锦屏中微子探测

Zhe Wang (for the research group)

Tsinghua University

May 18, 2024 @ νSTEP 杭州

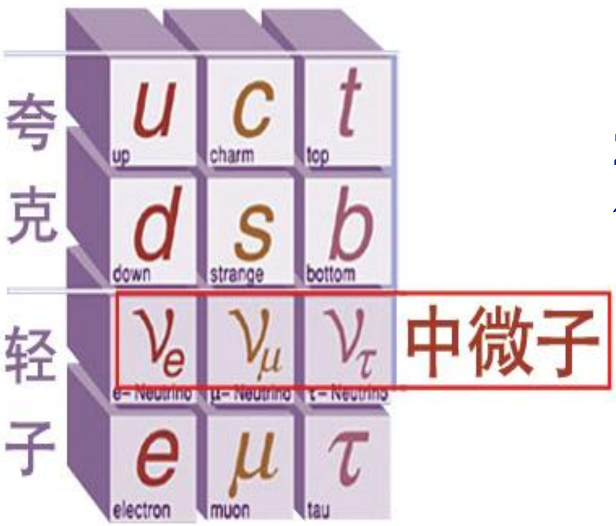
报告内容:

- 科学意义
- 实验建设进展
- 中微子探测介质研发
- 物理探测潜能

科学意义：中微子

作为物质构成的最基本单元，三种类型的电荷中性中微子与物质的反应几率极小，穿透力极强。历史上有四次诺贝尔物理学奖与中微子有关。

粒子物理标准模型



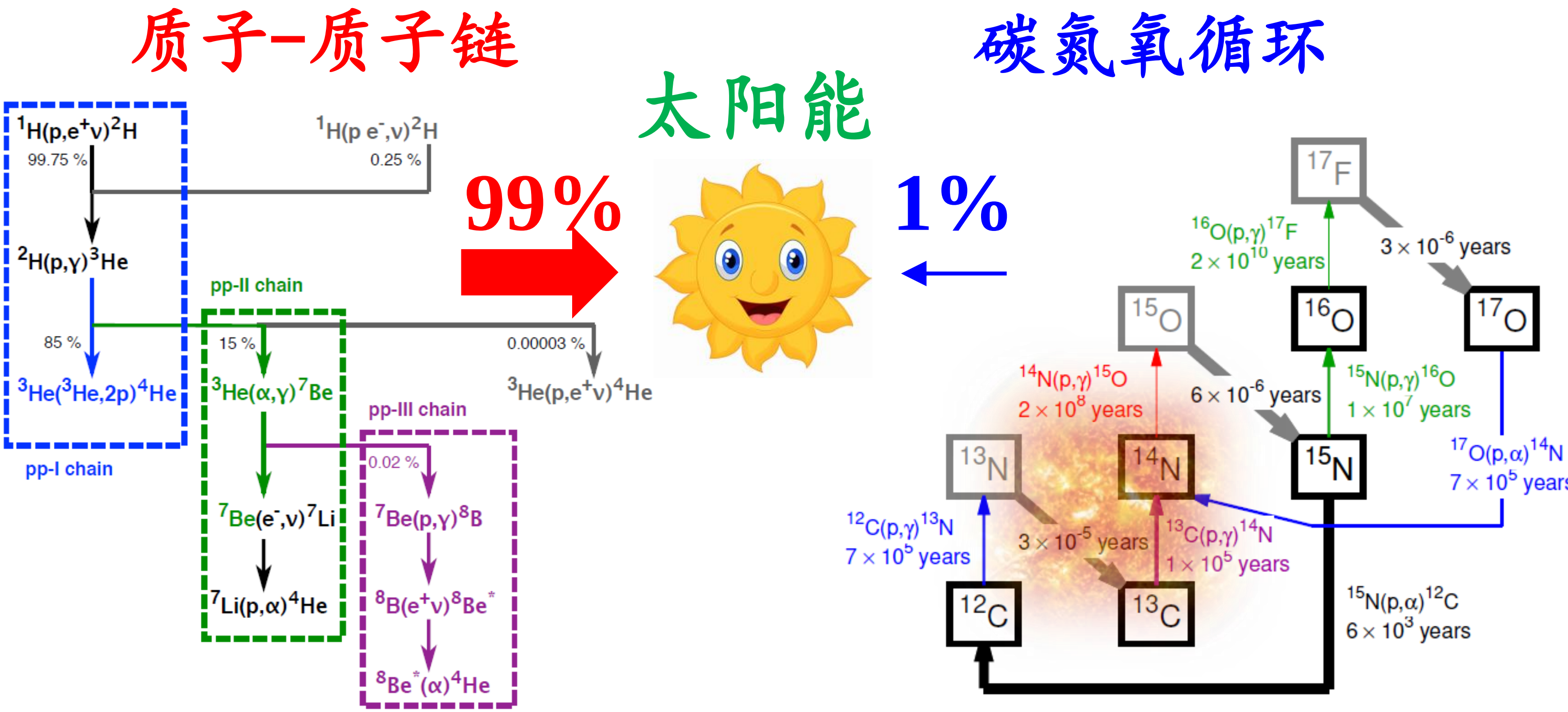
2015 年，Kajita 与 McDonald“发现中微子振荡并揭示其有质量。”

2002 年，Davis 与 Koshiba“对天体物理学，特别是宇宙中微子探测的开创性贡献。”

1995 年，Reines“对于轻子物理学和中微子探测的开创性实验贡献”

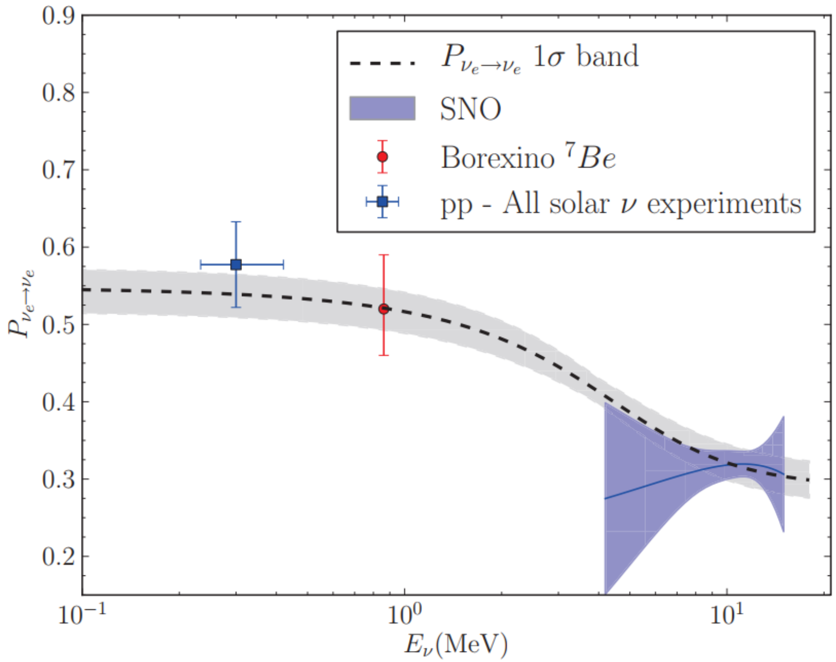
1988 年，Lederman, Schwartz, Steinberger“提出中微子束方法和通过发现μ子中微子证明轻子的偶极子结构。”

科学意义：标准太阳模型与太阳中微子

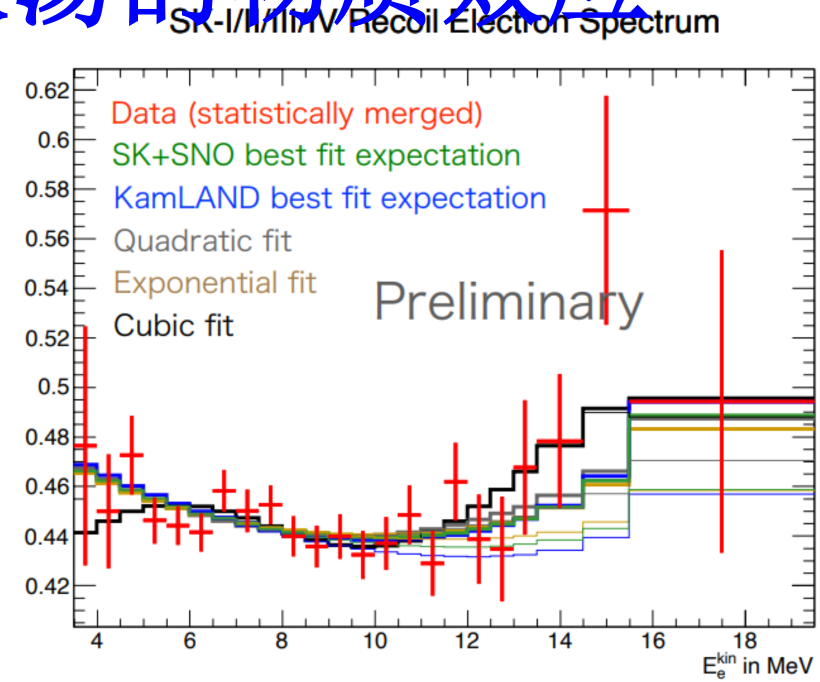


太阳中微子可以用来窥视太阳内部的热核反应，检验模型并探寻大质量恒星内部的动力学机制。

太阳中微子振荡的物质效应



SNO



Slightly favors up-turn, though need more data

SK

1. 太阳的物质效应导致电子中微子的存活概率随能量降低上升
2. 太阳中微子通量
3. 太阳金属丰度问题

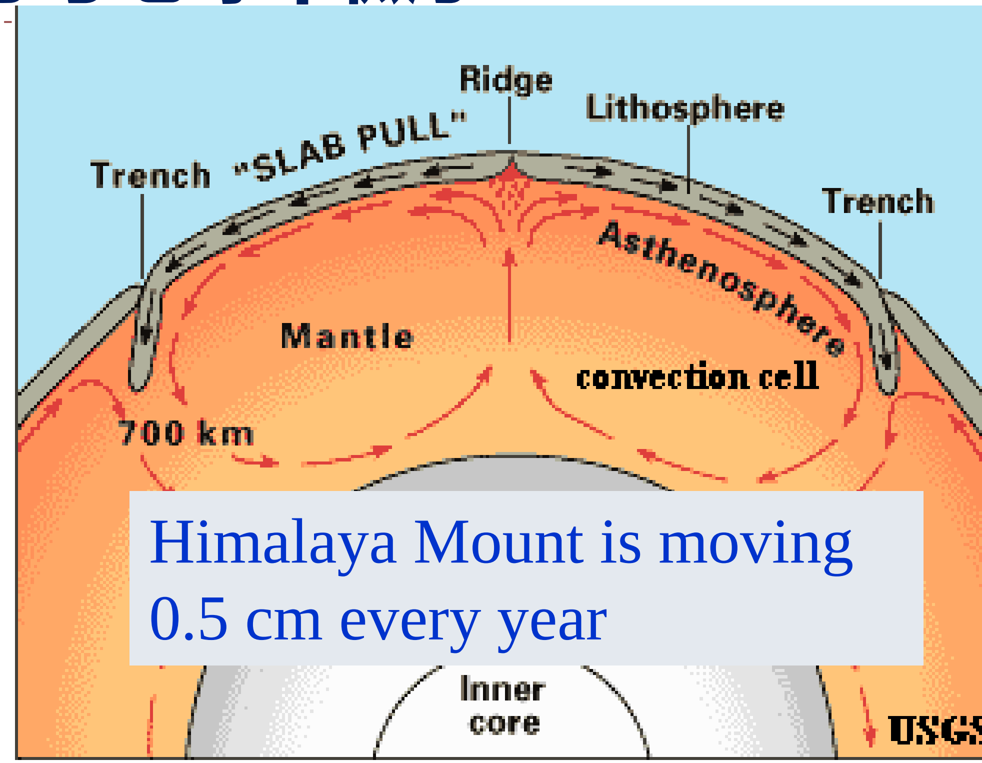
科学意义：地球驱动力与地球中微子

Diving power

- Initial gravity
- Nuclear power, U, Th, K decay

Knowledge:

- Global heat measurement 47±3 TW
- Theoretical predictions：
  - Low range 10 TW
  - Middle range15-30 TW
  - High range 20 TW
- Geoneutrinos from U, Th: 10-30 TW



- Still consuming initial gravitational power
- Need more measurement of mantle neutrinos

