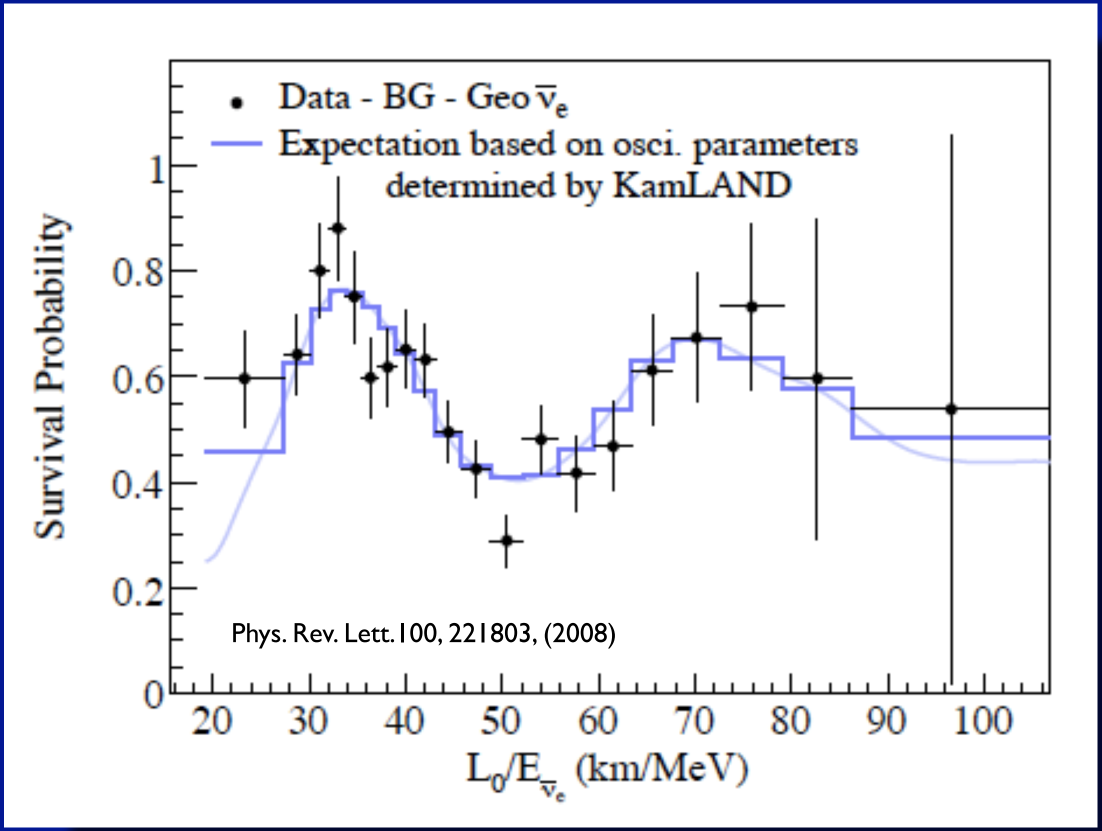
Prospects for Measuring θ_{13}

Aspen Winter Conference
February 13, 2009

Lindley Winslow

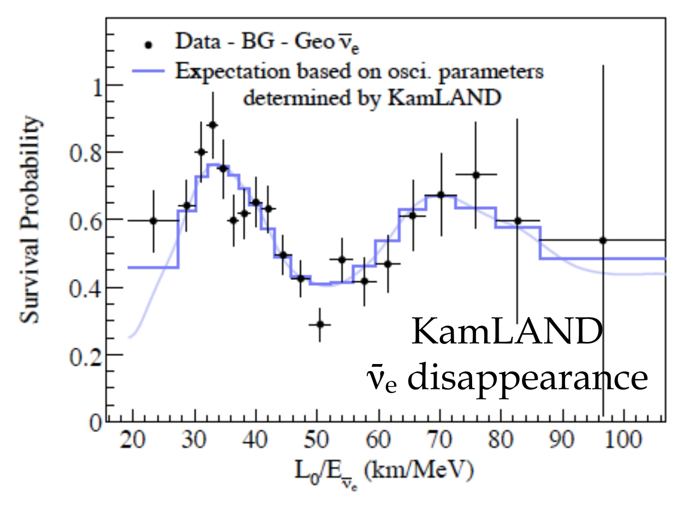
Neutrinos Oscillate:

$$P_{e,e} = 1 - sin^2 2\theta_{12} sin^2(1.27\Delta m^2_{12} L/E)$$

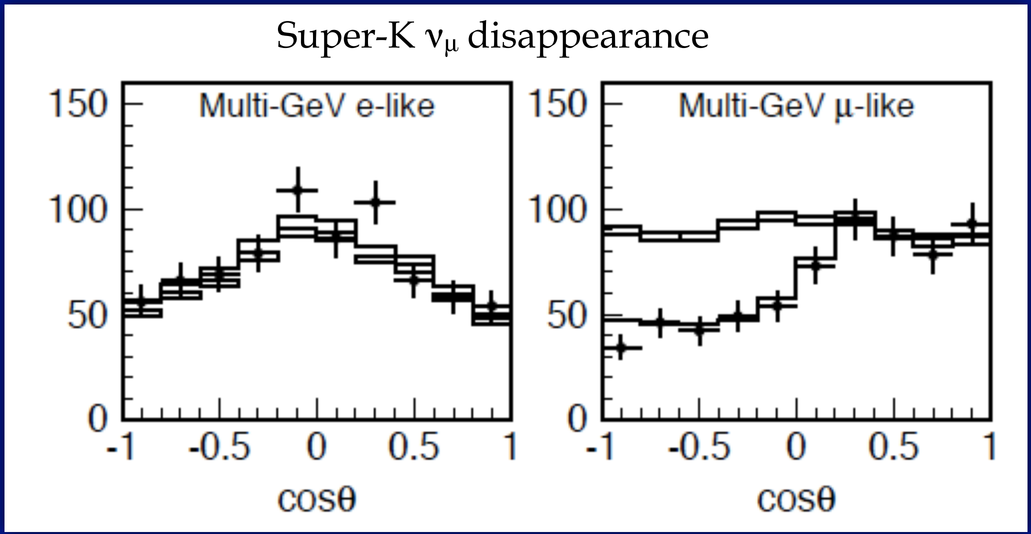


Phys. Rev. Lett.100, 221803, (2008)

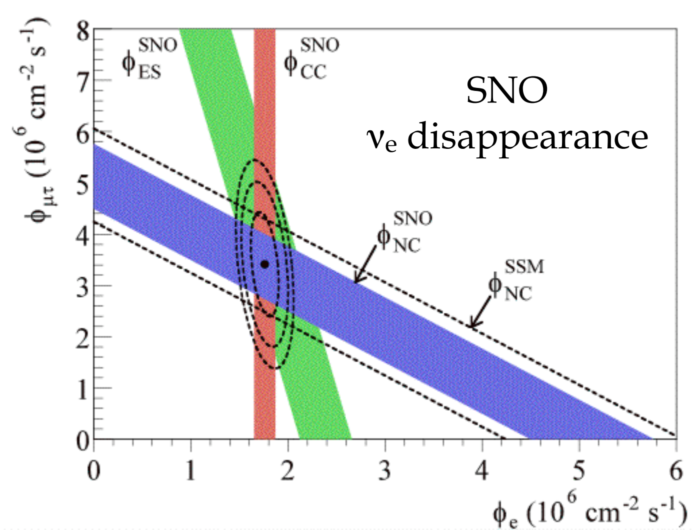
Neutrinos Oscillate:



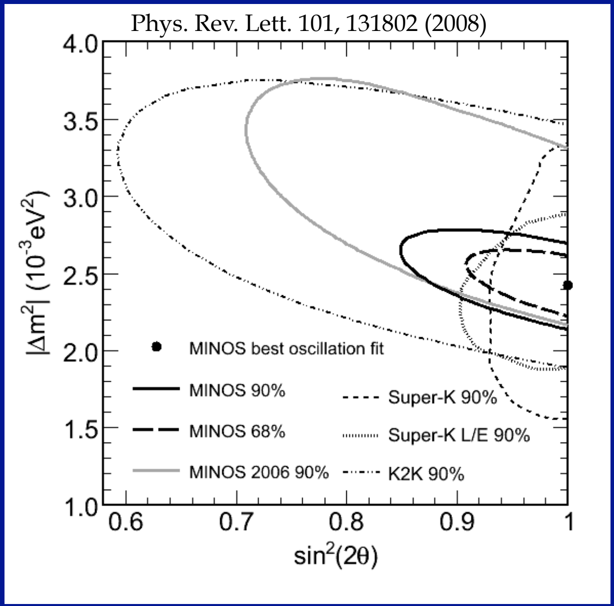
KamLAND
$\bar{\nu}_e$ disappearance



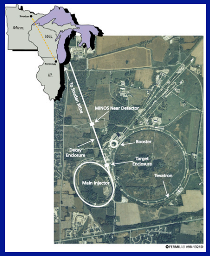
Super-K ν_μ disappearance



SNO
ν_e disappearance



Phys. Rev. Lett. 101, 131802 (2008)



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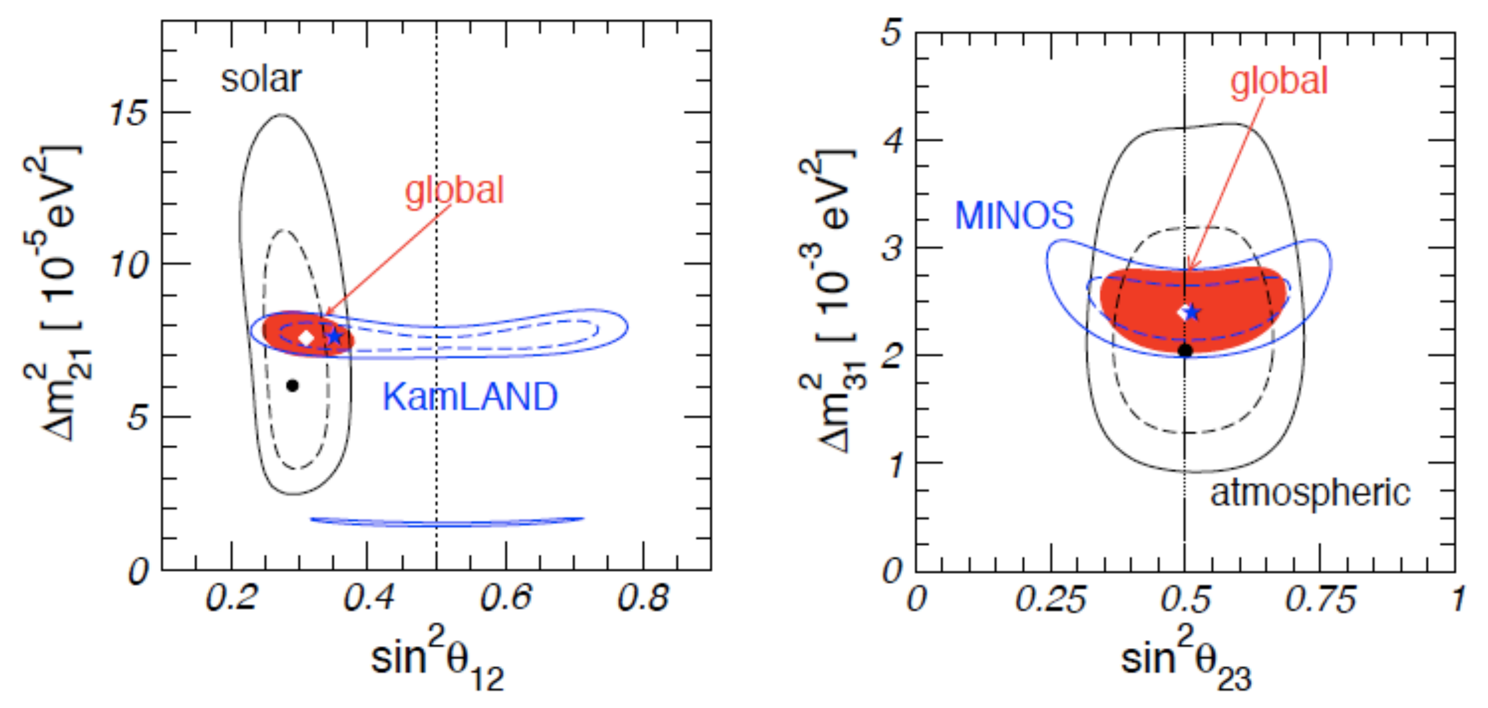
Global Fit to All Data:

Maltoni and Schwetz arXiv:0812.3161 [hep-ph]



Mixing in the Lepton Sector:

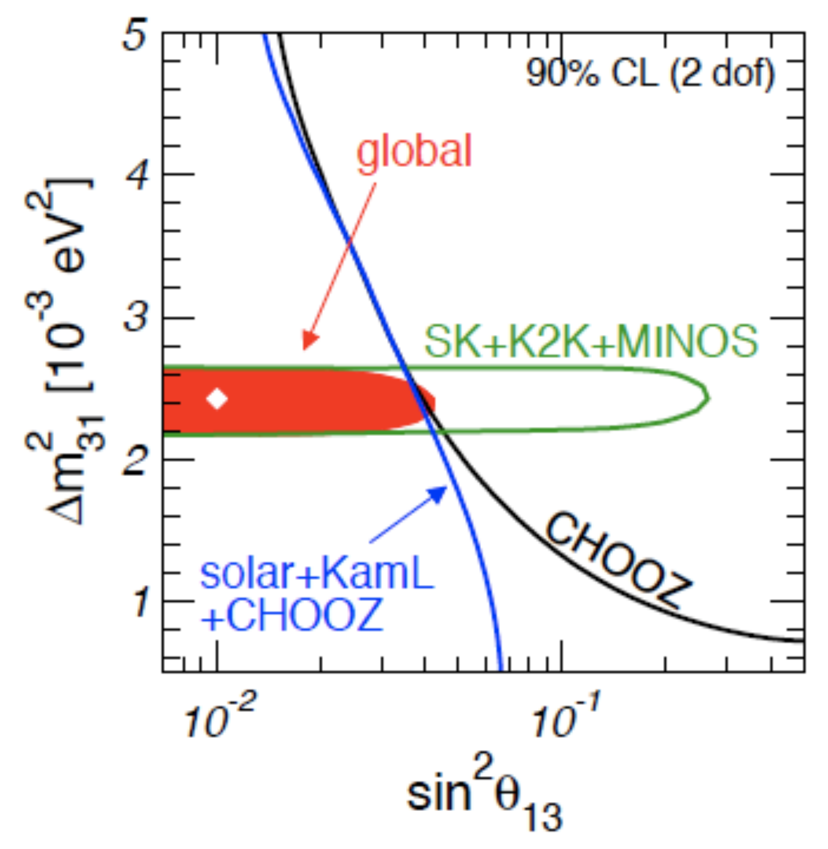
$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j}\,|\nu_j\rangle$$

$$U_{\alpha j} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\xi_1/2} & 0 & 0 \\ 0 & e^{i\xi_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

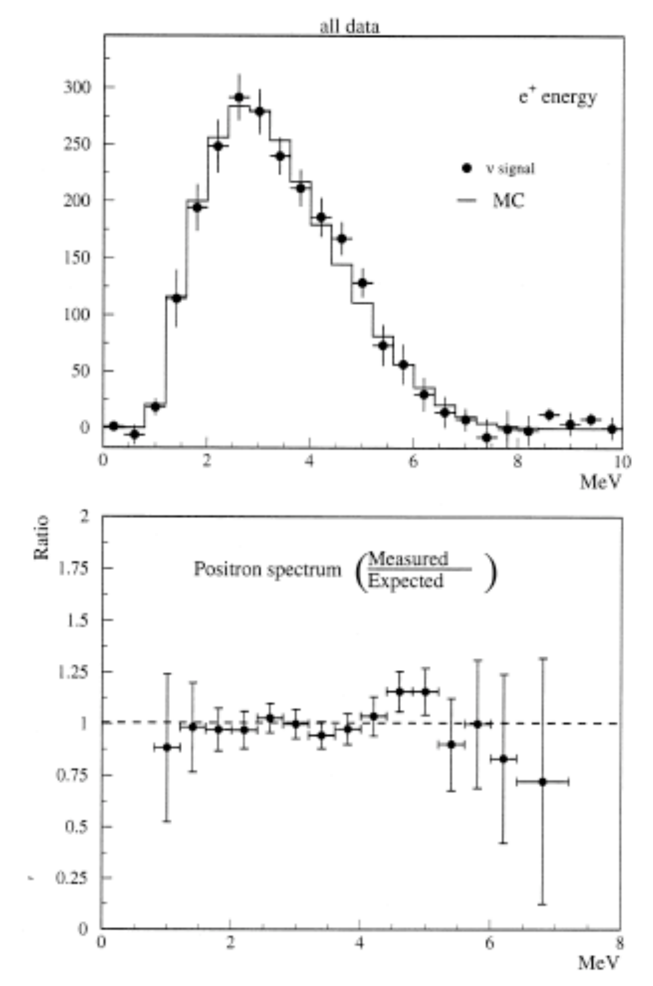
Not accessible to oscillation experiments, see Cuore, EXO, Majorana ....

Best θ_{13} Limit: Chooz Experiment

Maltoni and Schwetz arXiv:0812.3161 [hep-ph]



Phys. Lett. B 466, (1999) 415-430



$\sin^2\theta_{13}<0.056$ at 3σ → $\sin^2 2\theta_{13}<0.21$

The “Hard” Way:

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13}\, T_1 - \alpha \sin 2\theta_{13}\, T_2 + \alpha \sin 2\theta_{13}\, T_3 + \alpha^2 T_4$$

A ν_e appearance experiment

$$T_1 = \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$

$$x \equiv 2\sqrt{2} G_F N_e E / \Delta m^2_{31}$$

$$\alpha \equiv \Delta m^2_{21} / \Delta m^2_{31}$$

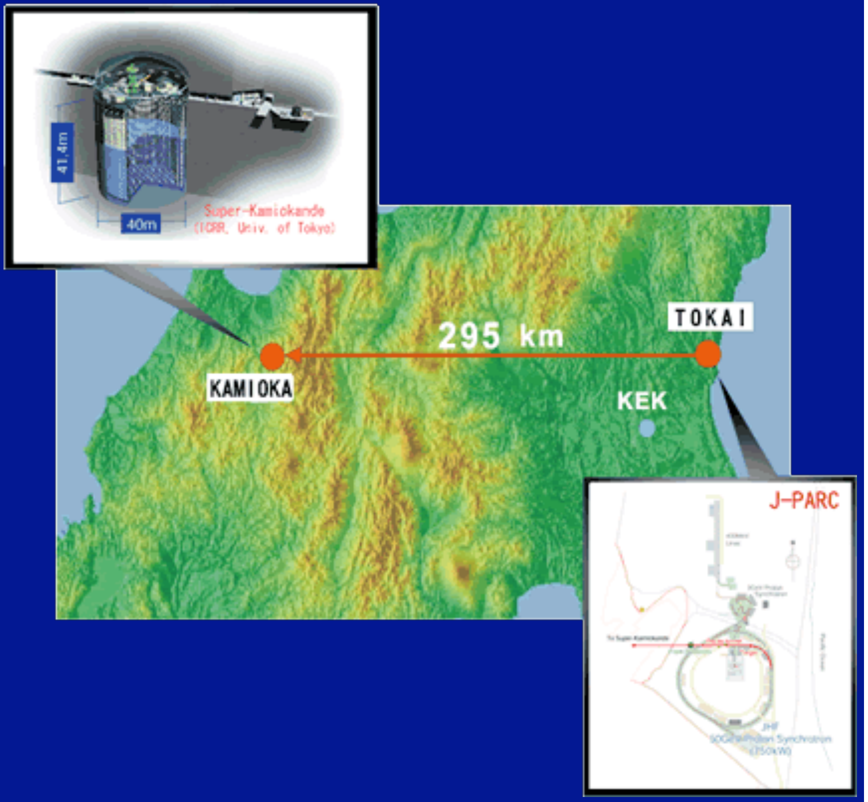
$$T_2 = \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$T_3 = \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

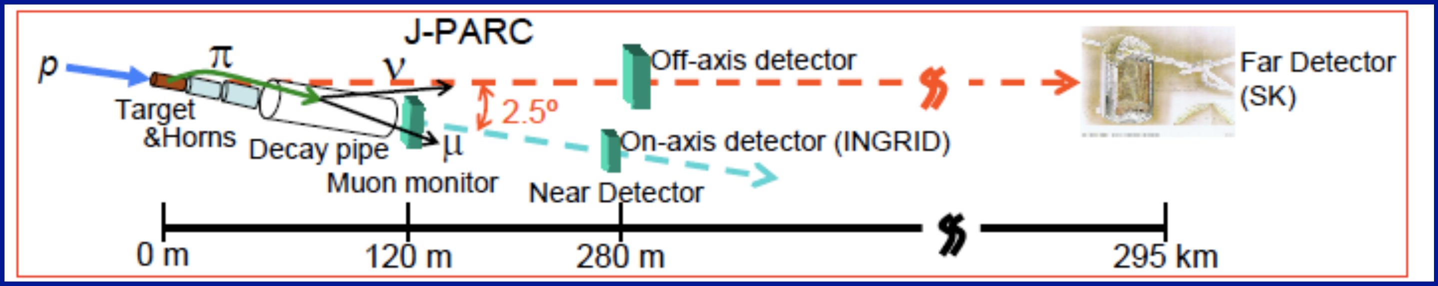
$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

T2K (Tokai to Kamioka):

- Accelerator is being commissioned.
- First Neutrino Beam April 2009.
- On-Axis detector will be complete.
- Off-Axis detector Fall 2009.
- Super-K upgrade is complete.



