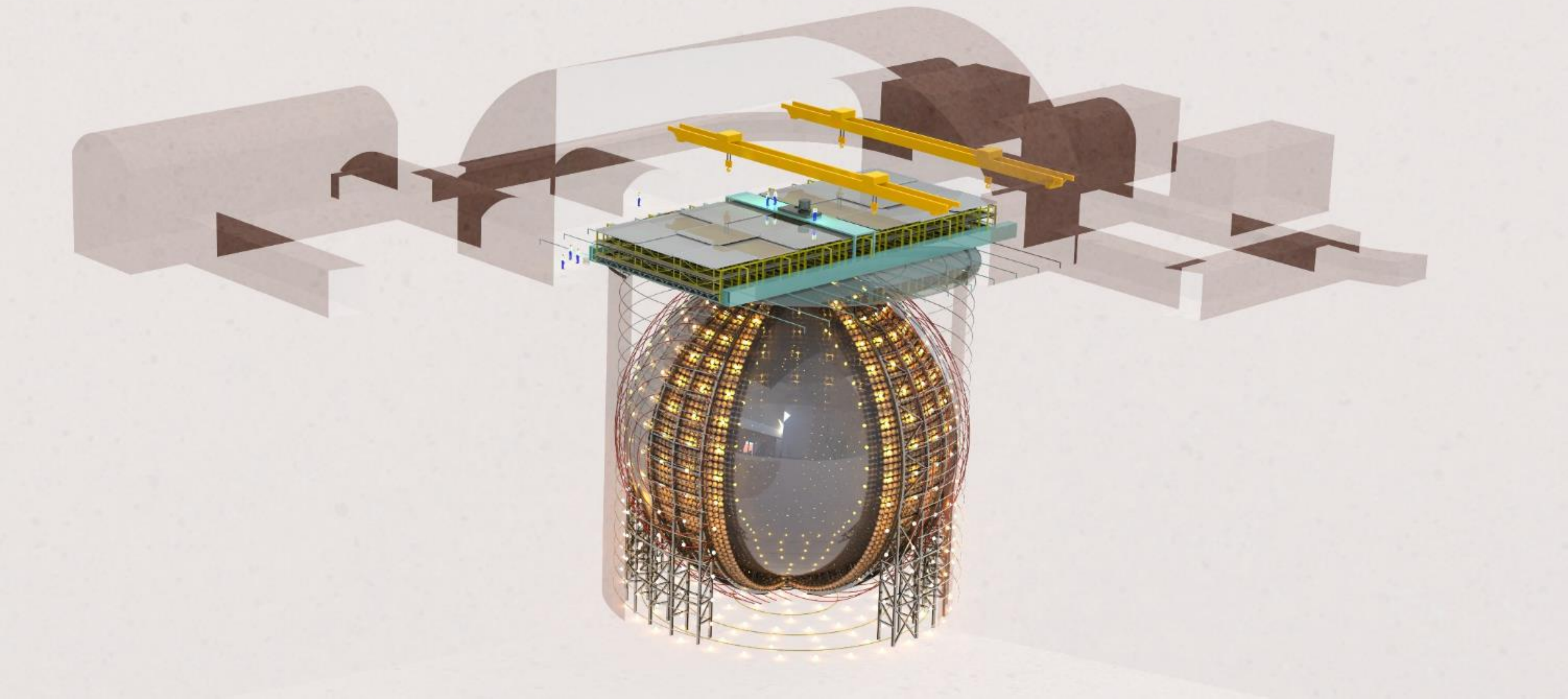
JUNO Experiment: Design and Status



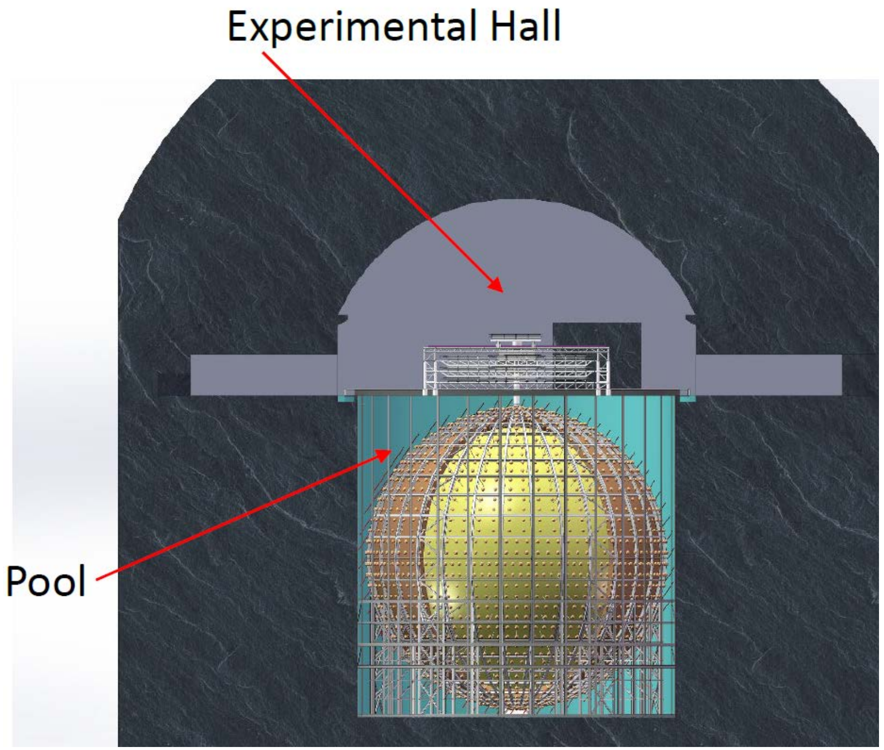
Paolo Lombardi
INFN Sez. Milano
On behalf of the JUNO collaboration

The JUNO Project – Introduction

Jiangmen Underground Neutrino Observatory

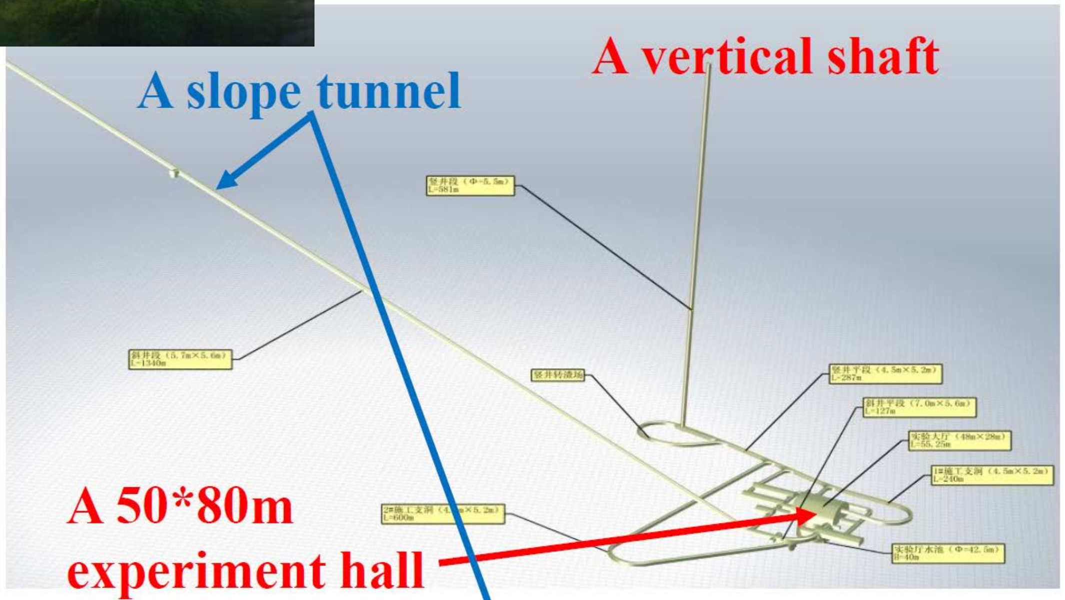
Multi-purpose experiment but with a main focus:
Measurement of the Neutrino Mass Ordering using reactor electron anti-neutrinos

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



JUNO Central Detector
20 kton Liquid Scintillator Target

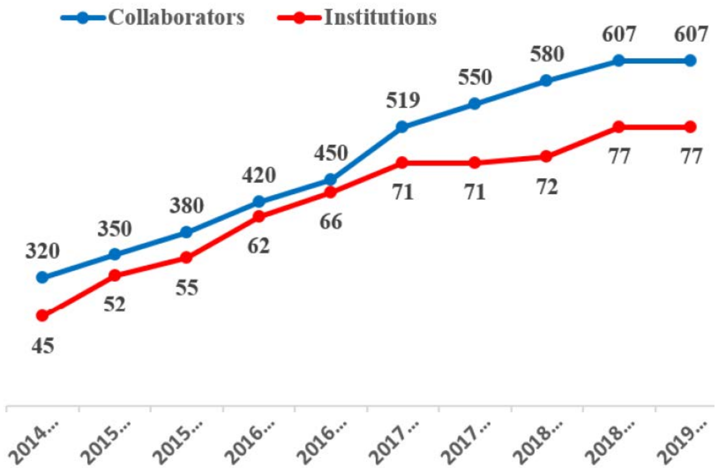
The JUNO Project – Layout



Underground Laboratory civil construction:

- Slope tunnel completed (1265 m)
- Vertical shaft completed (563 m)
- Excavating the experimental hall