历史背景

国际太阳（地球）中微子观测站

Homestake（美国）
680吨
四氯乙烯
1967-1994

Sage（俄罗斯）
50 吨
金属镓
1990-2007

Super-Kamiokande（日本）
22500吨
水
1996-至今

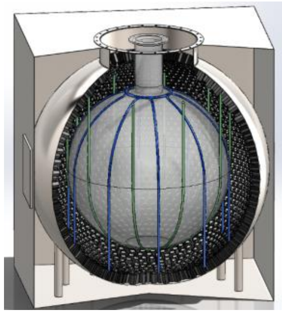
Kamiokande（日本）
1986-1995
680吨
水

GALLEX/GNO（意大利）
1991-2003
100 吨
氯化镓

SNO（加拿大）
1999-2006
800 吨
重水

Borexino（意大利）
2007-至今
278吨
偏三甲苯

本项目

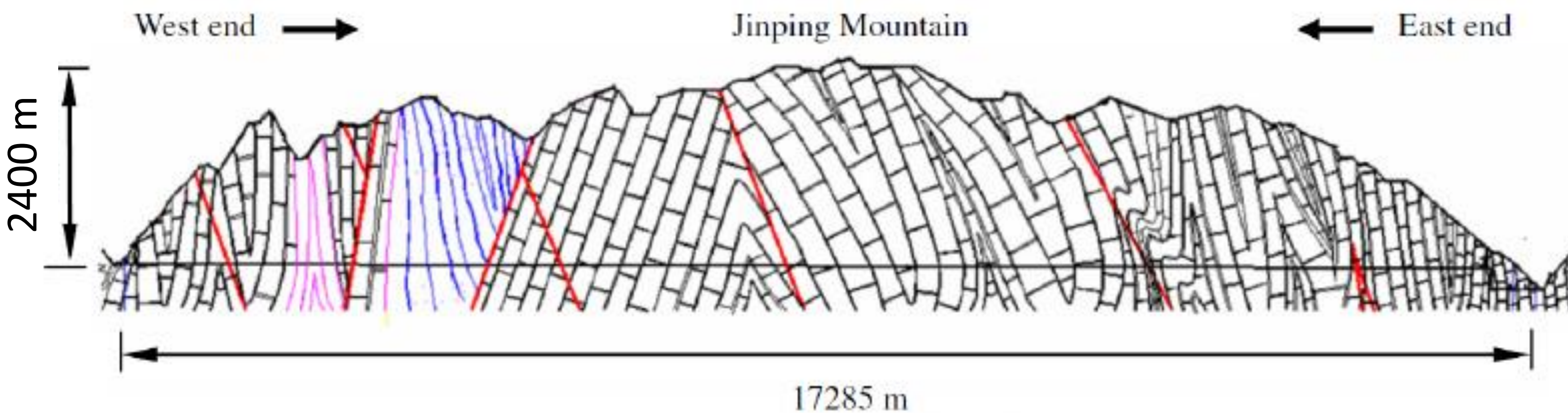


Location of Jinping Underground Laboratory

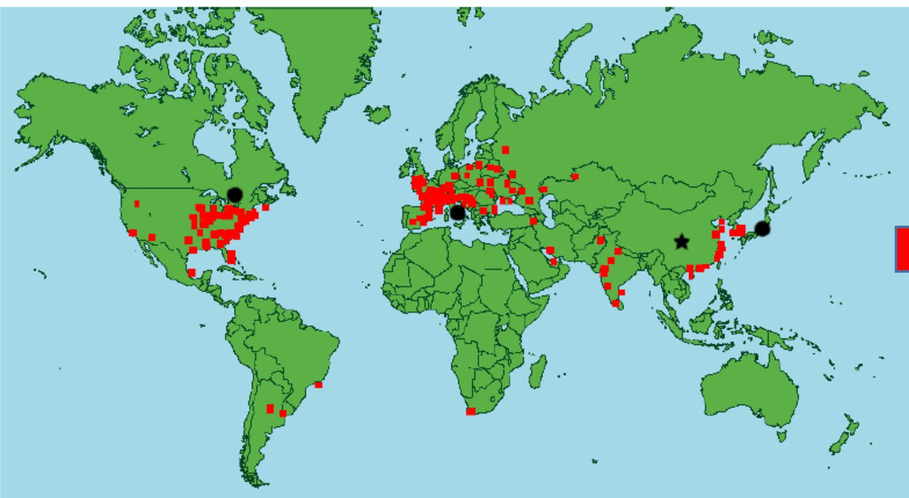
Southwestern region of China (Sichuan Province)

Direct flight from Beijing to Xichang + 2 hour drive

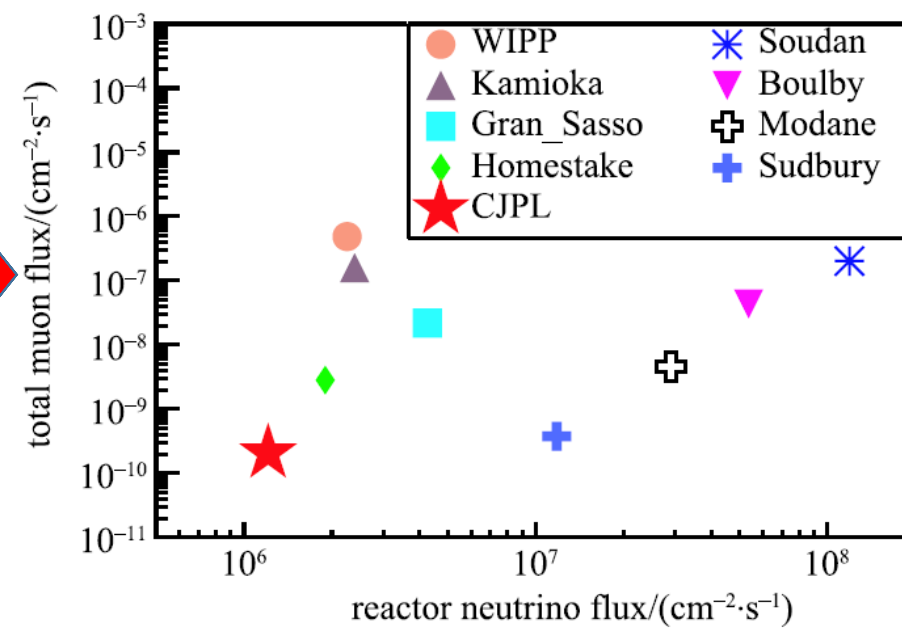
Low muon flux and reactor neutrino background



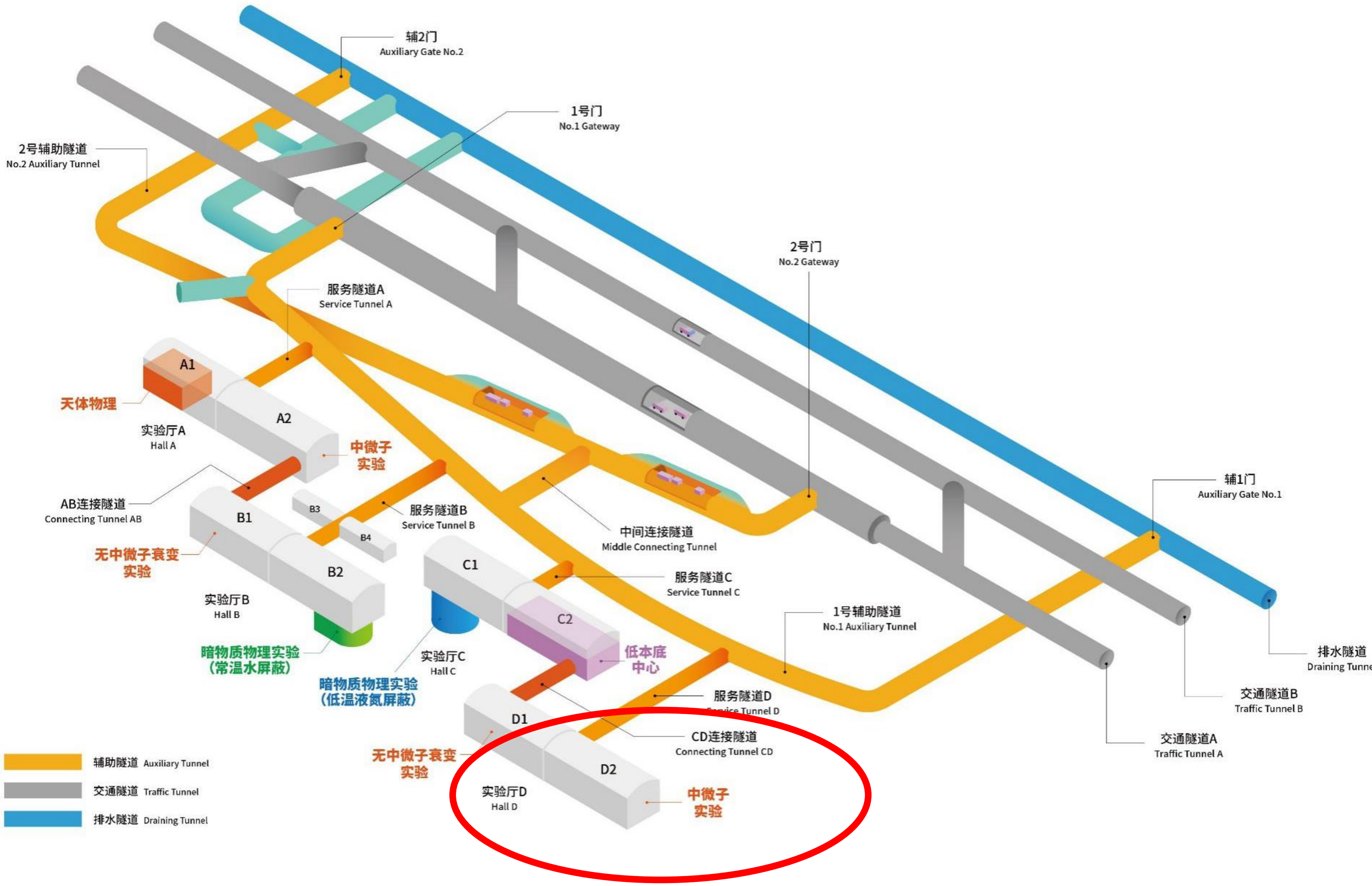
2400 m overburden, C10, C11 background suppressed



