JUNO

Status & Prospects

Donglian Xu[†] (TDLI)

On behalf of the JUNO Collaboration

XIX International Workshop on Neutrino Telescopes

Shanghai Jiao Tong University 1896

李政道研究所 Tsung-Dao Lee Institute

2021.02.18-26, Online

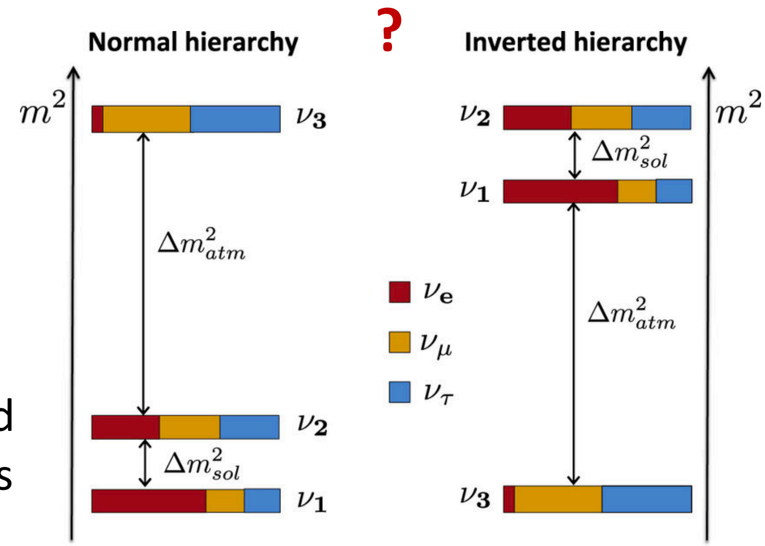
[†]donglianxu@sjtu.edu.cn

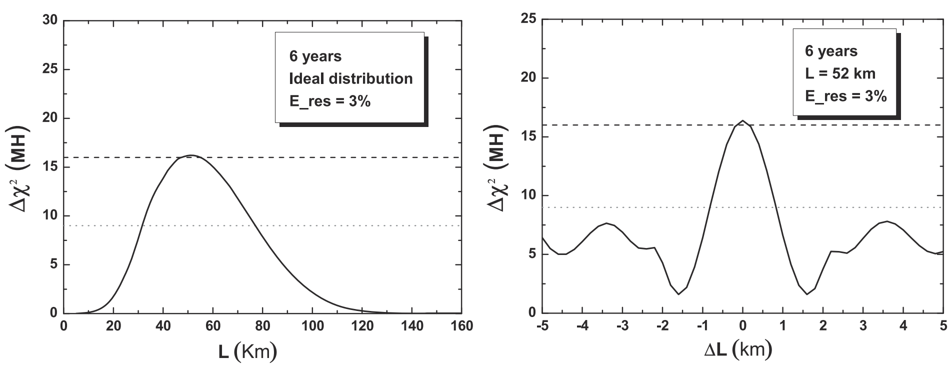
Outline

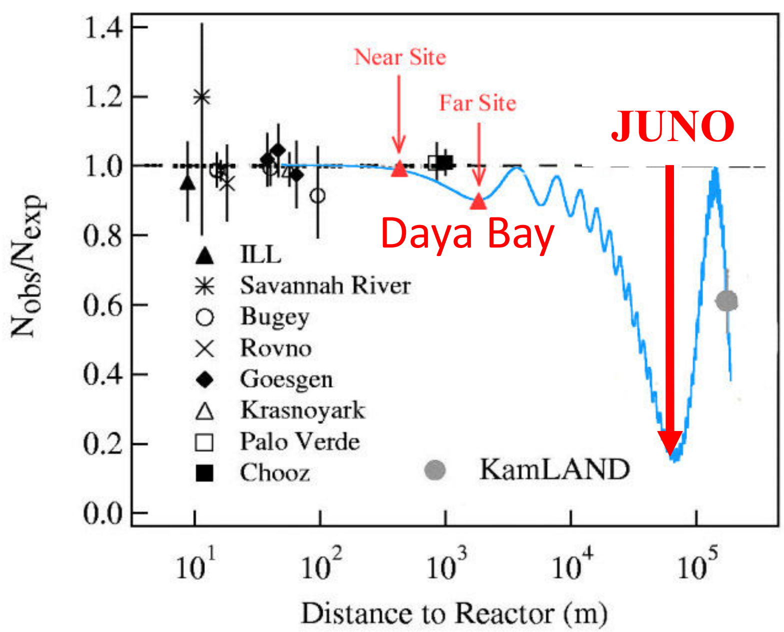
- **Overview**
- **Physics prospects**
  - Neutrino mass ordering
  - Precision measurement of neutrino mixing parameters
  - Astrophysical neutrinos (supernova, multi-messenger)
  - Solar, atmospheric, geo neutrinos
  - New physics (proton decay, sterile neutrinos, dark matter, etc.)
- **Detector**
  - Subsystems: central detector (CD); liquid scintillator (LS); PMTs; calibration system; veto system; JUNO-TAO
- **Civil construction & experiment timeline**
- **Summary**

Neutrino Mass Ordering

- **Large θ_{13}** opens the doors for **neutrino mass ordering (NMO)** determination and CP violating phase measurement via oscillation
- NMO can be probed with:
  - Matter effects of accelerator (DUNE, T2HK) and atmospheric (PINGU, ORCA, HK, INO) neutrinos
- **NMO with reactor neutrinos:**
  - Medium baseline (~50 km) is optimal
  - Multiple reactors may cancel the oscillation structure → baseline difference < 500 m

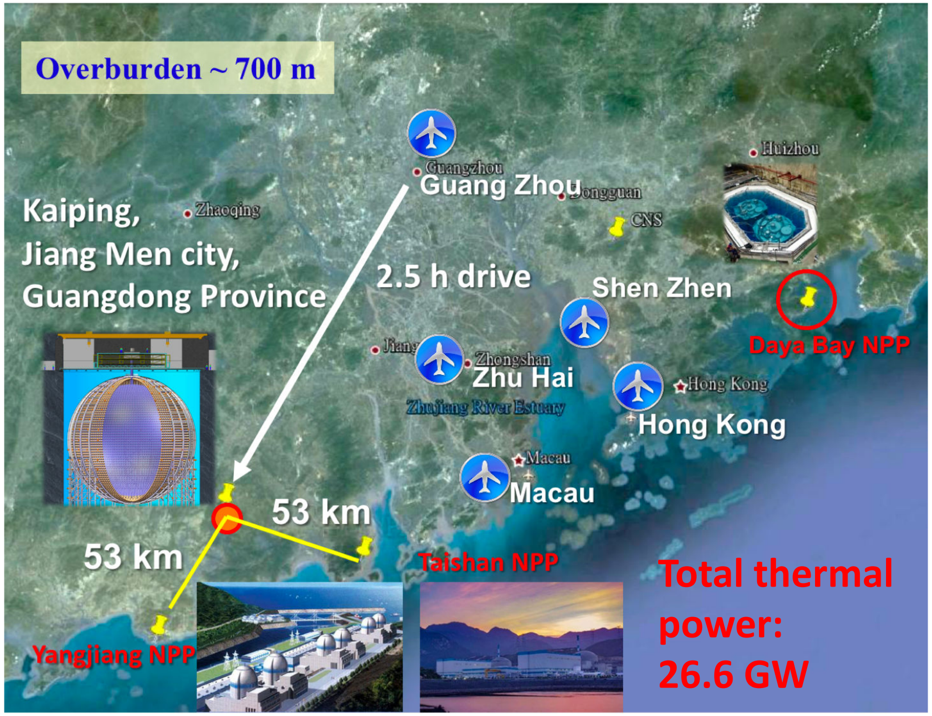






J. Phys. G43:030401 (2016)

Overview of JUNO



- **Power plants in operation:**

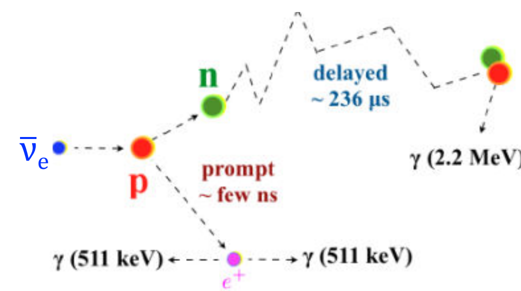
- **Yangjiang NPP 17.4 GW** (6 cores*2.6 GW)

- **Taishan NPP 9.2 GW** (2 cores*4.6 GW)

