Status of the JUNO experiment

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On behalf of the JUNO collaboration

HQL 2021: The XV International Conference on Heavy Quarks and Leptons

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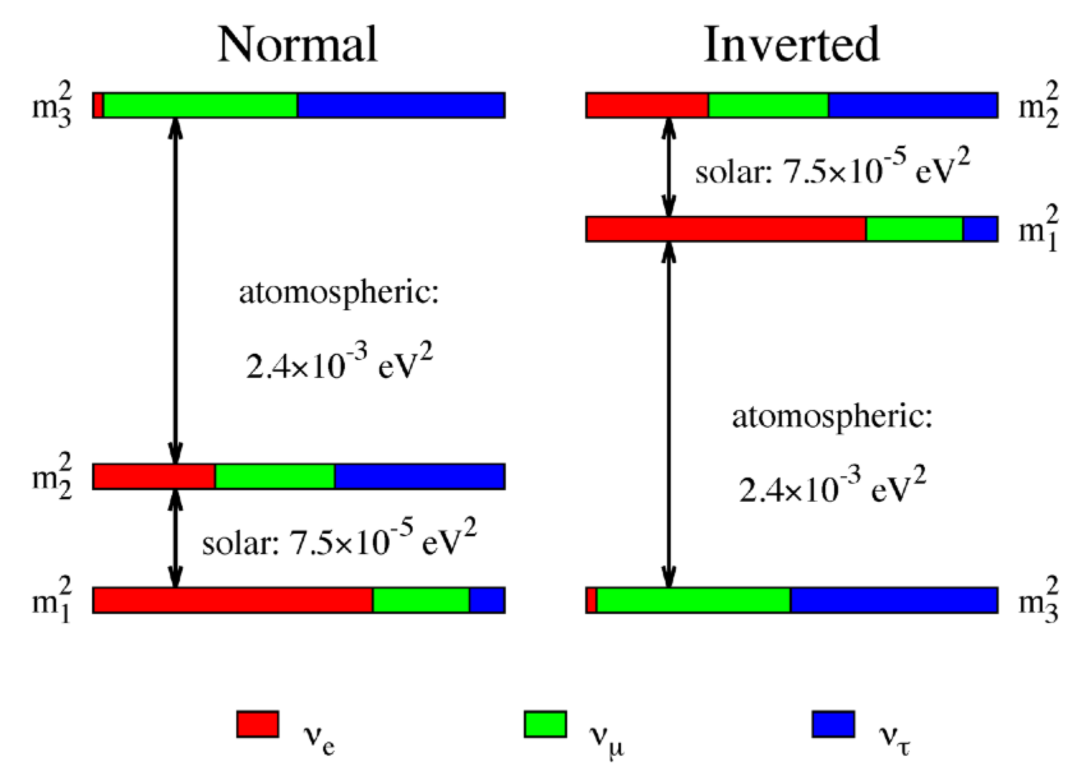
Open Question: Neutrino Mass Ordering

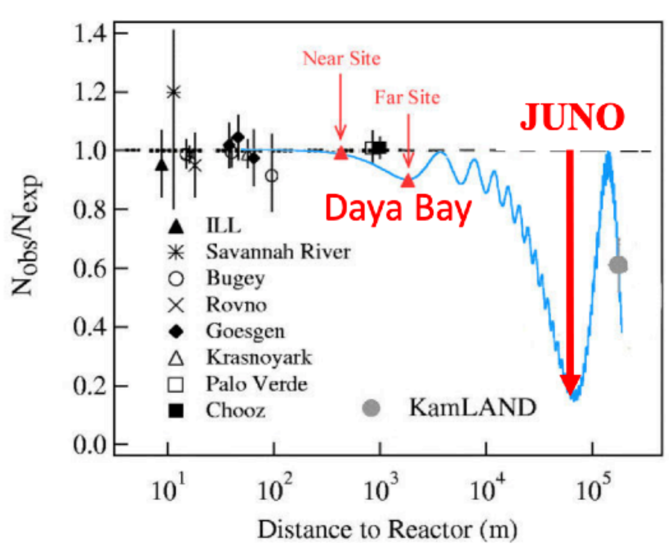
- Two possible Neutrino Mass Orderings (NMO): $m_3 > m_1$ or $m_1 > m_3$? (Δm^2_{31}/ Δm^2_{32} >0 or <0 ?)

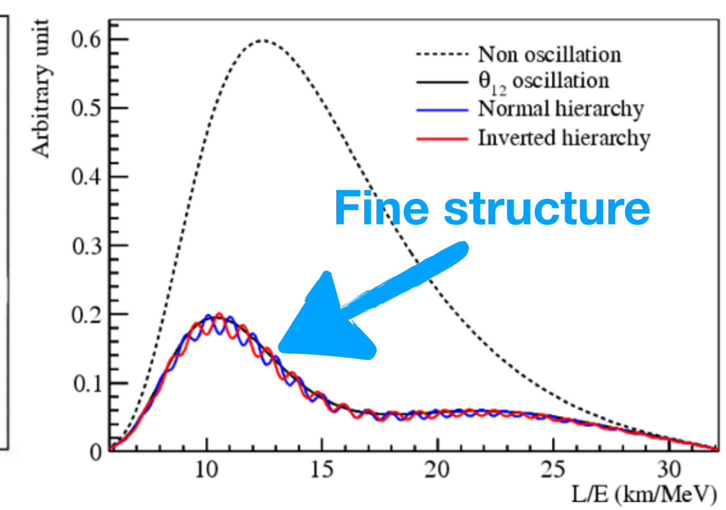
- NMO determination methods:

    - Terrestrial matter effects on Accelerator/Atmospheric neutrinos: T2K, NOνA, DUNE, HK, SK, ORCA, PINGU

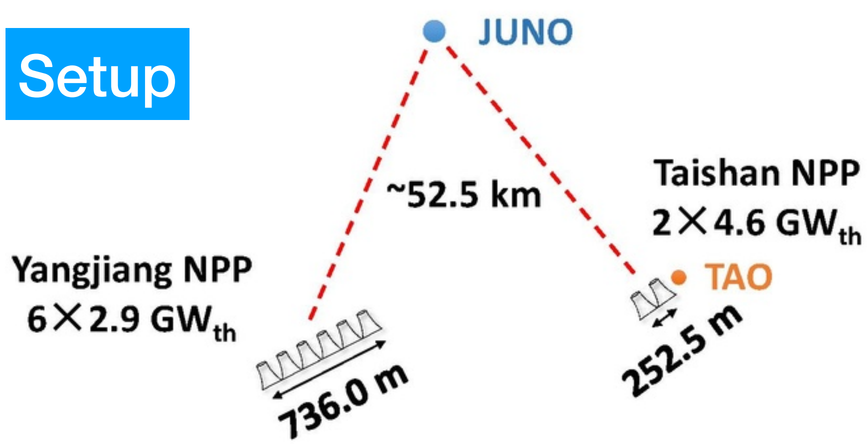
    - Reactor neutrinos (JUNO): Optimum baseline (~50 km) at the valley of Δm^2_{21} oscillations, corrected by fine structure of Δm^2_{31} oscillations.

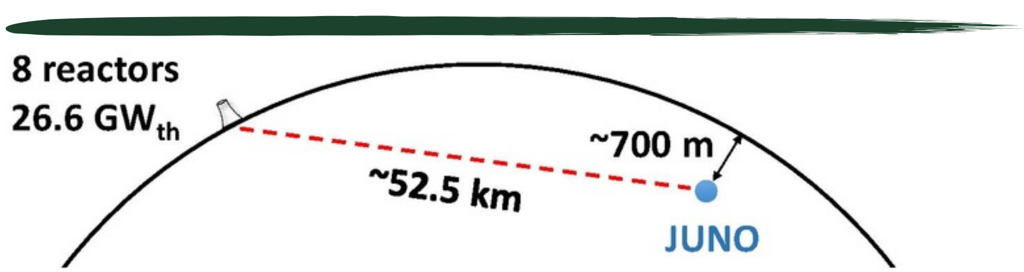






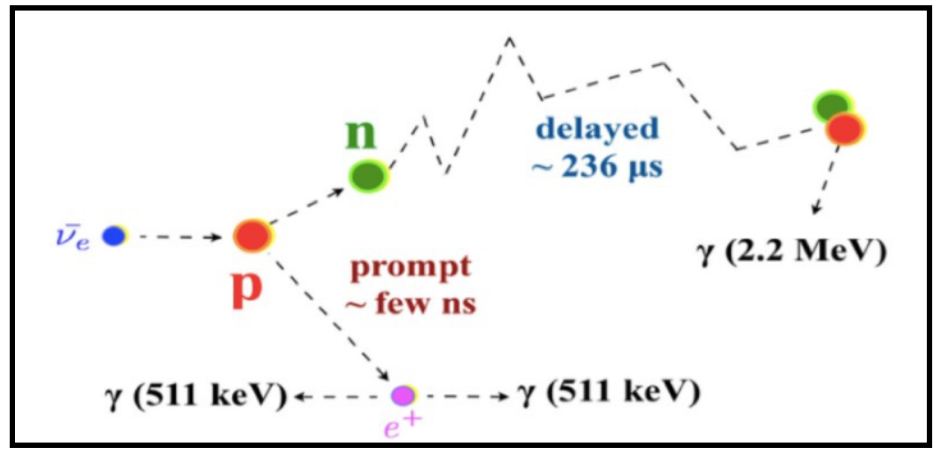
Jiangmen Underground Neutrino Observatory

