Search for the Neutrino Mixing Angle θ_{13}

with non-accelerator experiments

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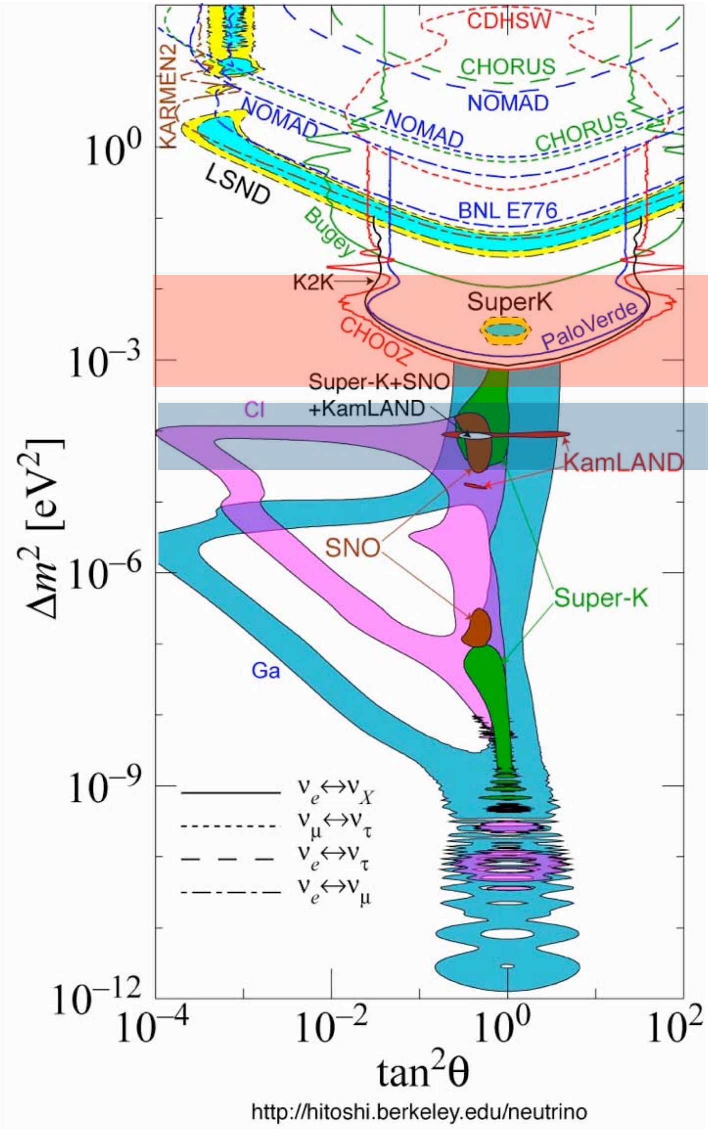
APS April Meeting, Jacksonville, Florida

Discovery Era in Neutrino Physics: 1998 - Present

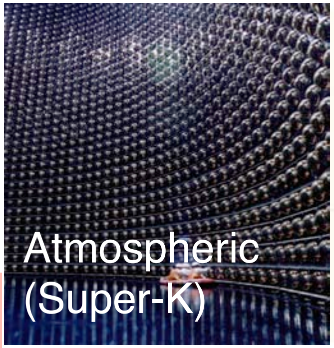


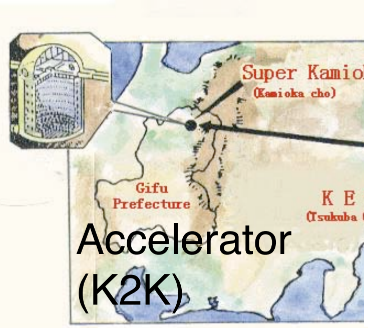
http://hitoshi.berkeley.edu/neutrino

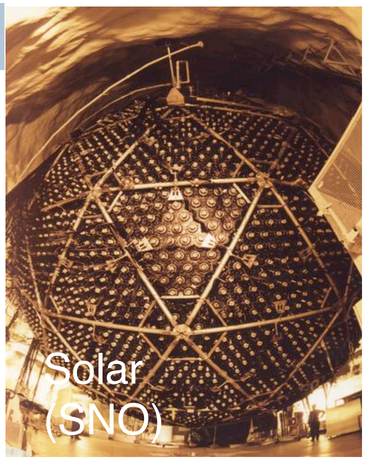
$\nu_\mu \Rightarrow \nu_\tau$

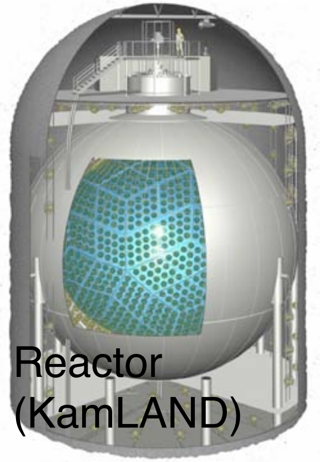
$\nu_e \Rightarrow \nu_{\mu,\tau}$

Δm_{ij}^2 measured *and* confirmed.



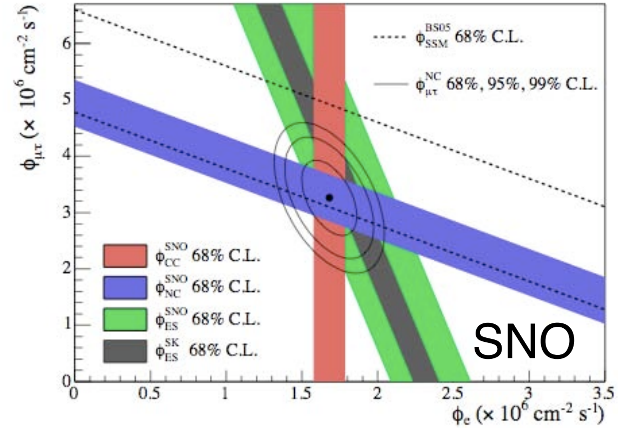


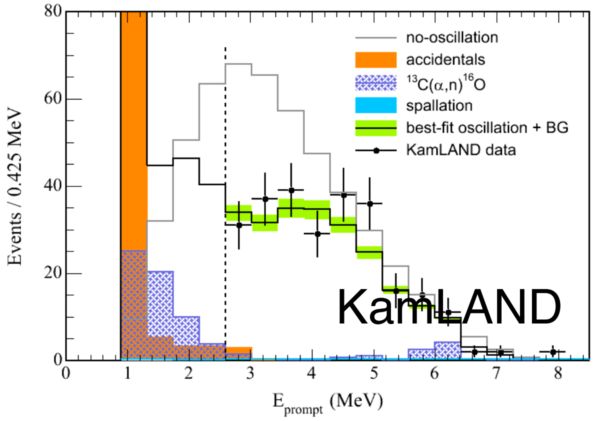


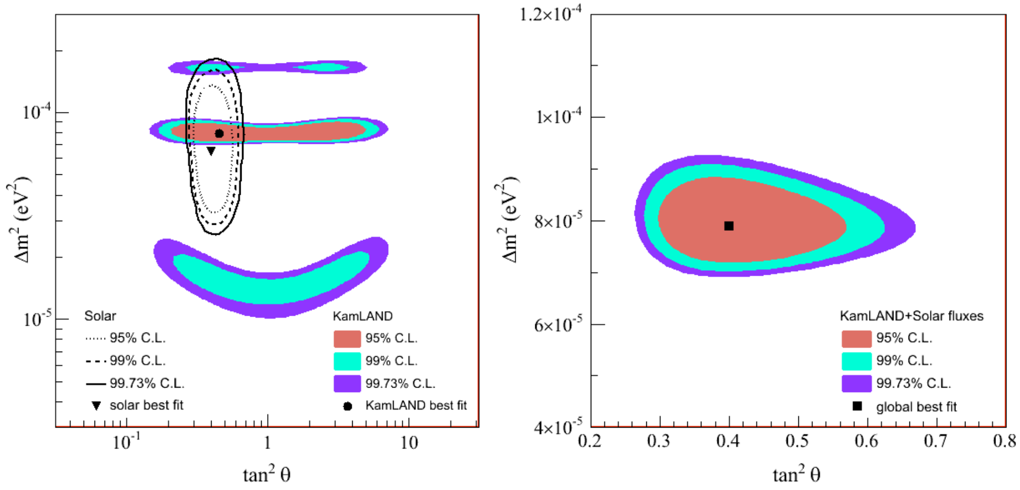


- Neutrinos are not massless
- Evidence for neutrino flavor conversion $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$
- Experimental results show that *neutrinos oscillate*

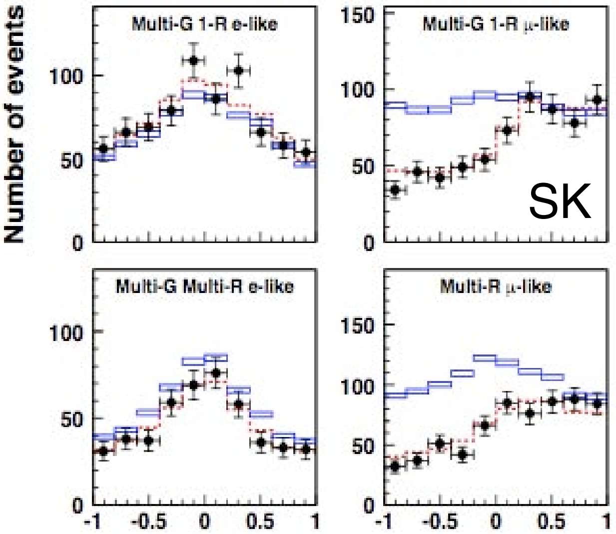
Constraints on Neutrino Mixing Angles from Solar, Atmospheric, And Reactor Experiments

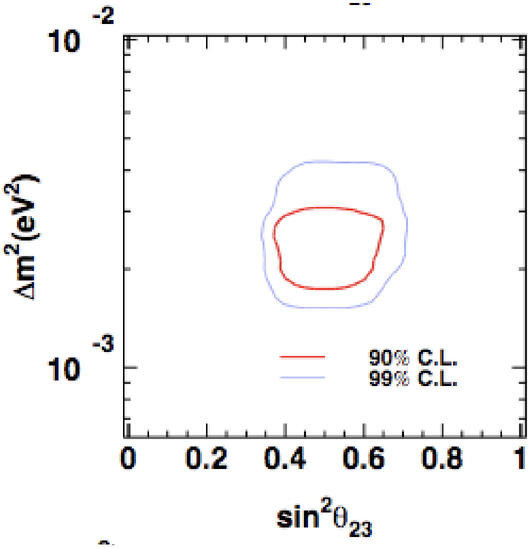






KamLAND





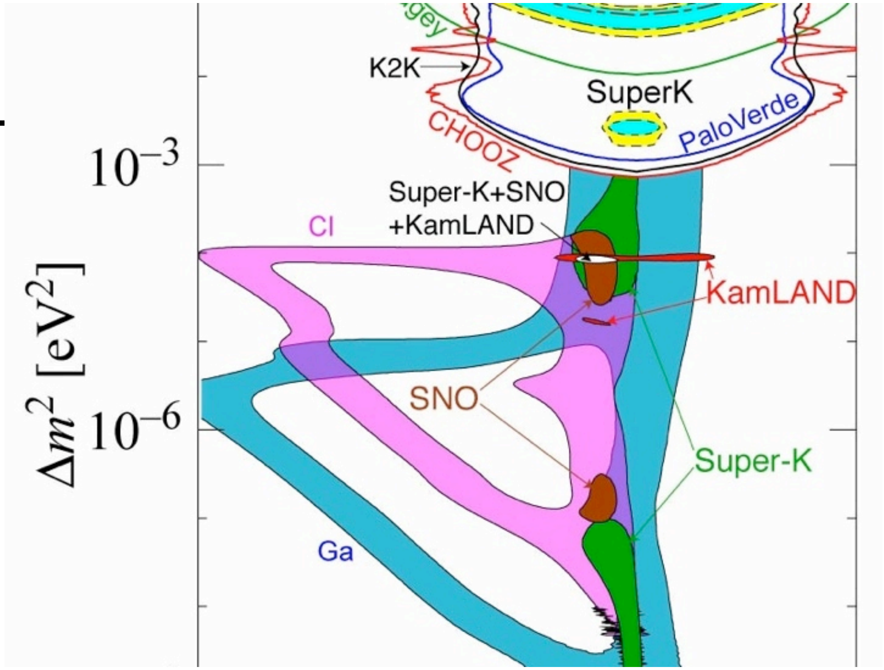
SK

Neutrino Mixing

U_{MNSP} Matrix

Maki, Nakagawa, Sakata, Pontecorvo

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$



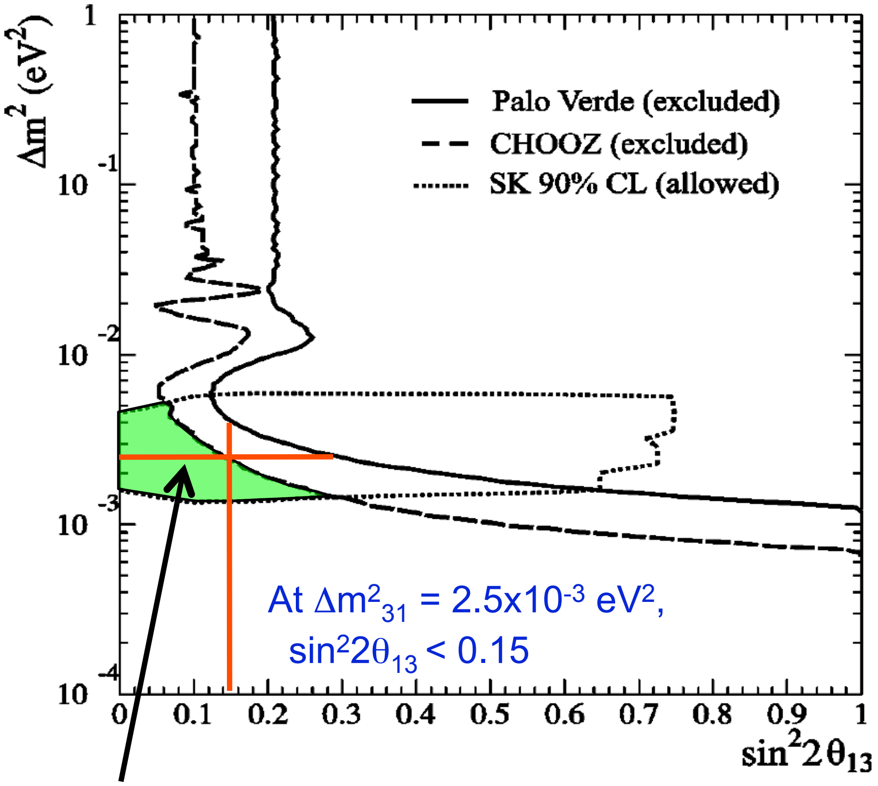
$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13}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

