Applications of Nuclear Technology Session Summary
-- Application and Detection Technology Development

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Tsinghua University

July 8, 2023 @ WIN2023, Zhuhai

Applications of Nuclear Technology

1. 16 parallel talks
2. Two plenary talks
   a. CEvNS with Noble Liquids, by Kaixuan Ni
   b. Neutrino Applications, by Jonathan Link

Contents

- Part 1. Reactor neutrino precision measurement and monitor

  a. TAO - Cryogenic liquid scintillator, high light yield
  b. CHANDLER – Compact , low cost, surface-level, mobile

Taishan Antineutrino Observatory (TAO) *arXiv: 2005.08745*

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

by Alexander Chepurnov

Physics goals:

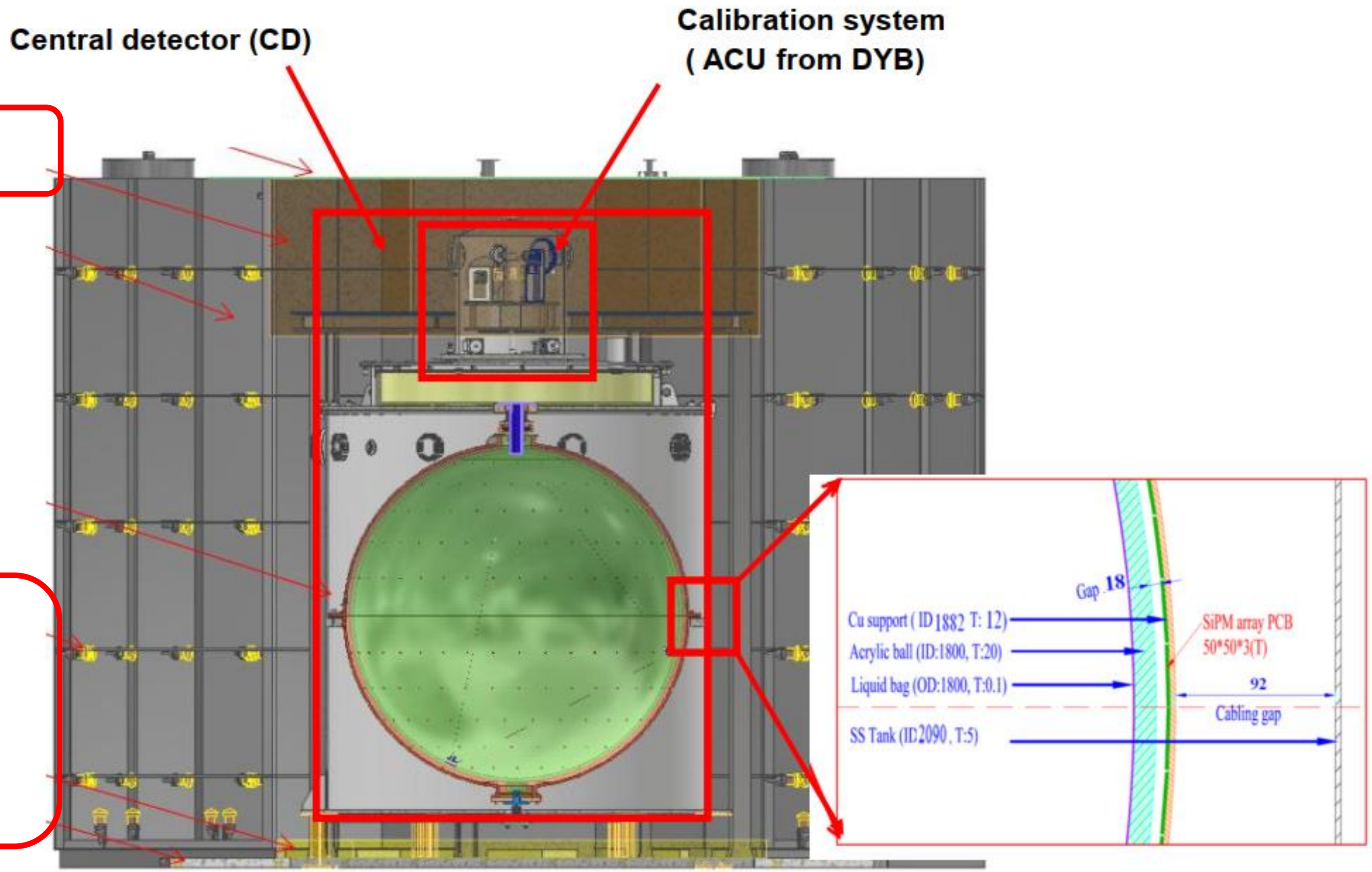
- **Measurement of a high-resolution antineutrino energy spectrum, which serves as a benchmark to test nuclear databases, provides increased reliability in measured isotopic antineutrino yields, and gives an opportunity to improve nuclear physics knowledge of neutron-rich isotopes**
- **Providing the 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°
- **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

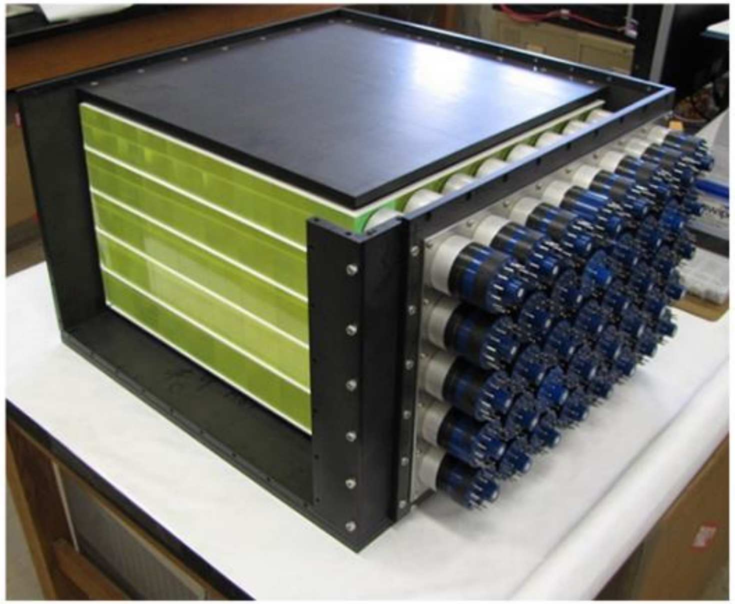
TAO Central detector

- **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]

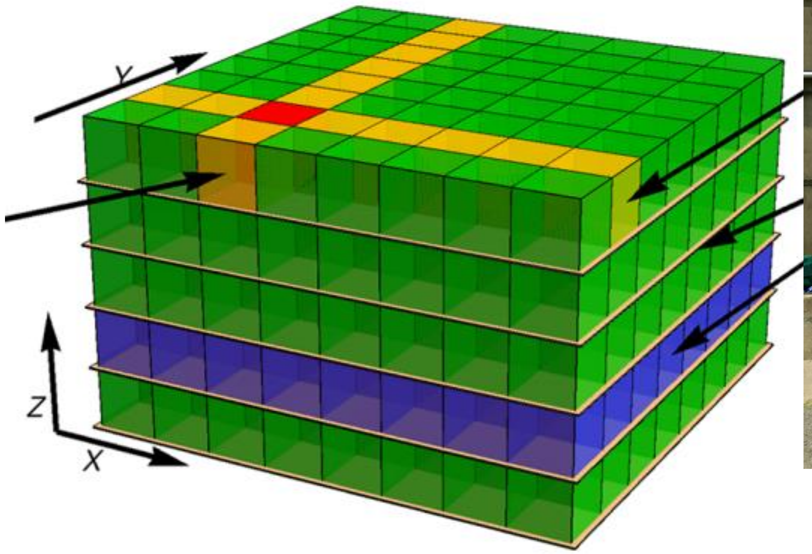


The Mobile Neutrino Lab —— MiniCHANDLER

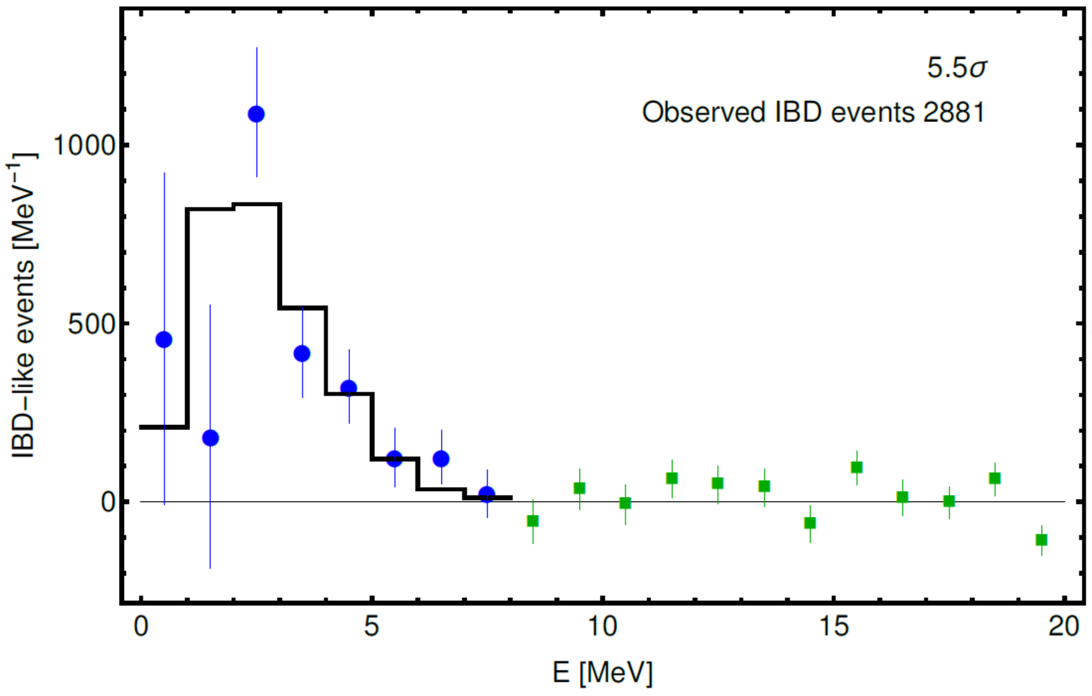
by Jonathan Link



1. The first demonstrated mobile neutrino detector,
2. The first unshielded reactor neutrino detector, and
3. One of the world's smallest neutrino detectors.



Observation of reactor neutrinos —— MiniCHANDLER



With the 80 kg prototype:

1. The detection of an antineutrino signal resulting from inverse beta decay at 5.5σ significance.
2. An observation of a positron spectrum in a small surface-deployed detector.

Going from MiniCHANDLER to full CHANDLER:

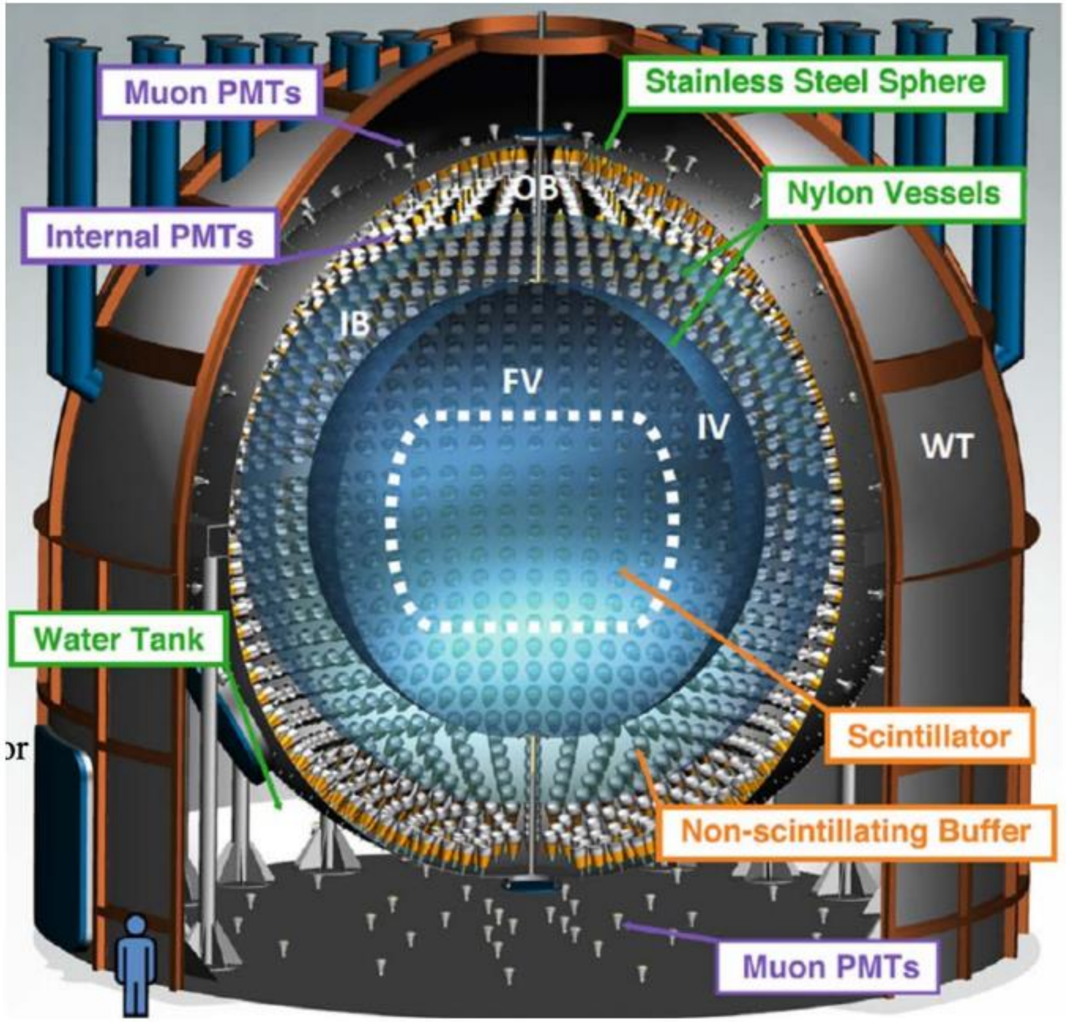
1. New optics; 2. Larger detector; 3. PMTs on four sides; 4. Half cubes.