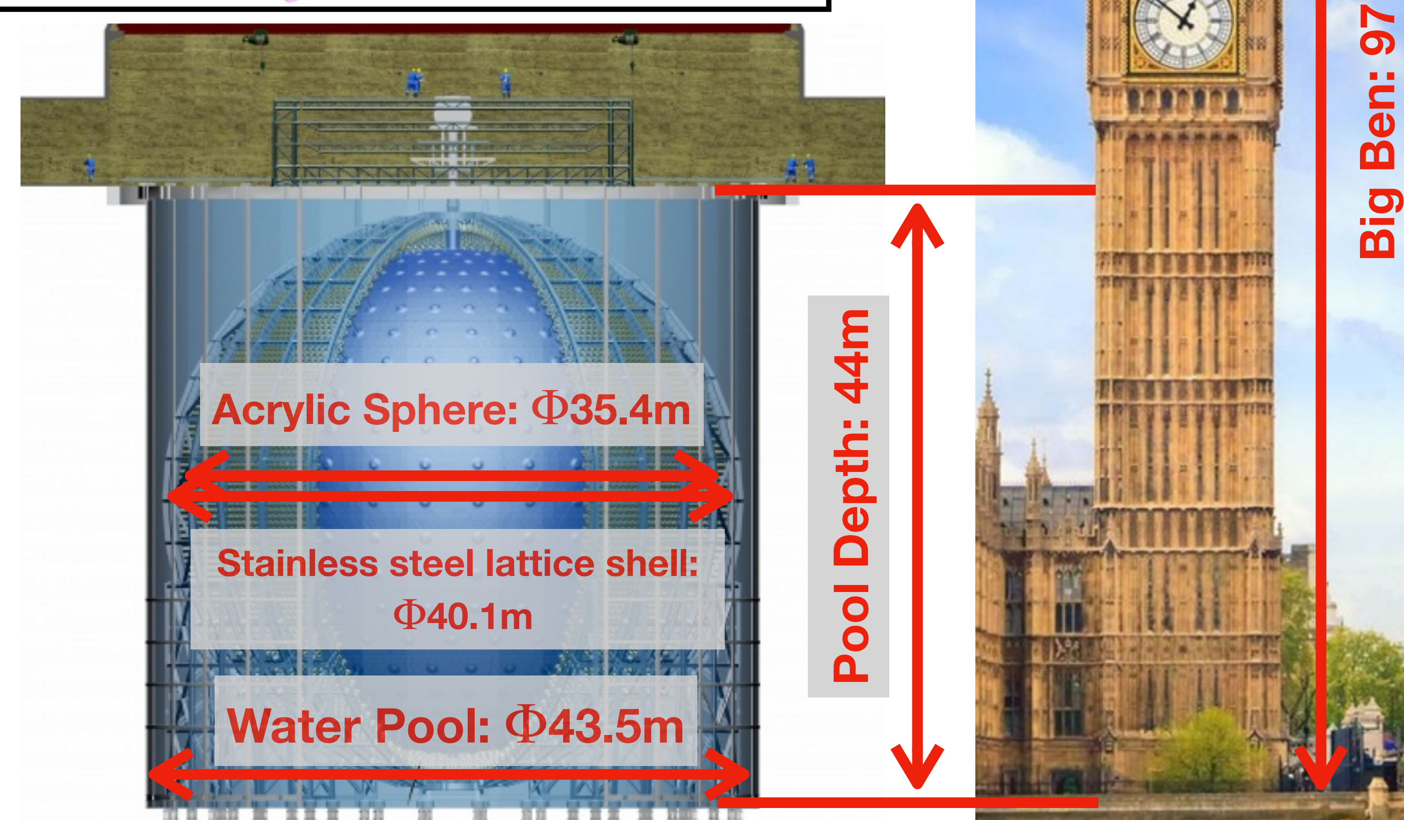




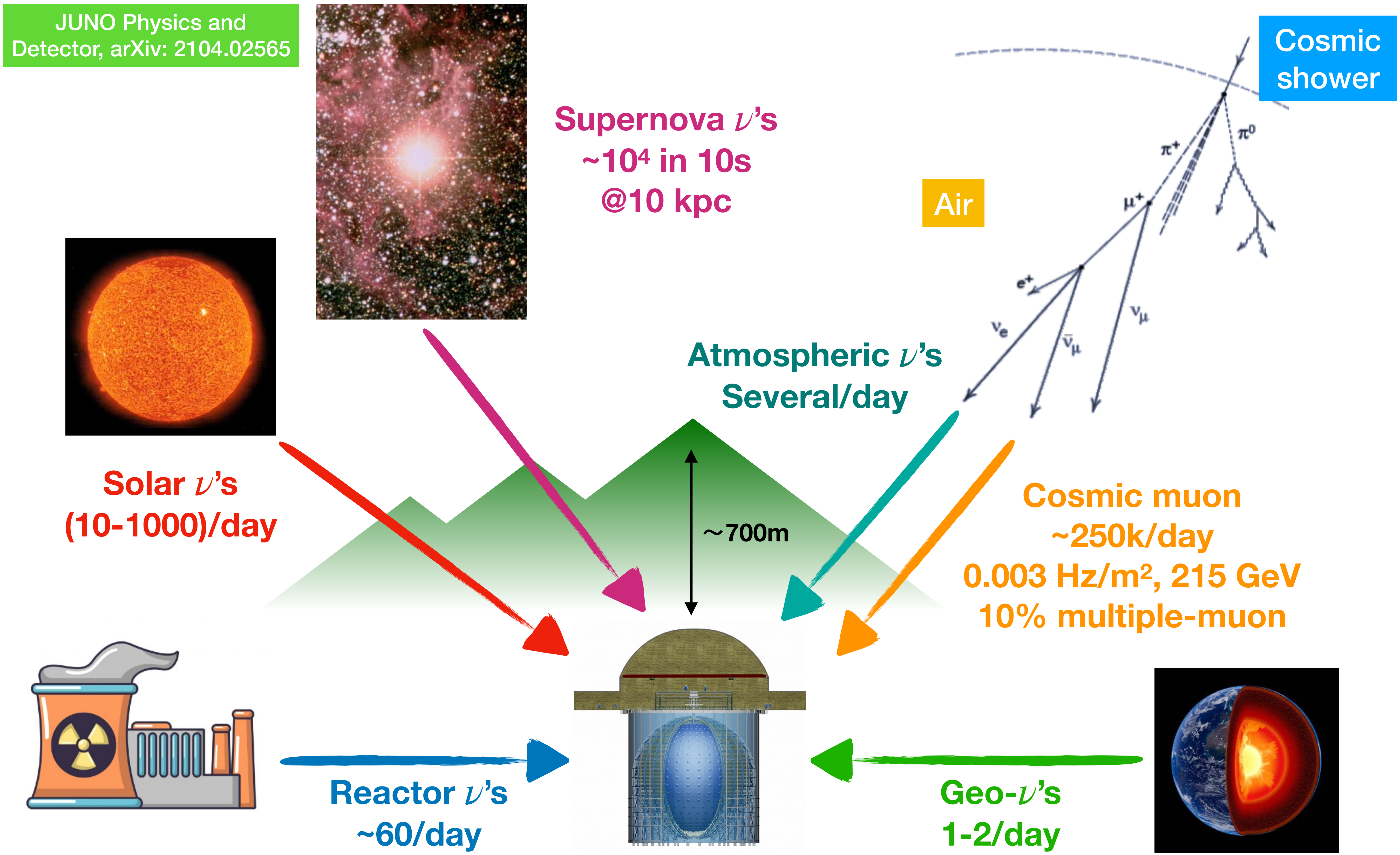
- JUNO is going to be the largest liquid scintillator detector (20 kton).
- The main physics target is the determination of NMO.
- **Inverse Beta Decay (IBD)**:

$$\bar{\nu}_e + p \rightarrow e^+ + n, \quad E_{\bar{\nu}_e} > 1.8\,\text{MeV}$$





Rich Physics Potential in JUNO



Reactor neutrino oscillation in JUNO

The reactor electronic antineutrino oscillation probability in vacuum:

$$\mathbb{P}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\frac{\Delta m^2_{21}L}{4E_{\bar{\nu}_e}}$$

$$-\frac{1}{2}\sin^2 2\theta_{13}\left(\sin^2\frac{\Delta m^2_{31}L}{4E_{\bar{\nu}_e}} + \sin^2\frac{\Delta m^2_{32}L}{4E_{\bar{\nu}_e}}\right)$$

$$-\frac{1}{2}\cos 2\theta_{12}\sin^2 2\theta_{13}\sin\frac{\Delta m^2_{21}L}{4E_{\bar{\nu}_e}}\sin\frac{(\Delta m^2_{31}+\Delta m^2_{32})L}{4E_{\bar{\nu}_e}}$$

arXiv:1808.02256

Slow osc.

Rapid osc.