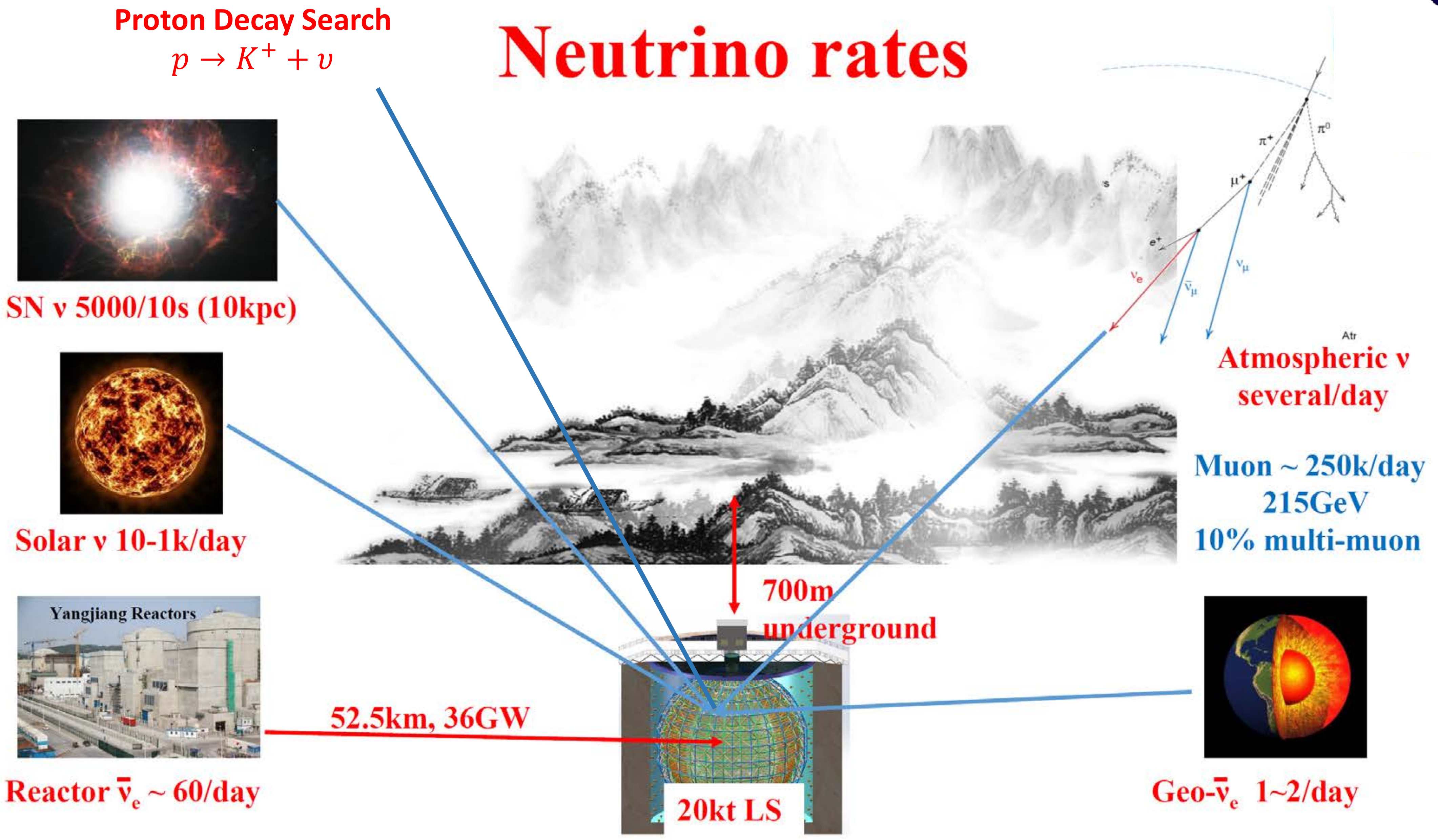
JUNO Collaboration



77 institution members
from 17 countries!
632 collaborators

Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	IMP-CAS	Germany	U. Mainz
Belgium	Universite libre de Bruxelles	China	SYSU	Germany	U. Tuebingen
Brazil	PUC	China	Tsinghua U.	Italy	INFN Catania
Brazil	UEL	China	UCAS	Italy	INFN di Frascati
Chile	PCUC	China	USTC	Italy	INFN-Ferrara
Chile	UTFSM	China	U. of South China	Italy	INFN-Milano
China	BISEE	China	Wu Yi U.	Italy	INFN-Milano Bicocca
China	Beijing Normal U.	China	Wuhan U.	Italy	INFN-Padova
China	CAGS	China	Xi'an JT U.	Italy	INFN-Perugia
China	ChongQing University	China	Xiamen University	Italy	INFN-Roma 3
China	CIAE	China	Zhengzhou U.	Latvia	IECS
China	DGUT	China	NUDT	Pakistan	PINSTECH (PAEC)
China	ECUST	China	CUG-Beijing	Russia	INR Moscow
China	Guangxi U.	China	ECUT-Nanchang City	Russia	JINR
China	Harbin Institute of Technology	Czech R.	Charles University	Russia	MSU
China	IHEP	Finland	University of Jyvaskyla	Slovakia	FMPICU
China	Jilin U.	France	LAL Orsay	Taiwan-China	National Chiao-Tung U.
China	Jinan U.	France	CENBG Bordeaux	Taiwan-China	National Taiwan U.
China	Nanjing U.	France	CPPM Marseille	Taiwan-China	National United U.
China	Nankai U.	France	IPHC Strasbourg	Thailand	NARIT
China	NCEPU	France	Subatech Nantes	Thailand	PPRLCU
China	Pekin U.	Germany	FZJ-ZEA	Thailand	SUT
China	Shandong U.	Germany	RWTH Aachen U.	USA	UMD1
China	Shanghai JT U.	Germany	TUM	USA	UMD2
China	IGG-Beijing	Germany	U. Hamburg	USA	UC Irvine
China	IGG-Wuhan	Germany	FZJ-IKP		

JUNO Physics - Neutrino Mass Ordering and Beyond



Method from Petcov and Piai, Physics Letters B 553, 94-106 (2002)

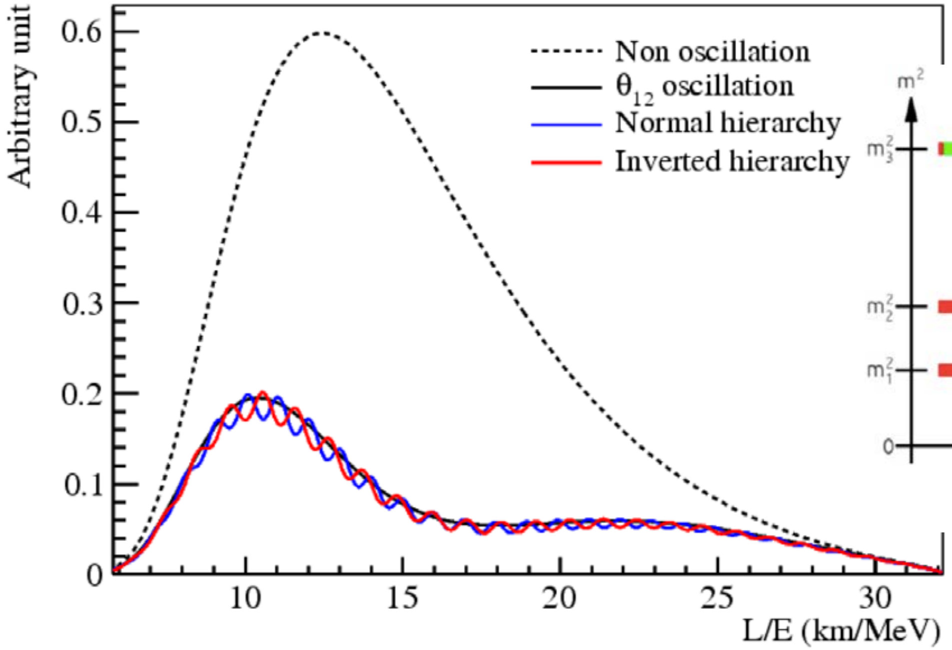
MH and Survival probability

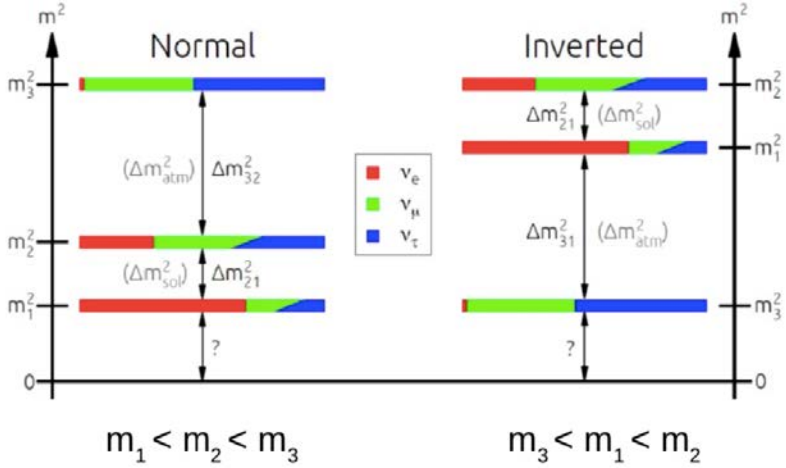
arXiv 1210.8141

$$P_{ee} = \left| \sum_{i=1}^{3} U_{ei} \exp\left(-i\frac{m_i^2}{2E_i}\right) U_{ei}^* \right|^2$$

$$= 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21}) - \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{31}) - \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{32})$$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu}, \quad (\Delta m_{ij}^2 \equiv m_i^2 - m_j^2)$$





