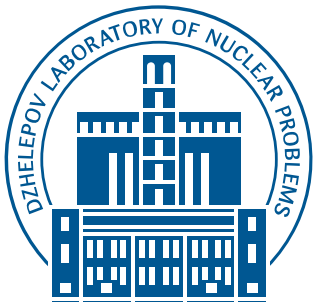


# JUNO's Sensitivity to Neutrino Mass Ordering

**Dmitrii Dolzhikov**



December 17, 2024

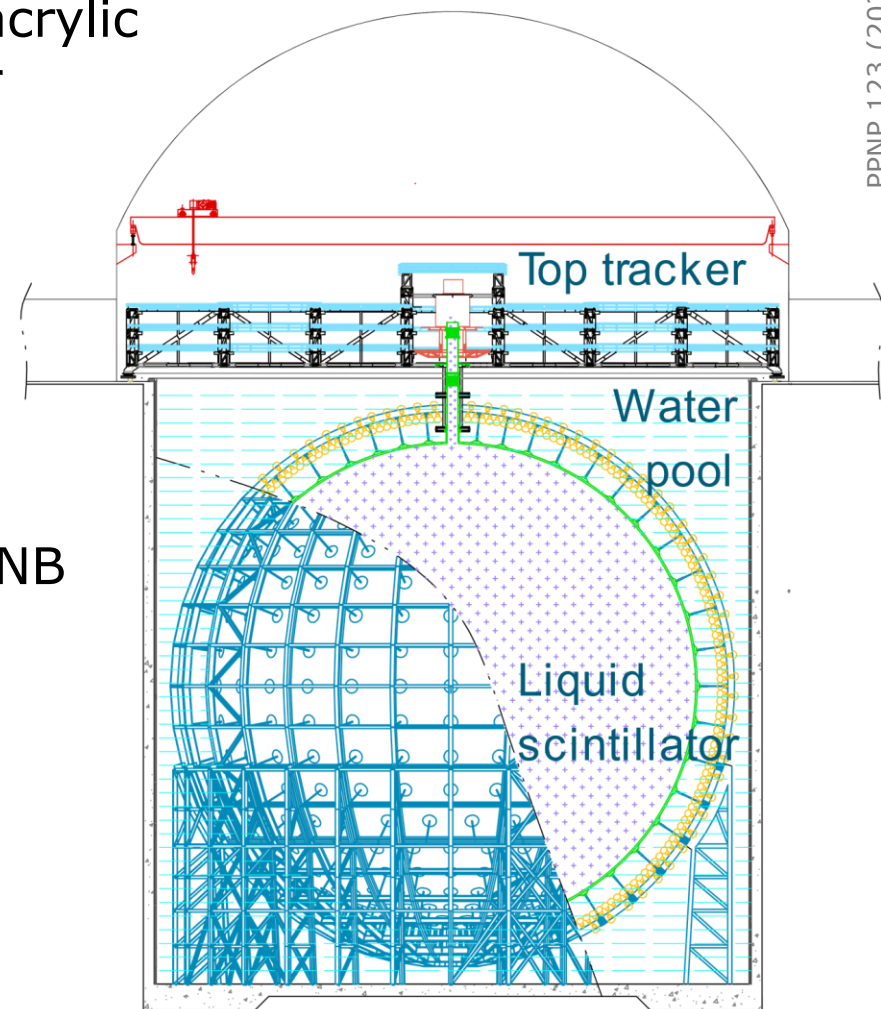


# JUNO and $\nu$ oscillations

# JUNO experiment

The **J**iangmen **U**nderground **N**eutrino **O**bservatory (**JUNO**) is a multi-purpose neutrino experiment under construction in South of China

- ❖ 20 kton of Liquid Scintillator (LS) inside a 35 m diameter acrylic sphere surrounded by a 35 kton water Cherenkov detector
- ❖ 52.5 km from 8 nuclear reactors (26.6  $\text{GW}_{\text{th}}$ )
- ❖ Energy resolution  $\sigma < 3\%$  at 1 MeV
- ❖ Energy scale uncertainty  $< 1\%$
- ❖ Rich physics program: reactor, solar, geo-, supernova, DSNB neutrinos and more



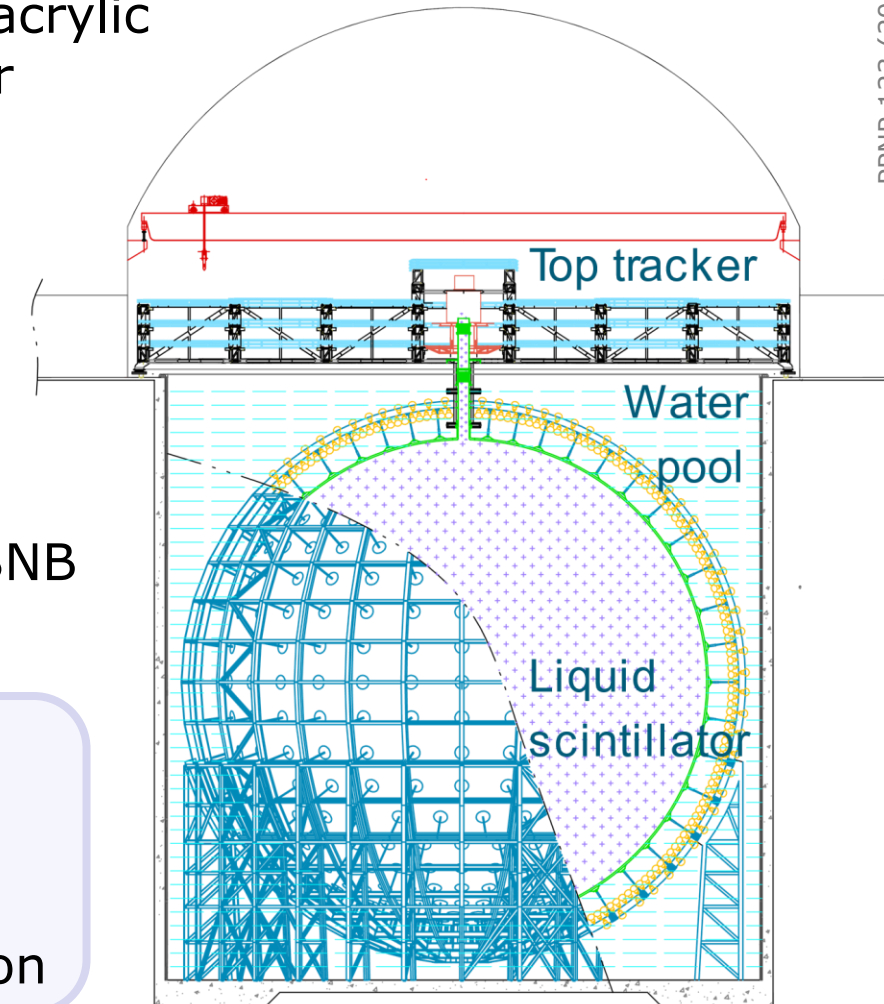
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Main physics goals with reactor antineutrinos:

- ❖ **Determine Neutrino Mass Ordering (NMO)**
- ❖ Measure oscillation parameters  $\sin^2 \theta_{12}$ ,  $\Delta m_{21}^2$ , and  $\Delta m_{31}^2$  with sub-percent precision



# Status of neutrino oscillation physics

What we know ([PDG 2024](#)):