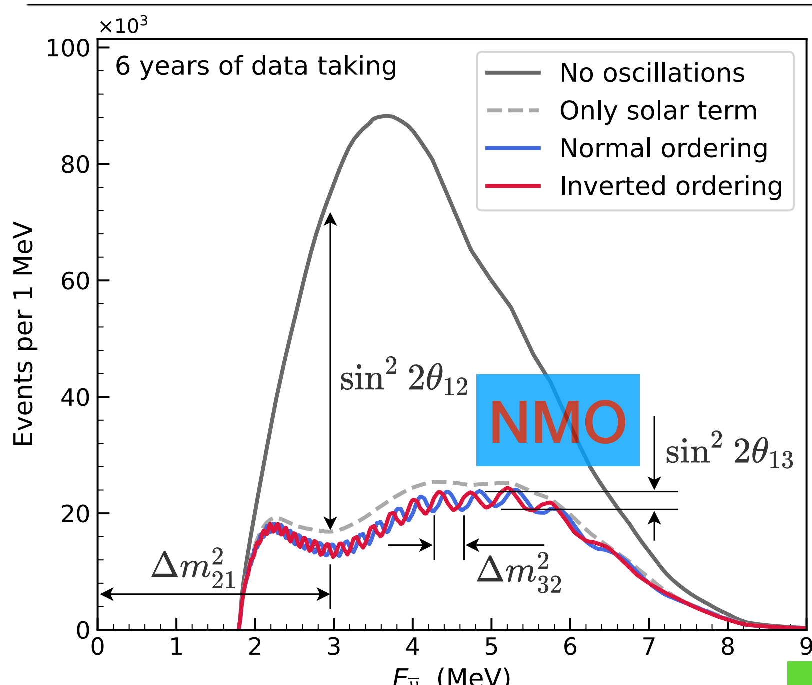
JUNO

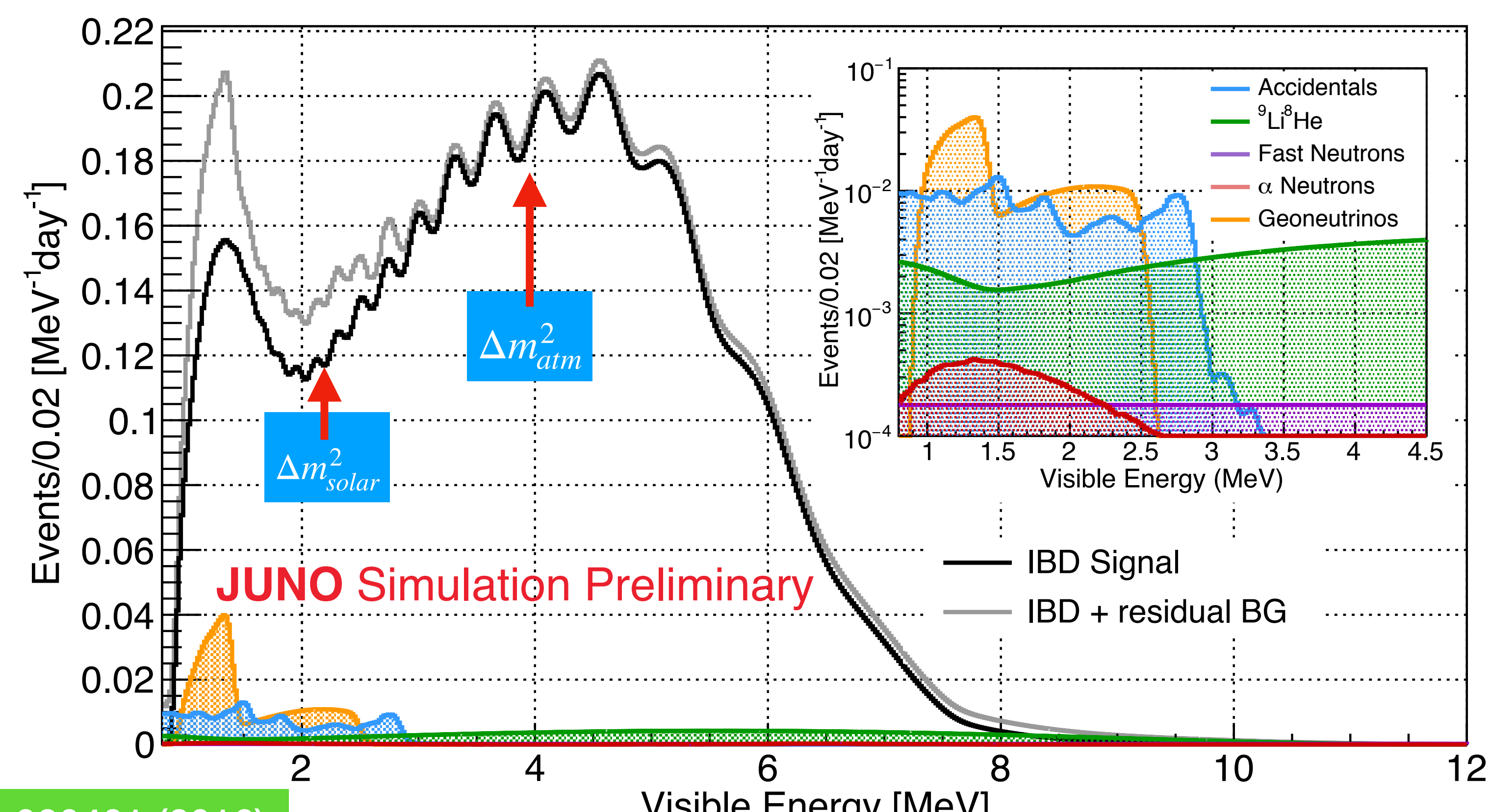
boosted NMO osc. by θ_{13} & medium L

No θ_{23}, No CP violating phase

NMO : $(\Delta m^2_{31} + \Delta m^2_{32})$ >0 or <0 ?

	Efficiency (%)	IBD Rate (day^{-1})
All IBDs	100	57.4
After Selection	82.2	47.1





J. Phys. G43:030401 (2016)

Sensitivities of NMO and precision measurement

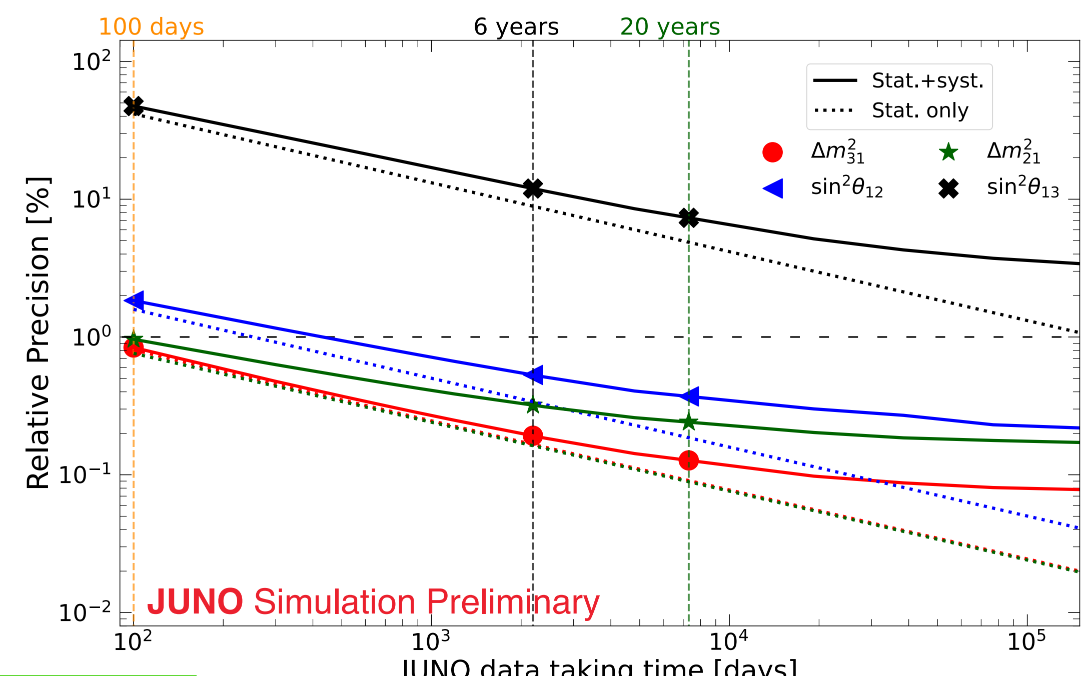
NMO

- JUNO will determine NMO at **3σ** in **6 years** of data taking.
- An unprecedented **Energy resolution of** $3\,\%/\sqrt{E(\mathrm{MeV})}$ is required for **3σ** NMO determination.
- Key points to reach such energy resolution requirement:
    1. High light yield liquid scintillator: attenuation length > 20 m @ 430 nm
    2. Large PMT coverage: ~78%
    3. PMT high quantum efficiency (QE): ~30%

Precision measurement

- Measure neutrino mixing parameters at sub-percentage level: Δm^2_{31}, Δm^2_{21}, $\sin^2\theta_{12}$

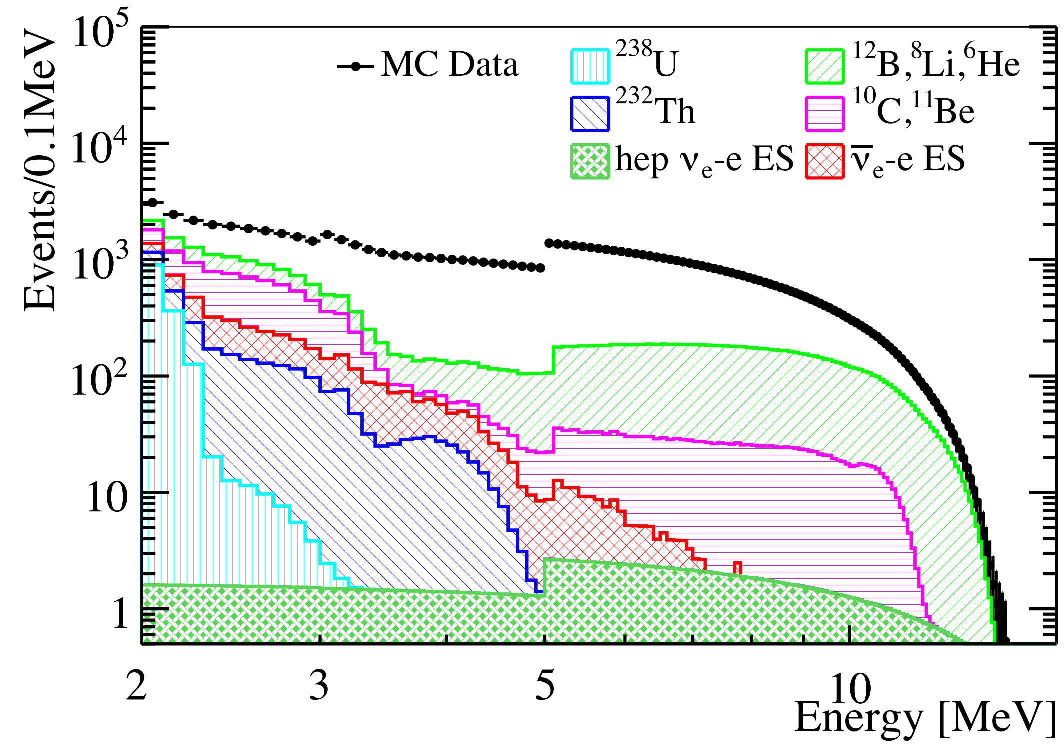
	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$
Dominant Exps.	T2K	KamLAND	SNO+SK
Individual 1σ	2.6%	2.4%	4.5%
PDG2020	1.4%	2.4%	4.2%
JUNO 6 years	~0.2%	~0.3%	~0.5%



