Measuring $\sin^2 2\theta_{13}$ at the Daya Bay Reactor Neutrino Experiment

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Outline

- Neutrino results which drive our plans
- The physics motivation for measuring θ_{13} precisely
- How Daya Bay will measure or place strict limits on the value of θ_{13}

Neutrino Oscillations

Postulated to be massless, but
Flavor eigenstates:

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i} \, |\nu_i\rangle \, , for \; \alpha = e, \mu, \tau$$

where $|\nu_i\rangle$ mass eigenstates. Time evolution:

$$|\nu_\alpha(t)\rangle = \sum_{i=1}^{3} U_{\alpha i} \exp\left(-i\hat{H}t\right) |\nu_i\rangle$$

Survival Probability:

$$P_{\nu_\alpha \rightarrow \, \nu_\alpha} = \left| \, \langle \nu_\alpha | \nu_\alpha(t) \rangle \, \right|^2$$

Two-flavor oscillations in vacuum

Two-Flavor Case:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

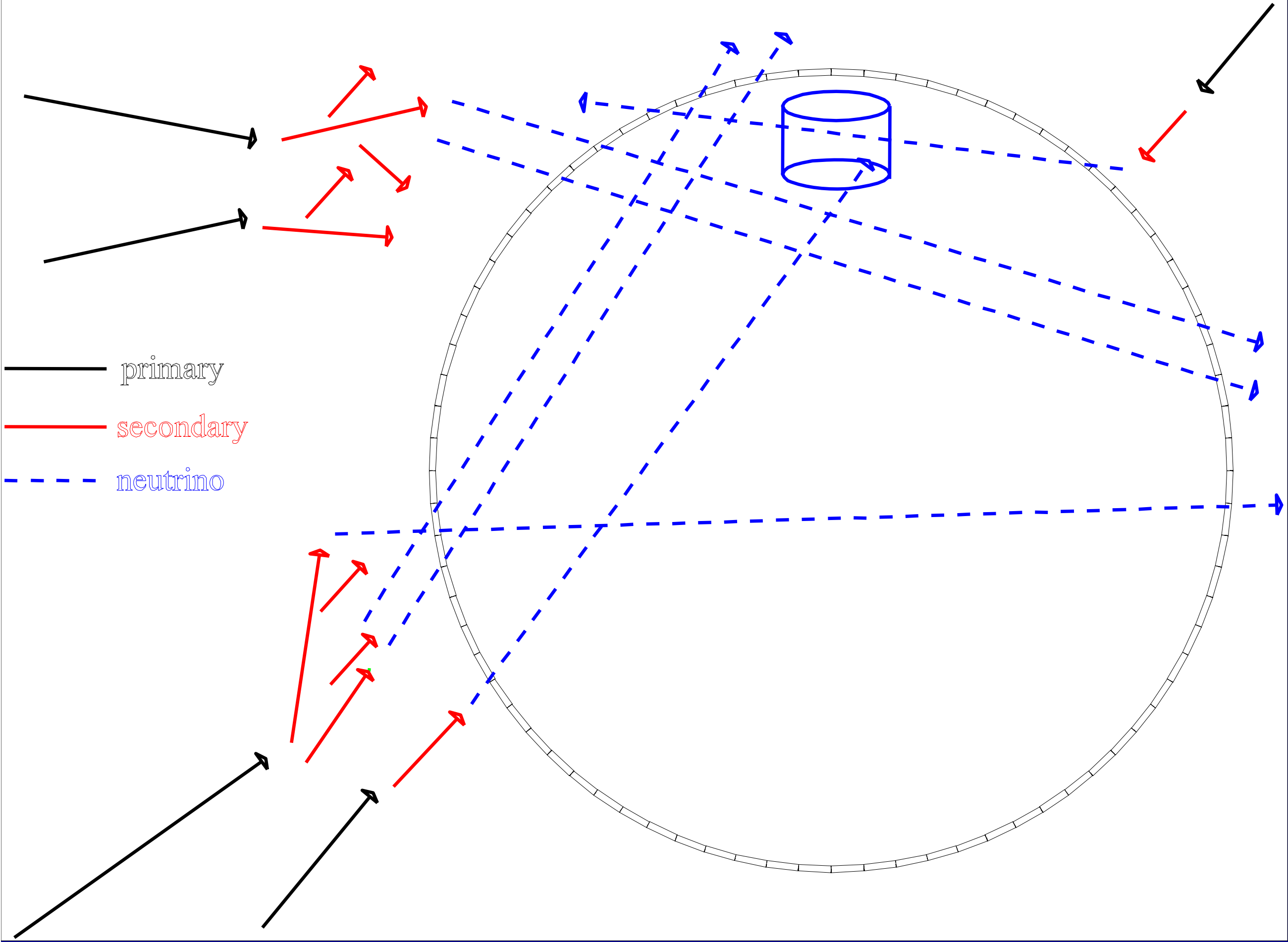
$$P_{\nu_e \rightarrow \nu_e} = |\langle \nu_e | \nu_e(t) \rangle|^2 = 1 - \sin^2 2\theta \sin^2 (1.27 \Delta m^2 \frac{L}{E})$$

$$\Delta m^2 = m_2^2 - m_1^2 \; (eV^2)$$

L distance from production (km) or (m)

E energy of neutrino (GeV) or (MeV)

