JUNO Physics Prospects

João Pedro Athayde Marcondes de André
for the JUNO Collaboration

IPHC/IN2P3/CNRS

The JUNO Collaboration

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Brazil	UEL	China	UCAS	Italy	INFN Catania
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Chile	UTFSM	China	U. of South China	Italy	INFN-Ferrara
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China	CAGS	China	Xi'an JT U.	Italy	INFN-Padova
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China	IGG-Beijing	Germany	TUM	USA	UC Irvine
China	IGG-Wuhan	Germany	U. Hamburg		

= 77 members

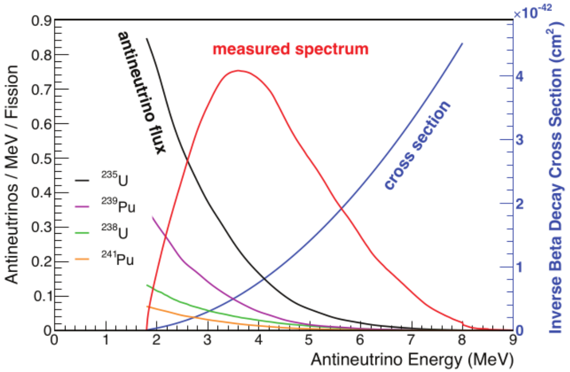
JUNO physics

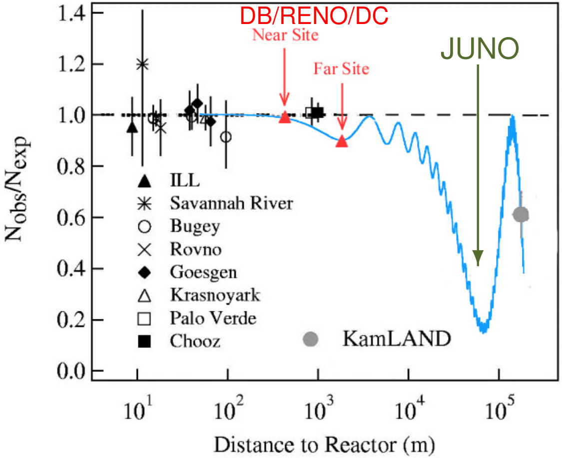
"Neutrino Physics with JUNO," J. Phys. G **43** (2016) no.3, 030401
"JUNO Physics and Detector," arXiv:2104.02565 (2021)

- Neutrino Mass Ordering (NMO)
- Precision measurement of oscillation parameters
- Atmospheric neutrinos
- Geoneutrinos
- Supernova (SN) neutrinos → see Xin Huang's talk
- Diffuse SN neutrino background → see Jie Cheng's talk
- Solar neutrinos → see Jie Zhao's poster
- 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

Neutrino oscillations with Reactor Antineutrinos

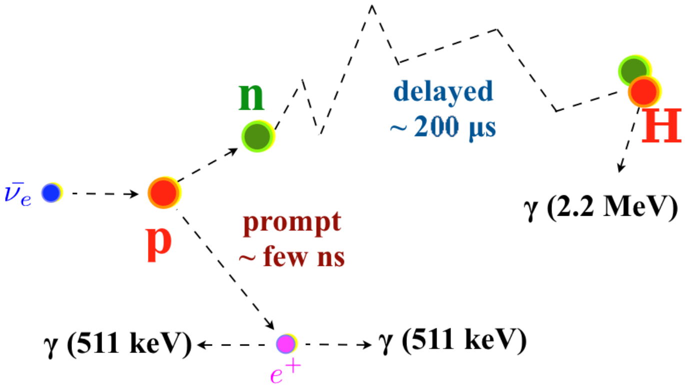




- Detected $\bar{\nu}_e$ energy 2–8 MeV
  - Only sensitive to $\bar{\nu}_e \to \bar{\nu}_e$
- Distance: selects “oscillation regime”
  - JUNO at maximum $\bar{\nu}_e$ disappearance
  - First experiment to see both Δm^2

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

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



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

JUNO site

Cores	YJ-1	YJ-2	YJ-3	YJ-4	YJ-5	YJ-6	TS-1	TS-2	DYB	HZ
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9	4.6	4.6	17.4	17.4
Baseline(km)	52.74	52.82	52.41	52.49	52.11	52.19	52.77	52.64	215	265

