



Short-baseline oscillations and sterile neutrinos (reactor/accelerators)

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2023.08.29

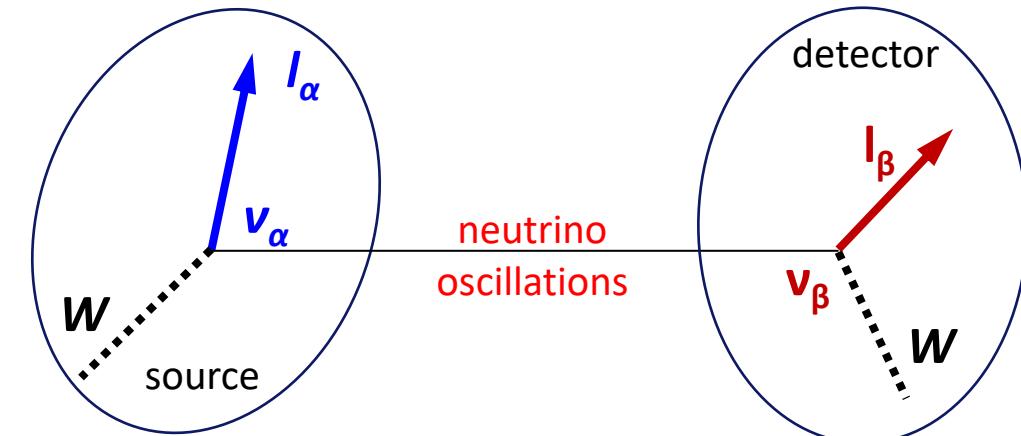


Neutrino Oscillations

Theory overview: Andre de Gouvea
Neutrino oscillations revisited: Fedor Šimkovic

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

Short-baseline oscillations (Reactor, Accelerators) will continue to play an critical role in solving the unknowns



ν prod. & detection: W^\pm weak interaction → identify flavor
 ν propagation: mass eigenstates (!= flavor eigenstates)

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

θ_{23} & Δm^2_{32}

Atmospheric,
Accelerator

θ_{13} & δ_{CP}

Reactor, Accelerator

θ_{12} & Δm^2_{21}

Reactor, Solar

Majorana phases

Double beta
decays

"Normal" hierarchy

$$\Delta m_{23}^2 \quad \left\{ \begin{array}{c} \mu \quad \tau \\ e \quad \nu_e \end{array} \right.$$

$$\Delta m_{12}^2 \quad \left\{ \begin{array}{c} e \quad \mu \quad \tau \\ e \quad \nu_e \quad \mu \quad \tau \end{array} \right.$$

"Inverted" hierarchy

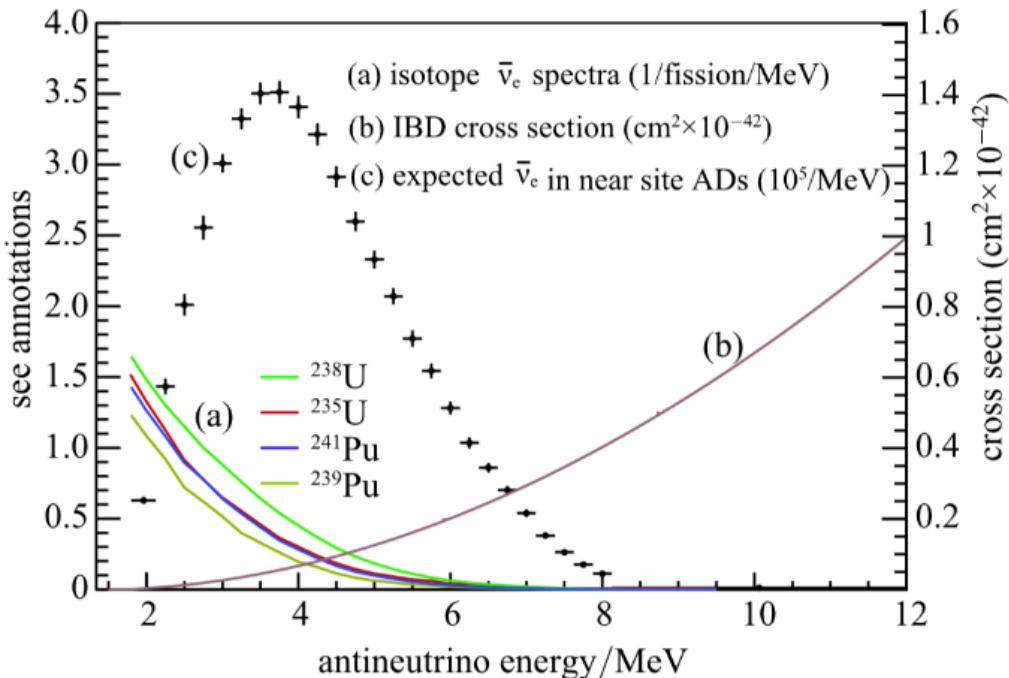
$$\Delta m_{12}^2 \quad \left\{ \begin{array}{c} e \quad \mu \quad \tau \\ e \quad \nu_e \quad \mu \quad \tau \end{array} \right.$$

$$\Delta m_{23}^2 \quad \left\{ \begin{array}{c} \mu \quad \tau \\ e \quad \nu_e \end{array} \right.$$

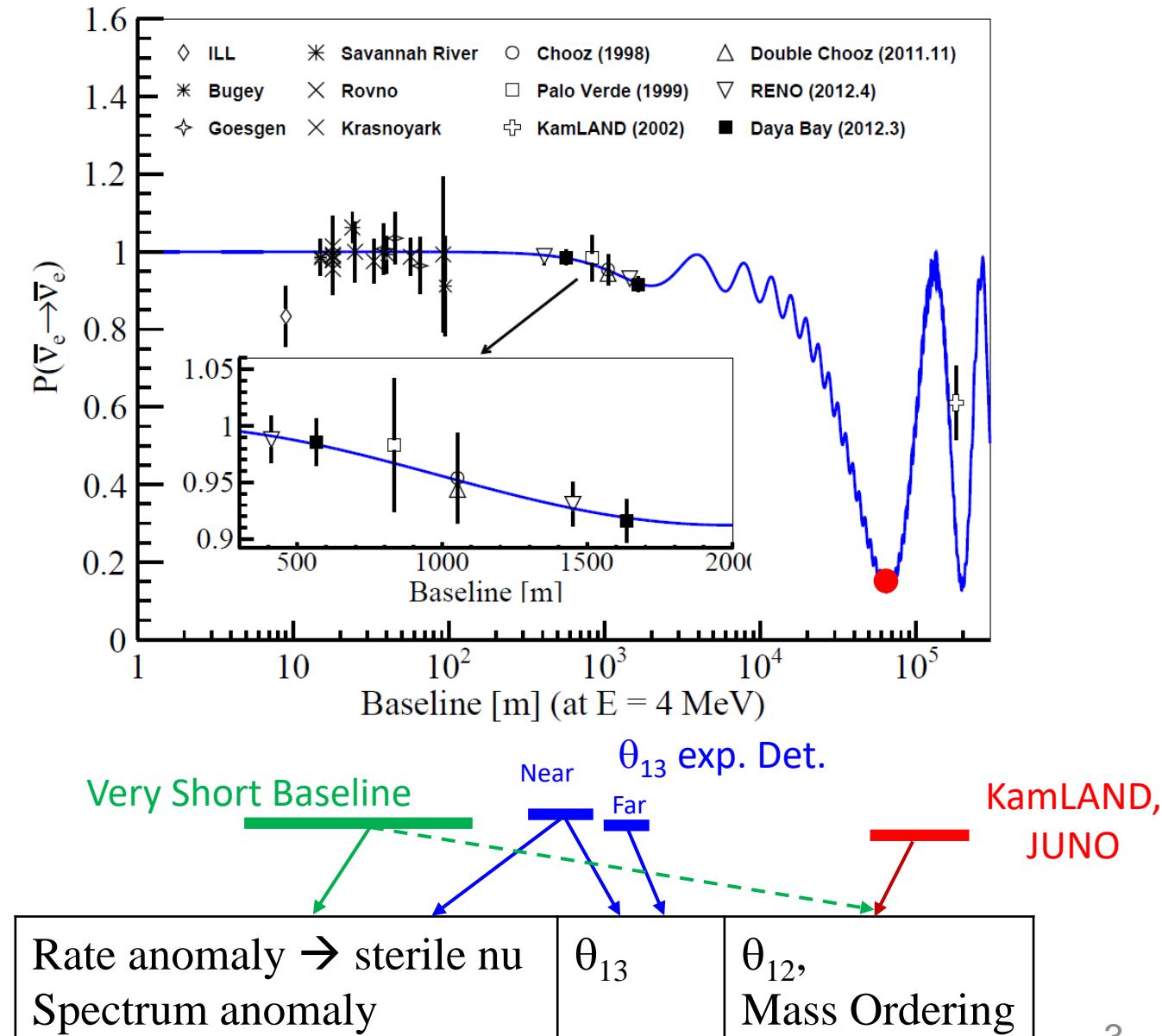
or



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

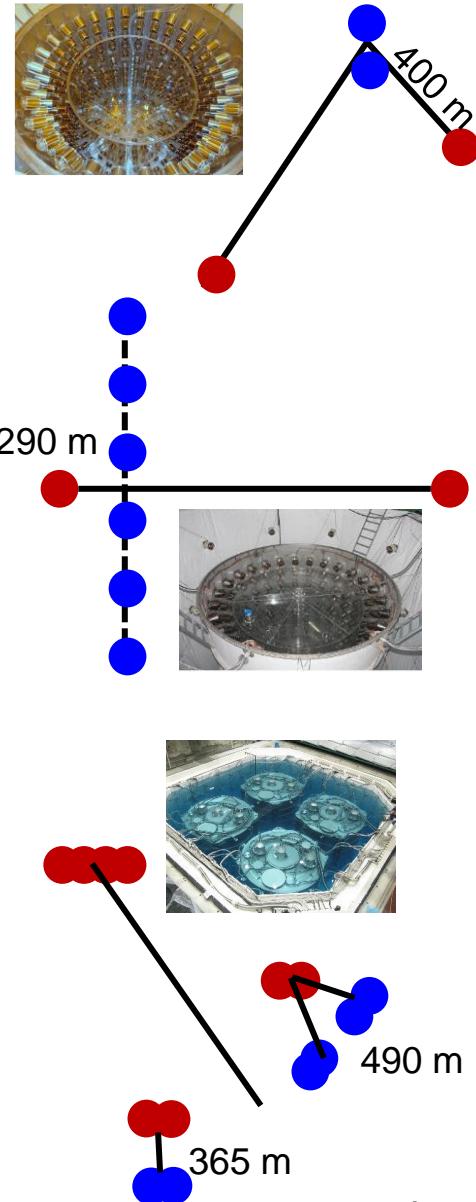
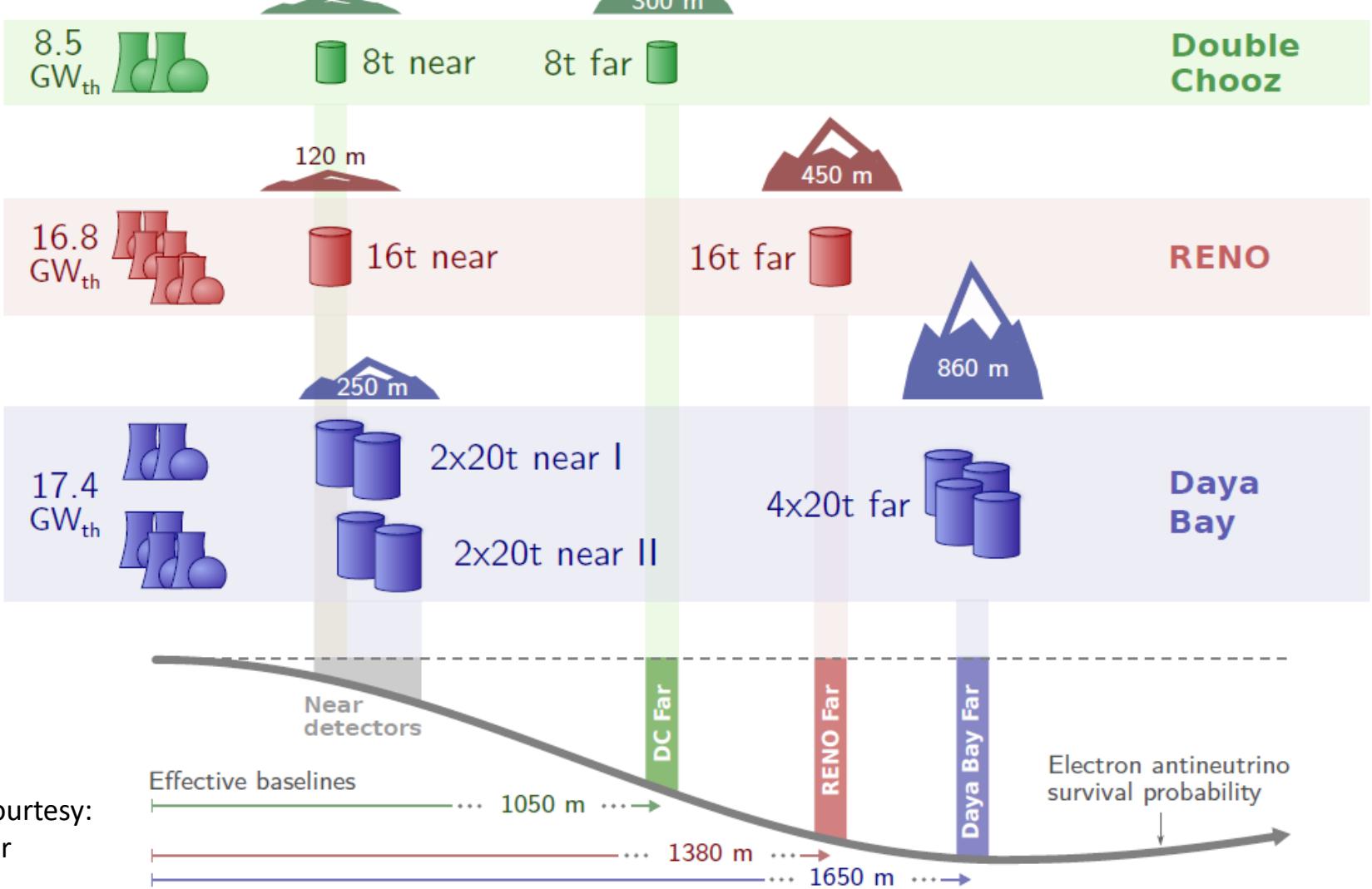
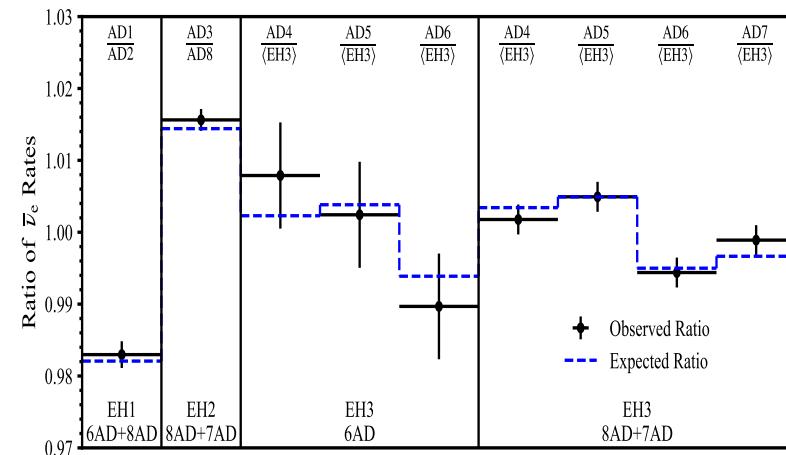
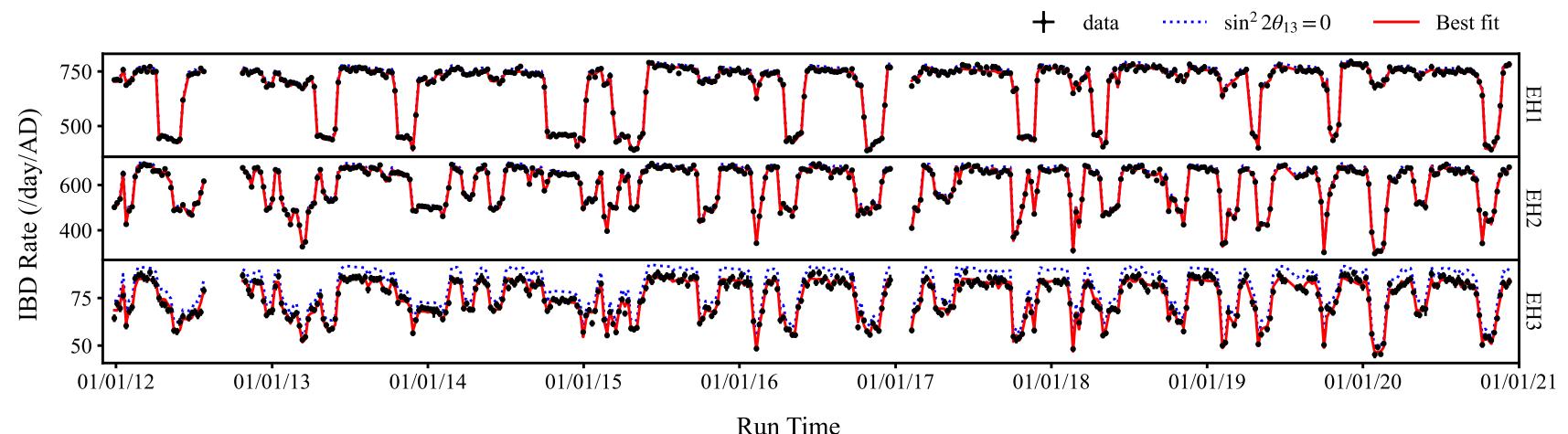


