JUNO-TAO Experiment with Large Area High Performance SiPMs

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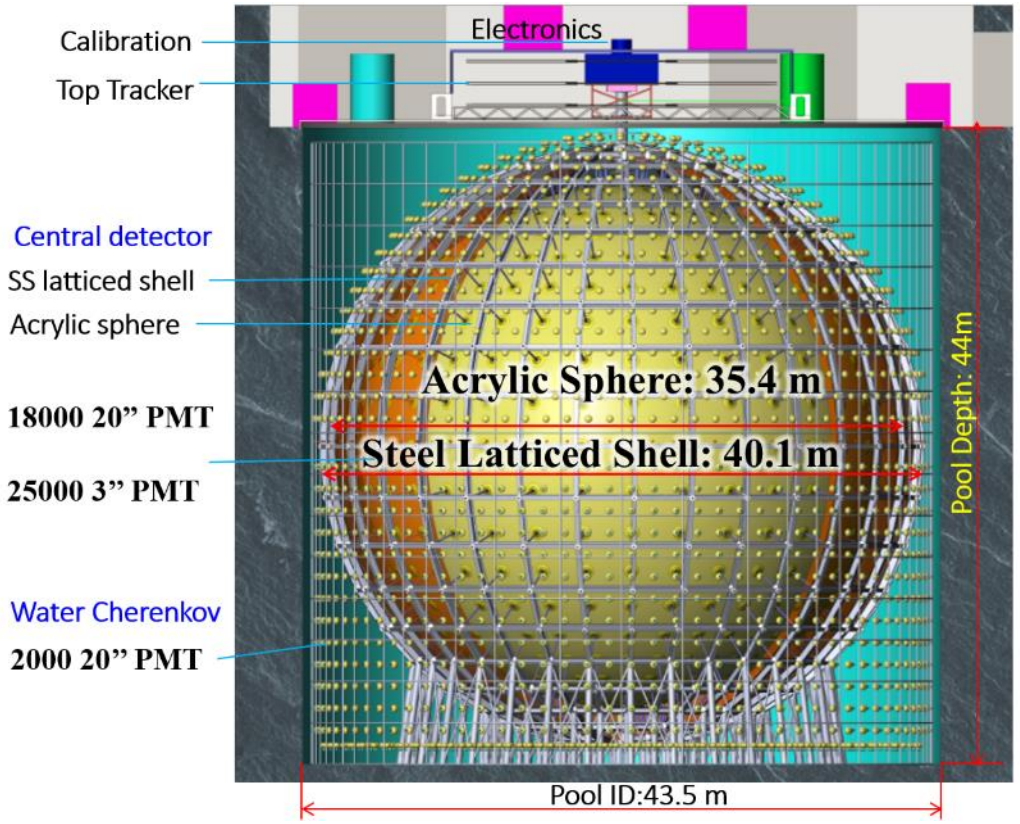
Institute of High Energy Physics

SiPM Workshop, Bari, October 2 – 4, 2019

Jiangmen Underground Neutrino Observatory, a multiple-purpose neutrino experiment, under construction, online in 2021

LS | 12 cm acrylic | 2.35 m water | SS lattice+PMTs | 1.2 m water+PMT | HDPE

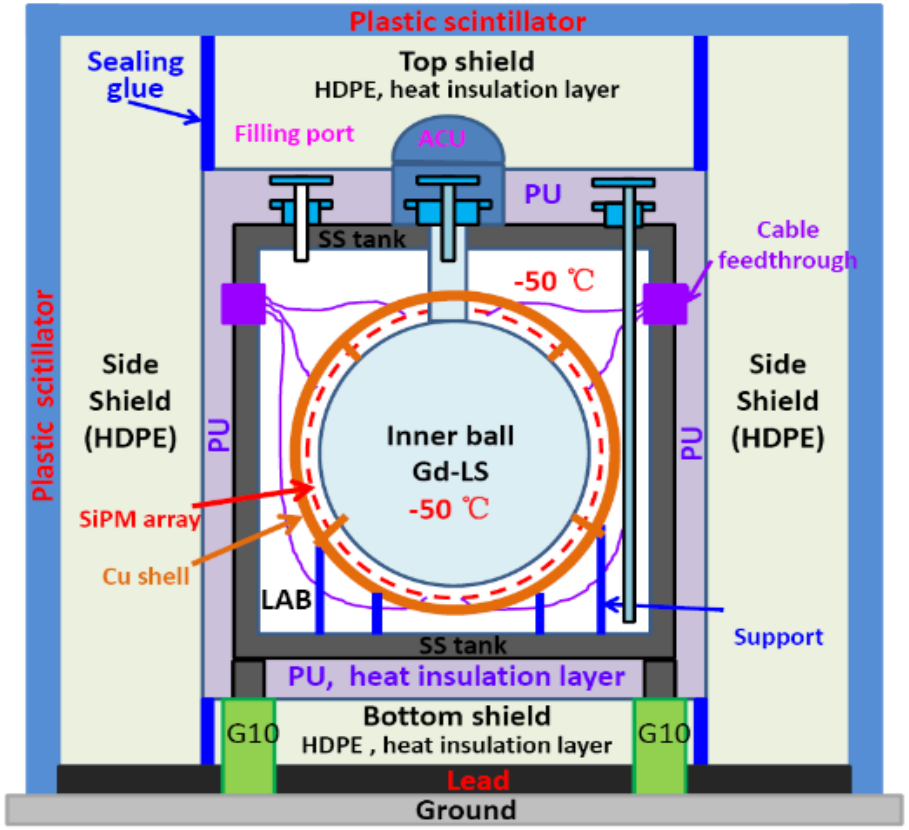
Inner → *Outside*



JUNO CDR, arXiv_1508.07166

- **20 kton LS detector**
- **$3\%/\sqrt{E(MeV)}$ energy resolution**
- **Rich physics possibilities**
  - ⇨ **Reactor neutrino for Mass hierarchy and precision measurement of 3 oscillation parameters**
  - ⇨ **Supernova neutrino**
  - ⇨ **Geo-neutrino**
  - ⇨ **Solar neutrino**
  - ⇨ **Proton decay**
  - ⇨ **Exotic searches**

- ❄ **Taishan Antineutrino Observatory (TAO), a satellite experiment of JUNO.**
  - ➢ **Taishan Nuclear Power Plant, 30 – 35 m from one of the 4.6 GW_{th} reactor cores**
  - ➢ **Total cost, 4-5 M$**
- ❄ **Measure reactor neutrino spectrum w/ sub-percent E resolution**
- ❄ **Ton scale Gd-doped Liquid Scintillator (Gd-LS)**
- ❄ **Full coverage of SiPM w/ PDE > 50%**
  - ➢ **$2.5\%/\sqrt{E(MeV)}$ energy resolution with PMTs of PDE 24%**
- ❄ **Operate at -50 ℃ (SiPM dark noise)**
- ❄ **4500 p.e./MeV**
- ❄ **Online in 2021**



