JUNO: status and physics potential

Davide Basilico on behalf of the JUNO collaboration
INFN Milano

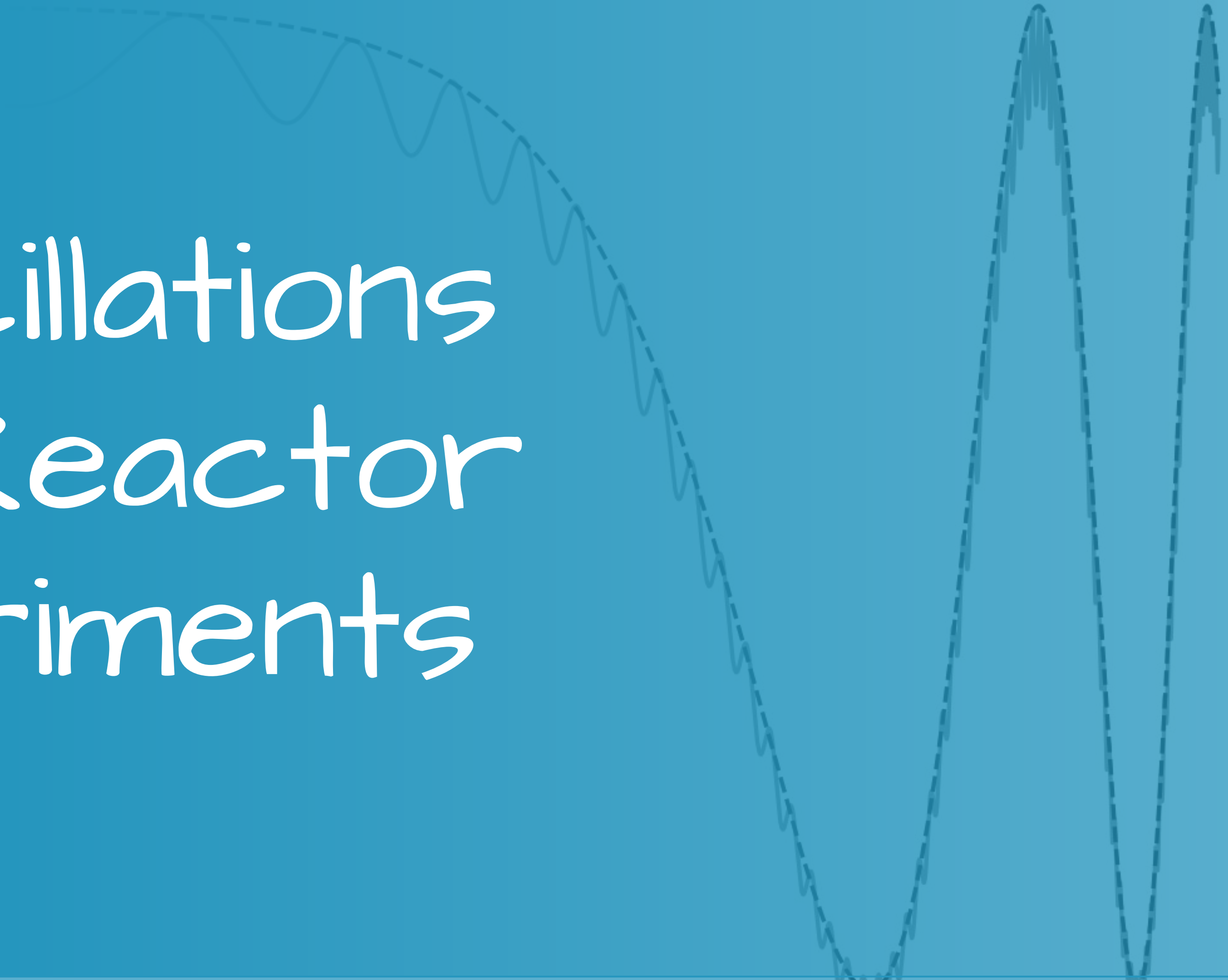
25th International Workshop on Neutrinos from Accelerators

Argonne National Laboratory, Illinois, US

2024 September 20

Istituto Nazionale di Fisica Nucleare

ν oscillations and Reactor experiments



Neutrino oscillations

Quantum superposition of ν mass eigenstates leads to ν oscillation

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}\,|\nu_i\rangle$$

PMNS mixing matrix
(rotation)

Neutrino oscillations

Quantum superposition of ν mass eigenstates leads to ν oscillation

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}\, |\nu_i\rangle$$

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

$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

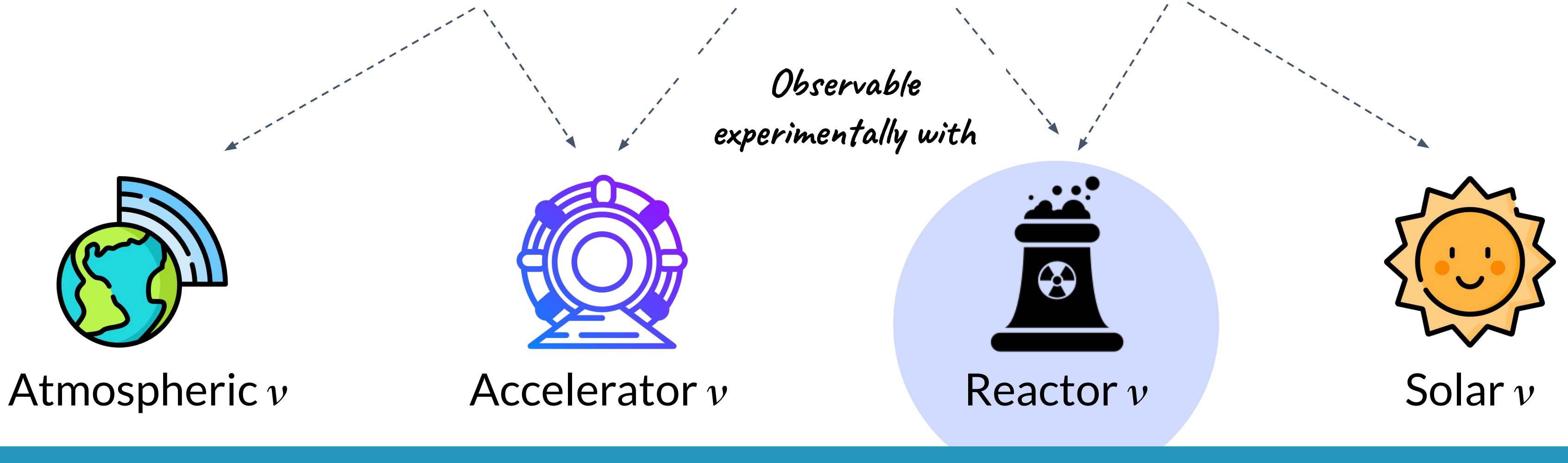
Neutrino oscillations

Quantum superposition of ν mass eigenstates leads to ν oscillation

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}\,|\nu_i\rangle$$

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

$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$



Observable experimentally with

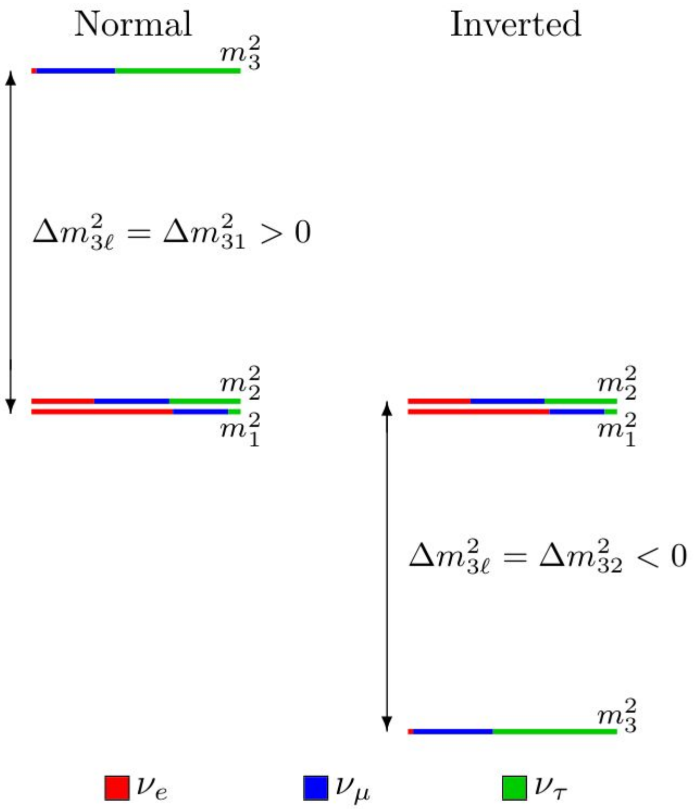
Atmospheric ν

Accelerator ν

Reactor ν

Solar ν

Neutrino Mass Ordering (NMO)



Two mass splittings:

$\Delta m_{21}^2 \sim 7 \cdot 10^{-5}\,\mathrm{eV}^2$

small mass splitting

$\Delta m_{3\ell}^2 \sim 3 \cdot 10^{-3}\,\mathrm{eV}^2$

large mass splitting

What is the correct NMO?

Normal Ordering → $\Delta m_{3\ell}^2 = \Delta m_{31}^2 > 0$

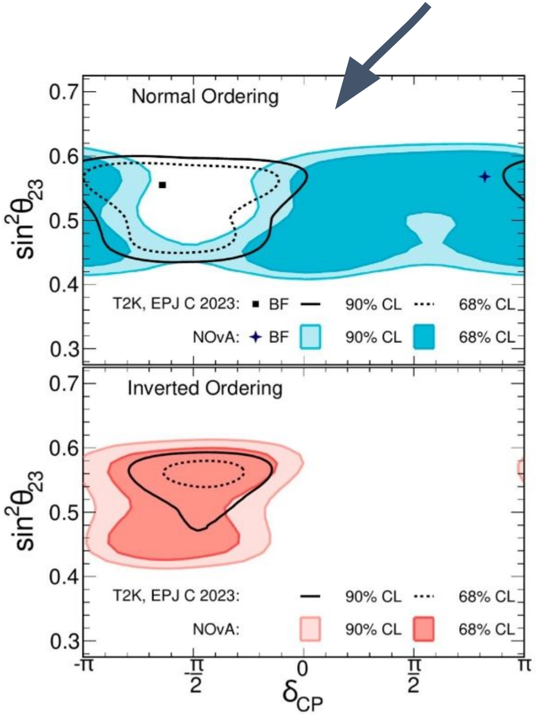
Inverted Ordering → $\Delta m_{3\ell}^2 = \Delta m_{32}^2 < 0$

Why NMO is important?

1) **Missing tile for the fundamental comprehension of neutrinos**
2) **Strictly connected to < 1% determination of θ_{23}, Δm^2 splittings**

Why NMO is important?

1) Missing tile for the fundamental comprehension of neutrinos
2) Strictly connected to < 1% determination of θ_{23}, Δm^2 splittings
3) **Remove the degeneracy between leptonic CP violation (δ_{CP}) and MO → T2K, NOvA, DUNE**

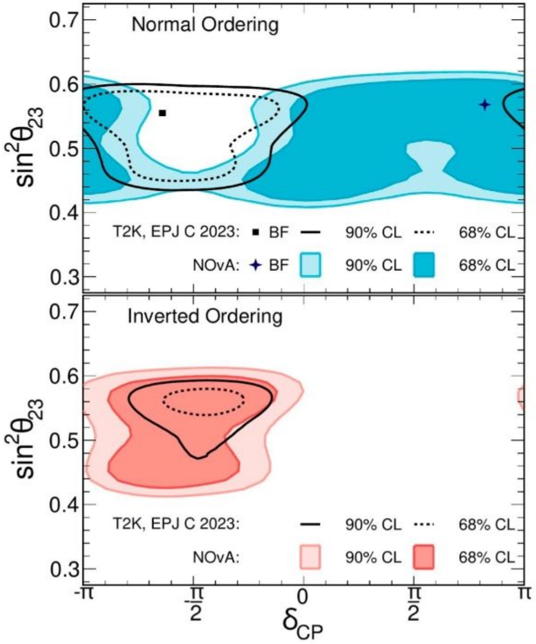


Eur. Phys. J. C (2023) 83: 782,

Phys. Rev. D 110, 012005

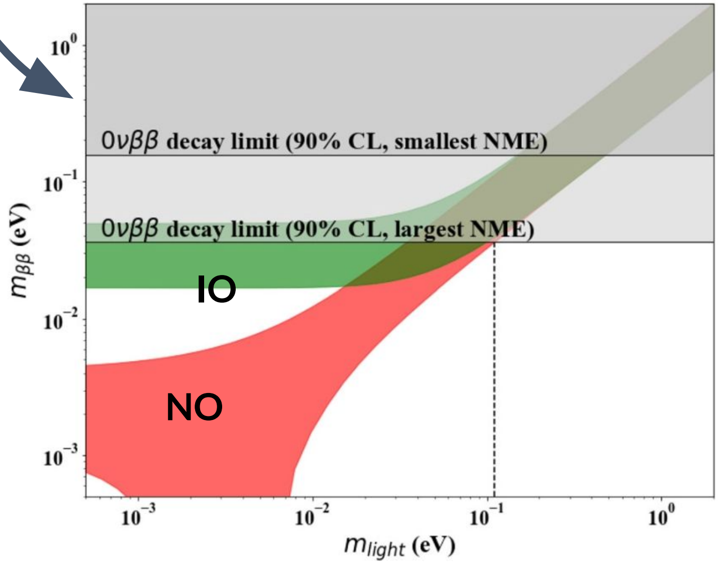
Why NMO is important?

1) Missing tile for the fundamental comprehension of neutrinos
2) Strictly connected to < 1% determination of θ_{23}, Δm^2 splittings
3) Remove the degeneracy between leptonic CP violation (δ_{CP}) and MO → T2K, NOvA, DUNE
4) **Driving the strategy for the next-gen $0\nu\beta\beta$ experiments: can they determine the Dirac/Majorana nature?**



Eur. Phys. J. C (2023) 83: 782,

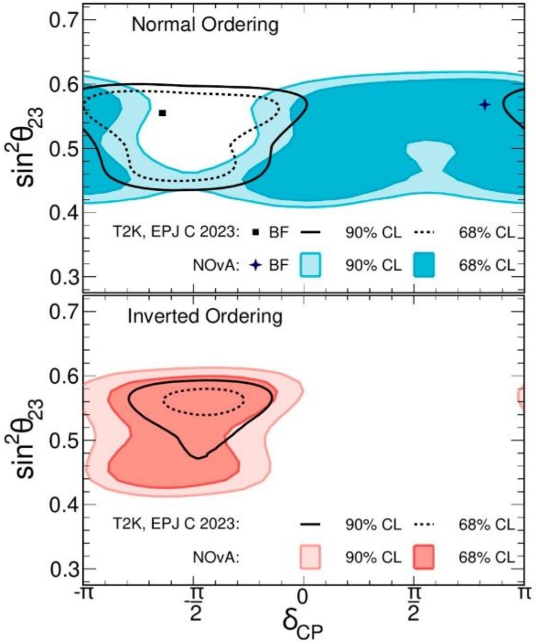
Phys. Rev. D 110, 012005



Gómez-Cadenas et al, Riv.Nuovo Cim. 46 (2023) 10, 619-692

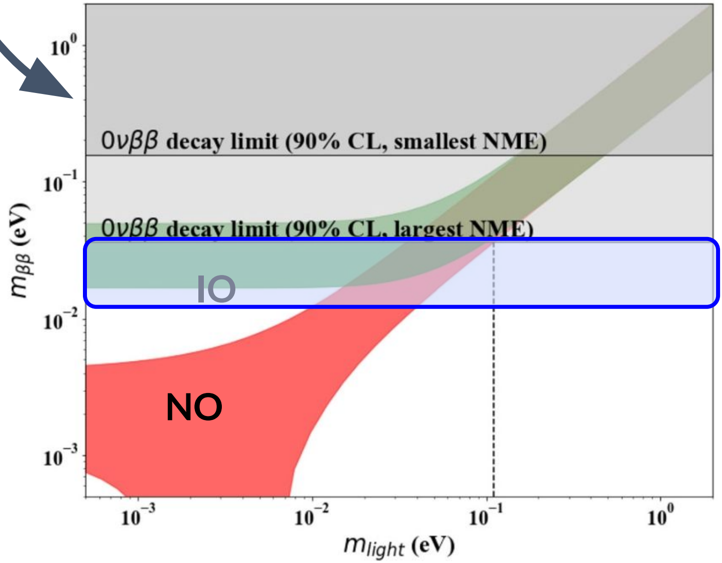
Why NMO is important?

