The JUNO-TAO detector is a unique tool for studying and monitoring nuclear reactors

On behalf of JUNO collaboration
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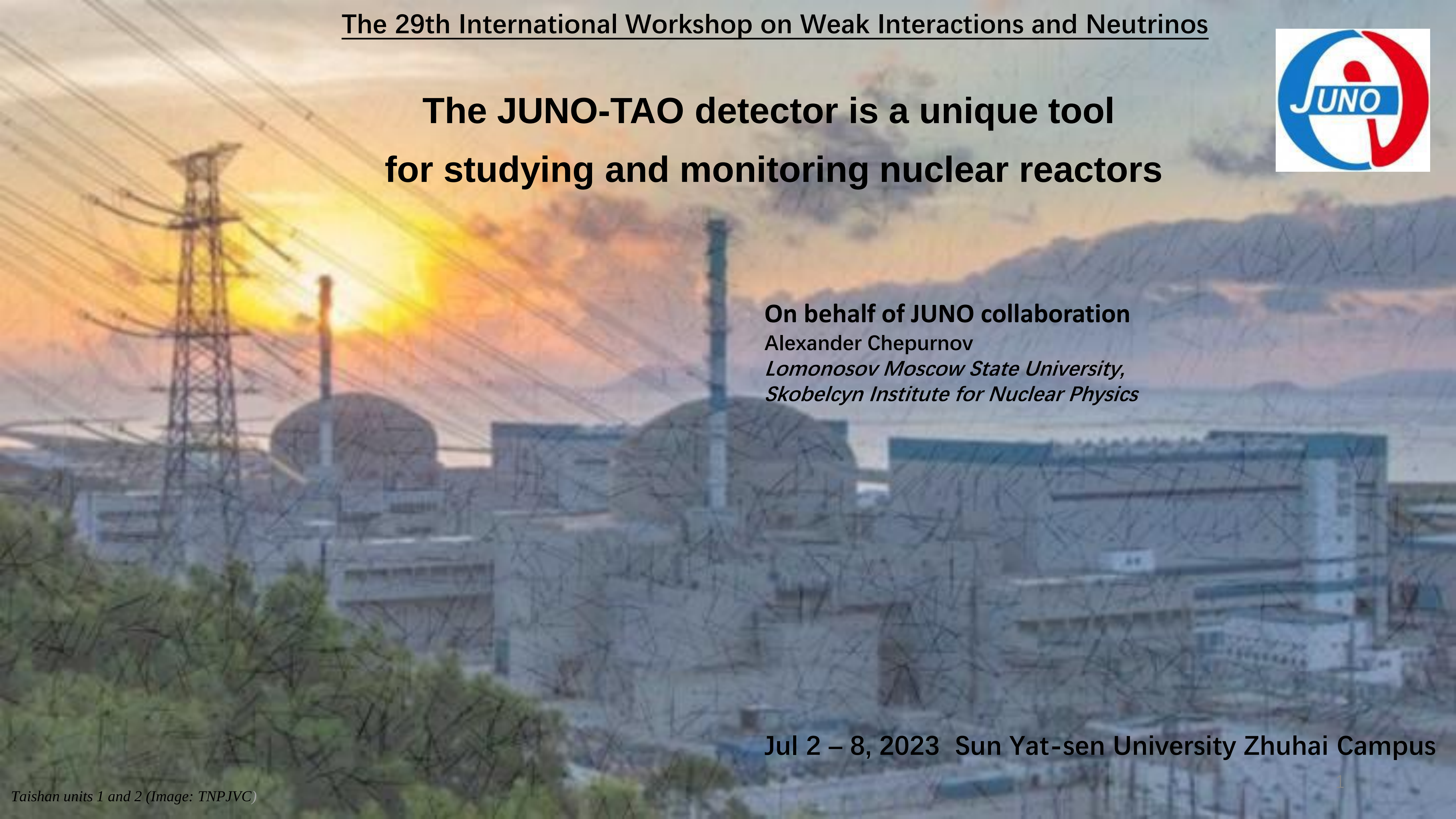
Jul 2 – 8, 2023 Sun Yat-sen University Zhuhai Campus

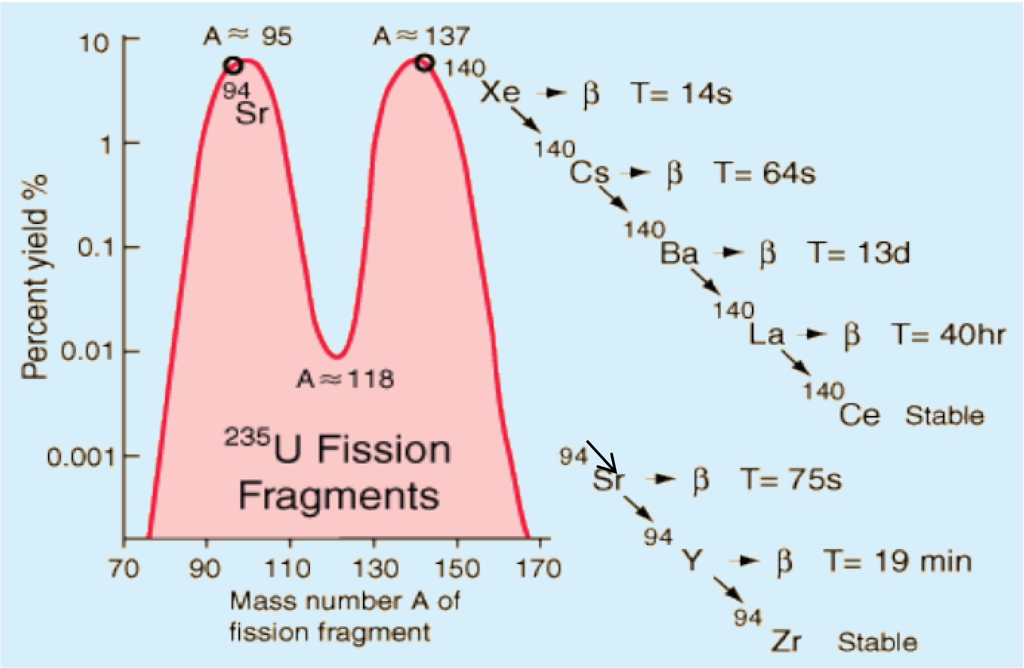


Taishan units 1 and 2 (Image: TNPJVC)

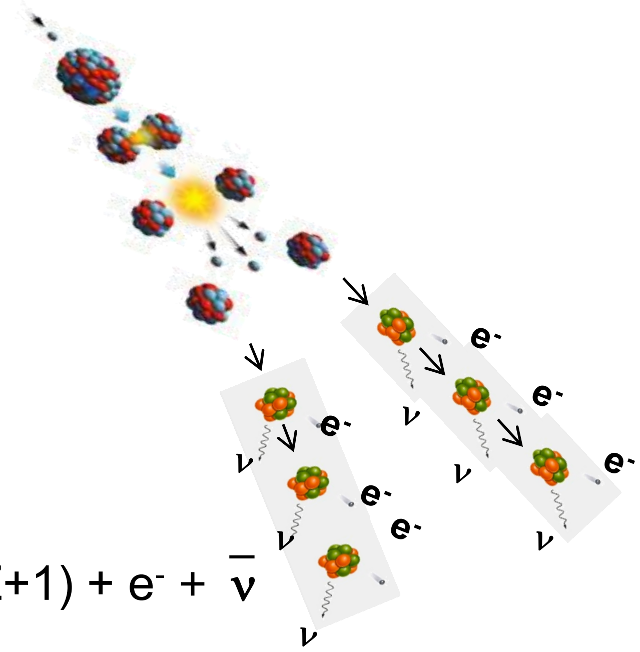
Nuclear reactor as a source of reactor antineutrinos

Fission isotopes have different fission product distributions.

$$n + {}^{235}U(Z=92, N=143) \rightarrow A_1(Z_1, N_1) + A_2(Z_2, N_2) + 2\,n$$



Unstable fission products are a source of antineutrinos.
Reactors produce electron antineutrinos via the β -decay of neutron rich fission daughter products



$$(A, Z) \rightarrow (A, Z+1) + e^- + \bar{\nu}$$

Fission isotopes have different fission product distributions.

The density of the antineutrino flux, measured remotely during the operation of the reactor, is directly proportional to the number of fissions, i.e. nuclear fuel burnup rate or nuclear reactor thermal power

BUT the neutrino flux and spectrum differs between isotopes

Nuclear power reactors are the most powerful controlled artificial sources of

$$\overline{\nu}_e$$

Applied antineutrino physics

- Non-proliferation of fissile materials
- Monitoring (measurement) of reactor thermal power
- Investigation of burnup processes for new types of nuclear fuel and new types of nuclear reactors

Fundamental physics

- Measuring of neutrino oscillation parameters
- Light sterile neutrinos search
- Measuring of the magnetic moment of an electron antineutrino
- Coherent scattering of neutrinos on nuclei

- Neutrino spectrum
- Neutrino isotopic yields
- Neutrino flux

Nathaniel Bowden, Reactor Neutrino Flux and Spectrum Measurements, (Neutrino 2022)

- Initial nuclear fuel composition
- Nuclear database
- Electron spectrums for thermal neutron fission of main U/Pu isotopes

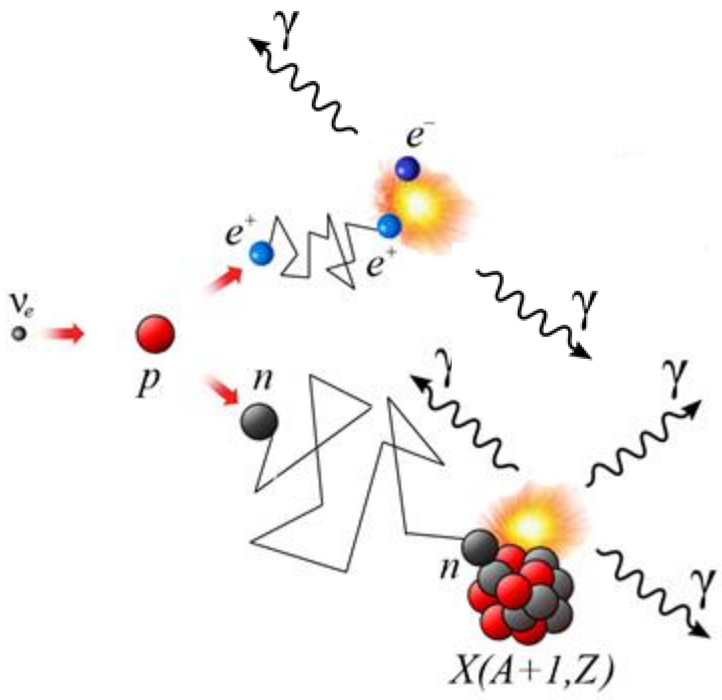
Inverse beta decay (IBD) is a magic reaction to catch reactor antineutrino

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$dN_{e+}(E_{e+})/dE_{e+} = dN_\nu(E_\nu)/dE_\nu \times N_p \times (4\pi L^2)^{-1} \times \sigma(E_\nu) \times \delta_{REC}$

$E_{e+} = E_\nu - (M_n – M_p) – m_e = E_\nu - 1.8$ MeV

$\sigma \sim 10^{-43}$ см^2
very small !!



