R&D Progress of the Jinping Neutrino Experiment

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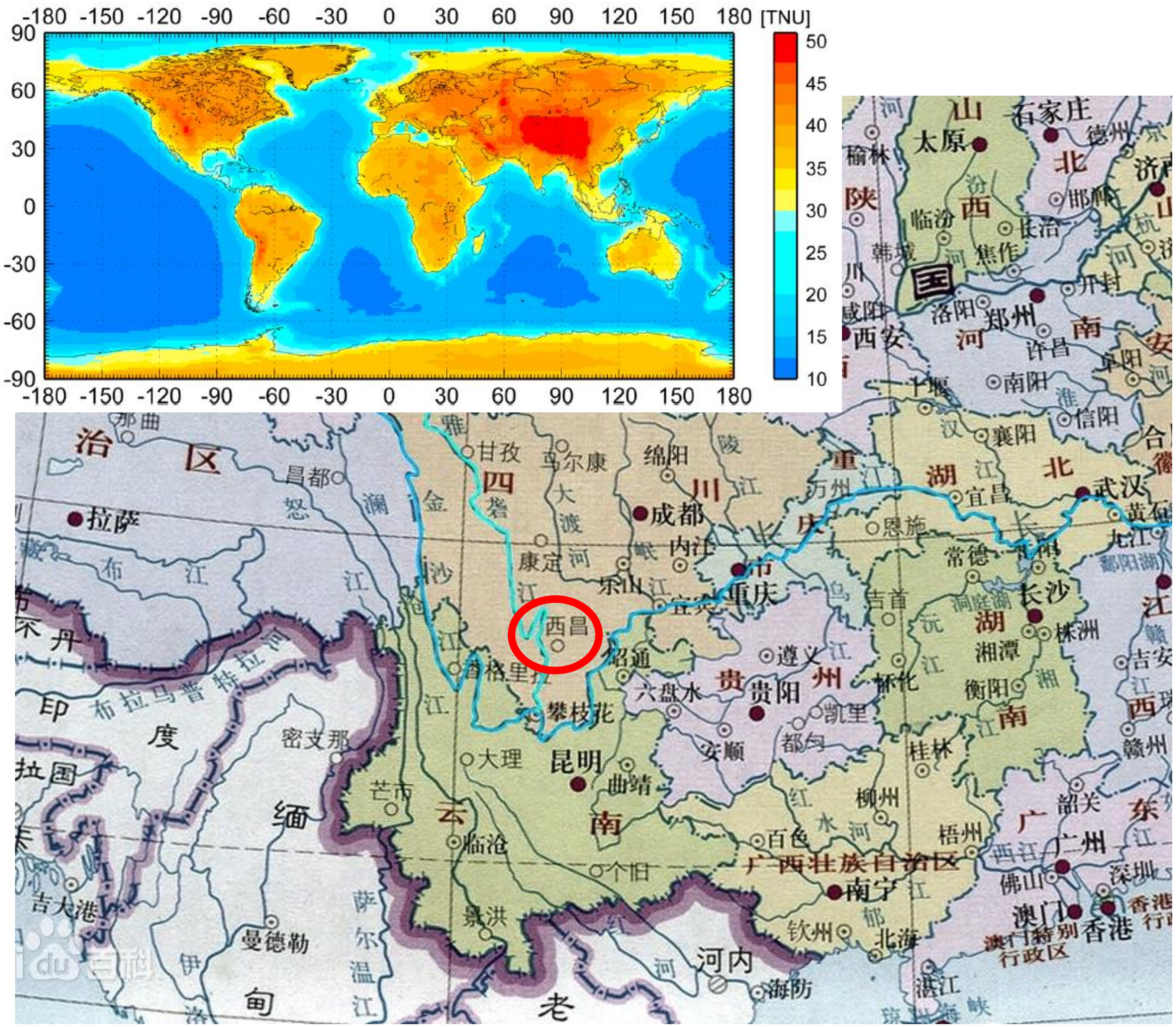
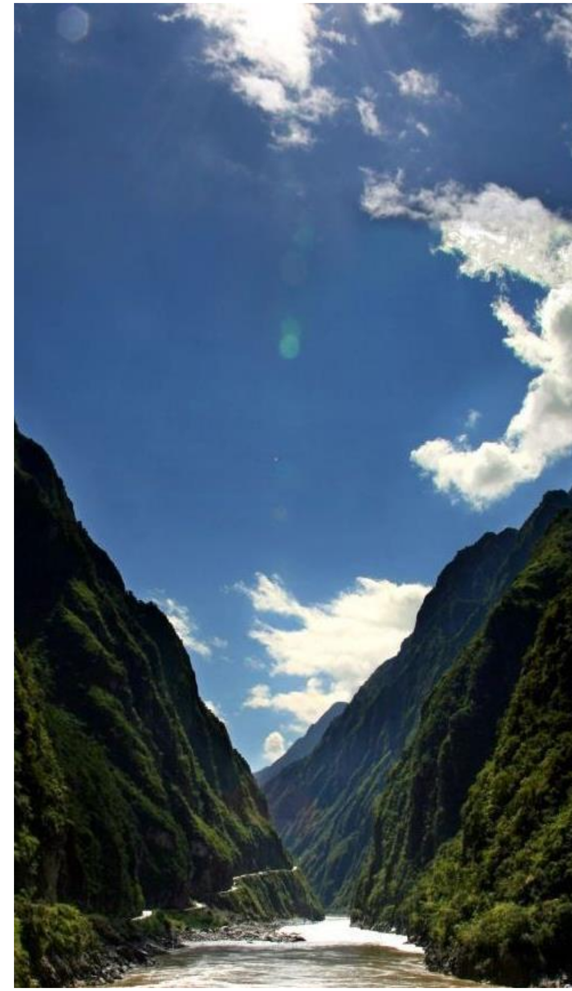
(On behalf of the research group)

