Systematics in Reactor Neutrino Oscillation Experiments

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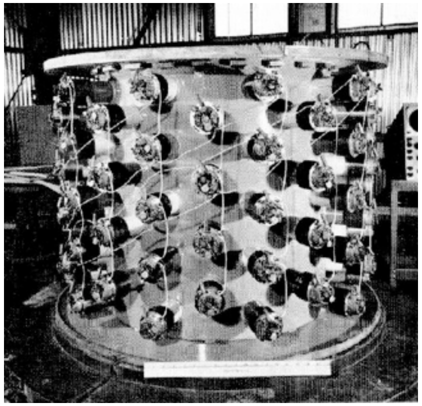
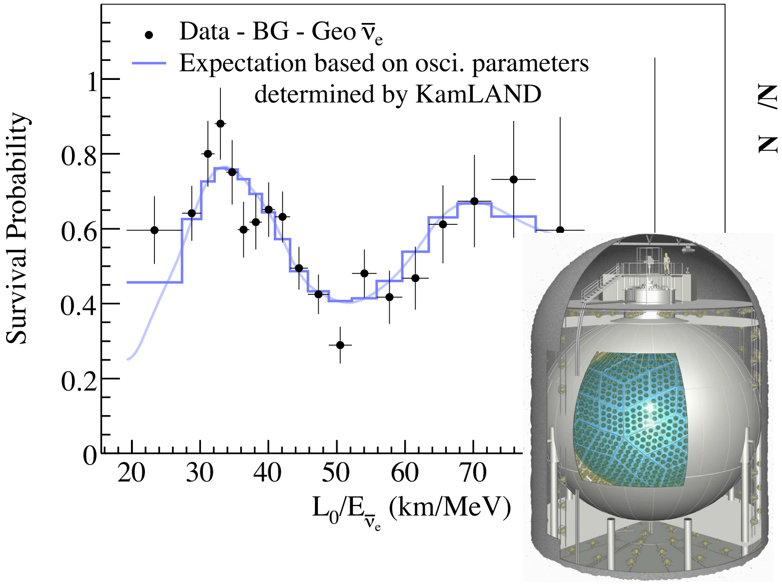
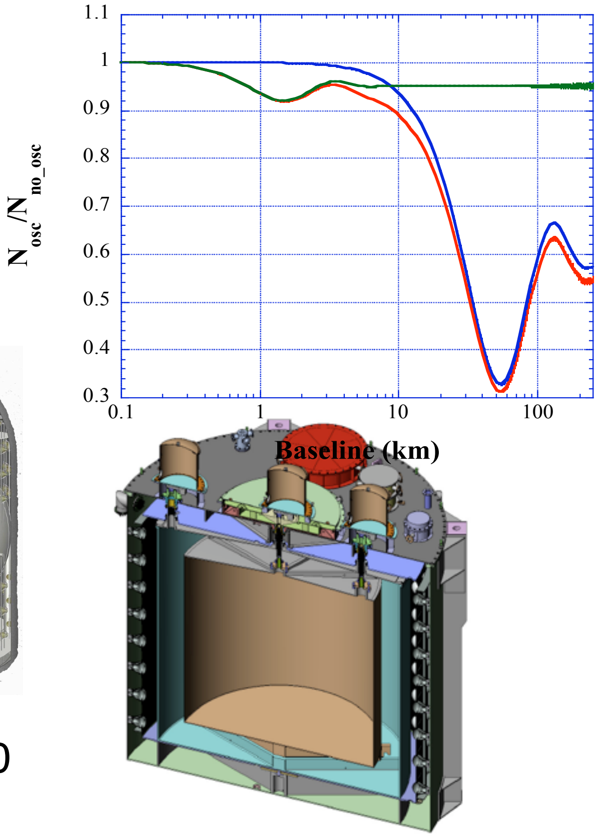






NuFact2010, October 23, 2010

Outline

- Measuring reactor antineutrinos
- Reactor neutrino oscillation measurements: status and prospects
- From one to multiple detectors
- Near-far detector concept
- Systematics in reactor experiments
  - reactor site
  - detector
  - backgrounds
- Sensitivity of future reactor experimenrs

Neutrino Physics at Reactors

History of reactor neutrino research

Next - Discovery and precision measurement of θ_{13}

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

2004 - Evidence for spectral distortion

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

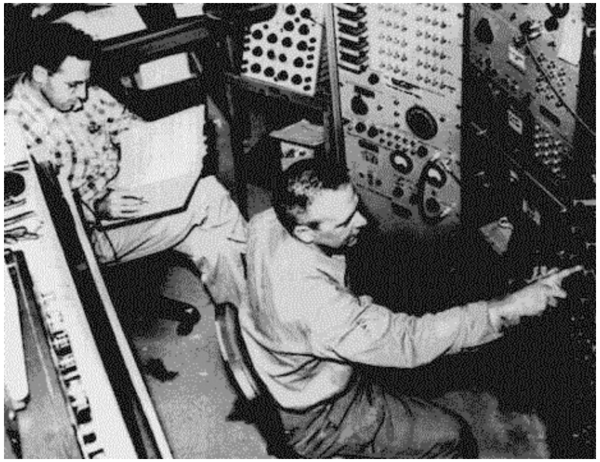
1956 - First observation of (anti)neutrinos

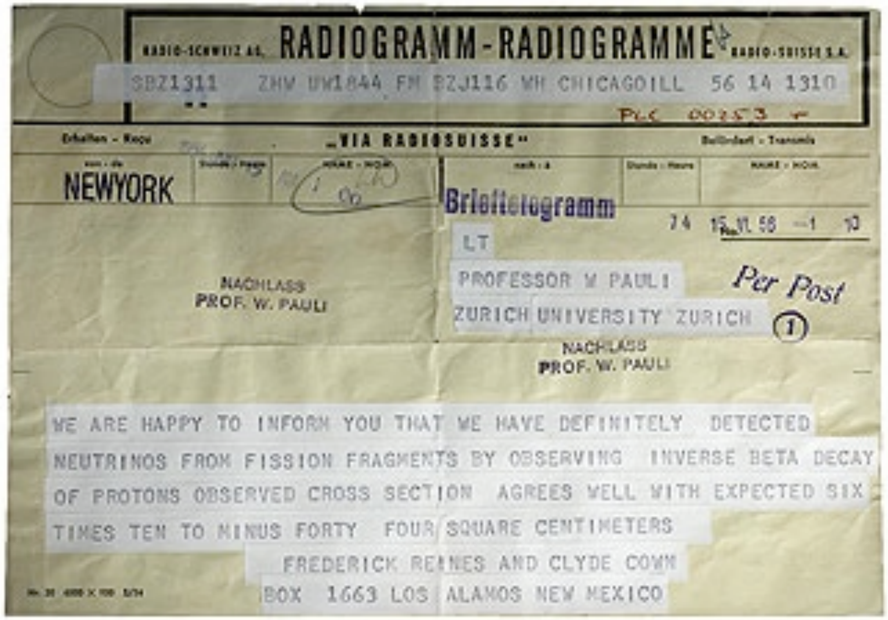
Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France