atmospheric, K2K | reactor and accelerator | SNO, solar SK, KamLAND | 0νββ

$\theta_{23} = \sim 45°$ | $\theta_{13} = ?$ | $\theta_{12} \sim 32°$

Current Knowledge of θ_{13}

Direct search at Chooz and Palo Verde

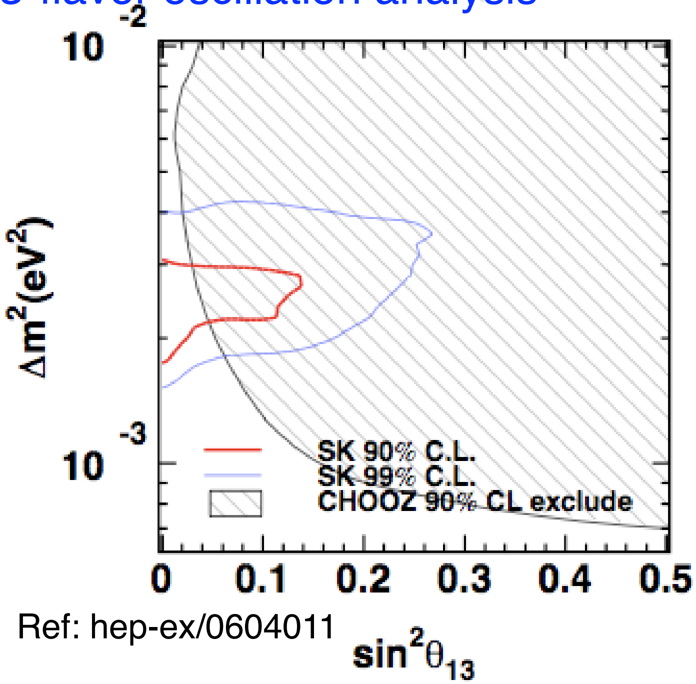


At $\Delta m^2_{31} = 2.5\text{x}10^{-3}$ eV^2,
$\sin^2 2\theta_{13} < 0.15$

allowed region

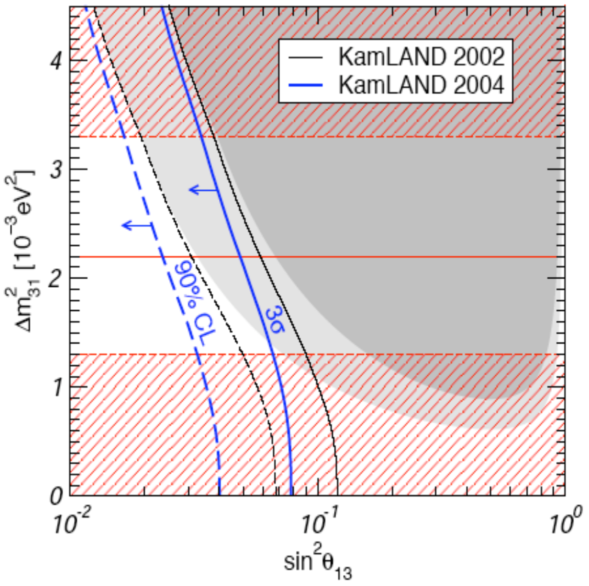
Matter enhancement separates the 1-2 and 1-3 oscillation effects in solar and reactor neutrinos

SK 3-flavor oscillation analysis



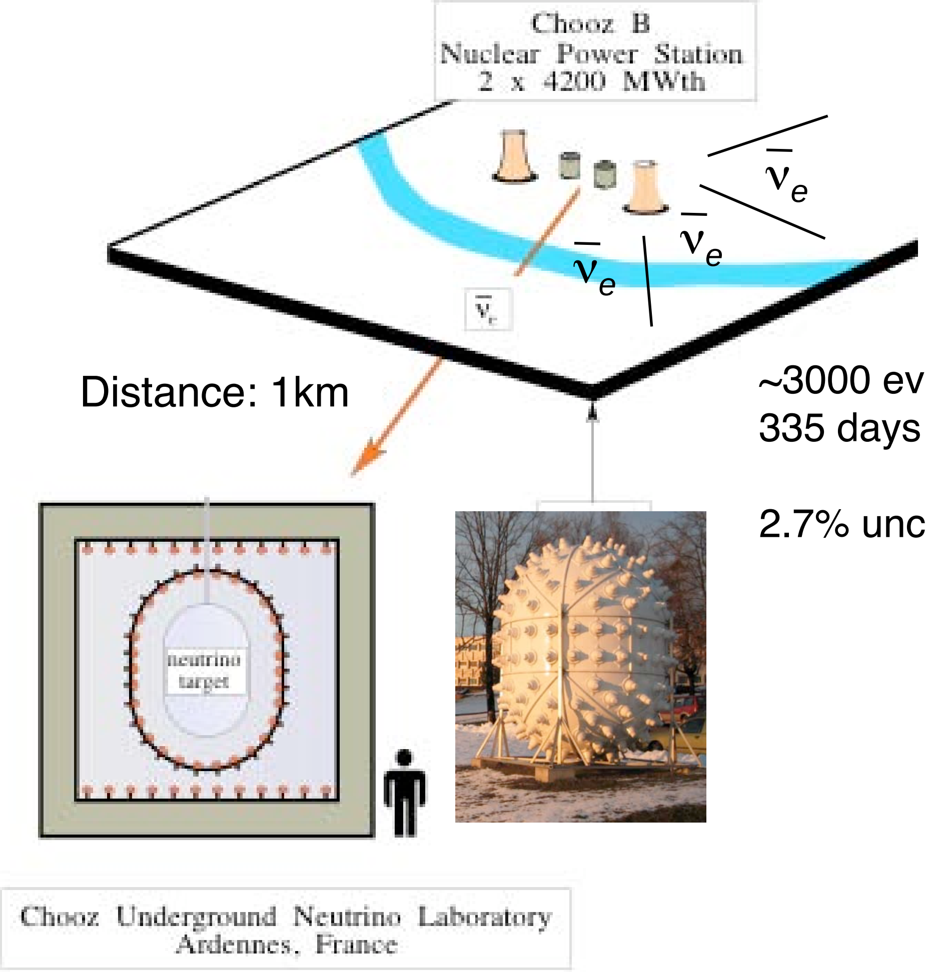
Ref: hep-ex/0604011

Global analysis of solar+other data



Neutrino Oscillation Search with Reactor Antineutrinos

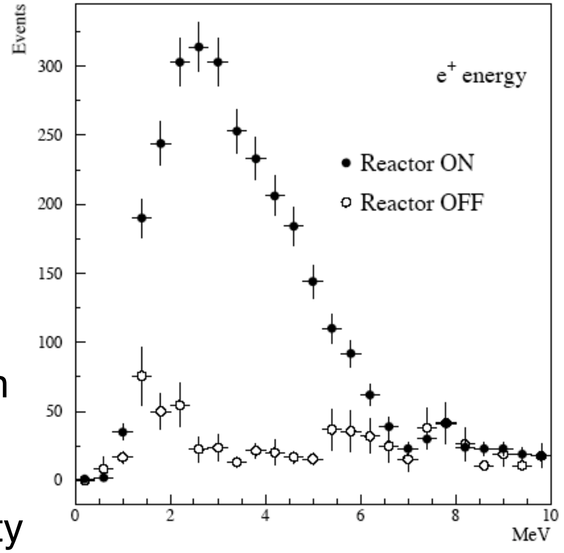
Oscillation Searches at Chooz + Palo Verde: $\bar{\nu}_e \rightarrow \bar{\nu}_x$

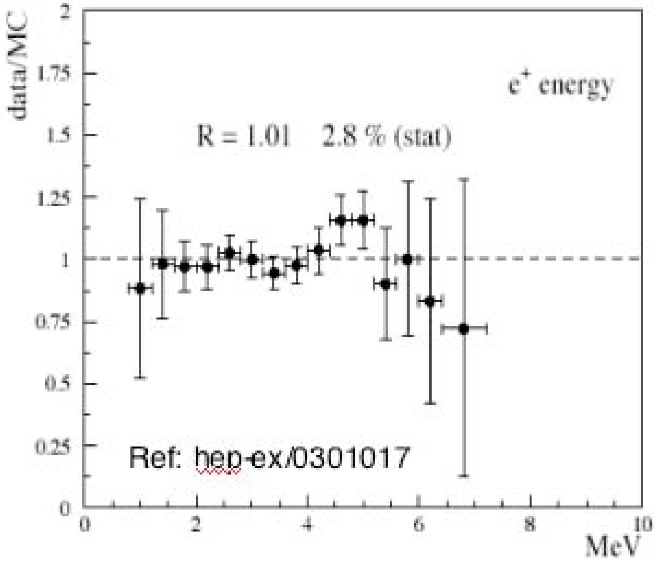


Distance: 1km

~3000 events in 335 days

2.7% uncertainty



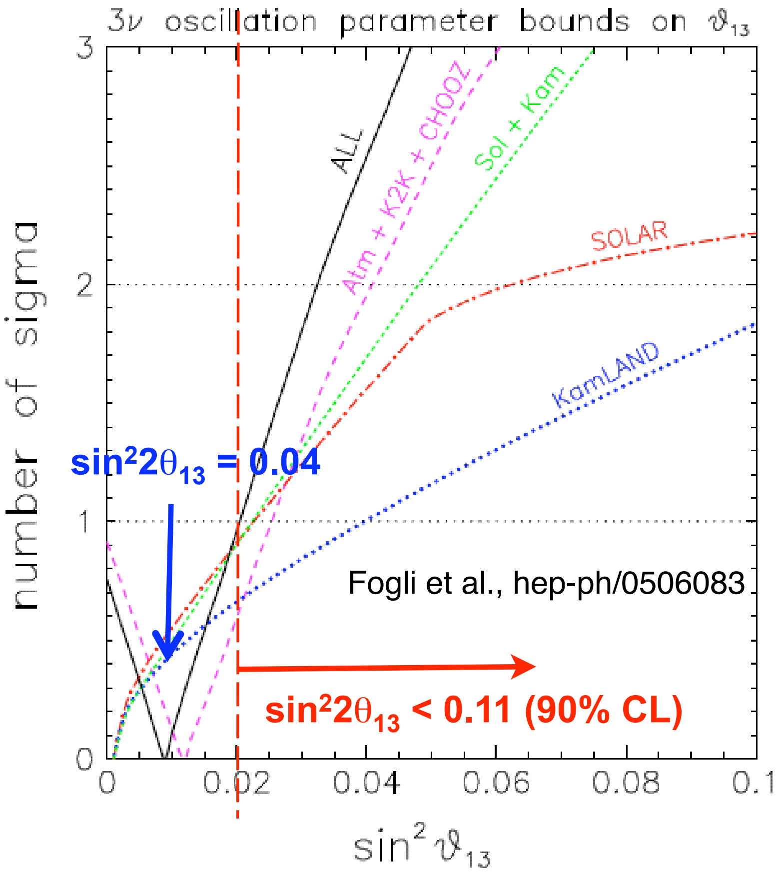


Ref: hep-ex/0301017

Absolute measurement with 1 detector

Experiment & Theory

Global Fit



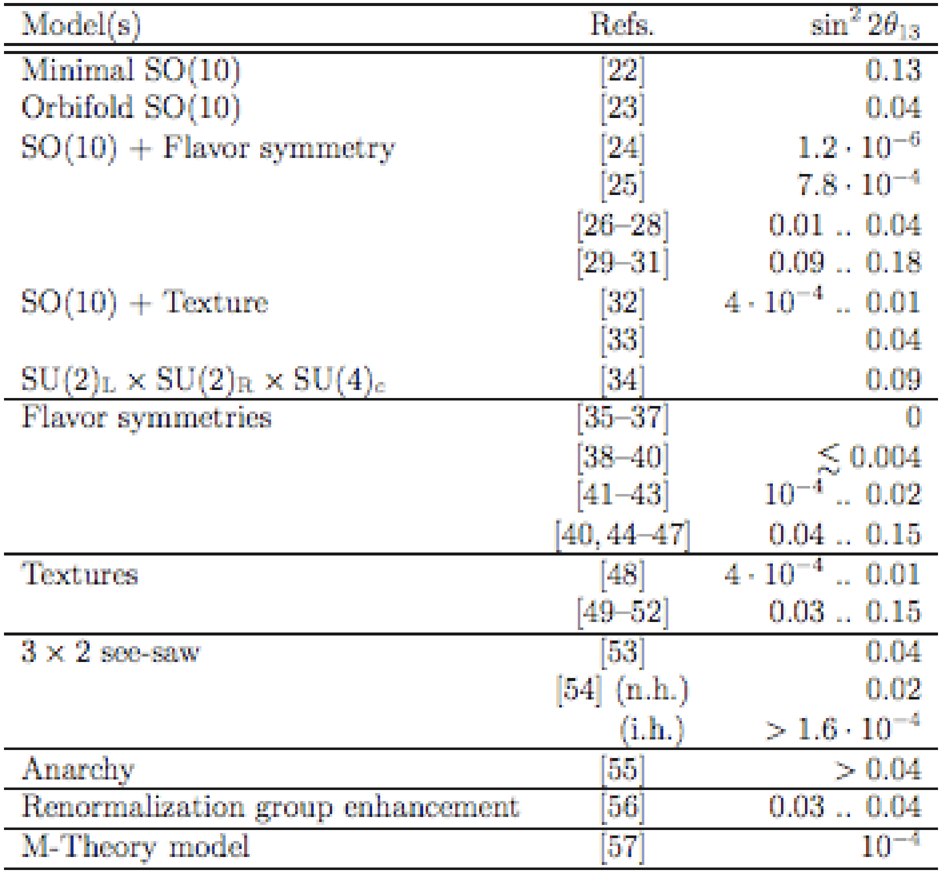
$\sin^2 2\theta_{13} = 0.04$

$\sin^2 2\theta_{13} < 0.11$ (90% CL)

