Measuring High Resolution Reactor Neutrino Spectrum with JUNO-TAO

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(on behalf of JUNO)

Institute of High Energy Physics

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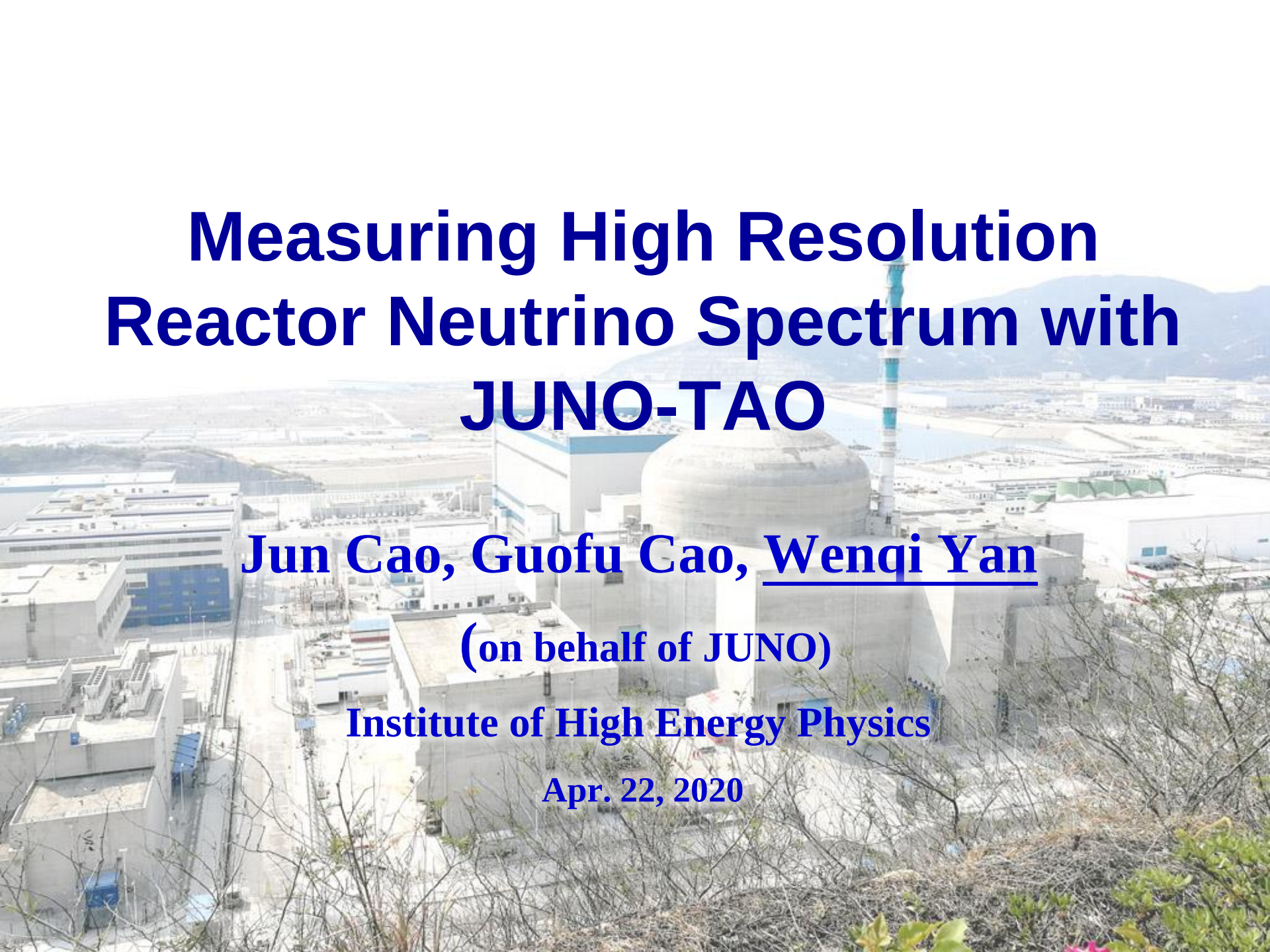


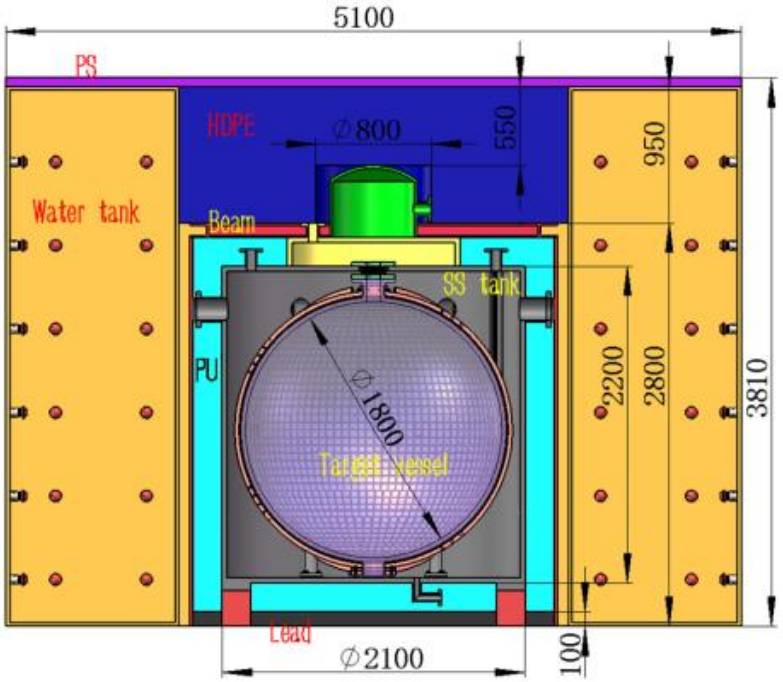
JUNO-TAO

- Taishan Antineutrino Observatory (TAO), a ton-level, high energy resolution LS detector at 30 m from the core, a satellite exp. of JUNO.

- Measure reactor neutrino spectrum w/ sub-percent E resolution.
  - ⇨ model-independent reference spectrum for JUNO
  - ⇨ a benchmark for investigation of the nuclear database

- Ton-level Liquid Scintillator (Gd-LS)
- Full coverage of SiPM w/ PDE > 50%
- Operate at -50 ℃ (SiPM dark noise)
- 4500 p.e./MeV

- Taishan Nuclear Power Plant,
  30-35 m from a 4.6 GW_th core
- 2000 IBD/day (4000)
- Online in 2021



Location of JUNO and JUNO-TAO

77 Institutions, 600 collaborators

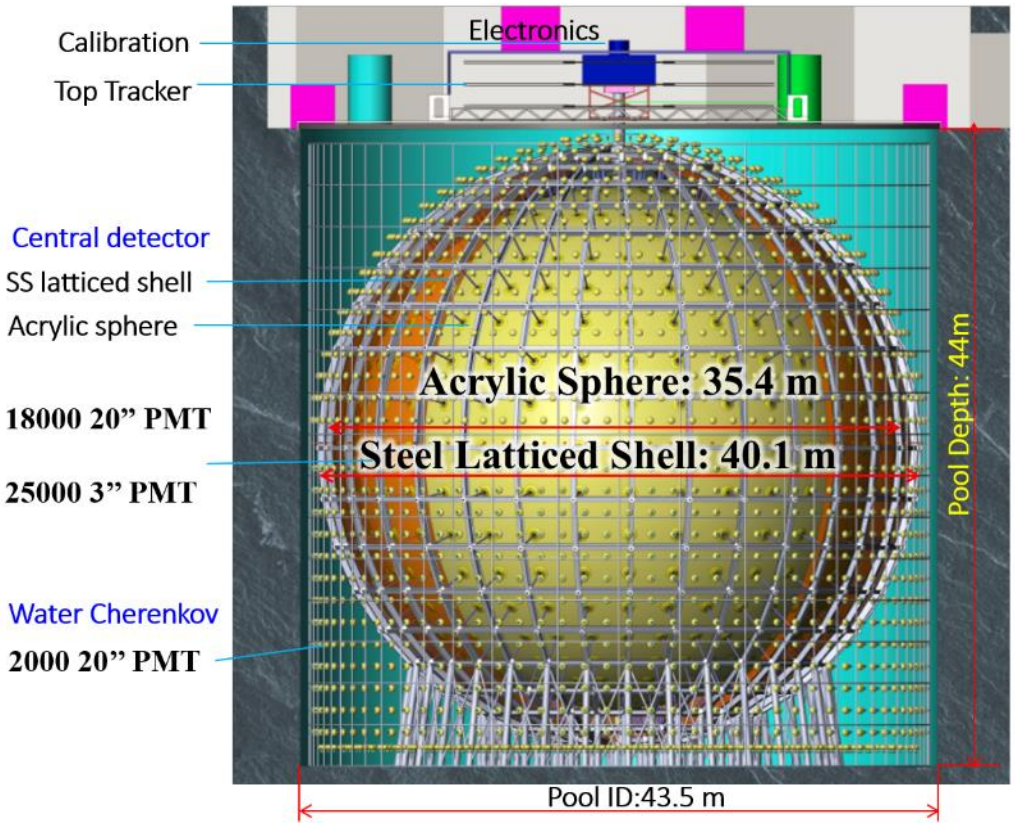
- China (34), Taiwan,China (3), Thailand (3), Pakistan, Armenia
- Italy (8), Germany (7), France (5), Russia (3), Belgium, Czech, Finland, Slovakia, Latvia
- Brazil (2), Chile (2), USA (3)

Yangjiang	Taishan
17.4 GW	9.2 + 9.2 GW

JUNO

Jiangmen Underground Neutrino Observatory, a multiple-purpose neutrino experiment, proposed in 2008, approved in 2013, online in 2021

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

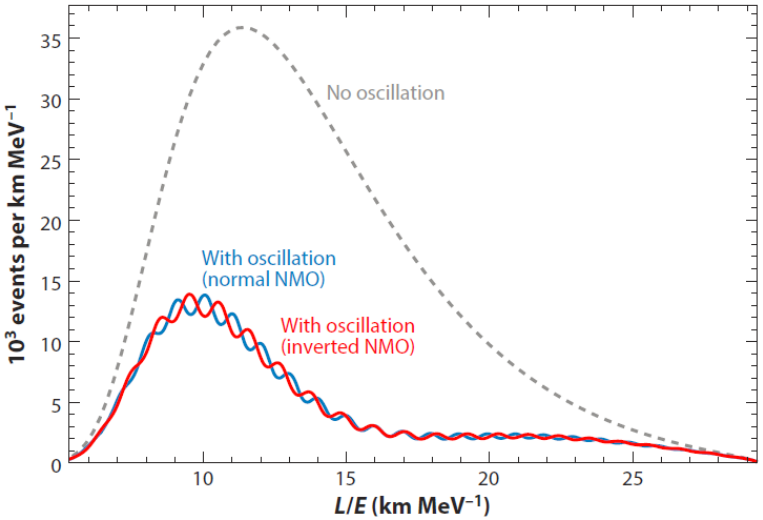


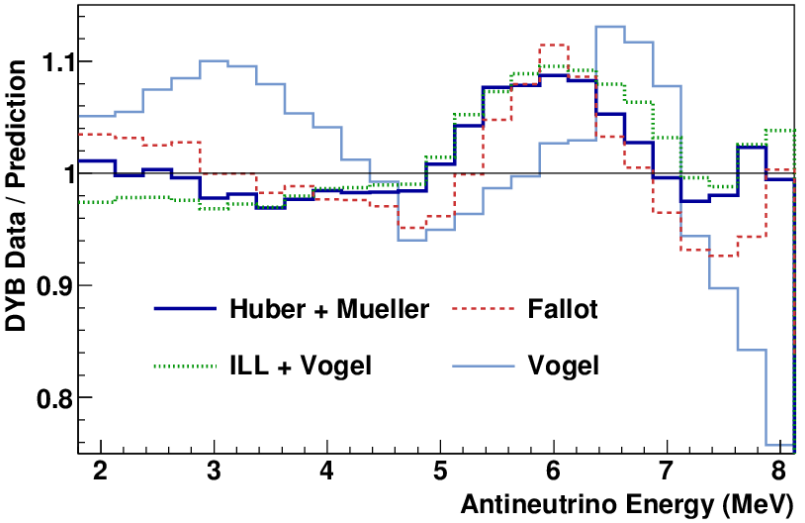
- **20 kton LS detector**
- **$3\%/\sqrt{E}$ energy resolution**
- **Rich physics possibilities**
  - ⇨ **Reactor neutrino for Mass hierarchy and precision measurement of 3 oscillation parameters**
  - ⇨ **Supernova neutrino**
  - ⇨ **Geo-neutrino**
  - ⇨ **Solar neutrino**
  - ⇨ **Proton decay**
  -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

