Neutrino Oscillation Studies with Reactors

Final Report

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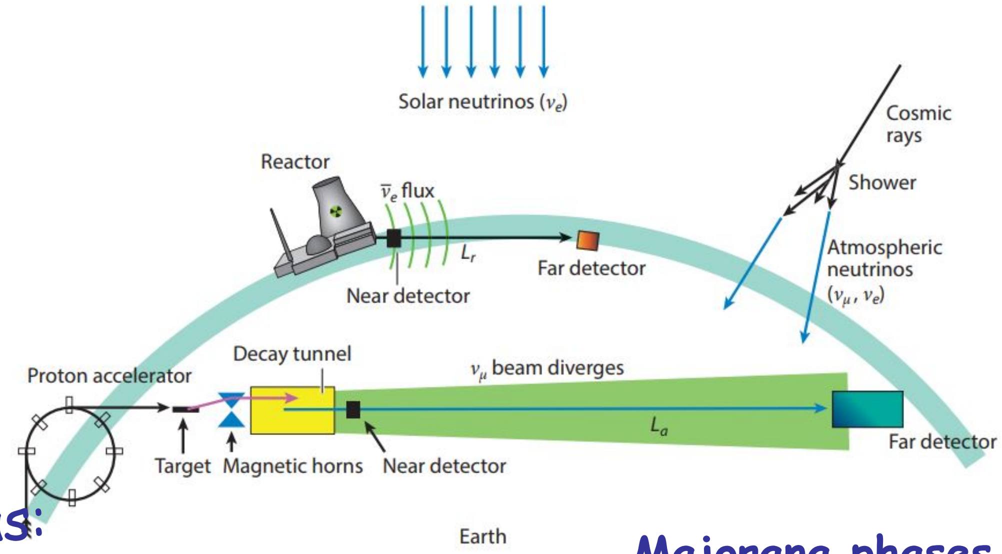
Neutrino Oscillation

- For three generations of massive neutrinos, the weak eigenstates are not the same as the mass eigenstates:

Pontecorvo-Maki-Nakagawa-Sakata Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



- Parametrize the PMNS matrix as:

Majorana phases

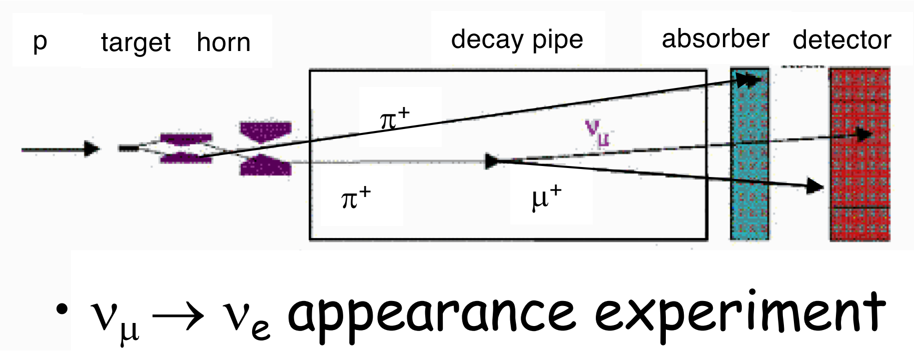
$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{12} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} e^{i\delta_1} & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

solar ν reactor $\bar{\nu}$	reactor $\bar{\nu}$ accelerator LBL ν	atmospheric ν accelerator LBL ν	neutrinoless double-β decay

