# Improved Limits on Sterile Neutrino Mixing from a Joint Search of the MINOS, MINOS+, Daya Bay, and Bugey-3 Experiments

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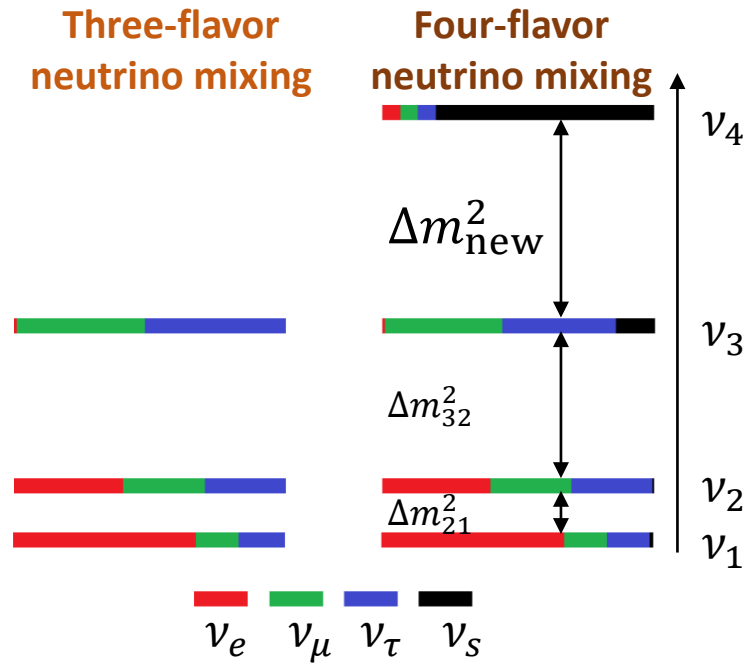
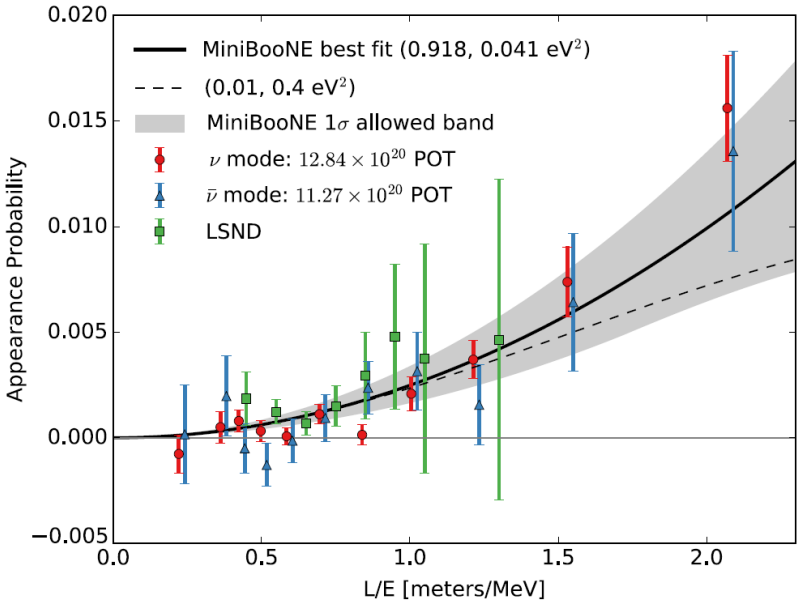
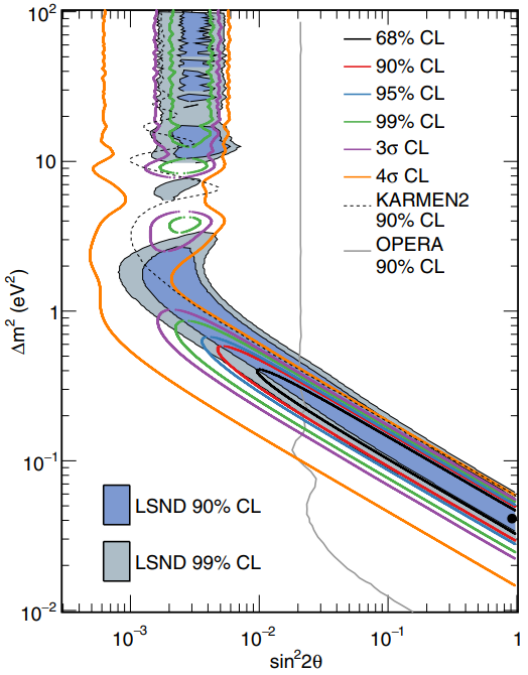
On behalf of the Daya Bay and MINOS/MINOS+ Collaborations

