中国科学院高能物理研究所

Liquid Scintillator Detectors for Neutrinos

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Outline

- Open questions in neutrinos
- Neutrino signal and background in Liquid Scintillator (LS)
- LS technologies (refer to Milind's presentation yesterday)
- Liquid scintillator detectors for neutrinos
  - LS-based reactor neutrino experiments
  - LS-based solar and $0\nu\beta\beta$ neutrino experiments
  - LS-based short baseline accelerator neutrino experiments (LSND, KARMEN, JSNS^2/JSNS^2-II, IsoDAR, etc)
- Future plans and summary

Neutrino discovery

In 1930, ν proposed by W. Pauli → In 1956, ν discovered by F. Reines and C. Cowan → In 1962, ν_μ discovered by L. Lederman, M. Schwartz and J. Steinberger → In 2000, ν_τ discovered by DONUT

Neutrino Mixing and oscillation

In 1960s, solar neutrino problem Homestake Gallium/Kamiokande → In 2002, MSW-LMA from SNO, Super-K and KamLAND (θ_{12}, Δm^2_{21})

In 2012, the last mixing angle θ_{13} measured Daya Bay, RENO, D-Chooz

In 1980s, atmospheric neutrino anomaly Kamiokande/IMB → In 1998, solution from Super-K (θ_{23}, $|\Delta m^2_{32}|$) → Neutrino Mixing and oscillation established

In 1960s, neutrino mixing proposed by B. Pontecorvo, Z. Maki, M. Nakagawa and S. Sakata

Mass ordering, CP phase, mass are still unknown, how long can we get the answers?

In the three neutrino framework

Neutrino flavour eigenstates ≠ Mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$V_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

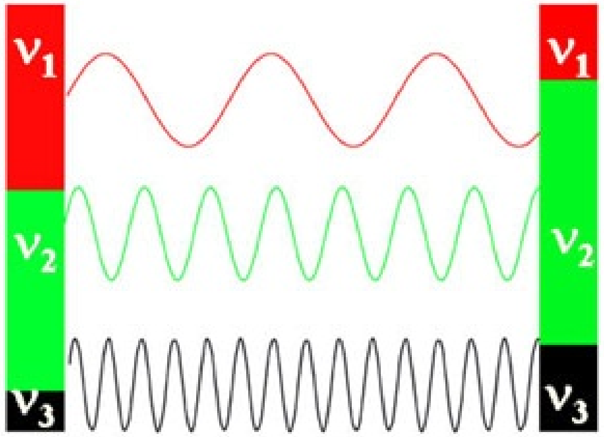
Atmospheric Accelerator	Reactor Accelerator	Solar Reactor	Double beta decay

⇒ Oscillation Probability:

$$P_{\nu_\alpha \to \nu_\beta} = 1 - 4 \sum_{i<j} |V_{\alpha j}|^2 |V_{\beta i}|^2 \sin^2 \frac{\Delta m_{ji}^2 L}{4E}$$

Amplitude ∝ $\sin^2 2\theta$

Frequency ∝ $\Delta m^2 L/E$



6 fundamental parameters to describe neutrino oscillation: θ_{23} & Δm^2_{32}, θ_{13}, θ_{12} & Δm^2_{21}, δ

A Huge Success of Three-flavour Oscillation

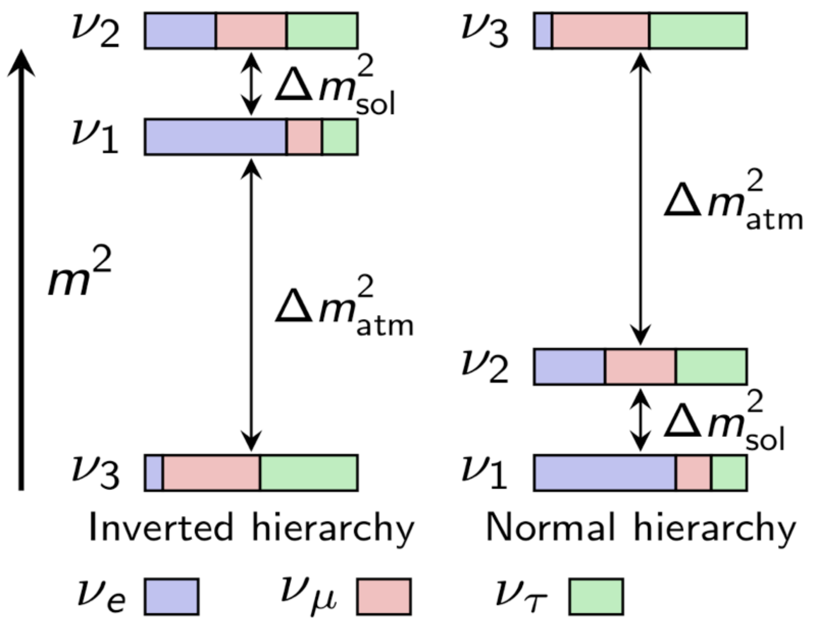
- **The discovery of neutrino oscillation provided the first evidence of new physics beyond the standard model**
  - **Neutrinos have non-zero masses, a huge impact to the particle physics and cosmology**
  - **A possible source of CP violation to explain the matter-antimatter asymmetry in the Universe**
- **Many experiments launched to measure the oscillation parameters and made a huge success**
  - **Liquid scintillator detectors played a critical role**

PDG 2022

Parameter	Central value	Uncertainty	Dominant Experiments
$\sin^2(\theta_{12})$	0.307	4.2%	Solar
Δm^2_{21}	7.53×10^{-5} eV^2	2.4%	Reactor LBL
$\sin^2(\theta_{23})$	0.546 (NO) 0.539 (IO)	4.2%	Accel LBL $\nu_\mu/\bar{\nu}_\mu$ Disapp.
$\lvert\Delta m^2_{32}\rvert$	2.453×10^{-3} eV2 (NO) 2.536×10^{-3} eV^2 (IO)	1.3%	Reactor MBL, Accel LBL $\nu_\mu/\bar{\nu}_\mu$ Disapp.
$\sin^2(\theta_{13})$	0.022	3.2%	Reactor MBL
δ_{CP}	1.36 (π rad)	14.7%	Accel LBL $\nu_e/\bar{\nu}_e$ App.

Open Questions in Neutrinos

- ❖ **Neutrino mixing and oscillation**
  - ➢ **Neutrino mass ordering still unknown**
  - ➢ **CP violation phase still unknown**
  - ➢ **θ_{23} octant still unknown**
  - ➢ **Precise oscillation parameters, sub-percent level**
- ❖ **Are neutrinos Majorana particles? (0νββ)**
- ❖ **Absolute neutrino mass?**
  - ➢ **Cosmology (~0.1 eV), β-decay (~0.8 eV), ββ-decay (~0.1 eV)**
- ❖ **Sterile neutrinos?**
  - ➢ **Reactor Antineutrino Anomaly (RAA)**
  - ➢ **Gallium anomaly [PRC 105, 065502]**
  - ➢ **LSND anomaly [PRD 64, 112007]**



	Isotope	Mass(t)	$\langle m_{\beta\beta}\rangle$,meV
SNO+	^{130}Te	8	19-46
KamLAND2-Zen	^{136}Xe	1	~20
NEXT-HD	^{136}Xe	1	14-40
nEXO	^{136}Xe	5	7-22
LEGEND-1000	^{76}Ge	1	10-40
AMoRE-II	^{100}Mo	0.1	12-22
CUPID	^{100}Mo	0.24	12-20
CUPID-1T	^{100}Mo	1	4-7
JUNO-ββ	^{136}Xe	50	4-10
	^{130}Te	100	3-14

Neutrino Signal and Background in LS Detectors

Neutrino Signals

- $\bar{\nu}_e + p \rightarrow e^+ + n$ (IBD)
  - 1.8 MeV threshold for free protons
  - Golden channel to detect $\bar{\nu}_e$, e.g. reactors
- $\nu + e^- \rightarrow \nu + e^-$ (ES)
  - Typical threshold ~10 eV – 100 keV
  - Sensitive to all flavours, e.g. solar neutrinos
- $\nu_e + n \rightarrow p + e^-$ (ν-capture)
  - No threshold for free neutrons, some in nuclei
  - Radiochemical experiments, cosmic ν bkg
- $\nu_l/\bar{\nu}_l + n/p \rightarrow p/n + l^-/l^+$ (Quasi-elastic)
  - Tens of MeV for ν_e, ~100 MeV for ν_μ
- $\nu_l/\bar{\nu}_l + n/p \rightarrow X + l^-/l^+$(Inelastic)
  - Hundreds of MeV threshold
  - Additional hadrons, detectable in LS

Backgrounds

- Radioactivity
  - Most less than ~3 - 4 MeV
  - Major task in a low background experiment
  - Careful material screening, environment cleanness, dust/radon control, etc
- Cosmic muon induced background
  - Spallation products, e.g. long-lived isotopes
  - Deep overburden
- Neutrino NC
  - Gammas, hadrons, etc
  - Pulse shape discriminator (PSD) could help
- Other neutrino sources
  - e.g. reactor neutrinos vs geo-neutrinos

Liquid scintillator detectors for neutrino detections

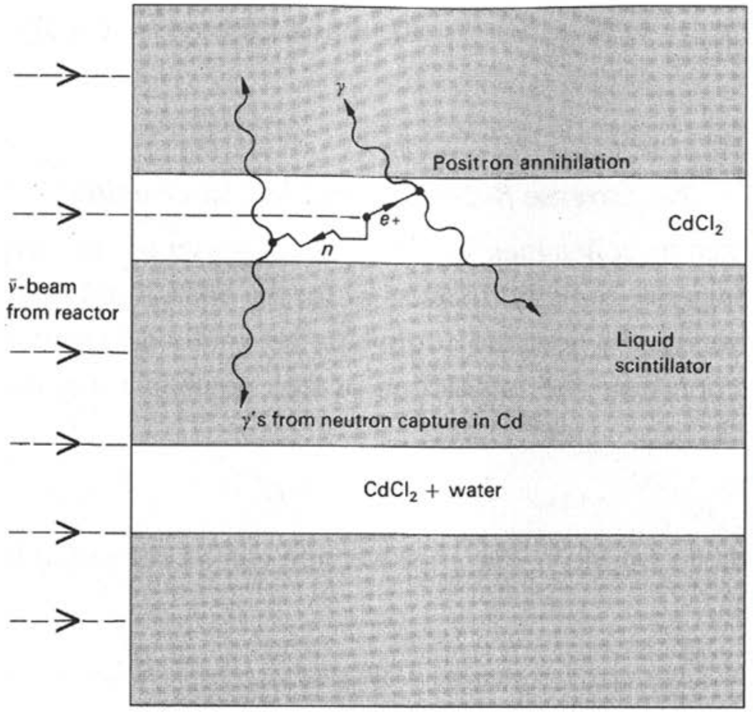
- ❖ **LS-based reactor neutrino experiments**
- ❖ **LS-based solar and 0νββ neutrino experiments**

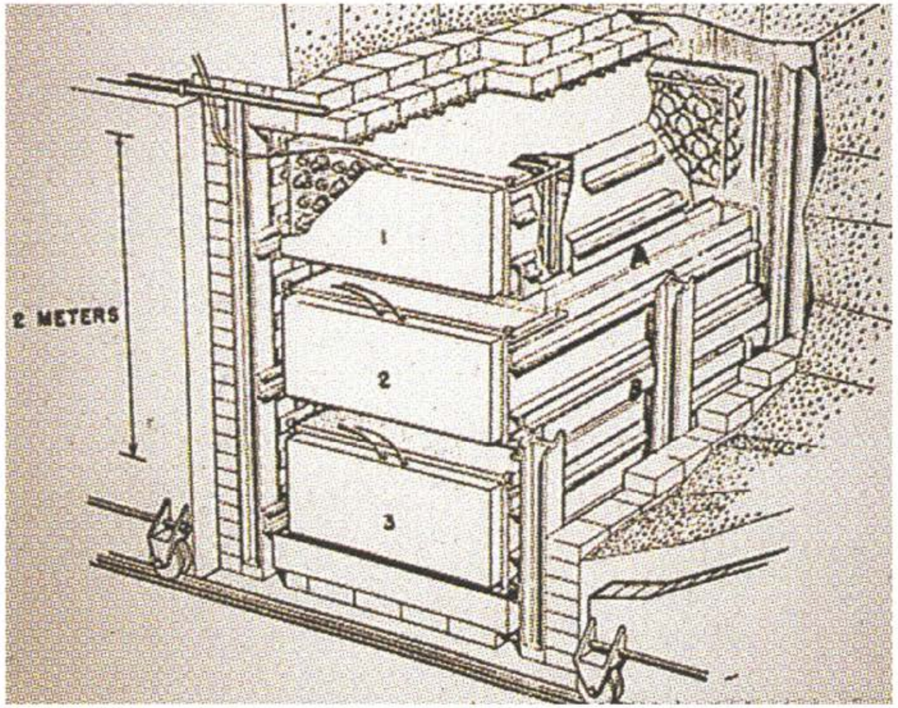
H.W. Wang Modified from Astropart. Phys. 97 (2018) 136-159

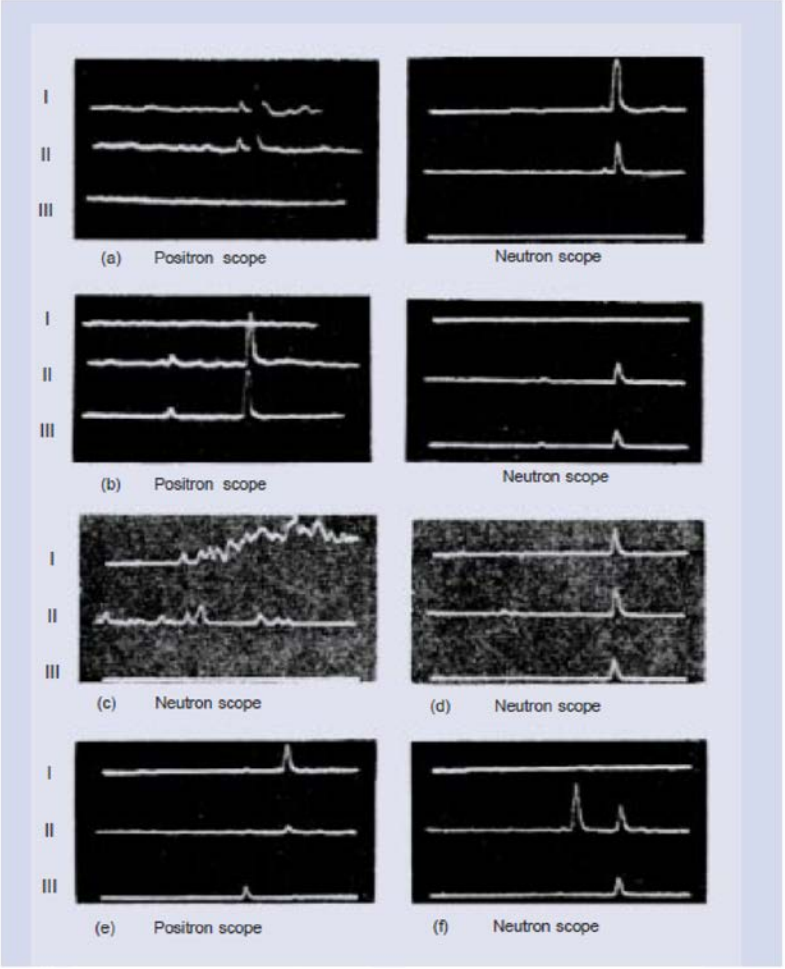
Experiment	Mass	LS composition	Physics investigation	Status
Chooz	5 t LS+Gd(0.1 %)+107 t LS	Gd-loaded: 50% Norpar-15, 50% IPB+hexanol and p-PTP+bis-MSB (1 g/l) unloaded: 92.8 % Mineral oil, 7.2 % IPB and PPO+DPA (1.5 g/l)	ν oscillations	past, 1998 - 1999
KamLAND	1kt LS	80% dodecane, 20% PC and 1.36± 0.03 g/l of PPO	ν oscillations	past, 2002 - 2011
Karmen	56t + Gd foils	75% MO + 25% PC + 2g/L PMP	ν oscillations	past, 1990 - 2001
LSND	167t LS	50,000 gallon Britol 6 NF HP White Mineral Oil + 6 kg b-PBD (0.031 g/l)	ν oscillations	past, 1993 - 1998
Palo Verde	11tLS + Gd(0.1%)	Gd "concentrate" (BC-521C), PC (with 4 g/l PPO and 100 mg/l bisMSB) and mineral oil (1:1:3)	ν oscillations	past, 1998 - 2000
Borexino	278t LS	Inner shell: PC and PPO (1.5 g/l) The 2nd and 3rd shell: PC and DMP (5 g/l)	ν oscillations	past, 2007 - 2020
Reno	16t LS+Gd(0.1 %)+30t LS	LAB, PPO, and bis-MSB + $Gd(TMHA)_3$	ν oscillations	past, 2011- 2023
Daya Bay	20t LS + Gd (0.1 %) + 20t LS	PC, PPO (3 g/l) and bis-MSB (15 mg/l) ($Gd(TMHA)_3$ as solute for the Gd-loaded LS)	ν oscillations	past, 2011 - 2020
Double Chooz	8t LS + Gd(0.1%) + 18t + 80tLS	NT: o-PXE/n-dodecane mixture (volume 20:80) + 0.123% Gd GC: same as NT + medicinal white oil	ν oscillations	past, 2011-2017
Juno	20kt LS	LAB, PPO (2.5 g/l) and bis-MSB (3 mg/l)	ν oscillations	under construction
JSNS²(-II)	17t 0.1%Gd doped LS	90%LAB, 10%DIN, PPO (3 g/l) and bis-MSB (15 mg/l)	ν oscillations	Ongoing, 2021 -
KamLAND-Zen	13t Xe-LS + 1 kt LS	Xe-LS: 82% decane, 18% PC by volume, PPO (2.4 g/l) and 3.13% enriched xenon by weight $(90.85 \pm 0.13)\%\,^{136}Xe$	$0\nu\beta\beta$ decay	Ongoing, 2011 -
SNO+	780t LS + Te(up to 3 %)	LAB, PPO (2 g/l) + Telluric acid	$0\nu\beta\beta$ decay	ongoing, 2017-
LVD	1008t LS	aliphatic and aromatic hydrocarbons (one counter doped with Gd in 2005)	SN ν	past, 1992 - 2020
JUNO-TAO	2.8t LS+Gd (0.1%)	PPO (3 g/l), bis-MSB (2 mg/l), LAB, $Gd(TMHA)_3$ and 0.5% DPnB	reactor ν	under construction
Neos/Neos-II	1t LS+Gd (0.5%)	LAB + DIN, PPO (3 g/l) and bis-MSB (30 mg/l) + Gd	sterile ν	Past, 2016 - 2020
Neutrino-4	0.35t LS + Gd(0.1%)	400l BC-525 + Gd (1 g/l),	sterile ν	Upgrading, 2014 - 2021
Prospect(-II)	3-13t LS + ^6Li	LAB, UltimaGold, and EJ-309 + ^6LiCl	sterile ν	Past (Planning) 2018 - 2018
Stereo	1800l LS + Gd (0.2 %)	LAB (75%), PXE (20%) and DIN (5%); PPO, bis-MSB and $Gd(thd)_3$ + THF (1:1 in mass)	sterile ν	Past, 2016 - 2020

The First LS Detector for Neutrinos

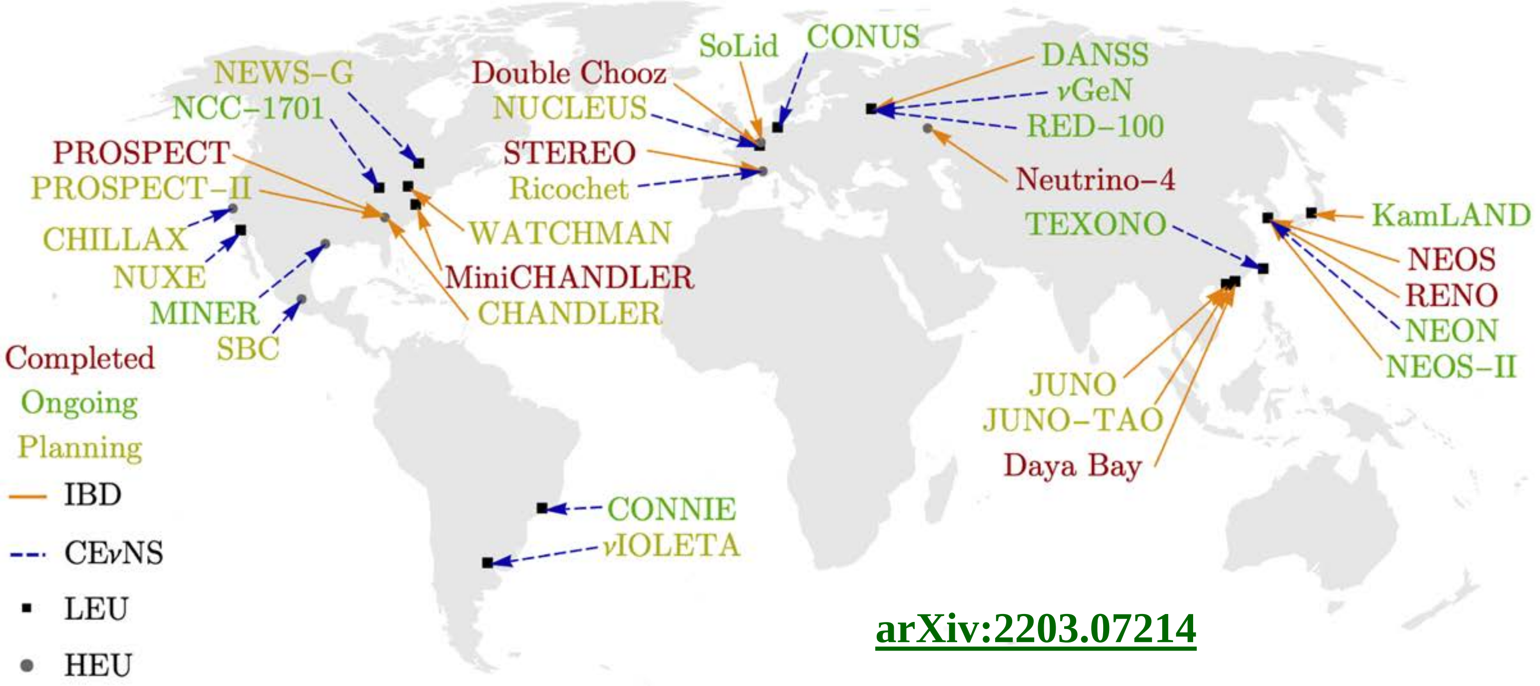
- ❖ **In 1956, F. Reines and C. Cowan discovered the electron anti-neutrino from the reactor** **[Science. 124 (3212): 103–4]**
- ❖ **Poltergeist Project: the first liquid scintillator detector used for neutrino detection**
  - ➢ **Detector: 3 tanks of LS, 183×132×56 cm^3/each**
  - ➢ **Target: 2 tanks of $CdCl_2$-doped water, sandwich structure**
  - ➢ $\bar{\nu}_e + p \rightarrow n + e^+$, **inverse beta decay**



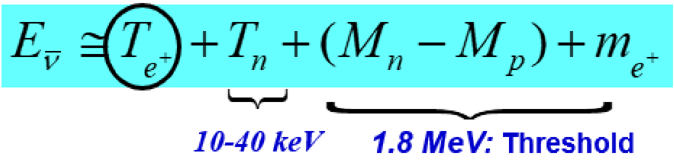




LS-based Reactor Neutrino Experiments

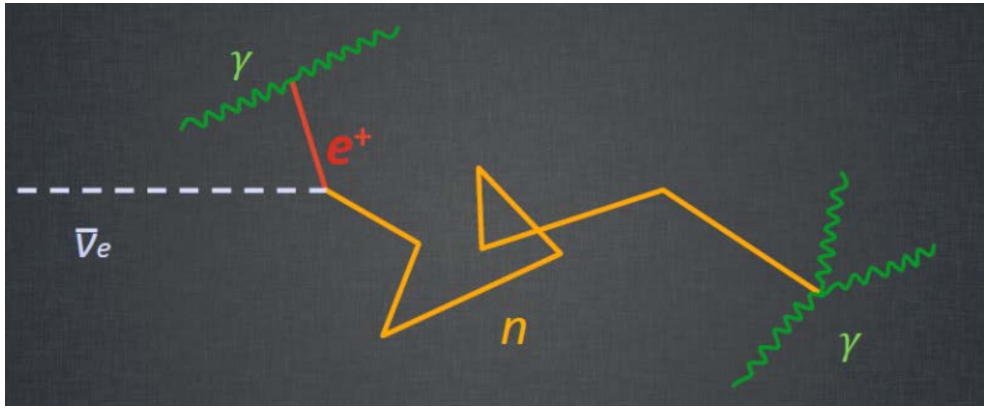


arXiv:2203.07214

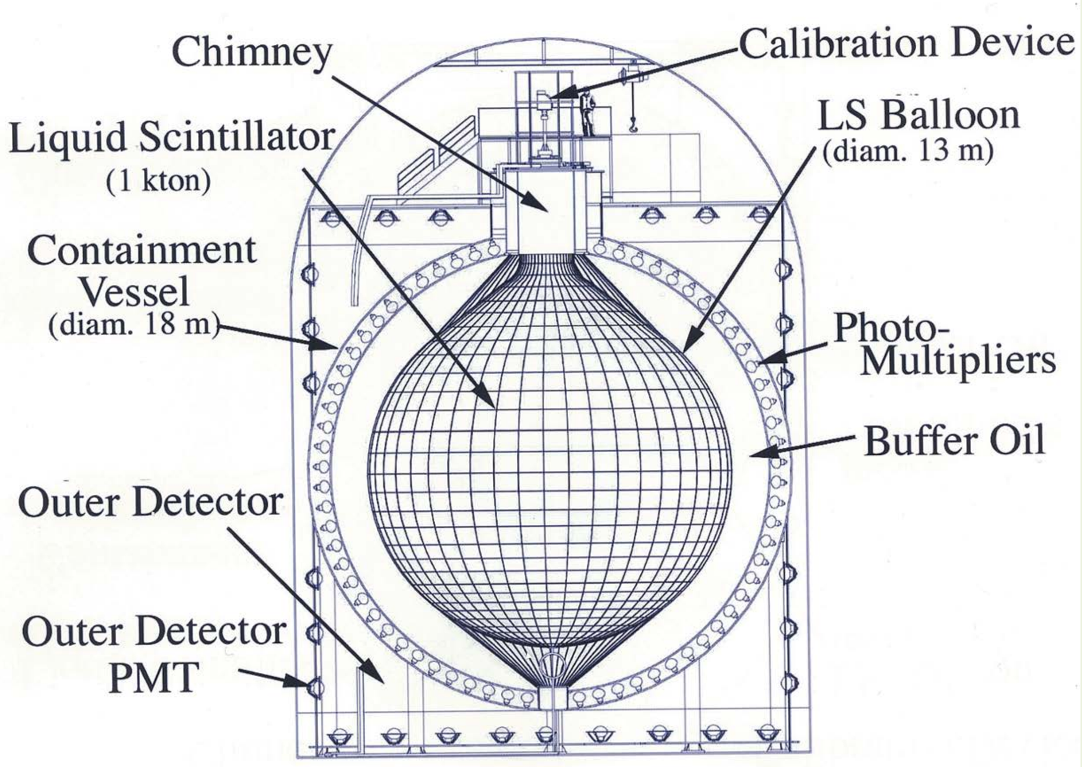


$$E_{\bar{\nu}} \cong T_{e^+} + \underbrace{T_n}_{10\text{-}40\ keV} + \underbrace{(M_n - M_p) + m_{e^+}}_{1.8\ MeV:\ \text{Threshold}}$$

- ❖ **Measure neutrino oscillations with different baselines**
  - ➢ **LBL (>100 km): KamLAND**
  - ➢ **MBL (<100 km): Daya Bay, D-Chooz, RENO, JUNO, etc**
  - ➢ **SBL (~10 m): Prospect, Stereo, NEOS, TAO, etc**
- ❖ **LS is a common use to detect neutrinos via IBD**



LBL Reactor Neutrino Experiment -- KamLAND

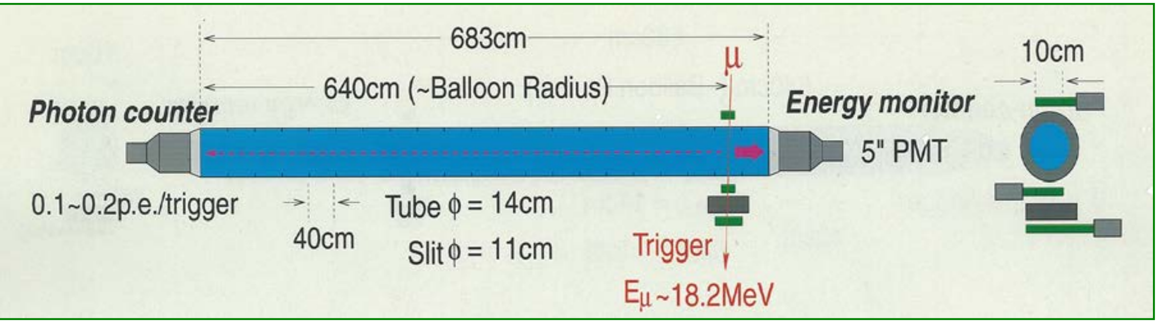


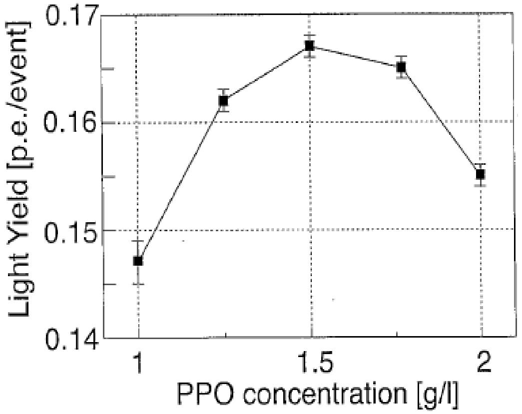
- Overburden: ~2700 mwe, baseline: 180 km
- 1000 t LS: 80% dodecane+20% pseudocumen (PC)+1.36 g/L PPO, enclosed in an EVOH/nylon balloon supported by a rope network
- LS balloon immersed in MO to shield external radiations
- 1325 17-inch PMTs + 554 20-inch PMTs → 34% coverage
- E resolution: $6.5\%/\sqrt{E(MeV)}$ R resolution: $\sim 12\ cm/\sqrt{E(MeV)}$
- OD: 3.2 kton water Cherenkov detector with 225 20-inch PMTs
- Data taking started in March 2002