Fogli et al., hep-ph/0506083

$$
\begin{aligned}
\sin^2\theta_{13} &= 0.9^{+2.3}_{-0.9} \times 10^{-2} \ , \\
\delta m^2 &= 7.92\,(1 \pm 0.09) \times 10^{-5}\ \mathrm{eV}^2 \ , \\
\sin^2\theta_{12} &= 0.314\,(1^{+0.18}_{-0.15}) \ , \\
\Delta m^2 &= 2.4\,(1^{+0.21}_{-0.26}) \times 10^{-3}\ \mathrm{eV}^2 \ , \\
\sin^2\theta_{23} &= 0.44\,(1^{+0.41}_{-0.22}) \ .
\end{aligned}
$$

Theory

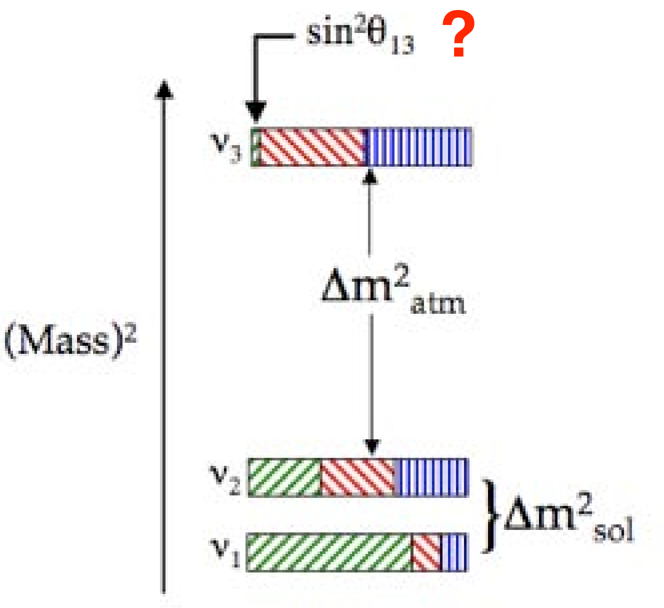


Model(s)	Refs.	$\sin^2 2\theta_{13}$
Minimal SO(10)	[22]	0.13
Orbifold SO(10)	[23]	0.04
SO(10) + Flavor symmetry	[24]	$1.2 \cdot 10^{-6}$
	[25]	$7.8 \cdot 10^{-4}$
	[26–28]	0.01 .. 0.04
	[29–31]	0.09 .. 0.18
SO(10) + Texture	[32]	$4 \cdot 10^{-4}$ .. 0.01
	[33]	0.04
$SU(2)_L \times SU(2)_R \times SU(4)_c$	[34]	0.09
Flavor symmetries	[35–37]	0
	[38–40]	$\lesssim 0.004$
	[41–43]	10^{-4} .. 0.02
	[40, 44–47]	0.04 .. 0.15
Textures	[48]	$4 \cdot 10^{-4}$ .. 0.01
	[49–52]	0.03 .. 0.15
3 × 2 see-saw	[53]	0.04
	[54] (n.h.)	0.02
	(i.h.)	$> 1.6 \cdot 10^{-4}$
Anarchy	[55]	> 0.04
Renormalization group enhancement	[56]	0.03 .. 0.04
M-Theory model	[57]	10^{-4}

we don't know θ_{13} ...

Ref: FNAL proton driver report, hep-ex/0509019

θ_{13} and Particle Physics



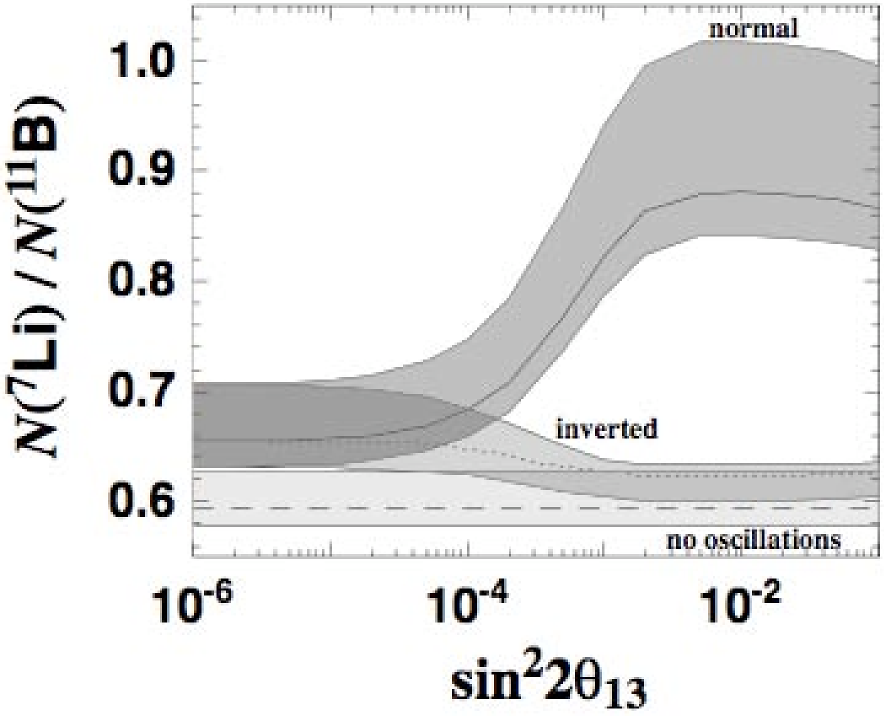
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} \boxed{s_{13} c_{13}^2} s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

Is there μ–τ symmetry in neutrino mixing?

Can we use ν to search for ~~CP~~?

θ_{13} and Nuclear Astrophysics

neutrino oscillation effects on supernova light-element synthesis



astr-ph/0606042

understanding the origin of matter (vs antimatter)

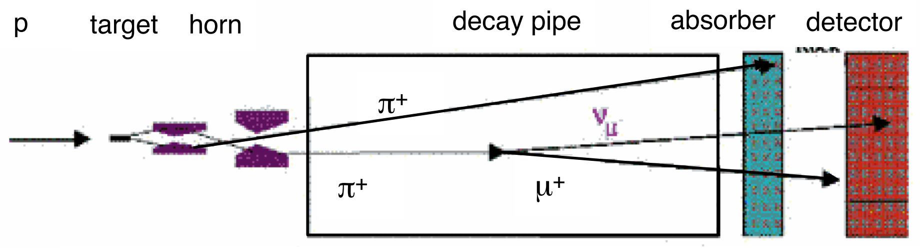
Leptogenesis

Fukugita, Yanagida, 1986

- Out-of-equilibrium L-violating decays of heavy Majorana neutrinos leading to L asymmetry but leaving B unchanged. B_L-L_L is conserved.

Measuring θ_{13}

Method 1: Accelerator Experiments

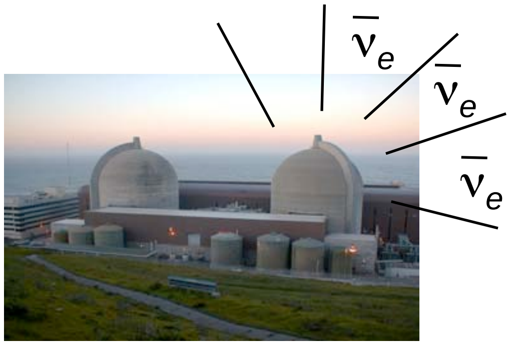


$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{31}{}^2 L}{4E_\nu} + \ldots$$

- appearance experiment $\nu_\mu \rightarrow \nu_e$
- measurement of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ yields θ_{13}, δ_{CP}
- baseline *O(100 -1000 km),* matter effects present

Method 2: Reactor Neutrino Oscillation Experiment

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



- disappearance experiment $\bar{\nu}_e \rightarrow \bar{\nu}_e$
- look for rate deviations from $1/r^2$ and spectral distortions
- observation of oscillation signature with 2 or multiple detectors
- baseline *O(1 km),* no matter effects

θ_{13} from Reactor and Accelerator Experiments

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

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

- Clean measurement of θ_{13}
- No matter effects

mass hierarchy

CP violation

matter

accelerator (ν_e appearance)

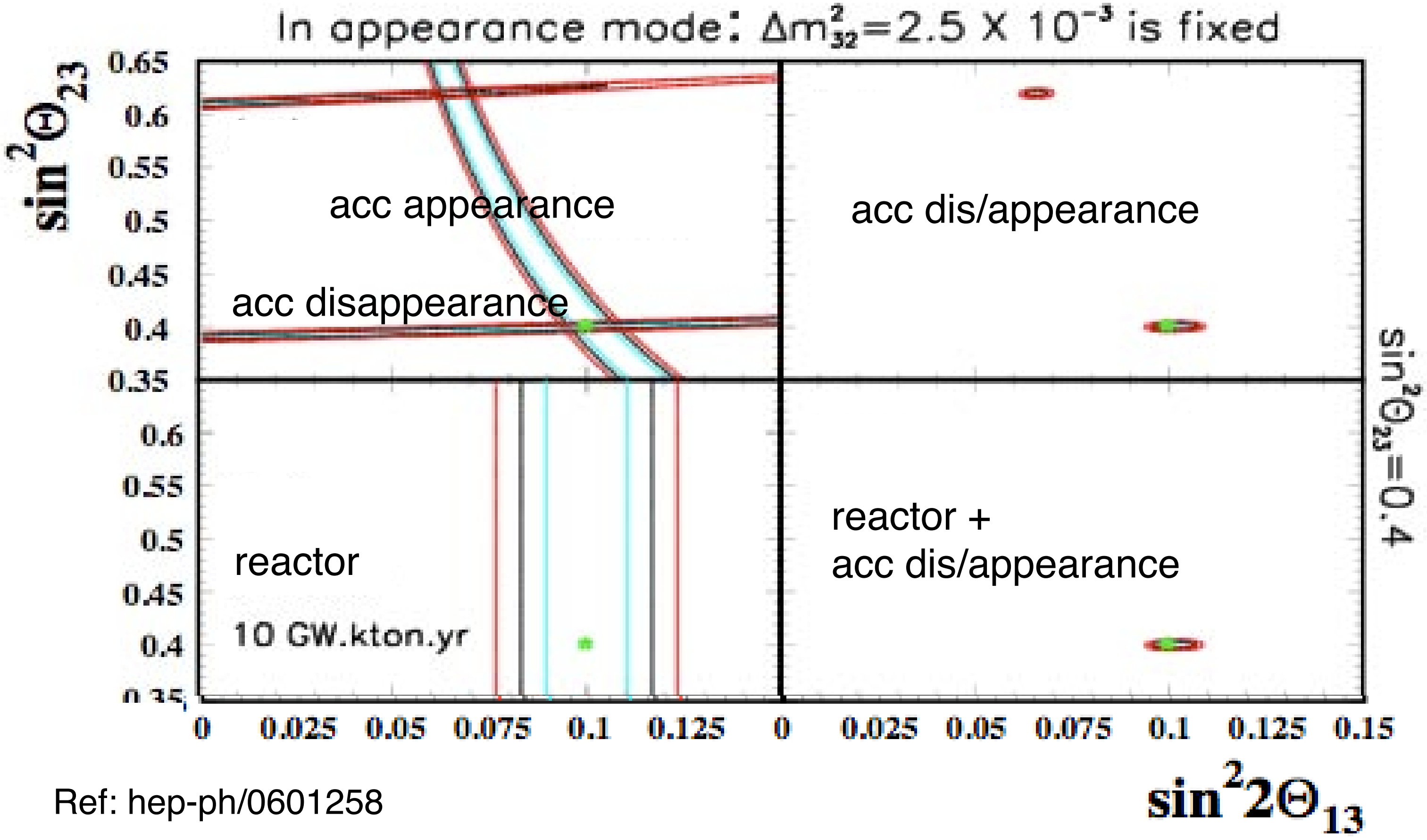
$$\begin{aligned} P(\nu_\mu \to \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \\ & + 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin\Delta_{31}\left[\cos\Delta_{32}\cos\delta - \sin\Delta_{32}\sin\delta\right]\sin\Delta_{21} \\ & - 8c_{13}^2 s_{13}^2 s_{23}^2 s_{12}^2 \cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} \\ & + 4c_{13}^2 s_{12}^2\left[c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\right]\sin^2\Delta_{21} \\ & - 8c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2)\frac{aL}{4E_\nu}\sin\Delta_{31}\left[\cos\Delta_{32} - \frac{\sin\Delta_{31}}{\Delta_{31}}\right] . \end{aligned}$$

