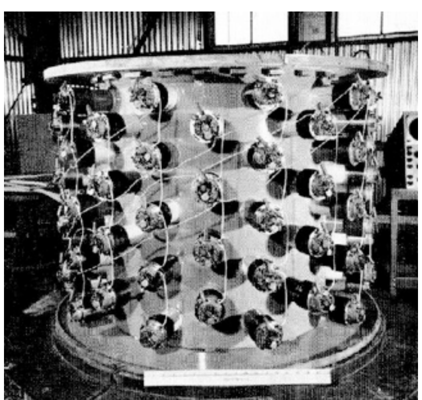
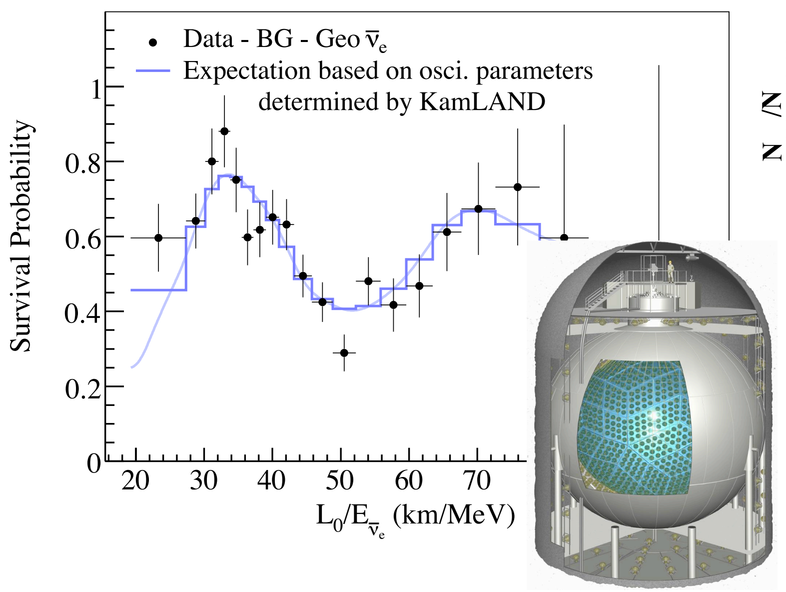
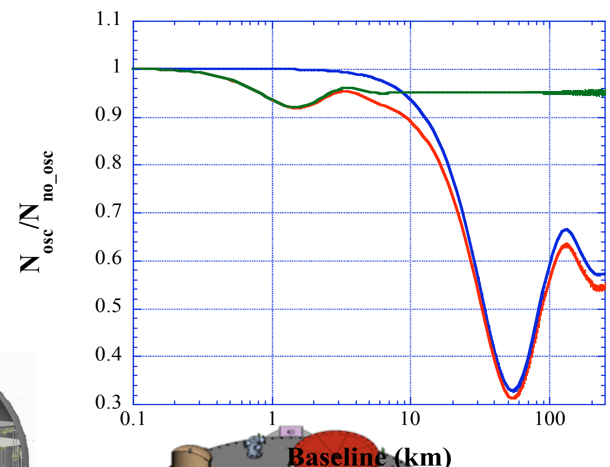
Reactor Neutrino Oscillation Experiments: Status and Prospects

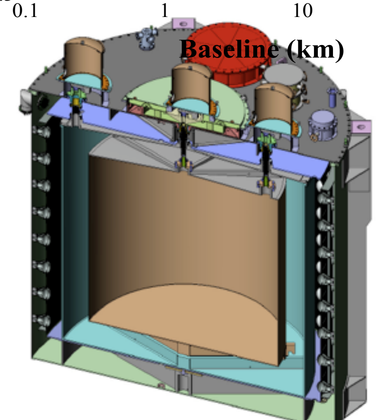
Karsten M. Heeger

University of Wisconsin









FNAL, May 12, 2011

Neutrino Physics at Reactors

?

Next - Discovery and precision measurement of θ_{13}

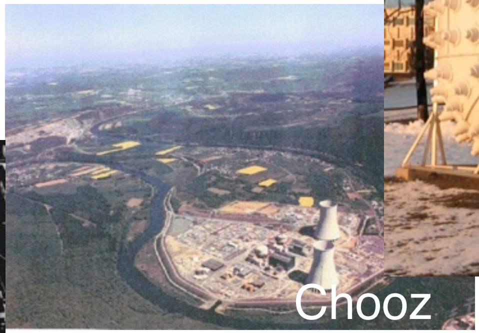
2008 - Precision measurement of Δm_{12}^2 . Evidence for oscillation

2003 - First observation of reactor antineutrino disappearance

1995 - Nobel Prize to Fred Reines at UC Irvine

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

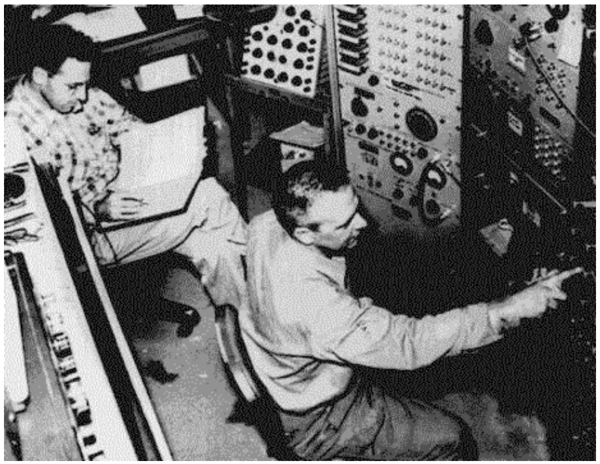
1956 - First observation of (anti)neutrinos

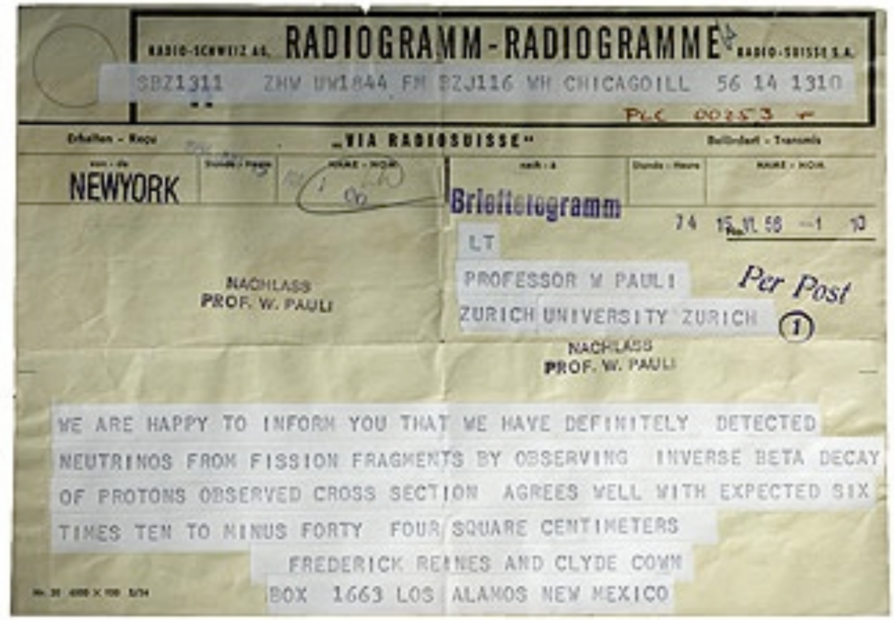


Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France

Discovery of the Neutrino

1956 - “Observation of the Free Antineutrino” by Reines and Cowan

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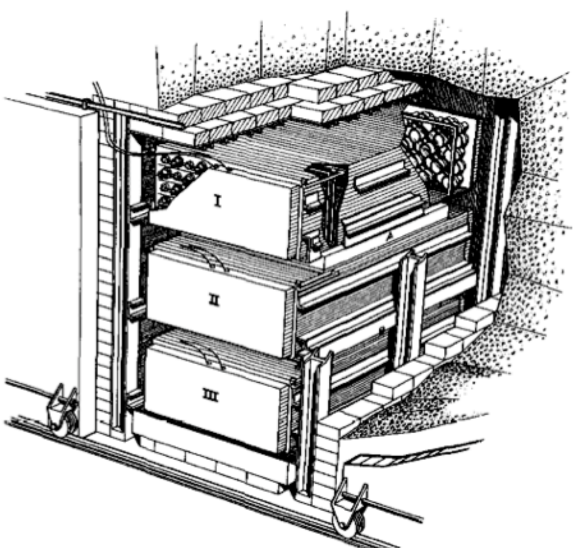
PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH
NACHLASS PROF. W. PAULI
Per Post

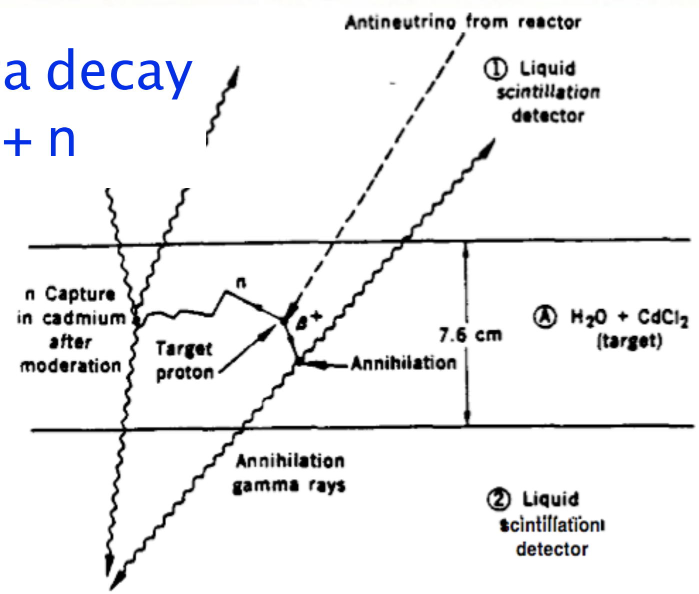
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWAN
BOX 1663 LOS ALAMOS NEW MEXICO



inverse beta decay

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



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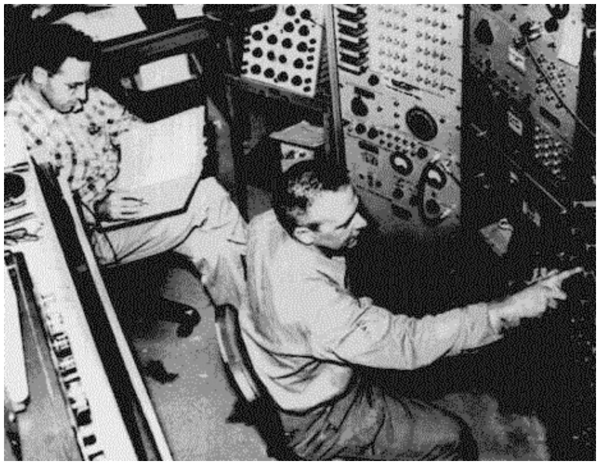

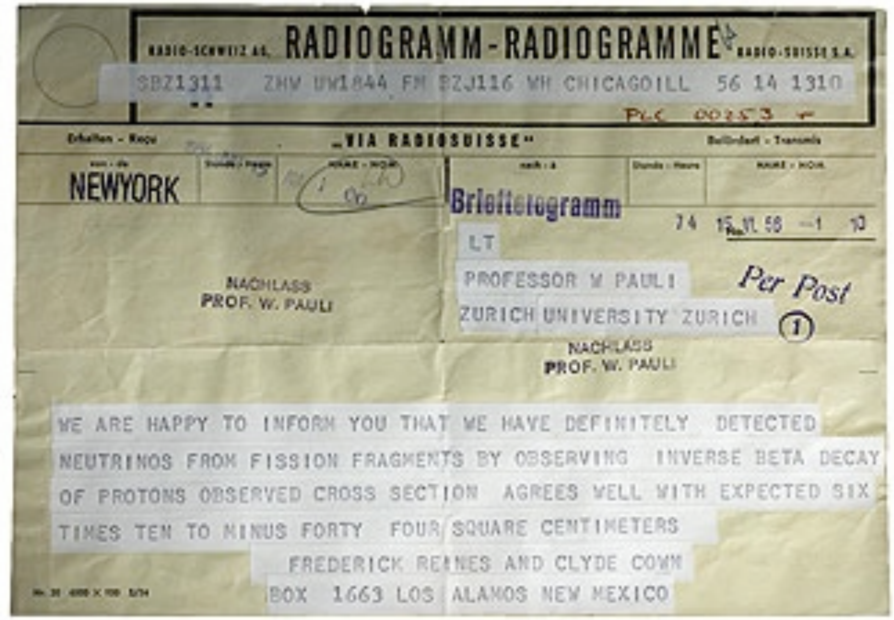
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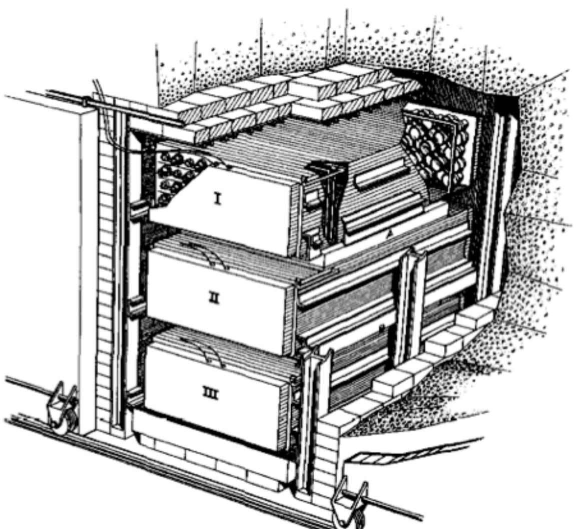

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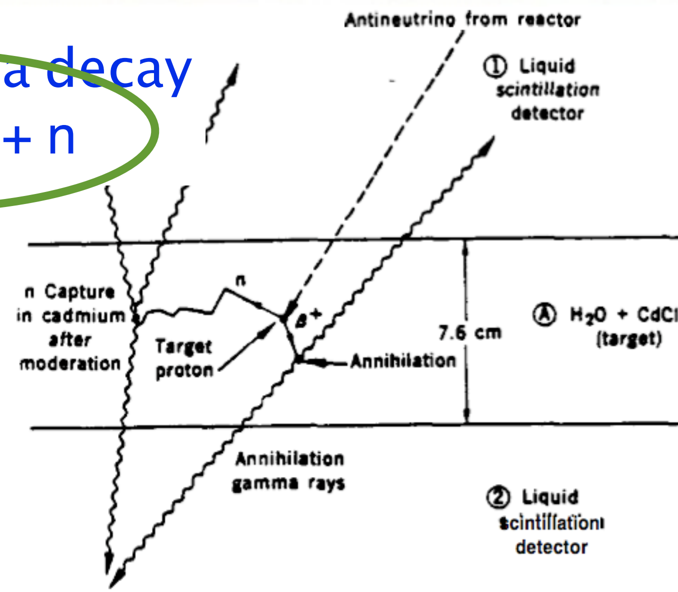


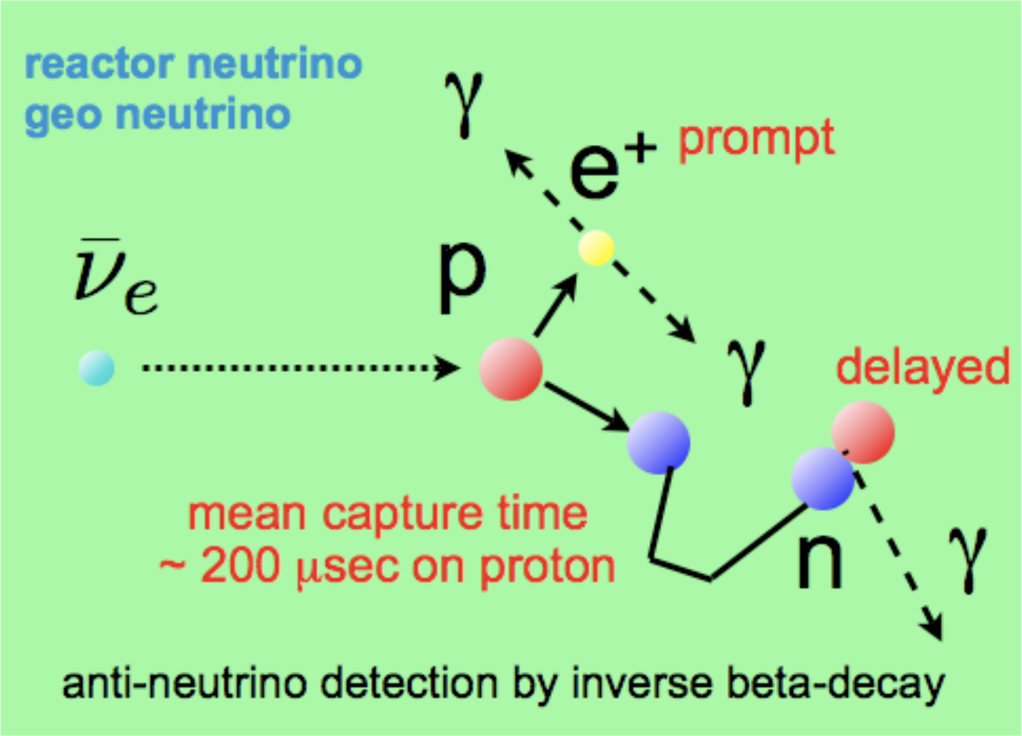
Antineutrino Detection

inverse beta decay

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

coincidence signature

prompt e^+ and delayed neutron capture



10-100 keV

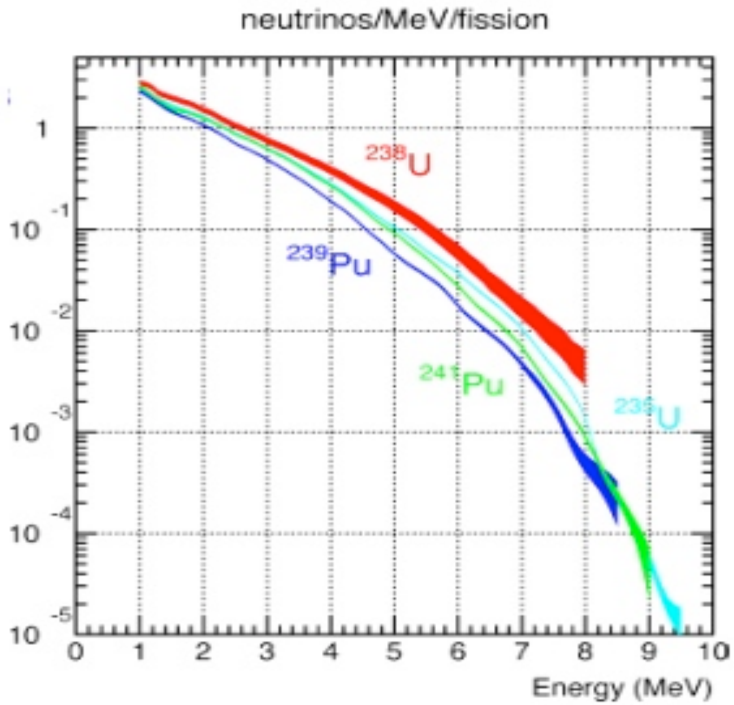
1.805 MeV

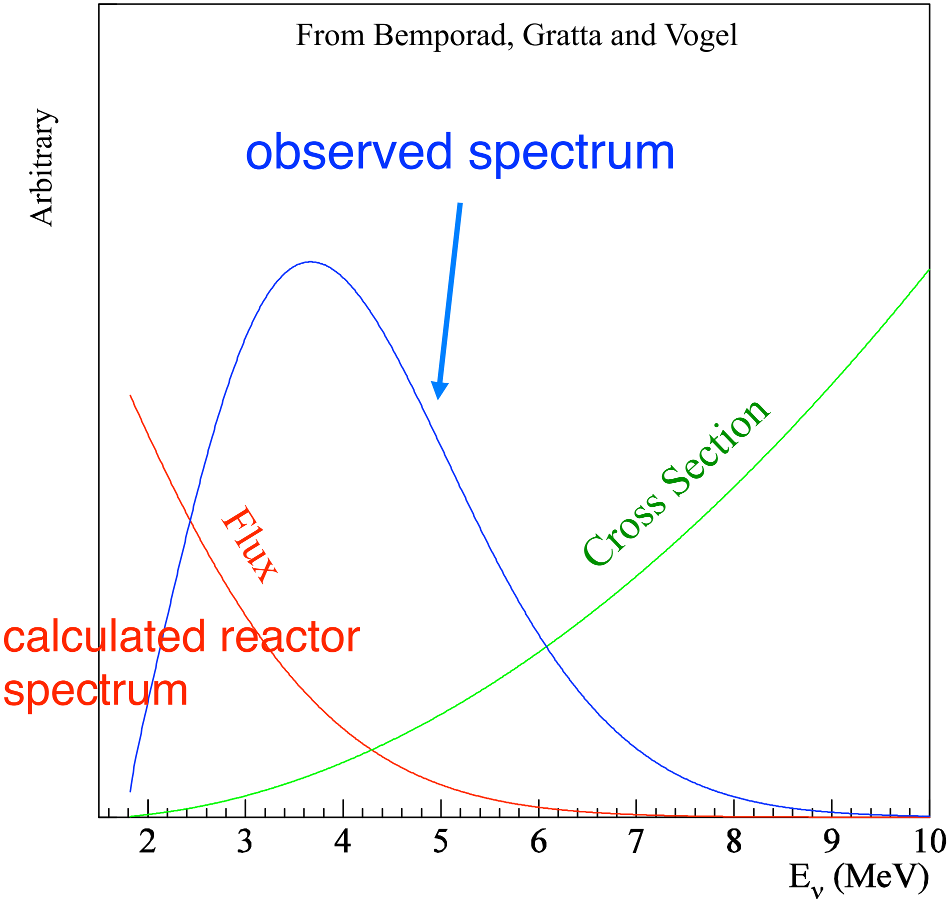
$$E_{\bar{\nu}_e} \cong E_{e^+} + E_n + (M_n - M_p) + m_{e^+}$$

