The 22nd international workshop on Next Generation Nucleon Decay and Neutrino Detectors (NNN23)
11–13 Oct 2023, Procida

Overview of Reactor Neutrinos Experiments

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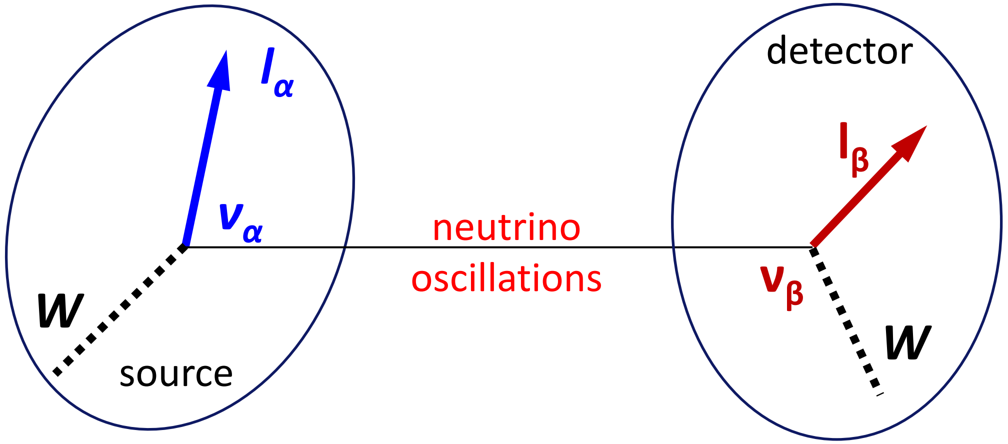
Neutrino Oscillations

- It proved that neutrinos have non-zero masses ➔ huge impact on particle physics & cosmology
- Neutrinos are the possible source of CP violation, which may explain the matter-antimatter asymmetry in the Universe



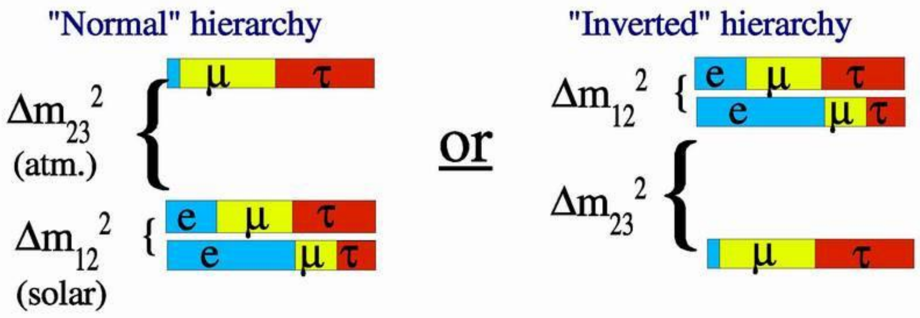
ν prod. & detection: W± weak interaction → identify *flavor*
ν propagation: *mass eigenstates (!= flavor eigenstates)*

- After 25 years of ν oscillations discovery, still unknow
  - **Mass ordering** ($\Delta m^2_{32}>0$?)
  - Leptonic CP phase (δ_{CP})
  - θ_{23} Octant
  - **Very precise knowledge of oscillation parameters**
  - New Physics? (sterile, ..)

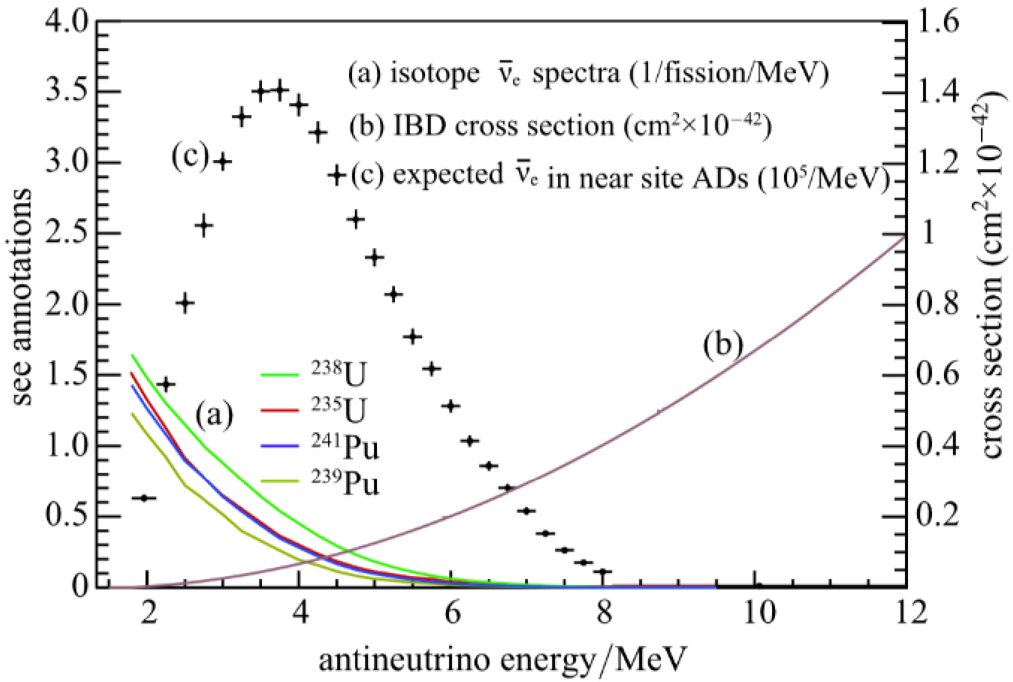
Reactor Neutrinos Experiments will continue to play an critical role in solving the unknowns

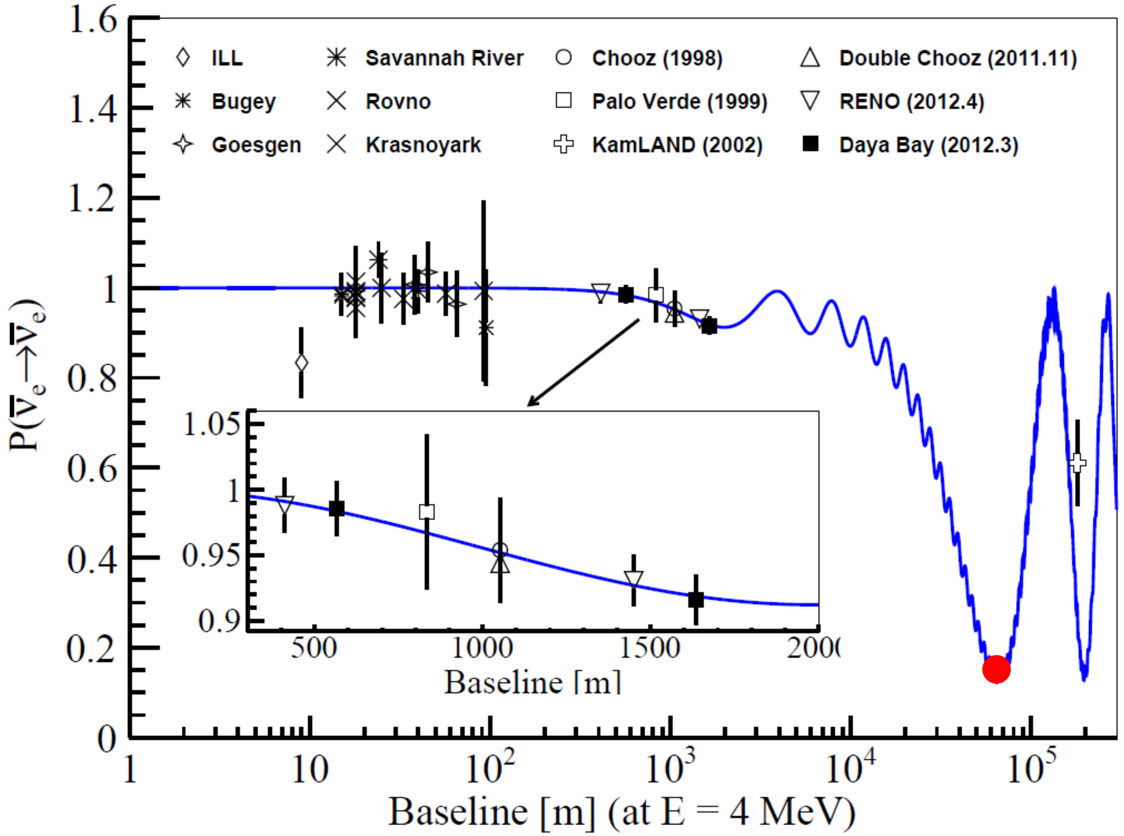
$$V=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\0&1&0\\-s_{13}e^{i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}e^{i\rho}&0&0\\0&e^{i\sigma}&0\\0&0&1\end{pmatrix}$$

θ_{23} & Δm^2_{32}	θ_{13} & δ_{CP}	θ_{12} & Δm^2_{21}	Majorana phases
Atmospheric, Accelerator	***Reactor**, Accelerator*	***Reactor**, Solar*	*Double beta decays*

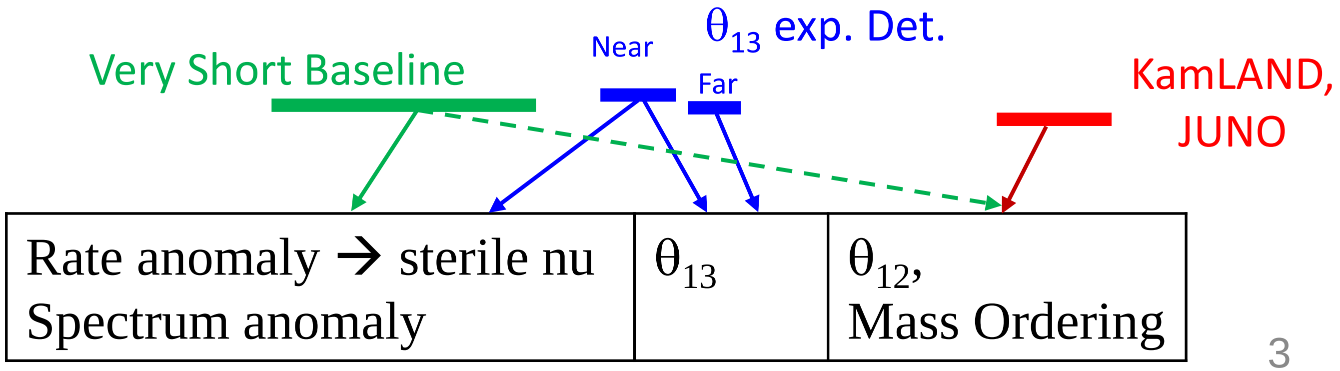


Reactor Neutrinos

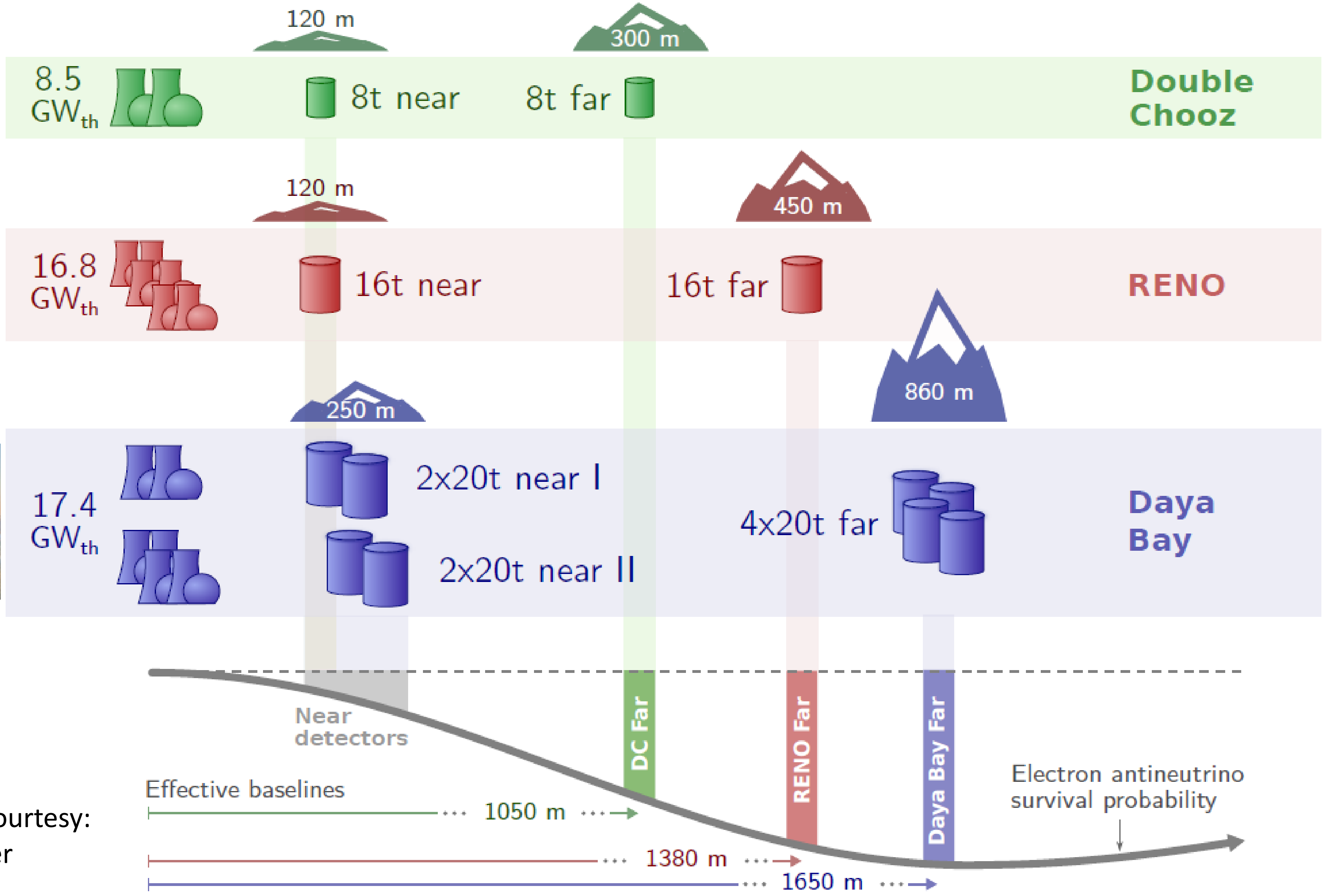




- Reactor antineutrino: $\bar{\nu}_e$ emitted as fission products decay
- Commercial reactor (LEU) ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu; Research HEU (^{235}U)
- Usually detected via Inverse Beta Decay (IBD)