Atmospheric Neutrino Production



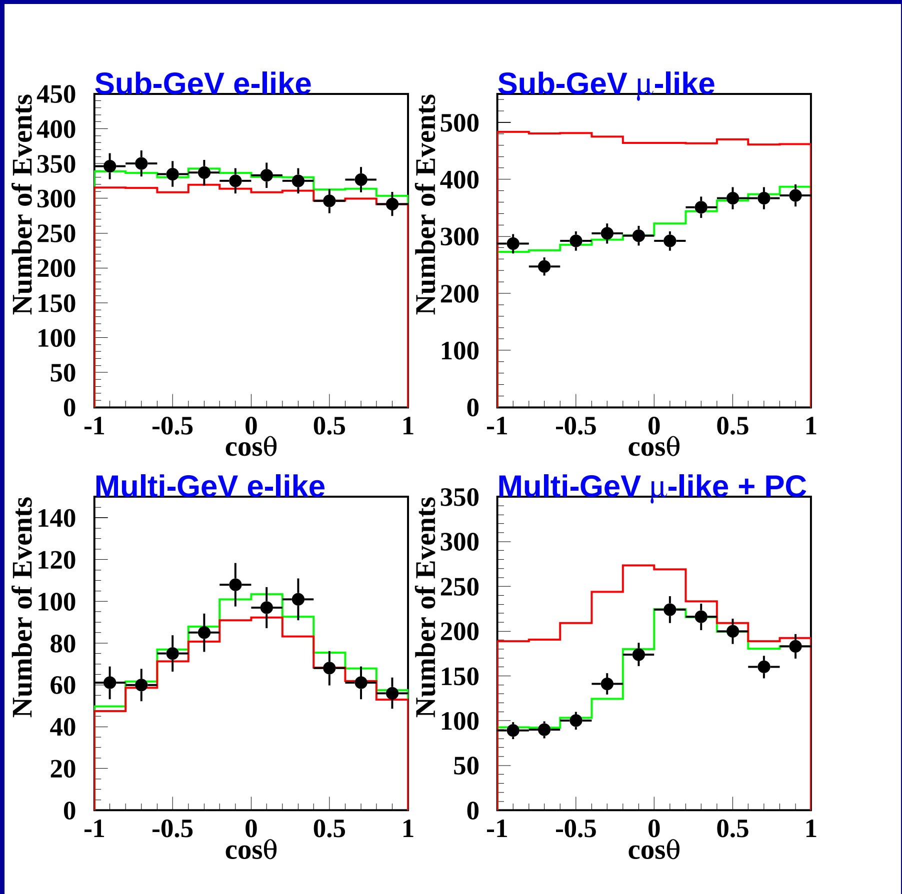
$$p + N \to N' + \pi^{\pm} + \cdots$$

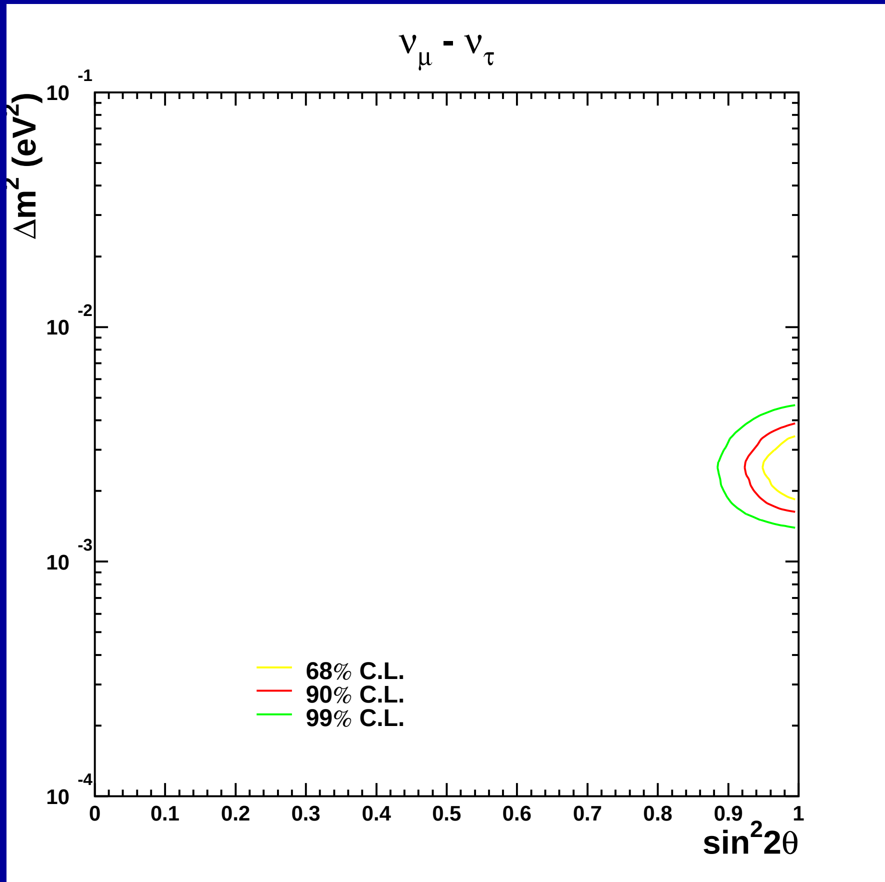
$$\pi^{+} \to \mu^{+} + \nu_{\mu}$$

$$\mu^{+} \to e^{+} + \bar{\nu}_{\mu} + \nu_{e}$$

$$\frac{\nu_{\mu} + \bar{\nu}_{\mu}}{\nu_{e} + \bar{\nu}_{e}} \approx 2$$

1998 SK Atmospheric Neutrino Results

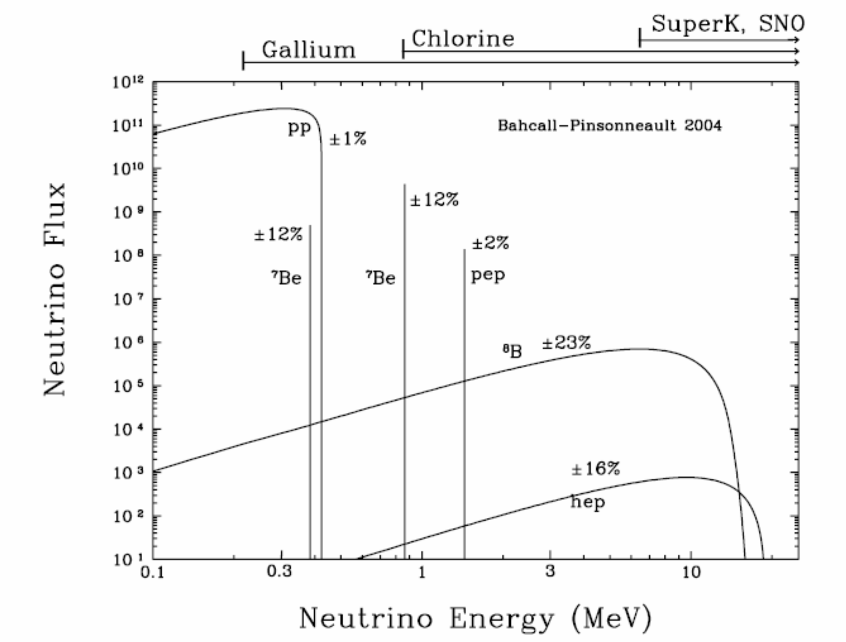


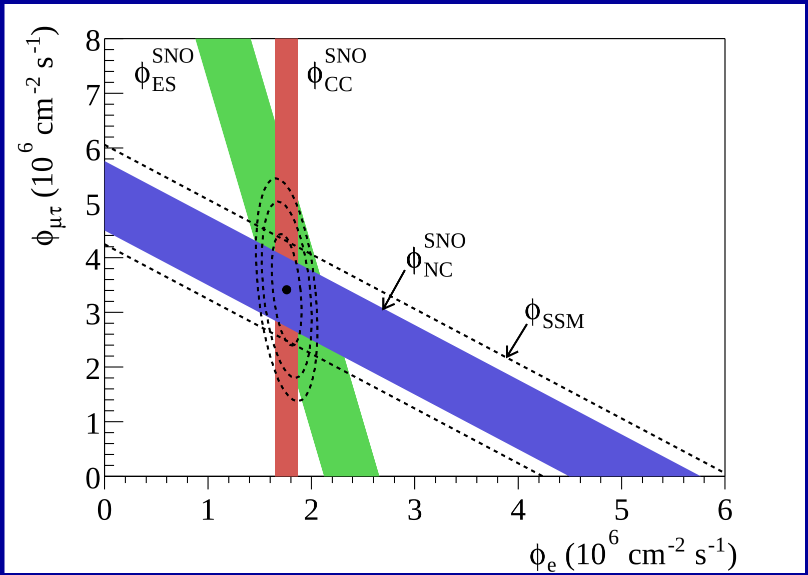


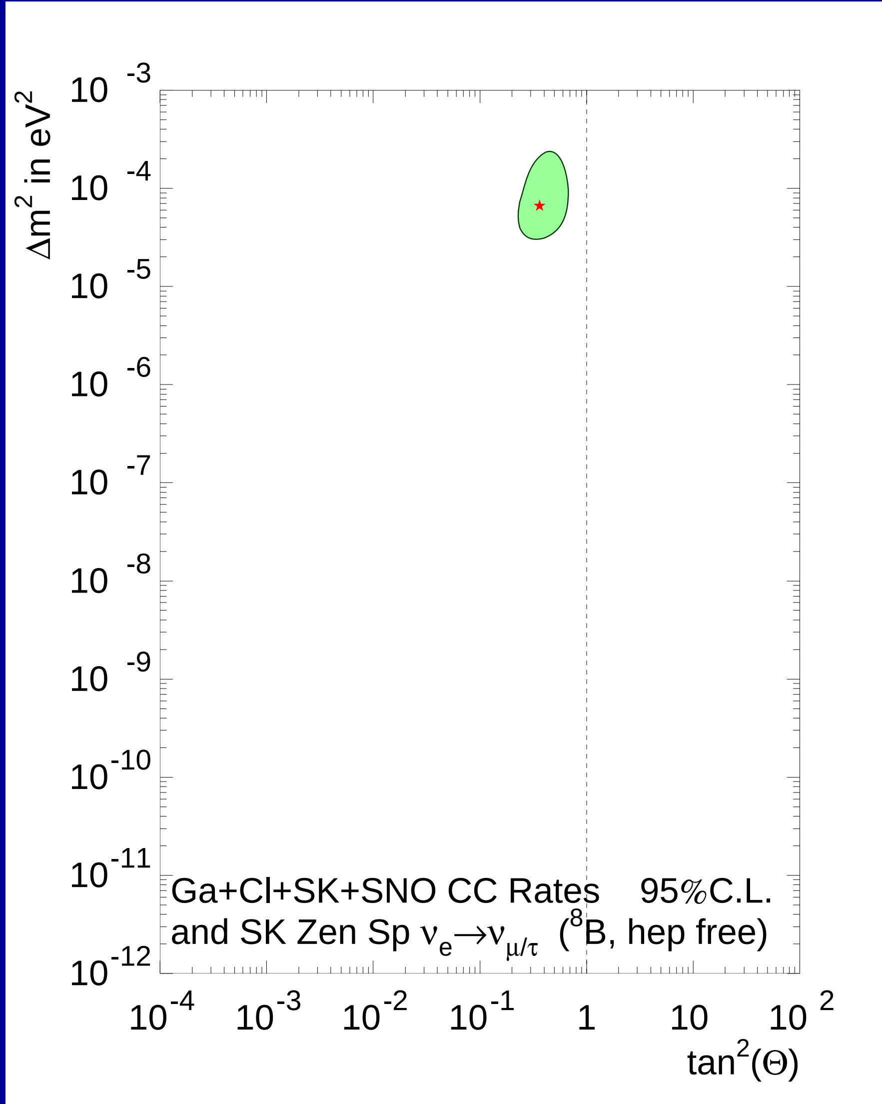
$$\Delta m^2 = 2.5 \times 10^{-3} eV^2, \sin^2 2\theta = 1.0$$

Confirmed by K2K and MINOS (see talk tomorrow)

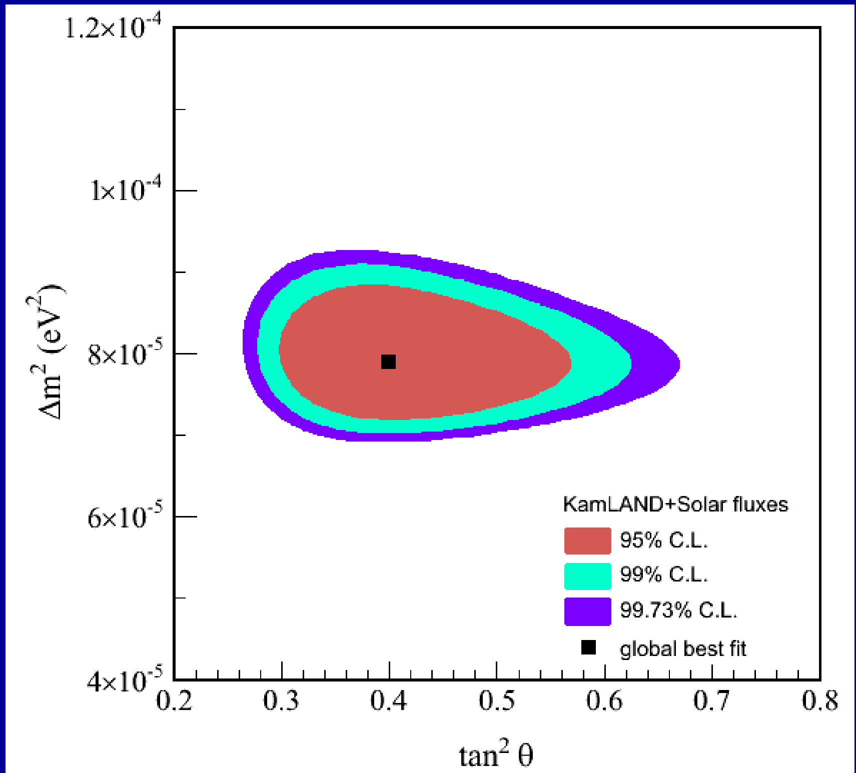
Solar Neutrinos (ν_e)