including E from e^+ annihilation, $E_{prompt} = E_{\bar{\nu}} - 0.8$ MeV

Reactor Antineutrinos

$\overline{\nu}_e$ from n-rich fission products





~ 200 MeV per fission

~ 6 $\overline{\nu}_e$ per fission

~ 2 x 10^{20} $\overline{\nu}_e/GW_{th}$-sec

mean energy of $\overline{\nu}_e$: 3.6 MeV

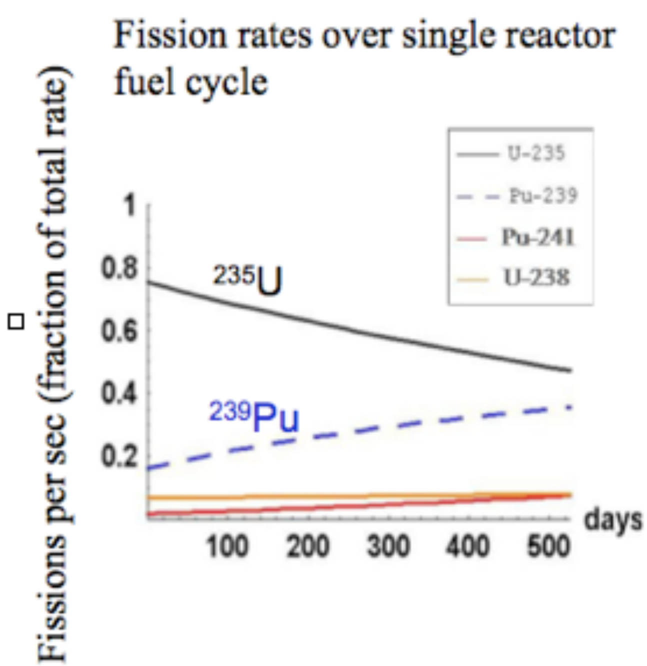
only disappearance experiments possible

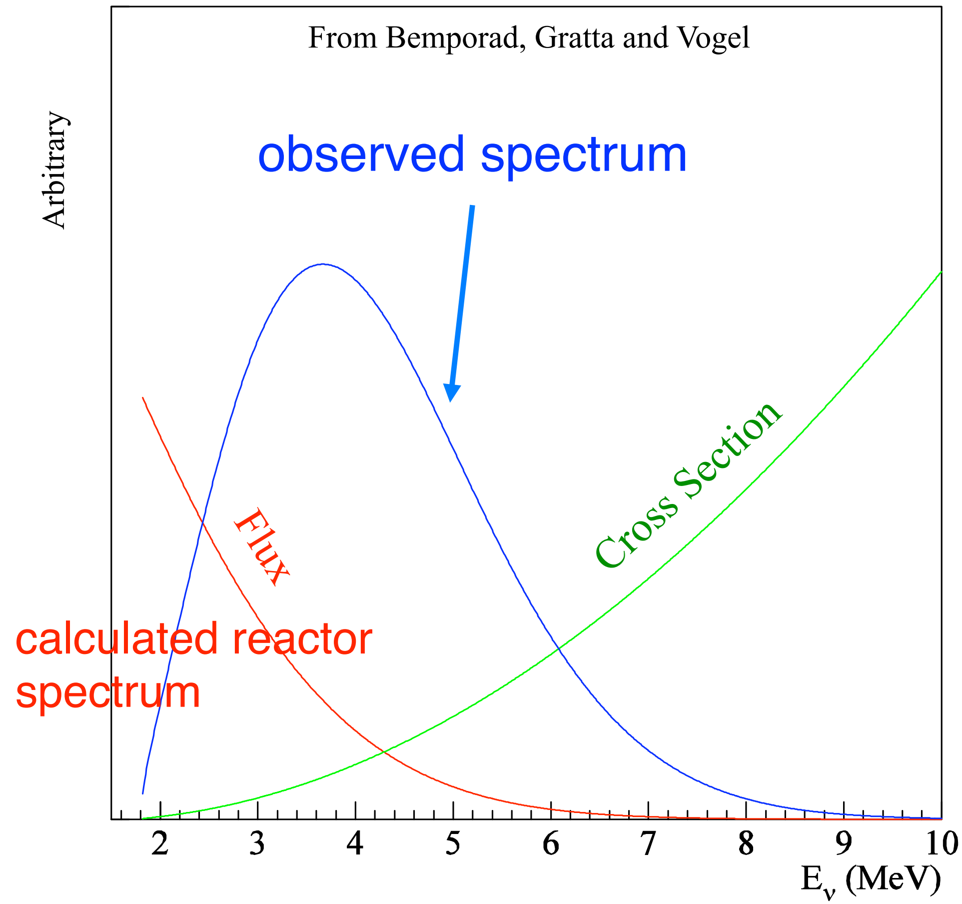
cross-section accurate to +/-0.2%

Reactor Antineutrinos

$\overline{\nu}_e$ from n-rich fission products

time-dependent rate and spectrum





threshold: neutrinos with E < 1.8 MeV are not detected

mean energy of $\overline{\nu}_e$: 3.6 MeV

only disappearance experiments possible

only ~ 1.5 $\overline{\nu}_e$/fission are detected

cross-section accurate to +/-0.2%

Measurement of Reactor Spectra

Goesgen Experiment (1980's)

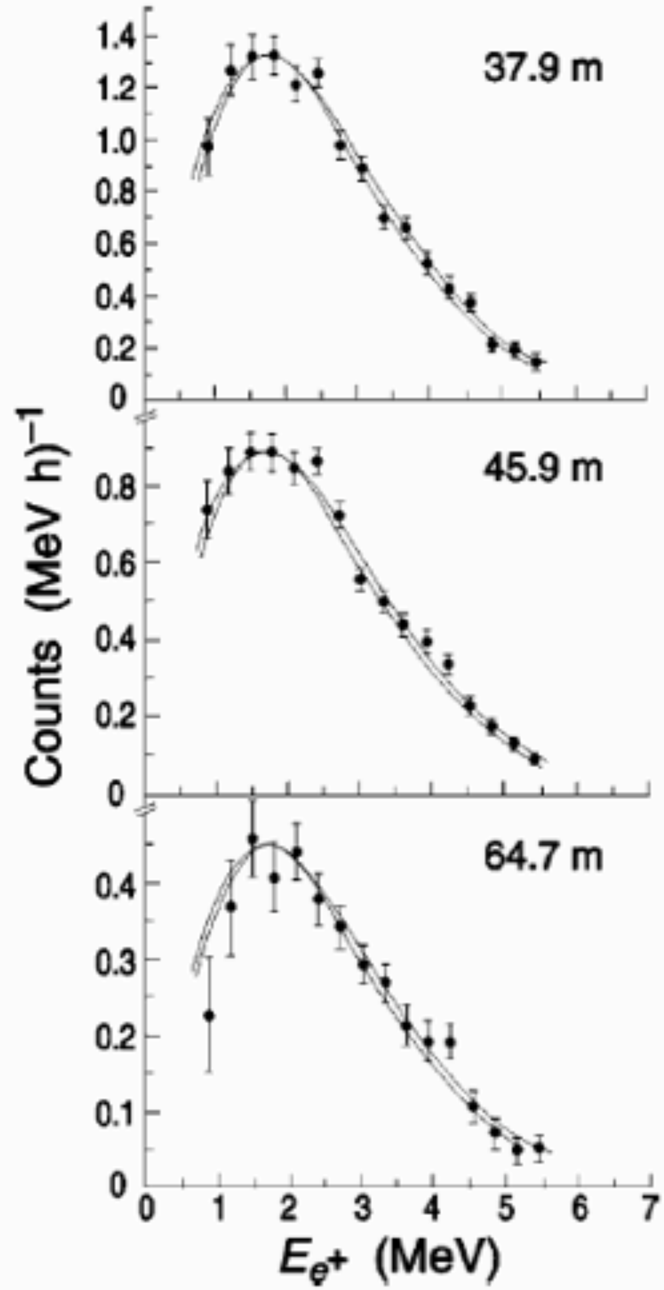
comparison of predicted spectra to observations

two curves are from fits to data and from predictions based on Schreckenbach et al.

3 baselines with one detector

flux and energy spectrum agree to ~ 1-2%

reactors are "calibrated" source of $\overline{\nu}_e$'s



Measurement of Reactor Spectra

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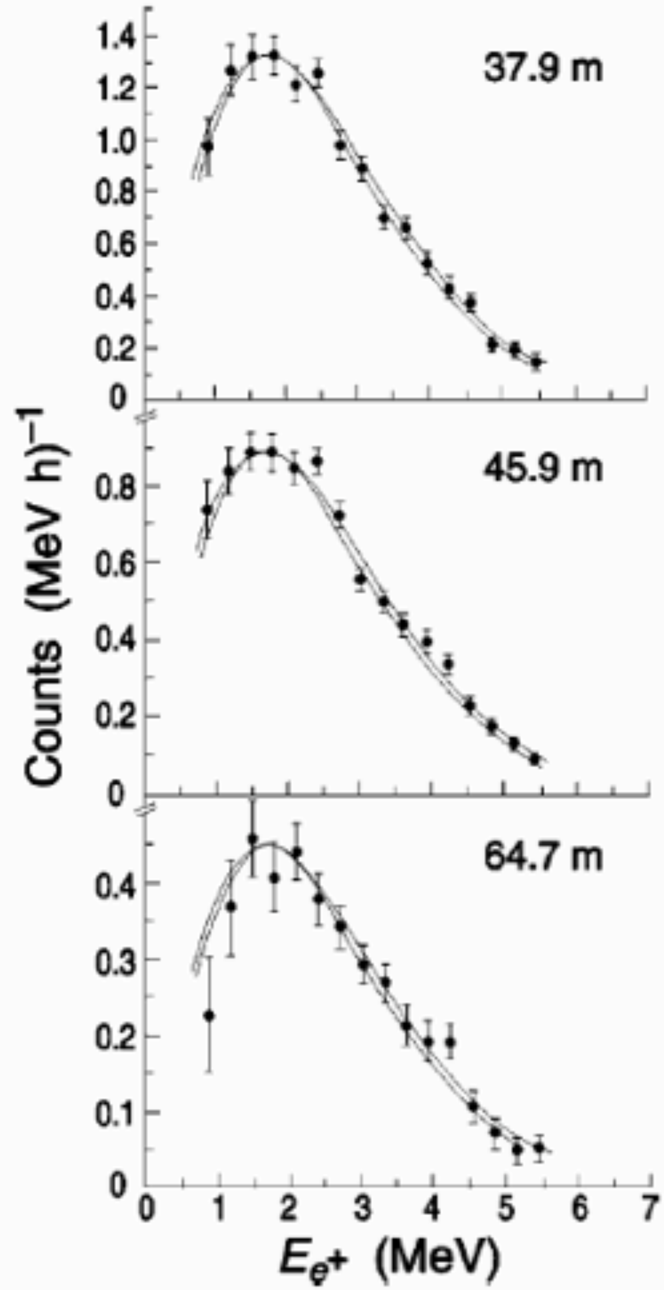
reactors are "calibrated" source of $\overline{\nu}_e$'s

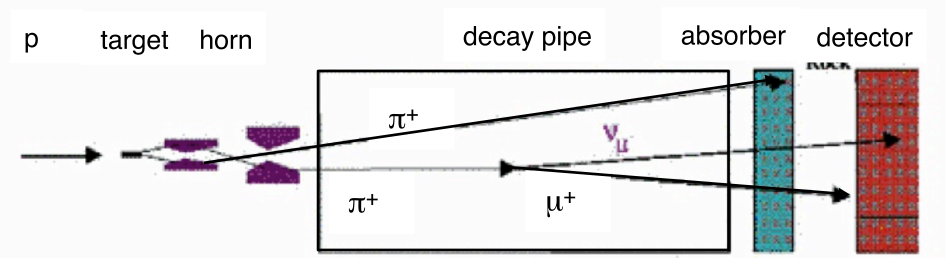
➔ but reactor anomaly...

are reactor flux predictions uncertain to 3%?



Reactor and Accelerator Experiments

Method 1: Accelerator Experiments

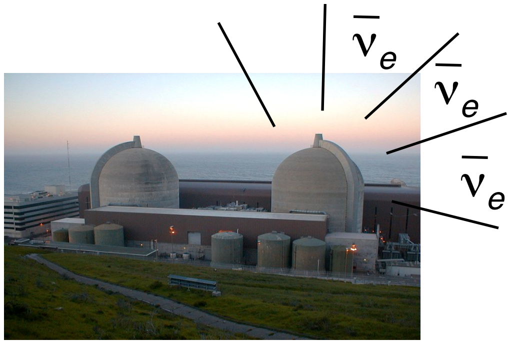


$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{31}^2 L}{4E_\nu} + \ldots$$

- appearance experiment $\nu_\mu \rightarrow \nu_e$
- measurement of $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ 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 $\overline{\nu}_e \rightarrow \overline{\nu}_e$
- 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

Oscillation Experiments with Reactors

experiments look for non-1/r² behavior of antineutrino interaction rate

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

for 3 active neutrinos, can study oscillation with two different oscillation length scales: Δm^2_{12}, Δm^2_{13}

$\Delta m^2_{12} \sim 8 \times 10^{-5}\ \mathrm{eV}^2$ → L ~ 1.8 km

$\Delta m^2_{13} \sim 2.5 \times 10^{-3}\ \mathrm{eV}^2$ → L ~ 60 km

What about reactor appearance experiments?

Mean antineutrino energy is 3.6 MeV.

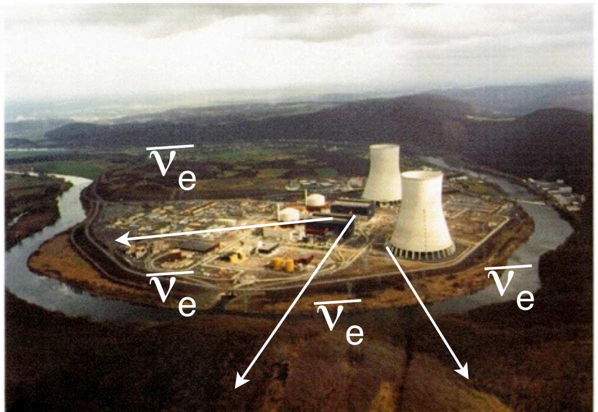
Only disappearance experiments are possible.