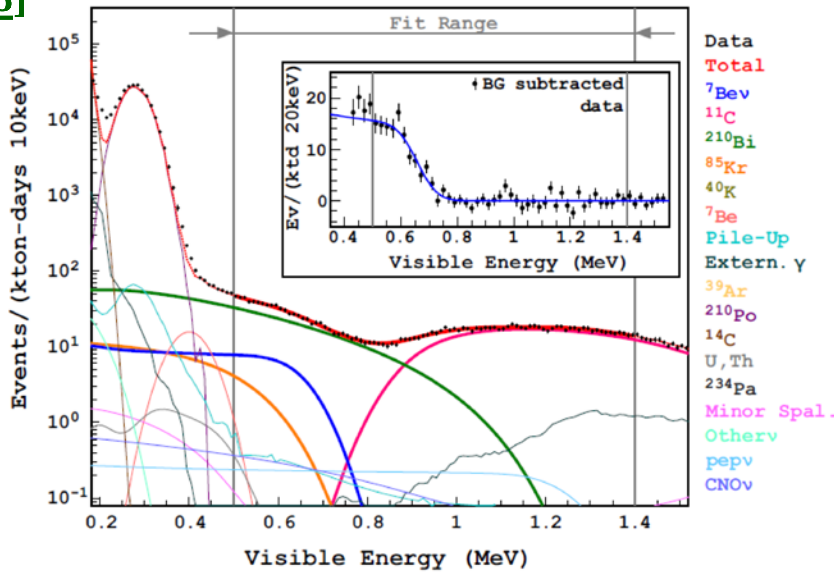
KamLAND LS

- PC + PPO was selected, diluted by normal-dodecane (ND), PPO concentration optimized
  - LAB was not discovered yet by M. Chen at that time
  - ND: safer for balloon, higher flash point (ND~80 °C, PC~54 °C), better transparency and stability
- LS radiopurity: $^{238}U \sim 10^{-18}$ g/g, $^{232}Th \sim 10^{-17}$ g/g, $^{40}K \sim 10^{-16}$ g/g, but relatively high rates of ^{85}Kr (883 μBq/kg) and ^{210}Pb (58.4 μBq/kg): ~5 orders higher than 500/kton/day of ^{7}Be solar neutrino rate
- Two purification campaigns in 2007 and 2008-2009 with distillation and nitrogen purge systems underground with reduction factors of ^{85}Kr: ~6×10^{-6}, ^{210}Bi: 8×10^{-4}, ^{210}Po: 5×10^{-2} [NIM A 769, 79 (2015)]
- Confirmed ^{7}Be neutrino flux, first observed by Borexino [PRC 92, 055808]

F. Suekane in 2019





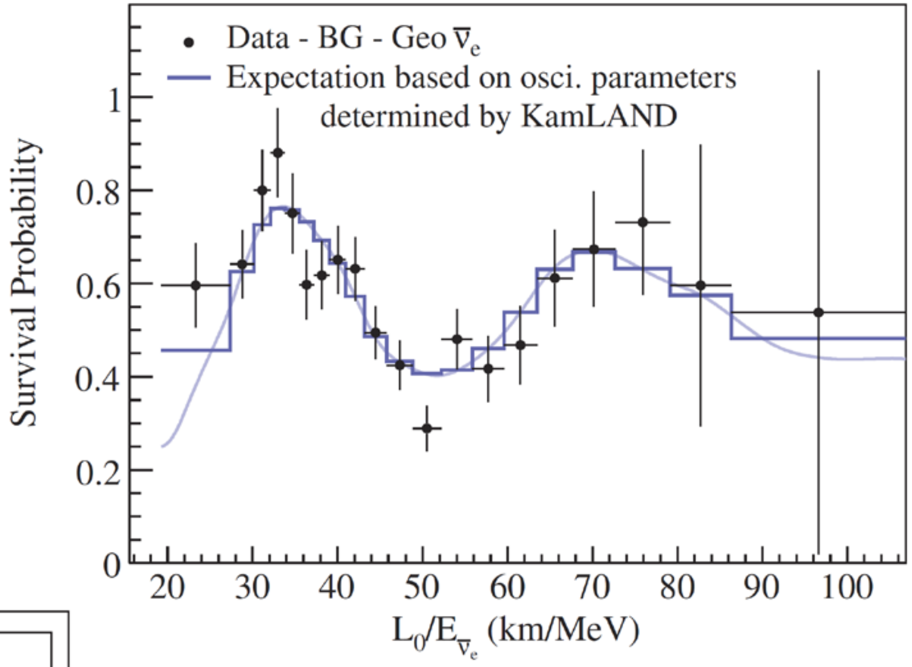


Major Results of KamLAND

Y. Koshio@Neutrino 2022

Discovery of Reactor Neutrino Oscillation

PRL 90, 2 (2003)



$\sin^2(\theta_{12}) = 0.316^{+0.034}_{-0.026}$

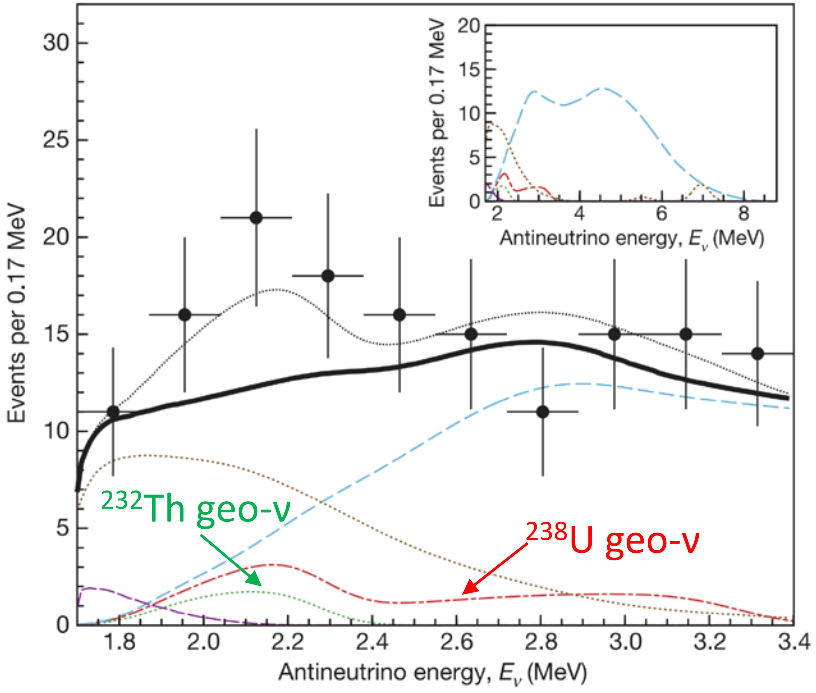
$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5} eV^2$

$\sin^2(\theta_{12}) = 0.305 \pm 0.014$

$\Delta m^2_{21} = 6.10^{+1.04}_{-0.75} \times 10^{-5} eV^2$

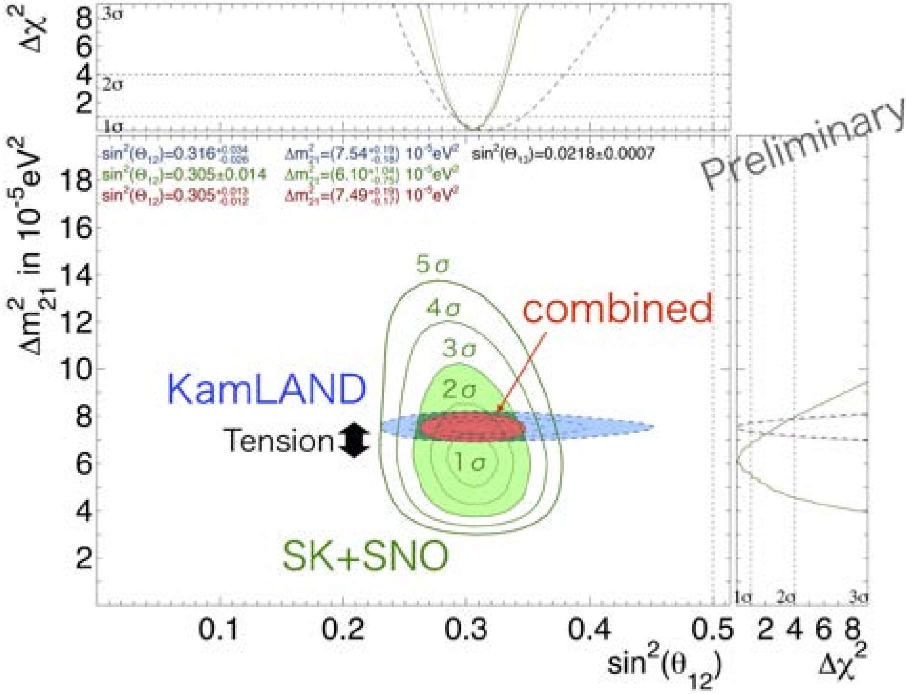
$\sin^2(\theta_{12}) = 0.305^{+0.013}_{-0.012}$

$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \times 10^{-5} eV^2$



The first measurement of geoneutrinos

Nature 436, 499 (2005)

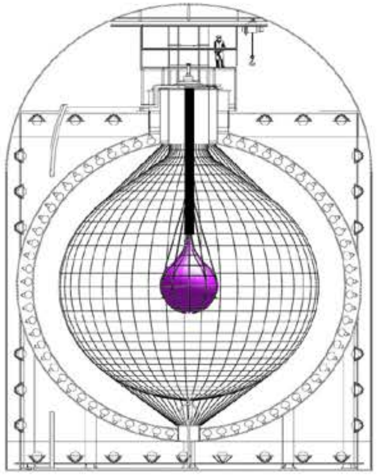


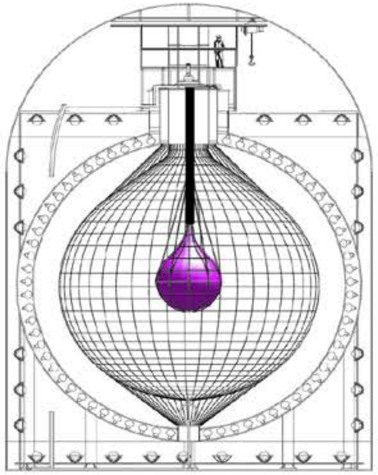
A. Gando @Neutrino2022

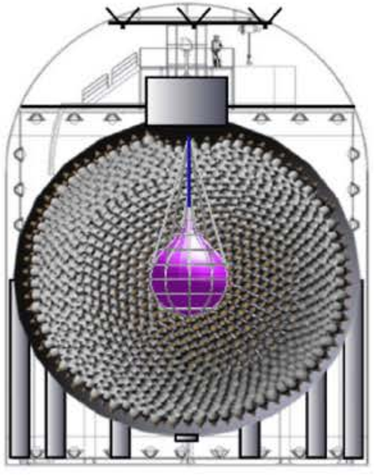
Search for neutrinoless double beta decay of ^{136}Xe (Q-value 2.458 MeV)

- ^{136}Xe loaded LS in a new Inner Balloon (IB) at KamLAND center
  - ~3% ^{136}Xe by weight, enrichment ~90%, LY is 3% lower than the undoped LS
- Unexpected background of ^{110m}Ag on IB from Fukushima-I fallout (March 2011) in KamLAND-Zen 400
- The purification was done from 2012 to 2013, after 3 times purification and circulation, 10× ^{110m}Ag less

Past	Present	Future
KamLAND-Zen 400	KamLAND-Zen 800	KamLAND2-Zen
320-380 kg of Xenon	~750 kg of Xenon	~1 ton of ^{136}Xe
Data taking in 2011 - 2015	DAQ started in 2019	Better energy resolution

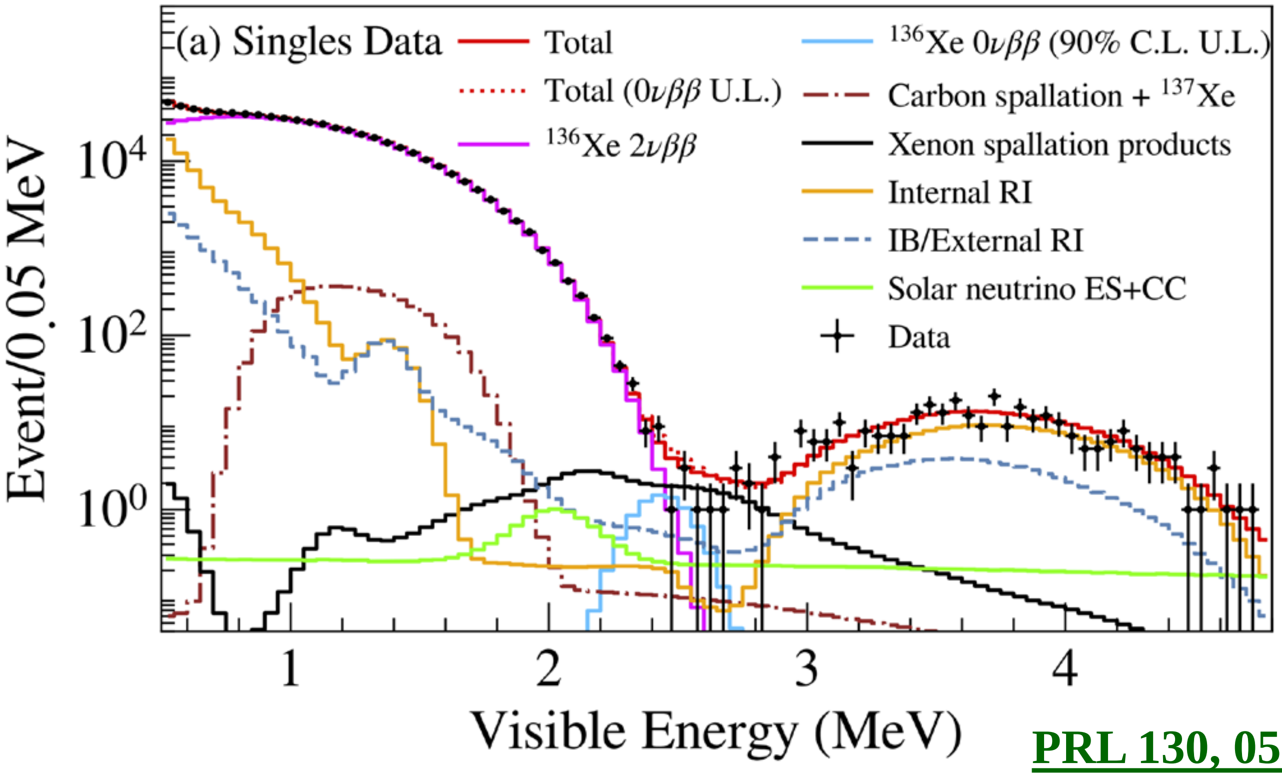




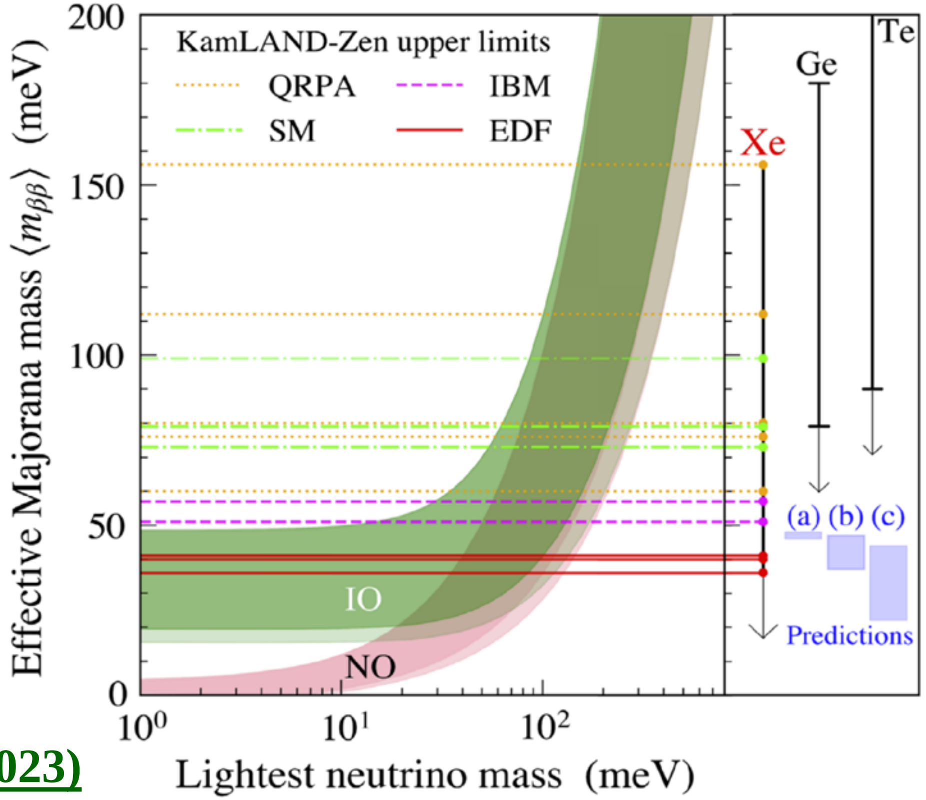


KamLAND-Zen 800

- In KamLAND-Zen 800, very careful radiopurity control for IB production @class 1 clean room, U/Th: ~3/40×10^{-12} g/g, 10× reduction compared with KamLAND-Zen 400, no ^{110m}Ag observed
- Combined result of KamLAND-Zen 400 and 800 gives the currently most strict limit:
  $T^{1/2}_{0\nu\beta\beta} > 2.3 \times 10^{26}\, yr\ (90\%\ C.L.)$ $\langle m_{\beta\beta}\rangle < (36 - 156)\ meV$
- Major backgrounds: Xenon/carbon spallation, radioactivity impurity and solar neutrinos



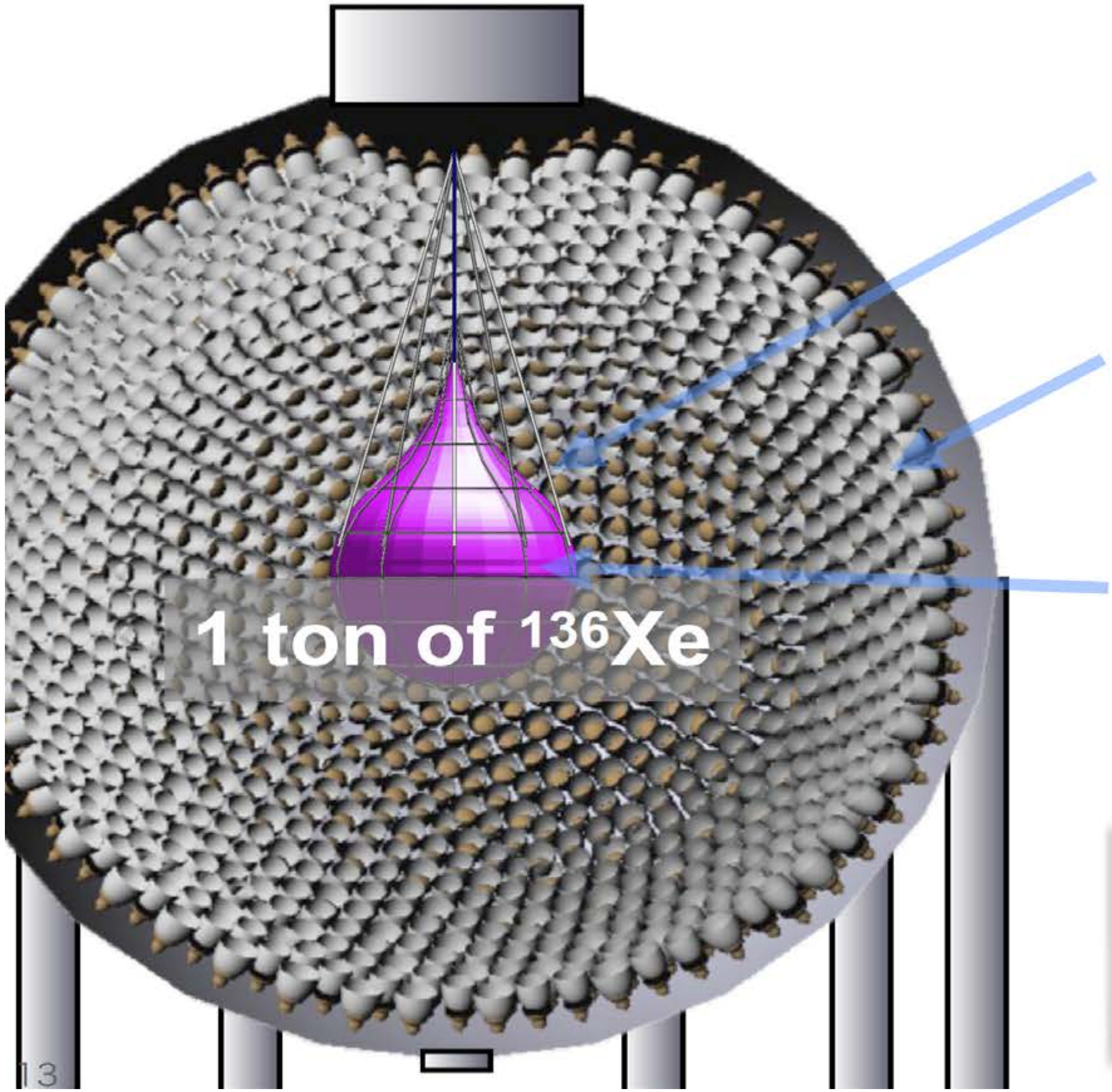
PRL 130, 051801 (2023)



KamLAND2-Zen

A. Gando @Neutrino2022

Enlarge opening
General use: accommodate various devices such as $CdWO_4$, NaI, CaF_2 detectors



New electronics
To improve background suppression.
Tagging long lived isotope from cosmic ray spallation.

Scintillation inner balloon
BG reduction from Xe-LS container

Winstone cone & High QE PMT
Improve light collection efficiency and photo coverage

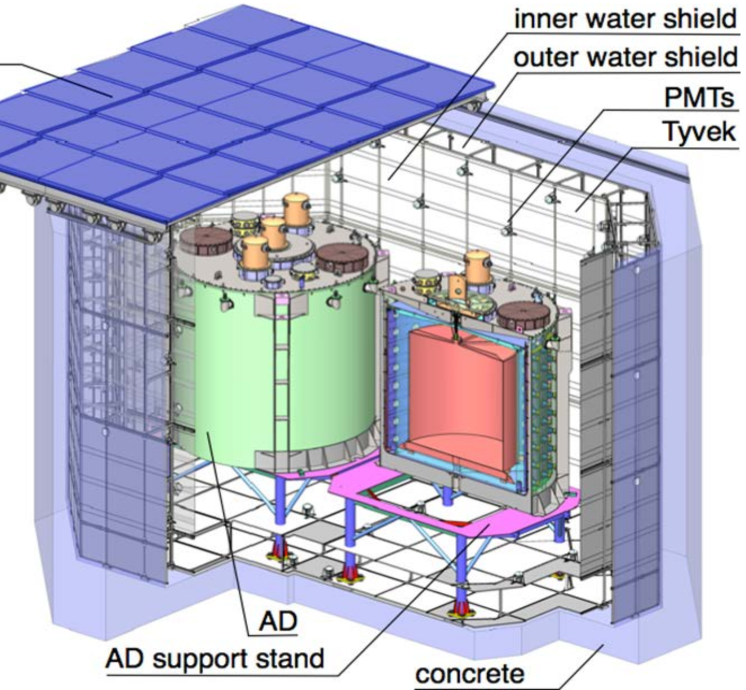
Brighter LS
Current LS ~8,000 photon/MeV
LAB based new LS ~12,000 photon/MeV

σ(2.6MeV) = 4% → ~2%
Target $\langle m_{\beta\beta} \rangle$ ~20 meV in 5 yrs

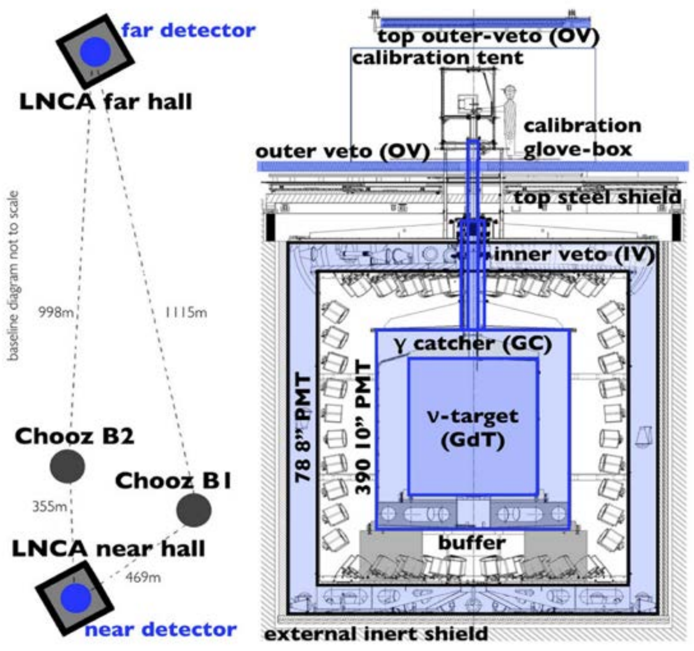
MBL -- Daya Bay, Double-Chooz and RENO

- ❖ Aimed to determine the last unknown mixing angle θ_{13}
- ❖ Near and far identical detectors help to eliminate systematic errors on absolute normalization scale
  - ➢ Daya Bay: 4 ND (~0.5 km) and 4 FD (~1.6 km), D-Chooz/RENO: 1 ND (~0.4/0.3 km) and 1 FD (~1/1.4 km)
- ❖ Similar detector structure: ν-target, γ-catcher, buffer, active μ-veto, calibration, etc
- ❖ 0.1% Gd-doped LS, similar recipe in DYB and Reno, different solvent in D-Chooz (n-dodecane/o-PXE)
- ❖ Similar Energy scales of DYB ~160 p.e./MeV, D-Chooz ~230 p.e./MeV, and RENO ~250 p.e./MeV

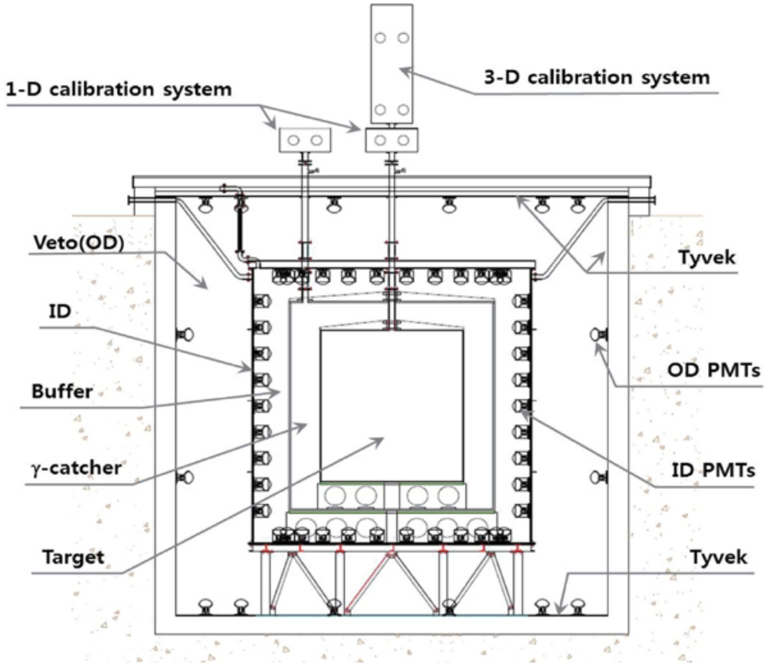
2011 - 2020



2011 - 2017

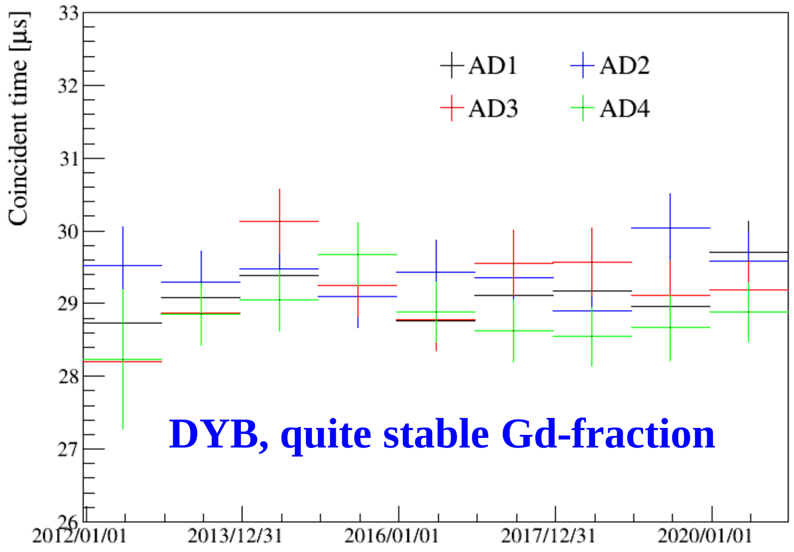


2011 - 2023

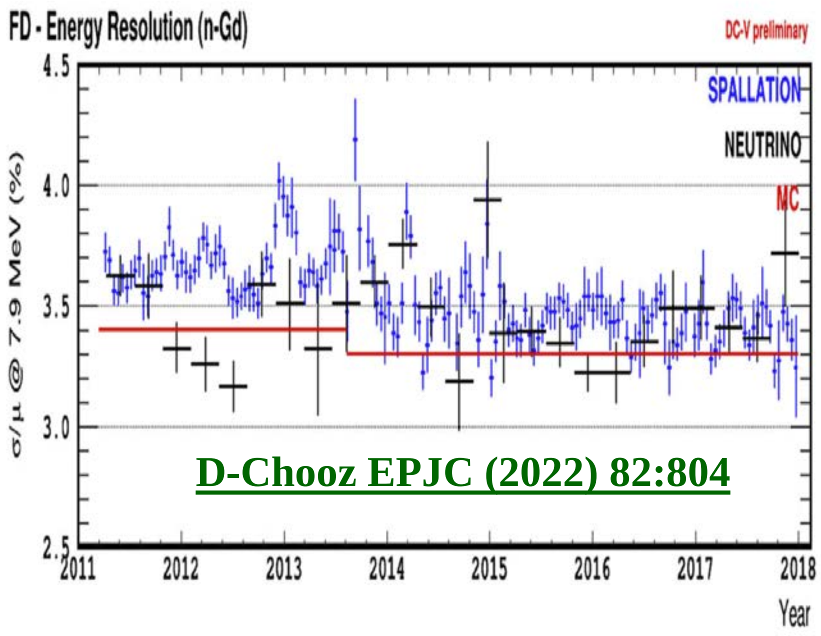


General Remarks

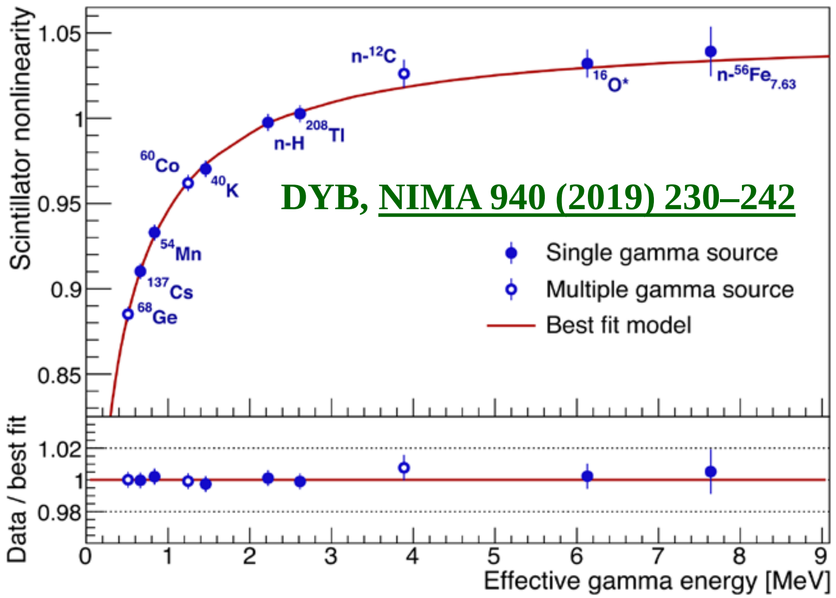
- ❖ First time to use LAB-based LS in Daya Bay and RENO, which was first proposed by M. Chen for SNO+
- ❖ A big achievement on both chemical and optical stability of Gd-LS at ~0.1% Gd level
- ❖ Very successful systematic error control on energy scale and response < 1%
- ❖ Major backgrounds: accidentals, fast n and isotopes ($^{9}Li/^{8}He$) from muons, and $^{13}C(\alpha, n)^{16}O$, S/N: ~20-30