1 – «Prompt event» – annihilation of positron and electron

$$e^+ + e^- \rightarrow 2\gamma$$

Visible energy under the condition of neglecting the recoil of the neutron

$$E_{pt} = E_{\nu e} - 1.8MeV + 2m_e$$

2 – «Delayed event» – neutron capture followed by γ- emission

$$n + (A,Z) \rightarrow (A+1,Z) + \gamma$$

Organic liquid/plastic scintillators - most popular target material for IBD detection

- **high H (p) concentration**
- **possible doping by Gd**
- **well developed technology**

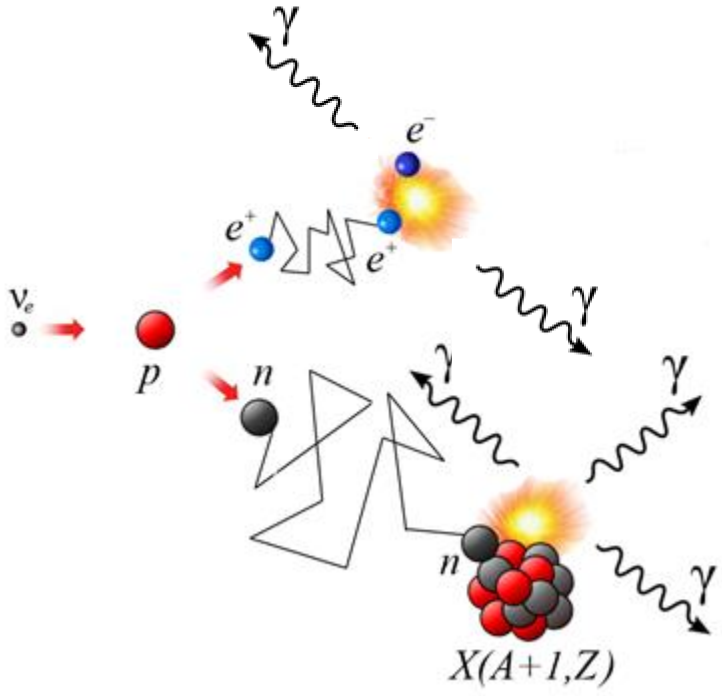
Inverse beta decay (IBD) is a magic reaction to catch reactor antineutrino

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$dN_{e+}(E_{e+})/dE_{e+} = dN_\nu(E_\nu)/dE_\nu \times N_p \times (4\pi L^2)^{-1} \times \sigma(E_\nu) \times \delta_{REC}$

$E_{e+} = E_\nu - (M_n - M_p) - m_e = E_\nu - 1.804$ MeV

$\sigma \sim 10^{-43}$ см^2
very small !!



TAO efforts:

<u>Design Optimization Goals:</u>

- **high light yield (LS properties)**
- **good light collection (general construction)**
- **avoid gamma leakages (general construction and data processing)**

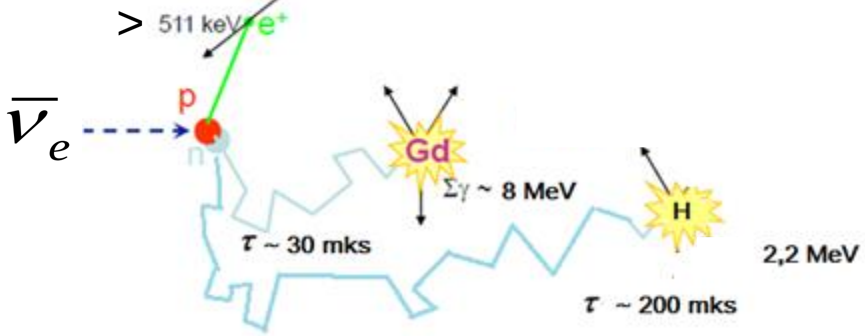
- **effective and fast neutron capture (LS properties)**

- **minimize external γ/n background mimic IBD signature**
  - **passive shielding**
  - **active muon veto**
  - **precise time/spatial event reconstruction**

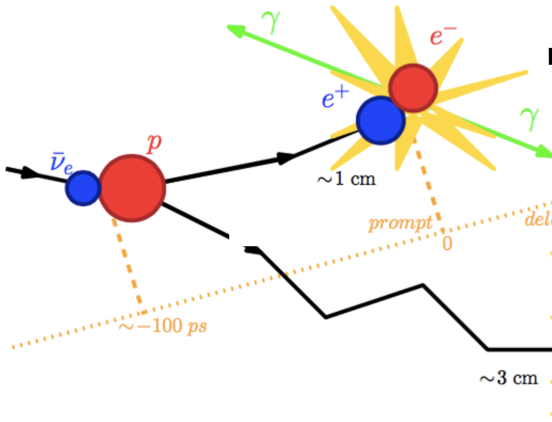
- development of optimal comprehensive electronics together with sophisticated software for direct data digitizing, timing, preprocessing, storage and analysis

IBD "Delayed Event” registration optimization options

RENO, NEOS, Neutrino-4, STEREO, PANDA, DANSS, iDREAM Rovno, Nuzifer, DayaBay, JUNO/TAO, WATCHMAN



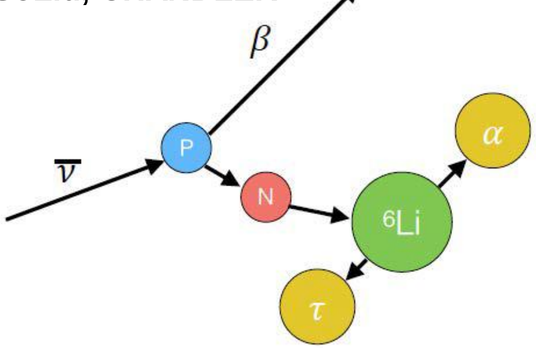
miniTimeCube



$$n + {}^{10}\mathrm{B} \to {}^{7}\mathrm{Li}^{*} + {}^{4}\mathrm{He}(1471\ \mathrm{keV})$$
$$\hookrightarrow {}^{7}\mathrm{Li}^{*} \to {}^{7}\mathrm{Li}(839\ \mathrm{keV}) + \gamma(478\ \mathrm{keV})$$

K. Nishimura - mTC @ AAP2015

PROSPECT, NuLat, SoLid, CHANDLER



(n + ^{6}Li → ^{4}He + ^{3}H + 4.8 MeV)

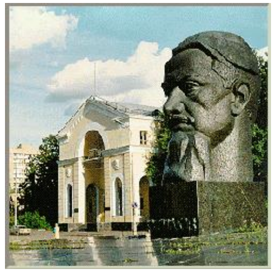
Karsten Heeger, AAP2015,

“Very first" option :

$$n + {}^{108}Cd \to {}^{109}Cd^{*} \to {}^{109}Cd + \gamma$$

"Detection of the Free Neutrino: A Confirmation", C. L. Cowan, Jr., F. Reines, F. B. Harrison, H. W. Kruse and A. D. McGuire, Science 124, 103 (1956).

The advent of applied antineutrino physics



1974-1977 Calculation and measurement of spectra from ^{235}U & ^{239}Pu & ^{238}U & ^{241}Pu
It was shown that the number of antineutrinos per ^{239}Pu fission is less than in ^{235} *U* fission.
A.Borovoi, Yu.Dobrunin, V.Kopeikin. Nucl. Phys. (Rus.), 1977, 25, 264

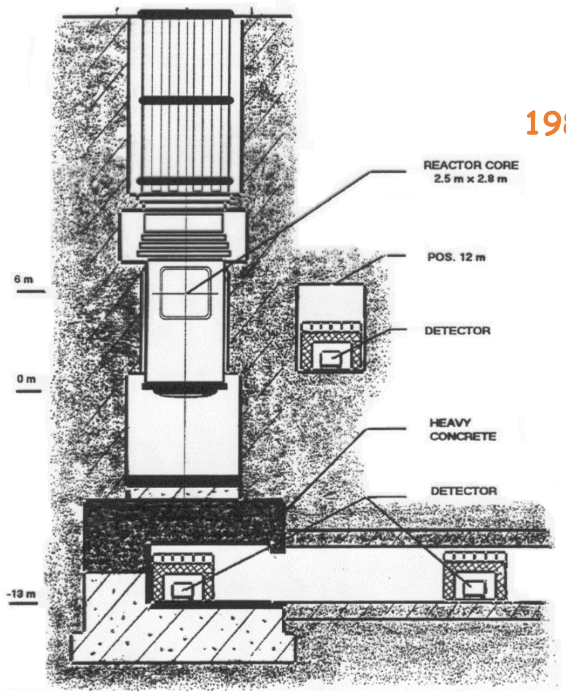
The following ideas where expressed by L.A. Mikaelyan during the *“Neutrino-77”:*

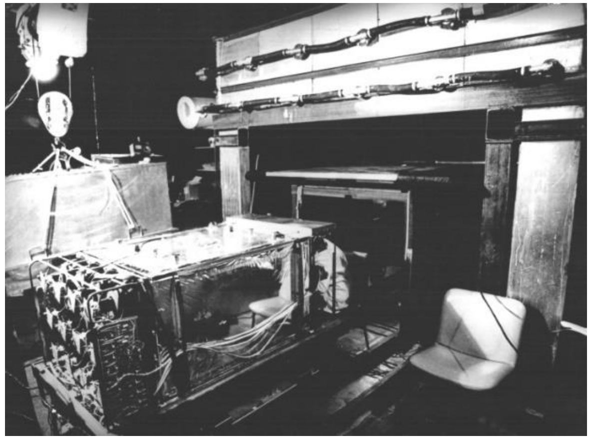
- antineutrino event count rate enables remote monitoring of the reactor output power due to the direct relationship between *N(antineutrino) ~ N(fissions),*
- the shape of the antineutrino spectra can be a source of additional information about the isotopic composition of the reactor core

1978-1982 Several types of detectors for reactor antineutrino research from reactors have been developed (KIAE)

1982 A neutrino laboratory was created at the Rovno NPP

1983-1994 The feasibility study of the method was confirmed in experiments at the Rovno NPP (USSR) and, later, at the NPP in Bug (France) (KIAE/IN2P3).





