Reactor IBD Selection and Background in JUNO

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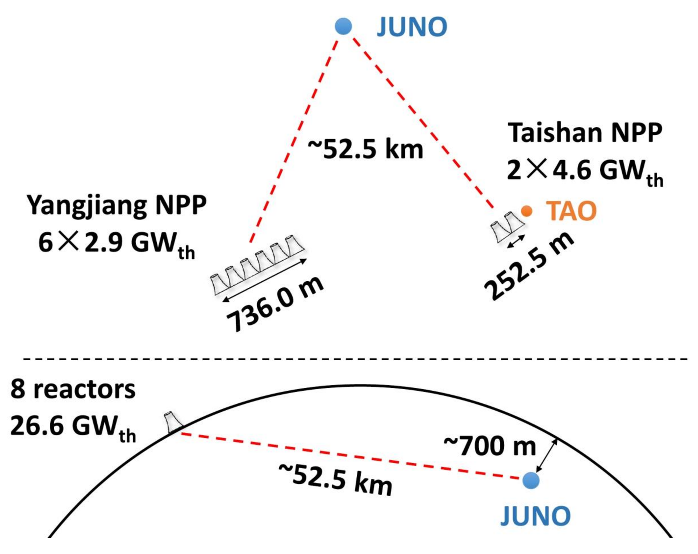
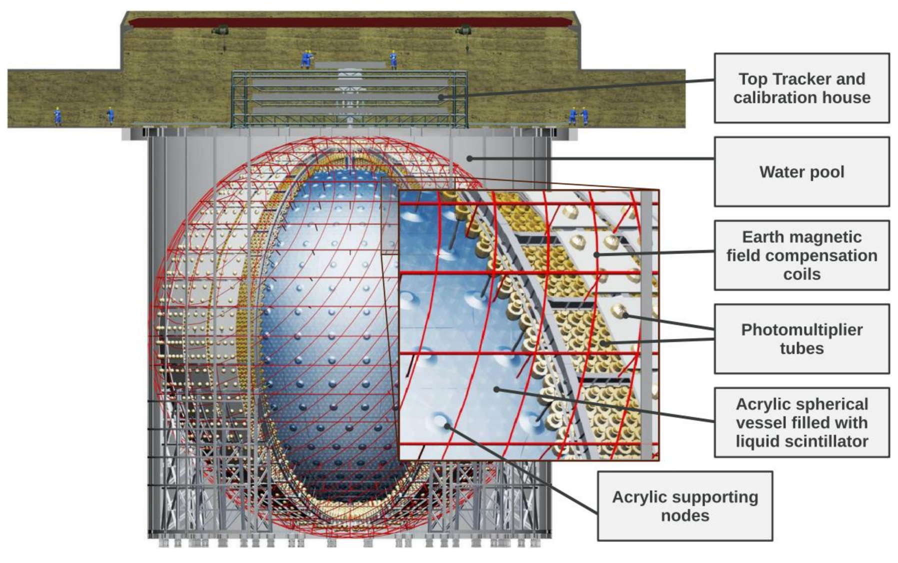
JUNO Introduction

- To determine the **neutrino mass ordering** (sign of Δm^2_{32}) independently of the CP phase δ and the θ_{23} octant
- To measure **neutrino oscillation parameters** to sub-percent precision



JUNO Location

Equal baseline of ~52.5 km to Yangjiang and Taishan reactor power plant



JUNO detector

- 20 kt liquid scintillator target
- LS transparency > 20m
- ~78% of PMT coverage
- Energy resolution < 3%@ 1 MeV

Neutrino Oscillation

Mixing matrix (PMNS):

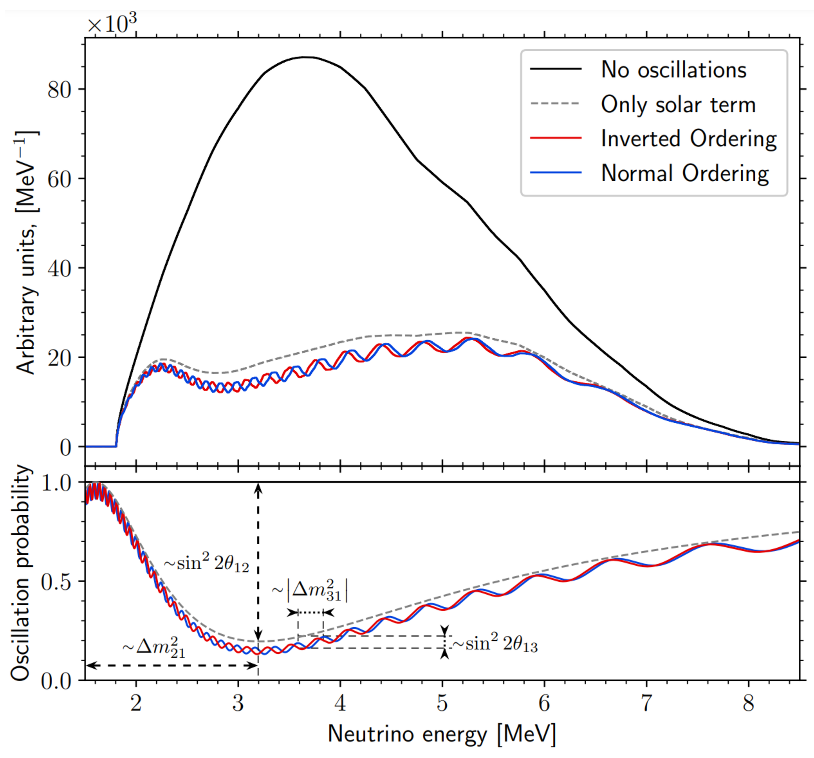
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}V_{e1} & V_{e2} & V_{e3}\\ V_{\mu1} & V_{\mu2} & V_{\mu3}\\ V_{\tau1} & V_{\tau2} & V_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric — reactor & CP phase — Solar — Majorana phase

