Neutrino Theory Overview in the current precision era

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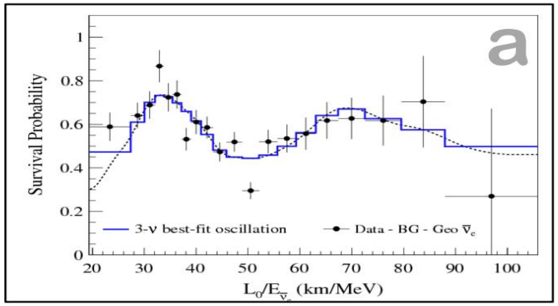
中微子及相关新物理研讨会

广东 珠海

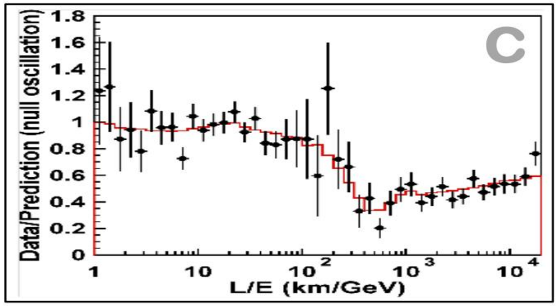
29th Nov. 2025

Neutrinos Do Oscillate!

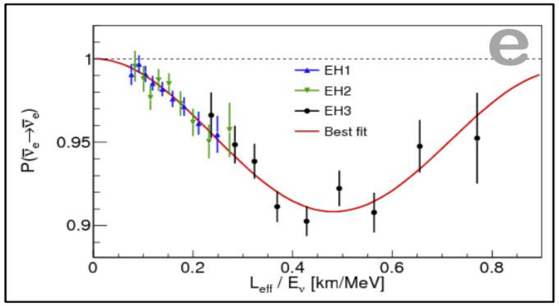
e→e



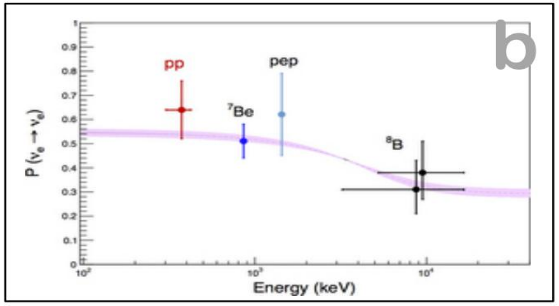
μ→μ



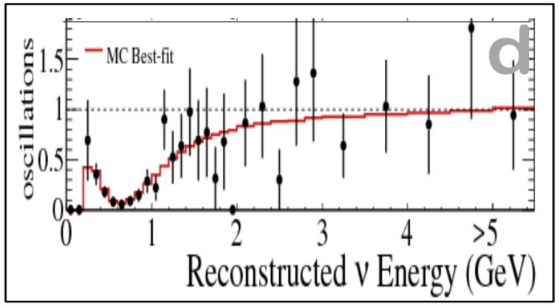
e→e



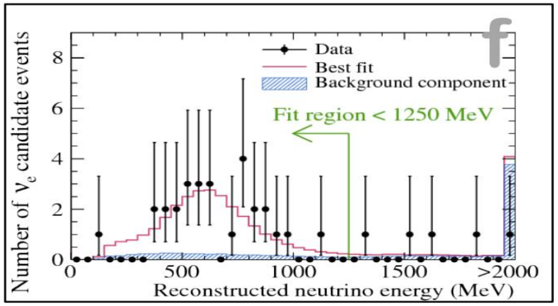
e→e



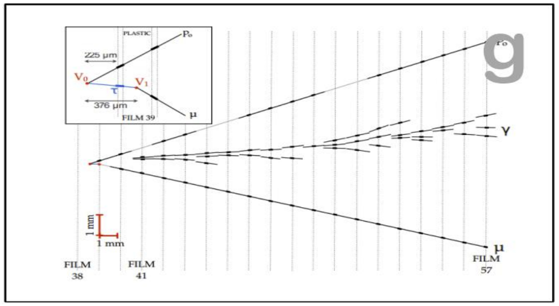
μ→μ



μ→e



μ→τ



Data from various types of neutrino experiments: (a) solar, (b) long-baseline reactor, (c) atmospheric, (d) long-baseline accelerator, (e) short-baseline reactor, (f,g) long baseline accelerator (and, in part, atmospheric).

(a) KamLAND [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), MINOS, K2K; (e) Daya Bay [plot], RENO, Double Chooz; (f) T2K [plot], MINOS, NOvA; (g) OPERA [plot], Super-K atmospheric.

Three Neutrino Paradigm

Standard Parameterization of Mixing Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$c_{ab} \equiv \cos\vartheta_{ab}$ $\quad s_{ab} \equiv \sin\vartheta_{ab}$ $\quad 0 \leq \vartheta_{ab} \leq \frac{\pi}{2}$ $\quad 0 \leq \delta_{13}, \lambda_{21}, \lambda_{31} < 2\pi$

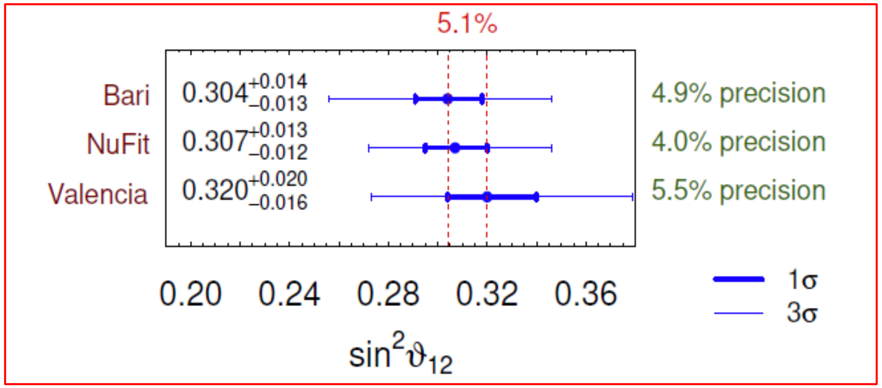
3 Mixing Angles: $\vartheta_{12}, \vartheta_{23}, \vartheta_{13}$

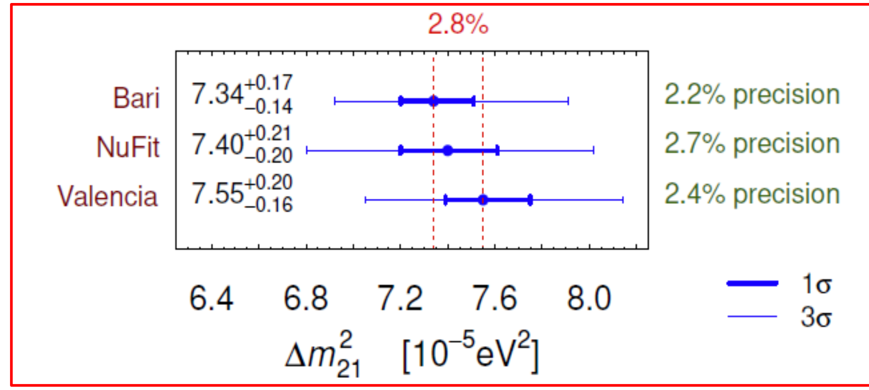
1 CPV Dirac Phase: δ_{13}

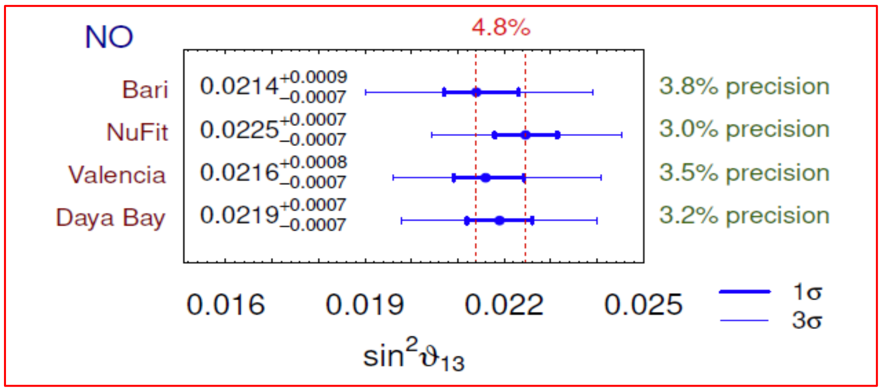
2 independent $\Delta m^2_{kj} \equiv m^2_k - m^2_j$: $\Delta m^2_{21}, \Delta m^2_{31}$

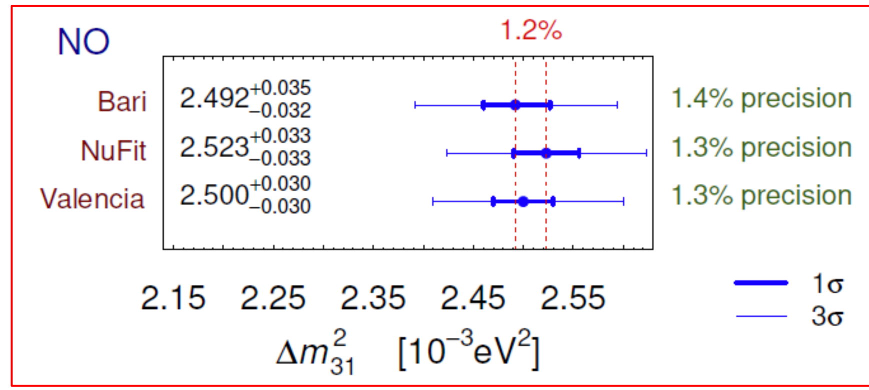
- **Absolute Mass Scale**
- **Two CPV Majorana Phases**