- $\sin^2 2\theta_{13}$ is missing key parameter for any measurement of δ_{CP}

Resolving the θ_{23} Parameter Ambiguity

Super-K, T2K ν_μ disappearance $\theta_{23} = 45 \pm 9°$

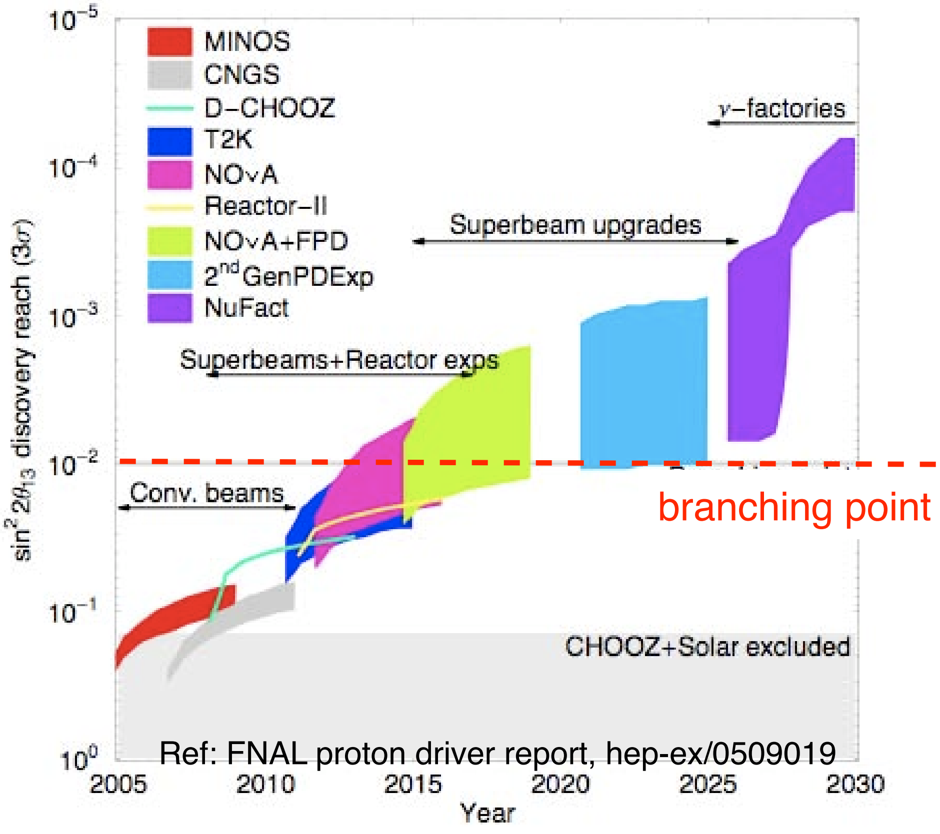
NOvA, T2K ν_e appearance experiments measure $P[\nu_\mu \rightarrow \nu_e]$



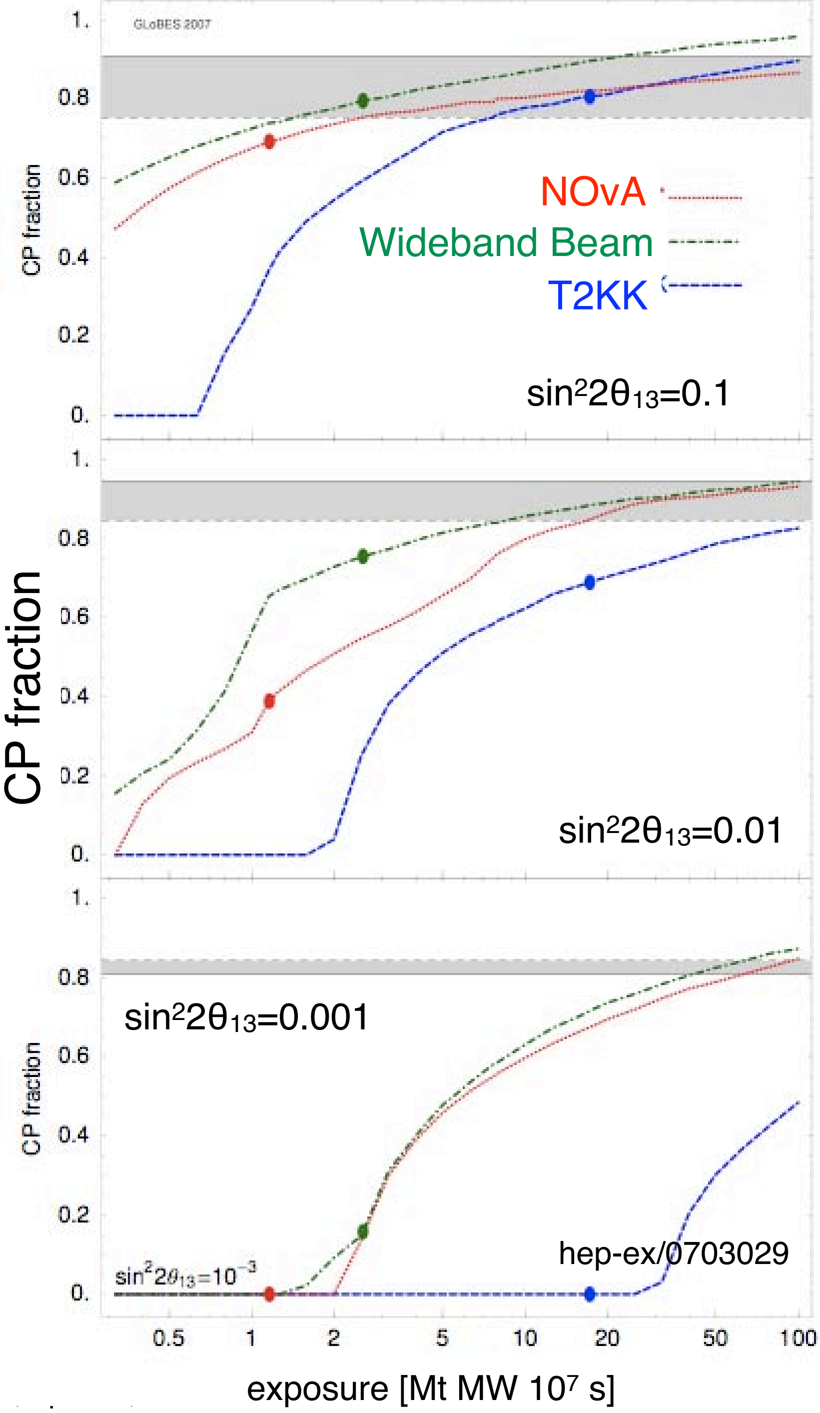
Ref: hep-ph/0601258

Branch Point: $\sin^2 2\theta_{13} < 0.01$

for techniques to measure CP violation ...



Ref: FNAL proton driver report, hep-ex/0509019



hep-ex/0703029

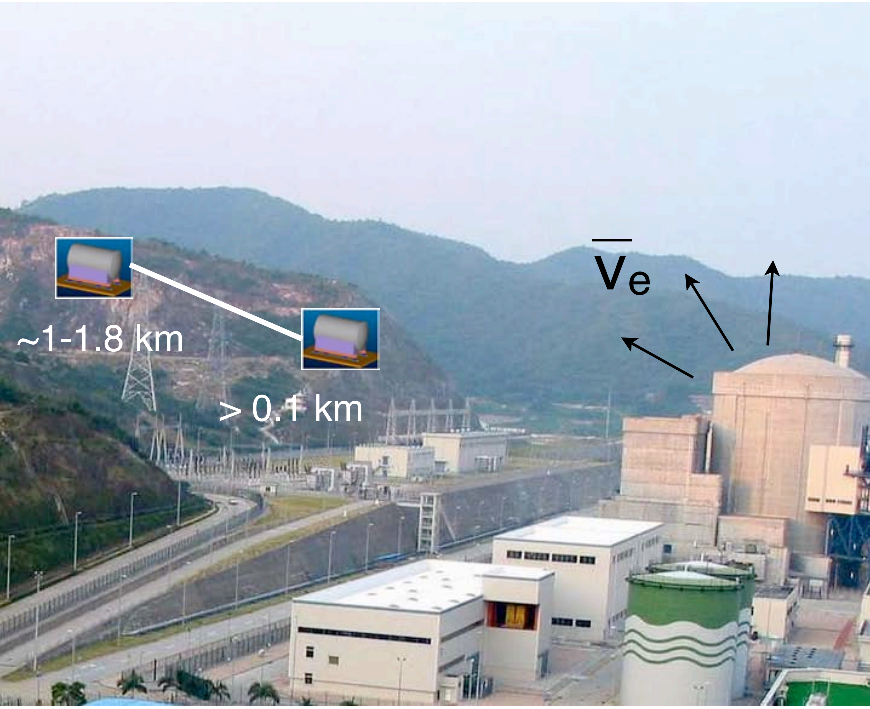
→ **U13.00001:** Summary of the US long Baseline Neutrino Experiment Study, Milind Diwan

→ **U13.00004:** Analysis of a Proposed Long Baseline Neutrino Oscillation Experiment, Christine Lewis

A High Precision Measurement of θ_{13} with Reactor Neutrinos

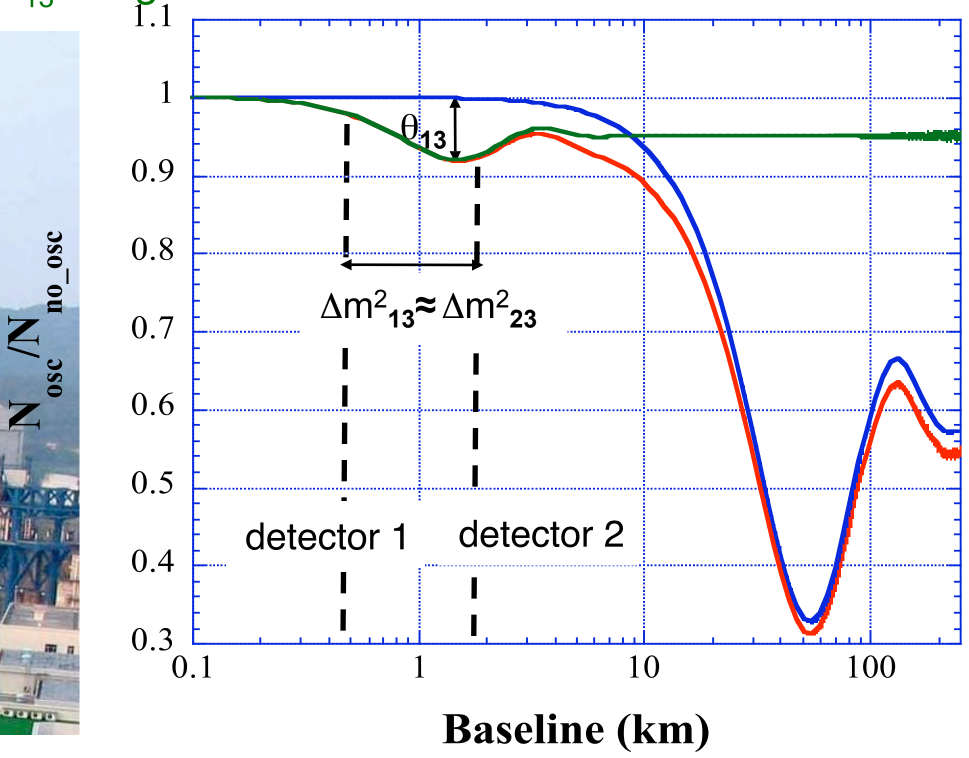
Search for θ_{13} in new oscillation experiment

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



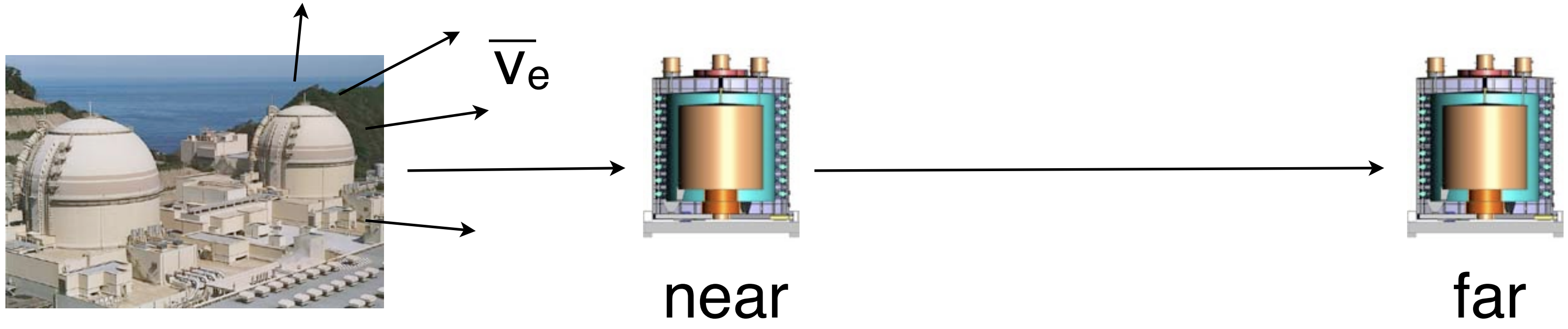
Small-amplitude oscillation due to θ_{13} integrated over E

Large-amplitude oscillation due to θ_{12}



Principle of Relative Measurement

Measure ratio of interaction rates in detector (+shape)



$$\frac{N_\mathrm{f}}{N_\mathrm{n}} = \left(\frac{N_\mathrm{p,f}}{N_\mathrm{p,n}}\right)\left(\frac{L_\mathrm{n}}{L_\mathrm{f}}\right)^2\left(\frac{\epsilon_\mathrm{f}}{\epsilon_\mathrm{n}}\right)\left[\frac{P_\mathrm{sur}(E,L_\mathrm{f})}{P_\mathrm{sur}(E,L_\mathrm{n})}\right]$$

