Physics prospects of JUNO

João Pedro Athayde Marcondes de André
for the JUNO Collaboration

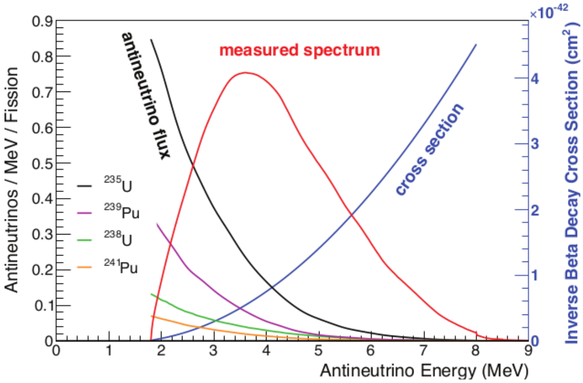
IPHC/IN2P3/CNRS

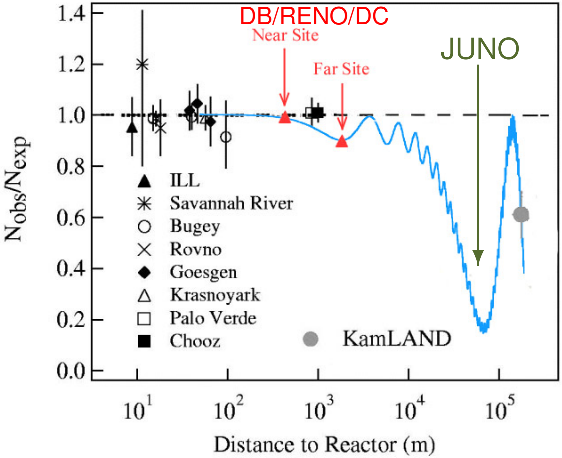
The JUNO Collaboration

Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	IMP-CAS	Germany	U. Mainz
Belgium	Universite libre de Bruxelles	China	SYSU	Germany	U. Tuebingen
Brazil	PUC	China	Tsinghua U.	Italy	INFN Catania
Brazil	UEL	China	UCAS	Italy	INFN di Frascati
Chile	PCUC	China	USTC	Italy	INFN-Ferrara
Chile	UTFSM	China	U. of South China	Italy	INFN-Milano
China	BISEE	China	Wu Yi U.	Italy	INFN-Milano Bicocca
China	Beijing Normal U.	China	Wuhan U.	Italy	INFN-Padova
China	CAGS	China	Xi'an JT U.	Italy	INFN-Perugia
China	ChongQing University	China	Xiamen University	Italy	INFN-Roma 3
China	CIAE	China	Zhengzhou U.	Latvia	IECS
China	DGUT	China	NUDT	Pakistan	PINSTECH (PAEC)
China	ECUST	China	CUG-Beijing	Russia	INR Moscow
China	Guangxi U.	China	ECUT-Nanchang City	Russia	JINR
China	Harbin Institute of Technology	Czech R.	Charles University	Russia	MSU
China	IHEP	Finland	University of Jyvaskyla	Slovakia	FMPICU
China	Jilin U.	France	LAL Orsay	Taiwan-China	National Chiao-Tung U.
China	Jinan U.	France	CENBG 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	FZJ-ZEA	Thailand	SUT
China	Shandong U.	Germany	RWTH Aachen U.	USA	UMD1
China	Shanghai JT U.	Germany	TUM	USA	UMD2
China	IGG-Beijing	Germany	U. Hamburg	USA	UC Irvine
China	IGG-Wuhan	Germany	FZJ-IKP		

= 77 members

Neutrino oscillations with Reactor Neutrinos

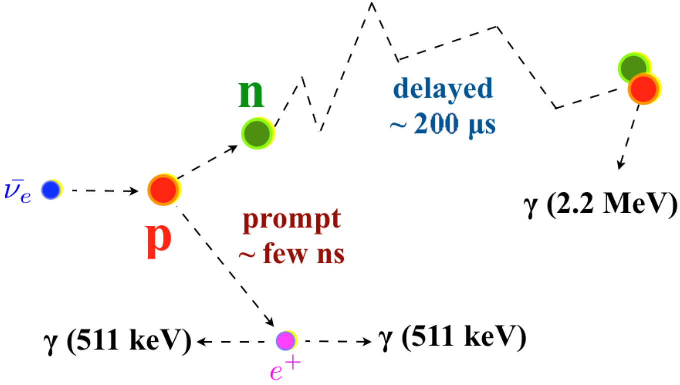




- Detected $\bar{\nu}_e$ energy 2–8 MeV
  - Only sensitive to $\bar{\nu}_e \to \bar{\nu}_e$
- Distance: selects "oscillation regime"
  - JUNO placed at Δm^2_{21} minimum
  - First experiment to see both Δm^2