$$V = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}\\ 0 & e^{-i\delta} & 0\\ -s_{13} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}e^{i\rho} & 0 & 0\\ 0 & e^{i\sigma} & 0\\ 0 & 0 & 1\end{pmatrix}$$

The formula for the survival probability of reactor antineutrinos:

$$\mathcal{P}(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{12}\, c_{13}^4 \sin^2\Delta_{21} - \sin^2 2\theta_{13}\left(c_{12}^2 \sin^2\Delta_{31} + s_{12}^2 \sin^2\Delta_{32}\right)$$

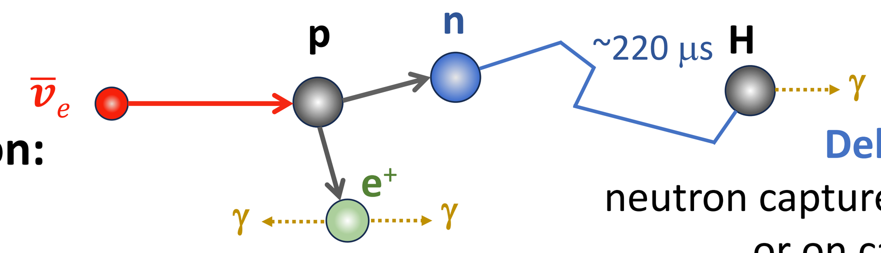


Known parameters: θ_{23}, θ_{12}, θ_{13}, $|\Delta m^2_{32}|$, Δm^2_{21}
Unknown parameters: sign of Δm^2_{32}, CP phase δ
JUNO will measure: sign of Δm^2_{32}, Δm^2_{21}, θ_{12}, θ_{13}

- Unoscillated reactor antineutrino spectrum given by TAO satellite detector
- Oscillated reactor antineutrino spectrum given by JUNO
- Shape described by Δm^2_{32}, Δm^2_{21}, θ_{12}, θ_{13}

IBD Signal and Selection Criteria

IBD reaction:



Delayed signal
neutron capture on hydrogen (2.2MeV) or on carbon (4.9MeV)

Prompt signal
deposited kinetic energy + two annihilation photons (2×0.511MeV)

Fiducial volume cut
- Candidates vertices distance from the detector center < 17.2 m

IBD pairing
- Candidate energy range:
  - prompt: [0.7, 12.0] MeV
  - delayed: [1.9, 2.5] or [4.4, 5.5] MeV
- Time separation: < 1.0 ms
- Spatial 3D separation: < 1.5 m

- FV cut and IBD selection criteria will be **further optimized**
- Muon veto strategy **optimized** by using a full muon simulation

Expected IBD rate in JUNO after oscillation

Reactor	Power [GW$_{th}$]	Baseline [km]	IBD Rate [day^{-1}]
Taishan	9.2	52.71	18.4
Core 1	4.6	52.77	9.2
Core 2	4.6	52.64	9.2
Yangjiang	17.4	52.46	35.3
Core 1	2.9	52.74	5.8
Core 2	2.9	52.82	5.8
Core 3	2.9	52.41	5.9
Core 4	2.9	52.49	5.9
Core 5	2.9	52.11	6.0
Core 6	2.9	52.19	5.9
Daya Bay	17.4	215	3.65
Total IBD rate			57.4

Expected full IBD rate: 57.4/day

event → FV cut → Muon veto → IBD pairing

muon veto
- 1ms veto for any muon in water pool or central detector
- 0.6 s, 0.4 s and 0.1 s on candidates with vertices less than 1 m, 2 m and 4 m away from muon tracks
- 1.2 s on candidates with vertices less than 3 m away from spallation neutrons
- 0.5 s veto on full central detector when ≥3 muons going through detector simultaneously

Efficiency of each selection criterion

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

IBD rate after selection : 47.1/day

Expected Backgrounds

Seven categories of backgrounds

① **Geoneutrinos**: $\overline{\nu}_e$ from U/Th decay chains in earth matter

② **World reactors**: $\overline{\nu}_e$ from reactors >300km away from JUNO detector

③ **Accidentals**: two uncorrelated events that accidentally mimic IBD signal
- prompt-signal: radiogenic events
- delayed-signal: radiogenic events and spallation neutrons

