Sterile neutrino analysis of reactor neutrino oscillation

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Introduction

- In spite of the confirmation of three flavors of neutrinos, we do not concretely exclude the existence of sterile neutrinos.
- Singlets generally come out of many BSM.

  (Remnants of GUT, seesaw mechanism, etc…)
- CMB, LSS and BBN prefer additional relativistic degree of freedom.
- Although sterile neutrinos do not interact with the electroweak gauge bosons, they can mix with three active neutrinos, leading to the oscillation between active and sterile neutrinos.

Evidence for sterile neutrino ?

- There exist some anomalies which cannot be explained within 3-flavor framework and might point towards the existence of additional ν's.
- LSND : evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ with $\triangle m^2 \sim 1\ eV^2$.
- MiniBooNE : a yet unexplained event excess in the low-E region of ν_e & anti-ν_e event spectra.
  - No significant excess is fond at higher E_ν.
  - Interpreting MiniBooNE in terms of oscillations, there are parameter regions consistent with LSND result.

- "Gallium anomaly" : Gallium radioactive source experiments SAGE and GALLEX have obtained an event rate which is somewhat lower than expected ➔ indication of ν_e disappearance,

  possibly due to $\nu_e \rightarrow \nu_s$

- "Reactor anomaly" : recent re-evaluation of the neutrino flux emitted by reactor led to increased fluxes compared with previous one. Inconsistent with measurements from short-baseline reactor experiments.

Four neutrino mixing

- Our aim : examine whether $\nu_s \leftrightarrow \nu_a$ is plausible, especially by interpreting the results released from Daya Bay and RENO.
- For simplicity, we introduce a sterile neutrino into the game.
- Since the setups of both exps. are optimized for $\triangle m_{31}^2$, the search for $\nu_s \leftrightarrow \nu_a$ is possible only if $\triangle m_{41}^2$ is not far different from $\triangle m_{31}^{2}$.
- Thus, our study does not cover the sterile neutrino introduced to reconcile the anomalies observed.

4-neutrino oscillations

- Unitary transformation from $(\nu_{\mathbf{1}}, \nu_{\mathbf{2}}, \nu_{\mathbf{3}}, \nu_{\mathbf{4}})$ to $(\nu_{\mathbf{e}}, \nu_{\boldsymbol{\mu}}, \nu_{\boldsymbol{\tau}}, \nu_{\mathbf{s}})$ parameterized by
  6 angles and 3 Dirac-type Phases.
- $U_{F} = R_{\mathbf{34}}(\Theta_{34})\ R_{\mathbf{24}}(\Theta_{24}, \delta_2)\ R_{\mathbf{14}}(\Theta_{14}) \cdot$
  $R_{\mathbf{23}}(\Theta_{23})\ R_{\mathbf{13}}(\Theta_{13}, \delta_1)\ R_{\mathbf{12}}(\Theta_{12}, \delta_3)$
  ($R_{\mathbf{ij}}(\Theta_{ij})$: rotation of i-j block by Θ_{ij})

- More explicitly except for phases,

$$
\begin{aligned}
\widetilde{U}_{\mathrm{F}} &= \begin{pmatrix} c_{14} & 0 & 0 & s_{14} \\ -s_{14}s_{24} & c_{24} & 0 & c_{14}s_{24} \\ -c_{24}s_{14}s_{34} & -s_{24}s_{34} & c_{34} & c_{14}c_{24}s_{34} \\ -c_{24}c_{34}s_{14} & -s_{24}c_{34} & -s_{34} & c_{14}c_{24}c_{34} \end{pmatrix} \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & 0 \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & 0 \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \\
&= \begin{pmatrix} c_{14}U_{e1} & c_{14}U_{e2} & c_{14}U_{e3} & s_{14} \\ \cdots & \cdots & \cdots & c_{14}s_{24} \\ \cdots & \cdots & \cdots & c_{14}c_{24}s_{34} \\ \cdots & \cdots & \cdots & c_{14}c_{24}c_{34} \end{pmatrix},
\end{aligned}
$$

Survival probability of $\bar{\nu}_e$

$$P_{\rm th}(\bar{\nu}_e \to \bar{\nu}_e) = |\sum_{j=1}^{4} |\widetilde{U}_{ei}|^2 \exp i \frac{\Delta m^2_{j1} L}{2E_\nu}|^2$$

$$= 1 - \sum_{i<j} 4|\widetilde{U}_{ei}|^2 |\widetilde{U}_{ej}|^2 \sin^2(\frac{\Delta m^2_{ij} L}{4E_\nu})$$