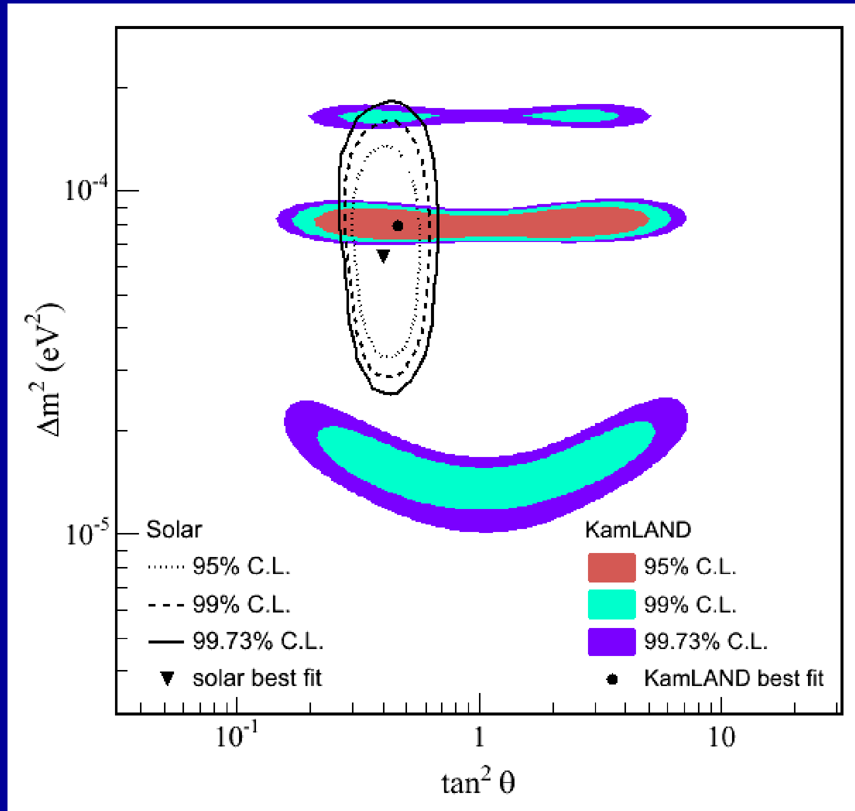






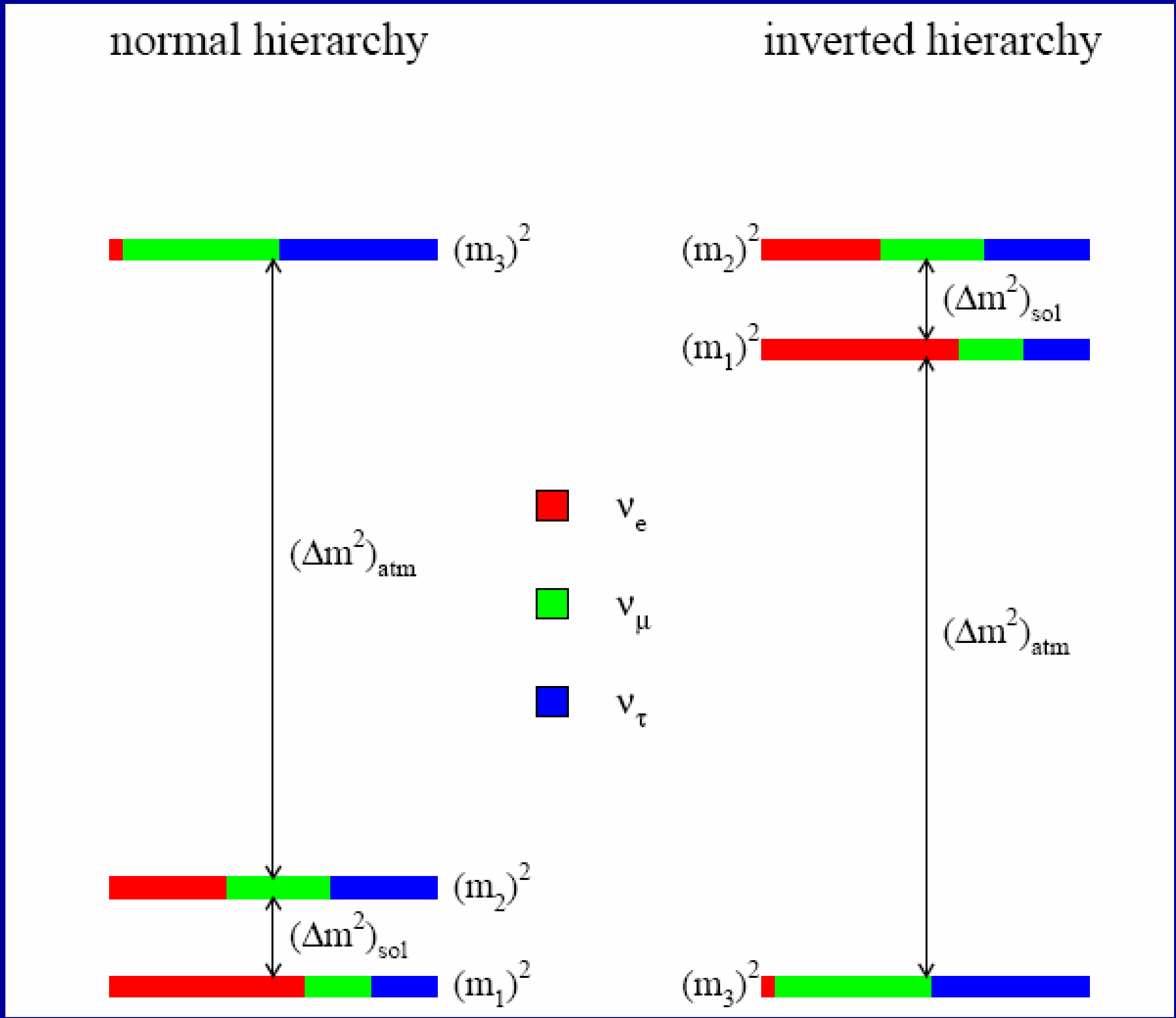
Reactor Neutrinos ($\bar{\nu}_e$)





- Best combined fit, $\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5}$ eV^2
- $\tan^2\theta = 0.40^{+0.10}_{-0.07}$
- KamLAND measurement consistent with solar

Neutrino Mass Hierarchy



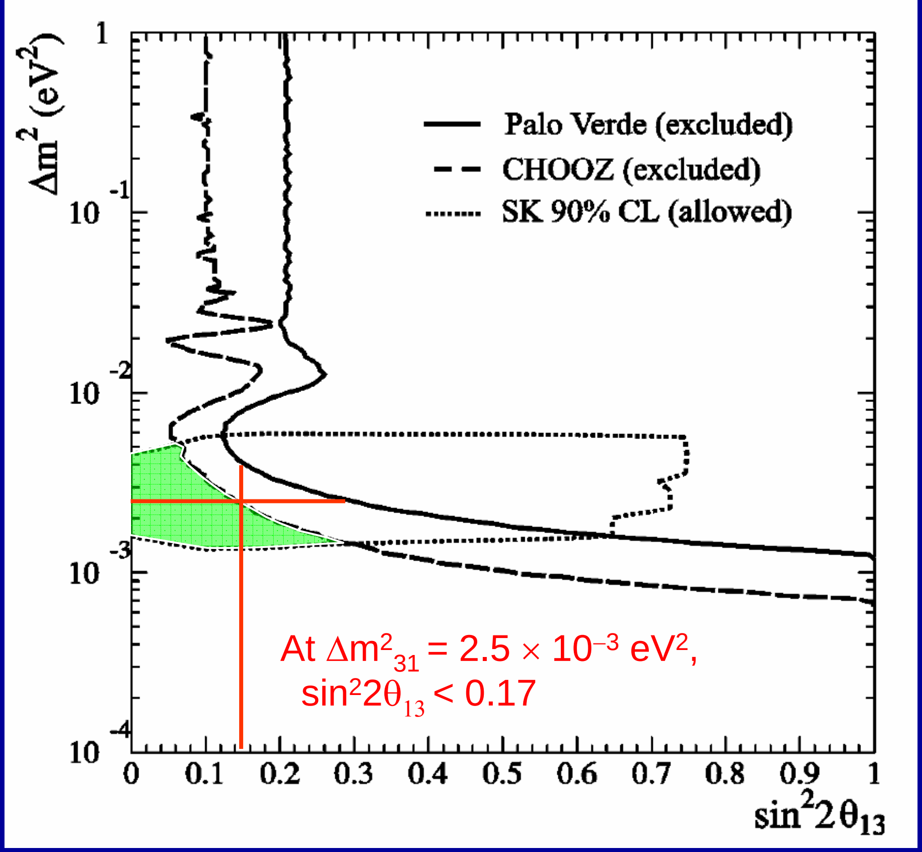
From: **hep-ph/0411274**

Mixing Matrix and Oscillation Probabilities

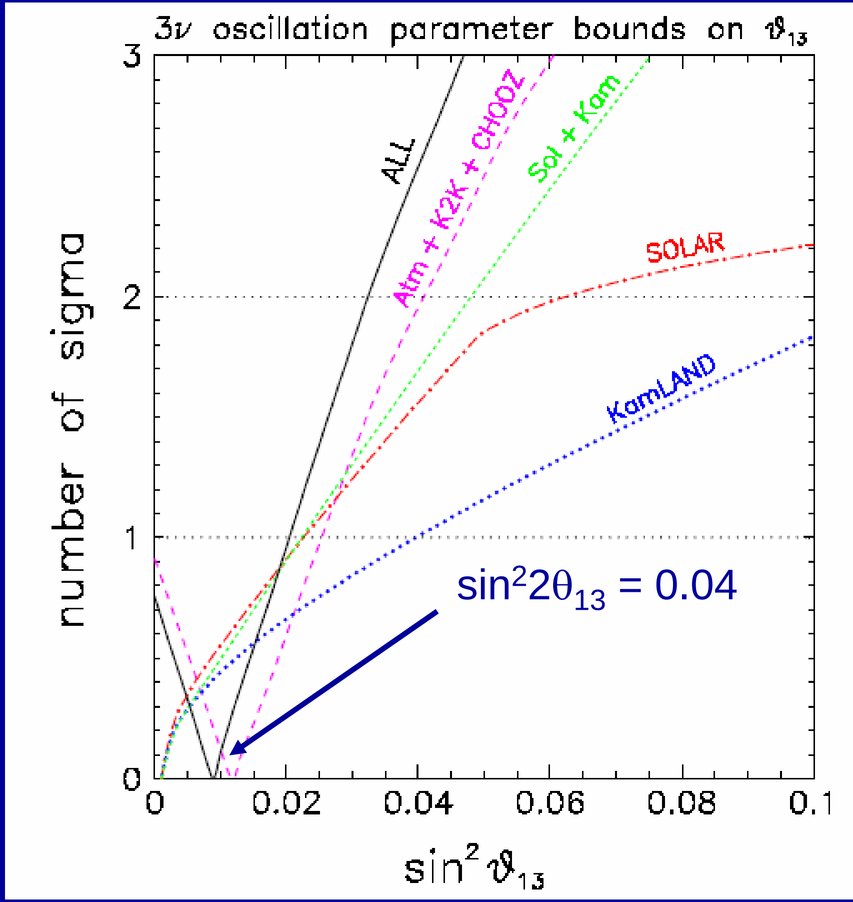
$$U = \begin{array}{c} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \end{array}$$

- The ``solar'' mixing angle is associated with θ_{12}
- The ``atmospheric'' mixing angle is associated with θ_{23}
- There are now only three remaining unmeasured quantities relevant to neutrino mixing
  - the mass hierarchy, sign of Δm_{31}^2
  - the CP violating phase , δ
  - the mixing angle, θ_{13}
- Our chances of measuring δ depend on the size of θ_{13}

Current Constraints on θ_{13}



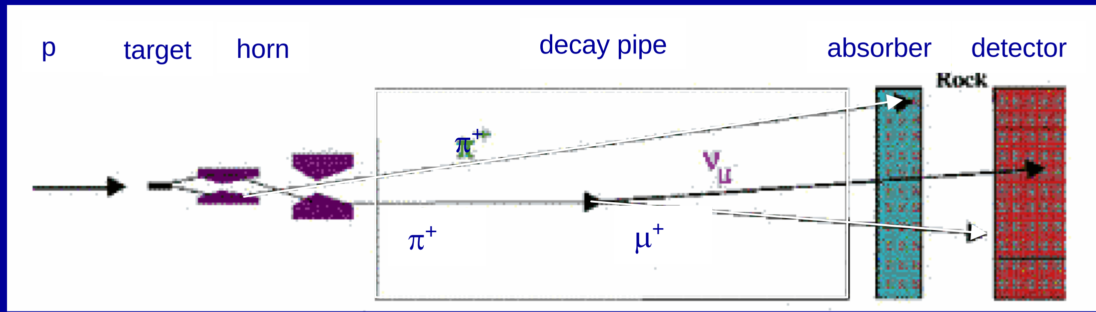
Direct Search



Global Fit by Fogli etal., hep-ph/0506083

How do we measure $\sin^2 2\theta_{13}$ to the 0.01 level?