950 km to closest reactor

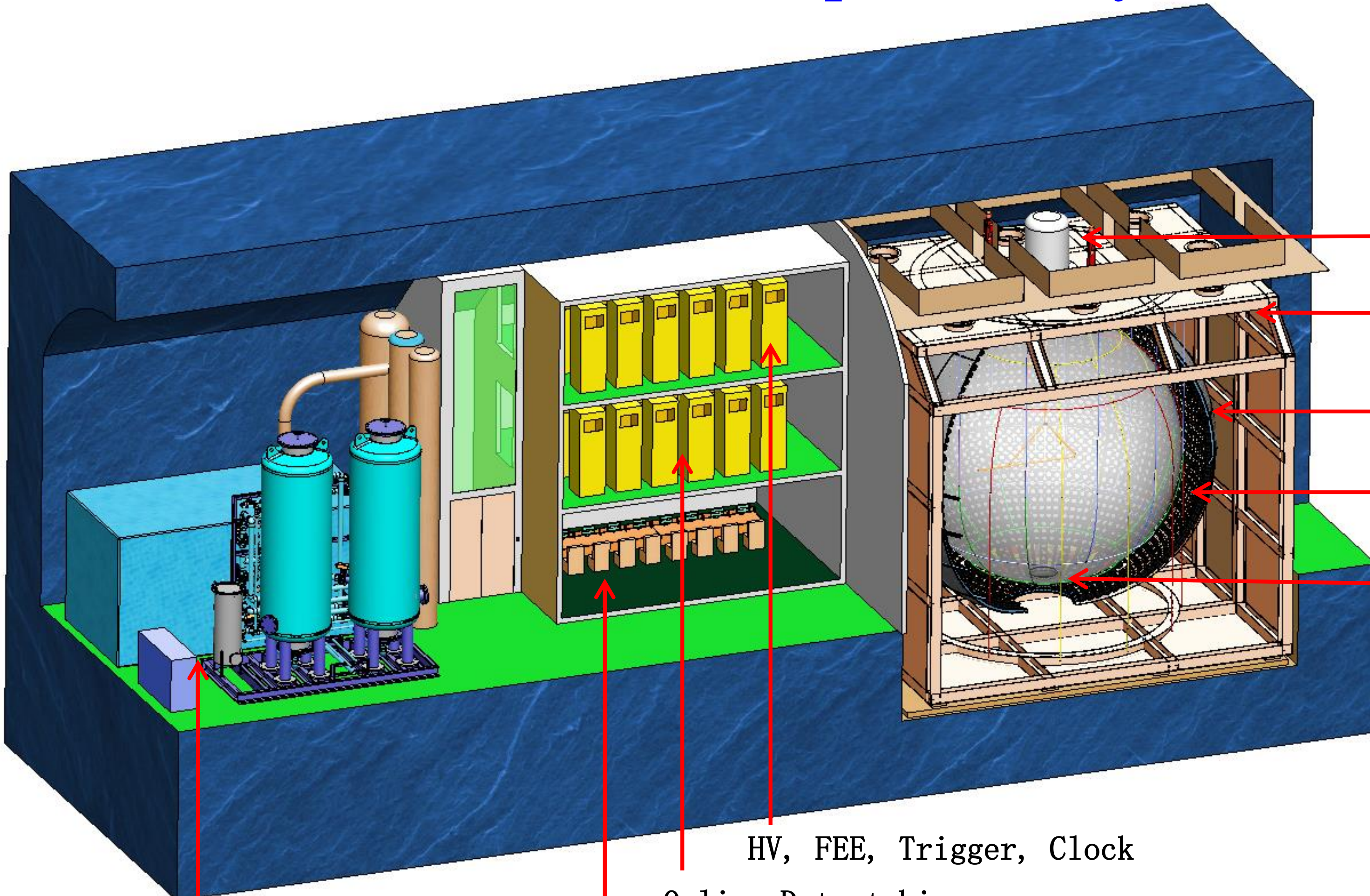


Jinping Neutrino Experiment at CJPL-II, hall D2



Current Status of the D2 hall

Hall D and Experiment Layout

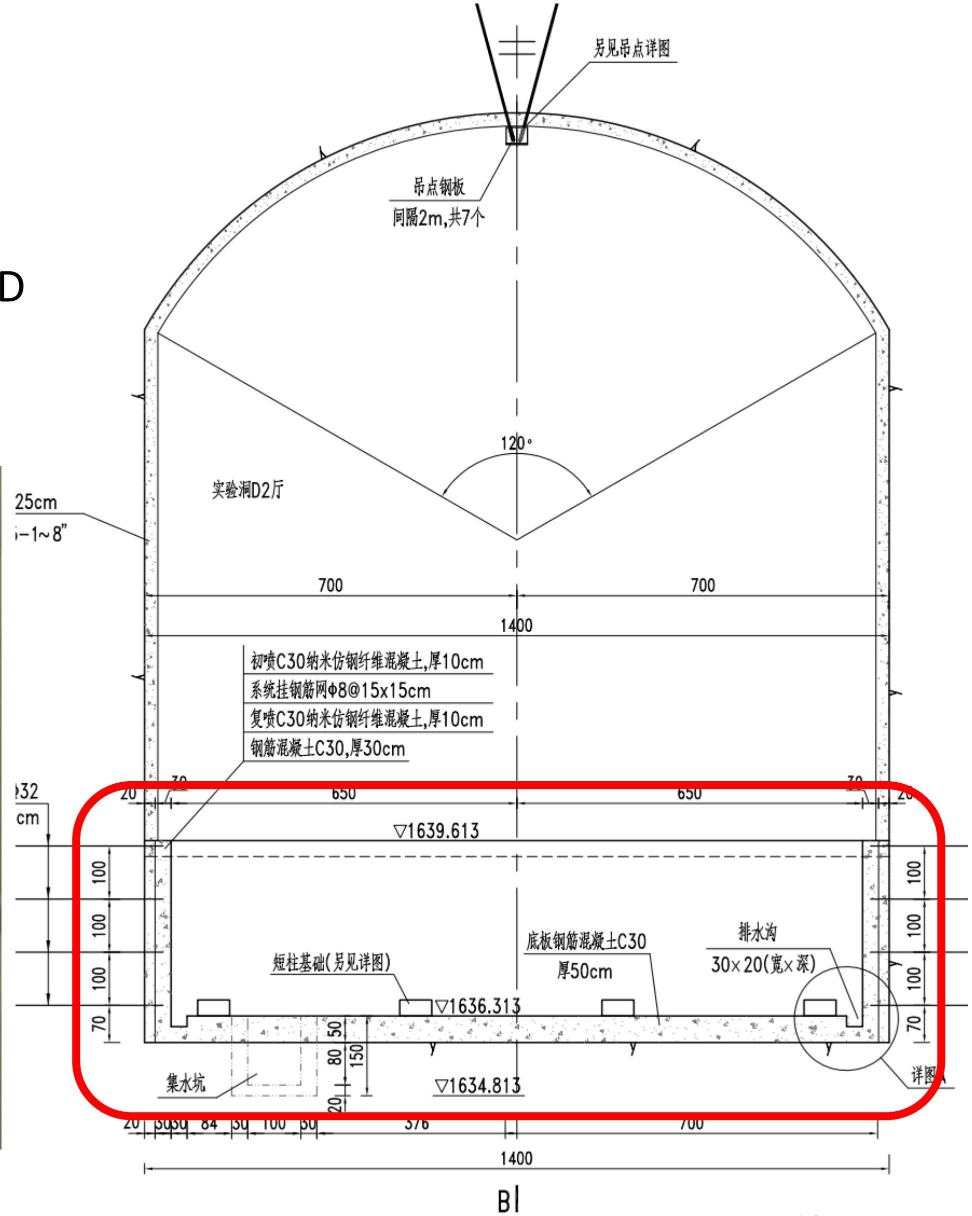


500 cubic meter target volume

Pit for Detector

Construction of the pit is finished 2023 summer

1. Designed by Huadong Engineering Corporation Limited
2. Constructed by Sinohydro Bureau 5 Co. LTD
3. Onsite management: Yalong Hydro CJPL Administration Bureau



Detector Design

Stainless steel tank:

14.5 m (L)*12.9 m (W)*13.2 m (H)

SST PMT truss:

12.16 m (Diameter)

Acrylic vessel:

9.96 m (Diameter), 0.05 m (Thickness)

500 cubic meter

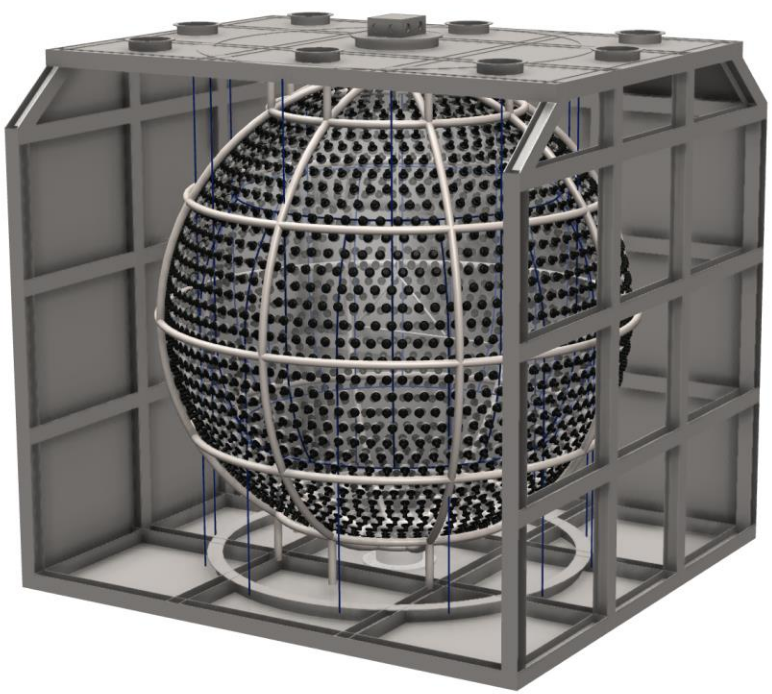
Rope network:

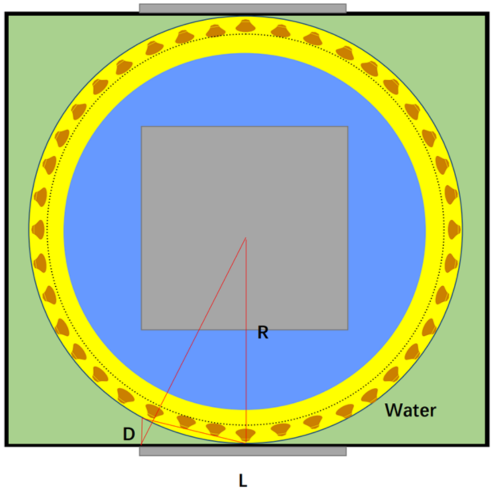
holding-up and holding-down

(Allow a detection material heavier or lighter than water with 20% density difference.)

Shieling material:

Water and SST (or lead)



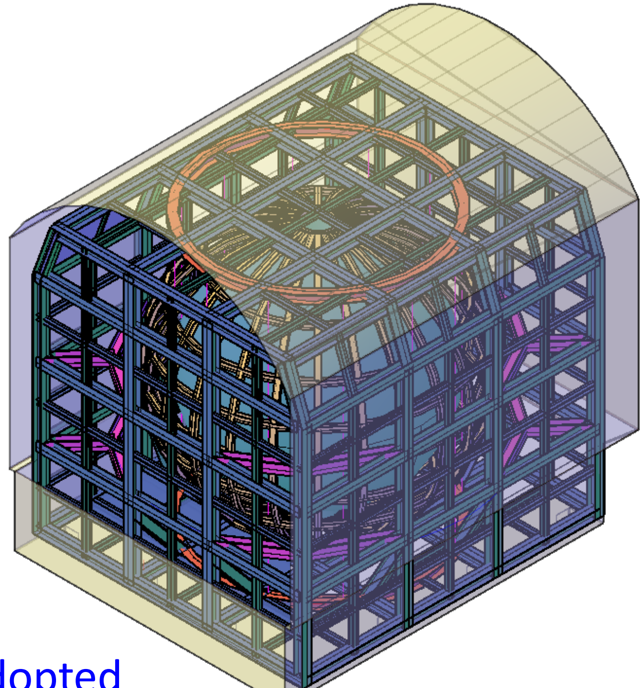


Shieling SST (or lead) planes

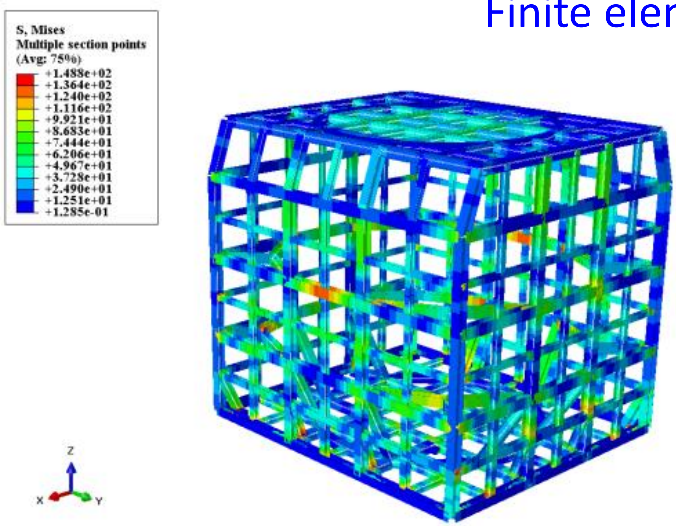
Water Tank

Requirement for the stainless steel tank:

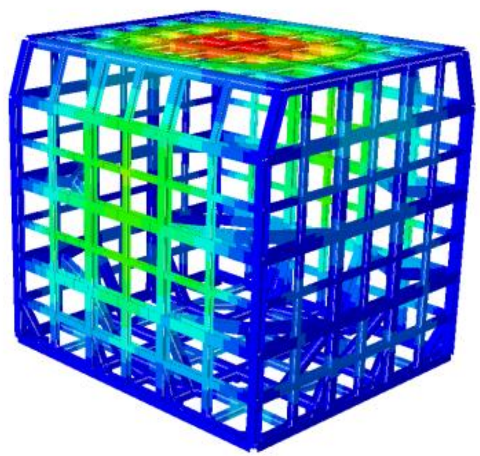
1. Hold the water and all inside structures (14.5 m*12.9 m*13.2 m)
2. Hold all equipment on the top the tank (calibration and other electronics)
3. Hold the shielding materials (SST or lead plates)



