Prospects of Neutrino Oscillation Physics in JUNO

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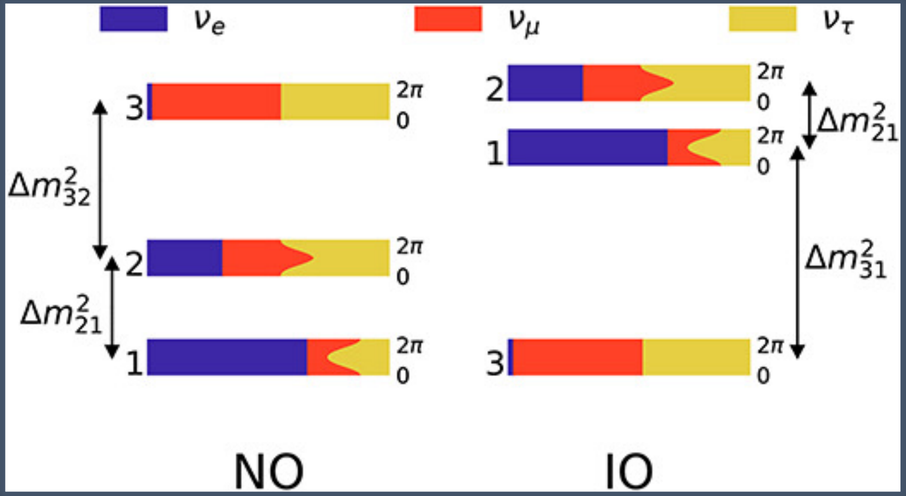
On behalf of the JUNO collaboration

9 September 2022

Open questions in ν oscillation physics

- **Mass ordering** "normal" or "inverted"? Is ν_1 lighter than ν_3?
- Precise values of neutrino **mixing angles and mass splittings**

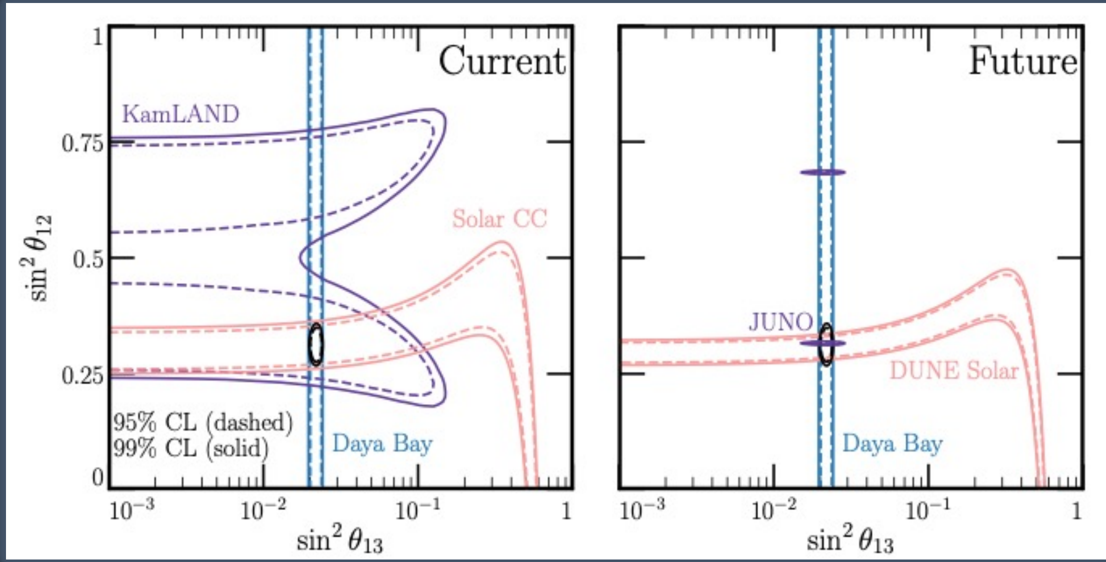
	PDG-2020	JUNO
Δm^2_{21}	$(7.53 \pm 0.18) \times 10^{-5}$ eV^2 (2.39%)	??
Δm^2_{32} (NO)	$(2.453 \pm 0.034) \times 10^{-3}$ eV^2 (1.39%)	??
Δm^2_{32} (IO)	$-(2.546 \pm 0.036) \times 10^{-3}$ eV^2 (1.41%)	??
$\sin^2 \theta_{12}$	0.307 ± 0.013 (4.23%)	??
$\sin^2 \theta_{13}$	0.0218 ± 0.0007 (3.21%)	??



- Do neutrino oscillations violate **CP symmetry**? $\delta_{CP} \neq 0, \pi$
- What is the **"octant" of θ_{23}**? Is the mixing maximal θ_{23} = 45°?
- **More than 3** neutrinos?

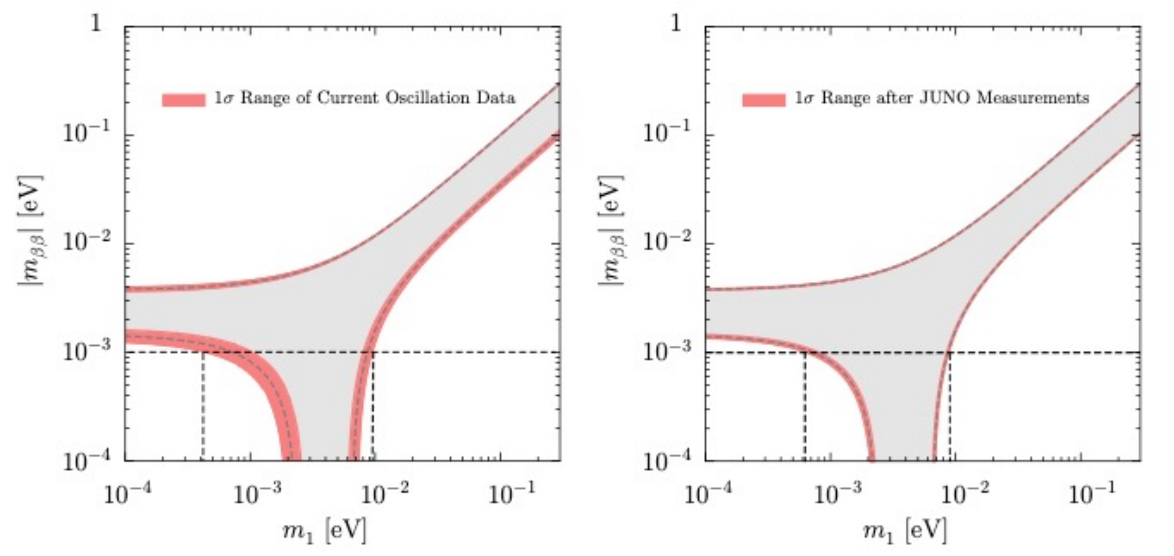
Impact of sub-percent precision

- Unitarity of PMNS matrix



S.A.R.Ellis, K.J.Kelly and S.W.Li, JHEP 12 (2020), 068

- Reduce the parameter space for $0\nu\beta\beta$

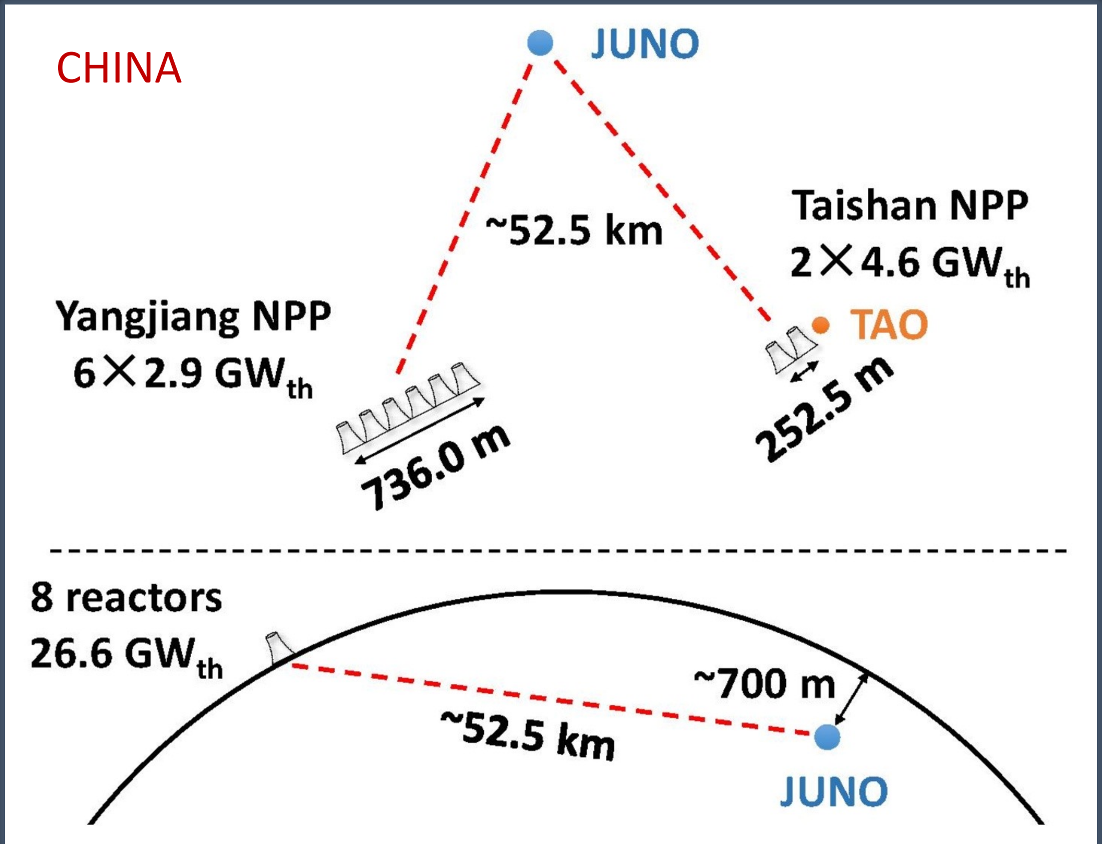


Jun Cao et al 2020 Chinese Phys. C 44 031001

- Reduce the parameter space for leptonic CP violation
- Powerful discriminator for models of the neutrino masses and mixing
- Test the mass sum rule: $\Delta m^2_{13} + \Delta m^2_{21} + \Delta m^2_{32} = 0$?
- Precision enable to identify discrepancies → new physics

JUNO experiment: oscillation physics

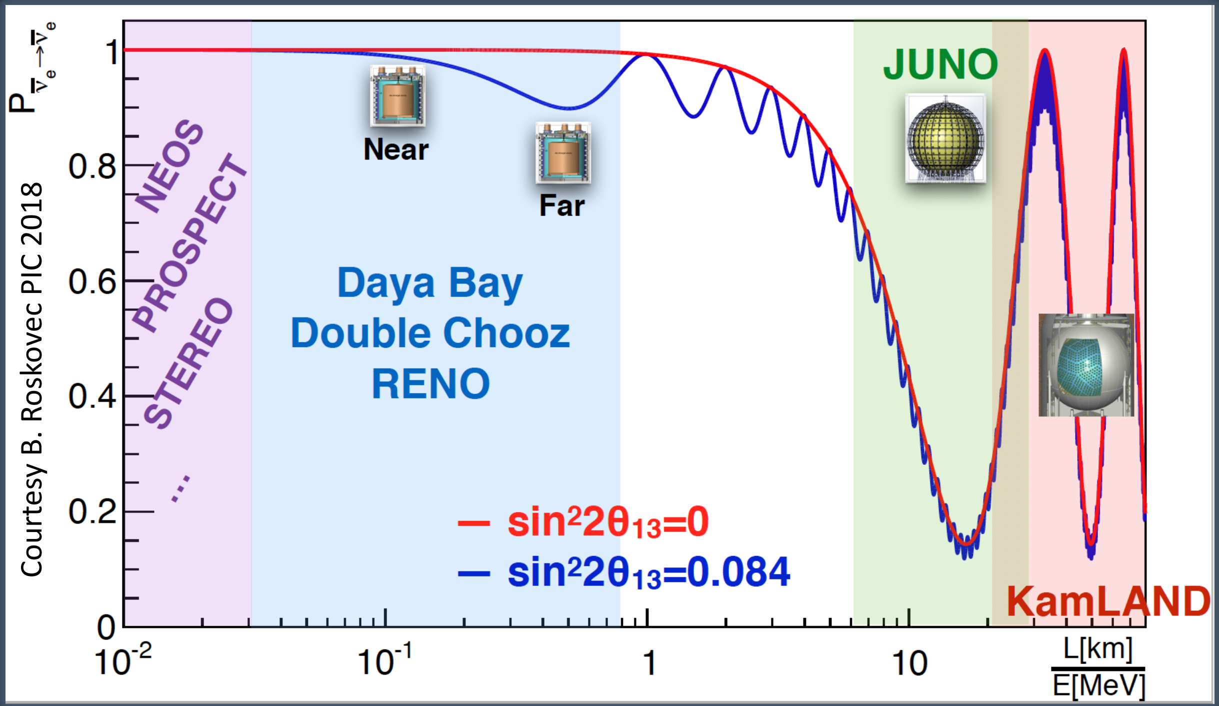
JUNO -Jiangmen Underground Neutrino Observatory
TAO - Taishan Antineutrino Observatory



Optimized baseline for NMO determination with $\bar{\nu}_e$

Multi-purpose liquid scintillator experiment

- Reactor $\bar{\nu}_e$ at ~53 km
  ~ 45 $\bar{\nu}_e$/day
  Neutrino Mass Ordering (NMO)
  Δm^2_{21}, Δm^2_{32}, $\sin^2\theta_{12}$



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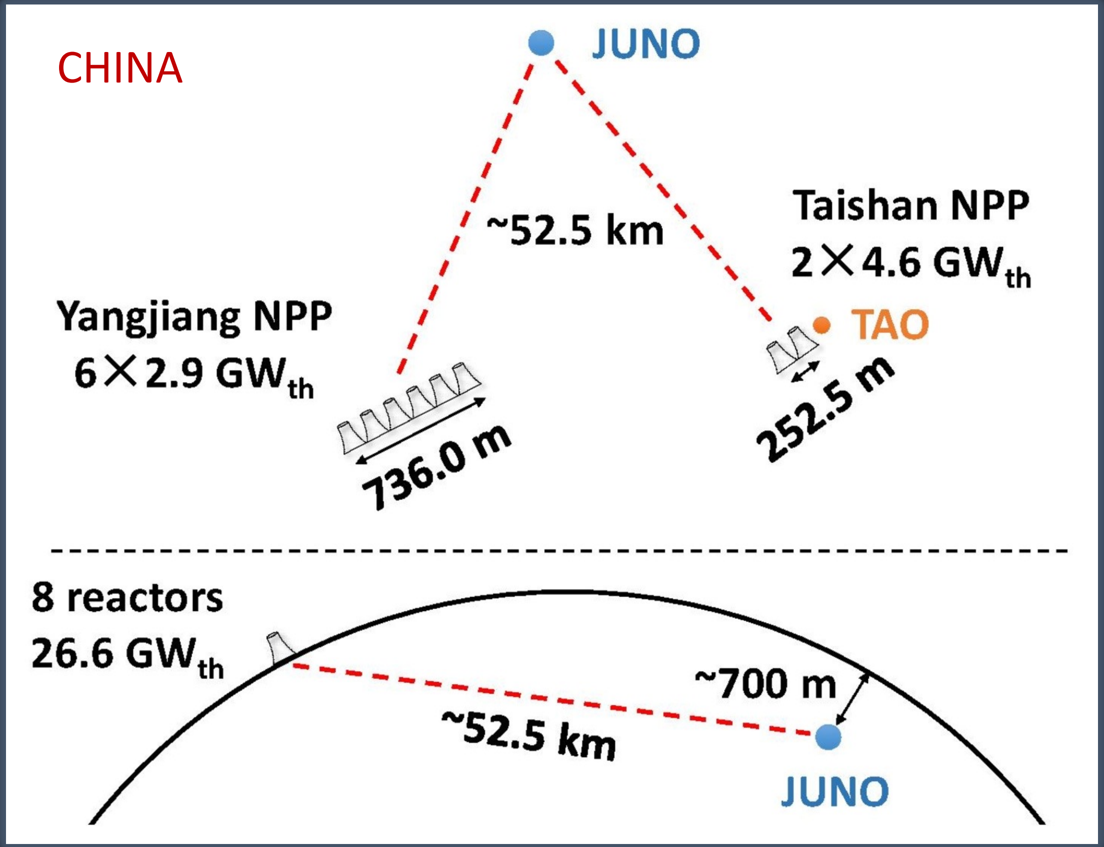


Optimized baseline for NMO determination with $\bar{\nu}_e$

Multi-purpose liquid scintillator experiment

- Reactor $\bar{\nu}_e$ at ~53 km
  $\sim$ 45 $\bar{\nu}_e$/day
  Neutrino Mass Ordering (NMO)
  Δm^2_{21}, Δm^2_{32}, $\sin^2\theta_{12}$
- Solar ν_e from ^8B
  $\sim$ 17 ν_e/day
  Δm^2_{21}, $\sin^2\theta_{12}$
- Atmospheric $\nu_\mu/\bar{\nu}_\mu$
  $\sim$ 1233/1035 events (200 kton-years)
  NMO
  $\sin^2\theta_{23}$
- Reactor $\bar{\nu}_e$ with TAO detector (~30 m)
  $\sim$ 2000 $\bar{\nu}_e$/day
  Δm^2_{41}, $\sin^2 2\theta_{14}$?