Daya Bay, RENO & Double Chooz



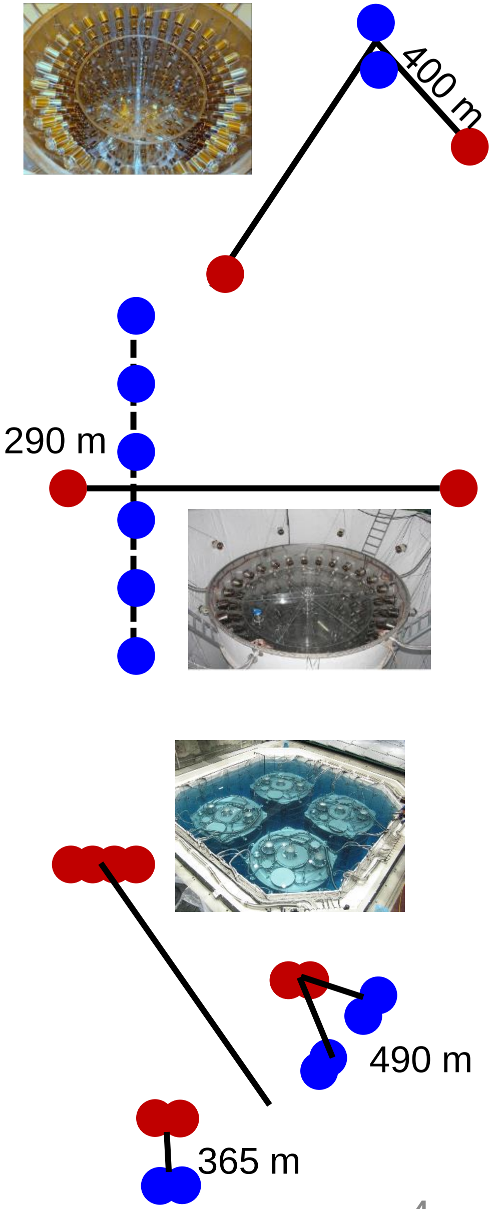
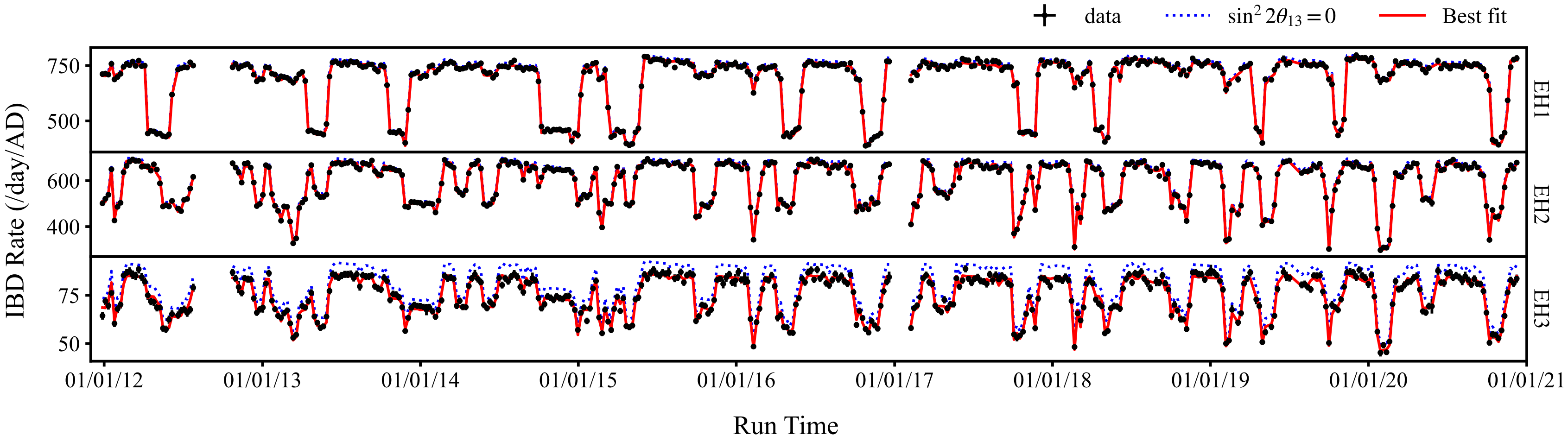
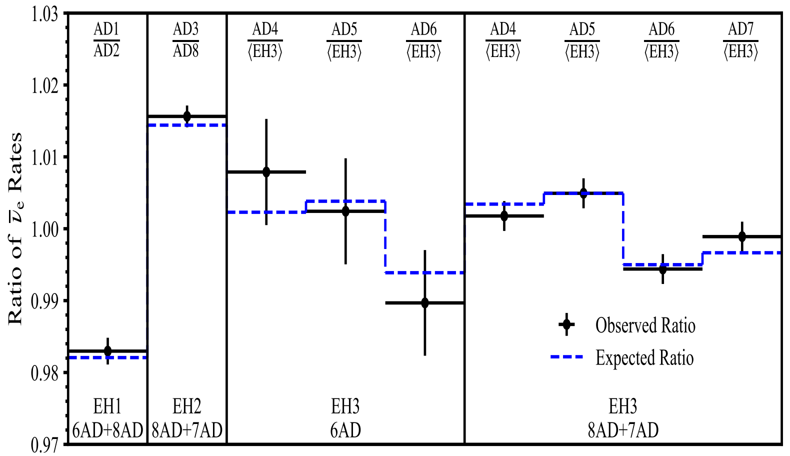


Diagram Courtesy:
Soren Jetter

Daya Bay

Updated Results from Daya Bay by Runze Zhao





Completed in Dec. 2020, 3158 days in total. Side-by-side measurements confirm the 0.13% uncertainty in Det. eff.

Best-fit results:

$$\sin^2 2\theta_{13} = 0.0851^{+0.0024}_{-0.0024} \quad (2.8\%)$$

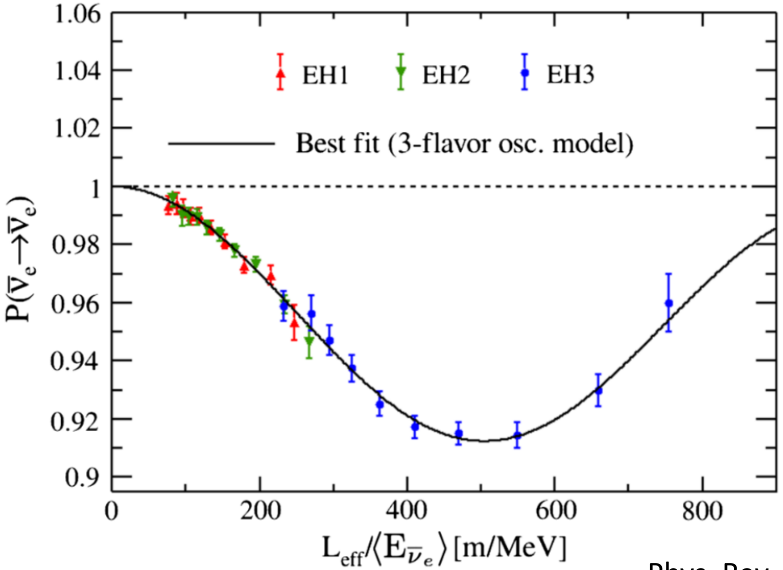
Normal hierarchy:

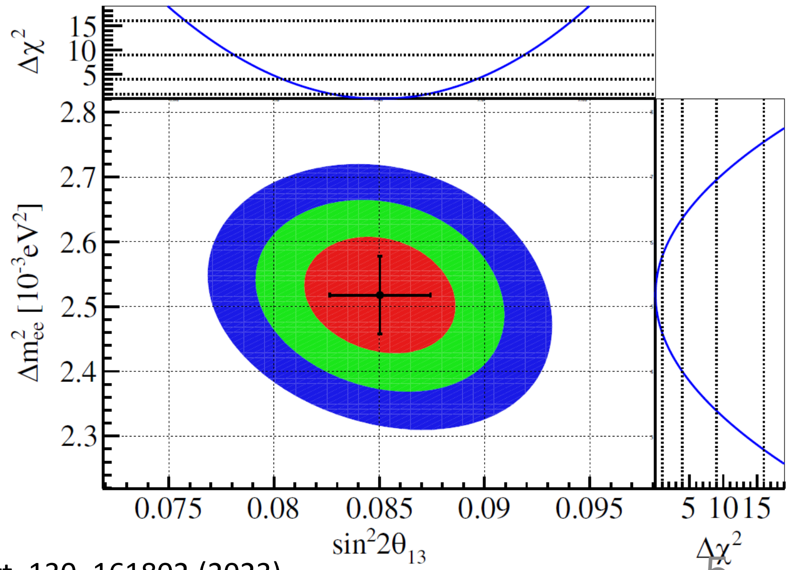
$$\Delta m^2_{32} = +(2.466^{+0.060}_{-0.060}) \times 10^{-3}\mathrm{eV}^2 \quad (2.4\%)$$

Inverted hierarchy:

$$\Delta m^2_{32} = -(2.571^{+0.060}_{-0.060}) \times 10^{-3}\mathrm{eV}^2 \quad (2.3\%)$$

Expect final results on combined nGd+nH analysis: 2.6% for $\sin^2 2\theta_{13}$





Phys. Rev. Lett. 130, 161802 (2023)

RENO & Double Chooz

RENO

@ Neutrino2022 (~2900 d)

$\sin^2 2\theta_{13}$=0.0892±0.0044(stat.)±0.0045(sys.) **(7.0%)**

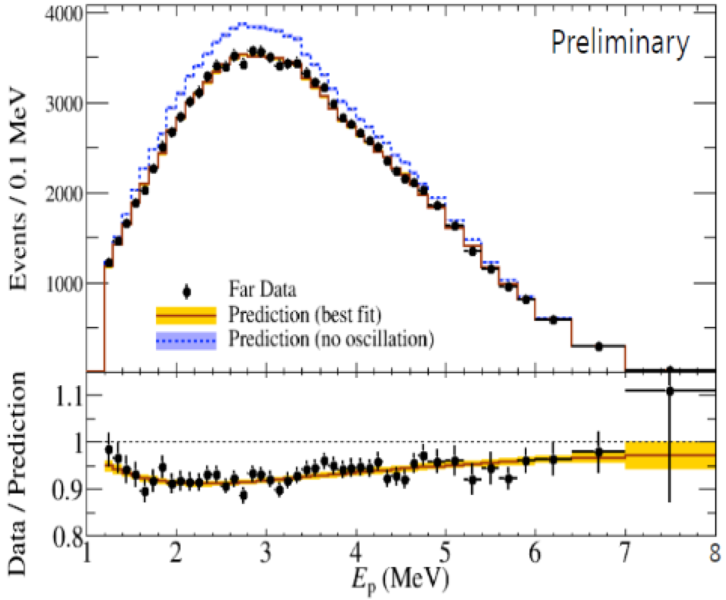
$|\Delta m^2_{ee}|$=2.74±0.10(stat.)±0.06(sys.)×10^{-3}eV^2 **(4.4%)**

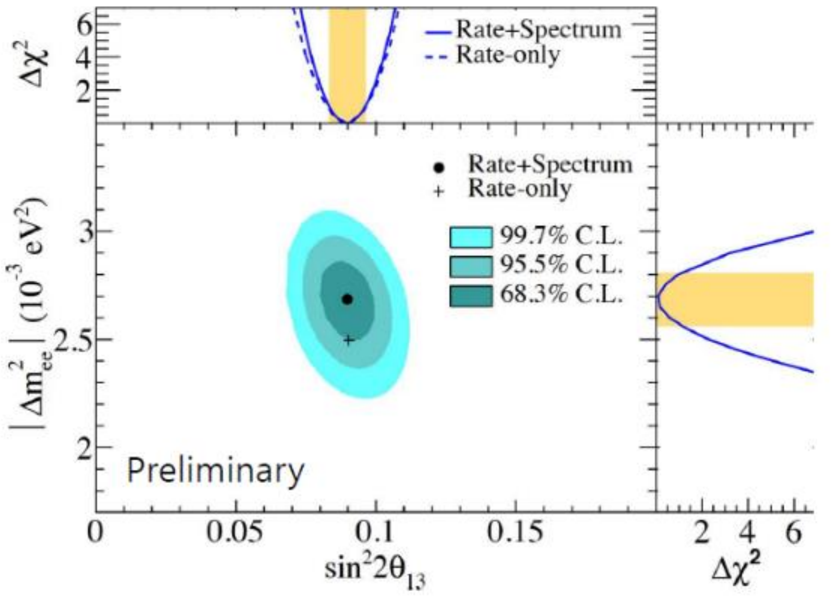
@ NuFact2023

Completed in 2023.03.16 (up to 3800 d), expect

$\sin^2 2\theta_{13}$: 6.3%, $|\Delta m^2_{ee}|$: 4.2%

Plan to reoperate the near detector for sterile ν

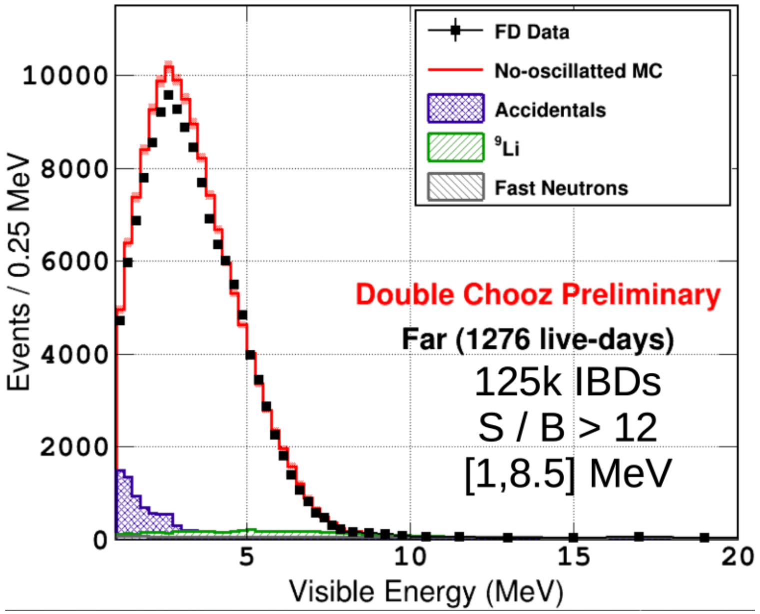


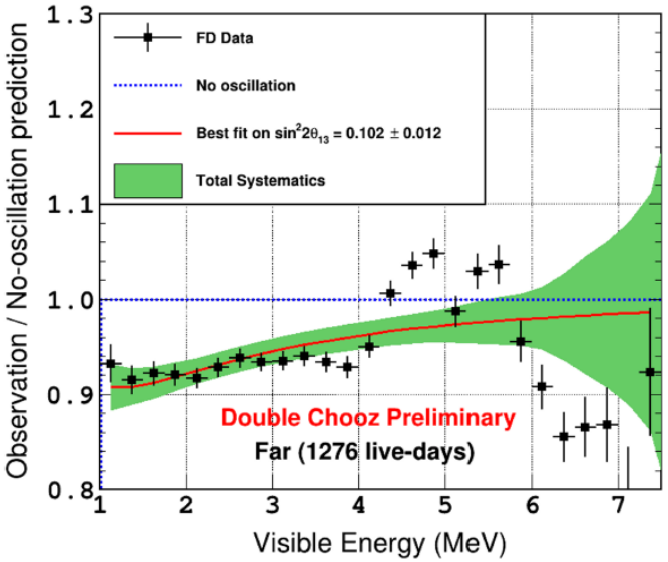


Double Chooz @ TAUP2023

$\sin^2 2\theta_{13}$=0.102±0.011 (syst.) ±0.004 (stat.) **(11.4%)**

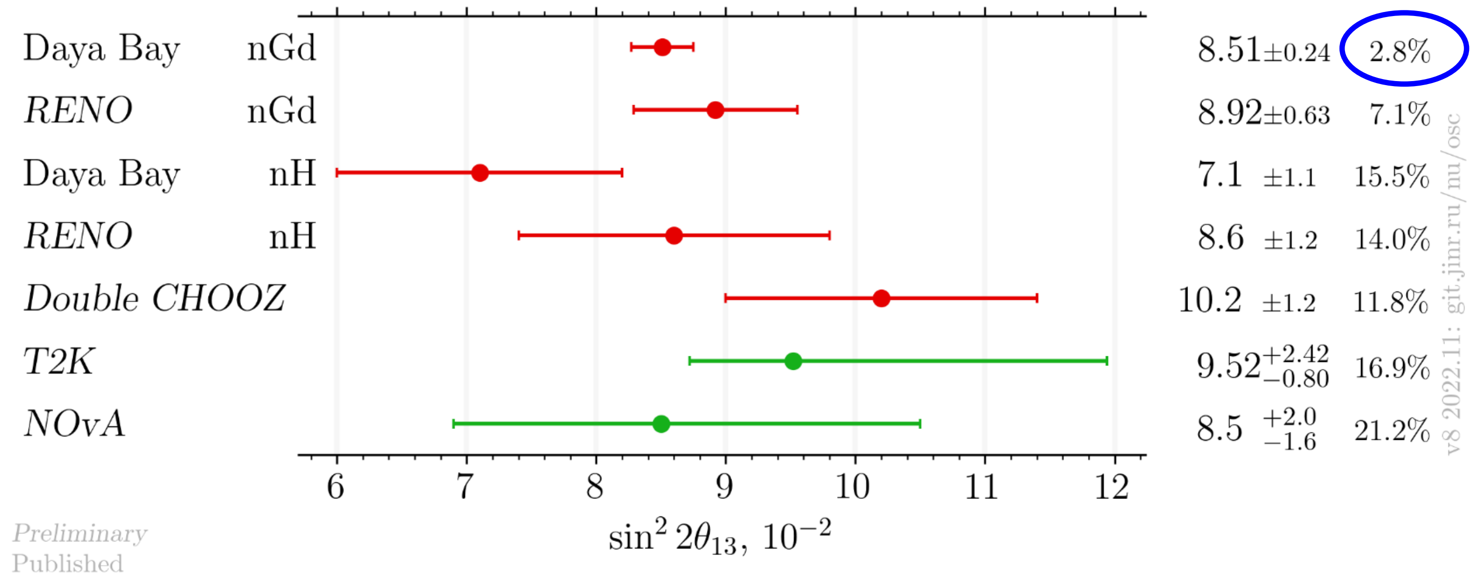
w/ 1276 live-days Far, 587 live-days Near