- Assuming $\Delta m^2_{41} \sim \Delta m^2_{42} \sim \Delta m^2_{43} > \Delta m^2_{31}$
  $|\widetilde{U}_{e3}|$ and $|\widetilde{U}_{e4}| \ll 1$

$$P_{\rm th}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - c_{14}^4 c_{13}^4 \sin^2 2\theta_{12} \sin^2(1.27 \Delta m^2_{21} \frac{L}{E})$$

$$- c_{14}^4 \sin^2 2\theta_{13} \sin^2(1.27 \Delta m^2_{31} \frac{L}{E})$$

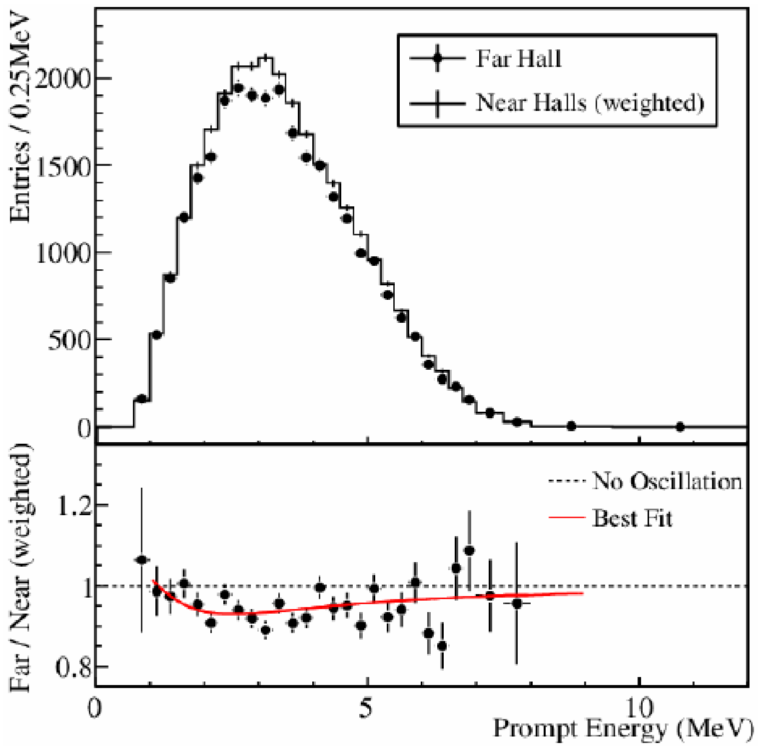
$$- \sin^2 2\theta_{14} \sin^2(1.27 \Delta m^2_{41} \frac{L}{E}).$$

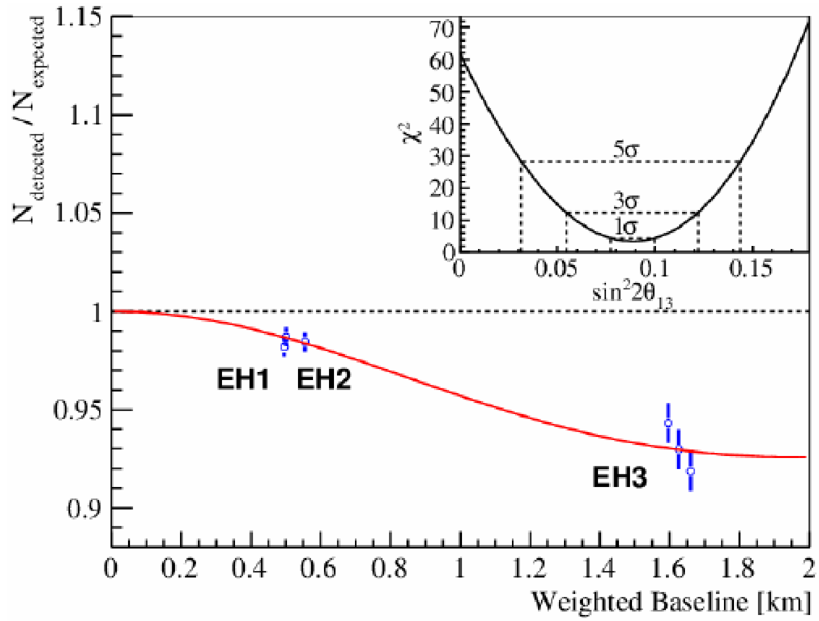
θ$_{13}$ at Daya Bay
(Xianonan Li, NOW2012)

The Daya Bay Experiment

- **6 reactor cores, 17.4 GW$_{th}$ total power**
- **Relative measurement**
  - 2 near sites, 1 far site
- **Multiple detector modules**
- **Good cosmic shielding**
  - 250 m.w.e @ Daya Bay near
  - 860 m.w.e @ far site

