JUNO – Detector Design and Status

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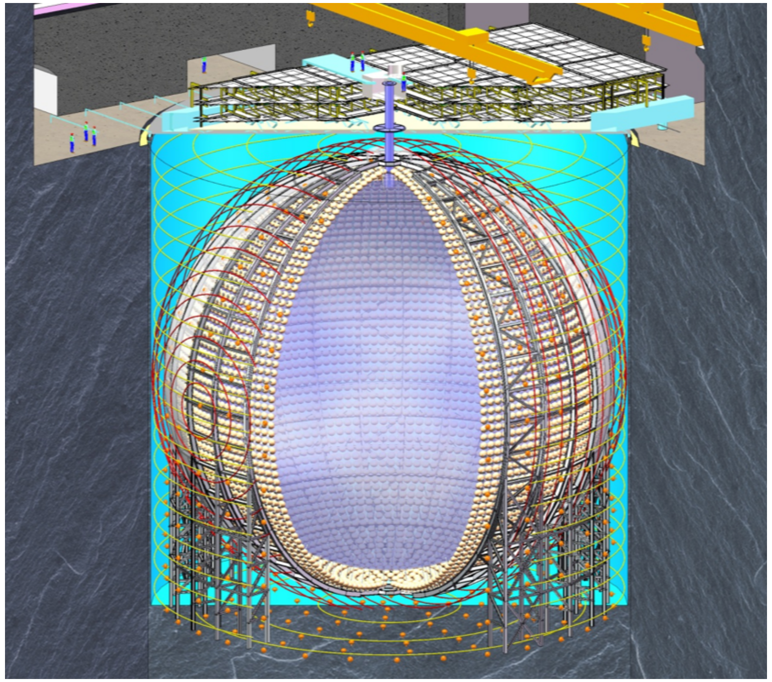
The JUNO Project – An Overview

Jiangmen Underground Neutrino Observatory

Multi-purpose experiment but with a main focus:
Measurement of the Neutrino Mass Ordering using reactor anti-electron neutrinos

Neutrinos from two Nuclear Power Plants
26.6 GW_{th} power by 2020 (35.8 GW_{th} final)



JUNO Central Detector
20 kt Liquid Scintillator Target

The JUNO Collaboration

78 members from 16 countries!
675 collaborators

Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	IMP-CAS	Germany	FZJ-IKP
Belgium	Universite libre de Bruxelles	China	SYSU	Germany	U. Mainz
Brazil	PUC	China	Tsinghua U.	Germany	U. Tuebingen
Brazil	UEL	China	UCAS	Italy	INFN Catania
Chile	PCUC	China	USTC	Italy	INFN di Frascati
Chile	UTFSM	China	U. of South China	Italy	INFN-Ferrara
China	BISEE	China	Wu Yi U.	Italy	INFN-Milano
China	Beijing Normal U.	China	Wuhan U.	Italy	INFN-Milano Bicocca
China	CAGS	China	Xi'an JT U.	Italy	INFN-Padova
China	ChongQing University	China	Xiamen University	Italy	INFN-Perugia
China	CIAE	China	Zhengzhou U.	Italy	INFN-Roma 3
China	DGUT	China	NUDT	Latvia	IECS
China	ECUST	China	CUG-Beijing	Pakistan	PINSTECH (PAEC)
China	Guangxi U.	China	ECUT-Nanchang City	Russia	INR Moscow
China	Harbin Institute of Technology	Croatia	UZ/RBI	Russia	JINR
China	IHEP	Czech	Charles U.	Russia	MSU
China	Jilin U.	Finland	University of Jyvaskyla	Slovakia	FMPICU
China	Jinan U.	France	IJCLab Orsay	Taiwan-China	National Chiao-Tung U.
China	Nanjing U.	France	CENBG Bordeaux	Taiwan-China	National Taiwan U.
China	Nankai U.	France	CPPM Marseille	Taiwan-China	National United U.
China	NCEPU	France	IPHC Strasbourg	Thailand	NARIT
China	Pekin U.	France	Subatech Nantes	Thailand	PPRLCU
China	Shandong U.	Germany	FZJ-ZEA	Thailand	SUT
China	Shanghai JT U.	Germany	RWTH Aachen U.	USA	UMD-G
China	IGG-Beijing	Germany	TUM	USA	UC Irvine
China	IGG-Wuhan	Germany	U. Hamburg		

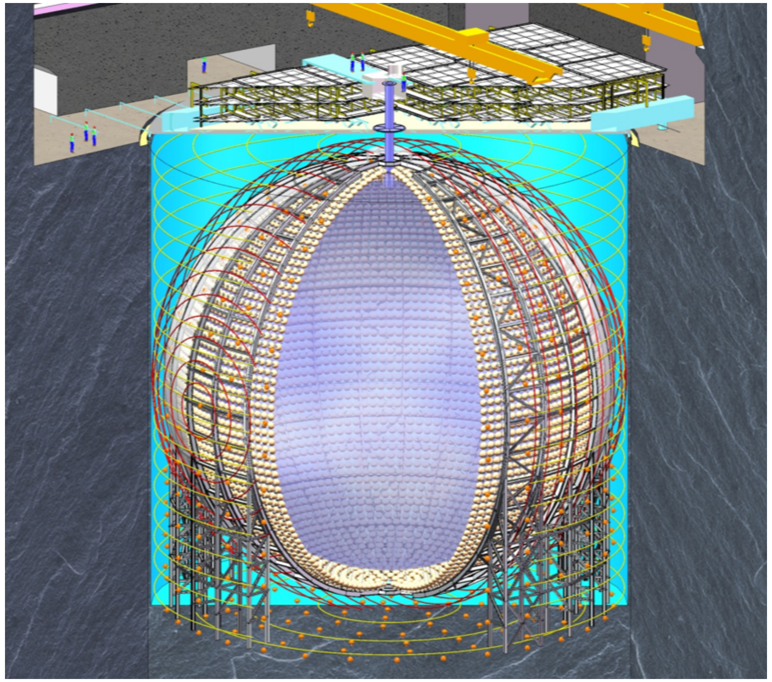
JUNO physics prospects - neutrino mass ordering and beyond

Supernova Neutrinos
(burst)
5000 in 10 s for 10 kpc

Diffuse Supernova Neutrinos
~ 3 / year

Solar Neutrinos
(~ 10000 / day)

Atmospheric Neutrinos
several / day



Proton Decay Search
$p \to K^+ + v$

Cosmic Muons
~ 250k / day, <E>=215 GeV

Reactor Neutrinos
~ 60 / day

Geo Neutrinos
~ 1 / day

JUNO Yellow Book
arXiv:1507.05613

The Neutrino Mass Ordering

$$\Delta m_{ij}{}^2 = m_i{}^2 \text{ - } m_j{}^2$$

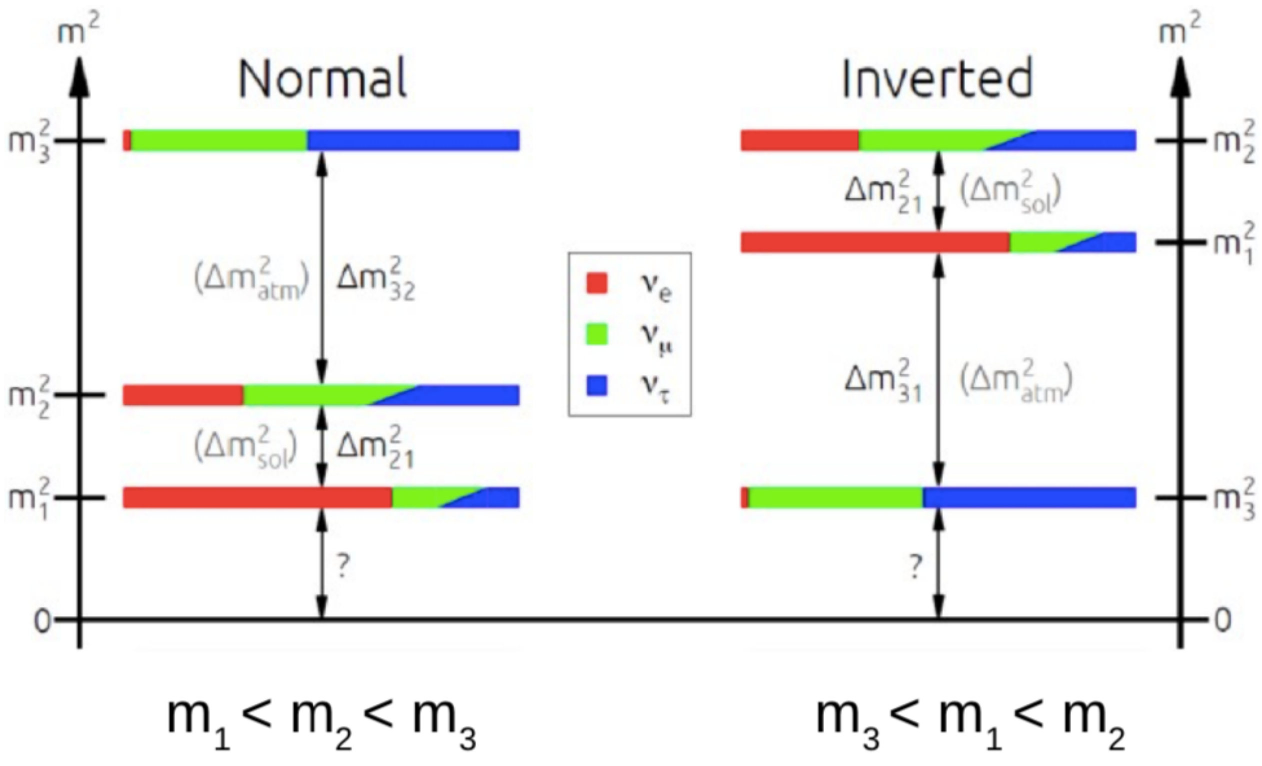
$$\Delta m_{21}{}^2 = 7.5 \times 10^{-5} (eV)^2$$ Slow Oscillation!

$$|\Delta m_{31}{}^2| = 2.4 \times 10^{-3} (eV)^2$$ Fast Oscillation!

The sign and the absolute value of $\Delta m_{31}{}^2$ depend on the **Neutrino Mass Ordering**!

