JUNO-TAO Status and Prospect

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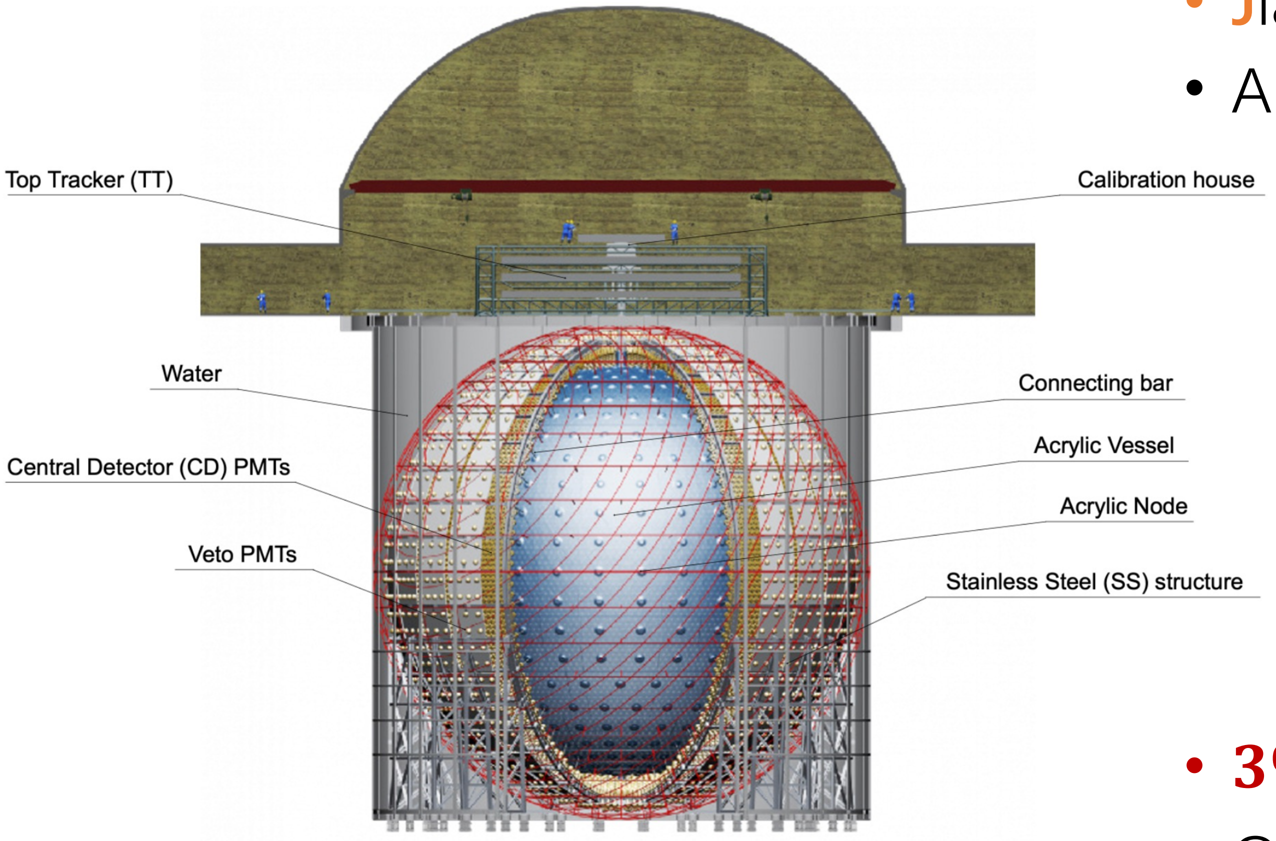
Institute of High Energy Physics
2023.1.17
2nd Technical Meeting on Nuclear Data Needs for Antineutrino Spectra Applications
IAEA

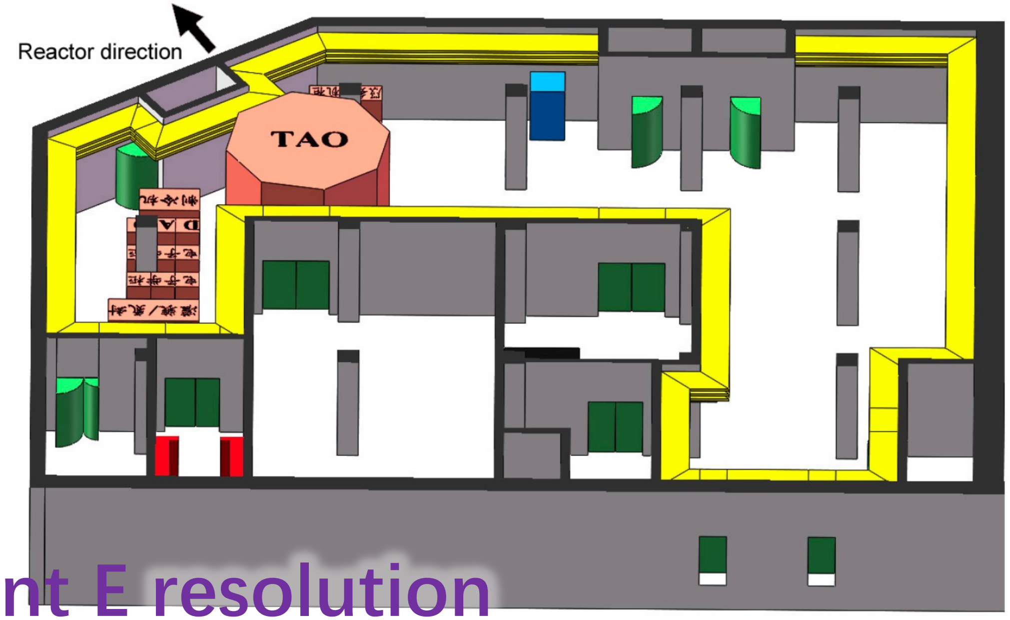
JUNO

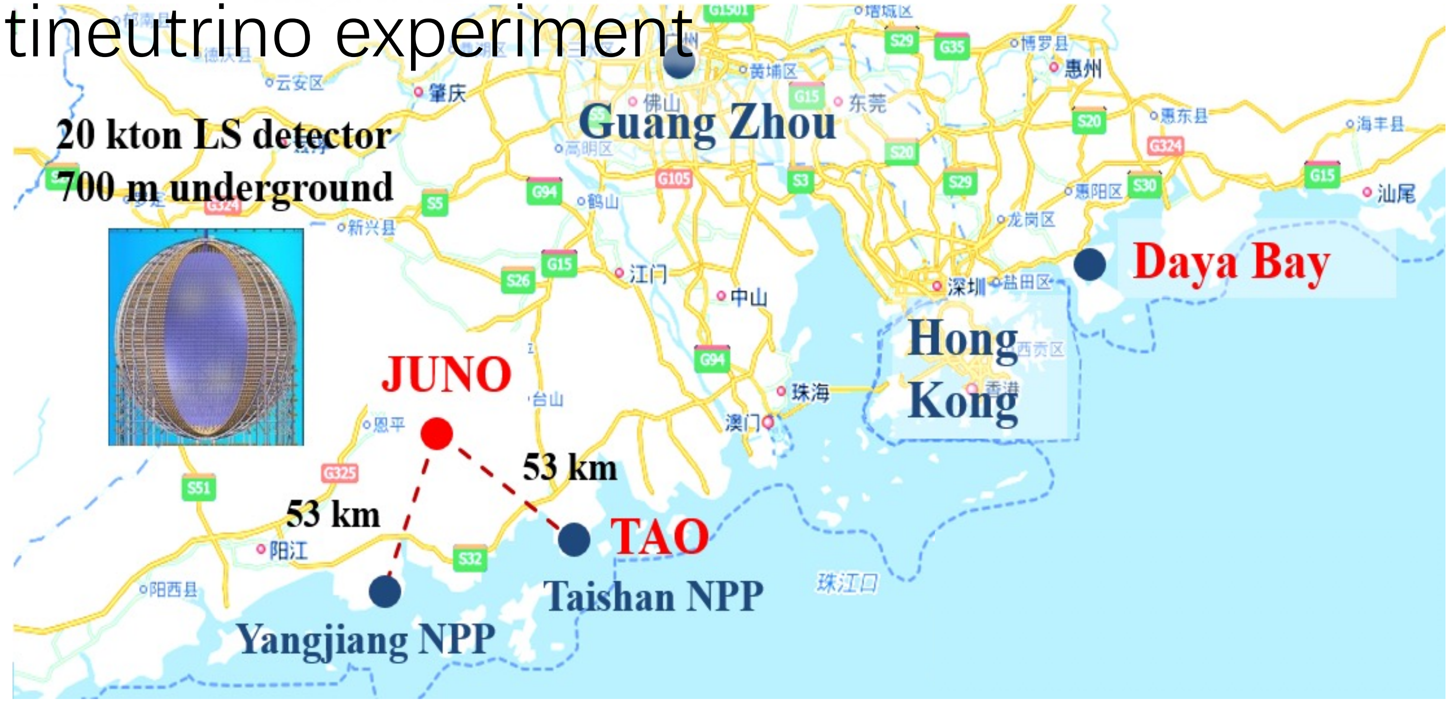


- Jiangmen Underground Neutrino Observatory
- A **multiple purpose** neutrino experiment
  - **Neutrino mass hierarchy**
  - Precision measurement of 3 oscillation parameters
  - Supernova neutrino
  - Geo-neutrino
  - Solar neutrino
  - Proton decay
  - …
- $\mathbf{3\%/\sqrt{E}}$ energy resolution, 20 kton LS
- Online in 2023