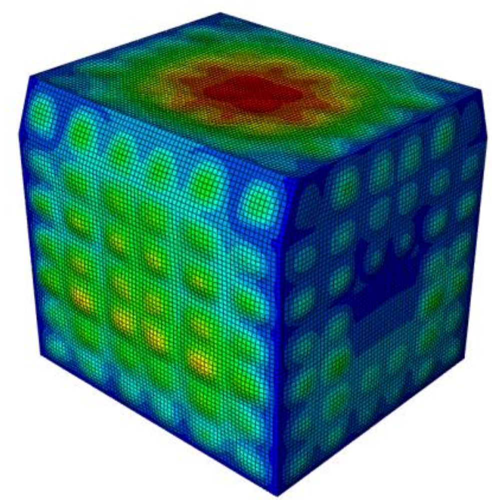
Finite element software ABAQUS is adopted



Stress contour diagram

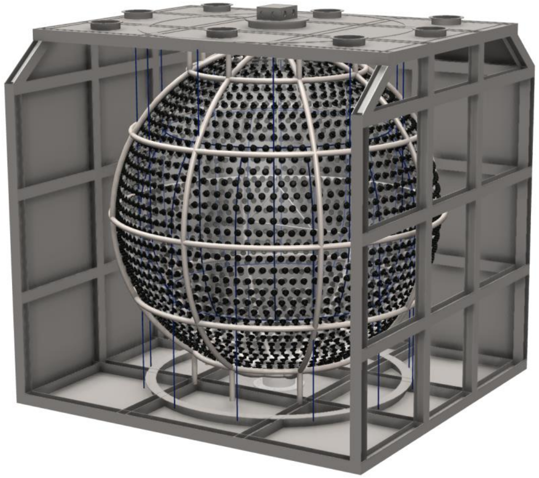


Displacement contour diagram



Stress contour diagram with covering SST plates

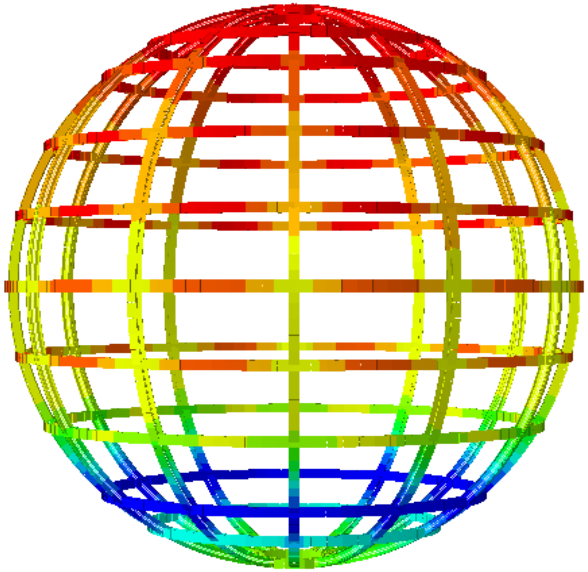
PMT Truss



Requirement for the PMT truss:

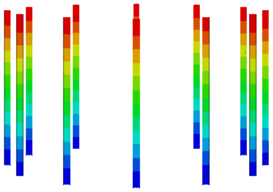
1. Hold 4000 PMTs

Structure



Axial force contour diagram for the sphere

Finite element software ABAQUS is adopted

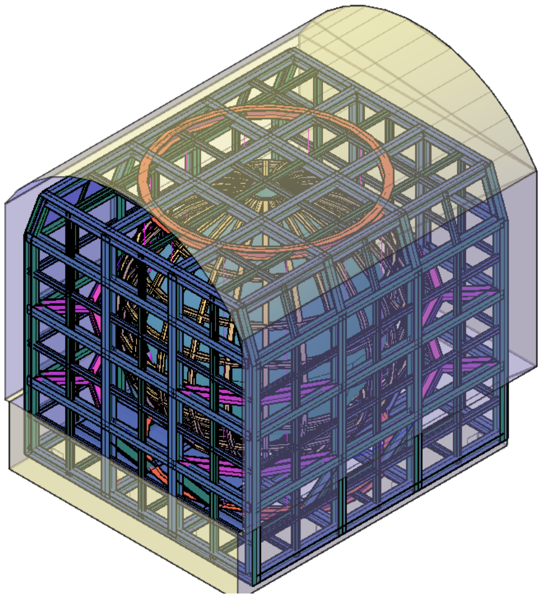


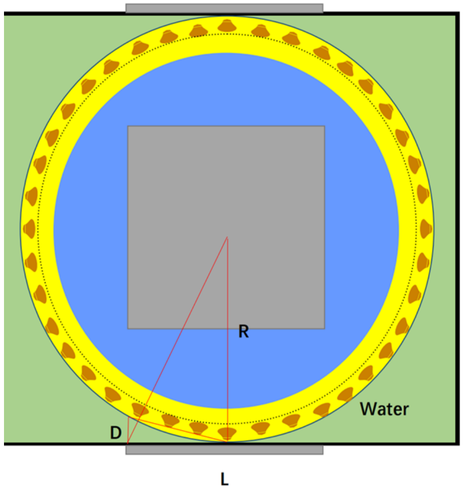
Axial force contour diagram for the legs

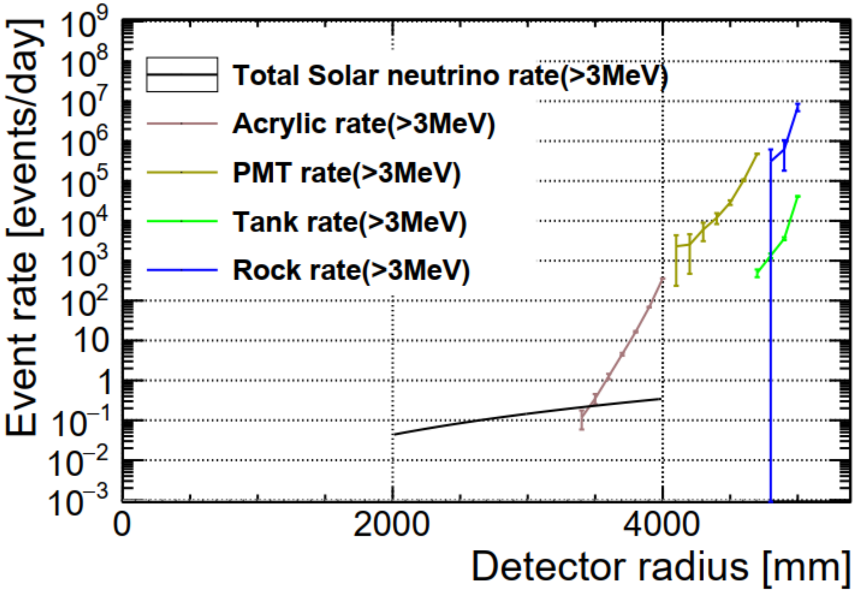
Shielding Plates

Requirements for Shield Plates

1. Shield concrete/rock background to 1 meter water equivalent
2. 7 m*7 m*20 cm steel (or lead) plates, 76 ton, on each side



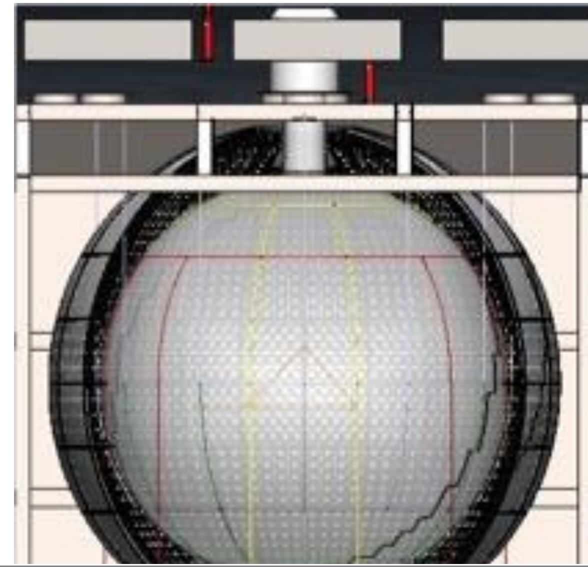




Narrow Hall D and all occupied.

Shield concrete and rock background

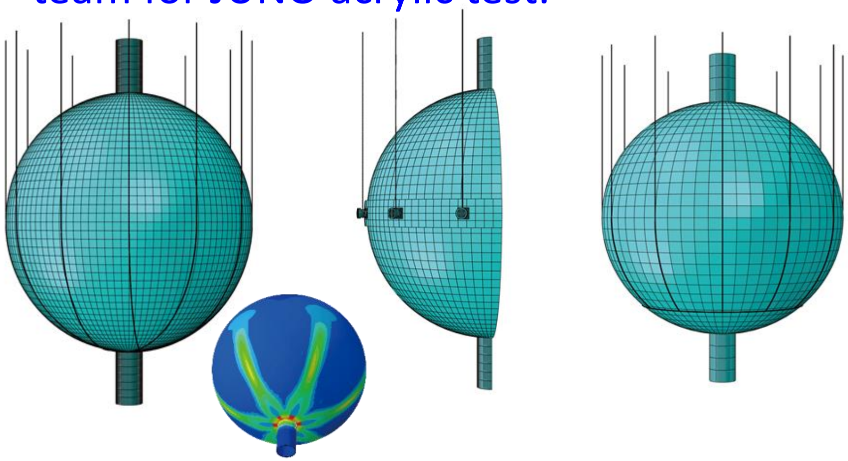
Acrylic Vessel



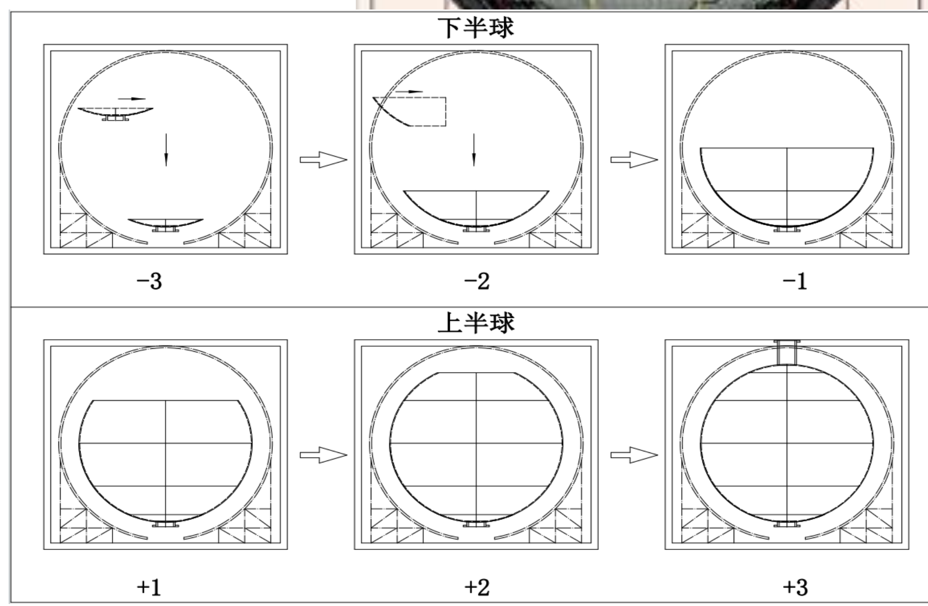
Requirement for the PMT truss:

1. Contain detection material
   Water, LS, or Doped LS
   Density difference to water: $\pm$20%
2. Low background

Plan to use JUNO acrylic. The same design team for JUNO acrylic test.