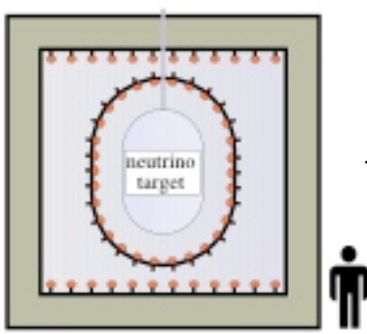
Oscillation Searches with Reactor Antineutrinos

1980-1990s

Chooz

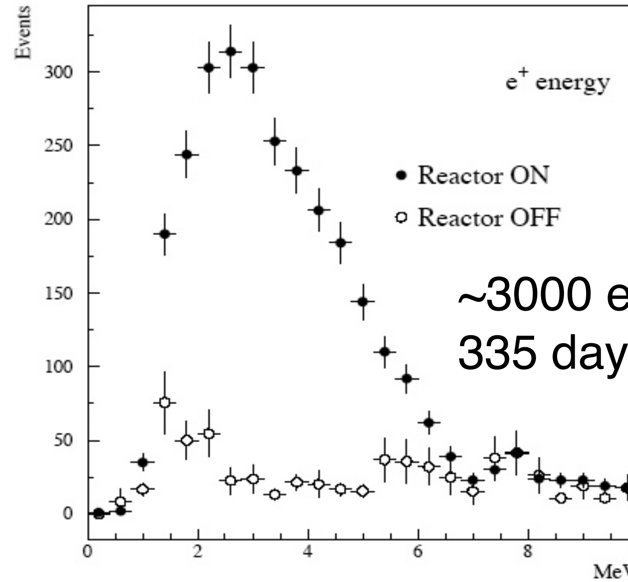
8.5GW power
1 km baseline



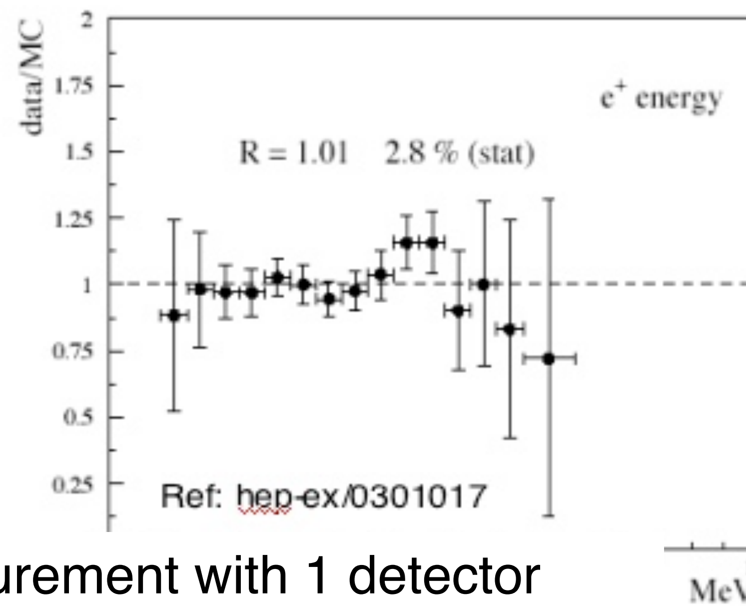


5 ton target

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



~3000 events
335 days



No evidence for oscillation, absolute measurement with 1 detector

Measuring Reactor Antineutrinos with KamLAND

Reactors in Japan

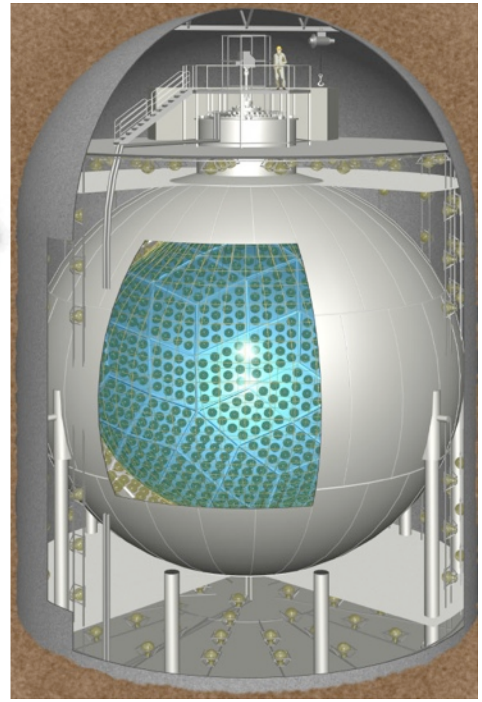
55 reactors

^{235}U:^{238}U:^{239}Pu:^{241}Pu = 0.570: 0.078: 0.0295: 0.057

reactor $\bar{\nu}$ flux at KamLAND

~ 6 x 10^6/cm^2/sec

KamLAND

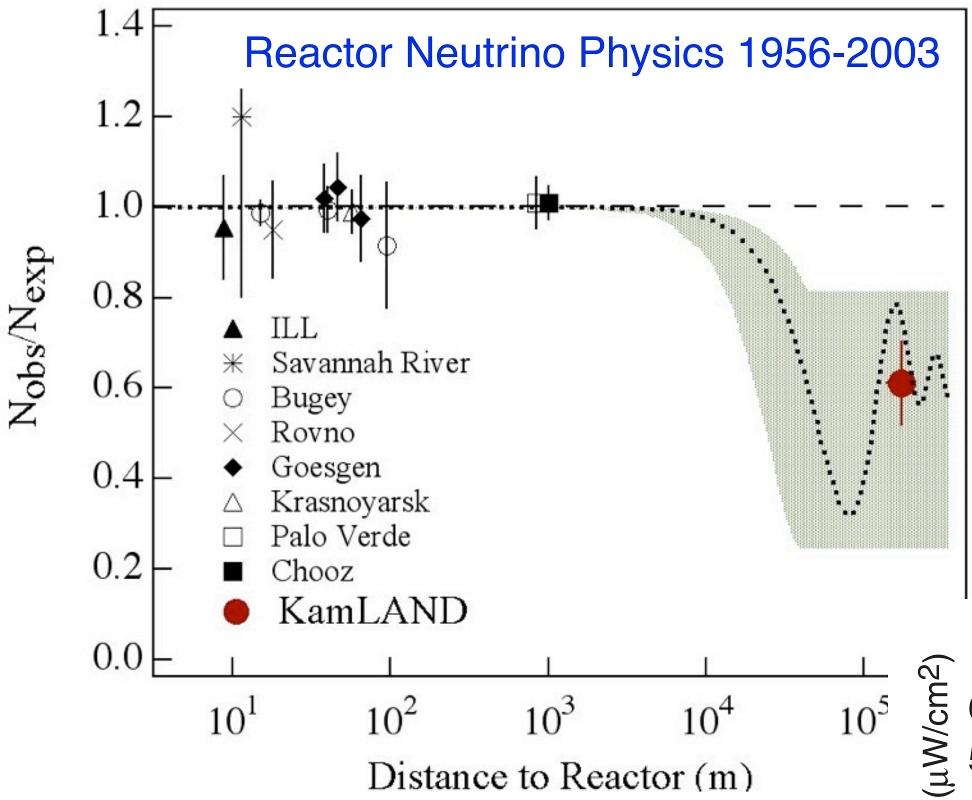


$\bar{\nu}_e + p \rightarrow e^+ + n$

through inverse β-decay

$$E_{\overline{\nu}_e} \simeq E_{\mathrm{p}} + \overline{E}_n + 0.8\,\mathrm{MeV},$$

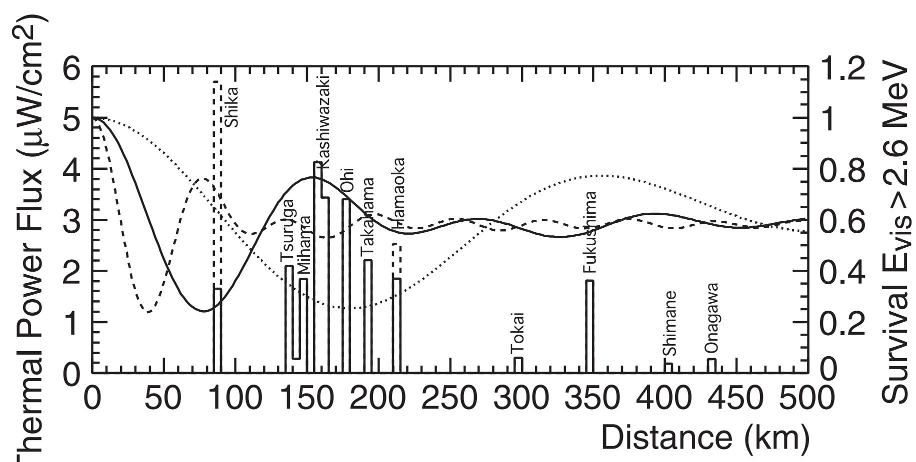
KamLAND 2003:
First Direct Evidence for Reactor $\overline{\nu}_e$ Disappearance



PRL 90:021802 (2003)

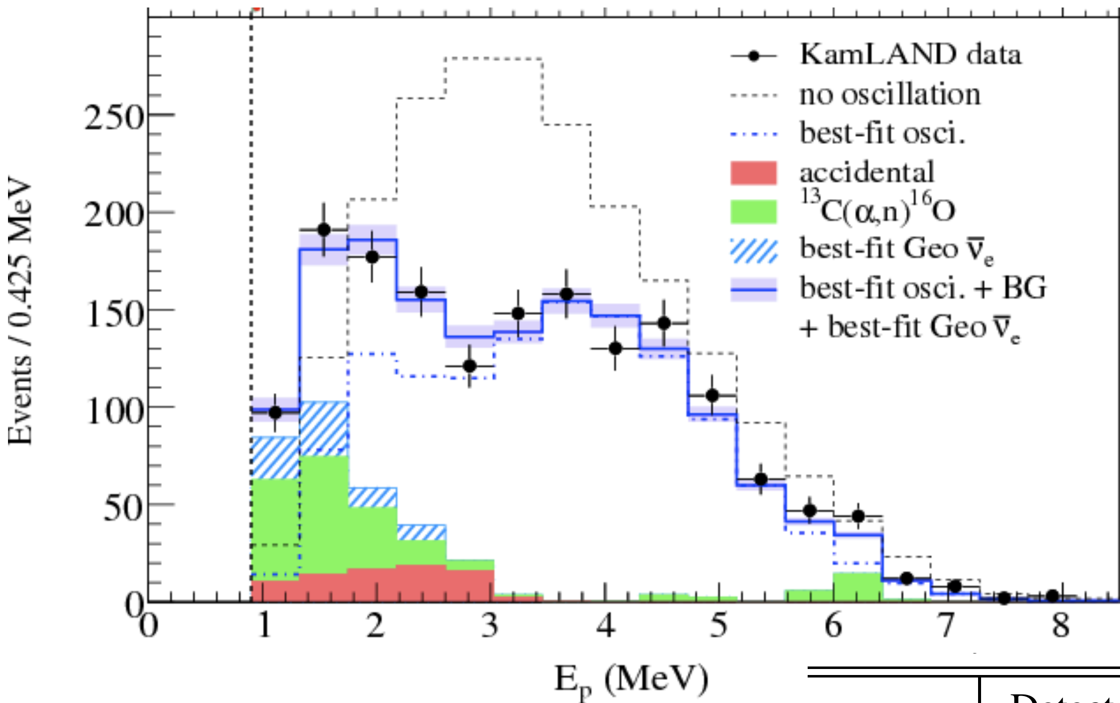
Observed $\overline{\nu}_e$	54 events
No-Oscillation	86.8 ± 5.6 events
Background	1 ± 1 events
Livetime:	162.1 ton-yr

mean, flux-weighted reactor distance ~ 180km



KamLAND 2008: Precision Measurement of Oscillation

Prompt event energy spectrum for $\overline{\nu}_e$



number of events

expected: 2179 ± 89 (syst)

observed: 1609

bkgd: 276 ± 23.5

significance of disappearance

(with 2.6 MeV threshold): 8.5σ

no-osc χ^2/ndf=63.9/17

significance of distortion: > 5σ

best-fit χ^2/ndf=21/16 (18% C.L.)

systematic uncertainties:

fiducial volume reduced from

4.7% → 1.8%

total systematics: 4.1%

	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.9	$\overline{\nu}_e$-spectra [7]	0.6
Event rate	Fiducial volume	1.8	$\overline{\nu}_e$-spectra	2.4
	Energy threshold	1.5	Reactor power	2.1
	Efficiency	0.6	Fuel composition	1.0
	Cross section	0.2	Long-lived nuclei	0.3

KamLAND 2008: Precision Measurement of Oscillation

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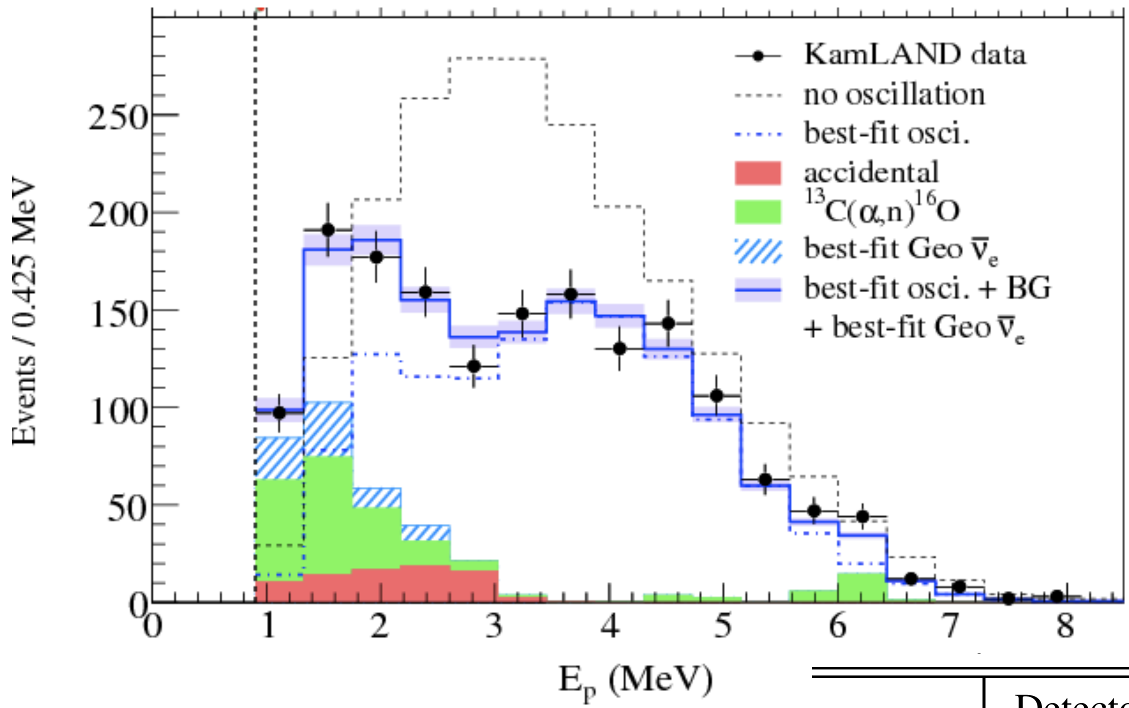

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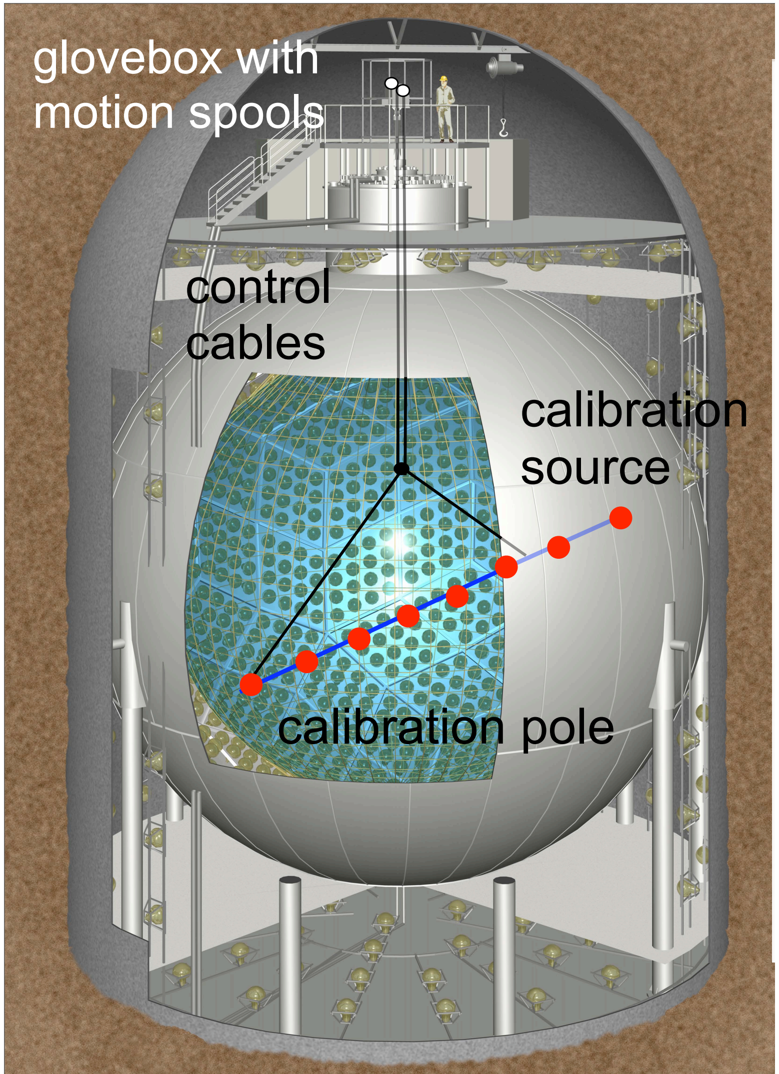
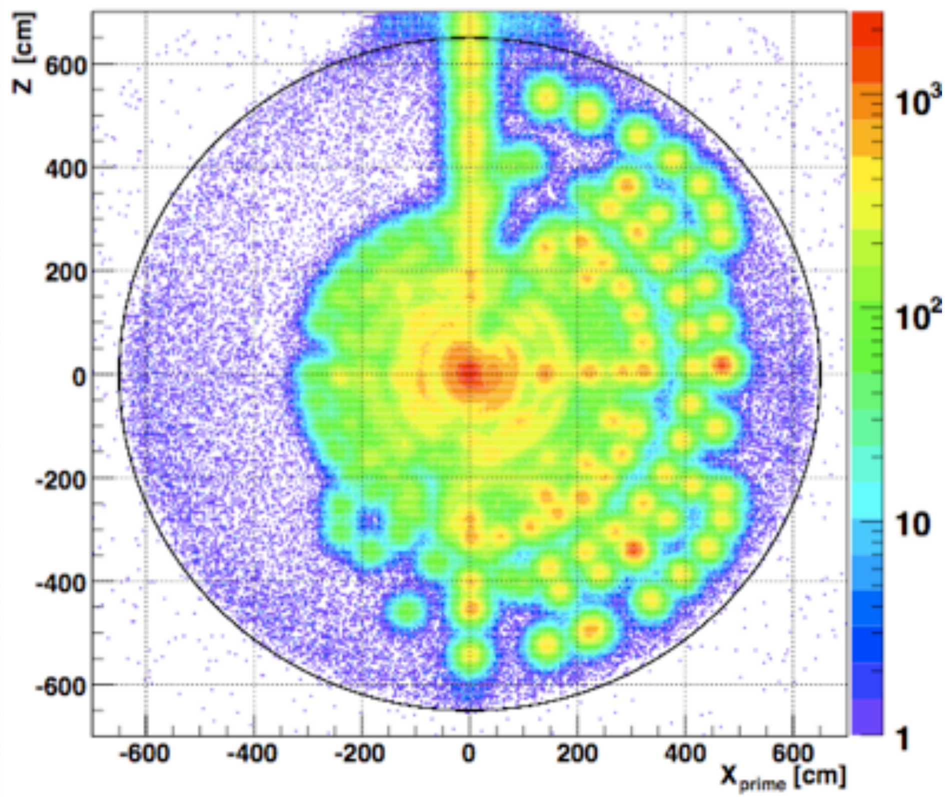
reactor flux and fiducial volume important for precision reactor experiments

KamLAND 2008: Precision Measurement of Oscillation

reduced systematics in target protons by calibrating fiducial volume





Neutrino Oscillation

Mixing Angles & Mass Splittings

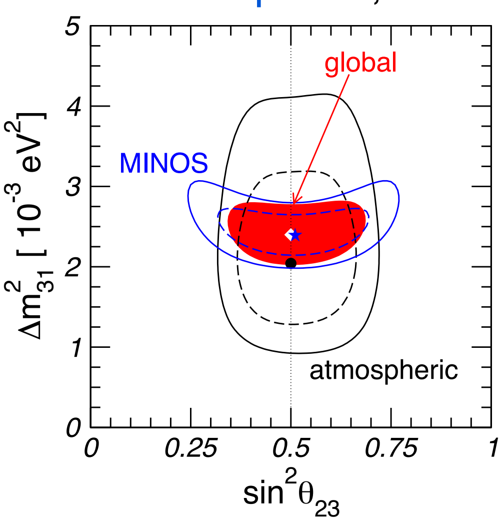
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

