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GEFÖRDERT VOM Bundesministerium für Bildung und Forschung
SFB 1258 Neutrinos Dark Matter Messengers
ORIGINS Excellence Cluster
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TAO - The Taishan Antineutrino Observatory

JUNO

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on behalf of the JUNO Collaboration

[1] Cluster of Excellence PRISMA+, Johannes Gutenberg Universität Mainz
[2] Technische Universität München, School of Natural Sciences, Physics Department

Scientific Motivation - The Taishan Antineutrino Observatory

JUNO:

Neutrinos from two Nuclear Power Plants

26.6 GW_{th} power

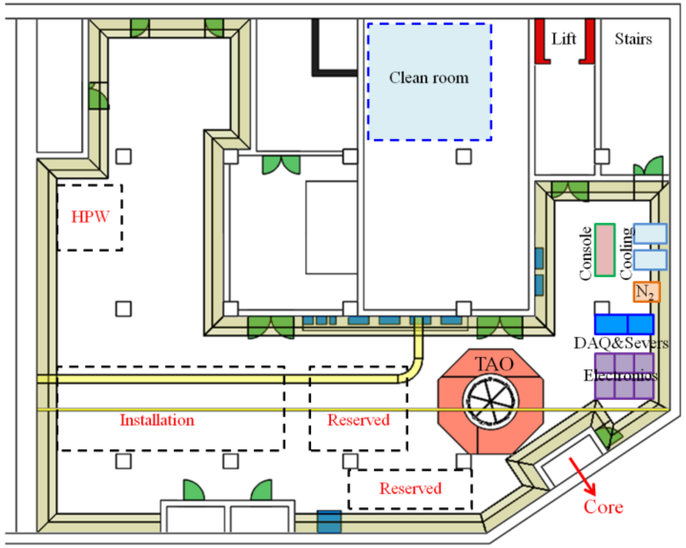
JUNO-TAO:

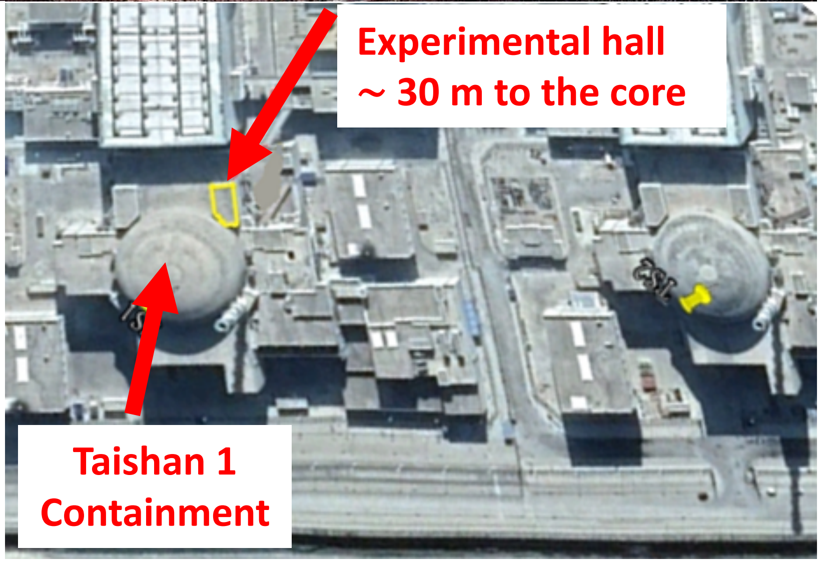
Located at Taishan 1 reactor core (4590 MW_{th})

~ 44 m distance to the core

~ 36 × JUNO statistics

~ 10% background-to-signal ratio





Scientific Motivation - Taishan Antineutrino Observatory

Measure reactor anti-neutrino spectrum with high resolution

- provide **model-independent reference for JUNO**
- benchmark to **test nuclear databases**
- Improved measurement of **isotopic antineutrino yields and spectra** improve nuclear physics **knowledge of neutron-rich isotopes**
- shed light on **reactor spectrum anomaly** (5 MeV bump)
- searching for **light sterile neutrinos** with a mass ~1 eV
- ~36 × JUNO statistics

TAO Design Features:

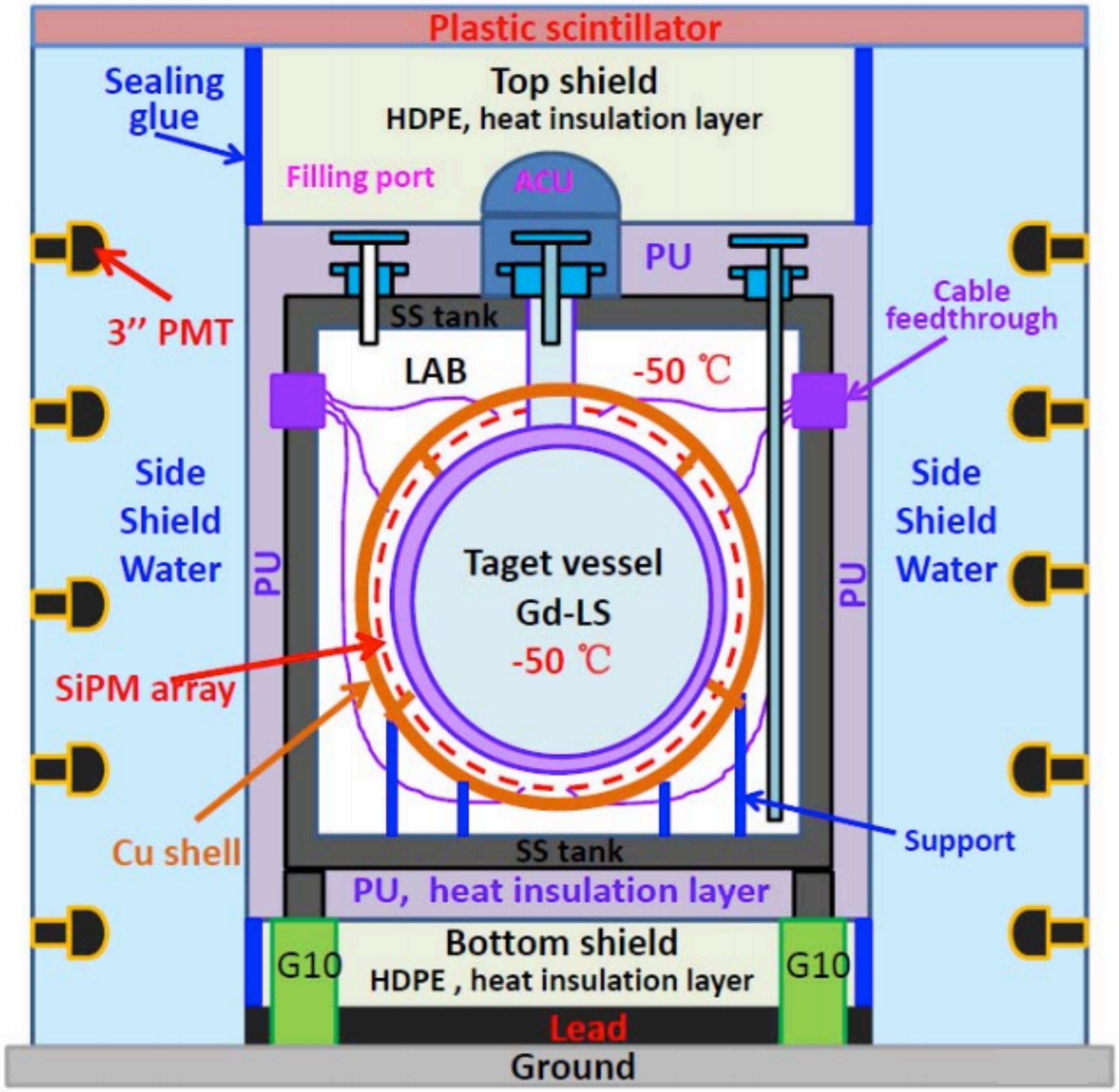
- **2.8 ton Gd-LS** as target material (1 ton fiducial mass)
- Detector placed at **44 m distance** from a **4.6 GW_{th}** reactor core
- **10 m² SiPM**, with **50% PDE, Coverage: > 94%**
- ***SiPMs and LS cooled down to -50 °C***