from the first discovery to precision physics

Discovery of the Neutrino

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





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Per Post

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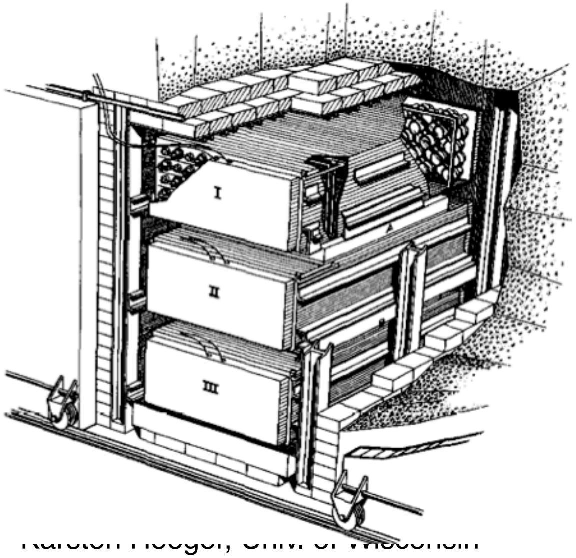
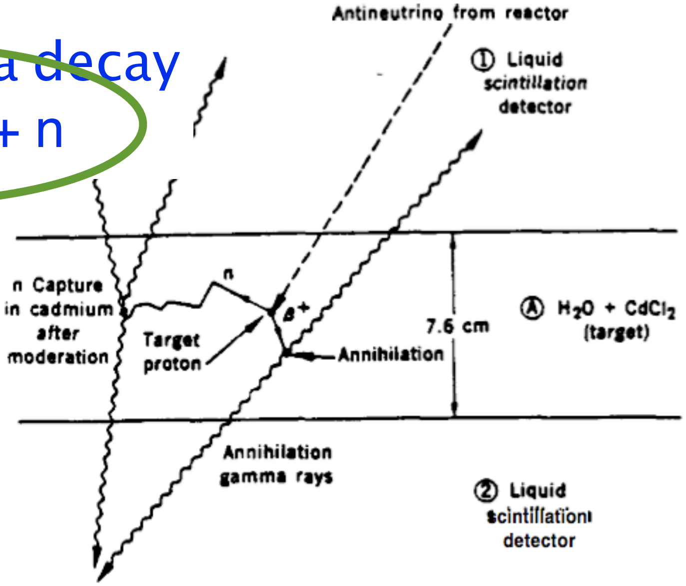
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN
BOX 1663 LOS ALAMOS NEW MEXICO



inverse beta decay

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



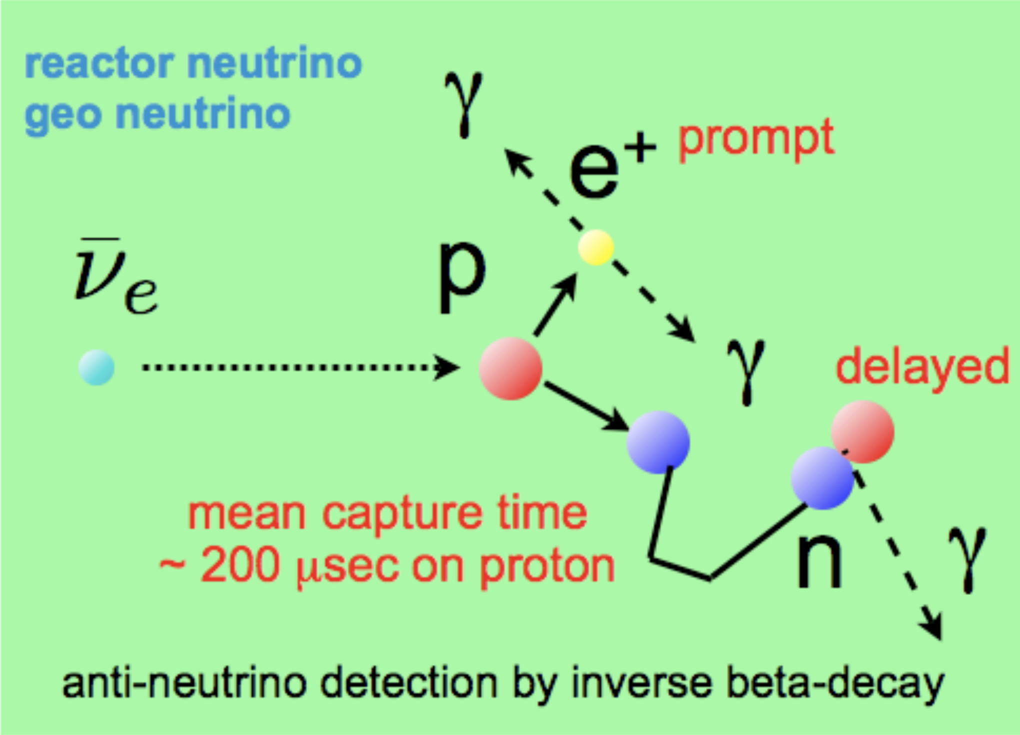
Antineutrino Detection

inverse beta decay

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

coincidence signature

prompt e^+ and delayed neutron capture

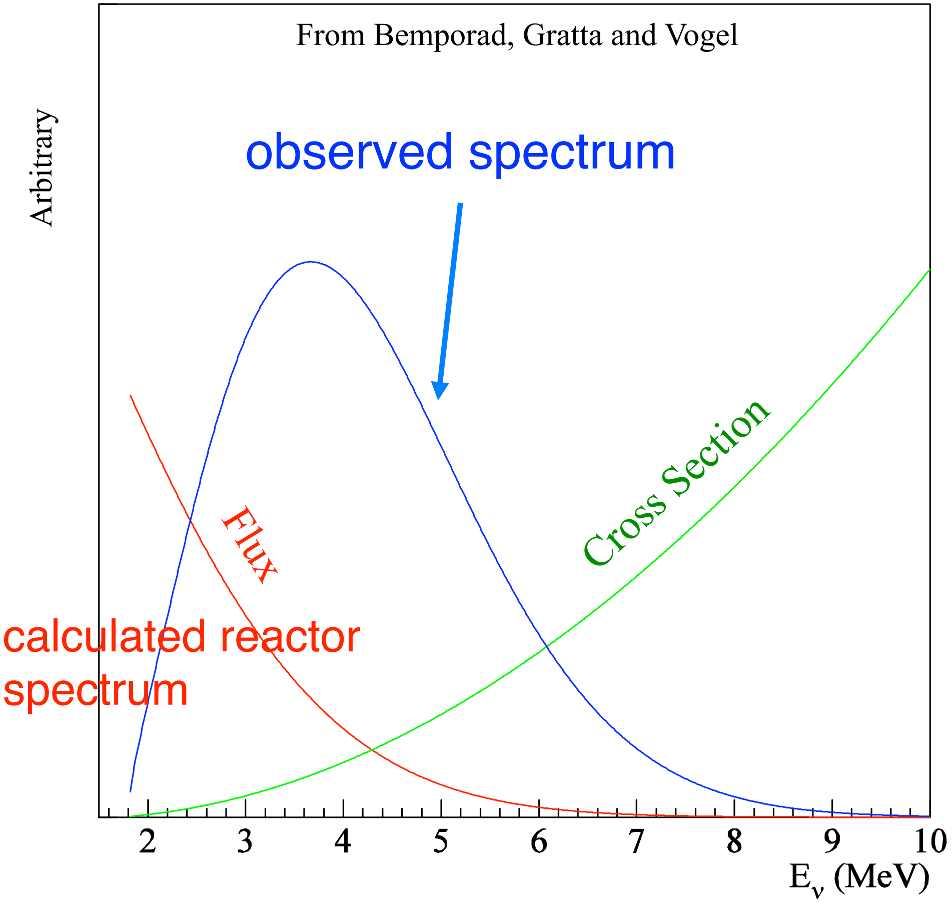


anti-neutrino detection by inverse beta-decay

$$E_{\bar{\nu}_e} \cong E_{e^+} + \overset{\text{10-100 keV}}{E_n} + \overset{\text{1.805 MeV}}{\boxed{(M_n-M_p) + m_{e^+}}}$$

