Neutrino Oscillation Physics in JUNO

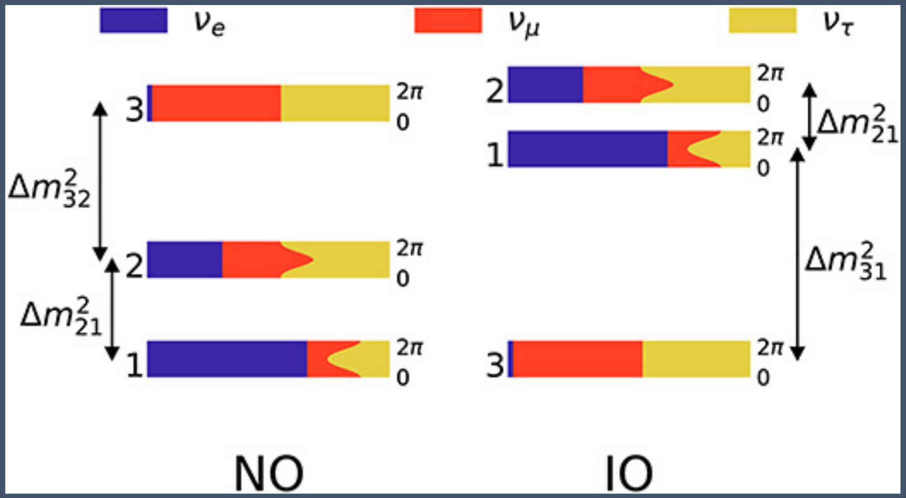
Diana Navas
On behalf of the JUNO collaboration

11 April 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}	$(7.53\pm0.18)\times10^{-5}$ eV^2 (2.39%)	??
Δm^2_{32} (NO)	$(2.453\pm0.034)\times10^{-3}$ eV^2 (1.39%)	??
Δm^2_{32} (IO)	$-(2.546\pm0.036)\times10^{-3}$ eV^2 (1.41%)	??
$\sin^2\theta_{12}$	0.307 ± 0.013 (4.23%)	??
$\sin^2\theta_{13}$	0.0218 ± 0.0007 (3.21%)	??



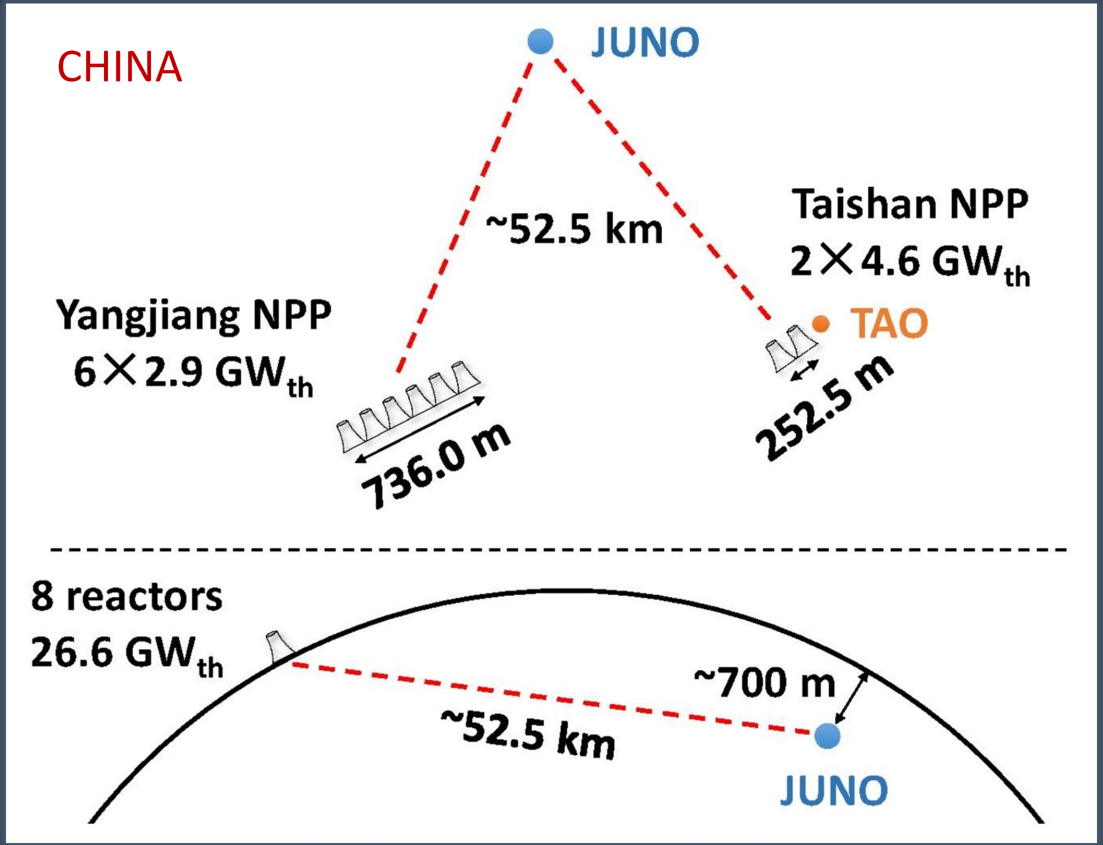
- Do neutrino oscillations violate CP symmetry? $\delta_{CP} \neq 0, \pi$
- What is the "octant" of θ_{23}? Is the mixing maximal θ_{23} = 45°?
- More than 3 neutrinos?

JUNO experiment: oscillation physics

Multi-purpose liquid scintillator experiment

- Reactor $\bar{\nu}_e$ at ~53 km
  $\sim 45\ \bar{\nu}_e$/day
  Neutrino Mass Ordering (NMO)
  $\Delta m^2_{21}, \Delta m^2_{32}, \sin^2\theta_{12}$
- Solar ν_e from ^{8}B
  $\sim 17\ \nu_e$/day
  $\Delta m^2_{21}, \sin^2\theta_{12}$
- 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
  $\Delta m^2_{41}, \sin^2 2\theta_{14}$?

JUNO - Jiangmen Underground Neutrino Observatory
TAO - Taishan Antineutrino Observatory



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

JUNO detector

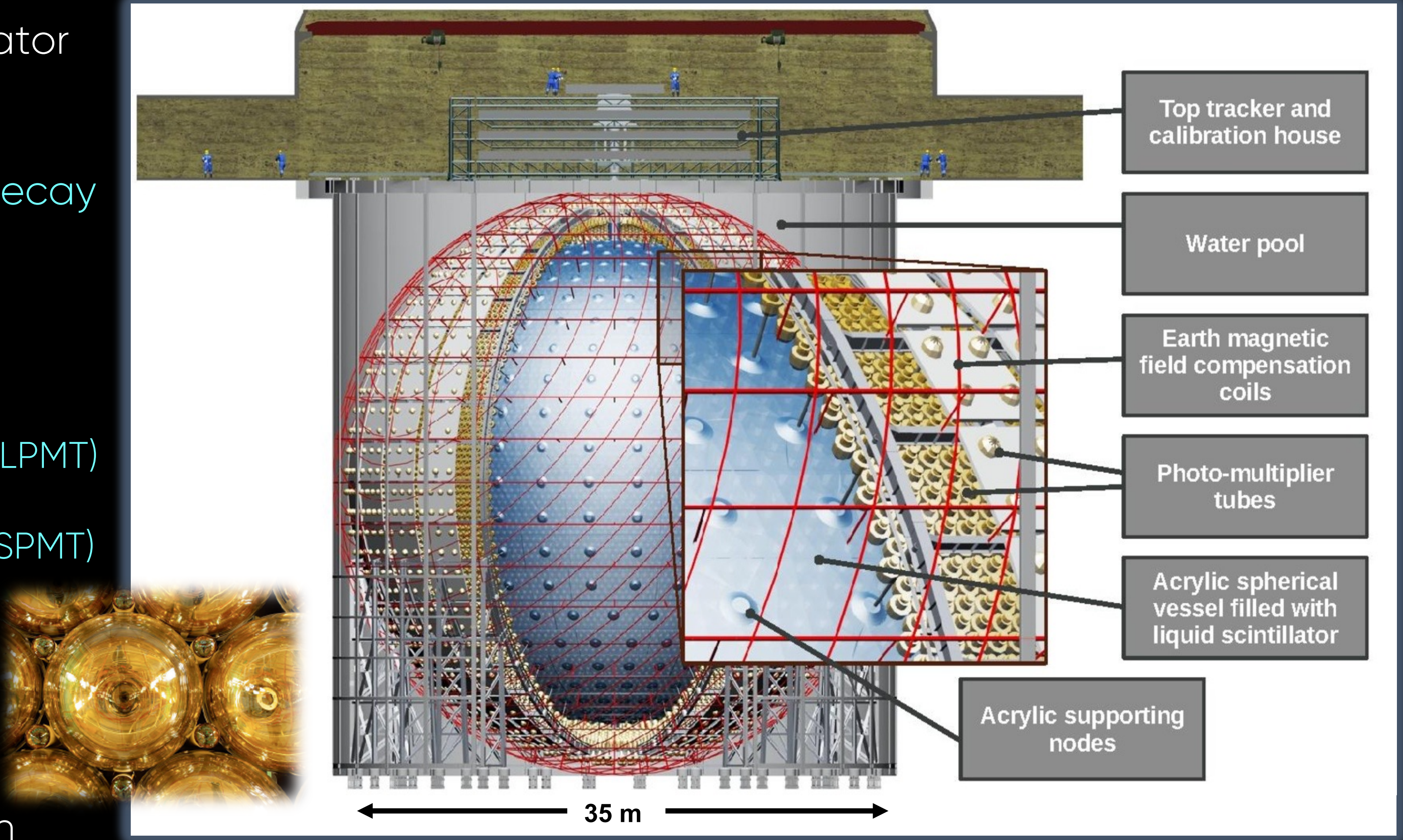
- World's largest Liquid Scintillator
  20 kton LAB-based liquid scintillator
  High PE yield: ~1350 PE / MeV

- 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: 18000 20" PMTs (LPMT) + 25600 3" PMTs (SPMT)

  Two independent PMT systems
  >75% photo-coverage

- Overburden: ~700 m
  Cosmic background suppression



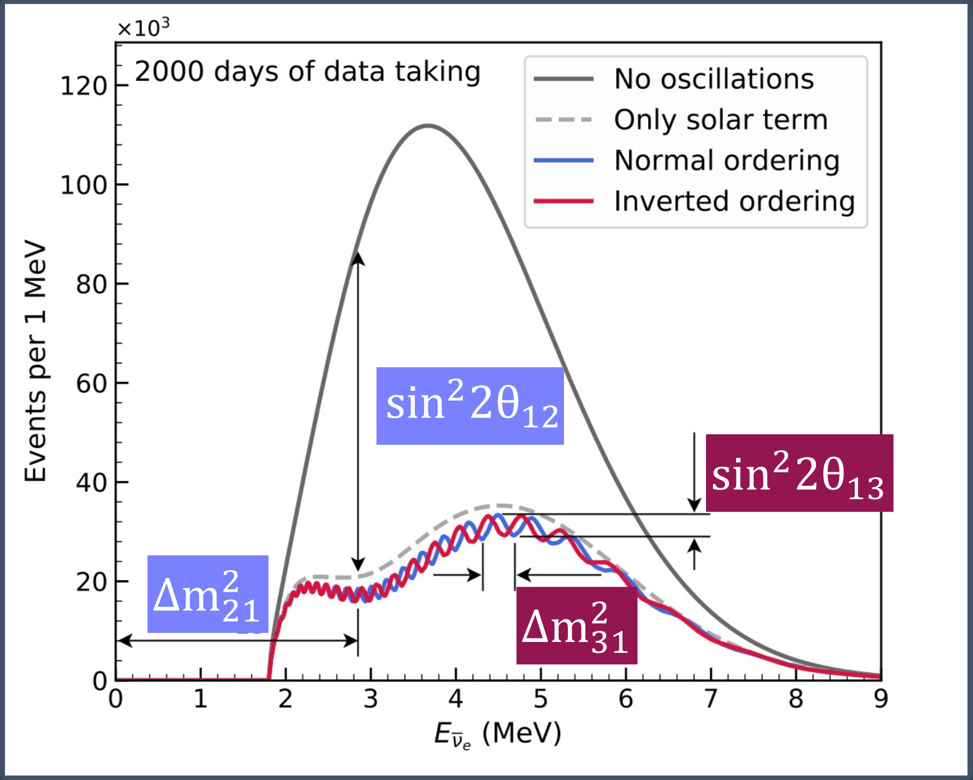
Reactor $\bar{\nu}_e$ spectrum at JUNO

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

Slow component (solar oscillation mode)

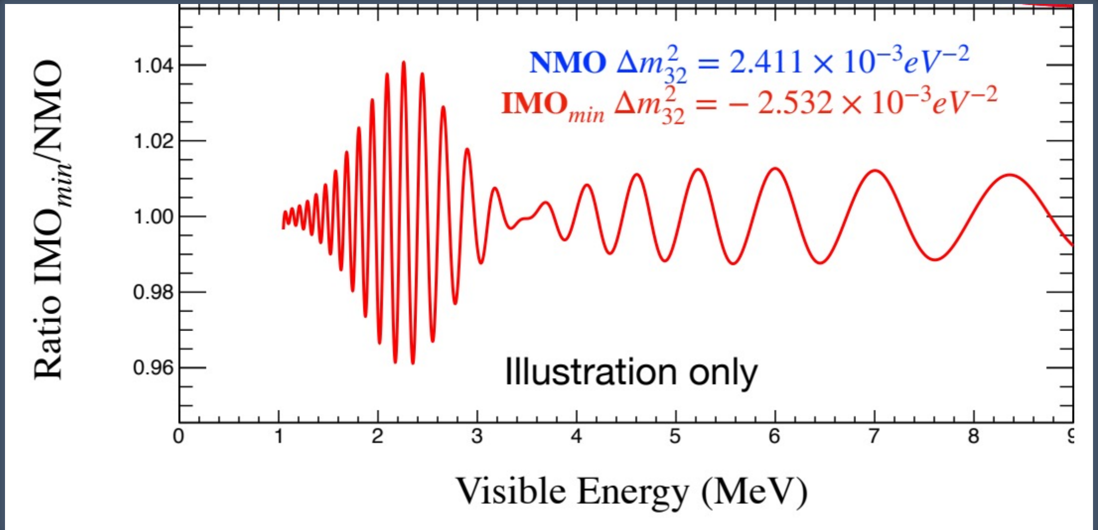
$$-\sin^2 2\theta_{13}\left[\cos^2\theta_{12}\,\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \sin^2 2\theta_{12}\,\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)\right]$$