Project Budget: 5 M€
Fully funded!
IHEP, INFN, JINR

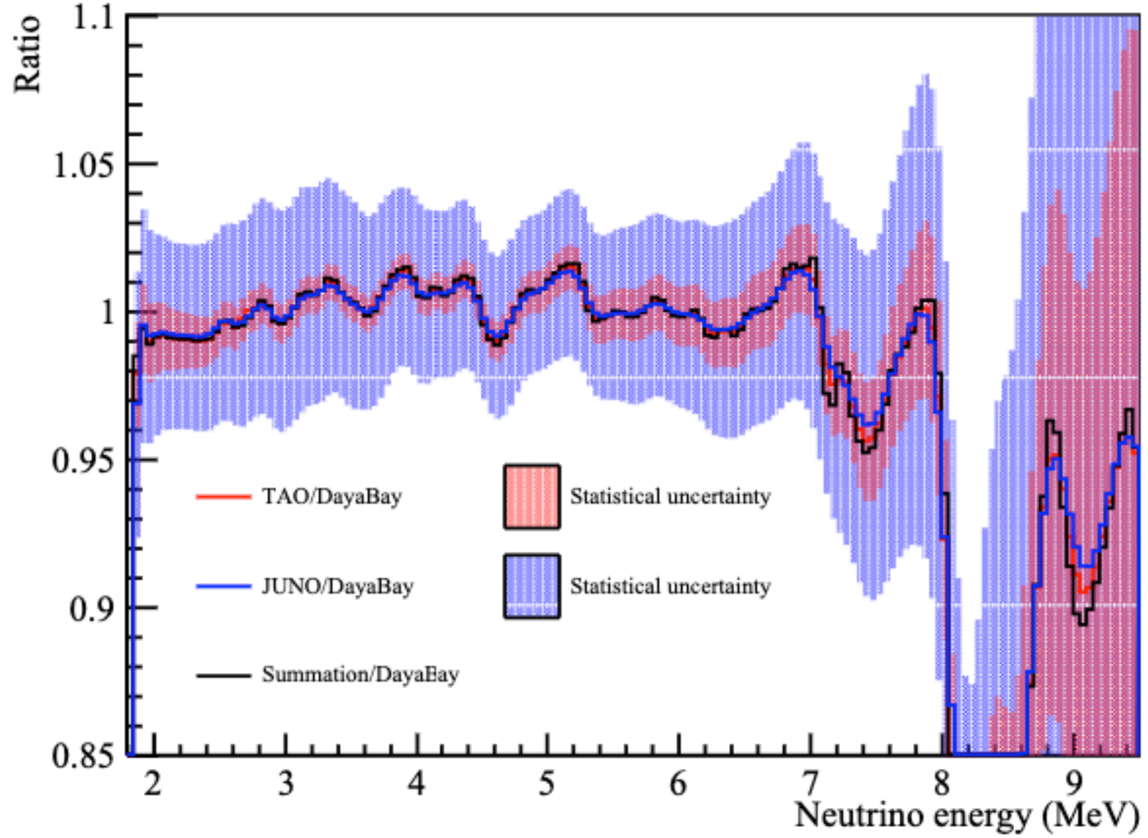
Expected Performance:

- **~ 4300 p.e. / MeV** collected charge
- Energy Resolution: **~ 2.0% @ 1 MeV, < 1.0% above 3 MeV**

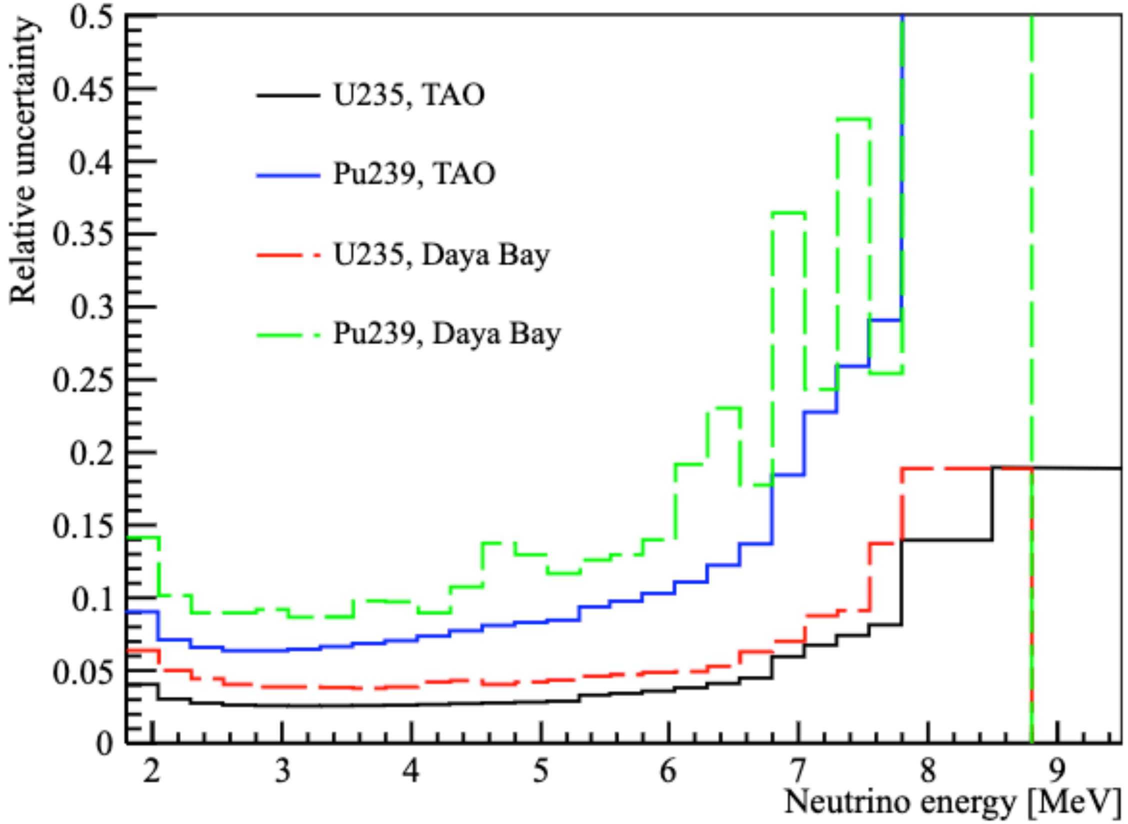
Conceptual Design Report
Released in May 2020!
arXiv: 2005.08745v1



Scientific Motivation - Taishan Antineutrino Observatory



Comparison of the summation spectrum and three convoluted energy spectra with respective energy resolutions of TAO, JUNO and Daya Bay.



The expected relative spectrum shape uncertainty (for ^{235}U and ^{239}Pu) spectra for 3 years of data taking copmared with Daya Bay

Conceptual Design Report, arXiv: 2005.08745v1

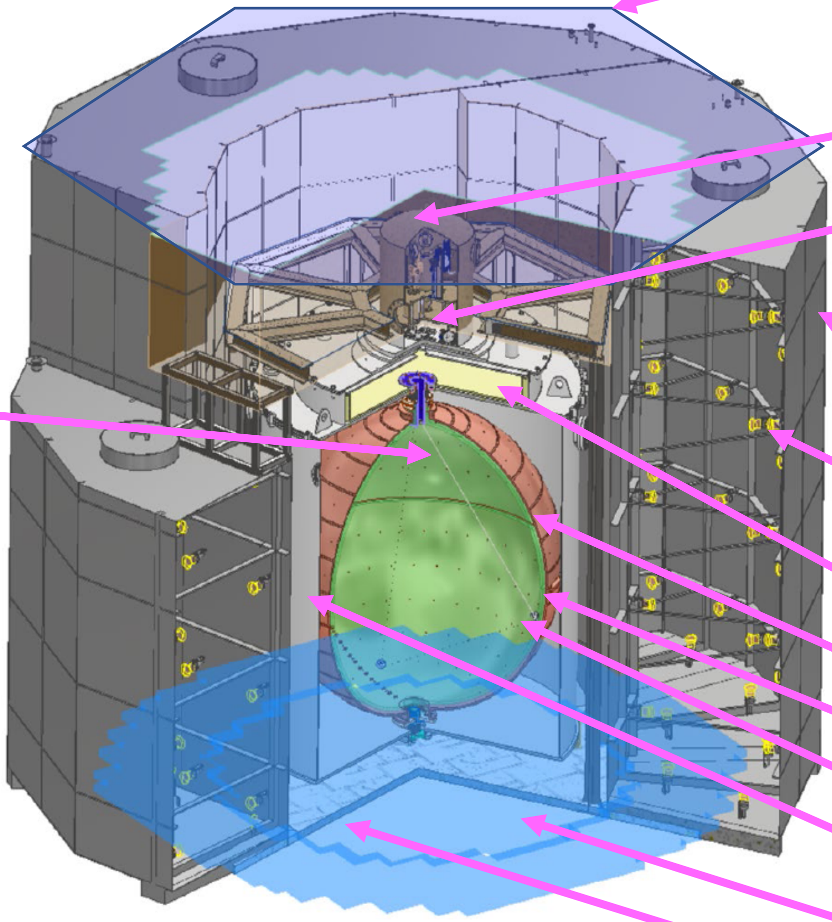
The TAO Detector Design

Highlights:

- Energy resolution < 2% @ 1 MeV
- SiPM PDE >50% (approx. 4500 p.e. / MeV)
- SiPM coverage: ~ 94% , ~ 10 m^2
- SiPM DCR: <100 Hz/mm^2 @ -50℃
- High performance Gd-LS

Central detector

- **Acrylic sphere:** 1.8m (ID), 20mm-thick with 2.8 t Low-T Gd-LS
- **Copper shell** 1.886 m (ID), 12mm-thick with **4024** pieces of 50x50mm^2 **SiPM tiles**
- **SS tank** 2.09m(ID), 10mm-thick with 3.2 t LAB/Gd-LAB
- **Cryogenic system:**
  4.5kW cooling power
  150mm-thick melamine foam insulation



Top Veto Tracker (TVT)
4-Layer PS, 160 strips
(Strip Size: 2 m×20 cm×2 cm)

Top Shield(HDPE)

ACU & CLS
6 types of exemption sources

Water Tank
3 irregular water tanks
~300 3" PMTs

Overflow Tank
Cu Shell
SiPM Array
Acrylic Vessel
SS Tank
Insulation (MF) Bottom
Shield(Lead)

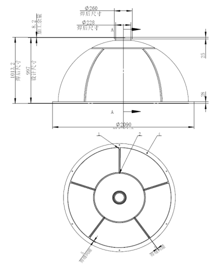
Copper shell production

- Started from March 2021, upper-semi CS done in Feb. 2023, lower-semi CS done in May 2023. *Welding is very difficult → patent granted!*
- Precision:
  - Inner diameter (1886.0 ± 0.5) mm, thickness (12.0 ± 0.2) mm
  - Flatness (1910.00 ± 0.08) mm
  - Hole diameters (5.30 ± 0.05) mm
  - Angular precision < 0.01°, Position (4π) < 0.04mm
  - Tile models mounting easy, gaps reasonable.

All surfaces in contact with detector liquids are coated with PTFE (25~50um) for LAB/LS compatibility requirement.

Uncovered half of the Copper Shell (CS)

Cutting → Molding →Welding → Machining



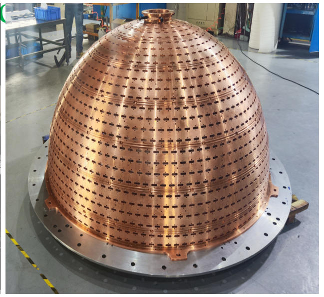
Dividing(8 parts)

Molding

Assembly & welding

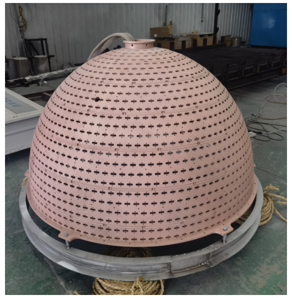
Welding done

Turning and milling

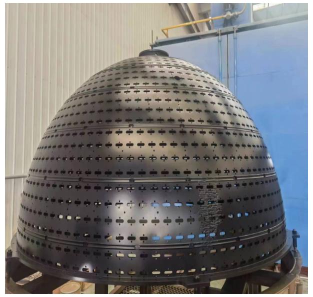


Machining done

Degreasing



Sandblasting



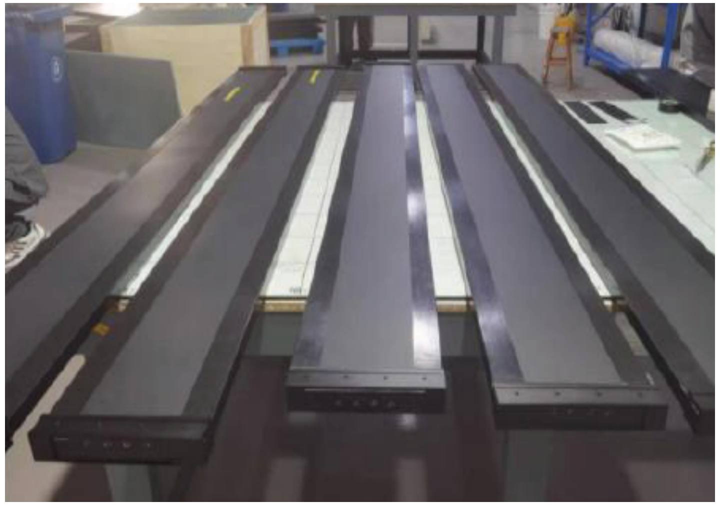
PTFE coating done

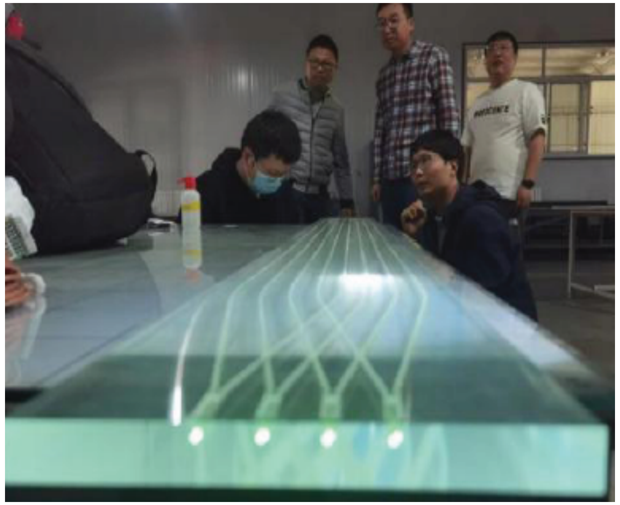
PTFE coated half-spheres

Muon Veto System

Top Veto Tracker (TVT)

- **Plastic scintillator + SiPM + WS-fiber**
- **> 99% μ tagging efficiency**
- 4-Layer PS, 160 strips, 2 m×20 cm×2 cm/strip 2.4m attenuation length, 9000 Photons / MeV
- 4 SensL J-40035 SiPMs one end, total 1320 pieces, coupled with optical grease
- **57 PS pieces produced and accepted**





Water Tank (WT)

- **3 irregular water tanks**
- ~ 300 x 3-inch PMT from JUNO
- Water quality was monitored for ~ 5 months,
  - no big change
  - no purification cycling needed
- Water tank prototype test ongoing

IBD signal	2000 events/day
Muon rate	70 Hz/m^2
Fast neutron background before veto	1880 events/day
Fast neutron background after veto	< 200 events/day
Singles from radioactivity	< 100 Hz
Accidental background rate	< 190 events/day
$^8He/^9Li$ background rate	~ 54 events/day

Calibration Systems: ACU (Automated Calibration Unit) & CLS (Cable Loop System)