- **Main detection channel:**

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

Inverse Beta Decay



Experiment	Daya Bay	Borexino	KamLAND	JUNO
Target mass [tons]	8 x 20	~300	~1,000	20,000
Photo electron collection [p.e./MeV]	~160	~500	~250	~1345
Energy resolution	~8.5%	~5%	~6%	~3%
Photocathode coverage	12%	34%	34%	78%
Energy calibration uncertainty	0.5%	1%	2%	<1%

Jiangmen Underground Neutrino Observatory

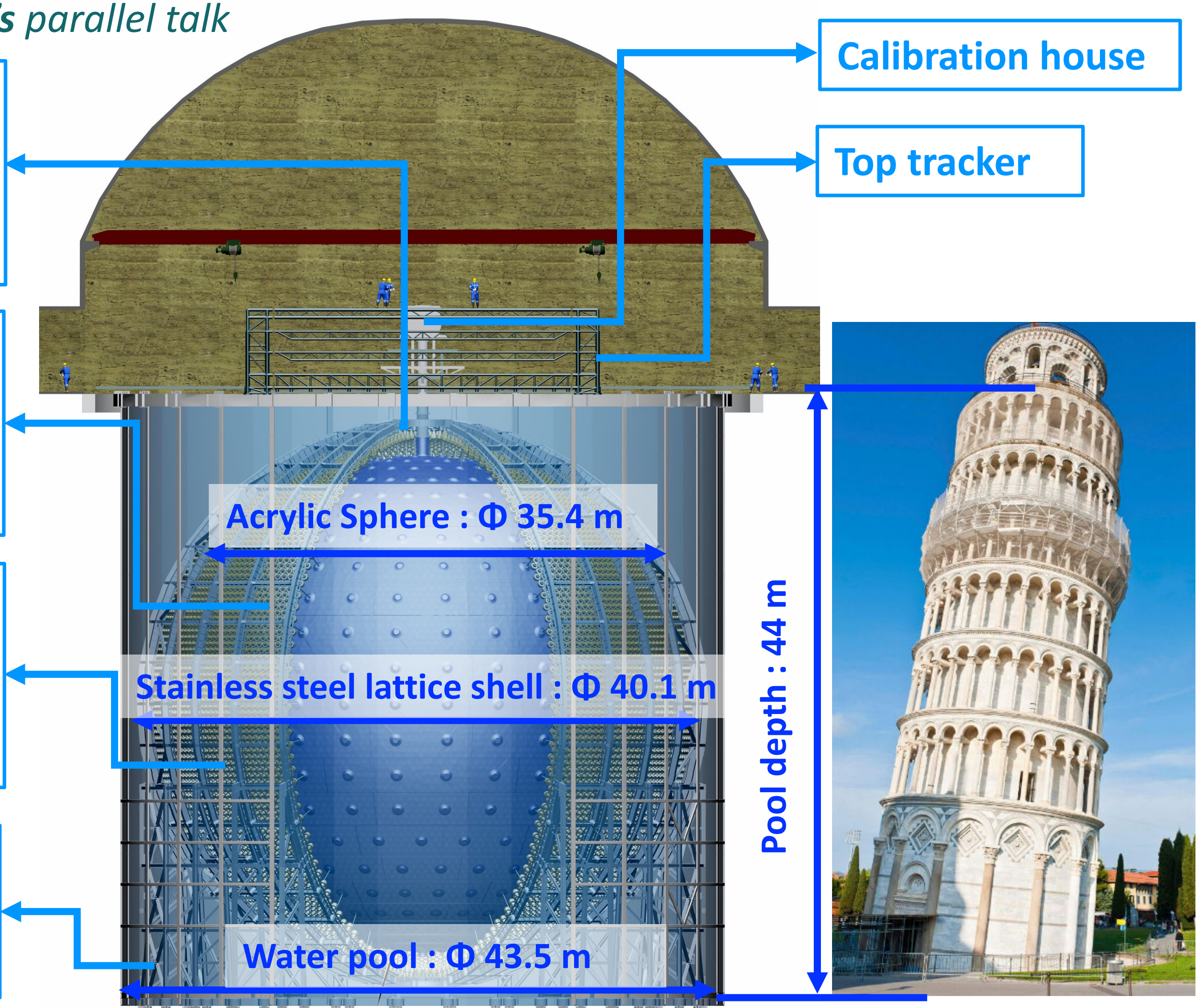
→ *See also **Hans Steiger's** parallel talk*

Central detector:
- *Steel structure*
- *Acrylic sphere*
- *20 kton LS*

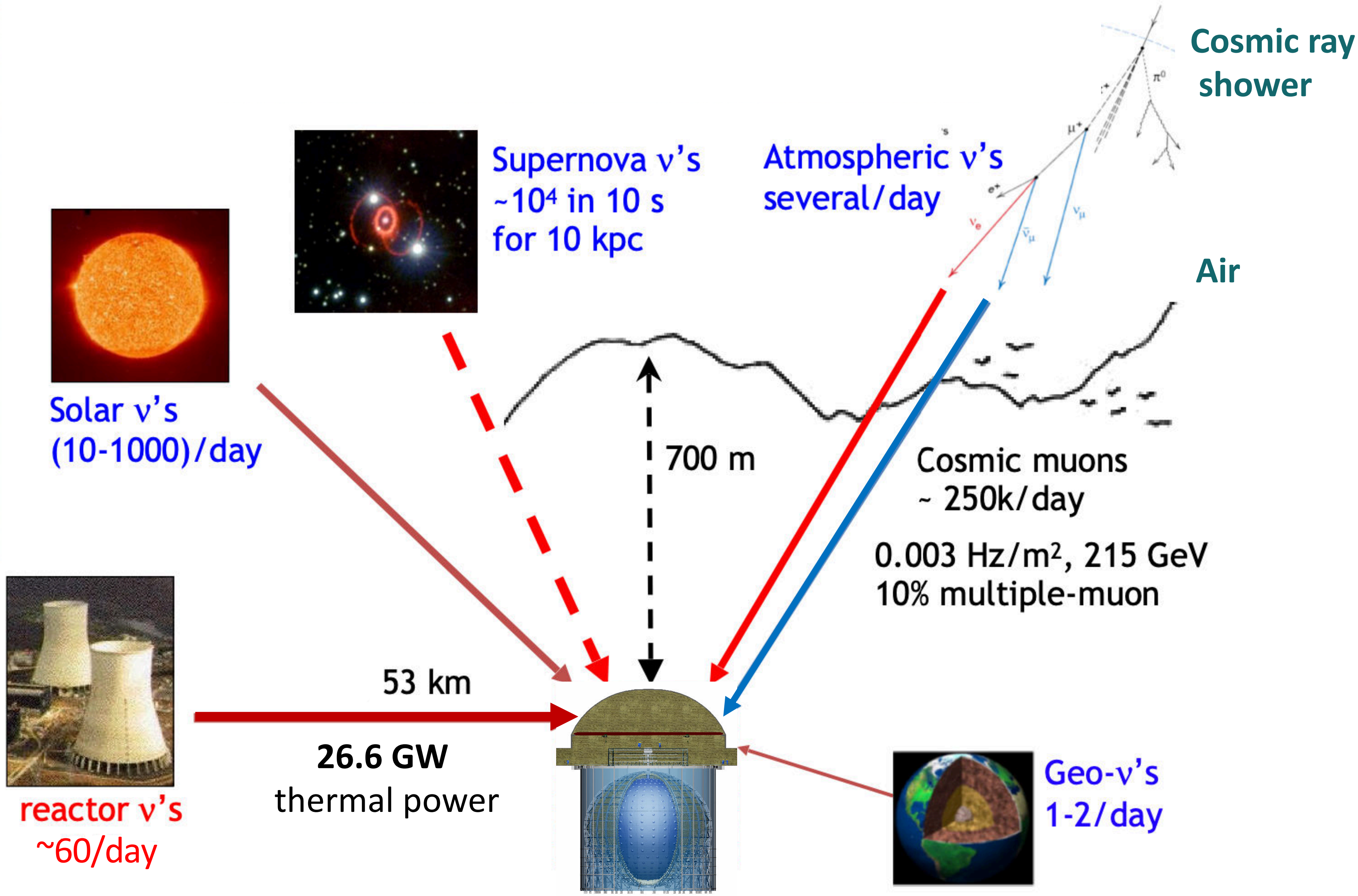
PMTs:
- *17612 20" HQE PMTs*
- *25600 3" PMTs*
- *78% coverage*