Fast component (atmospheric oscillation mode)



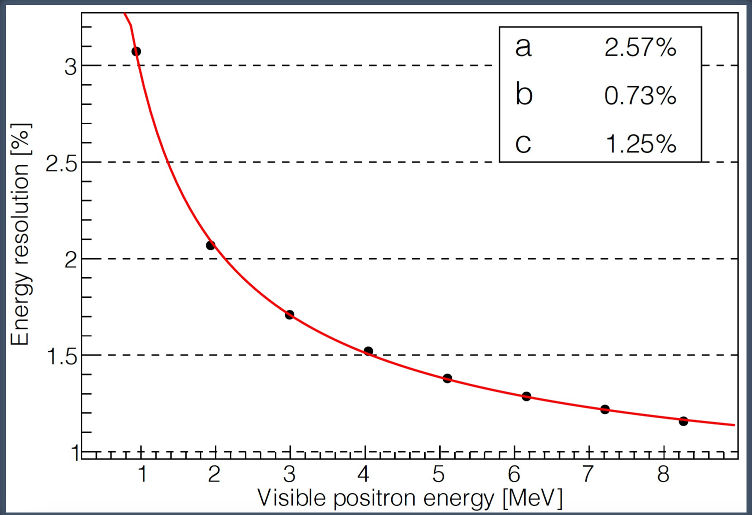
JUNO will be the first experiment to observe two modes of neutrino oscillations simultaneously

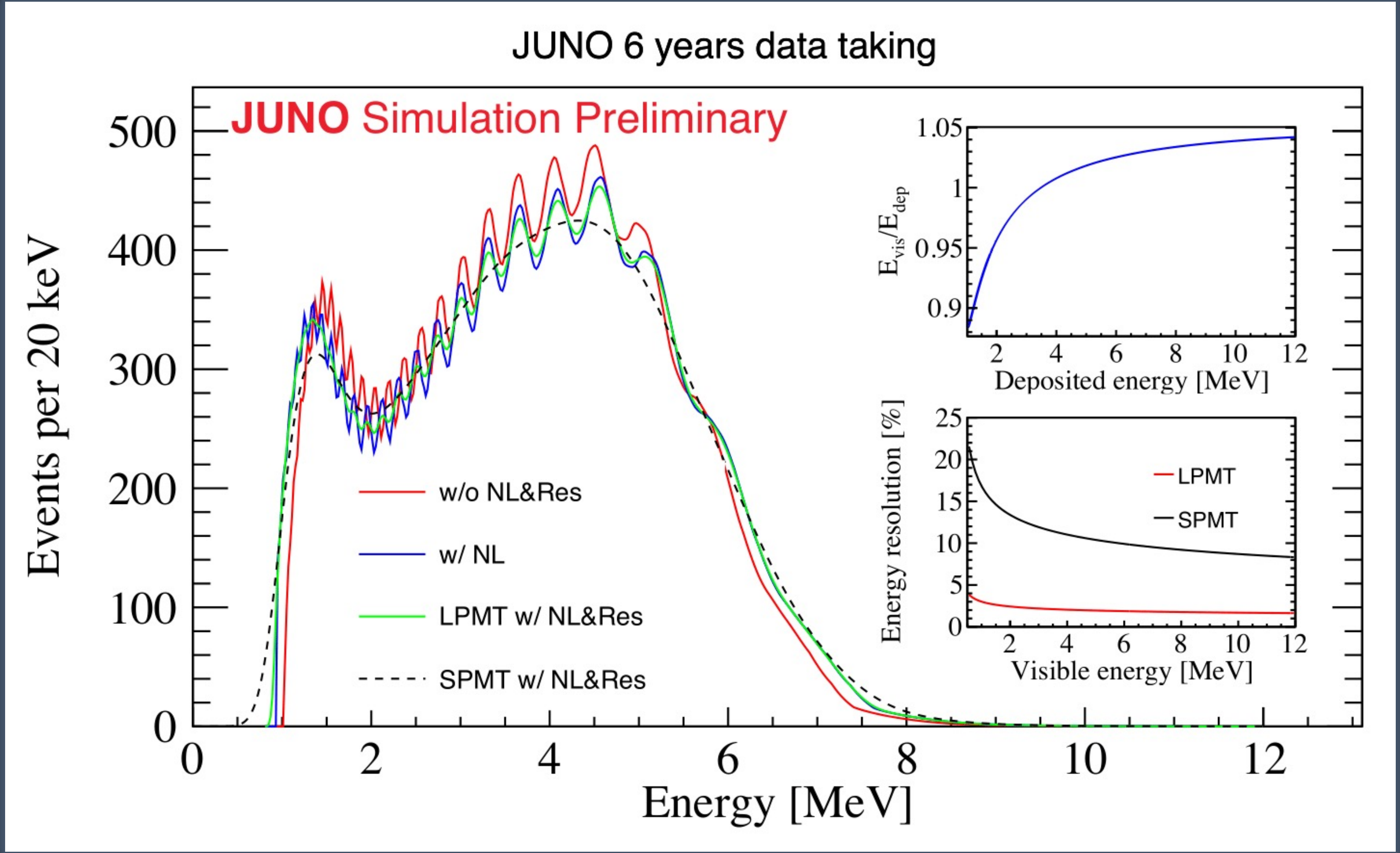
MO sensitivity from spectral shape analysis



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

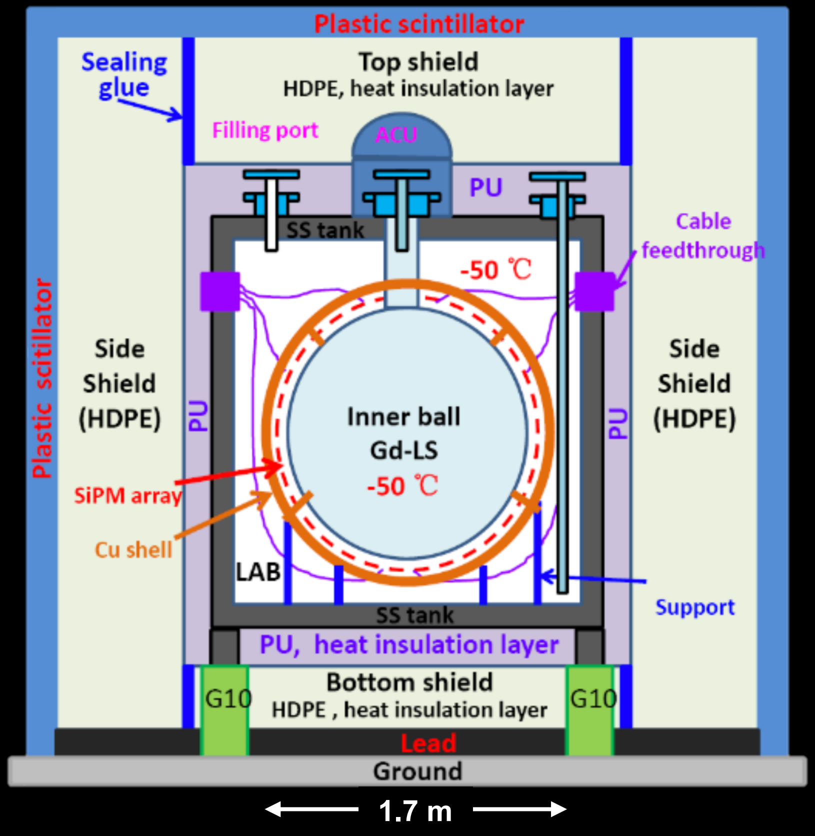




More info: Calibration Strategy of the JUNO experiment – JHEP 03 (2021) 004

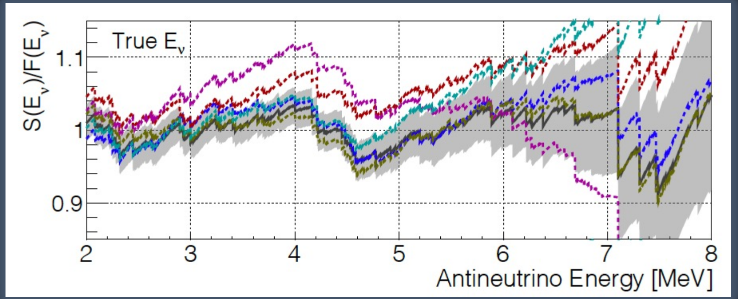
JUNO-TAO

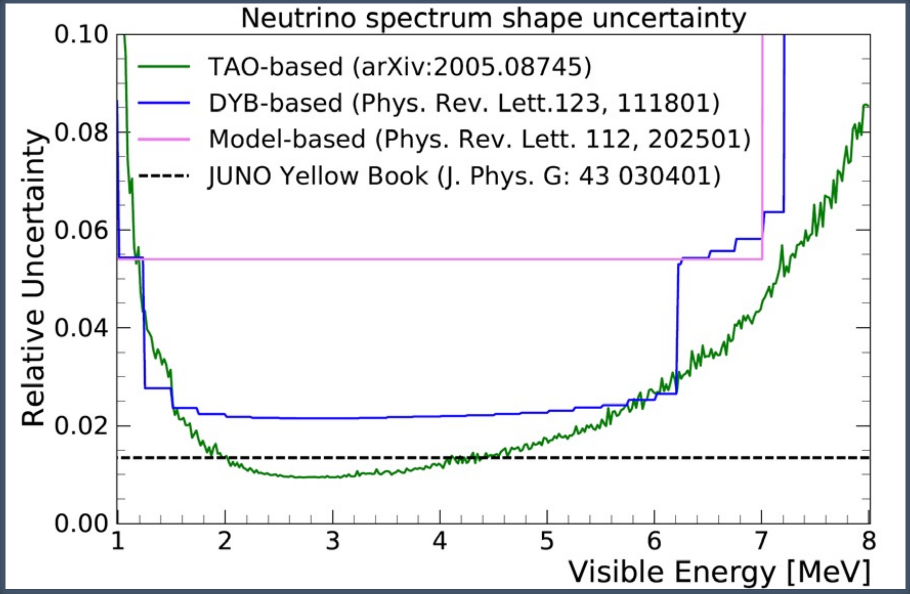
arXiv:2005.08745



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

Phys.Rev.Lett. 114, 012502 (2015)





- 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

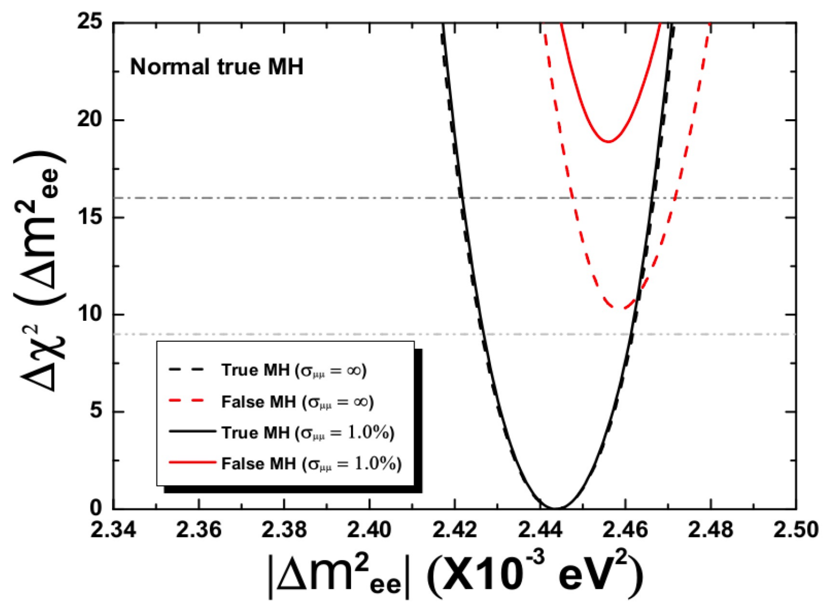
PUBLICATION COMING SOON

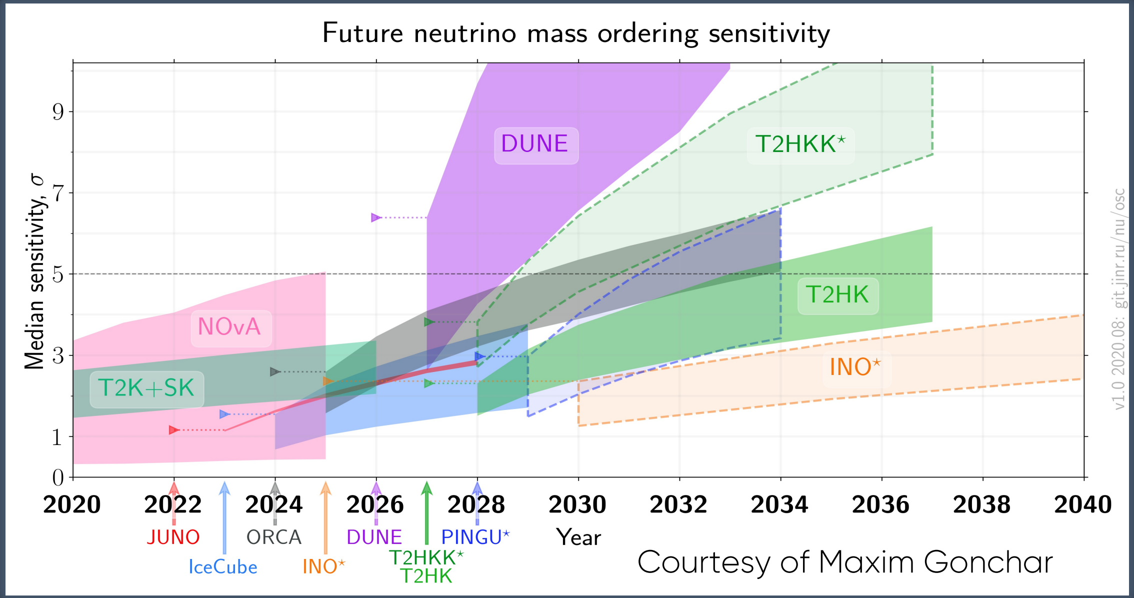
- JUNO is the only experiment exploiting vacuum oscillations
- No dependence on θ_{23} or δ_{CP}. Very little dependence on matter effects