Diagram Courtesy:
Soren Jetter



Daya Bay



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

Best-fit results:

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

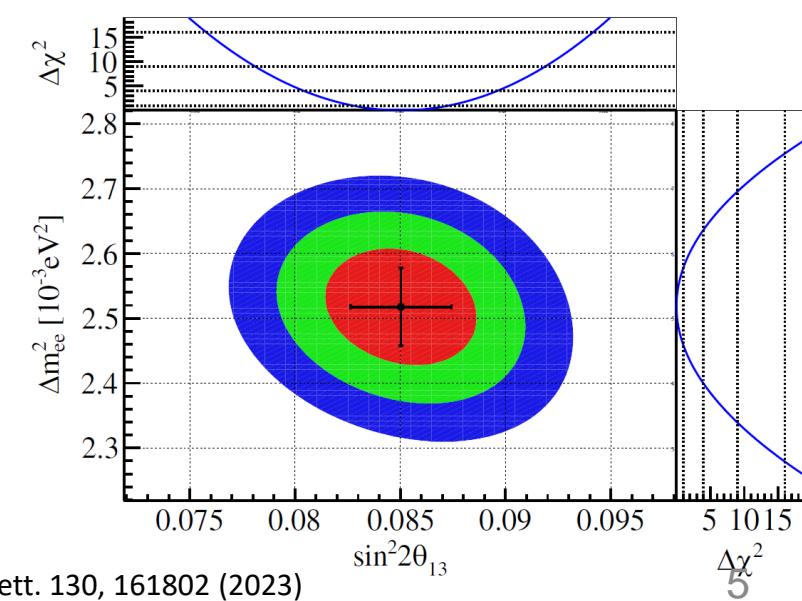
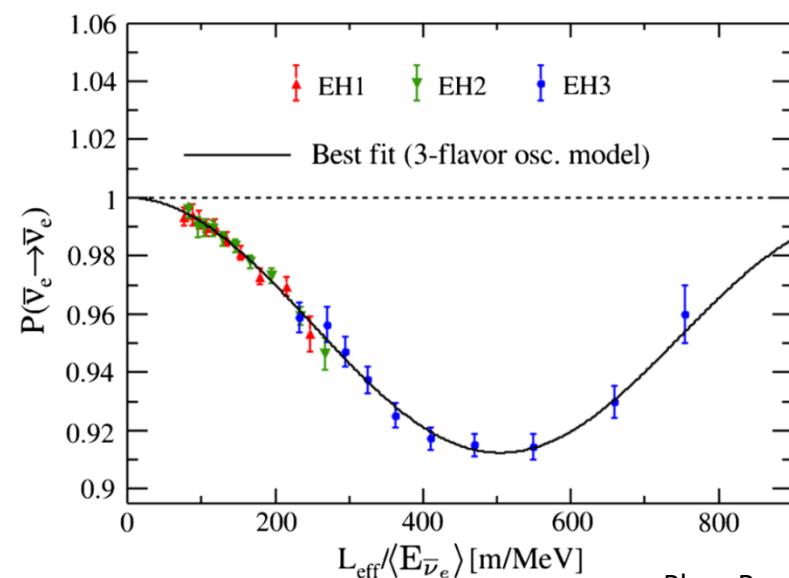
Normal hierarchy:

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

Inverted hierarchy:

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

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





RENO & Double Chooz

RENO

@ Neutrino2022 (~2900 d)

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

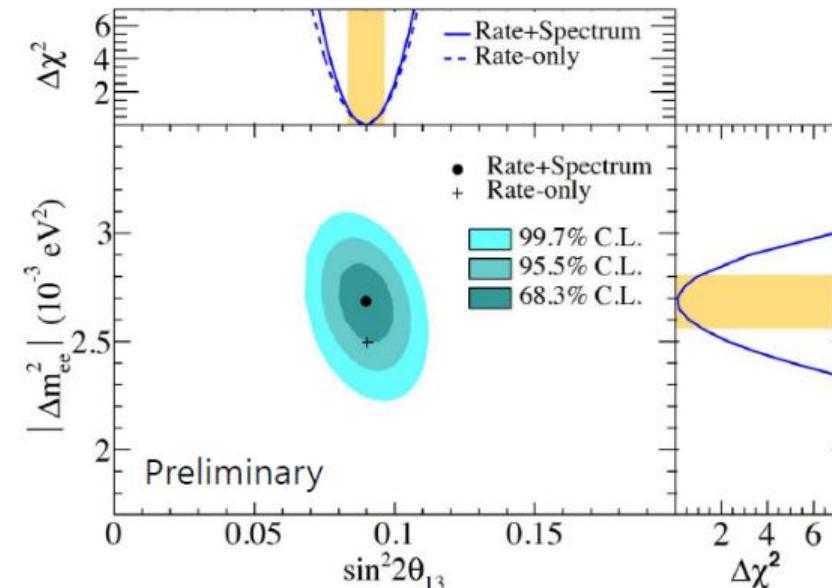
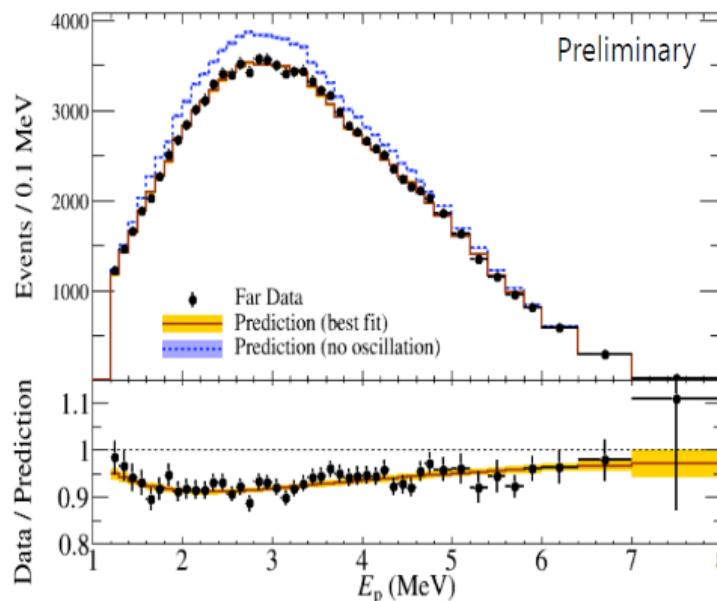
$$|\Delta m^2_{ee}| = 2.74 \pm 0.10(\text{stat.}) \pm 0.06(\text{sys.}) \times 10^{-3} \text{ eV}^2 \quad (4.4\%)$$

@ NuFact2023

Completed in 2023.03.16 (up to 3800 d), expect

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

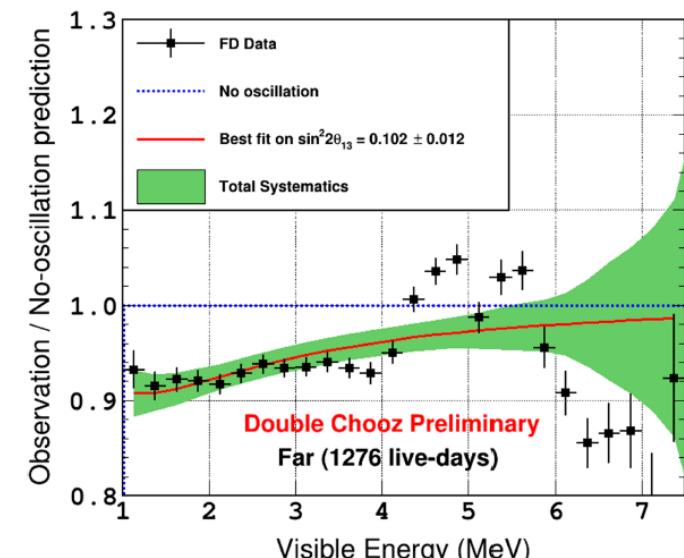
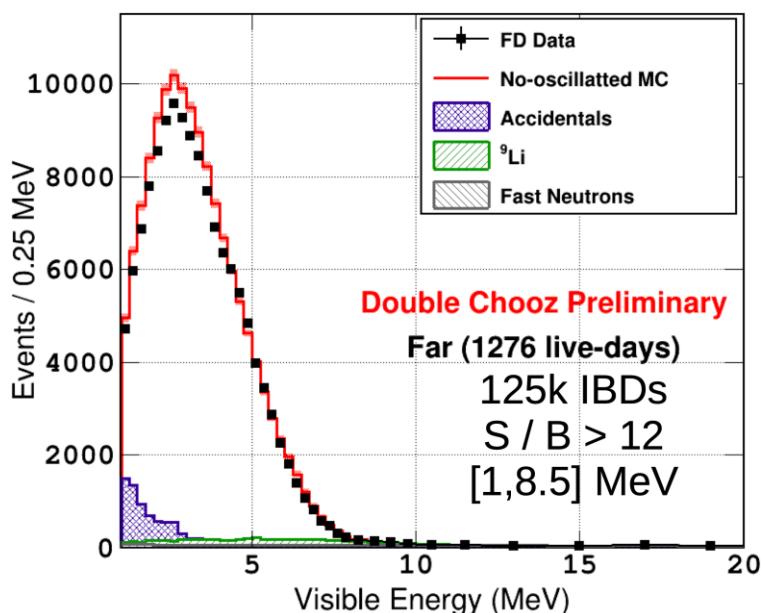
Plan to reoperate the near detector for sterile ν



Double Chooz @ TAUP2023

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

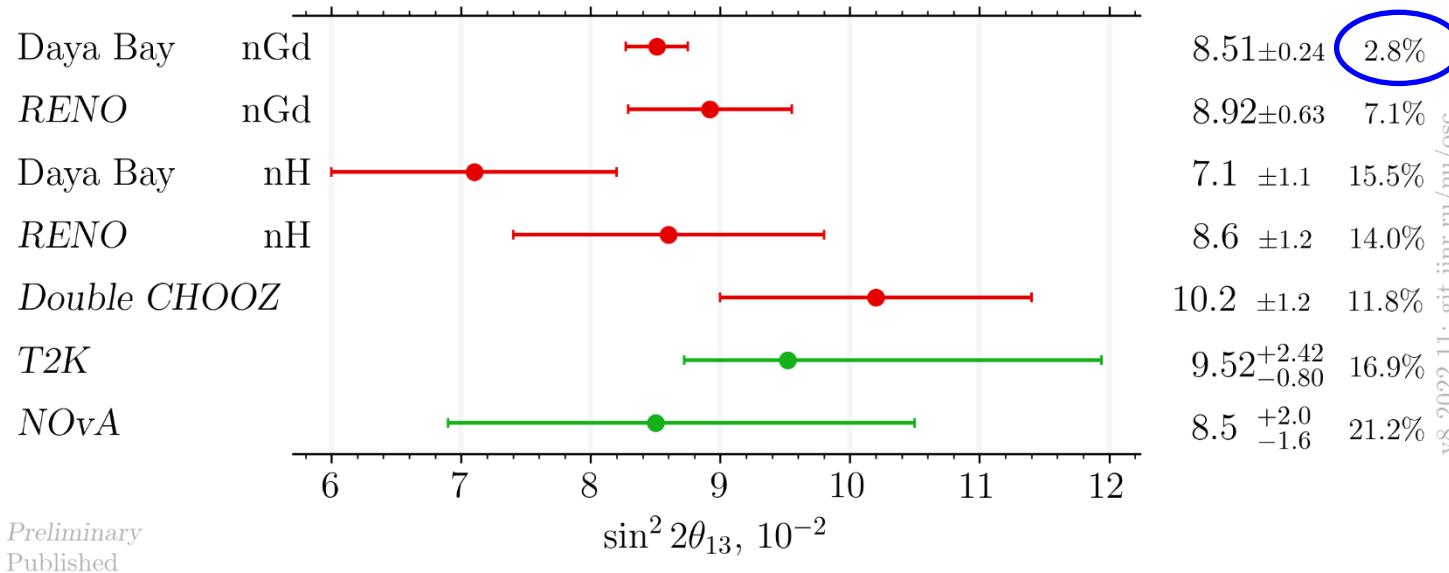
w/ 1276 live-days Far, 587 live-days Near





