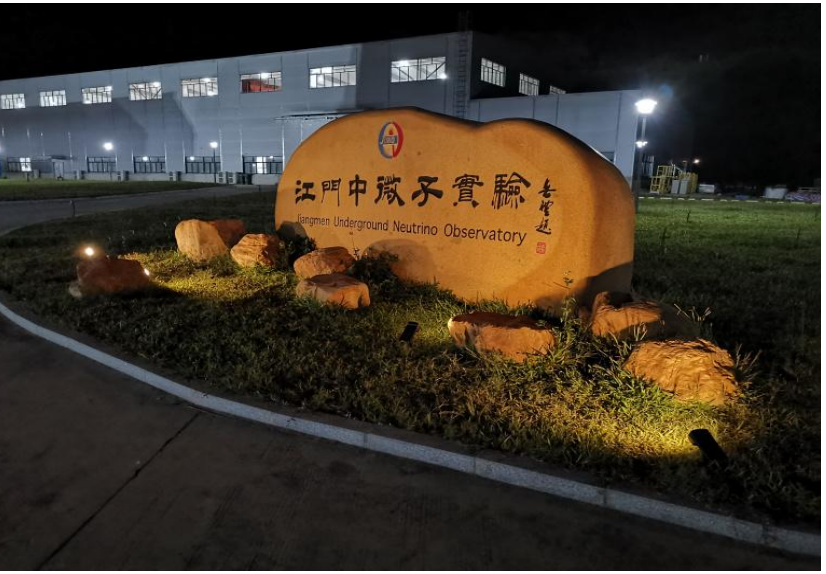
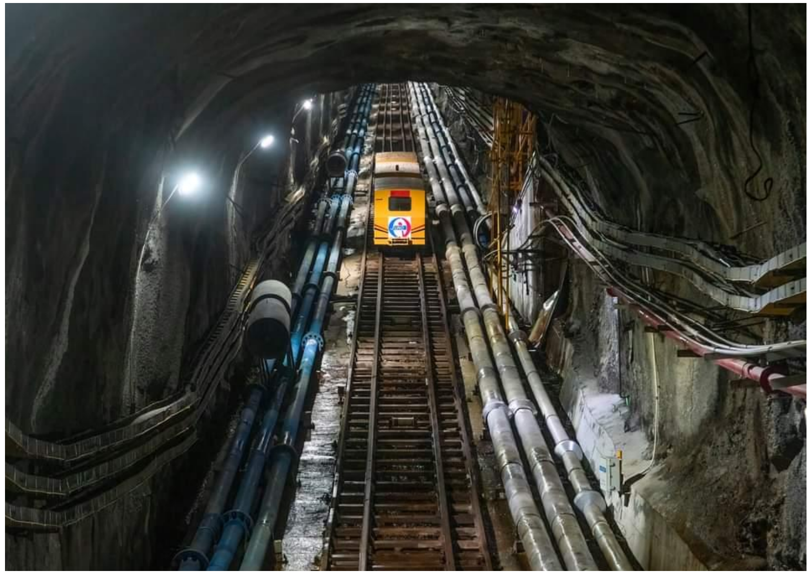




Status of the Jiangmen Underground Neutrino Observatory to measure Neutrino Mass Ordering

Mariam Rifai on behalf of the JUNO collaboration

34th Rencontres de Blois 2023

JUNO

Physics Institute III B | RWTH AACHEN UNIVERSITY

JÜLICH Forschungszentrum

Physics potential of JUNO

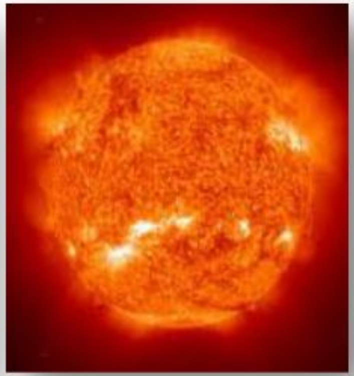
Reactor anti-ν

~47/day

Atmospheric ν

Several / day

Solar ν



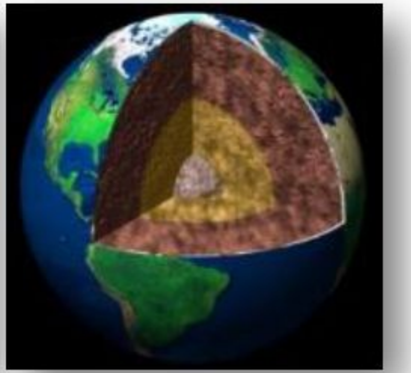
^{8}B: ~50/day
CNO: ~1000/day
^{7}Be: ~10000/day

Supernovae (SN) ν

Core Collapse SN @ 10 kpc: thousands in few sec.

Diffuse SN signal: few / year

Geoneutrinos



~400 / year

\+ New physics

Proton decay

Neutrino magnetic moment

Sterile neutrinos

Non standard interactions

Lorentz invariance

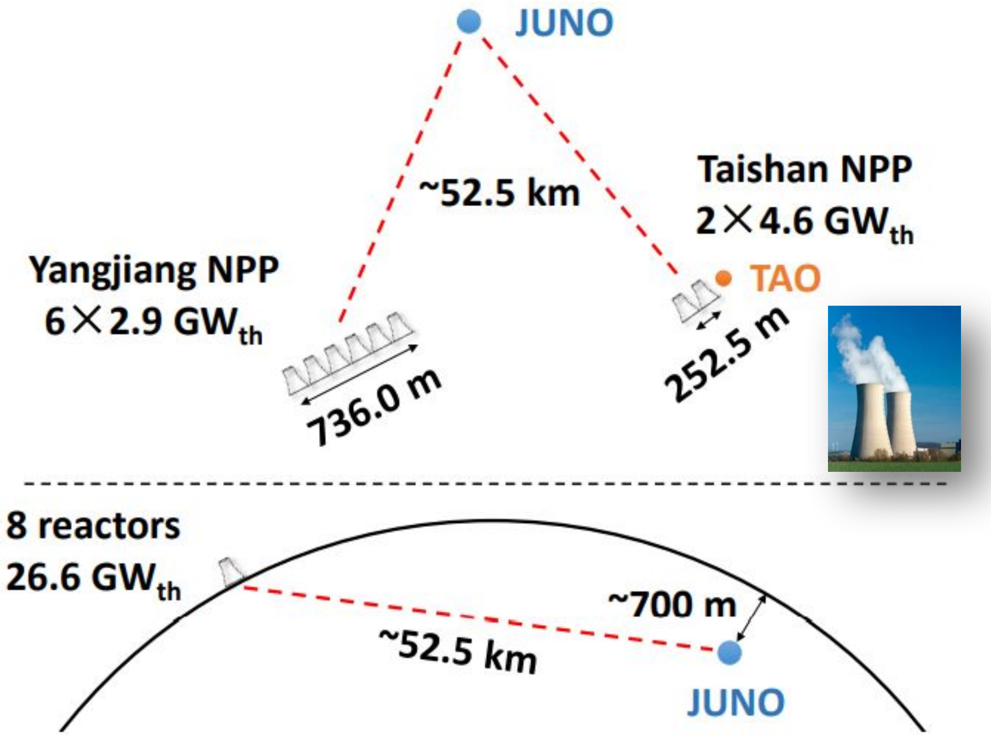
Others

- *A. Abusleme et al., JUNO physics and detector, Progr. Part. Nucl. Ph. 123 (2022) 103927*
- *A. Abusleme et al., JUNO sensitivity to 7Be, pep, and CNO solar neutrinos, submitted to Journal of Cosmology and Astroparticle Physics*
- *A. Abusleme et al., JUNO Sensitivity on Proton Decay $p \to \bar{\nu} K^+$ Searches, submitted to Chin. Phys. C.*
- *J. Zhao et al., Model Independent Approach of the JUNO B8 Solar Neutrino Program, submitted to APJ.*
- *A. Abusleme et al., Prospects for Detecting the Diffuse Supernova Neutrino Background with JUNO, J. Cos. Astro. Phys. 10 (2022) 033.*
- *A. Abusleme et al., JUNO sensitivity to low energy atmospheric neutrino spectra, Eur. Phys. J. C 81 (2021) 887.*

Jiangmen Underground Neutrino Observatory:

JUNO is the first multi-kton liquid scintillator (LS) detector ever built, located in China.

Main goal: determination of the Neutrino Mass Ordering (NMO), 3σ in 6 years



47 anti-ν_e /day after suppressing the cosmogenic backgrounds

vacuum oscillation pattern independent of δcp and θ_{23}

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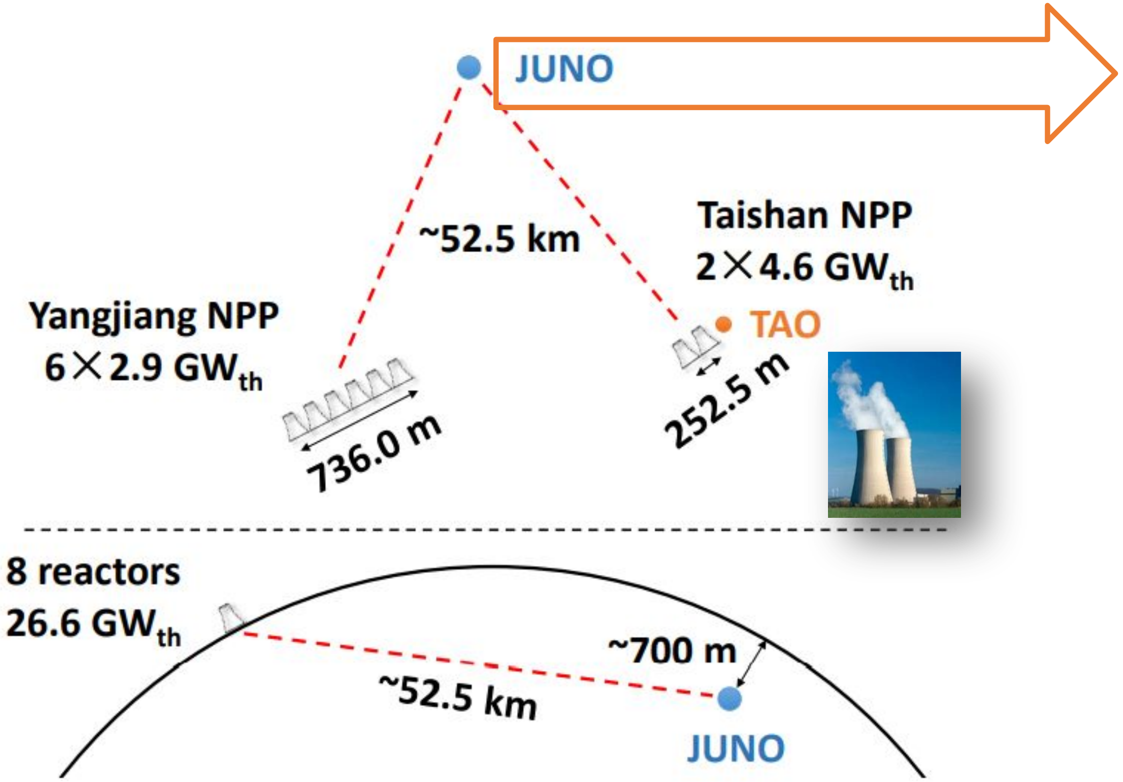
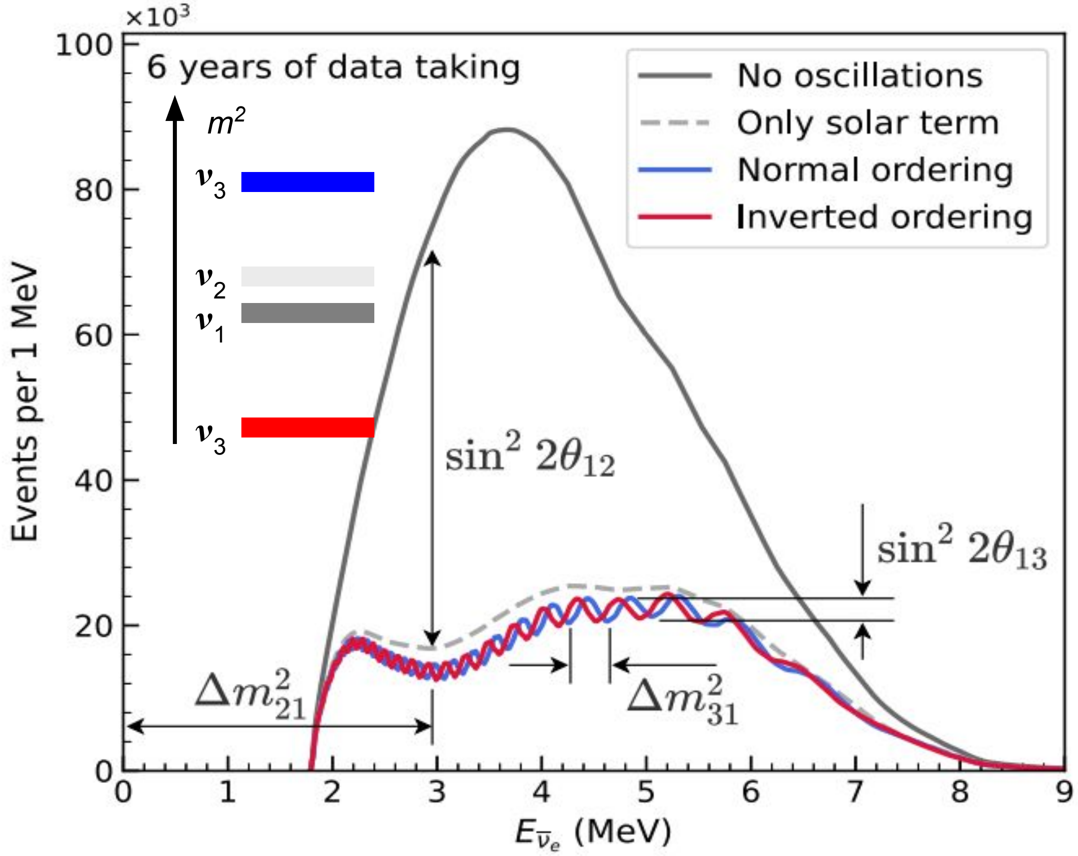