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

Reactor Antineutrinos



observed spectrum

calculated reactor spectrum

threshold: neutrinos with E < 1.8 MeV are not detected

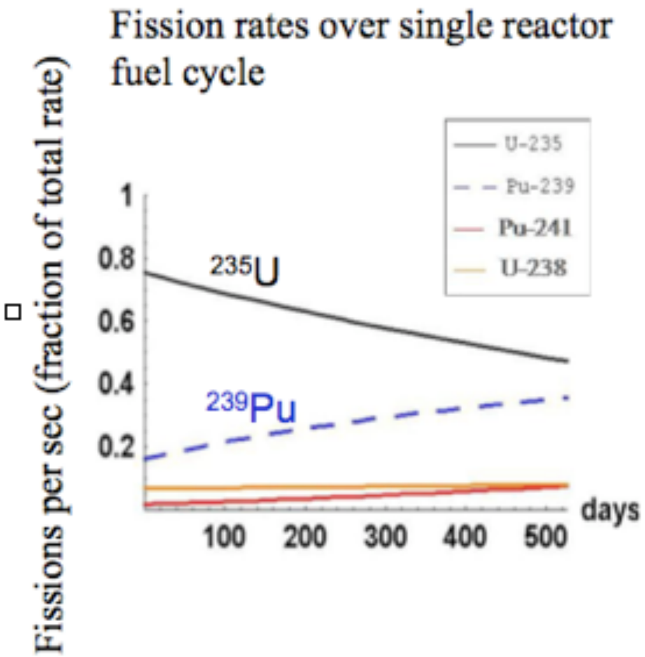
only ~ 1.5 $\overline{\nu}_e$/fission can be detected

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

only disappearance expts possible

cross-section accurate to +/-0.2%

time-dependent rate and spectrum


Fission rates over single reactor fuel cycle

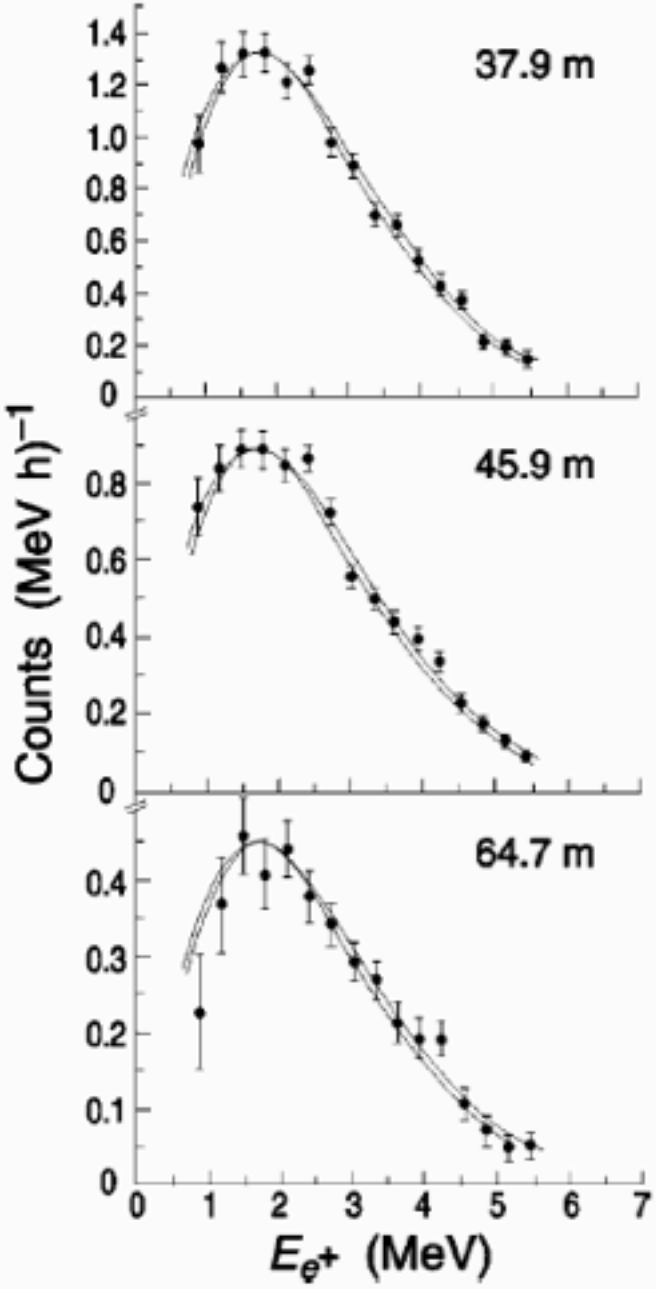
Measurement of Reactor Spectra

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

Oscillation Experiments with Reactors

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

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

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

$\Delta m^2_{12} \sim 8 \times 10^{-5}$ eV²
$\Delta m^2_{23} \sim 2.5 \times 10^{-3}$ eV²

→

L ~ 60 km
L ~ 1.8 km

$\Delta m^2_{13} \sim \Delta m^2_{23}$

search for θ_{13} at baseline of ~ 1.8km

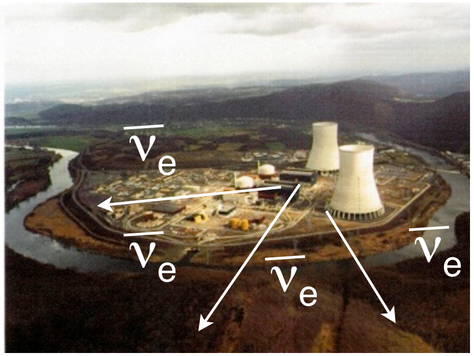
- look for rate deviations from 1/r² and spectral distortions
- baselines relatively short, no matter effects
- Mean antineutrino energy is 3.6 MeV, only disappearance experiments possible $\overline{\nu}_e \rightarrow \overline{\nu}_e$.

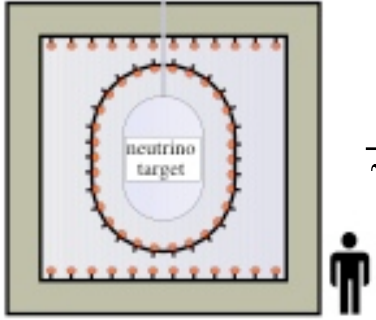
Oscillation Search at Baseline of 1km

Chooz (1998)

