The physics potentials of JUNO

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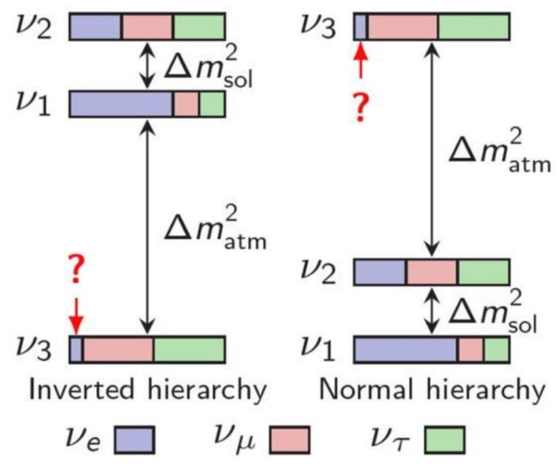
Outline

- Introduction
- JUNO physics
- JUNO detector status
- Summary

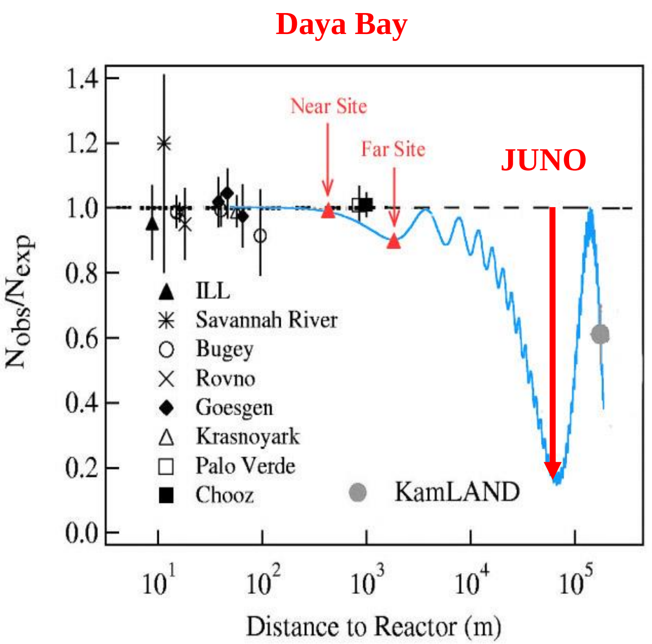
Neutrino Mass Ordering(MO) In a 3-ν framework

- Large θ_{13} opens a door to neutrino MO and CP violating phase, as the focus of next generation neutrino experiments.
- MO can be determined utilizing:
  - Matter effects of accelerator and atmospheric neutrinos;
  - Oscillation interference effects of reactor neutrinos driven by Δm^2_{32} and Δm^2_{31};



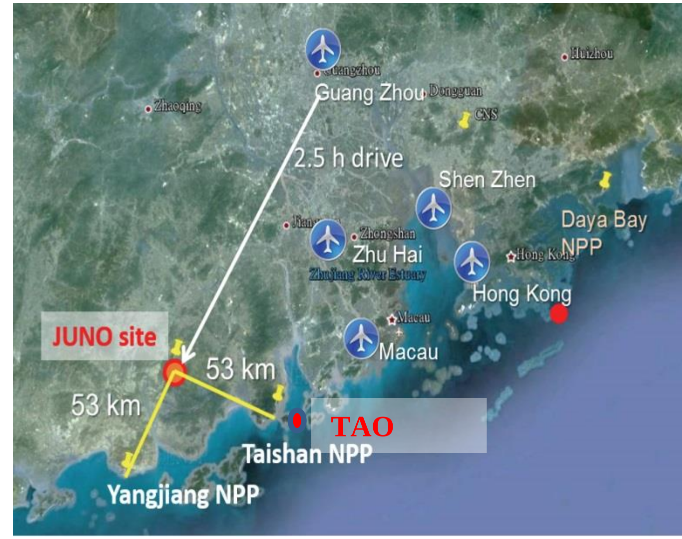
Measuring Mass Ordering with Reactor neutrinos

- Place detector at medium baseline (~50km) from reactors
- Observe the distortion of energy spectrum
- A clean measurements of parameters, oscillation probability independent of CP phase and θ_{23}



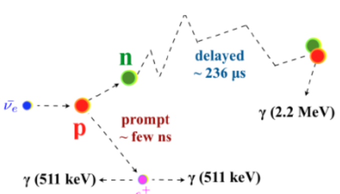
Jiangmen Underground Neutrino Observatory

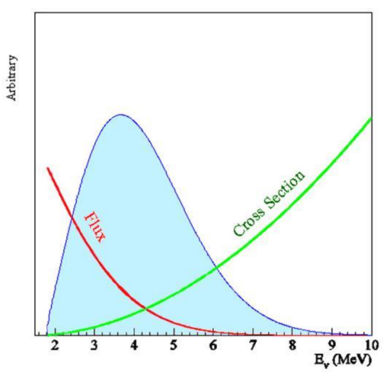
- **JUNO:**
  - 20 kton liquid scintillator (LS),under construction in southern of China.
  - Main physics goal:
    - Determine neutrino mass ordering by reactor antineutrinos.
  - Detector requirement:
    - 3% @ 1 MeV energy resolution, very high energy resolution
    - High transparency LS, high coverage of PMTs and low backgrounds.
  - The most challenging design in the reactor neutrino experiments throughout the world.



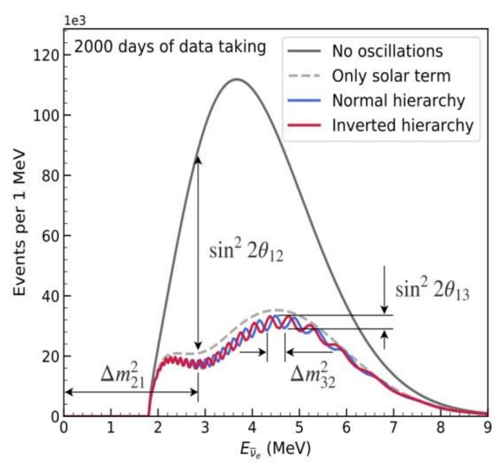
- Signal: Inverse beta decay reaction(IBD)

