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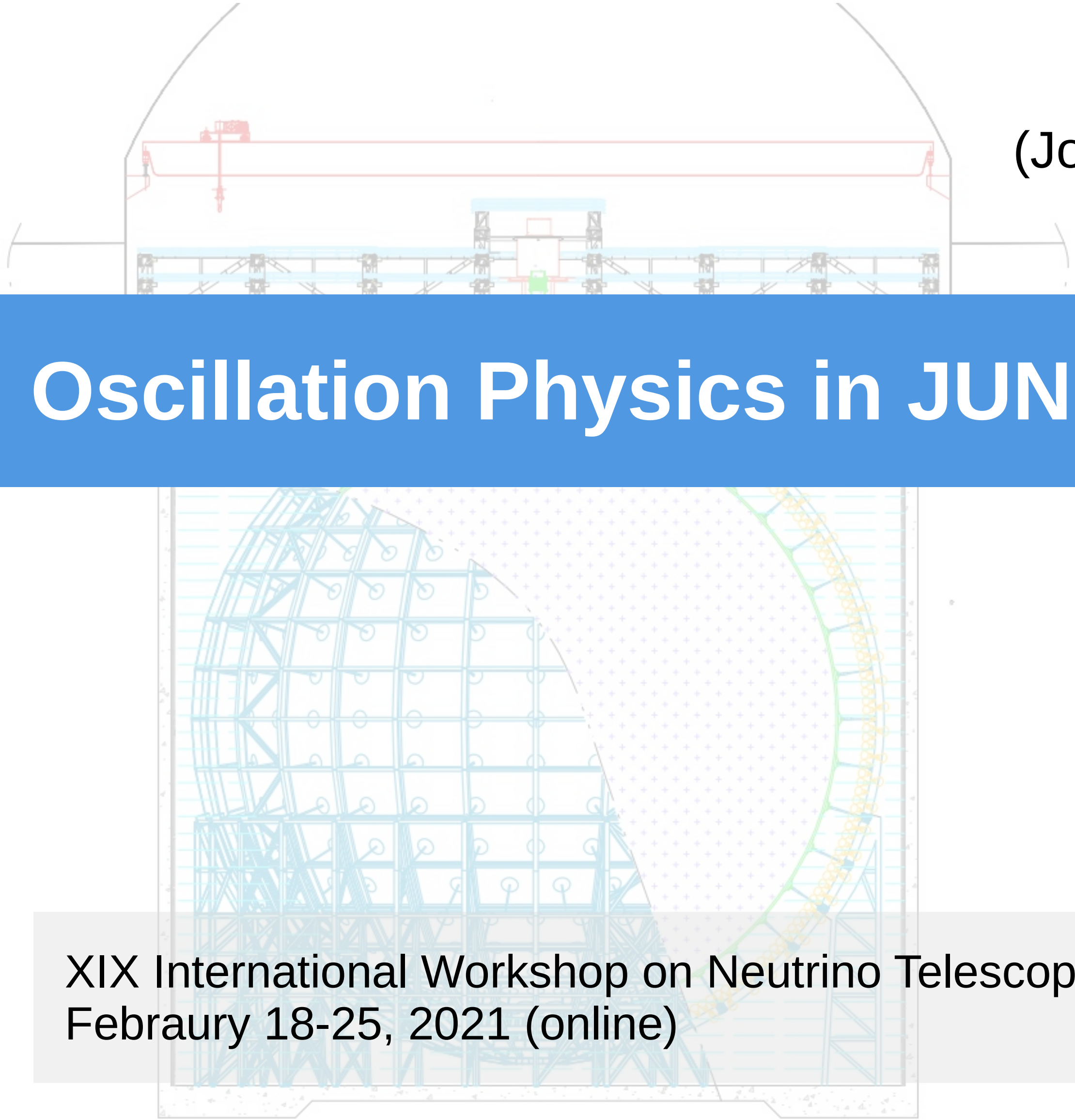
(Joint Institute for Nuclear Research)

for the JUNO Collaboration

Oscillation Physics in JUNO

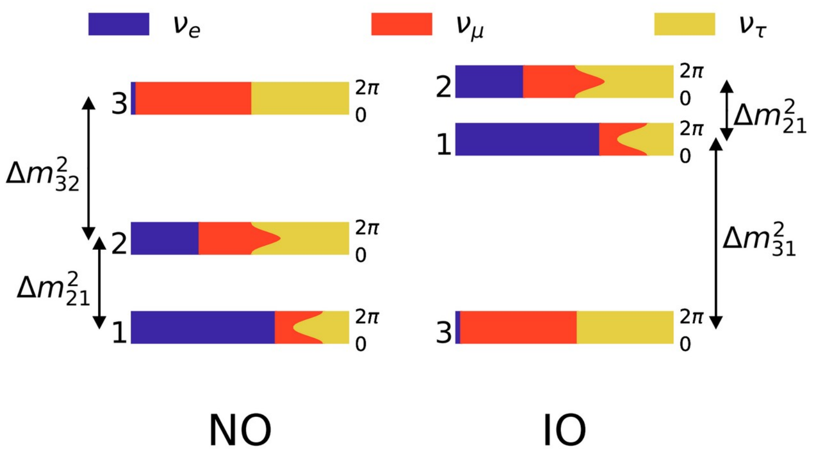
RSF grant #21-42-00023



XIX International Workshop on Neutrino Telescopes
Febraury 18-25, 2021 (online)

Open Questions in Neutrino Oscillation Physics

- Neutrino mass hierarchy: normal ordering (NO) or inverted ordering (IO)?
- Only 3 flavor or there are sterile states?
- Precise values of mixing angles and mass splittings
- CP violation?



Probability of finding the α neutrino flavor in the i-th neutrino mass eigenstate. The CP-violating phase is varied (0→2π).