thermal power 8.5 GW

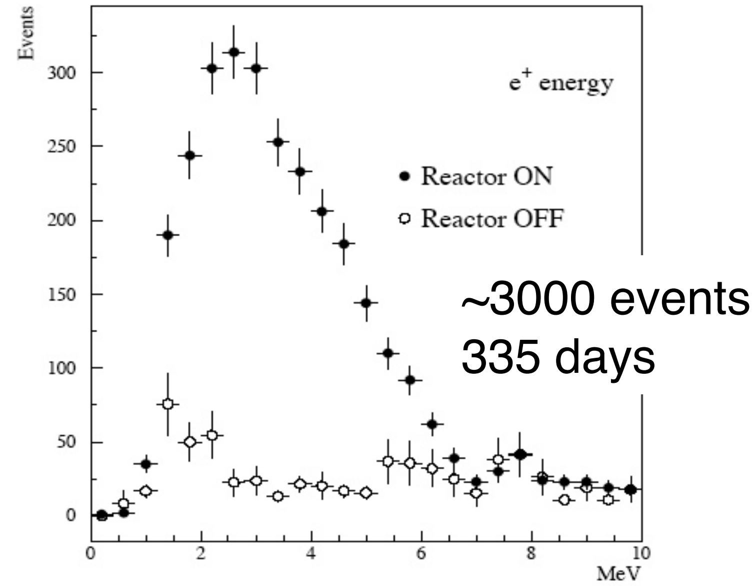
1 km baseline



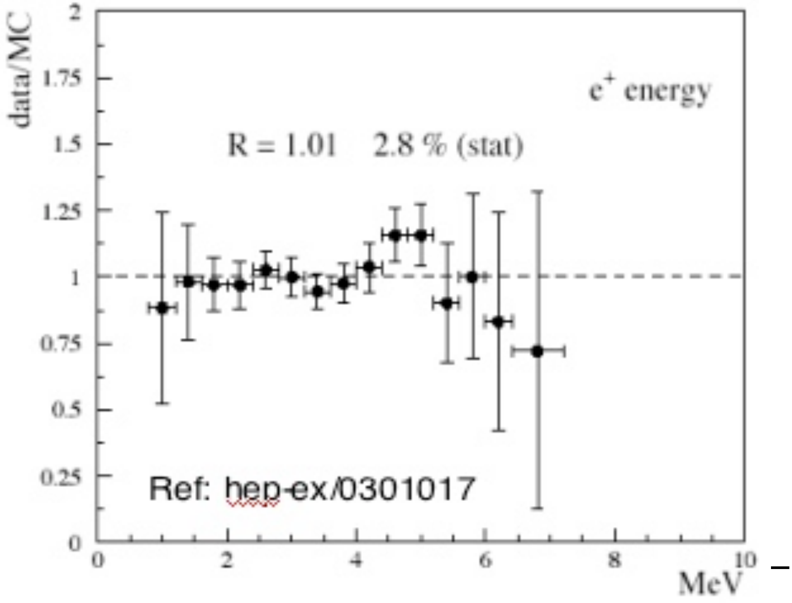


5 ton target

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



~3000 events
335 days



Ref: hep-ex/0301017

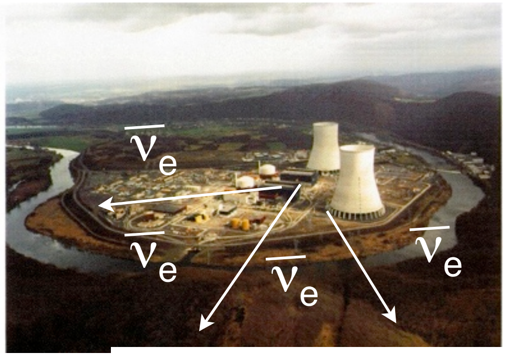
No evidence for oscillation, absolute measurement with 1 detector at ~1km

Oscillation Search at Baseline of 1km

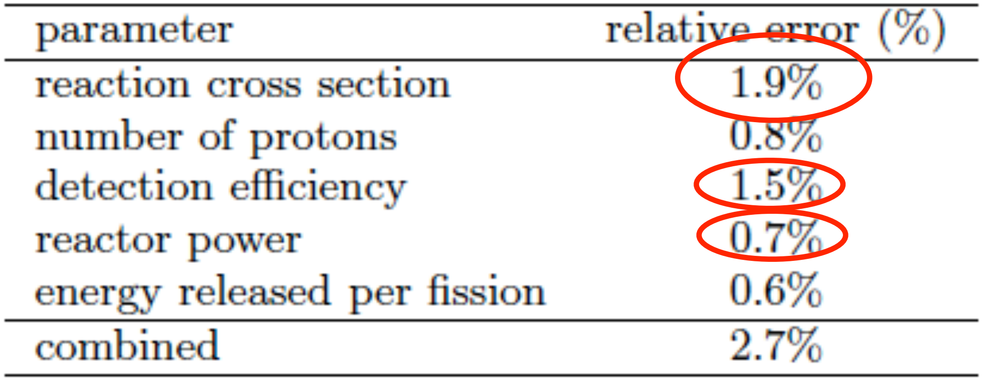
Chooz (1998)

thermal power 8.5 GW

1 km baseline



systematic uncertainty on normalization



parameter	relative error (%)
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%

systematic limitations on absolute measurement:

1. reactor power

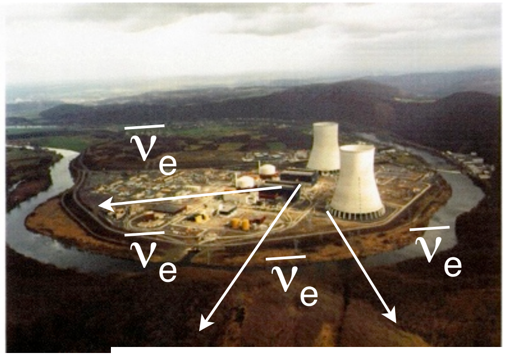
2. reaction cross-section
3. detection efficiency

Oscillation Search at Baseline of 1km

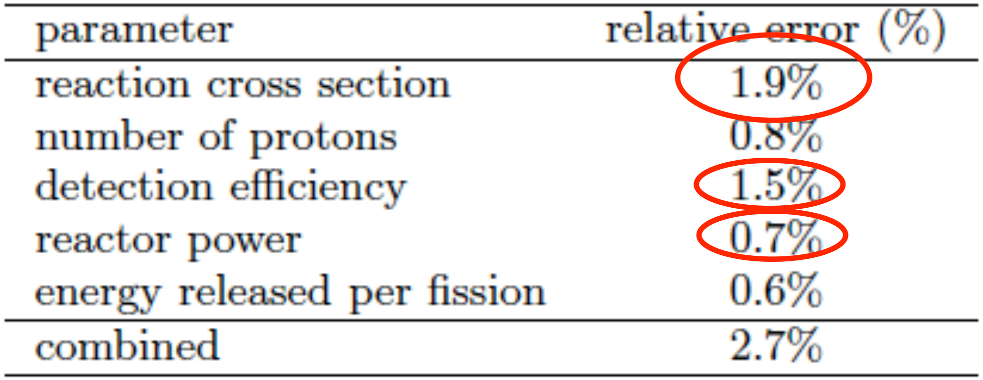
Chooz (1998)

thermal power 8.5 GW

1 km baseline



systematic uncertainty on normalization



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combined	2.7%

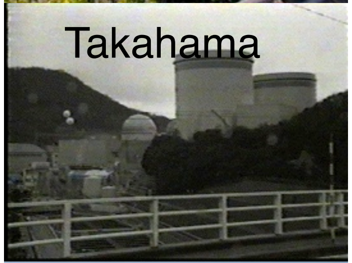
systematic limitations on absolute measurement:

1. reactor power → cancels with independent normalization of reactor source

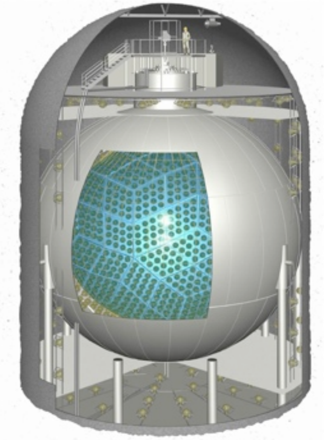
2. reaction cross-section
3. detection efficiency → cancels if we compared un-oscillated and oscillated antineutrino flux