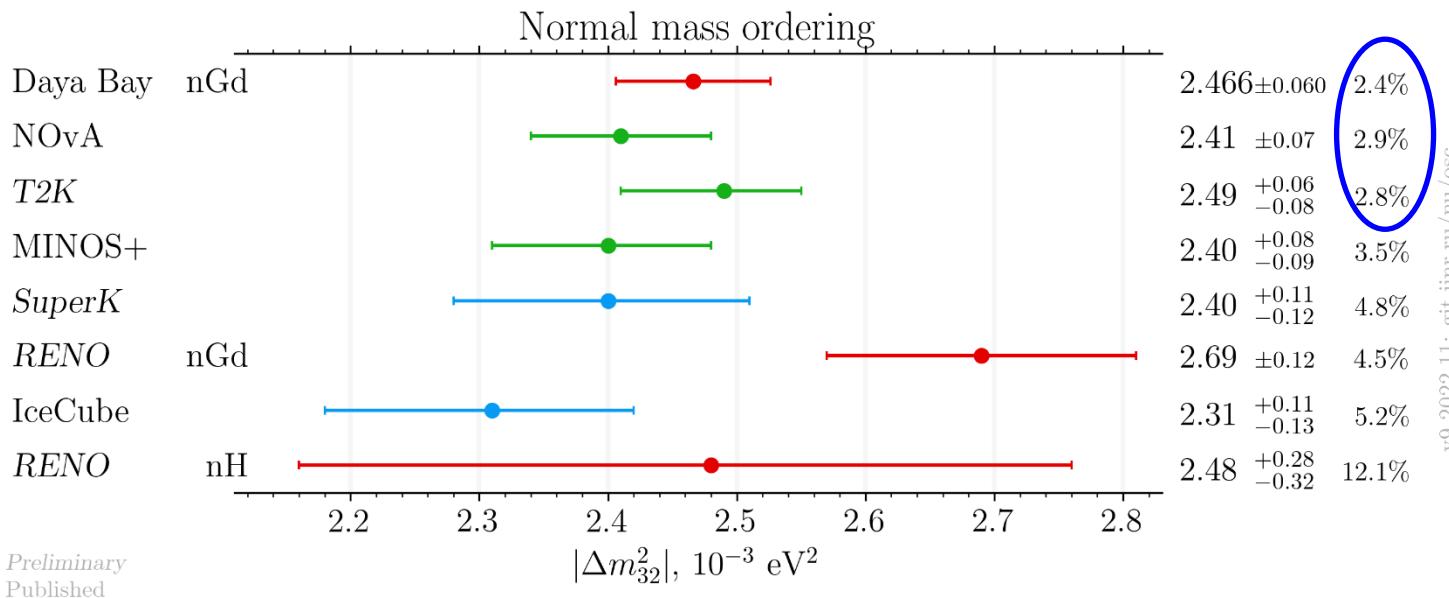
Global Picture for θ_{13}

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



Will likely be the best measurement in the foreseeable future

Δm_{32}^2 (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

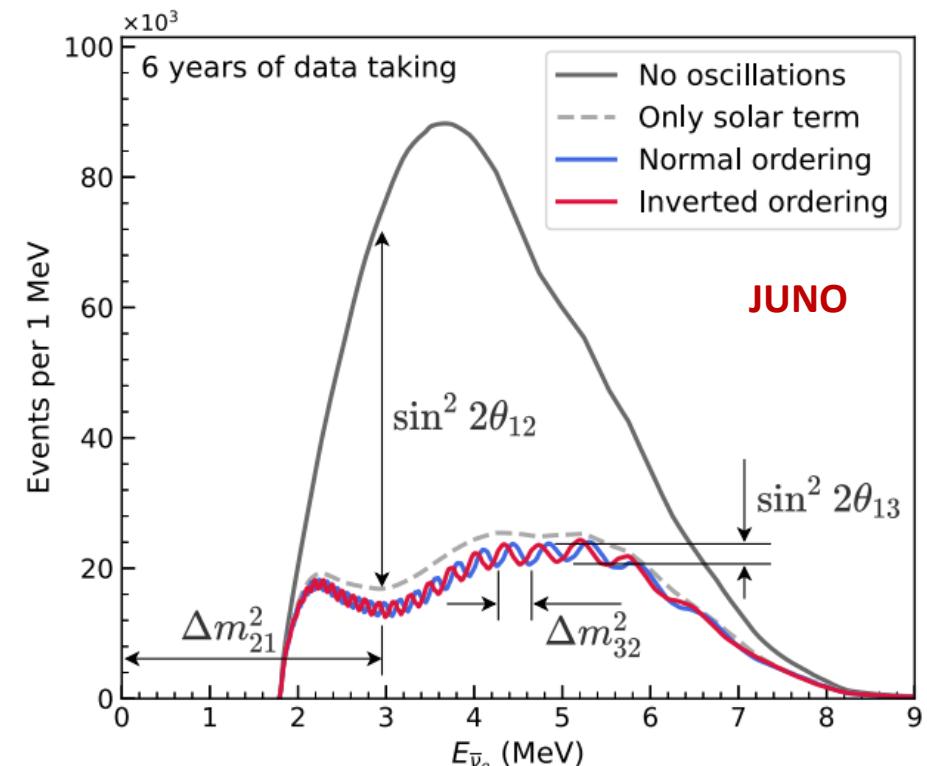
$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$

$$P_{21} = \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21})$$

$$P_{31} = \frac{\cos^2(\theta_{12}) \sin^2(2\theta_{13})}{\sin^2(\theta_{12}) \sin^2(2\theta_{13})} \underline{\sin^2(\Delta_{31})}$$

$$P_{32} = \underline{\sin^2(\theta_{12}) \sin^2(2\theta_{13})} \underline{\sin^2(\Delta_{32})}$$

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



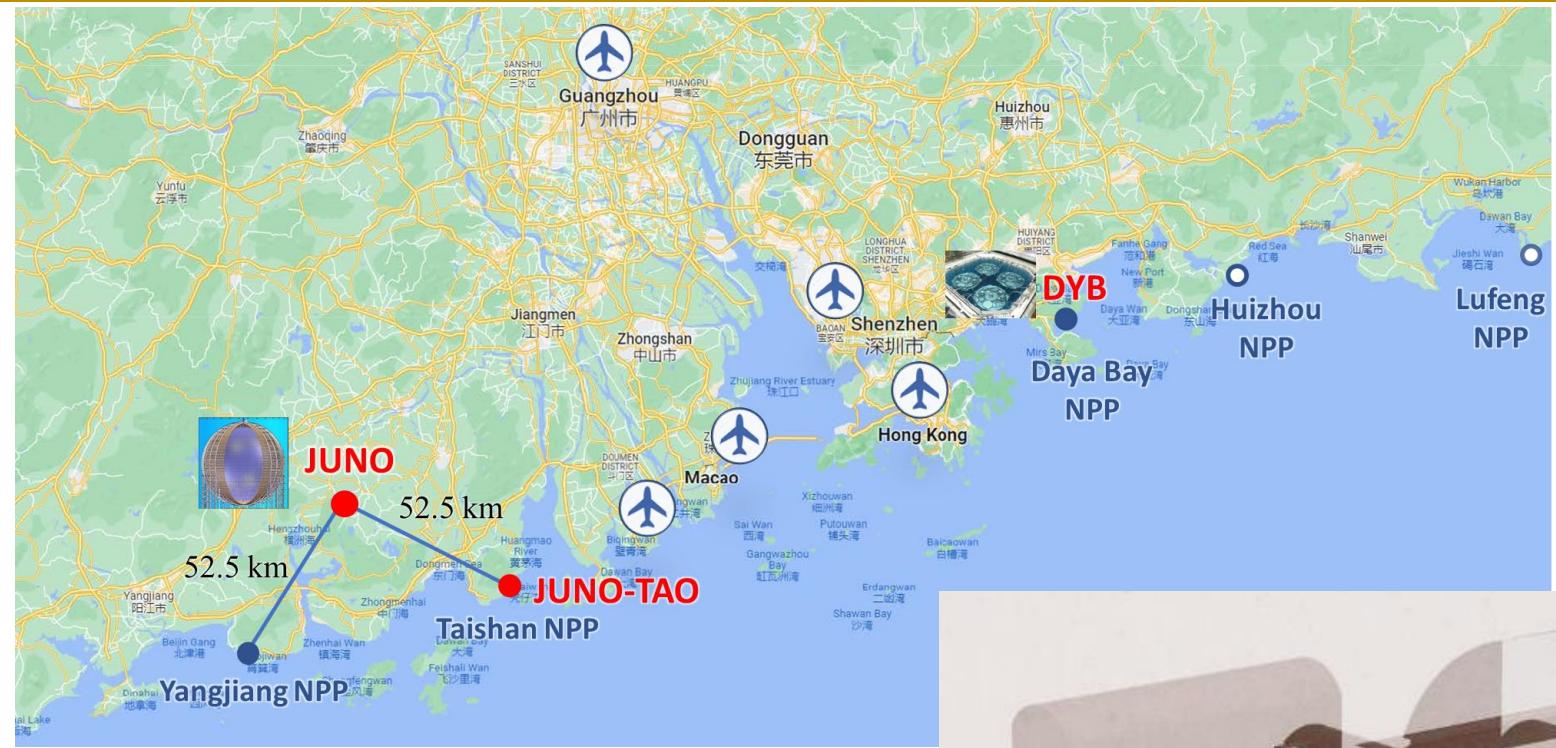
(matter effect contributes maximal ~4% correction at around 3 MeV, arXiv:1605.00900, arXiv:1910.12900)

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

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

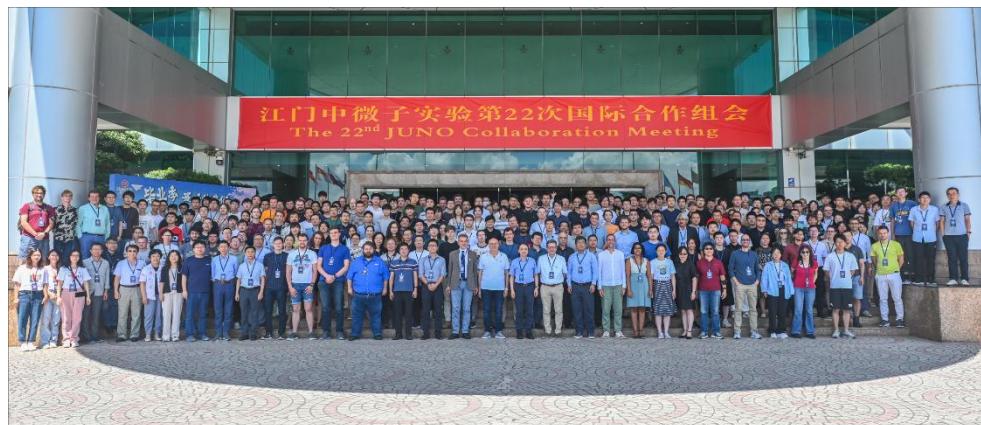
$$|\Delta m^2_{ee}| - |\Delta m^2_{\mu\mu}| = \pm \Delta m^2_{21} (\cos 2\theta_{12} - \cos \delta \sin \theta_{13} \sin 2\theta_{12} \tan \theta_{23})$$

Jiangmen Underground Neutrino Observatory (JUNO)

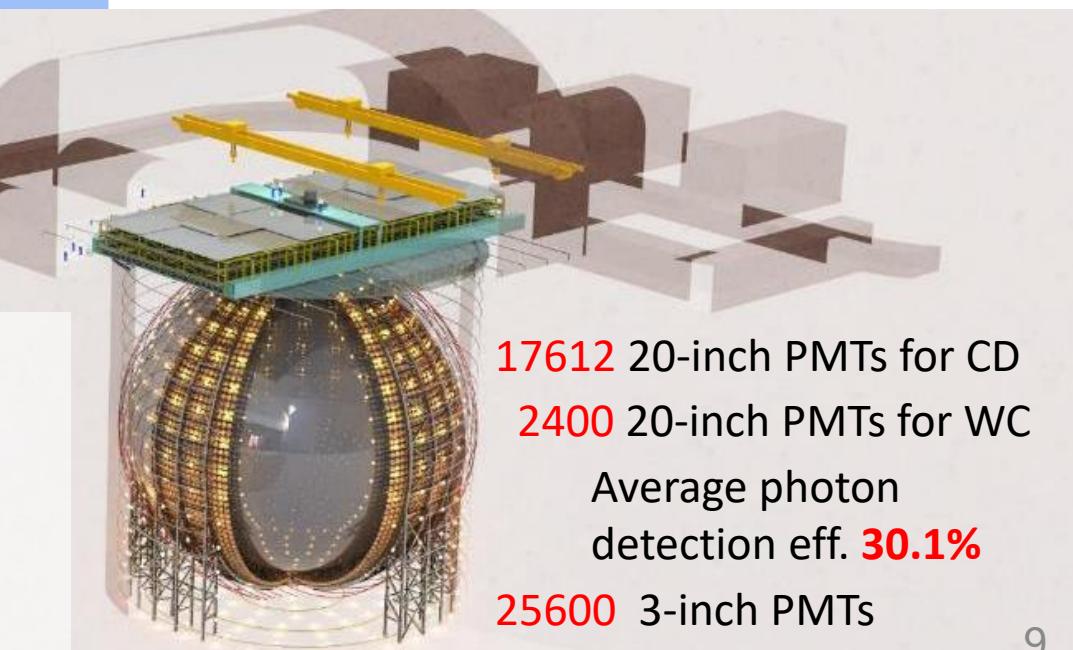


Yangjiang NPP: 2.9 GW x 6
Taishan NPP: 4.6 GW x 2
Equal baseline: 52.5 km

20 kton Liquid Scintillator
Spherical Acrylic Vessel $\phi 35.4$ m
35 kton water shielding
Cylindrical Water Pool 43.5x44 m
700 m overburden



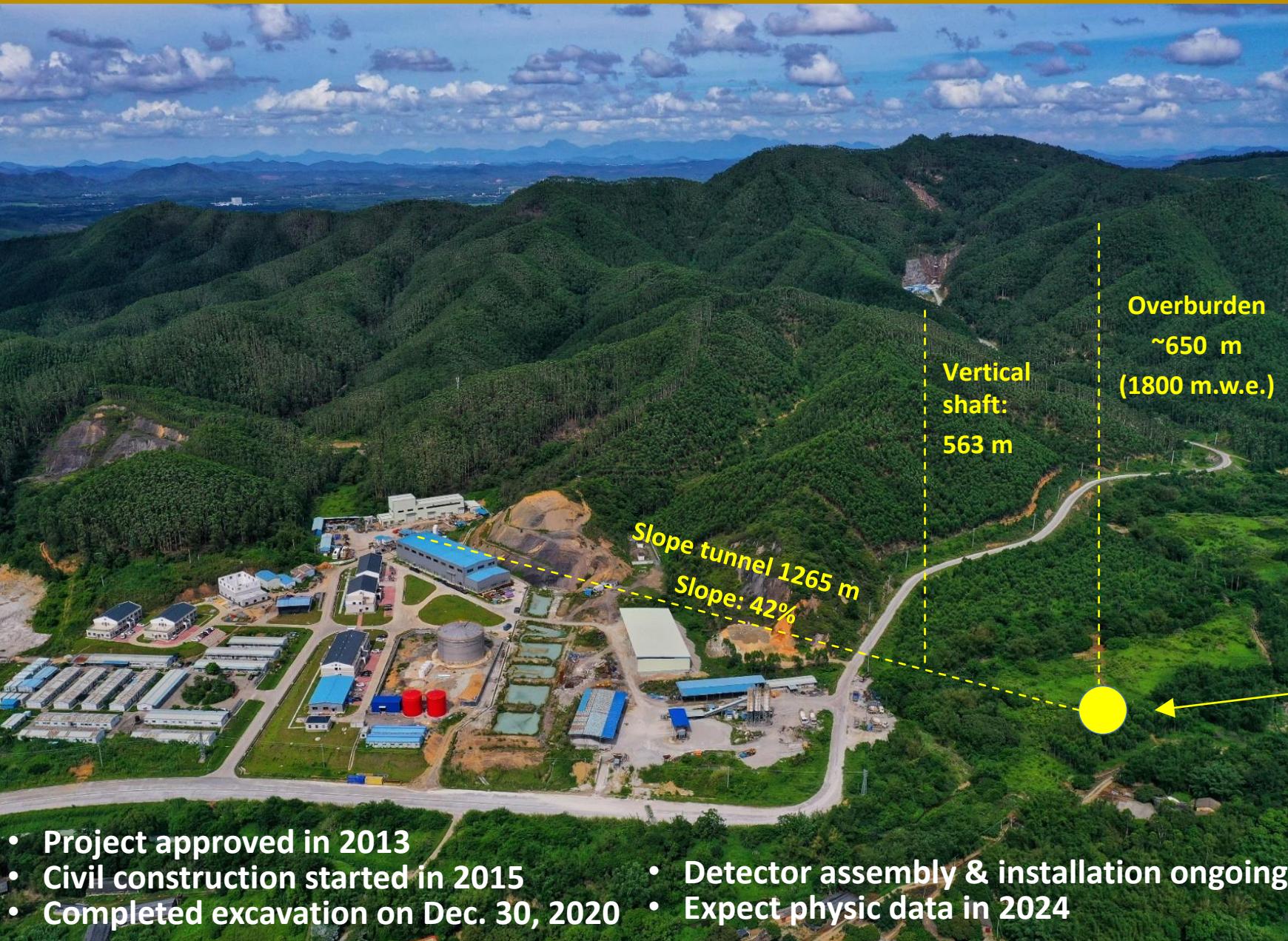
JUNO collaboration: >700 collaborators,
74 institutions, 17 countries/regions