JUNO-TAO

- TAO: **T**aishan **A**ntineutrino **O**bservatory
- A satellite experiment of **JUNO**
- Measure reactor neutrino w/ **sub-percent E resolution**
- Short-baseline reactor antineutrino experiment
- Location:
  - 30 m from Taishan NPP core (4.6 GW)





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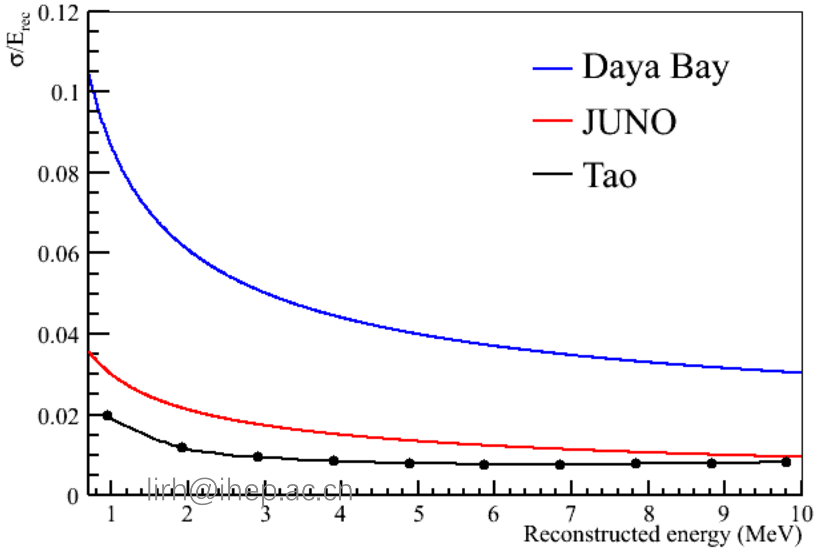
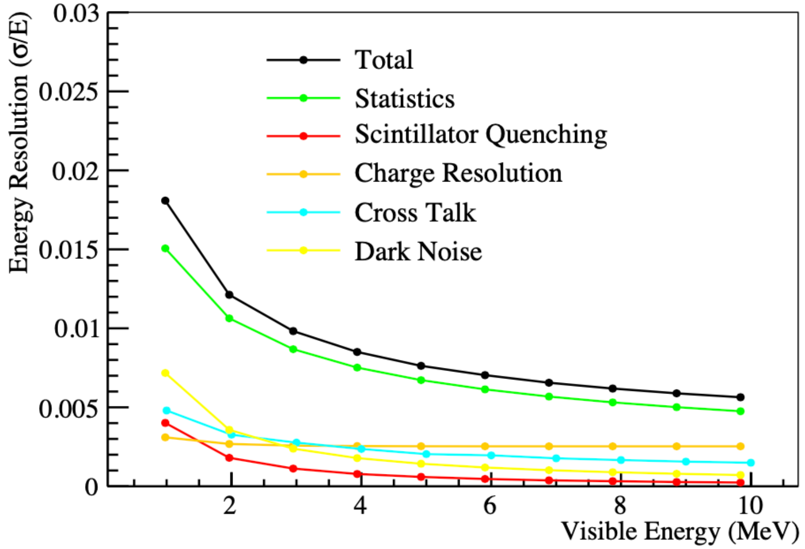
TAO Motivation

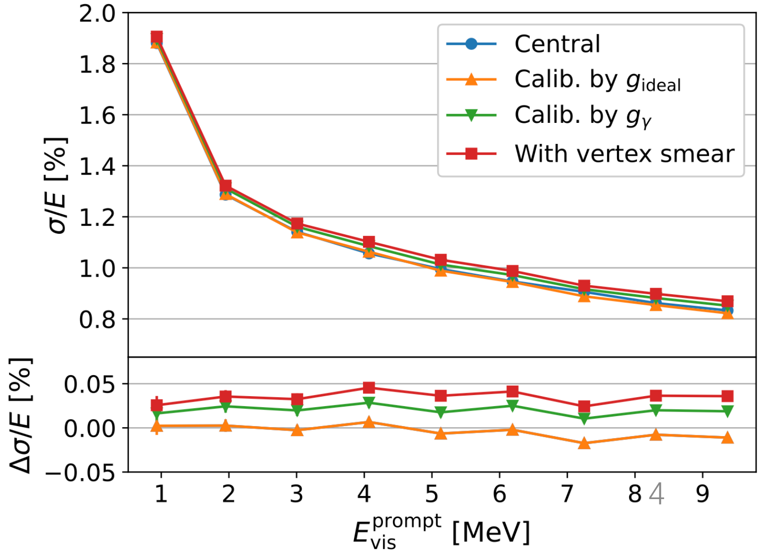
1. Provide reference spectrum for JUNO

- TAO can help to remove the model dependence by measuring fine structures in neutrino energy spectrum.
- The energy resolution of TAO must equal or better than $3\%/\sqrt{E}$ (now $<2\%/\sqrt{E}$).
- Reactor spectral shape precision better than 1% in 2-5 MeV