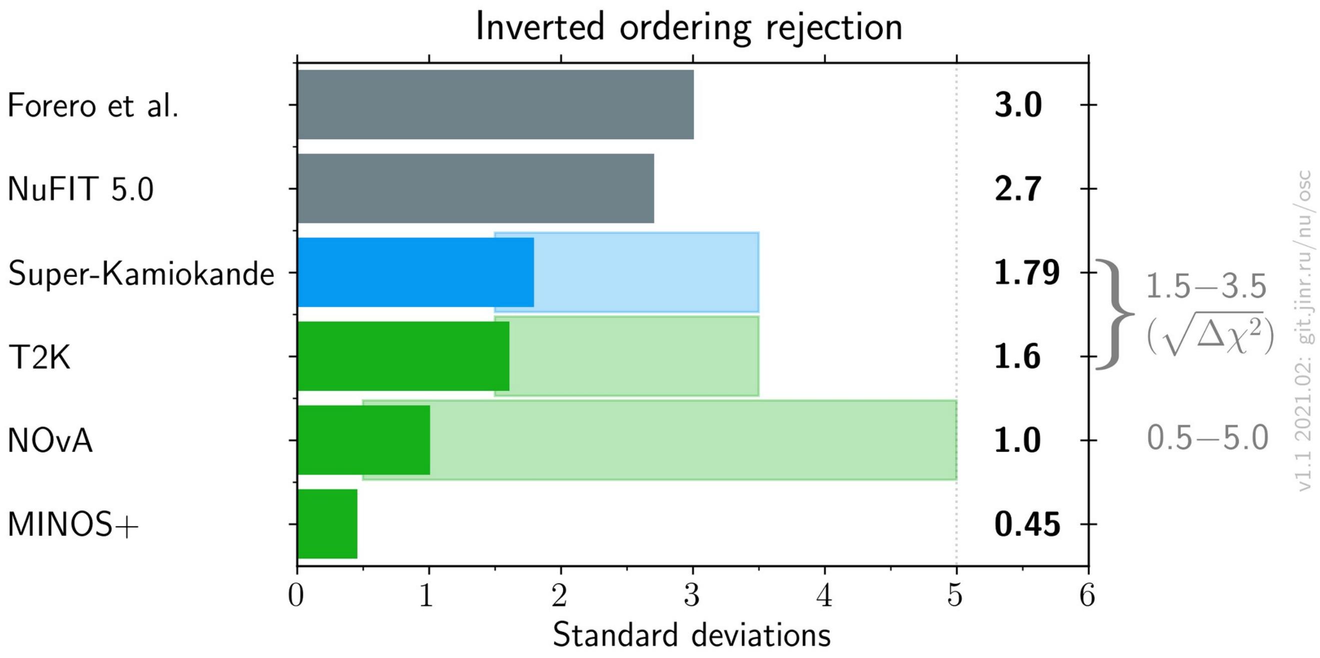
[P.F. de Salas et al, arXiv:1806.11051]

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}$$

$$P_{\alpha\to\beta} = |\langle\nu_\beta(L)|\nu_\alpha\rangle|^2 = \left|\sum_i U^*_{\alpha i}U_{\beta i}e^{-i\frac{m_i^2 L}{2E}}\right|^2$$

Neutrino Mass Ordering Status

Currently the normal mass ordering is slightly preferred: (as of Neutrino-2020)



Atmospheric and accelerator experiments rely on matter effects.

Their final sensitivities depend on (yet unknown) oscillation parameters.

Resolving 5σ sensitivity is not guaranteed.

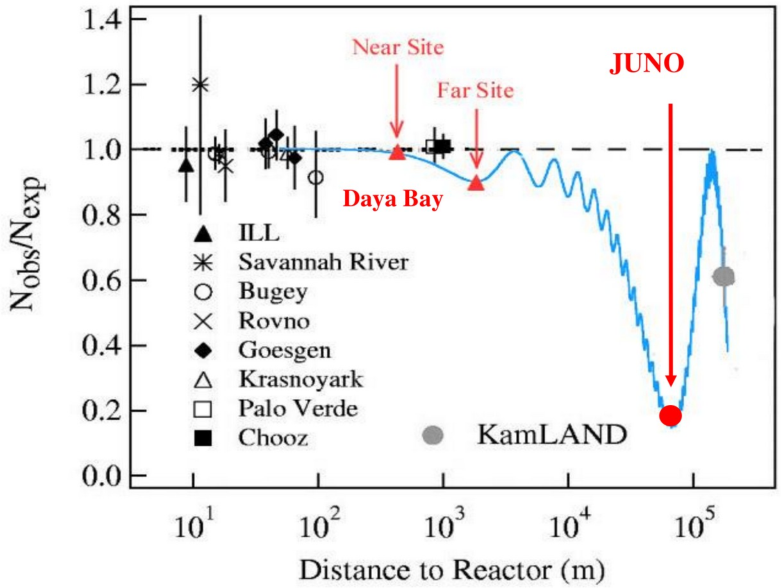
Additional experimental effort is crucial