1) Missing tile for the fundamental comprehension of neutrinos
2) Strictly connected to < 1% determination of θ_{23}, Δm^2 splittings
3) Remove the degeneracy between leptonic CP violation (δ_{CP}) and MO → T2K, NOvA, DUNE
4) **Driving the strategy for the next-gen $0\nu\beta\beta$ experiments: can they determine the Dirac/Majorana nature?**



Eur. Phys. J. C (2023) 83: 782,

Phys. Rev. D 110, 012005

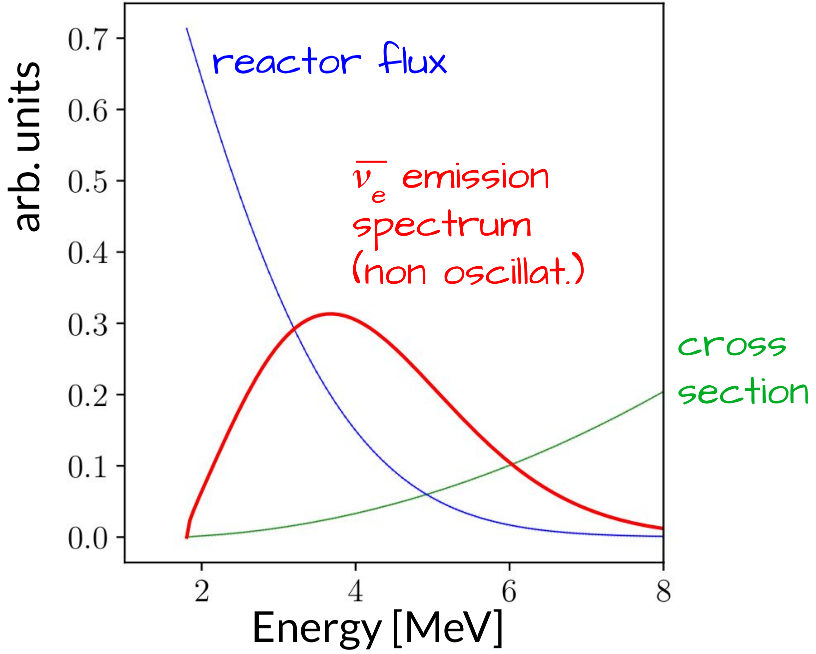


Next generation (ton-scale) experiments

Gómez-Cadenas et al, Riv.Nuovo Cim. 46 (2023) 10, 619-692

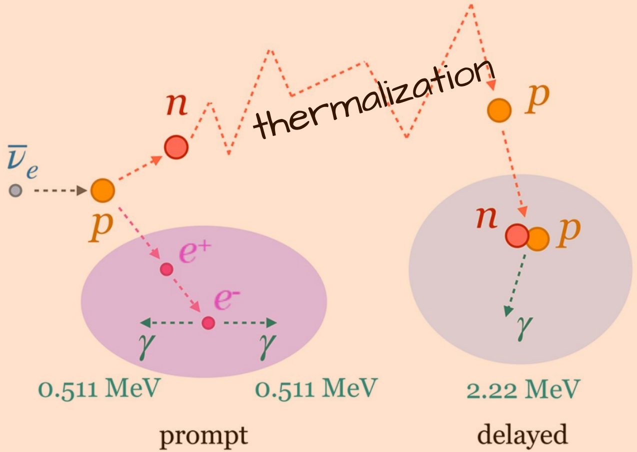
Reactor experiments

Artificial $\overline{\nu}_e$ source → unstable fragments: cascade of β decay of fission daughters of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu. Typical flux ~ $2{\cdot}10^{20}$ ν_e / s / GW$_{th}$, energy E < 10 MeV



Detection: Inverse Beta Decay reaction
prompt-delayed coincidence: energy, time, space

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



Reactor experiments

Wide L/E ranges to explore different oscillation features

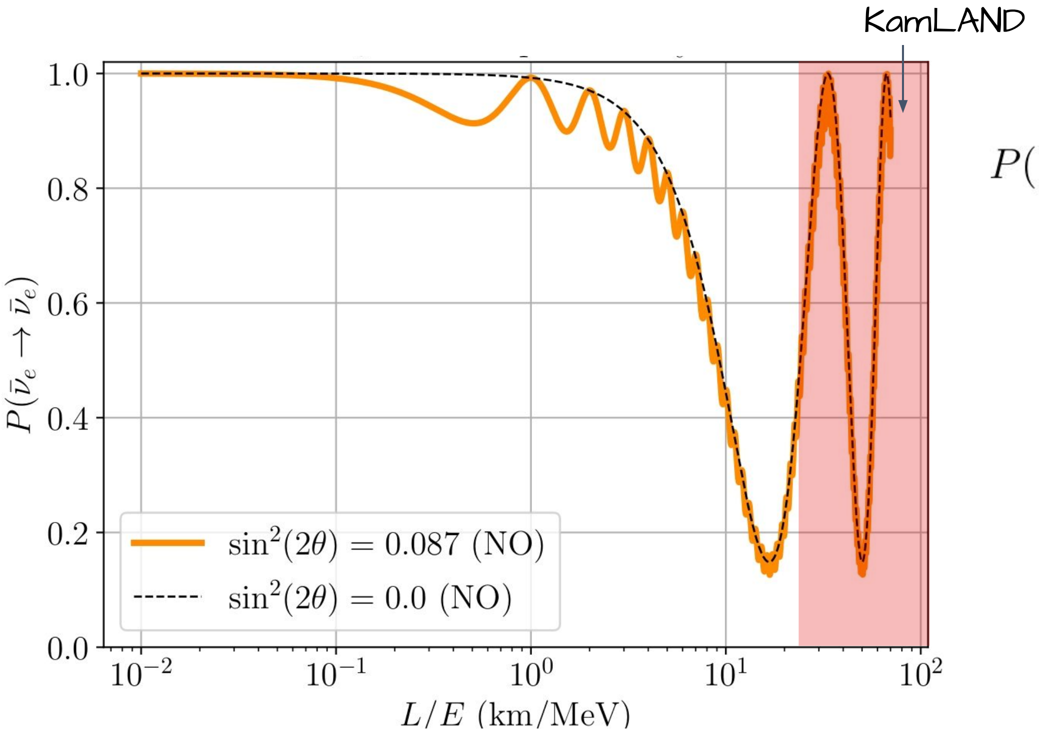
source-detector distance / neutrino energy

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

$$\Delta_{kj} = 1.27\Delta m^2_{kj}[\mathrm{eV}^2]\frac{L[\mathrm{m}]}{E[\mathrm{MeV}]}$$

Reactor experiments

Wide L/E ranges to explore different oscillation features



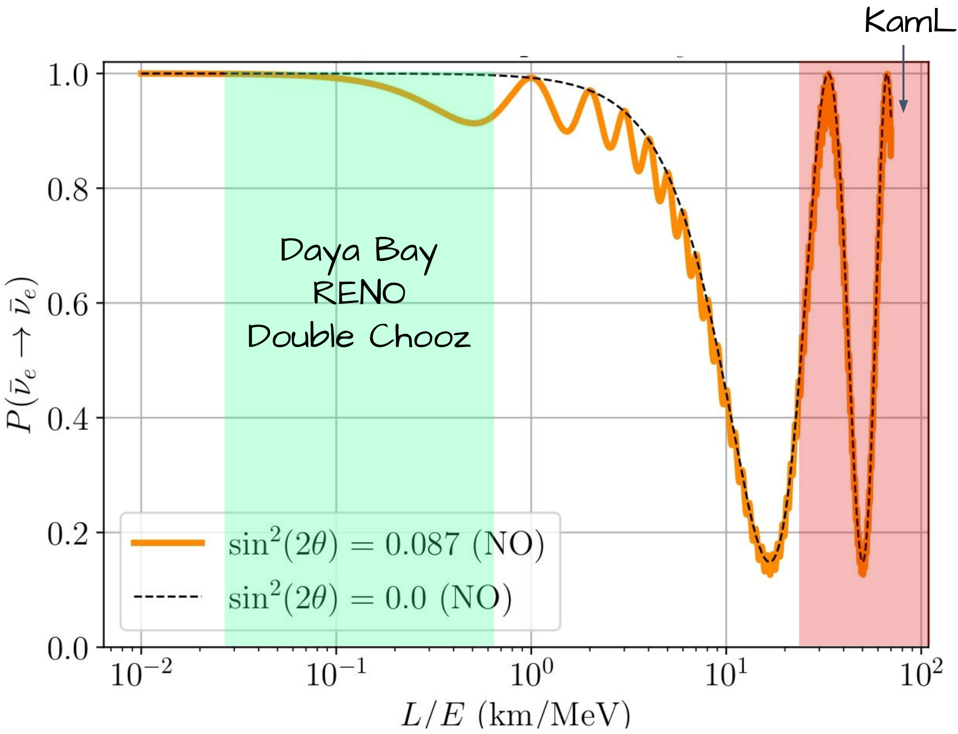
Medium baseline (θ_{12}, Δm^2_{12})

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

$$\Delta_{kj} = 1.27 \Delta m^2_{kj} [\text{eV}^2] \frac{L[\text{m}]}{E[\text{MeV}]}$$

Reactor experiments

Wide L/E ranges to explore different oscillation features



Medium baseline (θ_{12}, Δm^2_{21})

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

Short baseline (θ_{13}, Δm^2_{31})

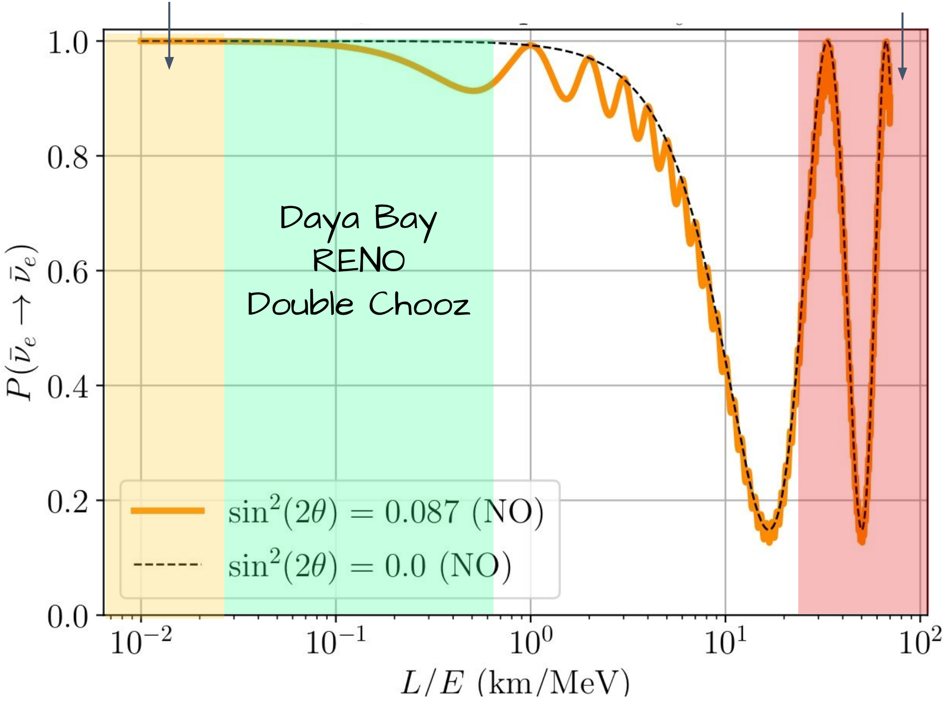
$$\Delta_{kj} = 1.27 \Delta m^2_{kj} [\mathrm{eV}^2] \frac{L[\mathrm{m}]}{E[\mathrm{MeV}]}$$

Reactor experiments

Wide L/E ranges to explore different oscillation features

Very short baseline: sterile ν?
NEOS, DANSS, PROSPECT, SoLid

KamLAND



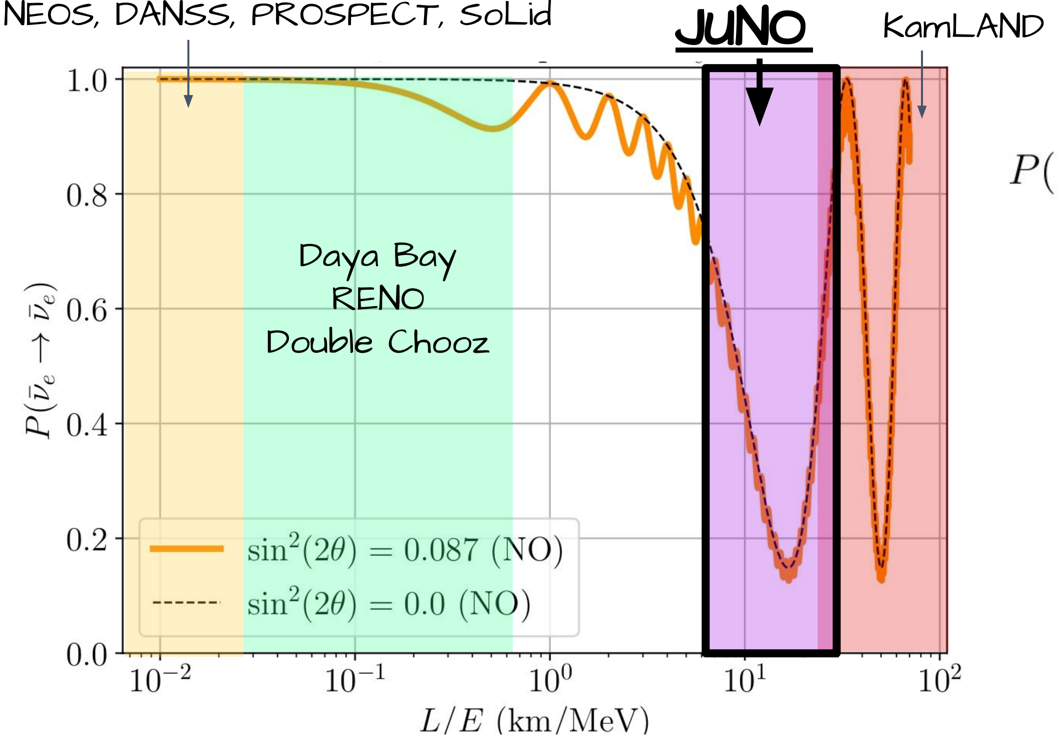
$$
\begin{aligned}
P(\nu_e \to \nu_e) = \; & 1 - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
& - \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
& - \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

$$\Delta_{kj} = 1.27\Delta m^2_{kj}[\mathrm{eV}^2]\frac{L[\mathrm{m}]}{E[\mathrm{MeV}]}$$

Reactor experiments

Wide L/E ranges to explore different oscillation features

Very short baseline: sterile ν?
NEOS, DANSS, PROSPECT, SoLid



Medium baseline (θ_{12}, Δm^2_{21})

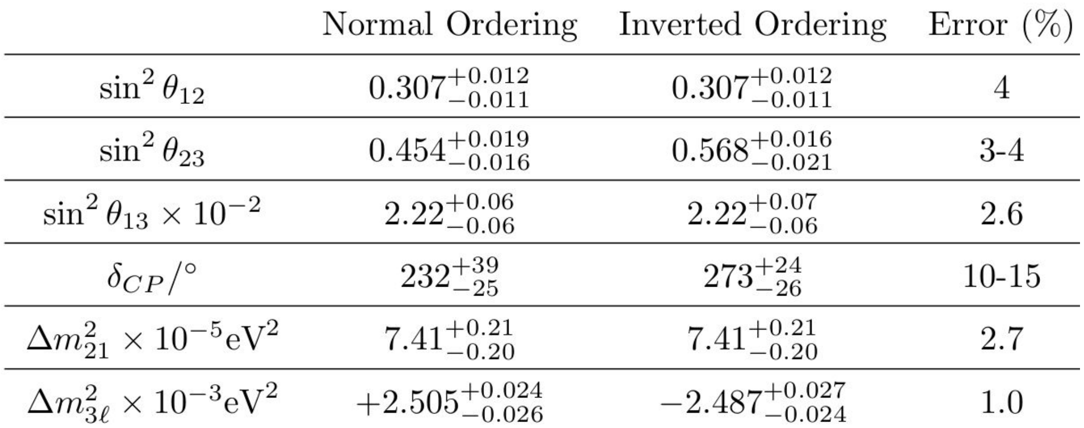
$$
\begin{aligned}
P(\nu_e \to \nu_e) = 1 & - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21}) \\
& - \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31}) \\
& - \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32})
\end{aligned}
$$

Short baseline (θ_{13}, Δm^2_{31})

$$\Delta_{kj} = 1.27 \Delta m^2_{kj} [\mathrm{eV}^2] \frac{L[\mathrm{m}]}{E[\mathrm{MeV}]}$$