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

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

— Using external $|\Delta m^2_{\mu\mu}|$(1% precision) → 4σ sensitivity in 6 years





Courtesy of Maxim Gonchar

- Strong synergies with other experiments:

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

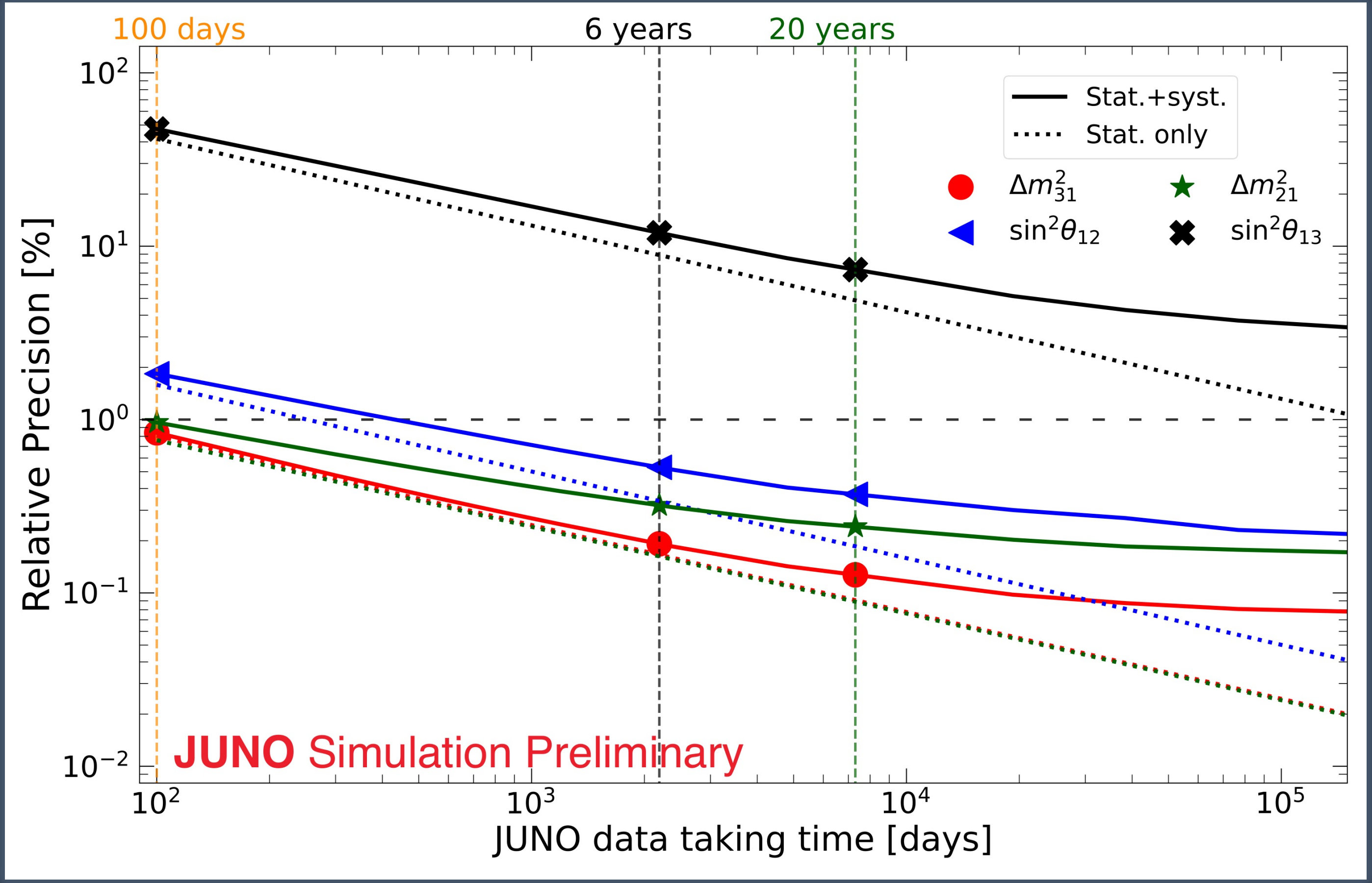
Through Δm^2_{31} for atmospheric neutrinos (KM3NeT/ORCA and IceCube) Phys. Rev. D 101, 032006 (2020)

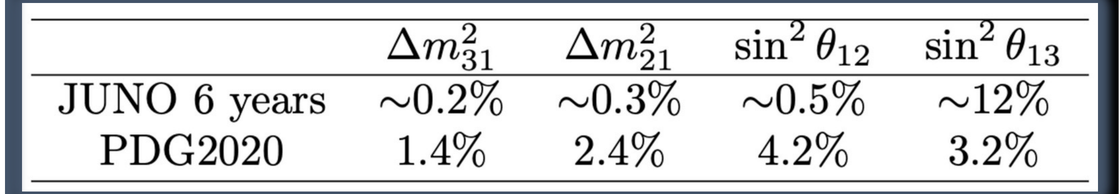
> 5σ sensitivity (in 6 years) in case of joint analysis

Neutrino Oscillation Parameters

PUBLICATION COMING SOON

- Precision measurement of oscillation parameters



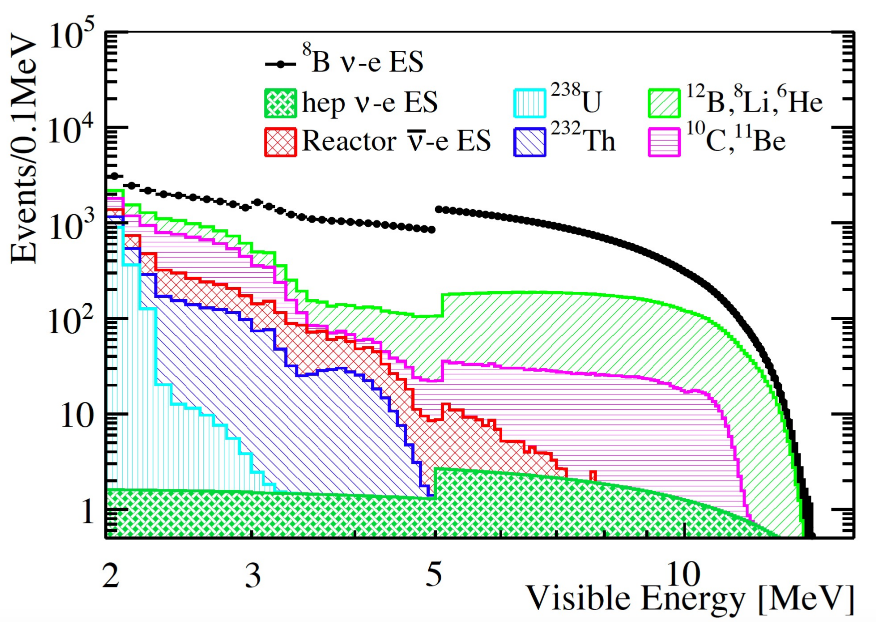


	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
JUNO 6 years	~0.2%	~0.3%	~0.5%	~12%
PDG2020	1.4%	2.4%	4.2%	3.2%

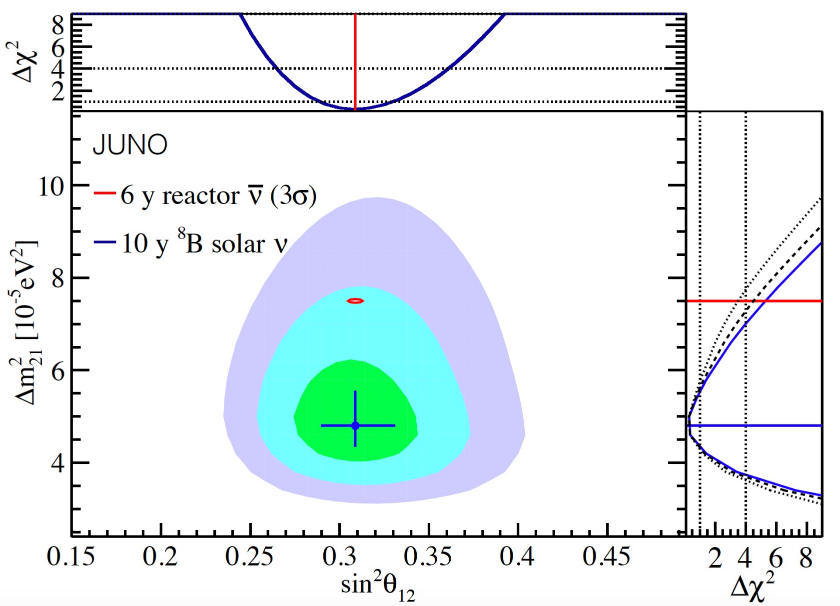
- JUNO will yield sub-percent precision after the nominal exposure of 6 years
- Improve today's precision by almost one order of magnitude in 3 of 6 oscillation parameters
- JUNO will help in testing the unitarity of the PMNS matrix and the mass sum rule

Solar ν_e from ^{8}B

Chinese Phys. C 45 023004

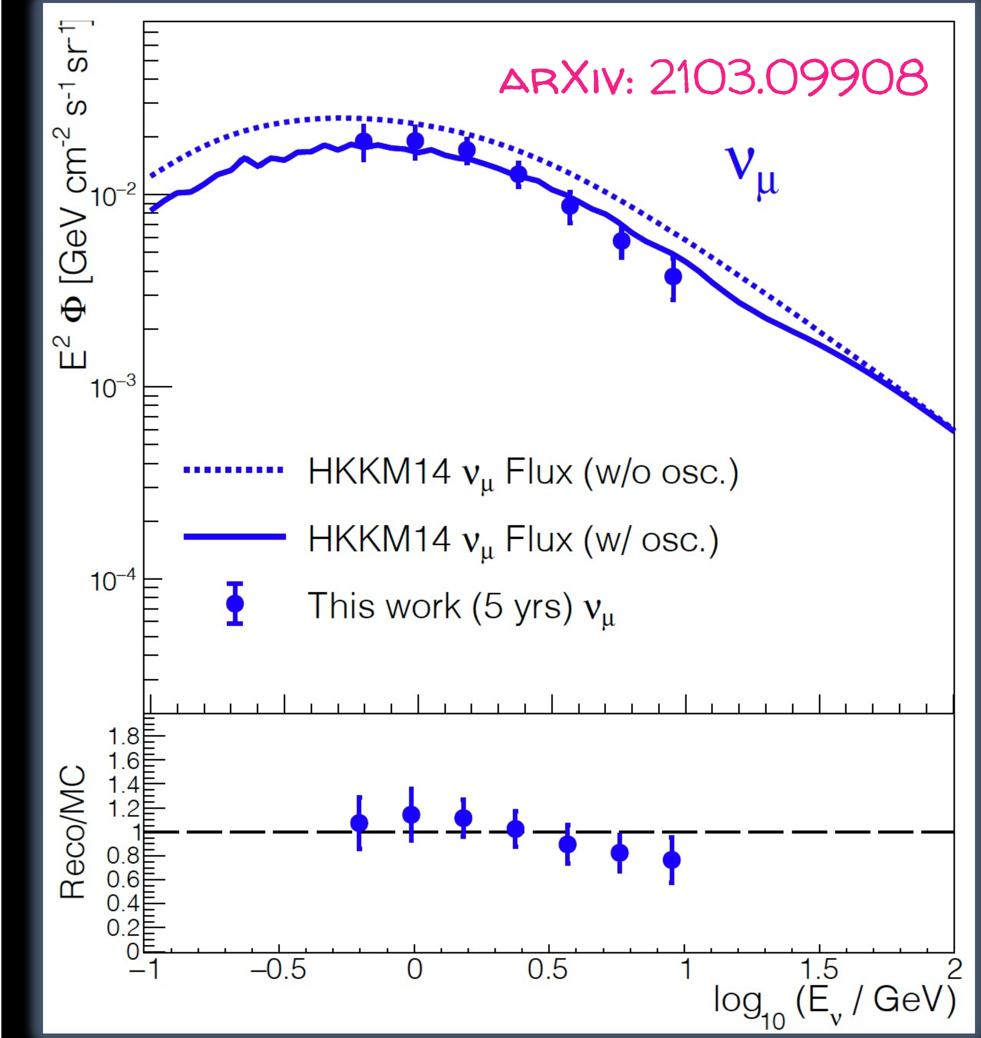


- Neutrino-electron elastic scattering process
- 2 MeV threshold on the recoil electron energy
- Higher energy resolution than water Cherenkov detectors
- Much larger target mass than previous LS detectors
- LS intrinsic radioactivity (10^{-17} g/g ^{238}U and ^{232}Th)
- Signal/background (10 years):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