- Neutrino oscillation
  - A neutrino created with a certain leptonic flavor can be found later to hold a different flavor.
  - Three neutrino weak states consist of superpositions of three mass states.
- Sterile neutrinos
  - Additional neutrino states that do not participate in any of the interactions in the Standard Model.
  - A fourth neutrino state may explain the anomalous excess observed by the Liquid Scintillator Neutrino Detector (LSND) and MinoBooNE experiments.

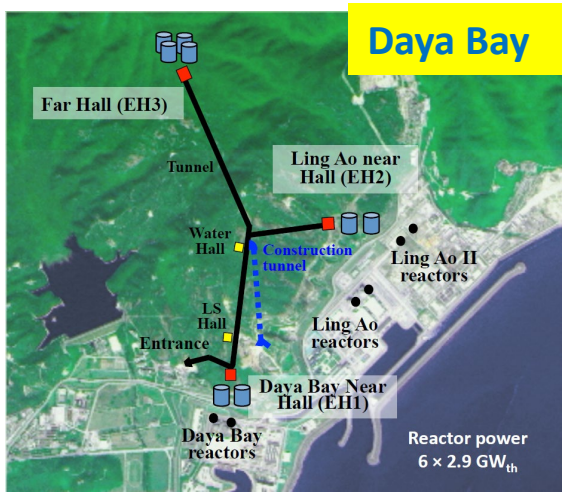


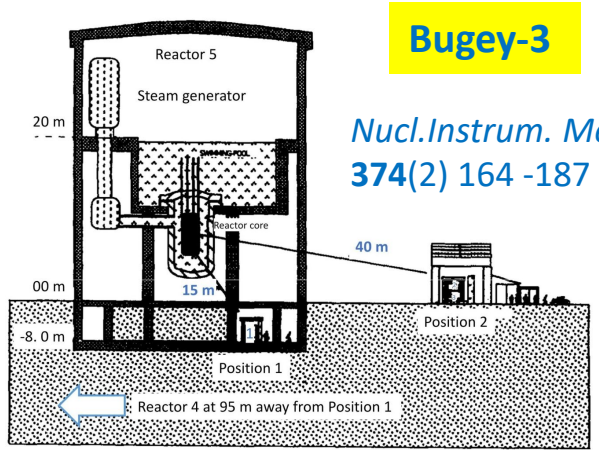

Significant excess by LSND and MiniBooNE: *Phys. Rev. Lett.* **121**, 221801 (2018).




MiniBooNE allowed regions and LSND allowed regions: *Phys. Rev. Lett.* **121**, 221801 (2018).

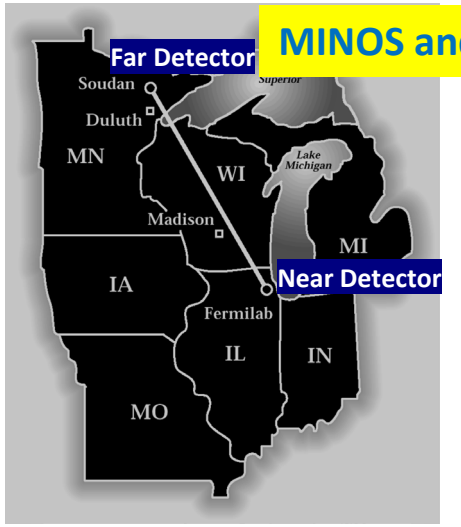



- reactor antineutrino disappearance.
- baselines. (~300 m - ~2000 m)