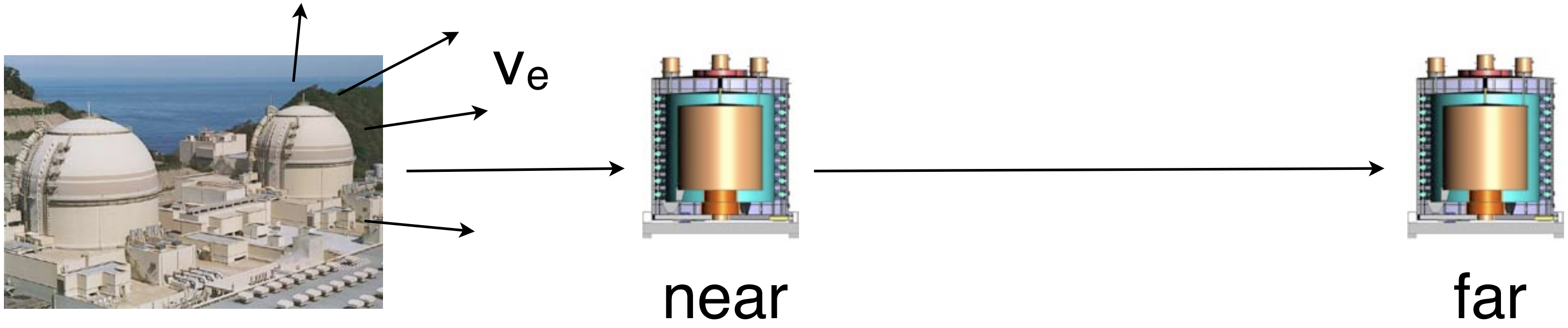
Measured Ratio of Rates

Detector Mass Ratio, H/C

Detector Efficiency Ratio

$\sin^2 2\theta_{13}$

Concept of Reactor θ_{13} Experiment



- relative measurement between detectors at different distances
- cancel source (reactor) systematics

→ need "identical detectors" at near and far site

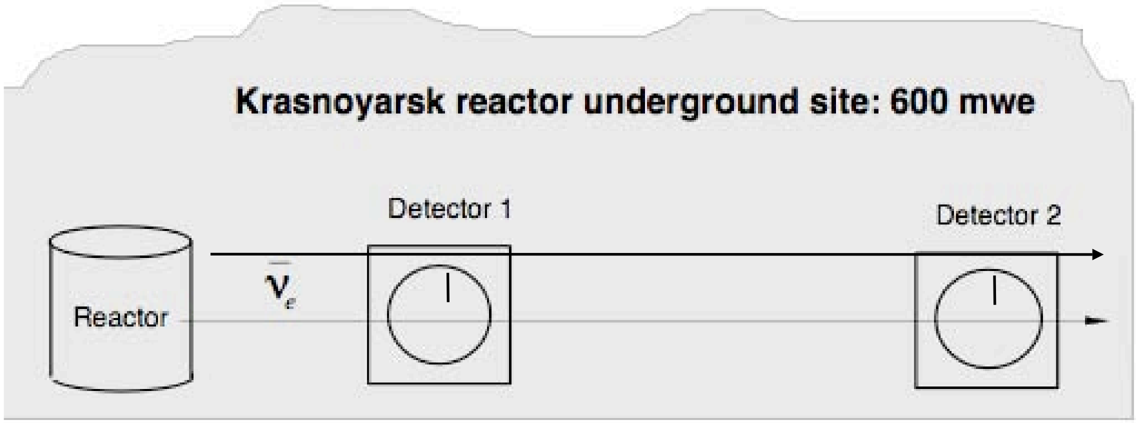
Detectors will never be "identical" but we can understand, measure, and control

	Daya Bay baseline (target)
→ relative target mass & composition to	< 0.30% (0.10%)
→ relative antineutrino detection efficiency to	< 0.25% (0.15%)

…between pairs of detectors.

Reactor θ_{13} Experiment at Krasnoyarsk, Russia

Original ideal, first proposed at Neutrino2000

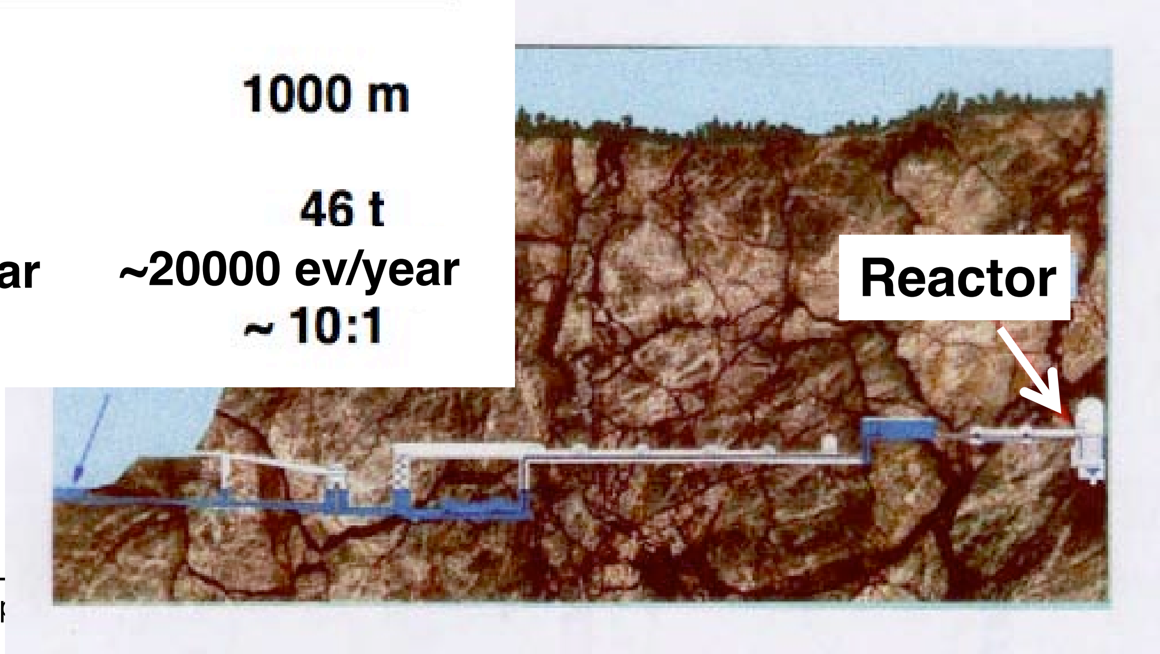


	115 m	1000 m
Target:	46 t	46 t
Rate:	~1.5 x 10^6 ev/year	~20000 ev/year
S:B	>>1	~ 10:1

ex/0211(

Krasnoyarsk
- underground reactor
- detector locations

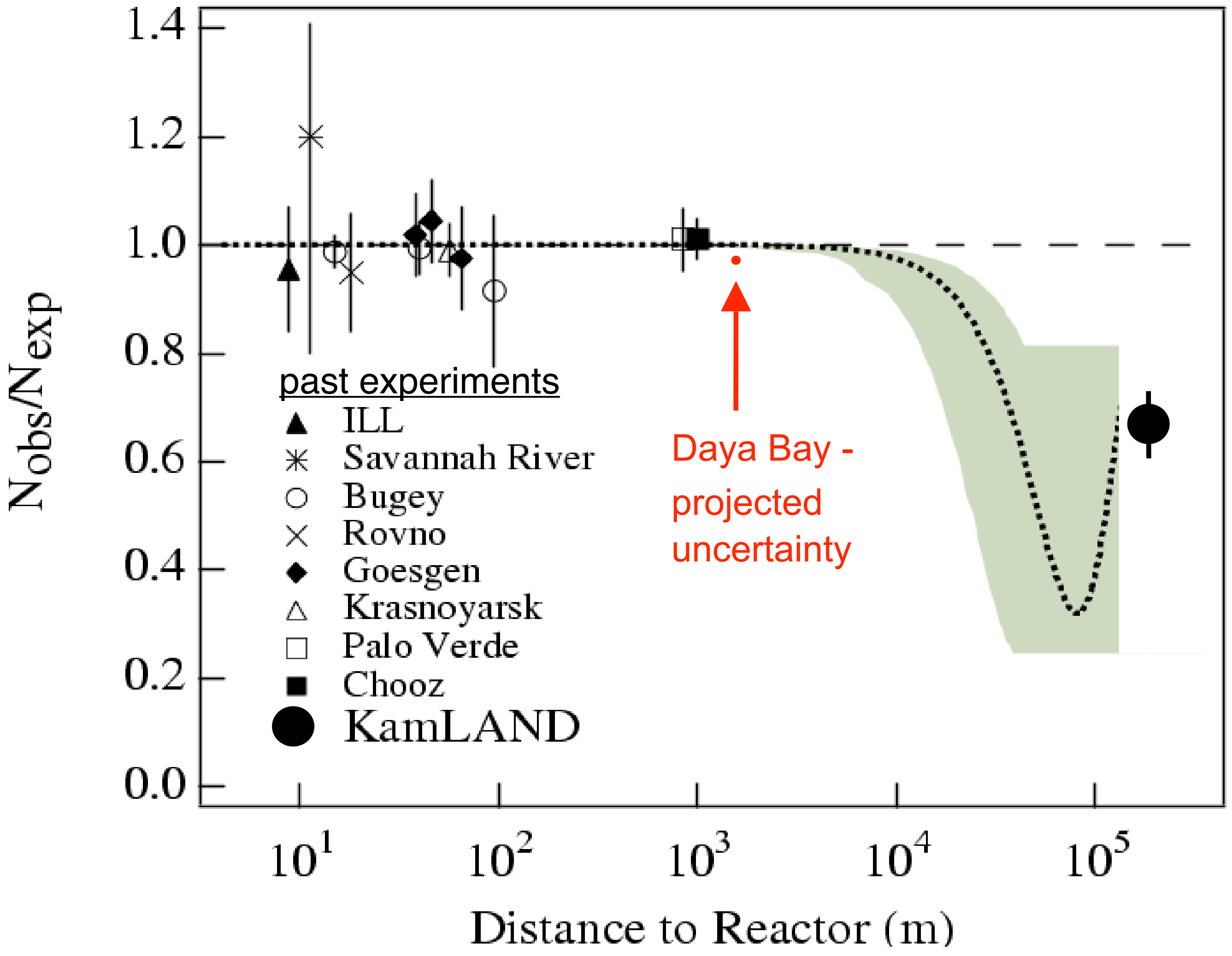
determined by infrastructure



Ref: Marteyamov et al, hep-ex/0211070

Ratio of Measured to Expected $\overline{\nu}_e$ Flux

Expected precision in Daya Bay to reach $\sin^2 2\theta_{13} < 0.01$



Daya Bay - projected uncertainty

past experiments = 1 detector

next generation > 2 detectors

Ref: KamLAND, Daya Bay, McKeown

World of Proposed Reactor θ_{13} Neutrino Experiments

Double Chooz and Daya Bay have strong international collaborations.
→Ready to start construction.

Proposed and R&D.