- ✓  $\Delta m_{21}^2 \sim 7.5 \times 10^{-5} \text{ eV}^2$  ( $\pm 2.4\%$ )
- ✓  $|\Delta m_{31}^2| \sim 2.5 \times 10^{-3} \text{ eV}^2$  ( $\pm 1.1\%$ )
- ✓  $\sin^2 \theta_{12} \sim 0.3$  ( $\pm 4.2\%$ )
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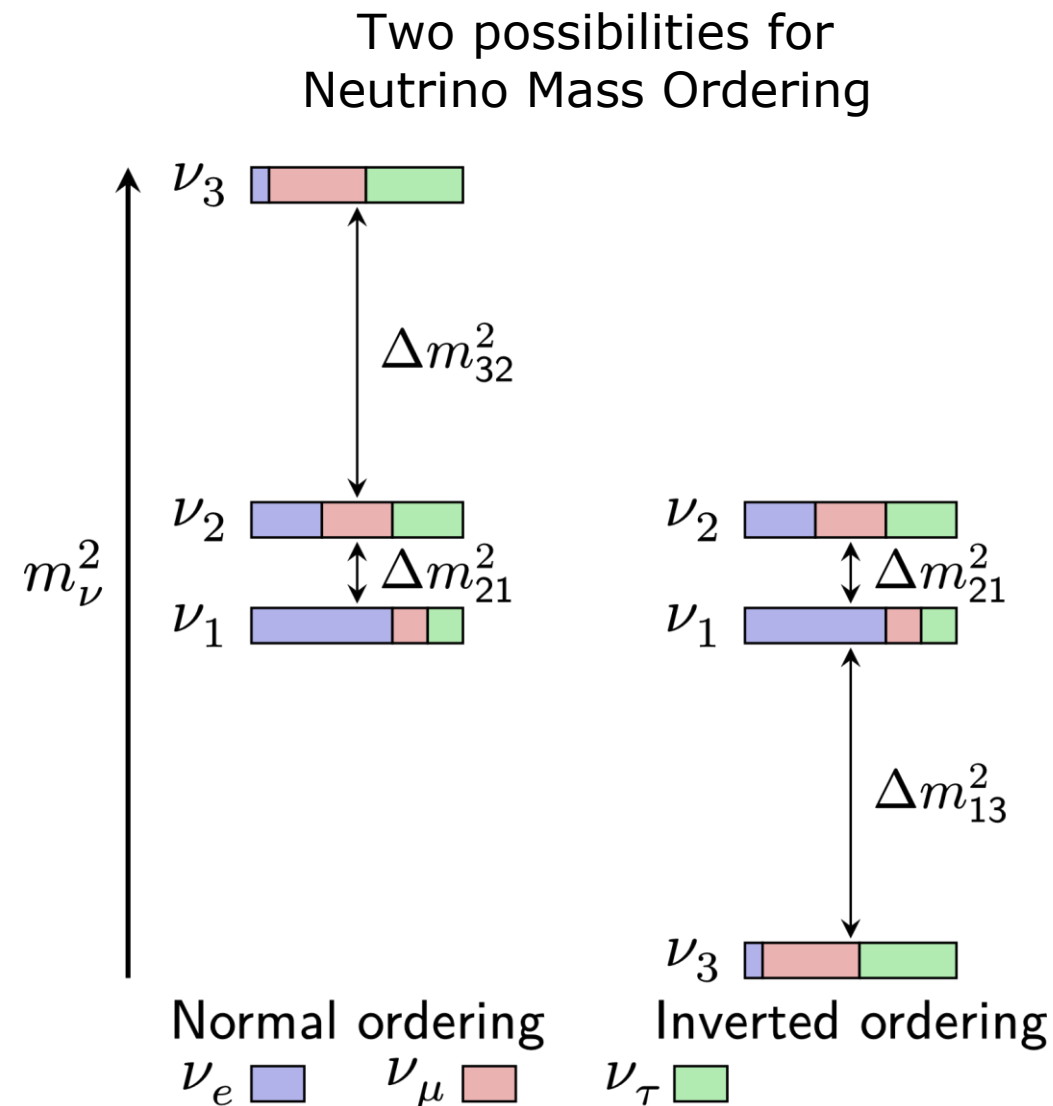
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Open questions:

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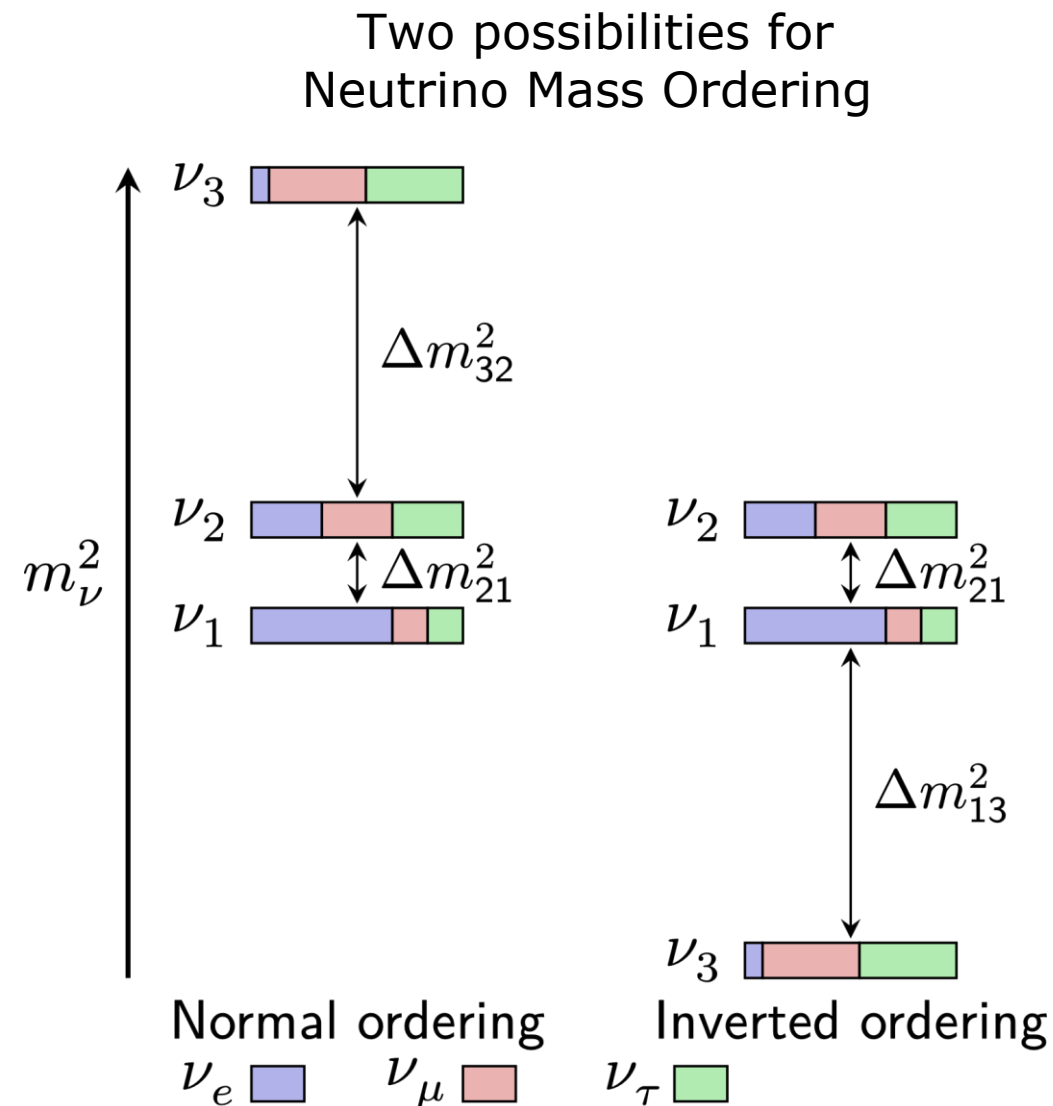
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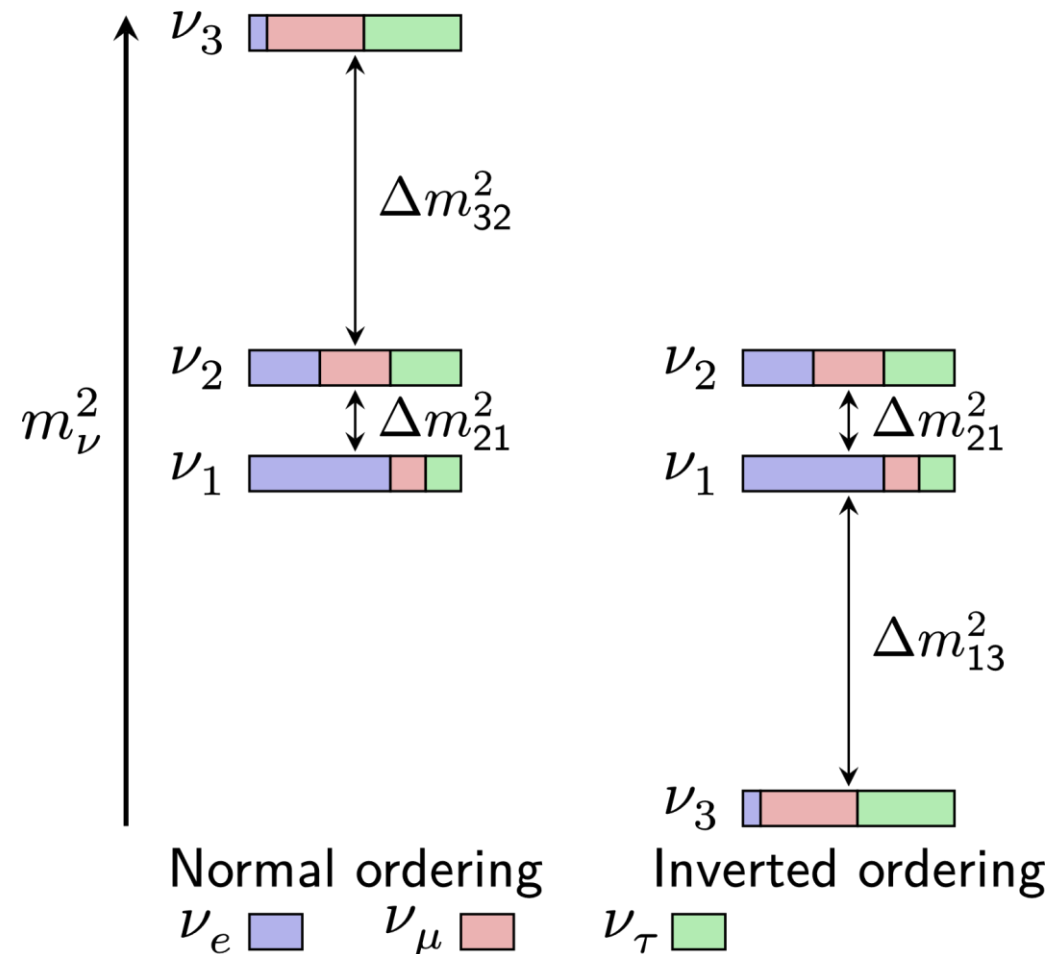
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JUNO will both contribute to precise measurements of oscillation parameters and answer the NMO question