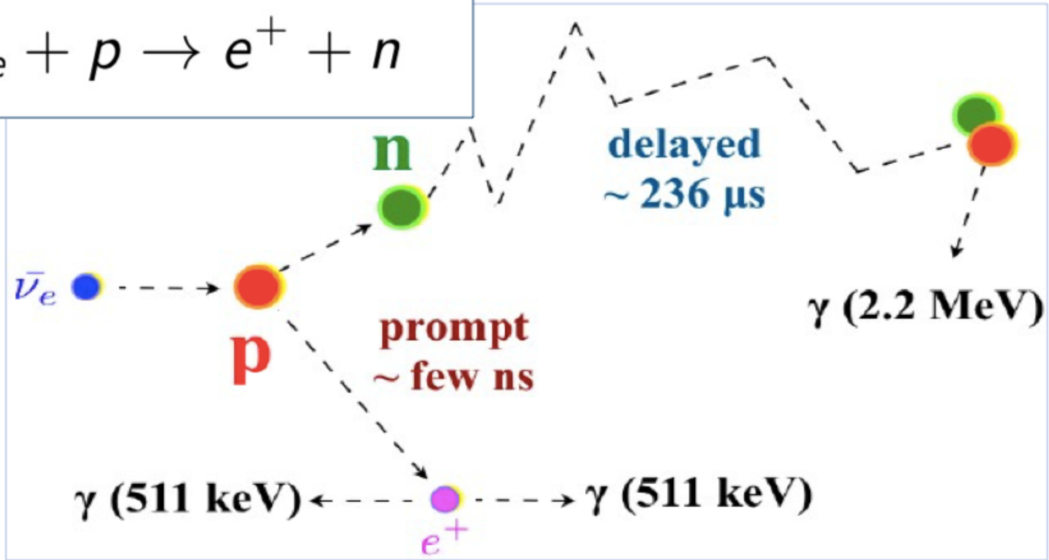
Solving the Mass Ordering problem is a key for other open questions in neutrino physics:

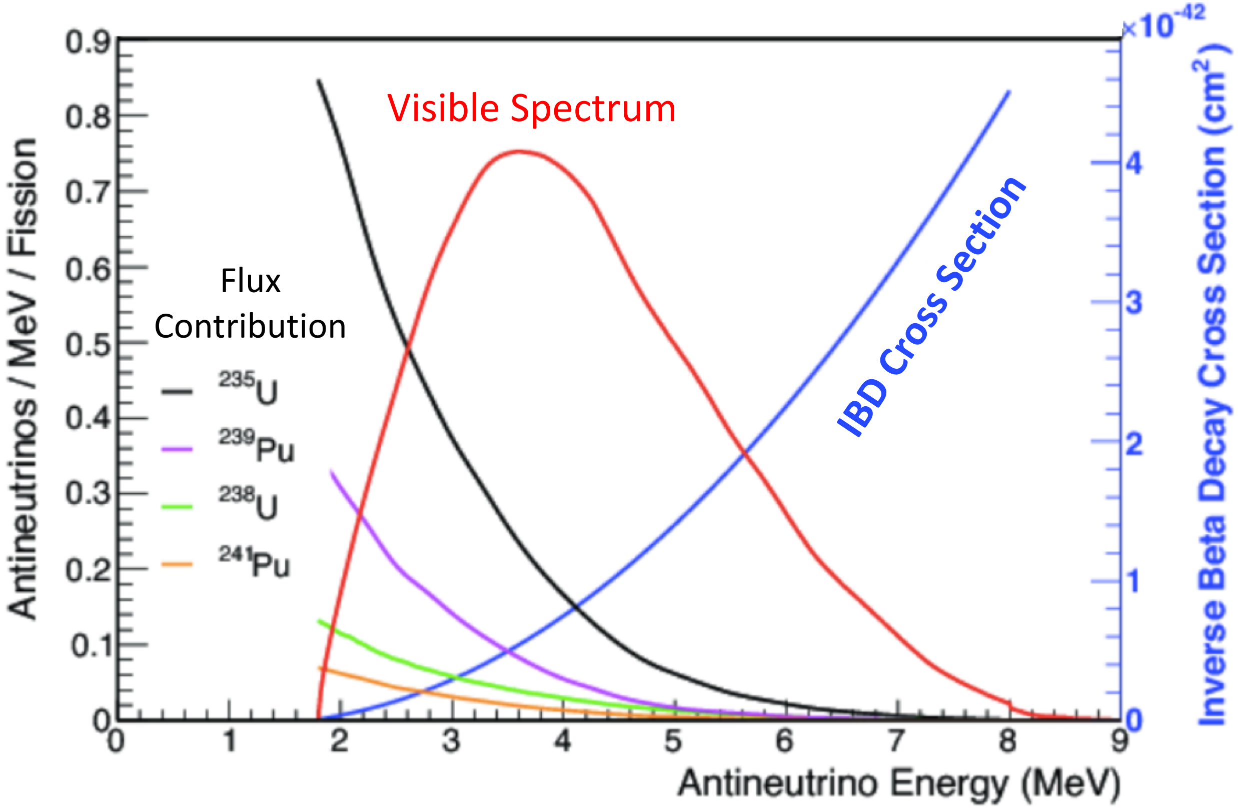
- $0\nu\beta\beta$ decay – Majorana or Dirac neutrinos?
- δ_{CP} in the neutrino sector?
- Octant of θ_{23}?



Detection of electron anti-neutrinos

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





Detection via the Inverse Beta Decay (IBD)

Golden Channel for the detection of neutrinos

- High cross section
- Two signal coincidence (~ 236 µs)
- ν energy can be reconstructed from e^+ signal
- Threshold of 1.8 MeV

Requirements for the JUNO Detector

Reactor baseline variation: < 0.5 km

JUNO site in Jiangmen meets this requirements!

Energy resolution: $\sim \frac{3\%}{\sqrt{E(MeV)}}$

This is a crucial parameter!

Energy scale uncertainty:

Large uncertainties and unknown non-linearity could lead to the wrong mass ordering result!

→ Meticulous Calibration!

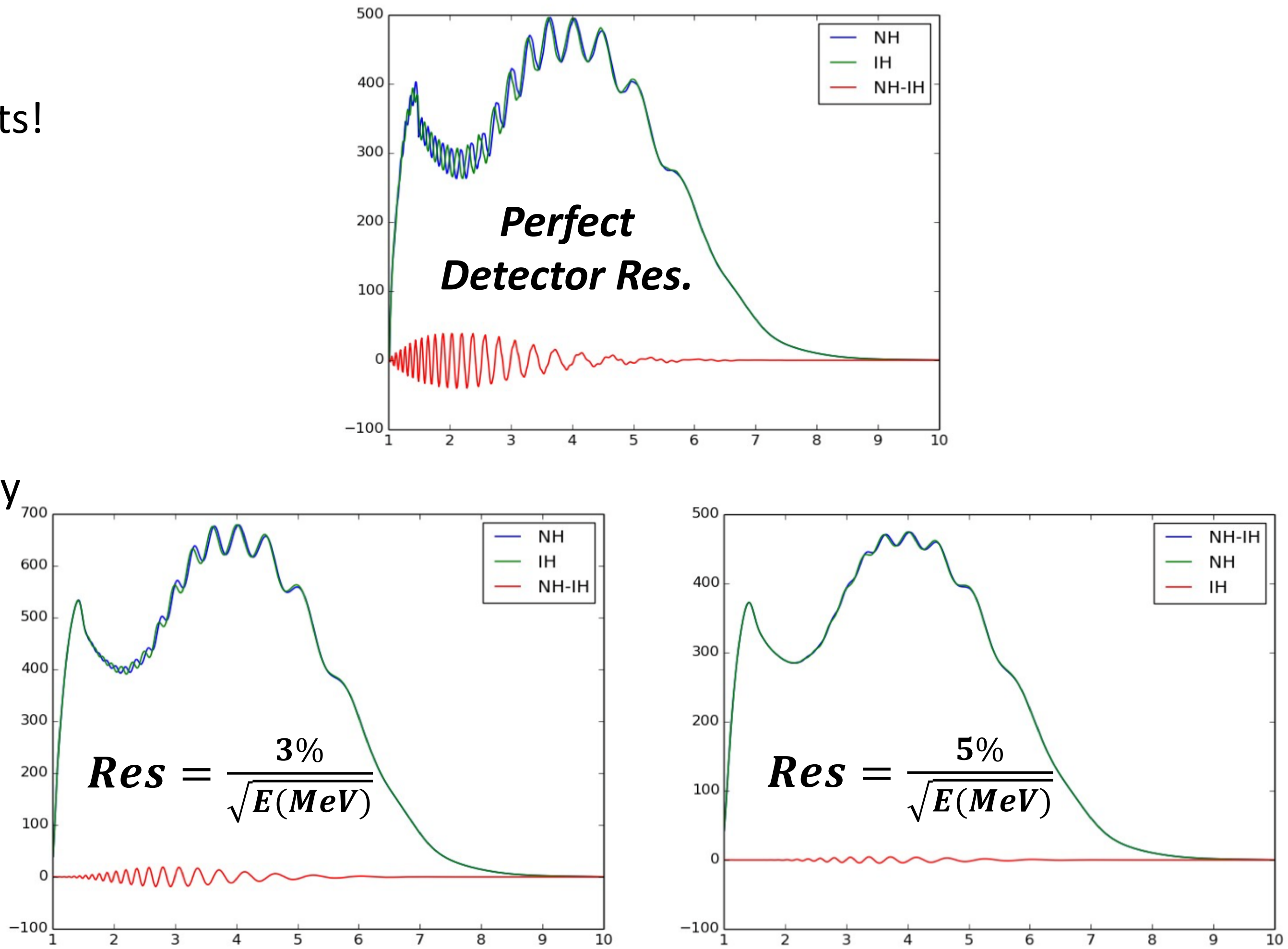
→ Double calorimetry (small + large PMTs)

Statistics: 100 kEvents within 6 years!