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

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



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

JUNO site

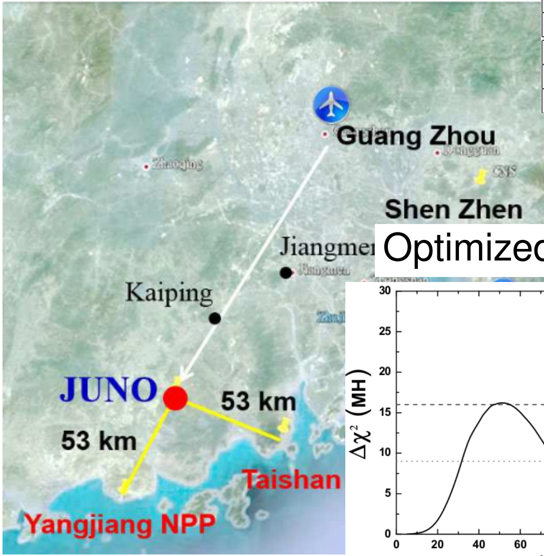
Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline(km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline(km)	52.76	52.63	52.32	52.20	215	265

by 2020: 26.6 GW

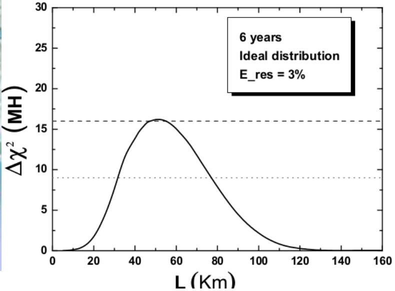
JUNO site

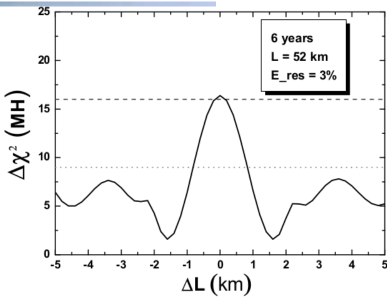
Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline(km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline(km)	52.76	52.63	52.32	52.20	215	265

by 2020: 26.6 GW

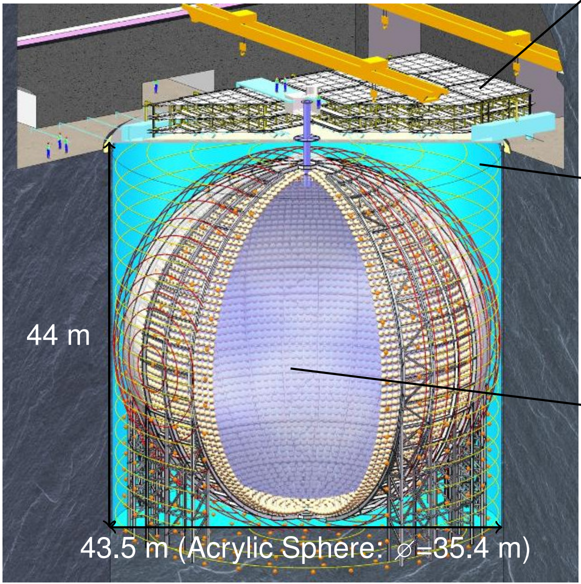


Optimized for Neutrino Mass Ordering (NMO)





The JUNO detector

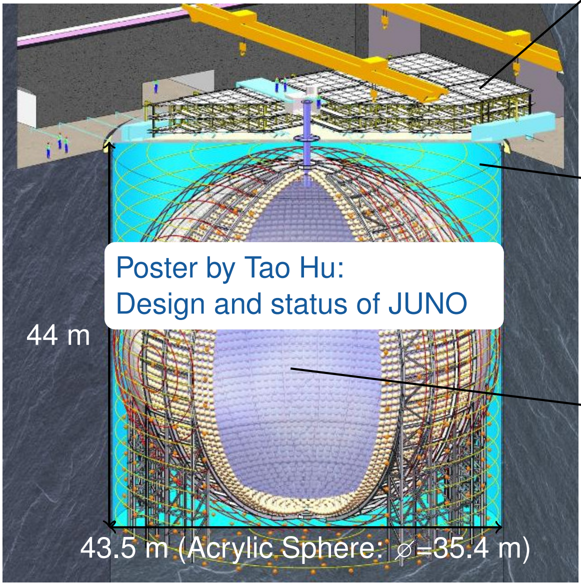


Top Tracker (TT)
- Precise μ tracker
- 3 layers of plastic scintillator
- $\sim$ 60% of area above WCD

Water Cherenkov Detector (WCD)
- 25 kton ultra-pure water
- 2.4k 20” PMTs
- High μ detection efficiency
- Protects CD from external radioactivity

Central Detector (CD) – $\bar{\nu}$ target
- Acrylic sphere with 20 kton liquid scint.
- 18k 20” PMTs + 25k 3” PMTs
- 3% energy resolution @ 1 MeV

The JUNO detector



Poster by Tao Hu:
Design and status of JUNO

Top Tracker (TT)

- Precise μ tracker
- 3 layers of plastic scintillator
- $\sim$ 60% of area above WCD

Water Cherenkov Detector (WCD)

- 25 kton ultra-pure water
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- High μ detection efficiency
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Central Detector (CD) – $\bar{\nu}$ target

Poster by Filippo Marini :
The JUNO Large PMT Readout electronics

JUNO physics

"Neutrino Physics with JUNO," J. Phys. G **43** (2016) no.3, 030401

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

JUNO physics

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Poster by Giulio Settanta:
Atmospheric neutrino spectrum reconstruction with JUNO

