Searching for a Light Sterile Neutrino at Daya Bay

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On behalf of the Daya Bay Collaboration

Partial support: CUHK VC Discretionary Fund, RGC CUHK3/CRF/10R

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The Daya Bay Reactor Neutrino Experiment

F. P. An et al., Daya Bay Collaboration, NIM A **811**, 133 (2016); PRD **95**, 072006 (2017).

3-flavor Neutrino Oscillations

- Each flavor state is a mixture of mass eigenstates
- Described by a neutrino mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

The Maki-Nakagawa-Sakata-Pontecorvo Matrix

- A freely propagating ν_e will oscillate into other types
- In general, $|<\nu_{\mu,\tau}(t)|\nu_e(0)>|^2 \neq 0$

$$|<\nu_e(t)|\nu_e(0)>|^2 \approx 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right)$$

Reactor expt.: a clean way to measure θ_{13}

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{ee} L}{4E_\nu} - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E_\nu}$$

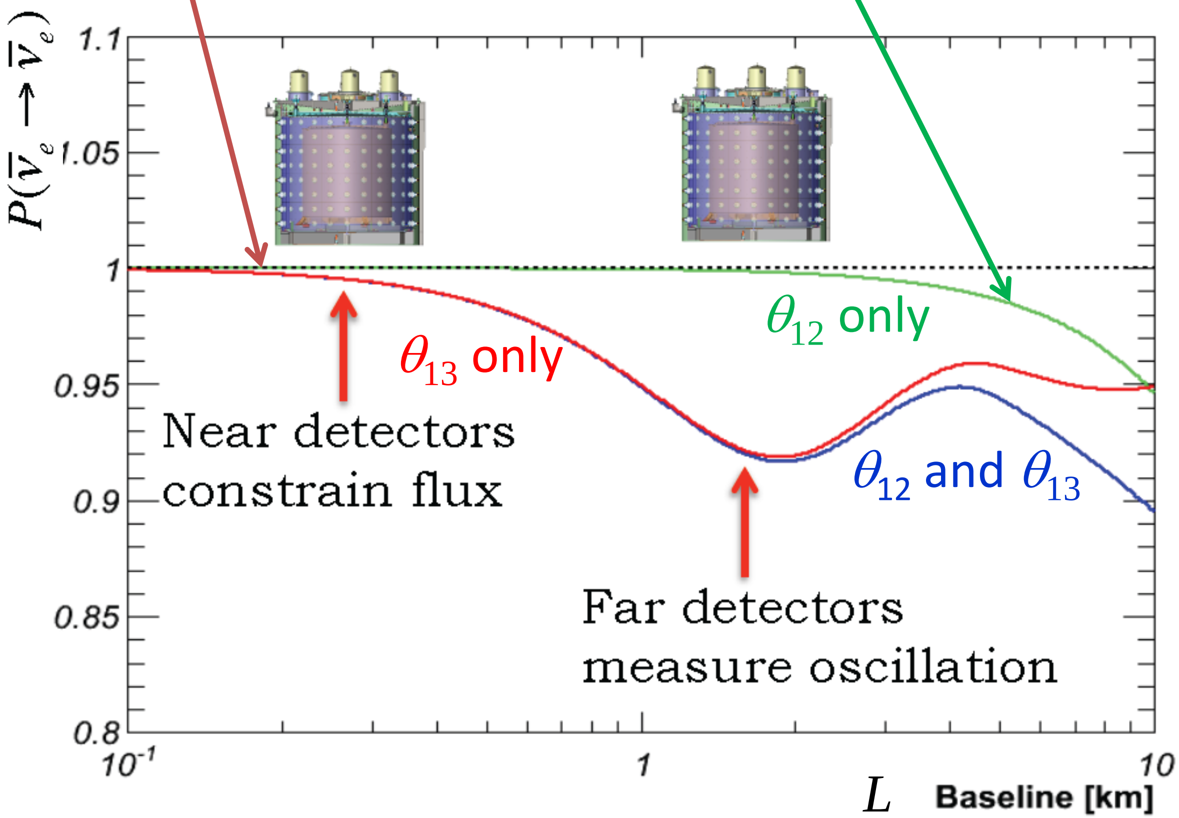
- Reactor: abundant, free, pure source of $\bar{\nu}_e$
- disappearance of $\bar{\nu}_e$ at small L depends only on θ_{13}

Near-far configuration

Near detectors: $\bar{\nu}_e$ flux and spectrum for normalization

Far detectors: near oscillation maximum for best sensitivity

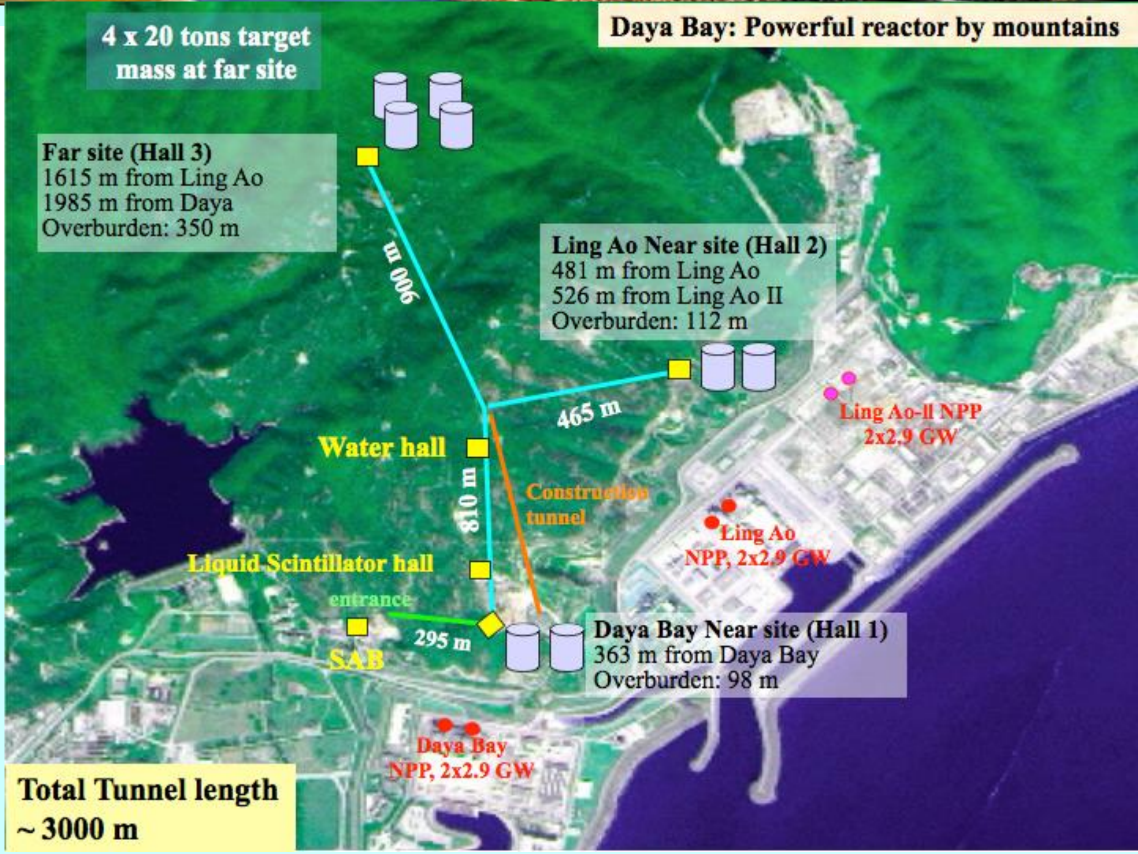
Relative measurement: cancel out most systematics