JUNO detector

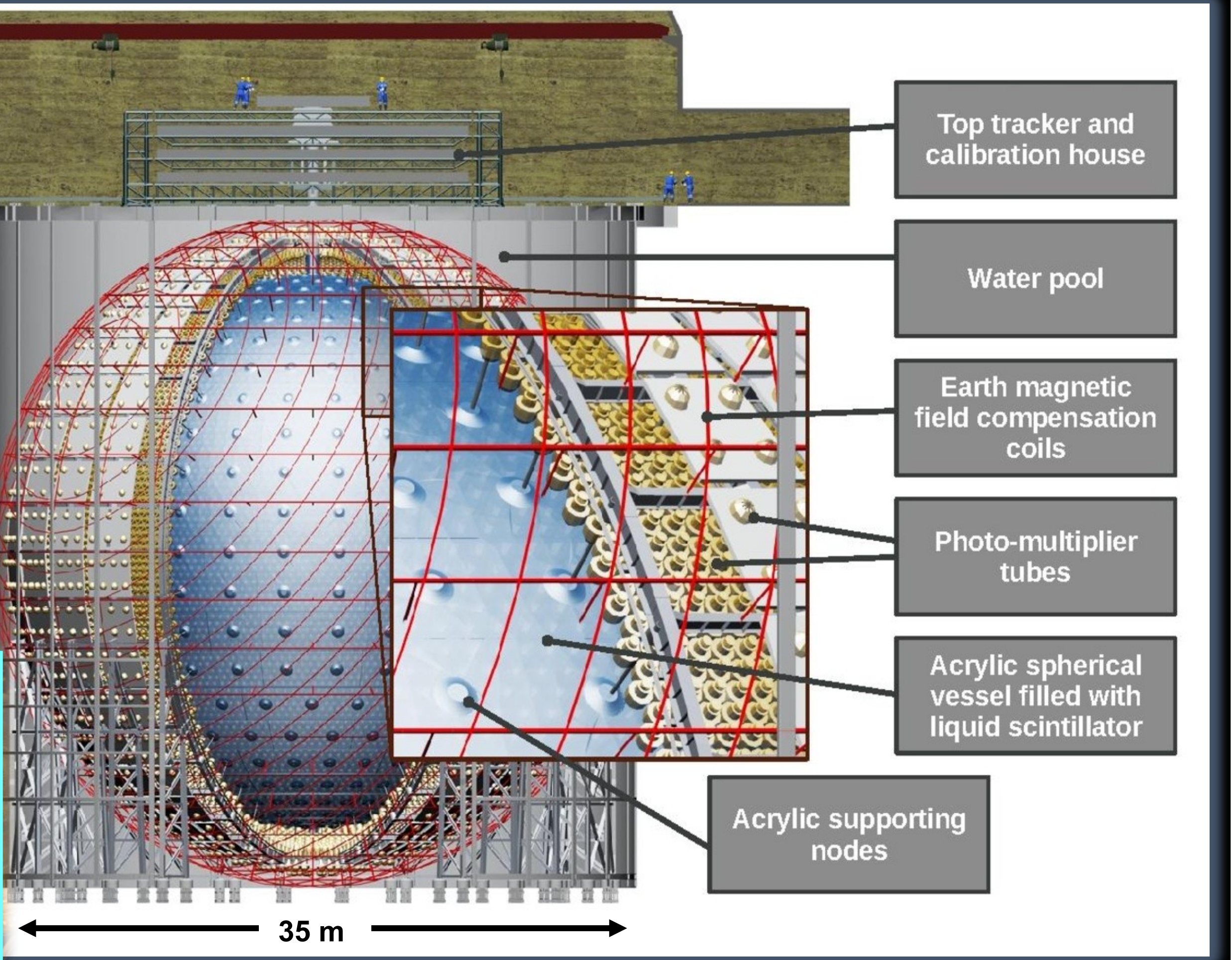
- World's largest Liquid Scintillator
  20 kton LAB-based liquid scintillator
  High PE yield: ~1350 PE / MeV

- Detection channel: Inverse Beta Decay
  $\bar{\nu}_e + p \rightarrow n + e^+$
  Time + position coincident signal
  $E_{vis} \simeq E_{\bar{\nu}_e}$ - 0.78 MeV

- Light detection: 17612 20" PMTs (LPMT) + 25600 3" PMTs (SPMT)

DUAL CALORIMETRY

Two independent PMT systems
>75% photo-coverage



- Overburden: ~700 m
  Cosmic background suppression

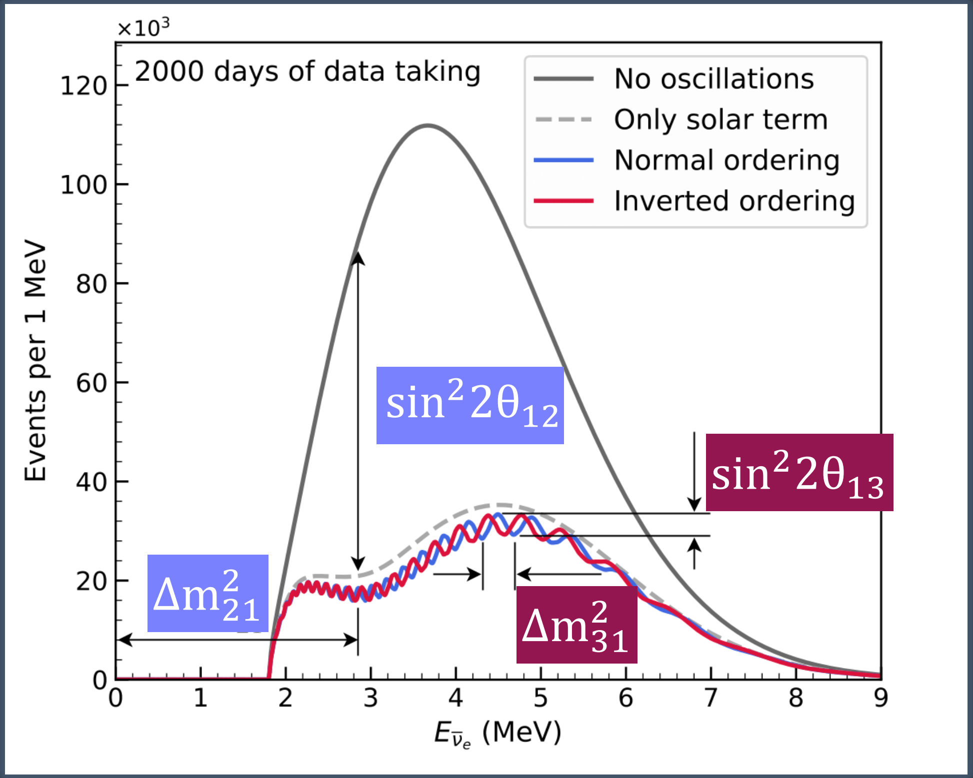
Reactor $\bar{\nu}_e$ spectrum at JUNO

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right)$$

Slow component (solar oscillation mode)

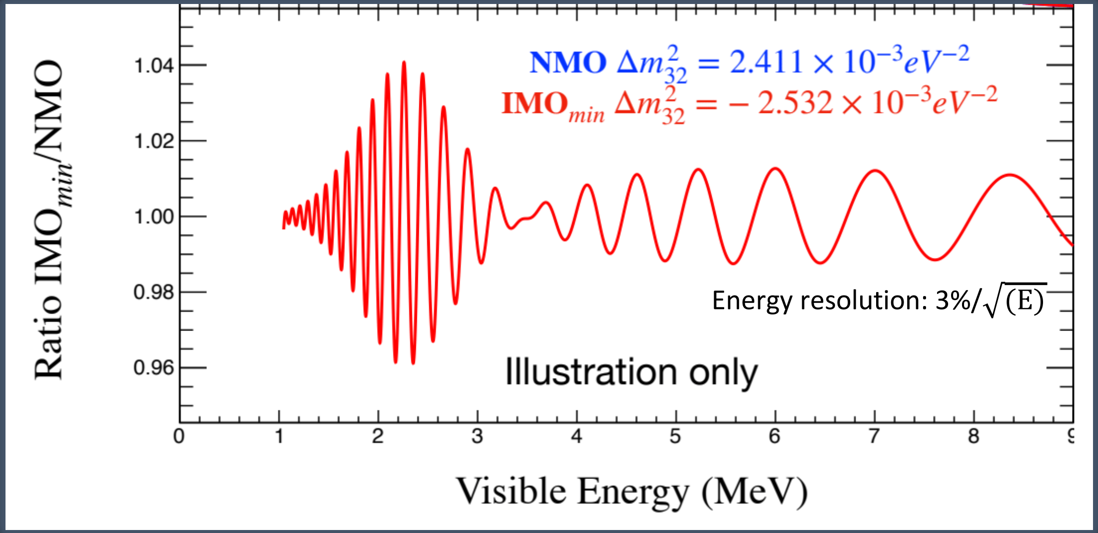
$$- \sin^2 2\theta_{13}\left[\cos^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)\right]$$

Fast component (atmospheric oscillation mode)

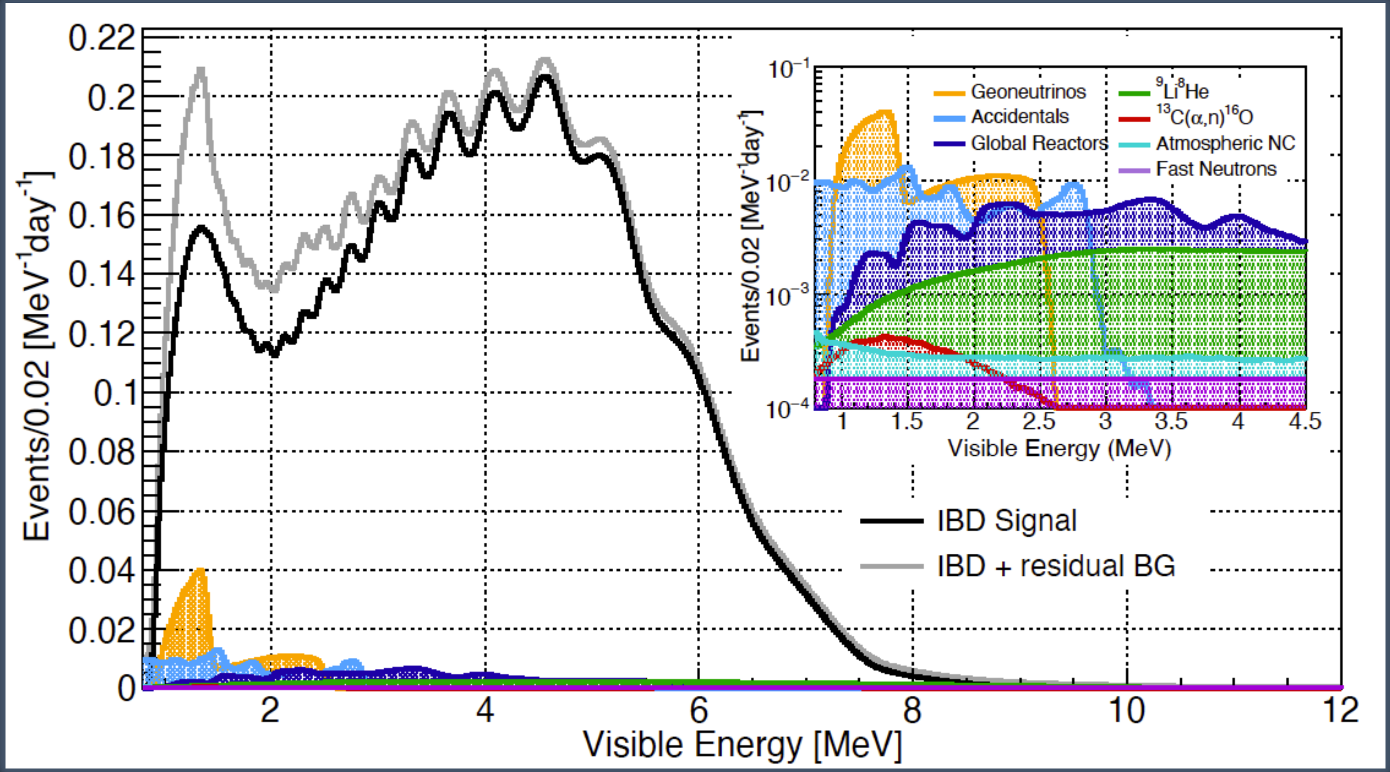


JUNO will be the first experiment to observe two modes of neutrino oscillations simultaneously

MO sensitivity from spectral shape analysis



$\bar{\nu}_e$ Signal and Backgrounds



	Efficiency (%)	IBD Rate (day^{-1})
All IBDs	100	57.4
After Selection	82.2	47.1

Muon veto efficiency improvement 83% → 91.6%

- **Detection channel: Inverse Beta Decay**
  Prompt + delayed space & time coincidence is an excpertional background suppressing tool!
- **Differential IBD cross-section** to account for neutron recoils

Phys. Rev. D 60, 053003 (1999)

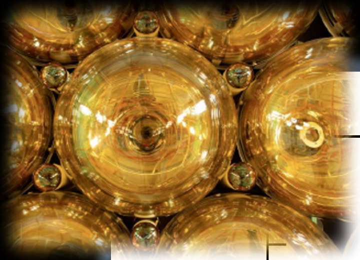
- **Matter effects**
  ρ = 2.45 g·cm^{-3} (6% uncertainty)

Background	Rate (day^{-1})	Rate Unc (%)	Shape Unc (%)
Geoneutrinos	1.2	30	5
World reactors	1.0	2	5
Accidentals	0.8	1	negligible
^{9}Li/^{8}He	0.8	20	10
Atmospheric neutrinos	0.16	50	50
Fast neutrons	0.1	100	20
^{13}C(α,n)^{16}O	0.05	50	50

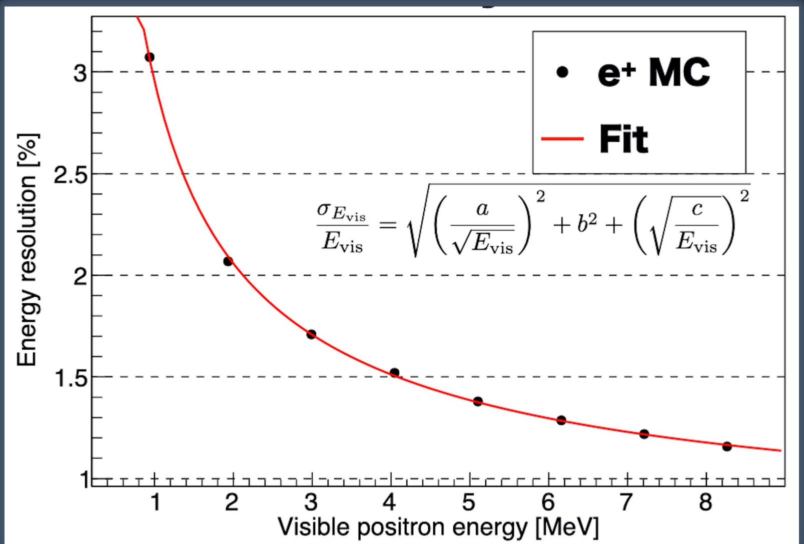
Prog.Part.Nucl.Phys. 123 (2022) 103927

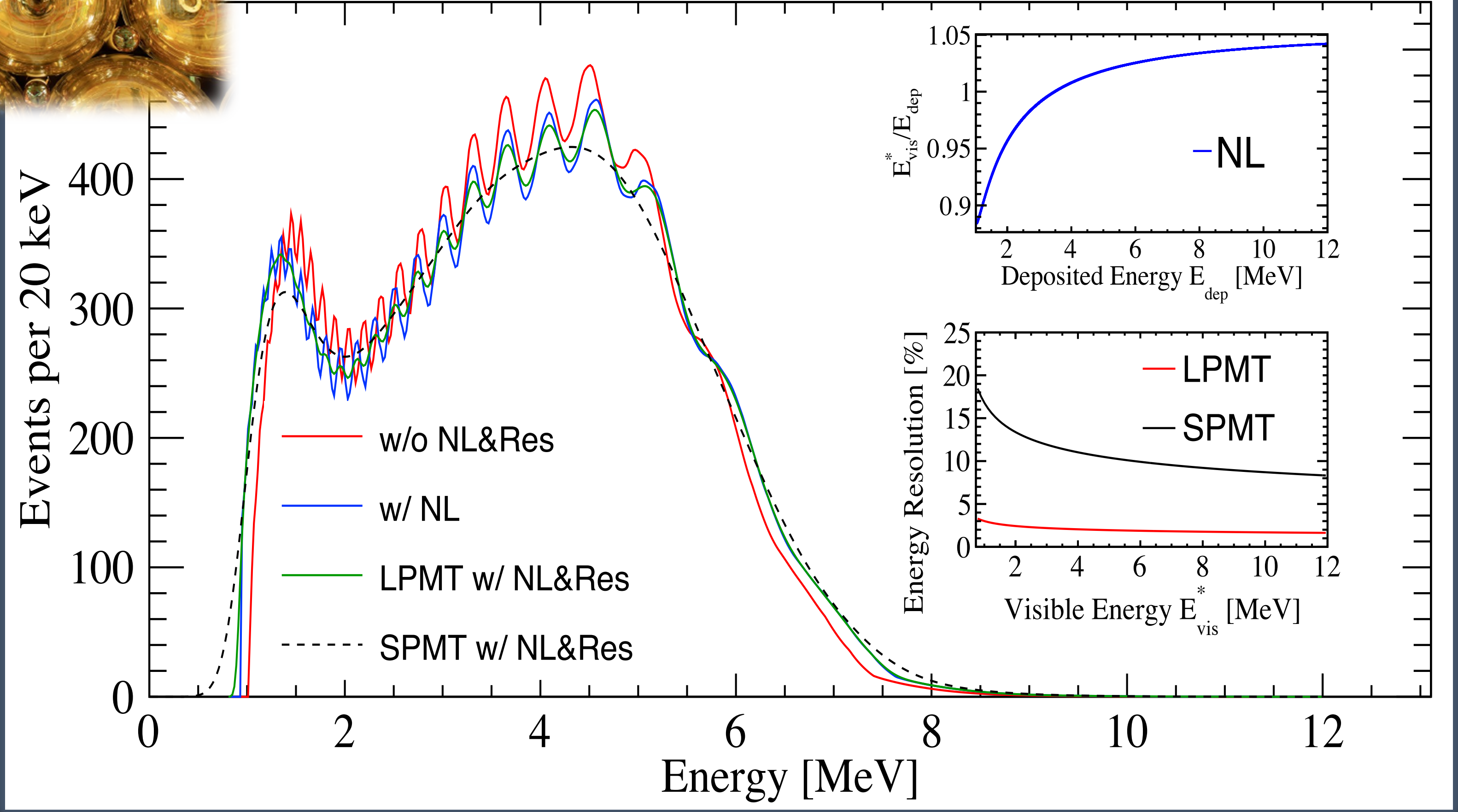
JUNO detector response

- Energy non-linearity
  Scale uncertainty < 1%
  Ensure the oscillation peak positions



- Energy resolution
  σ_E < 3% at 1 MeV
  Resolve the fast component oscillation peaks

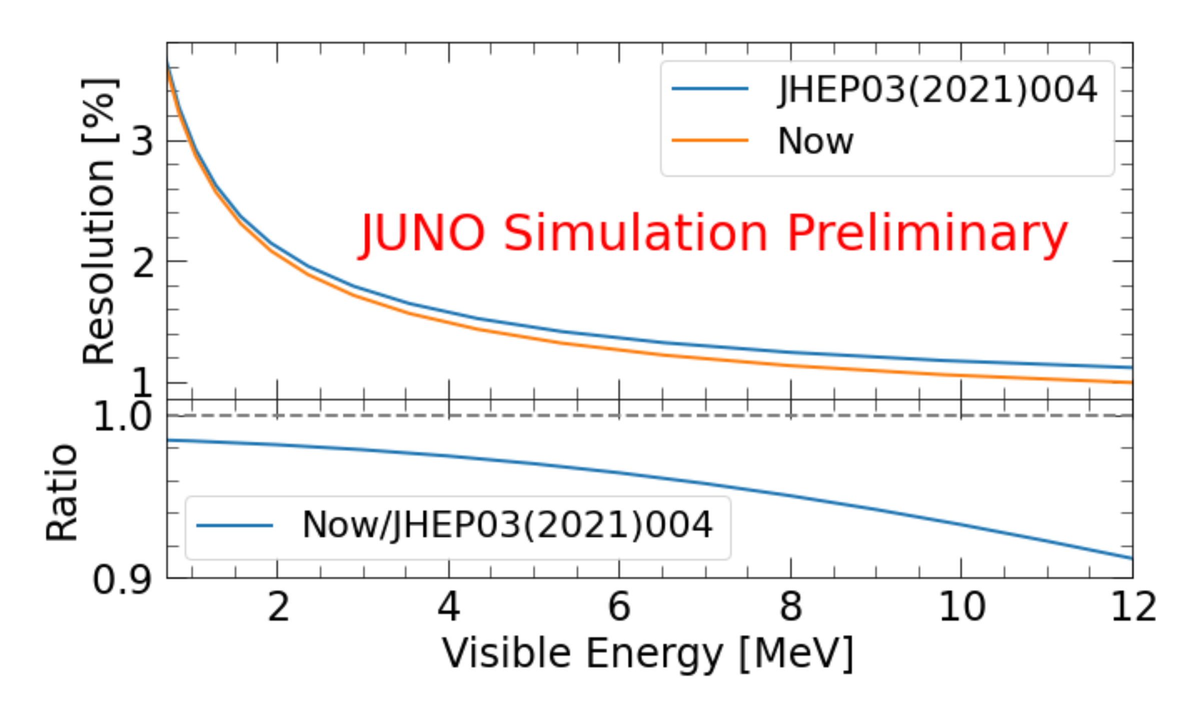




More info: Calibration Strategy of the JUNO experiment - JHEP 03 (2021) 004

Improvements on the energy resolution

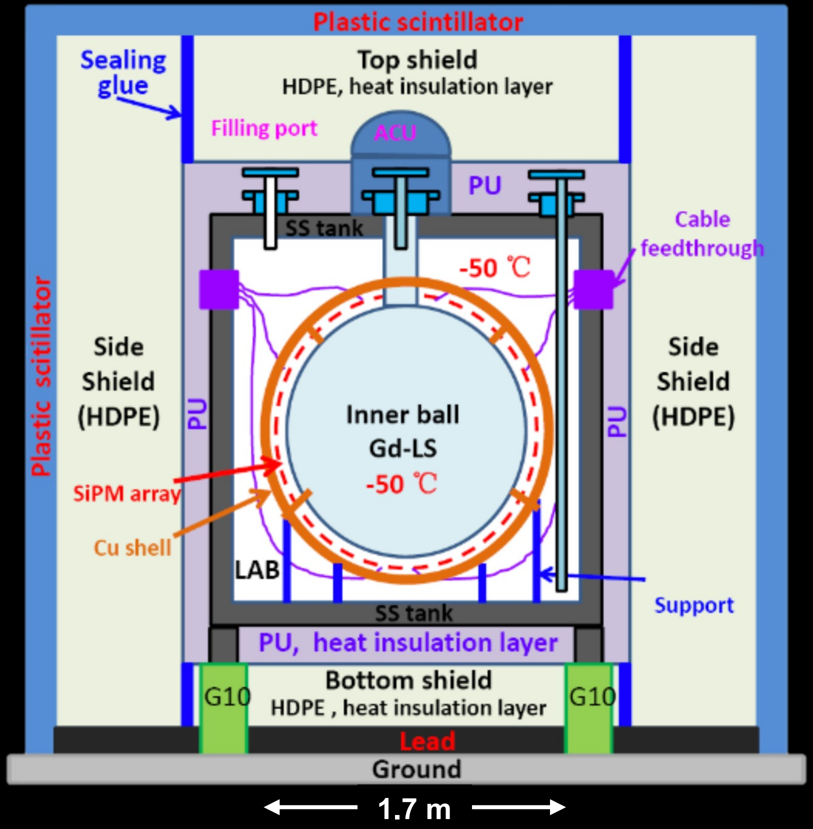
Change	Light yield in detector center [PEs/MeV]	Energy resolution	Reference
Previous estimation	1345	3.0% @1MeV	JHEP03 (2021) 004
Photon Detection Efficiency (27%→30%)	+11% ↑	2.9% @ 1MeV Poster #519 at Neutrino22	arXiv: 2205.08629
New Central Detector Geometries	+3% ↑		Poster #184 at Neutrino22
New PMT Optical Model	+8% ↑		EPJC 82 329 (2022)