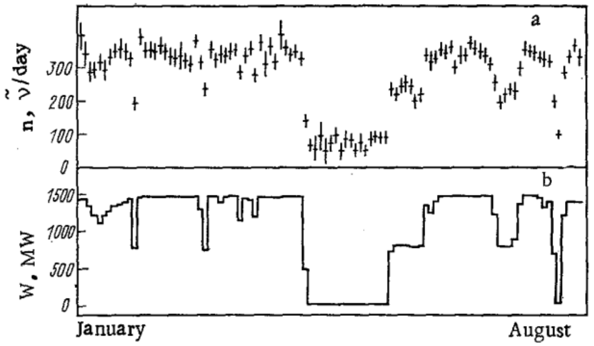


Fig. 2. Neutron instrumentation readings for January-August 1986 (a) and average daily reactor power based on data from thermal measurements (b).

Korovkin et al. 1988

Current state of nuclear reactor monitoring with neutrino

<u>Reactor Neutrino Detectors for flux and spectrum measurements:</u>

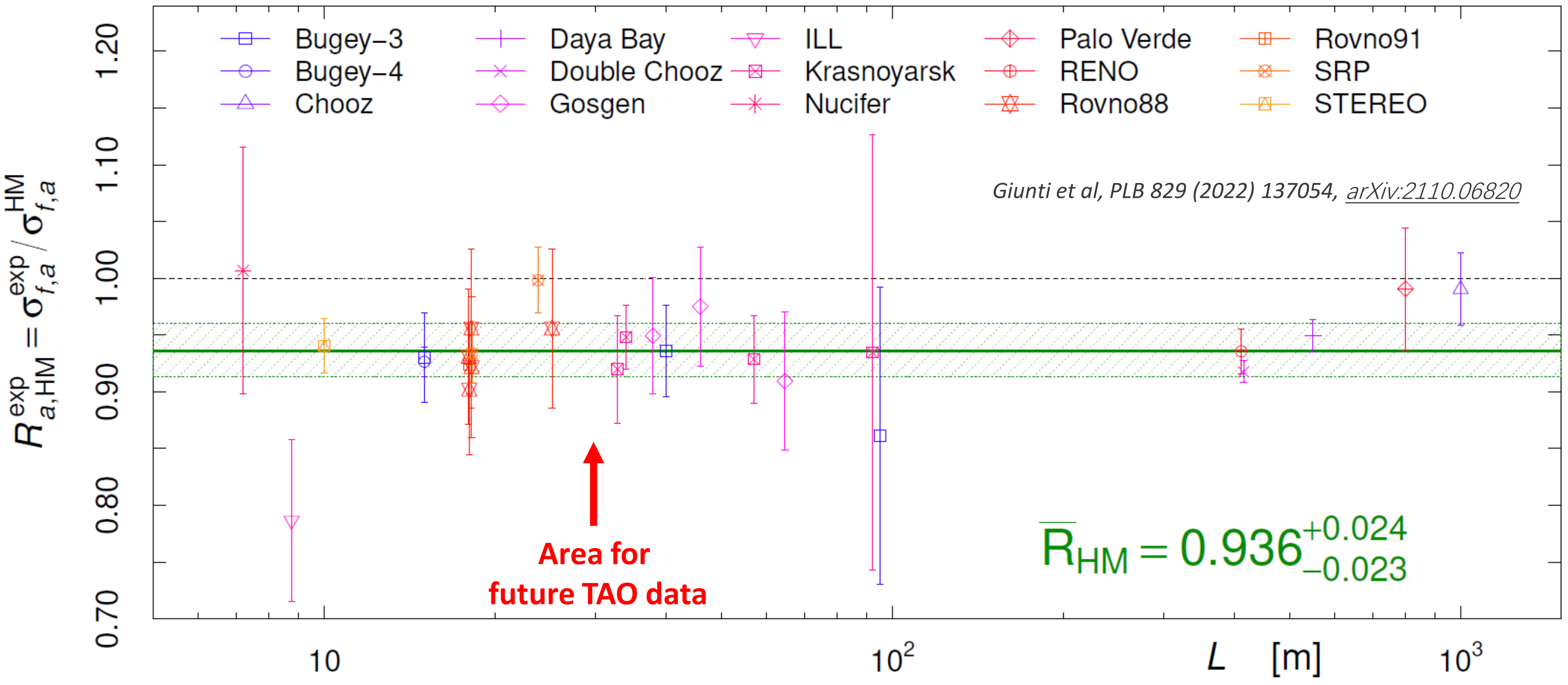
Θ_{13} - DayaBay, DoubleChooz, RENO, **JUNO/TAO**

Precision Instruments with percent-level control of detection efficiencies

Energy-scale and response well understood

SBL – NEOS (-II), STEREO, PROSPECT, Neutrino-IV, DANSS, iDREAM, **TAO**

Total neutrino yield measurements have achieved great precision



Ratio of measured and expected IBD yields for the reactor experiments as a function of the reactor-detector distance L. The error bars show the experimental uncertainties.

Nathaniel Bowden, Reactor Neutrino Flux and Spectrum Measurements, (Neutrino 2022)

Taishan Antineutrino Observatory (TAO) *arXiv: 2005.08745*

Taishan Antineutrino Observatory (TAO) is a satellite experiment of JUNO

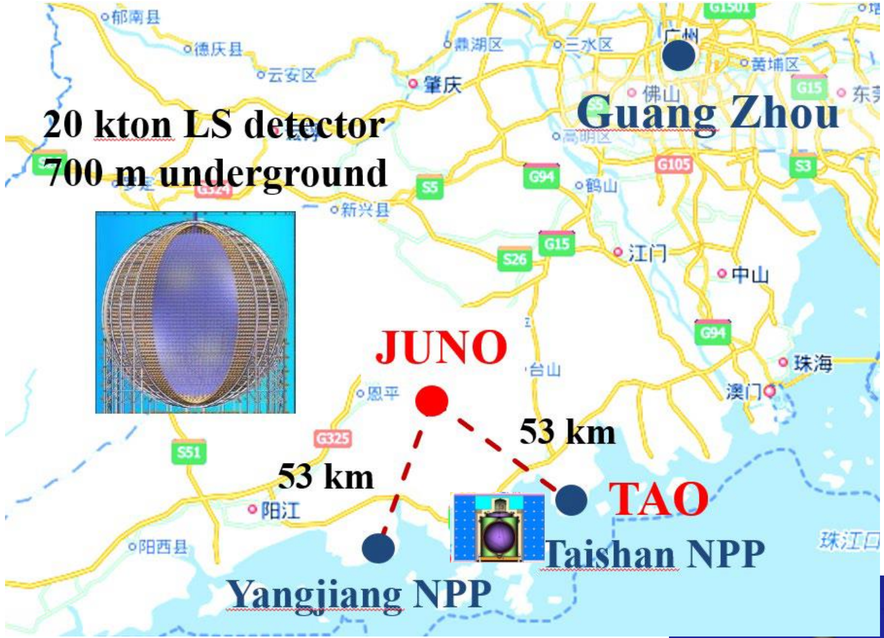
Physics goals:

- **Measurement of a high-resolution antineutrino energy spectrum, which serves as a benchmark to test nuclear databases, provides increased reliability in measured isotopic antineutrino yields, and gives an opportunity to improve nuclear physics knowledge of neutron-rich isotopes**
- **Providing the reference spectrum for JUNO to reduce the model dependence on the reactor antineutrino spectrum;**
- **Searching for light sterile neutrinos with a mass scale around 1 eV;**
- **Verification of the detector technology for reactor monitoring and safeguard applications**

Specification:

- **Expected energy resolution** - < 2% @ 1 MeV
- **Nuclear Reactor:**
  - Reactor Thermal Power - 4.59 GW
  - Reactor type – EPR
  - Baseline ~ 30 m
- **Detector operational temperature** - - 50C^o
- **Target**
  - spherical acrylic vessel diameter 1.8 m
  - spherical FV with radius 0.65 m
- **Photosensors - SiPM**
  - number of tiles ~ 4100
  - 50x50x3 mm 32 SiPMs per 1 tile
  - photon detection efficiency > 50%
  - coverage ~ 94%
  - dark current rate <100 [Hz/mm^2]
- **Scintillator**
  - LAB- based Gd-dopped
  - Light yield 12000 photons/MeV

TAO detector location



The Taishan **Nuclear Power Plant (台山核电站)** features two operational **EPR**.
Taishan 1 started commercial operation in December 2018. It was the first NPP with operational EPR unit.
Taishan 2 started commercial operation in September 2019