Sensitivity for 0.75kW and 5yrs:
$\sin^2 2\theta_{13} \sim 0.008$
Reduce uncertainty in
$\delta(\Delta m_{23}) < 10^{-4}\mathrm{eV}^2$
$\delta(\sin^2\theta_{23}) \sim 0.01$



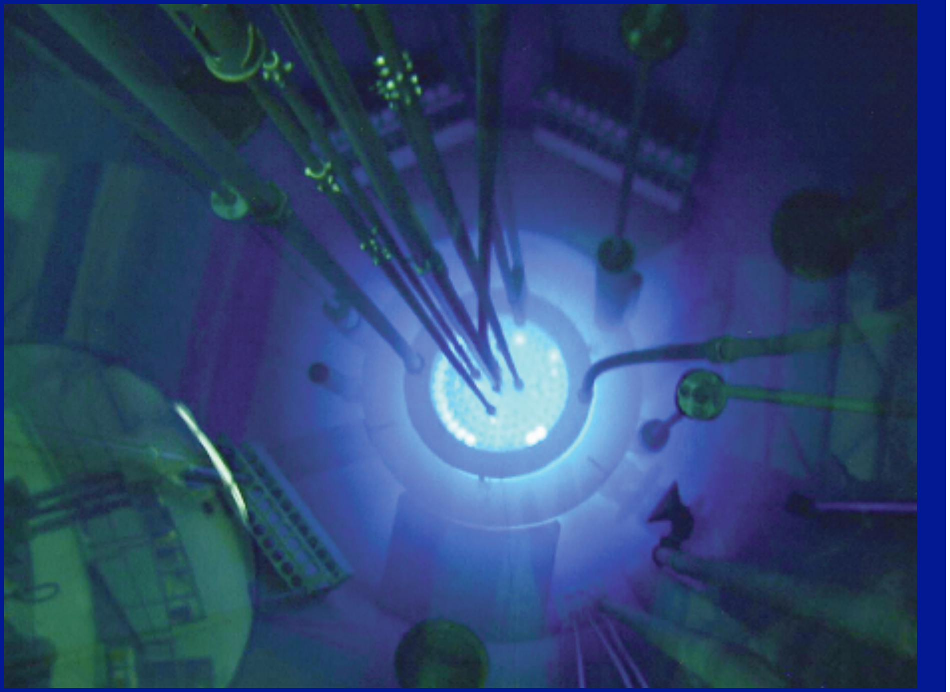
The “Easy” Way:

$$P_{ee}(E_{\overline{\nu}_e}, L, \Delta m^2_{31}, \theta_{13}) = 1 - \sin^2(2\theta_{13}) \sin^2\left(1.27\frac{\Delta m^2_{31}[10^{-3}\ \mathrm{eV}^2]L[\mathrm{km}]}{E_{\overline{\nu}_e}[\mathrm{MeV}]}\right)$$

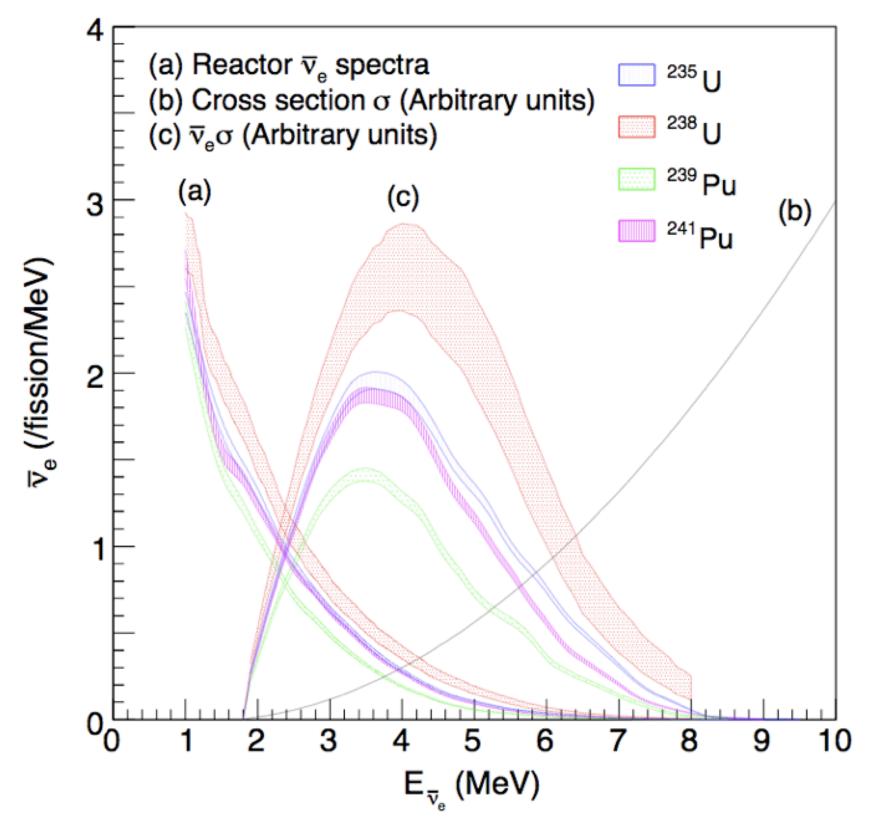
A $\bar{\nu}_e$ disappearance experiment

Reactors are a Good Source of Anti-Neutrinos!

Nakajima NIMA 569, 837-844 (2006)



$1\mathrm{GW}_{th} \sim 2\times10^{20}\ \bar{\nu}_e/s$



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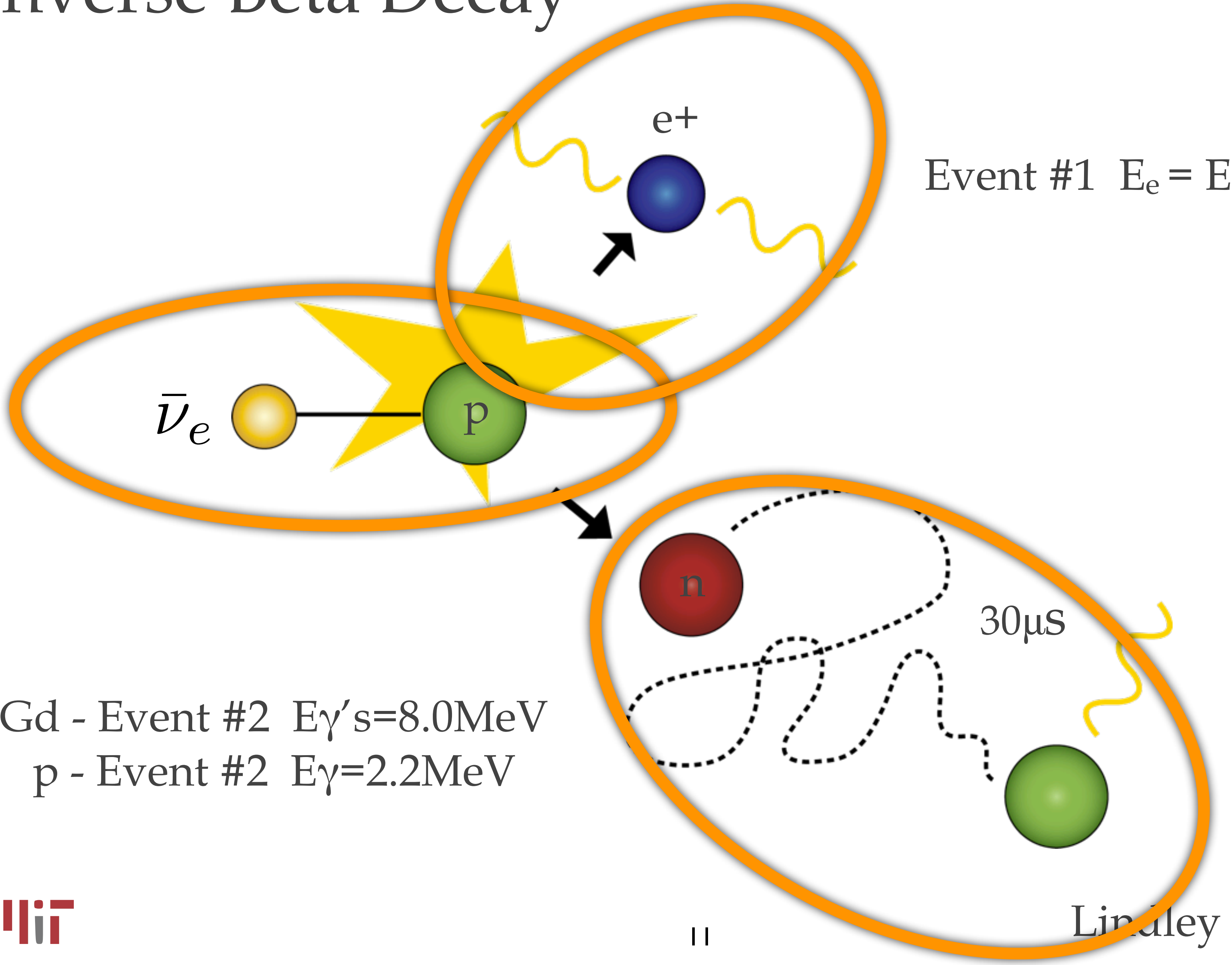
Anti-Neutrino Detection:
Inverse Beta Decay



Event #1 $E_e = E_\nu - 0.8\text{MeV}$

Gd - Event #2 Eγ's=8.0MeV

p - Event #2 Eγ=2.2MeV

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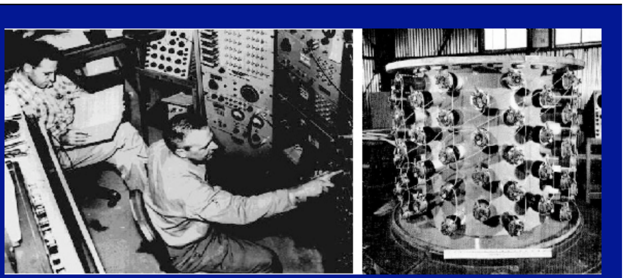
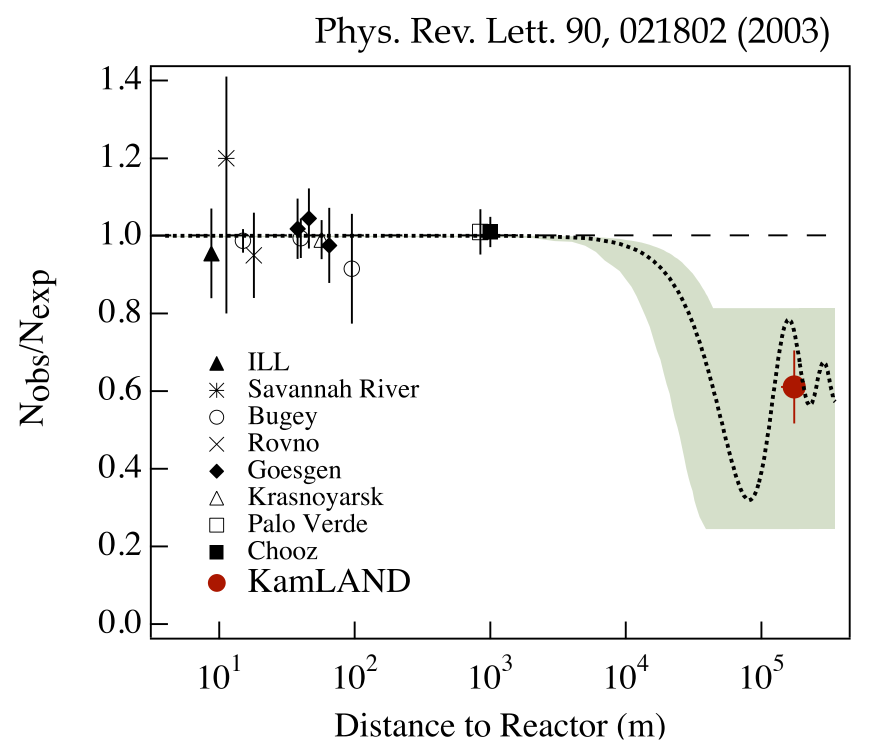
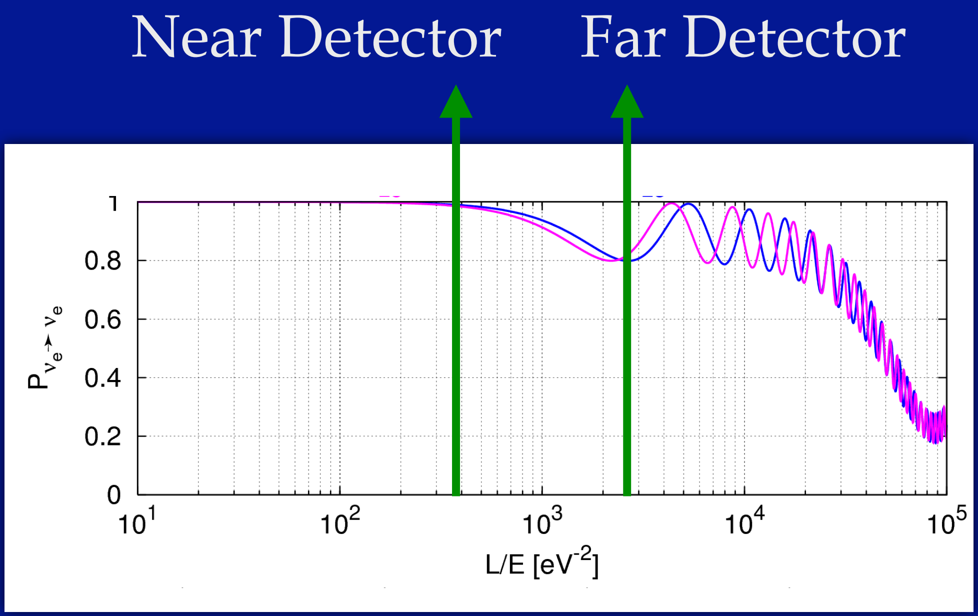
Reactor Neutrino Experiments:



