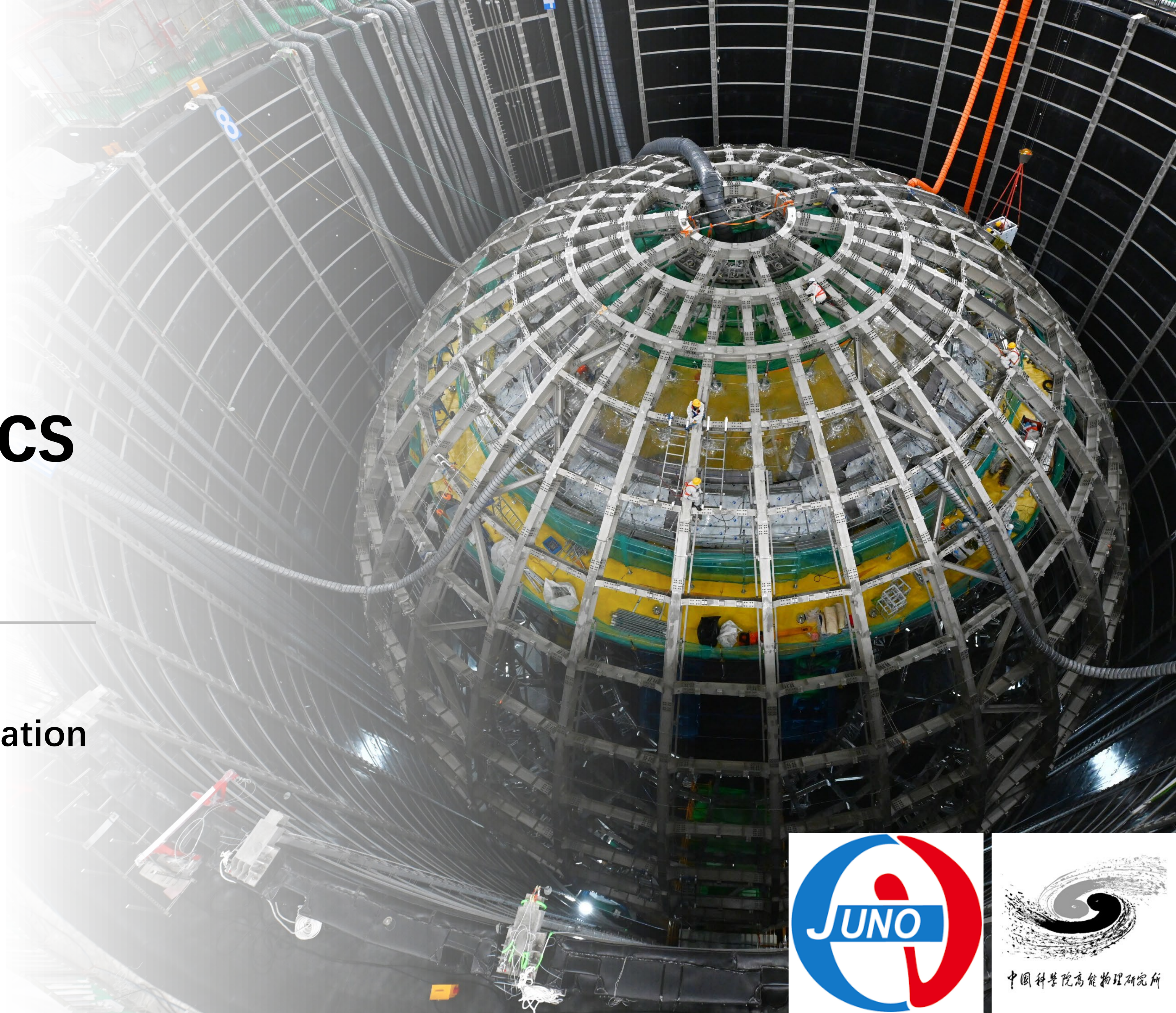
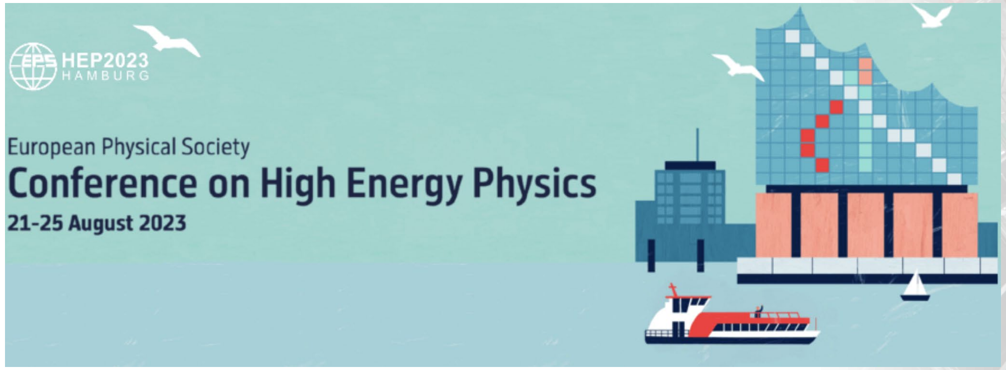
JUNO's Physics Potential