Location of JUNO and JUNO-TAO

20 kton LS detector
700 m underground

JUNO

53 km

53 km

TAO

Taishan NPP

Yangjiang NPP

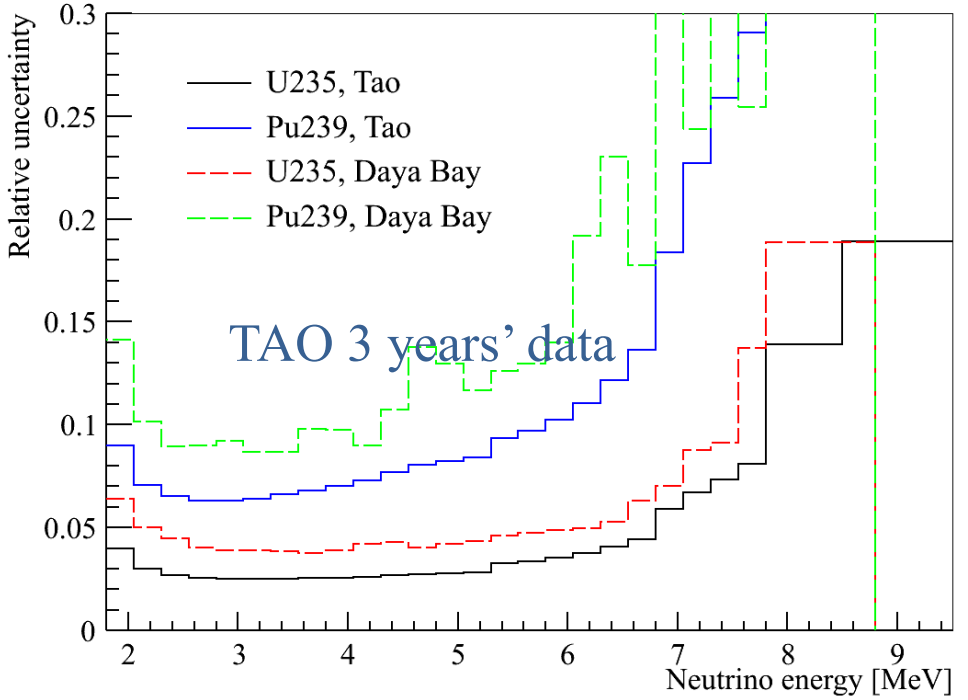
Guang Zhou

Hong Kong

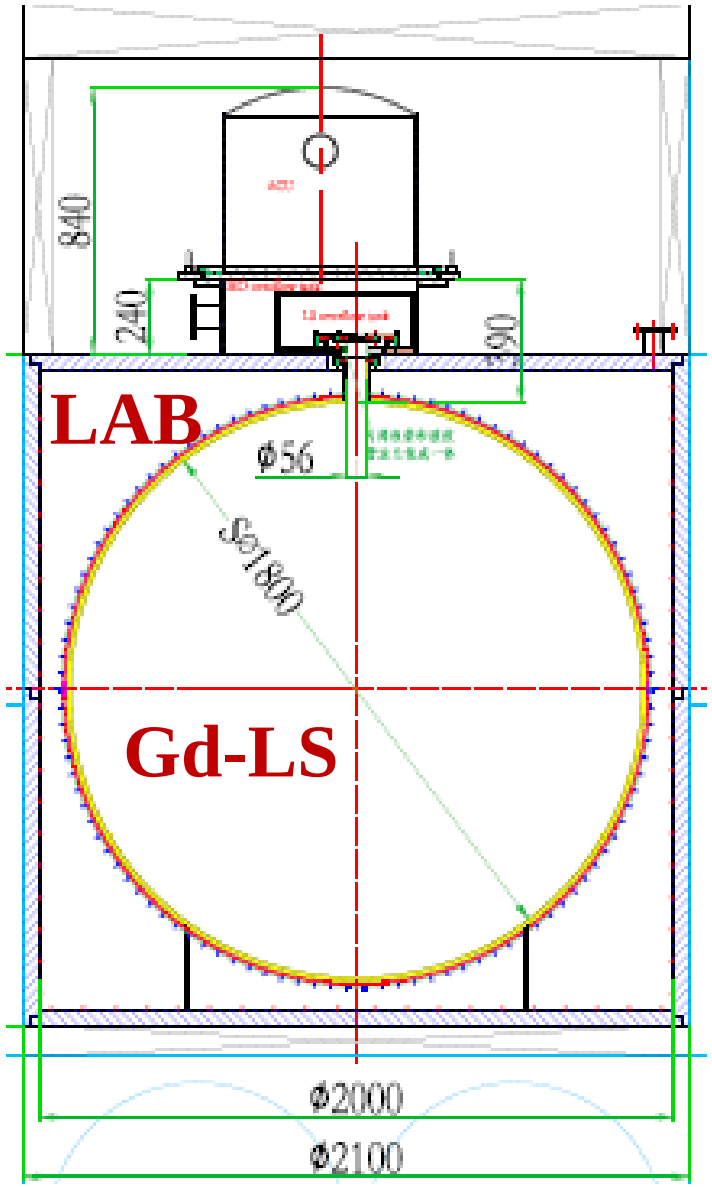
Daya Bay

Yangjiang	Taishan
17.4 GW	9.2 + 9.2 GW

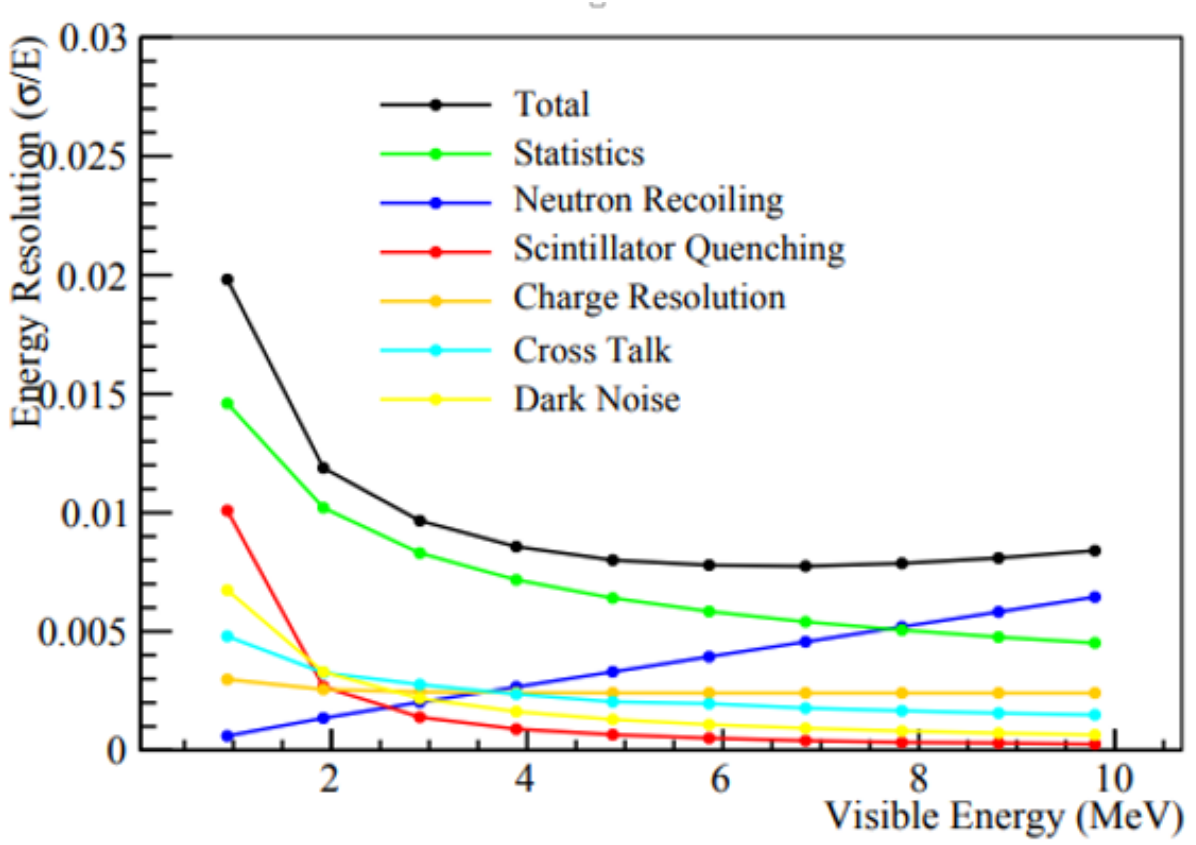
- **Provide reference spectrum for JUNO, to remove model dependence by measuring fine structures**
  - **Required equal or better energy resolution than JUNO → $3\%/\sqrt{E(MeV)}$**
- **Provide a benchmark to examine nuclear database, measuring fine structures**
  - **Design TAO w/ as high E resolution as possible (~1% at 1 MeV)**
- **Measuring isotopic neutrino spectrum**
  - **Extend to different fission fraction; test ab initio spectra**
- **Reactor monitoring**
- **Sterile neutrino**
- **Possible new findings w/ unprecedented resolution**



- ❄ **Laboratory in a basement at -10 m, 30-35 m from Taishan core (4.6 GW_{th})**
- ❄ **2.6 ton Gd-LS in a spherical vessel**
  - ➢ **1-ton FV, ~4000 IBDs/day**
  - ➢ **~2000 detected IBDs/day, due to 50% efficiency of muon veto and IBD neutron tagging**
- ❄ **10 m^2 SiPM of 50% PDE Operate at -50℃**
- ❄ **From Inner to Outside**
  - ➢ **Gd-LS**
  - ➢ **Acrylic vessel**
  - ➢ **SiPM and support (Cu shell)**
  - ➢ **Cryogenic vessel (SS + insulation)**
  - ➢ **1~1.5 m water or HDPE shielding**
  - ➢ **Muon veto**



- ❄ **Done by MC simulation, assumed parameters listed as follows.**
- ❄ **Dominated by statistics**
  - ➢ **SiPM coverage – 94%**
  - ➢ **SiPM PDE – 50%**
- ❄ **Scintillator quenching impacts more in low energy region**
- ❄ **IBD neutron recoil contributes to high energy region.**
- ❄ **Charge resolution – 16% (30% for PMTs)**
- ❄ **Optical cross talk – 10%**
- ❄ **Dark noise – 100 Hz/mm² at -50 ℃**



Parameters	Specification	Comments
Photon detection efficiency	> 50%	~400nm, not include correlated avalanches
Dark noise rate	< 100 Hz/mm^2	At -50 ℃
Probability of correlated noise	< 20%	Including optical cross talk, delayed optical cross talk and after pulsing
Uniformity of V_{bd}	< 10%	For the case w/o bias voltage tuning
Area per SiPM chip	>= 6 x 6 mm^2	For easy handling and high coverage
Coverage of SiPM chips in one tile	> 90%	Not included in PDE, TSV preferred
Radio-purity (Bq/kg)	U: < 4.4; Th: < 6.3; K: < 1	SiPM + resin + PCB + Elec.

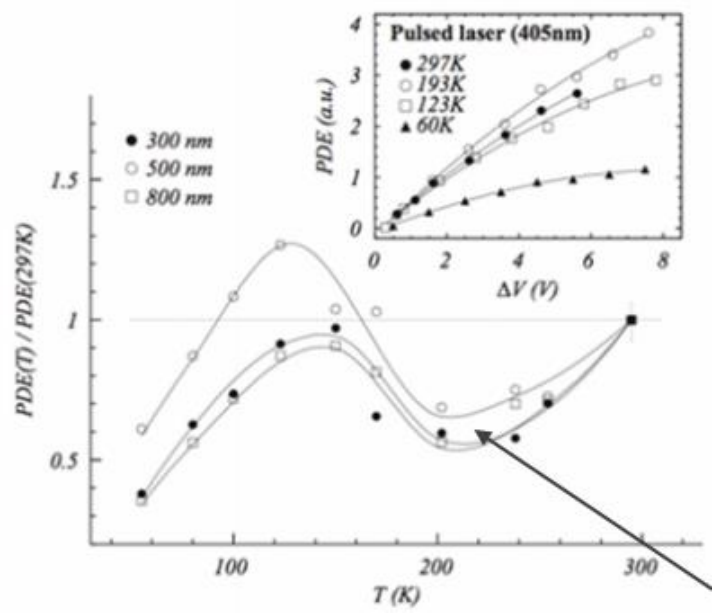
It’s a tradeoff between SiPM PDE and dark noise/correlated noise.

May not be up-to-date!	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

In table, Vop for Hamamatsu is 2.5 V, Vop = 5 V for SensL and FBK

The performance of some SiPMs looks promising.

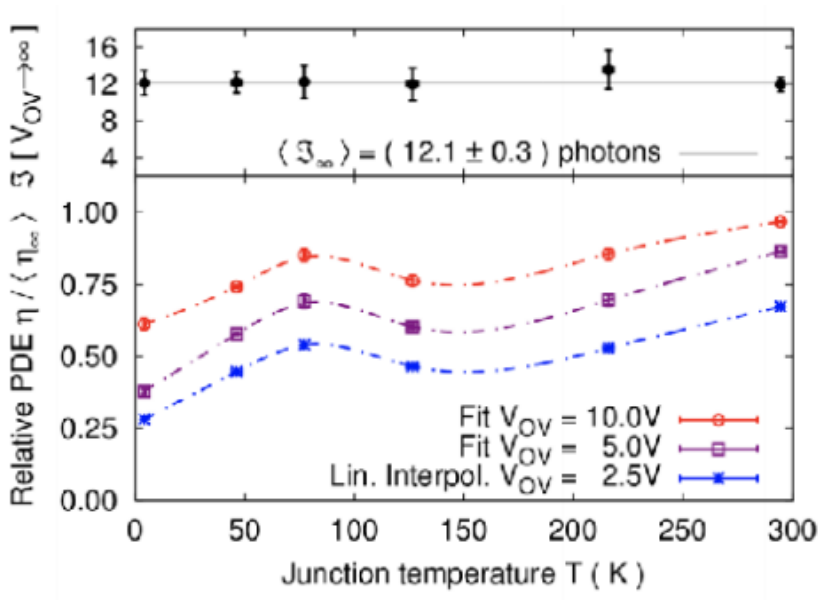
❄ PDE of SiPMs at low temperature (-50 ℃)