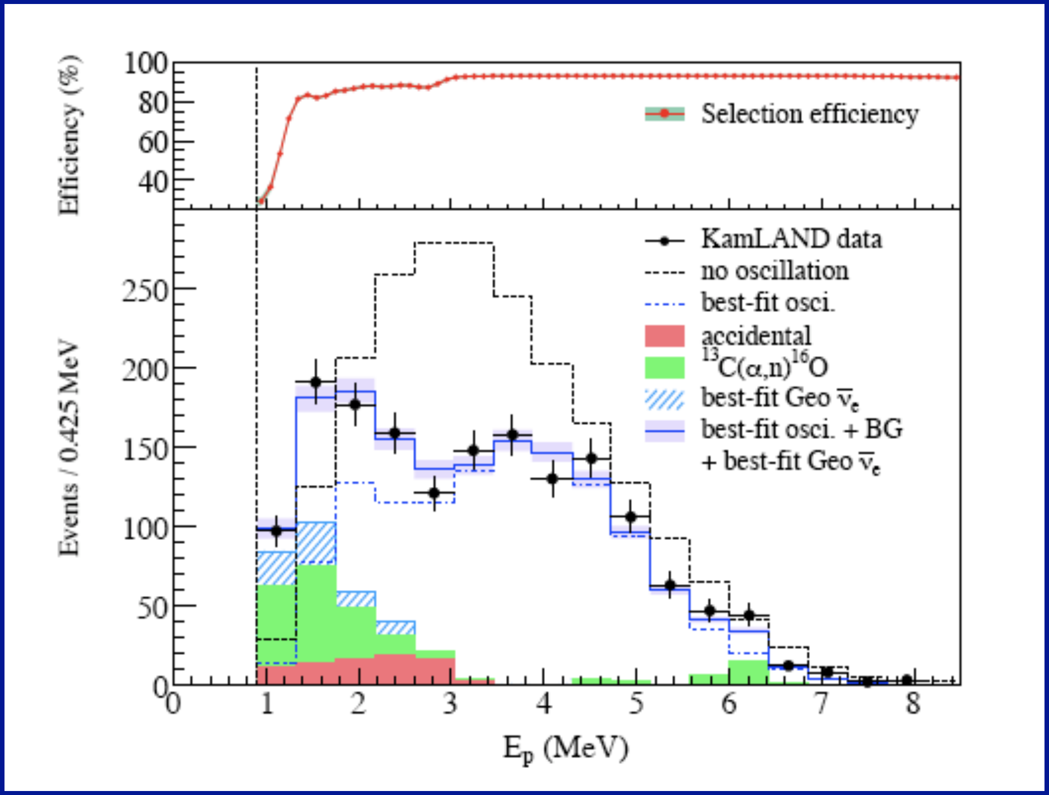


Phys. Rev. Lett. 90, 021802 (2003)

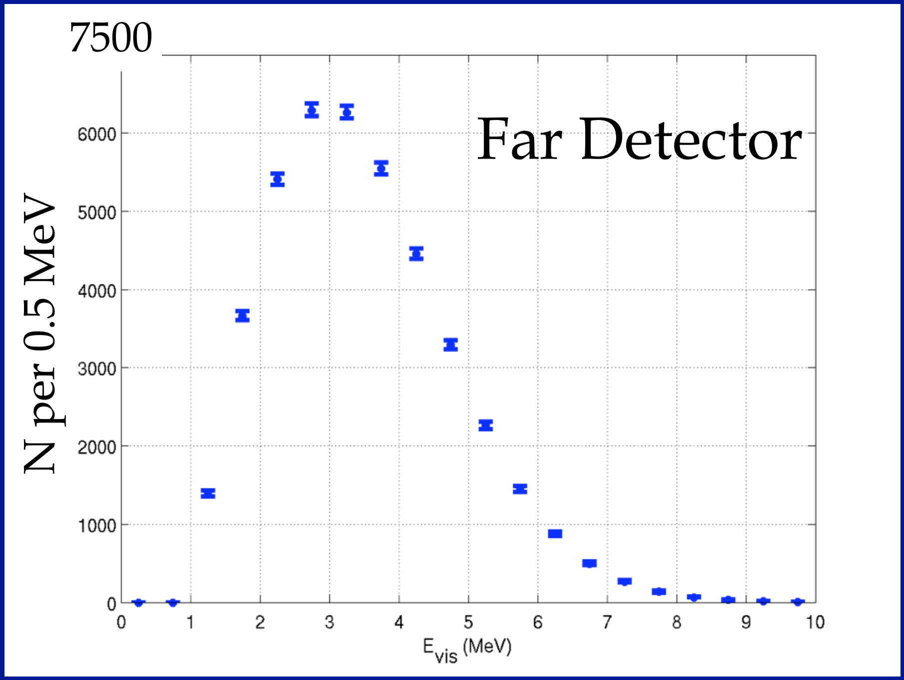


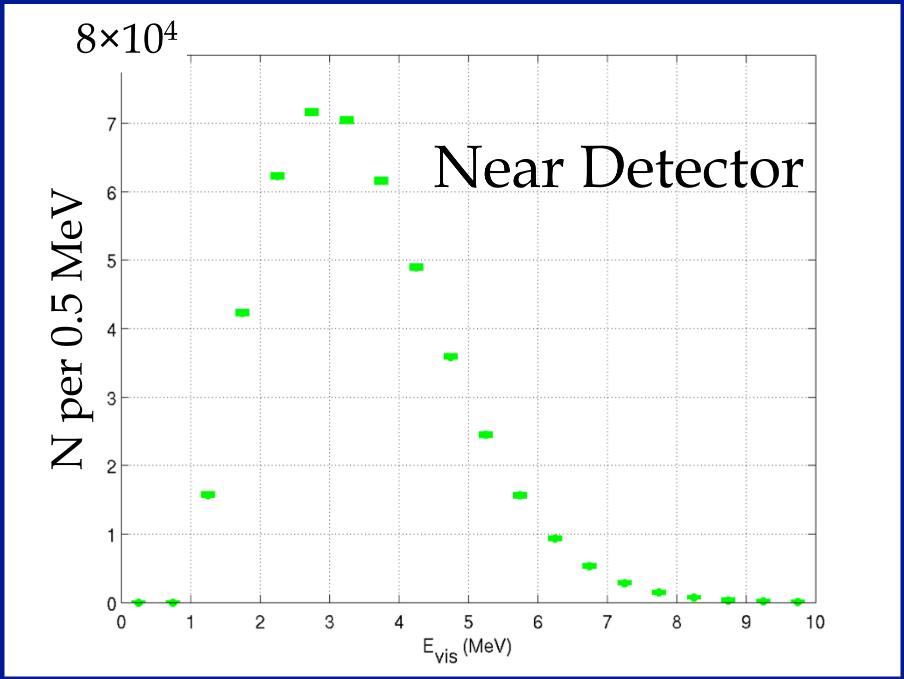
Reactor Systematics	Systematic	Chooz	2 Identical Detectors
	Flux, Cross Section	1.9%	< 0.1%
	E/Fission	0.7%	< 0.1%
	Thermal power	0.6%	< 0.1%
	Total	2.1%	< 0.1%

Reactor Neutrino Experiments:

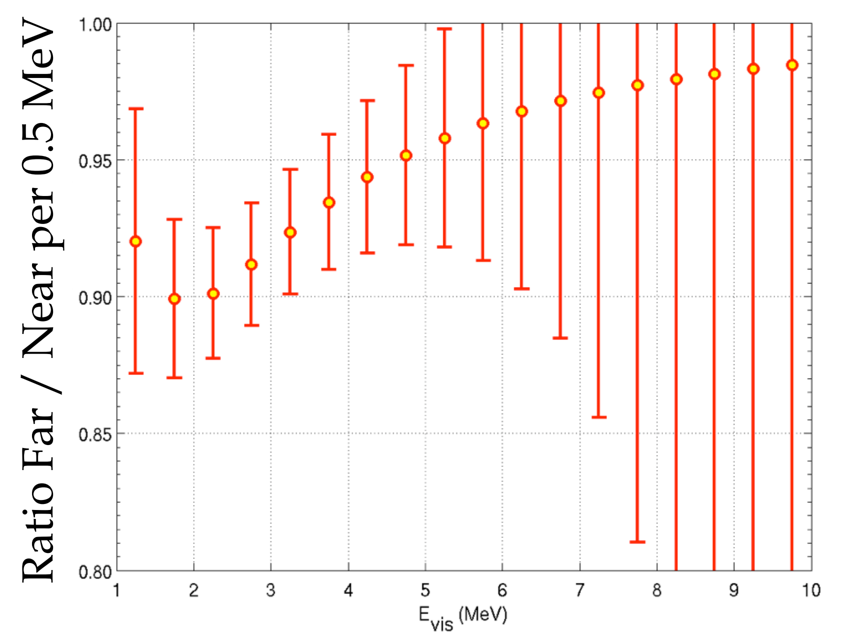


Neutrino Oscillation Predicts Energy Spectrum distortion!
Example: KamLAND's Spectrum.