Six parameters: 2 Δm^2, 3 angles, 1 phase + 2 Majorana phases

Determining θ_{13}

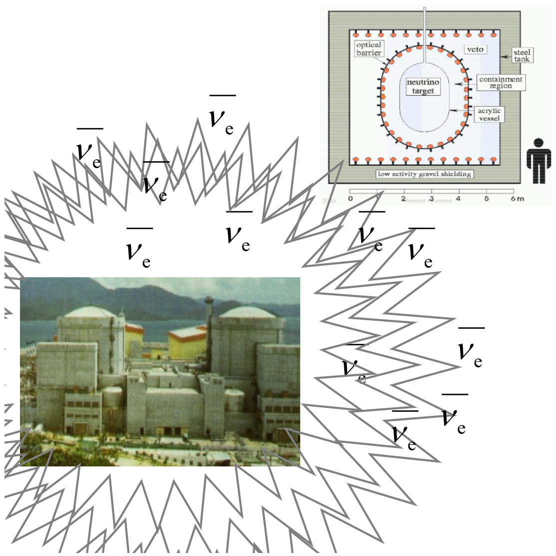
Method 1: Accelerator Experiments



$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) + \ldots$$

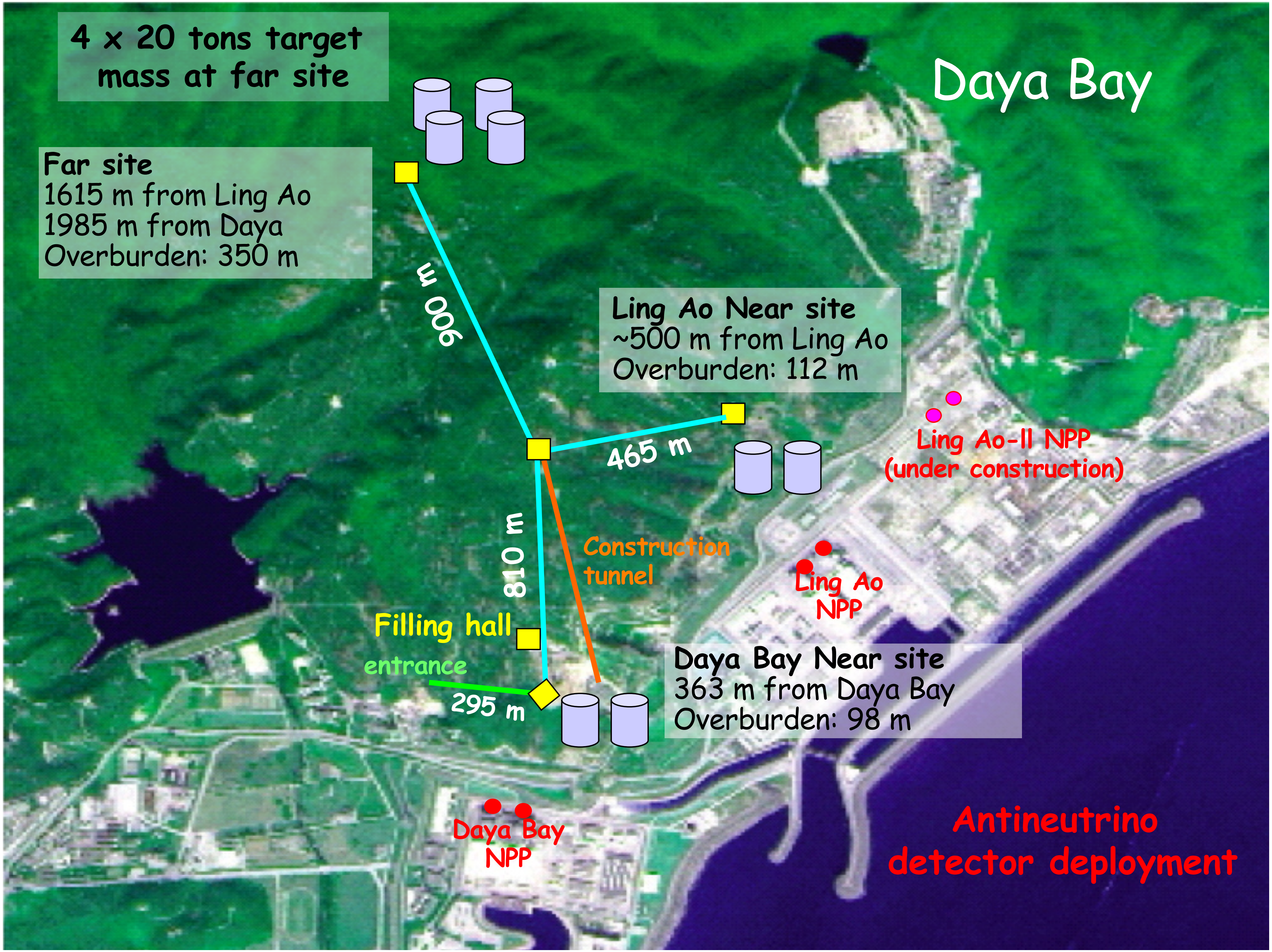
- $\nu_\mu \rightarrow \nu_e$ appearance experiment
- need other mixing parameters to extract θ_{13}
- baseline *O(100-1000 km)*, matter effects present
- expensive