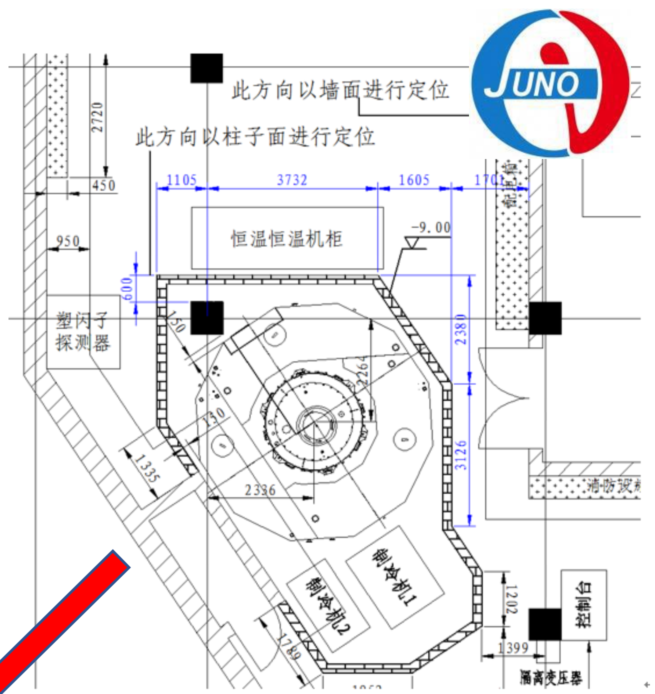
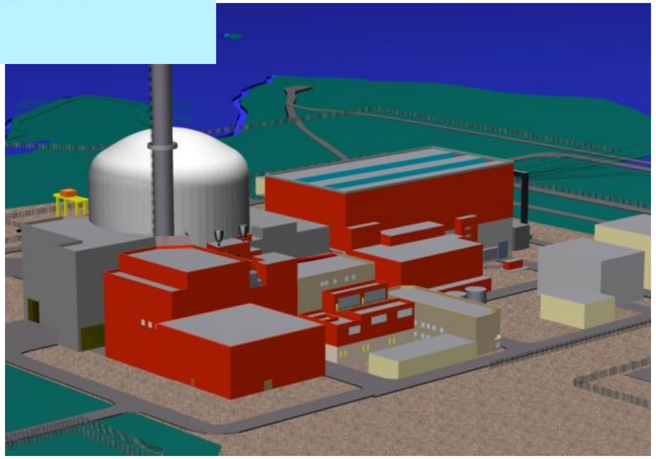
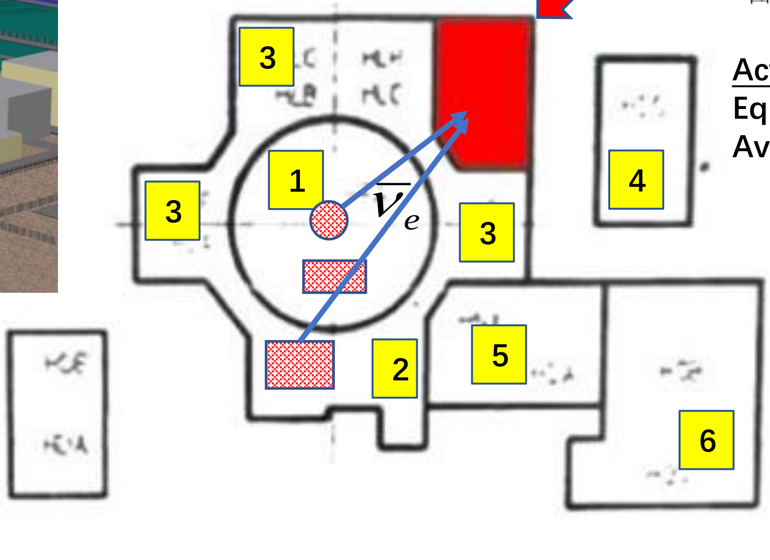


图 5.4-1 TAO 实验室消防围堰示意图

TAO will be located in a basement with floor height of -9.6m

The **EPR** is a third generation pressurized water reactor design. It has been designed and developed mainly by Framatome (part of Areva between 2001 and 2017) and Électricité de France (EDF) in France, and by Siemens in Germany.
In Europe this reactor design was called European Pressurized Reactor, and the internationalized name was Evolutionary Power Reactor, but is now simply named EPR

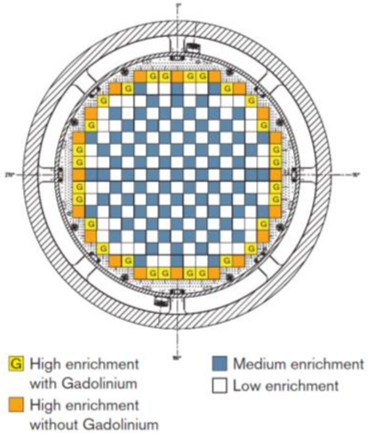




核电核岛平面图

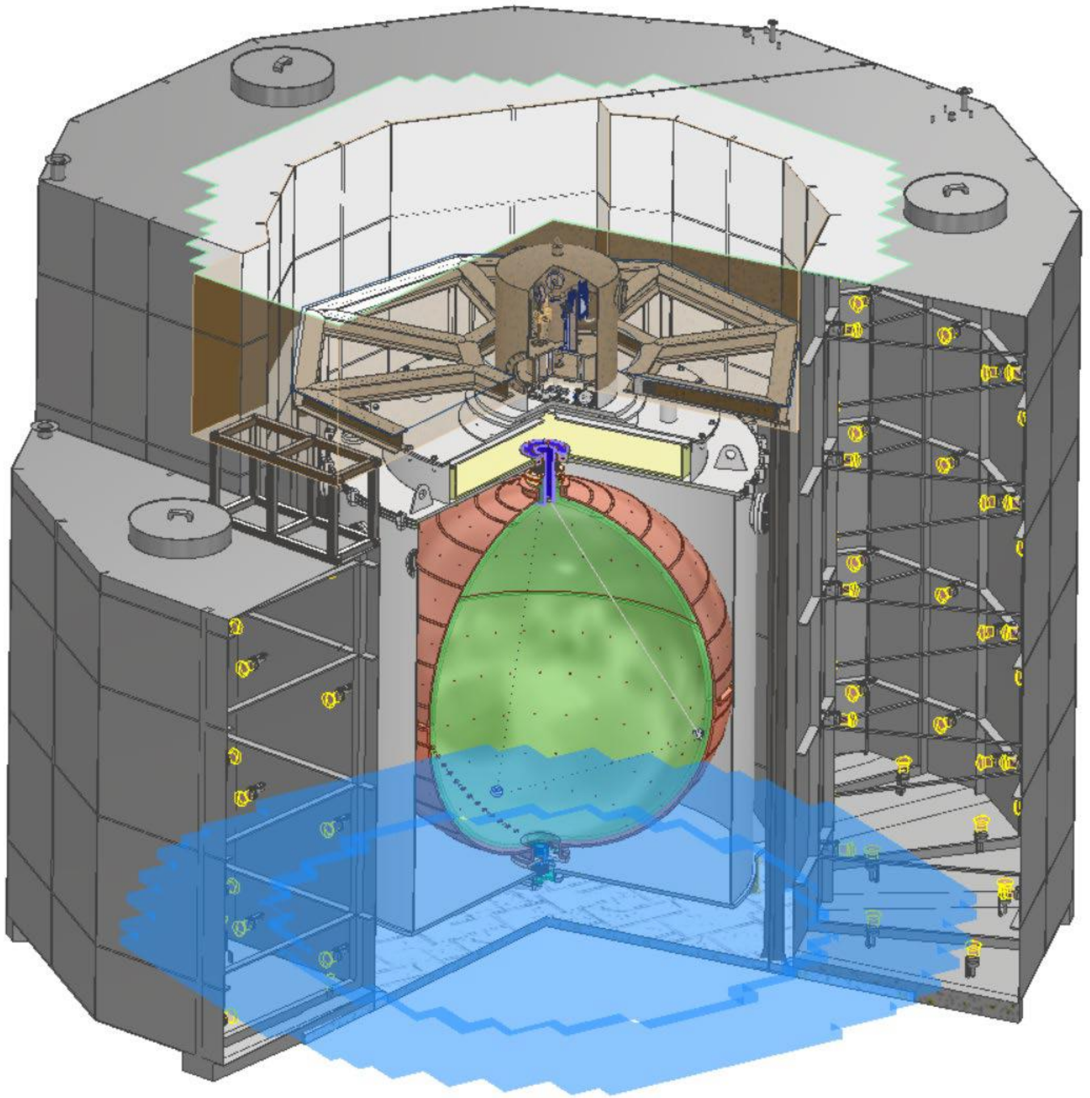
1. Reactor Building
2. Fuel Building
3. The Safeguard Buildings
4. Diesel Building
5. Nuclear Auxiliary Building
6. Waste Building

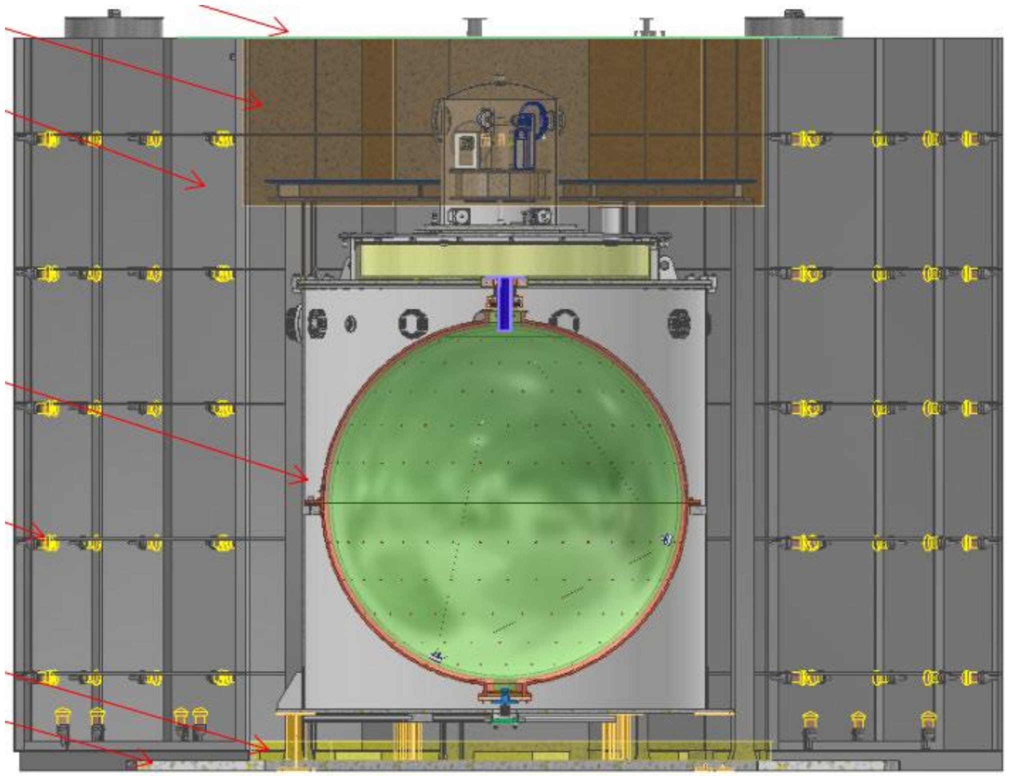
<u>Active core</u>
Equivalent diameter 3.7 m
Average active fuel height 4.2 m