Ratio of Far/Near Spectra



Predictions for Double Chooz
for 3 years of data with 2 detectors.
$\sin^2 2\theta_{13}=0.1$ and $\Delta m_{31}^2=2.5\times10^{-3}\mathrm{eV}^2$

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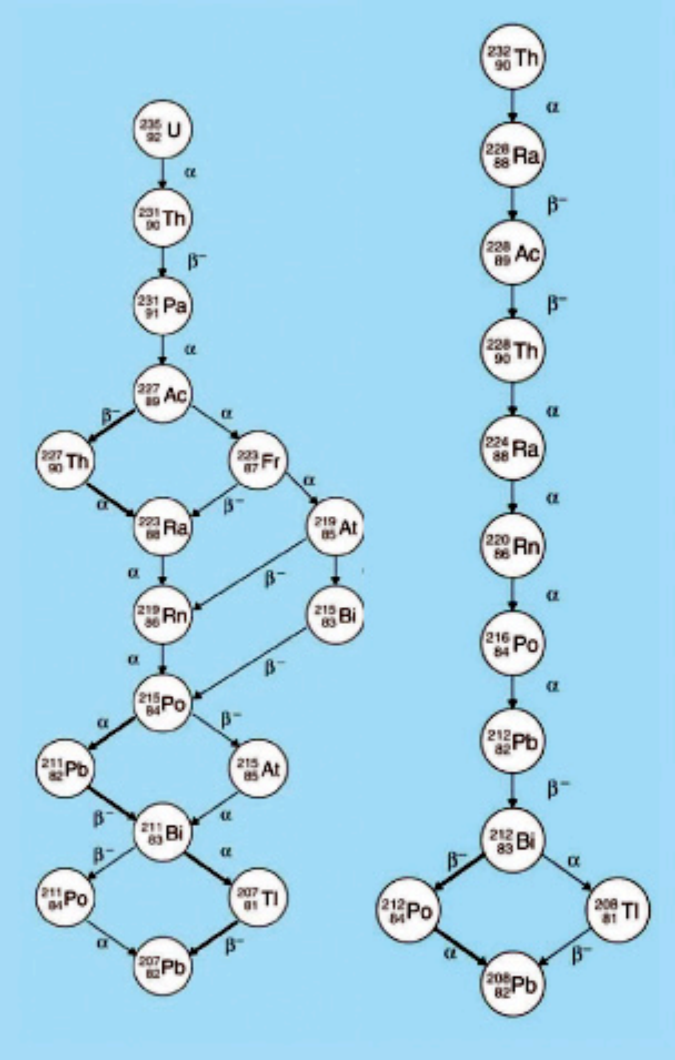
Sensitivity of Experiments:

- Reactor Power
- Baseline
- Target Mass
- Depth
- Radio-cleanliness
- Systematics

Backgrounds:

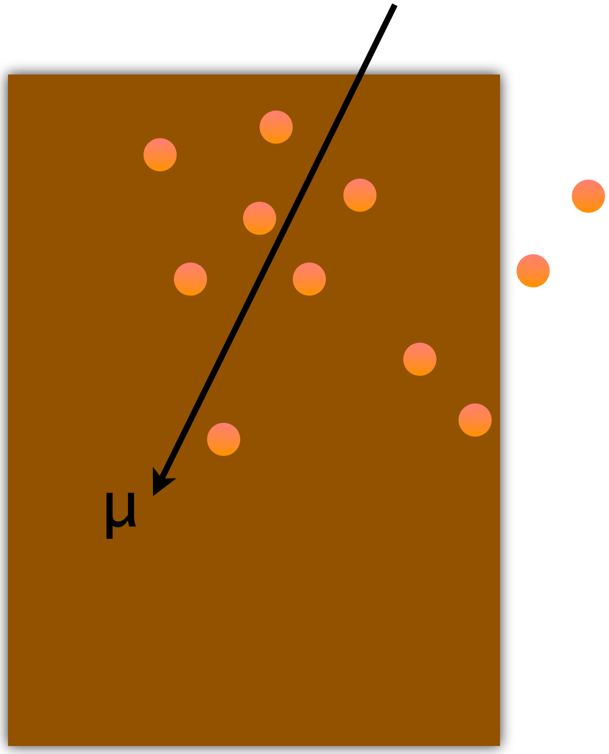
- Accidental coincidences.

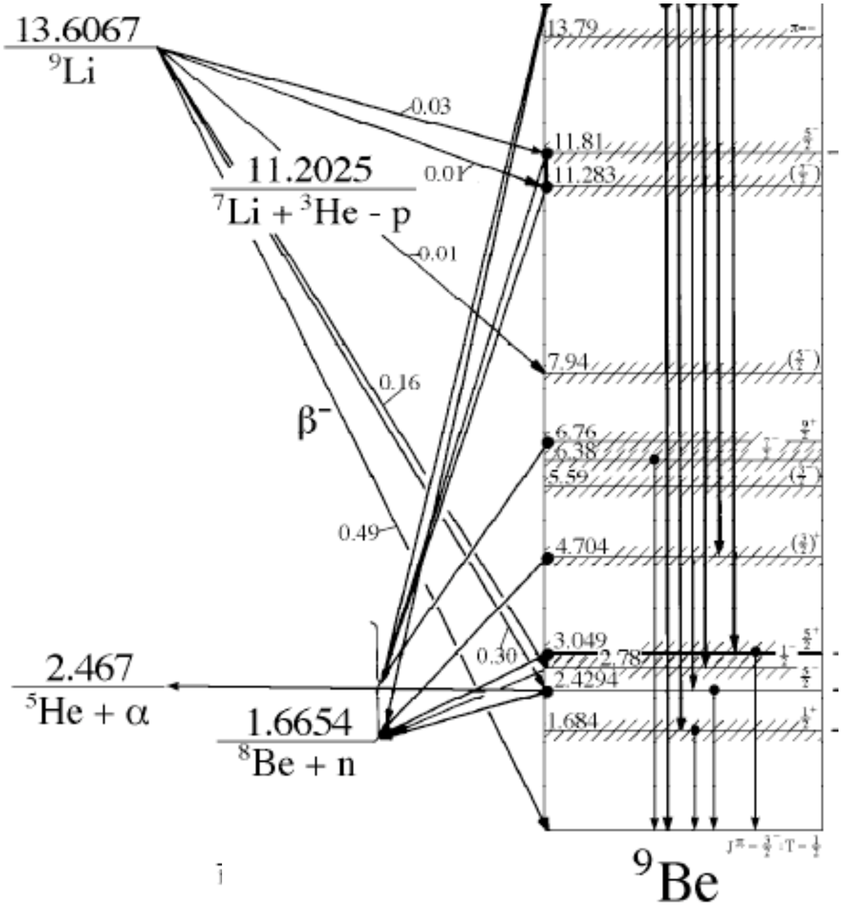
The single event rate will be dominated by the daughters of the ^{238}U and ^{232}Th decay chains and ^{40}K (in one way or another).



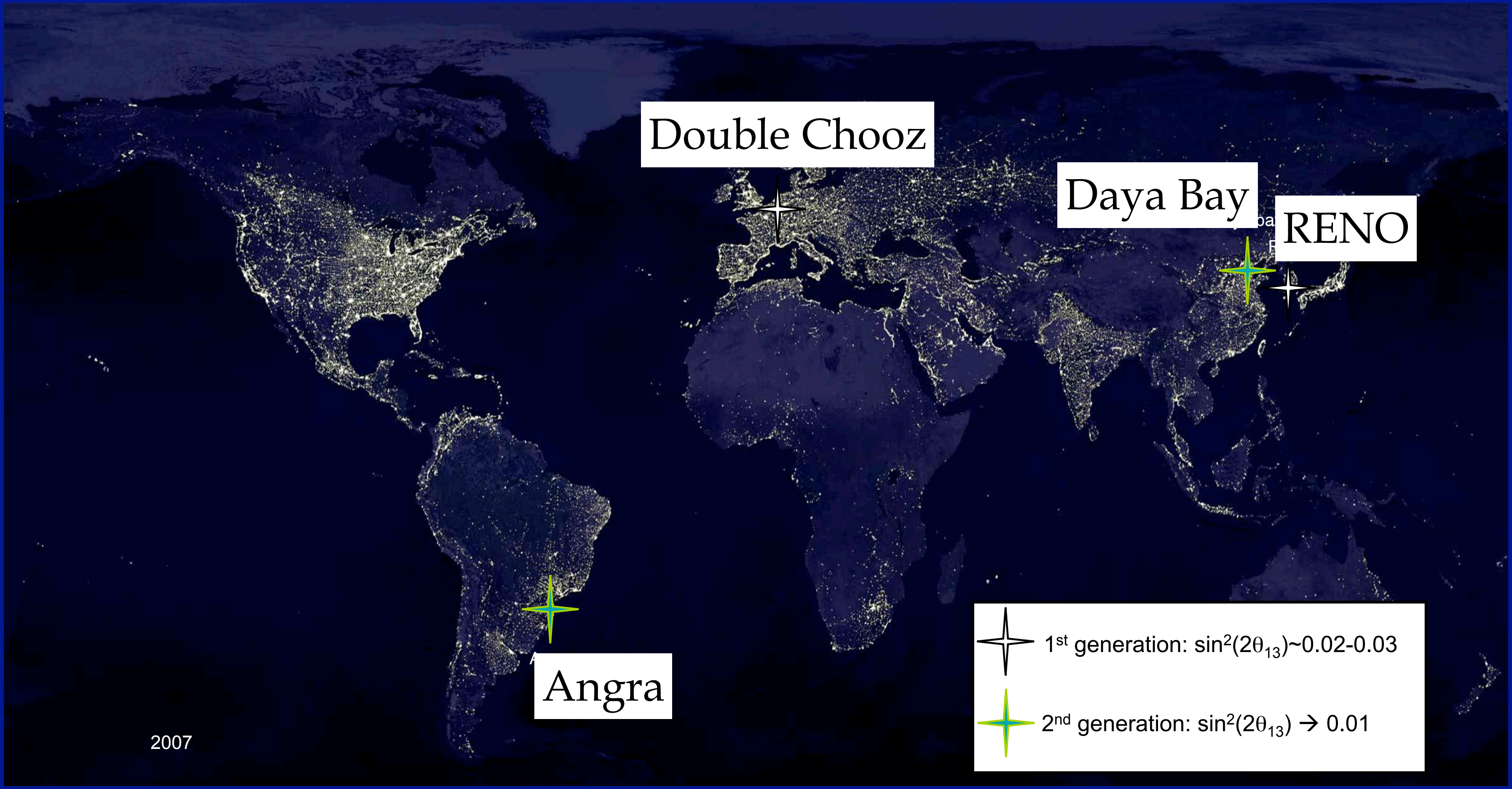
Backgrounds:

- Accidental coincidences.
- Fast neutrons.
- Beta delayed n emitters, ^{9}Li and ^{8}He.