Earth magnetic shielding coils:
- *For 20" PMTs*
- *Double coil system*

Water pool veto:
- *40 kton pure water*
- *2400 20" HQE PMTs*



A Multi-purpose Neutrino Observatory



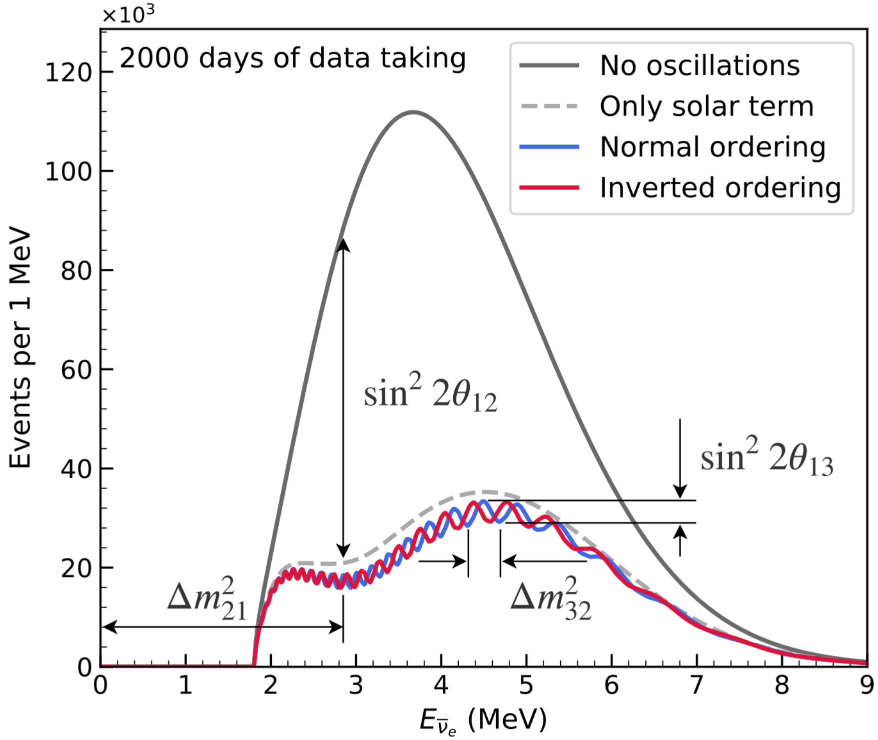
NMO with JUNO

The reactor antineutrino survival probability in vacuum:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

where $\Delta_{ij} = \Delta m^2_{ij} L/(4E) = (m_i^2 - m_j^2) L/(4E)$

→ *See also **Yury Malyshkin's** parallel talk*
→ *See also **Philipp Kampmann's** flash talk*



Neutrino Physics with JUNO, J. Phys. G43:030401 (2016)

- JUNO NMO sensitivity is based on **vacuum oscillations**, and has no dependence on the unknown CP-violating phase and the θ_{23} octant

  Phys. Lett. B533 (2002) 94;
  Phys. Rev. D78:111103,2008;
  Phys. Rev. D79:073007,2009

- Unprecedented **Energy resolution of 3% /$\sqrt{E(MeV)}$** is required for 3σ NMO determination in 6 years of data taking

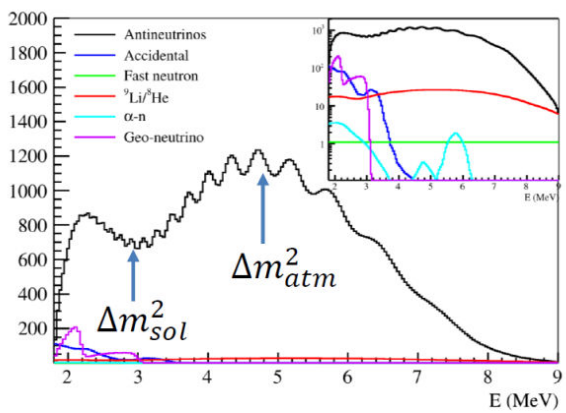
- Key elements to reach requirement:
  - High light yield liquid scintillator : attenuation len. > 20 m @ 430 nm
  - Large PMT coverage: ~78%
  - High QE PMT: ~30%

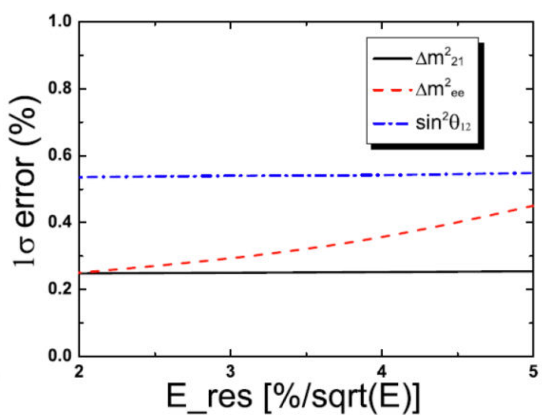
Precision Measurement of Mixing Parameters

- Precision of three **mixing parameters (Δm_{21}^2, Δm_{32}^2, and $\sin^2\theta_{12}$)** will reach **sub percent level**
- **Unitarity** of U_{PMNS} matrix probed 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%





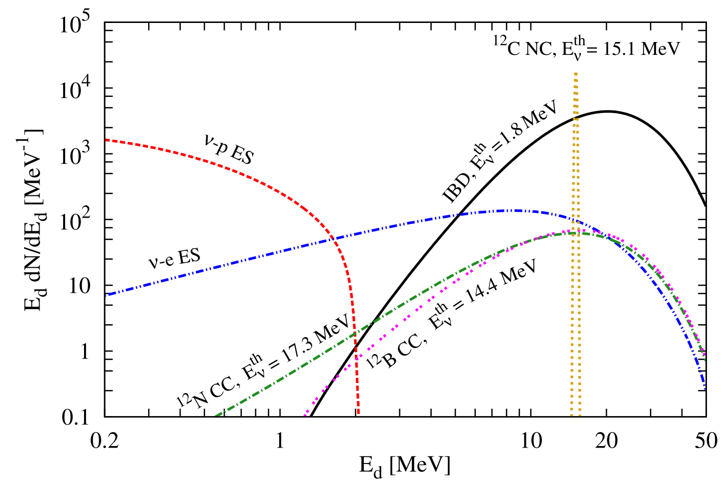
JUNO:

	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%**

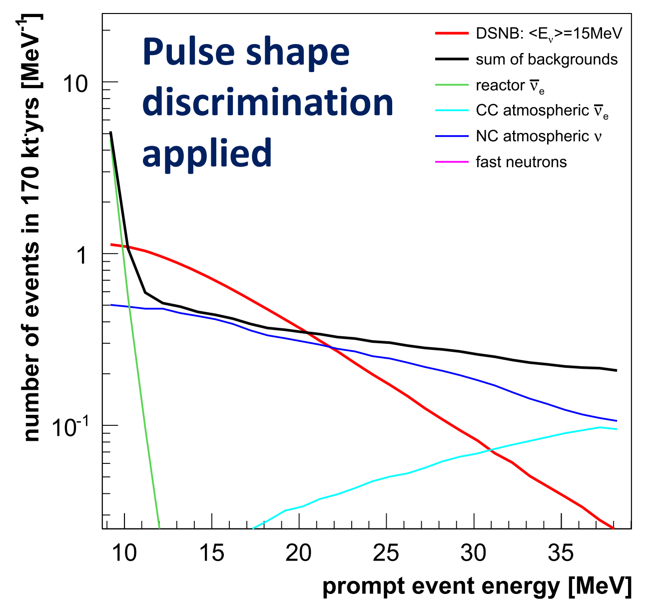
J. Phys. G43:030401 (2016)

Supernova Neutrinos

- **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 vpES** and **~4000 veES** 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



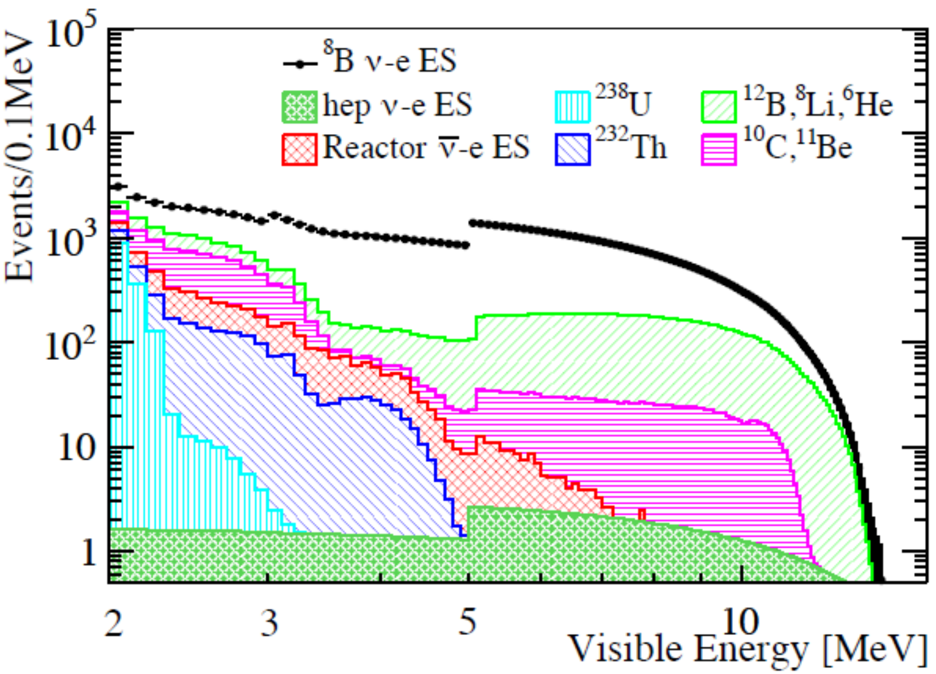
→ *See also **Huiling Li** and **Cristina Martellini's** flash talks*