JUNO CDR, arXiv_1508.07166

Mass Hierarchy at JUNO

- Measure energy spectrum at 60 km from reactors (3-4σ in 6 years)
  - ⇨ Very high precision measurement
  - ⇨ Interplay of Δm^2_{31} and Δm^2_{32}, frequencies differ by 3%
  - ⇨ Assumed 1% shape uncertainty on input spectrum
- Both conversion (H-M) and *ab initio* spectra show features
- Using Daya Bay measured spectrum
  - ⇨ Previously considered Gas TPC to reduce energy non-linearity uncertainty (causing flux shape and energy scale uncertainties)
  - ⇨ Can not constrain fine structures (8% energy resolution)

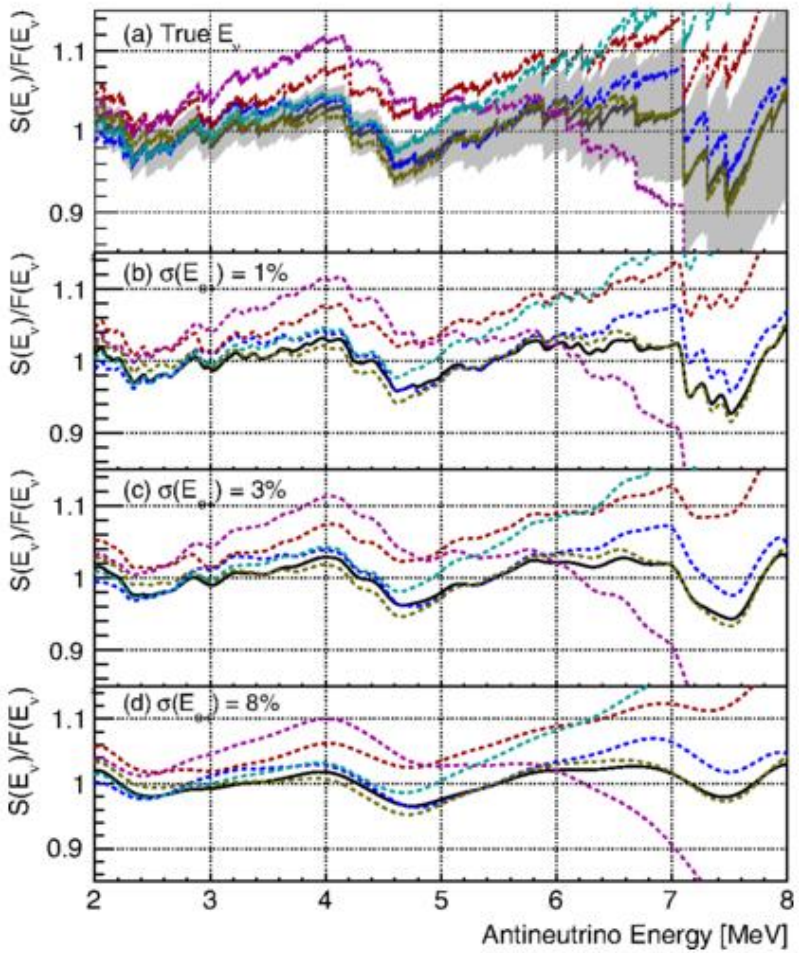




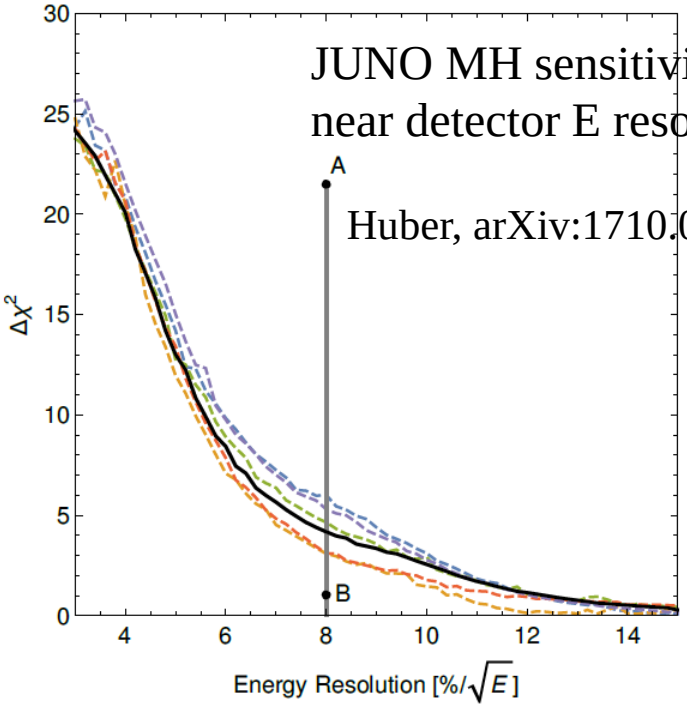
PRD78, 111103 (2008), J. Phys. G43, 030401 (2016) Credit: F.P. An

Fine Structures

- Large "bump" will not destroy MH sensitivity at JUNO
- Small peaks will bring model dependence → arbitrary sampling tests show no major effect on MH.



D. Dwyer et al. PRL114, 012502 (2015)



Represent the worst case: small peaks are unlikely to follow many oscillation circles in the spectrum

Motivation

- **Taishan Antineutrino Observatory (TAO), a ton-level, high energy resolution LS detector at 30 m from the core, a satellite exp. of JUNO.**
- **Measure reactor neutrino spectrum w/ sub-percent E resolution.**

1. ***Provides a reference spectrum for future experiments, like JUNO.***
   - **$3\%/\sqrt{E}$, 10 X statistics (can be achieved w/ LS+PMT)**
2. ***Provides a benchmark measurement to test nuclear databases***
   - **Design TAO w/ as high as possible energy resolution (1%)**
   - **State-of-the-art liquid scintillator detector (New findings?)**
3. ***Provides increased reliability in measured isotopic IBD yields due to a larger sampled range of fission fractions.***
4. ***Provides an opportunity to improve nuclear physics knowledge of neutron-rich isotopes***

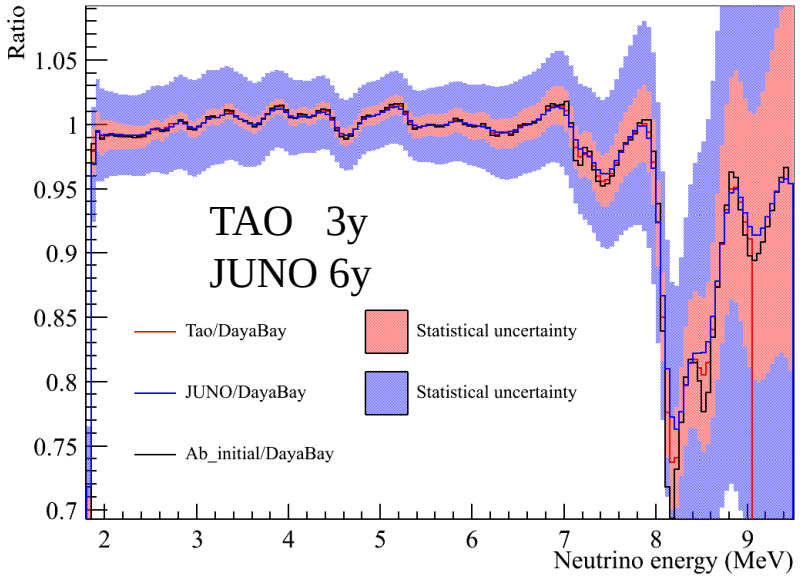
IAEA-INDC(NDS)-0786 (2019)

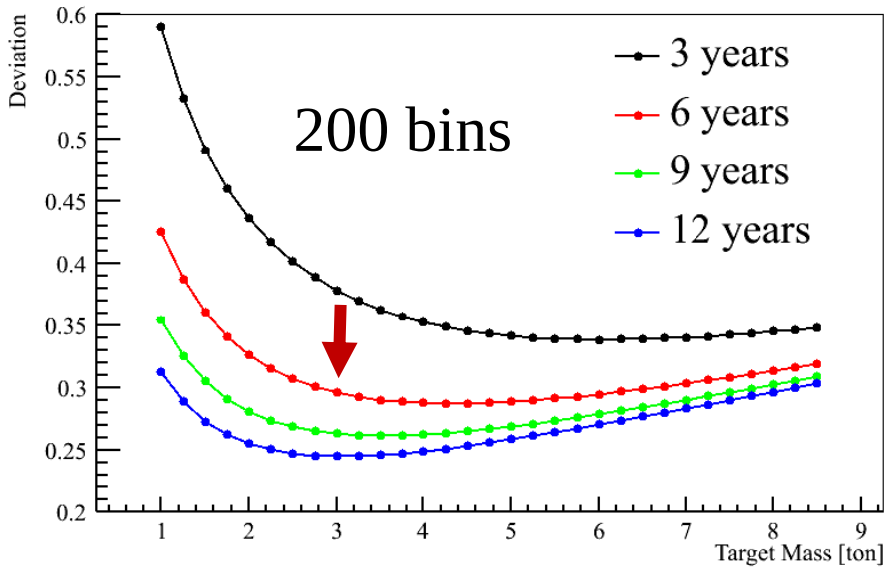
5. **Reactor monitoring, sterile neutrino, etc.**

	Distance	Mass	Power	Eff.	Oscillation	Statistics
$\frac{\text{TAO}}{\text{JUNO}}$	$\frac{53^2}{0.03^2}$	$\frac{1\ ton}{20000\ ton}$	$\frac{4.6}{36}$	$\frac{0.5}{0.8}$	$\frac{1}{0.321}$	
Factor	3.1×10^6	0.5×10^{-4}	0.128	0.625	3	**36 X**

