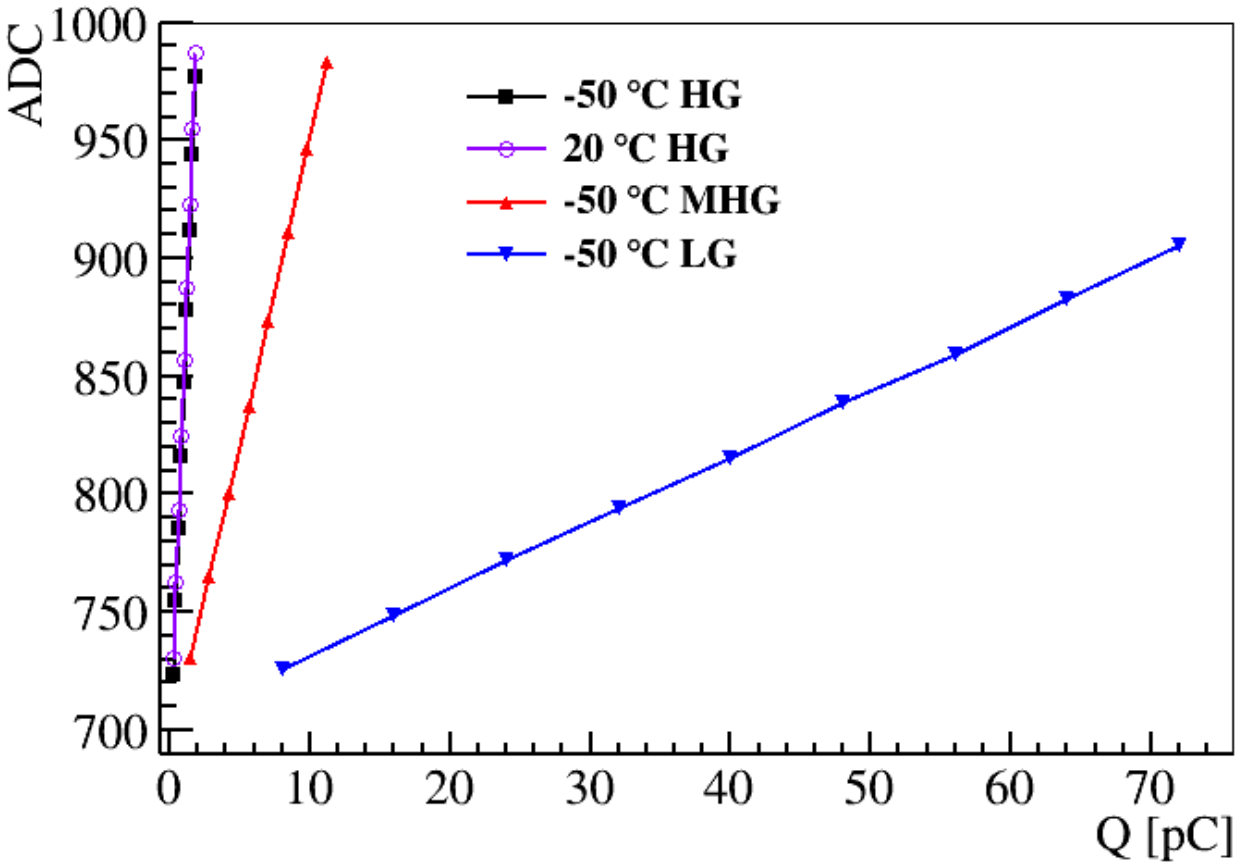
15 m HDMI cable

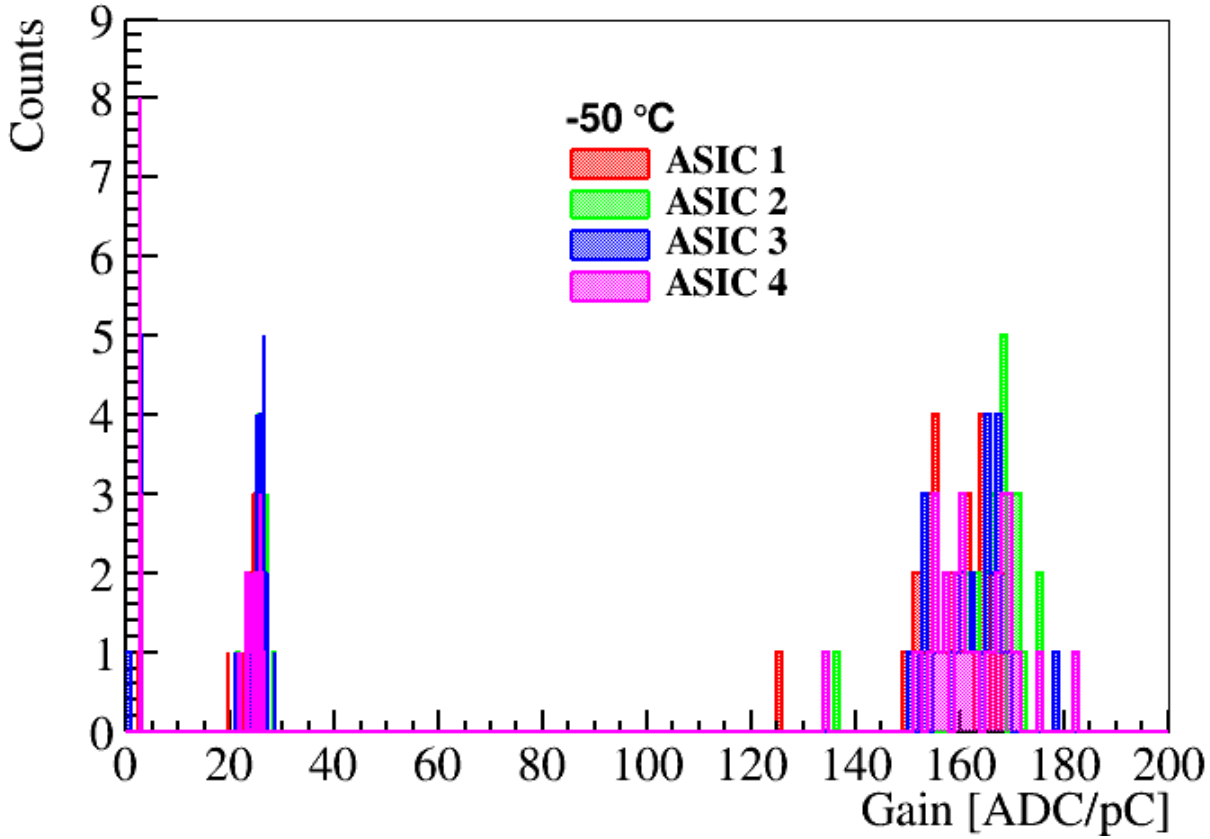


Ethernet

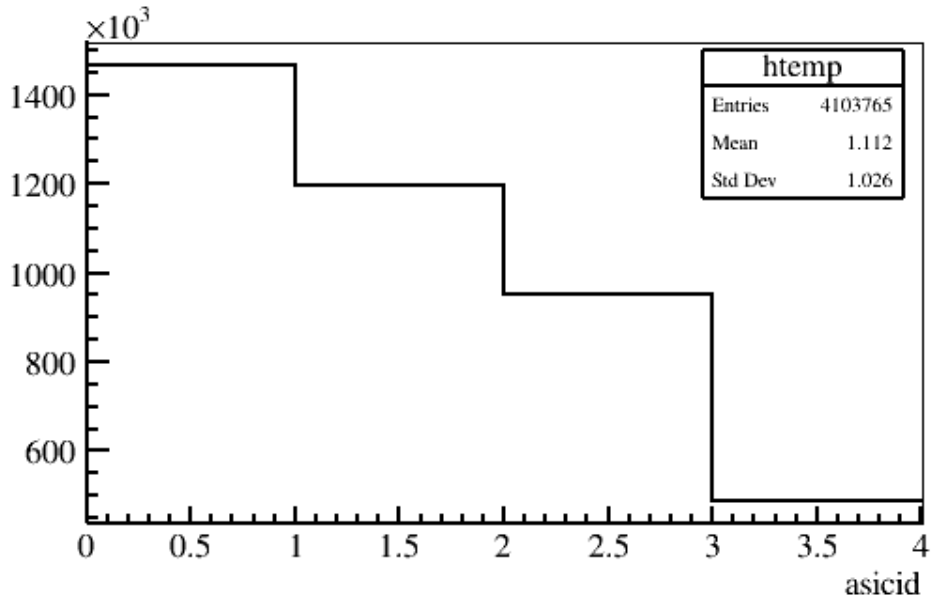


Gains in 3 branches (HG 1:1, MHG 1:7 and LG 1:40) have been characterized for 4 chips at low temperatures, which shows good linearity.