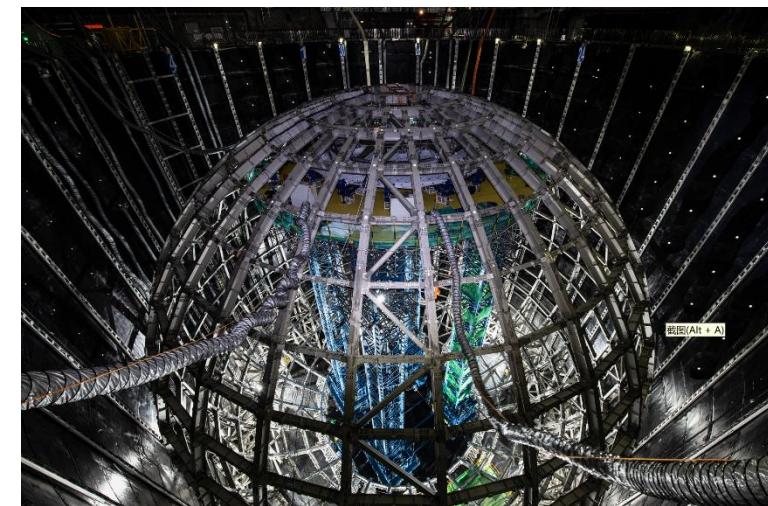
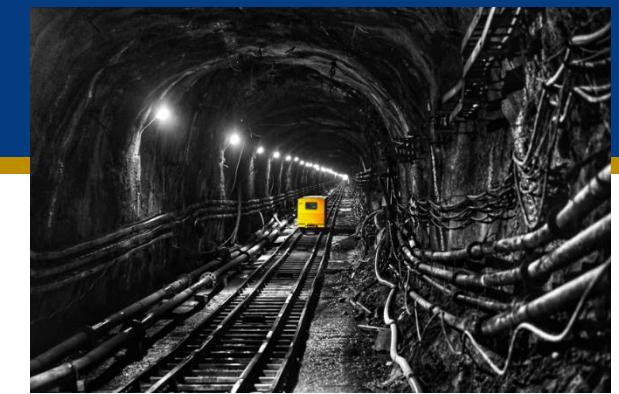
17612 20-inch PMTs for CD
2400 20-inch PMTs for WC
Average photon detection eff. 30.1%
25600 3-inch PMTs



JUNO Campus



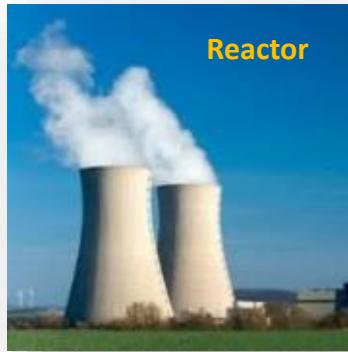
- Project approved in 2013
- Civil construction started in 2015
- Completed excavation on Dec. 30, 2020
- Detector assembly & installation ongoing
- Expect physic data in 2024





JUNO Physics

Oscillation physics by Rebin KARAPARAMBIL
Non-Oscillation physics by Gaosong LI
Background & veto strategies by Loïc LABIT
Neutron invisible decay by Cailian JIANG



Reactor



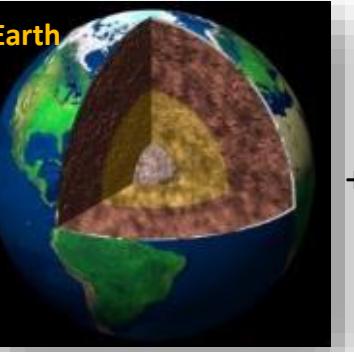
Atmosphere



Solar



Supernova



Earth

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

New
physics

~60 IBDs per day

Several per day

Hundreds per day

~5000 IBDs for
CCSN @10 kpc

Several IBDs per day

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_{21}^2 , $|\Delta m_{31}^2| < 0.5\%$ in 6 yrs ([2204.13249](#))

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

- **Nucleon Decays:** $p \rightarrow \bar{\nu}K^+$ 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 $0\nu\beta\beta$

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

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 PMT installation specification



20012 20" PMTs + 25600 3" PMTs

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



Liquid scintillator

- Four purification plants construction completed, under commissioning
- Target: Excellent transparency ($\lambda_{A.L.} > 20$ m) and ultra-low radioactivity (U/Th< 10^{-17} g/g)

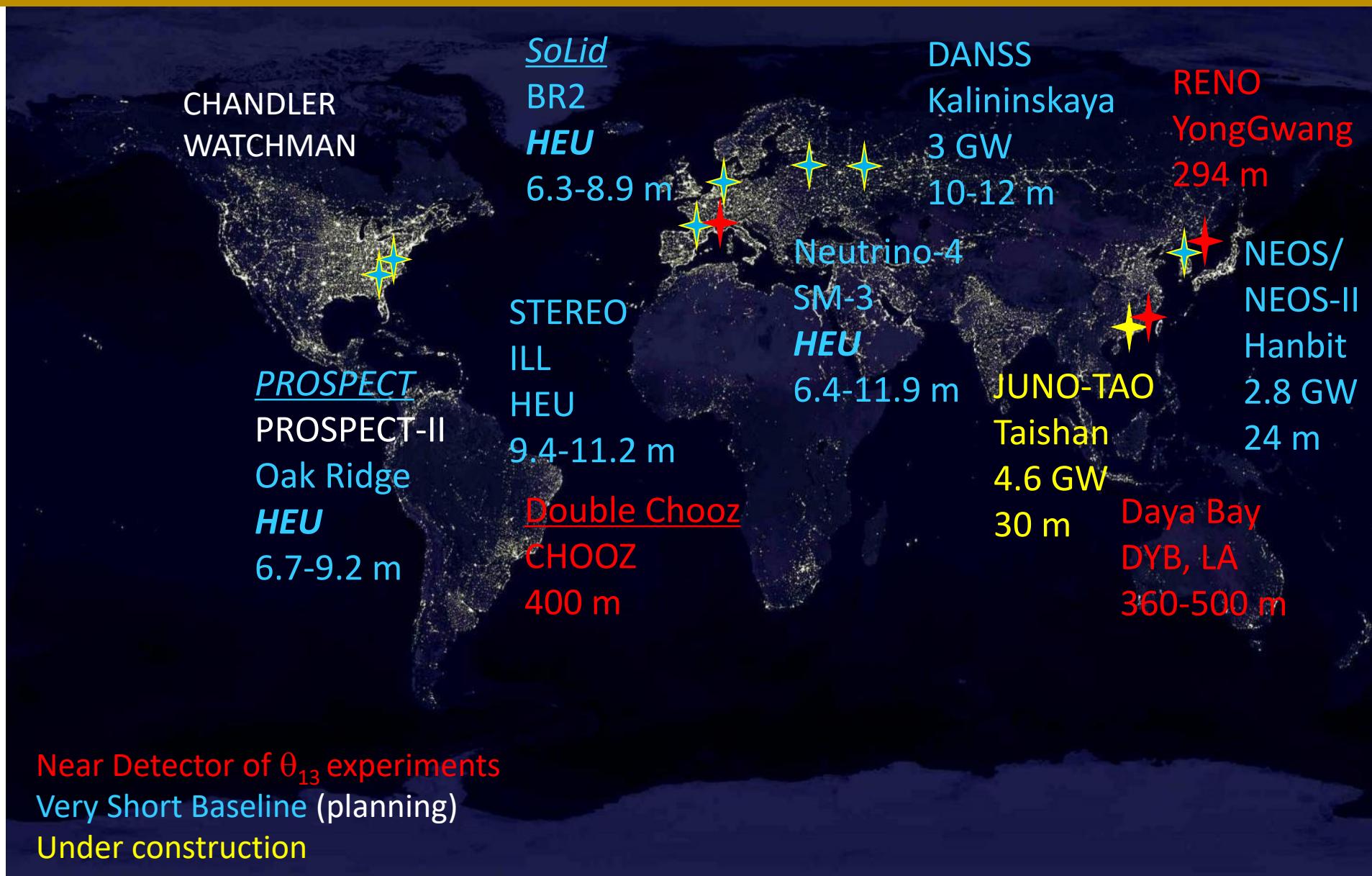


[JUNO detector](#), by Cong GUO
[Background control](#), by Jie ZHAO



VSBL & θ_{13} Near Detectors

eV sterile neutrino by Alessandro Minotti
Reactor and Gallium Anomalies by Yufeng Li



Low-Enriched Uranium (LEU) fueled reactor: Commercial, ~3 GW_{th};

Highly-Enriched Uranium (HEU)-fueled reactor: Research, 50-100 MW_{th}

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.

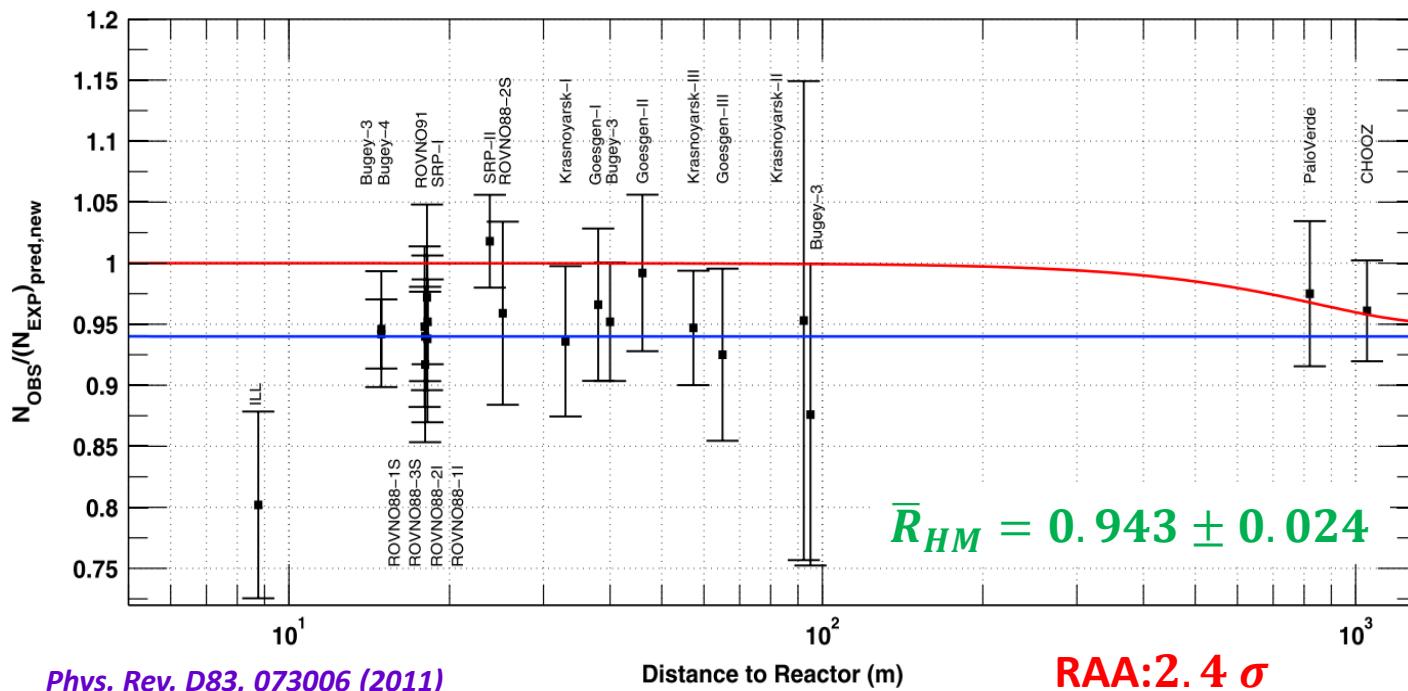
θ_{13} near detectors

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



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

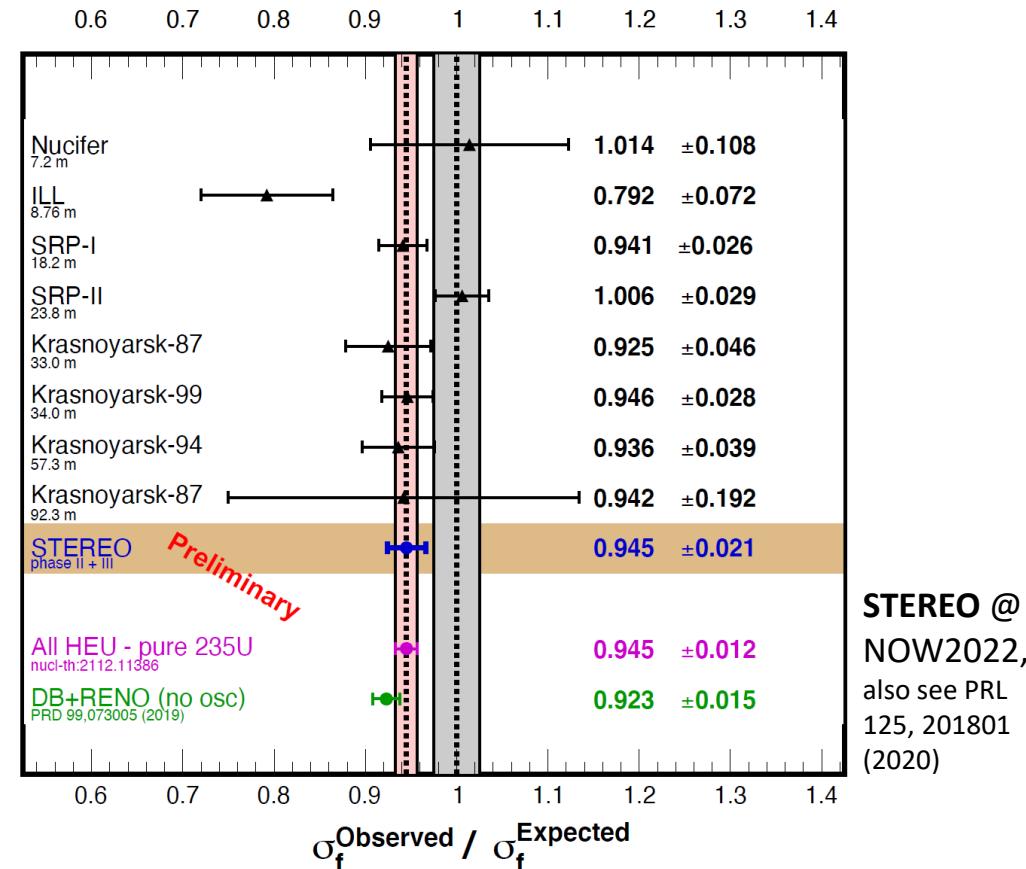
- Reactor Antineutrino Anomaly (RAA – rate deficit w.r.t the Huber-Mueller spectrum, see more discussions in [Y. F. Li's talk](#)) confirmed by many experiments



