A Brief Review of Recent Reactor Neutrino Experiments

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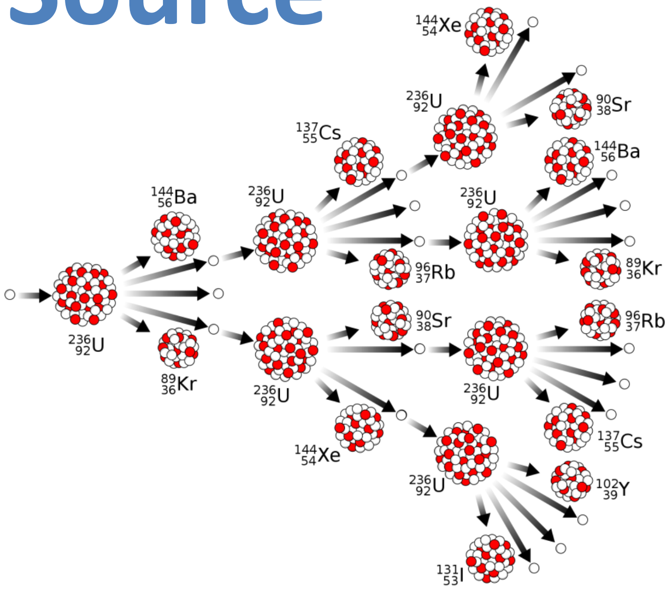
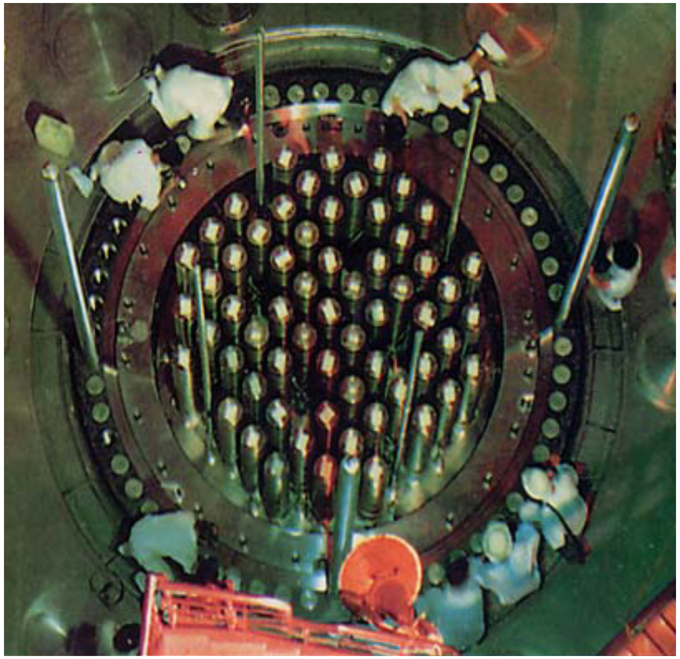
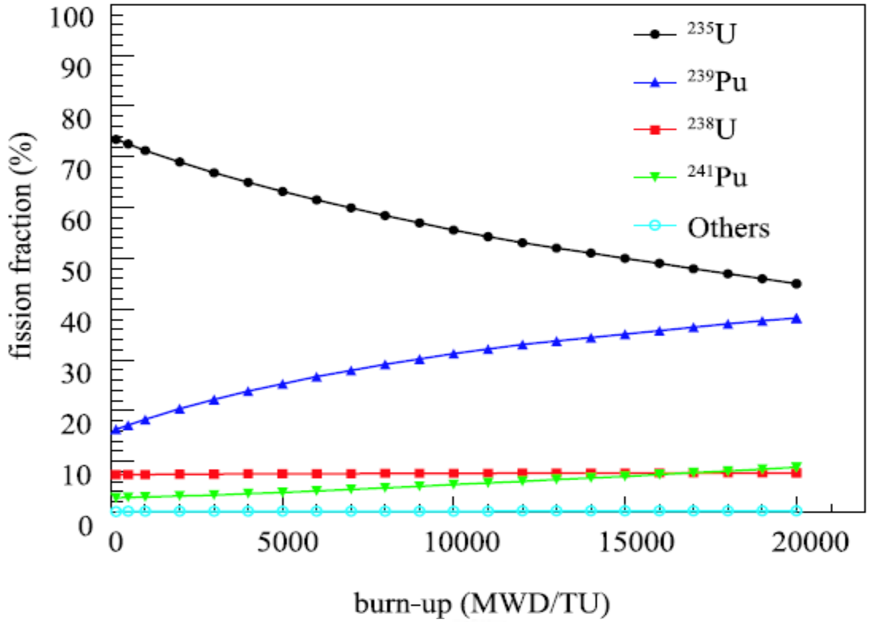


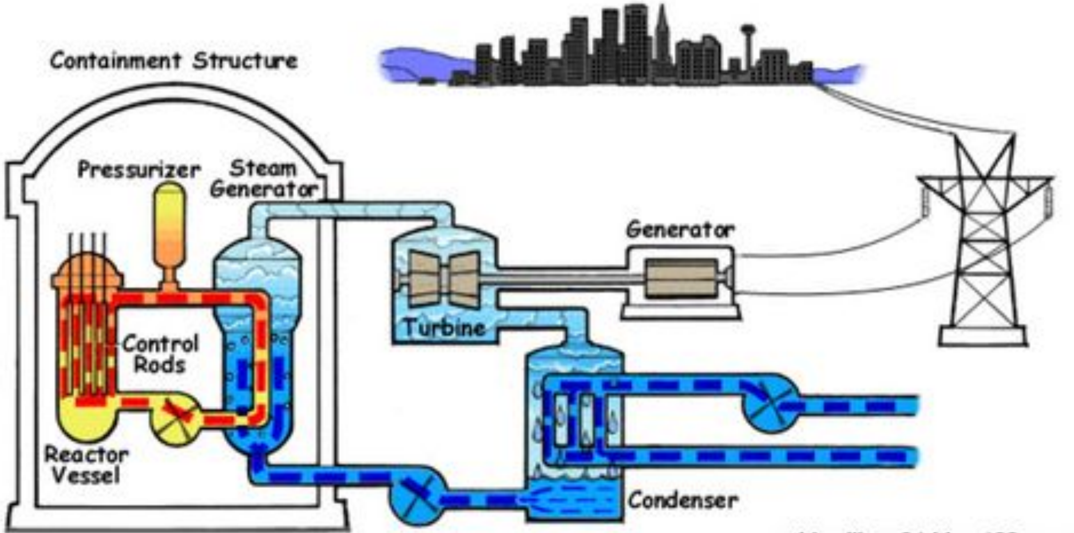
- Nuclear Chain Reaction
- Commercial reactors
  - Four fission isotopes: U-235, Pu-239, U-238, Pu-241
- Reactor size:
  - 3.7 m height, 3 m diameter (Daya Bay)
- Research reactors:
  - ex. U-235 rich, small size
- Beta decay of fission isotopes and fragments emits electron-antineutrinos



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
- Measurement of reactor powers





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Reactor Neutrino Flux and Spectrum

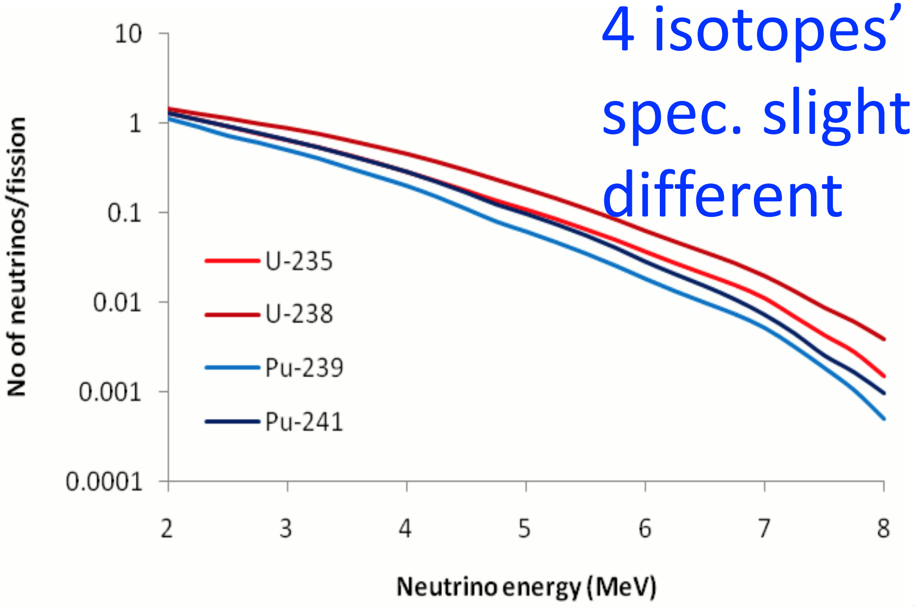
- Reactor neutrino flux
  - 2×10^{20} neutrinos/s/GW
  - Daya Bay: 6x2.9 GW