47 anti-ν_e /day after suppressing the cosmogenic backgrounds

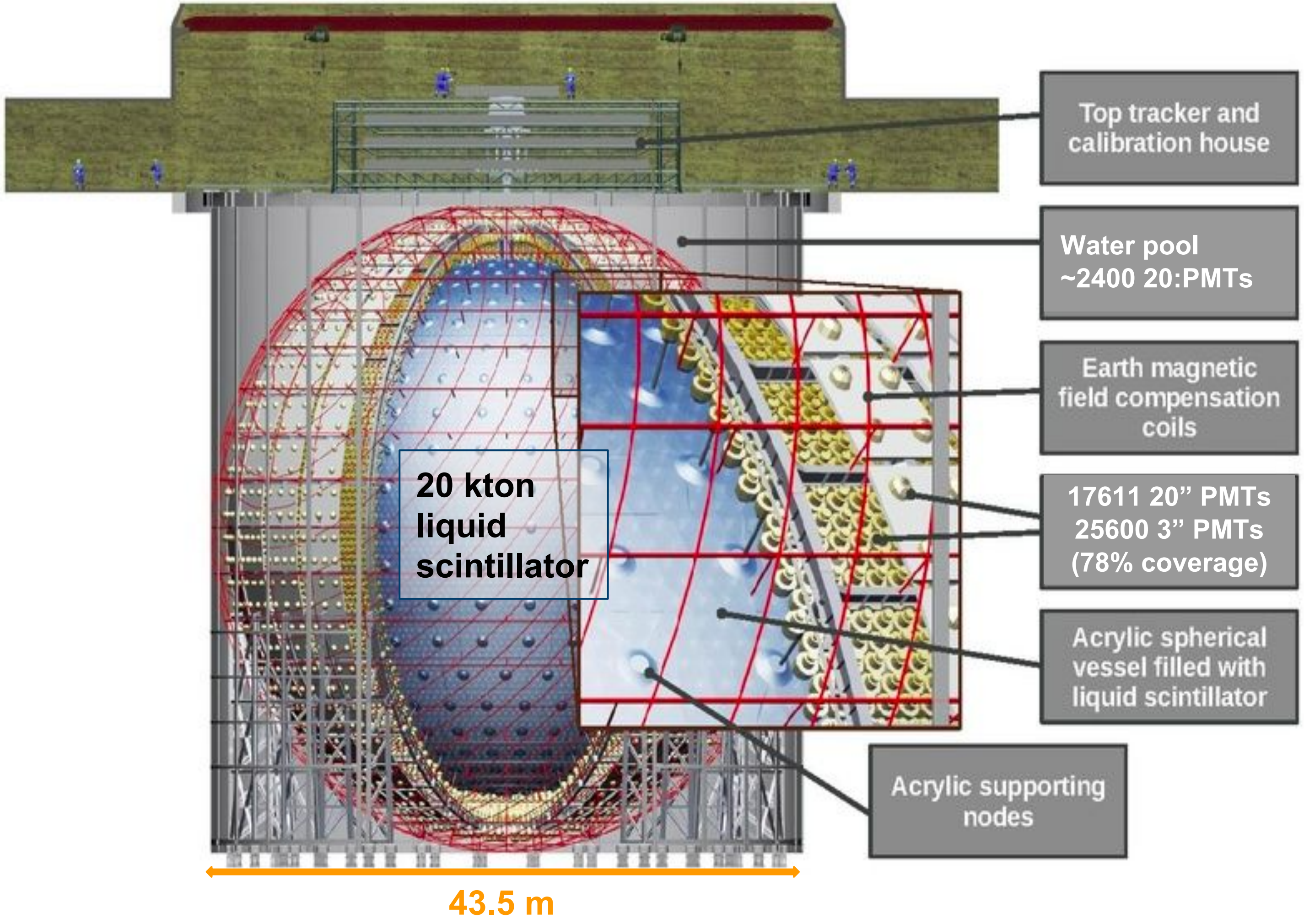
vacuum oscillation pattern independent of δcp and θ_{23}

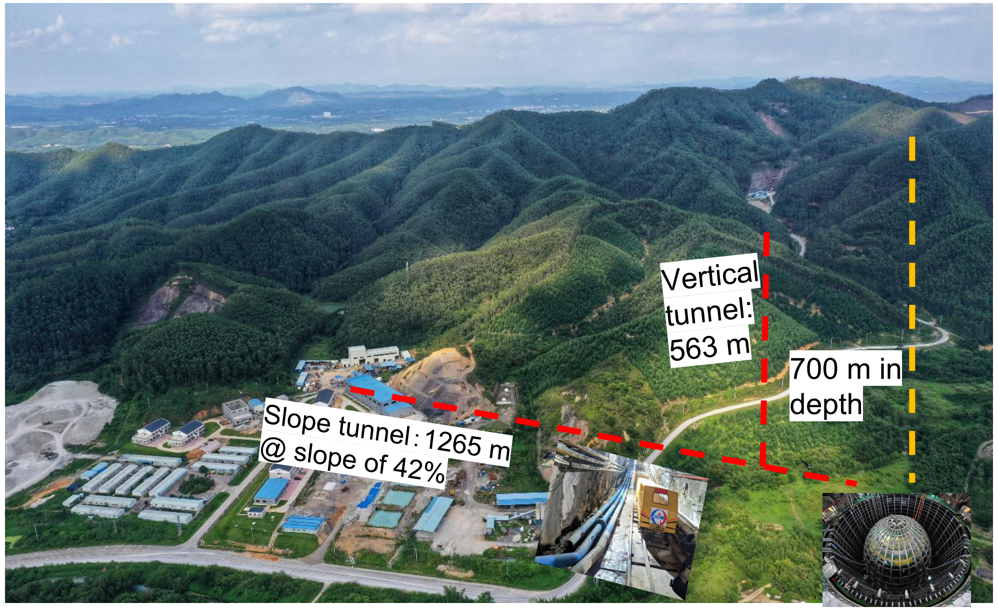
Reactor oscillated spectrum of electron anti-neutrinos spectrum detected by inverse beta decay IBD

JUNO requirements

- Large antineutrino statistics O(100k) @ 52.5 km baseline: 20 kton liquid scintillator powerful reactor (26.6 GW_{th})
- Resolving signature wiggles in the L/E spectrum
  - excellent **energy resolution 3% @ 1 MeV**
  - better than **1% understanding of the intrinsically non-linear energy scale of the liquid scintillator**
  - possible fine structures in the reactor spectrum under control -> **JUNO-TAO detector to measure shape uncertainty**
- Backgrounds:
  - radio-purity of all materials and depth of 700 m. *JUNO collaboration, JHEP 11 (2021) 102*
  - Muon veto system with > 99.5% efficiency

JUNO detector design



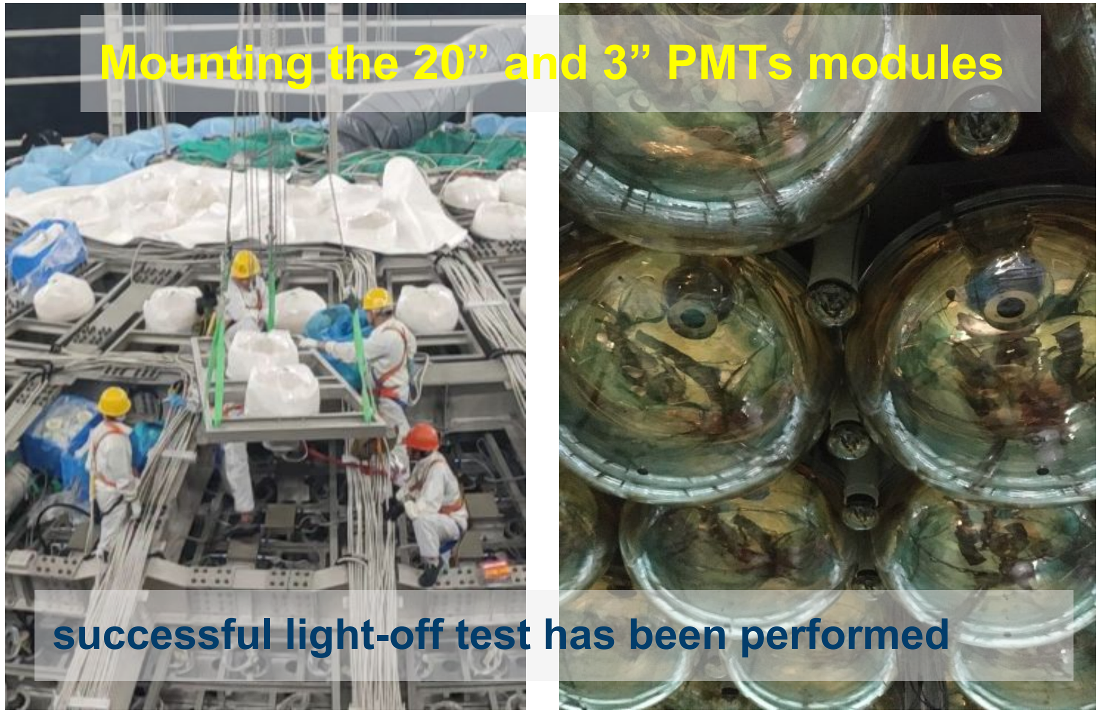


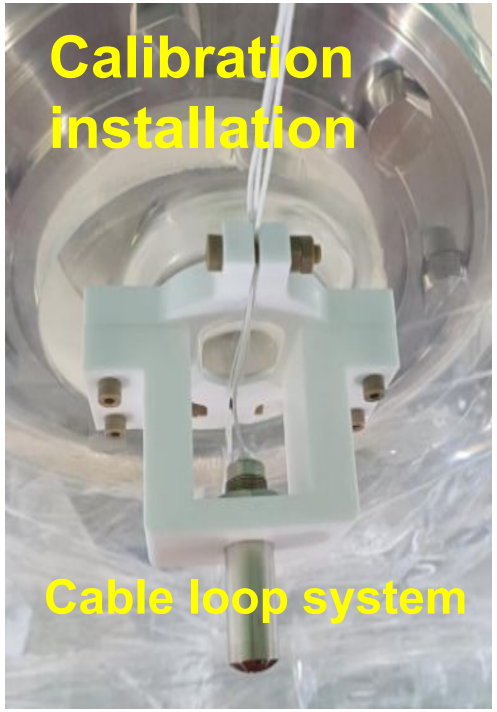
Detector Construction status

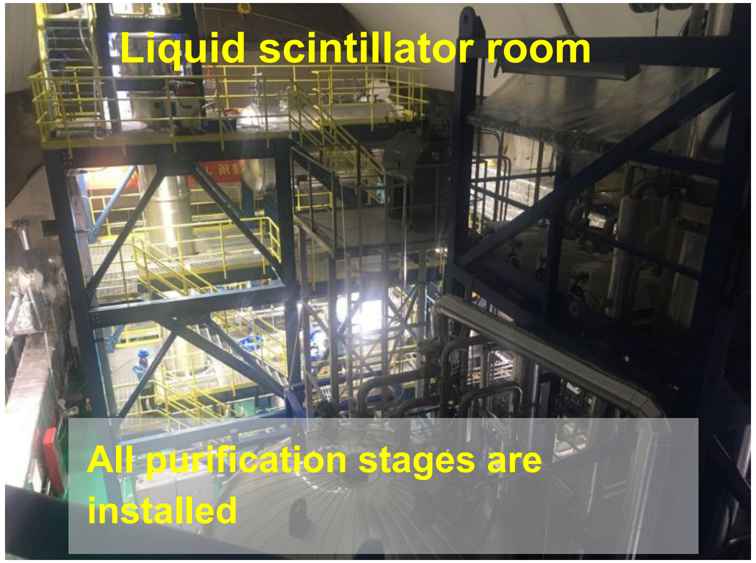
April 2023

Construction Highlights

Updates up to April 2023

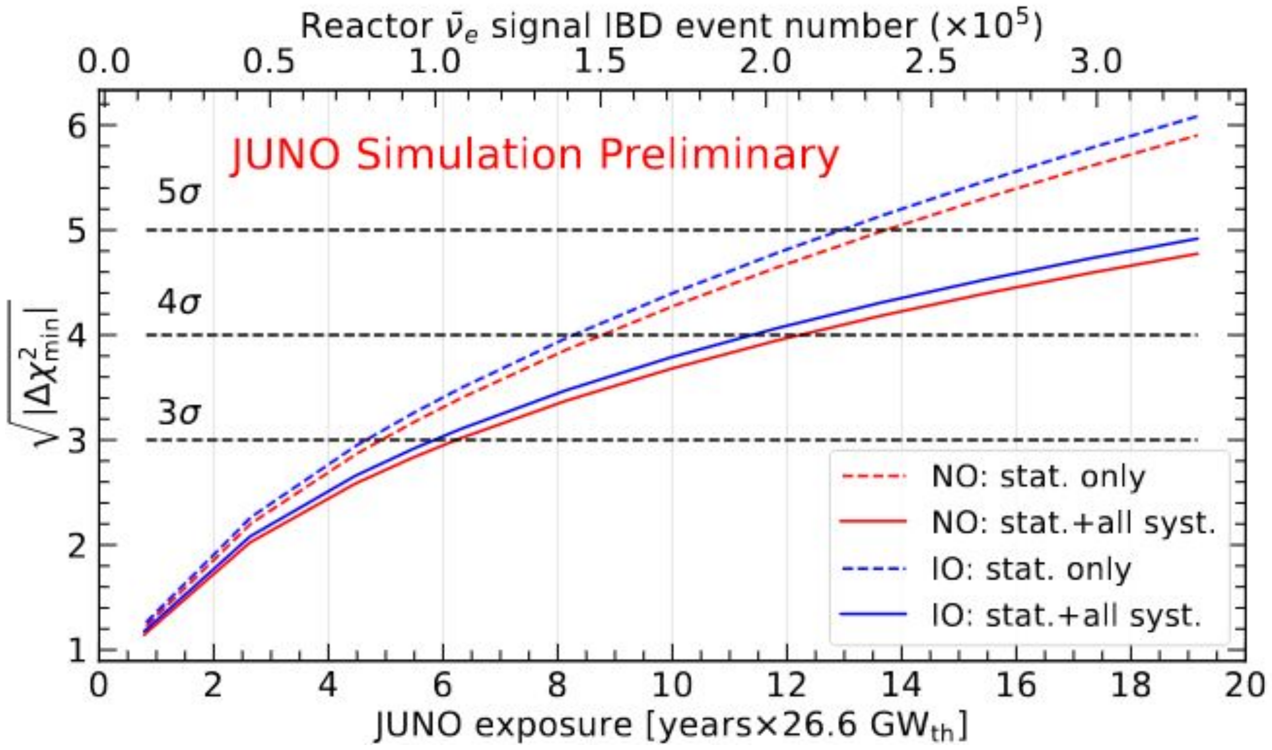




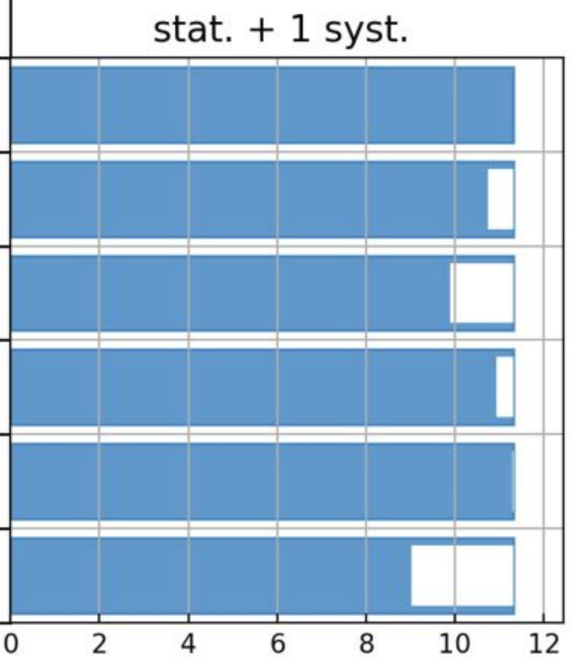


Neutrino mass ordering with reactor antineutrinos

Recent results



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



doi: 10.5281/zenodo.6683749
doi: 10.5281/zenodo.6775075

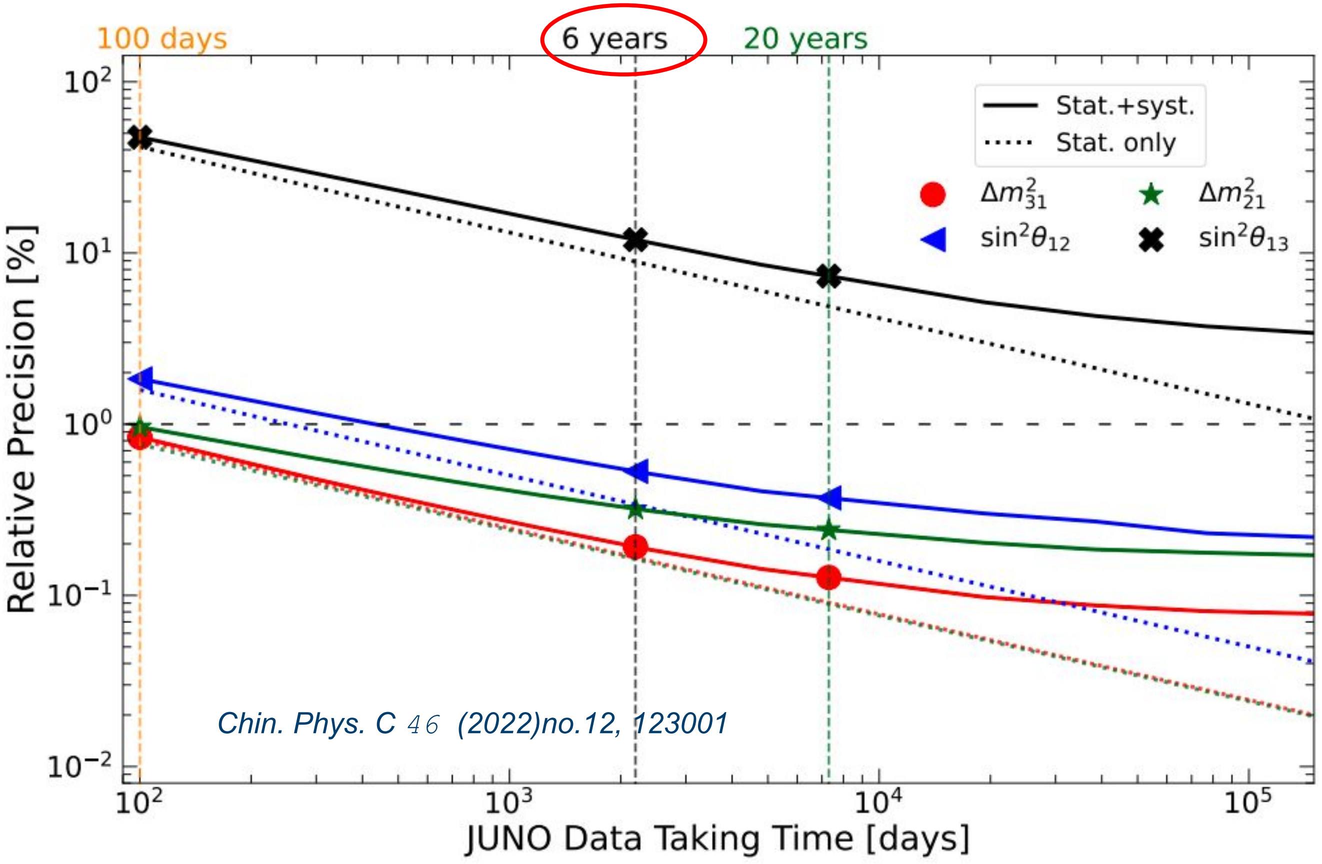
3σ (reactors only) @ ~6 yrs * 26.6 GW_{th} exposure

Collaboration paper is under preparation!