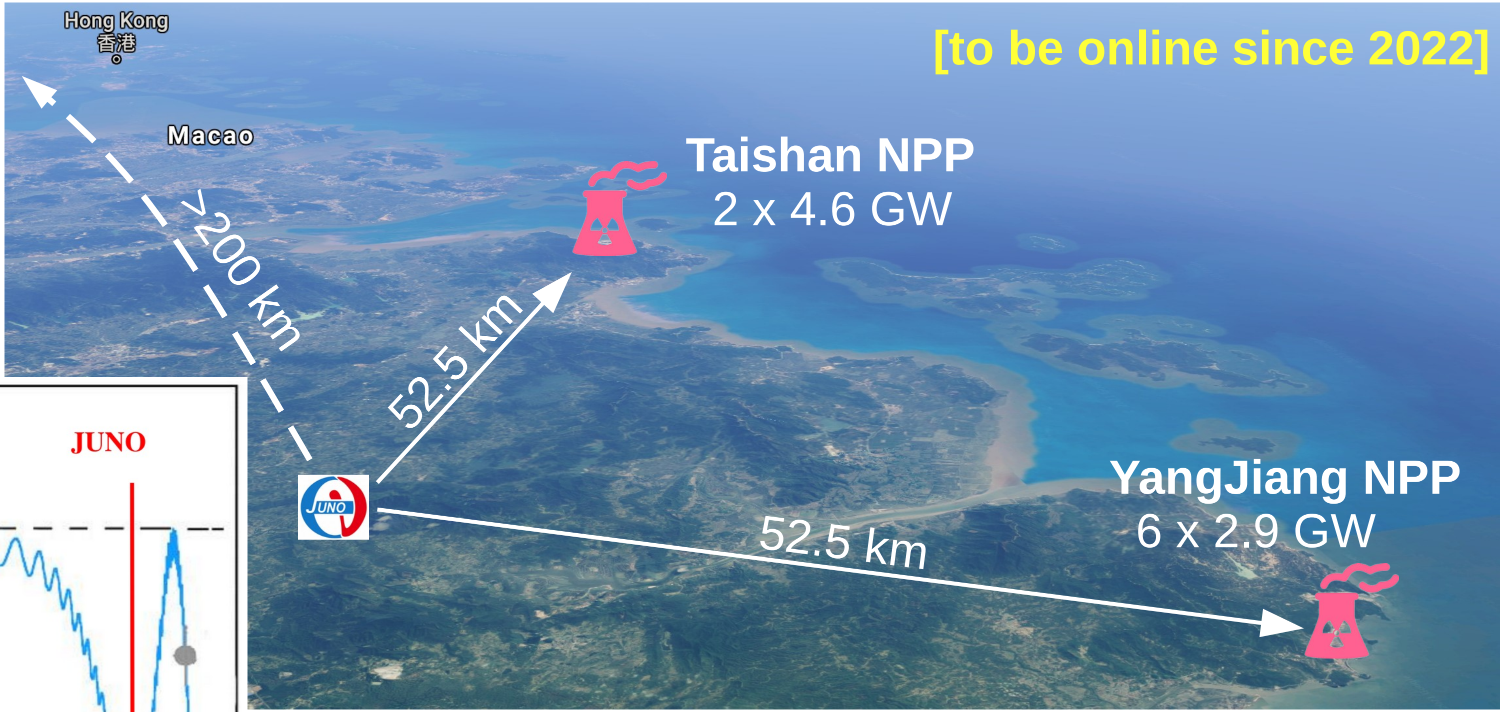
JUNO Experiment Layout

powerful source

+

optimized distance

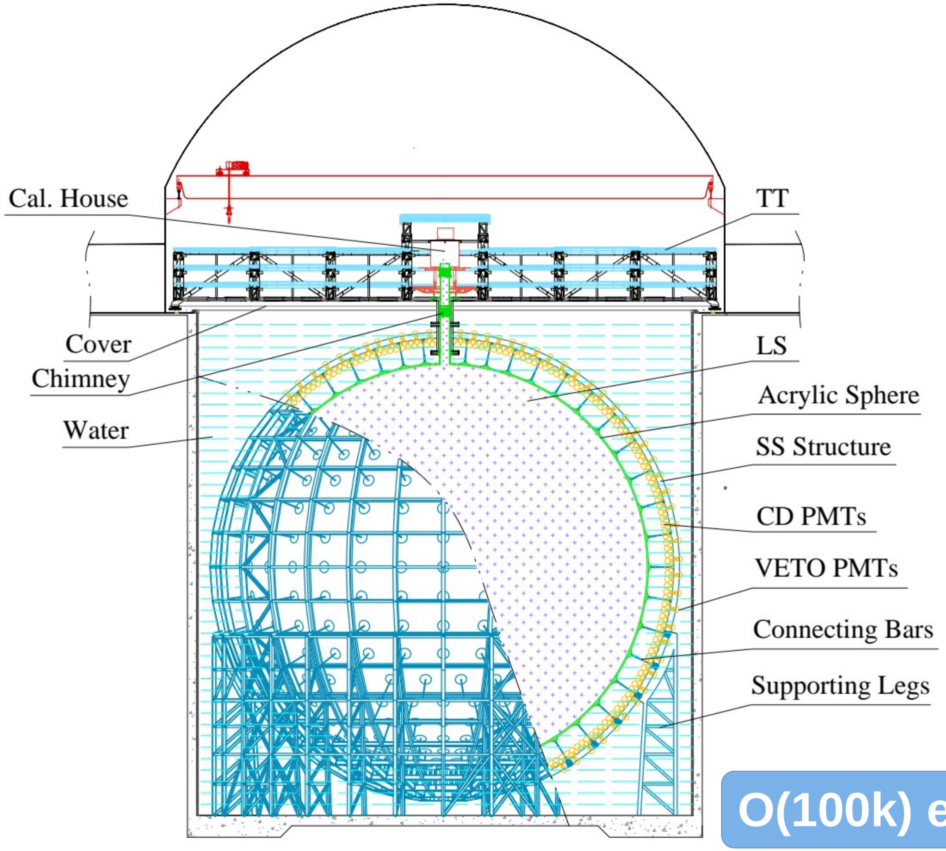




$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right) - \sin^2 2\theta_{13}\left[\cos^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \sin^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)\right]$$

JUNO Detector

See also talk by Hans T. D. Steiger:
"**JUNO Detector Design & Status**"



- **Source:** 8 reactor cores (2 NPPs)
  - Powerful and relatively well understood
- **Baseline:** 52.5 km
  - Optimized for resolving NMO
- **Overburden:** ~700 m
  - Cosmic background suppression
- **Detection channel:** $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Time coincident signal
  - Positron brings energy information
- **Target:** 20 kton of LAB-based liquid scintillator
  - Admixtures optimized for high light yield and transparency
  - ~1300 p.e. / MeV
- **Light detection:** 18000 20'' PMTs + 25600 3'' PMTs
  - >75% photo-coverage
  - two independent PMT systems