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

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

- Reactor neutrino spectrum

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



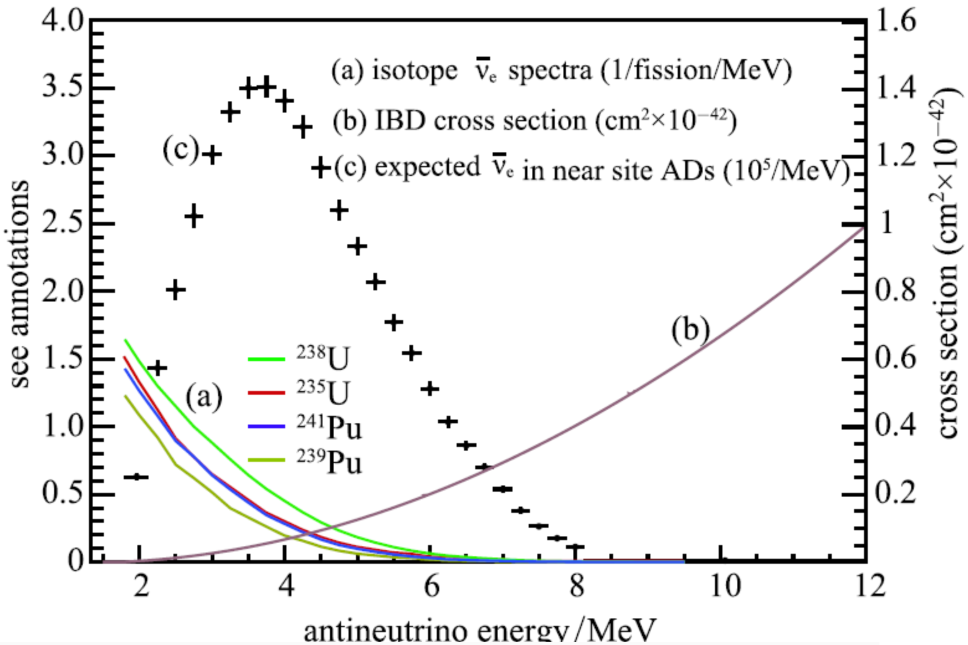
4 isotopes' spec. slightly different

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
- Neutron capture and delayed coincidence



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

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

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

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

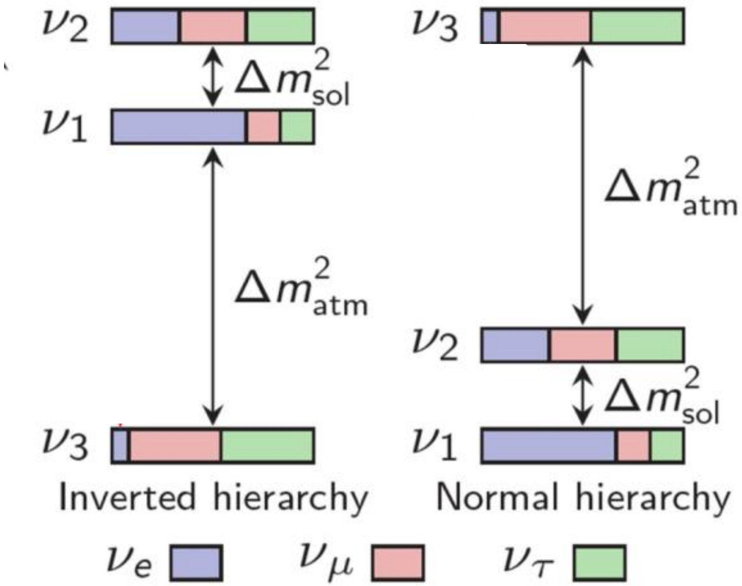
Three-Generation Neutrino Oscillation

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

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

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

$\theta_{12} \sim 34°$
Solar
Reactor



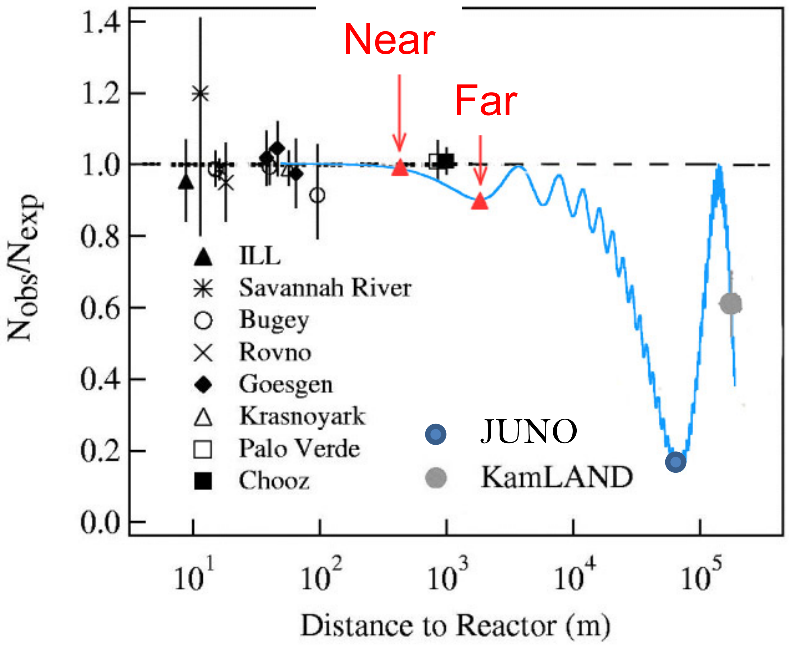
$|\Delta m^2_{31}| \sim 2.4\text{x}10^{-3}\ \text{eV}^2$

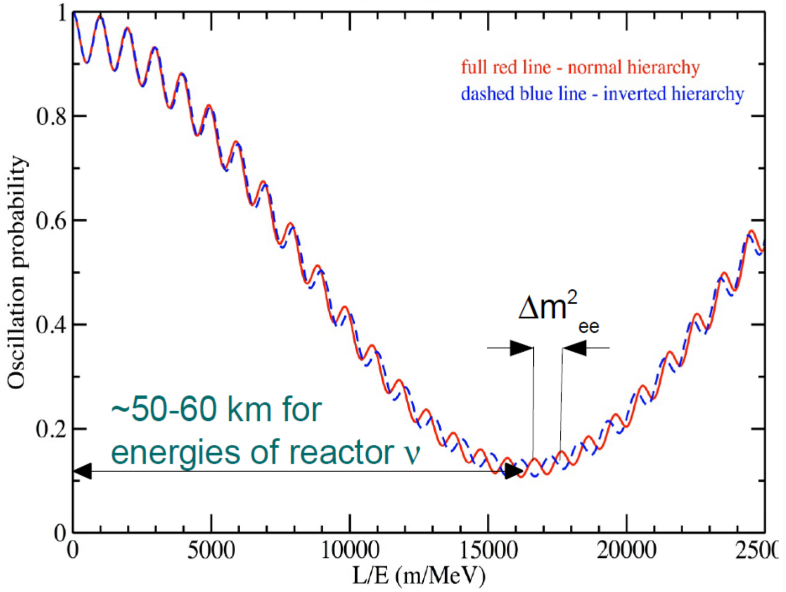
$\Delta m^2_{12} \sim 8\text{x}10^{-5}\ \text{eV}^2$

Three Neutrino Oscillation Measurement

$$\mathbf{P}(\bar\nu_e \to \bar\nu_e) = 1 - \boxed{\cos^4\theta_{13}\,\sin^2 2\theta_{12}\,\sin^2\Delta m^2_{21}\frac{L}{4E}} - \boxed{\sin^2 2\theta_{13}\left(\cos^2\theta_{12}\,\sin^2\Delta m^2_{31}\frac{L}{4E} + \sin^2\theta_{12}\,\sin^2\Delta m^2_{32}\frac{L}{4E}\right)}$$

$$\approx 1 - \boxed{\cos^4\theta_{13}\,\sin^2 2\theta_{12}\,\sin^2\Delta m^2_{21}\frac{L}{4E}} - \boxed{\sin^2 2\theta_{13}\,\sin^2\Delta m^2_{ee}\frac{L}{4E}}$$





- 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)