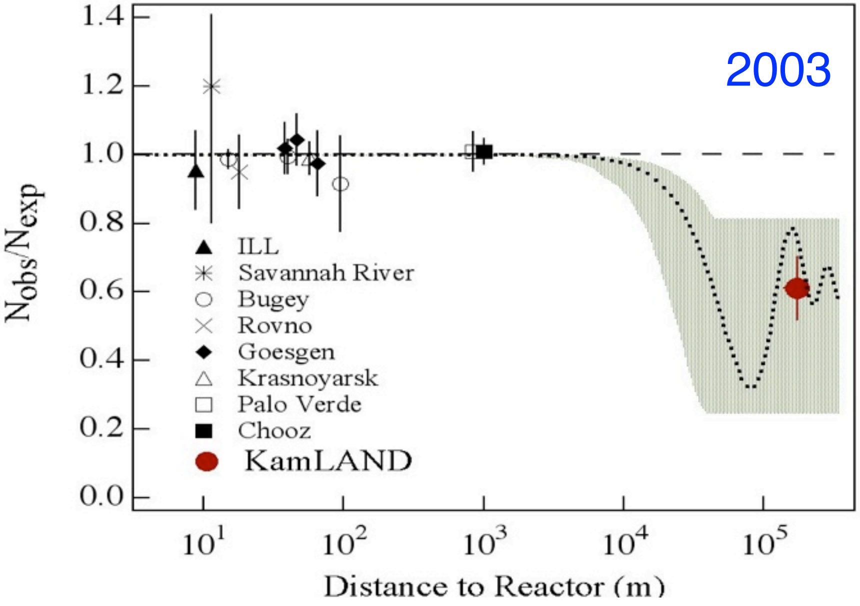
Oscillation Search at (Average) Baseline of 180km

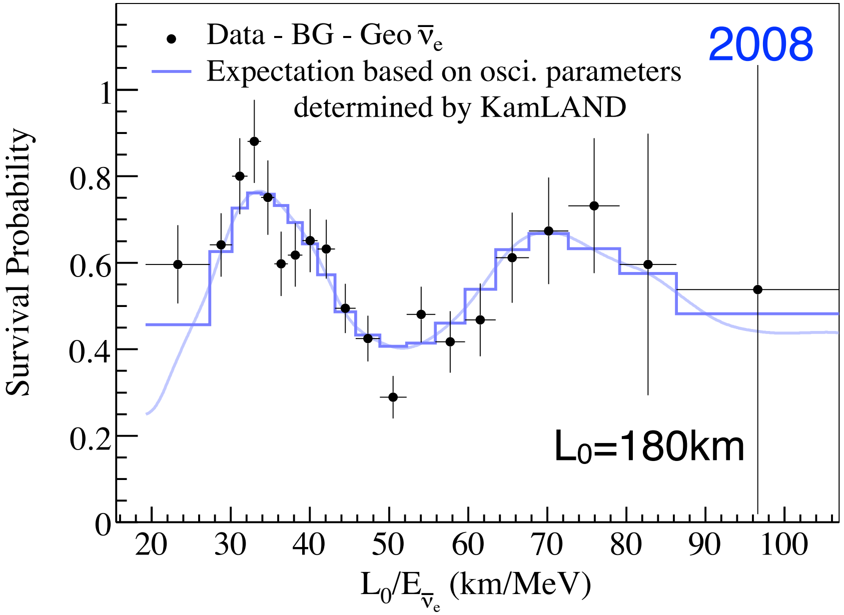
KamLAND (2003-present)



55 reactors



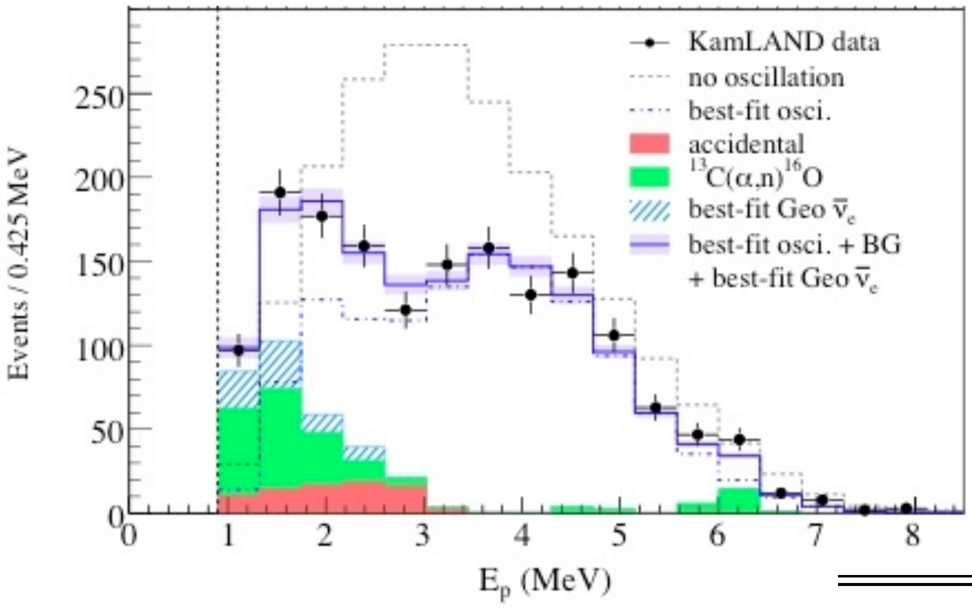




Oscillation Search at (Average) Baseline of 180km

KamLAND (2003-present)

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



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%

how to improve reactor neutrino measurements:

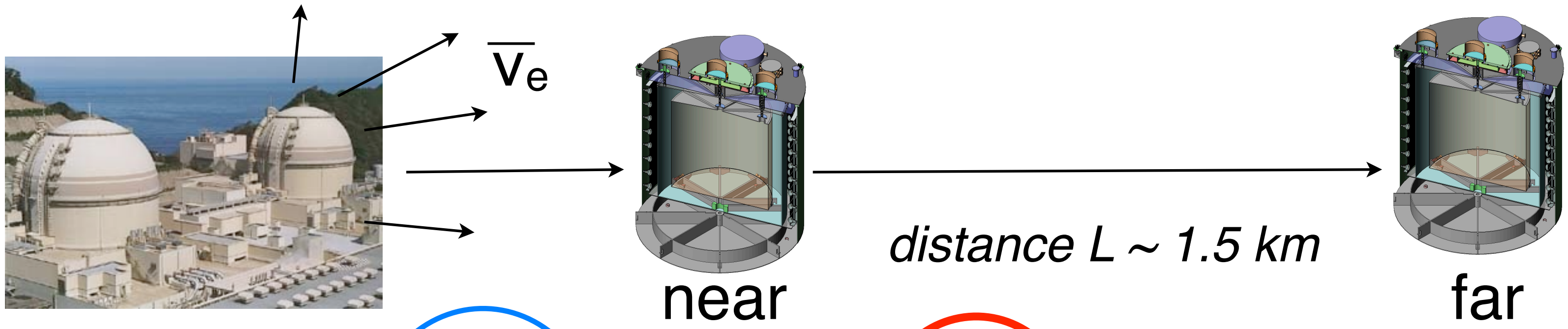
1. eliminate reactor source systematics
2. reduce detector fiducial volume error

	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

Next Generation Reactor Experiments

Applying the Lessons Learned from Chooz and KamLAND

1. Normalize flux from reactor source with near detectors
2. Identical detectors near and far
3. Detectors without fiducial volume cut