O(100k) events in 6 years

3% energy resolution @ 1 MeV

JUNO Spectrum Ingredients

- **Neutrino generated in reactor cores:**

  thousands of β-decays branches of fission reactions in reactor core (up to several MeV)

- **Observed via Inverse Beta-Decay (IBD):**

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

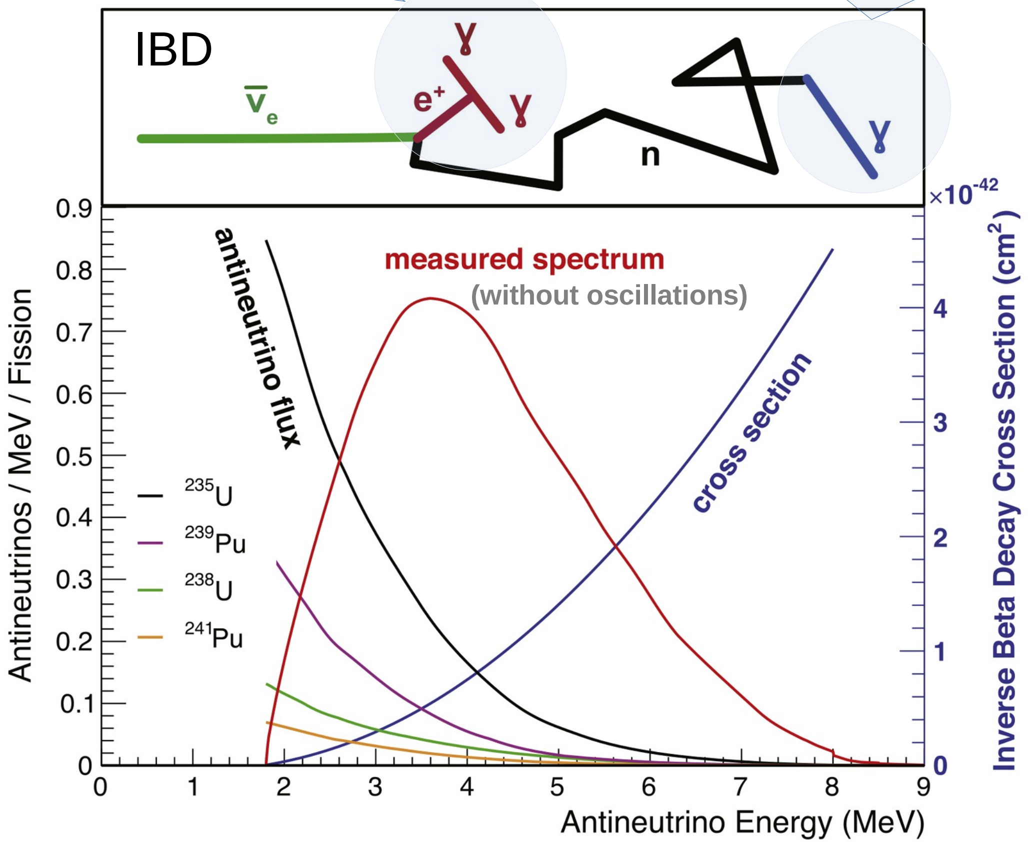
  (reaction threshold: 1.8 MeV)

- **Positron energy used to recover neutrino energy:**

$$E_\nu = E_{e^+} + \Delta m_{n-p} + T_n$$

handle for neutrino energy

IBD tag: 2.2 MeV within ~200 µs

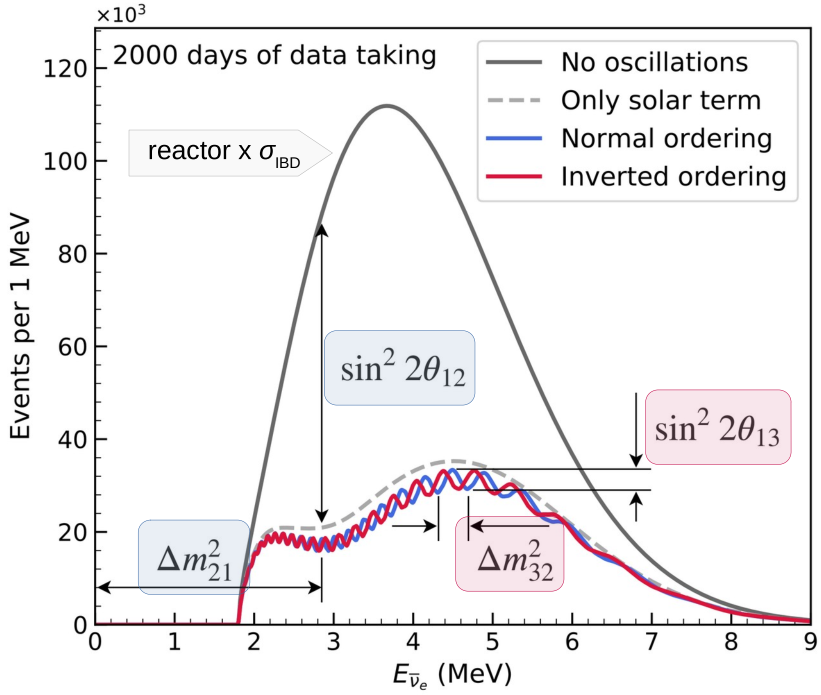


Information in JUNO Spectrum

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

+

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



Mass ordering:

$$\text{NO: } |\Delta m^2_{31}| = |\Delta m^2_{32}| + \Delta m^2_{21}$$

$$\text{IO: } |\Delta m^2_{31}| = |\Delta m^2_{32}| - \Delta m^2_{21}$$

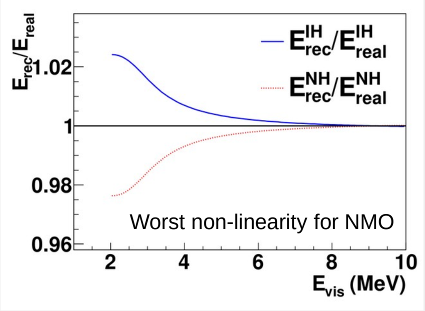
Results in a slight difference of the oscillation pattern, accessible for JUNO thanks to large θ_{13}!