Method 2: Reactor Experiments



$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) + \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

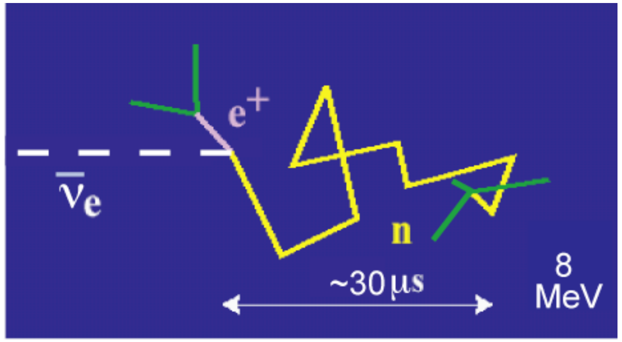
- $\bar{\nu}_e \rightarrow X$ disappearance experiment
- baseline *O(1 km)*, no matter effect, no ambiguity
- relatively cheap


4 x 20 tons target mass at far site
Daya Bay
Far site
1615 m from Ling Ao
1985 m from Daya
Overburden: 350 m
900 m
Ling Ao Near site
~500 m from Ling Ao
Overburden: 112 m
465 m
Ling Ao-II NPP
(under construction)
810 m
Construction tunnel
Ling Ao
NPP
Filling hall
entrance
295 m
Daya Bay Near site
363 m from Daya Bay
Overburden: 98 m
Daya Bay
NPP
Antineutrino
detector deployment

Detecting $\bar{\nu}$ in liquid scintillator: Inverse β Decay

The reaction is the inverse β-decay in 0.1% Gd-doped liquid scintillator:

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

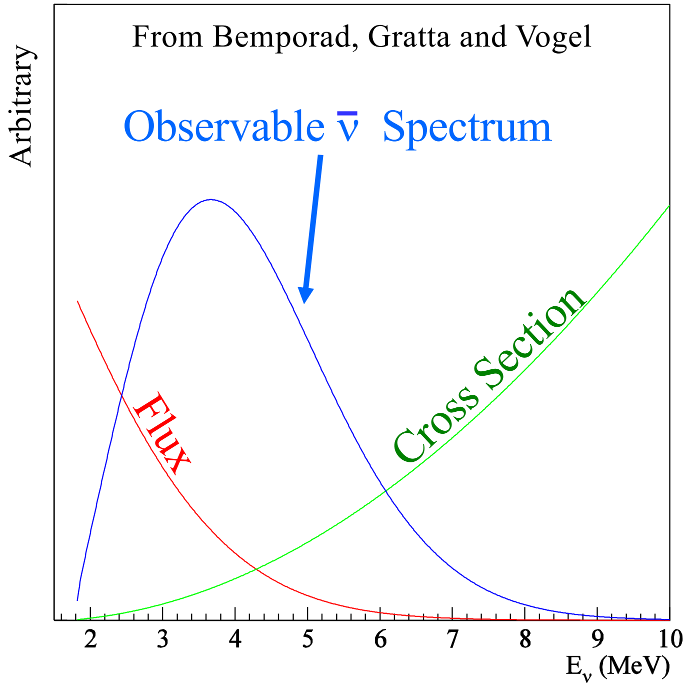


0.3b → + p → D + γ(2.2 MeV) (τ~180μs)

50,000b → + Gd → Gd*

→ Gd + γ's(8 MeV) (τ~30μs)

- Time- and energy-tagged signal is a good tool to suppress background events.
  - e+ annihilate, fast pulse
  - n slowed by p or Gd, slow pulse