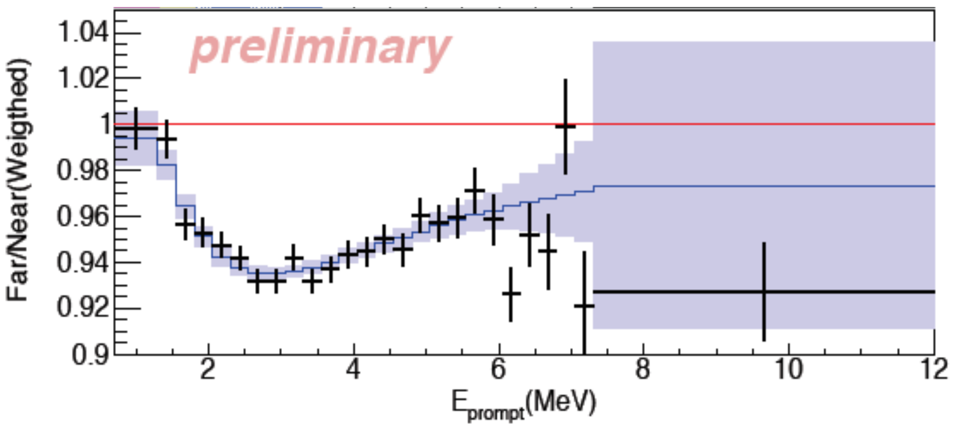
Relative measurement for θ_{13}

- Principle: Extract θ_{13} from

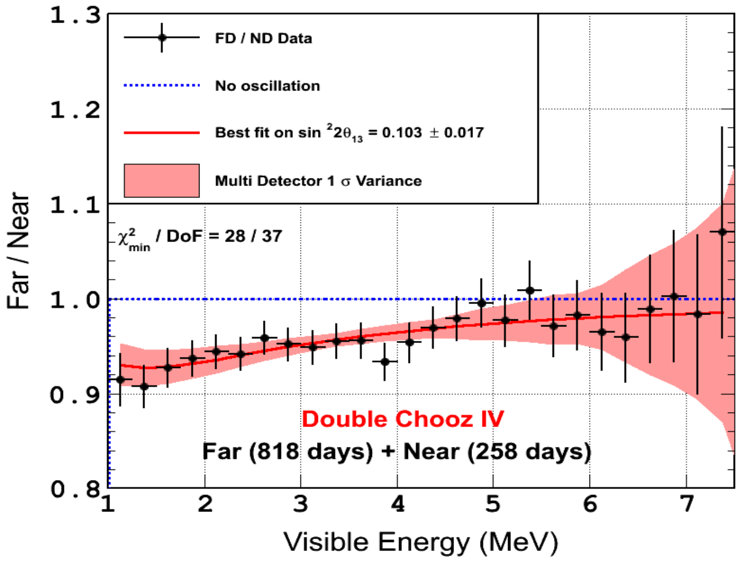
  Far/Near IBD events ratio, and IBD spectrum distortion of the Far and Near sites

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

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

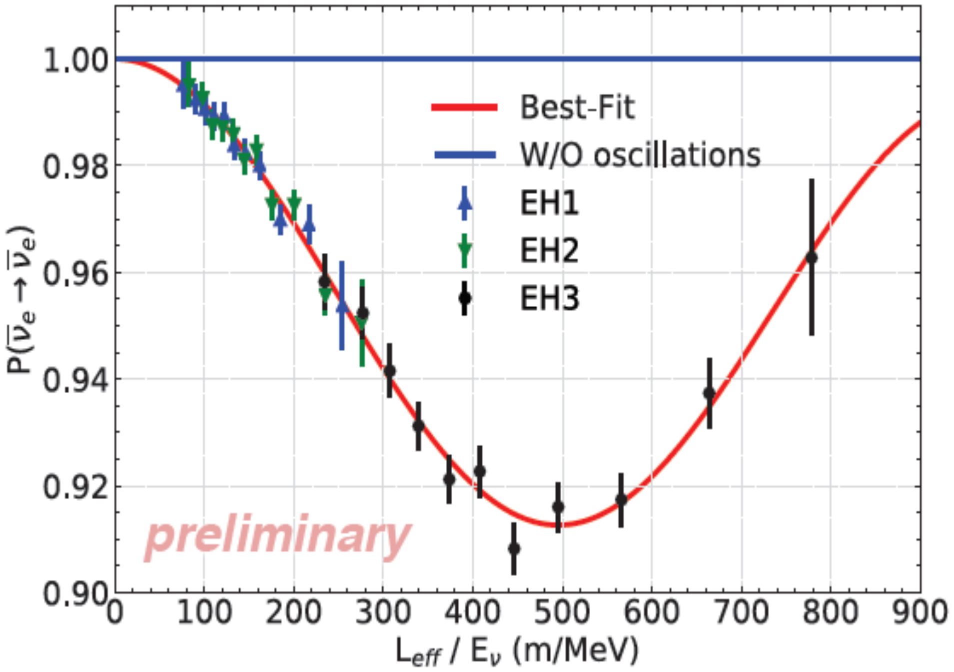


Plot from Daya Bay talk @ Neutrino 2018



Double Chooz talk @ Neutrino 2018

θ_{13} measurement



Plot from Daya Bay talk @ Neutrino 2018
Results from Daya Bay, RENO, DC @ 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

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

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

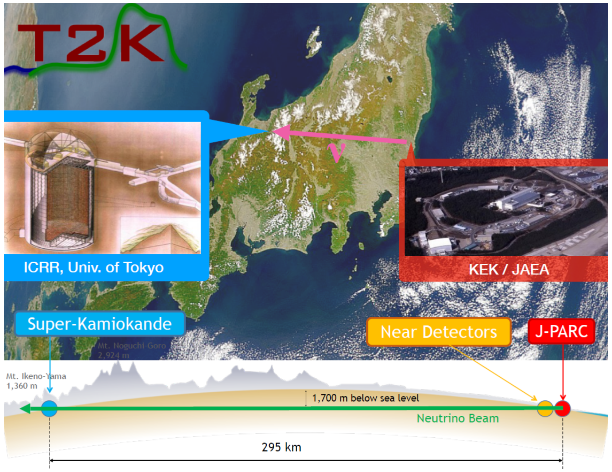
- Double Chooz

  nGd+nH oscillation analysis

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

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

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

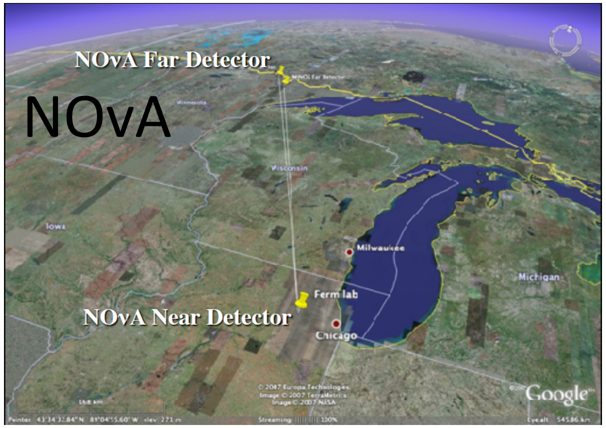


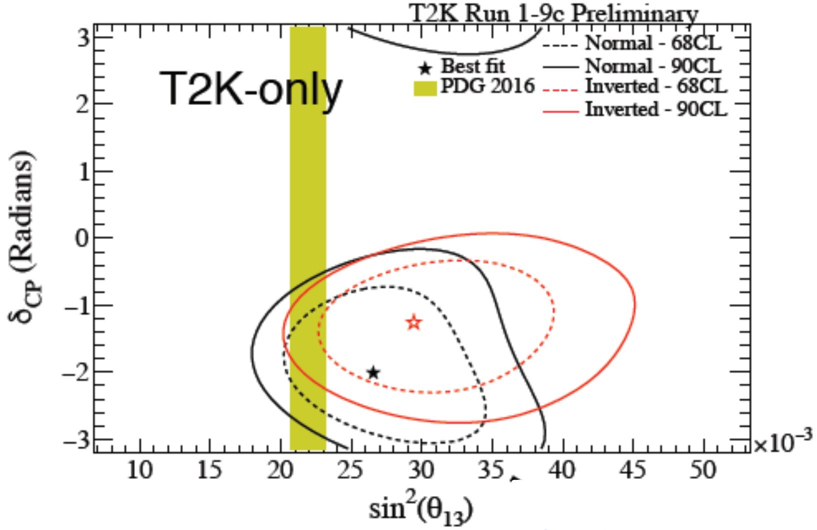
ν_e appearance probability:

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

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

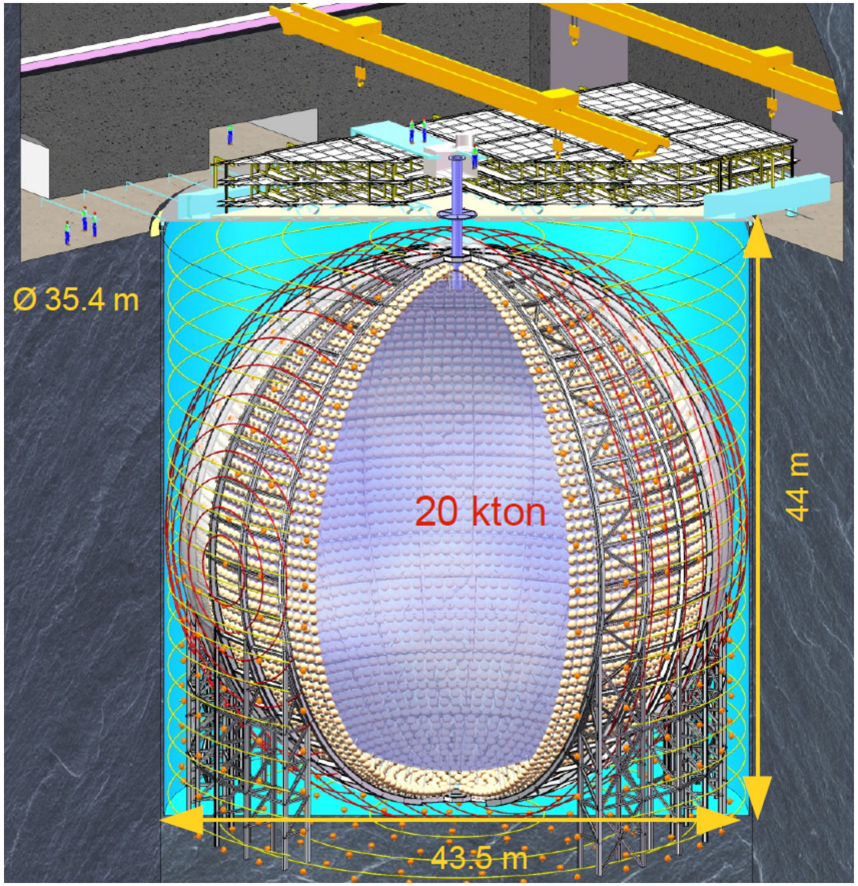
$$+(CP\,\text{even term, solar term, matter effect term}), \qquad (1)$$