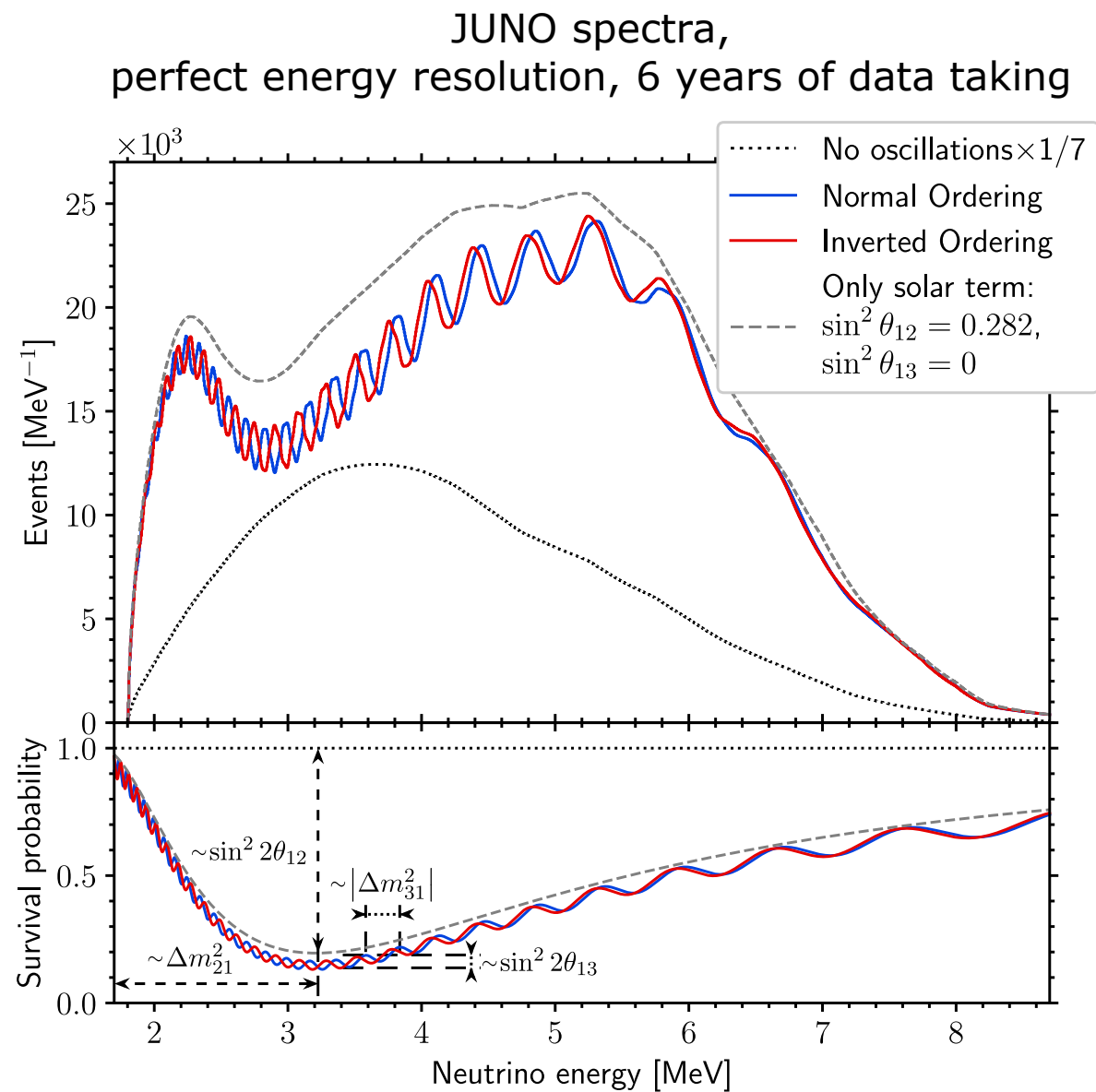
Two possibilities for Neutrino Mass Ordering





# $\bar{\nu}_e$ oscillations in JUNO

- ❖ JUNO studies fine interference pattern caused by quasi-vacuum oscillations in the oscillated antineutrino spectrum
- ❖ Interference pattern depends on NMO
- ❖ To resolve peaks → **need good energy resolution**
- ❖ To define peak positions → **need well defined energy scale**
- ❖ Complementary to other neutrino oscillation experiments (accelerator and atmospheric)

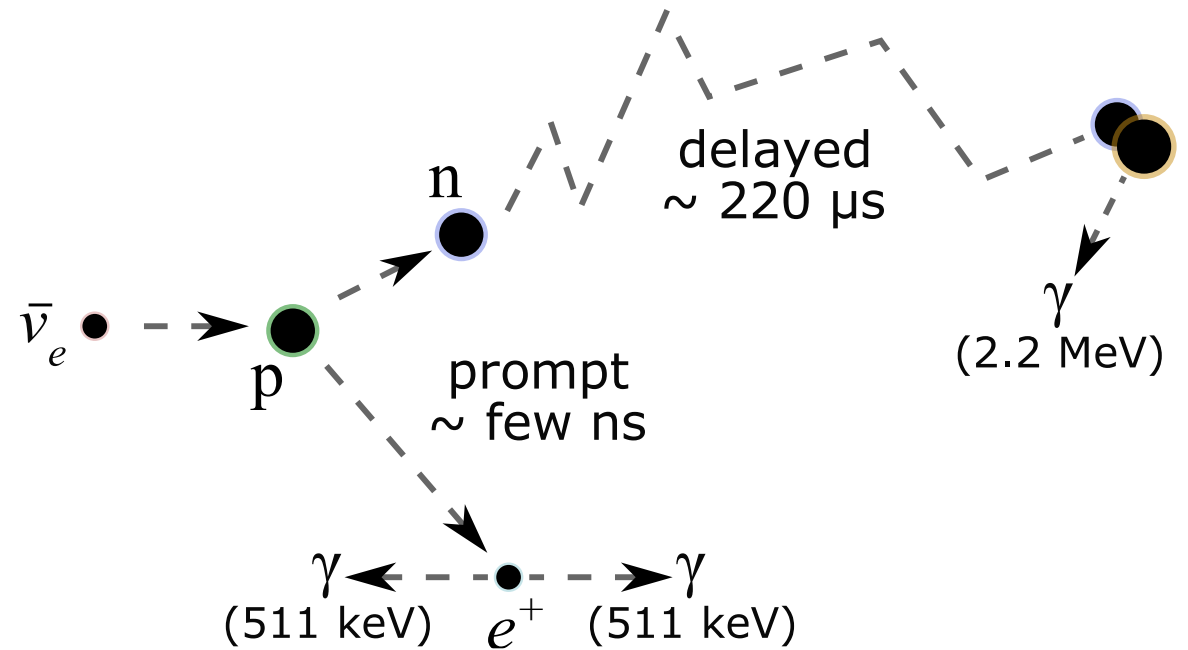


# Antineutrino detection in JUNO

- ❖ Inverse Beta Decay (IBD) reaction is used for  $\bar{\nu}_e$  detection:

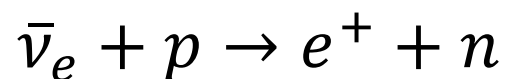


- ❖  $\bar{\nu}_e$  transfers most of its energy to the positron

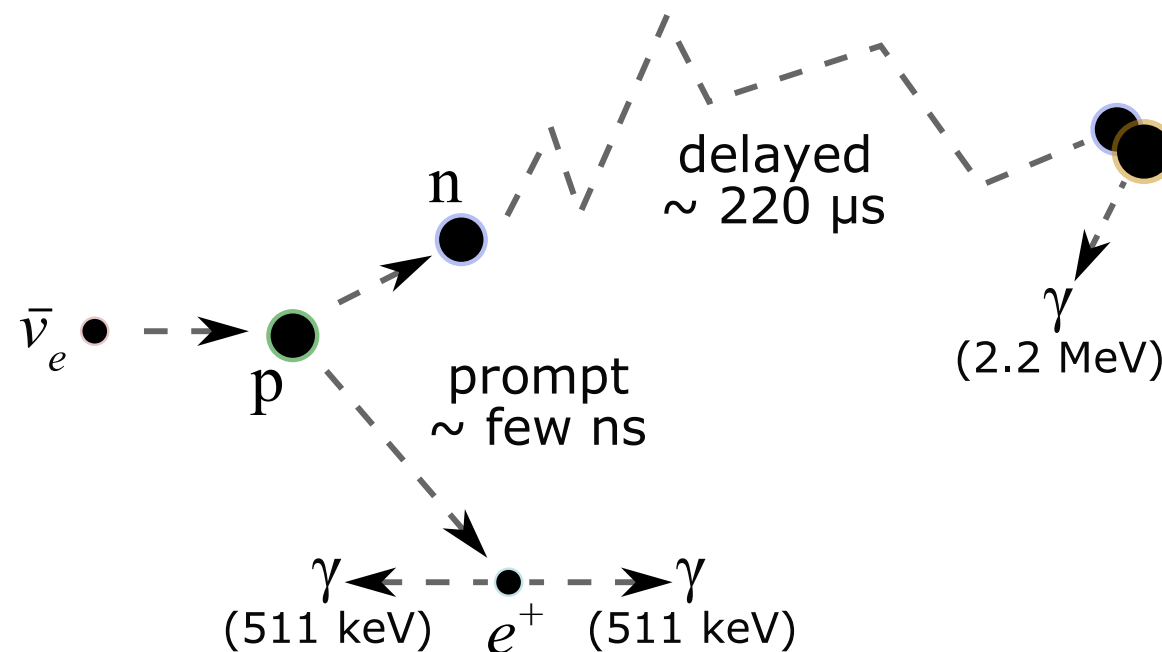


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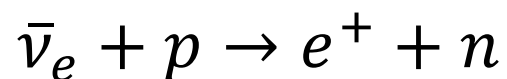


- ❖  $\bar{\nu}_e$  transfers most of its energy to the positron
- ❖ **Prompt signal:** energy deposited by positron in the LS (kinetic + annihilation),
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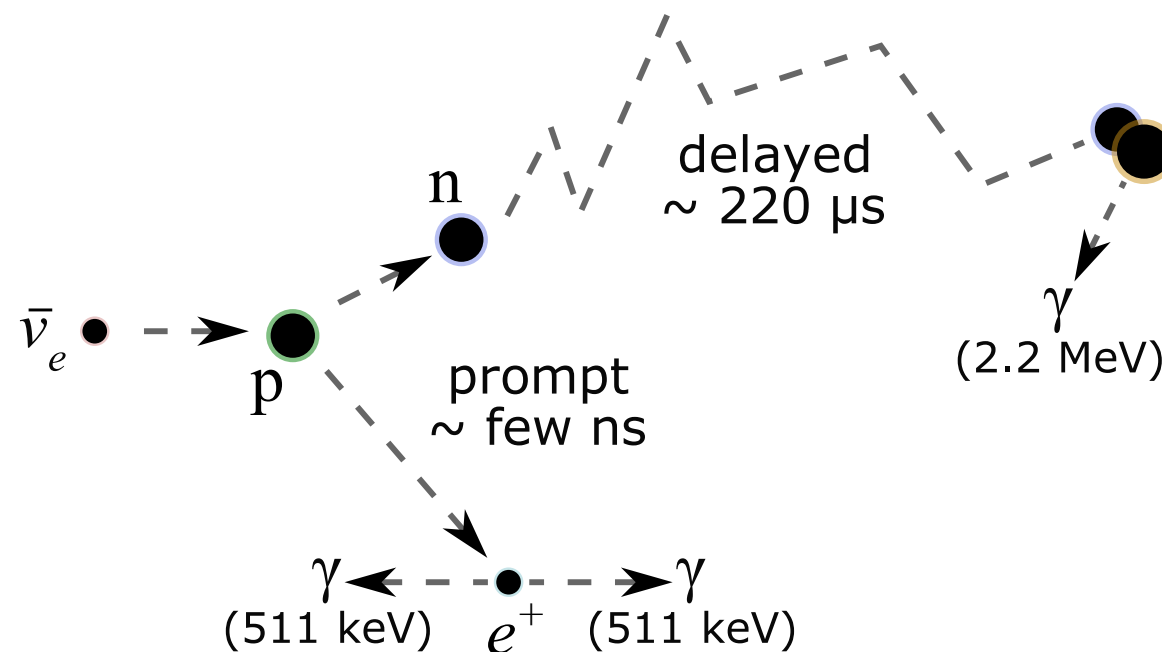


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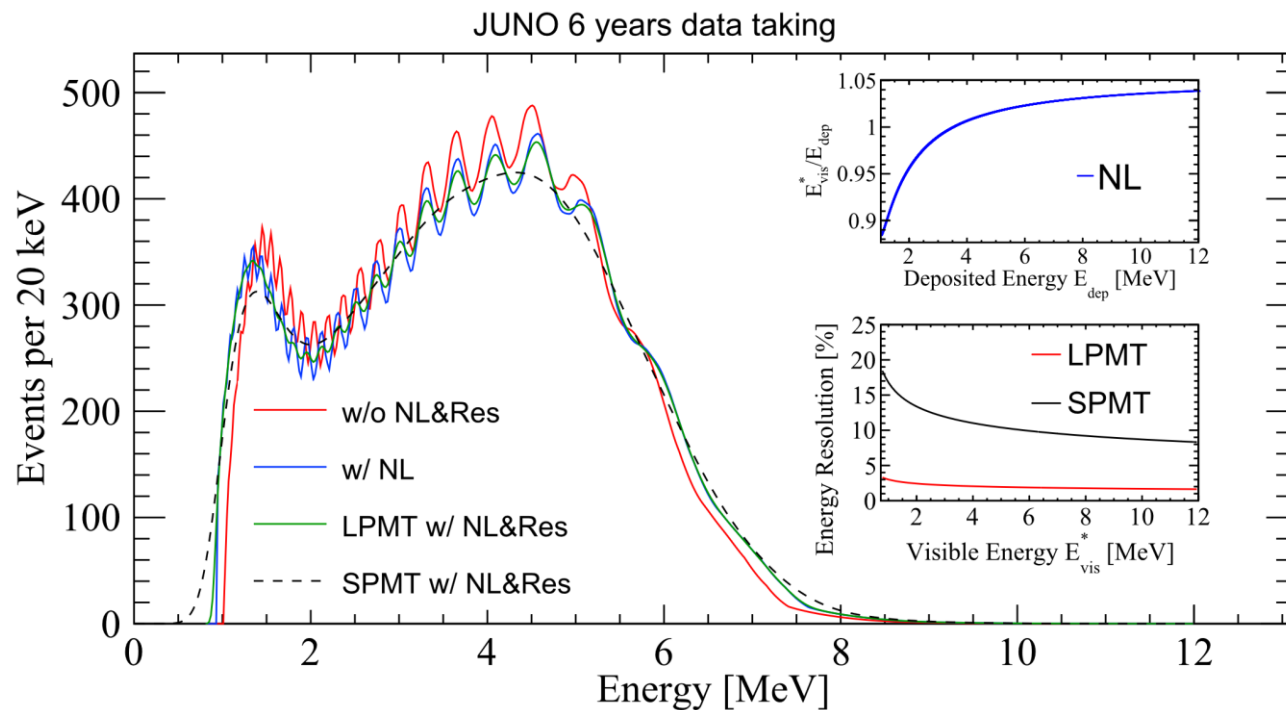
Energy signature, temporal and spatial correlation of prompt-delayed pairs allows effective separation of the signal from the background

# JUNO's detector response

Approximate energy conversion model

$$E_{\nu} \rightarrow E_{\text{dep}} \rightarrow E_{\text{vis}} \rightarrow E_{\text{rec}}$$

Antineutrino energy    Deposited energy    Visible energy    Reconstructed energy