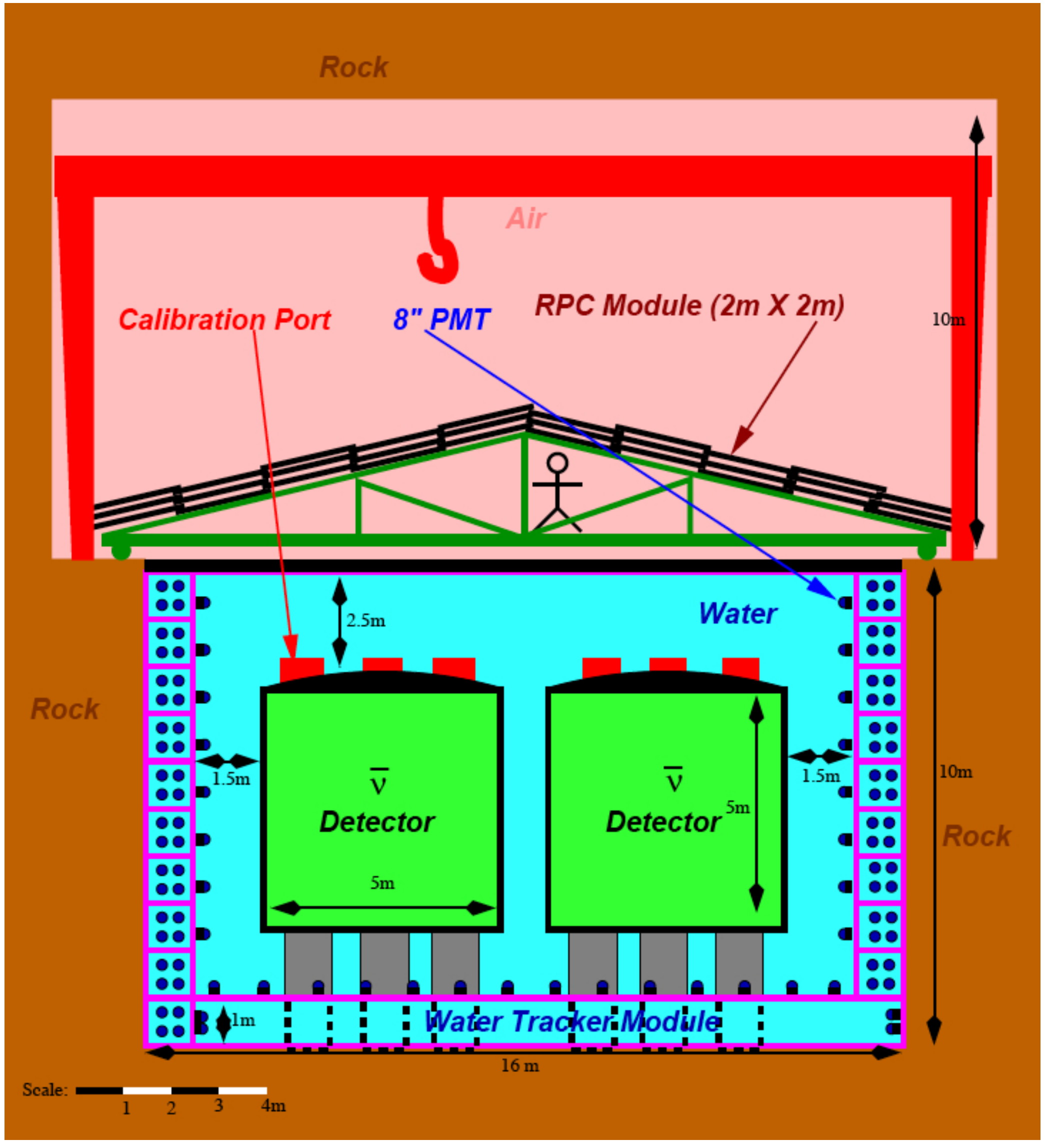


- Energy of $\bar{\nu}_e$ is given by:

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

10-40 keV

Shield and veto system (hall)