26.6 GW_{th} reactor power

20 kt detector target ($\sim$ 60 Evts. / Day)

Minimization of the vetoed volume by precise muon track reconstruction



Energy spectrum of the JUNO $\overline{\nu}_e$ events

(Effect of the energy resolution on the expected signal)

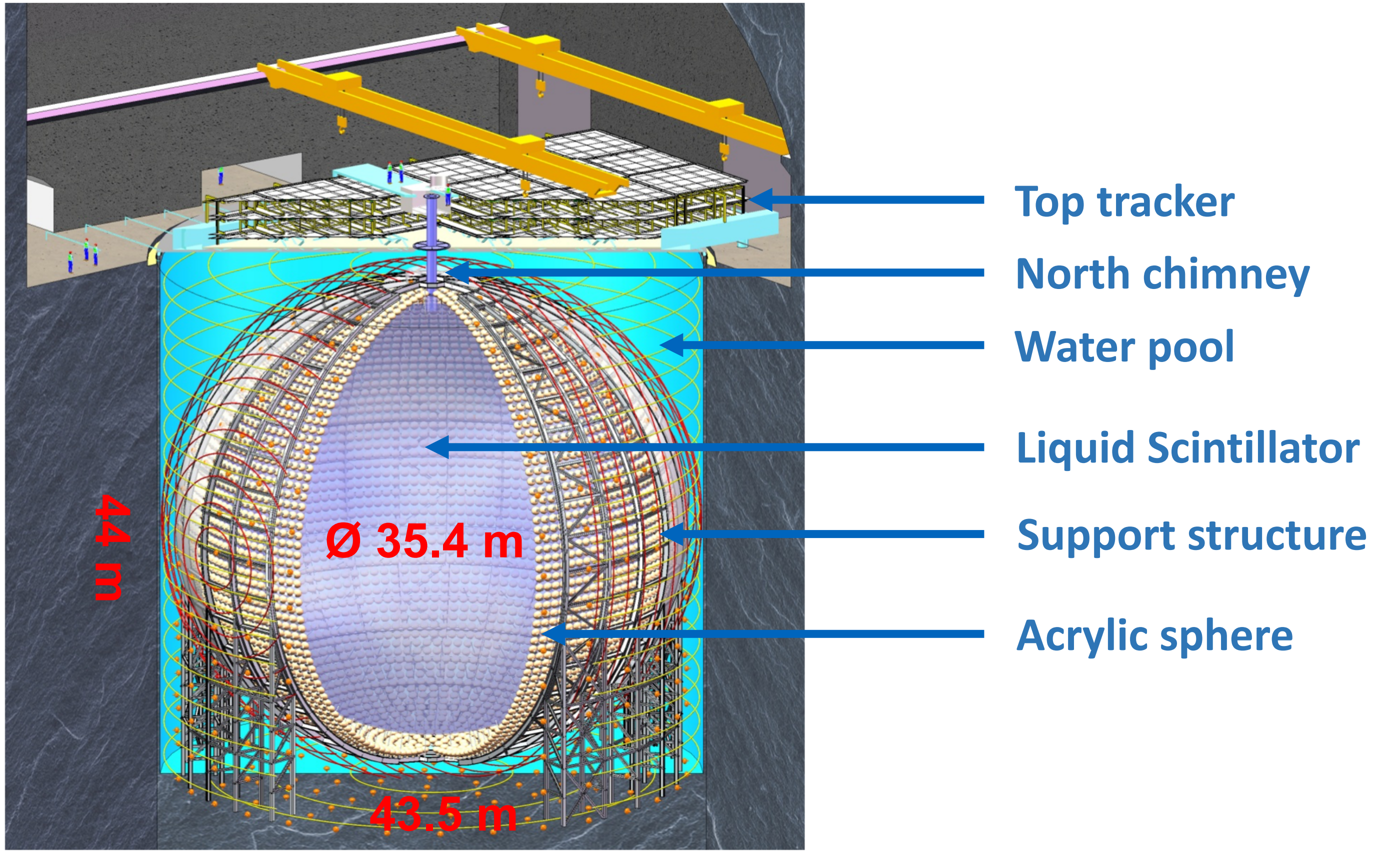
Overall Detector Design and Veto

Central detector:
- Acrylic sphere with liquid scintillator
- 17571 large PMTs (20-inch)
- 25600 small PMTs (3-inch)
- 78% PMT coverage
- PMTs in water buffer

Water Cherenkov muon veto:
- 2400 20” PMTs
- 35 ktons ultra-pure water
- Efficiency > 95%
- Radon control → less than 0.2 Bq/m3

Compensation coils:
- Earth magnetic field <10%
- Necessary for 20” PMTs

Top tracker:
- Precision muon tracking
- 3 plastic scintillator layers
- Covering half of the top area

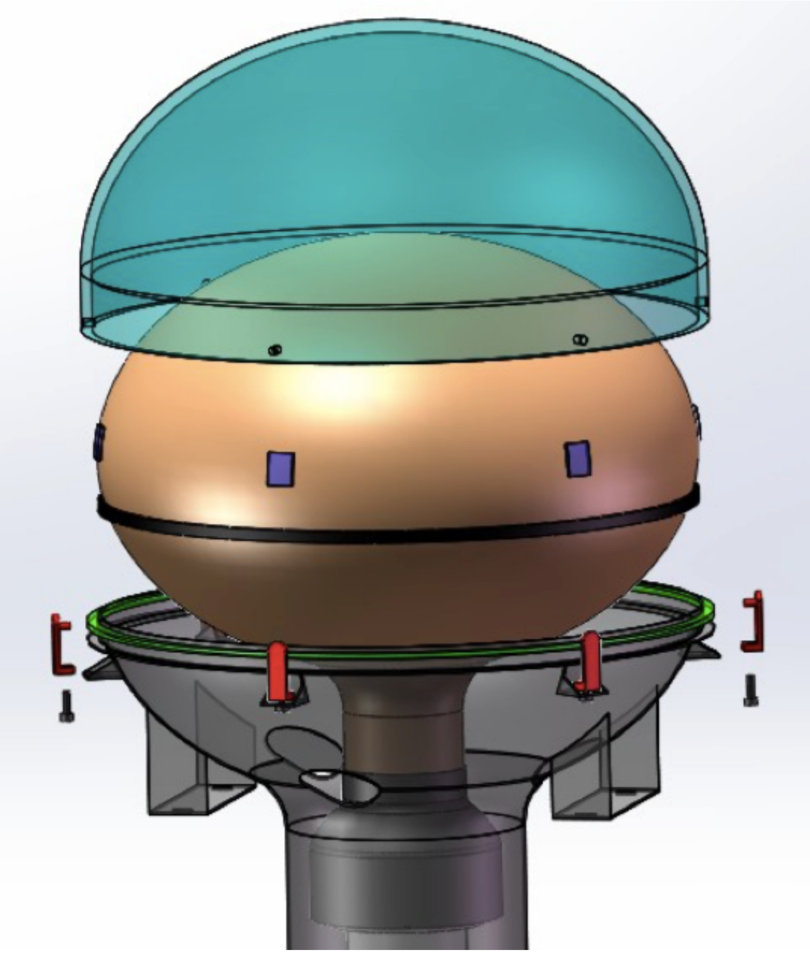


Experiment	Daya Bay	Borexino	KamLAND	JUNO
LS Target Mass [t]	8 x 20	~ 300	~ 1000	*20000*
Collected p.e./MeV	~ 160	~ 500	~ 250	*~ 1200*
Energy resolution @ 1 MeV	~ 8.5 %	~ 5 %	~ 6%	*~ 3 %*

Large PMT Array

- 15000 MCP-PMTs from NNVT (Northern Night Vision Technology)
- 5000 dynode PMTs from Hamamatsu (R12860 HQE)
- 17571 PMTs will read out the scintillation light of the Central Detector
- All PMTs delivered to the JUNO site!
- PMT testing:
    - Acceptance tests finished
    - Tests with final electronics ongoing

Specifications	Unit	MCP-PMT (NNVT)	R12860 Hamamatsu HQE
Det. Efficiency (QE*CE)	%	26.9% (**new Type: 30.1%**)	28.1%
Peak to Valley of SPE		3.5, (>2.8)	3, (>2.5)
TTS on the top point	ns	12, (<15)	**2.7, (<3.5)**
Rise time / Fall Time	ns	RT~2, FT~12	RT~5, FT~9
Anode Dark Count	kHz	20, (<30)	10, (<50)
After Pulse Rate	%	1, (<2)	10, (<15)
Radioactivity (glass)	ppb	**^{238}U: 50** **^{232}Th: 50** **^{40}K: 20**	^{238}U: 400 ^{232}Th: 400 ^{40}K: 40



Large PMT Testing

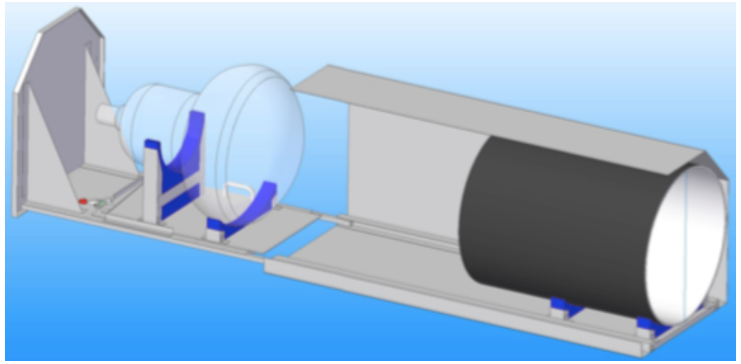
PMT Testing Containers (all PMTs):

- Capacity: 36 (-5) PMTs per Container
- Relative PDE Measurement
  - 1 fixed & 4 rotating reference PMTs
- Four containiers
- Magnetic shielding: 10% EMF
- Climate control systems
- Two light sources:
  - stabilized LED
  - Picosecond-Laser
- Averaged PDE: 28.7%, (28.1% for dynode PMTs, 28.9% for MCP-PMTs)

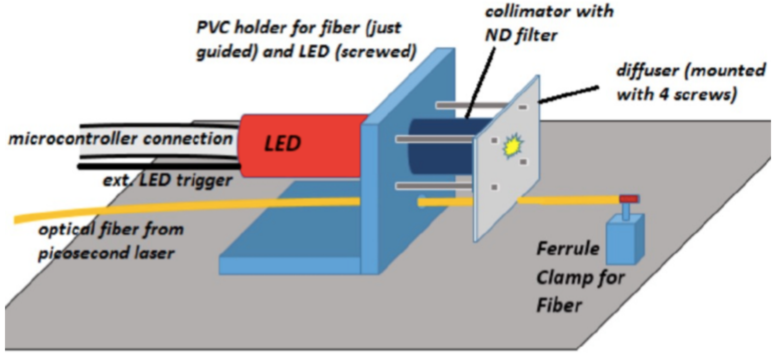
Scanning Station (5-10% of PMTs):

- Provide non-uniformity measurement of PMT parameters
- Study dependence of PMT performance on magnetic field
- Provide a tool for precise PMT studies and cross calibration

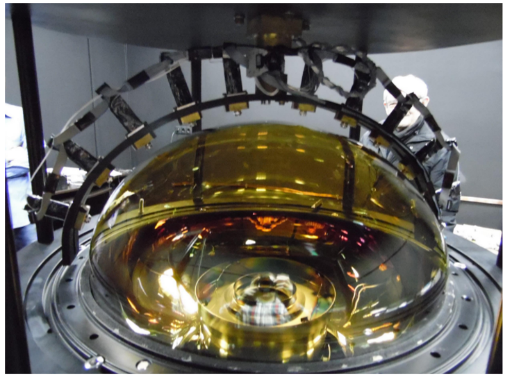
Two testing containers in Zhongshan (Pan-Asia).