Or to make the effect of the mass hierarchy explicit, exploiting the approximation $\Delta m^2_{32} \approx \Delta m^2_{31}$:

$$P_{ee} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21}) - \sin^2 2\theta_{13}\sin^2(|\Delta_{31}|) - \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{21})\cos(2|\Delta_{31}|) \pm \frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|),$$

+ NH
- IH

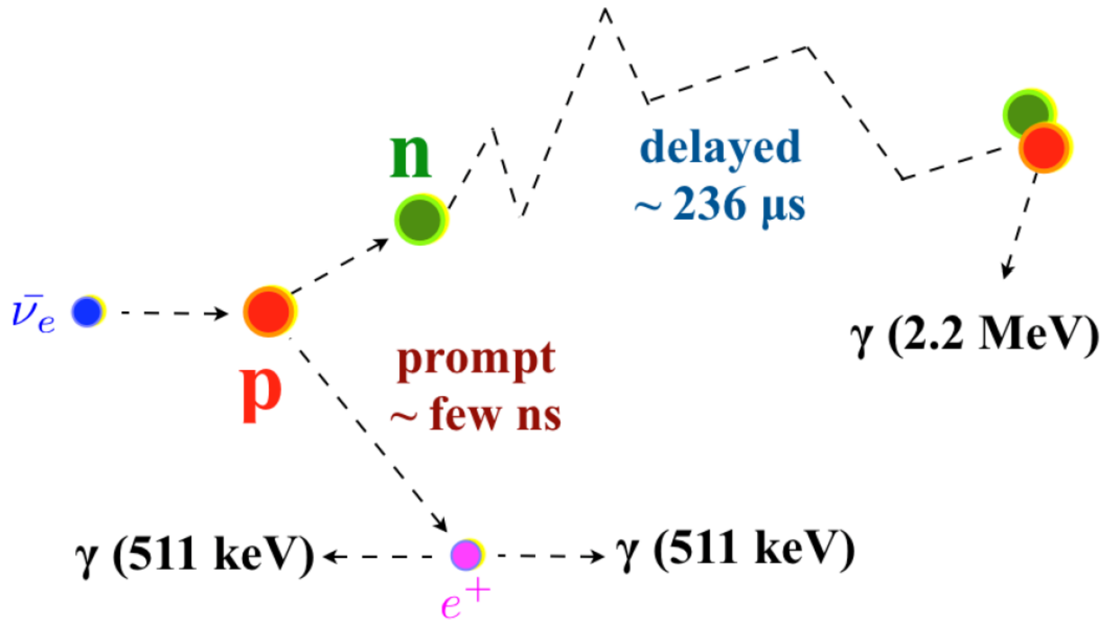
The big suppression is due to the "solar" oscillation → Δm^2_{21} , $\sin^2\theta_{12}$
The ripple is the "atmospheric" oscillation → $|\Delta m^2_{31}|$ from frequency
MH encoded in the phase
"high" value of θ_{13} crucial 7

Methodology to infer the Mass Hierarchy

The determination of the mass hierarchy relies on the identification on the positron spectrum of the "imprinting" of the anti-ν_e survival probability

Detection through the classical inverse beta decay reaction

$$\overline{\nu} + p \rightarrow n + e^{+}$$ $E_\nu > 1.8$ MeV



The time coincidence between the positron and the γ from the capture rejects the uncorrelated background

The "observable" for the mass hierarchy determination is the positron spectrum
It results that $E_{vis}(e^+) = E(\nu) - 0.8$ MeV

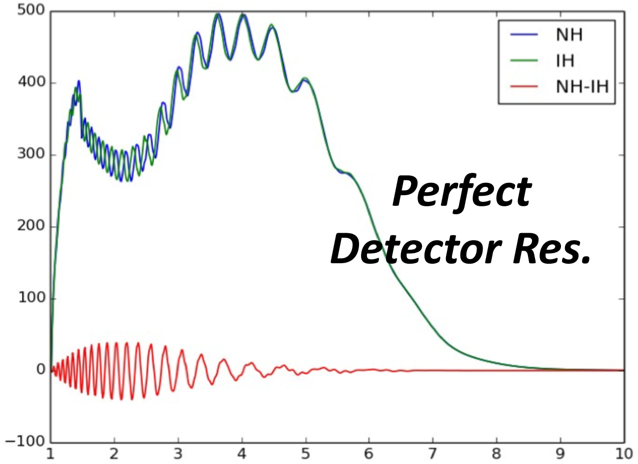
Requirements for the JUNO Detector

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!

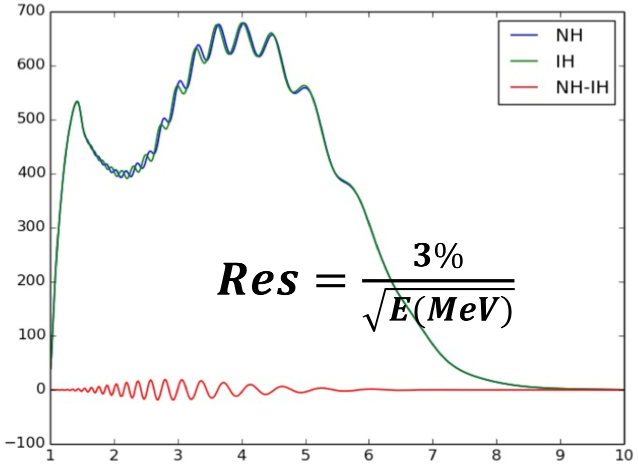
Energy scale uncertainty:
Large uncertainties and unknown non-linearity could lead to the wrong mass ordering result!
→ Meticulous Calibration!
→ Double calorimetry via small PMT system

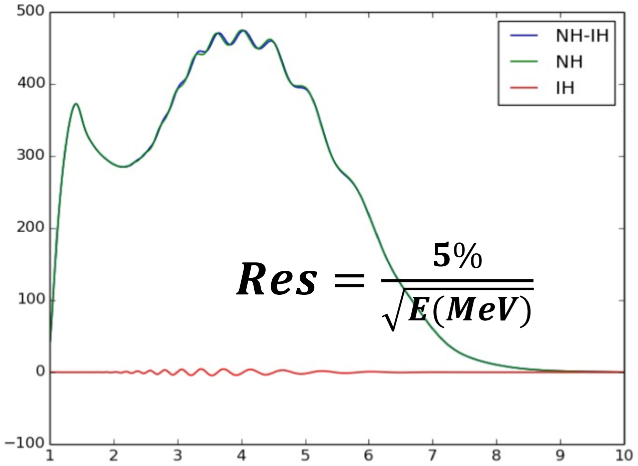
Statistics: 98.5k Events within 6 years!
26.6 GW_{th} reactor power
20 kt detector target (~ 45 Evts. / Day)
Minimization of the vetoed volume by precise muon track reconstruction



JUNO MH sensitivity with 6 years' data (nominal power):

PRD 88, 013008 (2013)	Relative Meas.	Use absolute Δm^2
Statistics only	4σ	5σ
Realistic case	3σ	4σ





Energy spectrum of the JUNO $\overline{\upsilon_e}$ events
(Effect of the energy resolution on the expected signal)