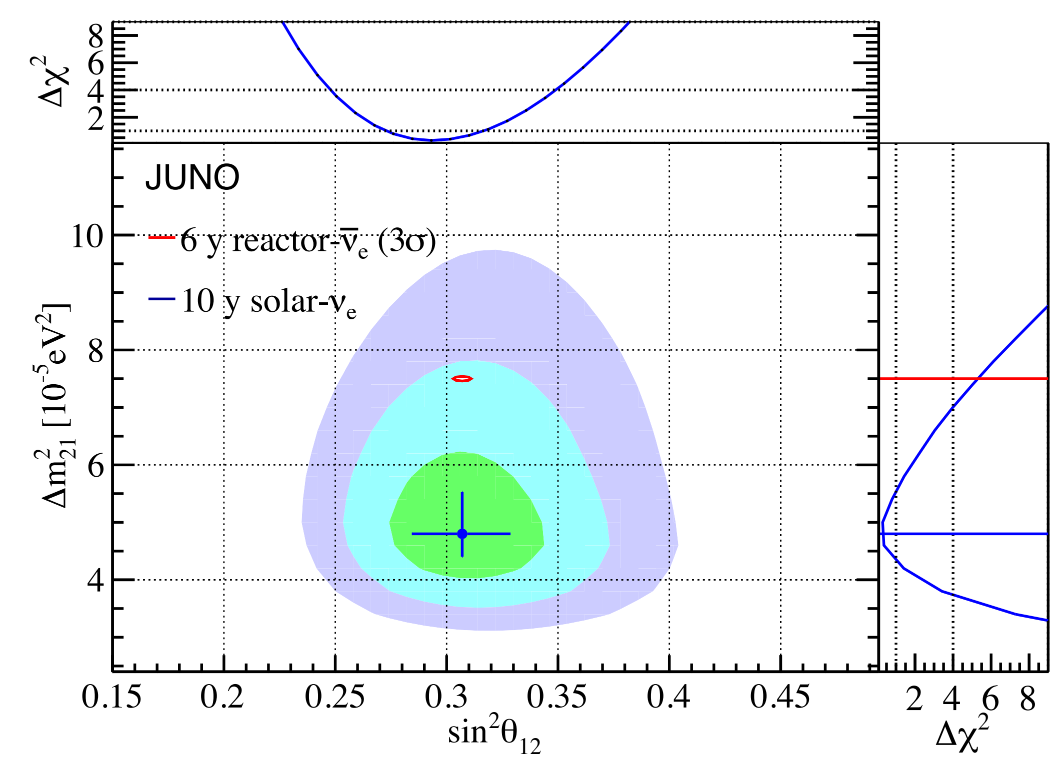
J. Phys. G43:030401 (2016)

Solar Neutrinos

- ^{8}**B solar neutrino** in JUNO:
  - Detection channel: neutrino electron elastic scattering (ES)
  - Radioactivity and cosmogenic background: rejection with time and volume
  - Radioactivity background: 10^{-17} g/g U/Th
  - 10-year event number: ~60,000 recoil electrons and ~30,000 background
- JUNO can independently check the tension of Δm^2_{21} with solar neutrinos and reactor neutrinos
- Upturn and day-night asymmetry
- ^{8}**B flux** model independent measurement: C^{13}(~1% in C) CC&NC
- ^{7}**Be, pp, pep**…



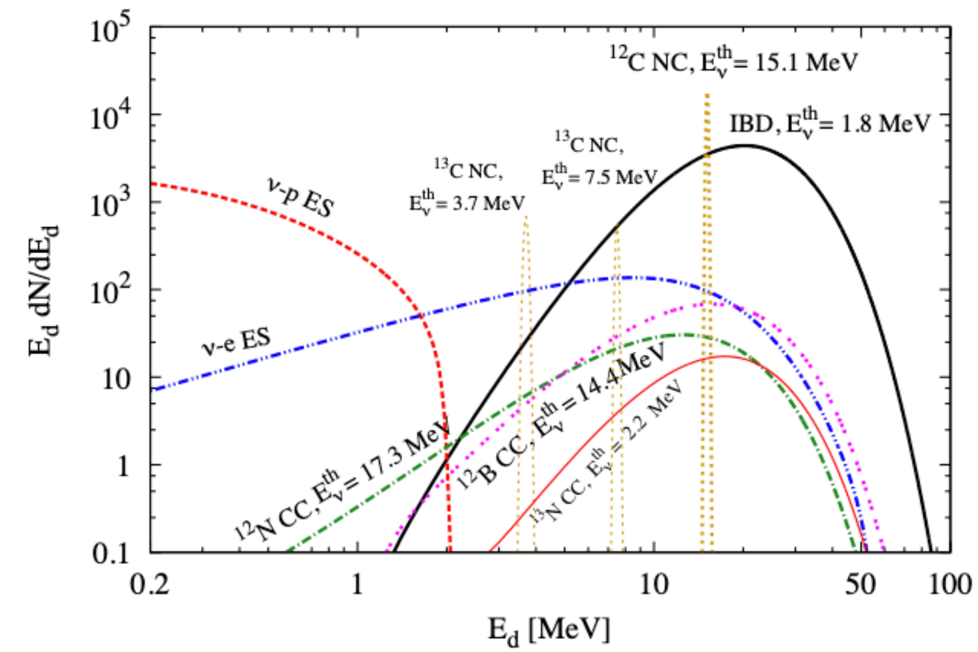
JUNO Physics and Detector, arXiv: 2104.02565

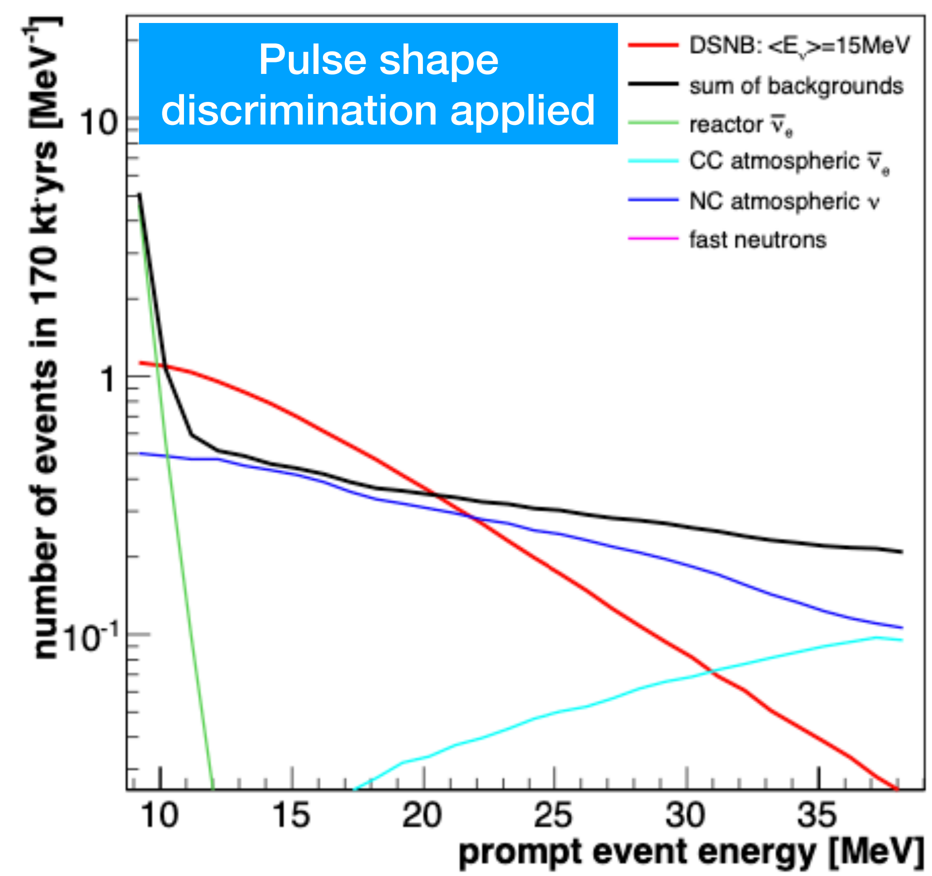


Chin. Phys. C 45 (2021) 2, 023004

Supernova Neutrinos

- **Supernova Burst Neutrinos**:
  - Core-collapse supernova (CCSN): explosion lasts **~10s**; >99% energy release in neutrinos; **2-3/century** in the Galaxy
  - Real-time detection of ~5000 IBD, ~1000 ν-p ES and ~4000 ν-e ES events for a CCSN @10kpc, assuming 0.2 MeV threshold and with special triggers design
  - Determination of flavor content, energy spectrum and time evolution
- **Diffuse Supernova Neutrino Background (DSNB)**:
  - Integrated neutrino flux from all CCSN in the visible Universe
  - Provide info for star formation rate, emission from CCSNe and BHs
  - Expected 3σ detection in 10 years of data taking