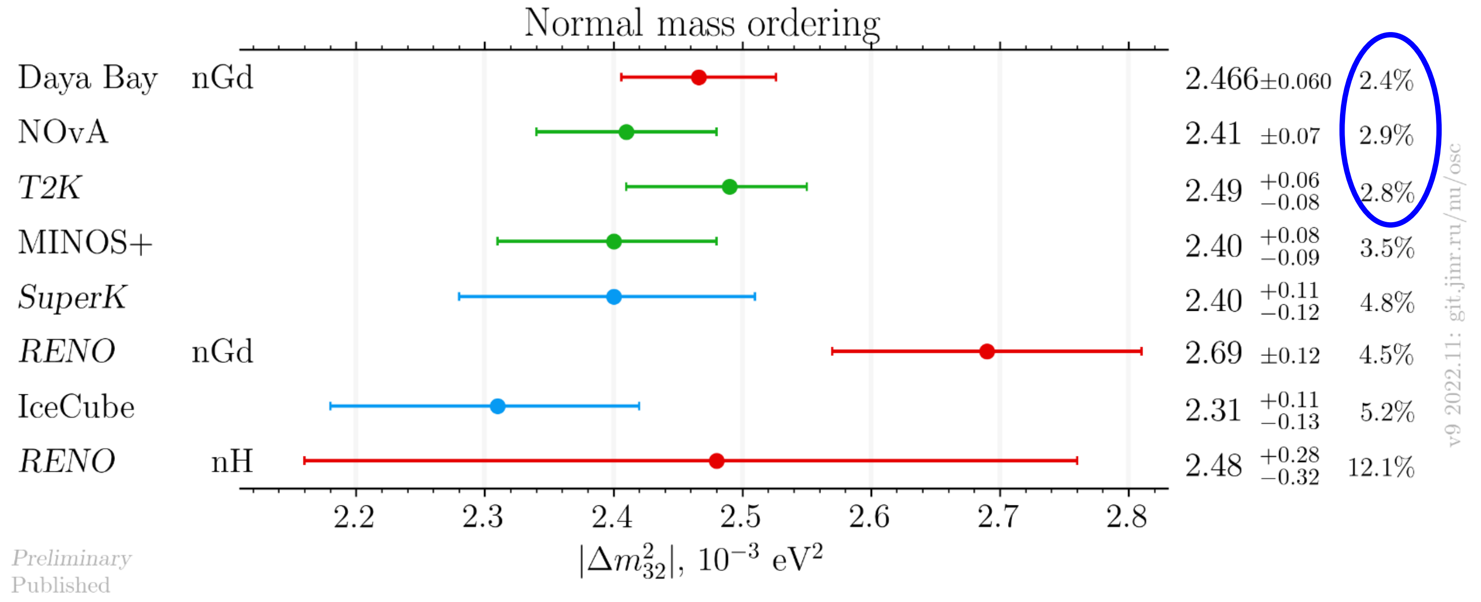


Global Picture for θ_{13}

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



Δm^2_{32} (NO)



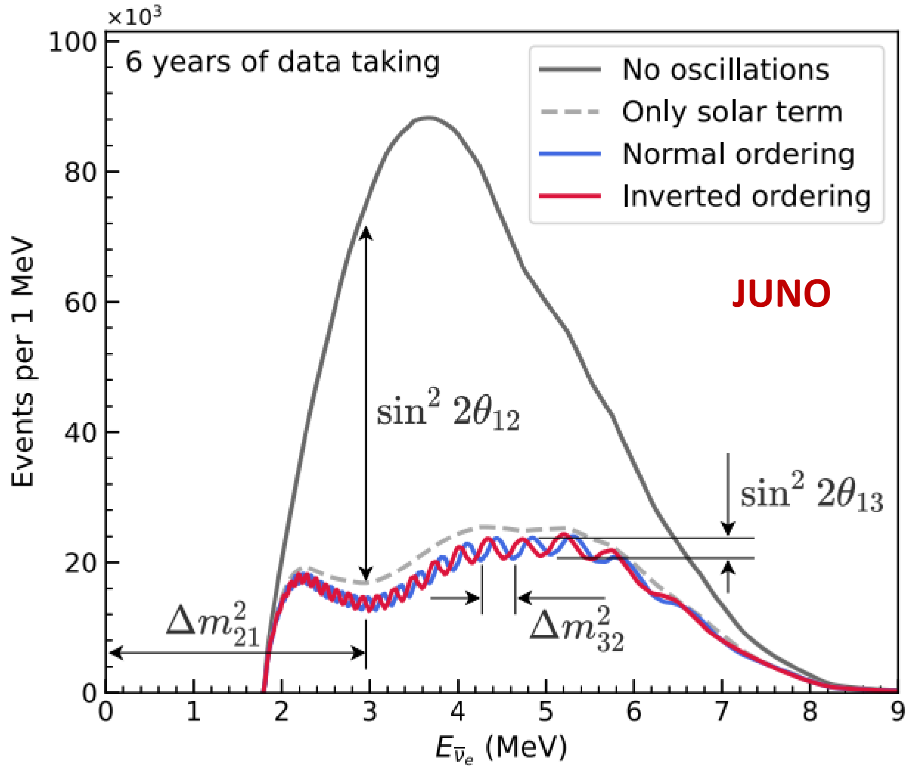
Greatly consistent results from $\bar{\nu}_e$ (reactor) and ν_μ (accelerator) measurements, strongly support 3-flavor framework

Mass Ordering w/ reactors

- 'Vacuum oscillation' with reactor neutrinos → unique and complementary with accelerator/atmospheric experiments to determine neutrino mass ordering

$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$
$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$

- Precision measurements of θ_{12}, Δm^2_{21}, Δm^2_{32}
- Require huge mass and high energy resolution



(matter effect contributes maximal ~4% correction at around 3 MeV, *arXiv:1605.00900, arXiv:1910.12900*)

Δm^2_{31} and Δm^2_{32} interplay	Δm^2_{ee} and $\Delta m^2_{\mu\mu}$ difference	Matter Effect

Reactor

Atmospheric

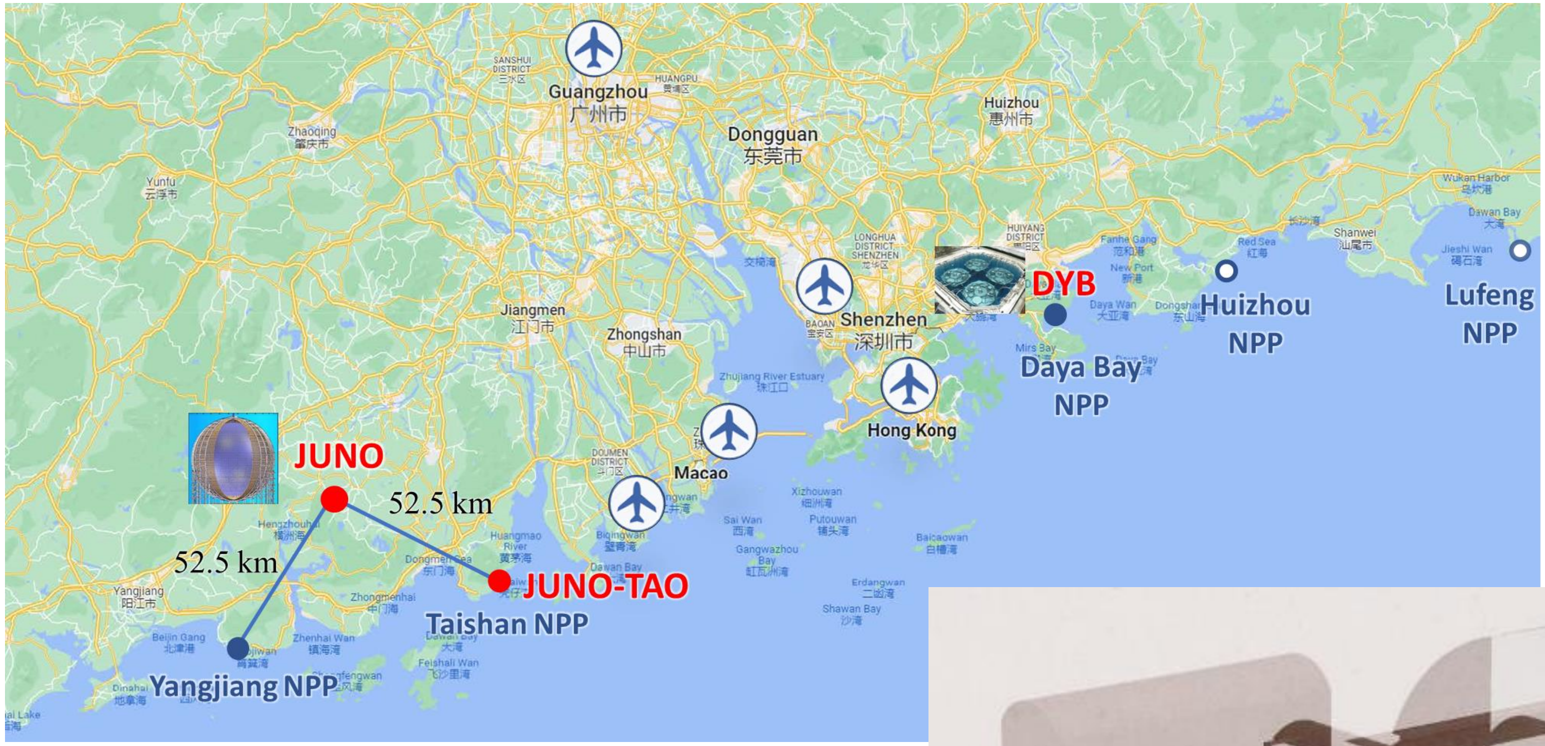
Accelerator

$$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

$$\Delta m^2_{\mu\mu} = \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32} + \cos\delta\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\Delta m^2_{21}$$

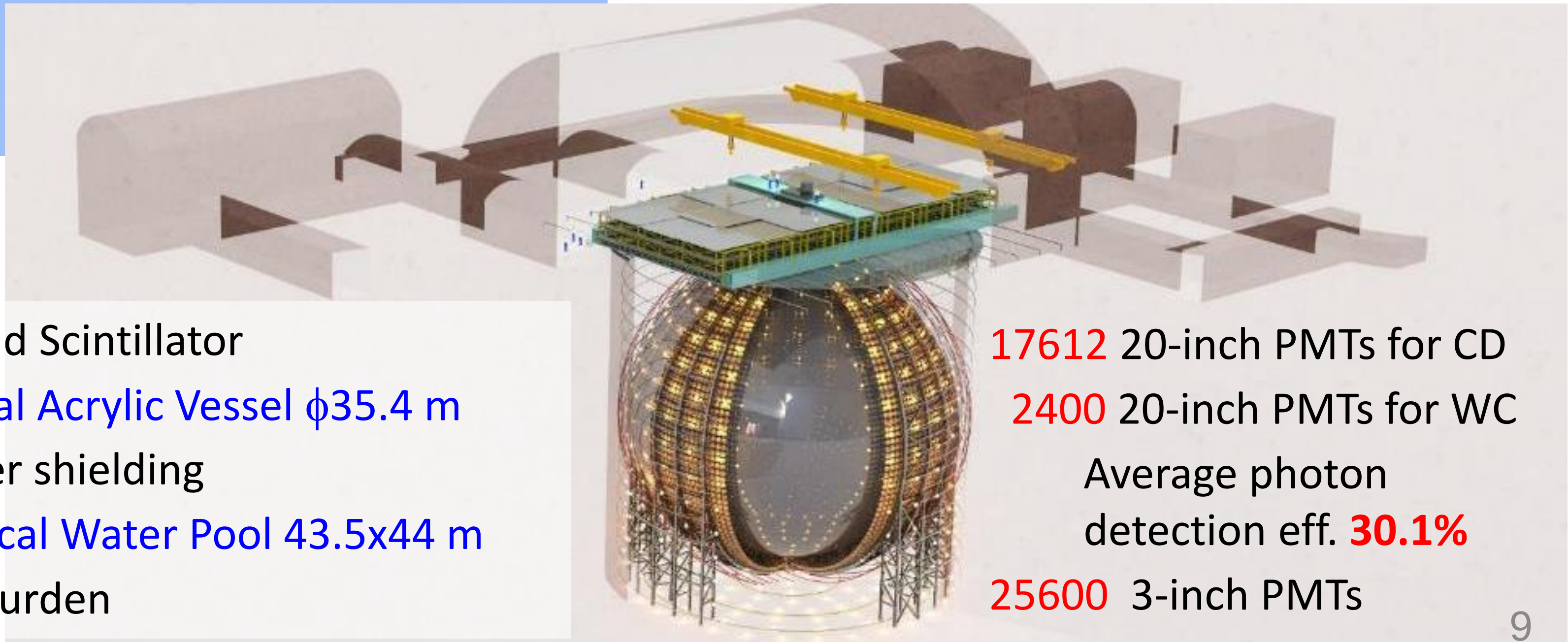
$$|\Delta m^2_{ee}| - |\Delta m^2_{\mu\mu}| = \pm\Delta m^2_{21}(\cos 2\theta_{12} - \cos\delta\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23})$$

Jiangmen Underground Neutrino Observatory (JUNO)



JUNO collaboration: >700 collaborators,
74 institutions, 17 countries/regions

Yangjiang NPP: 2.9 GW x 6
Taishan NPP: 4.6 GW x 2
Equal baseline: 52.5 km



20 kton Liquid Scintillator
Spherical Acrylic Vessel ϕ35.4 m
35 kton water shielding
Cylindrical Water Pool 43.5x44 m
700 m overburden

17612 20-inch PMTs for CD
2400 20-inch PMTs for WC
Average photon detection eff. **30.1%**
25600 3-inch PMTs

JUNO Status & Prospects by Marco Grassi

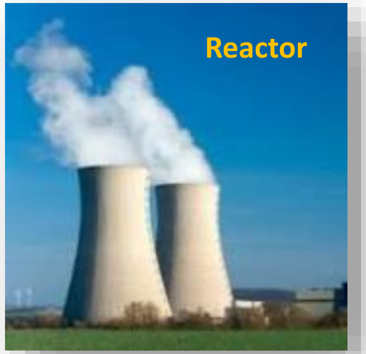
JUNO Campus

- Project approved in 2013
- Civil construction started in 2015
- Completed excavation on Dec. 30, 2020
- Detector assembly & installation ongoing
- Expect physic data in 2024

JUNO Physics

Machine Learning reconstruction: Arsenii Gavrikov
B8 solar neutrino (poster): Xin Zhang

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

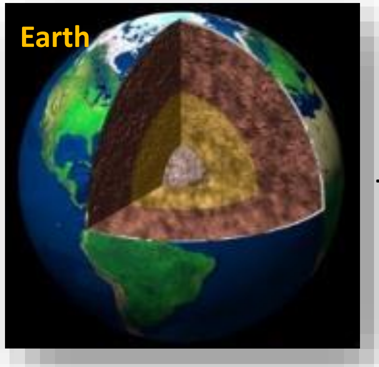


~60 IBDs per day

Several per day

Hundreds per day

~5000 IBDs for CCSN @10 kpc



Several IBDs per day

\+ New physics

IBD: inverse beta decay
CCSN: core-collapse supernova
DSNB: Diffused Supernova Neutrino Background

Neutrino oscillation & properties

Neutrinos as a probe

- Energy resolution **2.95%** @ 1MeV w/ full simulation
- **ν mass ordering: 3σ (reactor only)** @ ~6 yrs (*Neutrino 2022*), atmospheric ν oscillation being improved
- **ν oscillation parameters:** precision of $\sin^2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|$ **< 0.5%** in 6 yrs (2204.13249)

- **Supernova** ν: ~7300 of all-flavor neutrinos @ 10 kpc
- **DSNB**: **3σ** in 3 yrs (2205.08830)
- **Solar** ν:
  - ^{7}Be, pep, CNO (2303.03910)
  - ^{8}B flux (2210.08437)
- **Geo** ν: ~400 per year, 5% precision in 10 yrs