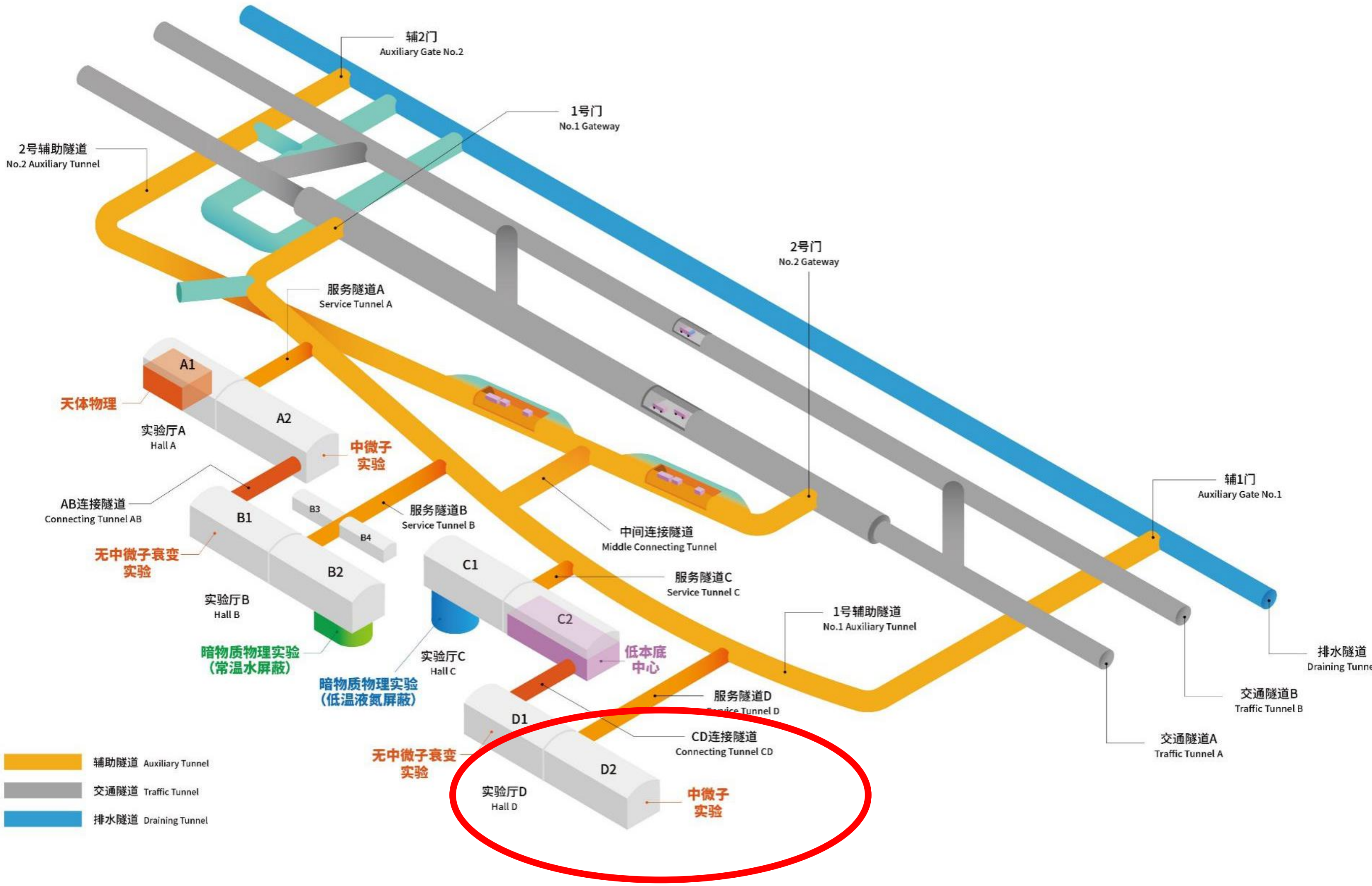
Jan. 12, 2024

China Jinping Underground Laboratory





Jinping Neutrino Experiment at CJPL-II, hall D2



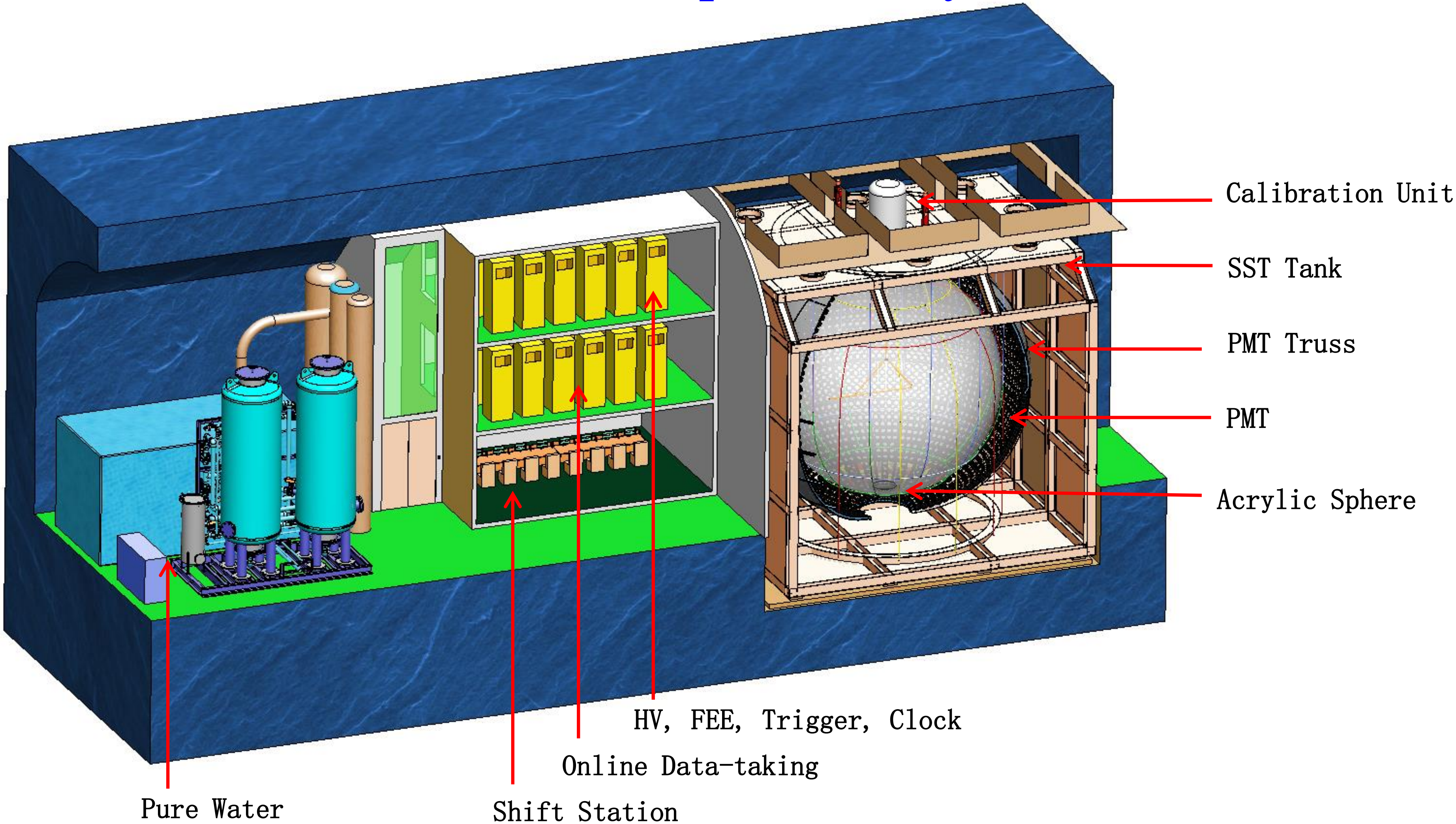
锦屏中微子实验的发展情况

- **想法形成于2014-2015年**
  - 希望构造千吨液体闪烁体中微子探测器
  - 使我们在太阳、地球、天体中微子等方向有世界领先结果
- **2017年自筹经费在锦屏建设1吨原型机**
  - 熟悉实验室，运行方式，地理环境
  - 广泛建立团队，多系，多高校研究团队
  - 上下游供应链，加工厂
  - 研制液闪，测量地下的本底
- **2015-2023年研发与实践**
  - 不断的调整优化方案，寻求更经济可行，物理更显著的方案

优化锦屏中微子实验方案

- **2015-2023年提升物理性能，压缩成本**
  - 探测介质体积，2000m³压至500m³，几亿压至几千万（成本是江门的1/100量级）
  - 有限的实验空间，以500m³，以3MeV阈值优化探测器设计，否则只有100-200m³
  - 建设实验基坑，否则只有250m³
  - 掺锂的水溶液，虽然体积减小，但基本维持物理目标的不变
  - 国产光电倍增管，成本减半
  - 希望继承大亚湾余留的1600只PMT
  - PMT集光器，节省20%的PMT
  - 国产的电子学芯片，每路10000元压至1000元
  - 将尝试316H不锈钢，成本是316L的一半

Hall D and Experiment Layout

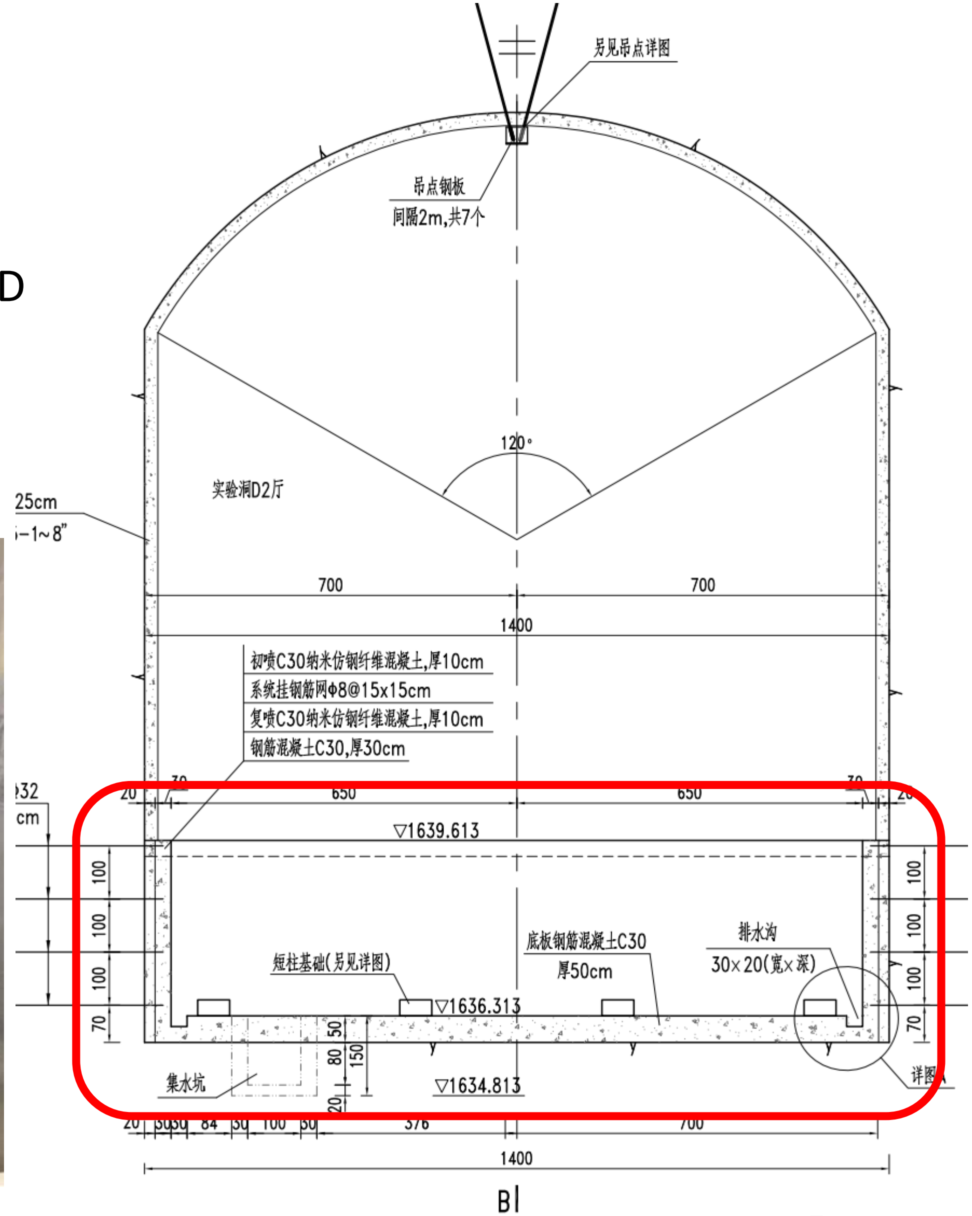


500 cubic meter target volume

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

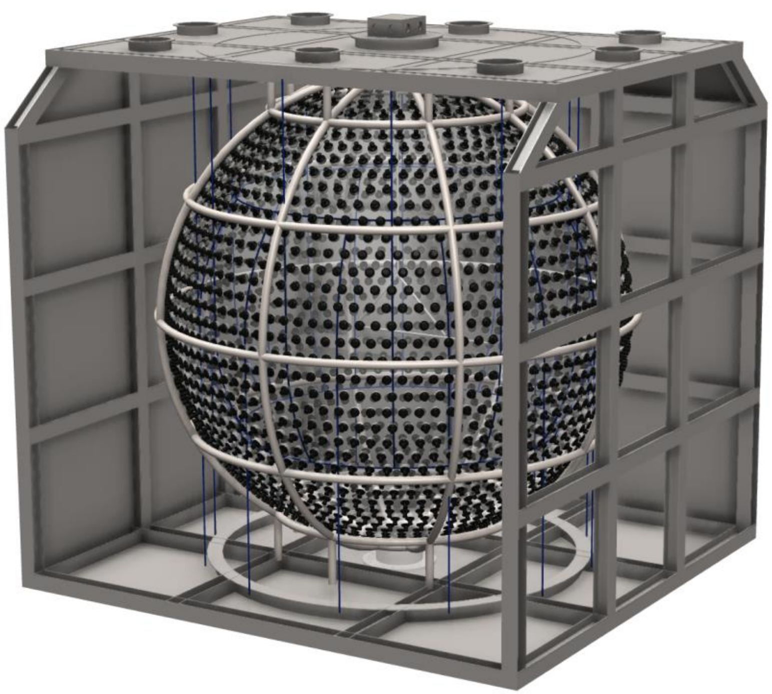
Rope network:

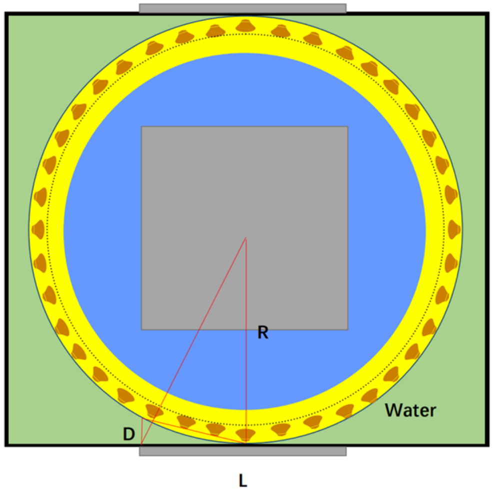
holding-up and holding-down

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

Shieling material:

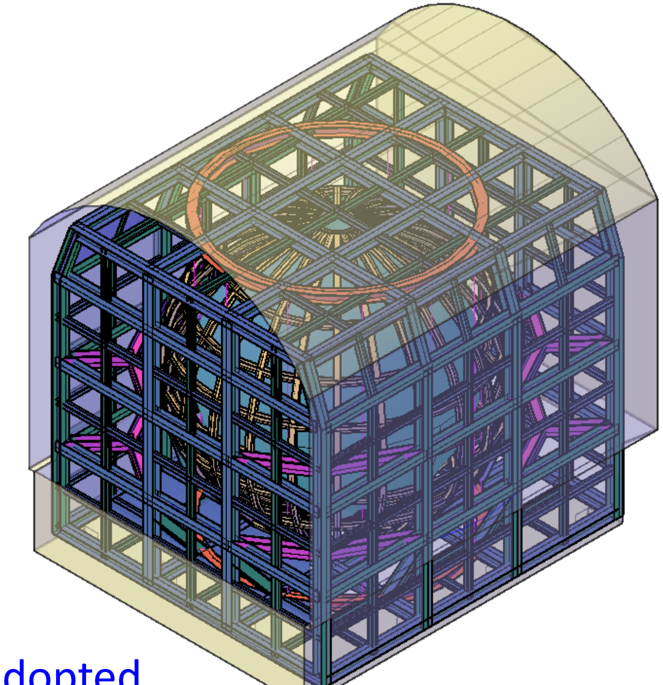
Water and SST (or lead)





Shieling SST (or lead) planes

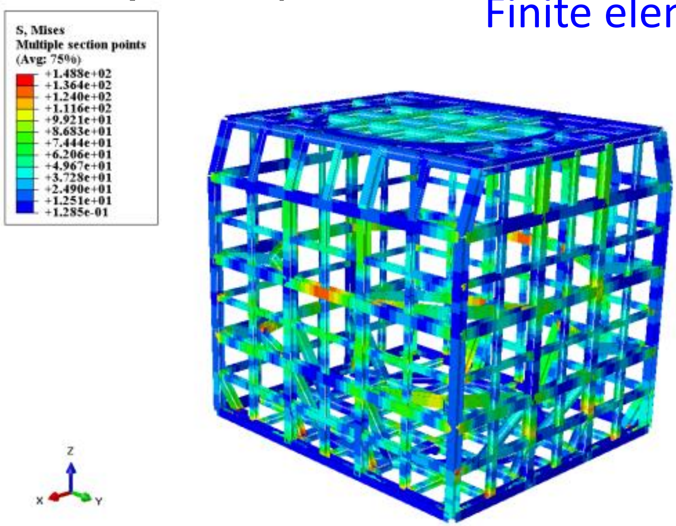
Water Tank



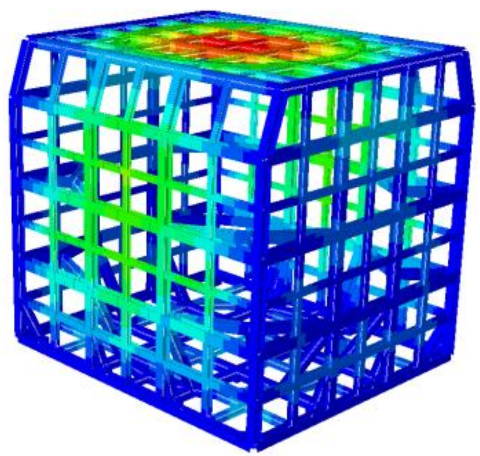
Requirement for the stainless steel tank:

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)

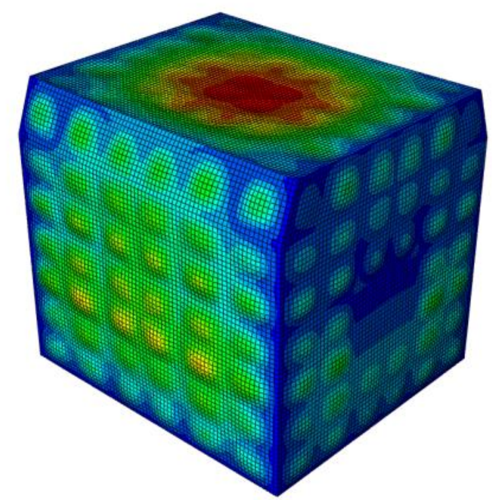
Finite element software ABAQUS is adopted



Stress contour diagram

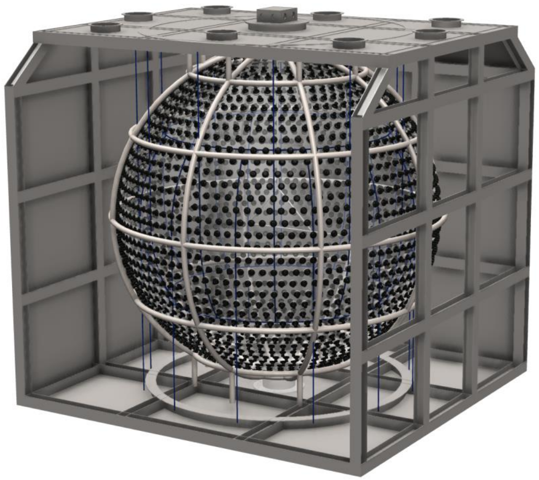


Displacement contour diagram



Stress contour diagram with covering SST plates

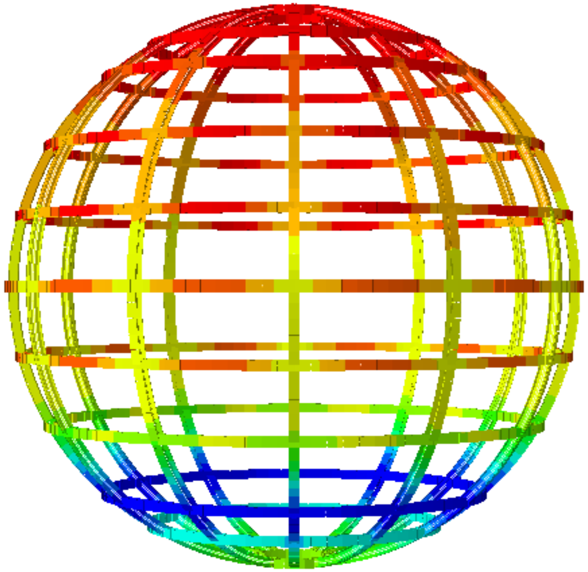
PMT Truss



Requirement for the PMT truss:

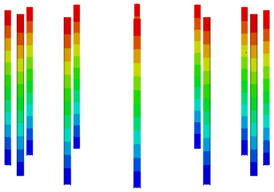
1. Hold 4000 PMTs

Structure



Axial force contour diagram for the sphere

Finite element software ABAQUS is adopted

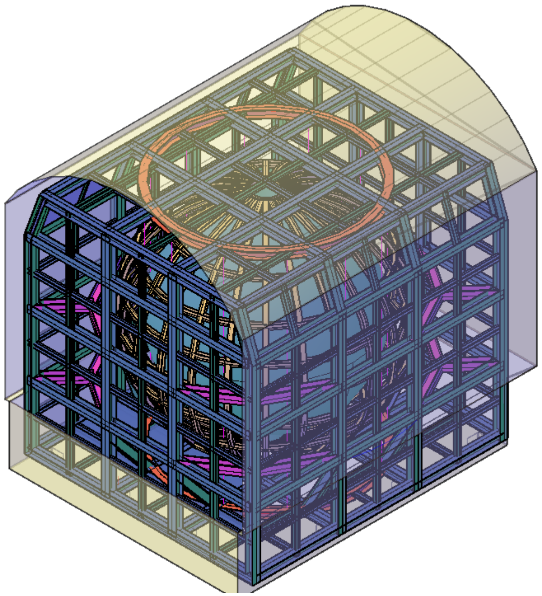


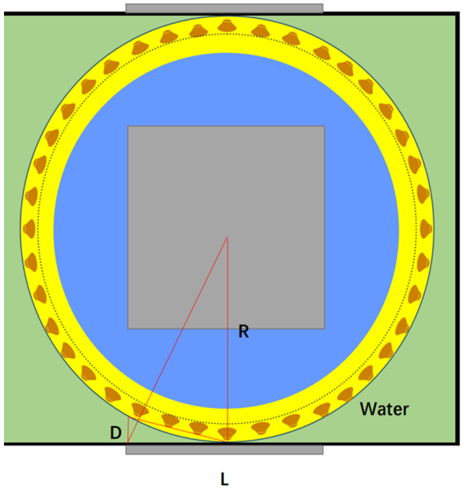
Axial force contour diagram for the legs

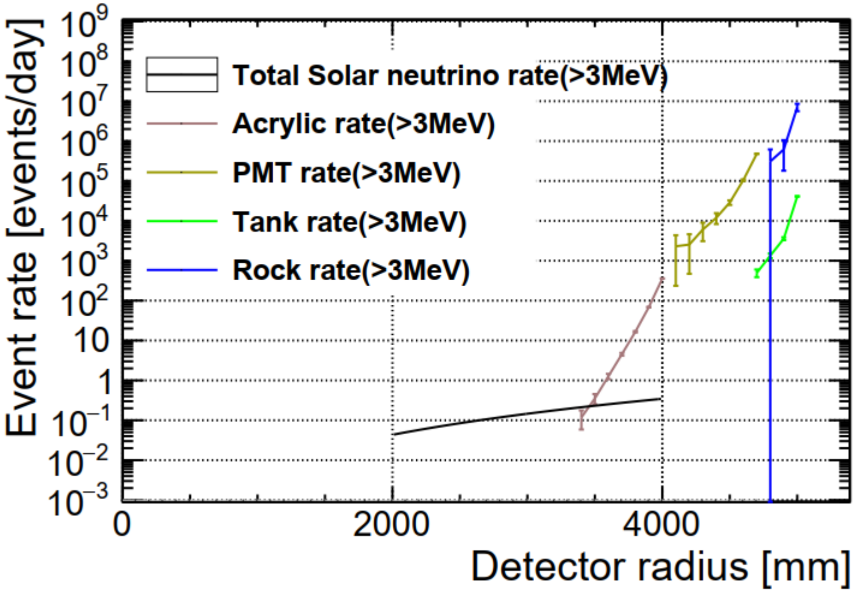
Shielding Plates

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







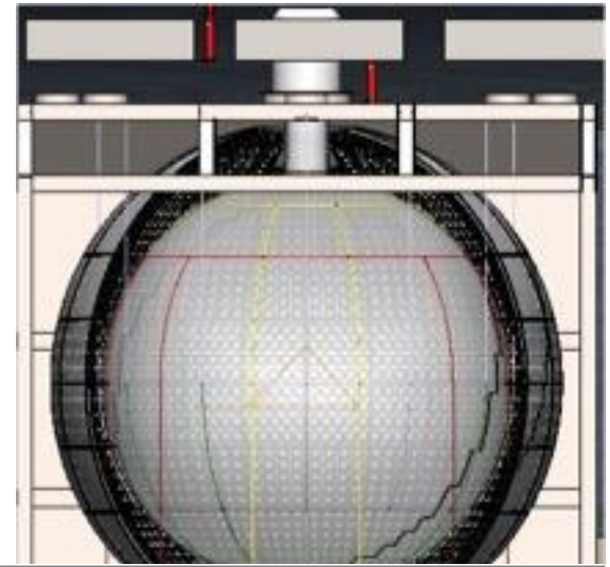
Narrow Hall D and all occupied.

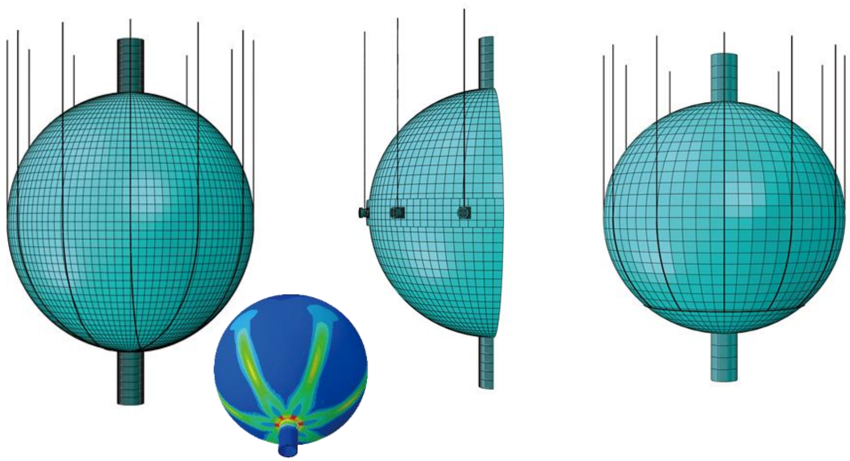
Shield concrete and rock background

Acrylic Vessel

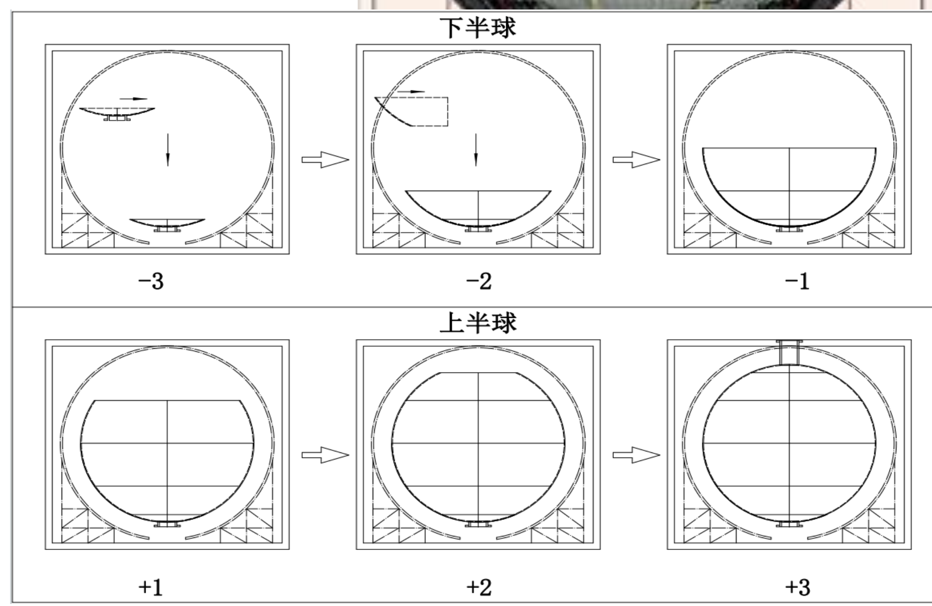
Requirement for the PMT truss:

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





Compared 3 holding designs
Last one presents least stress on acrylic

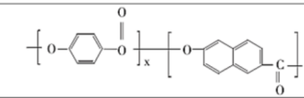
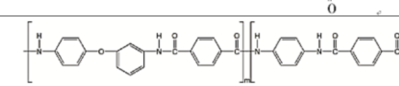