TAO detector construction

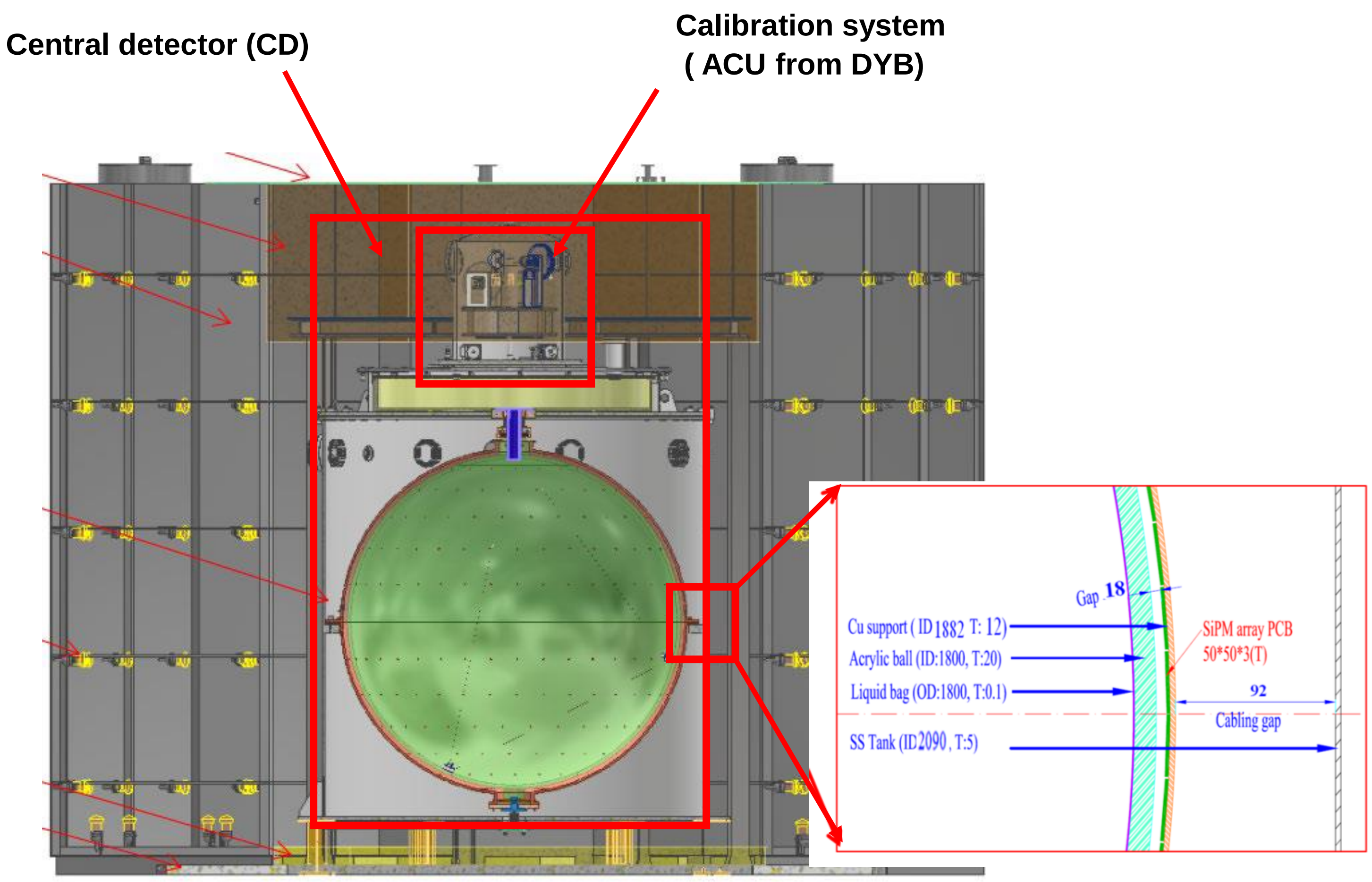
The design of the TAO detector combines the most advanced solutions in the field of LS-detectors to achieve unique characteristics.
Its design uses ideas and technical solutions implemented in such experiments as DayaBay, Borexino, Juno.





TAO Central detector

- **Multilayer container**
  - Stainless steel tank (SST)
  - Copper Shell (CS)
  - Acrylic sphere (AS) vessel diameter 1.8 m
- **Cryogenic box - (- 50C^o)**
  - Cooling pipes surrounding SST and CS feeding by external cooling machine
  - Melamine thermal insulation cover the SST
- **Target – LAB- based Gd-doping LS in AS**
  - Light yield 12000 photons/MeV
- **Buffer in SST - pure LAB**
- **Photosensors - 10 m^2 of SiPM array on the CS surface**
  - ~ 4100 50x50 mm SiPM
  - 32 SiPMs per tiles
  - photon detection efficiency > 50%
  - coverage ~ 94%
  - dark current rate < 100 [Hz/mm^2]

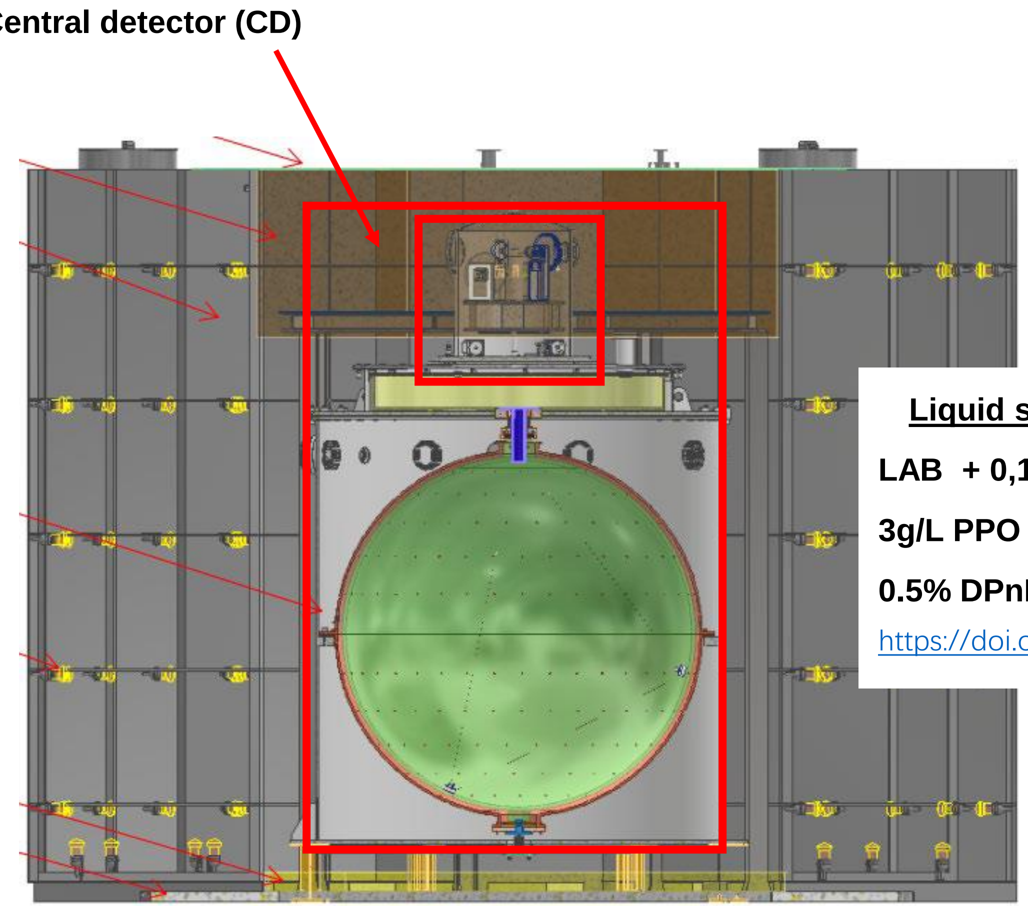


TAO Central detector

IS UNIQUE CRYOGENIC DETECTOR

- **Multilayer container**
  - Stainless steel tank (SST)
  - Copper Shell (CS)
  - Acrylic sphere (AS) vessel diameter 1.8 m
- **Cryogenic box - (- 50Cº)**
  - Cooling pipes surrounding SST and CS feeding by external cooling machine
  - Melamine thermal insulation cover the SST
- **Target – LAB- based Gd-doping LS in AS**
  - Light yield 12000 photons/MeV **~25% up**
- **Buffer in SST - pure LAB**
- **Photosensors - 10 m^2 of SiPM array on the CS surface**
  - ~ 4100 50x50 mm SiPM
  - 32 SiPMs per tiles
  - photon detection efficiency > 50%
  - coverage ~ 94%
  - dark current rate <100 [Hz/mm^2] **three orders of magnitudes down**