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





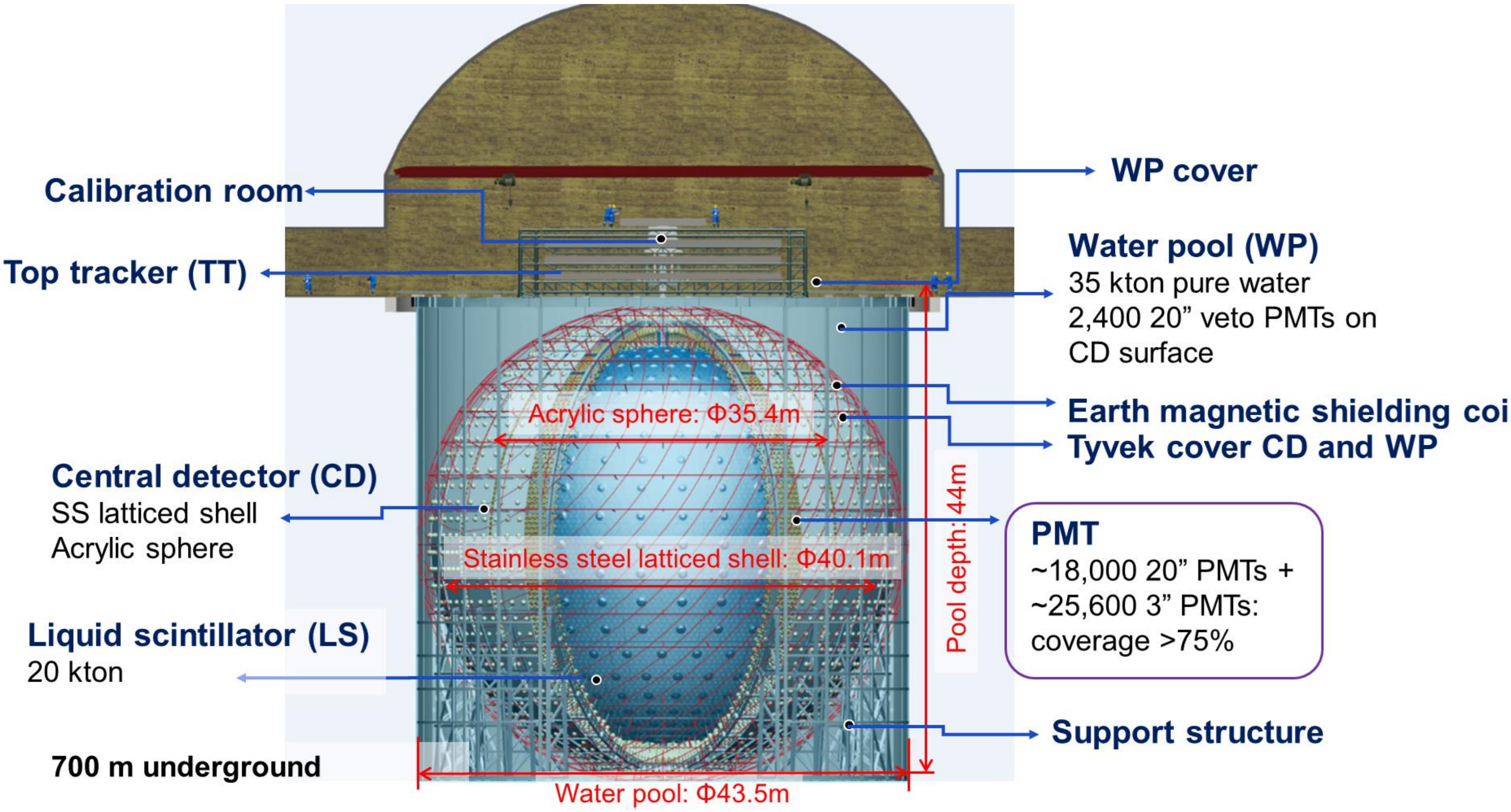
Antineutrino spectrum



Yangjiang NPP	Taishan NPP
17.4 GW	9.2 GW

All six 2.9 GW cores in Yangjiang NPP and two 4.6 GW cores in Taishan NPP are in operation now.

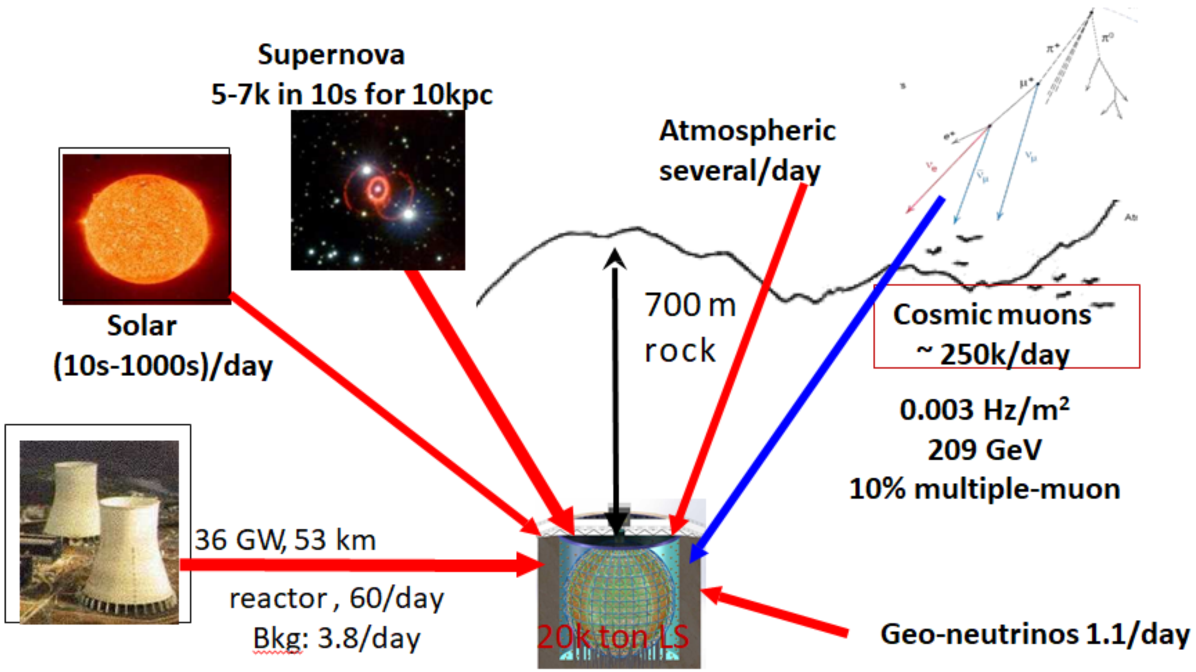
JUNO detector



Rich physics possibilities of JUNO

- Neutrino mass ordering
- Precision measurement of oscillation parameters
- Supernova neutrinos
- Solar neutrinos
- Atmospheric neutrinos
- Geo-neutrinos
- Nucleon decay & exotic searches