1. IBD reaction kinematics and annihilation  $\rightarrow e^+$  deposited energy:

$$E_{\text{dep}} \simeq E_{\bar{\nu}_e} - 0.782 \text{ MeV}$$

2. Quenching, Cherenkov radiation  $\rightarrow$  Liquid Scintillator **Non-Linearity** (NL):

$$E_{\text{vis}} = f_{\text{LSNL}}(E_{\text{dep}}) \cdot E_{\text{dep}}$$

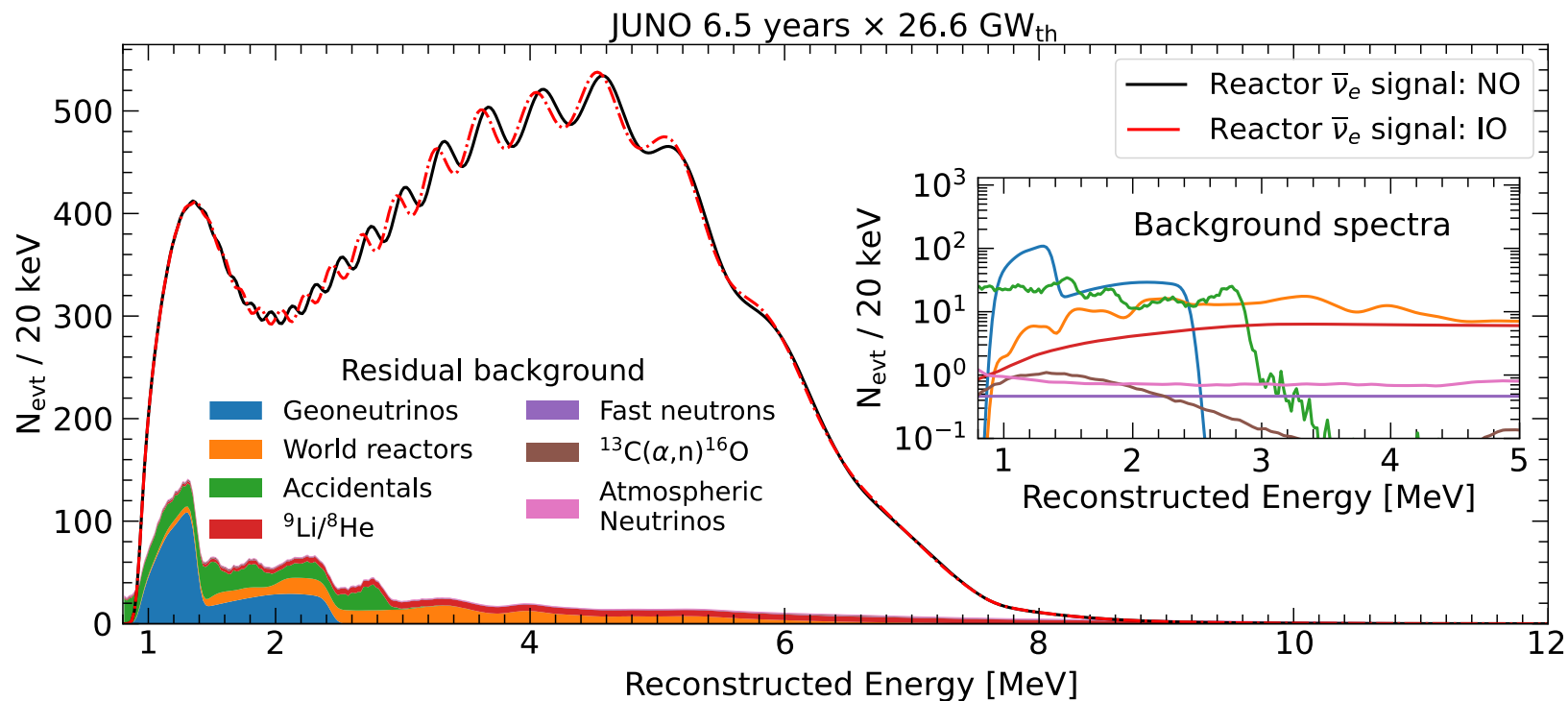
3. Smearing due to **Energy Resolution** (Res):

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

# JUNO's expected signal and backgrounds

- ❖ IBD selection efficiency: 82.2%
- Cuts: fiducial volume, energy, time, and relative distance
- Cosmogenic background rejection: muon veto

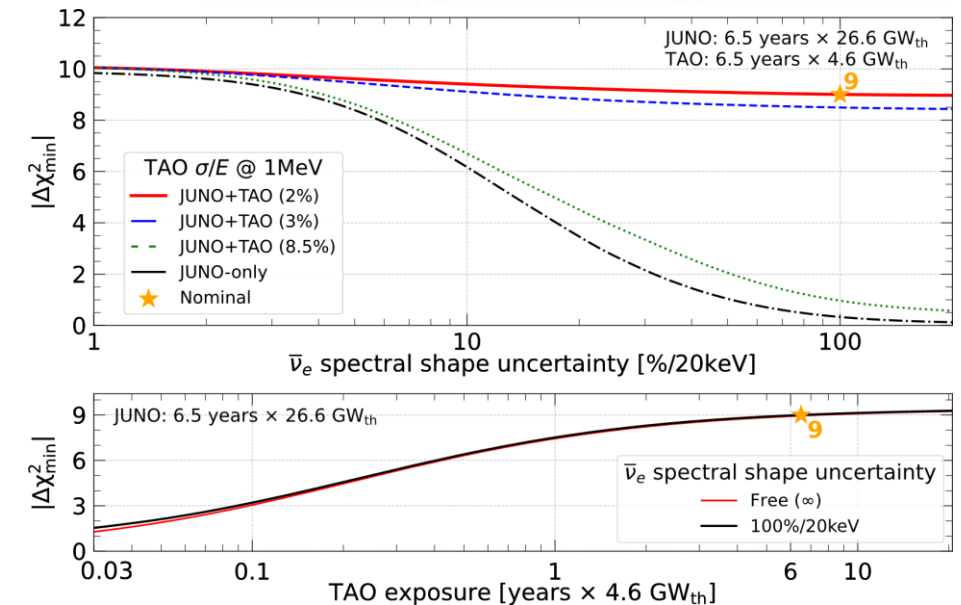
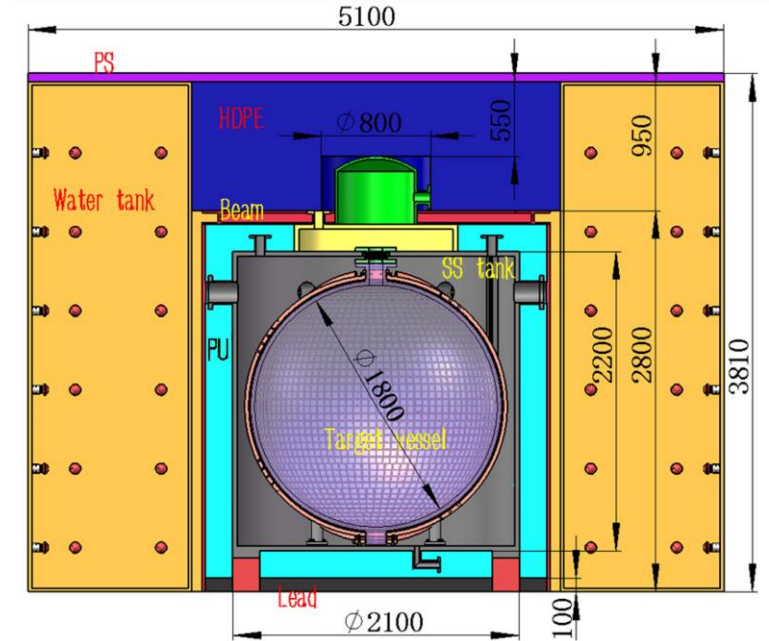
- ❖ Expected IBD rate: 47.1/day
- ❖ Expected Background rate: 4.11/day
- ❖ High signal to background ratio



# JUNO-TAO reference spectrum

Taishan Antineutrino Observatory (TAO) satellite detector:

- ❖ 44 m from one of the Taishan NPP cores (4.6 GW<sub>th</sub>)
- ❖ 2.8 ton of Gd-doped Liquid Scintillator
- ❖ SiPM and GD-LS at -50°C
- ❖ Energy resolution  $\sigma < 2\%$  at 1 MeV



