Plans and Preparation Status of the Sanmen Reactor Neutrino Laboratory

YANG Litao (杨丽桃)

Tsinghua University

Magnificent CEvNS 2024

Jun 12 - 14, 2024 @ Valencia, Spain

OUTLINE

1、Sanmen Reactor Neutrino Laboratory

2、RECODE Program (Ge)

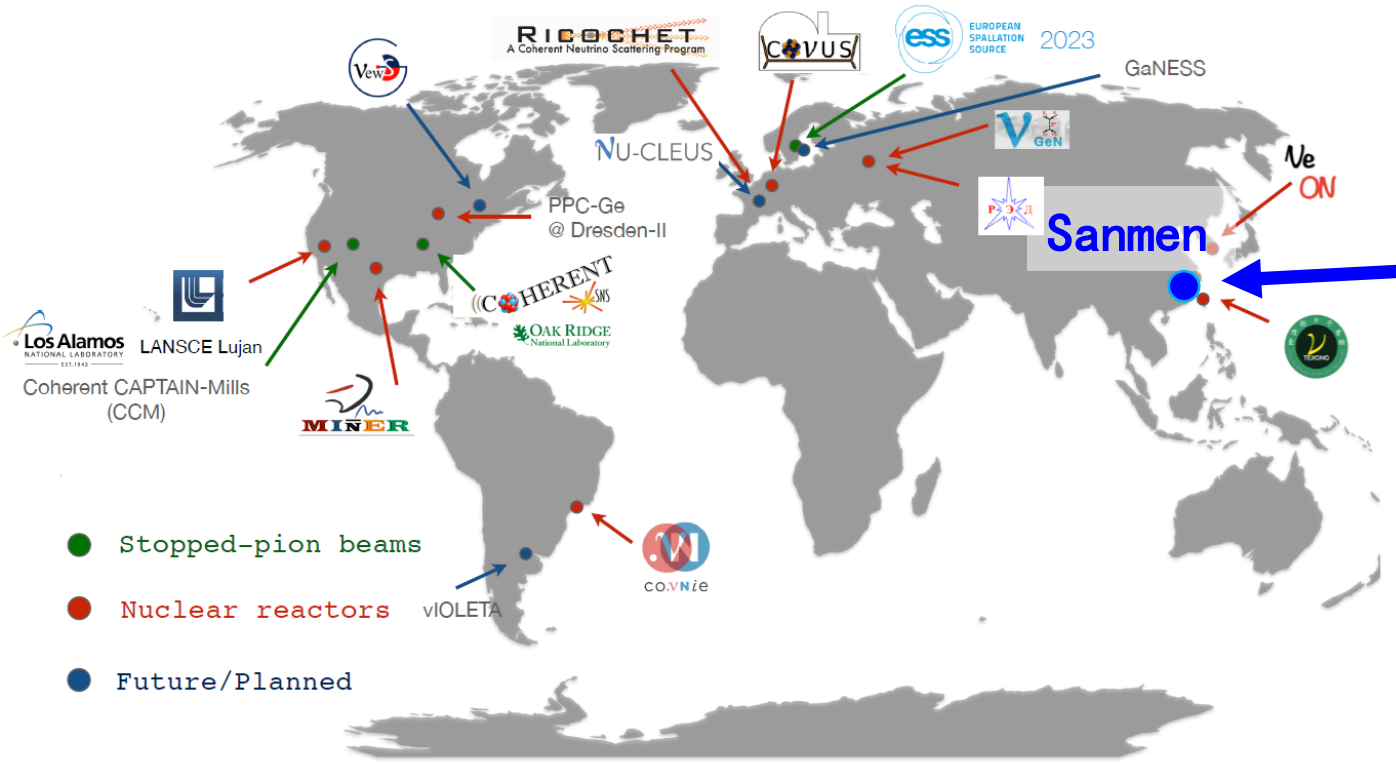
3、RELICS Program (Xe)

4、Prospects and summary

Sanmen Reactor Neutrino Laboratory

Sanmen Nuclear Power Plant (AP1000) @ Taizhou, Zhejiang, China

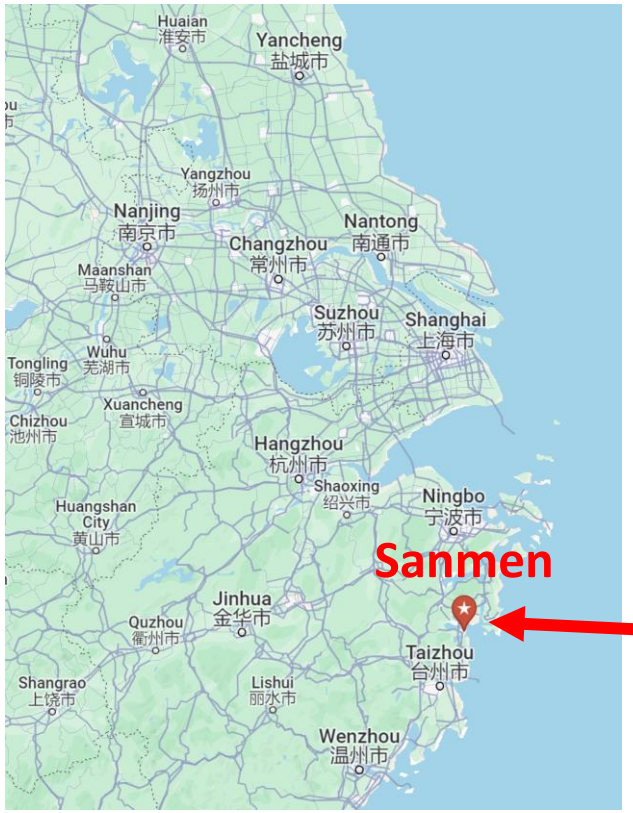
- Thermal power 3.4 GWth, ~22m /11m /7m from the core
- Neutrino flux > 1.4 × 10^{13} $cm^{-2}s^{-1}$