Accelerator measurement of θ_{13}



- Very intense beams of ν_μ to measure
  - ν_μ disappearance ($\sin^2 2\theta_{23}$)
  - ν_e appearance ($\sin^2 2\theta_{13}$)
- Tend to be statistics limited, rather than systematics limited
- Can potentially measure CP violation and the mass hierarchy
- Suffer from degeneracies which make determining θ_{13} difficult

Accelerator measurement of θ_{13}

$$P_{\mu e} \simeq \left| \sin 2\theta_{13} \, \sin\theta_{23} \sin\Delta_{31} e^{i(\Delta_{32} \pm \delta_{\rm CP})} + \cos\theta_{13} \, \cos\theta_{23} \sin 2\theta_{12} \sin\Delta_{21} \right|^2$$

$$\begin{aligned} &\approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\Delta_{31} \\ &\mp\alpha \, \sin 2\theta_{13} \sin\delta_{\rm CP} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \, \Delta_{31} \sin^2\Delta_{31} \\ &+\alpha \, \sin 2\theta_{13} \, \cos\delta_{\rm CP} \, \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \, \Delta_{31} \cos\Delta_{31} \sin\Delta_{31} \\ &+\alpha^2 \, \cos^2\theta_{23} \sin^2 2\theta_{12} \, \Delta_{31}^2 . \end{aligned} \quad (7)$$

$$\Delta_{ij} \equiv \Delta m^2_{ij} L/(4E) \qquad \alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$$

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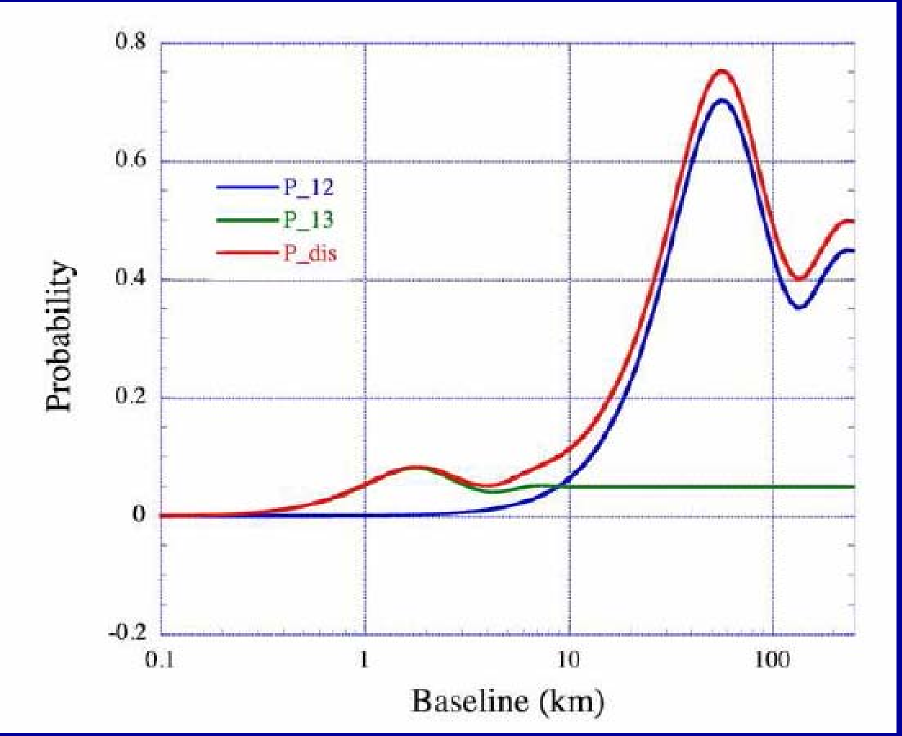
- Because they measure $\sin^2 2\theta_{23}$ by ν_μ disappearance, there is a quadrant ambiguity when they try to measure ($\sin^2 2\theta_{13}$)
- CP violation and matter effects can create more degeneracies, though for some part of parameter space two long baseline experiments at different distance could resolve them (T2K, NOVA complementarity)

Reactor method

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

- Look for disappearance of ν_e at a short distance from a nuclear reactor
- High flux – systematics limited
- Matter effects negligible
- Two-flavor-like neutrino oscillations



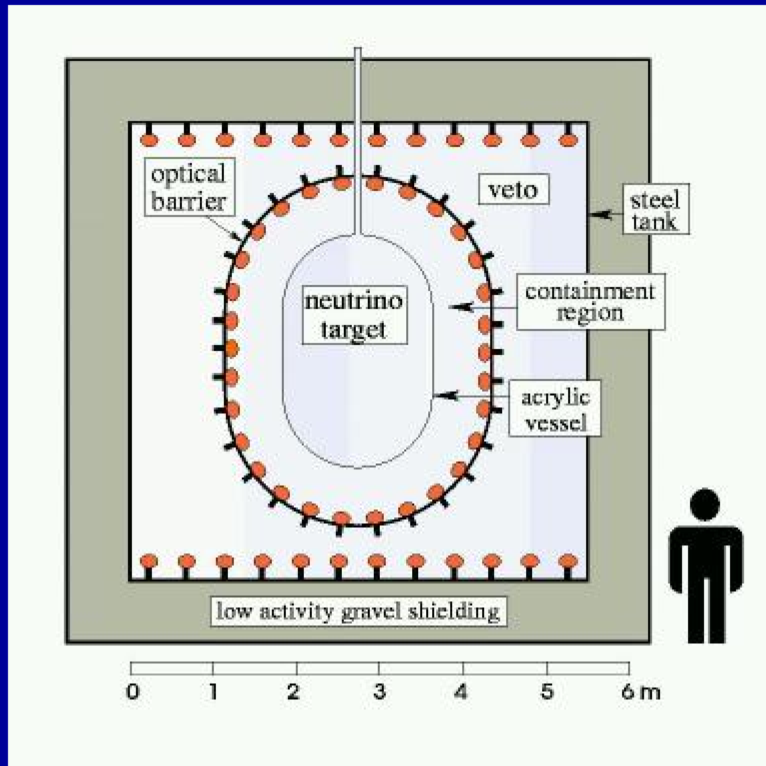
Reactor and accelerator measurements are complementary!

Previous reactor experiments

- CHOZ and Palo Verde were both designed to search for oscillations in the range of the atmospheric Δm^2
- Most future designs are based on CHOOZ – monolithic, Gd-loaded liquid scintillator