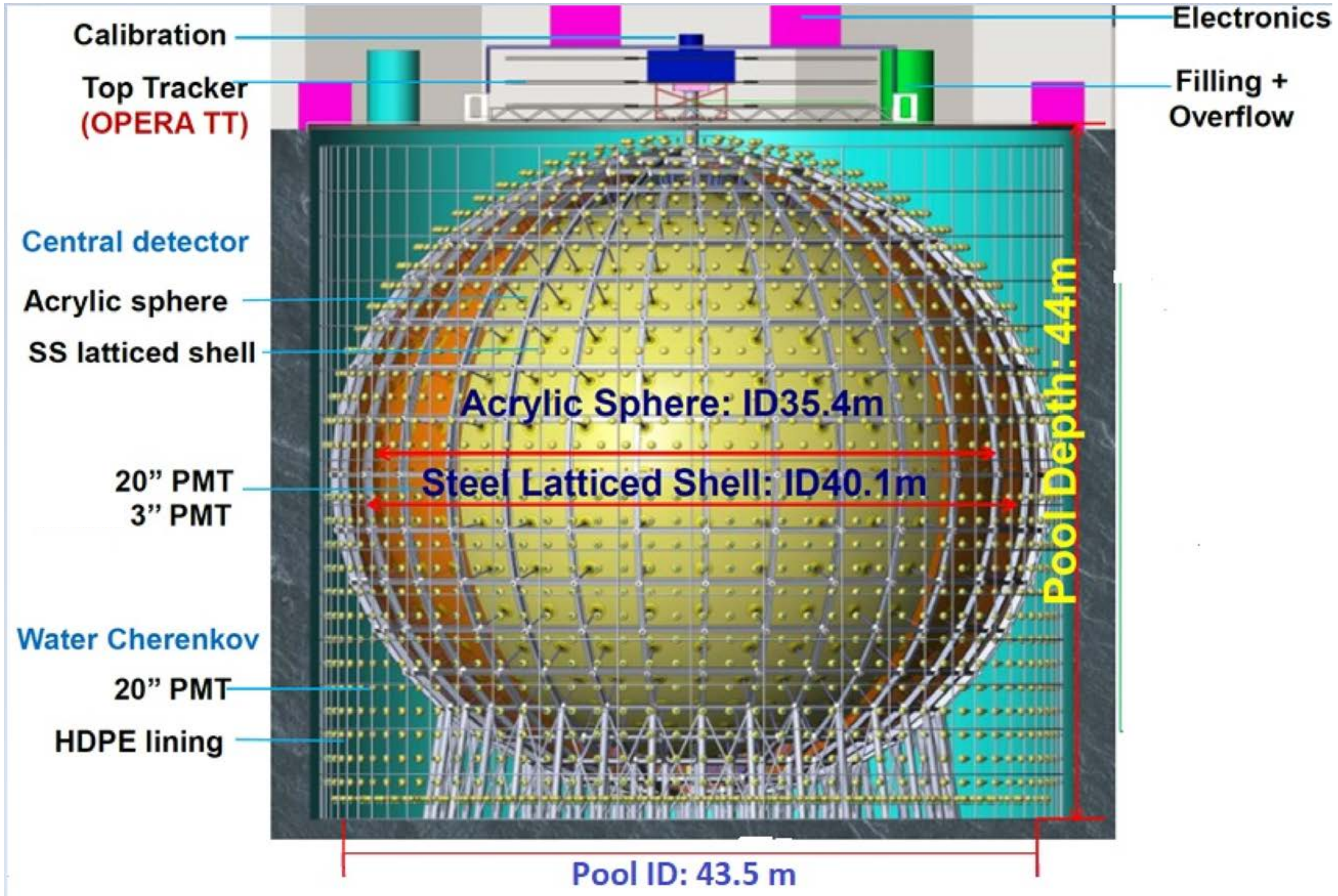
Overall Detector Design

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

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

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

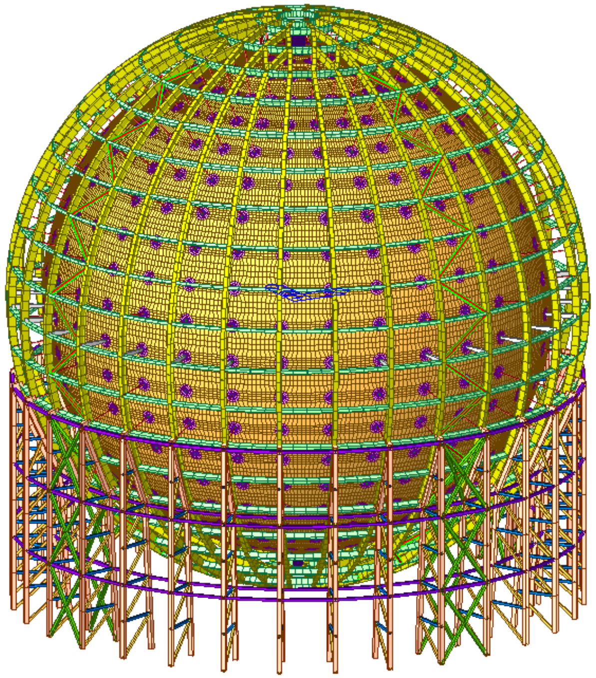
Top tracker:
- Precision muon tracking
- 3 plastic scintillator layers
- Covering half of the top area

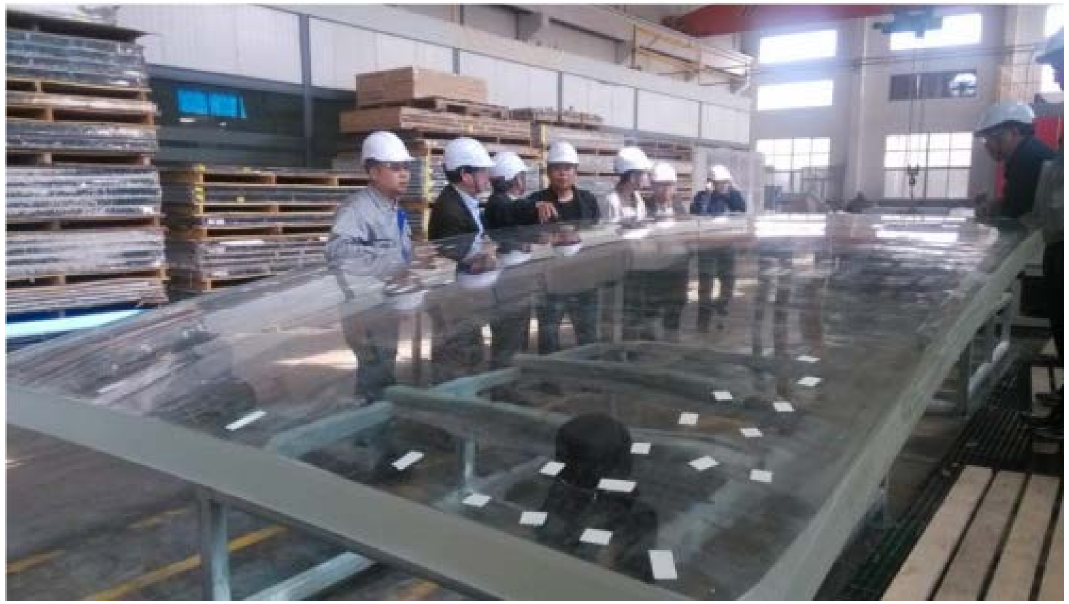


Experiment	Daya Bay	Borexino	KamLAND	JUNO
LS Target Mass [t]	8 x 20	~ 300	~ 1000	20000
Collected p.e./MeV	~ 160	~ 500	~ 250	~ 1200
Energy resolution @ 1 MeV	~ 7.5 %	~ 5 %	~ 6%	~ 3 %

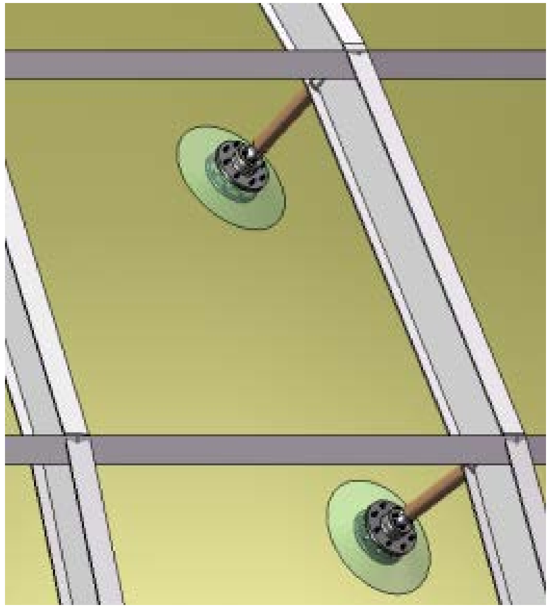
Central Detector Acrylic Sphere R&D

- SS structure to hold a acrylic sphere and to mount PMTs
  - Supporting bar to hold the Acrylic tank
  - Stress of acrylic <3.5 MPa everywhere
- Main issues:
  - Mechanical precision for 3 mm PMT clearance
  - Thermal expansion matching: 21°C ± 1°C
  - Earth quake and liquid-solid coupling
  - Transparency 96.5%, U/Th/K < 1 ppt
- Started panel production

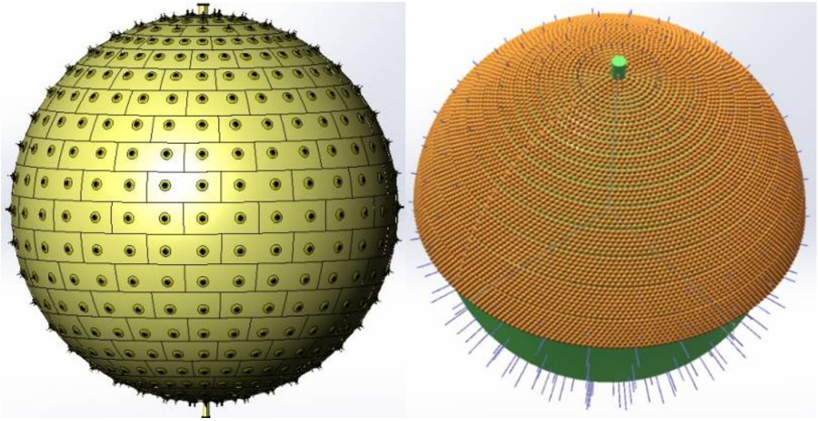




Panel size: 3m x 8m x 0.12m



Acrylic divided into 200+ panels

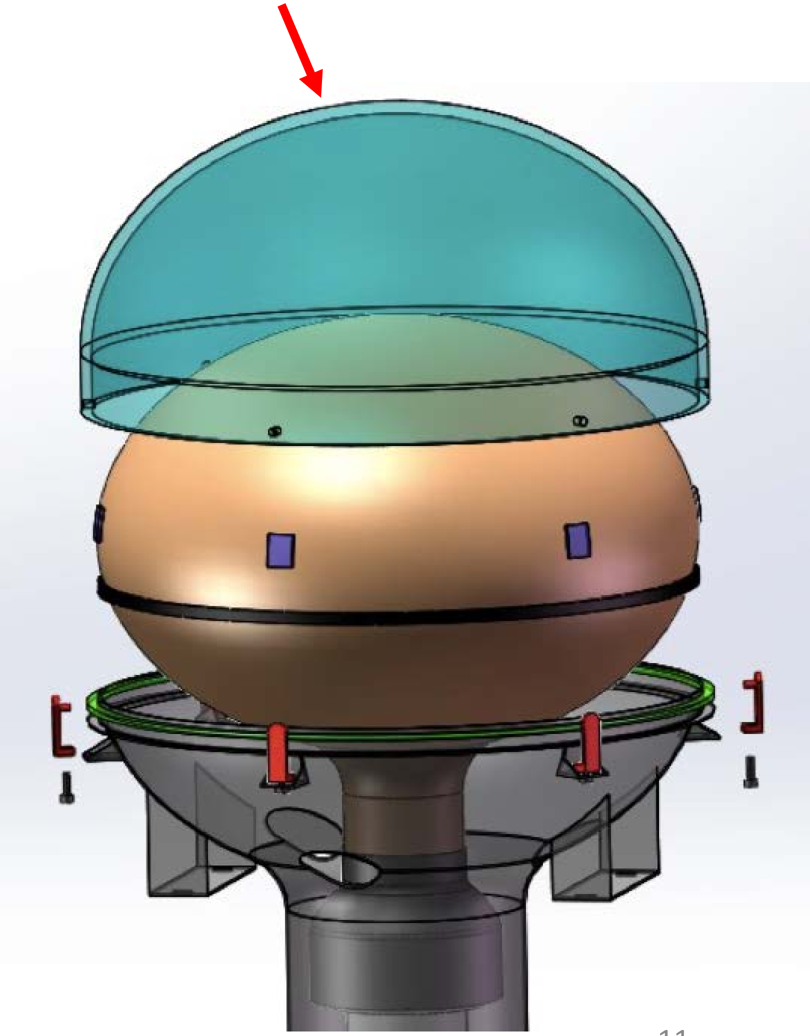


Large PMT array

- 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
- In production since 2016
- PMT testing:
  - Finished for dynode PMTs
  - ~10000 of 15000 MCP-PMTs already tested