Event Rate (after selection)



Neutrino Physics with JUNO, J. Phys. G 43, 030401 (2016)

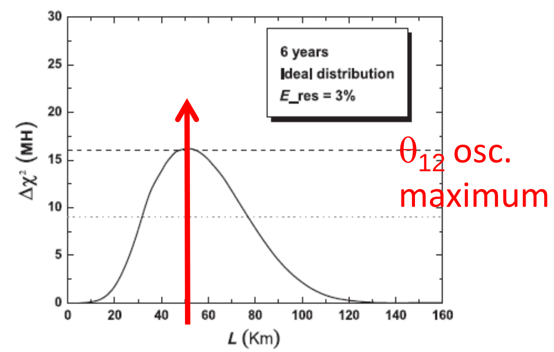
Neutrino mass ordering(I)

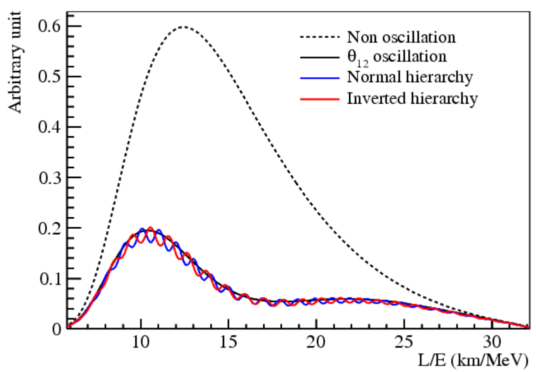
Antineutrino survival probability:

$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

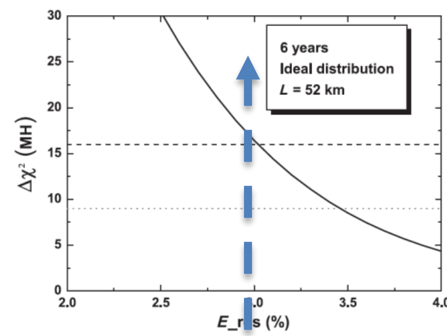
where $\Delta_{ij} = 1.27\Delta m^2_{ij} L/E$, Δm^2_{ij} is the neutrino mass-squared difference $(m_i^2 - m_j^2)$ in eV^2

Optimization baseline at the oscillation maximum of θ_{12}





Sensitivity for 100 k IBDs (20 kton × 35 GW × 6 years).



Energy resolution:

- 3%@1MeV energy resolution for 4 sigma sensitivity at ideal distribution.
- Experiment requirements to achieve such an unprecedentedly high energy resolution

To reach the required energy resolution:

- high light yield: Liquid scintillator attenuation length>20 m@430nm
- Large PMT coverage: PMT coverage: 75%
- High QE PMT: ~30%

Neutrino mass ordering(II)

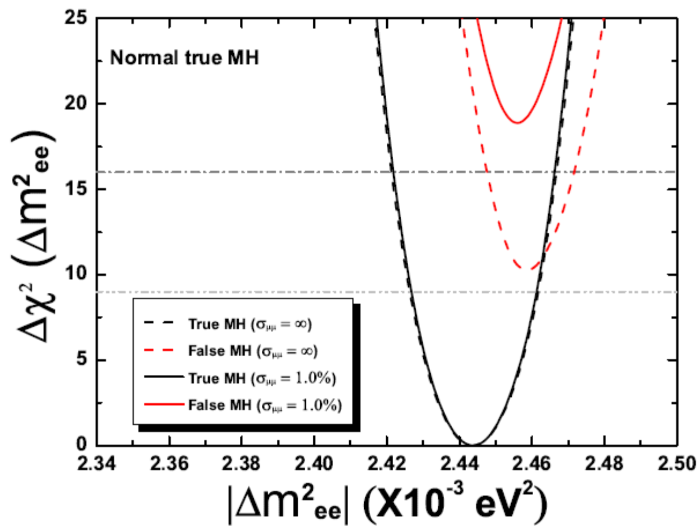
- A relative measurement (no constraint on Δm^2_{31}, **$\Delta\chi^2$>9**)
- An absolute measurement (**$\Delta\chi^2$>16)** accounting for constraints from long baseline experiments($\Delta m^2_{\mu\mu}$ precision of 1%).

$\Delta\chi^2$ of different parameter influence

	Size	$\Delta\chi^2_{MO}$
Ideal	52.5 km	+16
Core distr.	Real	-3
DYB & HZ	Real	-1.7
Spectral Shape	1%	-1
B/S (rate)	6.3%	-0.6
B/S (shape)	0.4%	-0.1

Sensitivity for 100 k IBDs
(20 kton × 35 GW × 6 years).

Improved by $\Delta m^2_{\mu\mu}$ precision of 1%



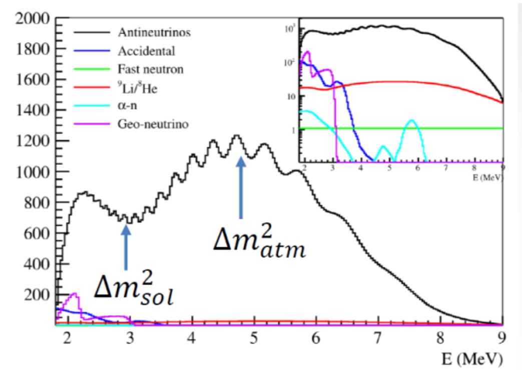
Precision measurement of oscillation parameters

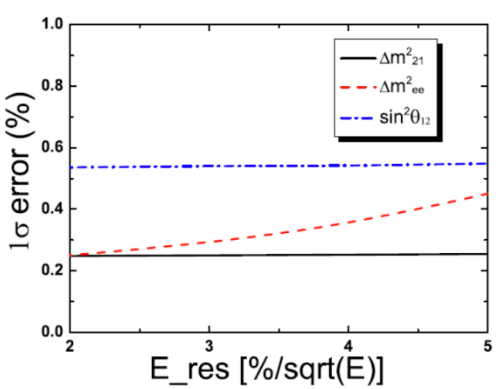
•Precision of three parameters (Δm^2_{21}, Δm^2_{32} and $\sin^2\theta_{12}$) will reach sub-percent level, several times improvement compared with current precision.

•Probing the unitarity of U_{PMNS} to ~1% level.