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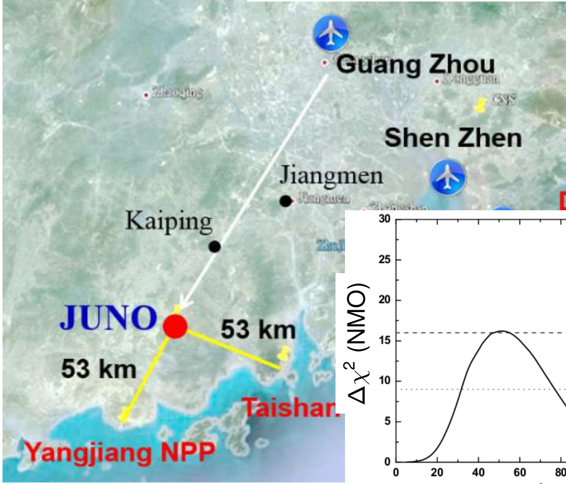
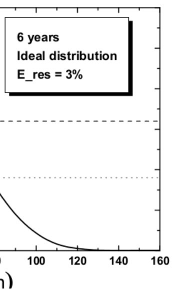
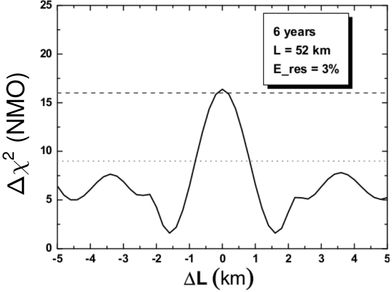


Optimized for NMO





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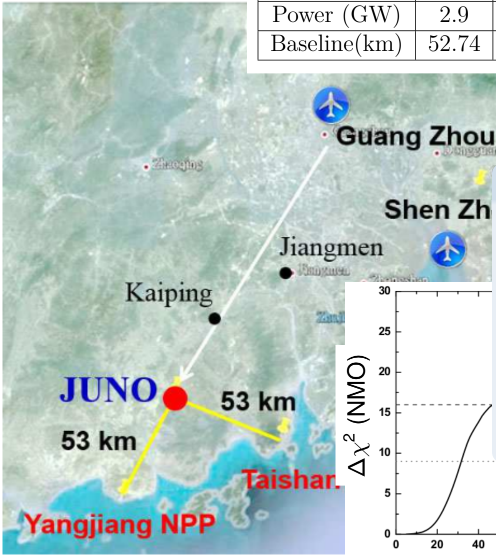
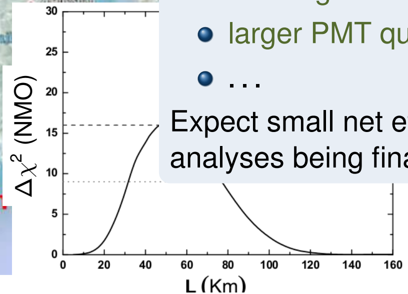
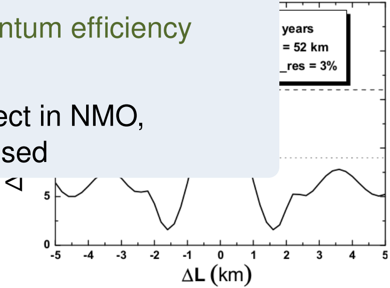




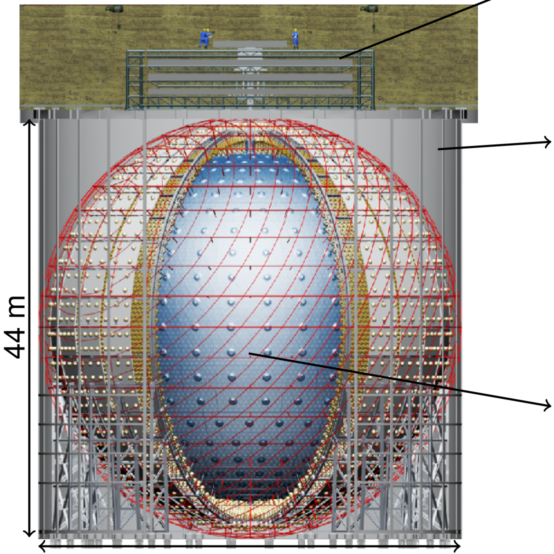


Since 2016

- 2 less reactor cores
- more light from LS
- larger PMT quantum efficiency
- ...