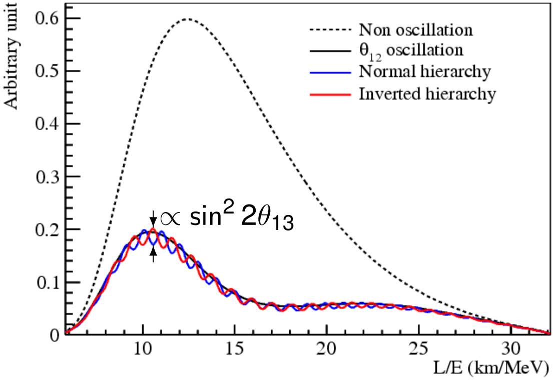
Measuring NMO with reactor neutrinos

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

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

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

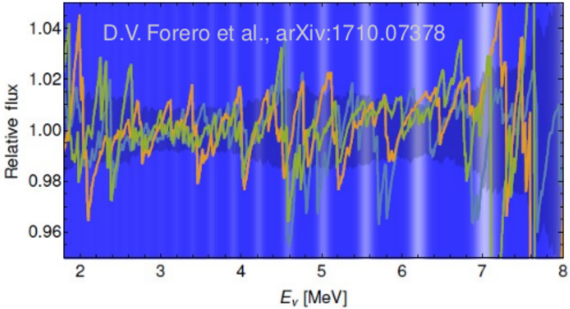
$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu}, \quad (\Delta m_{ij}^2 \equiv m_i^2 - m_j^2)$$



- 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



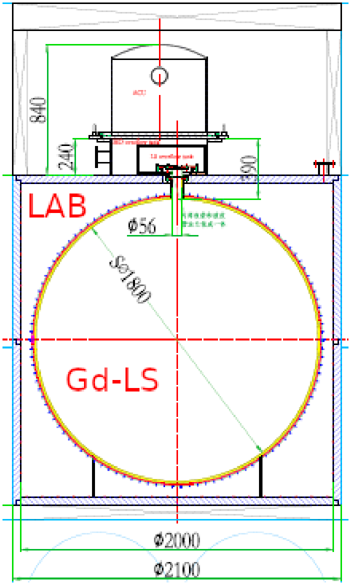
Relative difference of 3 synthetic spectra to spectrum predicted from ILL data (Huber+Mueller model)

JUNO-TAO

- JUNO-TAO (Taishan Antineutrino Observatory) provides reference for reactor spectrum
- Data driven approach to eliminate dependency of model of reactor neutrino spectrum
- Requirement: energy resolution of JUNO-TAO equal to or better than JUNO

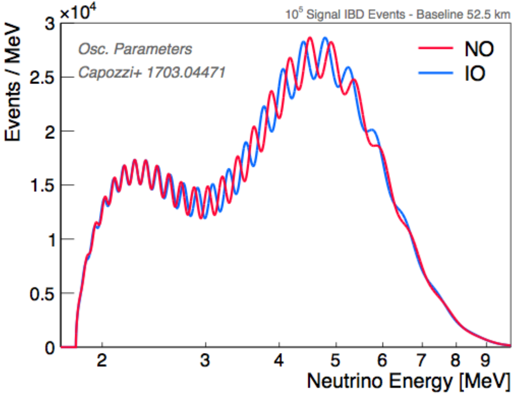
JUNO-TAO detector:

- 1 ton fiducial volume Gd-LS detector
  - 30 m from reactor core
  - 30$\times$ JUNO event rate
- 10 m^2 SiPM of 50% photon detection efficiency (PDE) operated at $-50°C$
  - Energy resolution: 1.7% @ 1 MeV



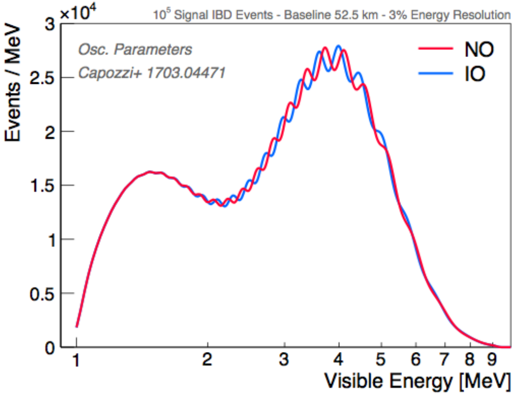
Measuring NMO with reactor neutrinos: impact of energy resolution