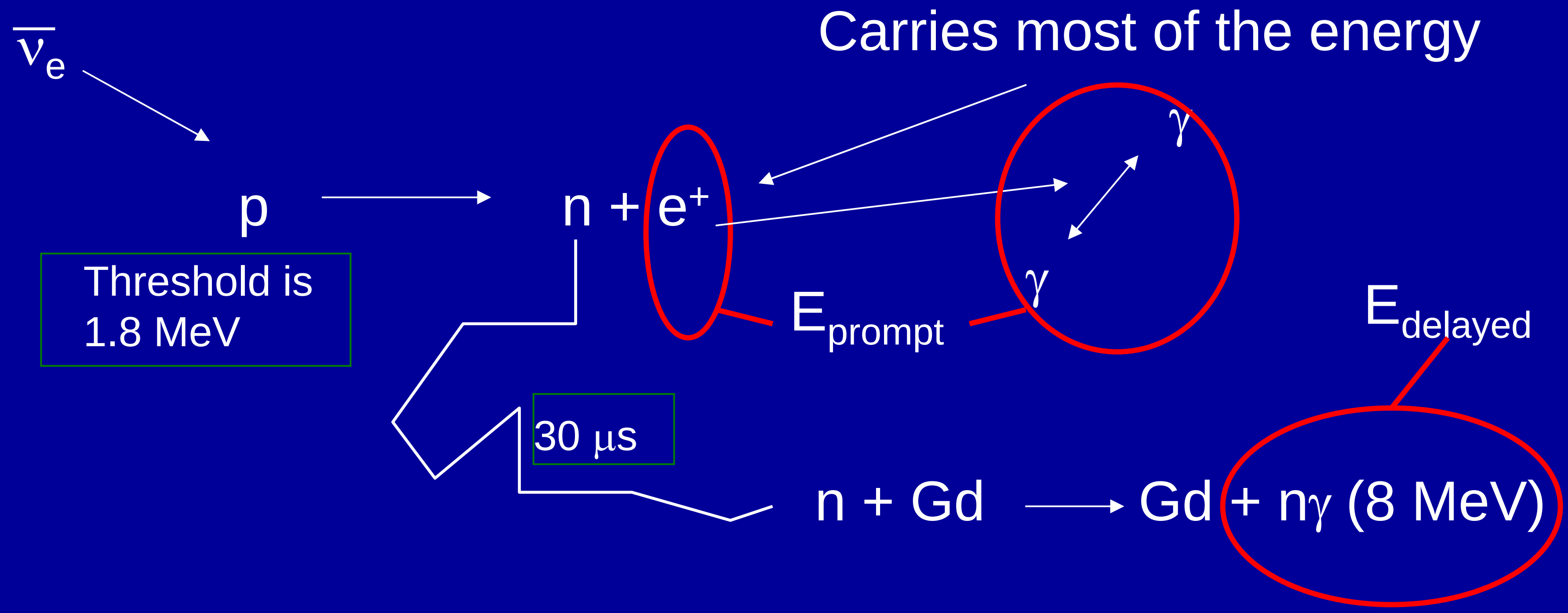
Reactor Cores

1.0 km



300 m.w.e. depth

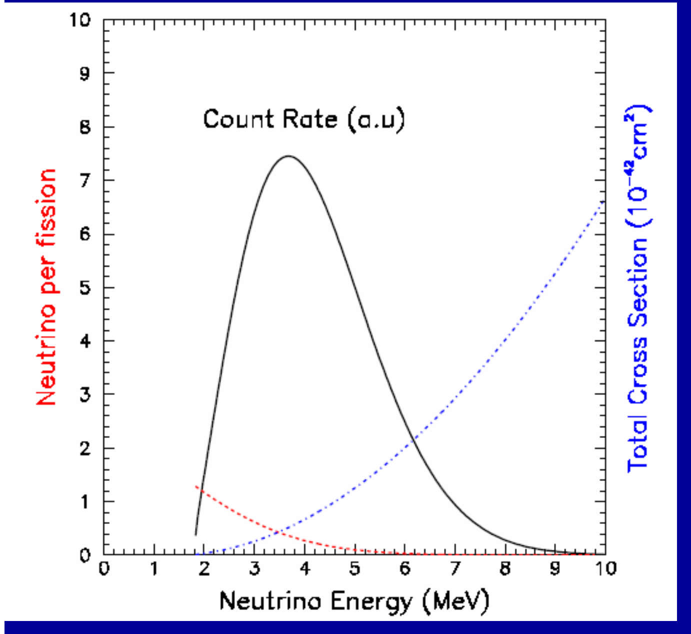
Gd-loaded $\bar{\nu}_e$ detection method

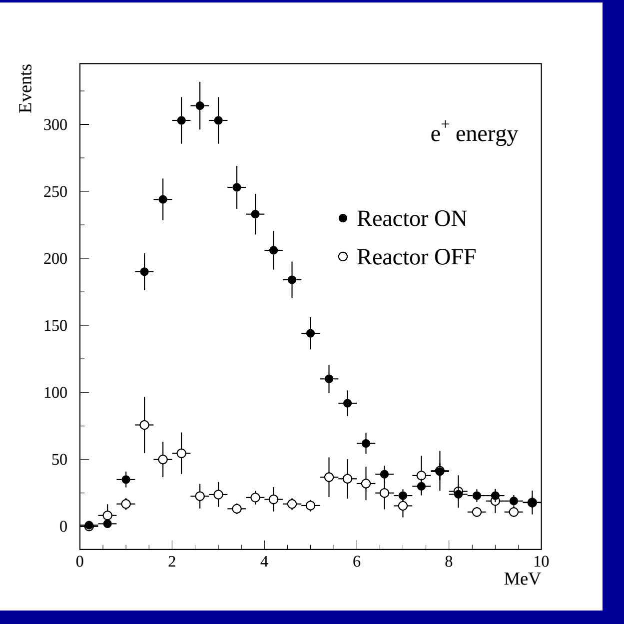


$$E_{prompt} = E_\nu - 0.8 \text{ MeV}$$

Inverse β–decay - Delayed Coincidence

What we learn from CHOOZ





- CHOOZ could use reactor-off time to evaluate backgrounds – for future projects this unlikely
- The backgrounds are rather large
- Both CHOOZ and Palo Verde observed yellowing of their Gd-loaded scintillator

Systematic Uncertainties

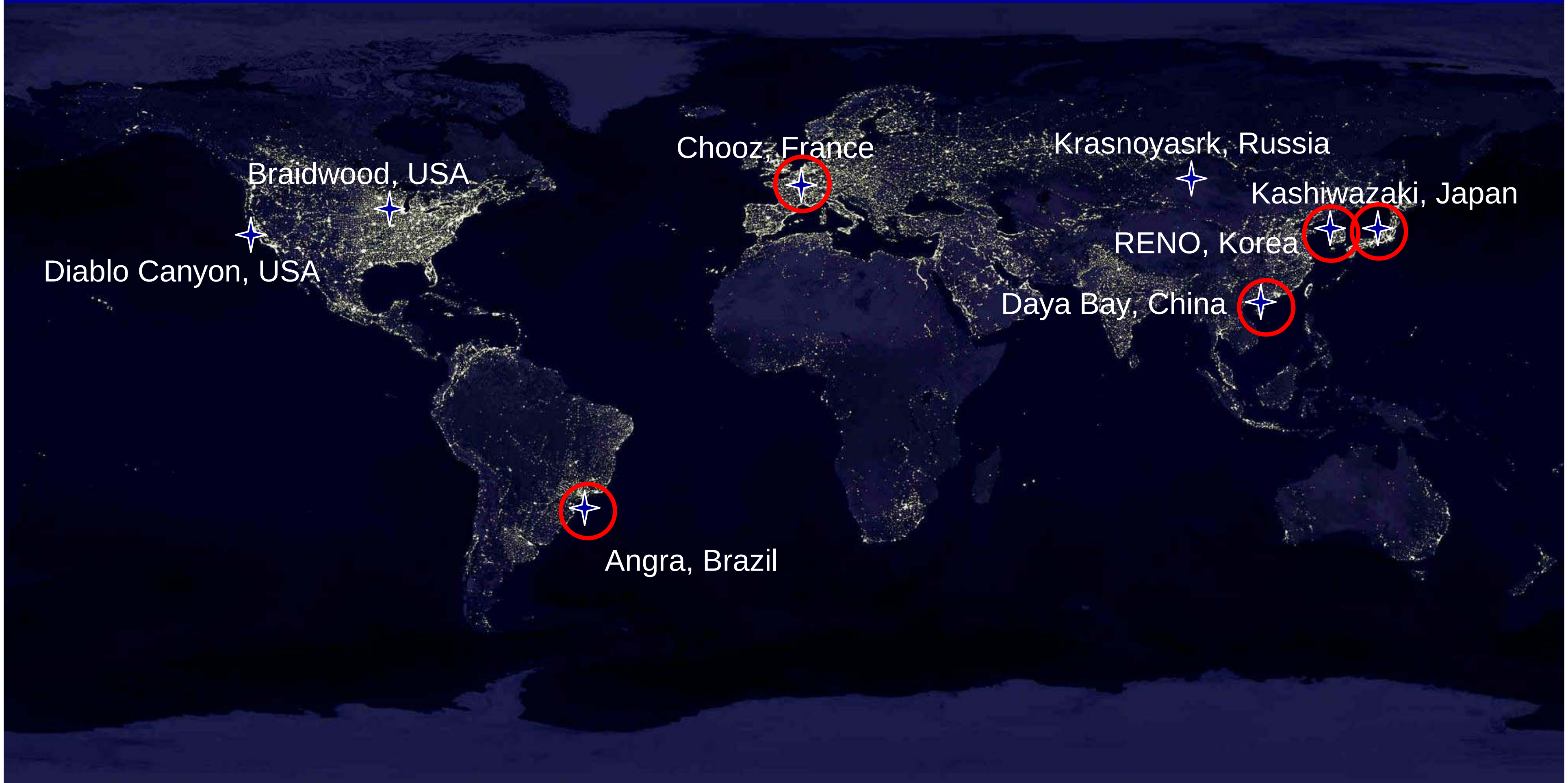
reaction cross section	1.9
number of protons	0.8
detection efficiency	1.5
reactor power	0.7
energy released per fission	0.6
combined	2.7

For future projects, keep ***detector-related*** and ***reactor-related*** uncertainties low

General reactor experimental strategy

- The current best limit is from the CHOOZ reactor neutrino experiment ($\sin^2 2\theta_{13}$<0.17 at $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 at 90 % C.L.
- To get to the level of $\sin^2 2\theta_{13}$~0.01 we must:
  - Increase the target mass and use a higher power reactor complex to reduce the statistical uncertainty
  - Use a near-far detector approach to minimize systematic uncertainties due to the neutrino flux
  - Use identical detectors to minimize detector-related systematic uncertainties in a relative measurement
  - Increase the distance to the far detector
  - Go deeper to reduce cosmogenic backgrounds
  - Build a comprehensive muon detector to measure the cosmogenic backgrounds