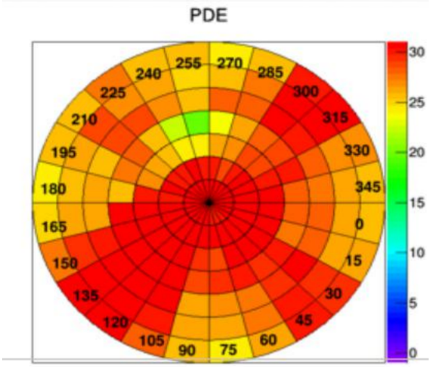
PMT test box with PMT holder



Light sources used in the testing containers



PMT in the scanning station



PDE differences (photocathode)

Small PMT Array

Double calorimetry

"Always" in photon counting mode

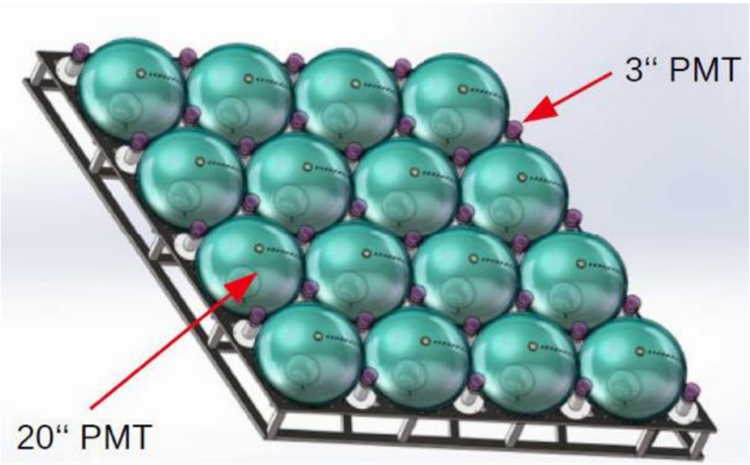
Less non-linearity: calibration of large PMT array

Better dynamic range for high energy signals

Higher granularity of the CD

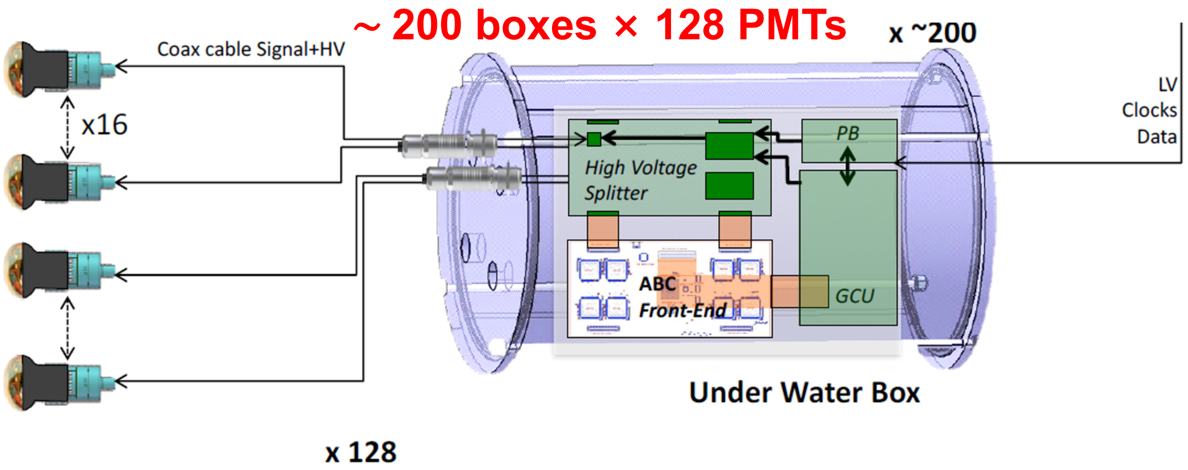
25600 PMTs in the Central Detector
- **2.5% coverage**
- Provided by HZC Photonics (Hainan, PR China)

Can effectively help in:
- Muon tracking (+ shower muon calorimetry)
- **Supernova readout**
- Solar oscillation parameter measurement



Arrangement of large and small PMTs

JUNO custom design: XP72B22
QE 24%, Peak / Valley 3.0, TTS 2-5 ns



Under water box provides supply for 128 PMTs
(Prototype already built and successfully tested!)

Liquid scintillator purification pilot plants (in Daya Bay)

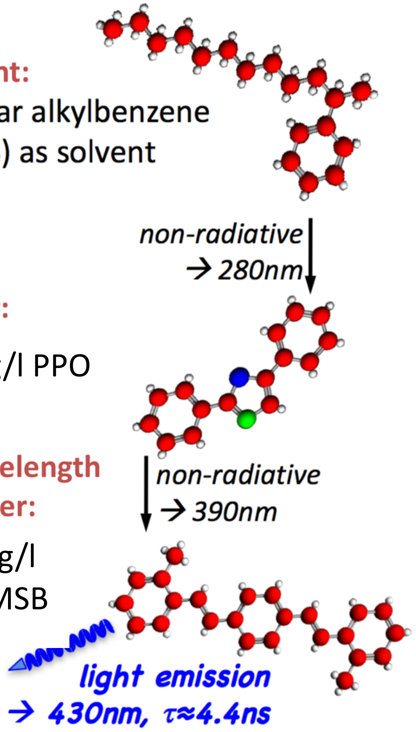
Solvent:
Linear alkylbenzene (LAB) as solvent

\+

Fluor:
2.5 g/l PPO

\+

Wavelength shifter:
3 mg/l bisMSB



Pilot plants for all purification steps with a capacity of **~100 l/h** were **installed in Daya Bay** in 2017.

Extensive **testing** with one of the **Daya Bay (DYB) antineutrino detectors** (AD1) in 2017-2019!

Purification of LAB in 4 Steps:

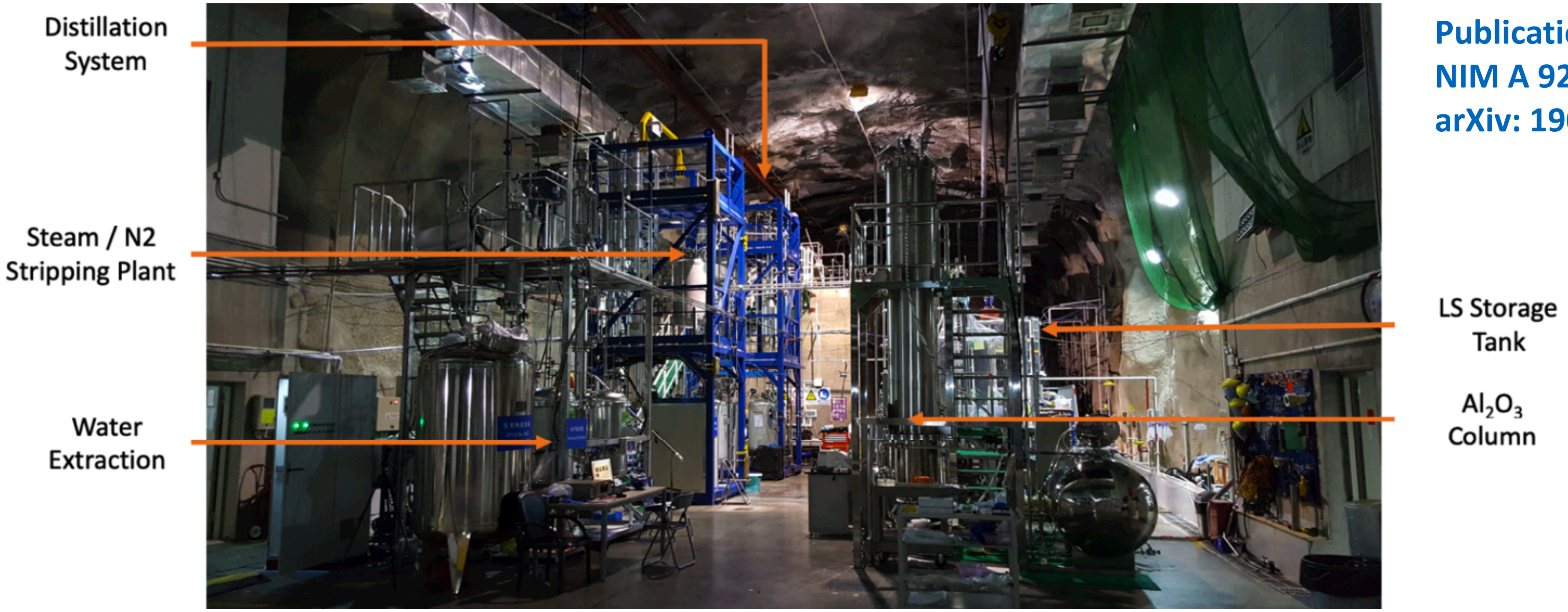
- **Al_2O_3 filtration column:** improvement of **optical properties**
- **Distillation:** removement of **heavy metals**, improvement of transparence
- **Water Extraction:** removement of **radio isotopes** from uranium and thorium chain and furthermore of ^{40}**K** **(underground)**
- **Steam / Nitrogen Stripping:** removement of **gaseous impurities** like Ar, Kr, and Rn **(underground)**

Optical Requirements:

Light output: **~10.000 Photons / MeV → ~1200 p.e. / MeV**
Attenuation length: **> 20 m @ 430 nm**

Required Radiopurity:

Reactor neutrinos: ^{238}**U /** ^{232}**Th < 10^{-15} g/g,** ^{40}**K < 10^{-16} g/g**
Solar neutrinos: ^{238}**U /** ^{232}**Th < 10^{-17} g/g,** ^{40}**K < 10^{-18} g/g,** ^{14}**C < 10^{-18} g/g**