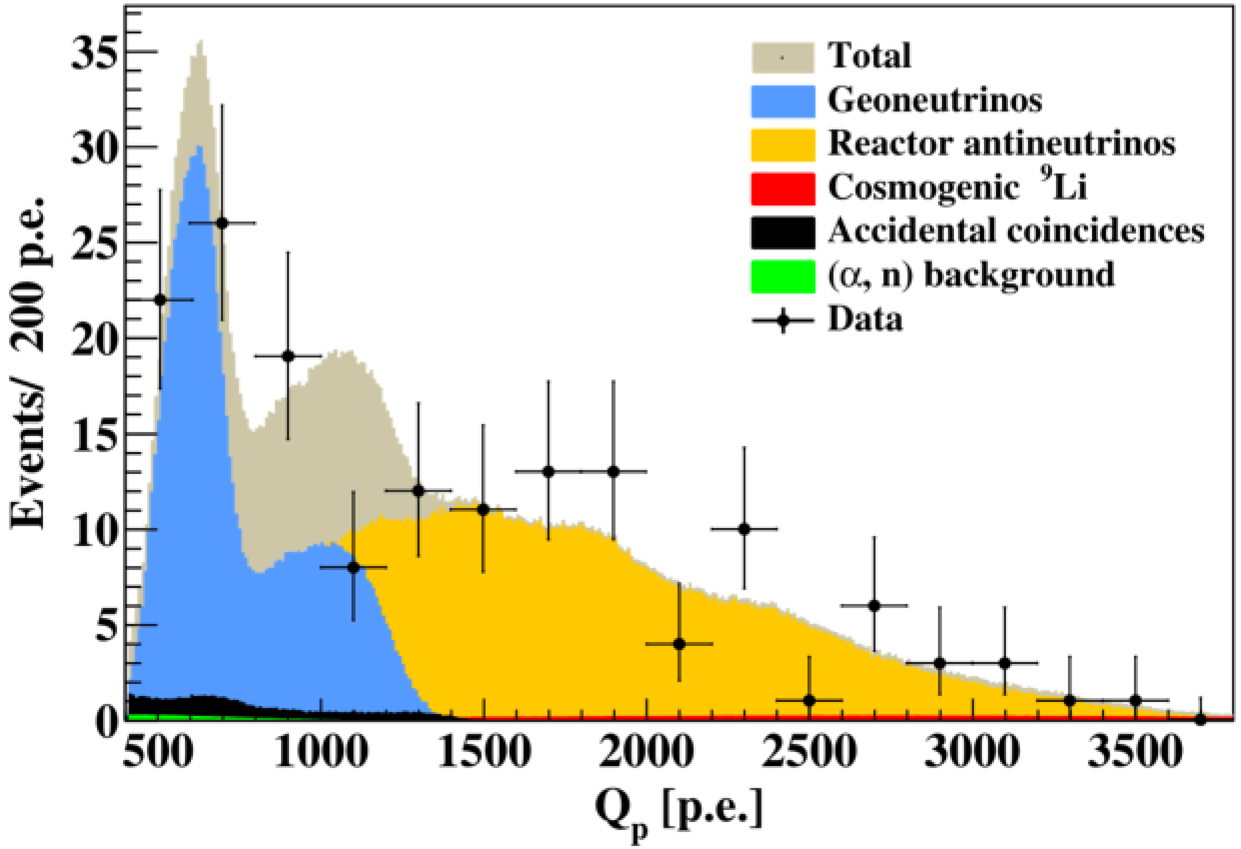
Part 2. Geoneutrino measurement and prediction

a. Measurements of Borexino and KamLAND
b. Prediction for JUNO

Geo-neutrino measurements with Borexino

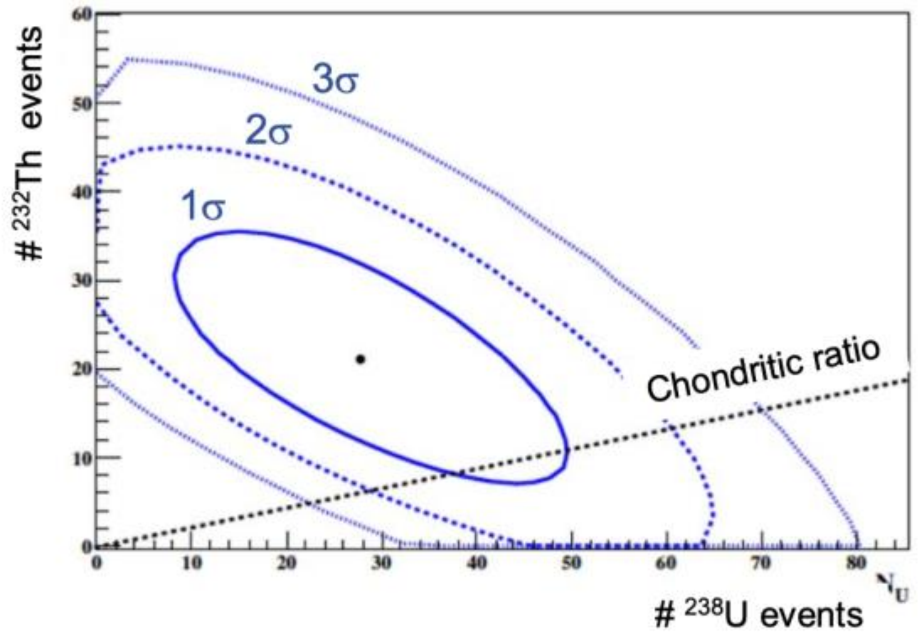
by Xuefeng Ding

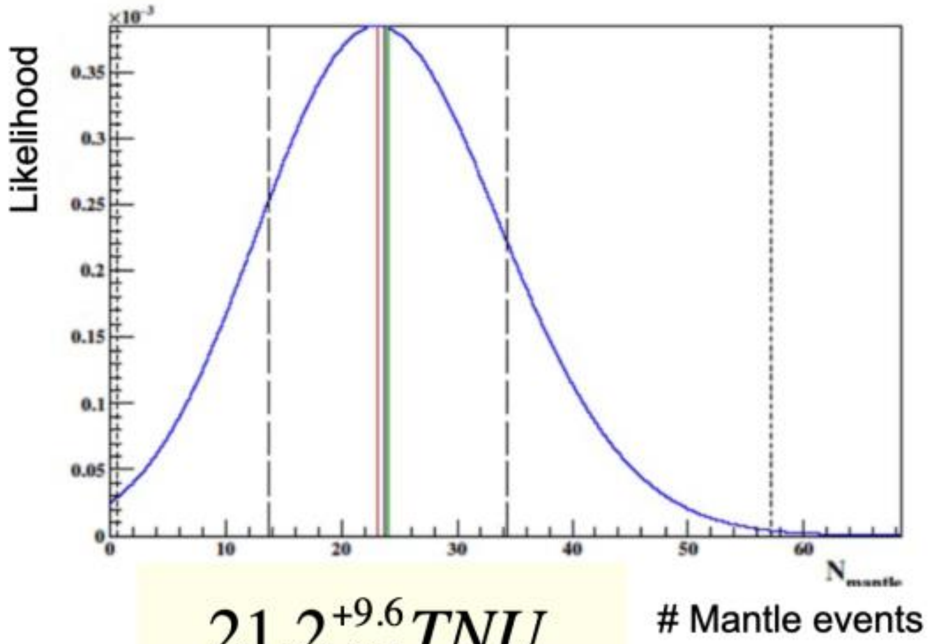




$52.6^{+9.4}_{-8.6}$ (stat) $^{+2.7}_{-2.1}$ (sys) geo-neutrinos seen by Borexino in ~3300 days

Geo-neutrino measurements with Borexino





$21.2^{+9.6}_{-9.1}\,TNU$

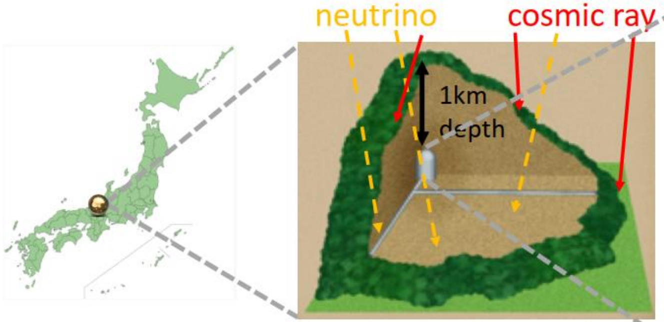
- Total: $47.0^{+8.4}_{-7.7}$ (stat) $^{+2.4}_{-1.9}$ (sys) TNU
- Mantle: $21.2^{+9.5}_{-9.0}$ (stat) $^{+1.1}_{-0.9}$ (sys) TNU
- Null mantle signal excluded at 99.0% C.L

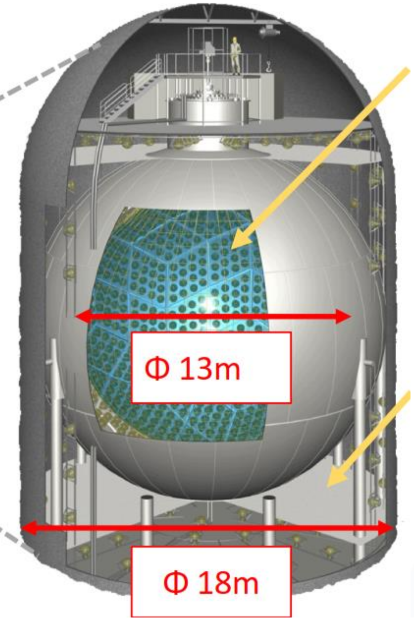
Geo-neutrino measurements with KamLAND

by Nanami Kawada

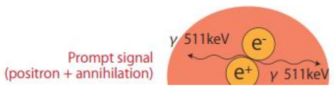
The KamLAND detector

Detector site and components

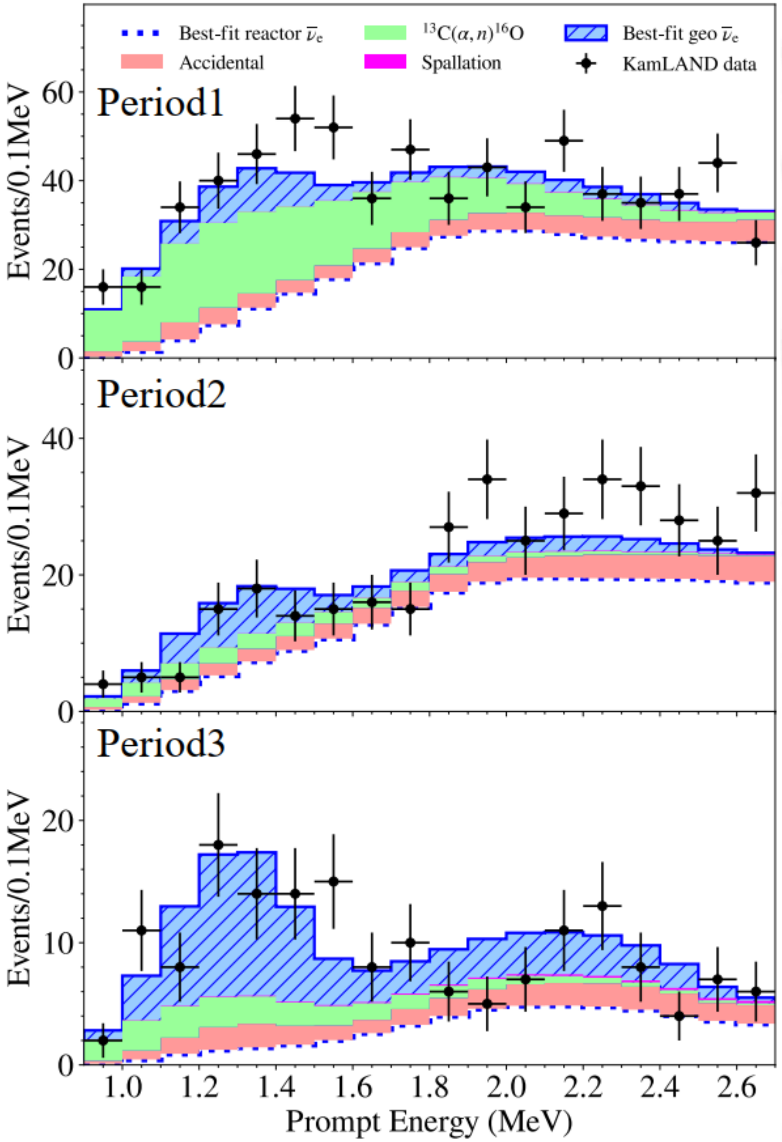




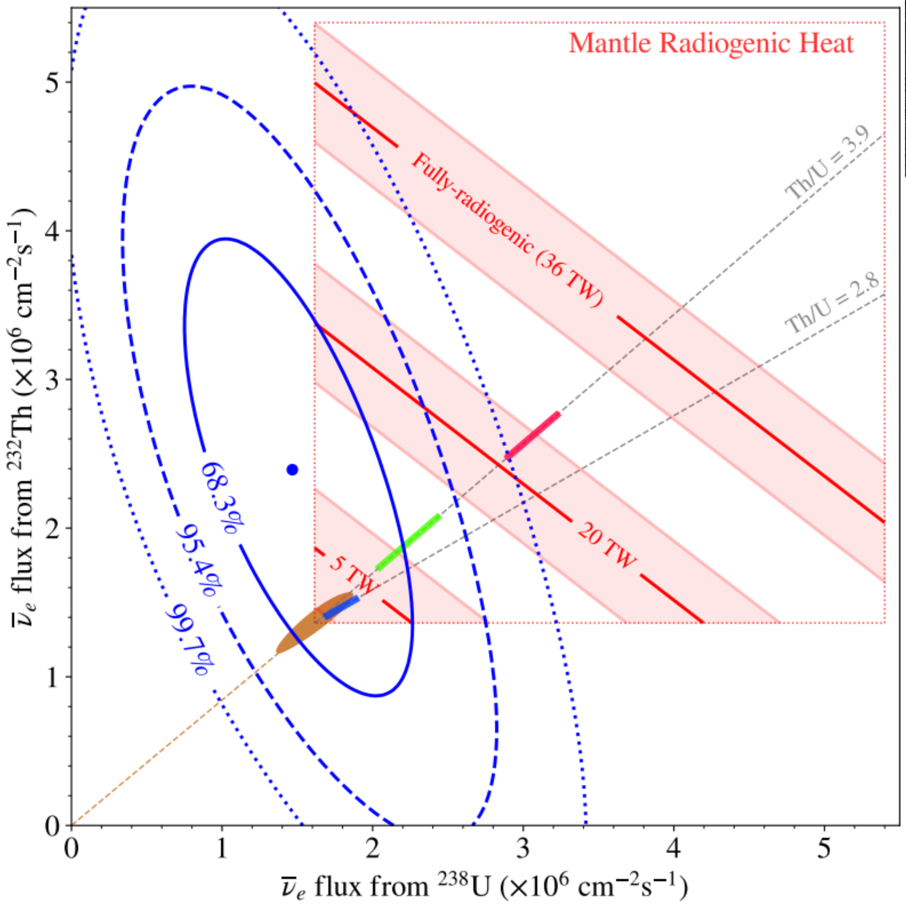
Neutrino detection channel



	$N_{\mathrm{U/Th}}$ [event]	flux [$\times 10^5$ cm^{-2}s^{-1}]	flux [TNU]	0-signal rejection
U	$116.6^{+41.0}_{-38.5}$	$14.7^{+5.2}_{-4.8}$	$19.1^{+6.7}_{-6.3}$	3.343σ
Th	$57.5^{+24.5}_{-24.1}$	$23.9^{+10.2}_{-10.0}$	$9.7^{+4.1}_{-4.1}$	2.386σ
U + Th	$173.7^{+29.2}_{-27.7}$	$32.1^{+5.8}_{-5.3}$	$28.6^{+5.1}_{-4.8}$	8.3σ



Comparison to Earth models



<u>Radiogenic heat</u>

$$Q^{\mathrm{U}} = 3.3^{+3.2}_{-0.8}\ \mathrm{TW}$$

$$Q^{\mathrm{Th}} = 12.1^{+8.3}_{-8.6}\ \mathrm{TW}$$

$$Q^{\mathrm{U}} + Q^{\mathrm{Th}} = 15.4^{+8.3}_{-7.9}\ \mathrm{TW}$$

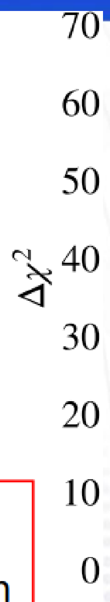
Convective Uray ratio = $0.13^{+0.15}_{-0.06}$

Assuming homogeneous mantle composition,

High-Q model is disfavored at 99.76%.