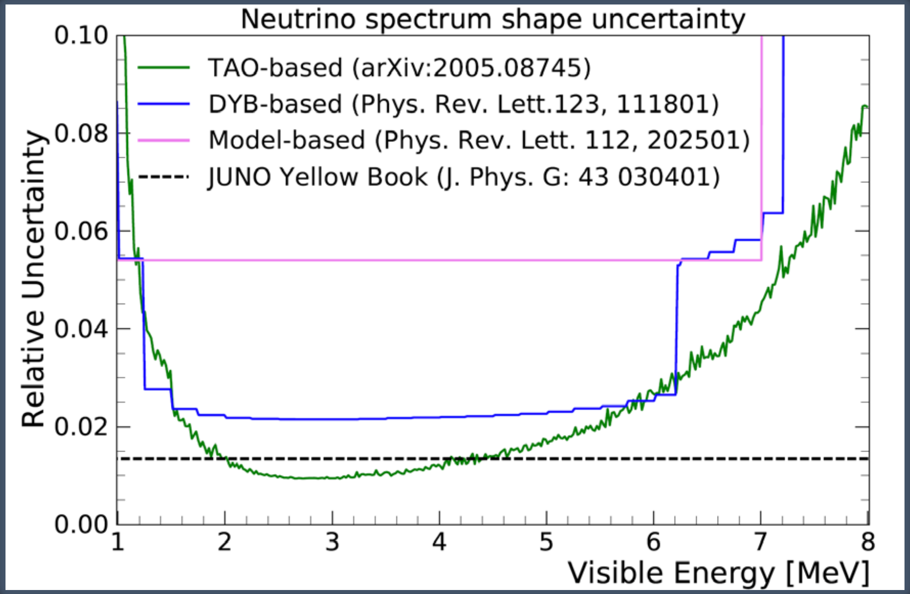
- New energy resolution curve Is provided as input for the NMO analysis
- Goal: combined analysis of JUNO+TAO data

JUNO-TAO

arXiv:2005.08745



- TAO will deliver precise $\bar{\nu}_e$ energy spectrum with sub-percent energy resolution in most of energy region of interest
- Minimize the possible model dependence due to fine structure in the reactor antineutrino spectrum
- The bin-to-bin spectral shape uncertainty can be reduced to ~1% level



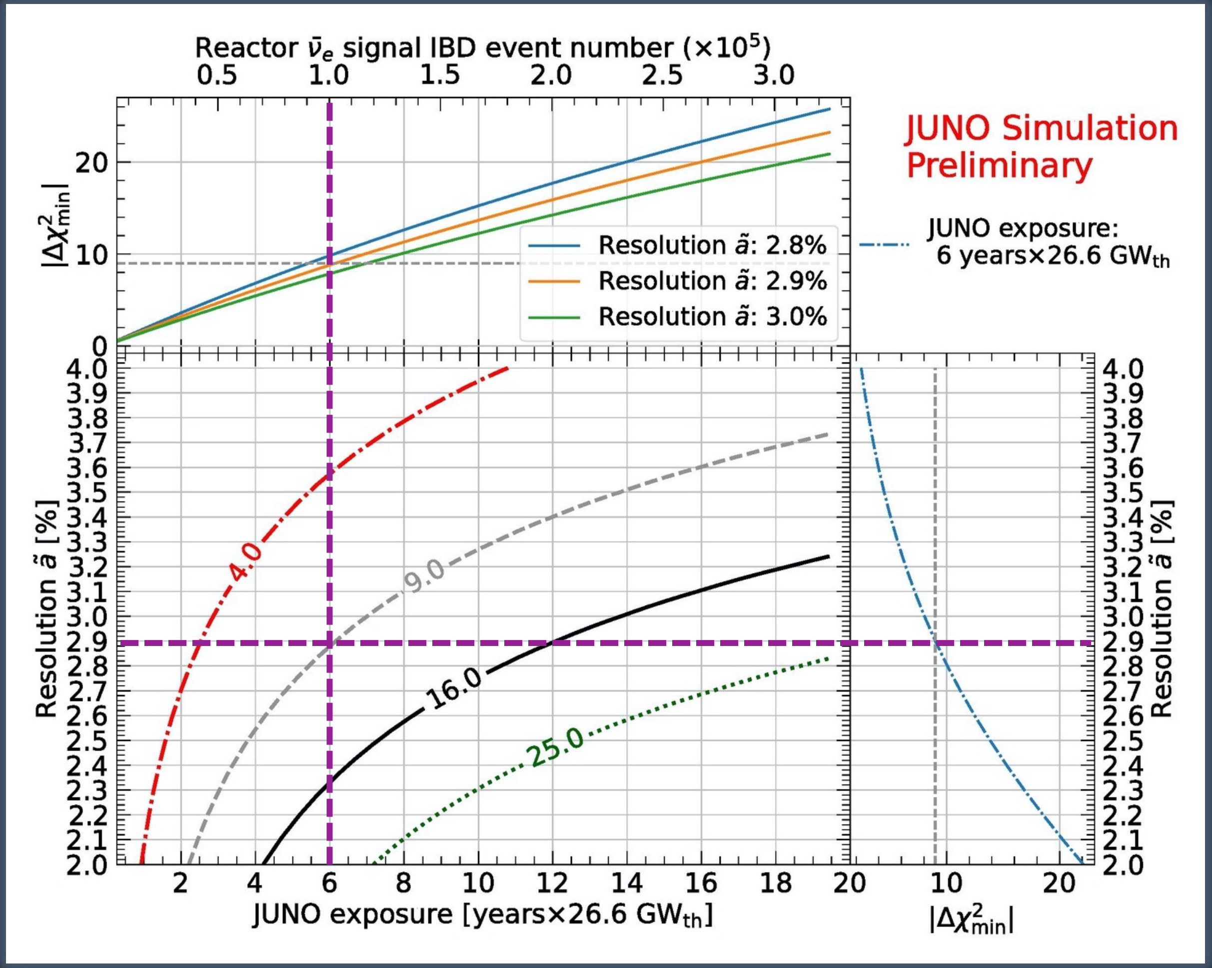
- 2.6 t GdLS
- ~30 m from reactor core
- ~2000 IBD events/day

- 12k PE/MeV
- >95% photo-coverage (4100 SiPM)
- Energy resolution ~2% @1 MeV

Neutrino Mass Ordering Sensitivity

PUBLICATION COMING SOON

- JUNO is the only experiment exploiting vacuum oscillations (Unique)
- No dependence on θ_{23} or δ_{CP}. Very little dependence on matter effects



$$\Delta\chi^2_{MO} = \left|\chi^2_{min}(NO) - \chi^2_{min}(IO)\right|$$

- Unconstrained (JUNO only) → **3σ** sensitivity in 6 years of data

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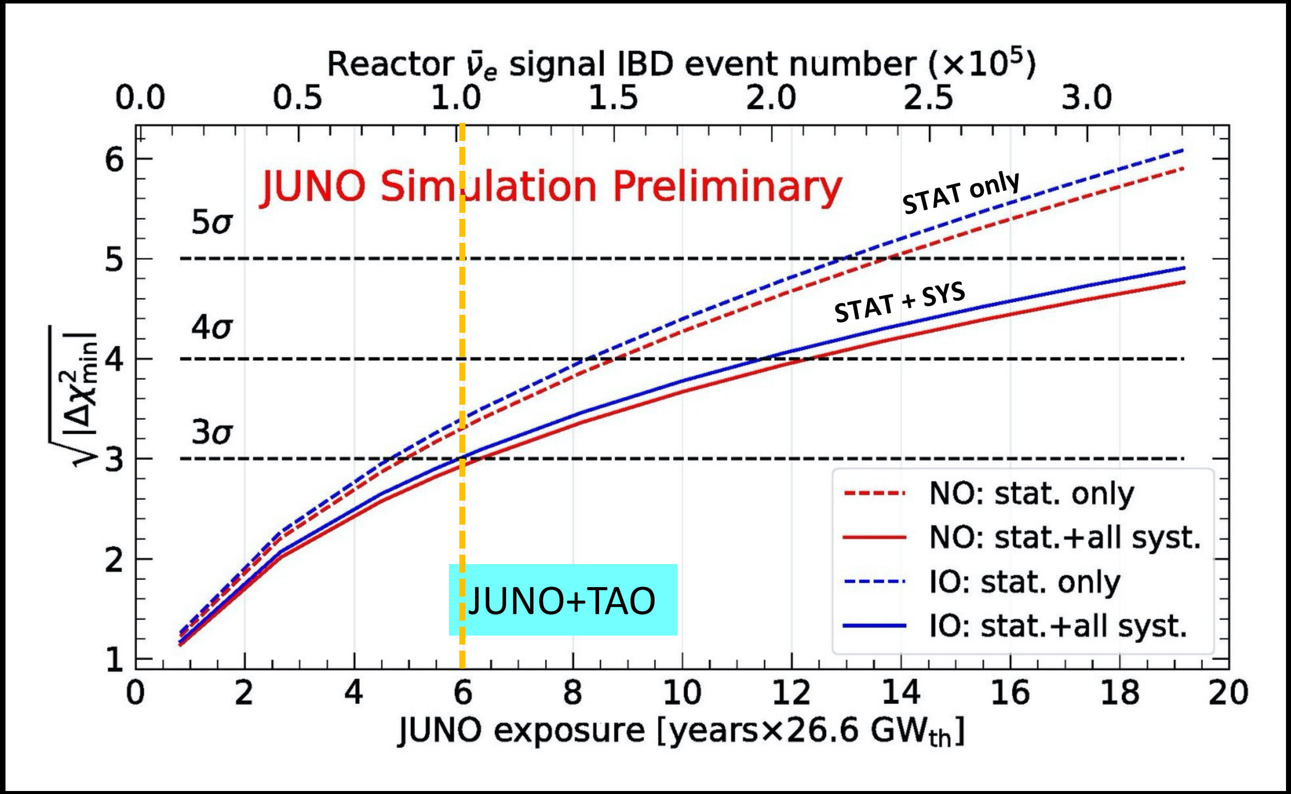

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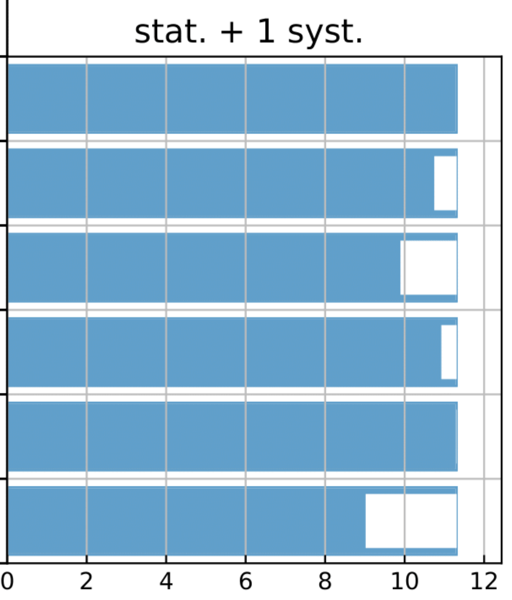
	$\Delta\chi^2_{min}$
Statistics	11.3
Stat.+Flux error	-0.6
Stat.+Backgrounds	-1.4
Stat.+Nonlinearity	-0.4
Stat.+Others	< -0.05
Total	9.0



JUNO Simulation Preliminary

Neutrino Mass Ordering Sensitivity

PUBLICATION COMING SOON

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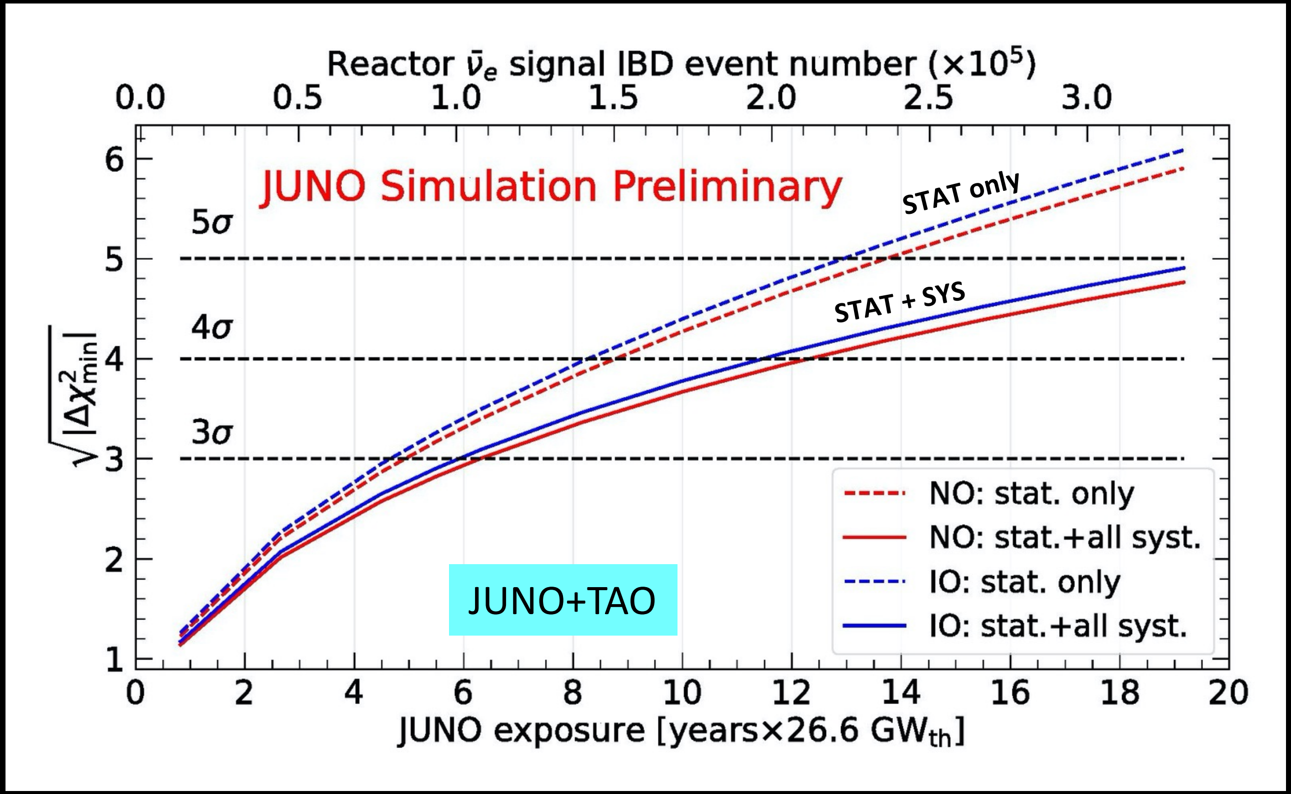


- Unconstrained (JUNO only) → **3σ** sensitivity in 6 years of data
- Using external $|\Delta m^2_{\mu\mu}|$(1% precision) → **4σ** sensitivity in 6 years
- Strong synergies with other experiments:

Through Δm^2_{32} for accelerator neutrinos (NOvA and T2K) Sci Rep 12, 5393 (2022)

Through Δm^2_{31} for atmospheric neutrinos (KM3NeT/ORCA and IceCube) Phys. Rev. D 101, 032006 (2020) JHEP 03 (2022) 055

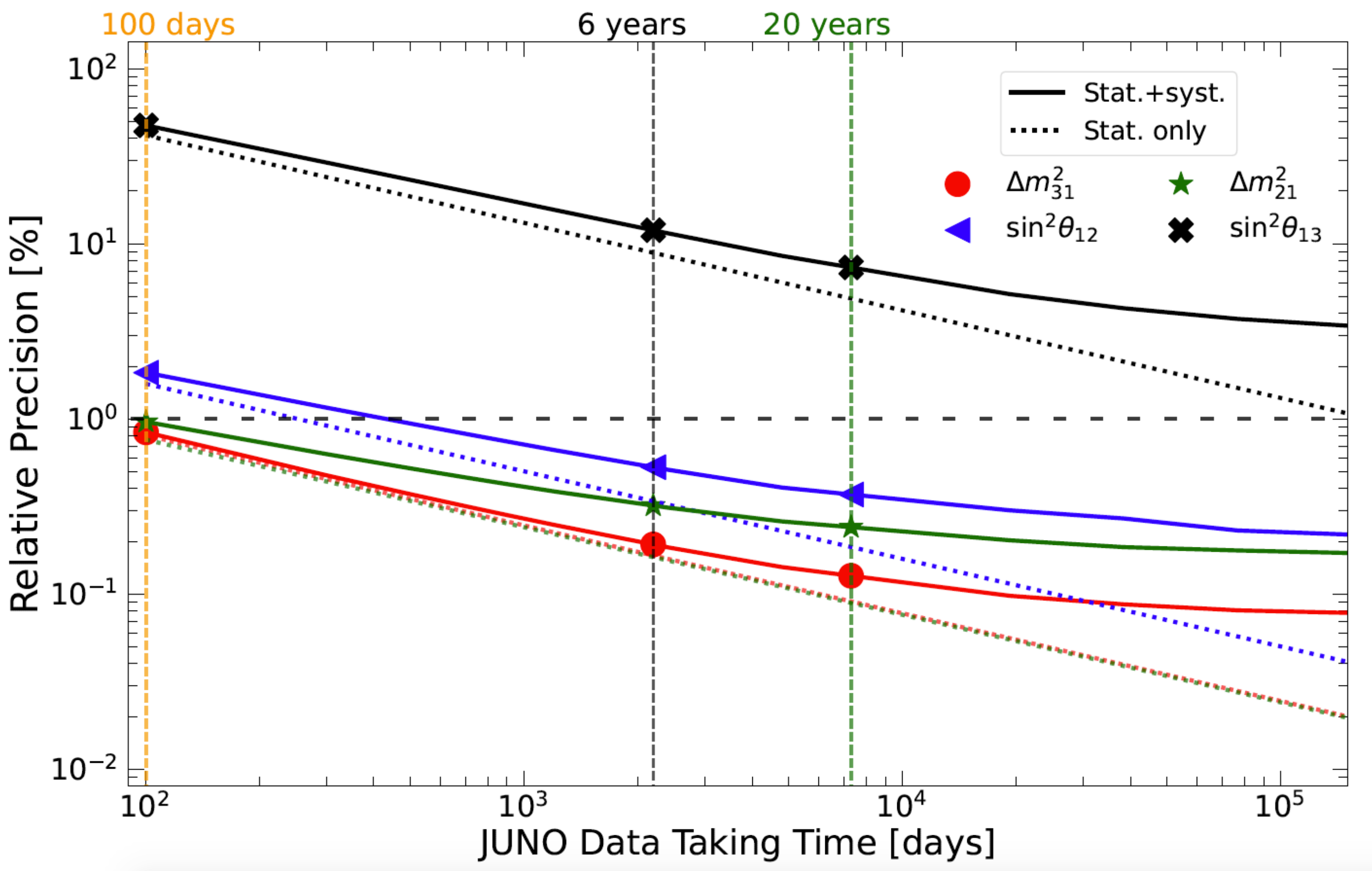
> 5σ sensitivity (in 6 years) in case of joint analysis