Zhen Liu,
On behalf of the JUNO Collaboration
Institute of High Energy Physics

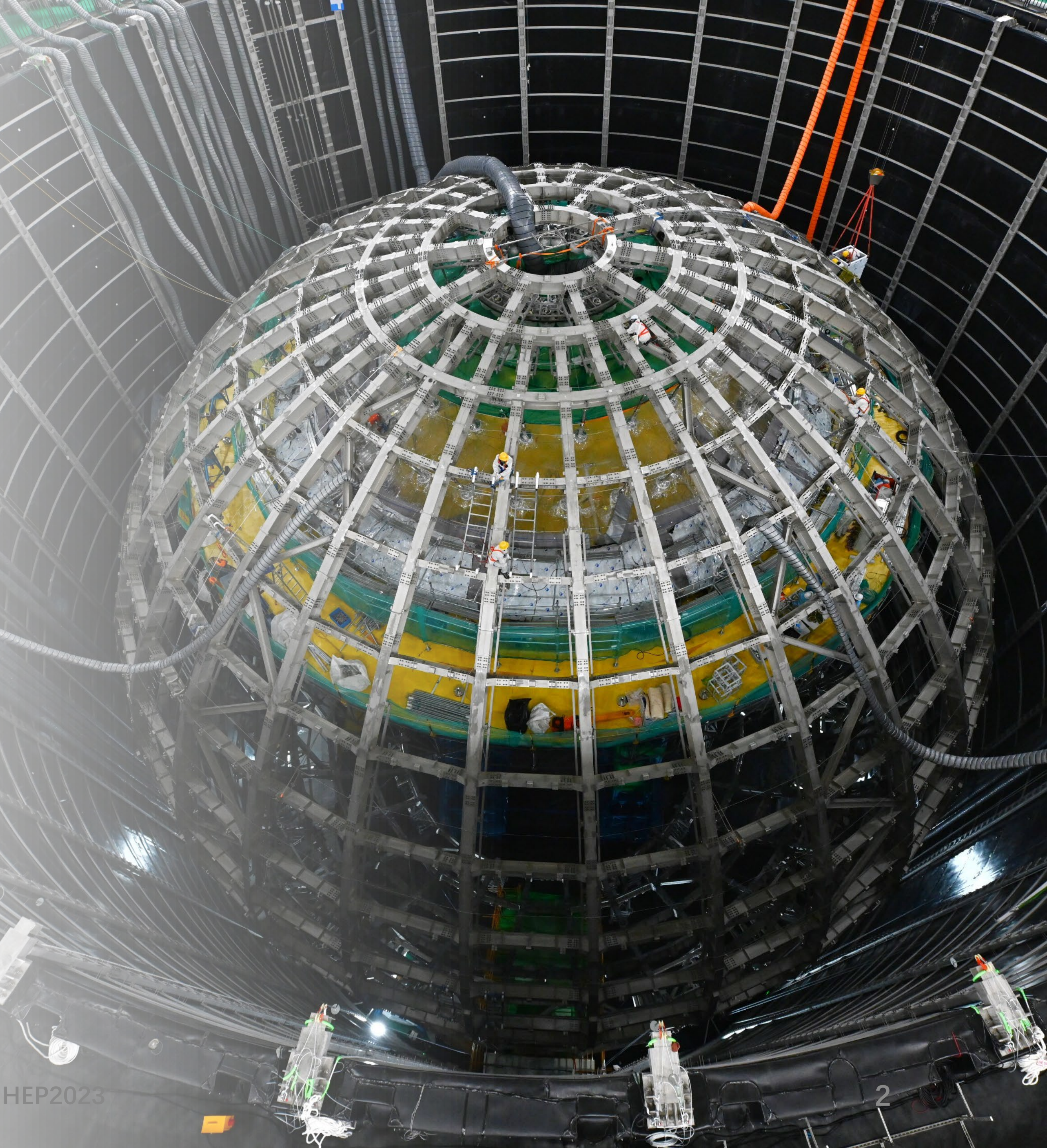
EPS-HEP2023, Hamburg, 22 August 2023



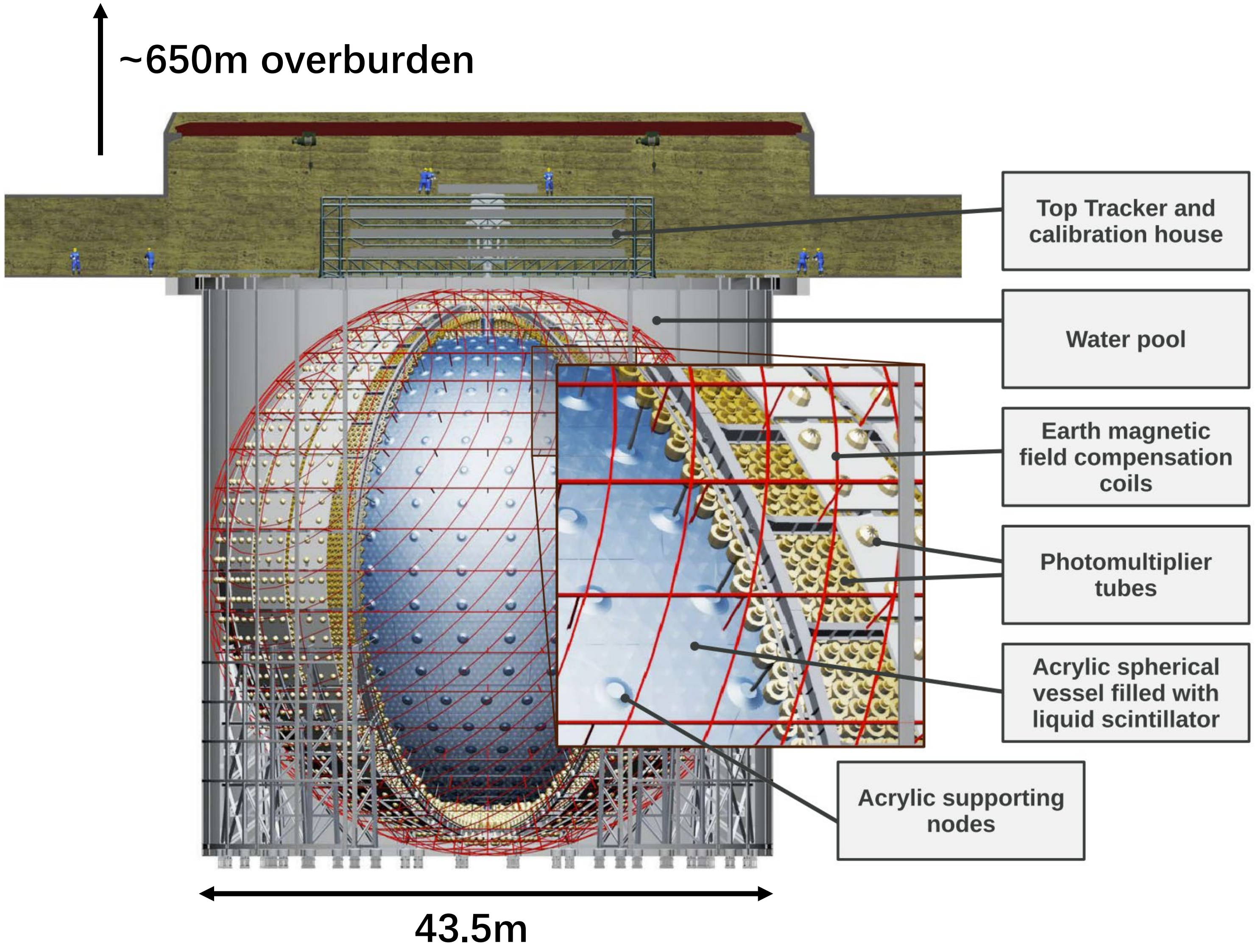


Reports of JUNO @ EPS-HEP 2023

- Zhen Liu, JUNO’s Physics Potential
- Claudio Lombardo, Detector design and current status of JUNO experiment
- Claudio Lombardo, JUNO-TAO design, prototype and its impact for JUNO physics (Poster #432)
- Deshan Sandanayake, The Top Tracker of the JUNO Experiment (Poster #549)
- Vanessa Cerrone, Prospects for Oscillation Physics in the JUNO Experiment (Poster #375)
- Arsenii Gavrikov, Reactor Neutrino Energy Reconstruction with Machine Learning Techniques for the JUNO Experiment (Poster #356)
- Zhen Liu, Prospects for atmospheric neutrino measurements in JUNO (Poster #156)
- Apeksha Singhal, JUNO's sensitivity to 7Be, pep and CNO solar neutrinos (Poster #436)



JUNO detector



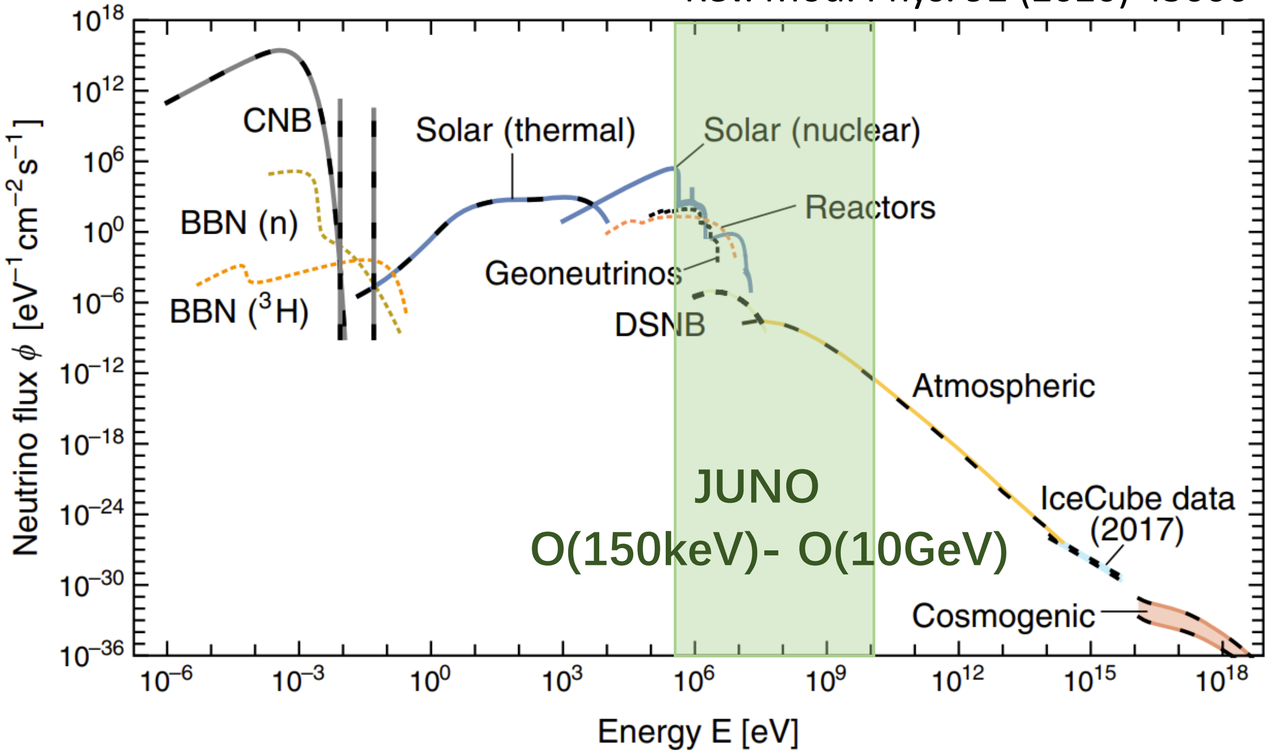
- 17’612 **20-inch PMTs** and 25’600 **3-inch PMTs**
- More than 1/3 of the PMTs have been installed as of the beginning of August.

JUNO's physics program

JUNO is a multi-purpose liquid scintillator experiment:

Research Topics	Expected Signal Rate
Reactor antineutrino	47/day
Atmospheric neutrino	Hundreds/year
Solar neutrino	3.5M/year for ^{7}Be 6.4K /year for ^{8}B
Supernova burst	at 10 kpc: thousands in few seconds
Diffuse Supernova Neutrino Background	2-4/year
Geoneutrino	~400/year

Rev. Mod. Phys. 92 (2020) 45006



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- **Neutrino mass ordering (NMO), Δm^2_{31}/ Δm^2_{32}, Δm^2_{21}, $\sin^2\theta_{12}$, $\sin^2\theta_{13}$**
- **NMO, θ_{23}**
- **$\sin^2\theta_{12}$ and Δm^2_{21}**

Neutrinos as a probe

Reactor neutrinos

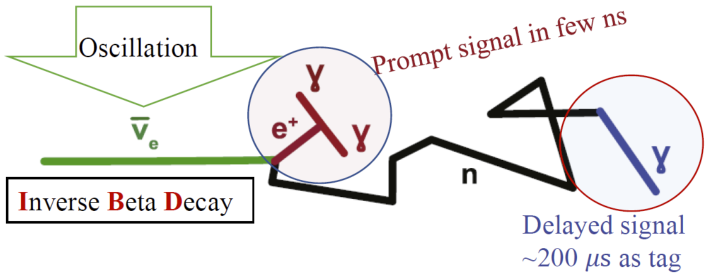
Primary goal: measurements of neutrino mass ordering (NMO) and oscillation parameters.

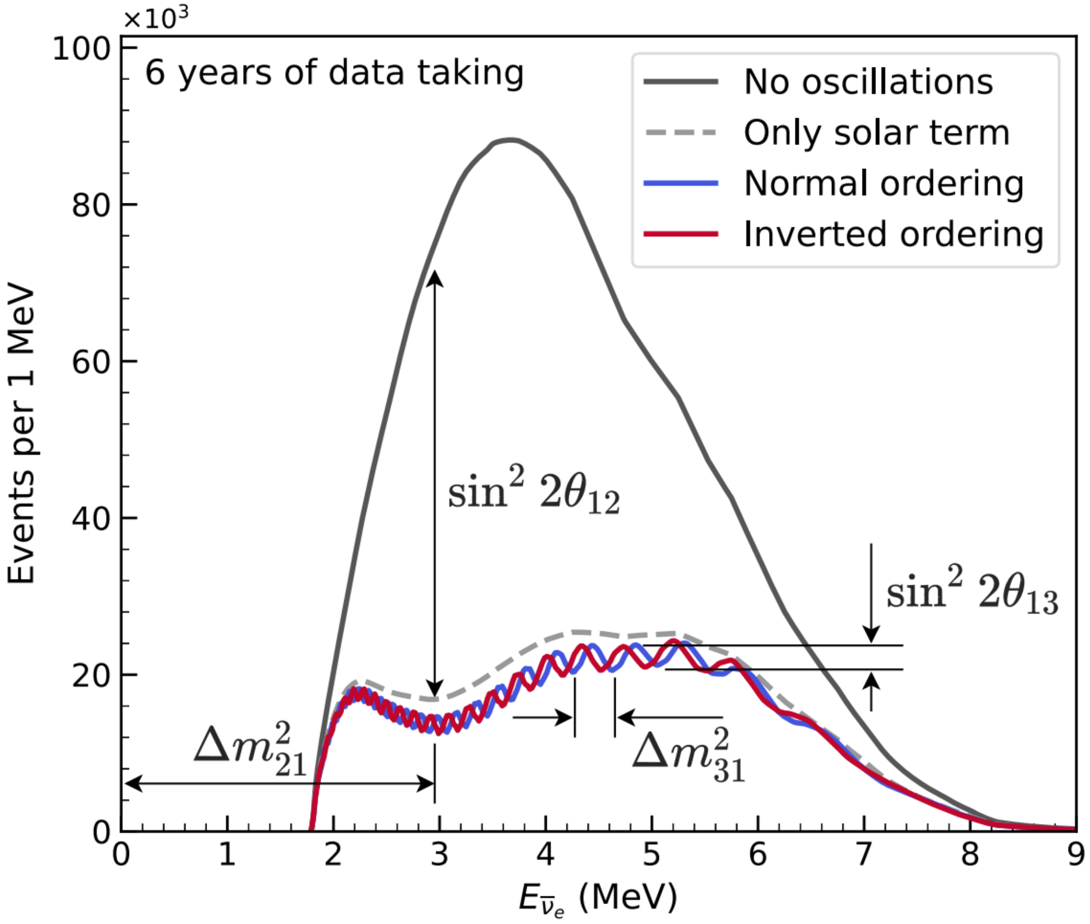
- **Signal source:**
  - Reactor $\bar{\nu}_e$
  - Optimized baseline, i.e., 52.5 km to two nuclear power plants
  - 26.6 $\mathrm{GW_{th}}$ reactor complexes