Assuming U and Th concentration at the mantle-core boundary,

High-Q model is disfavored at 97.9%.



High-Q model rationale

Seismology data → density/viscosity profile → 1-layer mantle convection Radiogenic heat : ~25 TW

High-Q model rejection indicates the need to modify the mantle density/viscosity profile or geodynamical modeling of mantle convection.

The KamLAND data favor Low-Q, Middle-Q model.

This result suggests mantle multi-layer convection.

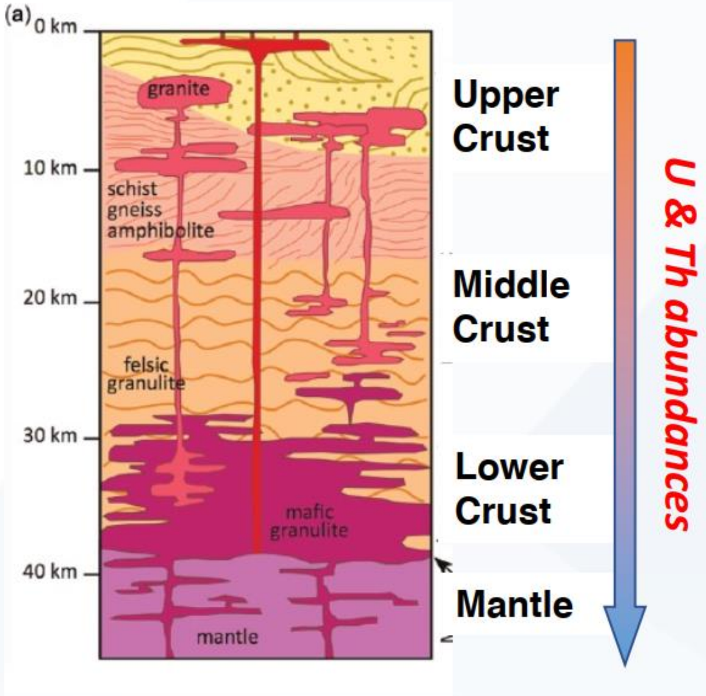
Geo-neutrino Signal Prediciton at JUNO

by Ruohan Gao

Geoscience inputs for geo-neutrino signal calculation

$$\Phi_i = A_i \cdot n_i \cdot P_{\nu_e - \nu_e}(E_\nu, |\vec{L}|) \cdot \int_V \frac{a_i(\vec{L}) \cdot \rho_i(\vec{L})}{4\pi |\vec{L}|^2} dV$$

- $A_i \cdot n_i$: Activity and number of produced geoneutrinos
- $P_{\nu_e - \nu_e}(E_\nu, |\vec{L}|)$: Survival probability function
- $a_i(\vec{L}) \cdot \rho_i(\vec{L})$: Abundance and density of the source unit
- $|\vec{L}|$: Distance between source unit and detector
- dV: Volume of source unit

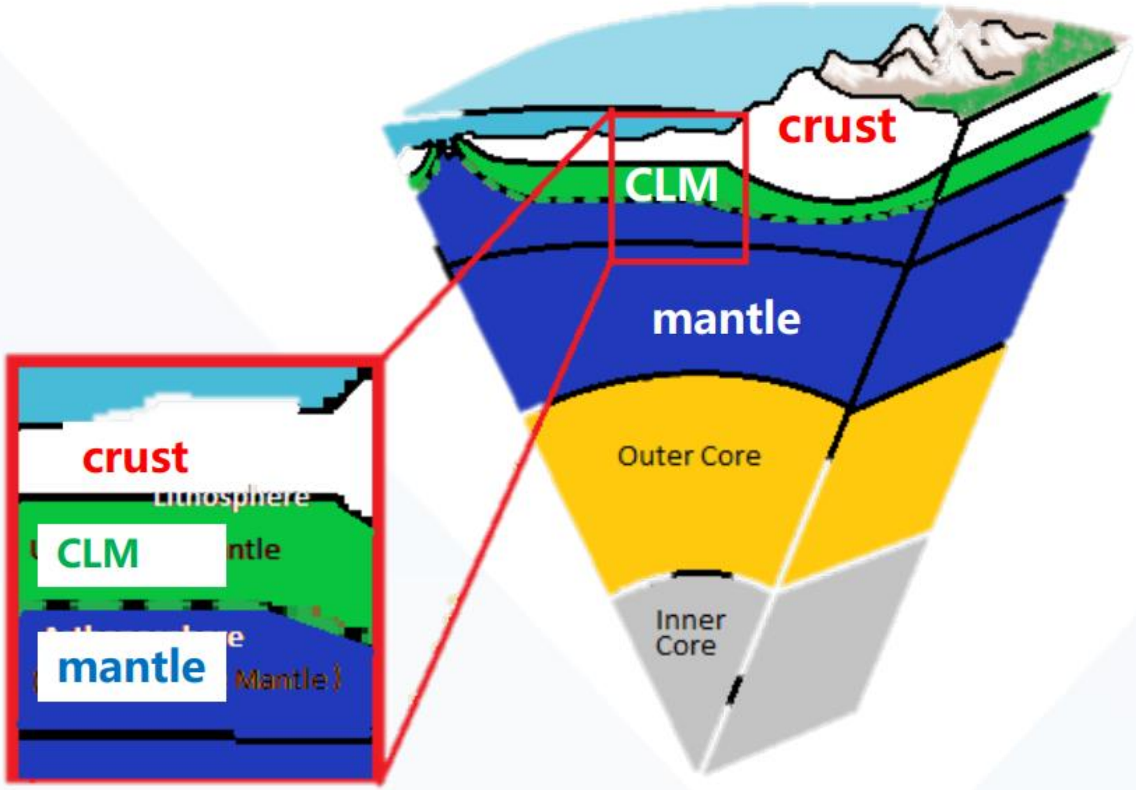


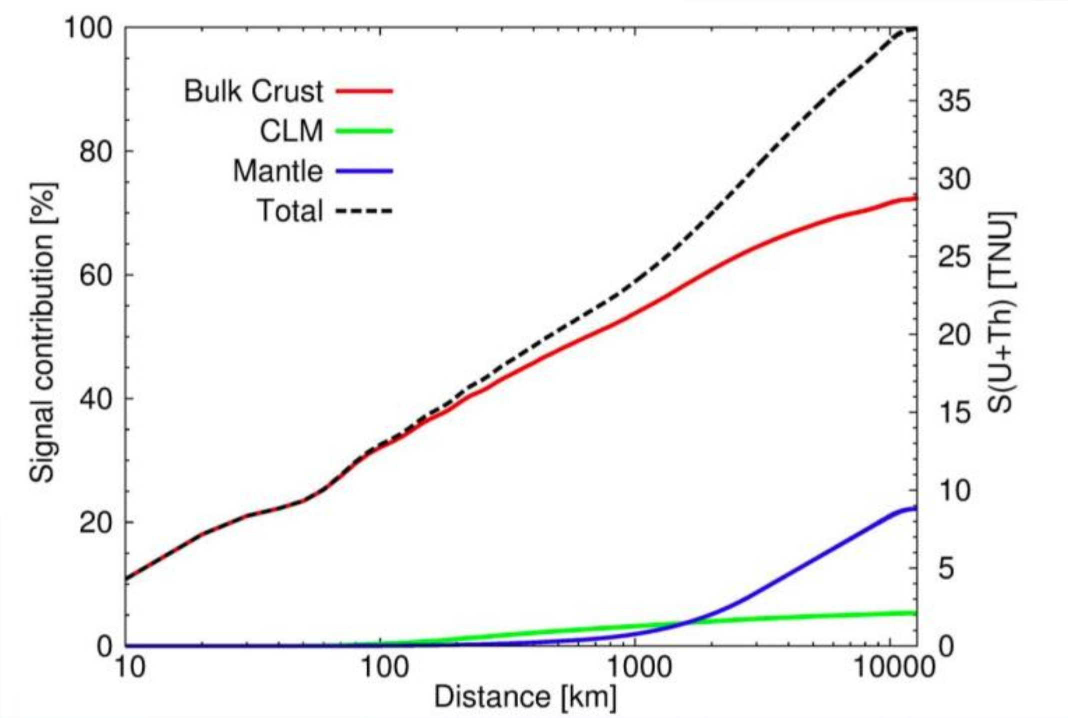
- **Geophysical models**
  - **Density** of source unit
  - **Earth's layers**
- **Geochemical models**
  - **U and Th abundances** of source unit

Earth's layers and their estimated geo-neutrino signal

- **Crust: high Th & U**
  - Continental crust
  - Oceanic crust
- **CLM (Continental Lithospheric Mantle): relatively low Th & U**
- **Mantle: very low Th & U, large volume**

$$S_{mantle} = S_{total} - (S_{crust} + S_{CLM})$$





(Strati et al., 2014)

Geo-neutrino Signal Prediciton at JUNO

JULOC

		$S_U \pm \sigma$	$S_{Th} \pm \sigma$	$S_{U+Th} \pm \sigma$
Upper Crust	Top layer	$10.5_{-0.7}^{+0.7}$	$3.2_{-0.3}^{+0.3}$	$13.8_{-0.7}^{+0.8}$
	Basement	$8.1_{-3.7}^{+7.0}$	$2.6_{-1.1}^{+1.8}$	$11.0_{-3.9}^{+5.9}$
Middle Crust		1.7 ± 1.0	0.4 ± 0.3	2.1 ± 1.1
Lower Crust		$1.9_{-1.3}^{+3.8}$	$0.8_{-0.7}^{+5.7}$	$1.7_{-1.2}^{+4.0}$
Oceanic Crust		0.2 ± 0.05	0.1 ± 0.01	0.3 ± 0.05
Total		21.3 ± 4.0	6.6 ± 1.3	28.5 ± 4.5

JULOC-I

Preliminary results

	S_U	S_{Th}	S_{U+Th}
Continental Crust	22.1	6.7	28.8
Oceanic Crust	0.2	0.1	0.3
Total	22.3	6.8	29.1

1. Geochemical model has larger influence on geo-neutrino signal prediction than geophysical model, as the earth's continental crust is highly heterogenous in terms of U and Th abundances.

2. Local crust model (JULOC/JULOC-I) predicts higher geoneutrino signal than global models.

3. This is consistent with the wide distribution of high U/Th granite intrusions in the Cathaysia region around JUNO

Part 3. CEvNS detection

a. COHERENT
b. CloverS
c. CICENNS
d. Dual phase argon TPC
e. RELICS
f. CONUS
g. νGen
h. RECODE

By Kaixuan Ni

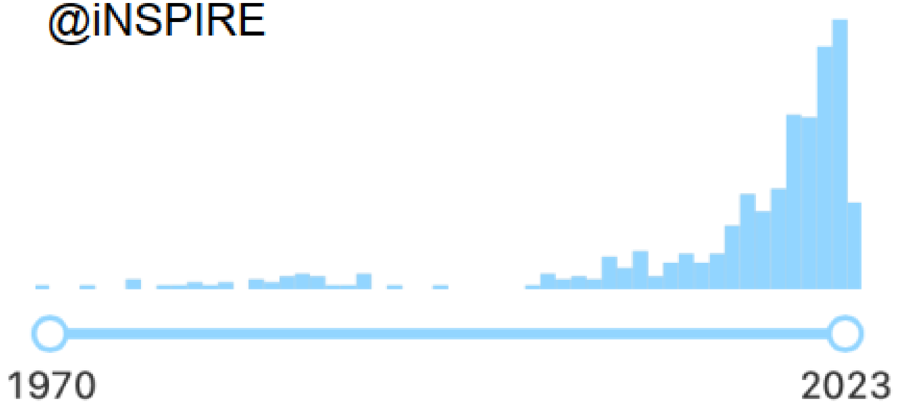
Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

- CEvNS is a standard model process predicted 50 years ago (D.Z. Freedman, 1973) and was first observed by the COHERENT collaboration at the Spallation Neutron Source (SNS) in 2017 [1708.01294]
- Particle physics:
  - weak mixing angle
  - neutrino EM properties: charge radius, magnet moments, millicharge
  - non-standard interactions (NSI), light mediators ....
- Nuclear physics
  - nuclear form factors, neutron radius…
- Astrophysics:
  - Solar neutrinos and supernova neutrinos
- New physics:
  - sterile neutrinos, dark matter
- Applications:
  - nuclear security, reactor fuel (spent fuel) monitoring

$$\frac{d\sigma}{dE_R} = \frac{G_F^2}{4\pi}(N - Z(1 - 4\sin^2\theta_w))^2 m_N (1 - \frac{m_N E_R}{2E_\nu^2}) F^2(E_R)$$

