Reactor Neutrino Oscillations

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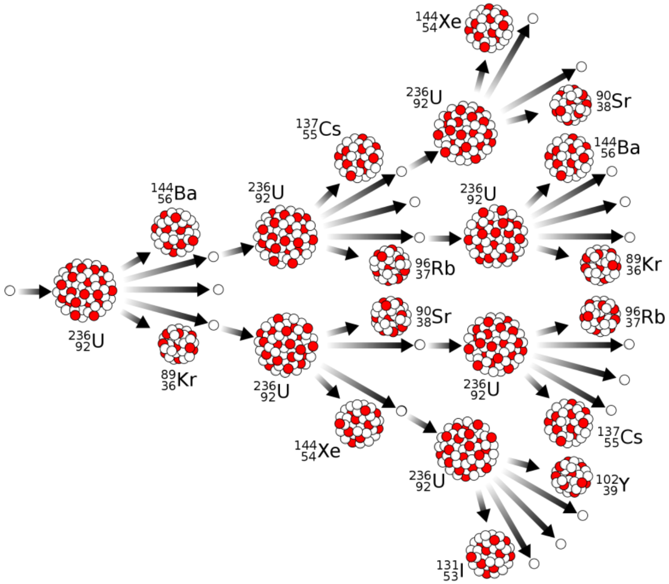
Many plots (slides) are from talks in the Neutrino 2018. Thanks for them.

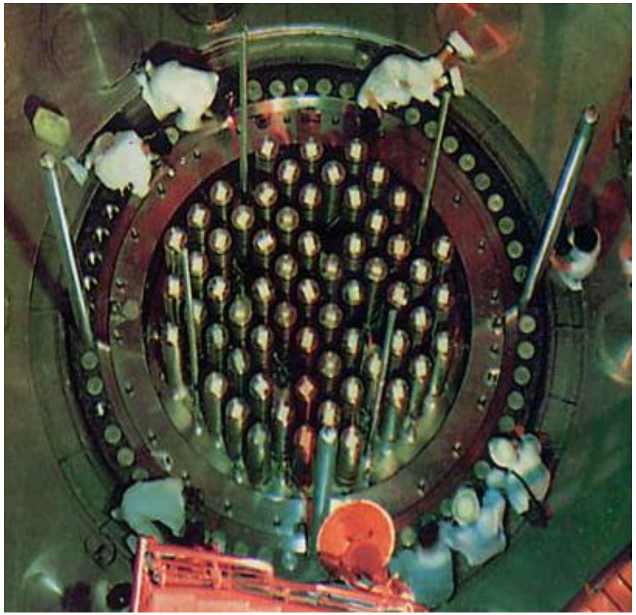
Contents

Feature of Reactor Neutrino Source

Reactor Neutrino Source

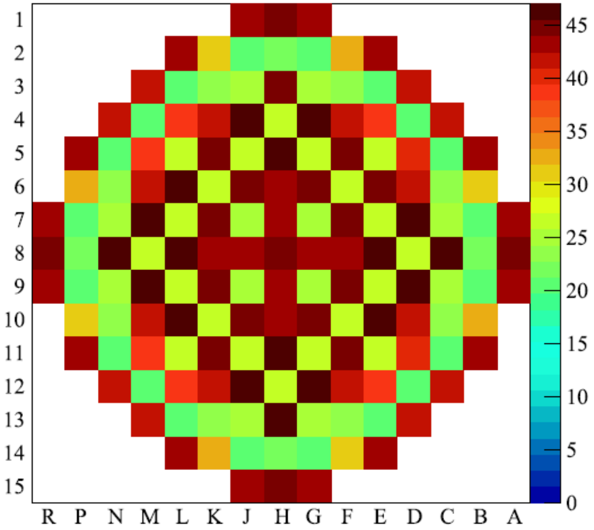
- Nuclear Chain Reaction
- Commercial reactors
  - Four fission isotopes: U-235, Pu-239, U-238, Pu-241
  - 3.7 m height, 3 m diameter (Daya Bay)
- Research reactors:
  - ex. U-235 rich, some are smaller
- Beta decay of fission isotopes and fragments emits electron-antineutrinos



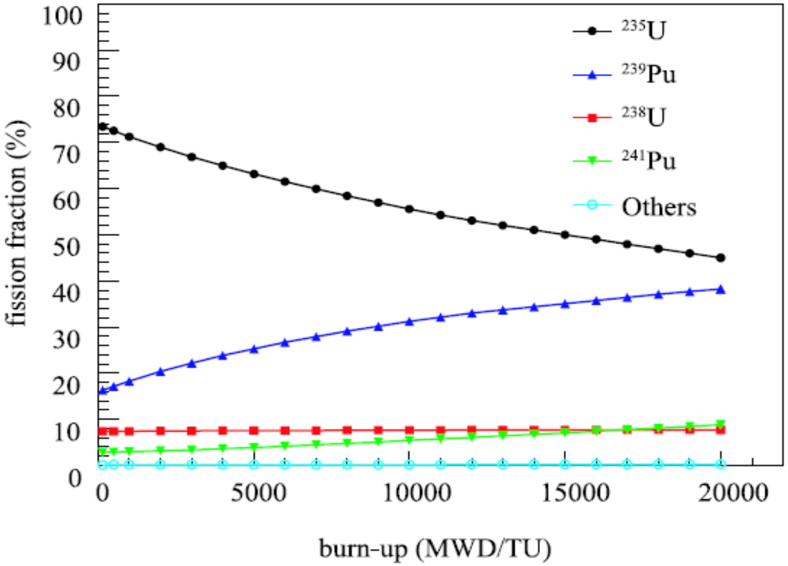


Reactor Neutrino Source

- A popular style:
  - French Pressurized Water Reactor (PWR)
- Running cycle:
  - Replace 1/3 (1/4) fuel every 18 (12) months
- Fuel evolution in a cycle
  - U-235 and Pu-239 dominant

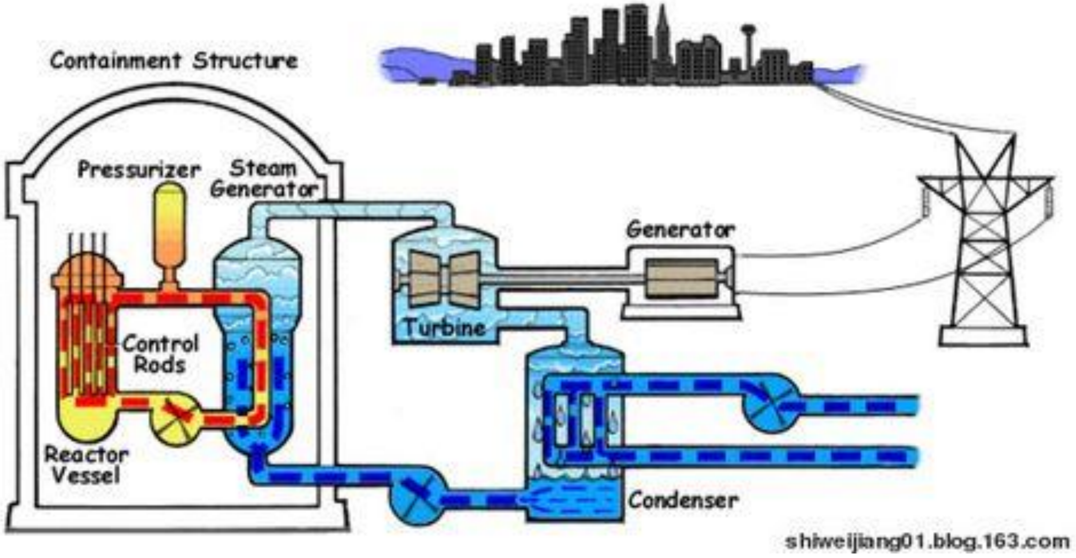


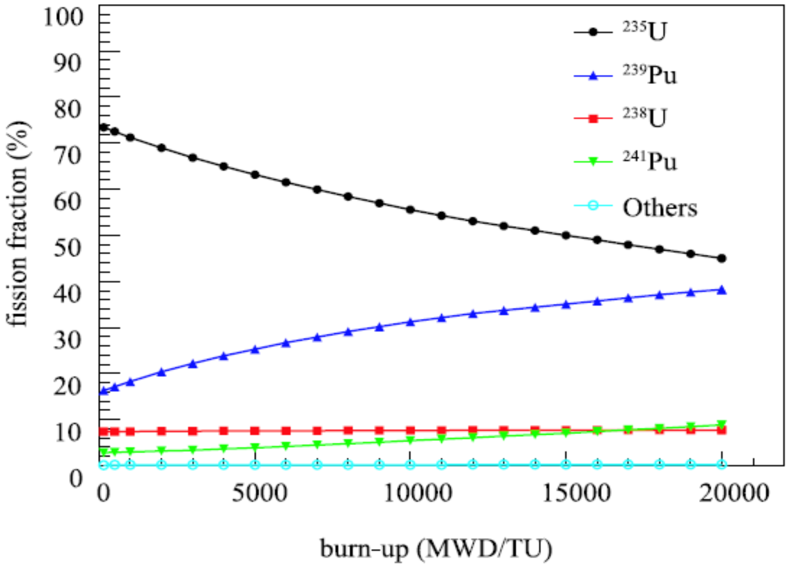
Reactor core map of fuel elements with different burn-up status



Reactor Neutrino Source

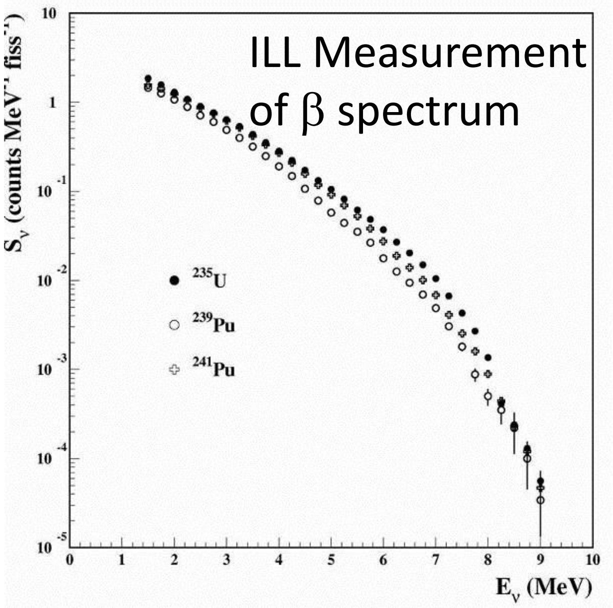
- Reactor power measurement
- Reactor simulation
  - APPOLO2
  - DRAGON
- Typical ave. fission fractions at Daya Bay
  - U-235: 0.564,
  - U-238: 0.076
  - Pu-239: 0.304
  - Pu-241: 0.056





Fission Spectra Predictions

- Method 1. β-conversion



ILL Measurement of β spectrum

FIT

Parameterized

$$S_\beta(E)=\sum_{i=1,30} a_i\, S^i(E,E_o^i)$$

$$S^i(E,E_0^i)=E_\beta p_\beta(E_0^i-E_\beta)^2F(E,Z_{eff})(1+\delta_{corrections})$$

Then replace E_β with $E-E_\nu$

- Method 2. Summation

Use database (ENDF, JEFF) information for fission yield and Beta-feeding

$$S(E_{\bar{\nu}})=\sum_{i=0}^{n}R_i\sum_{j=0}^{m}f_{ij}S_{ij}(E_{\bar{\nu}})$$

R_i, Decay rate of fission isotope *I*

f_{ij}, Beta-decay branch fraction of iso-*i of level-j*

Reactor Neutrino Flux and Spectrum

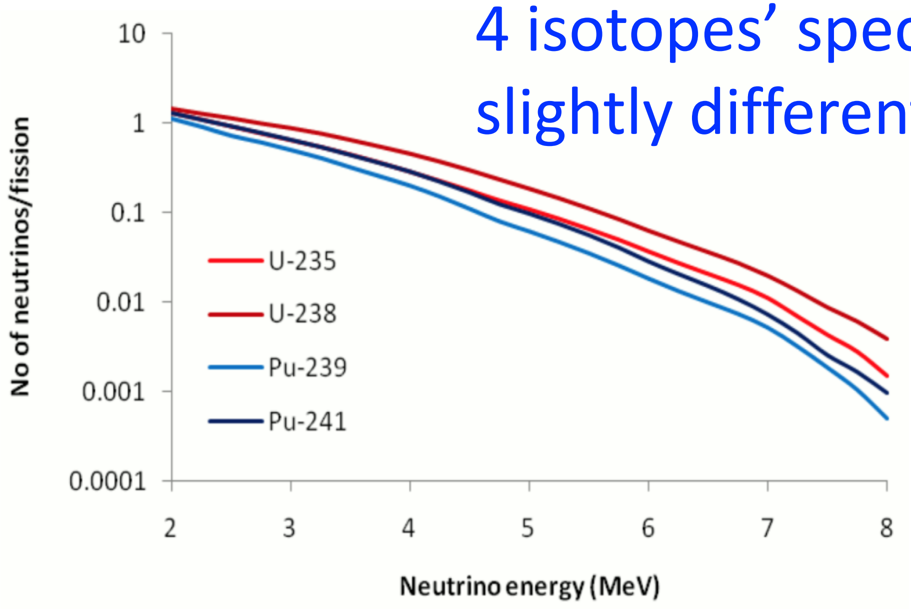
- Reactor neutrino flux
  - $2\text{x}10^{20}$ neutrinos/s/GW
  - Daya Bay: 6x2.9 GW
- Flux and spectrum

