Status of the JUNO experiment and its physics perspectives

Gioacchino RANUCCI

JUNO & INFN – Milano

Mayorana Workshop

Modica 13-July-2023

A large LS spherical detector

- LS large volume: ➔ for statistics
- High Light yield and transparency➔ for energy resolution 1200 pe/MeV

Key factors for resolution

- Large PMT number
- Optimal scint. optical properties
- Calibration

Steel Truss

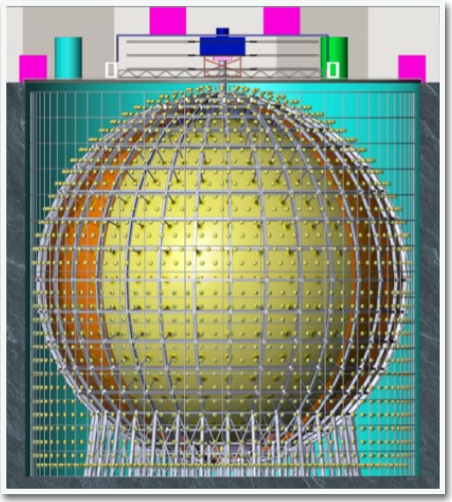
Holding PMTS

~20000 x 20”

~25000 x 3”

Acrylic Sphere

filled with 20 kton of liquid scintillator



JUNO has been approved in February 2013

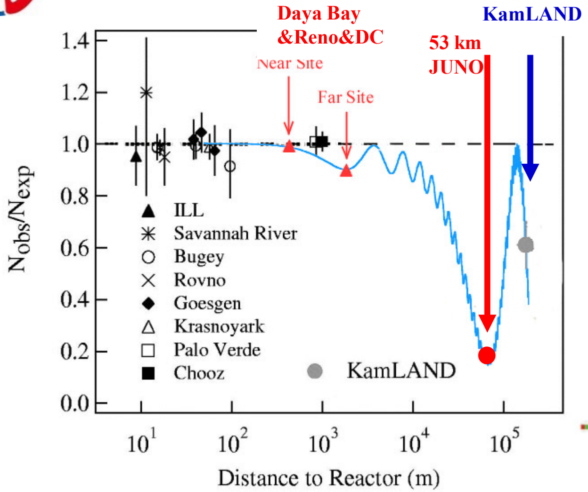
Approved funding from several countries:

- Armenia
- Belgium
- Brazil
- Chile
- Czech Republic
- Finland
- France
- Germany
- Pakistan
- People’s Republic of China
- Russia
- Slovakia
- Taiwan
- Thailand
- USA

75 institutes

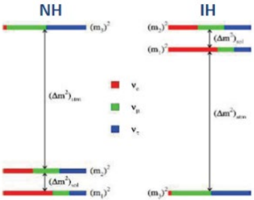
715 collaborators

JUNO physics summary



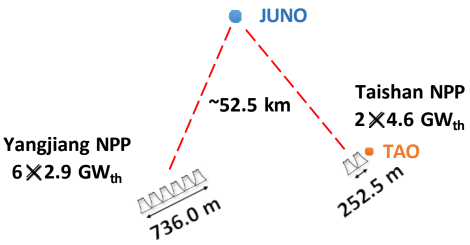
- **20 kton LS detector**
- **~3 % energy resolution-the greatest challenge for MH**
- Rich physics possibilities-neutrino oscillation and astroparticle program
  - ⇨ **Mass hierarchy**
  - ⇨ **Precision measurement of 3 mixing parameters Δm^2_{atm} Δm^2_{sol} θ_{12}**
  - ⇨ **Supernova neutrinos**
  - ⇨ **Diffuse supernova background**
  - ⇨ **Geo-neutrinos**
  - ⇨ **Solar neutrinos**
  - ⇨ **Atmospheric neutrinos**
  - ⇨ **Nucleon Decay**
  - ⇨ **Exotic searches**

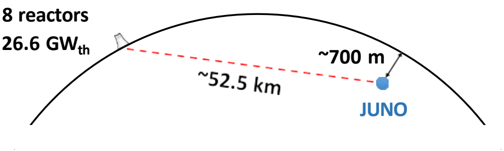
Neutrino Physics with JUNO, J. Phys. G 43, 030401 (2016)
JUNO physics and detector, Progress in Particle and Nuclear Physics 123, 103927 (2022)



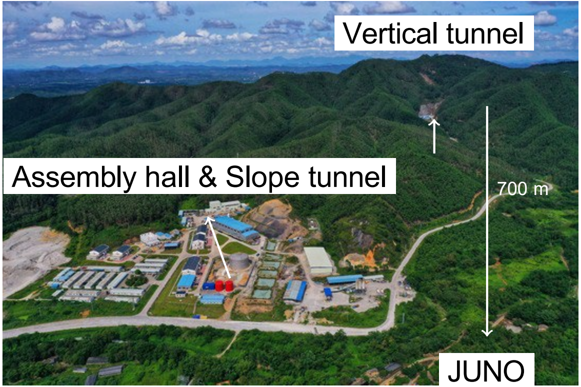
Background challenge especially for solar neutrinos - target range 10^{-15} (minimum requirement) 10^{-17} (ideal) g/g of U and Th