2. Provide a benchmark spectrum for nuclear database

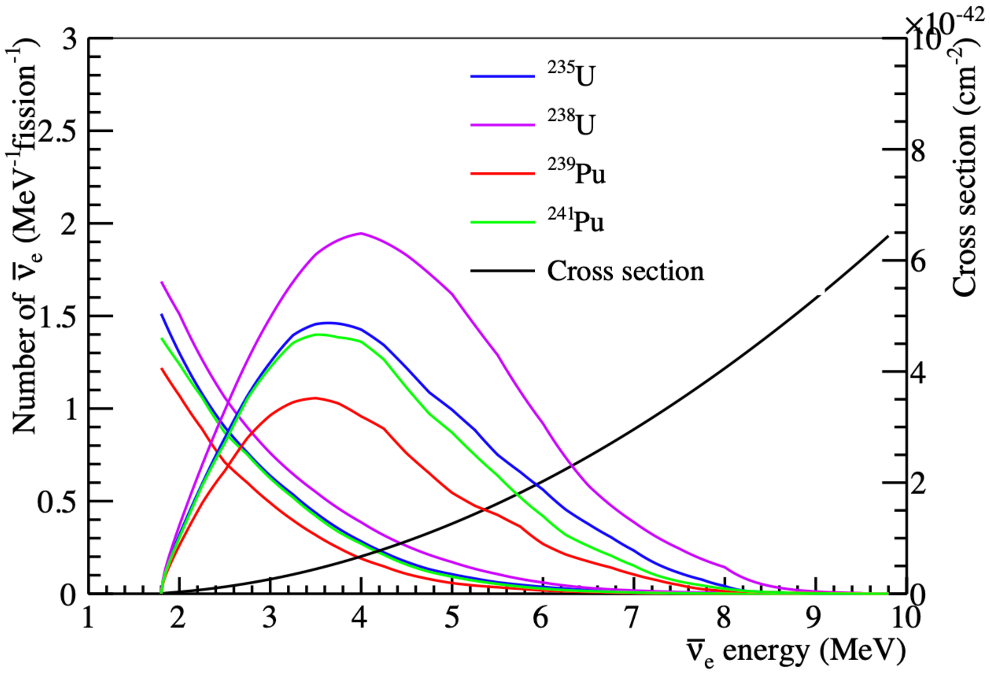


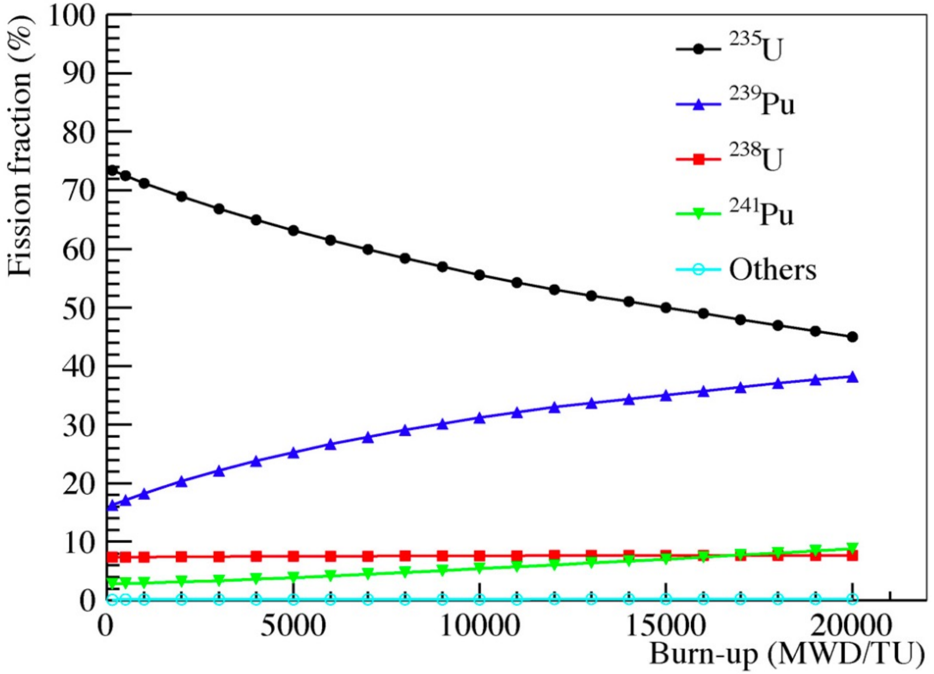




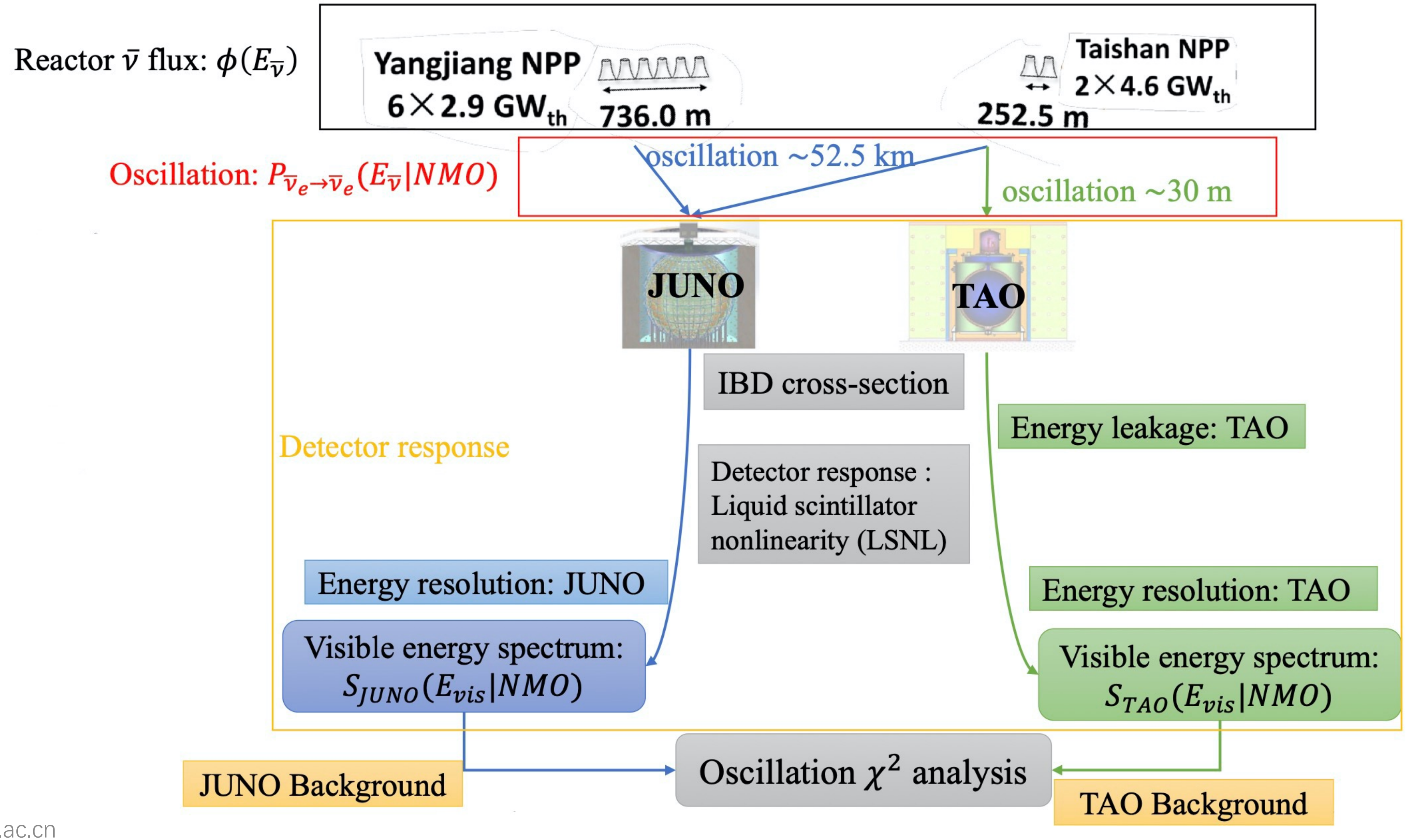
TAO Motivation

3. Measuring isotopic neutrino spectrum
4. Reactor monitoring
5. Sterile neutrino



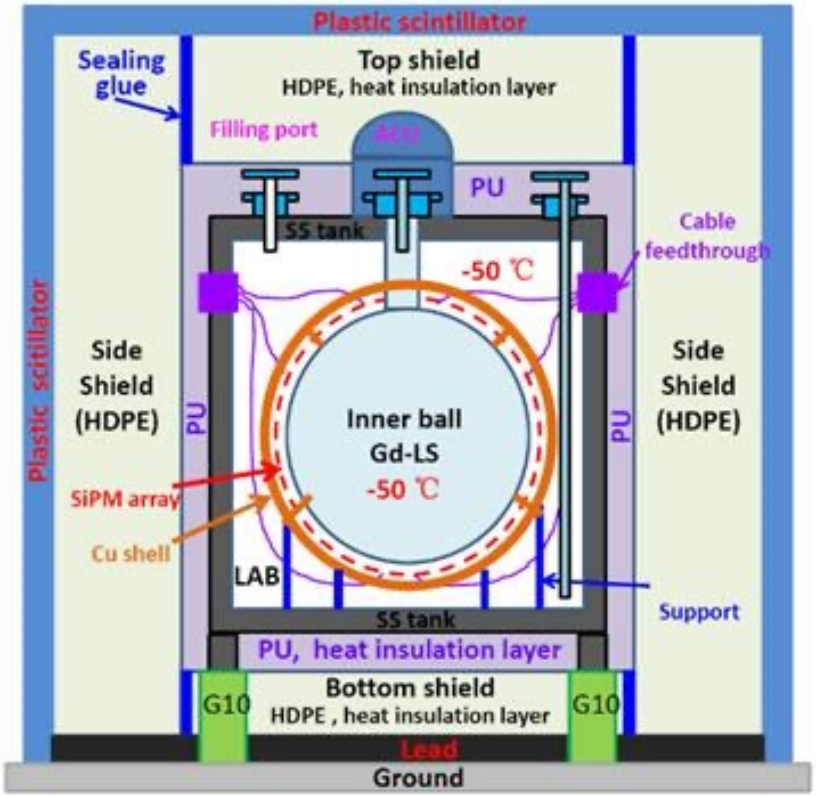


JUNO & TAO Combined Analysis



Since 2019 IAEA TM Meeting

- More detailed information of simulation & engineering
- Design optimization
  - To suppress background
  - Better for production
- The production of every part going well
- 1:1 prototype preparing, online in March 2023
- TAO commissioning online in Dec. 2023