F_i, Fission rate of isotope *i*
W_{th}, thermal power
f_i, fission fraction of *i*
E_k, Energy release/fission
i, *k*: four fission isotopes

$$F_i = \frac{W_{\text{th}} f_i}{\sum_k f_k E_k}$$

$$S(E) = \sum_i F_i S_i(E)$$

4 isotopes' spec. slightly different



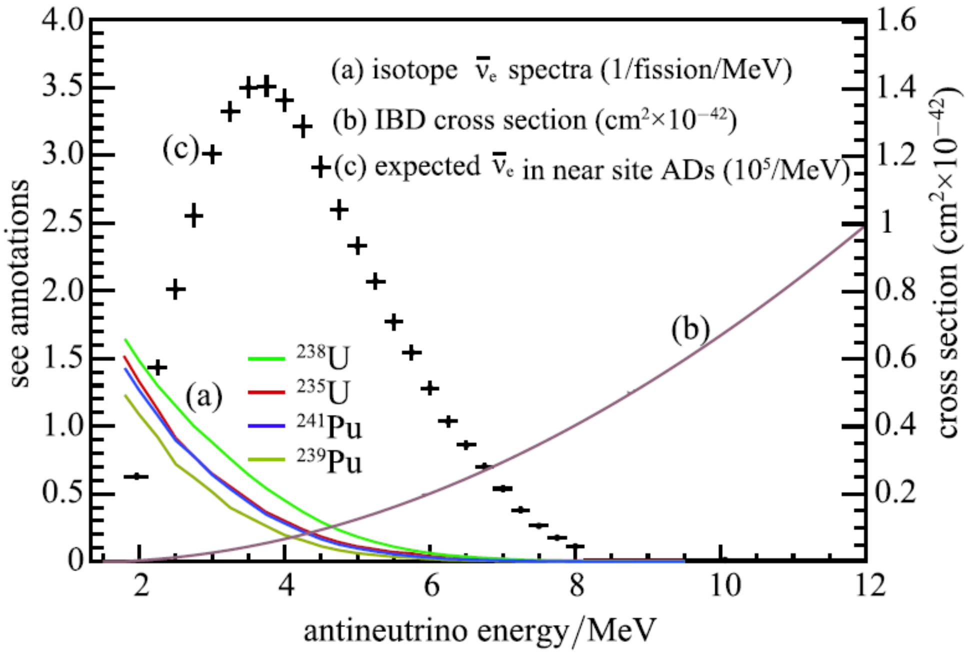
Reactor Neutrino Detection

Reactor Neutrino Detection with Liquid Scintillator

- Inverse Beta Decay with free proton (H)

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

- IBD cross-section
  - Threshold 1.8 MeV



- Neutrino energy reconstruction

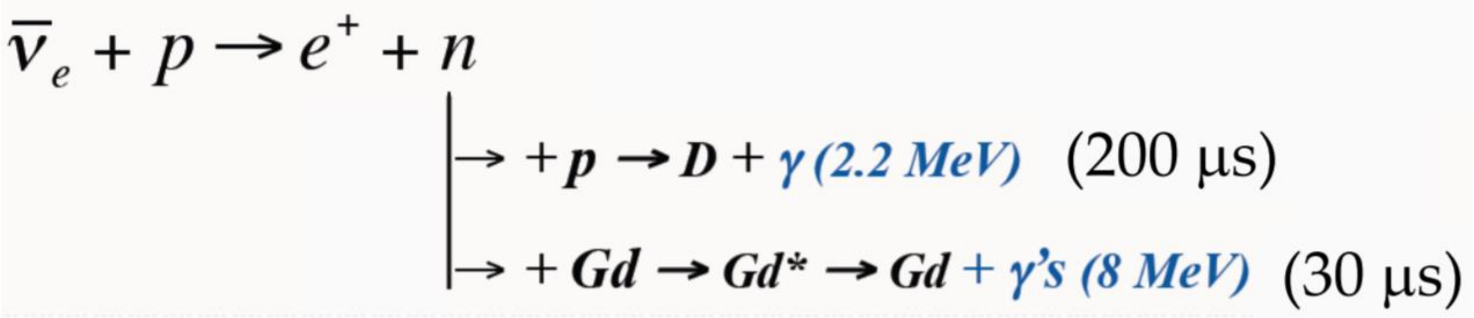
$$E_{\bar{\nu}_e} = E_{\text{prompt}} + \bar{E}_n + 0.78\ \text{MeV}$$

$$E_{\text{prompt}} = E_{e+} + E_{\gamma' s}$$

$$E_n \sim 10\ keV$$

Reactor Neutrino Detection with Liquid Scintillator

- Neutron capture and delayed coincidence
  - E_{prompt} vs $E_{delayed}$



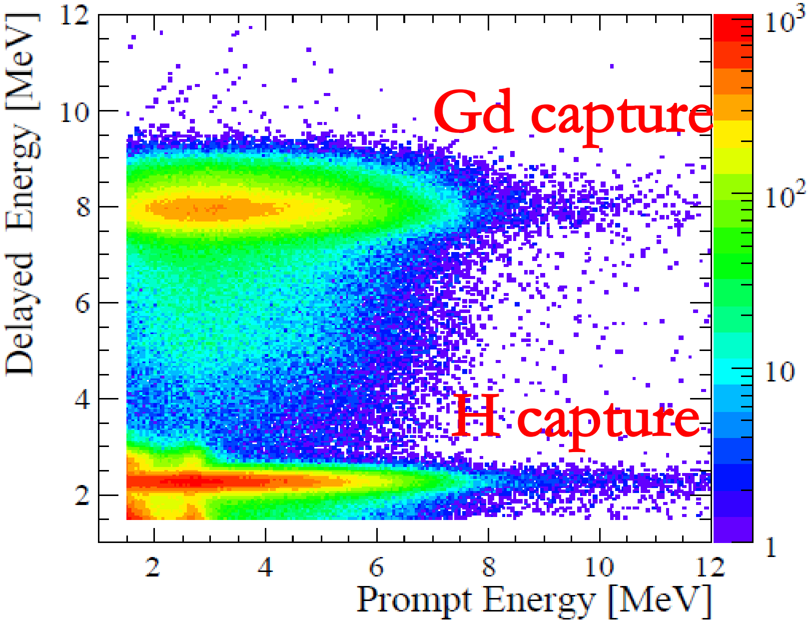
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$\rightarrow + p \rightarrow D + \gamma\,(2.2\ MeV) \quad (200\ \mu s)$$

$$\rightarrow + Gd \rightarrow Gd^* \rightarrow Gd + \gamma\text{'s}\,(8\ MeV) \quad (30\ \mu s)$$

- The requirement for low background is not critical

Technique used by KamLAND, Daya Bay, RENO, Double Chooz, etc.



Three-generation Oscillation Study

Three-Generation Neutrino Oscillation

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

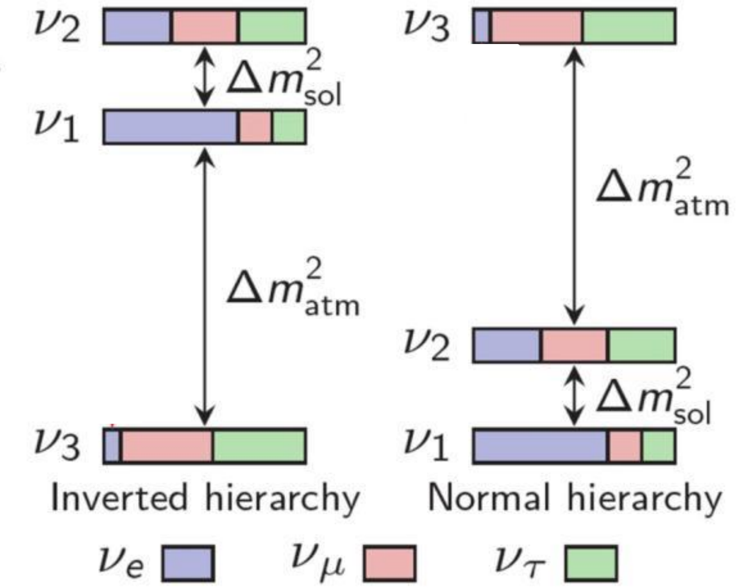
$\theta_{23} \sim 45°$
Atmospheric
Accelerator

$\theta_{13} \sim 8°$
Reactor
Accelerator

$\theta_{12} \sim 34°$
Solar
Reactor

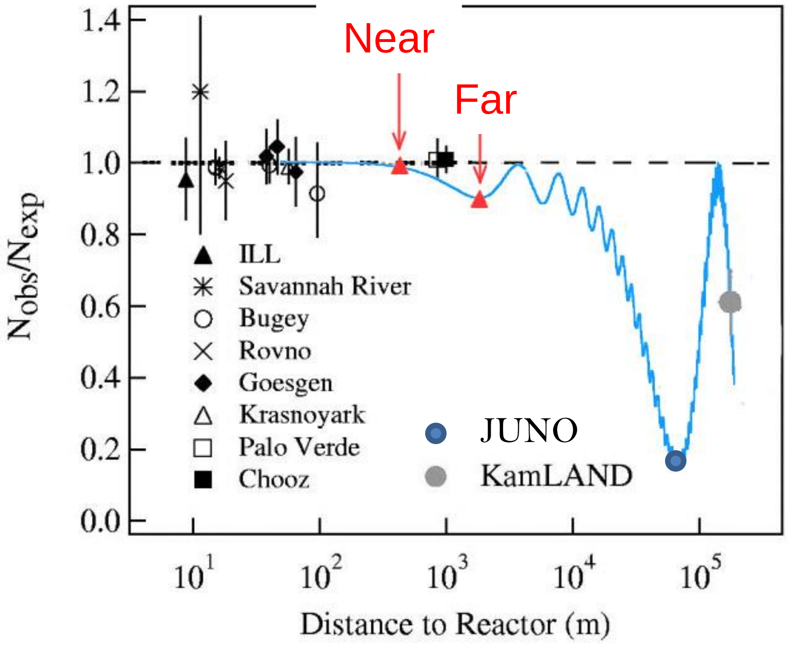
$|\Delta m^2_{31}| \sim 2.4\text{x}10^{-3}\ \text{eV}^2$

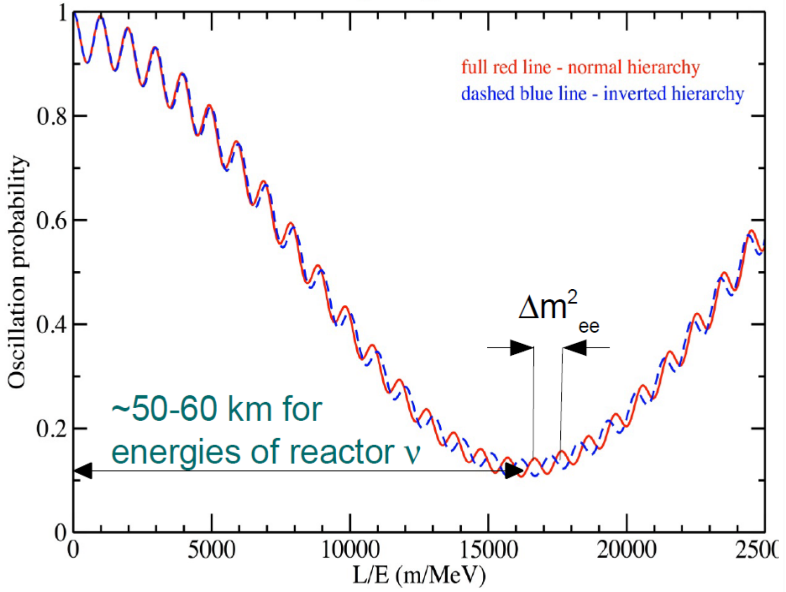
$\Delta m^2_{12} \sim 8\text{x}10^{-5}\ \text{eV}^2$