- ^{8}B 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}

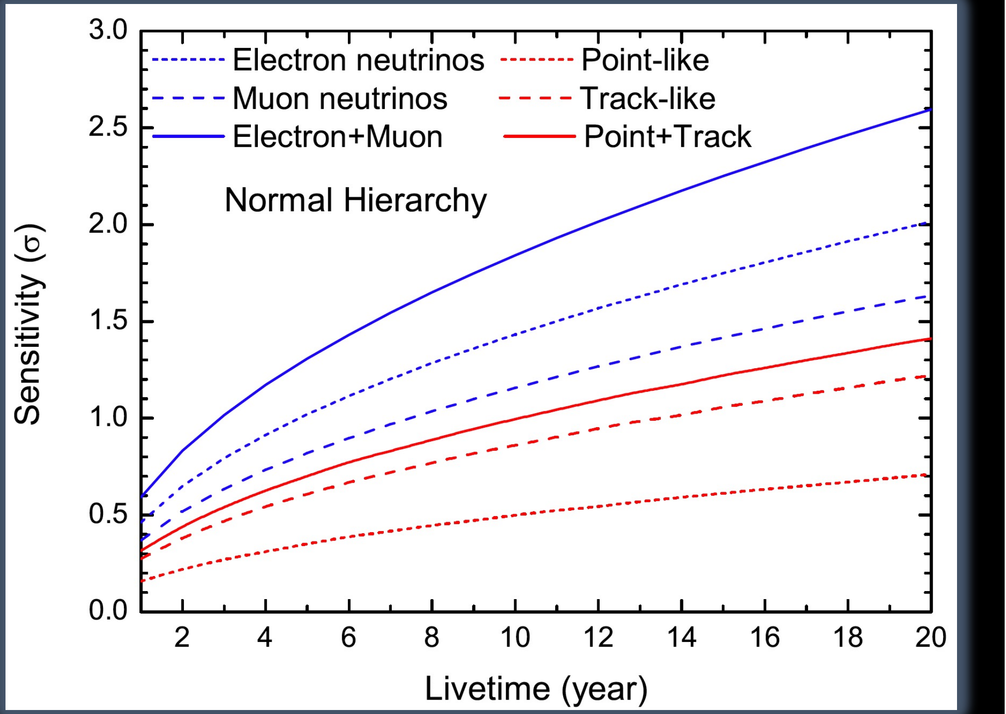
Atmospheric $\nu_\mu/\bar{\nu}_\mu$



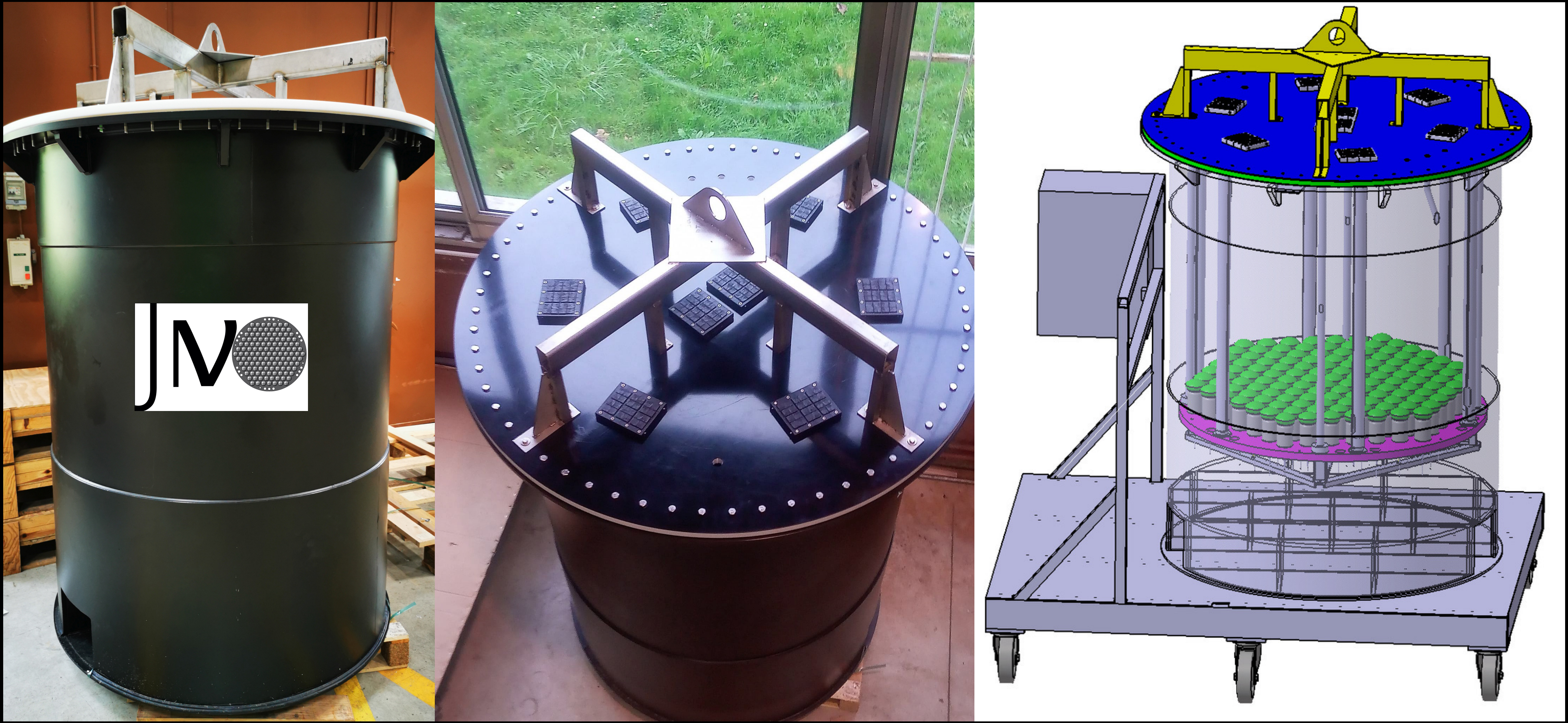
- JUNO will be able to detect several atmospheric neutrinos per day
- Preferred detection channels: ν_μ/ ν_e CC interactions
- ν_μ and ν_e interactions produce slightly different light pattern → flavor discrimination through the event time profile

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

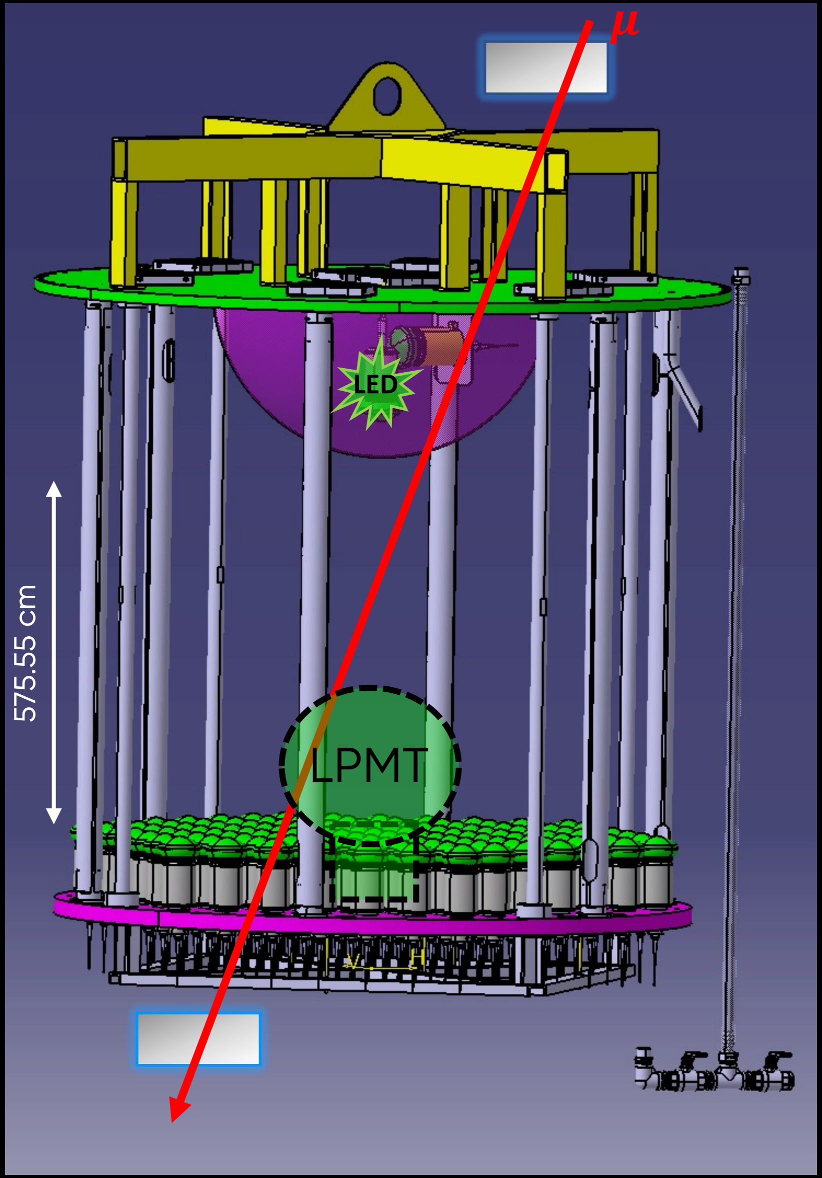
J. Phys. G43:030401 (2016)



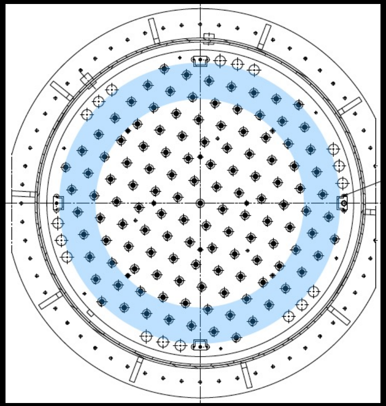
Bonus track: JINO

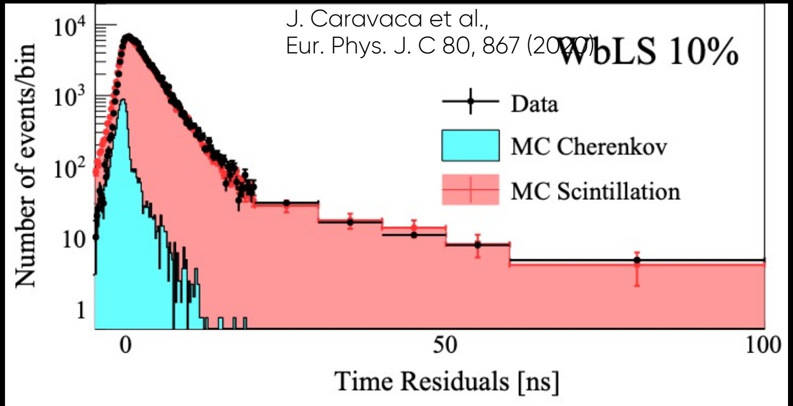


JINO



- Response test / validation / calibration
  - JINO-I
    - Single Calorimetry: 127 SPMT (bottom)
    - Dual Calorimetry Calibration: 127 SPMT+1 SPMT (source monitoring)
  - JINO-II
    - **Dual Calorimetry Readout: 1 LPMT + SPMT**
- Different light sources (no degeneracies)
  - Muon Cherenkov only (electronics performance)
  - Muon Cherenkov + Scintillation (JUNO-like)
  - UV LED + Scintillator
  - LED only (SN readout capabilities)





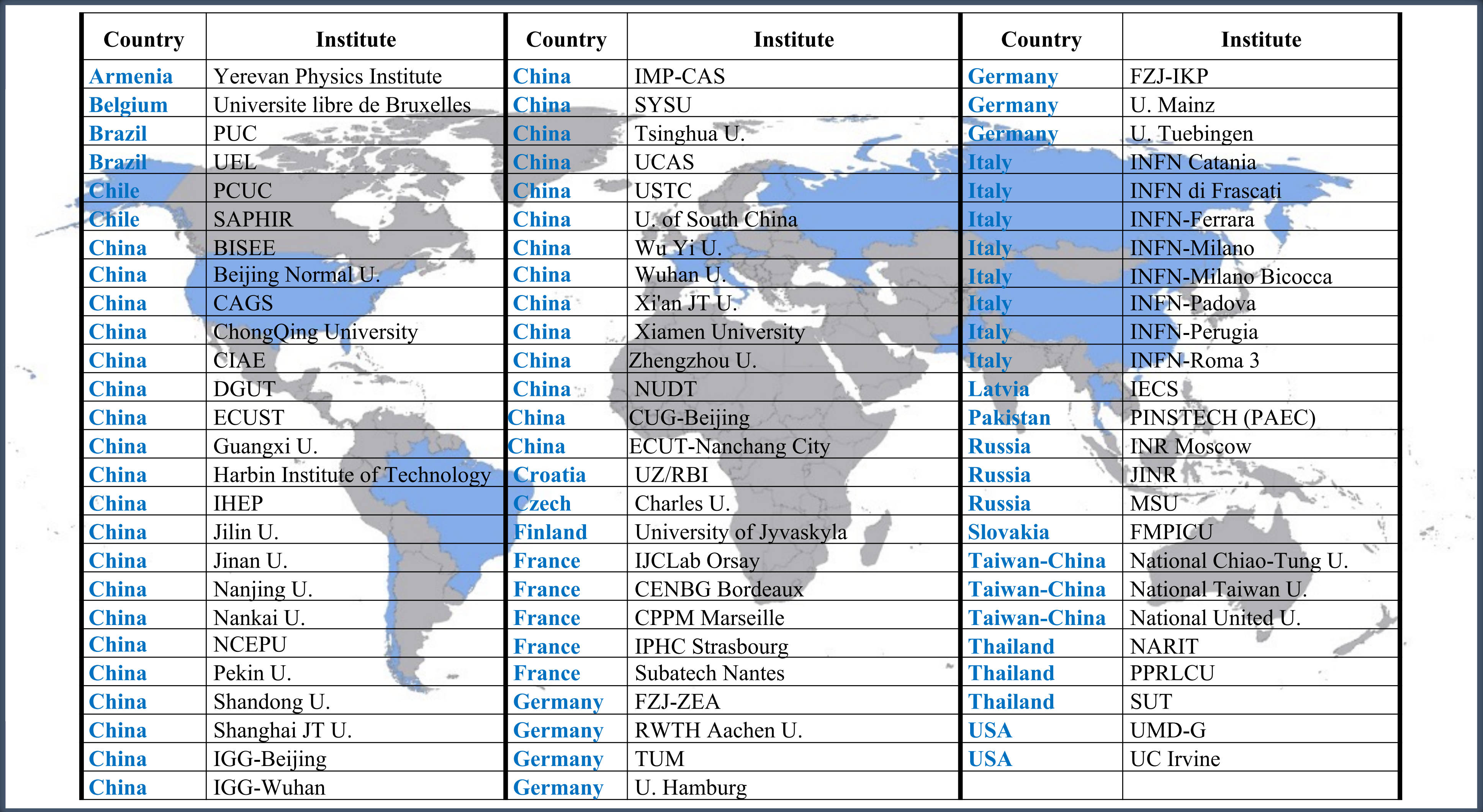
J. Caravaca et al., Eur. Phys. J. C 80, 867 (2020)

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 Δm^2_{21}, Δm^2_{32}, $\sin^2\theta_{12}$ at sub-percent precision level with reactor $\bar{\nu}_e$
- Independent measurement of Δm^2_{21} and $\sin^2\theta_{12}$ via solar neutrinos from ^{8}B
- θ_{23} measurement via atmospheric neutrinos