JUNO geometry and site

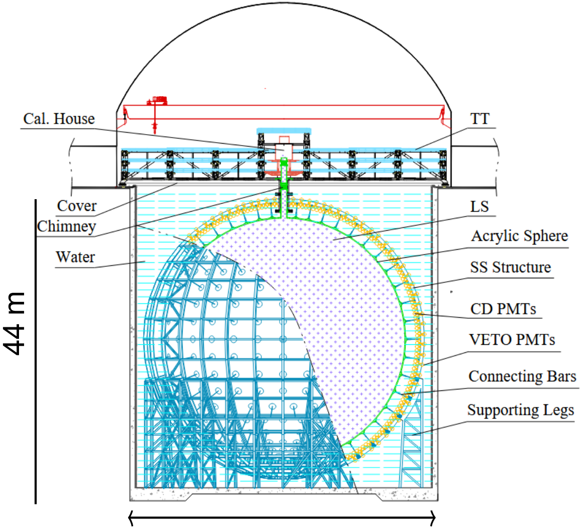




- **Civil construction finished: 12/2021**



The JUNO detector



43.5 m (Acrylic Sphere: D=35.4 m)

Top Tracker (TT)

- Precise μ tracker
- 3 layers of plastic scintillator
- ~ 60% of area above WCD

Calibration House

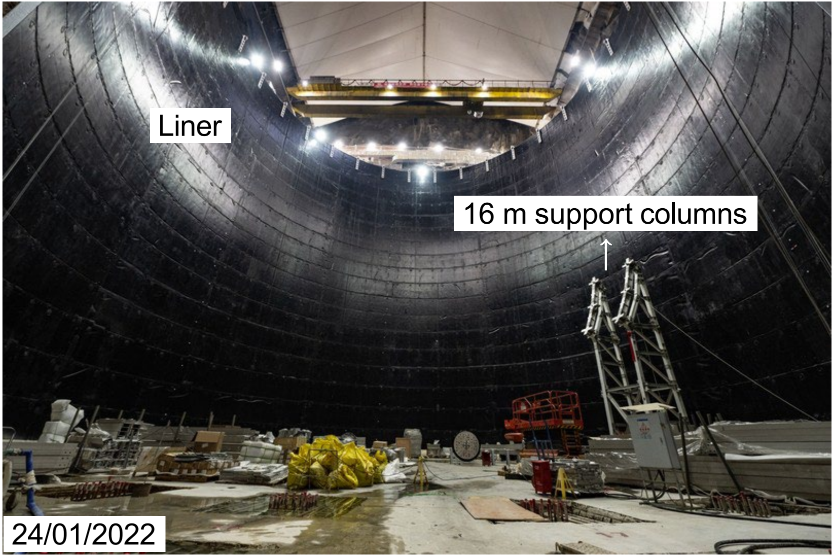
Water Cherenkov Detector (WCD)

- 35 kton ultra-pure water
- 2.4k 20" PMTs
- High μ detection efficiency
- Protects CD from external radioactivity & neutrons from cosmic-rays

Central Detector (CD) $\bar{\nu}$ target

- Acrylic sphere with 20 kton liquid scint.
- 17.6k 20" PMTs + 25.6k 3" PMTs
- 3% energy resolution @ 1 MeV

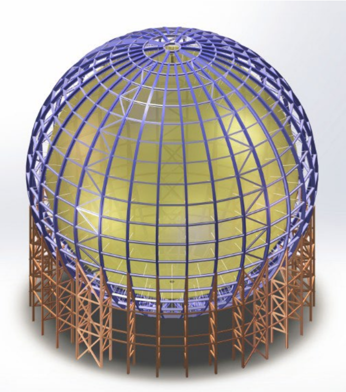
Detector installation start-up



After the deployment of the liner on the wall of the experimental pool (radon stopping) the installation of the detector started in January 2022

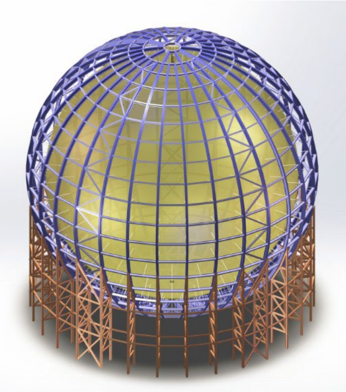
In the figure → first supporting leg of the steel truss

Installation of the supporting legs



- Acrylic Sphere supported by 590 connecting bars

Assembly of the Steel Support Structure and of the Lift Platform for Vessel installation