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

Measured Ratio of Rates

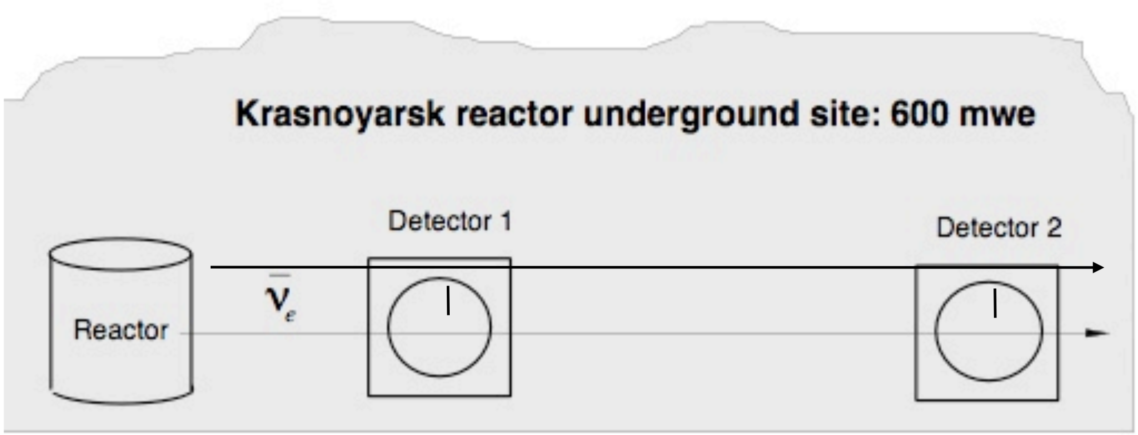
Detector Mass Ratio, H/C → *mass measurement*

Detector Efficiency Ratio → *calibration*

→ $\sin^2 2\theta_{13}$

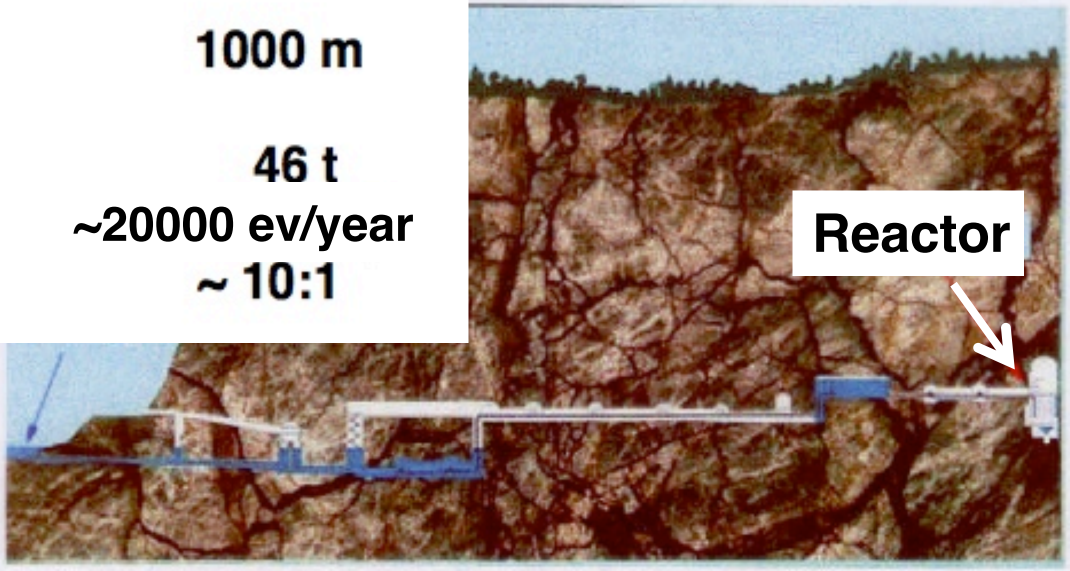
Reactor θ_{13} Experiment at Krasnoyarsk, Russia

Original Idea: First proposed at Neutrino2000



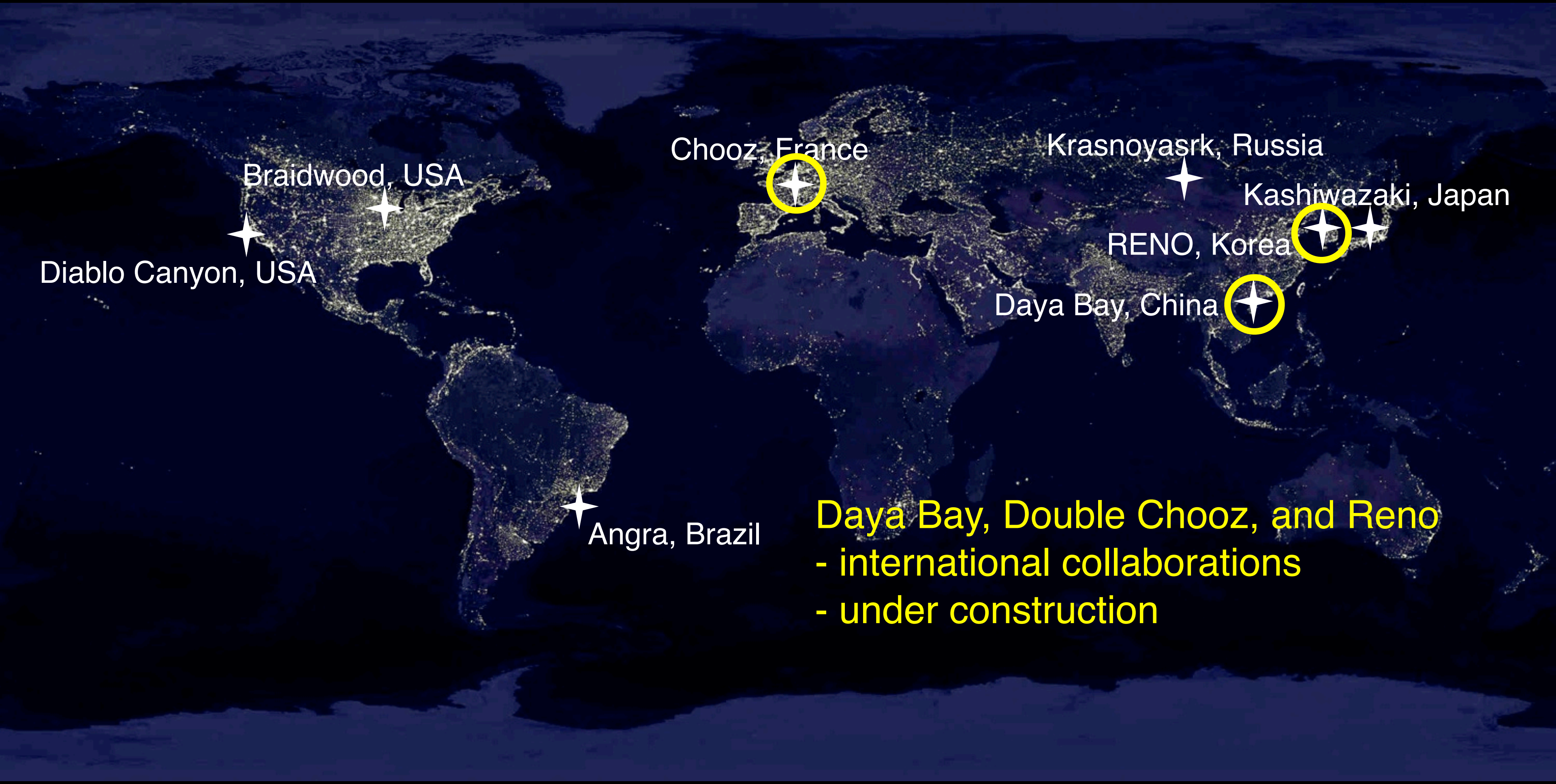
	115 m	1000 m
Target:	46 t	46 t
Rate:	~1.5 x 10^6 ev/year	~20000 ev/year
S:B	>>1	~ 10:1

Krasnoyarsk
- underground reactor
- detector locations determined by infrastructure



Ref: Marteyamov et al, hep-ex/0211070

Multi-detector Reactor θ_{13} Neutrino Experiments



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

Daya Bay
- most precise experiment
- only experiment to reach $\sin^2 2\theta_{13} < 0.01$

Use Daya Bay as example for discussion of issues that are common to reactor θ_{13} experiments.

