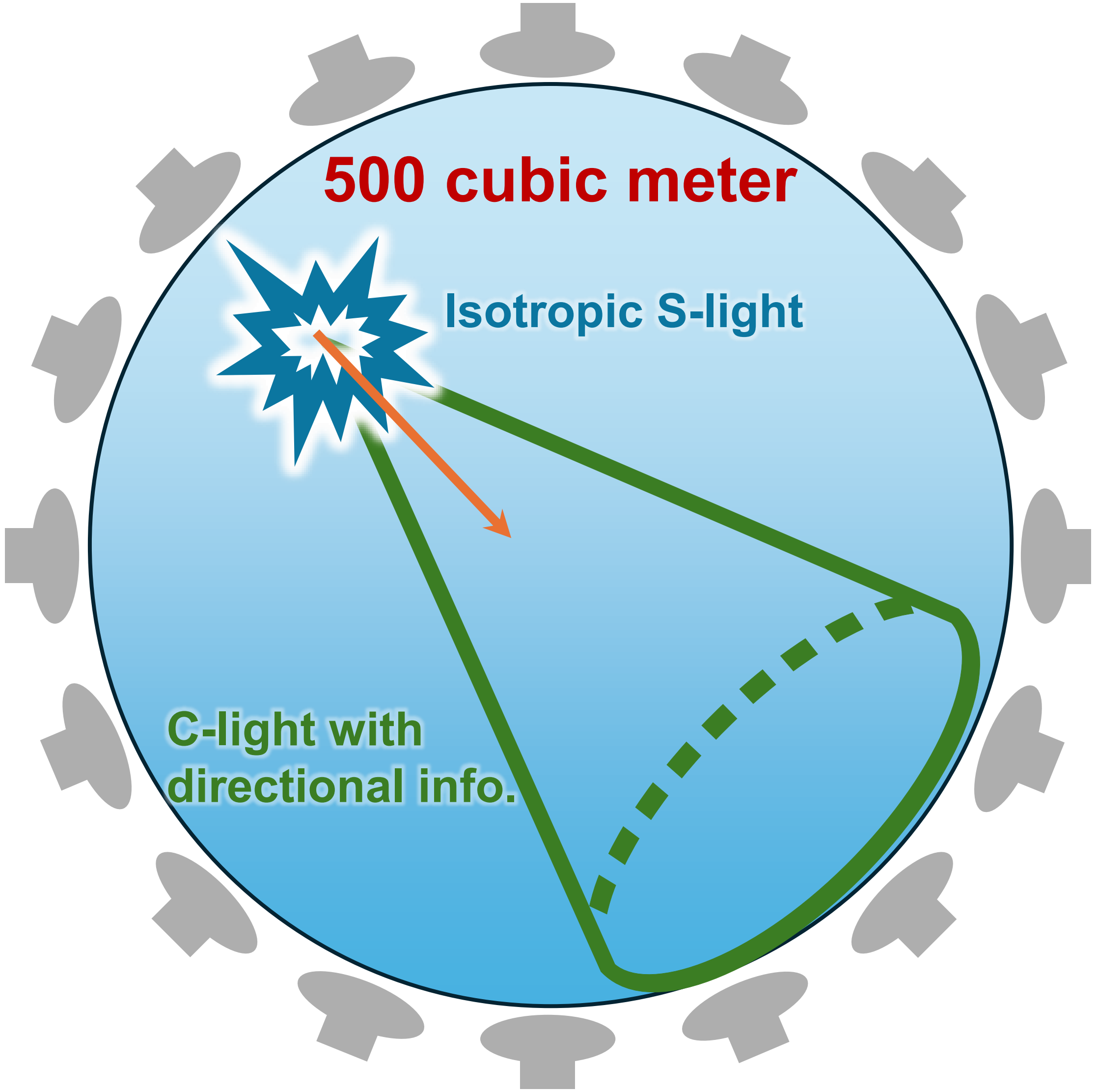
Research & Development of JinPing Neutrino Experiment (JNE)

Benda Xu & Wentai Luo
On behalf of JNE
Tsinghua University, Beijing

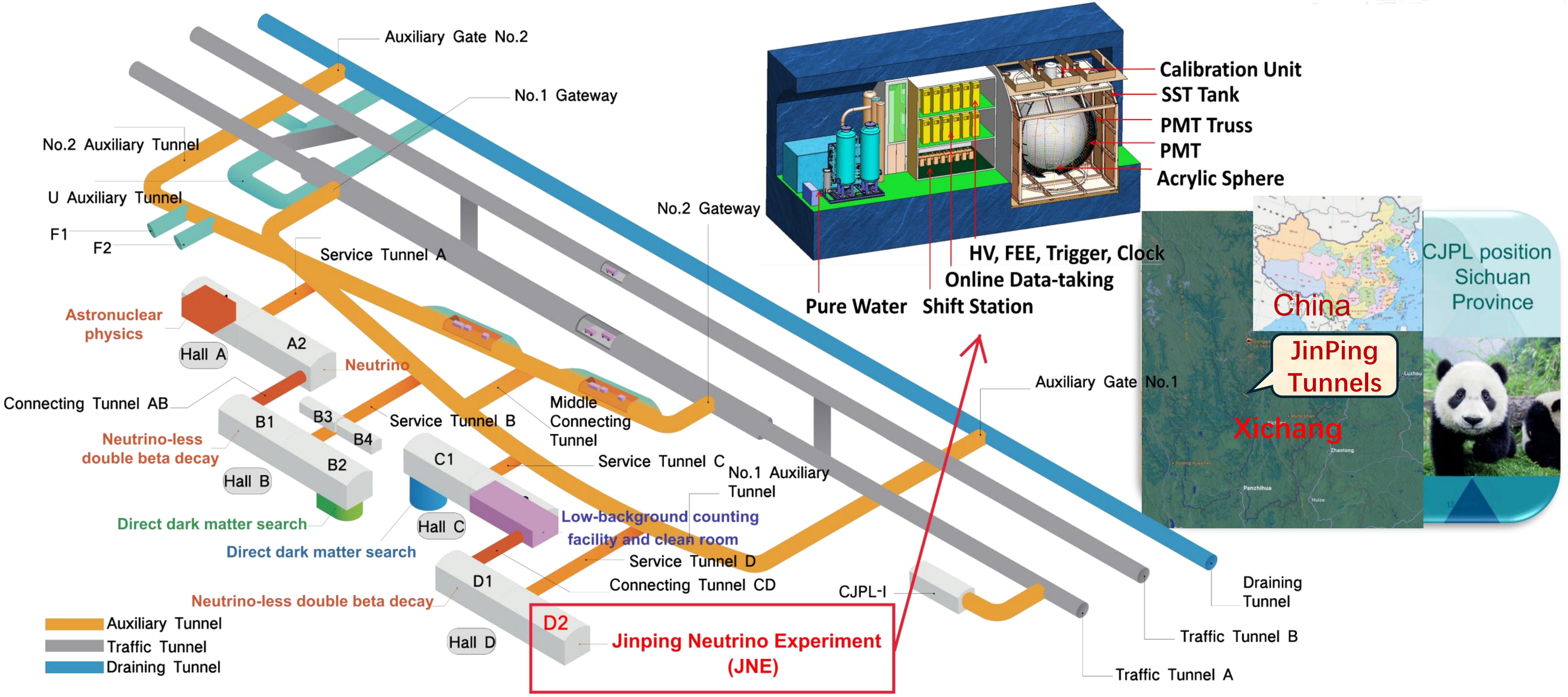
What is JNE?

- Solar neutrino observatory at China JinPing underground Laboratory(CJPL)

- Using Cherenkov light(C-light) and scintillation light(S-light) separation techniques to study MeV-scale neutrinos



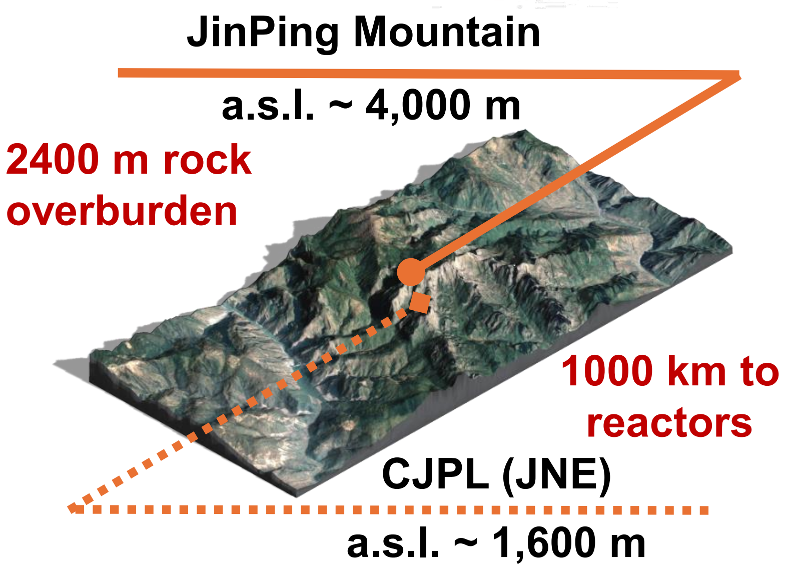
Where is JNE?

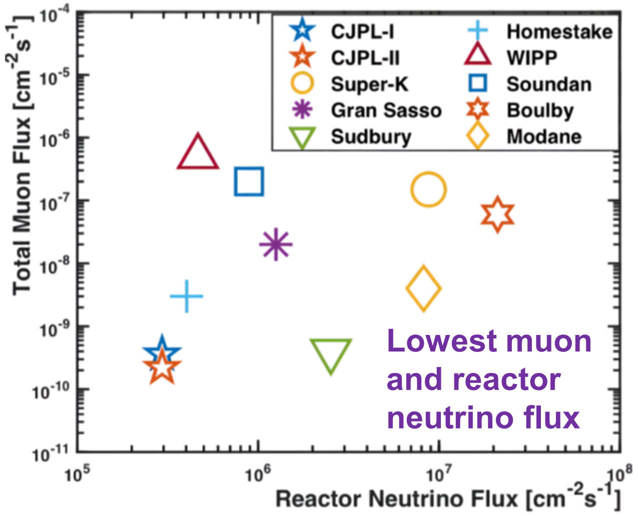


Auxiliary Gate No.2
No.1 Gateway
No.2 Auxiliary Tunnel
U Auxiliary Tunnel
F1
F2
Service Tunnel A
No.2 Gateway
Astronuclear physics
Hall A
A2
Neutrino
Connecting Tunnel AB
B1
B3
B4
B2
Service Tunnel B
Middle Connecting Tunnel
Neutrino-less double beta decay
Hall B
C1
Service Tunnel C
No.1 Auxiliary Tunnel
Hall C
Direct dark matter search
Direct dark matter search
Low-background counting facility and clean room
Service Tunnel D
D1
Connecting Tunnel CD
Neutrino-less double beta decay
CJPL-I
D2
Hall D
Jinping Neutrino Experiment (JNE)
Auxiliary Tunnel
Traffic Tunnel
Draining Tunnel
Auxiliary Gate No.1
Draining Tunnel
Traffic Tunnel B
Traffic Tunnel A
Calibration Unit
SST Tank
PMT Truss
PMT
Acrylic Sphere
HV, FEE, Trigger, Clock
Online Data-taking
Pure Water
Shift Station
CJPL position
Sichuan Province
China
JinPing Tunnels
Xichang

Why is JNE?

- **Lowest cosmogenic** and **reactor neutrino backgrounds**
- Extensive experience in the **oil-based** and **water-based** **slow liquid scintillator(LS) - LiCl aqueous solution**
  - High cross-section $\nu_e + {}^7\text{Li} \rightarrow {}^7\text{Be} + e^- (+\gamma)$
  - High natural abundance of Li-7: 92%
  - High solubility: 80 g LiCl in 100 g water
  - Spectrometer for ν_e and $\overline{\nu_e}$
- **Event-by-event direction reconstruction and particle identification(PID)**
- **Good chance for solar, geo, and supernova neutrinos**