U_{MNSP} Matrix

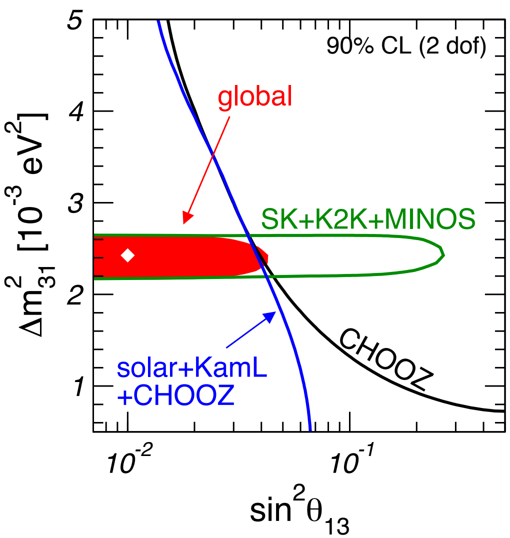
Maki, Nakagawa, Sakata, Pontecorvo

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

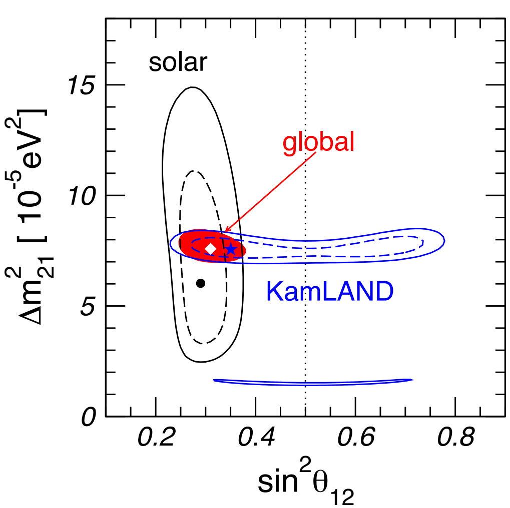
atmospheric, K2K



reactor and accelerator

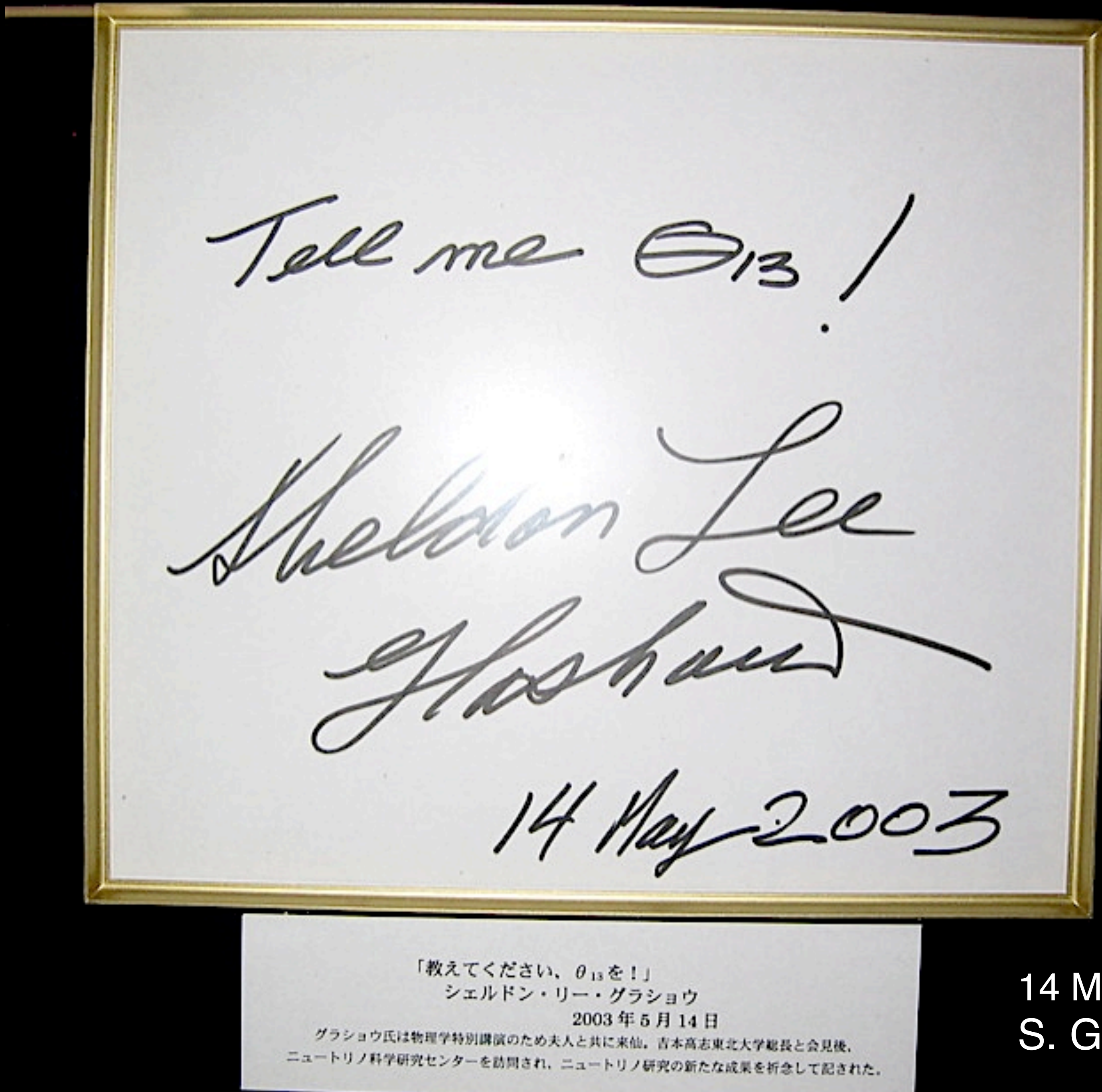


SNO, solar SK, KamLAND



$0\nu\beta\beta$

Schwetz et al
arXiv:0808.2016



14 May 2003
S. Glashow

Precision Measurement of θ$_{13}$ with Reactor Antineutrinos

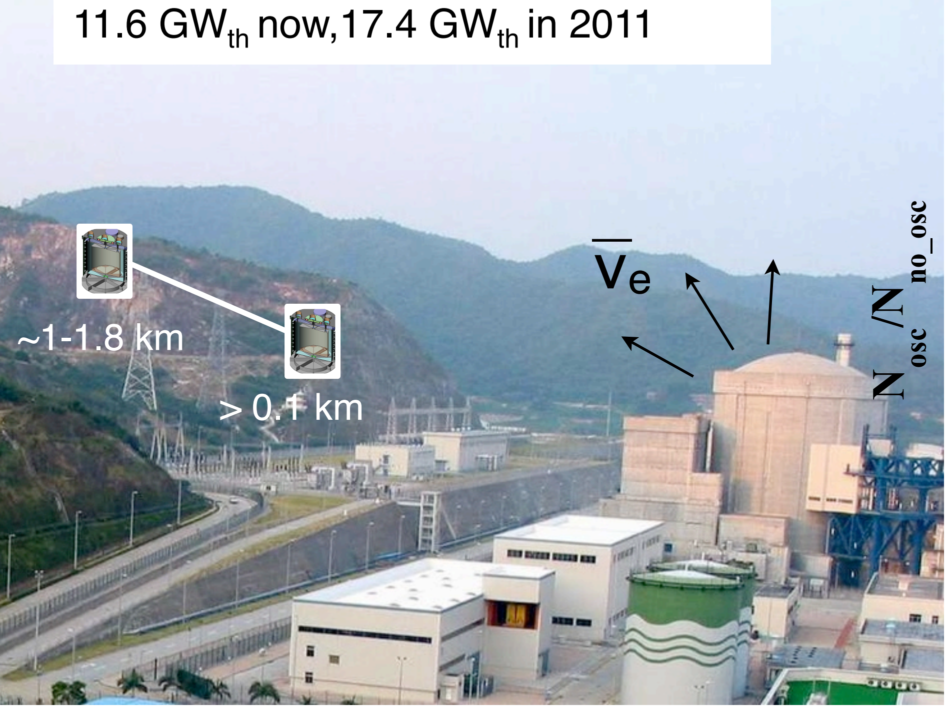
Search for θ$_{13}$ in new oscillation experiment with multiple detectors

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

Daya Bay Reactors:

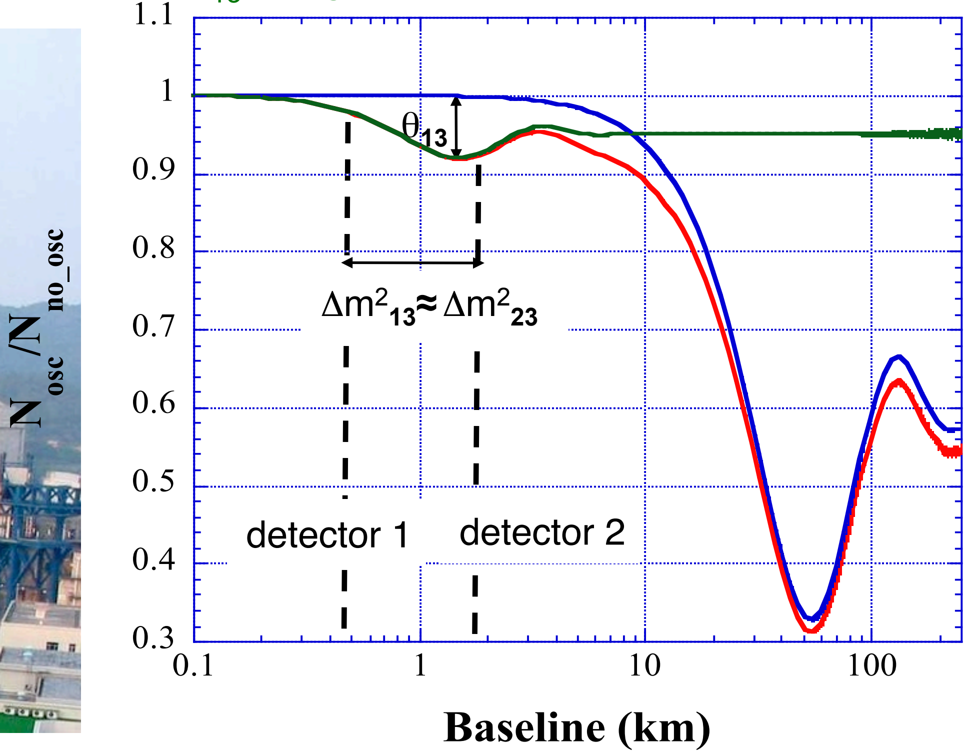
Powerful $\bar{\nu}_e$ source, multiple cores

11.6 GW$_{th}$ now,17.4 GW$_{th}$ in 2011



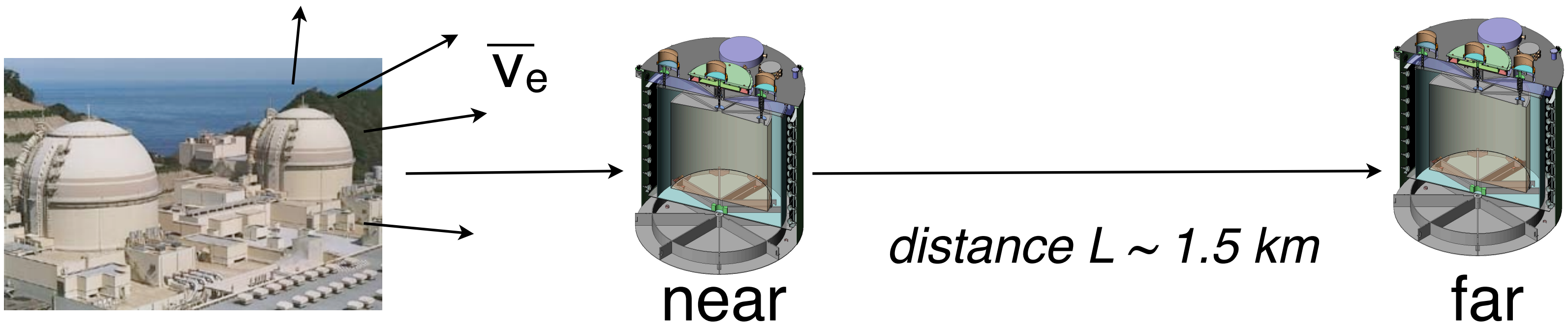
Small-amplitude oscillation due to θ$_{13}$ integrated over E

Large-amplitude oscillation due to θ$_{12}$



Concept of Reactor θ_{13} Experiments

Measure ratio of interaction rates in multiple detectors



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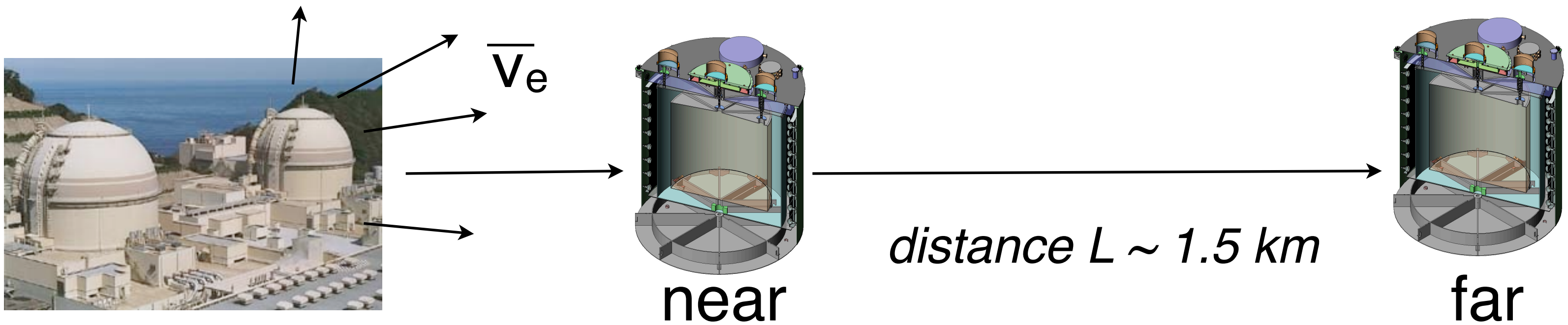


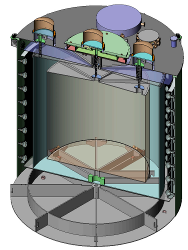
$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

Measured Ratio of Rates

Concept of Reactor θ_{13} Experiments

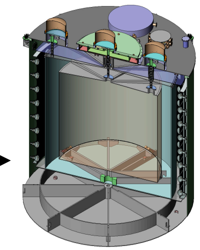
Measure ratio of interaction rates in multiple detectors

$\bar{\nu}_e$



near

distance L ~ 1.5 km



far

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

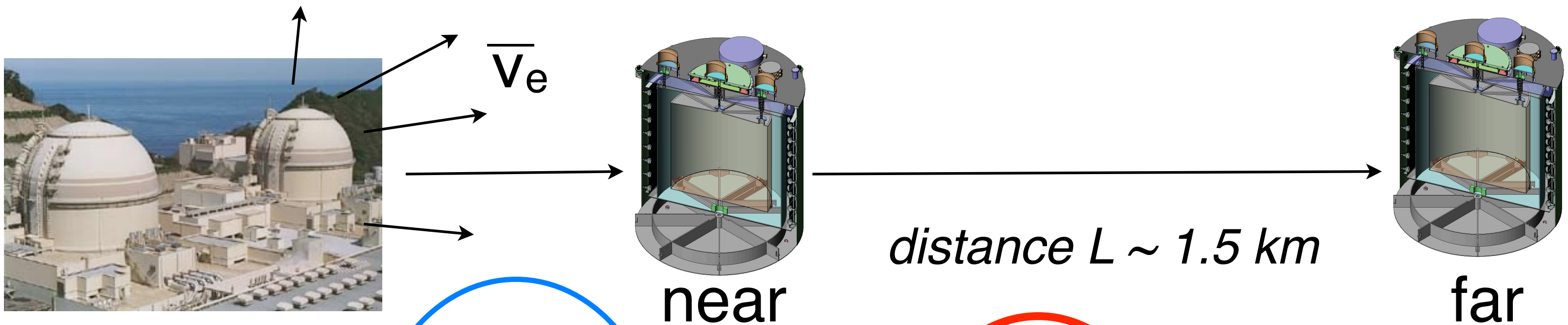
Measured Ratio of Rates

Detector Mass Ratio, H/C

mass measurement

Concept of Reactor θ_{13} Experiments

Measure ratio of interaction rates in multiple detectors



$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right]$$

Measured Ratio of Rates

Detector Mass Ratio, H/C

mass measurement

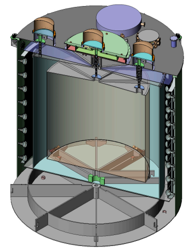
Detector Efficiency Ratio

calibration

Concept of Reactor θ_{13} Experiments

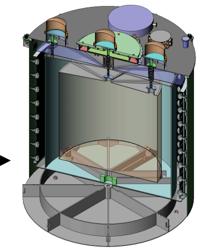
Measure ratio of interaction rates in multiple detectors

$\bar{\nu}_e$



near

distance L ~ 1.5 km



far

$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right]$$

Measured Ratio of Rates

Detector Mass Ratio, H/C

mass measurement

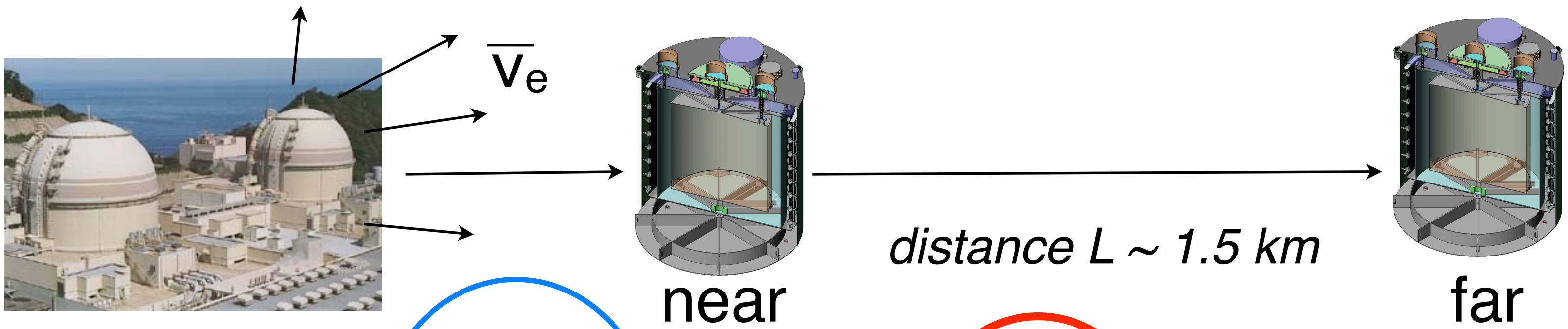
Detector Efficiency Ratio

calibration

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

Concept of Reactor θ_{13} Experiments

Measure ratio of interaction rates in multiple detectors



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

Measured Ratio of Rates

Detector Mass Ratio, H/C

mass measurement

Detector Efficiency Ratio

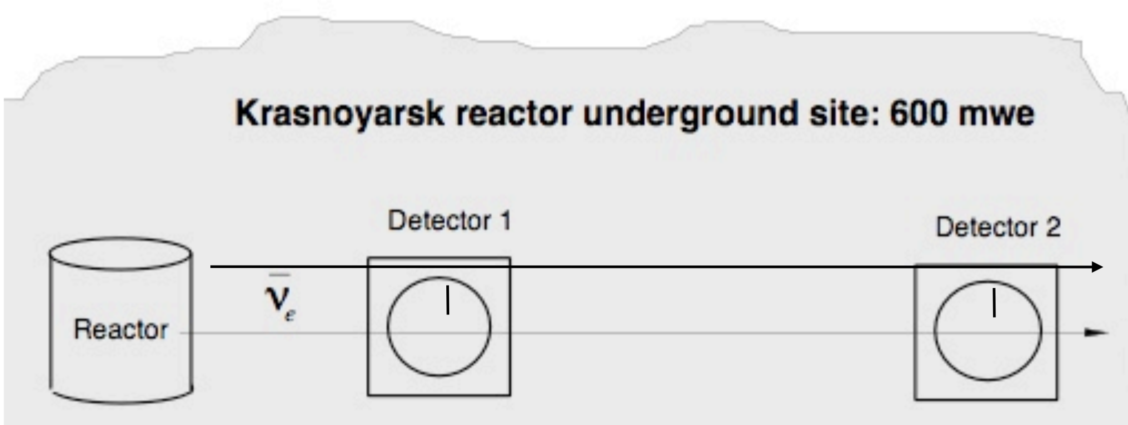
calibration

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

cancel reactor systematics, no fiducial volume cuts

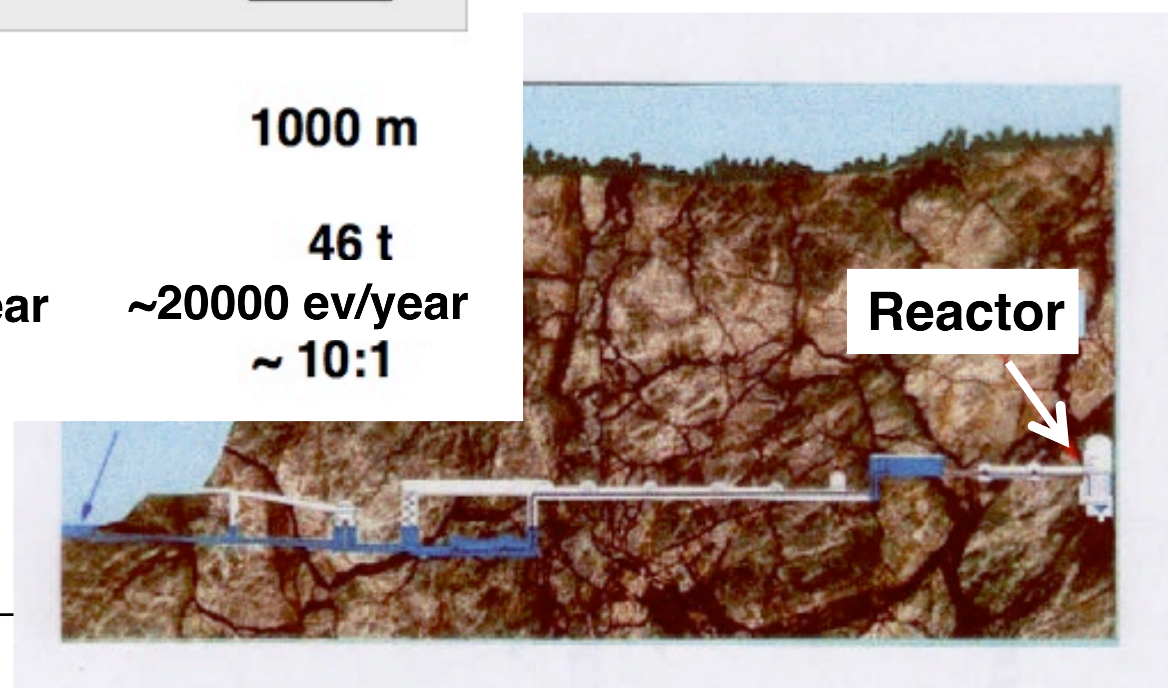
Reactor θ_{13} Experiment at Krasnoyarsk, Russia