Two Calibration Systems: ACU and CLS

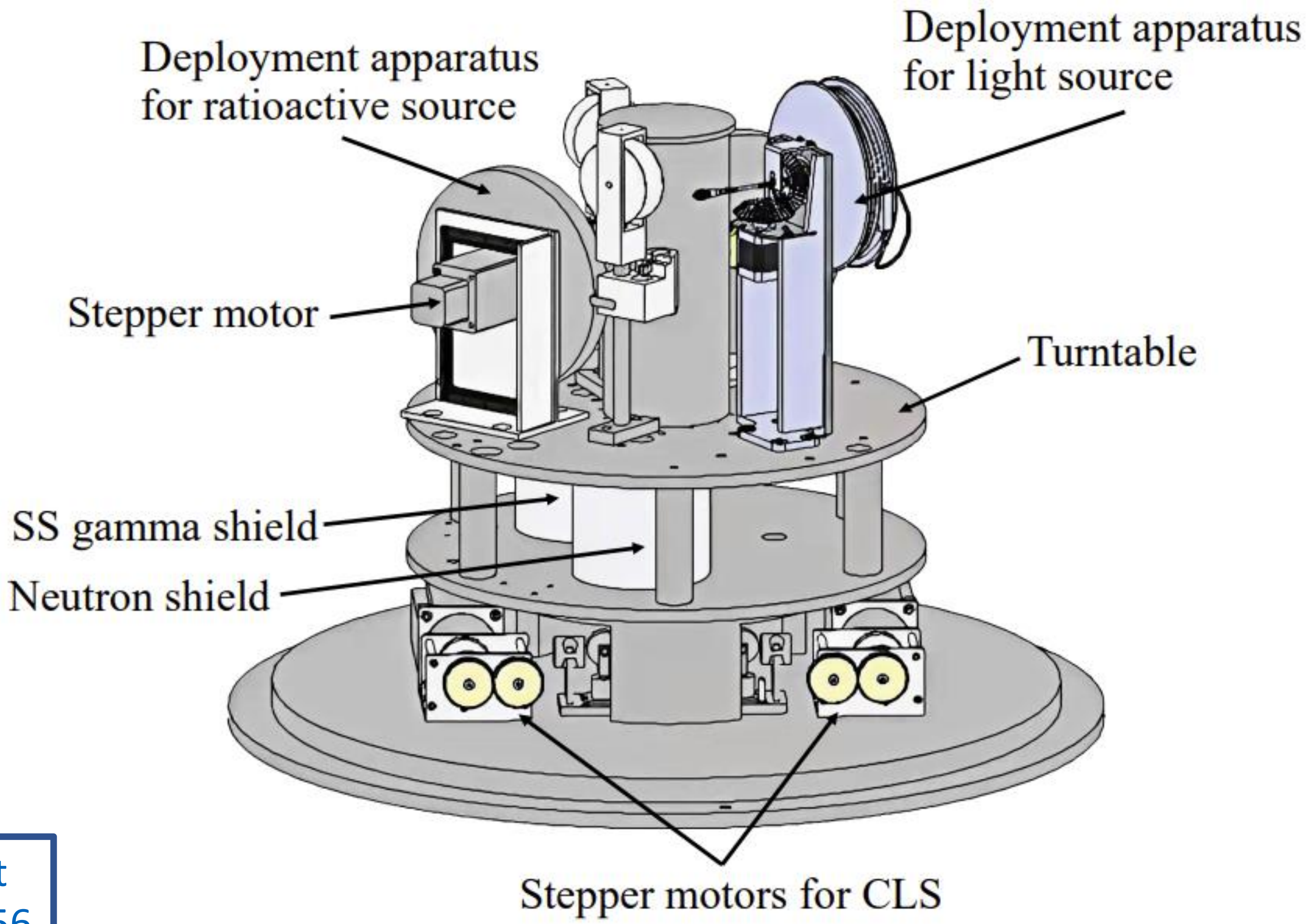
ACU:

- can deploy 3 different sources inside the detector alongside the z-axis
- a turntable revolves to a specific angle
- Light source: ultraviolet (UV)
- Radioisotopes:
  - ^{68}Ge source
  - combined source with multiple gamma emitters and one neutron source

Cable Loop System (CLS):

- designed with a single radioactive source
- that can be deployed off axis

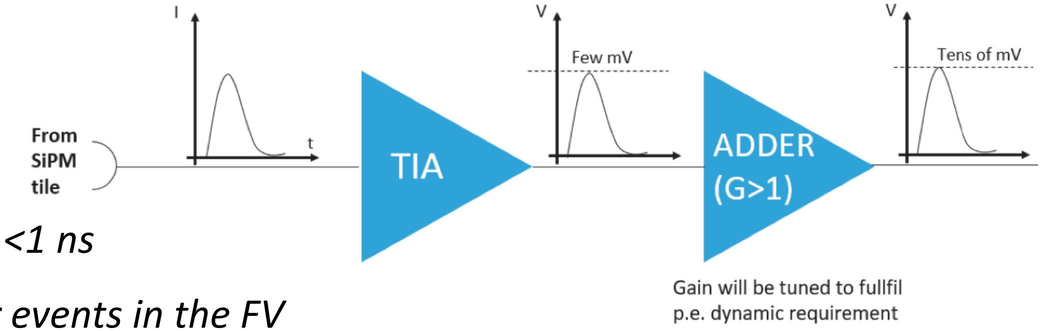
Calibration Strategy of the JUNO-TAO Experiment
Eur. Phys. J. C 82 (2022) 12, 1112, arXiv: 2204.03256

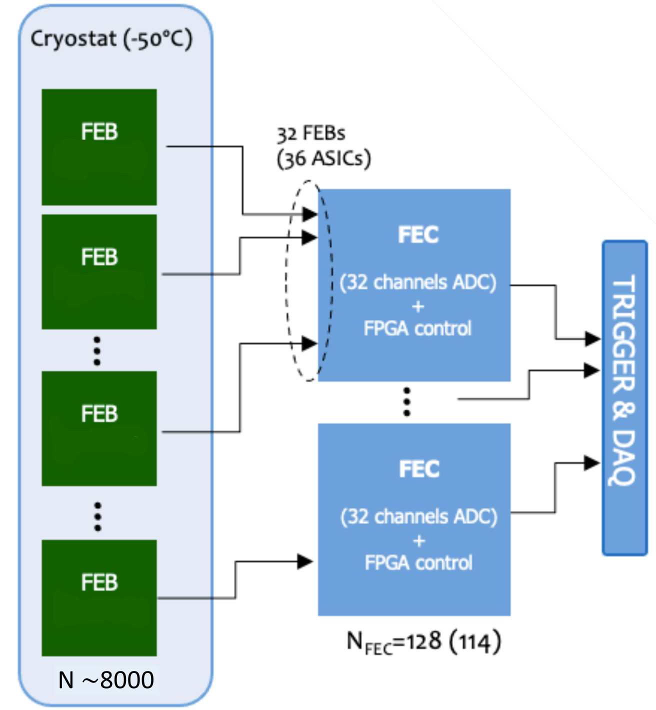


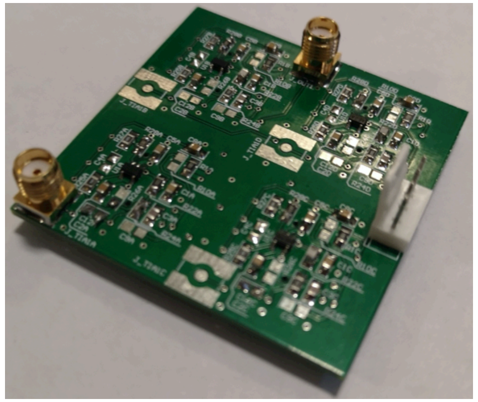
Schematic Drawing of the Automated Calibration Unit

Frontend Readout

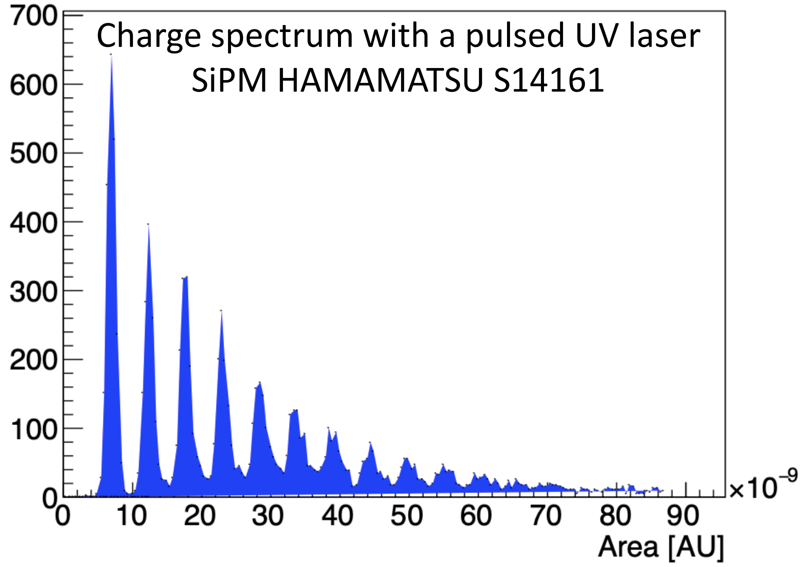
- *Equivalent noise charge < 0.1 p.e.*
- *Charge resolution: < 15%*
- *Timing: τ_1=4 ns in GdLS → time resolution <1 ns*
- *Dynamic range: <15 p.e./cm^2 on SiPMs for events in the FV*
  → 1-375 p.e (or 1-12 p.e.) depending on the number of channels/tile
- *Power consumption: inside the cryostat <3 kW (ΔT below ±0.5°C)*
- *Radio-purity: same consideration as for the PCB hosting the SiPM*
- *Discrete readout: 1 channel/tile*
  - *Easy, reliable and robust option with commercial ICs*
  - *Series/parallel connection to handle SiPMs capacitance*
  - *4 different Transimpedance Amplifiers*
    - *Two gain stages to reduce TIA instability at high gain*
    - *ADC in the FEC board*
- Trigger & DAQ
  - FECs manage the waveform integrations
  - FPGA based Central Unit (CU) manages the data stream and trigger algorithms