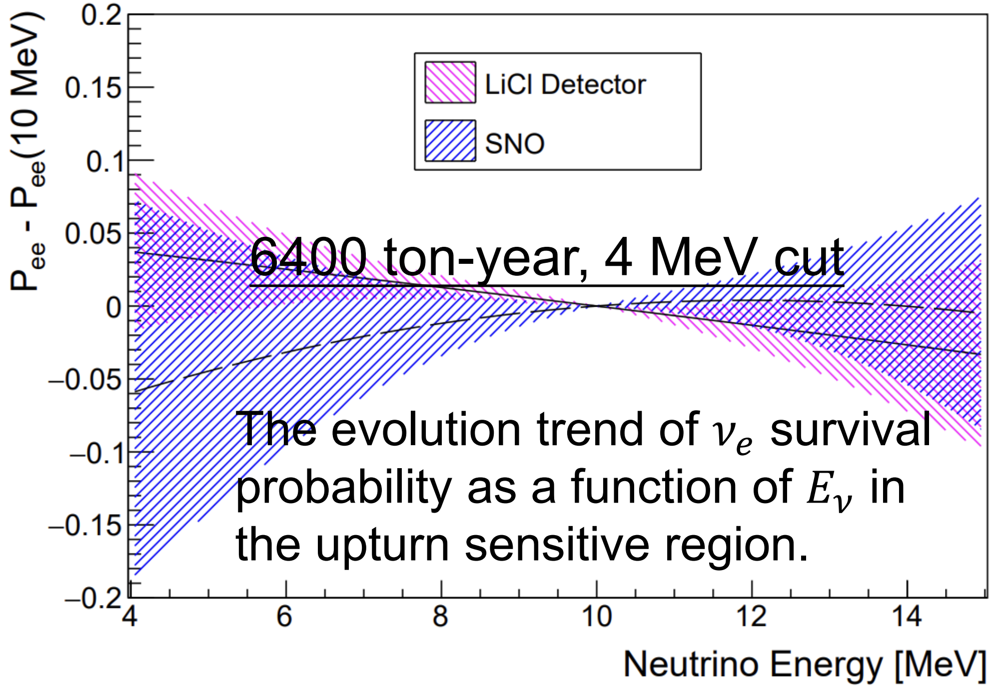


Why is JNE? Solar-ν

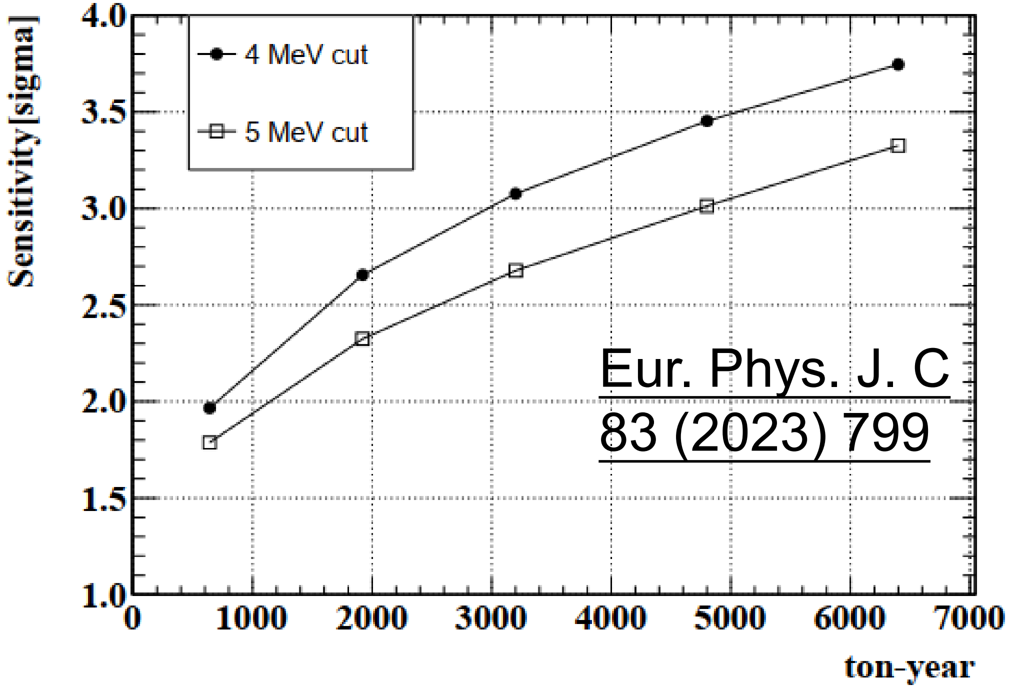
- **Charged current on Li-7 has an advantage than ν_e ES in measuring solar neutrino**

upturn effect

Solar neutrino survival probability-average versus energy

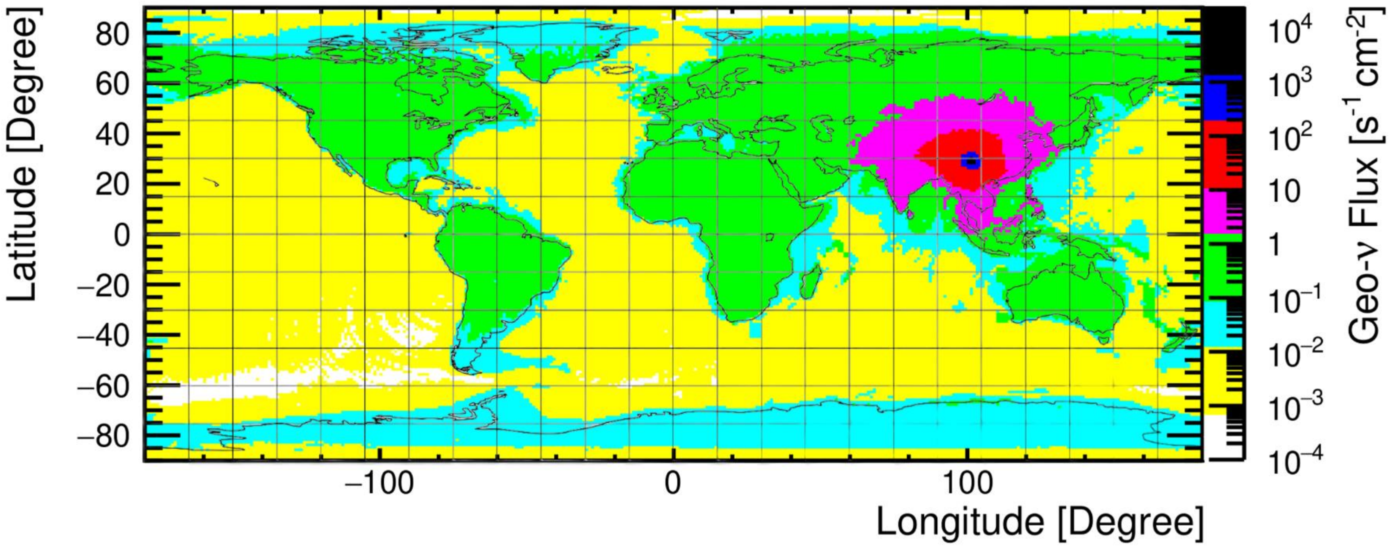


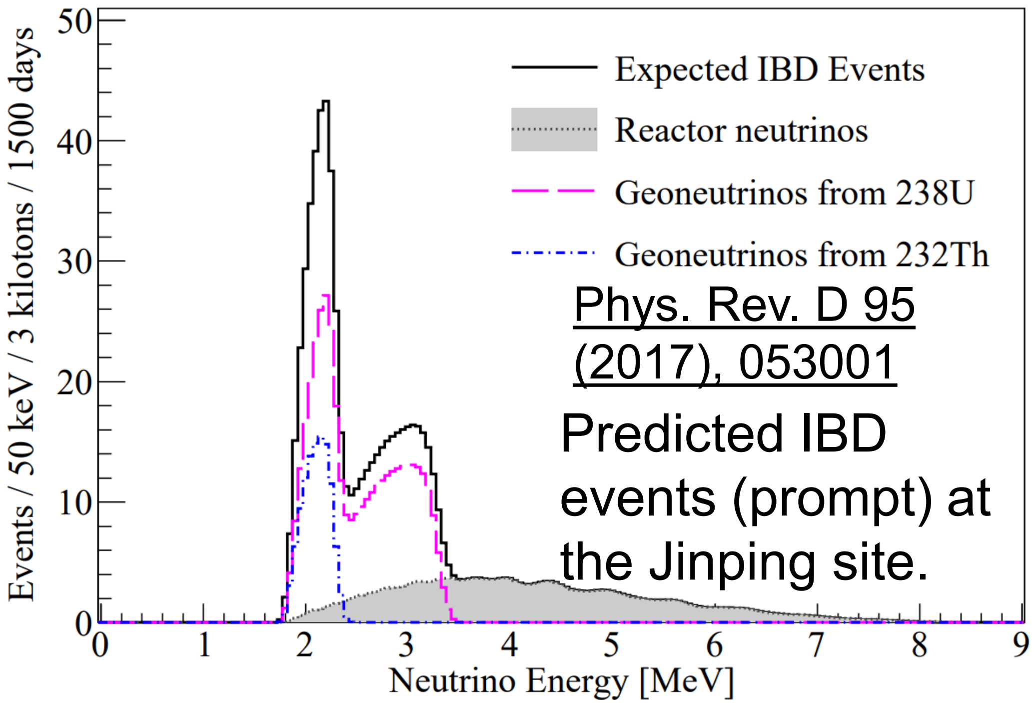
Upturn discovery sensitivity versus exposure



Why is JNE? Geo-ν

- JNE is very sensitive to Qinghai-Tibet plateau crust neutrinos
- With prompt-delayed signal detection: Expect tens of geoneutrinos in 5-10 years with the 500-ton detector



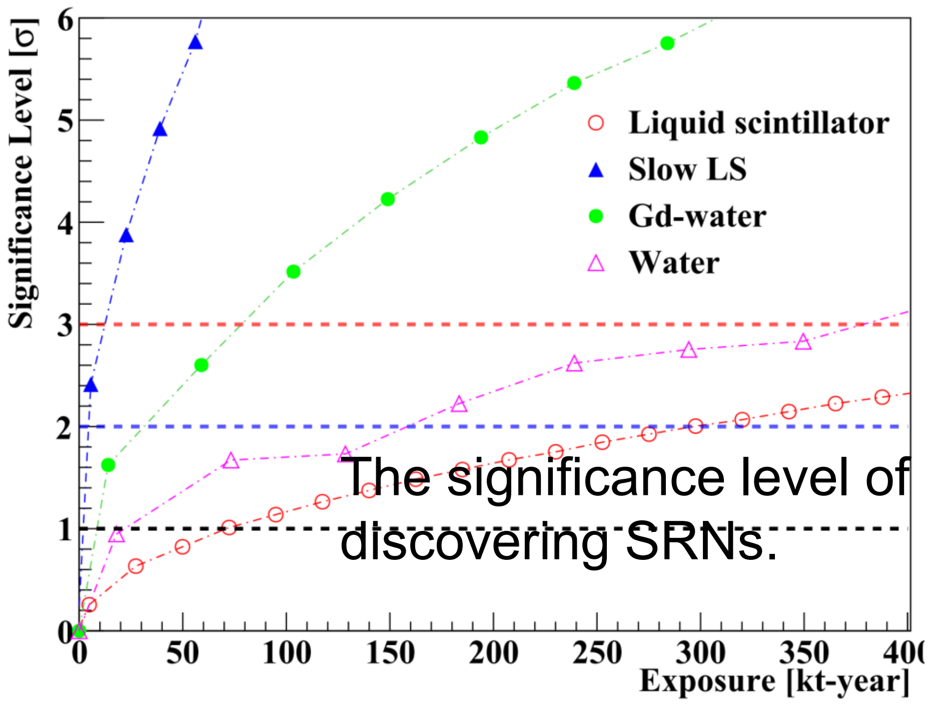


Phys. Rev. D 95 (2017), 053001

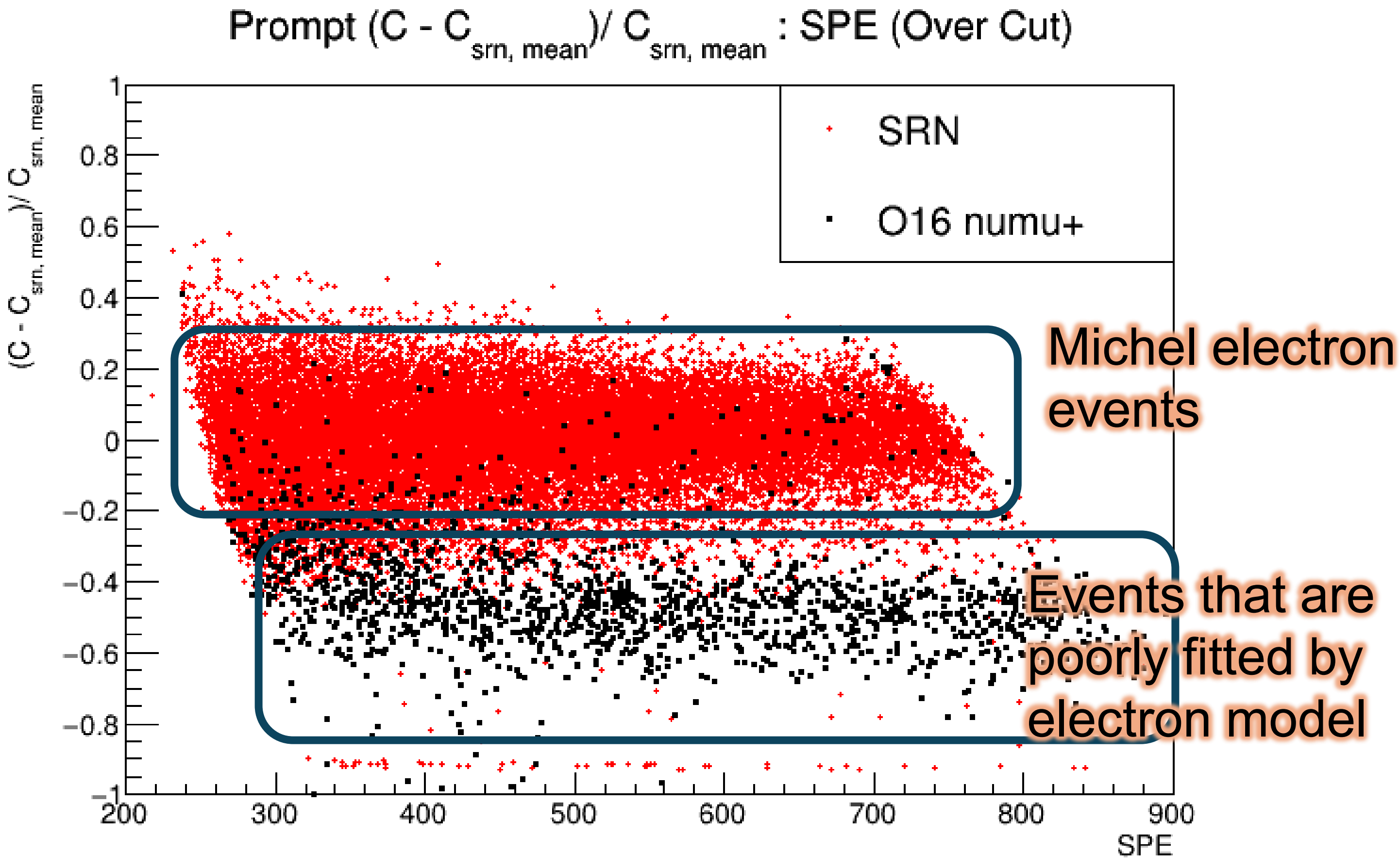
Predicted IBD events (prompt) at the Jinping site.