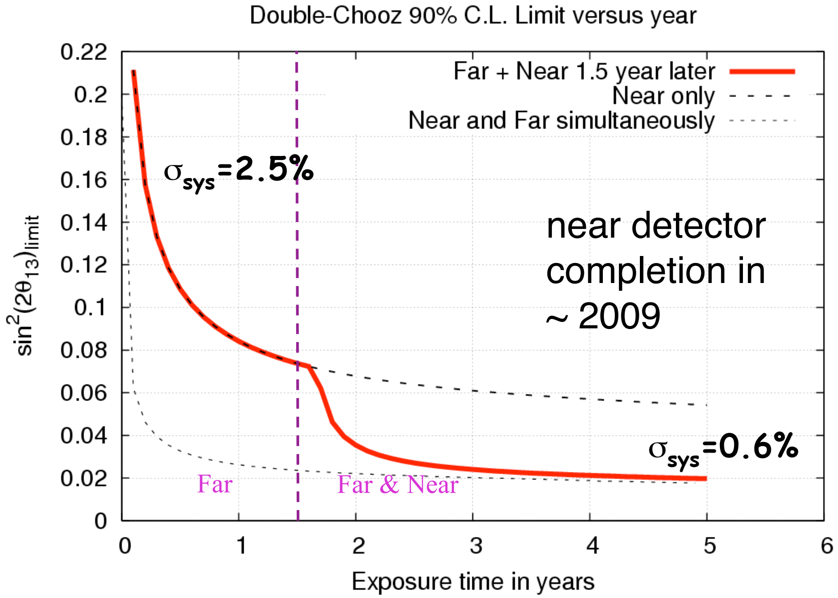
Double Chooz

10.2 tons detectors

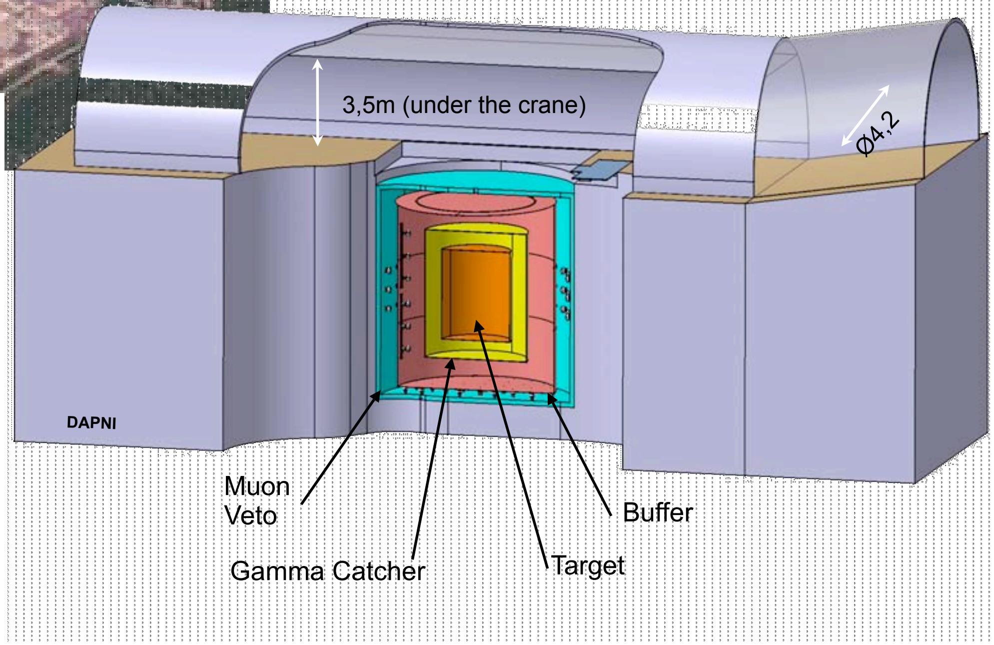
8.4 GW_{th} reactor power

300 mwe overburden at far site

60 mwe overburden at near site



near detector completion in ~ 2009



http://doublechooz.in2p3.fr/

Daya Bay, China

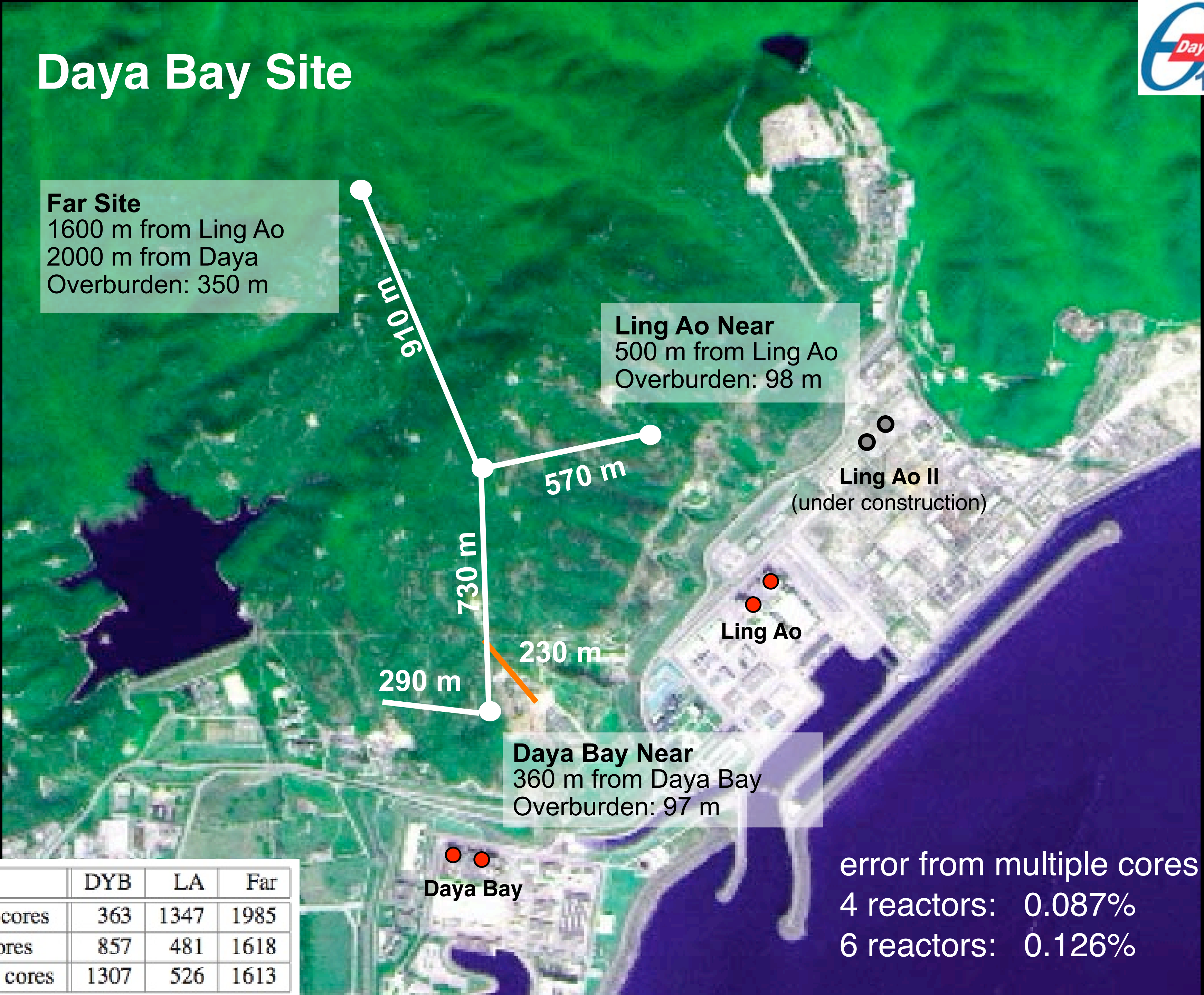
Powerful ν_e Source:
Multiple reactor cores.
(at present 4 units with 11.6 GW$_{th}$,
in 2011 6 units with 17.4 GW$_{th}$)

Shielding from Cosmic Rays:
Up to 1000 mwe overburden nearby.

Adjacent to mountain.

http://dayawane.ihep.ac.cn/

Daya Bay Site



Far Site
1600 m from Ling Ao
2000 m from Daya
Overburden: 350 m

Ling Ao Near
500 m from Ling Ao
Overburden: 98 m

Daya Bay Near
360 m from Daya Bay
Overburden: 97 m

Sites	DYB	LA	Far
DYB cores	363	1347	1985
LA cores	857	481	1618
LA II cores	1307	526	1613

error from multiple cores
4 reactors: 0.087%
6 reactors: 0.126%

Detecting Reactor $\bar{\nu}_e$

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

0.3 b ↳ $+ p \rightarrow D + \gamma$ (2.2 MeV) (delayed)

49,000 b ↳ $+ Gd \rightarrow Gd^*$ ↳ $\rightarrow Gd + \gamma$'s (8 MeV) (delayed)

coincidence signal allows background suppression

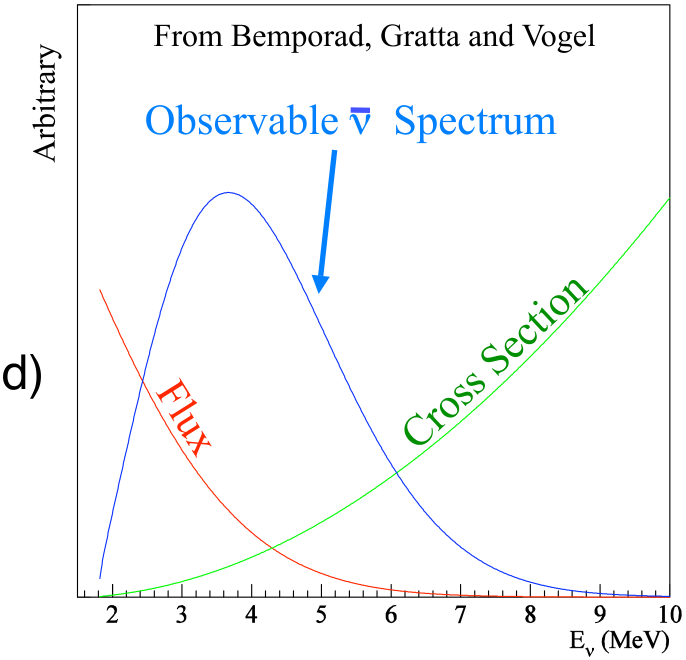
0.1% Gadolinium-Liquid Scintillator

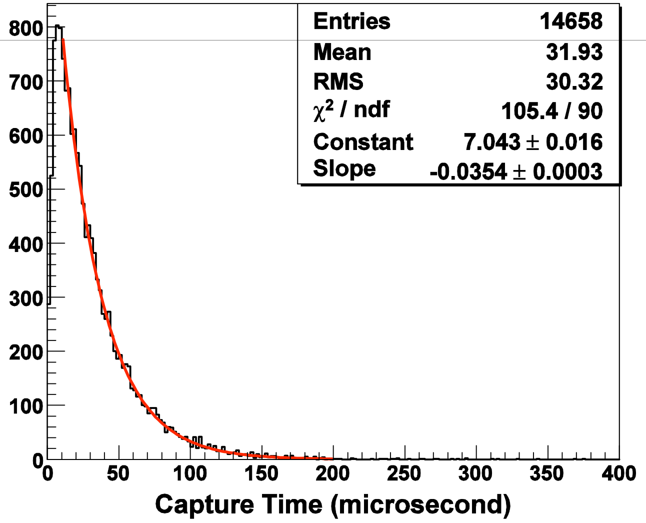
- Proton-rich target
- Easily identifiable n-capture signal above radioactive backgrounds
- Short capture time ($\tau \sim 28\ \mu s$)
- Good light yield

^{155}Gd $\Sigma\gamma$=7.93 MeV

^{157}Gd $\Sigma\gamma$=8.53 MeV

other Gd isotopes with high abundance have very small neutron capture cross sections