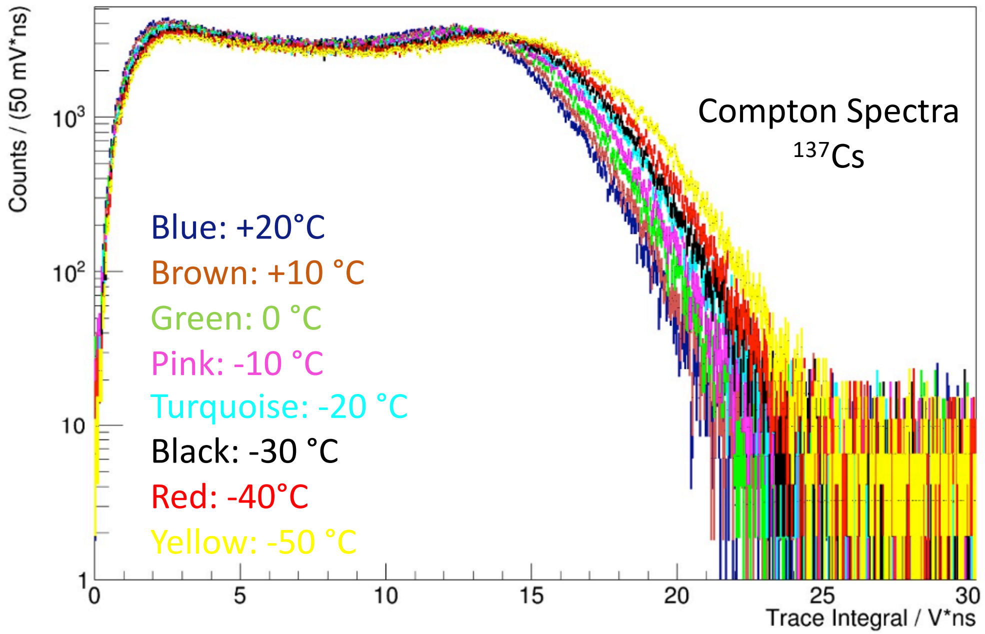
Discrete FEE Board

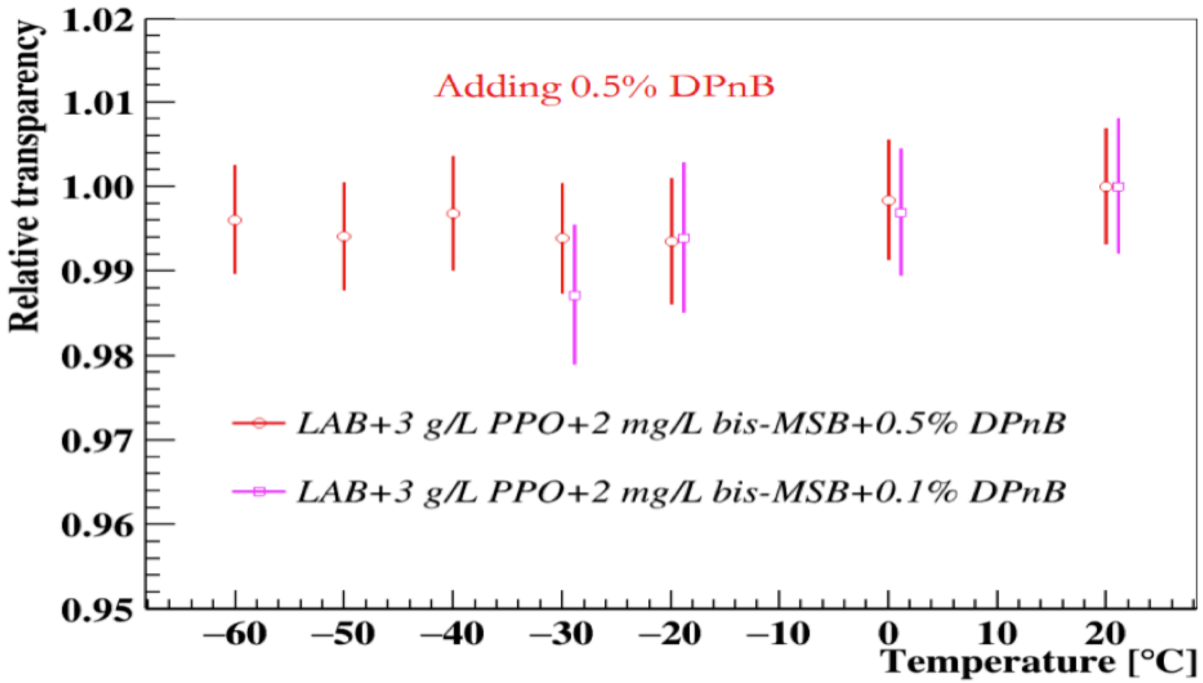


Gadolinium-loaded Liquid Scintillator (Gd-LS) for -50°C

- GdLS at -50 °C to lower SiPM dark noise
- transparency at -50 °C: A.L. >10m
- light yield at -50 °C: ~ 4300 p.e./MeV (incl. SiPMs PDE, coverage and A.L.)
- long-term stability of the light yield and transparency!
- Safety (low volatility & high flashpoint) → Nuclear Power Plant

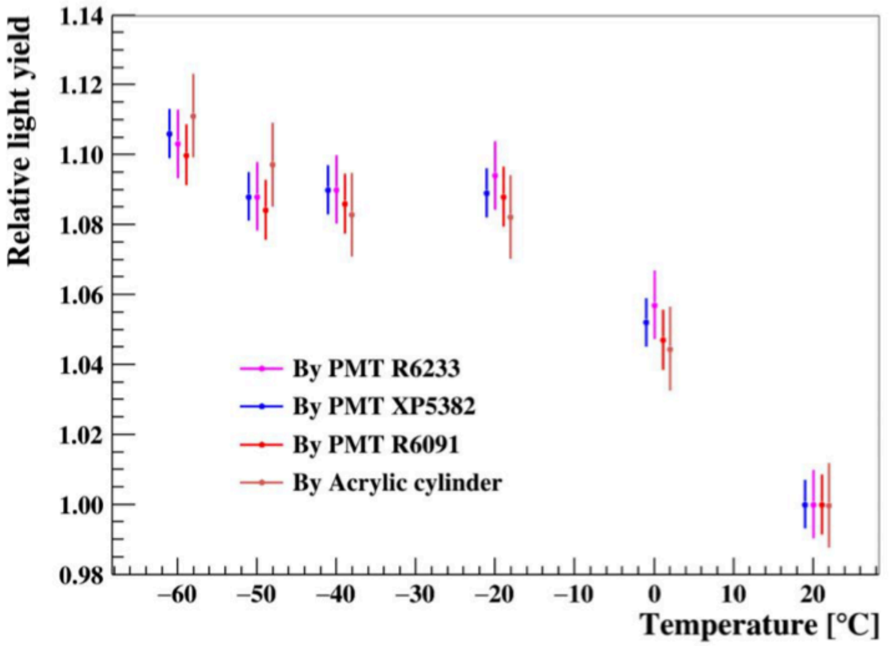
- Recipe:
  - **LAB** + **0.1%Gd** + **3g/L PPO** + **2mg/L bis-MSB** + **0.5% DPnB**