Improved results



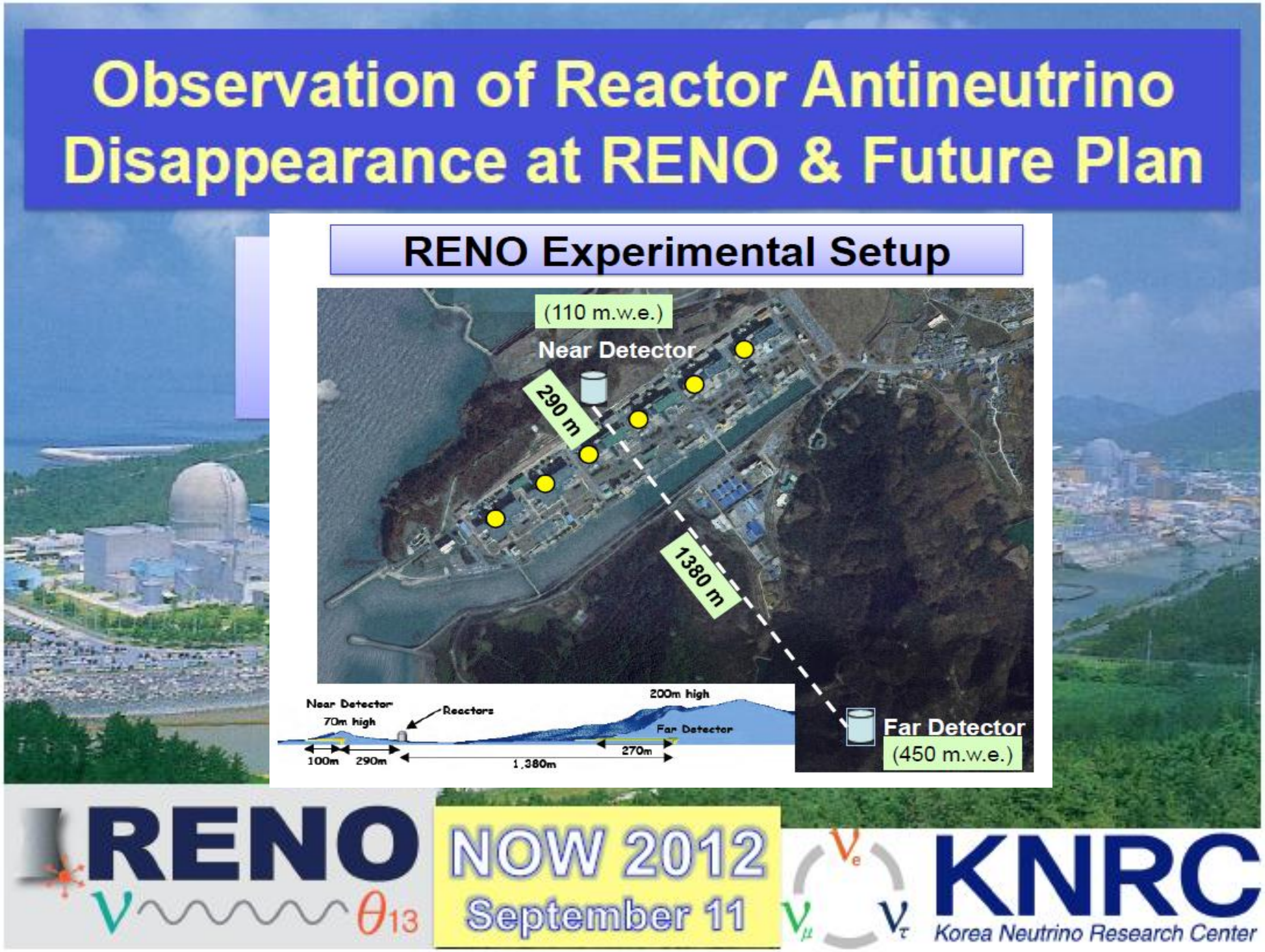


•R = 0.944 ± 0.007 (stat) ± 0.003 (syst)

•$\sin^2 2\theta_{13}$=0.089±0.010(stat)±0.005(syst)