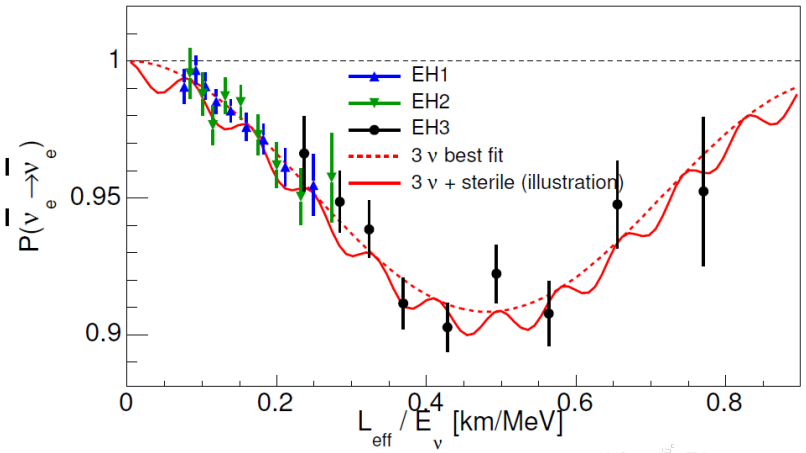

*Nucl.Instrum. Meth. A* **374**(2) 164 -187 (1996)

- reactor antineutrino disappearance.
- baselines. (15 m, 45 m, 90 m)




- accelerator neutrino disappearance.
- baselines. (ND 1 km, FD 735 km)

In presence of one sterile neutrino state, oscillation effects would appear in **disappearance** measurements as additional rate deficit and spectral distortion.




*additional spectral distortion expected with sterile neutrino oscillations at Daya Bay

$\bar{\nu}_e$ disappearance (reactor)

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E} - \sin^2 2\theta_{14} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

$\nu_\mu(\bar{\nu}_\mu)$ disappearance (accelerator)

$$P_{\nu_\mu \to \nu_\mu} \approx 1 - \sin^2 2\theta_{23} \cos 2\theta_{24} \sin^2 \frac{\Delta m^2_{31} L}{4E} - \sin^2 2\theta_{24} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

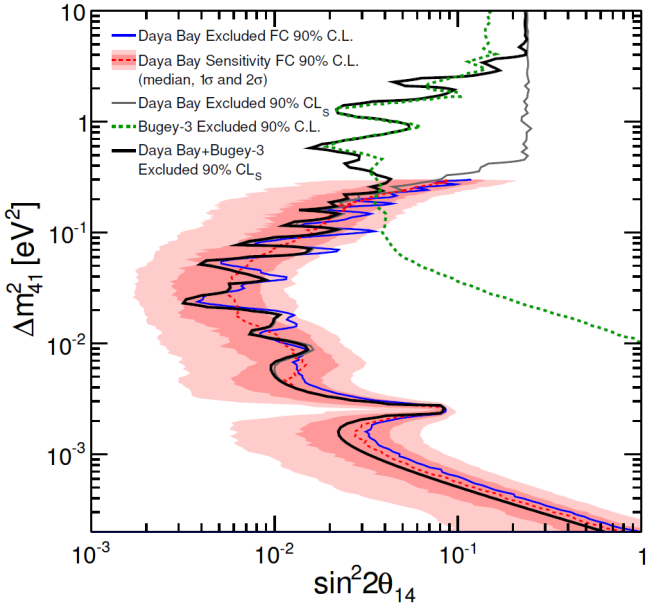
**Combination of two disappearance channels can constrain**

The LSND and MinoBooNE **appearance** probability

$$P^{SBL}_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41} L}{4E}, \text{ where } \sin^2 2\theta_{\mu e} \equiv \sin^2 2\theta_{14} \sin^2 \theta_{24}$$