Three Neutrino Oscillation Measurement

$$\begin{aligned} P(\bar{\nu}_e \to \bar{\nu}_e) &= 1 - \boxed{\cos^4\theta_{13}\,\sin^2 2\theta_{12}\,\sin^2\Delta m^2_{21}\frac{L}{4E}} - \boxed{\sin^2 2\theta_{13}\left(\cos^2\theta_{12}\,\sin^2\Delta m^2_{31}\frac{L}{4E} + \sin^2\theta_{12}\,\sin^2\Delta m^2_{32}\frac{L}{4E}\right)} \\ &\approx 1 - \boxed{\cos^4\theta_{13}\,\sin^2 2\theta_{12}\,\sin^2\Delta m^2_{21}\frac{L}{4E}} - \boxed{\sin^2 2\theta_{13}\,\sin^2\Delta m^2_{ee}\frac{L}{4E}} \end{aligned}$$



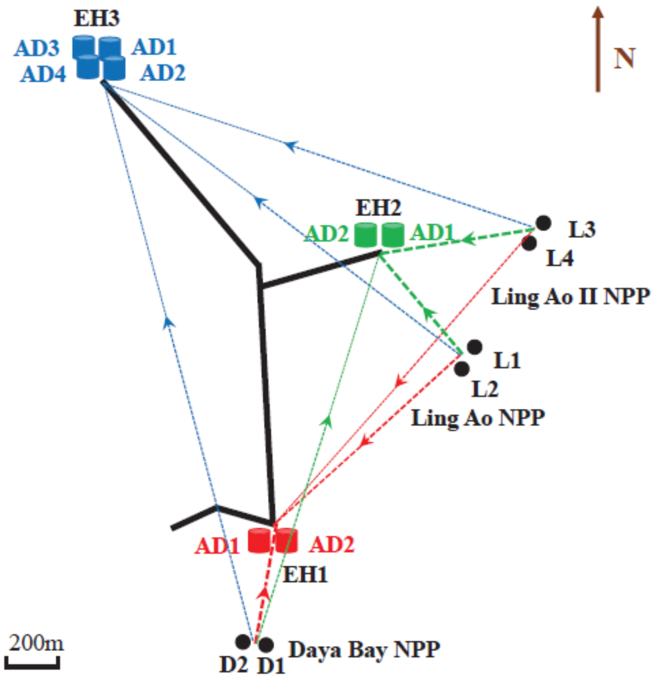


- Small oscillation period and amplitude: θ_{13} and $|\Delta m^2_{31}|$ (Daya Bay, RENO, DC, etc.)
- Large period and amplitude: θ_{12} and Δm^2_{12} (KamLAND)
- Fine structure: mass hierarchy (JUNO)

Relative measurement for θ_{13}

- Principle: Extract θ_{13} from
  Far/Near IBD events ratio and IBD spectrum distortion of the Far and Near sites

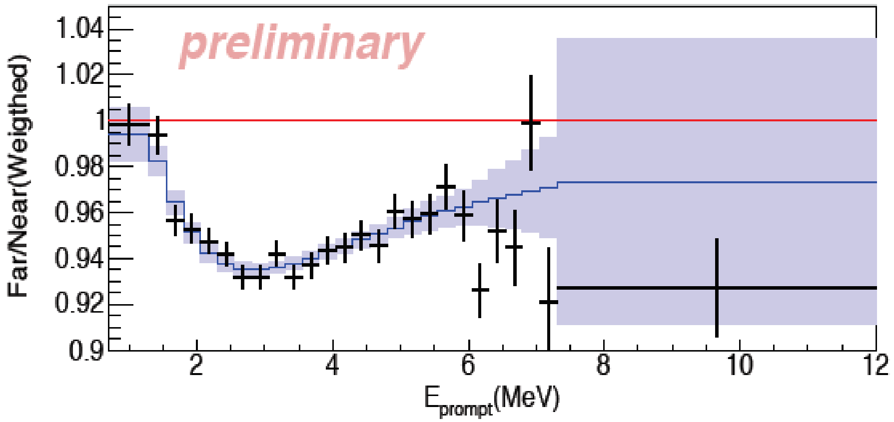
$$\frac{N_\mathrm{f}}{N_\mathrm{n}} = \left(\frac{N_\mathrm{p,f}}{N_\mathrm{p,n}}\right)\left(\frac{L_\mathrm{n}}{L_\mathrm{f}}\right)^2\left(\frac{\epsilon_\mathrm{f}}{\epsilon_\mathrm{n}}\right)\left[\frac{P_\mathrm{sur}(E,L_\mathrm{f})}{P_\mathrm{sur}(E,L_\mathrm{n})}\right]$$



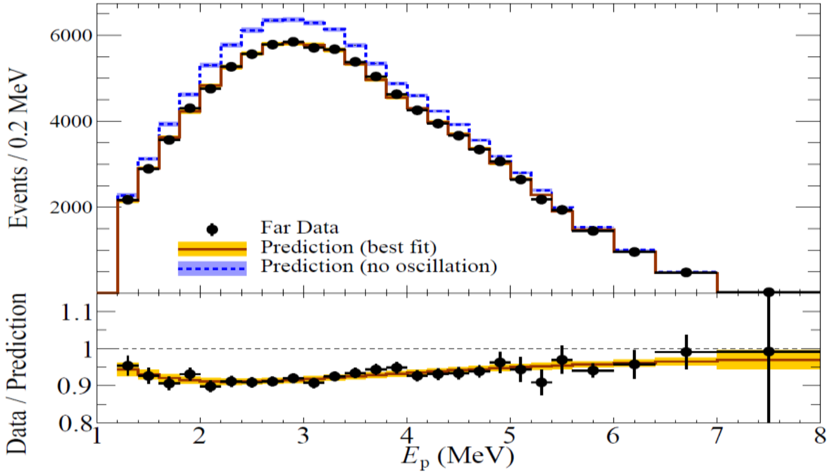
- Fit the detected prompt energy spectra at near and far sites simultaneously with large reactor flux and spectrum uncertainties as common floating parameters

This makes the θ_{13} result largely independent of the absolute reactor flux and spectrum

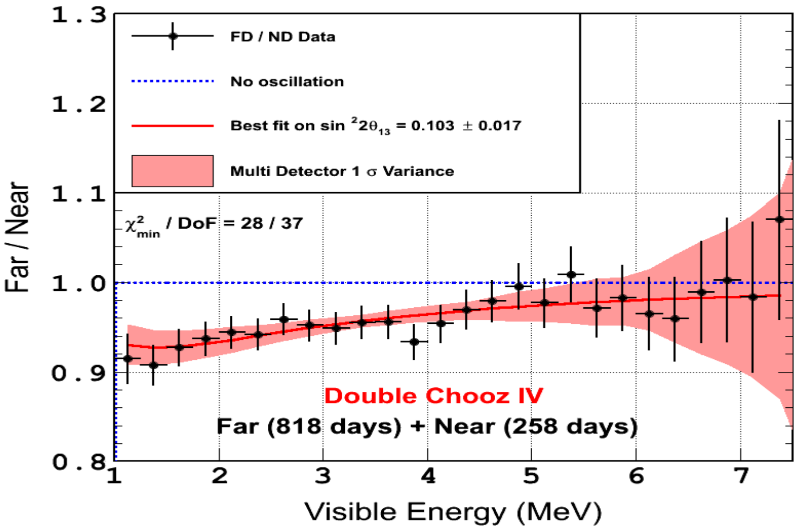
Fit to the Prompt Energy Spectra (DYB, RENO, Double Chooz)



Daya Bay talk @ Neutrino 2018

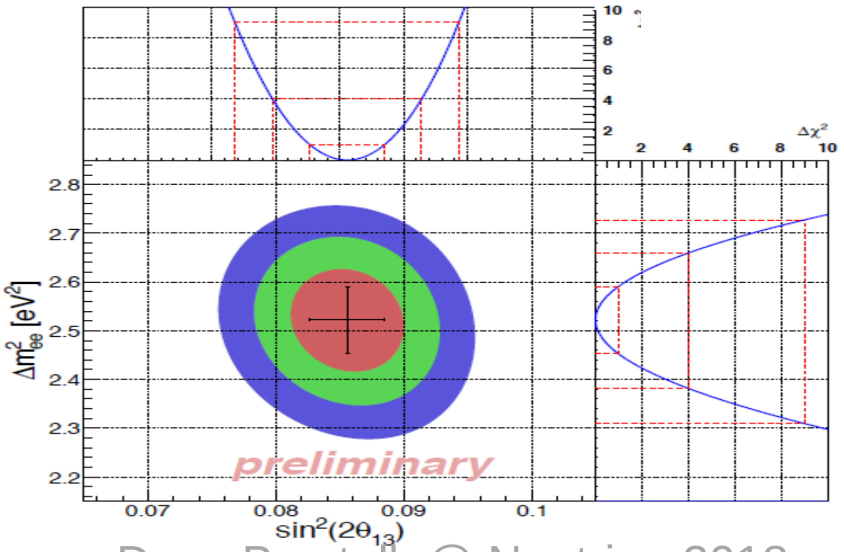


RENO talk @ Neutrino 2018

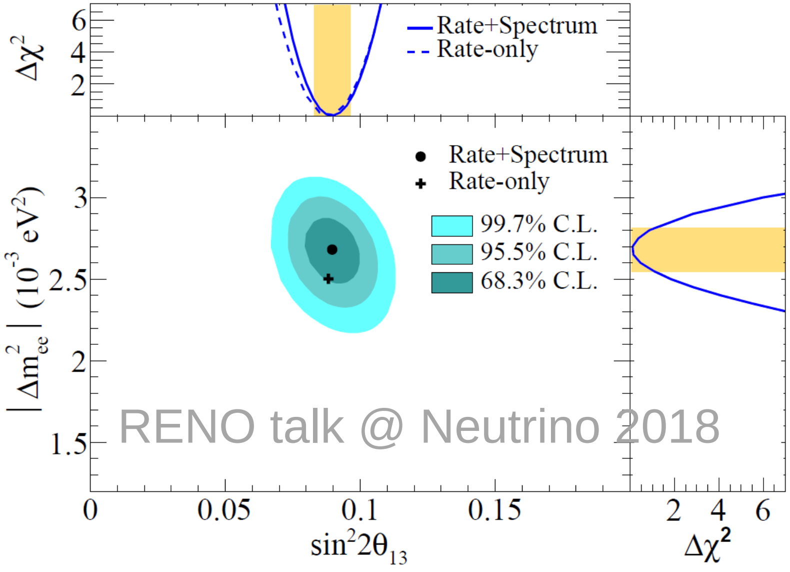


Double Chooz talk @ Neutrino 2018

θ_{13} and Δm^2_{ee} Measurement



Daya Bay talk @ Neutrino 2018



RENO talk @ Neutrino 2018

- Daya Bay

1958 days nGd oscillation analysis

$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$

$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$

621 days nH oscillation analysis

$\sin^2 2\theta_{13} = 0.071 \pm 0.011$

- RENO

nGd oscillation analysis

$\sin^2 2\theta_{13} = 0.0896 \pm 0.0068$

$|\Delta m^2_{ee}| = (2.68 \pm 0.14) \times 10^{-3}\ \mathrm{eV}^2$

nH oscillation analysis

$\sin^2 2\theta_{13} = 0.094 \pm 0.015$

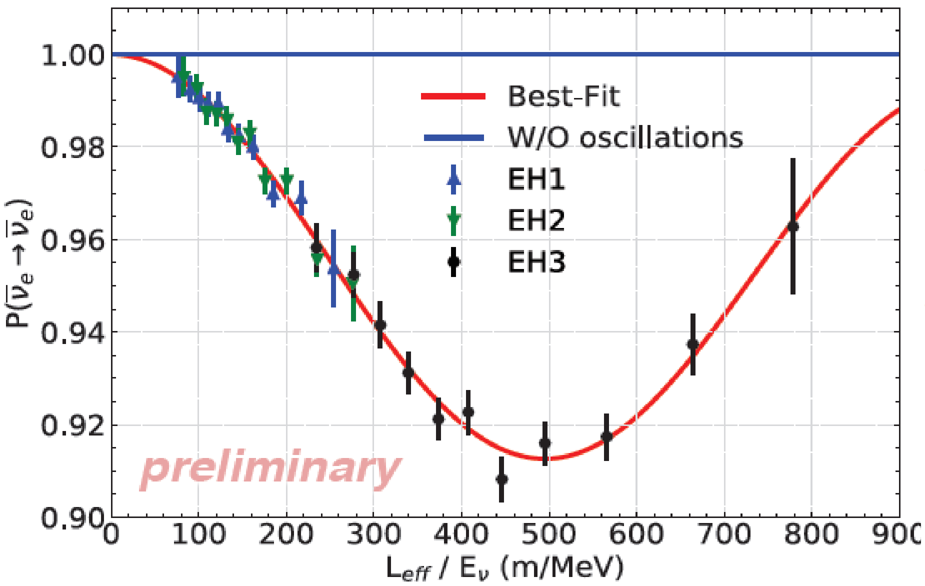
$|\Delta m^2_{ee}| = (2.53^{+0.28}_{-0.32}) \times 10^{-3}\ \mathrm{eV}^2$