$\bar{\nu}_e$ oscillated spectrum



- Ideal case
- Exposure: 20 kt · 6 years

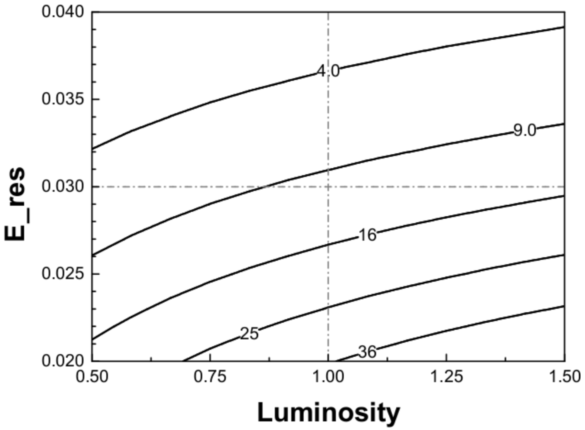
+ energy resolution



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

NMO sensitivity with JUNO

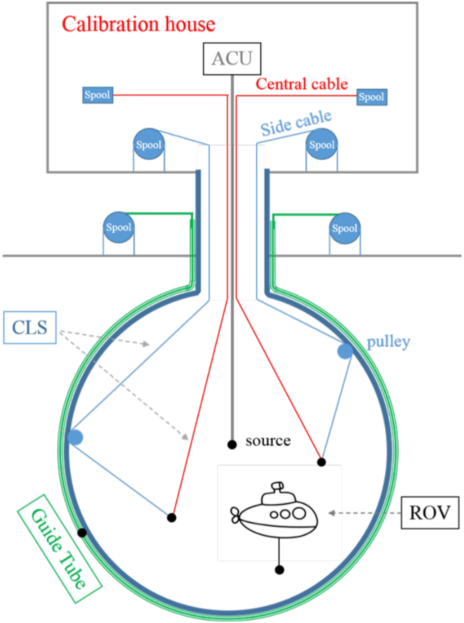
- NMO sensitivity calculated using Asimov sample
- $\Delta\chi^2 = 11$ – stat only, with 3% energy resolution @1 MeV
  - To reach required energy resolution: high light yield + large PMT coverage + good calibration
- Accounting for systematic uncertainties: $\Delta\chi^2 \approx 10 \Rightarrow 3-4\ \sigma$
- External constraints on $\Delta m^2_{(\nu_\mu \to \nu_\mu)}$ w/ 1% precision $\Rightarrow$ improved sensitivity



	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%
$\Delta\chi^2_{\mathrm{MH}}$	$+16$	-3	-1.7	-1	-0.6	-0.1	$+(4-12)$

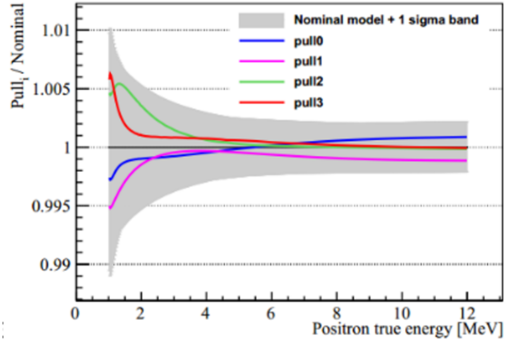
Calibration systems

- Goals:
  - 3% energy resolution @1 MeV
  - energy scale uncertainty $< 1\%$
  - This is essential for NMO
- 4 complementary calibration systems:
  - Automated Calibration Unit: vertical shaft
  - Cable Loop System: move source in LS within given plane
  - Guide Tube: check calibration near FV boundary
  - Remotely Operated Vehicle: full detector scan
- Many radioactive sources used

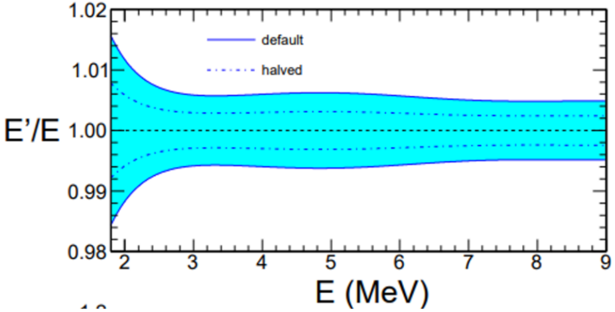


Calibration systems: Daya Bay experience

Updated Daya Bay relative uncertainty



Uncertainty in arxiv:1508.01392



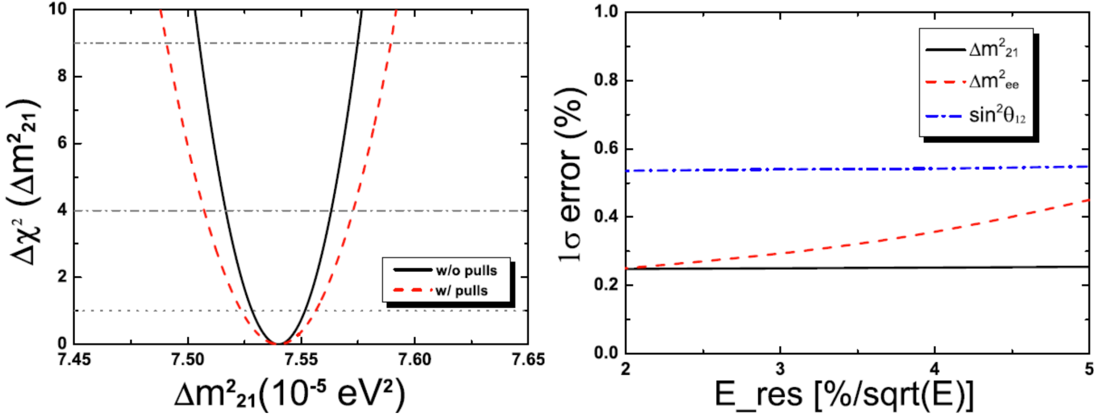
- Extensive calibration procedure in Daya Bay shows signifcant reduction of non-linearity uncertainty
- Current Daya Bay non-linearity within requirement for JUNO

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

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

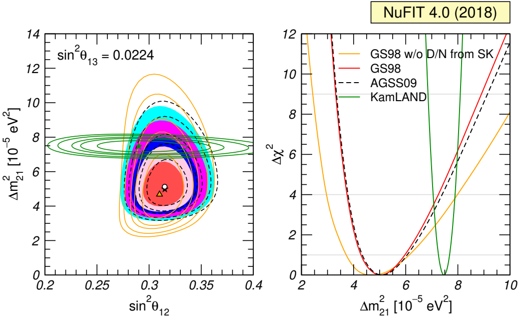
$\Rightarrow$ can also profit to extract particular oscillation parameters with precision <1%

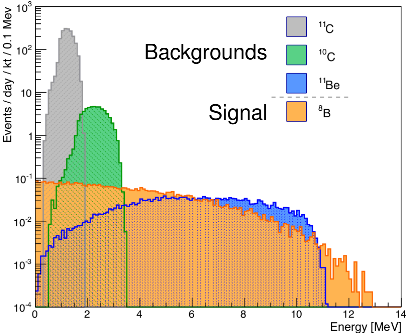
- And test oscillations over several periods, probing simultaneously Δm^2_{21}-driven and $\Delta m^2_{32}/\Delta m^2_{31}$-driven oscillation modes.