JUNO Collaboration

THANK YOU FOR YOUR ATTENTION



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

Back-up

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

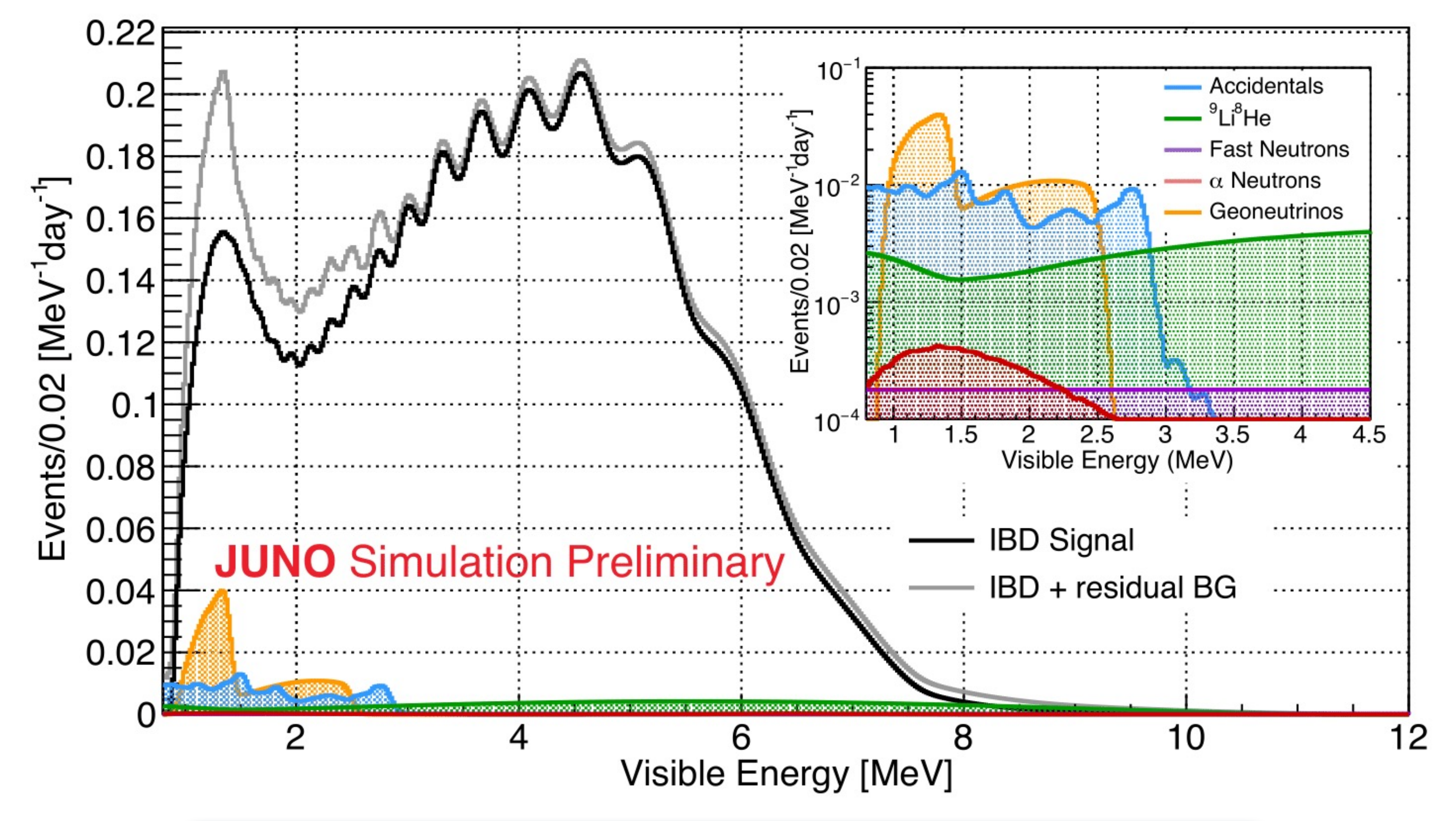
Good news

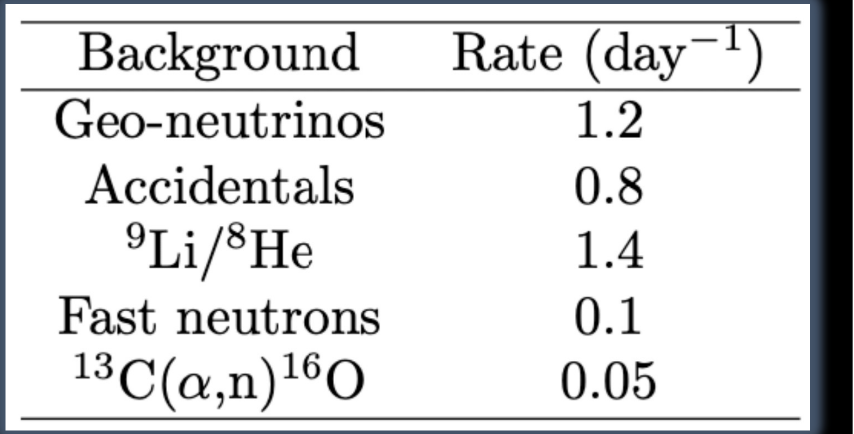
- ▲ Background control: more realistic measurements and simulations
- ▲ Optimized event selection and muon veto strategies: IBD selection efficiency: **73% → ~ 82%**
- ▲ More realistic PMT and liquid scintillator optical → model Higher LS light yield
- ▲ Higher 20-inch PMT photon detection efficiency: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

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

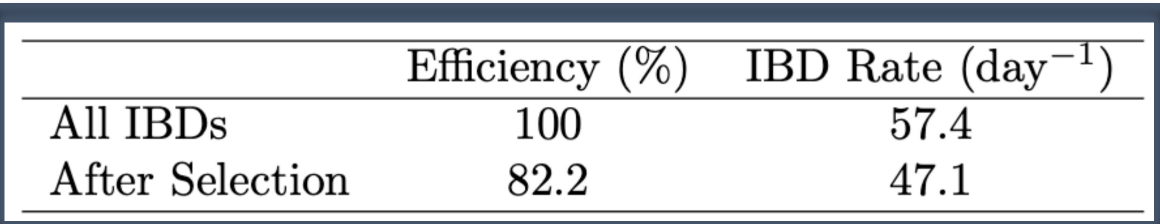
$\bar{\nu}_e$ signal and backgrounds





Background	Rate (day^{-1})
Geo-neutrinos	1.2
Accidentals	0.8
^{9}Li/^{8}He	1.4
Fast neutrons	0.1
^{13}C(α,n)^{16}O	0.05

arXiv:2104.02565



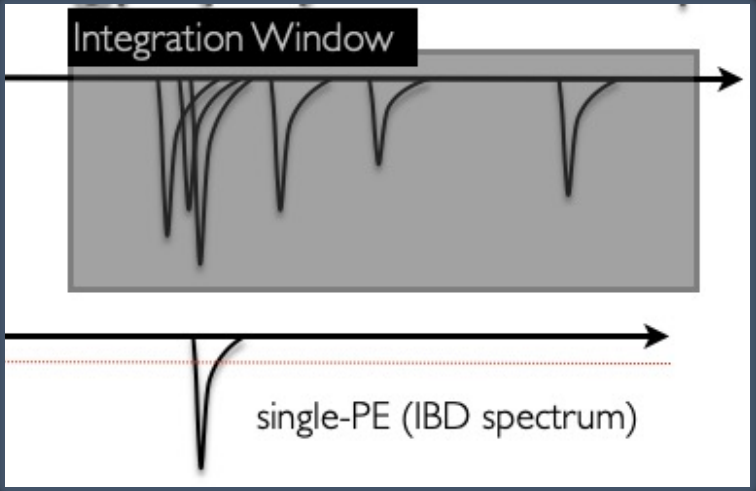
	Efficiency (%)	IBD Rate (day^{-1})
All IBDs	100	57.4
After Selection	82.2	47.1

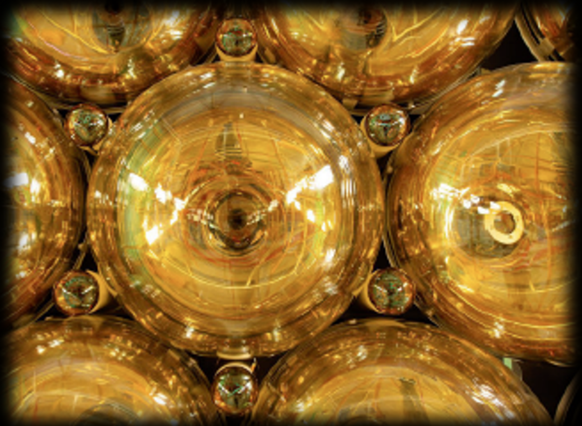
Dual Calorimetry

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

20” LPMT

3” SPMT





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

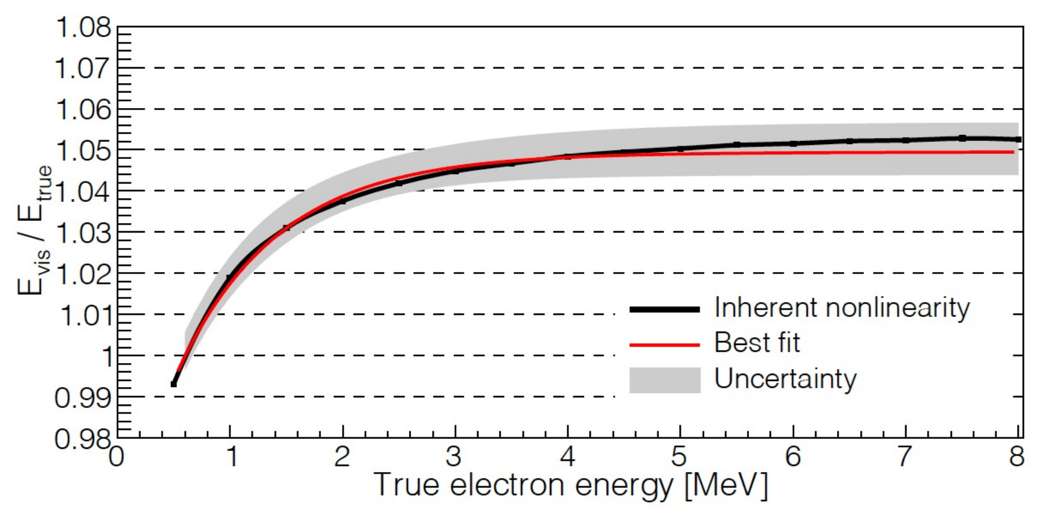
↓

Charge linear reference to the LPMT.

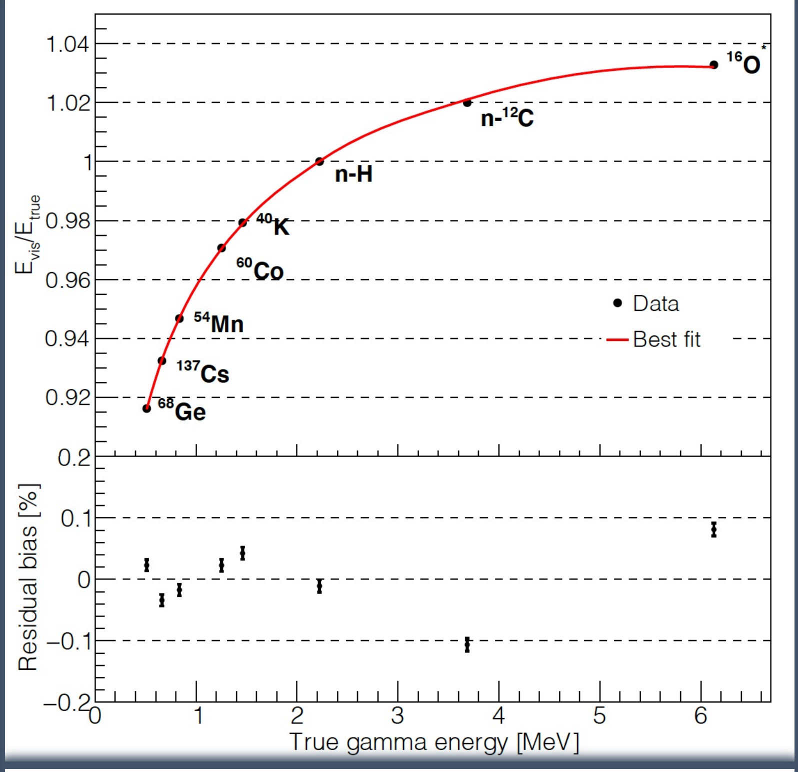
Energy Scale

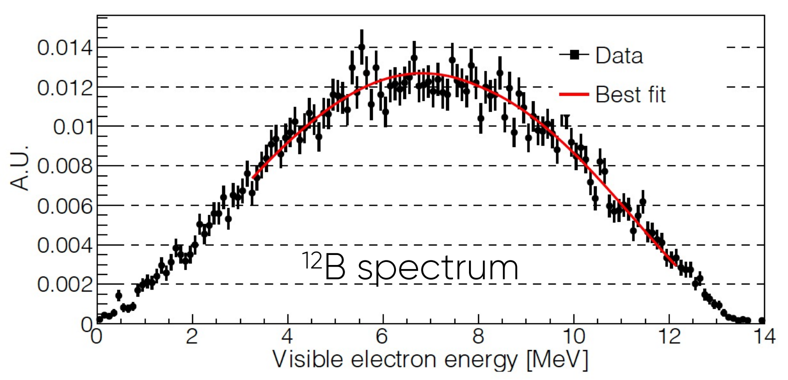
Non-linearity is composed of:

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



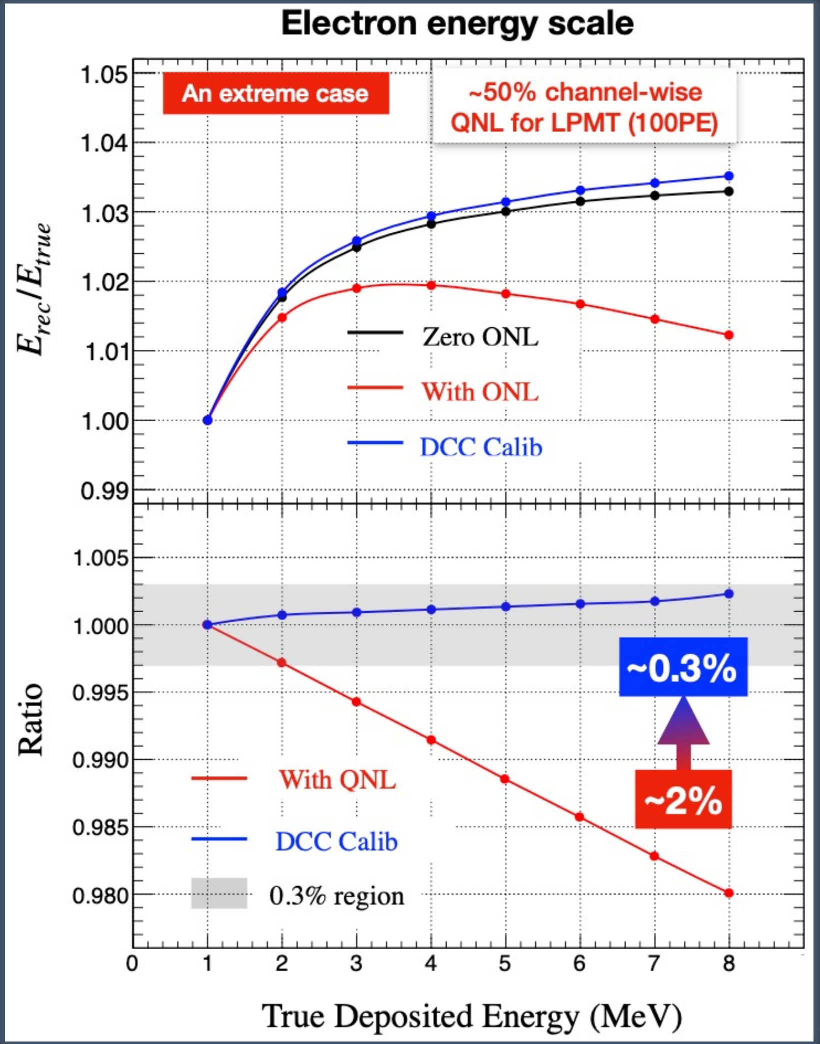
< 1% energy scale uncertainty





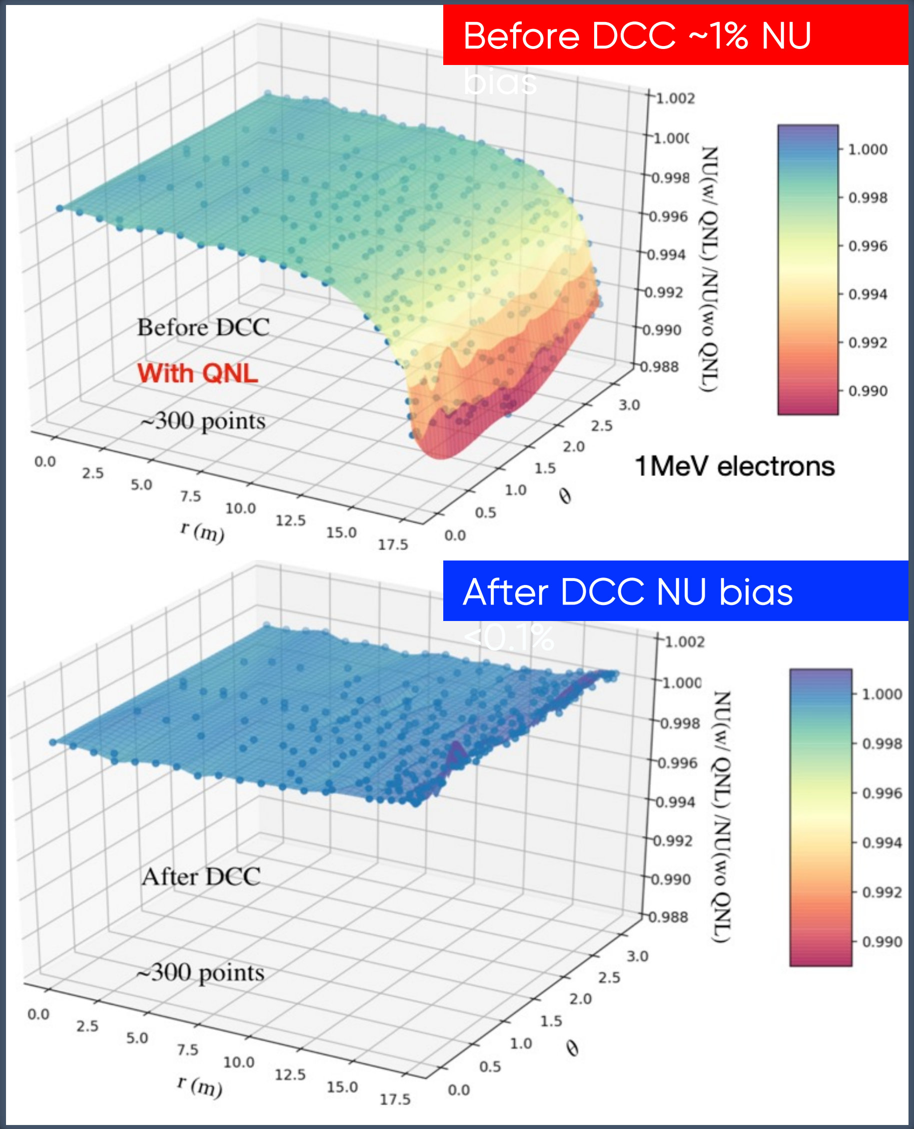
Energy Scale after Dual Calorimetry Calibration

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



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

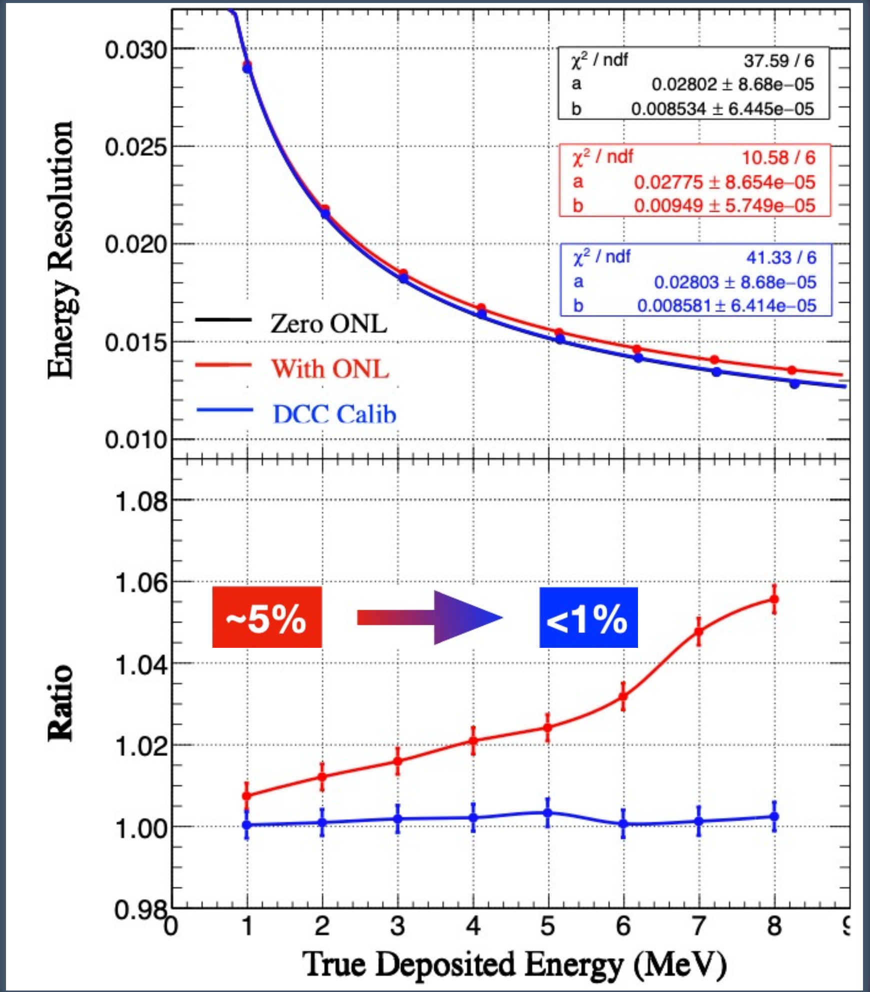

Before DCC ~1% NU bias

After DCC NU bias <0.1%

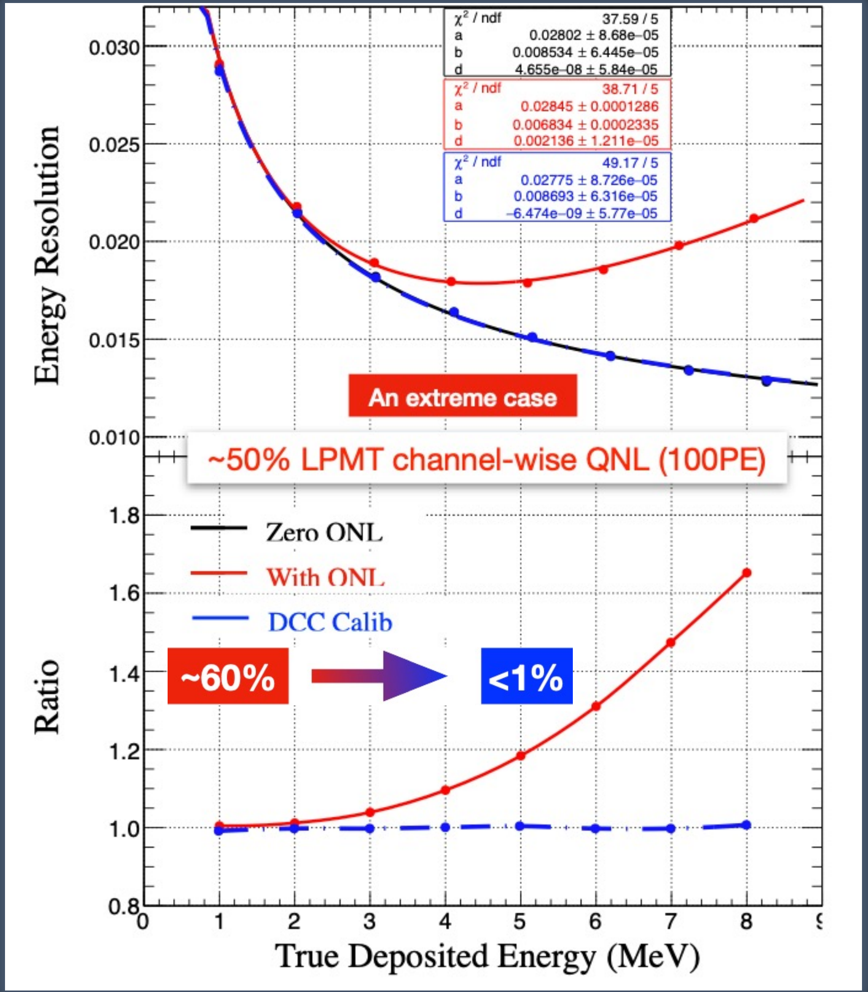
Energy Resolution after Dual Calorimetry Calibration

$$\frac{\sigma_E}{E} = \sqrt{\frac{\sigma^2_{stochastic}}{E} + \sigma^2_{non-stochastic}(E)}$$

$\sigma_{non-stochastic} < 1\%$



~5% → <1%

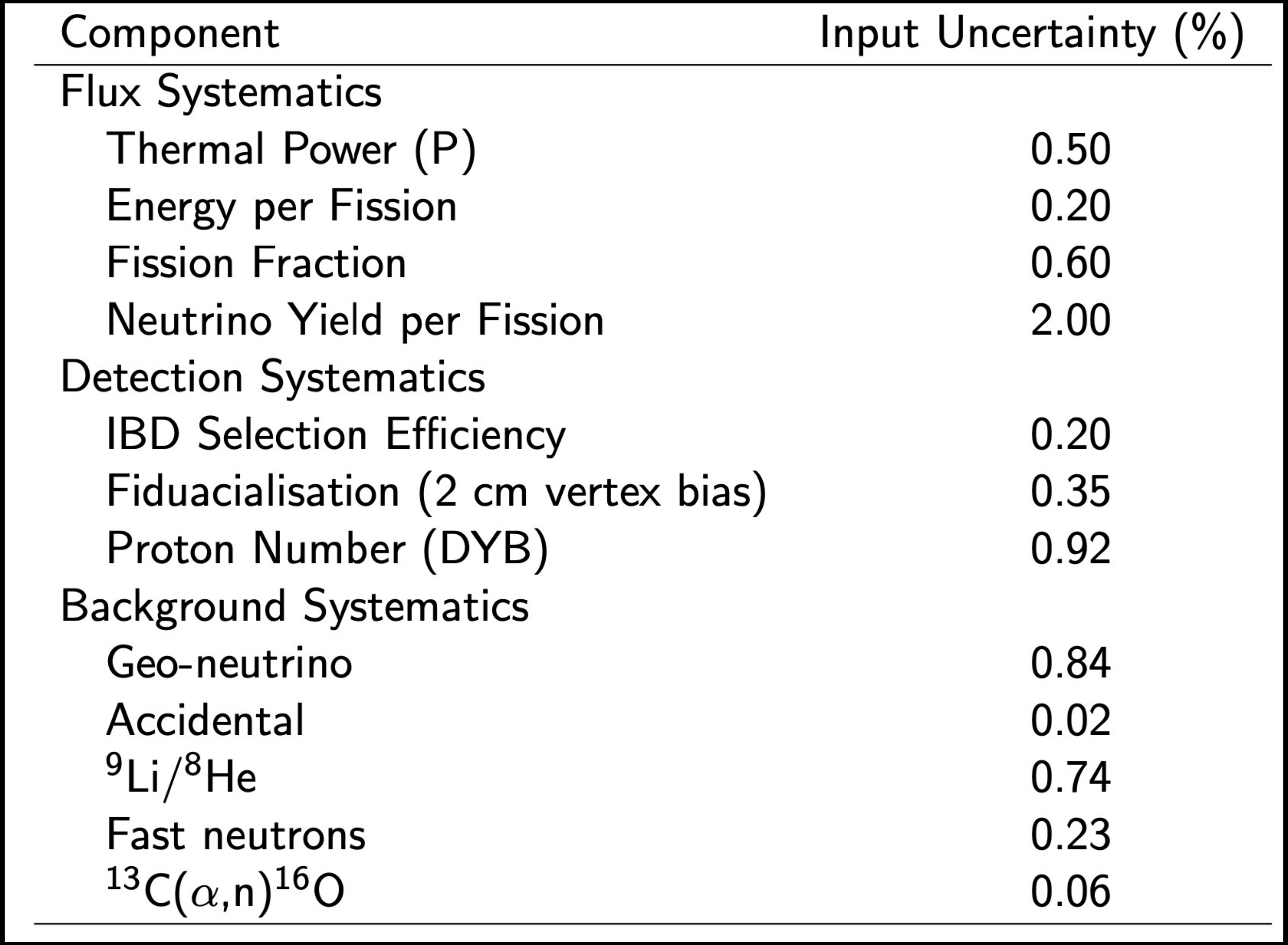


An extreme case

~50% LPMT channel-wise QNL (100PE)