Publication:
NIM A 925 (2019) 6, arXiv: 1902.05288

Liquid scintillator purification pilot plants (in Daya Bay)

Optical properties:

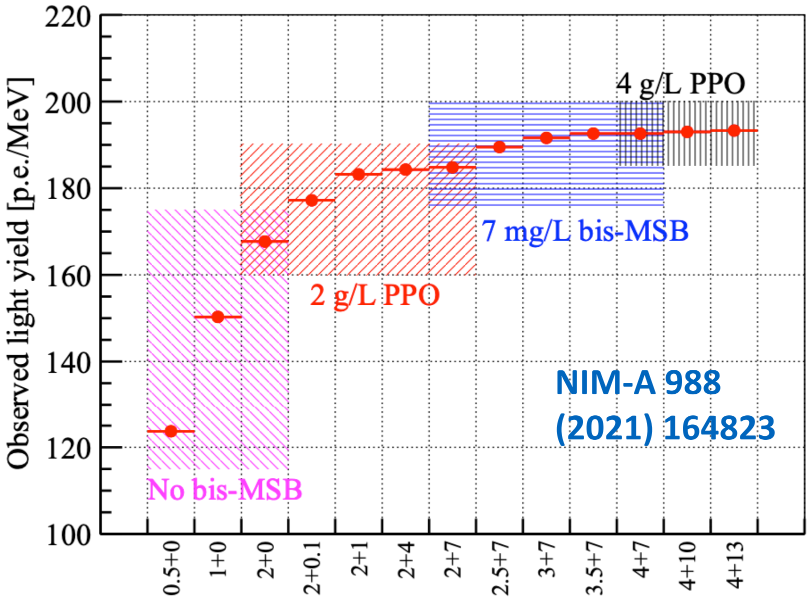
During extensive calibrations the recipe of the LS was refined.

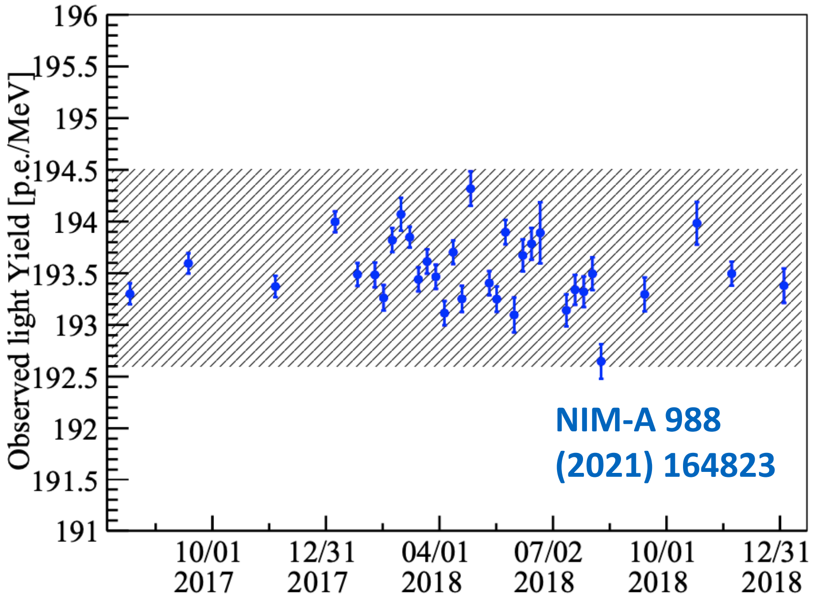
Light Yields above 10.000 Photons / MeV were achieved.

Excellent stability of the light yield in the detector was observed during 14 month of measurement.

Preliminary JUNO mixture: **LAB + 2.5 g/l PPO + 3mg/l bisMSB**

Attenuation length of LAB improved by the purification from ~ 14 m to ~ 28 m @ 430 nm





Radiopurity:

The concentrations of ^{238}U / ^{232}Th were determined with the 24 t DYB AD1 exploiting the fast Bi/Po-coincidences of the decay chains.

Results: (Test in 2017)

$$C(^{238}U) = (7.52 \pm 1.41(sys.) \pm 0.37(stat.)) \times 10^{-15} g/g$$

$$C(^{232}Th) = (3.24 \pm 1.00(stat.) \pm 0.66(sys.)) \times 10^{-15} g/g$$

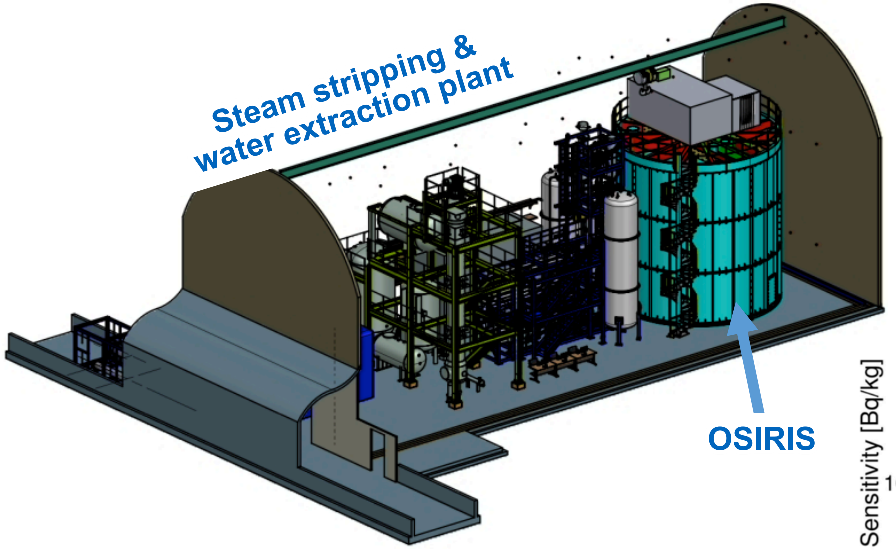
OSIRIS - Online Scintillator Internal Radioactivity Investigation System

Liquid Scintillator purity monitor

Idea:

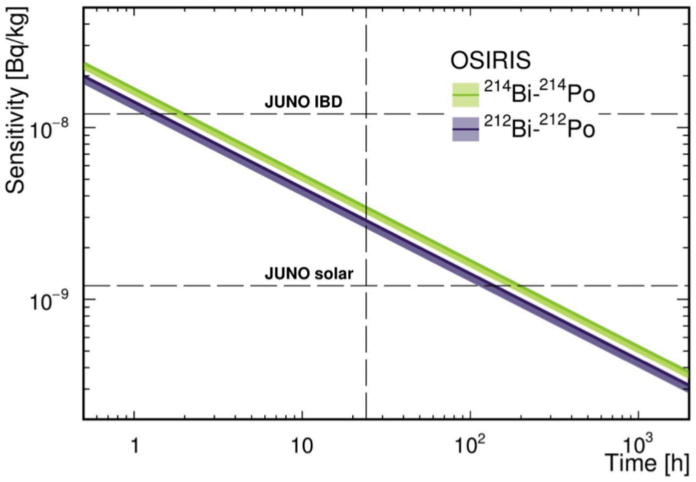
Detect radioactive contaminated scintillator ***after purification***
but ***before filling*** *it into the acrylic vessel!*

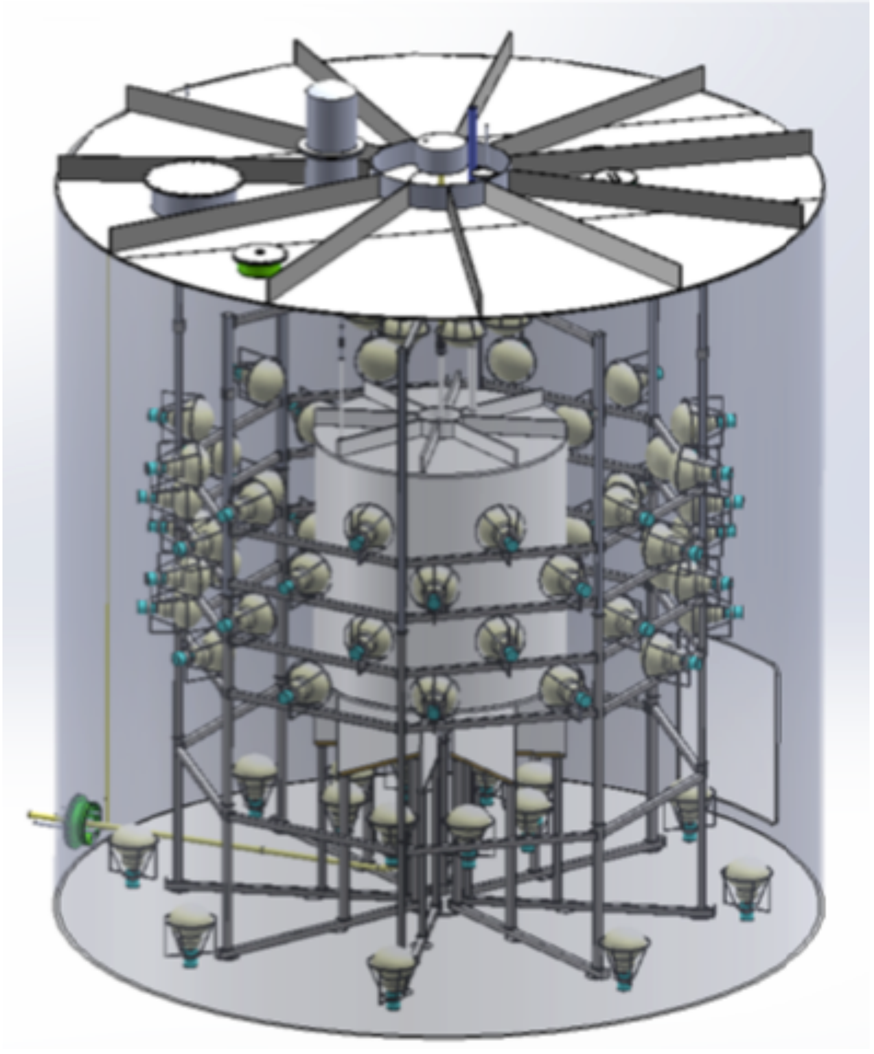
Exploit fast coincidences in the ^{238}U and ^{232}Th chains!