Why is JNE? SRN or DSNB

- Have the capability for PID to suppress atmospheric neutrino neutral current background



Phys. Lett. B 769 (2017) 255-261



JNE Timeline

- Structure design of the **multi-hundred ton detector**
- Event-by-event direction reconstruction & PID-**Q**iScin**T**
- Novel 8-inch MCP-PMT study
- FADC and readout design and testing

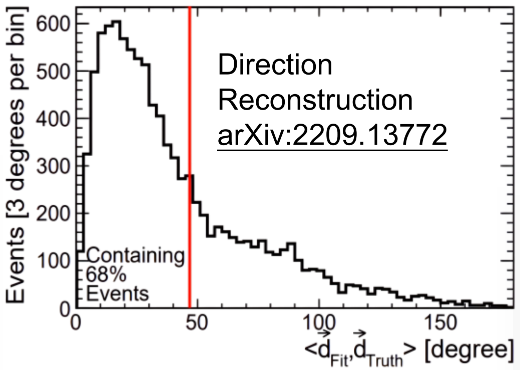
Letter of Intent
arXiv:1602.01733

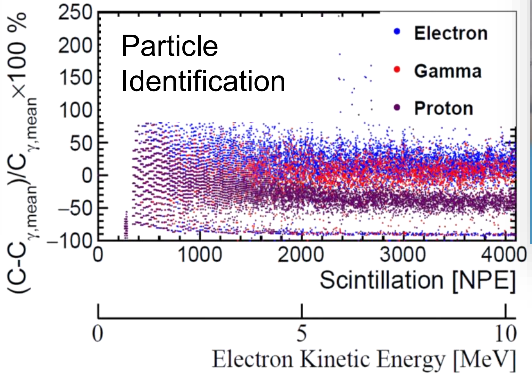
Multi-hundred ton detector commissioning

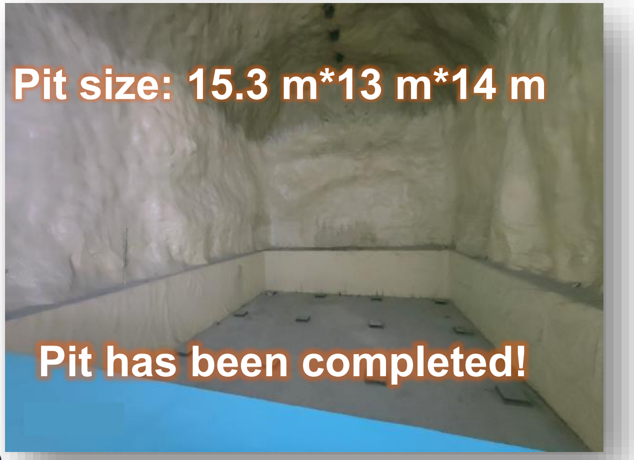
2015 | **2017** | **2023** | **2024** | **2026**

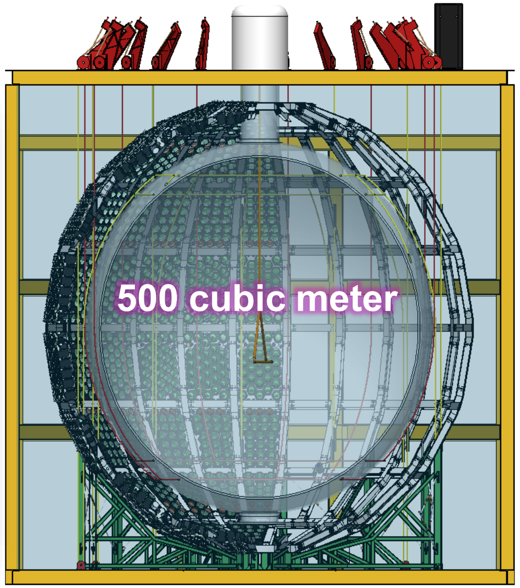
1-ton Prototype data taking

Multi-hundred ton detector **construction begins**

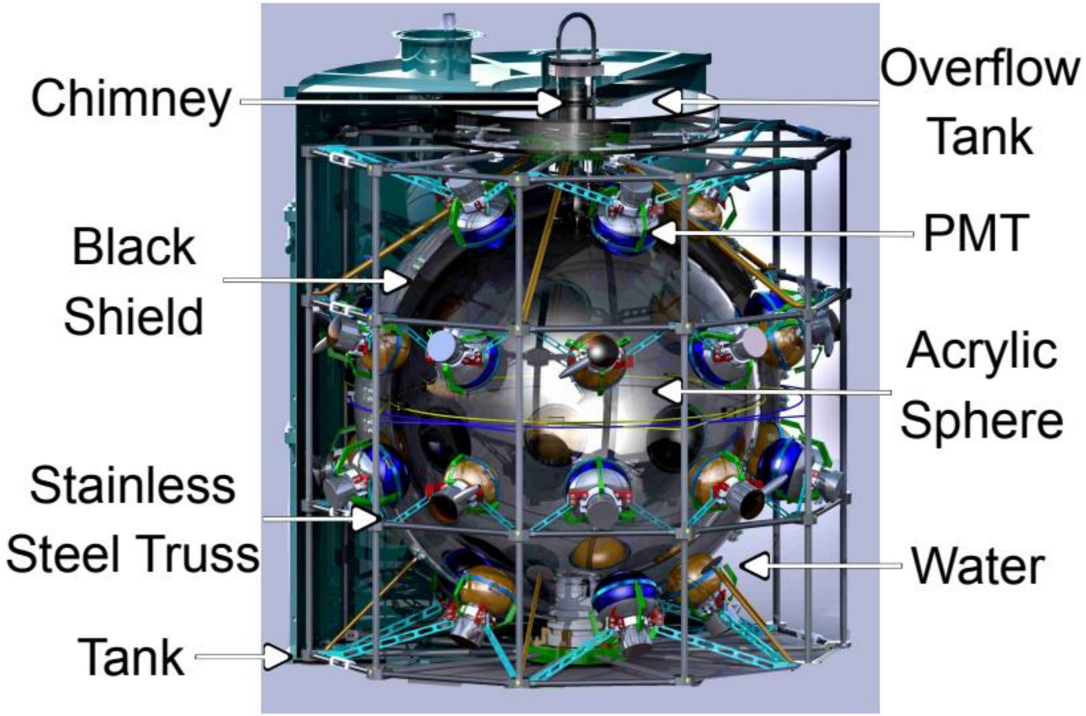








1-ton Prototype

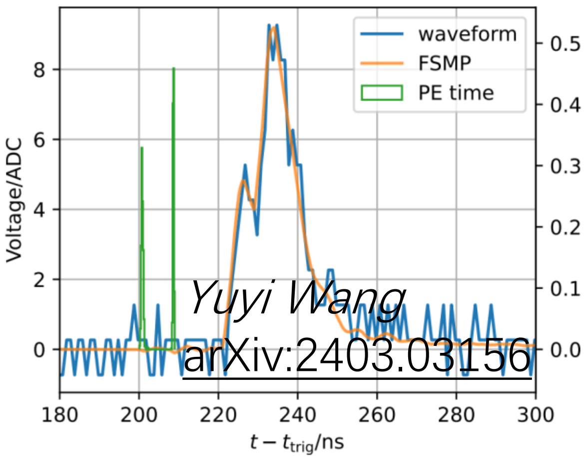


30ch 1-ton prototype at CJPL-I
Running for ~7 years

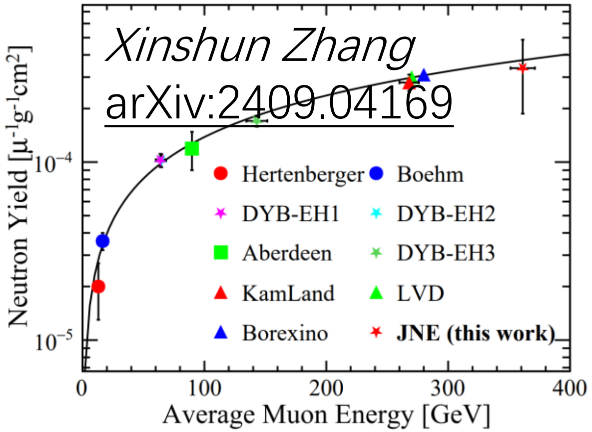
ID: #375, Upgrade Wednesday by Haozhe

Background measurement *Yiyang Wu* arXiv:2212.13158

		PMT	LS
Decay rate [Bq/g]	^{214}Bi	-	$(1.59 \pm 0.20) \times 10^{-8}$
	^{208}Tl	$(1.64 \pm 0.47) \times 10^{-3}$	-
	^{212}Bi	-	$<(1.01 \pm 0.20) \times 10^{-9}$
	^{40}K	$(1.24 \pm 0.35) \times 10^{-2}$	-
Contamination level [g/g]	^{238}U	-	$(1.28 \pm 0.16) \times 10^{-12}$
	^{232}Th	$(1.12 \pm 0.32) \times 10^{-6}$	$<(2.49 \pm 0.50) \times 10^{-13}$
	^{40}K	$(4.67 \pm 1.35) \times 10^{-8}$	-



Waveform analysis, total reflection reconstruction

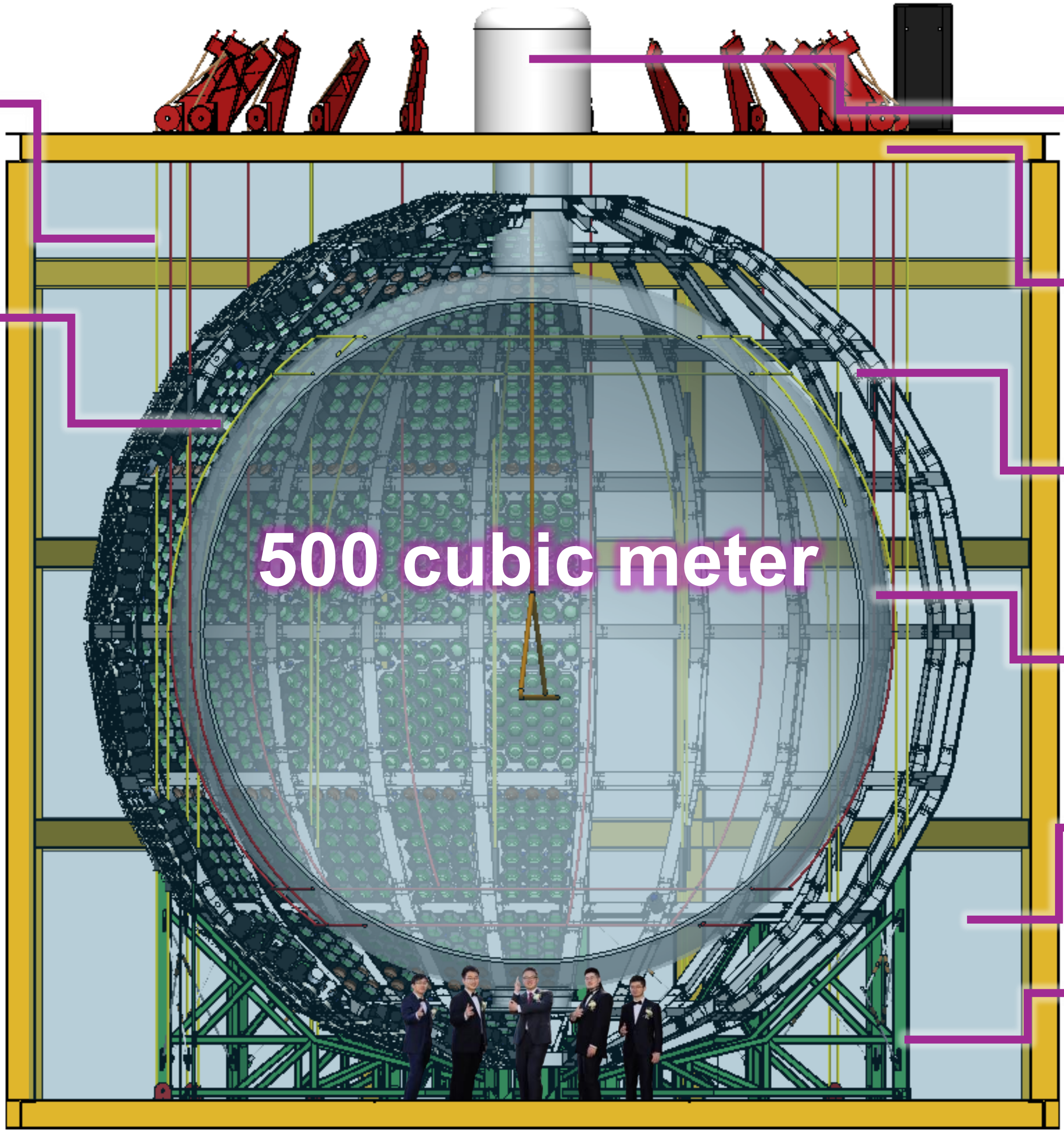


Muon flux and muon-induced neutron yield

Multi-hundred ton Detector

Rope System
holding-up and holding-down

8-inch MCP-PMT
+Light Concentrator
~3000, ~40% Coverage



Calibration Unit

Stainless Steel Tank(SST)
14.5 m *12.9 m *13.2 m

SST PMT Truss
Inner diameter(ID): 12.16 m

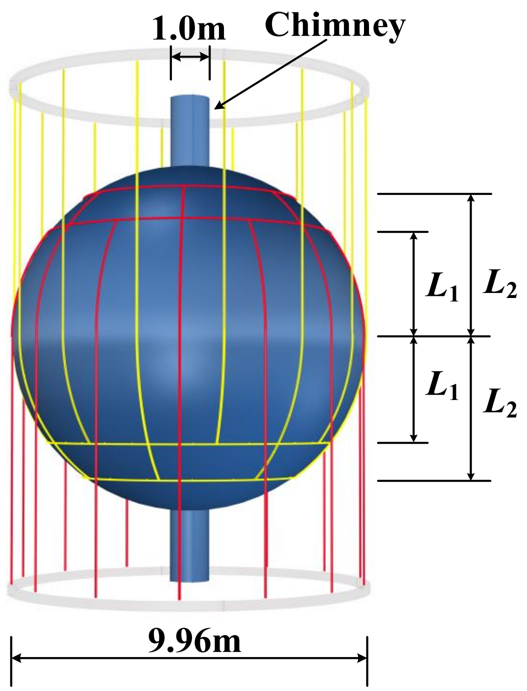
Acrylic Vessel
ID: 9.96 m, Thickness: 5 cm

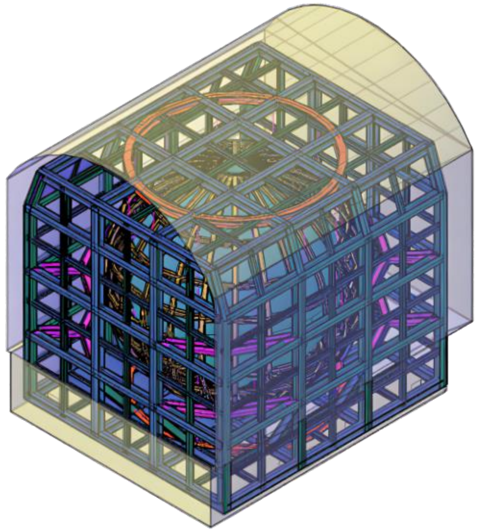
Shieling Material
Water and SST (or lead)