Preliminary installation plan
Division, bonding, and cleaning

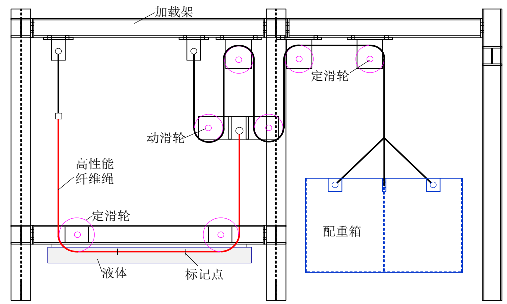
Ropes

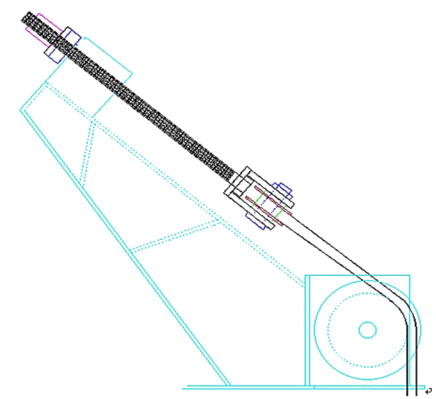
Requirement for the Ropes:

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	$H_3C-[CH_2-CH_2]_n-CH_3$
Kevlar 纤维	$-[NH-C_6H_4-NH-CO-C_6H_4-CO]-$
Vectran 纤维	
Technora 纤维	

Breaking experiments





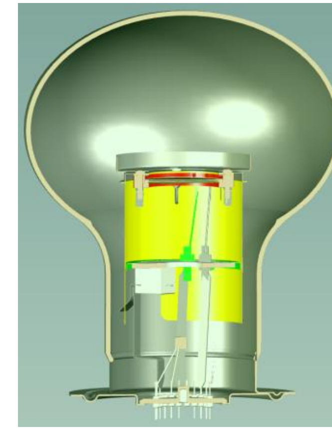
Tension monitor and length adjustment

Preparing for chemical analysis

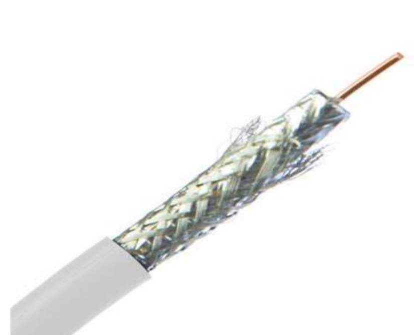
Creeping experiments

MCP-PMT

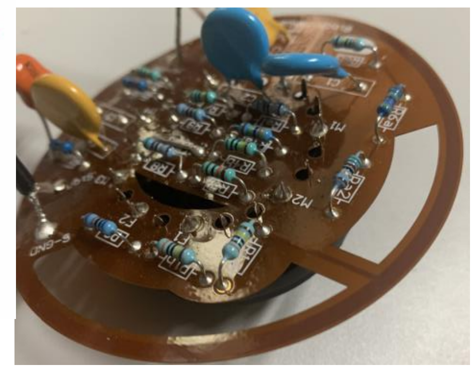
Material control



Structure



Cable



HV divider

New 8-inch MCP PMTs

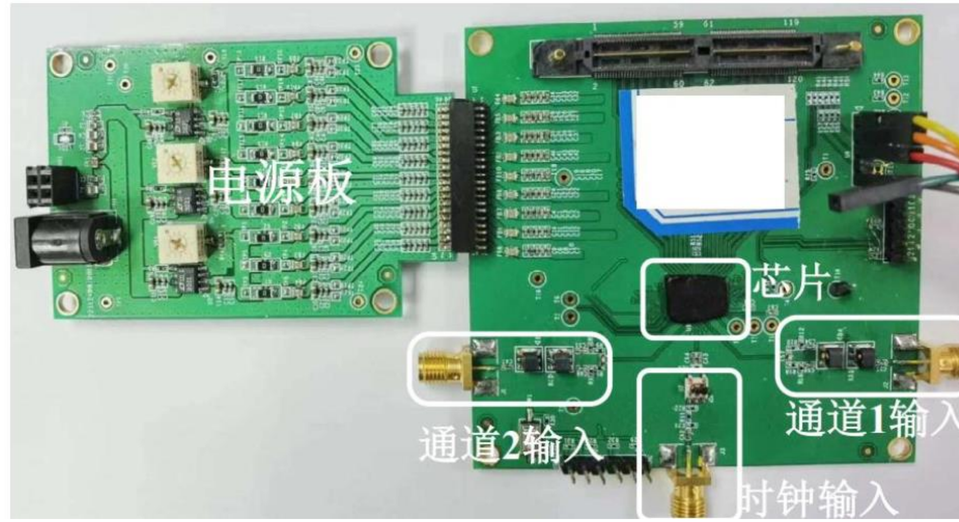
1. U、Th: <4E-8 g/g
2. K-40: <4e-9 g/g
3. High QE: 30%
4. Good timing: TTS<1.8 ns

600 produced.

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)

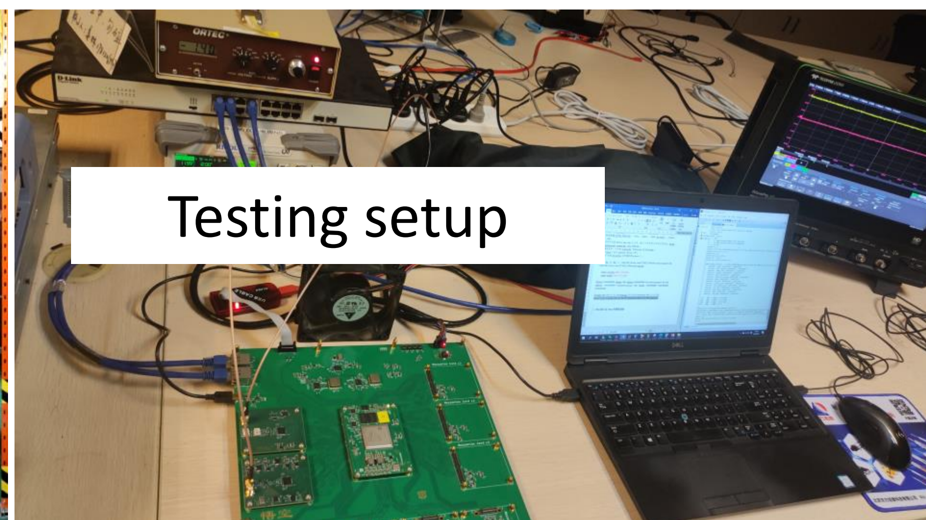


Readout board

Bandwidth 300 MHz, 40Gbps

Testing setup

The whole system will be tested on the one-ton prototype this year.



Physics program

The construction and testing running of the detector is expected at 2027. Physics runs follow...