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

Protection acrylic cover for protecting implosion chain reaction



Large PMT testing facility

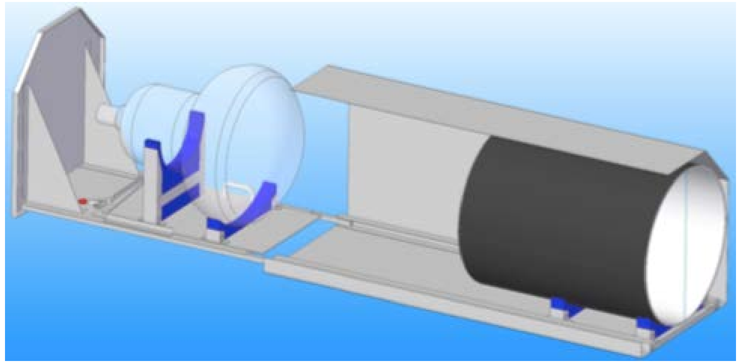
PMT Testing Containers (all PMTs):

- Capacity: 36 (-5) PMTs per Container
- Relative PDE Measurement
  - 1 fixed & 4 rotating reference PMTs
- Four containers
  - 1 & 2 operational
  - 3 & 4 in commissioning
- Magnetic shielding: 10% EMF
- Climate control systems
- Two light sources:
  - stabilized LED
  - Picosecond-Laser

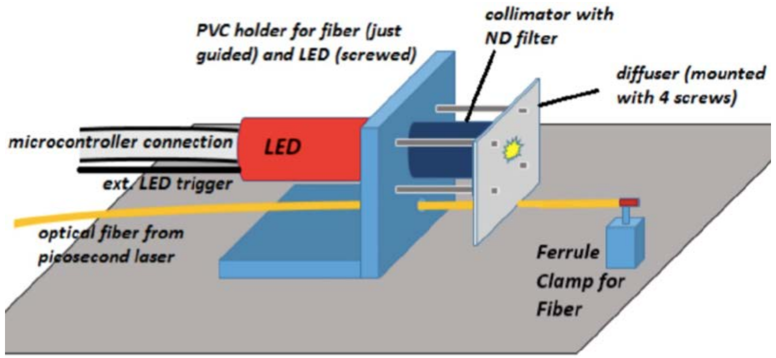
Scanning Station (5-10% of PMTs):

- 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

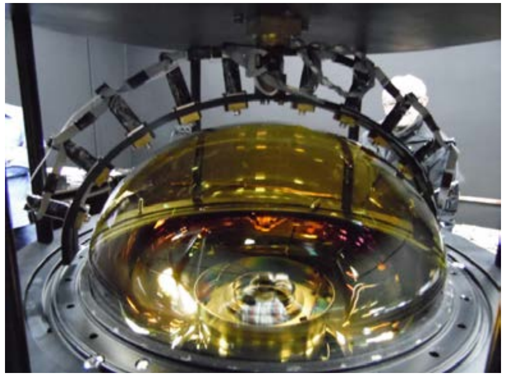
Two testing containers in Zhongshan (Pan-Asia).



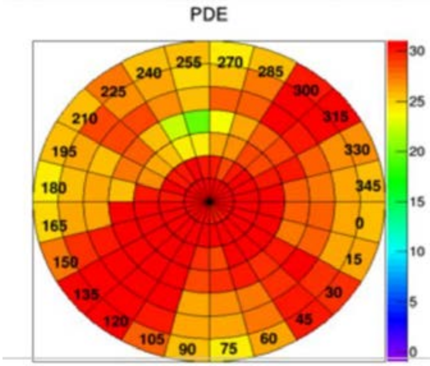
PMT test box with PMT holder



Light sources used in the testing containers



PMT in the scanning station



PDE differences (photocathode)

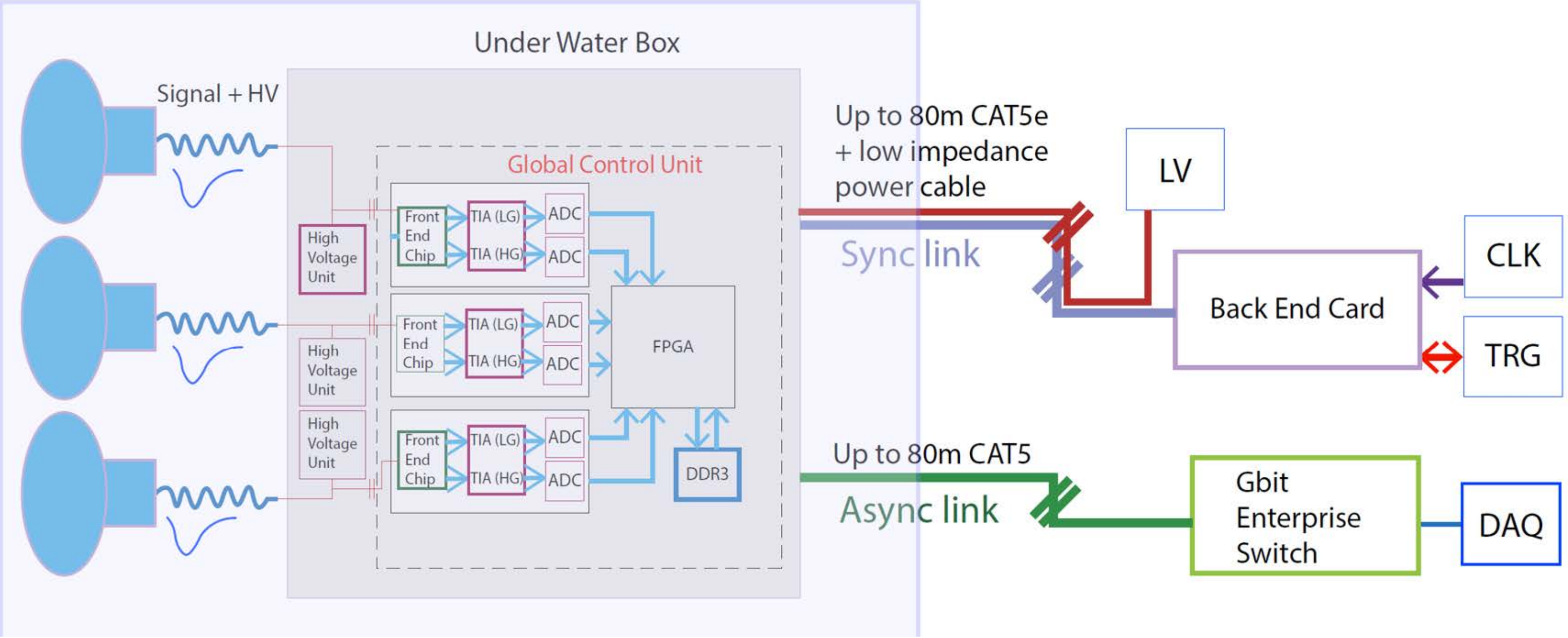
JUNO CD Electronics Readout Scheme

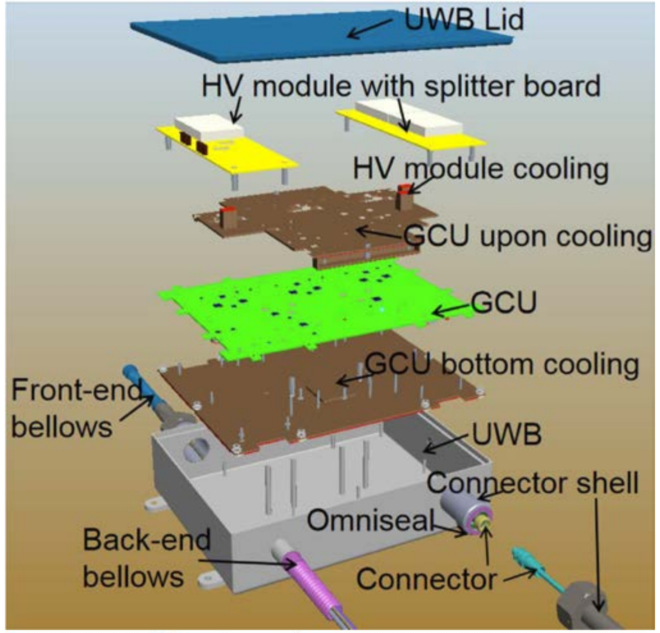
INFN Istituto Nazionale di Fisica Nucleare