18 t LS volume (Ø=3 m, H=3 m)

Instrumentation:
~68x 20” PMTs for the scintillator
~12x 20” PMTs for the muon veto

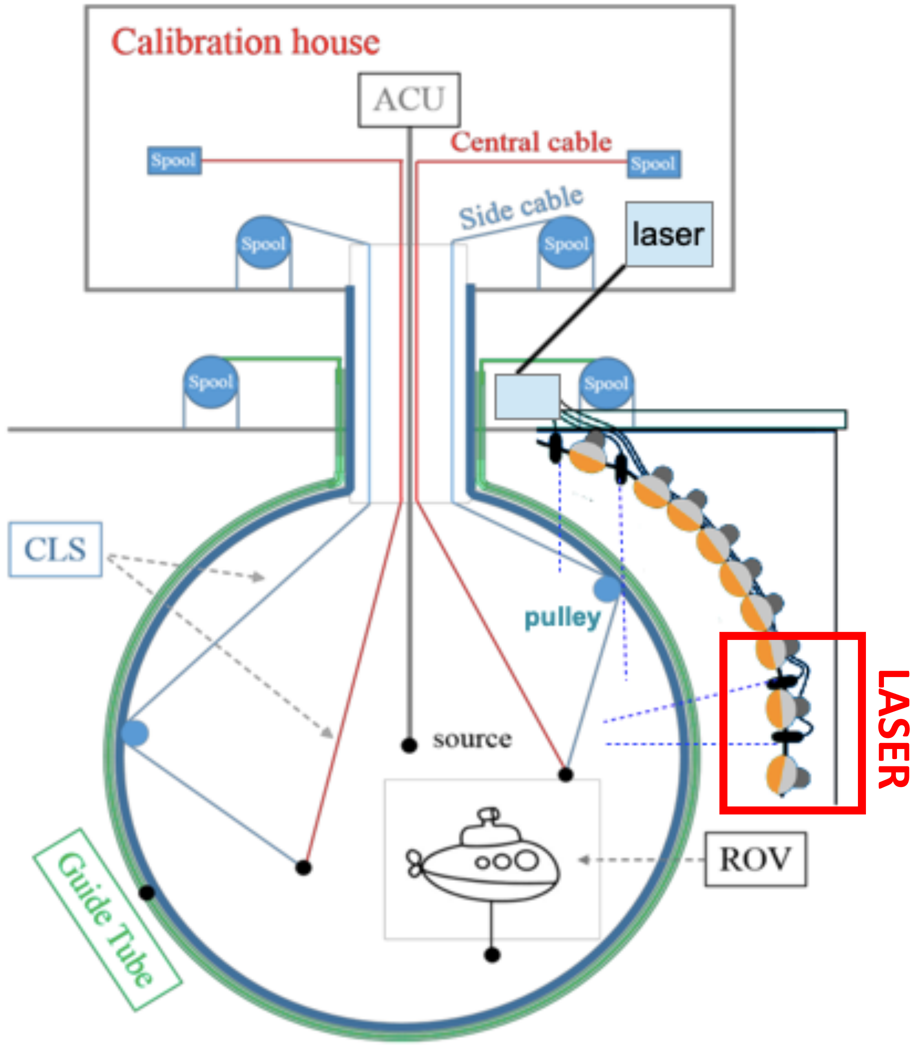




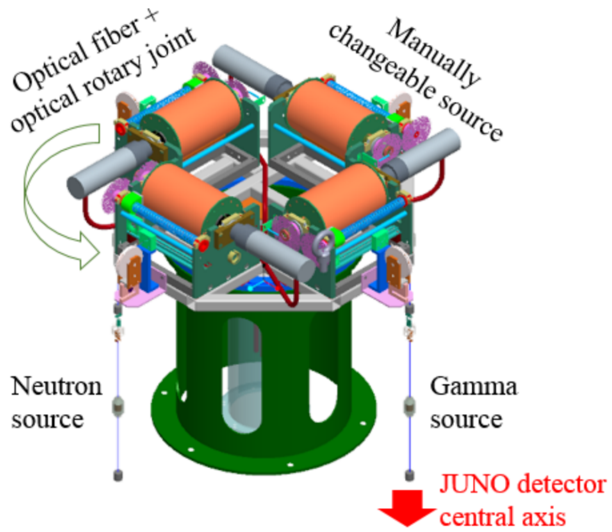
Expected Sensitivity (Simulation):
JUNO IBD limit within a few hours
JUNO solar limit possible

Calibration Systems

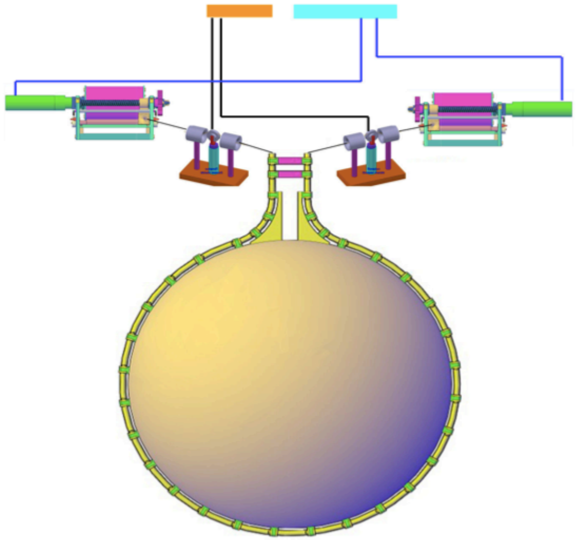
Paper: Calib. Strategy arXiv:2011.06405



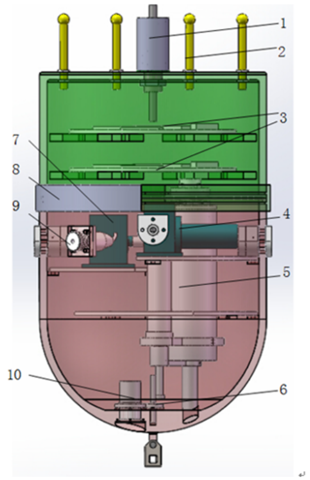
Overview of JUNO‘s Calibration Systems (including laser calibration system)



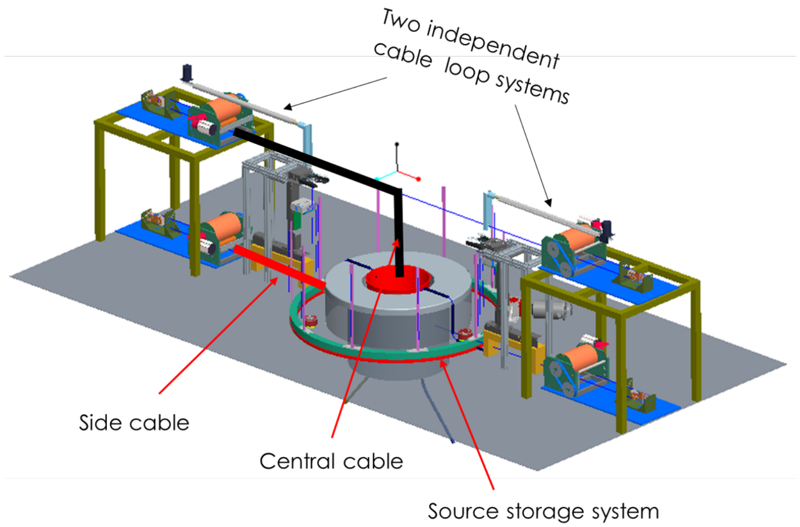
ACU (Automatic Calibration Unit)



Guide Tube System



ROV (Remotely Operated Vehicle)



Cable Loop System

JUNO TAO - Taishan Antineutrino Observatory

Measure reactor anti-neutrino spectrum with high resolution

- provide **model-independent reference for JUNO**
- benchmark to **test nuclear databases**
- provides increased reliability in measured **isotopic antineutrino yields**
- improve nuclear physics **knowledge of neutron-rich isotopes**
- shed light on **reactor spectrum anomaly** (5 MeV bump)
- searching for **light sterile neutrinos** with a mass ~1 eV
- ~36 × JUNO statistics

TAO Design Features:

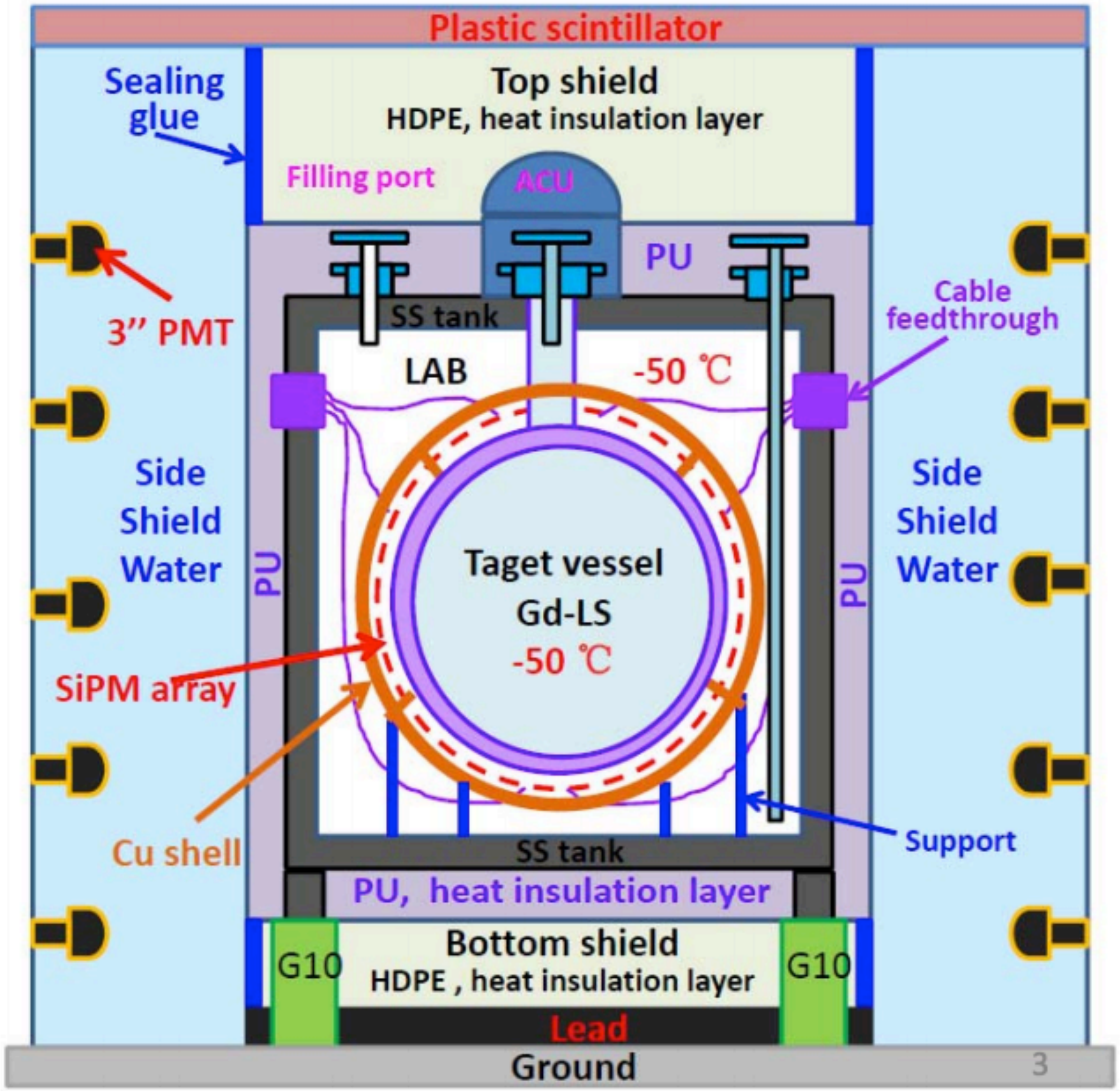
- **2.6 ton Gd-LS** as target material (1 ton fiducial mass)
- Detector placed at **30 m distance** from a **4.6 GW$_{th}$** reactor core
- **10 m² SiPM**, with **50% PDE, Coverage: > 95%**
- ***SiPMs and LS cooled down to -50 °C (-60 °C)***