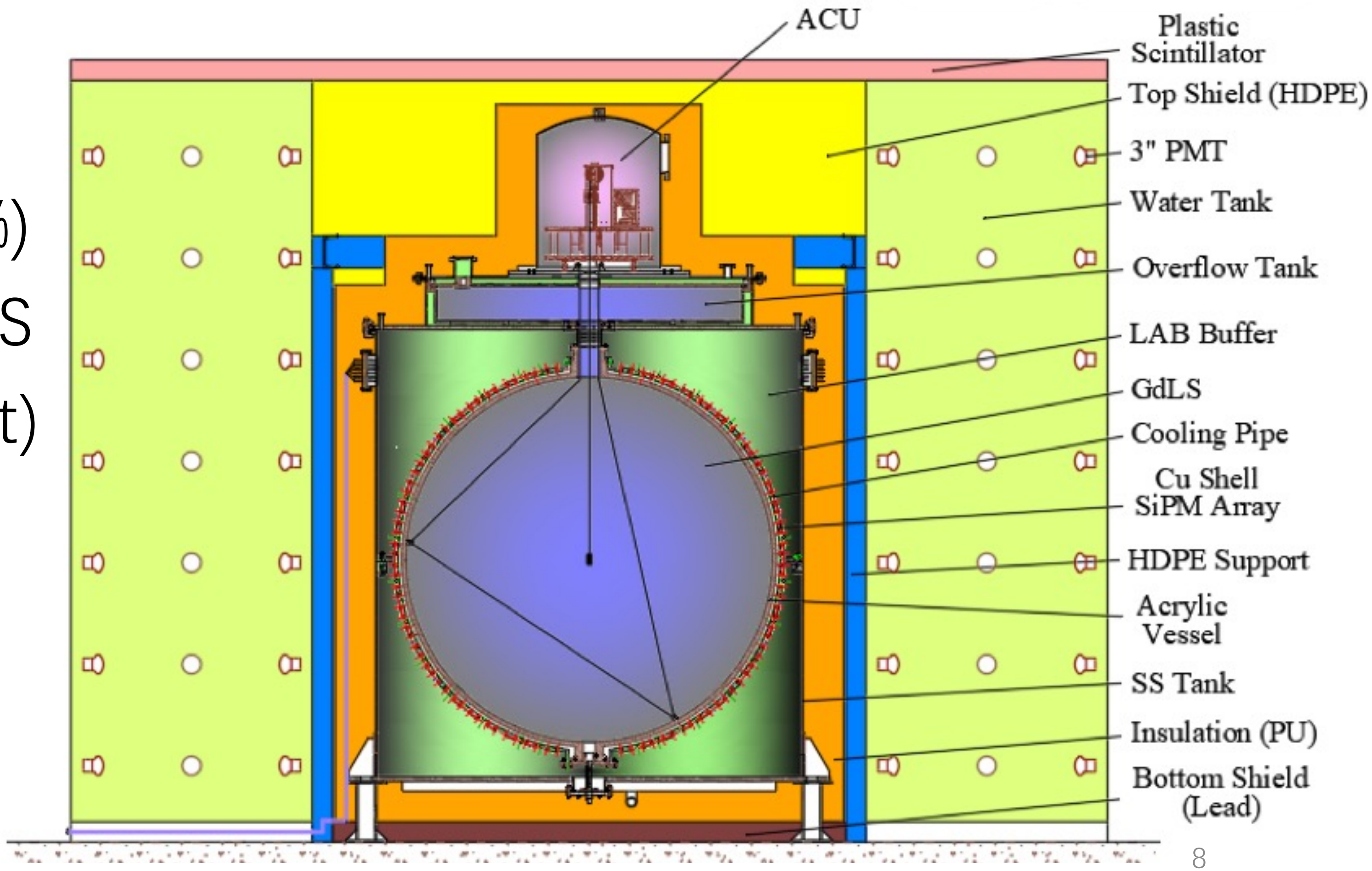
2019

TAO Detector

Inner → **Outside**

Gd-LS ⇨ acrylic vessel ⇨ SiPM & support ⇨ LAB buffer ⇨ cryogenic vessel ⇨ water & HDPE shield ⇨ muon veto

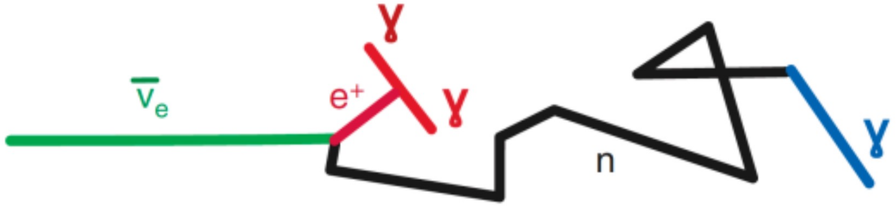
- -9.6 m underground
- ~ 10 m^2 SiPM coverage (95%)
- 1.8 m diameter, 2.8 ton GdLS (1 ton for fiducial volume cut)
- Operate at -50°C
- 4000 IBD/day (2000 w/ FV)
- 4500 p.e/MeV



Background Study

- For short baseline neutrino experiments, cosmogenic backgrounds are a crucial issue because of the shallow overburden
- Correlation of prompt & delayed signal is powerful to suppress backgrounds
  - Correlated bkg.: Fast neutrons, double neutrons, accidental backgrounds
- For TAO, **Cosmogenic Neutron Background/Signal ~1.8%**
  - In TAO Concept Design Report (2020) ~10%

arXiv:2005.08745



Background Study

- IBD & background simulation results in TAO CDR

IBD signal	2000 events/day	
Muon rate	70 Hz/m^2	
Cosmogenic neutron backgrounds	< 200 events/day	10%
Singles from radioactivity	< 100 Hz	
Accidental background rate	< 190 events/day	10%
$^8He/^9Li$ background rate	~ 54 events/day	

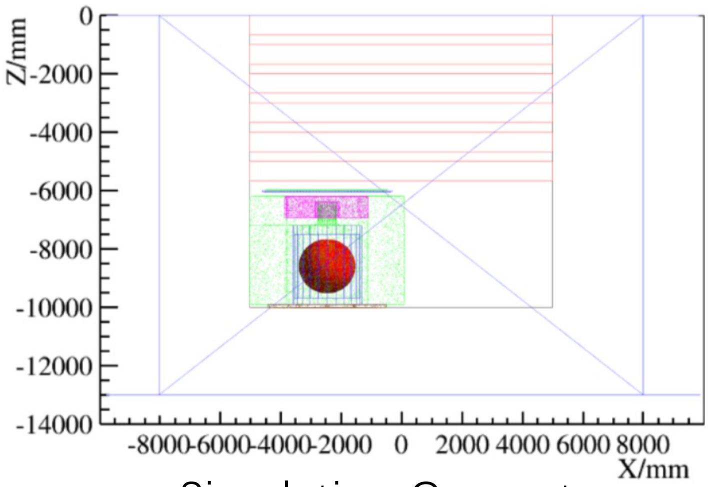
Without fiducial volume cut

We want to suppress cosmogenic neutron backgrounds.

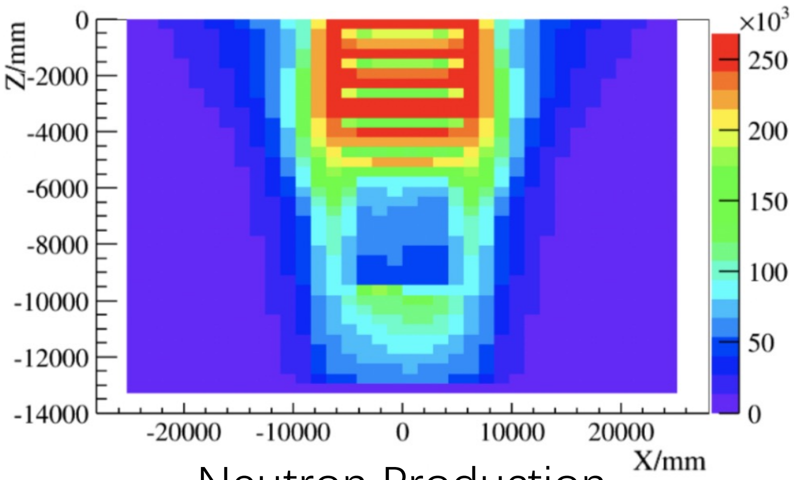
Background Study

- Floor plates neutron production is the highest.
- High-Z materials generate more neutrons in unit mass.

	Water	HDPE	Pb	SST	LAB	Cu	GdLS
Neutron rate (Hz)	60.8	7.4	80	5.8	2.2	3.3	1.2
Mass (t)	56.2	5.6	13.9	1.4	4.0	1.1	2.6



Simulation Geometry



Neutron Production

Background Study

- Double neutron backgrounds dominate.
  - Caused by spill-in & spill-out of neutrons between GdLS & LAB
  - GdLS capture time ~28 μs, LAB capture time ~200 μs
- **Dope 0.1% Gd in LAB**

(/day)	Before veto	After Veto	Tagged muon	Untagged muon
Double-neutron	373	309	300	9
Fast-neutron	2858	53	0	53
Other	1178	9	0	9
All	4409	371	300	71

Double neutron: Two neutrons produced by a same muon are captured and form prompt-delayed signal
Fast neutron: Prompt signal is proton recoil, delayed signal is neutron capture signal
Other: Gammas released by neutron capture in rock, Michel electrons, other correlated backgrounds

Background Study

- Double neutron backgrounds dominate.
  - Caused by spill-in & spill-out of neutrons between GdLS & LAB.
  - GdLS capture time ~28 μs, LAB capture time ~200 μs
- **Dope 0.1% Gd in LAB**

(per day)	Without Gd in LAB		Adding 0.1% Gd in LAB	
	w/o FV	w/ FV	w/o FV	w/ FV
Double-neutron background	309	72	179	37
Fast-neutron background	53	12	45	11
Other	9	2	15	0
All	371	86	239	48

Doping 0.1% Gd suppresses ~1/2
Fiducial volume cut suppresses ~ 3/4

Background Study

- Double neutron backgrounds dominate.
  - Caused by spill-in & spill-out of neutrons between GdLS & LAB.
  - GdLS capture time ~28 μs, LAB capture time ~200 μs
- **Dope 0.1% Gd in LAB**
- **PTFE coating for stainless steel tank & copper shell**
  - **Including flanges and screws**
- **Compatibility of electronics & SiPM with GdLAB is good**
- **PCB coating is still under study**

Background Study

- High-Z materials generate large amount of neutrons
  - Copper shell: main source of double neutron ~ 40 mm from GdLS
- Lead generates some neutrons
  - **Add 10 cm HDPE above lead**

(per day)	Cu	Pb	GdLS	Outside	Others	All
Double-neutron	216	34	13	4	42	309
Fast-neutron	11	0	0	36	6	53