DYB, quite stable Gd-fraction



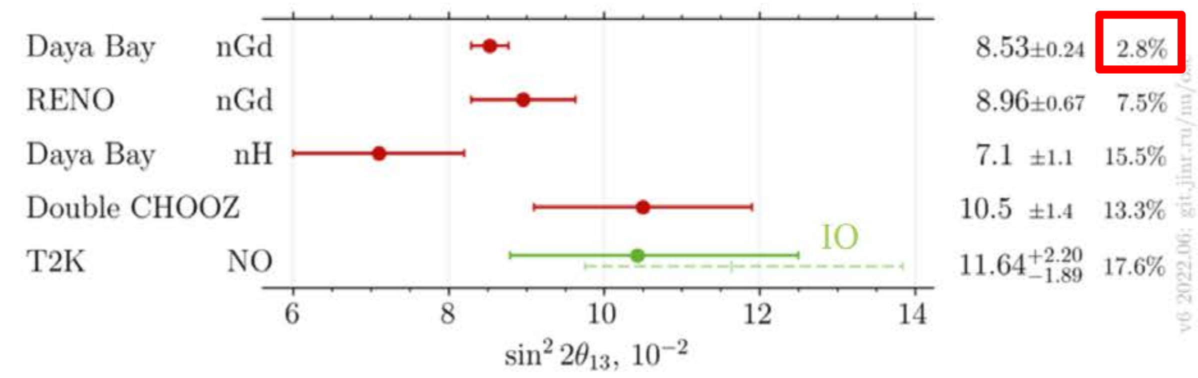
D-Chooz EPJC (2022) 82:804



DYB, NIMA 940 (2019) 230–242

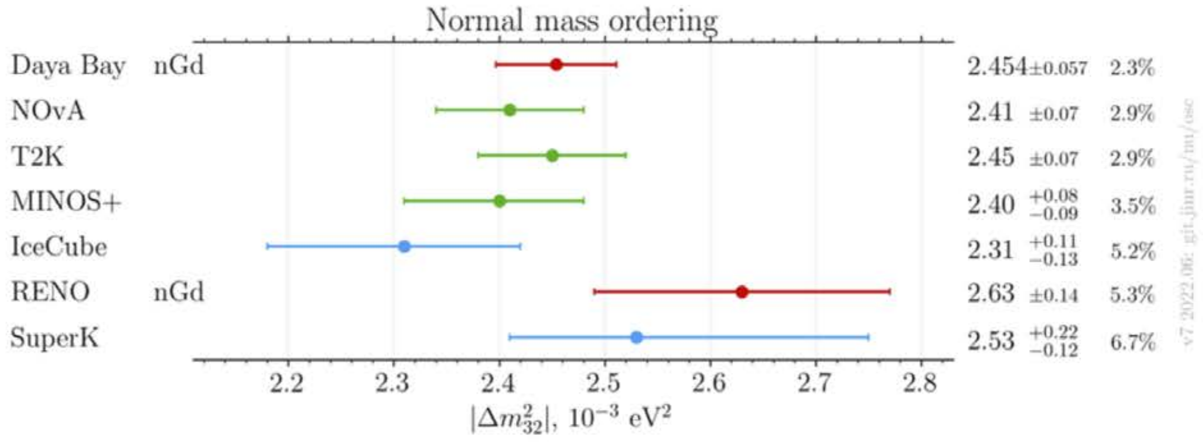
Great Precisions on Oscillation Parameters

$\sin^2 2\theta_{13}$

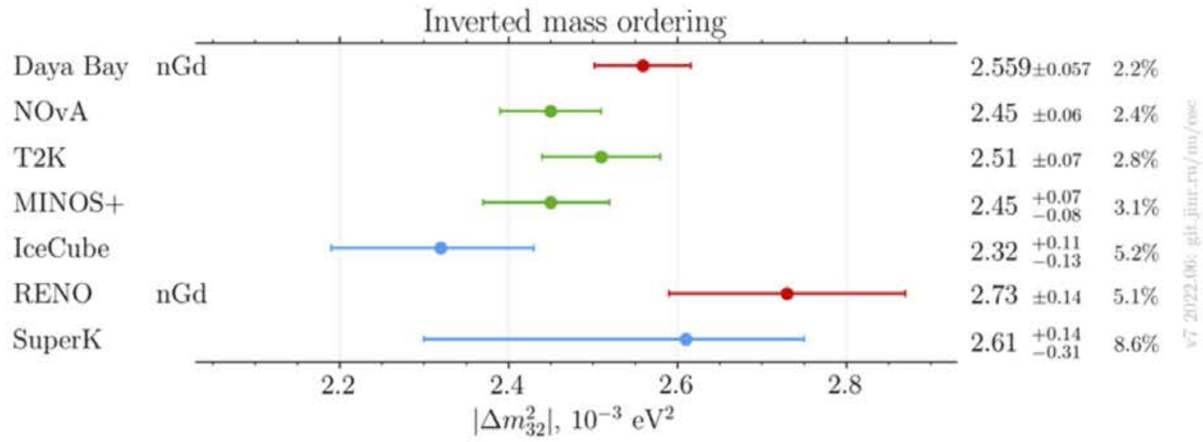


Will likely be the best measurement in the foreseeable future

Δm^2_{32} (NO)

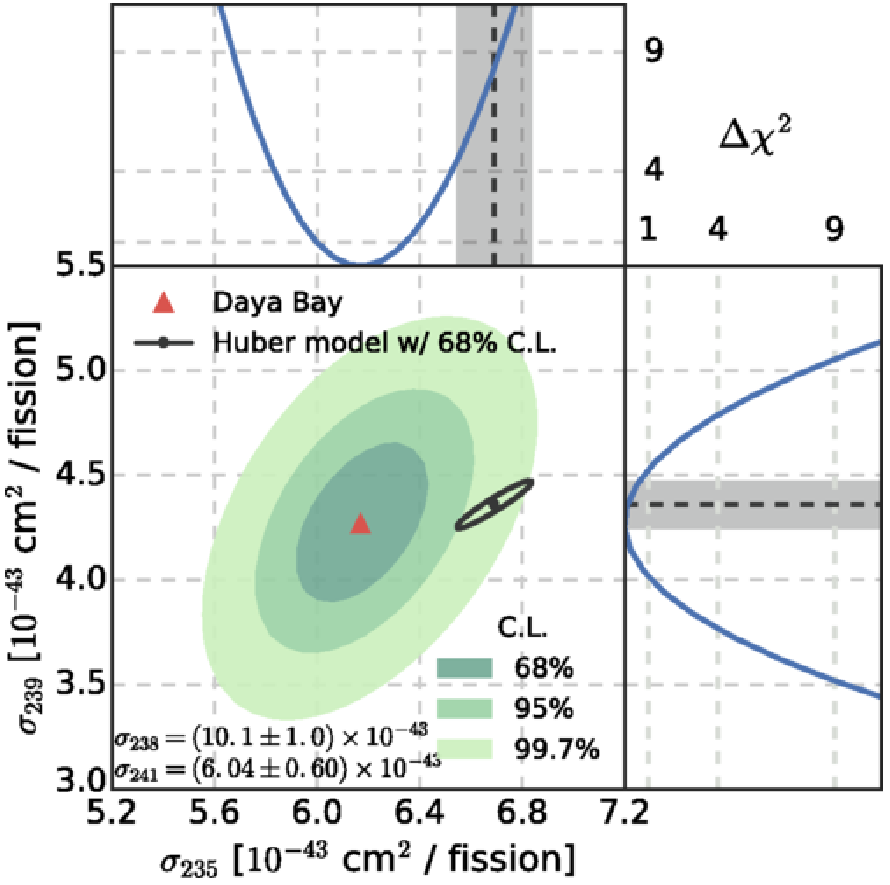


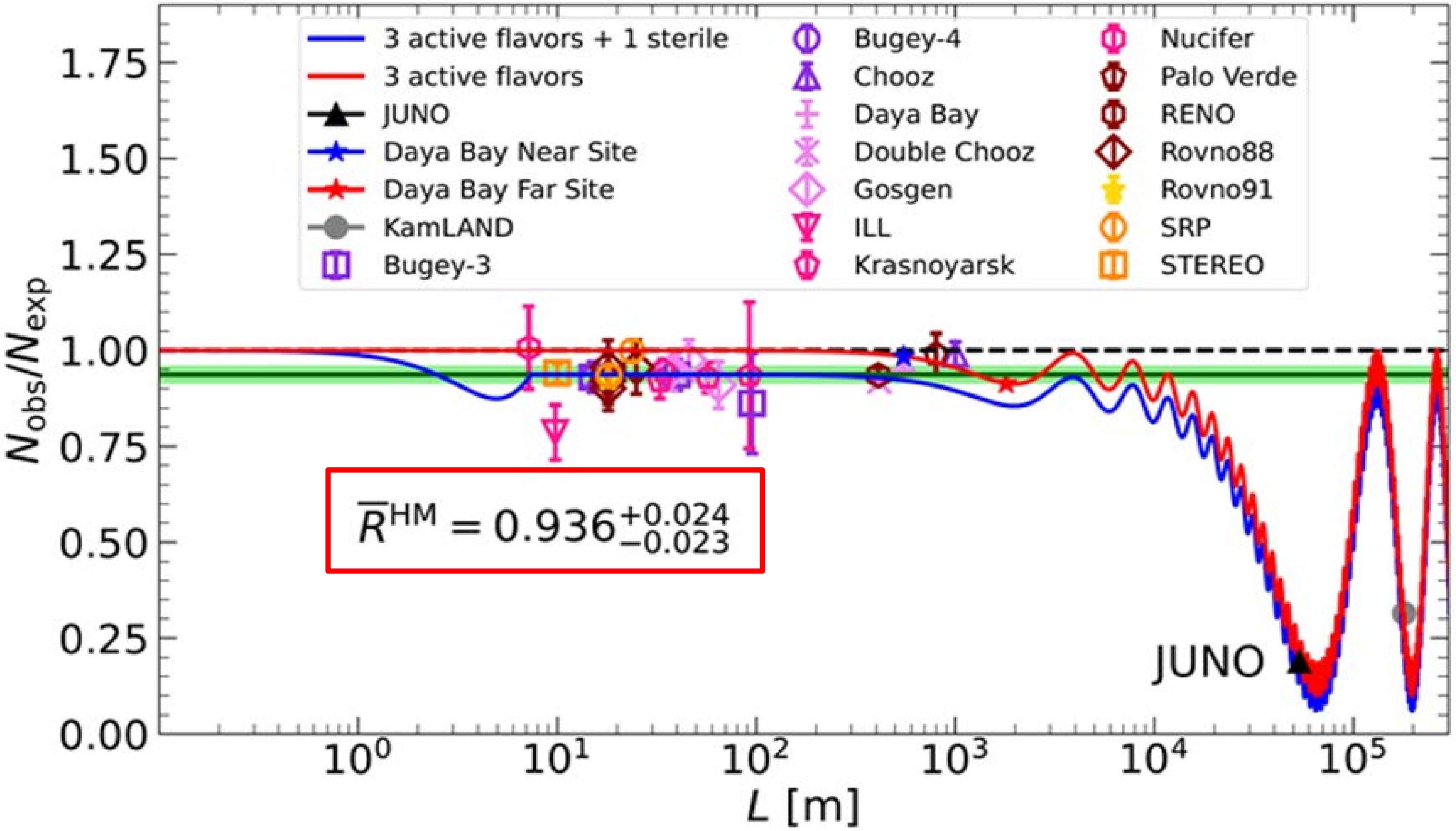
Δm^2_{32} (IO)



Kam-Biu Luk @Neutrino 2022

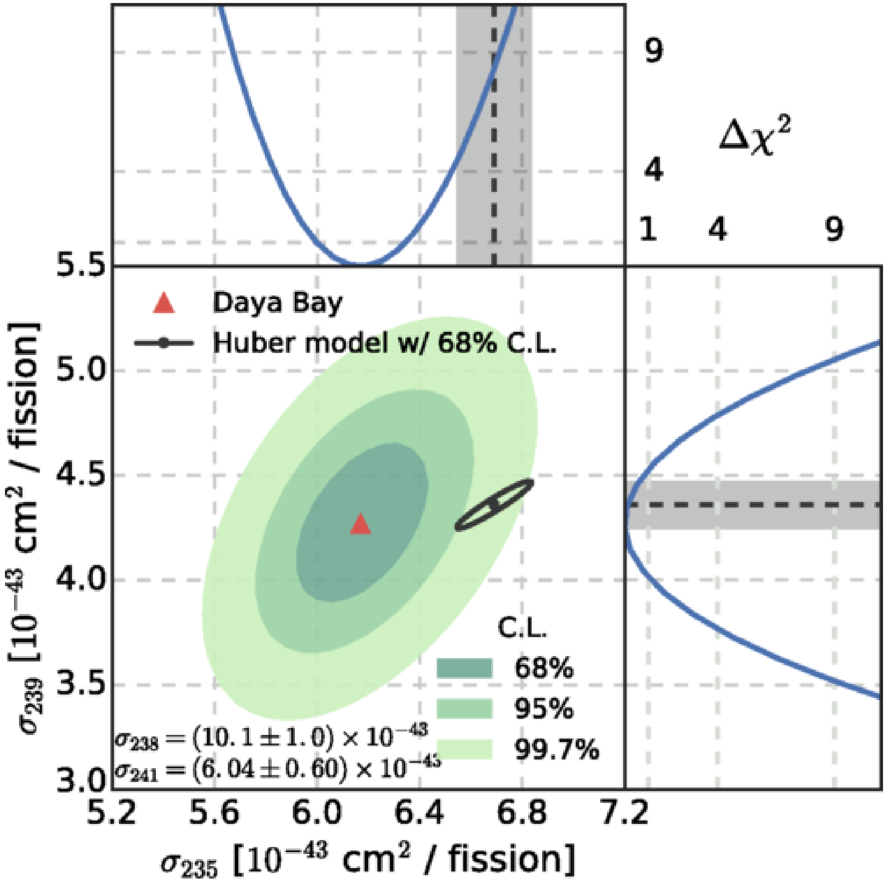
Precise Measurements on Reactor Neutrino Flux

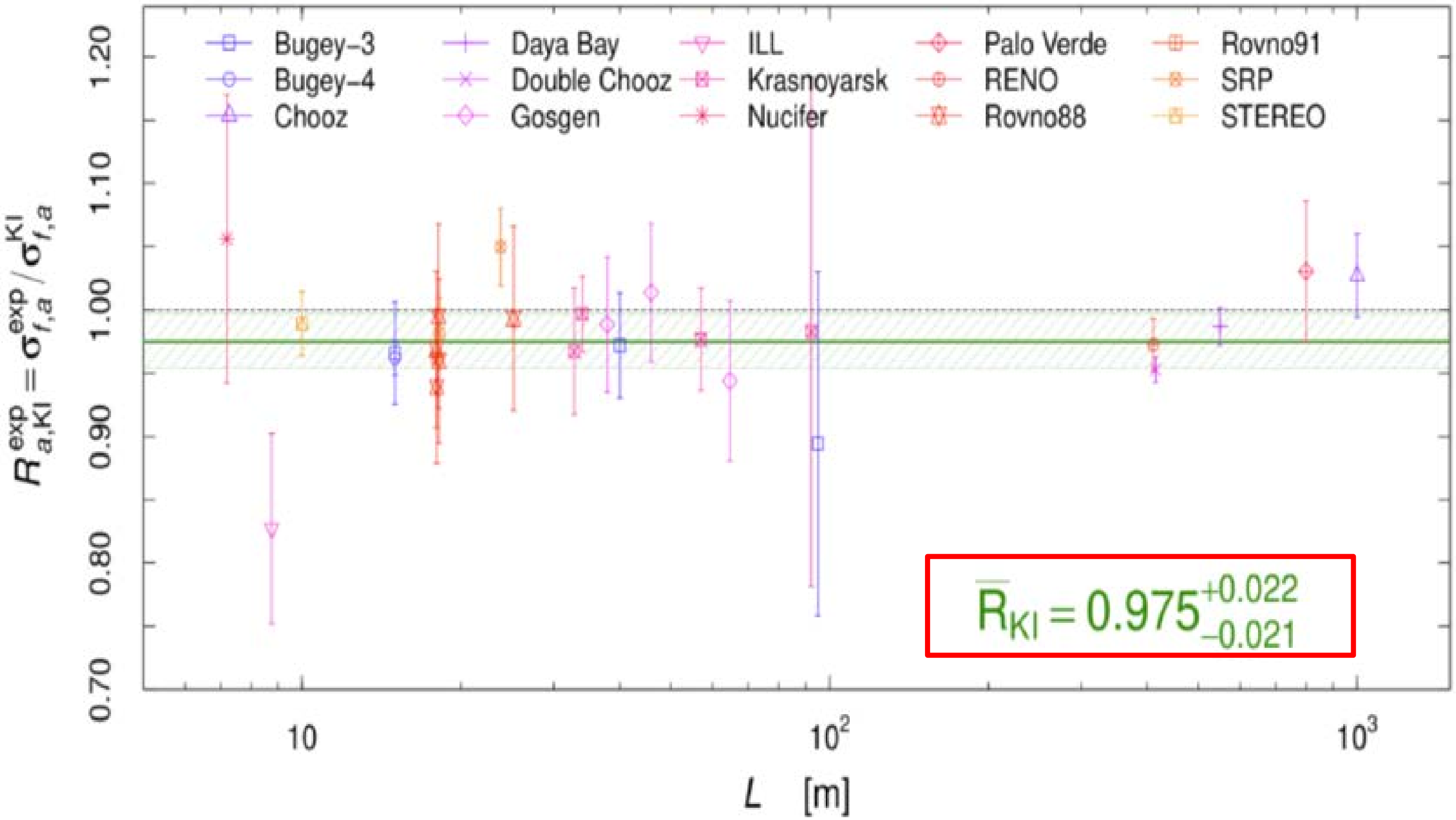




- ❖ Daya Bay reported that the flux deficit is mostly from ^{235}U, confirmed by others [PRL 118, 251801 (2017)]
- ❖ Current reactor neutrino flux calculations show no deficit, but the 5 MeV bump is still there (next slide)
  - ➢ Summation with improved nuclear data [PRL 123, 022502 (2019)]
  - ➢ Conversion with recent ^{235}U/^{239}Pu fission beta ratio measurements [Phys. Atom. Nucl. 84 1–10, PRD 104, L071301 (2021), etc]

Precise Measurements on Reactor Neutrino Flux





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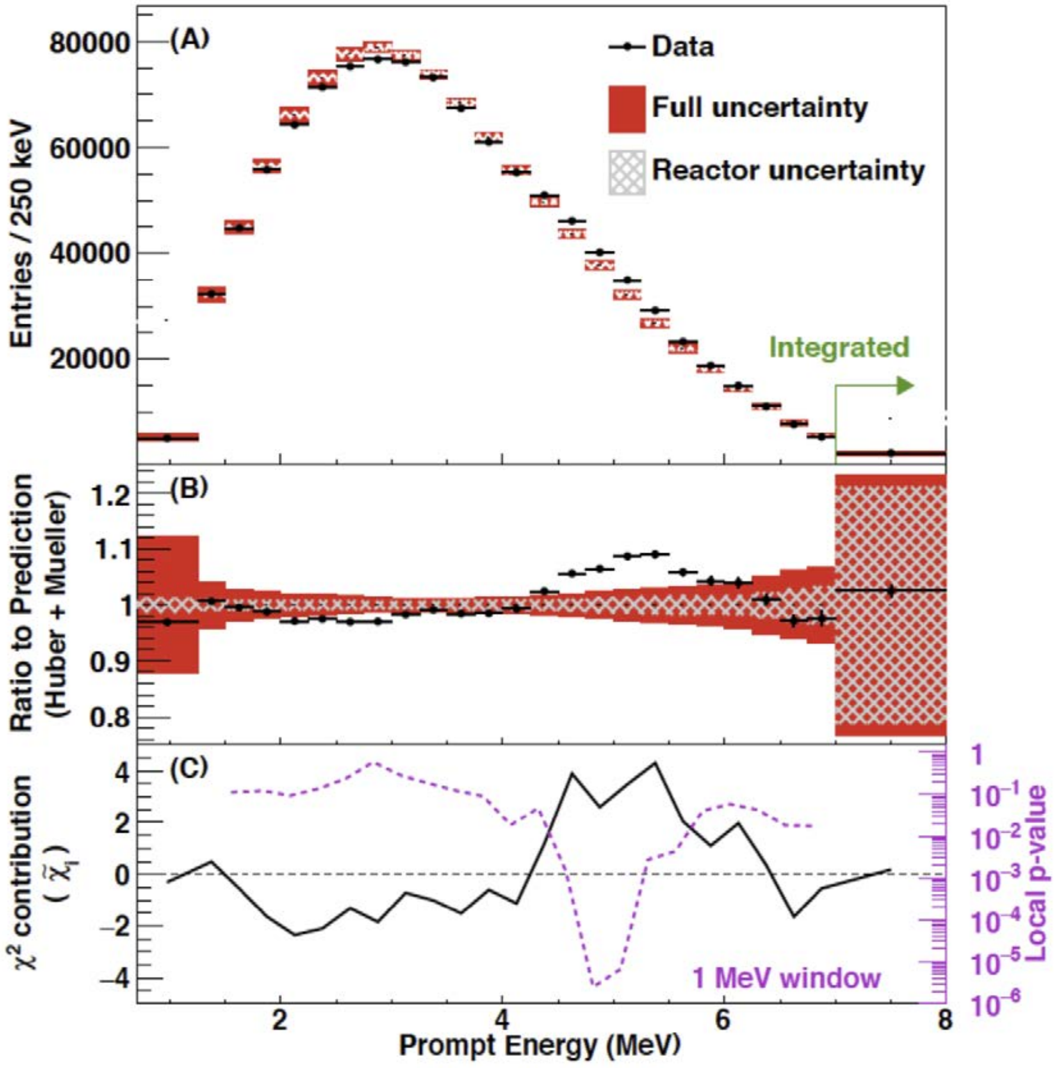
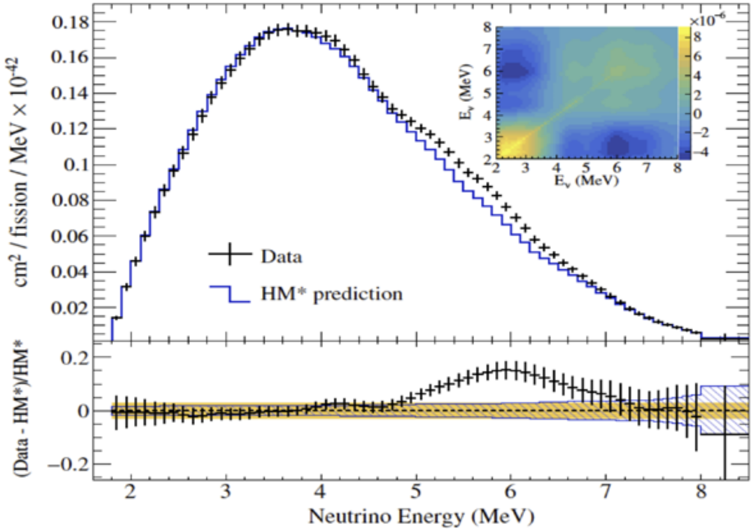
Spectrum Anomaly (5 MeV bump)

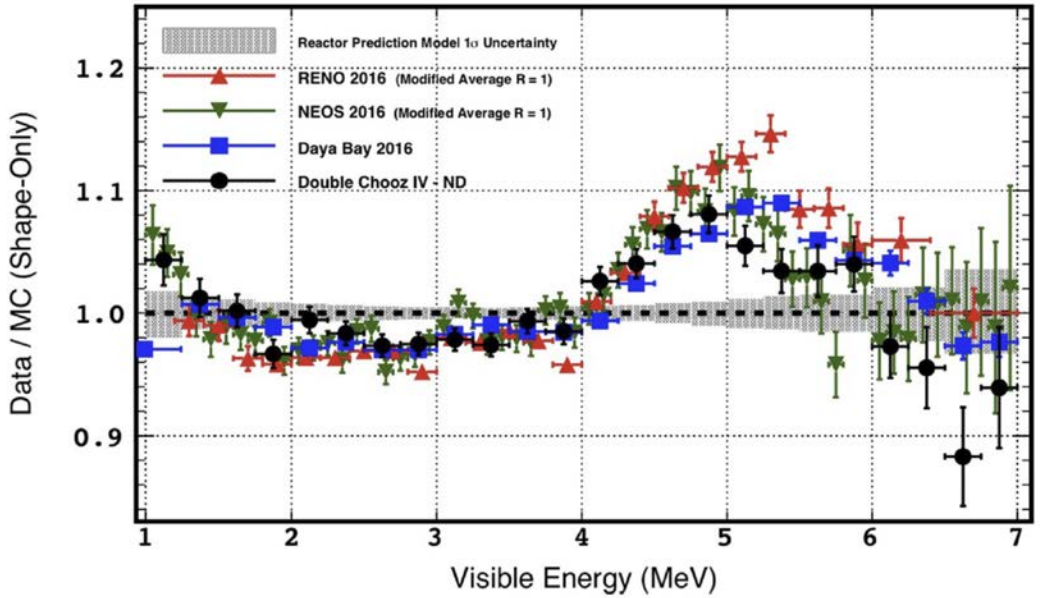
N. Bowden @Neutrino 2022



Daya Bay, [CPC, 2017, 41(1): 13002]

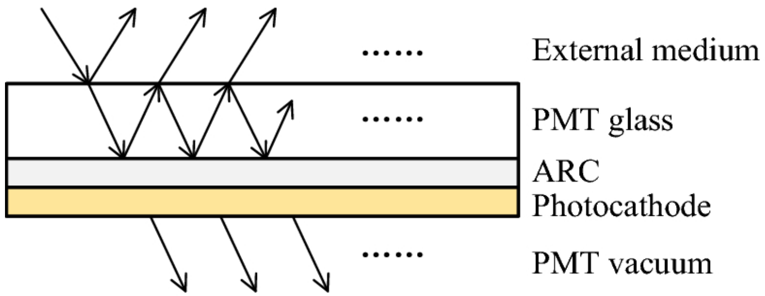


RENO, [PRD 104, L111301 (2021)]

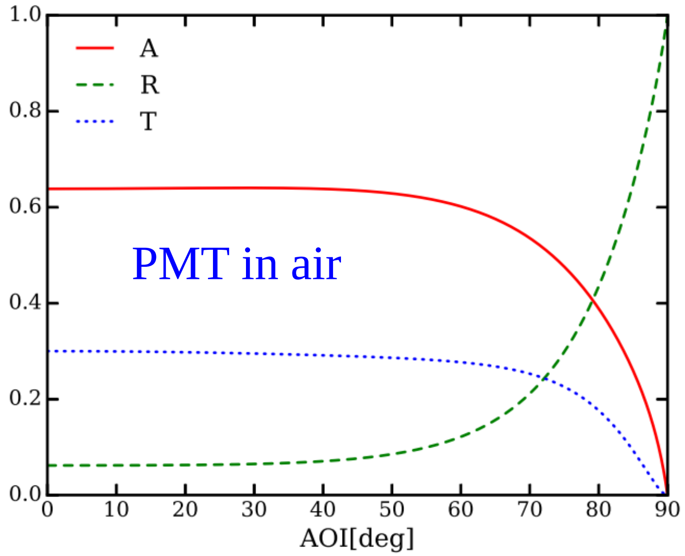


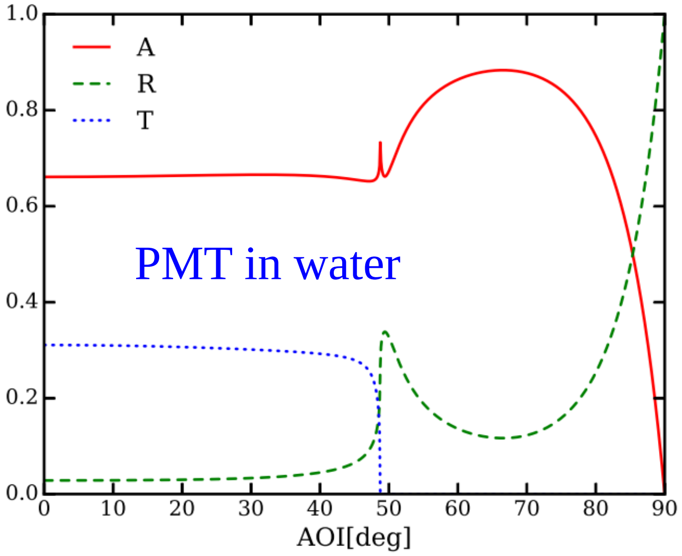
From Double Chooz, [Nature Phys. 16 (2020) 558]

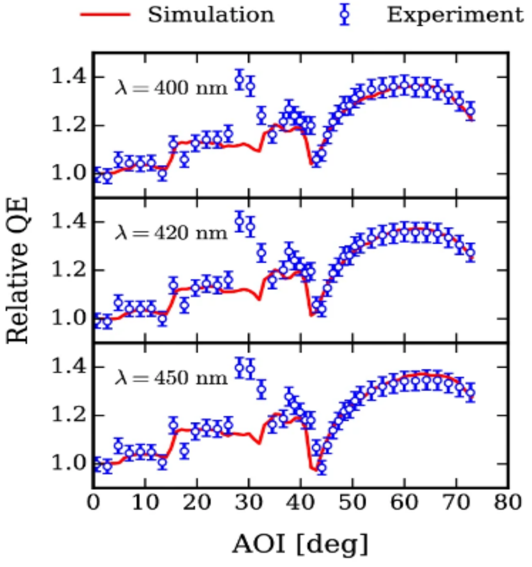
Light Yield Puzzle?