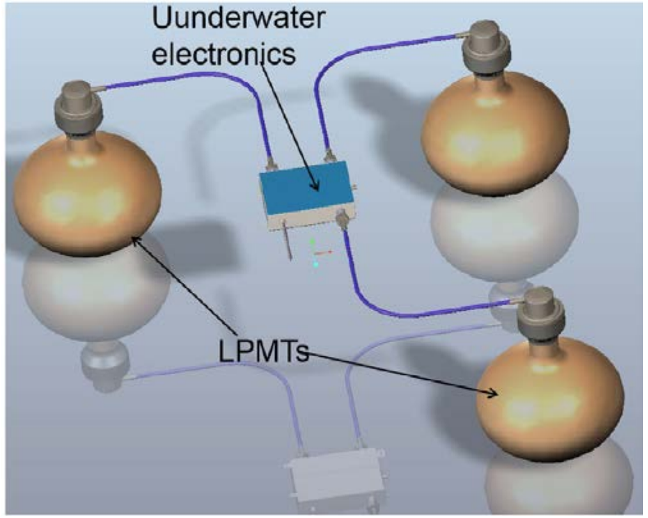
- Signal is digitized very close to the PMT voltage divider
- 20000 ch for LPMT & 100 m cable needed
- Dynamic range: 1- 4000 PE
- Noise: < 10% @ 1 PE
- Resolution: 10%@1PE, 1%@100 PE
- Failure rate: < 0.5%/6 years
- Final solution: **1 GHz sampling FADC** in a small box (×3 ch) in water; all cables in corrugated pipes

Under Water Electronics

Dry Electronics







Small PMT array

Double calorimetry

Always in photon counting mode

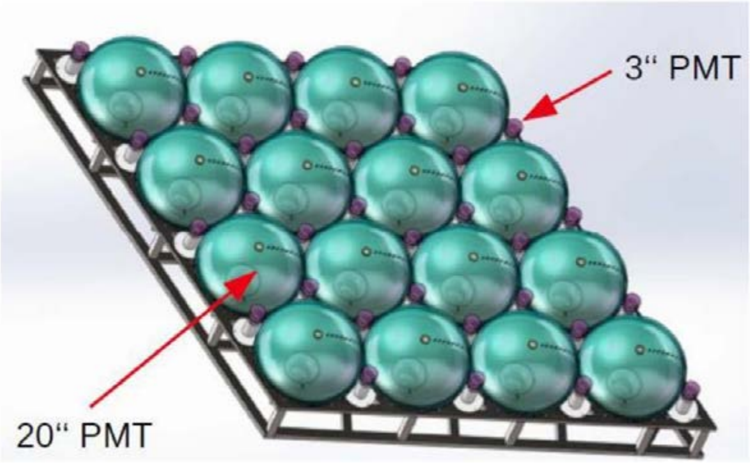
Less non-linearity: calibration of large PMT array

Better dynamic range for high energy signals

Higher granularity of the CD

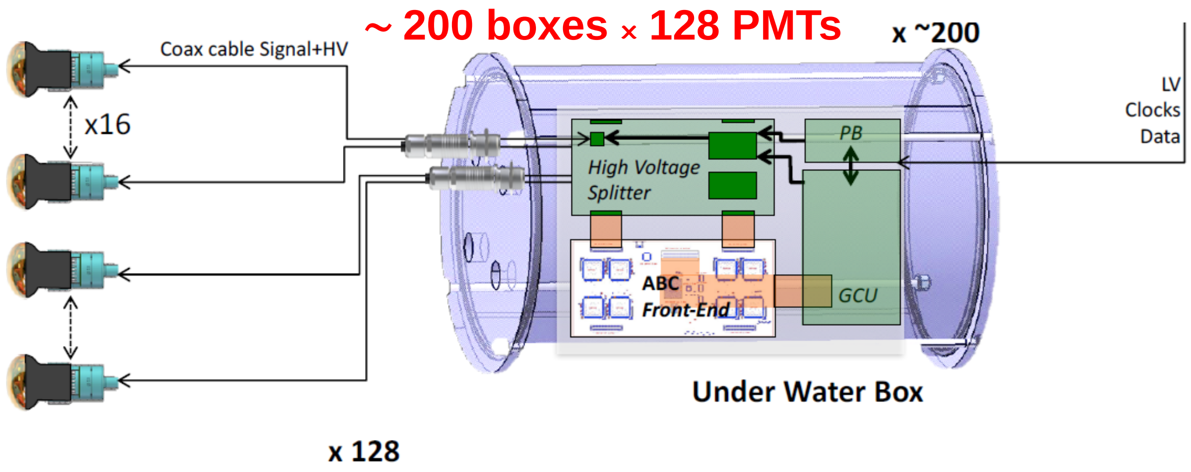
25600 PMTs in the Central Detector
- **2.5% coverage**
- Provided by **HZC Photonics** (Hainan, PR China)

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: 20 kton of Linear Alkyl-Benzene

Purification of LAB in 4 Steps:

- **Al_2O_3 filtration column:** improvement of **optical properties**
- **Distillation:** removal of **heavy metals**, improvement of transparency
- **Water Extraction:** removal of **radio isotopes** from uranium and thorium chain and furthermore of ^{40}**K** **(underground)**
- **Steam / Nitrogen Stripping:** removal of **gaseous impurities** like ^{39}**Ar**, ^{85}**Kr**, and ^{222}**Rn** **(underground)**

Optical Requirements:

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

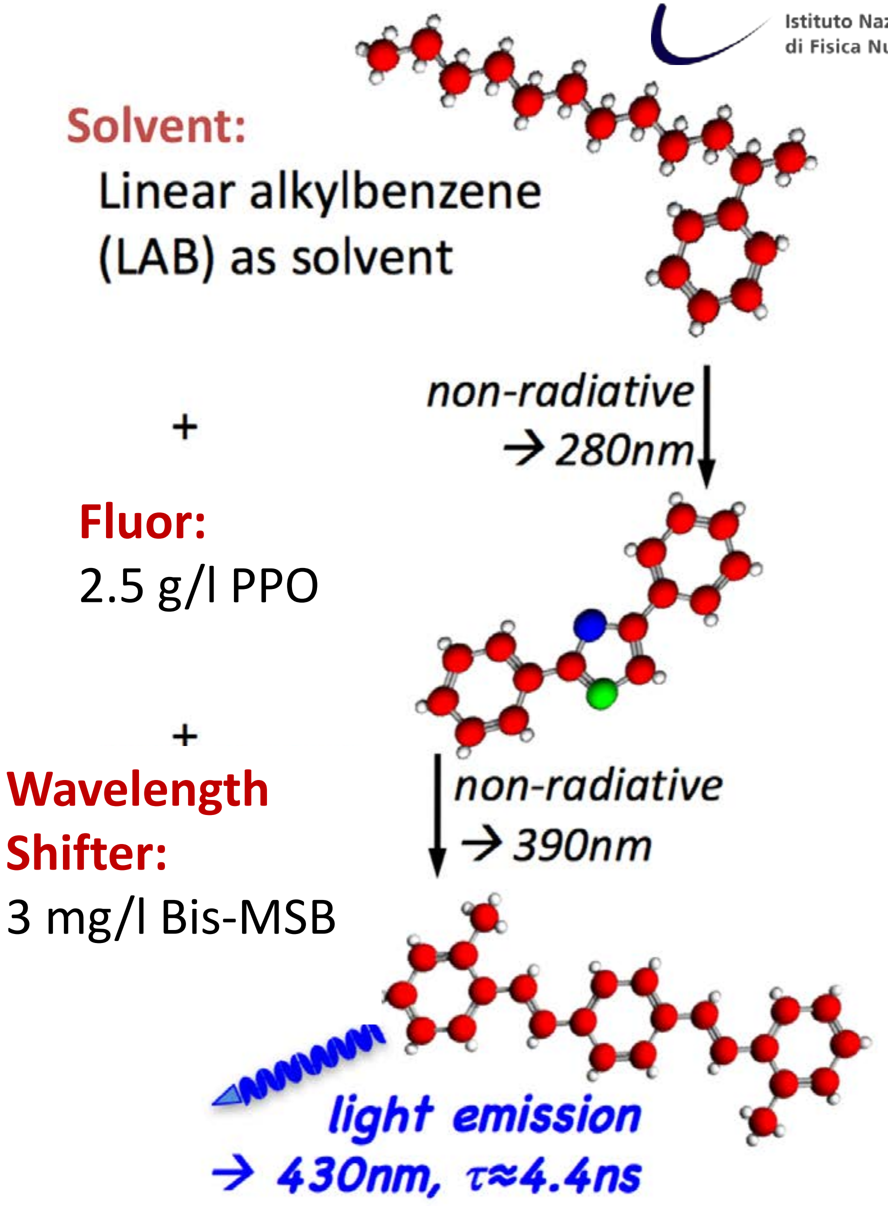
Required Radio-purity:

Reactor anti-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



Liquid scintillator purification pilot plants (in one Daya Bay detector)

Paper Stripping & Distillation pilot plants:

NIM A 925 (2019) 6, arXiv: 1902.05288

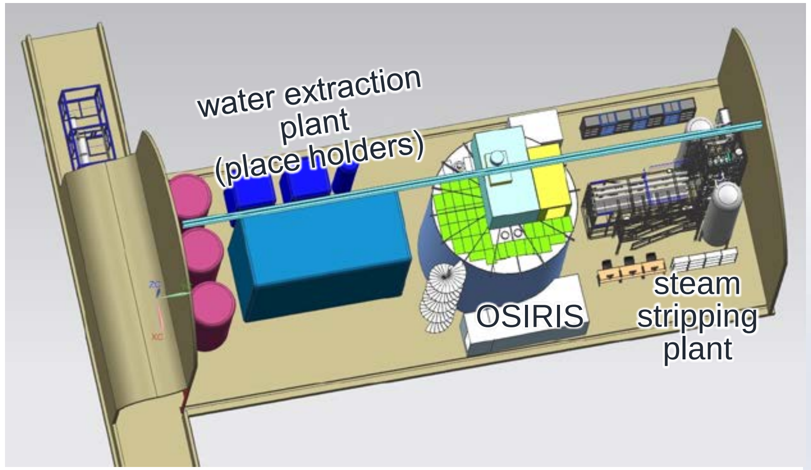
OSIRIS - Online Scintillator Internal Radioactivity Investigation System

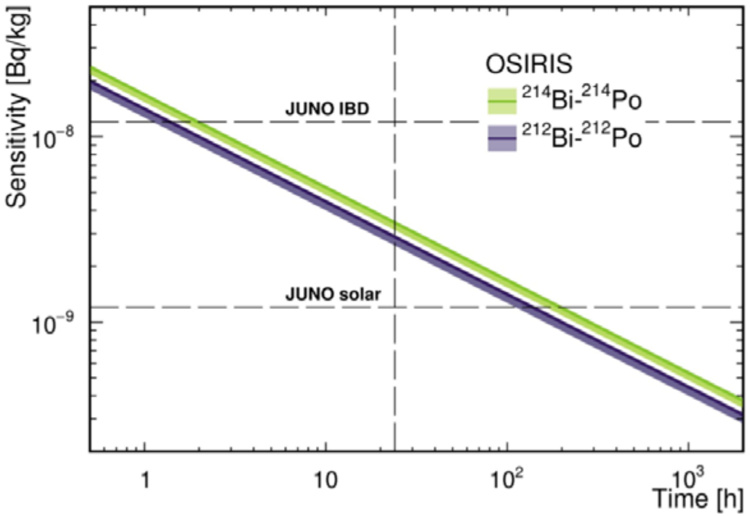
Liquid Scintillator purity monitor:

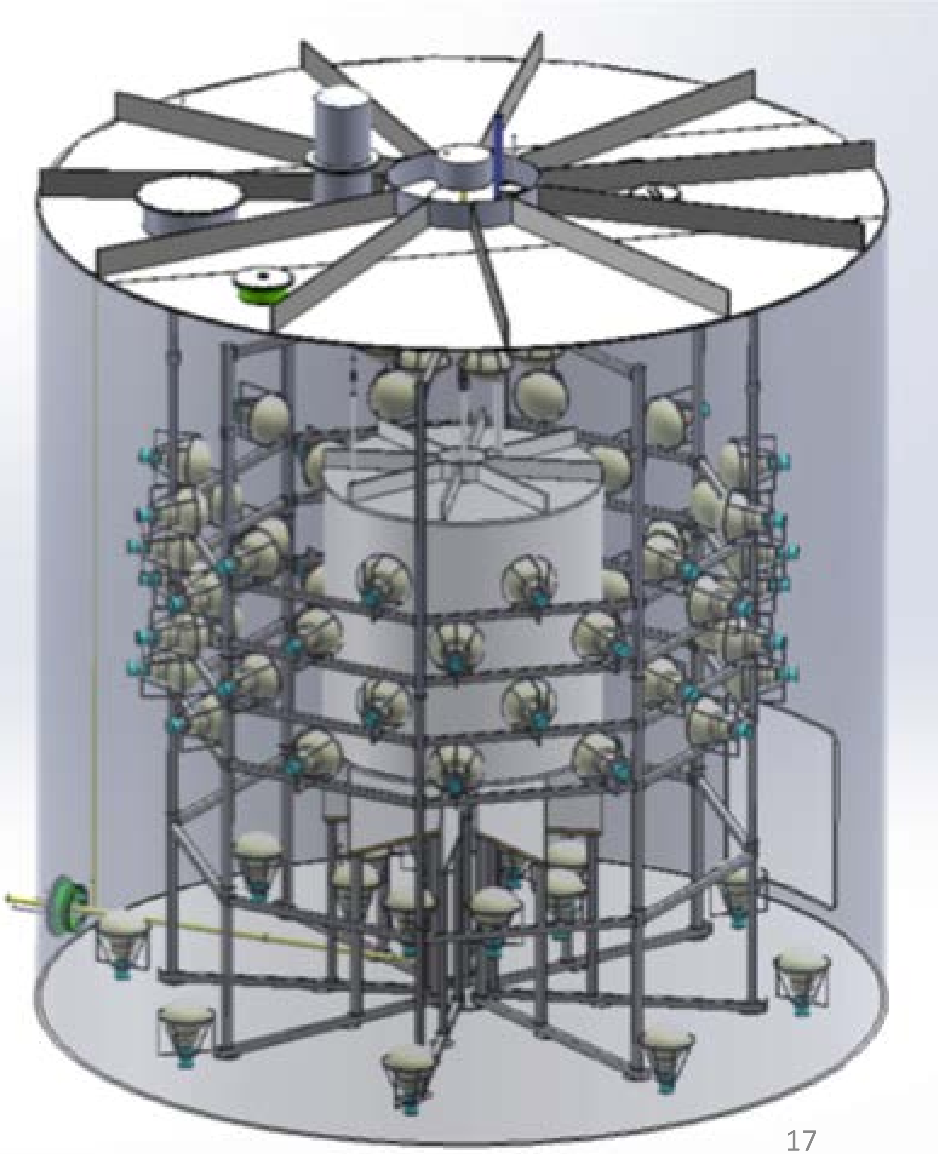
*Detect radioactive contaminated scintillator **after purification** but **before filling** it into the acrylic vessel!*

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

18t LS volume (Ø=3 m, H=3 m)
Instrumentation:
68x 20" PMTs for the scintillator
12x 20" PMTs for the muon veto

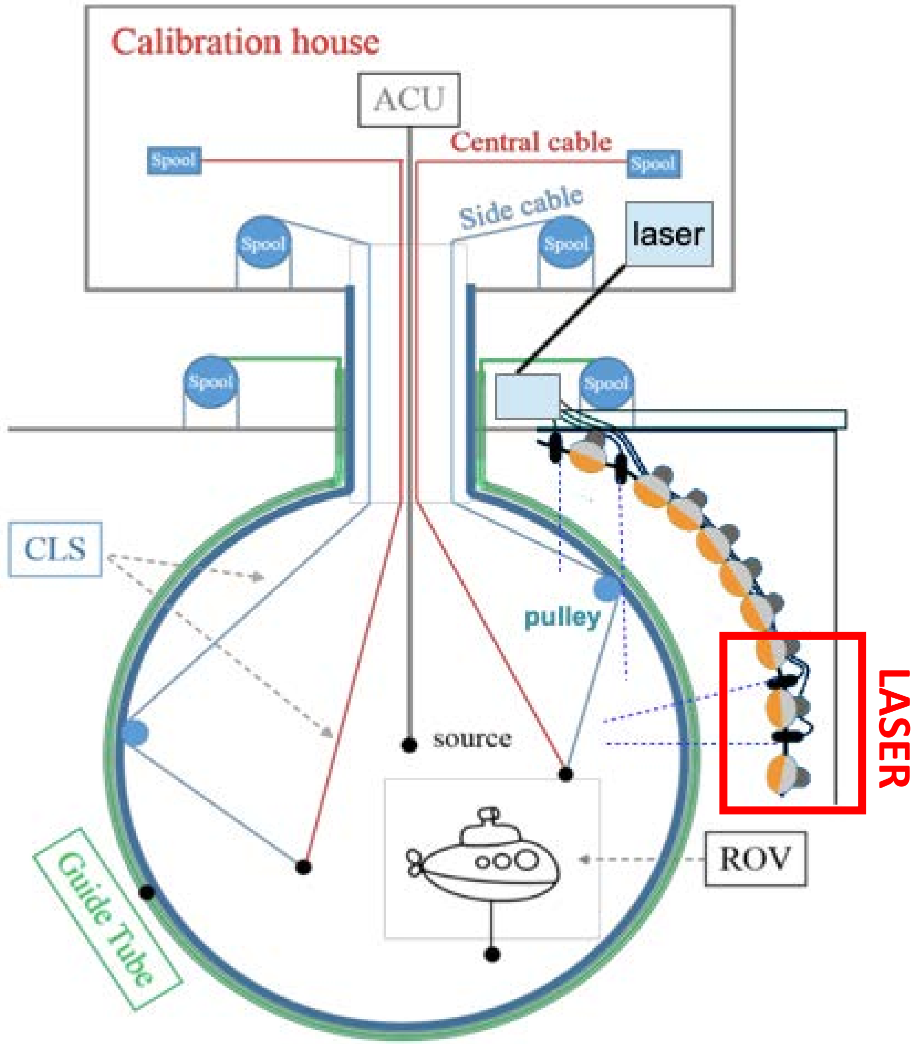




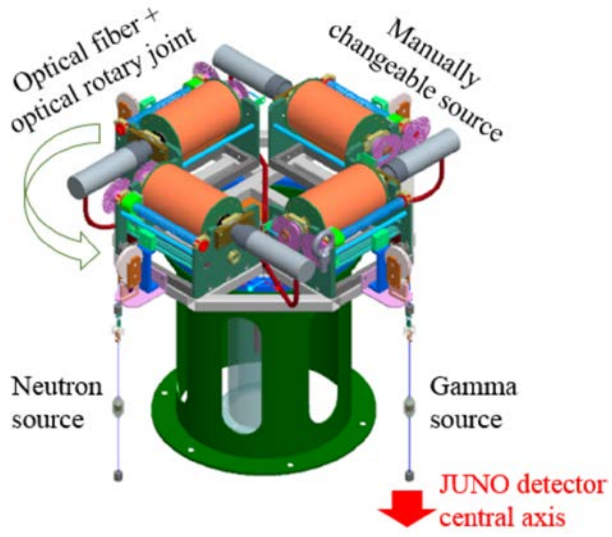


Expected Sensitivity (Simulation):
JUNO IBD limit within a few hours
JUNO solar limit possible