FBK SiPM

G. Collazuol [a], M.G. Bisogni [a,b], S. Marcatili [a,b], C. Piemonte [c], A. Del Guerra [a,b]

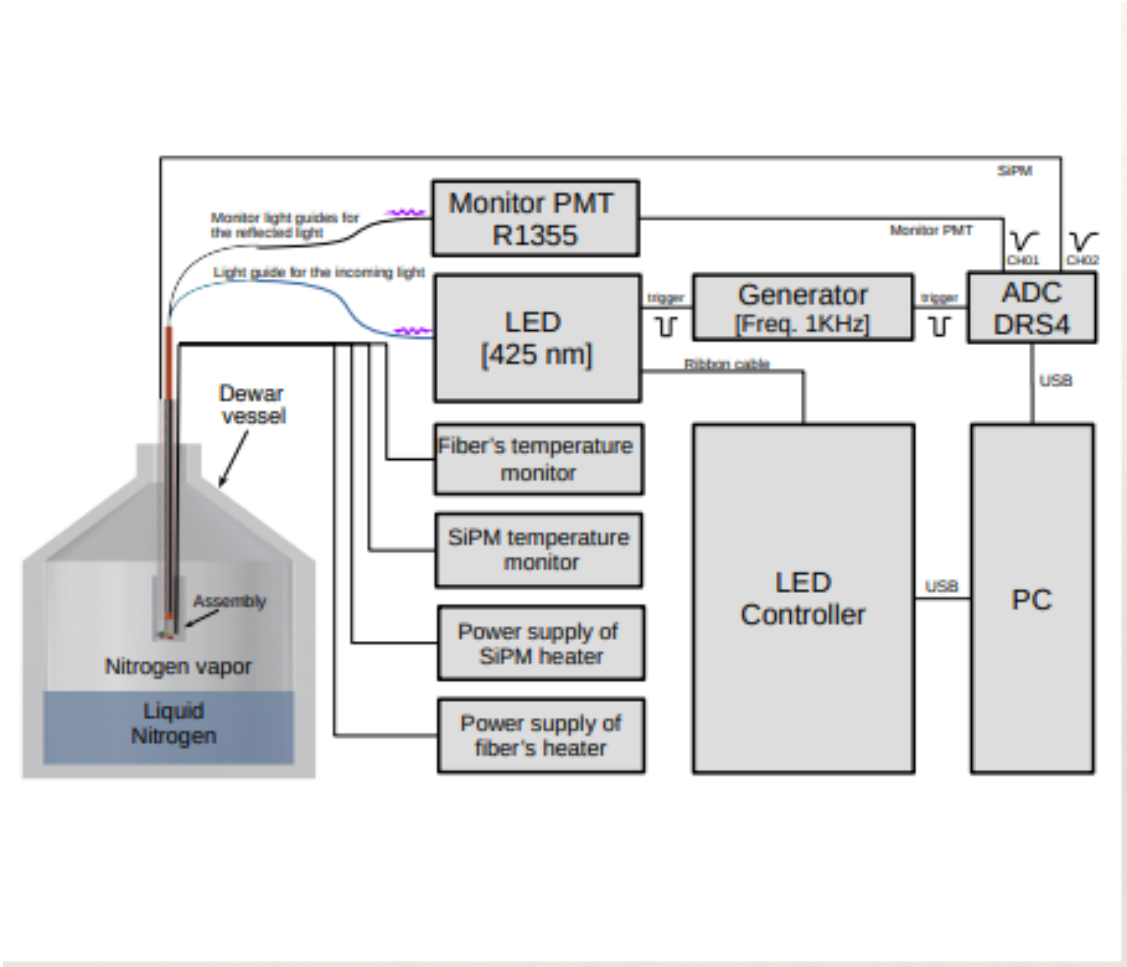
Studies of silicon photomultipliers at cryogenic temperatures

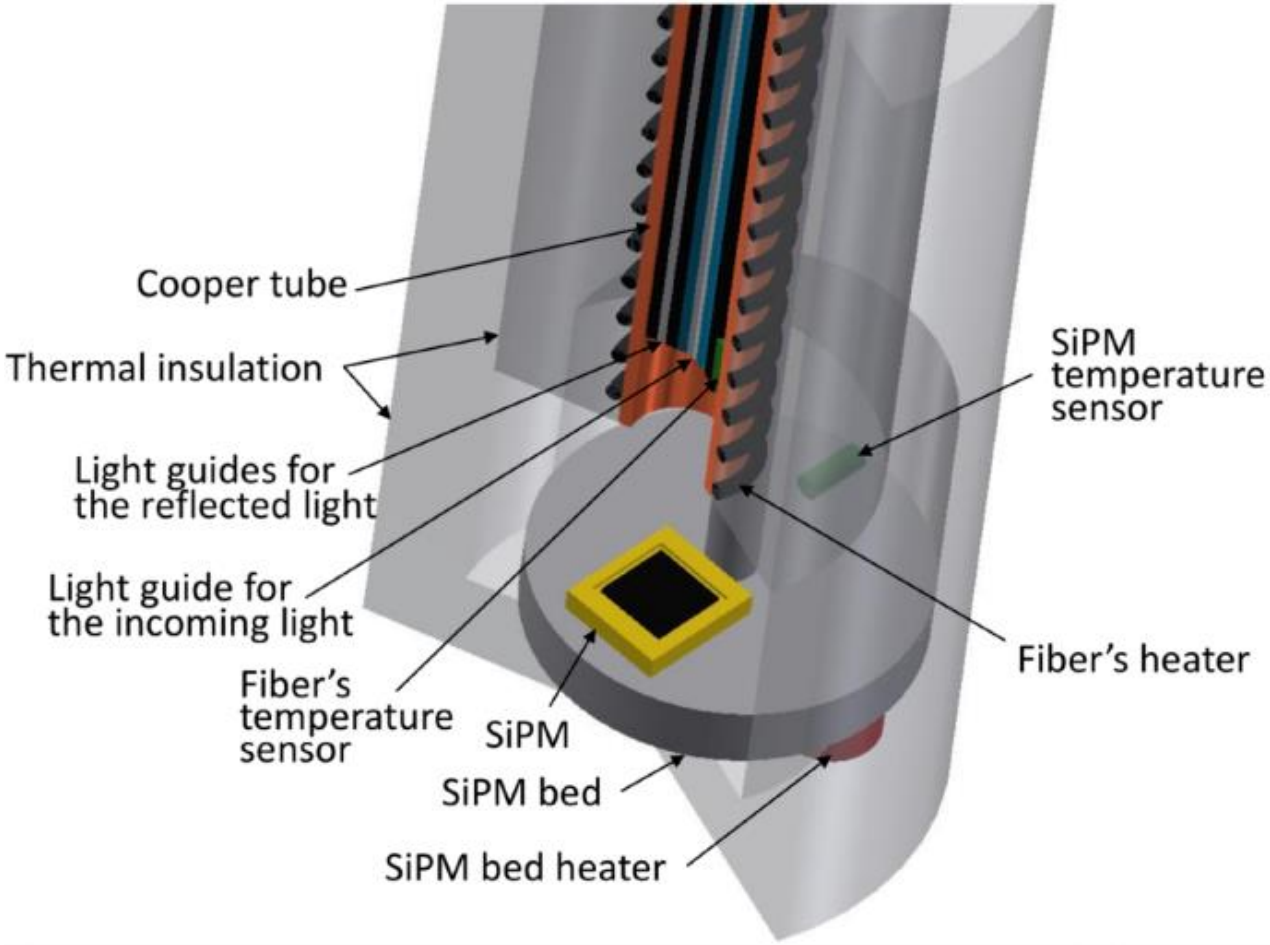


Maik Biroth, ICASiPM

PDE of SiPMs decreases at low temperature? even by a factor of 2?

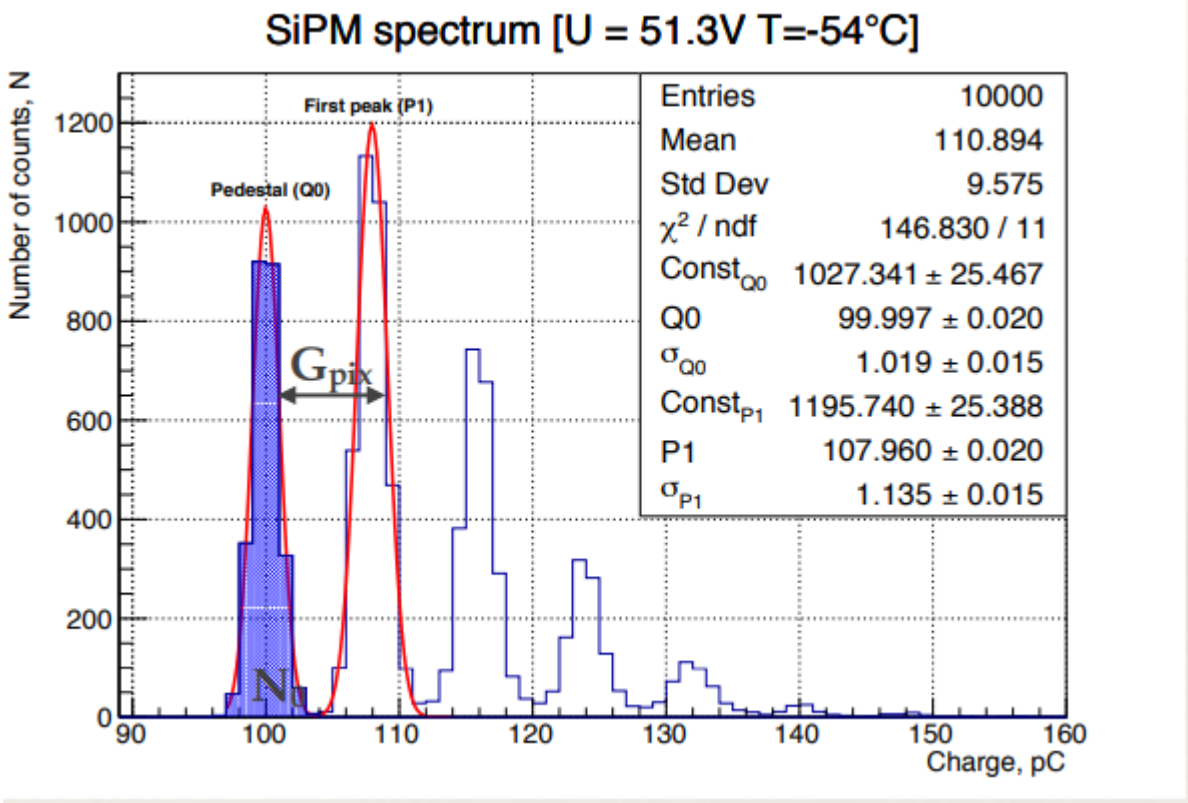
Temperature dependence of PDE needs to be carefully investigated for TAO.