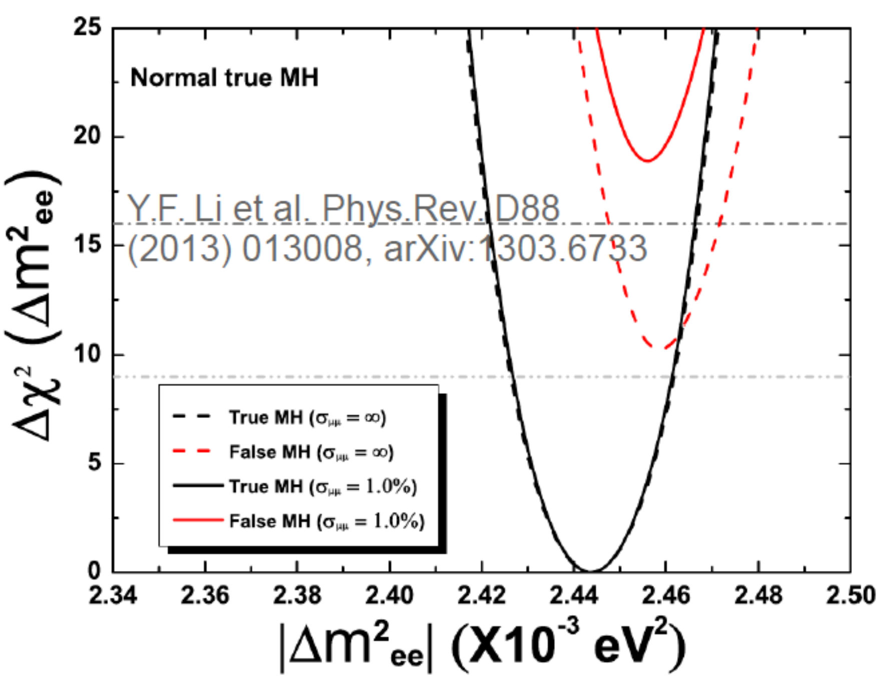




Both T2K and NOvA favor Normal Hierarchy and $\delta_{CP}=-\pi/2$:

Reactor Mass Hierarchy Measurement - JUNO





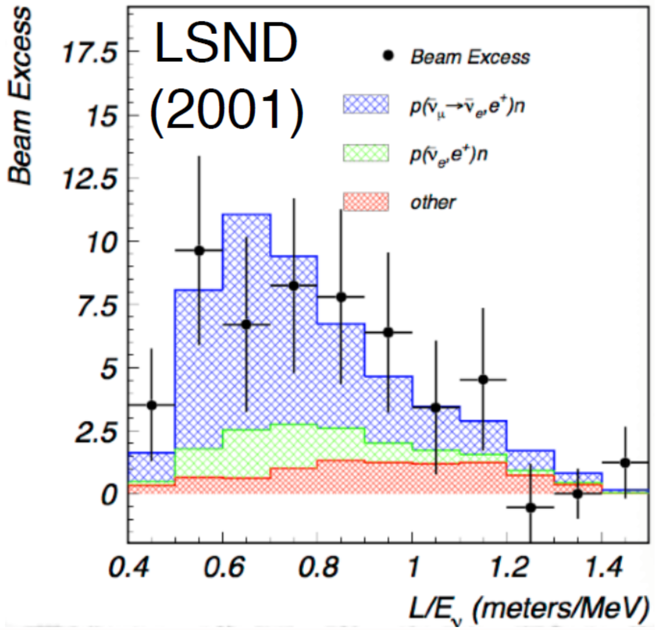
Y.F. Li et al. Phys.Rev. D88 (2013) 013008, arXiv:1303.6733

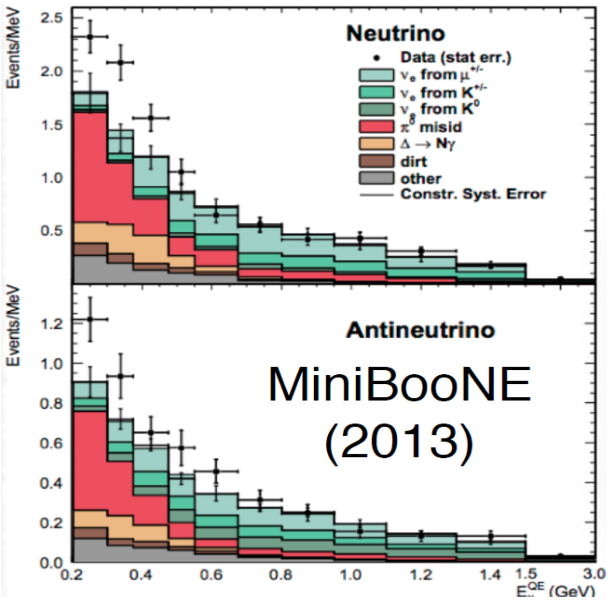
- Data taking will start in 2021

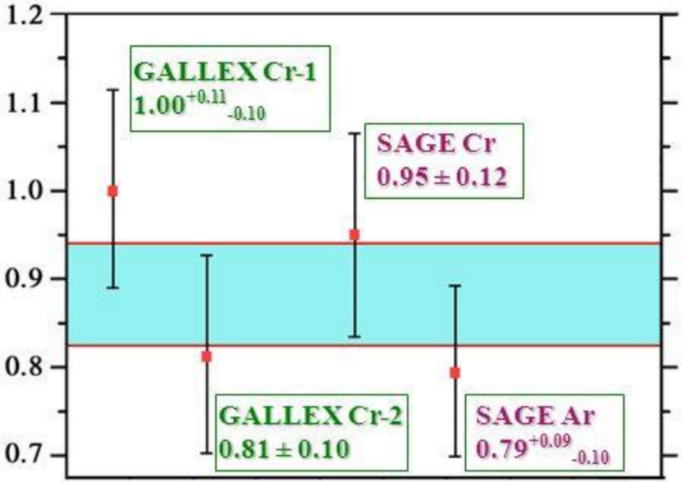
Björn Wonsak, Neutrino 2018

- 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)