Target Mass

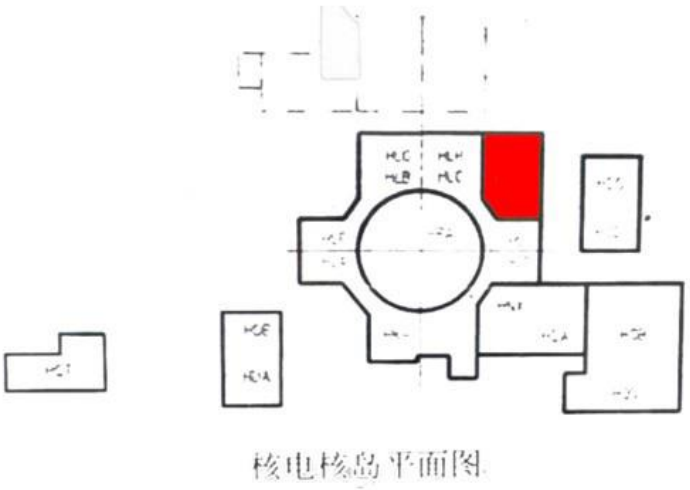
- **For JUNO**
  - ⇨ **1 ton fiducial volume is enough → Φ130 cm**
  - ⇨ **Additional 25-cm to contain gamma energy → Φ 180 cm, 2.6 ton, 10 m^2 SiPM**
- **For fine structure (nuclear database), how fine is enough?**
  - ⇨ **200 bins, 6 year → 3 ton FV is optimal, given fixed total SiPM area**
  - ⇨ **Φ 240 cm, 6.2 ton, 18 m^2 SiPM**
- **We keep 1-ton FV since no specific motivation for how fine we need**

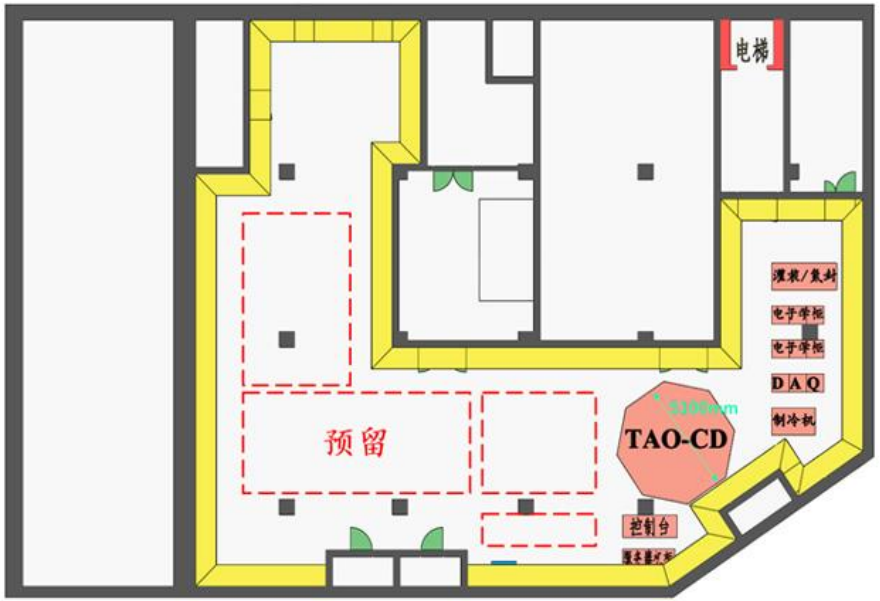


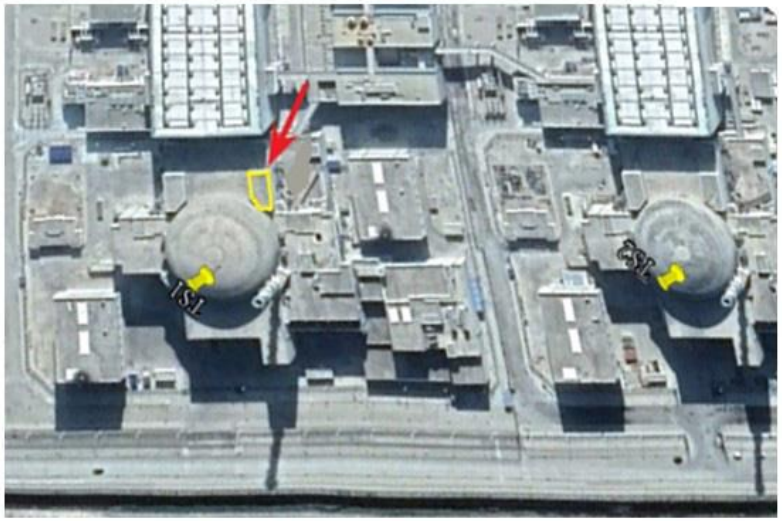


M. Estienne, et al. PRL123, 022502

Location and Layout







Laboratory in the Power Plant

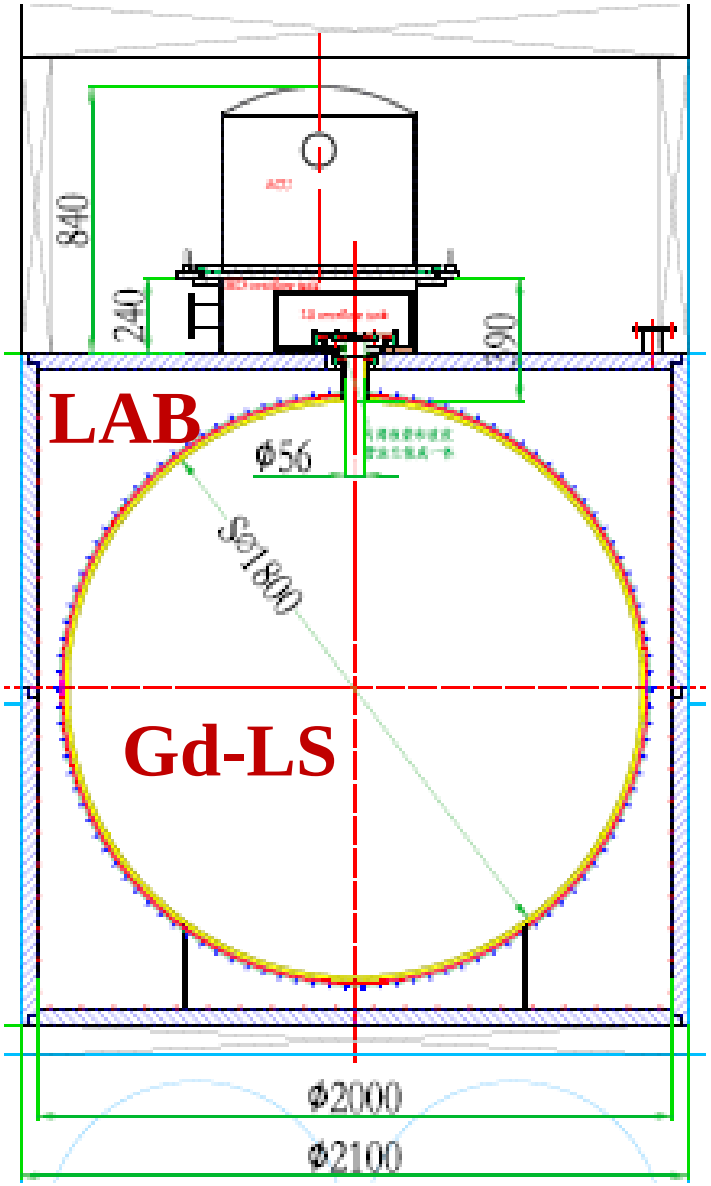
- **Power supply: OK**
- **N2 supply: OK**
- **Water supply: OK**
- **Ventilation: 1000 m^3/h**
- **Measured Muon flux**
  - ⇨ 1/3 surface
- **Neutron flux/spectrum**
  - ⇨ 40% surface
- **Gamma radioactivity**
  - ⇨ 3 times of my office
- **Need further discussion**
  - ⇨ **Clean grounding**
- **Transportation Constraint**
  - ⇨ **Elevator 2x1.4x2 m**
- **Height Constraint 3.85m**

Survey of the room and transportation

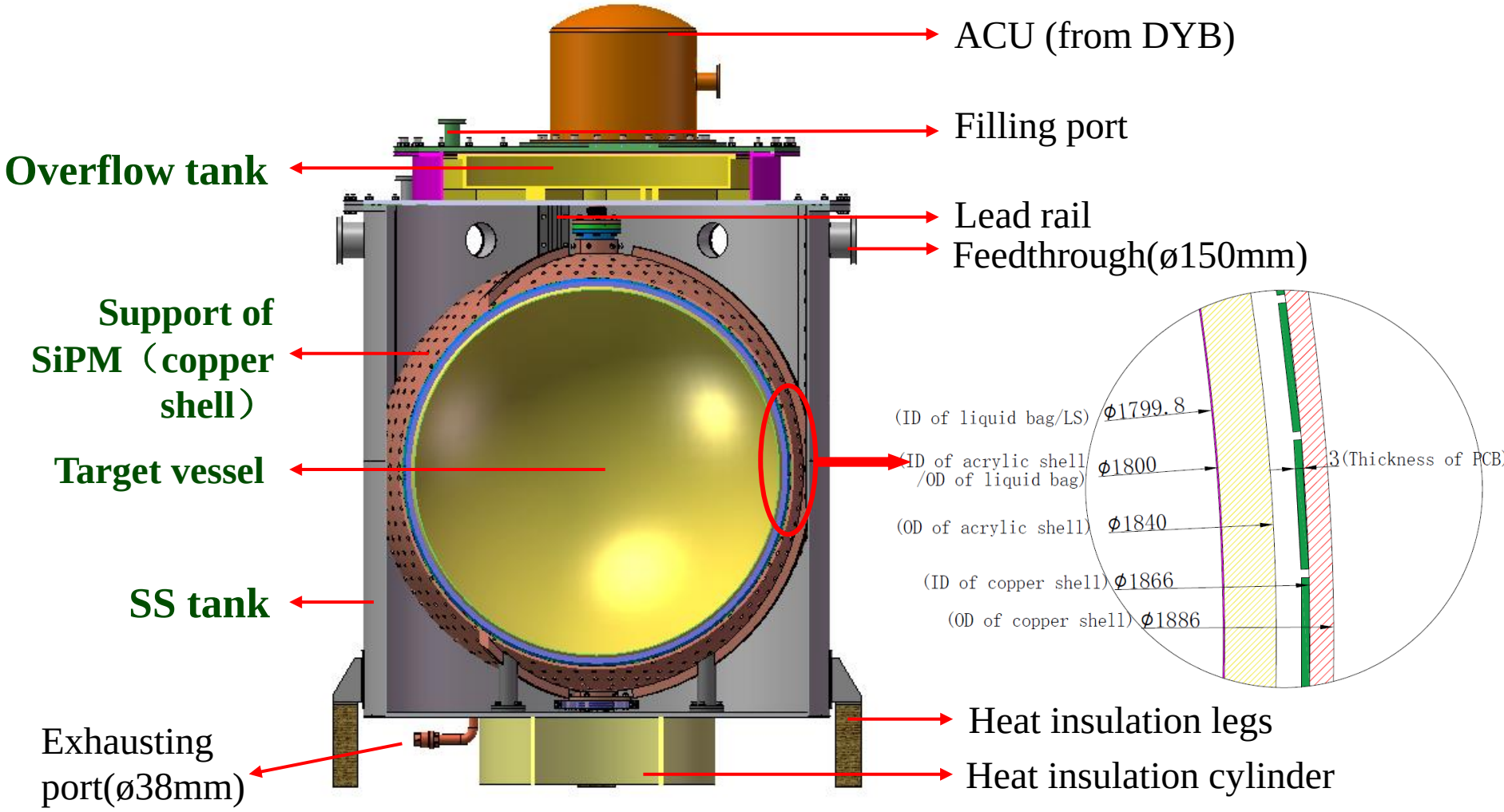
In Dec. 2018, after the start of commercial operation of Taishan-1