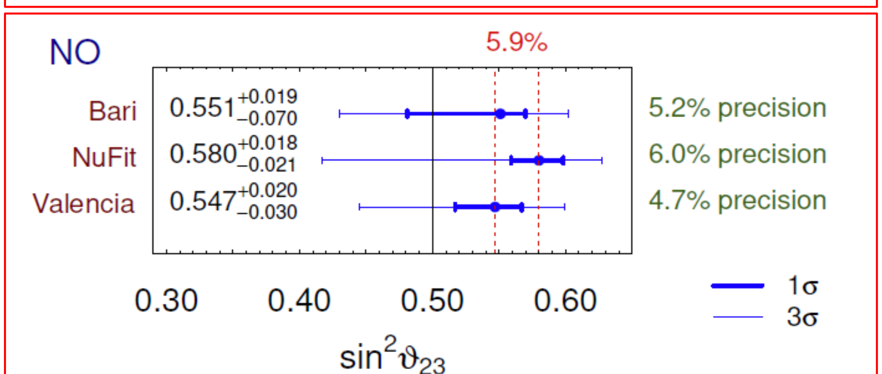
Global picture









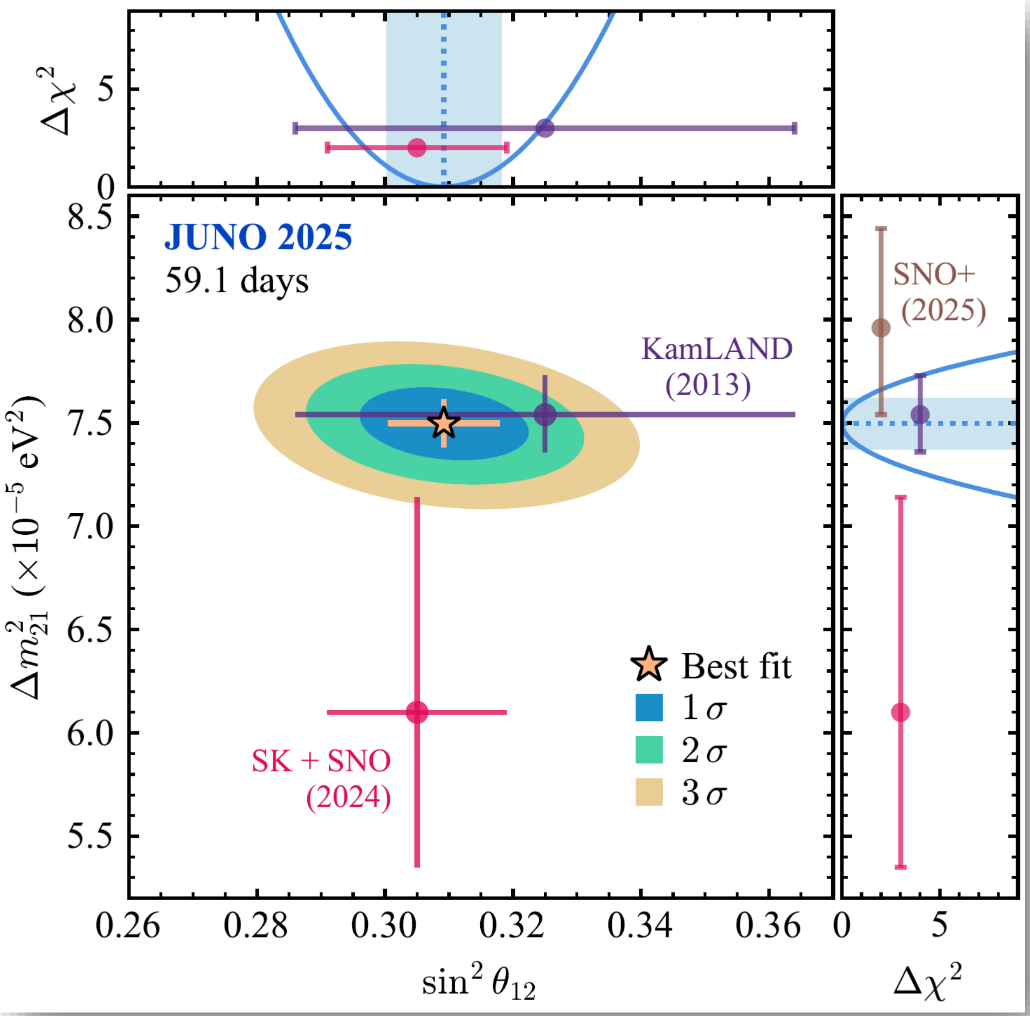


- **5 parameters: well measured**
- **Mass ordering, CP violation: to be determined**
- **Probing new physics!**

Open questions in ν physics

- $\vartheta_{23} \lesseqgtr 45^\circ$?
  - T2K (Japan), NOνA (USA), ...
- CP violation ? $\delta_{13} \approx 3\pi/2$?
  - T2K (Japan), NOνA (USA), DUNE (USA), HyperK (Japan), ...
- Mass Ordering ?
  - JUNO (China), PINGU (Antarctica), ORCA (EU), INO (India), ...
- Absolute Mass Scale ?
  - β Decay, Neutrinoless Double-β Decay, Cosmology, ...
- Dirac or Majorana ?
  - Neutrinoless Double-β Decay, ...
- Beyond Three-Neutrino Mixing ? Sterile Neutrinos ?

New era of precision measurement with JUNO



- **Best measurement of the so-called solar sector.**
- **A factor of 1.6 improvement compared to world combination (20+ yrs)**
- **E. Lisi (Bari): "Setting new world record of two fundamental parameters … …"**
- **Entering into precision era of neutrino physics!**

Phenomenological implications

First measurement of reactor neutrino oscillations at JUNO #3

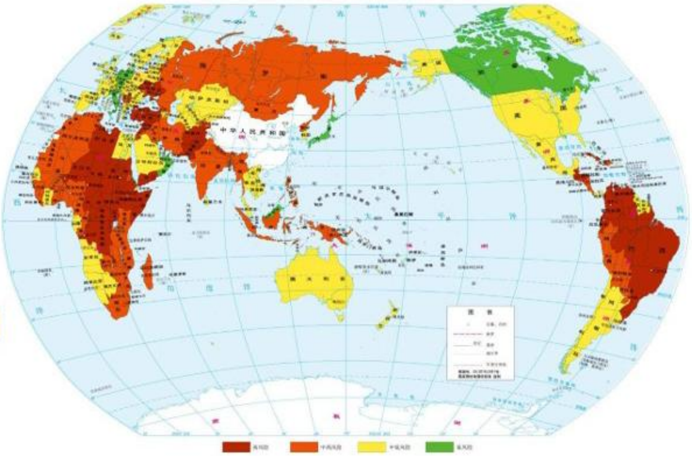
JUNO Collaboration • Angel Abusleme (Chile U., Catolica) et al. (Nov 18, 2025)

e-Print: 2511.14593 [hep-ex]

pdf cite claim reference search 16 citations

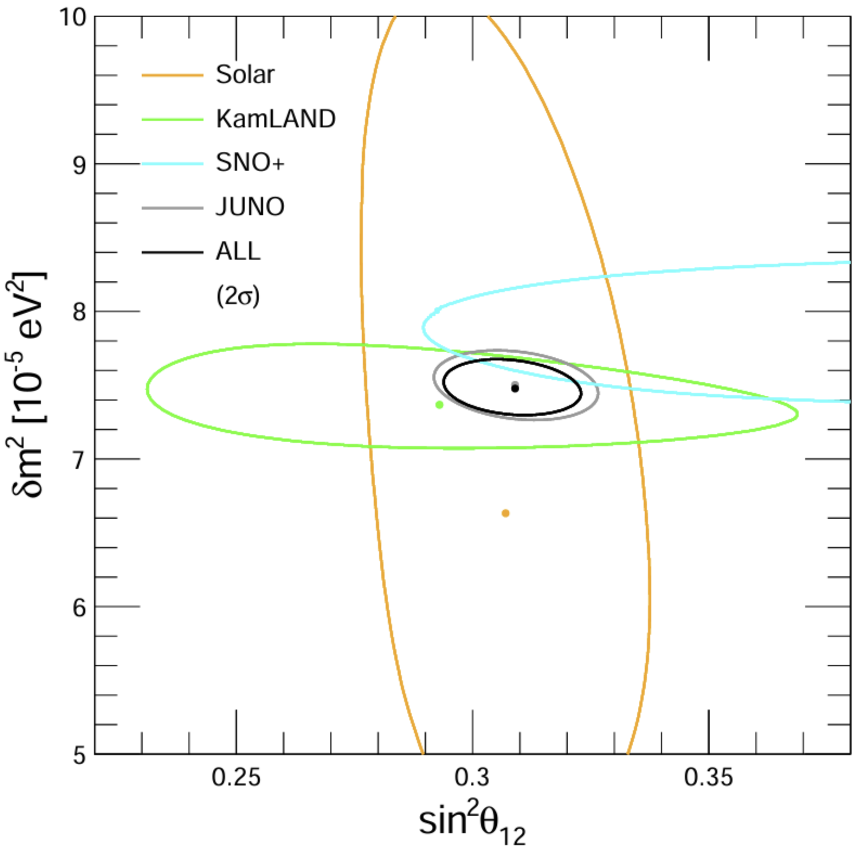
01. 2511.15127 (Zhi-Zhong Xing) 北京
02. 2511.15391 (Shao-Feng Ge, Chui-Fan Kong, Manfred Lindner) 上海 + 大田 + 海德堡
03. 2511.15442 (Shao-Feng Ge, Chui-Fan Kong, Joao Paulo Pinheiro) 上海 + 大田
04. 2511.15494 (Wei Chao) 北京
05. 2511.15525 (Jihong Huang, Shun Zhou) 北京
06. 2511.15654 (Di Zhang) 慕尼黑
07. 2511.15702 (Yu-Feng Li, Jing-yu Zhu) 北京 + 兰州
08. 2511.15978 (Xiao-Gang He) 上海
09. 2511.16196 (Zi-Qiang Chen, Gao-Xiang Fang, Ye-Ling Zhou) 杭州
10. 2511.16348 (Wen-Hao Jiang, Ruiwen Ouyang, Ye-Ling Zhou) 杭州
11. 2511.16942 (Shu Luo) 厦门
12. 2511.19408 (Serguey Petcov, Arsenii Totov) 德里亚斯特 + 帕多瓦
13. 2511.19420 (Susobhan Chattopadhyay, Amol Dighe) 孟买
14. 2511.21650 (Francesco Capozzi, Eligio Lisi, Francesco Marcone, Antonio Marrone, Antonio Palazzo) 巴里