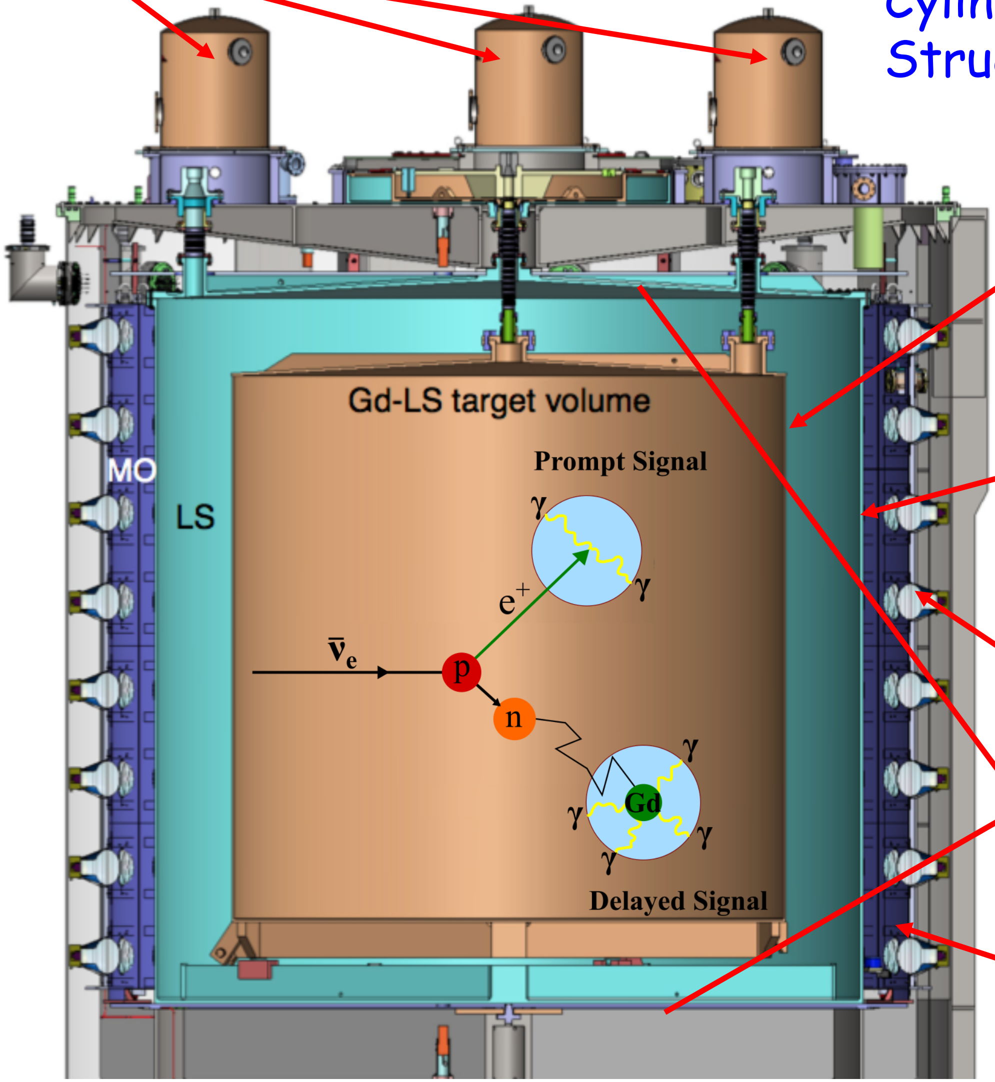


- Surround detectors with at least 2.5m of active water shield
- Water shield also serves as a Cherenkov counter for tagging muons
- Augmented with a muon tracker: RPCs
- Combined efficiency of Cherenkov and tracker > 99.5% with error measured to better than 0.25%

Center Detector

Automated Calibration Units
(A Led, A Ge-68, A Am-241 and Co-60
Combined)

Cylindrical(5m diam., 5m height) three-Zone
Structure:



Inner Acrylic Vessel
- I. Target: 0.1% Gd-loaded liquid scintillator(LS)