DPnB to increase solubility of WLSs

Light output increases towards lower T



Gadolinium-loaded Liquid Scintillator (Gd-LS) for -50°C
PSD and p-quenching study at the INFN-LNL

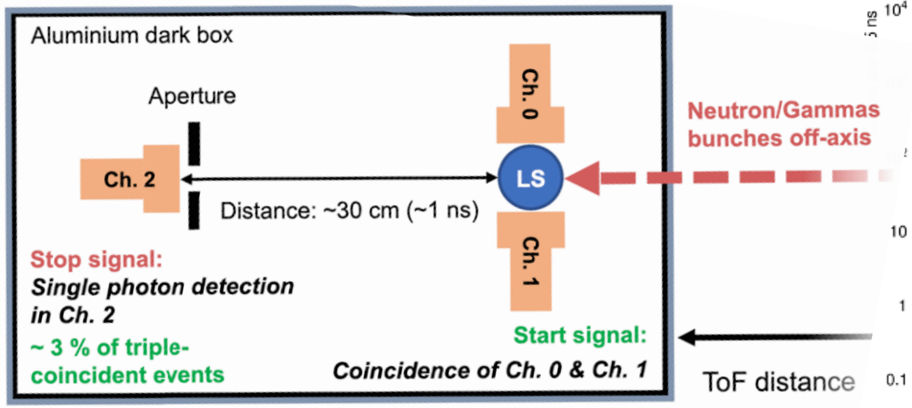
Study:

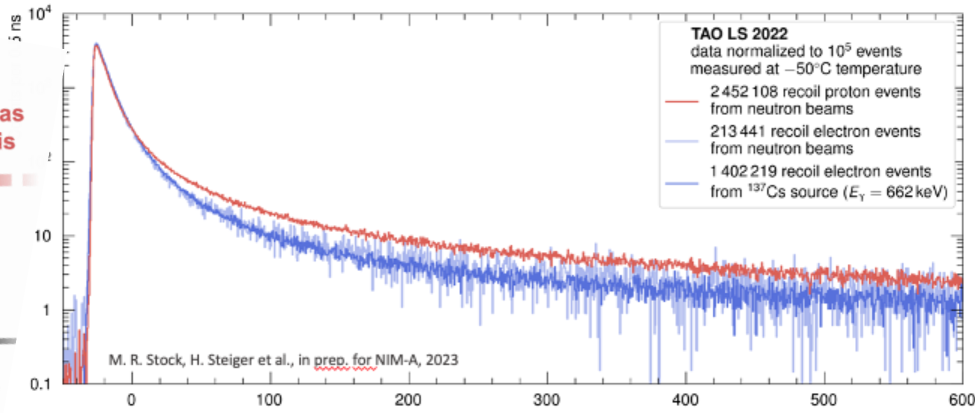
- **time profiles** for gamma and neutron excitation
- **QFs** for gamma and **neutron** interactions

Successfully measuring the scintillation time profiles and quenching factors for JUNO LS and JUNO-TAO Gd-LS allows us to **improve our understanding of the energy transfer mechanism** in these substances even at low T!

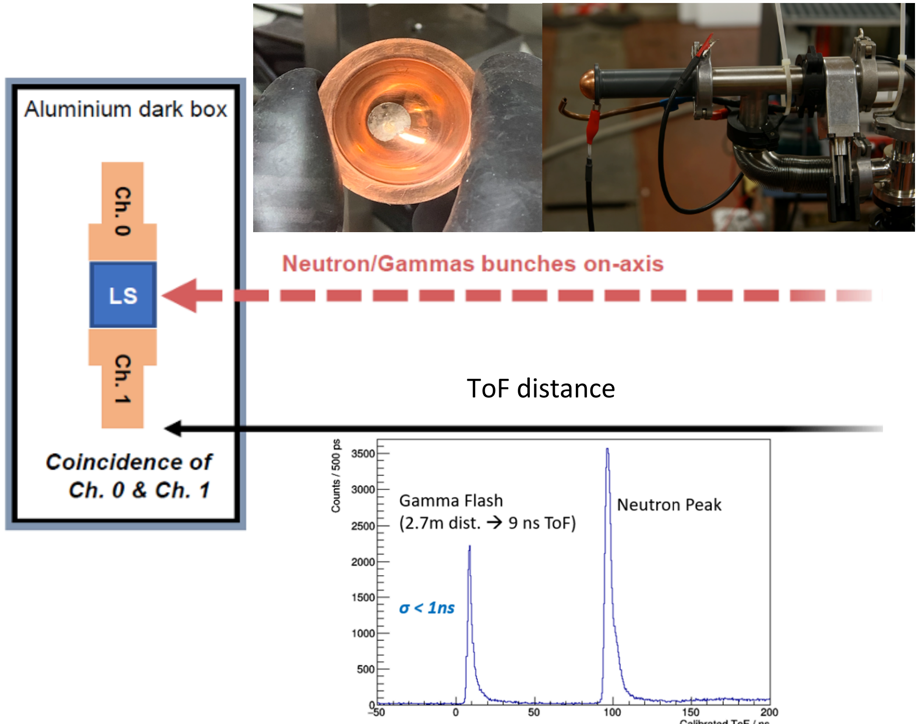
Measurements provide valuable input data for **TAO (also for JUNO)**:

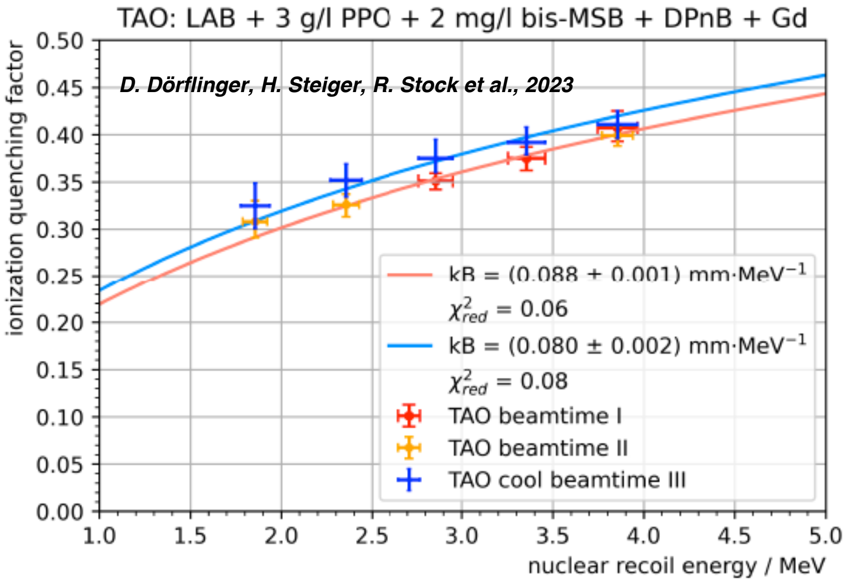
- Basis **for reliable Monte Carlo simulations**
- Development of **event reconstruction algorithms and PSD techniques**





PSD: Scintillation Time Profiles at -50°C





QF for proton recoils in the warm and cold TAO scintillator

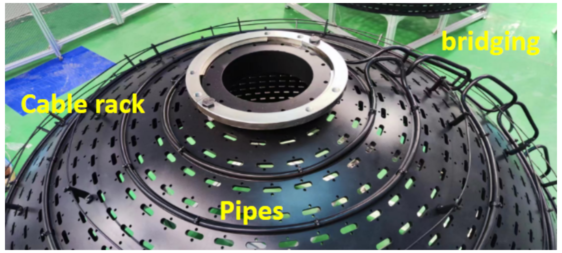
1:1 Prototype Experiment

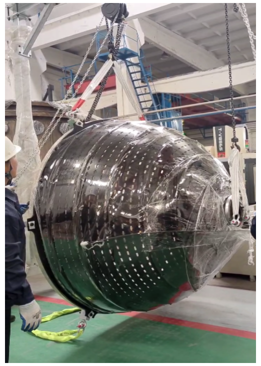
Purpose:

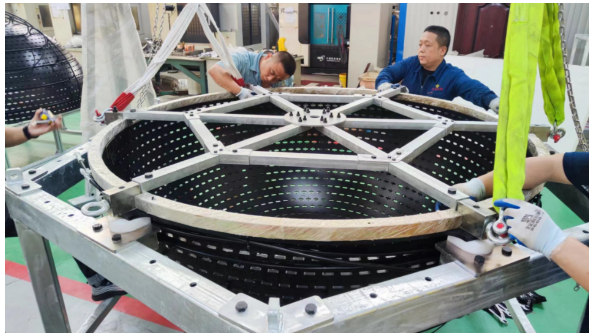
- Test key installation procedures
- avoid big issues and save time on site in Taishan
- Critical: CS rotation, SiPM assembly, cabling, tools)
- Test performance of cryogenic system, real SiPM tiles, LS, calibration system, etc..