2025全球安全风险地图



First JUNO result vs. the world data

First Global fit from Bari group 2511.21650



- **Dominated in the solar sector, as expected.**
- **Consistent with other measurements**
- **Solar-reactor tension persists (will discuss later)**
- **Many sub-leading effects would be very relevant in the near future !**

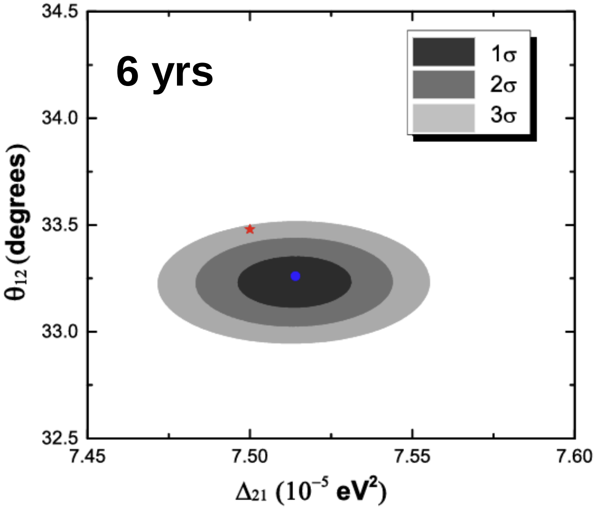
Subtle matter effects

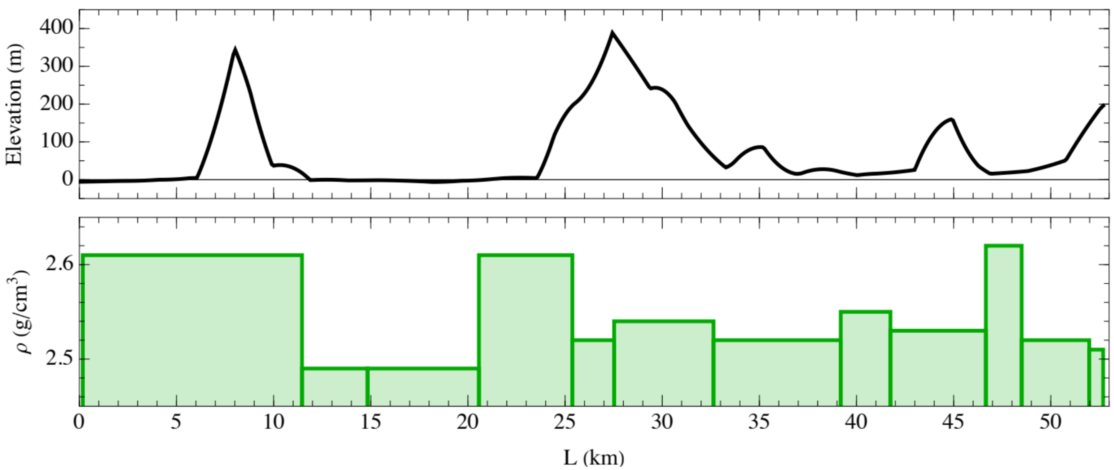
- **It is generally believed that matter effect is negligible in reactor neutrino experiments → It is not the case for JUNO**
- **Matter effect matters for solar parameters!** *Y.F.Li, et al. CPC 40 (2016) 9, 091001*
- **Contribute to O(1%) → compatible or larger than expected precision.**

$$\rho_{\rm YJ}^{\rm Average} \simeq (2.554 \pm 10\%)\ {\rm g/cm^3}\ .$$

Y.F.Li, et al. 2511.15702

Used in JUNO data analysis





Status of the PMNS mixing matrix

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

$$|U|_{1\sigma}^{\text{w/ JUNO2025}} = \begin{pmatrix} 0.818 \to 0.827 & 0.543 \to 0.556 & 0.145 \to 0.149 \\ 0.292 \to 0.372 & 0.581 \to 0.629 & 0.710 \to 0.735 \\ 0.431 \to 0.488 & 0.550 \to 0.600 & 0.662 \to 0.689 \end{pmatrix}$$

- **First row totally determined by θ_{12} and θ_{13}**
- **Both from reactor experiments (Daya Bay & JUNO)**
- **Achieved 1σ range at the percent level for the first row !**
- **Other components driven by: θ_{23} and δ**

Implication on flavor ratios of Icecube

- **Flavor ratios at source are important indicator for the acceleration and production mechanism of UHE νs.**
- **Connection between observed and original flavor ratios.**

$$\begin{bmatrix} \Phi_e \\ \Phi_\mu \\ \Phi_\tau \end{bmatrix} = \begin{pmatrix} P_{ee} & P_{e\mu} & P_{e\tau} \\ P_{\mu e} & P_{\mu\mu} & P_{\mu\tau} \\ P_{\tau e} & P_{\tau\mu} & P_{\tau\tau} \end{pmatrix} \begin{bmatrix} \phi_e \\ \phi_\mu \\ \phi_\tau \end{bmatrix}$$

- **The matrix is singular and non-reversible in the mu-tau symmetry limit → only two out of three are measurable!**

$$\begin{aligned} P_{ee}\eta_e + P_{e\mu}\left(\eta_\mu + \eta_\tau\right) &= f_e \\ P_{e\mu}\eta_e + P_{\mu\mu}\left(\eta_\mu + \eta_\tau\right) &= f_\mu \end{aligned}$$

- **Totally depend on θ_{12} and θ_{13} ,** *Z.Z. Xing, 2511.15127*
- **Flavor ratios are one of important topics in future experiments**

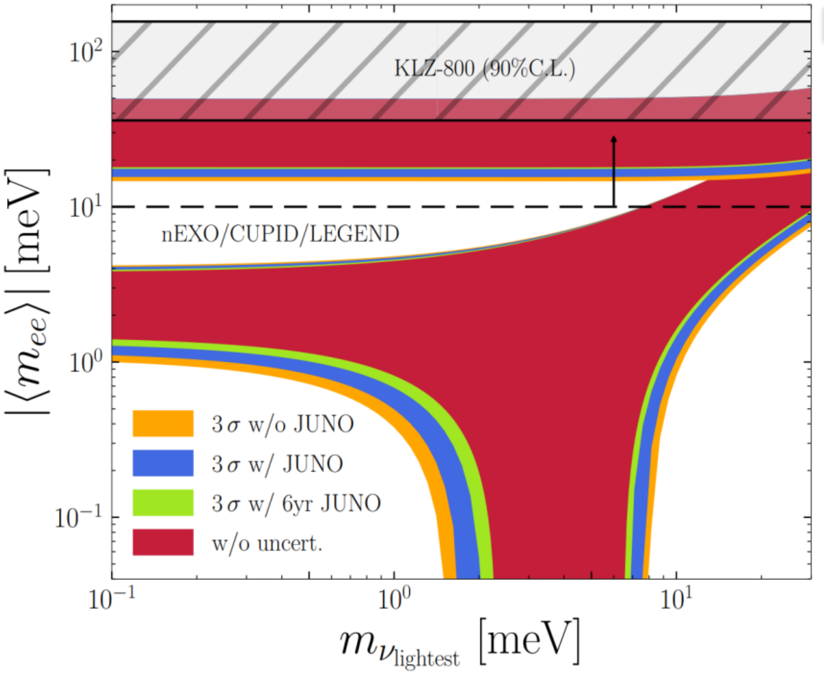
Talks of HUNT, TRIDENT, NEON on 30 th

Implication on the ββ0ν searches

- **ββ0ν is among the most promising approach to probe the neutrino nature and mass generation mechanism.**
- **JUNO will practically eliminate most of uncertainties from oscillation parameters**

→ Absolute neutrino mass & Majorana phases

S.F. Ge et al. 2511.15391



- **The lower boundaries strong depend on solar parameters**

See also:1103.4152 1507.05514, 1908.08355

- **Absolute mass: cosmology?**
  Talk later by J.Q. Xia
- **The remaining outstanding issue:**
  Nuclear Matrix Element
  See later and talk by J.M. Yao