J. Phys. G43:030401 (2016)

Solar Neutrinos

- ^{8}B solar neutrino in JUNO: → *See also **Jie Zhao's** parallel talk*
  - Detection channel: neutrino-electron elastic scattering (veES)
  - Effective cosmogenic background rejection with time and volume
  - Radioactivity background: 10^{-17} g/g U/Th
  - **Event rate: ~60,000** recoil electrons and **~30,000 background** events in 10 years of data taking

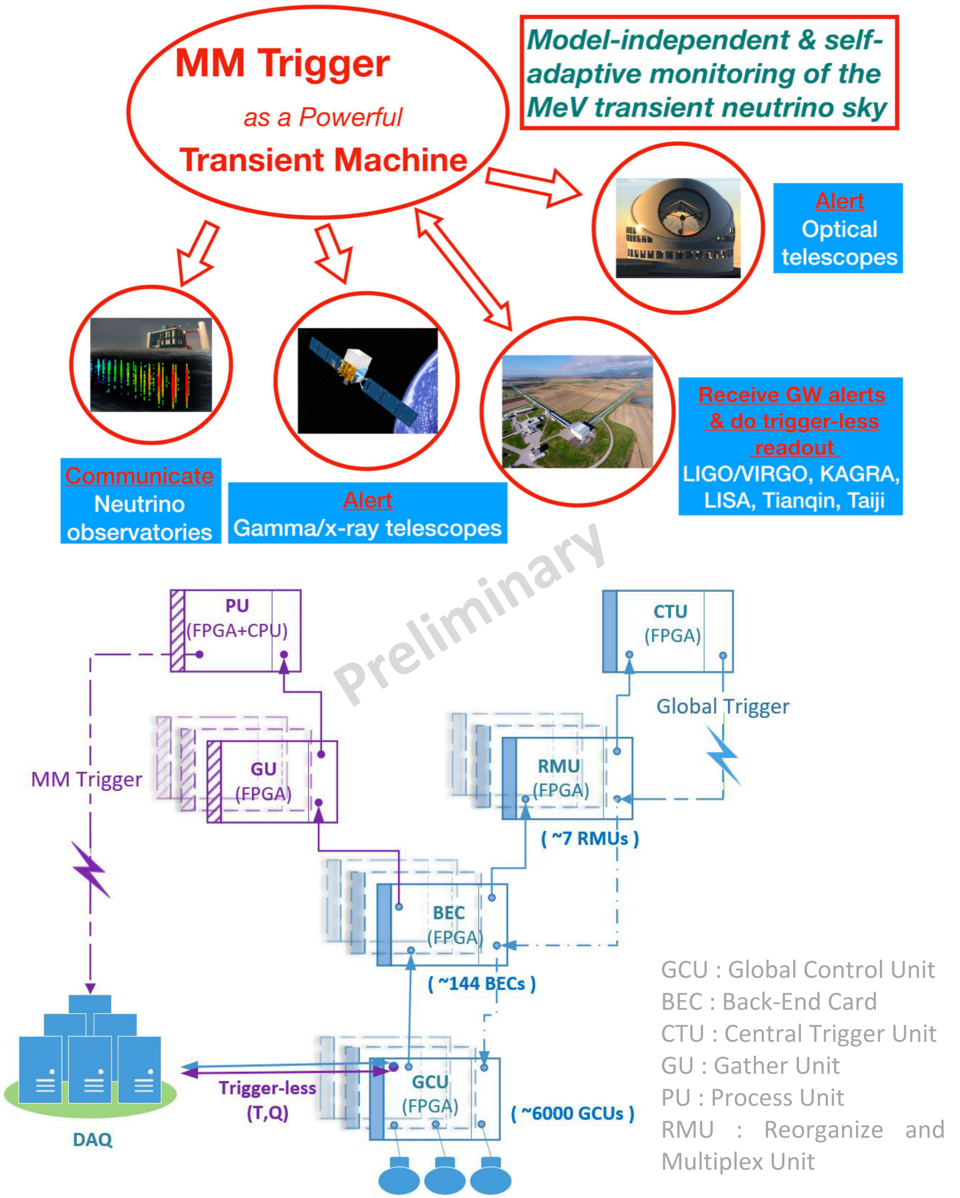
- **Measure and cross validate Δm^2_{21}** with solar neutrinos and reactor antineutrinos
- Shed new light on solar metallicity problem



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

Multi-Messenger & Low-threshold Physics

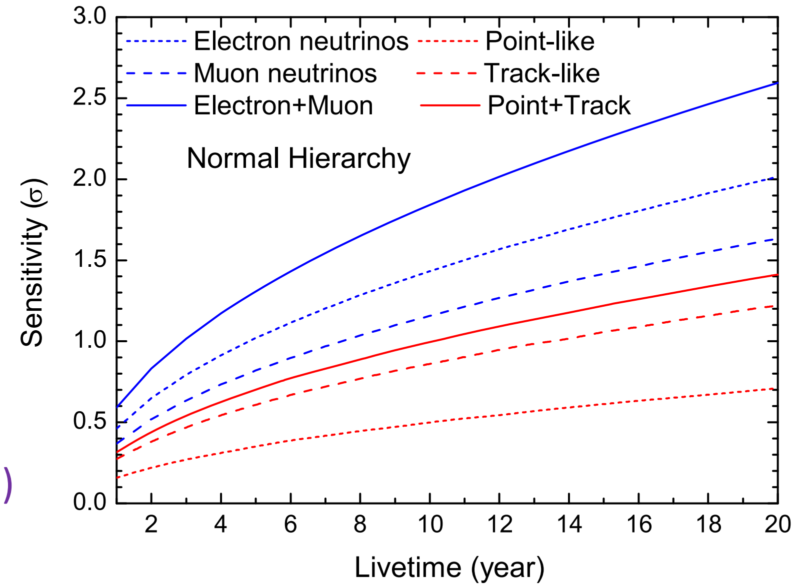
- **Two major trigger systems in JUNO:**
  - Global trigger (threshold ~ 200 keV)
  - Multi-messenger trigger (threshold ~ 20 keV)
- **Multi-messenger (MM) Trigger**
  - Hardware + firmware + DAQ solution
  - Fast filtering algorithms on FPGA to reject >99.9% dark noise and achieve O(10) keV physics triggers
- **Low threshold physics potential**
  - Will significantly improve physics potential in this unprecedentedly low-threshold territory, e.g. low energy solar neutrinos



Atmo. & Geo Neutrinos

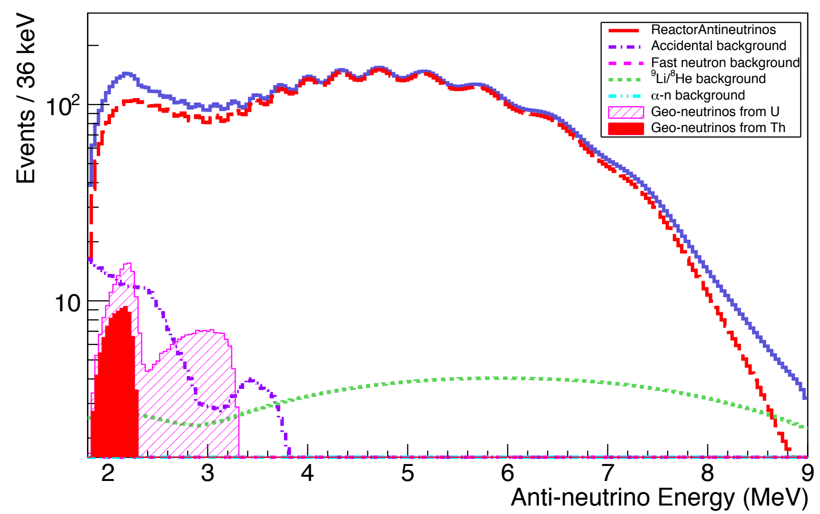
- **Atmospheric Neutrinos:**
  - Complimentary neutrino mass ordering sensitivity via matter effect
  - Measure θ_{23} with 6° precision
  - Atmo. neutrino flux and spectra measurement