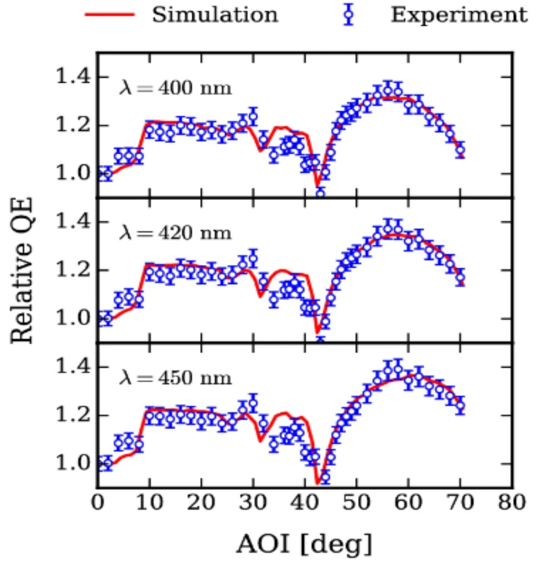
- ❖ 20~30% higher light yield than expectations when turned on the detector
  - ➢ Daya Bay: ~20%, RENO: ~21%, KamLAND: ~80%, Borexino: ~25%, etc
- ❖ A recent study [EPJC (2022) 82:329] indicates that this might be caused by the usage of the simplified PMT model
  - ➢ A simplified model: photons absorbed by photocathode converted to p.e. by QE measured in air
  - ➢ The new proposed model predicts 20% to 30% more light yield, consistent with observations
  - ➢ More excess in KamLAND is caused by scattering and re-emission







(a) Hamamatsu PMT



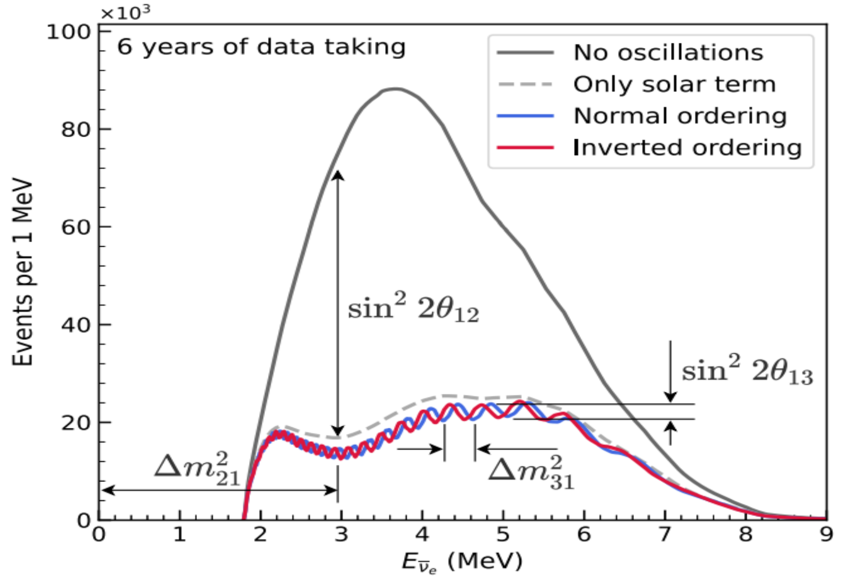
(b) NNVT high-QE PMT

Jiangmen Underground Neutrino Observatory (JUNO)

- Proposed to determine **Neutrino Mass Ordering (NMO)** via detecting reactor neutrinos
  - Independent of the CP phase, and the large θ_{13} makes it easier
- Critical requirements to make it to be realized
  - Site selection → optimum baseline (oscillation maximum of θ_{12})
  - Sufficient statistics → large LS detector and powerful reactors
  - Good E resolution → highly transparent LS and high LY, highly efficient PMTs and high coverage
  - Shape uncertainty → satellite detector (TAO) provides reference spectrum, comprehensive calibration system
  - Low BKG → good overburden, highly efficient veto and shielding, material screening, clean installation

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2\frac{\Delta m^2_{21} L}{4E} - \frac{1}{2}\sin^2 2\theta_{13}\left[\sin^2\frac{\Delta m^2_{31} L}{4E} + \sin^2\frac{\Delta m^2_{32} L}{4E}\right] \boxed{- \frac{1}{2}\cos 2\theta_{12}\sin^2 2\theta_{13}\sin\frac{\Delta m^2_{21} L}{4E}\sin\frac{(\Delta m^2_{31} + \Delta m^2_{32}) L}{4E}}$$

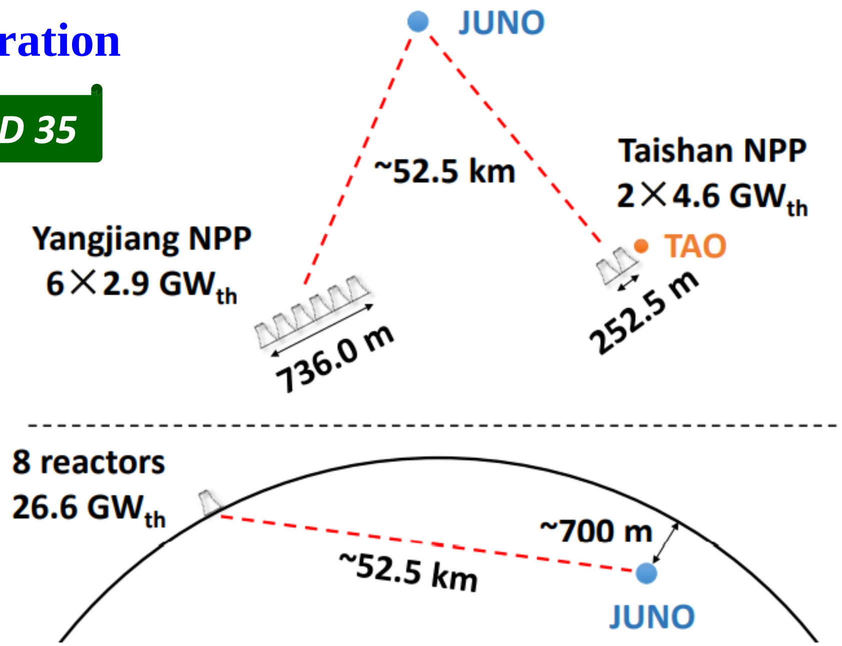
Sensitive to mass ordering



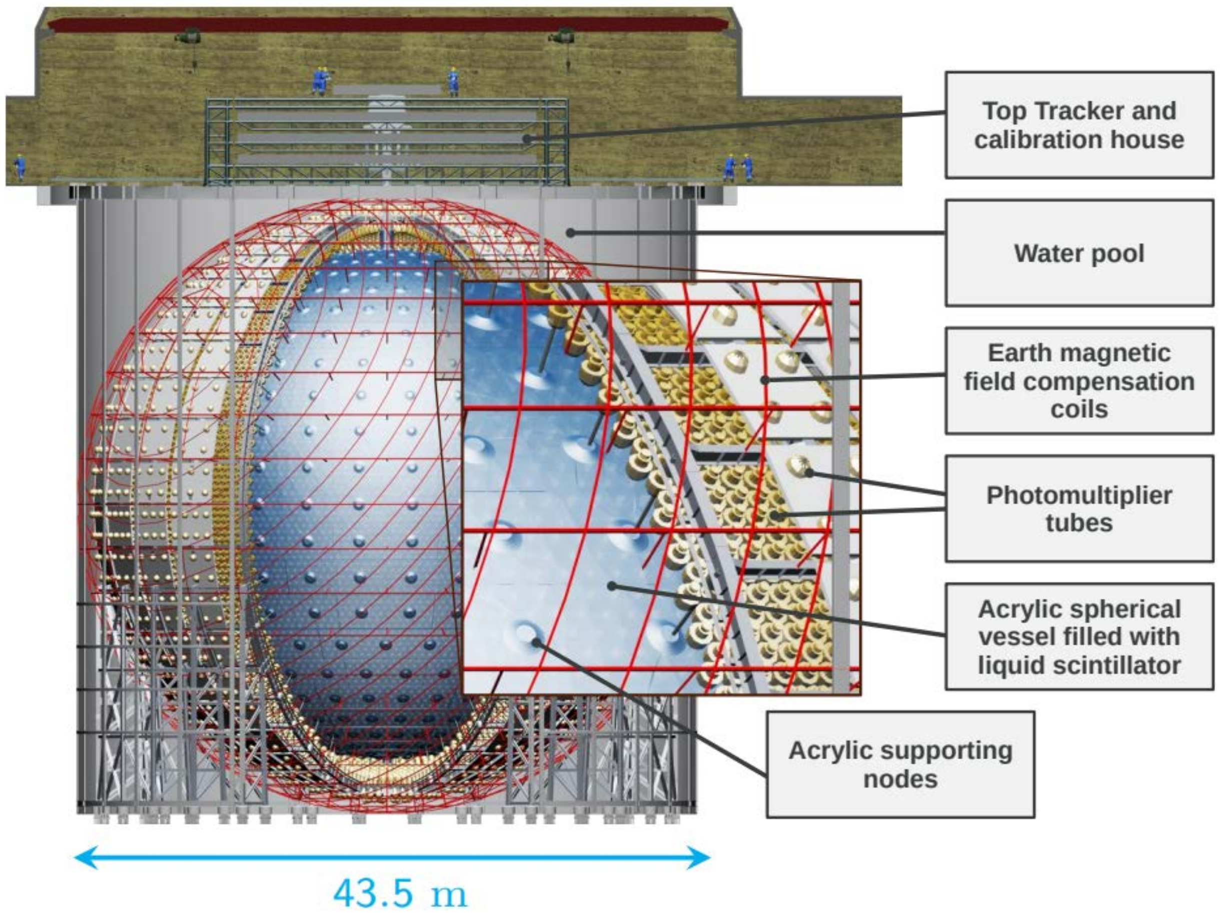
JUNO Detector – a 20k ton LS detector

- ❖ **52.5 km baseline, ~700 m overburden**
- ❖ **Central Detector**
  - ➢ **20 kton LAB-based liquid scintillator**
  - ➢ **Acrylic panels, 265 pieces in total, bonding onsite**
  - ➢ **~45,000 20”+3” PMTs with 78% coverage**
  - ➢ **Stainless Steel structure**
  - ➢ **Calibration**

Contribution ID 35



- ❖ **Veto detectors** ***Contribution ID 92***
  - ➢ **Water Pool (2400 20-inch PMTs)**
  - ➢ **Top Tracker (plastic scintillators)**



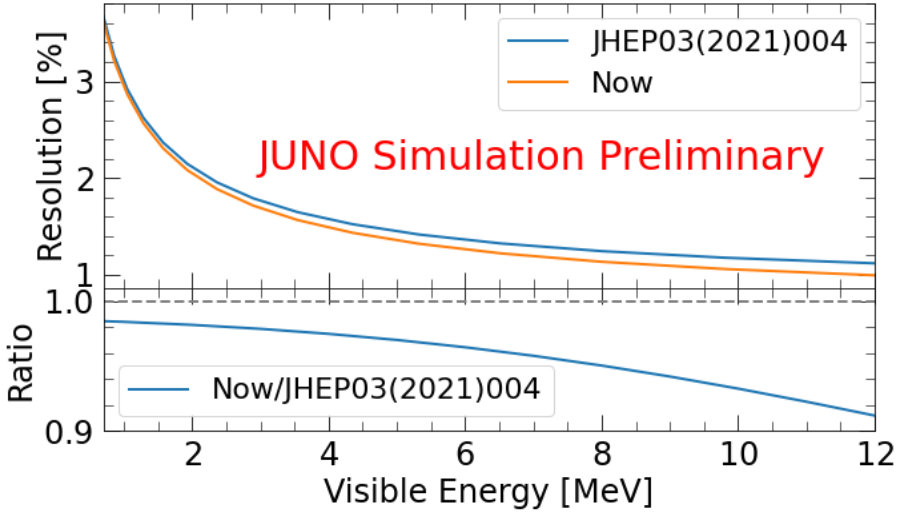
Predicted Energy Resolution in JUNO

Change	Light yield in detector center [PEs/MeV]	Energy resolution	Reference
Previous estimation	**1345**	**3.0% @1MeV**	***JHEP 03 (2021) 004***
Photon Detection Efficiency (27%→30%)	**+11%↑**		***EPJC 82 1168 (2022)***
New Central Detector Geometries	**+3%↑**	**2.9% @ 1MeV**	
New PMT Optical Model	**+8%↑**		***EPJC 82 329 (2022)***

Positron energy resolution is understood:

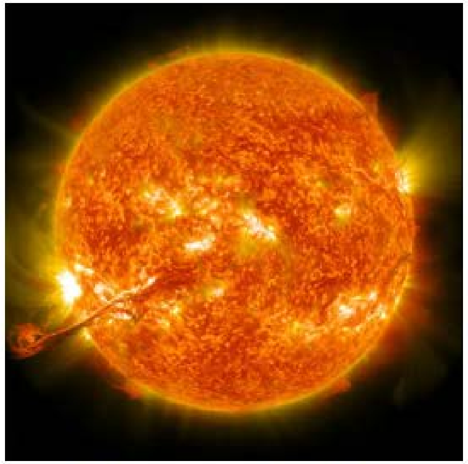
$$\frac{\sigma}{E_{\rm vis}} = \sqrt{\left(\frac{a}{\sqrt{E_{\rm vis}}}\right)^2 + b^2 + \left(\frac{c}{E_{\rm vis}}\right)^2}$$

- **Photon statistics**
- **Annihilation-induced γs**
- **Dark noise**
- **Scintillation quenching effect**
  - LS Birks constant from table-top measurements
- **Cherenkov radiation**
  - Cherenkov yield factor (refractive index & re-emission probability) is re-constrained with Daya Bay LS non-linearity
- **Detector uniformity and reconstruction**

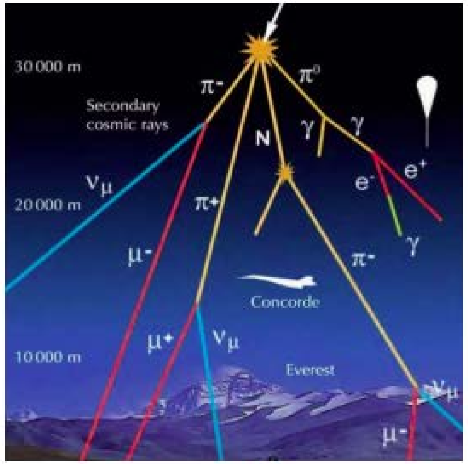


A Rich Physics Program in JUNO

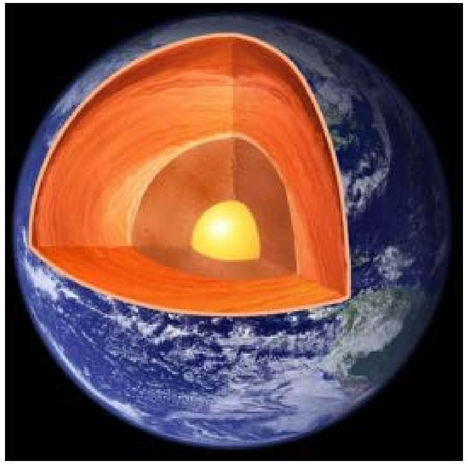
$\sim 50/\text{day}$



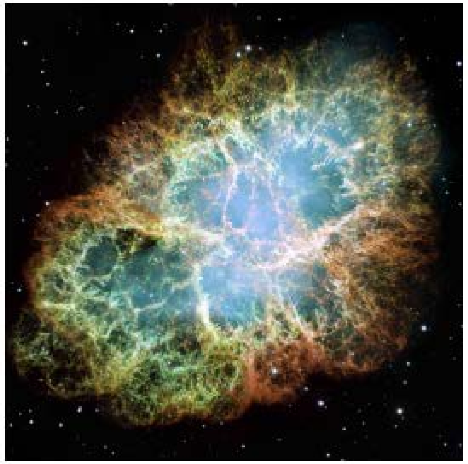
$\mathcal{O}(1000)/\text{day}$



$\sim 10/\text{day}$



$\sim 1 - 2/\text{day}$



CCSN @10kpc : $\mathcal{O}(1000)/\text{s}$
DSNB: few/year

New Physics

Proton decay
etc

- **NMO sensitivity: 3σ in 6 years**
- **Determine most of oscillation parameters to a sub-percent level**
  - **Chinese Phys. C 46 123001 (2022)**

	Current (PDG2020)	JUNO (100 d)	JUNO (6 y)
Δm^2_{31} Δm^2_{32}	1.3%	0.8%	0.2%
Δm^2_{21}	2.4%	1.0%	0.3%
$\sin^2\theta_{12}$	4.2%	1.9%	0.5
$\sin^2\theta_{13}$	3.2%	47.9%	12.1%

- **More refer to Prog. Part. Nucl. Phys. 123, (2022) 103927**

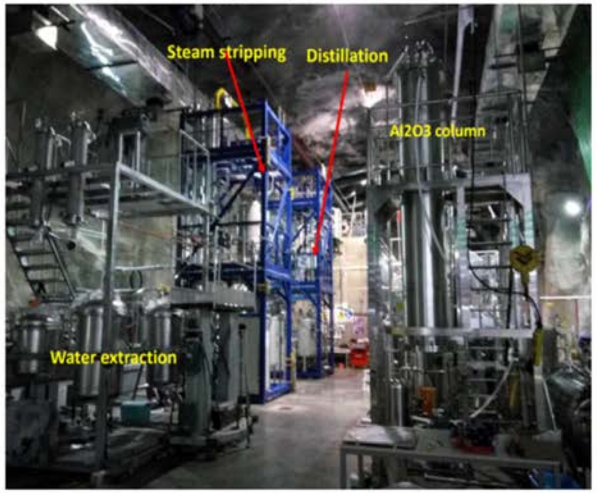
Contribution ID 50

Contribution ID 95

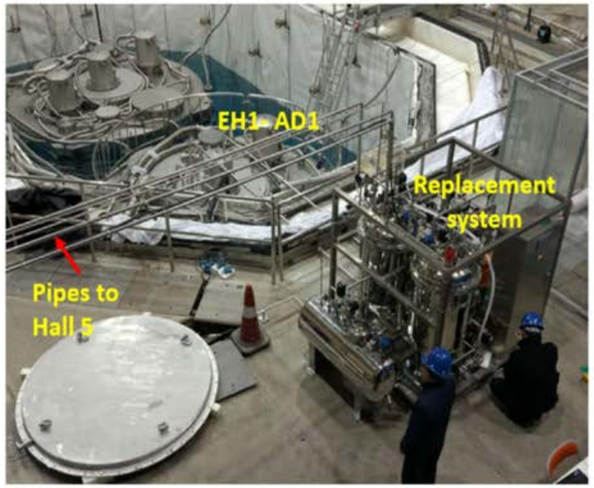
JUNO LS Cocktail

JUNO&Daya Bay, NIMA 988 (2021) 164823

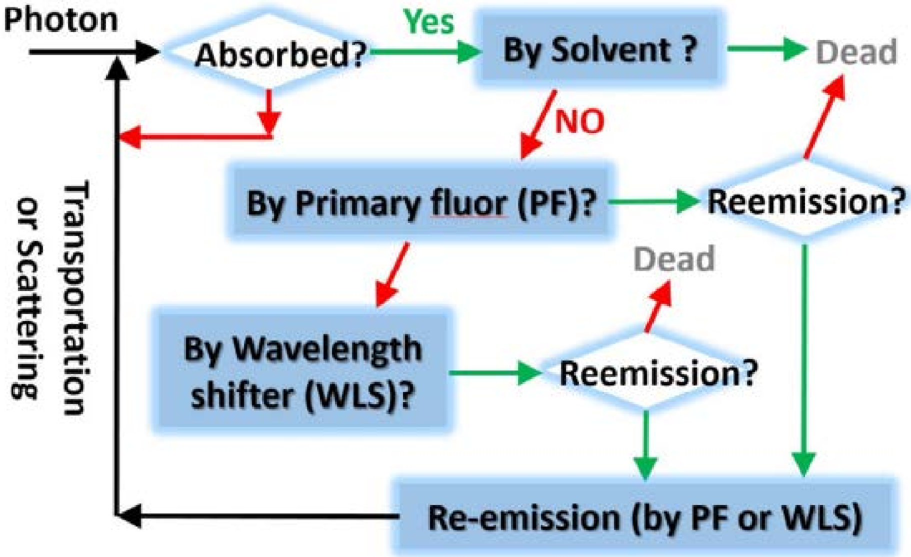
LS pilot plant at Hall 5

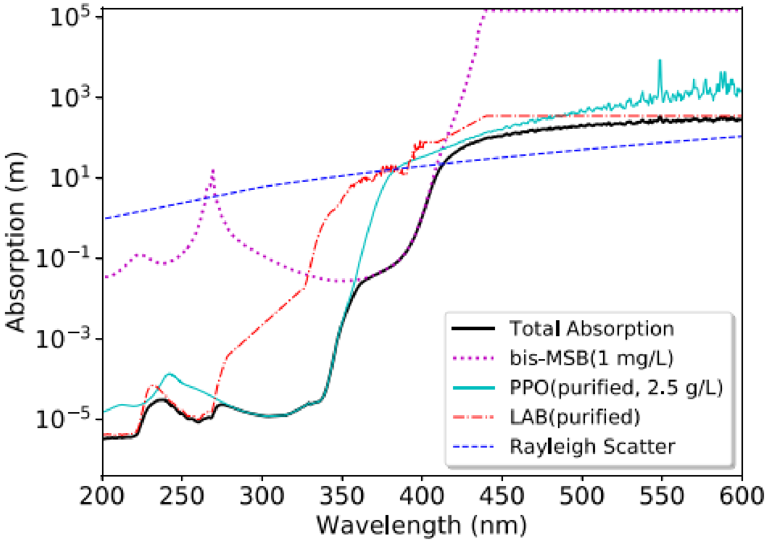


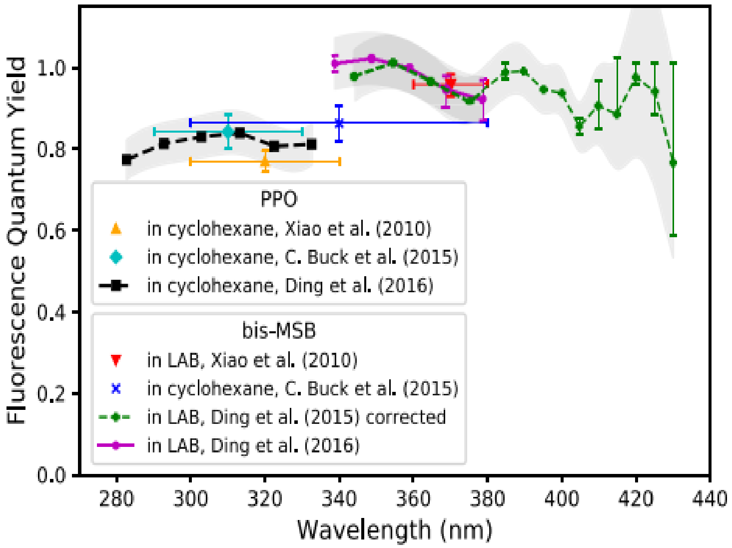
Experimental Hall 1



- ❖ High transparency and low radioactivity → No Gd
- ❖ Use one Daya Bay AD to optimize JUNO LS recipe
- ❖ A newly developed optical model used to consider the detector size difference (35 m vs 4 m) [NIM A 967 (2020) 163860]
  - ➢ Model absorption and re-emission processes in LS
  - ➢ Key inputs include absorption, scattering, re-emission, etc



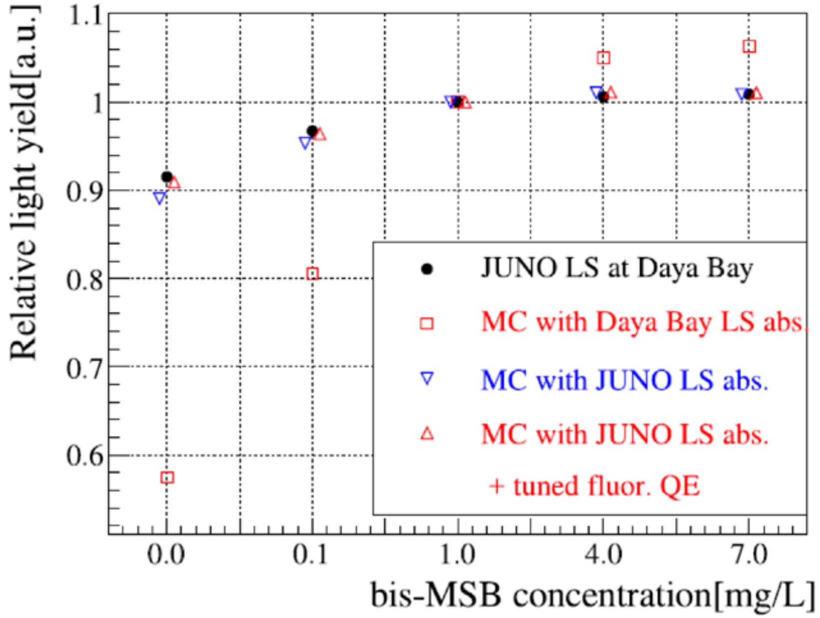


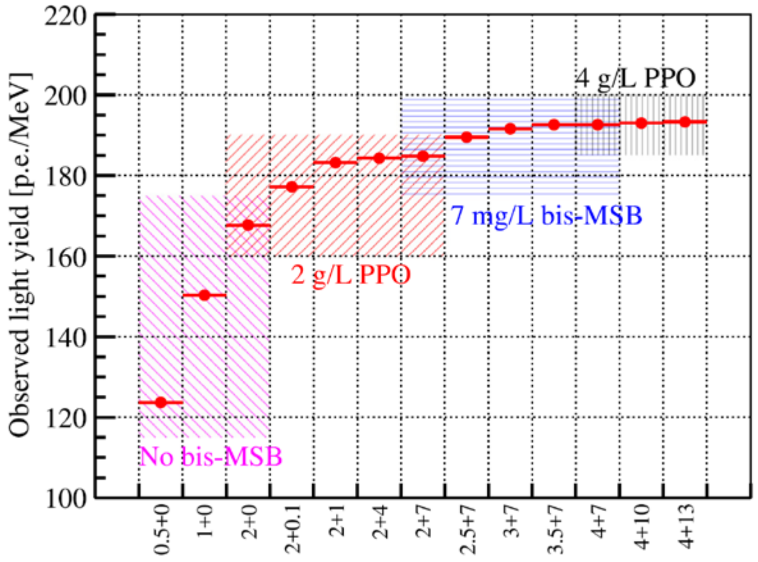


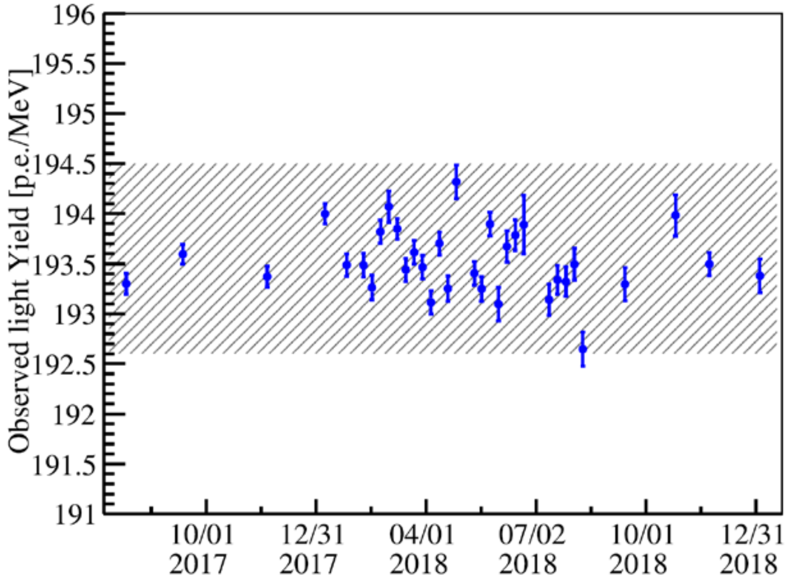
Final Solution of JUNO LS Cocktail

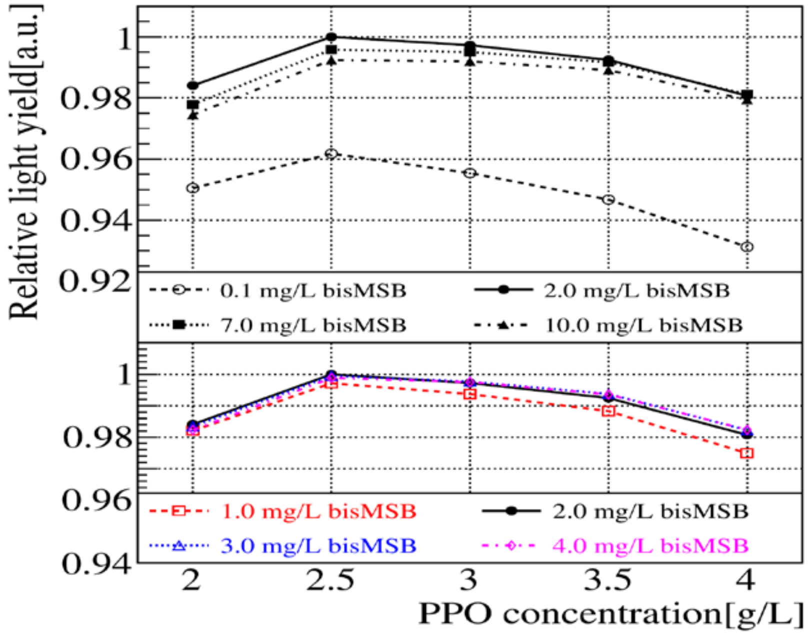
- ❖ **Different LS recipes were checked by the DYB detector**
- ❖ **Good agreements between the LS model and data taken at Daya Bay**
- ❖ **Final solution: LAB + 2.5 g/L PPO + 3 mg/L bis-MSB**
- ❖ **The LS recipe showed the good stability**

JUNO&Daya Bay, NIMA 988 (2021) 164823









Th/U in 35.4 ton PPO (60 ton in total)