  → Powerful and pure $\bar{\nu}_e$ source
- **Oscillation:**
  - $\bar{\nu}_e$ survival probability in vacuum

  → Optimized oscillation distance
- **Target:**

  → 20k ton large Liquid Scintillator (LS)
- **Detection channel:** inverse beta decay (IBD)





Energy resolution and background suppression

High energy resolution (2.95%@1MeV):

- Large liquid scintillator (LS) in JUNO detector
- Highly transparent LS: attenuation length >20m @430nm
- Highly efficient PMT: average PMT detection efficiency: ~30%
- Very high PMT photo-coverage: 78%

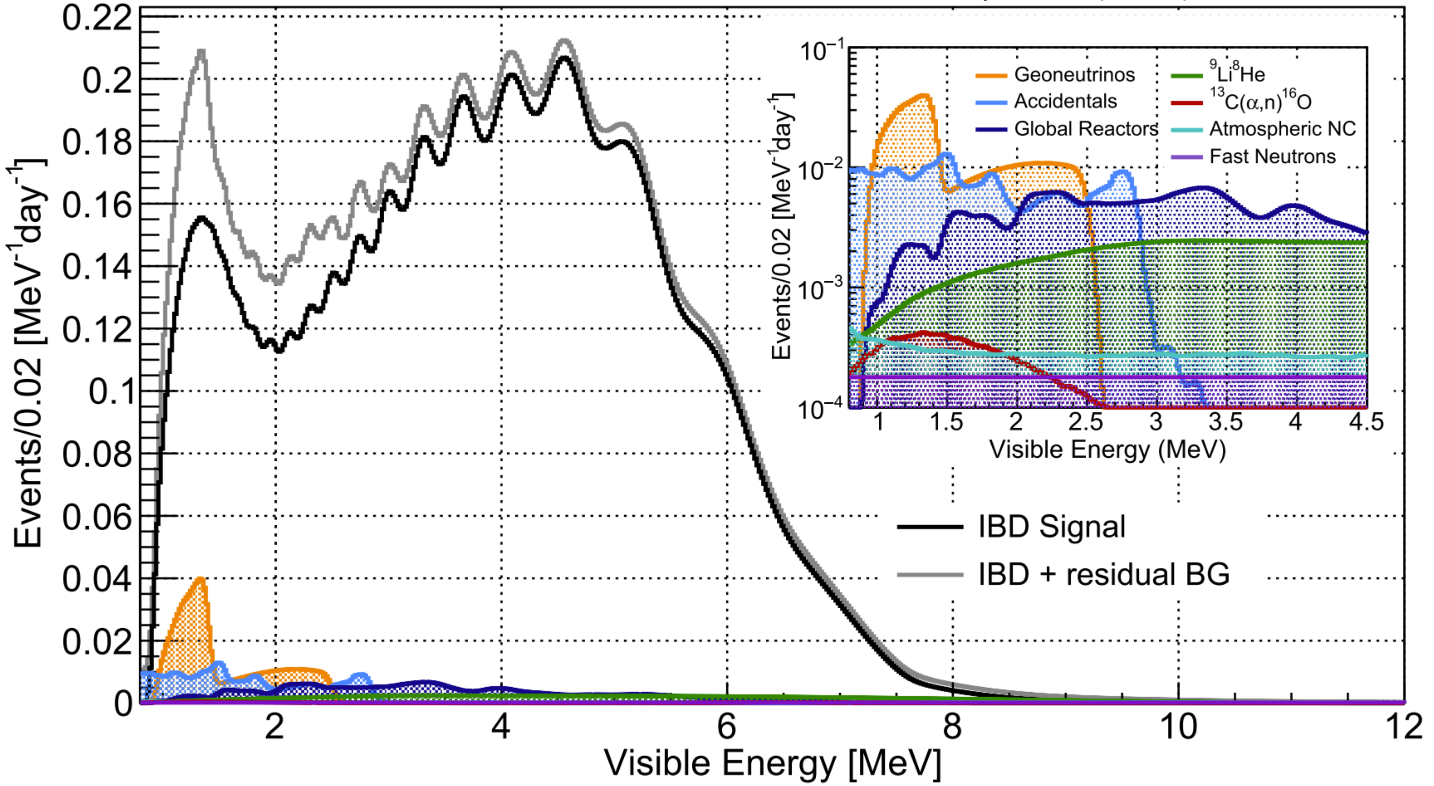
Background controls:

- Good overburden (~650 m)
- Highly-efficient veto system: >99.5%
- Material screening
- Clean installation

Event selection:

- With fiducial volume, energy selection, time coincidence, vertex correlation, and muon veto
- ~82% efficiency for IBD events

Chin.Phys.C 46 (2022) 12, 123001

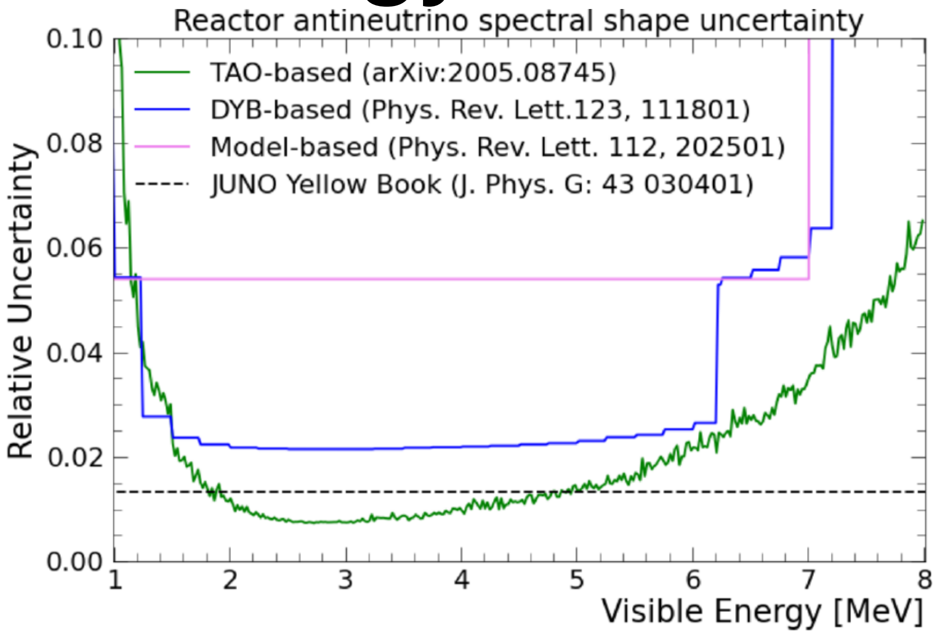


Spectral shape uncertainty and energy scale uncertainty

The satellite detector (JUNO-TAO) provides reference for reactor spectrum

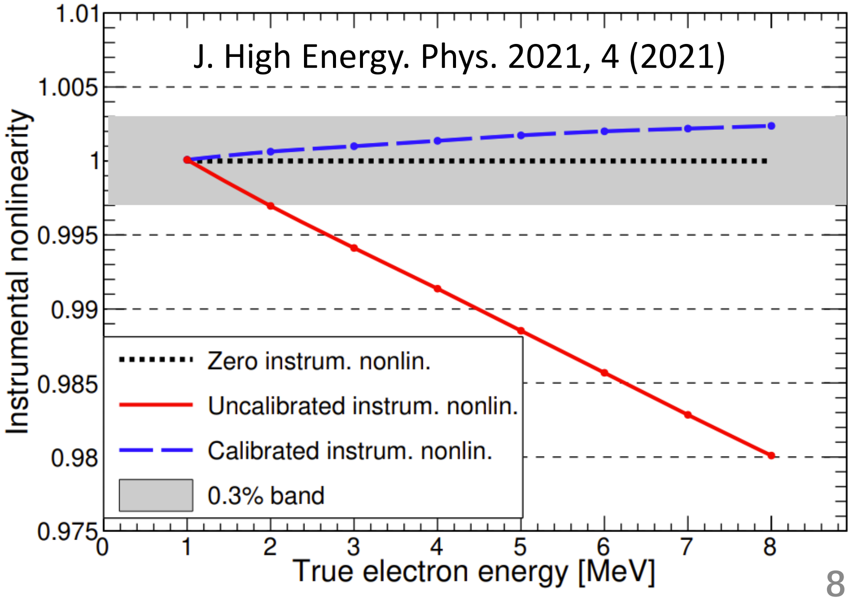
- **<2% energy resolution @1 MeV**

→ JUNO-TAO provides precise measurement of $\overline{\nu}_e$ spectra.