J. Phys. G43:030401 (2016)



→ *See also **Giulio Settanta's** parallel talk*

- **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

Nucleon Decays

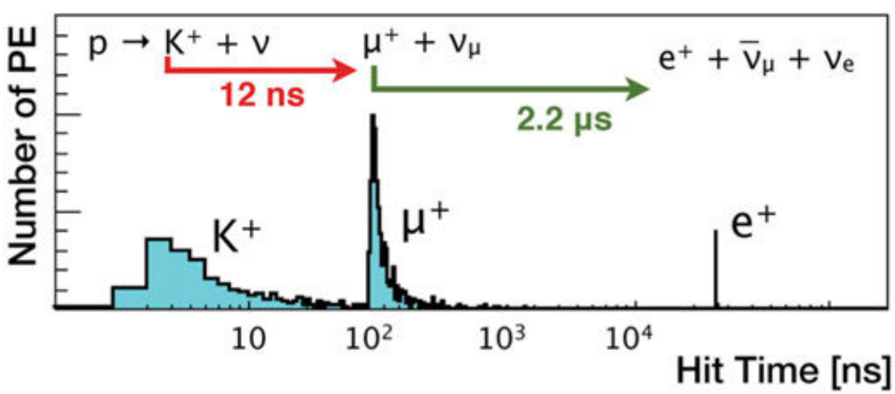
Two popular decay modes:

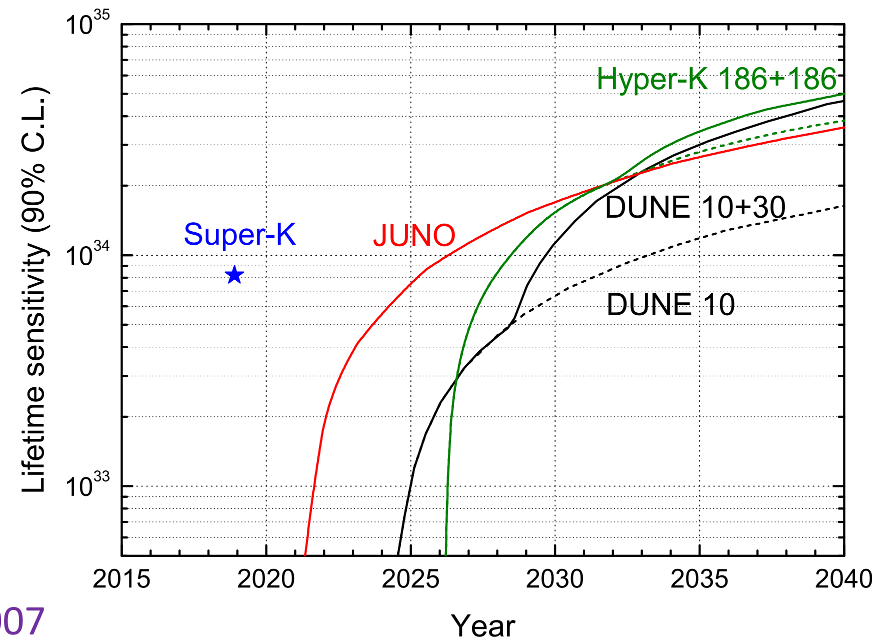
$$p \to \pi^0 + e^+$$ **favored by GUT**

$$p \to K^+ + \nu$$ **favored by SUSY**

- Current best limit set by Super-K : $\boldsymbol{\tau}$ ($p \to \boldsymbol{\pi}^0 + e^+$) > 1.4×10^{34} years
- Kaon is invisible in a water Cherenkov detector
- JUNO will be advantageous in the kaon mode with LS technique
- JUNO will be sensitive to: $\boldsymbol{\tau}$ ($p \to K^+ + \nu$) ~ 2×10^{34} years

Simulated triple coincidence signal





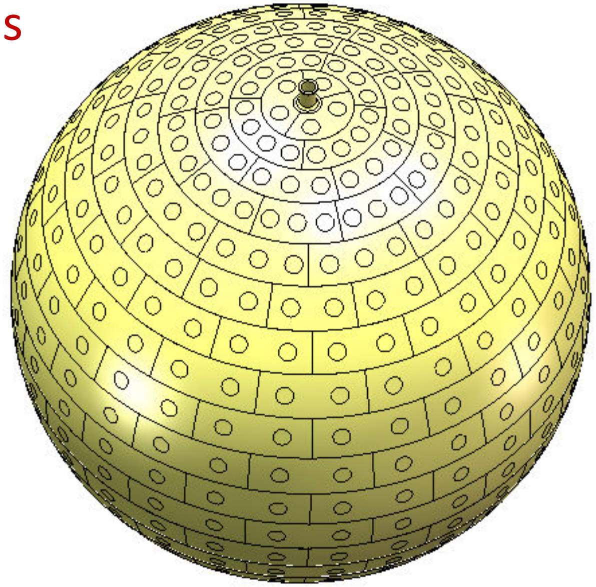
J. Phys. G43:030401 (2016) ; *PoS* NuFact2019 (2020) 007

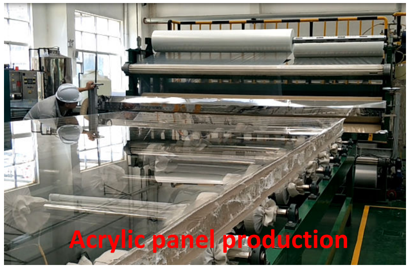
Central Detector

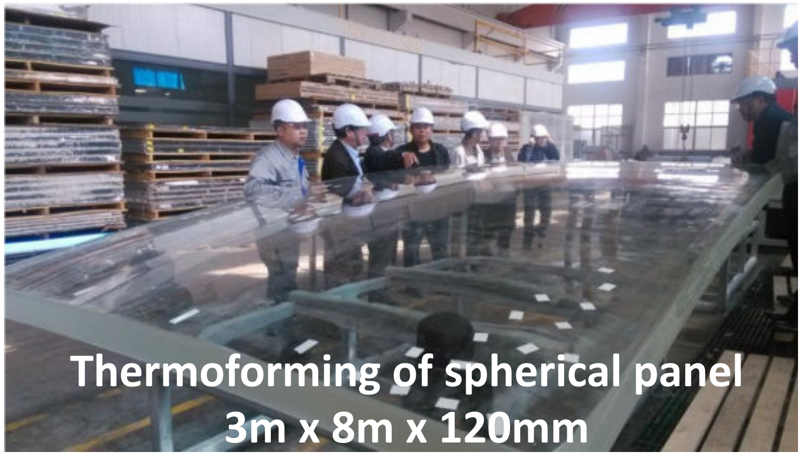
CD : Acrylic Sphere + Stainless Steel Support

- Acrylic sphere composed of ***265*** spherical panel pieces
- Thickness: 120 mm, ***net weight: ~600 tons***
- **Transparency > 96%** in pure water
- DonChamp won the bid in 2017.02 and a new production line for JUNO has been finished
- Strict control for low radioactive backgrounds, acrylic samples have ***met the 1 ppt requirement*** for U/Th/K

Acrylic Sphere







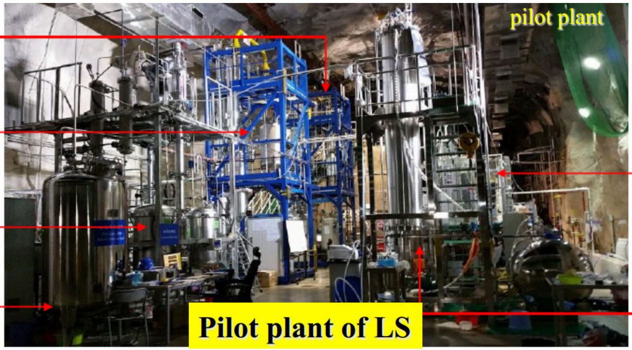
Liquid Scintillator

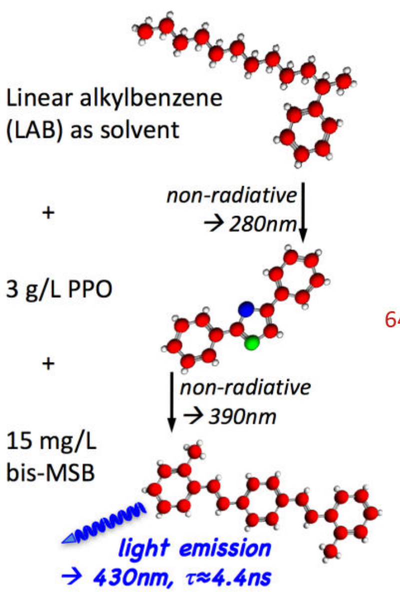
- **JUNO LS recipe**:

LAB ***+ 2.5 g/L*** *PPO* ***+ 3 mg/L*** *Bis-MSB*

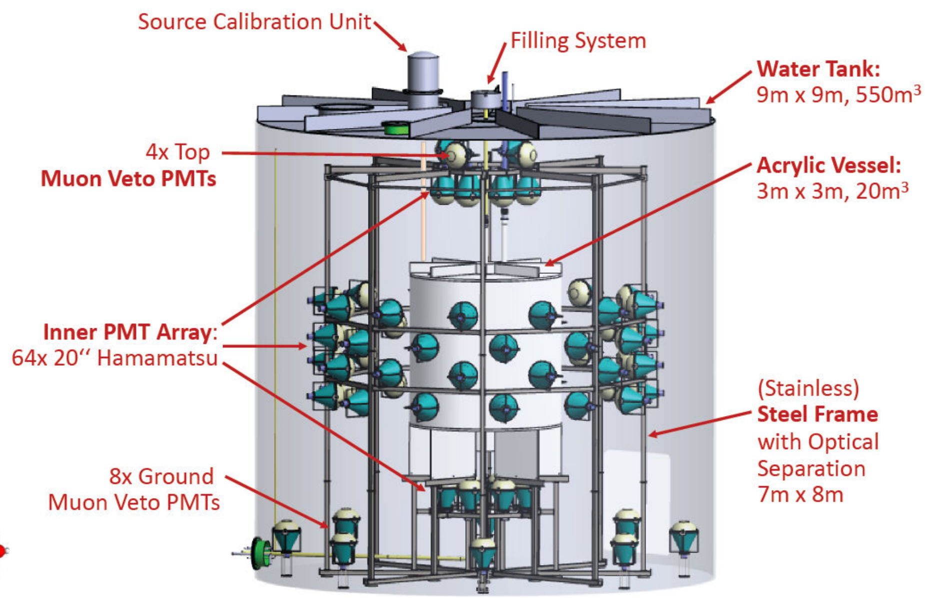
→ Higher light yield; more transparent!

- **Attenuation length: >20 m @ 430 nm**





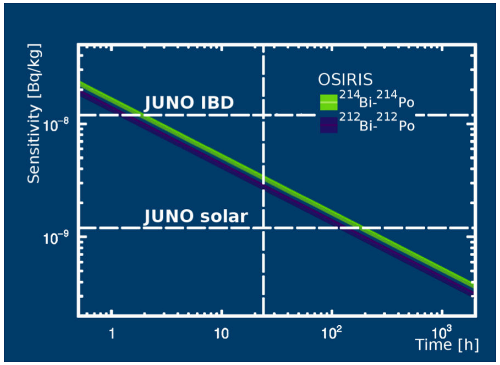
LS recipe for Daya Bay



Online **S**cintillator **I**nternal **R**adioactivity **I**nvestigation **S**ystem (**OSIRIS**)

- **Low radioactive backgrounds:**

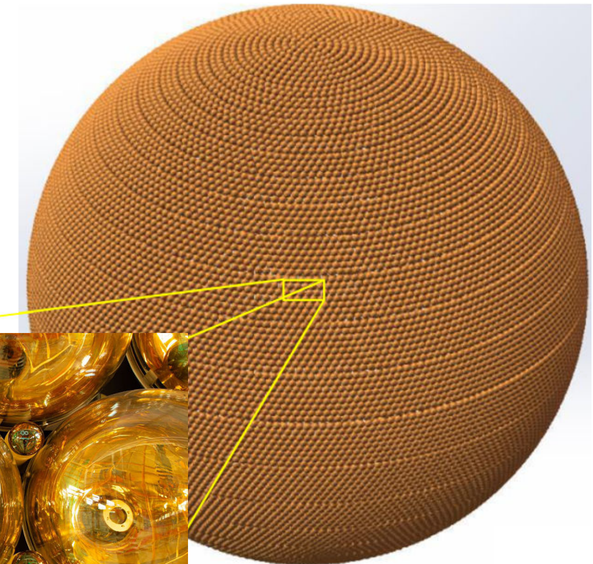
10^{-15} g/g for neutrino mass ordering determination; 10^{-17} g/g for solar neutrino detection

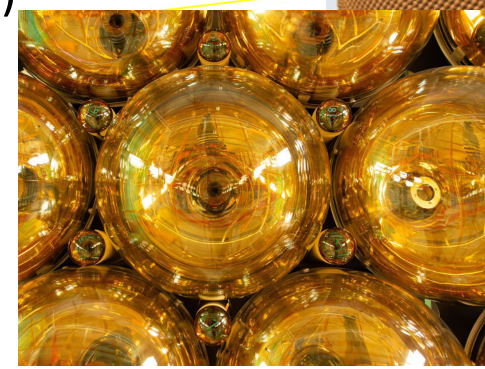


→ *See also* ***Runxuan Liu, Michele Montuschi,*** *&* ***Tobias Sterr's*** *flash talks*

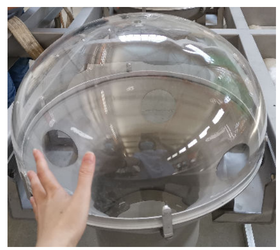
JUNO PMTs

- 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**

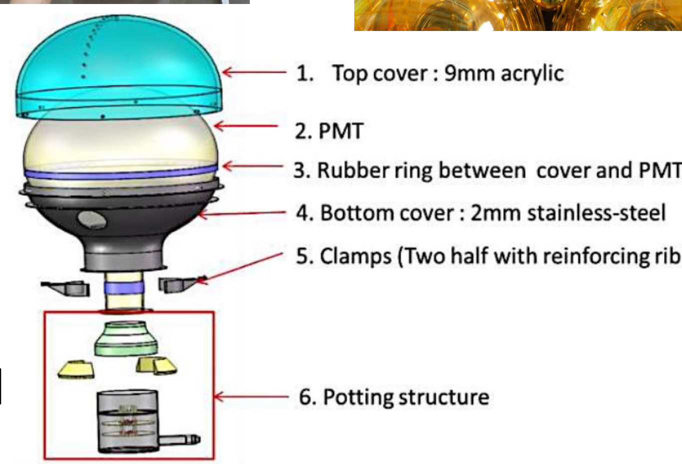




- Implosion protection



- Waterproof potting
- Custom made divider and electronics
- Stringent quality control

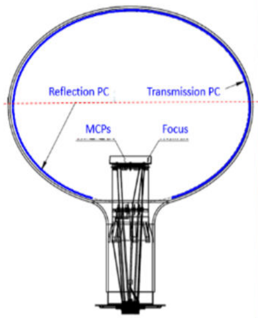


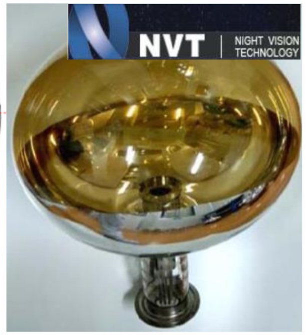
→ *See also* ***Alexander Tietzsch’s*** *flash talk*

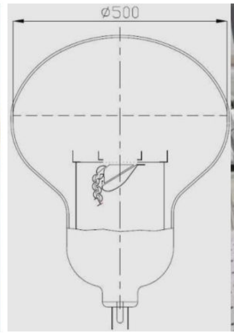
JUNO PMTs

20-inch PMTs

3-inch PMTs







Microchannel plate (MCP) PMTs

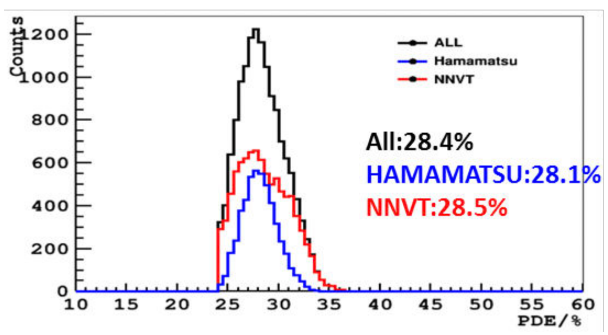
- Developed for JUNO
- Use transmission and reflection cathodes to increase quantum efficiency