- Acrylic Sphere supported by 590 connecting bars

The JUNO detector – CD Support Structure and Lift Platform

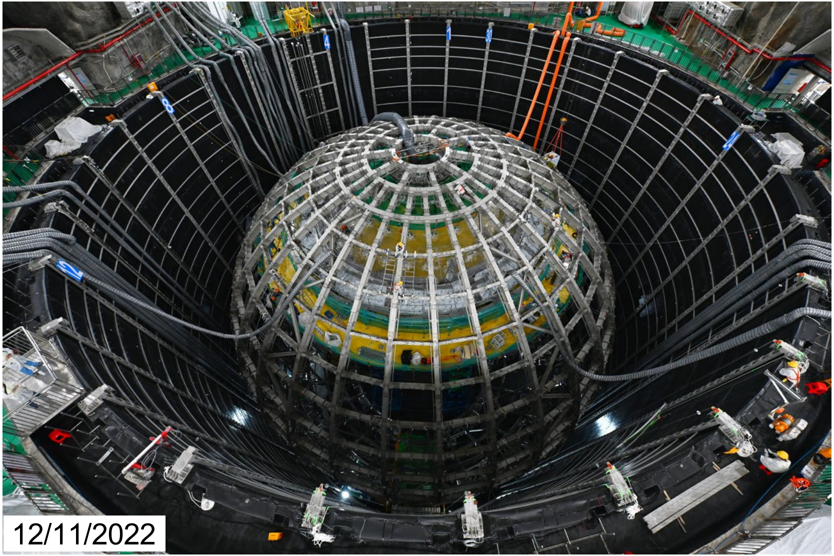
- Assembly of SS truss finished last summer
- Installation of acrylic sphere started in July 2022

The JUNO detector – Acrylic Sphere


Assembly test in factory

- 265 acrylic plates
- thickness: 124±4 mm
- radiopurity: U/Th/K < 1 ppt
- Each plate:
  - polished
  - cleaned
  - PE protective film added
- PE film to be removed after installation

Progress of the overall central detector installation

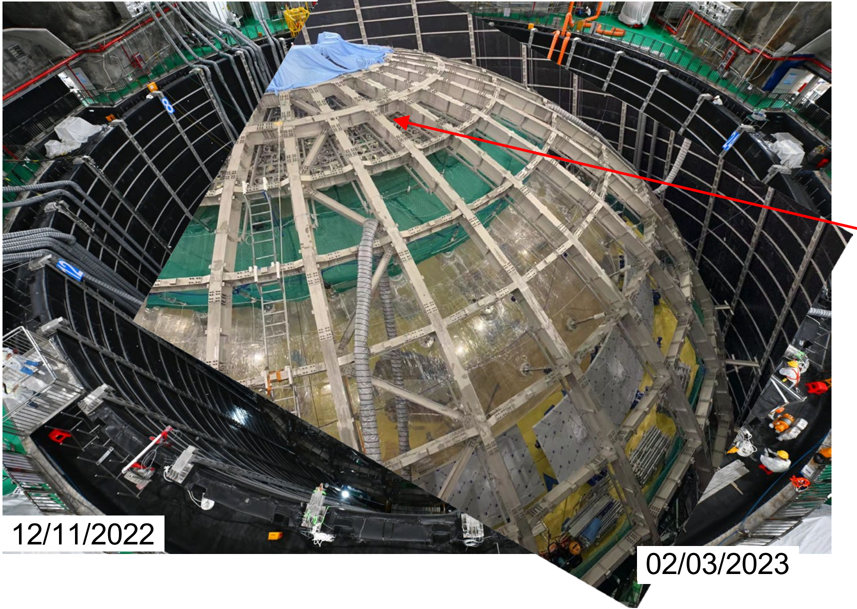


In the past Fall

Support structure completed

Top part of the vessel under construction

Installation status

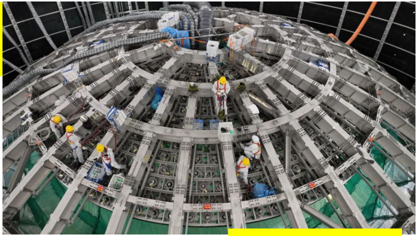


Next stage

PMTs and electronics being installed!

Details of the ongoing parallel installation of the acrylic vessel, PMTs and electronics

PMT modules installation



Underwater box containing the PMT electronics

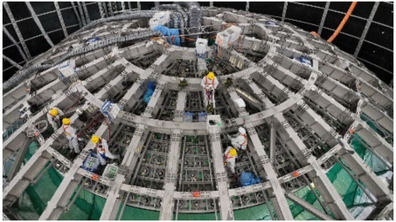
Inner view of the mounted portion of the acrylic vessel

Inner view of the installed PMTs

Details of PMT & Electronics Installation

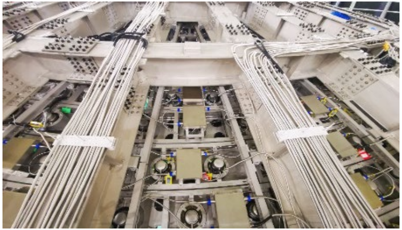
Installation of PMT and the readout electronics with cables is in progress
4600 20” PMTs, 3600 3” PMTs, and 900 underwater electronics boxes in place

PMT cables deployment



PMT installation ongoing

Installed 20”&3” PMTs



Installed underwater electronics & cables

underground electronics room

Recent global view of the progressing detector construction

Top part almost completed

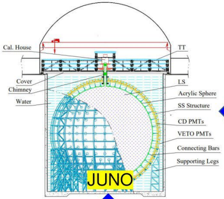
The JUNO detector – Liquid Scintillator

Four purification plants to achieve target radio-purity 10^{-17} g/g U/Th and 20 m attenuation length at 430 nm.