Solar ν

- Challenging measurement due to
  - low overburden
  - no IBD signature $\rightarrow$ drives JUNO radiopurity requirements
- Mild tension between Solar and KamLAND ν oscillations
  - JUNO will measure reactor and solar ν osc. with same detector
- Constraints on solar metalicity composition





Atmospheric Neutrinos Flux Unfolding

- Poster by Giulio Settanta
- ν_e and ν_μ flux unfolding around 1 GeV
- First unfolding of atm. ν flux with LS detector

6. Spectrum reconstruction

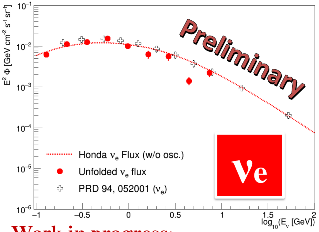
Probabilistic unfolding algorithm (based on the Bayes theorem)

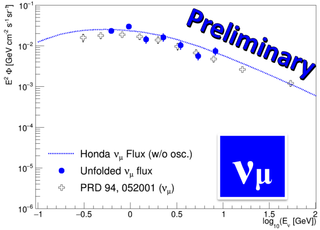
Unfolded spectrum

Detector observable

$$\boxed{P(E)^{\nu_\alpha}} = P(E|NPE_{LPMT})^{\nu_\alpha} \cdot \boxed{P(NPE_{LPMT})^{\nu_\alpha}}$$

<u>**The algorithm has been tested on an independent 10k ν sample**</u>



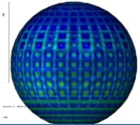


Work in progress:

- **Study of residual contamination;**
- **evaluation of systematic effects;**
- **spectrum distorsion introduced by flavor oscillations.**

JUNO Milestones & Schedule

2014
:
- International collaboration established
- Start civil construction



2015
:
- PMT production line setup
- CD parts R&D

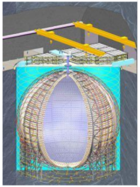
2016
:
- Start PMT production
- Start CD parts production

2017
:
- Start PMT testing
- TT arrived

2018
:
- PMT potting
- starts Delivery of surface buildings
- Start production of acrylic sphere

2019-2020:

- Electronics production starts
- Civil work and lab preparation Completed
- Detector constructing



2021
:
- Detector ready for Data taking!

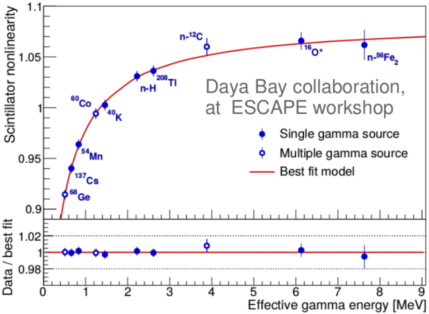
Conclusion

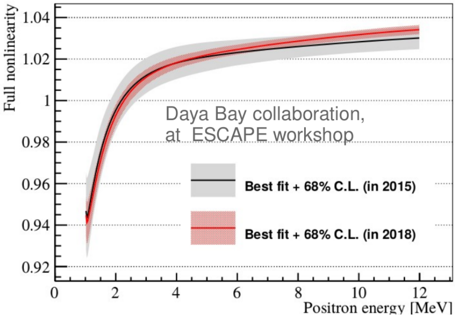
- JUNO will have unique properties: large target mass & good energy resolution
  - Measurement of NMO not relying on matter effects
    - $> 3\sigma$ with JUNO only, can reach $> 4\sigma$ with $\Delta m^2_{\mu\mu}$ constraint
  - First observation of several ν oscillation peaks within single experiment
  - Exquisite $< 1\%$ precision on $\sin^2\theta_{12}$, Δm^2_{21}, and Δm^2_{ee}
  - Rich physics & astrophysics program beyond reactor-ν analysis
- To get there need good understanding of detector response and energy scale
  - Very large detection efficiency/coverage/LS light yield
  - Extensive calibration apparatus
  - Double calorimetry system
  - JUNO-TAO for reference reactor spectrum
  - ...
- JUNO on track to start data taking on 2021!