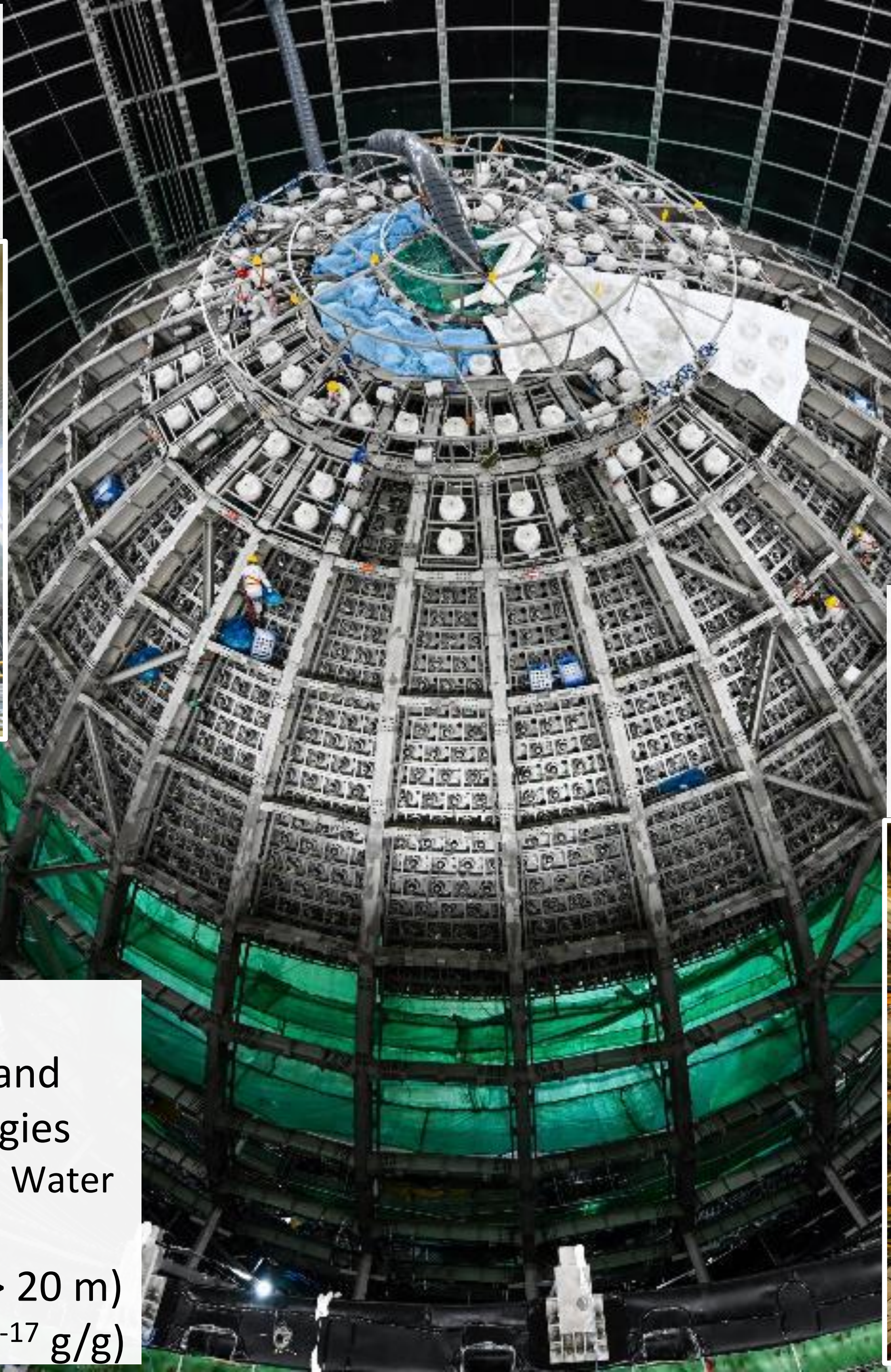
- **Nucleon Decays**: $p \to \bar{\nu} K^+$ 9.6×10^{33} yrs (90% C.L.) in 10 yrs (2212.08502), neutron invisible decay (ongoing)
- **Indirect DM search:** ~good sensitivity in 15-100 MeV region (2306.09567)
- **Future upgrade (2030s) : searching for 0νββ**

Spherical acrylic vessel

- All 265 panels fabricated, ultra-low U/Th impurities (< 1 ppt)
- >50% sphere is finished

Stainless Steel structure

- Sub-centimeter precision, satisfies precision requirement of PMT installation



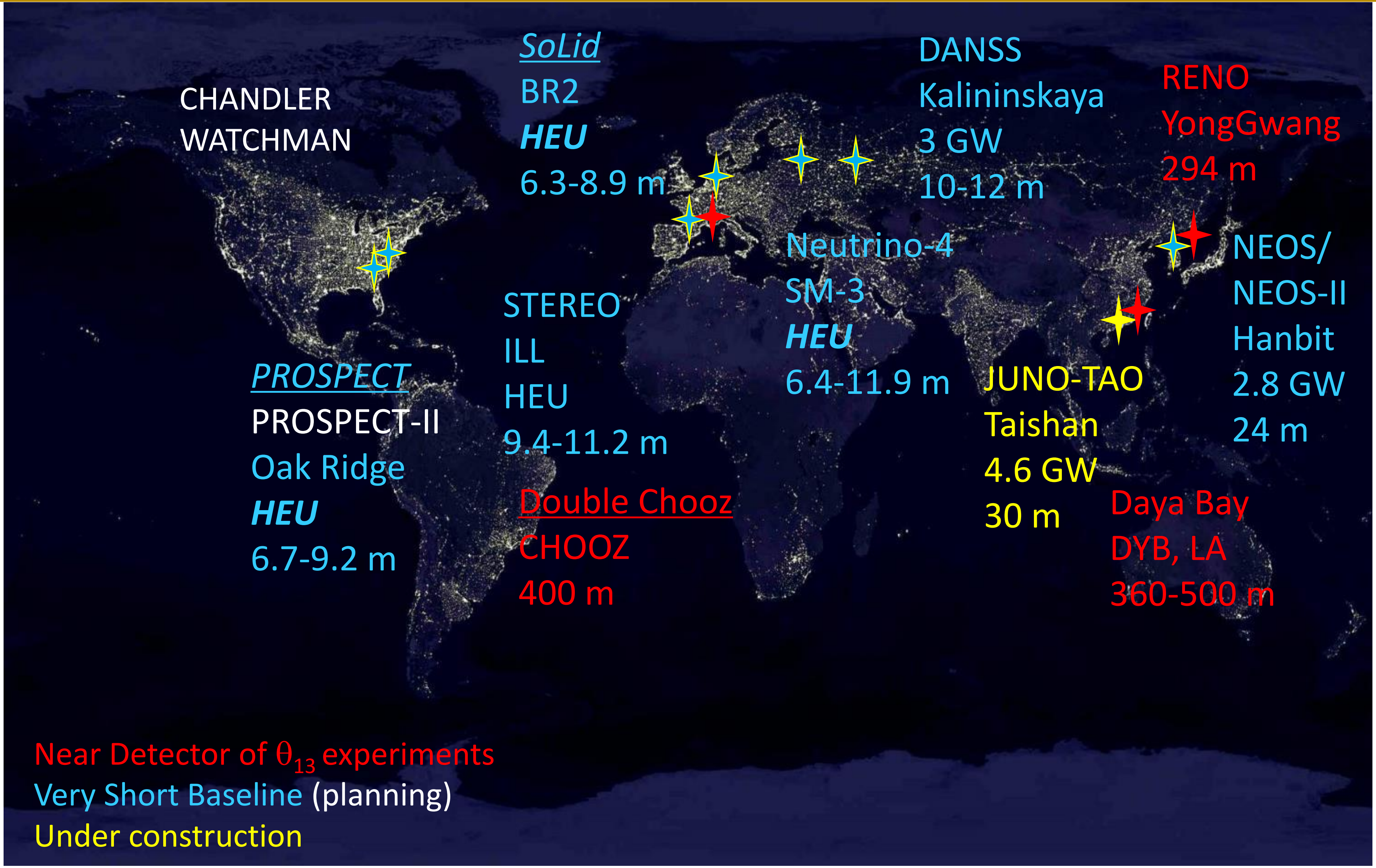
20012 20’’ PMTs + 25600 3’’ PMTs

- High performance MCP-PMT achieved
- Production and performance test done
- >30% LPMTs & SPMTs installed

Liquid scintillator

- The most complex system designed and built, with four purification technologies (Al_2O_3 filtration, Distillation, Gas tripping, Water extraction), under commissioning
- Target: Excellent transparency ($\lambda_{A.L.}$ > 20 m) and ultra-low radioactivity (U/Th<10^{-17} g/g)

VSBL & θ_{13} Near Detectors



VSBL experiments

- Segmented/movable detectors → allow a oscillation measurement within/with the same detector
- 0.9 – 4 tons @ O(10 m)

JUNO-TAO

- Homogeneous, 2.8 ton
- High E-res: <2%@1 MeV
- High precision of E calib.

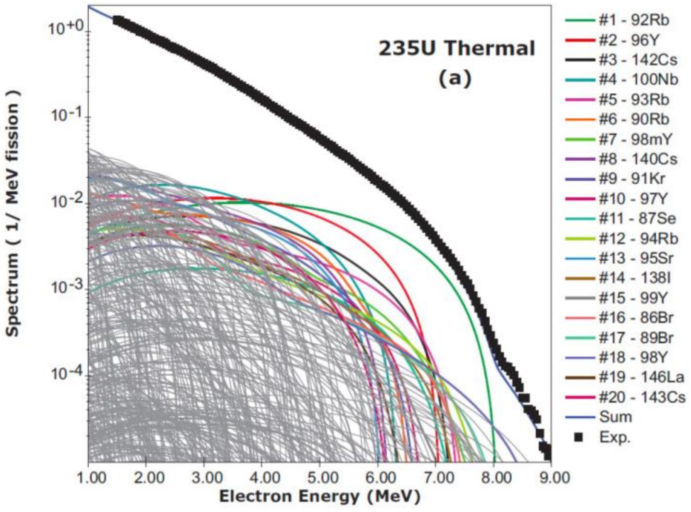
θ_{13} near detectors

- Homogeneous, 16-80 ton
- O(300-500 m)
- High precision of E calib.

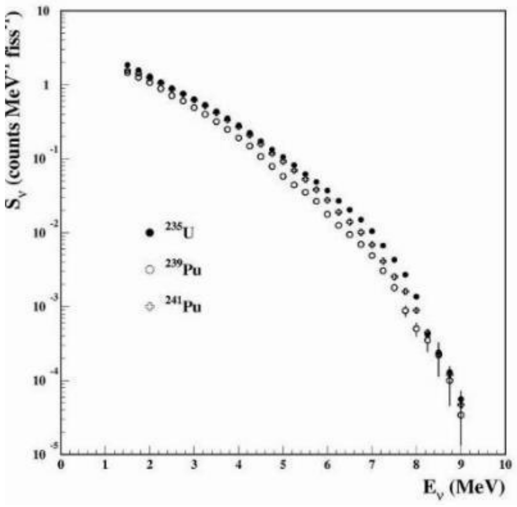
Low-Enriched Uranium (**LEU**) fueled reactor: Commercial, ~3 GW_{th}; Highly-Enriched Uranium (HEU)-fueled reactor: Research, 50-100 MW_{th}

Predicting the Flux and Spectrum

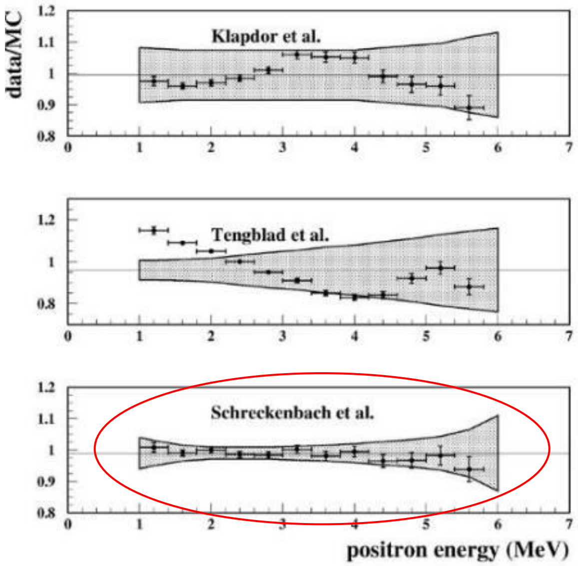
- **Summation (ab initio): Nuclear database, Σ fragments, Σ chains, Σ branches**
  (e.g. Vogel et al., PRC24, 1543 (1981), Estienne, et al, PRL 123, 022502 (2019))
- **Conversion: ILL measured the β-spectra → convert to neutrino spectra**
  - ⇨ **ILL spectra: Use spectra of 30 virtual (allowed) decays, fit amplitude and endpoints (ILL-Vogel spectra)**
  - ⇨ **Mueller: 90% ab initio + 10% fit → rate anomaly** *Mention et al. Phys. Rev. D83, 073006 (2011)*
  - ⇨ **Huber: fit w/ improved nuclear effects (Huber-Mueller spectra)** *Huber. Phys. Rev. C 84, 024617 (2011)* *Mueller et al, Phys. Rev. C 83, 054615 (2011)*



A. Sonzogni, PRC 91, 011301(R) (2015)



K. Schreckenbach et al. PLB118, 162 (1985)
A.A. Hahn et al. PLB160, 325 (1985)

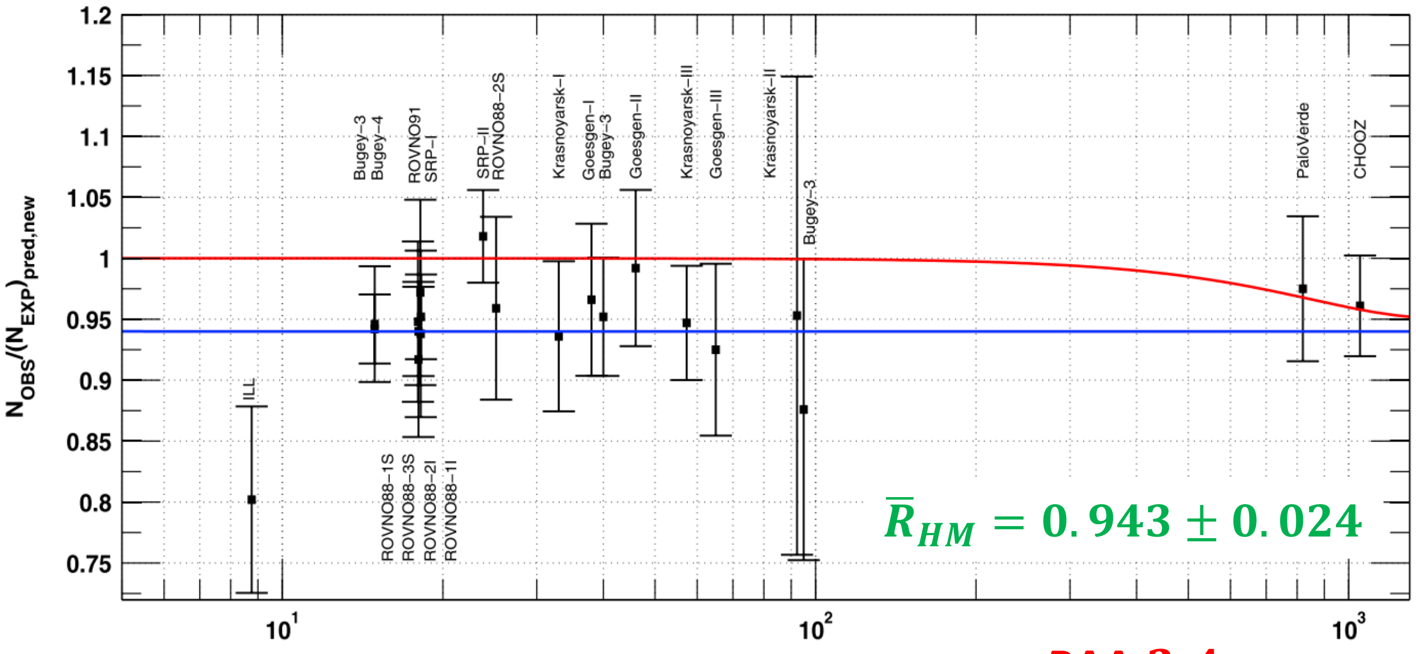


B. Achkar et al., PLB374 (1996) 243-248

Shape verified by Bugey-3 data
Normalization by Bugey-4, 1.4%, see Declais et al. (Bugey), Phys. Lett. B338 (1994) 383-389.

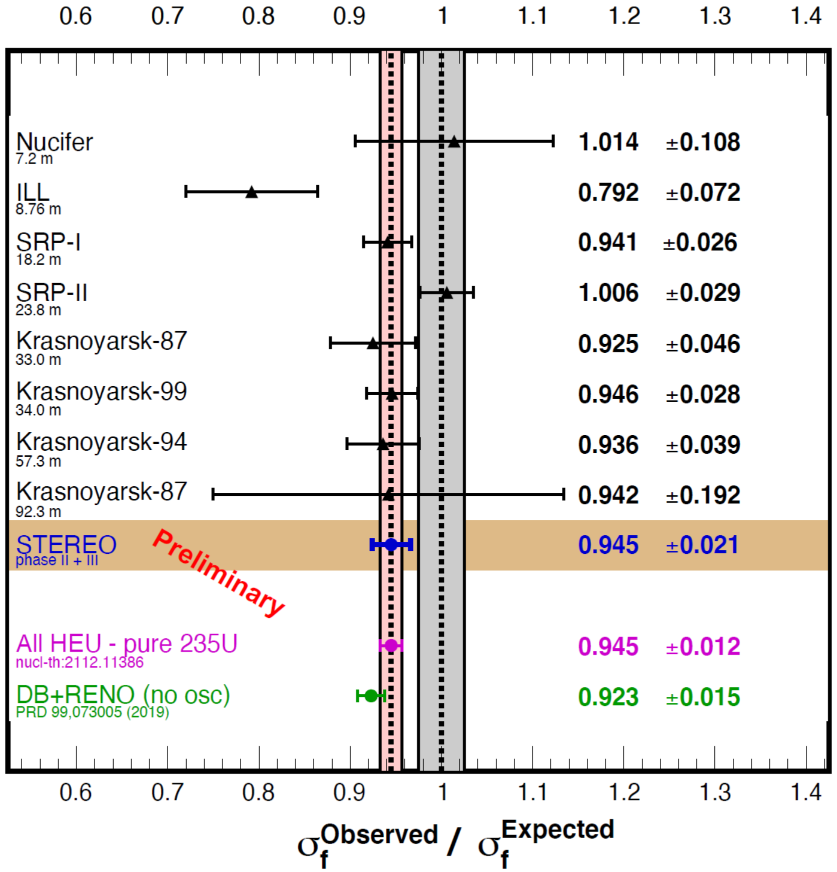
Reactor Anomaly Confirmed (w.r.t to H-M model)

- Reactor Antineutrino Anomaly (RAA – rate deficit w.r.t the Huber-Mueller spectrum) confirmed by many experiments



Mention et al. Phys. Rev. D83, 073006 (2011)

RAA: $2.4\ \sigma$



STEREO @ NOW2022, also see PRL 125, 201801 (2020)

- data/H-M ratio
  - Average ~0.936 for all
  - Average ~0.945 for pure U235

Model	H-M	HKSS	KI	HKSS-KI	EF
R	$0.936^{+0.024}_{-0.023}$	$0.925^{+0.025}_{-0.023}$	$0.975^{+0.022}_{-0.021}$	$0.964^{+0.023}_{-0.022}$	$0.960^{+0.033}_{-0.031}$
RAA	$2.5\ \sigma$	$2.9\ \sigma$	$1.1\ \sigma$	$1.5\ \sigma$	$1.2\ \sigma$

HKSS: Hayen-Kostensalo-Severijns-Suhonen KI: Kurchatov Institute EF: Estienne-Fallot

KI and EF models compatible with NO osci.