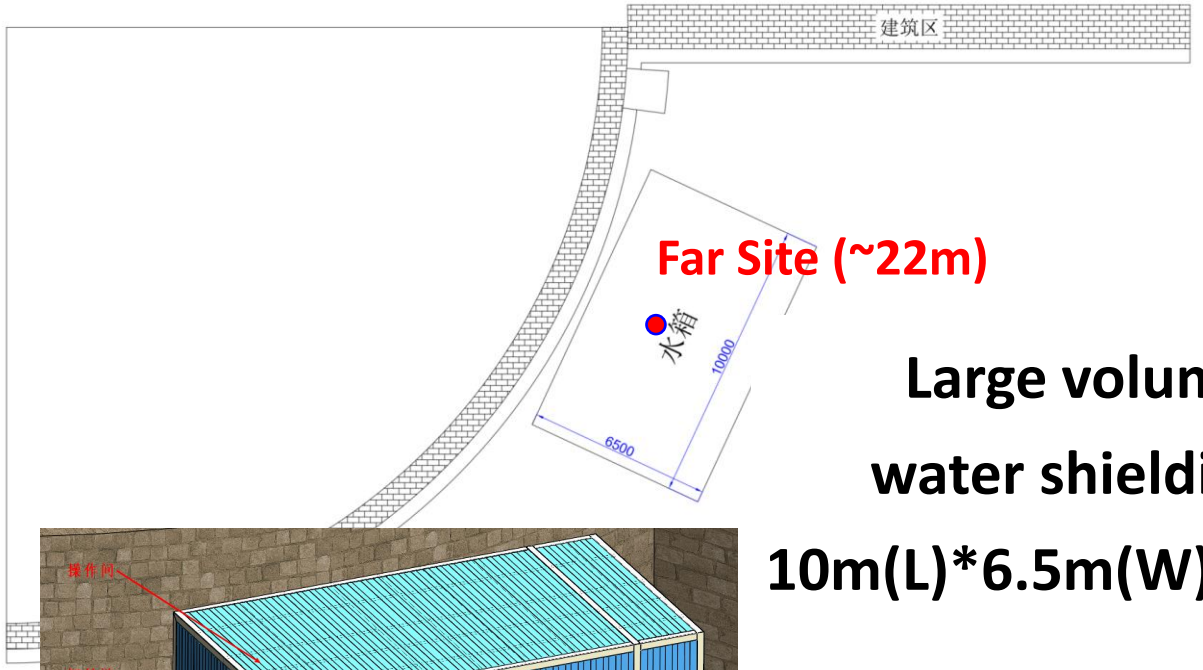
Sanmen Reactor Neutrino Laboratory

Sanmen Nuclear Power Plant (AP1000) @ Taizhou, Zhejiang, China

- Thermal power 3.4 GWth, ~22m /11m /7m from the core
- Neutrino flux > 1.4 × 10^{13} $cm^{-2}s^{-1}$



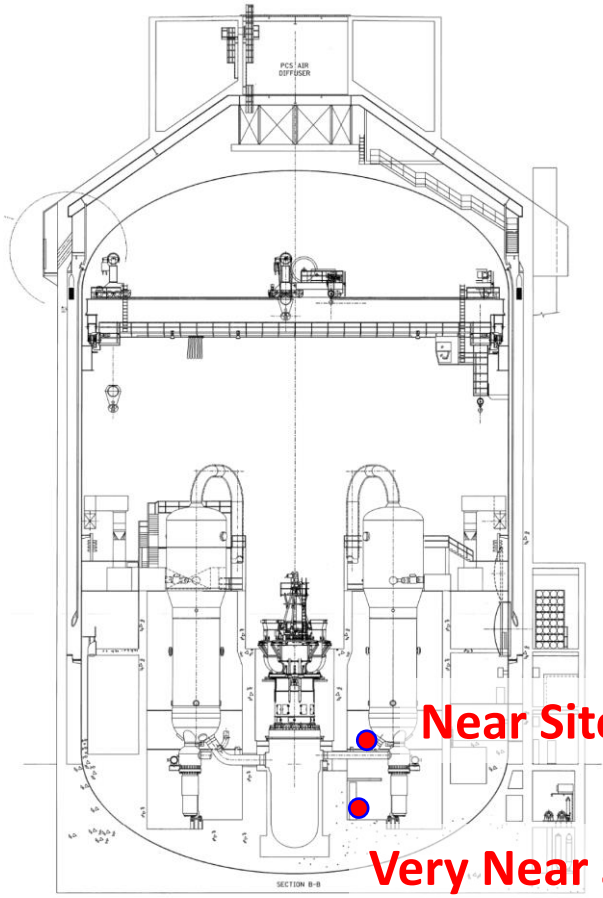
Project Location



Far Site (~22m)

Large volume water shielding: 10m(L)*6.5m(W)*6m(H)

Outside of reactor containment



Near Site (~11m)

Very Near Site (~7m)

Inside of reactor containment （NS: 11m; VNS: 7m）

Solid combination shielding: copper, lead, polyethylene, etc.

Location and Technical route

Two layouts (Far, Near) with three sites (FS, NS + VNS):

- **Far Site** (22m distance to reactor core, outside of Containment, no overburden)
- **Near Site** (11m, overburden>15m.w.e, Maintainable during reactor operation)
- **Very Near Site** (7m, overburden>20m.w.e., Not maintainable during operation)
- **Far-Near Joint analysis**: reduce systematic uncertainty, improve the sensitivity

Shielding for FS/NS, according to the overburden:

- Far Site: 400 tons of pure Water shielding, 10m(L) X 6.5m(W) X 6m(H)
- Near Site: composite shielding with Lead, Copper, and Polyethylene…

Two technologies (Ge, Xe):

- RECODE (PPCGe): Liquid nitrogen cooling (FS), Electric cooling (NS/VNS)
- RELICS (Liquid xenon TPC) : FS

Key parameters comparison

Sanmen Nuclear Power Plant (AP1000) @ Taizhou, Zhejiang, China

- Thermal power 3.4 GWth, ~22m /11m /7m from the core
- Neutrino flux > 1.4 × 10^{13} $cm^{-2}s^{-1}$

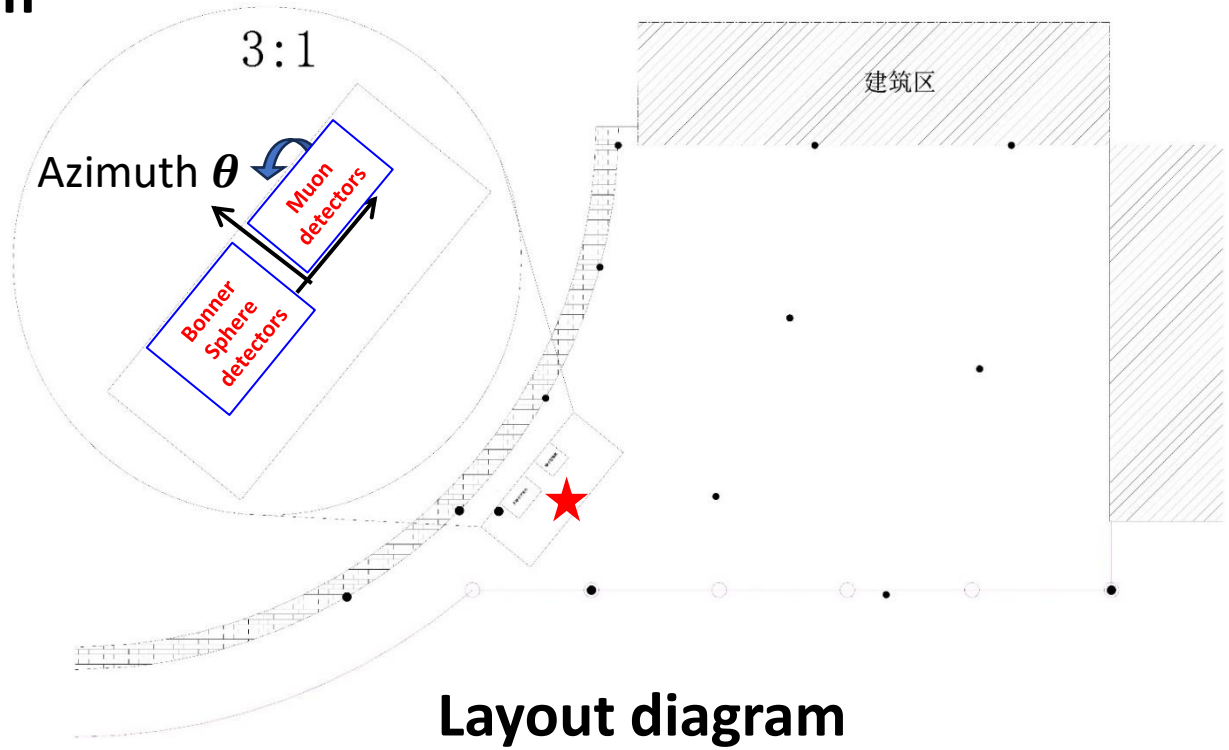
Experiment	Target	Mass	Threshold	Reactor	Distance to reactor core	Thermal power	Neutrino Flux	Location
CONNIE	Si CCDs	50 g	~ 40 eVee	Angra 2 reactor	30 m	3.8 GWth	7.8*10^{12} ν/cm^2/s	Brazil
MINER	Ge/Si	4 kg	~ 100 eVnr	TRIGA reactor	2~10m	1 MWth	~10^{12} ν/cm^2/s	USA
RICOCHET	Ge & Zinc	32 g (Ge)	55 eVee	ILL reactor	8 m	58 MWth	1.6*10^{12} ν/cm^2/s	France
CONUS	HPGe	3.74 kg	~ 210 eVee	Kernkraftwerk Brokdorf	17 m	3.9 GWth	2*10^{13} ν/cm^2/s	Germany
COUNS+	HPGe	3.74 kg	~150 eVee	Leibstadt NPP	20.7m	3.6 GWth	1.45*10^{13} ν/cm^2/s	Switzerland
Nu-Gen	HPGe	1.6 kg	350 eVee	Kalinin NPP	10 m (adjust)	3.2 GWth	5.4*10^{13} ν/cm^2/s	Russia
TEXONO	HPGe	1 kg	~200 eVee	Kuo-Sheng NPP	28m	2.9 GWth	6.4*10^{12} ν/cm^2/s	Taiwan, China
RECODE	**HPGe**	**1-2kg**	**~160 eVee**	**Sanmen NPP**	**NS ~ 11m**	**3.4GWth**	**5.6*10^{13} ν/cm^2/s**	**China**
	HPGe	**10kg**	**~160 eVee**		**FS ~ 22m**	**3.4GWth**	**1.4*10^{13} ν/cm^2/s**	**China**
RELICS	**LXe**	**50kg**	**~1 keVnr**	**Sanmen NPP**	**22m**	**3.4GWth**	**1.4*10^{13} ν/cm^2/s**	**China**