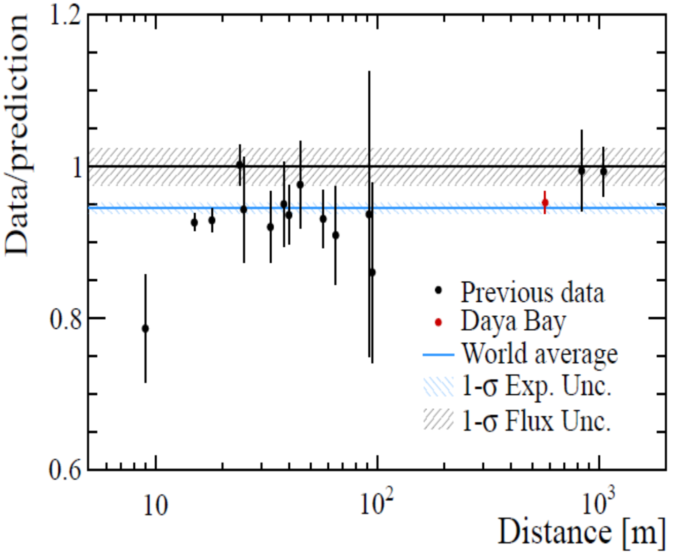
Hint of Sterile Neutrino







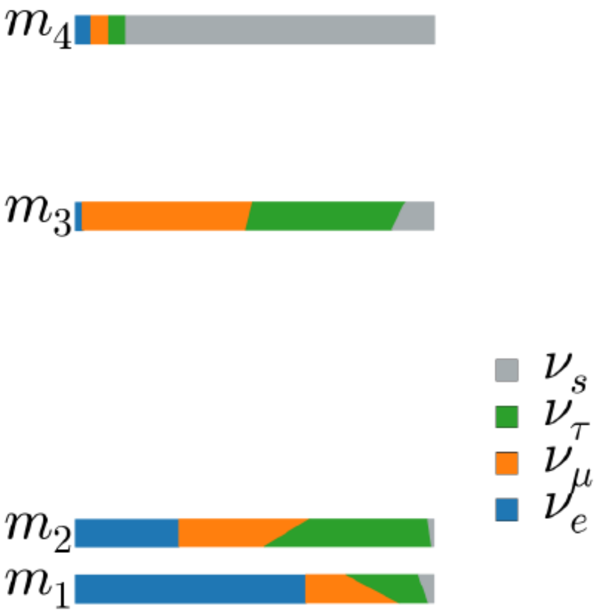
Reactor Antineutrino Anomaly



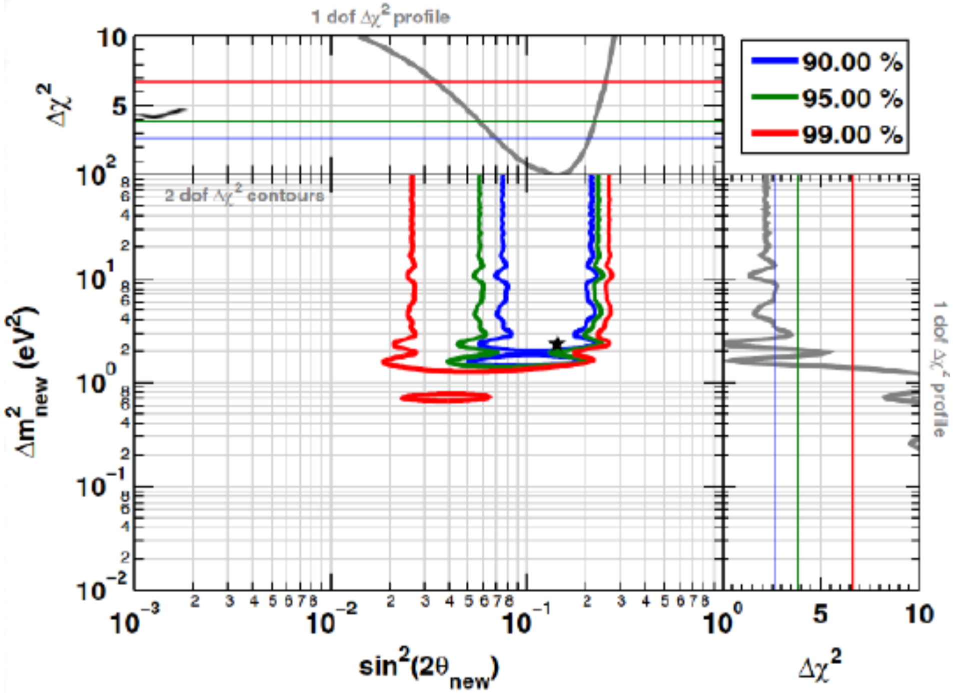
Sterile Neutrino

- 3+1 model
- Does not couple 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?



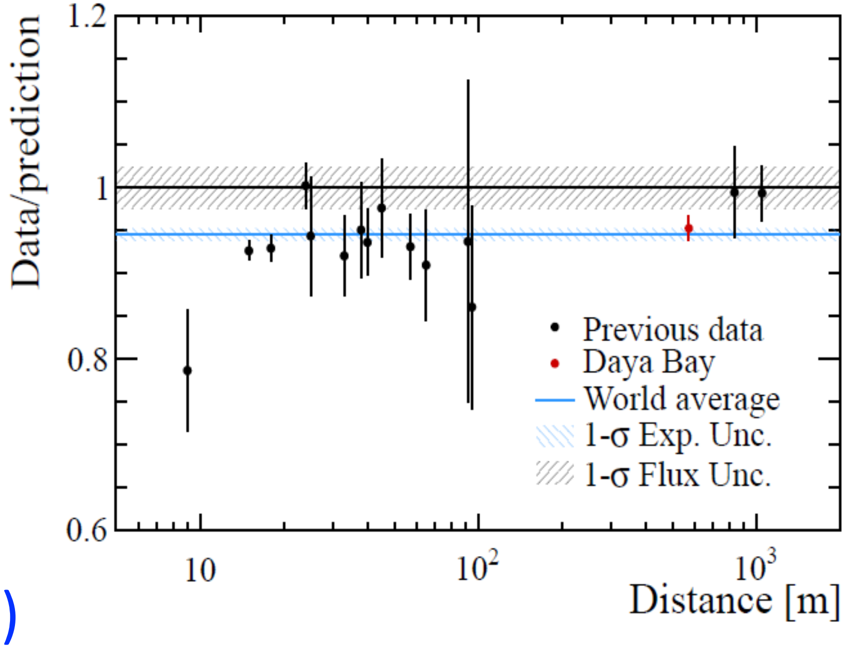
Mention 2011

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)

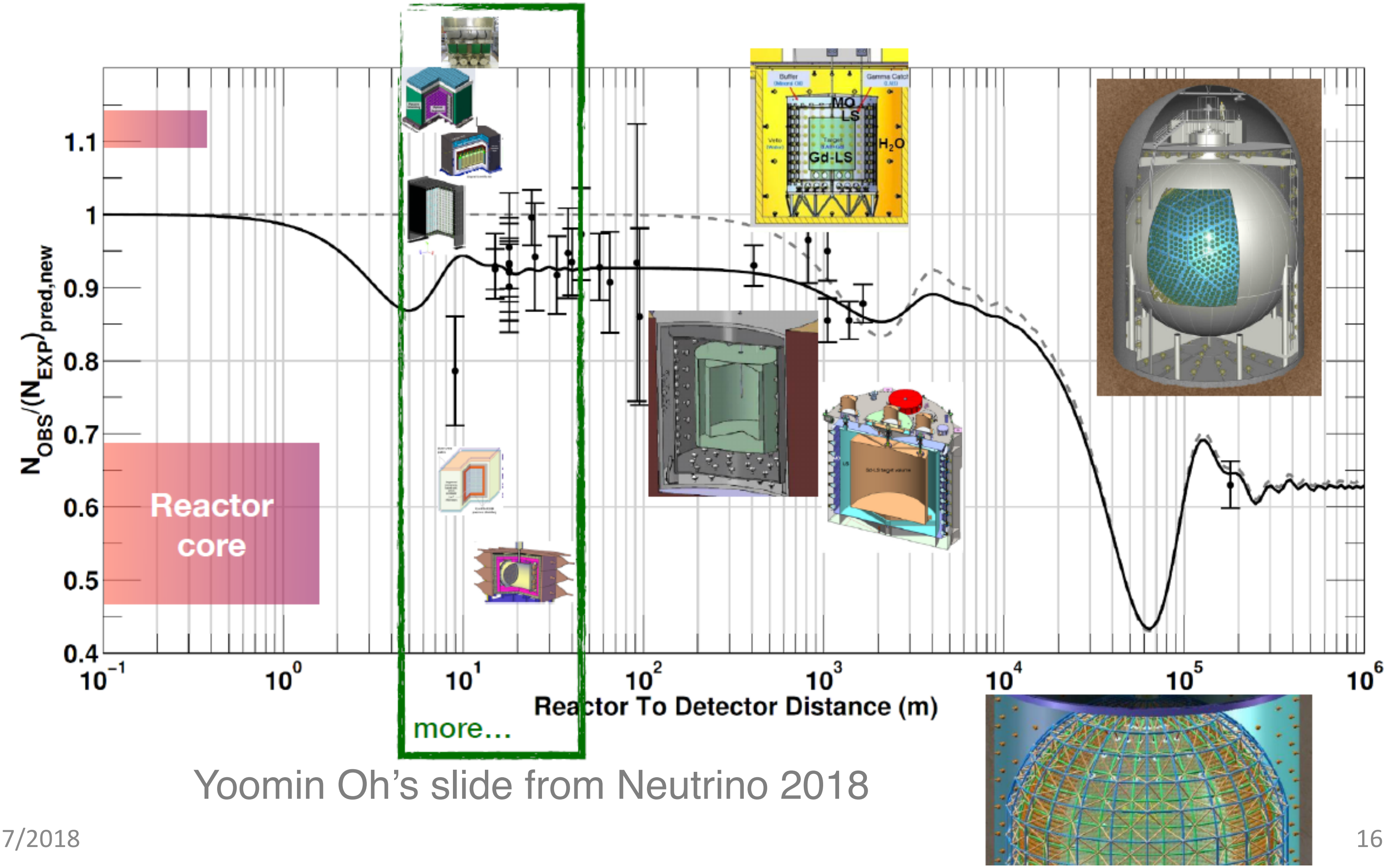
◆ 5-6% higher than reactor measurement



Short Baseline Reactor Neutrino Experiments

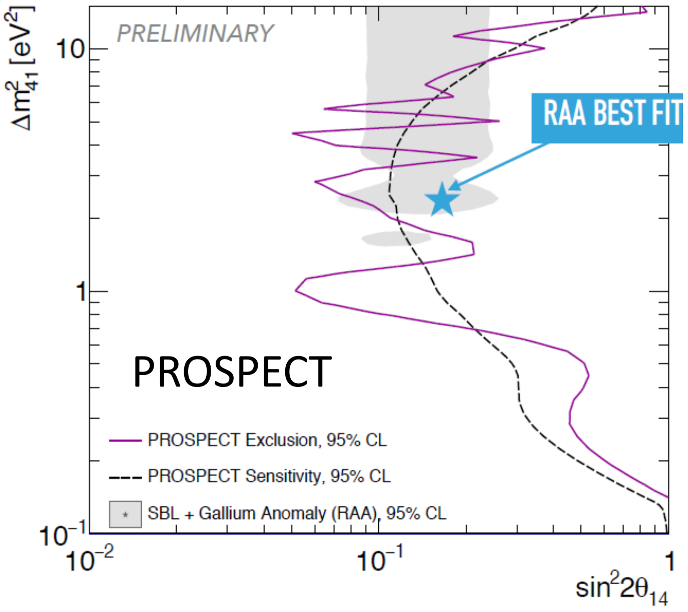
Sensitive to the $\Delta m^2 \sim eV^2$ sterile neutrino region for LSND, MiniBooNE, Gallex/SAGE, Reactor anomaly