Date of paper

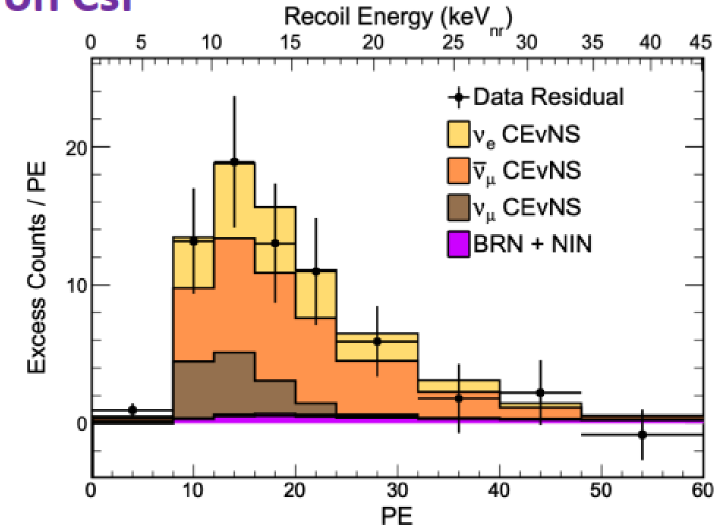
@iNSPIRE

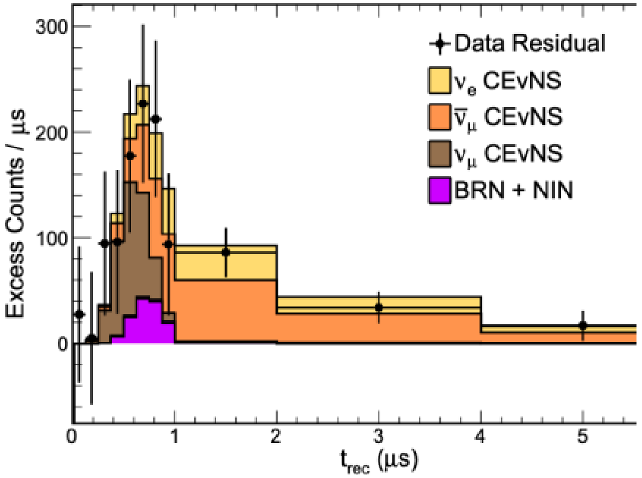


COHERENT

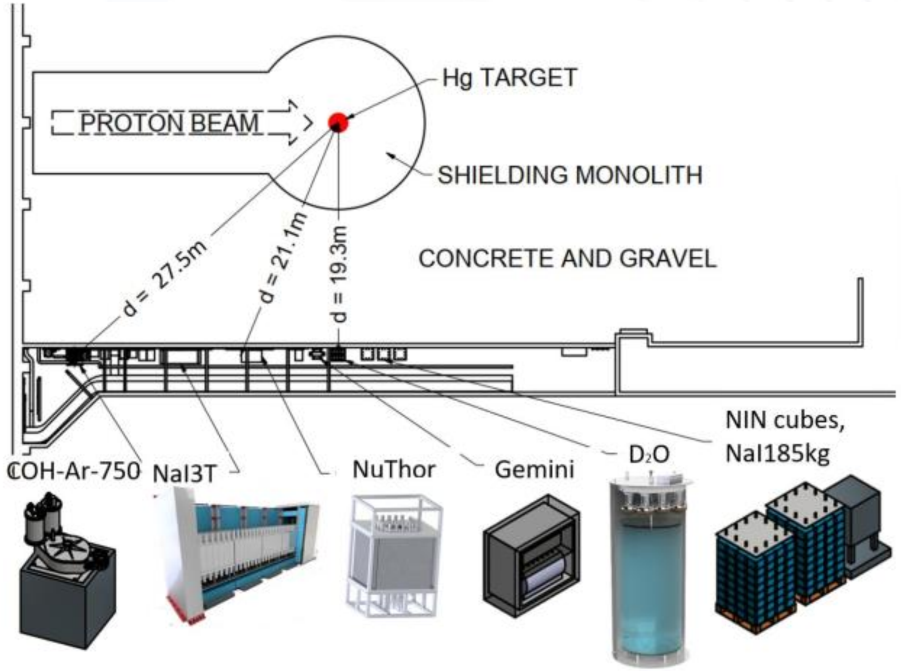
by Keyu Ding

CEvNS on CsI

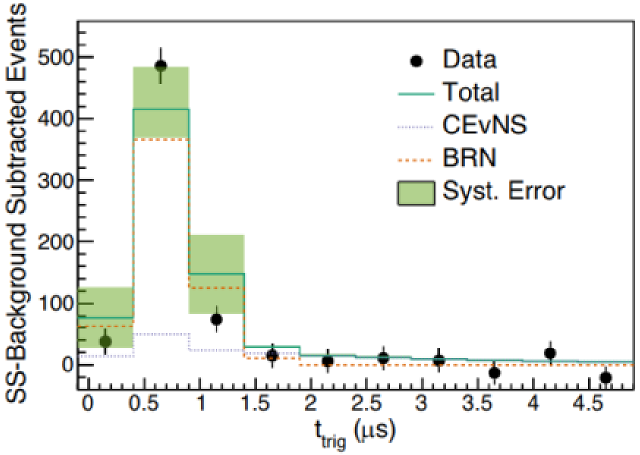


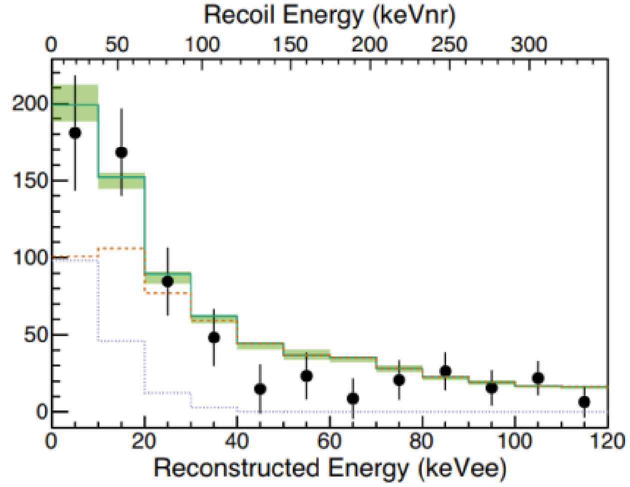


*COHERENT, PRL **129** (2022) 081801*



CEvNS on Ar





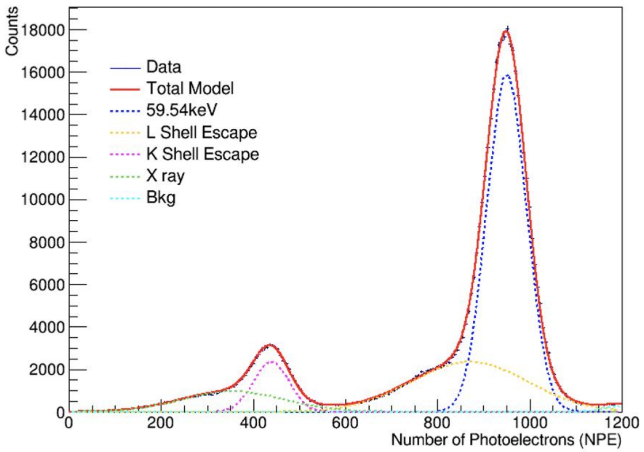
*COHERENT, PRL **126** 012002 (2021)*

Ongoing effort:

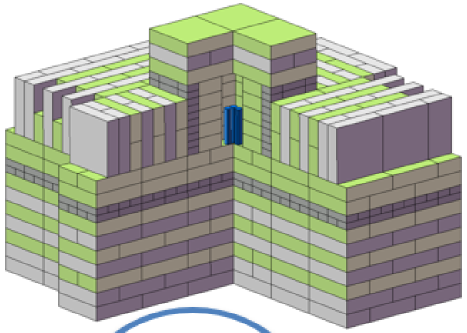
- 24 kg Ar, Single phase
- 16 kg Ge
- 3.4 ton NaI
- ...

CloverS - Cryogenic undoped CsI, SNS, 12 kg, CSNS, China

by Qian Liu



- 77K big CsI crystal light yield test～15.8p.e/keVee
- The light yield can be further improved by enhancing the optical coupling and employing wavelength shifters, etc.



- 2022: On site background study; Detector assembly fabrication
- 2023: Start commissioning
- 2024: Start data taking
- 2025: Accumulate the first year data

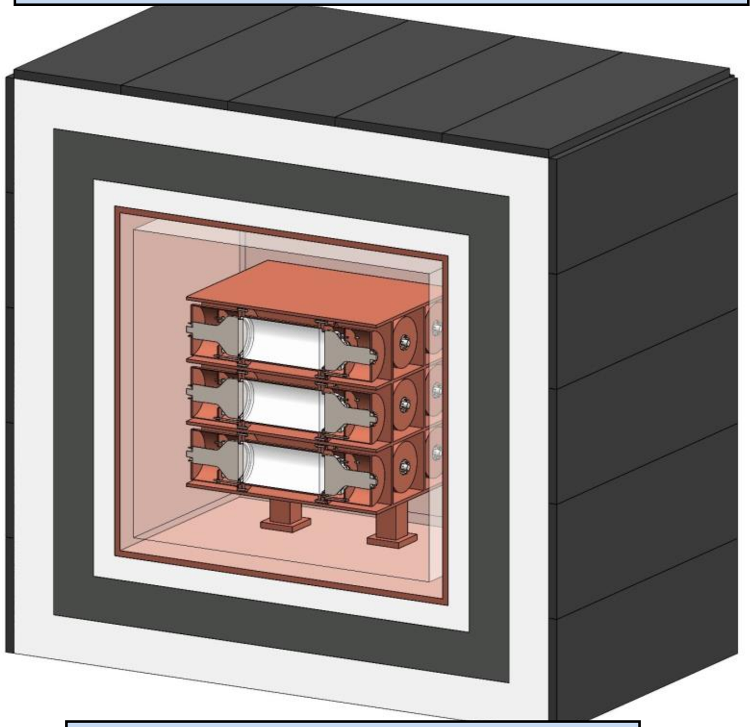
Scanning the neuron counting rate at different positions in CSNS

	-2	-1	0	1	2	3	4	5
-1			123.25					
0	620	424.75	136	51.75	46.25	54	47.25	35.75
1			96.25					

CICENNS - CsI(Na), SNS, 300 kg, CSNS, China

by Soo-Bong Kim

- 20 kg CsI(Na) x 15
- 14 cm (ϕ) x 28.7 cm each
- Two 5-inch SBA PMTs



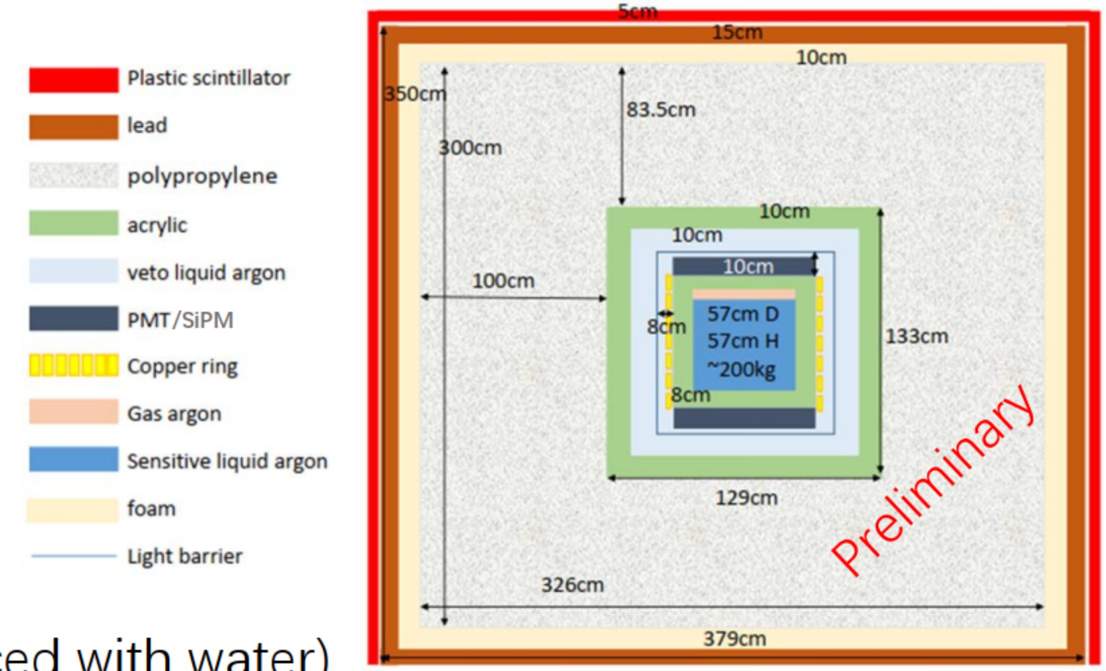
- 35 tons of shielding with Cu, LS, Pb, and HDPE

- Oct. 2022: Fund request submitted to SYSU.
- Nov. 2022: Instrumentation fund obtained.
- Dec. 2022: Bidding was completed for procurement.
- Dec. 2022 - present.: Negotiation with CsI(Na) crystal manufacturers
  Technical Design Report in preparation
  Finalize the detector design with a full simulation
  Under purchasing parts
- Dec. 2023: All of detector components will be delivered.
- May 2024: Completion of detector assembly
- Aug. 2024: Cosmic muon data at SYSU
- Sep. 2024: Deploy the detector at CSNS and take beam data.

Dual phase argon - Ar, Reactor, 200 kg, Taishan, China by Yongpeng Zhang

Detector conceptual design

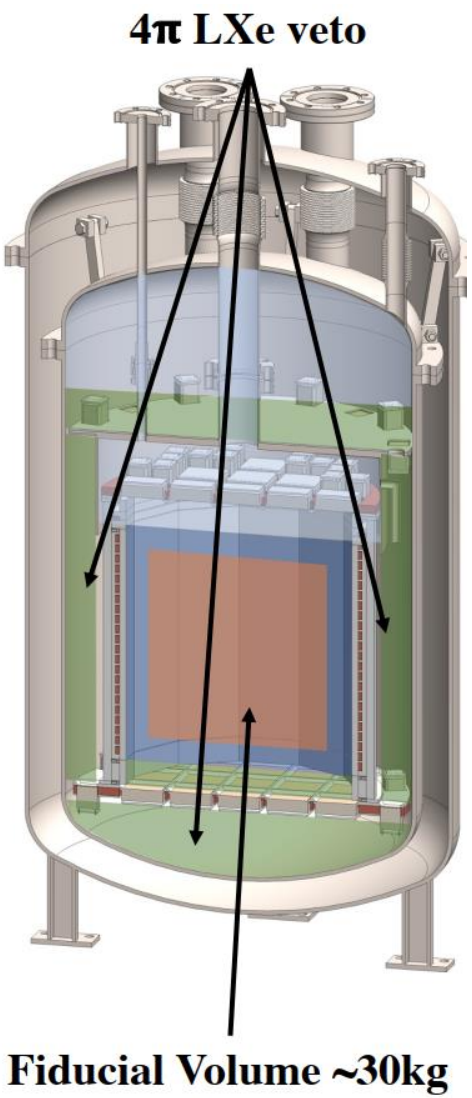
- Dual phase UAr TPC with ~200 kg fiducial mass
- Background source:
  - ✓ Muon and secondary particles
  - ✓ Radioactivity from detector material and rock
- Strategy for reducing background
  - ✓ Using UAr and material screening
  - ✓ Passive shield: Lead + polypropylene (maybe replaced with water)
  - ✓ Active shield: Active muon-veto (plastic scintillators) + Veto LAr (single phase detector)