Oscillation parameters:

Simultaneous sensitivity to amplitudes and frequencies of **‘solar’** and **‘atmospheric’** oscillation modes

Energy Scale in JUNO

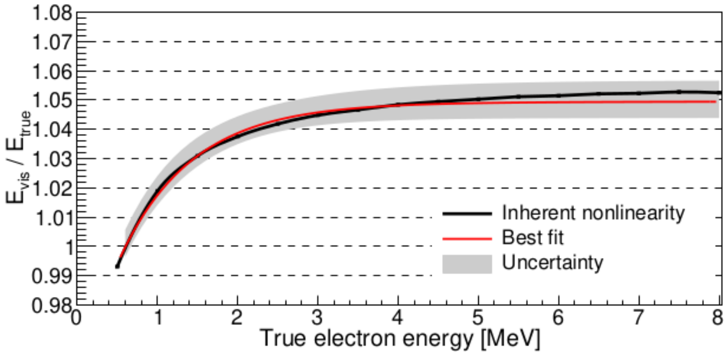
Unaccounted non-lineairity may mimic wrong NMO:



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, channel-wise response.

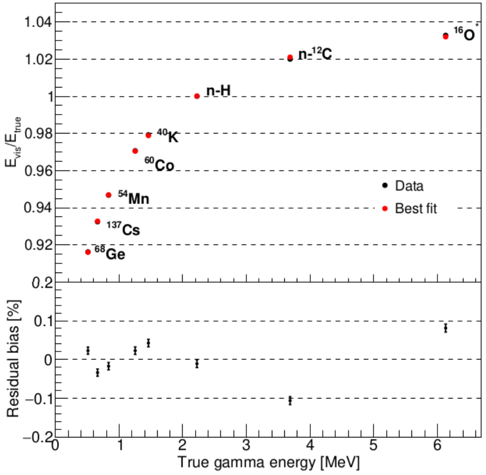
The dynamic range for 20'' PMT is about 2 orders of magnitude, so one has to be very careful – see talk by Yang Han about Dual Calorimetry (a novel approach to mitigate this kind of non-linearity).



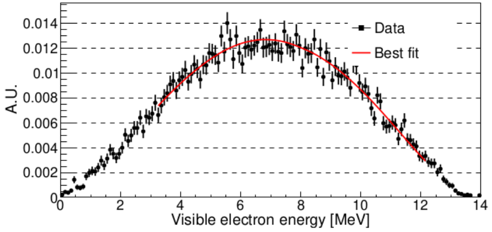
< 1% energy scale uncertainty

[see arXiv:2011.06405 for more details]

In JUNO the energy scale will be calibrated with multiple discreet sources as well as with ^{12}B spectrum:



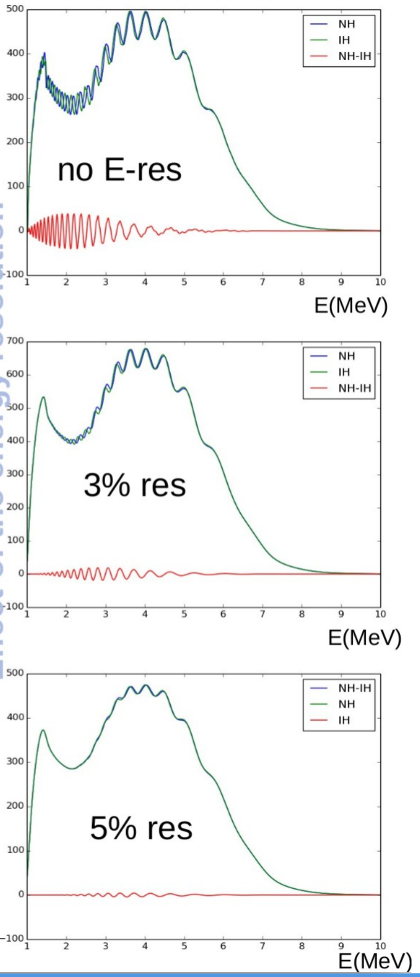
(a) Gamma non-linearity



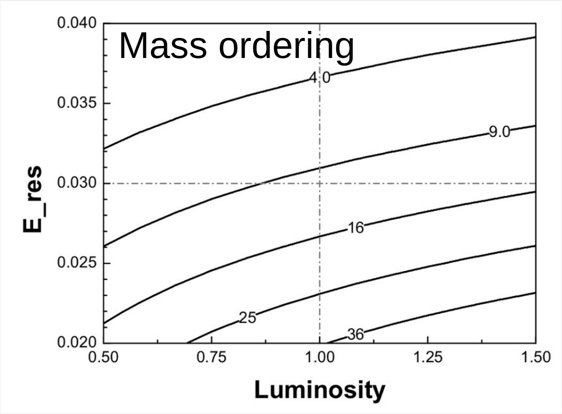
(b) Boron Spectrum

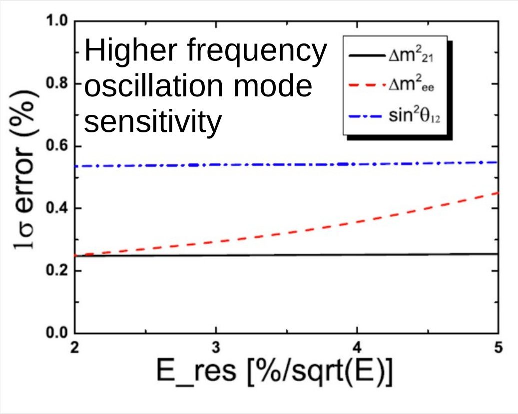
Energy Resolution in JUNO

Effect of the energy resolution



Crucial for sensitivity to:

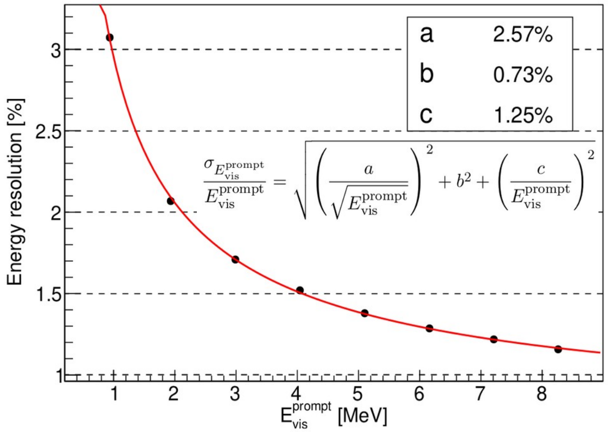




Mainly defined by:

- LS light yield (photon statistics)
- PMT detection efficiency
- Performance of energy reconstruction

The goal is 3% at 1 MeV



Mass Ordering Determination Prospects

- Independent on δ_{CP} and θ_{23}

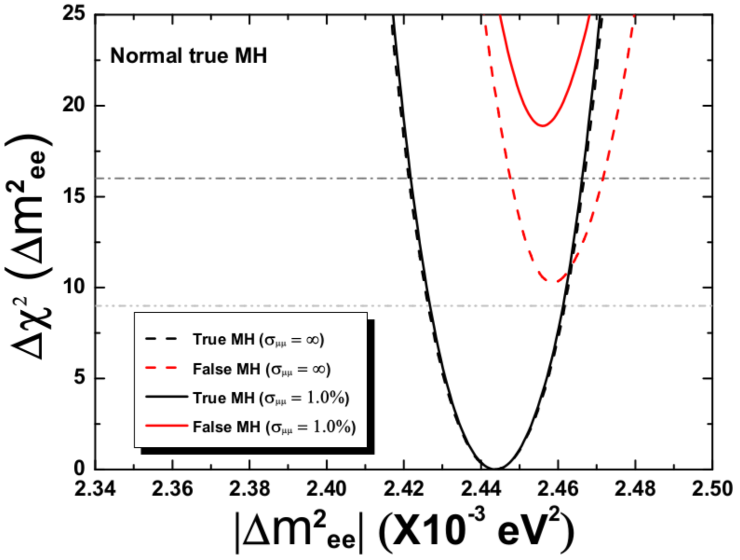
3σ sensitivity
in 6 years of data taking

- With $|\Delta m^2_{\mu\mu}|$ input JUNO sensitivity might be further improved:

> 4σ (in 6 years)
for 1% external uncertainty for $|\Delta m^2_{\mu\mu}|$

- Strong synergies with other experiments:
  - through Δm^2_{31} for atmospheric neutrinos (KM3NeT/ORCA and IceCube)
  - through Δm^2_{32} for accelerator neutrino (NOvA and T2K)

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



See talk on JUNO/ORCA combination by Chau Thien Nhan

Measurement of Oscillation Parameters

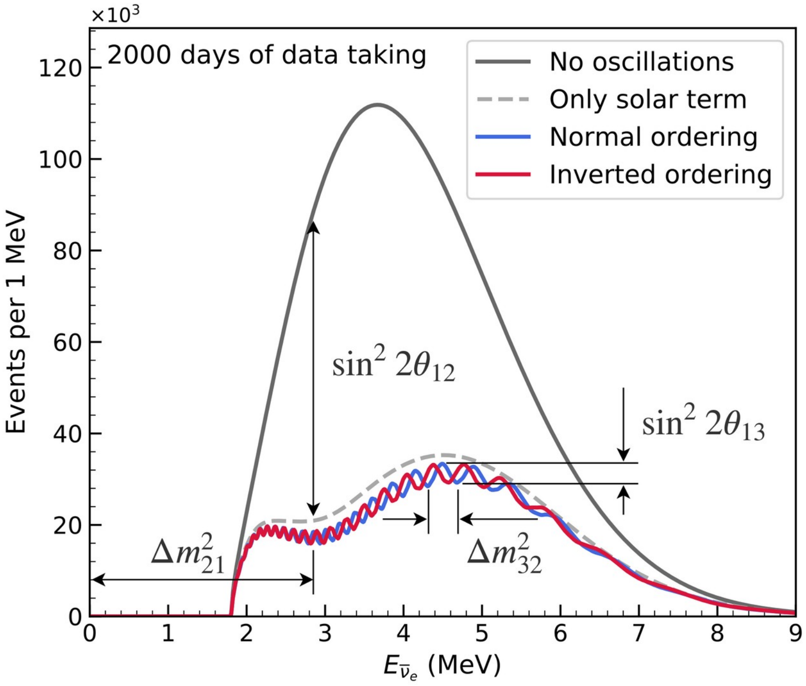
JUNO will be the first experiment to observe two modes of neutrino oscillations simultaneously:

‘solar’, driven by $\sin^2\theta_{12}$ and Δm^2_{21}

‘atmospheric’, driven by $\sin^2\theta_{13}$ and Δm^2_{31} (Δm^2_{32})

Main factors affecting sensitivity to oscillation parameters:

- reactor rate and shape uncertainty ← *TAO helps here!*
- backgrounds: mainly accidentals and geo-neutrino



(in %)	$\sin^2\theta_{12}$	Δm^2_{21}	$\sin^2\theta_{13}$	Δm^2_{31} / Δm^2_{32}
Current precision (NuFIT)	4.0	2.8	2.8	1.1
JUNO (6 years)	<0.6	<0.6	~10	<0.6