Oscillations global analysis

3ν fit based on data up to March 2024 - NuFIT 5.3 (2024), www.nu-fit.org



	Normal Ordering	Inverted Ordering	Error (%)
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.307^{+0.012}_{-0.011}$	4
$\sin^2\theta_{23}$	$0.454^{+0.019}_{-0.016}$	$0.568^{+0.016}_{-0.021}$	3-4
$\sin^2\theta_{13}\times 10^{-2}$	$2.22^{+0.06}_{-0.06}$	$2.22^{+0.07}_{-0.06}$	2.6
$\delta_{CP}/^\circ$	232^{+39}_{-25}	273^{+24}_{-26}	10-15
$\Delta m^2_{21}\times 10^{-5}\mathrm{eV}^2$	$7.41^{+0.21}_{-0.20}$	$7.41^{+0.21}_{-0.20}$	2.7
$\Delta m^2_{3\ell}\times 10^{-3}\mathrm{eV}^2$	$+2.505^{+0.024}_{-0.026}$	$-2.487^{+0.027}_{-0.024}$	1.0

Oscillations global analysis

3ν fit based on data up to March 2024 - NuFIT 5.3 (2024), www.nu-fit.org

	Normal Ordering	Inverted Ordering	Error (%)
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.307^{+0.012}_{-0.011}$	4
$\sin^2\theta_{23}$	$0.454^{+0.019}_{-0.016}$	$0.568^{+0.016}_{-0.021}$	3-4
$\sin^2\theta_{13}\times10^{-2}$	$2.22^{+0.06}_{-0.06}$	$2.22^{+0.07}_{-0.06}$	2.6
$\delta_{CP}/°$	232^{+39}_{-25}	273^{+24}_{-26}	10-15
$\Delta m^2_{21}\times10^{-5}\mathrm{eV}^2$	$7.41^{+0.21}_{-0.20}$	$7.41^{+0.21}_{-0.20}$	2.7
$\Delta m^2_{3\ell}\times10^{-3}\mathrm{eV}^2$	$+2.505^{+0.024}_{-0.026}$	$-2.487^{+0.027}_{-0.024}$	1.0

KamLAND, solar experiments

Daya Bay + (SK+T2K) + NOvA + MINOS + IceCube

(SK+T2K) + NOvA + IceCube-DeepCore + MINOS + **Daya Bay + RENO + DoubleChooz**

Oscillations global analysis

3ν fit based on data up to March 2024 - NuFIT 5.3 (2024), www.nu-fit.org

	Normal Ordering	Inverted Ordering	Error (%)
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.307^{+0.012}_{-0.011}$	4
$\sin^2\theta_{23}$	$0.454^{+0.019}_{-0.016}$	$0.568^{+0.016}_{-0.021}$	3-4
$\sin^2\theta_{13}\times 10^{-2}$	$2.22^{+0.06}_{-0.06}$	$2.22^{+0.07}_{-0.06}$	2.6
$\delta_{CP}/°$	232^{+39}_{-25}	273^{+24}_{-26}	10-15
$\Delta m^2_{21}\times 10^{-5}\mathrm{eV}^2$	$7.41^{+0.21}_{-0.20}$	$7.41^{+0.21}_{-0.20}$	2.7
$\Delta m^2_{3\ell}\times 10^{-3}\mathrm{eV}^2$	$+2.505^{+0.024}_{-0.026}$	$-2.487^{+0.027}_{-0.024}$	1.0

← mass ordering?

KamLAND, solar experiments

Daya Bay + (SK+T2K) + NOvA + MINOS + IceCube

(SK+T2K) + NOvA + IceCube-DeepCore + MINOS + **Daya Bay + RENO + DoubleChooz**

Oscillations global analysis

3ν fit based on data up to March 2024 - NuFIT 5.3 (2024), www.nu-fit.org

	Normal Ordering	Inverted Ordering	Error (%)
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.307^{+0.012}_{-0.011}$	4
$\sin^2\theta_{23}$	$0.454^{+0.019}_{-0.016}$	$0.568^{+0.016}_{-0.021}$	3-4
$\sin^2\theta_{13}\times 10^{-2}$	$2.22^{+0.06}_{-0.06}$	$2.22^{+0.07}_{-0.06}$	2.6
$\delta_{CP}/^\circ$	232^{+39}_{-25}	273^{+24}_{-26}	10-15
$\Delta m^2_{21}\times 10^{-5}\mathrm{eV}^2$	$7.41^{+0.21}_{-0.20}$	$7.41^{+0.21}_{-0.20}$	2.7
$\Delta m^2_{3\ell}\times 10^{-3}\mathrm{eV}^2$	$+2.505^{+0.024}_{-0.026}$	$-2.487^{+0.027}_{-0.024}$	1.0

mass ordering?

JUNO

KamLAND, solar experiments

Daya Bay + (SK+T2K) + NOvA + MINOS + IceCube

(SK+T2K) + NOvA + IceCube-DeepCore + MINOS + **Daya Bay + RENO + DoubleChooz**

JUNO status

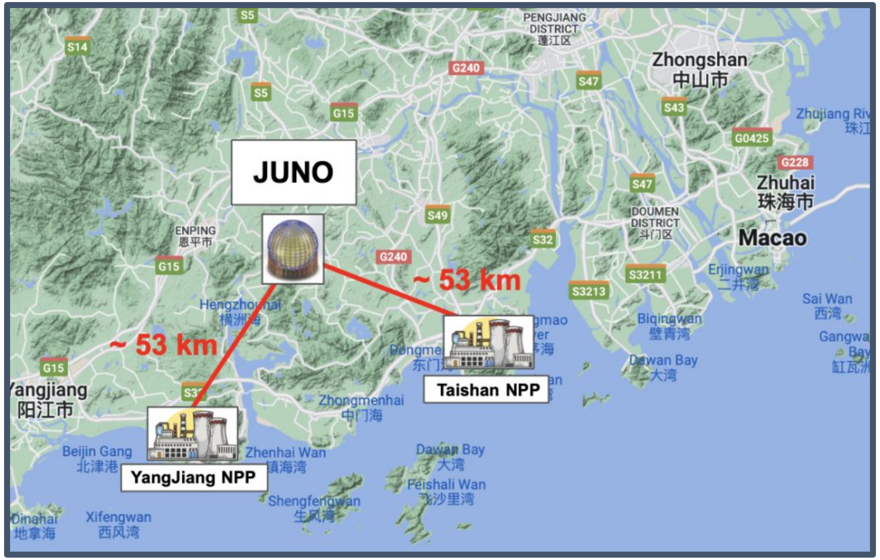
Jiangmen Underground Neutrino Observatory

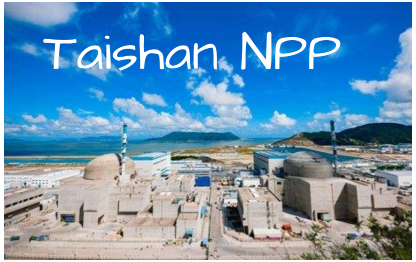
Huge and multipurpose **liquid-scintillator** detector underground in Southern China.

Jiangmen Underground Neutrino Observatory

Huge and multipurpose **liquid-scintillator** detector underground in Southern China.

Main goal: determine the NMO and measure Δm^2 splittings and $\sin^2\theta_{12}$ at <1% level via reactor anti-ν_e oscillations (52.5 km baseline)





Two nuclear power plants, 8 reactor cores, $26.6\ \mathrm{GW}_{th}$

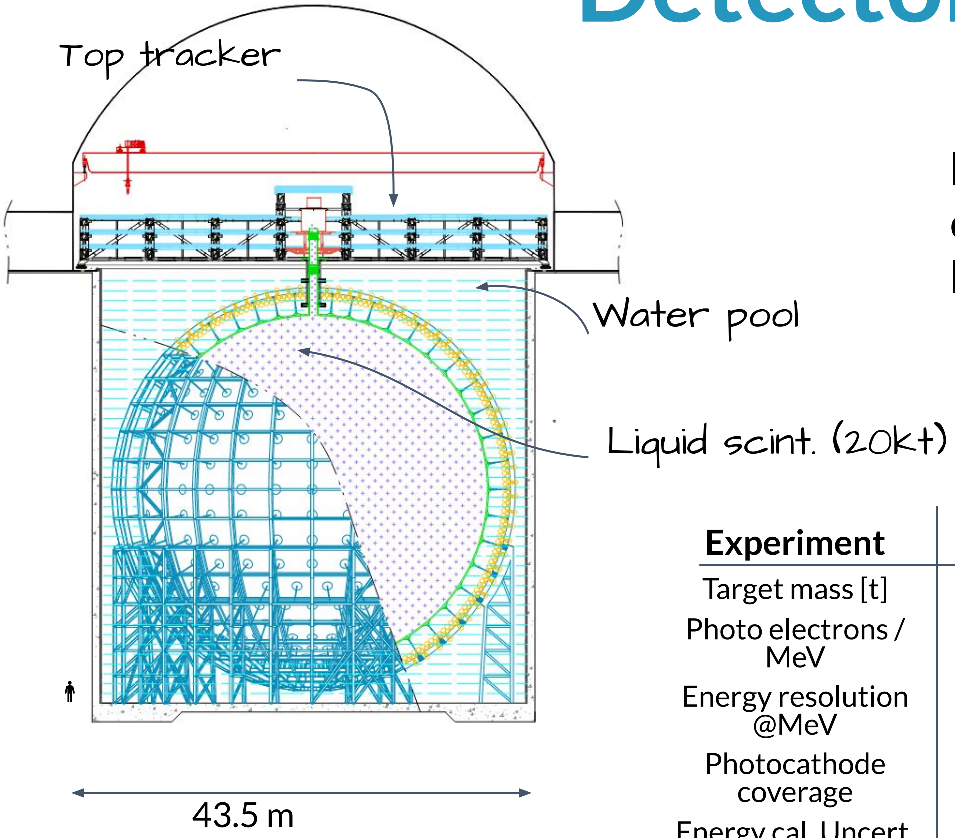
JUNO collaboration

Collaboration established in 2014.
More than 700 collaborators from 74 institutions in 17 countries/regions

24th JUNO collaboration meeting in Kaiping (city close to the exp. site), June 29- July 5, 2024

~240 participants

Detector design



Largest liquid scintillator ever (20 kton), equipped with **17612 large PMTs + 25600 small PMTs** to collect scintillation light

Experiment	**Daya Bay**	**Borexino**	**KamLAND**	**JUNO**
Target mass [t]	160	~300	~1000	**~20000**
Photo electrons / MeV	~160	~500	~250	**~1600**
Energy resolution @MeV	~8.5%	~5%	~6%	**~3%**
Photocathode coverage	12%	34%	34%	**78%**
Energy cal. Uncert.	0.5%	1.0%	2.0%	**<1%**

Central detector status

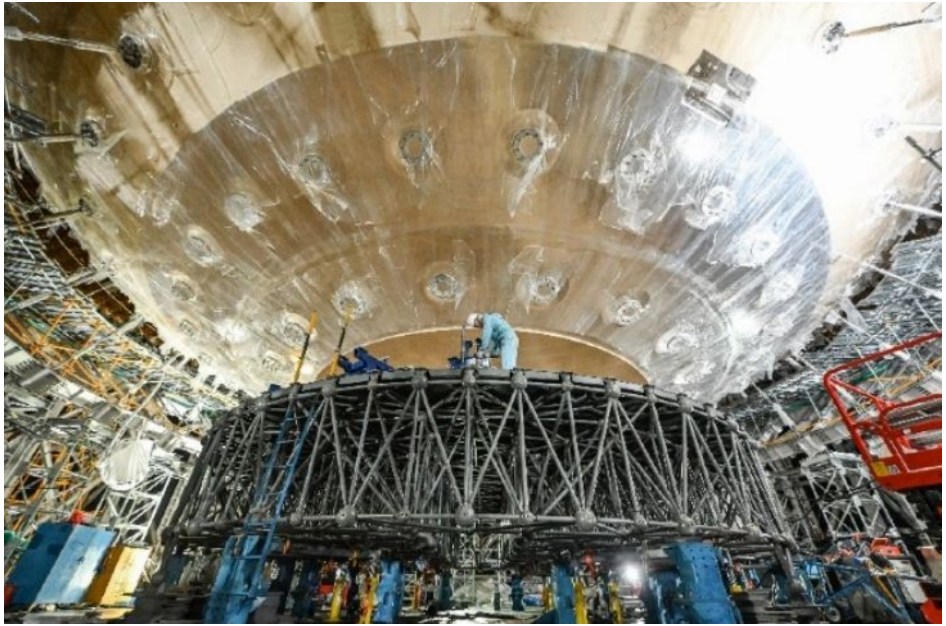
Talk: M. Beretta, “Design and status of the JUNO detector”, WG6

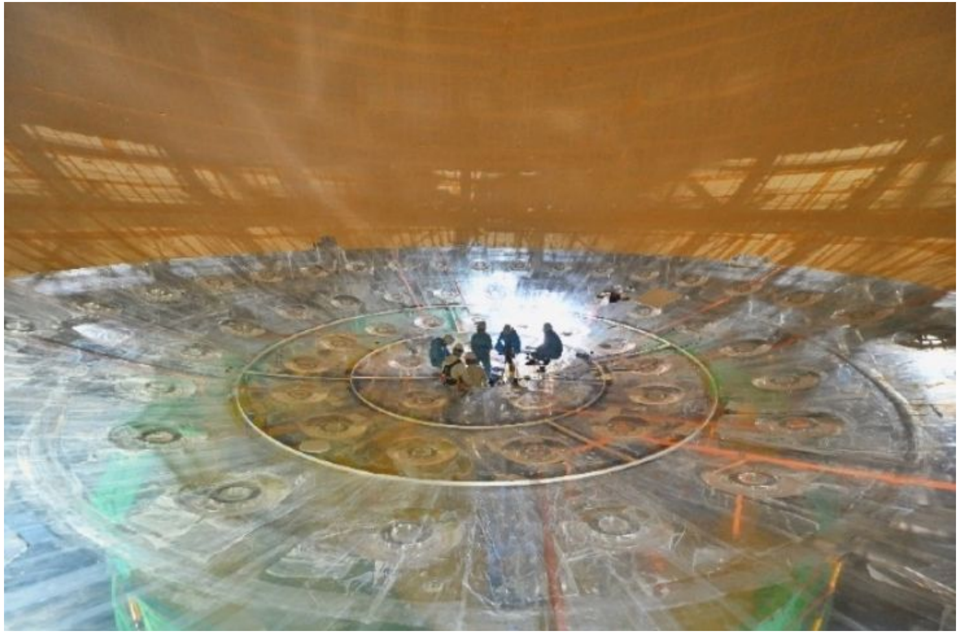
Central detector status

- Stainless Sphere structure completed except bottom 4 layers
- Acrylic vessel construction ongoing from the top to bottom (2 layers missing)
- **Data taking: 2025**

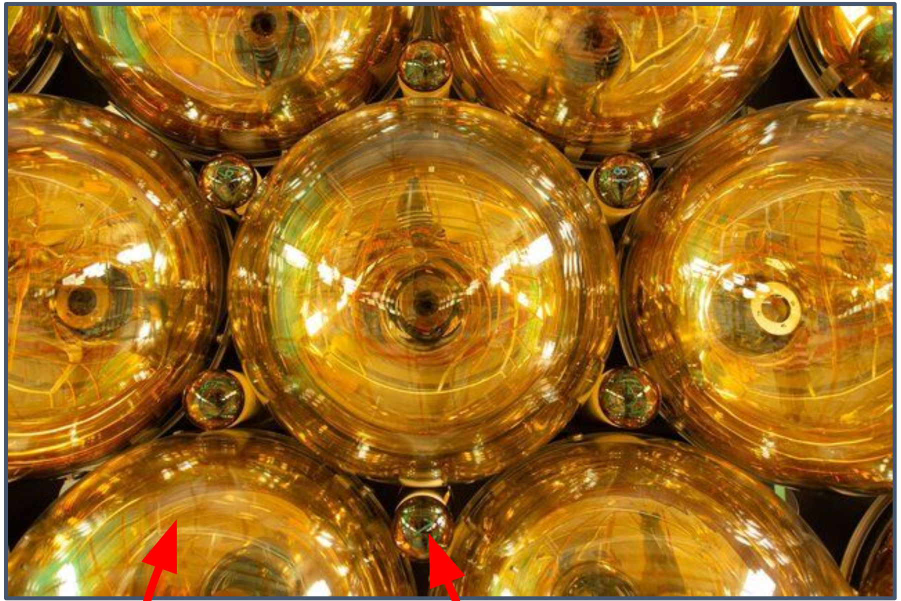
Talk: M. Beretta, “Design and status of the JUNO detector”, WG6

Where are we?