Dynode PMTs

- 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**



PDE of 20-in PMTs

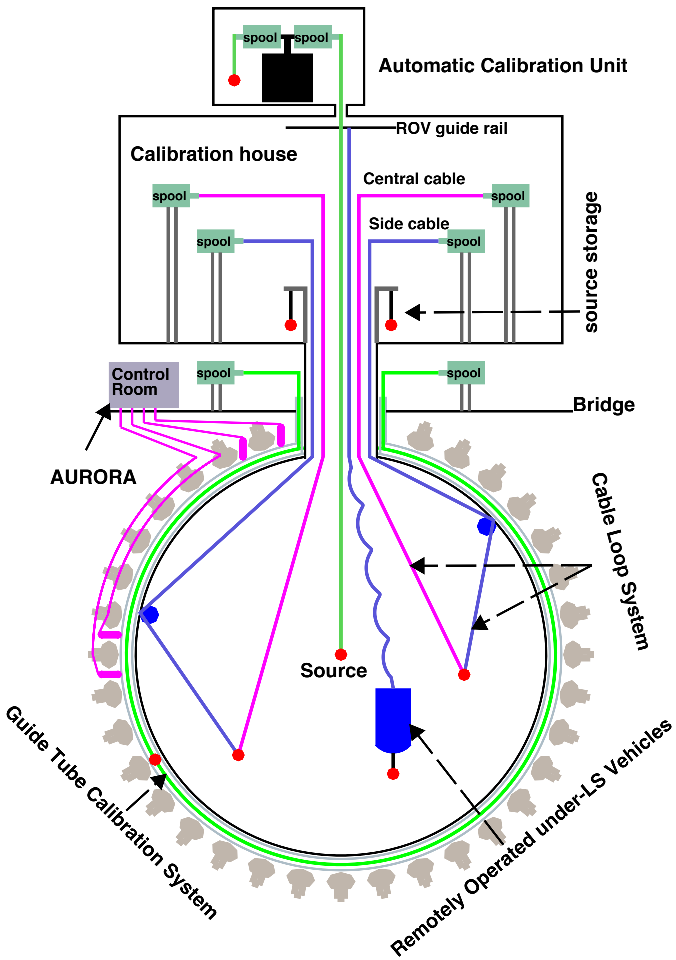
JUNO uses:
13,000 MCP-PMTs (NNVT)
+ 5000 dynode PMTs
(Hamamatsu, R12860HQE)

→ *See also* ***Yang Han's*** *flash talk*

Status: production and characterization all done.

Calibration System

Calibration layout

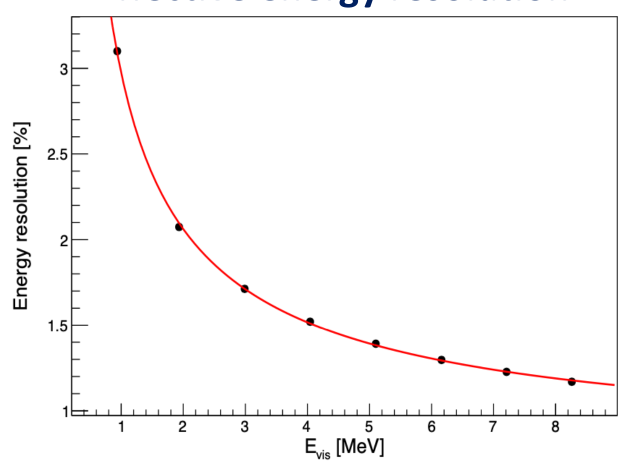


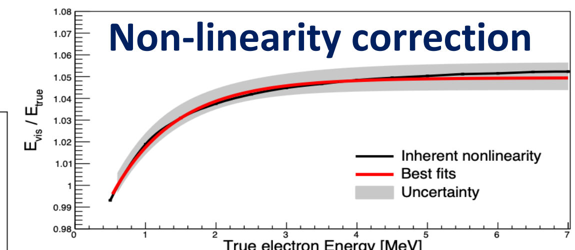
Calibration strategy of the JUNO Experiment,
arXiv:2011.06405; accepted by JHEP

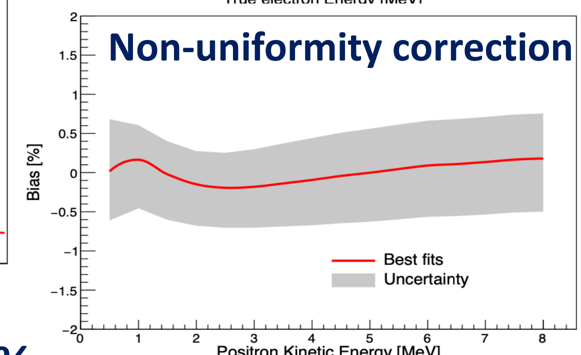
Calibration Systems

1D: Automatic Calibration Unit (ACU)
2D: Cable Loop System (CLS) & 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)

Effective energy resolution







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

Veto Systems

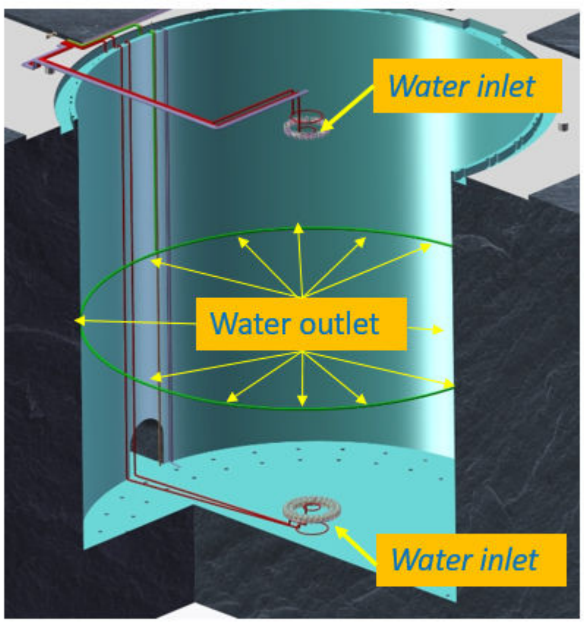
Active and passive shielding for CD

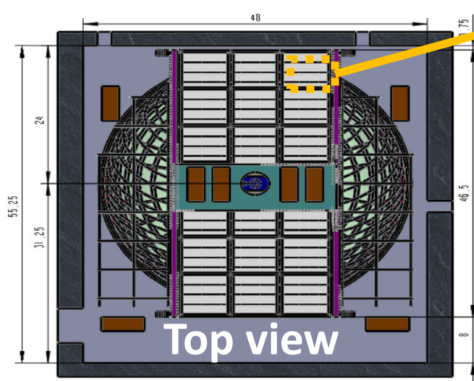
Water Cherenkov Detector

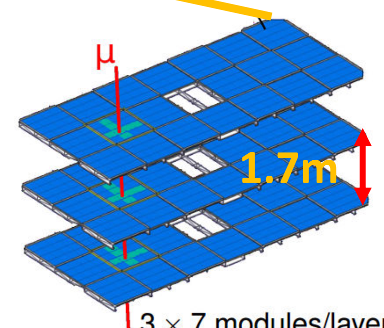
- Shield ambient radioactivity and neutrons induced by cosmic rays
- Veto muon induced backgrounds
- 2400 20” MCP-PMTs
- 35 kton ultra pure water with circulation
- Efficiency > 99%

Top Tracker (TT)

- Precise muon tracking
- Recycling the *plastic scintillators from OPERA* Target Tracker
- New electronics cards designed to account for *100 x higher radioactivity* from rocks at JUNO site