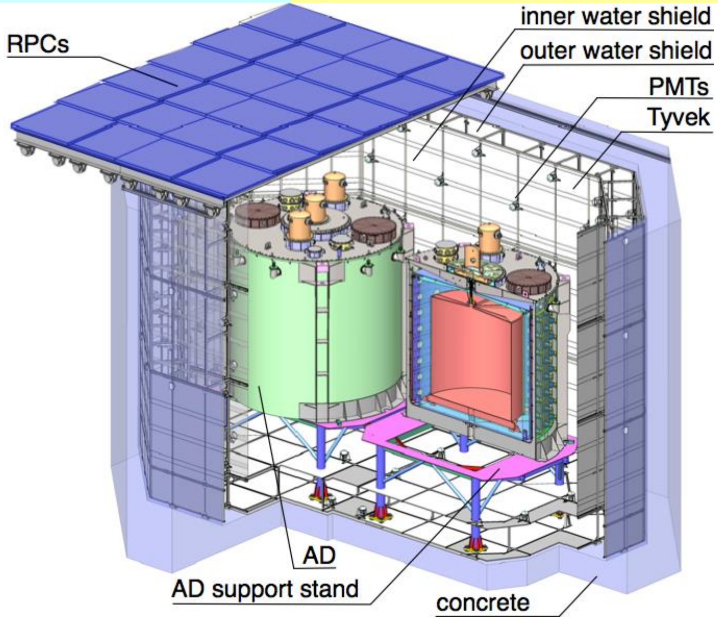
Daya Bay (China)

Daya Bay Experiment

- Top five most powerful nuclear plants (17.4 GW_{th})
→ large number of $\bar{\nu}_e$ ($3\text{x}10^{21}$/s)
- Adjacent mountains shield cosmic rays



Daya Bay detectors

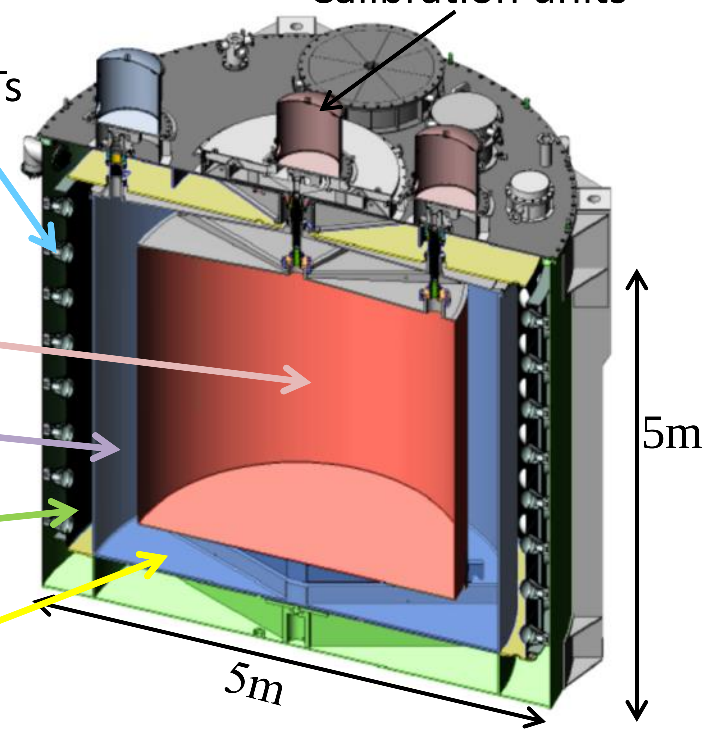


RPC : muon veto
Water pool: muon veto + shielding from environmental radiations (2.5m water)

8 functionally identical anti-neutrino detectors (AD) to suppress systematic uncertainties

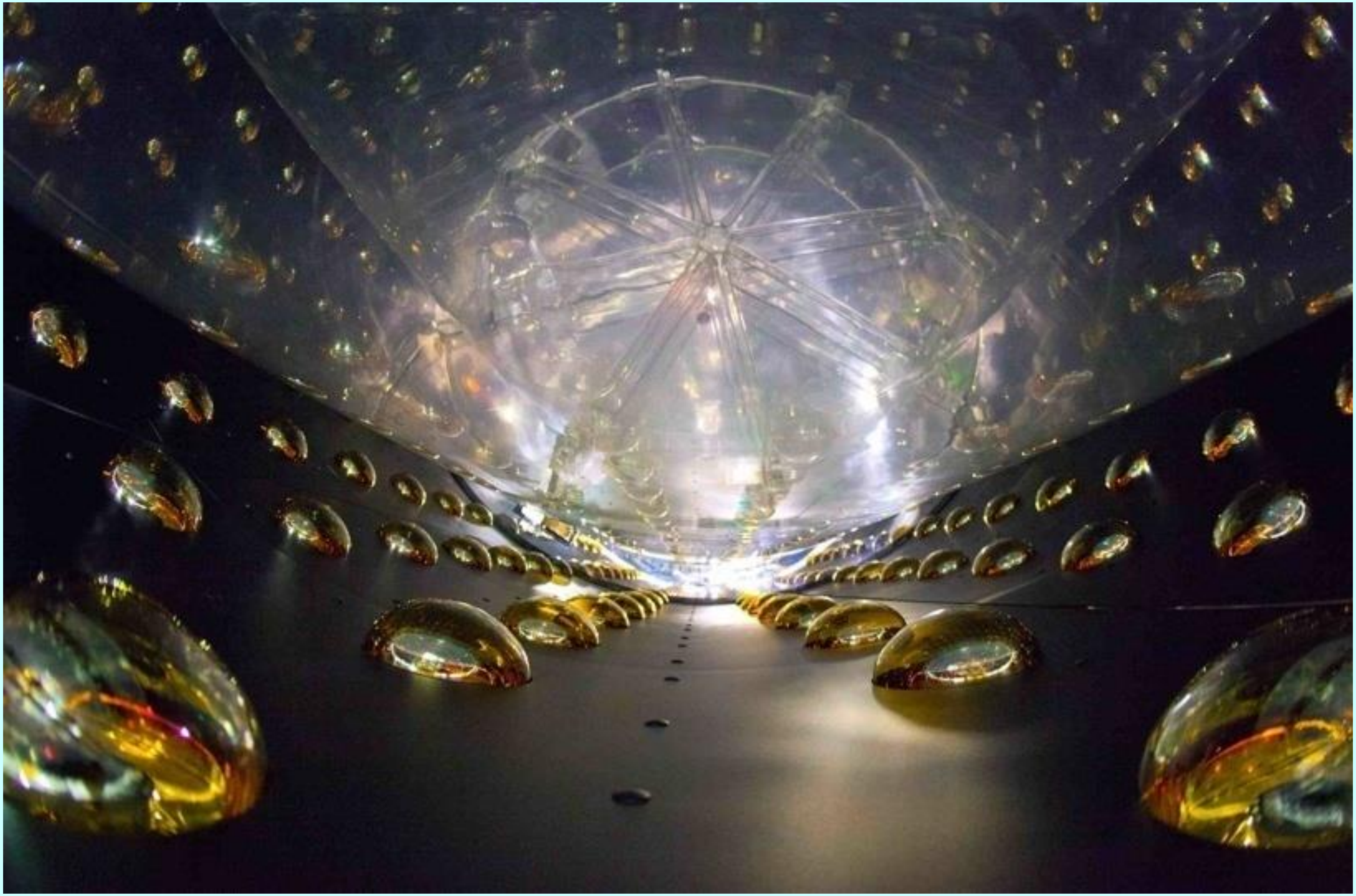
3 zone cylindrical vessels

	Liquid	Mass	Function
Inner acrylic	Gd-doped liquid scint.	20 t	Antineutrino target
Outer acrylic	Liquid scintillator	20 t	Gamma catcher
Stainless steel	Mineral oil	40 t	Radiation shielding