Determination of Th&U in PPO

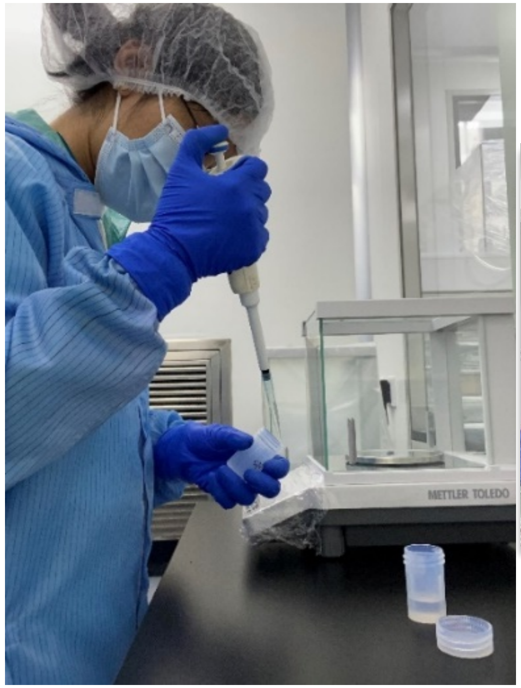
Method detection limit (ICP-MS):

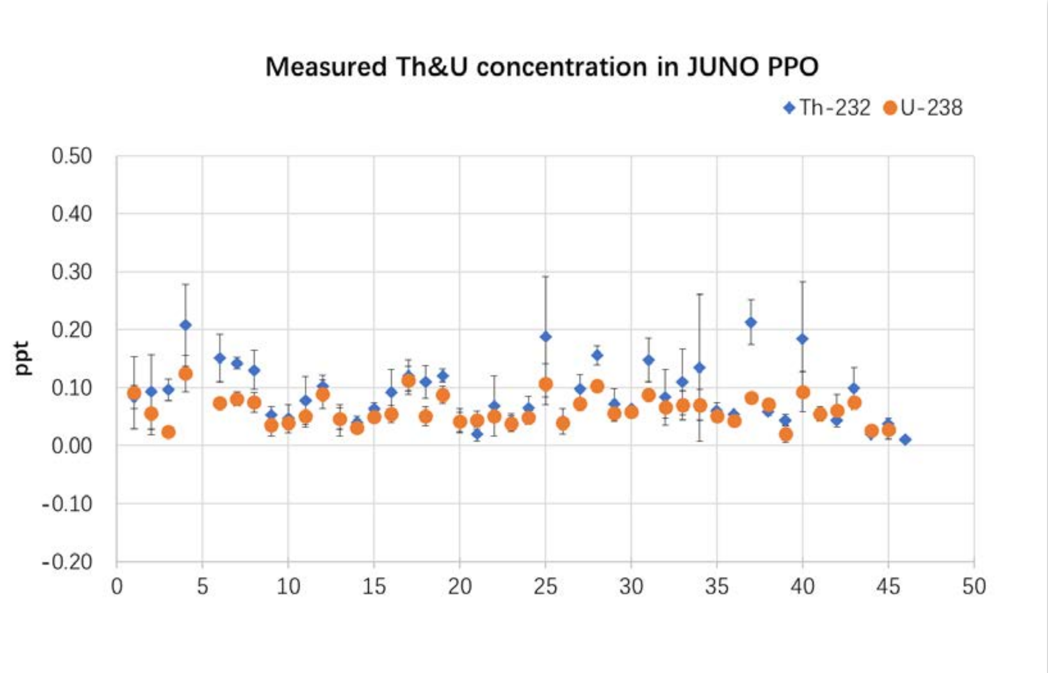
- 0.033 ppt for ^{232}Th
- 0.040 ppt for ^{238}U

M. Liu, Y. Ding* et al., NIM A 1041 (2022) 167323

Mass weighted mean value for 35.4t PPO from ~45 batches

^{232}Th/^{238}U ~ 0.1 ppt





JUNO LS Purification

NIM A 908 (2021) 164823

Four purification plants to achieve target radio-purity 10^{-17} g/g U/Th and 20 m attenuation length at 430 nm

5000 m^3 LAB tank

Al_2O_3 to remove particles

Distillation to remove radioactive impurities

Add 2.5 g/L PPO and 3 mg/L bis-MSB

SS pipes to underground

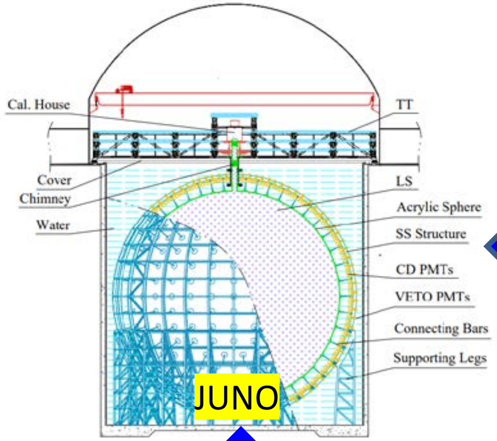
Joint commissioning of all LS plants will start in this autumn

Water extraction to remove radioactive impurities

Gas stripping to remove Rn and O_2

15%

OSIRIS for LS qualification



JUNO

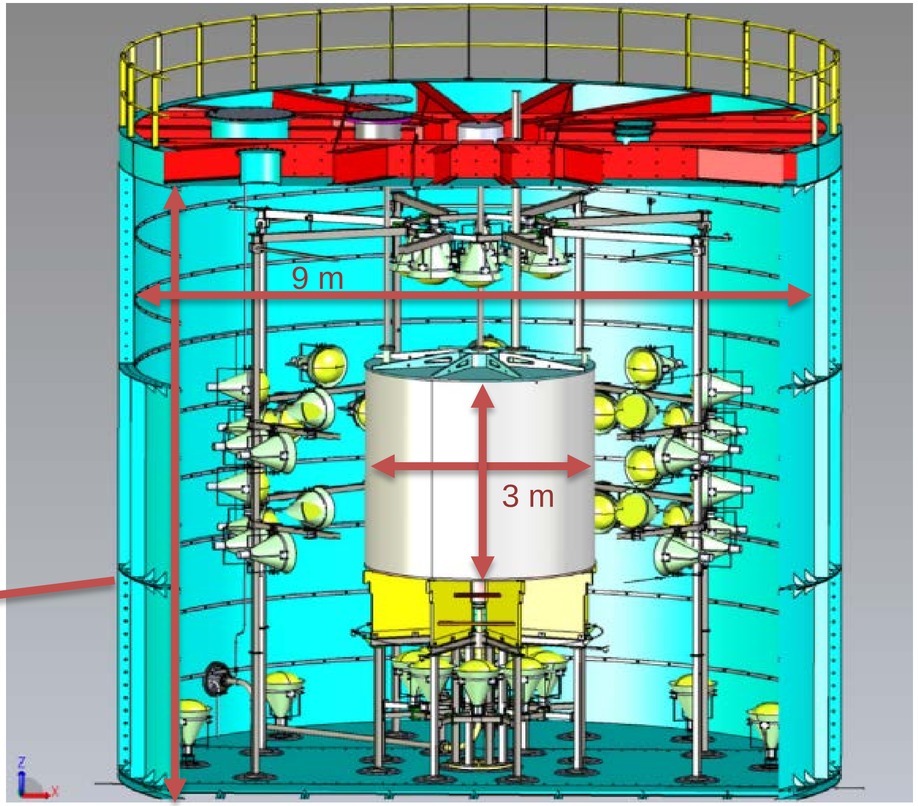
85%

Contribution ID 35

Online Scintillator Internal Radioactivity Investigation System (OSIRIS)

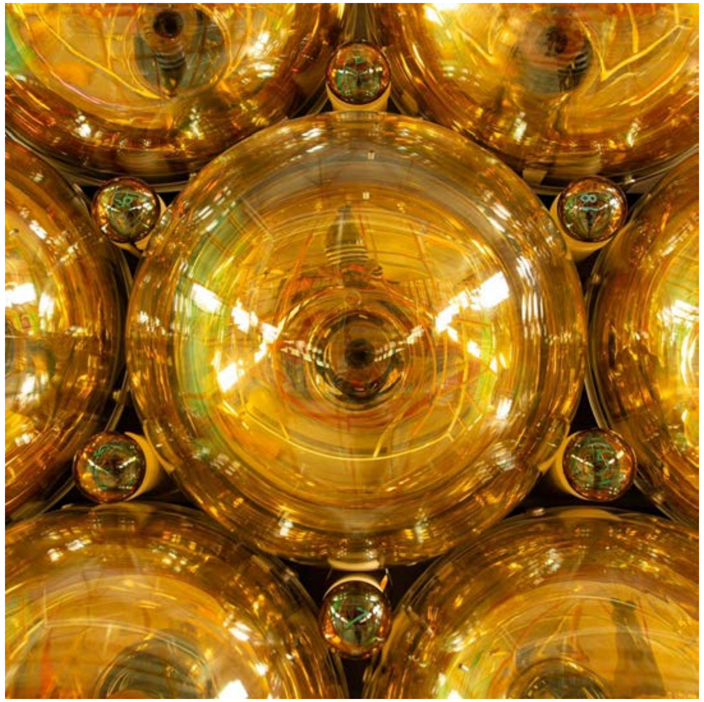
[Eur.Phys.J.C 81 (2021) 11, 973]

- **A 20t detector to monitor radiopurity of LS before and during filling to the central detector**
  - **A few days**: U/Th (Bi-Po) ~ **1 × 10^{-15} g/g** (reactor baseline case)
  - **2~3 weeks**: U/Th (Bi-Po) ~ **1 × 10^{-17} g/g** (solar ideal case)
  - Other radiopurity can also be measured: ^{14}C, ^{210}Po and ^{85}Kr
- **Commissioning will start soon**

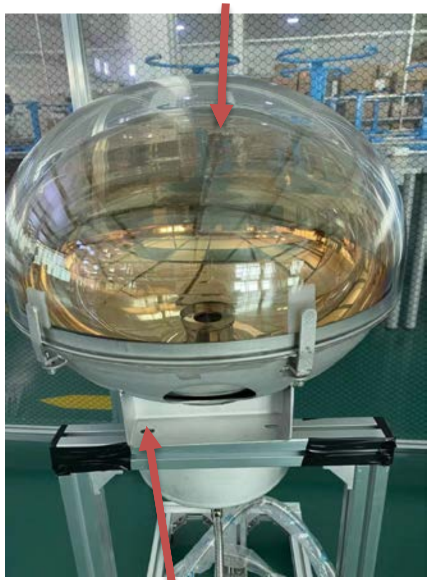


- **Possible upgrade to Serappis (SEarch for RAre PP-neutrinos In Scintillator)** [arXiv: 2109.10782]
  - **A precision measurement of *pp* solar neutrino flux on the few-percent level**

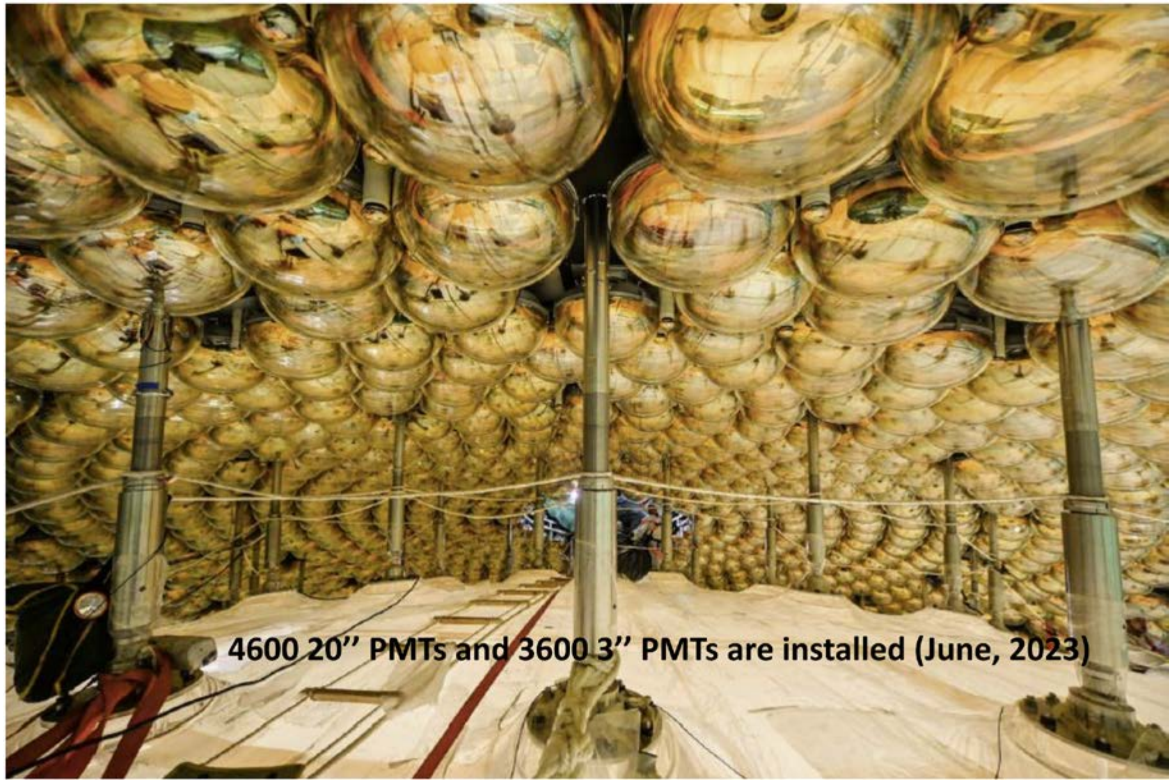
- **17612 20-inch PMTs (75% coverage) in CD, 2400 20-inch PMTs in the veto detector** *Contribution ID 97*
  - **15012 20-inch MCP-PMTs, produced by NNVT, with higher PDE**
  - **5000 20-inch dynode PMTs from Hamamatsu, with better TTS**
- **25,600 3-inch PMTs (3% coverage) in CD to ensure energy resolution and charge linearity** *Contribution ID 91*
- **All PMTs have been produced, tested, and instrumented with waterproof potting**



Acrylic cover



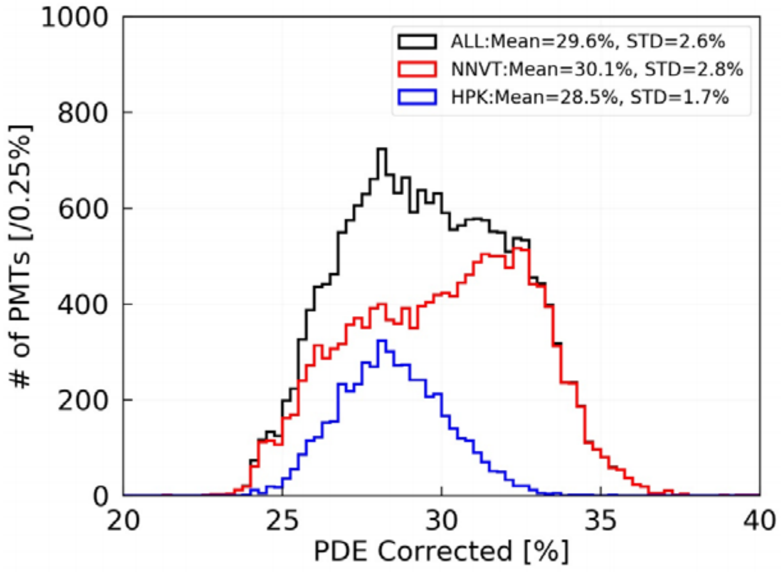
Stainless Steel cover



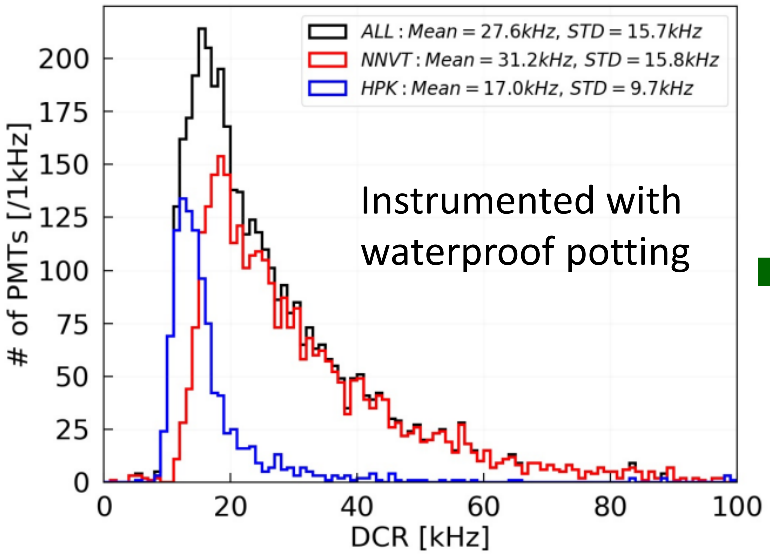
Clearance between PMTs: 3 mm → Assembly precision: < 1 mm

PMT Performance

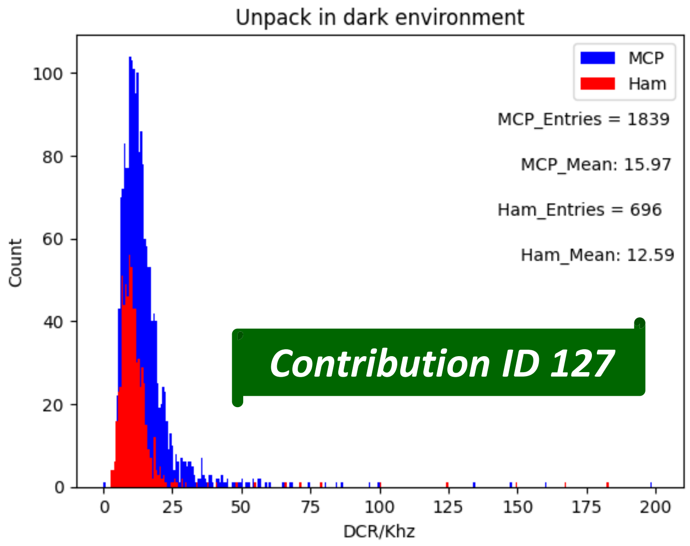
Photon Detection Efficiency, PDE



Dark Counting Rate, DCR



		LPMT (20-inch)		SPMT (3-inch)
		Hamamatsu	NNVT	HZC
Quantity		5000	15012	25600
Charge Collection		Dynode	MCP	Dynode
Photon Detection Efficiency		28.5%	30.1%	25%
Mean Dark Count Rate [kHz]	Bare	15.3	49.3	0.5
	Potted	17.0	31.2	
Transit Time Spread (σ) [ns]		1.3	7.0	1.6
Dynamic range for [0-10] MeV		[0, 100] PEs		[0, 2] PEs
Coverage		75%		3%
Reference		Eur. Phys. J. C (2022) 82:1168		NIM.A 1005 (2021) 165347



❖ **Mass testing was done with the commercial electronics**

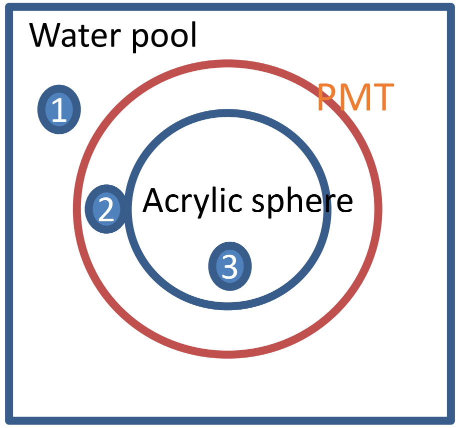
❖ **With JUNO's electronics, MCP-PMTs present the similar DCR with HPK's**

Radiopurity Control

JHEP 11 (2021) 102

Good radiopurity control on raw material, reduced by 15% compared to the design

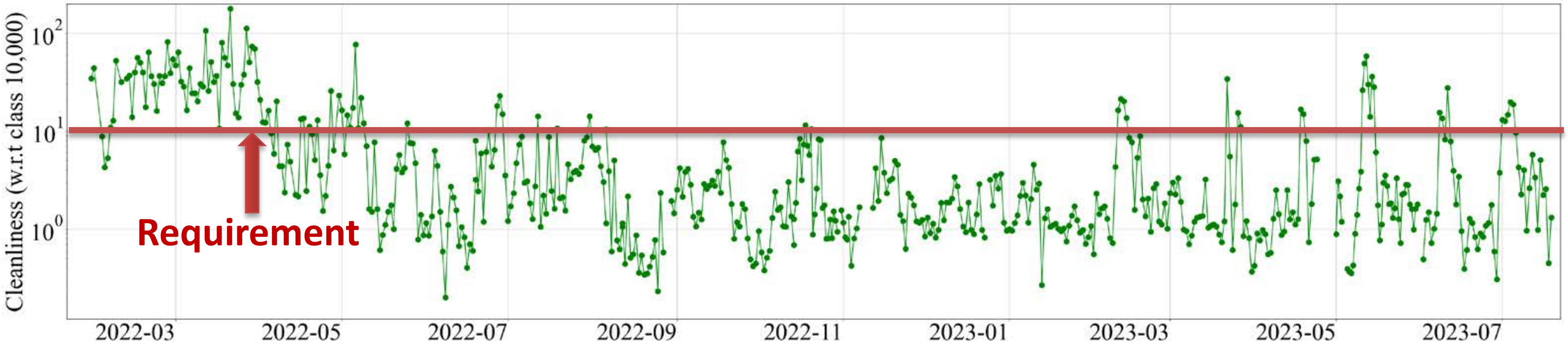
Singles (R < 17.2 m, E > 0.7 MeV)	Design [Hz]	Change [Hz]	Comment
LS	2.20	0	
Acrylic	3.61	-3.2	10 ppt -> 1 ppt
Metal in node	0.087	+1.0	Copper -> SS
PMT glass	0.33	+2.47	Schott -> NNVT/Ham
Rock	0.98	-0.85	3.2 m -> 4 m
Radon in water	1.31	-1.25	200 mBq/m^3 -> 10 mBq/m^3
Other	0	+0.52	Add PMT readout, calibration sys
Total	8.5	-1.3	



Region	Level
1	Class 100,000
2	Class 10,000
3	Class 1000

Temperature: 21℃±1℃

With great efforts on onsite cleanliness control, the cleanliness in the hall reaches better than Class 100,000 and radon concentration in the air < 100 Bq/m^3



Radiopurity Control during LS Filling

To improve the air quality on both dust and radon daughters

CD construction completed → DI water spray → Remove film on acrylic by water jet → Cleaning in CD → Water exchange → LS filling

Requirement on filling water is proposed (U/Th<10^{-15} g/g, ^{226}Ra < 0.1 mBq/m^3)

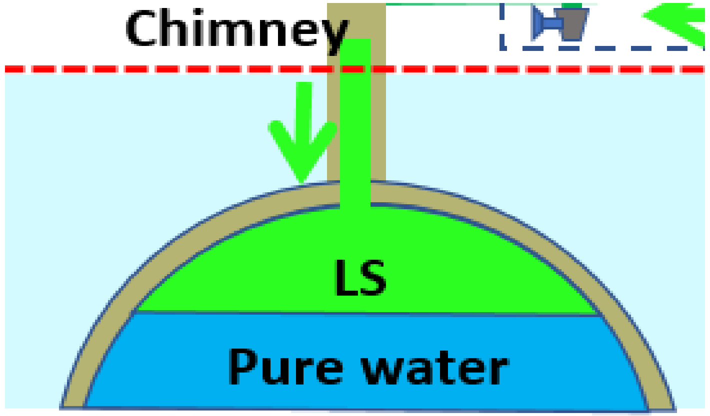
❖ **Recirculation is impossible at JUNO due to its large size**

→ **Target radiopurity need to be obtained from the beginning**

❖ **Strategies:**

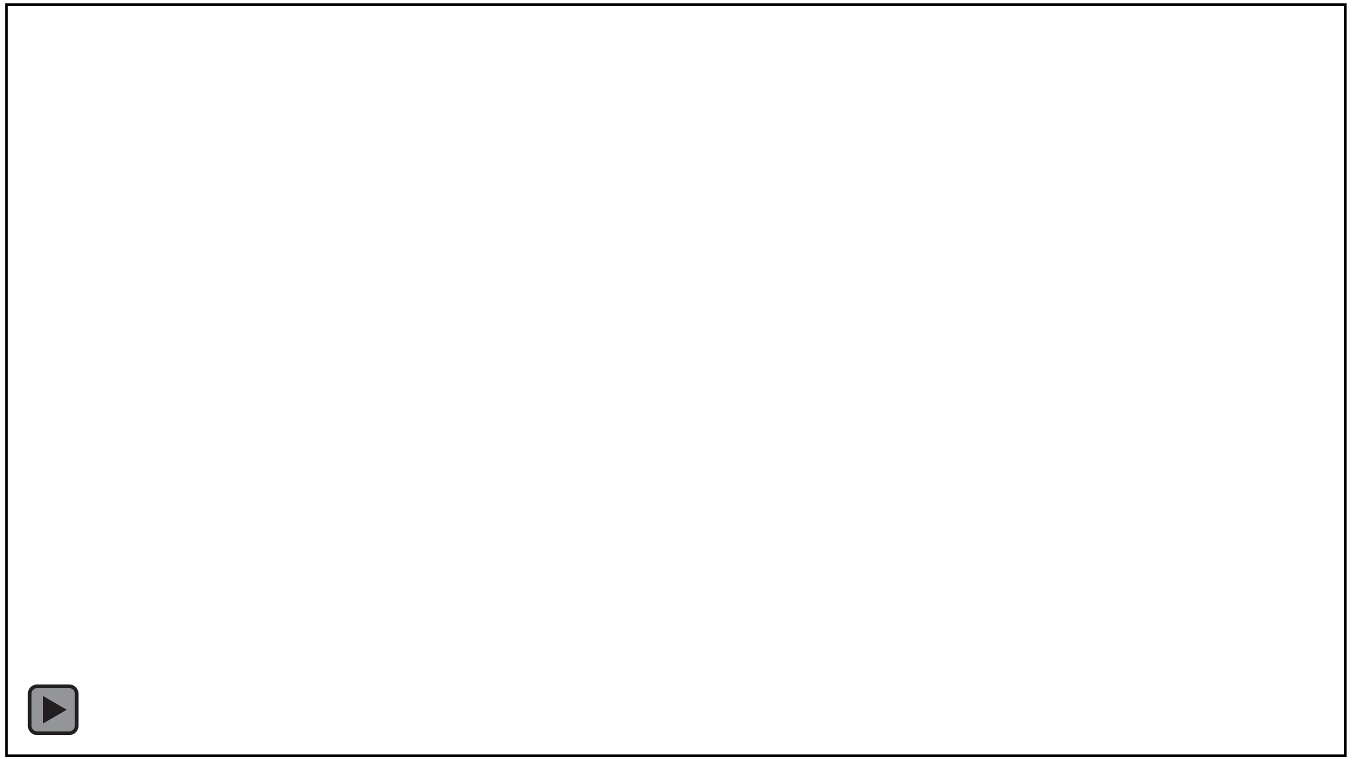
1. **Leakage** (single component: 10^{-7} – 10^{-8} mbar·L/s)
2. **Cleaning vessel** before filling
3. **Clean environment**
4. **Water/LS filling**

Cleaning test on 3 m prototype with 3D-high pressure water jet



Detector Installation Ongoing

- ❖ JUNO was approved in 2013
- ❖ Civil construction done, 2015 – 2021
- ❖ Detector installation started in 2022, will be completed in 2023
- ❖ Filling will start in 2024
- ❖ Lots of technical issues have been addressed during the civil construction and detector installation
- ❖ Installation going smoothly
- ❖ More information, refer Xiaoyan Ma and Xiaonan Li’s talks on this Monday

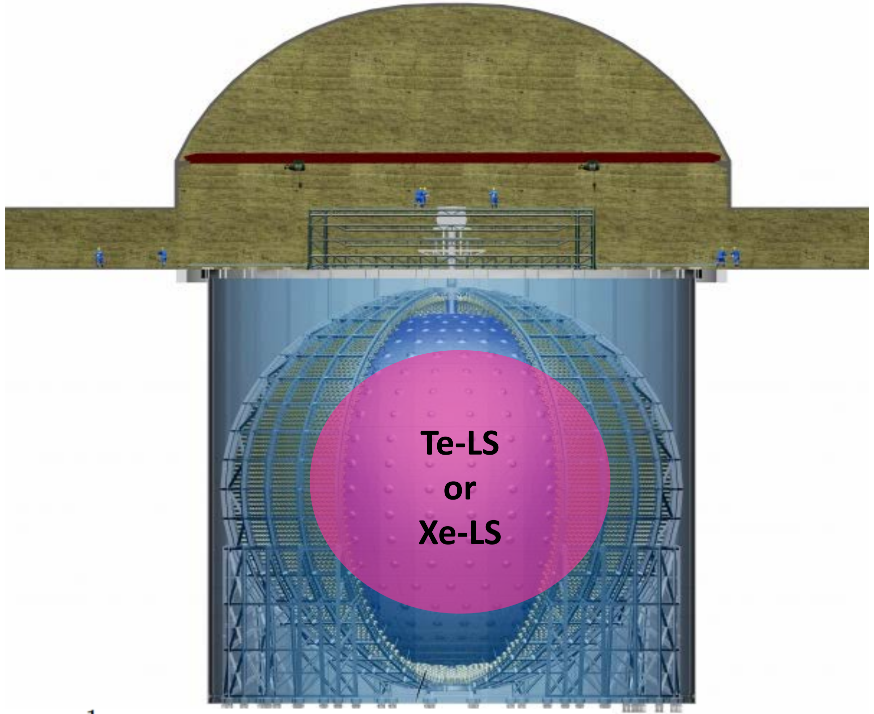


Contribution ID 57,86

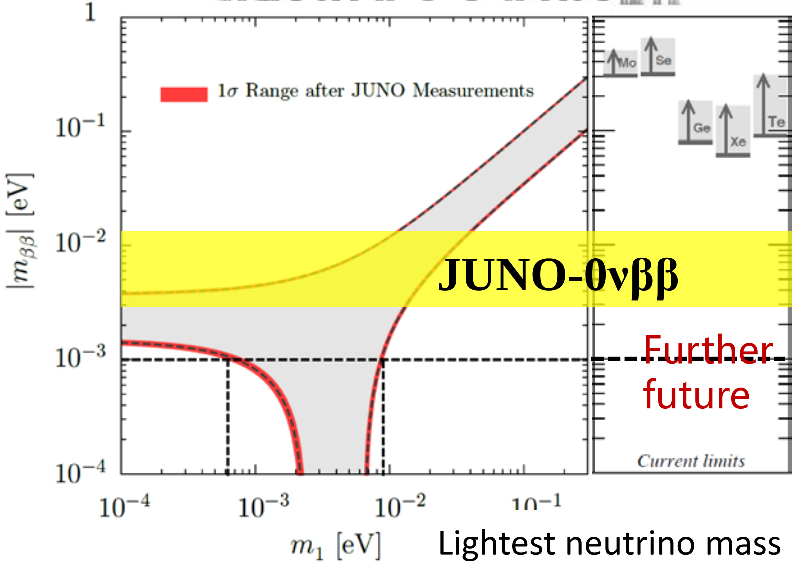
JUNO-0νββ

- JUNO offers an unique opportunity to search for 0νββ after completion of mass ordering measurements (~2030)
  - Large target mass: 20 kton LS → **100-ton scale isotope loading**
    e.g., Tellurium, no enrichment (~34% ^{130}Te), cost effective
  - Low background
  - Energy resolution < 3% @ 1 MeV