Neutron background production location

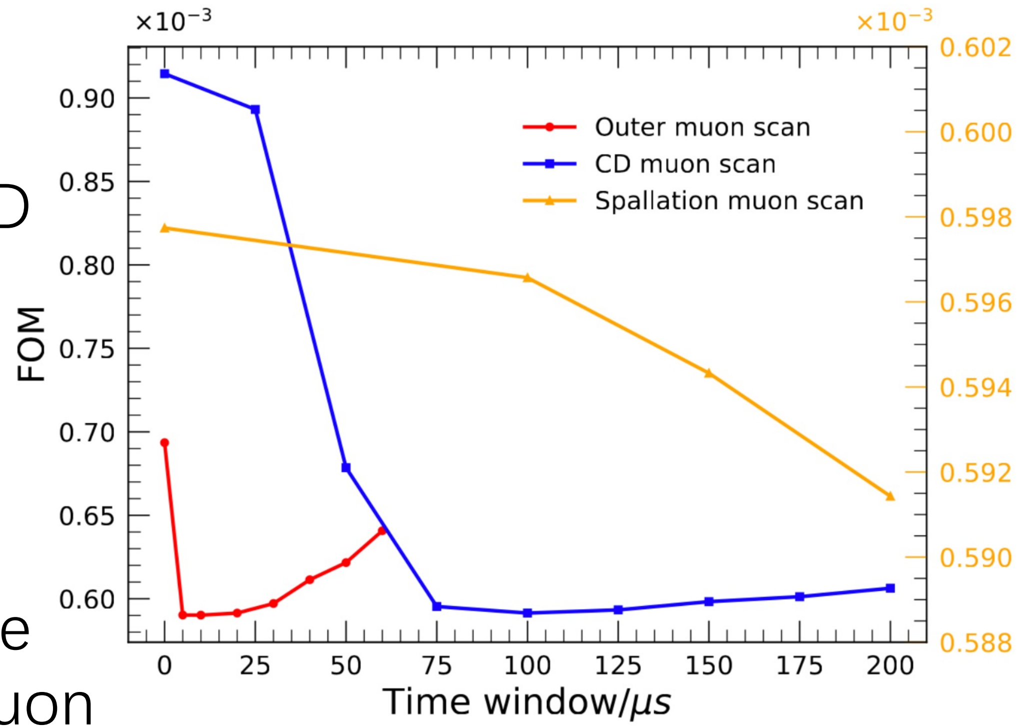
- Neutrons generated outside the detector are very few
  - Doping boric in water tank/adding more HDPE at the top is useless

Background Study

- Veto time window optimization

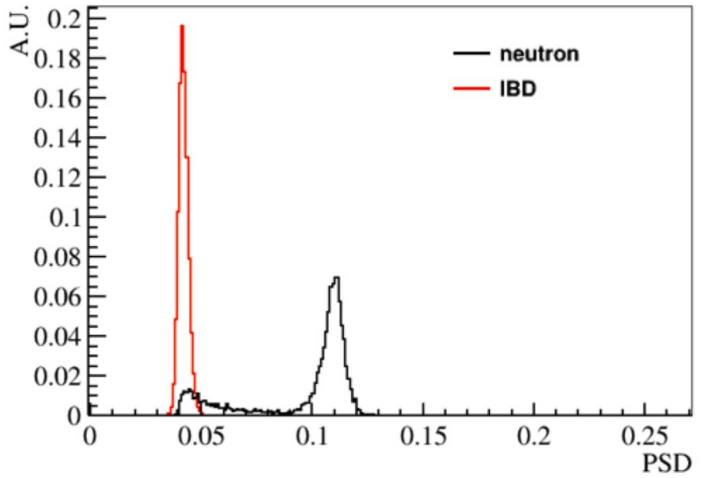
$$FOM = \frac{1}{N_S} + (\sigma_B \times \frac{N_B}{N_S})^2 \qquad \sigma_B = 1/\sqrt{90 \times N_B/300}$$

- Outer muon veto: 20 μs
  - Muon tagged by veto detector but not by CD
- CD muon veto: 100 μs
  - Muon tagged by veto detector
  - CD event >0.7 MeV in 100 ns
- Spallation muon veto: 200 μs
  - 6-10 MeV signal in outer/CD muon veto time
  - >10 MeV signal in 20 μs after any tagged muon

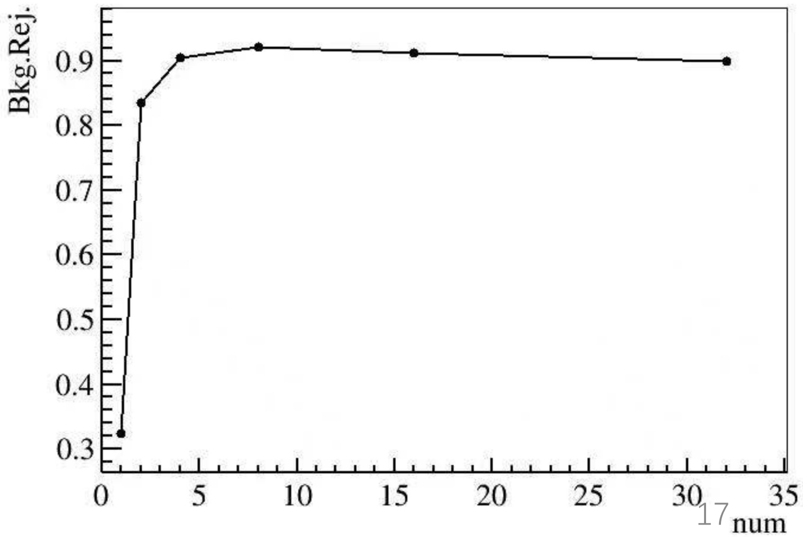


Pulse Shape Discrimination

- Main influence: gamma from neutron inelastic
- 4482 tiles
  - Discrete components: 1 channel per tile
  - ASIC: 32 channel per tile
- ASIC is not stable at low temperature
- **2 channels for one tile is the best**
  - Considering cost & PSD effect



	Without Electronics Effect	Discrete Components	ASIC
Signal Efficiency	99.35%	91.59%	99.18%
Bkg. Rejection	94.40%	90.64%	91.21%



Background Study

IBD	1838/day
Singles from radioactivity	100 Hz
Muon rate	67 Hz/m^2
IBD-like before veto	3682/day
IBD-like after veto	44/day
Accidental background	129/day
^{8}He & ^{9}Li	<20/day

B/S is 2.4%, w/ PSD it will be **1.8%**.

Risk: High Energy environmental neutrons

DOI: 10.1088/1748-0221/17/09/P09024
JINST 17 (2022) 09, P09024

Status of Every Part

- GdLS: Production finished, store in IHEP
- SiPM: Efforts of QA/QC is ongoing
- Central detector:
  - Copper shell: Up semi-sphere almost finished, down semi-sphere will be finished in a mouth
  - Stainless steel tank: Finished, store in IHEP
  - Acrylic sphere: Finished, delivered to IHEP this week
- Calibration:
  - Simulation study finished. Production finished, test is going on
- Muon veto: Design finished, top veto tracker production ongoing
- Electronics: Front-end production ongoing, back-end production almost finished
- TDAQ: Test almost finished, stability test ongoing
- 1:1 prototype in IHEP: Assembly in March, 2023

GdLS & LAB Buffer

- GdLS recipe: Gd-LAB + 3 g/L PPO + 2 mg/L bis-MSB + 0.5% DPnB
- High light yield (15640)/flash point (> 100 ^{o}C)/transparency
- Good stability at -50°C
- 3200 L, **production finished in Sept. 2022**, store in IHEP.
- Gd-LAB production will be started after prototype assembly