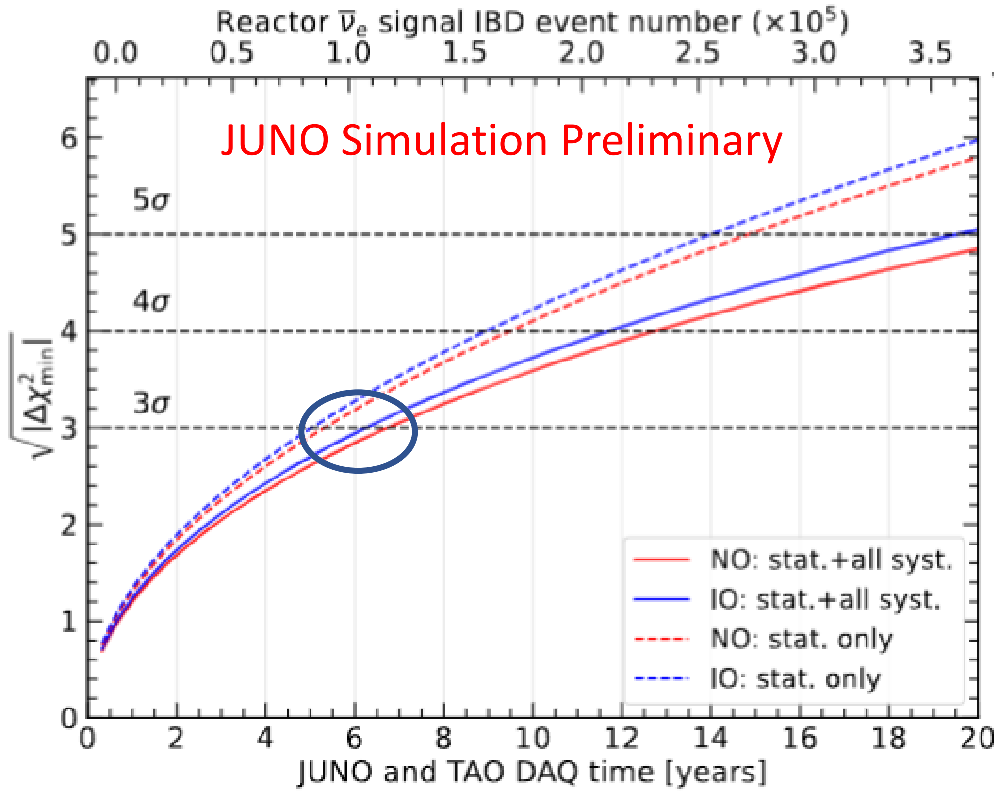


Dual Calorimetry Calibration compares Large-PMT charge to Small-PMT charge under same source

→ Absolute energy scale uncertainty <1%.



Neutrino Mass Ordering from reactor $\bar{\nu}_e$ analysis

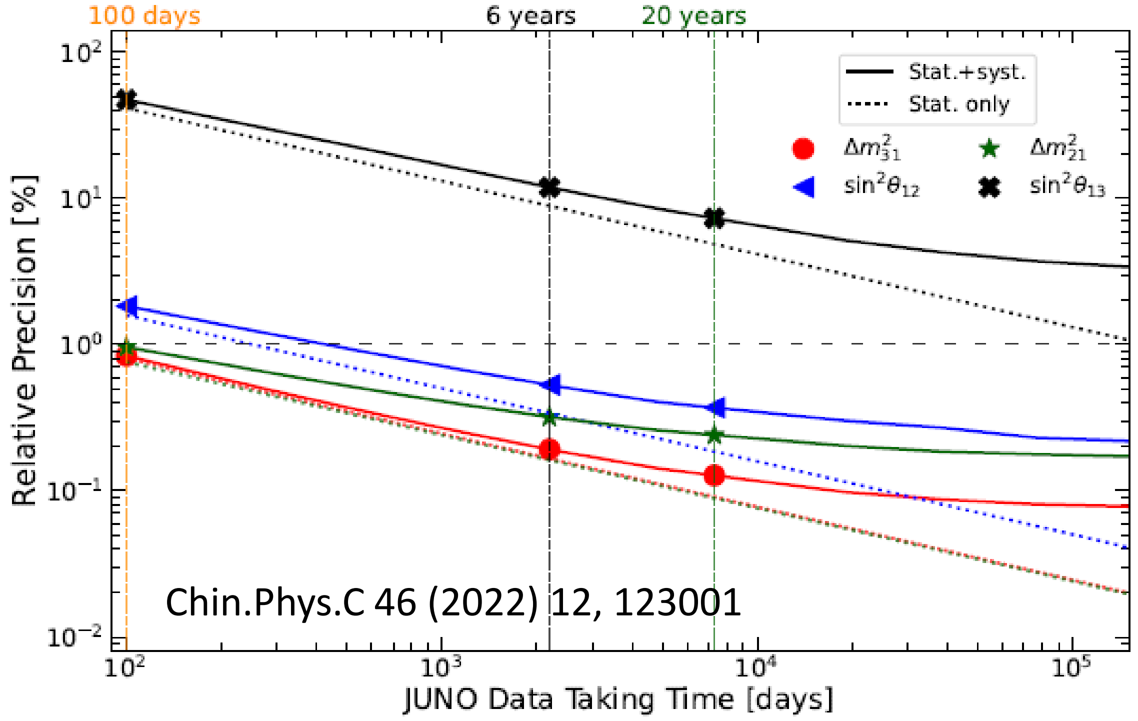


	Design *	Now
Thermal Power	36 GW_{th}	26.6 GW_{th} (26%↓)
Overburden	~700 m	~ 650 m
Muon flux in LS	3 Hz	4 Hz (33%↑)
Muon veto efficiency	83%	91.6% (**11%↑**)
Signal rate	60 /day	47.1 /day (22%↓)
Backgrounds	3.75 /day	4.11 /day (10%↑)
Energy resolution	3% @ 1 MeV	**2.95%** @ 1 MeV
Shape uncertainty	1%	JUNO+TAO
3σ NMO sens. exposure	**< 6 yrs × 35.8 GW_{th}**	**~ 6 yrs × 26.6 GW_{th}**

* J. Phys. G 43:030401 (2016)

- **JUNO NMO sensitivity: 3σ (reactors only) @ ~6 yrs * 26.6 GW_{th} exposure.**
- **Combined reactor + atmospheric neutrino analysis is in progress: further improve the NMO sensitivity.**

Neutrino oscillation parameters

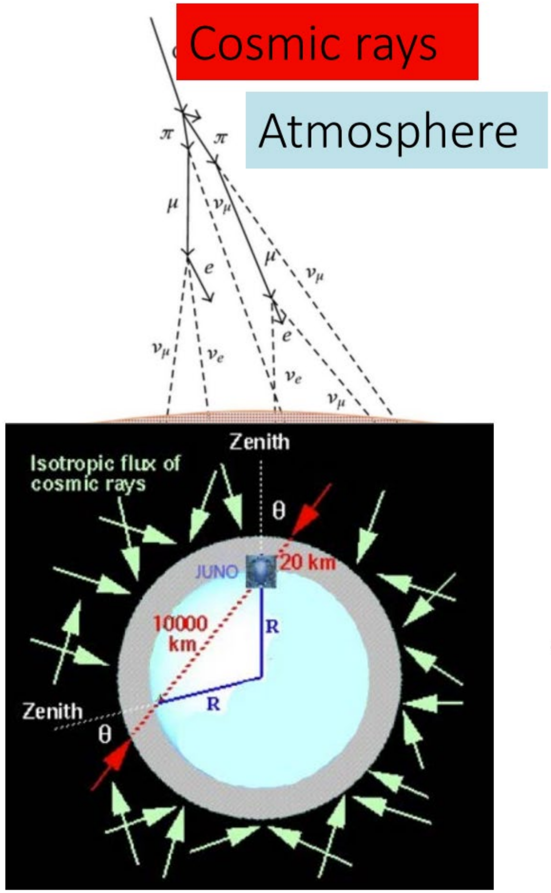


- JUNO will lead the precision of $\boldsymbol{\Delta m^2_{31}}$/ $\boldsymbol{\Delta m^2_{32}}$, $\boldsymbol{\Delta m^2_{21}}$, $\boldsymbol{\sin^2\theta_{12}}$ in 1 year.
- Precision will improve to sub-percent level in 1-2 years.

→ JUNO will provide the best measurement for the foreseeable future.

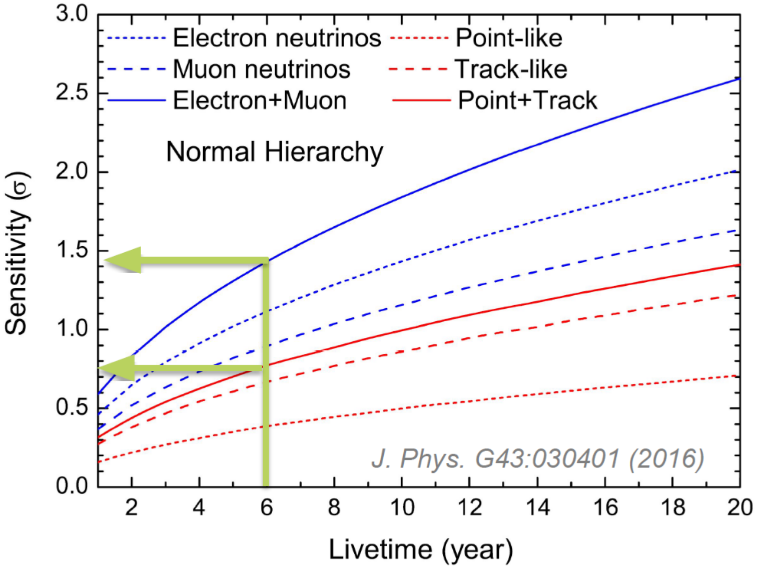
	Central Value	PDG2022	JUNO 100 days	JUNO 6 years
Δm^2_{31} ($\times 10^{-3}$eV^2)	2.5283	±0.033 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)
Δm^2_{21} ($\times 10^{-5}$eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.1%)	±0.010 (47.9%)	± 0.0026 (12.1%)

Motivation of atmospheric neutrino oscillation analysis



Major flavors:
$\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$

Atmospheric neutrino oscillation measurement provides independent sensitivity to NMO → JUNO's total sensitivity can be enhanced by combining the measurements of reactor $\bar{\nu}_e$ and atmospheric ν.