Neutrino Oscillation Parameters

- Comparison of nominal spectrum against model based on the standard parametrization

$$X^2 \equiv \left(M - T(\theta,\alpha)\right)^T \cdot V^{-1} \cdot \left(M - T(\theta,\alpha)\right) + \sum_i \left(\frac{\alpha_i}{\sigma_i}\right)^2$$

Pull terms can substitute any covariance matrix (systematics) and vice-versa



	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
JUNO 6 years	~0.2%	~0.3%	~0.5%	~12%
PDG2020	1.4%	2.4%	4.2%	3.2%

- JUNO will yield sub-percent precision after the nominal exposure of 6 years
- Improve today's precision by almost one order of magnitude in 3 of 6 oscillation parameters
- JUNO will help in testing the unitarity of the PMNS matrix and the mass sum rule

Paper accepted for publication by Chinese Physics C

Breakdown of Systematic Uncertainties

stat	Statistical (reactor $\bar{\nu}_e$ events only)
eff	Detection efficiency
runc	Reactor $\bar{\nu}_e$ flux reactor-uncorrelated
rcor	Reactor $\bar{\nu}_e$ flux reactor-correlated
b2bTAO	Reactor $\bar{\nu}_e$ spectrum shape based on TAO measurement
snf	$\bar{\nu}_e$ flux from spent nuclear fuel)
noneq	Non-equilibrium correction to reactor $\bar{\nu}_e$ flux
abc	Energy resolution (JHEP03,004(2021))
nl	Liquid scintillator non-linearity (NIMA940,230(2019))
bg	Backgrounds
ME	Earth's matter density
all syst	All systematics above

The dominant systematics for precision measurement:

- Δm^2_{31} / Δm^2_{32} : reactor spectrum shape
- Δm^2_{21} : backgrounds, non-equilibrium effect
- $\sin^2\theta_{12}$, $\sin^2\theta_{13}$: normalization rate (reactor and detection efficiency)

Spectral info provides good constraint on the normalization

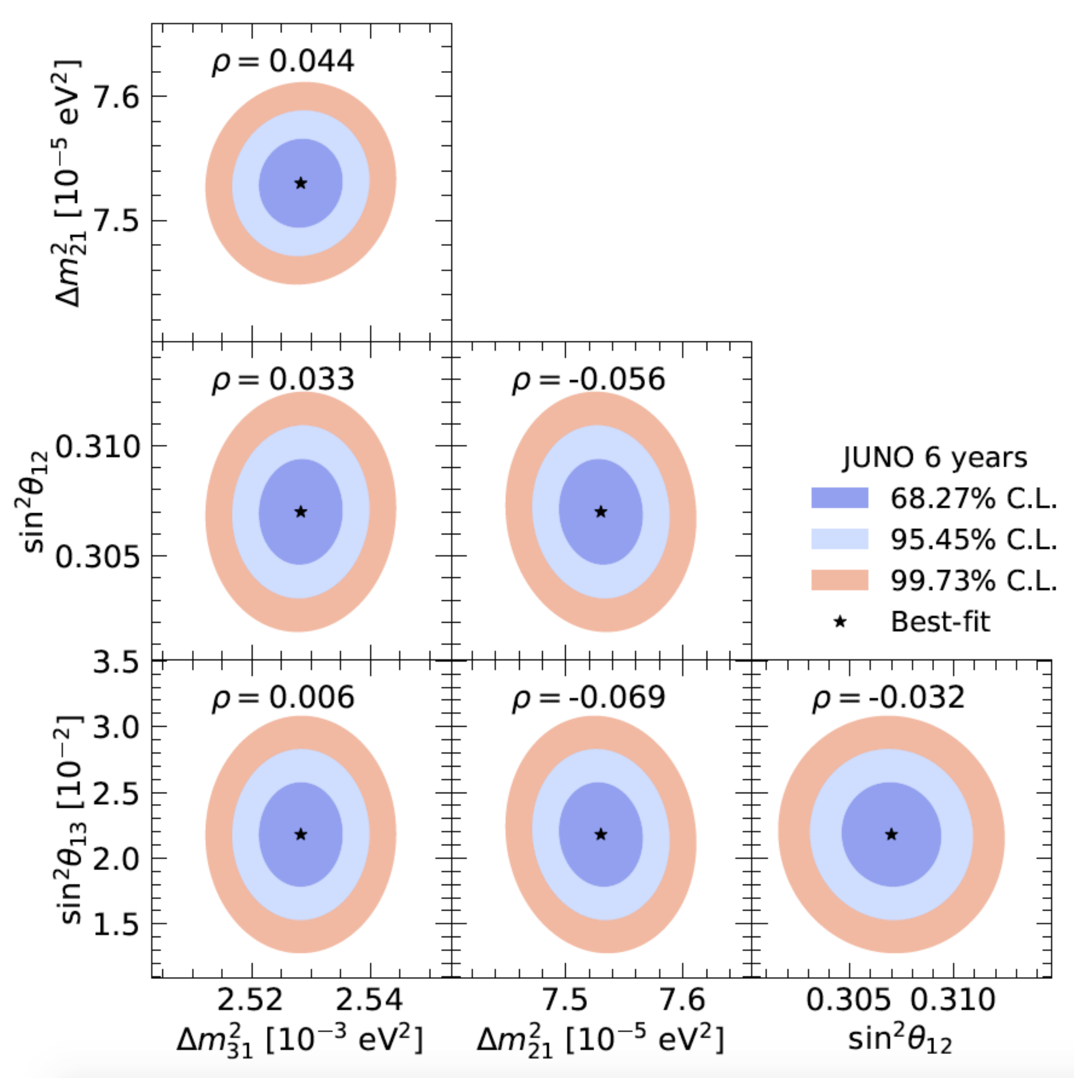
Δm^2_{31}	1σ (%)
Statistics	0.17
Reactor:	
- Uncorrelated	< 0.01
- Correlated	0.01
- Reference spectrum	0.05
- Spent Nuclear Fuel	< 0.01
- Non-equilibrium	< 0.01
Detection:	
- Efficiency	0.01
- Energy resolution	< 0.01
- Nonlinearity	0.04
- Backgrounds	0.04
Matter density	0.01
All systematics	0.08
Total	0.19

Δm^2_{21}	1σ (%)
Statistics	0.16
Reactor:	
- Uncorrelated	0.01
- Correlated	0.03
- Reference spectrum	0.07
- Spent Nuclear Fuel	0.07
- Non-equilibrium	0.14
Detection:	
- Efficiency	0.02
- Energy resolution	0.01
- Nonlinearity	0.05
- Backgrounds	0.18
Matter density	0.01
All systematics	0.27
Total	0.32

$\sin^2\theta_{12}$	1σ (%)
Statistics	0.34
Reactor:	
- Uncorrelated	0.10
- Correlated	0.27
- Reference spectrum	0.09
- Spent Nuclear Fuel	0.05
- Non-equilibrium	0.10
Detection:	
- Efficiency	0.23
- Energy resolution	0.01
- Nonlinearity	0.09
- Backgrounds	0.20
Matter density	0.07
All systematics	0.40
Total	0.52

$\sin^2\theta_{13}$	1σ (%)
Statistics	8.94
Reactor:	
- Uncorrelated	2.53
- Correlated	6.83
- Reference spectrum	3.48
- Spent Nuclear Fuel	1.55
- Non-equilibrium	2.65
Detection:	
- Efficiency	5.81
- Energy resolution	0.39
- Nonlinearity	2.09
- Backgrounds	4.89
Matter density	0.98
All systematics	8.16
Total	12.11

Oscillation Parameters Correlation



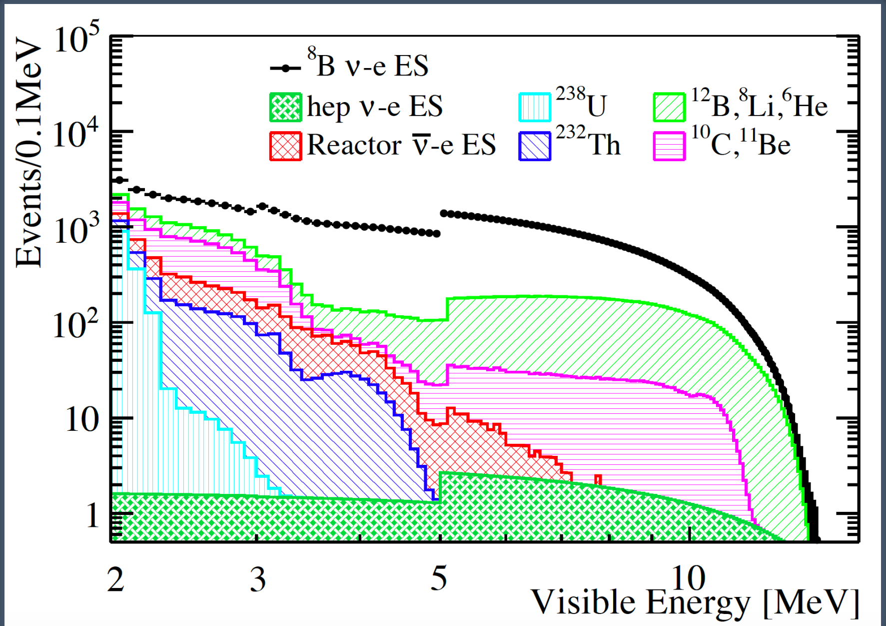
- Oscillation parameters nearly uncorrelated
- <0.3% improvement when constraining $\sin^2\theta_{13}$ from PDG

Extra information:

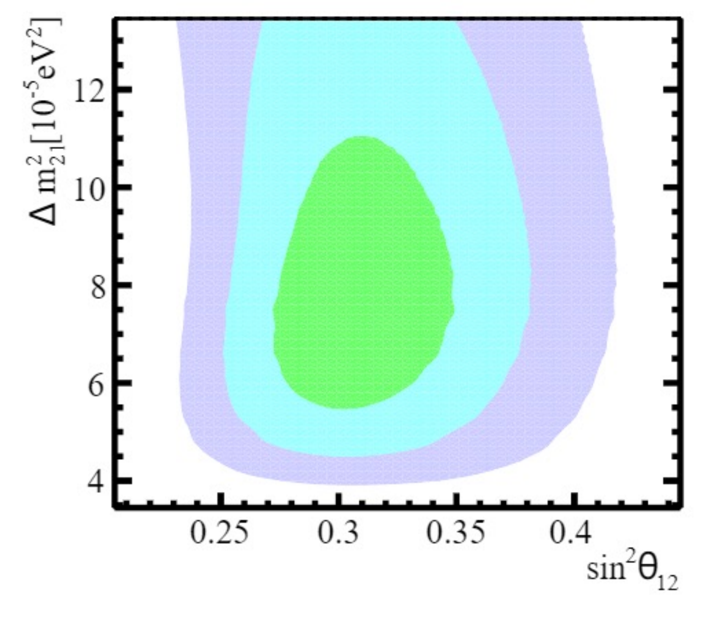
- Negligible impact of neutrino mass ordering choice
- Wrong ordering produce sensitivities no larger than 5% of the nominal values
- SPMT can measure solar parameters with similar precision as LPMT $\Longrightarrow$ crosscheck

Solar ν_e from ^8B

Chinese Phys. C 45 023004



- Neutrino-electron elastic scattering process
- 2 MeV threshold on the recoil electron energy
- Higher energy resolution than water Cherenkov detectors
- Much larger target mass than previous LS detectors
- LS intrinsic radioactivity (10^{-17} g/g ^{238}U and ^{232}Th)
- Signal/background (10 years): 60k/30k



- ^8B ν_e sensitive to the matter effect: Day/Night asymmetry
- 0.9% sensitivity to Day/Night asymmetry (1.1% in SK)
- 20% sensitivity to Δm^2_{21} and 8% sensitivity to $\sin^2\theta_{12}$
- Complementarity to JUNO reactor Δm^2_{21}

Conclusions

- JUNO will be the first experiment to observe two modes of neutrino oscillations simultaneously
- JUNO will achieve an unprecedented 3% energy resolution at 1 MeV with an energy scale calibration uncertainty of 1%
- TAO will provide high precision reactor neutrino spectrum
- Neutrino mass ordering determination >3σ in 6 years via reactor $\bar{\nu}_e$
  - +1σ using 1% external uncertainty for $|\Delta m^2_{\mu\mu}|$
  - >5σ when combined with accelerator and/or atmospheric experiments
  - The only experiment able to resolve MO via vacuum dominant oscillations
- Measurement of $\mathbf{\Delta m^2_{21}}$, $\mathbf{\Delta m^2_{32}}$, $\mathbf{\sin^2\theta_{12}}$ at sub-percent precision level with reactor $\bar{\nu}_e$
  - SPMT crosscheck Δm^2_{21}, $\sin^2\theta_{12}$
- Independent measurement of $\mathbf{\Delta m^2_{21}}$ and $\mathbf{\sin^2\theta_{12}}$ via solar neutrinos from ^8B

JUNO Collaboration

THANK YOU FOR YOUR ATTENTION

Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	Tsinghua U.	Germany	U. Tuebingen
Belgium	Universite libre de Bruxelles	China	UCAS	Italy	INFN Catania
Brazil	PUC	China	USTC	Italy	INFN di Frascati
Brazil	UEL	China	U. of South China	Italy	INFN-Ferrara
Chile	PCUC	China	Wu Yi U.	Italy	INFN-Milano
Chile	SAPHIR	China	Wuhan U.	Italy	INFN-Milano Bicocca
China	BISEE	China	Xi'an JT U.	Italy	INFN-Padova
China	Beijing Normal U.	China	Xiamen University	Italy	INFN-Perugia
China	CAGS	China	Zhengzhou U.	Italy	INFN-Roma 3
China	ChongQing University	China	NUDT	Latvia	IECS
China	CIAE	China	CUG-Beijing	Pakistan	PINSTECH (PAEC)
China	DGUT	China	ECUT-Nanchang City	Russia	INR Moscow
China	Guangxi U.	Croatia	PDZ/RBI	Russia	JINR
China	Harbin Institute of Technology	Czech	Charles U.	Russia	MSU
China	IHEP	Finland	University of Jyvaskyla	Slovakia	FMPICU
China	Jilin U.	France	IJCLab Orsay	Taiwan-China	National Chiao-Tung U.
China	Jinan U.	France	LP2i 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	RWTH Aachen U.	Thailand	SUT
China	Shandong U.	Germany	TUM	U.K.	U. Warwick
China	Shanghai JT U.	Germany	U. Hamburg	USA	UMD-G
China	IGG-Beijing	Germany	FZJ-IKP	USA	UC Irvine
China	SYSU	Germany	U. Mainz		

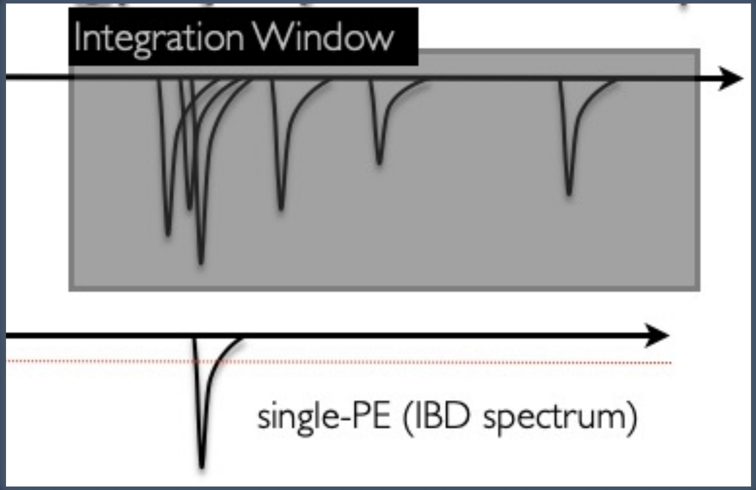
Back-up

Dual Calorimetry

20” LPMT

3” SPMT

$$\frac{R^{LPMT}}{R^{SPMT}} = \frac{R^{L}_{QNL}}{R^{S}_{QNL}}$$



Charge integration (QI)

FADC electronics

Photon-counting (PC)

95% of the charge detected in single PE regime for IBD events

Electronics could provide analog charge information (signal pulse amplitude and time over threshold)

Energy (PC) & Energy (QI) are complementary

SPMT charge detection is robust and redundant by design

↓

Charge linear reference to the LPMT.

Dual Calorimetry Strategy

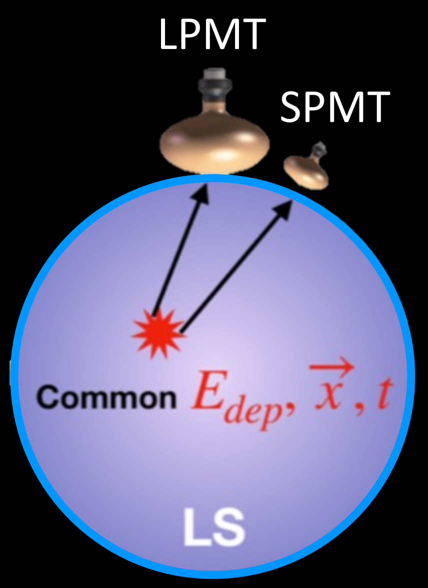
Objective: disentanglement of the degeneracy between the non-linearity and non-uniformity

	Fully correlated	Partially correlated		Non correlated
$R^{LPMT} =$	R^{L}_{LSNL} ·	R^{L}_{NU} ·	R^{L}_{NS} ·	R^{L}_{QNL}
	↑ Cancels ↓	↑ Cancels ↓	↑ Cancels ↓	
$R^{SPMT} =$	R^{S}_{LSNL} ·	R^{S}_{NU} ·	R^{S}_{NS} ·	R^{S}_{QNL}

✓ Same energy deposition

✓ Common event vertex

✗ PMT-to-PMT difference needs proper treatment

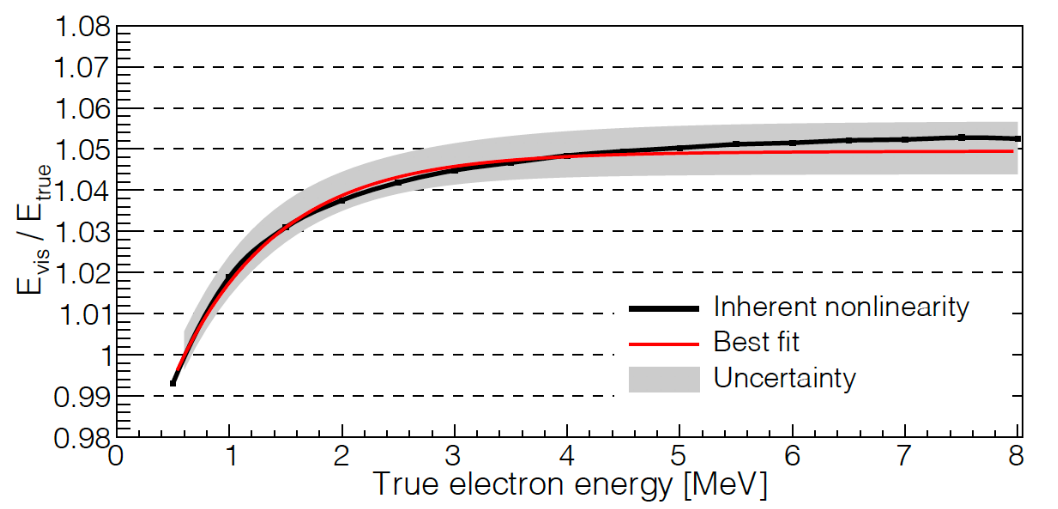


Direct response comparison between LPMT calorimetry and SPMT calorimetry

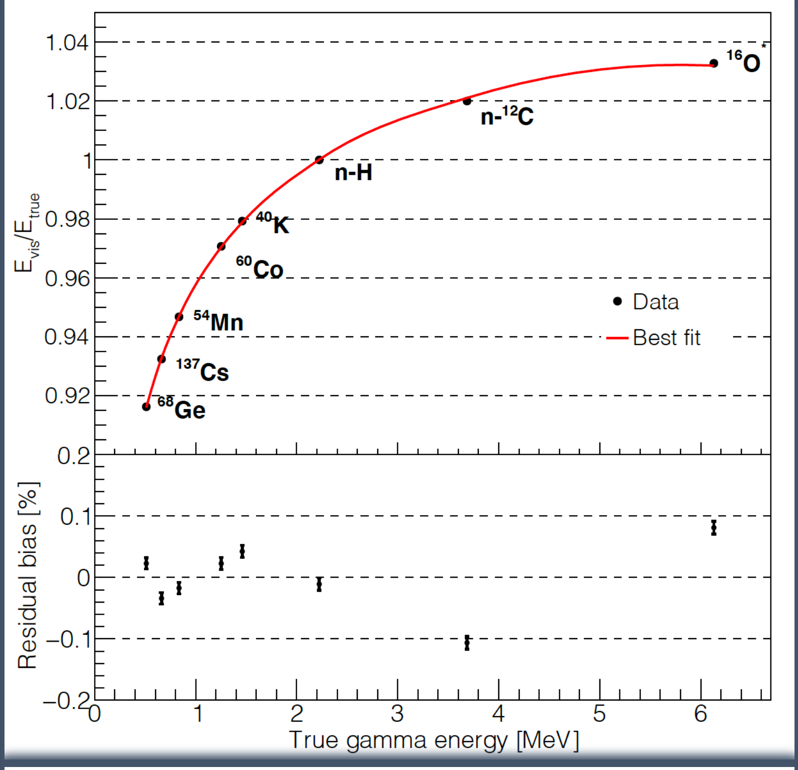
Energy Scale

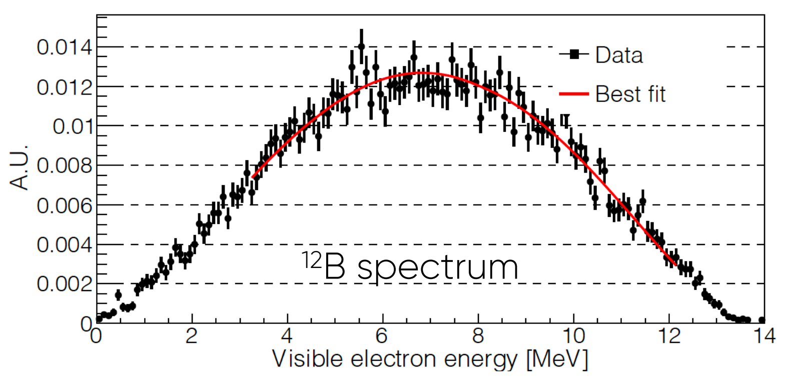
Non-linearity is composed of:

1. Physics non-linearity:
   - Scintillation quenching, following Birks' law.
   - Cherenkov emission dependence on particle's velocity.
2. Instrumental non-linearity:
   - PMT instrumentation and electronics, channelwise response



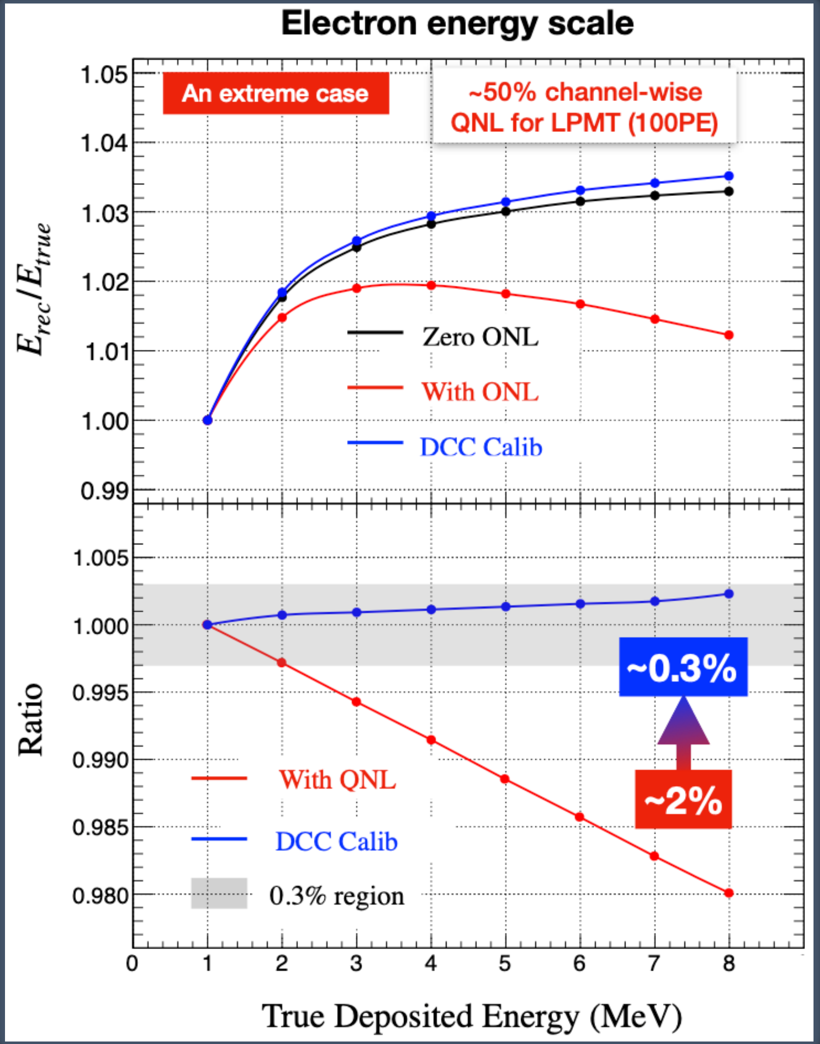
< 1% energy scale uncertainty





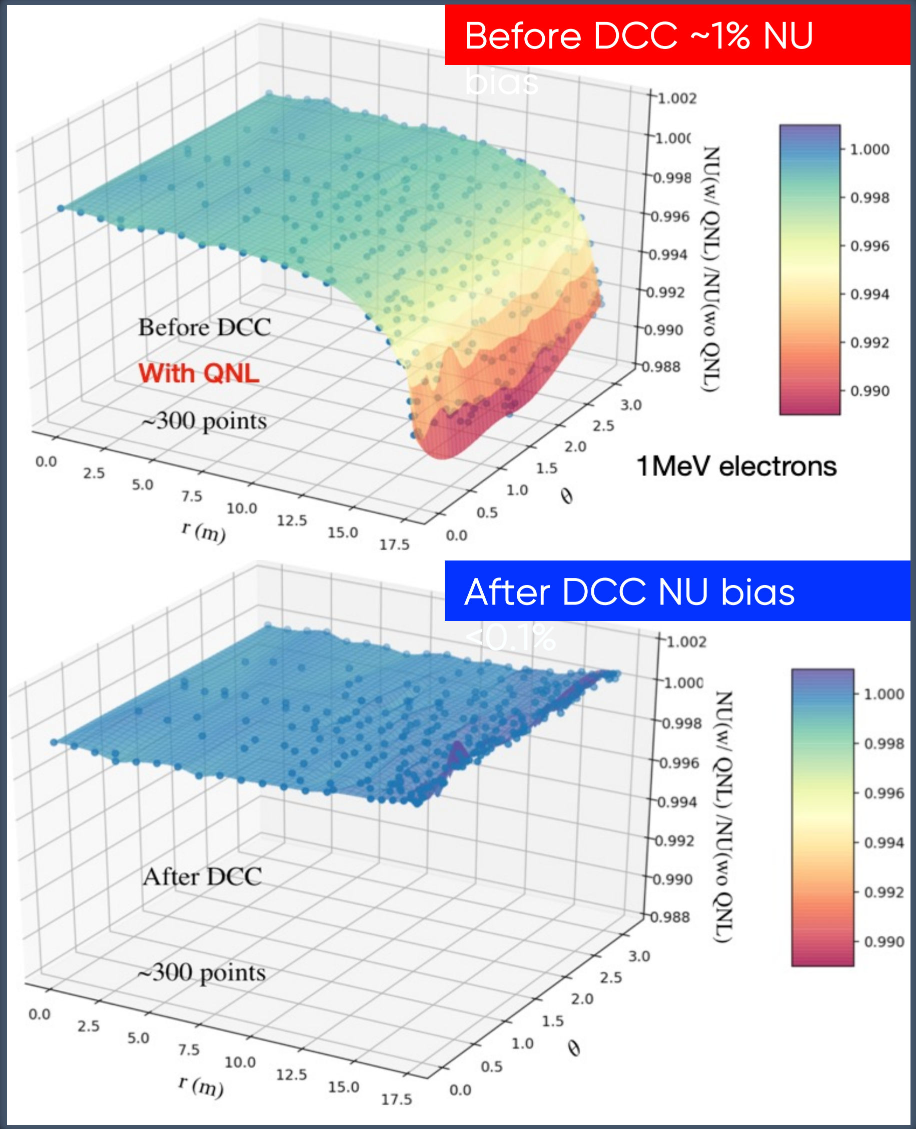
Energy Scale after Dual Calorimetry Calibration

$E_{dep} = Q_{PE} \times f_{PE/MeV} \times f_{LSNL} \times f_{NS} \times f_{NU} \times f_{QNL}$

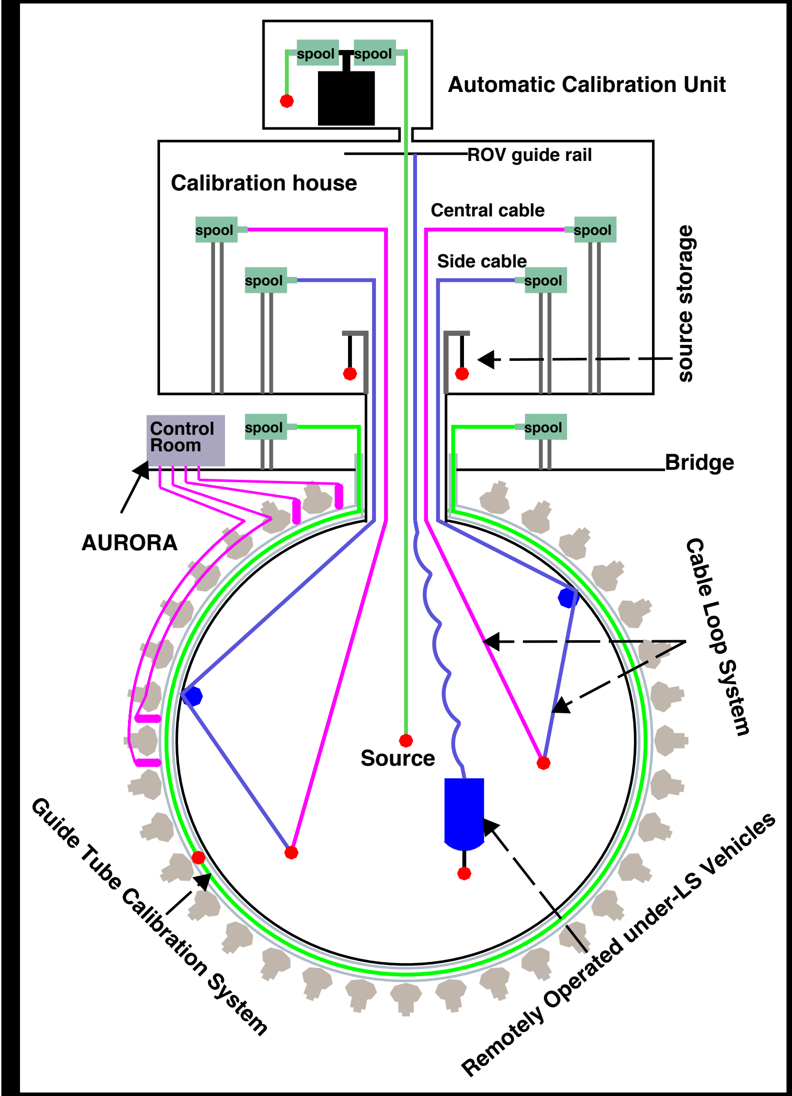


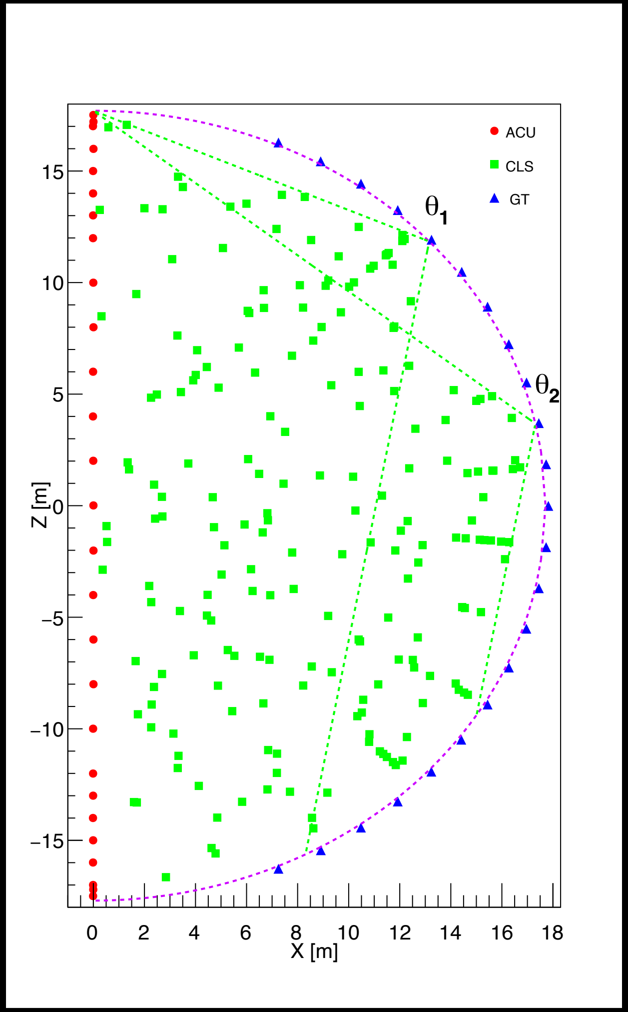
Almost negligible role of QNL effects upon the DCC application ~0.3%

The DCC can control the QNL induced NU bias to 0.1% level



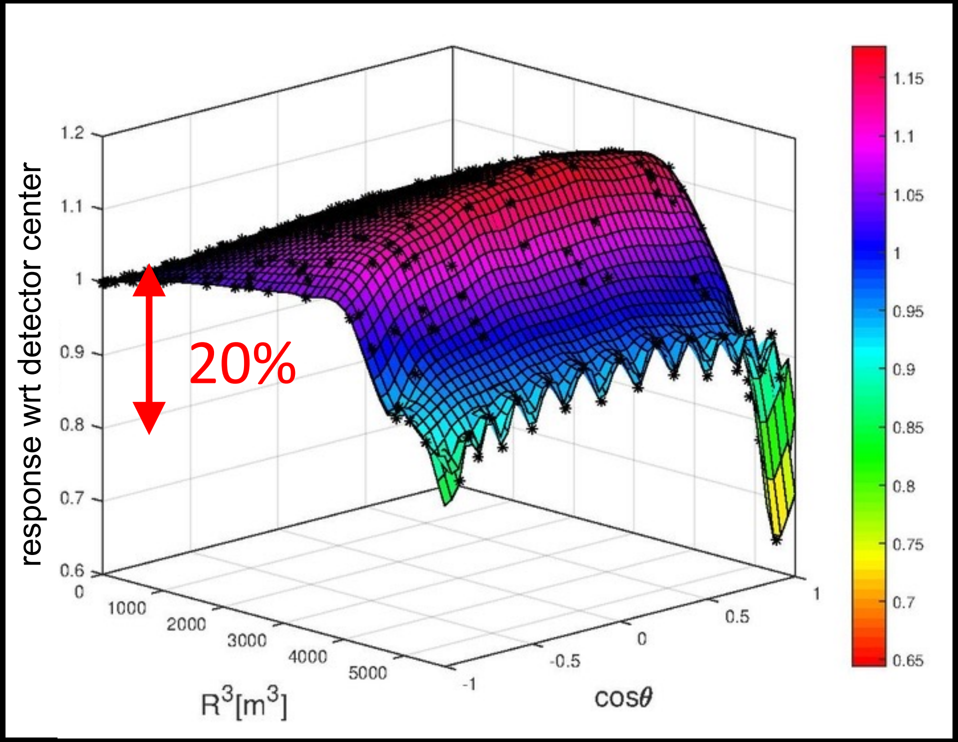
Non-Uniformity calibration





Azimuthal symmetry assumed

Non-Uniformity in one vertical plane

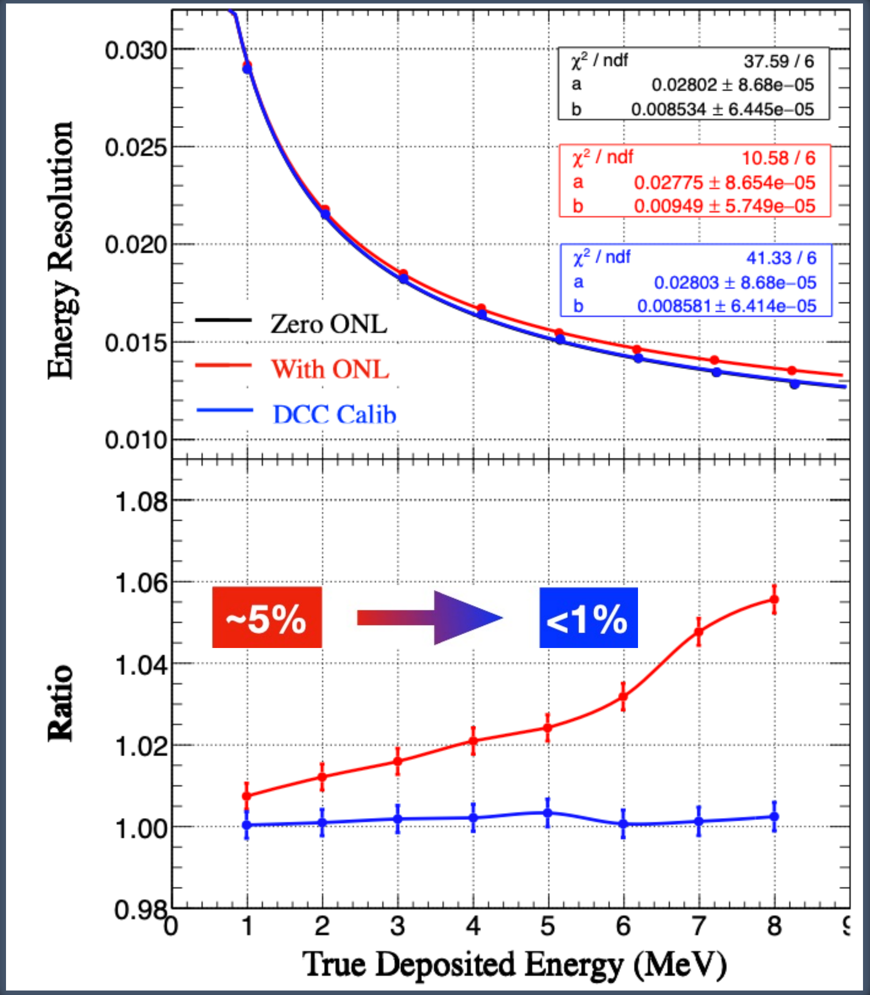


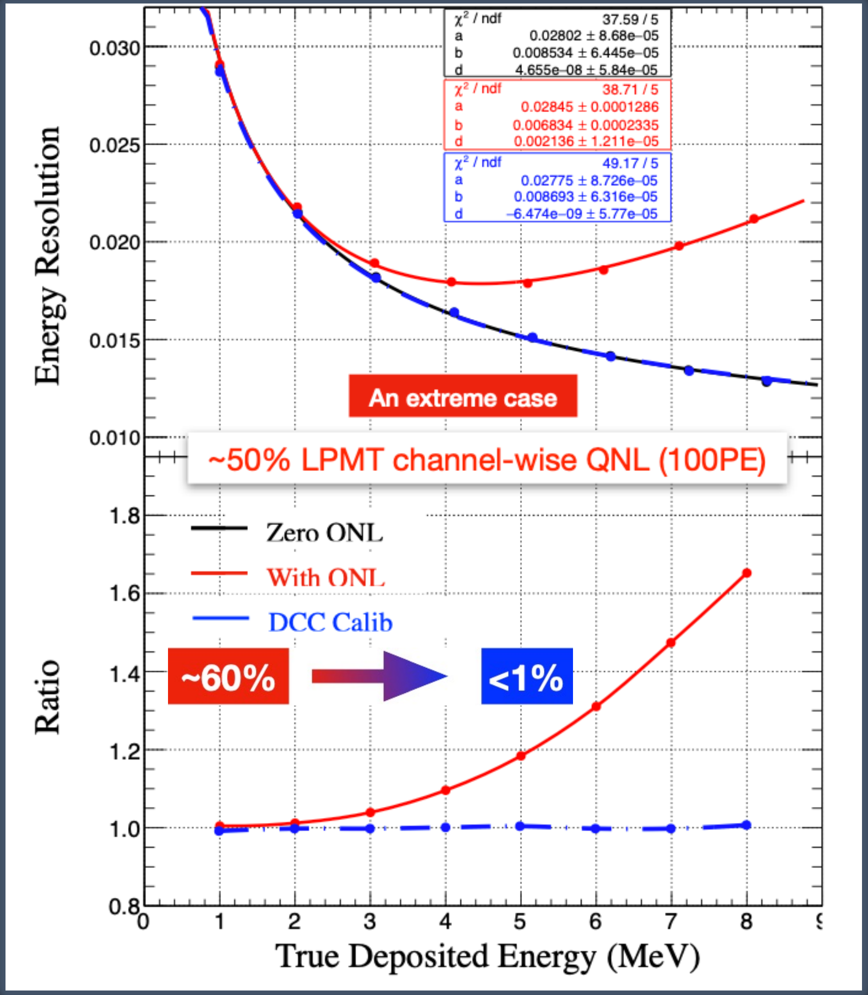
JUNO simulation

JHEP 03, 004 (2021)