Environmental background measurement @Sanmen

- A series of environmental background measurement technologies have been dev eloped in CJPL, which can be directly applied to the **environmental background measurement near the reactor**, providing key inputs for the shield design;

- **Cosmic ray muon measurement system**

- **Bonner Sphere detectors**



Layout diagram

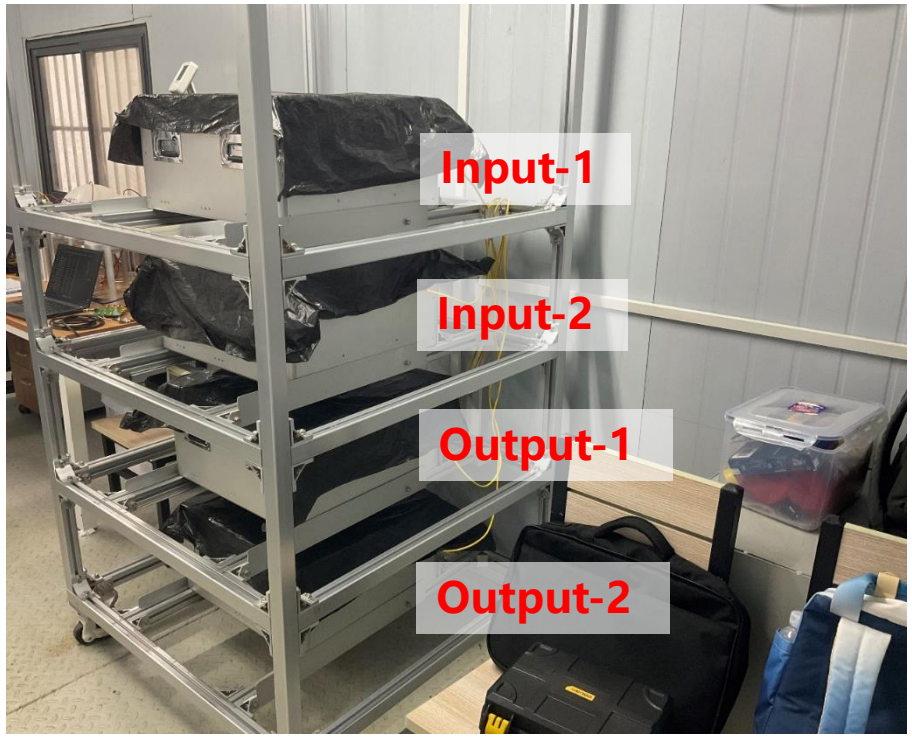
Neutron measurement: Bonner Sphere detectors

Layout of Bonner Sphere detectors

- MNS IL100 Bonner Sphere detectors
- ZJ230-3 He-3 pipe
- Polyethylene ball radius (mm): R0, R50, R60, R80, R100, R120, and R150
- Key parameters:
  - Dead time: approximately 10 μs
  - Effective cross-section: radius 15 mm
  - Polyethylene density: 0.92~0.95 g/cm^3

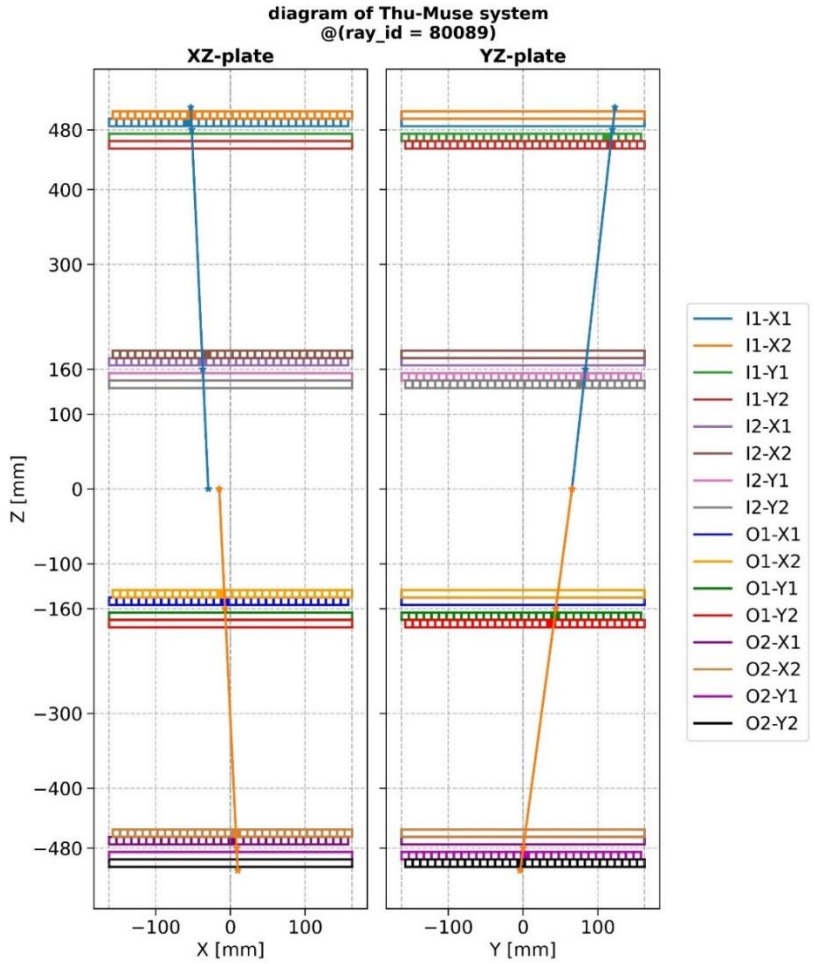
- **Preliminary results [Neutron spectrum analysis is in progress]:**
- Neutron flux @10MeV: **10^{-4}-10^{-3} [1/cm^2/s]**
- Neutron flux for thermal neutron-20MeV: 4.92×**10^{-3} [1/cm^2/s]**
- Surrounding dose equivalent rate magnitude **[nSv/h]**