All LS plants ready to produce the first test batch of scintillator for OSIRIS

SS pipes to underground

15%



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NIM.A 908 (2021) 164823

Eur. Phys. J. C **81** (2021) no.11, 973

Multiple approach for target optical and radioactive purity

Huge effort for radiopurity control

Radiopurity of materials

Singles (R < 17.2 m, E > 0.7 MeV)	Design [Hz]	Change [Hz]	Comment
LS	2.20	0	
Acrylic	3.61	-3.2	10 ppt -> 1 ppt
Metal in node	0.087	+1.0	Copper -> SS
PMT glass	0.33	+2.47	Schott -> NNVT/Ham
Rock	0.98	-0.85	3.2 m -> 4 m
Radon in water	1.31	-1.25	200 mBq/m³ -> 10 mBq/m³
Other	0	+0.52	Add PMT readout, calibration sys
Total	8.5	-1.3	

Radiopurity control of raw material:

- ✓ Careful material screening
- ✓ Meticulous Monte Carlo Simulation
- ✓ Accurate detector production handling

Better than spec. by 15%

Good enough for MH from reactor ν's

10^{-15} g/g for U and Th already demonstrated by the Daya Bay test

The Kr value takes into account the release from acrylic and the analysis approach to cope with it for solar ^{7}Be

LS for solar neutrinos:

U/Th<10^{-17} g/g, $^{40}K<10^{-18}$ g/g,
$^{85}Kr<50\ \mu Bq/m^3$,
$^{226}Ra<5\times10^{-24}$ g/g (0.1 $\mu Bq/m^3$),
$^{210}Pb<10^{-24}$ g/g ($^{222}Rn<5\ mBq/m^3$)

Crucial the initial purification recirculation much more difficult than Borexino, KamLAND, SNO+,…

Radiopurity control for LS:

- Leak check(single component < 10^{-6} mbar·L/s) of all joints to reduce 222Rn and 85Kr
- Cleaning of all pipes, vessels to remove dust (check water cleanness)
- Clean room environment during installation
- Surface treatment of the acrylic vessel (Rn daughters)
- LS filling strategy

JUNO physics

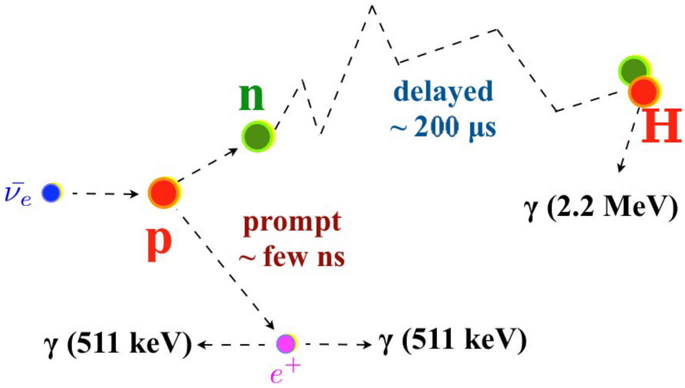
["Neutrino Physics with JUNO," J. Phys. G **43** (2016) no.3, 030401]
["JUNO Physics and Detector," Prog. Part. Nucl. Phys. **123** (2022), 103927]

- Neutrino Mass Ordering (NMO)
- Precision measurement of oscillation parameters
- Atmospheric neutrinos
- Geoneutrinos
- Supernova (SN) neutrinos
- Diffuse SN neutrino background
- Solar neutrinos
- Nucleon decay & Exotic searches

Research	Expected signal	Energy region	Major backgrounds
Reactor antineutrino	60 IBDs/day	0–12 MeV	Radioactivity, cosmic muon
Supernova burst	5000 IBDs at 10 kpc 2300 elastic scattering	0–80 MeV	Negligible
DSNB (w/o PSD)	2–4 IBDs/year	10–40 MeV	Atmospheric ν
Solar neutrino	hundreds per year for ^{8}B	0–16 MeV	Radioactivity
Atmospheric neutrino	hundreds per year	0.1–100 GeV	Negligible
Geoneutrino	$\sim$ 400 per year	0–3 MeV	Reactor ν

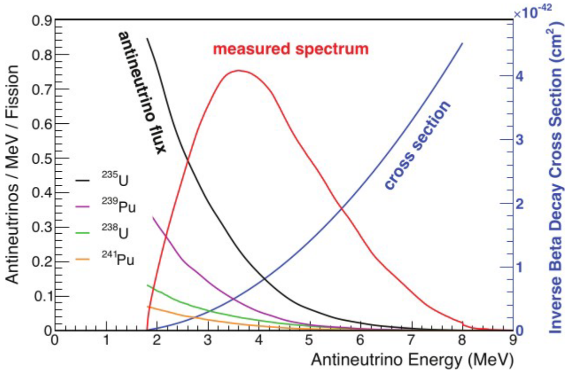
Measuring reactor $\bar{\nu}_e$ inverse Beta Decay (IBD)

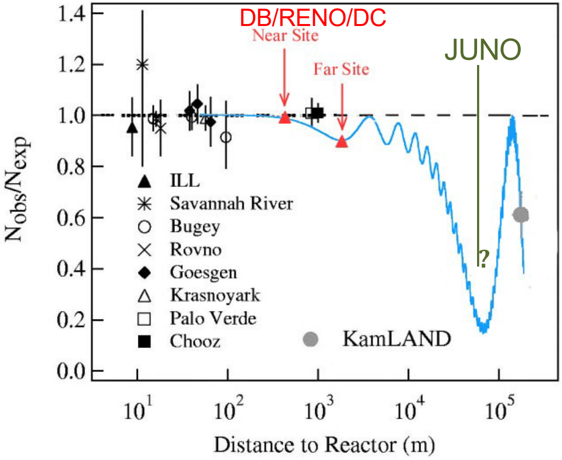
- Detected via IBD: $\bar{\nu}_e + p \rightarrow n + e^+$
  - IBD used since discovery of neutrino
  - Prompt+delayed signal ⇒ large background suppression