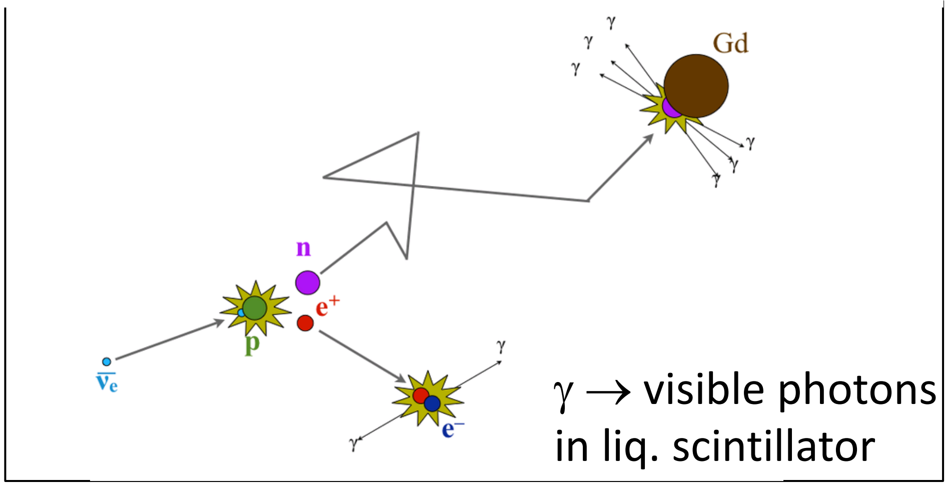
Top and bottom reflectors: more light, more uniform detector response

Interior of an AD

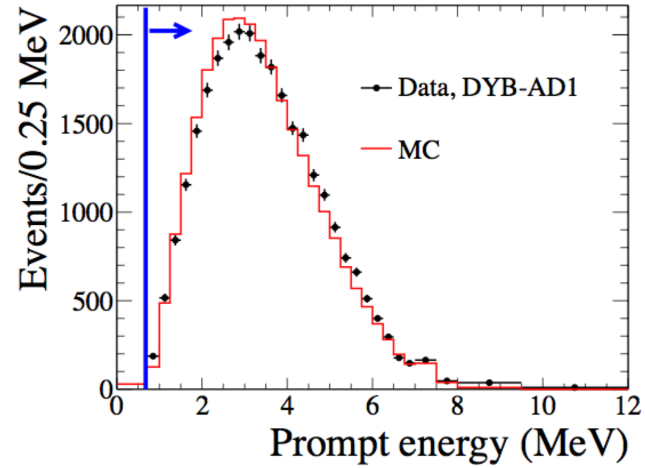


Anti-neutrino detection

$\overline{\nu}_e$ detected via inverse beta-decay (IBD):



Prompt Signal



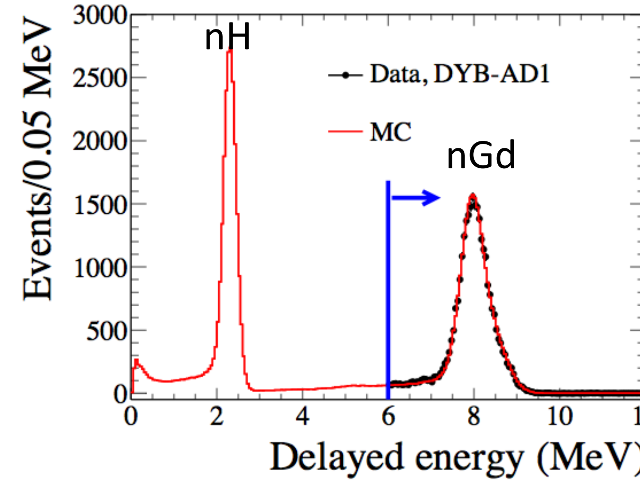
$\overline{\nu}_e + p \rightarrow e^+ + n$ (prompt signal)

~180μs $\rightarrow$ + p $\rightarrow$ D + γ (2.2 MeV)

~30μs for 0.1% Gd $\rightarrow$ + Gd $\rightarrow$ Gd* $\rightarrow$ Gd + γ's (8 MeV)

(delayed signal)

Delayed Signal



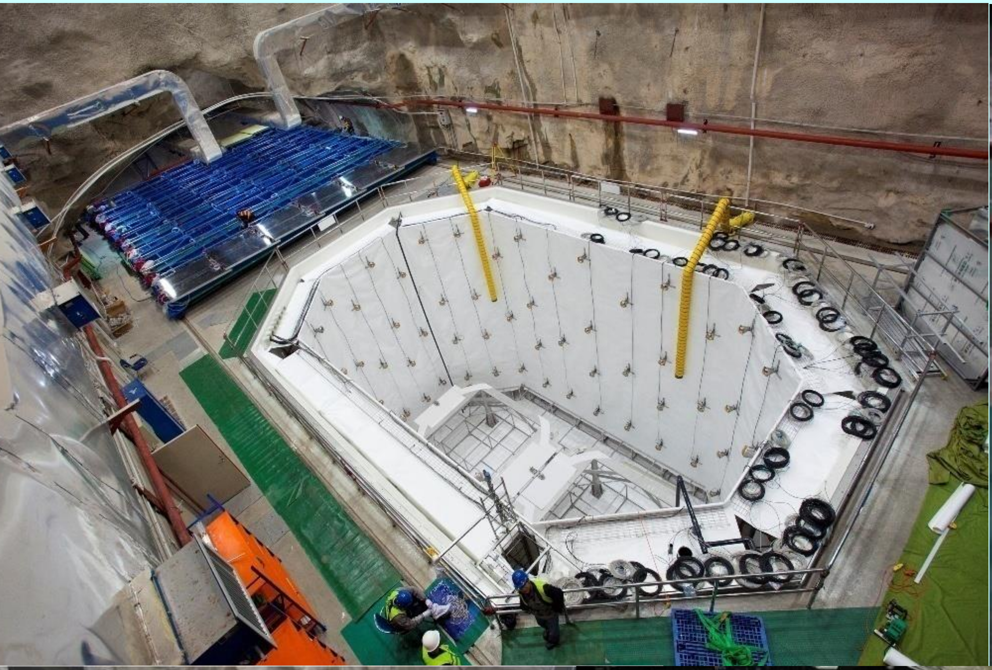
Powerful background rejection!

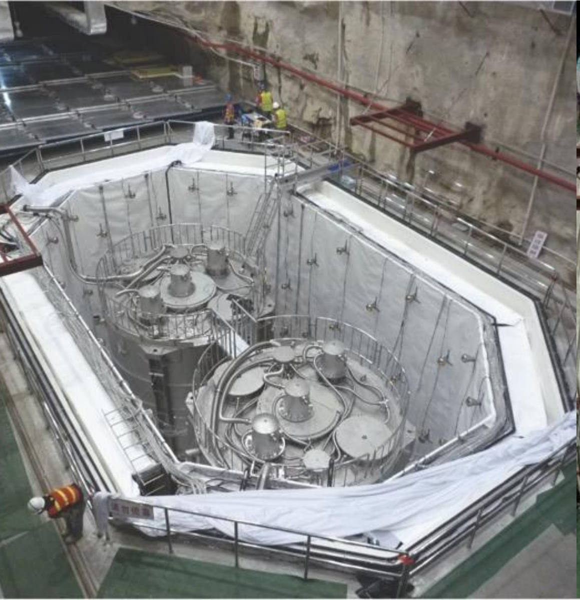
$$E_\nu \approx T_{e+} + T_n + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8 \text{ MeV}$$