Muon flux measurement: ThuMuse system



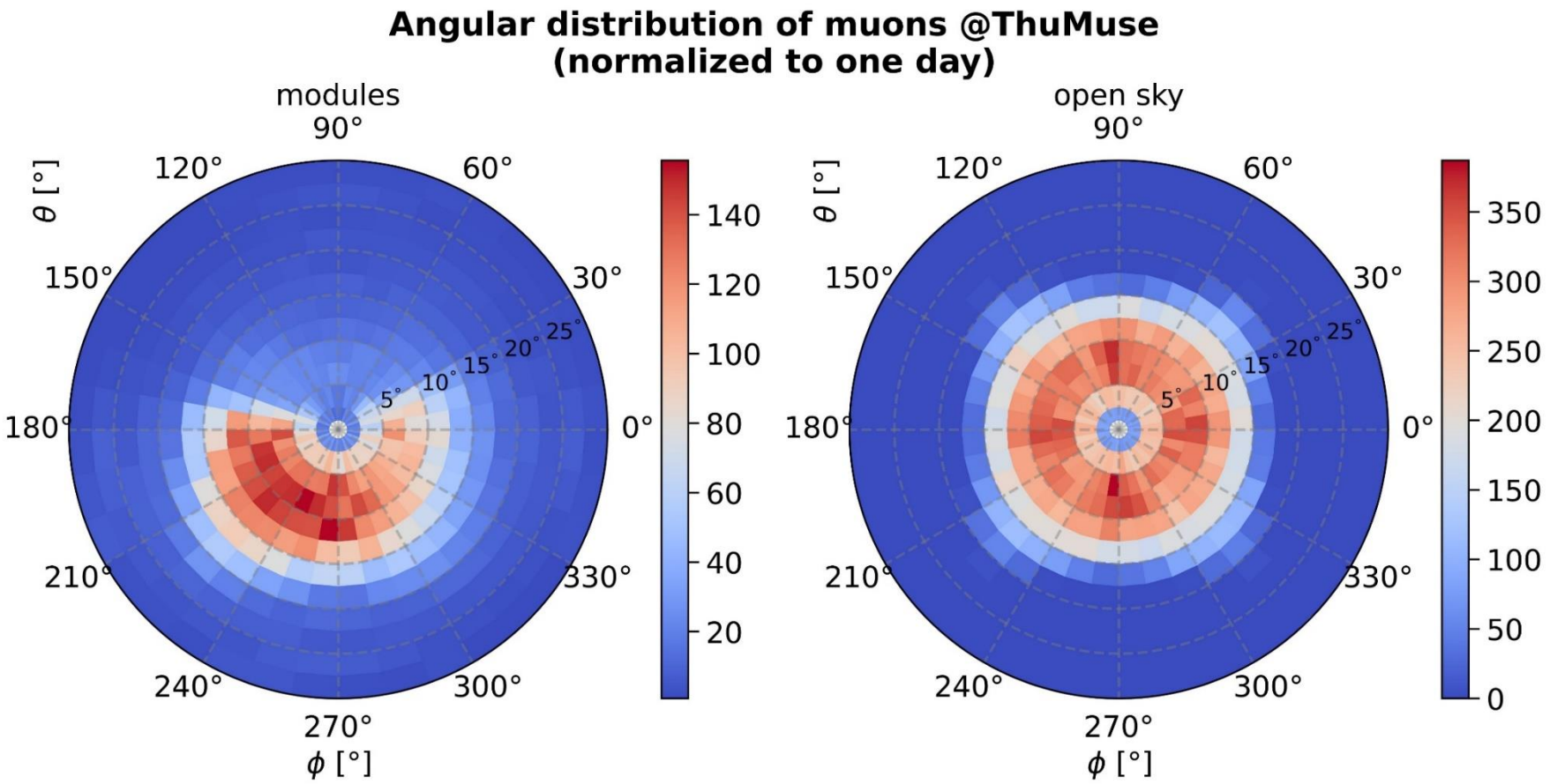
Layout of ThuMuse system

- ThuMuse system consists of **4 layers of plastic scintillator strips modules**, which has XY two-dimensional positioning capability
- Layer spacing is fixed at 320mm, the geometric acceptance [Quadruple] is about 3.41%



Schematic diagram of screening tracks for Muon events

Muon flux measurement: ThuMuse system



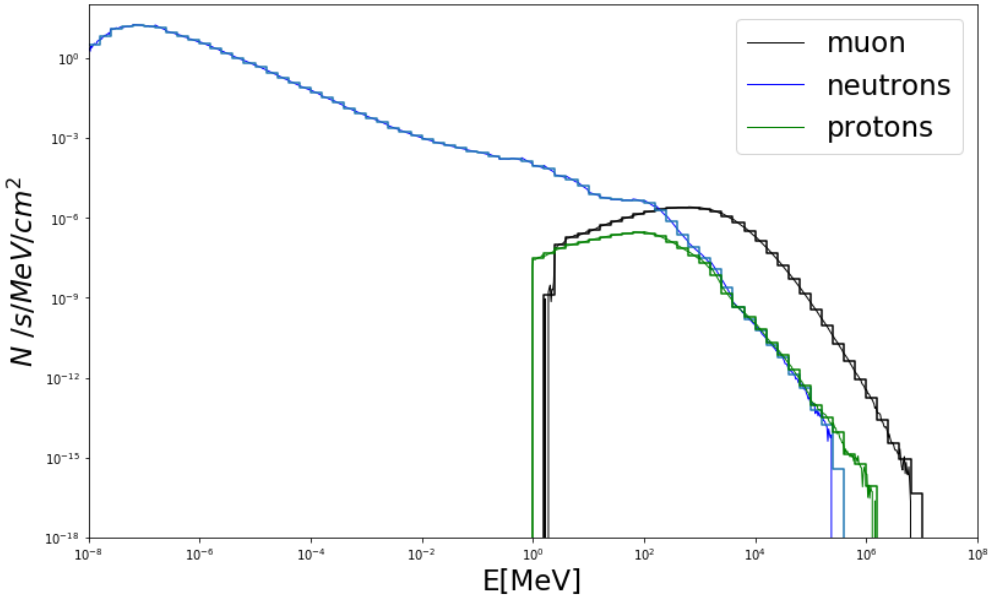
Measured zenith angle-azimuth distribution

Simulated distribution in open scenes

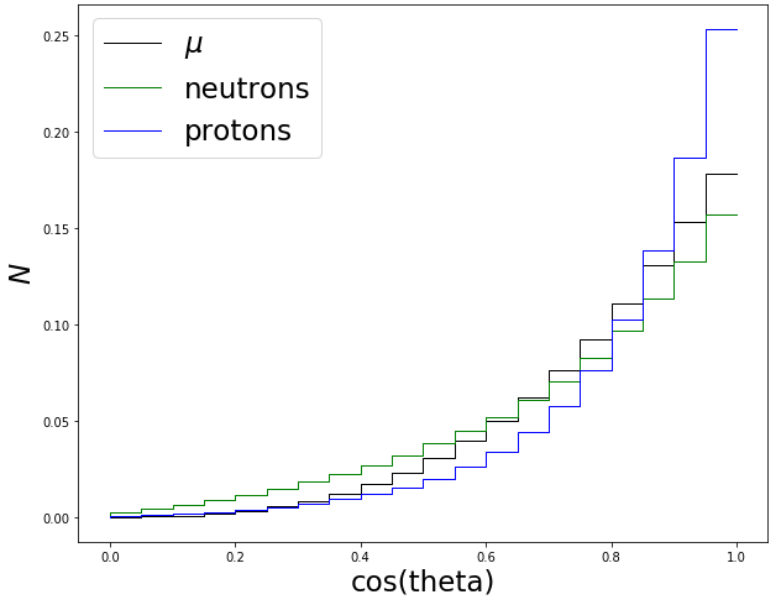
- **Measured zenith angle-azimuth distribution is consistent with the experimental site conditions: low muon flux near the Reactor Concrete Containment side, ~1/3 of muons can be shielded**