Backup

Calibration systems: Daya Bay experience

New calibration results from Daya Bay at ESCAPE workshop @Heidelberg June 2018





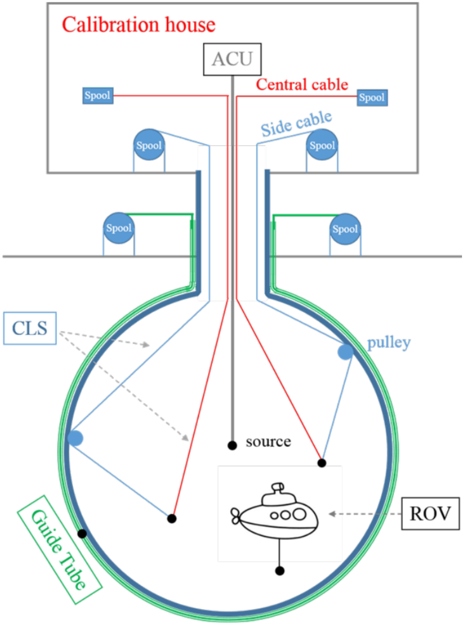
- Extensive calibration procedure in Daya Bay shows signifcant reduction of non-linearity uncertainty
- This will be a critical point for JUNO

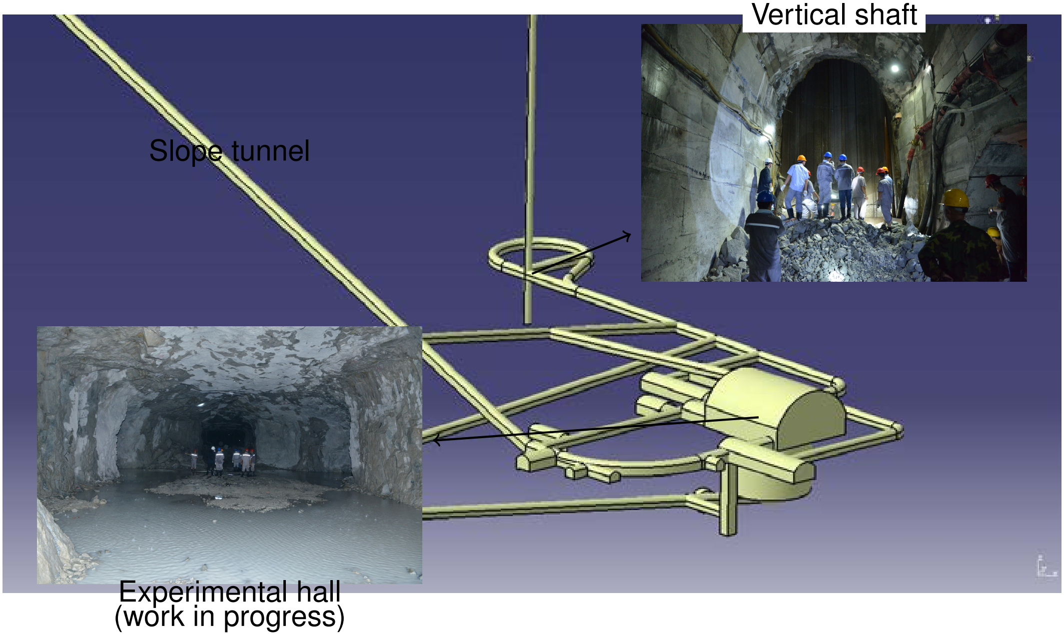
Calibration systems

- Goal: 3% en. res. @1 MeV, en. scale uncertainty $< 1\%$
- Many radioactive sources used

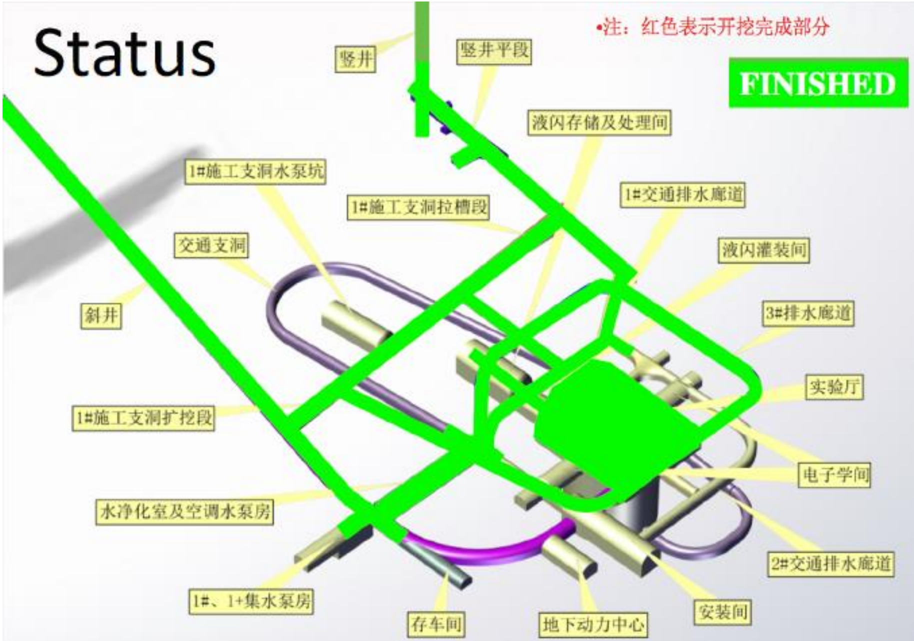
Source	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	**γ**	**1.173 + 1.333 MeV**
^{40}K	**γ**	**1.461 MeV**
^{68}Ge	**e^+**	**annil 0.511 + 0.511 MeV**
^{22}Na	e^+	annil + 1.275 MeV
^{40}K	**e^-**	**0~1.31 MeV**
^{90}Sr	e^-	0~2.28 MeV
^{241}Am-Be	n, γ	neutron + 4.43 MeV
^{241}Am-^{13}C or ^{241}Pu-^{13}C	n, γ	neutron + 6.13 MeV
^{252}Cf	multiple n, multiple γ	prompt γ's, delayed n's