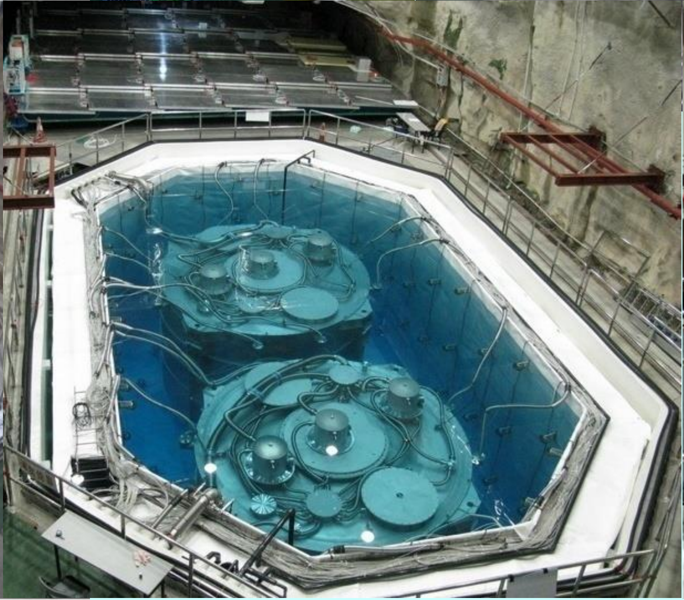
The Daya Bay Collaboration

42 Institutes, ~ 203 collaborators from China, USA, Hong Kong, Taiwan, Chile, Czech Republic and Russia

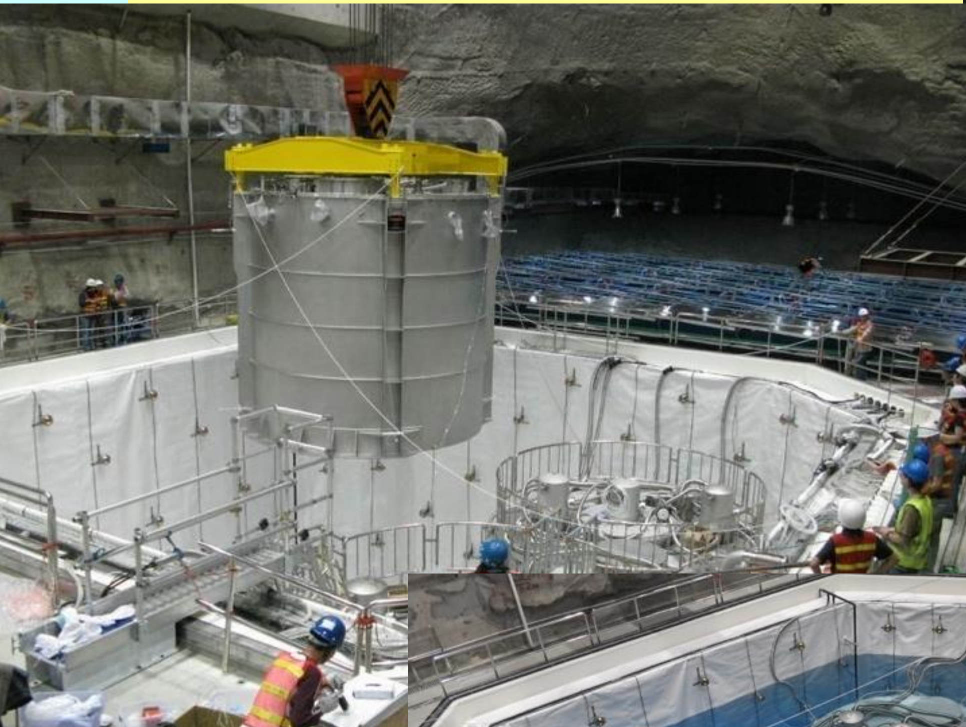
AD Installation - Near Hall

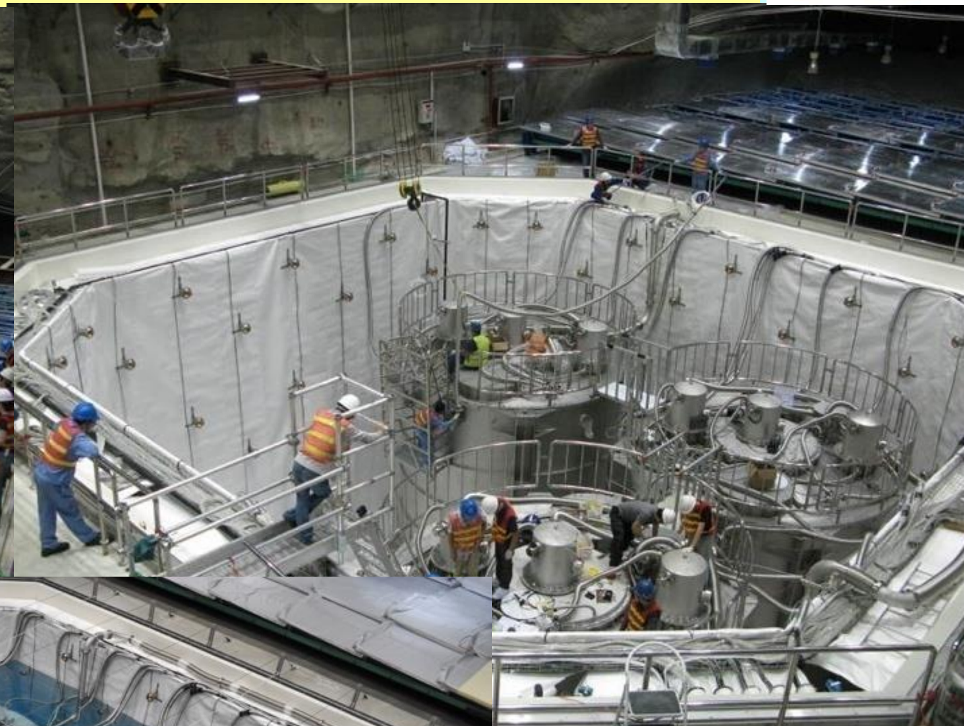


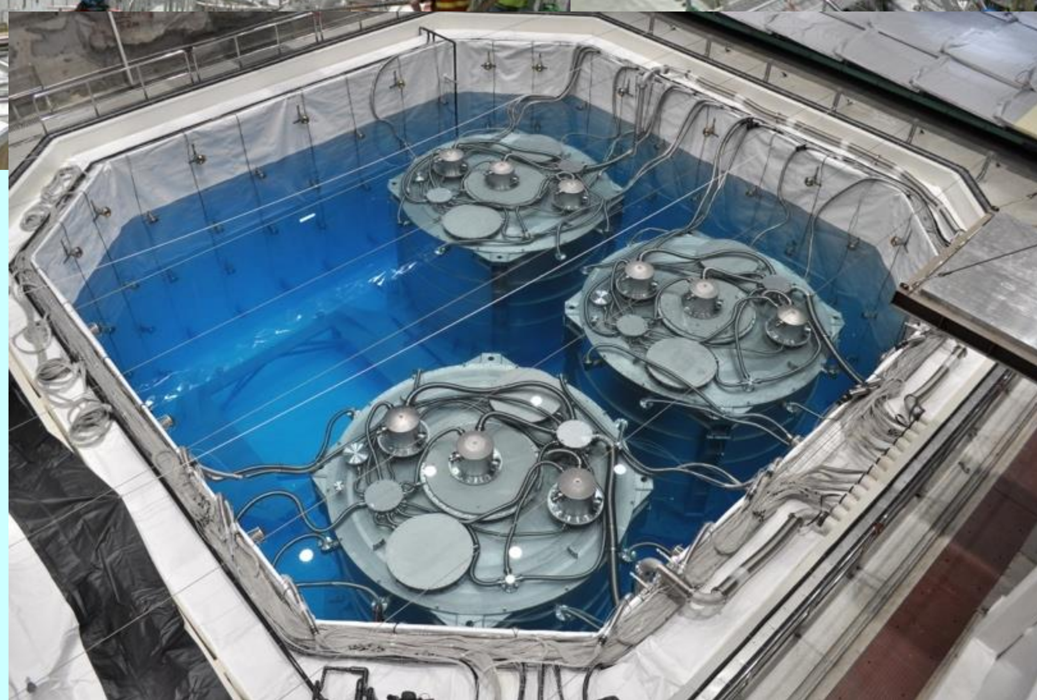




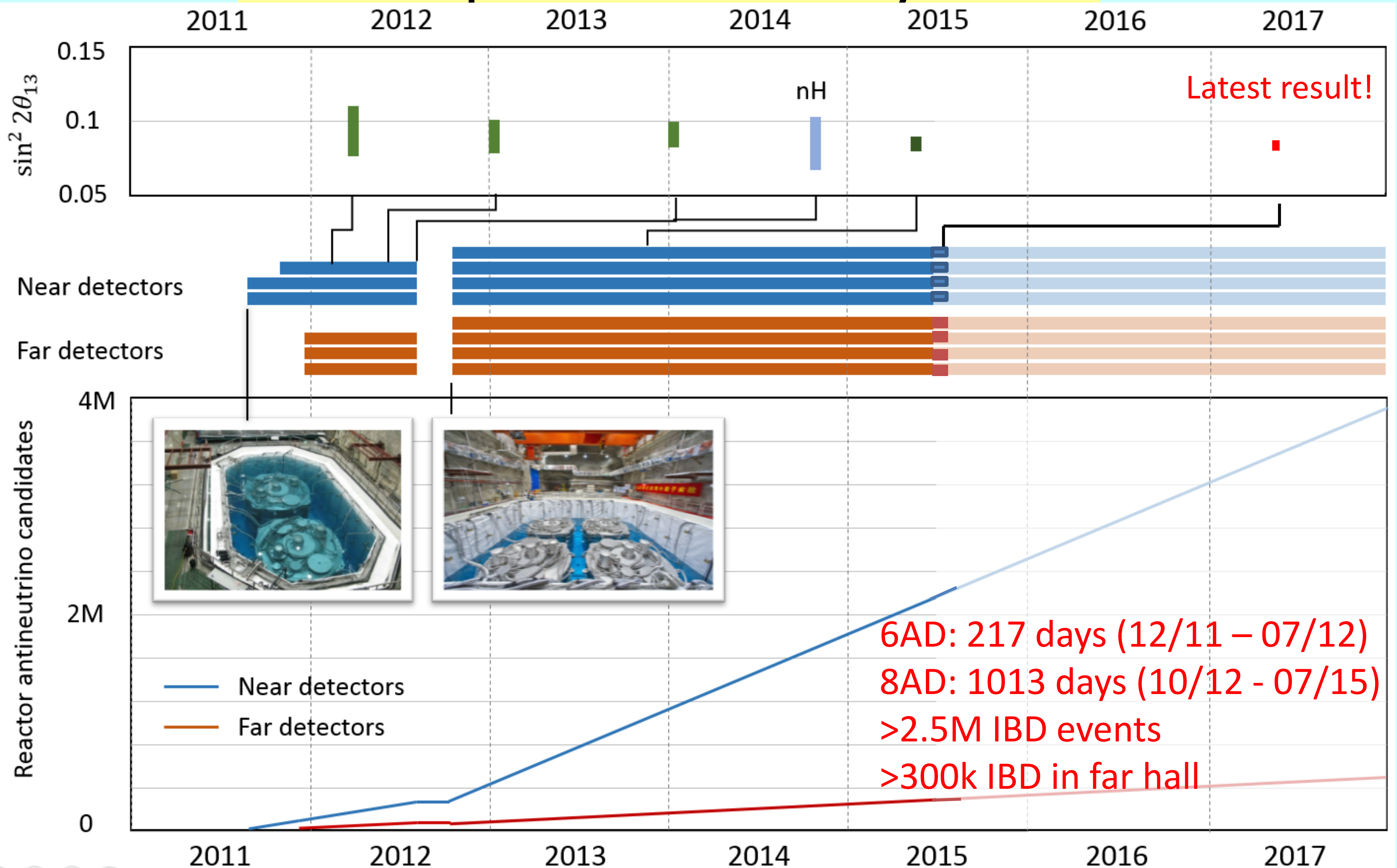