Energy Resolution after Dual Calorimetry Calibration

$$\frac{\sigma_E}{E} = \sqrt{\frac{\sigma^2_{stochastic}}{E} + \sigma^2_{non-stochastic}(E)} \qquad \sigma_{non-stochastic} < 1\%$$

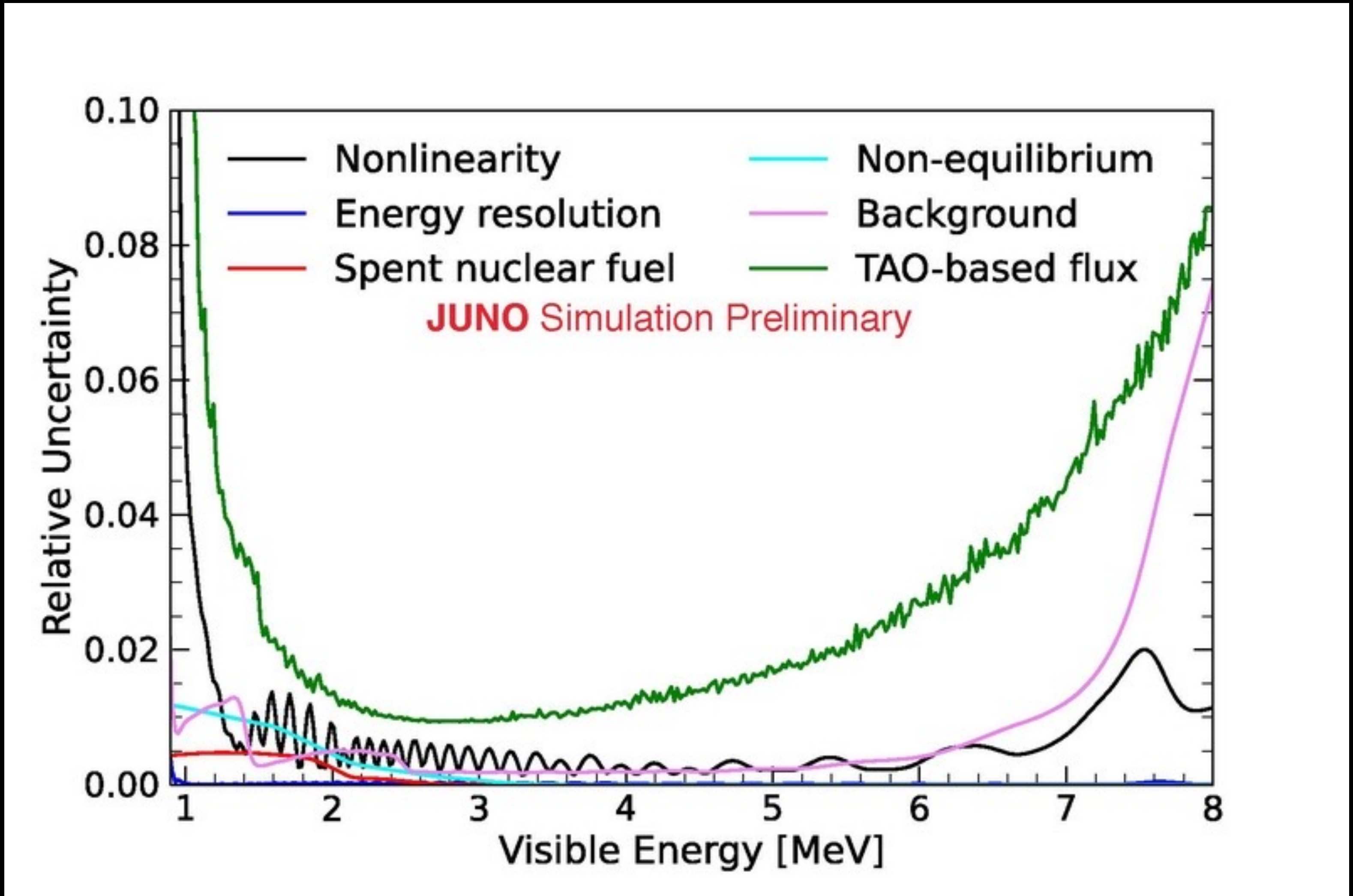




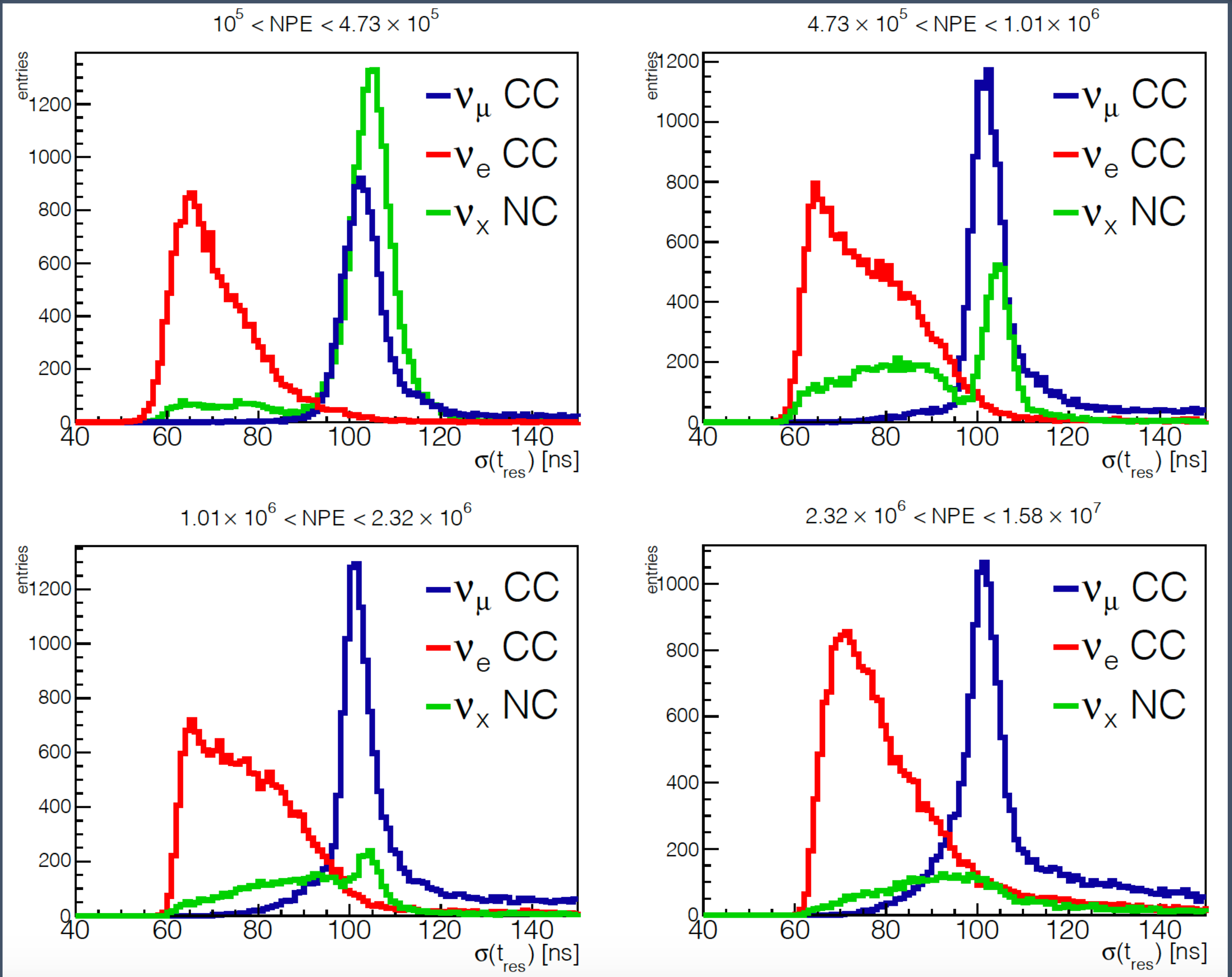
Rate Uncertainties

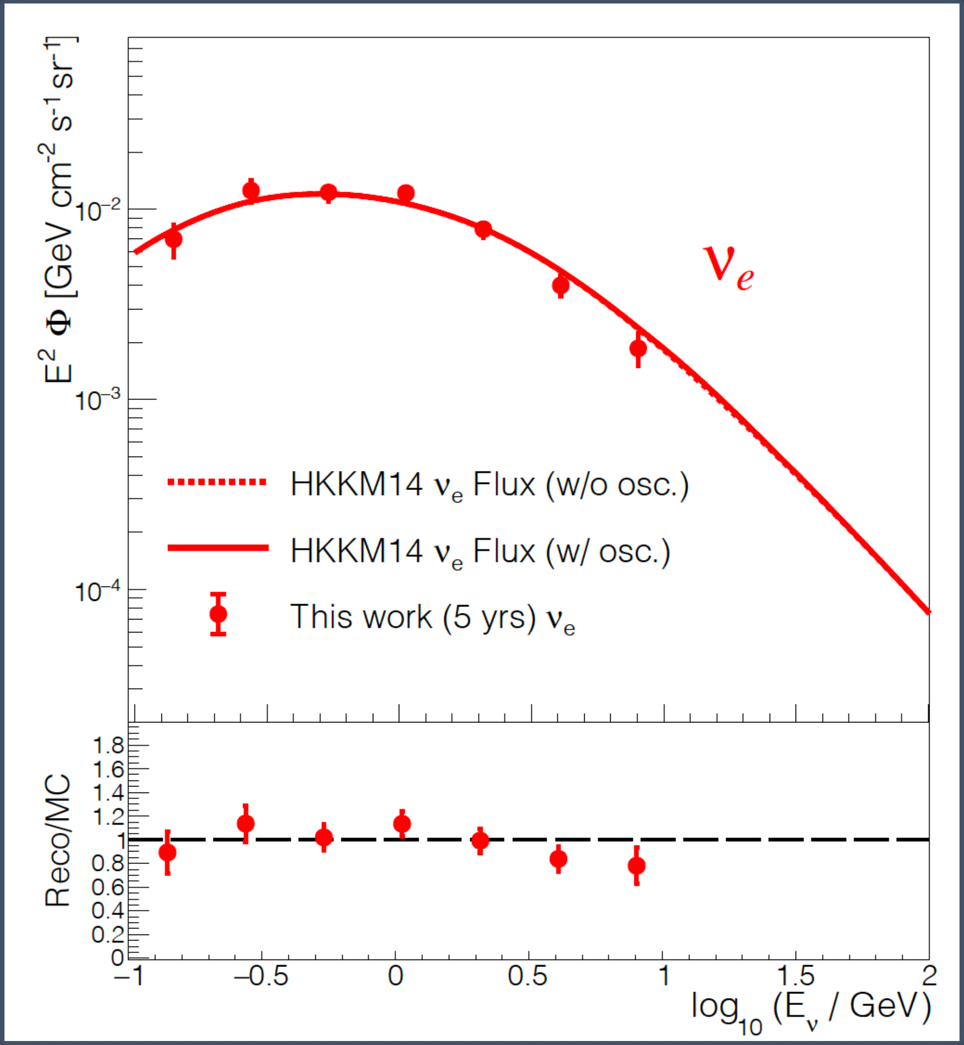
Component	Input Uncertainty (%)
Flux Systematics	
Thermal Power (P)	0.50
Energy per Fission	0.20
Fission Fraction	0.60
Neutrino Yield per Fission	2.00
Detection Systematics	
IBD Selection Efficiency	0.20
Fiducialisation (2 cm vertex bias)	0.35
Proton Number (DYB)	0.92
Background Systematics	
Geo-neutrino	0.84
Accidental	0.02
^{9}Li/^{8}He	0.74
Fast neutrons	0.23
^{13}C(α,n)^{16}O	0.06

Shape Uncertainty

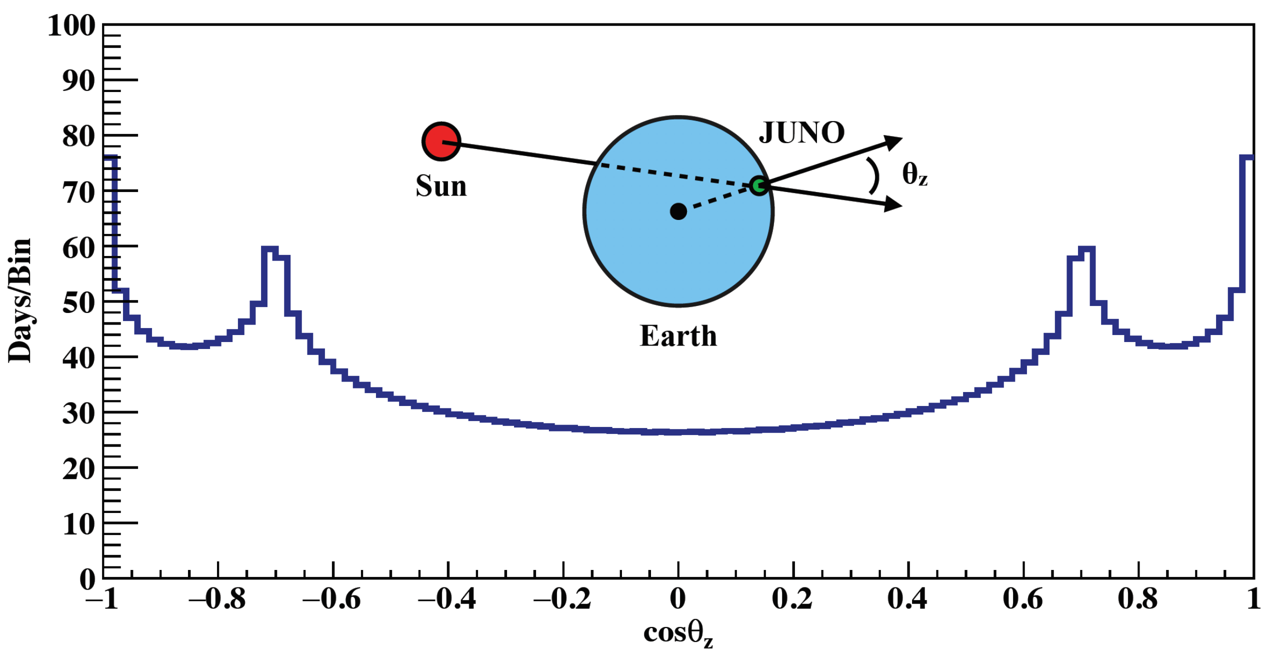


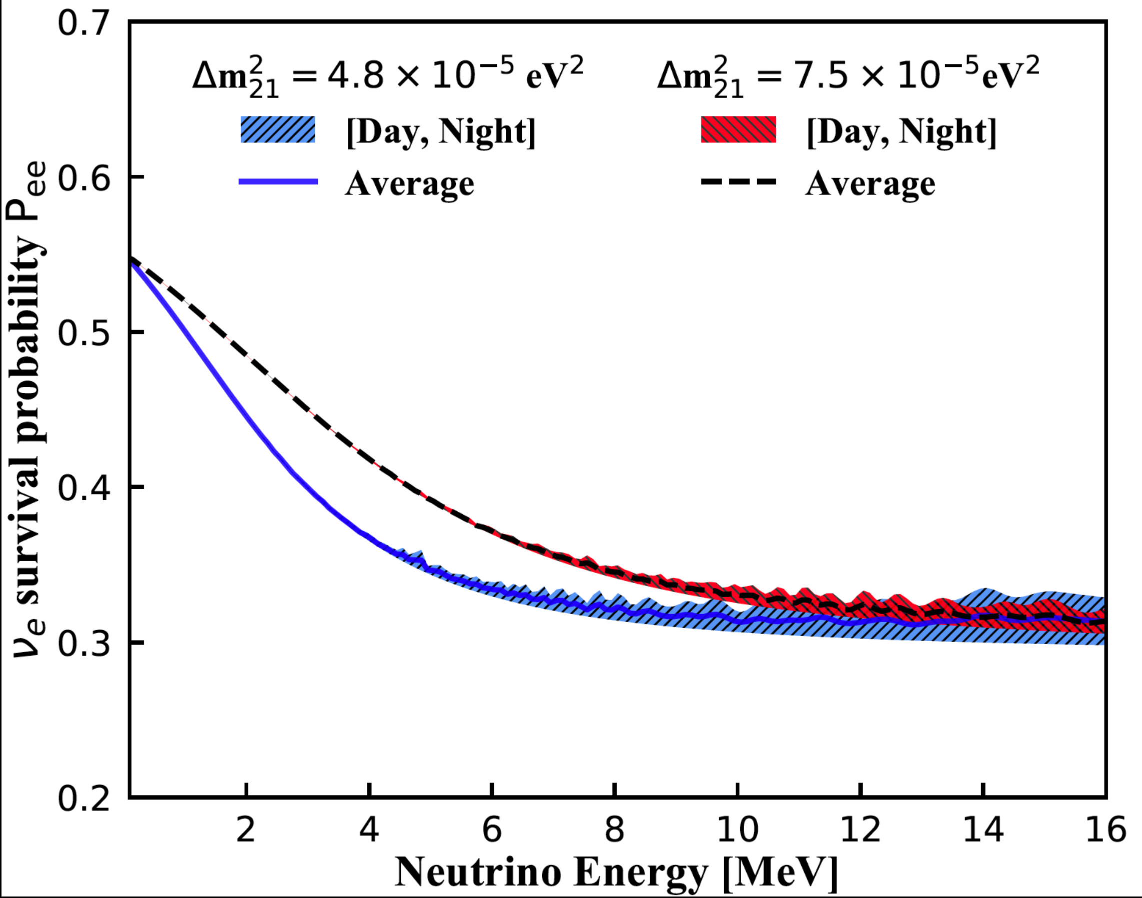
Atmospheric neutrino flavour identification