- Double Chooz

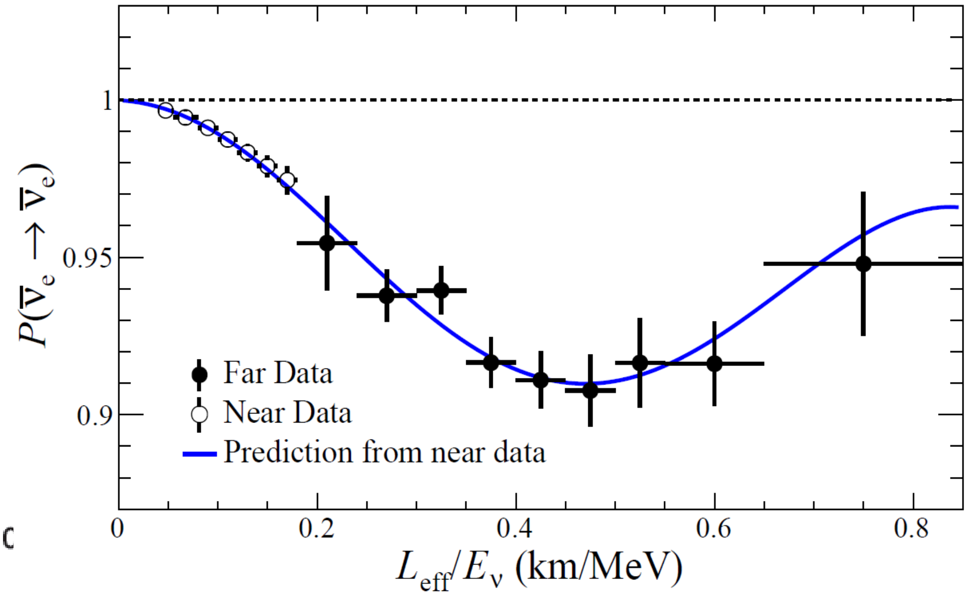
nGd+nH oscillation analysis

$\sin^2 2\theta_{13} = 0.105 \pm 0.014$

L/E Oscillation Feature



Daya Bay talk @ Neutrino 2018

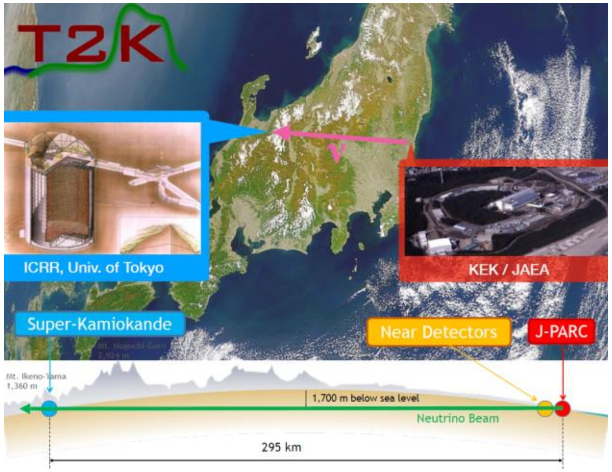


RENO talk @ Neutrino 2018

Although the nice chi2/ndf from DYB, RENO and DC give the clear evidence of L/E dependent oscillation feature, the Prob vs L/E plots are striking.

Impact of θ_{13} value on CP and Mass Hierarchy

- θ_{13} value has a strong impact on Mass Hierarchy and CP phase determination

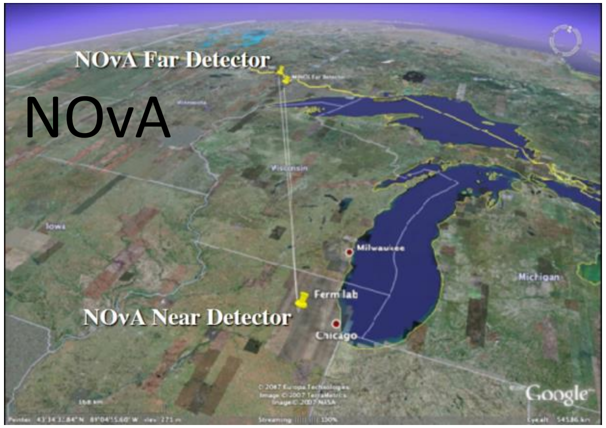


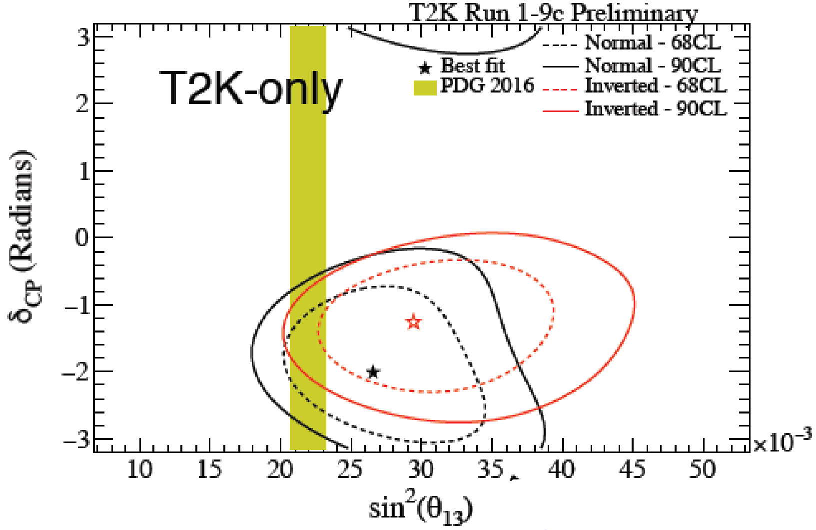
ν_e appearance probability:

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E}$$

$$-\frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin\frac{\Delta m^2_{21}L}{4E}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E}\sin\delta_{CP}$$

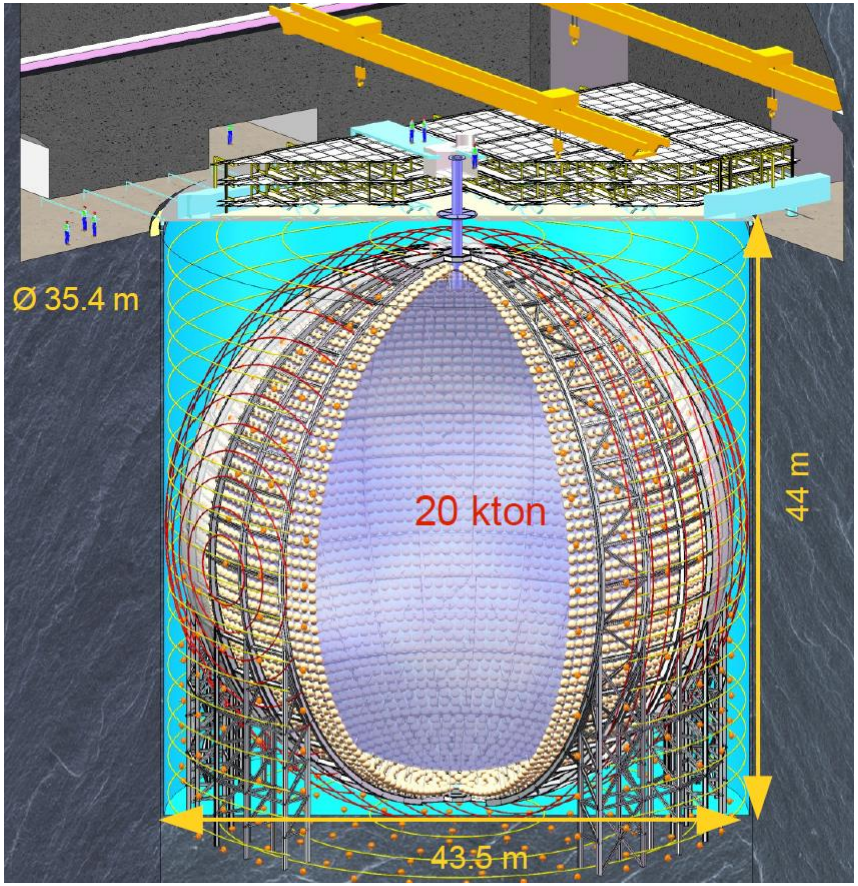
$$+(CP\,\text{even term, solar term, matter effect term}), \qquad (1)$$





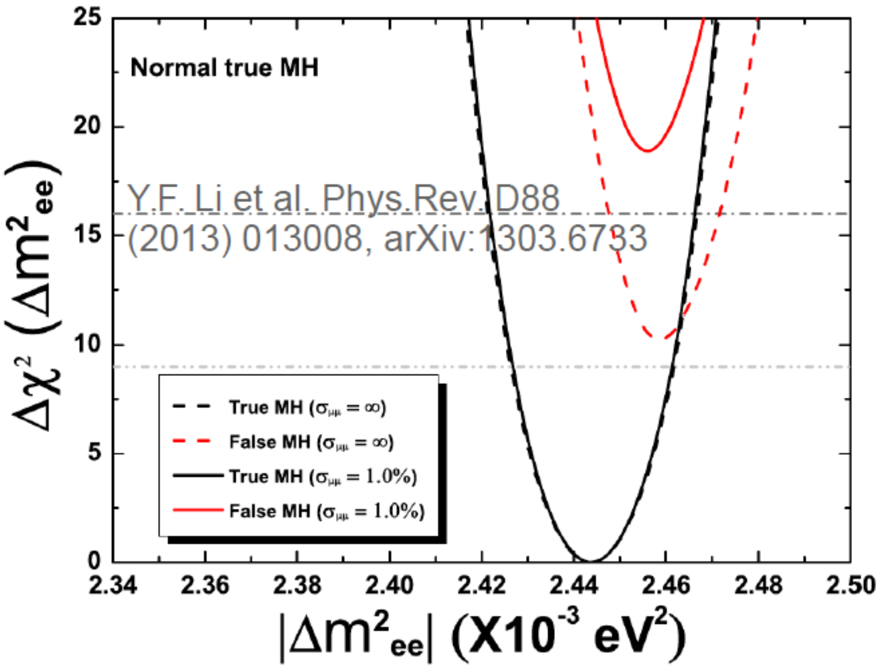
Both T2K and NOvA favor Normal Hierarchy and δ_{CP}=-π/2

Reactor Mass Hierarchy Measurement - JUNO



- Data taking will start in 2021

Björn Wonsak, Neutrino 2018



Y.F. Li et al. Phys.Rev. D88 (2013) 013008, arXiv:1303.6733

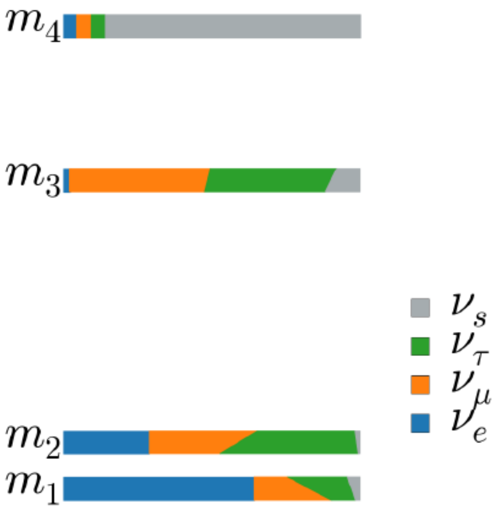
- MH sensitivity: $\overline{\Delta\chi^2} > 9$ ($\overline{\Delta\chi^2} > 16$ with 1% constraint on $\Delta m^2_{\mu\mu}$, strong synergy with long-baseline program)