AD Installation - Far Hall







Operation history

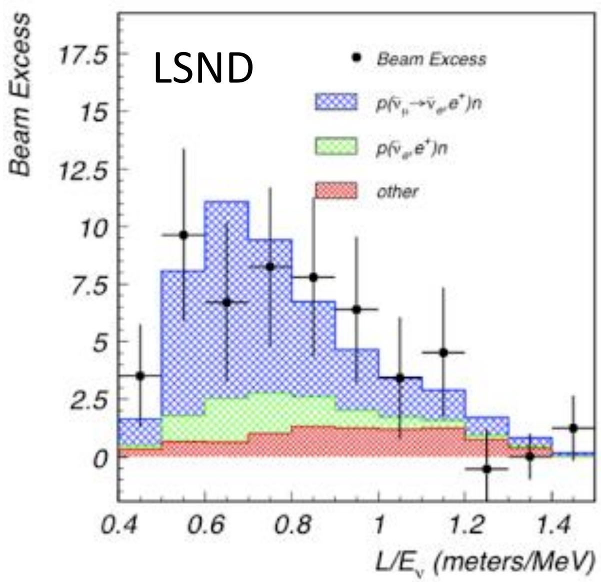


Search for a light sterile neutrino

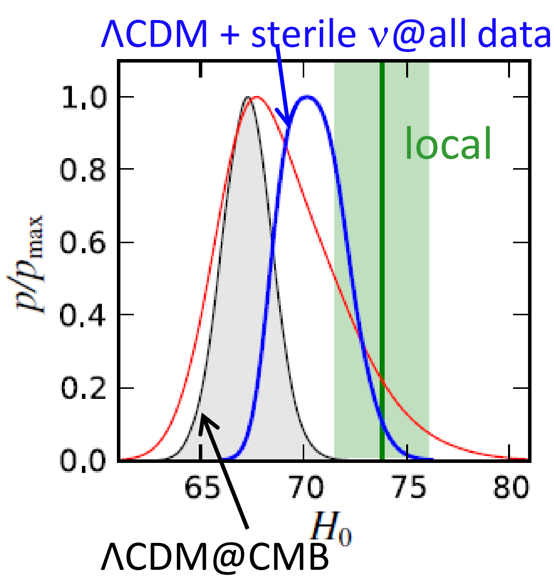
F. P. An et al., Daya Bay Collaboration, PRL **117**, 151802 (2016);
PRL **113**, 141802 (2014).
Daya Bay and MINOS Collaborations, PRL **117**, 151801 (2016).