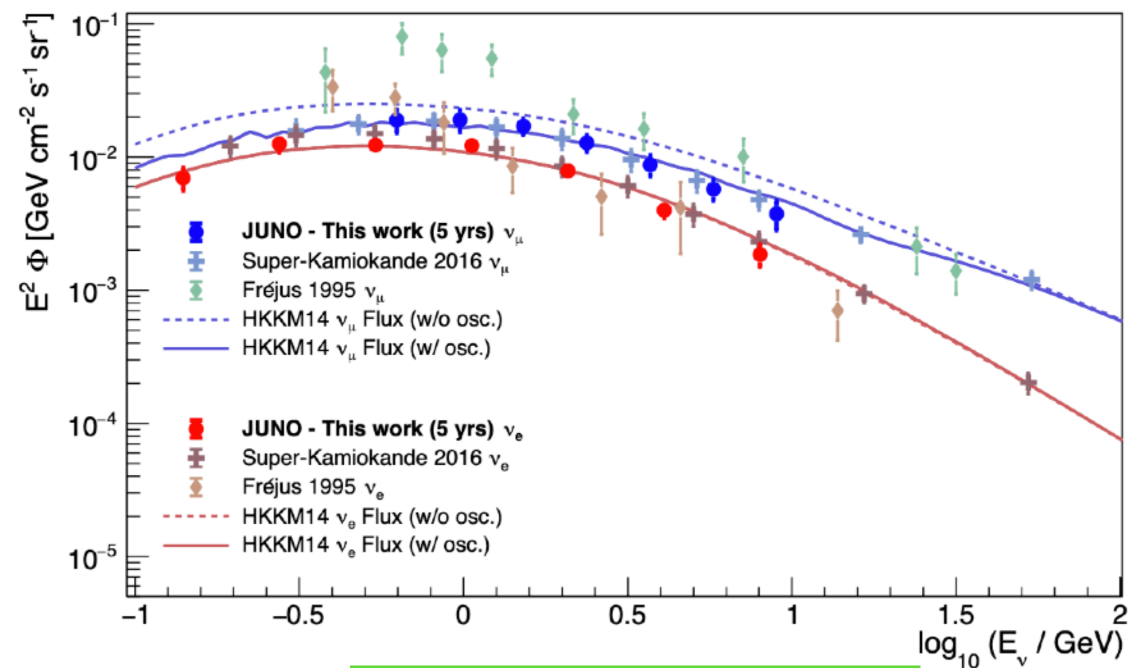




JUNO Physics and Detector, arXiv: 2104.02565

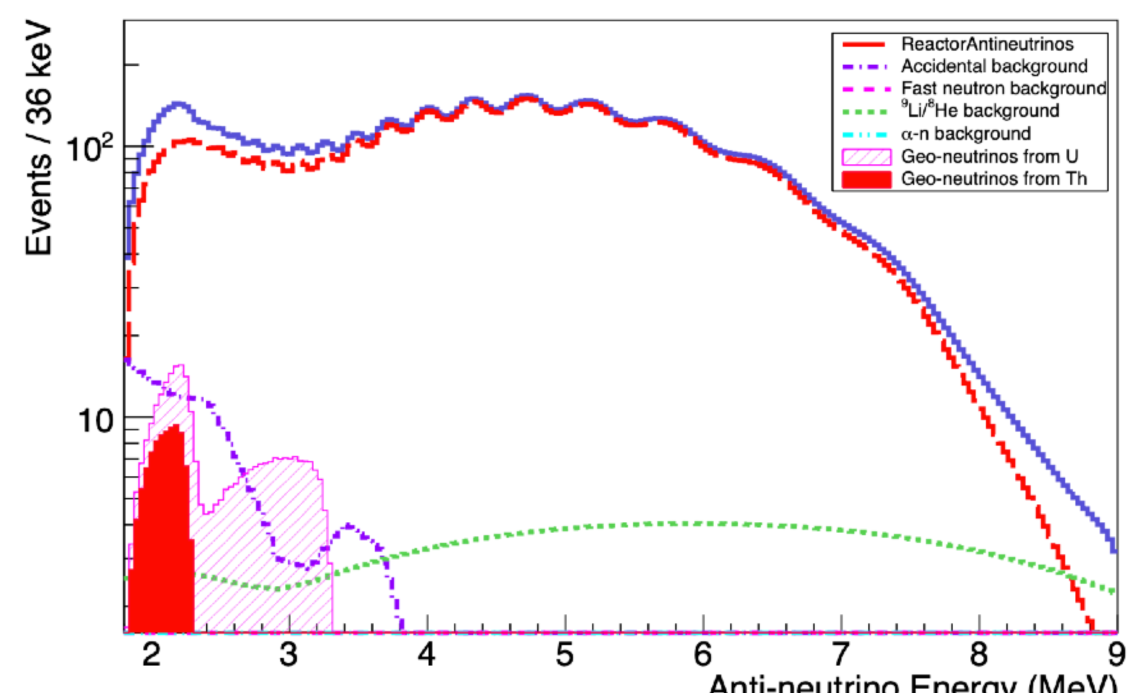
Atmospheric & Geo Neutrinos

- **Atmospheric Neutrinos**:
  - Complimentary neutrino mass ordering sensitivity via matter effect
  - Measure θ_{23} with 6° precision
  - Atmospheric neutrino flux and spectra measurement



JUNO Physics and Detector, arXiv: 2104.02565

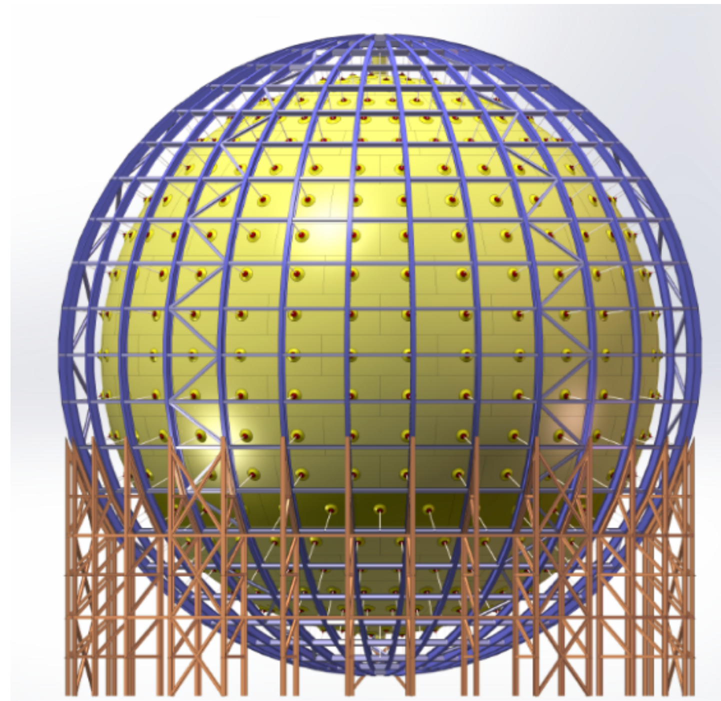
- **Geo-Neutrinos**:
  - Explore origin and thermal evolution of the Earth
  - Expected 400-500 IBDs / year
  - Precision 6% in 10 years



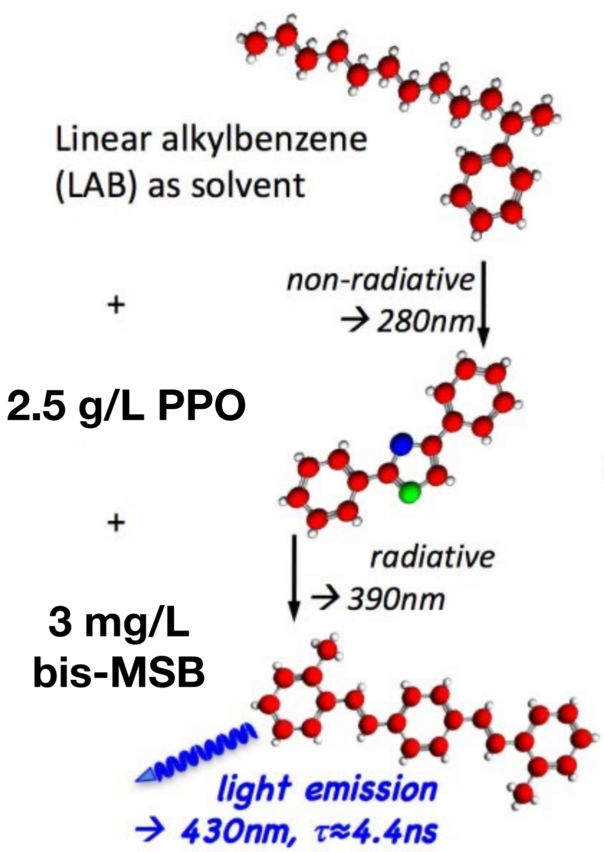
Chin. Phys. C 40 (2016) 3, 033003

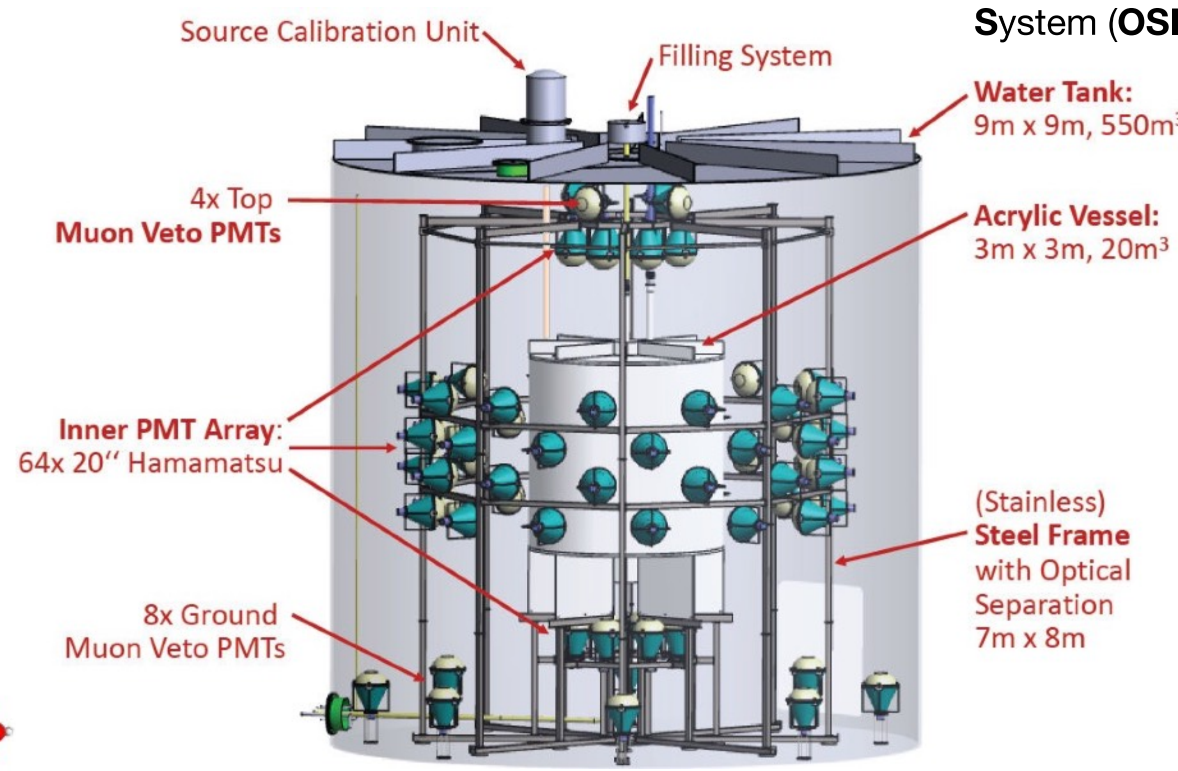
Central Detector & Liquid Scintillator

CD : Acrylic Sphere + Stainless Steel Support



- Acrylic sphere composed of ***265*** spherical panel pieces
- Thickness: 120 mm, net weight: ~600 tons
- **Transparency > 96%** in pure water
- Strict control for low radioactive backgrounds, acrylic samples have ***met the 1 ppt requirement*** for U/Th/K