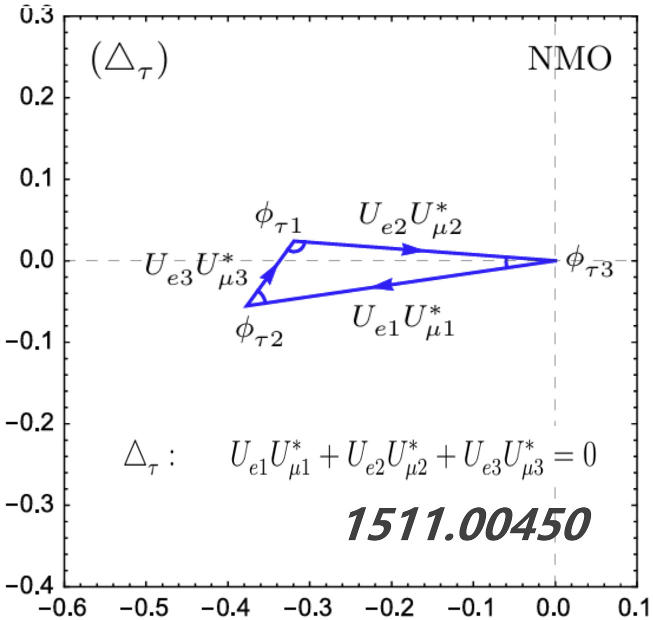
→Probe mass generation mechanism

Unitarity Test

Unitarity test is a low energy test of neutrino mass model (seesaws)

- **Six normalization condition**
- **Unitary Triangle:** graphic description of flavor mixing and CP violation *S. Luo, 2511.16942*
- **Direct test of the first-row normalization?**

$$|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 \stackrel{?}{=} 1 \,.$$



- **Need a careful treatment of production/oscillation/detection processes:**

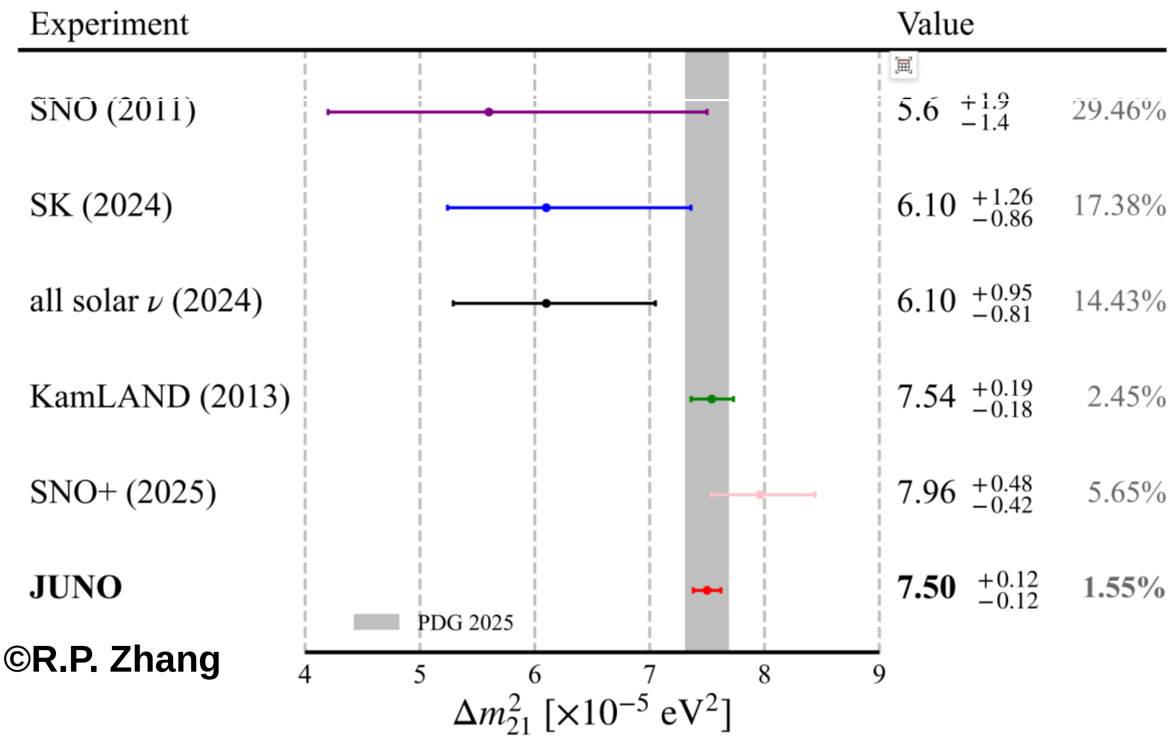
J.H. Huang, S. Zhou, 2511.15525
See also: Y.F. Li et al. 1802.04964

$$G_\mu^{\rm exp} = G_\mu^{\rm SM}\sqrt{(NN^\dagger)_{ee}\,(NN^\dagger)_{\mu\mu}}$$

$$P_{\alpha\beta} = \frac{1}{(NN^\dagger)_{\alpha\alpha}(NN^\dagger)_{\beta\beta}}\left[\left|(NN^\dagger)_{\alpha\beta}\right|^2 - 4\sum_{i<j}{\rm Re}\mathcal{N}^{ij}_{\alpha\beta}\sin^2 F_{ji} + 2\sum_{i<j}{\rm Im}\mathcal{N}^{ij}_{\alpha\beta}\sin 2F_{ji}\right]$$

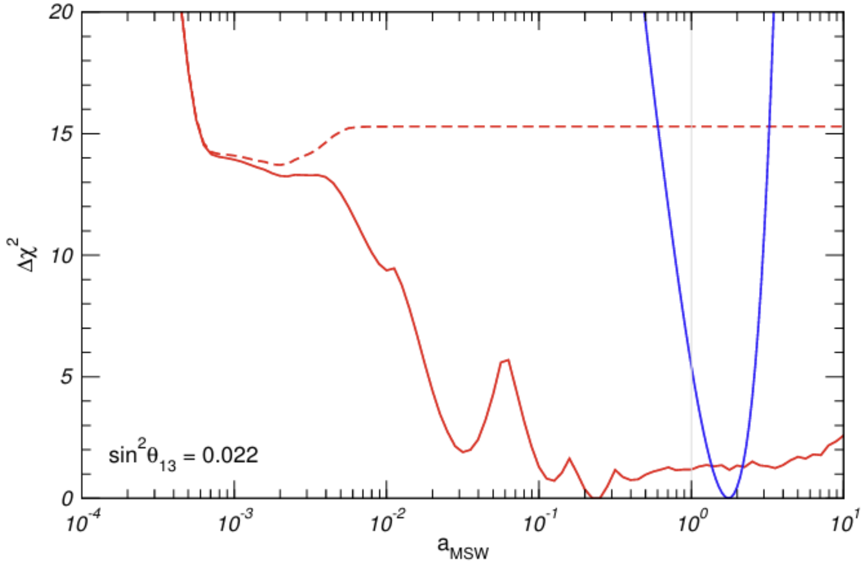
Δm^2_{21} : Solar-Reactor tension?

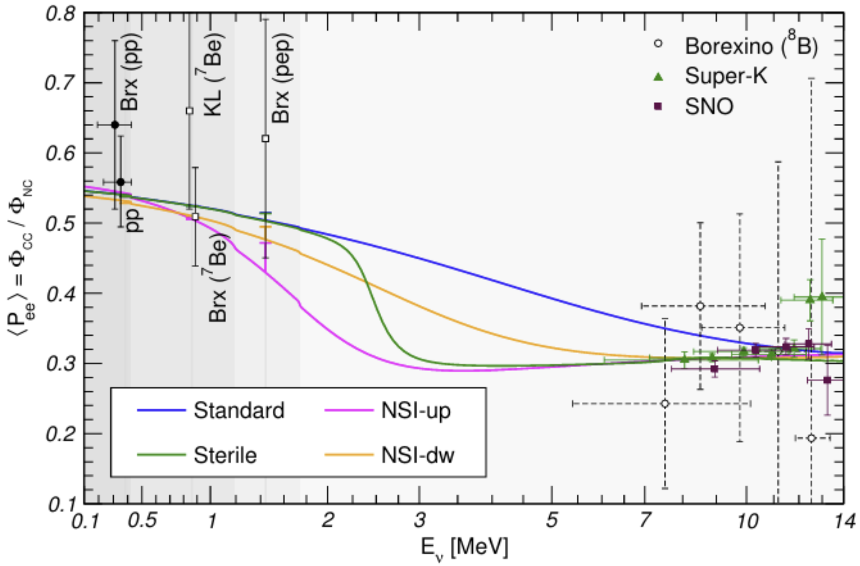
- It is only 1.5σ →not worrisome?
- Persist between two different measurements
- Solar neutrinos vs. Reactor antineutrinos; Vacuum vs. Matter
- quantum vs. classical: Δm^2_{21} → θ^m_{12} → $<P_{ee}>$



Solar-Reactor tension: new physics?