Expect small net effect in NMO, analyses being finalised

The JUNO detector



Top Tracker (TT)
- Precise μ tracker
- 3 layers of plastic scintillator
- $\sim$ 60% of area above WCD

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.
- 18k 20” PMTs + 26k 3” PMTs
- 3% energy resolution @ 1 MeV

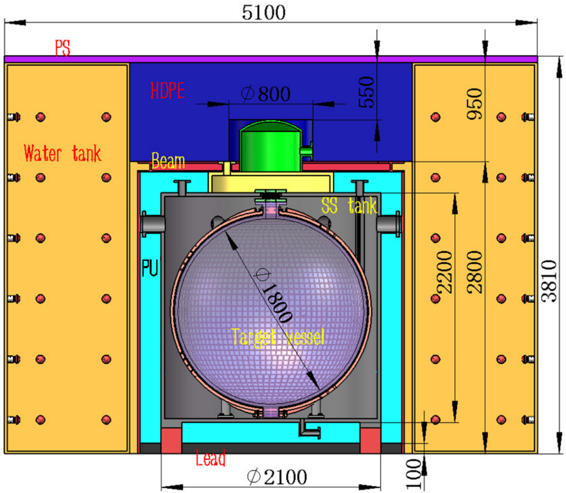
JUNO-TAO

TAO CDR, arXiv:2005.08745

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

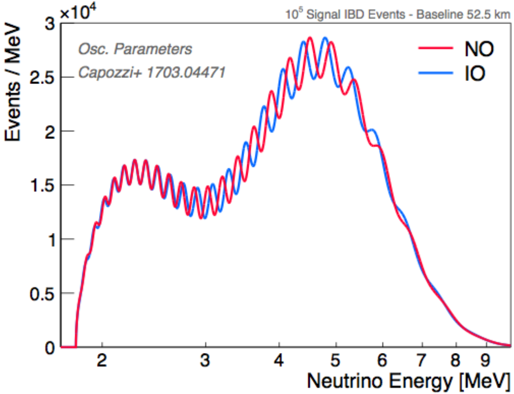
JUNO-TAO detector:

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



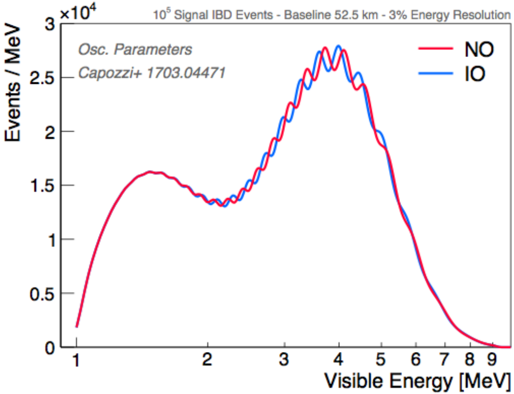
Measuring NMO with reactor $\bar{\nu}_e$: impact of energy resolution

$\bar{\nu}_e$ oscillated spectrum



- Ideal case
- Exposure: 20 kt · 6 years

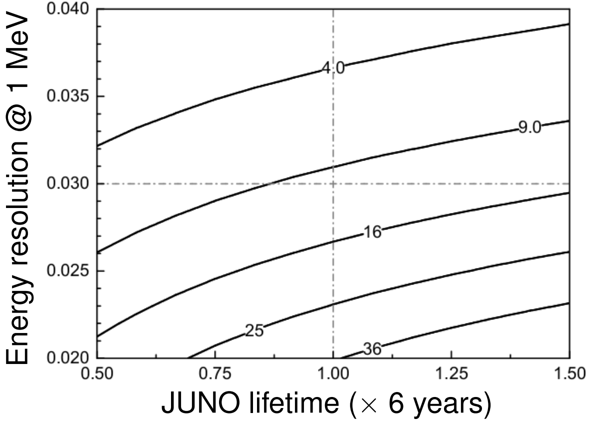
+ energy resolution



- E_{vis} from e^+ used rather than E_ν
- Assuming $3\%/\sqrt{E[\text{MeV}]}$ energy resolution