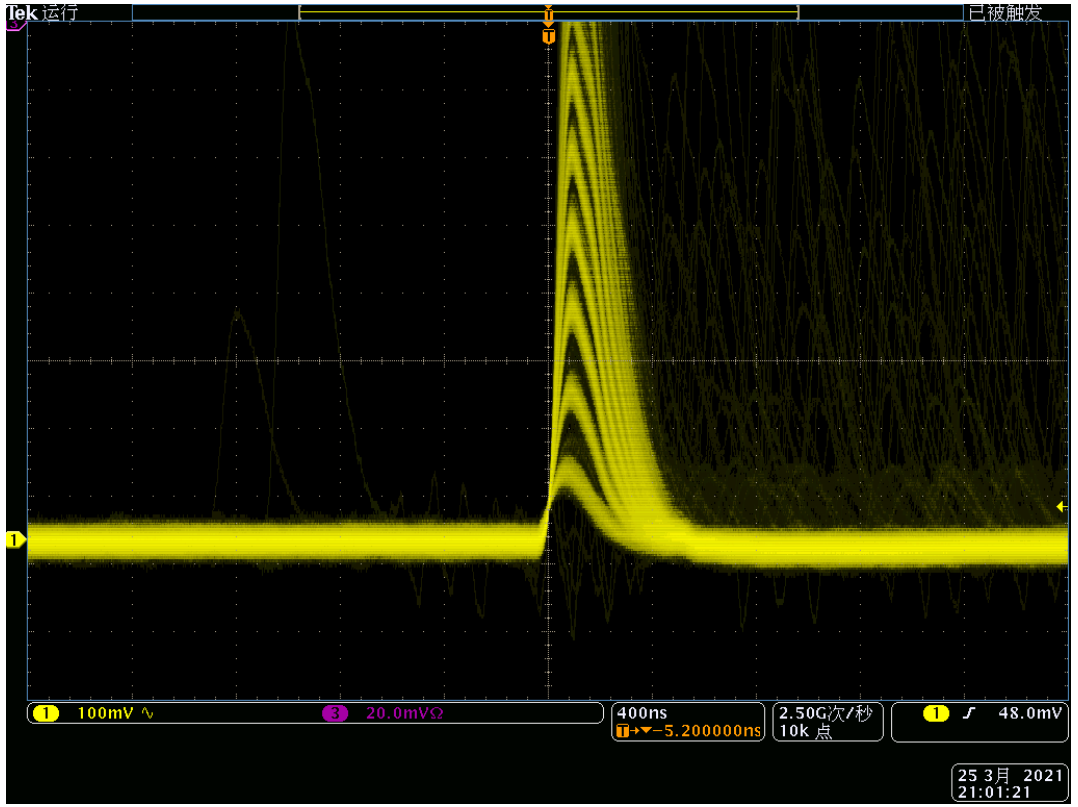




Bias voltage 53 V, break voltage 50.8V.