JUNO-TAO Detector Concept

- Laboratory in a basement at -10 m, 30-35 m from Taishan core (4.6 GW)
- 2.6 ton Gd-LS in a spherical vessel
  - ⇨ 1-ton FV, 4000 ν's/day
  - ⇨ 50% efficiency due to muon veto and IBD neutron tagging
- 10 m^2 SiPM of 50% PDE
  Operate at -50°C
- From Inner to Outside
  - ⇨ Gd-LS
  - ⇨ Acrylic vessel (Balloon optional)
  - ⇨ SiPM and support (Cu shell)
  - ⇨ Cryogenic vessel (SS + insulation)
  - ⇨ 1.2 m water or HDPE shielding
  - ⇨ Muon veto



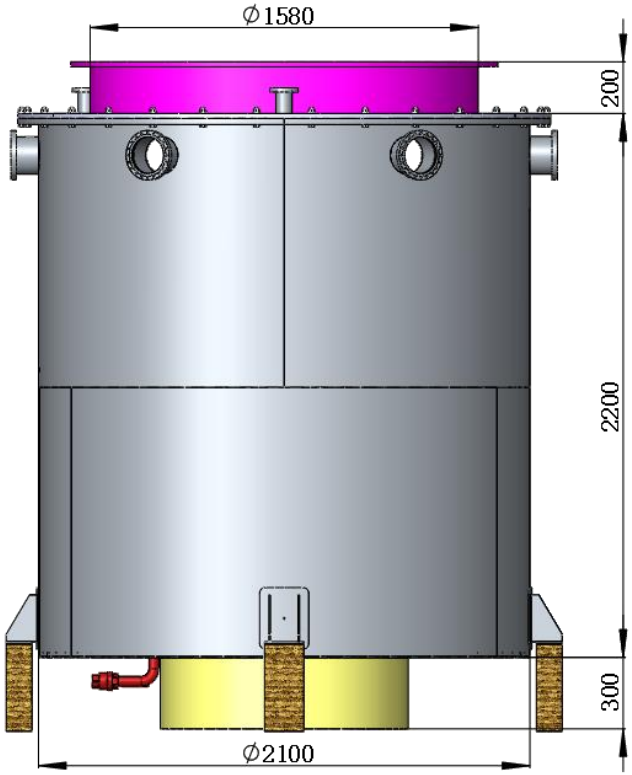
1. Central Detector

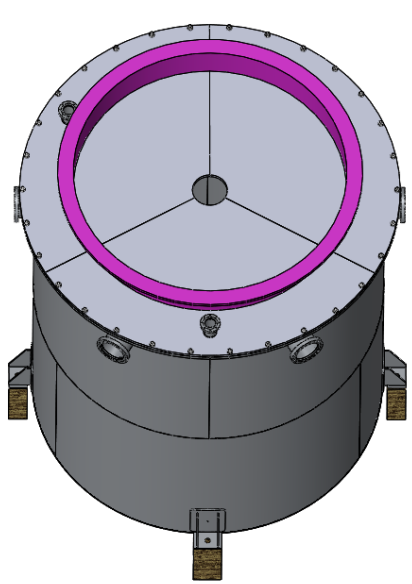


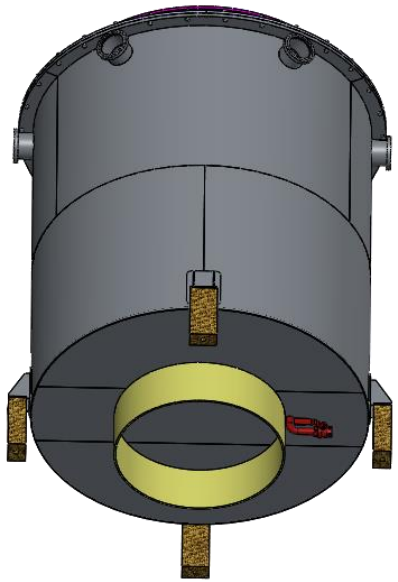
Stainless Steel Tank and Acrylic Vessel

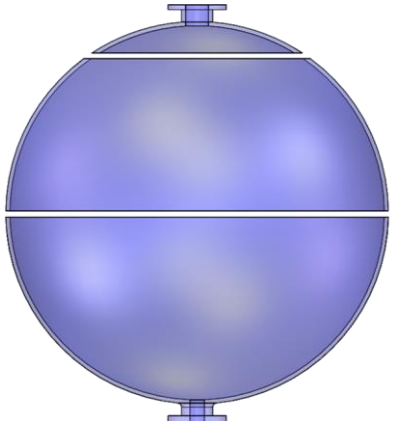
Elevator dimensions to the lab:

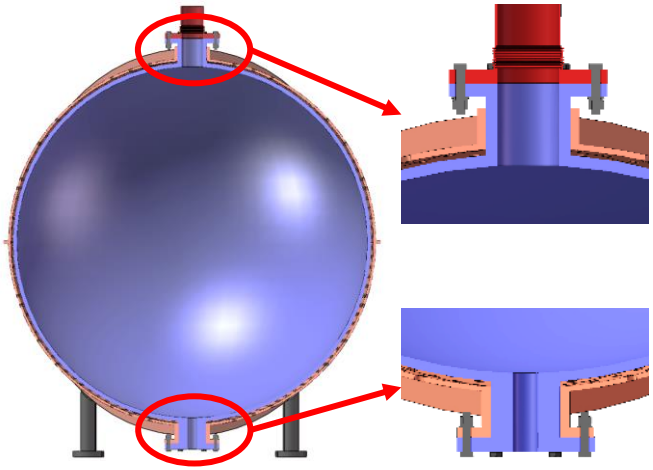
1.99m×1.99m×1.39m

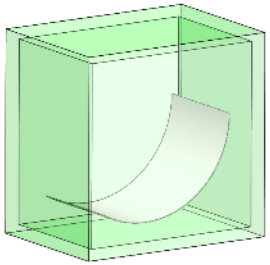




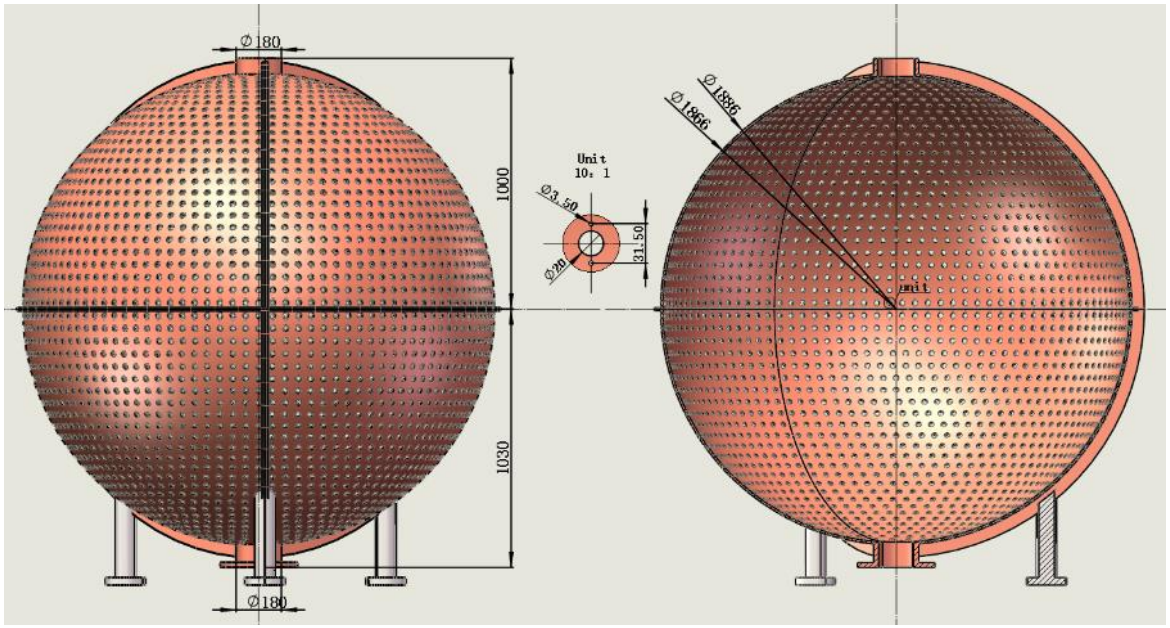


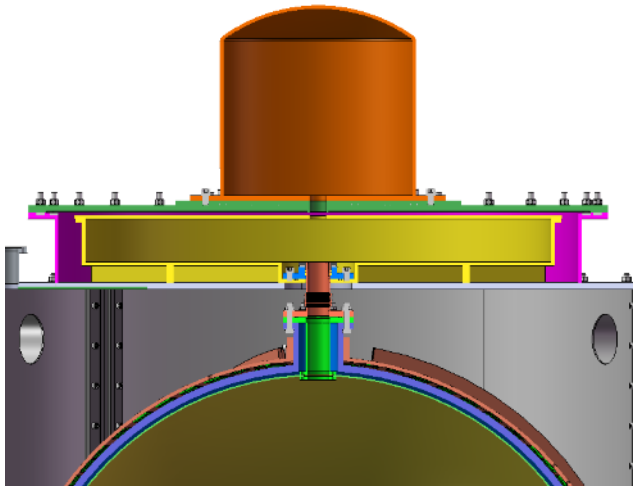


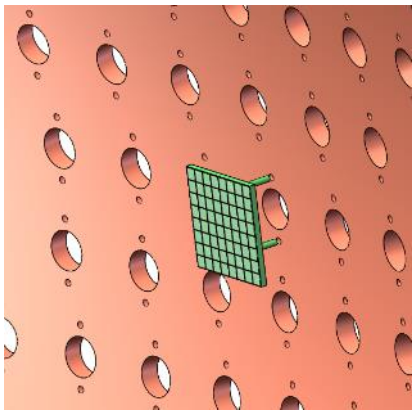


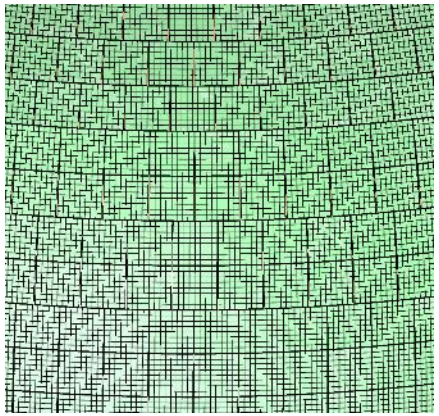


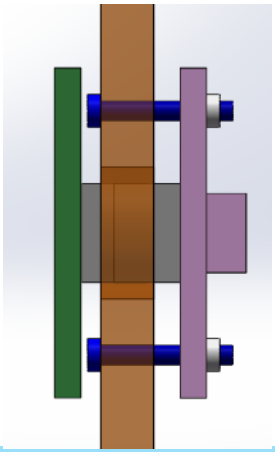
Copper Shell and 5x5 cm SiPM Module

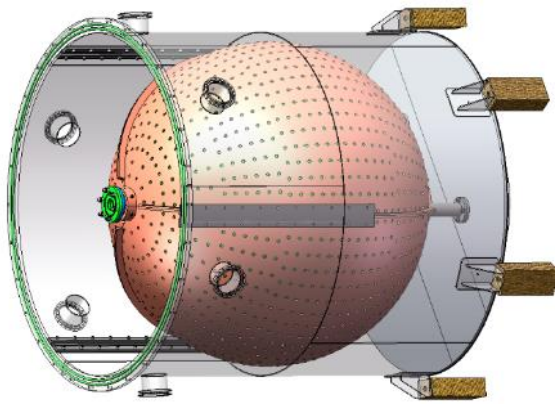






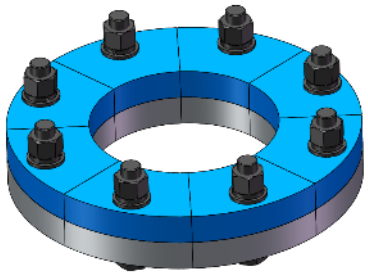




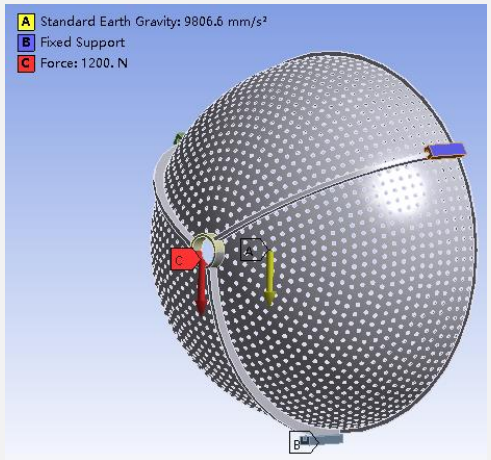


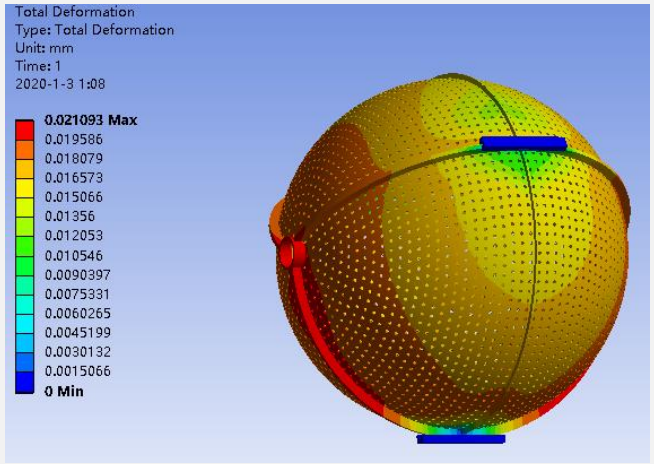
Mechanical, Thermal Analysis, Material

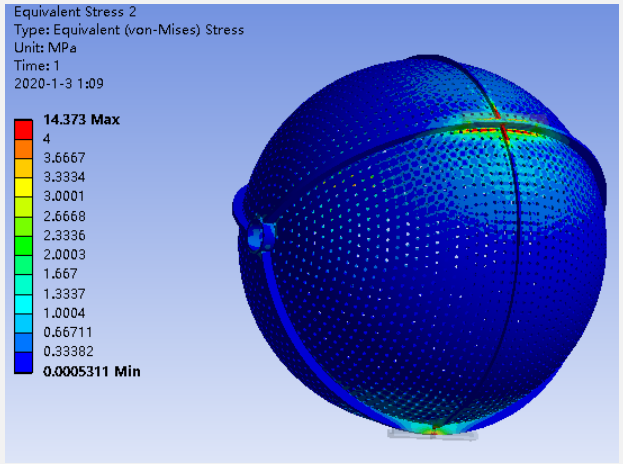
- FEA for different work condition
- Mechanical safety analysis from 25℃ to -50℃
- Material (sealing, support) at -50℃
  - ⇨ Fluorosilicone rubber
  - ⇨ X Fluororubber, Silicone rubber, Nitrile rubber
  - ⇨ Copper flange



✓ The third condition: Horizontal installation (with acrylic vessel)



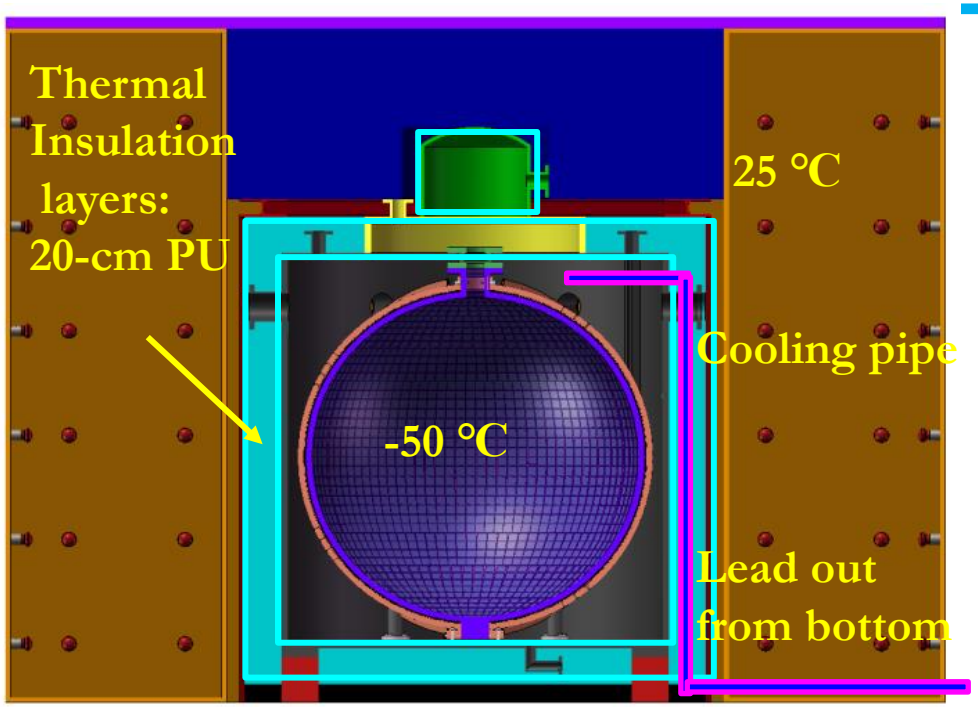




Max deformation=0.02mm<0.1mm;
Max von-Mises Stress=14.4MPa<270MPa.

Safe!

Cryogenic System



1) T limit: - 60 ℃

2) T uniformity in Φ1.8m: ±0.5℃

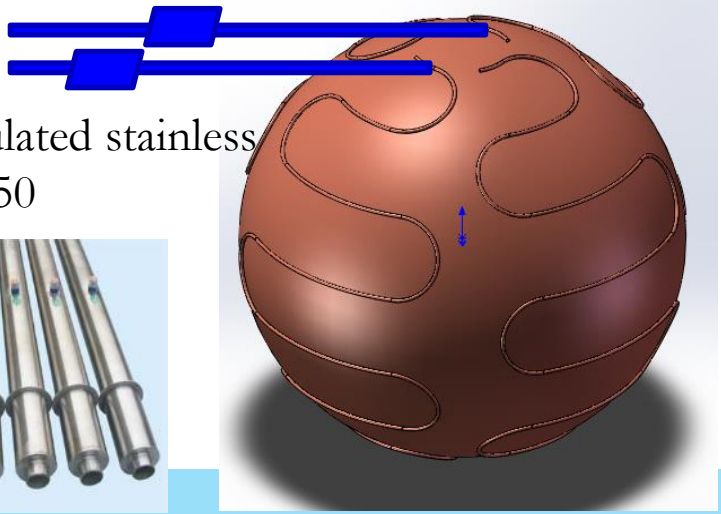
3) Cooling Capacity 2 kW at -50℃

- ⇨ Electronics 1 kW
- ⇨ Heat leakge 0.5 kW

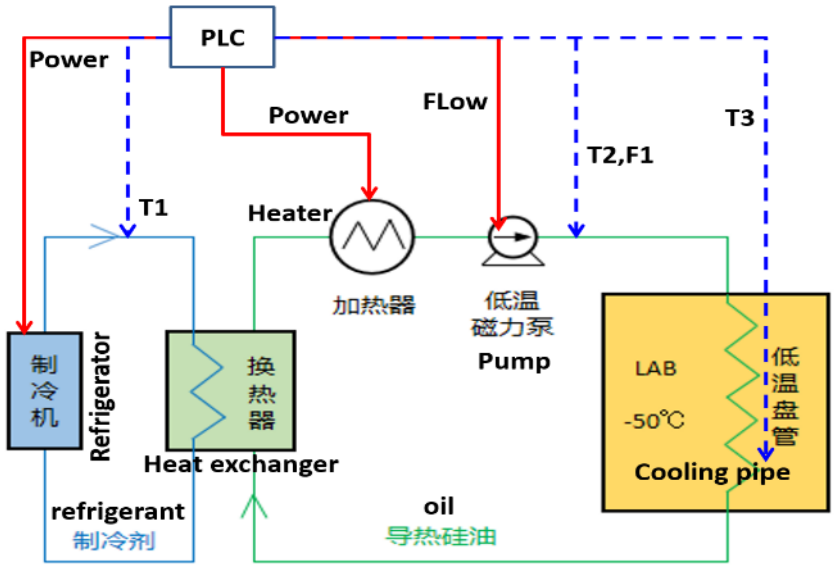
4) Cooling time: ~2 weeks

Successfully tested at prototype

With a section of bellow for deformation

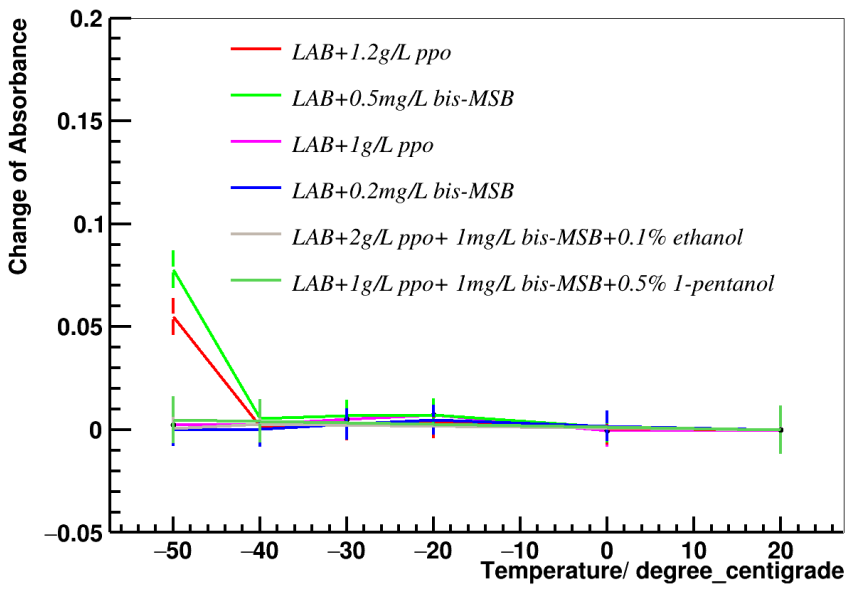


vacuum insulated stainless steel pipe: ø50



LS at -50℃

- **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
  + **0.1% ethanol**
- **Water content: nitrogen bubbling**
  Gd-LS < 10 ppm, LAB < 5 ppm



- **0.1% ethanol may be volatile, sensor to monitor ethanol in cover gas**

Temperature	-20°C	-30°C	-40°C	-50°C
Viscosity (mm^2/s)	54.2	114.7	283.4	802.5
Density (g/mL)	0.896	0.902	0.908	0.914
Specific Heat Capacity (J/(g·K))	1.784	1.761	1.740	1.727
Thermal Conductivity (W/(m·K))	0.143	0.142	0.140	0.139