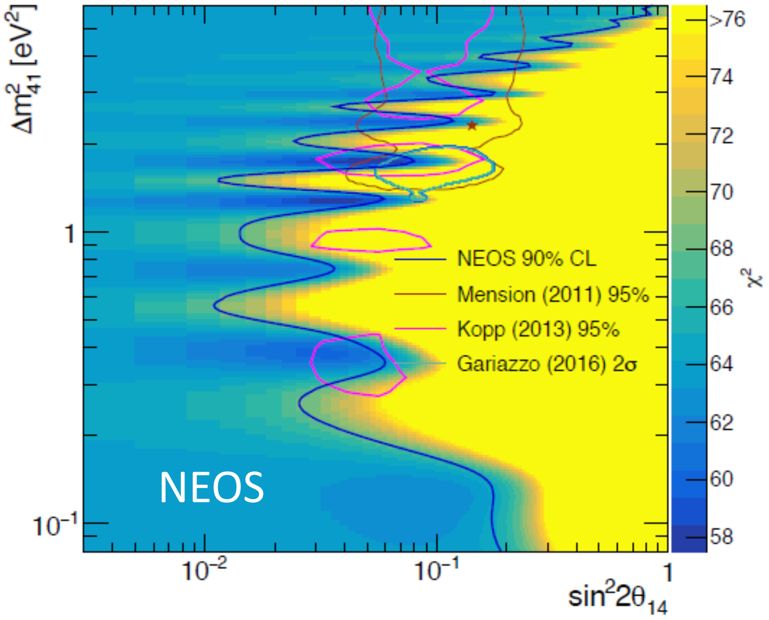
Exp: DANSS, NEOS, STEREO, PROSPECT…

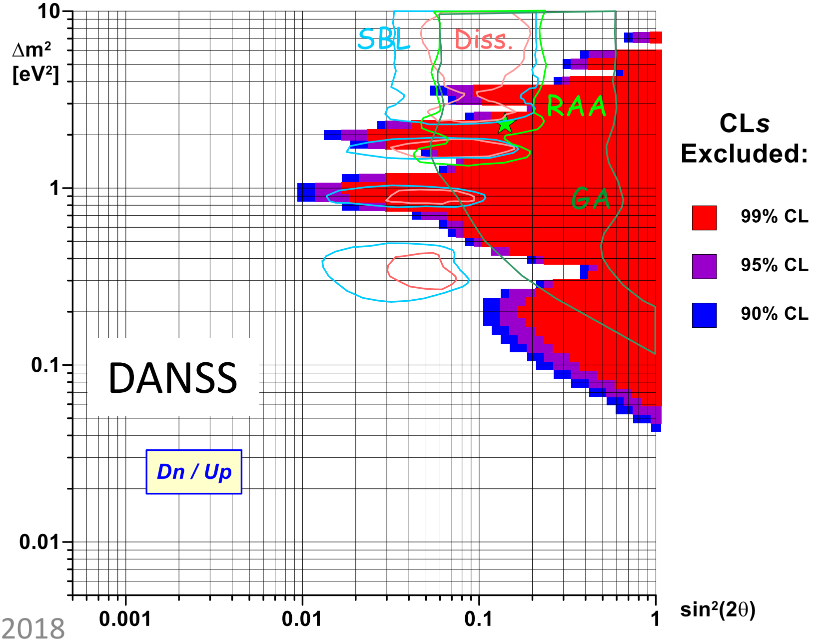


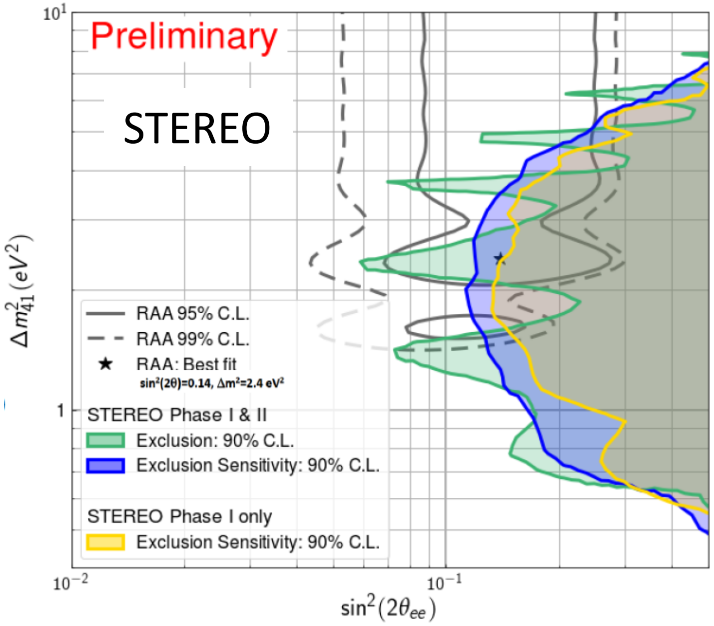
Yoomin Oh's slide from Neutrino 2018

The best RAA fit is disfavored

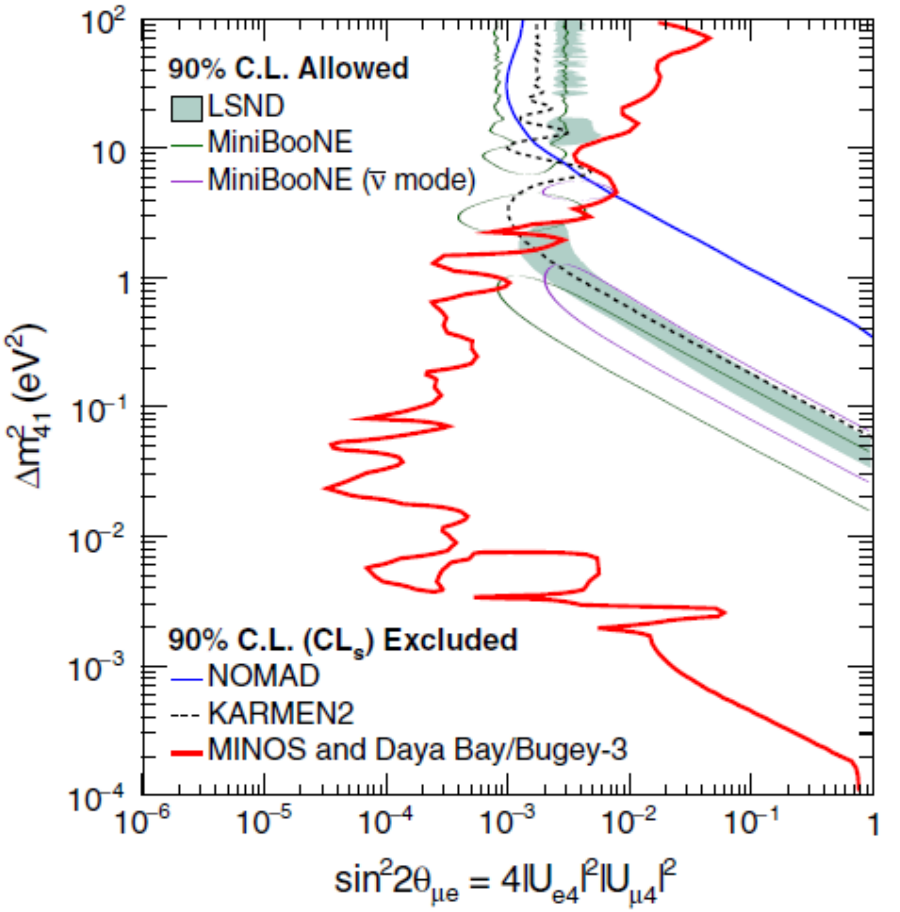


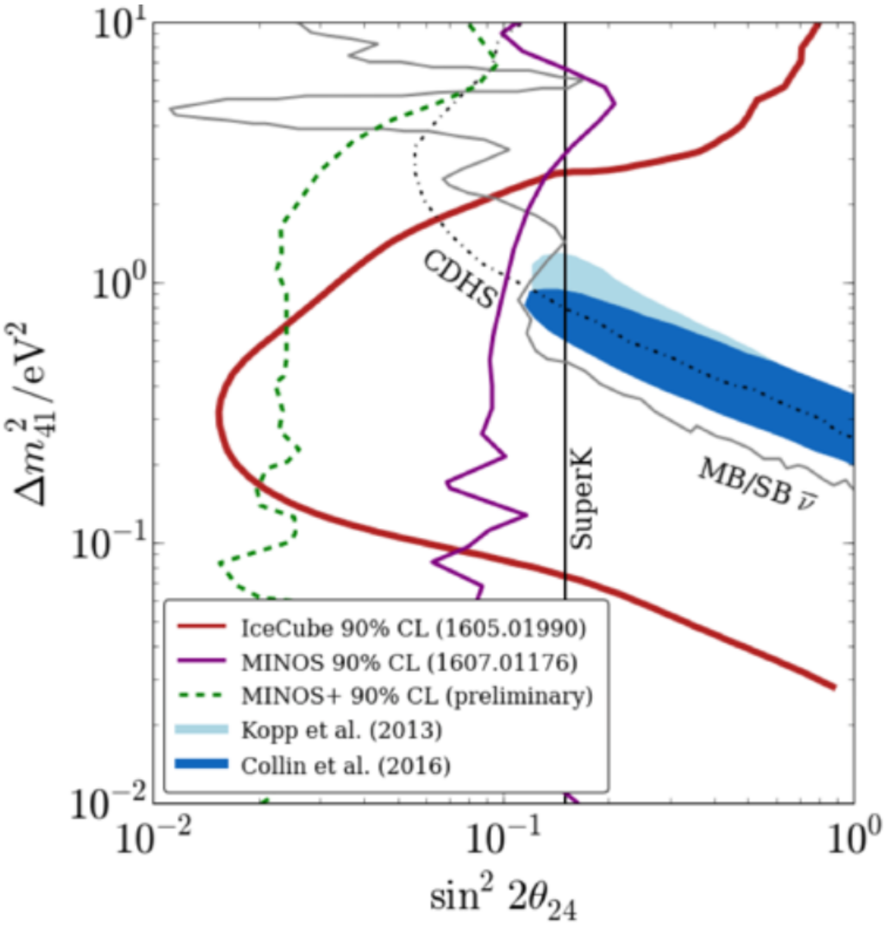






Daya Bay + Bugey + MINOS, IceCube

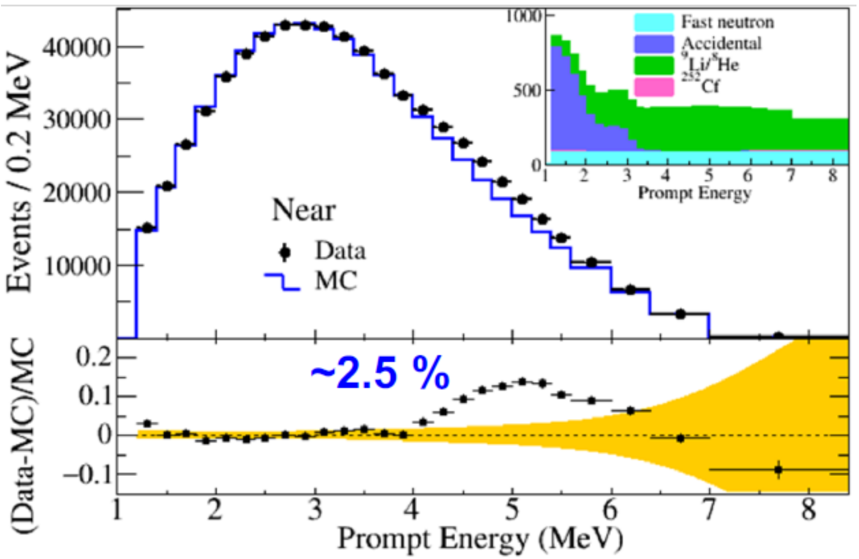




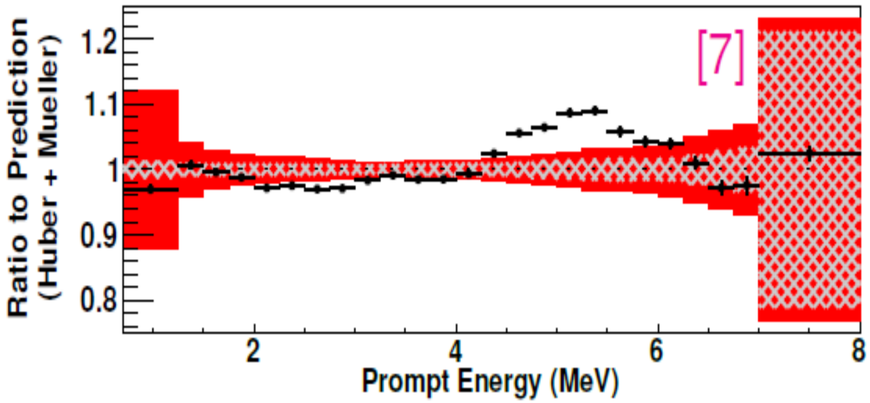
Reactor Neutrino Spectrum Problem

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