Compared 3 holding designs
Last one presents least stress on acrylic

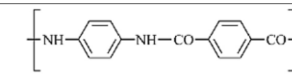
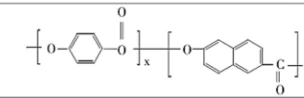
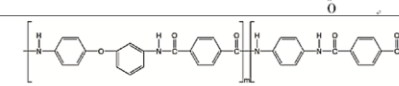


Preliminary installation plan
Division, bonding, and cleaning

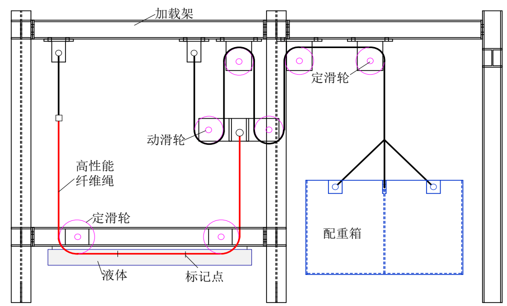
Ropes

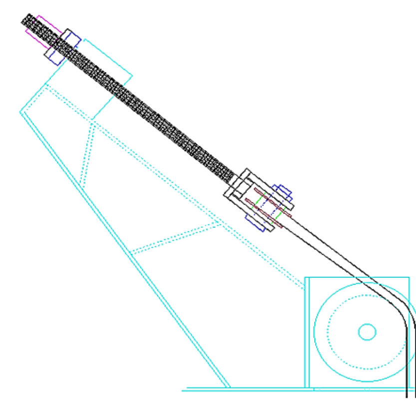
Requirement for the Ropes:

1. Hold acrylic sphere
   Water, LS, or Doped LS
   Density difference to water: ±20%
2. Low background
3. High strength, low creeping, water compatibility

品种	化学式
UHMWPE 纤维	$H_3C\text{-}[CH_2\text{-}CH_2]_n\text{-}CH_3$
Kevlar 纤维	
Vectran 纤维	
Technora 纤维	

Breaking experiments





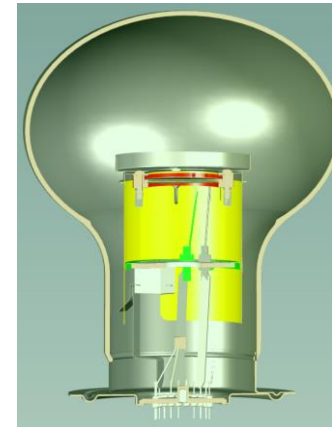
Tension monitor and length adjustment

Preparing for chemical analysis

Creeping experiments

MCP-PMT

Material control

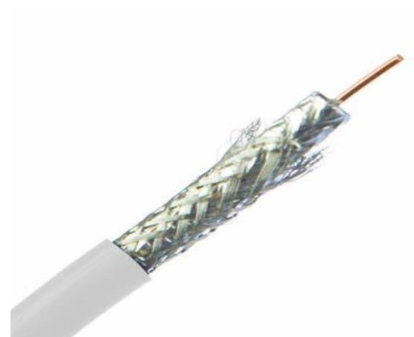


Structure

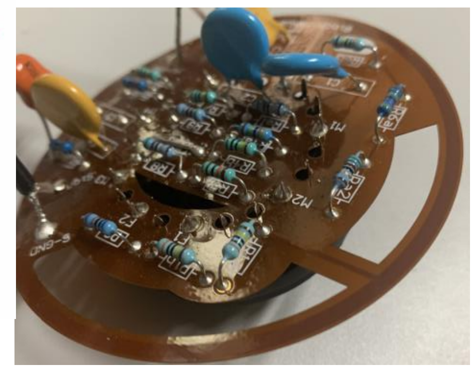
New 8-inch MCP PMTs

1. U、Th: <4E-8 g/g
2. K-40: <4e-9 g/g
3. High QE: 30%
4. Good timing: TTS<1.8 ns

400 produced.



Cable

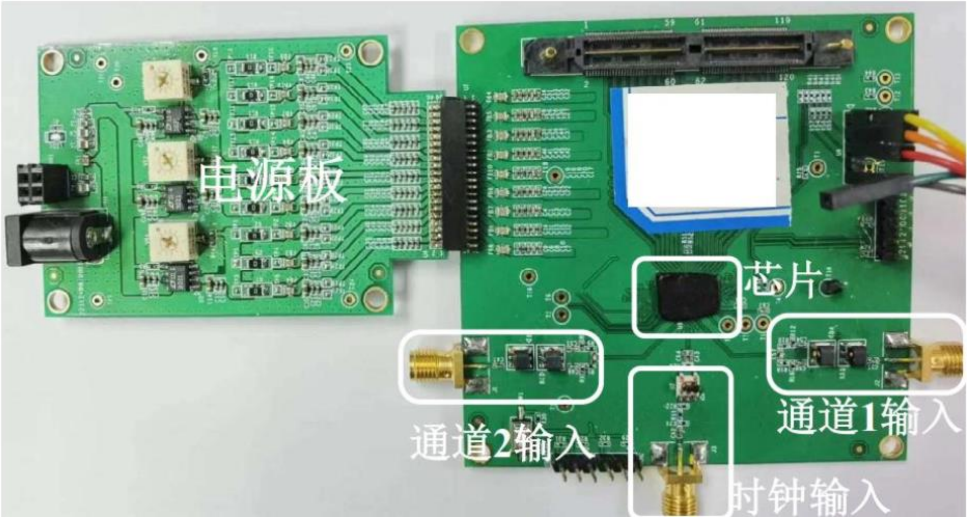


HV divider

FADC and Readout

FADC for PMT waveform readout

350 mW, 12 bit, 1 GSps
(based on the development for JUNO, but with even lower power consumption than 800 mW)

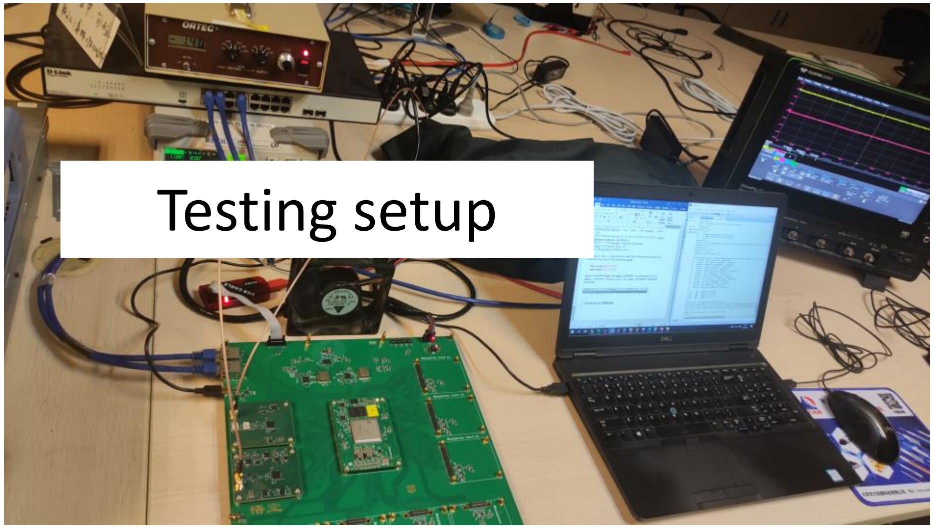


Readout board

Bandwidth 300 MHz, 40Gbps

Testing setup

A 30-channel system has been tested on the one-ton prototype this year.

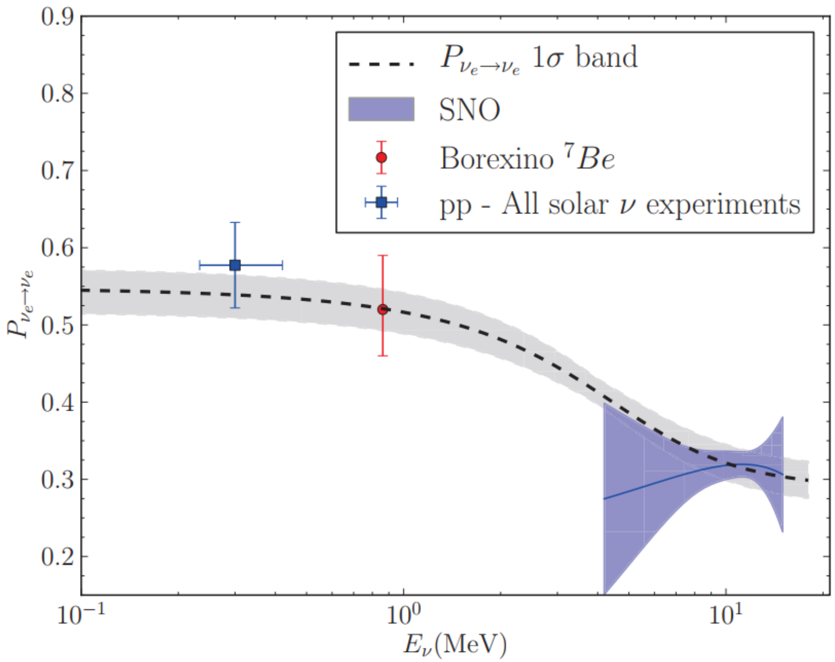


Physics program

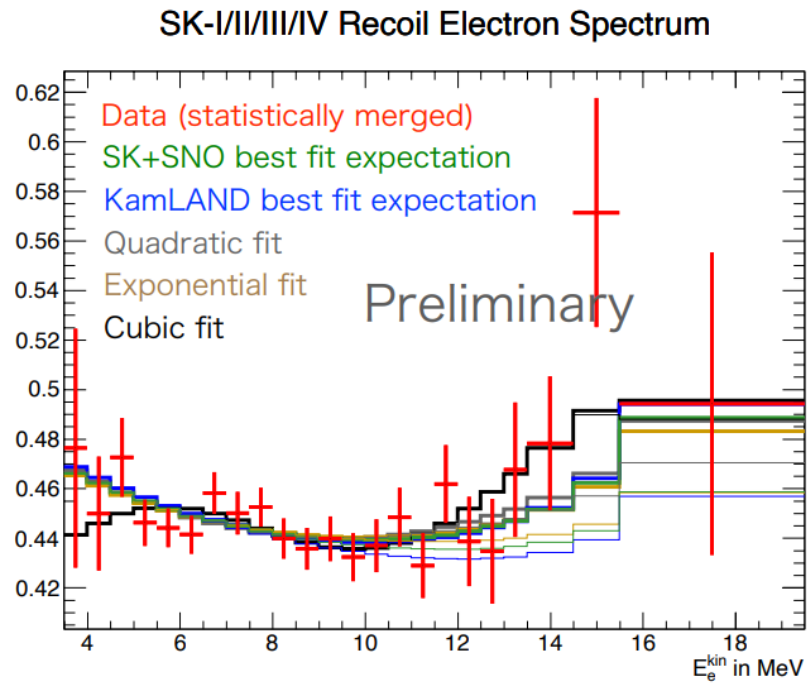
The construction and testing running of the detector is expected in 3-5 years. Physics runs follow...

1. **Solar neutrino upturn effect, oscillation parameter measurement**
2. **Geoneutrino measurement, Tibet crust geoneutrinos**
3. **Supernova relic neutrinos**
4. **Double beta decay**
5. **Others: sterile neutrino, neutrino cross-section, nuclear physics, etc.**

Loose constrain of the Solar neutrino upturn effect



SNO

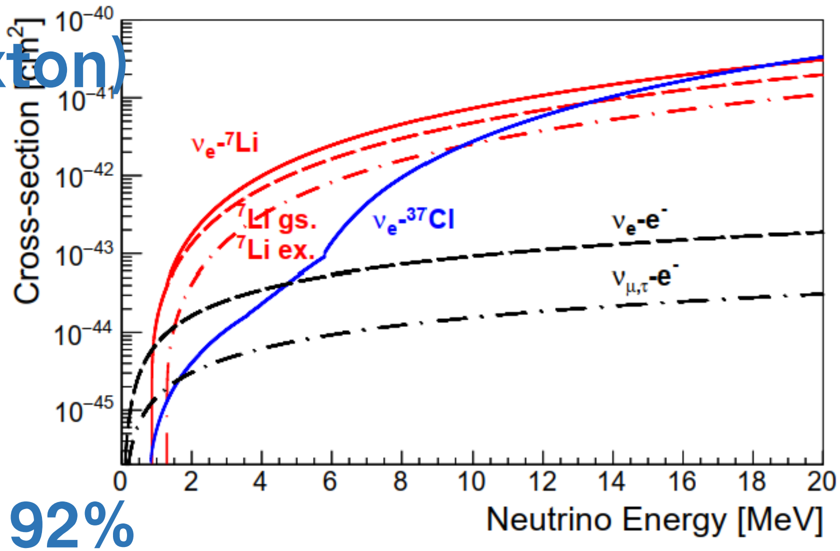


Slightly favors up-turn, though need more data

SK

太阳的物质效应导致电子中微子的存活概率随能量降低上升

Solar Neutrino Physics with LiCl Solution



1. **CC process for ν_e: (Bahcall, Haxton)**

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

   Measure neutrino energy
2. **High cross−section:**

   ν_e-Li7: 60 times of ν_e-e elastic scattering for solar B8 neutrinos
3. **High natural abundance of Li7: 92%**
4. **High solubility: 80 g LiCl in 100 g water**