Sterile Neutrinos

- right-handed neutrinos (no weak interactions) in many Beyond Standard Model theories
- May explain some experimental anomalies: LSND, MiniBooNE ($m_s \sim \mathrm{eV}$)
- Dark matter candidate ($m_s \sim \mathrm{keV}$)
- May alleviate tension in Hubble parameter between Planck and local measurement ($m_s \sim \mathrm{eV}$)

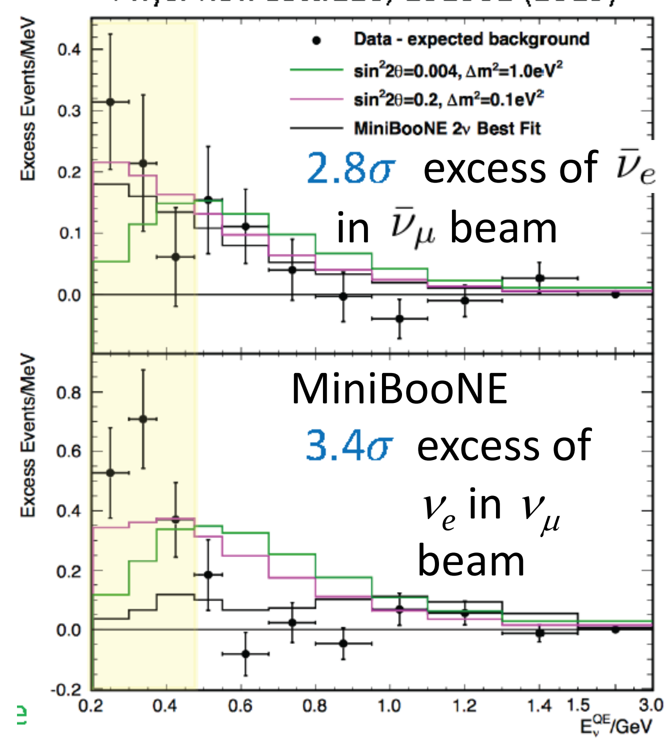


3.8σ excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam
PRD **64**, 112007 (2001).



PRL **112**, 051302 (2014).

Phys. Rev. Lett.110, 161801 (2013)



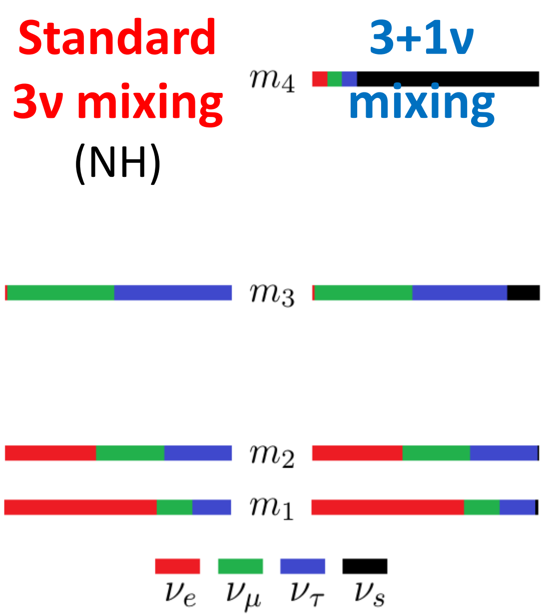
3+1 Neutrino Oscillations

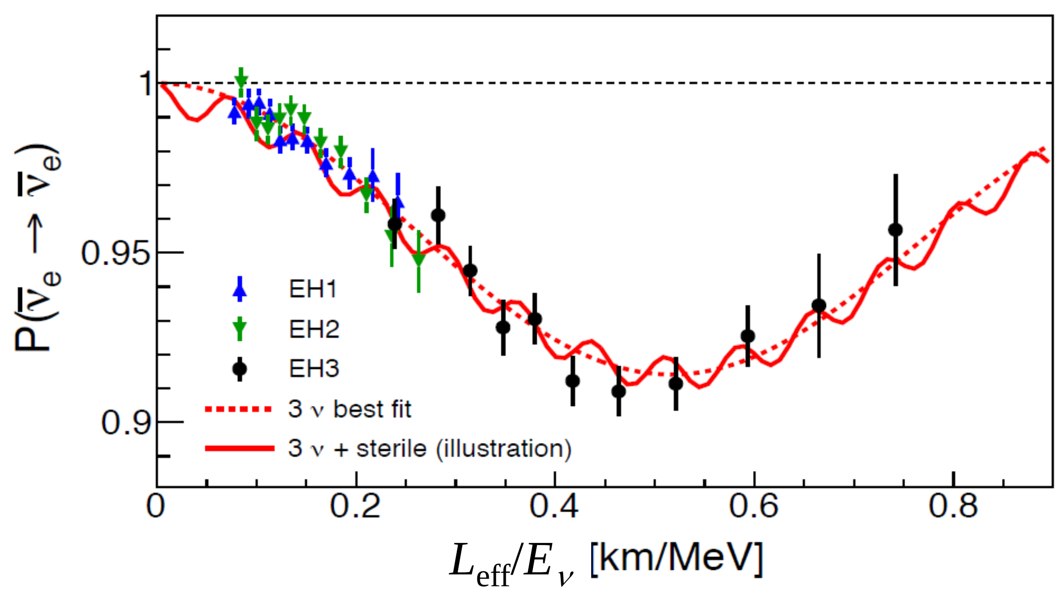
Simplest extension:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

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

$$P_{ee} \rightarrow P_{ee} - \sin^2 2\theta_{14} \sin^2(1.267 \Delta m^2_{41} L/E_\nu)$$