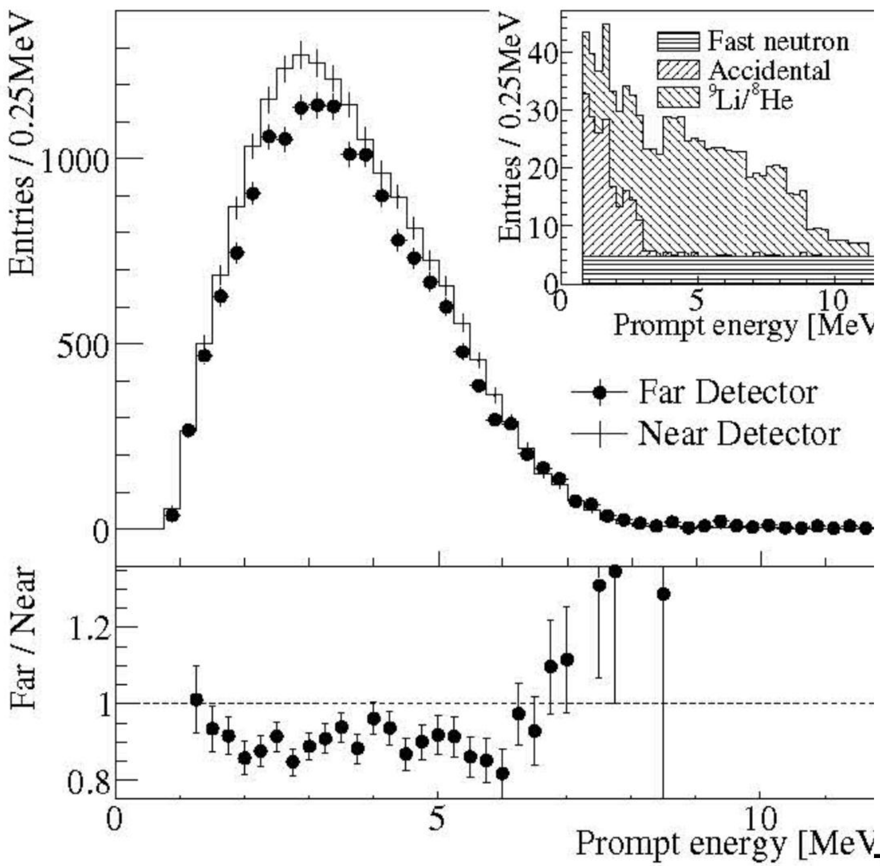
•With 2.5x more statistics, an improved measurement to θ_{13}

θ_{13} at RENO
(Seon-Hee Seo, NOW2012)



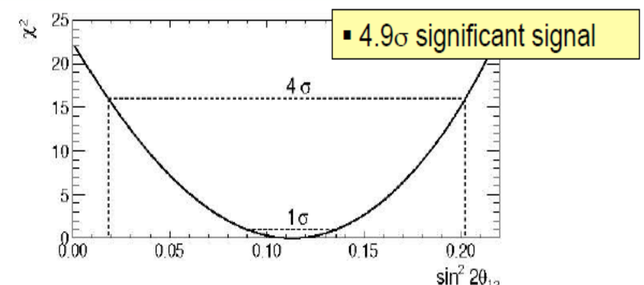
Reactor Antineutrino Disappearance

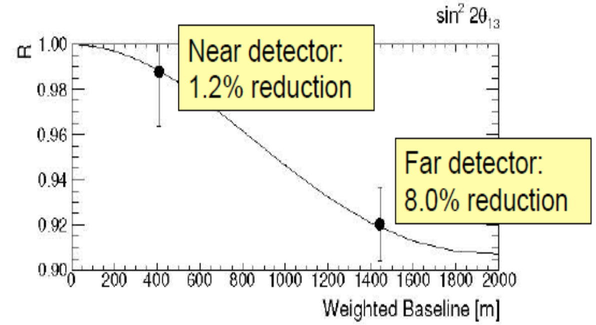
$$R = \frac{\Phi^{Far}_{observed}}{\Phi^{Far}_{expected}} = 0.920 \pm 0.009(stat) \pm 0.014(syst)$$



Definitive Measurement of θ_{13}

$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat.) \pm 0.019(syst.)$$





Rate-only analysis

- Averaging the survival probability over E_ν :

$$\langle P \rangle = \frac{\int P_{\rm s}(E)\sigma_{\rm tot}(E)\phi(E)dE}{\int \sigma_{\rm tot}(E)\phi(E)dE}$$

$\sigma_{\mathbf{tot}}$(E) : total cross section of inverse beta decay

(Voget PRD60)

Φ(E) : neutrino flux distribution from reactors (Huber PRC84)

Ps(E) : survival prob. at each detector

- Baselines

  Daya Bay : EH1=494m, EH2=554m (near)

  EH3=1628m (far)

  RENO : (near)={660,445,302,340,520,746}m

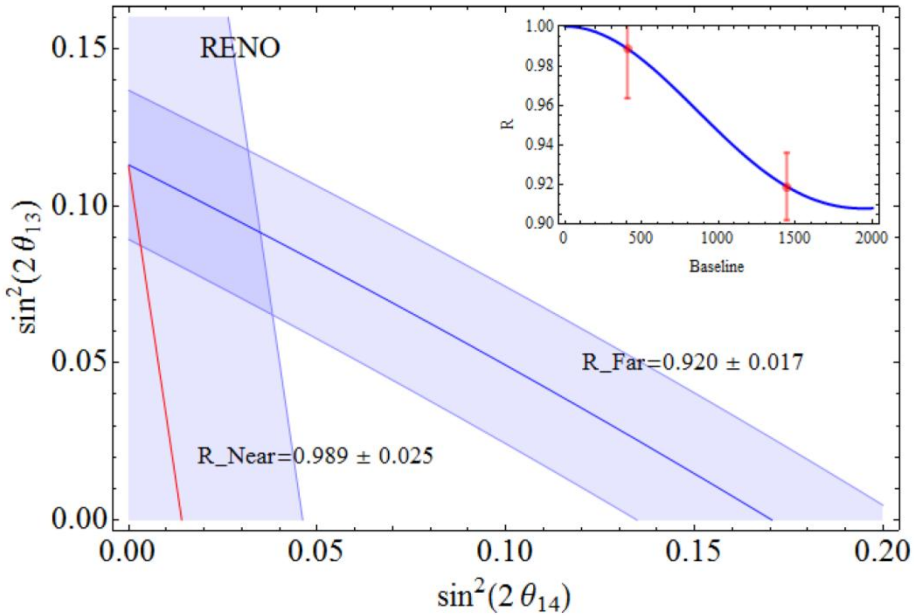
  (far)={1560,1460,1400,1380,1410,1480}m