Cosmic ray simulation

- The cosmic rays that travel through the atmosphere can produce a variety of radiati on particles, such as neutrons, protons, gammas, and pions...
- In addition to the muon, we should also consider the **high-energy cosmic-ray neutr ons**, which can easily pass through the shield and deposit energy in the detector;
- Cosmic-ray Shower Library (CRY) to calculate their flux;



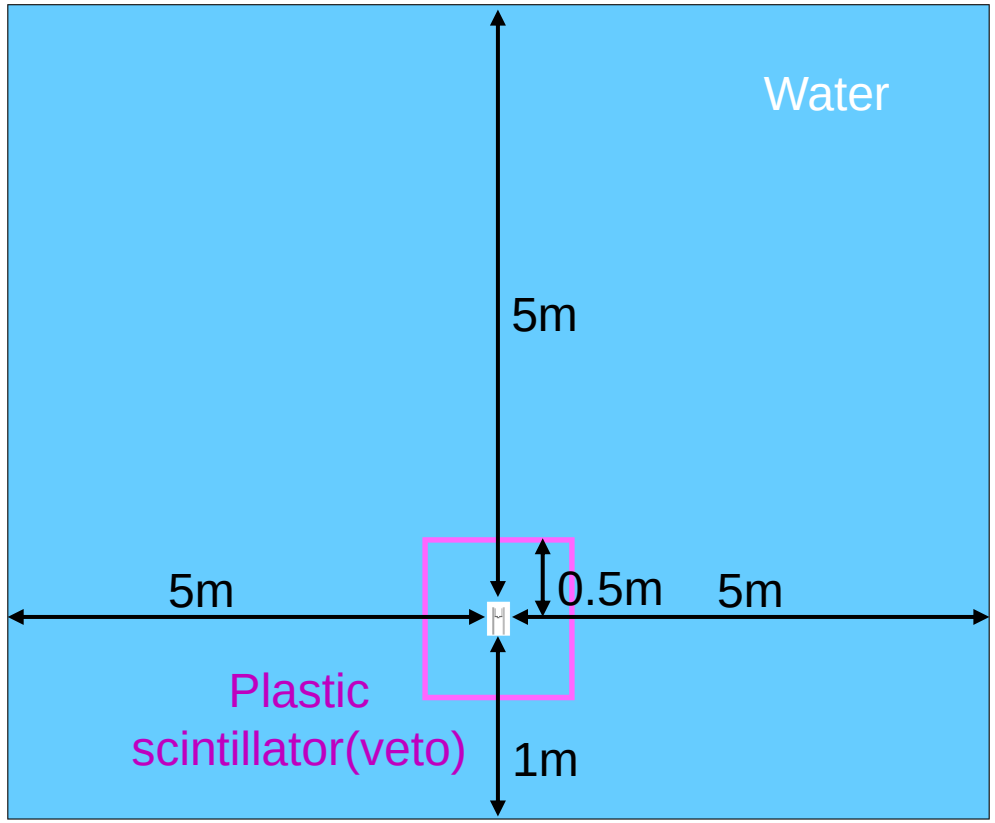
Spectra of cosmic-ray neutrons, protons, and muons at Sanmen sea level

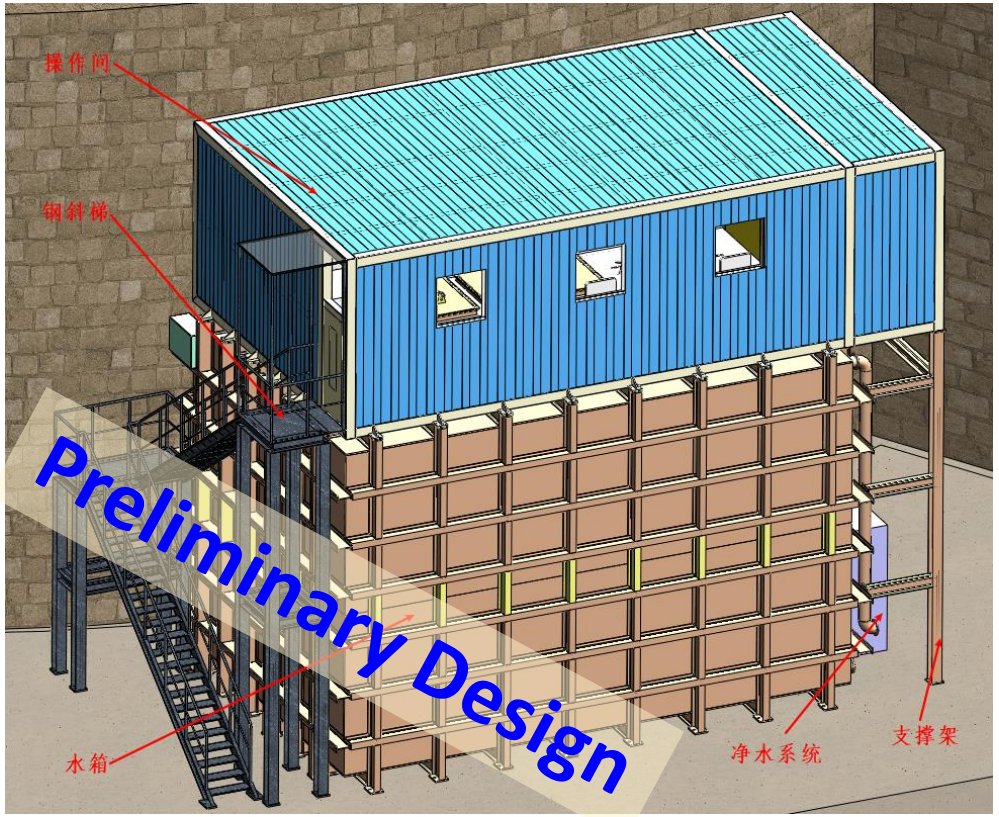


Angular distribution of cosmic-ray at Sanmen sea level

Water shield simulation design

- 5 m water shield on top can suppress the cosmic-ray neutron-induced backgroun d to a controlled level;
- Water tank (inner): 10m(L)*6.5m(W)*6m(H); The detector is placed in the water t ank on the side close to the reactor concrete containment.