SST Supporting Legs

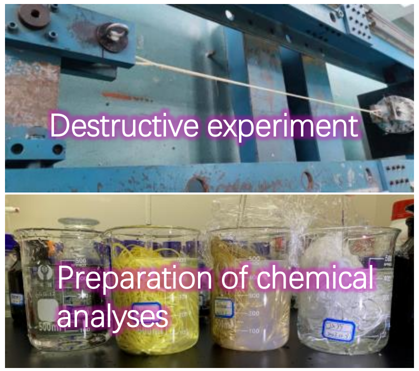
Central Detector

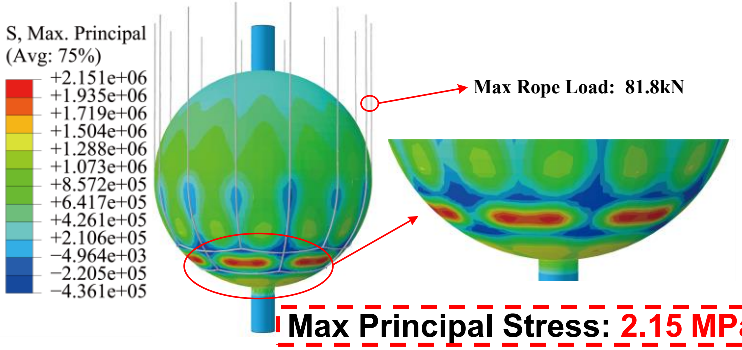
- 9.96 m spherical acrylic vessel, 500 cubic meter(Water, SlowLS, or LiCl aqueous solution)
- Rope to hold the acrylic vessel
- **Density difference to water: ±20%(Gravity or buoyancy)**
- Low background
- High strength, low creeping, water compatibility
- Mechanical analysis of the SST framework has been finished
- Finite element software ABAQUS is adopted





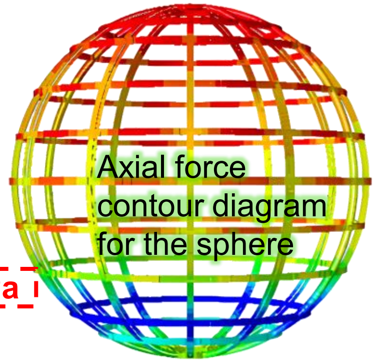
SST Frame

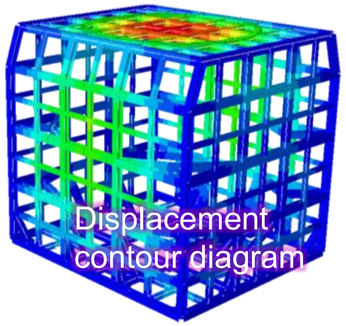




Max Principal Stress: 2.15 MPa

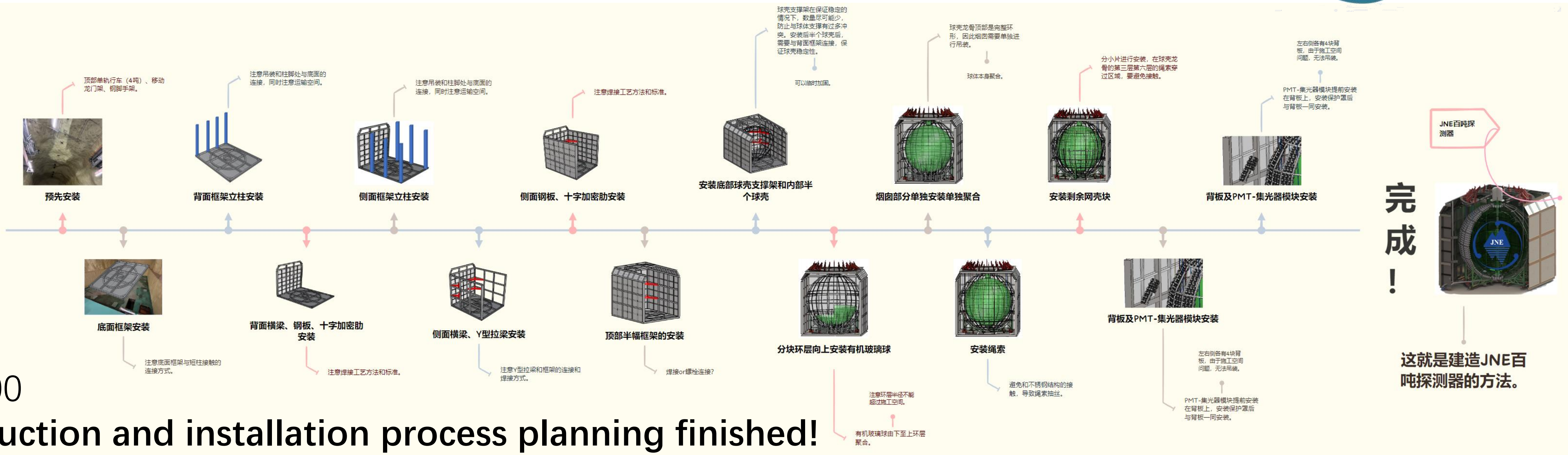
ArXiv: 2406.12899





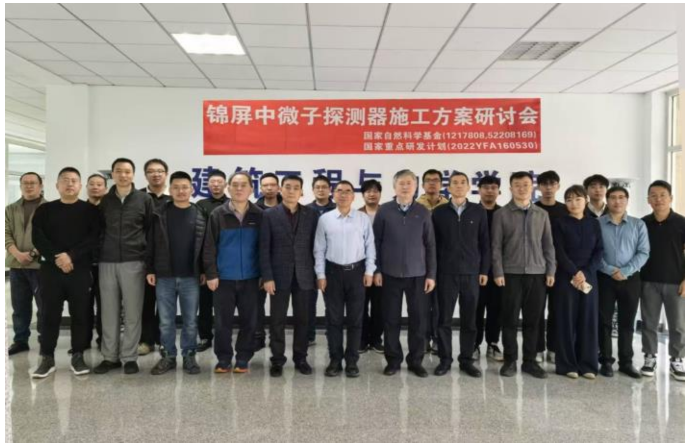
JNE-500 Installation Process

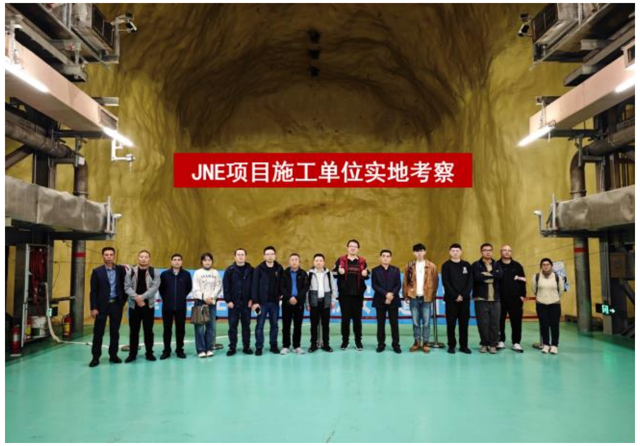
JNE百吨探测器施工安装流程



JNE-500

Construction and installation process planning finished!



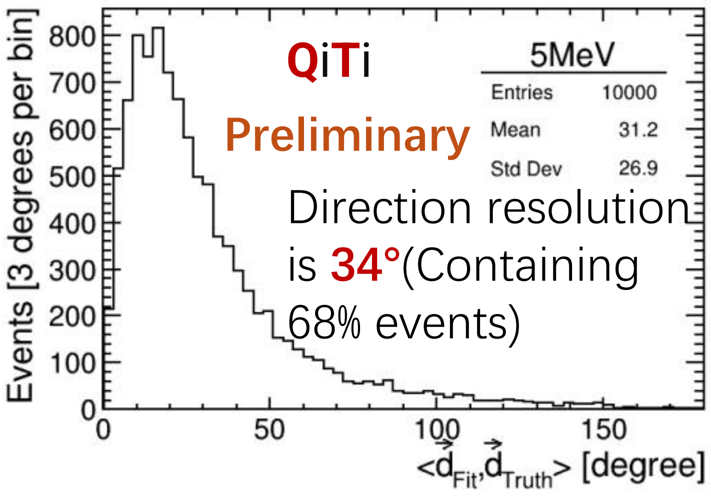


JNE-500 Planning

2027 — 2028 — 2038

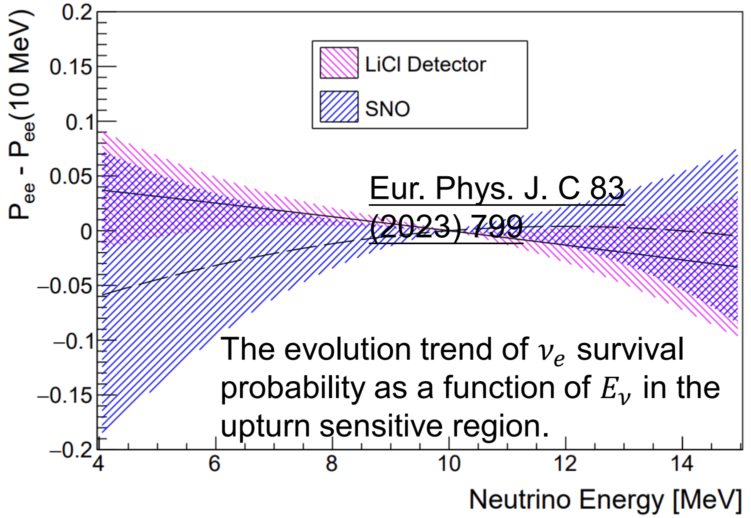
Phase Ⅰ

- **Target material:** Water
- **Reconstruction algorithm:** **Q**i**T**i
- **Purpose:** Checking detector operation



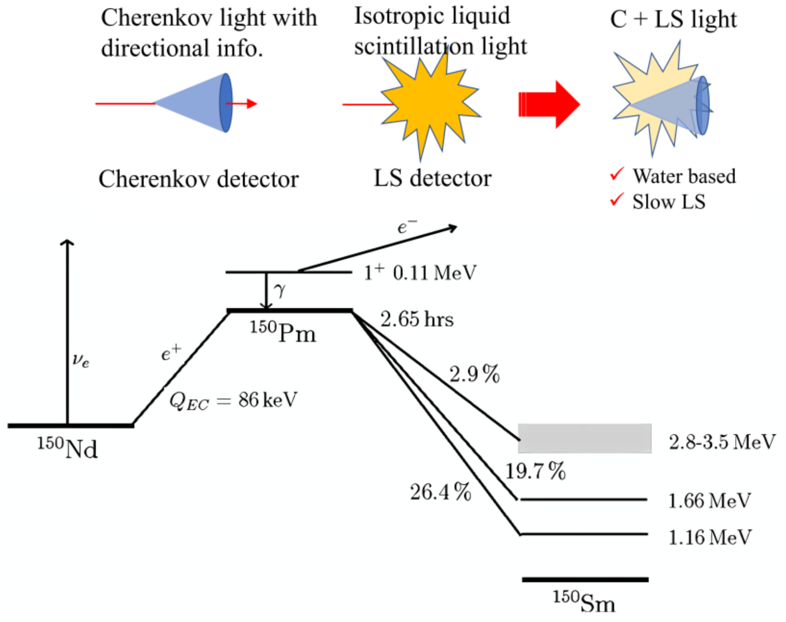
Phase Ⅱ

- **Target material:**
  LiCl aqueous solution (water-based)
  Slow liquid scintillator (oil-based)
- **Reconstruction algorithm:** **Q**iScin**T**
- **Purpose:** Solar, Geo and Supernova ν



Phase Ⅲ

- **Target material:**
  Nd-doped liquid scintillator
- **Purpose:** $0\nu\beta\beta$ study



JNE-500 CDR & TDR

- 2024.08.19: Completed the first draft of the **conceptual design report (CDR)** of the "Jinping Neutrino Detector" and passed the scientific review.

- 2024.10.18: Completed the first draft of the **technical design report (TDR)** of the "Jinping Neutrino Detector" and passed the technical review.

深地兆电子伏能区太阳中微子观测站概念设计报告

--中微子“清心”计划

陈少敏　安海鹏　陈晖有　付昊阳　宫　辉　龚光华　郝传晖　姜　林　李福乐
李进京　梁　晔　刘　灵　刘学伟　骆文泰　邵文辉　孙昊哲　王　青　王宇逸
王元清　王　喆　魏昌旭　文敬君　翁　俊　武益阳　徐　闯　徐　彤　续本达
薛　涛　杨玉梓　张爱强　张　彬　张天雄　张昕舜　张志财

清华大学

卜宜都　林子信

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李贝贝

合肥工业大学

凌家杰

中山大学

郑阳恒　刘　倩

中国科学院大学

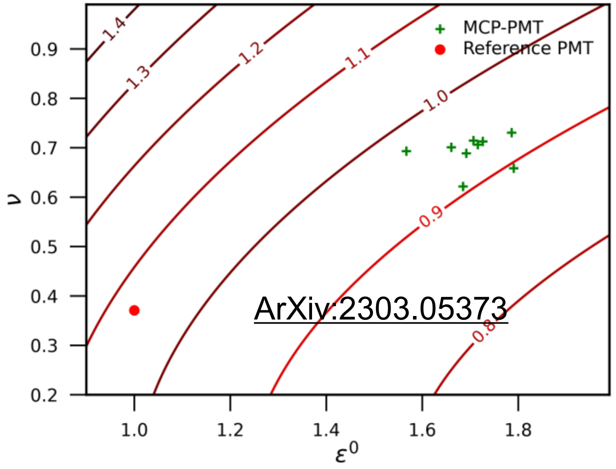
JNE-500 CDR

JNE-500 TDR

MCP-PMTs & Electronics

~3,000 novel 8-inch MCP-PMTs

- U、Th: <4e-8 g/g，K-40: <4e-9 g/g
- High QE: ~30%
- Good TTS: <1.8 ns



light concentrator

- Mean square deviation and relative photon detection efficiency distribution of PMT charge spectra

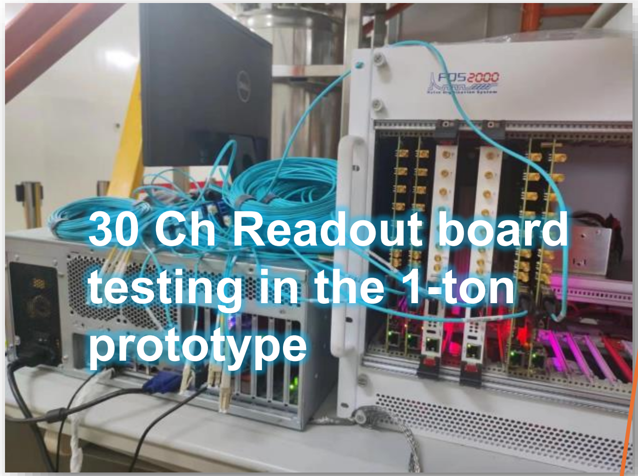
ID: #219, Light concentrator Poster by Shuai

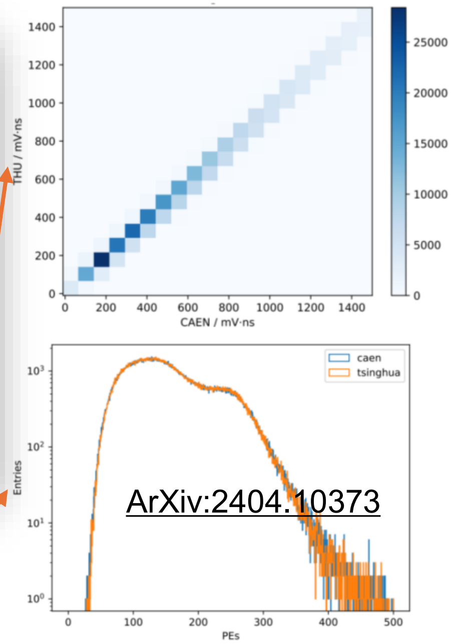
FADC for PMT waveform readout

- 350 mW/ch, 12-bit, 1 GSps
- Readout board, Bandwidth 300 MHz, 40Gbps

The whole system has been tested on the one-ton prototype this year.