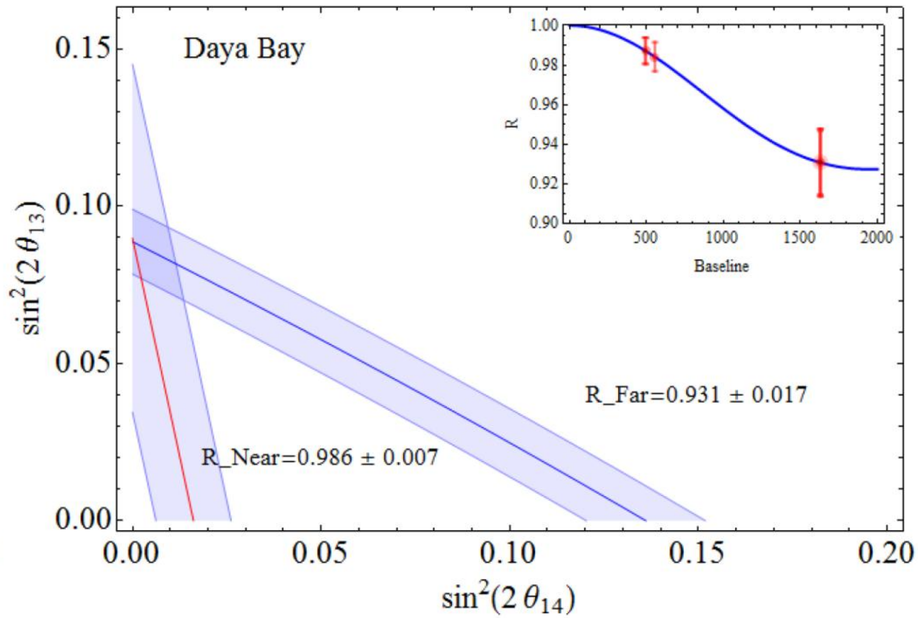
  ➔ flux-weighted averages :

  (near)=407.3m (far)=1443m

- Taking into account detection efficiency at each detector.

Averaged $N_{\mathbf{obs}}/N_{exp}$ in terms of 4-neutrino oscillation





- RENO :

$$< P_{near} > = 0.989 \pm 0.025 \quad < P_{far} > = 0.920 \pm 0.017$$

Daya Bay :