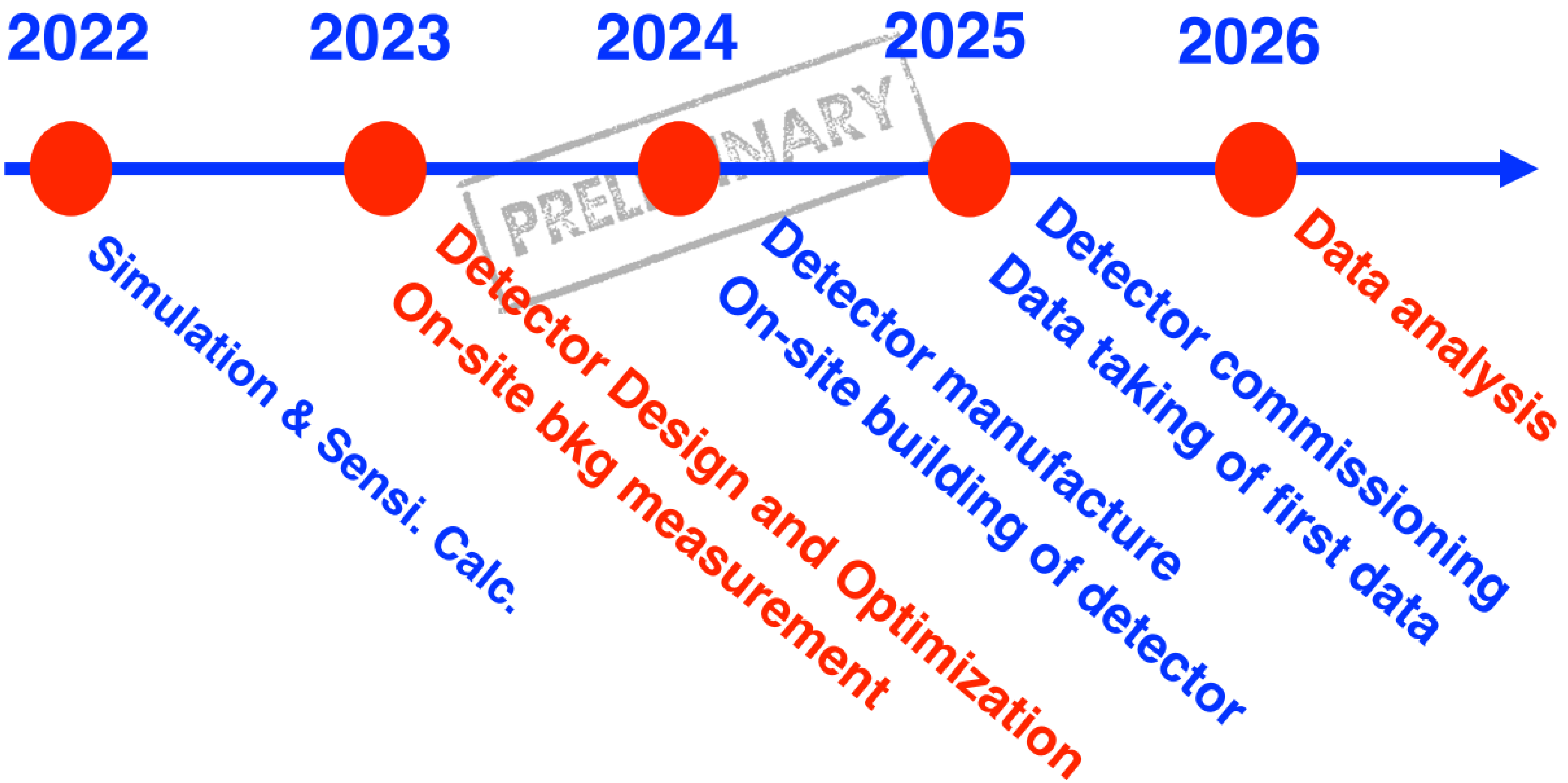


Wei, YT., Prospects of detecting the reactor $\bar{\nu}_e$-Ar coherent elastic scattering with a low threshold dual-phase argon time projection chamber at Taishan. RDTM 5, 297–306 (2021)

RELICS - Xe, Reactor, 30 kg, Taizhou, China

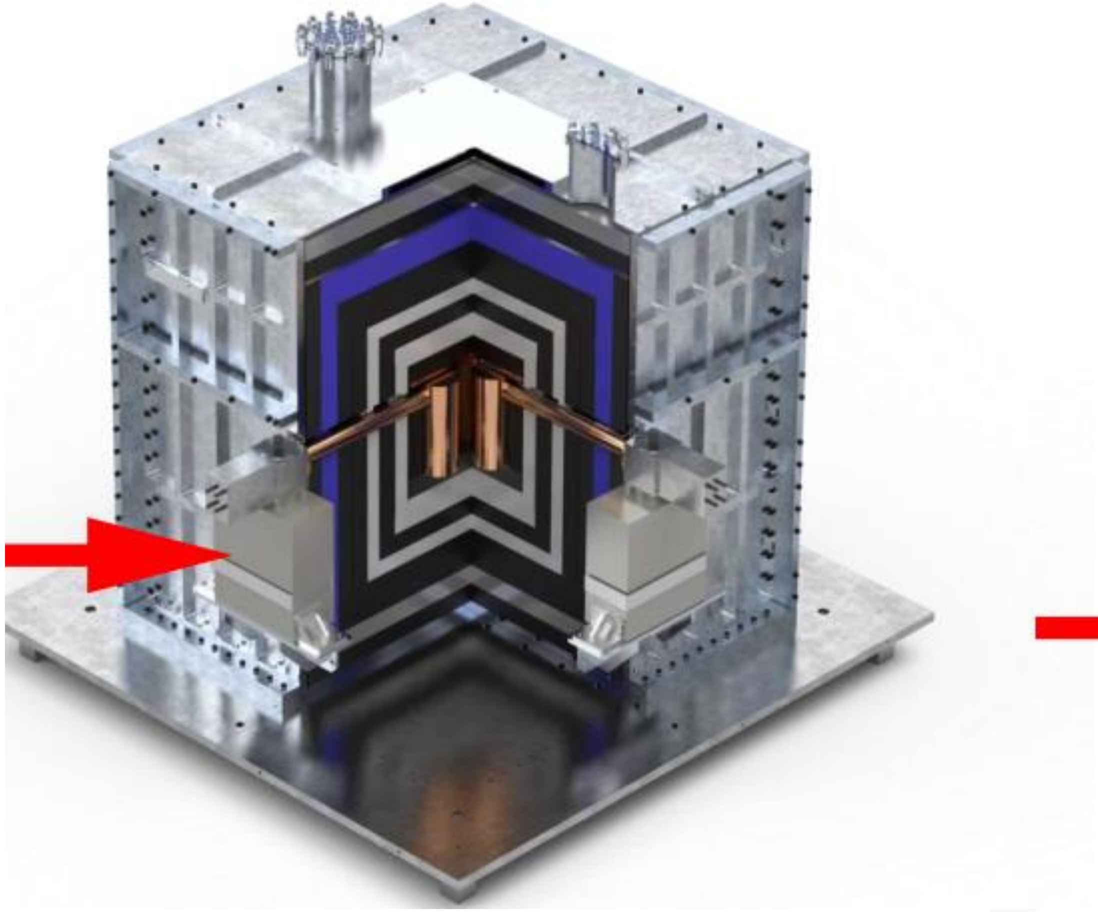
by Qing Lin

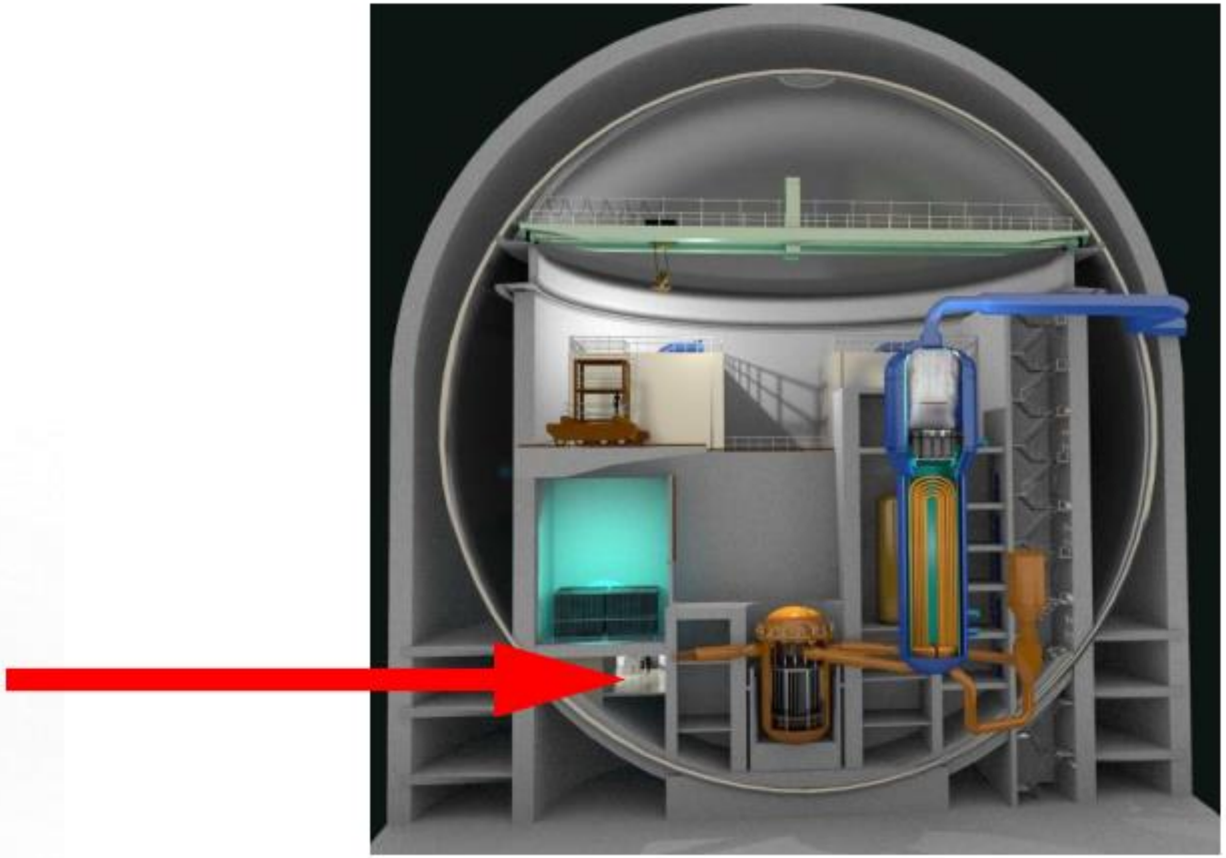




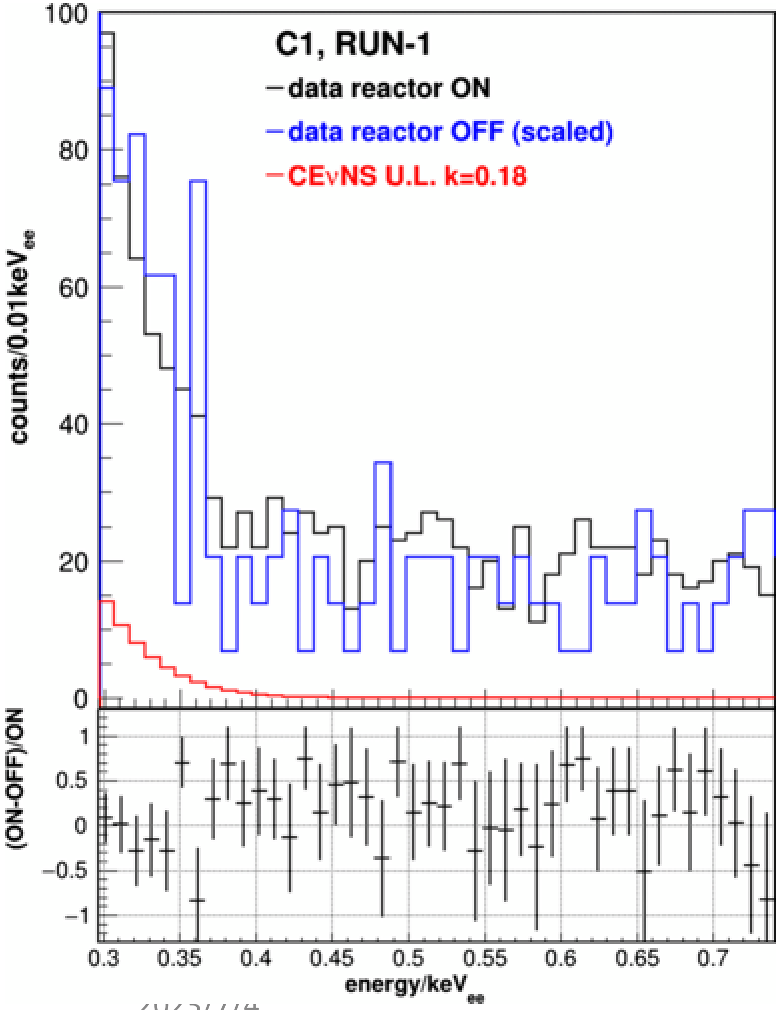
CONUS, - Ge, Reactor, 4 kg, KFR, Germany

by Kaixiang Ni





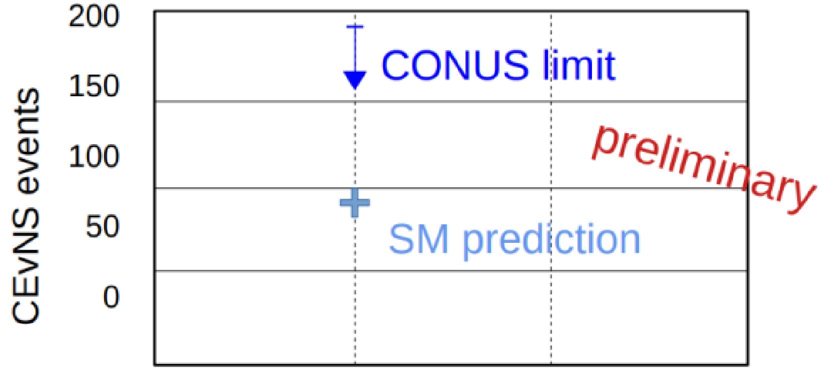
- Data: 248.7kg-d ON, 58.8kg-d OFF
- Threshold: ~300eV
- Binned Likelihood:
    - Simultaneously fit ON/OFF data
    - Poisson distribution in each bin