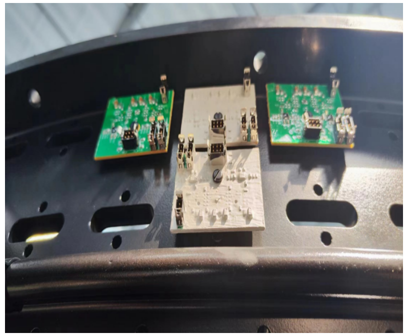
Progress:

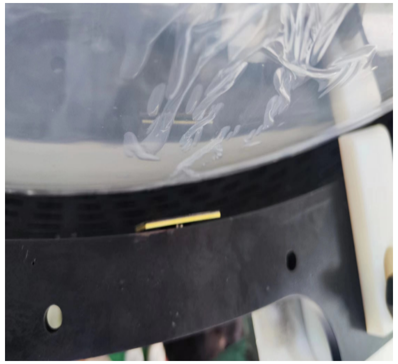
- All key installation steps and tools verified.
- SiPM tiles assembly procedure optimized (10k class clean room)
- Commissioning ongoing! → stay tuned!

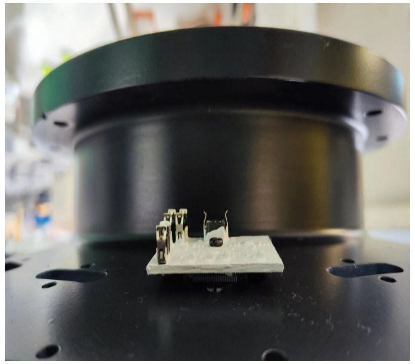












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Thank you for your attention!

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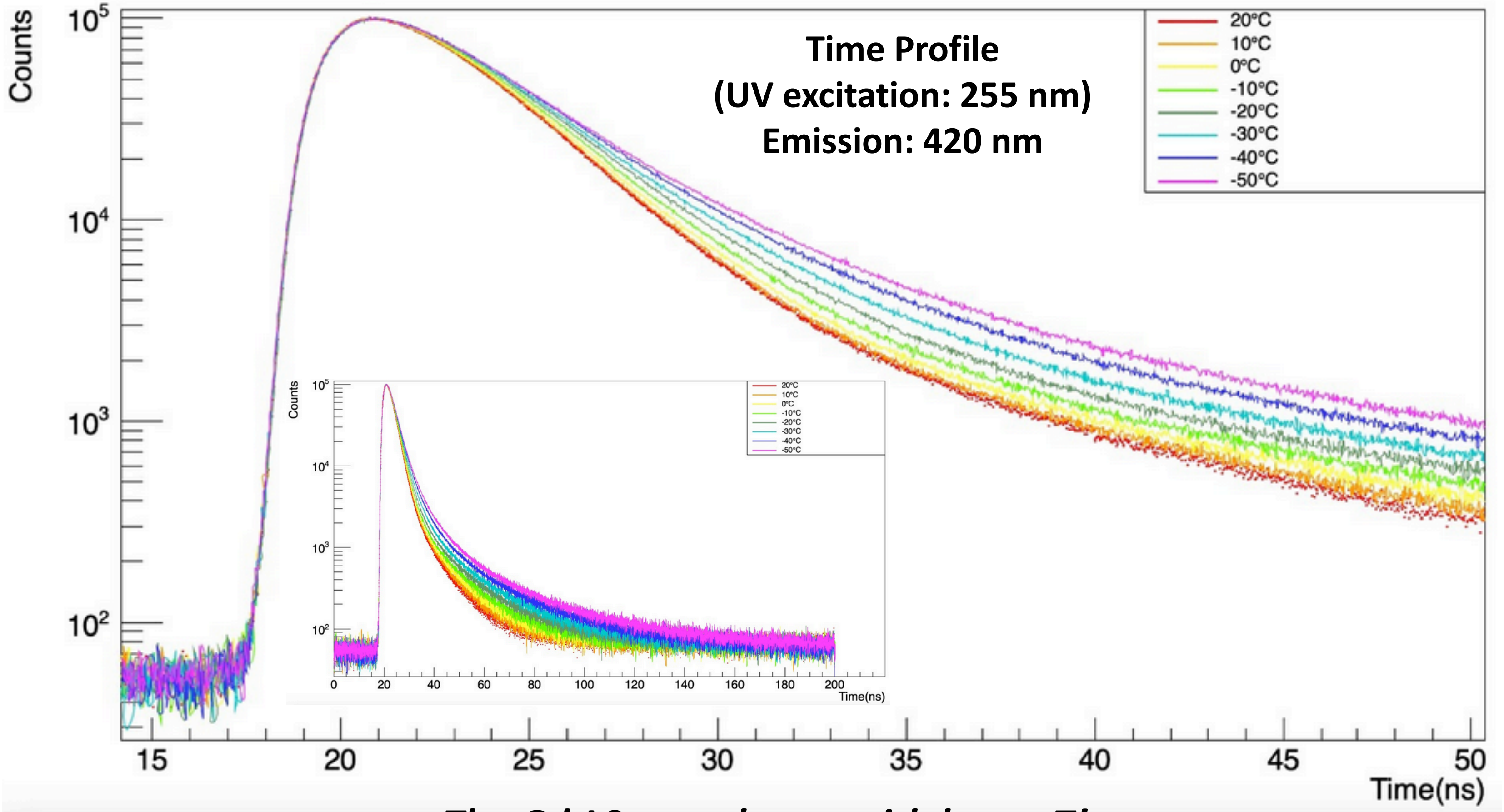
Backup Slides

Cooling Down the Gd-LS makes it slower: Time Profiles at low Temperatures with UV-Excitation

Spectrofluorometer: Edinburgh Instruments FS-5 with TCSPC modules

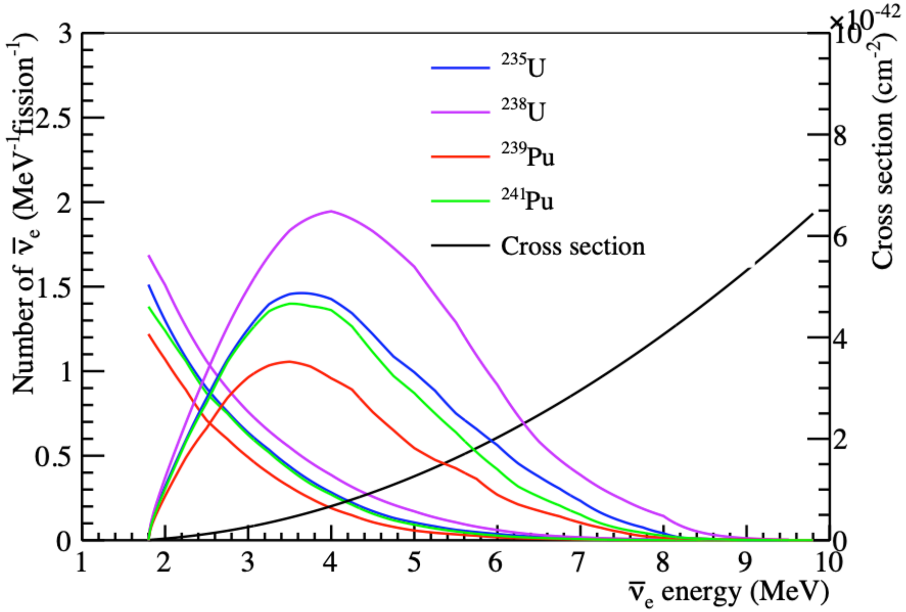
- *Cuvette: 10x10x40mm³*
- *Active cooling down to -50°C*
- *Dryed nitrogen to flush the detector chamber!*
- *Strong increase in first decay time component!*