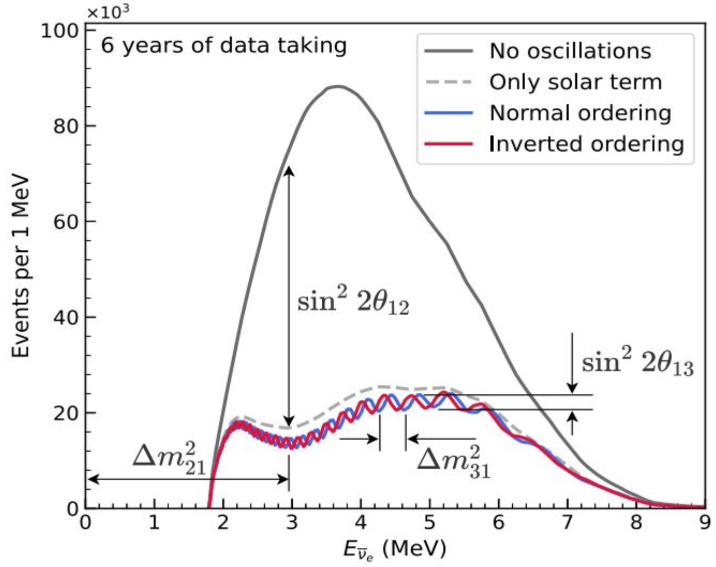
Complementary to other experiments based on matter effects

Precision Measurement of Neutrino Oscillation Parameters

- **JUNO will measure $\sin^2\theta_{12}$, Δm^2_{13}, Δm^2_{12} with <1% precision level**



	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%



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-> In contrast to the previous JUNO NMO sensitivity estimation, F. An et al. (JUNO), J. Phys. G 43, 030401 (2016),

-> The new NMO sensitivity results consider the following changes:

- the final location and overburden of the experimental site
  - JUNO experimental hall 60 m shallower -> 30% higher flux of cosmic muons
- 8 reactor cores, instead of 10 cores
- updated background estimation *(Chin. Phys. C 46 (2022)no.12, 123001)*
- electron anti-neutrino spectral shape uncertainty -> TAO (arXiv:2005.08745 (2020))
- more realistic detector response model: calibration plan *(JHEP03(2021)004)*
- updated estimation of energy resolution from 3 -> 2.9 @ 1MeV, *(Eur.Phys.J.C 82 (2022) 12, 1168)*

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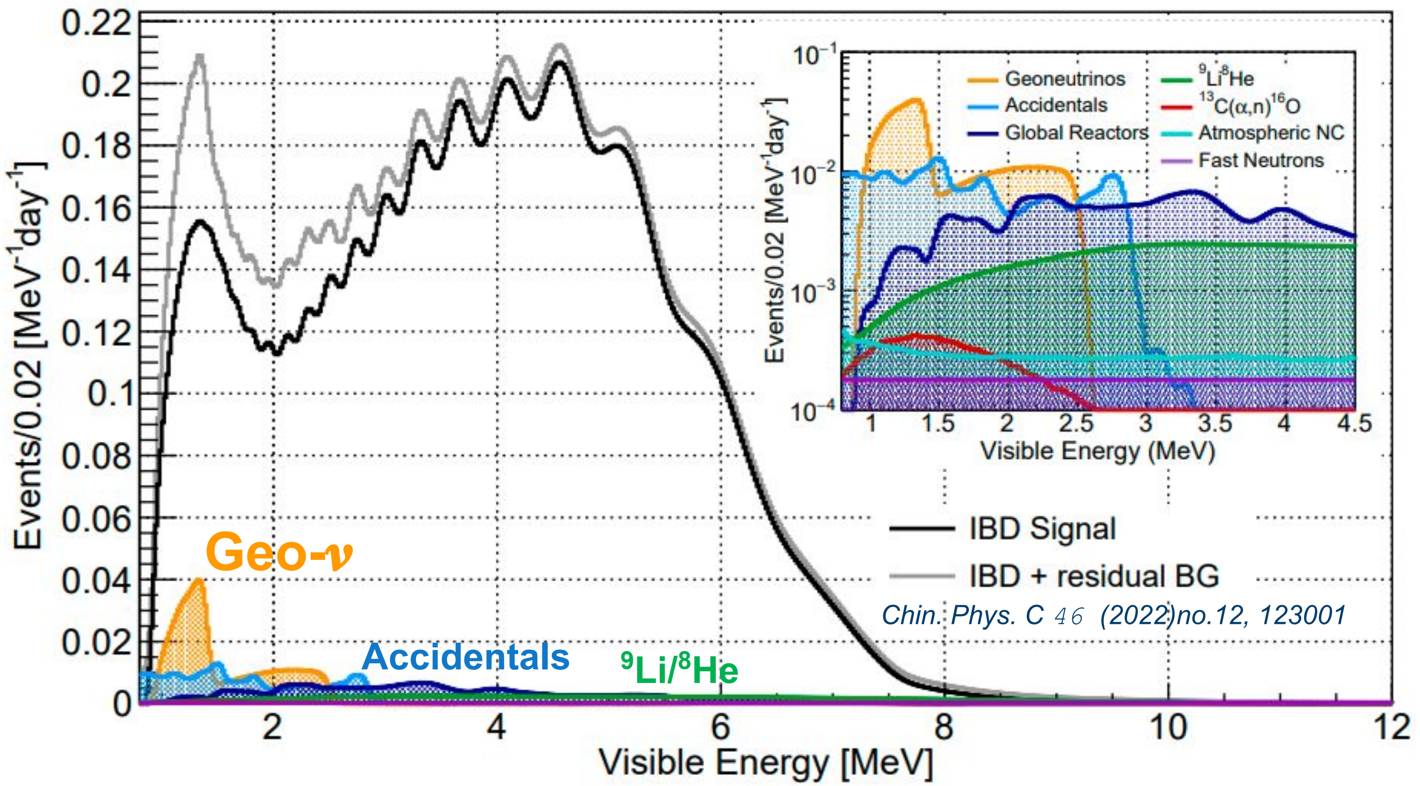
JUNO Inverse beta decay detection and backgrounds

$$\bar{\nu}_e + p \rightarrow e^+ + n$$ Prompt

$$n + p \xrightarrow{\tau \sim 200\,\mu s} D + \gamma\ (2.2\ \mathrm{MeV})$$ Delayed



Chin. Phys. C 46 (2022)no.12, 123001

Rates after selection cuts

Event type	Rate [/day]	Relative rate uncertainty	Shape uncertainty
Reactor IBD signal	60 → 47	-	-
Geo-ν's	1.1 → 1.2	30%	5%
Accidental signals	0.9 → 0.8	1%	negligible
Fast-n	0.1	100%	20%
^{9}Li/ ^{8}He	1.6 → 0.8	20%	10%
$^{13}C(\alpha,n)^{16}O$	0.05	50%	50%
Global reactors	0 → 1.0	2%	5%
Atmospheric ν's	0 → 0.16	50%	50%

J. Phys. G 43:030401 (2016) → **this update**

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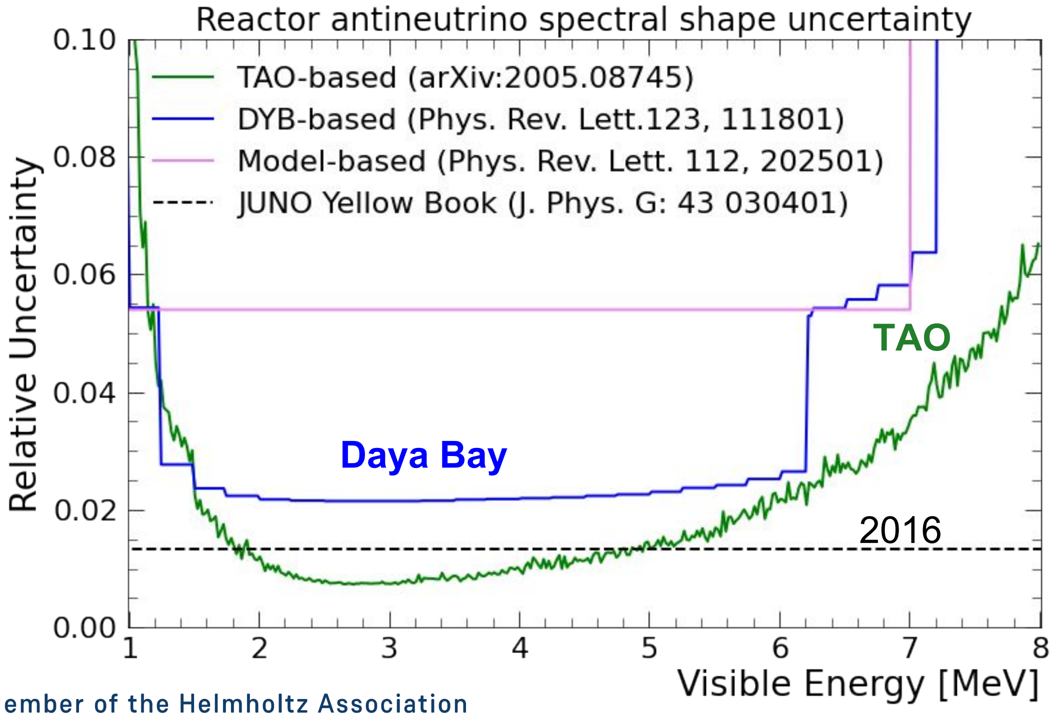
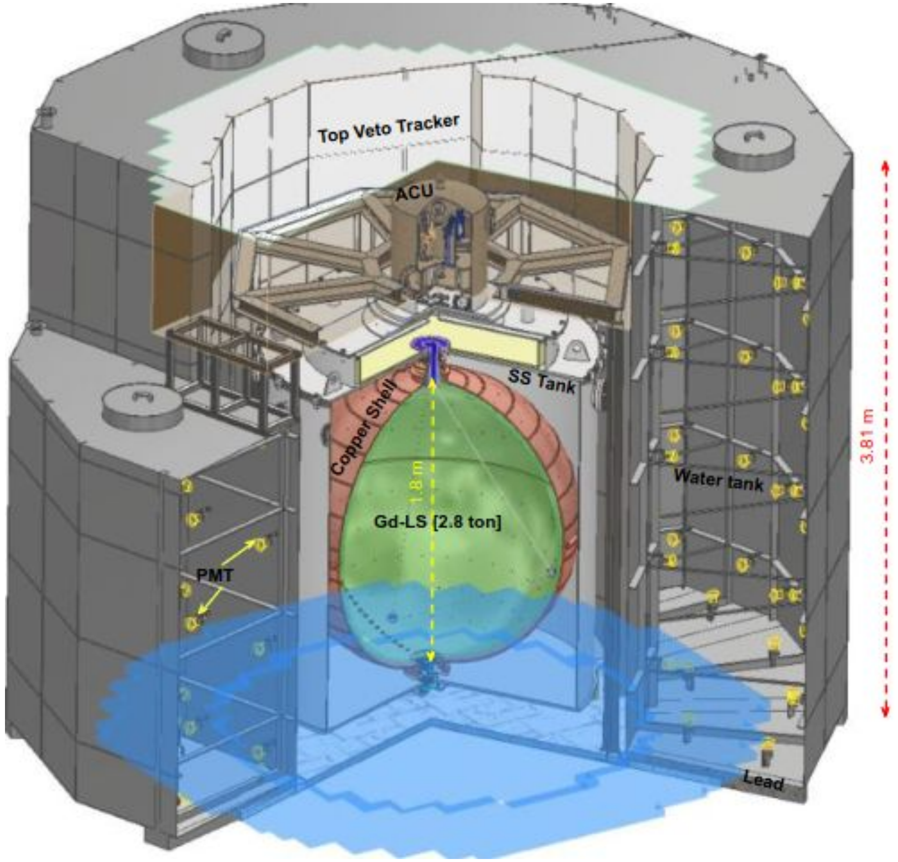
Taishan Anti-neutrino Observatory (TAO)

Physics Goals:

- provide model-independent reference spectrum for JUNO
- provide benchmark to examine nuclear databases
- reactor monitoring, sterile neutrino…



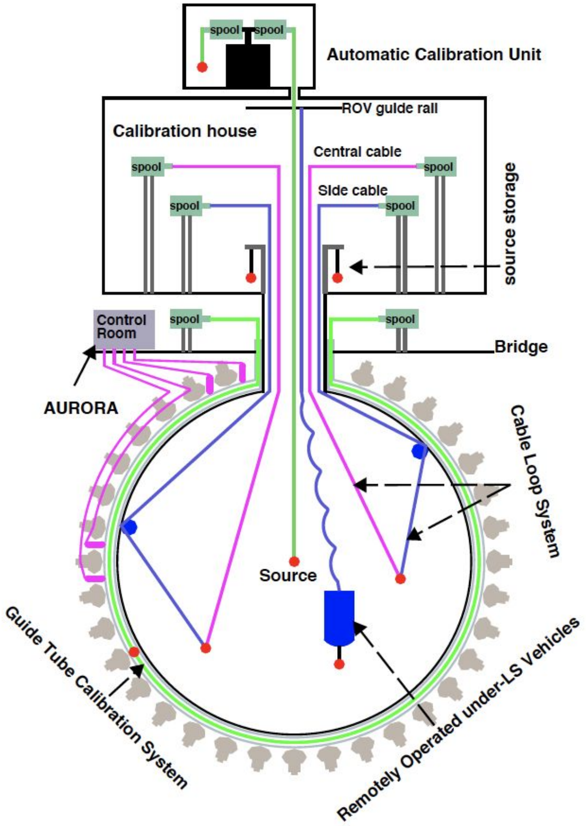


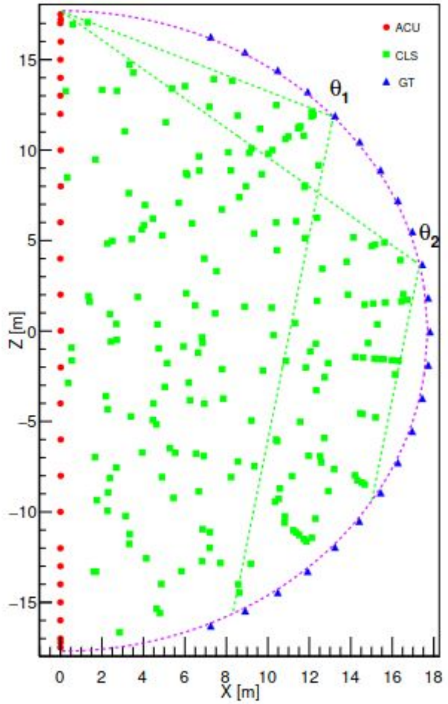
- 2.8 ton Gd-loaded liquid scintillator detector at -50°C at ~30 m baseline from the Taishan-1 reactor core (4.6 GW th)
- reactor anti-neutrino signal ~2000/day
- < 2% energy resolution @ 1 MeV

Calibration system

How to reach <1% uncertainty on the energy scale ?
Meticulous Calibration!