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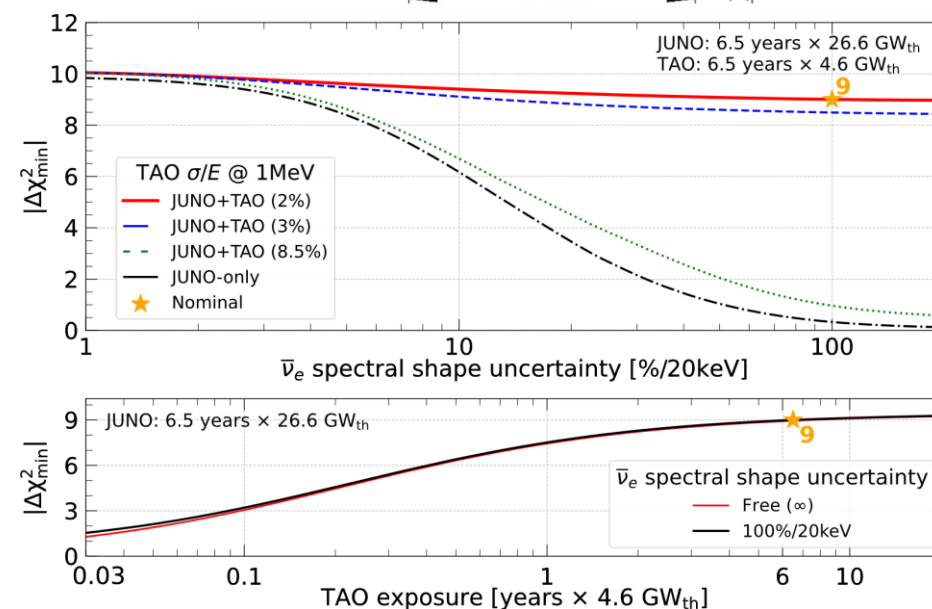
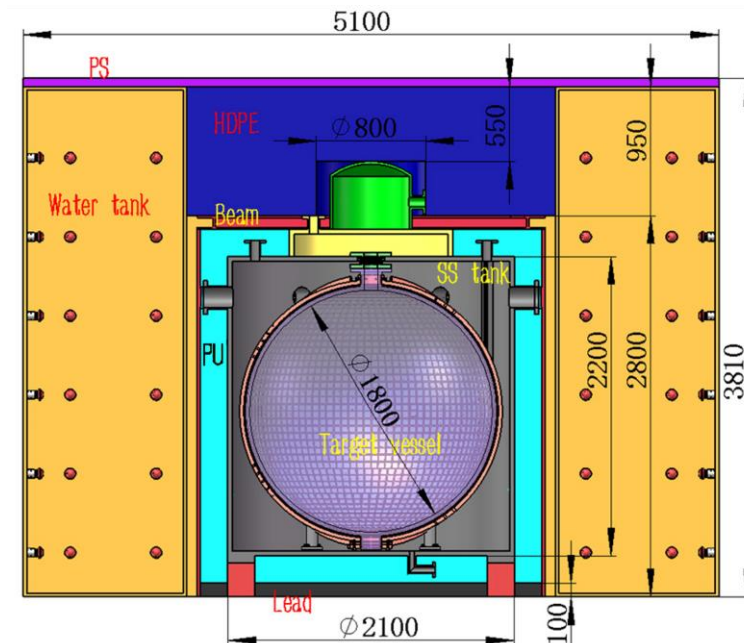
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**Main goals:** provide reference antineutrino spectrum for JUNO

**Why:** to eliminate antineutrino model dependence in the determination of NMO

**How:** by simultaneously analyzing JUNO and TAO spectra





# Sensitivity to NMO

Median sensitivity to NMO is based on Asimov dataset:  $\Delta\chi_{\min}^2 = \min \chi_{\text{IO}}^2 - \min \chi_{\text{NO}}^2$

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model

data

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$\sin^2 \theta_{13}$

uncor. nuisance parameters

cor. nuisance parameters

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model

data

free parameters

$\sin^2 \theta_{13}$

$\sin^2 \theta_{13}$  nuisance part

syst. bin-to-bin uncertainties

uncor. nuisance parameters

uncor. parameters nuisance part

stat. uncertainties

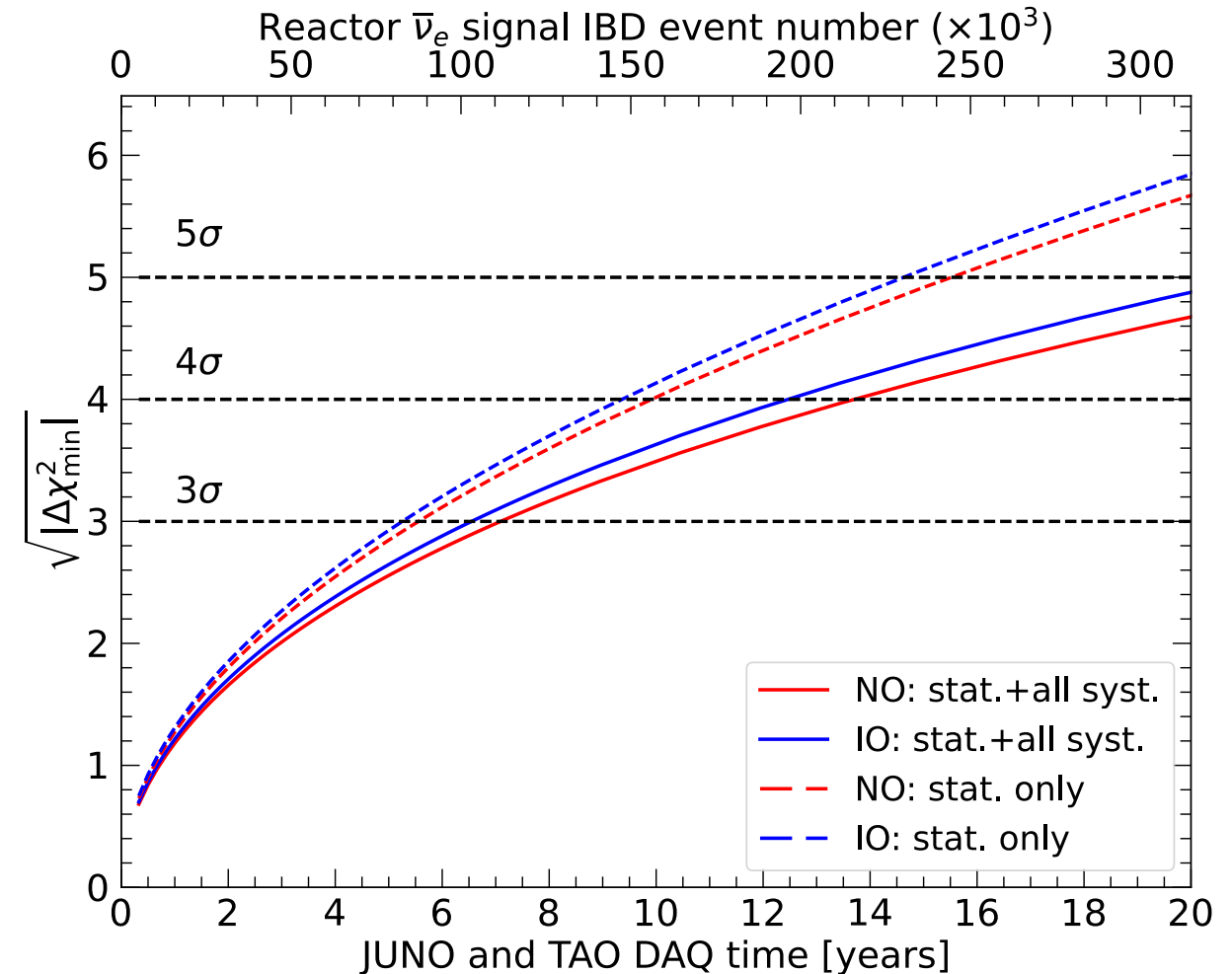
cor. nuisance parameters

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# Sensitivity to Neutrino Mass Ordering

## ❖ $3\sigma$ median sensitivity to NMO after 7.1 years of data taking

- using only reactor  $\bar{\nu}_e$
- assuming 11/12 duty cycle
- 6.5 years  $\times$  26.6 GW<sub>th</sub> exposure
- Asimov results are consistent with the ones from Monte-Carlo study