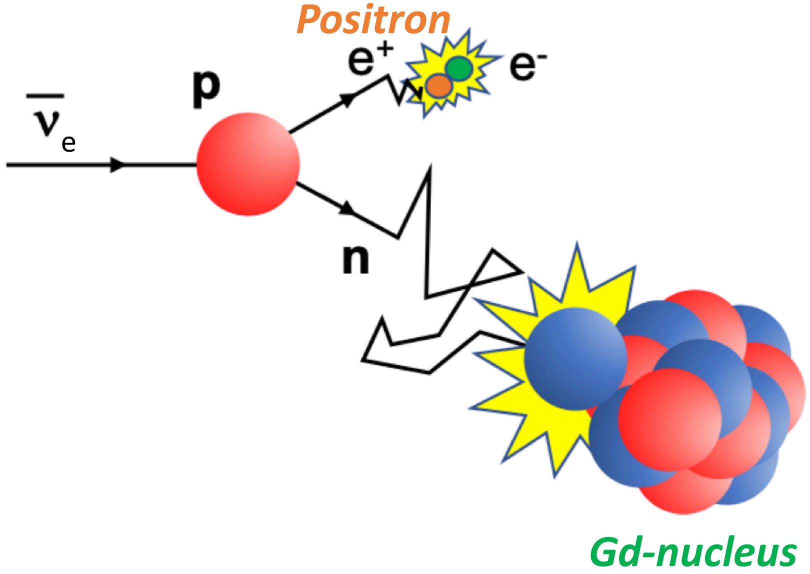


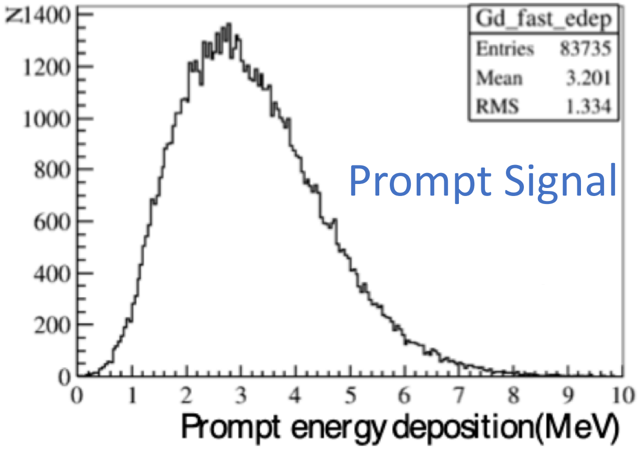
The Gd-LS gets slower with lower T!

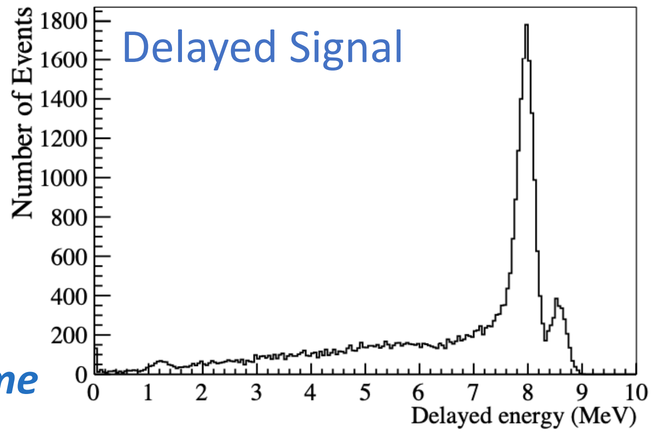
TAO: Signal

- Inverse β-decay (**IBD**) in the Gd-doped scintillator:
  - Characteristic signature: **prompt e^+ related scintillation + delayed neutron capture**
  - Probability for neutron capture by Gd: 87%
  - Delayed Coincidence: several γ's form a large **~ 8 MeV signal!**
  - Average capture time: **~ 30 μs** with $0.1\%_m$ Gd loaded in the scintillator
- Neutrino energy:
  - $E_{\overline{\nu}_e} = E_{e^+} + (m_n - m_p - m_e)$ neglecting K_n O(10 keV)







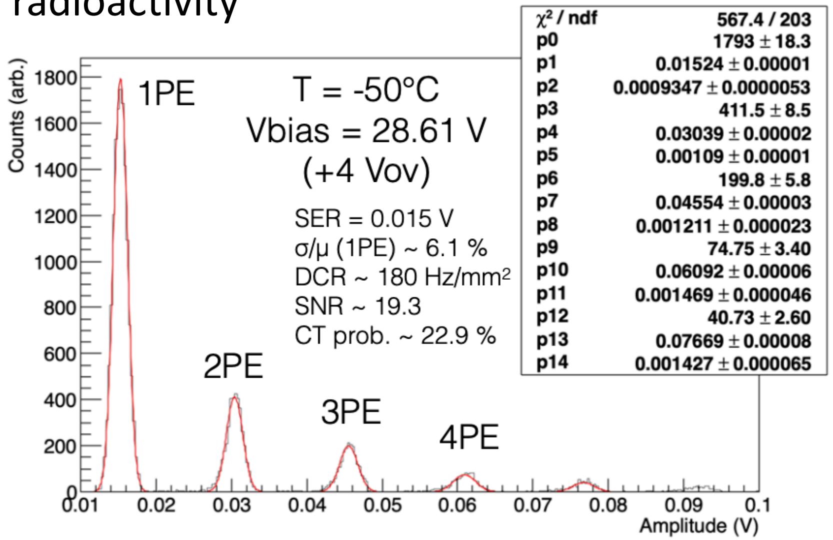


TAO: ~2000 IBD events/day in the fiducial volume

SiPMs

SiPMs are one of the key ingredients of TAO:

- PDE higher compared to PMTs needed for the desired energy resolution
- PDE correlates with Dark Noise
- PDE correlates with cross-talk and afterpulsing
  - → find the optimal tradeoff
- R&D with different companies finished
- HPK won the bid!
- Low-background materials are needed for PCBs (for both tiles and electronics) to meet the overall requirements on detector internal radioactivity



SiPM qualification test at low T

Parameter	Specification	Comments
PDE	> 50 %	@ 400 nm
DCR	< 100 Hz/mm^2	@ -50 °C
Correlated Noise	< 20 %	cross-talk and afterpulses
Uniformity of V_{bd}	< 10 %	Avoid bias voltage tuning
SiPM size	> 6 x 6 mm^2	simplicity and high coverage
SiPM tile size	> 50 x 50 mm^2	reduce number of channels
SiPM coverage in a tile	> 90 %	not included in PDE

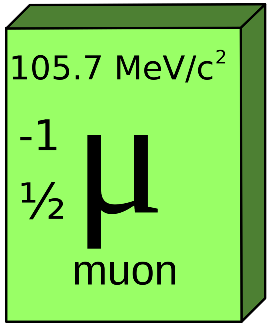
Low Background Material for PCBs

Isotope	CuFlon [mBq/kg]	Arlon NT [mBq/kg]	Pyralux [mBq/kg]	Aramid [mBq/kg]
^{226}Ra	1.4	-	2.6	-
^{228}Th	1.2	100	1.4	260
^{40}K	140	1000	4	1000

TAO: Backgrounds

Muons:

- Muon rate in TAO hall (~ 9.6m): **~ 70Hz**
- Veto: **20 µs** veto signal by **Top Veto** or **Water Tank**
- less than 10% dead time.



Muon induced backgrounds:

- Fast neutrons:
  - **recoil proton** (prompt) + thermalized **neutron capture** (delayed)
  - mimic IBD
  - **Muon veto** time cuts most of the fast neutrons.
- Delayed-like signals:
  - neutron captures not rejected by the muon veto (rate ~ 0.2 Hz)
  - mimic IBD signal if in coincidence with a prompt signal from radioactive decays
- **Cosmogenic** radioactive isotopes: ^{9}**Li** and ^{8}**He**
  - decay emitting a **prompt β** and a **delayed n**

IBD signal	2000 events/day
Muon rate	70 Hz/m^2
Fast neutron background before veto	1880 events/day
Fast neutron background after veto	$<$ 200 events/day
Singles from radioactivity	$<$ 100 Hz
Accidental background rate	$<$ 190 events/day
$^{8}He/^{9}Li$ background rate	$\sim$ 54 events/day

Natural radioactivity:

- major source of prompt events
  - from concrete walls: use **passive shielding**
  - internal: **careful material selection** (PCBs in SiPMs and electronics)