Active Sites:



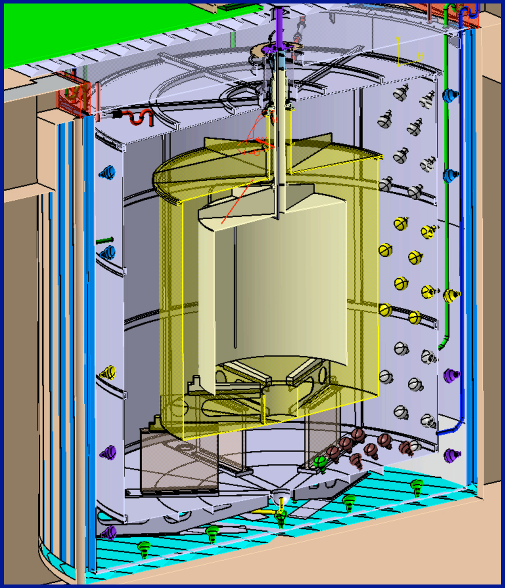
Comparing the Sites:

	Double Chooz	Daya Bay	RENO
Reactor Cores	2 Cores	6 Cores	6 Cores
Total Power	8.54 GW	11.6 GW[†]	16.4 GW
Target Mass	8.24 tons	20 tons	15 tons
Near Distance	400m	300-500m[†]	290m
Near Overburden	115 m.w.e	~100 m.w.e[†]	130 m.w.e
Far Distance	1.05km	1.6-1.9km	1.4km
Far Overburden	300 m.w.e.	350 m.w.e	460 m.w.e.
Events per Day	425/43	1600/400[†]	5000/100

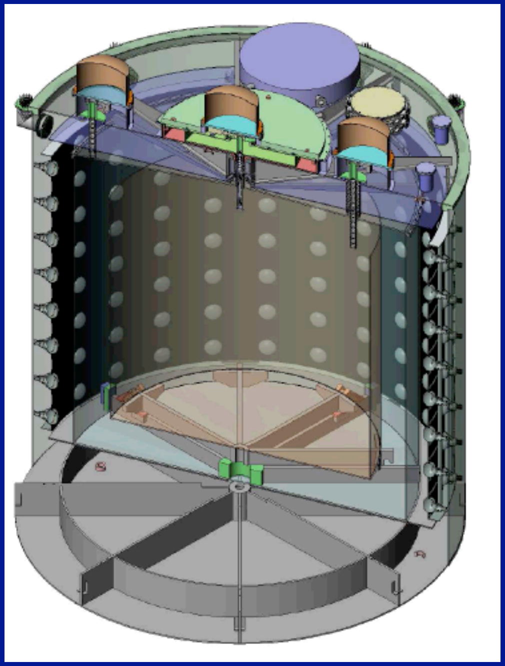
[†] Daya Bay will increase to 17.4GW in 2011, has two near sites, and uses multiple detectors per site.

The Detectors:

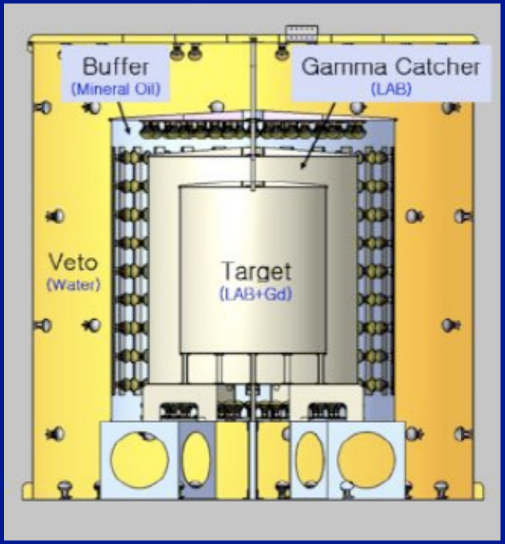
Double Chooz



Daya Bay



RENO



The Double Chooz Collaboration

Univ. of Alabama, ANL,
Univ. of Chicago, Columbia,
U.C. Davis, Drexel Univ.,
Kansas State, Illinois Inst. Tech.,
LLNL, MIT, Notre Dame, SNL,
Univ. of Tennessee

APC Univ. of Paris,
SUBATECH (Nantes)
IRFU CEA/Saclay
Strasbourg

Aachen Univ., Hamburg Univ.,
MPIK Heidelberg, T.U. München,
E.K. Univ. Tubingen,

CBPF, UNICAMP

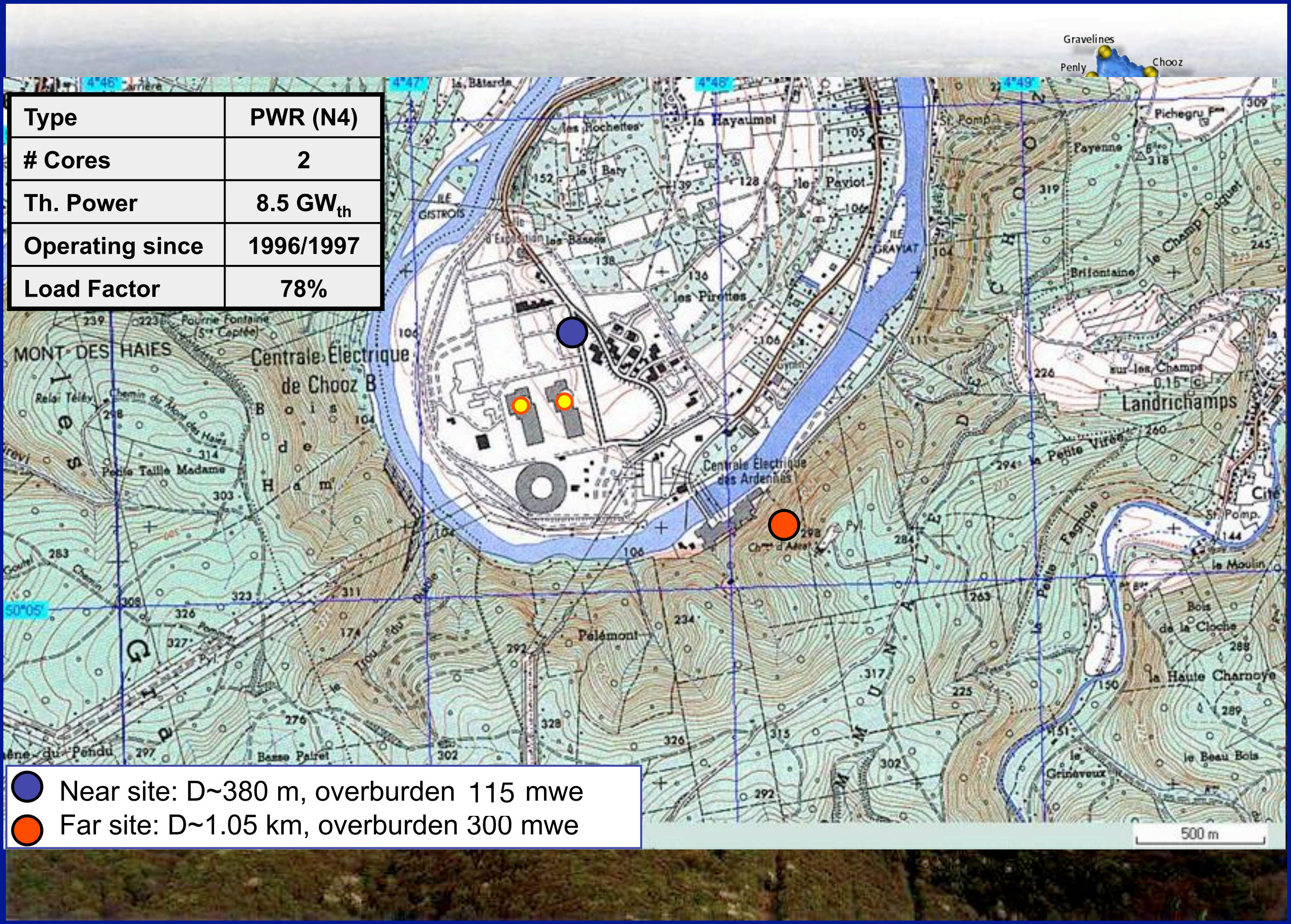
INR-RAS, IPC-RAS,
RRC Kurchatov

Hiroshima Inst. Tech.,
Kobe Univ., Miyagi Univ.,
Niigata Univ., Tohoku Univ.,
Tohoku Gakuin Univ.,
Tokyo Metro. Univ.,
Tokyo Inst. Tech.

CIEMAT Madrid

Univ of Sussex

Double Chooz Site:

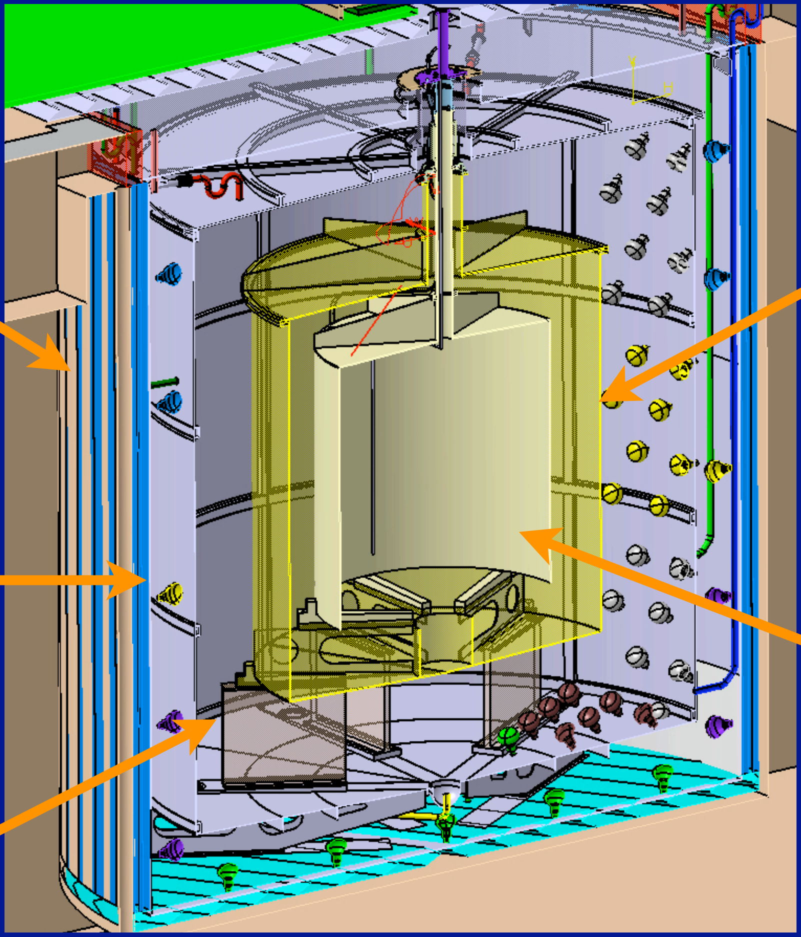


Type	PWR (N4)
# Cores	2
Th. Power	8.5 GW_{th}
Operating since	1996/1997
Load Factor	78%

● Near site: D~380 m, overburden 115 mwe

● Far site: D~1.05 km, overburden 300 mwe

Double Chooz Detector:



Shielding
Inner Height = 6.84m
Inner R=3.47m
Thickness = 150mm

Inner Veto
(90m^3 LAB LS)
Inner Height = 7m
Inner R=3.27m
Tank Thickness = 10mm

Buffer
(110m^3 Mineral Oil)
Inner Height = 5.67m
Inner R=2.76m
Tank Thickness = 3mm
390 PMTs - Low Bkg 10" HPK

Gamma Catcher
(22.6 m^3 LS)
Inner Height=3.55m
Inner R=1.7m
Acrylic Thickness = 10mm

Target
(10.3m^3 Gd doped LS)
Inner Height=2.48m
Inner R=1.15m
Acrylic Thickness = 8mm