$$< P_{near} > = 0.986 \pm 0.007 \quad < P_{far} > = 0.931 \pm 0.017$$

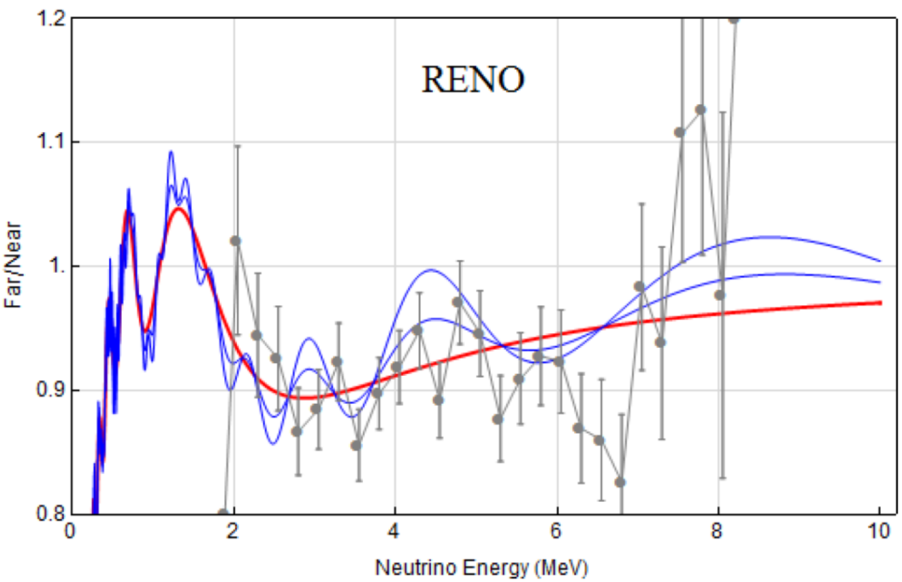
Spectral-shape analysis

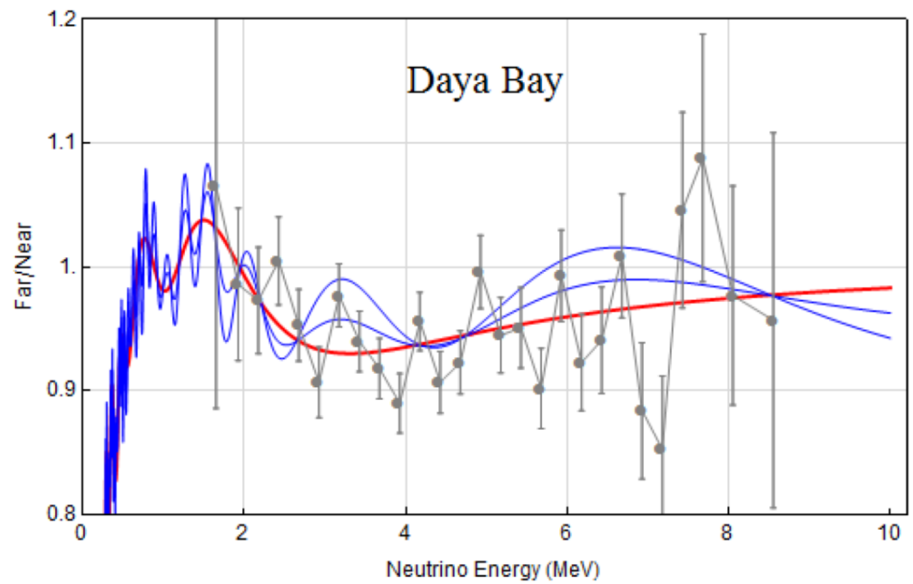
- $R \equiv \frac{\#\ of\ events\ at\ FD}{\#\ of\ events\ at\ ND}$

  → data obtained per 0.25MeV bin as E varies from 1.8MeV to 8.5 MeV

We plot the curve for $R = \frac{P_{th}(L_{far})}{P_{th}(L_{near})}$

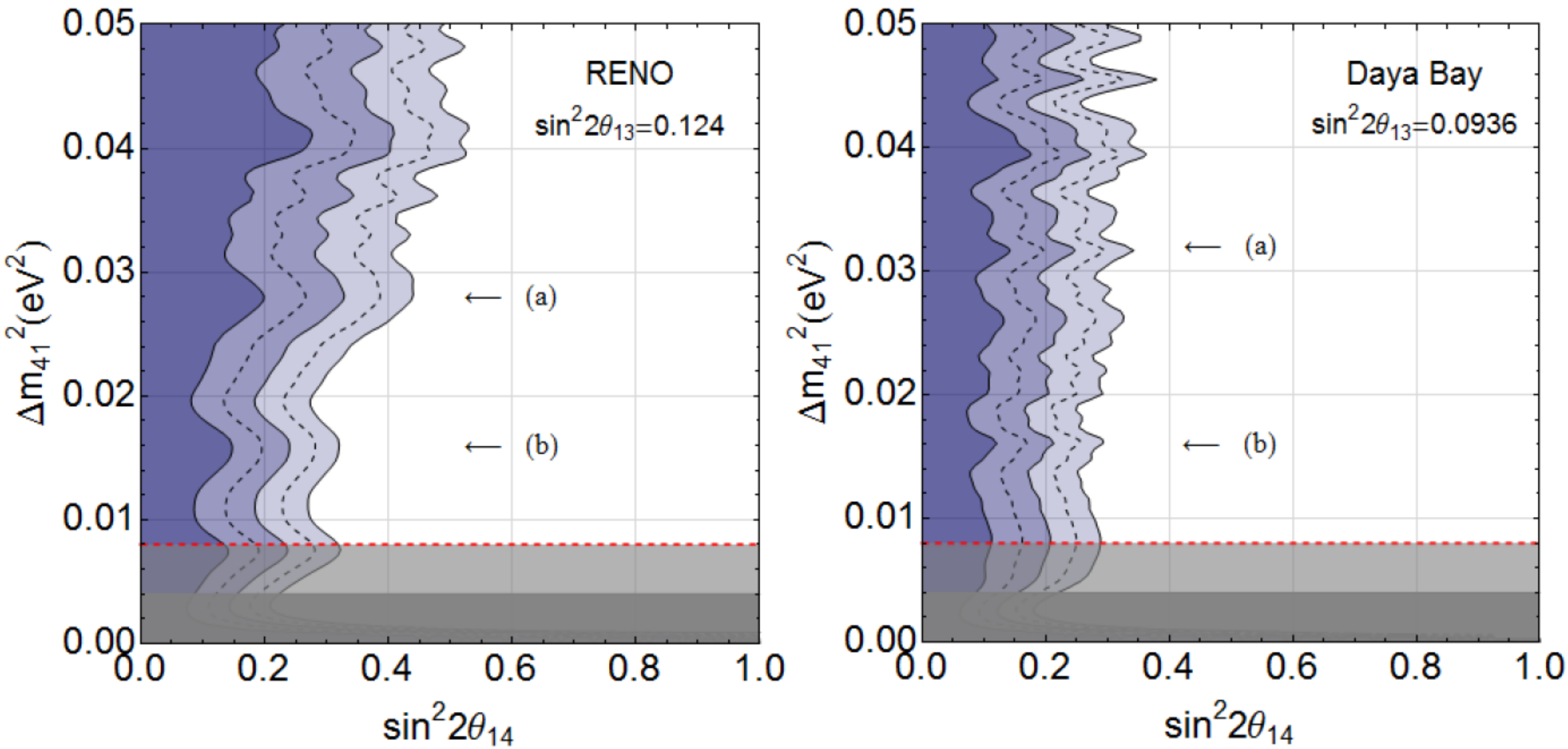
Far-to-near ratio in terms of 4-neutrino oscillation