Original Idea: First proposed at Neutrino2000



Krasnoyarsk
- underground reactor
- detector locations determined by infrastructure

	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

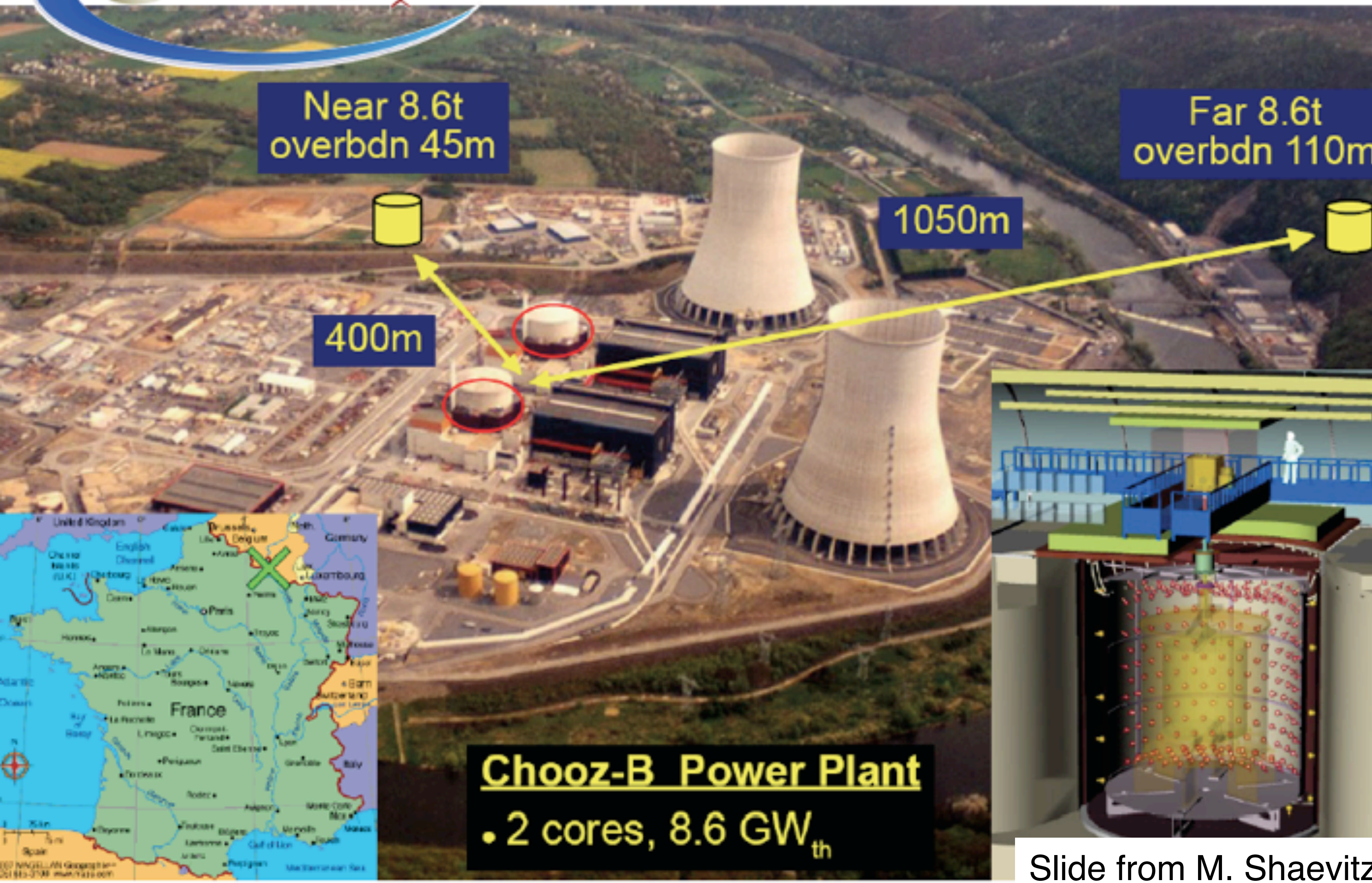


Ref: Marteyamov et al, hep-ex/0211070

World of Reactor θ_{13} Neutrino Experiments

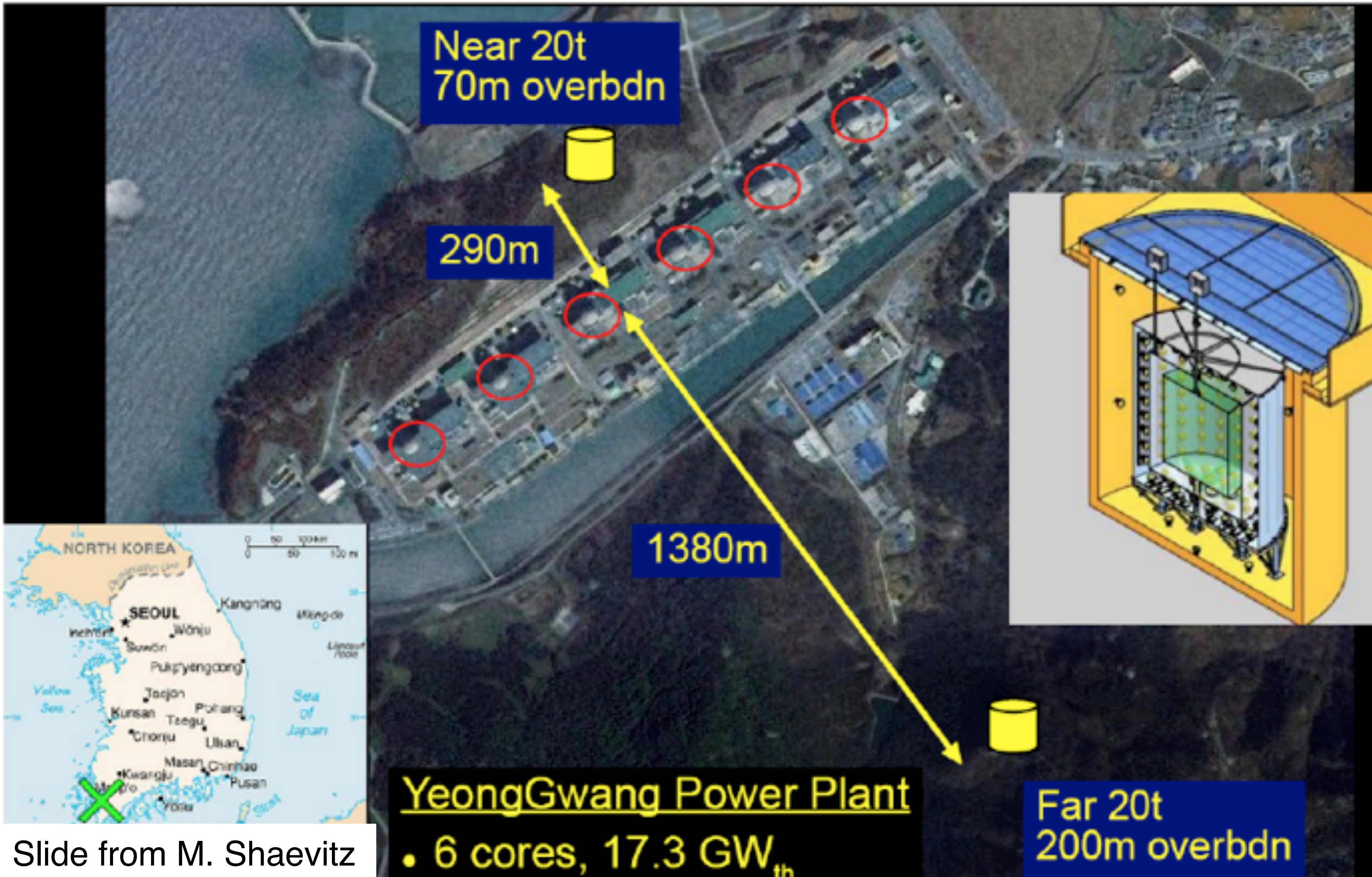
Daya Bay, Double Chooz, and Reno
- international collaborations
- under construction/taking data

Double Chooz Reactor Experiment in Ardennes, France



Slide from M. Shaevitz

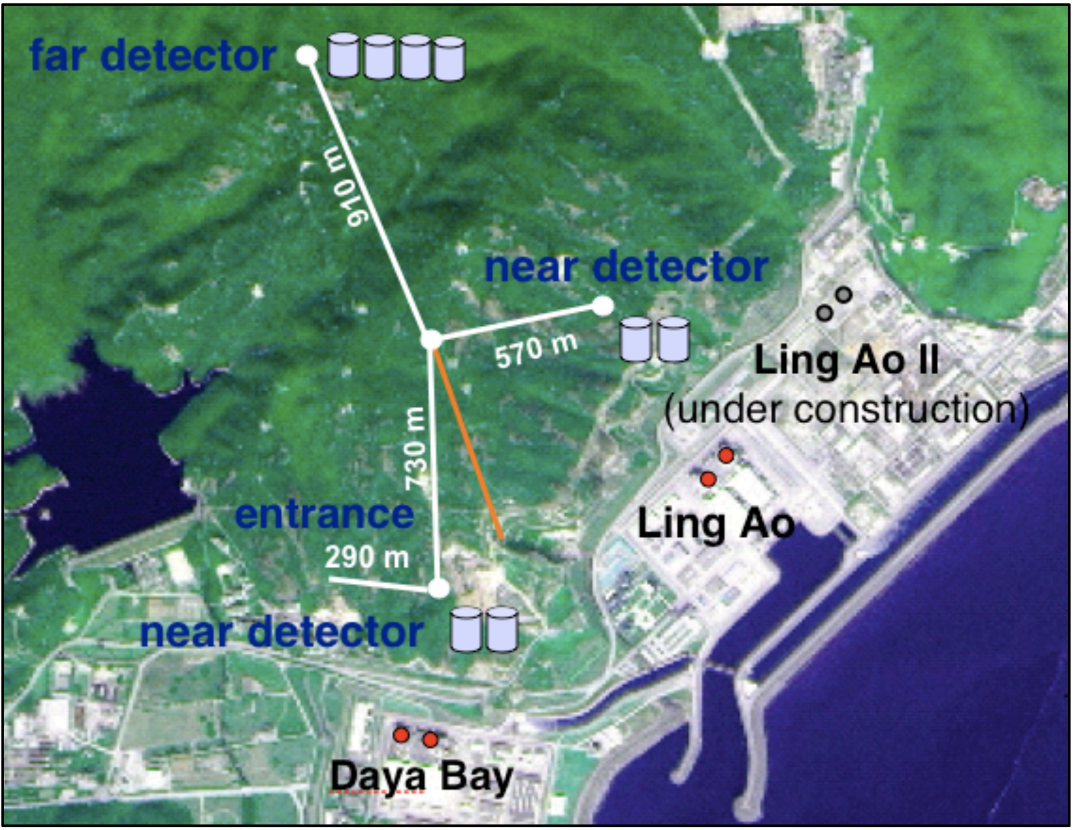
RENO: Reactor Experiment for Neutrino Oscillations at YoungGwang in Korea



Slide from M. Shaevitz

Daya Bay, China

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



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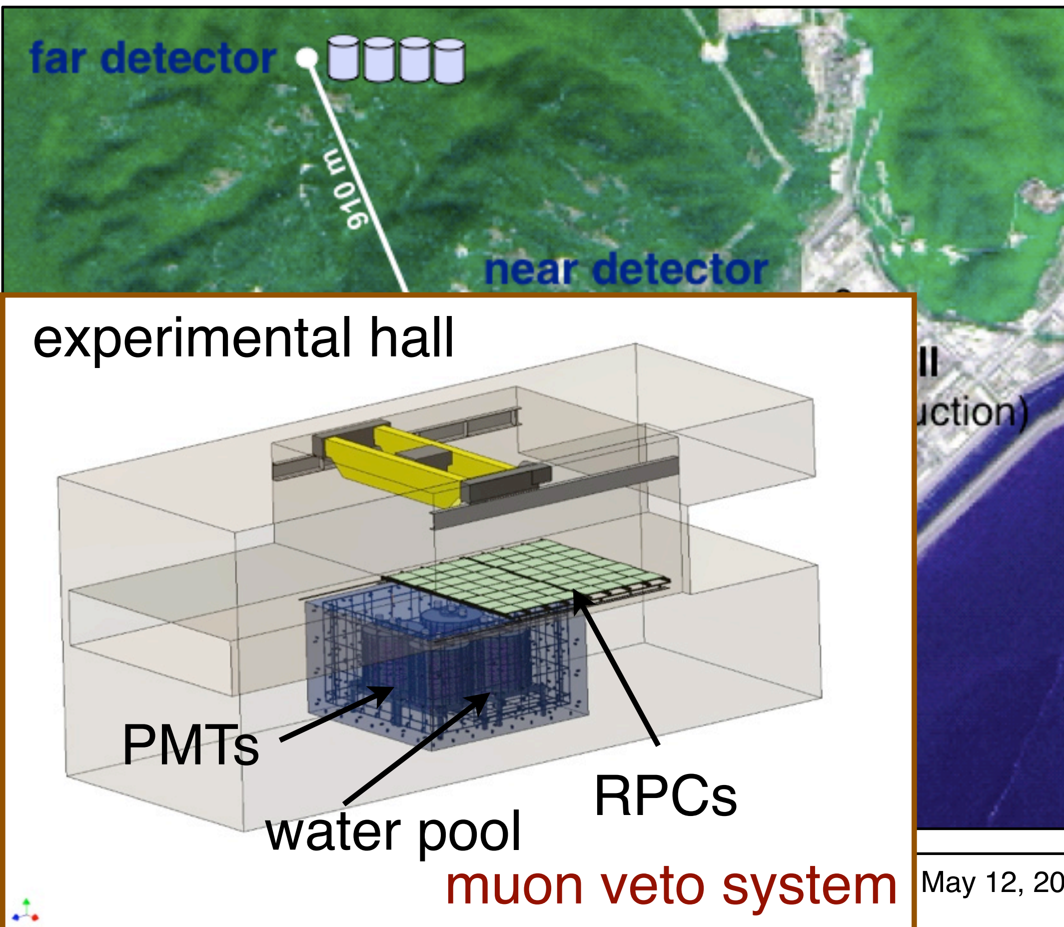

Daya Bay, China

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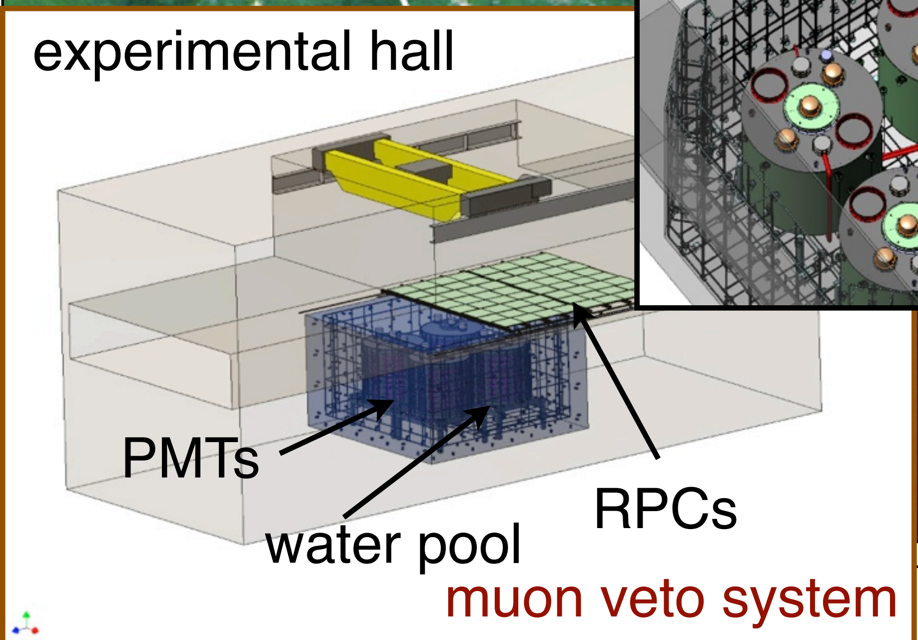