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	2.5σ	2.9σ	1.1σ	1.5σ	1.2σ

KI: Kurchatov Institute,

EF: Estienne-Fallot

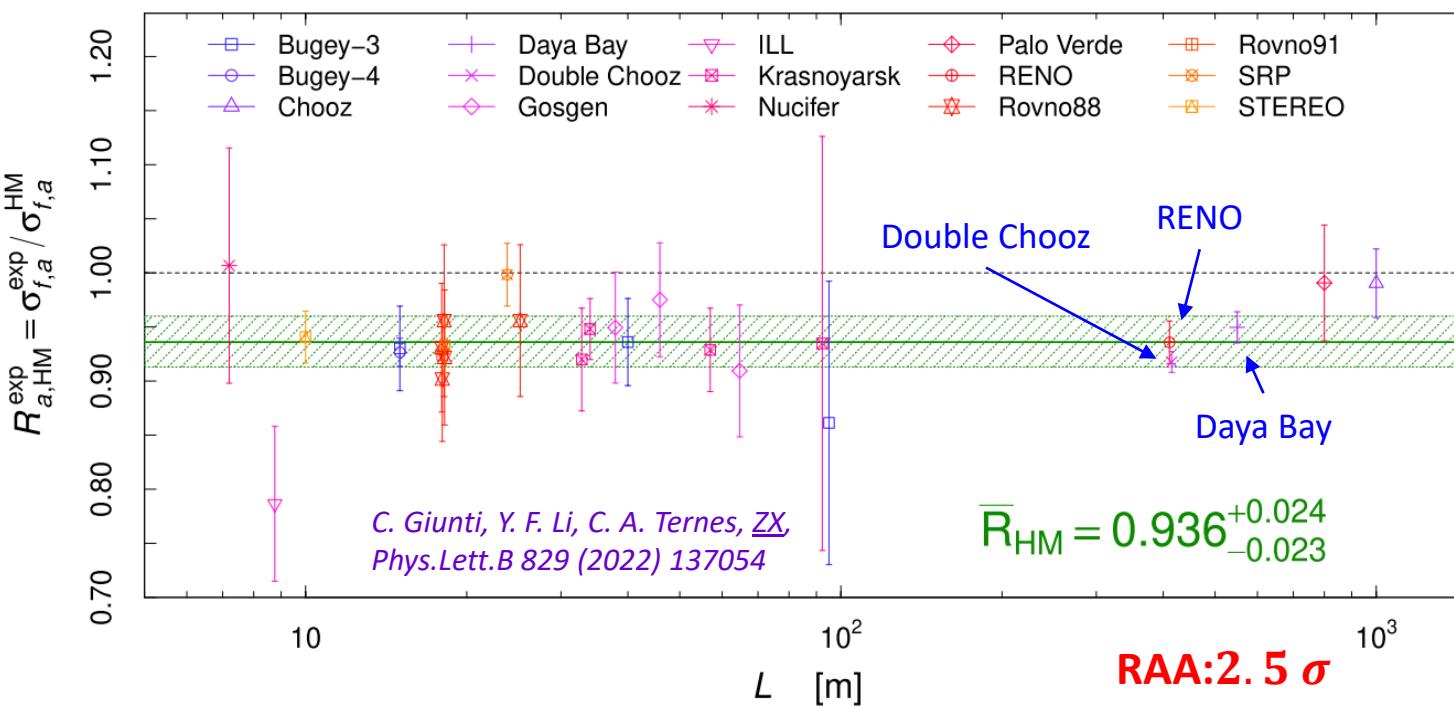


- data/H-M ratio
 - Average ~ 0.936 for all
 - Average ~ 0.945 for pure U235
- KI and EF models compatible with NO osci.



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

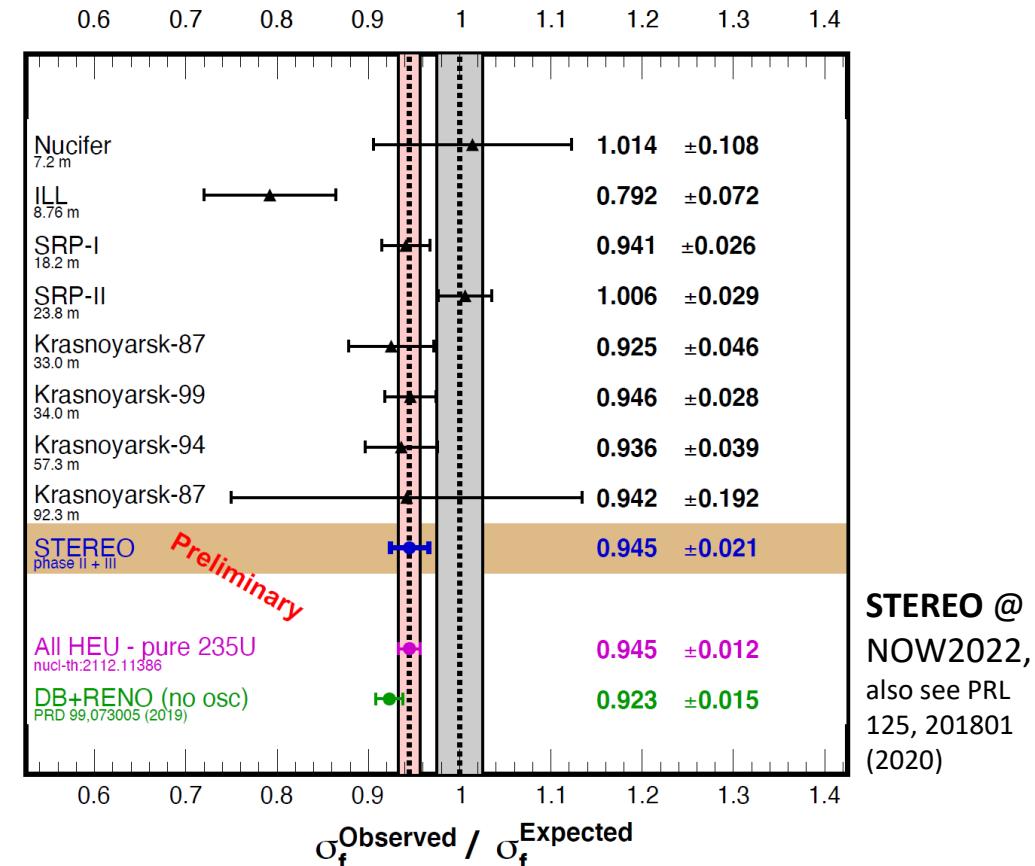
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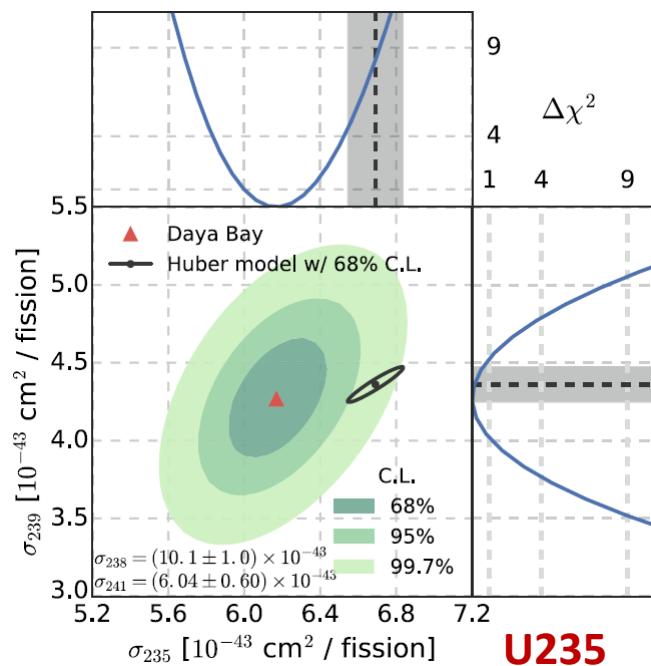
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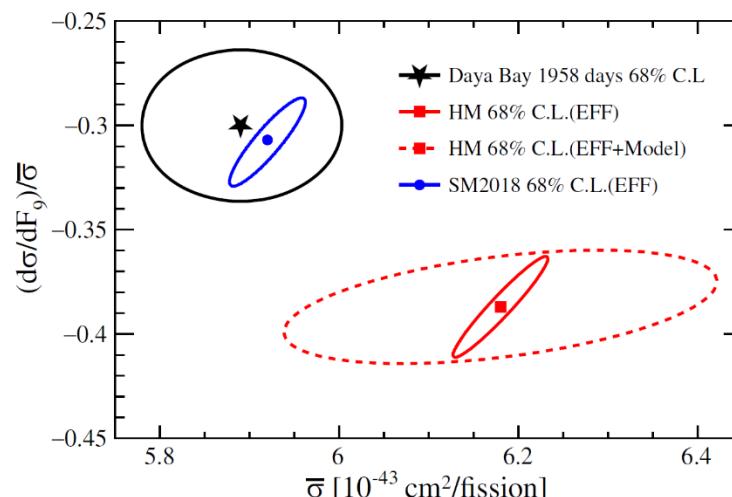
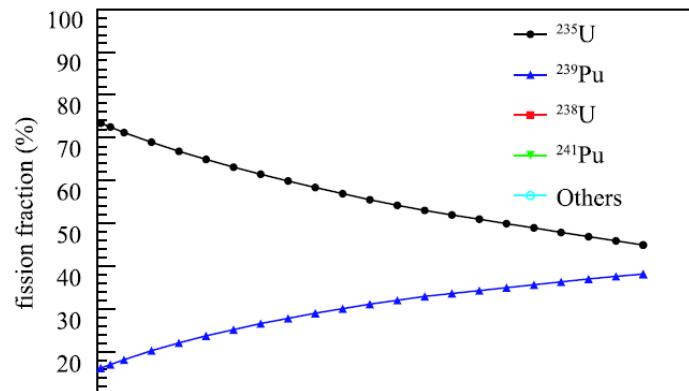
RAA not likely due to Sterile Nu

Fuel evolution

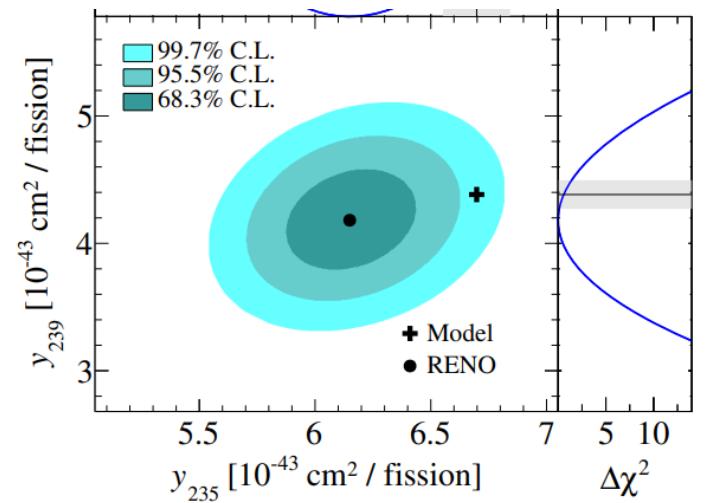
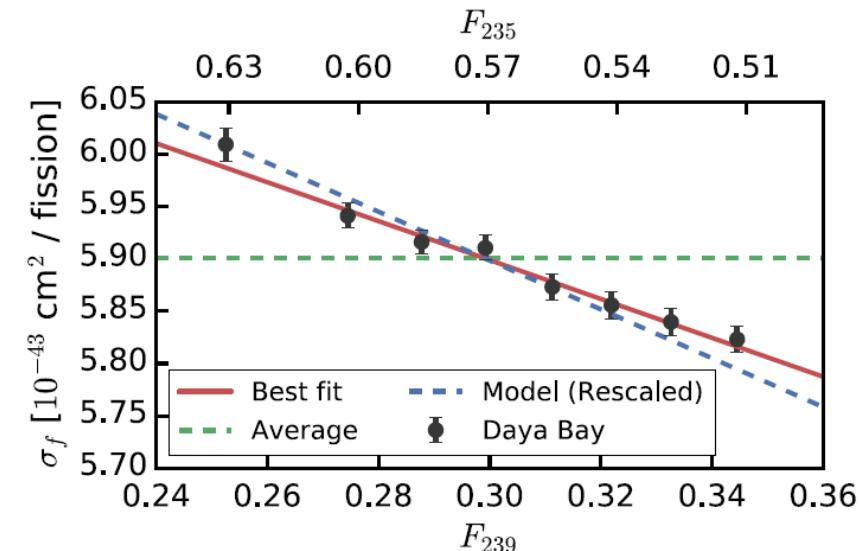
- ONLY U235 has deficit, NOT Pu239
- NOT due to oscillation



Daya Bay, PRL 118, 251801 (2017)



Daya Bay, RPL 130, 211801 (2023)



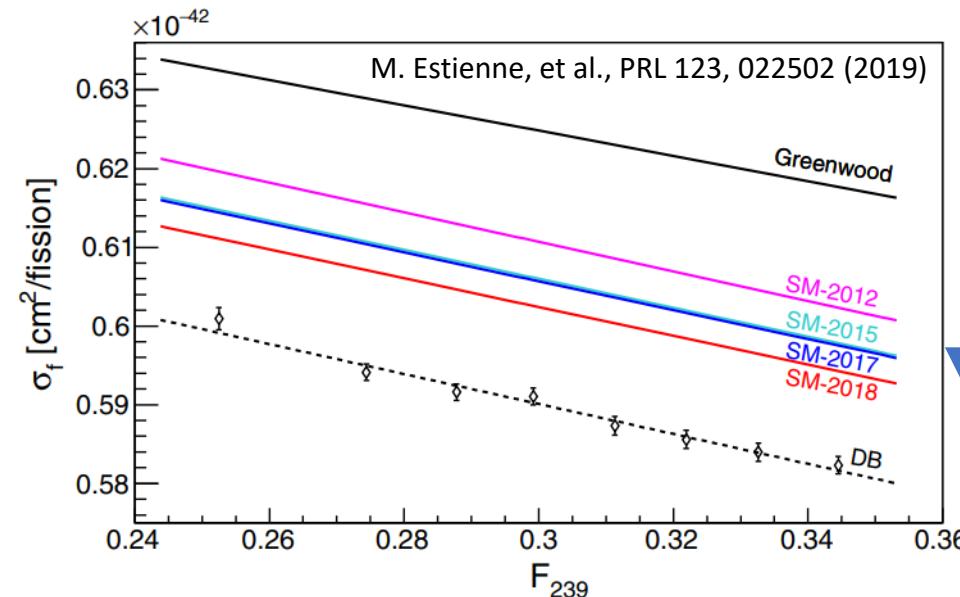
RENO, PRL 122, 232501 (2019)