Measured SiPMs:

- **Model S13360 – 6025CS from HPK**
- **ASD-NUV4S-P-4x4TD from AdvanSiD**



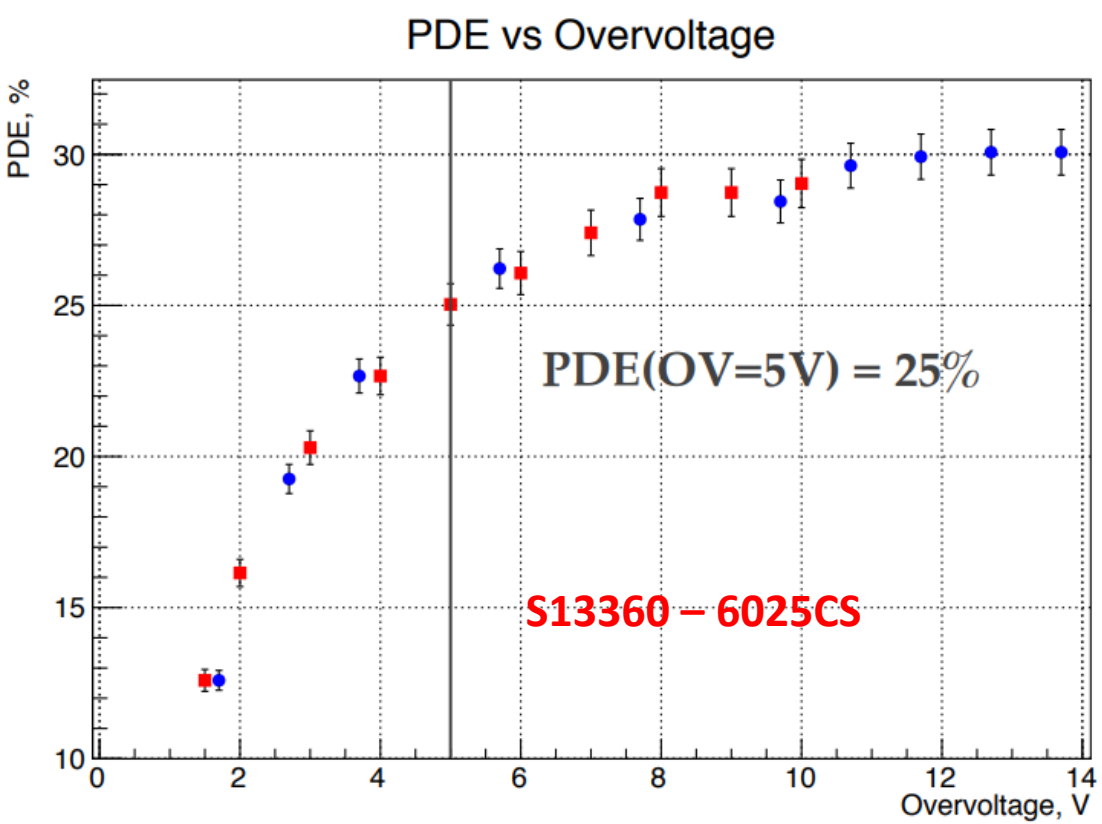
pe number per pulse is a distribution of poisson :

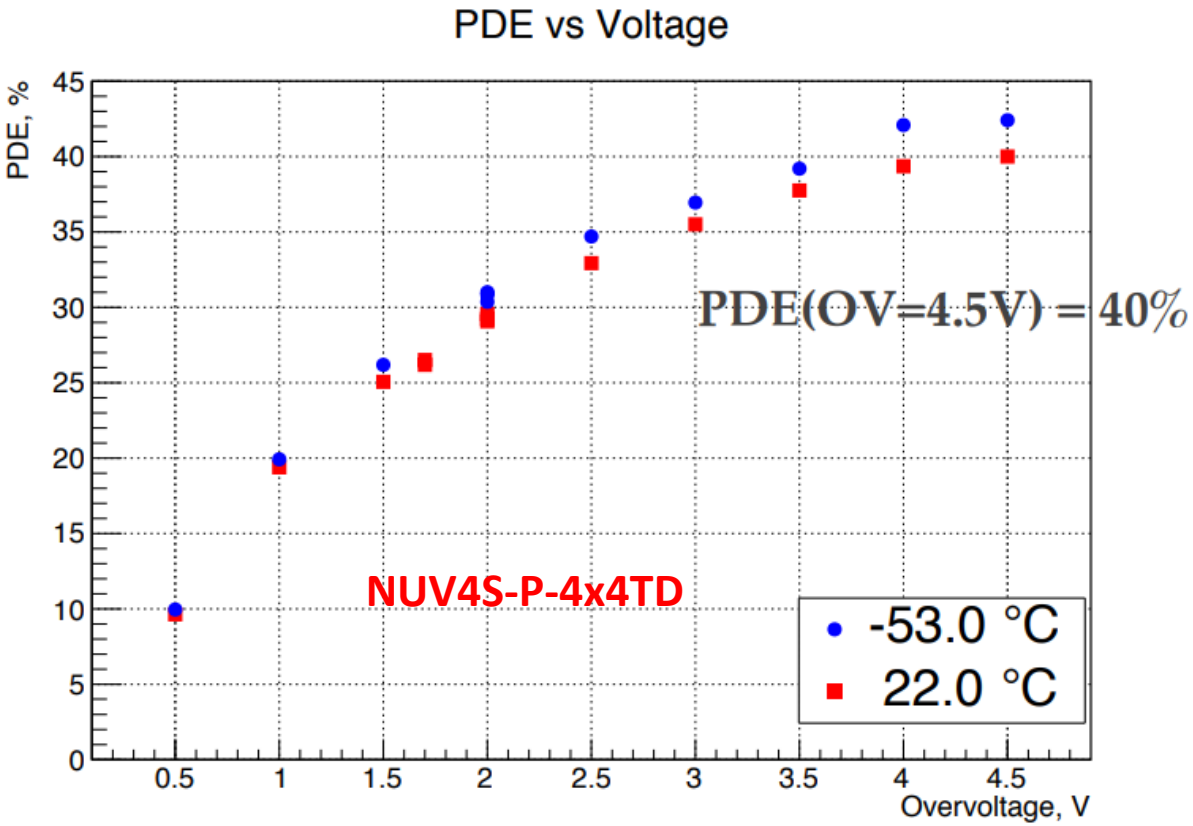
$$f(k) = \frac{\mu^k}{k!} e^{-\mu}$$

By intergrating the entry of the peak(k=0):

$$f(0) = e^{-\mu} = \frac{N_{peak}}{N_{total}}$$

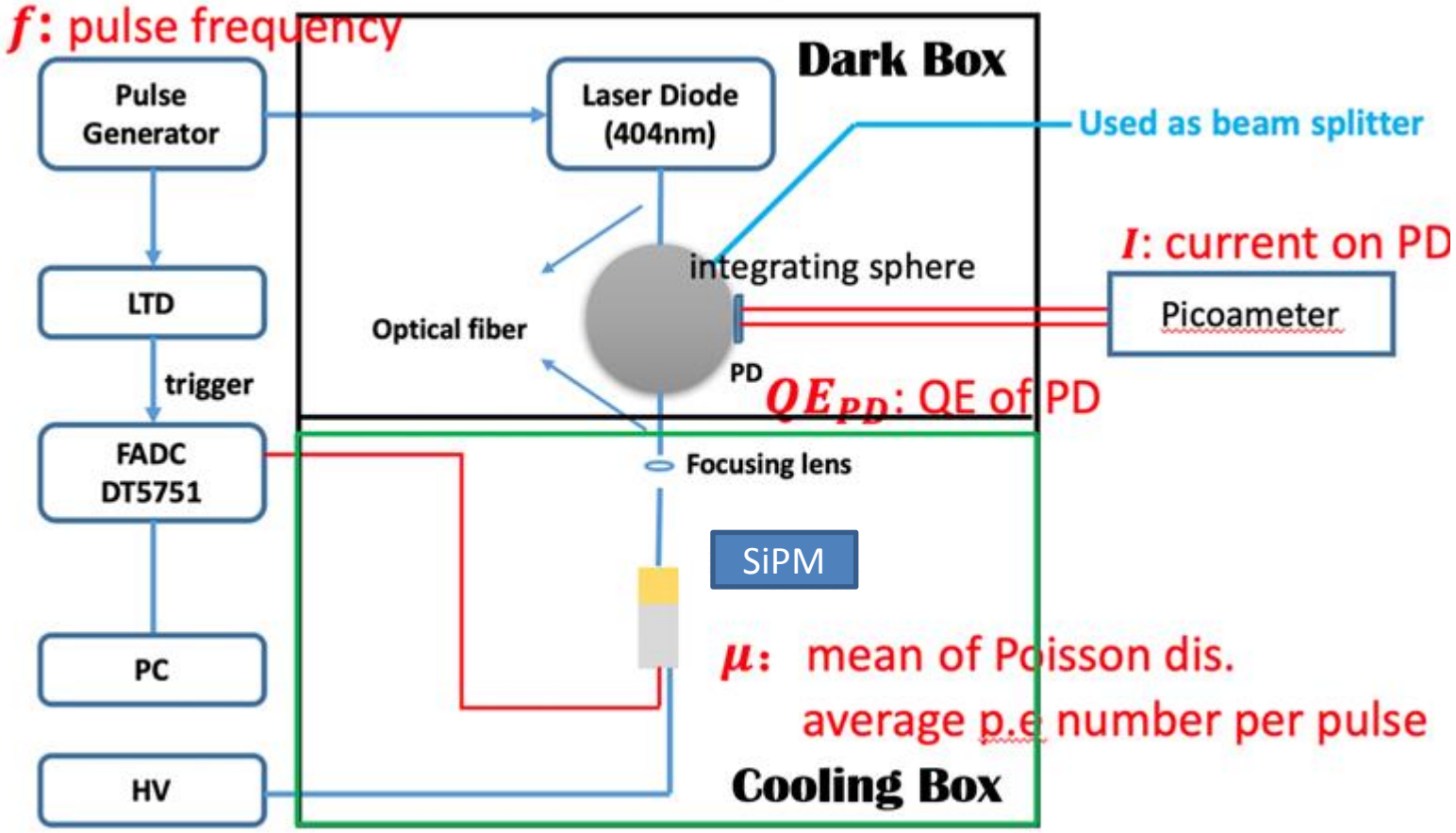
SiPM PDE at room T and -50 ℃

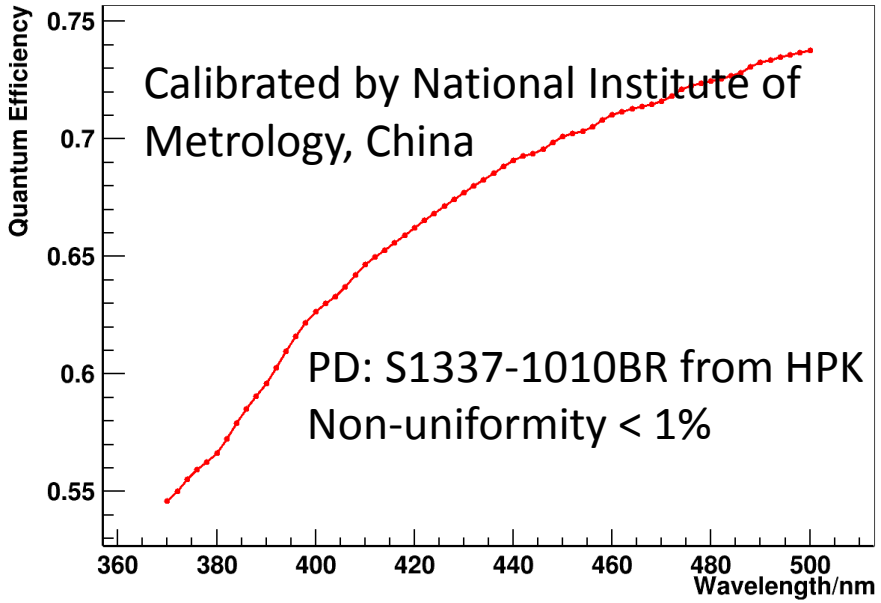


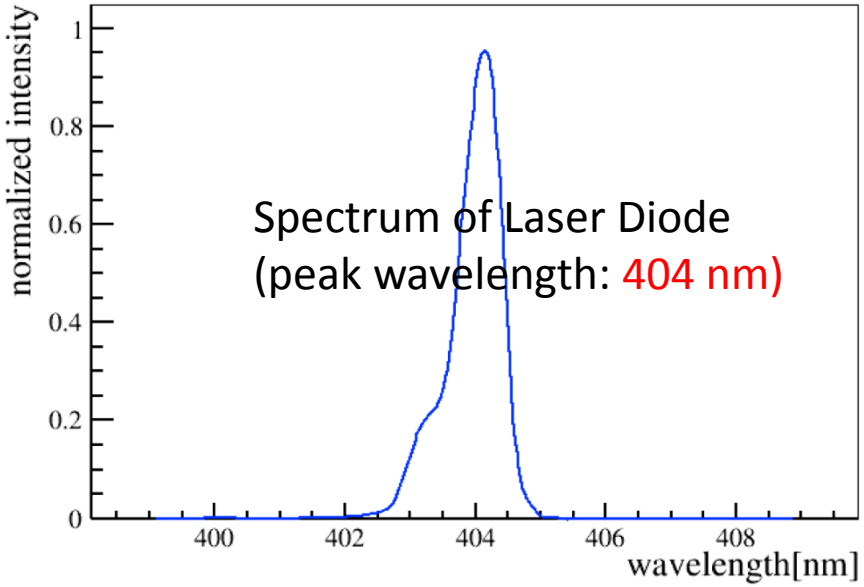


- **The absolute PDE is normalized to the number given in datasheet.**
- We **did not** observe significant differences of PDE at room temperature and -50 ℃, for SiPMs -- **S13360 – 6025CS and ASD-NUV4S-P-4x4TD.**