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

Solar Neutrino Physics with LiCl Solution

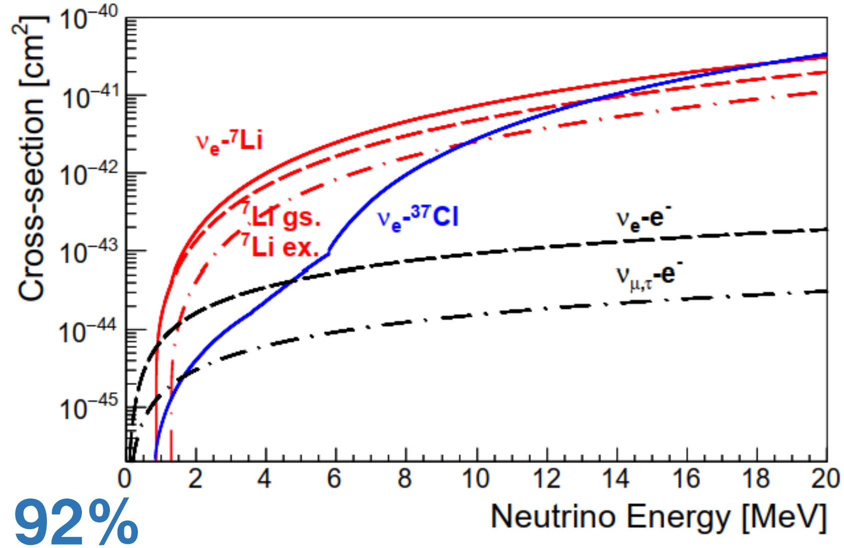
1. **CC process for ν_e:**

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

   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:**

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

Measure neutrino energy

$$T = E_\nu - 0.862\ \text{MeV}$$

2. **Elastic scatter on e^-:**

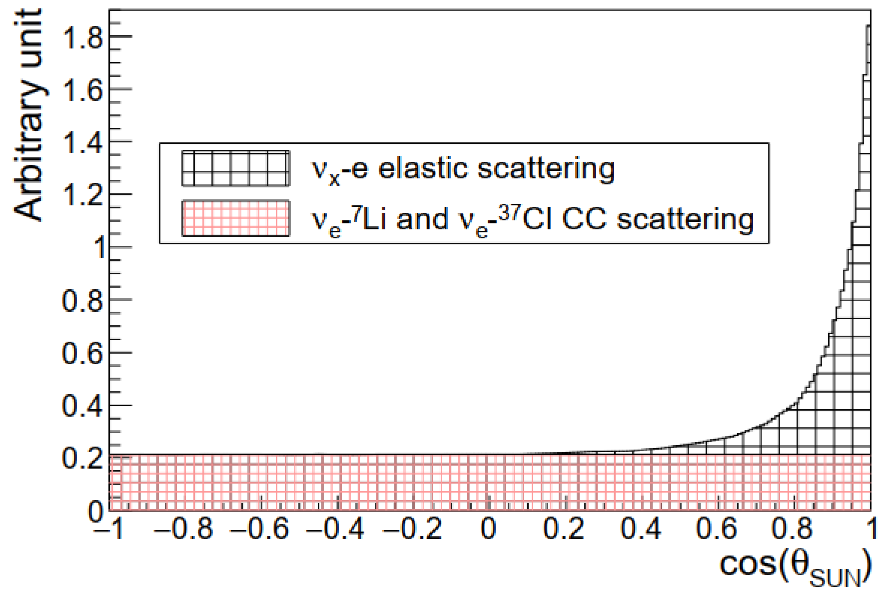
Separation by solar angle

3. **Delaved coincidence for $\bar{\nu}_e$**

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

with neutron capture on H, Li6, and Cl35

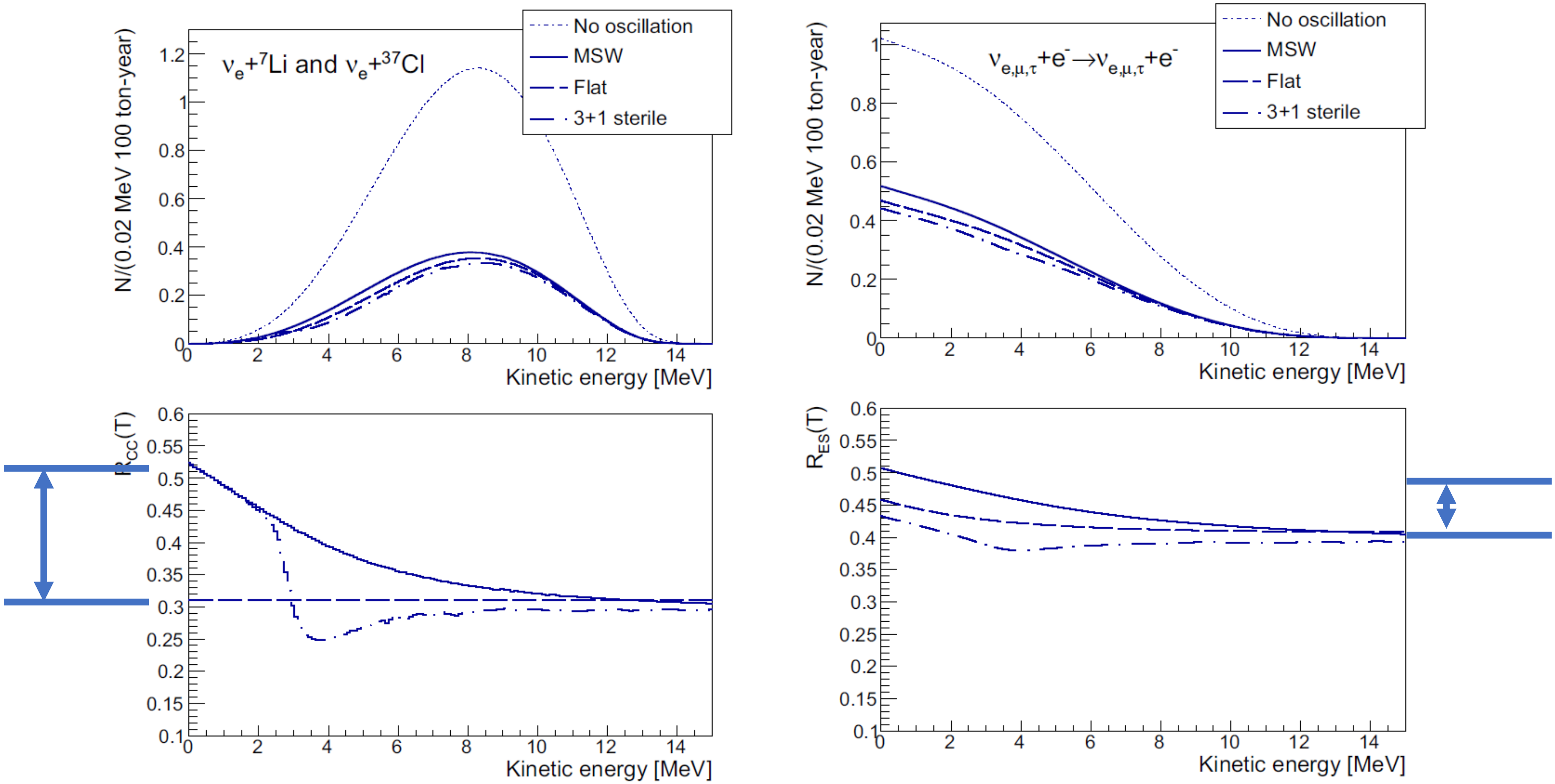
measure $\bar{\nu}_e$ energy



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

Good chance for solar, geo, and supernova neutrinos

CC vs ES for solar neutrino oscillation study

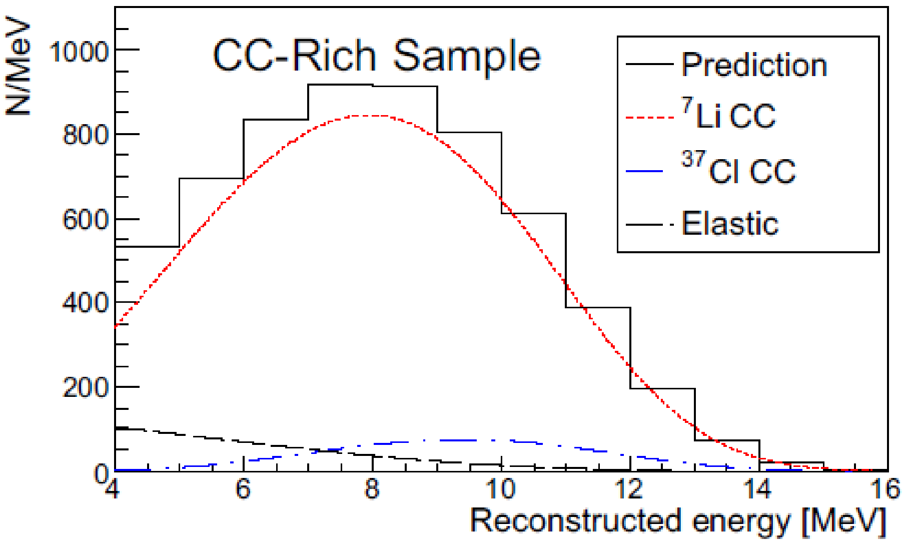


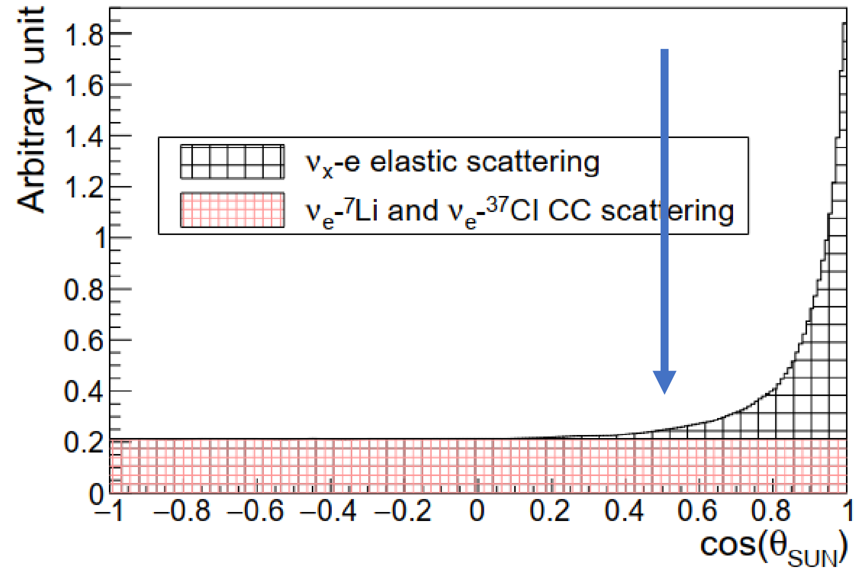
ES过程中，单能的中微子，测量结果是一个平台

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

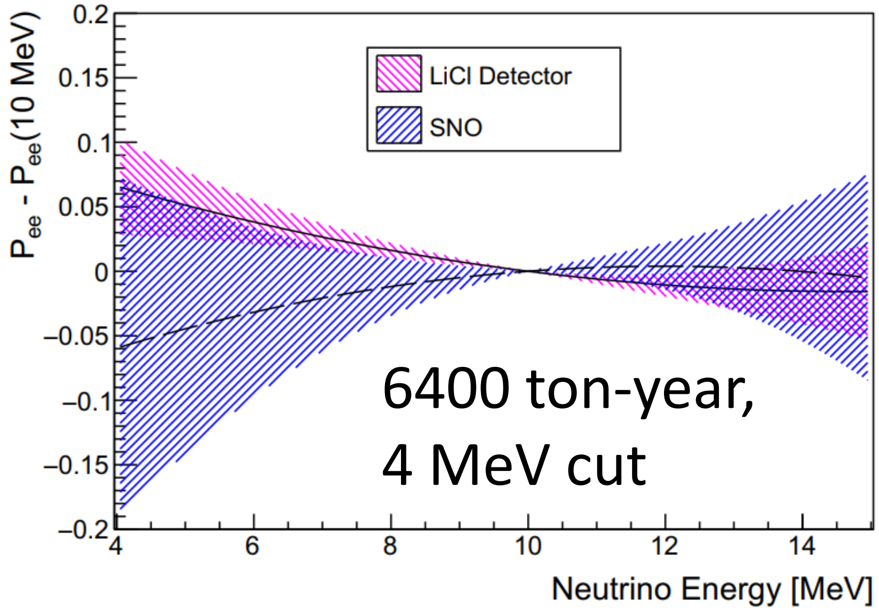




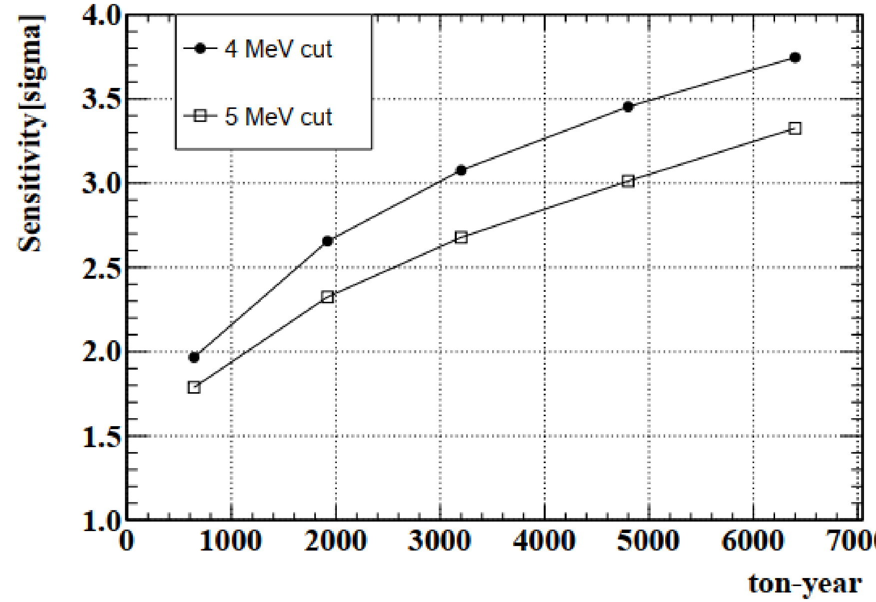
With a solar angle cut, CC process signals can be clearly extracted.
Serve as an solar neutrino spectrometer.

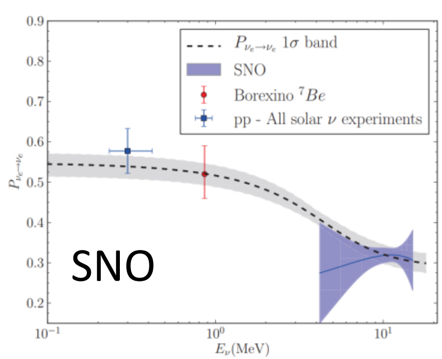
Solar Neutrino Physics with LiCl Solution

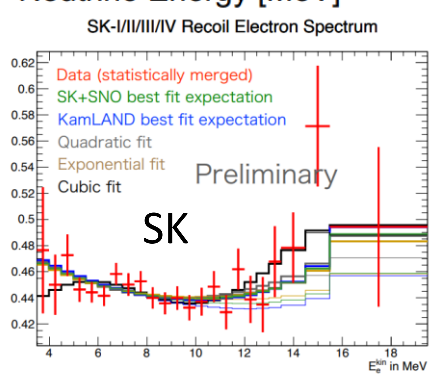
Solar neutrino survival probability-average vs energy



Upturn discovery sensitivity versus exposure



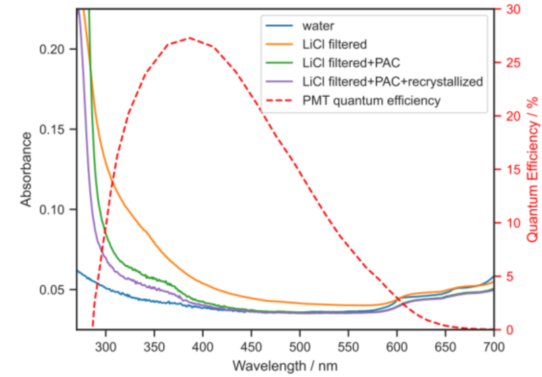




Slightly favors up-turn, though need more data

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，小体积探测器可以和HK以及DUNE相比

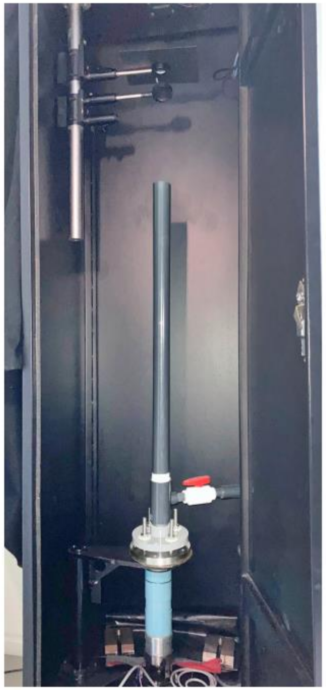
LiCl Water Solution



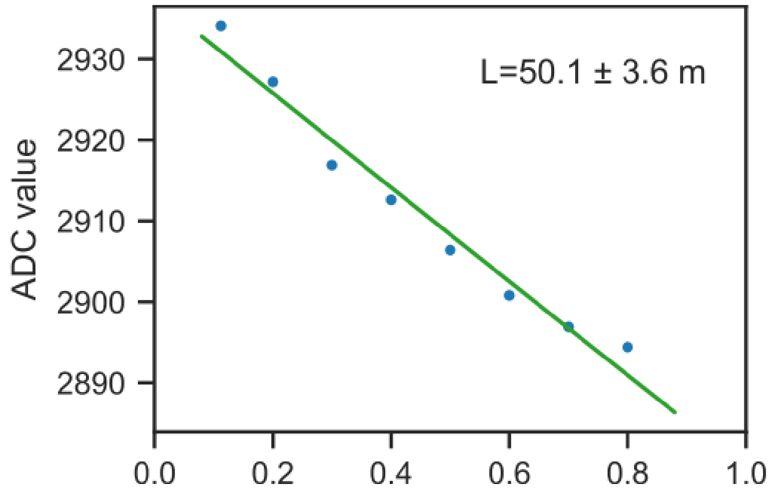
LiCl water solution

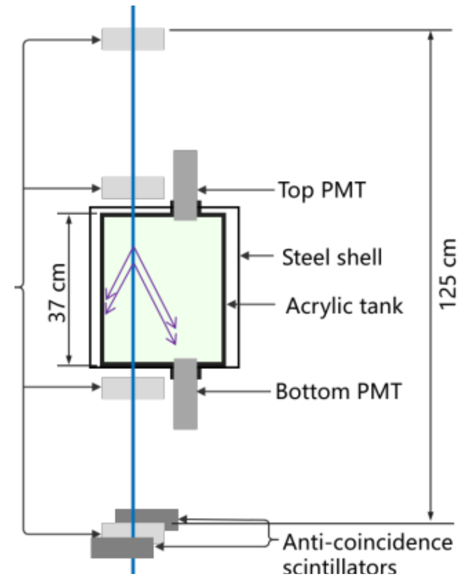
Ideal for solar neutrino upturn effect study