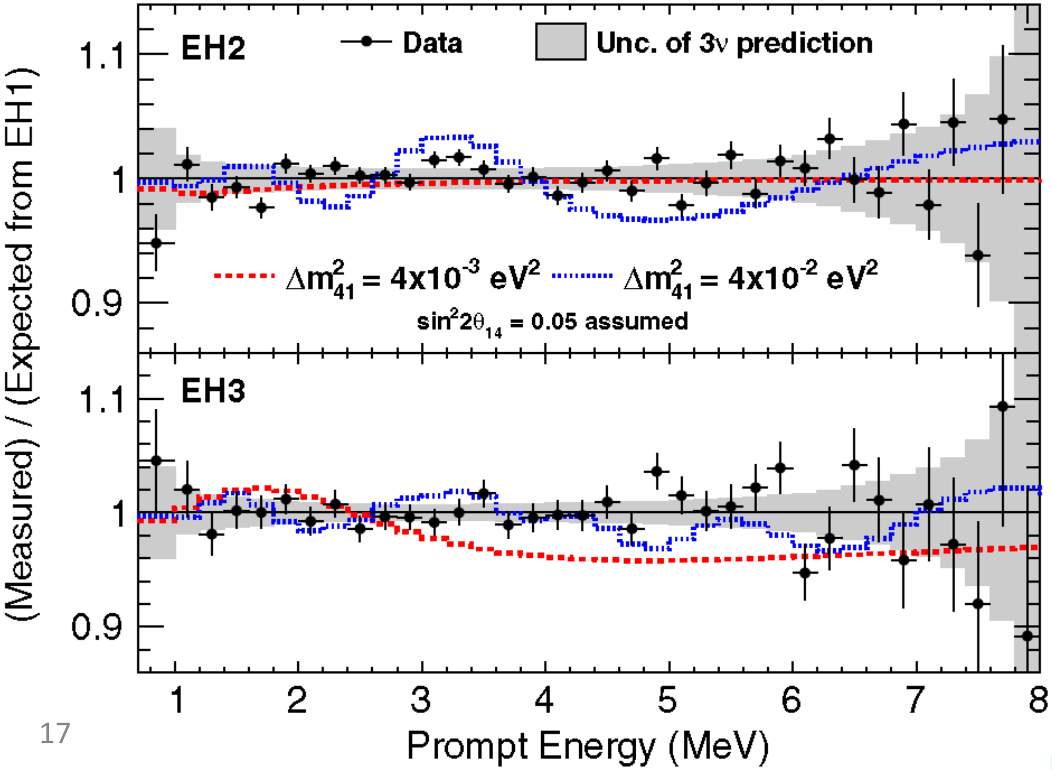
Search for a light sterile neutrino

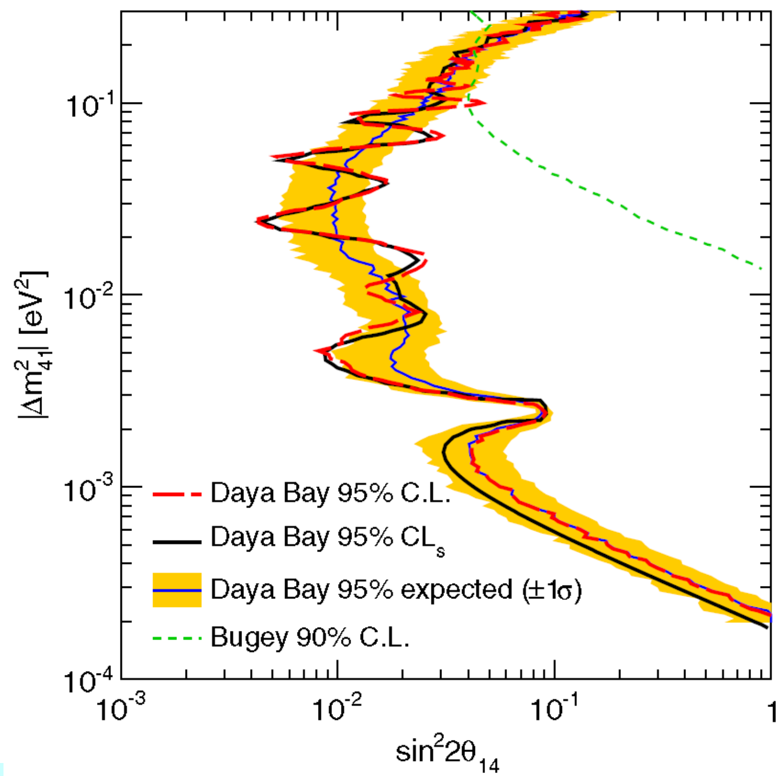
PRL **117**, 151802 (2016).

- Sterile neutrino: additional oscillation mode θ_{14}:

$$P_{ee} \rightarrow P_{ee} - \sin^2 2\theta_{14} \sin^2(1.267\Delta m^2_{41} L/E_\nu)$$

- 3 expt. halls → multiple baselines
  - Relative measurement at EH1 (~350m), EH2 (~500m), EH3 (~1600m)
  - Unique sensitivity at 10^{-3} eV^2 < Δm^2_{41} < 0.1 eV^2
- most stringent limit on $\sin^2 2\theta_{14}$ for 2x10^{-4} eV^2 < Δm^2_{41} < 0.2 eV^2

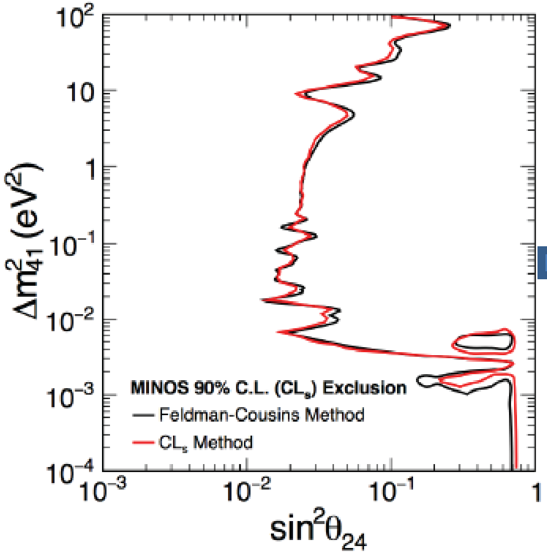




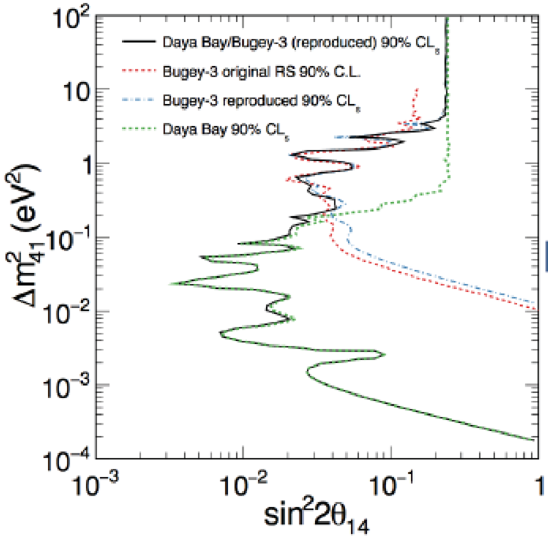
Daya Bay + Bugey-3 + MINOS

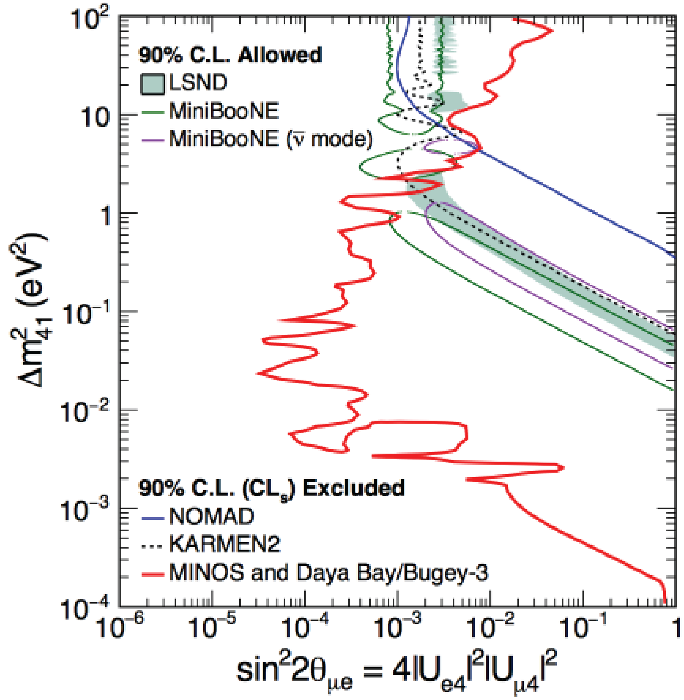
PRL 117, 151801 (2016)