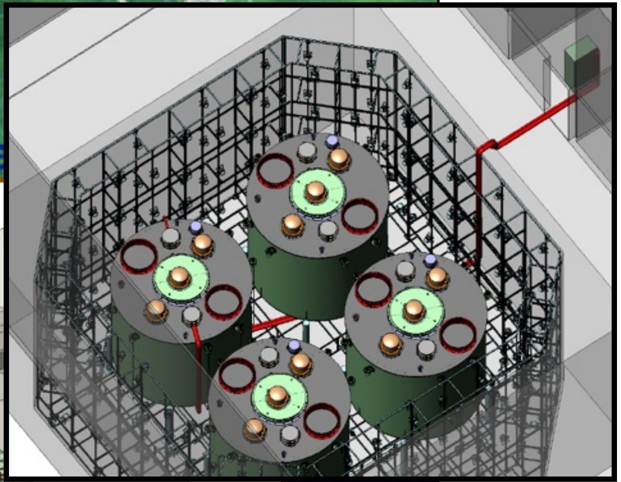

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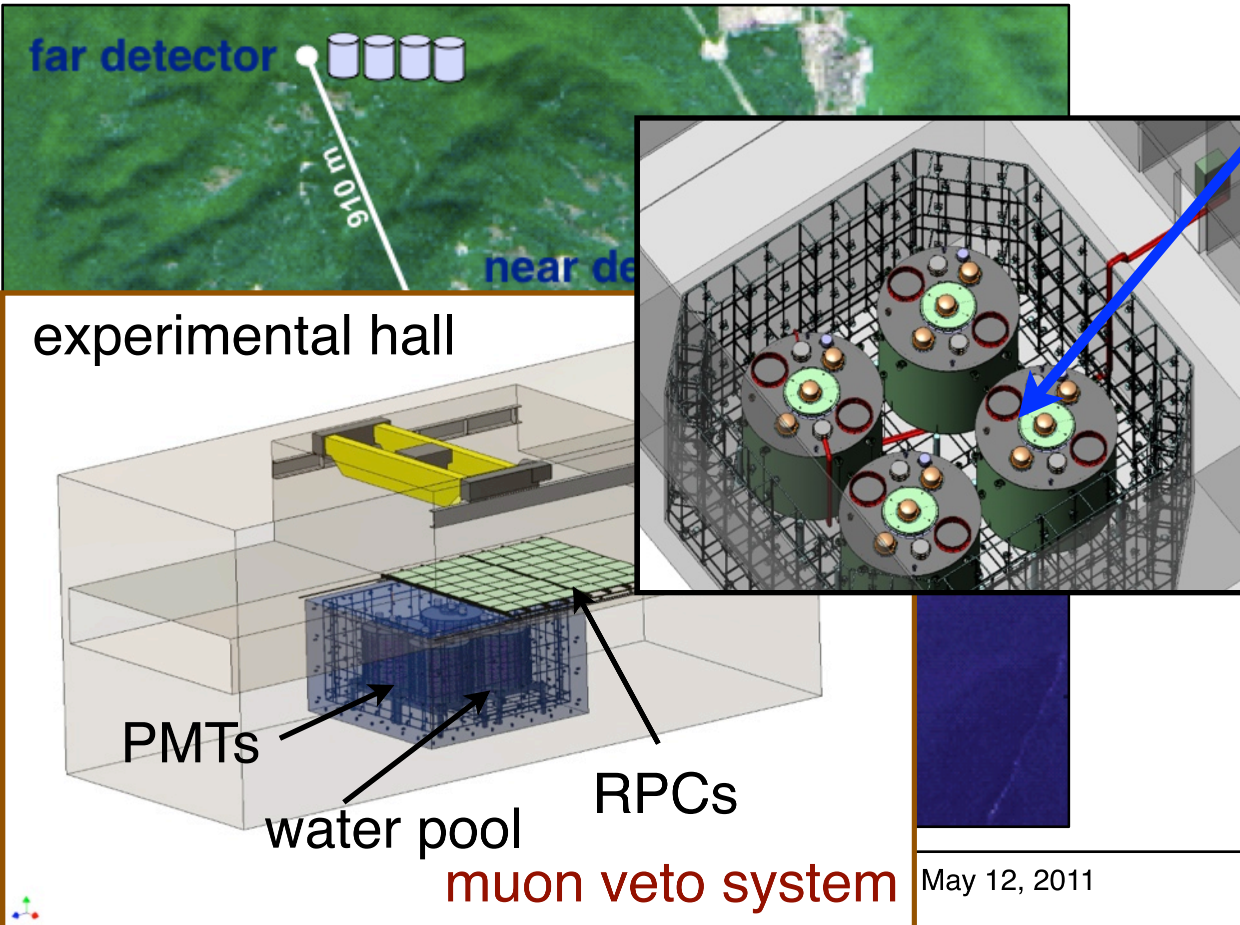
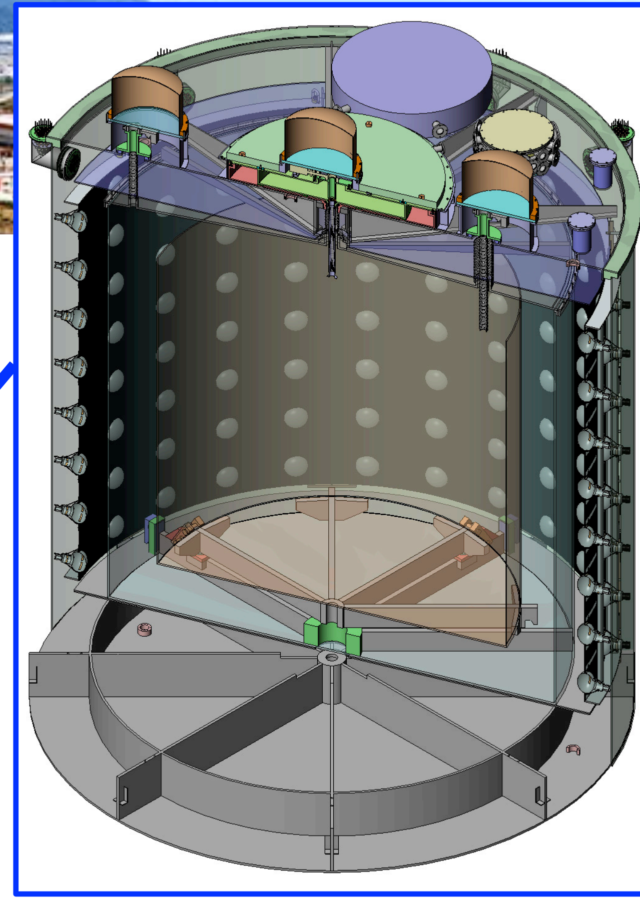
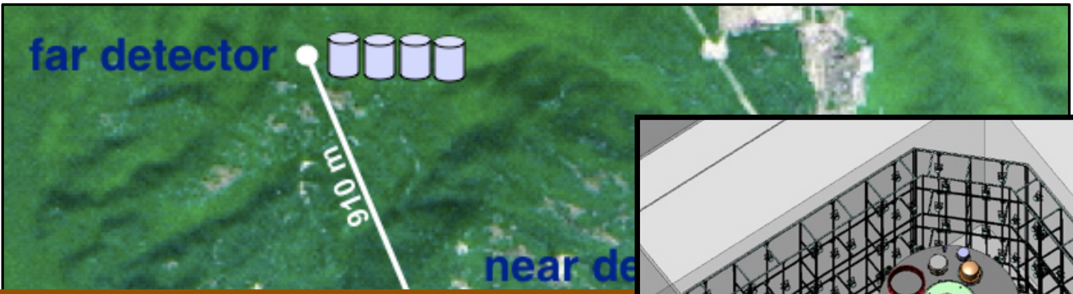