④ **^{9}Li/^{8}He**: β-n correlated decays mimicking IBD signal, produced by muons
- strong time and space correlation with parent muon
- can be effectively suppressed by muon veto strategy

⑤ **Atmospheric neutrinos**: producing neutrons, protons, α and excited nuclei
- mainly from neutral-current (NC) interactions, especially quasi-elastic scattering (QE) and two-particle two-hole interaction (2p2h) between ν_{atm} and ^{12}C dominant

⑥ **Fast neutrons**: neutrons produced by muons going through peripheral materials of detector
- prompt-signal: neutron scatter off protons
- delayed-signal: neutron capture
- can be rejected mostly if parent muon tagged by muon veto system

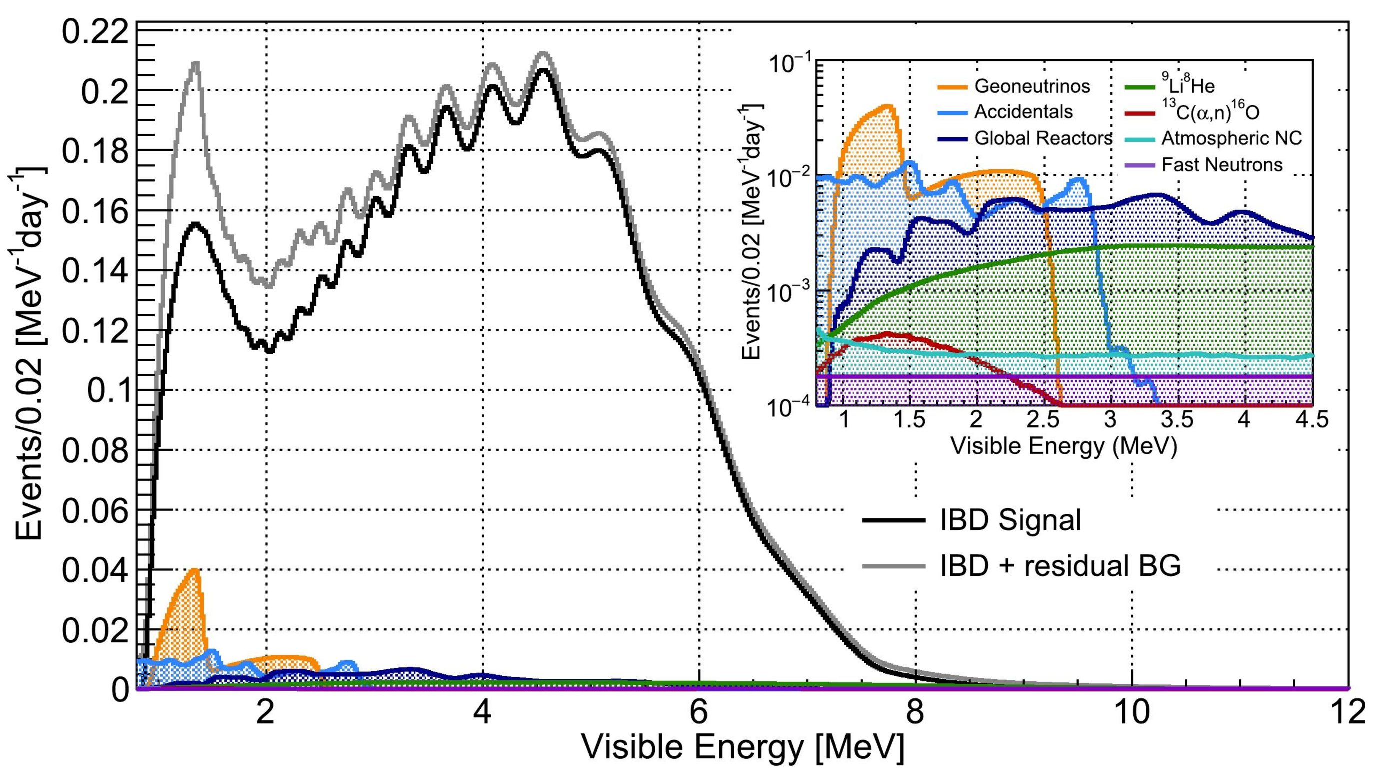
⑦ **$^{13}C(\alpha, n)^{16}O$**: α from natural radioactivity
- prompt-signal: ^{16}O deexcitation
- delayed-signal: neutron capture

Backgrounds will be measured with data once JUNO begin data collection, and we are exploring avenues to optimize the selection using machine learning methods

After IBD selection criteria

Residual background

Backgrounds	Rate [day^{-1}]	B/S [%]	Rate Unc. [%]	Shape Unc. [%]
Geoneutrinos	1.2	2.5	30	5
World reactors	1.0	2.1	2	5
Accidentals	0.8	1.7	1	negligible
^{9}Li/^{8}He	0.8	1.7	20	10
Atmospheric neutrinos	0.16	0.34	50	50
Fast neutrons	0.1	0.21	100	20
$^{13}C(\alpha,n)^{16}O$	0.05	0.01	50	50
Total backgrounds	4.11	8.7		



Visible energy spectrum expected in JUNO with (grey) and without (black) backgrounds

Reference

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