World of Proposed Reactor Neutrino Experiments



The Daya Bay Collaboration

Collaboration Institutes: Asia (17), US (14), Europe (3)
~130 collaborators

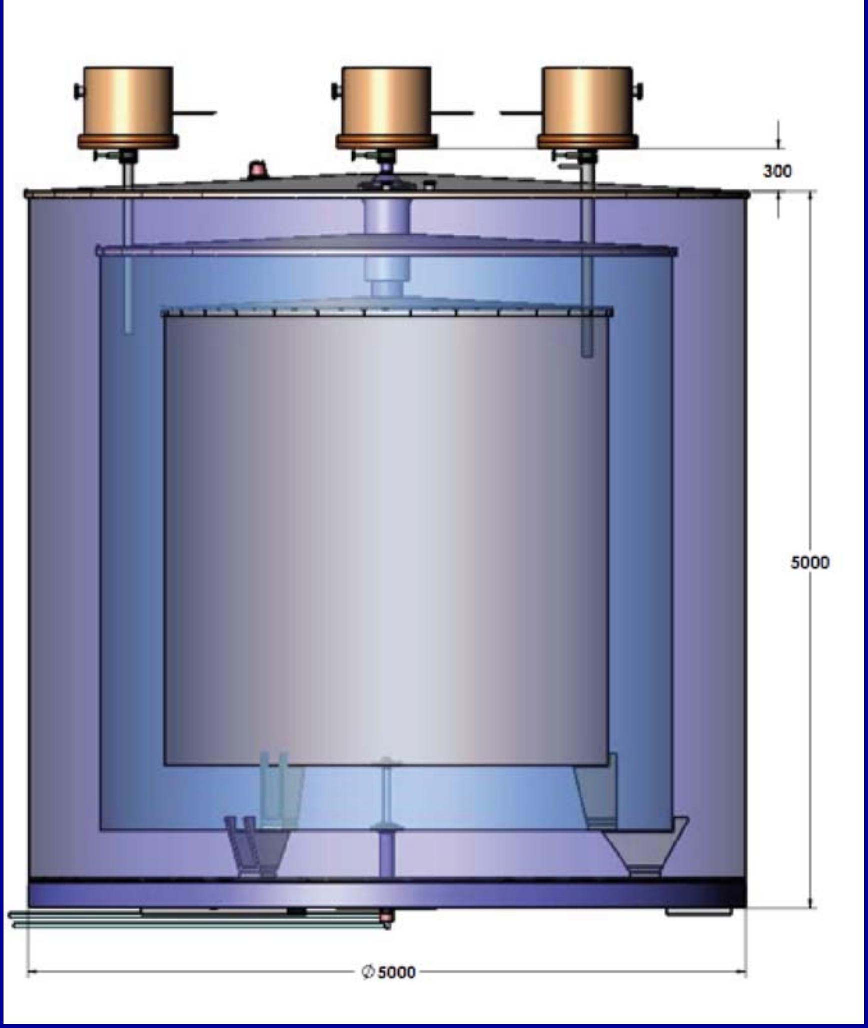
Location of Daya Bay

- 45 km from Shenzhen
- 55 km from Hong Kong

Daya Bay Nuclear Power Plant

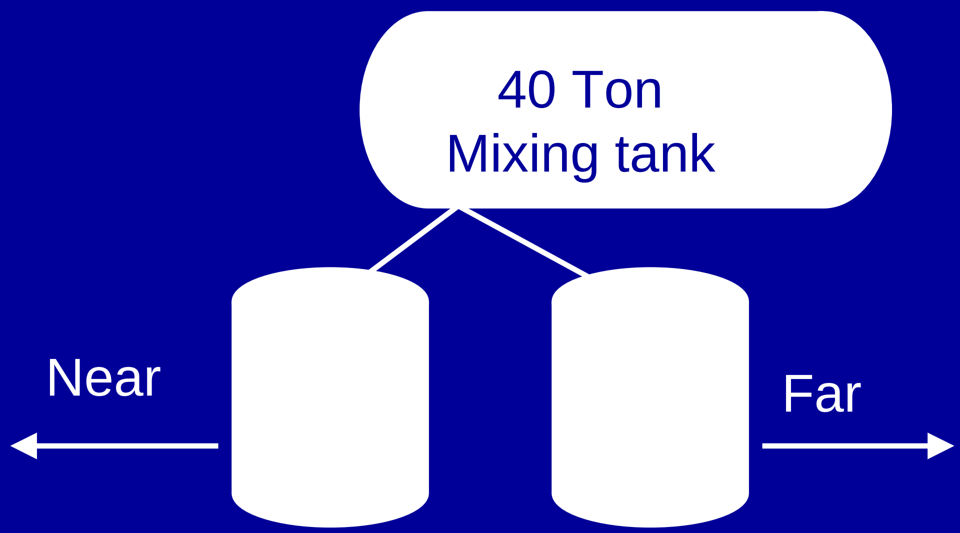
- Currently, 12th most powerful in the world (11.6 GW_{th})
- Will be the fifth most powerful by 2011 (17.4 GW_{th})
- Adjacent to mountain range, construct tunnels and underground laboratories to suppress cosmogenic background – far site will have an overburden of 355 m of rock (~900 mwe)

Antineutrino Detectors (AD's)

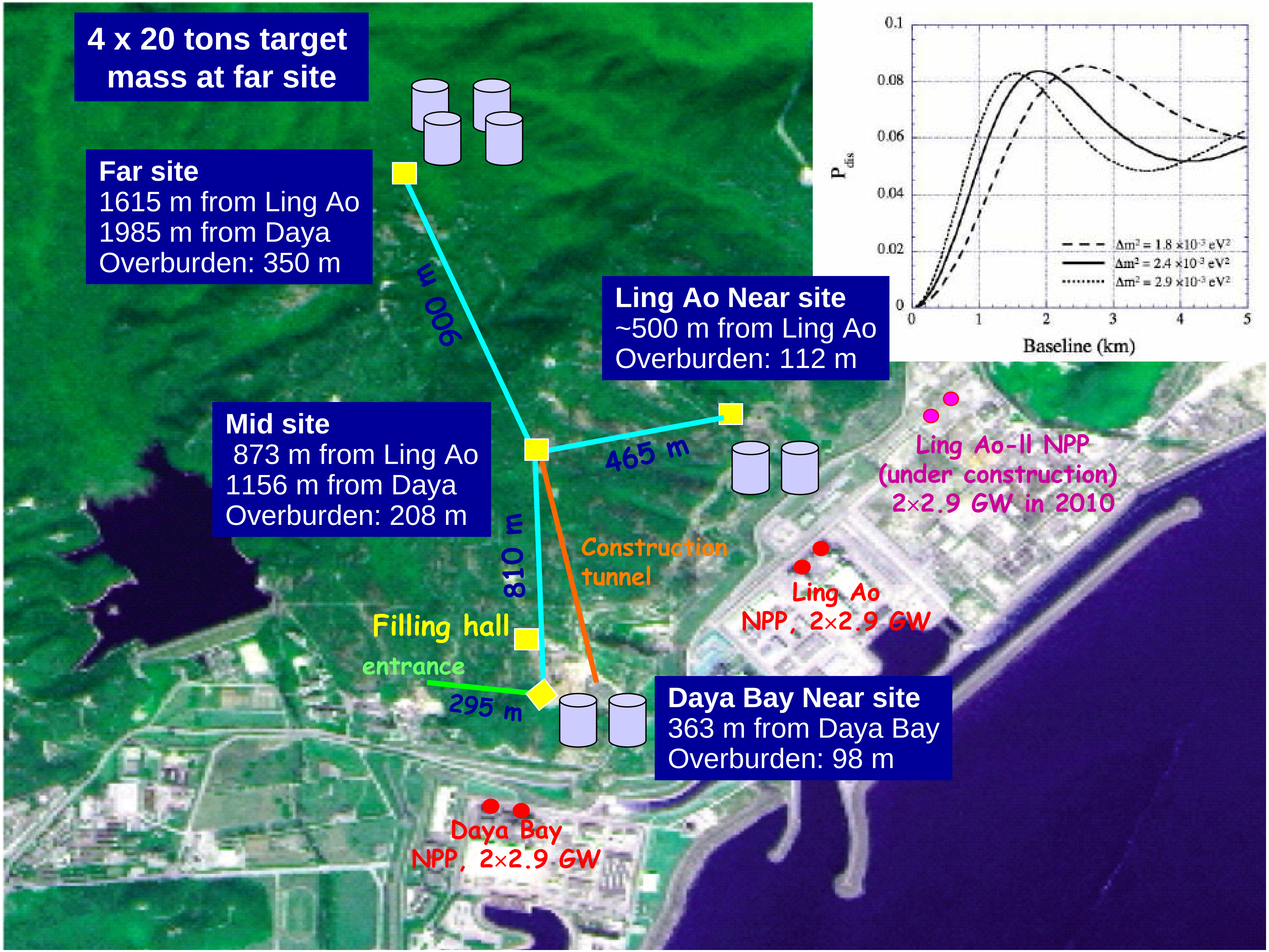


- Cylindrical 3-zone detector – stainless steel vessel with two concentric acrylic vessels
  - Innermost volume is 0.1% Gd-loaded LS (radius = half-height – 1.55 m, 20 tons)
  - The gamma-catcher is non-loaded LS, 42.5 cm thick
  - The outermost volume is mineral oil – 48.8 cm thick
- 224 8-inch PMTs on the circumference
- Reflectors on the top and bottom
- Light modular design – can be filled in one location and moved to another
  - Allows simultaneous filling of two modules to be deployed in different halls
  - Allows for swapping of modules to reduce the detector-related systematic uncertainty if necessary

Deployment scheme



- Total of 8 modules deployed in three halls
- Two detectors will be filled at a time to ensure the same chemical mixture of the liquid scintillator (C:H, C:Gd ratios the same)
- Coriolis mass flow meters, volume flow meters, thermometers in the filling station and load sensors on the detectors will be used to measure the volume and mass of LS. Volume flow meters have an absolute accuracy of 0.2% and a repeatability of 0.02%. We can know the relative volumes – and therefore the number of protons – to < 0.1%.

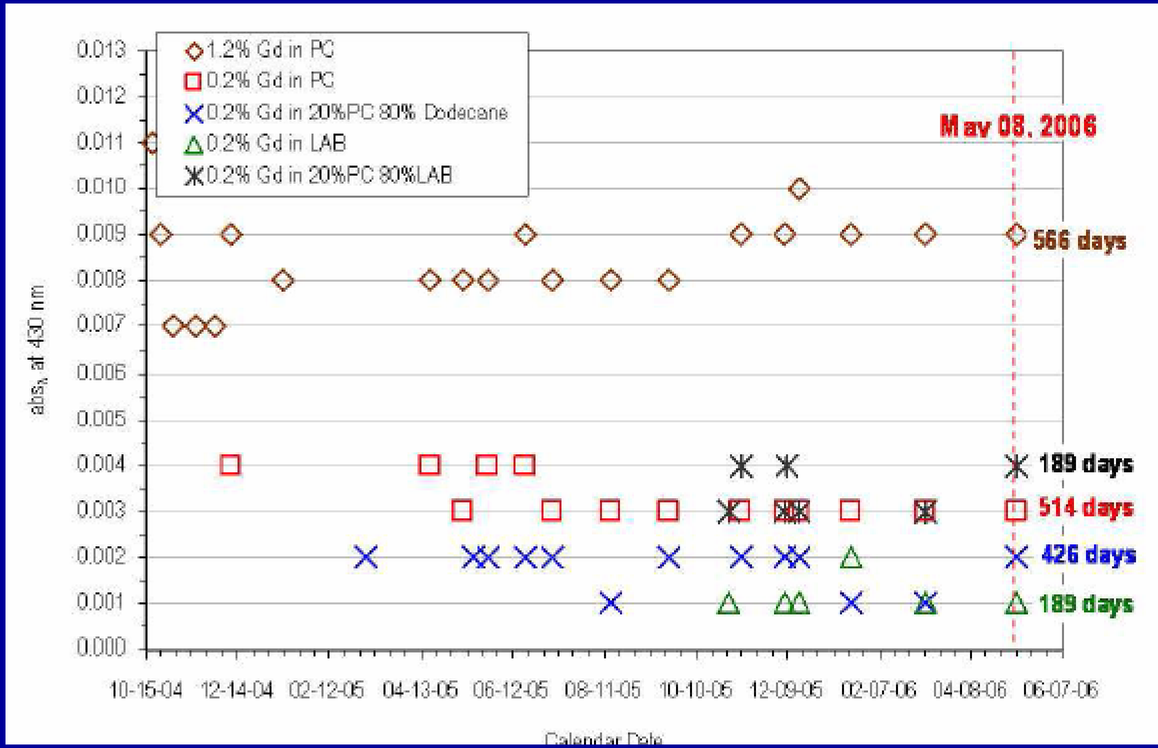


4 x 20 tons target mass at far site
Far site
1615 m from Ling Ao
1985 m from Daya
Overburden: 350 m
900 m
Ling Ao Near site
~500 m from Ling Ao
Overburden: 112 m
Mid site
873 m from Ling Ao
1156 m from Daya
Overburden: 208 m
465 m
810 m
Construction tunnel
Ling Ao-II NPP
(under construction)
2×2.9 GW in 2010
Ling Ao
NPP, 2×2.9 GW
Filling hall
entrance
295 m
Daya Bay Near site
363 m from Daya Bay
Overburden: 98 m
Daya Bay
NPP, 2×2.9 GW
P dis
Baseline (km)
Δm² = 1.8 ×10⁻³ eV²
Δm² = 2.4 ×10⁻³ eV²
Δm² = 2.9 ×10⁻³ eV²