Sterile Neutrino Search

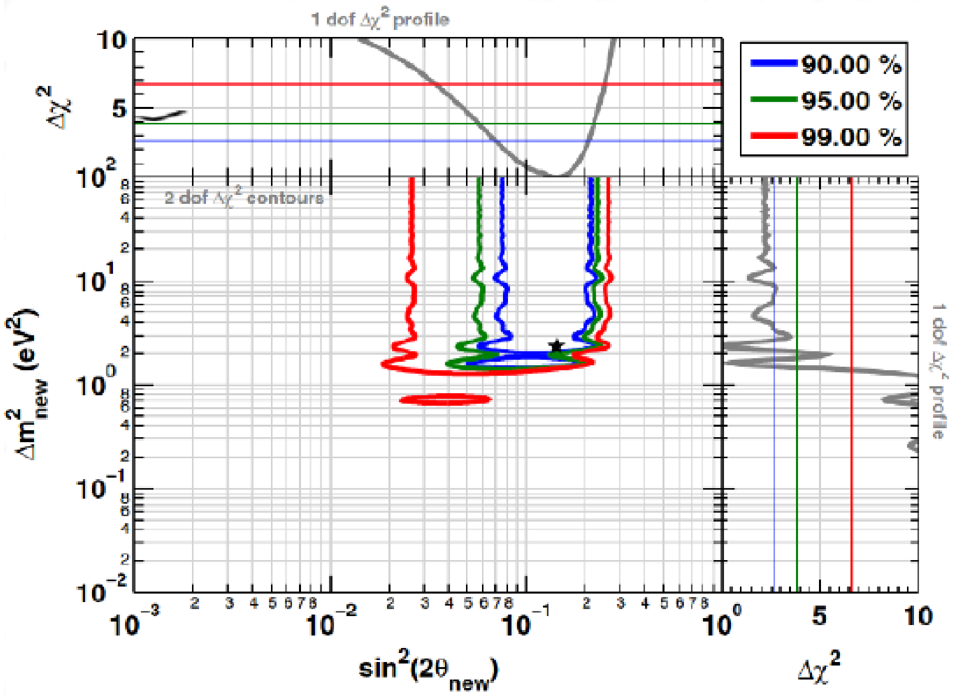
Sterile Neutrino

- 3+1 model
- No coupling to Z boson

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

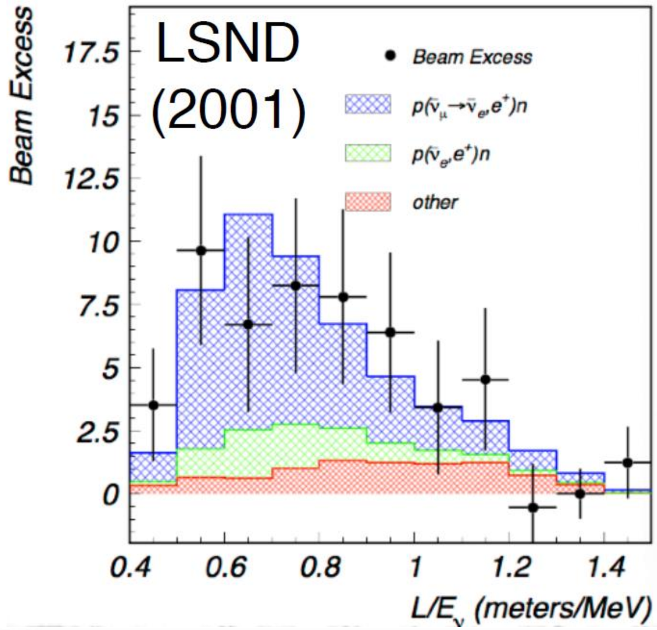


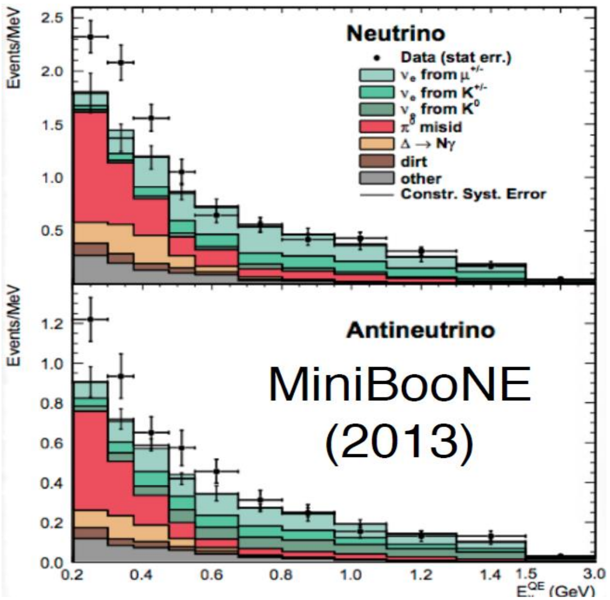
1 eV sterile neutrino?

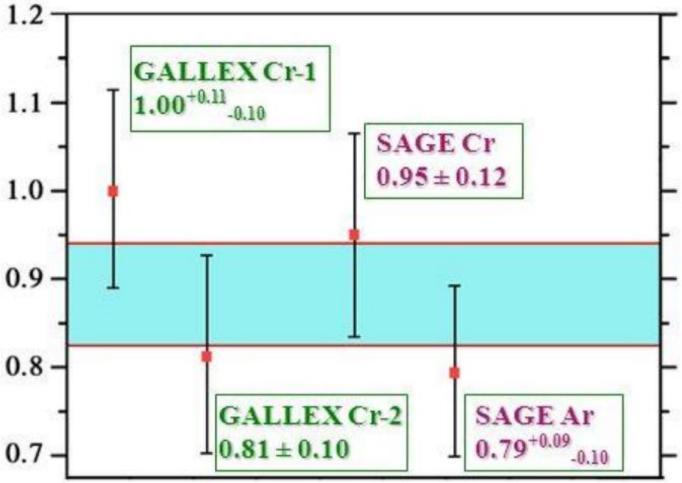


Mention 2011

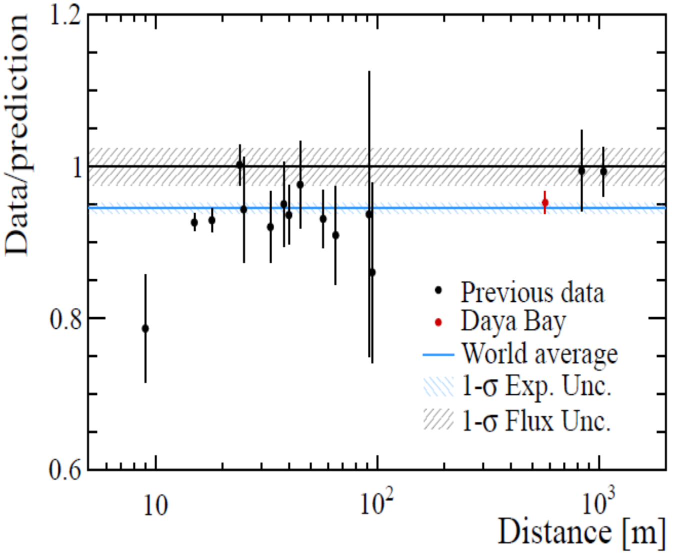
Hint of Sterile Neutrino







Reactor Antineutrino Anomaly



Reactor Antineutrino Anomaly

Reactor flux and spectrum prediction

- *ab initio* method - Summation of all beta decay branches in database
  - Uncertainty 10-20% (Mueller 2011)
- β-conversion
  - ILL measurement of β spectra of U-235, Pu-239, and Pu-241 (Thermal neutron)
  - Effective charge Z is fit to the ILL measurement, and predict neutrino spectra
  - ab initio approach for U-238 (fast neutrons)
  - Uncertainty < 5% (Huber-Mueller)

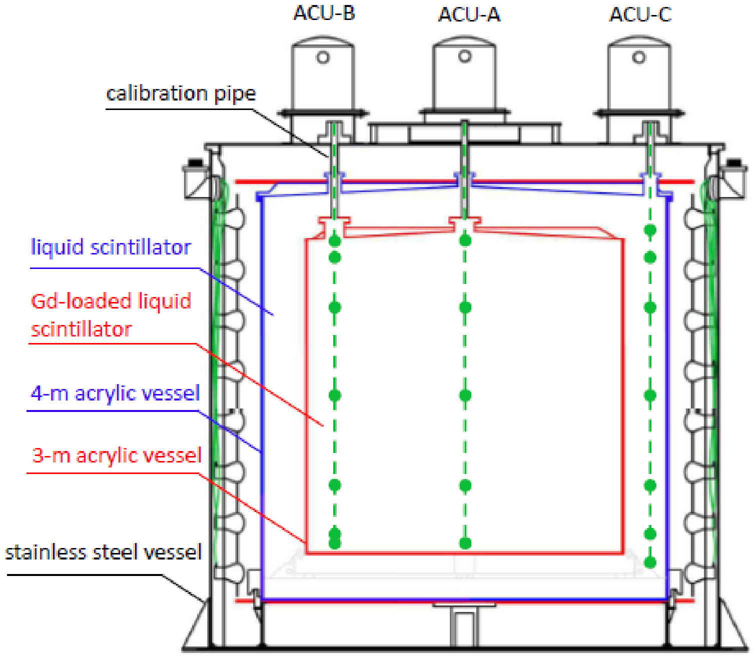
→

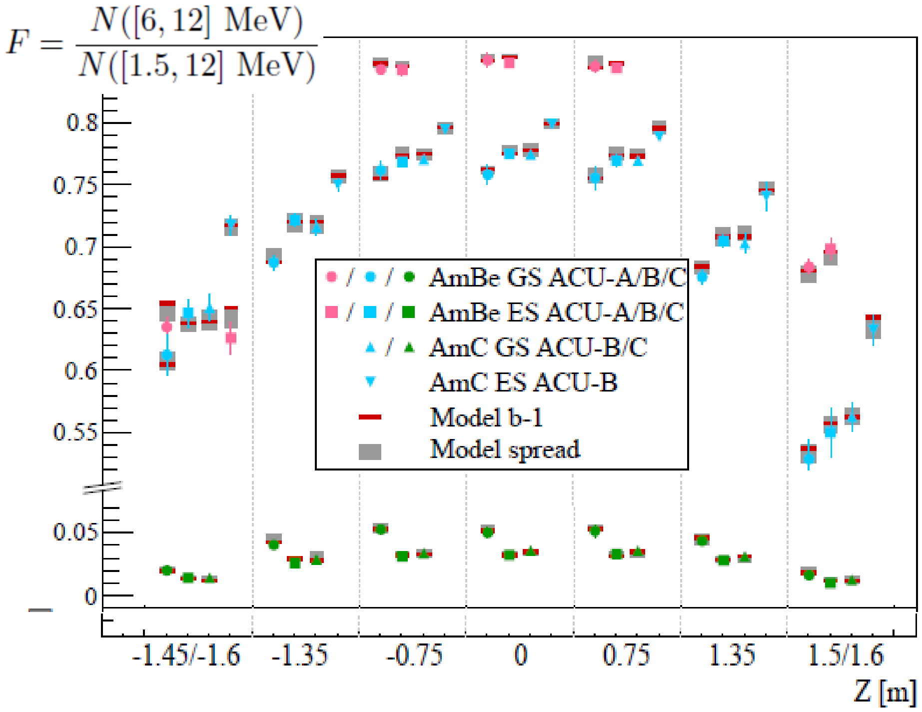
- ◆ Latest prediction from Huber-Mueller
- ◆ which is 5-6% higher than reactor measurement
- ◆ Reactor Antineutrino Anomaly

New Reactor Neutrino Flux Measurements

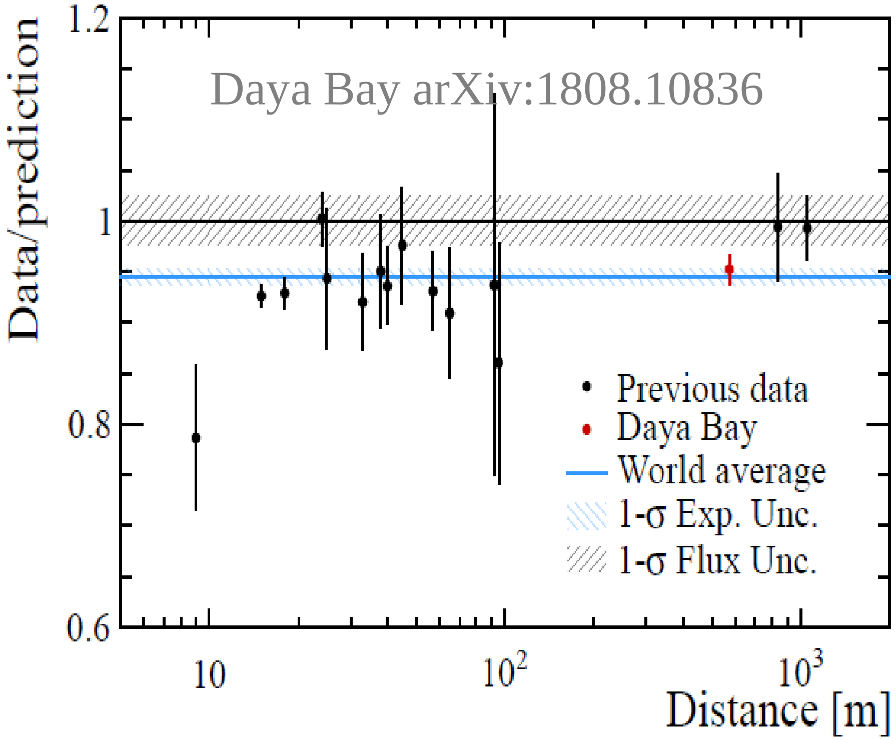
New flux measurement from Daya Bay

- *A through detector calibration*
  - *Many locations: green points*
  - *Neutrons sources from AmC and AmBe ground and excited states*
- *Good agreement between calibration and simulation*