ID: *#503*, Electronics *by Haoyan*

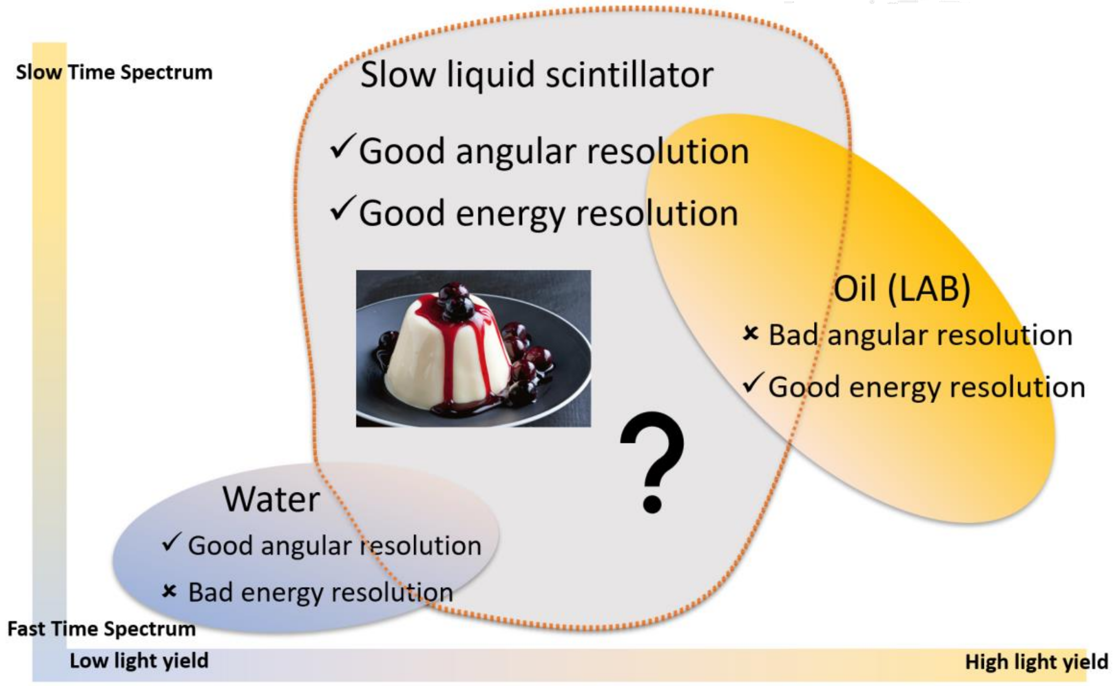


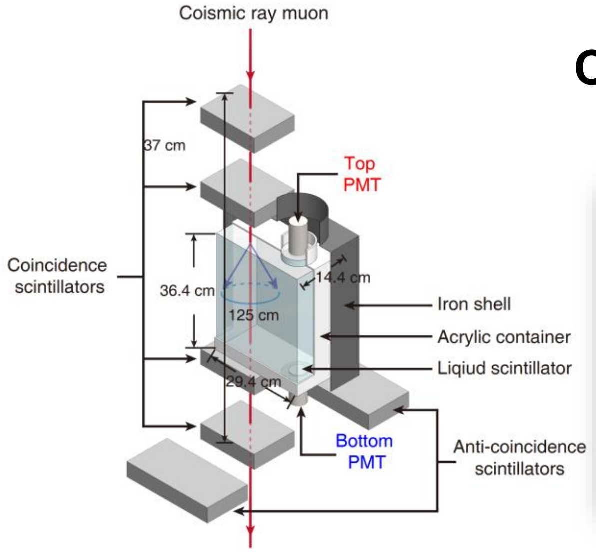


Charge spectrum(top) and PE spectrum(bottom) comparison between THDAQ system and CAEN DAQ system

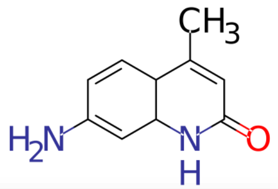
Slow Liquid Scintillator

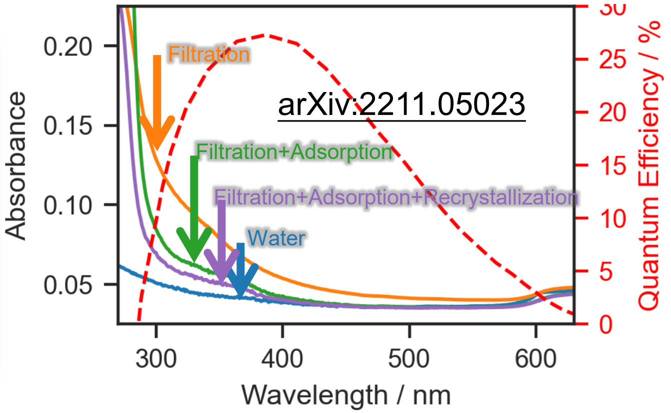
- Have good angular resolution and energy resolution
- **Reduce the interference of S-light**
  → **Get direction**
  - Control the S-light yield(**water-based LS**)
  - Control the emission speed(**oil-based LS**)

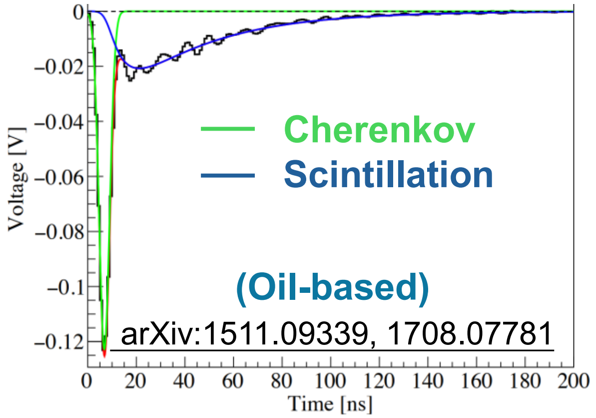




CS-124:





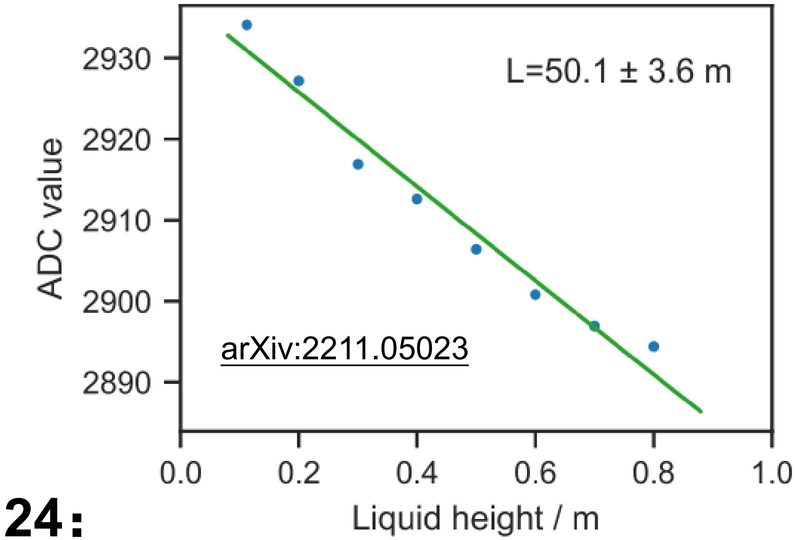


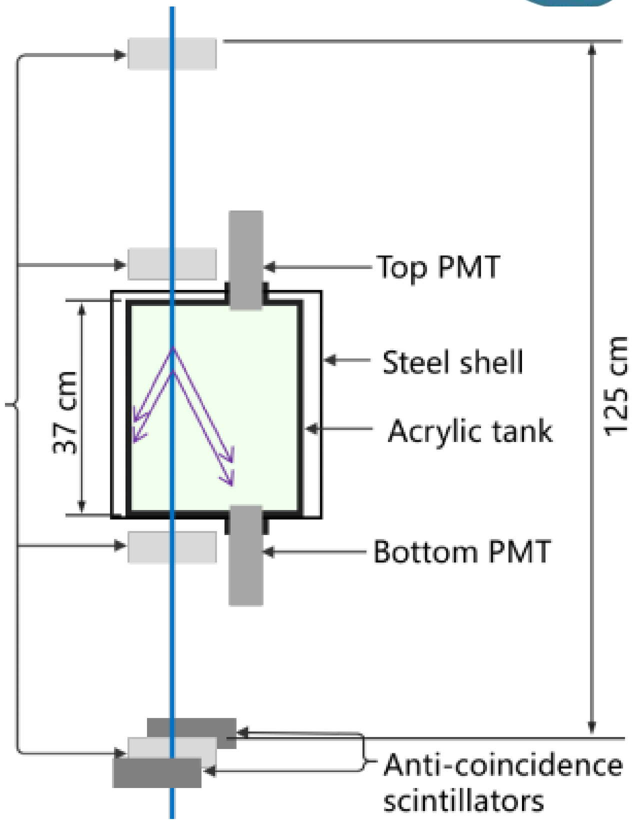
LiCl Aqueous Solution

Ideal for solar neutrino upturn effect study

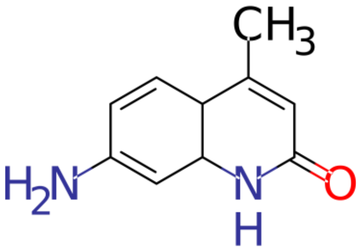
- Attenuation length at 430 nm is greater than 50 m
- CS-124 can be added to enhance light yield

(b)





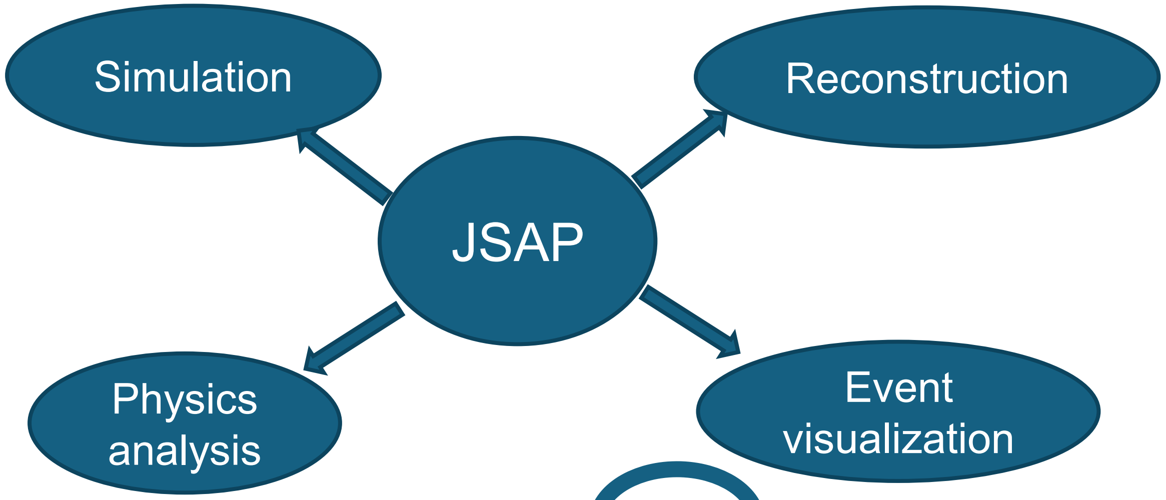
CS-124：

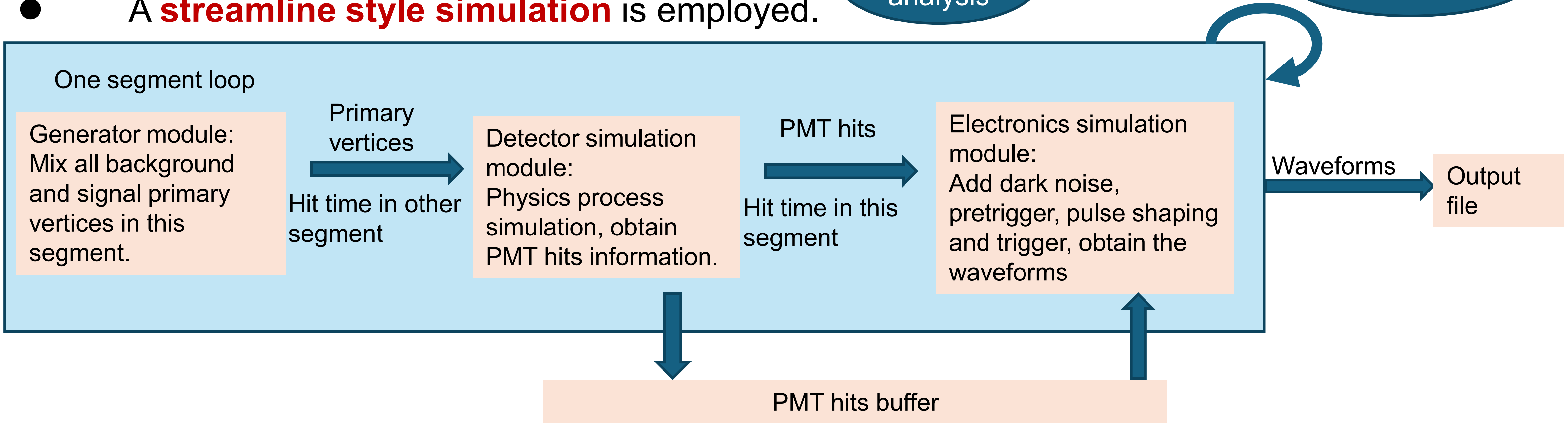


	Top PMT PEs	Bottom PMT PEs
Water	0.76 ± 0.08	15.8 ± 1.5
Saturated LiCl solution	0.54 ± 0.08	17.2 ± 1.5
Saturated LiCl solution with 1 ppm C-124	3.7 ± 0.4	16.0 ± 1.6

Jinping **S**im. & **A**na. **P**ackage

- JSAP uses **Geant4** and **GDML** for studying various detector geometries like spherical and cylindrical detectors.
- Electronics and trigger simulations are included, offering waveform readout.
- A **streamline style simulation** is employed.