A dual PMT system

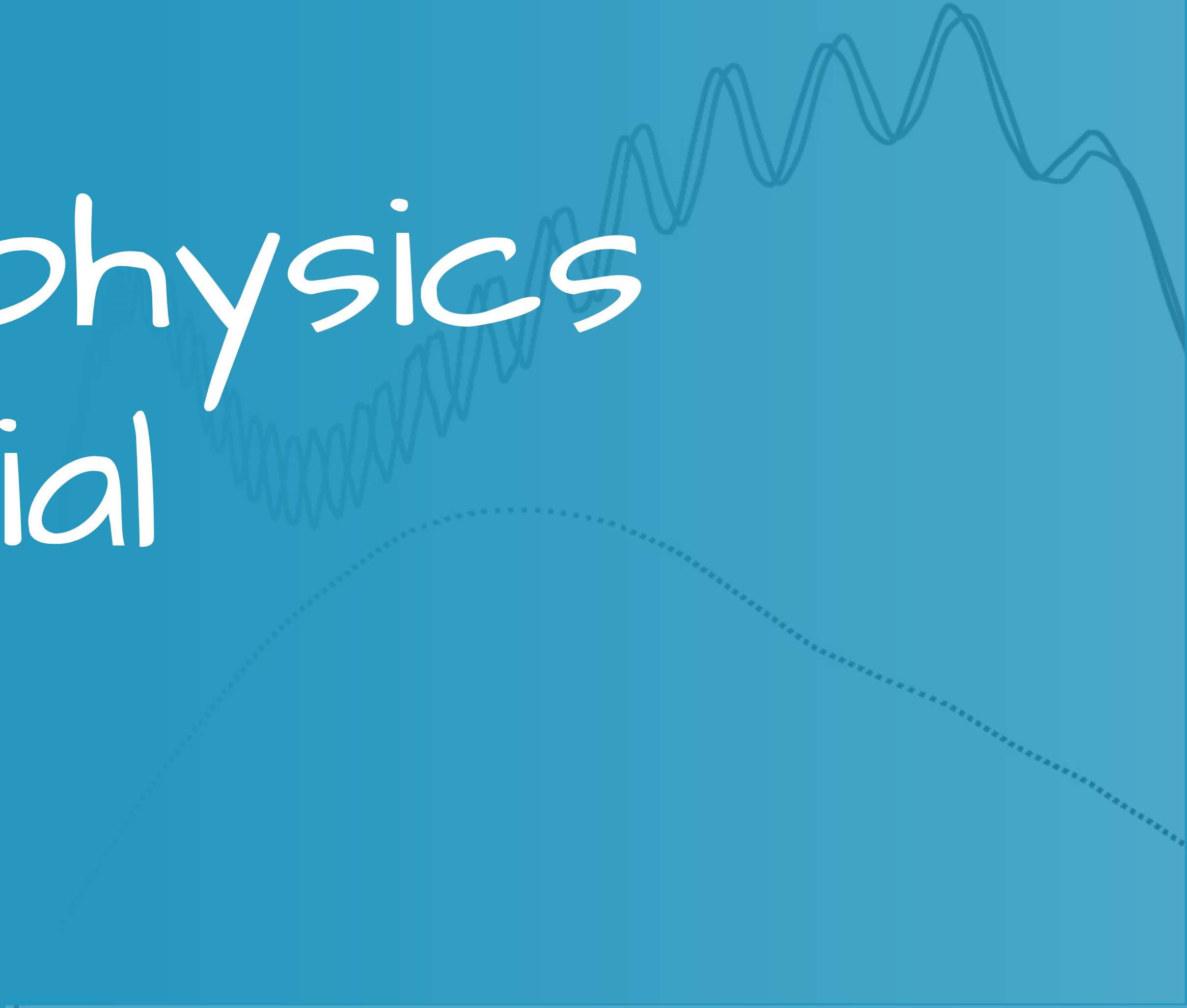


JUNO: a **dual-calorimetric detector**
- 20-inch (**large**) PMTs: 1200 p.e./MeV: main calorimetry
- 3-inch (**small**) PMTs: 40 p.e./MeV: → control energy bias + redundancy

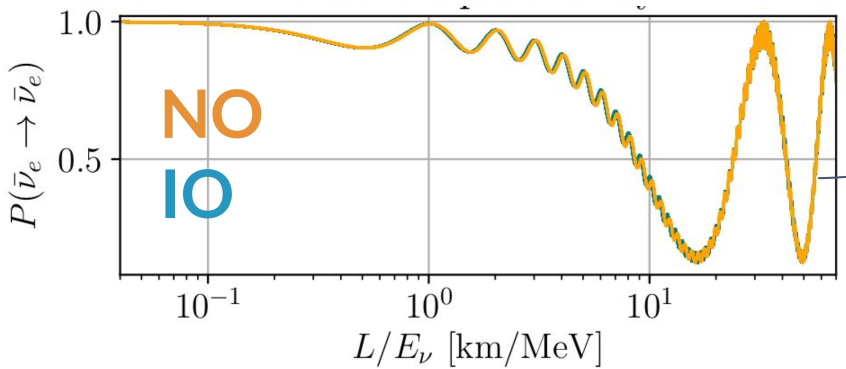
Status: production and testing done for all PMTs, installation close to completion


Inner view of PMTs arrays

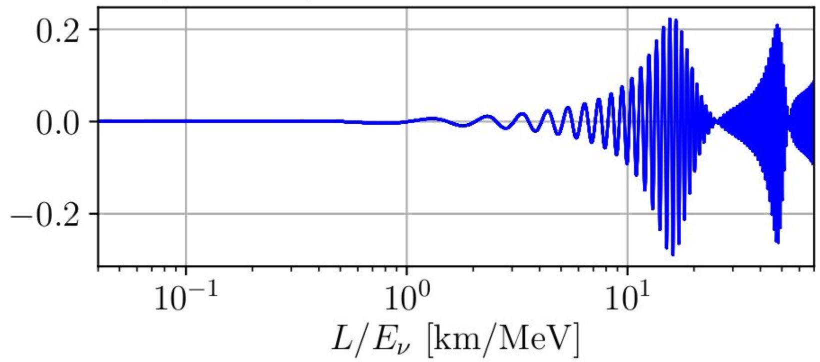
JUNO physics potential



Why JUNO?



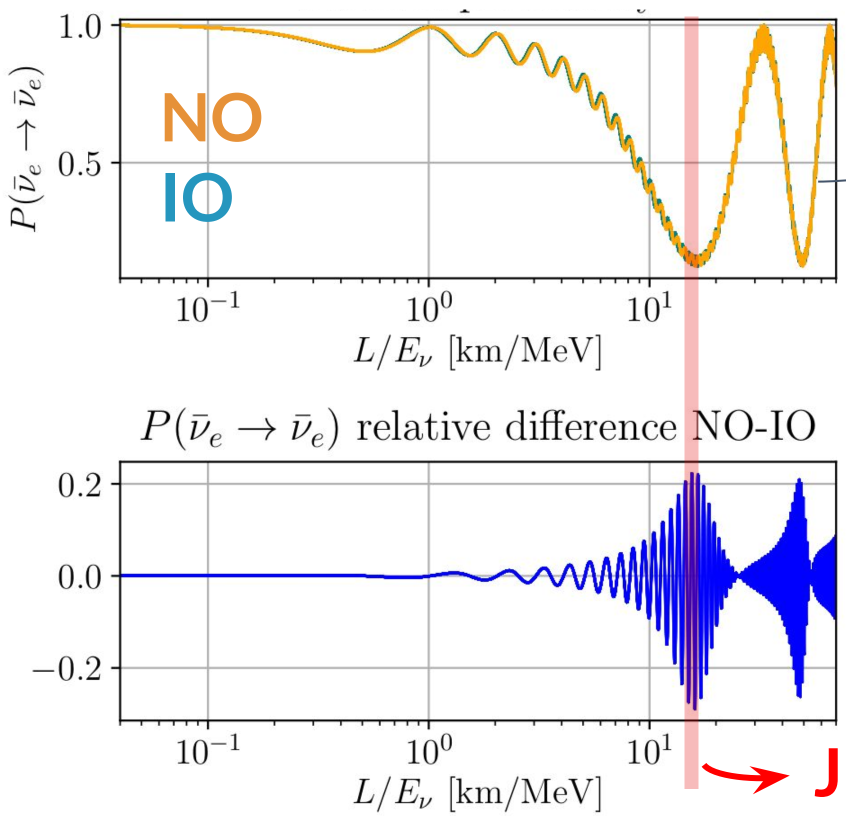
$P(\bar{\nu}_e \to \bar{\nu}_e)$ relative difference NO-IO



$$
\begin{aligned}
P(\nu_\mathrm{e} \to \nu_\mathrm{e}) = \; & 1 - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21}) \\
& - \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31}) \\
& - \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32})
\end{aligned}
$$

NMO drives the sign and the absolute value of $|\Delta m^2_{3\ell}| \rightarrow$ differences in oscillation L/E profiles!

Why JUNO?



JUNO

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

NMO drives the sign and the absolute value of $|\Delta m^2_{3\ell}|$ → differences in oscillation L/E profiles!

Maximum relative NO/IO difference: optimized baseline L = 52.5 km
[JHEP 01 (2019) 106]

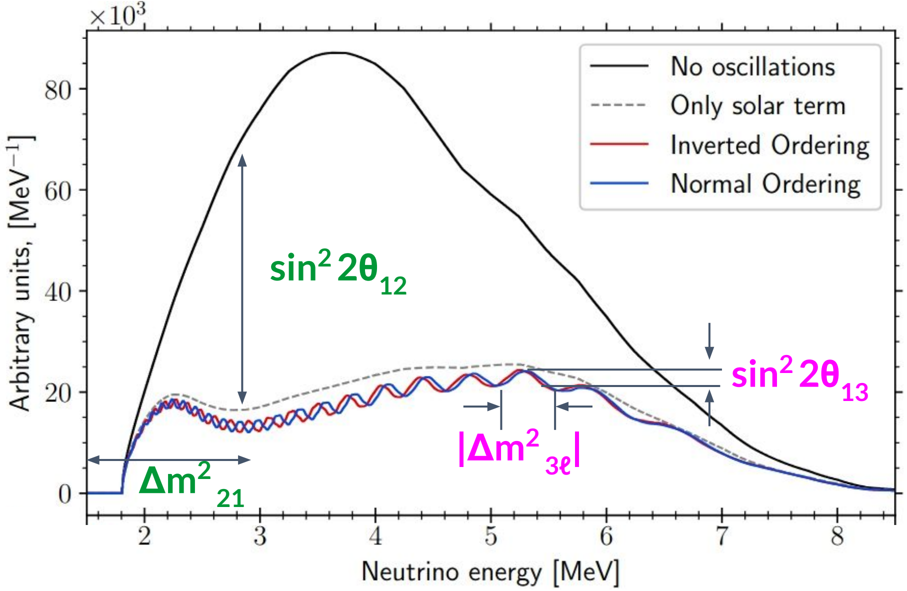
Why JUNO?

First experiment to observe both **fast** ($\sin^2\theta_{13}$, $|\Delta m^2_{3\ell}|$) and **slow** ($\sin^2\theta_{12}$, Δm^2_{21}) oscillations **in vacuum**

→ **interference pattern depends on NMO**

… no dependence on θ_{23}, δ_{CP}, small dependence on matter effects: **no degeneracies!**

Exemplary spectrum, 6y
(10^5 events, σ_E/E = 2.95% @ 1 MeV)



Key challenges for JUNO

1) Large statistics

→ huge scintillator mass, powerful nuclear reactors

Key challenges for JUNO

1) Large statistics

→ huge scintillator mass, powerful nuclear reactors

2) Energy resolution: 2.95% @ 1MeV + 1% understanding of the intrinsically non-linear energy scale

→ LS optical properties + light collection + calibrations

energy non-uniformity (~0.8%)

$$\frac{\sigma_E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}$$

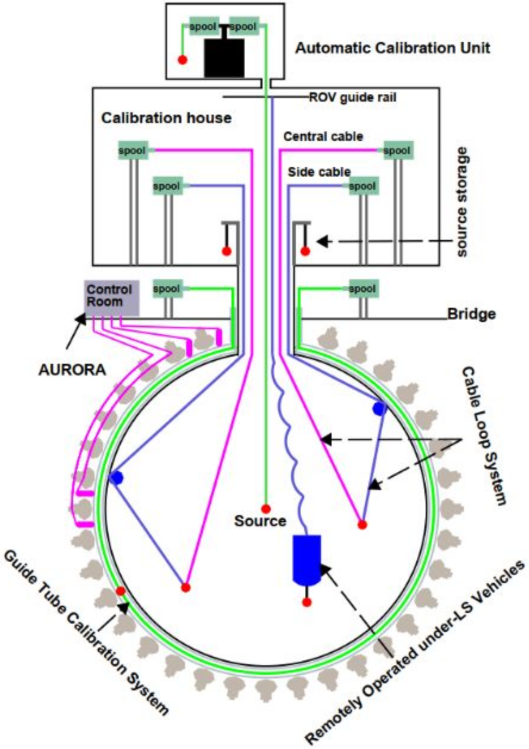
Poisson statistical fluctuations (~2.6%)

noise, Cherenkov (~1%)

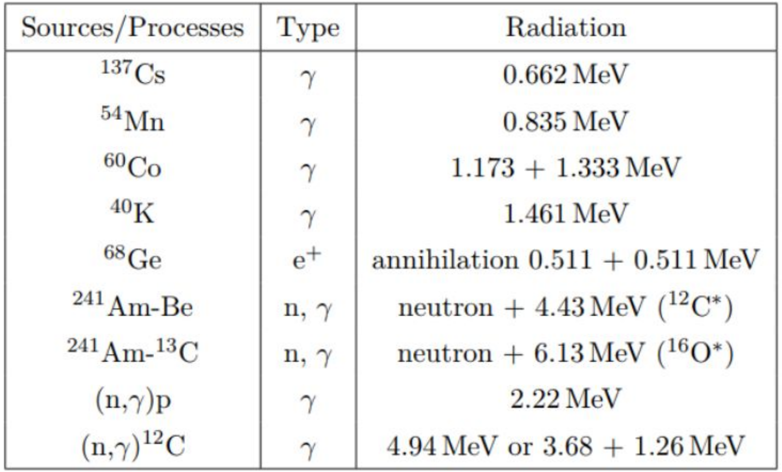
Calibrations in JUNO

JHEP 03 (2021) 004

Determination of e^+ non-linearity at <1% + optimization of energy resolution at <3% level



Radioactive sources (100-200 Hz) + Laser sources



Sources/Processes	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^+	annihilation 0.511 + 0.511 MeV
^{241}Am-Be	n, γ	neutron + 4.43 MeV (^{12}C*)
^{241}Am-^{13}C	n, γ	neutron + 6.13 MeV (^{16}O*)
(n,γ)p	γ	2.22 MeV
(n,γ)^{12}C	γ	4.94 MeV or 3.68 + 1.26 MeV

Talk: A. Takenaka, “Detector calibration in the JUNO experiment”, WG6

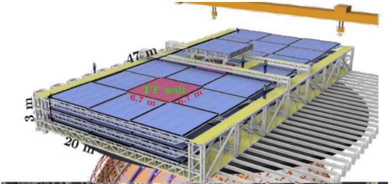
Key challenges for JUNO

1) **Large statistics**
→ huge scintillator mass, powerful nuclear reactors

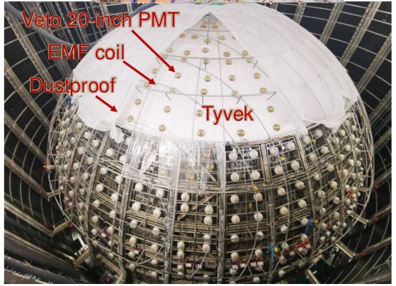
2) **Energy resolution: 2.95% @ 1MeV + 1% understanding of the intrinsically non-linear energy scale**
→ LS optical properties + light collection + calibrations

3) **Low background**
→ underground + scintillator purification system + material screening + veto systems

distillation plant



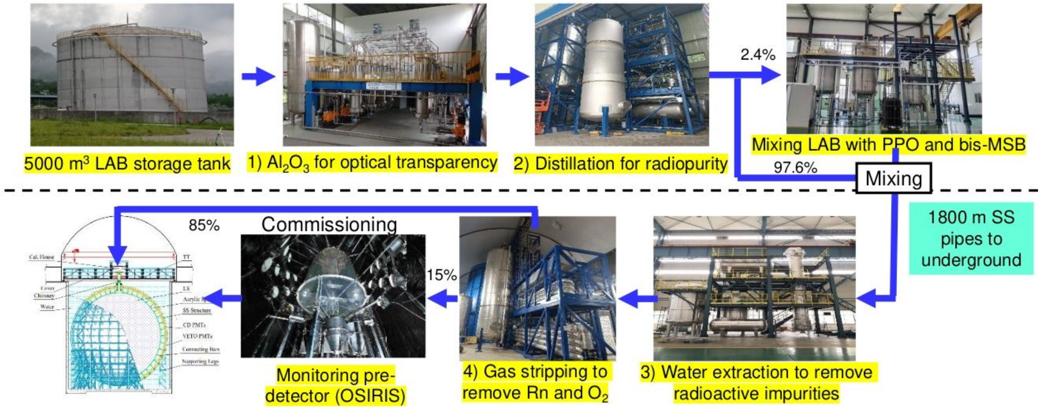
Top Tracker



Water Pool

Liquid scintillator purification chain

- An industrial scale purification process is needed
- Radiopurity U/Th requirements: for NMO ~10^{-15} g/g, for solar ν campaign ~10^{-17} g/g