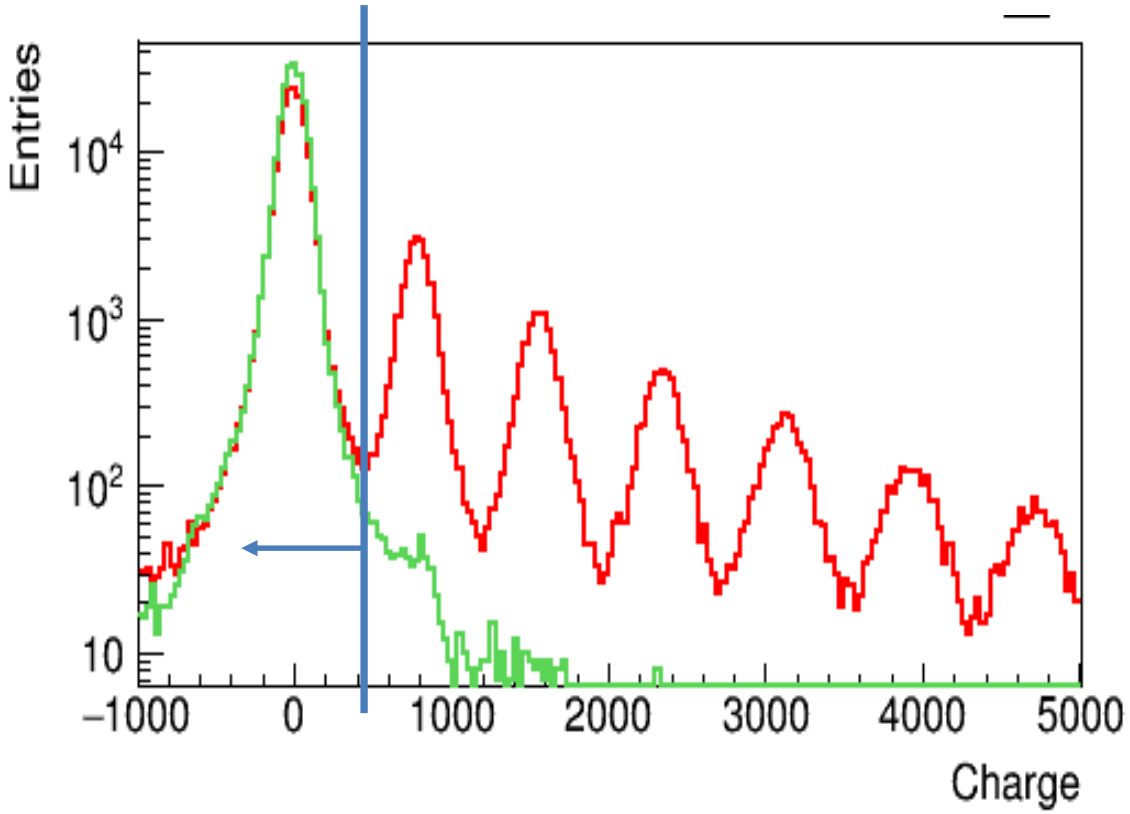
$$PDE = \frac{pe_{signal}}{pe_{incoming\ light}} = \mu * f / (\frac{I}{Q_e * QE_{PD} * R})$$