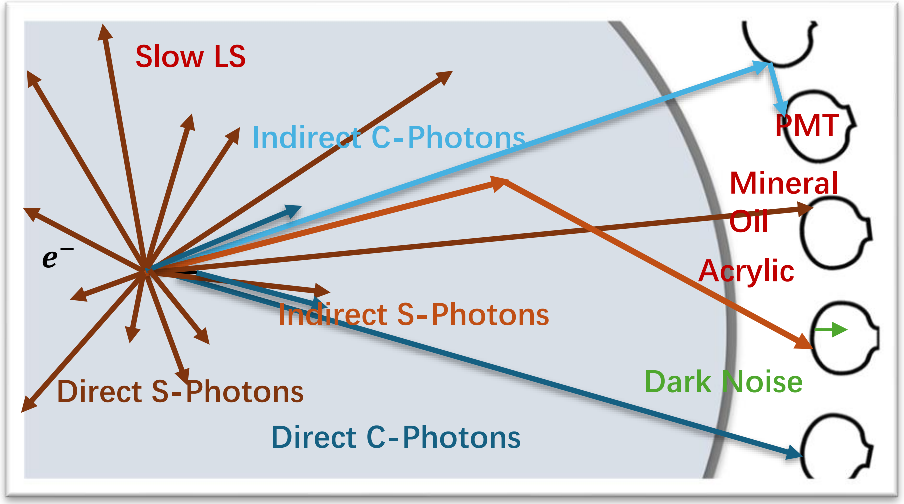
SlowLS Recon. QiScinT

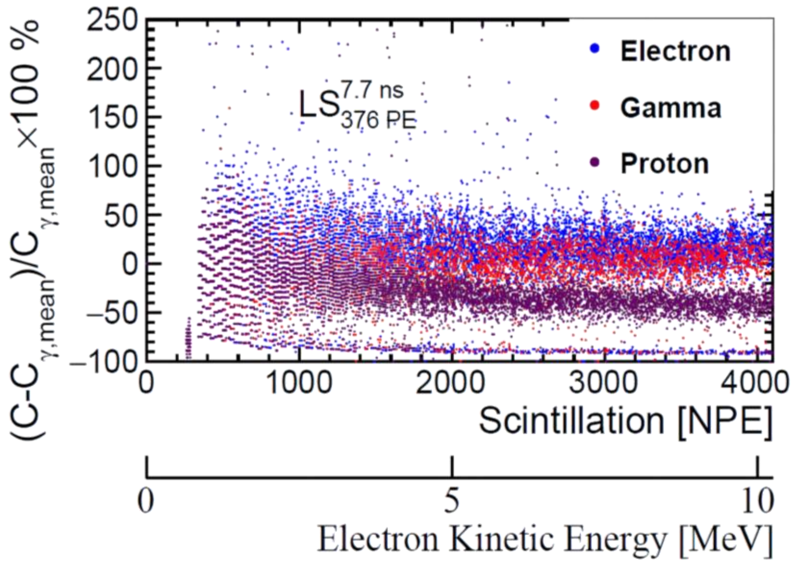
- Reconstruct both Cherenkov light and scintillation light
- Event-by-event **direction**, energy, position reconstruction
- C-light emission capability ranking:

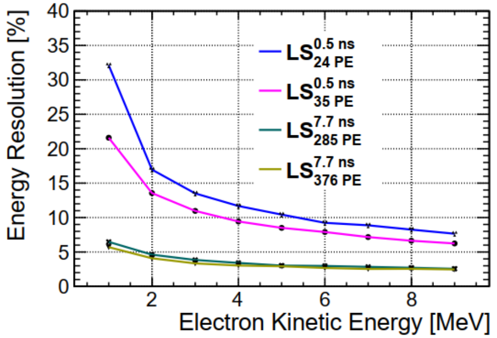
$e > \gamma > p \approx \alpha$

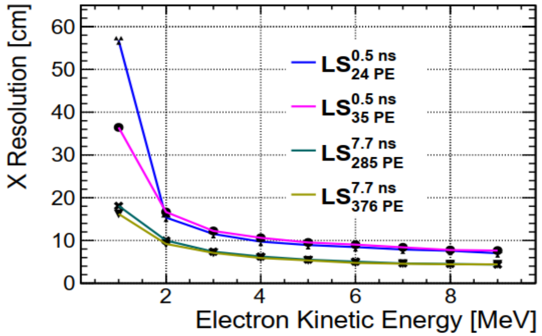
Particle identification

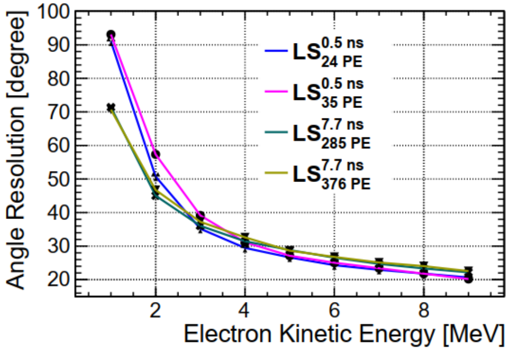
Guide liquid scintillator development, arXiv:2209.13772





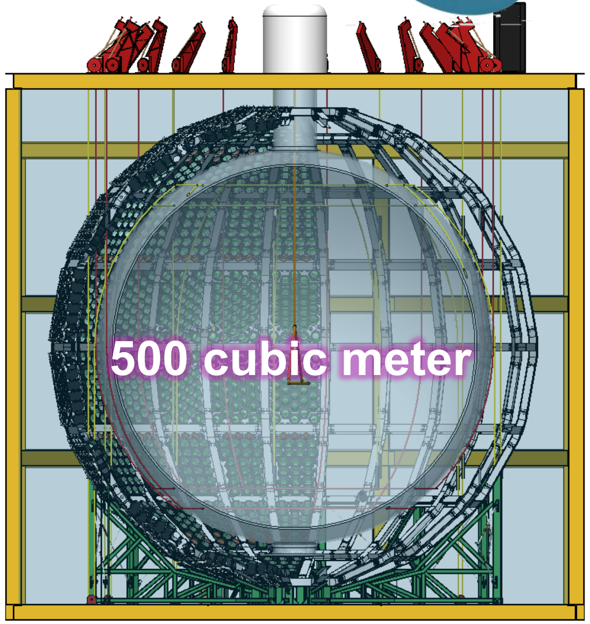




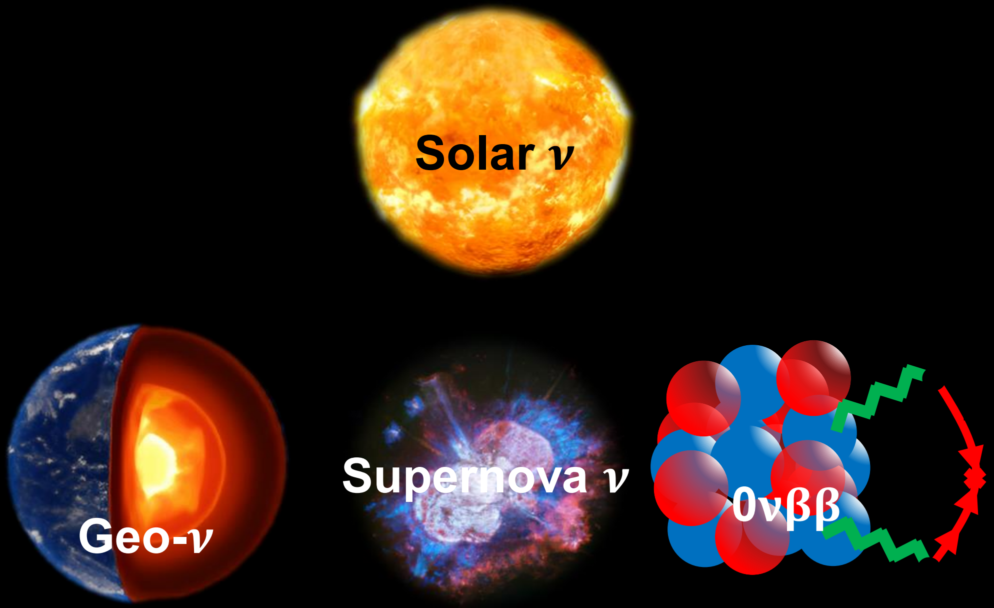


Summary

- Multi-hundred ton solar neutrino observatory at CJPL-II will be constructed by **2026**.
- **Novel 8-inch MCP-PMT**, low background, fast, high QE.
- ADC chips and waveform readout electronics under design and testing.
- Explored the option with **LiCl aqueous solution and slow LS**.
- Successfully developed the reconstruction algorithms **Q**iScin**T** and **Q**i**T**i based on slow LS and water, capable of **direction reconstruction and particle identification**.



- Rich physics with MeV-scale neutrinos at CJPL-II, see http://jinping.hep.tsinghua.edu.cn



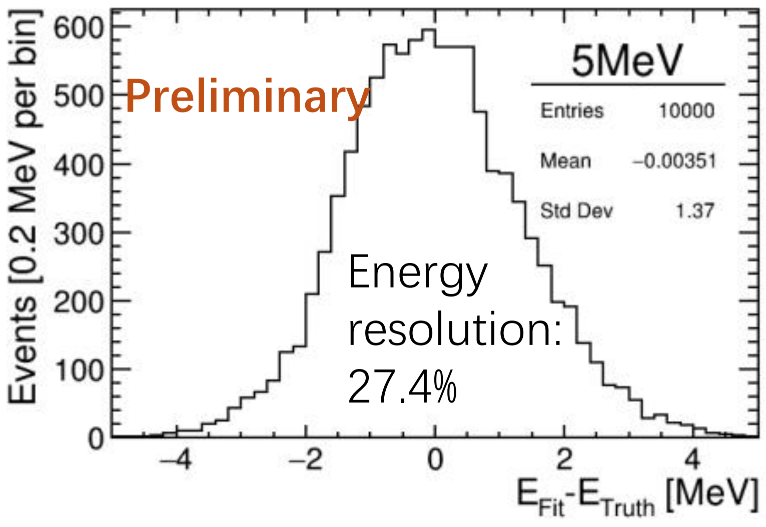
Thank You！

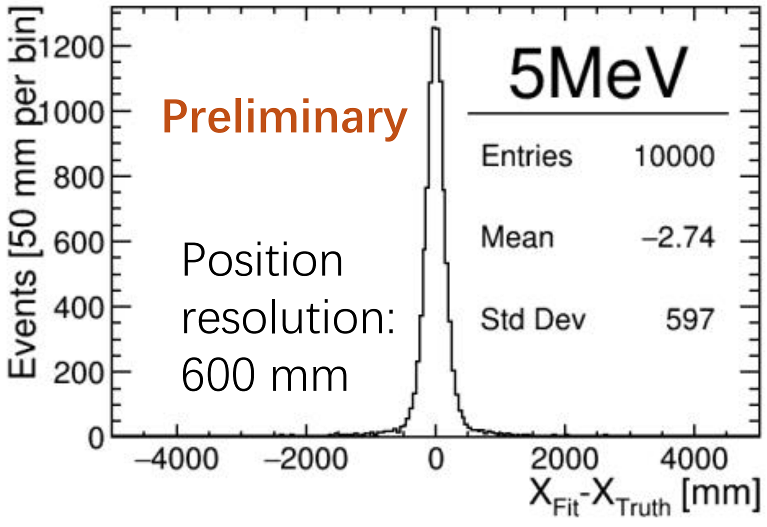
http://jinping.hep.tsinghua.edu.cn

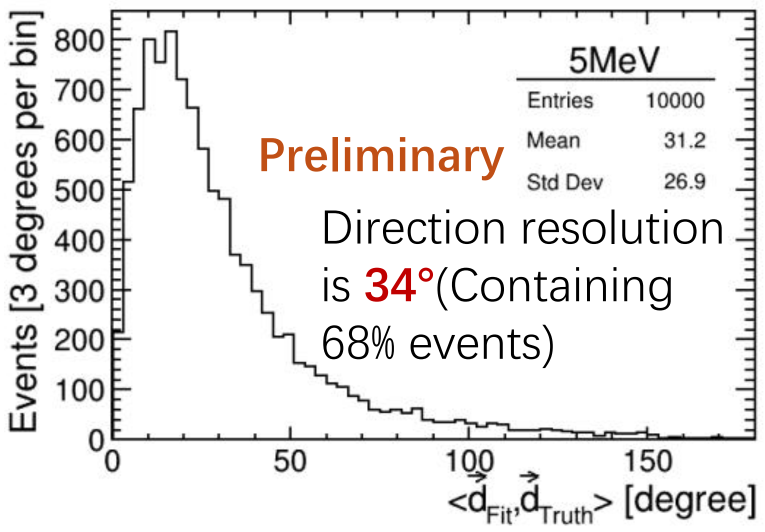
Water Recon. QiTi

- For **water phase (phase 1)** of JNE-500
- ~18% PMT photocathode Coverage
- Referring to the **Q**iScin**T** and the **BONSAI** algorithm
- **T**i is pronounced closer to tai (Wentai)
- Solved the local minima problem by improving the angular resolution from 42° to 34°