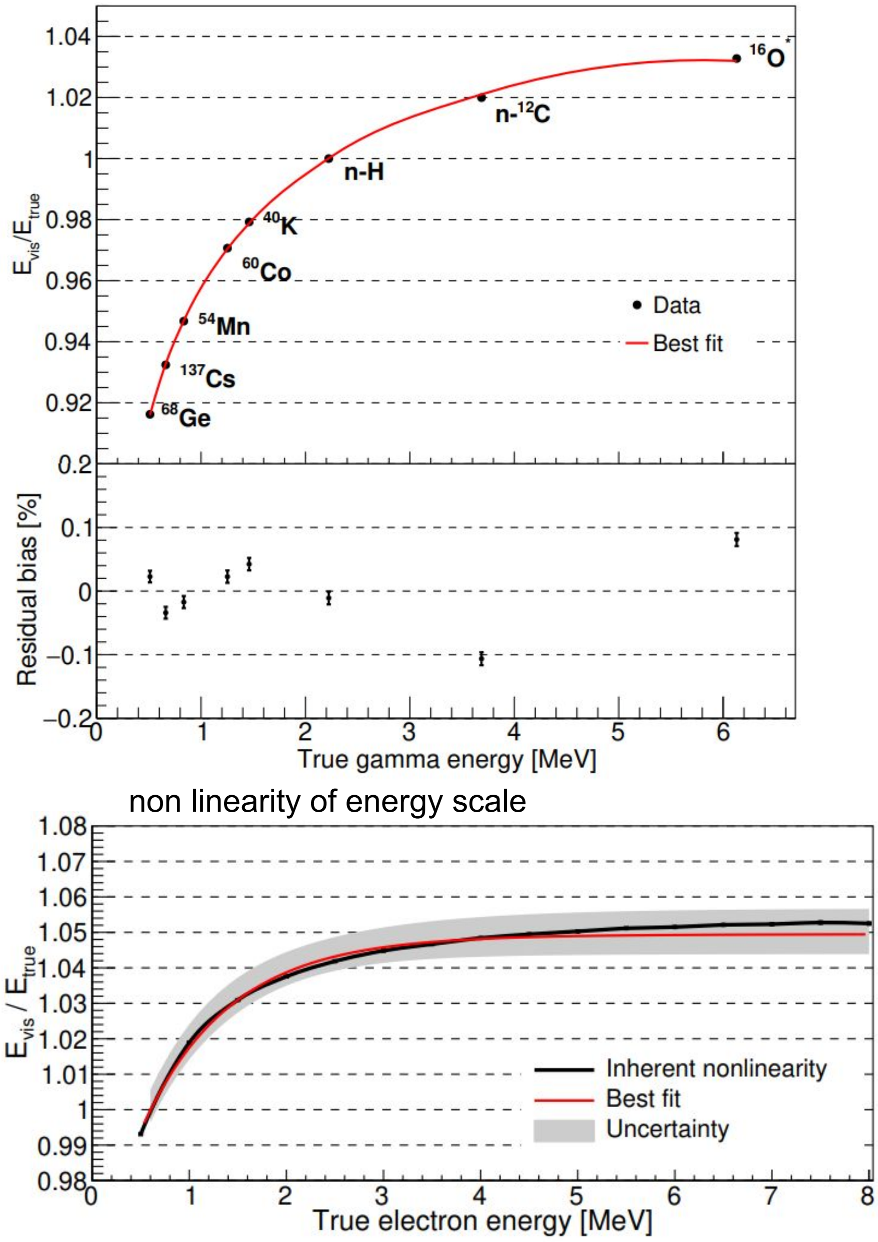
- **1D, 2D, 3D scan systems with many sources over the whole energy range, controlled by γ/α/β, UV-laser, and light pulses sources**
- **many positions to keep residual non-uniformity low**





250 calibration points in a half vertical plane of the JUNO CD

JHEP03(2021)004



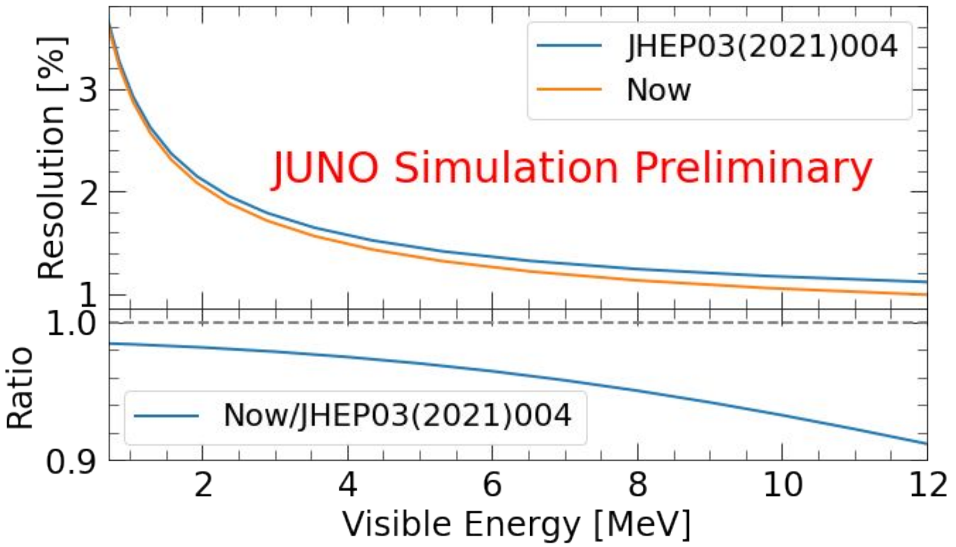
Updates on the energy resolution

High light yield (LY ~ 10^4 photons/MeV)

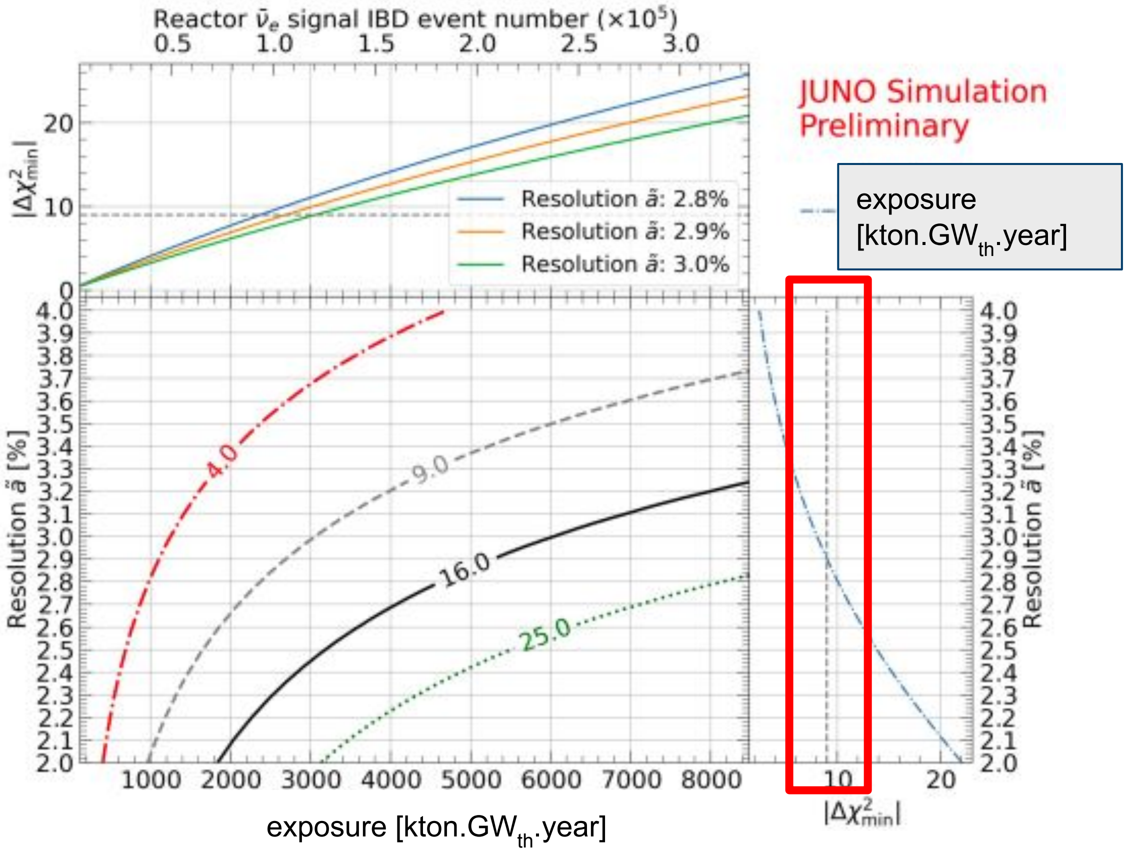
- good transparency: λ_{att} > 20 m @ 430 nm
- very high PMT coverage 78%

New reference

- photo detection efficiency (PDE) 29.1% -> 30.1% (Mass PMT testing data) *Eur.Phys.J.C 82 (2022) 12, 1168*
- more realistic PMT optical model. *10.5281/zenodo.6785356*
- new detector geometry. *10.5281/zenodo.6805544*



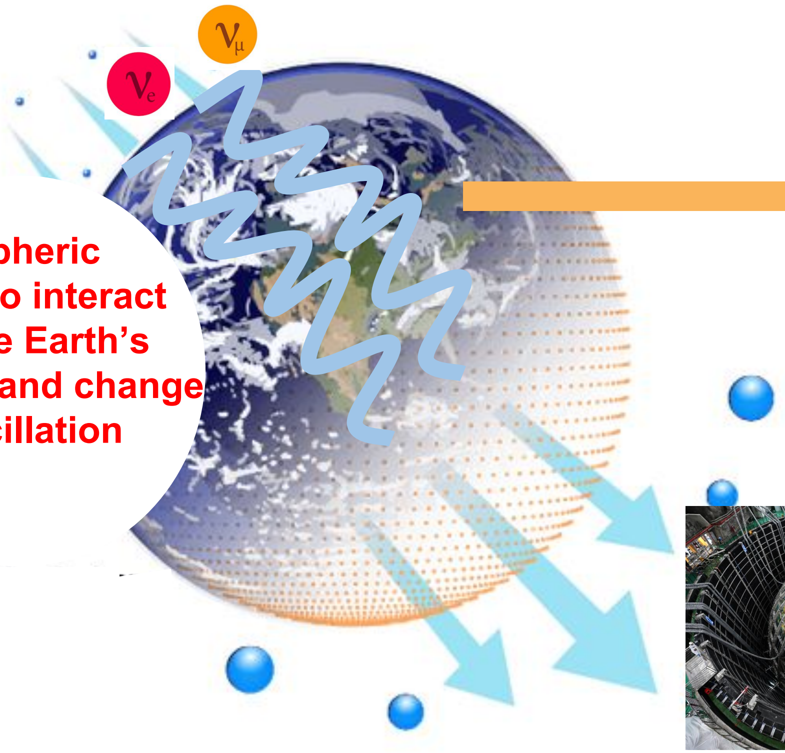
NMO dependence on resolution and exposure



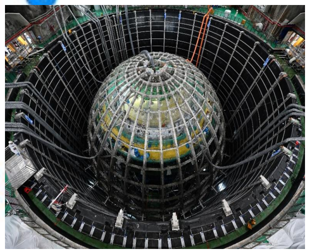
Excellent **energy resolution 2.9% @ 1 MeV**

Atmospheric neutrinos: accessible from the first year of data taking

~15 events/day

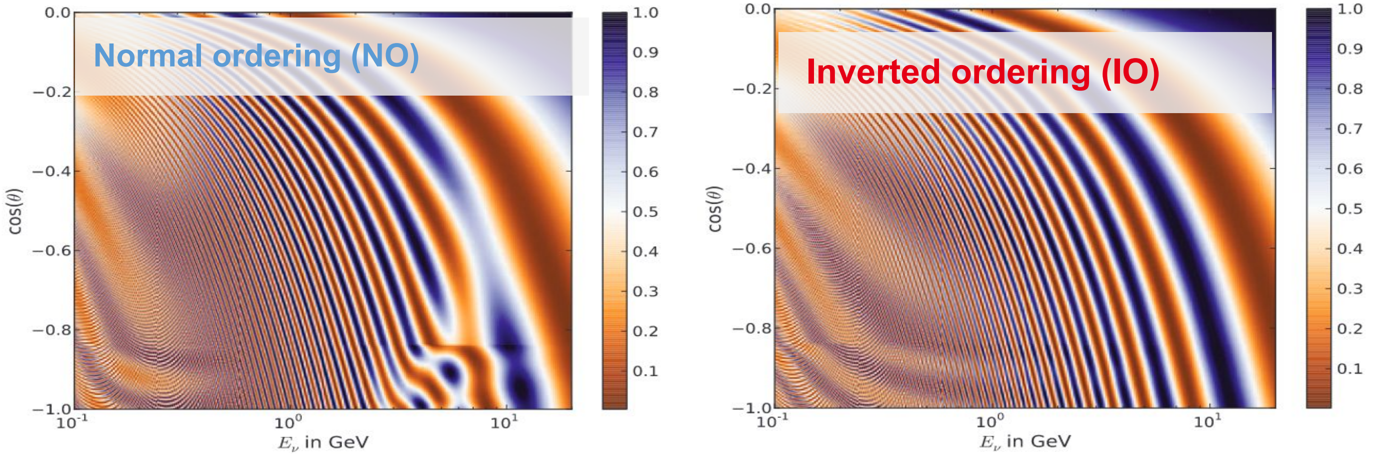


Atmospheric neutrino interact with the Earth's matter and change the oscillation pattern



https://www-sk.icrr.u-tokyo.ac.jp/en/sk/neutrino/about/

$P_{\nu\mu \to \nu\mu}$



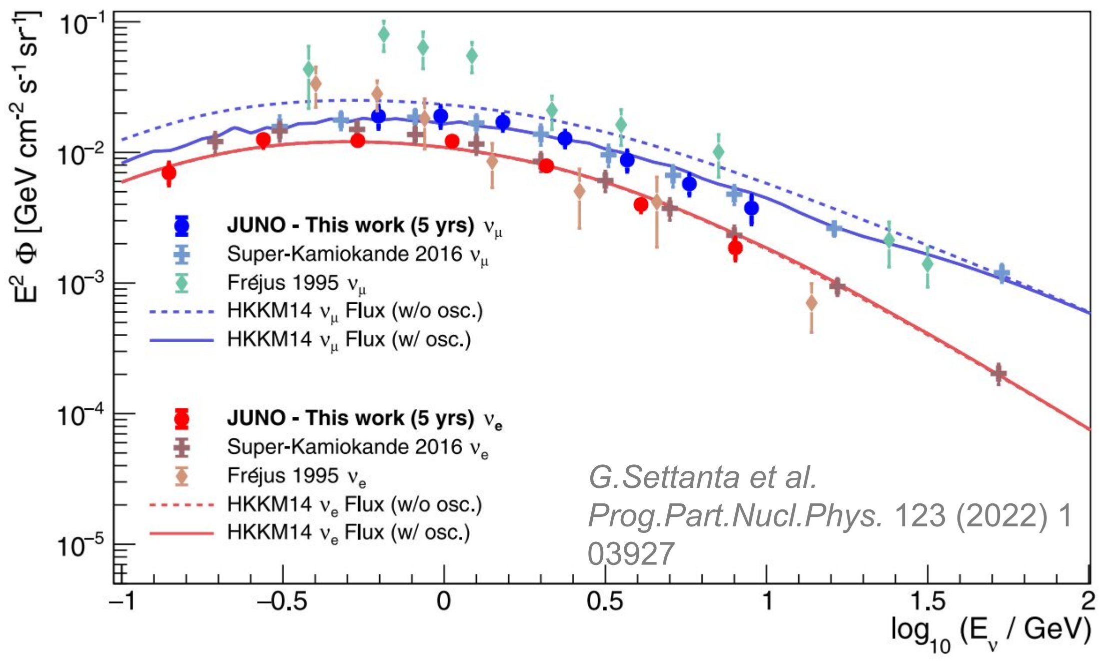
$$P_{NO}(\nu_\alpha \to \nu_\beta) \approx P_{IO}(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