Phys.Rev.Lett. 126 (2021) 4, 041804

Run5 update

More statistics: in total 458kg-d ON, 293kg-d OFF



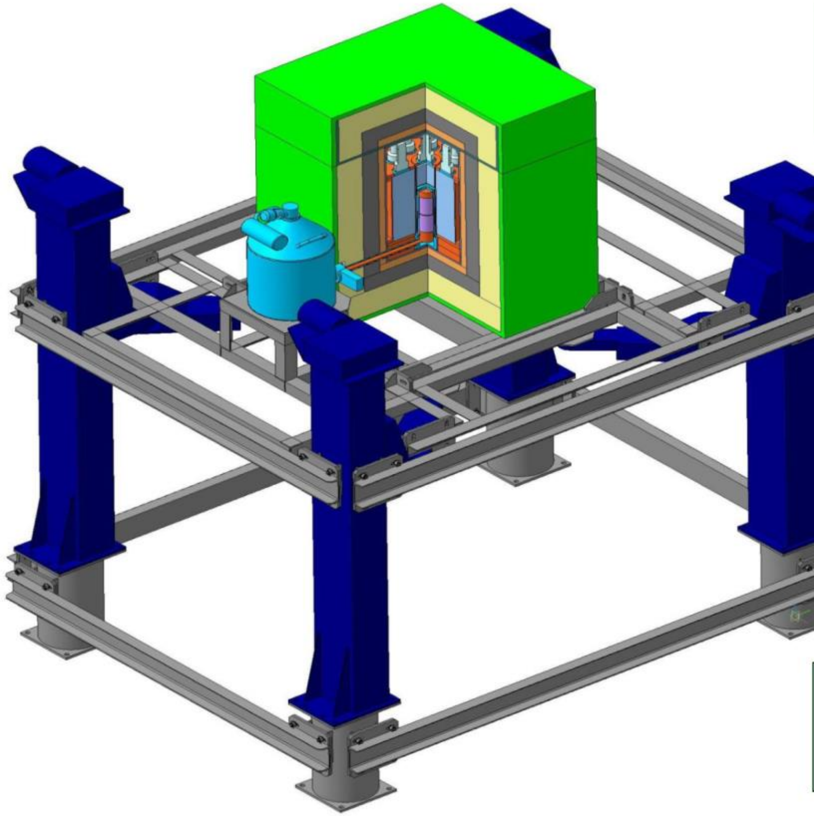
From CONUS to CONUS+

1. New Reactor: Kernkraftwerk Leibstadt (KKL), Switzerland
2. Upgraded Ge detectors

- **Ge refurbishment:** reduced point-contact size
- **ASIC upgrade:** higher trigger efficiency at low energy.
- **Cryostat upgrade:** water-cooled to reduce vibration and microphonic noise
- Under test in MPIK!
- Target:
    - Resolution: <55eV
    - Threshold: <200eV

nGen - Ge, Reactor, 1.4 kg, KNPP, Russia

by A.Lubashevskiy



A s
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11.09 m – top position (current)

12.14 m – first position

~12.5 m – lower position

Ch
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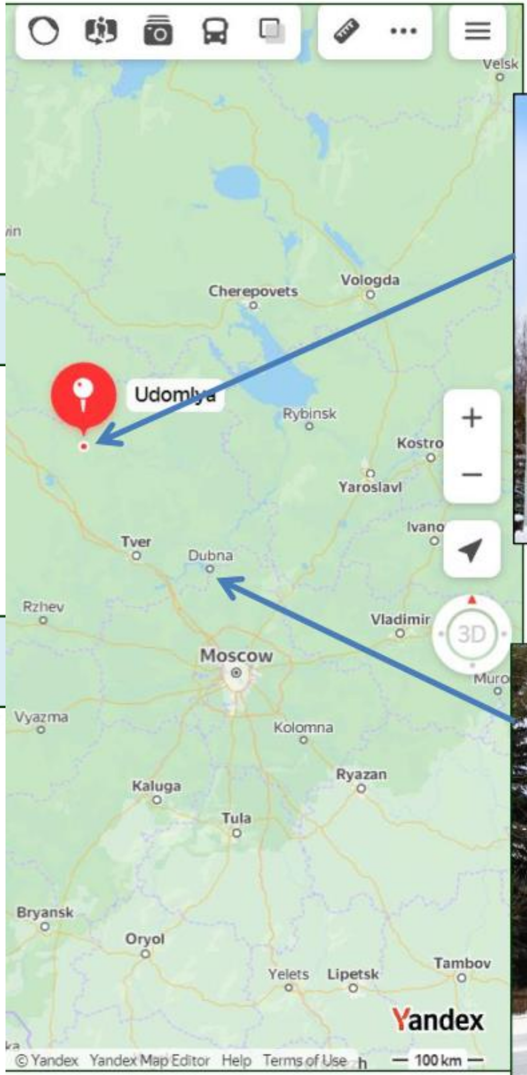
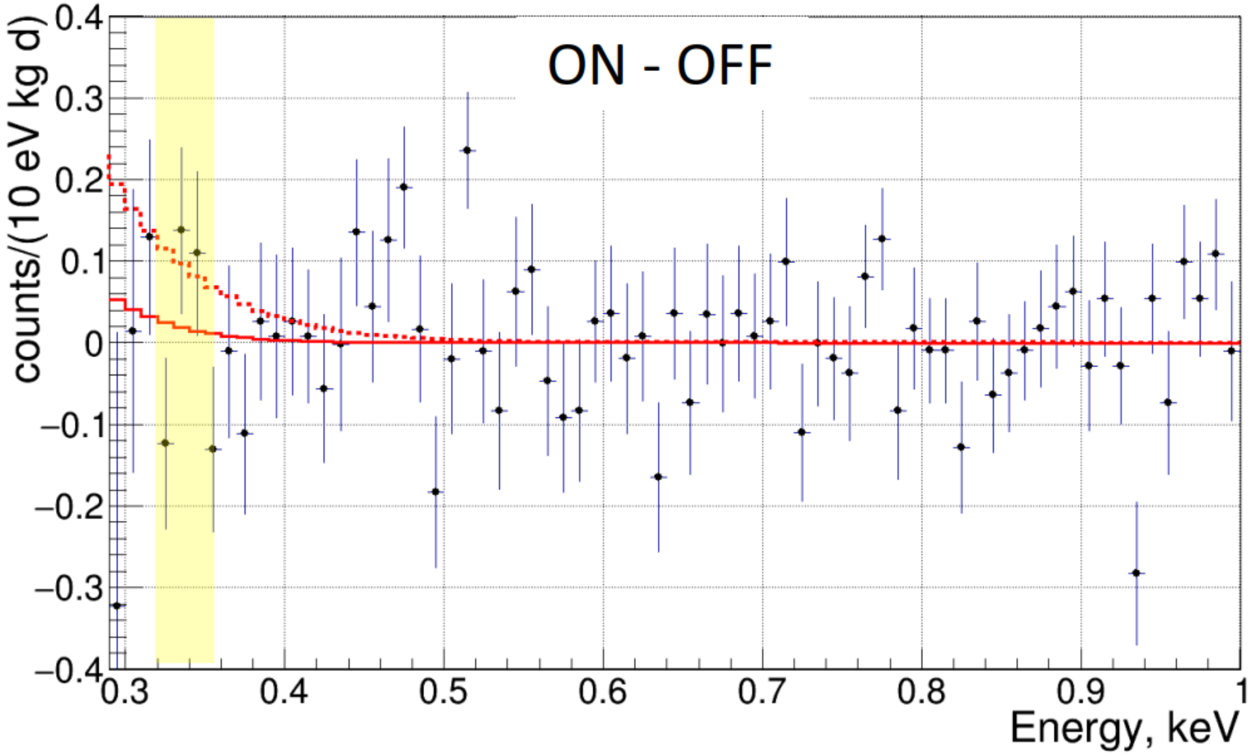


Kalinin Nuclear Power Plant (KNPP) 4xWWER – 3.1 GW_{th}

JINR, Dubna, 285 km from KNPP



2022 ANALYSIS

Analysis of the first data showed no significant difference in background level during reactor ON and OFF regimes. No excess at low energy connected with the CEνNS has been observed. The upper limit on the quenching parameter **k < 0.26** with 90% CL has been obtained (dashed line). Red solid line for k = 0.179.

	Counts in region [320..360] eV	Measurement time, days	Counts per kgd (stat. error only)
Reactor ON	251	94.5	2.32 ± 0.15
Reactor OFF	126	47.1	2.34 ± 0.21
ON-OFF			-0.017 ± 0.255
CEνNS, k = 0.26	55		0.46

- More than 1200 kgd of data has been accumulated so far.
- The optimization of data taking is performed as well. New results in the upper position with more statistics are expected soon.

RECODE - Ge, Reactor, 10 kg, Taizhou

by Litao Yang

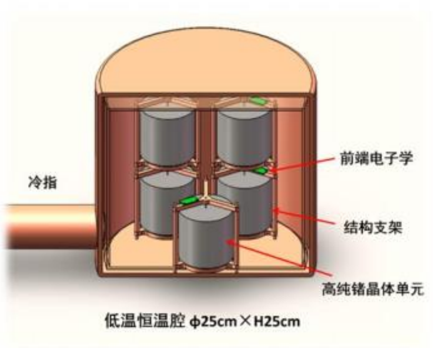
Schedule

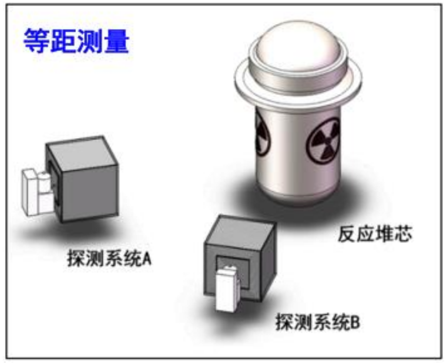
Experience from CDEX@CJPL

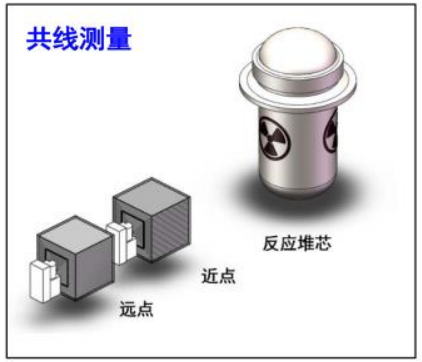
2023	2024	2025	2026	2027
✓ On site environmental bkg measurement/estimation ✓ Design, production, and processing of various subsystems	✓ Subsystem independent testing ✓ Joint testing work	✓ Transport to nuclear power plant, installation, testing ✓ First physics run	✓ Change working mode ✓ Second physics run ✓ Data analysis	✓ Change working mode ✓ Third physics run ✓ Data analysis

Subsystems testing @CJPL and ground

Physics Run @nuclear power plant







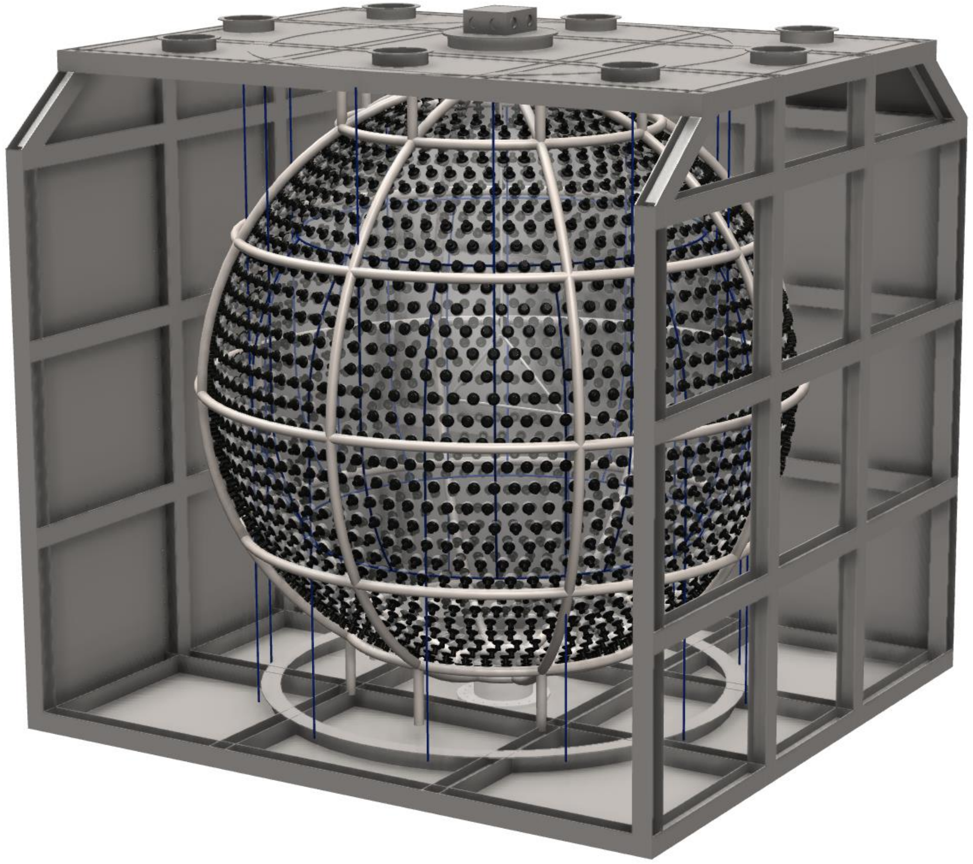
Part 4. Others

a. Jinping Neutrino Experiment – A solar and geo neutrino observatory
b. Muon tomography – Structure imaging
c. Bolometer development – for $0\nu\beta\beta$ and CEvNS

R&D of Jinping Neutrino Experiment

by Zhe Wang

1. **500 Hundred–ton solar neutrino observatory at CJPL II**
   a. Detector construction
   b. Replaceable detection media, allowed density range ± 20% wrt water, oil- or water- based liquid scintillator
2. **Solar B–8 neutrino detection with water first**
3. **Explored the option with LiCl aqueous solution**



Under construction.
Coming up soon.