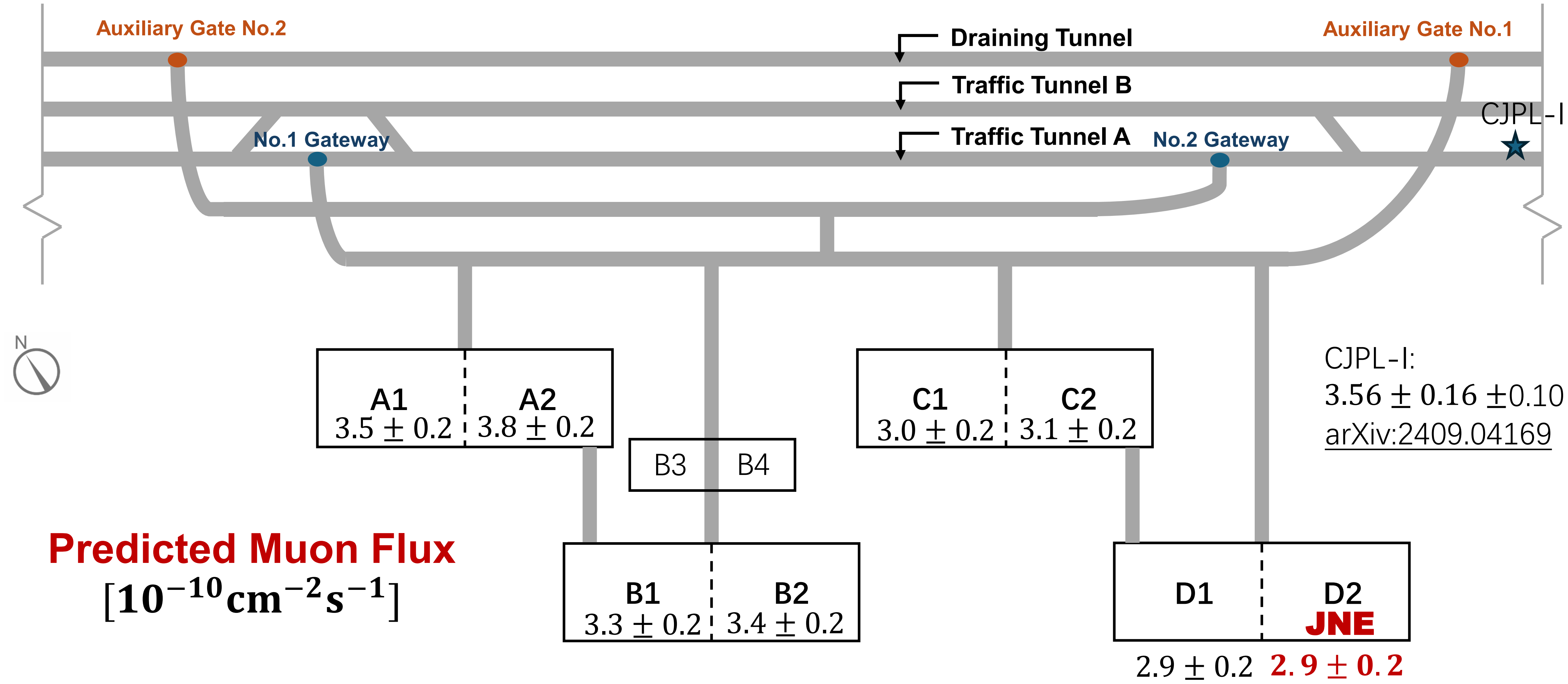
BONSAI : doi: 10.1016/j.phpro.2014.12.068







Muon Flux Predictions

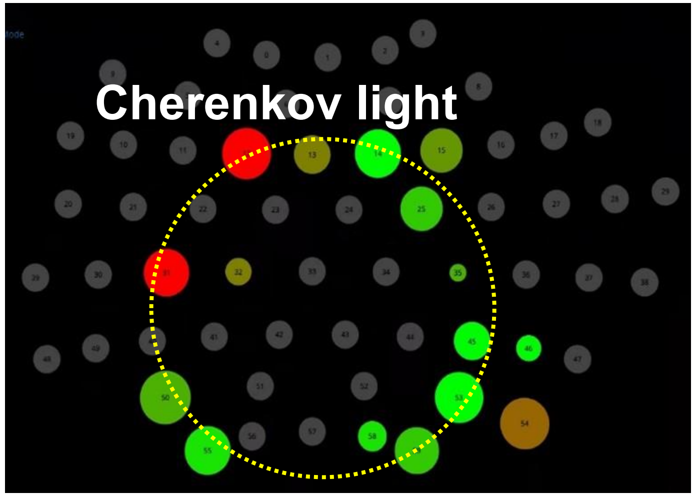


CJPL-I:
$3.56 \pm 0.16 \pm 0.10$
arXiv:2409.04169

Predicted Muon Flux
$[10^{-10}\text{cm}^{-2}\text{s}^{-1}]$

1-ton Prototype Upgrade

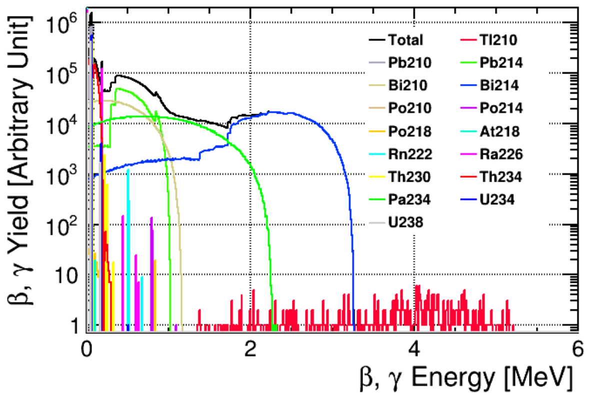
Upgrade: 30 PMTs → 60 MCP-PMTs



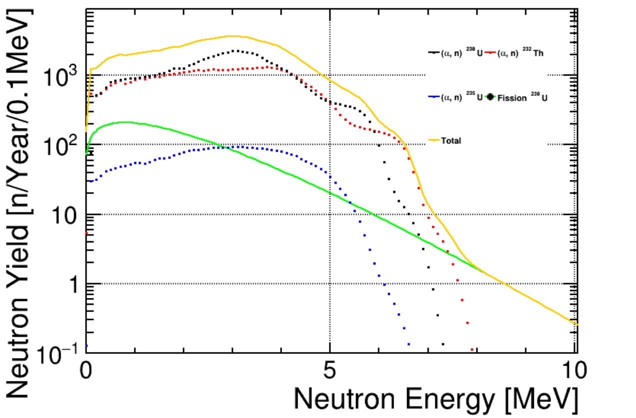
Phase	Time	Target	Research contents
Phase-I	Aug.→Dec. 2024	Water	Calibration, Cherenkov light
Lead shielding installation and new DAQ system upgrade			
Phase-II	Jan.→Jun. 2025	Slow LS	Calibration, light separation
Phase-III	Jul.→Dec. 2025	LiCl solution	Performance and stability

Radiogenic Background Shielding

- Radiogenic background
  - β, γ background
  - Neutron-related background
    - (α, n) neutron
    - ^{238}U Self-fission

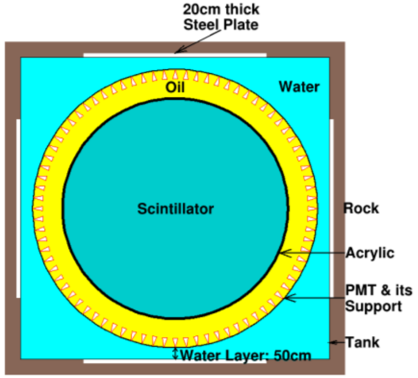


β, γ spectrum from ^{238}U

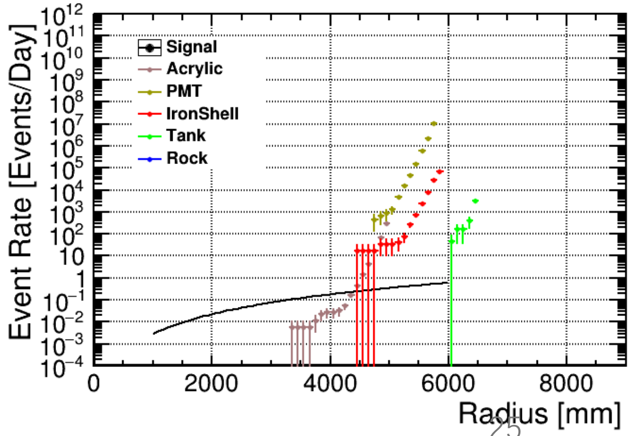


Neutron spectrum of PMT glass

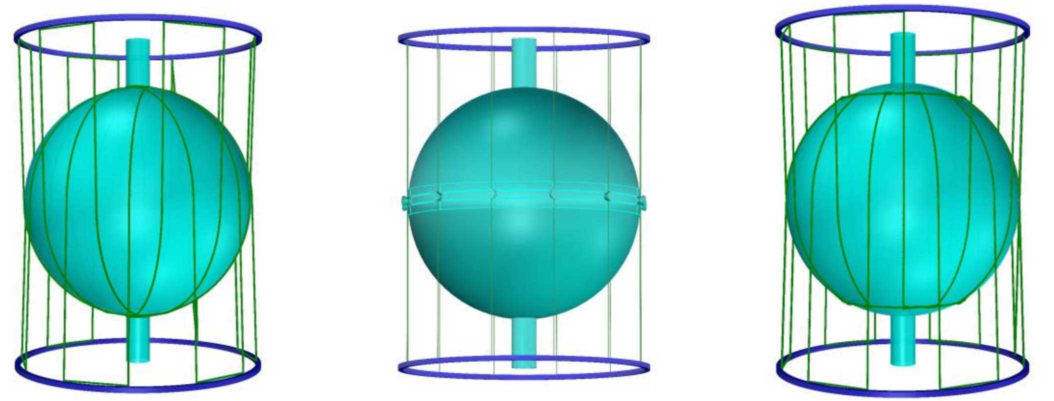
- Working flow
  - background spectrum → simulation for different shielding plans → background rates → determine the best shielding detector plan
- The best shielding plans
  - 50cm Water
  - 7m×7m×20cm Steel plate
  - Boron-doped PE PMT encapsulation



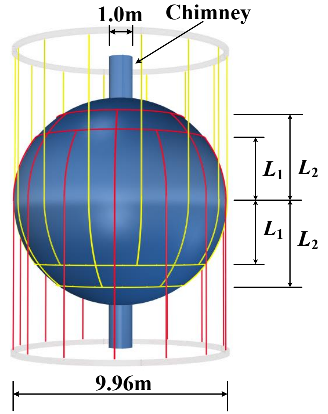
The best shielding plan



Background rates for the best shielding plan

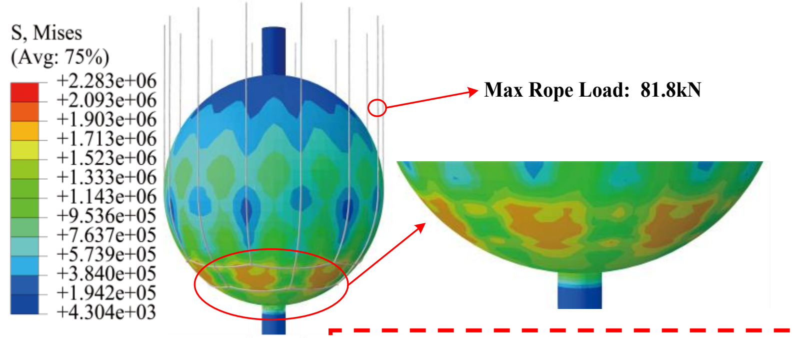


Scheme 1 | Scheme 2 | Scheme 3

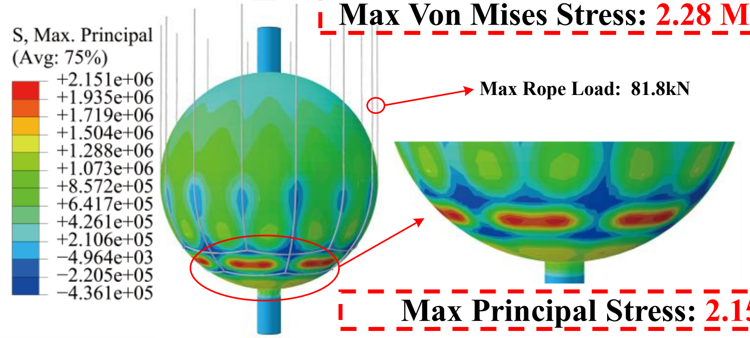


- Double loop
- Double chimney structure
- Diameter 9.96 m, shell thickness 50 mm
- Volume 500 m^3
- Rope diameter 35mm

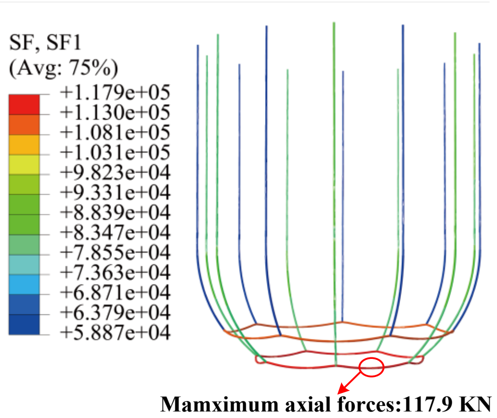
Final Scheme



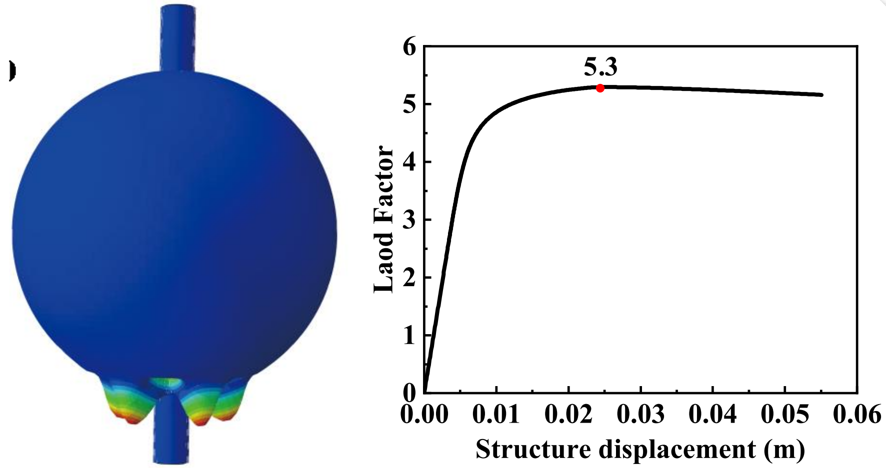
Max Von Mises Stress: 2.28 MPa



Max Principal Stress: 2.15 MPa



Max Rope Axial Force: 117.9 kN



Linear Buckling Analysis Safety Factor 14.72

Risk Analysis Safety Factor 5.3

Rope diameter analysis | Rope Young's modulus analysis | Shell Thickness analysis