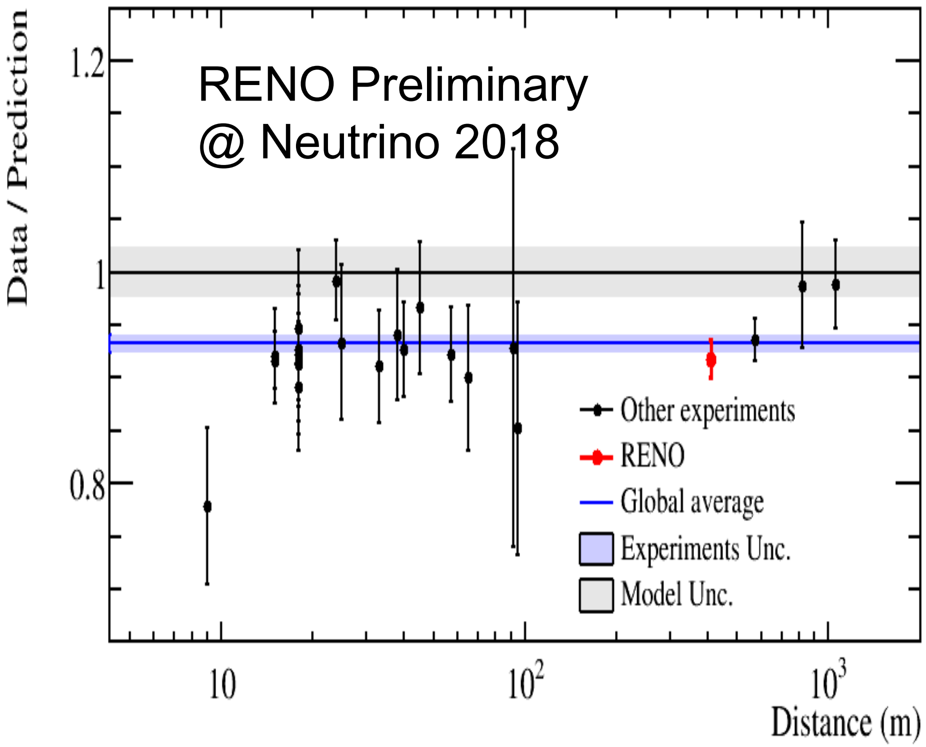
Flux measurement/Prediction
Daya Bay and RENO



Ratio to H-M prediction:

$0.952 \pm 0.014 \pm 0.023$

(Exp.) (The.)



Ratio to H-M prediction:

0.918 +- 0.018

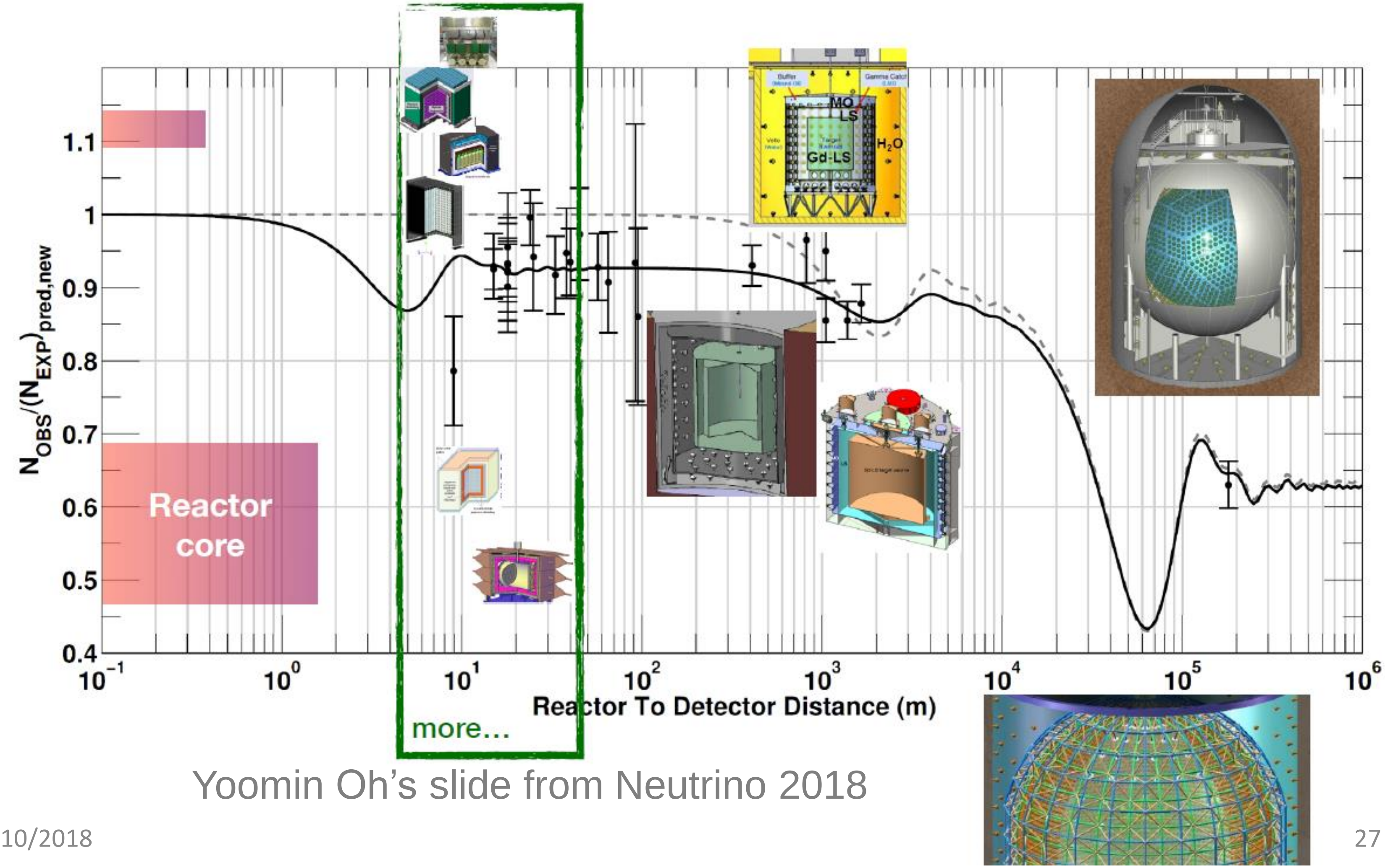
(Exp.)

RAA is likely from theoretical side.

Short Baseline Reactor Neutrino Experiments

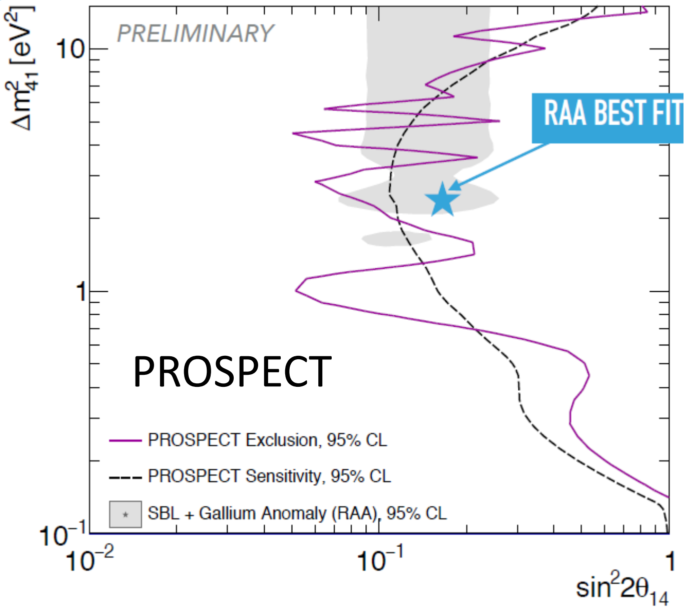
Sensitive to the $\Delta m^2 \sim 1\ \mathrm{eV}^2$ sterile neutrino region for LSND, MiniBooNE, Gallex/SAGE, Reactor anomaly