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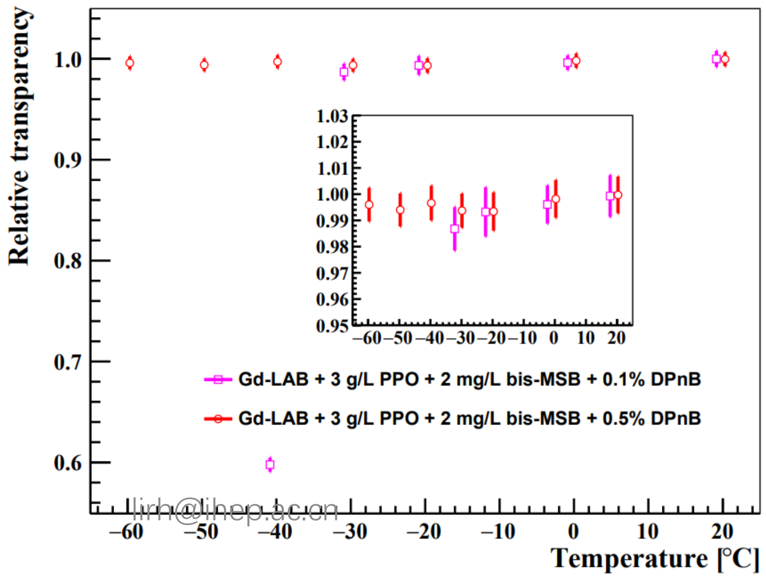
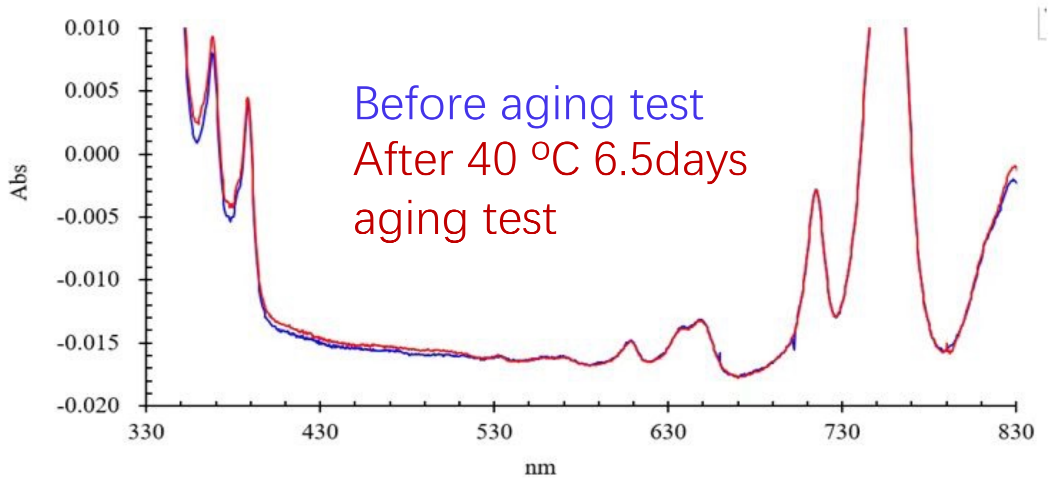
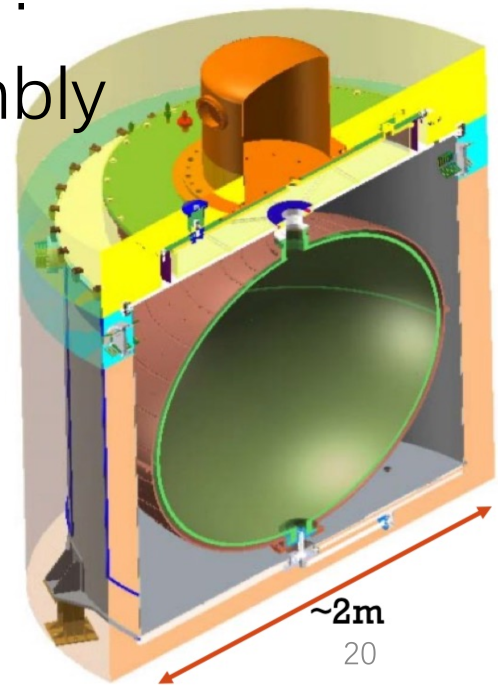
Nucl.Instrum.Meth.A 1009 (2021) 165459







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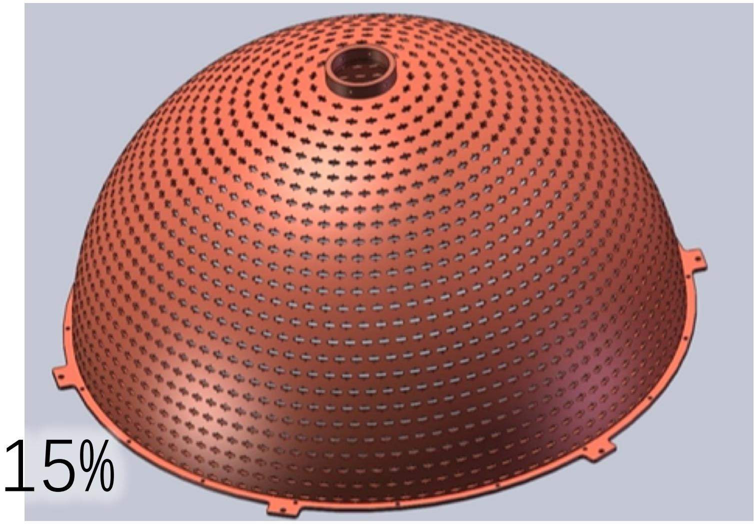
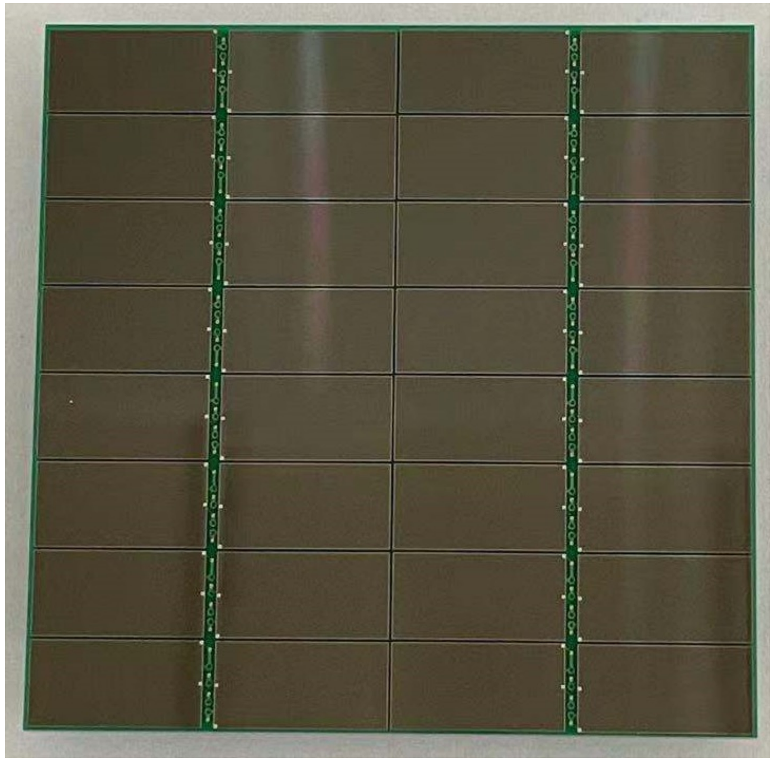
SiPM

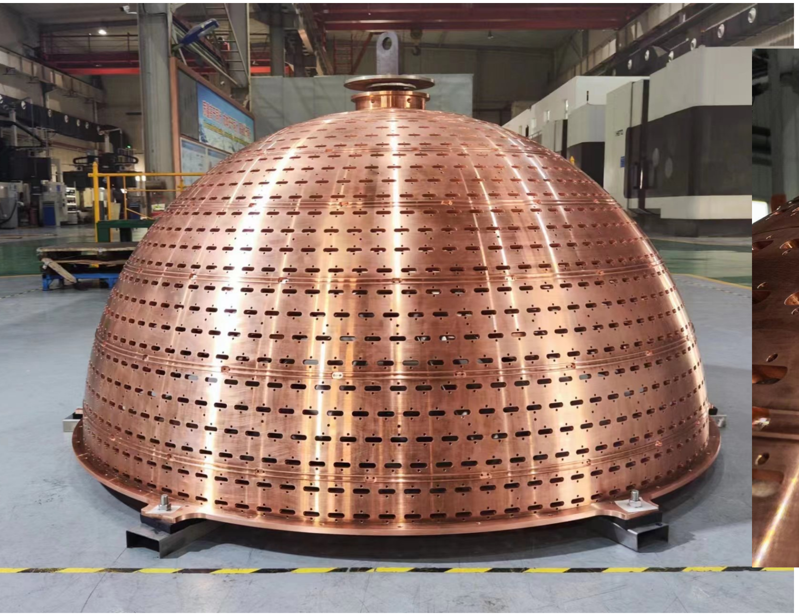
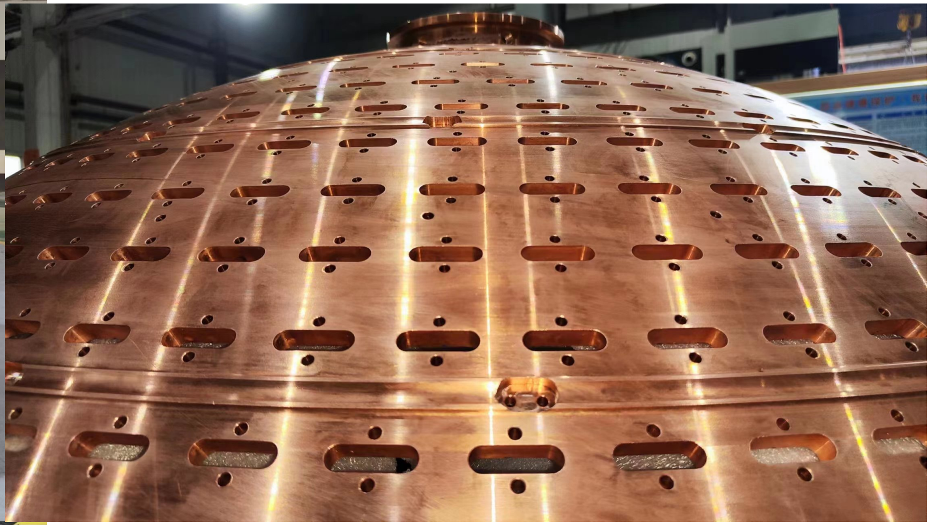
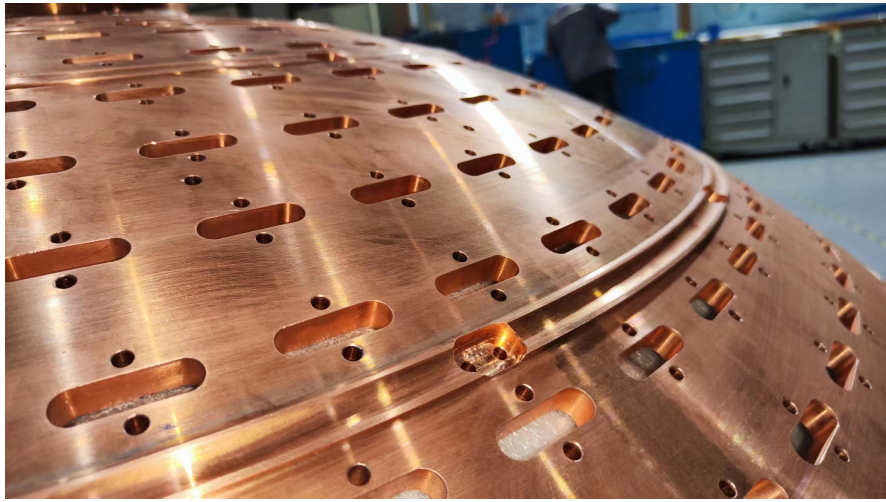
- Tile 50.8 x 50.8 mm^2, 4024 tiles from **HPK**
- ~ 8000 channels, charge resolution per channel ⩽ 15%
- Supported & cooled by **copper shell**
- Work at **-50°C** to lower dark noise by 2-3 orders
- Characterizations have been conducted
- Efforts on QA/QC are ongoing
- Surface defect & burn-in test passed
  - First batch, 100 tiles