Solar ^{8}B Neutrinos

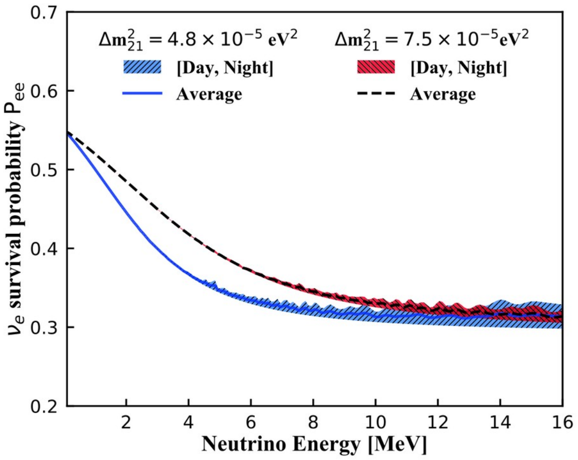
Another channel to measure solar oscillation parameters!

Oscillation media: Sun + Earth

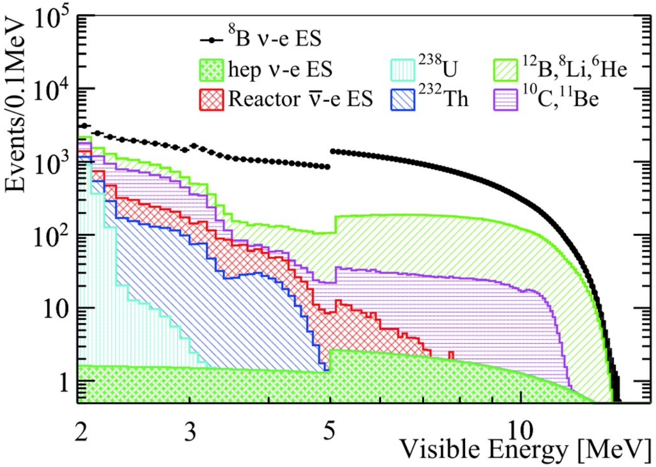
Detection channel: elastic scattering on electrons

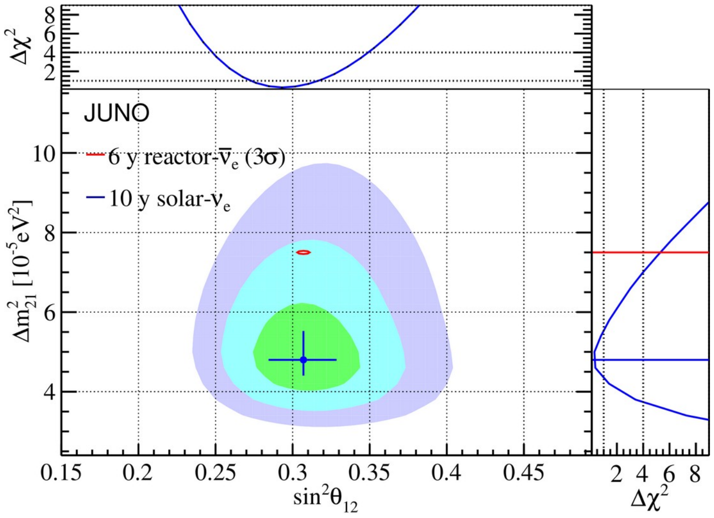
Energy threshold: 2 MeV

Signal / background: 60k / 30k (10 years)



10^{-17} g/g ^{238}U and ^{232}Th



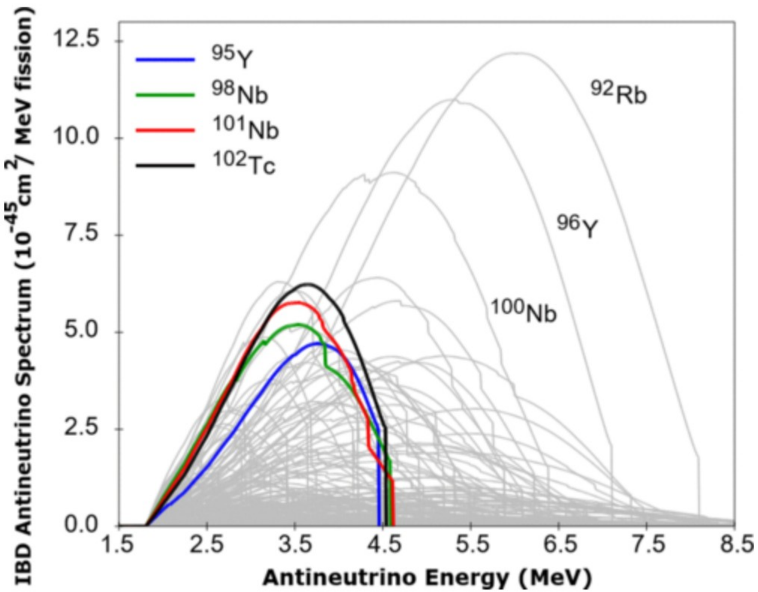


- 0.9% sensitivity to Day/Night asymmetry (1.1% in Super-K)
- Smaller Δm^2_{21} leads to a larger Day-Night asymmetry
- Δm^2_{21} measurement precision similar to the current global precision

Slight 1.4σ tension for Δm^2_{21} between KamLAND ($7.5\cdot10^{-5}$ eV^2) and SNO+SK ($6.1\cdot10^{-5}$ eV^2)

Reactor Anti-Neutrino Spectrum Fine Structure

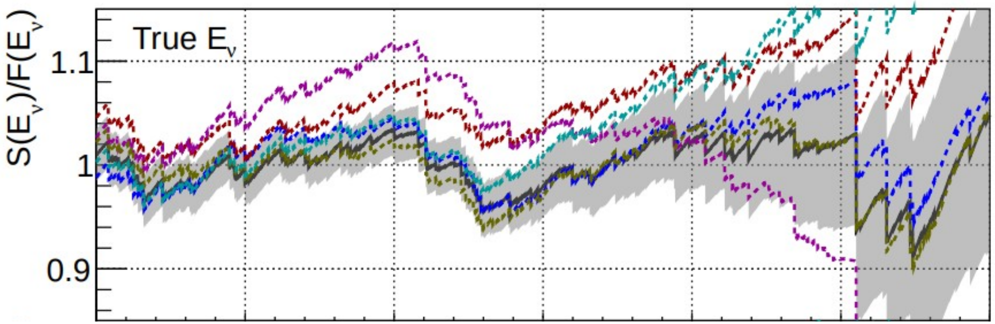
Reactor $\bar{\nu}_e$ spectrum is composed of thousands of β-decay branches and might have fine structures.