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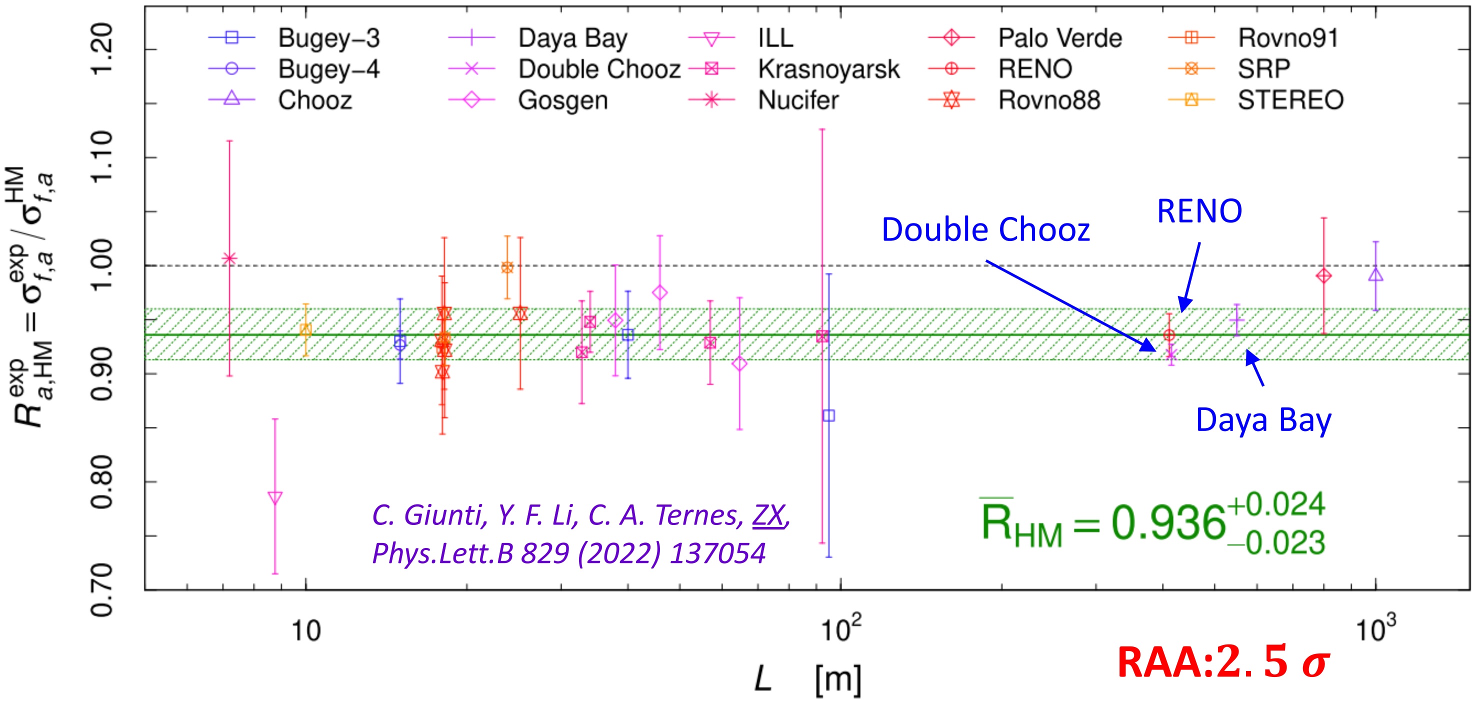
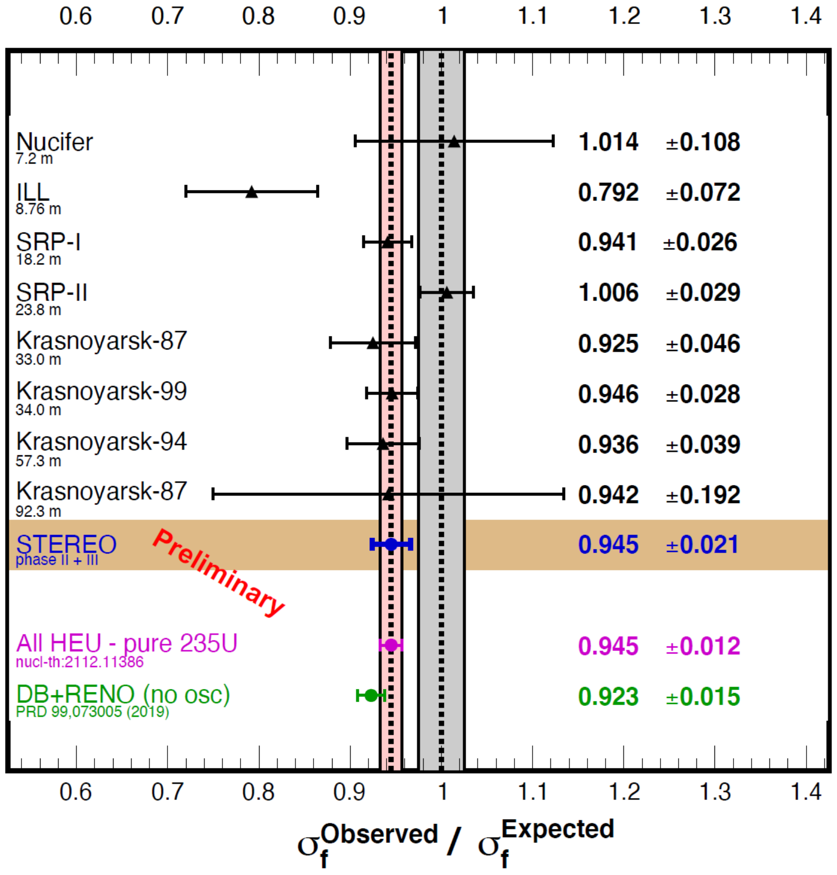


RAA:2.5 σ



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R	$0.936^{+0.024}_{-0.023}$	$0.925^{+0.025}_{-0.023}$	$0.975^{+0.022}_{-0.021}$	$0.964^{+0.023}_{-0.022}$	$0.960^{+0.033}_{-0.031}$
RAA	2.5 σ	2.9 σ	1.1 σ	1.5 σ	1.2 σ

HKSS: Hayen-Kostensalo-Severijns-Suhonen KI: Kurchatov Institute EF: Estienne-Fallot

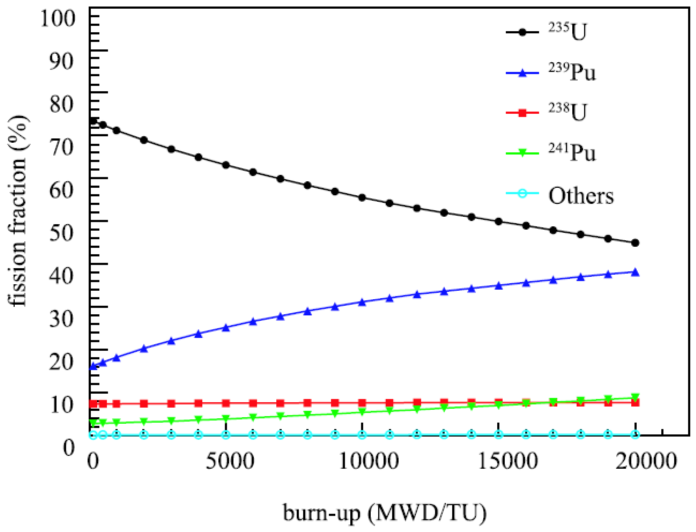
KI and EF models compatible with NO osci.

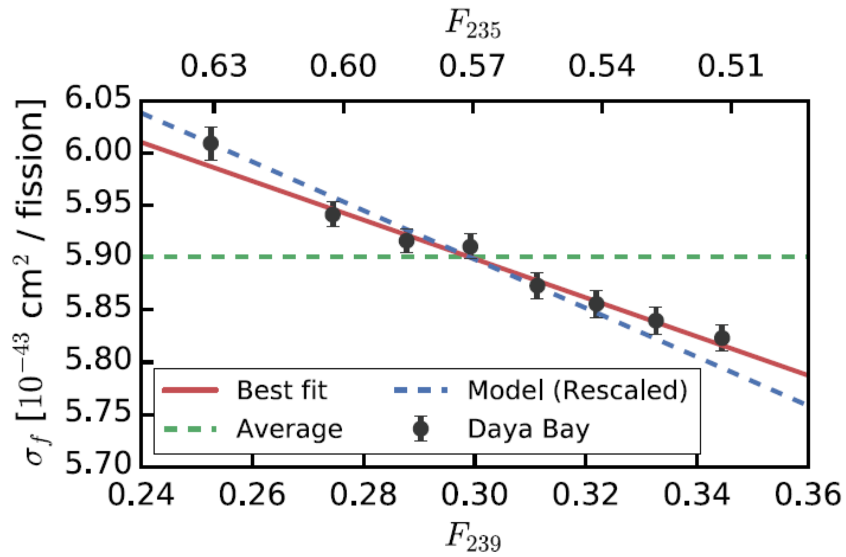
RAA not likely due to Sterile Nu

Fuel evolution

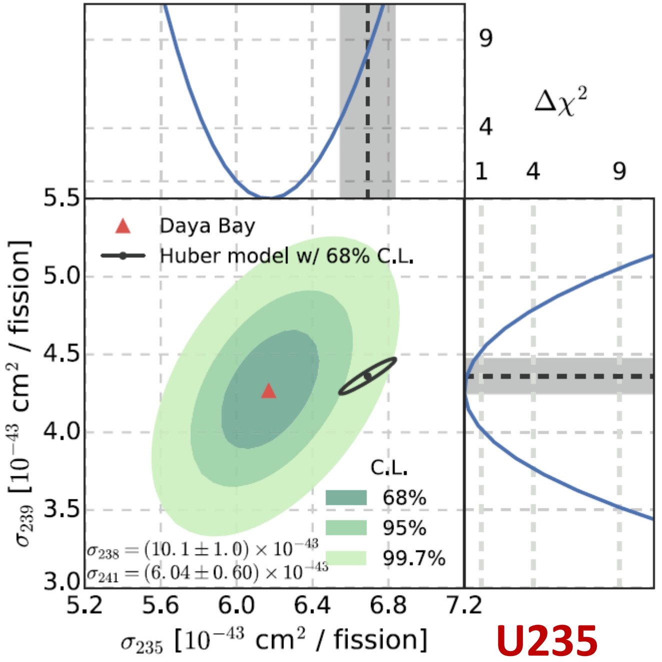
→ **ONLY U235 has deficit, NOT Pu239**

→ **NOT due to oscillation**



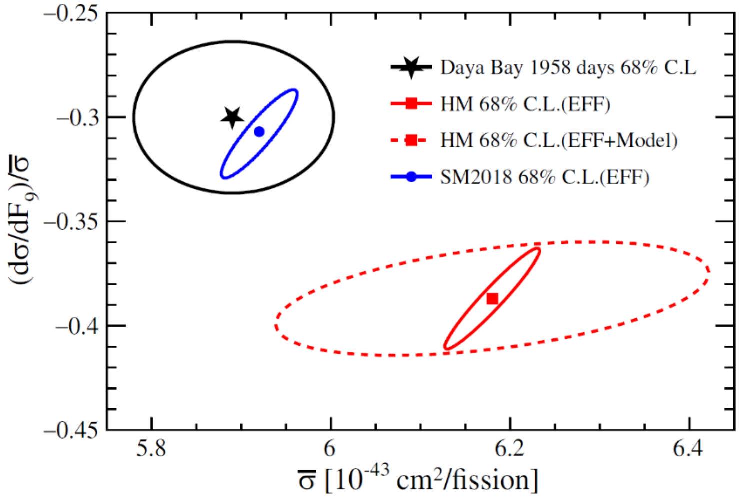


Pu239

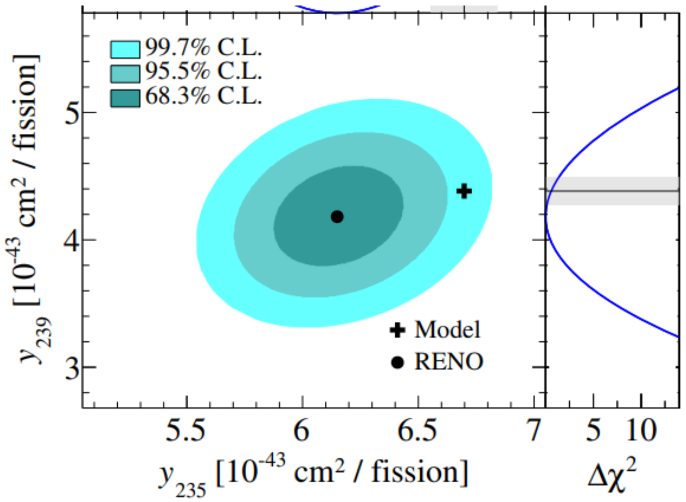


U235

Daya Bay, PRL 118, 251801 (2017)



Daya Bay, RPL 130, 211801 (2023)



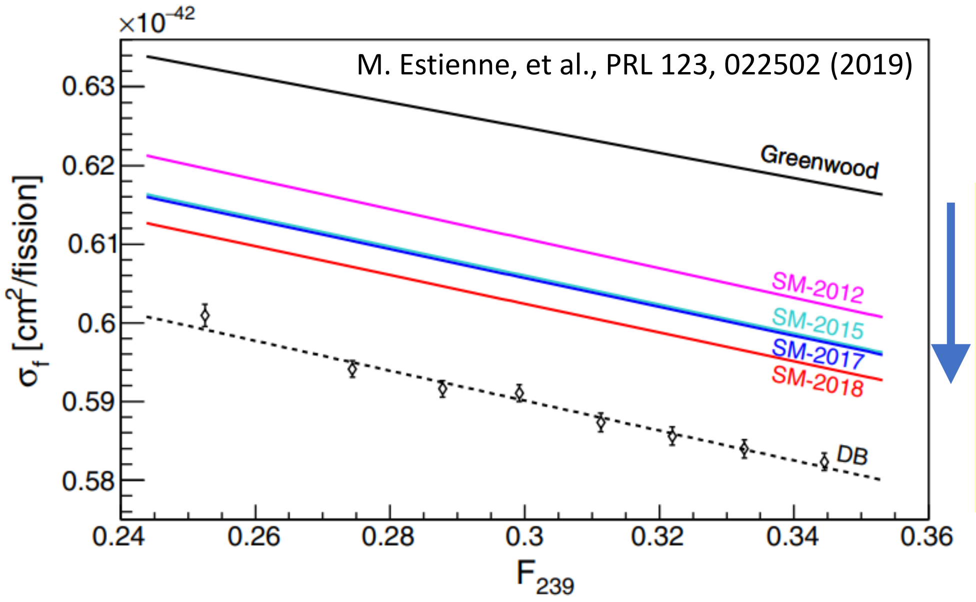
RENO, PRL 122, 232501 (2019)

Updated Reactor Neutrino Model

Summation (or, Ab Initio) Method

- Pandemonium effects - undetected weak beta transitions and low-intensity γ radiation (J. Hardy et al. 1977).