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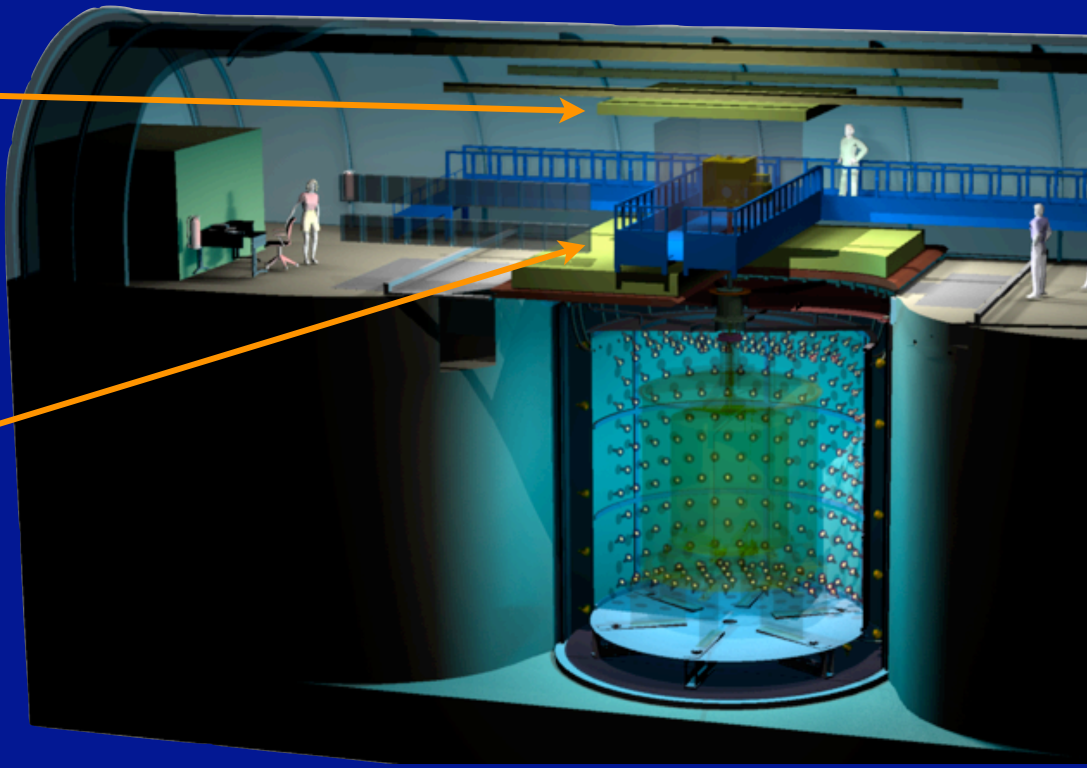
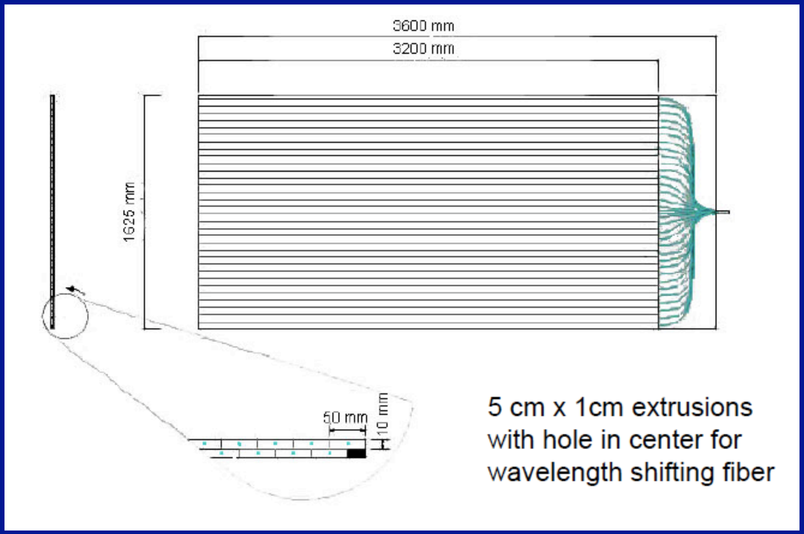
Double Chooz Detector:

Outer Veto muon tracking system, Constucted from 36 and 8 modules respectively.

Each module is constructed from extruded scintillator strips and 1.5mm wavelength shifting fiber readout with a M64 PMT.



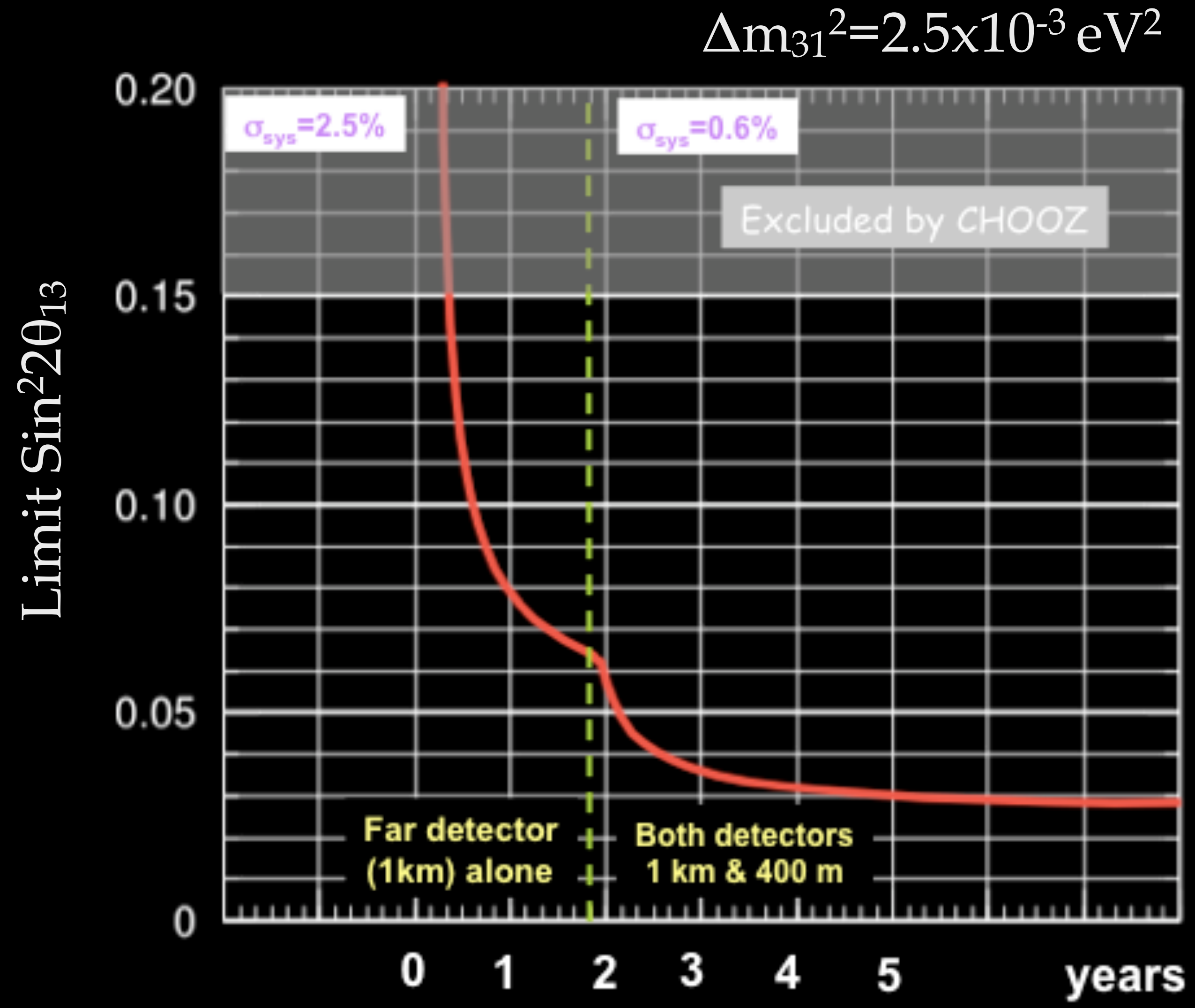


5 cm x 1cm extrusions with hole in center for wavelength shifting fiber

Double Chooz Systematics:

		Chooz	Double Chooz
Reactor	ν flux and spectrum	1.9%	<0.1%
	Reactor Power	0.7-2%	<0.1%
Detector	Solid Angle	0.3%	<0.1%
	Target Mass	0.3%	0.2%
	Density	0.3%	<0.1%
	H/C and Gd ratio	1.2%	<0.2%
	Spatial Effects	1.0%	<0.1%
	Live time	-	<0.2%
Analysis	From 3-7 cuts.	1.5%	0.2-0.3%
	Total	2.7%	<0.6%

Sensitivity:



G. Mention et al. arXiv:0704.0498v2

Double Chooz Status:

May 2008

Double Chooz Status:

On track for first neutrinos at the end of the year!

Double Chooz Current Schedule:

Far Detector:

- Installation of Inner Veto PMTs now.
- Buffer PMT installation May 2009.
- Acrylic installation August 2009.
- Filling December 2009.
- Neutrinos Detected!

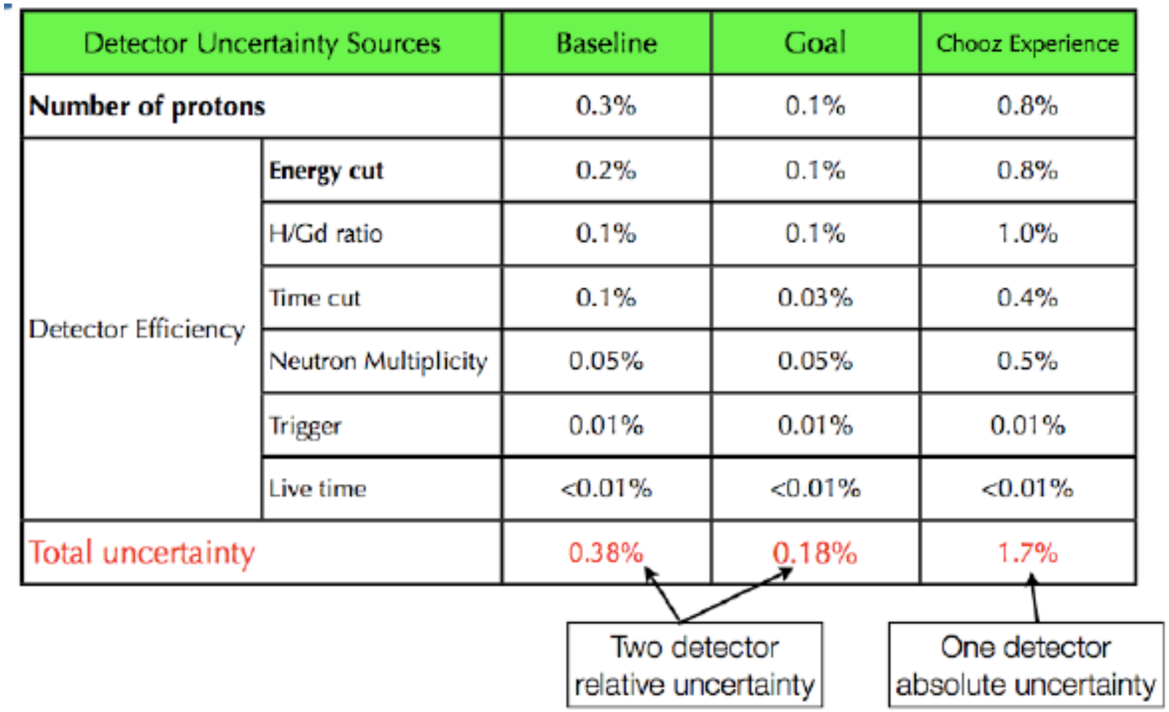
} Total 1.5 years

Near Detector:

- Civil Construction will start end 2009.
- Civil Construction Complete 2010.
- Assume slightly shorter construction time.
- Two Detector Data 2011!