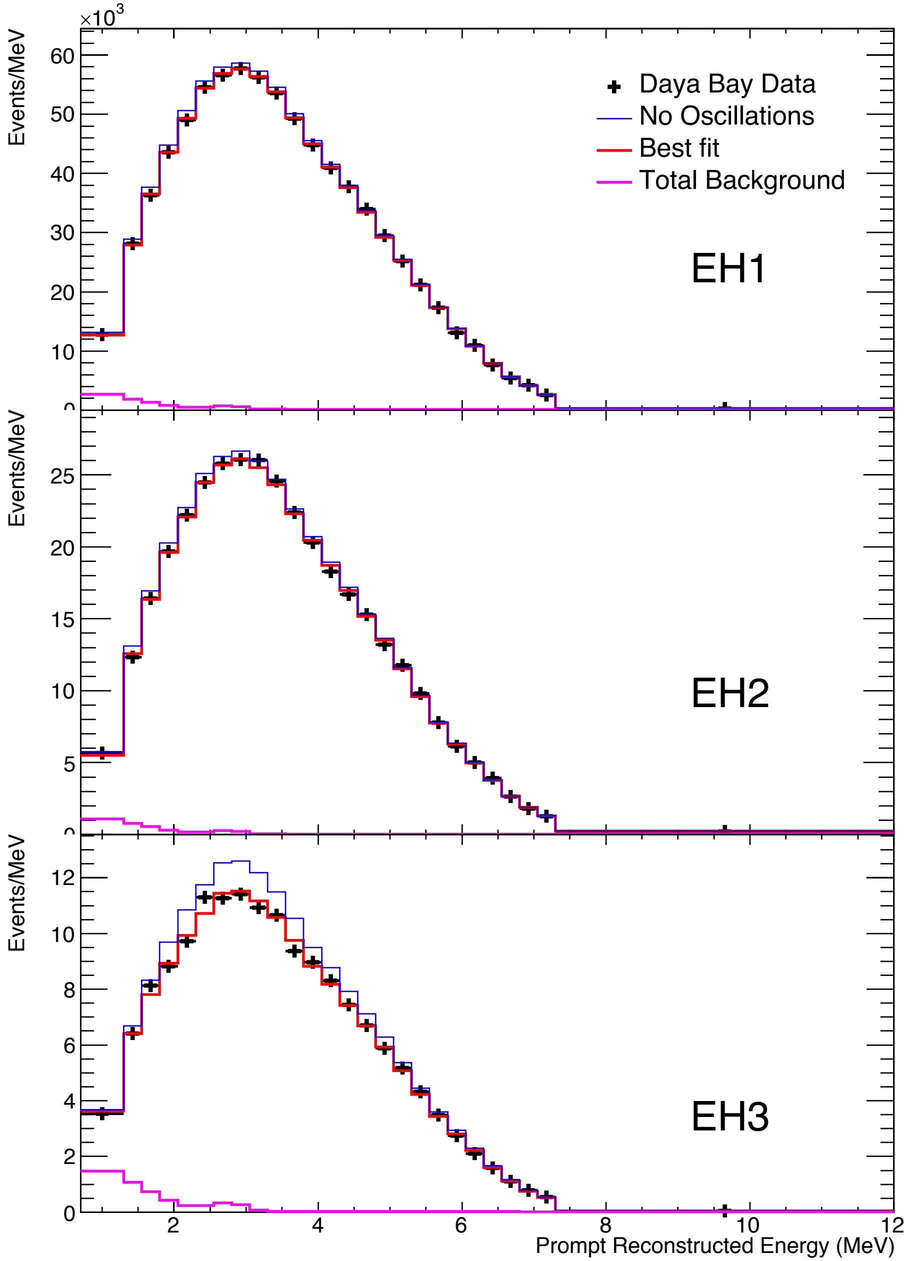
Outer Acrylic Vessel
- II. γ-catcher: liquid scintillator(LS