arXiv: 2005.08745



Liquid scintillator recipe

LAB + 0,1% Gd

3g/L PPO + 2 mg/L bis-MSB

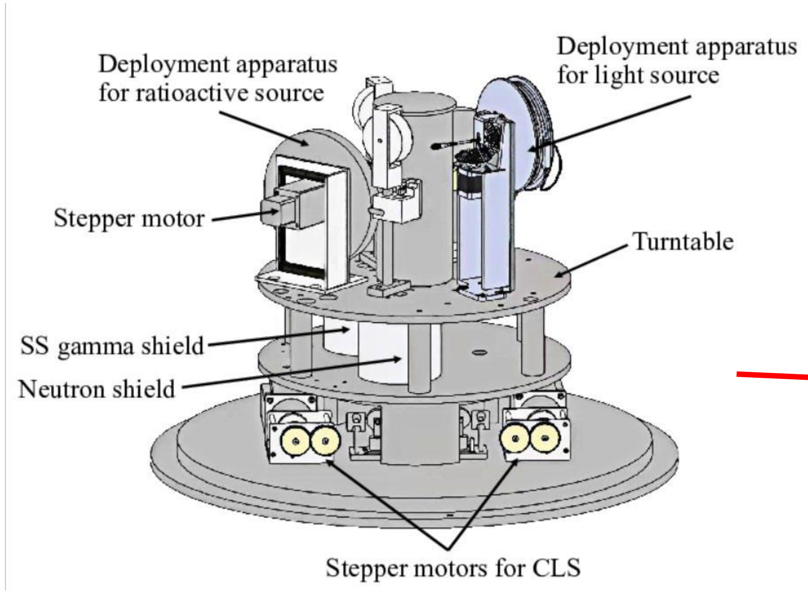
0.5% DPnB

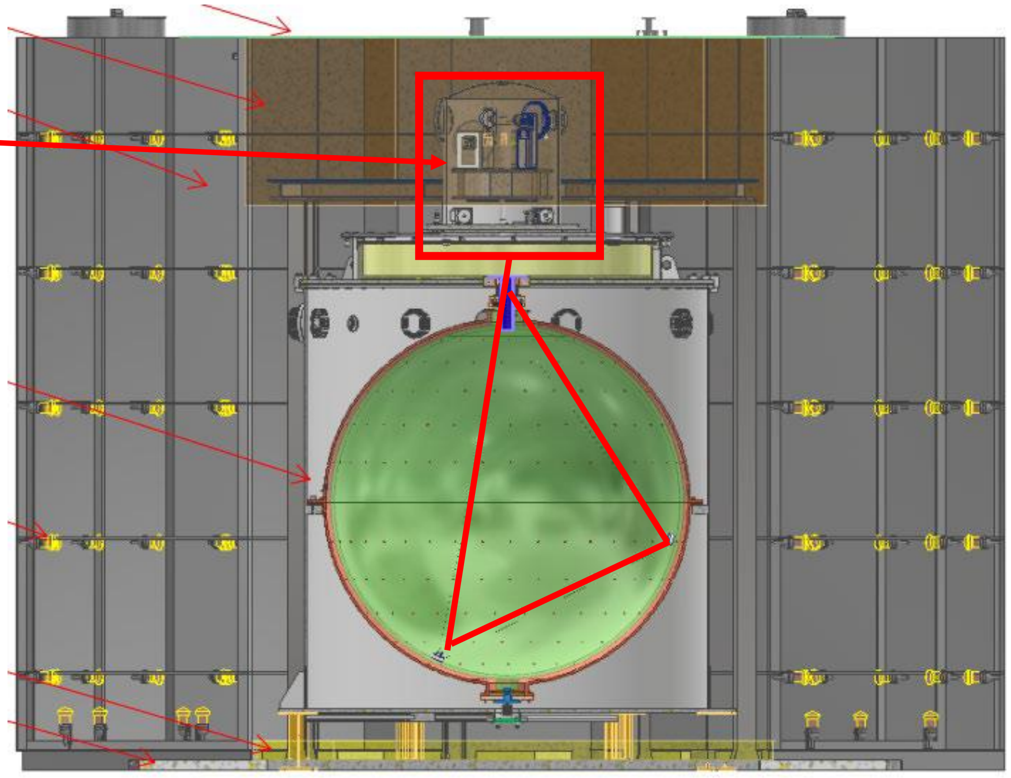
https://doi.org/10.48550/arXiv.2012.11883

TAO calibration system

arXiv: 2204.03256 Calibration Strategy Paper Eur.Phys.J.C82(2022)12,1112

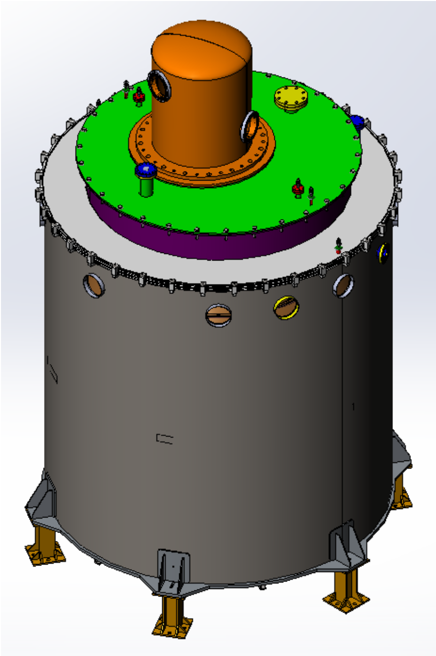
Modified from DayaBay
Automated Calibration Unit (ACU)

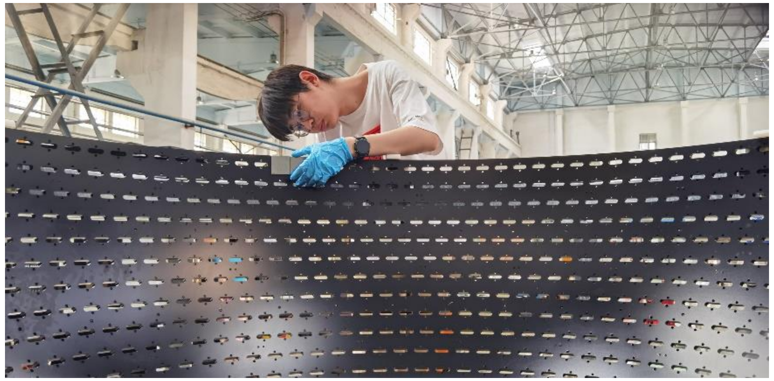




- **3 vertical deployment systems**
  - **- gamma sources:** ^{68}Ge, combined (^{137}Cs,^{54}Mn, ^{40}K,^{60}Co)
  - - **neutron source** (^{241}Am-^{13}C)
  - **- LED calibration system** (UV + blue)
- **cable loop system with** ^{137}Cs **gamma source**
- **PLC-based control system**

1:1 prototype of TAO Central Detector including ACU



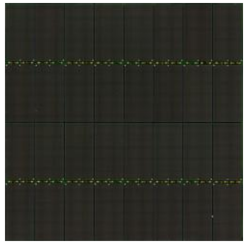


TAO prototype is under final assembling stage

- **LS filling**
- **cooling down**
- **Muon and calibration sources tests**

<u>are coming with the next two months</u>

TAO scintillation photons detectors

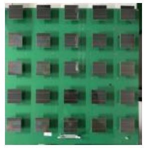


SiPM tile

- number of tiles ~ 4100
- 50x50x3 mm 32 SiPMs per 1 tile
- photon detection efficiency > 50%
- coverage ~ 94%
- dark current rate ~100 [Hz/mm^2]

Burn-in Test

- 400 tiles in one test operate for two weeks with the over voltage of ~3 V at room temperature
- the dark current of each tile is sampled



3000 SiPM tiles are ready for tests

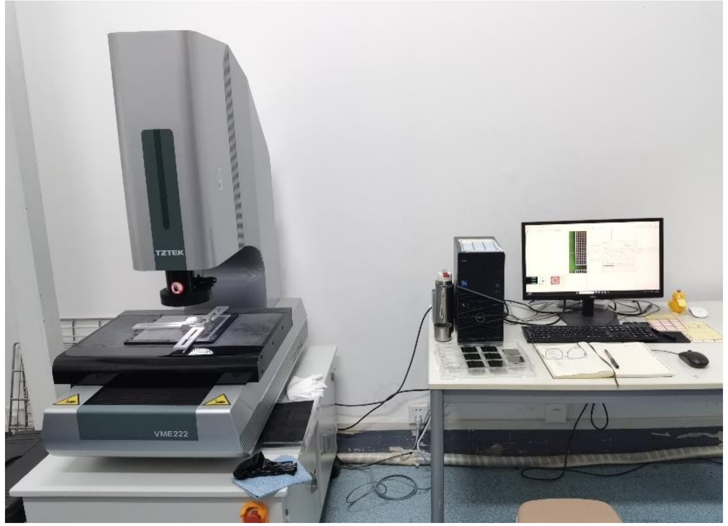
SiPM tile surface defect check

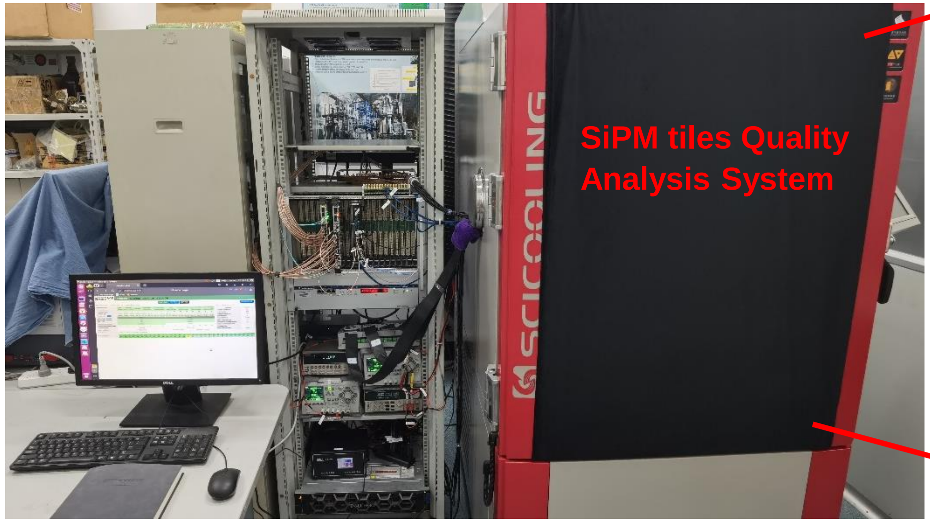
Requirement: surface defect area < 0.25%