Current precision

	Δm^2_{21}	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	δ
Dominant Exps.	KamLAND	T2K	SNO+SK	Daya Bay	NOνA	T2K
Individual 1σ	2.4%	2.6%	4.5%	3.4%	5.2%	70%
Nu-FIT 4.0	2.4%	1.3%	4.0%	2.9%	3.8%	16%





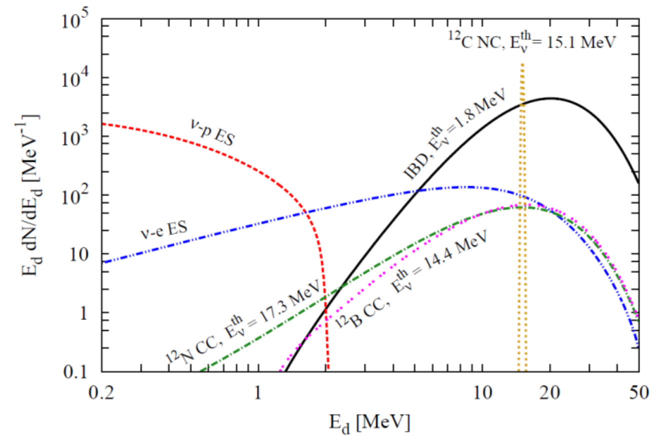
JUNO

	Nominal	+BG, +1% b2b +1% EScale , +1% EnonL
$\sin^2\theta_{12}$	0.54%	**0.67%**
Δm^2_{21}	0.24%	**0.59%**
Δm^2_{32}	0.27%	**0.44%**

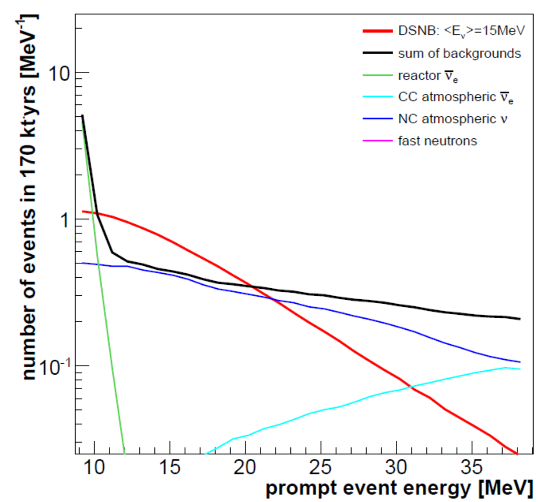
J. Phys. G43:030401 (2016)

Supernova neutrinos

- **Galactic core-collapse supernova neutrinos (CCSN):**
  - Core collapse SN emits 99% of energy in form of ν
  - SN rate: ~ 3 per century
  - Low energy threshold: ~0.2 MeV
  - Real-time detection of SN burst neutrinos in ~10 s
  - Determination of flavor content, energy spectrum and time evolution
  - Golden channel: IBD, ~5000 events for SN@10 kpc
- JUNO is part of the SNEWS project (SuperNova Early Warning System).



- **Diffuse Supernova Neutrino Background (DSNB):**
  - DSNB rate: approx. **10 core collapse/sec** in the visible universe
  - Integrated neutrino flux from all past core-collapse events in the visible universe
  - Provide information of star formation rate, emission from average CCSNe and BHs
  - Expected detection of ~3σ after 10 years data taking.
  - Leading constraint if DSNB is not observed
    - the upper limit on the flux above 17.3 MeV would be ~0.2 cm^{-2}s^{-1}(90%.C.L.) after 10 years.

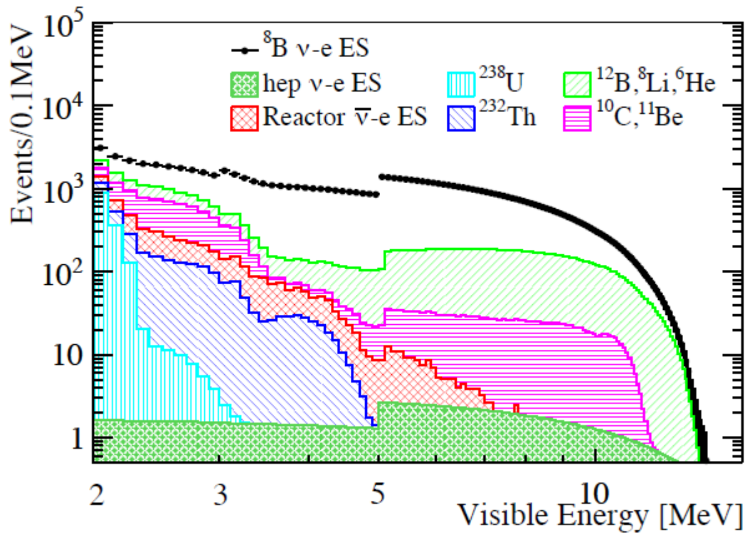


- **Multi-messager astrophysics:**
  - Energy threshold lower to O(10) keV
  - Realtime monitoring of the MeV transient neutrino sky

Solar neutrinos

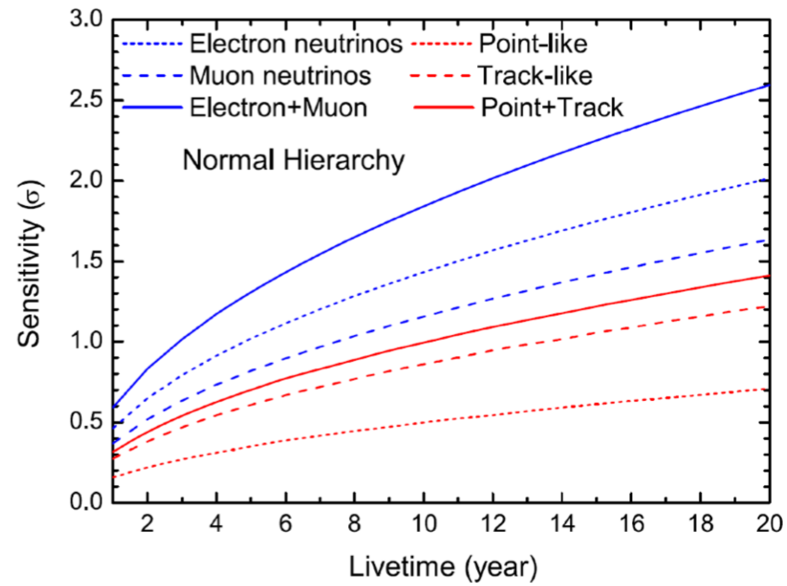
- ^{8}B solar neutrino detection
  - Via neutrino-electron elastic scattering in JUNO
  - Large target mass(20kton LS)
  - Effective cosmogenic background rejection(both time and volume)
  - Radioactivity background (10^{-17} g/g U/Th)
- Event rate:
  - Signal~ 60,000 recoil electrons , background event ~30,000 in 10 years of data taking.
- Shed new light on current tension in Δm^2_{21} between solar and reactor neutrinos measurement with the same detector。