- 4 complementary calibration systems:
  - Automated Calibration Unit: vertical shaft
  - Cable Loop System: move source in LS within given plane
  - Guide Tube: check calibration near FV boundary
  - Remotely Operated Vehicle: full detector scan




Vertical shaft
Slope tunnel
Experimental hall
(work in progress)

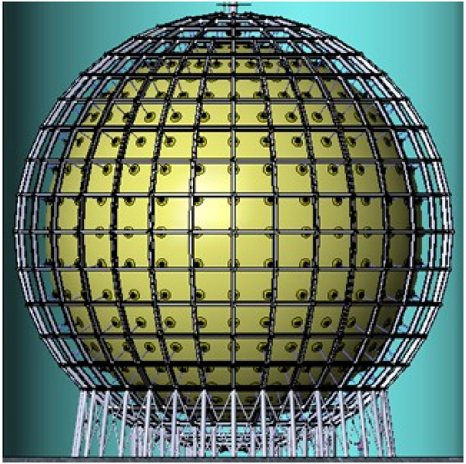
Status



•注：红色表示开挖完成部分
FINISHED
竖井
竖井平段
液闪存储及处理间
1#施工支洞水泵坑
1#施工支洞拉槽段
1#交通排水廊道
交通支洞
液闪灌装间
斜井
3#排水廊道
实验厅
1#施工支洞扩挖段
电子学间
水净化室及空调水泵房
2#交通排水廊道
1#、1+集水泵房
存车间
地下动力中心
安装间

Central Detector

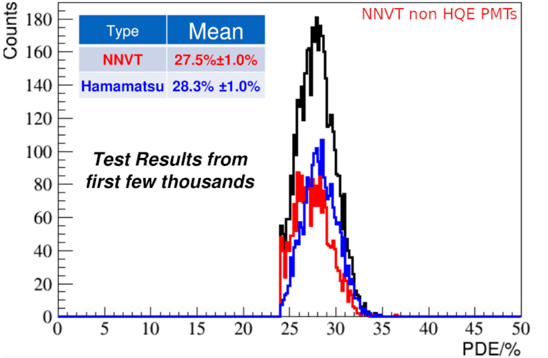
- Liquid Scintillator-based calorimeter
- Stell structure supporting PMTs + Acrylic Sphere
- 18k 20” PMTs
- 25k 3” PMTs
  - Double Calorimetry
  - 78% coverage
- 1200 PE/MeV
  - High light-yield liquid scintillator
  - KamLAND: $\sim$ 250 PE/MeV



20” PMTs

- 20k PMTs: 15k Micro-Channel Plate PMTs (MCP-PMTs) from NNVT; 5k dynode PMTs from Hamamatsu
  - About 10k delivered, more than 6k tested
- New High Quantum Efficiency (HQE) MCP-PMT this year: 10% more PDE!
  - PDE = photon detection efficiency
- Final design of protection covers finished, bidding done

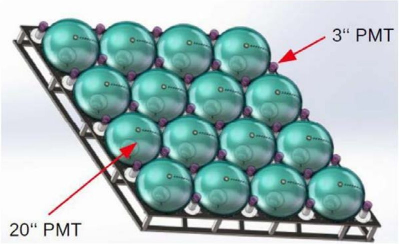
Characteristics	unit	MCP-PMT (NNVT)	R12860 (Hamamatsu)
Detection Efficiency (QE*CE)	%	27%	27%
P/V of SPE		3.5, > 2.8	3, > 2.5
TTS on the top point	ns	~12, < 15	2.7, < 3.5
Rise time/ Fall time	ns	R~2, F~12	R~5,F~9
Anode Dark Count	Hz	20K, < 30K	10K, < 50K
After Pulse Rate	%	1, <2	10, < 15
Radioactivity of glass	ppb	238U:50 232Th:50 40K: 20	238U:400 232Th:400 40K: 40

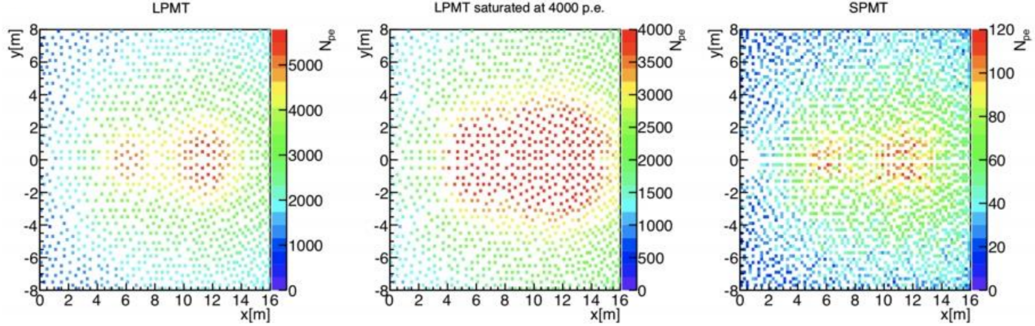


3" PMTs

- 25k PMTs contracted at HZC
  - Very short transient time spread (TTS) < 5 ns
  - 8k already produced and tested at HZC
- Extend dynamic range

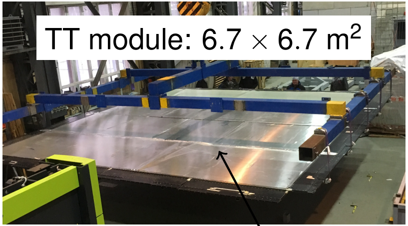
⇒ Better control of systematics and large signals