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



(b)



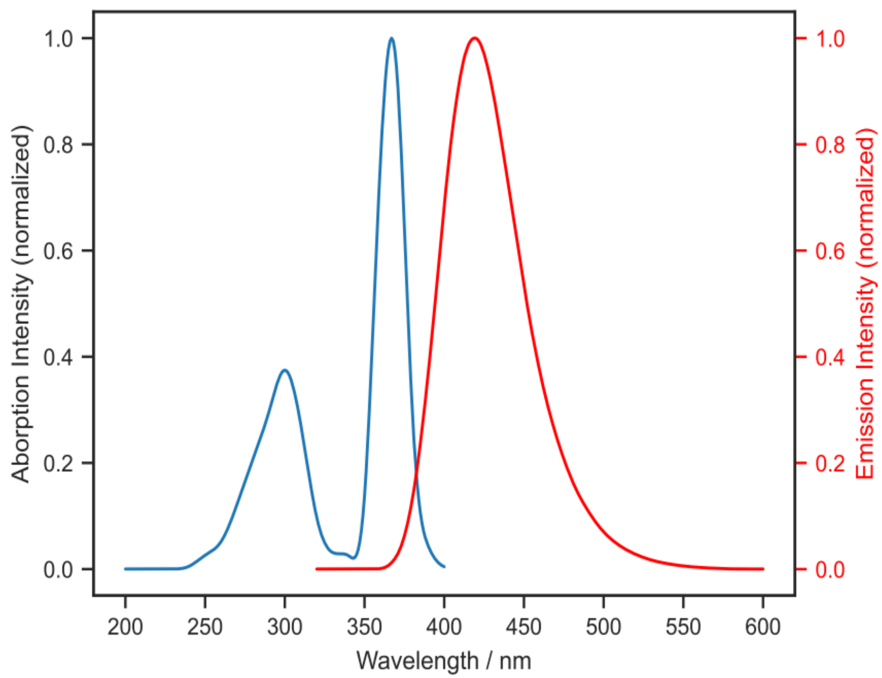


	Top PMT PEs	Bottom PMT PEs
Water	0.76 ± 0.08	15.8 ± 1.5
Saturated LiCl solution	0.54 ± 0.08	17.2 ± 1.5
Saturated LiCl solution with 1 ppm C-124	3.7 ± 0.4	16.0 ± 1.6

LiCl aqueous solution with carbostyril 124

Adding 1 ppm C124 to LiCl aqueous solution

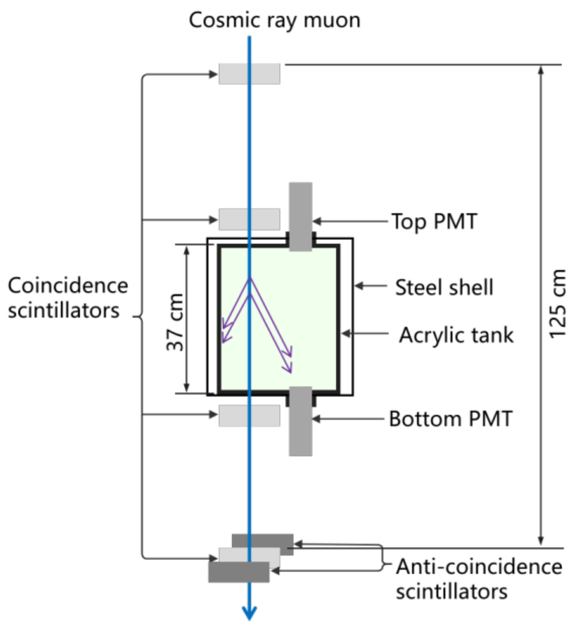
1. Convert short wavelength UV to longer wavelength
2. Convert short attenuation length UV to long attenuation length visible light

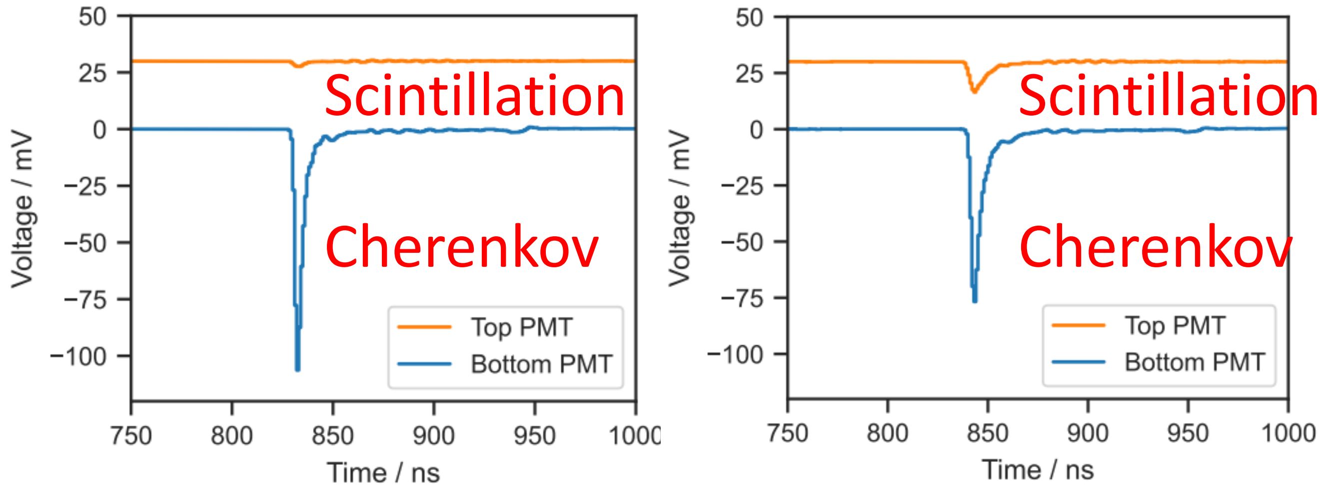


C124 absorption and emission spectra

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

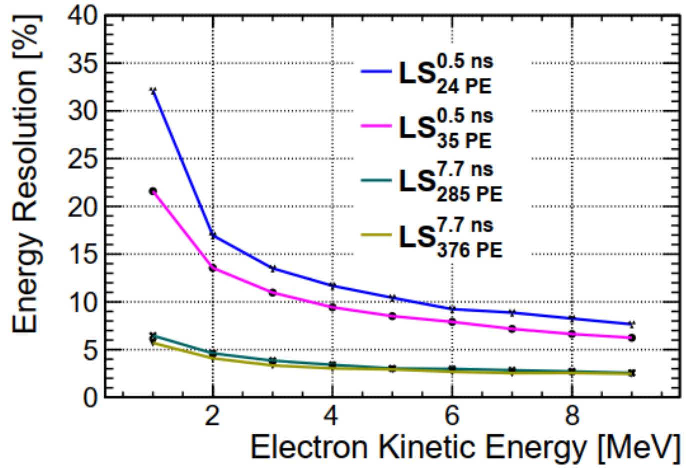
12.3 PE for Cherenkov

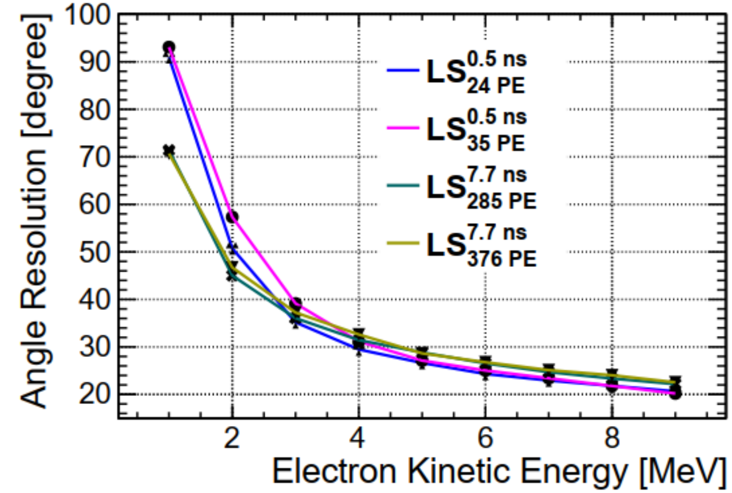
Cherenkov Liquid Scintillator Reconstruction

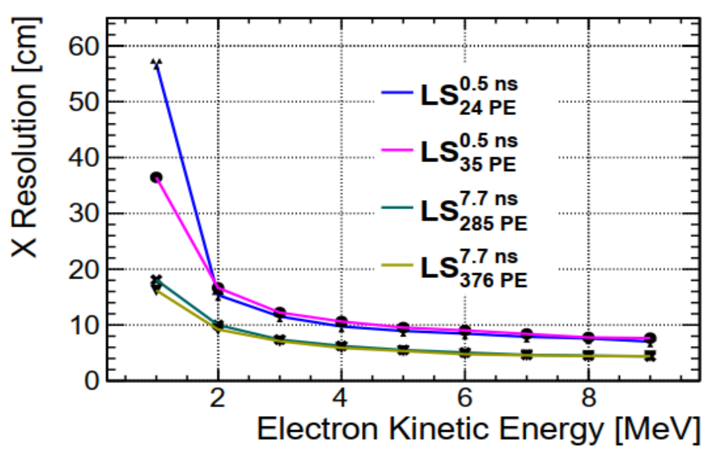
Reconstruct both Cherenkov light and scintillation light

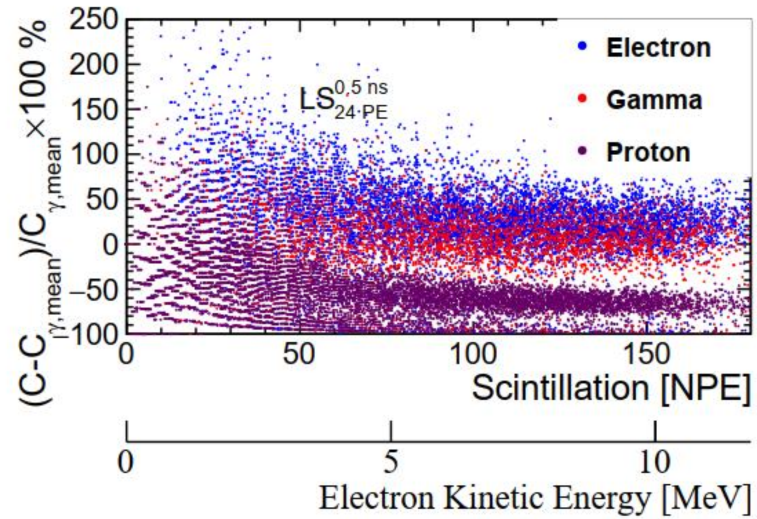
1. Energy; 2. Direction; 3. Position; 4. **Particle identification**