5000 m³ LAB storage tank

1) Al_2O_3 for optical transparency

2) Distillation for radiopurity

2.4%

Mixing LAB with PPO and bis-MSB

97.6%

Mixing

1800 m SS pipes to underground

3) Water extraction to remove radioactive impurities

4) Gas stripping to remove Rn and O_2

15%

Monitoring pre-detector (OSIRIS)

Commissioning

85%

Bkg scenario	^{238}U and ^{232}Th [g/g]	Reference
High	10^{-15}	minimum NMO requirement
Medium	10^{-16}	10x worse wrt Borexino Phase-I
Low	10^{-17}	100x worse wrt Borexino Phase-I
Very Low	~10^{-19} (^{238}U) ~$5\cdot10^{-19}$ (^{232}Th)	Borexino Phase-III

Talk: M. Beretta, “Design and status of the JUNO detector”, WG6

Key challenges for JUNO

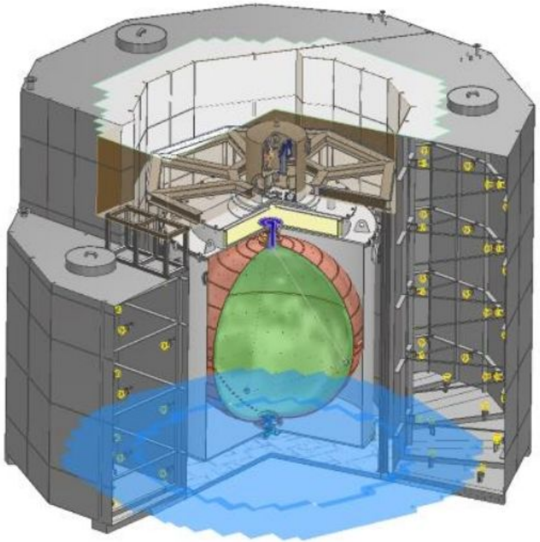
1) Large statistics
→ huge scintillator mass, powerful nuclear reactors

2) Energy resolution: 2.95% @ 1MeV + 1% understanding of the intrinsically non-linear energy scale
→ LS optical properties + light collection + calibrations

3) Low background
→ underground + scintillator purification system + material screening + veto systems

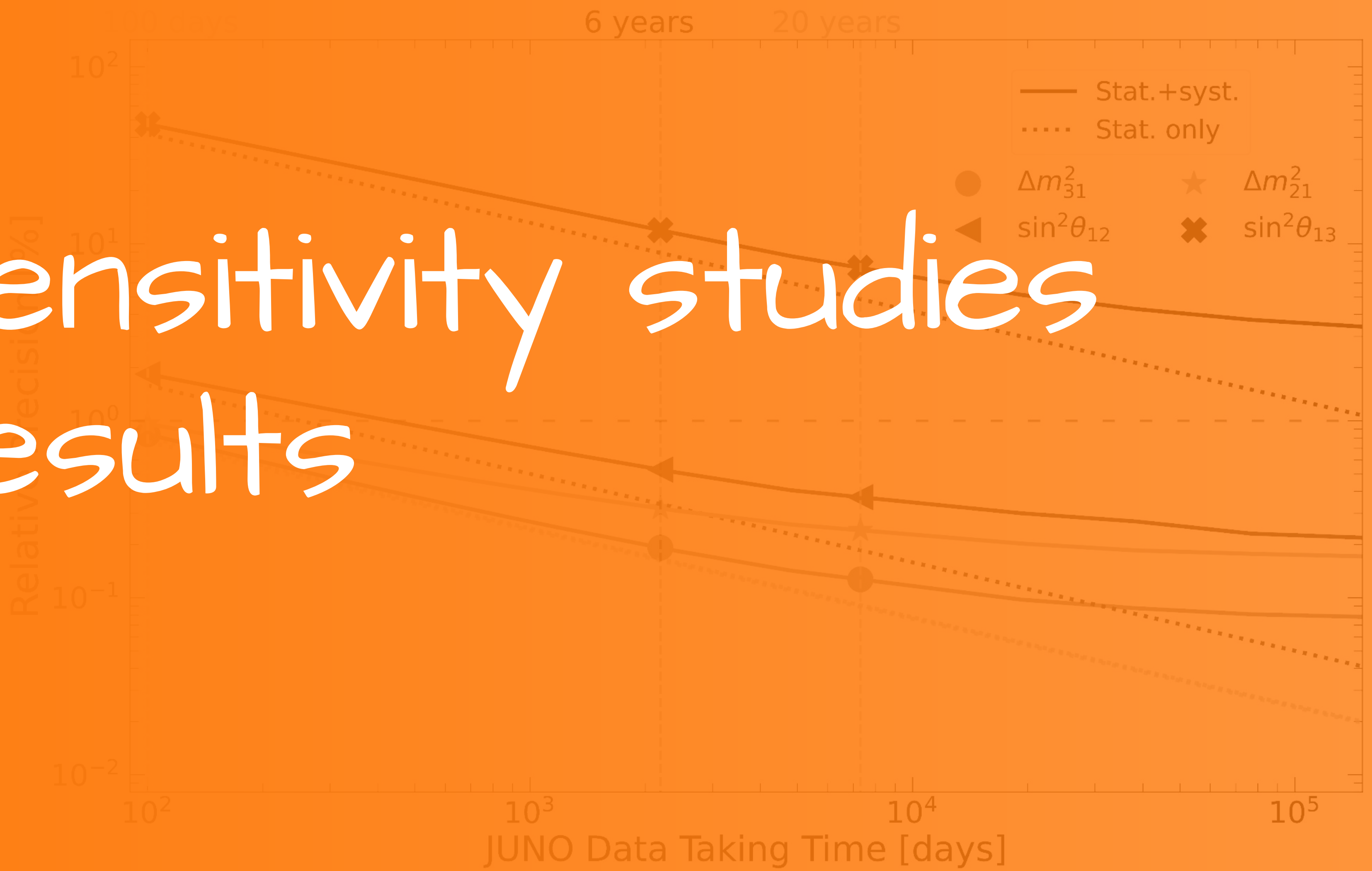
4) Knowledge of reactor spectra at sub-% level
→ near detector: Taishan Antineutrino Observatory (TAO) at 44 m from Taishan reactor → reduce spectral shape systematics

TAO detector

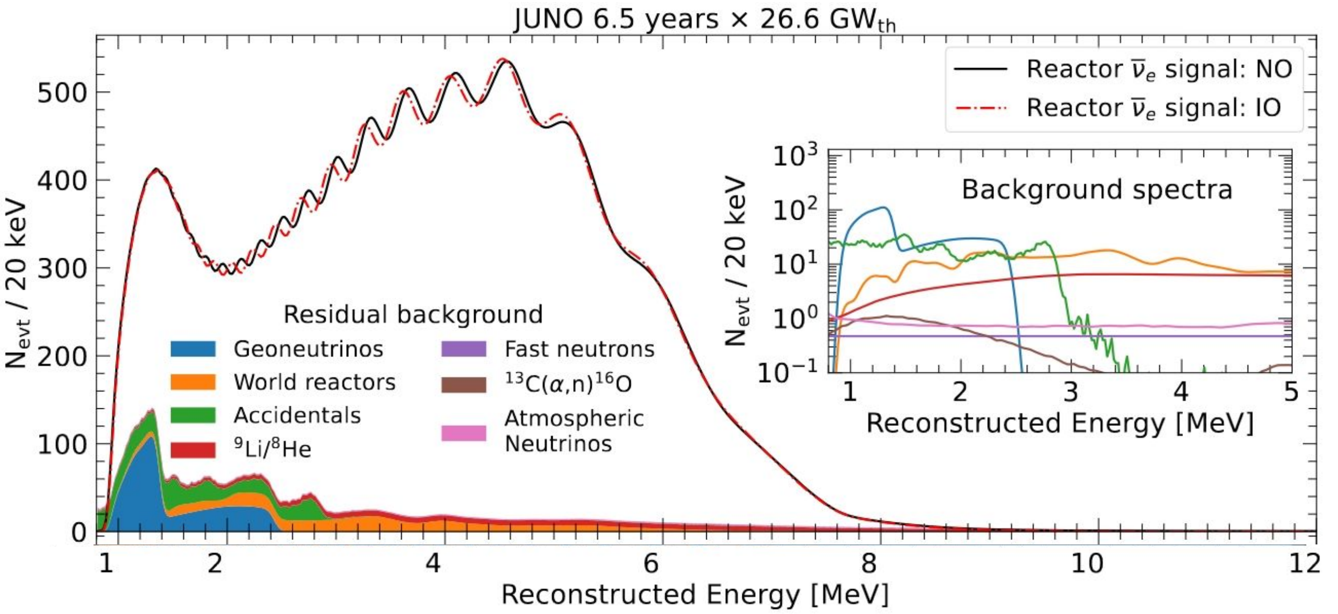


arXiv:2005.08745

Sensitivity studies results



Signal and backgrounds



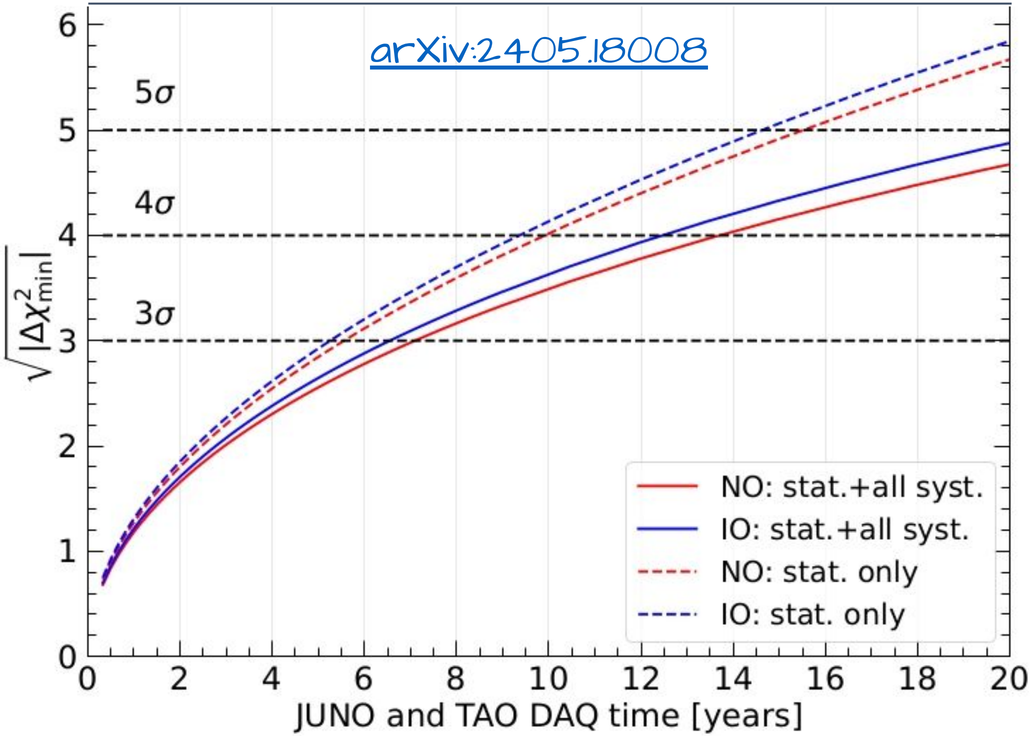
- Prompt + delayed coincidences → high s/b ratio
- 47 Inverse Beta Decay candidate events/day expected (~16k / year) , 7% irreducible background

Sensitivity to NMO

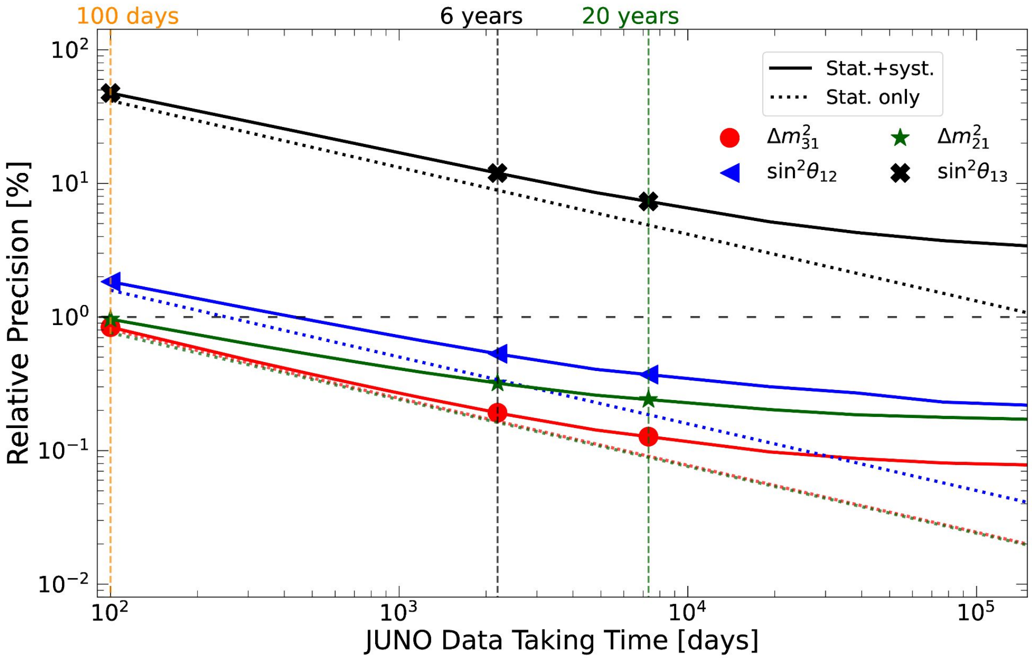
Fit data against both NO and IO scenarios
$\Delta\chi^2$: Fitting wrong model - Fitting correct one

Several experimental factors as systematics: knowledge of energy resolution and linearity, background shapes, …

Reactor ν oscillation analysis: median 3σ sensitivity to NMO in 7.1 years.



Oscillation parameters: precision measurements

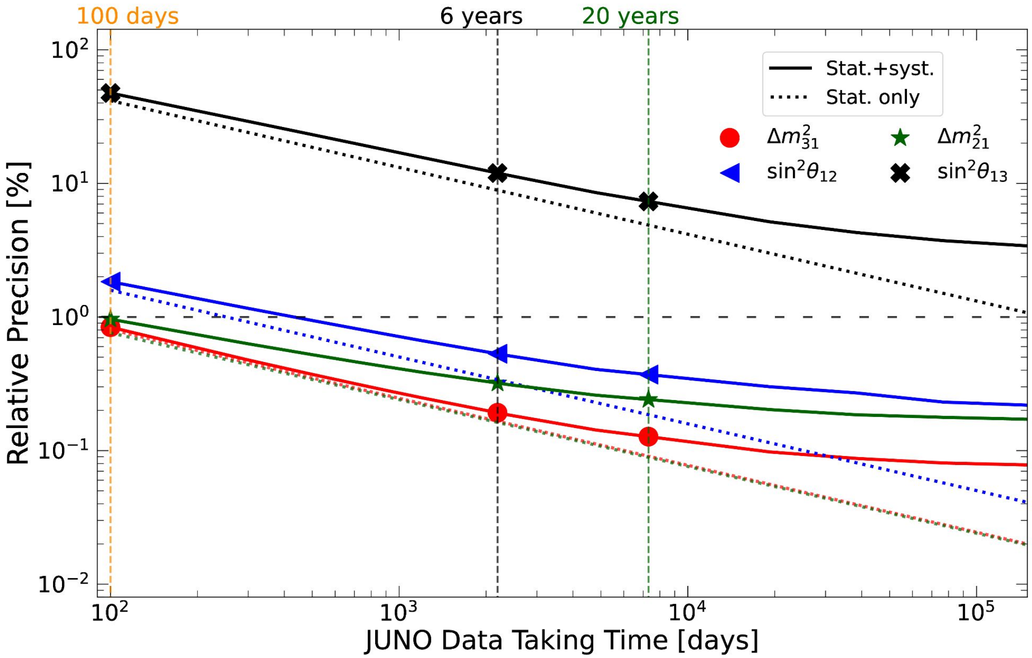


$\sin^2\theta_{12}$, Δm^2_{21} , $|\Delta m^2_{31}|$:
100 days: leading measurements
6 years: precision <0.5%,
10x improvement!

Chin. Phys. C46 (2022) 12, 123001

	Central Value	PDG2020	100 days	6 years	20 years
$\lvert\Delta m^2_{31}\rvert(\times 10^{-3}\ \mathrm{eV}^2)$	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
$\Delta m^2_{21}\ (\times 10^{-5}\ \mathrm{eV}^2)$	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)	±0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)	±0.0016 (7.3%)

Oscillation parameters: precision measurements



$\sin^2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|$:

100 days: leading measurements

6 years: precision <0.5%,

10x improvement!