	^{7}Li	^{37}Cl	All CC	e^-
Molarity (mol/L)	11	2.9	NA	610
Event rate (No Osci)	305	22.7	328	271
Event rate (Osci)	101	7.28	108	124
Event rate (Osci & >4 MeV)	94.5	7.24	102	48.0
Event rate (Osci & >5 MeV)	87.3	7.17	94.4	34.5

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

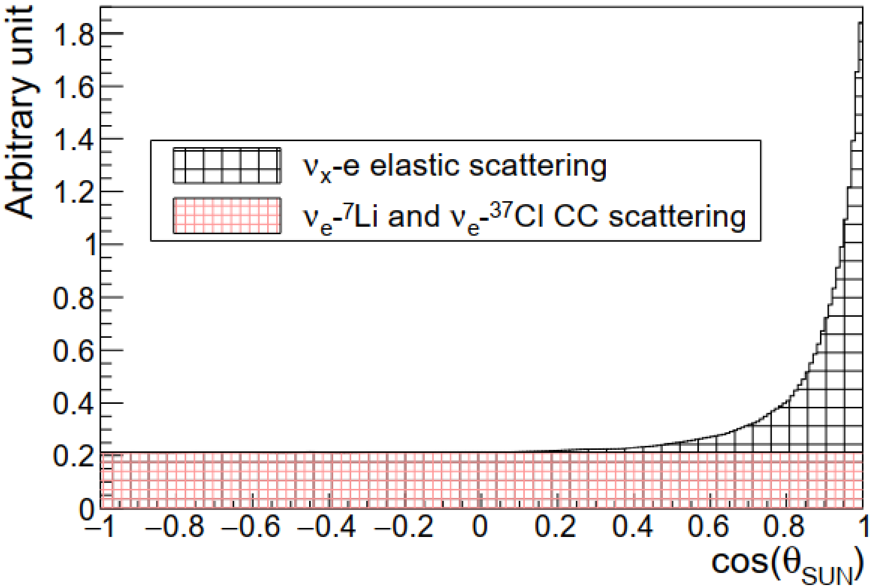
1. **Elastic scatter on e⁻:**

2. **Delayed coincidence for $\bar{\nu}_e$**

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

with neutron capture on H, Li6, and Cl35

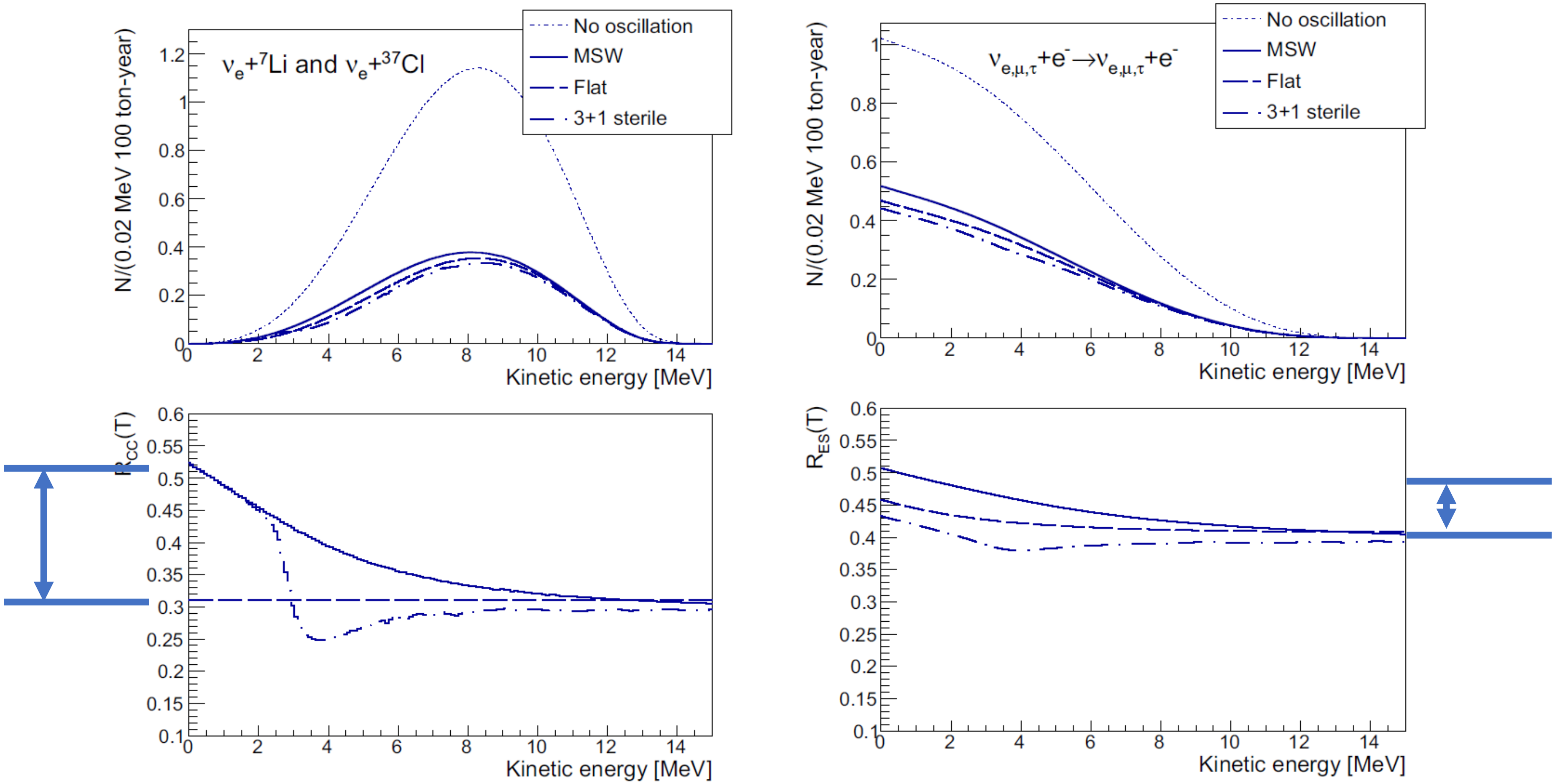
measure $\bar{\nu}_e$ energy



Spectrometer for ν_e and $\bar{\nu}_e$

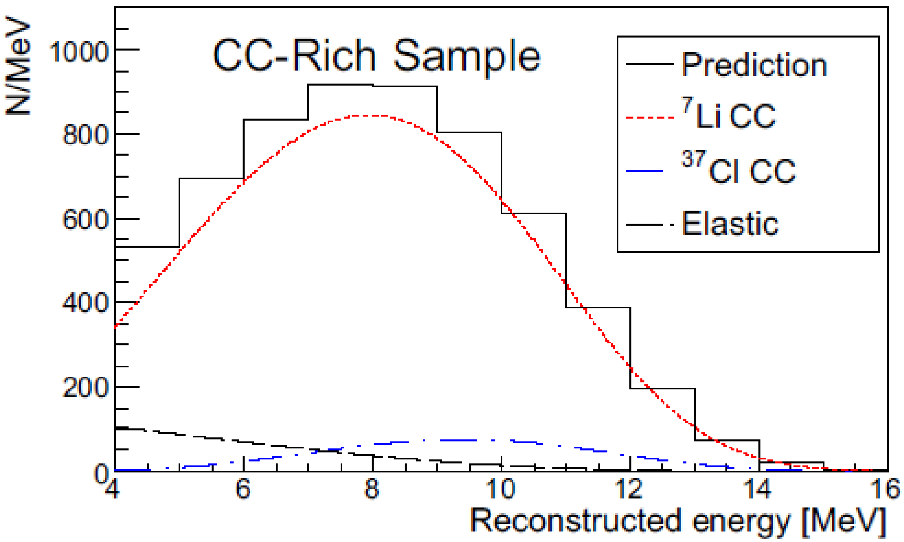
Good chance for solar, geo, and supernova neutrinos

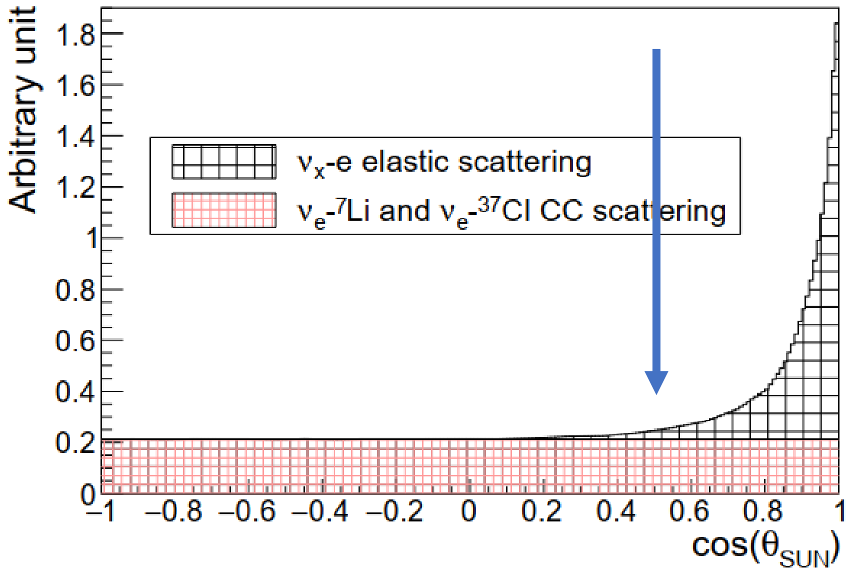
CC vs ES for solar neutrino oscillation study



ES过程中，单能的中微子，测量结果是一个平台
CC过程中，单能的中微子，测量结果是一个单能峰
CC过程对能谱相关的太阳中微子振荡研究特别适合。

Solar neutrino spectrometer and B8 neutrino measurement





With a solar angle cut, CC process signals can be clearly extracted.

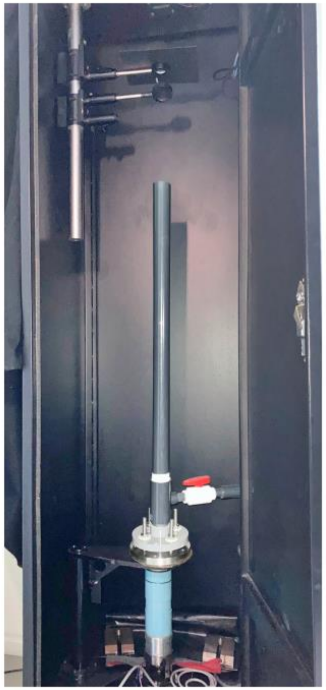
Serve as an solar neutrino spectrometer.