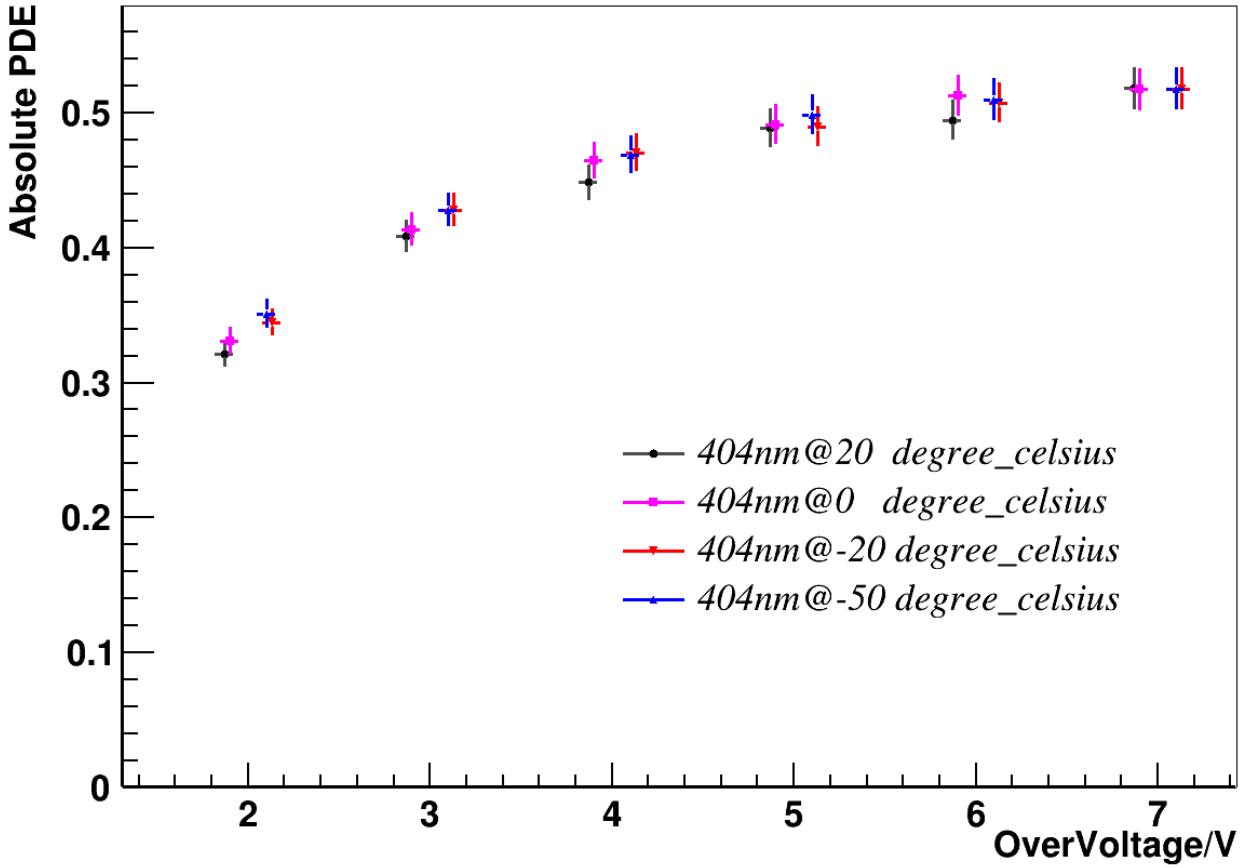






$$f(0) = e^{-\mu} = \frac{N_{peak}}{N_{total}}$$

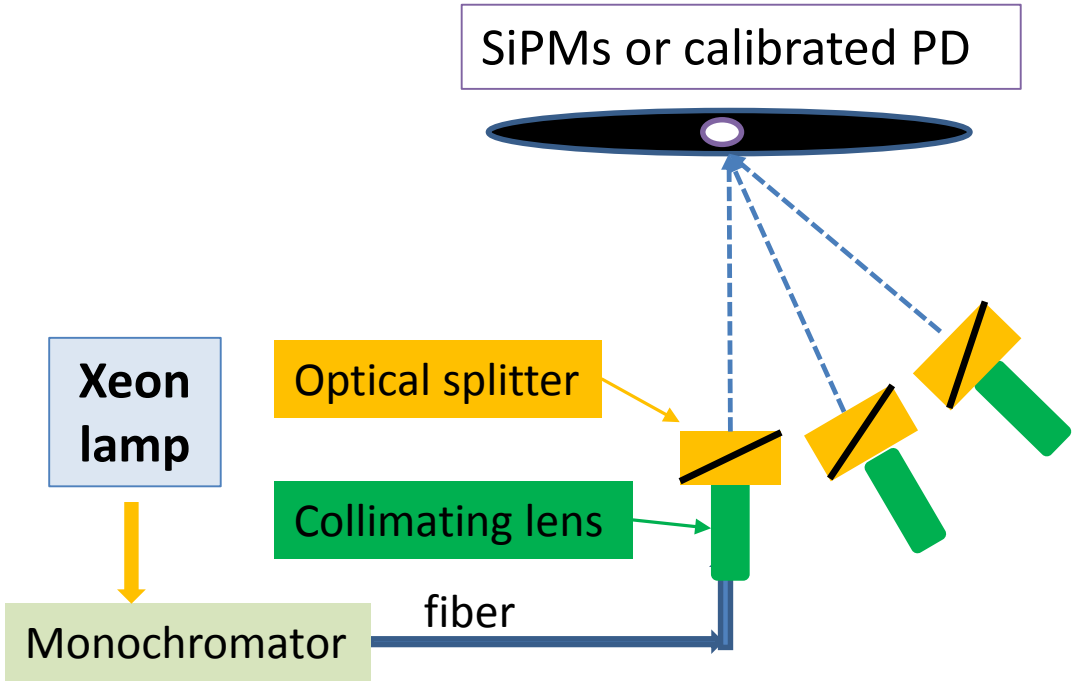


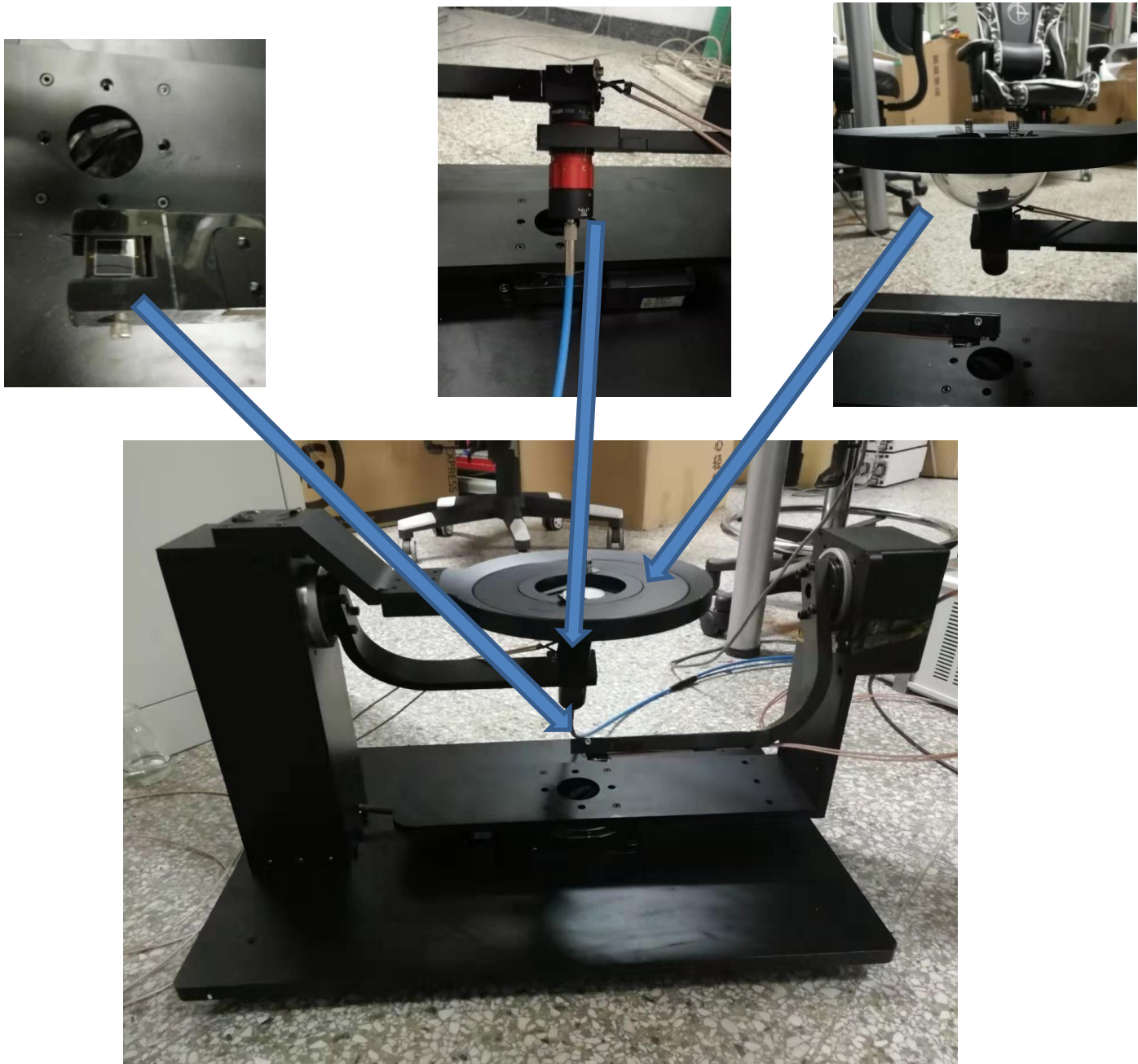


The absolute PDE keeps **UNCHANGED** from room temperature to -50 ℃, for SiPM -- **NUV-HD-LowCT (6 mm*6 mm) from FBK**

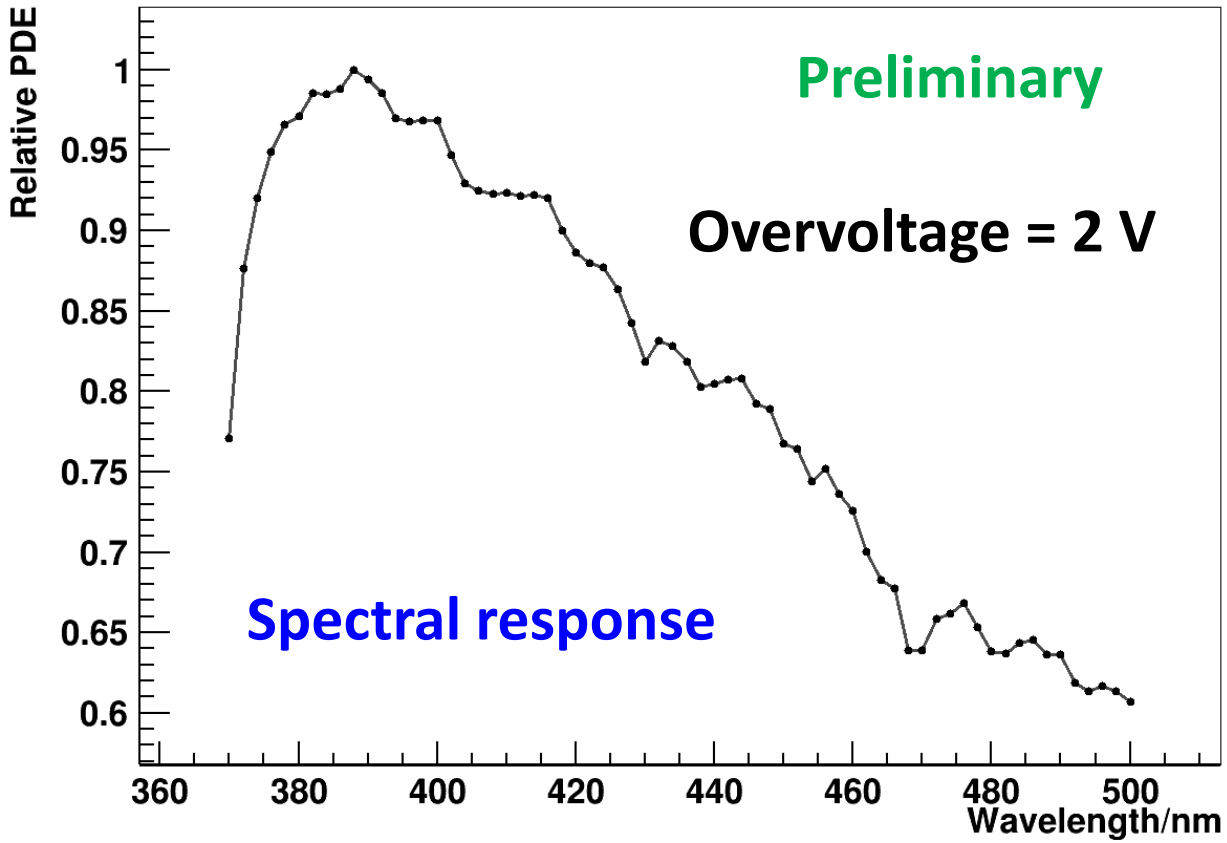
A setup built at IHEP, to measure

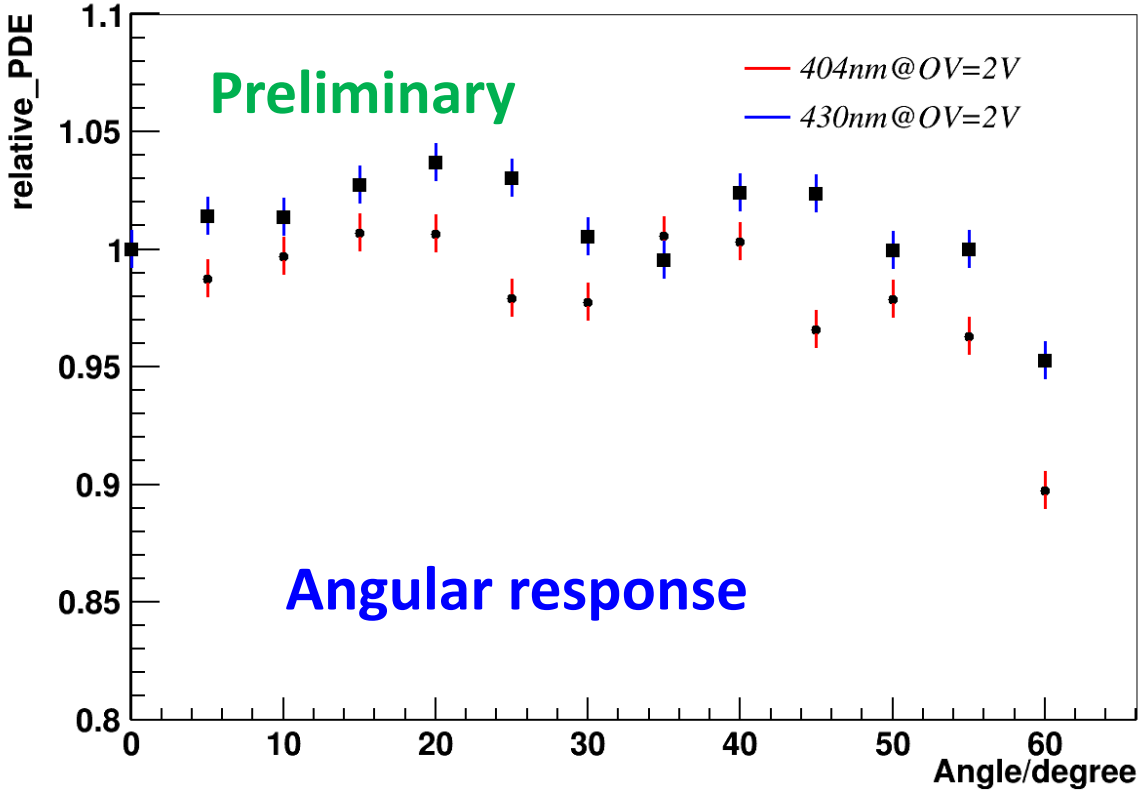
- ✓ Spectral response of SiPMs
- ✓ Angular response of SiPMs
- ✓ Relectivity of samples in liquid