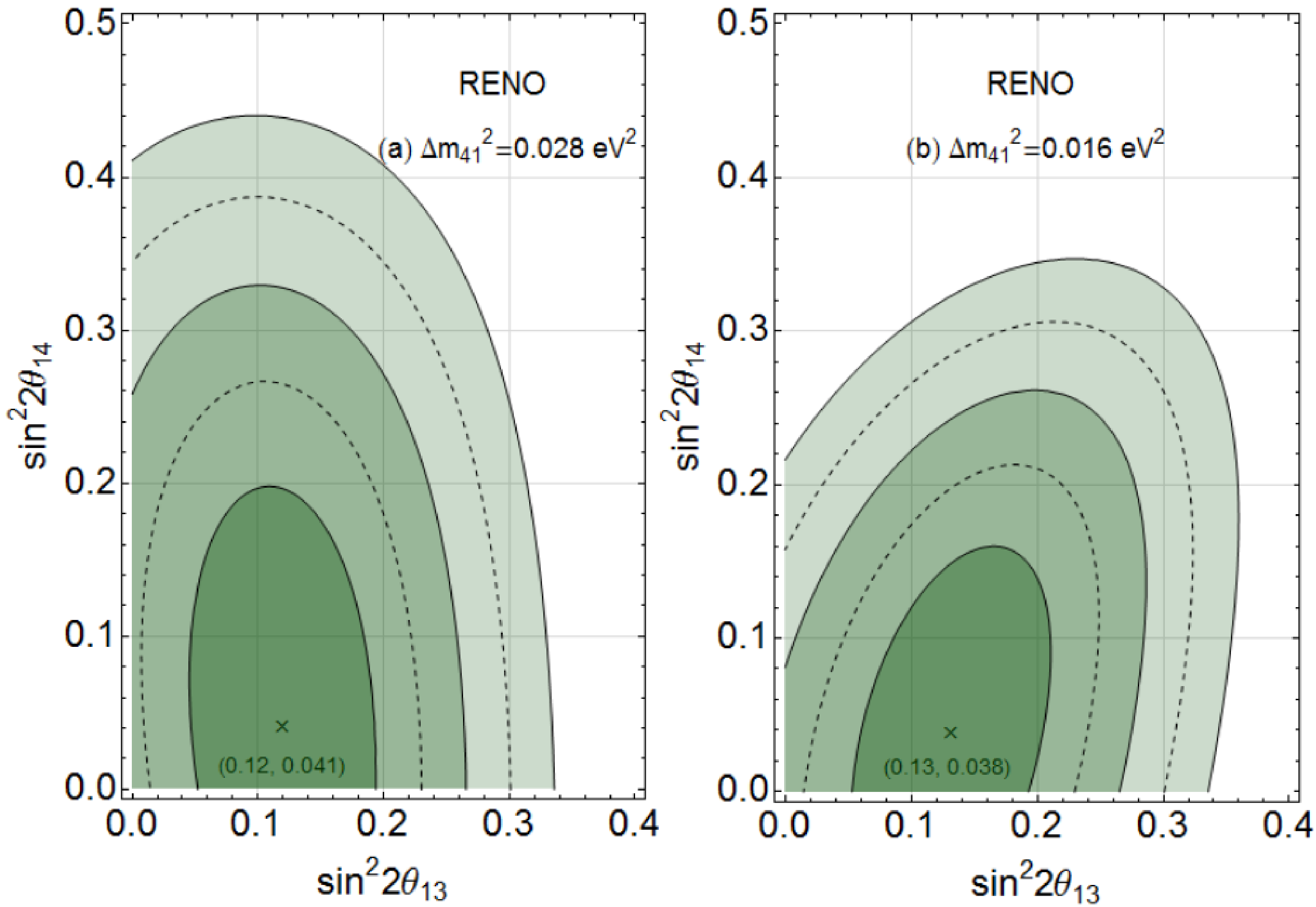


- Red curves : θ_{14} =0 & corresponding to the best fit points in the rate-only analysis
- Blue curves : $\sin^2 2\theta_{14}$ =0.05, 0.1
  $\triangle m_{41}^2$ =0.0185, 0.008 eV^2