LiCl Water Solution

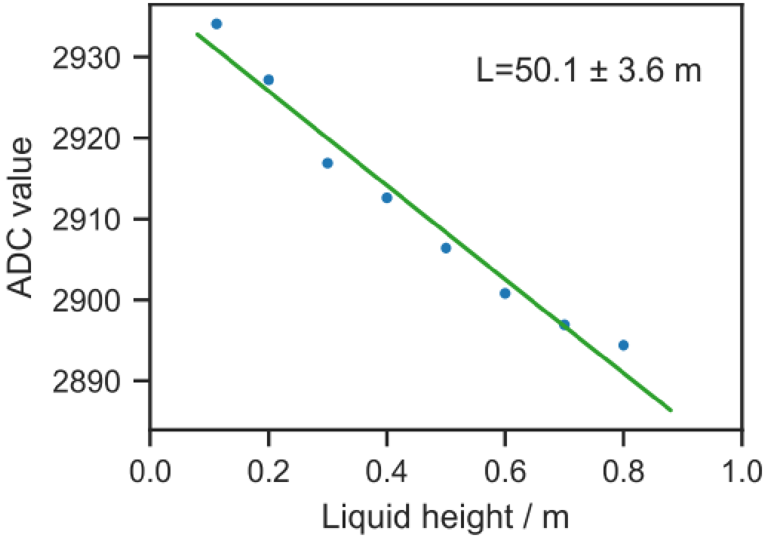
Thick LiCl water solution (Originally abandoned by SNU for light absorption)

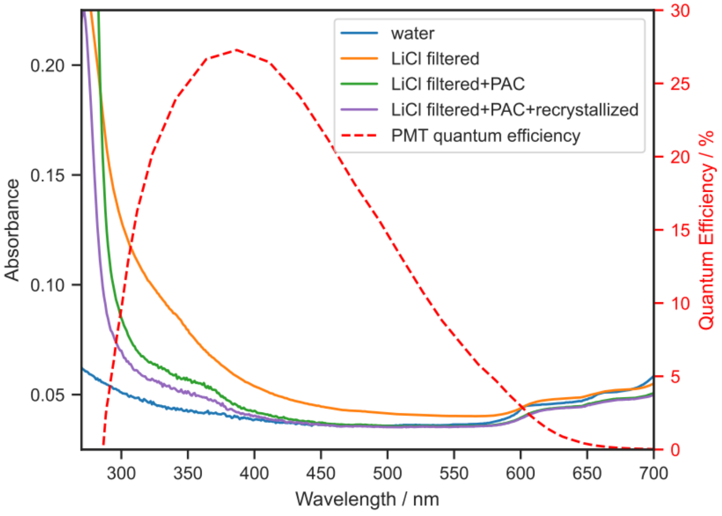
Ideal for solar neutrino upturn effect study

1. Attenuation length at 430 nm is greater than 50 meters
2. C124 can be added to enhance light yield



(b)

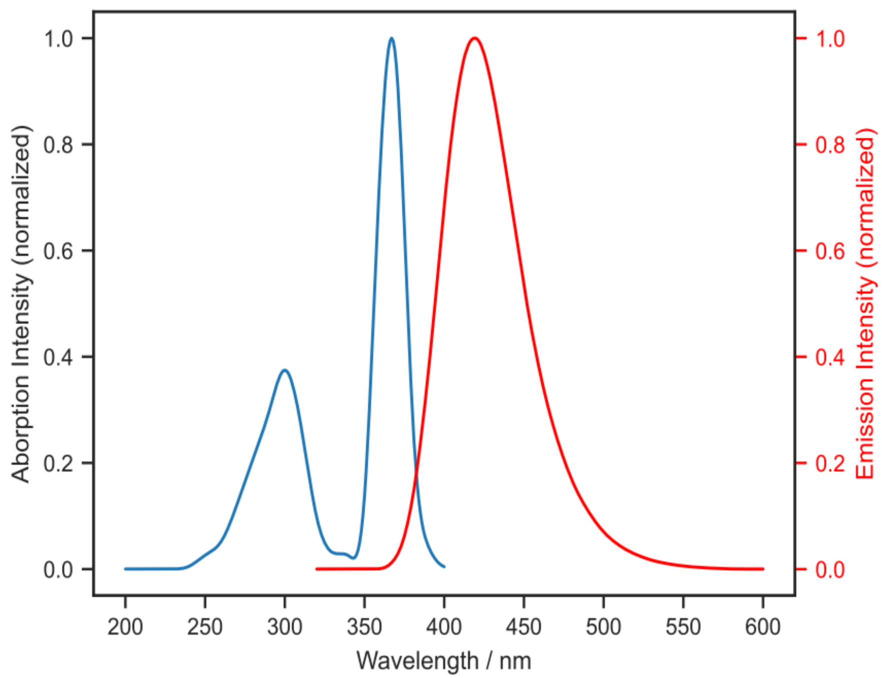




LiCl aqueous solution with carbostyril 124

Adding 1 ppm C124 to LiCl aqueous solution

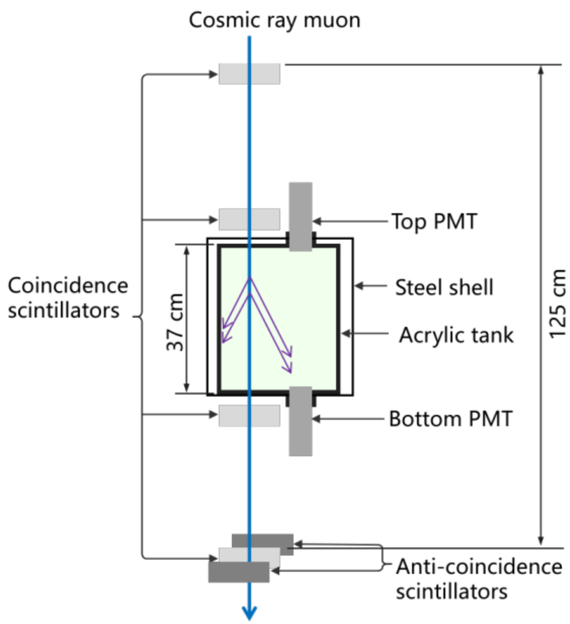
1. Convert short wavelength UV to longer wavelength
2. Convert short attenuation length UV to long attenuation length visible light

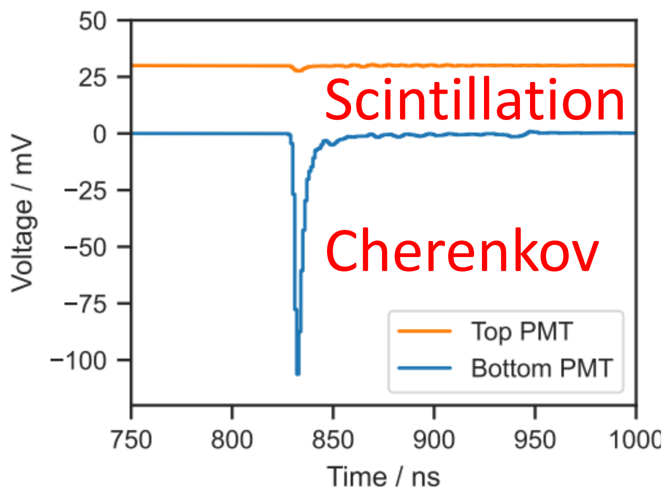


C124 absorption and emission spectra

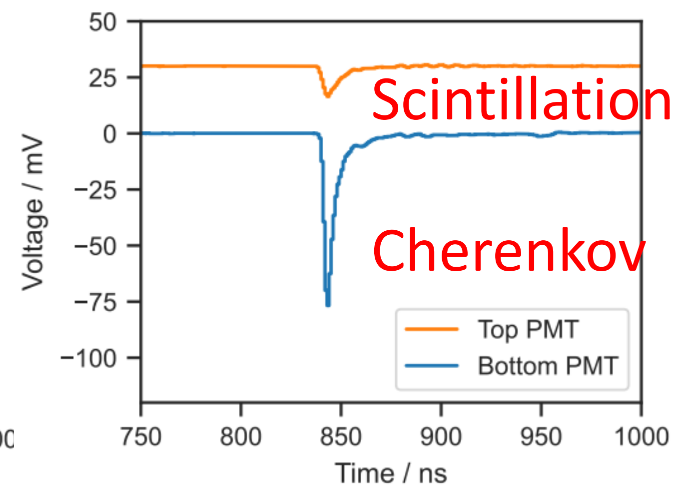
LiCl aqueous solution with carbostyril

Light yield verification with a muon telescope





(a) LiCl



(b) LiCl with 1 ppm C-124

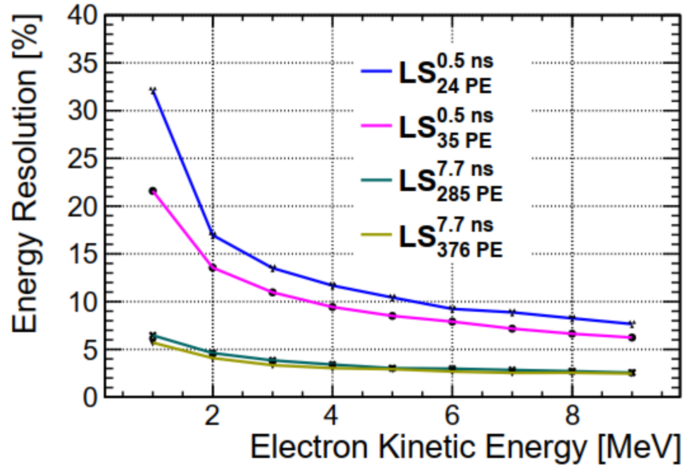
3.7 PE detected from isotropic scintillation
12.3 PE for Cherenkov

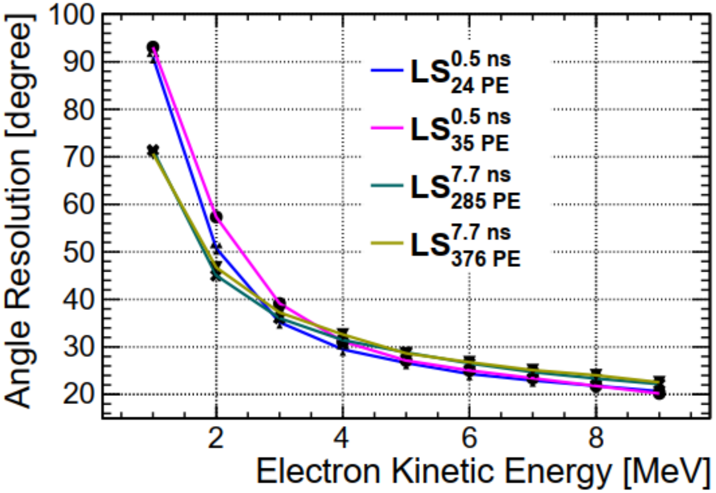
Cherenkov Liquid Scintillator Reconstruction

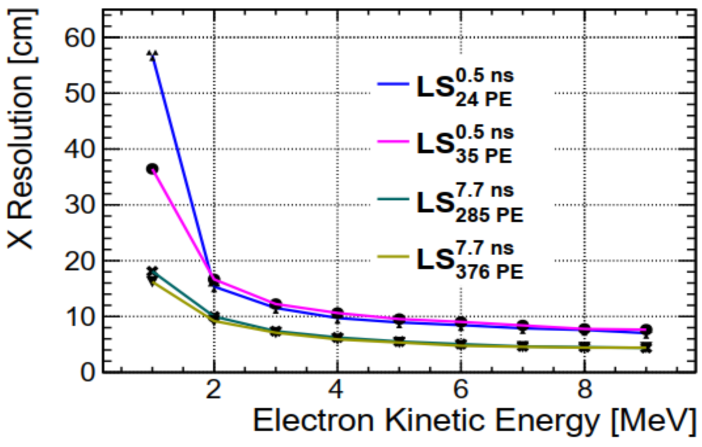
Reconstruct both Cherenkov light and scintillation light

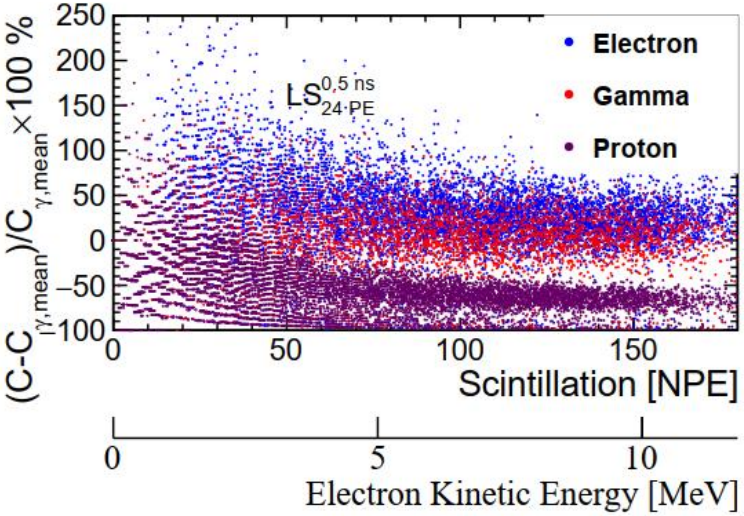
1. Energy; 2. Direction; 3. Position; 4. **Particle identification**