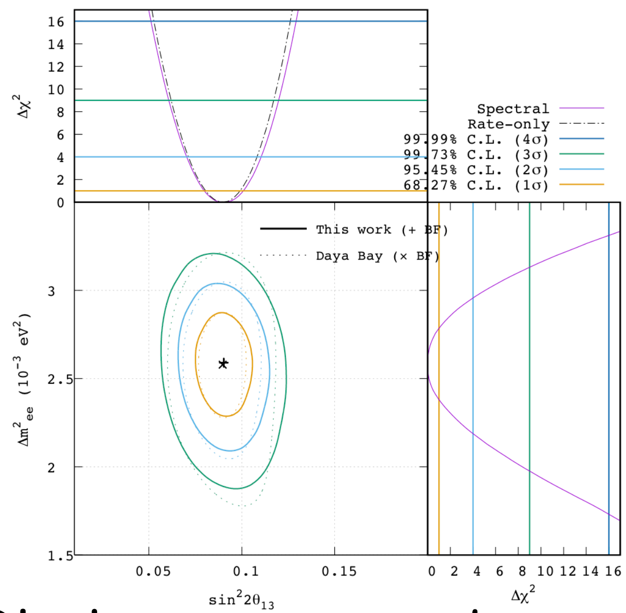
PMTs

Reflector: redirect scintillation light towards the PMTs

- III. Buffer: Mineral Oil

Results from Daya bay



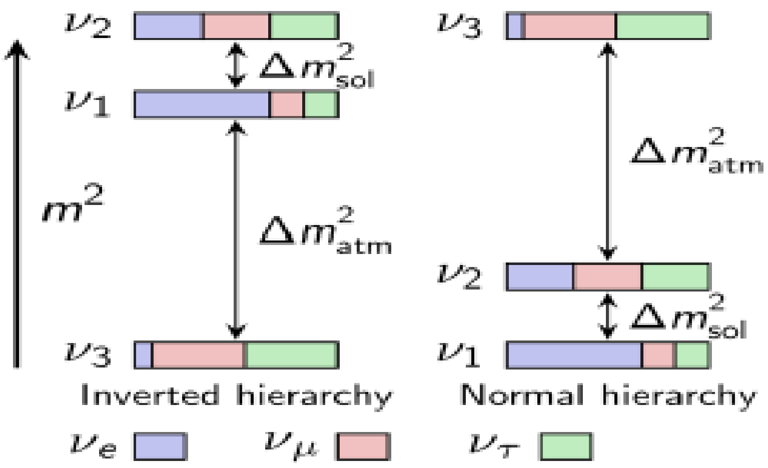


- Black crosses are data
- blue (red) line shows the MC expected no-oscillation (best fit) spectra.
- EH1 and EH2 are near site
- EH3 is far site

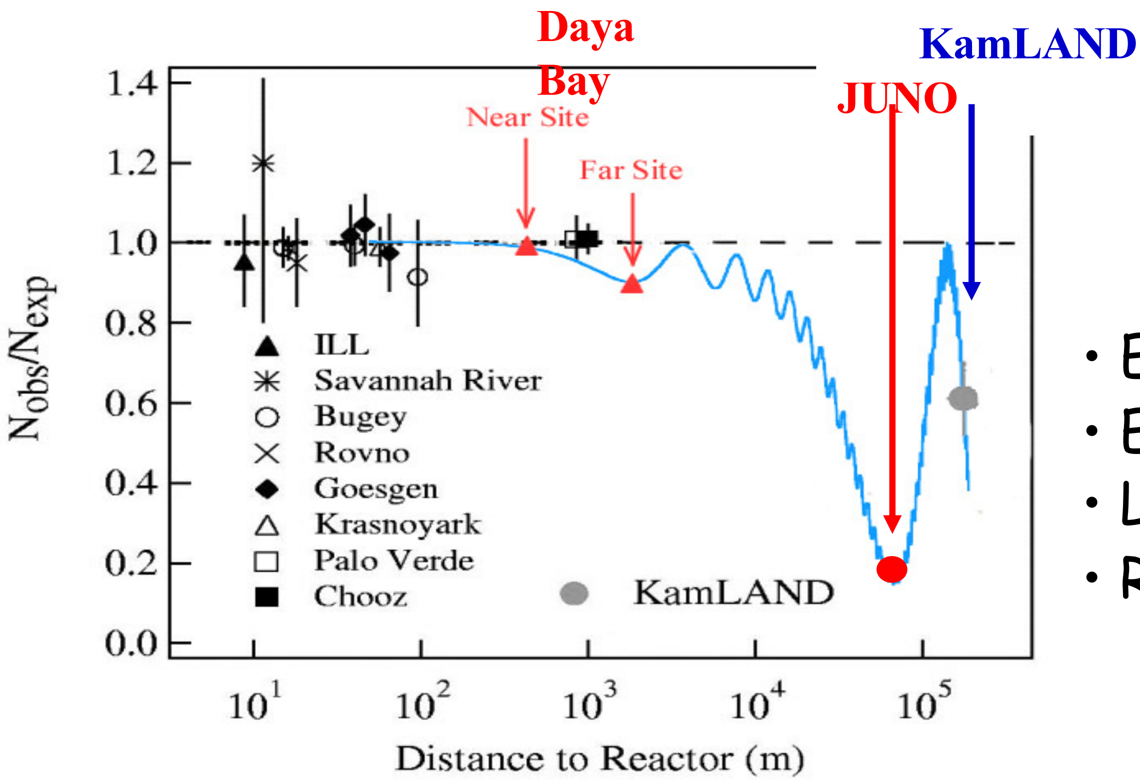
$Sin^2 2\theta_{13} = 0.091^{+0.009}_{-0.012}$