Guide liquid scintillator development





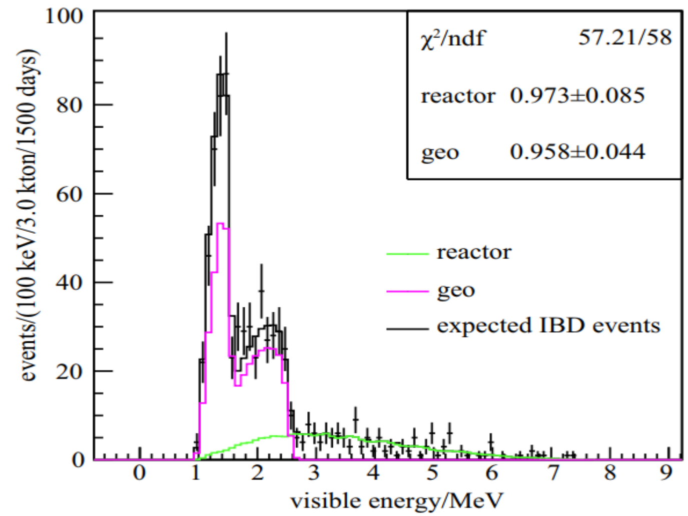


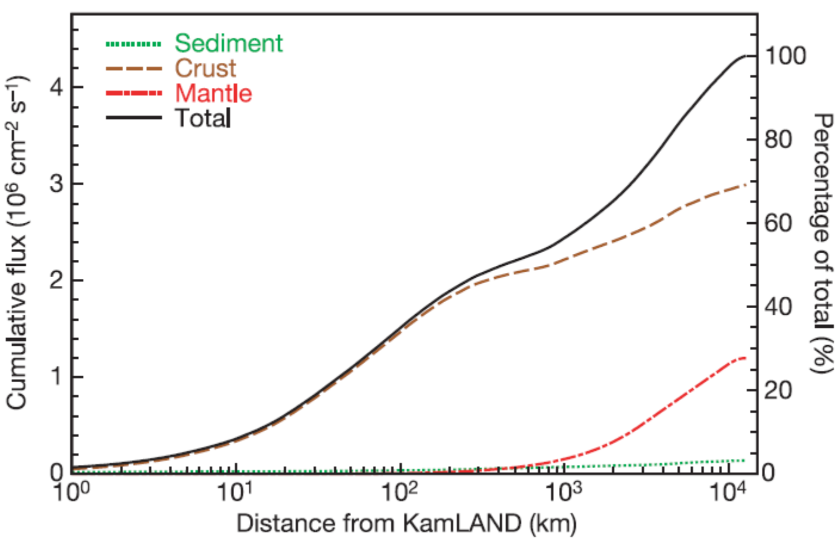


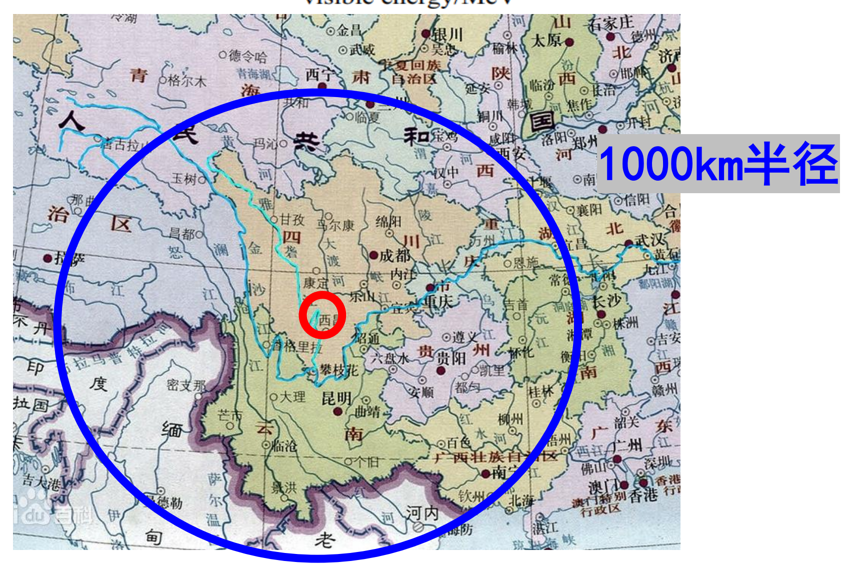
Geo Neutrino

With prompt-delayed signal detection:

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







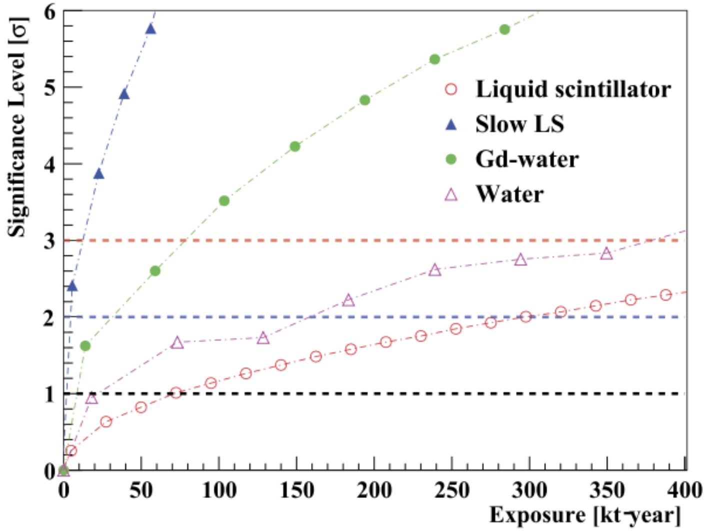
对喜马拉雅山地区的地球中微子测量

Supernova Relic Neutrinos

With Cherenkov-scintillation liquid scintillator:

Have the capability for particle identification to suppress neutral current background

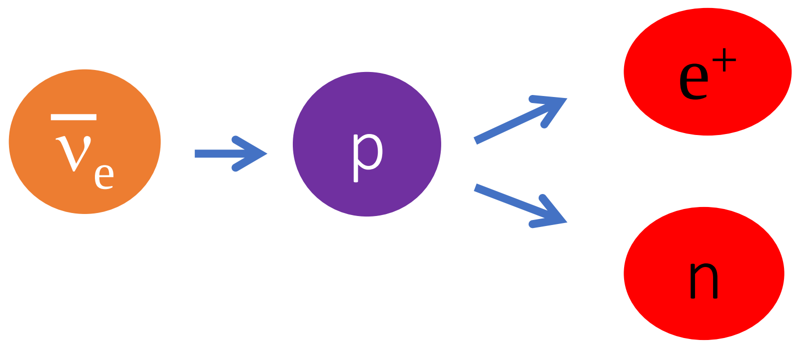
Expect a few golden candidate supernova relic neutrinos in 5-10 years with the 500-ton detector

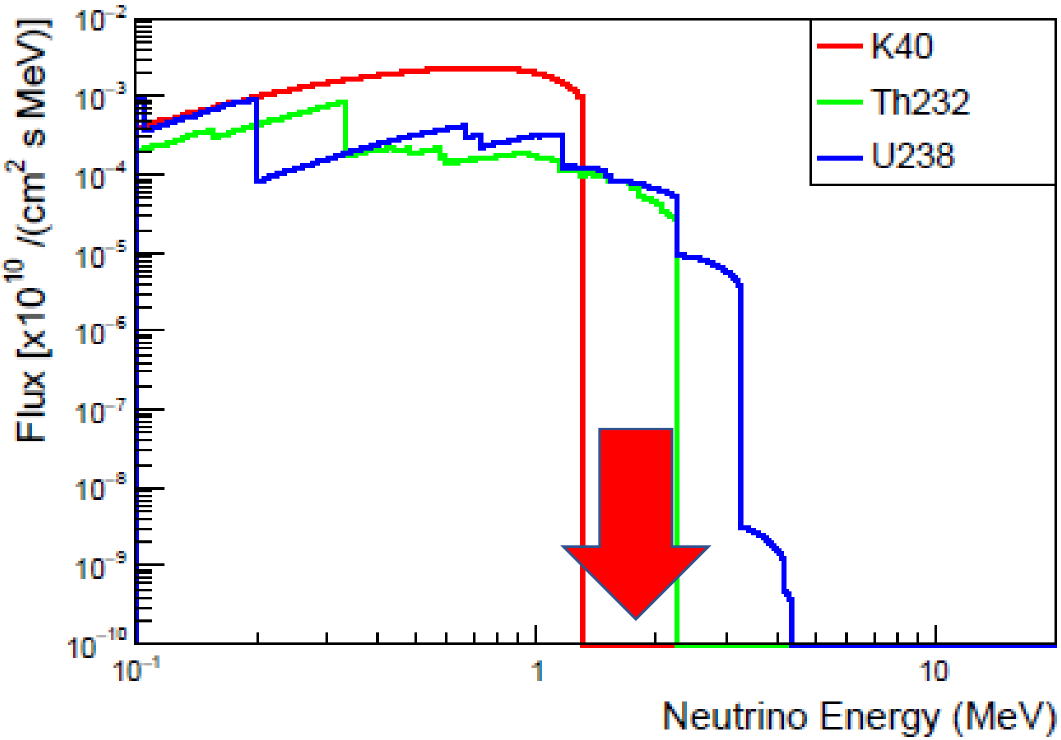


Expect an improvement better than this figure. Work in progress.

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

K40 geoneutrino Detection

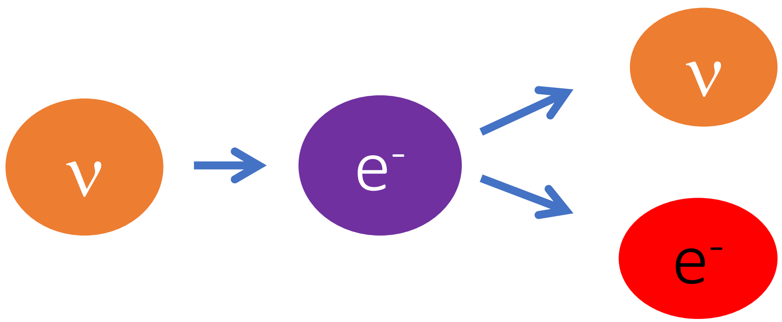




- IBD threshold = 1.8 MeV
- U, Th neutrinos only

- K-40 geoneutrino maximal energy 1.31 MeV
- K-40 not accessible

Neutrino-Electron Scattering



Pro:

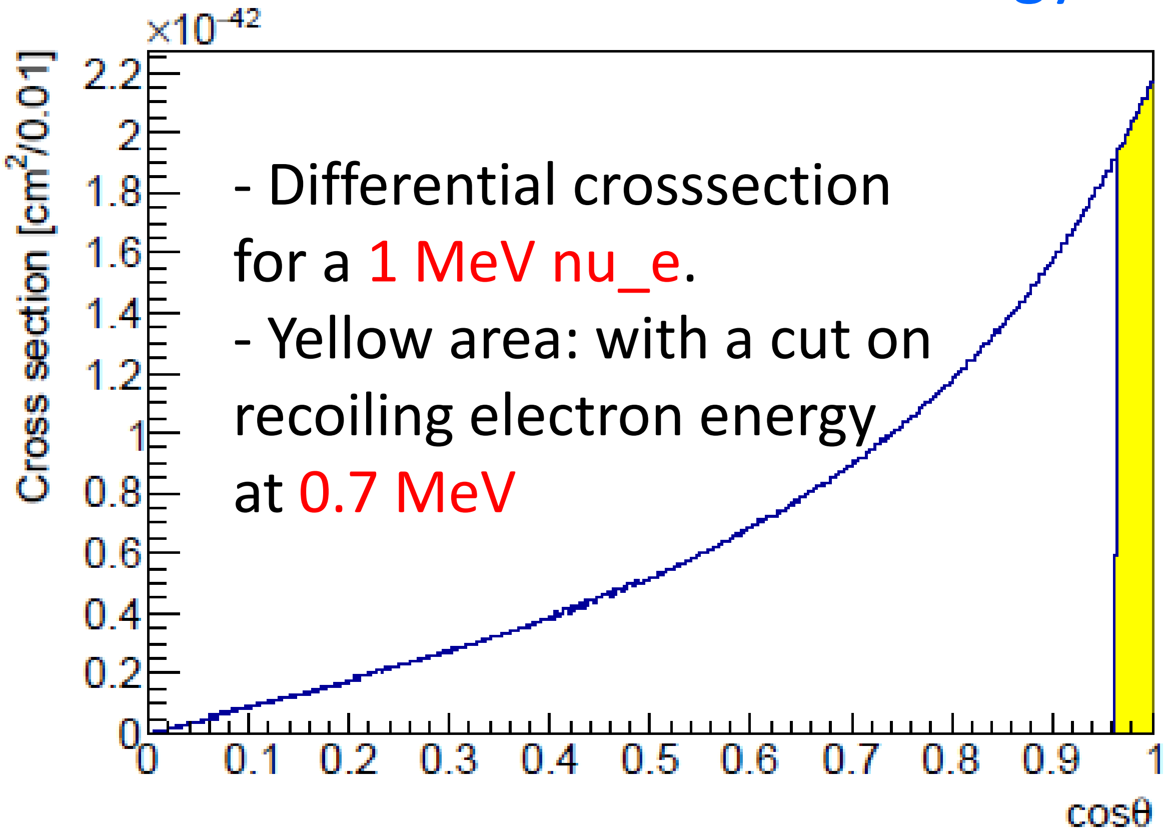
- No threshold

Con:

- Conventional liquid-scintillator detector: Geoneutrino signals overwhelmed by solar signals
- Water Cherenkov detector: Very few photons, poor energy resolution, not easy to trigger.