Precision Measurement of θ_{13} with Reactor Antineutrinos

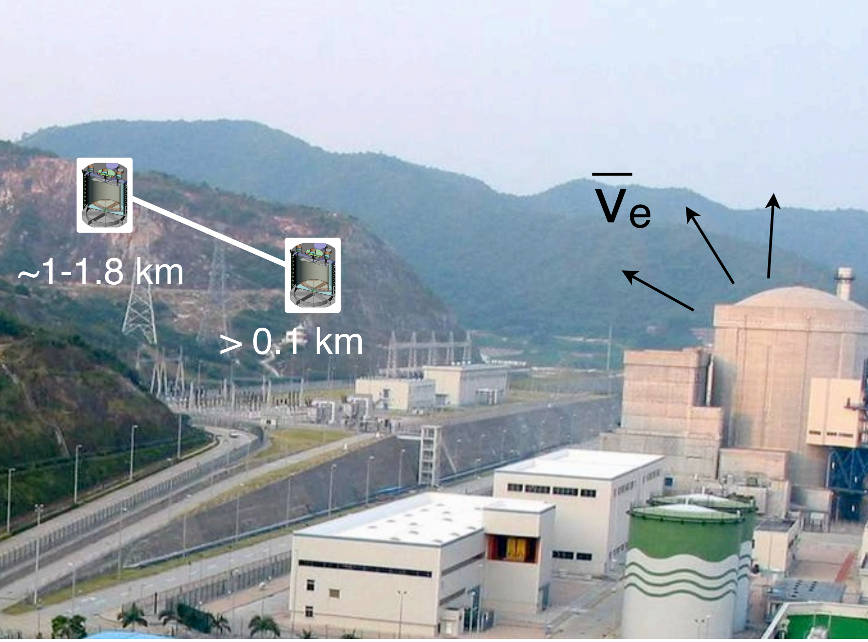
Search for θ_{13} in new oscillation experiment with multiple detectors

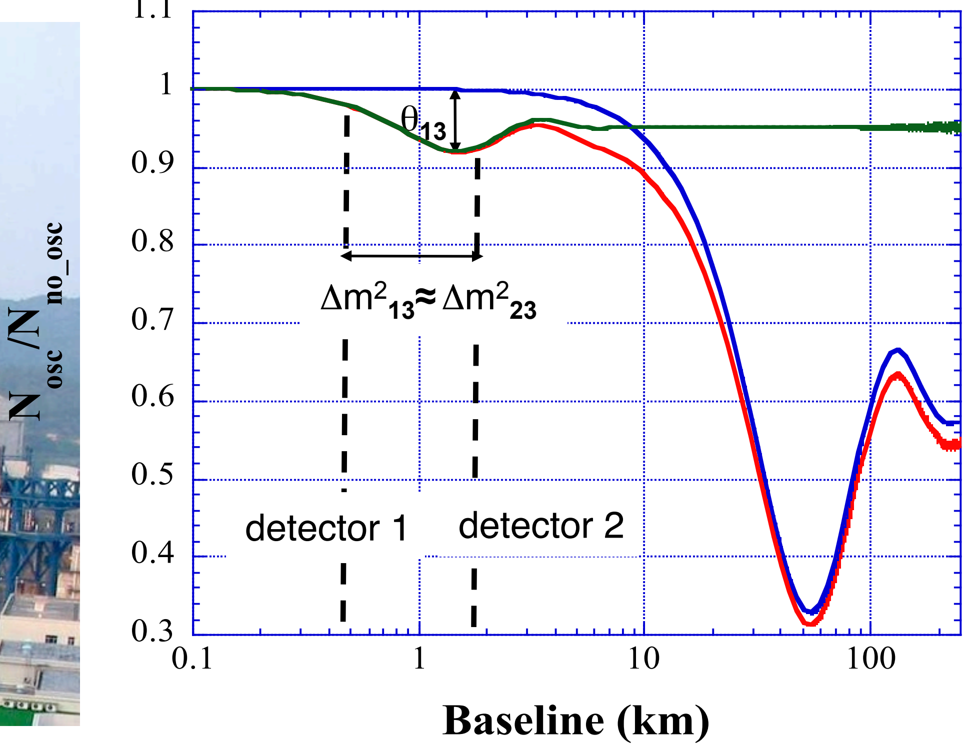
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

Daya Bay Reactors:

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

11.6 GW_{th} now, 17.4 GW_{th} in 2011





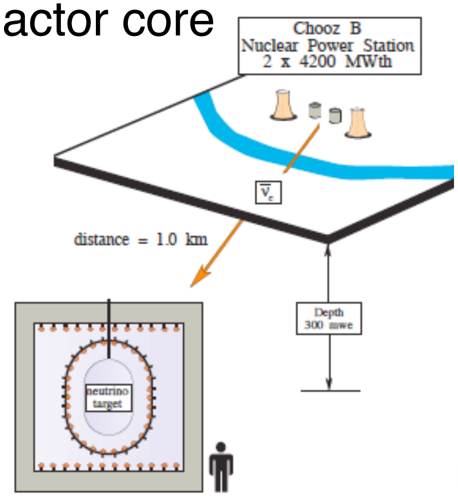
Small-amplitude oscillation due to θ_{13} integrated over E

Large-amplitude oscillation due to θ_{12}

Reactor Source

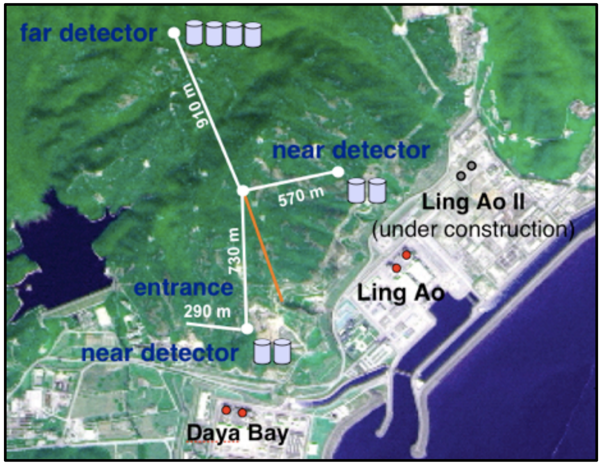
Multiple Reactor Sources

Chooz has double reactor core



KamLAND used >55 reactors with flux-averaged baseline

Daya Bay uses 6 reactors and 8 detectors (48 baselines)