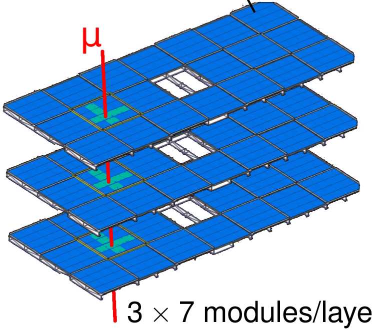




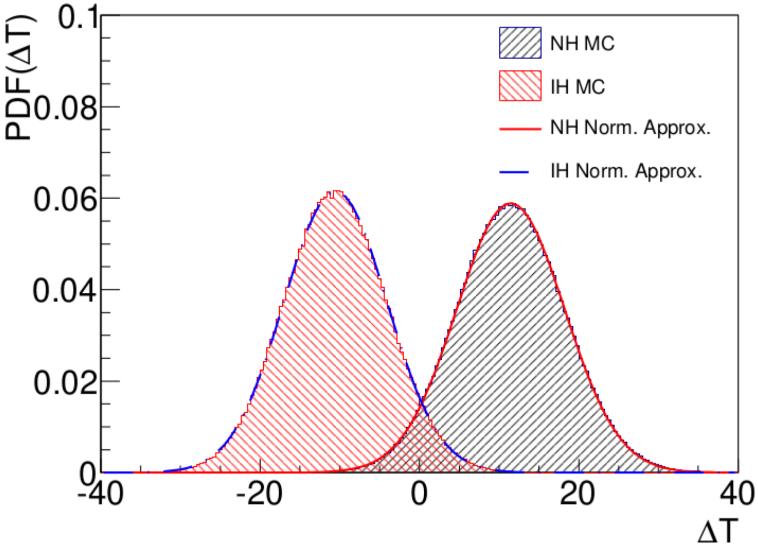
Top Tracker

- Plastic scintillators from OPERA Target Tracker
  - Design of new supporting structure finished
  - New electronics cards being designed to account for 100$\times$ higher radioactivity from rock in JUNO site
- Very precise μ tracking
  - Detector granularity 2.6×2.6 cm^2 in X–Y
  - 3 Layers separated by 1.5 m
  - $\Rightarrow$ 0.2° median resolution
  - Well known real μ data for calibration
- Plastic Scintillator modules already in China
  - No significant aging observed





Test Statistic for NMO

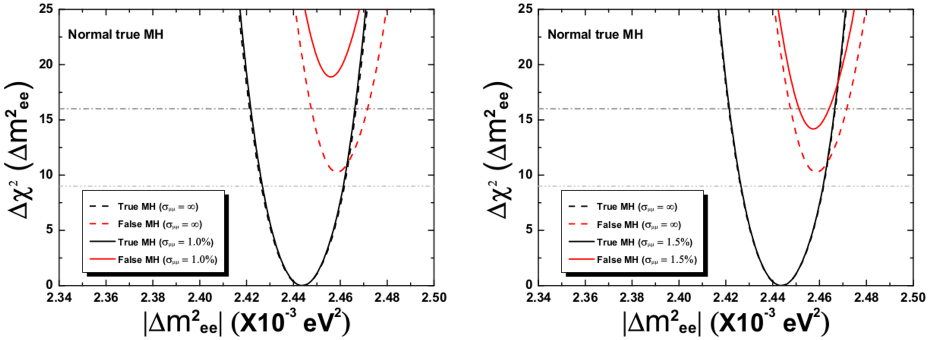


NMO sensitivity with JUNO + external constraints on Δm^2

- Due to intrinsic differences between $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_\mu$, precise measurements of Δm^2 effectively measure a different Δm^2

$$|\Delta m^2_{ee}| - |\Delta m^2_{\mu\mu}| \quad = \quad \pm\Delta m^2_{21}(\cos 2\theta_{12} - \sin 2\theta_{12} \sin\theta_{13} \tan\theta_{23} \cos\delta) \,,$$

- Using a 1% external constraint in $|\Delta m^2_{\mu\mu}|$ increases $\Delta\chi^2$ by 4 – 12



- NMO sensitivity: $> 3\sigma$ with JUNO only, can reach $> 4\sigma$ with $\Delta m^2_{\mu\mu}$ constraint

- Reactor ν oscillation

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

- Daya Bay's 2-ν approximation

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

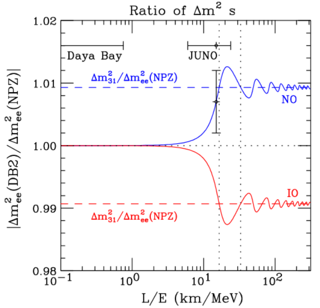
  - ⇨ In the standard 3-ν framework: $\sin^2\Delta_{ee} \equiv \cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}$

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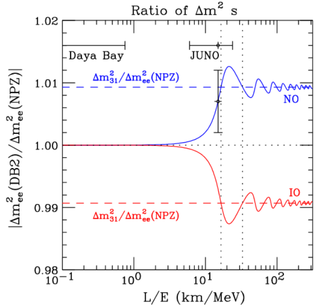
Attention: although in this plot, Δm^2_{ee}(NPZ) is a constant for a given MH, but it is meaningless since the 2-ν oscillation formula is then not a good approximation at JUNO's baseline.



- 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 →