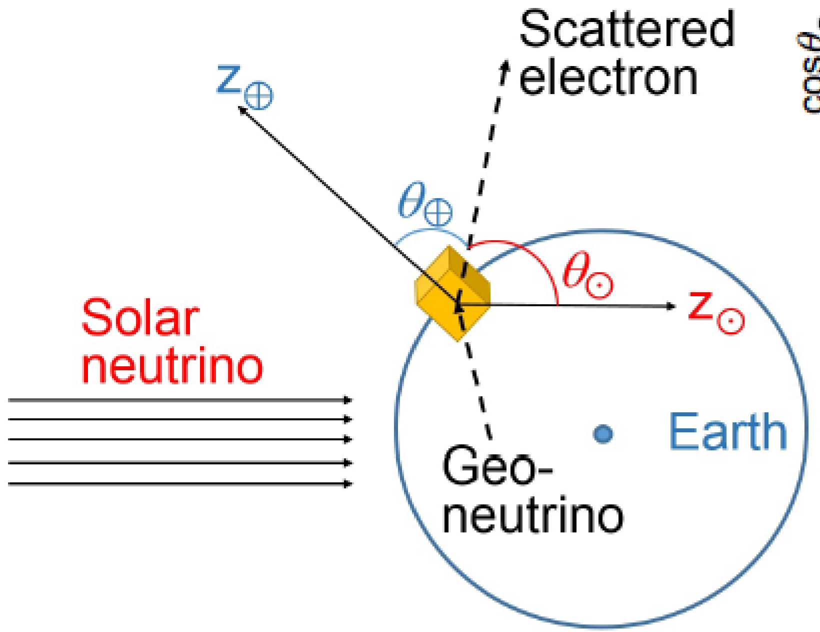
Strong Direction Correlation at Low E

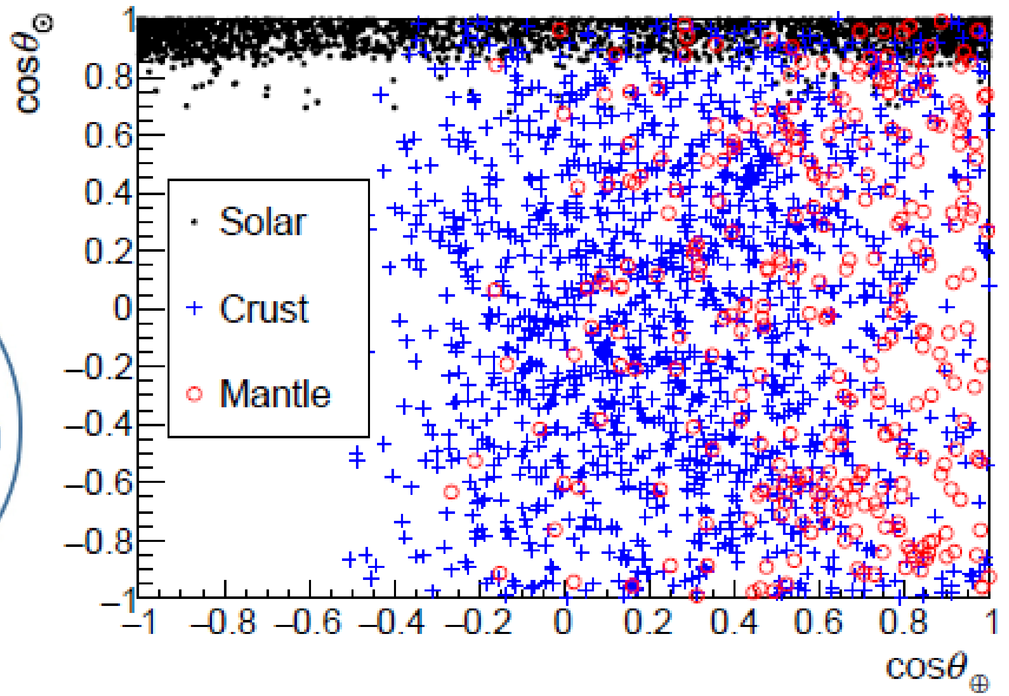
Even at low energy (<2 MeV) recoil electrons can still point back to the Sun after an energy cut



θ: the angle between neutrino and electron direction

Theoretical Distributions





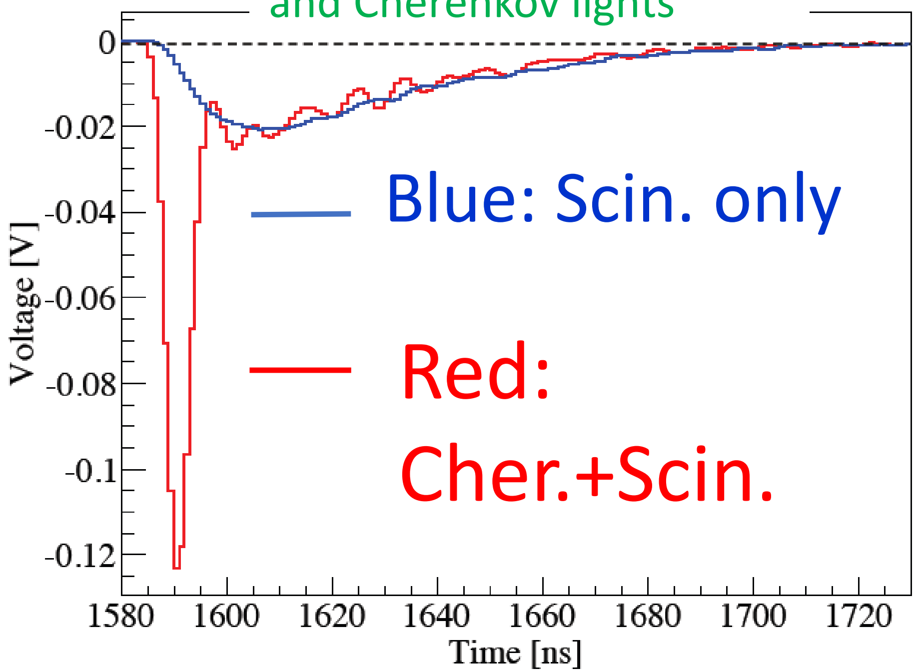
Solar and geo neutrinos can be well separated after requiring $K_e > 0.7$ MeV

Slow Liquid Scintillator, for example LAB

- Cherenkov emission: prompt
- Scintillation emission time constant: 10-20 ns (slow)
- PMT: TTS 1 ns

Other liquid-scintillator Cherenkov detector schemes also work.

Time profile of scintillation and Cherenkov lights

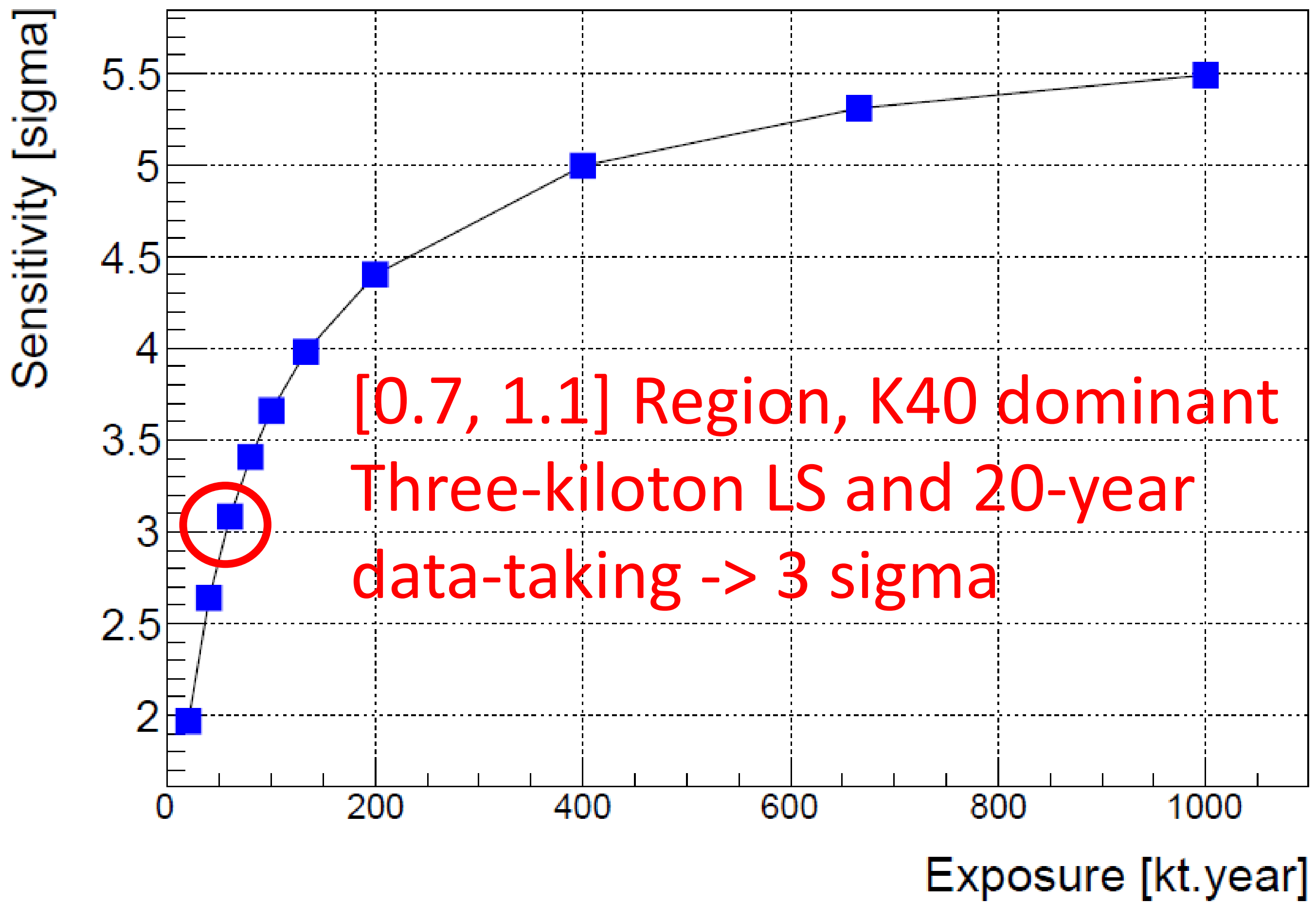


Feature: Both direction and energy measurements

Question: With electron scattering, electronics, offline Cherenkov recognition, can Slow-LS work out at less than 2 MeV?

K-40 Geoneutrino Signal uncertainty

$$\text{sensitivity} = N_{geo}/\sigma_{geo}$$



The sensitivity U, Th window is poor.

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

Looking for new collaborations...

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.
12. Linyan Wan, Ghulam Hussain, Zhe Wang, and Shaomin Chen, Geoneutrinos at Jinping: flux prediction and oscillation analysis. Phys. Rev. D 95 (2017), 053001
13. Zhe Wang, Shaomin Chen, Hunting potassium geoneutrinos with liquid scintillator Cherenkov neutrino detectors, Chinese Physics C Vol. 44, No. 3 (2020) 033001

Thank you.
We are still working on new physics
and new techniques.
Thank all my collaborators.