[Sonzogni et al, PhysRevC 98 014323]

State-of-the-art knowledge does not provide data beyond its energy resolution:

- 5-8% @ 1 MeV in Daya Bay, Double Chooz and RENO
- Huber-Mueller model uses about 30 virtual β-spectra without detailed structure



[Dwyer and Lingford, Phys.Rev.Lett. 114]

An unknown fine structure might mimic wrong ordering oscillation pattern
➔ harmful for JUNO mass ordering measurement!

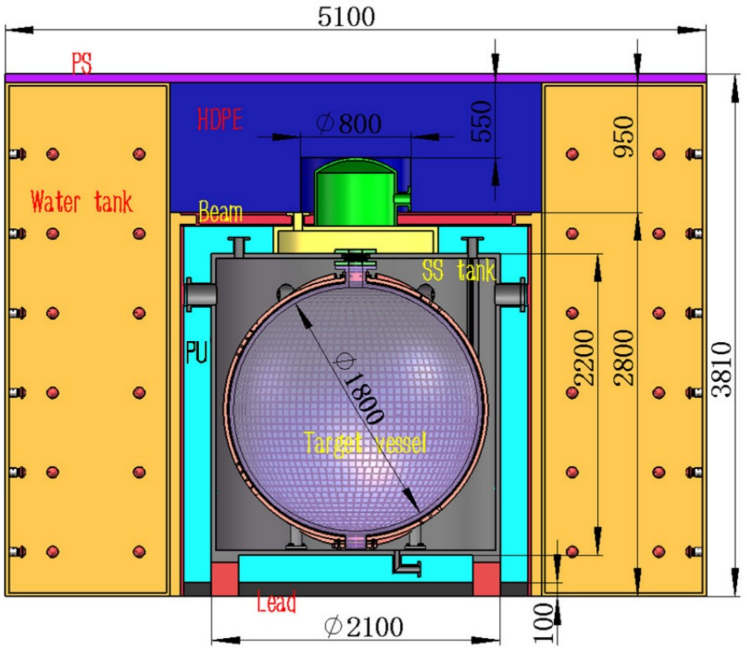
TAO (Taishan Antineutrino Observatory)

An innovative apparatus:

- 1 ton fiducial volume / 2.6 tons of Gd-LS
- Almost full coverage with SiPM (~50% PDE @ -50°C)

30 x JUNO statistics

~2% at 1 MeV energy resolution



Measurement of reactor $\bar{\nu}_e$ spectrum at 30 m distance from a Taishan NPP core (almost no oscillations):

- ➔ Provide model-independent reference for JUNO
- ➔ Improvement of nuclear databases

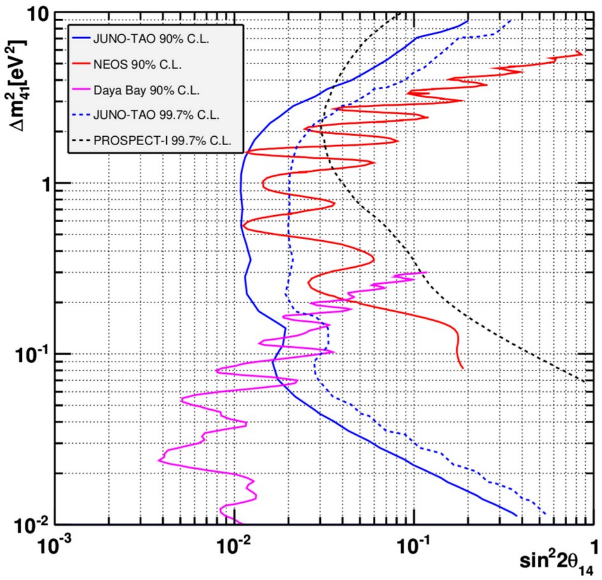
Planned to be online in 2022

TAO Light Sterile Neutrino

Motivation – observed tensions with 3-flavor paradigm:

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

Sterile neutrino could explain these anomalies



Setup:

baseline: ~30 m

detection efficiency: 50%

3 years of data taking (~1.8M events)

5% bin-to-bin uncertainty in 50 keV bins

TAO will provide new constraints in 0.1–3 eV² Δ*m*² region

Summary

Neutrino Mass Ordering

- Observing reactor neutrino at 52.5 km distance JUNO will see an oscillation pattern of two oscillation modes
- The higher frequency pattern will bring information on NMO: **3σ sensitivity in 6 years**
- Independent from matter effects and complementary to other experiments
- Strong synergy with atmospheric and long-baseline experiments: **5σ+ sensitivity**

Oscillation Parameters

- Significant precision improvement for $\sin^2\theta_{12}$, Δm^2_{21} and $\Delta m^2_{31(32)}$ – at sub-percent level
- Estimate of $\sin^2\theta_{12}$, Δm^2_{21} from solar neutrino
  – different channel
  – comparable with current precision

TAO

- Measurement of reactor spectrum fine structure – a proxy for JUNO and valuable data for future experiments
- Improved constrain on sterile neutrino in 0.1-3 eV² Δm^2 region

Thank you for your attention!

See also: Donglian Xu “JUNO” on 25/02/2021
and other talks