  ➔ Improving with the Total Absorption Gamma Spectrometers (TAGS) measurements in the past decade



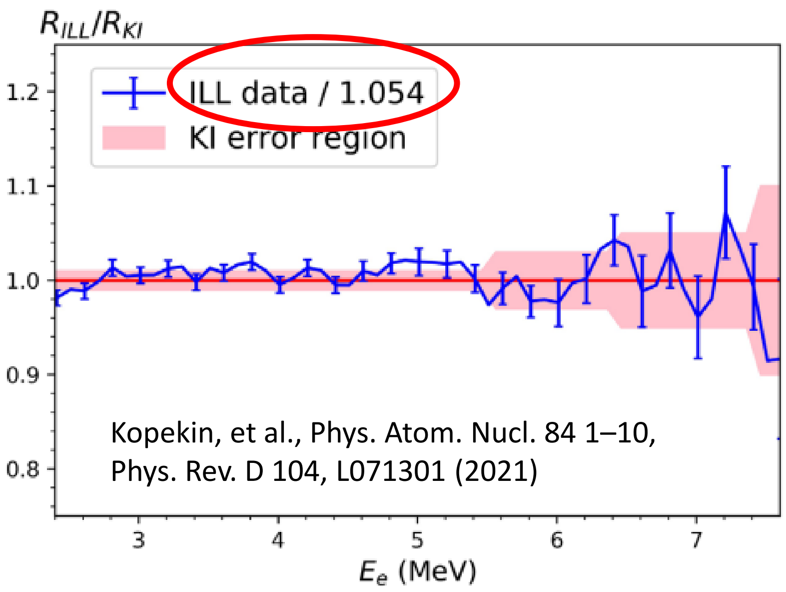
Reproduce fuel evolution slope

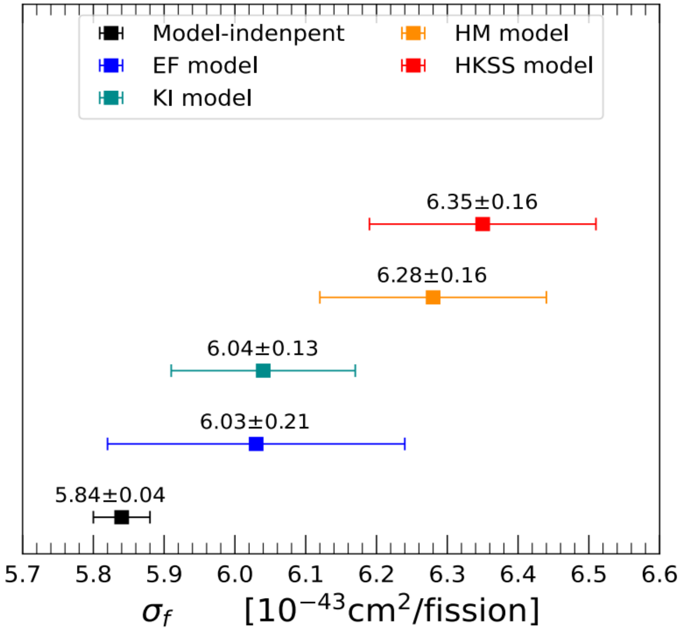
Rate deficit also exists w.r.t. the summation prediction, but shrinking w/ new data.
Now 1.9% deficit.

Conversion Method

- New measurement of $^{235}U/^{239}Pu$ fission beta spectrum ratio at Kurchatov Institute

  ➔ ILL normaliation





Data-driven model:

A global fit

Y. F. Li, ZX,
PRD 105 (2022) 7, 073003

Spectrum Anomaly

Spectrum Anomaly Significance

Daya Bay:

- **5.3 σ** (overall)
- **6.3 σ** (in 4-6 MeV bump)

also seen in RENO, Double Chooz

STEREO: 4.6 σ (bump)

NEOS/NEOS-II: deficit & 5 MeV bump for ^{235}U from HM model, not conclusive for ^{239}Pu

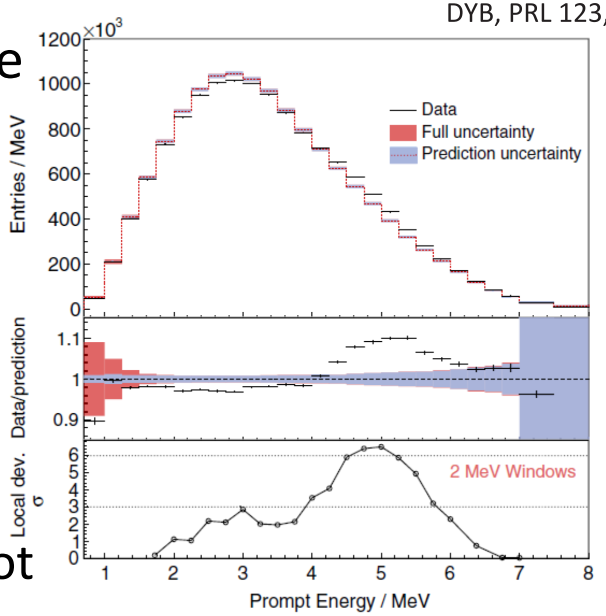
PROSPECT: 3.7 σ (no-^{235}U hypo.) & **2.0 σ** (all-^{235}U hypo.) for 5-7 MeV excess

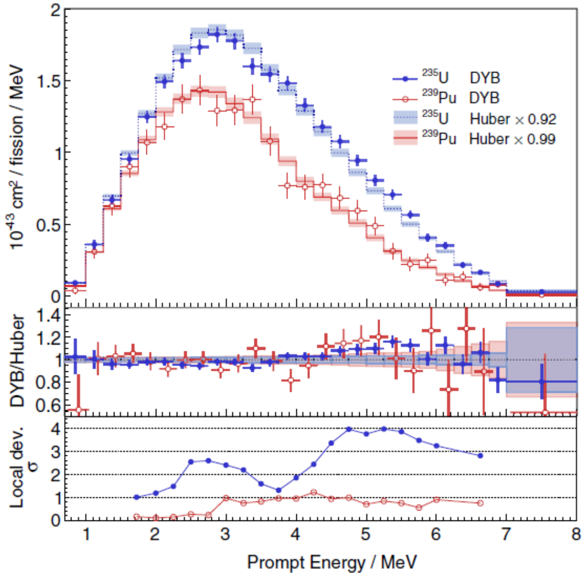
PRL 131, 021802 (2023)

Similar shape for Summation and Conversion, & in both ^{235}U and ^{239}Pu

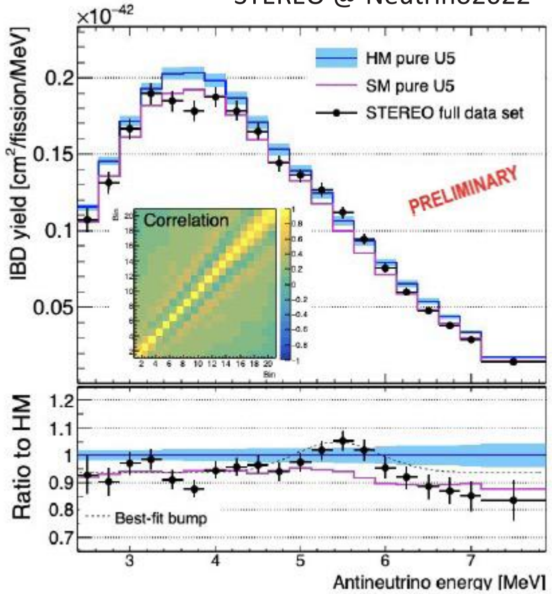
Forbidden beta decay? Others sources?

DYB, PRL 123, 111801 (2019)

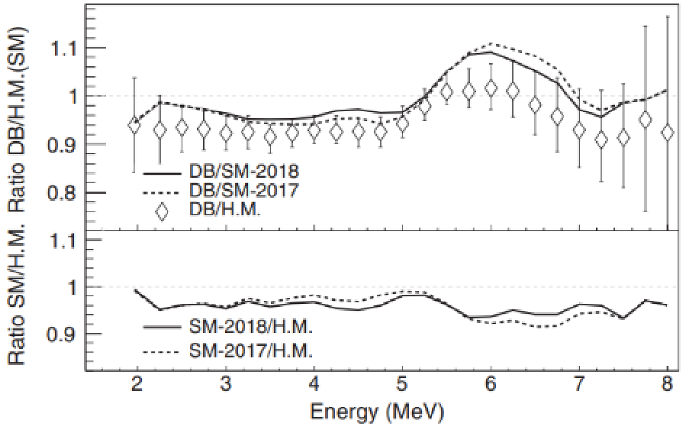


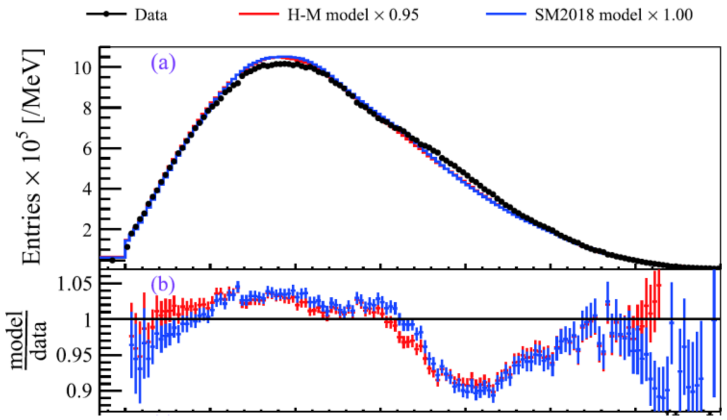


STEREO @ Neutrino2022



Estienne, et al, , PRL 123, 022502 (2019)





Daya Bay, CPC 2021, 45(7): 073001

Spectrum Anomaly

Spectrum Anomaly Significance

Daya Bay:

- **5.3 σ** (overall)
- **6.3 σ** (in 4-6 MeV bump)

also seen in RENO, Double Chooz

STEREO: 4.6 σ (bump)

NEOS/NEOS-II: deficit & 5 MeV bump for ^{235}U from HM model, not conclusive for ^{239}Pu

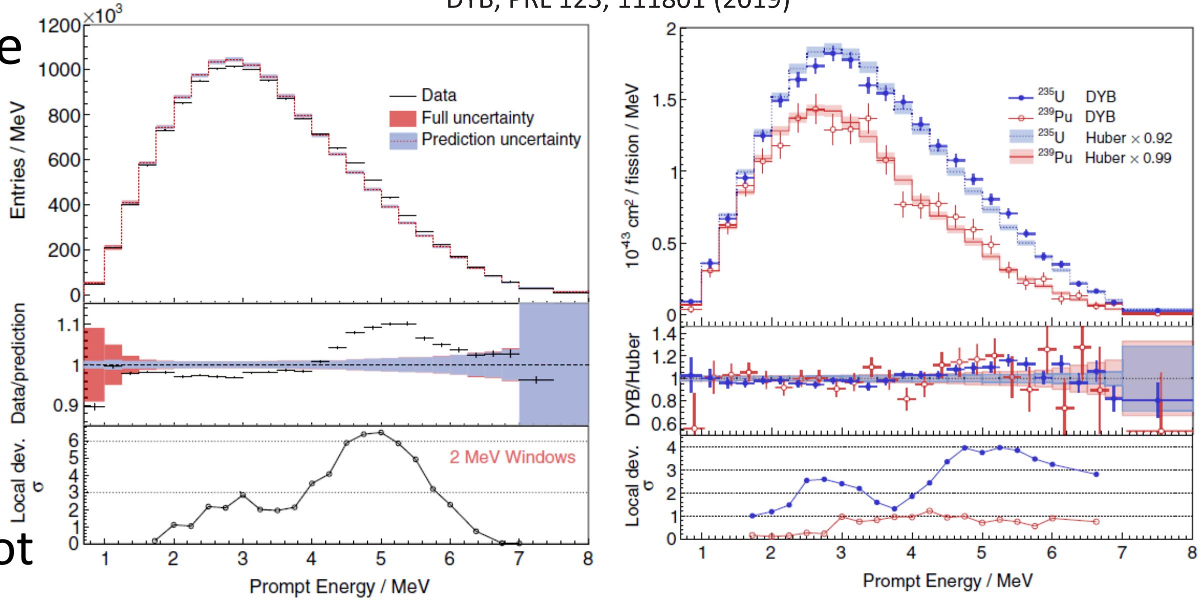
PROSPECT: 3.7 σ (no-^{235}U hypo.) & **2.0 σ** (all-^{235}U hypo.) for 5-7 MeV excess

PRL 131, 021802 (2023)

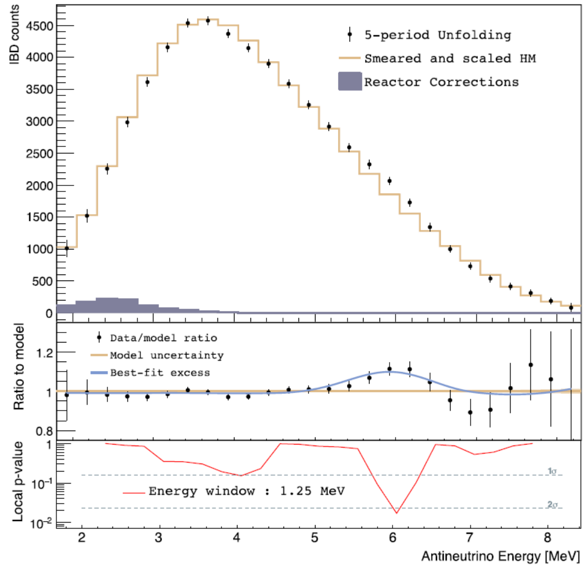
Similar shape for Summation and Conversion, & in both ^{235}U and ^{239}Pu

Forbidden beta decay? Others sources?

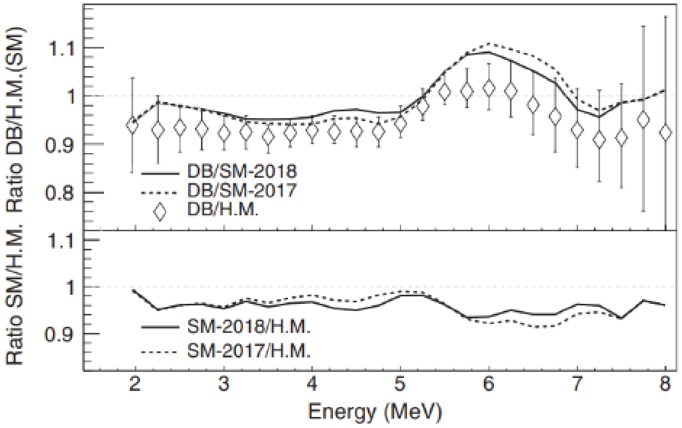
DYB, PRL 123, 111801 (2019)

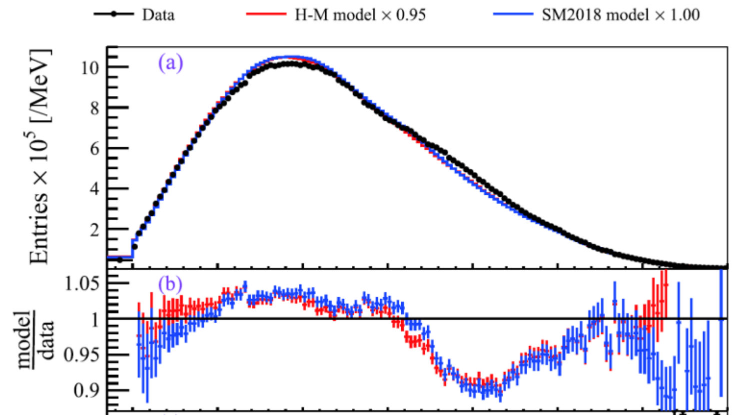


PROSPECT-I : PRL 131, 021802 (2023)



Estienne, et al, , PRL 123, 022502 (2019)

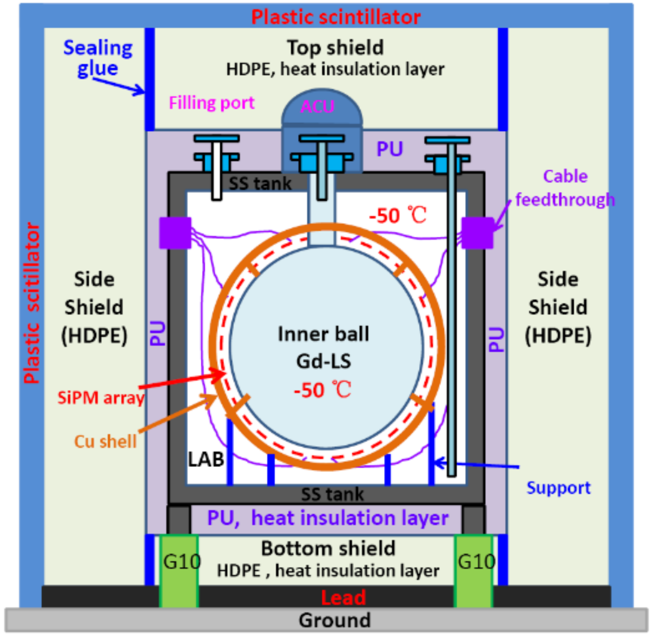




Daya Bay, CPC 2021, 45(7): 073001

Fine Structures in the Spectrum (JUNO-TAO)