From Bemporad, Gratta and Vogel

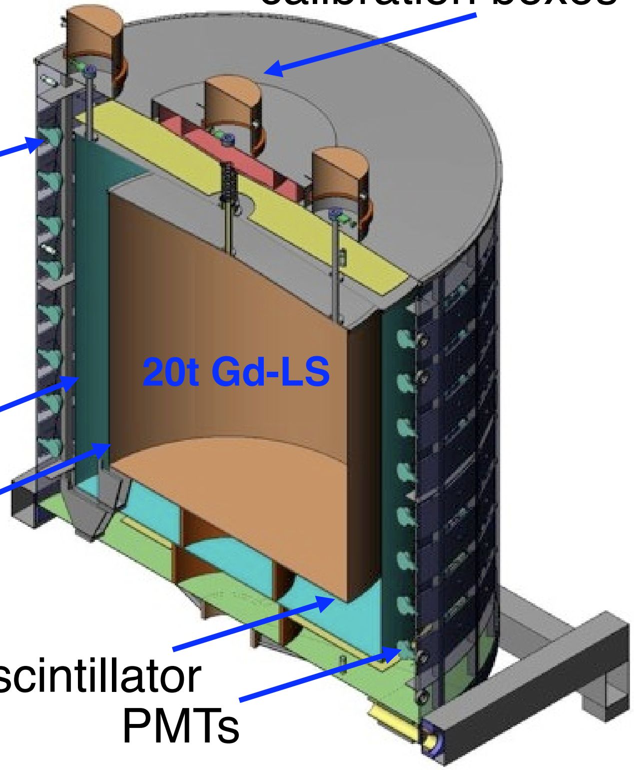


Baseline Design of Detector and Halls

multiple 3-zone antineutrino detectors

muon detectors

- water pool and Cherenkov counter
- RPC on top for tracking muons



calibration boxes

steel tank

20t Gd-LS

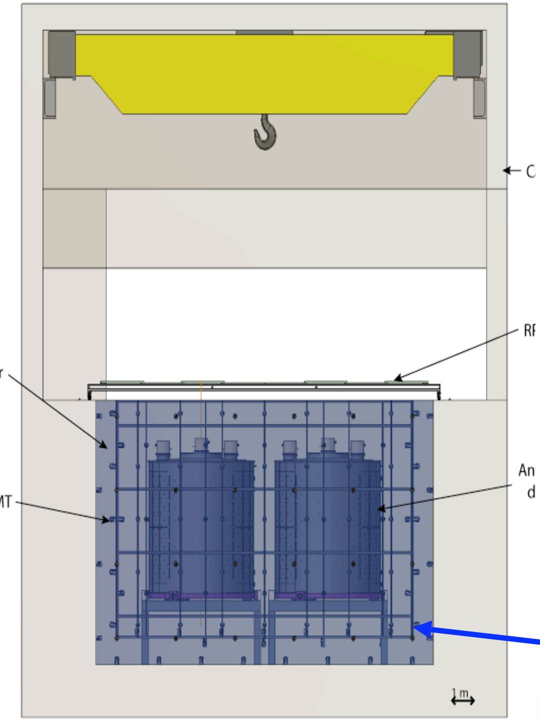
outer acrylic tank

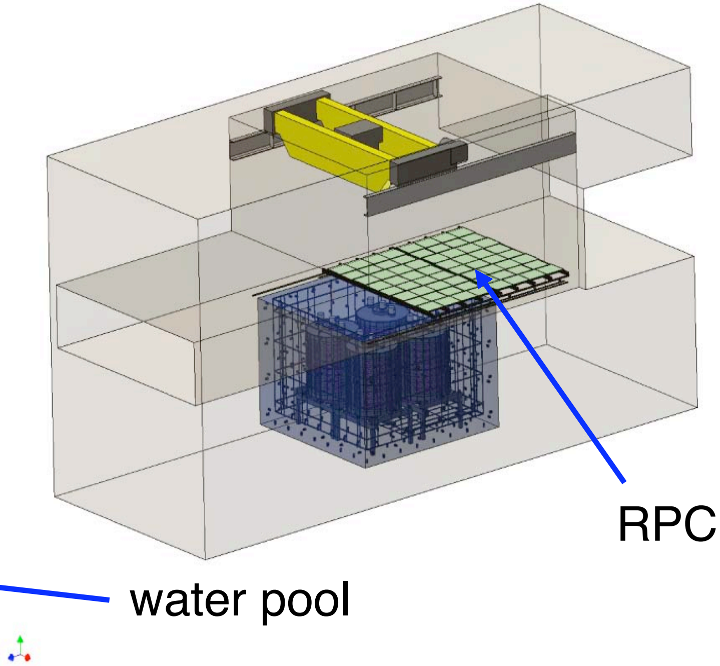
inner acrylic tank

scintillator

PMTs

8 antineutrino detectors



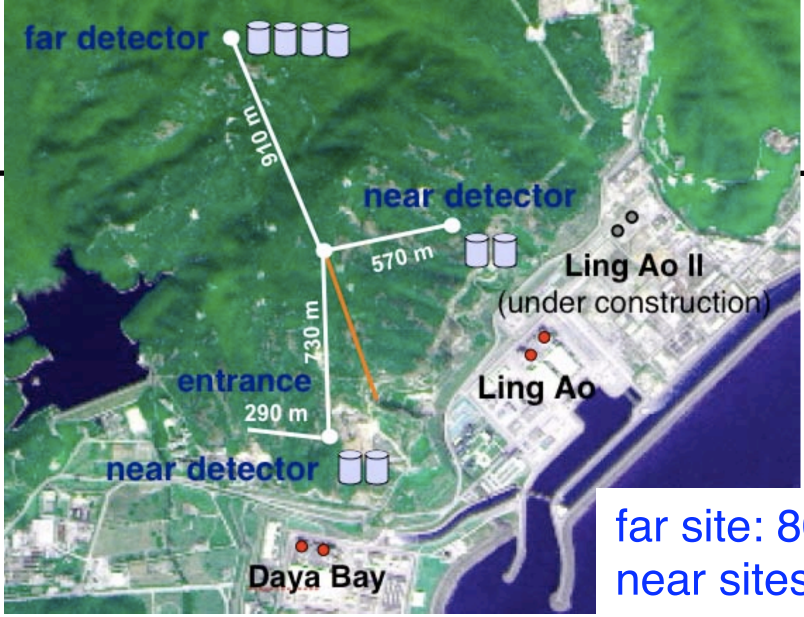


water pool

RPC

3 experimental halls and muon systems

Event Rates and Signal



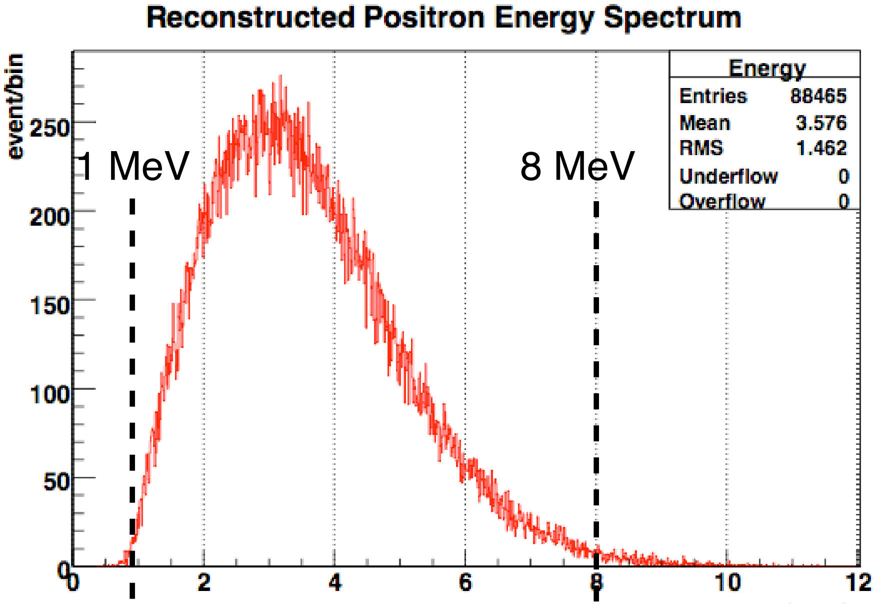
far site: 80 tons
near sites: 40 tons

Antineutrino Interaction Rates

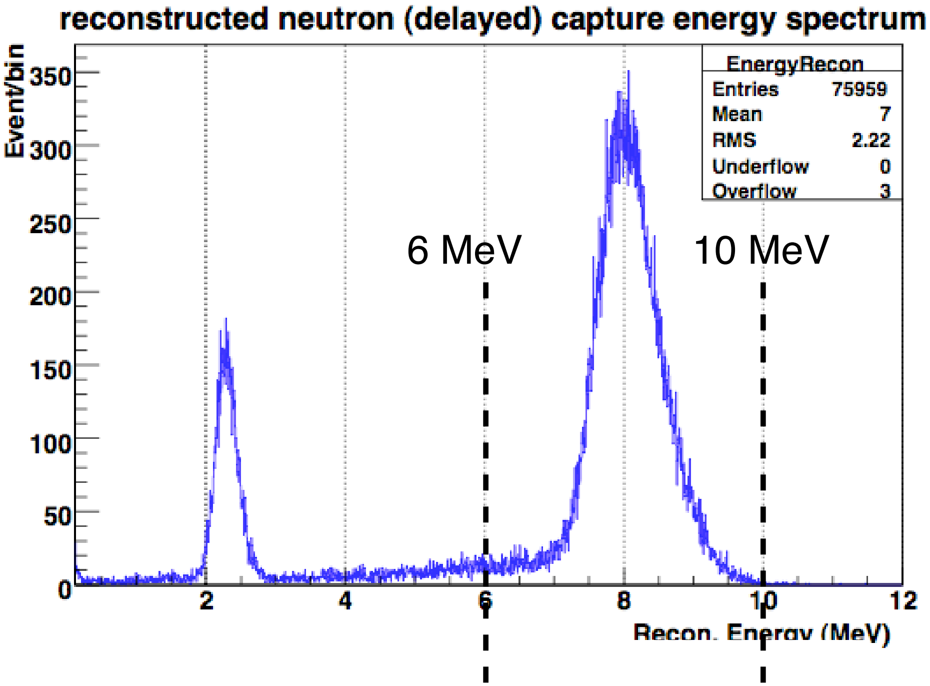
(events/day per 20 ton module)

Daya Bay near site	960
Ling Ao near site	~760
Far site	90

Prompt Energy Signal



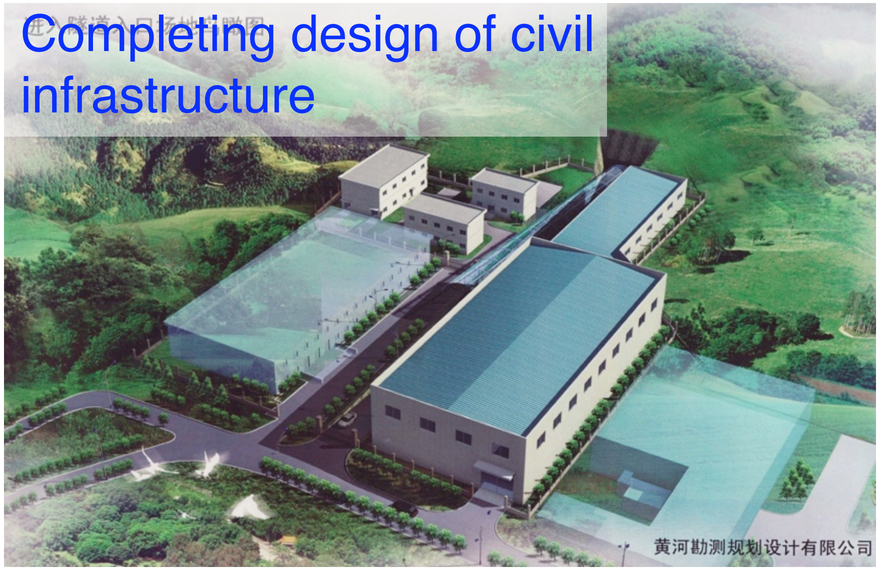
Delayed Energy Signal



Statistics comparable to single detector in far hall

Design, R&D, and Prototyping for Daya Bay

Completing design of civil infrastructure

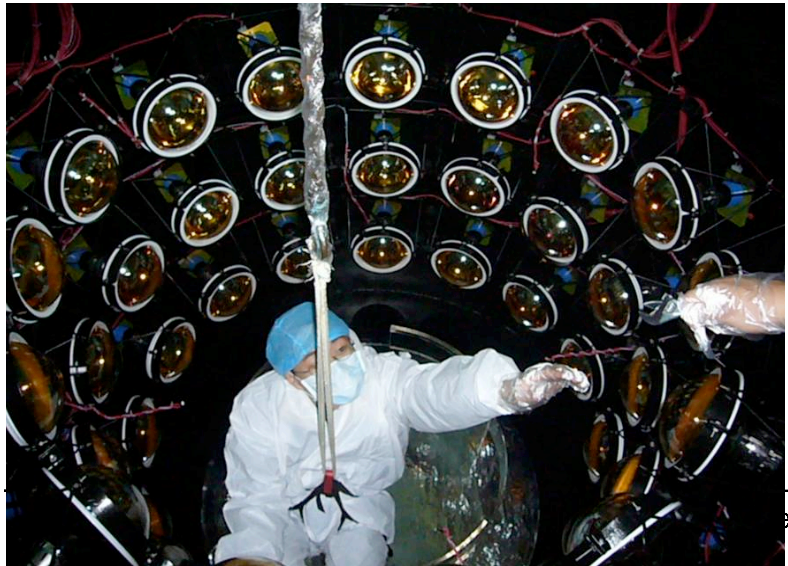


Gd-LS R&D in US and China

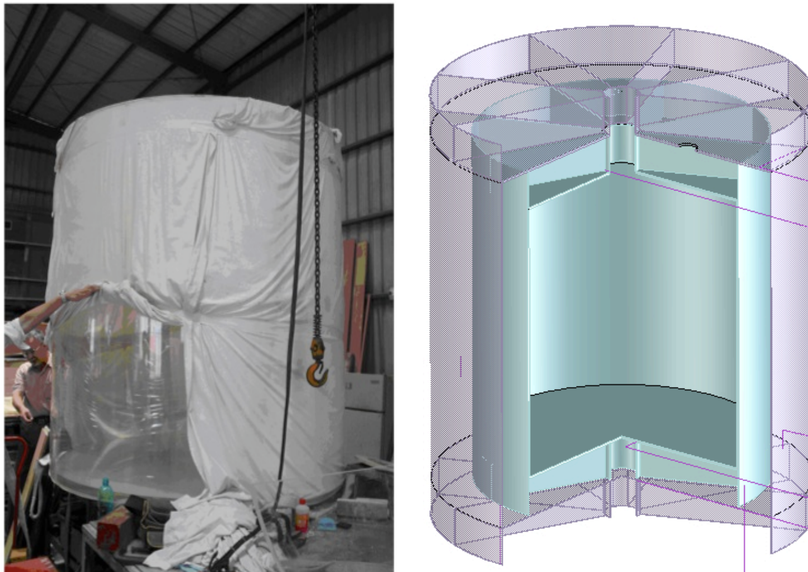

solvent extraction


solid dissolution

Detector Prototypes at IHEP and in Hong Kong



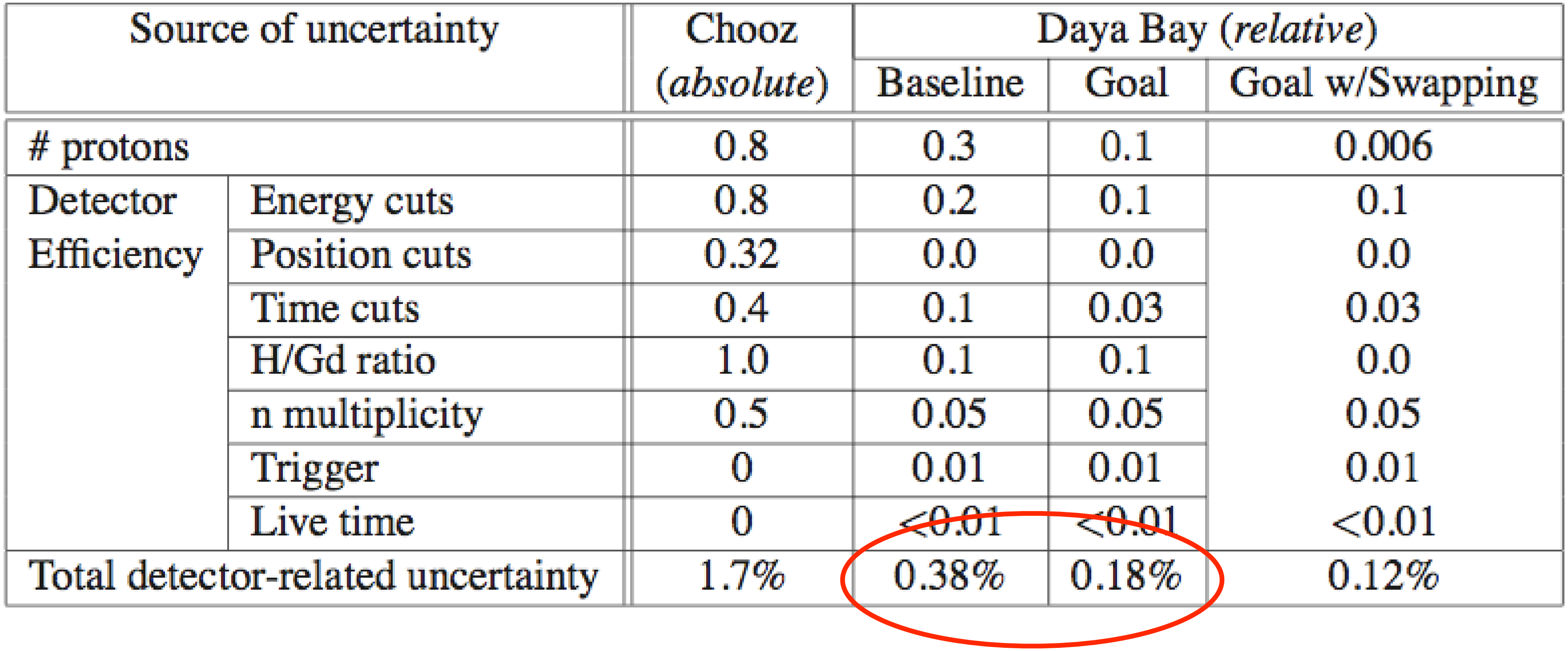
Acrylic Vessel R&D



Detector-related Uncertainties

Absolute measurement

Relative measurement



Source of uncertainty		Chooz (*absolute*)	Daya Bay (*relative*)		
			Baseline	Goal	Goal w/Swapping
# protons		0.8	0.3	0.1	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%