NMO sensitivity with JUNO

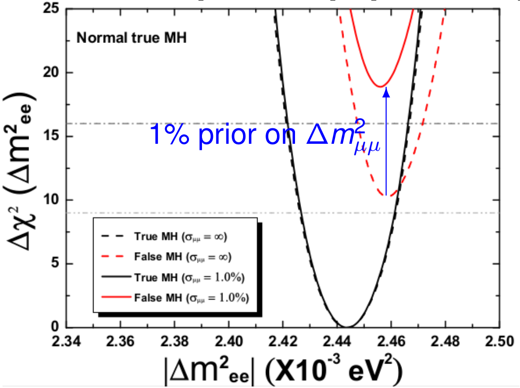
- NMO sensitivity calculated using Asimov sample
- $\Delta\chi^2 = 16$ (ideal case)
- Accounting for systematic uncertainties: $\Delta\chi^2 \approx 10 \Rightarrow \sim 3\ \sigma$
- To reach required energy resolution: high light yield + large PMT coverage + good calibration



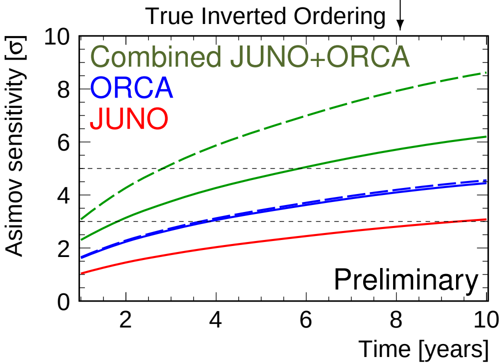
	Stat.	Core dist.	DYB & HZ	Shape	B/S (stat.)	B/S (shape)	$\lvert\Delta m^2_{\mu\mu}\rvert$
Size	52.5 km	Tab. 1-2	Tab. 1-2	1%	6.3%	0.4%	1%
$\Delta\chi^2_{MH}$	$+16$	-3	-1.7	-1	-0.6	-0.1	$+(4-12)$

NMO via combined fits of JUNO and other experiments

- Intrinsic differences between $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_\mu$, precise measurements of Δm^2 obtain different best-fit values for Δm^2_{31} when wrong ordering assumed
  - JUNO independent of δ_{CP}, θ_{23}, and doesn't rely on matter effects
- Dedicated studies performed with external priors and with other experiments
  - IceCube [1306.3988] & [1911.06745], accelerators [2008.11280], KM3NeT/ORCA



(From J. Phys. G 43 (2016), no.3, 030401)



(See poster #1260 by J. P. A. M. de André)

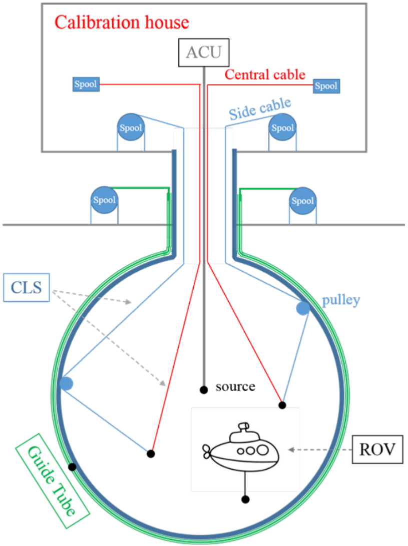
Calibration strategy

"Calibration Strategy of the JUNO Experiment," JHEP **03** (2021), 004

- Goals (essential for NMO):
  - 3% energy resolution @1 MeV
  - energy scale uncertainty $< 1\%$
- 4 complementary calibration systems:
  - Automated Calibration Unit: vertical shaft
  - Cable Loop System: positioning in one plane
  - Guide Tube: check calibration near FV boundary
  - Remotely Operated Vehicle: full detector scan
- Many radioactive sources used
- 3" PMTs: correct any intrinsic 20" PMT non-linearity

Assumptions	a	b	c	$\tilde{a} = \sqrt{a^2 + (1.6b)^2 + (\frac{c}{1.6})^2}$	energy bias (%)
Central IBDs	2.62(2)	0.73(1)	1.38(4)	2.99(1)	-
Ideal correction	2.57(2)	0.73(1)	1.25(4)	2.93(1)	-
Azimuthal symmetry	2.57(2)	0.78(1)	1.26(4)	2.96(1)	-
Single gamma source	2.57(2)	0.80(1)	1.24(4)	2.98(1)	-
Finite calibration points	2.57(2)	0.81(1)	1.23(4)	2.98(1)	-
Vertex smearing(8 cm/$\sqrt{E(\text{MeV})}$)	2.60(2)	0.82(1)	1.27(4)	3.01(1)	-
PMT QE random variations	2.61(2)	0.82(1)	1.23(4)	3.02(1)	0.03(1)