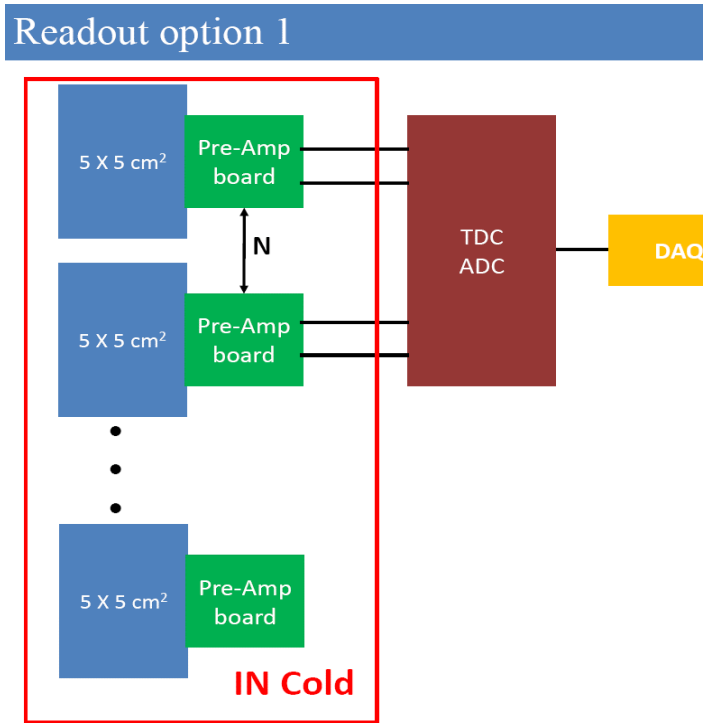


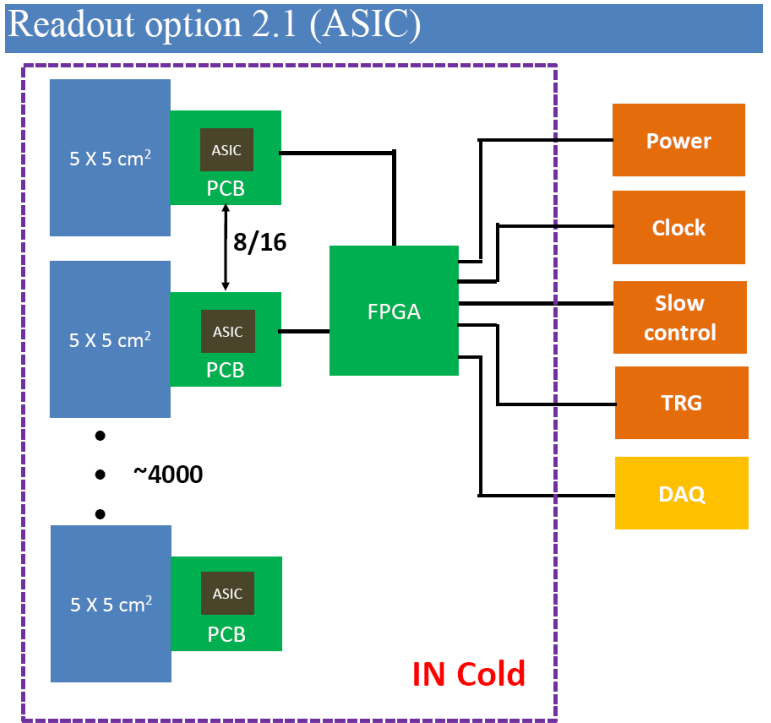
FBK-NUV-HD-LowCT

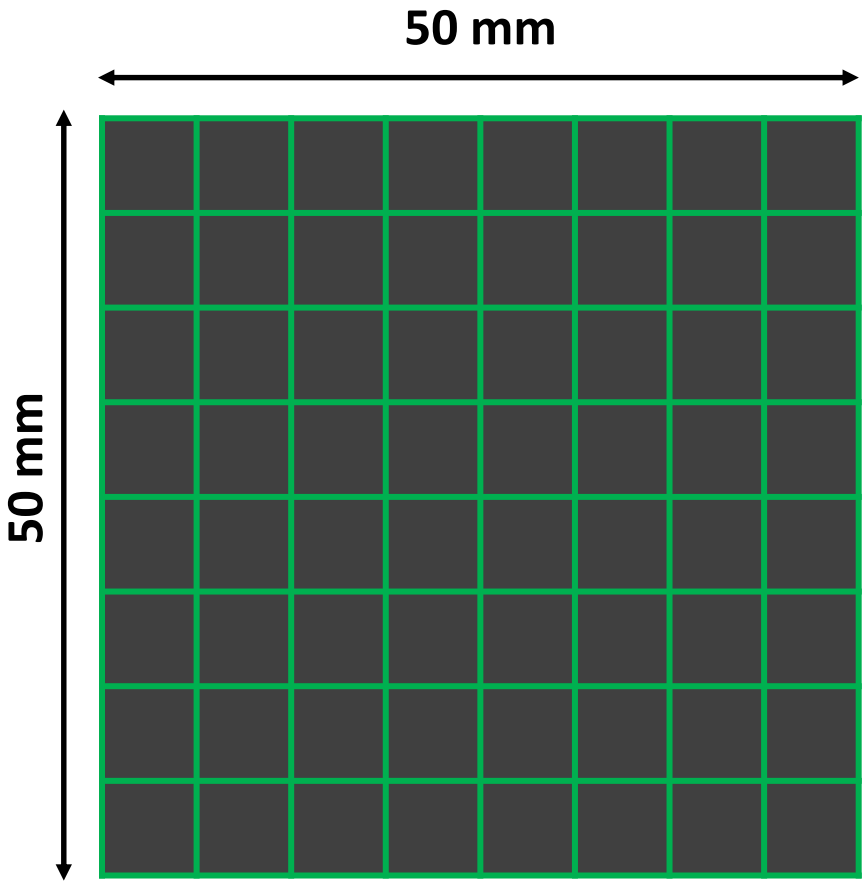


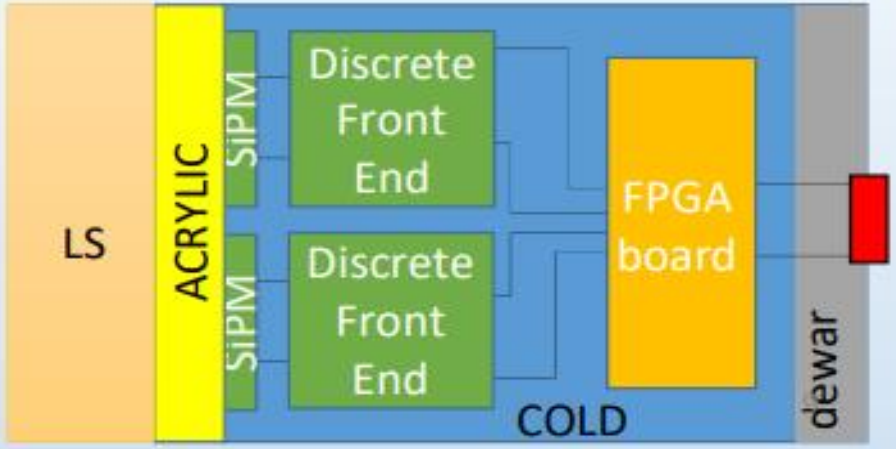


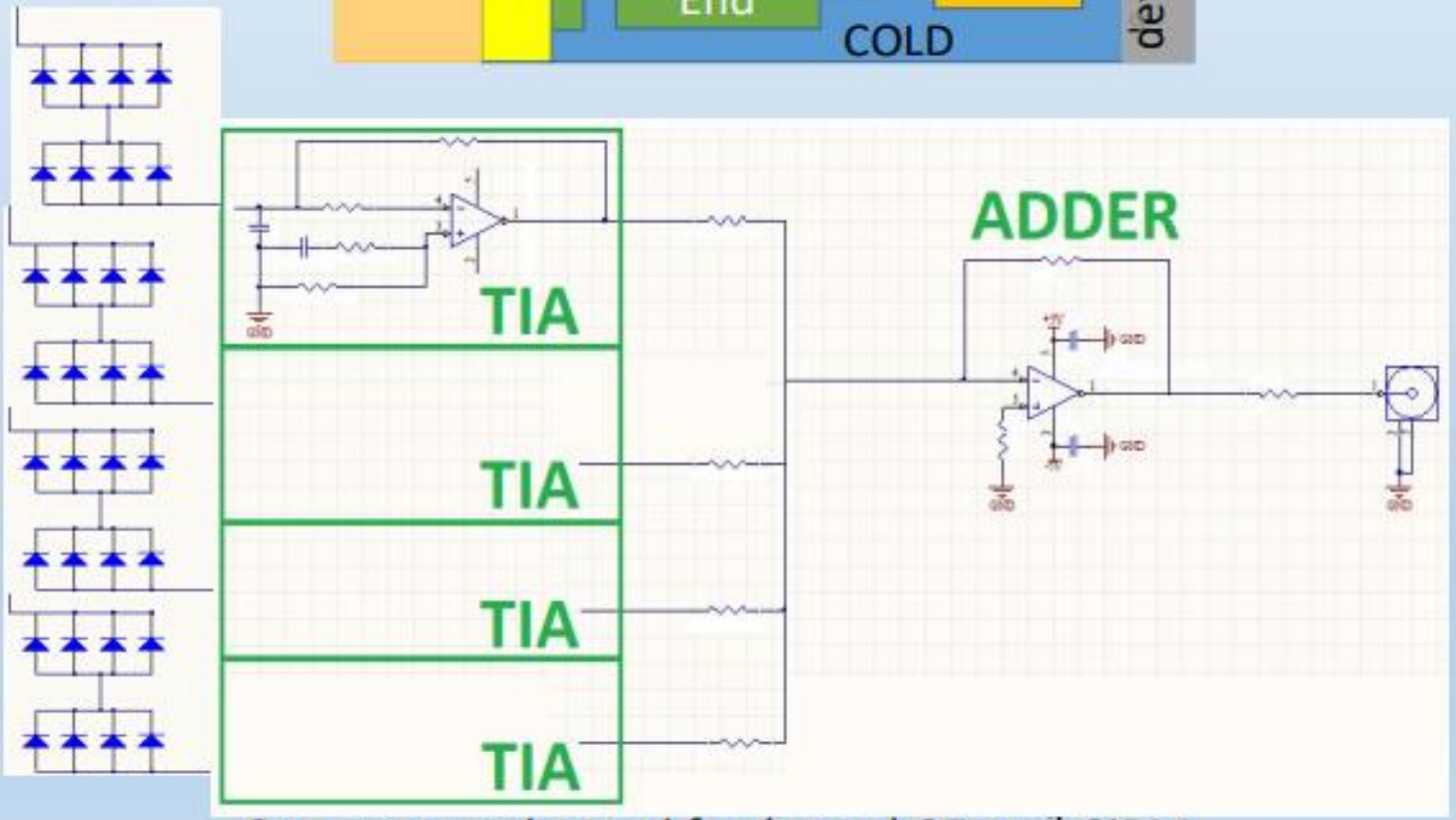
- Size of a single SiPM device -- 6 x 6 mm^2
- One tile consists of 8 x 8 SiPMs – 25 cm^2
- Possible readout schemes
  - Option 1: discrete components, one tile one channel
  - Option 2: ASIC, one tile one ASIC (~30 channels)
- Open to other options