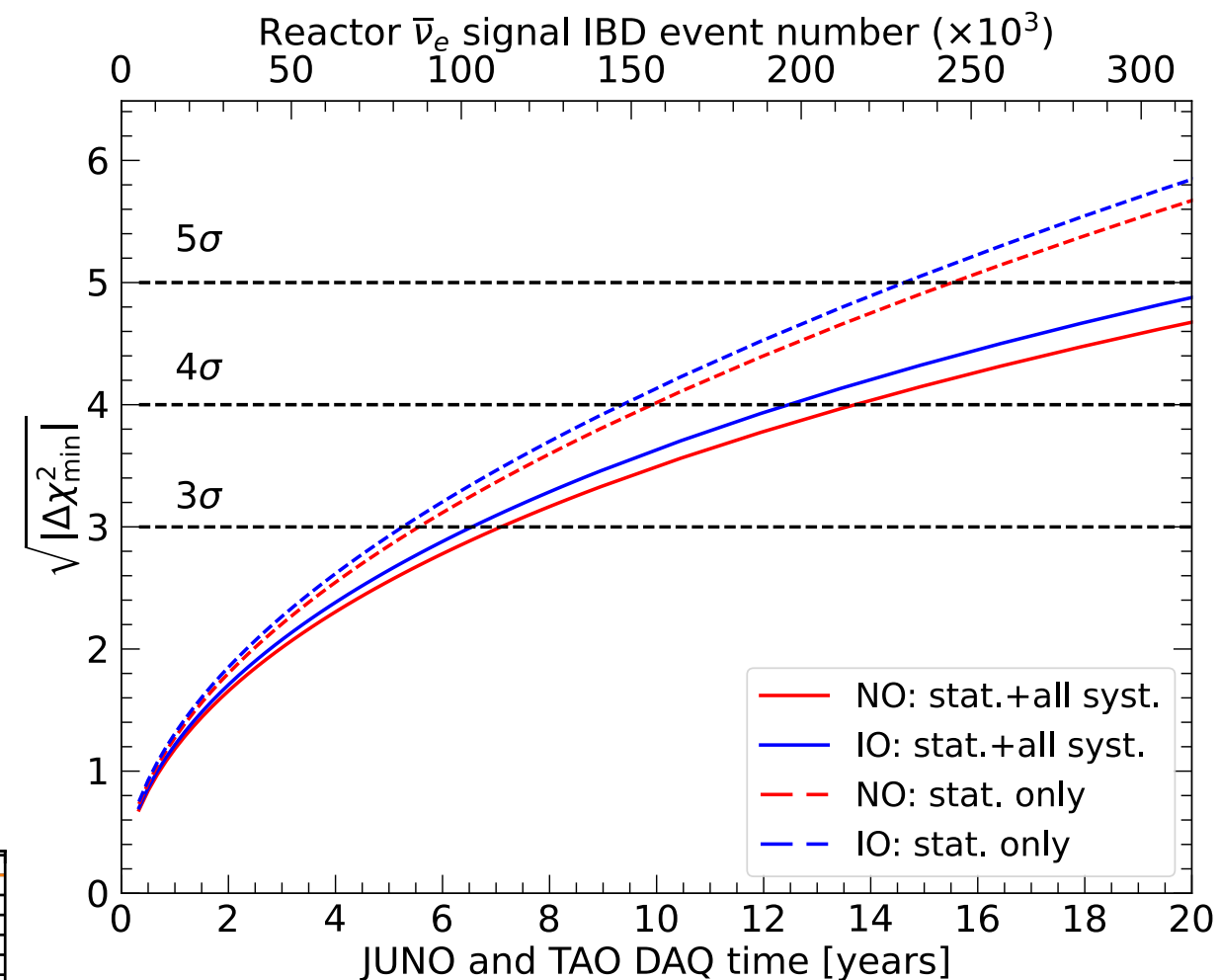
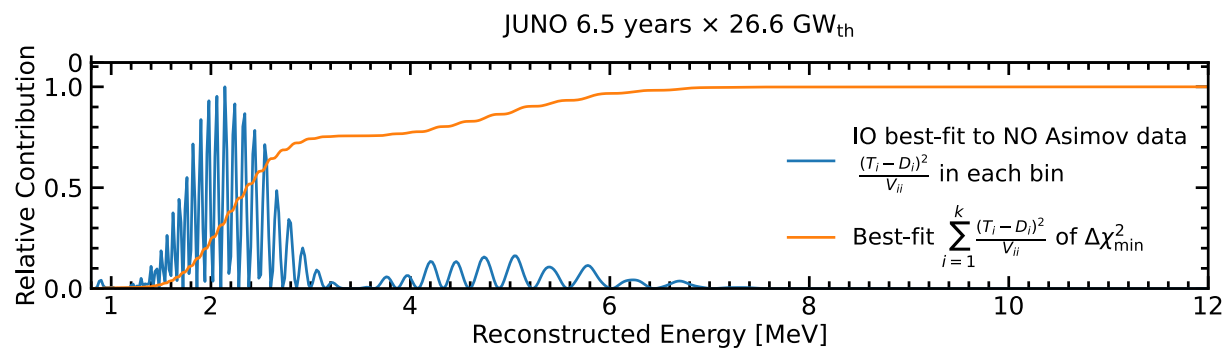


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## ❖ Most sensitive energy region: 1.5-3 MeV:



# Systematic uncertainties

## ❖ JUNO and TAO common uncertainties:

- Reactors information
- Liquid Scintillator non-linearity parameters

## ❖ JUNO only uncertainties:

- Oscillation parameter  $\sin^2 2\theta_{13}$
- Reference antineutrino spectrum
- Detector normalization
- Background rate and shapes
- Energy resolution
- Matter density (MSW effect)

## ❖ TAO only uncertainties:

- Background rate and shapes
- Energy scale
- Fiducial volume

## Relative impact on the NMO sensitivity:

Uncertainties	$ \Delta\chi_{\min}^2 $	$ \Delta\chi_{\min}^2 $ change
Statistics of JUNO and TAO	11.5	
+ Common uncertainty	10.8	-0.7
+ TAO uncertainty	10.2	-0.6
+ JUNO geoneutrinos	9.7	-0.5
+ JUNO world reactors	9.4	-0.3
+ JUNO accidental	9.2	-0.2
+ JUNO ${}^9\text{Li}/{}^8\text{He}$	9.1	-0.1
+ JUNO other backgrounds	9.0	-0.05
Total	9.0	

Dominant sources of uncertainty:  
backgrounds, reference spectrum, non-linearity

# Conclusion

- ❖ JUNO will have rich physics program that includes reactor, solar, geo-, supernova, DSNB neutrinos and more
- ❖ Using only reactor  $\bar{\nu}_e$  oscillations, JUNO:
  - Will achieve sub-percent precision on  $\Delta m_{31}^2$ ,  $\Delta m_{21}^2$ , and  $\sin^2\theta_{12}$  during first two years of data taking
  - Will determine the **Neutrino Mass Ordering with a median sensitivity of  $3\sigma$**  after about 7 years of data taking
- ❖ Start of the JUNO filling is planned for December 2024



- ❖ Автор является членом коллаборации JUNO с 2020 г. и принимает активное участие в исследованиях, связанных с осцилляциями реакторных антинейтрино
- ❖ Доложенные результаты основаны на статье:  
JUNO collaboration, "Potential to Identify the Neutrino Mass Ordering with Reactor Antineutrinos in JUNO". В: (май 2024). [arXiv: 2405.18008 \[hep-ex\]](https://arxiv.org/abs/2405.18008) (принята к публикации в Chinese Physics C.)
- ❖ Автор принимал непосредственное участие в анализе по оценке чувствительности эксперимента JUNO к упорядоченности масс нейтрино:
  1. Совместно с научным руководителем Гончаром М.О. разрабатывал модель эксперимента JUNO в ПО GNA
  2. Получал промежуточные и финальных результаты анализа, а также участвовал в их обсуждении и перекрестных проверках в рамках внутренних совещаний коллаборации
  3. Проводил анализ по оценке значимости точного измерения спектра антинейтрино от реакторов экспериментом TAO для определения упорядоченности масс нейтрино в эксперименте JUNO
  4. Представлял результаты проделанной работы на конференциях:
    - 43rd International Symposium on Physics in Collision (PIC 2024) – *JUNO's Physics with Reactor Antineutrinos* – Athens, Greece – NCSR "Demokritos" – 2024 – устный доклад
    - AYSS-2024 – *JUNO's Sensitivity to Neutrino Mass Ordering* – Dubna, Russia – JINR. – 2024. – устный доклад
    - XXXI International Conference on Neutrino Physics and Astrophysics (Neutrino 2024) – *JUNO's Sensitivity to Neutrino Mass Ordering* – Milan, Italy – University of Milano-Bicocca, University of Milano, INFN – 2024. – стендовый доклад

# Backup Slides

# Neutrino mixing

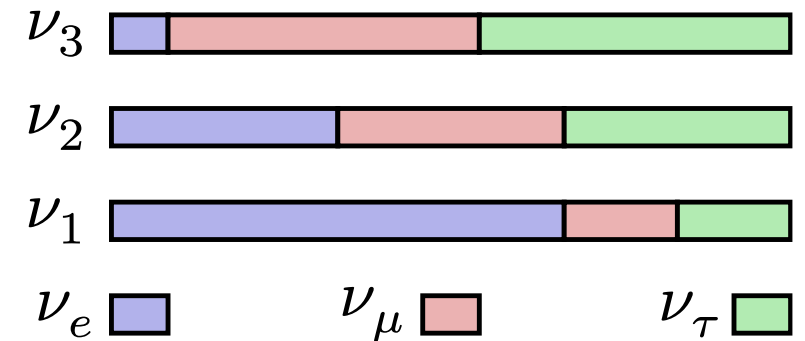
Weak ( $e, \mu, \tau$ ) and mass (1,2,3) eigenstates differ:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{ij} \equiv \cos \theta_{ij}, s_{ij} \equiv \sin \theta_{ij}$

Mixing is parametrized by:

- ❖ Three mixing angles:  $\theta_{12}, \theta_{23}, \theta_{13}$
- ❖ CP-violating phase:  $\delta_{\text{CP}}$



Three neutrino mass splittings ( $\Delta m_{ij}^2 = m_i^2 - m_j^2$ ):

- ❖ Involved in oscillation probability calculations
- ❖ Only two independent:  $\Delta m_{21}^2, |\Delta m_{31}^2|$  (or equivalently  $|\Delta m_{32}^2|$ )