JUNO NMO sensitivity from atmospheric neutrinos **was** estimated to be 0.7~1.4σ @ ~6 yrs.
(J. Phys. G43:030401 (2016))

- **Neutrino direction resolution and $\nu/\bar{\nu}$ discrimination are two of the key factors in NMO analysis.**
- **Recently, the machine learning approaches have been developed to achieve high precision event reconstruction and high efficiency/purity PID (flavor identification and $\nu/\bar{\nu}$ discrimination).**

Updated atmospheric neutrino analysis

	Design (J. Phys. G43:030401 (2016))	New estimation
Event selection	Hadron-to-total energy ratio < 0.5	-
Direction	Constant resolution: $\sigma_{\theta_\mu} = 1^\circ$, $\sigma_{\theta_\nu} = 10^\circ$	$\nu_e/\bar{\nu}_e$ ($\nu_\mu/\bar{\nu}_\mu$): σ_{θ_ν}<10° at E>4(3) GeV
Energy	Visible energy: σ_E=1%@1GeV	Neutrino energy: σ_{E_ν}=10%@1GeV
PID ($\nu/\bar{\nu}$ discrimination)	-	Efficiency: 70%-85%
PID (ν_e-CC/ν_μ-CC/NC discrimination)	Idealistic assumptions	Efficiency>80%

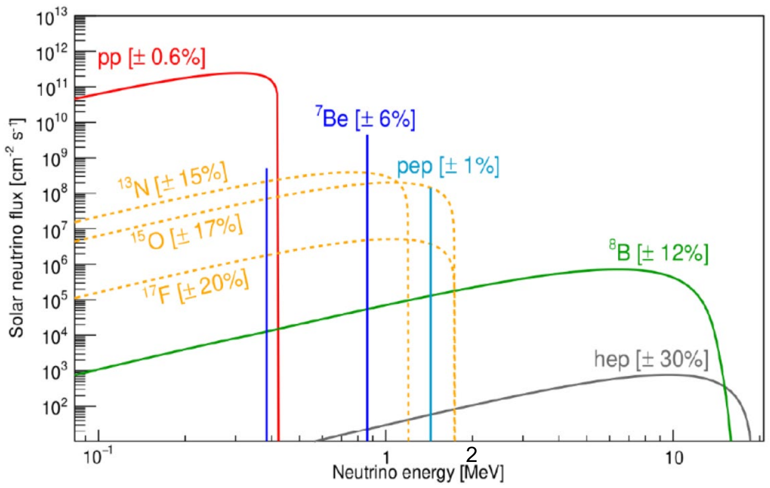
Work in progress

Improvements:

- **Statistics increased by ~30%;** (due to event selection removal).
- **Improved direction reconstruction performance;**
- **$\nu/\bar{\nu}$ separation.**

JUNO's NMO sensitivity from atmospheric neutrinos will be improved.

Solar neutrinos (Evis<2MeV)

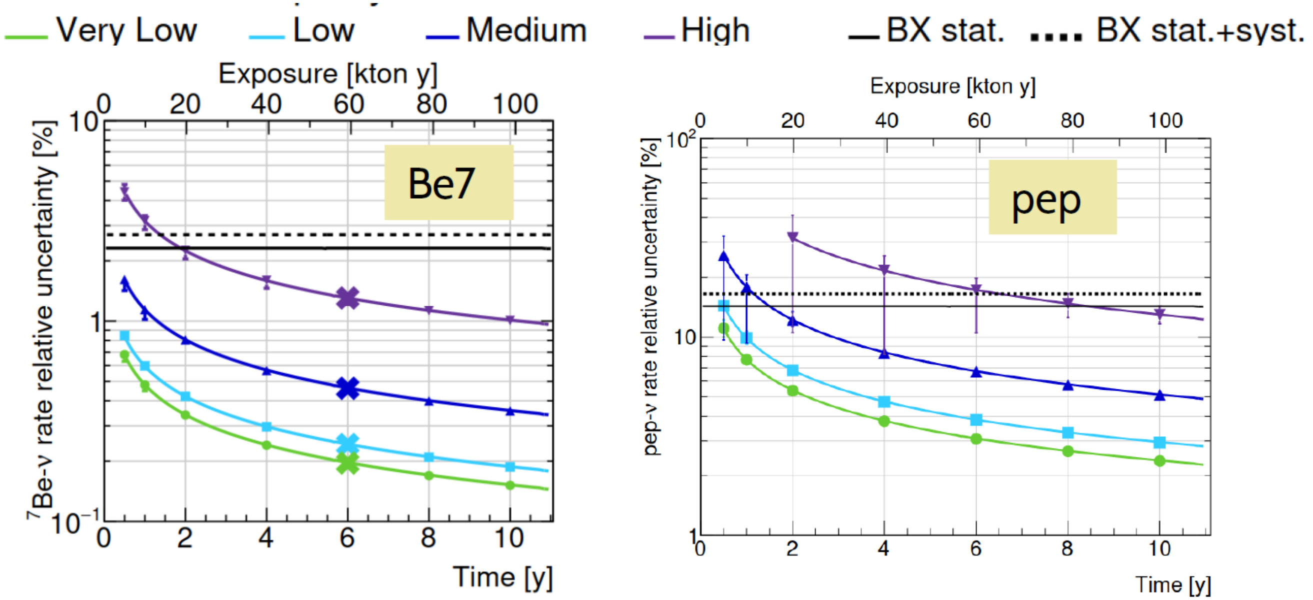


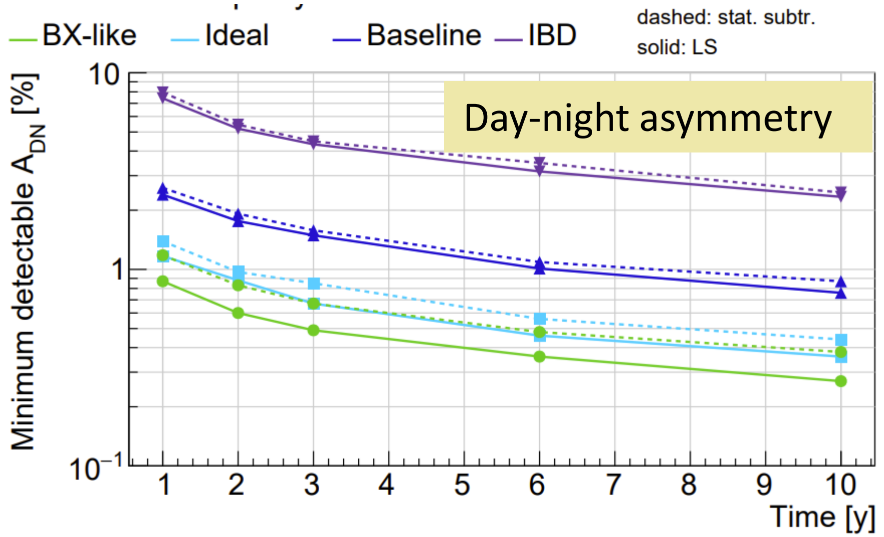
JUNO is able to simultaneously measure the intermediate energy solar neutrinos: pep, ^{7}Be and CNO neutrinos.

(arXiv: 2303.03910)

Different radiopurity scenarios considered:

- **Very-Low** radioactivity scenario: radio-purity of Borexino Phase-3;
- **Low / Medium** radioactivity scenario;
- **High** radioactivity scenario: ^{238}U and ^{232}Th 10^{-15} g/g (minimum requirement for MH discrimination)

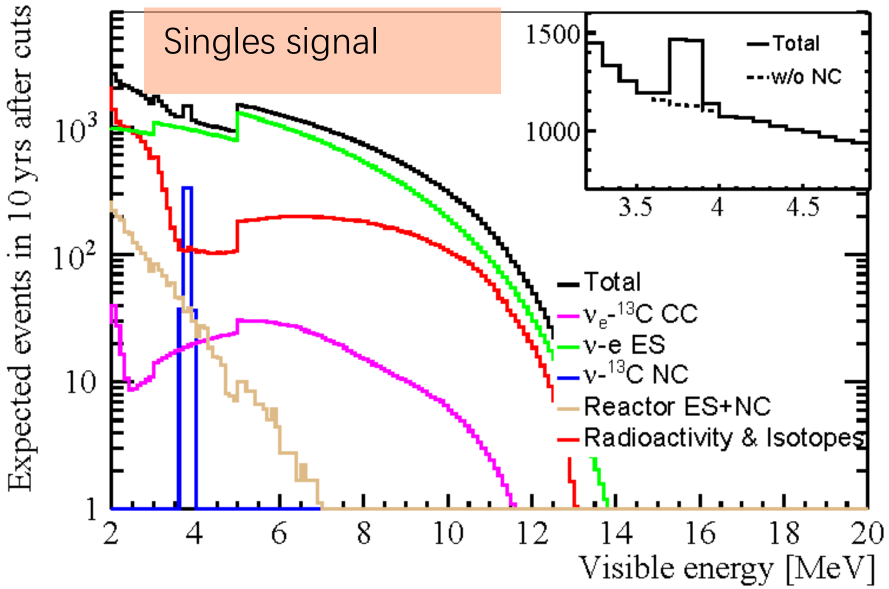




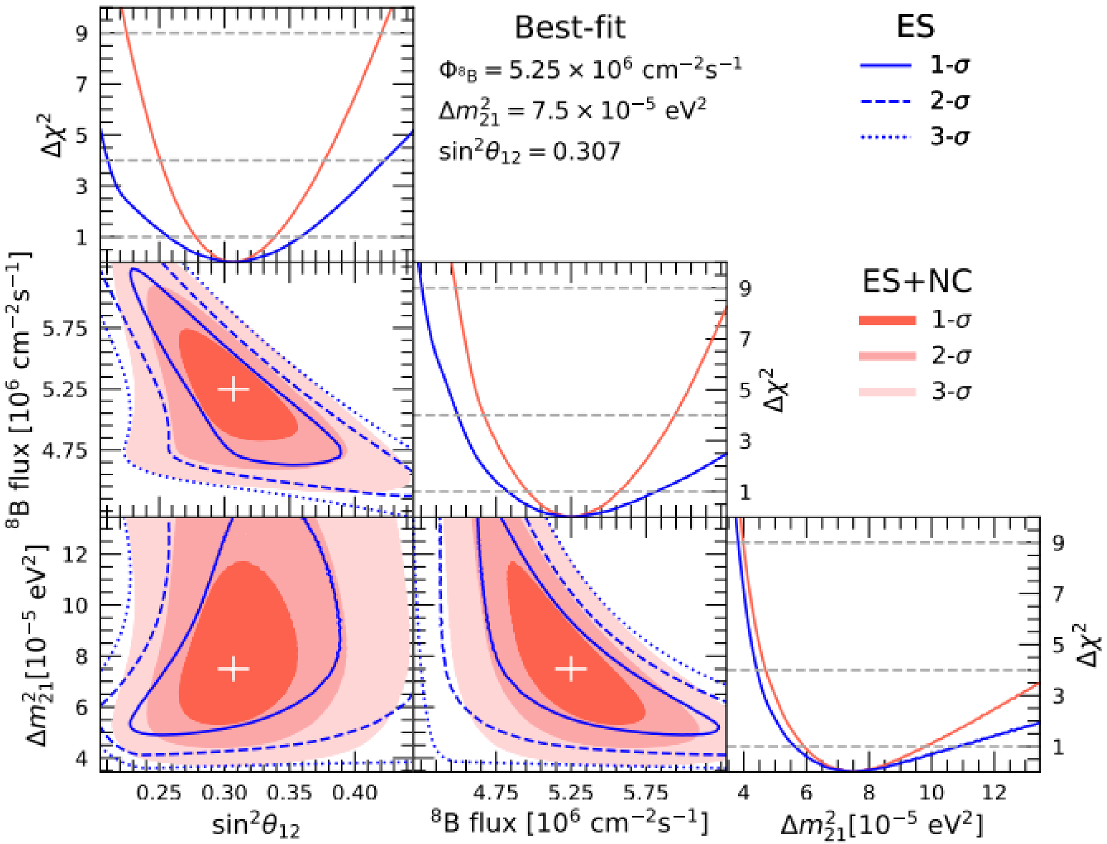
Solar neutrinos (Evis>2MeV)

The largest ever mass of 13C (~0.2kt) in JUNO LS and the excellent signal-to-background ratios
→ enable the simultaneously observation of ^{8}B solar neutrino in CC, NC, and ES interactions for the first time.