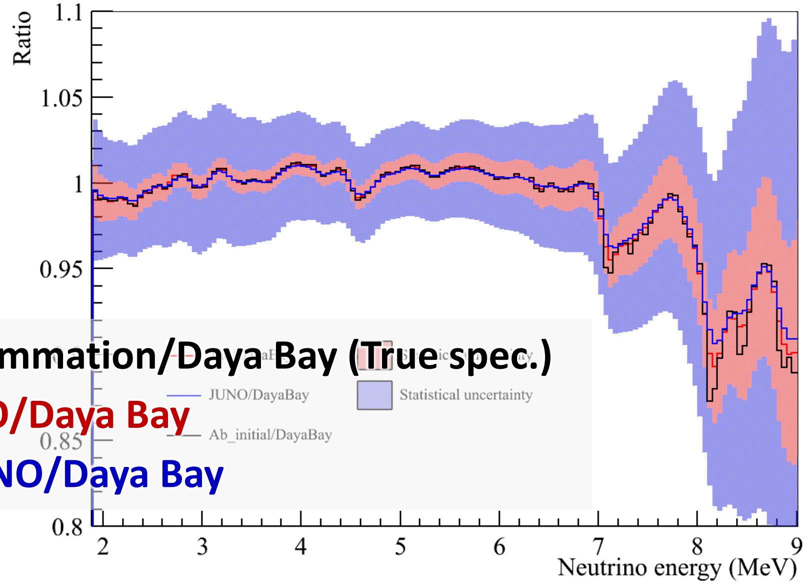
- **Taishan Antineutrino Observatory (TAO), a ton-level, high energy resolution LS detector at 30 m from the 4.6 GW_{th} core, a satellite exp. of JUNO.**
- **Measure reactor neutrino spectrum w/ high E resolution.**
  - **Model-independent reference spectrum for JUNO**
  - **A benchmark for testing the nuclear database**



CDR: 2005.08745

Calibration strategy: 2204.03256

- **Detector Features**
  - 2.8 ton Gd-LS, 10 m^2 SiPM (84.6% photocathode coverage) w/ PDE > 50%
  - Operate at -50 ℃ (SiPM dark noise)
  - 4500 p.e./MeV, <2% resolution @ 1MeV
- **Expected online in 2024**



Solid: Summation/Daya Bay (True spec.)
RED: TAO/Daya Bay
Blue: JUNO/Daya Bay

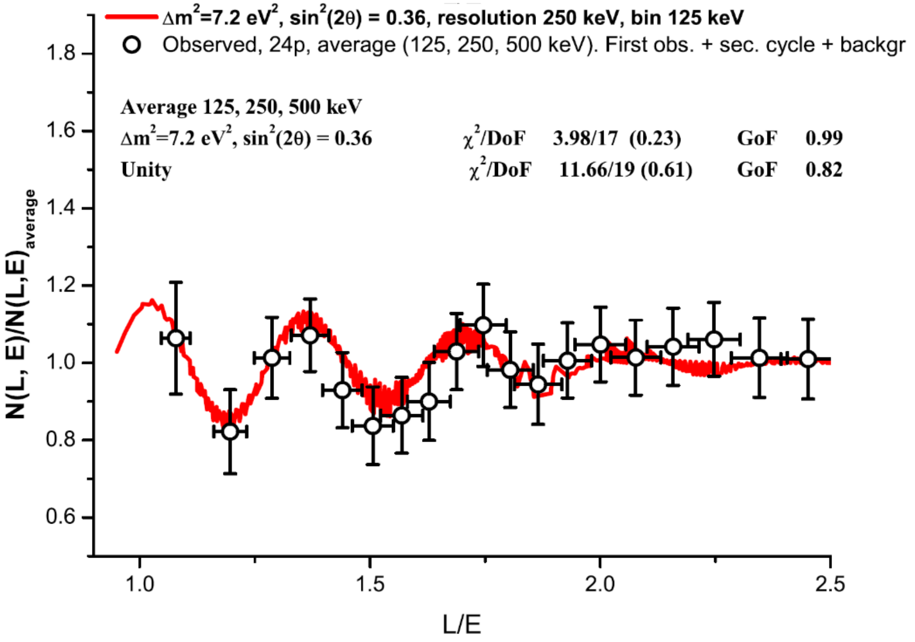
Constrain the fine structure in [2.5, 6] MeV to < 1%

2111.10112

Sterile ν searches – Positive

- If oscillating into sterile neutrino of ~ 1 eV mass → baseline ~10 m

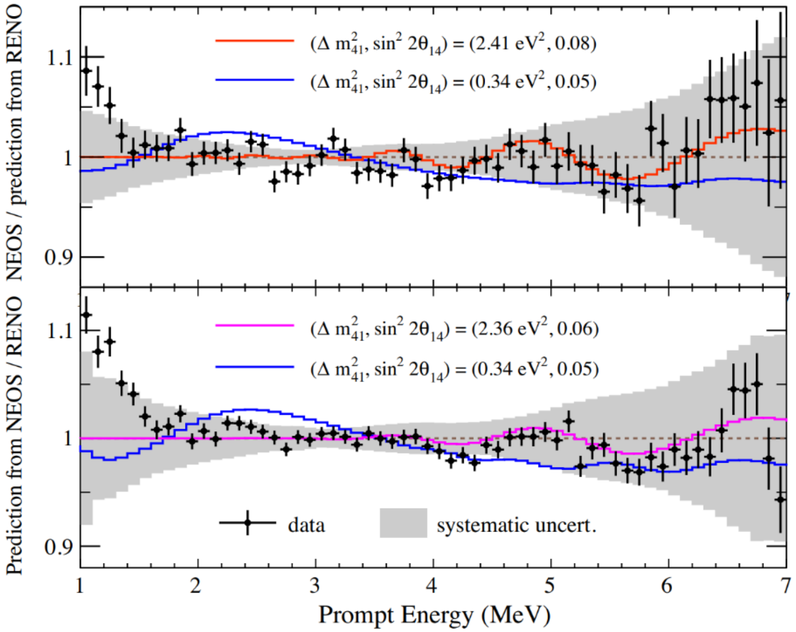
$$P_{ee} = 1 - \cos^4\theta_{41}\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}L}{4E_{\bar{\nu}_e}}\right) - \sin^2(2\theta_{41})\sin^2\left(\frac{\Delta m^2_{41}\,L}{4E_{\bar{\nu}_e}}\right)$$



$$\Delta m^2_{14} = (7.3 \pm 0.13_{st} \pm 1.16_{syst})\ \mathrm{eV}^2 = (7.3 \pm 1.17)\ \mathrm{eV}^2$$

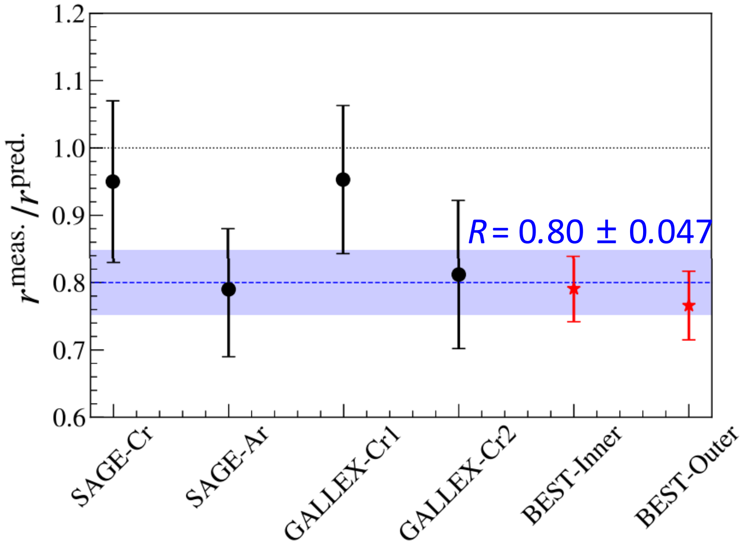
$$\sin^2 2\theta = 0.36 \pm 0.12_{stat}(2.9\sigma)$$

Neutrino-4, PRD 104 (2021) 032003



$(\Delta m^2_{41}, \sin^2 2\theta_{14}) = (2.41\ \mathrm{eV}^2, 0.08)$

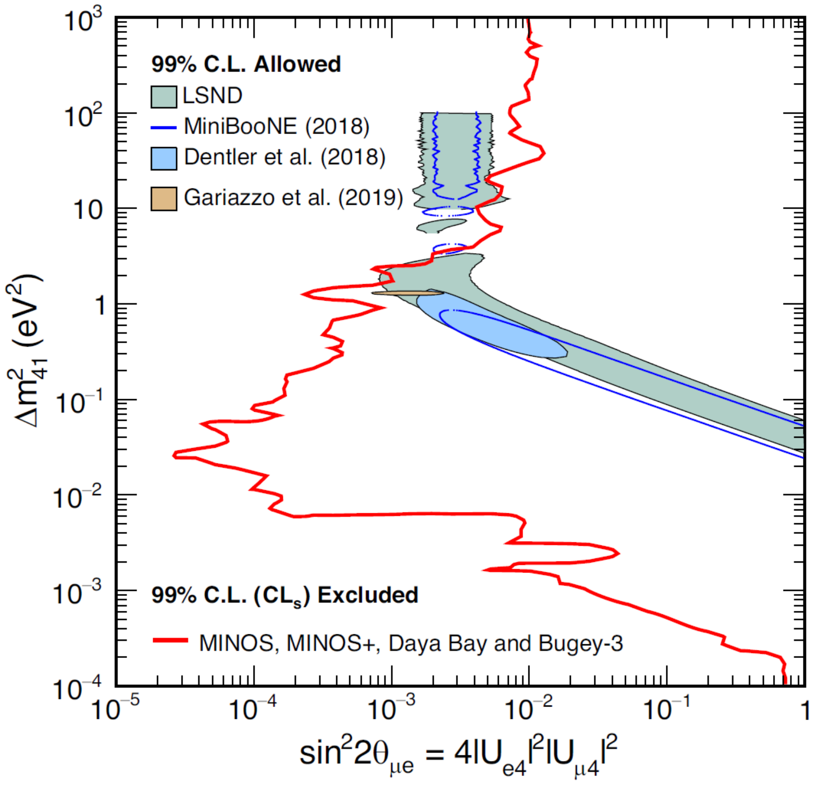
RENO-NEOS, arXiv:2011.00896, *PRD* 105 (2022) 11, L111101

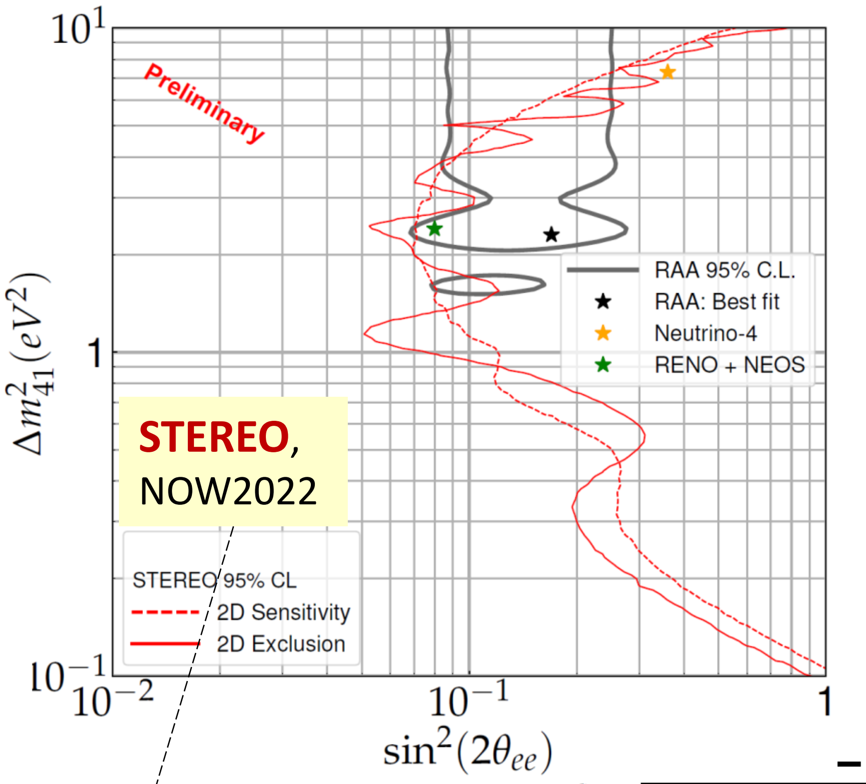


$\Delta m^2 > 0.5\ \mathrm{eV}^2$, $\sin^2 2\theta \sim 0.42$

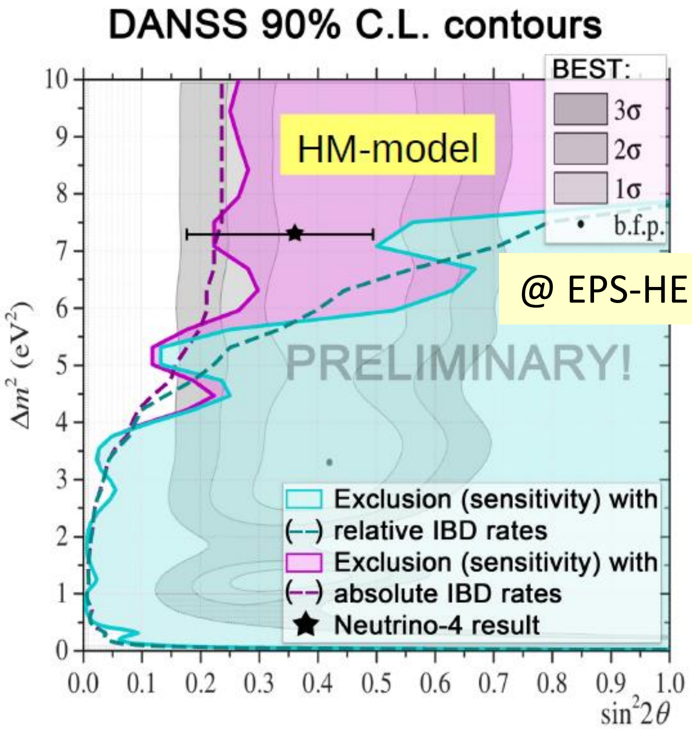
BEST, *PRL* 128, 232501 (2022) *PRC* 105, 065502 (2022)

Sterile ν searches – Negative *w/ reactors*





STEREO, NOW2022



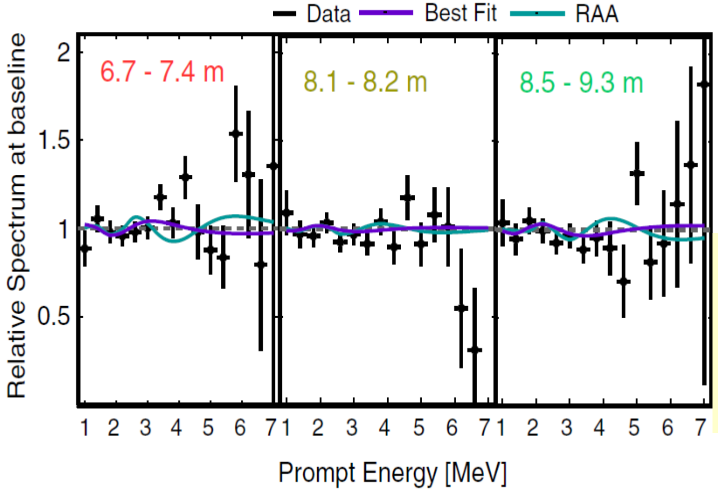
@ EPS-HEP2023

Daya Bay+MINOS+,
PRL 125, 071801 (2020)

Also **Double Chooz**

- No oscillation ***not*** excluded (p-value=0.54)
- RAA best fit excluded at $\gtrsim 4\ \sigma$
- Neutrino-4 best fit excluded at 3.1 σ
- RENO+NEOS best fit excluded at 2.8 σ

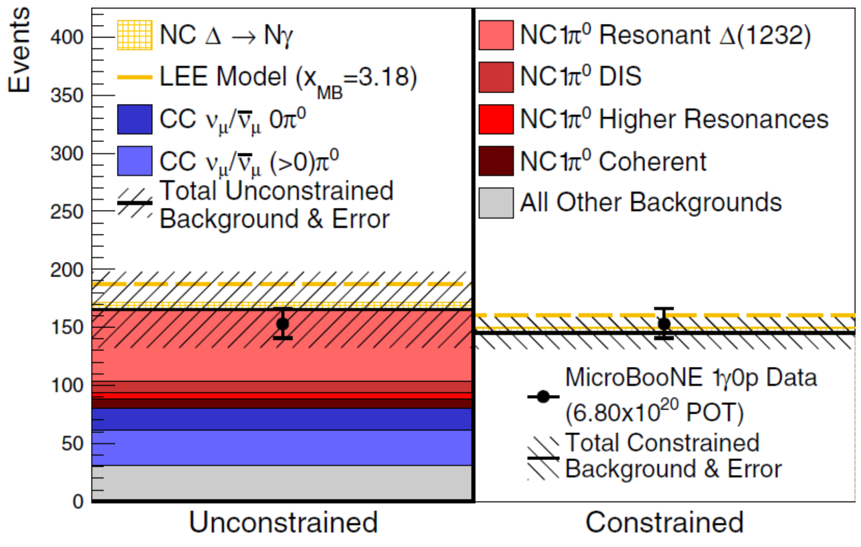
RAA: Reactor Antineutrino Anomaly



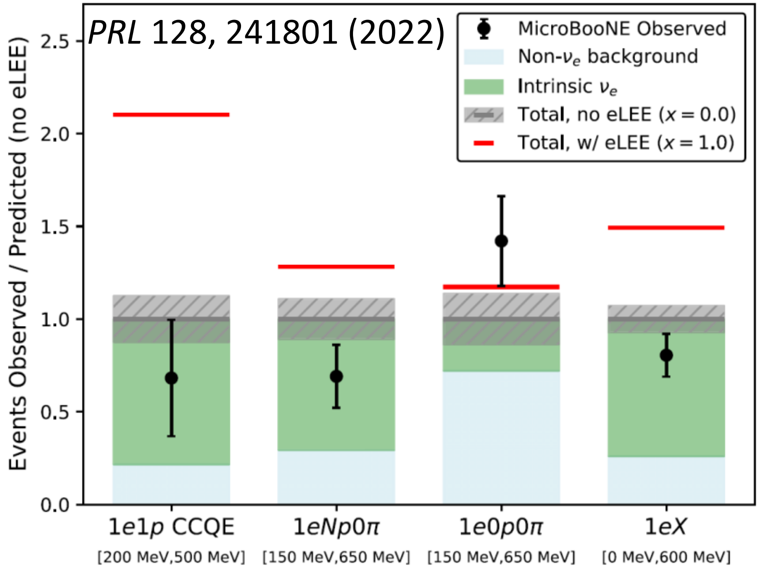
PROSPECT,
PRD 103 (2021) 032001

Sterile ν searches – Negative *at MicroBooNE*

MicroBooNE's latest results by Lu Ren



PRL 128, 111801 (2022)