LS at -50℃

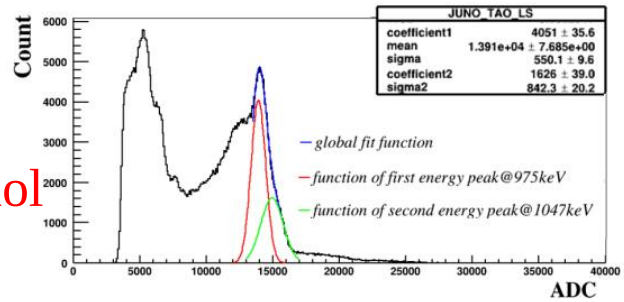
- **Light yield relative measurement**:
- JUNO-TAO :Recipe :

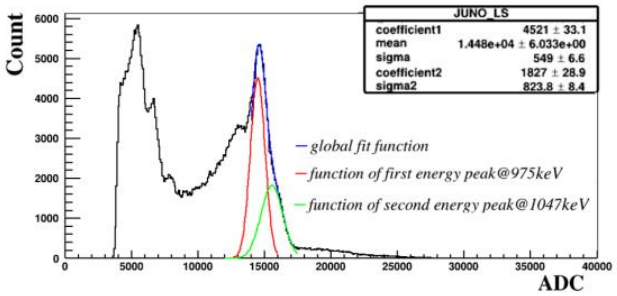
  *LAB+2g/L ppo +1mg/L bis-MSB + 0.05%ethanol

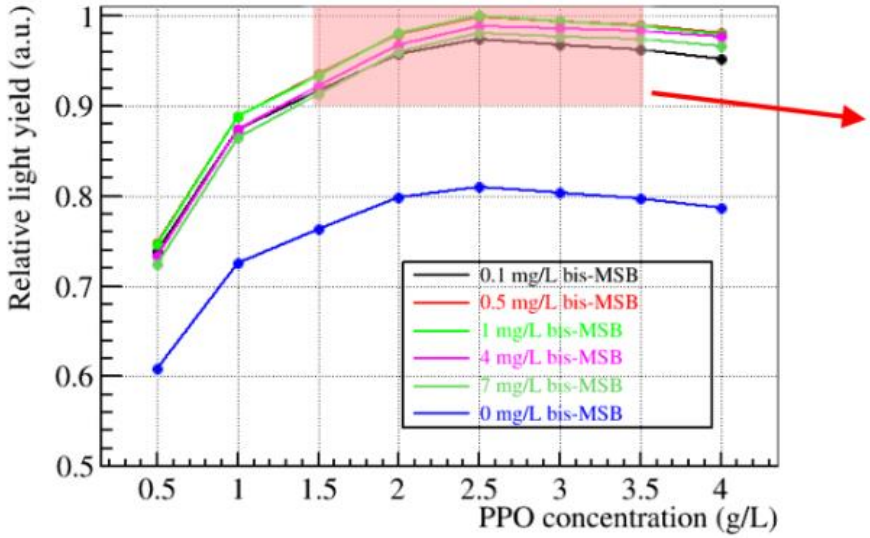
  Light yield: 13910
- JUNO :

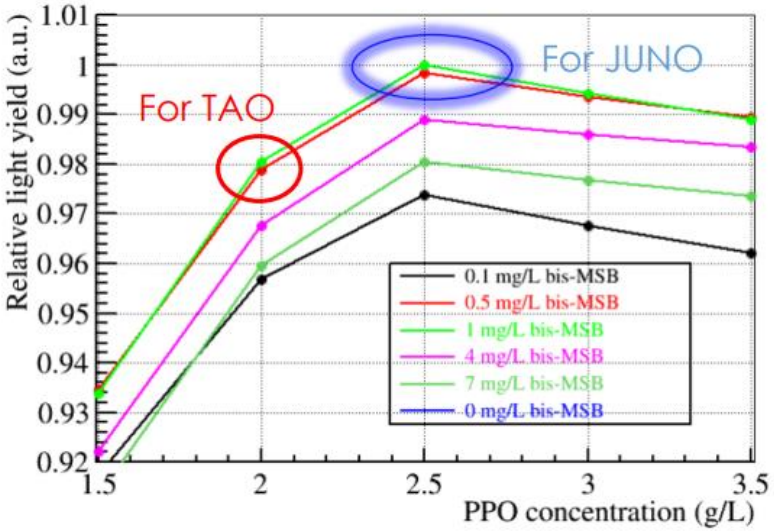
  *LAB+2.5g/L ppo +3mg/L bis-MSB

  light yield: 14480



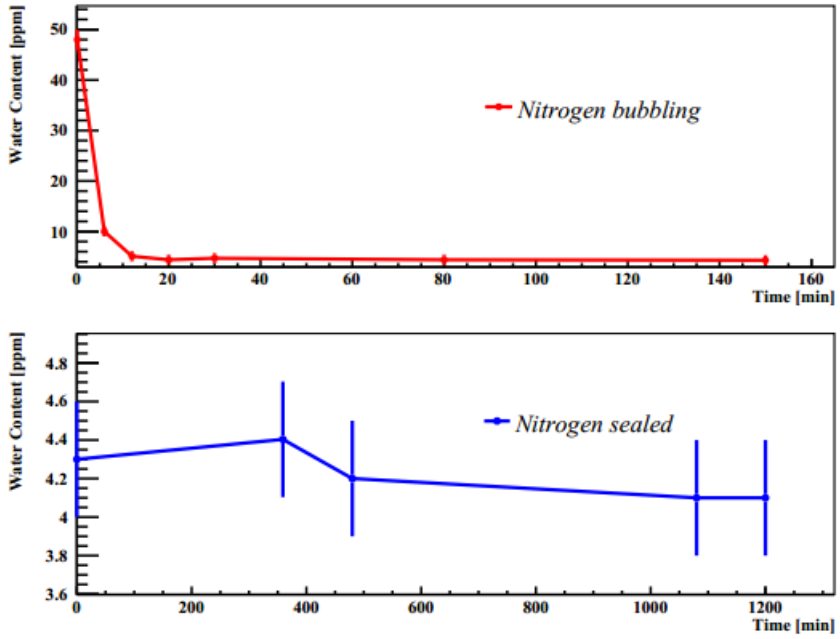


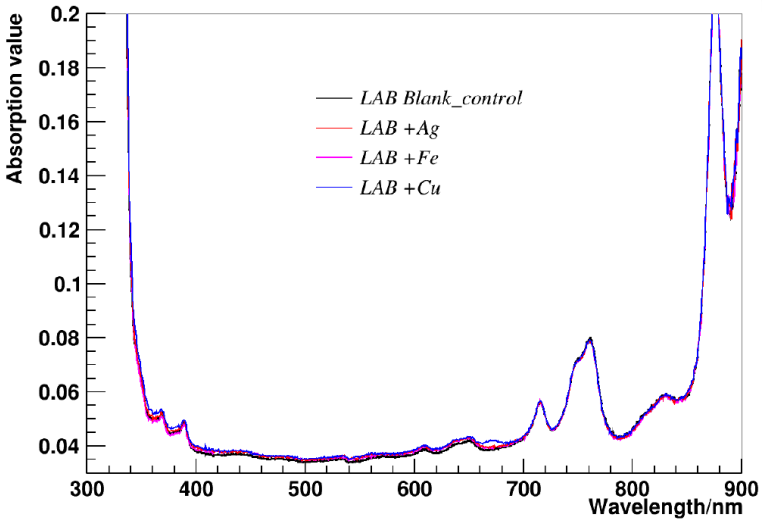


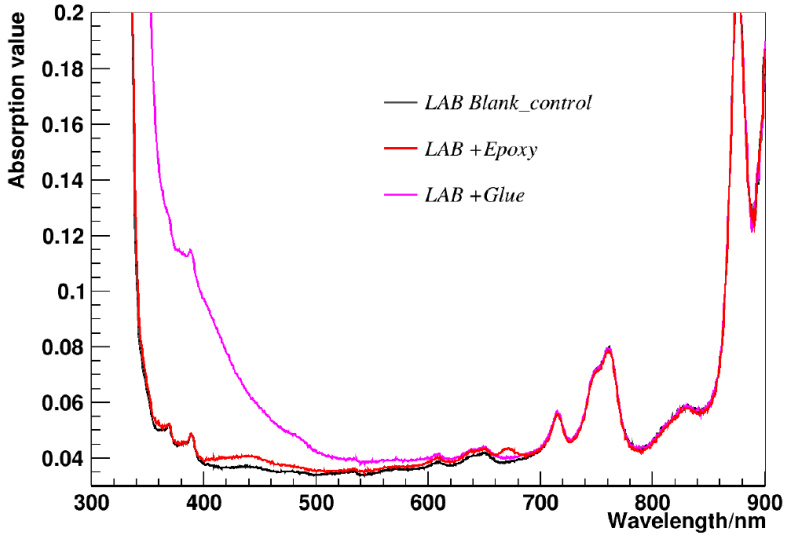


LS at -50℃

- **Compatibility**:
  A strict selection for materials with UV spectrometer
- **Remove water and protection**
  Avoid freezing under Low-T



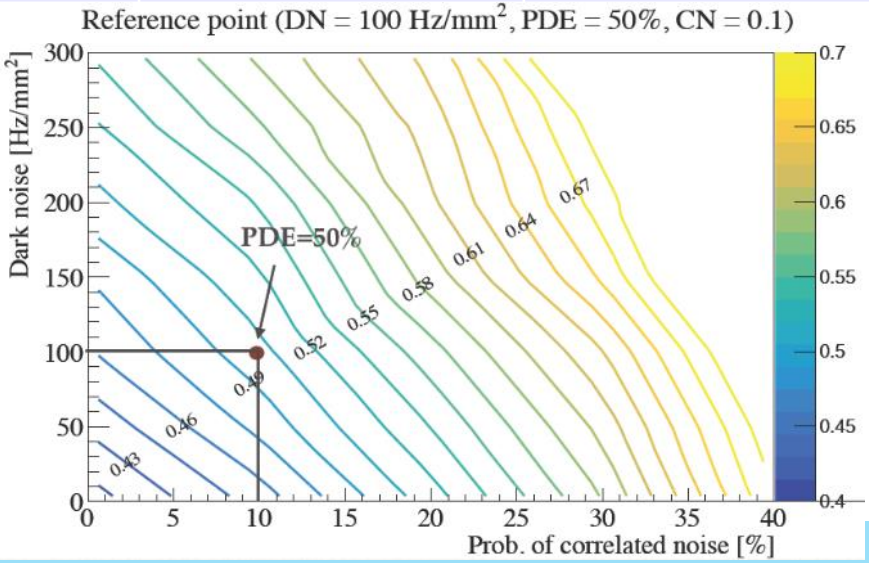




3. SiPM

On the market	SensL	Hamamatsu	FBK
Type	**MicroFJ-60035**	**S13361, 14160**	**NUV-HD**
Cell size (μm)	35	50	35
Cell Fill factor (%)	76	74	81
PDE (%)	**51**	**40, 50**	**50**
Peak wavelength (nm)	420	450	420
Dark count rate -50°C(Hz/mm^2)	70?	90, **1000**	**~500**
Gain	6.0X10^6	4X10^6, 2.5X10^6	3.5X10^6
Crosstalk probability (%)	**20**	7	**25**