Talk: Neutrino Oscillation Physics with JUNO, S. Kumaran, WG1

Chin. Phys. C46 (2022) 12, 123001

	Central Value	PDG2020	100 days	6 years	20 years
$\|\Delta m^2_{31}\|(\times 10^{-3}\ \mathrm{eV}^2)$	2.5283	± 0.034 (1.3%)	± 0.021 (0.8%)	± 0.0047 (0.2%)	± 0.0029 (0.1%)
$\Delta m^2_{21}\ (\times 10^{-5}\ \mathrm{eV}^2)$	7.53	± 0.18 (2.4%)	± 0.074 (1.0%)	± 0.024 (0.3%)	± 0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	± 0.013 (4.2%)	± 0.0058 (1.9%)	± 0.0016 (0.5%)	± 0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	± 0.0007 (3.2%)	± 0.010 (47.9%)	± 0.0026 (12.1%)	± 0.0016 (7.3%)

Boosting NMO sensitivity w/ atmospheric ν

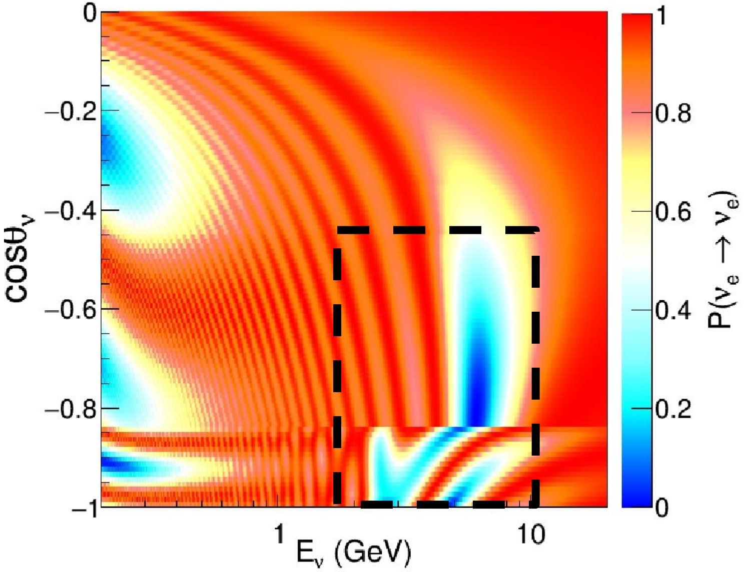
Key idea for upward 3-10 GeV ν or anti-ν crossing Earth:

MSW resonance takes place in according to the sign of $A/\Delta m^2_{3\ell}$

(A = ν-matter interaction potential)

ν: A > 0 → MSW if $\Delta m^2_{3\ell} > 0$ → NO

anti-ν: A < 0 → MSW if $\Delta m^2_{3\ell} < 0$ → IO

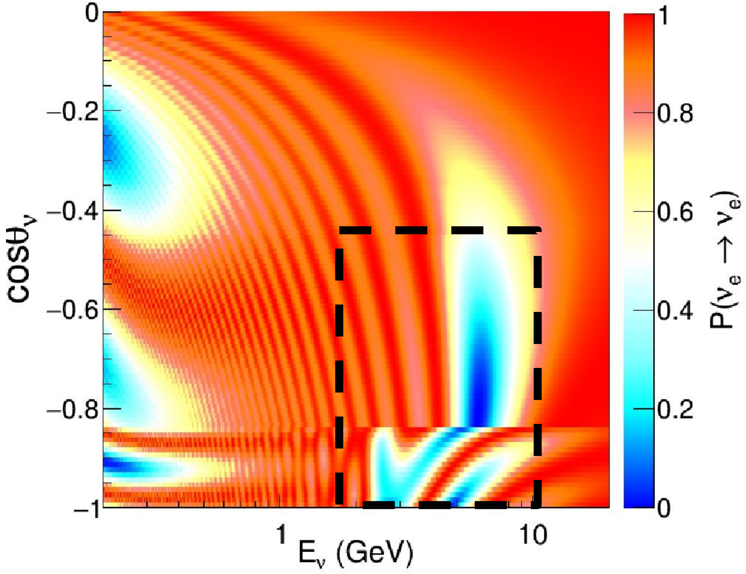


ν_e survival probability

Boosting NMO sensitivity w/ atmospheric ν

Key idea for upward 3-10 GeV ν or anti-ν crossing Earth:
MSW resonance takes place in according to the sign of $A/\Delta m^2_{3\ell}$
(A = ν-matter interaction potential)

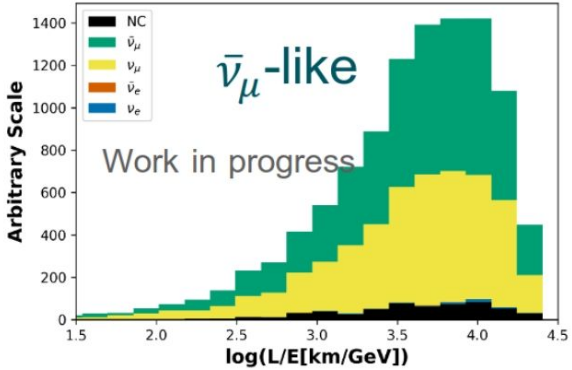
ν: A > 0 → MSW if $\Delta m^2_{3\ell} > 0$ → NO
anti-ν: A < 0 → MSW if $\Delta m^2_{3\ell} < 0$ → IO



ν_e survival probability

particle identification:
ν_e/anti-ν_e/ν_μ/anti-ν_μ/

Conventional PID techniques +
Machine learning approaches



Joint reactor-atmospheric analysis in progress

Neutrinos from natural sources

Solar ν
0.1-10 MeV

Geo ν
few MeV

Supernova ν
tens of MeV

Atmospheric ν
~0.5-100 GeV

Energy

Expected rates

^{7}Be: ~10000/day
CNO: ~1000/day
^{8}B: ~90/day

~400 / year

- Core Collapse SN
@ 10 kpc: ~10^3 in sec.
- Diffuse SN: few / year

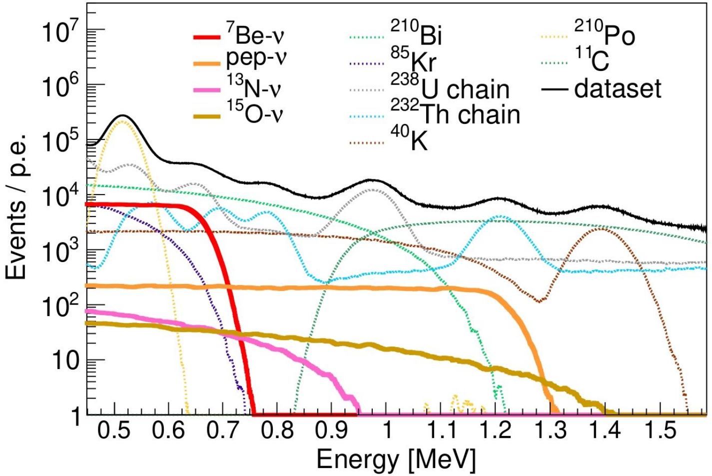
Several / day

Talk: Prospects for Neutrinos from Natural Sources in JUNO, Iwan M. Blake, WG1

Highlights: sensitivity to MeV solar ν

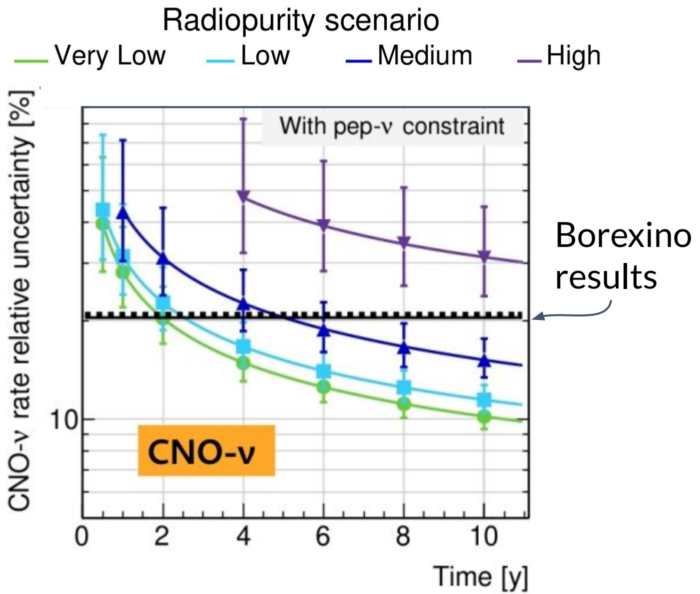
Goals: solar metallicity puzzle (mainly based on CNO ν) + oscillations + Non-Standard Interactions

Expected energy spectrum, 6y, Medium bkg scenario (10^{-16} g/g for ^{238}U and ^{232}Th)



spectral analysis →

JCAP 10 (2023) 022



For most of the background scenarios JUNO will improve the best results on solar ν fluxes.

Conclusions

A **giant 20-kton liquid scintillator $\boldsymbol{\nu}$ detector** with a rich and multipurpose physics program.

Challenges: excellent energy resolution, scintillator radiopurity, background rejection techniques.

Conclusions

A **giant 20-kton liquid scintillator ν detector** with a rich and multipurpose physics program.

Challenges: excellent energy resolution, scintillator radiopurity, background rejection techniques.

Physics potential:

- **Δm^2_{21}, $|\Delta m^2_{31}|$, and $\sin^2\theta_{12}$** measurements with **<0.5%** precision in 6 years;
- **Mass Ordering** via oscillation interference in vacuum: **3σ** significance in 7.1 years;
- neutrino spectroscopy from **natural sources** (atmosphere, Sun, Earth, supernovae).

Conclusions

A **giant 20-kton liquid scintillator ν detector** with a rich and multipurpose physics program.

Challenges: excellent energy resolution, scintillator radiopurity, background rejection techniques.

Physics potential:

- **Δm^2_{21}, $|\Delta m^2_{31}|$, and $\sin^2\theta_{12}$** measurements with **<0.5%** precision in 6 years;
- **Mass Ordering** via oscillation interference in vacuum: **3σ** significance in 7.1 years;
- neutrino spectroscopy from **natural sources** (atmosphere, Sun, Earth, supernovae).

Detector construction close to completion: **first data are expected in 2025**.

Thanks!

Backup

JUNO site

Surface buildings / campus

- Surface Assembly Building
- LAB storage (5 kton)
- Water purification / Nitrogen
- Computing
- Power station
- Cable train
- Office / Dorm

~240 people working onsite now

Vertical Shaft, 563 m put into use in 2023

Slope tunnel, 1265m

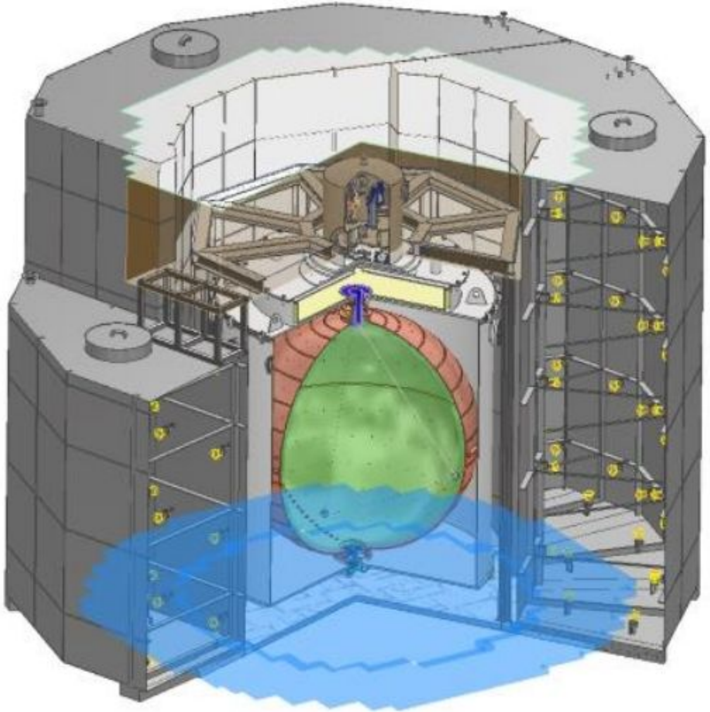
~ 650 m m.w.e.
R_μ ~ 0.004 Hz/m^2
$\langle E_\mu \rangle$ ~ 207 GeV

TAO: Taishan Antineutrino Observatory

Satellite detector located at 44 m from Taishan reactor
- 10 m2 SiPM + 2.8 ton Gd-loaded LS @-50 °C
- Energy resolution: <2%/√E, 4500 p.e./MeV

Main goal: measure the reactor neutrino spectrum (as a reference to JUNO) → sub-percent precision → reduce spectral shape systematics

Status:
Assembled at IHEP with ~100 SiPM
Disassembling, to be re-installed in the Taishan Nuclear Power Plant in 2024



arXiv:2005.08745

LPMTs main specifications

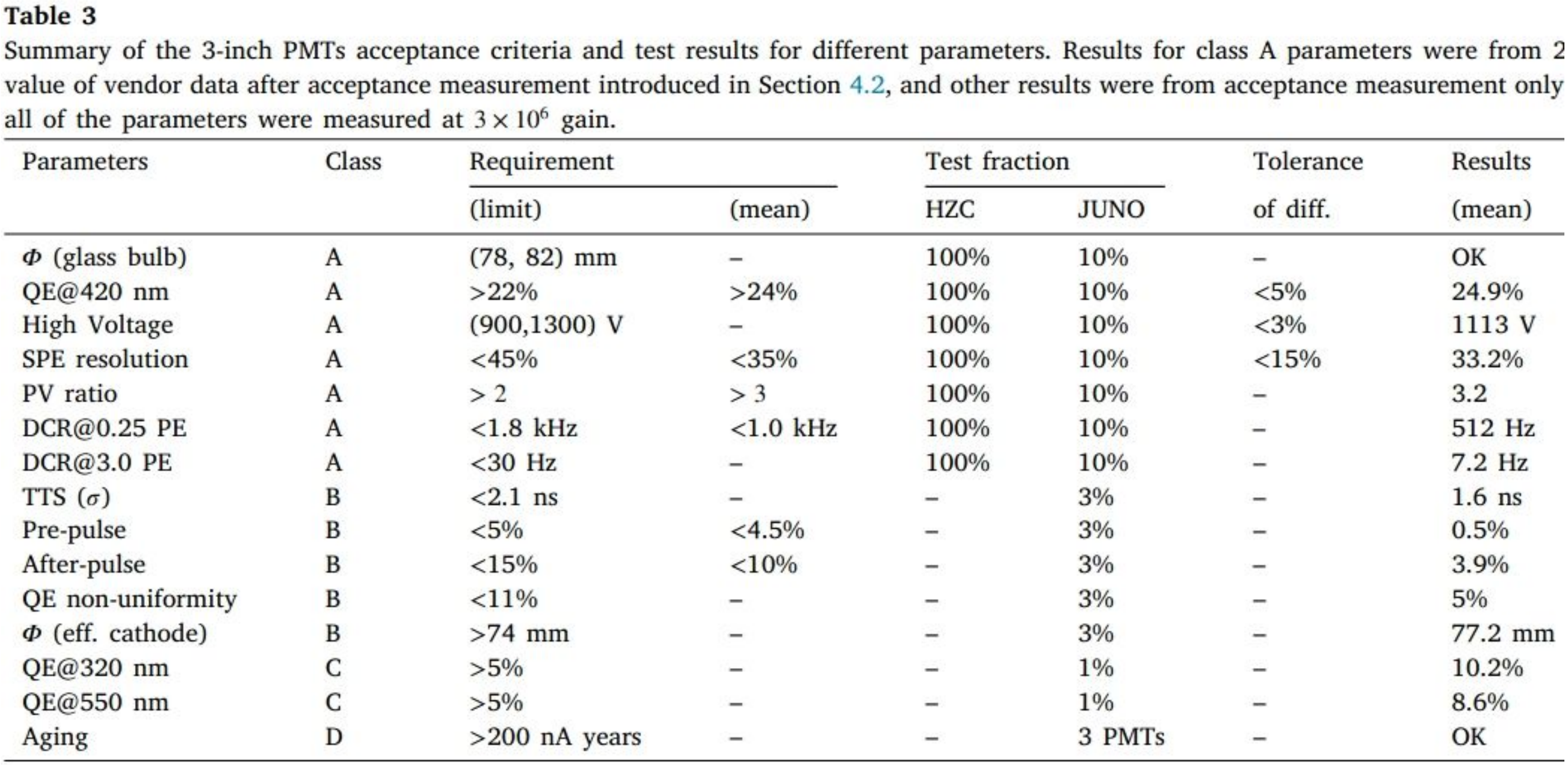


Table 3

Summary of the 3-inch PMTs acceptance criteria and test results for different parameters. Results for class A parameters were from 2 value of vendor data after acceptance measurement introduced in Section 4.2, and other results were from acceptance measurement only all of the parameters were measured at 3×10^6 gain.