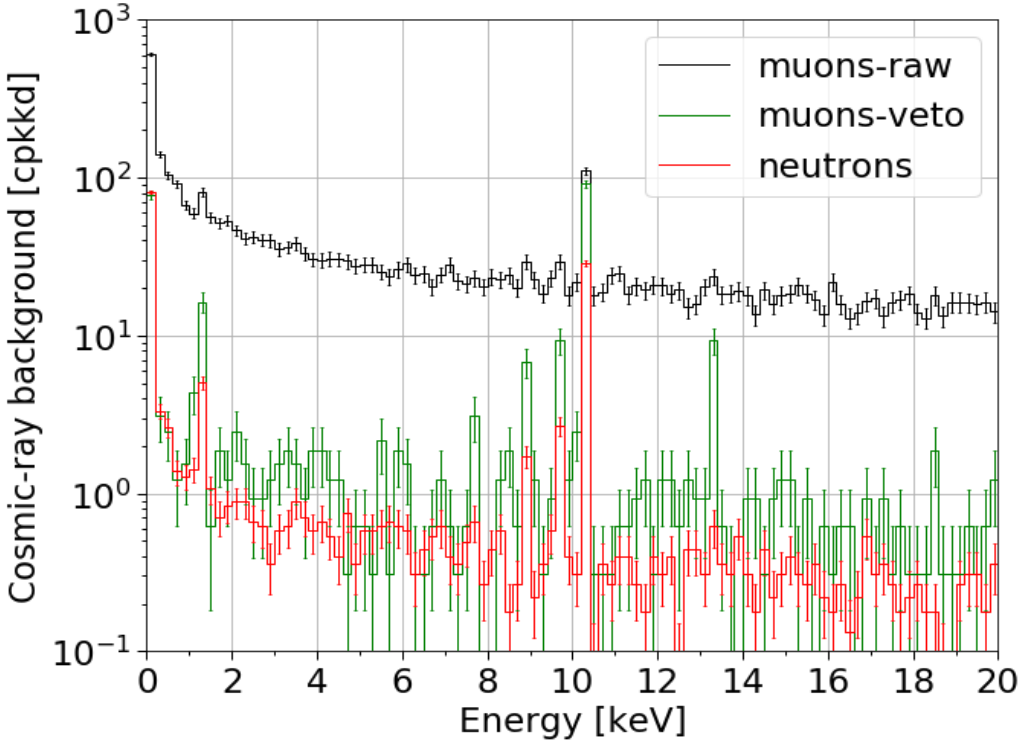




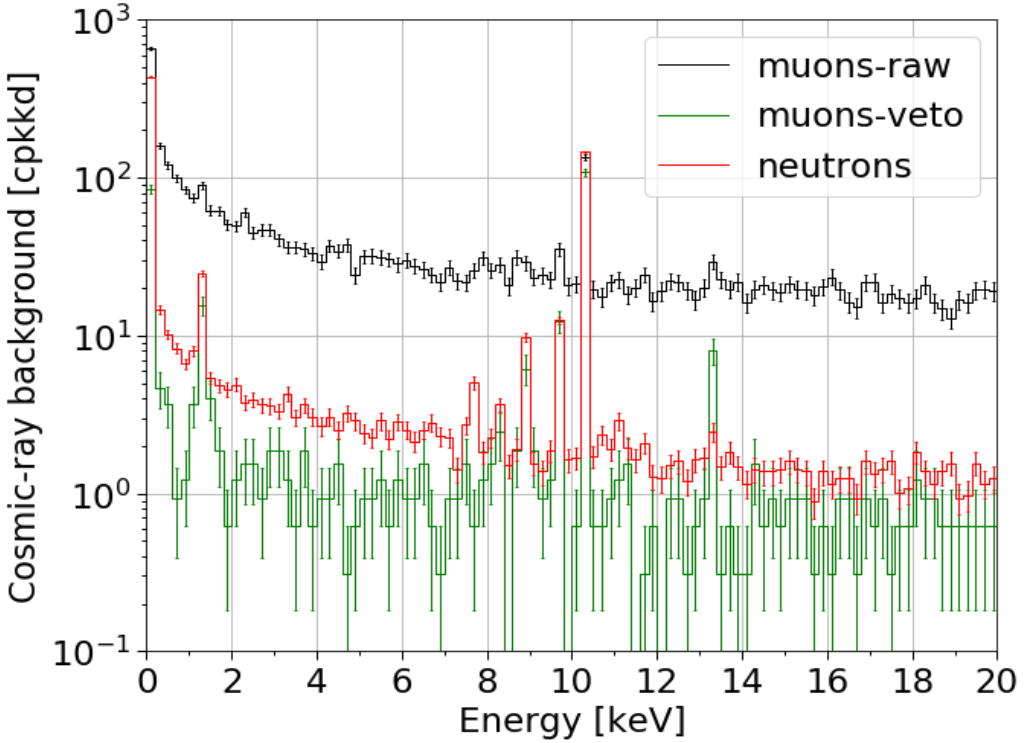
Water shield simulation design

- The size of the water tank has been optimized based on the MC simulation, espe cially the **cosmic-ray neutrons**, to satisfy the requirement of CEvNS detection;
- 5 m water shield on top can suppress the cosmic-ray neutron-induced backgroun d to a controlled level.

Water thickness 5m



Water thickness 3m

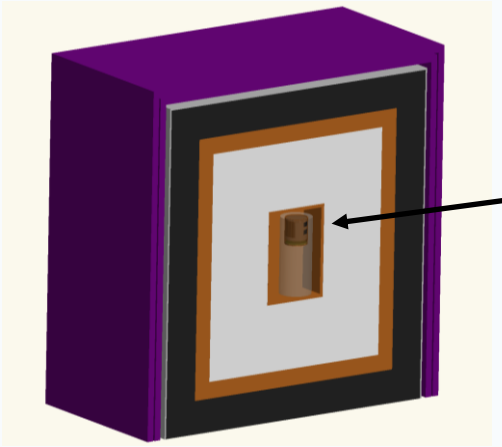


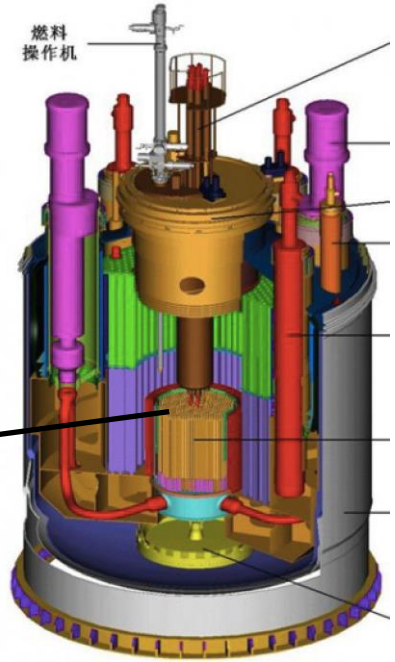
RECODE

- RECODE（REactor neutrino COherent scattering Detection Experiment）
- Low threshold PPCGe detectors, and related technology come from CDEX experiment

Project goals：

- Two Ge arrays（Far Site + Near Site /Very Near Site, ~10kg in total）
- Energy threshold ~1 keVnr (~160eVee)
- Joint measurement and analysis to reduce the systematical uncertainty