Gd-loaded Liquid Scintillator

- Needs:
  - High light transmission
  - High light output
  - ***Long-term stability*** – both CHOOZ and Palo Verde had trouble with this issue

Gd-loaded Liquid Scintillator

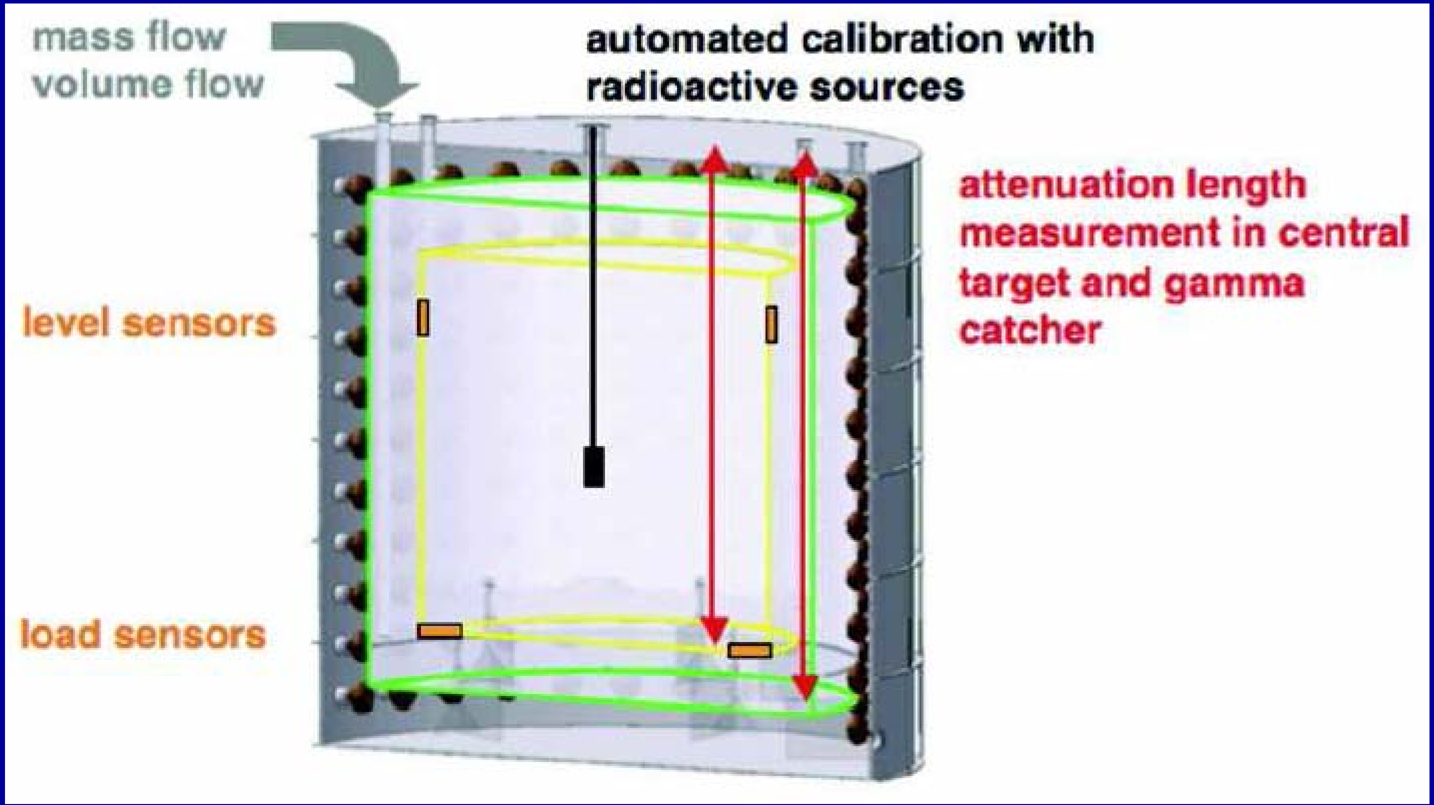


- Linear alkyl benzene (LAB), first suggested by SNO+, will be used
- In addition to good stability, it has a high flashpoint, low vapor pressure, safer for health and the environment and it is commercially available (it is used in detergents)

Daya Bay Antineutrino Event Selection

- Antineutrino events defined by neutron capture signal of 8 MeV preceded by an event of appropriate energy
  - 6 MeV < Delayed event energy < 10 MeV
  - 1 MeV < Prompt < 8 MeV
  - $0.3\ \mu s < t_{prompt} - t_{delayed} < 200\ \mu s$
- There is no fiducial volume cut (and thus, no associated systematic uncertainty).
- We expect:
  - 930 events per day/module at the Daya Bay near site
  - 760 events per day/module at the Ling Ao near site
  - 90 events per day/module at the far site

Calibration and Monitoring

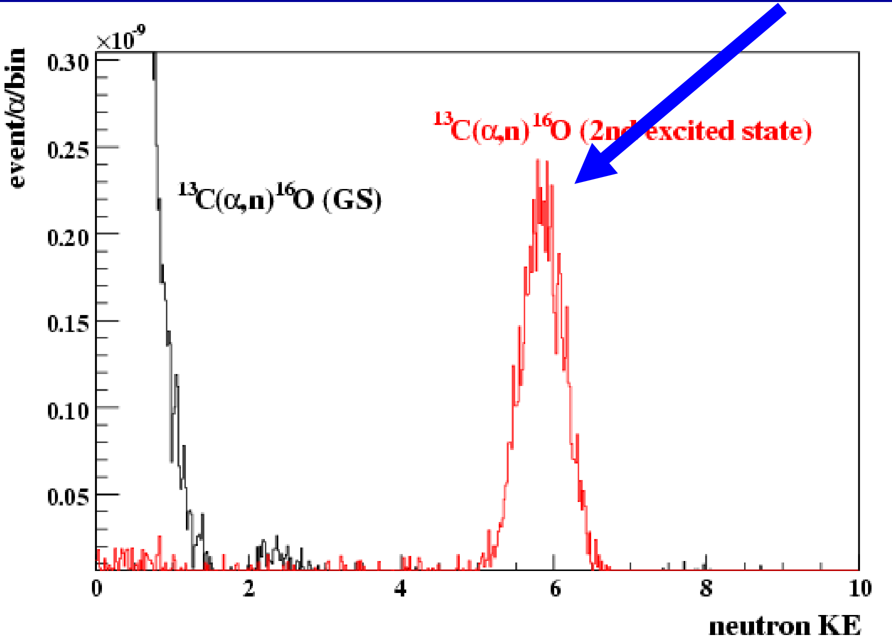


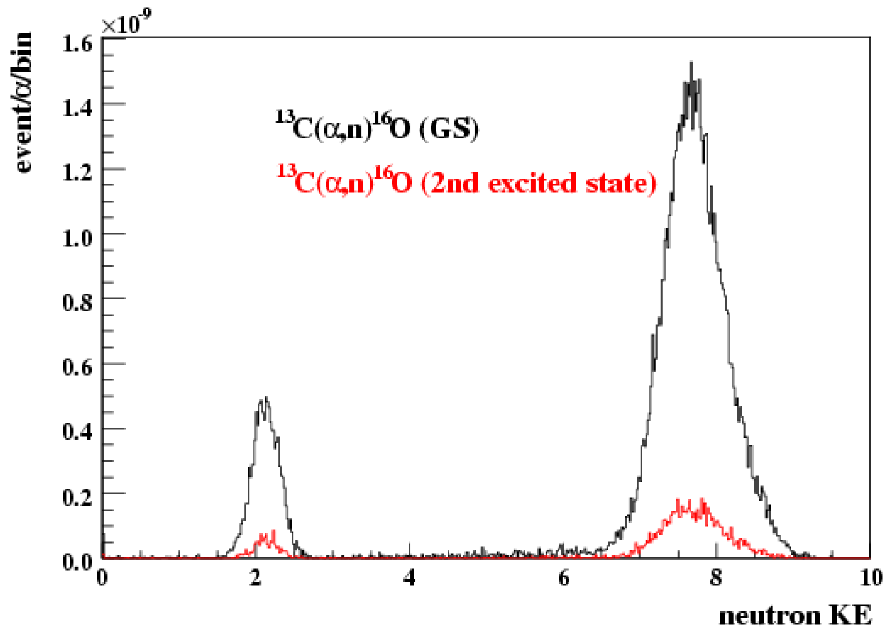
- Level, load and temperature sensors will be monitored with slow control
- An automated calibration system will deploy sources and an LED through several access ports on a weekly (or more often) basis
- A separate manual system will allow for full-volume calibrations as needed