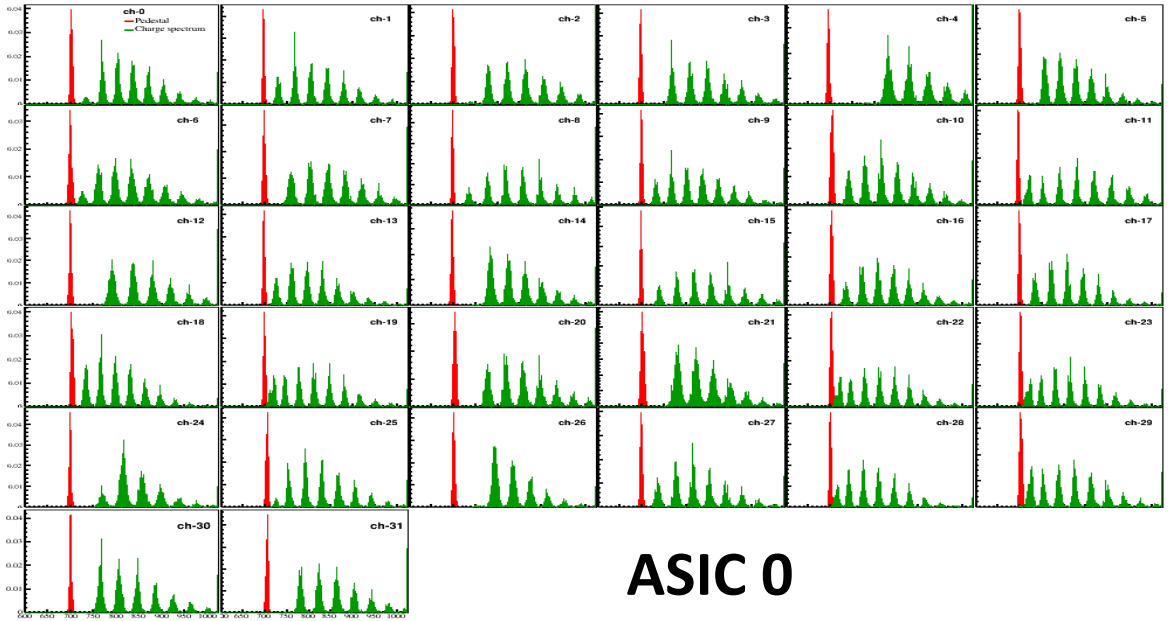


Distribution of chip ID

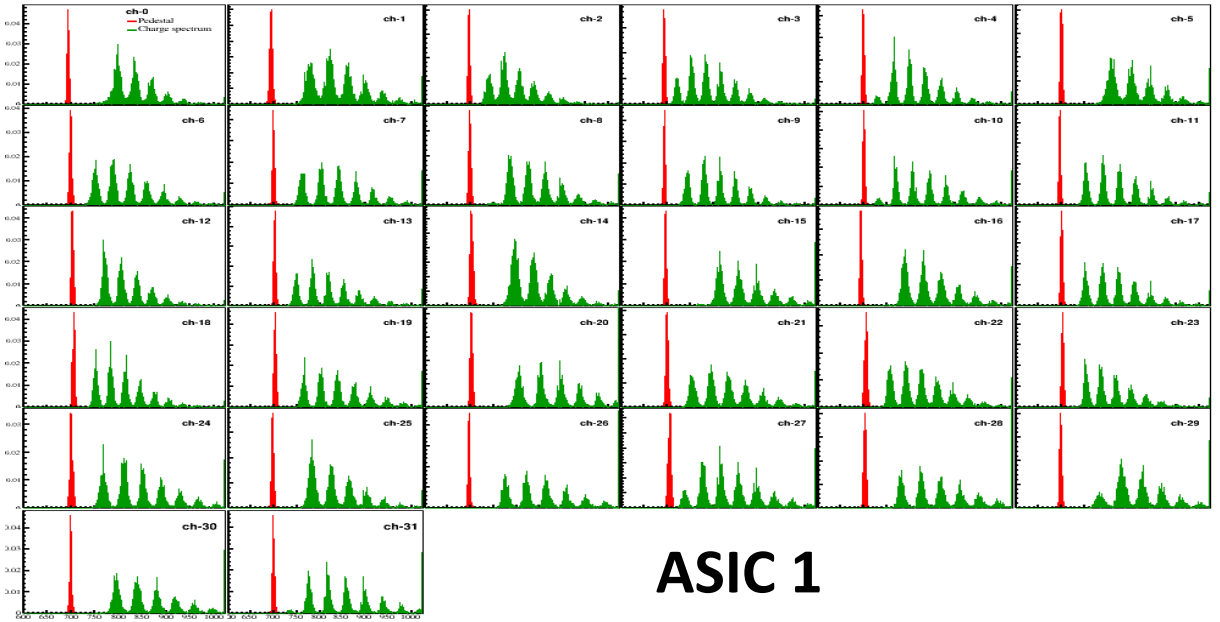


The analog signals after the shaper are monitored by an oscilloscope.