$E_{vis}(e^+) \simeq E(\bar{\nu}_e)$ - 0.8 MeV ← used as proxy for antineutrino energy

Neutrino oscillations with Reactor Antineutrinos





Detected $\bar{\nu}_e$ energy 2–8 MeV

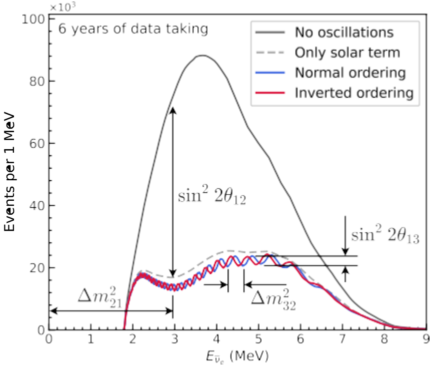
- Only sensitive to $\bar{\nu}_e \to \bar{\nu}_e$

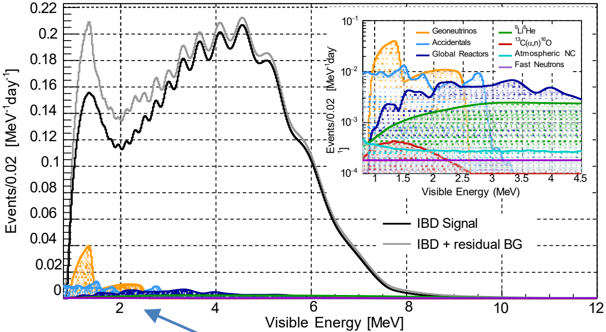
Distance: selects "oscillation regime"

- JUNO at maximum $\bar{\nu}_e$ disappearance
- First experiment to see both Δm^2

Expected reactor $\overline{\nu}_e$ spectrum in JUNO

"Sub-percent precision measurement of neutrino oscillation parameters with JUNO," Chin. Phys. C **46** (2022) no.12, 123001





In real life low energy background

Energy resolution smears low energy oscillations

- critical importance of energy resolution
- Mass ordering determination via the phase of the superimposed ripple → detectable with resolution better than 3% → Huge calibration effort

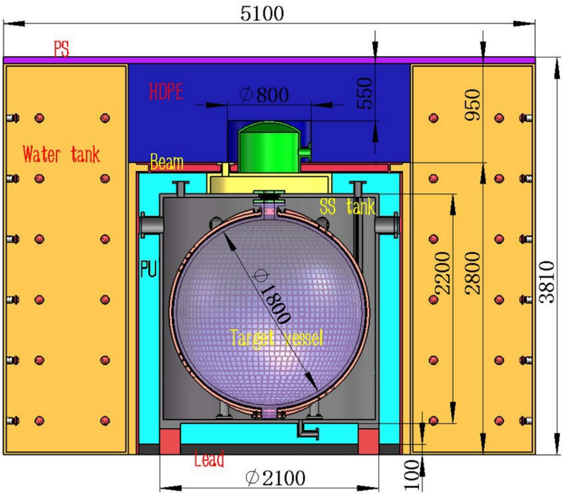
JUNO-TAO

[“TAO Conceptual Design Report: A Precision Measurement of the Reactor Antineutrino Spectrum with Sub-percent Energy Resolution,” arXiv:2005.08745]

- JUNO-TAO provides reference for reactor spectrum
- Better energy resolution than JUNO (4500 PE/MeV)

JUNO-TAO detector:

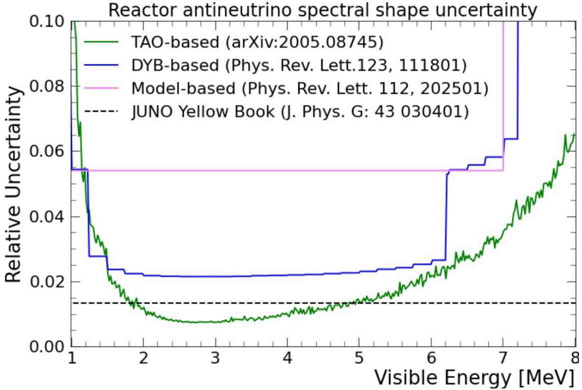
- 1 ton fiducial volume Gd-LS detector
  - 30 m from one of Taishan’s 4.6 GW_{th} reactor core
  - 30× JUNO event rate
- 10 m^2 SiPM of 50% photon detection efficiency (PDE) operated at −50°C
  - >95% photo-coverage



JUNO-TAO – Physics potential

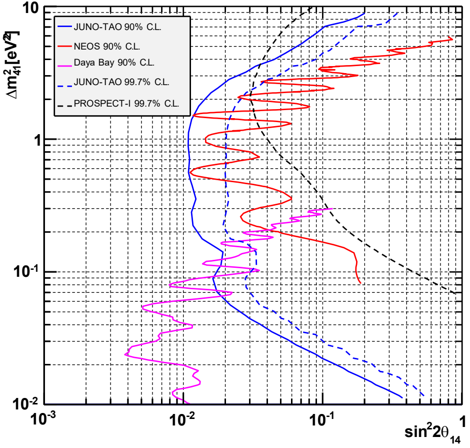
[“TAO Conceptual Design Report: A Precision Measurement of the Reactor Antineutrino Spectrum with Sub-percent Energy Resolution,” arXiv:2005.08745]