- **If it comes from solar neutrino part:** *Maltoni & Smirnov, 1507.05287*
- **Absence upturn and too large day night asymmetry**



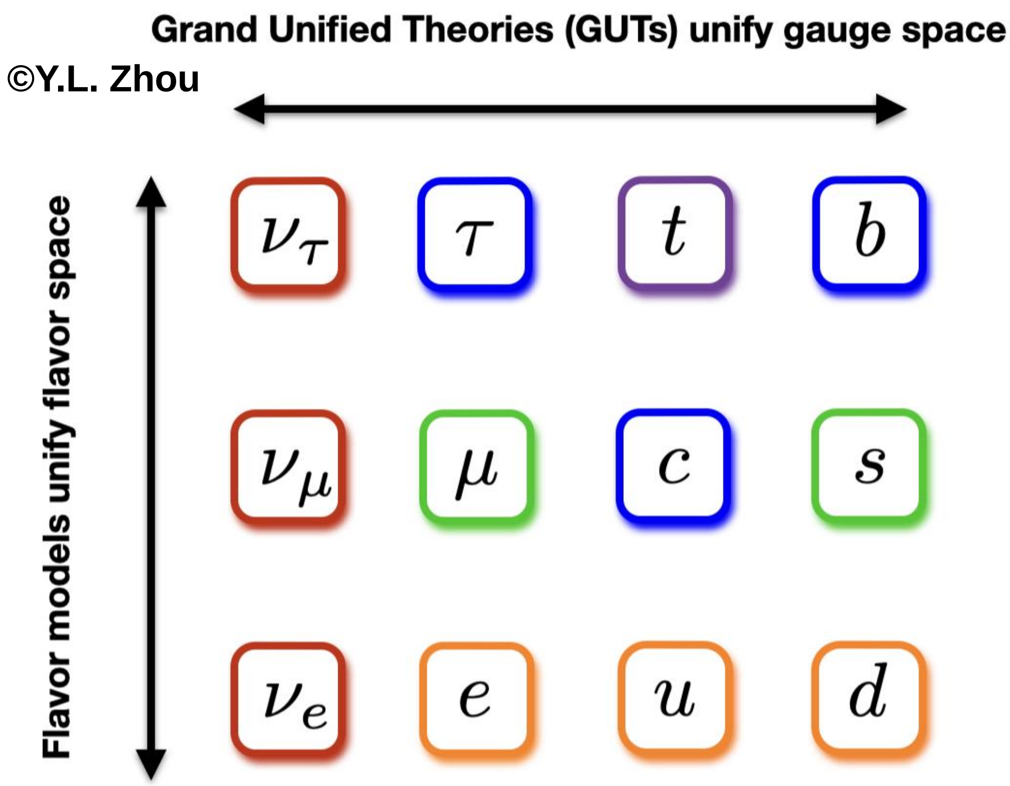


- **Rescaled CC matter potential by ~60%?**
- **Adiabaticity violation (such as density anomaly)?**
- **New physics: NSI or very light steriles?**
- **Other possibility: neutrino-DM connection?** *W. Chao, 2511.15494*

Testing the underlying mechanism

- **Status of neutrino mass and mixing mechanism?**
- **Flavor (horizontal) symmetry connecting flavors (generations)**
- **GUTs connecting quarks and leptons**

Talk later by G.J. Ding on Modular symmetry



Variants of constant mixing patterns

- **Several constant mixing patterns differ by the value of θ_{12}**
- **Variant of tribimaximal mixing:**

$$U_{\rm TM1} = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{\cos\theta}{\sqrt{3}} & \frac{\sin\theta}{\sqrt{3}}e^{-{\rm i}\phi} \\ -\frac{1}{\sqrt{6}} & \frac{\cos\theta}{\sqrt{3}} - \frac{\sin\theta}{\sqrt{2}}e^{{\rm i}\phi} & \frac{\cos\theta}{\sqrt{2}} + \frac{\sin\theta}{\sqrt{3}}e^{-{\rm i}\phi} \\ \frac{1}{\sqrt{6}} & -\frac{\cos\theta}{\sqrt{3}} - \frac{\sin\theta}{\sqrt{2}}e^{{\rm i}\phi} & \frac{\cos\theta}{\sqrt{2}} - \frac{\sin\theta}{\sqrt{3}}e^{-{\rm i}\phi} \end{pmatrix}$$

$$U_{\rm TM2} = \begin{pmatrix} \frac{2\cos\theta}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{2\sin\theta}{\sqrt{6}}e^{-{\rm i}\phi} \\ -\frac{\cos\theta}{\sqrt{6}} - \frac{\sin\theta}{\sqrt{2}}e^{{\rm i}\phi} & \frac{1}{\sqrt{3}} & \frac{\cos\theta}{\sqrt{2}} - \frac{\sin\theta}{\sqrt{6}}e^{-{\rm i}\phi} \\ \frac{\cos\theta}{\sqrt{6}} - \frac{\sin\theta}{\sqrt{2}}e^{{\rm i}\phi} & -\frac{1}{\sqrt{3}} & \frac{\cos\theta}{\sqrt{2}} + \frac{\sin\theta}{\sqrt{6}}e^{-{\rm i}\phi} \end{pmatrix}$$

- **TM1: one of the most favored patterns**
- **TM2 disfavored at more than 3σ**

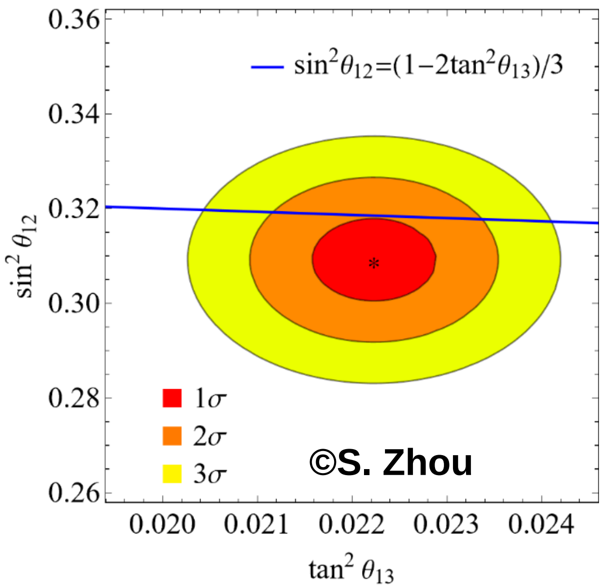
  D. Zhang, 2511.15654, X.G. He, 2511.15978

- **TM1: First proposed in**

Xing & Zhou hep-ph/0607302 & Lam hep-ph/0611017

- **First named by**

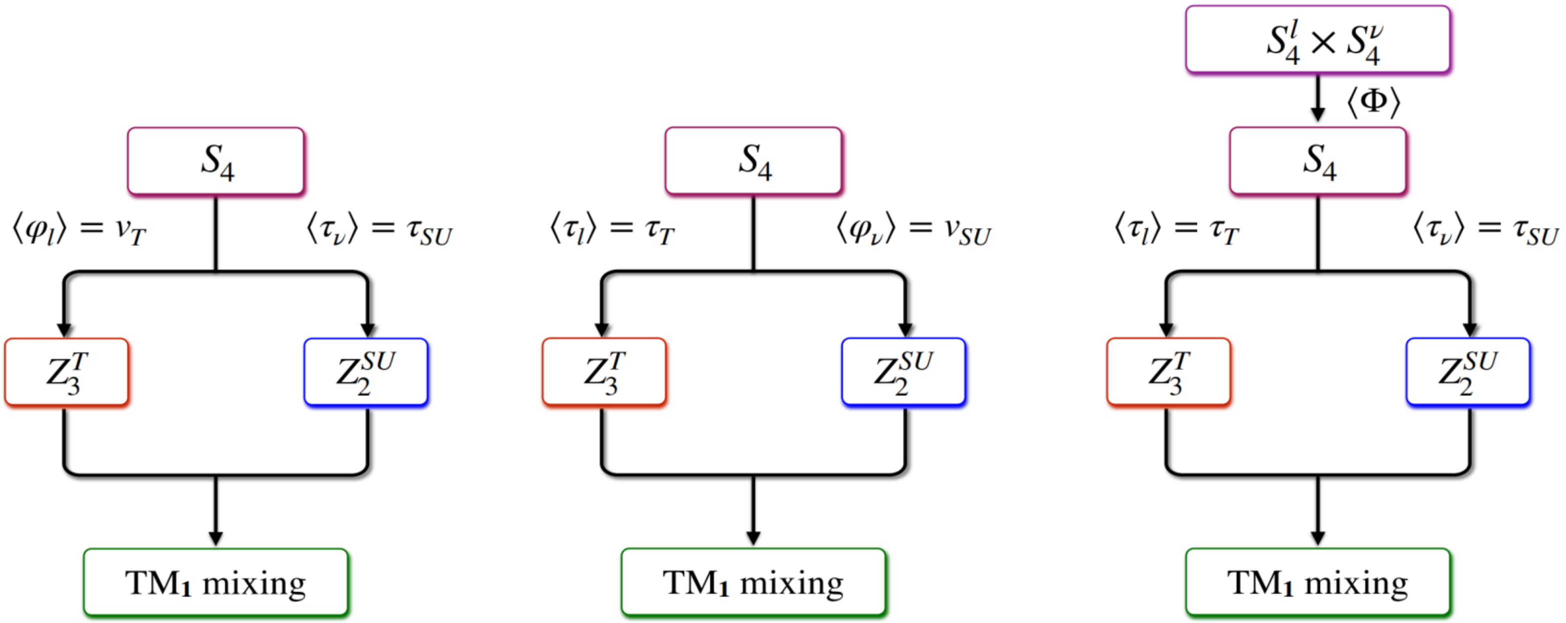
Albright and Rodejohann, 0812.0436



TM1 from symmetry realizations

- **Take the latest study:** *W.H. Jiang, R. Ouyang, Y.L. Zhou, 2511.16348*
- **Residual symmetries of Z_3 and Z_2 in charged lepton and neutrino sectors**
- **Either via Modular symmetry or flavons**