RENO

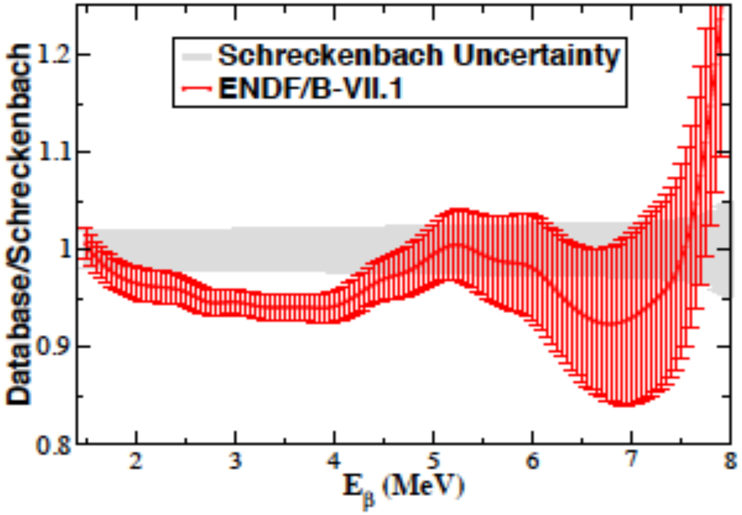


Daya Bay

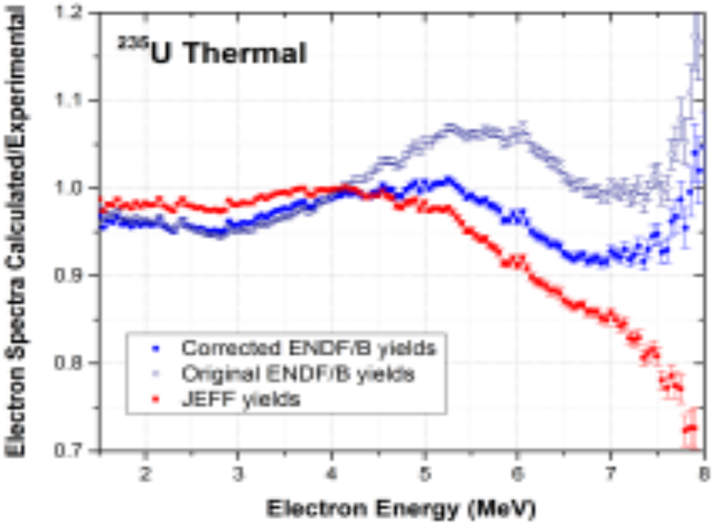


1. Important for experiments using reactor spectrum information, e.g. JUNO, NEOS, etc.
2. Understand reactor related nuclear physics

Possible reason for the bump



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

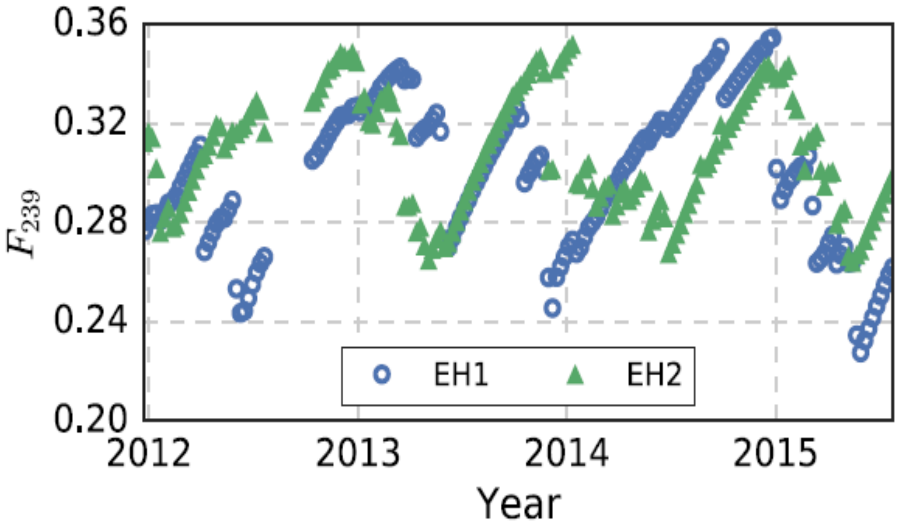


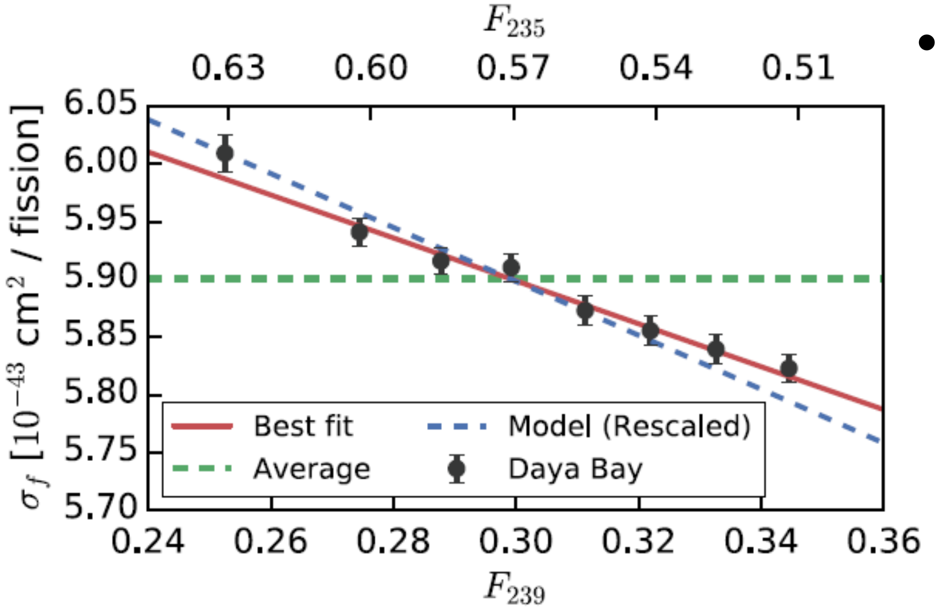
- Songzoni (2016) updated in the database for fission yields and ENDF no longer predicts a bump.