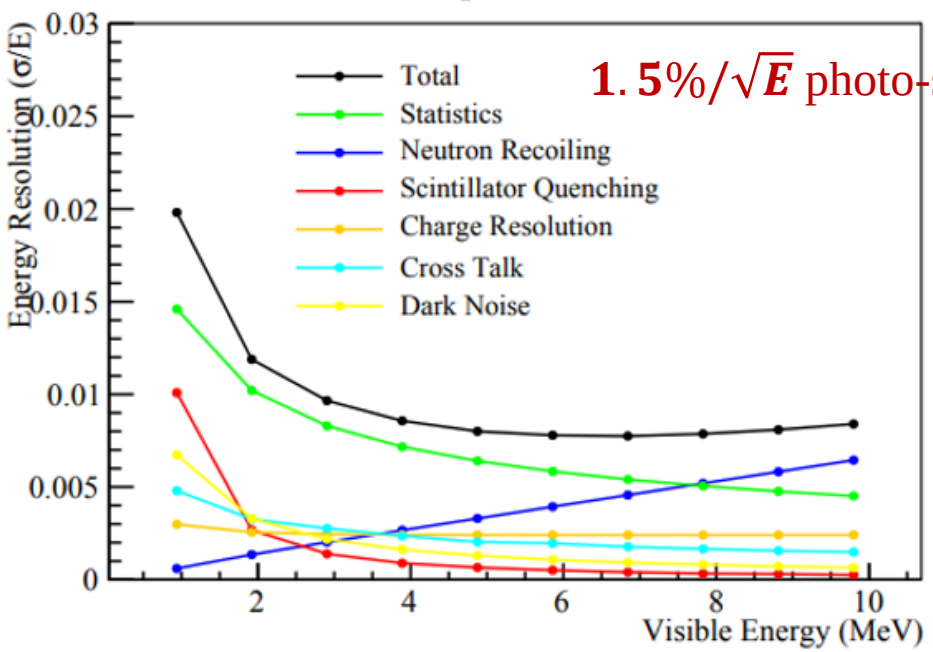
- **R&D with FBK and Hamamatsu in 0.5-1 year**
  - ⇨ **Reducing dark counts to <100 Hz/mm^2 at -50°C**
  - ⇨ **Reducing optical cross talk to <10%**



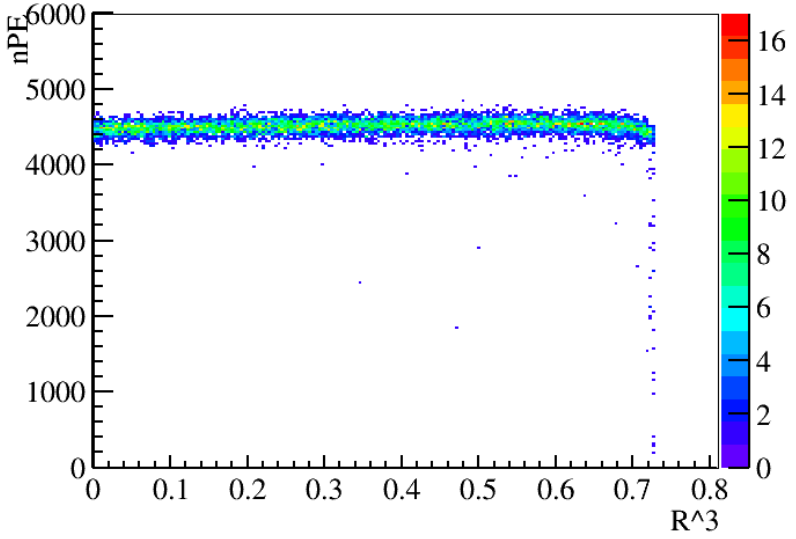
Energy Resolution

- Rough estimation →
- MC simulation
  - ⇨ Neutron recoil changes the $1/\sqrt{E}$ behavior
  - ⇨ Quenching contributes
  - ⇨ 94% coverage w/ mechanics
  - ⇨ Cross talk, charge resolution, etc.

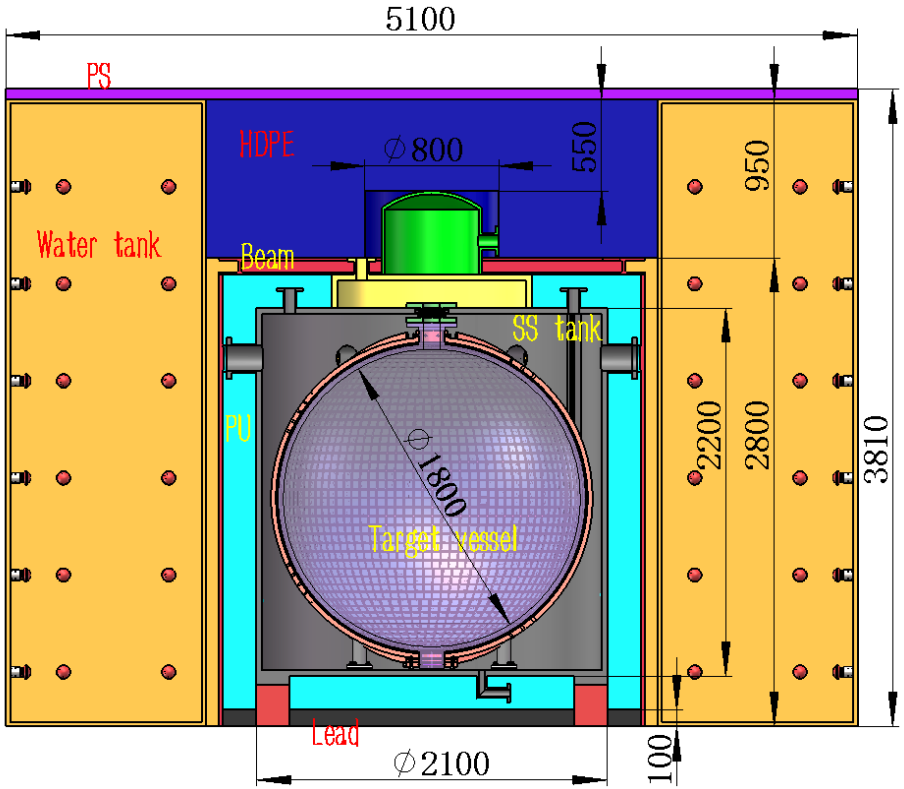
Compare w/ JUNO	1200pe/MeV
Cov. 75%→100%	X 1.33
PDE 27% → 50%	X 1.85
LS temp. at -50℃	X 1.25
Less absorption	X 1.4
1.4% photo-statistics	X4.3



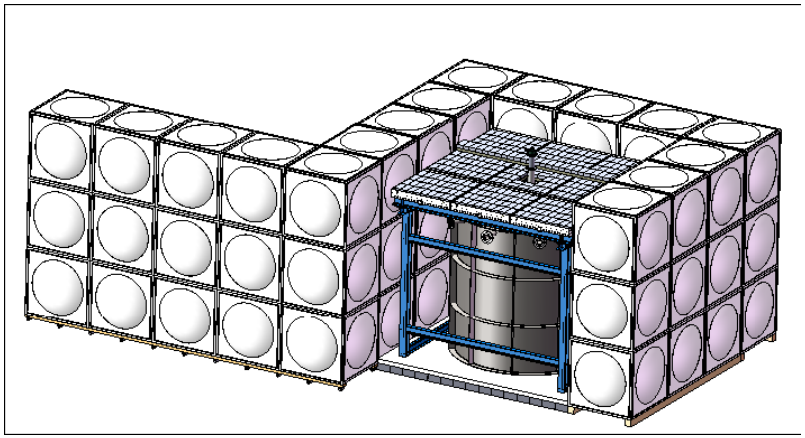
$1.5\%/\sqrt{E}$ photo-statistics



2. Veto and Shielding



- Side
  - ⇨ 1.2 m water shielding
  - ⇨ 200 3-in PMT
- Top
  - ⇨ 1.2 m HPDE
  - ⇨ Plastic scintillator
- Bottom, 12-cm lead



- May add HDPE bricks above 3.85 m
- Backgrounds have been well studied
- Water Cherenkov detector and plastic scintillator need design

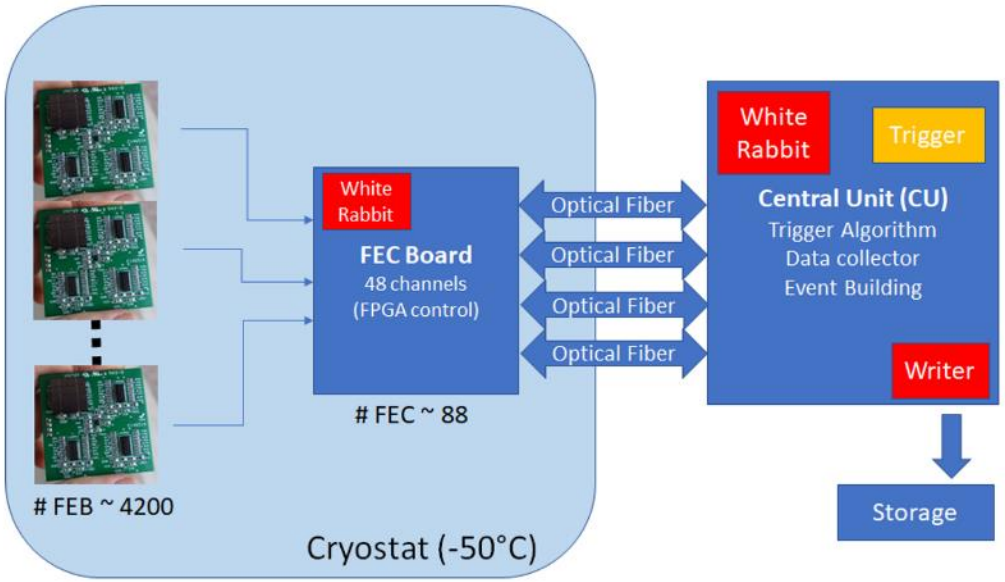
Backgrounds

Veto time window	[0~20us]
Veto efficiency	95%
Fast -n from muon veto inefficiency	108/day
Fast -n from rock	36/day
Total fast-n bkg.	144/day
Dead time	9%

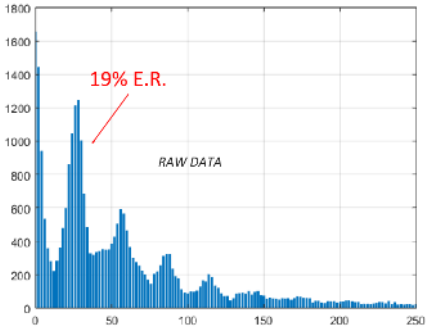
- **Signal: 2000/day**
- **Fast-n: 144/day before PSD**
- **Accidental: 100 Hz singles ~ 189/day**
- **He8/Li9 not yet**