Temperature analysis | Rope position analysis | Rope failure analysis | … … …

ν_e CC, ES, and $\bar{\nu}_e$ detection

1. CC process for ν_e:

$$\nu_e + {}^7\mathrm{Li} \rightarrow {}^7\mathrm{Be} + e^-(+\gamma)$$

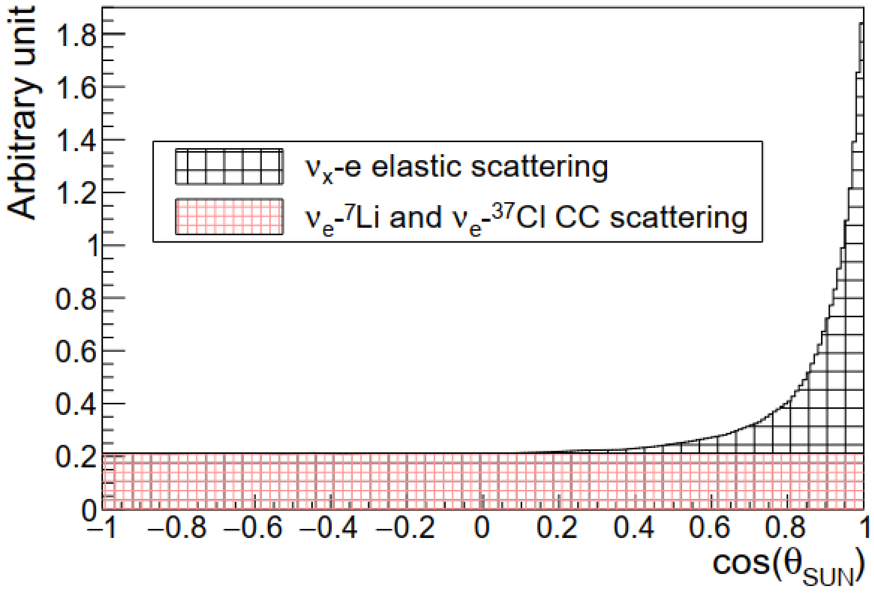
Measure neutrino energy

1. Elastic scatter on e⁻:

2. Delayed coincidence for

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

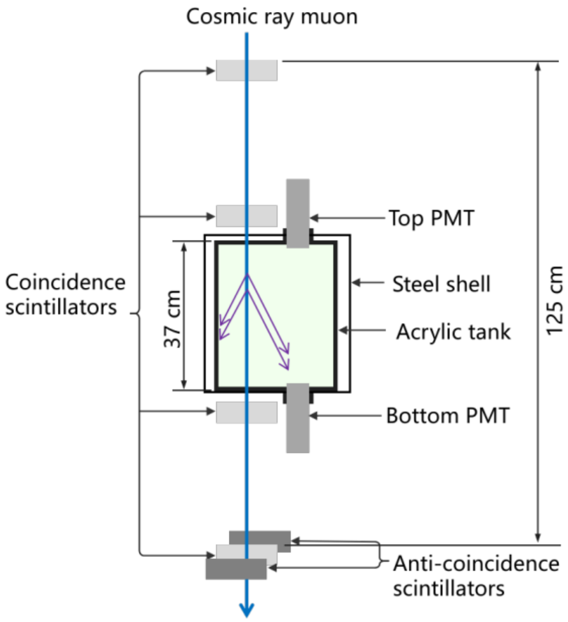
with neutron capture on H, Li6, and Cl35 measure $\bar{\nu}_e$ energy

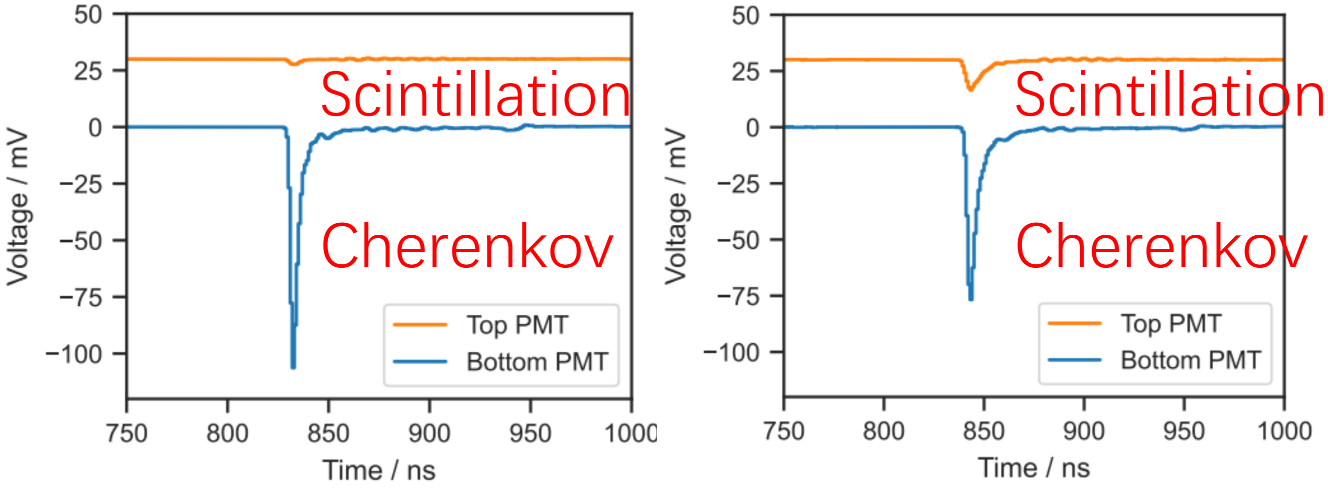


Spectrometer for ν_e and $\bar{\nu}_e$
Good chance for solar, geo, and supernova neutrinos

LiCl aqueous solution with carbostyril

Light yield verification with a muon telescope





(a) LiCl → (b) LiCl with 1 ppm C-124

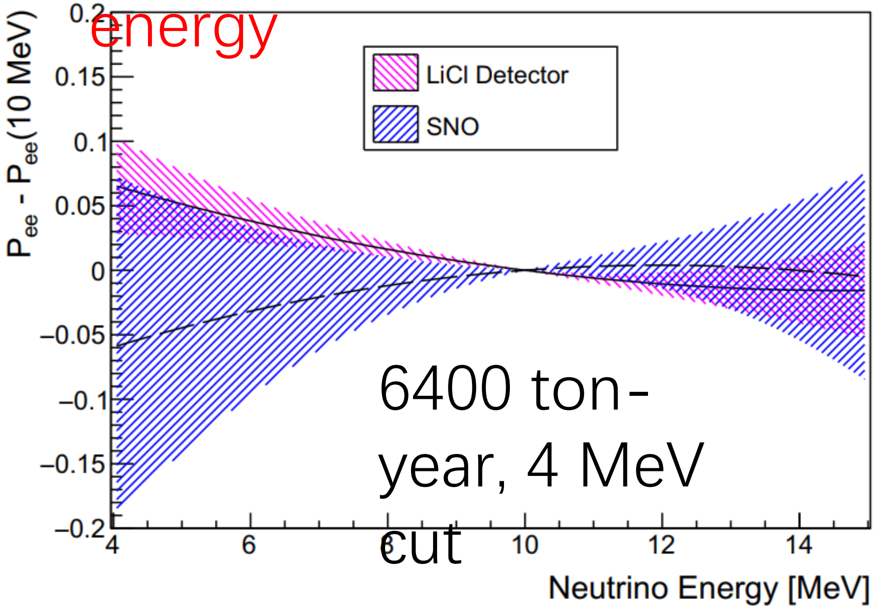
3.7 PE detected from isotropic scintillation

12.3 PE for Cherenkov

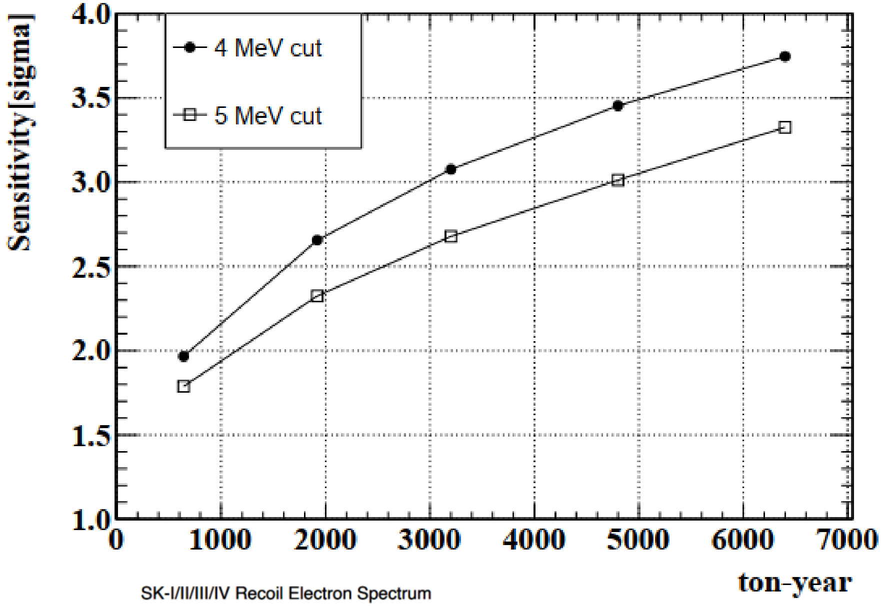
Solar Neutrino Physics with LiCl Solution

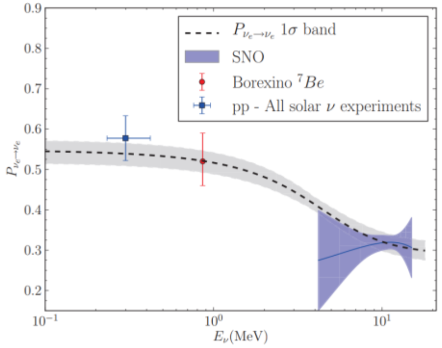
Solar neutrino survival probability-average vs energy

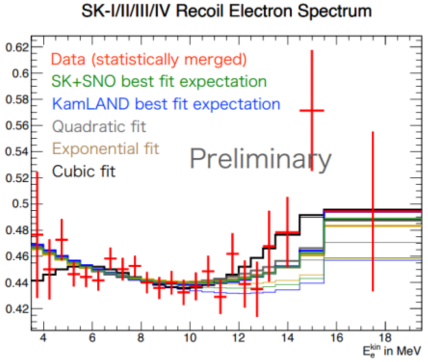
Upturn discovery sensitivity versus exposure



6400 ton-year, 4 MeV cut





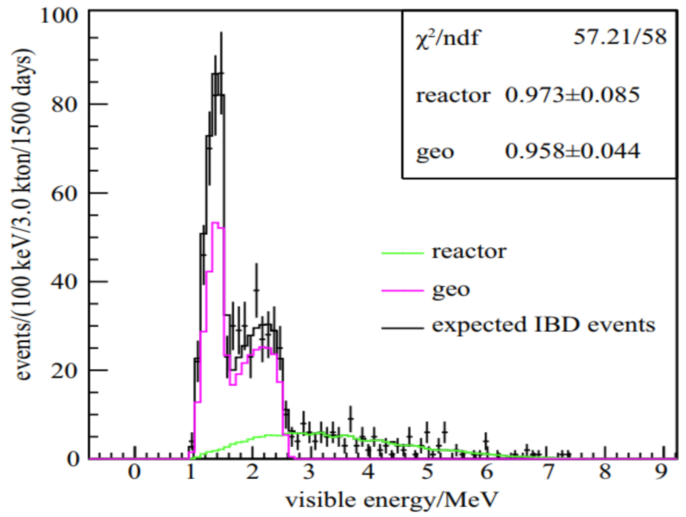


Slightly favors up-turn, though need more data

Geo Neutrino and Supernova Relic Neutrinos

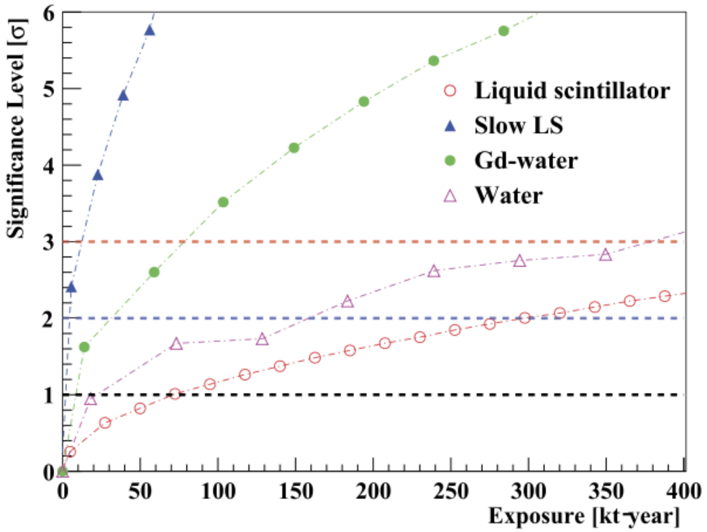
With prompt-delayed signal detection:

Expect tens of geoneutrinos in 5-10 years with the 500-ton detector



With Cherenkov-scintillation liquid scintillator:

Expect a few golden candidate supernova relic neutrinos in 5-10 years with the 500-ton detector



Expect an improvement better than this figure. Work in progress.