Parameters	Class	Requirement		Test fraction		Tolerance	Results
		(limit)	(mean)	HZC	JUNO	of diff.	(mean)
Φ (glass bulb)	A	(78, 82) mm	–	100%	10%	–	OK
QE@420 nm	A	>22%	>24%	100%	10%	<5%	24.9%
High Voltage	A	(900,1300) V	–	100%	10%	<3%	1113 V
SPE resolution	A	<45%	<35%	100%	10%	<15%	33.2%
PV ratio	A	> 2	> 3	100%	10%	–	3.2
DCR@0.25 PE	A	<1.8 kHz	<1.0 kHz	100%	10%	–	512 Hz
DCR@3.0 PE	A	<30 Hz	–	100%	10%	–	7.2 Hz
TTS (σ)	B	<2.1 ns	–	–	3%	–	1.6 ns
Pre-pulse	B	<5%	<4.5%	–	3%	–	0.5%
After-pulse	B	<15%	<10%	–	3%	–	3.9%
QE non-uniformity	B	<11%	–	–	3%	–	5%
Φ (eff. cathode)	B	>74 mm	–	–	3%	–	77.2 mm
QE@320 nm	C	>5%	–	–	1%	–	10.2%
QE@550 nm	C	>5%	–	–	1%	–	8.6%
Aging	D	>200 nA years	–	–	3 PMTs	–	OK

Atmospheric neutrinos and MSW

$$P(\nu_e \to \nu_\mu) \approx P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13}^{\mathrm{m}} \sin^2\left[1.27\left(\Delta m_{31}^2\right)^{\mathrm{m}} \frac{L}{E_\nu}\right];$$

$$\boxed{\sin^2 2\theta_{13}^{\mathrm{m}} = \frac{\sin^2 2\theta_{13}}{\left(\cos 2\theta_{13} - A/\Delta m_{31}^2\right)^2 + \sin^2 2\theta_{13}}.}$$

Downward events: they don't cross relevantly the Earth, so A ~ 0, therefore the oscillation probablity in vacuum holds and there are no differences between NO and IO.

Upward events: MSW resonance takes place according to the sign of the ratio $A/\Delta m^2_{31}$.
For ν, $A > 0$ holds: MSW takes place if $\Delta m^2_{31} > 0$, that is NO
For anti-ν, $A < 0$ holds: MSW takes place if $\Delta m^2_{31} < 0$, that is IO

$$P_{\mathrm{NH}}(\nu_\alpha \to \nu_\beta) = P_{\mathrm{IH}}(\bar{\nu}_\alpha \to \bar{\nu}_\beta),\ P_{\mathrm{IH}}(\nu_\alpha \to \nu_\beta) = P_{\mathrm{NH}}(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

Calibration strategy

Calibration of non-linearity

1) physics non-linearity → radioactive sources + cosmogenic isotope ^{12}B
2) instrum. non-linearity → laser source

Systematics understanding and control

→ rad. sources syst (shadowing, non uniformity)
→ PMTs syst. (dark noise, non linearity, …)

Optimization and calibration of energy resolution

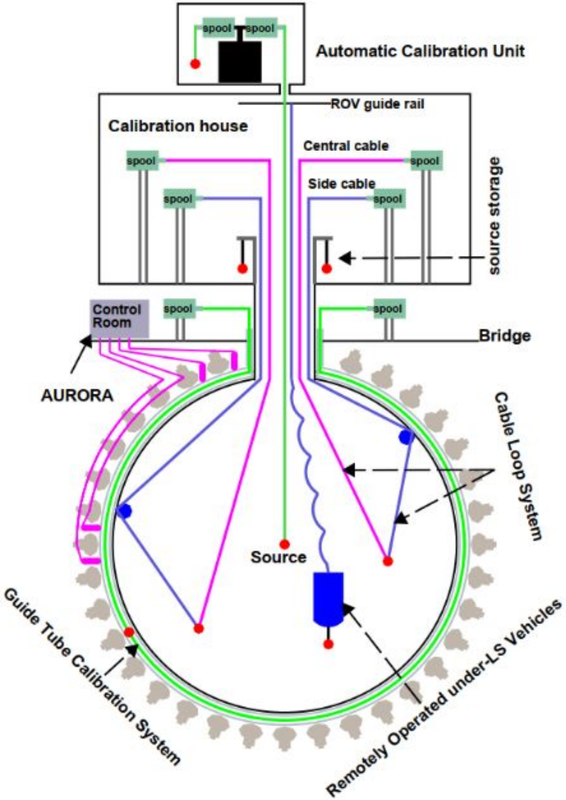
→ position non-uniformity: source in multiple positions

Non-linearity

Systematics

Resolution

Hardware & sources



- 1D: Automatic Calibration Unit (ACU)
- 2D: Cable Loop System (CLS)
- 3D: Remotely Operated under-LS Vehicles (ROV)

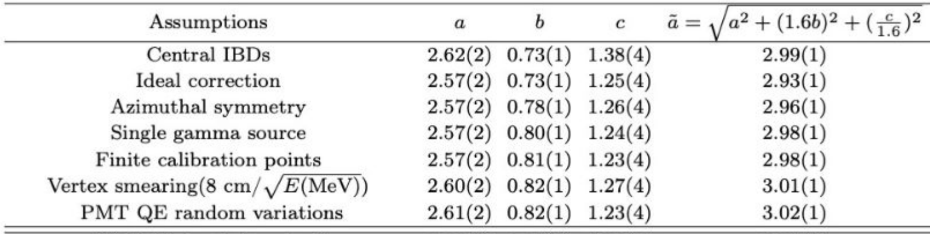
Optimization of energy resolution

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

Effective parametrization for energy resolution
→ each terms cover multiple effects, but mainly:

- "a" term → Poisson statistical fluctuations (~2.6%)
- "b" term → energy non-uniformity (~0.8%)
- "c" term → background noise term (~1%)

enabling non-ideal effects



Assumptions	a	b	c	$\tilde{a} = \sqrt{a^2 + (1.6b)^2 + (\frac{c}{1.6})^2}$
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/$\sqrt{E(\mathrm{MeV})}$)	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)

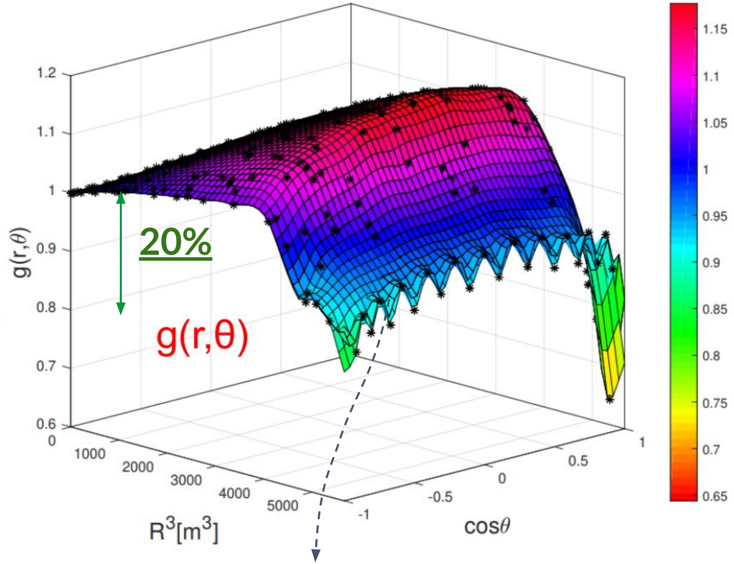
Non-uniformity is corrected by calibrations with radioactive sources located in multiple positions
→ radial-angular function to correct reconstructed energy

("*optimizing energy resolution*")

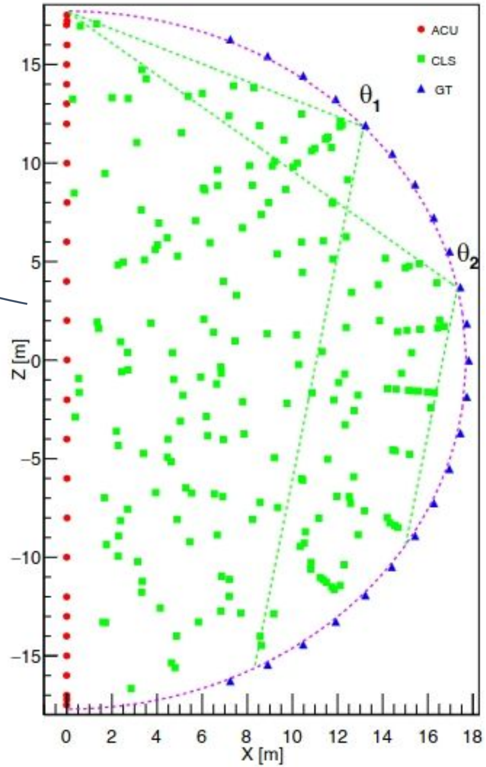
Calibrations: non uniformity correction

Non-uniformity is corrected by calibrating multiple positions with radioactive (AmC) sources

g(R,θ): radial-angular non-uniformity correction



* marks calibration points



Mapping the detector with AmC source

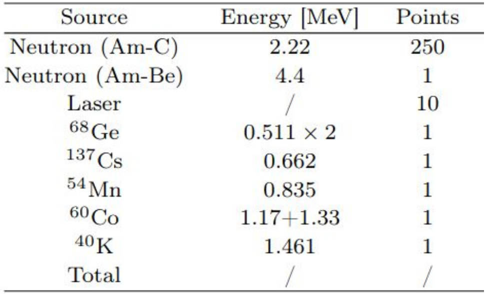
Talk: A. Takenaka, “Detector calibration in the JUNO experiment”, WG6

Calibration program

Program structured following three time periods

1) Comprehensive calibrations

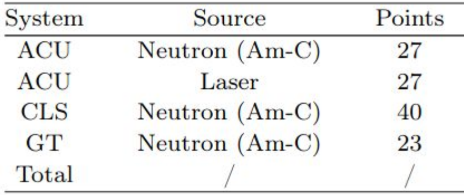
- basic understanding of the CD performance
- At the beginning of data-taking
- > 250 points, ~48h



Source	Energy [MeV]	Points
Neutron (Am-C)	2.22	250
Neutron (Am-Be)	4.4	1
Laser	/	10
^{68}Ge	0.511 × 2	1
^{137}Cs	0.662	1
^{54}Mn	0.835	1
^{60}Co	1.17+1.33	1
^{40}K	1.461	1
Total	/	/

2) Monthly calibrations

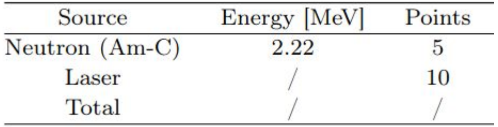
- Monitor non-uniformity
- ~100 points, ~11h



System	Source	Points
ACU	Neutron (Am-C)	27
ACU	Laser	27
CLS	Neutron (Am-C)	40
GT	Neutron (Am-C)	23
Total	/	/

3) Weekly calibrations

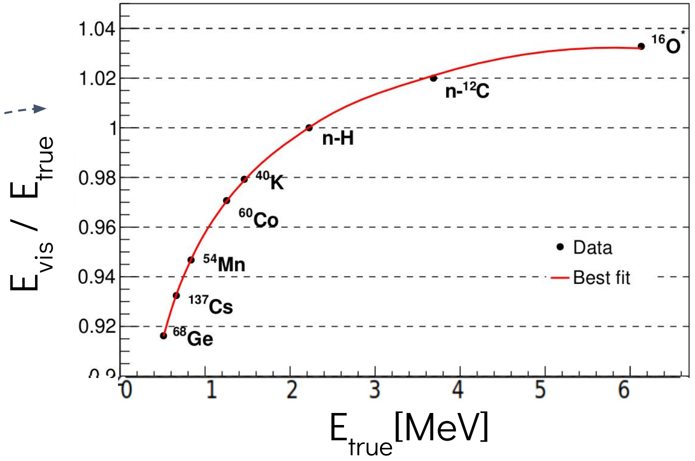
- track major changes of the detector → variations in the light yield of the LS, PMT gains, and electronics
- central axis, 0.1% precision on gamma peaks



Source	Energy [MeV]	Points
Neutron (Am-C)	2.22	5
Laser	/	10
Total	/	/

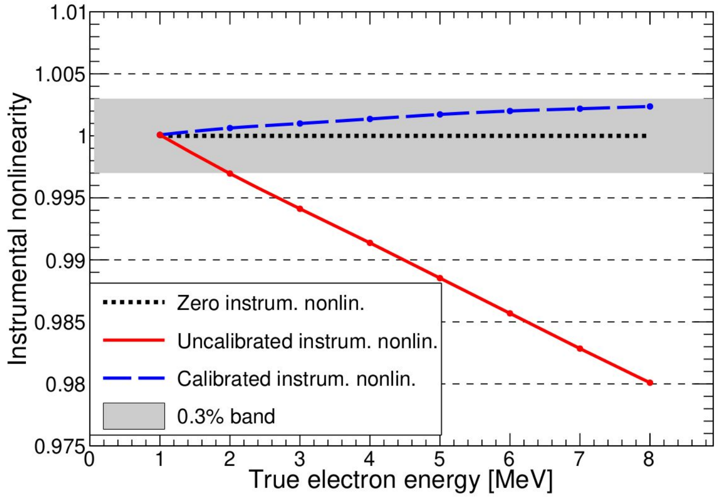
Non-linearity optimization

- **Physics nonlinearity** = non-linearity between particle energy and scintillating/Cherenkov photon
    - LS property, position independent
    - γ calibration sources + ^{12}B cosmogenic isotope



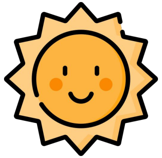
- **Instrumental nonlinearity** = nonlinearity between photon and charge for each channel.
    - PMT instrumentation property
    - Position dependent
    - Laser calib. source

→ dual calorimetry technique → compare LPMTs and sPMTS response



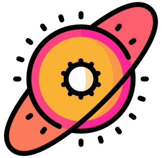
Goal: determination of e+ non-linearity at <1% level

Neutrinos from natural sources



Solar ν
0.1-10 MeV

Geo ν
few MeV



Supernova ν
tens of MeV

Atmospheric ν
~0.5-100 GeV

Energy

Expected rates

^{7}Be: ~10000/day
CNO: ~1000/day
^{8}B: ~90/day

~400 / year

- Core Collapse SN @ 10 kpc: ~10^3 in sec.
- Diffuse SN: few / year

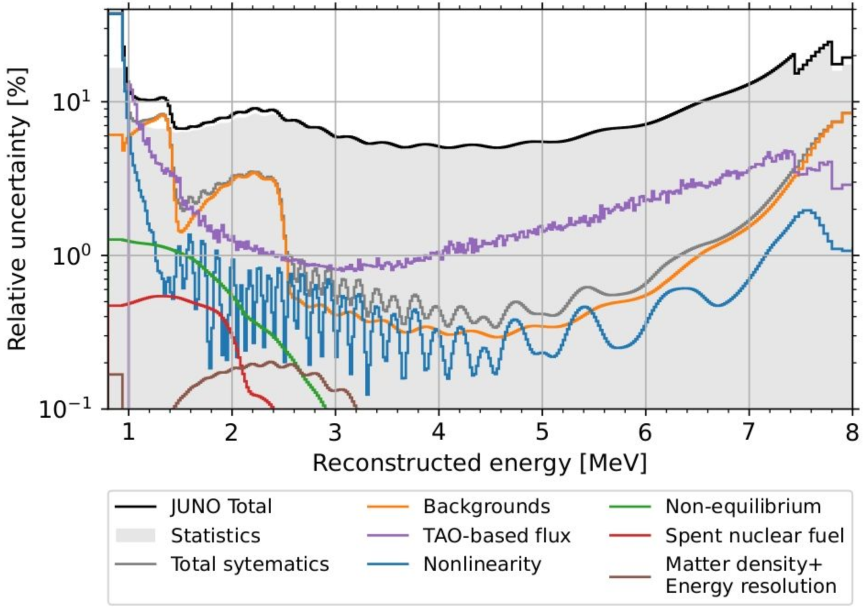
Several / day

New physics?