ν_e CC, ES, and $\bar{\nu}_e$ detections with saturated LiCl aqueous solution

1.CC process for ν_e:

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

Measure neutrino energy

High concentration: 11 mol/L

2. Elastic scatter on e^-:

3.Delayed coincidence for $\bar{\nu}_e$:

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

with neutron capture on

H, Li6, and Cl35

measure $\bar{\nu}_e$ energy

Saturated LiCl solution

1. Attenuation length: 50 m at 430 nm
2. Adding 1 ppm C124 to LiCl aqueous solution, scintillation+Cherenkov

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

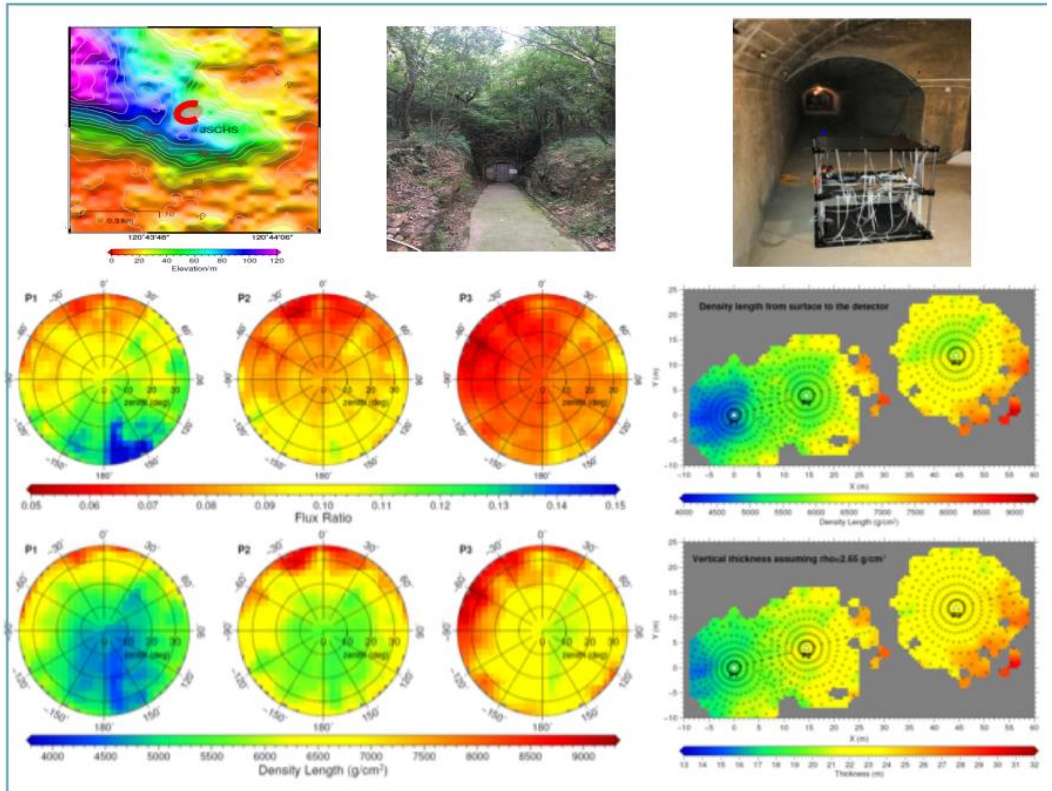
Good chance for solar and geo neutrinos

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

Muon Tomography

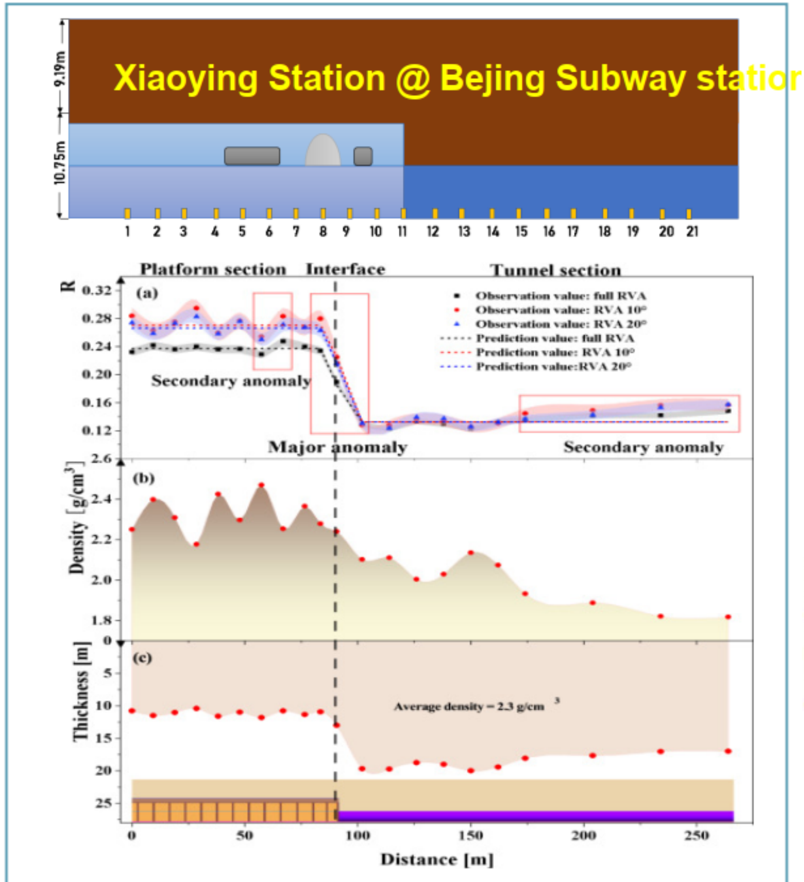
by Ran Han

Tunnel -- Changshu seismic station

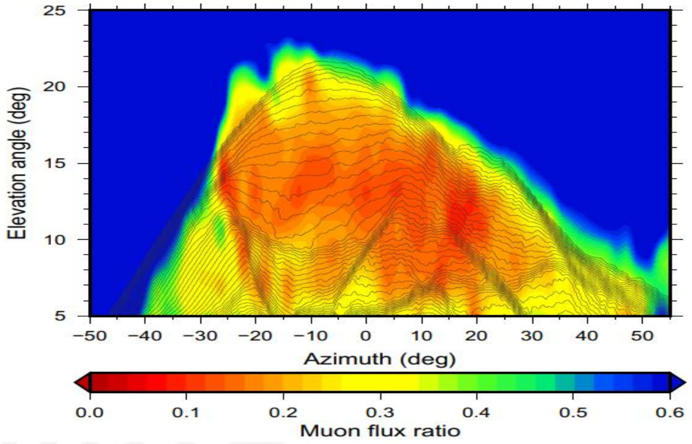


Muon ratio and density structure from the perspective of a

Tunnel -- Xiaoying subway station

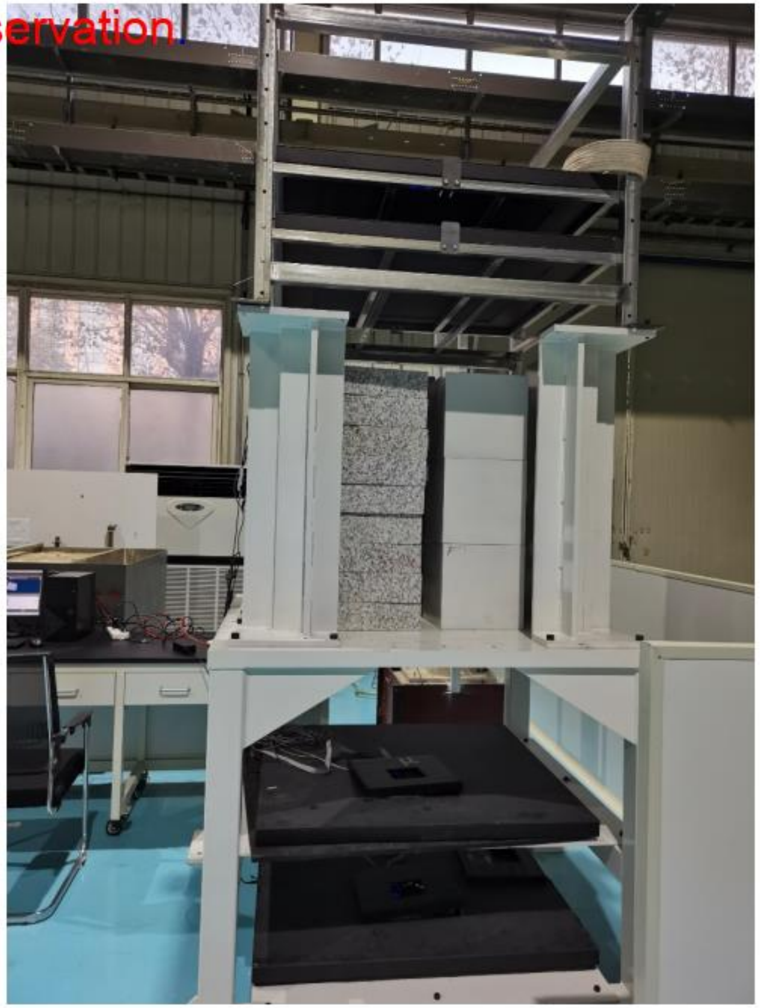


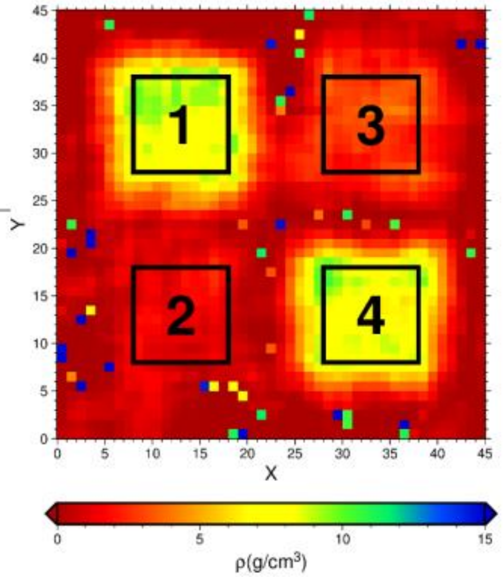
Volcano

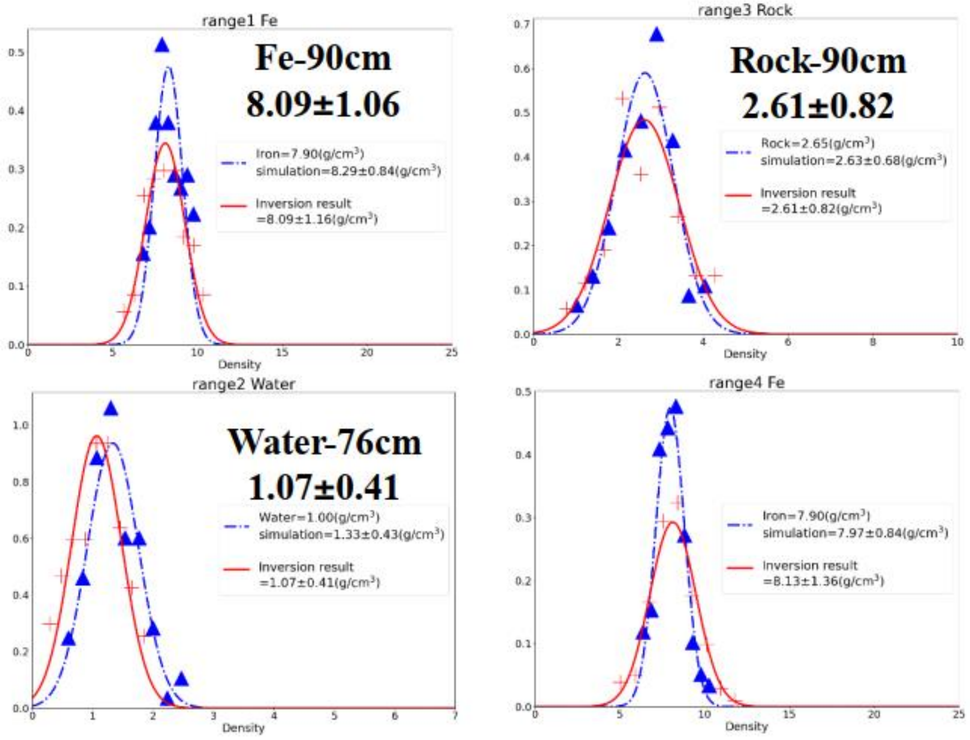


Absolute density inversion

Accurate 2D density measurement of samples with dimensions of several tens of centimeters can be achieved through 200 hours of observation.





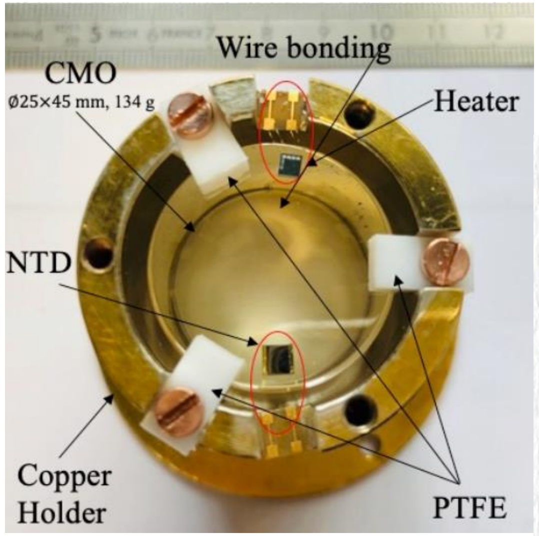


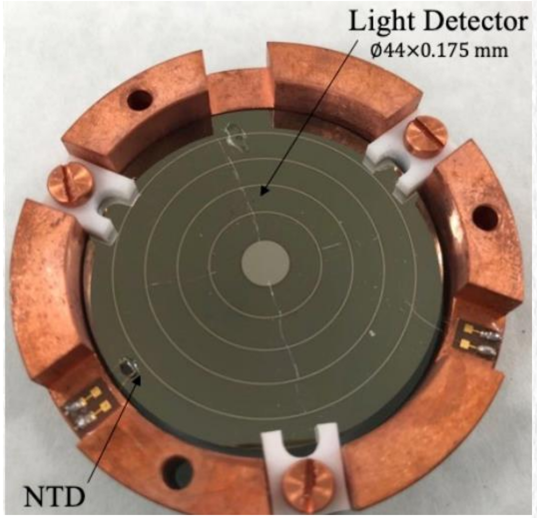
Density results from Data(red) and Simulation(blue)

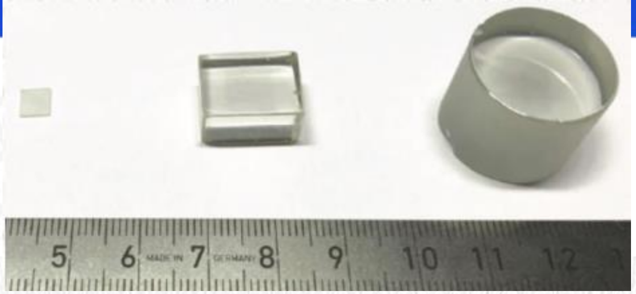
Cryogenic phonon-scintillating bolometer technology and applications

by Mingxuan Xue

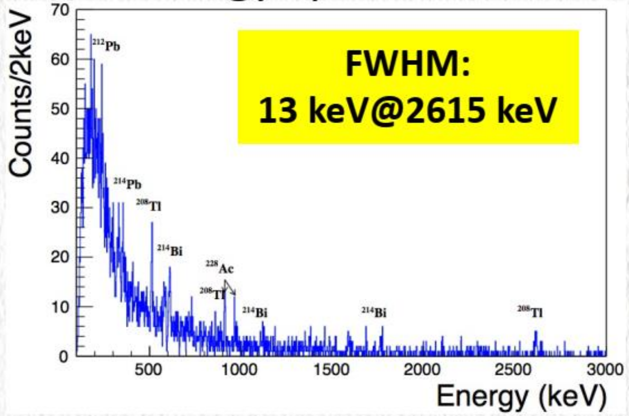
$CdMoO_4/Li_2MoO_4/Gd_2SiO_5$ bolometer for $0\nu\beta\beta$ search