- **Determine NMO by probing Earth matter effects on the oscillation of atmospheric neutrinos in the GeV energy range.**

Measurement of energy spectra and flavor identification

Eur. Phys. J. C 81 (2021) 887

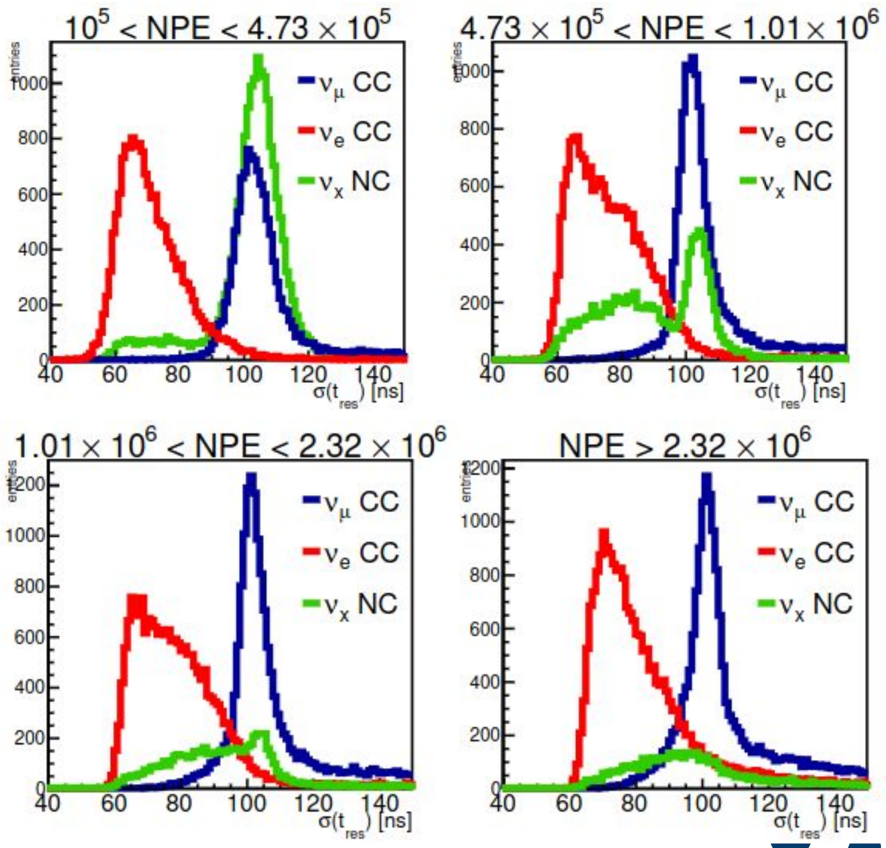
Energy spectra



G.Settanta et al. *Prog.Part.Nucl.Phys.* 123 (2022) 103927

Applied an unfolding method to extract the energy spectrum: 25% precision after 5 years

Flavor identification, $\nu e/\nu\mu$, based on the charge detected by the PMTs (NPE) and the residual time



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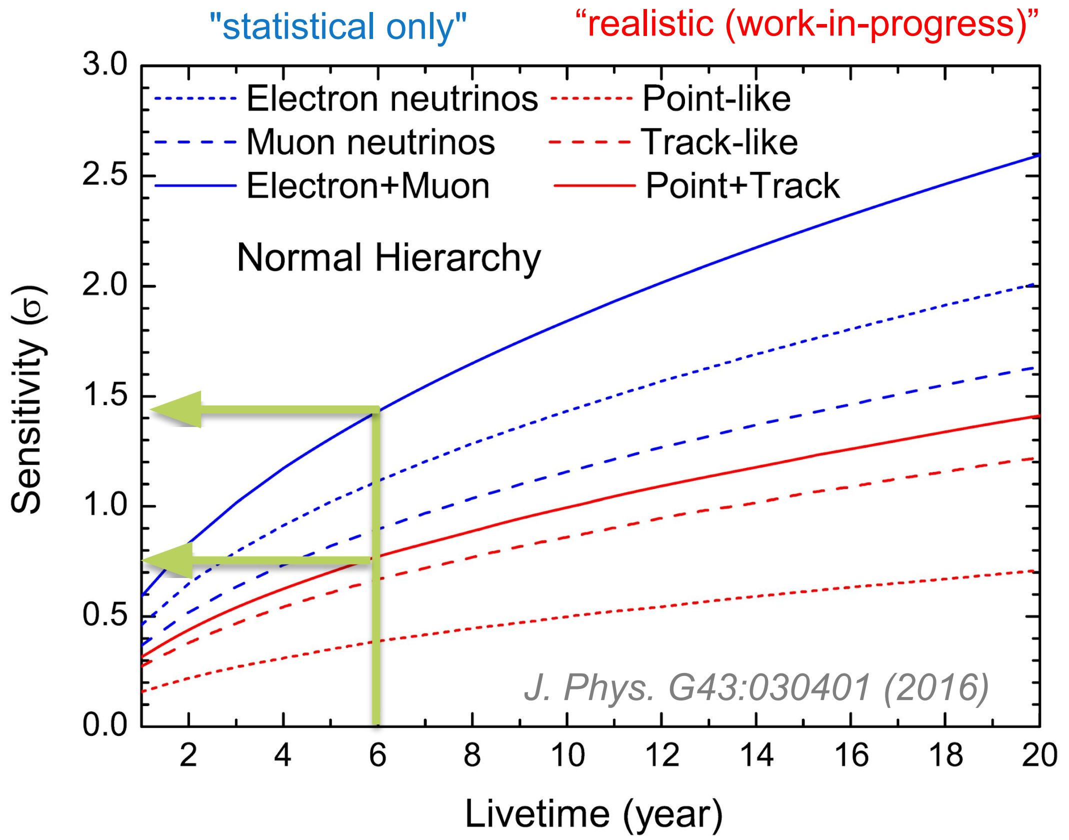
Atmospheric neutrino sensitivity to NMO



JUNO sensitivity on NMO:

0.7~1.4 σ (atmospheric only) @ ~6 yrs exposure

statistcal only (blue) and realistic (work in progress) (red) scenarios for NMO sensitivities as a function of lifetime for the true NH

[1] DOI: 10.5281/zenodo.6769313. [2] DOI: 10.5281/zenodo.6782362. [3] DOI: 10.5281/zenodo.6785153. [4] DOI: 10.5281/zenodo.6804861

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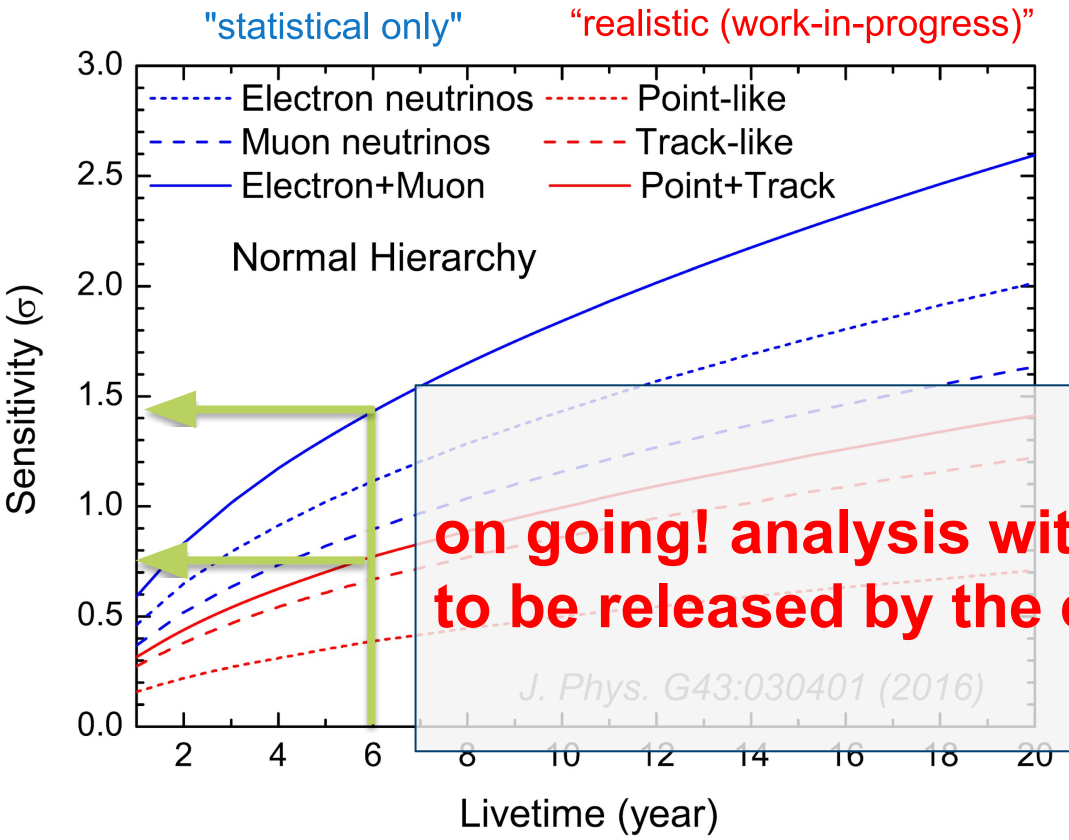
Atmospheric neutrino sensitivity to NMO



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on going! analysis with the new detector updates to be released by the end 2023!

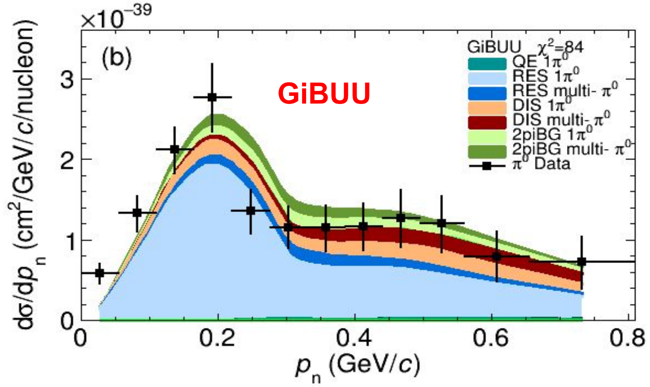
[1] DOI: 10.5281/zenodo.6769313. [2] DOI: 10.5281/zenodo.6782362. [3] DOI: 10.5281/zenodo.6785153. [4] DOI: 10.5281/zenodo.6804861

All analysis ingredients in progress

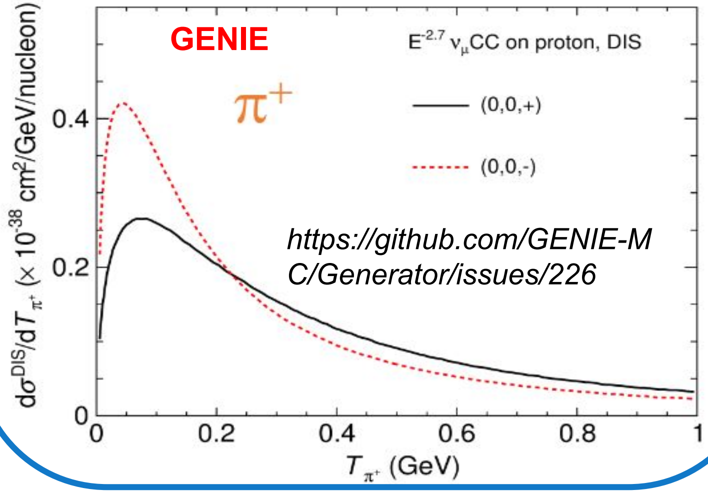
Neutrino model interaction

3 Generators is being implemented in JUNO: GENIE, NuWro and GiBUU

Validation physics w.r.t to transverse Kinematic imbalance

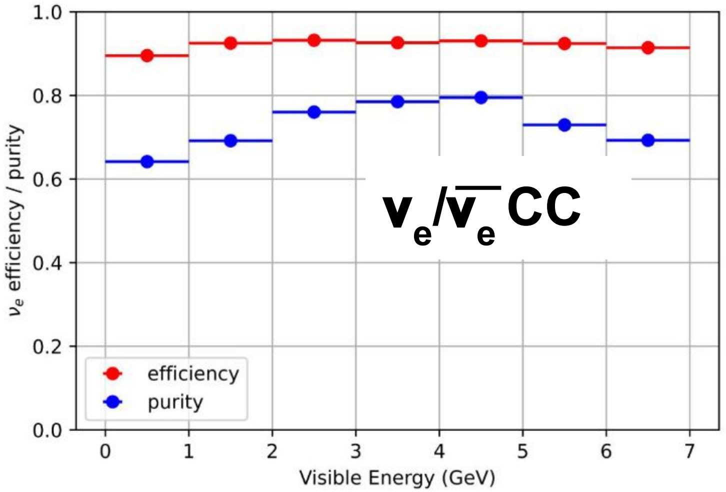


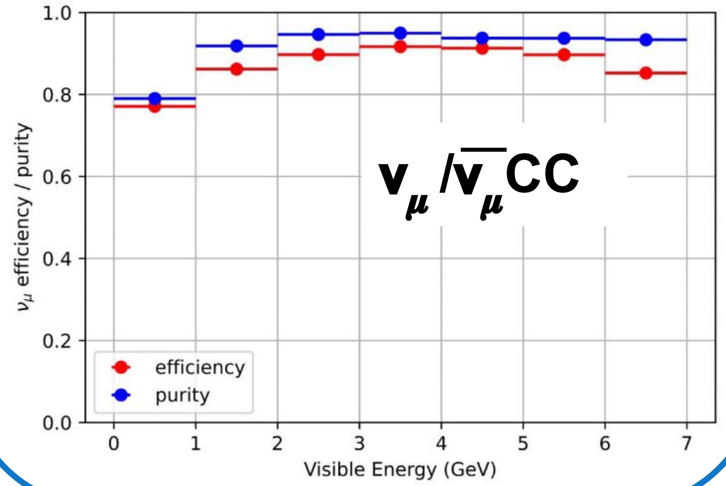
Improving generator: Fixing GENIE AGKYLowW (DIS) and aka directionality bug