More details in Talk by R. Ouyang



(A) (B) (C)

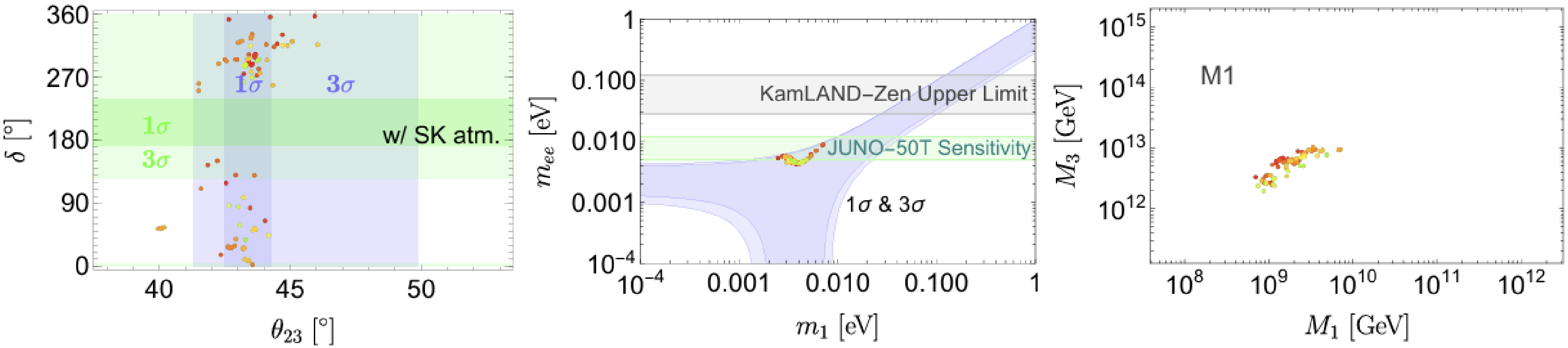
Quark-lepton correlation vs. JUNO data

- **Quark-lepton correlation of GUTs can be tested via precise flavor mixing**
- **Depends on Yukawa sectors**

  Z.Q. Chen, G.X. Fang & Y.L. Zhou 2511.16196

Model	Main features	$n_{\rm para}$
M1	Only Y_{10}, Y_{126}	19
M2	Real Y_{10}, Y_{126}, Y_{120}	19
M3	Hermitian Y_u, Y_d, Y_e, Y_ν	18

- **With first JUNO data：**
- **Normal mass ordering is favored**



- **Other probes include proton decay & leptogenesis**

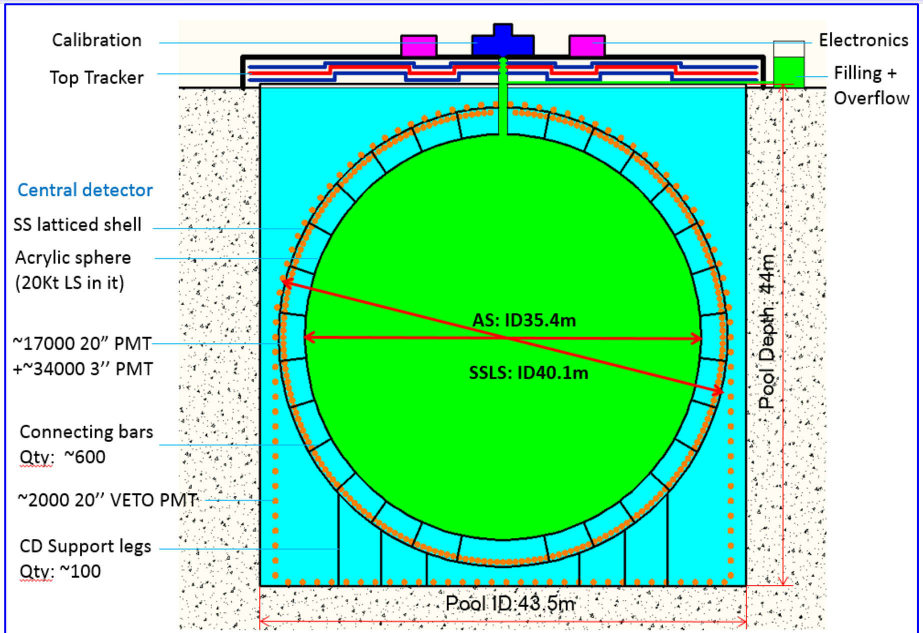
Outlook

- **What one should do in the precision era to search for new physics ?**

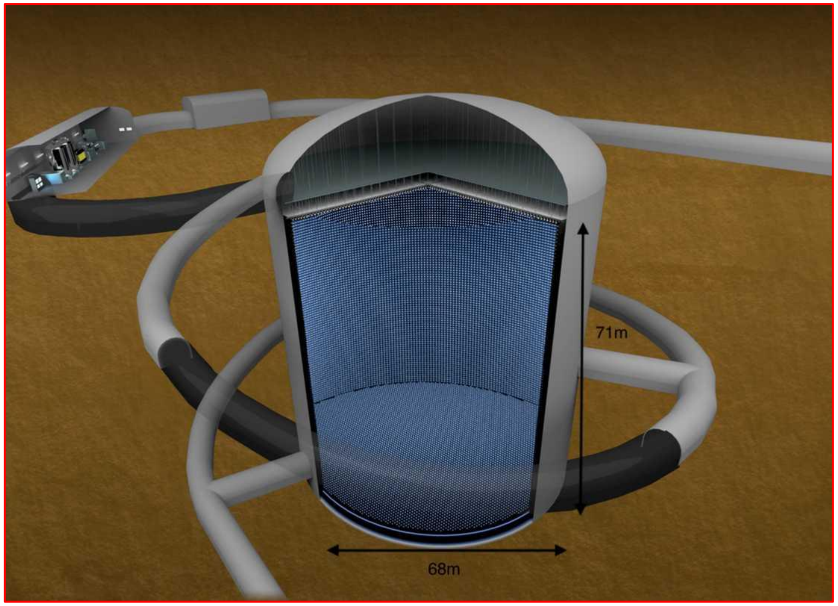
- **With precision neutrino data in hand, and do our best to match the accuracy of theory calculation with the data**