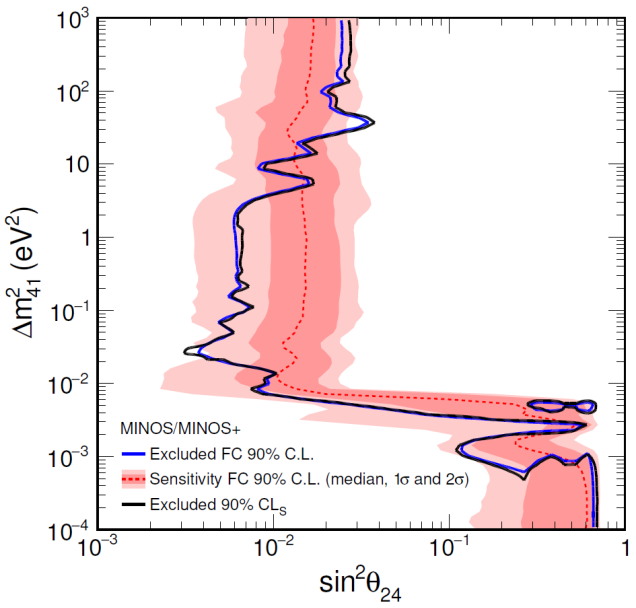
- Assuming presence of a light sterile neutrino, searches for sterile neutrino mixing are performed using $\bar{\nu}_e$ and $\nu_\mu(\bar{\nu}_\mu)$ disappearance, respectively.

**Daya Bay + Bugey-3**



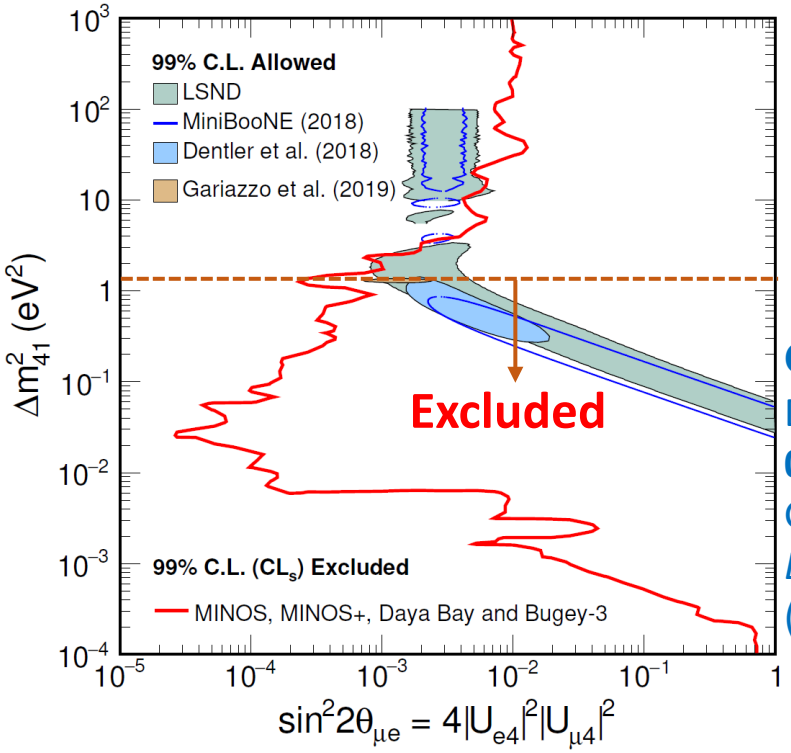

**MINOS and MINOS+**

Phys. Rev. Lett. **122**, 091803 (2019)




- Both are worlding-leading limits on sterile neutrino mixing.
- The disappearance measurements are combined using $CL_s$ method.

**PRL accepted**




**Global fits**:
Dentler et al. *JHEP* **08**, 010 (2018)
Gariazzo et al. *Phys. Lett. B.* **782**, 13 (2018)

- Tension between the $\overset{(-)}{\nu}_e$ appearance indications and the null results from disappearance channels is increased.
- We hope additional data from MINOS+ and Daya Bay can further quantify this tension in the future.

**Thank you! Stay tuned**