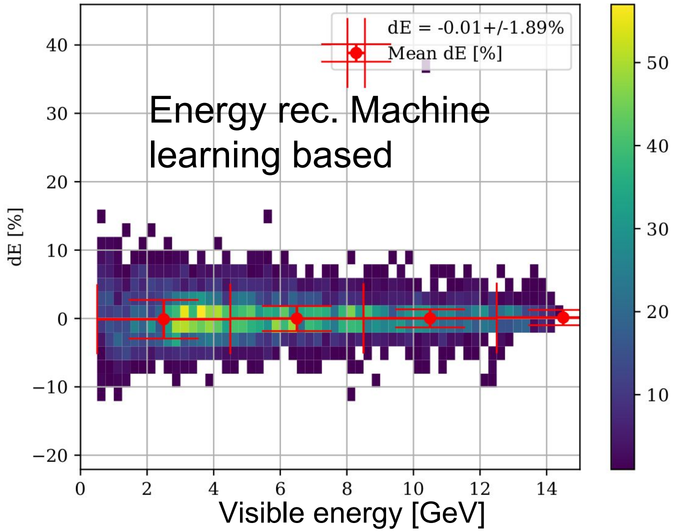
anti-/particles identification

Method based on DeepSphere Machine learning

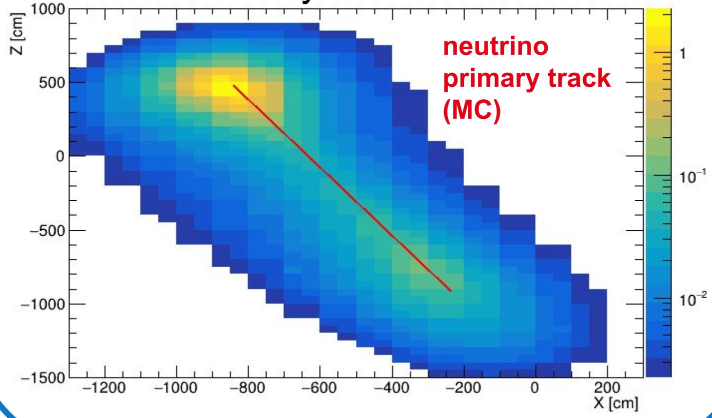




Energy and direction reconstructions

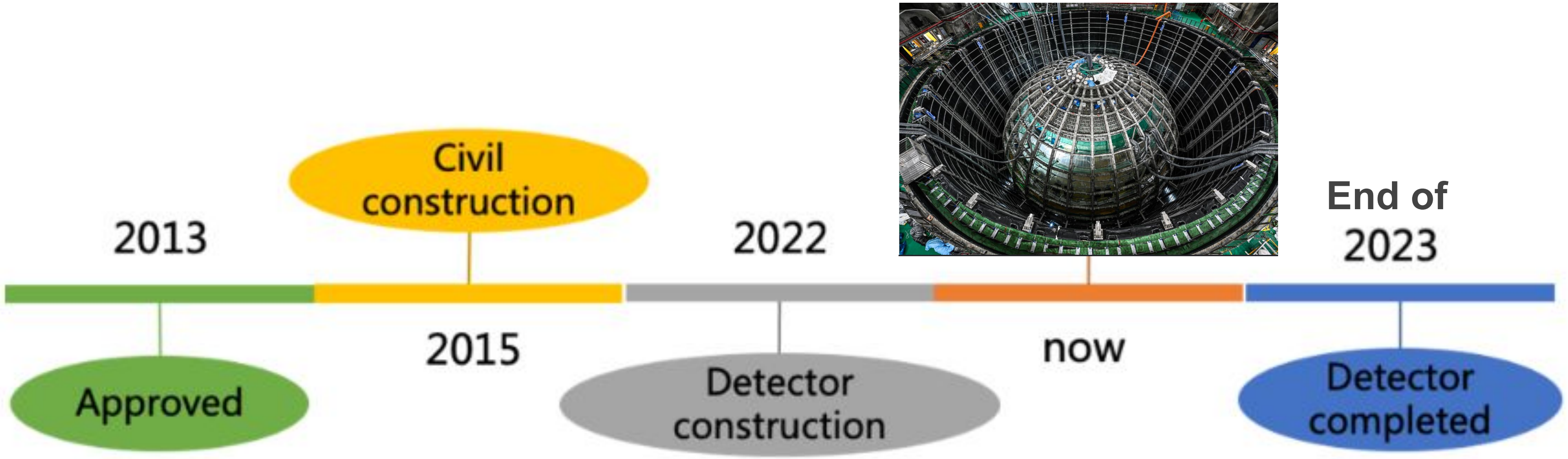


Directionality rec. conventional



[1] DOI: 10.5281/zenodo.6769313. [2] DOI: 10.5281/zenodo.6782362. [3] DOI: 10.5281/zenodo.6785153. [4] DOI: 10.5281/zenodo.6804861 [5]DOI: 10.5281/zenodo.6774990 [6]DOI: 10.5281/zenodo.6785153

Summary and outlook



- neutrino mass ordering: 3σ in about 6 years with reactor antineutrinos
- joint analysis with atmospheric neutrinos will enhance the sensitivity (release expected this year)
- $\sin^2\theta_{12}$, Δm^2_{13}, Δm^2_{12} sub-percent level in 6 years
- several others goal in neutrinos and astroparticle physics

Thank you!

Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	SYSU	Germany	U. Mainz
Belgium	Universite libre de Bruxelles	China	Tsinghua U.	Germany	U. Tuebingen
Brazil	PUC	China	UCAS	Italy	INFN Catania
Brazil	UEL	China	USTC	Italy	INFN di Frascati
Chile	PCUC	China	U. of South China	Italy	INFN-Ferrara
Chile	SAPHIR	China	Wu Yi U.	Italy	INFN-Milano
Chile	UNAB	China	Wuhan U.	Italy	INFN-Milano Bicocca
China	BISEE	China	Xi'an JT U.	Italy	INFN-Padova
China	Beijing Normal U.	China	Xiamen University	Italy	INFN-Perugia
China	CAGS	China	Zhengzhou U.	Italy	INFN-Roma 3
China	ChongQing University	China	NUDT	Latvia	IECS
China	CIAE	China	CUG-Beijing	Pakistan	PINSTECH (PAEC)
China	DGUT	China	ECUT-Nanchang City	Russia	INR Moscow
China	Guangxi U.	China	CDUT-Chengdu	Russia	JINR
China	Harbin Institute of Technology	Czech	Charles U.	Russia	MSU
China	IHEP	Finland	University of Jyvaskyla	Slovakia	FMPICU
China	Jilin U.	France	IJCLab Orsay	Taiwan-China	National Chiao-Tung U.
China	Jinan U.	France	LP2i 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	RWTH Aachen U.	Thailand	SUT
China	Shandong U.	Germany	TUM	U.K.	U. Warwick
China	Shanghai JT U.	Germany	U. Hamburg	USA	UMD-G
China	IGG-Beijing	Germany	FZJ-IKP	USA	UC Irvine

75 institutes, over 650 collaborators

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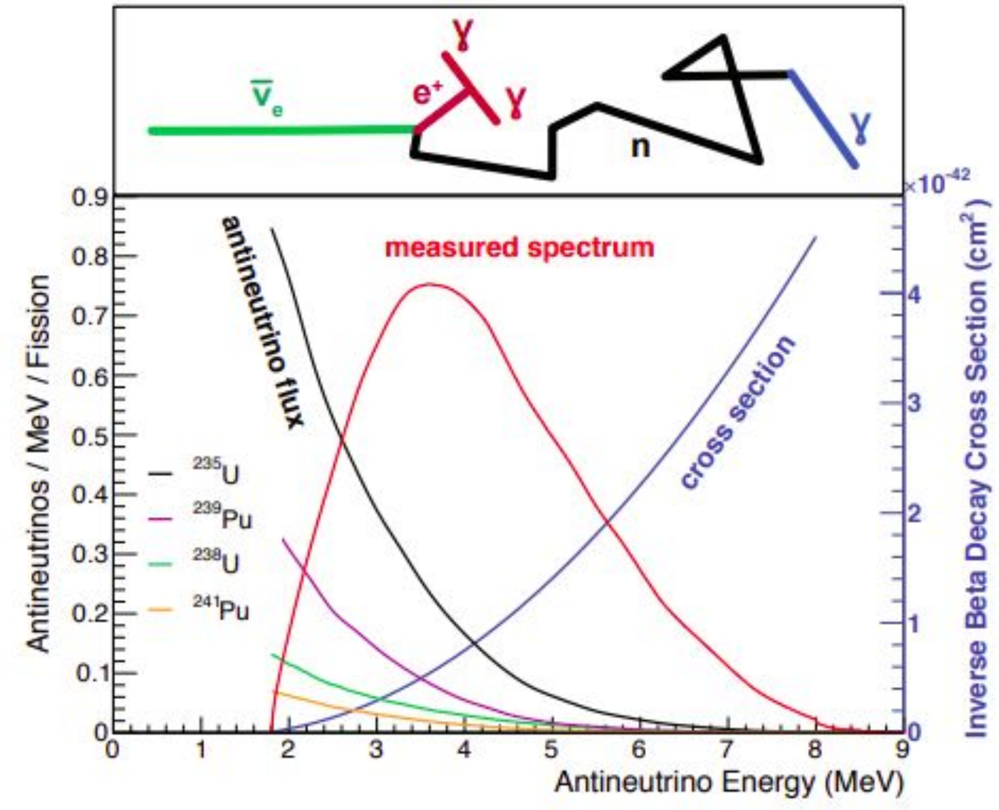
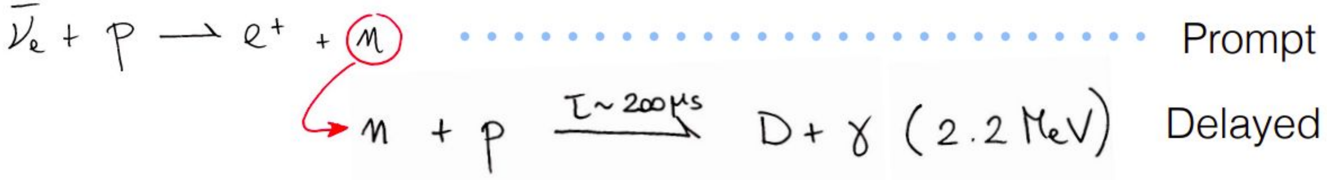
Backup

Electron antineutrino detection :



$E_{vis} = E_{\bar{\nu}_e}$ - 0.78 MeV

Non oscillated spectrum:
Reactor $\bar{\nu}_e$ flux + IBD cross section

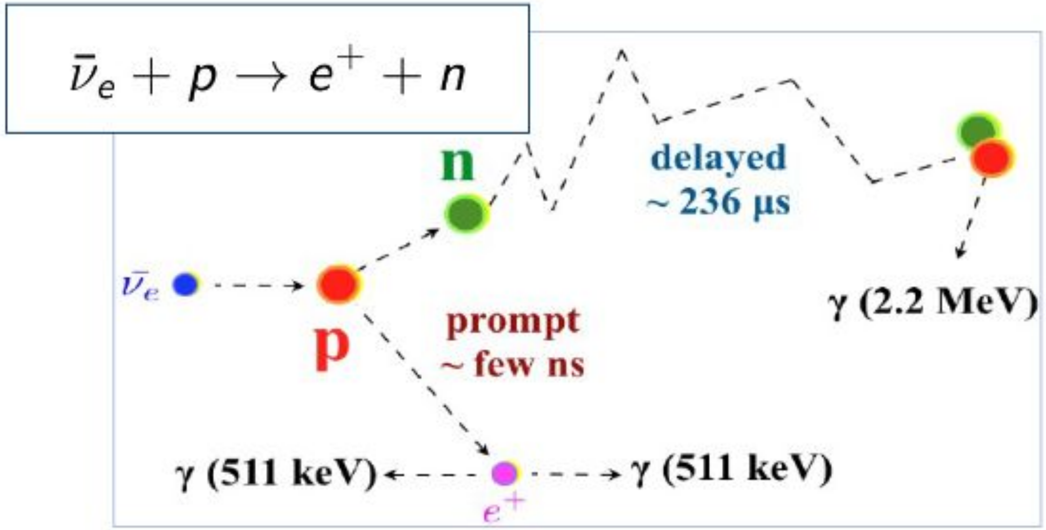


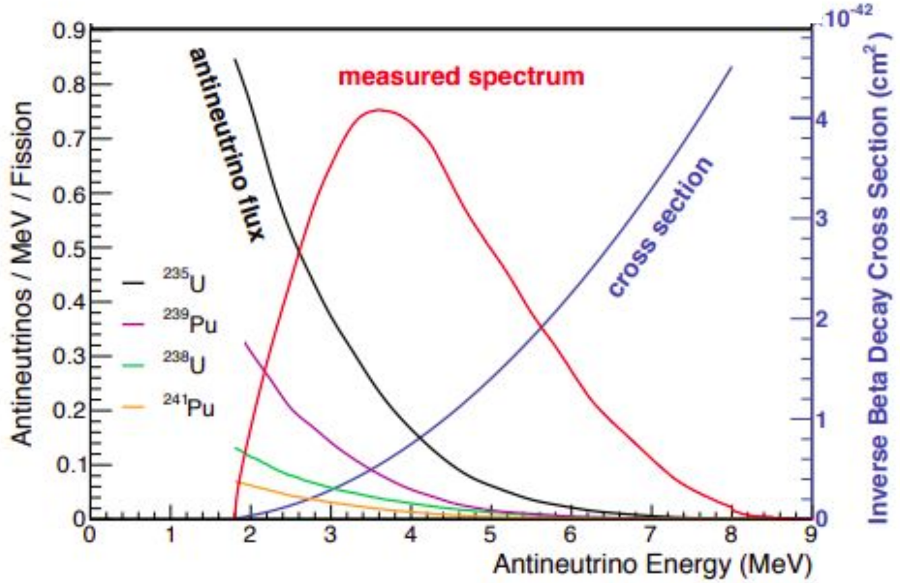
- Golden channel for neutrino detection:
  - High cross section (about ×10 wrt. ve -elastic scattering @3 MeV)
- Two-signal coincidence:
  - Prompt signal: annihilation of positron.
  - Delayed signal: neutron capture after ~200 μs.
- Neutrino energy can be reconstructed from positron energy
  - Threshold of 1.8 MeV

Detection via the Inverse Beta Decay (IBD)

- Golden channel for neutrino detection:
  - High cross section (about ×10 wrt. ve -elastic scattering @3 MeV)
- Two-signal coincidence:
  - Prompt signal: annihilation of positron.
  - Delayed signal: neutron capture after ~200 µs.
- Neutrino energy can be reconstructed from positron energy
  - Threshold of 1.8 MeV