→ Potential to explore normal mass ordering parameter space of Majorana neutrino mass



- Critical R&D in progress
  - Te loaded LS requirements: high light yield, transparency and solubility and stability
  - Background rejection (^{8}B solar neutrinos, Te muon-spallation products)



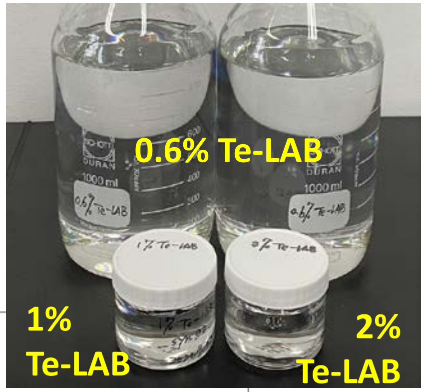
Contribution ID 93

Critical R&D: the JUNO recipe of Te-LS

NIM A 1049 (2023) 168111

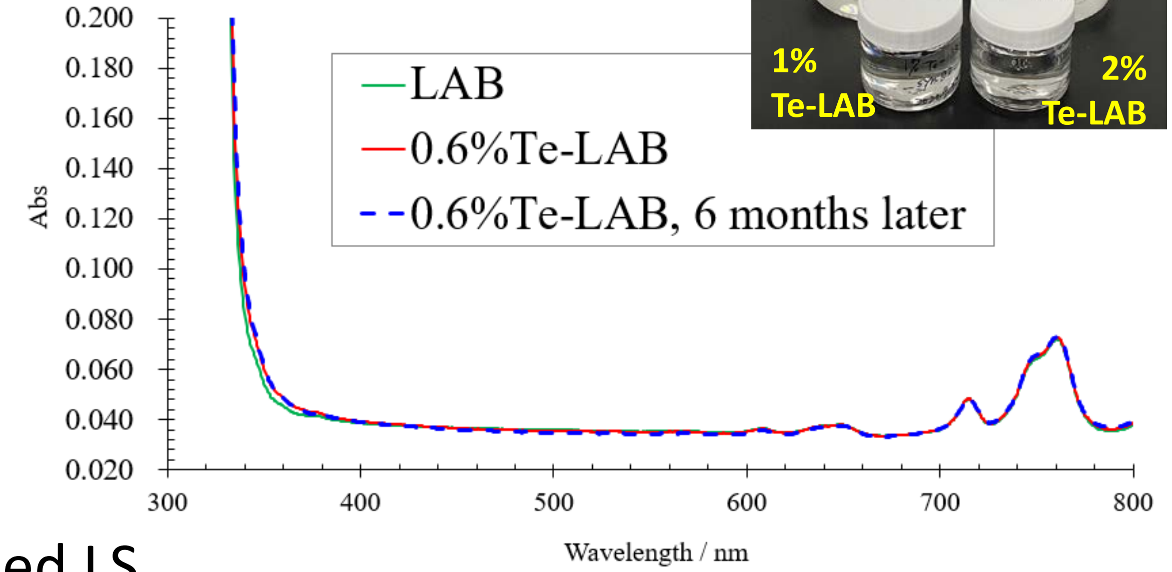
A promising recipe under R&D

$Te(OH)_6$ + $R_3CH(OH)\text{-}CR_1(OH)R_2$ → One-step synthetic method → Te-organic compounds → Direct dissolve into LAB + PPO, bis-MSB → Te-LS

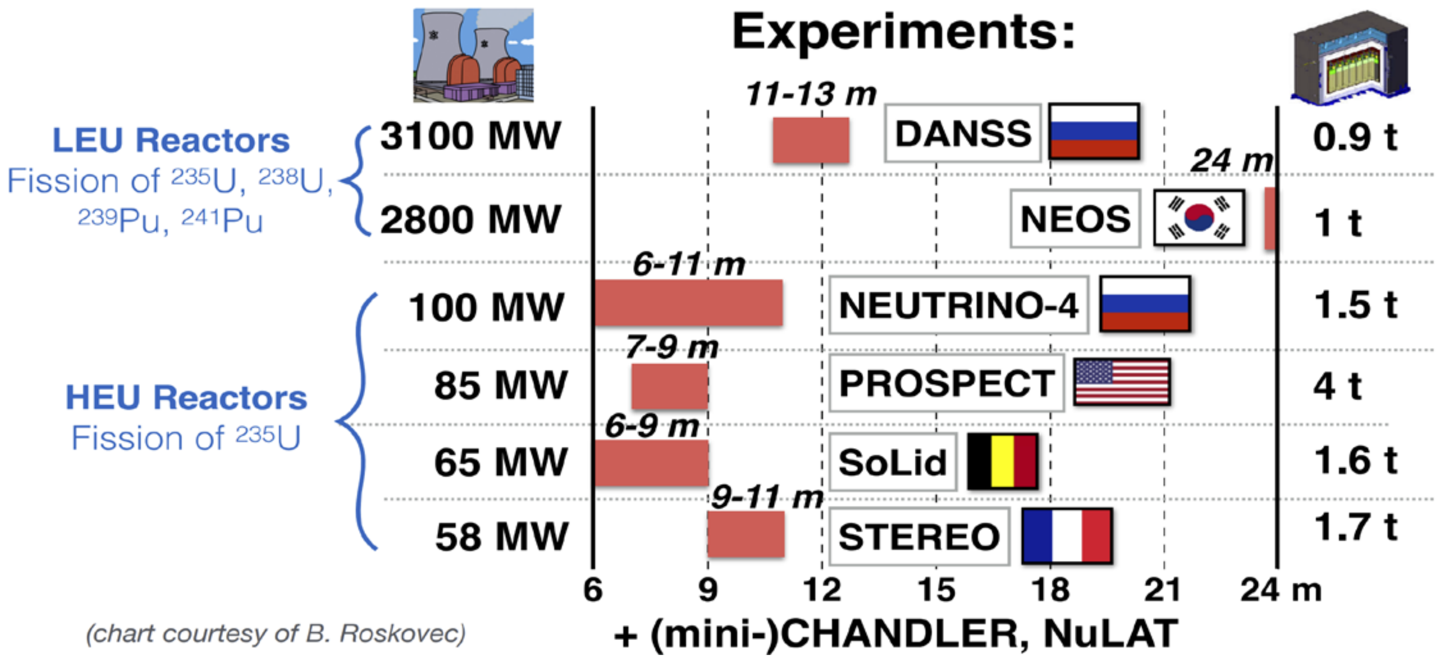


❖ Promising one-step synthetic method, capability of Te loading in LAB: > 3%
- ➢ Good stability, transparency and solubility of Te-compounds
- ➢ Quick, convenient and applicable for most diols

❖ Current characteristics w/ 0.6% Te-loading
- ➢ Good UV-Vis spectra for Te-LAB
  - NO visible difference (Δ_{ABS}<0.002 for λ>370 nm) compared to the purified LAB (A.L. > 20m)
  - NO degradation after 6 months
- ➢ Relative light output: 60%~70% w.r.t un-loaded LS



SBL Reactor Neutrino Experiments



- **Search for sterile neutrino, L~O(10 m) sensitive to large Δm^2**
- **Reactor Antineutrino Anomaly**

Experiment	Solid	Neutrino-4	PROSPECT (II)	STEREO	DANSS	NEOS	JUNO-TAO
Power [MW]	80	100	85	58	3,100	2,800	4,600
Baseline [m]	6 – 9	6 – 12	7 – 9	9 – 11	10 – 13	24	~44
Detector mass [t]	1.6	1.5	4	1.7	0.9	1	2.8
Detector technology	Seg. ^{6}Li-PS	Seg. Gd-LS	Seg. ^{6}Li-LS	Seg. Gd-LS	Seg. Gd-PS	Unseg. Gd-LS	Unseg. Gd-LS
Energy resolution	14%	25%	4.5%	7%	34%	5%	< 2%
Overburden [mwe]	8	3.5	0.5	15	50	20	10
S/B	1/3	0.54	1.4	1.1	58	>20	10

Challenges of SBL Experiments

- ❄ **Close to the reactor core, ~10 m**

- ❄ **Constraints from the reactor site**
  - ➢ **Limited space and floor load → small detector size (a few tons) and limited shielding**
  - ➢ **Strict safety regulation → detector materials with high flash point, less toxicity, etc**

- ❄ **Large backgrounds**
  - ➢ **Shallow overburden (~10 mwe) → high muon rate and cosmogenic backgrounds**
  - ➢ **Limited amount of shielding → high fast neutron flux and high radioactivity**

- ❄ **L/E resolution**
  - ➢ **LEU reactor cores ~ 3 m → larger L/E smearing ~ 10%, powerful reactor**
  - ➢ **HEU reactor cores ~ 0.5 m → segmented detector, smaller L/E smearing ~ 2%, less powerful reactor**

NEUTRINO-4 and STEREO

- Movable segmented detector, optically separated
  - 50 cells = 10 rows × 5 column, 22.5 × 22.5 × 85 cm[3] each
- BC-525 + 0.1% Gd, Single PMT readout, active/passive shielding

- 4× detectors → 3× larger volume, double PMT readout
- New LS with PSD capability → 4× less correlated bkg
- More Gd → 4× less accidental bkg

PRD 104, 032003 (2021)

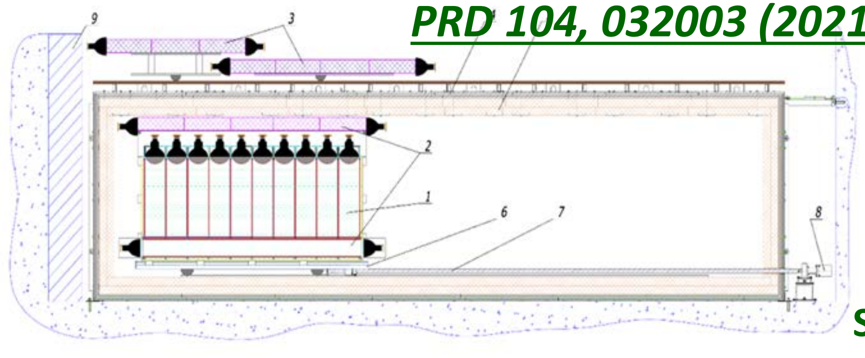
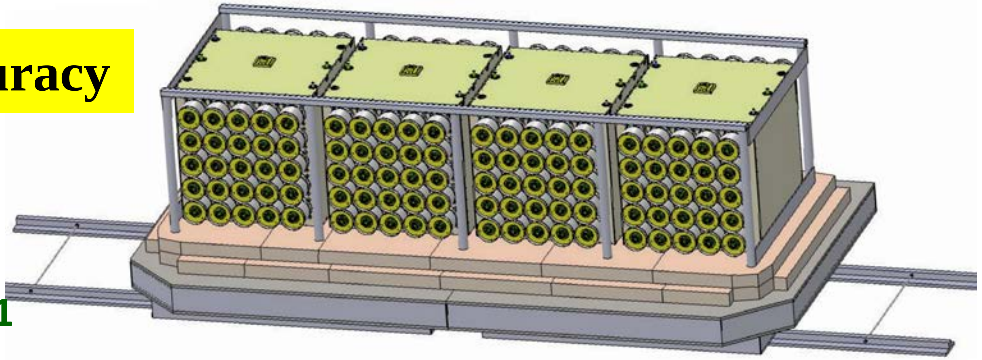


FIG. 18. General scheme of an experimental setup. 1—detector of reactor antineutrino, 2—internal active shielding, 3—external active shielding (umbrella), 4—steel and lead passive shielding, 5—borated polyethylene passive shielding, 6—moveable platform, 7—feed screw, 8—step motor, 9—shielding against fast neutrons made of iron shot.

3× more accuracy

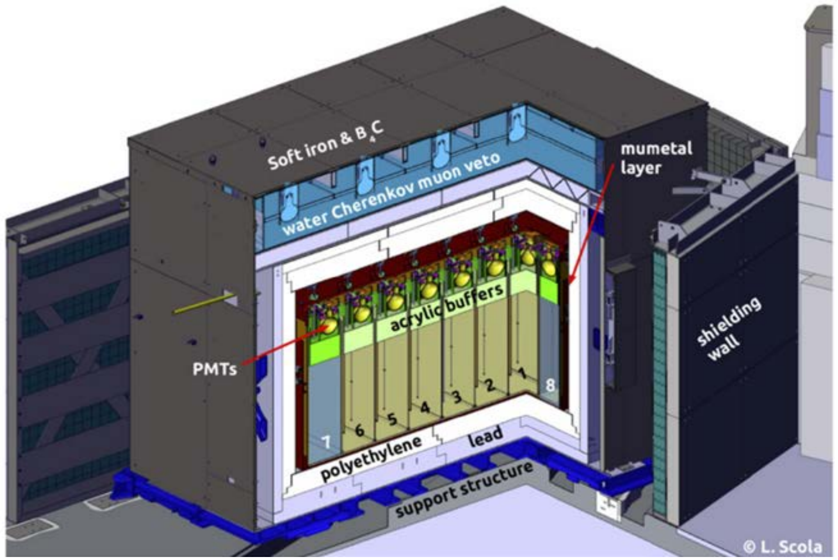
Being upgraded

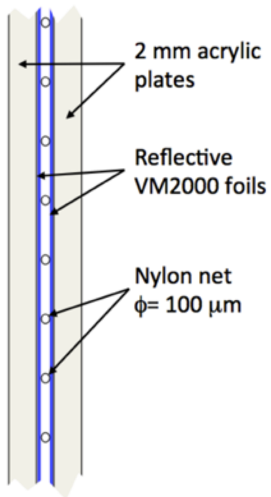
Samoilov R.M. @NUCLEUS2021



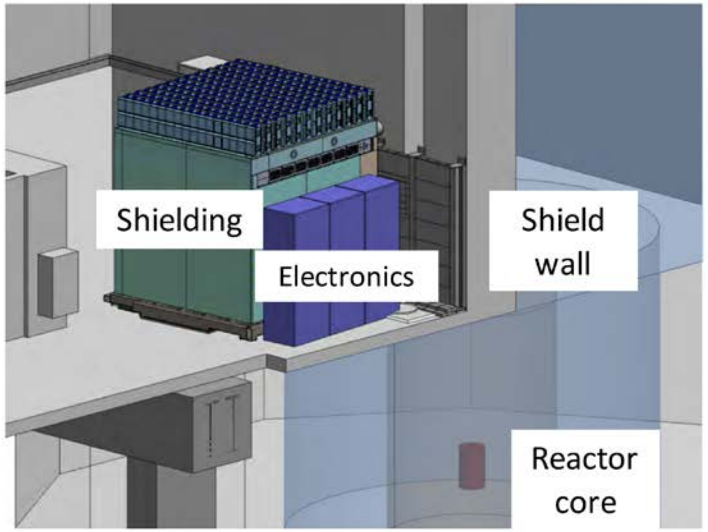
Neutrino-4

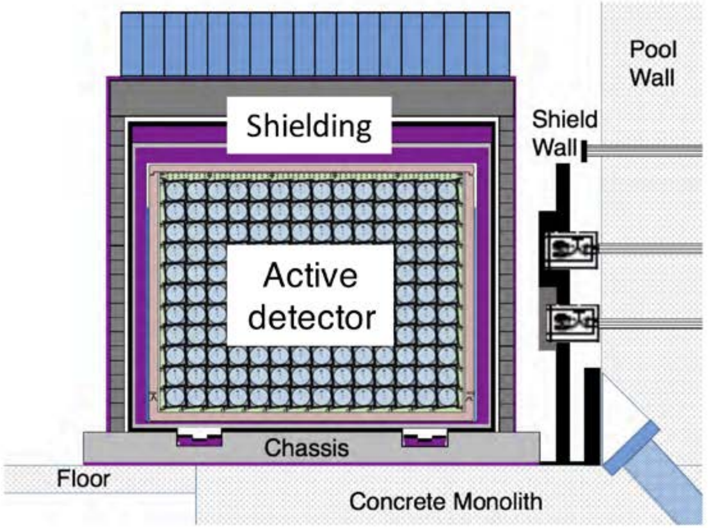
STEREO

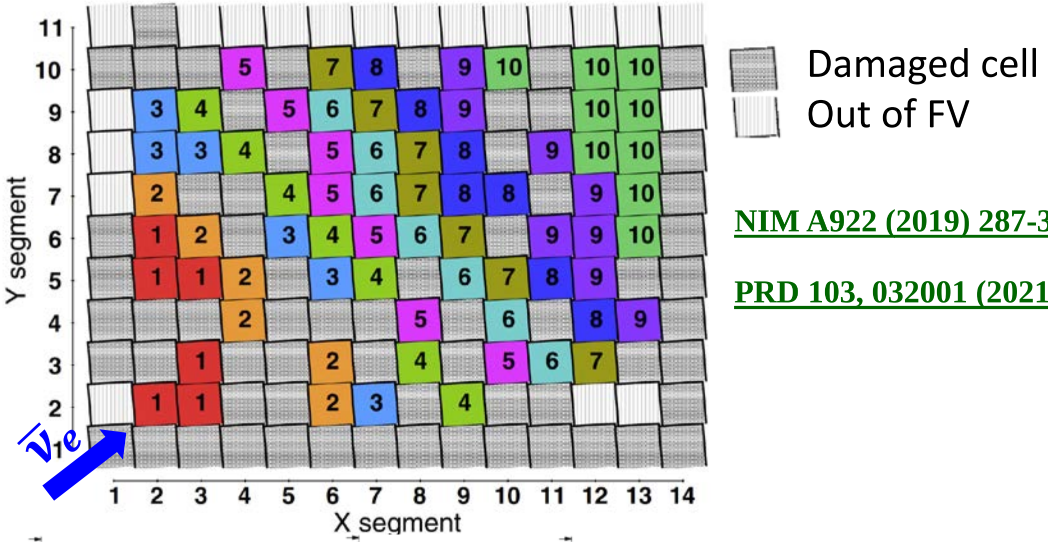




- 6 identical and optically separated cells, 4 8-inch PMTs for each cell
  - 0.369 m × 0.892 m × 0.918 m each, ESR on side wall and bottom
- 0.2% Gd + 75% LAB + 20% PXE + 5% DIN + 7 g/L PPO + bis-MSB
- γ-catcher: identical to Gd-LS, but no Gd and less PPO
- MO buffer between PMTs and LS, Water Cherenkov + passive shielding
- Better E resolution: 7% vs ~20% of Neutrino-4, with PSD





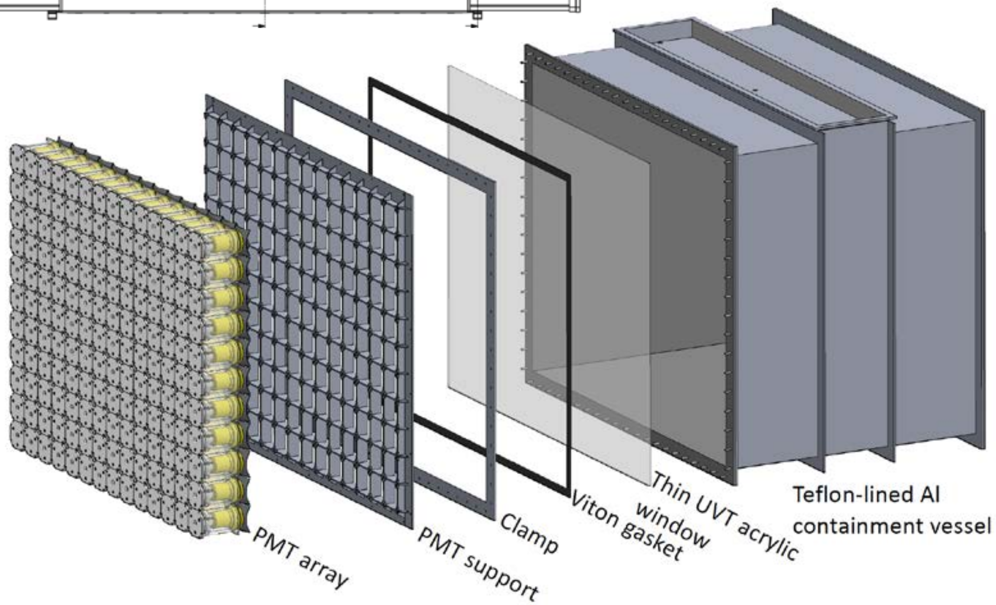


[NIM A922 (2019) 287-309](#)

[PRD 103, 032001 (2021)](#)

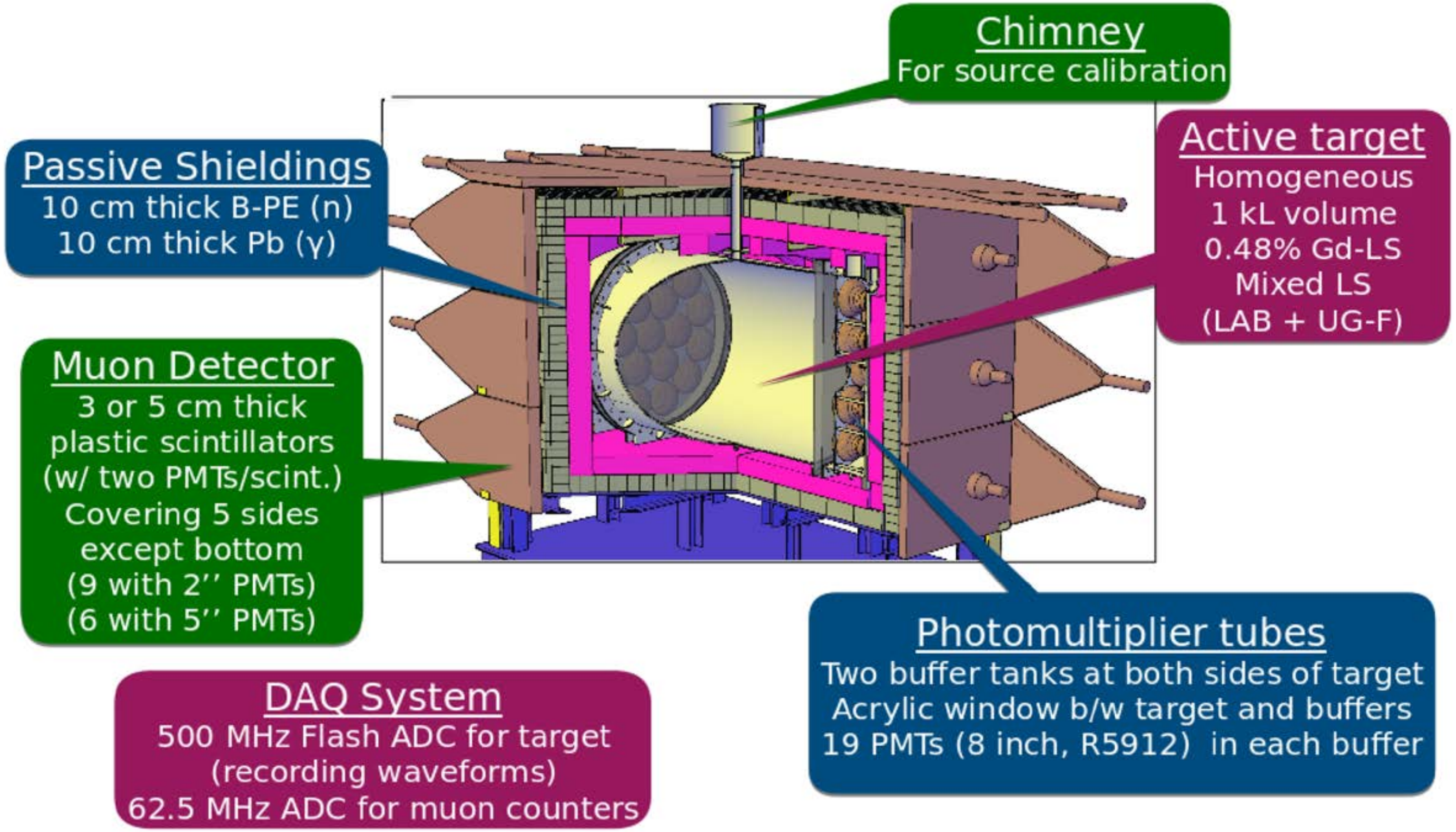
$$n + {}^{6}Li \rightarrow \alpha + t + 4.8\ MeV$$

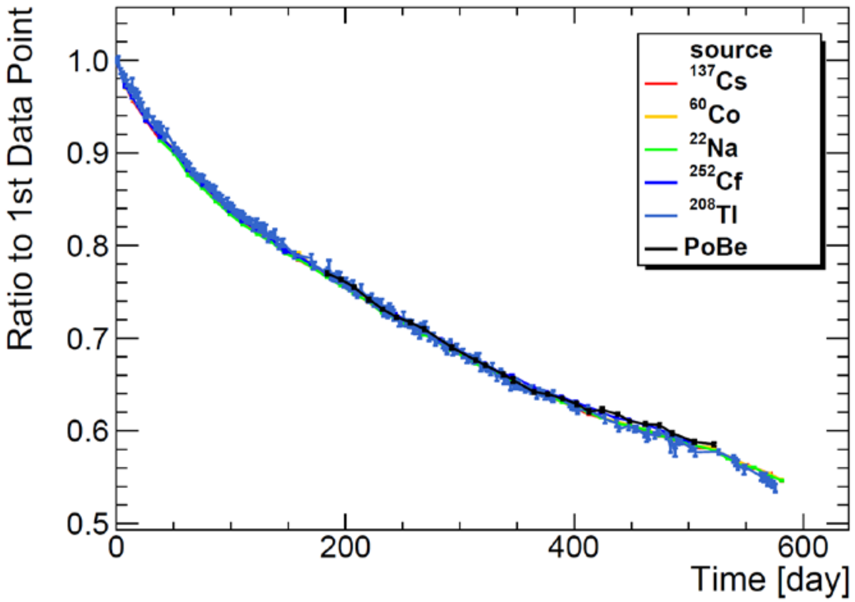
- 14 × 11 cells, optically separated, viewed by 2 PMTs on both ends
- DIN-based EJ-309 + PPO + bis-MSB + 0.08% ^{6}Li
- Excellent PSD power, both for prompt and delayed signals
- PMT housing immersed in LS, part of cells damaged due to LS leakage

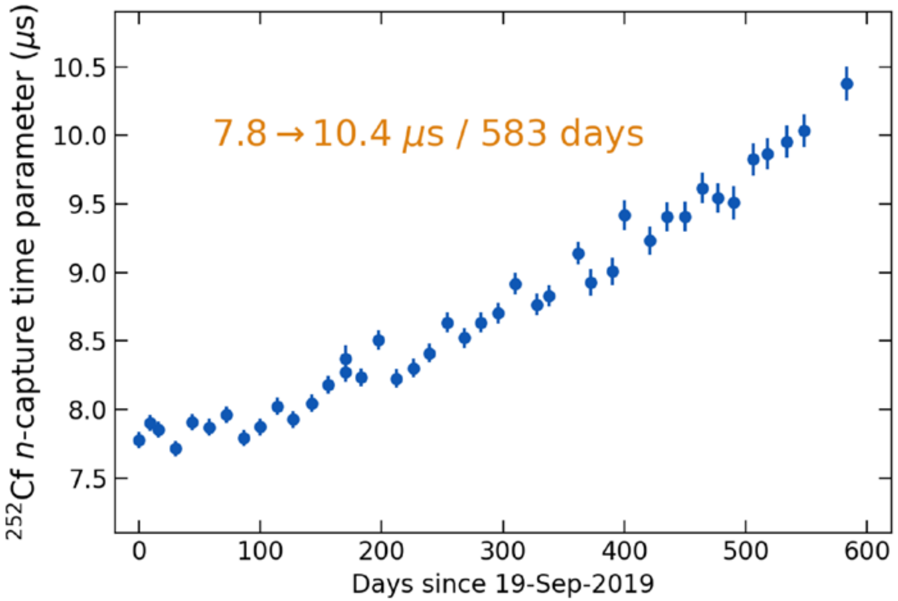


- PROSPECT-II will address technical challenges of PROSPECT-I
- Option for target volume increase
- Relocatable between HEU and LEU reactors