arXiv: 2006.11760



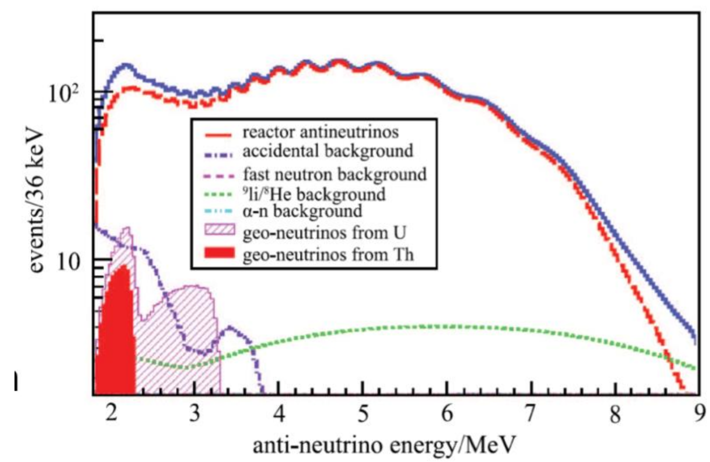
Atmospheric neutrinos

- **Atmospheric neutrinos:**
- Complimentary neutrino mass ordering sensitivity via matter effect
- Sensitivity to θ_{23}
  - the wrong θ_{23} octant could be ruled out at 1.8σ (0.9σ) for the true normal (inverted) hierarchy and θ_{23} =35 °
  - Measure θ_{23} with 6° precision.



Geo-neutrino

- Explore origin and thermal evolution of the Earth
- Expected 400-500 IBD/y, larger than all accumulated geo-ν events before
- Precision can achieve at 6% (10 years)
- Challenging S/B ratio:
  - Same detection channel as reactor neutrinos
  - Strong reactors!



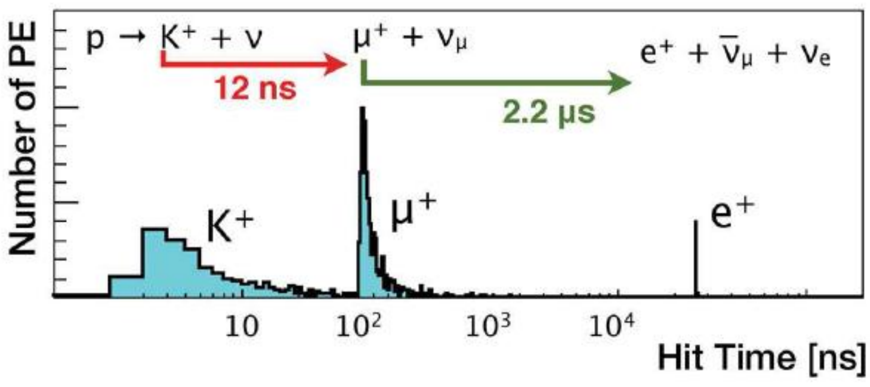
Proton decay

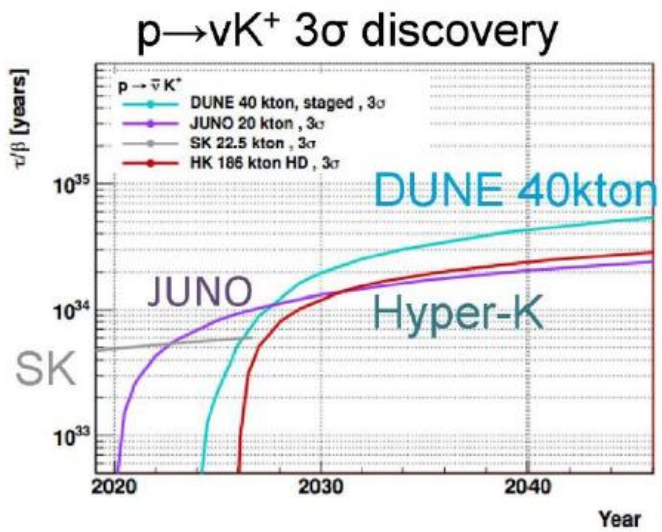
Two possible decay channels:

$$p \to \pi^0 + e^+ \qquad \text{(favored by GUT)}$$
$$p \to K^+ + \nu \qquad \text{(favored by SUSY)}$$

- Current best limits set by the Super-Kamiokande experiment
- Kaon is invisible in a water Cherenkov detector
- JUNO will focus on the K decay mode to take advantage of the LS technique
- Competitive sensitivity to proton decay searches .
  - JUNO will be sensitive to τ ~2×10^{34} years.

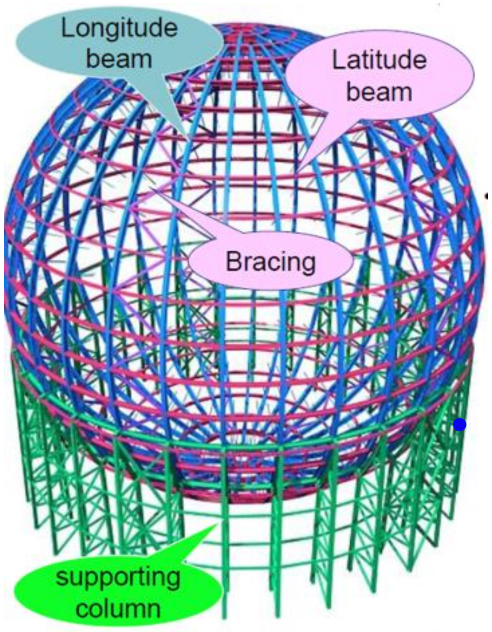
- Triple coincidence signal





Central detector(CD)

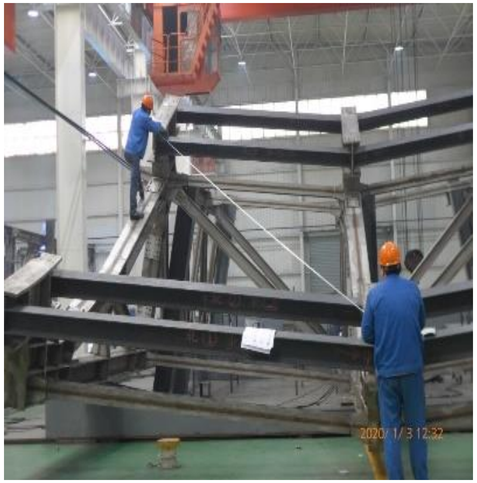
Acrylic sphere + SS truss



- Acrylic spherical vessel
  - Φ 35.4 m acrylic spherical vessel
  - acrylic sheets: 8 m × 3 m ×12 cm
  - Solved technical problems: high precision curved sheet, anti-seismic, transparency, low bkg, fast bonding and annealing.
- Acrylic vessel panels and SS structure are in production.