JUNO baseline detector

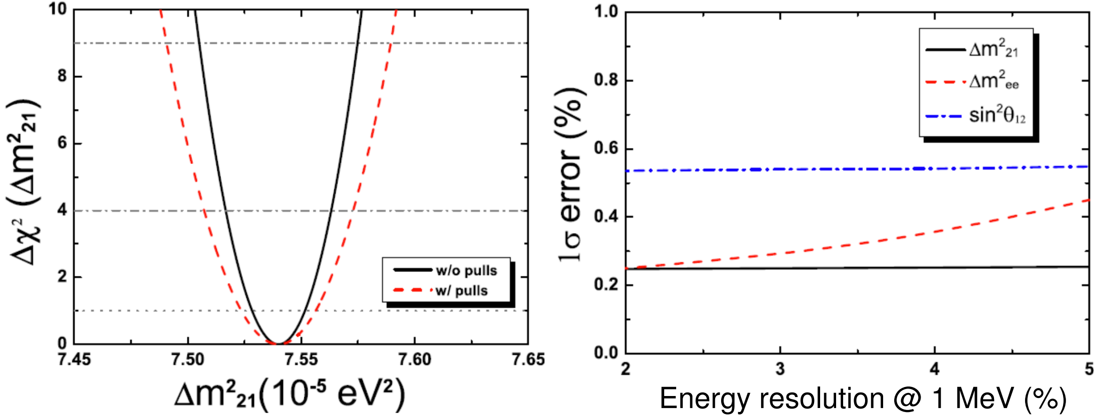


Precision measurements of $\bar{\nu}$ oscillations

- In order to measure NMO, need exquisite details of oscillation pattern

$\Rightarrow$ can also profit to extract particular oscillation parameters with precision <1%

- And test oscillations over several periods, probing simultaneously Δm^2_{21}-driven and $\Delta m^2_{32}/\Delta m^2_{31}$-driven oscillation modes.



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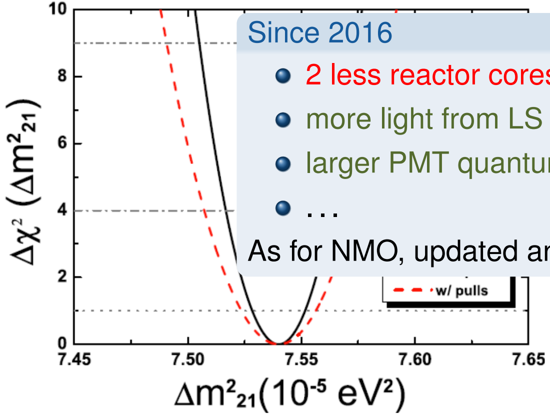
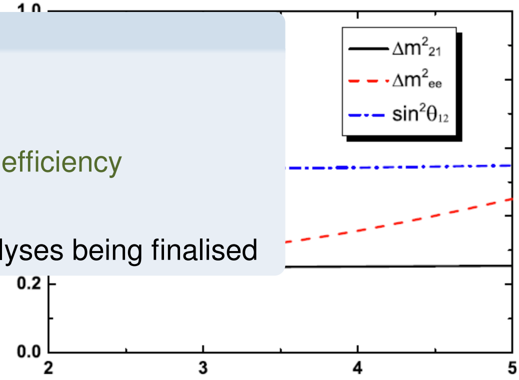