MINOS



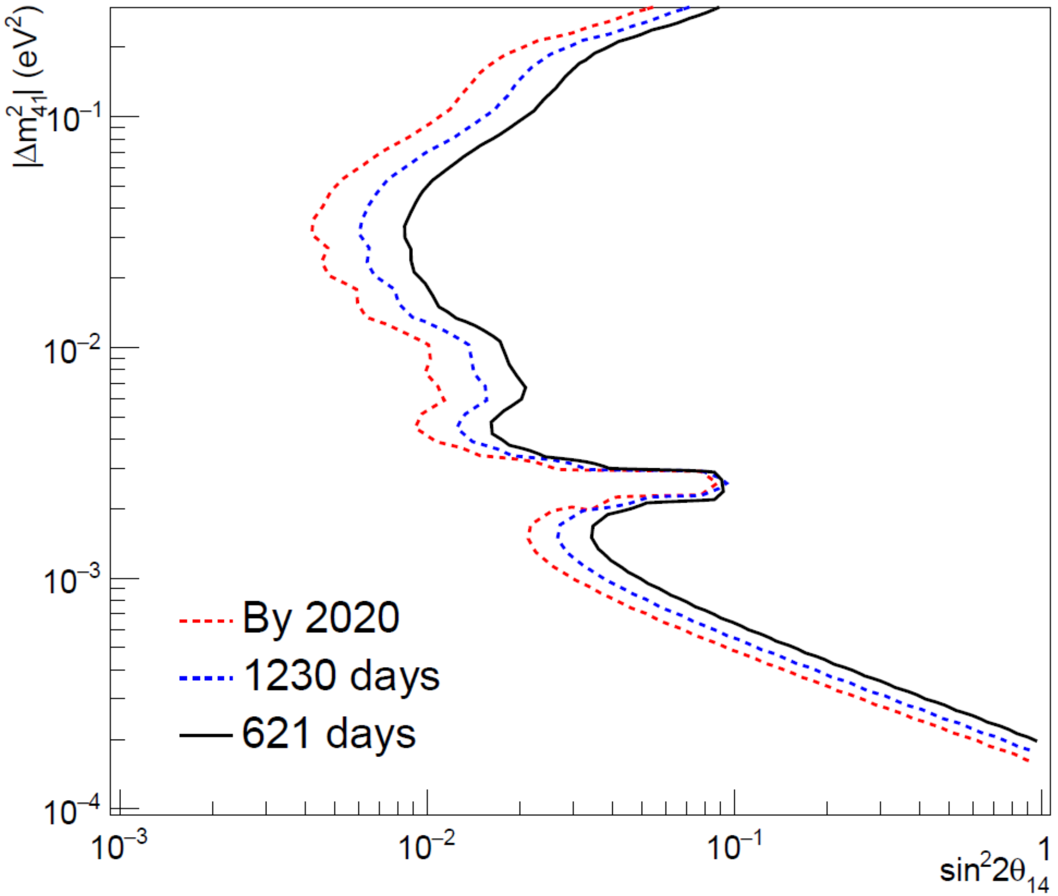
Daya Bay + Bugey-3





- Constrain $\nu_\mu \rightarrow \nu_e$ by combining constraints on $\sin^2 2\theta_{14}$ from $\overline{\nu}_e$ disappearance in Daya Bay and Bugey with constraints on $\sin^2 2\theta_{24}$ from $\overline{\nu}_\mu$ disappearance in MINOS
- Set constraints over 6 orders of magnitude in $\Delta m^2{}_{41}$.
- Exclude MiniBooNE and LSND parameters for $\Delta m^2{}_{41} < 0.8\ \mathrm{eV}^2$.

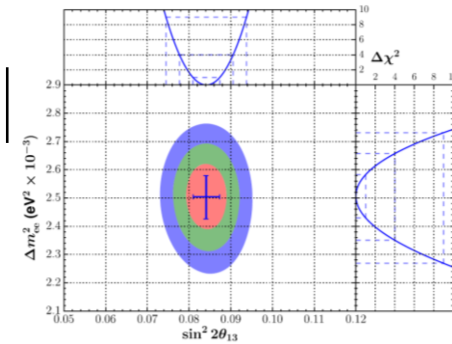
Better Limits to come

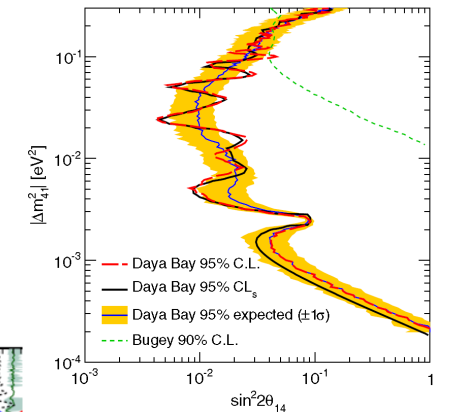


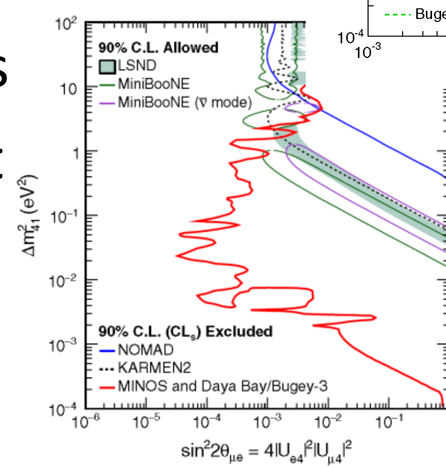
Expect ~2 improvement by 2020

Summary

- Daya Bay
  - Most precision measurement of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$
  - Multiple baselines: Unique sensitivity at $10^{-3}\ \mathrm{eV}^2 < \Delta m^2_{41} < 0.1\ \mathrm{eV}^2$
- Set **new limit** to light sterile neutrinos
  - Daya Bay alone: $2\mathrm{x}10^{-4}\ \mathrm{eV}^2 \leq |\Delta m^2_{41}| \leq 0.2\ \mathrm{eV}^2$
  - Combined DB/Bugey-3/MINOS: $|\Delta m^2_{41}| \leq 0.8\ \mathrm{eV}^2$ at 95% C. L.,
  - excluded LSND/MiniBooNE parameters
- Will continue till 2020, ~2x improvement







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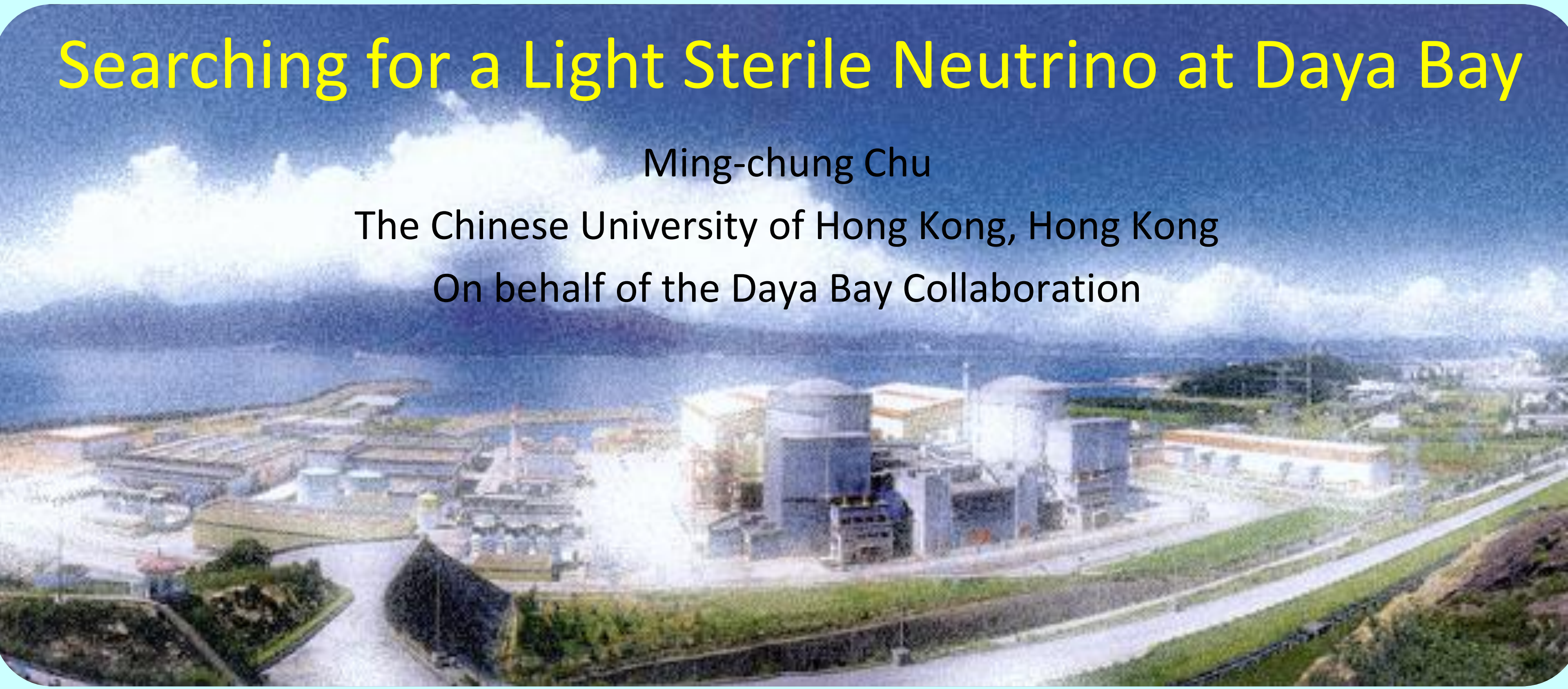

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