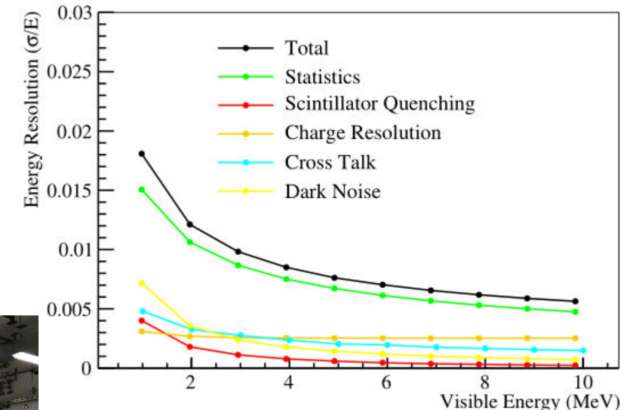


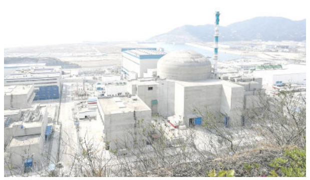
JUNO-TAO

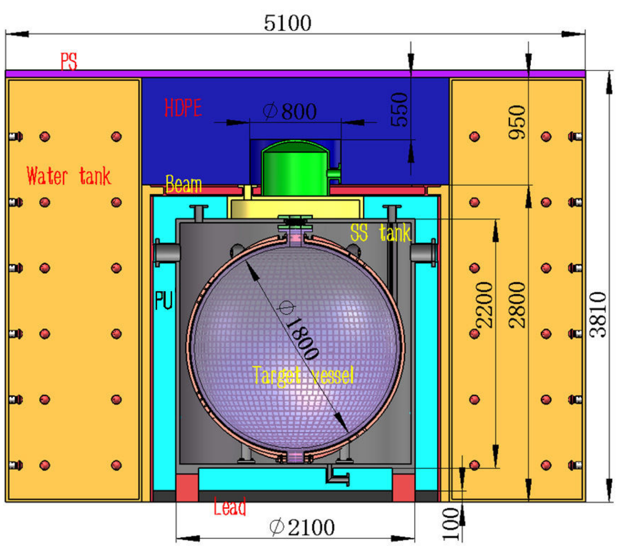
Taishan Antineutrino Observatory

A satellite experiment of JUNO

➢ **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:**

TAO CDR, arXiv:2005.08745

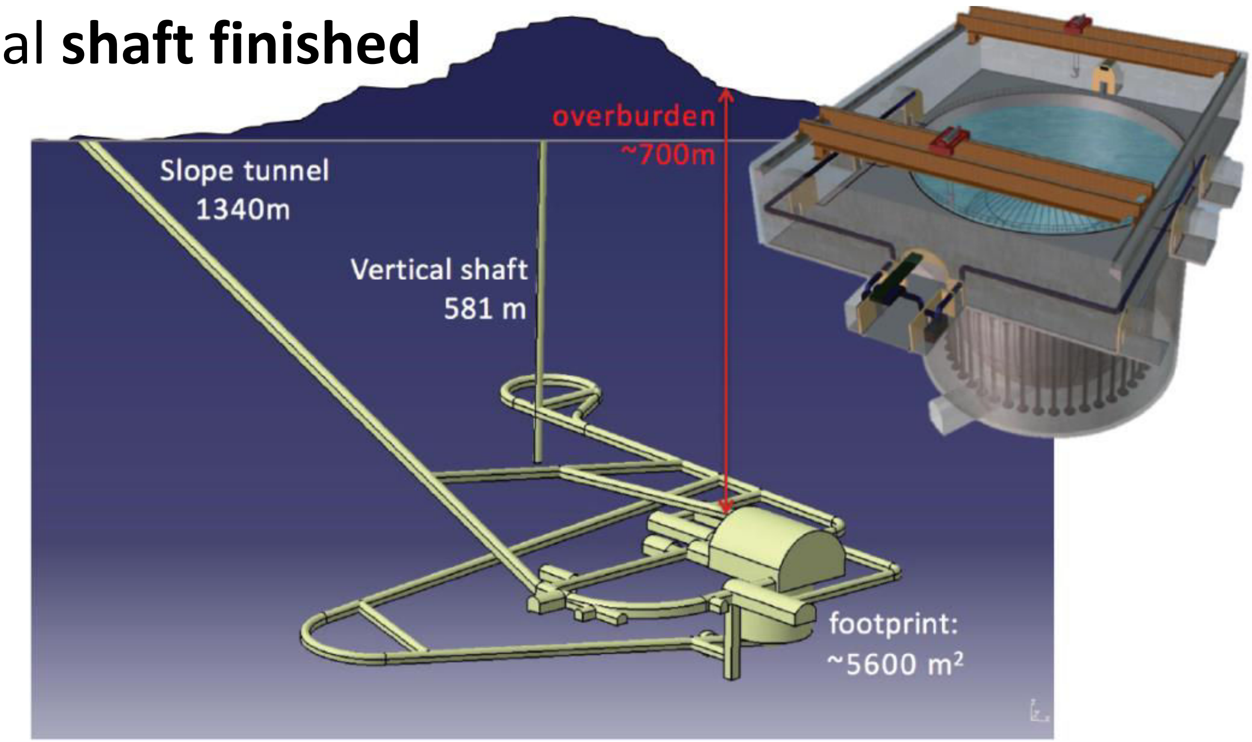
- ~30 m from a Taishan reactor core (4.6 GW)
- Ton-level Gadolinium-doped LS at **-50 °C**
- 10 m^2 SiPM with PDE>50% and >90% coverage
- **4500 PE / MeV → Energy res. : ~1.5% /** $\sqrt{E(MeV)}$

→ *See also **Fabrizio Petrucci's** parallel talk*

→ *See also **Claudio Lombardo's** flash talk*

Civil Construction

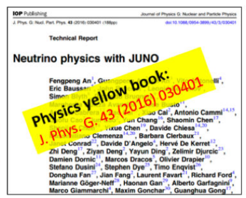
- Slope **tunnel** & vertical **shaft finished**
- Experiment **cavern** digging **completed** in **Dec. 2020**
- Detector installation will begin this summer



JUNO Timeline

2014
- International collaboration established;

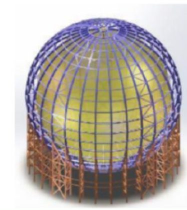
2015
- PMT production line setup
- CD parts R&D
- Civil construction started



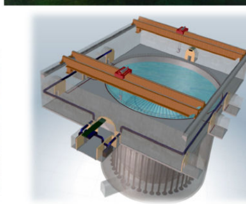
2016
- PMT production start
- CD parts production start
- Yellow book published

2017
- PMT testing start
- TT arrived

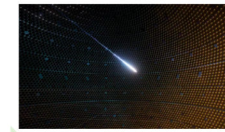
2018
- PMT potting
- Start delivery of surface building
- Start production of acrylic sphere



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



2022
- Detector ready for data taking



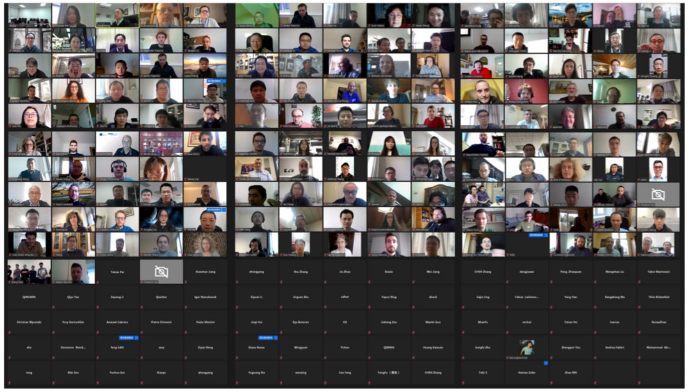
Neutrinos detected

JUNO 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	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		

669 members from **17** countries and **77** institutes

17th JUNO Collaboration Meeting
3~5 Feb 2021 Online



Summary

- With 20 kton LS and an unprecedented energy resolution of 3% @ 1MeV, JUNO will determine the neutrino mass ordering at 3-4σ in 6 years of data taking
- JUNO will be a versatile multi-purpose neutrino observatory:
  - Precision measurement of mixing parameters to percent-level
  - Astrophysical (e.g. supernova, multi-messenger) neutrinos
  - Solar, atmospheric and geo neutrinos
  - New physics (proton decays, sterile neutrinos, dark matter, ...)
- JUNO subsystem development and production programs are well underway
- Civil construction is finalizing; detector installation will start in summer 2021; data taking will begin in 2022

Stay tuned !

Other JUNO Talks

Parallel

Yury Malyshkin: *Oscillation Physics in JUNO* (02.24 10:20 CET)
Fabrizio Petrucci: *JUNO-TAO: Status and Prospects* (02.26 10:40 CET)
Giulio Settanta: *Atmospheric Neutrino Physics with JUNO* (02.22 10:20 CET)
Hans Steiger: *JUNO: Detector Design and Status* (02.22 18:10 CET)
Jie Zhao: *B-8 Neutrinos in JUNO* (02.24 10:40 CET)

Flash

Yang Han: *Dual Calorimetry of JUNO* (02.25 12:05 CET)
Philipp Kampmann: *Event Reconstruction in JUNO* (02.26 12:15 CET)
Huiling Li: *Core-collapse Supernova Neutrinos in JUNO* (02.19 12:05 CET)
Runxuan Liu: *JUNO ORSIRIS Online Trigger* (02.22 11:40 CET)
Claudio Lombardo: *Study of SIPMs for the JUNO-TAO detector* (02.22 11:35 CET)
Cristina Martellini: *Supernova Neutrino Energy Spectrum Unfolding with a Probabilistic Unfolding Method in JUNO (02.19 11:50 CET)*
Michele Montuschi: *The Liquid Scintillator of JUNO* (02.24 12:20 CET)
Tobias Sterr: *JUNO OSIRIS Calibration Systems* (02.25 11:40 CET)
Alexander Tietzsch: *JUNO PMT Testing Systems and Progress* (02.25 11:35 CET)