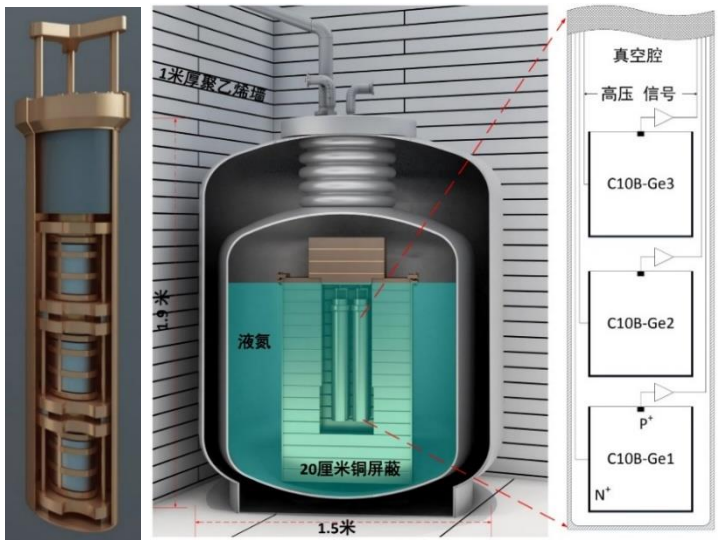


Reactor

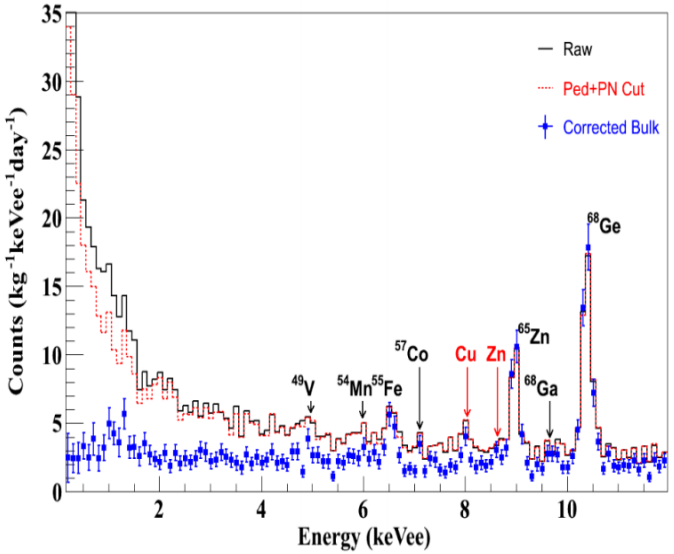
Neutrino flux ~10^{13}/cm^2/s

RECODE Far Site (based on CDEX-1/10)

CDEX-1B (1kg PPCGe), cooled with the cooling finger and LN2 Dewar

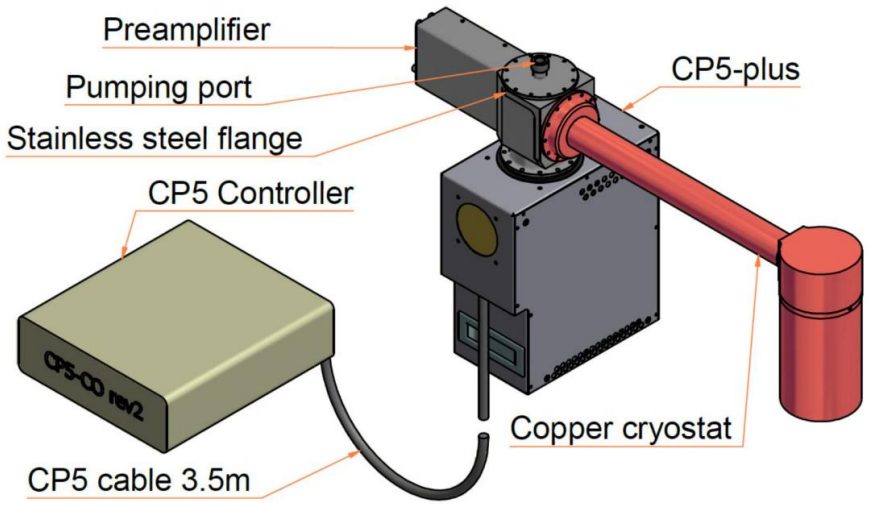


CDEX-10 (9*1kg PPCGe), cooled with the vacuum cryos tat directly immersed into LN2



CDEX-10 measured spectrum@CJPL, ~2 cpkkd@2keV, threshold 160 eVee

RECODE Near Site/Very Near Site



Electric cooled HPGe

From HT Wong

Mass (g)	Pulsar FWHM (eV_{ee})	Threshold (eV_{ee})
500	70	200
900	70	~230
1430	~60	~160
1430	70	200

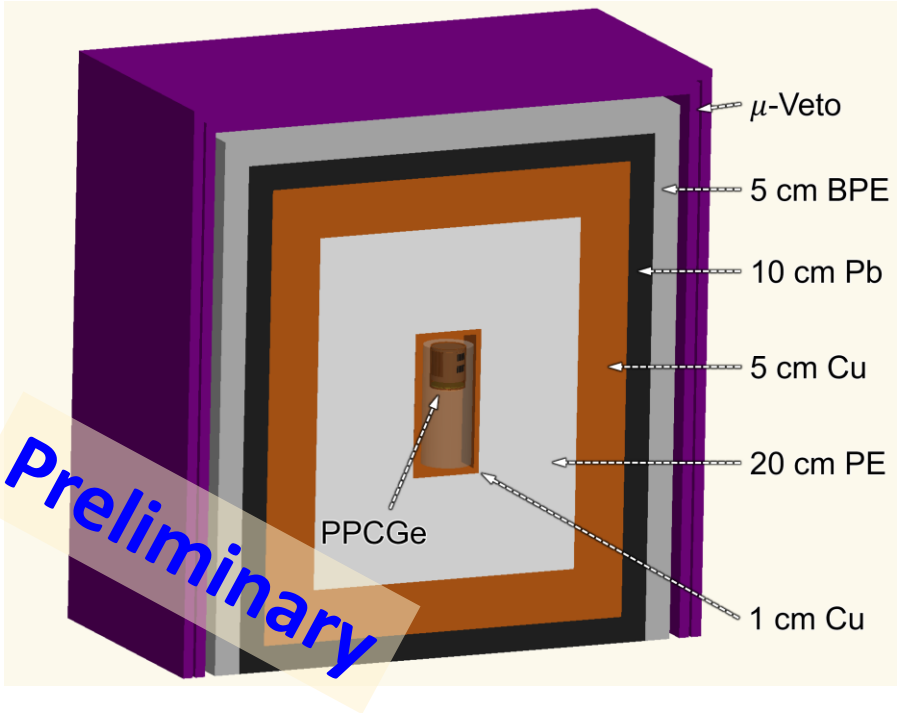
Advantages of electrical cooled HPGe:

- ✓ **No need to regularly replenish liquid nitrogen**
- ✓ **Controllable crystal temperature**
- ✓ **Real-time monitoring of Refrigerator performance**
- ✓ **Good long-term stability**

Preliminary Design of the shielding (Near Site)

- **Shielding design and optimization (Near Site)**
  - Anti coincidence efficiency of Cosmic ray:>99%
  - Gamma current strength: reduced by 5 orders of magnitude
  - Neutron current intensity: reduced by 3 orders of magnitude

- **From outer to inner (Preliminary):**
  - ✓ Muon veto detector
  - ✓ Boron doped polyethylene (BPE)
  - ✓ Lead (Pb)
  - ✓ Coper (Cu)
  - ✓ Polyethylene (PE)
  - ✓ Coper (Cu)



Schedule

2023	2024	2025	2026
✓ On site environmental background measurement/estimation ✓ Design, production, and processing of various subsystems	✓ Subsystem independent testing ✓ Joint testing work	✓ Transport to NPP, installation, testing ✓ First physics run	✓ Second physics run ✓ Data analysis