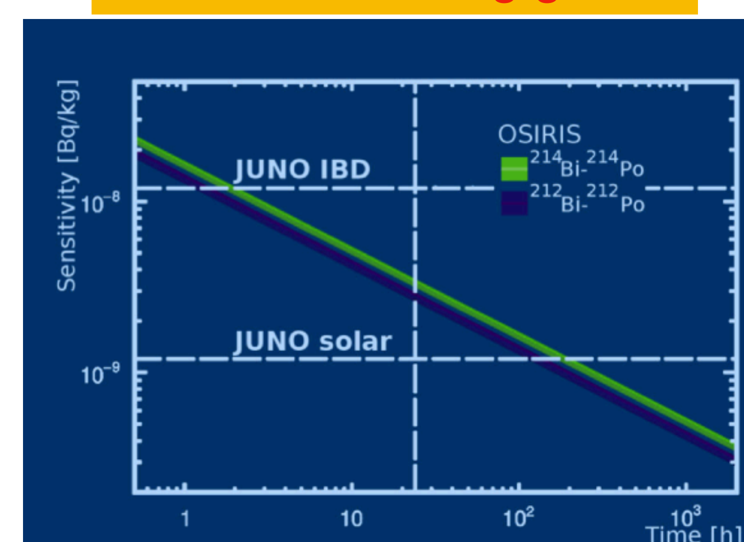


Radioactivity control, arXiv:2107.03669
LS recipe, NIMA 988, 164823 (2021) ,arXiv: 2007.00314
OSIRIS, 2103.16900

LS: JUNO liquid scintillator composition: LAB + PPO (2.5 g/L) + bis-MSB (3 mg/L)

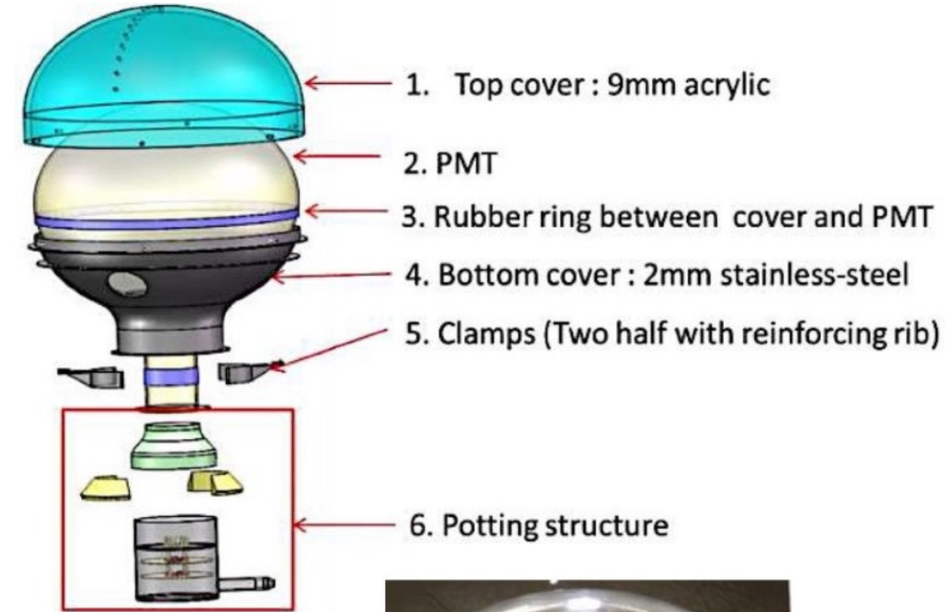
- LAB purification in four steps:
  1. Al_2O_3 filtration column (optical properties improvement)
  2. Distillation (heavy elements removal/transparency improvement)
  3. Water extraction (U/Th/K radioisotopes removal)
  4. Steam/Nitrogenstripping(Gaseous impurities-Ar,Kr,Rn-removal)
- **O**nline **S**cintillator **I**nternal **R**adioactivity **I**nvestigation **S**ystem (**OSIRIS**): LS purity measurement

Radiopurity requirements:
Reactor neutrinos:
U/Th < 10^{-15} g/g
Solar neutrinos:
U/Th < 10^{-17} g/g



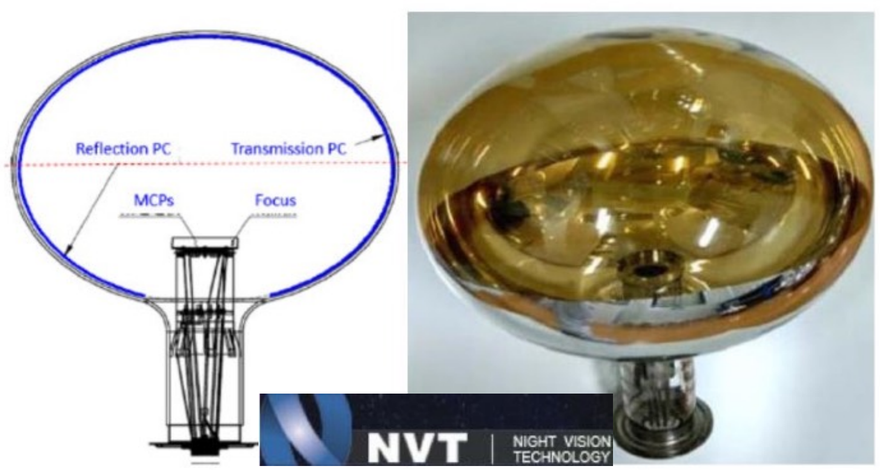
Photomultiplier Tubes

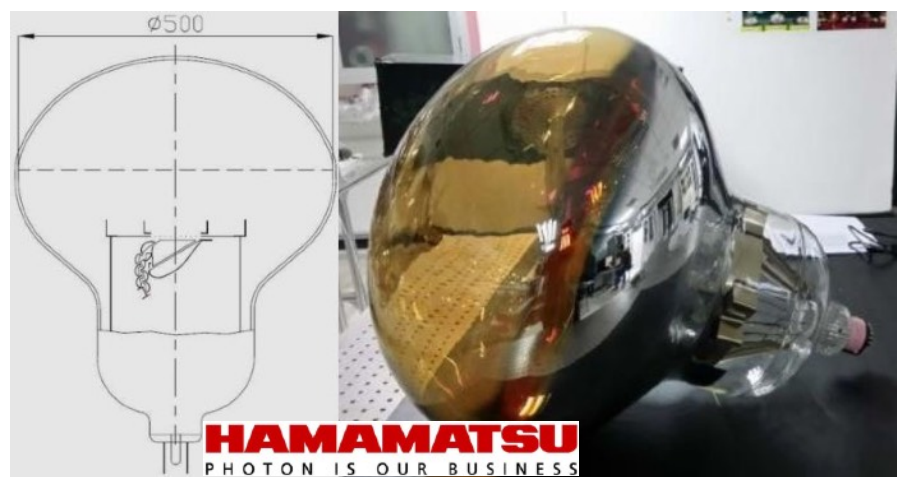
- **Two sizes (20” and 3”)** of PMTs are used to fully (78%) cover the CD
  - 17,612 20” large PMTs for CD (~75.2%)
    + 2,400 20” large PMTs for veto
  - 25,600 3” small PMTs for CD (~2.7%)
  - Large & small PMTs interleaving



20-inch PMTs

3-inch PMTs





HZC Photonics

Microchannel plate (MCP) PMTs

- Developed for JUNO
- Use transmission and reflection cathodes to increase quantum efficiency

Dynode PMTs

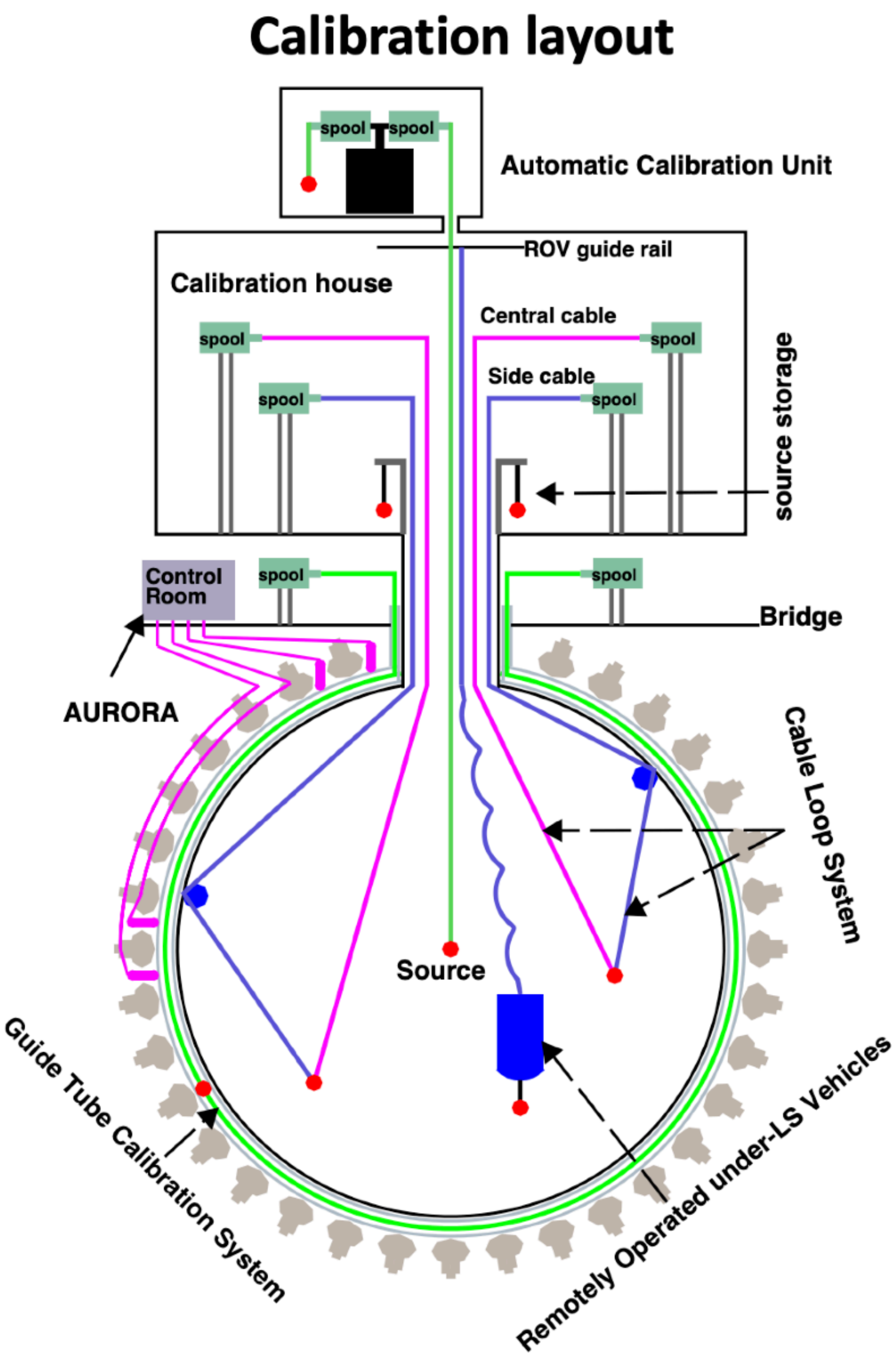
- Developed for JUNO New type of bialkali photocathode
- Excellent TTS (2.7 ns FWHM)