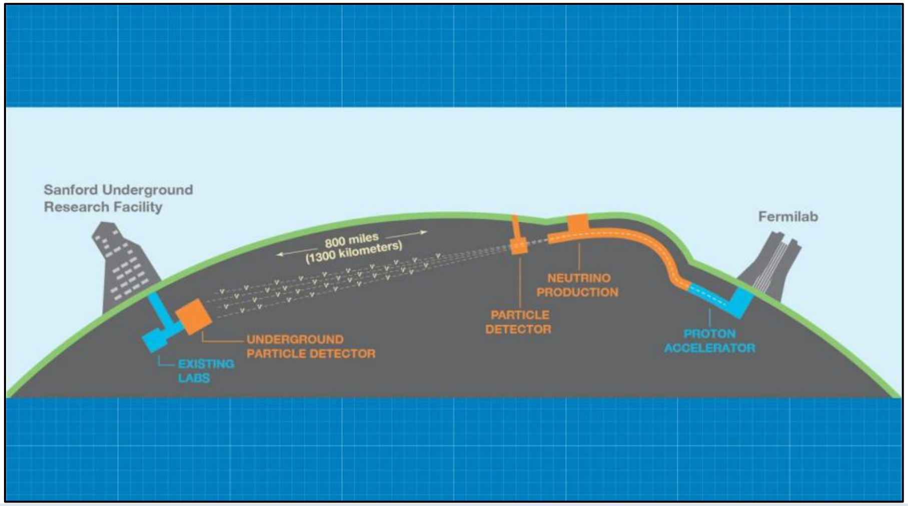
- **… …**

Three oscillation experiments



AS: Acrylic sphere; SSLS: stainless steel latticed shell





JUNO: 2025.8 (officially started)
Reactor neutrinos for MO

Hyper-Kamiokande: 2028
Acc. & Atm. neutrinos, MO & CP

DUNE: 2031
Acc. & Atm. neutrinos, MO & CP

Non-oscillation probes

- **Beta decay:**

  KATRIN: 200 meV, Project 8: 40 meV,

- **Bβ0ν:** Talk by Hao. Ma

  Current O(100) kg → Ton Scale: Legend, Cupid, nEXO

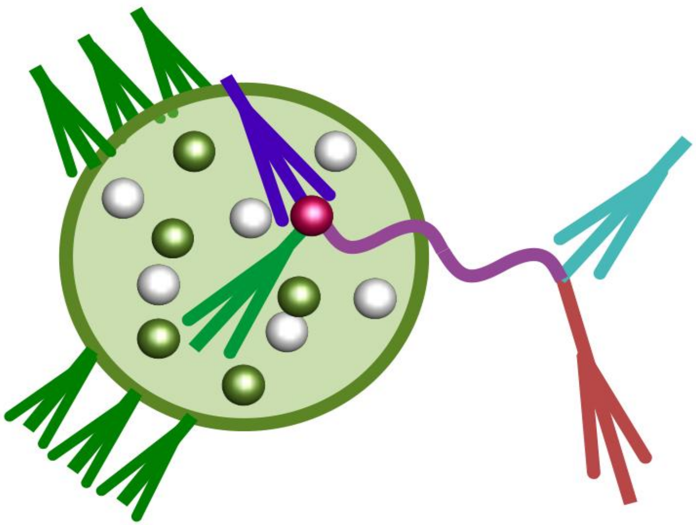
  Initiatives at CJPL, and JUNO-upgrade

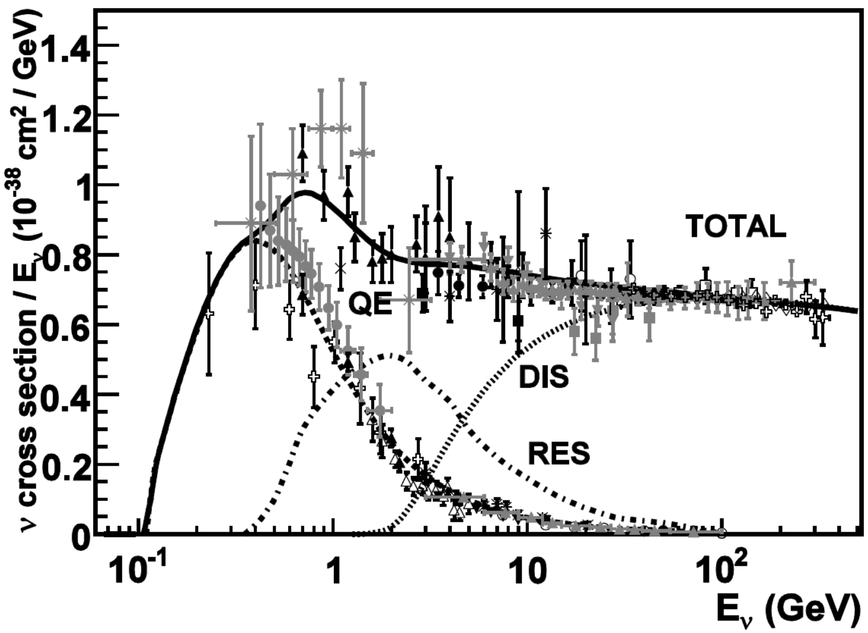
- **Cosmological probe (CMB, LSS, BBN)**

  15 meV precision & Neff: 0.03

- **Neutrino scattering, astrophysical neutrino detection, … …**

GeV neutrino-nucleus interactions



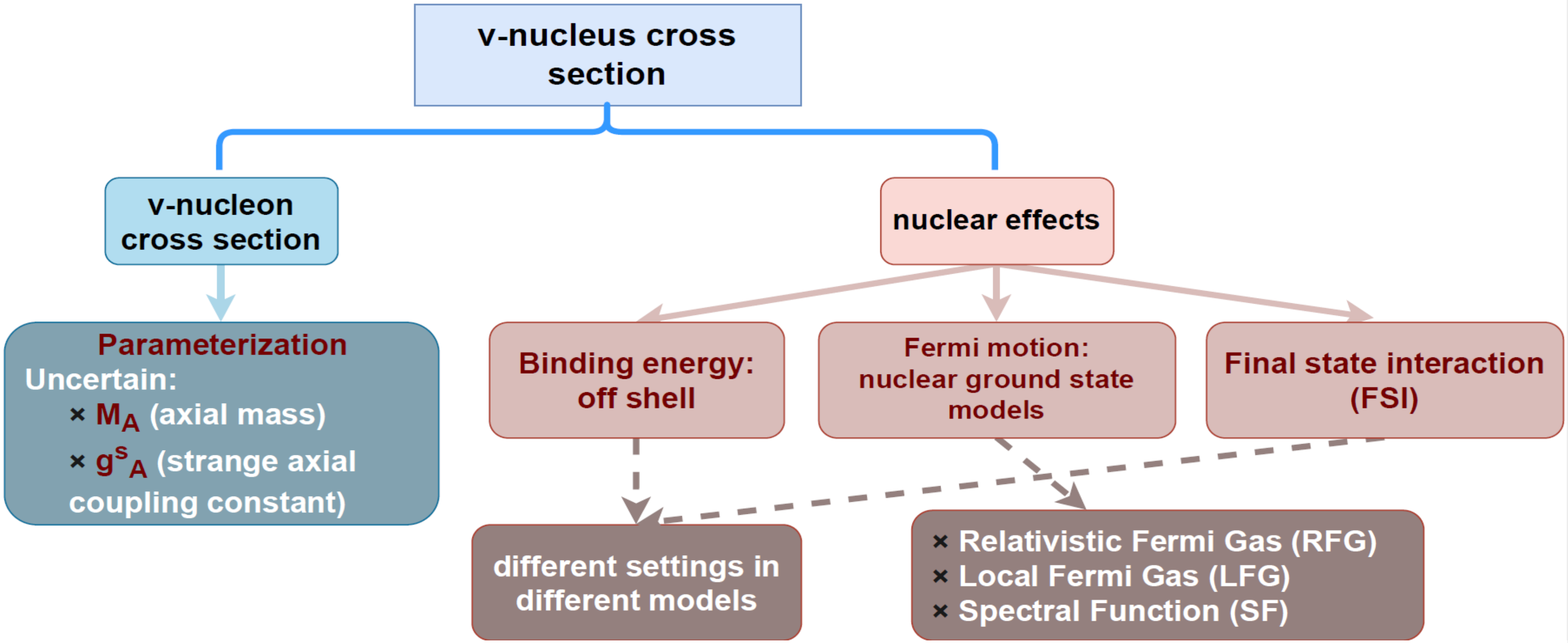


Talk by O. Tomalak

quasielastic scattering	resonance production	deep-inelastic scattering
$\nu_l + n \to l^- + p$	$\nu_l + n \to l^- + \Delta^+$	$\nu_l + N \to l^- + N' + n\pi$
$\overline{\nu_l} + p \to l^+ + n$	$\nu_l + p \to l^- + \Delta^{++}$	$\overline{\nu_l} + N \to l^- + N' + n\pi$
	$\overline{\nu_l} + n \to l^+ + \Delta^-$	
	$\overline{\nu_l} + p \to l^+ + \Delta^0$	
Fermi motion, binding energy, M_A, 2p2h, … …	**Hardon production, FSI**	**Parton Model, FSI**

General components in GeV interactions

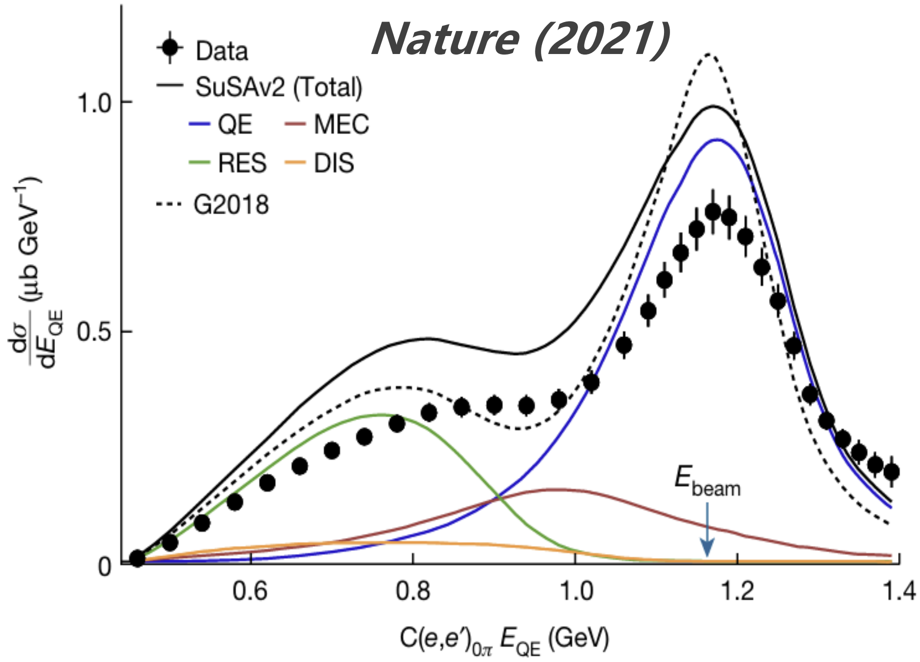
Brief summary of GeV neutrino interaction models

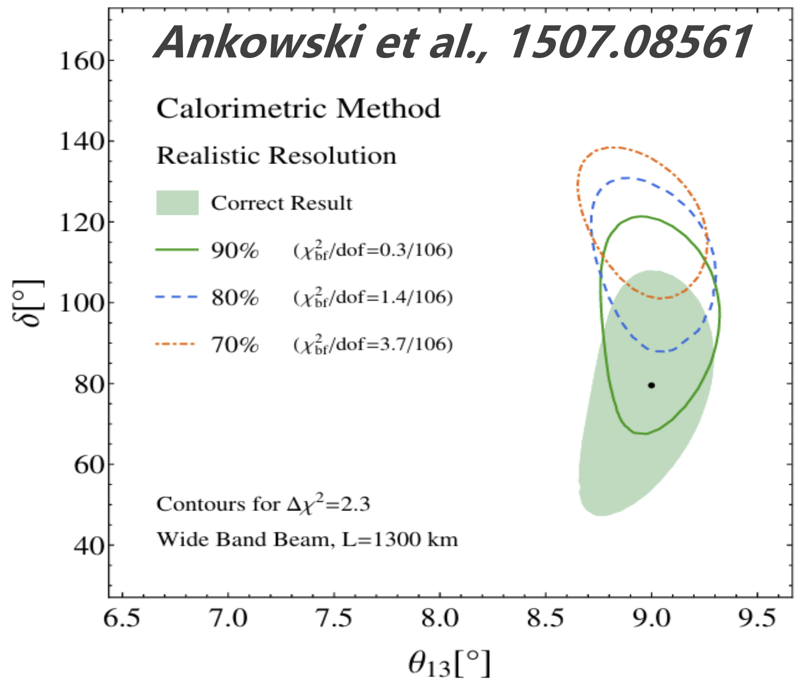


$$\frac{d\sigma^{\mathrm{IA}}_{\ell A}}{d\omega\, d\Omega} = \sum_N \int d^3p\, dE\, P^N_{\mathrm{hole}}(\mathbf{p}, E)\, \frac{M}{E_{\mathbf{p}}} \frac{d\sigma^{\mathrm{elem}}_{\ell N}}{d\omega\, d\Omega}\, P^N_{\mathrm{part}}(\mathbf{p}', \mathcal{T}')$$

average over the initial nucleon state | nucleon cross section | final-state interactions