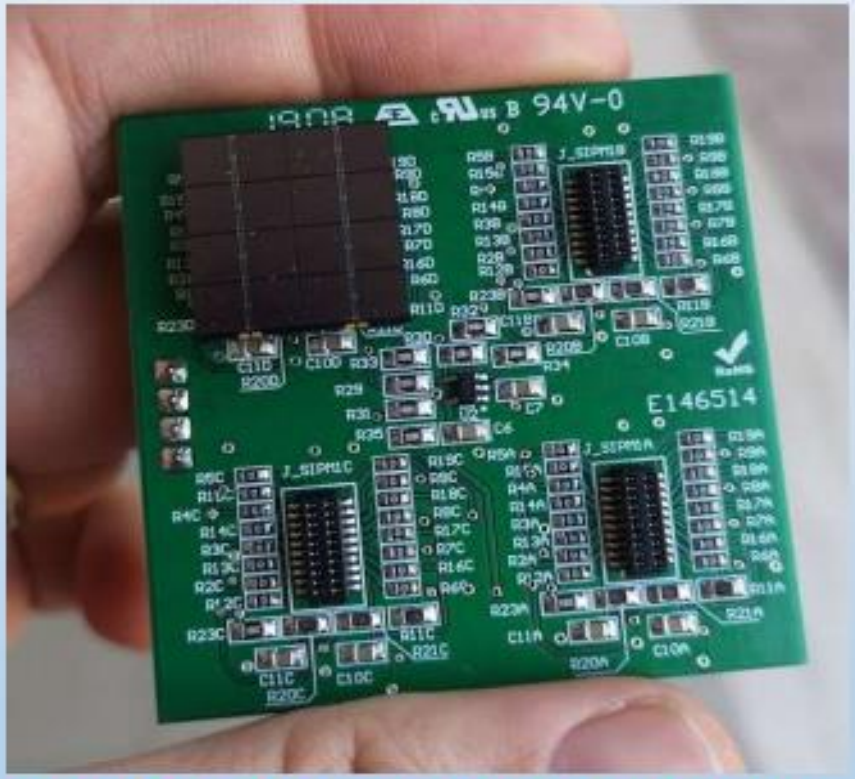






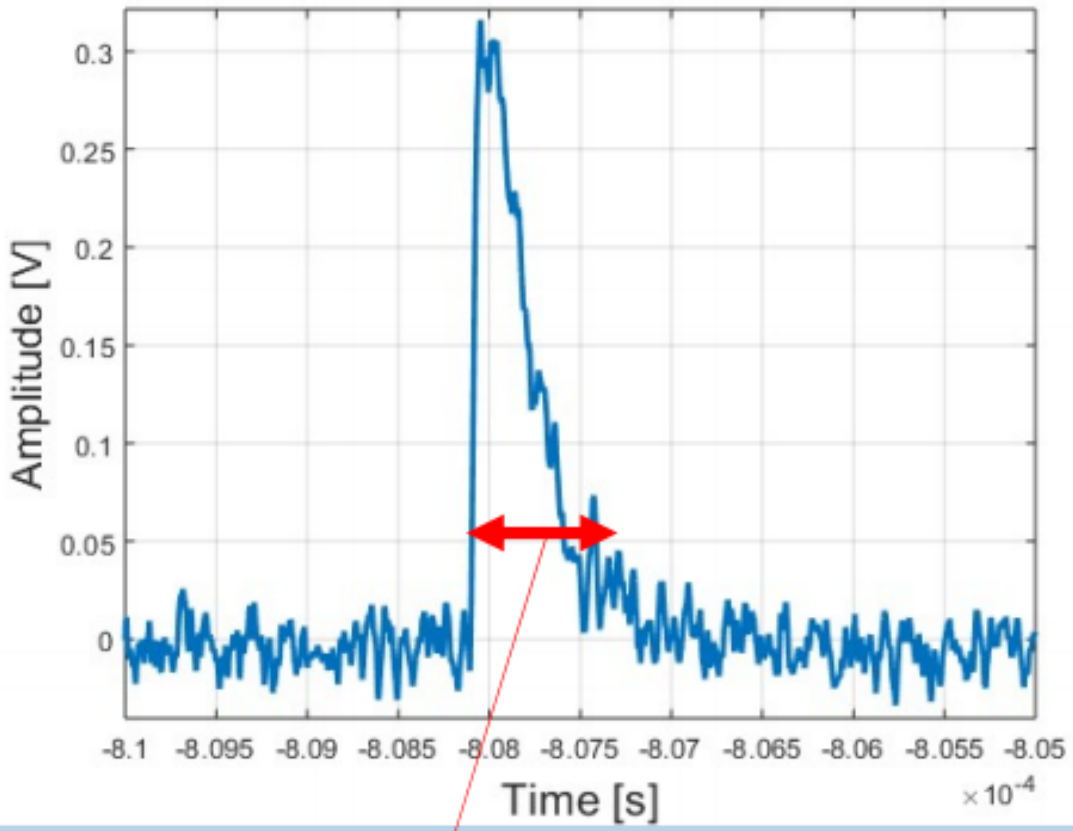
One output channel for (up to) 25 cm² SiPM
SIPM in series/parallel configuration

64 SiPM elements, $V_{bias} < 60$ V (series of two SiPM).



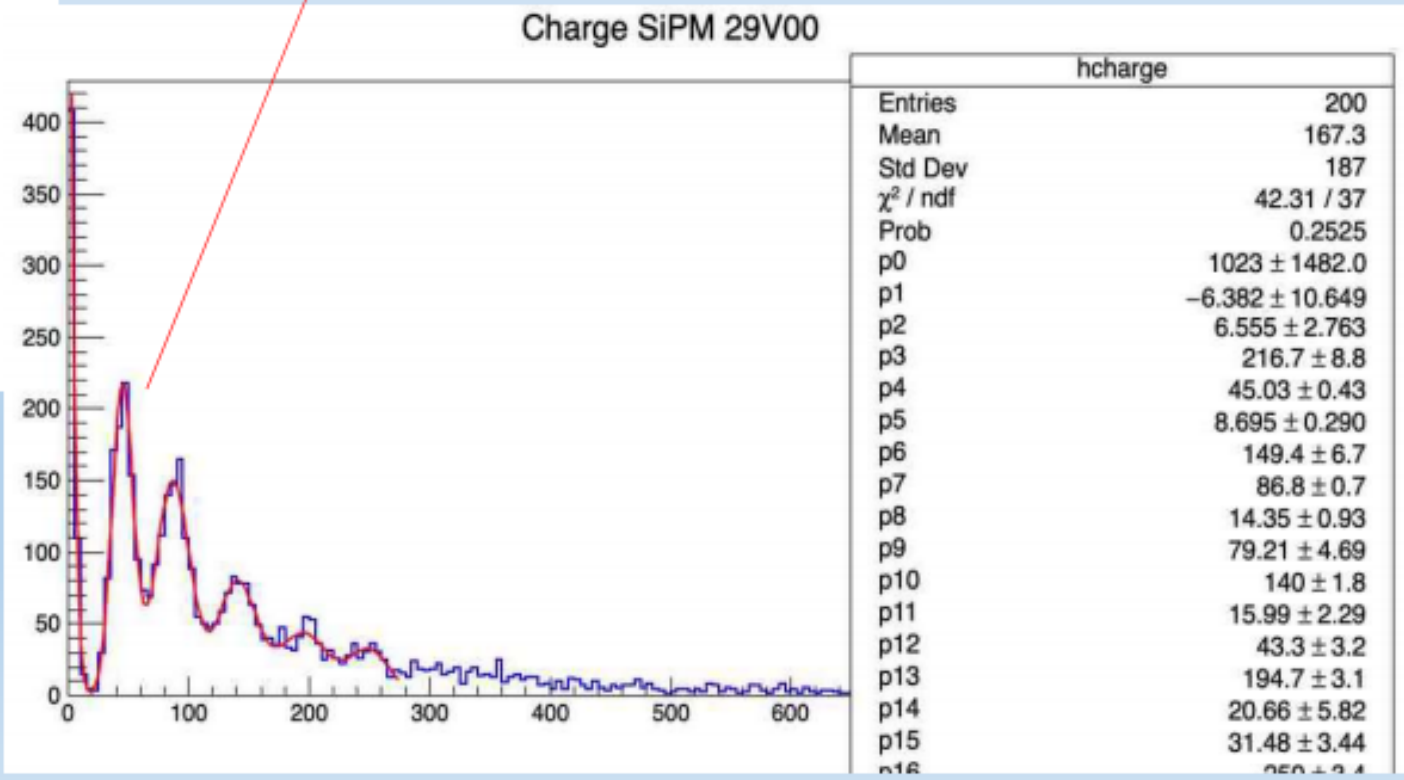
Front end board with 4 NUV-4S tiles delivered at IHEP (July 2019).

FE board + NUV-4S at -50 ℃ (Rome3)



600 ns

19% Resolution @1 p.e.



❄ **JUNO-TAO is proposed to precisely measure reactor neutrino energy spectrum.**

❄ **Sub-percent energy resolution can be achieved by using SiPMs in a ton-scale LS detector, operating at -50 ℃.**

❄ **PDE of SiPMs has been carefully studied in JUNO-TAO for several SiPMs from different vendors.**

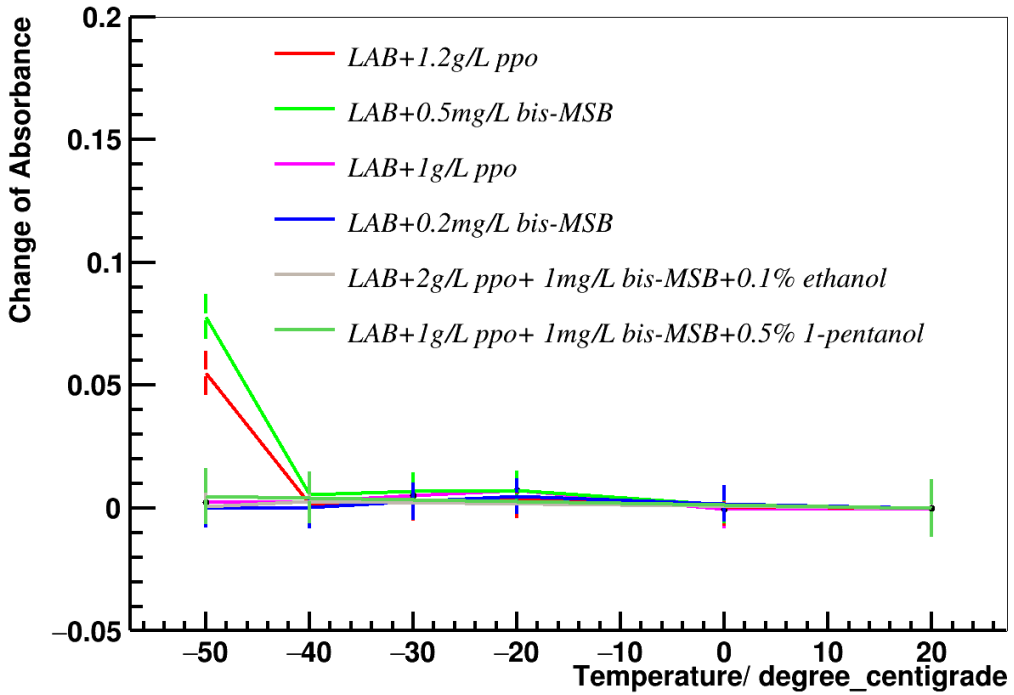
- **No significant difference of PDE at room temperature and -50 ℃**

❄ **Full characterization of SiPMs is ongoing, dark noise rate/optical cross talk/after pulse/…**

❄ **Good progress on readout development and testing.**

❄ **Welcome suggestions and new collaborators!**

- **JUNO**: LAB+2.5g/L PPO+1~3mg/L bis-MSB
- **Solubility at -50℃ :**
  1 g/L < PPO <1.2 g/L;
  0.2 mg/L < bis-MSB < 0.5 mg/L
- **Cured w/ co-solvent**
  LAB + 2 g/L PPO + 1 mg/L bis-MSB + **0.5% pentanol** (or 0.1% ethanol)



- **Survey of the room and transportation**
- **Power supply: OK**
- **N2 supply: OK**
- **Water supply: OK**
- **Ventilation: 1000 m^3/h**
- **Measured Muon flux**
  - 1/3 surface
- **Neutron flux/spectrum**
  - 40% surface
- **Gamma radioactivity**
  - 3 times of my office

Need further discussion

- **Clean grounding**

In Dec. 2018, after the start of commercial operation of Taishan-1

- ❄ **A LS detector uniformly at -50℃ has a lot of challenges**
- ❄ **Normal 2-m SST**
  - ➢ **w/ 20-cm PU insulation instead vacuum interlayer**
  - ➢ **Heat leakage 337 W**