Since 2016

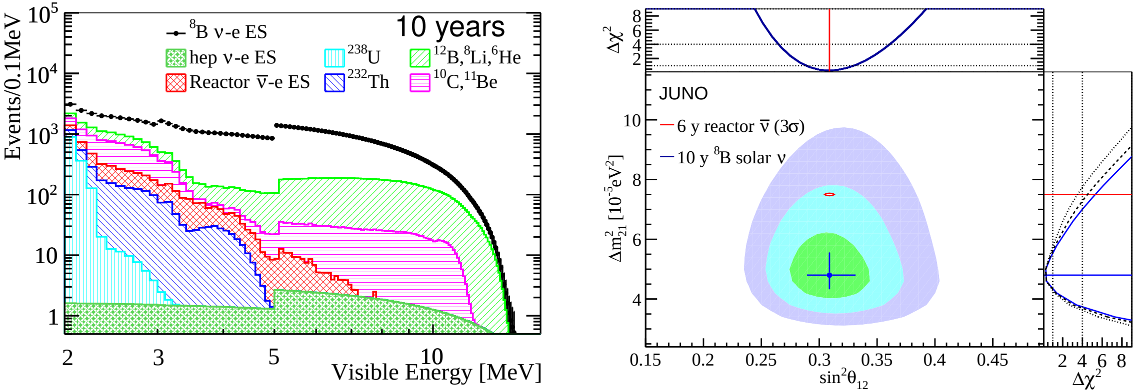
- 2 less reactor cores
- more light from LS
- larger PMT quantum efficiency
- …

As for NMO, updated analyses being finalised



Solar ν

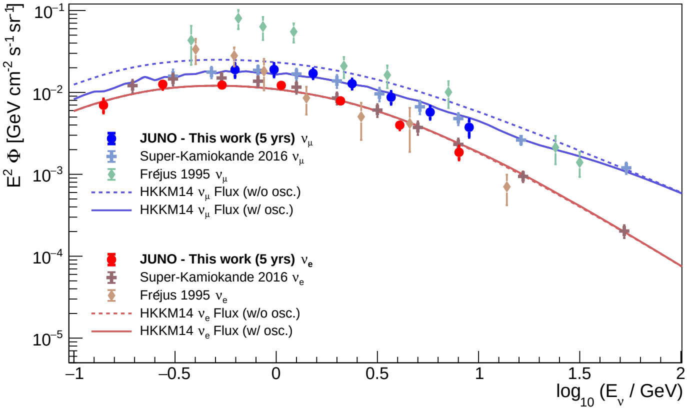
See also poster #1084 by Jie Zhao



- Solar ν harder to detect given no prompt-delayed signature
- Analysis possible assuming 10^{-17} g/g level for intrinsic ^{238}U and ^{232}Th contamination
- JUNO alone has similar precision to Solar global fit
  - Check tension in between solar ν exps. and KamLAND with single experiment!

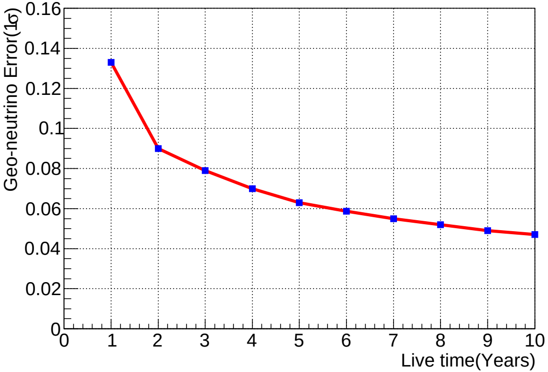
Atmospheric ν

- Lower sensitivity to NMO (1.8 σ w/ 10 years)
- Ongoing Atmo.+Reactor analysis
- Also able to measure Atmospheric ν spectrum
  - Uncertainties between 10% and 25% w/ 5 years of data expected
  - More info on arXiv:2103.09908



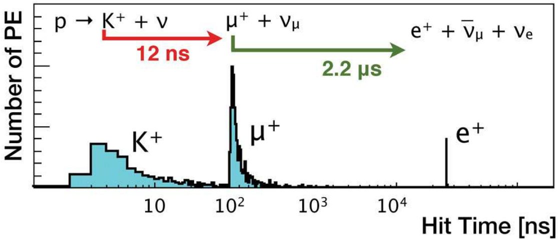
Other topics in JUNO

Geo $\bar{\nu}$



- Also potential to constrain Th/U ratio

Nucleon decay



- Triple coincidence signature from $p \rightarrow \bar{\nu} + K^{+}$
- Other nucleon decay modes also being investigated

Among other topics discussed in J. Phys. G **43** (2016) no.3, 030401 and in arXiv:2104.02565 (2021)