Key features

- ✓ **Thickness of Acrylic: 120mm**
- ✓ **Acrylic panels(21/23 layers + top chimney+ bottom flange): ~260 pieces**
- ✓ **Connecting nodes: ~590**
- ✓ **Total Weight: 600 tons of acrylic and 600 tons of steel**



Pre-assembly in the manufacturer

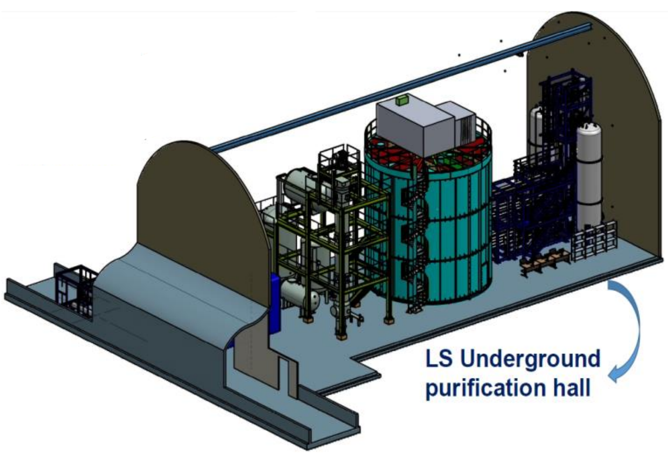
Bonding test of one ring acrylic

Liquid scintillator(LS)

Requirement for LS:

- 2.5 g/L PPO + 3 mg/L Bis-MSB
- Long Attenuation Length: >20m@430nm
- Low background: ^{238}U, ^{232}Th, ^{40}K <10^{-15}g/g;
  - 10^{-15} g/g for reactor antineutrinos
  - 10^{-17} g/g for solar neutrinos

- OSIRIS: Online Scintillator Internal Radioactivity Investigation System
  - 20 t LS and water tank 9 m x 9 m
  - Sensitivity of 10^{-15} g/g per day.



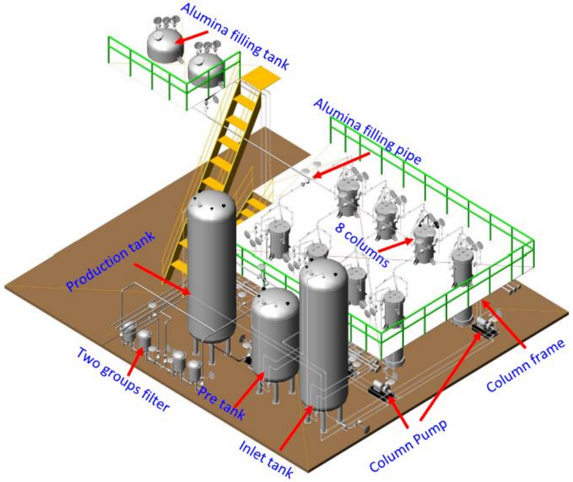
LS Production:

In order to get good quality LS

•Use Al_2O_3 column for LS purification to increase the attenaution length;

•Use distillation, water extraction and steam stripping to reduce the radiation background for background control.

LS purification pilot plant has been bulit in Daya Bay LS hall as a pre-study for JUNO LS mass production.



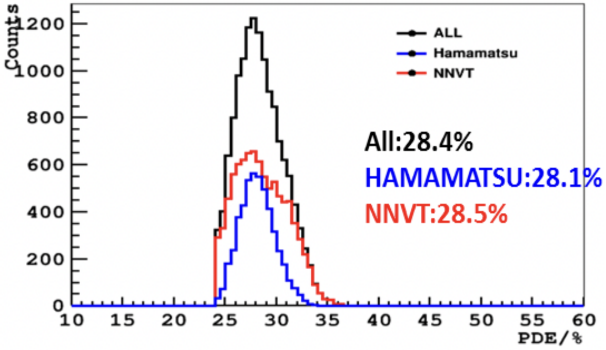
Purification system @ JUNO surface

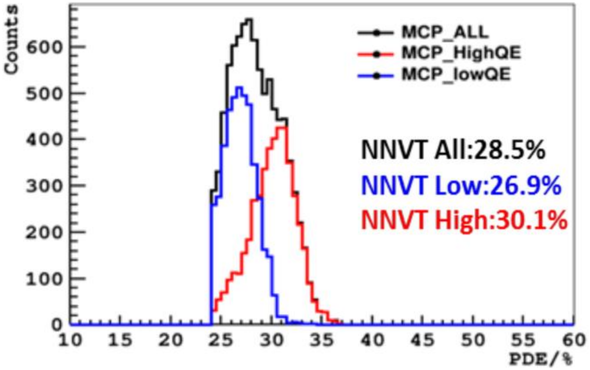
20 inch high QE PMTs

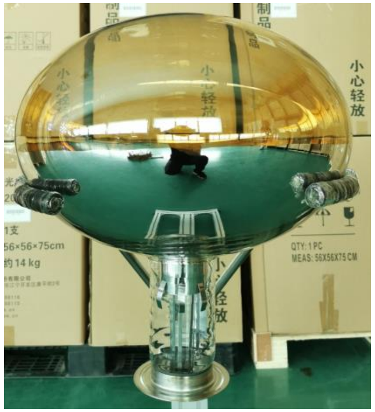
Two types of 20 inch PMTs used in JUNO

- 15k NNVT MCP-PMT: newly developed by North Night Vision Technology (NNVT), used for central detector and veto detector.
- 5k Hamamatsu R12860: used for central detector.

- Almost all bare PMTs are delivered, acceptance test going well.
- Mass potting is on going (36%) and in good shape.
- Implosion protection cover mass production started.



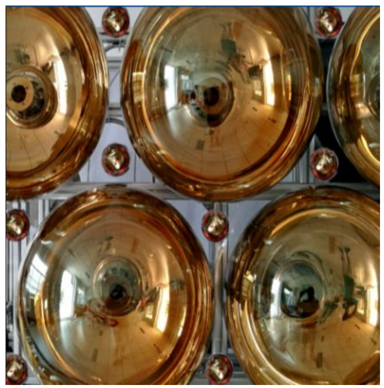




The photon detection efficiency (PDE) of new MCP-PMT is >27%(the requirement).