Updated Reactor Neutrino Model

Summation (or, Ab Initio) Method

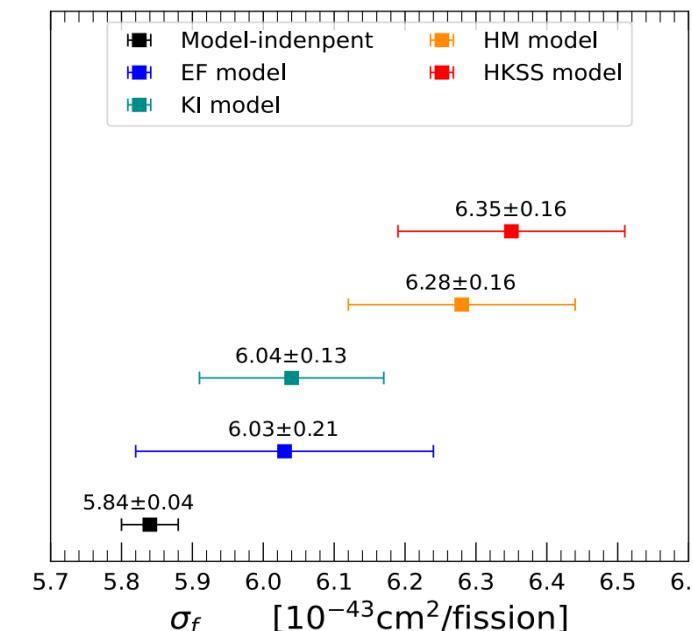
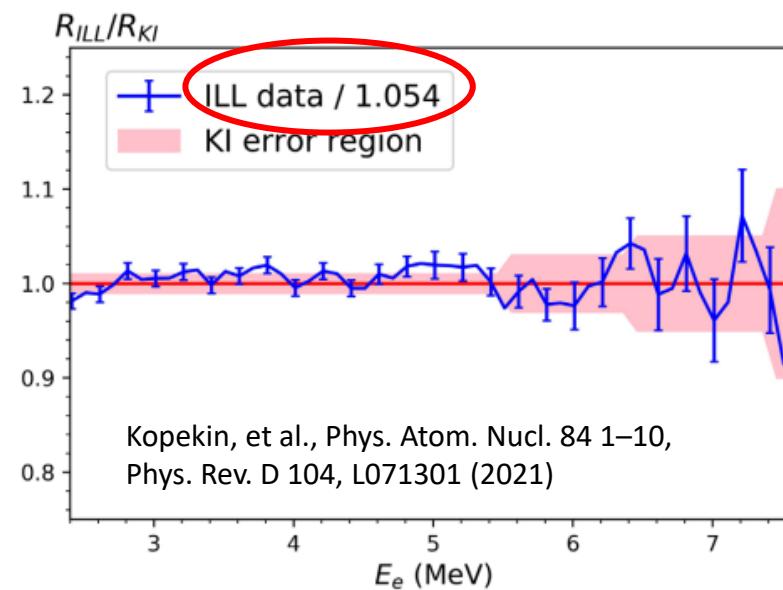
- Pandemonium effects - undetected weak beta transitions and low-intensity γ radiation (J. Hardy et al. 1977).
 - Improving with the Total Absorption Gamma Spectrometers (TAGS) measurements in the past decade



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 $^{235}\text{U}/^{239}\text{Pu}$ fission beta ratio at Kurchatov Institute
 - ILL normalization



Data-driven model:
A global fit

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



Spectrum Anomaly

Spectrum Anomaly Significance

Daya Bay:

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

also seen in RENO, Double Chooz

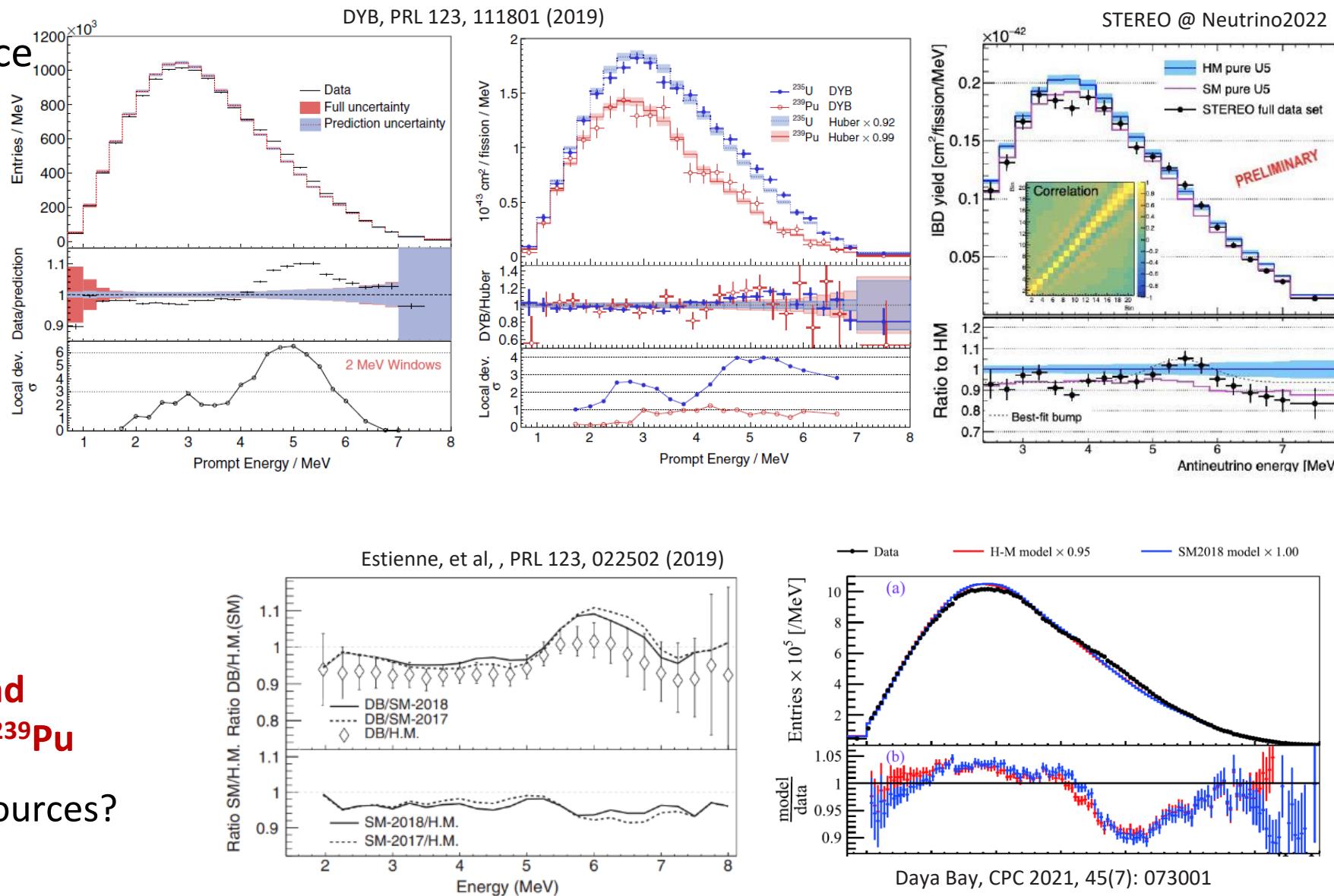
STEREO: 4.6σ (bump)

STEREO + PROSPECT: 4.7σ

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

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

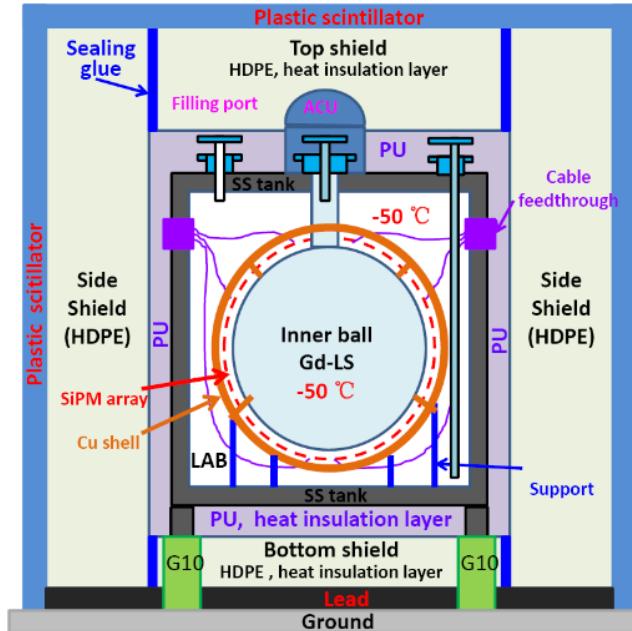
Forbidden beta decay? Others sources?





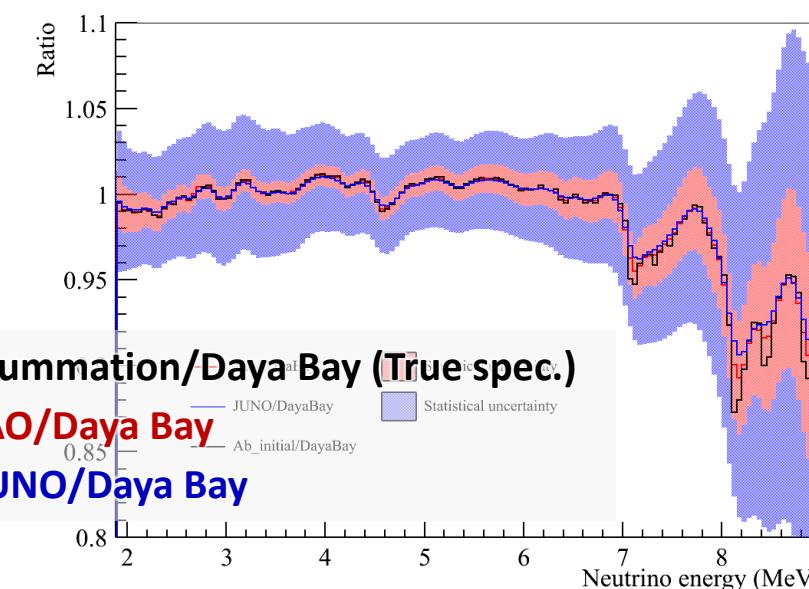
Fine Structures in the Spectrum (JUNO-TAO)

- **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**
- **Detector Features**
 - 2.8 ton Gd-LS, Full **coverage** of SiPM w/ PDE > 50%
 - Operate at **-50 °C** (SiPM dark noise)
 - 4500 p.e./MeV, **<2% resolution @ 1MeV**
- **Expected online in 2024**



CDR:
2005.08745

Calibration strategy:
2204.03256



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

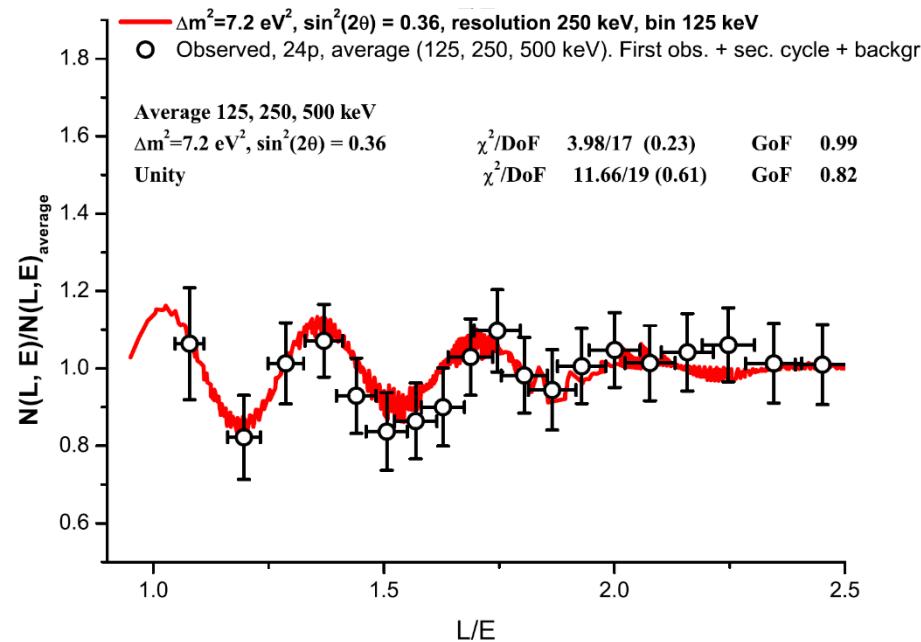
[2111.10112](#)