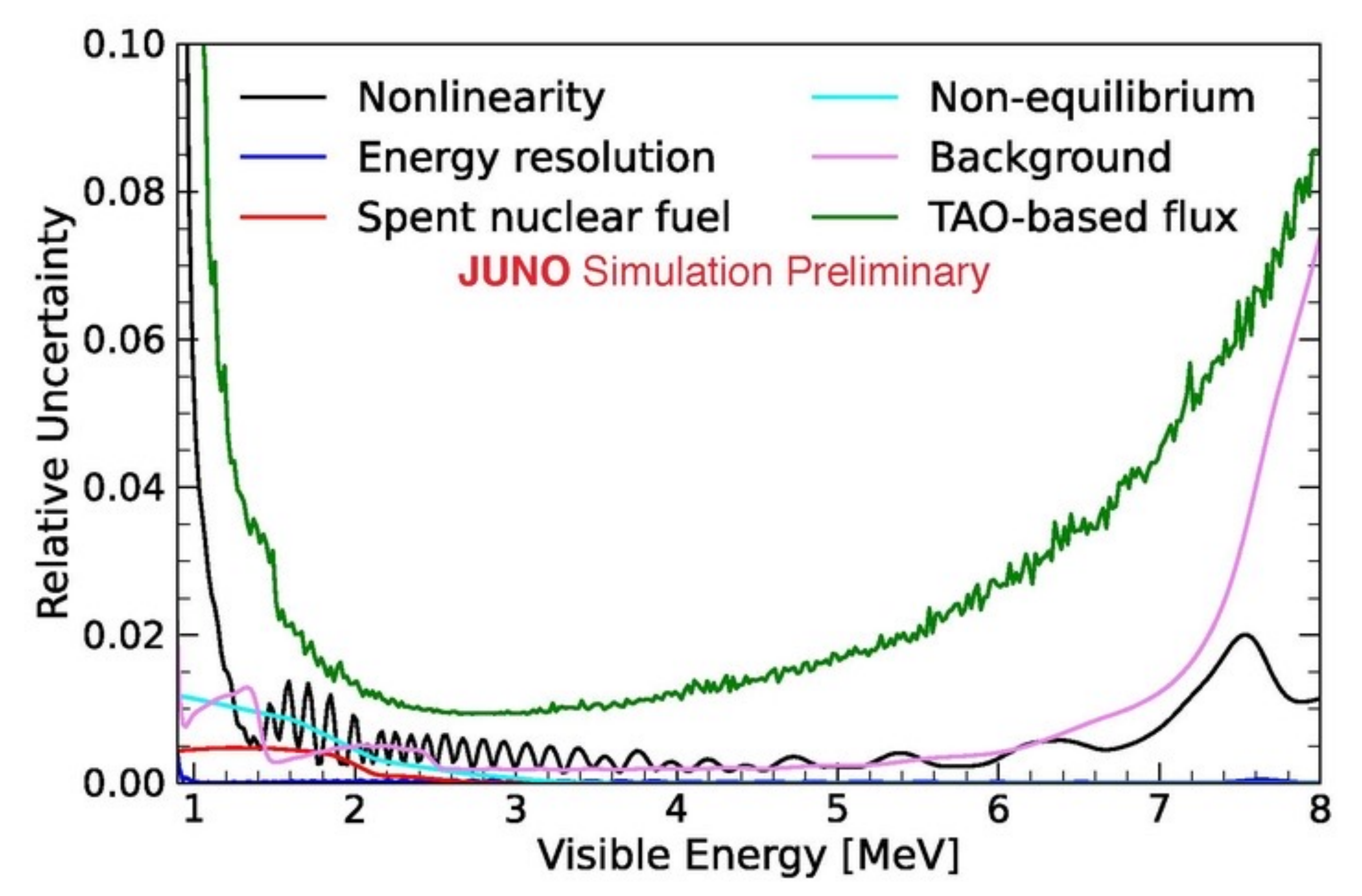
~60% → <1%

Rate Uncertainties

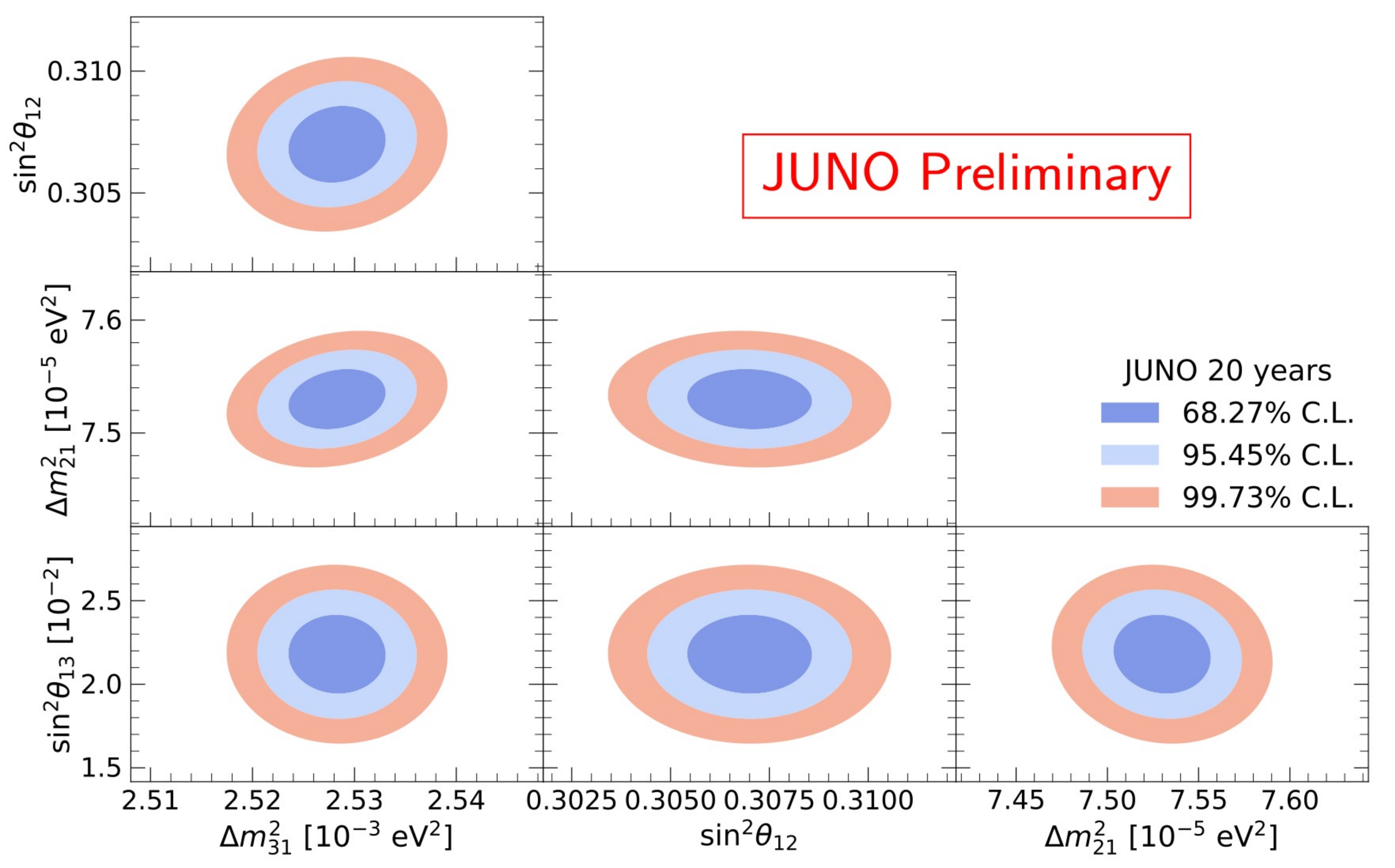


Component	Input Uncertainty (%)
Flux Systematics	
Thermal Power (P)	0.50
Energy per Fission	0.20
Fission Fraction	0.60
Neutrino Yield per Fission	2.00
Detection Systematics	
IBD Selection Efficiency	0.20
Fiducialisation (2 cm vertex bias)	0.35
Proton Number (DYB)	0.92
Background Systematics	
Geo-neutrino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