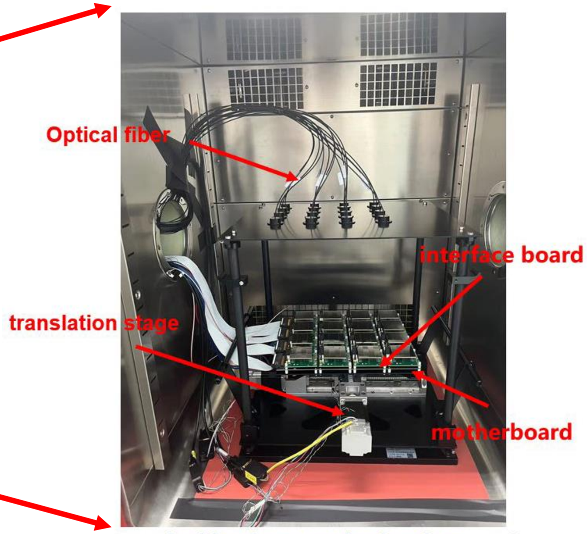
Computer vision system to analyze the photo

Mass testing - analysis of the quality of each SiPM at an operating temperature of -50

- PDE
- dark current over temperature
- cross talks







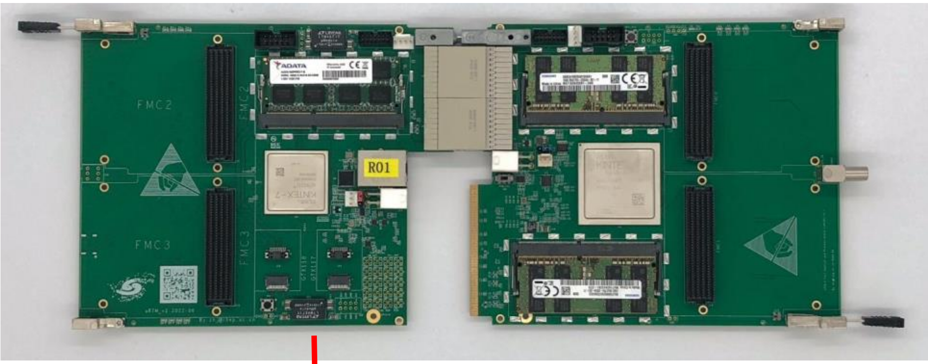
Inside of cryogenic chamber

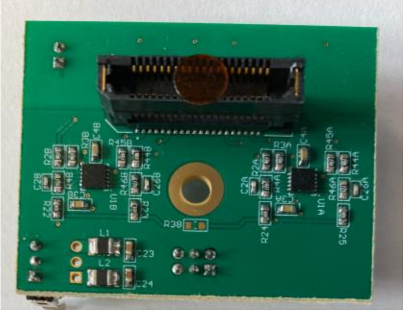
TAO Central Detector electronics

Front End controller (FEC) outside the cryostat
- FMC carrier for ADC board and WR- board
- Digitize, preprocess, timestamp and pack data to send to DAQ over FO

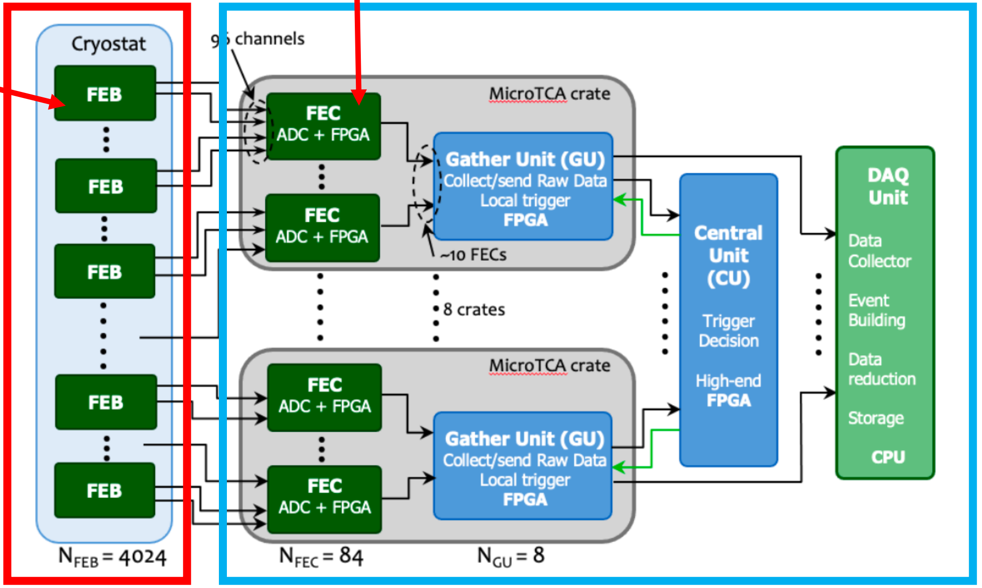
Mini-WR FMC board

ADC FMC board
- ADC is on FEC, used to digitize analog signals from FEB
- FPGA & Power boards in MicroTCA.4 crate
- Q/T information is extracted with FPGA (waveform analysis)





Front End Board (FEB) - inside the cryostat
- 1 tile → 2 channels
- Total 8048 channels
- Tile and FEB by connectors
- Analog signals from FEB will be transferred to FEC via differential pairs



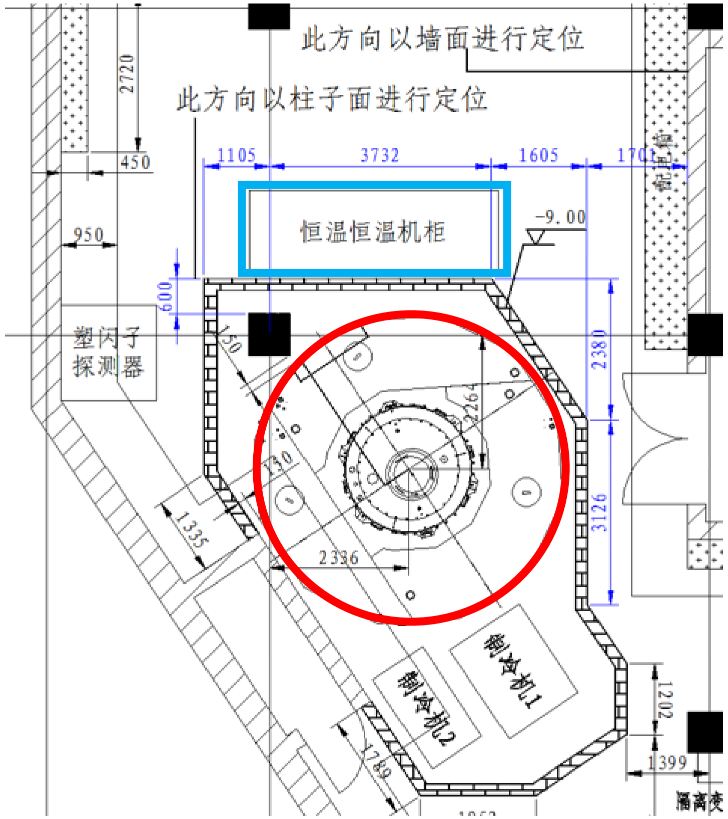
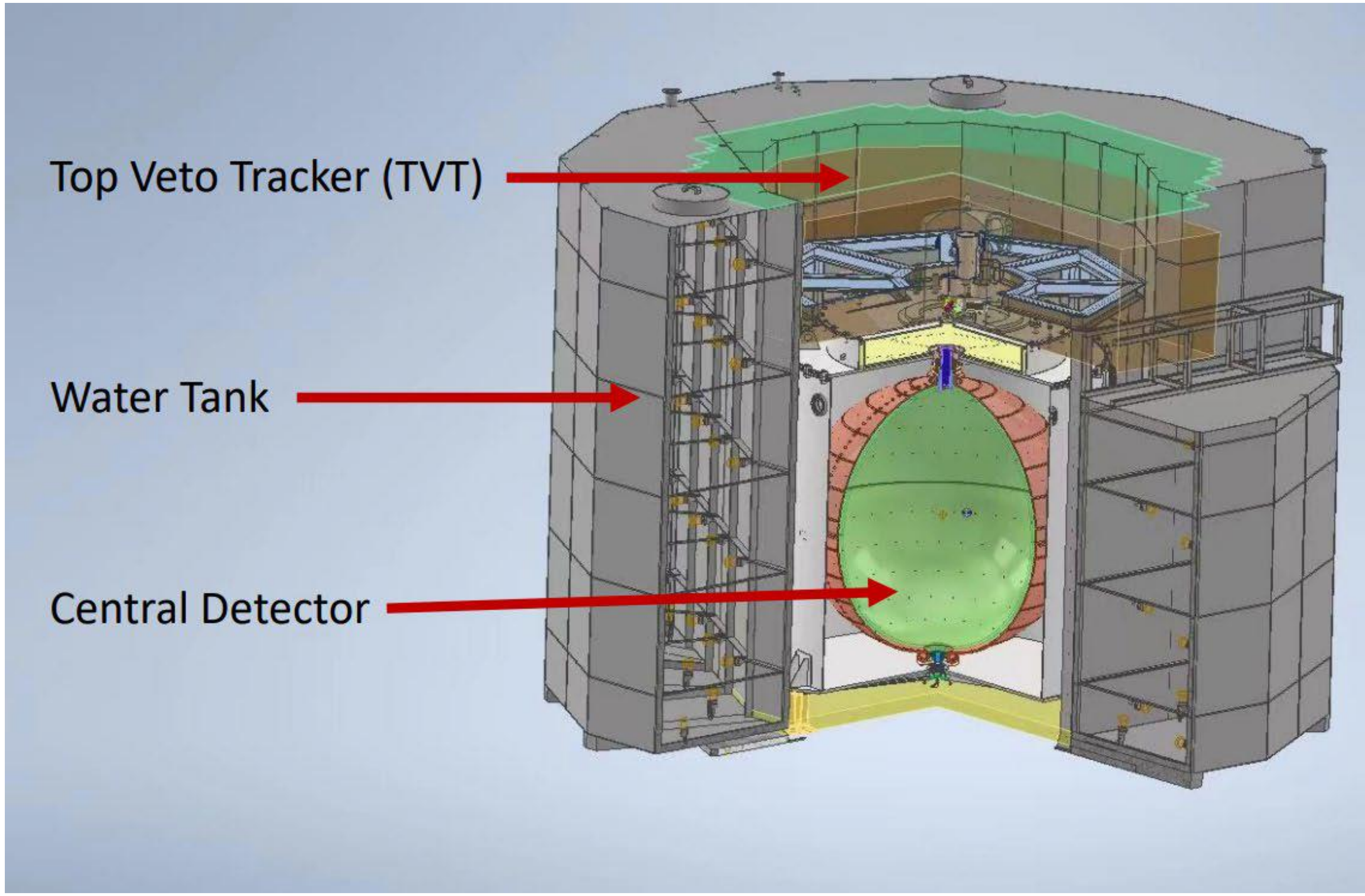