Central Detector

- **Copper shell**
  - Cutting → Forming →Welding → **Machining** →Coating(PTFE)
  - Up semi-sphere machining finished, **cleaning & coating.**
    - Will be ready after Chinese new year
    - Hole position precision: 0.1%, hole diameter error<0.1 mm
  - Down semi-sphere machining ongoing. Ready in March 2023.

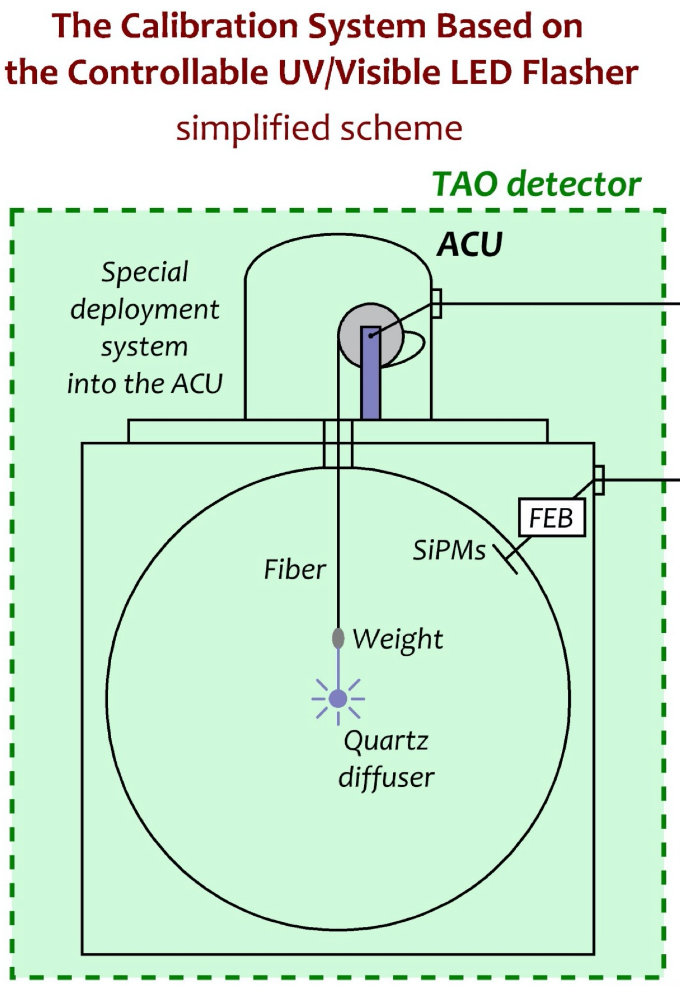




Central Detector

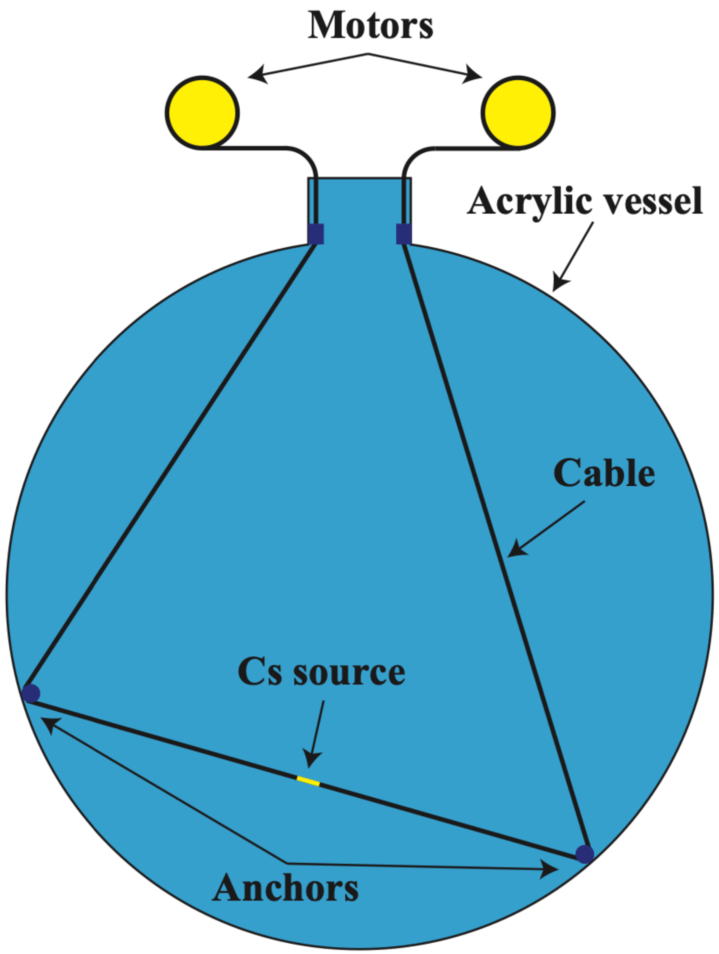
- **Stainless steel tank**
  - Production finished in May 2022
  - PTFE coating inside
  - Acceptance check was passed
  - **Store in IHEP**

- **Acrylic sphere**
  - Production finished in Nov. 2021
  - **Delivered to IHEP this week**