Customized 3-inch PMTs for JUNO

- Systematics control: determine non-linear response of 20-in PMTs
- **Increase dynamic range:** improve muon reco. res.; detect very near supernova
- Standalone measurement of solar parameters

JUNO uses:
13,000 MCP-PMTs (NNVT) + 5000 dynode PMTs (Hamamatsu, R12860HQE)

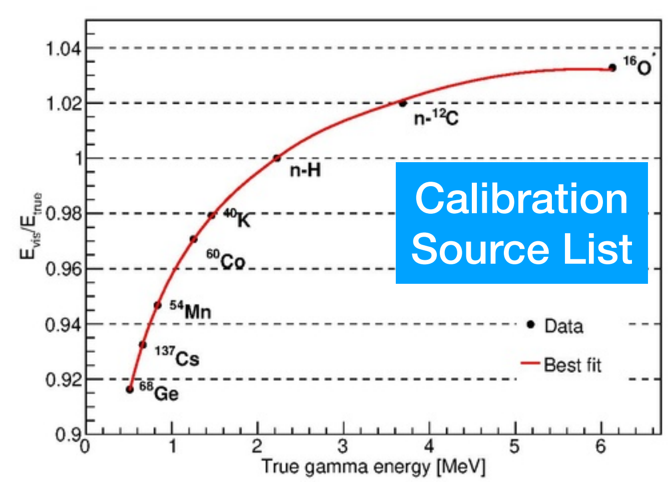
Calibration Systems

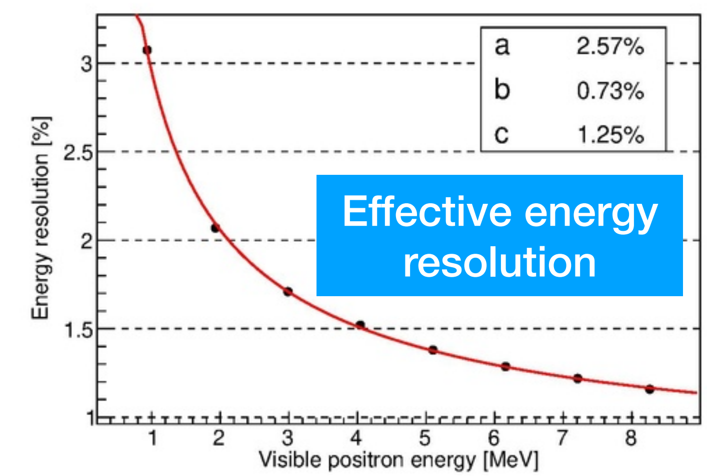


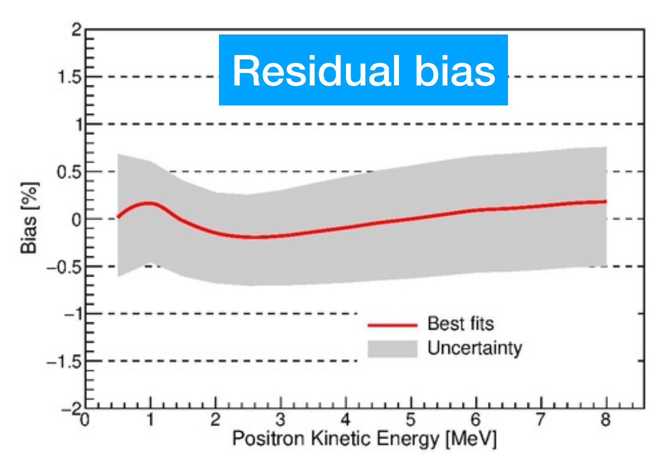
JUNO Calibration, *JHEP* 03 (2021) 004, arXiv:2011.06405

Calibration Systems

1. **1D:** Automatic Calibration Unit (ACU)
2. **2D:** Cable Loop System (CLS) & Guide Tube Calibration System (GTCS)
3. **3D:** Remotely Operated Vehicle (ROV)
4. **Auxiliary systems:** Calibration house, Ultrasonic Sensor System (USS), CCD and A Unit for Researching Online the LSc tRAnsparency (AURORA)

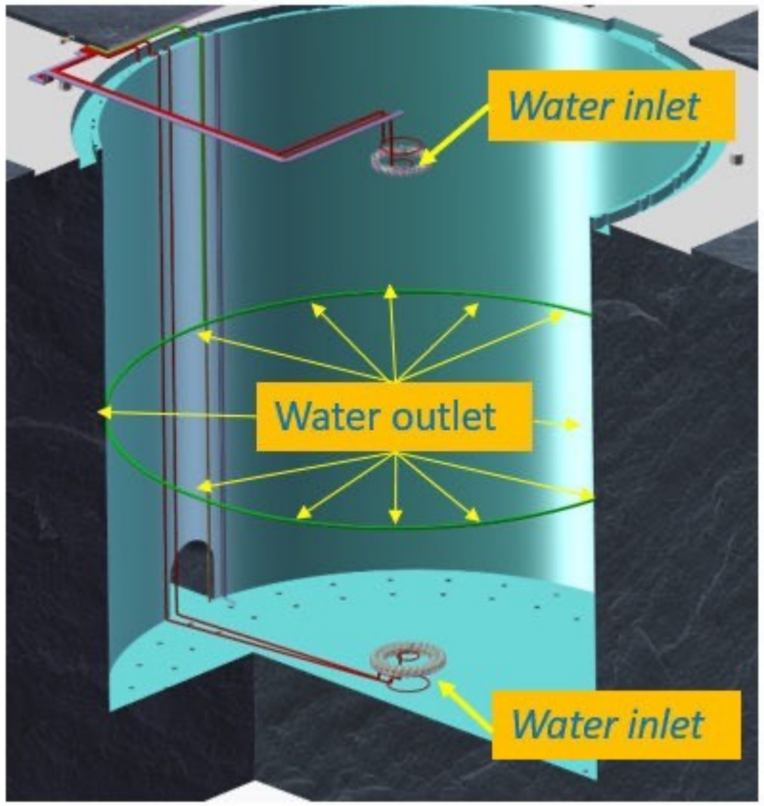


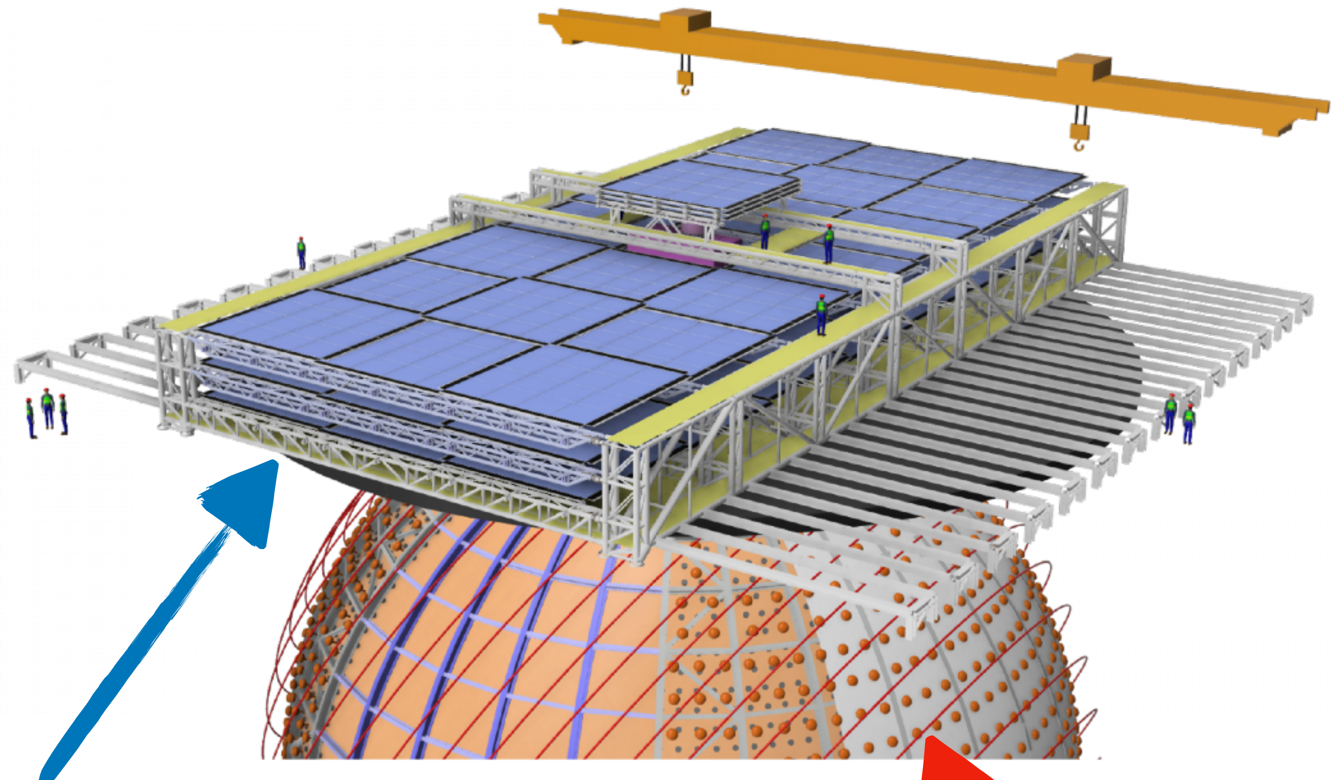




Bias in reco. energy < 1%
Effective energy res. better than 3% at 1- 8 MeV

Veto Systems





Water Cherenkov Detector
1. Shield ambient radioactivity and neutrons induced by cosmic rays
2. Veto muon induced backgrounds
3. 2400 20" MCP-PMTs
4. 35 kton ultra pure water with circulation
5. Efficiency > 99%