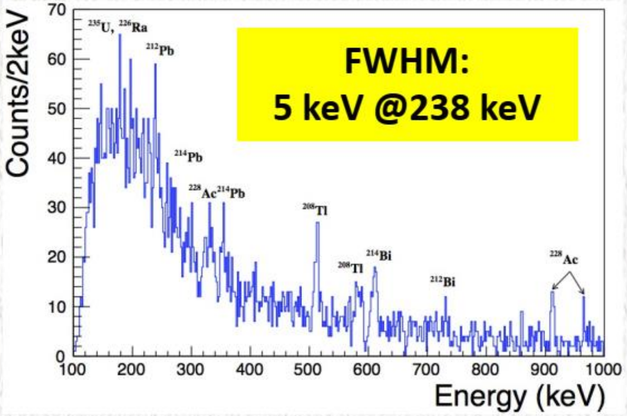


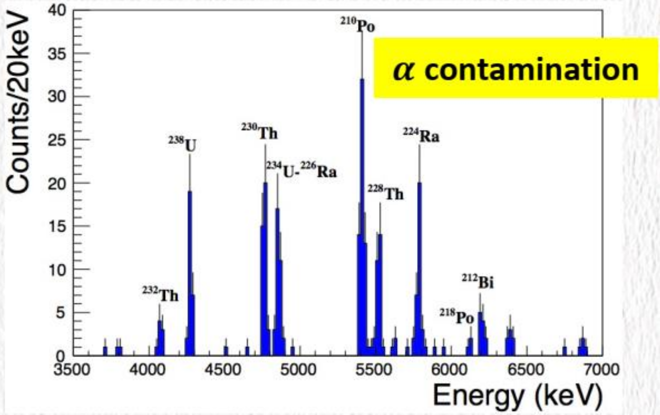




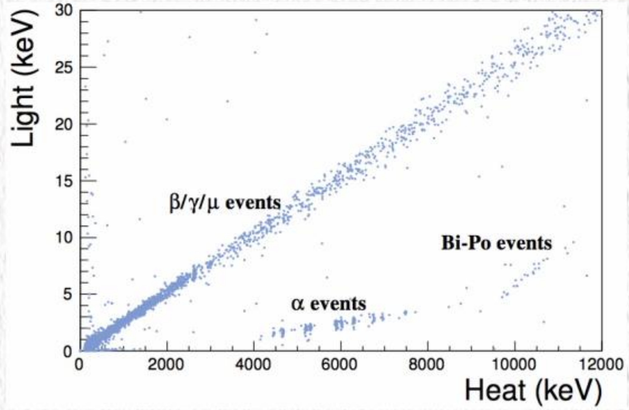
❀ Energy spectrum

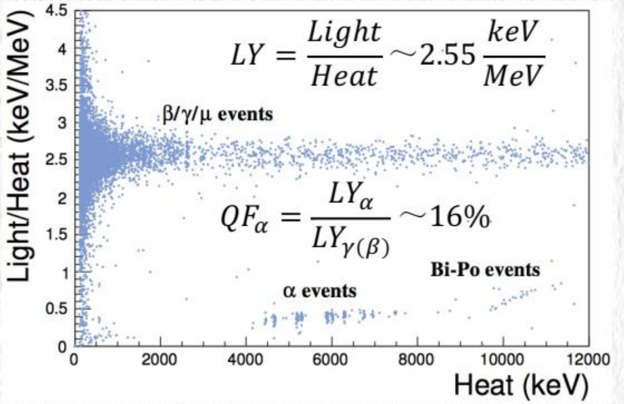


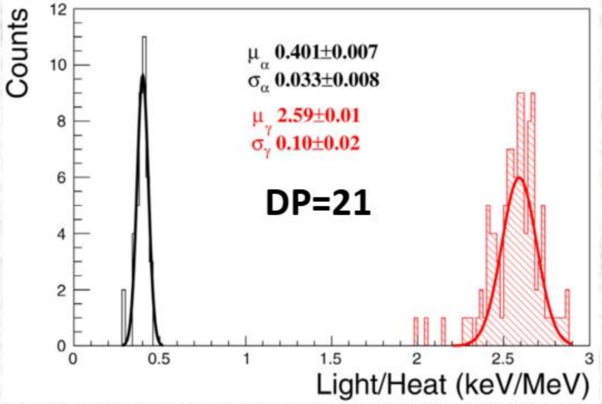




❀ Light yield and quenching factor, discrimination power

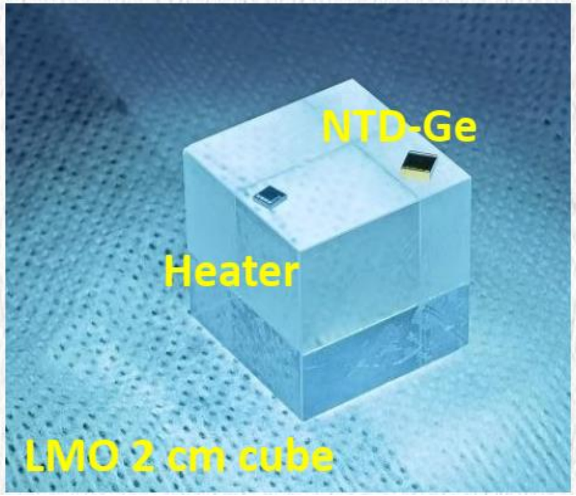




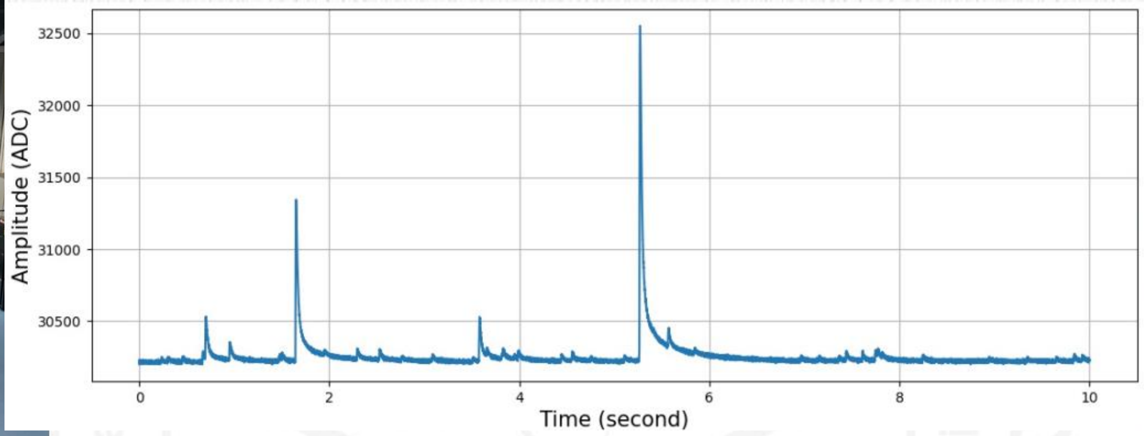


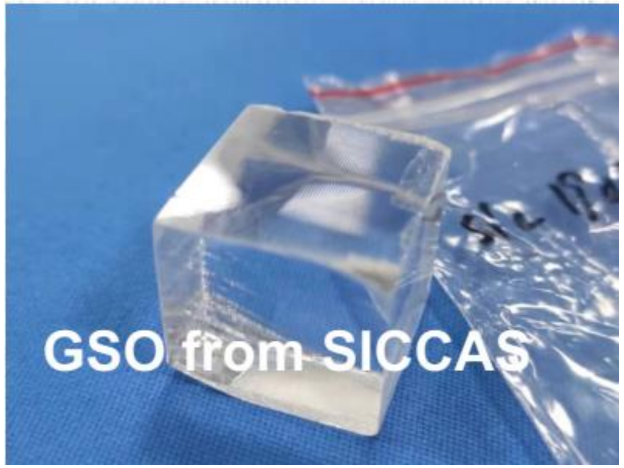
$CdMoO_4/Li_2MoO_4/Gd_2SiO_5$ bolometer for $0\nu\beta\beta$ search

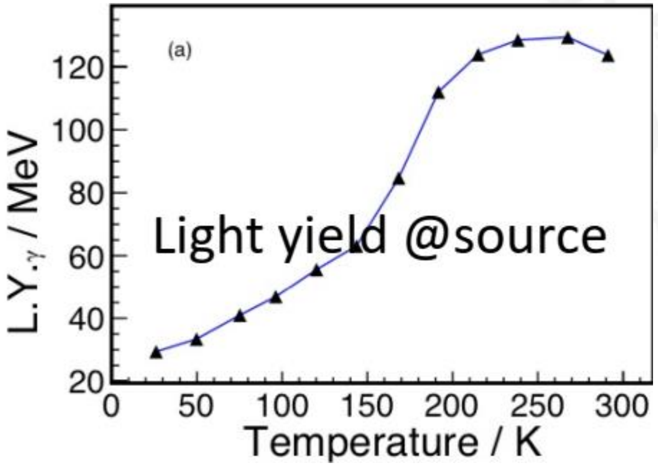
❀ Small LMO 2×2×2 cm³

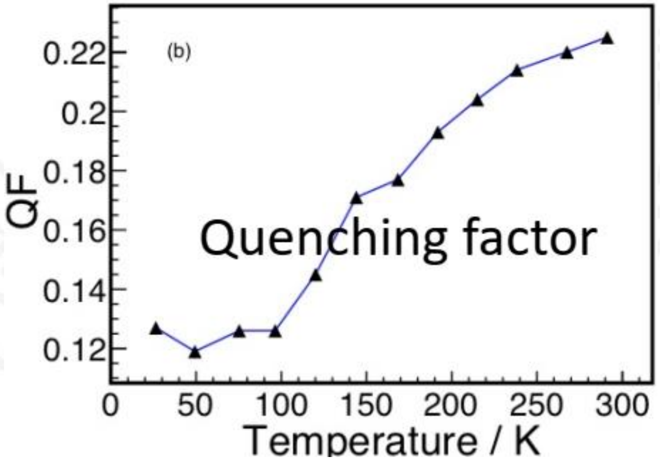


❀ Running @10 mK in USTC_DU



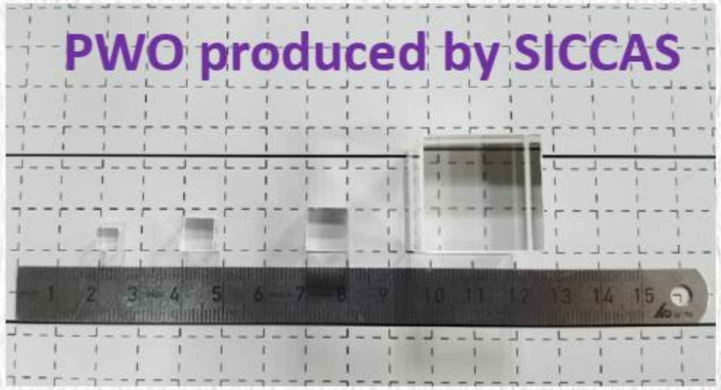


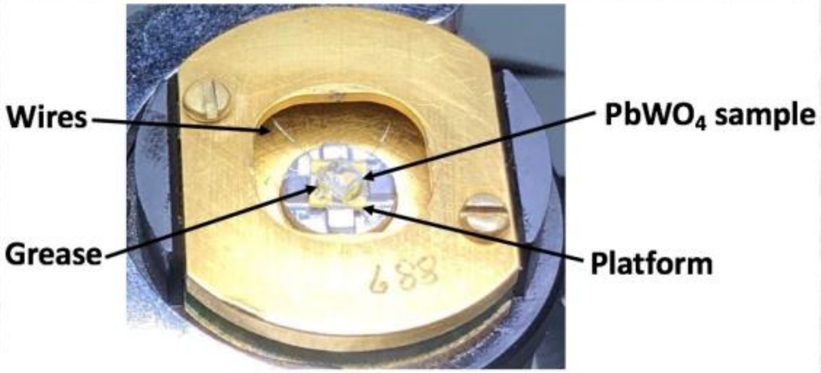


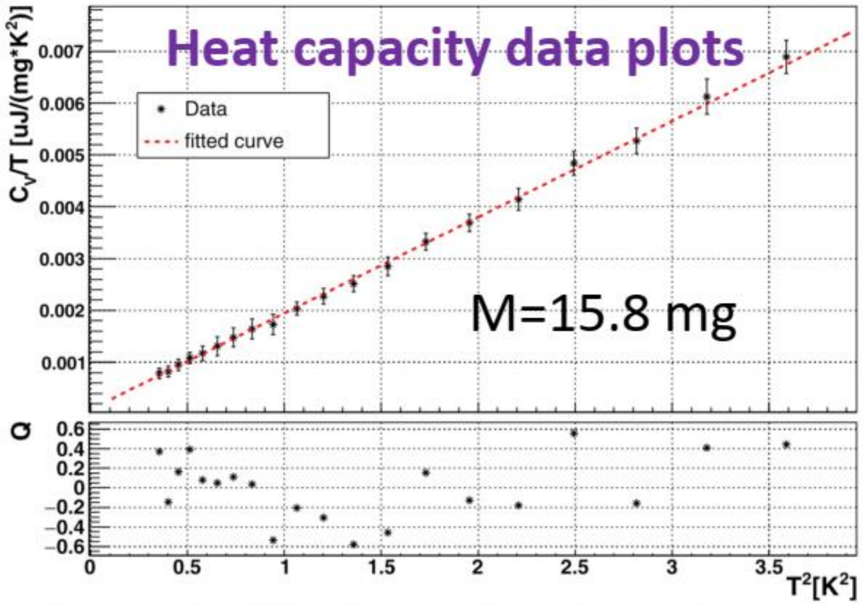


PbWO4 bolometer for reactor CEvNS observation

- Essential idea for using PWO in reactor neutrino CEνNS experiment:
  - **Neutron-enriched** elements to enhance interaction rates
  - **Low heat capacity** (C) at working temperature (10 mK) to guarantee sensitivity to such small recoil energy deposition, $C \propto T^3$







- 1 kg PWO crystal absorber

	counts/[kg day] E_{th} = 10 eV	counts/[kg day] E_{th} = 20 eV	counts/[kg day] E_{th} = 50 eV
$PbWO_4$	221.0	170.8	88.5
W	96.9	75.7	40.1
Pb	123.1	94.2	47.7
O	1.0	0.9	0.7

Summary

1. Reactor neutrino precision measurement and monitor
   a. TAO and CHANDLER
2. Geoneutrino measurements and prediction
   a. Borexino and KamLAND; b. JUNO pred.
3. CEvNS detection: 8 Exp. coming up
4. Others:
   a. Jinping Neutrino Experiment coming up
   b. Muon tomography results
   c. Bolometer development

Thank you.

Apologize for the missing details and key points due to my limited knowledge.