Day/Night asymmetry





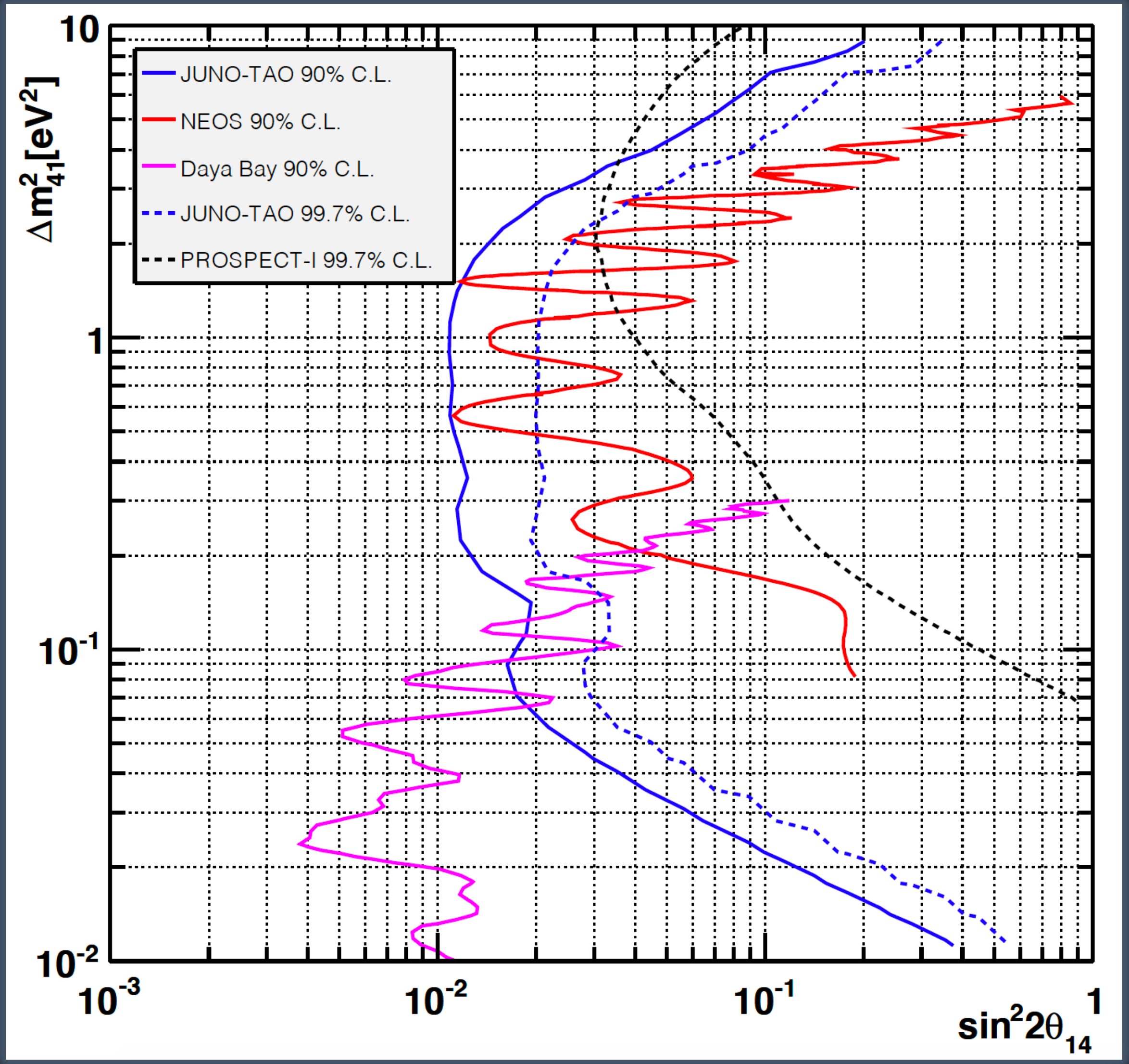
Sterile neutrinos

Motivation – observed tensions with 3-flavor paradigm:

- Reactor $\bar{\nu}_e$ deficit with respect to the state-of-the-art prediction models
- Anomalous $\bar{\nu}_e$ appearance in the ν_μ beam at the LSND and MiniBooNE
- Deficit in number of ν_e from radioactive calibration source in gallium experiments

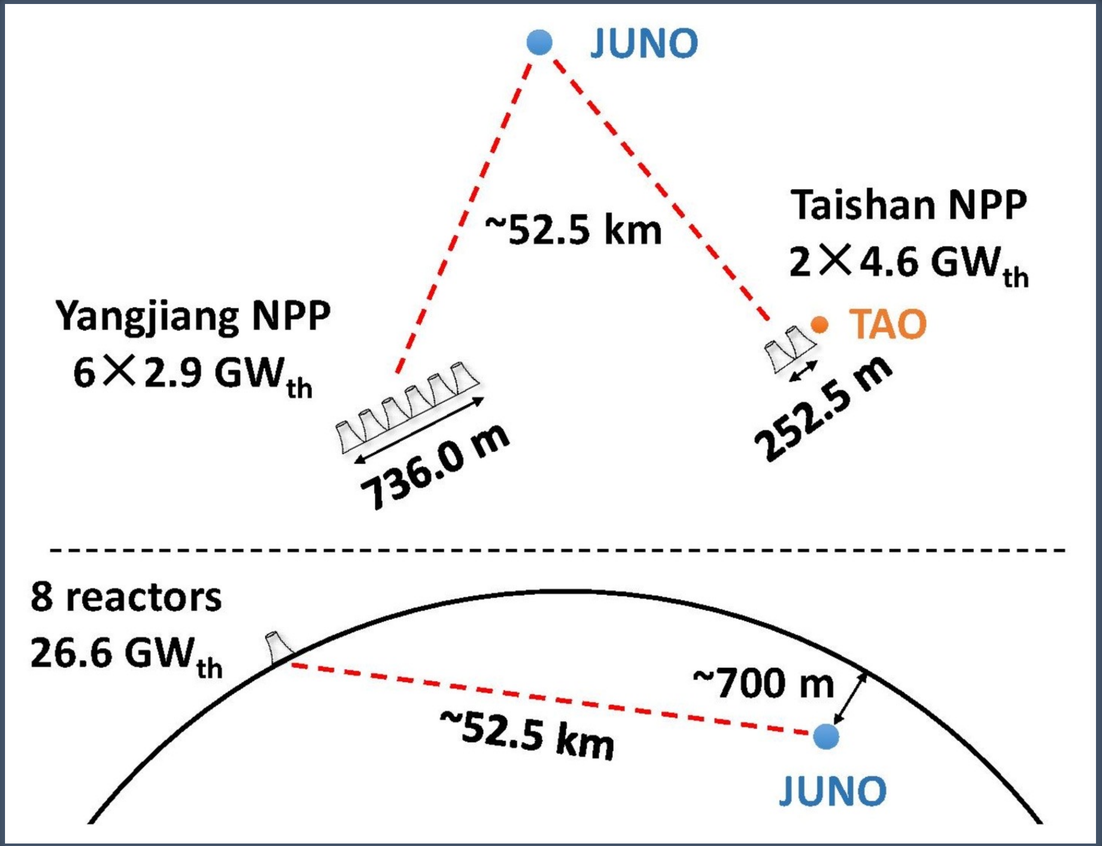
TAO detector

- Inverse beta decay with nGd tag
- Baseline ~ 30 m
- Expected rate: 2000 $\bar{\nu}_e$/day
- Relevant range: $0.5\ \text{eV}^2 < \Delta m^2_{41} < 5\ \text{eV}^2$



JUNO NPPs

- Reactor $\bar{\nu}_e$ at ~53 km
  $\sim 45\ \bar{\nu}_e/\mathrm{day}$



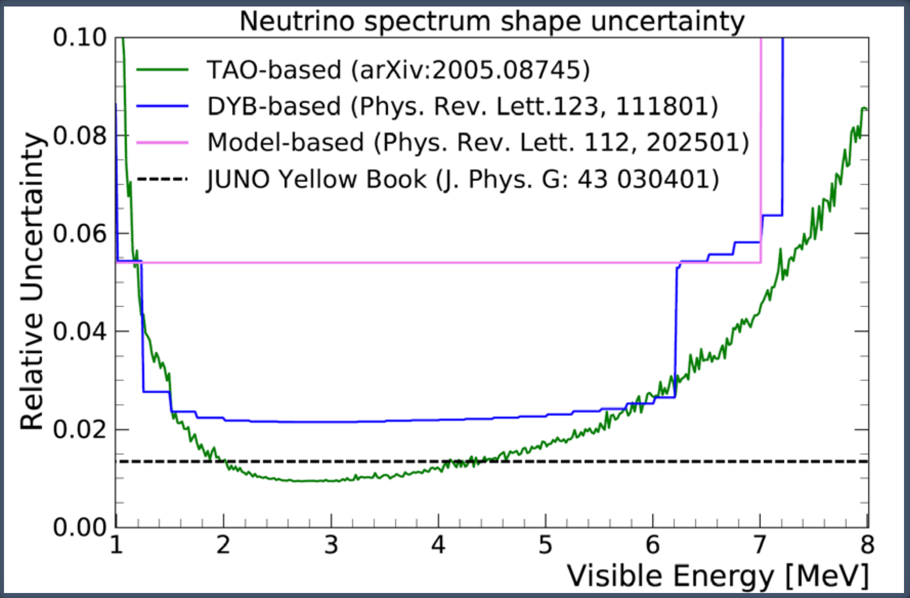
Name	Power (GW)	Baseline (km)
YJ-C1	2.9	52.75
YJ-C2	2.9	52.84
YJ-C3	2.9	52.42
YJ-C4	2.9	52.51
YJ-C5	2.9	52.12
YJ-C6	2.9	52.21
TS-C1	4.6	52.76
TS-C2	4.6	52.63
DYB	17.4	215

HuiZhou reactor will not be ready at the beginning of data taking

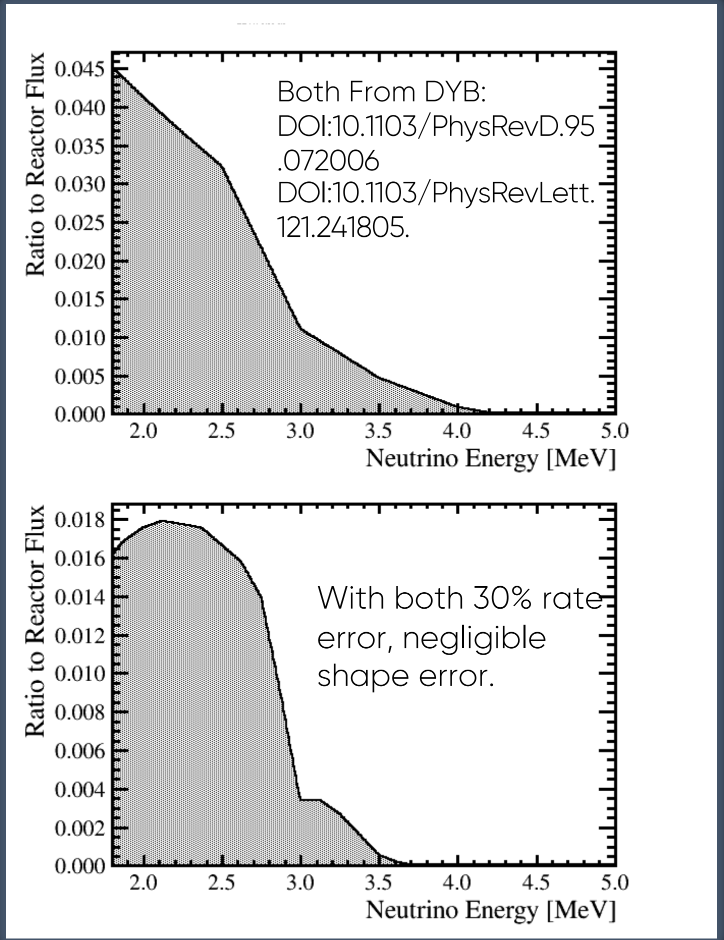
- NPPs > 300 km are treated as backgrounds (~1 ev/day)
- Control of the reactor neutrino flux is crucial
- TAO will provide accurate control of flux energy dependence using one of the Taishan reactors

Reactor antineutrino flux

Flux Component	Input Uncertainty (%)
Total	2.2
Baseline (L)	-
Energy per Fission	0.2 (Correlated)
Thermal Power (P)	0.5 (Uncorrelated)
Fission Fraction	0.6 (Uncorrelated)
Mean Cross-Section per Fission	2.0 (Correlated)



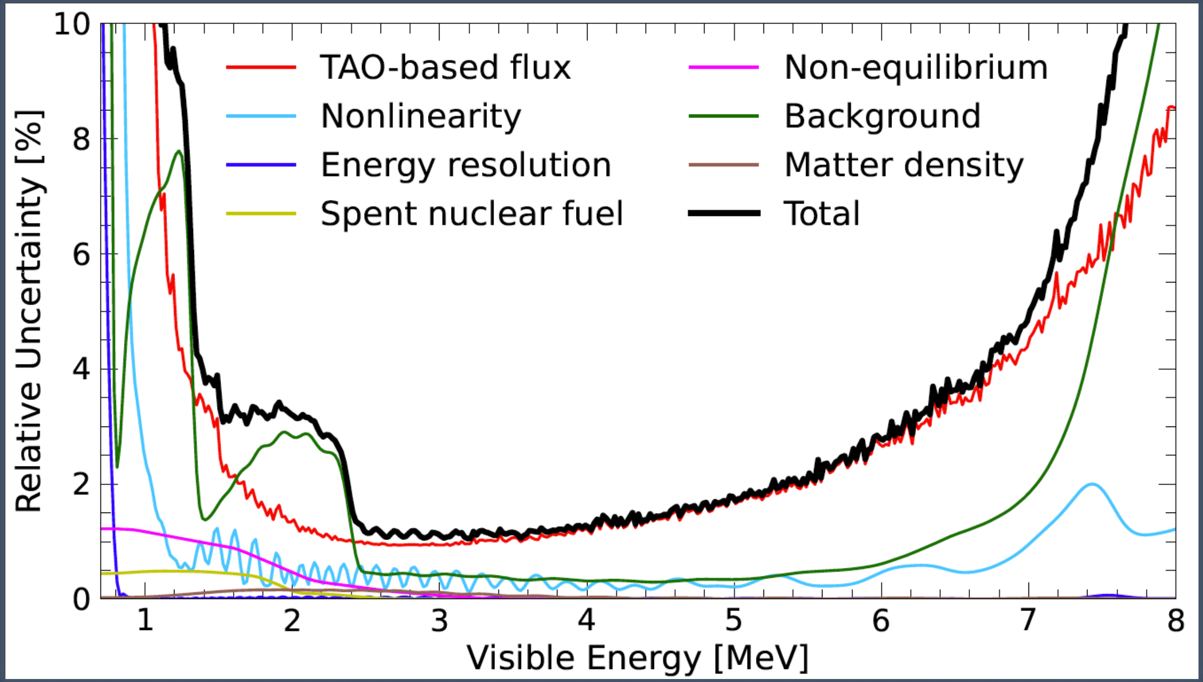
- TAO will deliver precise $\bar{\nu}_e$ energy spectrum with sub-percent energy resolution in most of energy region of interest
- The bin-to-bin spectral shape uncertainty uncertainty can be reduced to below 1% level



Additional corrections: non-equilibrium and spent nuclear fuel

Summary of systematic sources

Source of systematics	Details	Rate/Shape
Statistics	6 years nominal exp. ~94k events	-
Detection Efficiency	IBD selection, fiducial volume, muon track veto	Rate
BG	Similar residual BGs as in reactor-θ13 experiments	Both
Energy	Energy resolution	Shape
	LS Non-linearity	Shape
Reactor flux	Reactor correlated	Both
	Reactor uncorrelated	Both
	Reactor shape from TAO (bin to bin)	Shape
	Non-equilibrium + SNF	Rate
Matter effects	Matter density	Shape



Shape systematics largely dominate

The main contributions are reactor antineutrino spectrum and background systematics uncertainties

$\bar{\nu}_e$ reactor analysis update

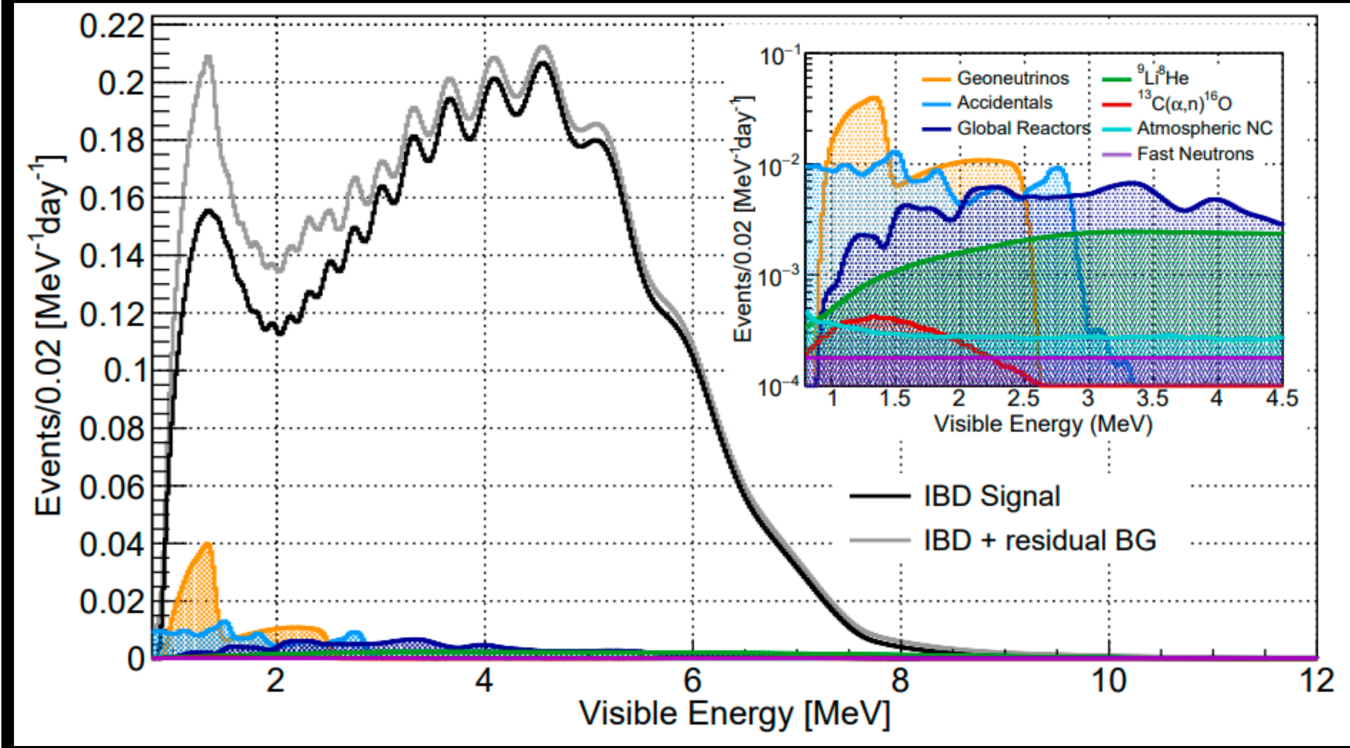
Good news

- ▲ Background control: more realistic measurements and simulations
- ▲ Optimized event selection and muon veto strategies: IBD selection efficiency: **73% → ~ 82%**
- ▲ More realistic PMT and liquid scintillator optical model → higher LS light yield
- ▲ Higher 20-inch PMT photon detection efficiency: ~27% → ~29%
- ▲ Combined analysis with TAO
- ▲ Earth's matter effects taken into account

Bad news

- ▼ Two of Taishan reactor cores will not be built → Reactor flux decreased by ~ 25%
- ▼ Experiment hall shifted by ~ 60 m (lower overburden) → Cosmic muon flux increased by ~ 30%
- ▼ World reactors: more background

Reactor Signal and IBD-like BG Spectra



arXiv: 2204.13249

NEW FROM NEUTRINO 2022

J. Phys. G 43:030401 (2016)

Design in Physics book → this update

Event type	Rate [/day]	Relative rate uncertainty	Shape uncertainty
Reactor IBD signal	60 → **47**	-	-
Geo-ν's	1.2	30%	5%
Accidental signals	0.8	1%	negligible
Fast-n	0.1	100%	20%
^{9}Li/ ^{8}He	1.4 → **0.8**	20%	10%
$^{13}C(\alpha, n)^{16}O$	0.05	50%	50%
Global reactors	0 → **1.0**	**2%**	**5%**
Atmospheric ν's	0 → **0.16**	**50%**	**50%**

Improvements on the energy resolution

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%↑	2.9% @ 1MeV Poster #519 at Neutrino22	arXiv: 2205.08629
New Central Detector Geometries	+3%↑		Poster #184 at Neutrino22
New PMT Optical Model	+8%↑		EPJC 82 329 (2022)

Positron energy resolution is understood:

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

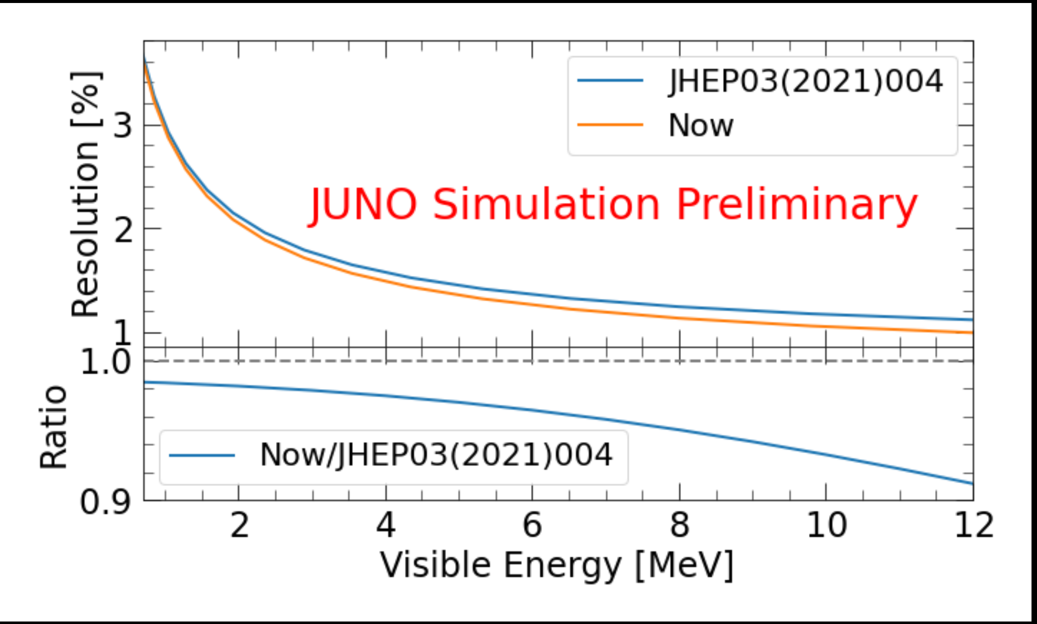
Parameter a – photon statistics

Parameter b:

- Scintillation quenching
- Contribution of Cherenkov light
- Non-uniformity and reconstruction

Parameter c:

- γs related to annihilation
- PMT Dark Noise



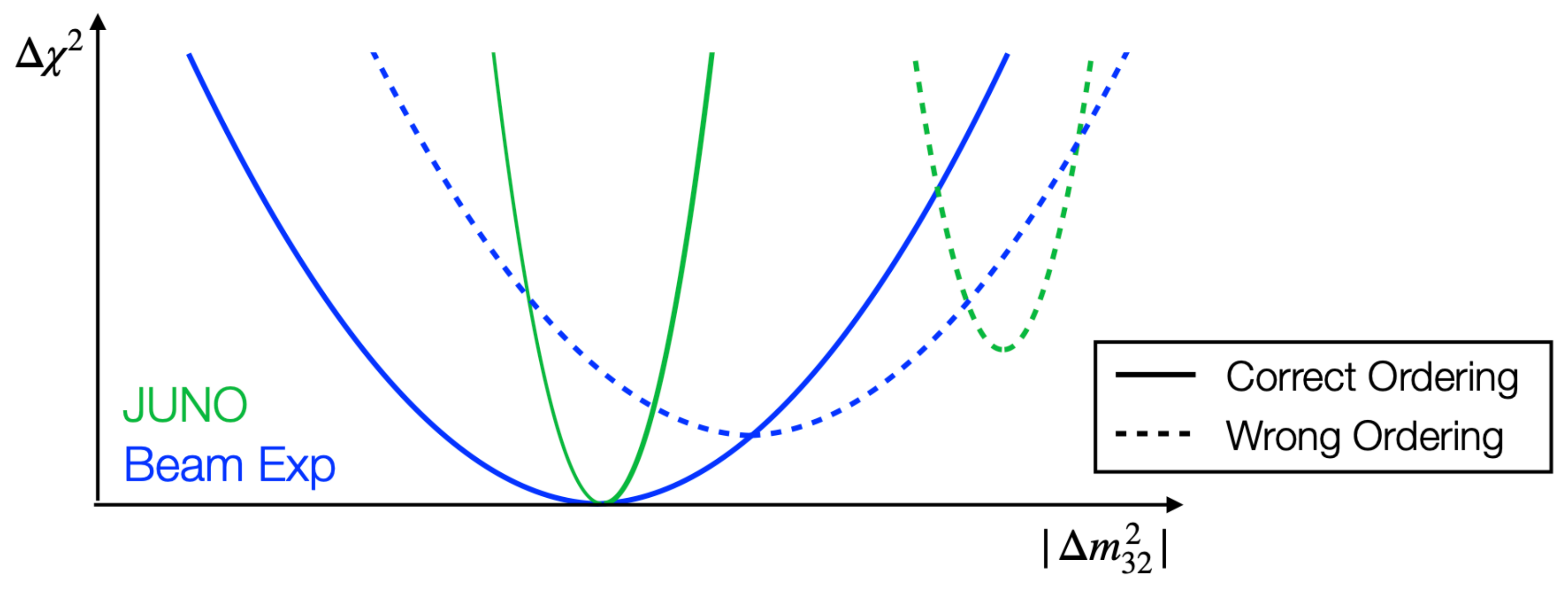
Synergy in Determining Mass Ordering

Disappearance -- $\bar{\nu}_e \rightarrow \bar{\nu}_e$ ---- Reactor

Appearance ----- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\nu_\mu \rightarrow \nu_e$ ---- Beam

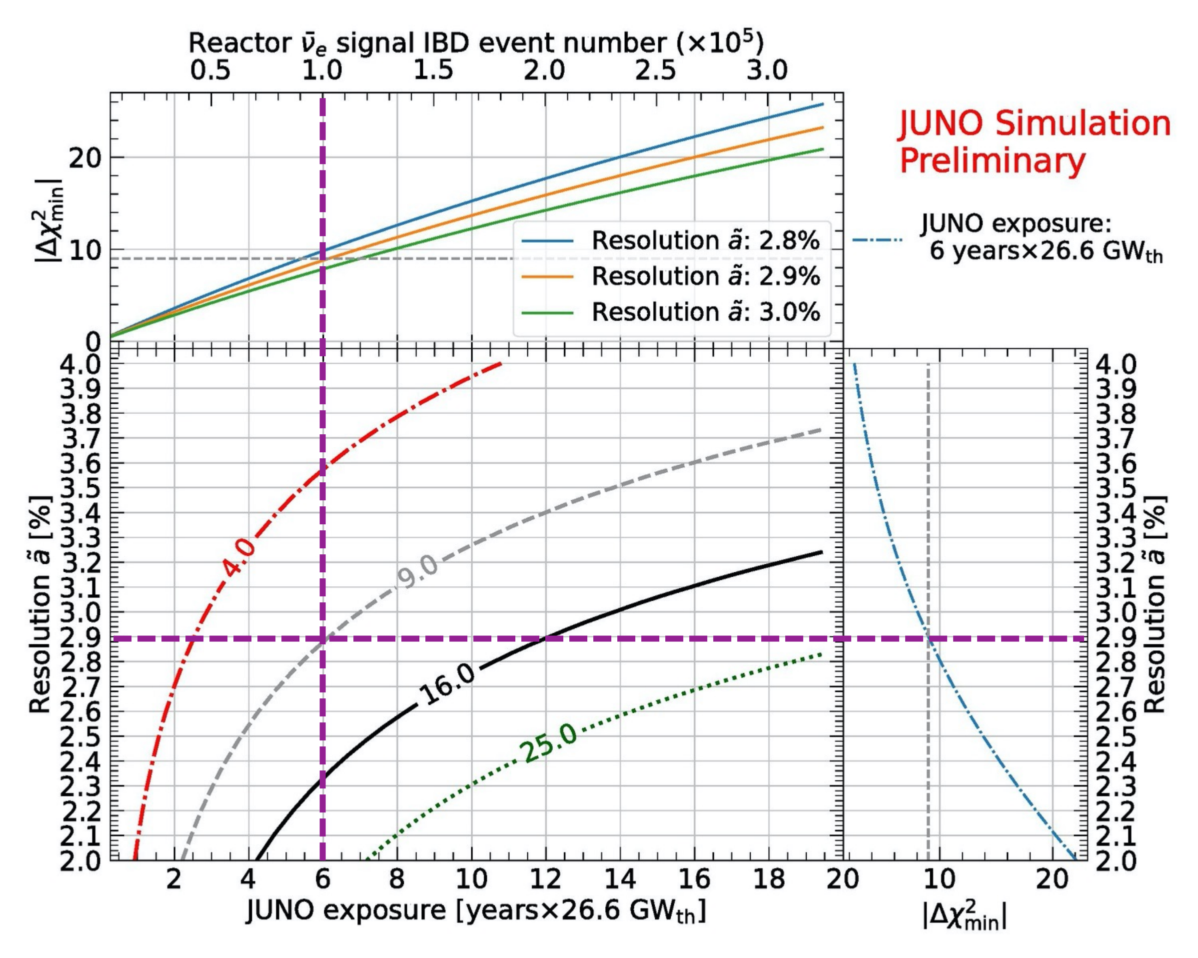
Both sensitive to atmospheric mass splitting Δm^2_{32}

Values are expected to agree only when correct ordering is assumed



Combined analysis expected to yield significance > 4σ

JUNO sensitivity to Neutrino Mass Ordering

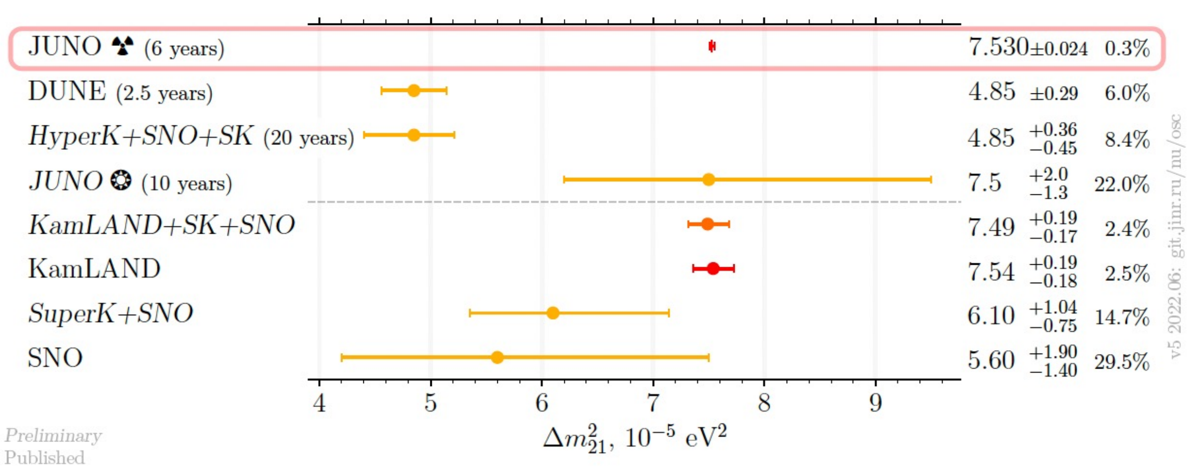


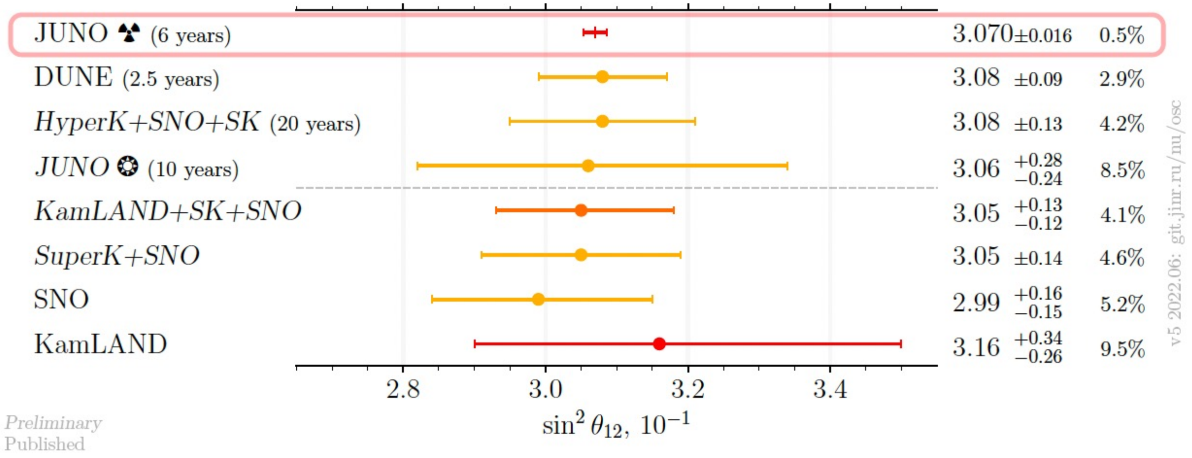
	JUNO Yellow Book (J. Phys. G 43:030401 (2016))	Neutrino 2022
Thermal Power	36 GW_{th}	26.6 GW_{th} (26%↓)
Overburden	~700 m	~650 m
Muon flux in LS	3 Hz	4 Hz (33%↑)
Muon veto efficiency	83%	93% (12%↑)
Signal rate	60 /day	47.1 /day (22%↓)
Backgrounds	3.75 /day	4.11 /day (10%↑)
Energy resolution	3% @ 1 MeV	2.9% @ 1 MeV (3%↑)
Shape uncertainty	1%	JUNO+TAO
3σ NMO sensitivity exposure	< 6 yrs × 35.8 GW_{th}	~ 6 yrs × 26.6 GW_{th}

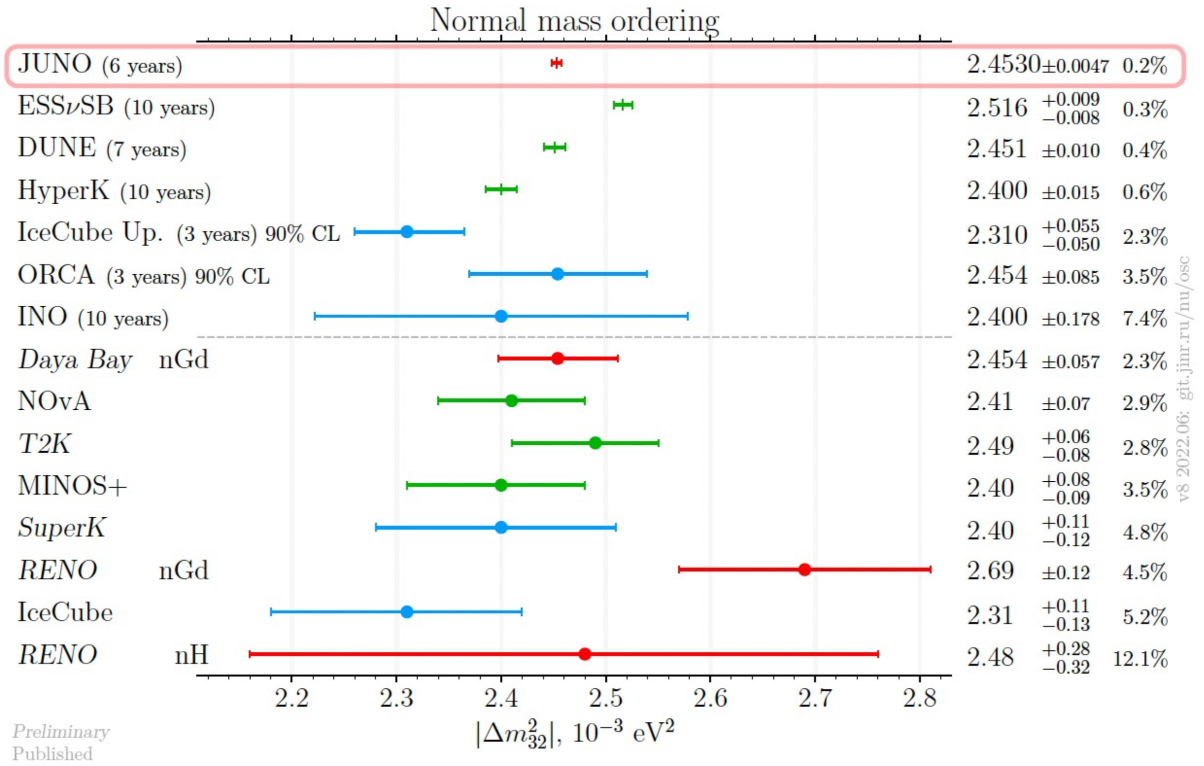
JUNO sensitivity on neutrino mass ordering: 3σ (reactors only) @ ~6 yrs * 26.6 GW_{th} exposure

Estimation of combined sensitivity with reactor + atmospheric neutrino analysis under preparation

Global oscillation parameters

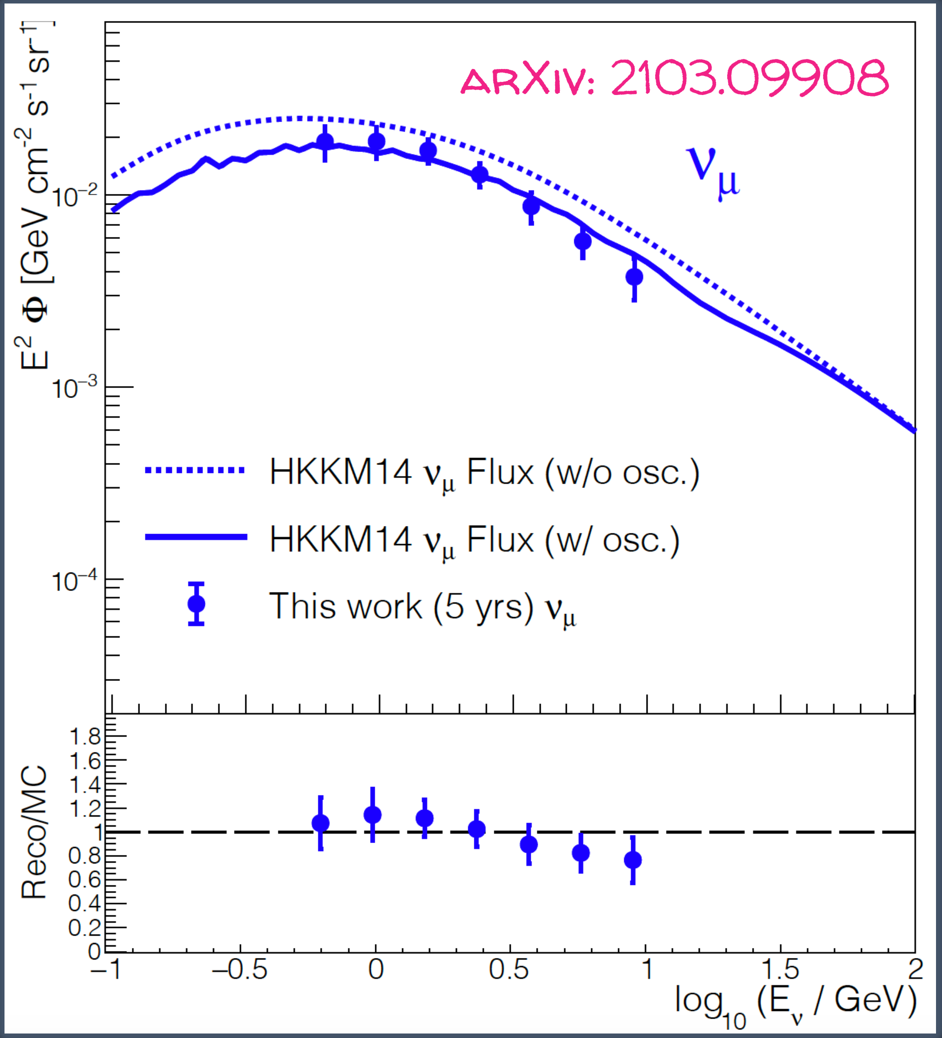






✓ Almost no correlation between measured parameters.

Atmospheric $\nu_\mu/\bar{\nu}_\mu$



- JUNO will be able to detect several atmospheric neutrinos per day
- Preferred detection channels: ν_μ/ ν_e CC interactions
- ν_μ and ν_e interactions produce slightly different light pattern → flavor discrimination through the event time profile

- ~1σ sensitivity to mass ordering in 10 years
- θ_{23} accuracy of 6°
- Potential combination with reactor analysis

J. Phys. G43:030401 (2016)