Conclusions

- JUNO will have unique properties: large target mass & good energy resolution
  - Measurement of NMO not relying on matter effects
    - $> 3\sigma$ with JUNO only, very complementary with other experiments (5σ within reach!)
  - First observation of several $\bar{\nu}_e$ oscillation peaks within single experiment
  - $< 0.6\%$ precision on $\sin^2 2\theta_{12}$, Δm^2_{21}, and Δm^2_{32}
  - New measurement of atmospheric neutrino spectra in 100 MeV – 10 GeV region
  - Rich physics & astrophysics program beyond reactor-$\bar{\nu}$ analysis
    - Please refer to other JUNO talks/posters @ICRC for some other topics!
- To get there need good understanding of detector response and energy scale
  - JUNO-TAO for reference reactor spectrum
  - Very large photo-coverage & high LS light yield
  - Comprehensive calibration strategy $\rightarrow$ clear path to 3% energy resolution
- JUNO expected to start data taking in 2022

Backup

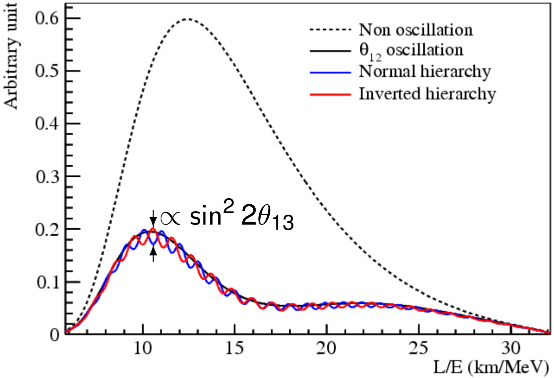
Measuring NMO with reactor neutrinos

method: S. T. Petcov, M. Piai, Phys. Lett. B **533** (2002) 94; formulas: S. F. Ge, *et al*, JHEP **1305** (2013) 131

$$P_{ee} = \left| \sum_{i=1}^{3} U_{ei} \exp\left(-i \frac{m_i^2}{2E_i}\right) U_{ei}^* \right|^2$$
$$= 1 - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(\Delta_{21})$$
$$- \cos^2\theta_{12} \sin^2 2\theta_{13} \sin^2(\Delta_{31})$$
$$- \sin^2\theta_{12} \sin^2 2\theta_{13} \sin^2(\Delta_{32}),$$

$$P_{ee} = 1 - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(\Delta_{21})$$
$$- \sin^2 2\theta_{13} \sin^2(|\Delta_{31}|)$$
$$- \sin^2\theta_{12} \sin^2 2\theta_{13} \sin^2(\Delta_{21}) \cos(2|\Delta_{31}|)$$
$$\pm \frac{\sin^2\theta_{12}}{2} \sin^2 2\theta_{13} \sin(2\Delta_{21}) \sin(2|\Delta_{31}|),$$

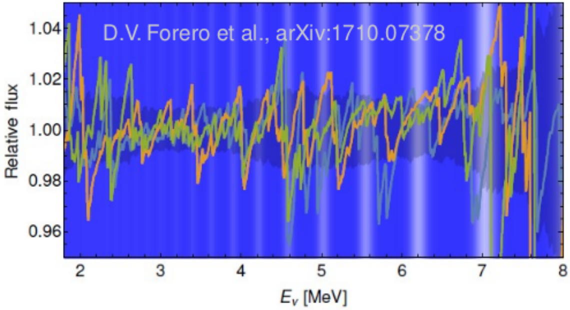
$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu}, \quad (\Delta m_{ij}^2 \equiv m_i^2 - m_j^2)$$



- Normal(+)/Inverted(−) Ordering → measurable only if θ_{13} "large"
- Need excellent energy resolution to distinguish fast oscillation