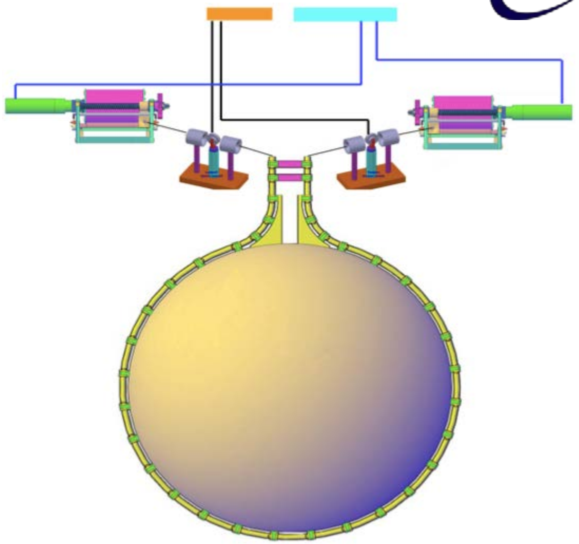
Calibration Systems



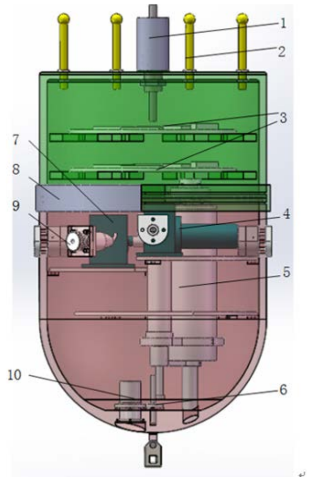
Overview of JUNO‘s Calibration Systems
(including laser calibration system)



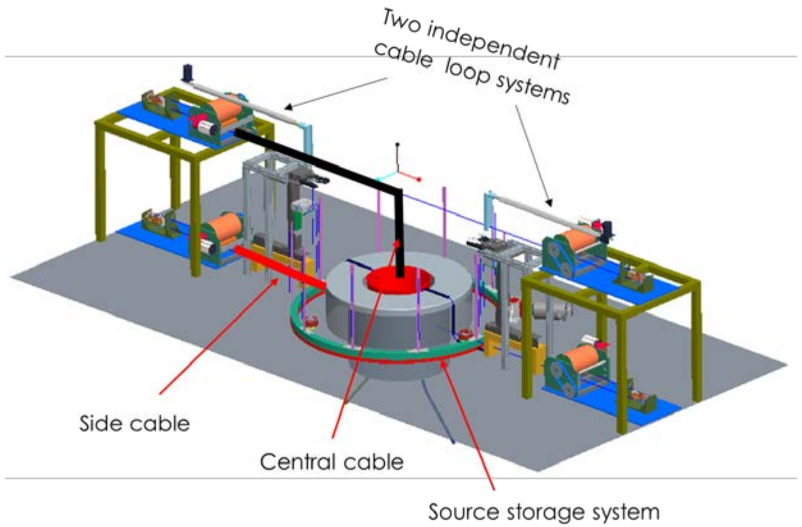
ACU (Automatic Calibration Unit)



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
- Possible improvement of nuclear databases
- Shed light on reactor spectrum anomaly (5 MeV bump)
- 30 × JUNO statistics

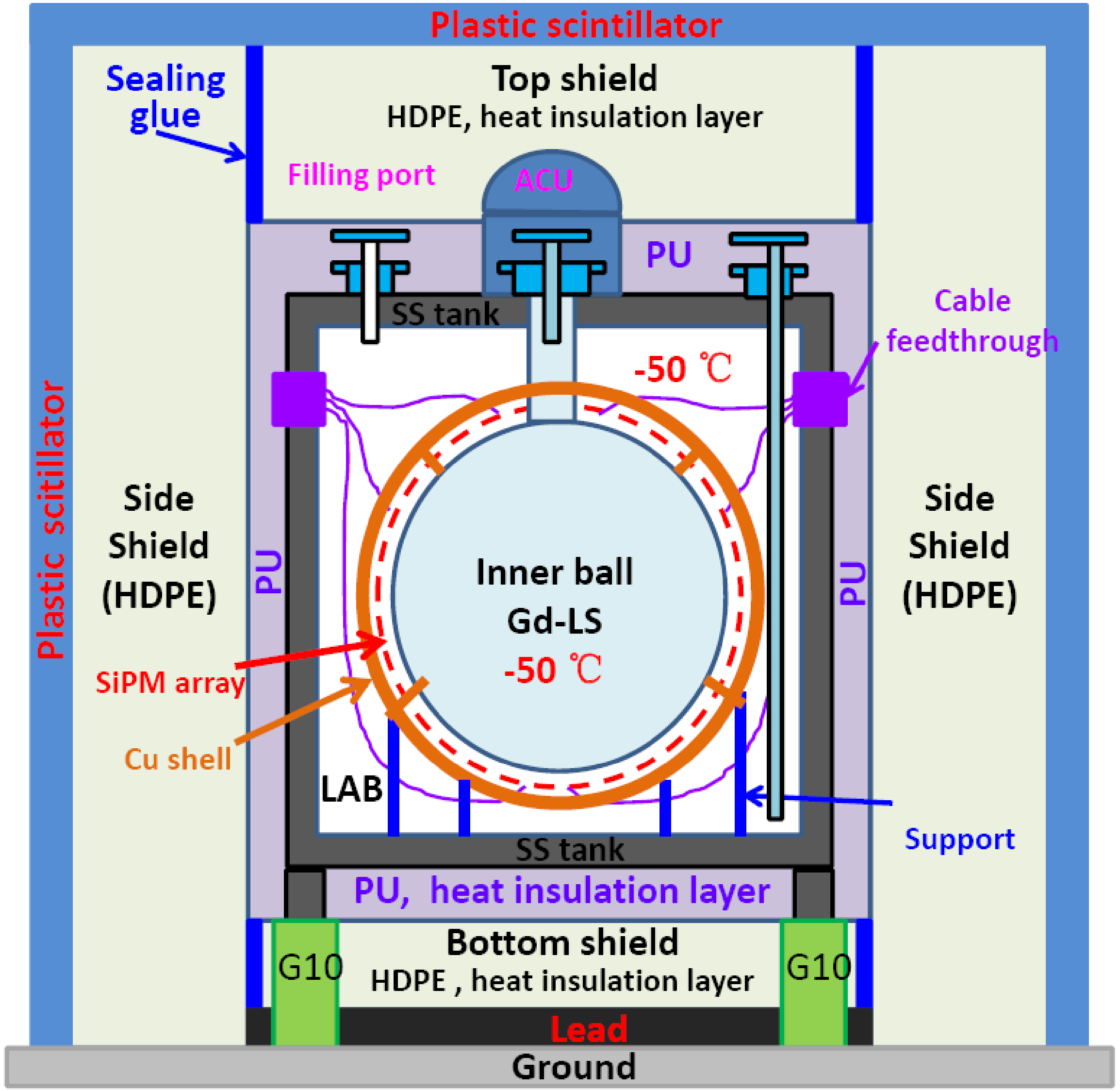
TAO Design Features: at the Taishan NPP

- Detector placed at **30 m distance** from one reactor core
- **2.6 ton Gd-LS** as target material (1 ton fiducial target)
- 10 m^2 **SiPM**, with **50% PDE**, **Coverage: > 94%**
- SiPMs and LS **cooled down to -50 °C**

Expected Performance:

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

Planned to be online in 2021!



Schedule & Milestones

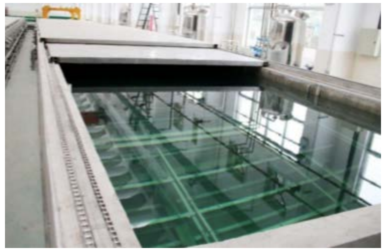
INFN Istituto Nazionale di Fisica Nucleare

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

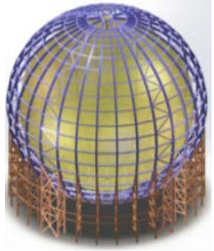
- Start PMT testing
- Top Tracker arrived!
- Daya Bay LS tests

2018

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

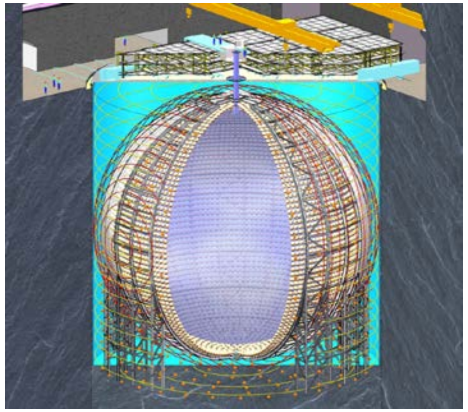
2019-20

- Electronics production starts
- Civil work and lab preparation completed
- Detector construction



2021

- Detector filled & commissioned
- TAO ready
- Detector ready



Data Taking

Thanks you for your attention!