Precise measurement of $\overline{\nu}_e$ spectra



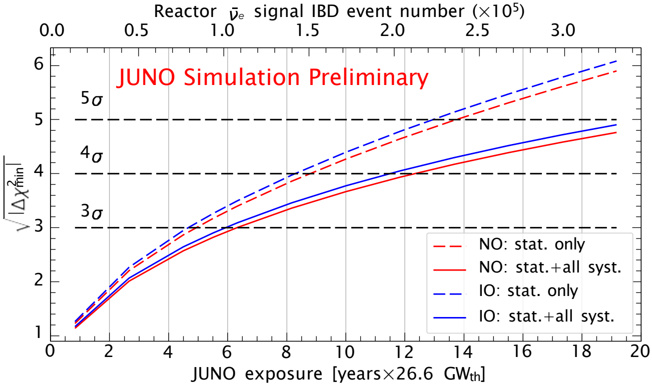
TAO energy resolution <2% @ 1 MeV

Sterile Neutrino searches

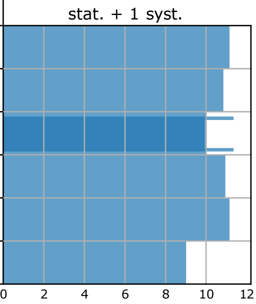


Neutrino Mass Ordering

See poster 10.5281/zenodo.6775075 from Neutrino 2022



6 years	$\Delta\chi^2_{min}$
Statistics	11.3
Stat.+Flux error	-0.6
Stat.+Backgrounds	-1.4
Stat.+Nonlinearity	-0.4
Stat.+Others	< -0.05
Total	9.0



JUNO Simulation Preliminary

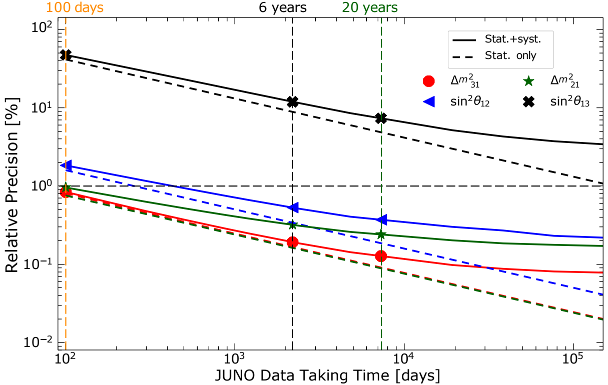
Number of σ ≅ $\sqrt{\square\ 2}$

Reactor only: 3σ in ~6 years × 26.6 GW$_{th}$ exposure → 2 reactors at Taishan and 6 at Yangjiang

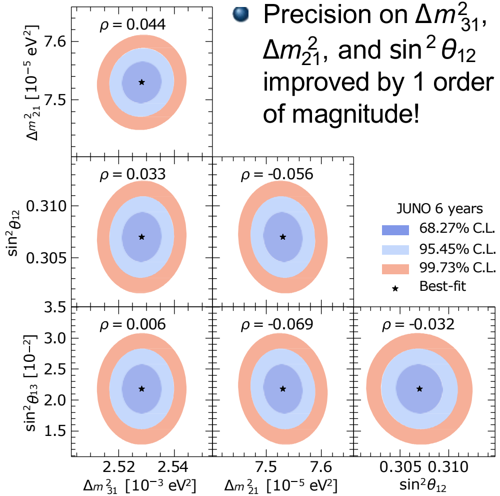
Working into possibility to combine with JUNO Atmospheric result

Precision Measurement of Neutrino Oscillation Parameters

"Sub-percent precision measurement of neutrino oscillation parameters with JUNO," Chin. Phys. C **46** (2022) no.12, 123001

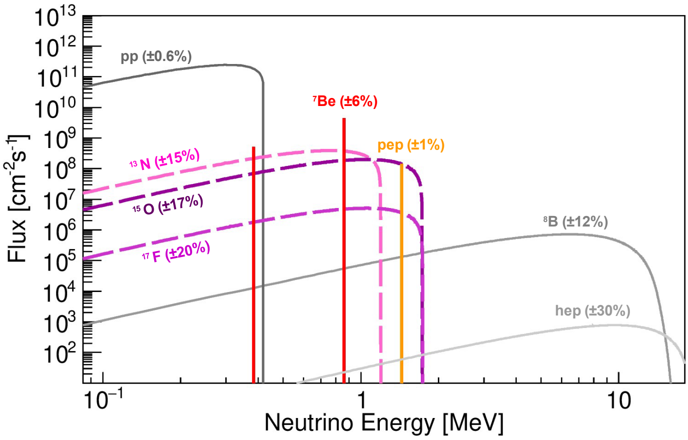


	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
JUNO 6 years	~0.2%	~0.3%	~0.5%	~12%
PDG2020	1.4%	2.4%	4.2%	3.2%



- Precision on Δm^2_{31}, Δm^2_{21}, and $\sin^2\theta_{12}$ improved by 1 order of magnitude!