# Reactor $\bar{\nu}_e$ oscillations

❖ JUNO will observe deficit of  $\bar{\nu}_e$  due to oscillation

❖  $\bar{\nu}_e$  survival probability:

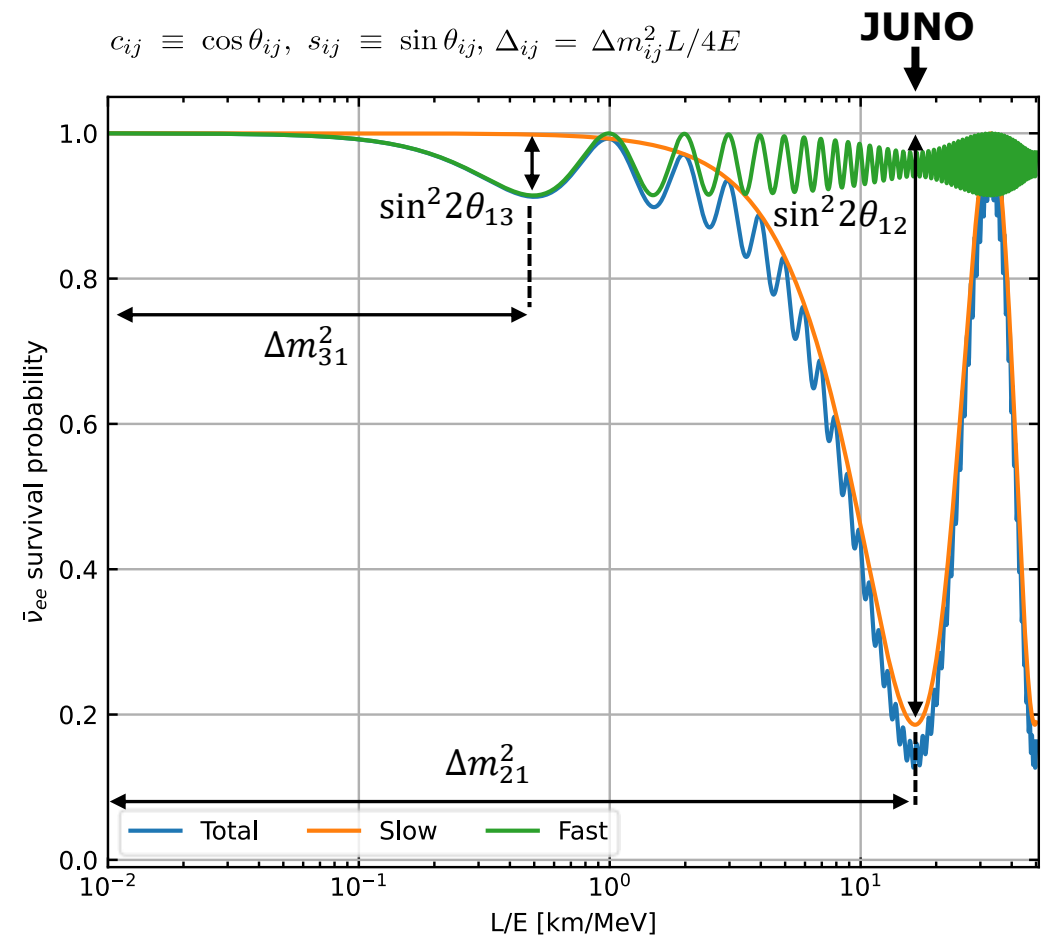
$$\mathcal{P}(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \boxed{\sin^2 2\theta_{12} c_{13}^4 \sin^2 \Delta_{21}} \quad \text{SLOW}$$

$$- \boxed{\sin^2 2\theta_{13} c_{12}^2 \sin^2 \Delta_{31}} \quad \text{FAST}$$

$$- \boxed{\sin^2 2\theta_{13} s_{12}^2 \sin^2 \Delta_{32}}$$

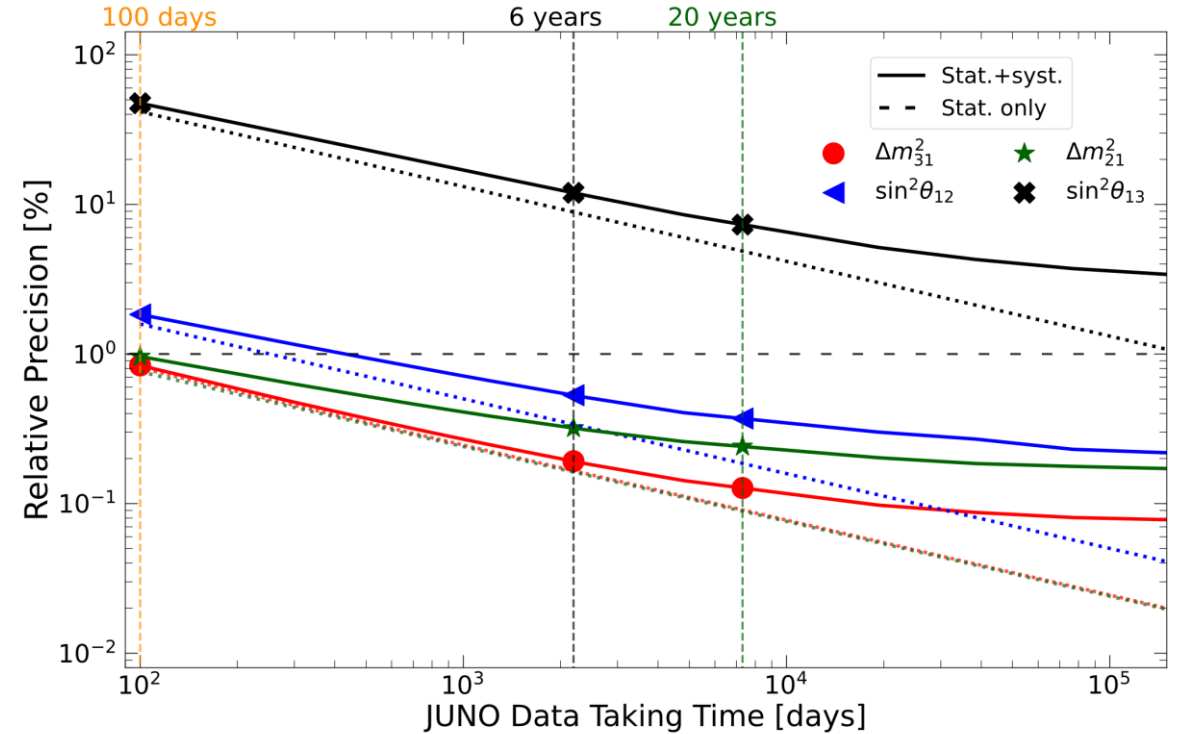
❖ JUNO sensitive to the  $\Delta m_{31}^2$ ,  $\Delta m_{21}^2$ ,  $\sin^2 \theta_{12}$ , and  $\sin^2 \theta_{13}$

❖ Probability does not depend on  $\delta_{CP}$  and  $\theta_{23}$   
→ no degeneracies



# JUNO's sensitivity to oscillation parameters

- ❖ JUNO will achieve **sub-percent precision** on  $\Delta m_{31}^2$ ,  $\Delta m_{21}^2$ , and  $\sin^2\theta_{12}$  during first 2 years of data taking
- ❖ Sub-percent measurements can:
  - be used as inputs to other experiments
  - provide constraints for model building
  - enable more precise searches of physics beyond Standard Model



	Central value	PDG2020	100 days	6 years
$\Delta m_{31}^2 (\times 10^{-3} \text{ eV}^2)$	2.5253	$\pm 0.034$ (1.3%)	$\pm 0.021$ (0.8%)	$\pm 0.0047$ (0.2%)
$\Delta m_{21}^2 (\times 10^{-5} \text{ eV}^2)$	7.53	$\pm 0.18$ (2.4%)	$\pm 0.074$ (1.0%)	$\pm 0.024$ (0.3%)
$\sin^2\theta_{12}$	0.307	$\pm 0.013$ (4.2%)	$\pm 0.0058$ (1.9%)	$\pm 0.0016$ (0.5%)
$\sin^2\theta_{13}$	0.0218	$\pm 0.0007$ (3.2%)	$\pm 0.010$ (47.9%)	$\pm 0.0026$ (12.1%)



# Oscillation parameters systematic uncertainties

Dominant systematic uncertainties sources:

- ❖  $\Delta m_{31}^2$ : antineutrino spectrum shape uncertainty, detector non-linearity, backgrounds
- ❖  $\Delta m_{21}^2$ : backgrounds, spent nuclear fuel, non-equilibrium (particularly in the low energy region)
- ❖  $\sin^2 \theta_{12}, \sin^2 \theta_{13}$ : reactor flux normalization, detector efficiency