$$E_{\bar{\nu}_e} = E_{e^+} + (m_n - m_p)$$



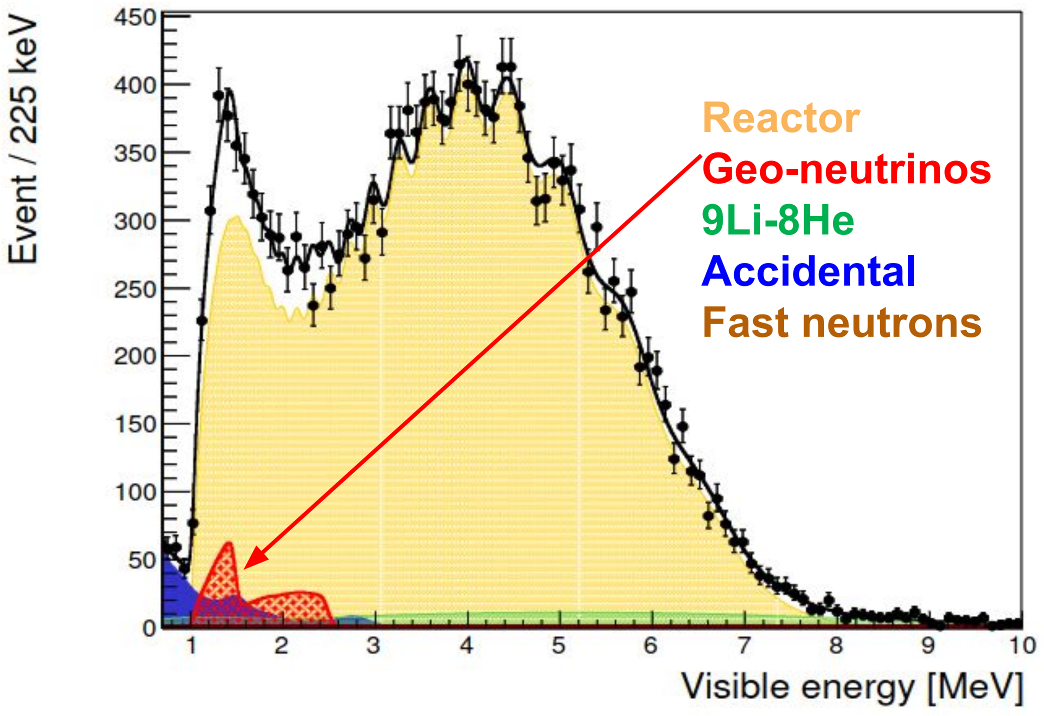


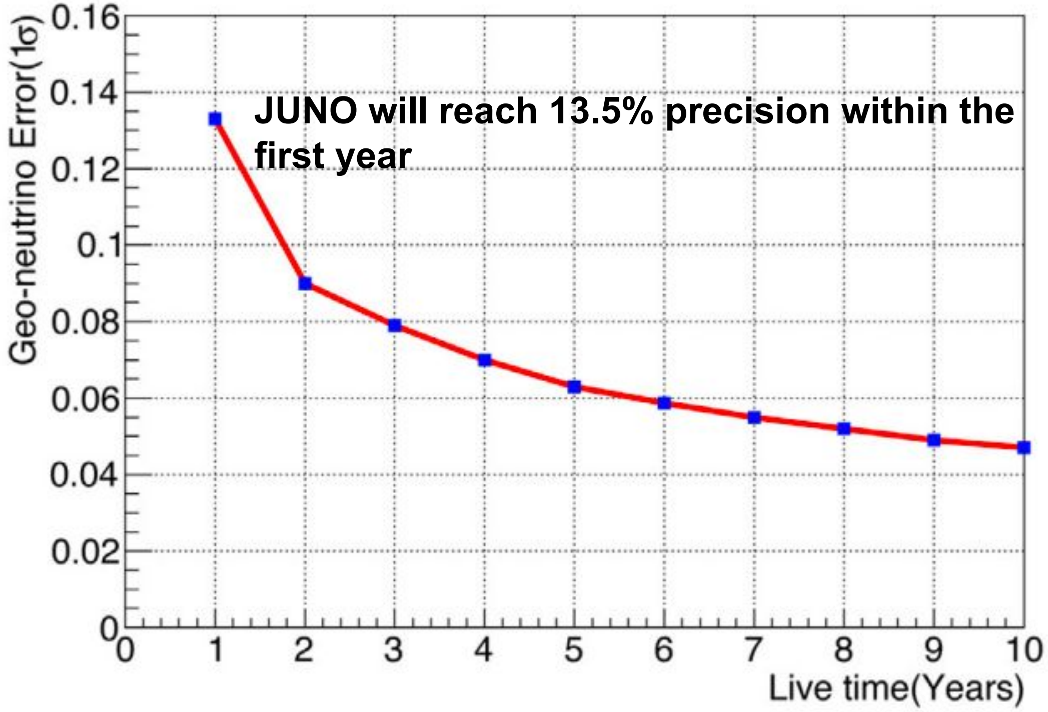
Geoneutrinos

Main goal: understanding the radiogenic heat distribution in the Earth

- Detected channel: inverse beta decay
- Geo-neutrinos from 238U and 232Th decay chains in earth: 400/year
- High Statistic of IBD
- Significant constraint from the reactor neutrinos

IBD spectrum - 1 year simulated data





JUNO will outnumber the current precision of Borexino and KamLAND

JÜLICH Forschungszentrum

“Model Independent Approach of the JUNO 8B Solar Neutrino Program,”arXiv:2210.0843

Solar Neutrinos: ^{8}B

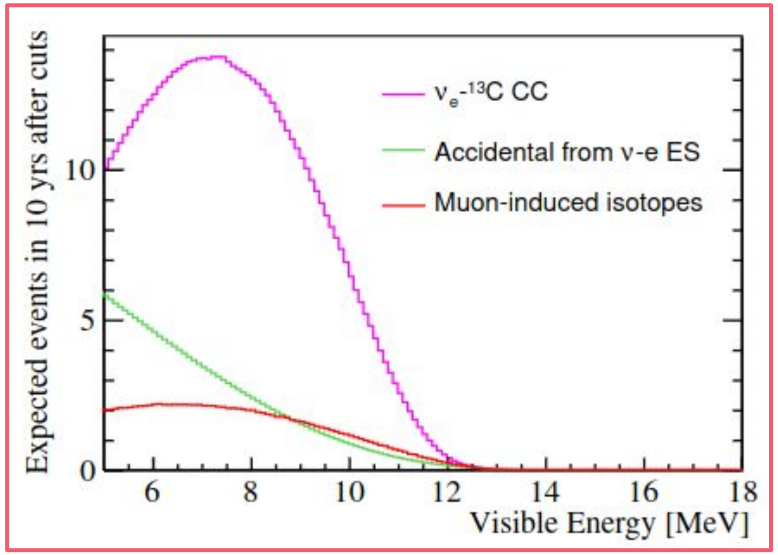
~0.2 ktons of ^{13}C in the LS -> potential model independent observation of B8 solar neutrino (CC, NC and ES)

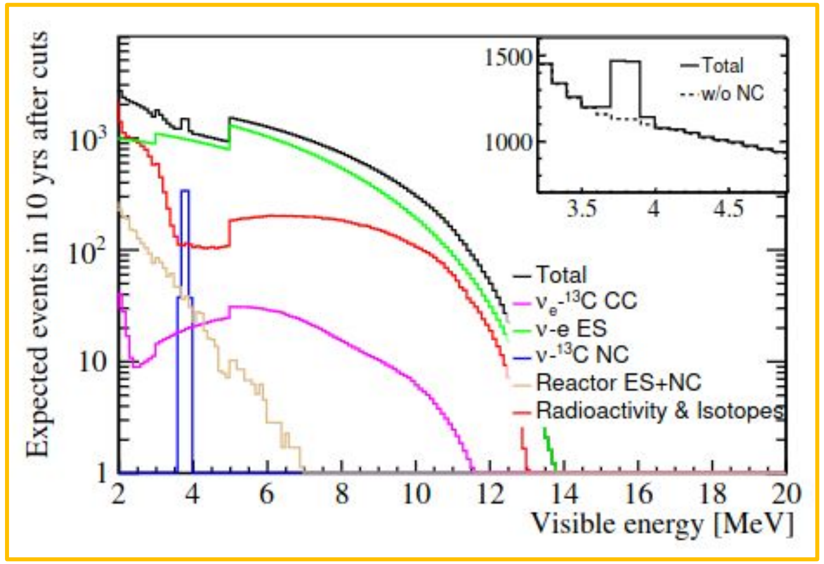
Channels		Threshold [MeV]	Signal	Event numbers [200 kt×yrs]	Event numbers after cuts
CC	$\nu_e + ^{13}\mathrm{C} \rightarrow e^- + ^{13}\mathrm{N}\,(\frac{1}{2}^-;\mathrm{gnd})$	2.2 MeV	$e^- + ^{13}$N decay	3929	647
NC	$\nu_x + ^{13}\mathrm{C} \rightarrow \nu_x + ^{13}\mathrm{C}\,(\frac{3}{2}^-;3.685\,\mathrm{MeV})$	3.685 MeV	γ	3032	738
ES	$\nu_x + e \rightarrow \nu_x + e$	0	e^-	3.0×10^5	6.0×10^4

Correlated events

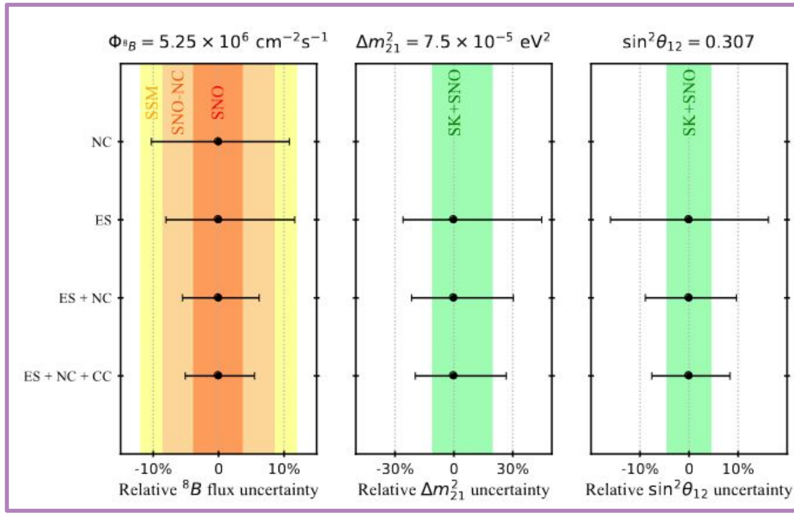
Singles event

Low threshold of 2 MeV for elastic scattering (ES)





Potential to measure 8B solar neutrinos with 5% precision in 10 years



"JUNO sensitivity to 7Be, pep, and CNO solar neutrinos," arXiv:2303.03910

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

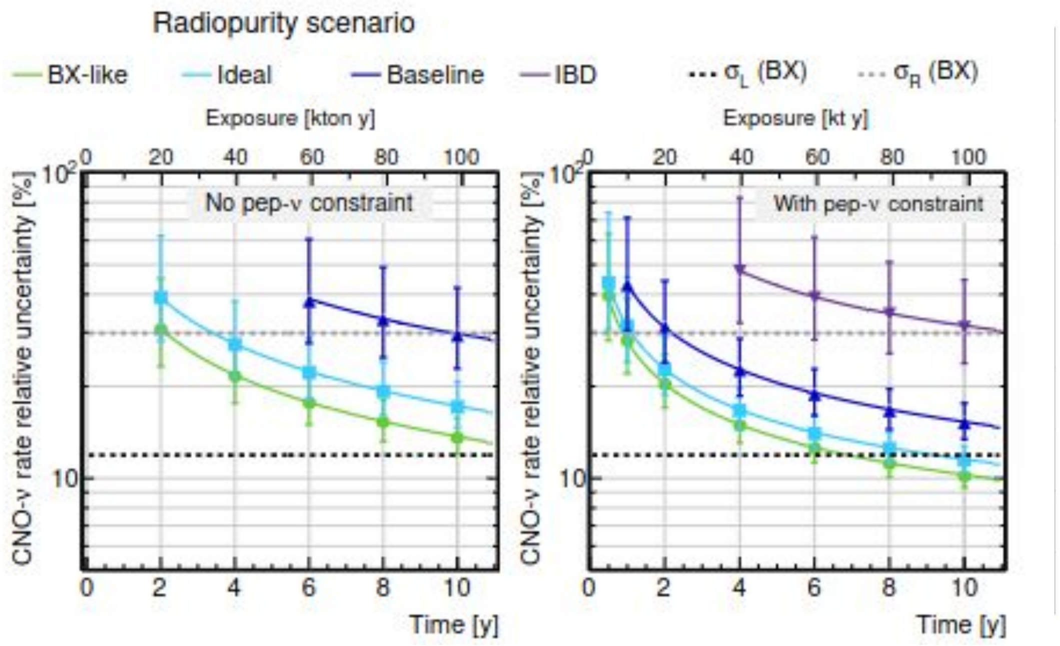
Potential to improve the precision of the existing Borexino measurements

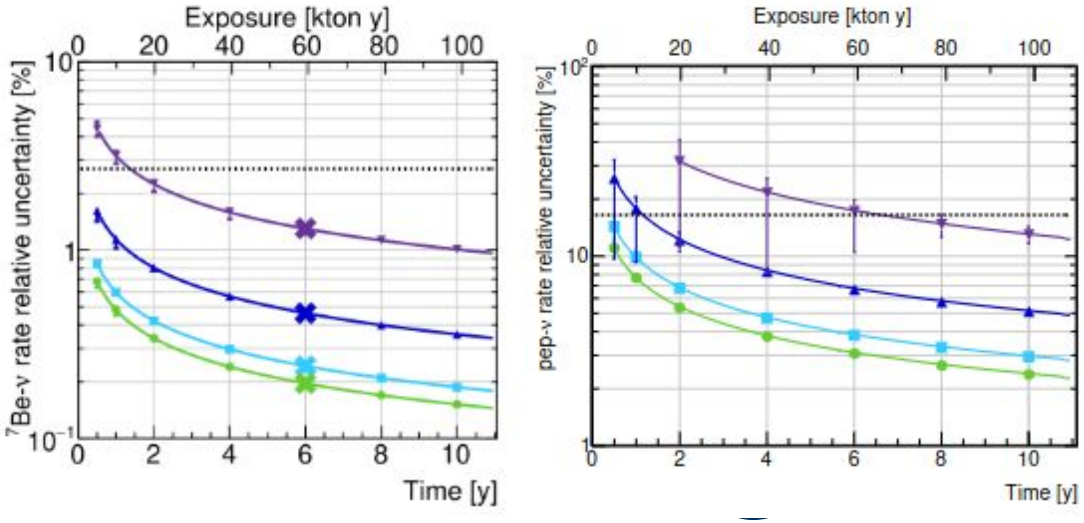
- 7Be: in 1-2 years time < 2.7% for all radiopurity scenarios
- pep: in 1-2 years time < 17%, for the most radiopurity scenario
- CNO: 20% precision might be feasible for the first time without constraint on

210Bi internal background (constraining pep solar neutrino rate is crucial)

Critical backgrounds:

- 7Be → 85Kr, 226Ra, 210Po
- pep → 11C, TFC parameters
- CNO → 210Bi, (pep), 11C, TFC parameters

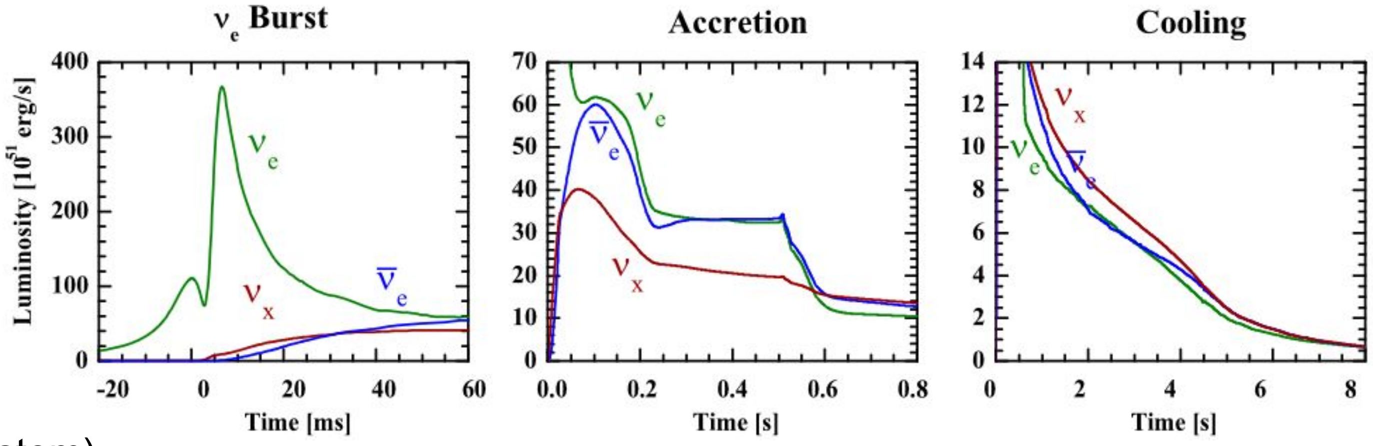




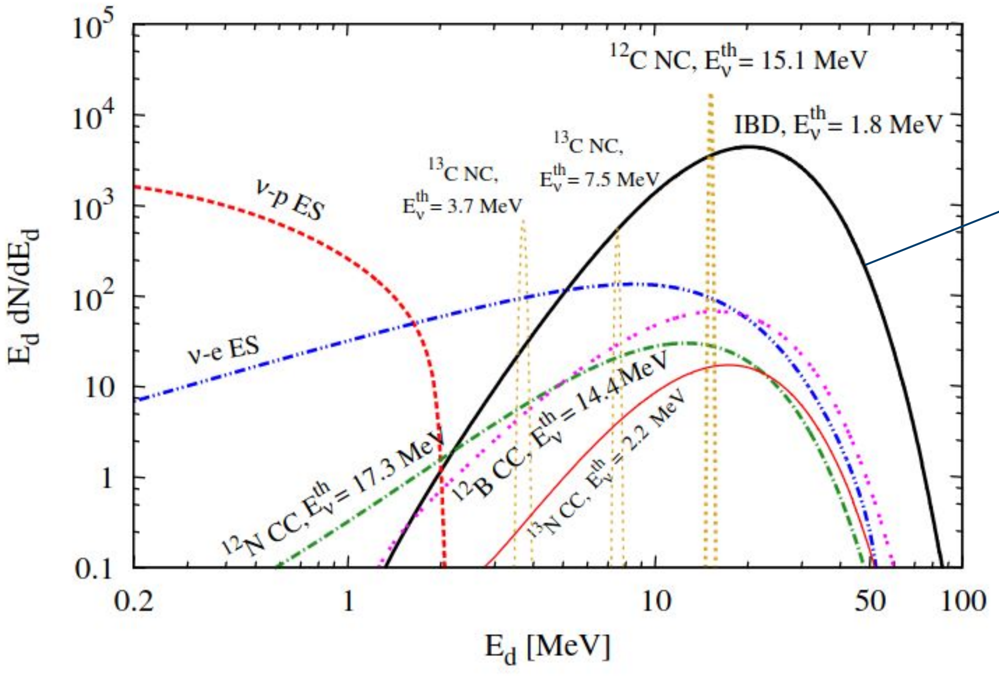
Supernova Neutrinos

99% of a supernova burst's energy is released via neutrinos

- JUNO is able to observe the 3 supernova phases
- Better understanding of supernova models
- Obtain informations about Mass Hierarchy
- Take part in multi-messenger astronomy
    - part of SNEWS (SuperNova Early Warning System)