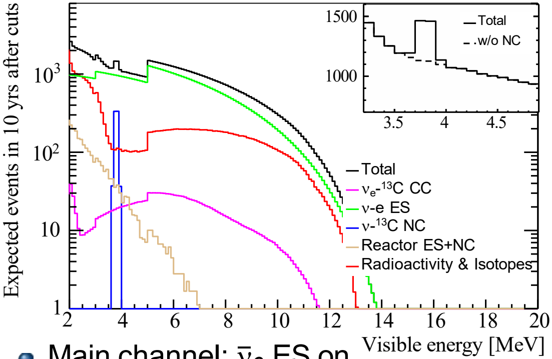
Solar Neutrinos



- Nuclear fusion in Sun ⇒ ν_e
  - ν energy depends on specific reaction
  - Probe Sun composition
- JUNO expected to be able to measure ^{8}B, ^{7}Be, pep, CNO
  - Main limitation from radioactive backgrounds

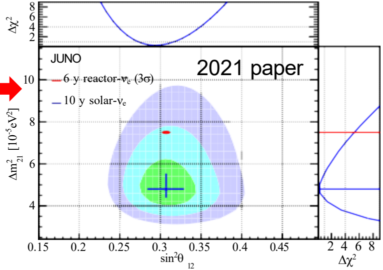
Solar Neutrinos: ^{8}B @ JUNO

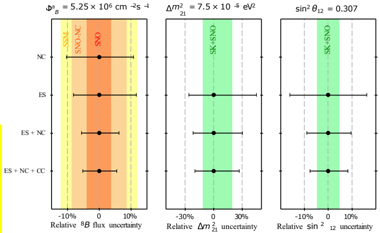
"Feasibility and physics potential of detecting ^{8}B solar neutrinos at JUNO," Chin. Phys. C **45** (2021) no.2, 023004 and "Model Independent Approach of the JUNO ^{8}B Solar Neutrino Program," arXiv:2210.08437



- Main channel: $\bar{\nu}_e$ ES on electrons - Also visible:
  - $\nu_x + {}^{13}C$ NC: 3.7 MeV γ
  - $\nu_e + {}^{13}C$ CC: 2.2 MeV β^+

Test of the current tension between KamLAND and solar





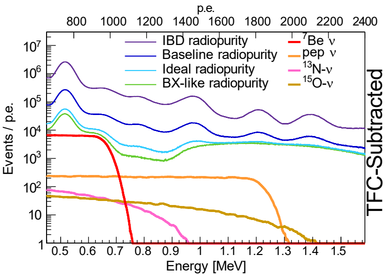
2022 paper

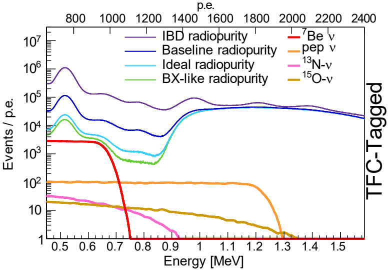
Flux precision at 6% level

*BX: Borexino

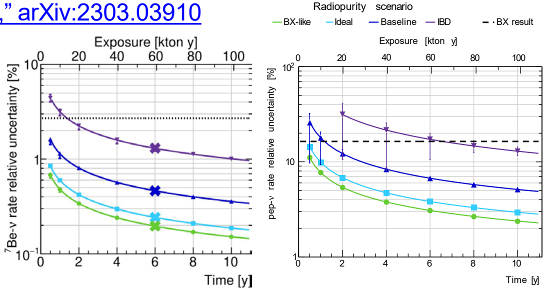
Solar Neutrinos: ^{7}Be, pep, CNO @ JUNO

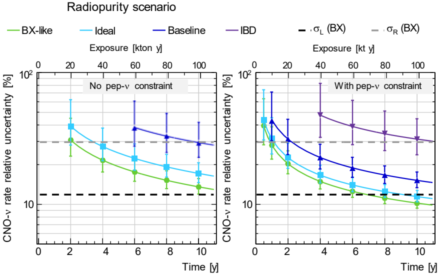
“JUNO sensitivity to ^{7}Be, *pep*, and CNO solar neutrinos,” arXiv:2303.03910





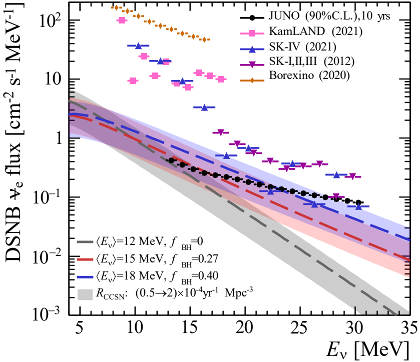
Possible significant improvements over Borexino purification effort crucial

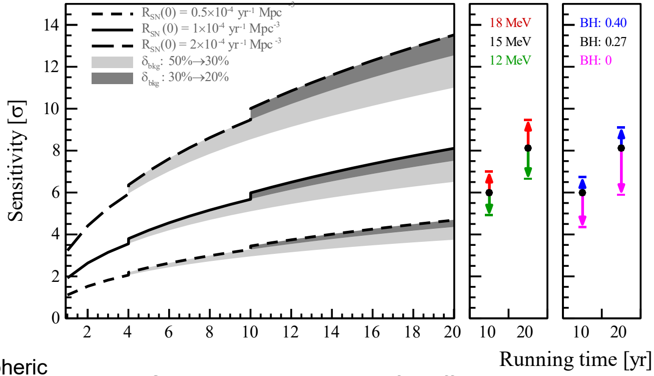




Diffuse Supernova Neutrino Background

[“Prospects for Detecting the Diffuse Supernova Neutrino Background with JUNO,” JCAP **10** (2022), 033](#)