3 inch PMTs

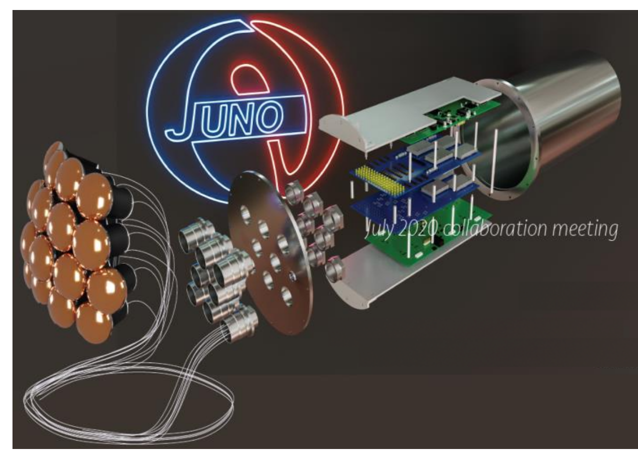
- The Double Calorimetry for central detector
  - ~26000 3” PMT
  - 3” PMTs are put into the gap between large 20” PMTs



XP72B22

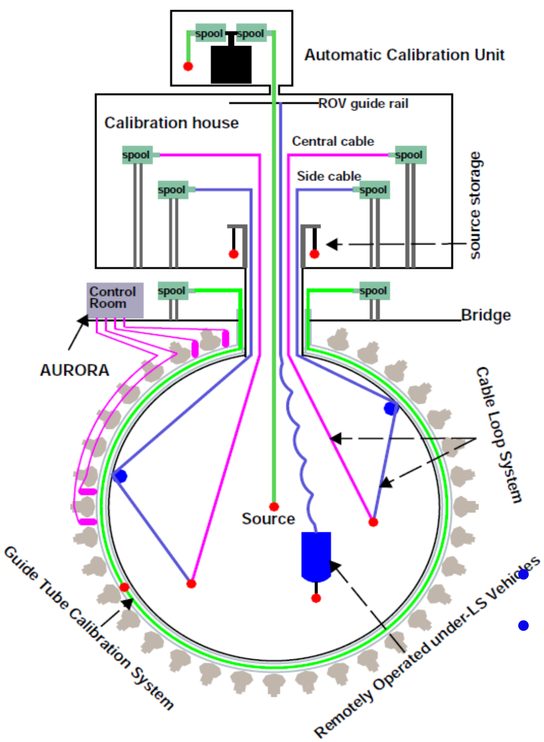
HZC Photonics
Custom 3-inch
PMTs for JUNO

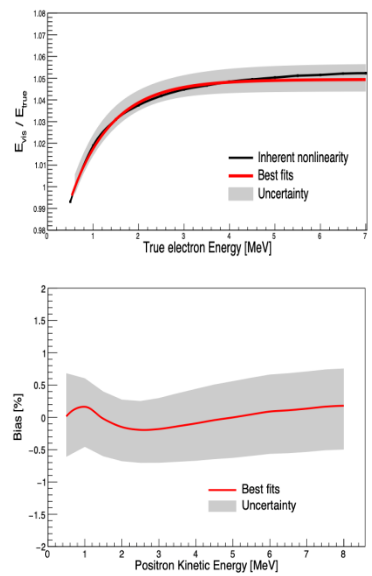
- An Independent system to cross calibrate the 20” PMT system;
- Extend the energy dynamical range beyond the region where large PMT are no more linear or even saturated for muon physics;
- Independent system for supernova and solar neutrino oscillation parameter measurement.
- In good progress:
  - ~26,000 PMTs were produced.
  - Others (HV divider, potting, cable, connector, HV splitter, electronics, under water box) are all going well.

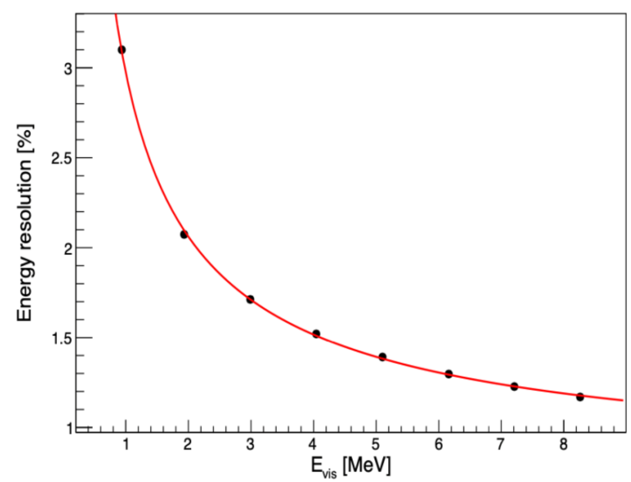


Calibration system

- Requirement: 3% energy resolution@1MeV and 1% energy scale uncertainty.
- Different tools for detector calibration
  - **1D:** Automatic Calibration Unit (ACU)
  - **2D:** Cable Loop System (CLS) and Guide Tube Calibration System (GTCS)
  - **3D:** Remotely Operated Vehicle (ROV)
  - **Auxiliary systems:** Calibration house, Ultrasonic Sensor System (USS), CCD and A Unit for Researching Online the LSc tRAnsparency (AURORA)







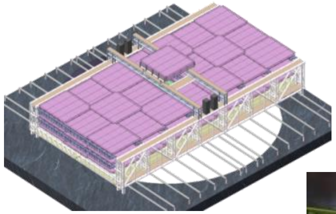
- The bias in the reconstructed energy is expected to be less than 1%.
- The effective energy resolution is expected to be less than 3.0% between 1 MeV and 8 MeV.

Veto system

- **Veto system**
  - Water Cherenkov detector+Top tracker system

Water Pool

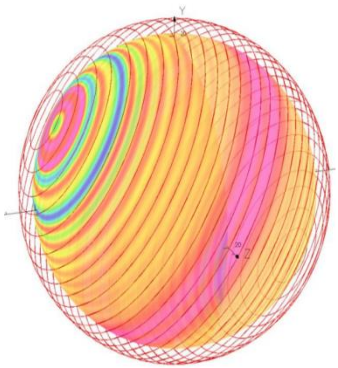
- 35 kton ultrapure water
  - Active veto for muon tagging for muon induced background reduction.
  - Passive shielding for rock neutrons and for material radioactivity
- 2400 20-inch MCP-PMTs on CD surface facing outside.
- Water circulation study in good shape, temperature control within (21±1)℃
- Earth magnetic shielding coils
  - Residual B <10% of local earth magnetic field for CD PMT, <20% for Veto PMT.
- HDPE lining
  - Prevent diffusion of Radon from rocks and keep water clean.