Calibration



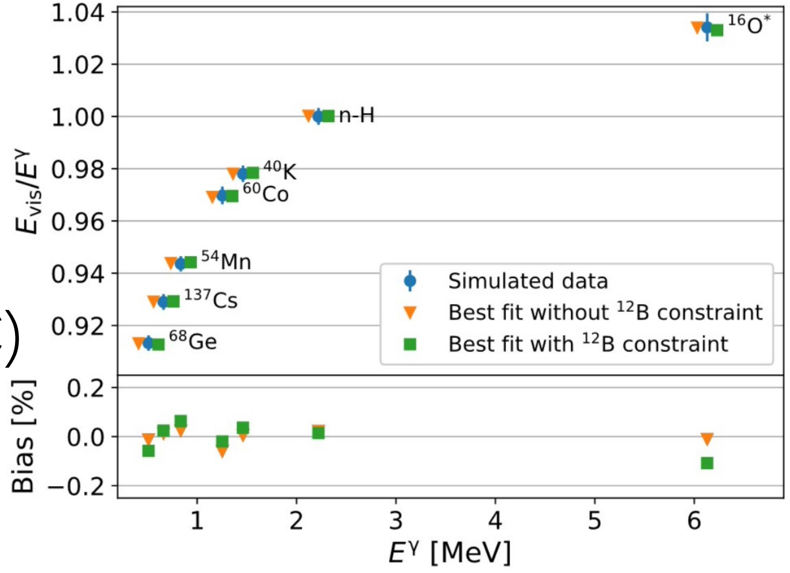
Automated Calibration Unit

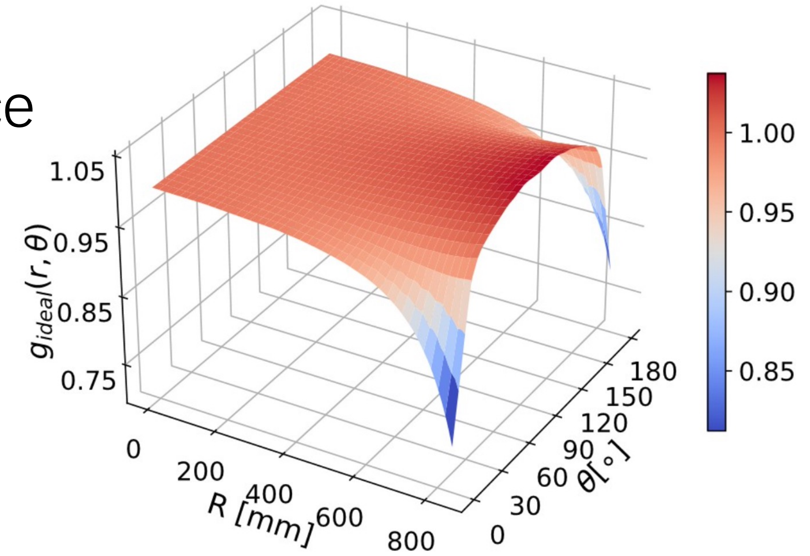


Cable Loop System

Calibration

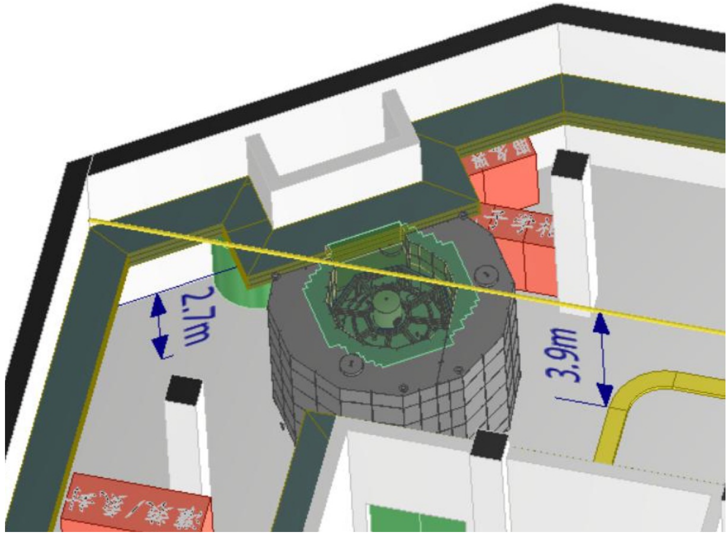
- Non-linearity
  - Use gamma sources(^{137}Cs, ^{54}Mn, ^{40}K, ^{60}Co, ^{68}Ge, ^{241}Am-^{13}C)
  - For electron & positron, physics non-linearity **<0.6%**
  - w/ ^{12}B data of three years, physics non-linearity **<0.4%**
- Non-uniformity
  - Use ACU & CLS to deploy 110 positions for gamma source
  - w/ FV, residual non-uniformity is **<0.2%**
  - Energy resolution degradation **<0.05%**
  - Energy bias **<0.3%**





Doi: 10.1140/epjc/s10052-022-11069-3
Eur.Phys.J.C 82 (2022) 12, 1112

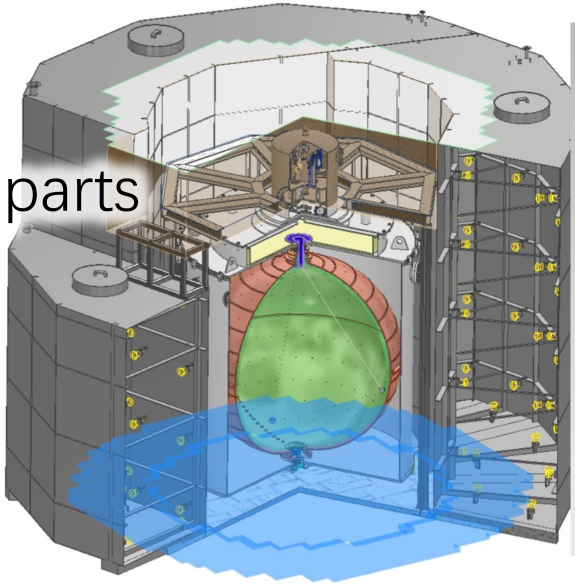
Muon Veto

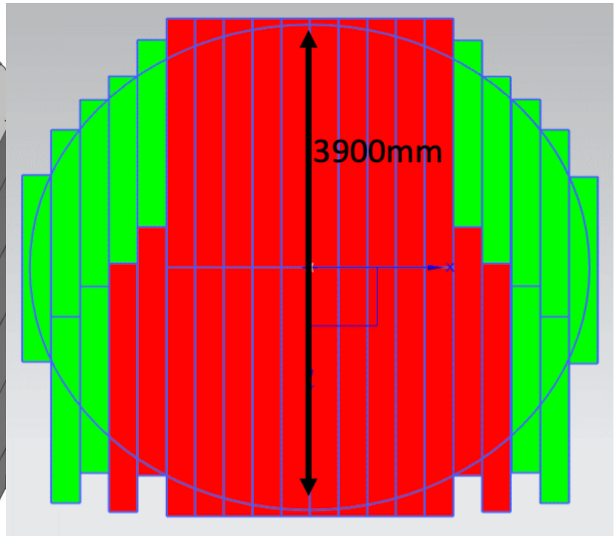


Enhancing muon veto efficiency to reject more bkg.

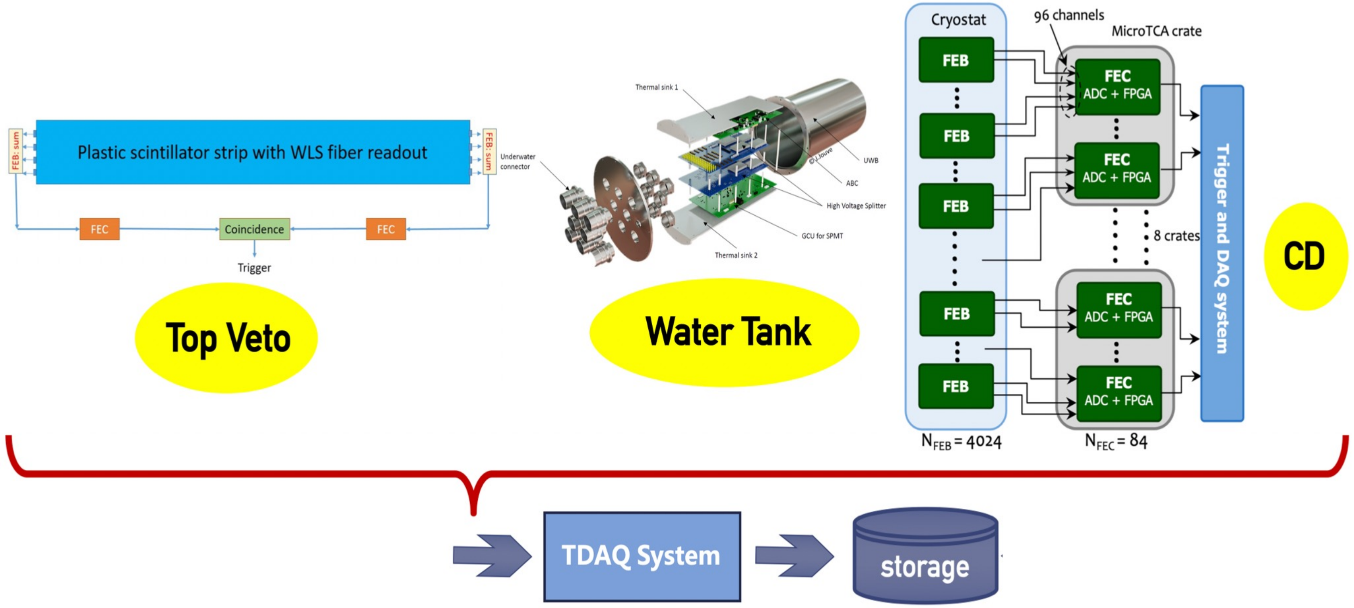
Two combined active shielding, design is completed

- **Top veto tracker**
  - 4 layers with each 2cm thickness, 1 mm gap between strips
  - Muon veto efficiency ~ 99% (3/4)
- **Water tank**
  - Dodecagon, 1.2 m thickness, 3 standalone parts
  - Tyvek applied
  - 300 3" PMTs, muon veto efficiency > 99%
  - High fault-tolerant ability:
    - PMT num, absorption lenth…





Electronics & TDAQ



Data Stream	Interface	DAQ Data input	Data Merge	SW Trigger	Compression	Storage
CD	SiTCP	~Gbps	Y	N	Y	<80Mbps
WT	IPbus/TCP	~105Mbps	Y	Y	Y	<10Mbps
TPS	SiTCP	~40Mbps	Y	Y	N	<1Mbps
SUM						<100Mbps*

- Electronics of central detector (CD)
  - FEB based on discrete components
  - Waveform digitized by ADC (250MHz)
  - FPGA calculates Q/T, sent to TDAQ
- Electronics of veto detectors
  - Same strategy with CD for TPS
  - Same with 3'' PMTs electronics in JUNO

1:1 Prototype

- Will be assembled in **March, 2023** in IHEP
- Including:
  - LS & LAB (w/o Gd)
  - Acrylic sphere
  - Copper shell
  - Stainless steel tank
  - Part of TVT
- **Leakage hunting**
- **Commissioning**

Clean room

Summary

- TAO will measure reactor antineutrino spectrum with sub-percent E resolution (**<2%/$\sqrt{E}$**)
- The production of every part is going well
- 1:1 prototype preparing, expected **in March 2023**
- TAO will start commissioning **in Dec. 2023**