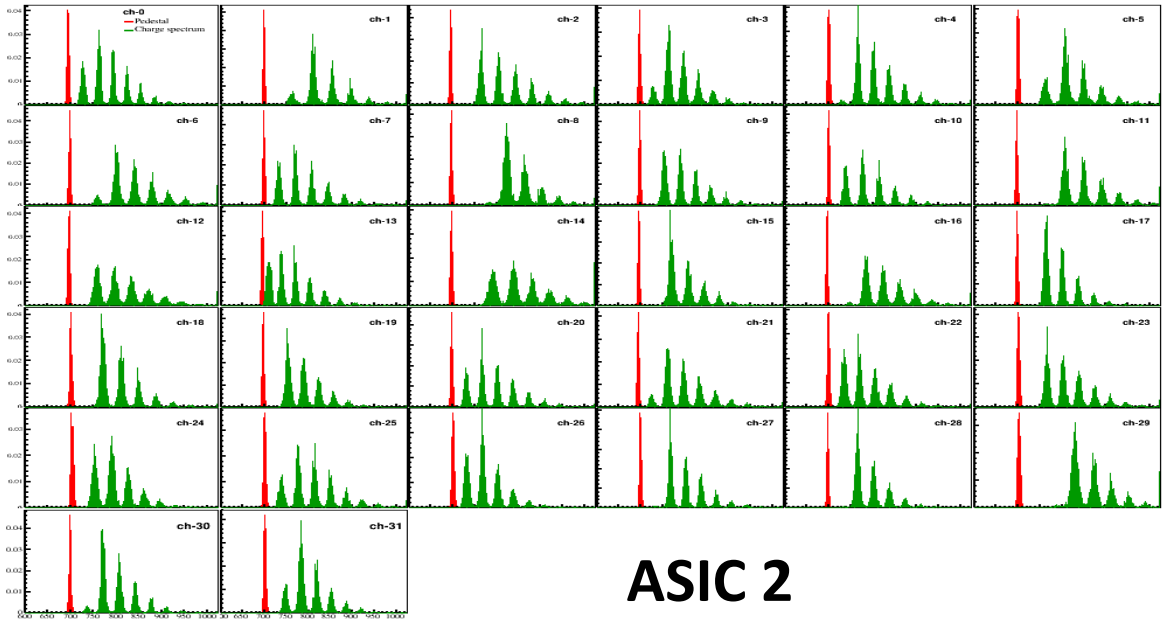
Charge spectra from 4 chips @ OV = ~2 V



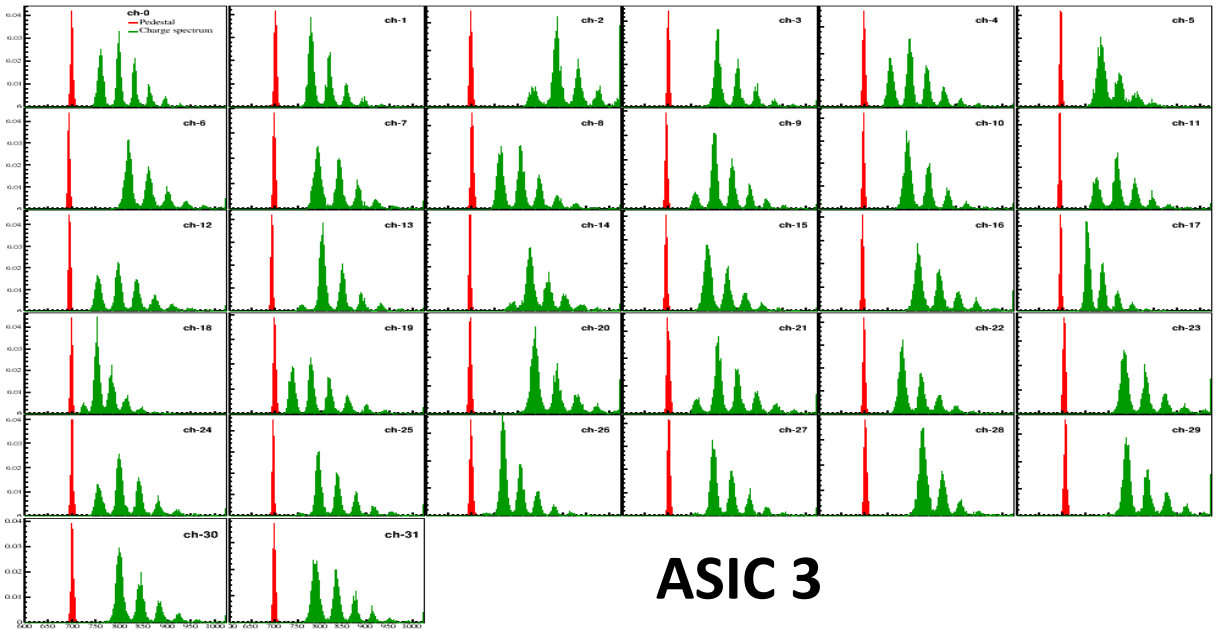
ASIC 0



ASIC 1