(arXiv: 2210.08437)



10 yrs of ^{8}B solar neutrino flux (~5%)



Oscillation parameters:

- $\sin^2\theta_{12}$: $+9\%/-8\%$
- Δm^2_{21}: $+27\%/-17\%$

Also contributes to:

- solving metallicity puzzle,
- understanding day/night asymmetry,
- exploring new physics.

Supernova neutrinos

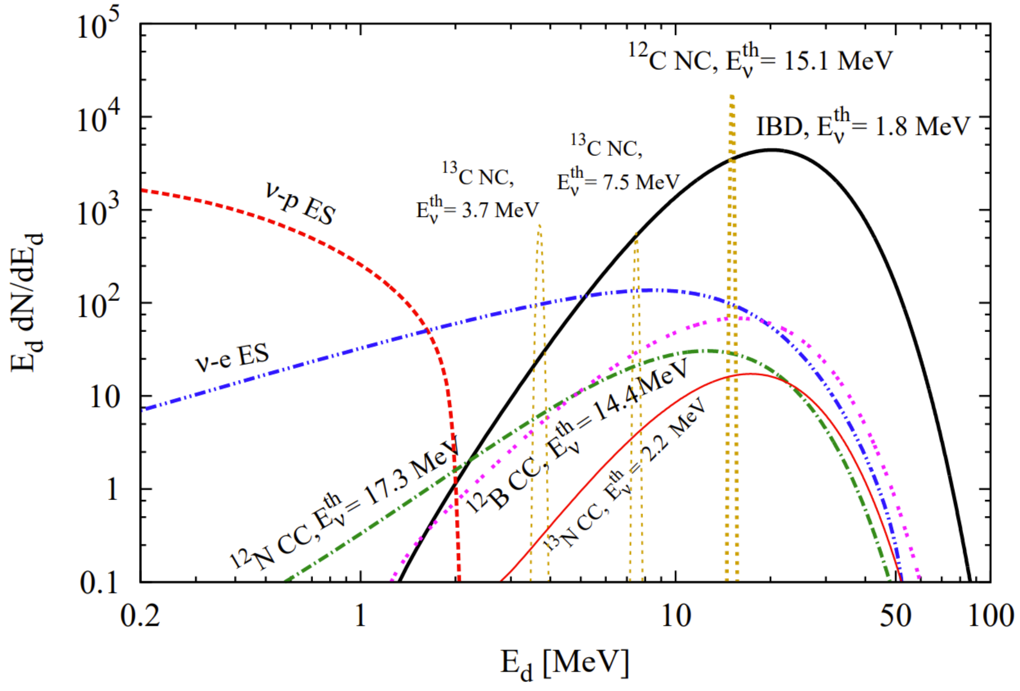
- **Motivation**: a high-statistics detection of neutrinos from a galactic SN will provide us with precious information about the explosion mechanism and intrinsic properties of neutrinos themselves.
- **JUNO has excellent capability of detecting all flavors of the O(10 MeV) post-shock neutrinos.**

→ Study of flavor composition, time evolution, and energy spectrum of supernova burst neutrinos

- Low detection threshold (sub-MeV)
- Expected events of supernova burst ν at 10kpc:

Detection channels	Expected events
IBD	~5000
ν-p ES	~2000
ν-e ES	~300
CC	~200
NC	~300

(assuming 0.2MeV threshold and with special trigger design)

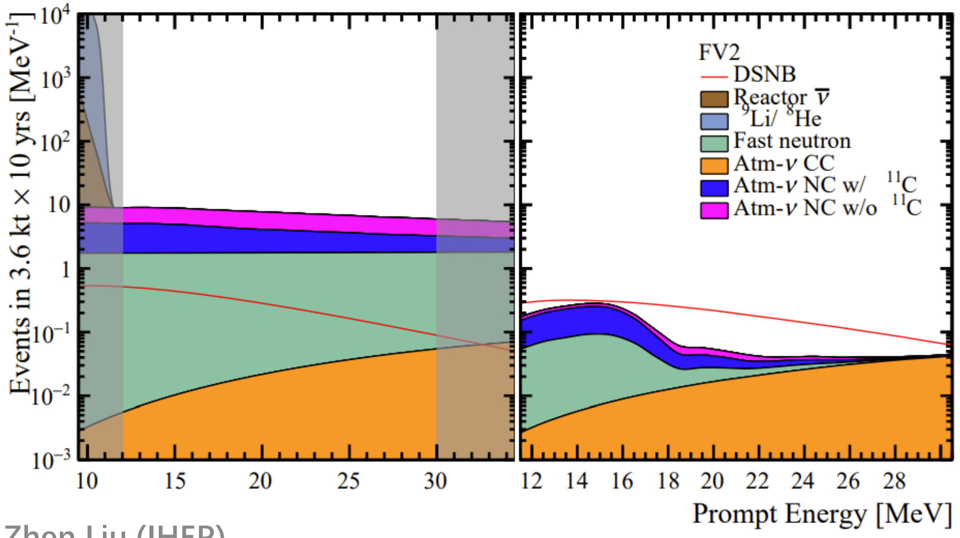


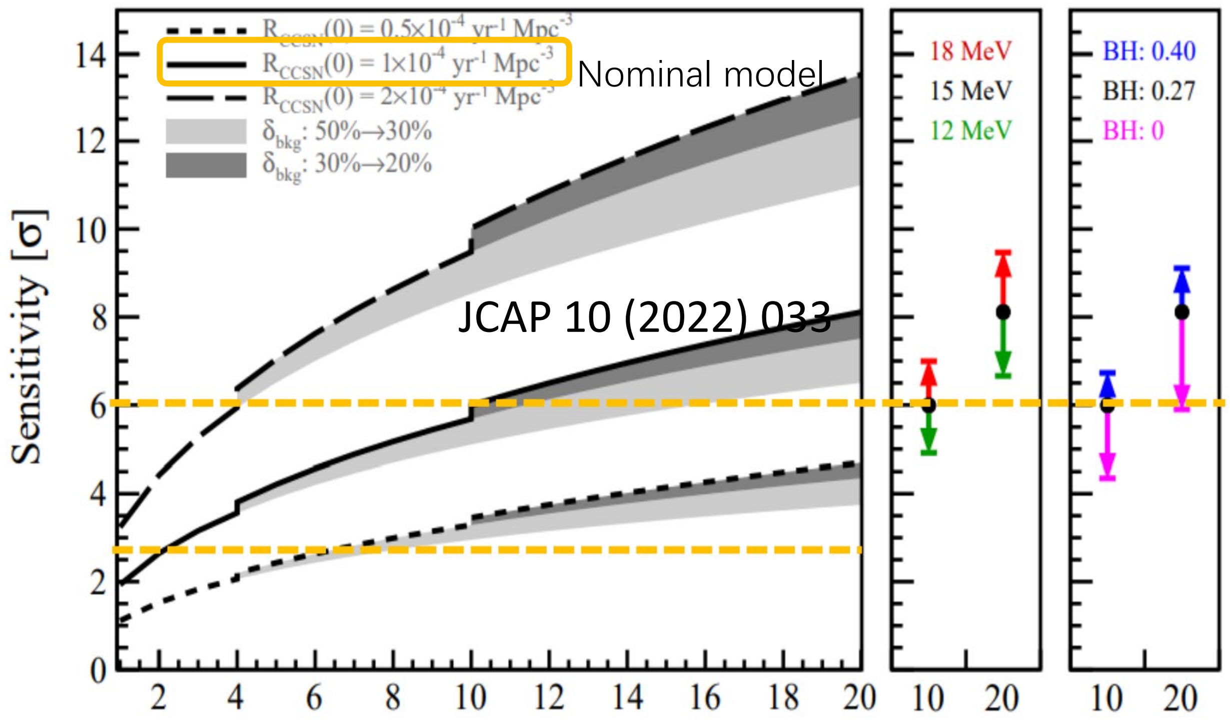
Diffuse Supernova Neutrino Background (DSNB)

DSNB provide information: the red-shift dependent supernova rate, average SN neutrino energy spectrum and the fraction of black hole formation in core-collapse SNe.
JUNO will be one of the most powerful tools to detect the DSNB signal.

Background suppression:

- $\bar{\nu}_e$ from reactor and atmospheric neutrinos suppressed with visible energy range (10 , 30) MeV cut;
- atmospheric neutrino NC events suppressed with Pulse Shape Discrimination;
- cosmogenic isotopes/fast neutron suppressed with muon veto.