Jinyu Kim @Neutrino2022

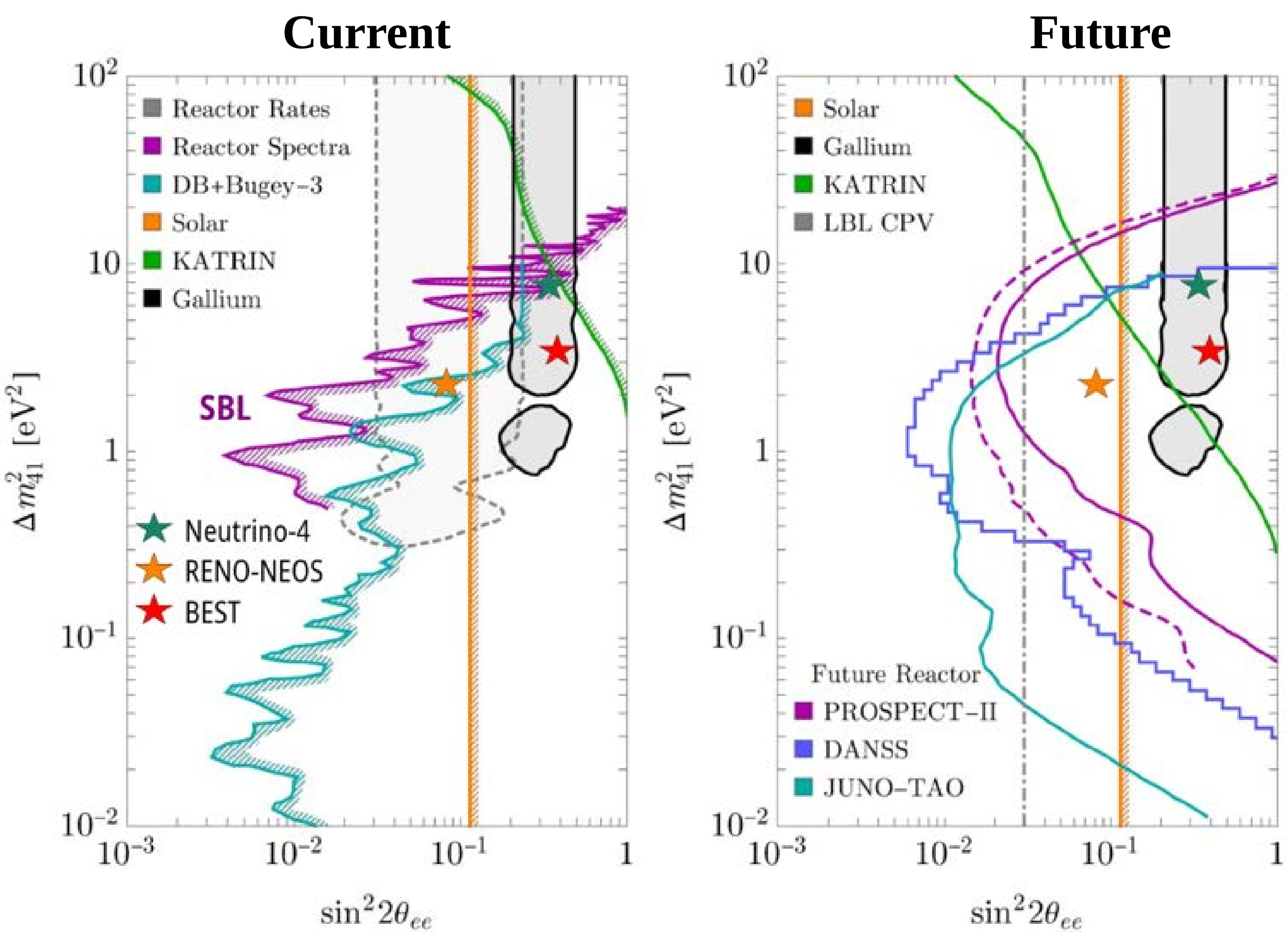






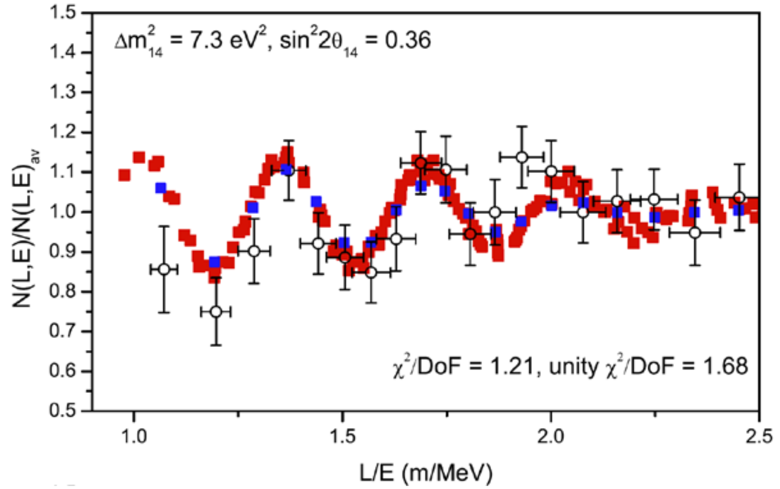
- ❖ **0.5% Gd-LS with PSD, NEOS-I started data taking from 2015 to 2016**
- ❖ **Replaced with new LS in NEOS-II, due to large LS aging effect**
- ❖ **NEOS-II data taking completed, 2018 ~ 2020, 45/388/67 days, reactor off/on/off**
- ❖ **Both chemical and optical stabilities seem not good, due to high Gd concentration**

Landscape of Sterile Neutrinos and Prospects



Modified by M. Licciardi from arXiv:2203.07214

PRD 104, 032003 (2021)



- **Almost all SBL reactor experiments reported results**
- **Most regions of Ga anomaly excluded by SBL reactors, DB+Bugey-3 and KARTRIN**
- **Positive observation of Neutrino-4 (2.7σ), but disfavored by Stereo at 3.1σ**
- **BEST confirmed Gallium deficit, but seems no oscillation over baseline**

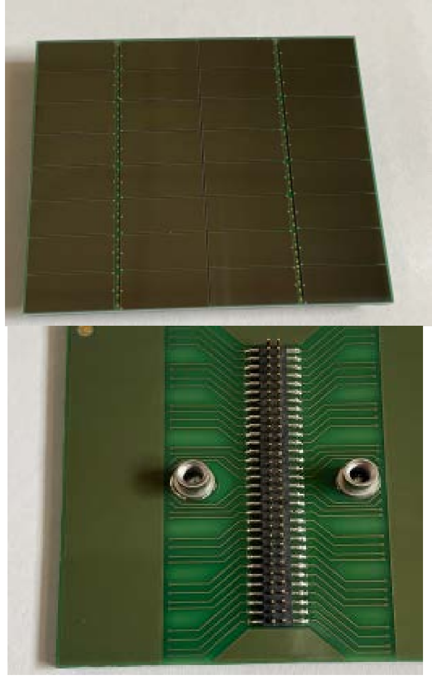
- Taishan Antineutrino Observatory (TAO), a satellite experiment of JUNO, a 2.8 t Gd-LS detector
- Full coverage of SiPMs ($10\ m^2$) w/ PDE > 50%
- LY: ~4000 p.e./MeV, resolution: < 2% @1 MeV
- Operated at -50 °C, low temperature LS
- Under construction, online in 2024

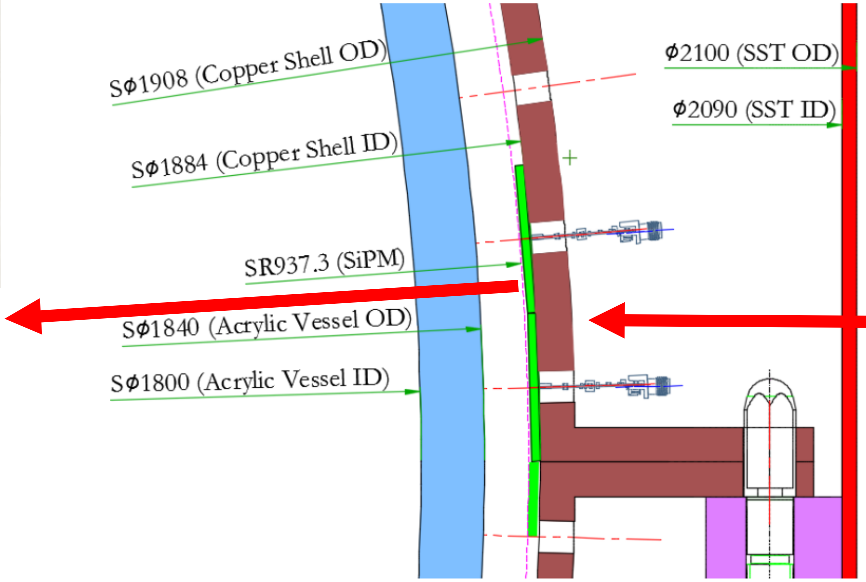
- Provide reference spectrum for JUNO to boost NMO sensitivity
- Provide a benchmark to examine nuclear database, first time to measure fine structures
- Measure isotopic neutrino spectrum
- Sterile neutrino search

Contribution ID 58

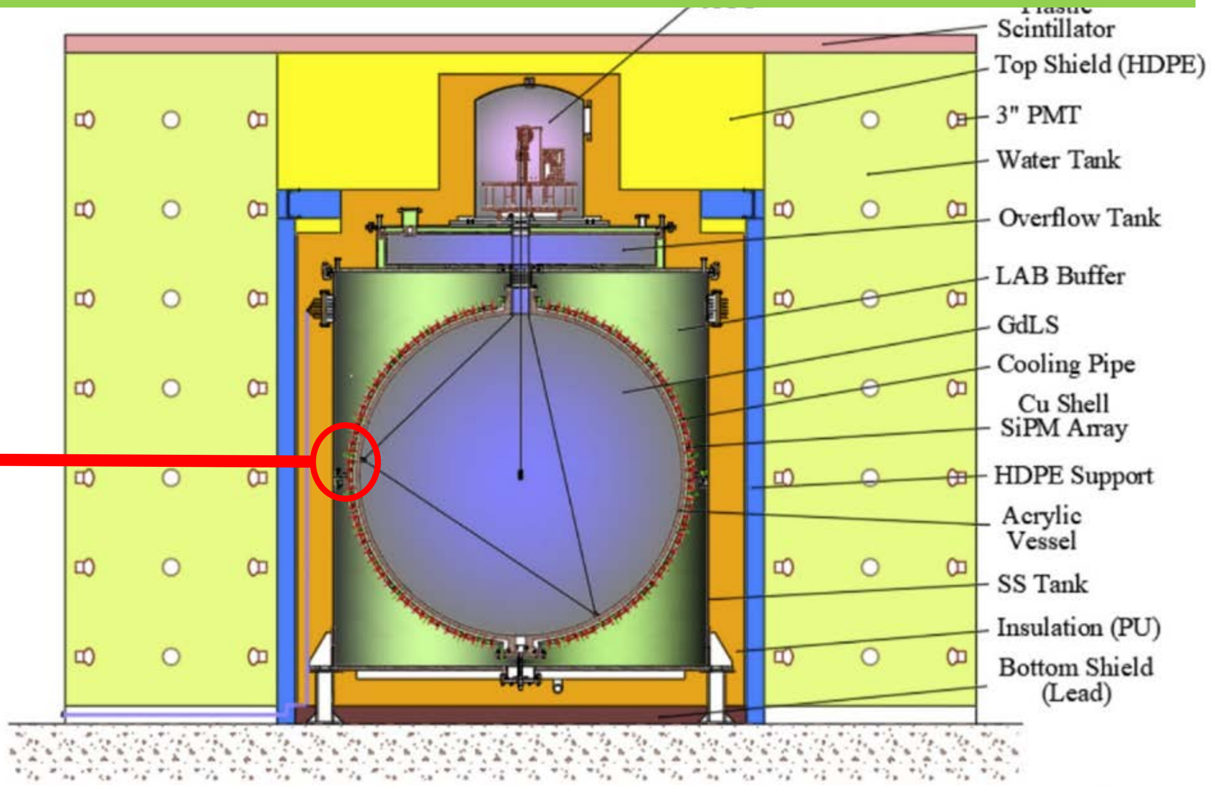
Contribution ID 43

arXiv:2005.08745





One SiPM tile: $5 \times 5\ cm^2$

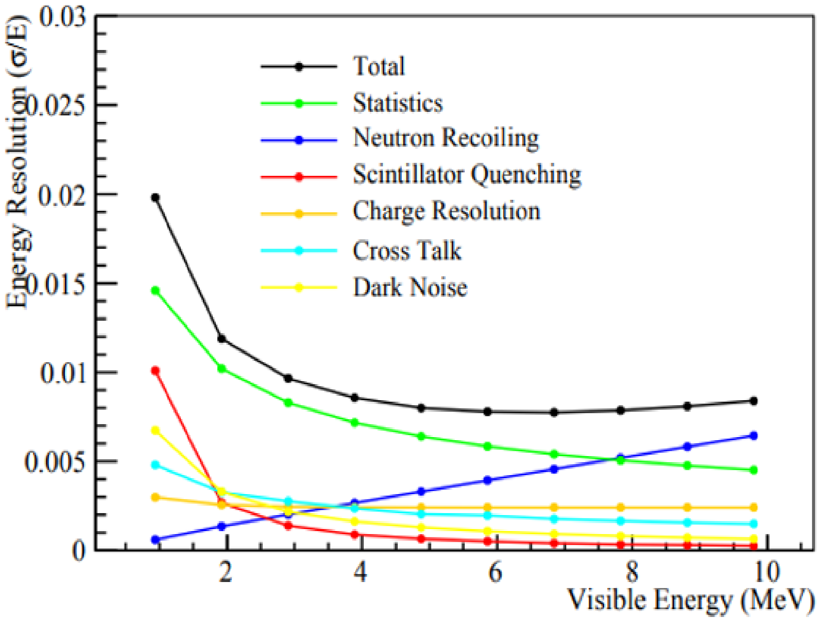


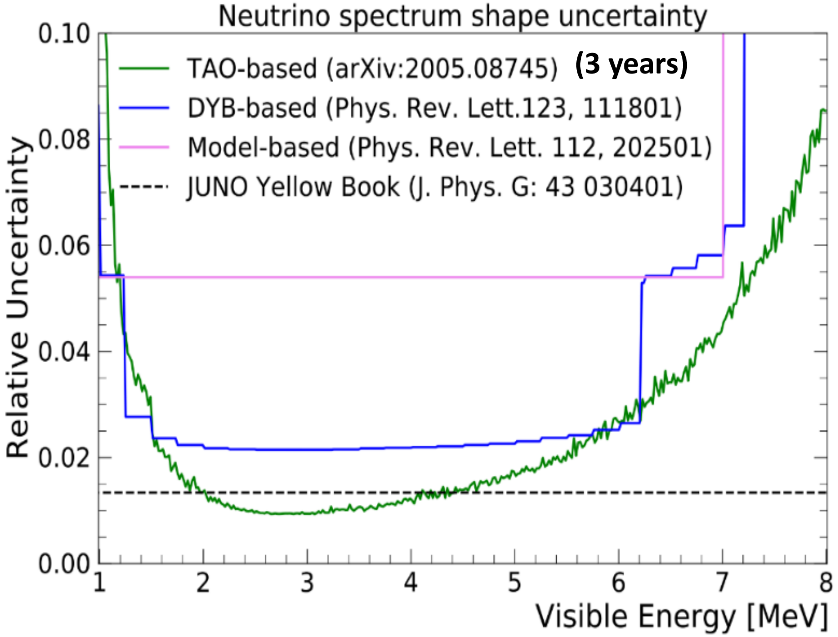
Predicted Performance of TAO

Charge resolution: 16%

Correlated noise: 10%

DCR: 100 Hz/mm^2 at -50 °C

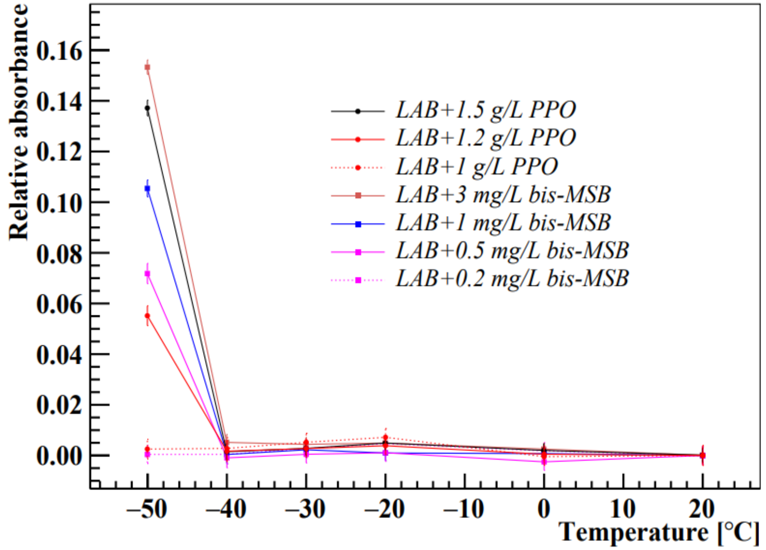


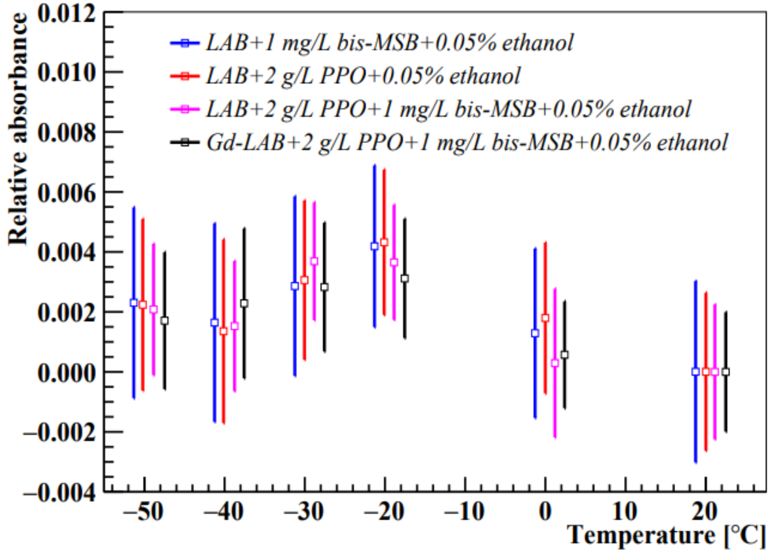


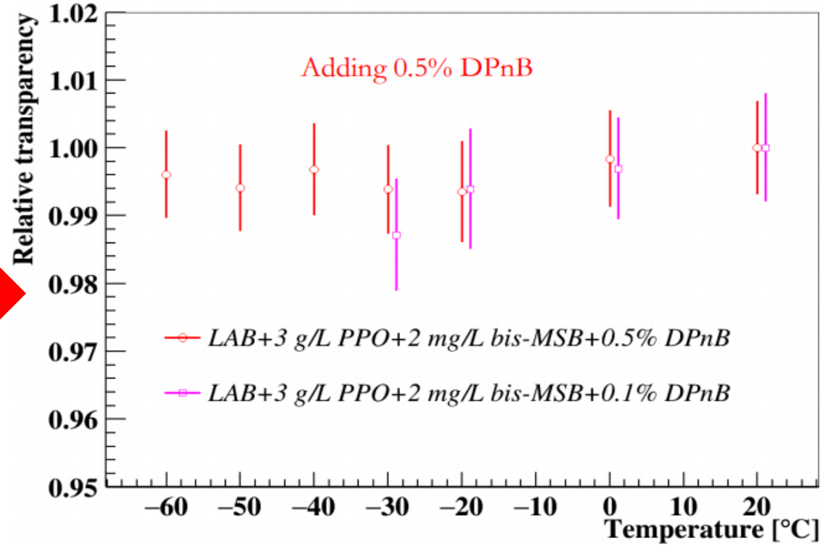
	Chooz	Palo Verde	Daya Bay	D-Chooz	RENO	KamLAND	Borexino	SNO+	JUNO	NEOS (II)	Stereo	Prospect (II)	Neutrino-4	JUNO-TAO
Baseline	M	M	M	M	M	L	--	--	M	S	S	S	S	S
Mass (t)	5	~11	~20	~8	~16	1000	278	780	20,000	1	1.7	4 (~5)	1.5	2.8
Energy Resolution @1 MeV	~9%	~20%	~8%	~7%	~7%	6.5%	5%	~5%	3%	5→7%	~7%	~4.5%	25%	< 2%
Light Yield [p.e./MeV]	~130	~25	~160	~230	~250	250	511	~520	~1500	--	~350	500	~16	~4000

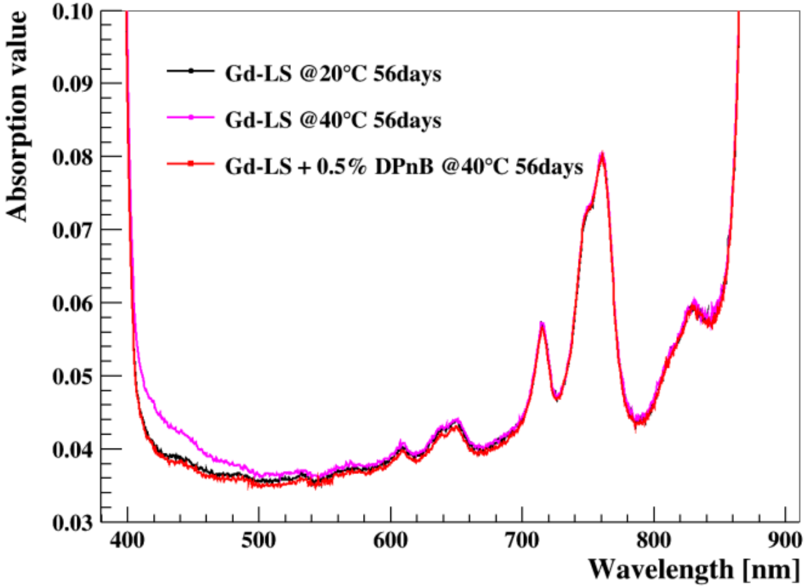
Low Temperature Gd-LS

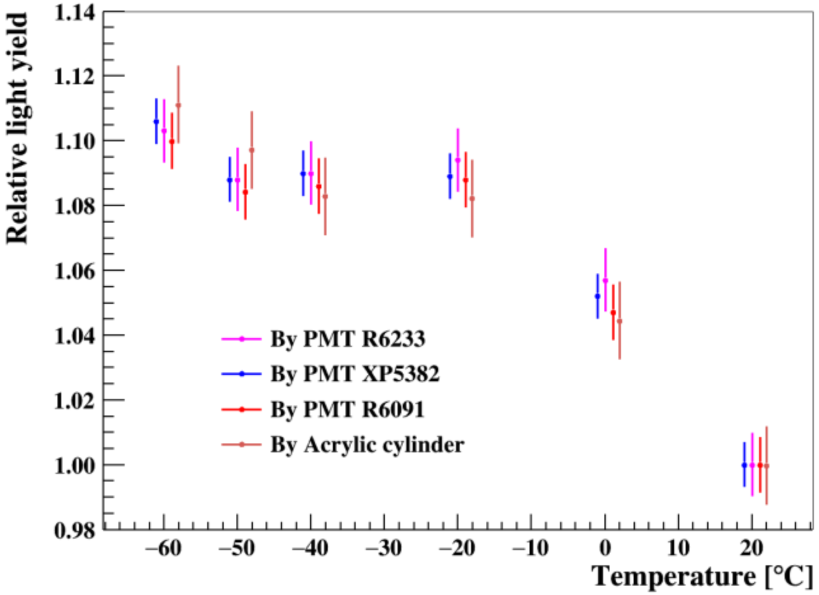
<u>**NIM A 1009 (2021) 165459**</u>







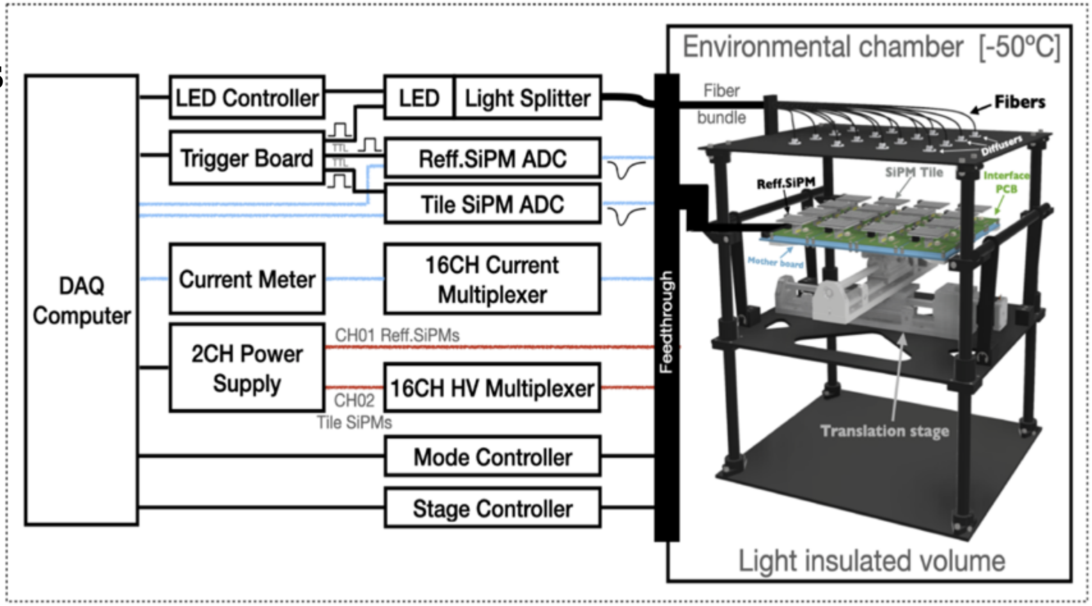


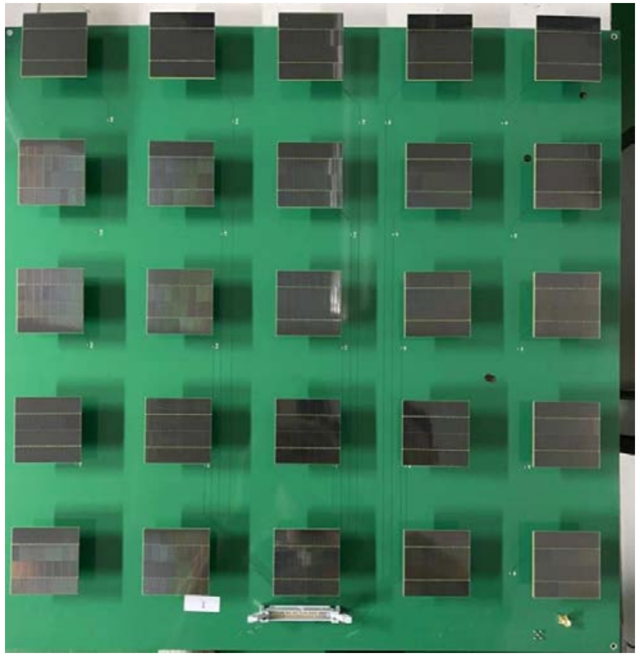


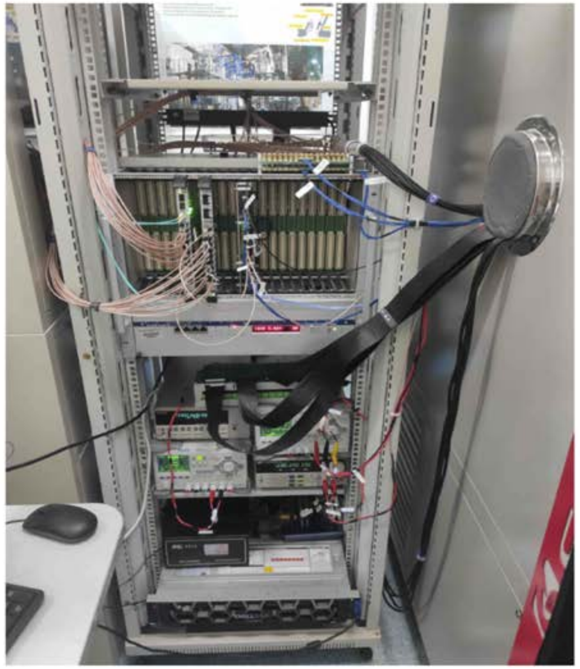
- ❖ **A big effort to investigate Gd-LS recipe at low temperatures**
- ❖ **Solution: LAB + 3 g/L PPO + 2 mg/L bis-MSB + 0.5% DPnB + 0.1% Gd**
- ❖ **Both optical properties and stability have been carefully checked**
- ❖ **Lots of compatibility checks**

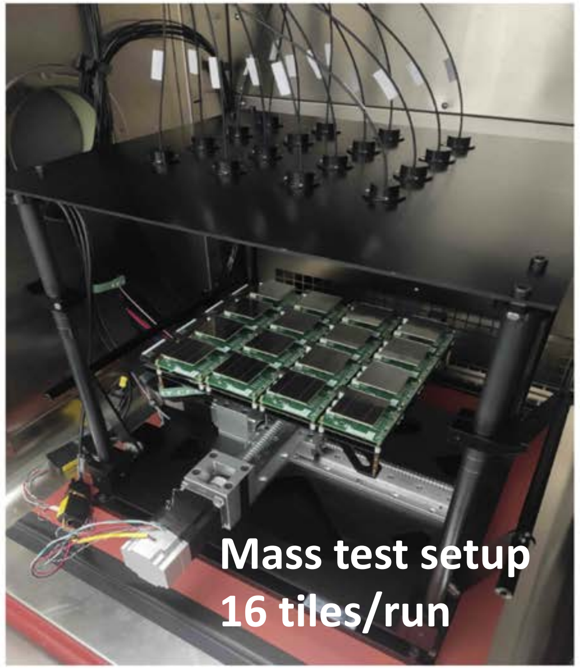
SiPMs

- ❖ **All SiPM tiles have been produced and delivered by HPK, 4100 pcs**
- ❖ **3/4 of them completed mass tests at IHEP**
- ❖ **3 steps mass testing**
  - ➢ **Visual check**
  - ➢ **Burn-in test at room temperature for 2 weeks**
  - ➢ **Mass test at -50 °C for each channel (65,600)**



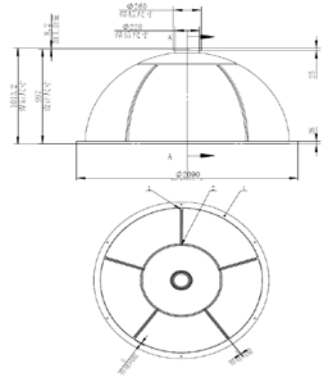






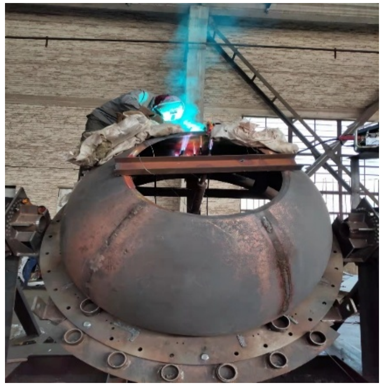
Copper Shell Fabrication

A non-trivial task, 2 m diameter, 28 mm thickness (12 mm after machining), took 2 years to successfully make it