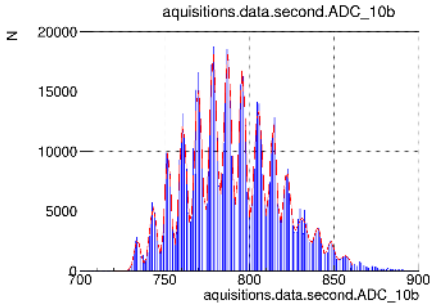
Material	Mass	Radioactivity(Bq/kg)			Singles(Hz)	Reference
		U238	Th232	K40		
Concrete	227t	58	79	780	40 (1.2 m water)	
normal PCB	33 kg	4.4	6.3	<1	102Hz	JUNO materials
organic PCB	33 kg	0.25	0.26	<1	7 Hz	Yuguang, doc 4926
Stainless Steel	975 kg	1.20E-03 (0.097ppb)	8.00E-03 (1.97ppb)	1.34E-03 (0.05ppb)	0.24Hz	JUNO materials
Water	57 t	0.2Bq/m3(Radon)			<1Hz	
Acrylic	183 kg	1.24E-05 (1ppt)	4.00E-06 (1ppt)	2.60E-04 (1ppt)	<1Hz	
GdLS&LAB	5.7t	4.96E-07 (0.04ppt)	4.00E-05 (10ppt)	2.60E-04 (1ppt)	<1Hz	Daya Bay GdLS
HDPE	0.23t	<0.18 (14.52ppb)	<0.11 (27.5ppb)	<0.60 (2.32ppb)	<7Hz	

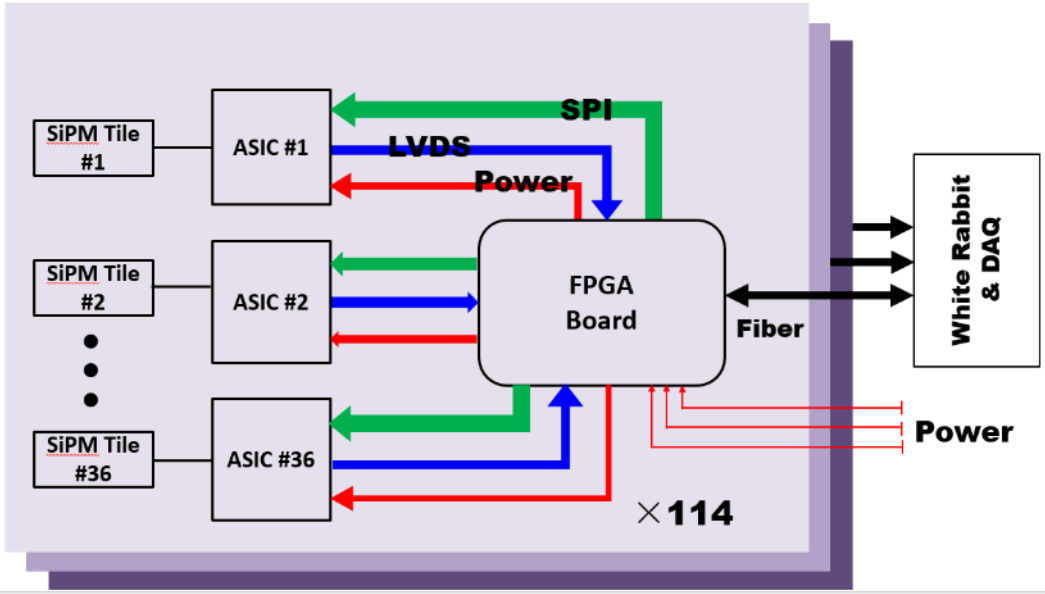
4. Readout Schemes



Discrete Component:
5x5 cm^2 tile/channel
Almost ready



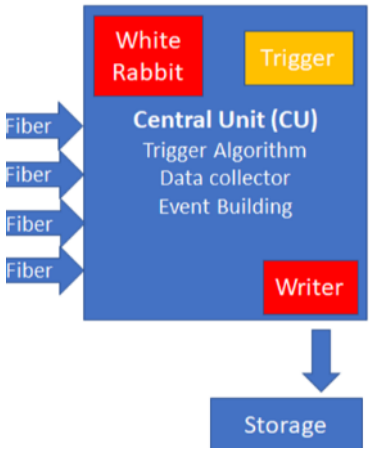




ASIC readout (Klauss5 tested)
2x6x6 mm^2 /channel, 4000 chips,
36 channels/chip
144,000 channels, 3 mW/channel
Likely have <1ns timing, PSD

5. Trigger/DAQ

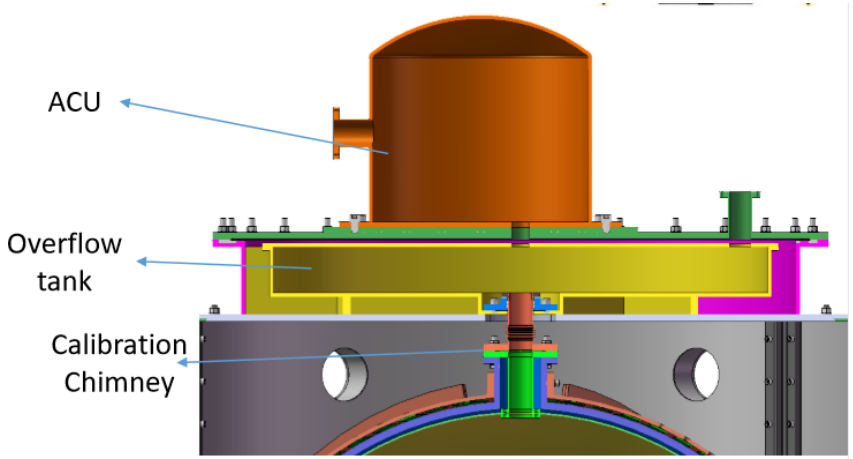
- High-end FPGA based trigger
- Discrete option ~10MB/s
- ASIC option, need data reduction to 100 Mbps.
  - ⇨ For example, save 1/100 or sum up 100 channels for muons, and save 1/10 of singles. Doc-3912

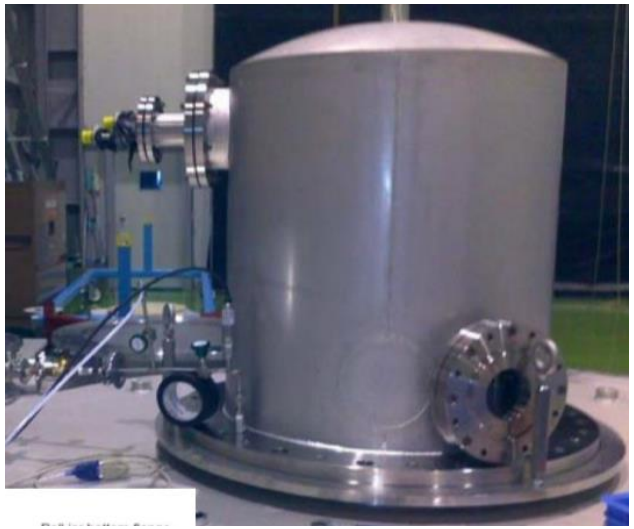


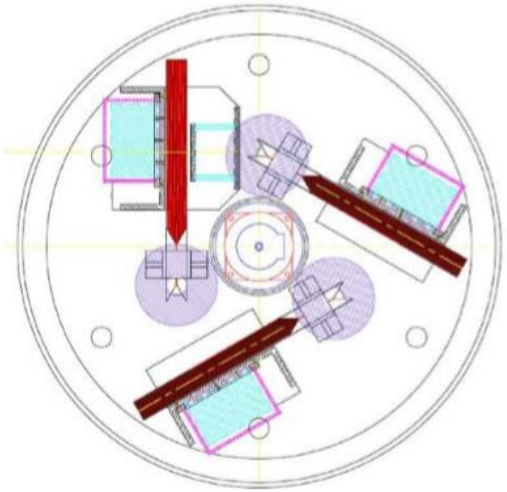
ASIC	Averaged energy (MeV)	Event rates	Data rate (Mbps)	
			Self trigger	Global Trigger
Muons	223	153 Hz	2,200	2,200
Muon daughter	23	13 Hz	78	78
Radioactivity	1.5	100 Hz	42	42
IBD Events	~4	4000/day	0	0
Dark Noise		100 Hz/mm^2	52,000	0
Total			54,320	2,320

6. Calibration

- Use Automatic Calibration Unit (ACU) of Daya Bay
- Very little work done.



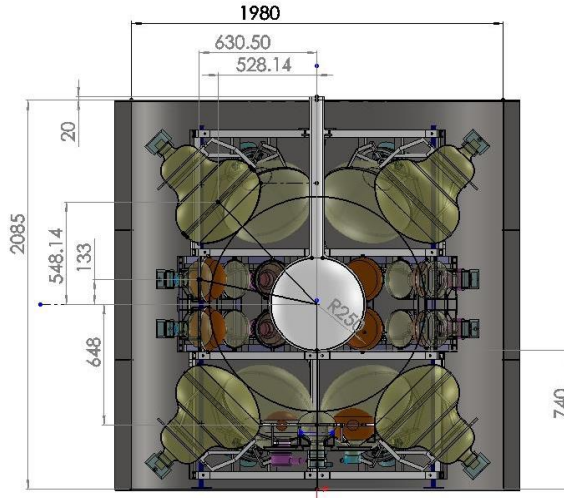


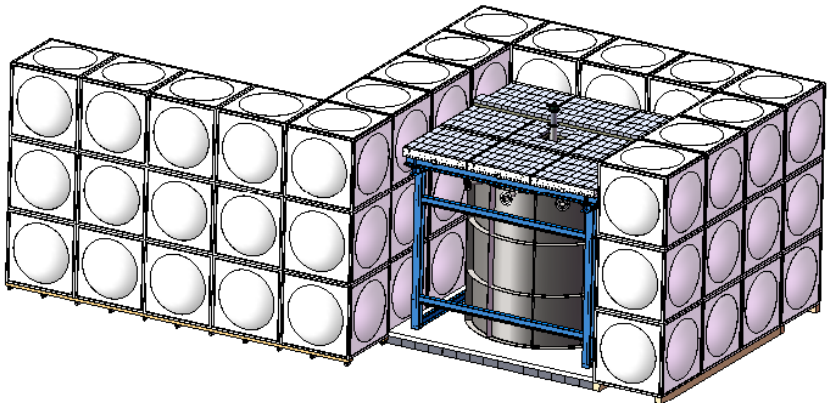


- 3 slots, how many sources in combo need more studies
- Only on vertical axis
- w/ backgrounds

Prototyping

- IHEP prototype for JUNO, testing PMTs, potting and electronics
- Refurbish for TAO prototype: low temperature LS detector
  - ⇨ 70L Gd-LS + PMTs + two 5cmX5cm SiPM
  - ⇨ Insulated the prototype, refrigerating system
  - ⇨ Replaced parts for low temperature
- Successfully lowered -50 ℃
  - ⇨ Temperature uniformity is good
  - ⇨ Buffer liquid polluted by potting
  - ⇨ INFN SiPM tile has large noise (readout, laboratory grounding), IHEP SiPM has damage.
- Need more work





Summary

- **A ton-level detector w/ sub-percent energy resolution can be realized w/ Gd-LS + SiPM**
- **Operate at -50℃ (or lower)**
- **Unprecedented energy resolution allows**
  - ⇨ **Reference spectrum for JUNO**
  - ⇨ **Nuclear database testing (via *at initio* spectrum)**
  - ⇨ **New findings?**
- **Although feasible in principle, a lot of challenges for a new concept detector**

Thanks!

TAO (道)

- **In the context of traditional Chinese philosophy and religion, Tao is the natural order of the universe whose character one's human intuition must discern in order to realize the potential for individual wisdom. (Wikipedia)**

Statue "Tao of Matter" motivated by T.D. Lee.

The bagua, a symbol commonly used to represent the Tao and its pursuit.

物之道：道生物，物生道，道为物之行，物为道之成，天地之艺物之道。李政道，二OO一年四月十日