Calibrating the Energy Cuts

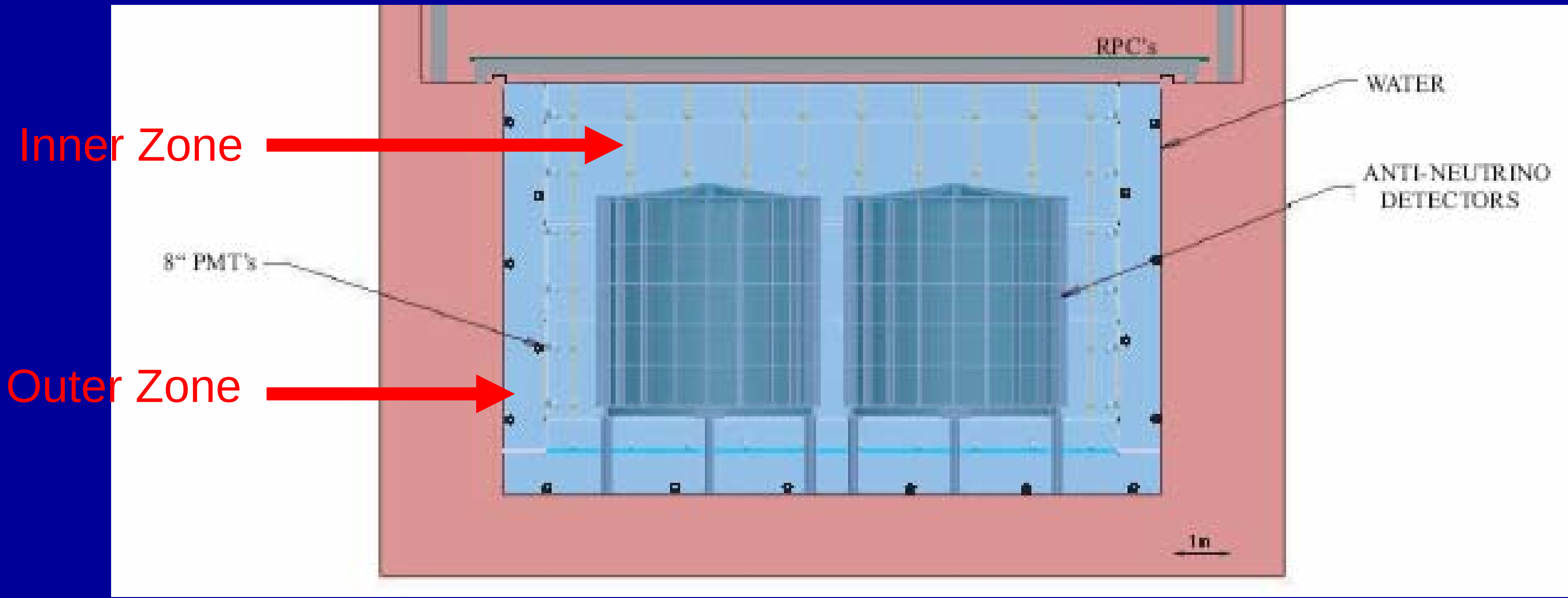
- Automated calibration will be done with three sources
  - ^{68}Ge – e^+ gives e^+-e^- annihilation – 2 0.511 MeV γ's
  - ^{60}Co – 2.6 MeV in γ's
  - ^{238}Pu- ^{13}C (α-n source) – gives neutrons as well as 6.13 MeV γ-ray from the ^{16}O excited state decay

So we can calibrate the low energy side of the neutron energy cut using the ^{16}O excited state decay





Muon System



- Near sites – two AD's deployed in a water pool
- Far site – four AD's deployed in a water pool
- Each pool completely surrounds the AD's with a minimum of 2.5 m of water
- The pools are instrumented with 8-inch PMTs and are used as Cherenkov detectors – there are zones optically separated allowing moderate reconstruction abilities
- RPC's cover the top of the pool allowing for redundancy to achieve the goal of 99.5 % muon detection efficiency
- The muon system is capable of tagging muons to allow measurements of two important backgrounds

Backgrounds

- Any set of events which mimics a delayed coincidence sequence is background
- The primary backgrounds are:
  - The β-delayed neutron emitters: ^{9}Li and ^{8}He
  - Fast neutrons
  - Accidentals
- All of the above can be measured

Background to Signal Events

	Daya Bay	Ling Ao	Far Site
^{9}Li and ^{8}He	0.3 %	0.2 %	0.2 %
Fast neutrons	0.1 %	0.1 %	0.1 %
Accidentals	< 0.2 %	< 0.2 %	< 0.1 %

Systematic Uncertainty Budget

Detector Related Uncertainties

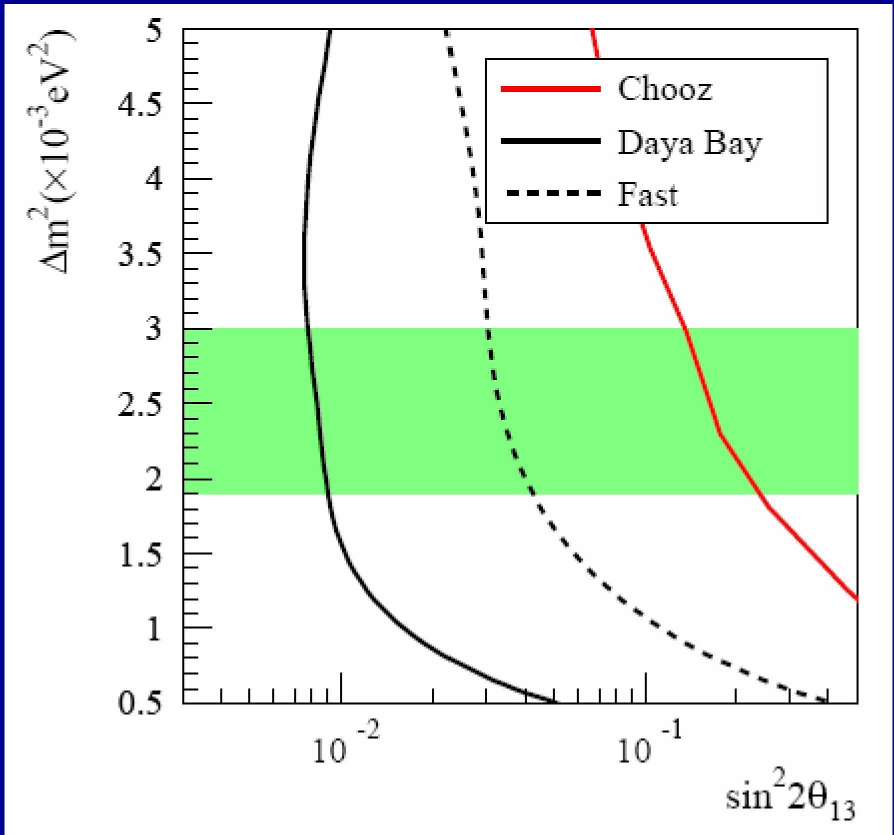
Source of uncertainty		Chooz (*absolute*)	Daya Bay (*relative*)		
			Baseline	Goal	Goal w/Swapping
# protons	H/C ratio	0.8	0.2	0.1	0
	Mass	-	0.2	0.02	0.006
Detector Efficiency	Energy cuts	0.8	0.2	0.1	0.1
	Position cuts	0.32	0.0	0.0	0.0
	Time cuts	0.4	0.1	0.03	0.03
	H/Gd ratio	1.0	0.1	0.1	0.0
	n multiplicity	0.5	0.05	0.05	0.05
	Trigger	0	0.01	0.01	0.01
	Live time	0	< 0.01	< 0.01	< 0.01
Total detector-related uncertainty		1.7%	0.38%	0.18%	0.12%

- Baseline is what we anticipate without further R&D
- Goal is with R&D
- We have made the modules portable so we can carry out swapping if necessary

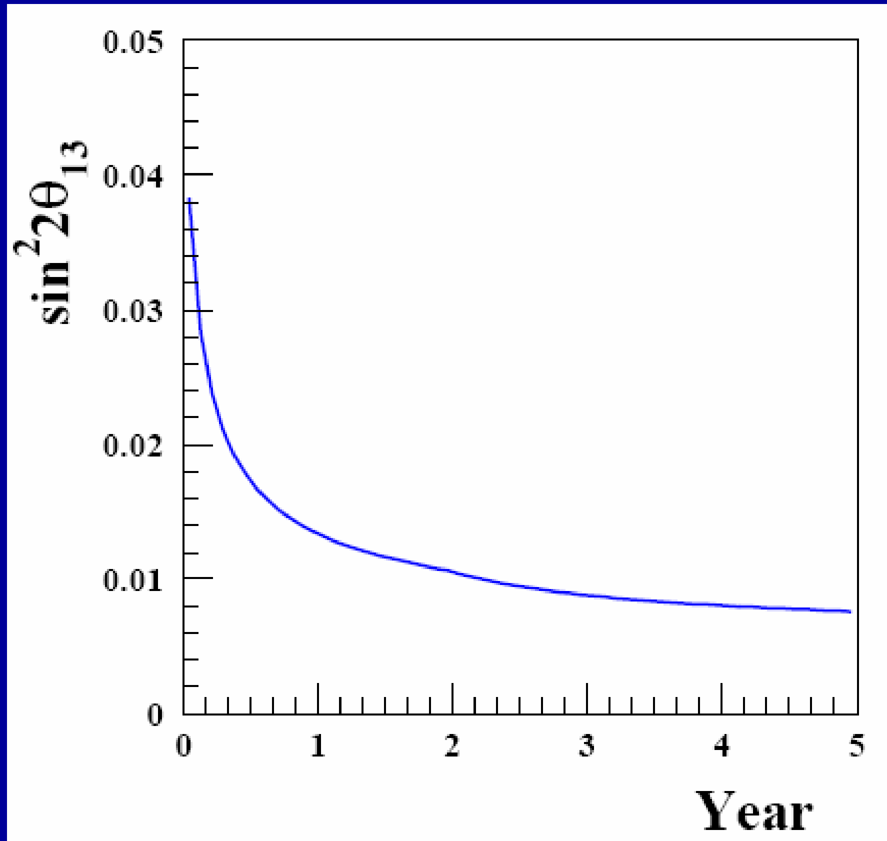
Reactor Related Uncertainties

- By using near detectors, we can achieve the following relative systematic uncertainties:
  - With four cores operating 0.087 %
  - With six cores operating 0.126 %

Sensitivity



Projected sensitivity after three years of running. The fast option is if we would place detectors at the mid-site for nine months before the far site is completed.



Projected sensitivity vs. time where one year is three hundred live-days.

Schedule and Funding

China plans to provide civil construction and ~half of the detector cost

U.S. will provide ~half of the detector cost

Funding in China is far along

Funding in the U.S.

R&D funding from DOE

CD1 review in April will hopefully allow full funding in fiscal year 2008

Funding from other organizations and regions is proceeding

- Begin civil construction summer 2007
- Begin commissioning the first two detectors summer 2009
- Begin near-far data-taking in 2010

Conclusions

- Using the high-power Daya Bay Nuclear Power Plant and a large target mass of liquid scintillator, the Daya Bay Neutrino Experiment is poised to make the most sensitive measurement yet of $\sin^2 2\theta_{13}$
- With high statistics and strict control of systematic uncertainties, Daya Bay will make a strong contribution to the understanding of neutrino oscillation physics
- Combined with accelerator projects, we hope to find the way forward to exploring leptonic CP violation
- This next generation of experiments opens the door to precision neutrino oscillation physics