Many thoughts on this:

1. Several isotopes contribute to 5 MeV region: Y96, Rb92, Cs142 …
2. New total absorption spectroscopy study of Rb92, Cs142 …
3. Arise from U-238, harden neutron spectrum in light-water power reactor
4. Error in ILL β-spectra measurement

Reactor Evolution Analysis



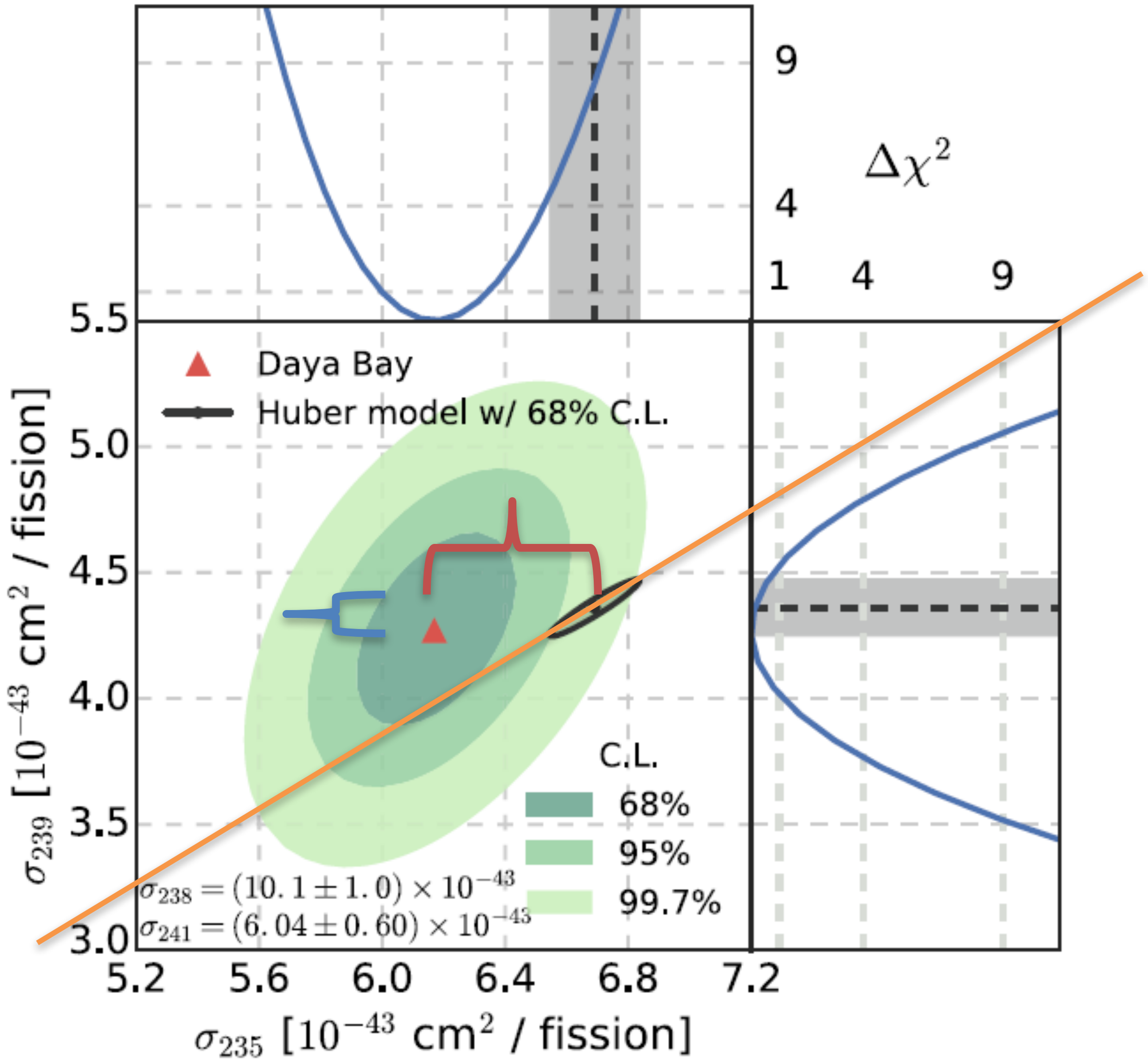


- Reactor flux and spectrum changes along with reactor burn-up
- Deficit should be a constant with burn-up for sterile neutrino assumption
- Experimental observations show a lightly difference in reactor neutrino flux vs fission fraction of Pu-239 (or U-235)

U-235 prediction off

Pu-239 prediction close

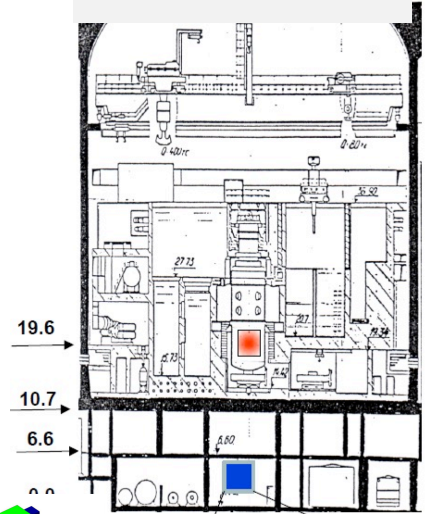
Equal deficit

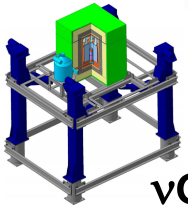


Hard to distinguish model prediction issue or sterile neutrino assumption with the current uncertainty

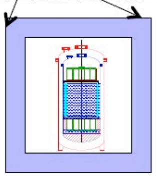
Neutrino Nucleus Coherent Scattering

Kalinin 3 GW Power Reactor





νGen



RED-100

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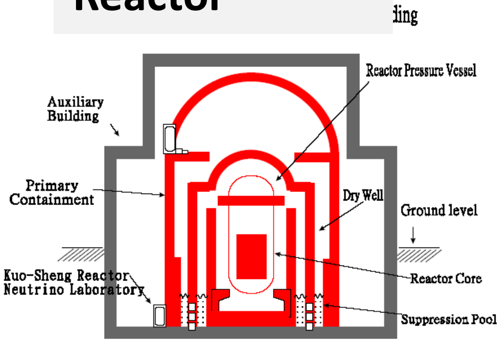
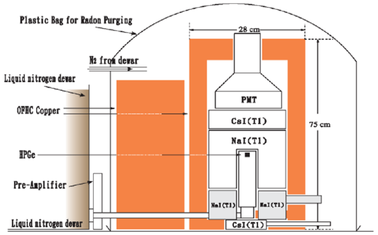
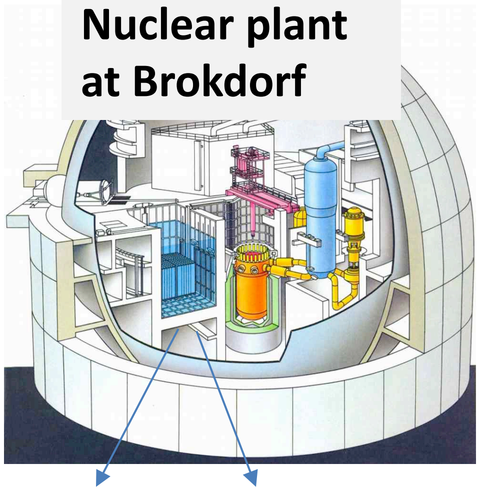
Kuo-Sheng Reactor

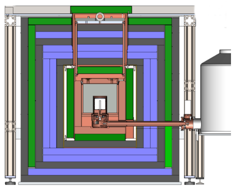




TEXONO

Nuclear plant at Brokdorf





CONUS

$$\nu + A(Z,N) \rightarrow \nu + A(Z,N)$$

1. A new way to detect neutrinos
2. Future background floor for dark matter search
3. Can be a sensitive probe SM (BSM)

Summary

- θ_{13} is measured with good precision
- Sterile neutrinos (1 eV) are not favored by reactor neutrino experiments and others
- Questions (5 MeV Bump, RAA) for reactor related nuclear physics remains
- Reactor neutrinos is a good source for many SM (BSM) physics research, coherent scattering, neutrino magnetic moment, NSI (not fully covered)