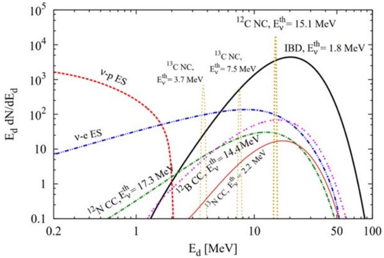


- Below 12 MeV reactors - above 30 MeV atmospheric neutrinos
- Attainable 90% CL limit in JUNO in case of no detection in 10 years
- For comparison signal models with different average ν energy, fraction of failed supernovae f_{BH} and present supernova rate R_{CCSN}

- DSNB discovery sensitivity for different models
- @10 years → 5σ sensitivity for reference model (solid line)
- Crucial background rejection
  - Muon veto suppression
  - Pulse shape discrimination for event of different types

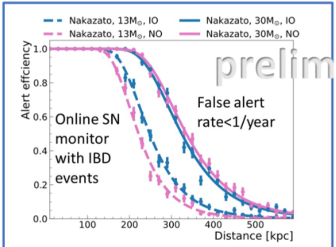
Core Collapse Supernova Neutrinos

See poster 10.5281/zenodo.6785184 from Neutrino 2022

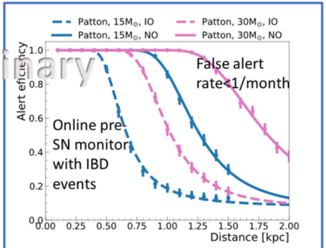


Multichannel detection of CCSN

Interaction channels	IBD	pES	eES	C12, NC	C12, CC
Statistics for SN@10kpc [1]	5000	2000	300	300	200



Alert efficiency for SN of online monitor. False alert rate is set to be smaller than 1/year.



Alert efficiency for pre-SN of online monitor. False alert rate is smaller than 1/month.

SN detection efficiency

Pre-SN alert signal
Betelgeuse at 197 parsec

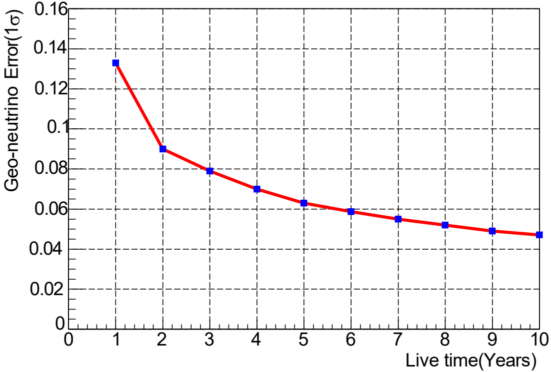
Capability to detect pre-SN neutrinos from close SN-candidates

>50% efficiency to detect CCSN up to 250–300 kpc

- For reference: Milky Way diameter ~30 kpc; Andromeda galaxy distance ~ 780 kpc

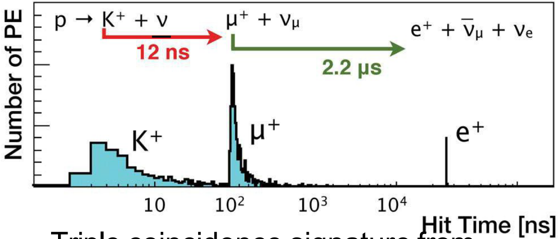
Other topics in JUNO

Geo $\bar{\nu}$



Also potential to constrain Th/U ratio in Earth

Nucleon decay



Triple coincidence signature from $p \rightarrow \bar{\nu} + K^+$ arXiv:2212.08502

90% CL limit to proton lifetime 1.1×10^{34} years after 10 years of data taking

Other nucleon decay modes explored

Among other topics discussed in J. Phys. G **43** (2016) no.3, 030401 and Prog. Part. Nucl. Phys. **123** (2022), 103927

Conclusions

JUNO will have unique properties: large target scint. mass & good energy resolution

- Very large photo-coverage & high LS light yield and transparency
- JUNO-TAO for reference reactor spectrum
- Multipronged strategy towards 3% energy resolution including calibration
- Huge effort for challenging radiopurity targets

Precision oscillation measurements with reactor $\bar{\nu}_e$ flux

- First simultaneous observation of solar and atmospheric oscillations in same experiment
- Measurement of NMO not relying on matter effects ⇒ 3σ in $\sim$ 6 years (reactor only)
- $<$ 0.5% precision on $\sin^2\theta_{12}$, Δm^2_{21}, and Δm^2_{32}

Vast astroparticle program beyond reactor $\bar{\nu}_e$ analysis

- DSNB discovery possible within JUNO
- CCSN field of view extended to $\sim$300 kpc
- Improved precision in Solar ν studies, particularly for some radiopurity scenarios
- ...

Detector construction progressing rapidly ⇒ detector fill and first data within 2024