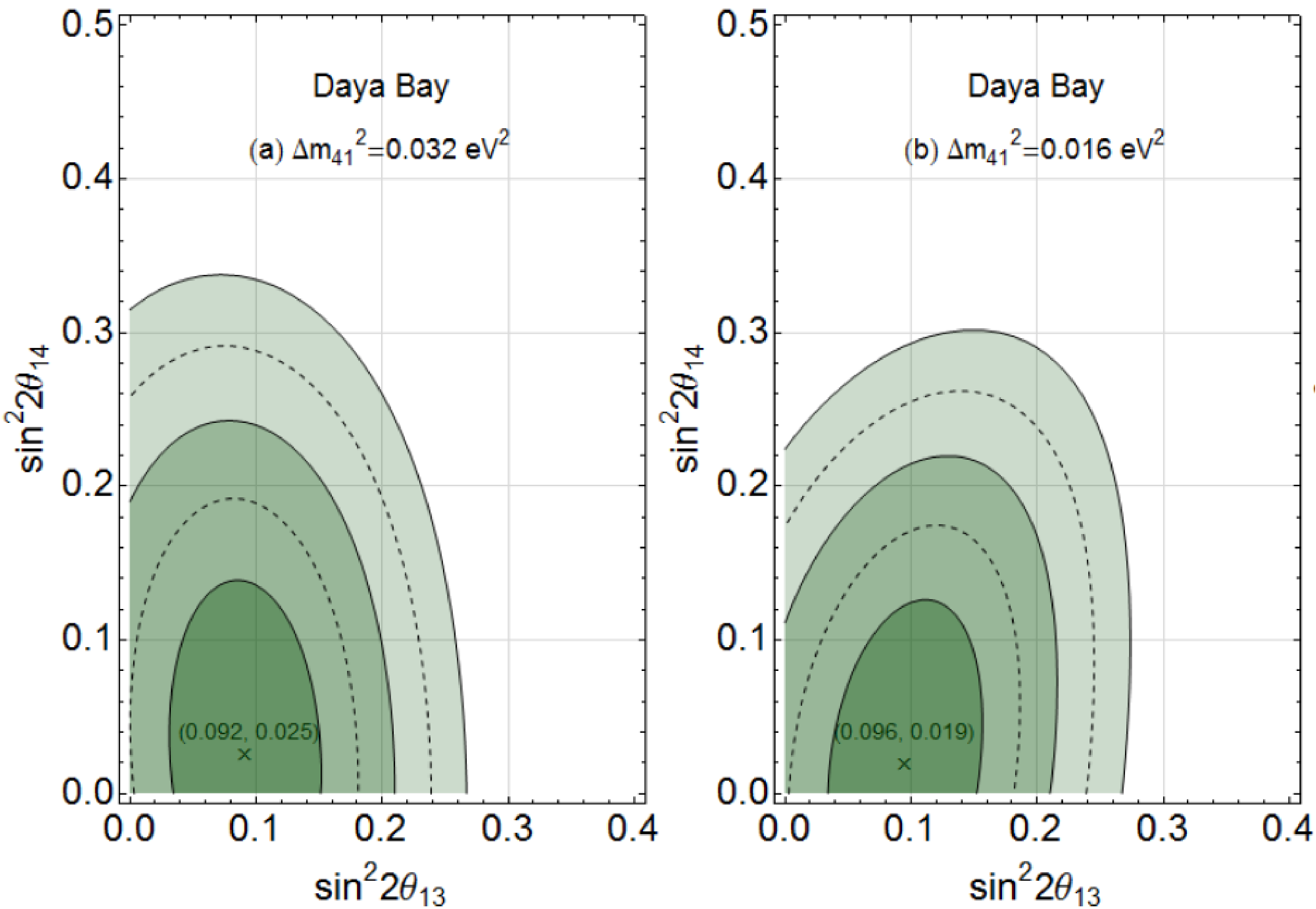
Exclusion curves
(RENO)



Allowed regions in $(\theta_{13}, \theta_{14})$
(RENO)



Allowed regions in (θ_{13}, θ_{14})
(Daya Bay)



Summary

- We have examined whether oscillation between a sterile neutrino and active neutrinos is plausible at Daya Bay & RENO experiments.
- Under a few assumptions, our analysis shows that $\nu_s \leftrightarrow \nu_a$ is plausible and gives even better bit compared with 3-flavor framework analysis.