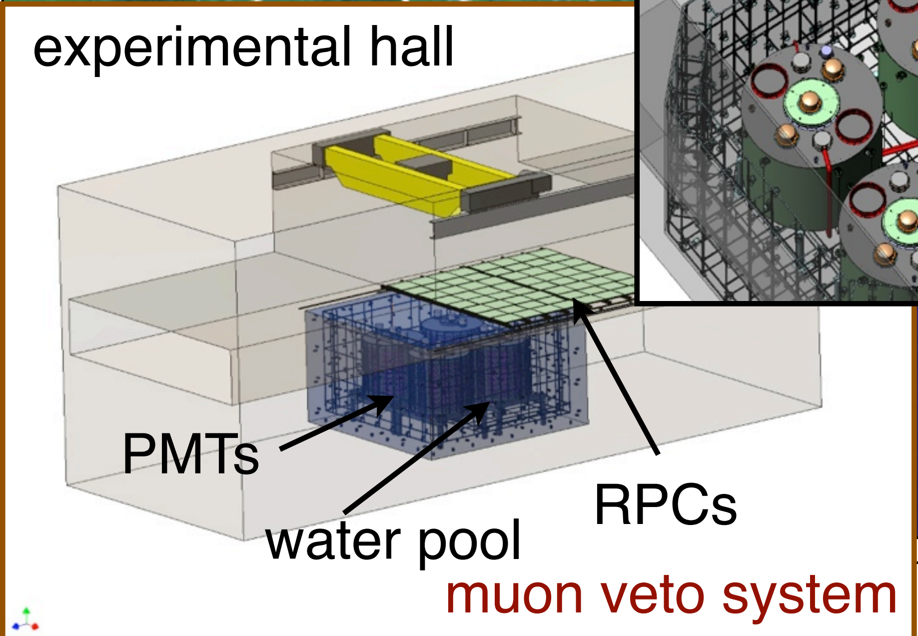


antineutrino detectors

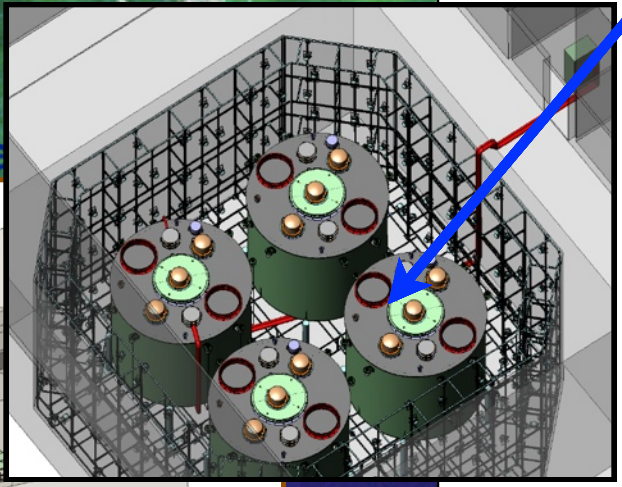
Daya Bay, China

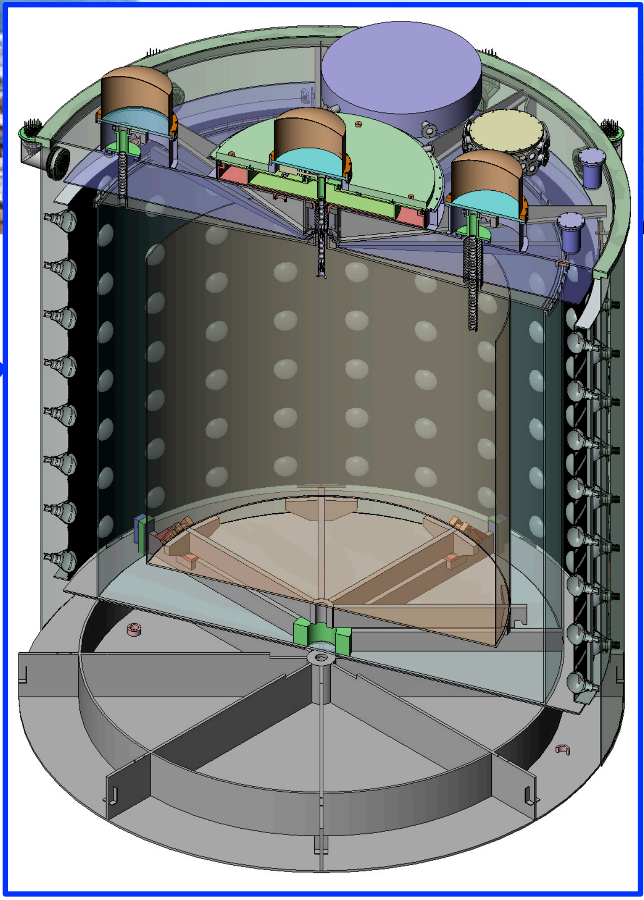
http://dayawane.ihep.ac.cn/





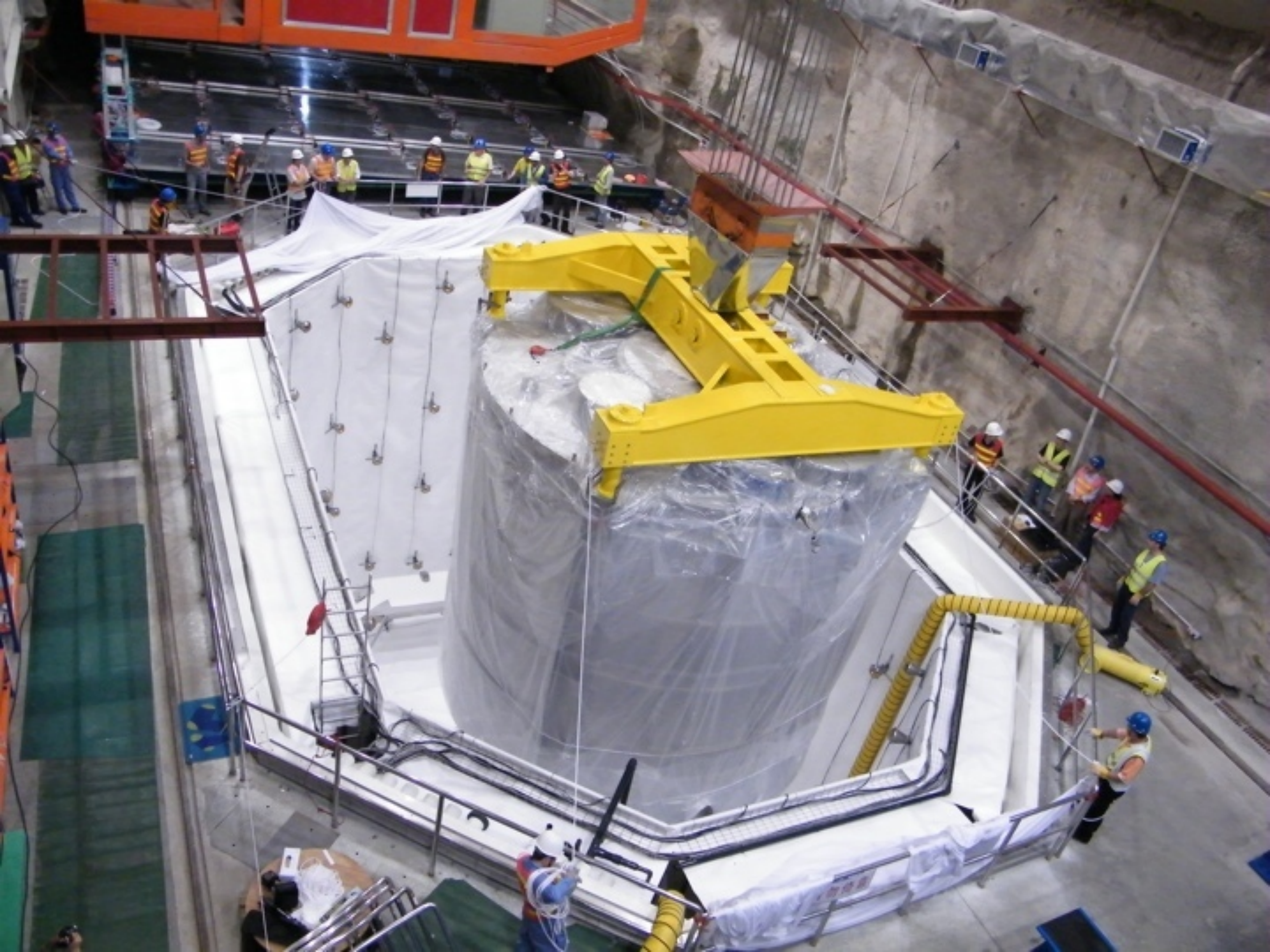
muon veto system

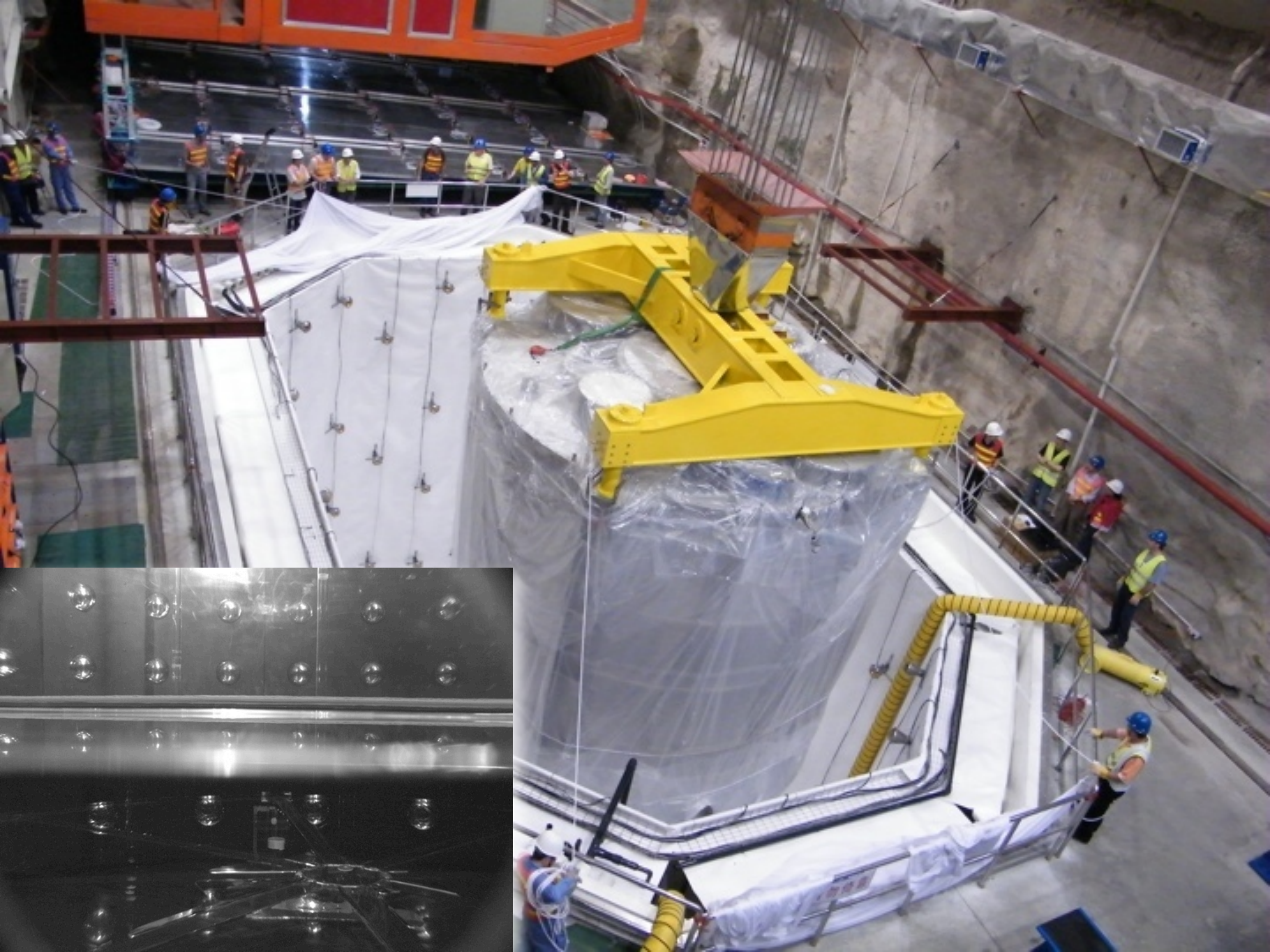




antineutrino detectors

multiple detectors per site
cross-check efficiency



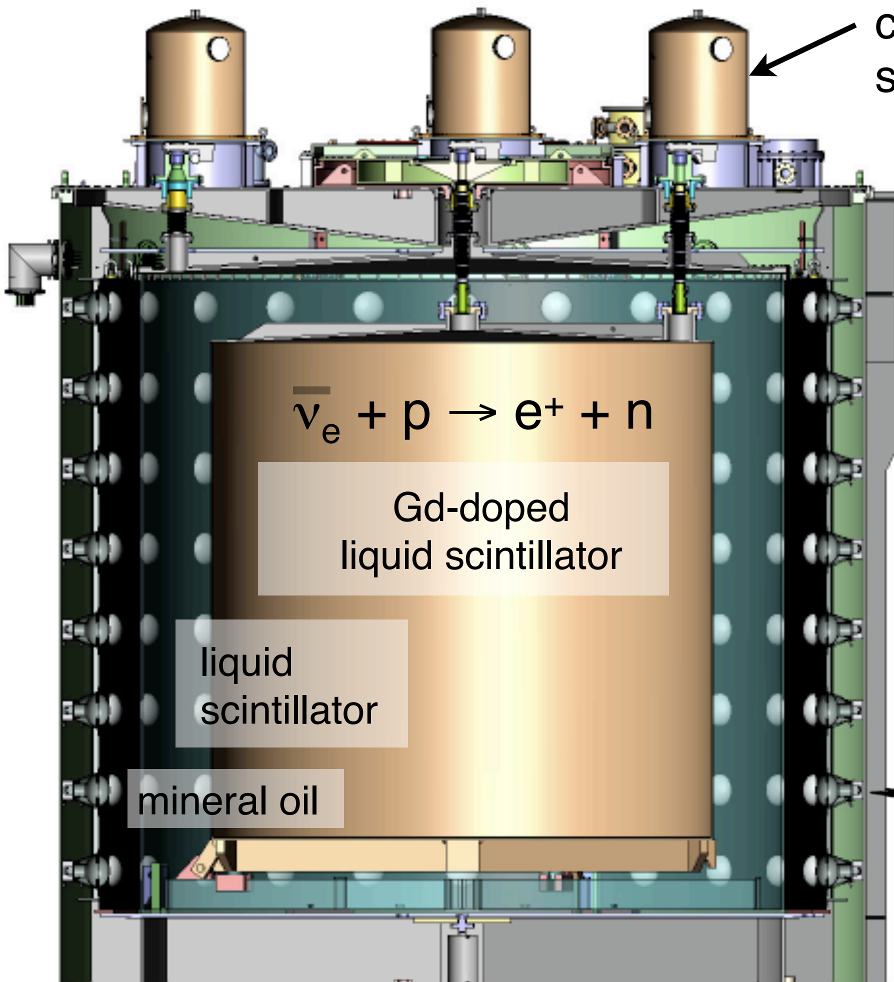


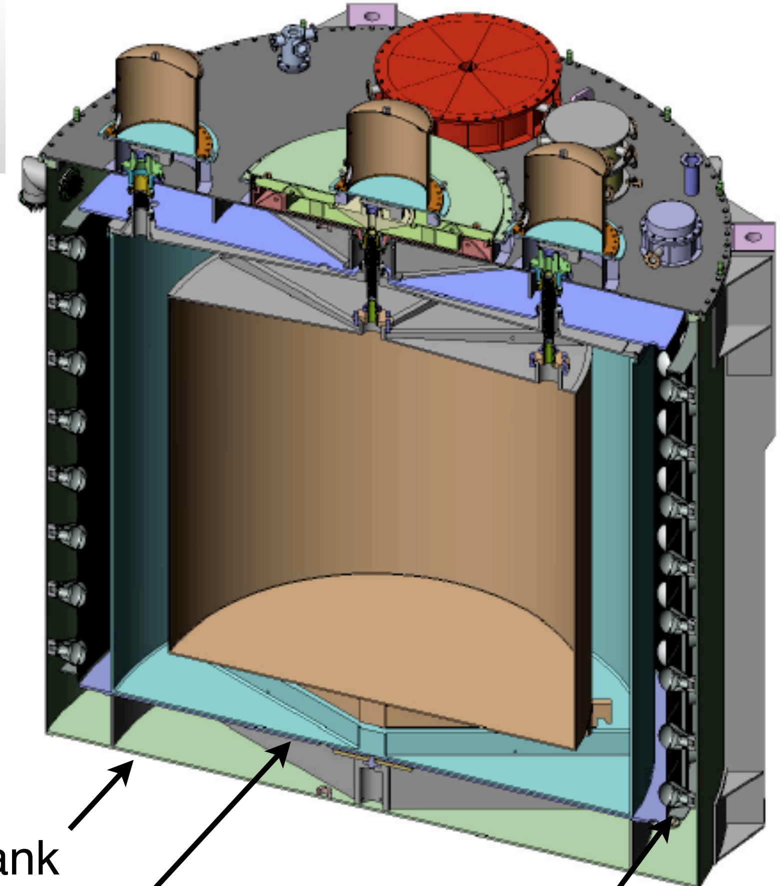
Reactor θ_{13} Experiments

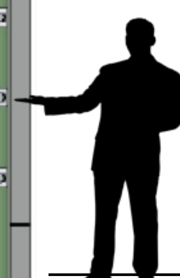
Experiment	Thermal Power (GW)	Distances Near/Far (m)	Depth Near/Far (mwe)	Target Mass (tons)	Start Date Near/Far	Sensitivity @2.5×10^{-3} eV^2 90% CL, 3 years
Double-CHOOZ (France)	8.6	410/1050	115/300	8.8/8.8	2012/2011	0.03
RENO (So. Korea)	17.3	290/1380	120/450	20/20	2011/2011	0.02
Daya Bay (China)	17.4	363(481) / 1985(1613)	260/910	40(×2) / 80	2011/2012	0.008

Daya Bay Antineutrino Detectors

- 8 “identical”, 3-zone detectors
- no position reconstruction, no fiducial cut

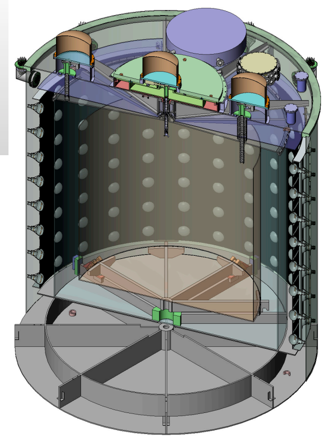






target mass:	20t per detector
detector mass:	~ 110t
photosensors:	192 PMTs
energy resolution:	12%/√E

Antineutrino Detection



Signal and Event Rates

Daya Bay near site	840
Ling Ao near site	760
Far site	90

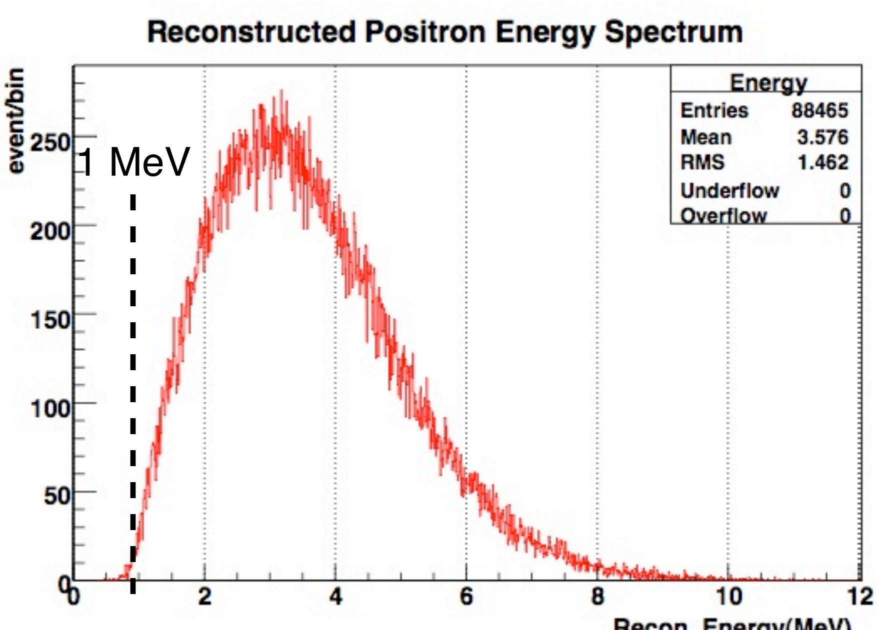
events/day per 20 ton module

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

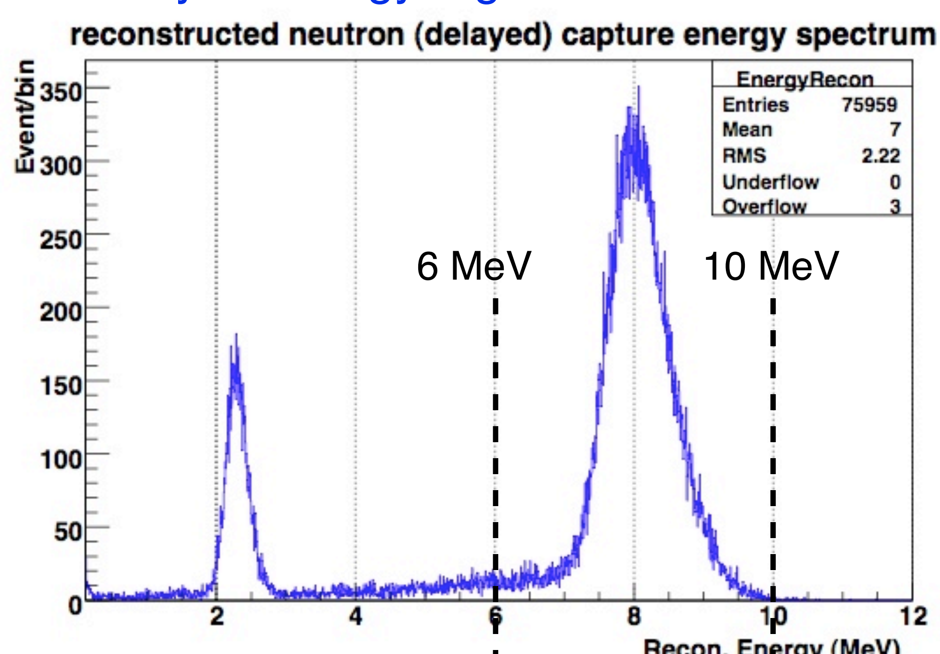
0.3 b $\mapsto + p \rightarrow D + \gamma$ (2.2 MeV) (delayed)

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

Prompt Energy Signal



Delayed Energy Signal



Systematic Uncertainties

Detector-Related Uncertainties

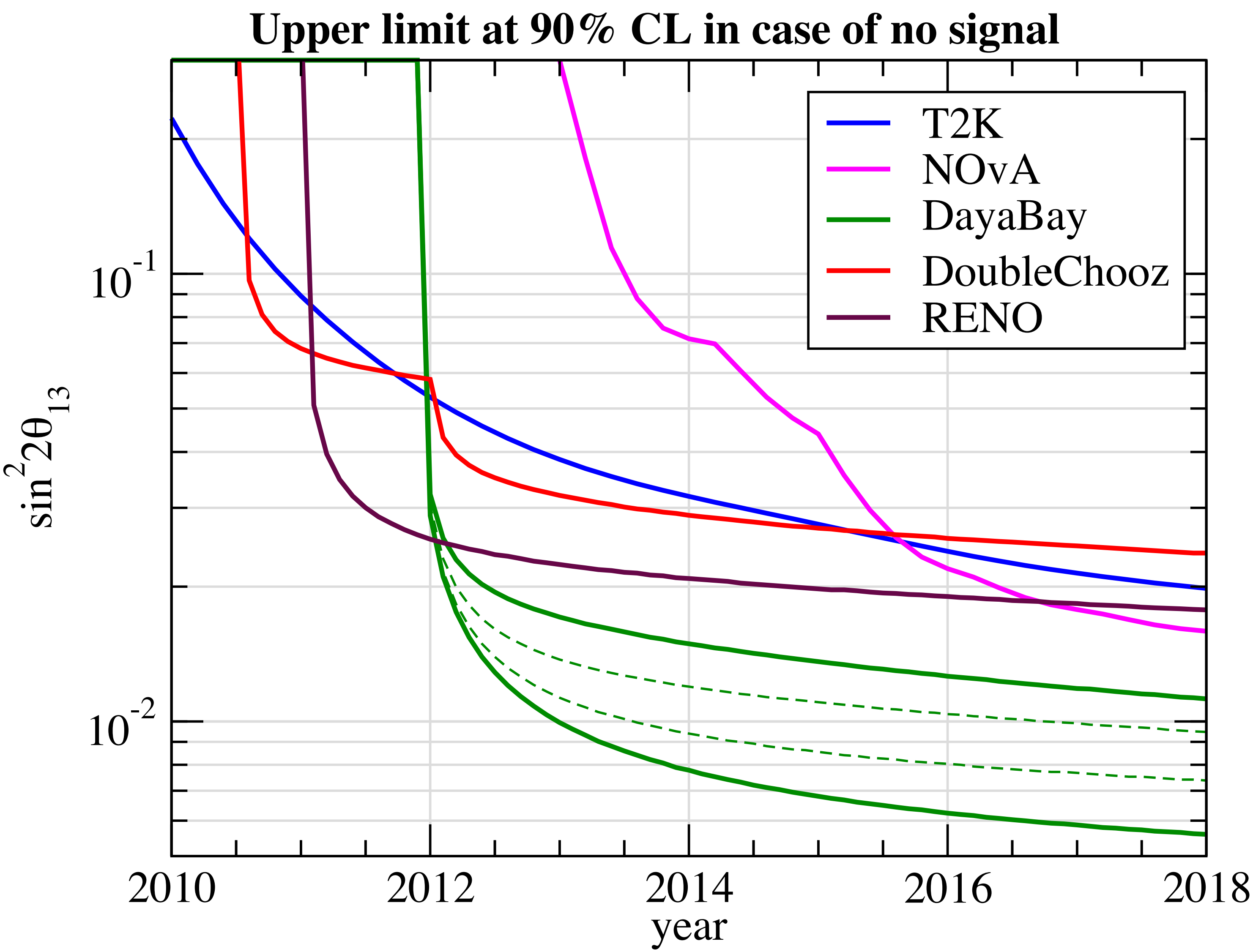
Absolute measurement **Relative measurement**

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%

Ref: Daya Bay TDR

O(0.2-0.3%) precision for relative measurement between detectors at near and far sites

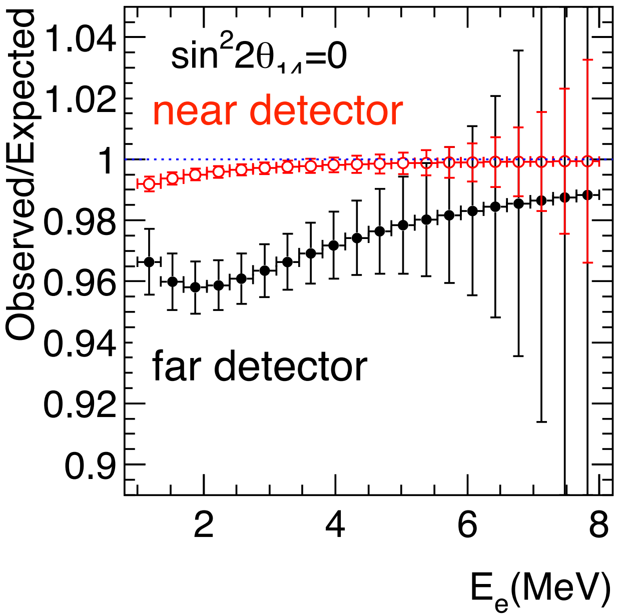
Measuring θ_{13}: A Possible Scenario

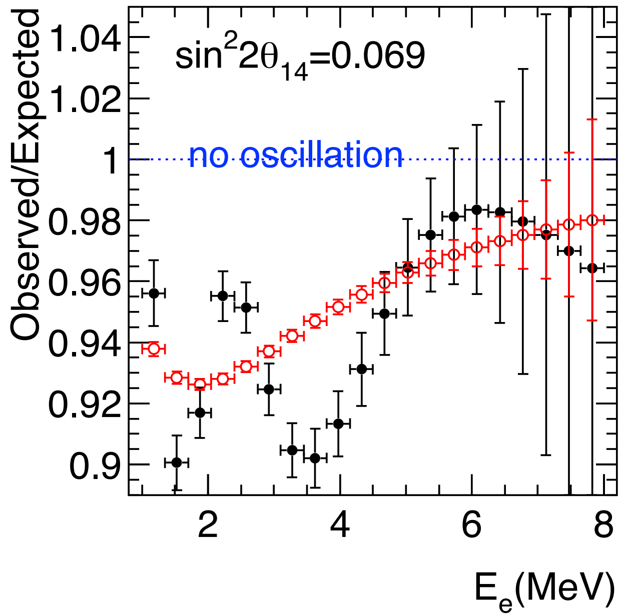


Mezzetto et al
arXive/1003.5800v1

What about sterile neutrinos?