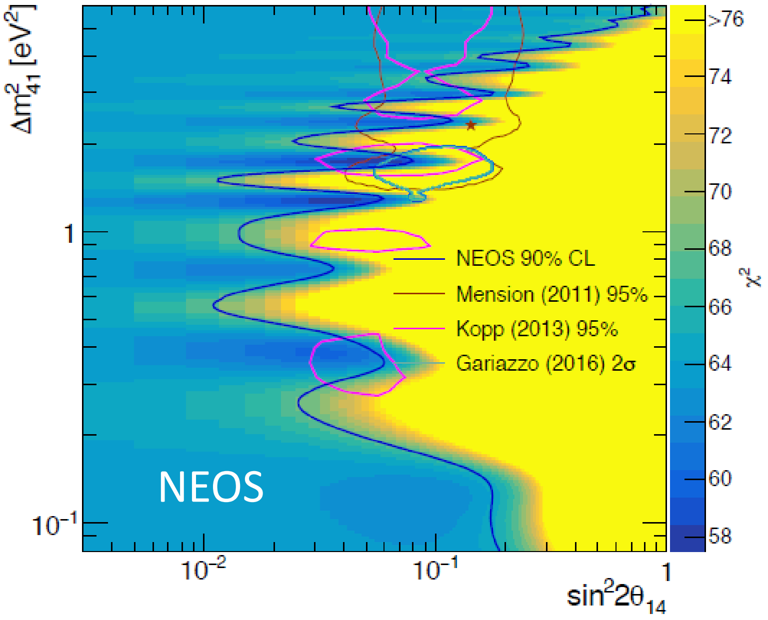
Exp: DANSS, NEOS, STEREO, PROSPECT…

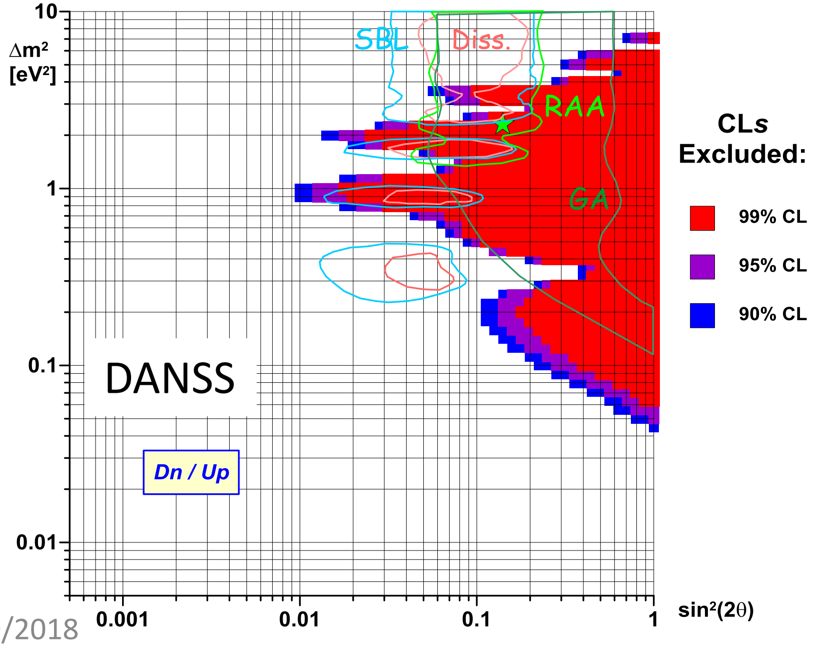


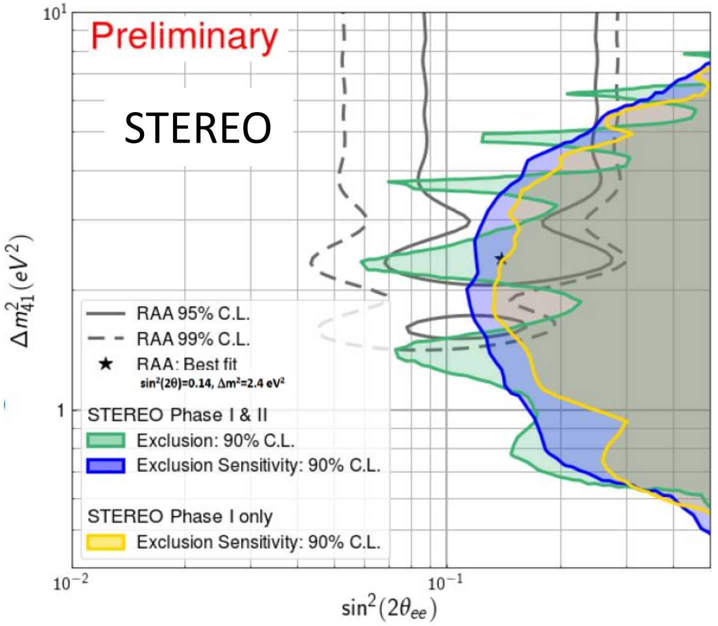
Yoomin Oh’s slide from Neutrino 2018

The best RAA fit is disfavored

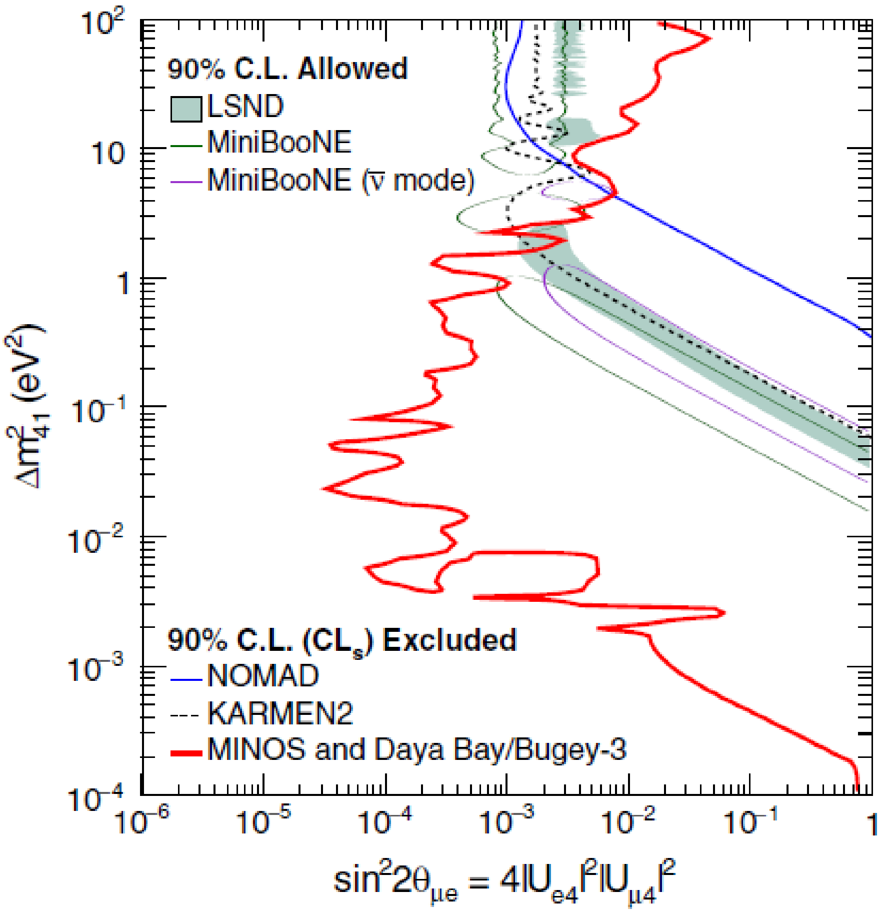


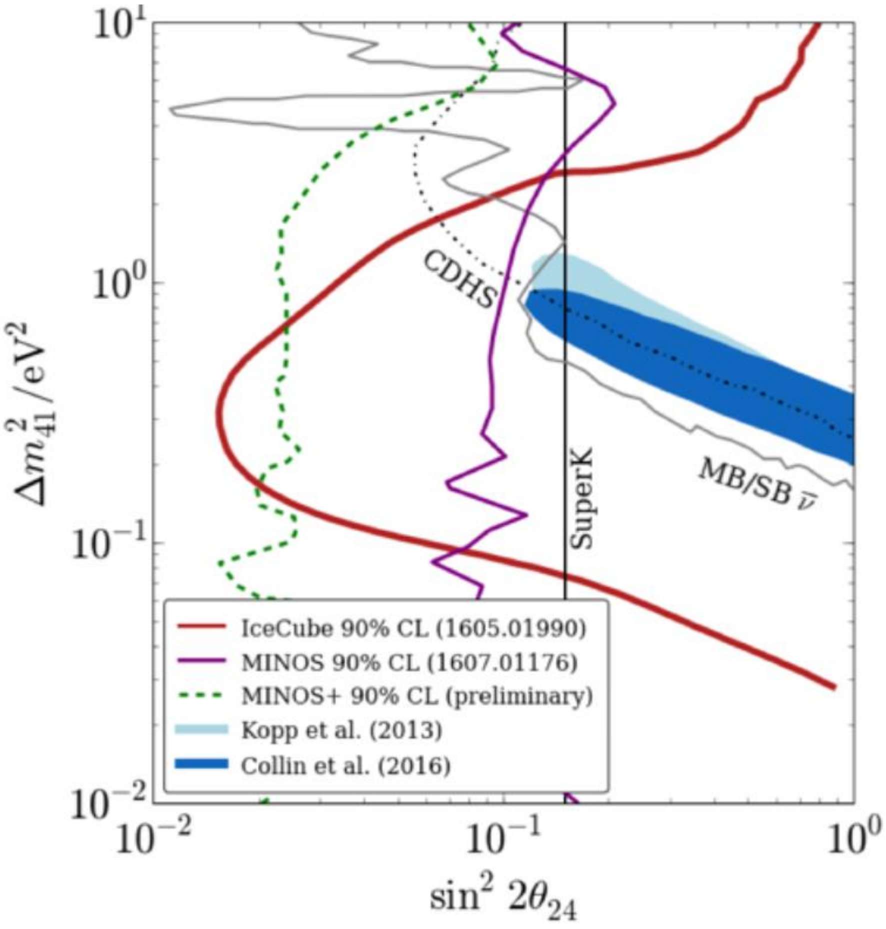






Daya Bay + Bugey + MINOS and IceCube



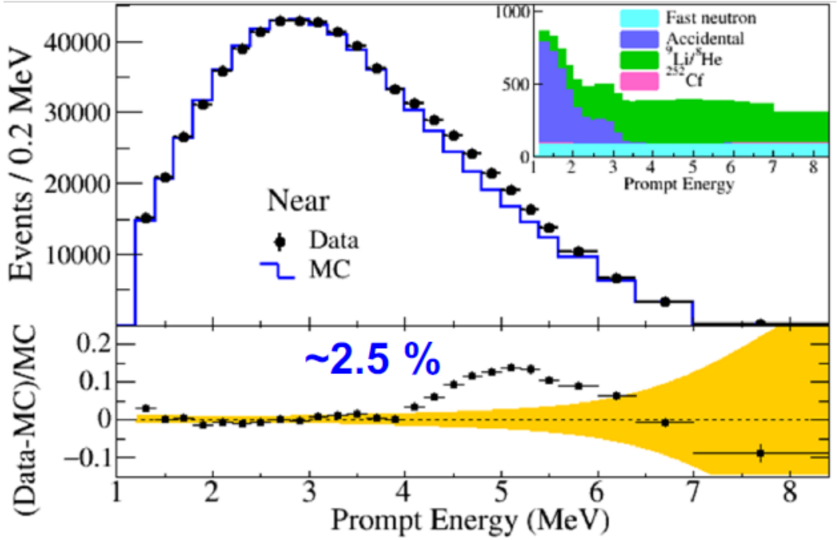


Reactor Antineutrino Spectrum Problem - 5 MeV Bump

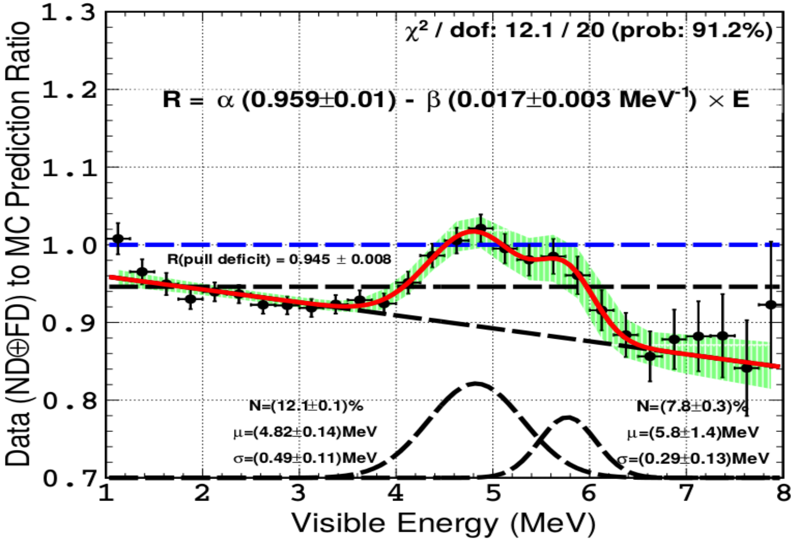
Reactor Neutrino Spectrum 5 MeV Bump

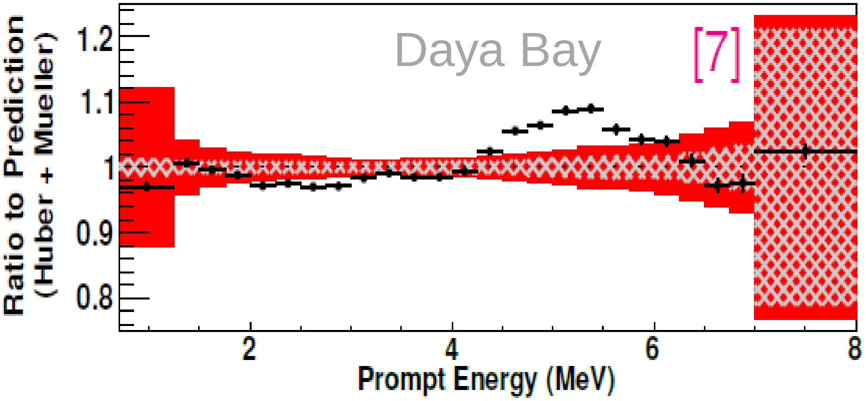
- All recent reactor neutrino experiments found a bump at 4-6 MeV comparing to Huber-Mueller Model

RENO



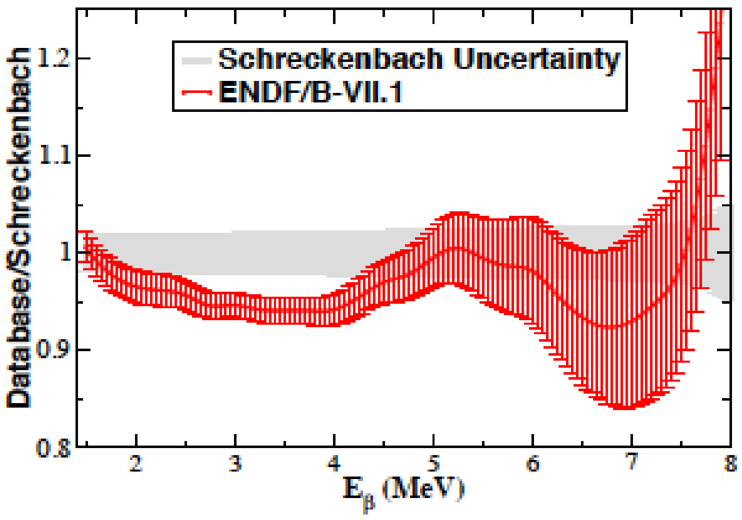
Double Chooz

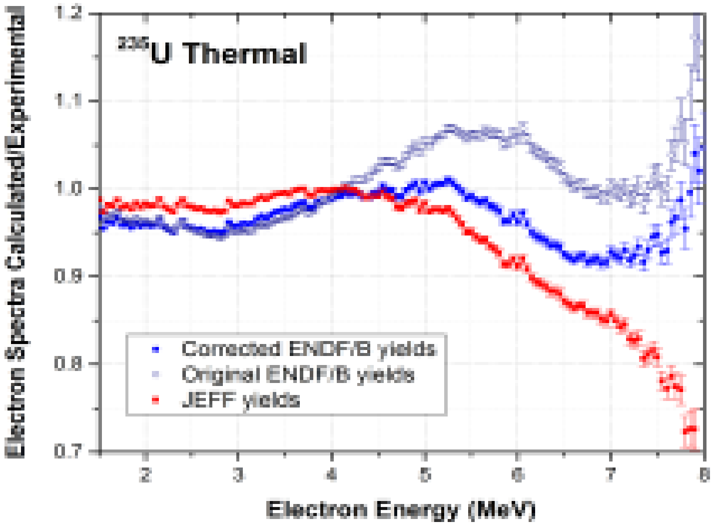




- Important for experiments using reactor spectrum information, e.g. JUNO, NEOS, etc.
- Understand reactor related nuclear physics

Possible reason for the bump





- Dwyer and Langford (2014) pointed out that the ENDF database predicts an analogous bump

- Songzoni (2016) updated in the database for fission yields and ENDF no longer predicts a bump.