8 pcs for each semi-sphere

Casting completed



Welding

Welding completed

PTFE coating

Sandblasting

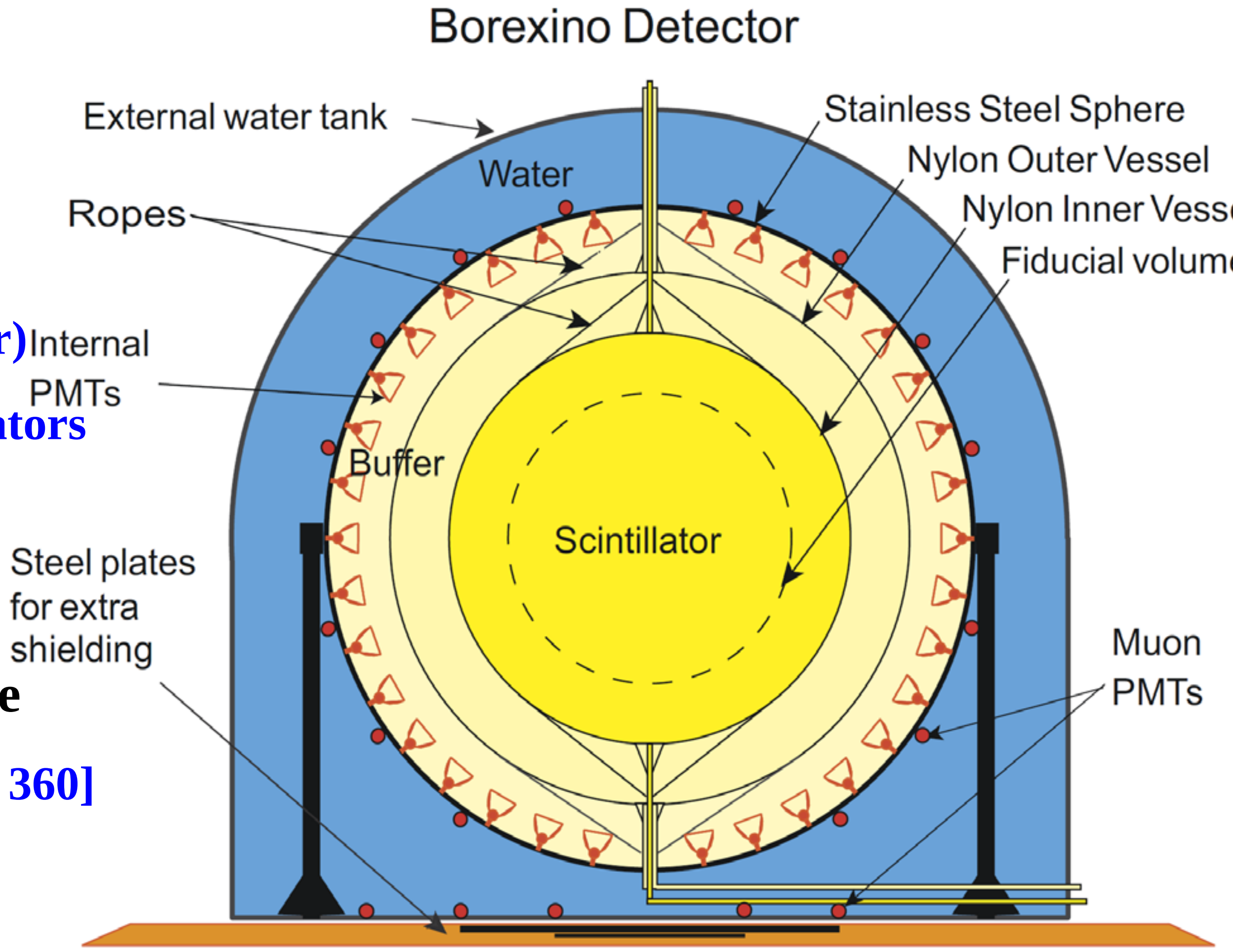
Degreasing

Machining done

Turning & milling

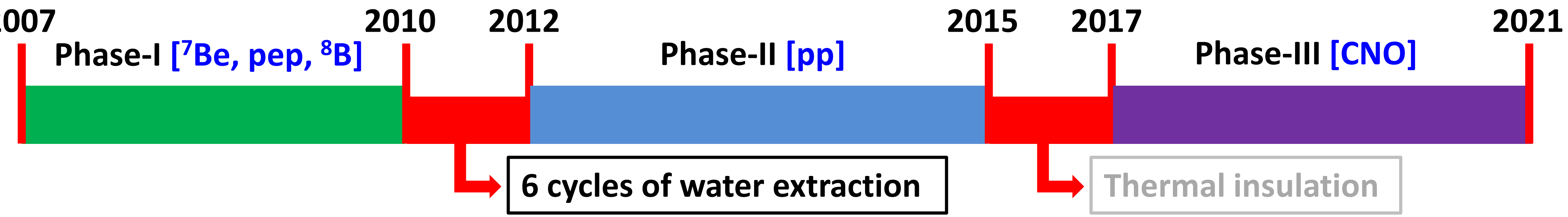
LS-based Solar Neutrino Experiment -- BOREXINO

- A successful LS-based solar neutrino experiment [2007 - 2021]
- Deep underground at Gran Sasso, ~3800 mwe
- Inner detector, enclosed by a stainless steel sphere
  - Two nylon vessels (0.125 mm thick)
  - ~278 t LS (PC+1.5 g/L PPO) in the inner vessel
  - 2 shells of buffer (PC + 2.8 g/L DMP light quencher)
  - 2212 8-inch PMTs, 1828 PMTs with light concentrators
- Outer detector
  - Water Cherenkov detector with 208 PMTs
- A long R&D phase to address the radiopurity issue
  - Prototype, counting test facility [NIM A 440 (2000) 360]
- A big achievement of radiopurity in LS
  - ^{238}U < 9.4×10^{-20} g/g, ^{232}Th < 5.7×10^{-19} g/g
  - ^{210}Bi < 10.8 cpd/100ton, the major CNO background

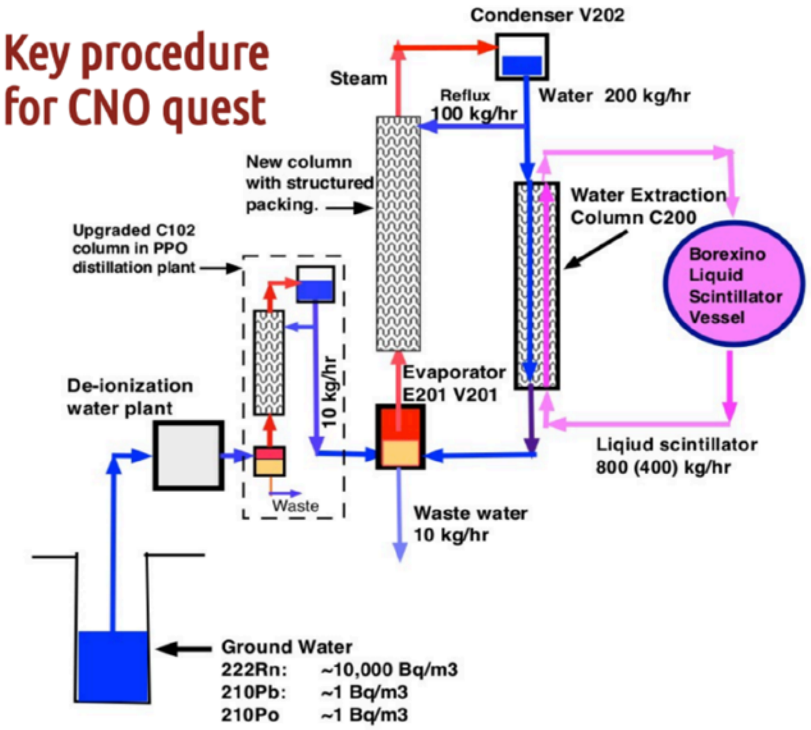


NIM A 600 (2009) 568–593

Radiopurity Control



Key procedure for CNO quest

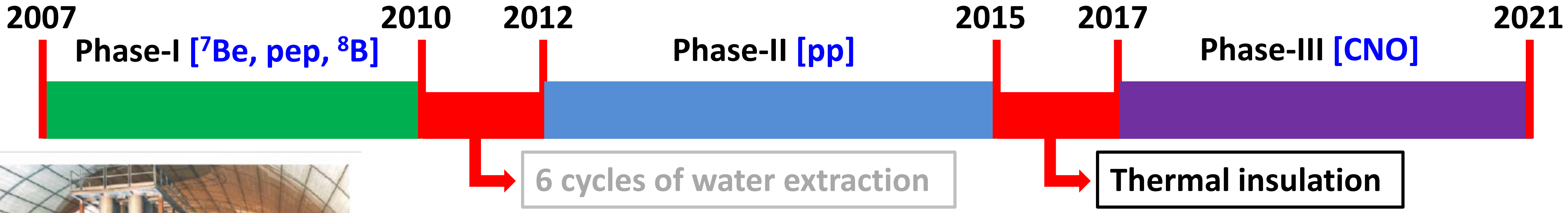


Six cycles of water extraction from mid-2010 to mid-2011

Isotope	Initial impurity	Final impurity
^{85}Kr	~30 cpd/100t	<5 cpd/100t
^{238}U(^{226}Ra) ^{214}Bi—^{214}Po	(5.3±0.5) x10^{-18} g/g	<9.5x10^{-20} g/g 95% C.L.
^{232}Th ^{212}Bi—^{212}Po	(3.8±0.8) x10^{-18} g/g	<5.7x10^{-19} g/g 95% C.L.
^{210}Bi	~70 cpd/100t	~20 cpd/100t
^{210}Po	~700 cpd/100t (avg)	~40 cpd/100t (Avg)

Nicola Rossi @20th Lomonosov conference

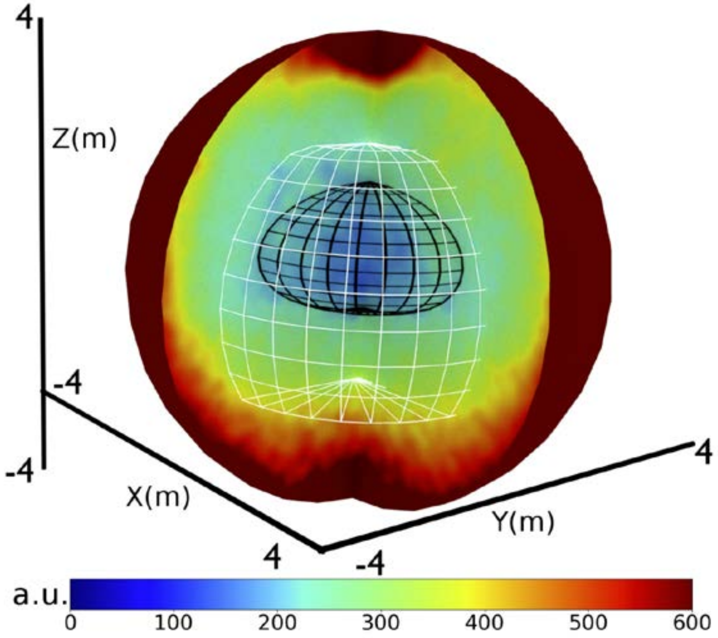
Radiopurity Control



^{210}Pb → ^{210}Bi + β^- (τ=33y)

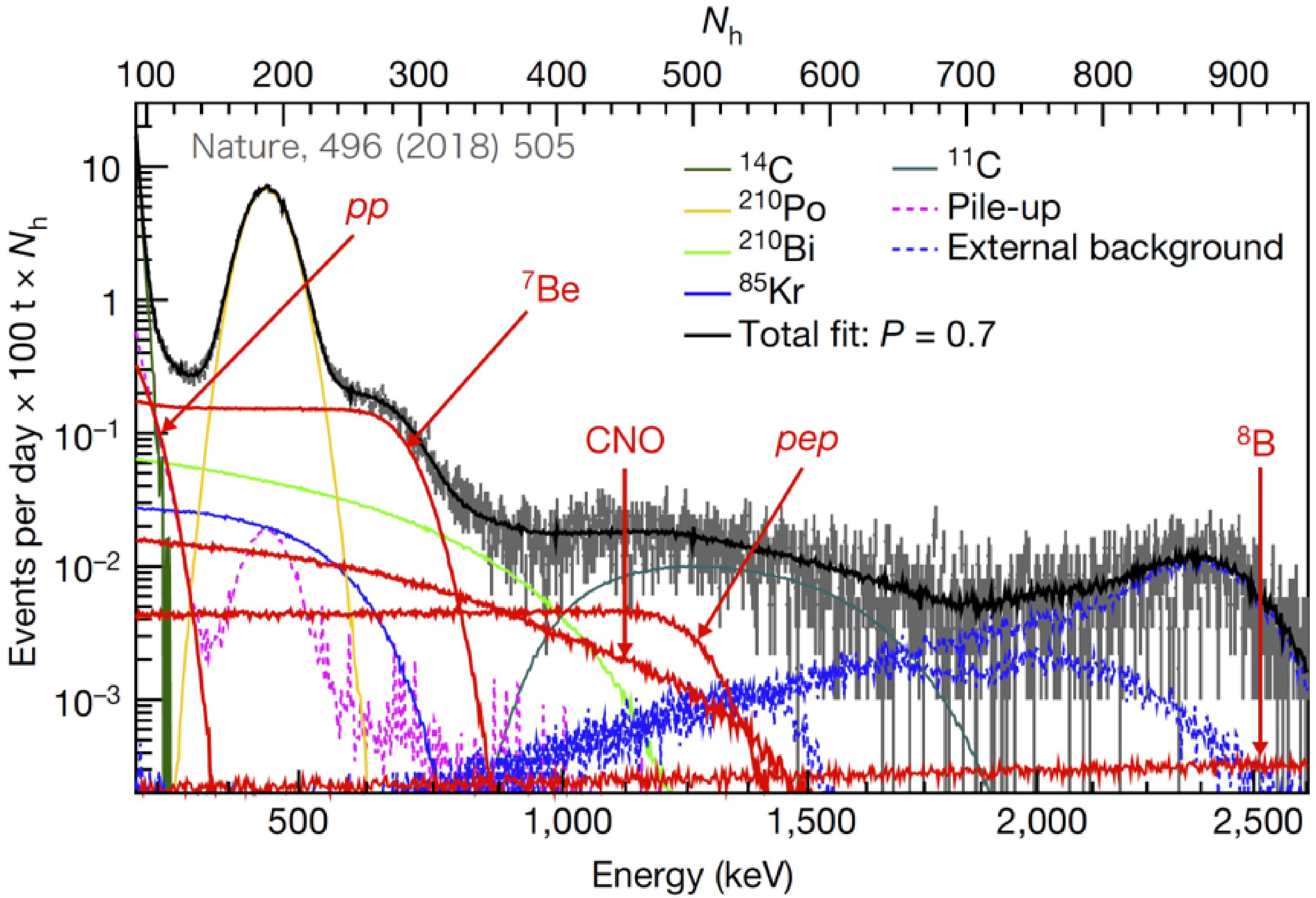
^{210}Bi → ^{210}Po + β^- (τ=7d)

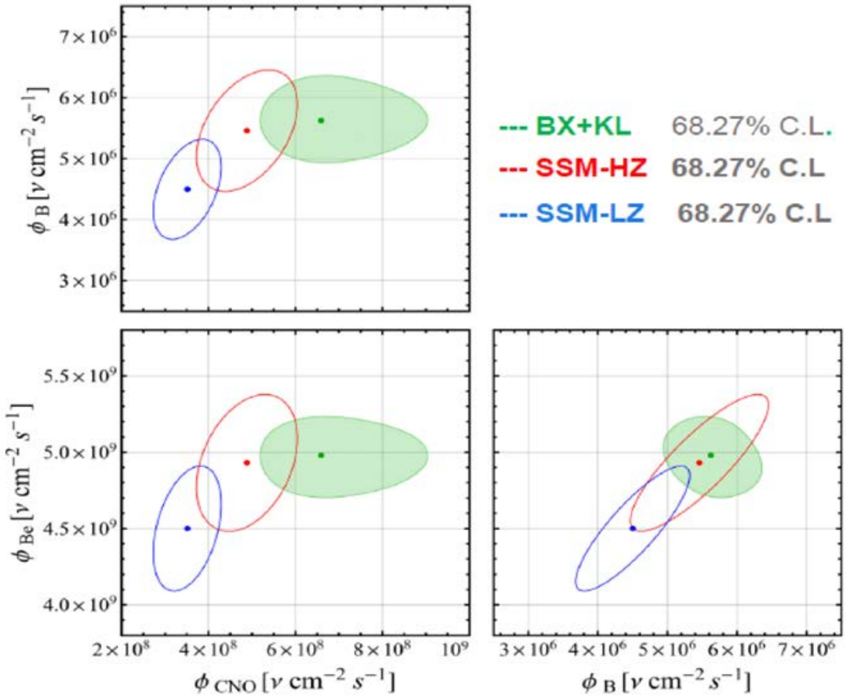
^{210}Po → ^{206}Pb + α (τ=200d)



- The rate and shape of CNO and ^{210}Bi are similar
- ^{210}Po can be used to constrain R(^{210}Bi), but R(^{210}Po) is not stable, due to convective motions
- Efforts made to stabilize the detector
  - 20 cm rock wool to insulate the detector (2015)
  - Active temperature control on the top (2016)
  - Experimental hall temp. stabilization (2019)

Major Results of BOREXINO



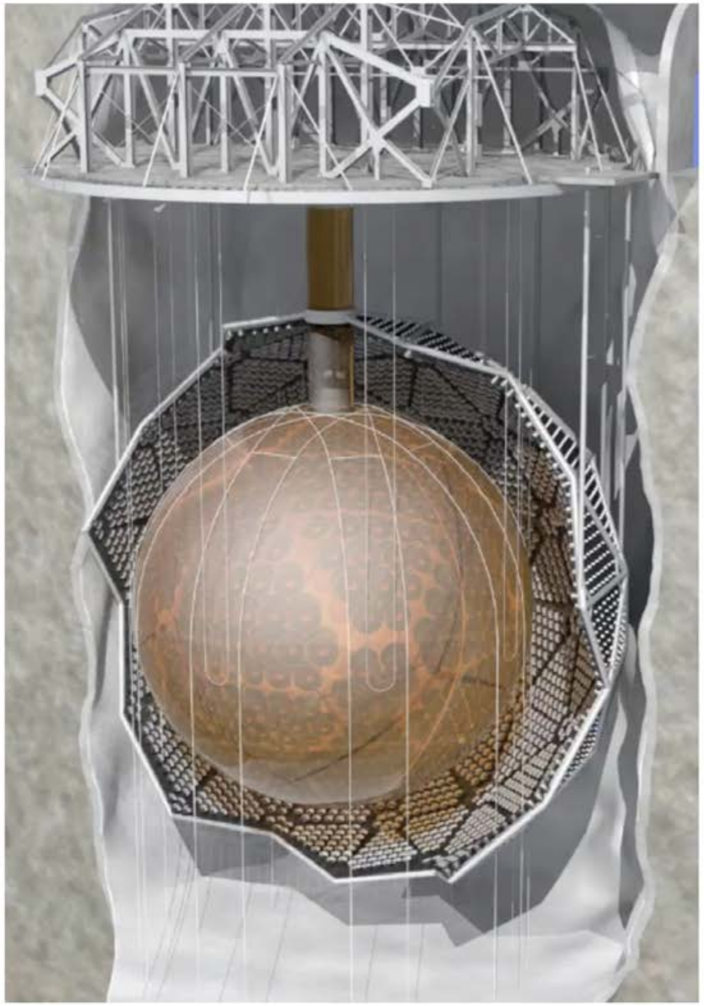


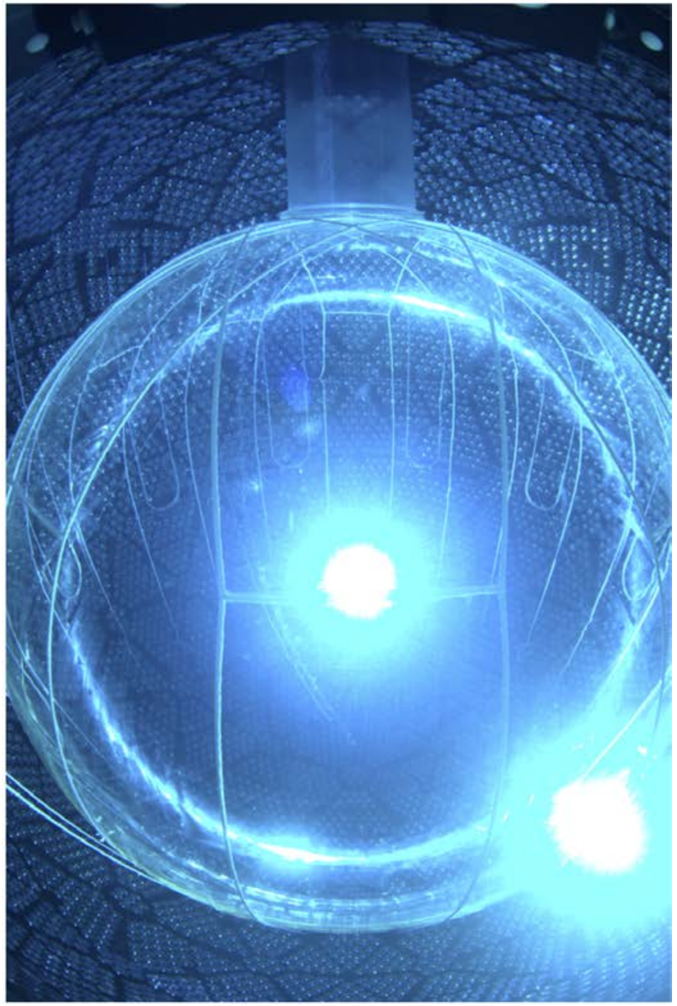
- ❖ First direct measurements of ^{7}Be, pep, pp, and CNO neutrinos
- ❖ Important datasets to study the neutrino oscillation, MSW effect and SSM
- ❖ Insight to the solar metallicity problem, disfavor SSM-LZ at 3.1σ by combining CNO + ^{7}Be + ^{8}B flux

LS-based 0νββ Experiment -- SNO+

A 780 t deep underground (6010 m.w.e.) LS detector at the SNO lab

Multi-purpose: 0νββ of ^{130}Te, solar neutrinos, geo- and reactor neutrinos, supernova, exotic searches





- ^{nat}Te loaded LS in a 12-m diameter acrylic sphere with a hold-down rope-net (polyethylene fibres)
- 9362 8-inch PMTs with light concentrators, effective coverage ~54%
- ~2.4 m shielding with ultra-purity water (UPW) from target to PMTs (7000 t)
- Three operating phases
  - UPW phase: Done, May 2017 – July 2019
  - LS phase: 2.2 g/L PPO in LAB, data taking ongoing
  - 0νββ phase: Te-loading in 2024, 0.5% (1.3 t ^{130}Te) in the 1st step ($T^{1/2}_{0\nu\beta\beta}$~2.1×10^{26} y, 5 yr)
- R&D on higher (up to 3%) Te-loading ongoing

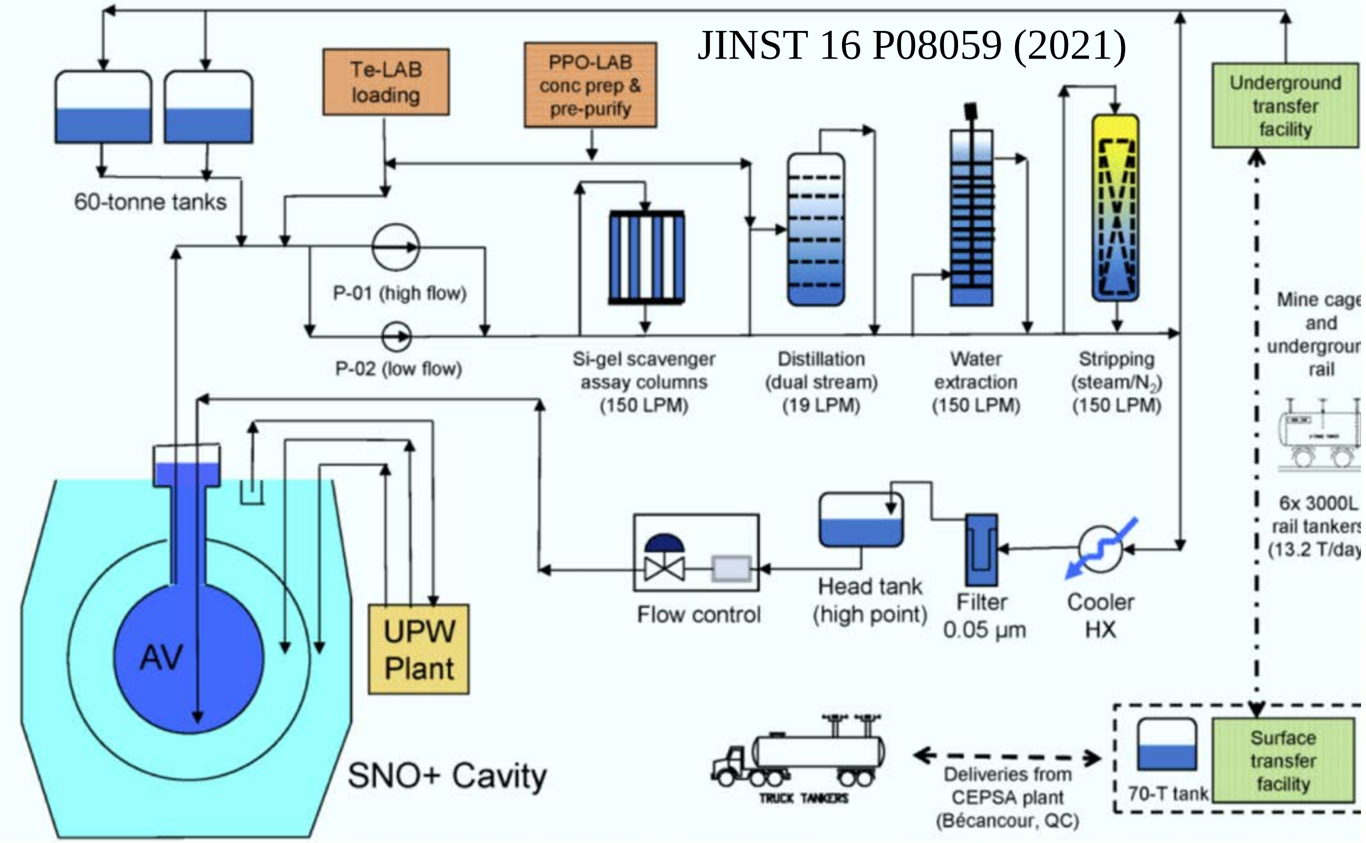
Purification Plant

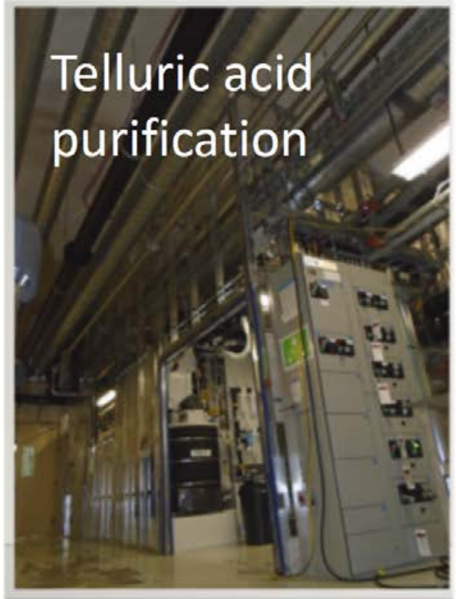
Target of Te-LS radiopurity (0νββ): < $\mathcal{O}(10^{-15} g/g)$

1. UPW system 2. LS purification system 3. Tellurium process system

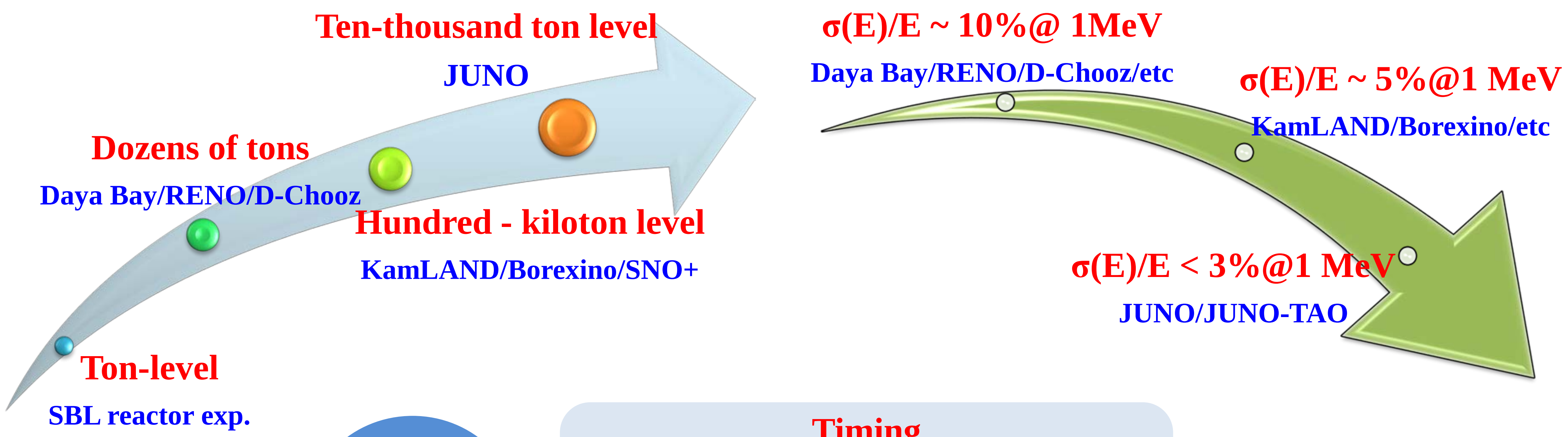
LS purification system

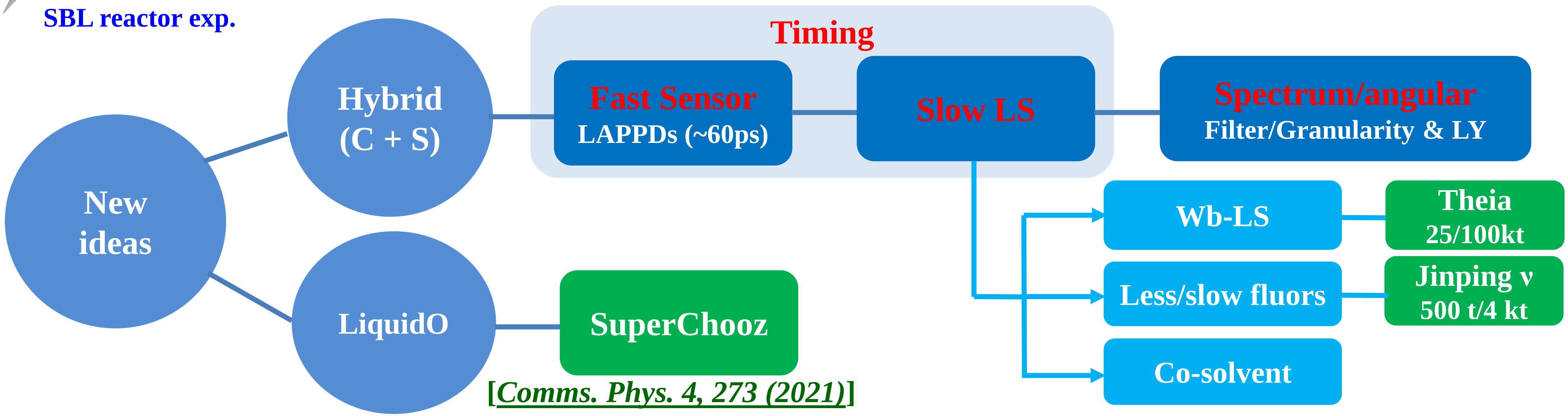
- Leakage: $< 1 \times 10^{-6}$ mbar $\cdot\, L/s$, surface treatment: electropolished 316L stainless steel
- Purification plant:
  - multi-stage distillation
  - Water extraction
  - Gas stripping
  - Metal scavenging
- Being recirculated after filling
  - 1 volume per 100 hours
- Measured RI in the LS phase
  - ^{238}U: 4.7×10^{-17} g/g
  - ^{232}Th: 5.3×10^{-17} g/g





Future Plans





- **Neutrino opens a window to new physics beyond the Standard Model**
- **LS-based detectors played a critical role in neutrino discovery and oscillation parameter measurements in the past**
- **A bunch of LS-based experiments are going to be online to address the open questions of neutrinos**
  - **Small → large (JUNO 20kt, Theia 25kt/100kt), along with many technical challenges**
  - **Precise energy measurements ~10%@1 MeV → < 3% (JUNO/TAO), where is the limit?**
  - **For metal loading (Gd, Te, etc), More R&D required to achieve high concentration**
- **Many new ideas proposed to enhance LS detector capability and reduce costs**
- **A bright future along with challenges**

Thank you