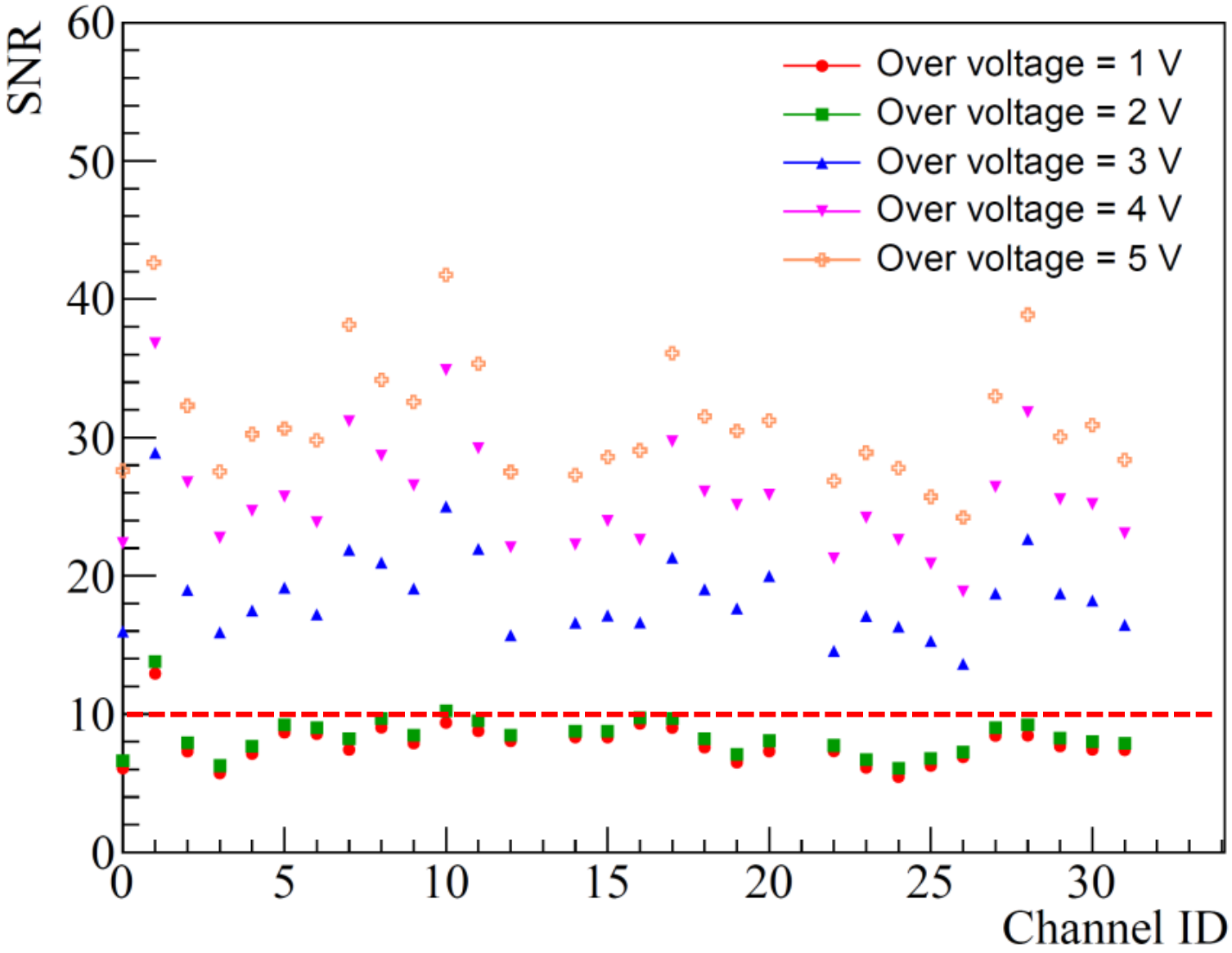


ASIC 2



ASIC 3

SNR of HG branch at -50 ℃



https://doi.org/10.1088/1748-0221/21/03/c03024

Some efforts ongoing to test the new chips