J. Phys. G: Nucl. Part. Phys. 43（2016） 030401



Visible energy distribution in JUNO of a typical SN at 10 kpc

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\bar{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}C \to \nu + {}^{12}C^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}C \to e^- + {}^{12}N$	CC	0.5×10^2	0.9×10^2	1.6×10^2
$\bar{\nu}_e + {}^{12}C \to e^+ + {}^{12}B$	CC	0.6×10^2	1.1×10^2	1.6×10^2

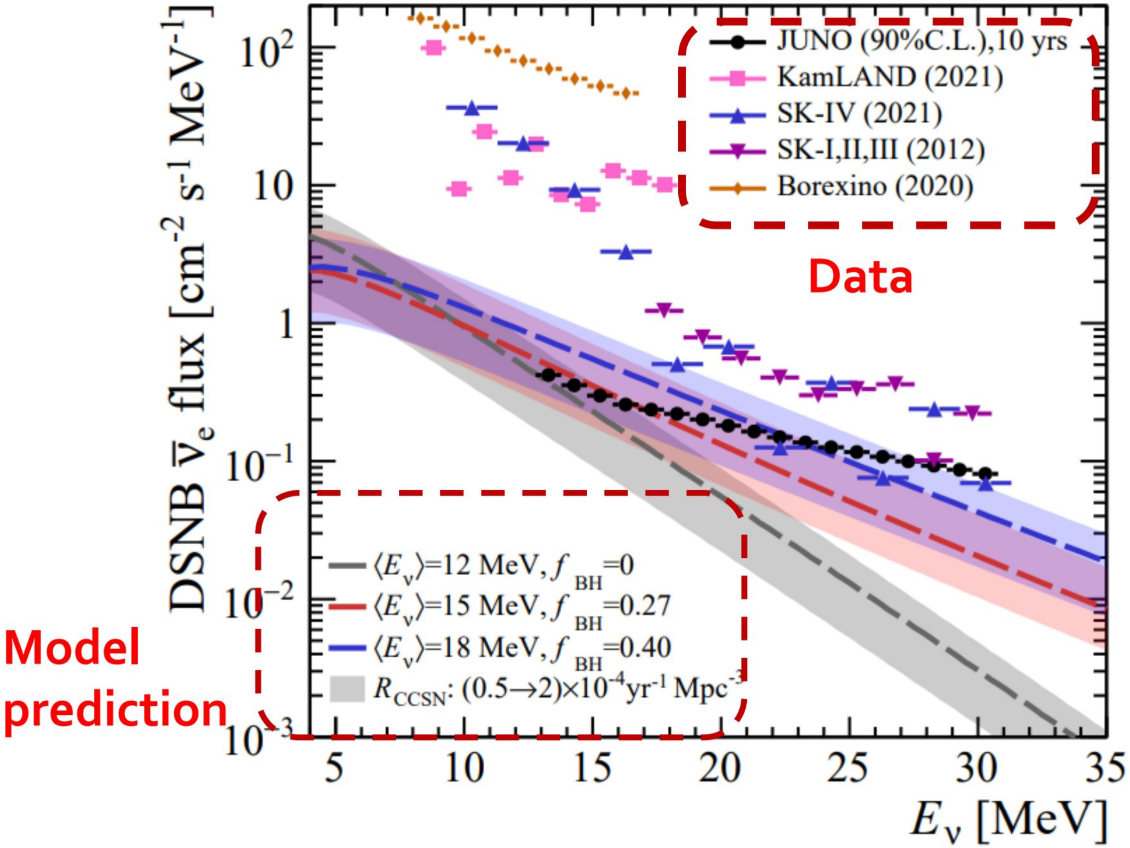
Main channel: IBD ~5000 events in 10s (for a 10 kpc SN)

Diffuse Supernova Neutrino Background

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

- DSNB: isotropic flux of neutrinos from extra-galactic supernovae
- Detection via inverse beta decay (IBD)
- It holds precise information on the
  - The average core-collapse SN neutrino spectrum
  - The cosmic star formation rate
  - The fraction of failed black hole forming SNe

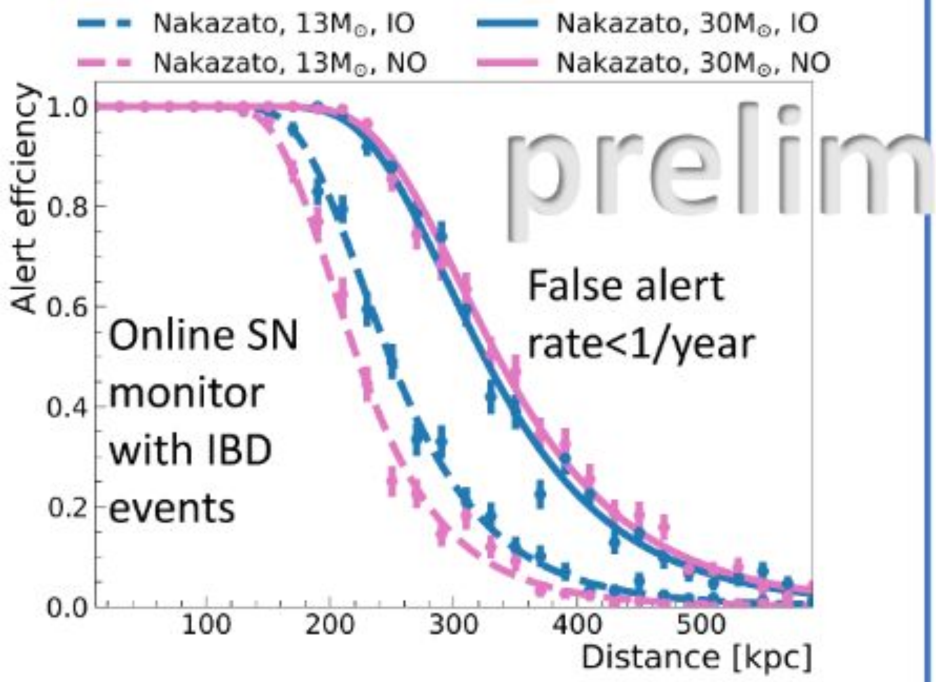
- Background:
  - NC interaction of atmo -v -> pulse shape discrimination (eff 80%)
  - Reactor neutrinos -> go above 10 MeV



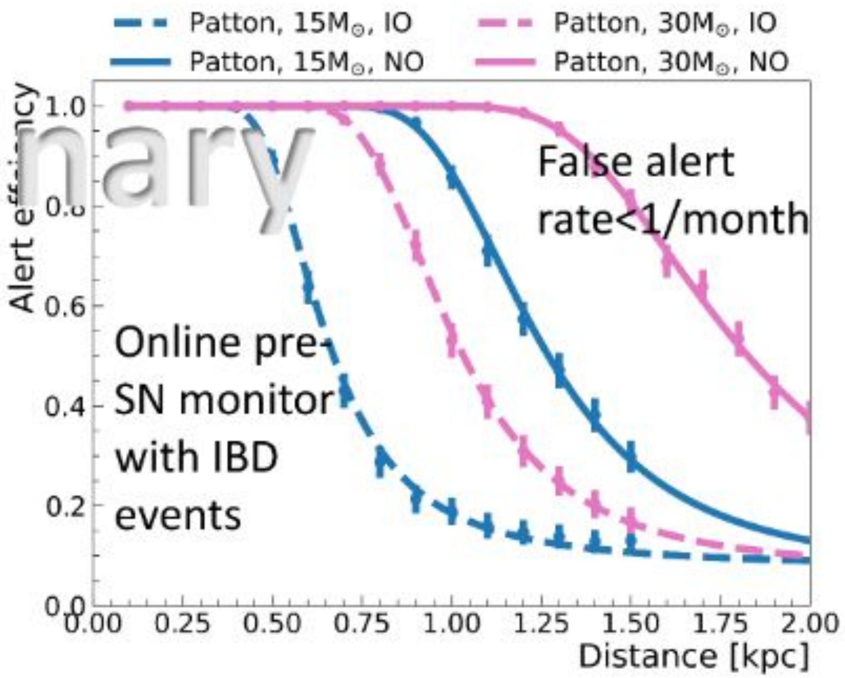
DSNB discovery potential: 3σ in 3 years with nominal models

Core Collapse Supernova Neutrinos

See poster 10.5281/zenodo.6785184 from Neutrino 2022, paper in preparation



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.

- 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

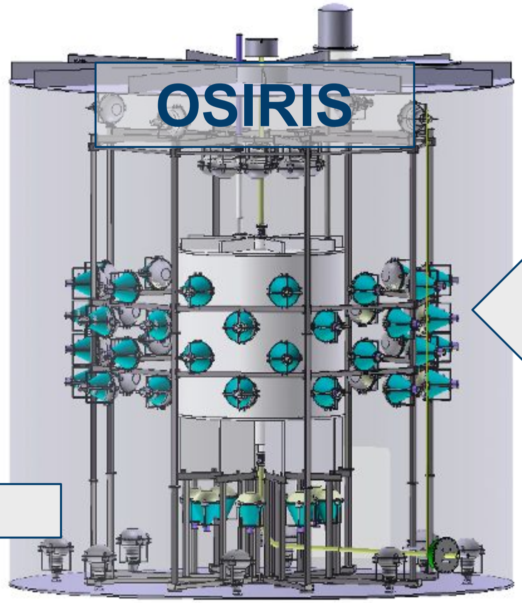
Satellite detectors of JUNO

1. **The JUNO OSIRIS detector (Online Scintillator Internal Radioactivity Investigation System)**
   IDea: Monitors scintillation radiopurity during filling

Idea: Detect radioactive contaminated scintillator

- After purification
- Before filling into acrylic vessel

- 18t LS volume (Ø=3 m, H=3 m)
- Instrumented by
  - 64 20” PMTs for the scintillator
  - 16 20” PMTs for the water cherenkov veto
- Can reach the sensitivity of 10^{-16} g/g of 238U and 232Th
- Requirements for JUNO:
- solar ν : < 10^{-16} g/g
- MH (IBD) : < 10^{-15} g/g

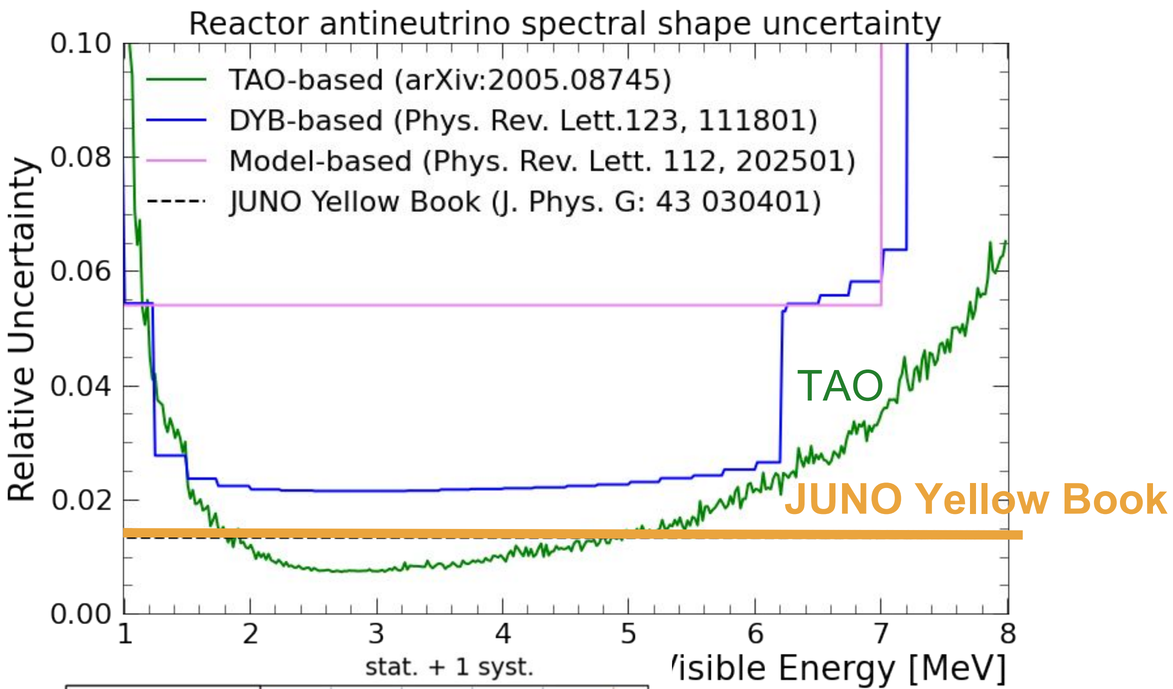


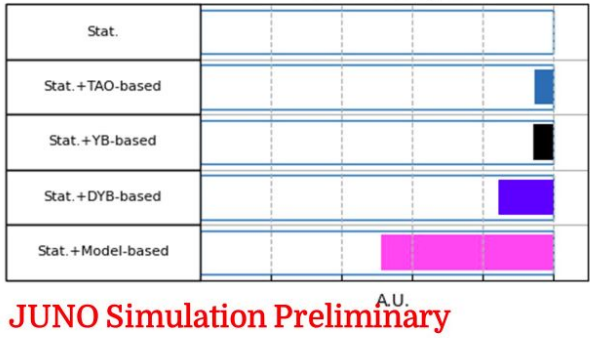
Central detector of JUNO

Purification plant being tested at Daya Bay

Satellite detectors of JUNO- Taishan Anti-neutrino Observatory (TAO)

- 2.8 ton Gd-loaded liquid scintillator detector at ~30 m
- Baseline From the Taishan (1 reactor core).
- Measure the reactor spectrum for JUNO
  - Provide model-independent reference for JUNO
  - Possible improvement of nuclear databases
  - 30 × JUNO statistics
- ~Full coverage with SiPMs with ~50% PDE (@-50°C)
  - ~4500 p.e./MeV
  - 1.5% energy resolution @1 MeV
  - <2% resolution at 1 MeV





Muon veto strategy

Selection Criterion	Efficiency (%)	IBD Rate /day^{-1}
All IBDs	100.0	57.4
Fiducial Volume	91.5	52.5
IBD Selection	98.1	51.5
Energy Range	99.8	–
Time Correlation (ΔT_{p-d})	99.0	–
Spatial Correlation (ΔR_{p-d})	99.2	–
Muon Veto (Temporal⊕Spatial)	91.6	47.1
Combined Selection	82.2	47.1