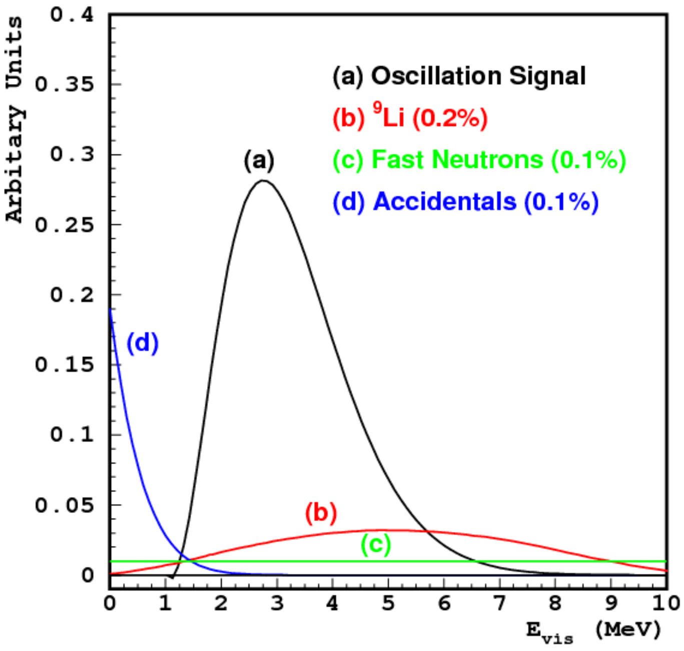
Baseline: currently achievable **relative** uncertainty without R&D
Goal: expected **relative** uncertainty after R&D

for relative measurement between detectors at near and far sites

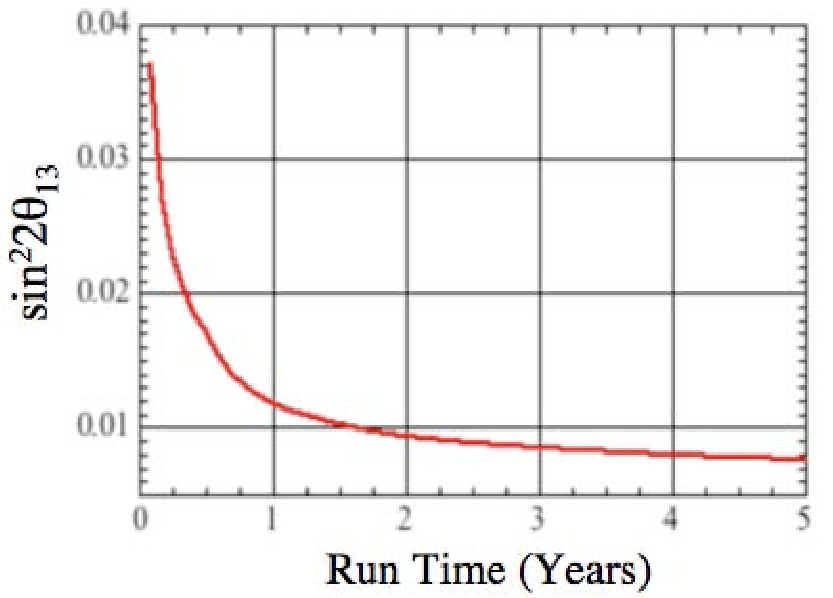
Daya Bay Background Summary

	Daya Bay site	**Ling Ao site**	**Far site**
Accidental/signal	<0.2%	<0.2%	<0.1%
Fast n / signal	0.1%	0.1%	0.1%
^{9}Li-^{8}He / signal	0.3%	0.2%	0.2%

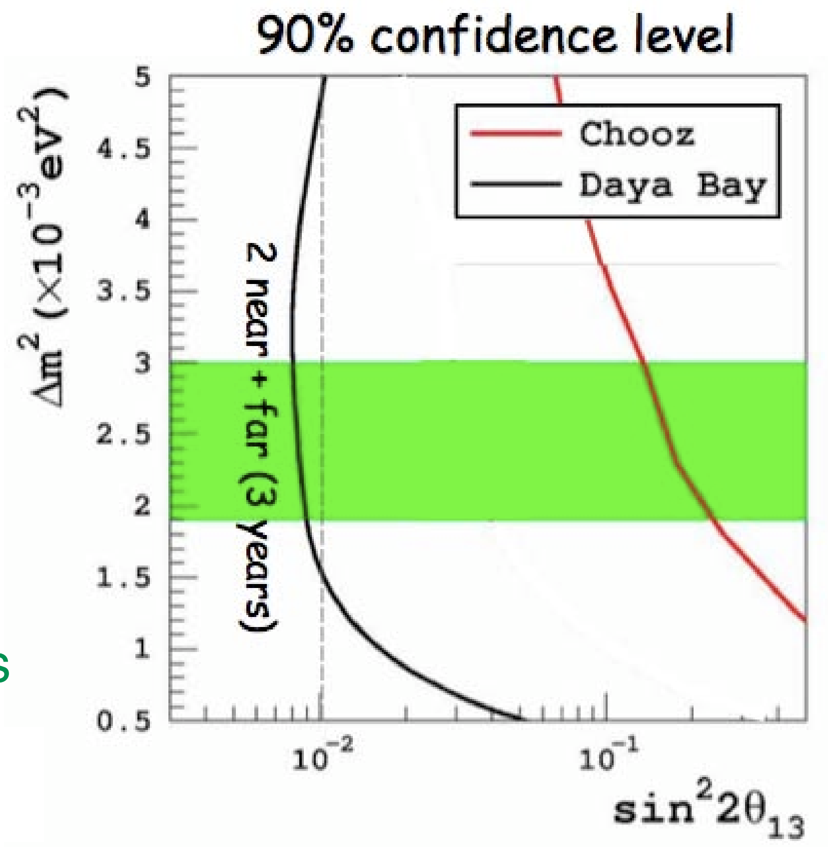
- B/S ~ same for near and far sites
- constrained by measurements to required precision
- input to sensitivity calculations (assume 100% uncertainty)



Daya Bay Sensitivity & Milestones



- Reactor-related systematics: 0.09% (4 cores)
  0.13% (6 cores)
- Relative detector systematics: 0.38% (baseline)
- Backgrounds will be measured: < 0.2%



- Apr ‘07 completed DOE CD-1 review

- Jul ‘07 start civil construction
- Oct ‘08 delivery of Gd-LS to Daya Bay
- Aug-Dec ‘08 assembly of first detector pair

- May ‘09 start data taking at near site
- Mar ‘10 start data taking at near+far sites

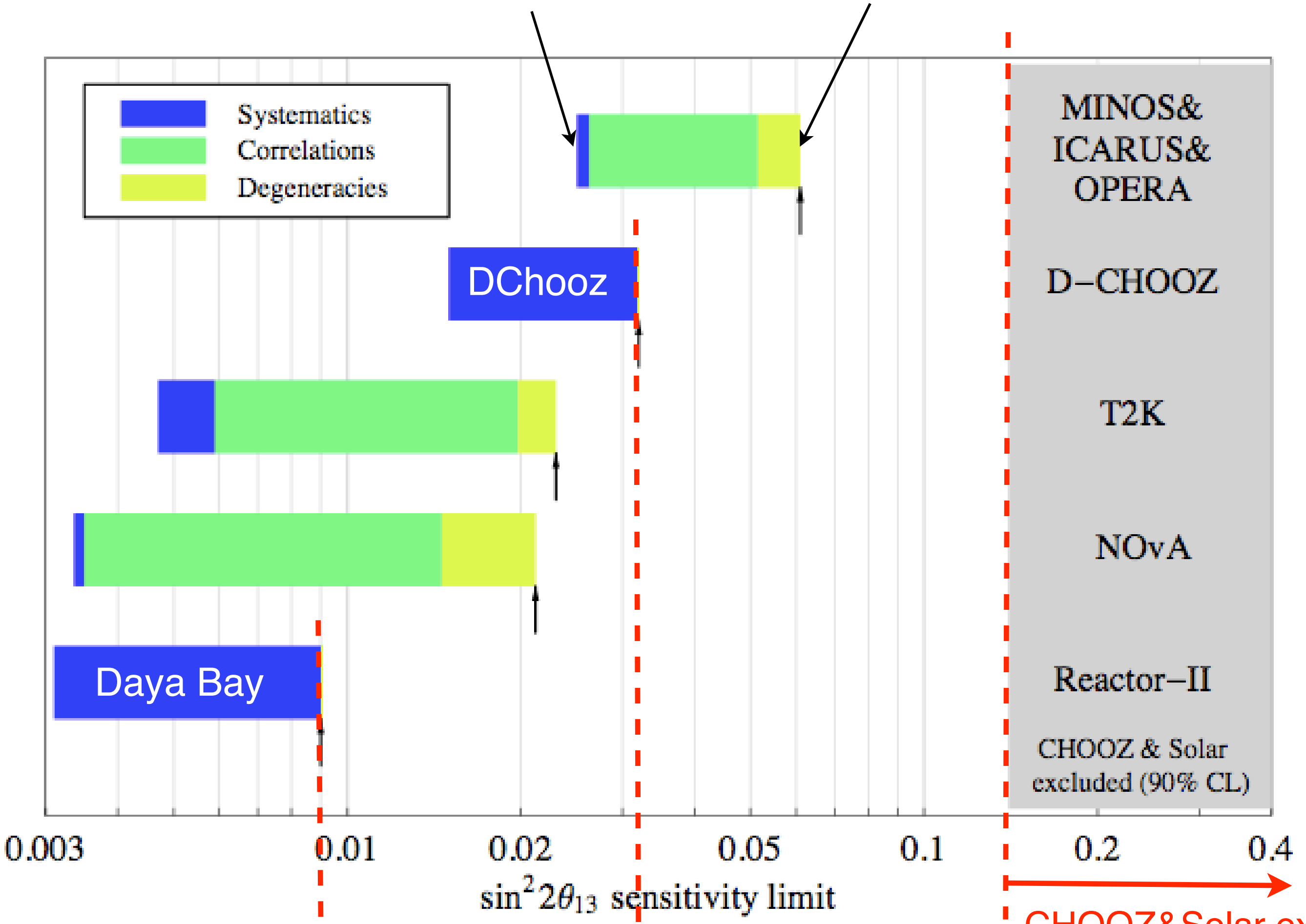
→**U13.00005:** The Daya Bay Reactor Neutrino Experiment
Mary Bishai

Proposed Reactor θ_{13} Neutrino Experiments

	Location	Thermal Power (GW)	Distances Near/Far (m)	Depth Near/Far (mwe)	Target Mass (tons)
Angra *proposed*	Brazil	4.1	300/1500	250/2000	500
Daya Bay *construction start in ‘07*	China	11.6 17.4 after 2010	360(500)/1750	260/910	80
Double-CHOOZ *under construction*	France	8.7	150/1067	60/300	10.2
RENO *R&D*	Korea	17.3	150/1500	230/675	20

** experiments that are underway*

$\sin^2 2\theta_{13}$ Sensitivity Limits



statistics limit

systematics limit

2011-13

2010-12

CHOOZ&Solar excluded now

Ref: FNAL proton driver report, hep-ex/0509019

Neutrino Physics at Reactors

Past Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France
Reactors in Japan

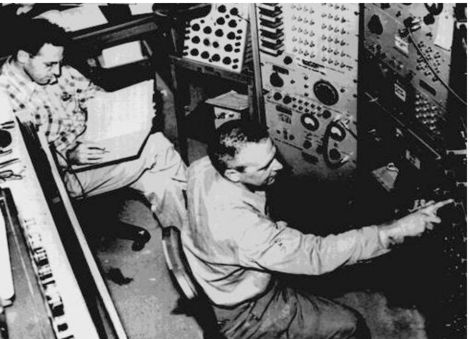
Next step
High-precision measurement of θ_{13}
....open door for CP violation searches

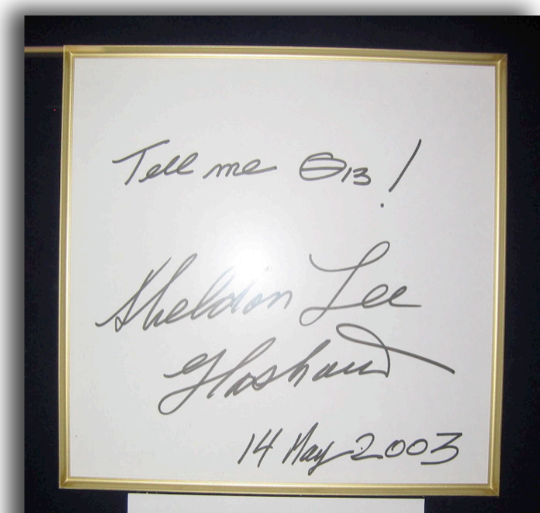
2002
Discovery of reactor antineutrino oscillation

1995
Nobel Prize to Fred Reines at UC Irvine

1980s & 1990s
Reactor neutrino flux measurements in U.S. and Europe

1956
First observation of neutrinos





Tell me Θ_{13}!
Sheldon Lee Glashow
14 May 2003