DSNB discovery potential:

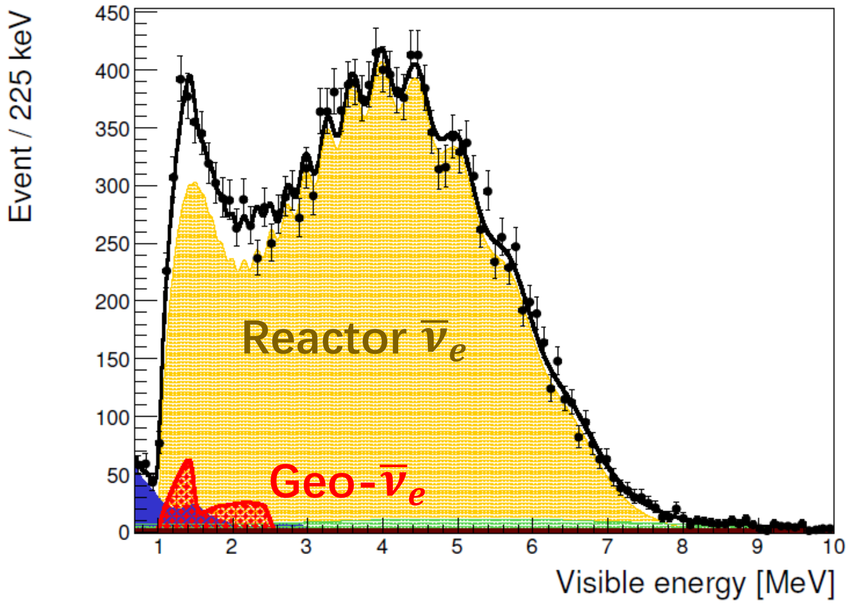
- **3σ in 3 yrs with nominal model**

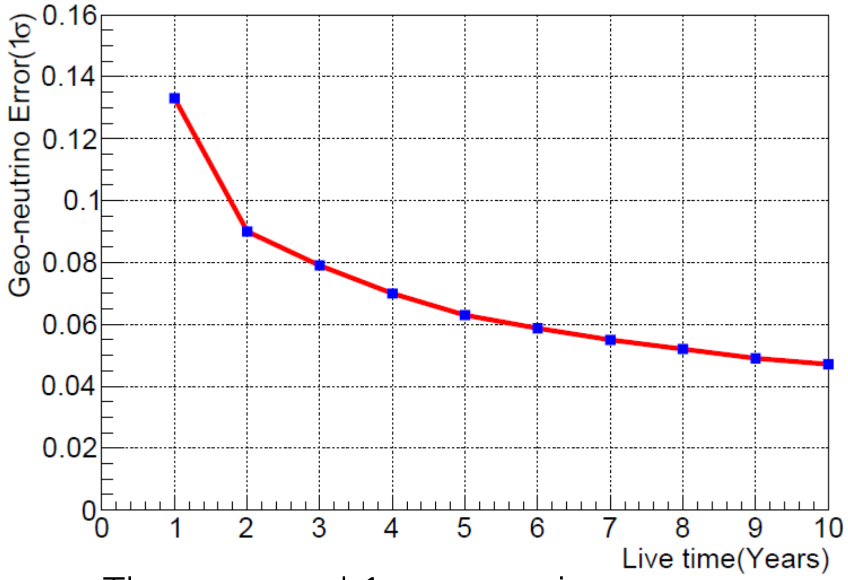
Geoneutrinos

JUNO is able to measure the geoneutrinos produced from the decays of radionuclides (U/Th/K) within the Earth

→Unique neutrino source to probe the inner structure of Earth, from ^{238}U and ^{232}Th decays in Earth's mantle and crust

→JUNO is also possible to measure the thorium to uranium ratio, and provide insight to the Earth's origin and evolution.



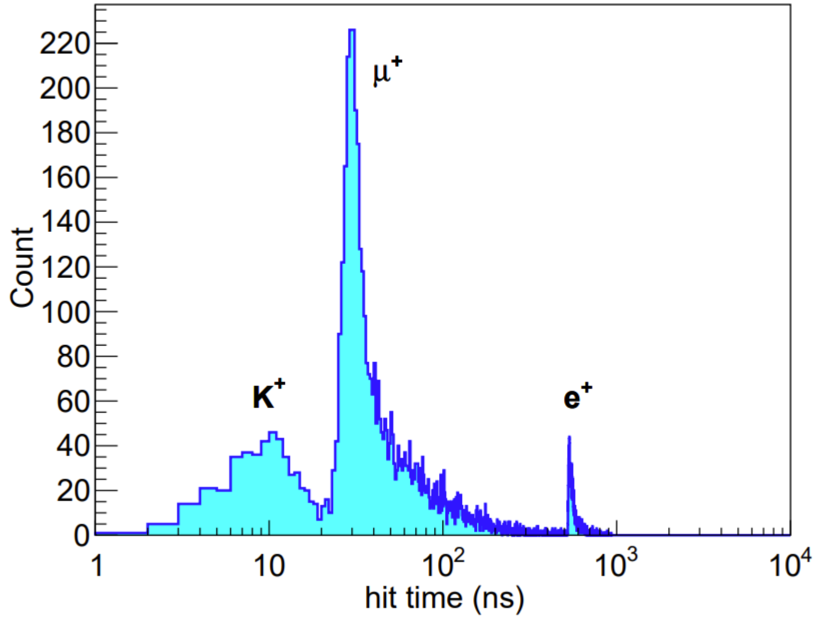


The expected 1σ uncertainty
for geoneutrino measurement with a fixed chondritic Th/U ratio

6% stat. uncertainty (1σ)
@6 year livetime
(with fixed U/Th ratio)

Probes of new physics

arXiv:2212.08502



Nucleon decays

Main search channel: $p \rightarrow \overline{\nu}+K^+$, clear signature from 3–fold coincidence in JUNO:

$$p \rightarrow \overline{\nu}+K^+ \quad \rightarrow \mu^+ + \nu_\mu \quad \rightarrow e^+ + \overline{\nu}_\mu + \nu_e$$

Expect sensitivity: 9.6×10^{33} years (90% C.L.) for 193 kton*yrs fiducial exposure

Other new physics:

- ✓ Indirect dark matter search
- ✓ Lorentz Invariance Violation and non-standard neutrino interactions search
- ✓ Light sterile neutrino searches
- ✓ Exotic particles produced in cosmic-ray interactions or the early Universe.
- ✓ Majorana neutrinos (Phase 2, upgraded JUNO)
- ✓ …

Summary of JUNO's physics potential

Physics	Sensitivity
Neutrino Mass Ordering	3σ in 6 years by reactor neutrinos
	Sensitivity from Atmospheric neutrinos will be improved
Neutrino Oscillation Parameters	Precision of $\sin^2\theta_{12}$, Δm^2_{21}, $\lvert\Delta m^2_{31}\rvert$ < 0.5% in 6 years
Solar Neutrino	Measure ^{7}Be, pep, CNO simultaneously, measure ^{8}B flux independently
Supernova Burst (at 10 kpc)	~7800 of all-flavor neutrinos
DSNB	3σ discovery potential in 3 years
Geo-neutrino	6% stat. uncertainty @6 year livetime (assuming fixed chondritic U/Th)
New physics	Nucleon Decays: 9.6×10^{33} years (90% C.L.) for $p \rightarrow \bar{\nu} + K^+$ in 10 years
	Good potential for other topics such as indirect dark matter search

Summary of JUNO's physics potential

Data taking kicks off next year.
Exciting times ahead!

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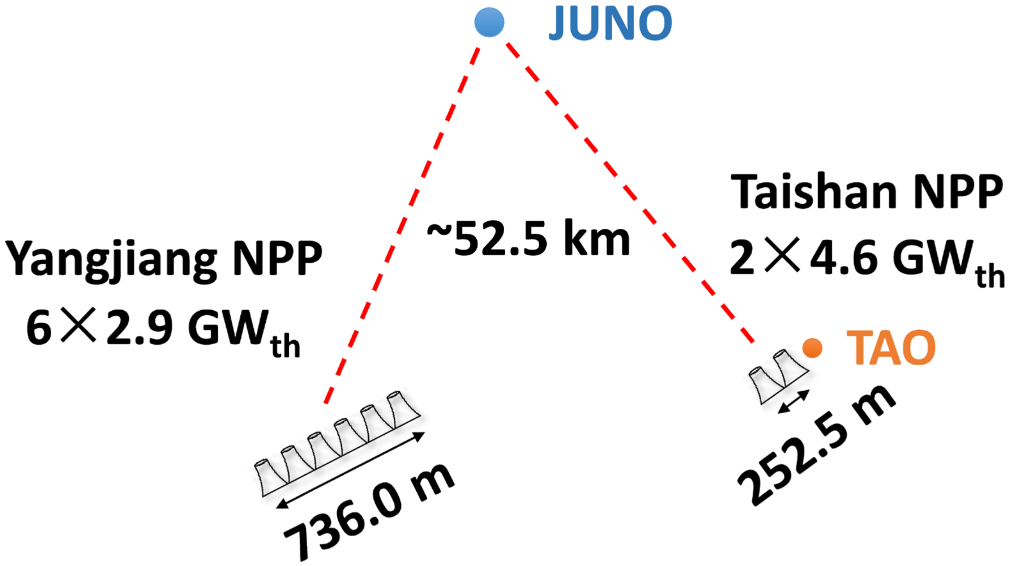
Backups

JUNO site



Optimized baseline, i.e., 52.5 km to two nuclear power plants

Reactor $\bar{\nu}_e$ detection

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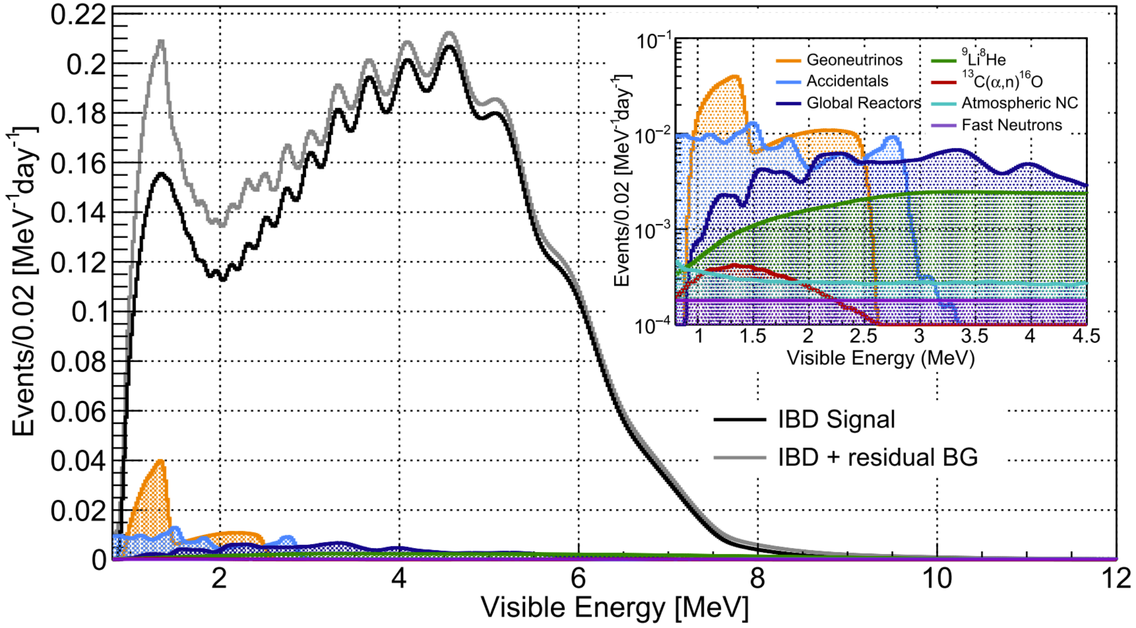