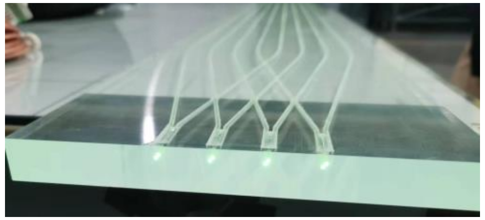
图 5.4-1 TAO 实验室消防围堰示意图

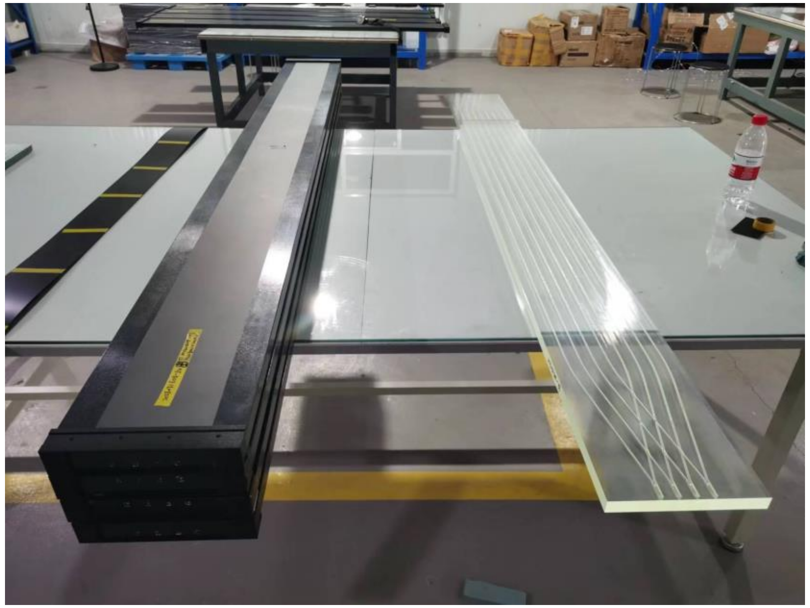
TAO background shielding and muon veto system



Muon veto efficiency :
TVT ~98.4%
Water tank >99%

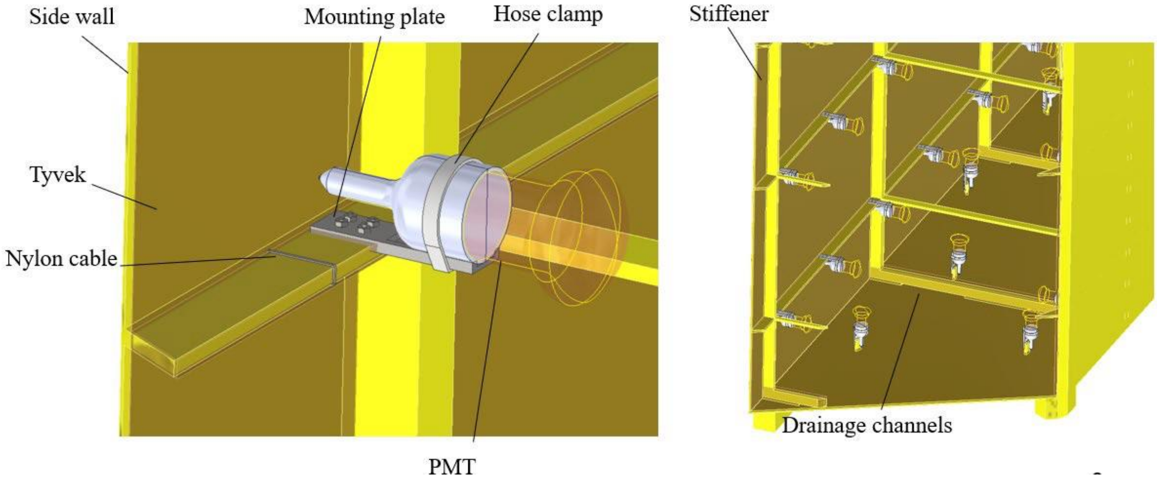
TVT system

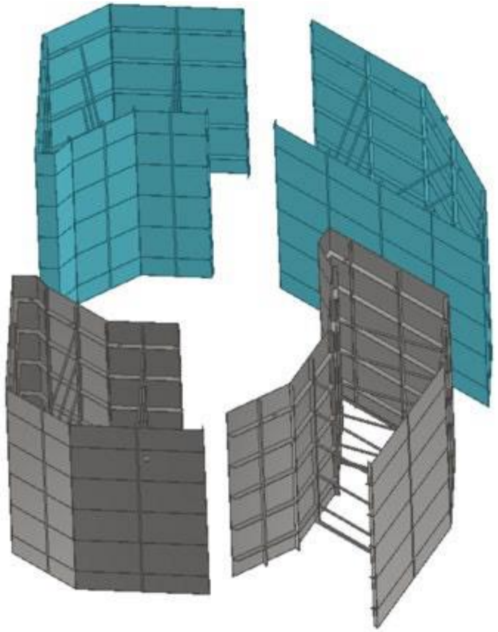




- > 98.4% efficiency
- 4 layers, 2 cm thickness each, 1 mm gap
- 160 strips, double-end readout by SiPM
- Strip layout optimization (fiber diameter/layout, strip size)
- Mass production is running

WT VETO system





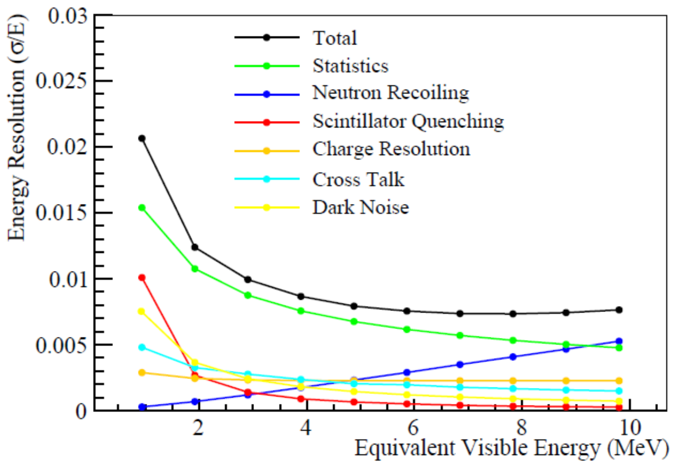
- > 99% efficiency
- 300 3” PMT
- Uses JUNO sPMT & electronics

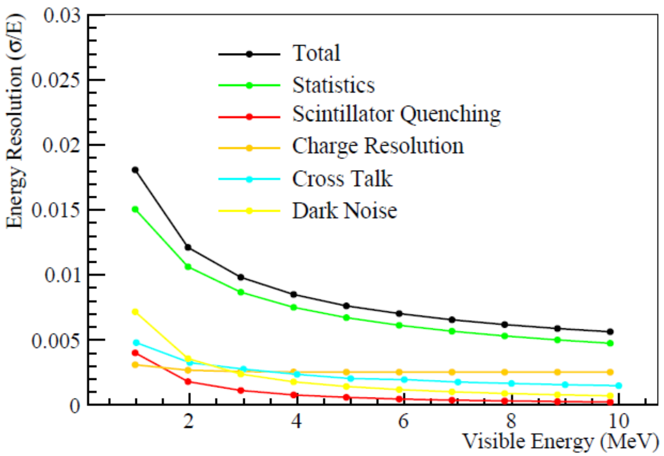
Expected TAO energy resolution and event rate

High energy resolution of TAO is determined by the statistics of the collected photoelectrons (p.e.)

- 4500 p.e./MeV is expected considering the following improvements.
- The coverage of photon sensors is improved to 95% from 75% in JUNO.
- The photon detection effciency is improved to 50% using SiPMs.
- Smaller dimension of the TAO detector increases the photoelectron statistics by 40% due to less photons absorption in LS.
- Low temperature at -50C could increase the photon yield of LS by 25%

IBD signal	2000 events/day
Muon rate	70 Hz/m^2
Singles from radioactivity	< 100 Hz
Fast neutron background after veto	< ~~200~~ events/day ~40
Accidental background rate	< 190 events/day
^{8}He/^{9}Li background rate	∼ 54 events/day





Optimization of the detector resulted in decreasing background-to-signal ratio from 10% to 2% for the cosmogenic neutron backgrounds

arXiv:2206.01112v4

Left: energy resolution for reactor antineutrinos versus equivalent visible energy defined as the reconstructed neutrino energy minus a constant shift of 0.78 MeV due to the IBD reaction kinetics. It includes the effect from the spread of the neutron kinetic energy in the IBD reaction. Right: energy resolution for electrons without the effect of neutron kinetic energy.

In most of the energy region of interest, the energy resolution of TAO will be sub-percent.

Conclusions:

- Unprecedented energy resolution of TAO-detector is expected due to symmetrical construction, low temperature scintillator and cooled photo sensors together with comprehensive active and passive shielding.

- These features open a way for precise reactor antineutrino flux and spectrum measurement which making TAO-detector a promising tool to contribute greatly to applied antineutrino physics and open a possibility for industrial tool development.