Many thoughts on this:

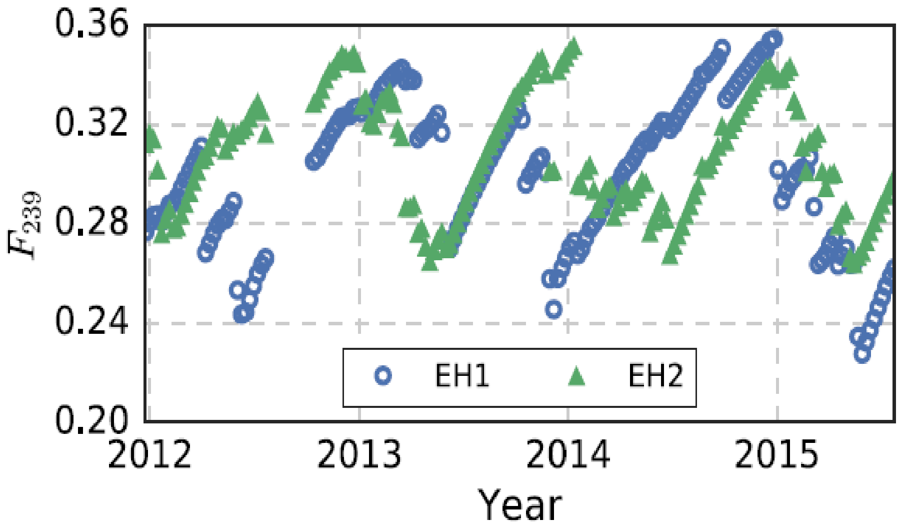
1. Forbidden decay contribute to 5 MeV region: Y96, Rb92, Cs142 …
2. Fast neutron component in PWR
3. Arise from U-238, harden neutron spectrum in light-water power reactor
4. Error in ILL β-spectra measurement

See the theoretical papers by Hayes, Bryce, Dan, Huber, Sonzogni, and their colleagues

Reactor Flux and Spectrum Evolution

Hard to categorize this study into previous slides.
May contribute to several of studies.

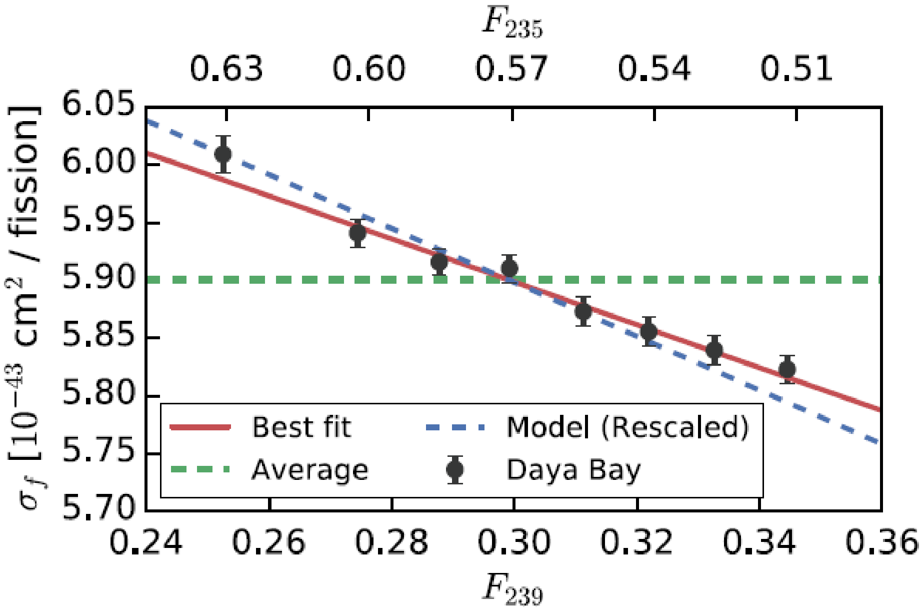
Reactor Evolution Analysis

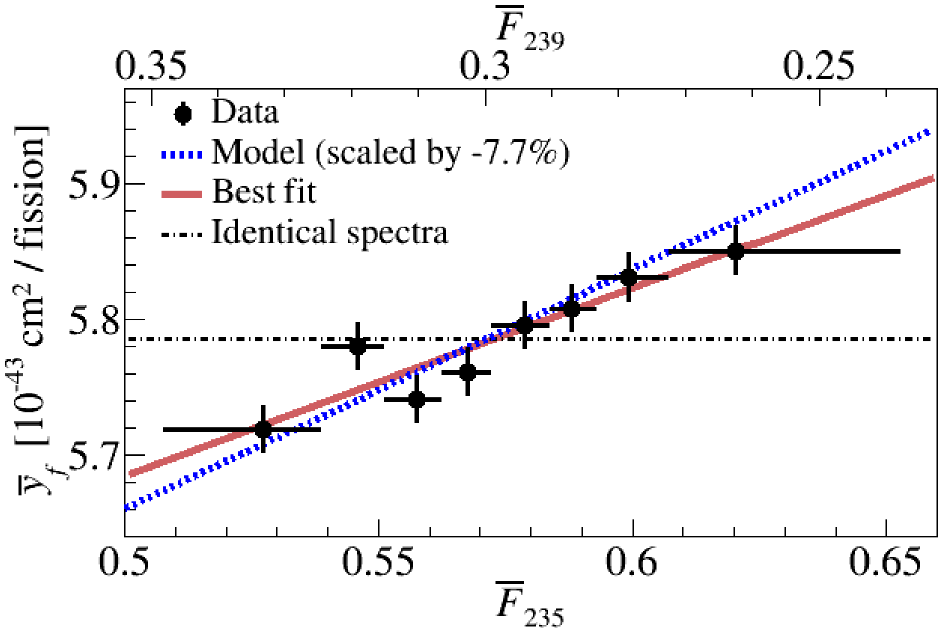


Daya Bay F-239 history data

- Reactor flux and spectrum changes along with reactor burn-up
- Offer a second dimension to study reactor oscillations
- Deficit (RAA) should be a constant with burn-up for sterile neutrino assumption
- Otherwise it indicates other physics problems

Reactor Evolution Results from Daya Bay and RENO





- The flux measurements of Daya Bay and RENO follows the prediction of reactor simulation
- Minor discrepancy observed.

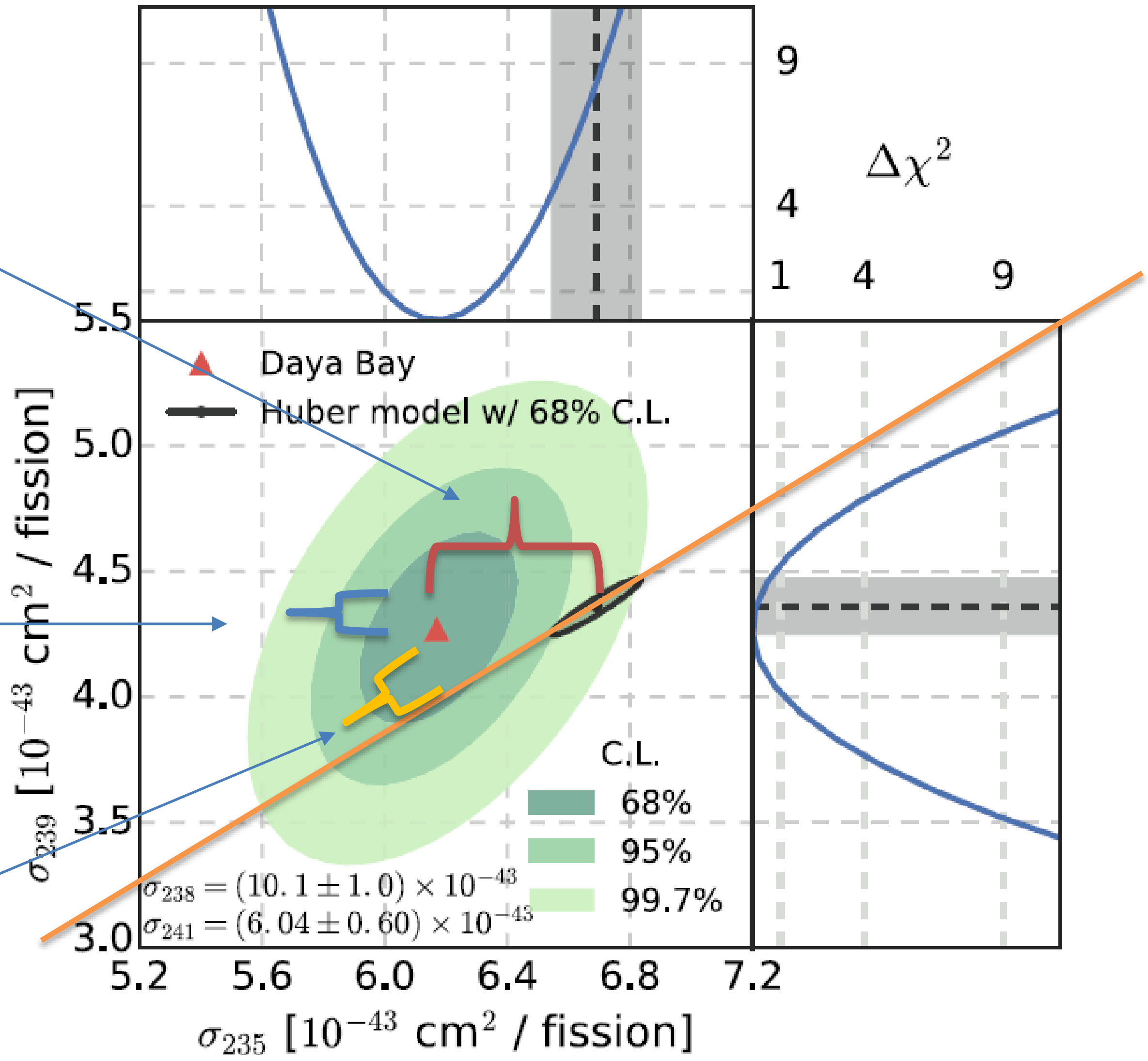
$$\sigma_f^a = \sum_i F_i^a \sigma_i \qquad \chi^2 = (\boldsymbol{\sigma}_f - F\boldsymbol{\sigma})^\top V^{-1} (\boldsymbol{\sigma}_f - F\boldsymbol{\sigma})$$

(see the next page)

U-235 prediction off

Pu-239 prediction close

Equal deficit



Hard to distinguish model prediction issue or sterile neutrino assumption with the current uncertainty

Summary

- θ_{13} and Δm^2_{ee} are measured with good precisions
- Sterile neutrinos (1 eV) are not favored by reactor neutrino experiments and others and RAA is more likely from theoretical side
- Questions on the 5 MeV Bump for reactor related nuclear physics remains
- Many discussions are going on.

Thank you.
Questions and comments are welcome.

BACKUP

- ν_e and ν_μ disappearance experiments measure different effective atmospheric mass-squared differences

$$\boxed{\begin{aligned}&\Delta m^2_{ee} \simeq \cos^2(\theta_{12}) \cdot \Delta m^2_{31} + \sin^2(\theta_{12}) \cdot \Delta m^2_{32}\\ &\Delta m^2_{\mu\mu} \simeq \sin^2(\theta_{12}) \cdot \Delta m^2_{31} + \cos^2(\theta_{12}) \cdot \Delta m^2_{32} + \sin(2\theta_{12}) \sin(\theta_{13}) \tan(\theta_{23}) \cos(\delta) \cdot \Delta m^2_{21}\end{aligned}}$$

- With precision measurements of Δm^2_{ee} and $\Delta m^2_{\mu\mu}$, the difference

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

(+: NH, -: IH) allows to determine the MH and possibly even cosδ at high precision of Δm^2_{ee} and $\Delta m^2_{\mu\mu}$