Interaction effects on oscillations

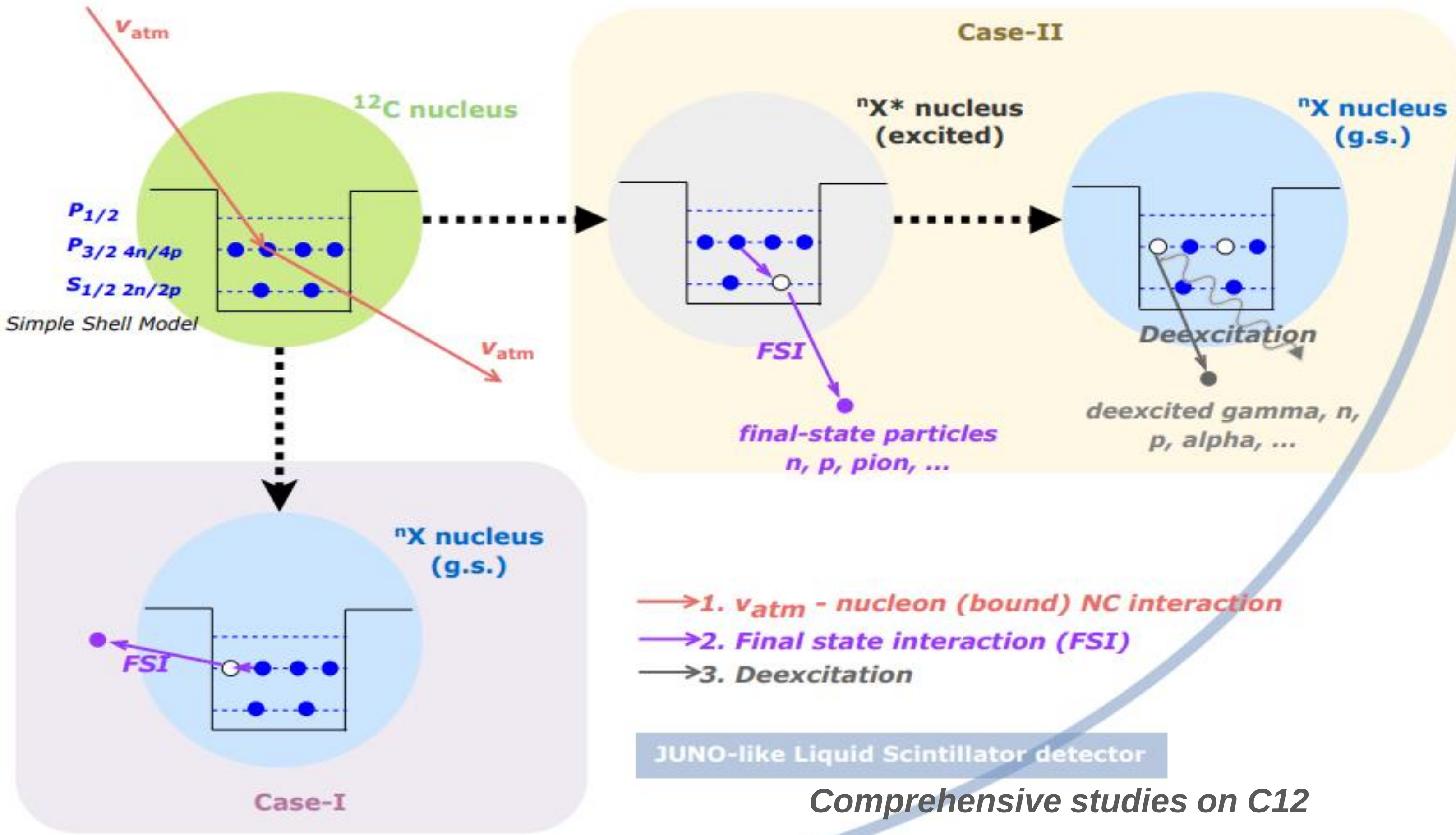




$$E_\nu^{\rm cal} = E_\ell + \sum_i T_i^N + \epsilon_n + \sum_j E_j,$$

- **Missing neutrons and pions may bias the reconstructed energy**
- **and then result in wrong oscillation parameters.**

New Methodology: adding deexcitation



Comprehensive studies on C12

Cheng, YFL, et al., Phys. Rev. D 103, 05001 (2021)

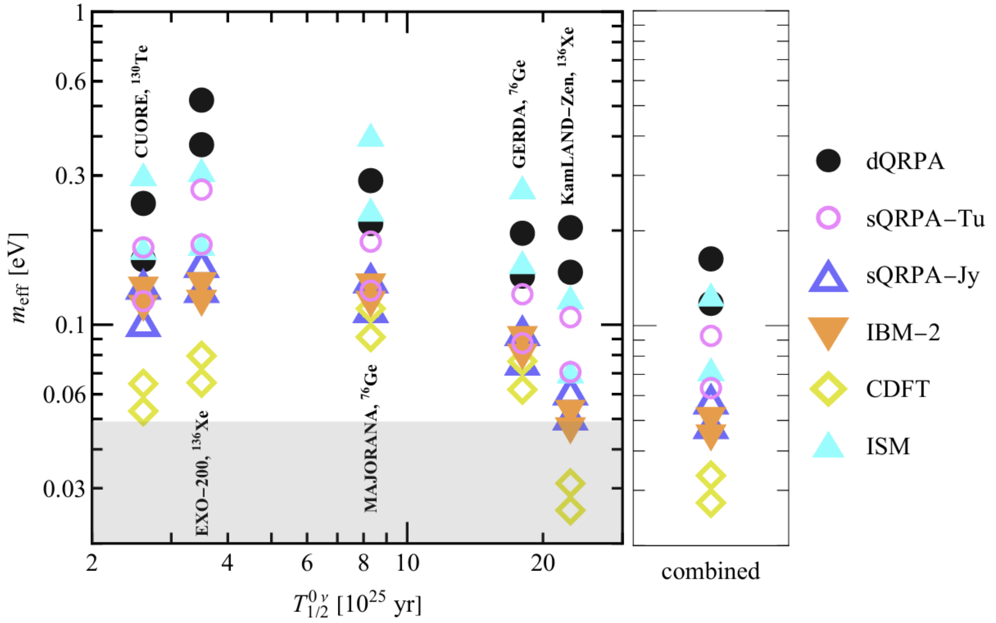
Cheng, YFL, et al., Phys.Rev.D 103, 053002 (2021)

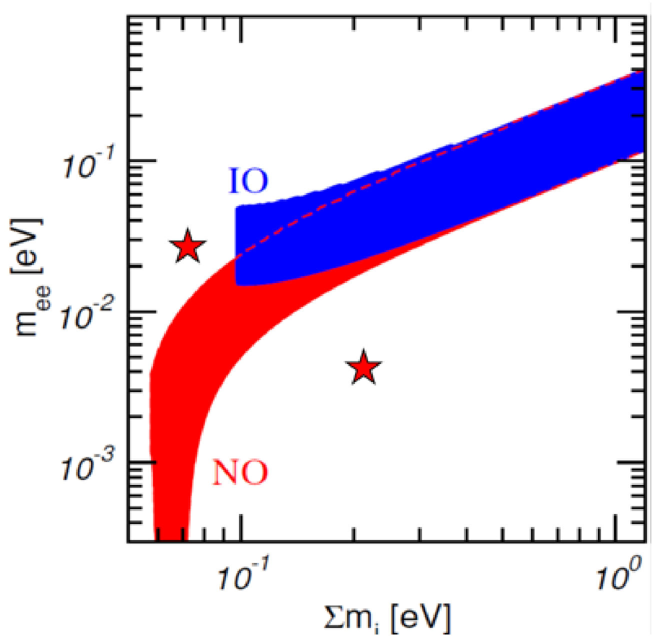
Cheng, Li,YFL, et al, Eur.Phys.J.C 85, 295 (2025)

ββ0ν→ NMEs and dominant mechanisms

D.L. Fang, Y.F. Li, Y.Y. Zhang, J.Y Zhu, 2404.12316

- **How to reduce the NME uncertainty (via theory & experiment)**
- **How to verify various mechanisms beyond light mass exchange**





- **Combination of different data is a must!**

Conclusion

- **JUNO first two months data: set world record for two parameters**

  → even exciting and bright future in next years!

- **From theory point of view:**

  →broad and important implications in many aspects

Outlook:

→precision theory calculation to match precision data

Thank you!

Workshop Advertisement

<u>Please contact Ye-ling Zhou, Shao-feng Ge, Shun Zhou & YFL (Myself)!</u>