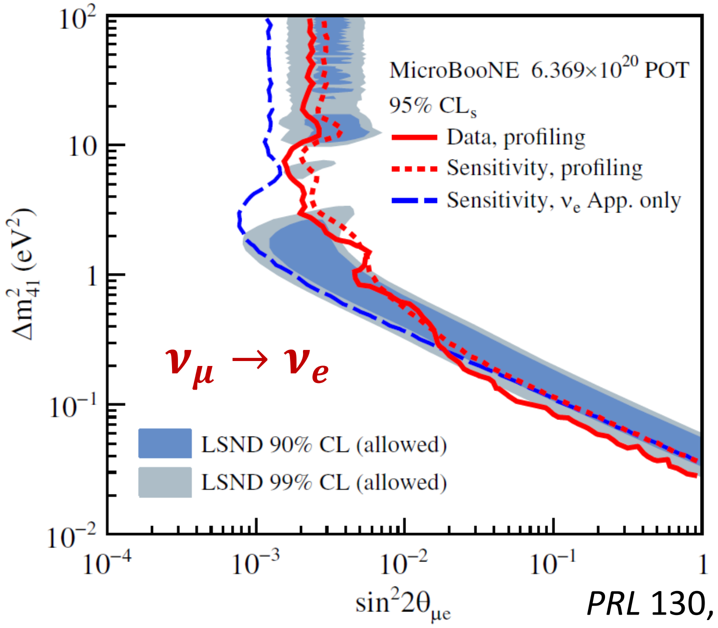


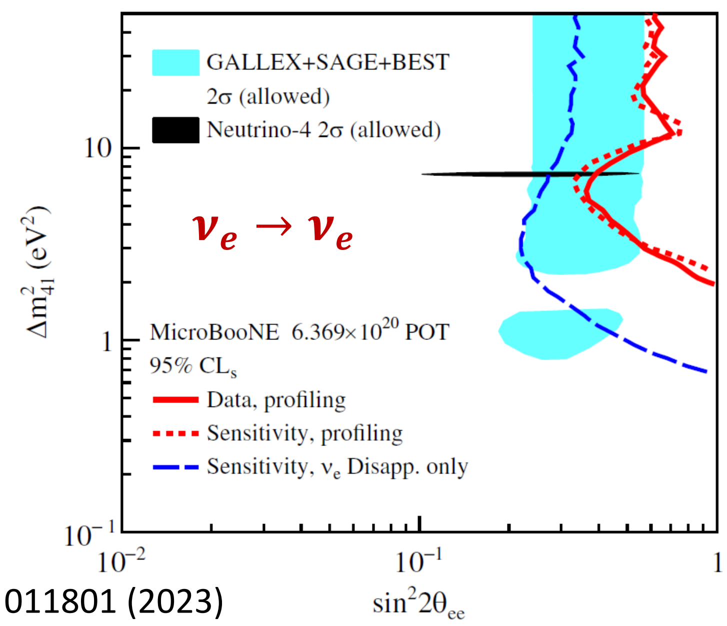
No evidence of underestimation of **Δ→Nγ** decay background (94.8% C.L.)

No evidence of ν_e background enhancement at low energy (>97% C.L.)

No evidence of ("vanilla" 3+1) sterile neutrino oscillation

→ Parts of MiniBooNE, LSND, gallium allowed regions excluded



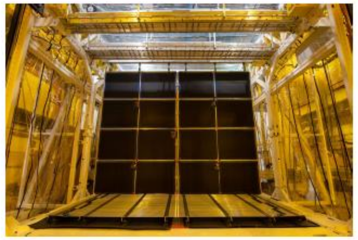


PRL 130, 011801 (2023)

Sterile Searches Prospect -- accelerators

ICARUS
600 m baseline
476 t active volume
Data Taking

SBND
110 m baseline
112 t active volume
Under Completion



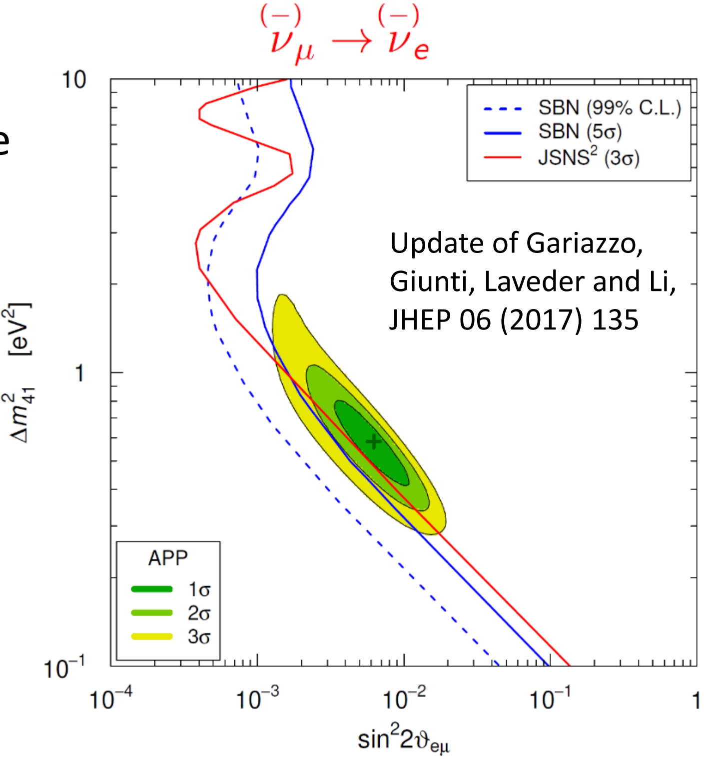
[SBND status and prospects by Miquel Nebot-Guinot]

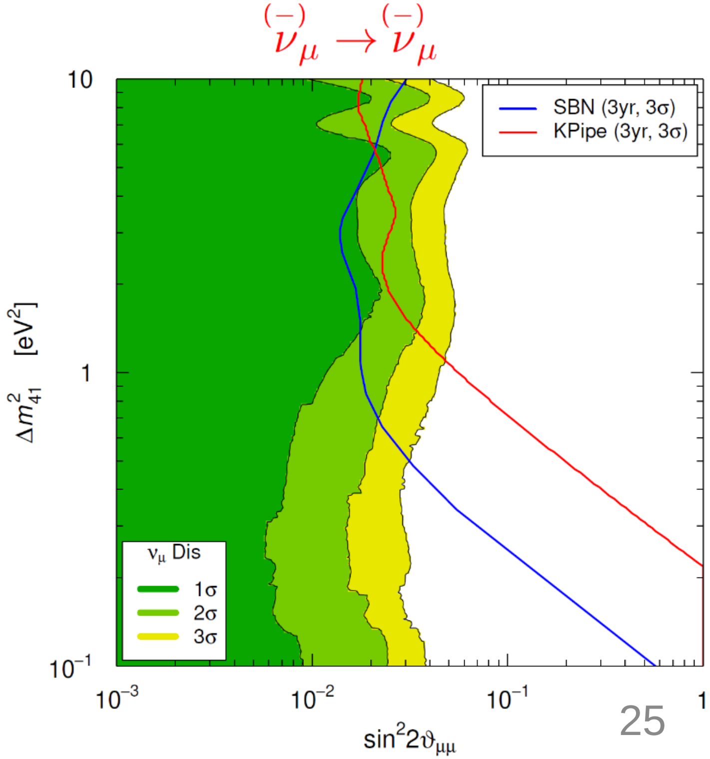
BNB
8 GeV protons
E_ν (on axis)= 0.8 GeV
95% ν_μ and <1%ν

Short Baseline Neutrino Program (SBN) at FNAL

➔ search for sterile neutrino oscillations both in appearance & disappearance channels at ~eV^2 scale

➔ multi-LArTPCs, at 110 m, 470 m, 600 m baselines



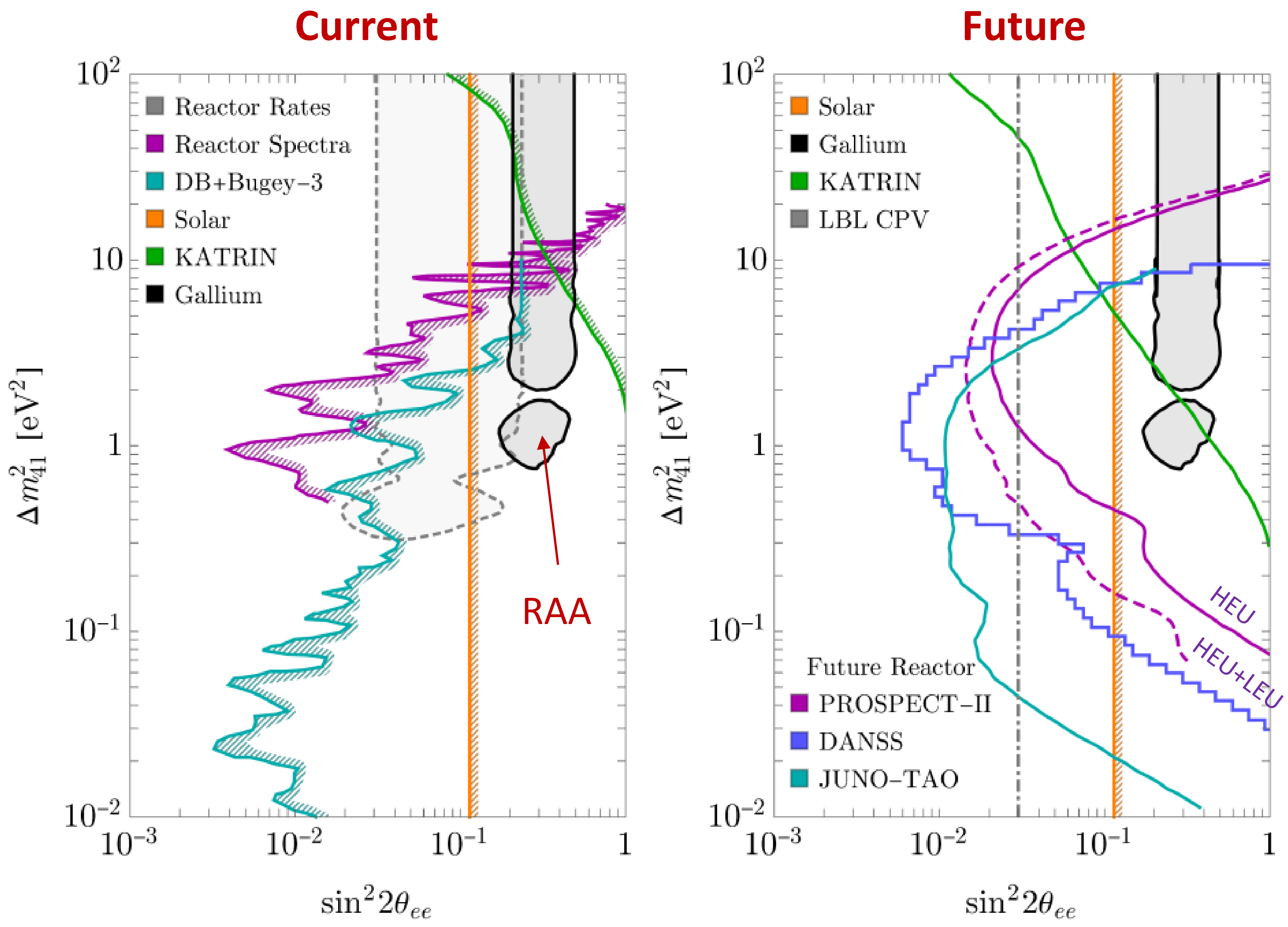


JSNS² @ J-PARC

➔ search for sterile neutrino via $\bar{\nu}_\mu \to \bar{\nu}_e$, same oscillation channel and detection principle as LSND

➔ **JSNS²-II:** Near-Far, 24 m (17 tons), 48 m (32 tons)

Sterile Searches Prospect -- reactors



HEP Physics Opportunities Using **Reactor Antineutrinos**:
A Snowmass 2021 White Paper Submission, arXiv:2203.07214

Current

- BEST confirmed GALLEX & SAGE deficit, but no dependence on the oscillation baseline.
- Katrin + Reactor experiments excluded most regions of the Ga anomaly.
- The solar constraint and the gallium preference are in 3σ tension

➔ Seems not due to sterile neutrinos but other explanations should be looked for.

Future

- New data from Prospect-II, DANSS and JUNO-TAO

Summary

- Neutrinos oscillations at reactors can precisely understand neutrino mixing parameters
  - θ_{13} by Daya Bay (2.8%)
  - θ_{12} , Δm^2_{21} , Δm^2_{32} by JUNO (<0.5% in 6 yrs)
  - **Mass ordering** w/ reactor by JUNO (3σ in 6 yrs)
- Sterile neutrinos, an active area in short-baseline reactor (& accelerator) experiments
  - Unlikely the cause of reactor anomalies (rate, spectrum)
  - Negative from accelerators on the LSND anomaly
  - Several new experiments will be operational, new results are expected

Thanks!

Updated reactor neutrino models

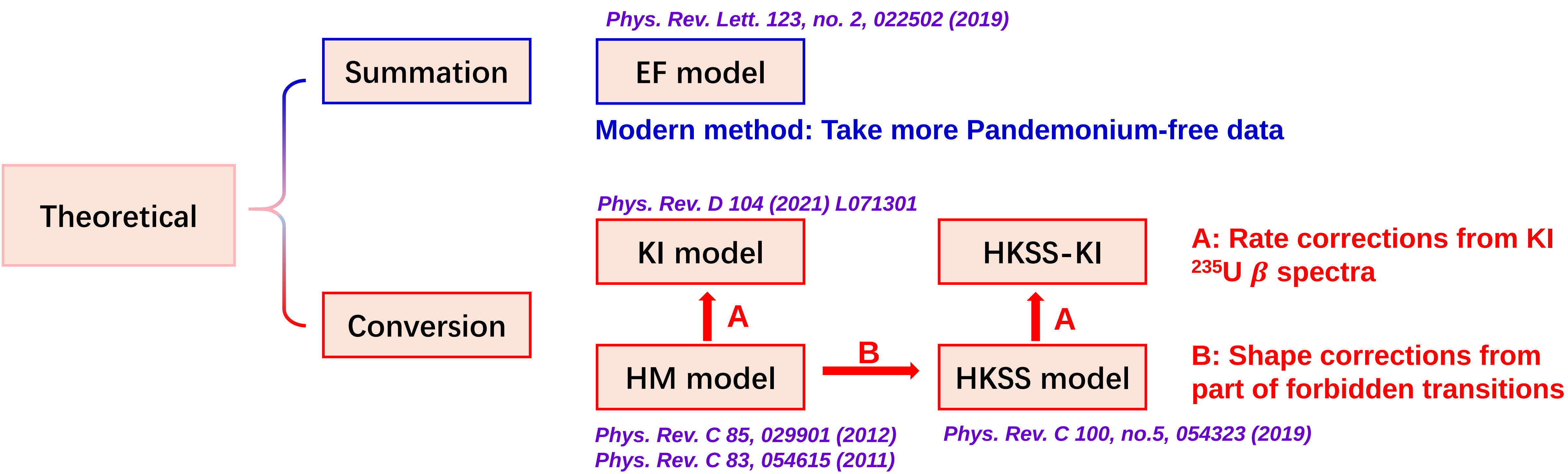


Diagram Courtesy: XIN Zhao

- Huber-Mueller model
- Hayen-Kostensalo-Severijns-Suhonen model
- Recent Kurchatov Institute measurements
- HM → KI model
- HKSS → HKSS-KI model
- Estienne-Fallot summation model