Top Tracker (TT)
1. Precise muon tracking
2. Recycling the plastic scintillators from OPERA Target Tracker
3. New electronics cards designed to account for 100 x higher radioactivity from rocks at JUNO site

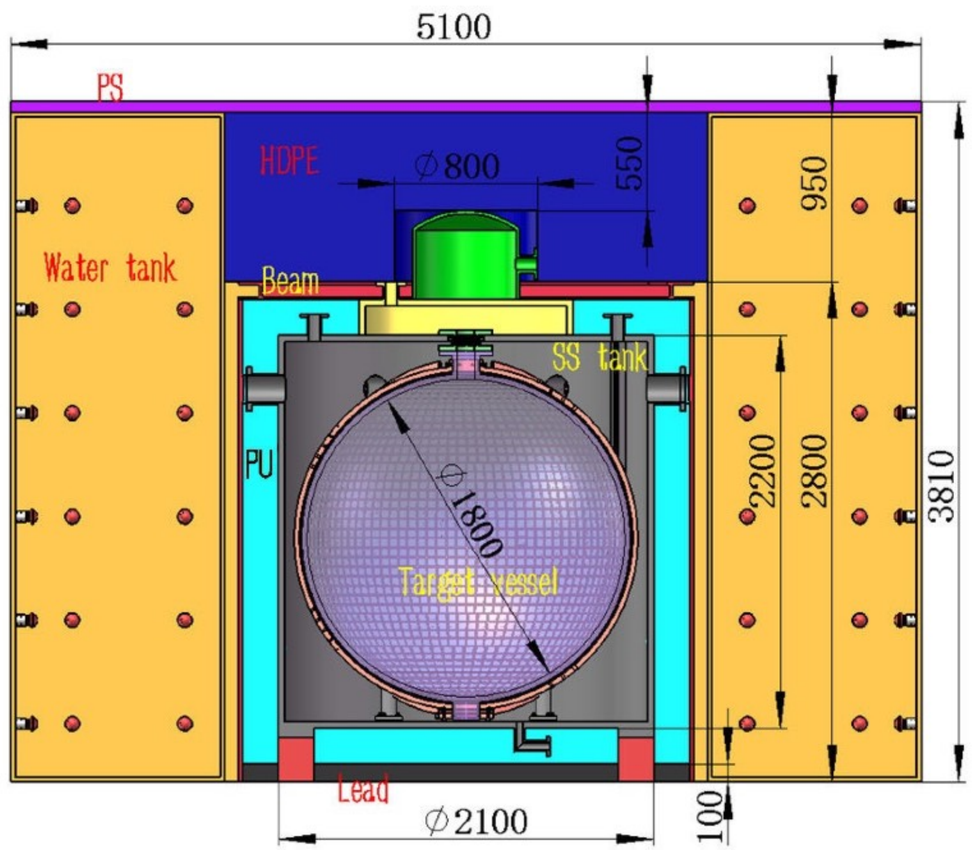
Earth magnetic shielding coils for *20" PMTs*

JUNO-Taishan Antineutrino Observatory

Tao is the reference detector for JUNO at Taishan NPP.

Physics goals:

- Precisely measure reactor antineutrino spectrum
- Provide a model-independent reference spectrum for JUNO's NMO determination
- Reactor monitoring and safeguard
- Search for new physics



Detector design:

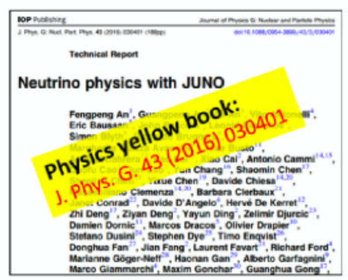
- 1 ton fiducial volume / 2.6 tons of Gd-LS
- ~30 m from a Taishan reactor core (4.6 GW)
- Ton-level Gadolinium-doped LS at **-50 °C**
- 10 m^2 SiPM with PDE>50% and >90% coverage
- **4500 PE / MeV** → Energy resolution: $< 2\,\%/\sqrt{E(\mathrm{MeV})}$
- Event Rate： **~2000/day** **(FV & efficiency)**
- **Planned to be online in 2022**

TAO *CDR,* arXiv:2005.08745

JUNO Schedule

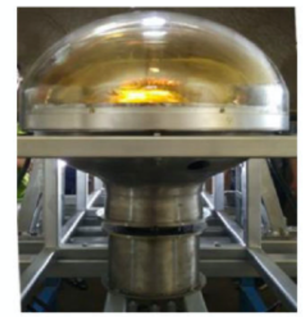
2014
- International collaboration established;

2015
- PMT production line setup
- CD parts R&D
- Civil construction started

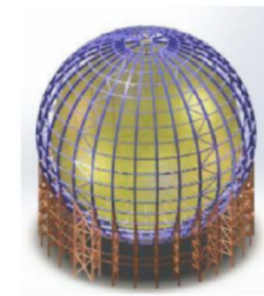


2016
- PMT production start
- CD parts production start
- Yellow book published

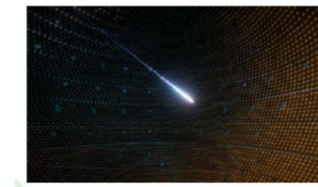
2017
- PMT testing start
- TT arrived



2018
- PMT potting
- Start delivery of surface building
- Start production of acrylic sphere

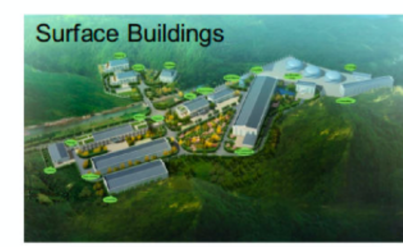


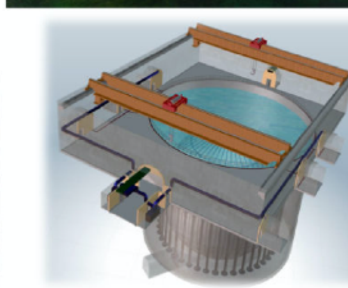
2019-2021
- Electronics production starts
- Civil construction and lab preparation completed
- Detector installation begins



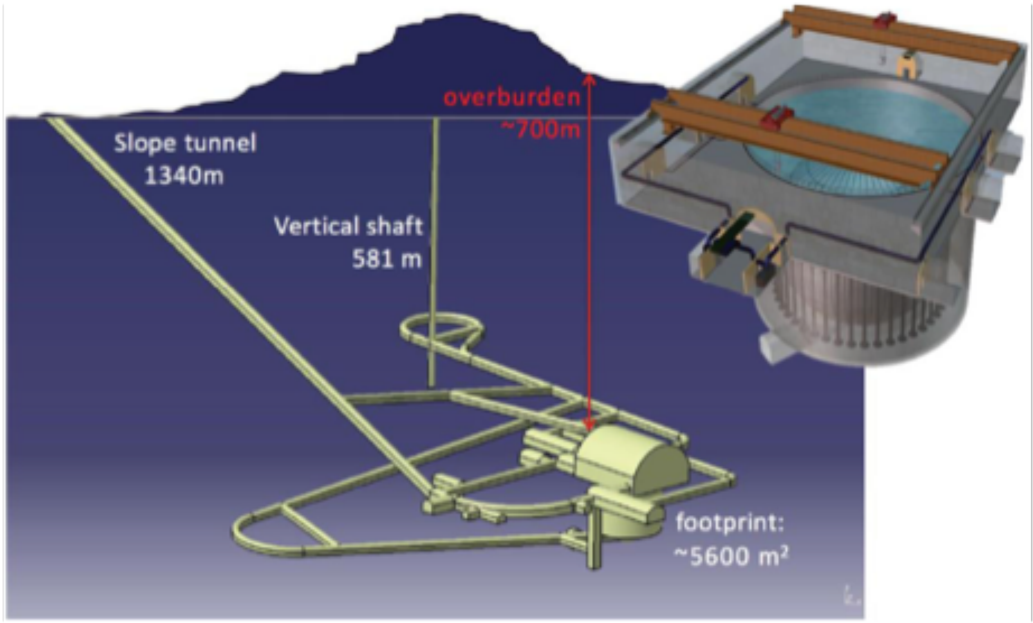
2022
- Detector ready for data taking

Neutrinos detected





JUNO Civil Construction



- Slope tunnel & vertical shaft finished
- Blasting completed in December 2020
- Digging in the experimental hall cavern is completed


Surface building


Pool status, 31 August, 2021

JUNO Collaboration

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	SAPHIR	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		

Collaboration established in 2014.
At present 77 institutions, more than 600 collaborators.

Summary

- With 20 kton LS and an unprecedented energy resolution of 3% @ 1MeV, JUNO will determine the neutrino mass ordering at 3-4σ and measure 3 neutrino oscillation parameters to sub-percent level in 6 years of data taking.

- JUNO also has a rich physics potential with solar neutrinos, supernova neutrinos, atmospheric neutrinos and geo-neutrinos, and other exotic physics such as proton decay.

- Civil engineering on the way (water pool civil construction completed, surface laboratory active).

- Production/assembly of detector components going on. 20-inch PMTs testing is done. Acrylic Sphere is almost done, waiting for splicing and installation.

- Installation is starting. JUNO is expected to be completed before the end of 2022.

Stay tuned!