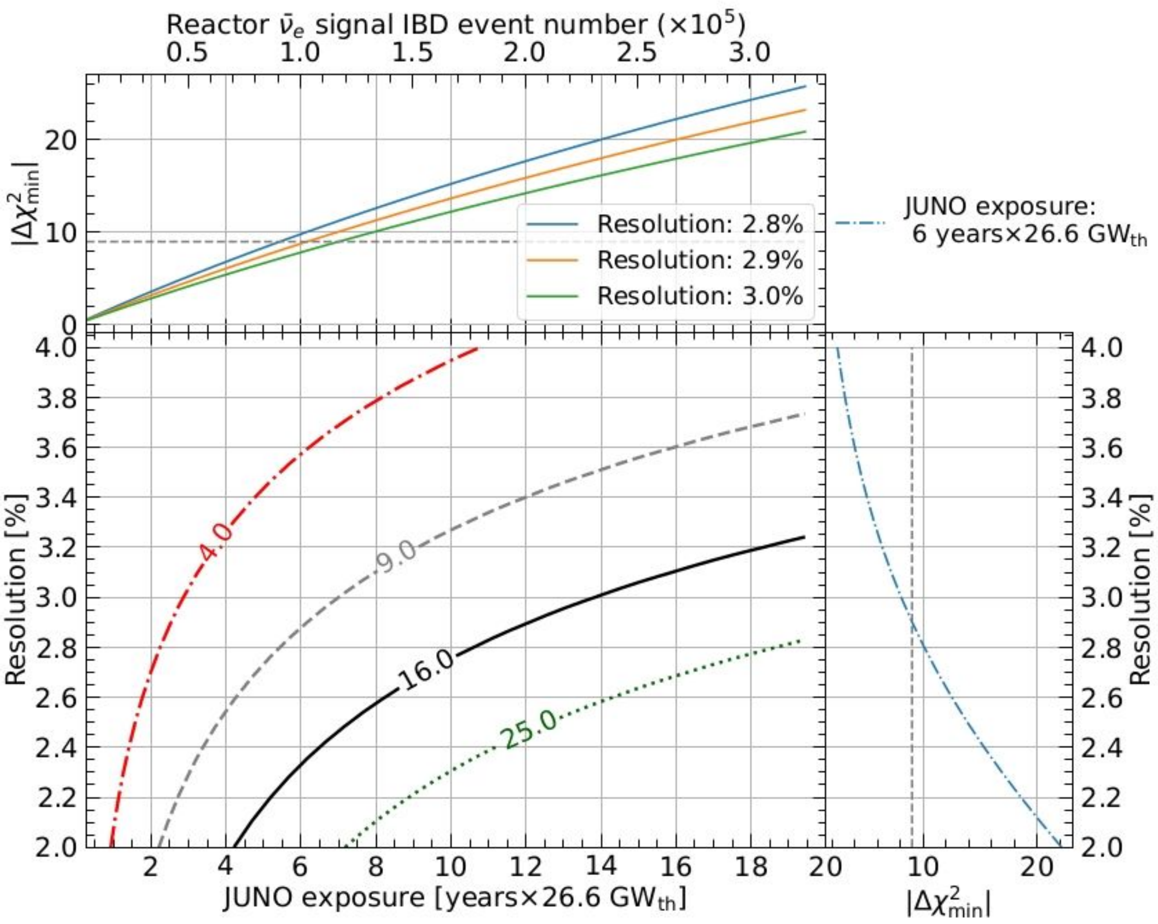
- Proton decay
- Neutrino magnetic moment
- Sterile neutrinos
- Non Standard Interactions
- Lorentz invariance
- Others

Talk: [Prospects for Neutrinos from Natural Sources in JUNO](), Iwan M. Blake, WG1

Shape uncertainties of the JUNO detector



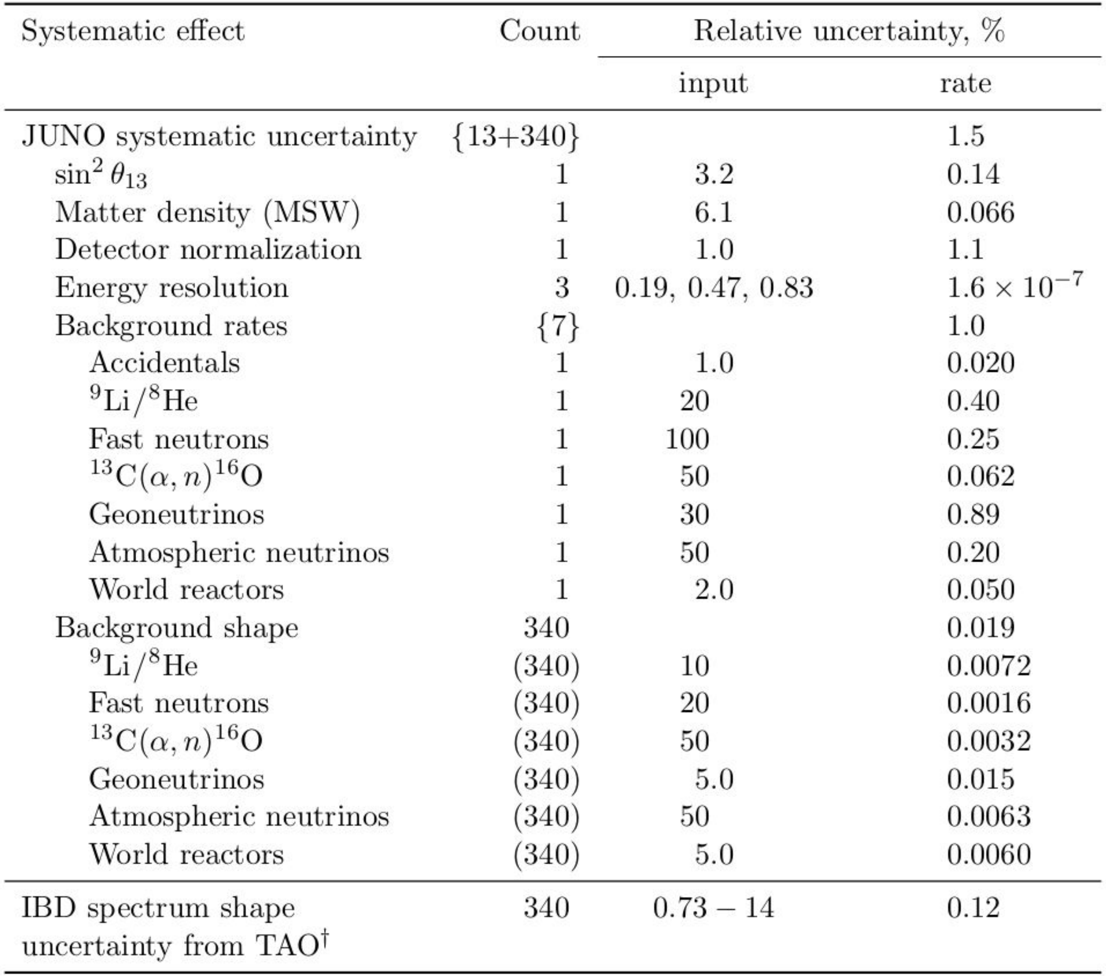
Shape uncertainties of the JUNO detector, presented relative to the number of IBD events from Taishan and Yangjiang reactors in each bin. The absolute uncertainties are obtained by generating simulated samples where systematic parameters are varied based on their assumed uncertainties and taking square roots of diagonal elements of the resulting covariance matrices.



The NMO discriminator contour for JUNO exposure and energy resolution at 1 MeV for NO Asimov data set.

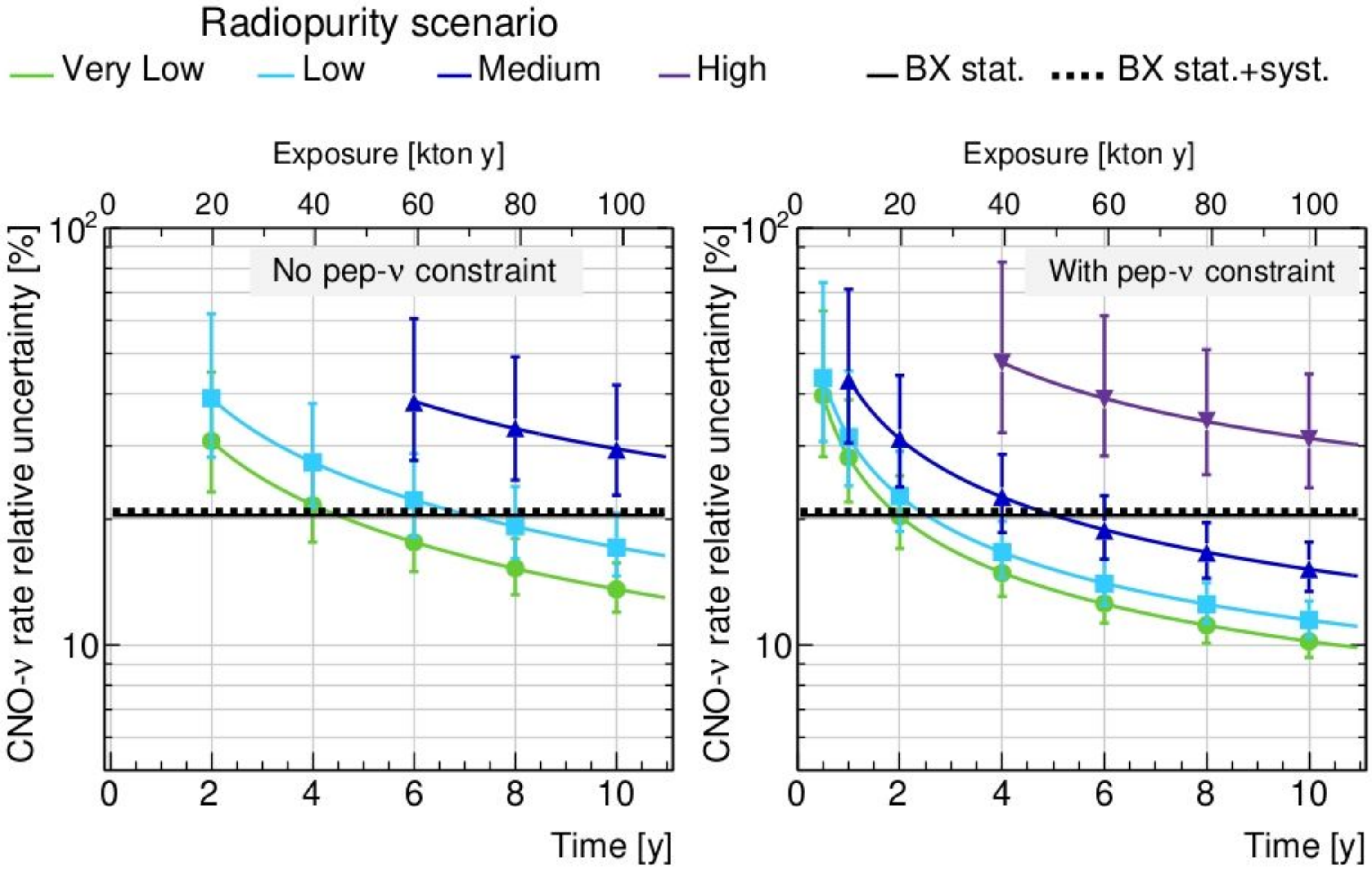
The resolution is scanned by varying a and fixing $b = 0.64 \times 10^{-2}$, $c = 1.20 \times 10^{-2}$ MeV.

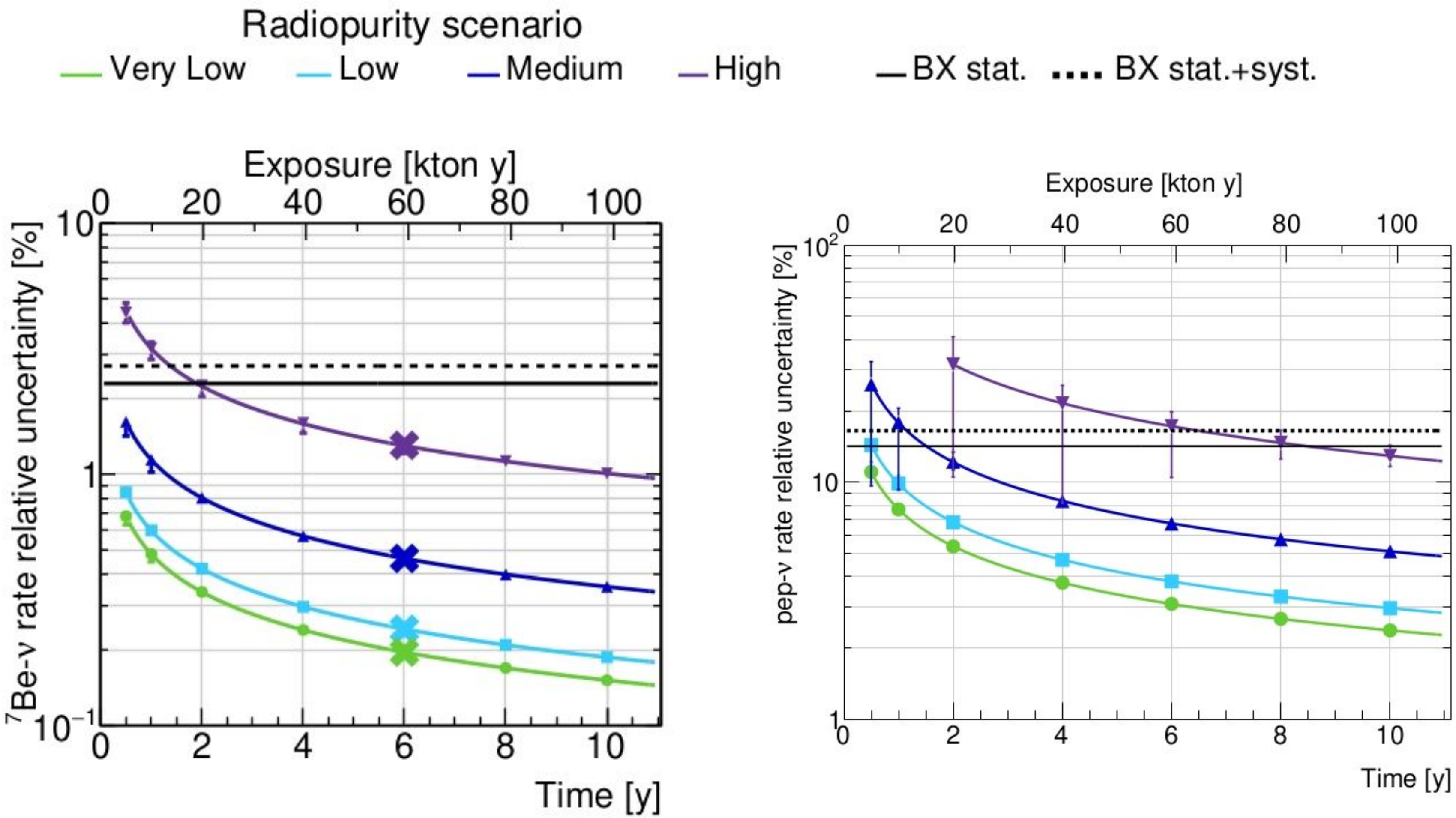
The gray, black, and green contour lines stand for 3σ, 4σ, and 5σ significance. The top pad shows the time evolution of the $|\Delta\chi^2_{\mathrm{min}}|$ under the 2.8%, 2.9%, and 3.0% energy resolution at 1 MeV. The right pad shows the required energy resolution to achieve different $|\Delta\chi^2_{\mathrm{min}}|$ under the JUNO exposure of ~6 years×26.6 GWth (data taking time of 6.7 years).



Systematic effect	Count	Relative uncertainty, %	
		input	rate
JUNO systematic uncertainty	{13+340}		1.5
$\sin^2\theta_{13}$	1	3.2	0.14
Matter density (MSW)	1	6.1	0.066
Detector normalization	1	1.0	1.1
Energy resolution	3	0.19, 0.47, 0.83	1.6×10^{-7}
Background rates	{7}		1.0
Accidentals	1	1.0	0.020
^{9}Li/^{8}He	1	20	0.40
Fast neutrons	1	100	0.25
$^{13}C(\alpha,n)^{16}O$	1	50	0.062
Geoneutrinos	1	30	0.89
Atmospheric neutrinos	1	50	0.20
World reactors	1	2.0	0.050
Background shape	340		0.019
^{9}Li/^{8}He	(340)	10	0.0072
Fast neutrons	(340)	20	0.0016
$^{13}C(\alpha,n)^{16}O$	(340)	50	0.0032
Geoneutrinos	(340)	5.0	0.015
Atmospheric neutrinos	(340)	50	0.0063
World reactors	(340)	5.0	0.0060
IBD spectrum shape uncertainty from TAO†	340	0.73 – 14	0.12

Summary of the systematic effects which impact the JUNO detector.


Radiopurity scenario
Very Low
Low
Medium
High
BX stat.
BX stat.+syst.
Exposure [kton y]
0
20
40
60
80
100
10^2
10
CNO-ν rate relative uncertainty [%]
No pep-ν constraint
With pep-ν constraint
0
2
4
6
8
10
Time [y]


Radiopurity scenario
Very Low
Low
Medium
High
BX stat.
BX stat.+syst.
Exposure [kton y]
0
20
40
60
80
100
^{7}Be-ν rate relative uncertainty [%]
10^{0}
1
10^{-1}
0
2
4
6
8
10
Time [y]
Exposure [kton y]
0
20
40
60
80
100
pep-ν rate relative uncertainty [%]
10^{2}
10
1
0
2
4
6
8
10
Time [y]