Conceptual Design Report Released in May 2020! arXiv: 2005.08745v1

Expected Performance:

- **~ 4500 p.e. / MeV** collected charge
- Energy Resolution: **~ 1.7% @ 1 MeV, < 1.0% above 3 MeV**

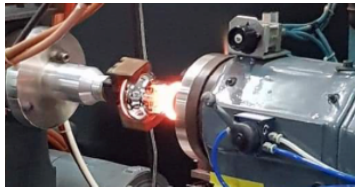
Planned to be online when JUNO starts the data taking!



Schedule & Milestones

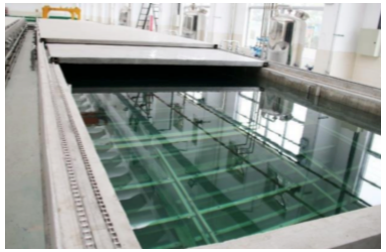
2014

- Int. Collaboration established!



2015

- PMT production line setup
- Start civil construction
- CD parts R&D



2016

- Start PMT production
- Start CD parts production

2017

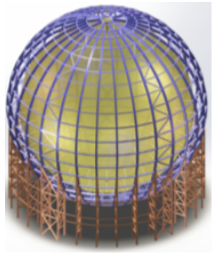
- Start PMT testing
- Top Tracker arrived!
- Daya Bay LS tests

2018

- PMT potting start
- Delivery of surface buildings
- Start production of acrylic sphere
- OSIRIS was funded
- TAO working group formed

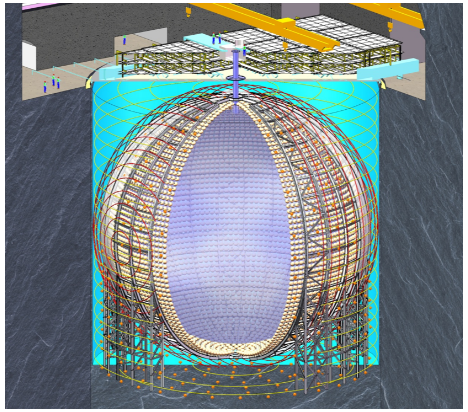
2019-20

- Electronics production starts
- Civil work and lab preparation
- Det. construction starts



2021-22

- Det. assembly completed
- Det. filling & comissioning
- TAO construction



Data Taking


Thank you for your attention!

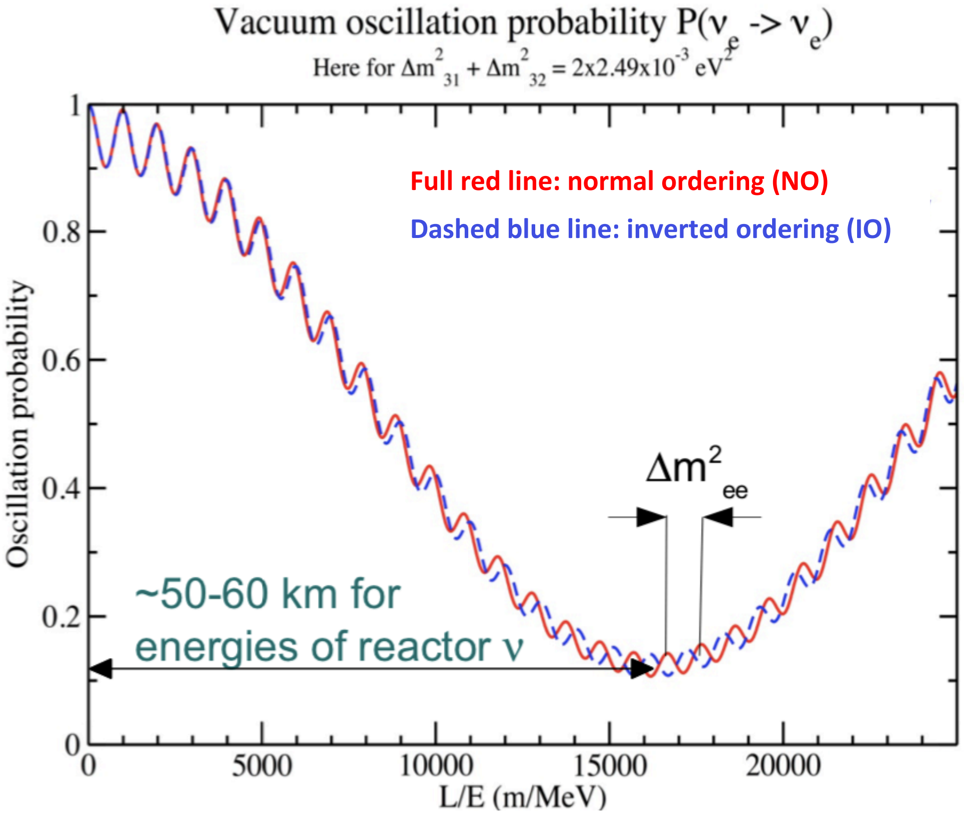
Backup Slides

The Neutrino Mass Ordering

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

$$\approx \boxed{1 - cos^4\theta_{13} sin^2 2\theta_{12} sin^2 \Delta m^2_{21} \frac{L}{4E}} - \boxed{sin^2\theta_{13} sin^2 \Delta m^2_{ee} \frac{L}{4E}} \quad for \quad \Delta m^2_{12} \ll \Delta m^2_{32}$$

Δm^2_{ee}
effective ν-mass-squared difference
(beat frequency)



With:

$\Delta m^2_{12} \ll \Delta m^2_{32}$

$$\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$$

NO: $|\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$

IO: $|\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$

Different beat frequency Δm^2_{ee} for both orderings!

How to control the energy scale uncertainties?

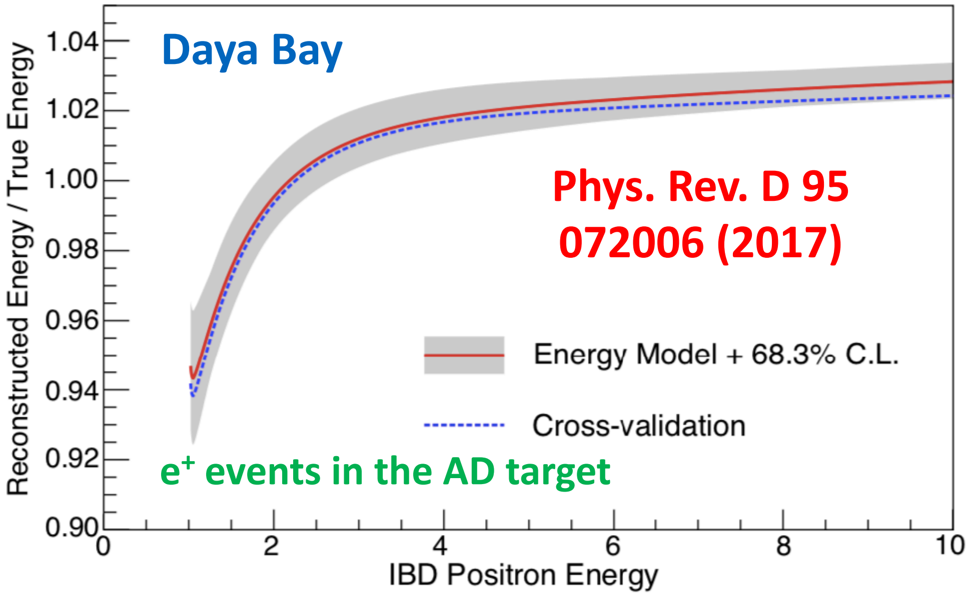
How to reach <1% uncertainty on the energy scale?