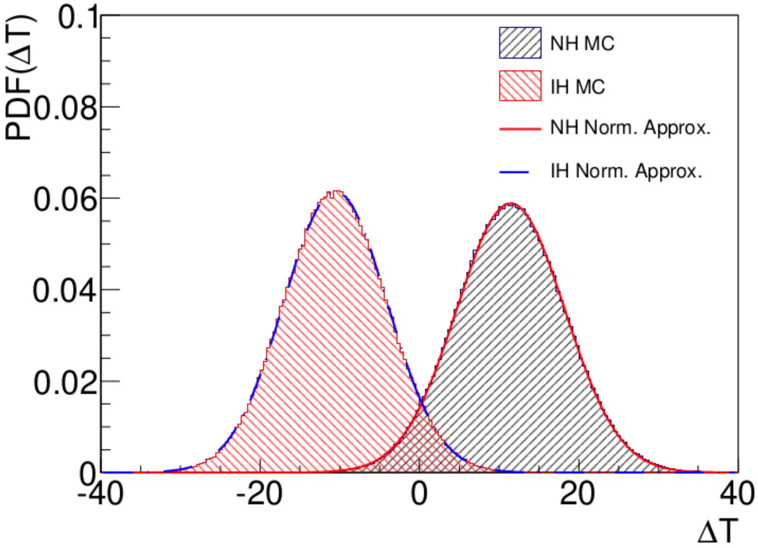
Substructures in the reactor spectrum

- The reactor neutrino spectrum prediction has a series of limitations
  - 5 MeV bump, “reactor neutrino anomaly”, . . .
  - These “large structures” have minor impact on NMO sensitivity
- However, when trying to fix the model “fine structures” can appear
  - Current data from Daya Bay cannot distinguish these differences



Relative difference of 3 synthetic spectra to spectrum predicted from ILL data (Huber+Mueller model)

Test Statistic for NMO



- Reactor ν oscillation

$$P = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

- Daya Bay's 2-ν approximation

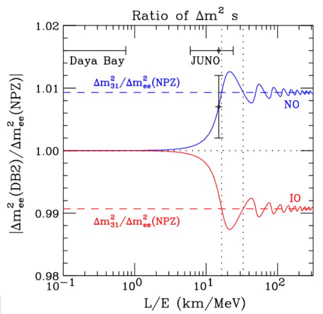
$$P_{sur} \simeq 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{ee}$$

  - ⇨ In the standard 3-ν framework: $\sin^2\Delta_{ee} \equiv \cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}$

- "Comments on the Daya Bay's definition and use of Δm_{ee}^2", S. Parke and R. Zukanovich Funchal, arXiv:1903.001
  - ⇨ (Daya Bay's definition) obfuscates the simple relationship between such an effective Δm^2 and the fundamental parameters
  - ⇨ $\Delta m^2_{ee}(\mathrm{NPZ}) \equiv \cos^2\theta_{12}\Delta \mathrm{m}^2_{31} + \sin^2\theta_{12}\Delta \mathrm{m}^2_{32}$ should be used, since at JUNO's baseline, 6<L/E<25 km/MeV, Daya Bay's definition has a 1% jump.

- S. Parke and R. Zukanovich Funchal, arXiv:1903.001:
  - ⇨ Submitted to PRL

[9] Until JUNO determines the mass ordering, which is highly non-trivial due to stringent requirements on the resolution and linearity of the neutrino energy reconstruction, Δm^2_{ee} is the only atmospheric Δm^2 that JUNO can report without having to give separate measurements for each mass ordering, as would be needed for Δm^2_{31} (or Δm^2_{32}), since $\Delta m^2_{31} = \pm|\Delta m^2_{ee}| + \sin^2\theta_{21}\Delta m^2_{21}$.



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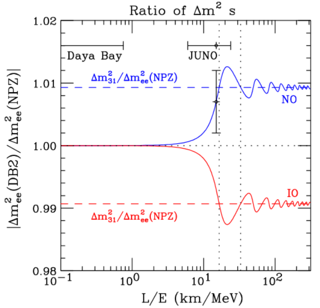
Attention: although in this plot, Δm^2_{ee}(NPZ) is a constant for a given MH, but it is meaningless since the 2-ν oscillation formula is then not a good approximation at JUNO's baseline.



- Response to "Comment on Daya Bay's definition and use of Δm^2_{ee}", **Daya Bay collaboration**, arXiv:1905.03840
  - DYB's definition is

$$P_{sur} \simeq 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{ee}$$

    where Δm^2_{ee} is a (model independent) fitting parameter based on experimental facts. It enables multiple interpretations, either in the 3-ν framework or beyond.
  - DYB did not define Δm^2_{ee} using fundamental parameters.
  - At JUNO's baseline, the 2-ν approximation is no longer valid. We shouldn't use Δm^2_{ee} (in any definitions). Instead, the fundamental parameters Δm^2_{31} and Δm^2_{32} should be used.

We indeed used Δm^2_{ee} in our Yellow Book →