$\Delta m^2_{ee} = (2.60^{0.18}_{-0.22}) \times 10^{-3} eV\text{^}2$

Neutrino Mass Hierarchy



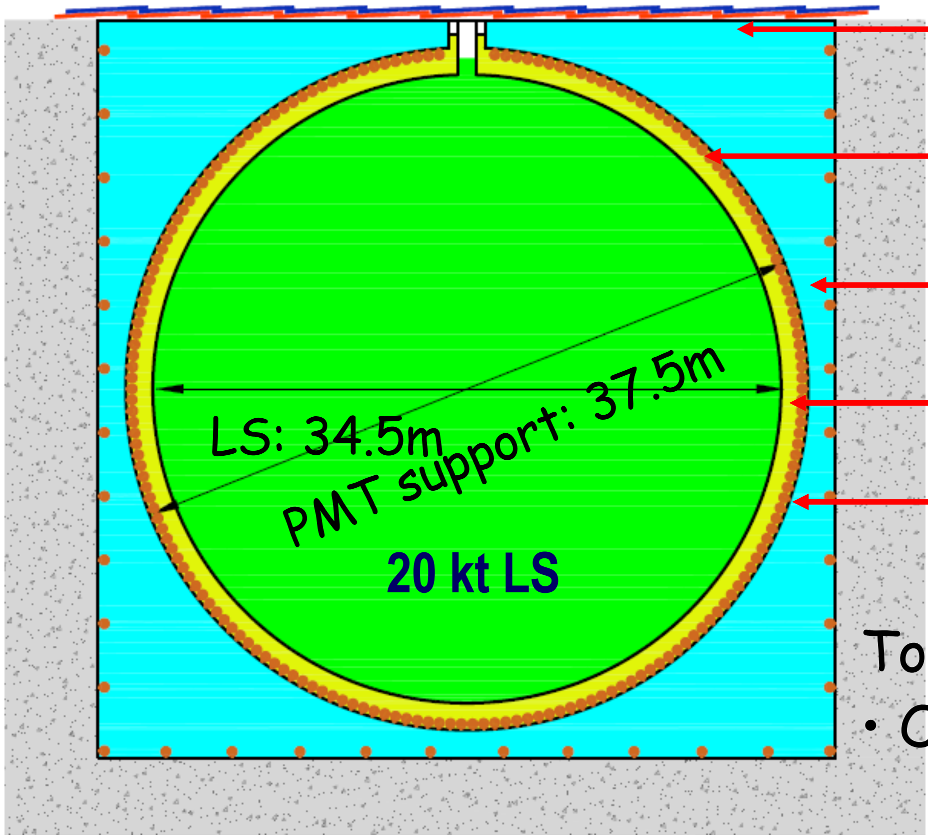
- KamLAND (long-baseline) measures the solar sector parameters
- Short-baseline reactor neutrino experiments designed to utilize the oscillation of atmospheric scale



Both scales can be studied by observing the spectrum of neutrino flux

- Energy resolution: ~3%/sqrt(E)
- Energy scale uncertainty: < 1%
- Large amount of statistics
- Reactor distribution: < ~0.5km

Large LS detector of JUNO



Muon detector

Stainless steel tank or truss

Water Cherenkov veto and radioacti

Mineral oil

~15000 PMTs coverage: ~80%

To reach ~3% energy resolution,

- Obtain as many photons as possible
  - high light yield scintillator
  - high photocathode converge
  - high detection efficiency PMTs
- Keep the detector as uniform as possible
  - a spherical detector
- Keep the noise as low as possible
  - clean materials and quiet PMTS

Summary

- The Daya Bay experiment delivers the most precise theta13 measurement
- The value of theta13 has enabled the possibility of resolving neutrino mass hierarchy in medium-baseline reactor neutrino experiments
- A medium-baseline reactor neutrino project in China, JUNO is being constructed
- JUNO has great potential in resolving neutrino mass hierarchy, guarantees precision measurements, and offers other rich physics

Thank you!