Daya Bay Experiment:

Daya Bay Systematics:



Detector Uncertainty Sources		Baseline	Goal	Chooz Experience
Number of protons		0.3%	0.1%	0.8%
Detector Efficiency	**Energy cut**	0.2%	0.1%	0.8%
	H/Gd ratio	0.1%	0.1%	1.0%
	Time cut	0.1%	0.03%	0.4%
	Neutron Multiplicity	0.05%	0.05%	0.5%
	Trigger	0.01%	0.01%	0.01%
	Live time	<0.01%	<0.01%	<0.01%
Total uncertainty		0.38%	0.18%	1.7%

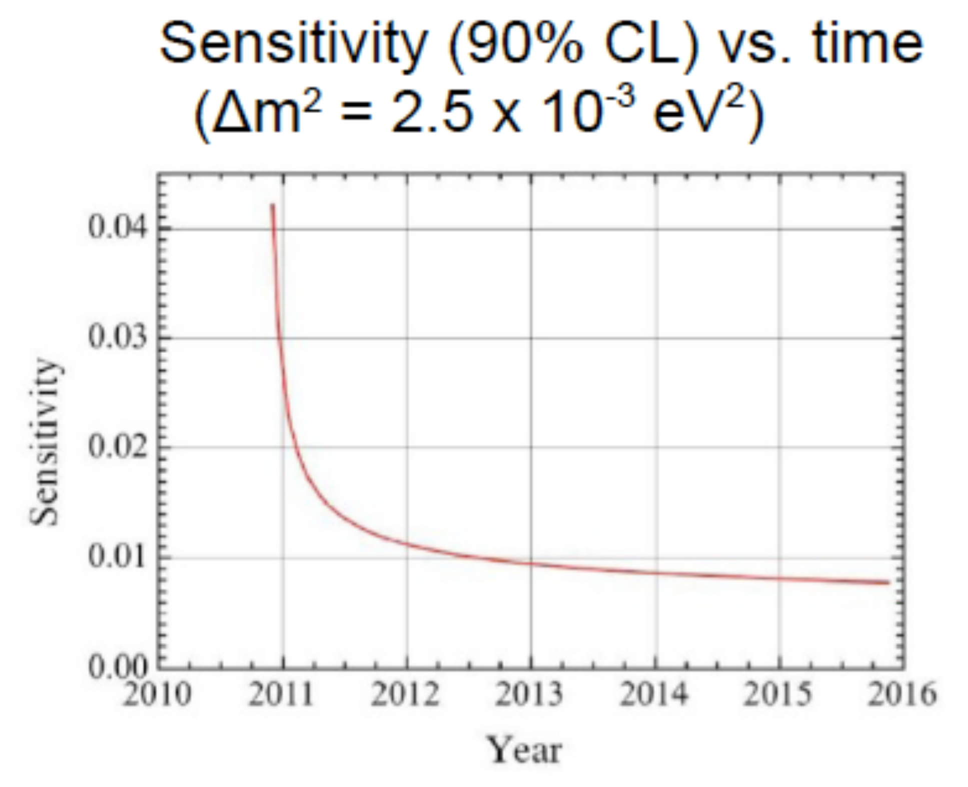
Two detector relative uncertainty

One detector absolute uncertainty

From: D. Dwyer, DNP October 2008
For Reference: arXiv:hep-ex/0701029v1

Daya Bay Sensitivity:

With Baseline Systematics



Daya Bay Current Schedule:

Nov 2007: Civil Contruction Began

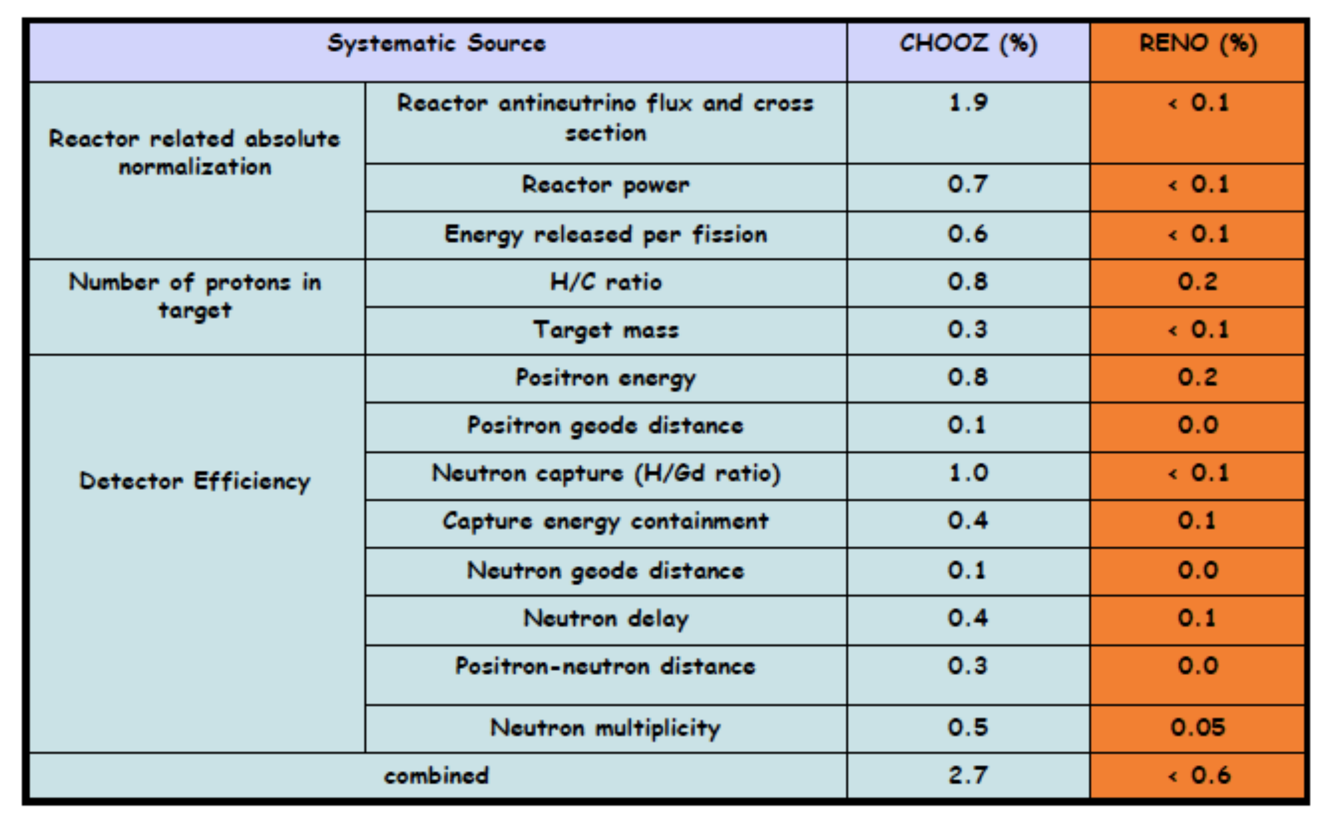
Aug 2008: CD-3b Approval

Nov 2008: Occupancy of onsite assembly building

Winter 2009: Install first pair of detectors at Daya Bay near site

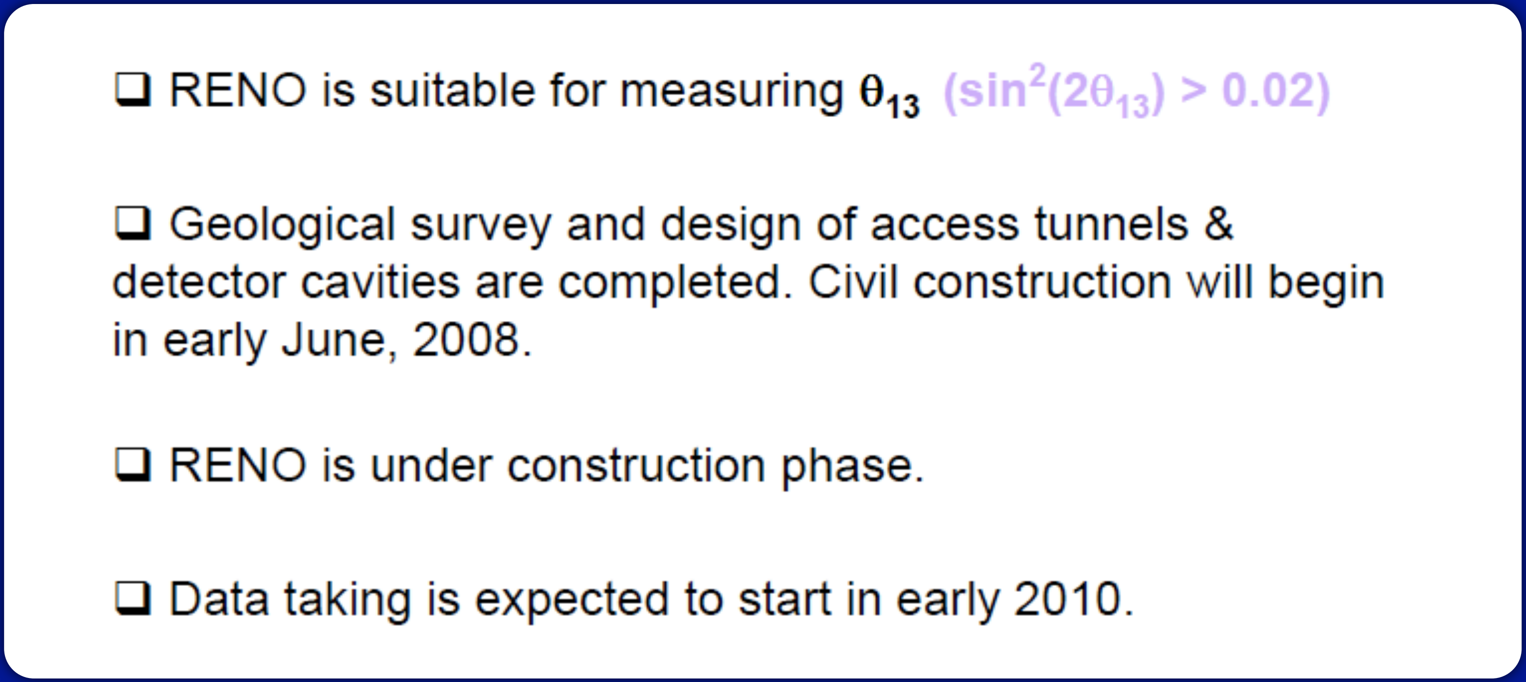
Winter 2010: Begin data taking with both near and far sites

Slides from D. White Neutrino 2008
for Soo-Bong Kim, Seoul National University



Systematic Source		CHOOZ (%)	RENO (%)
Reactor related absolute normalization	Reactor antineutrino flux and cross section	1.9	< 0.1
	Reactor power	0.7	< 0.1
	Energy released per fission	0.6	< 0.1
Number of protons in target	H/C ratio	0.8	0.2
	Target mass	0.3	< 0.1
Detector Efficiency	Positron energy	0.8	0.2
	Positron geode distance	0.1	0.0
	Neutron capture (H/Gd ratio)	1.0	< 0.1
	Capture energy containment	0.4	0.1
	Neutron geode distance	0.1	0.0
	Neutron delay	0.4	0.1
	Positron-neutron distance	0.3	0.0
	Neutron multiplicity	0.5	0.05
combined		2.7	< 0.6

RENO Current Schedule:



❑ RENO is suitable for measuring θ_{13} $(\sin^2(2\theta_{13}) > 0.02)$

❑ Geological survey and design of access tunnels & detector cavities are completed. Civil construction will begin in early June, 2008.

❑ RENO is under construction phase.

❑ Data taking is expected to start in early 2010.

Summary:

Anti-Neutrino data in the next year looks promising for Double Chooz, Daya Bay, and RENO.