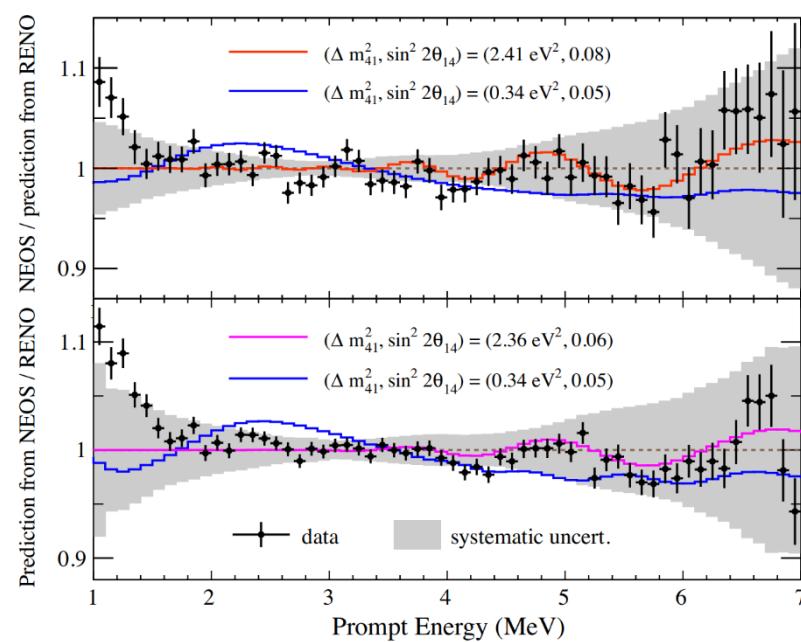
Sterile ν searches – Positive

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

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

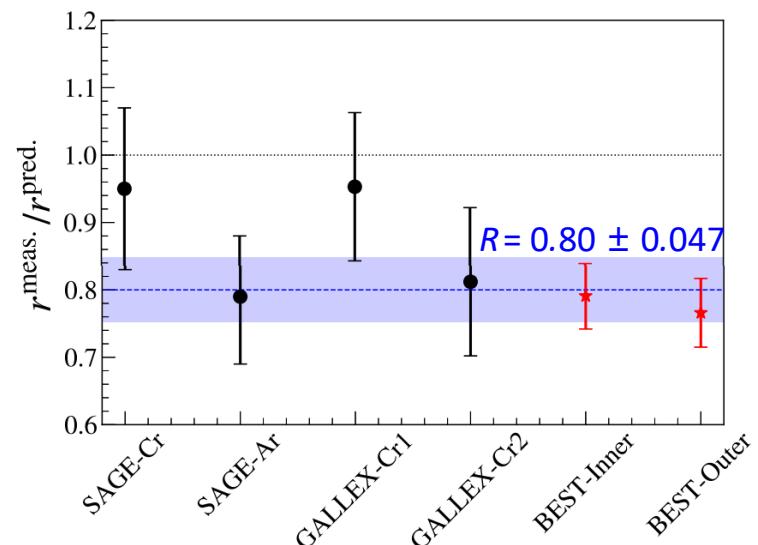


Neutrino-4, PRD 104 (2021) 032003



$$(\Delta m_{41}^2, \sin^2 2\theta_{14}) = (2.41 \text{ eV}^2, 0.08)$$

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

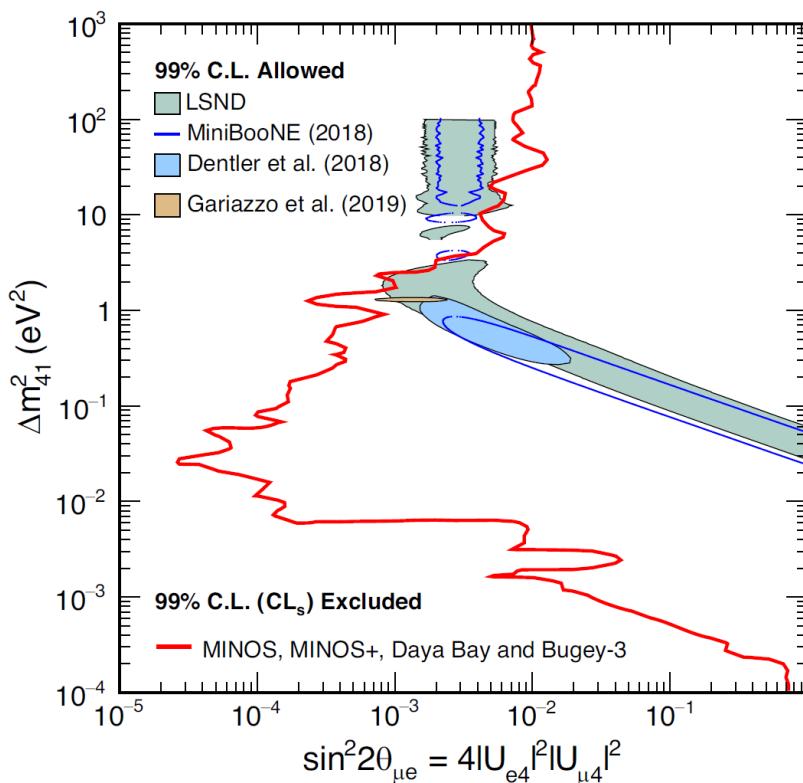


$$\Delta m^2 > 0.5 \text{ eV}^2, \sin^2 2\theta \sim 0.42$$

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

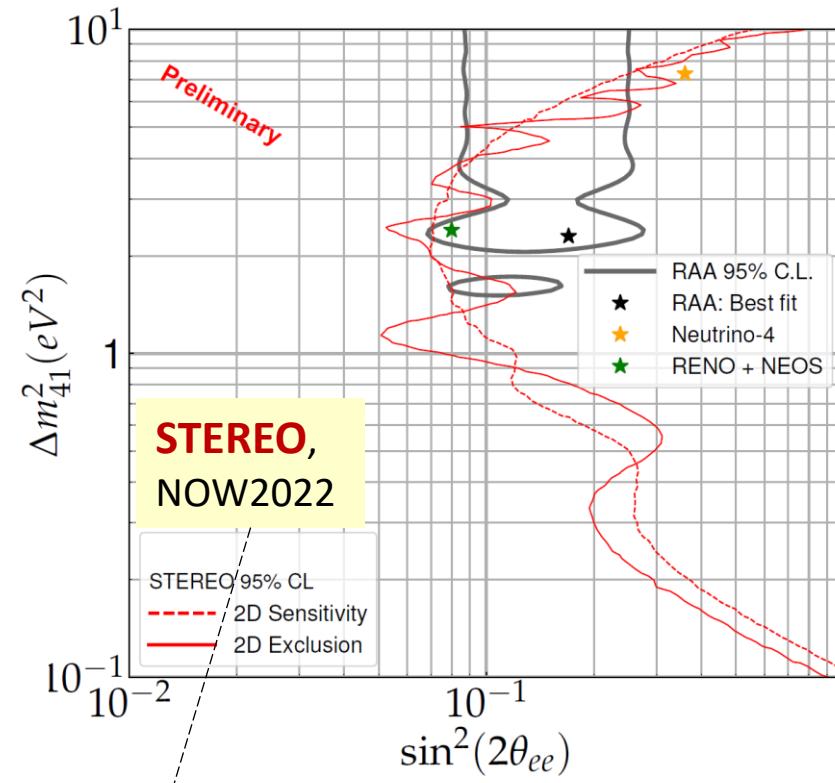


Sterile ν searches – Negative w/ reactors



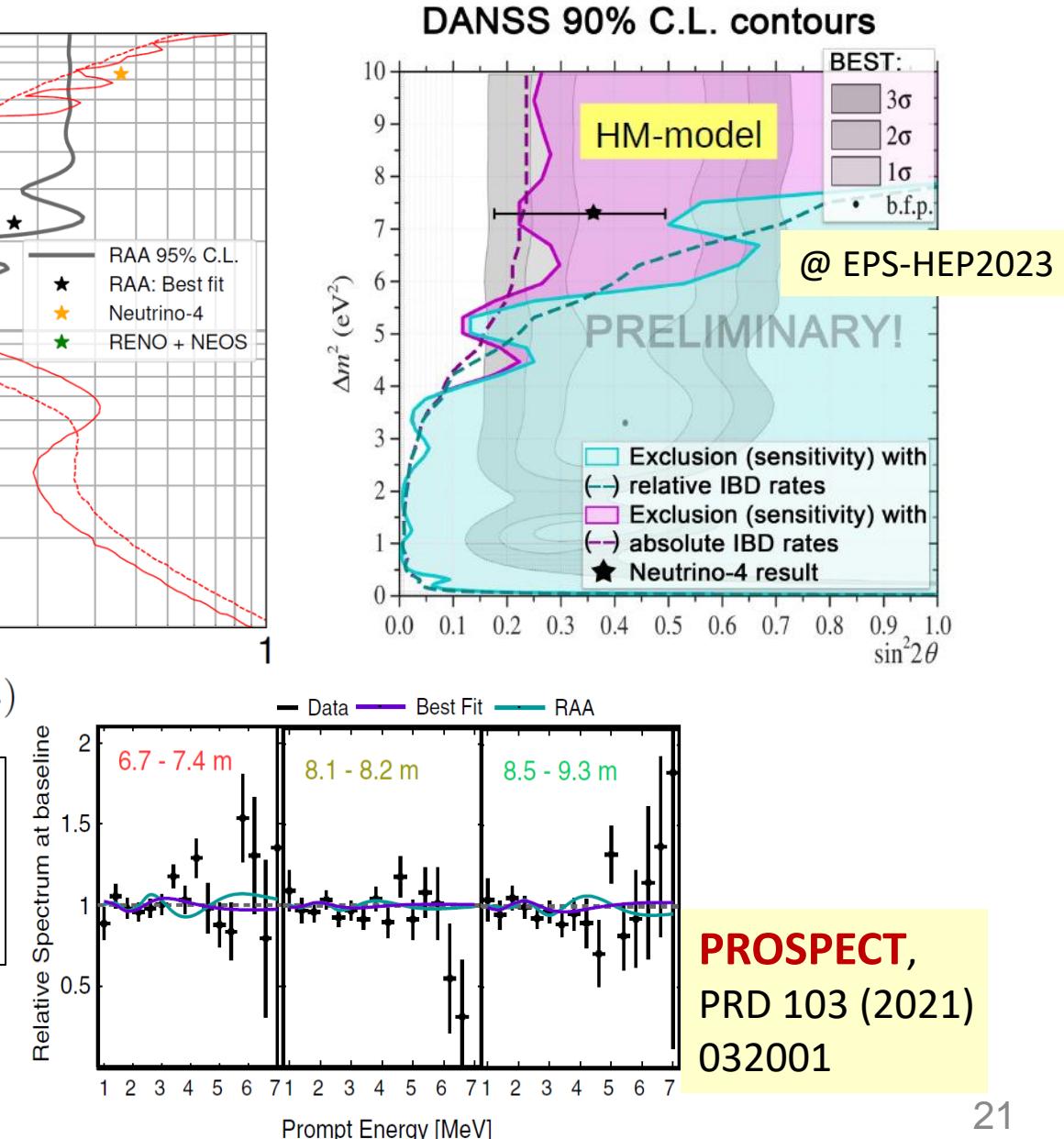
Daya Bay+MINOS+,
PRL 125, 071801 (2020)

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 3.1σ
- RENO+NEOS best fit excluded at 2.8σ

RAA: Reactor Antineutrino Anomaly

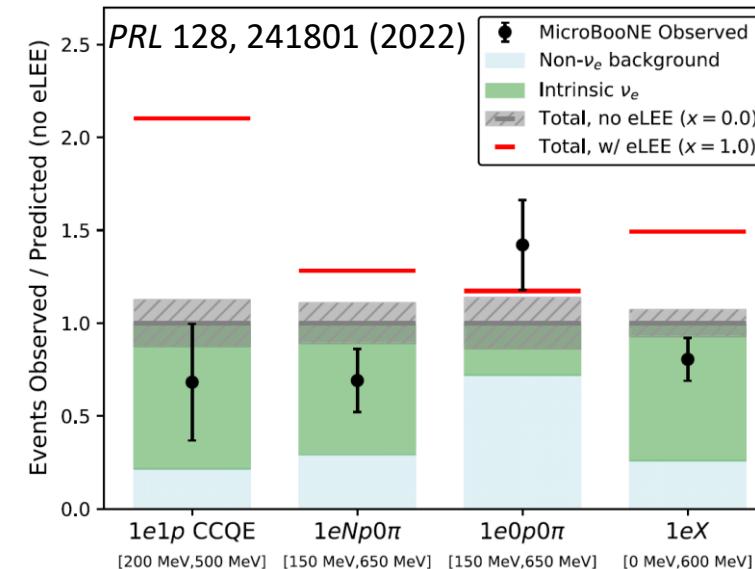
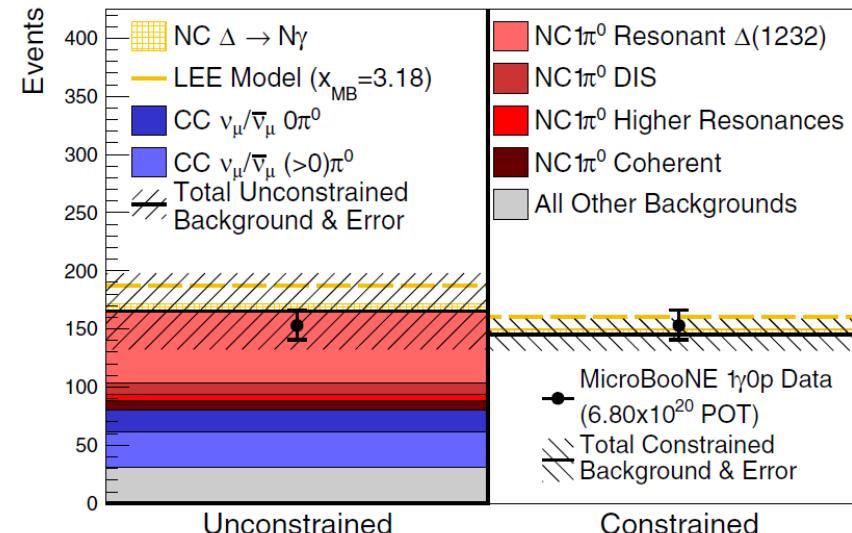


PROSPECT,
PRD 103 (2021)
032001



Sterile ν searches – Negative at MicroBooNE

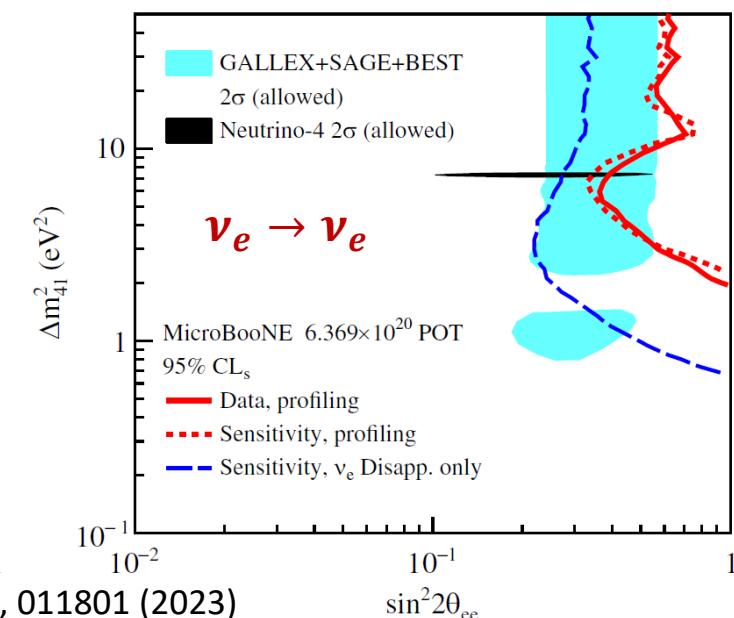
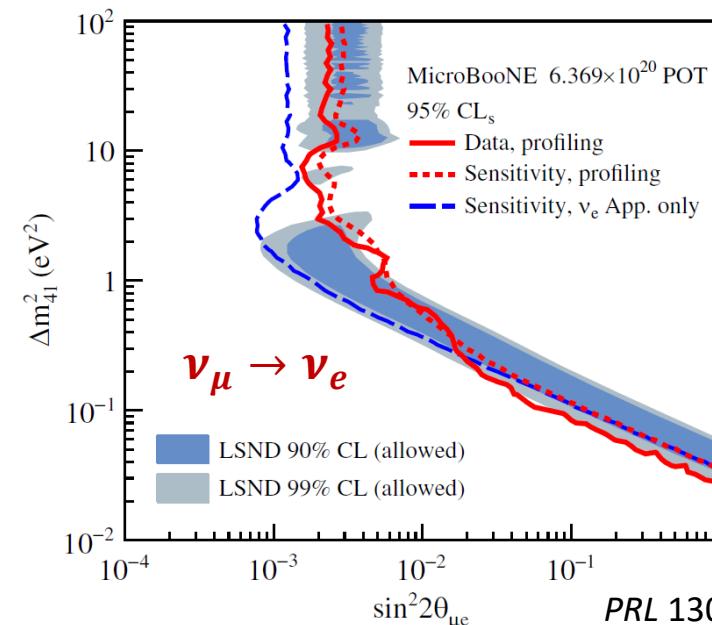
MicroBooNE: Jessie Micallef
MiniBooNE: Michael Shaevitz



No evidence of underestimation of $\Delta \rightarrow \text{Ny}$ 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