Subsystems testing @CJPL and ground, Sanmen Laboratory preparation

Physics Run (FS, NS, VNS) @Sanmen NPP

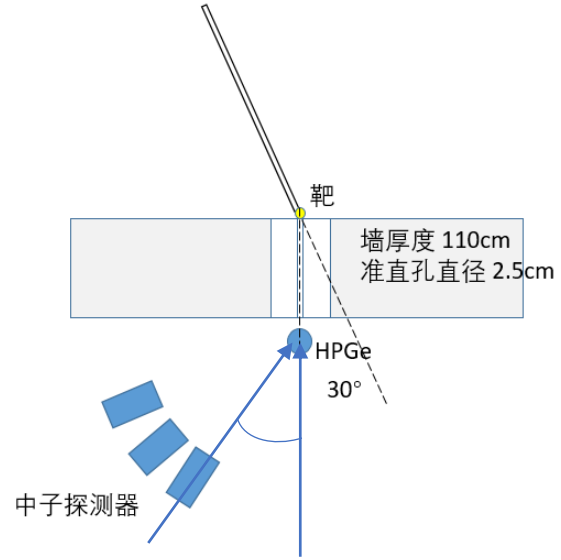
Measurement of quenching factor

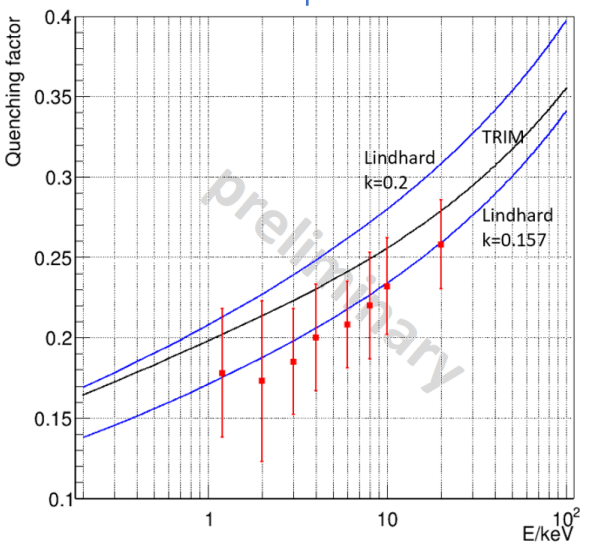
➢ Measurement of Ge QF @ 1-10keV

- ✓ 10g ultra-low threshold HPGe
- ✓ High Voltage Multiplier at CIAE
- ✓ EJ-301/BC-501A liquid Scintillator
- ✓ QF measurement results @1.2keV-20keV

➢ Future plans

- ✓ Use californium fission chambers or tandem accelerators to conduct more accurate measurements
  - more accurate measurement @ 1-20keV
  - Conduct measurement and research below 1keV

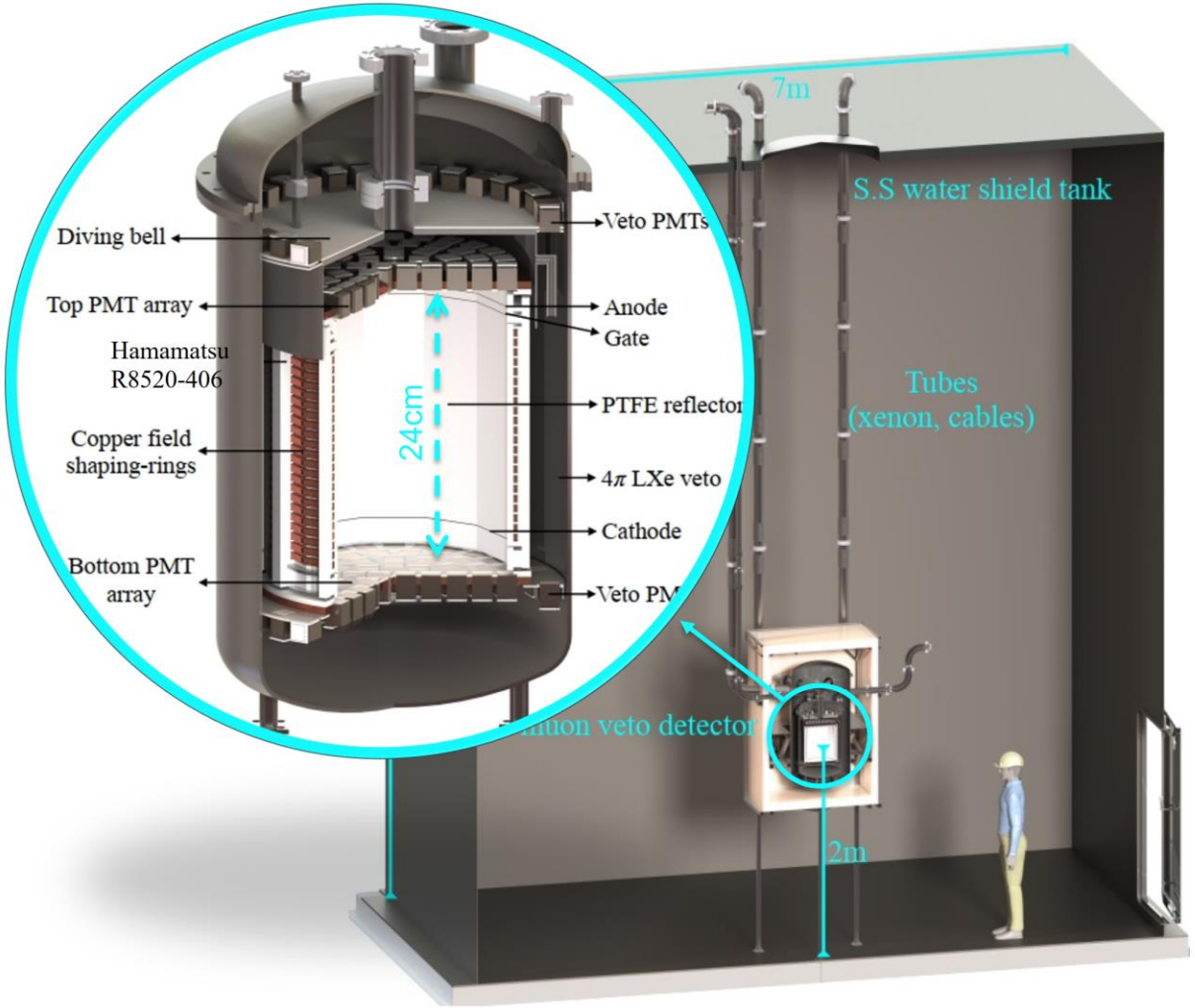




RELICS

RELICS
REactor neutrino LIquid xenon
Coherent elastic Scattering

■ RELICS（REactor neutrino LIquid xenon Coherent elastic Scattering）



- 7m passive water shield
- Plastic scintillator muon veto
- 32kg fiducial volume TPC
- 4π skin for gamma/beta veto
- Two 64 one-inch PMT array
- High E-field for high efficiency
- Low-background materials

Details in arXiv: 2405.05554

Summary

- Reactor neutrino CEvNS detection has great scientific significance for the verification of SM at low energy scale and the accurate measurement of weak mixing angle;
- The Sanmen Reactor Neutrino Laboratory is currently being under construction as the CEvNS experimental platform, which is located at the Sanmen NPP in Zhejiang, China;
- Two different detector technologies: HPGe (RECODE) and LXe TPC (RELICS), will be used to jointly measure the reactor neutrino CEvNS at multiple experimental sites;
- By joint measurements and analysis, the experimental systematic uncertainty can be significantly reduced and then improve the sensitivity.

Summary

- Reactor neutrino CEvNS detection has great scientific significance for the verification of SM at low energy scale and the accurate measurement of weak mixing angle;
- The Sanmen Reactor Neutrino Laboratory is currently being under construction as the CEvNS experimental platform, which is located at the Sanmen NPP in Zhejiang, China;
- Two different detector technologies: HPGe (RECODE) and LXe TPC (RELICS), will be used to jointly measure the reactor neutrino CEvNS at multiple experimental sites;
- By joint measurements and analysis, the experimental systematic uncertainty can be significantly reduced and then improve the sensitivity.

Thank you!

Litao YANG (杨丽桃), yanglt@mail.tsinghua.edu.cn