θ_{13} Experiments and Light Sterile Neutrinos (0.01-0.1 eV^2)





$\Delta m_{14}^2 = 1.0 \times 10^{-2}$ eV^2

Daya Bay setup

θ_{14}-driven oscillations affect far and near detector data differently

θ_{14}-driven effects impact ones ability to measure $\sin^2 2\theta_{13}$, shape analysis can disentangle θ_{13} from θ_{14}-driven effects.

roles of near and far detectors may be reversed compared to those associated to studying θ_{13} effects

de Gouvea and Wytock
arXive:0809.5076

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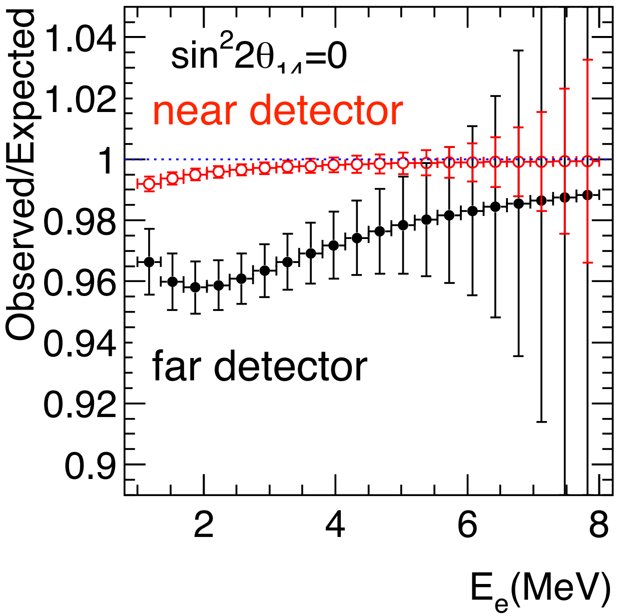

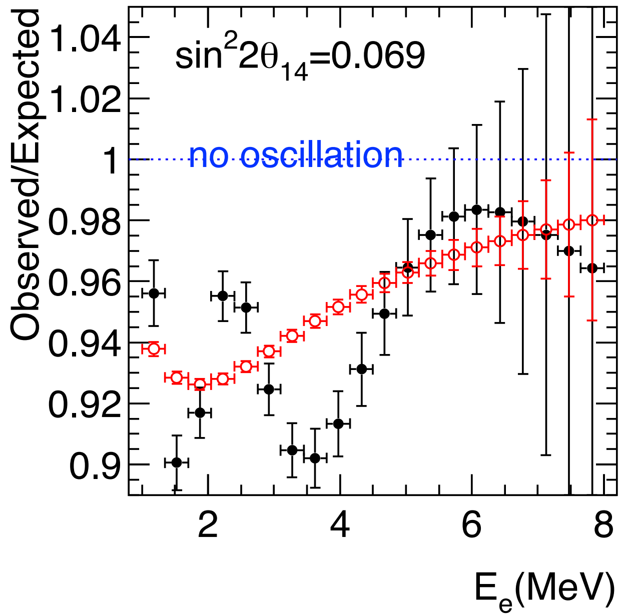

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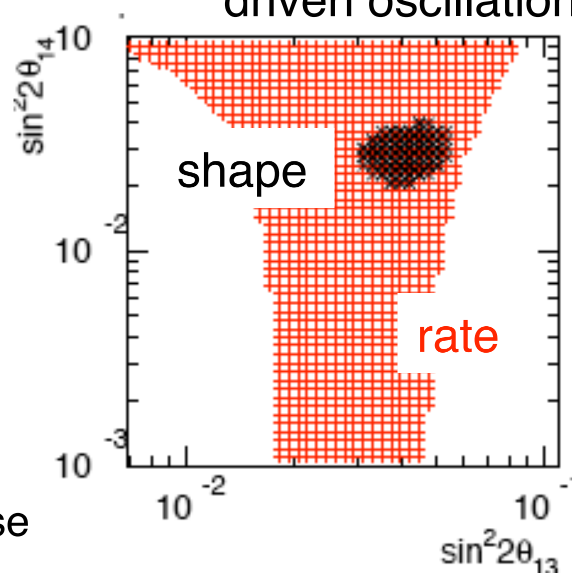
θ_{13} and θ_{14} driven oscillation



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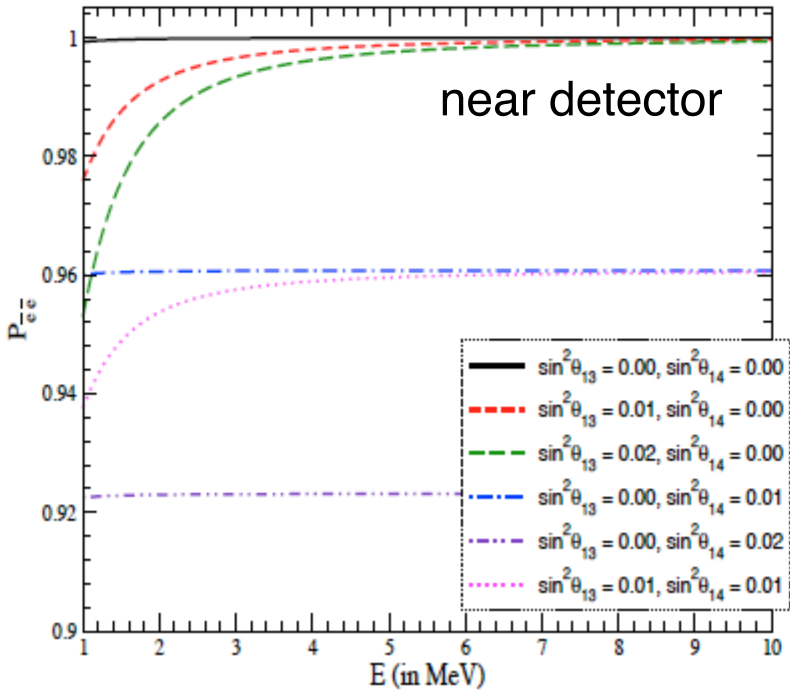
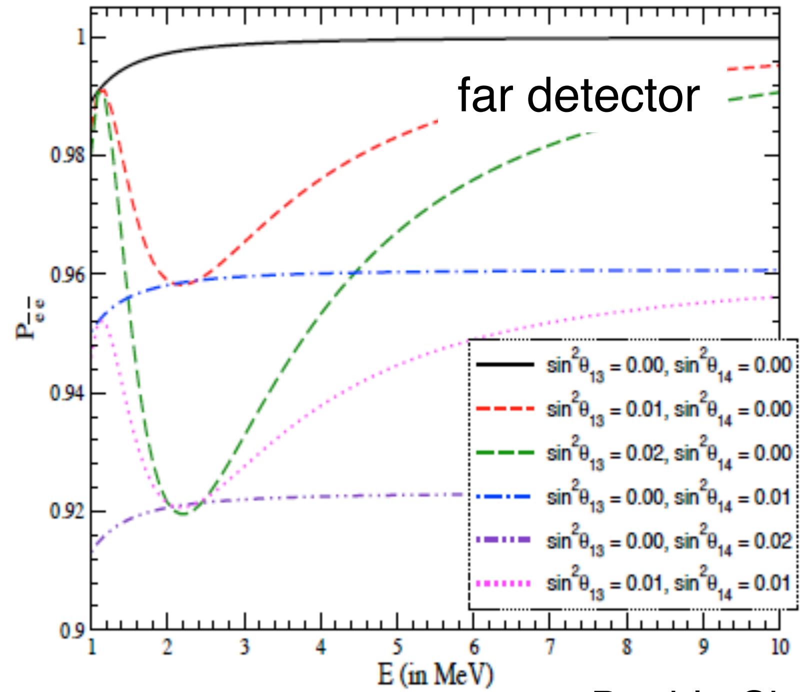
de Gouvea and Wytock
arXive:0809.5076

What about sterile neutrinos?

θ_{13} Experiments and 3+2 Sterile Neutrinos (~1 eV^2)





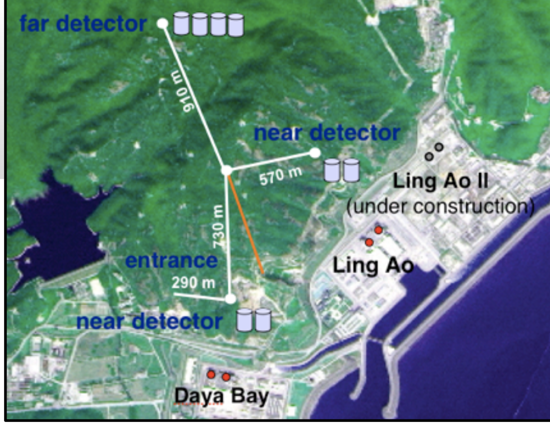
Double Chooz setup

oscillations driven by the extra sterile neutrinos would produce a constant suppression at both the near and far detectors

data from near and far detectors can be used to probe θ_{13} and θ_{14}-driven effects

Bandyopadhyaya and Choubey arXive:0707.2481v1

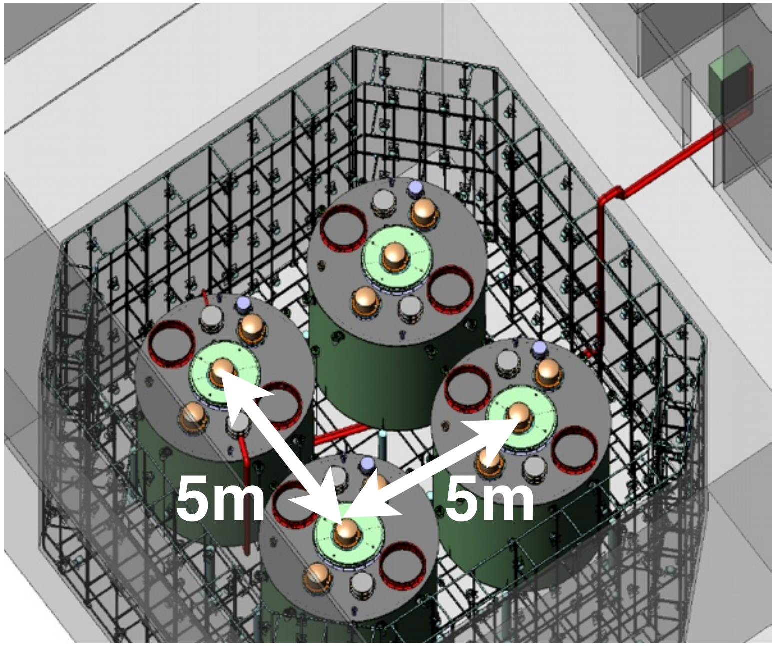
Very Short Baseline Oscillation Search?



Daya Bay Far Hall

reactor $\overline{\nu}_e$
from 1.8km distance

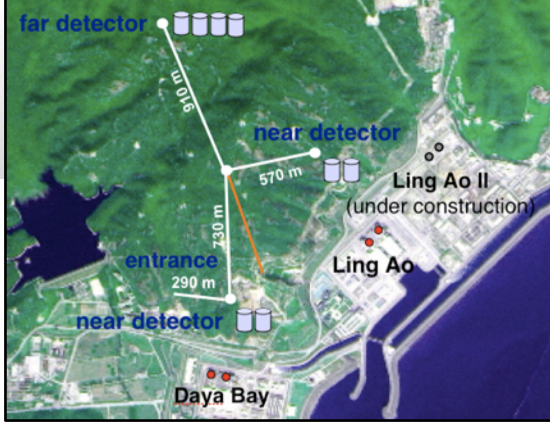
~90 events/
day/detector



a multi-detector experiment with
baseline O(10m) in experimental hall

Littlejohn, KMH

Very Short Baseline Oscillation Search?



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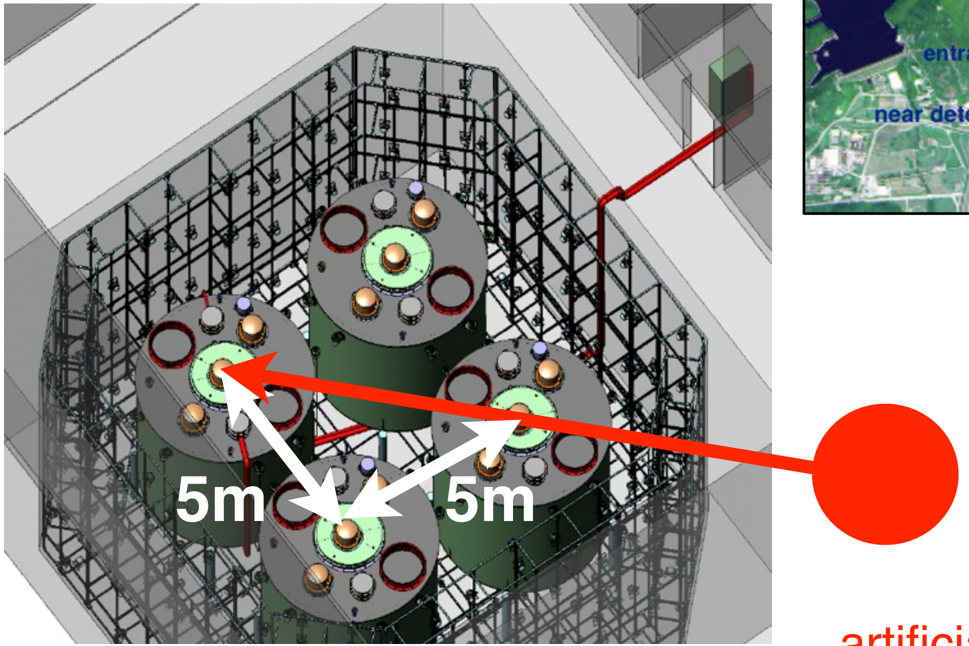


$\bar{\nu}_e$ source

artificial sources of $\bar{\nu}_e$?
spent nuclear fuel?

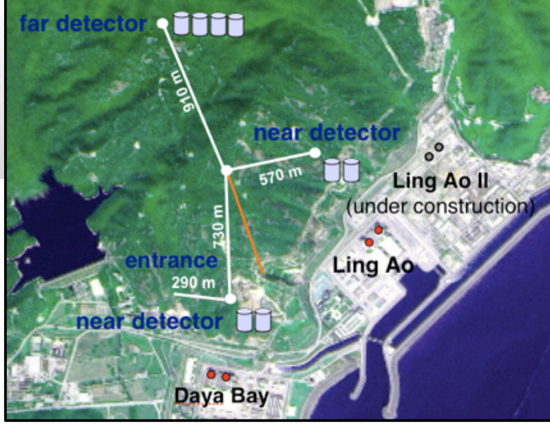
a multi-detector experiment with
baseline O(10m) in experimental hall

Look for very short-baseline variations on top of the reactor $\bar{\nu}_e$ background

➔ sterile oscillations?
➔ Pontecorvo $\nu \rightarrow \bar{\nu}$ oscillations?
➔ flavor change from magnetic moment scattering?

Littlejohn, KMH

Very Short Baseline Oscillation Search?



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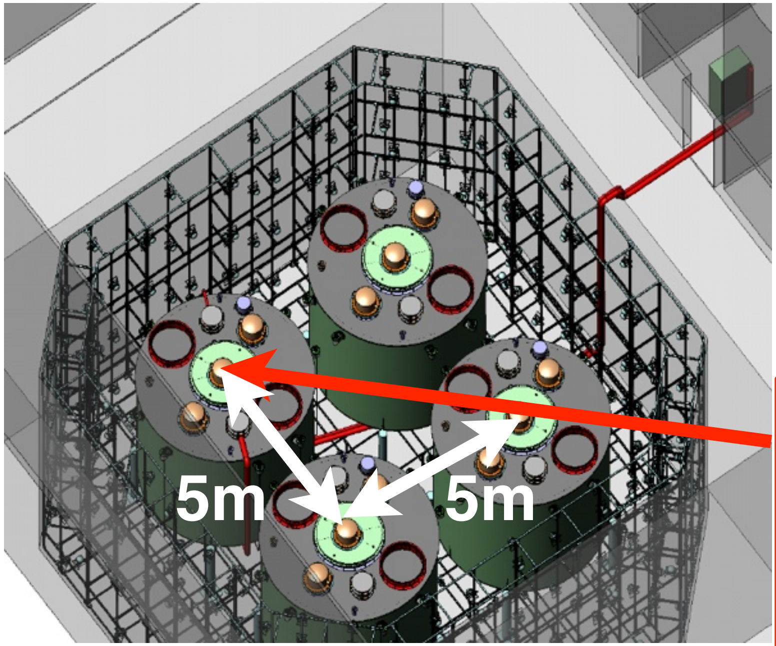
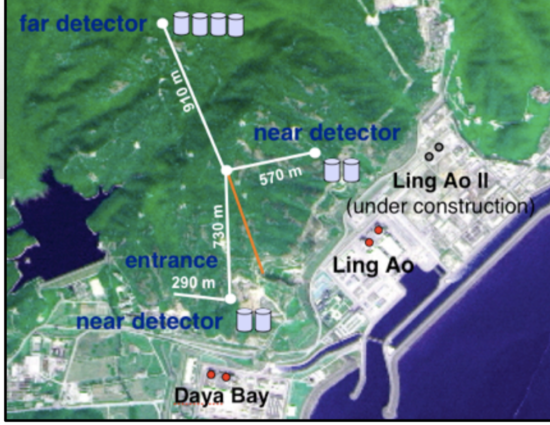


Littlejohn, KMH

Very Short Baseline Oscillation Search?



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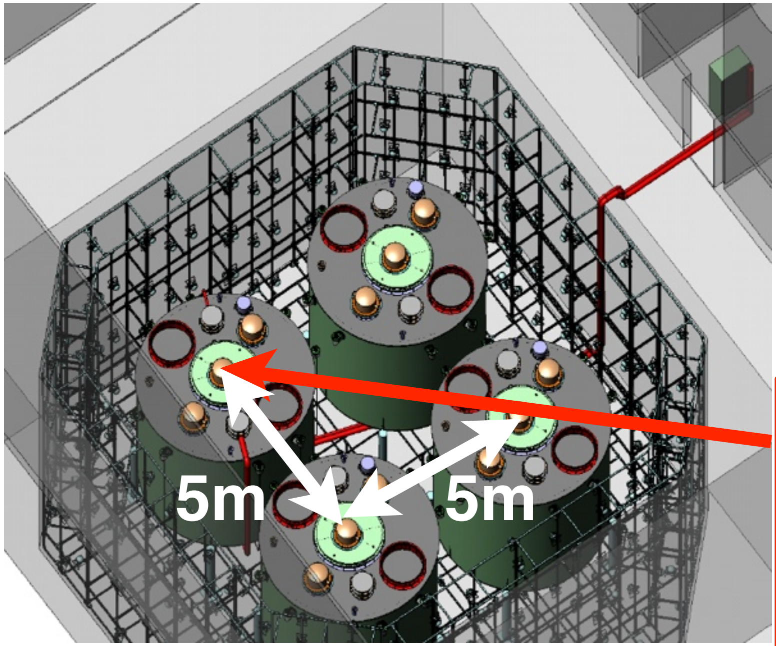

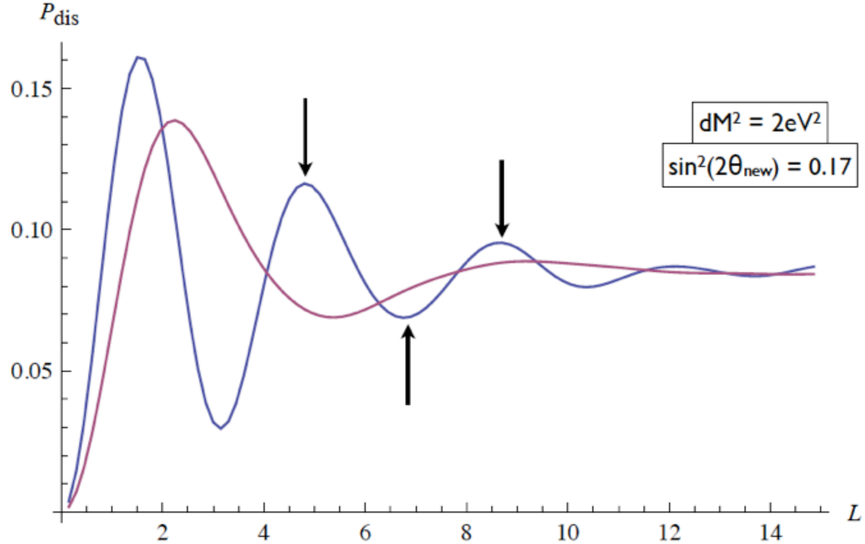

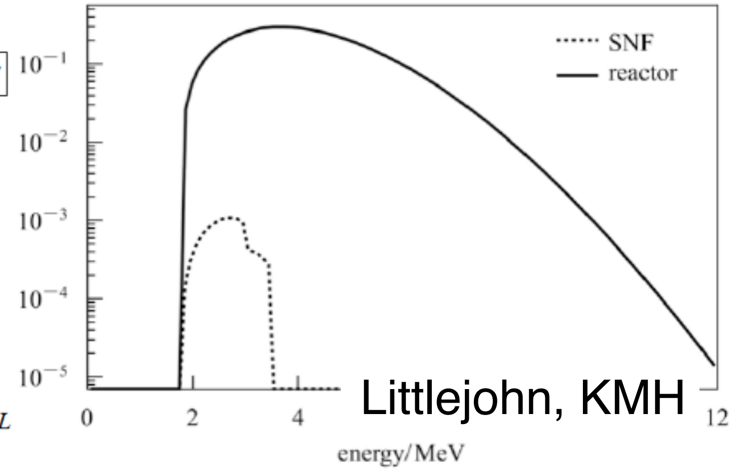

Littlejohn, KMH

Summary and Conclusions

• Atmospheric, solar and reactor experiments were **key to the discovery of neutrino mass and oscillation** in the past decade (1998 -).

• **Upcoming reactor experiments will measure** θ_{13}. Key to model building. Measurement of $\sin^2 2\theta_{13} > 0.01$ is key to planning leptonic CPV searches in long-baseline ν oscillation experiments.

• Future intermediate/long-baseline reactor antineutrino experiments may be used for a precision measurement of θ_{12} (using baseline from $\Delta m^2_{12} = \Delta m^2_{sol}$).

• Determination of mass hierarchy with kt-size detectors is being explored.

• New experiments with multiple detectors at distances of 5-15m may offer opportunities for very short baseline oscillation searches with appropriate $\bar{\nu}_e$ source