Event type	Rate [/day]	Relative rate uncertainty	Shape uncertainty
Reactor IBD signal	60 ➔ 47	-	-
Geo-ν's	1.1 ➔ 1.2	30%	5%
Accidental signals	0.9 ➔ 0.8	1%	negligible
Fast-n	0.1	100%	20%
^{9}Li/ ^{8}He	1.6 ➔ 0.8	20%	10%
^{13}C (α, n) ^{16}O	0.05	50%	50%
Global reactors	0 ➔ 1.0	2%	5%
Atmospheric $\nu'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

Design (*J. Phys. G43:030401(2016)*) ➔ **updated**

Updates for the spectra and rates since JUNO (2016)

- ☹ 2 fewer reactor cores in Taishan
- 😆 Better muon veto strategy
- 😆 Improved energy resolution: 3.0% @1MeV ➔ 2.95% @1MeV
- 😆 Signal and backgrounds now assessed with full JUNO simulation
- ☹ Slight less overburden
- 😆 Lower radioactivity background based on latest measurements on material radiopurities

Energy resolution in reactor $\bar{\nu}_e$ measurements

Change	Light yield in detector center [PEs/MeV]	Energy resolution	Reference
Previous estimation	1345	3.0% @1MeV	JHEP03(2021)004
Photon Detection Efficiency (**27%→30%**)	**+11%↑**	**2.95% @ 1MeV**	arXiv: 2205.08629
New Central Detector Geometries	**+3%↑**		
New PMT Optical Model	**+8%↑**		EPJC 82 329 (2022)

Positron energy resolution is understood:

$$\frac{\sigma}{E_{\mathrm{vis}}} = \sqrt{\left(\frac{a}{\sqrt{E_{\mathrm{vis}}}}\right)^2 + b^2 + \left(\frac{c}{E_{\mathrm{vis}}}\right)^2}$$

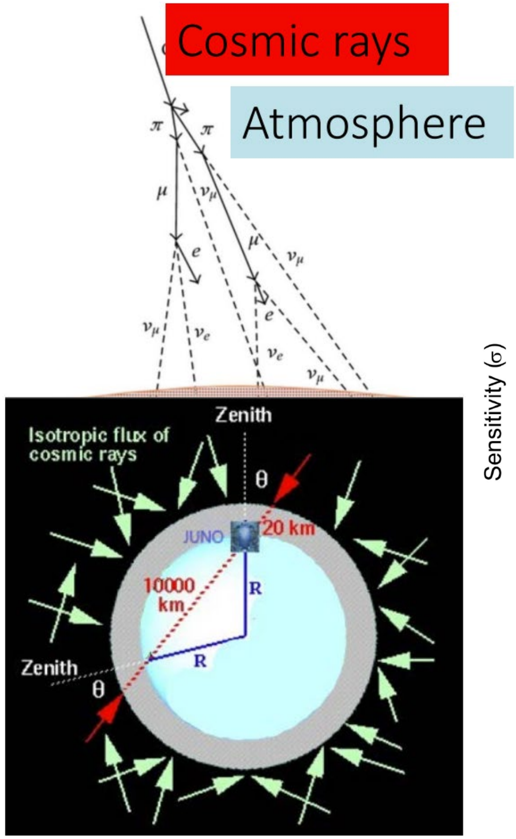
- **Photon statistics**

- **Annihilation-induced γs**
- **Dark noise**

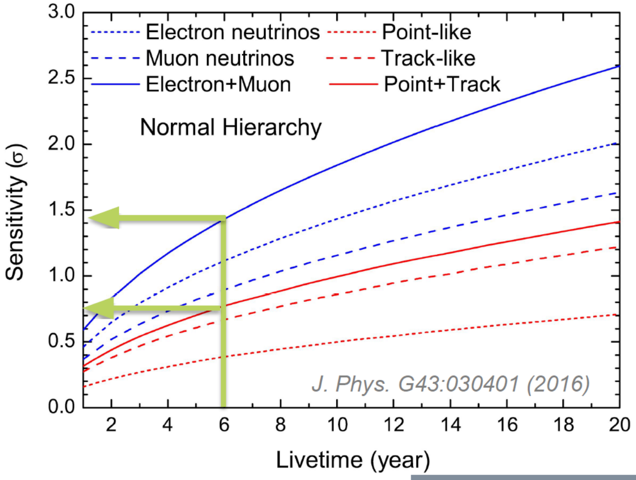
- **Scintillation quenching effect**
  - LS Birks constant from table-top measurements
- **Cherenkov radiation**
  - Cherenkov yield factor (refractive index & re-emission probability) is re-constrained with Daya Bay LS non-linearity
- **Detector uniformity and reconstruction**

Atmospheric neutrinos in the synergy of the NMO determination

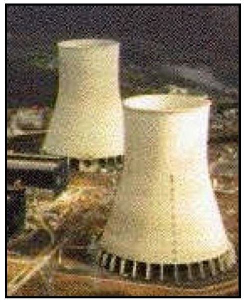
Atmospheric neutrinos at high energies (GeV level) provide independent NMO sensitivity.

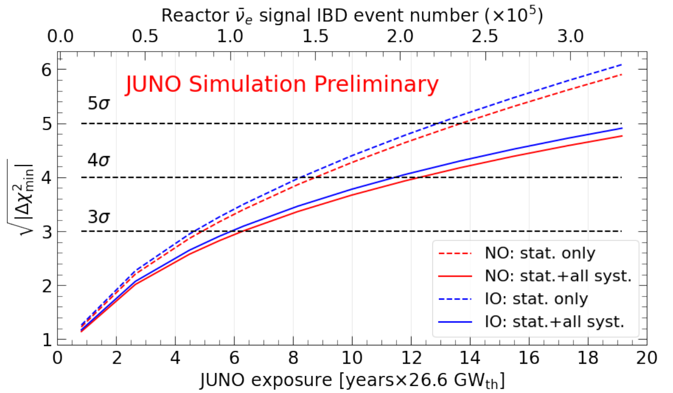


Major flavors: $\nu_\mu, \overline{\nu}_\mu, \nu_e, \overline{\nu}_e$



reactor ν (MeV)



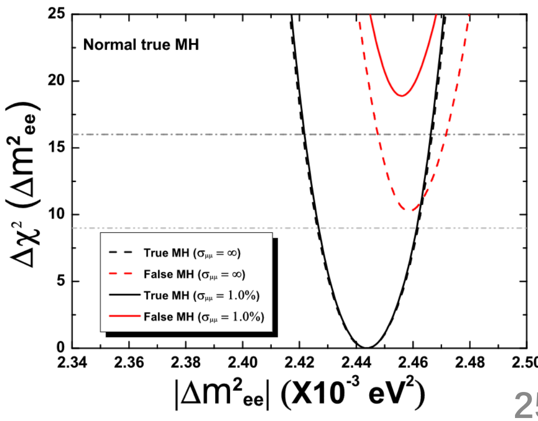


Neutrino Mass Ordering

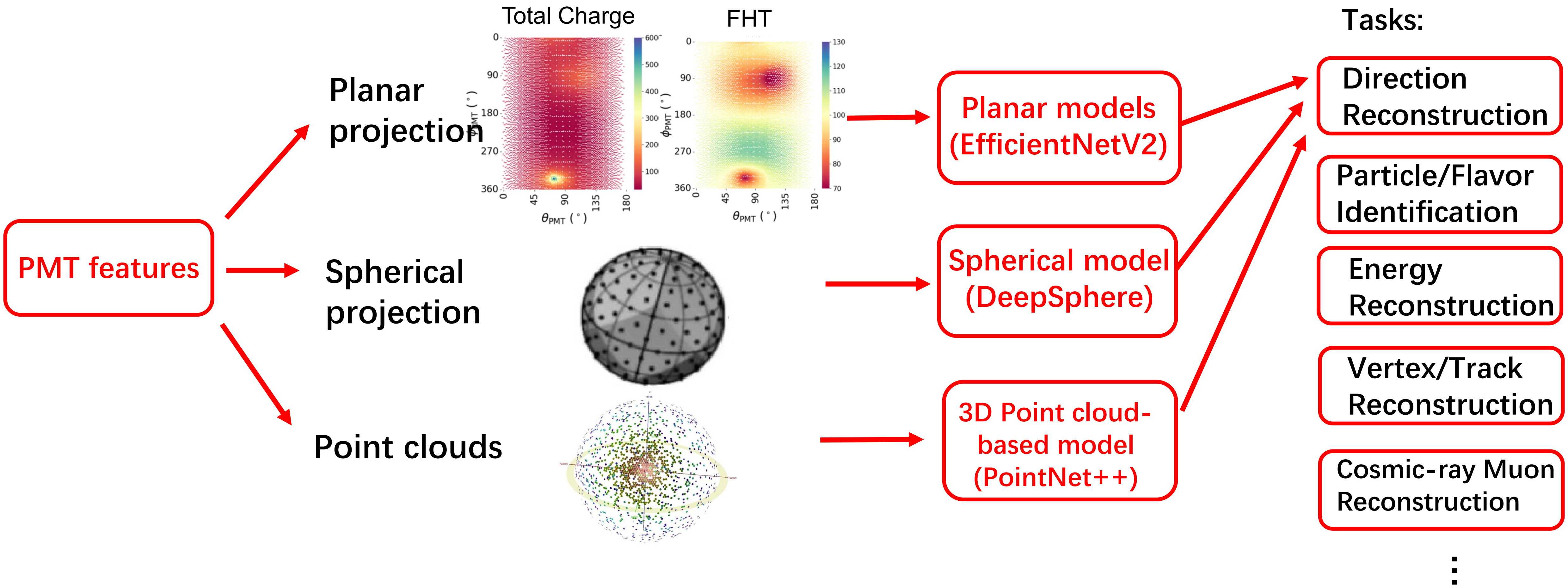
Atm. ν (GeV)

Atm. mass-squared splitting $|\Delta m^2_{\alpha\alpha}|$

Phys. Rev. D 88 (2013) 013008



A multi–purpose machine learning method for the reconstruction and PID of GeV events



Reconstruction and PID for GeV events

- Neutrino direction resolution and $\nu/\bar{\nu}$ discrimination are two of the key factors in NMO analysis.
- Machine learning approaches have been developed to achieve high precision event reconstruction and high efficiency/purity PID (flavor identification and $\nu/\bar{\nu}$ discrimination).