Sterile Searches Prospect -- accelerators

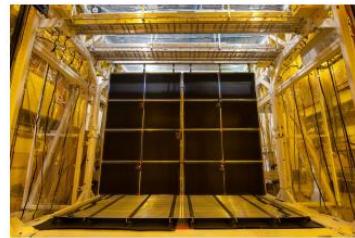


ICARUS

600 m baseline
476 t active volume
Data Taking

SBND

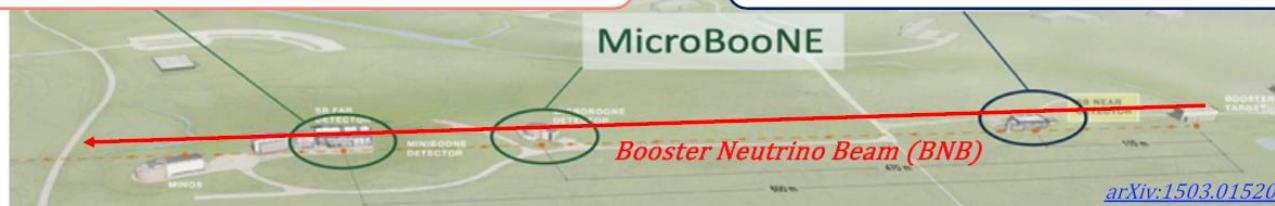
110 m baseline
112 t active volume
Under Completion



SBND Trigger: Tereza Kroupova

SBND status: Lauren Yates

ICARUS status: Diana Patricia Mendez

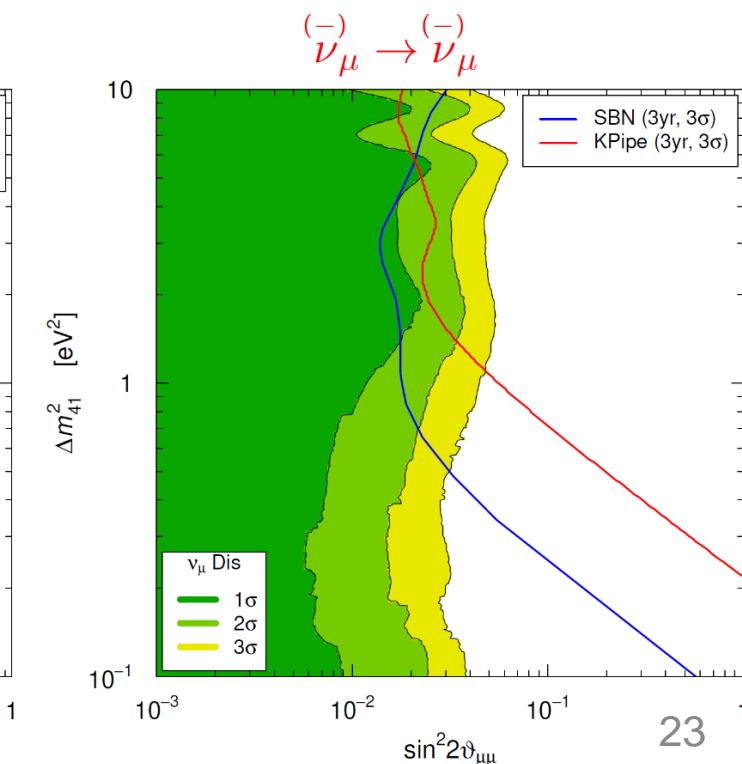
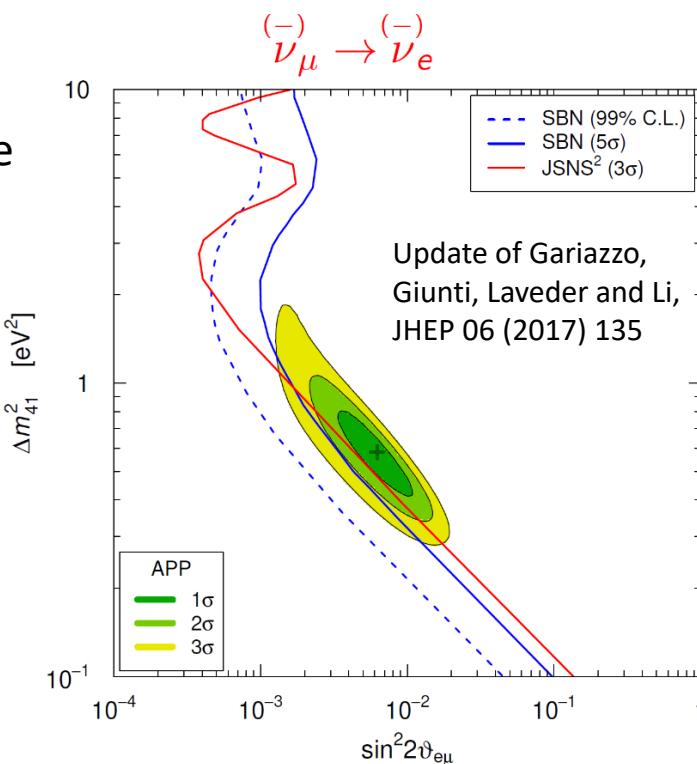


Short Baseline Neutrino Program (SBN) at FNAL

- search for sterile neutrino oscillations both in appearance & disappearance channels at $\sim \text{eV}^2$ scale
- multi-LArTPCs, at 110 m, 470 m, 600 m baselines

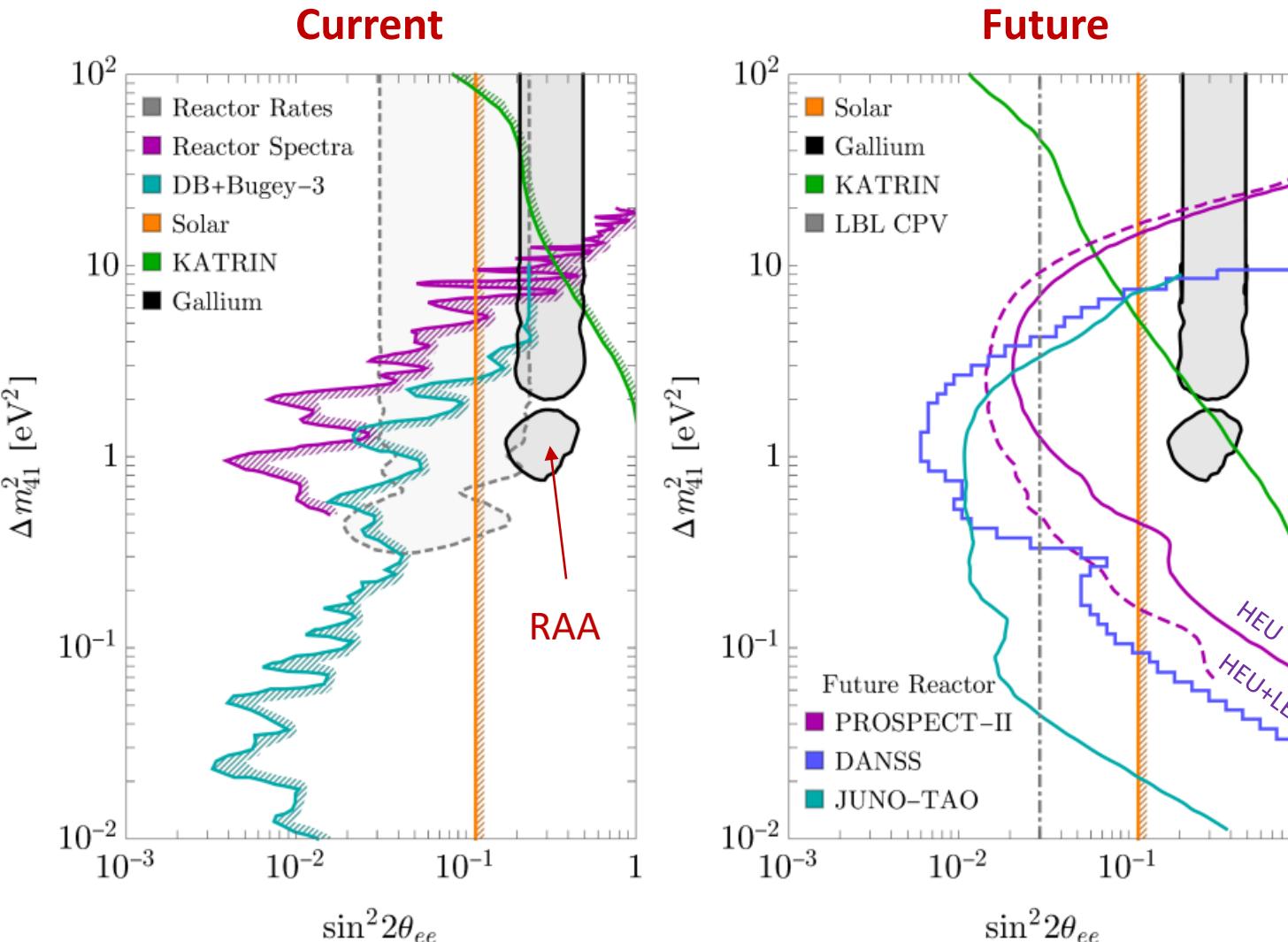
JSNS² @ J-PARC

- search for sterile neutrino via $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, 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

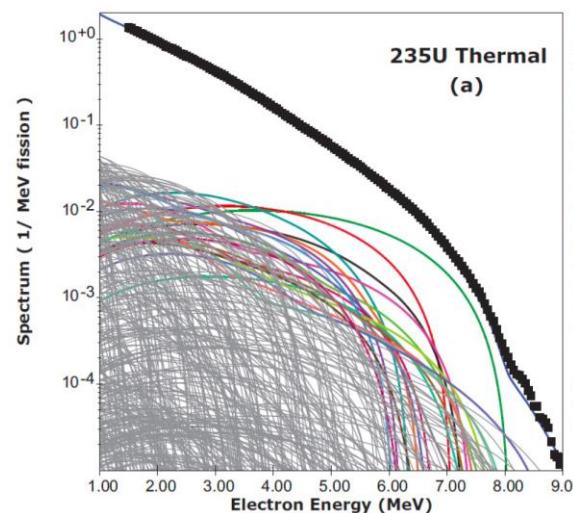
- Short-baseline oscillations at reactors can precisely understand neutrino mixing parameters
 - θ_{13} by Daya Bay (2.8%)
 - $\theta_{12}, \Delta m^2_{21}, \Delta m^2_{32}$ by JUNO (<0.5% in 6 yrs)
 - **Mass ordering** w/ reactor by JUNO (3 σ in 6 yrs)
- Sterile neutrinos, an active area in both short-baseline 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!

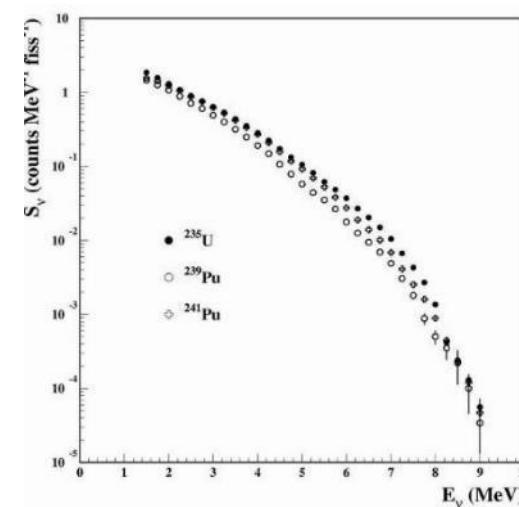


Predicting the Flux and Spectrum

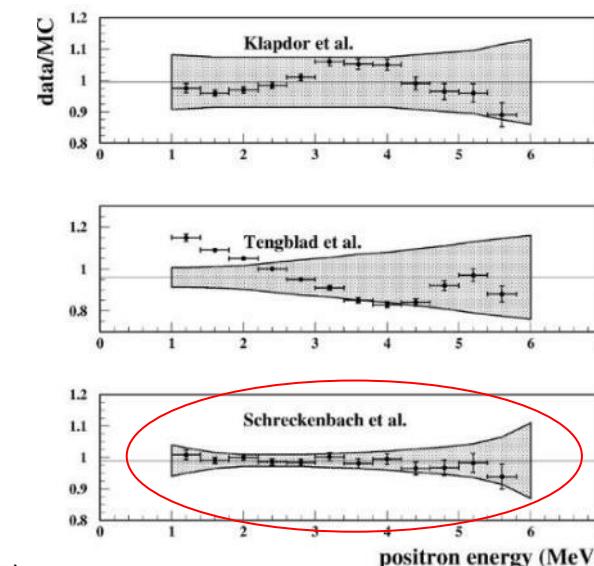
- ◆ **Summation (ab initio): Nuclear database, Σ fragments, Σ chains, Σ branches**
(e.g. Vogel et al., PRC24, 1543 (1981), Estienne, et al, PRL 123, 022502 (2019))
- ◆ **Conversion: ILL measured the β -spectra \rightarrow convert to neutrino spectra**
 - ⇒ **ILL spectra:** Use spectra of 30 virtual (allowed) decays, fit amplitude and endpoints (ILL-Vogel spectra)
 - ⇒ **Mueller:** 90% ab initio + 10% fit \rightarrow rate anomaly
 - ⇒ **Huber:** fit w/ improved nuclear effects (Huber-Mueller spectra)



A. Sonzogni, AAP 2019



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



Shape verified by Bugey-3 data
Normalization by Bugey-4, 1.6%



Updated reactor neutrino models

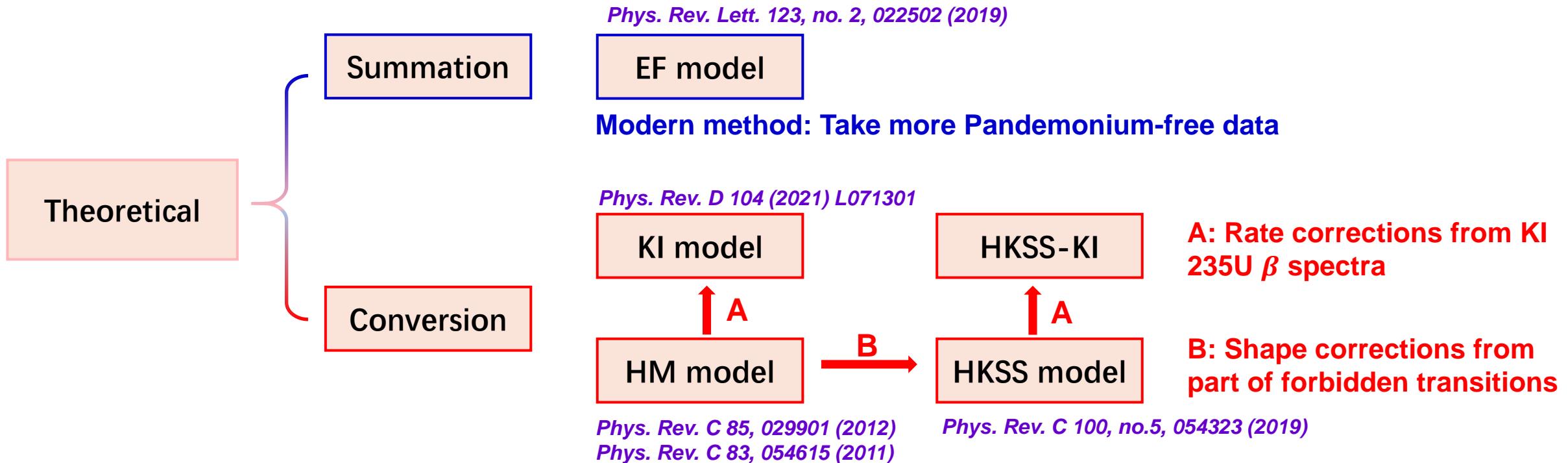


Diagram Courtesy: XIN Zhao