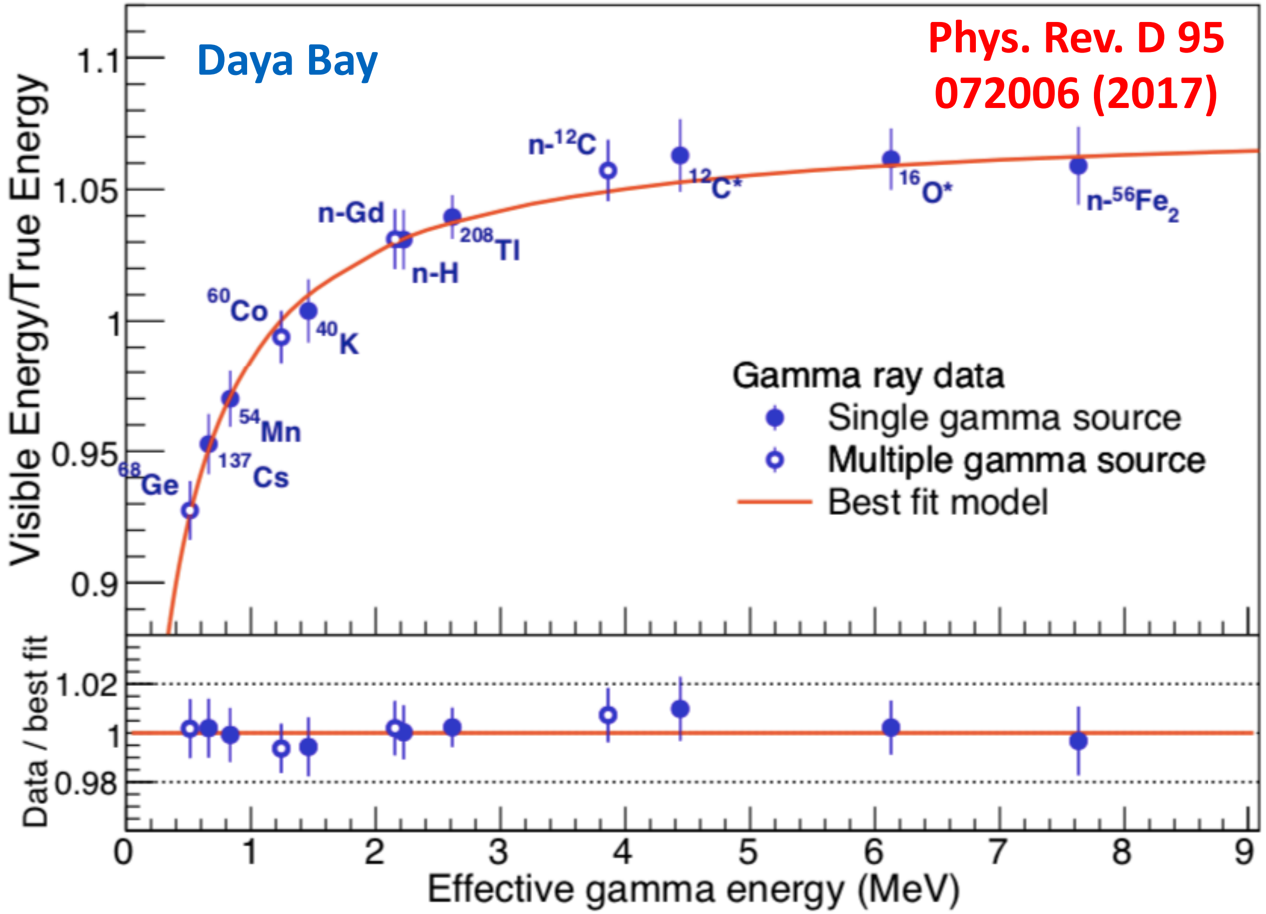
Answer: Meticulous Calibration!

- **Many sources** over the whole energy range!
- Many positions to **keep residual non-uniformity low**!

Other experiments already achieved 1% accuracy:

- Daya Bay: ~0.5%, Double Chooz: 0.74%
- Borexino <1% (at low energies), KamLAND 1.4%





Ratio of observed energy to true energy for γ-rays

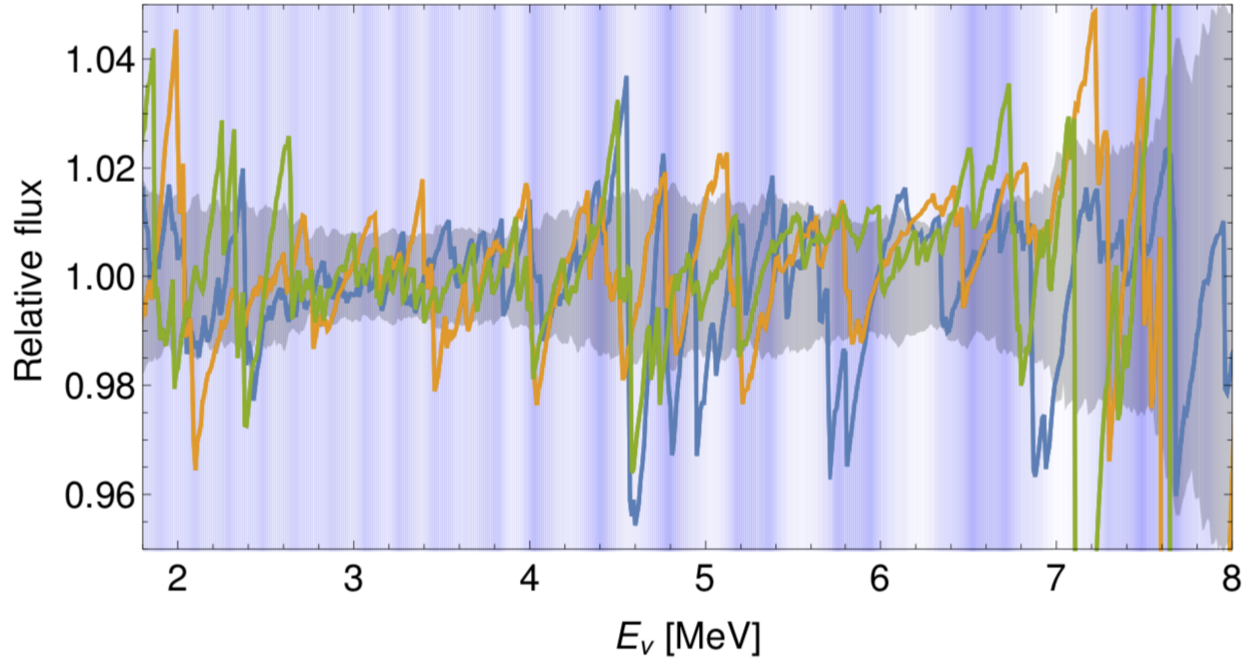
E_{rec} / E_{true} for positron interactions

68 % C.L. region constrains the ratio to better than 1%

Reactor spectrum uncertainties

- Reactor spectrum might show **micro-structure**
  - A. A. Sonzogni, et al. arXiv:1710.00092
  - D. A. Dwyer & T. J. Langford, Phys. Rev. Lett. 114,012502 (2015)
- It might **degrade the MO sensitivity** by mimicking the periodic oscillation structures
- A known fine structure does not hurt for the Mass Ordering measurement!
  - Tested with multiple test spectra from an ab-initio calculation (PRL 114, 012502 (2015))
- An **unknown fine structure might be harmful**!
  - Current **databases rely on experimental data**!
  - **No information beyond measured energy resolution** in the databases!

arXiv:1710.07378

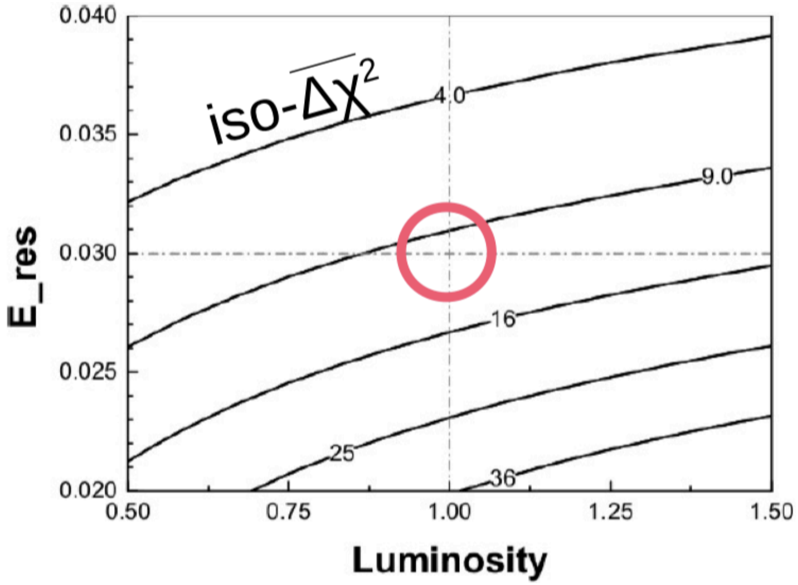


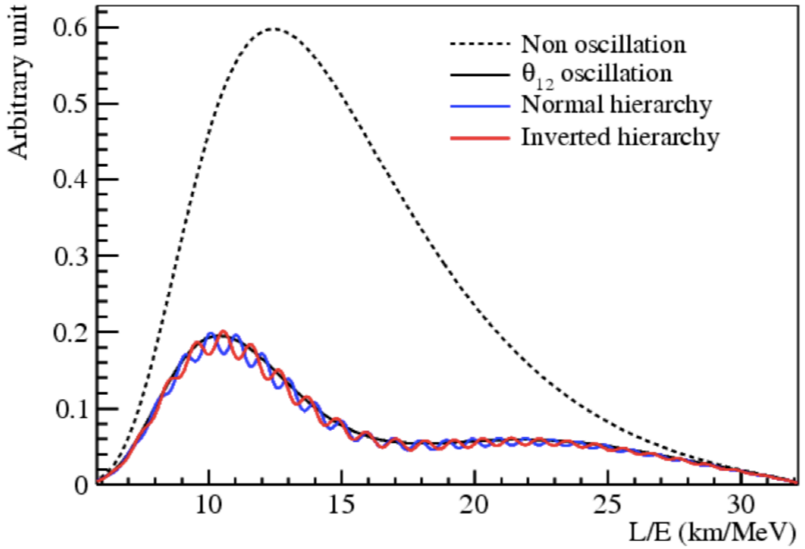
Relative differences of 3 synthetic spectra to ILL-data (Huber-Mueller-model)

Sensitivity to the Neutrino Mass Hierarchy

Sensitivity with 100k Events ($\sim$ 6 years with 35.8 GW_{th}):

- No external constraints: $\overline{\Delta\chi^2} > 9$
- With 1% constraint: $\overline{\Delta\chi^2} > 16$





Requirements:

- Energy resolution of < 3% at 1 MeV
- Energy scale uncertainty < 1%
- Reactor core dispersion < 0.5 km

Strong synergy with long-baseline ν program:

See: H. Nunokawa et al., Phys.Rev. D72 (2005) 013009

$$|\Delta m^2_{ee}| - |\Delta m^2_{\mu\mu}| = \pm \Delta m^2_{21}\left((\cos(2\theta_{12})) - \sin(2\theta_{12})\sin(2\theta_{13})\tan(\theta_{12})\cos(\delta)\right)$$

Sign defined by the Mass Ordering

$\Delta\chi^2(MH)$ dependence for different input errors of $\Delta m^2_{\mu\mu}$