Guide liquid scintillator development



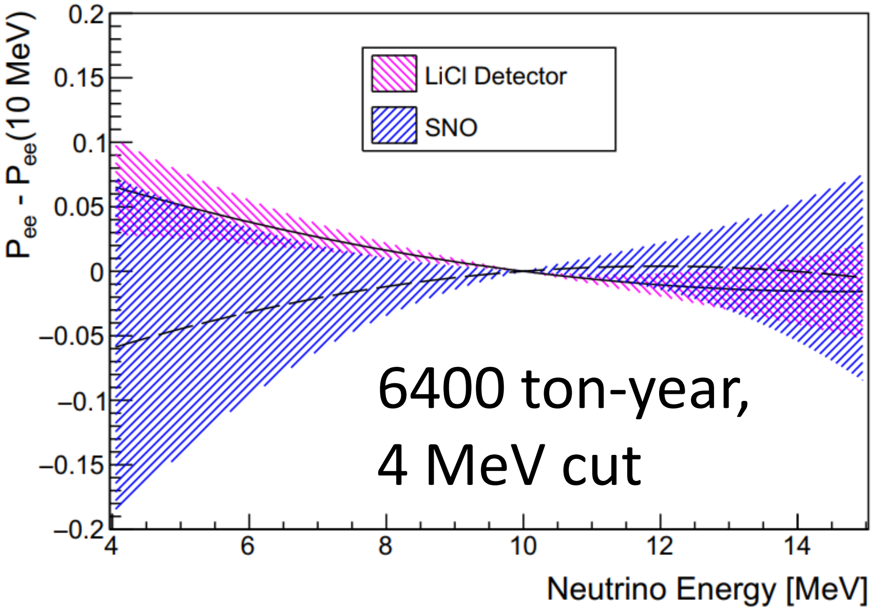




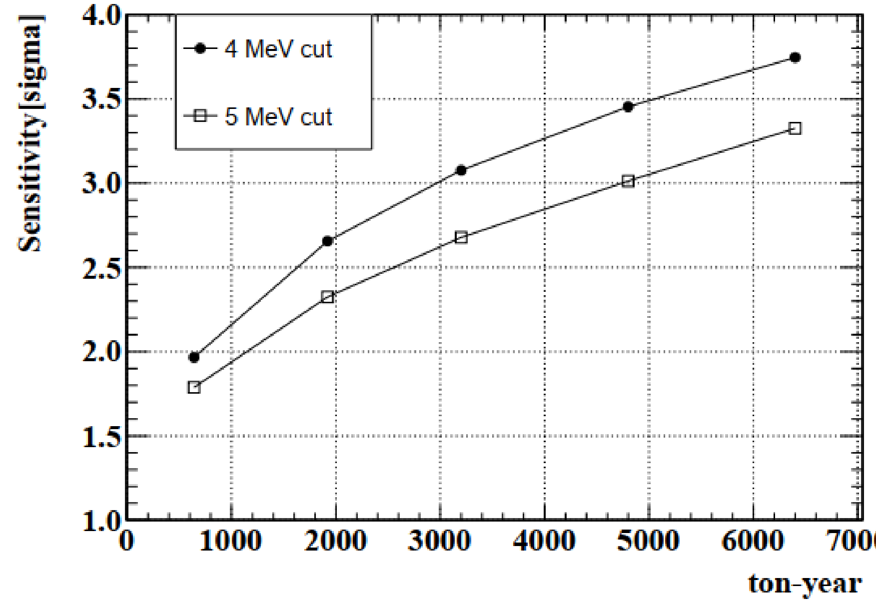


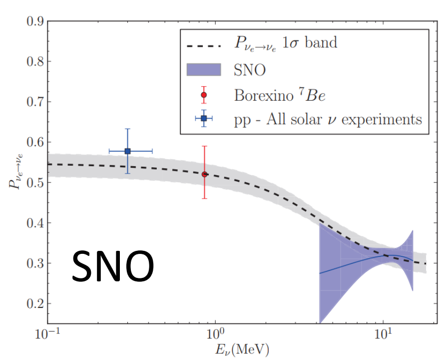
Solar Neutrino Physics with LiCl Solution

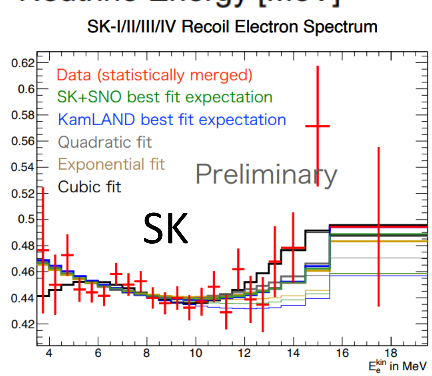
Solar neutrino survival probability-average vs energy



Upturn discovery sensitivity versus exposure







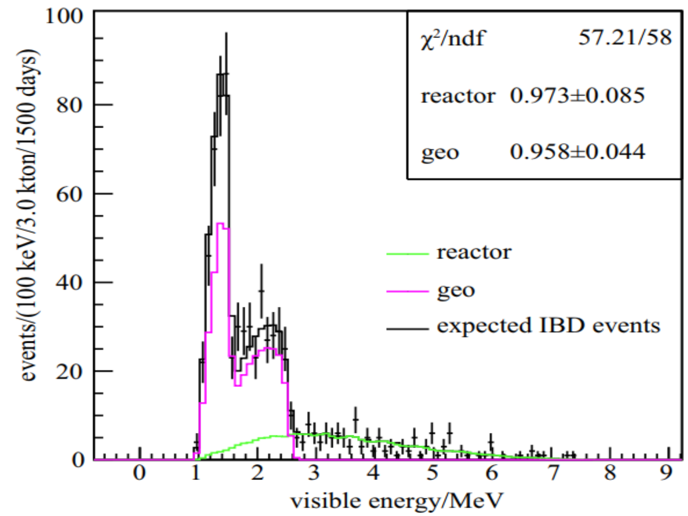
Slightly favors up-turn, though need more data

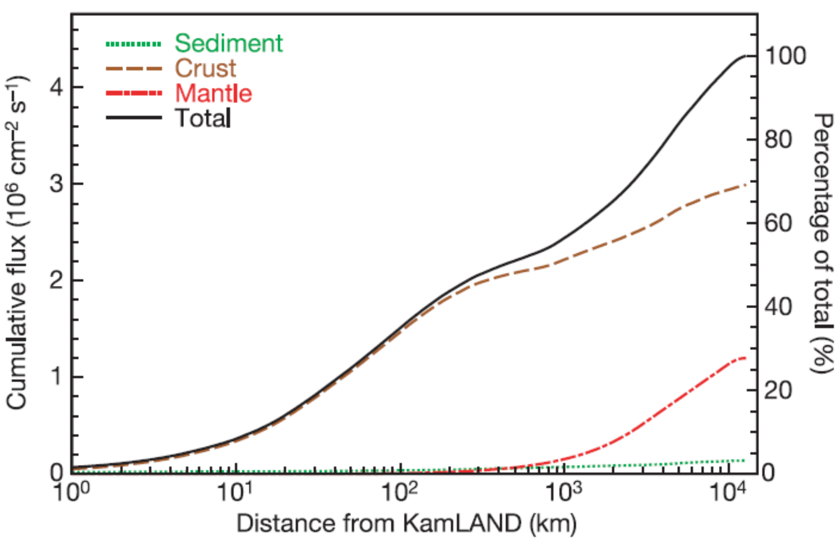
由于CC过程比ES过程有天然的优势，对太阳中微子振荡曲线的测量，Li特别有优势，<u>小体积探测器可以和HK以及DUNE相比</u>

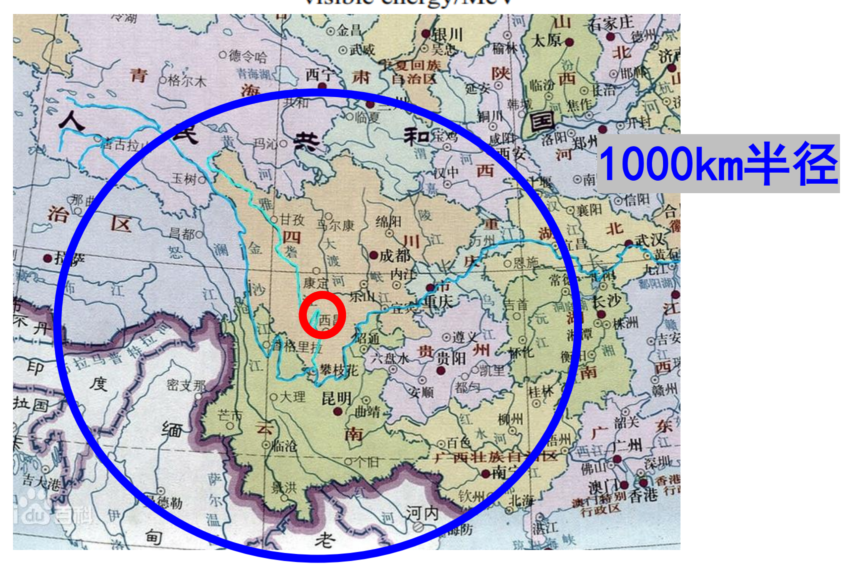
Geo Neutrino

With prompt-delayed signal detection:

- Expect tens of geoneutrinos in 5-10 years with the 500-ton detector
- LiCl detector can be used







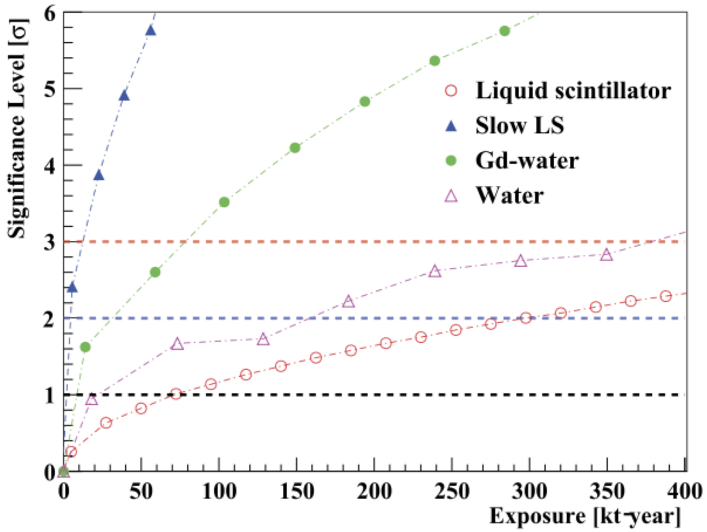
对喜马拉雅山地区的地球中微子测量

Supernova Relic Neutrinos

With Cherenkov-scintillation liquid scintillator:

Have the capability for particle identification to suppress neutral current background

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.

- LiCl aqueous solution with C124 is such a Cherenkov-scintillation detector.

Summary

1. **500 hundred-ton neutrino detector at CJPL II**
    a. Detector design and construction
    b. Replaceable detection media, allowed density range ± 20% wrt water, oil- or water- based liquid scintillator
2. **New MCP-PMT, Low background, fast, high QE**
3. **ADC chips and waveform readout electronics under design and testing**
    a. AD chips， 12 bit, GSPS, 350mW
    b. waveform readout， 300 Mz, 40Gbps
4. **LiCl aqueous solution for solar neutrinos （可与体量大两个数量级的SK和DUNE相比）**
5. **Geoneutrinos （世界唯一喜马拉雅山区地球中微子测量）**
6. **Supernova relic neutrinos （与SK-Gd可比的灵敏度）**

成本是各种大型中微子实验的1/100量级

Thank you. Stay tuned.

欢迎您的批评和建议

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

Related publications

1. Wenhui Shao, et al., The potential to probe solar neutrino physics with LiCl water solution, Eur. Phys. J. C 83 (2023) 799.
2. John F. Beacom, et al., Physics prospects of the Jinping neutrino experiment, Chinese Physics C 41 (2017) 023002.
3. Hanyu Wei, Zhe Wang, Shaomin Chen, Discovery potential for supernova relic neutrinos with slow liquid scintillator detectors, Physics Letters B 769 (2017) 255.
4. Aiqiang Zhang, et al., Performance evaluation of the 8-inch MCP-PMT for Jinping Neutrino Experiment, Nucl.Instrum.Meth.A 1055 (2023) 168506.
5. Ye Liang, et al., Optical property measurements of lithium chloride aqueous solution for a novel solar neutrino experiment, JINST 18 (2023) P07039.
6. D.C. Xu, et al., Towards the ultimate PMT waveform analysis, JINST 17 (2022), P06040.
7. Wentai Luo, et al., Reconstruction algorithm for a novel Cherenkov scintillation detector, Journal of Instrumentation, 2023, 18(02): P02004.
8. Wei Dou, et al., Reconstruction of Point Events in Liquid-Scintillator Detectors Subjected to Total Reflection, ArXiv:2209.10993.
9. Ziyi Guo, et al., Muon Flux Measurement at China Jinping Underground Laboratory, Chin.Phys.C 45 (2021) 2, 025001.
10. [] Lin Zhao, et al., Measurement of Muon-induced Neutron Production at China Jinping Underground Laboratory, Chin.Phys.C 46 (2022) 2, 025001.
11. [] Yiyang Wu, et al., Performance of the 1-ton Prototype Neutrino Detector at CJPL-I, Nucl.Instrum.Meth.A 1054 (2023) 168400.