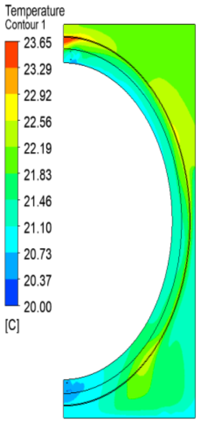


Read Out & Front End Boards

Top Tracker

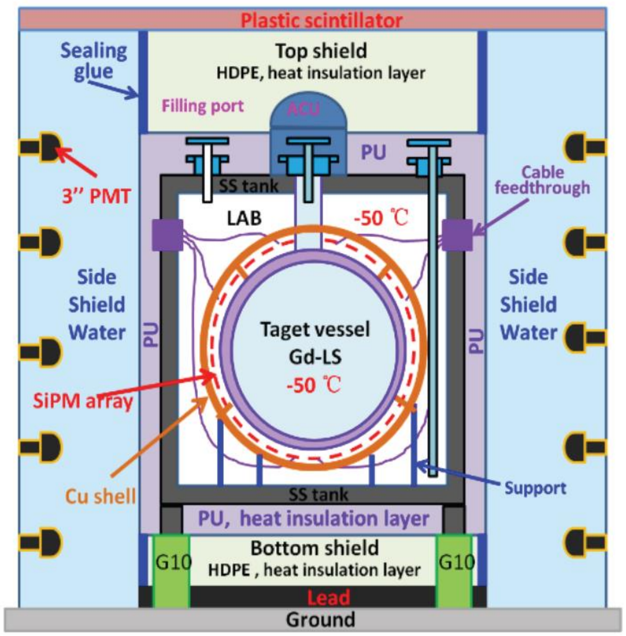
- Reuse the target tracker walls of the OPERA experiment
- 3-layers XY plastic scintillator modules
- Good muon tracking
- The modules are already at JUNO site
- Front End Boards are all produced and other boards in production and going on well.

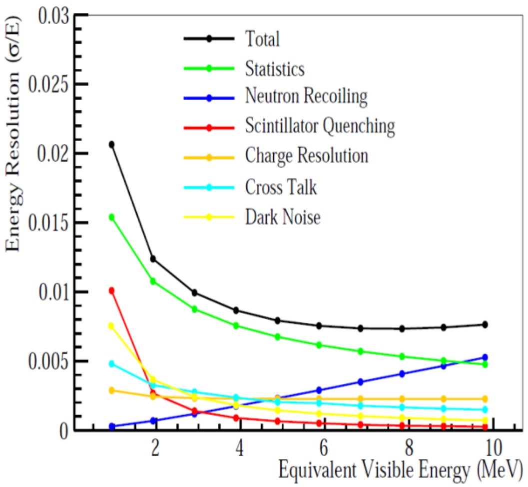




JUNO-TAO

- **Taishan Antineutrino Observatory (TAO)**
  - high energy resolution LS detector ;
  - a ton-level
  - 30 m from one of the Taishan reactor cores
- Purposes:
  - Precisely measure the reactor antineutrino spectrum;
  - A model-independent reference spectrum for JUNO.
  - Benchmark for investigation of the nuclear database.
- Detector Design:
  - 2.8 ton Gadolinium dopped liquid scintillator
  - 10 m^2 95% coverage with SiPM
  - Operate at -50 ℃ (SiPM dark noise)
  - Photon detect efficiency > 50%
  - 4500 p.e./MeV
  - 2000 reactor antineutrinos / day
- **Start operation in 2022**

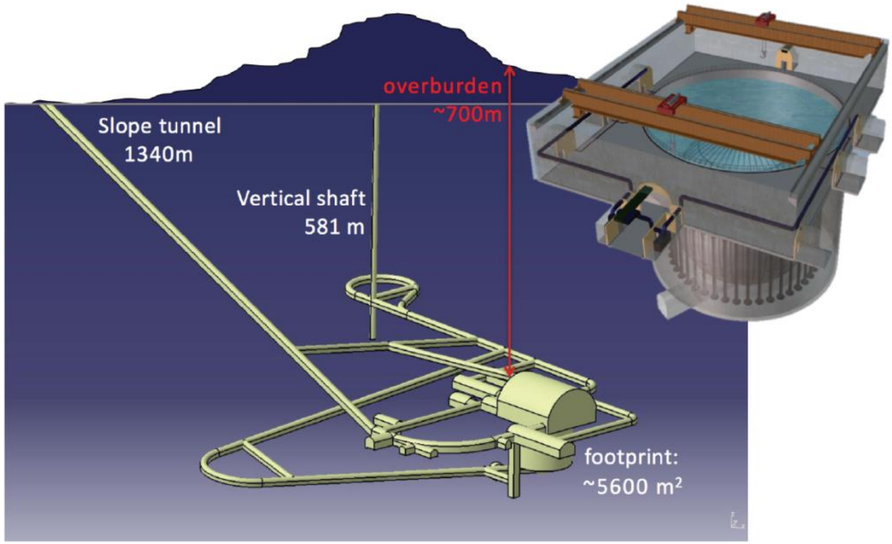




Conceptual Design Report, arXiv:2005.08745v1

Civil Progress

- Slope tunnels and vertical shafts are finished.
- Experimental cavern digging is ongoing.
- Expect to finished in 2020.



JUNO Timeline

2014

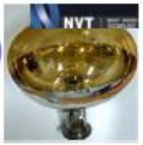
- International collaboration established
- Conceptual design

2015

- PMT production line setup
- CD parts R&D
- Civil construction start

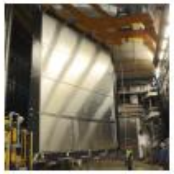
2016

- PMT production start
- CD parts production start
- Yellow book published



2017

- PMT testing start
- TT arrived



2018

- PMT potting
- Start delivery of surface building
- Start production of acrylic sphere

2019-2021

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

2022

- Detector ready for data taking

Summary

- JUNO will measure mass hierarchy (3—4 σ with 6 years data taking) and 3 oscillation parameters to <1% level.
- JUNO also has a rich physics potential with supernova neutrinos, geo-neutrinos, solar neutrinos, and other oscillation physics such as searches for sterile neutrinos, among others.
- The production programme and civil progress are well underway.
- The experiment is expect to start running in 2022.

JUNO Collaboration

77 members, ~600 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	LAL 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		

Thanks!