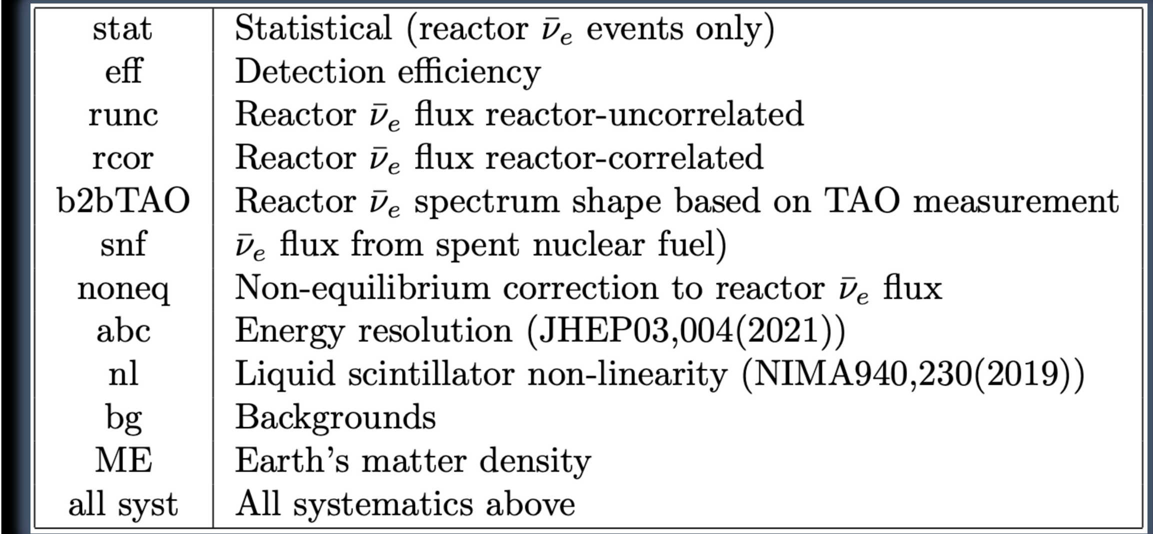
Shape Uncertainty



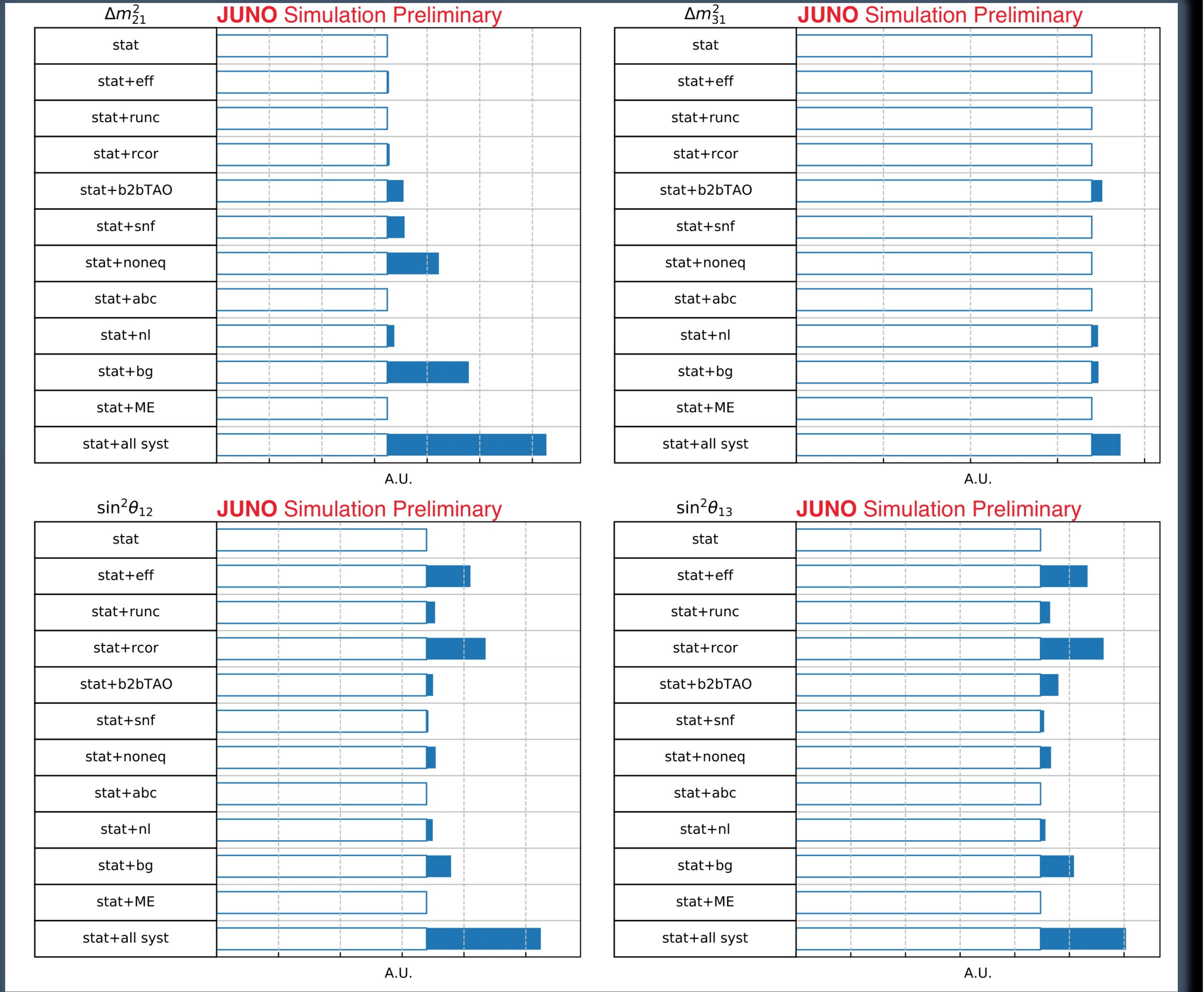
Oscillation Parameters correlation



Oscillation parameters: systematics



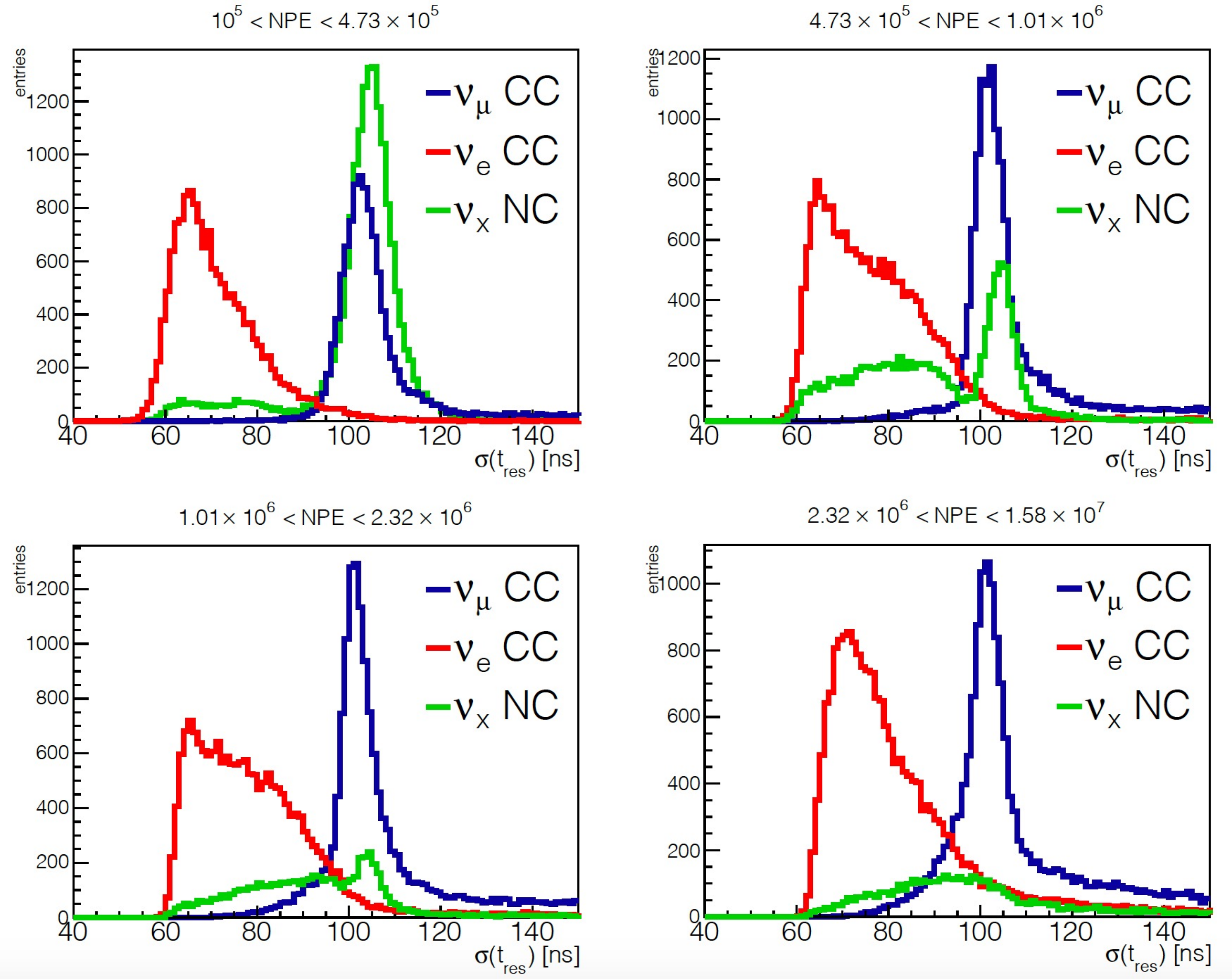
stat	Statistical (reactor $\bar{\nu}_e$ events only)
eff	Detection efficiency
runc	Reactor $\bar{\nu}_e$ flux reactor-uncorrelated
rcor	Reactor $\bar{\nu}_e$ flux reactor-correlated
b2bTAO	Reactor $\bar{\nu}_e$ spectrum shape based on TAO measurement
snf	$\bar{\nu}_e$ flux from spent nuclear fuel)
noneq	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

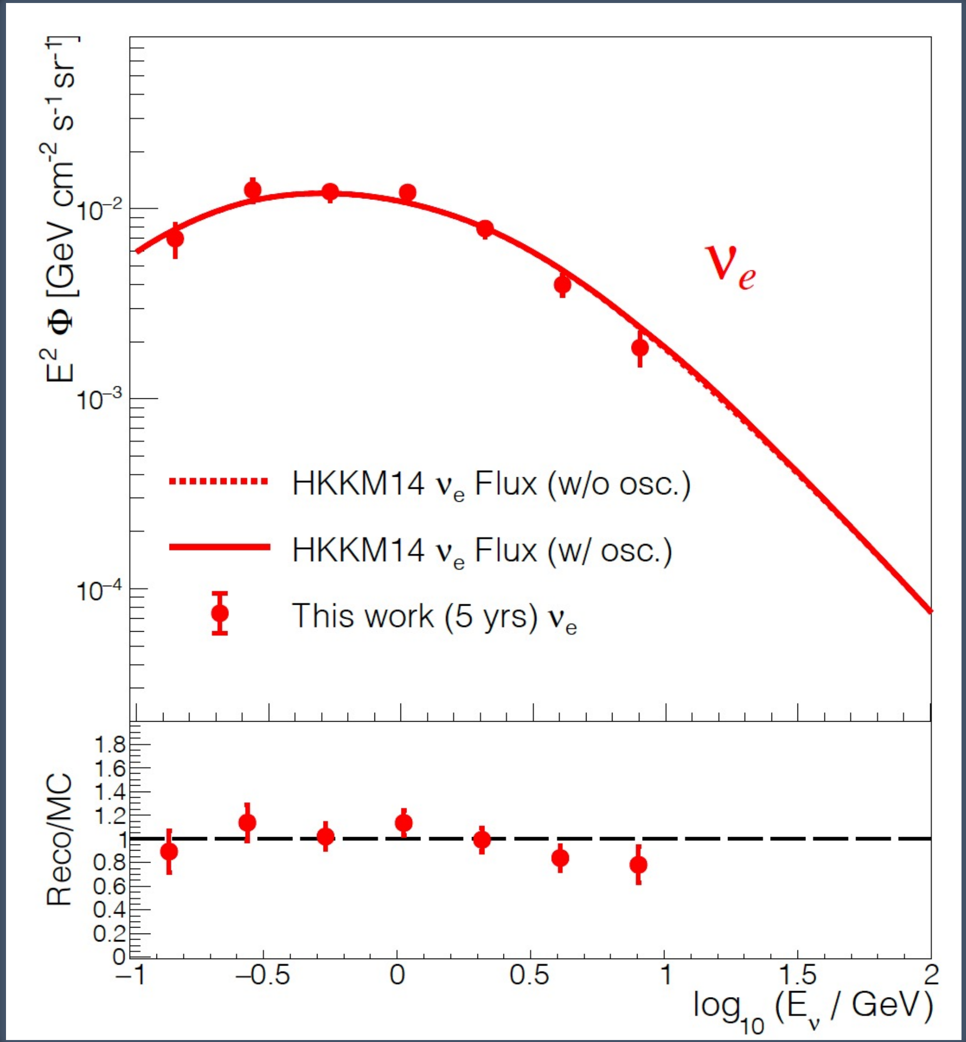


The dominant systematics for precision measurement:

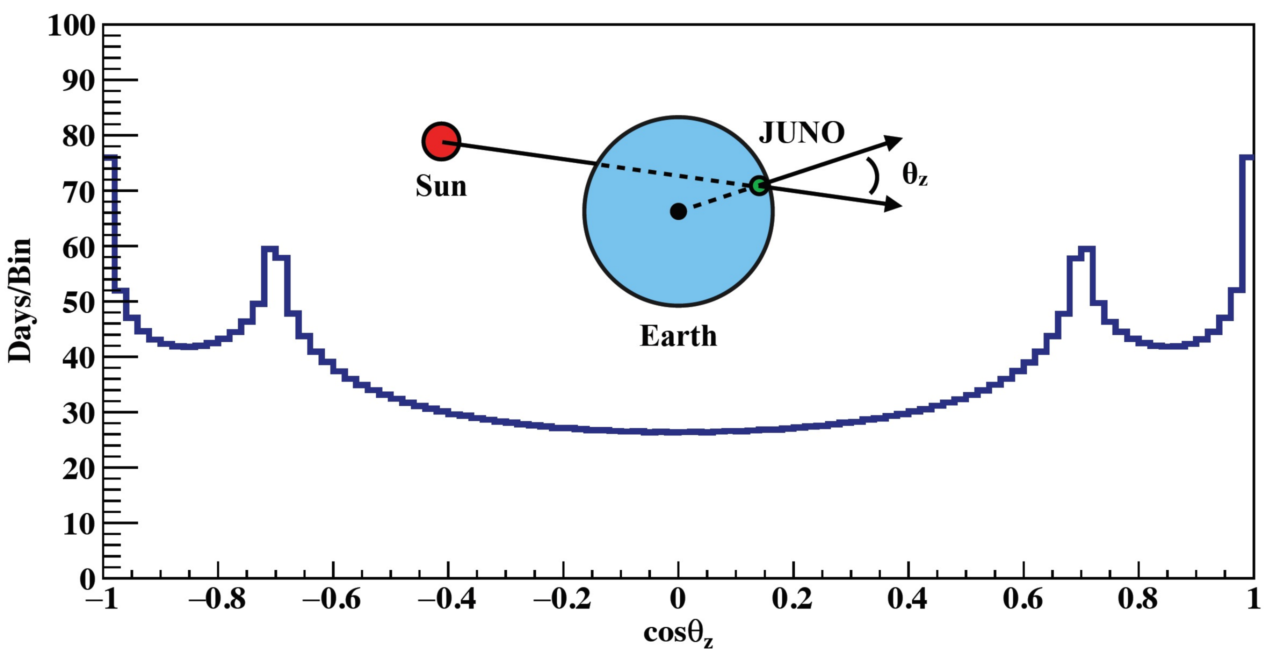
- Δm^2_{31} / Δm^2_{32} : reactor spectrum shape
- Δm^2_{21} : background, non-equilibrium effect
- $\sin^2\theta_{12}$, $\sin^2\theta_{12}$: normalization rate

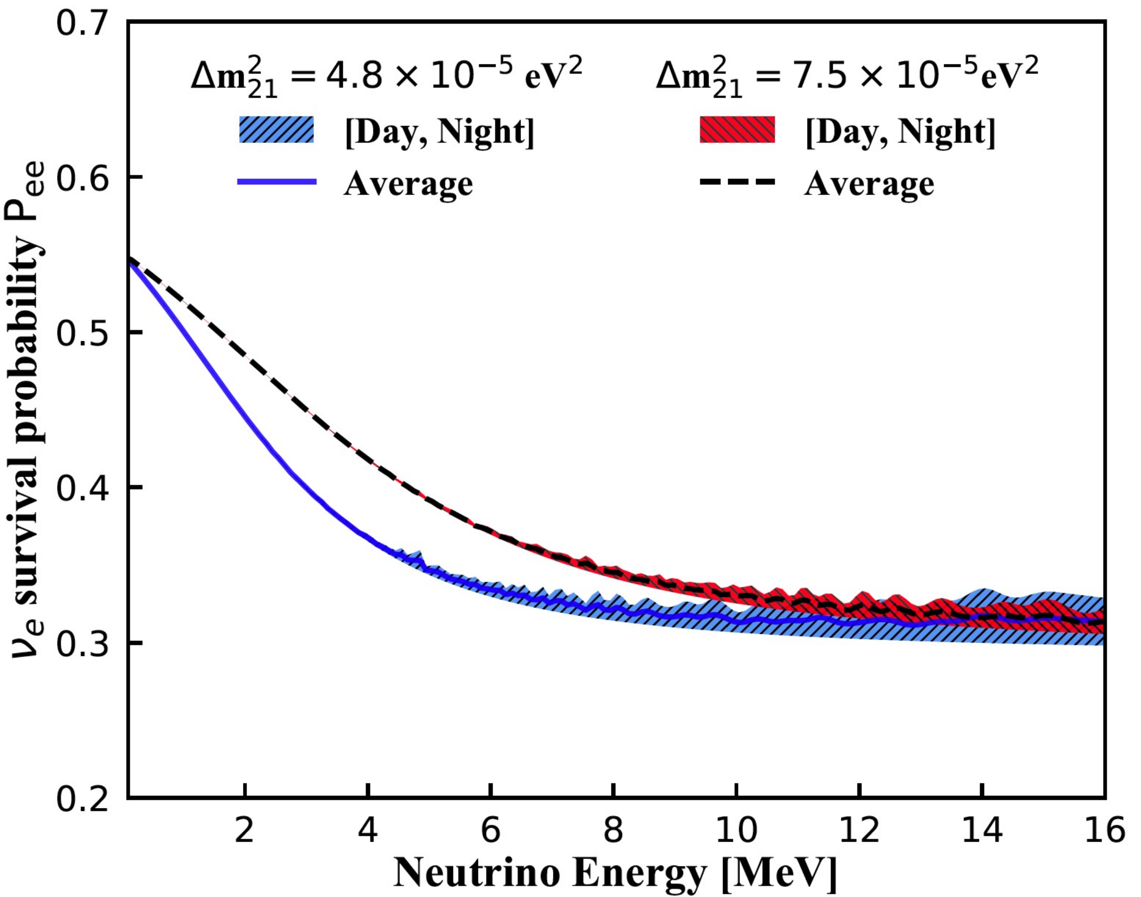
Atmospheric neutrino flavour identification





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: $0.5\ \mathrm{eV}^2 < \Delta m^2_{41} < 5\ \mathrm{eV}^2$