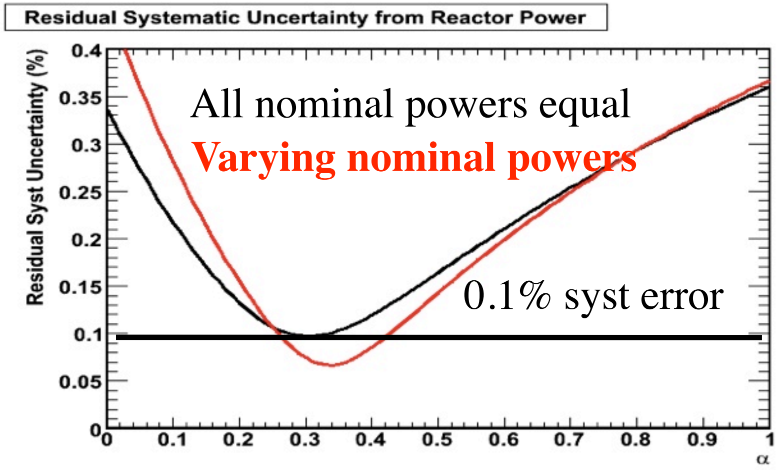


can analyze near-far pairs of detectors

Reactor Power Fluctuation in Multiple Reactor Cores

$$\frac{\text{(Daya Bay near)} + \text{Ling Ao near}}{\text{Far}}$$

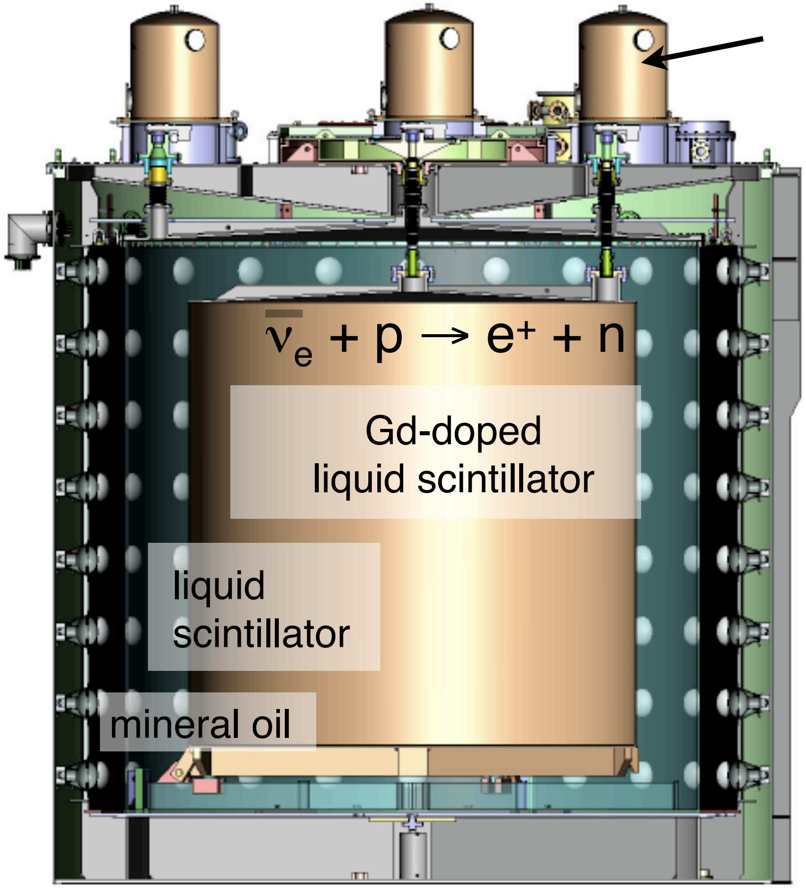
2% uncertainty per core in reactor power
→ residual systematic uncertainty is < 0.1%



Daya Bay Antineutrino Detectors

Detector Design

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



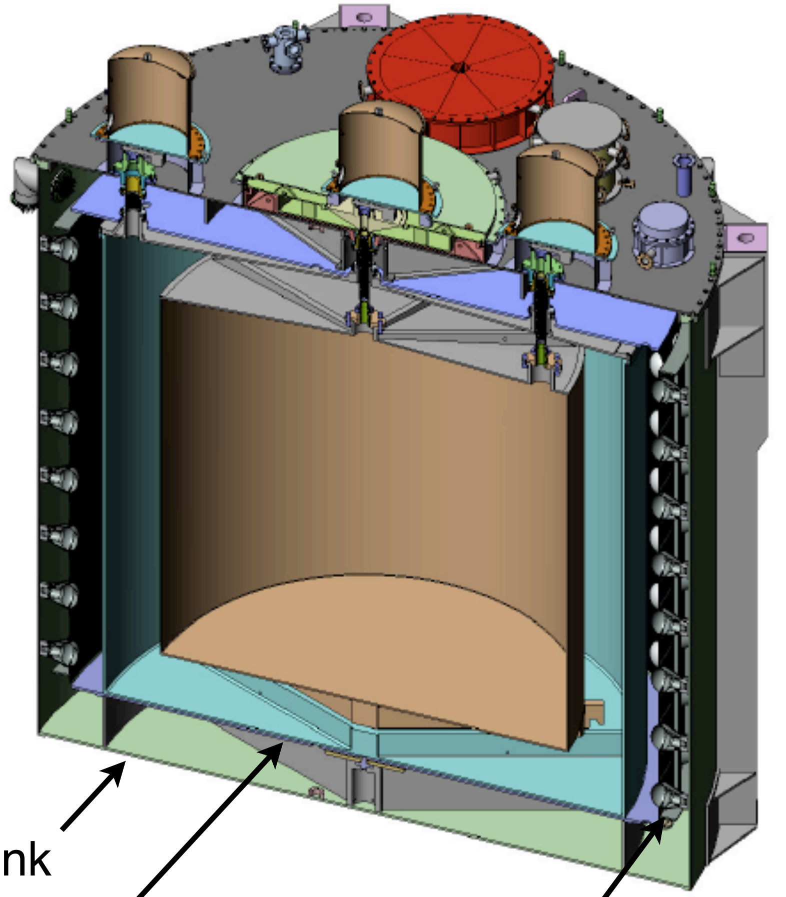
calibration system

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

Gd-doped liquid scintillator

liquid scintillator

mineral oil



steel tank

acrylic tanks

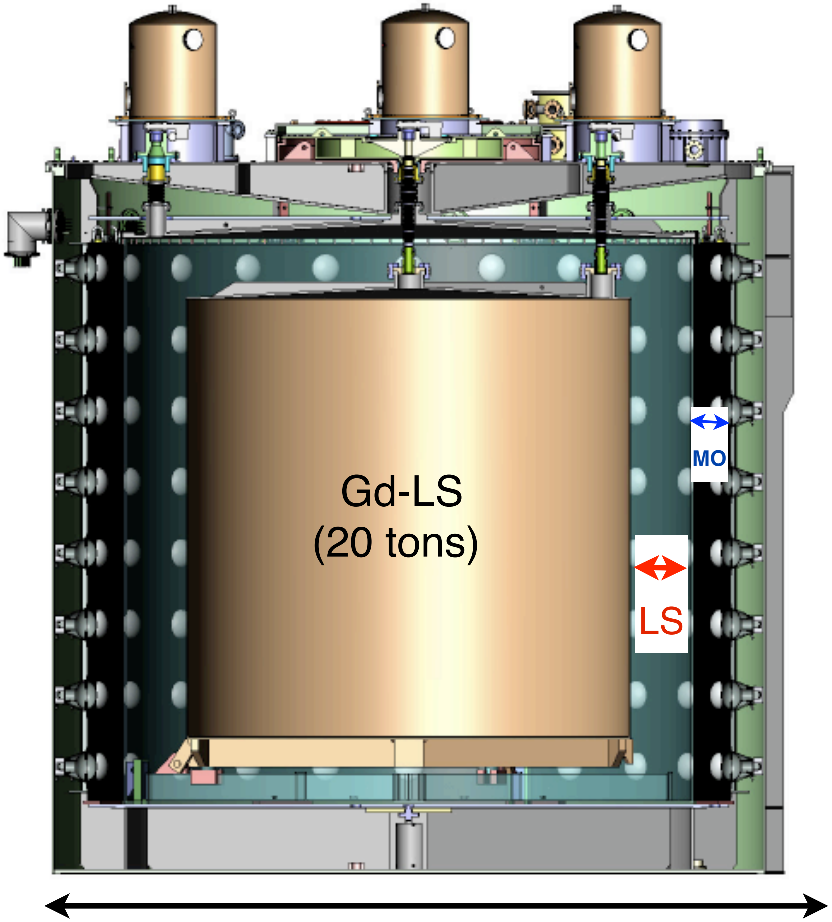
photomultipliers

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

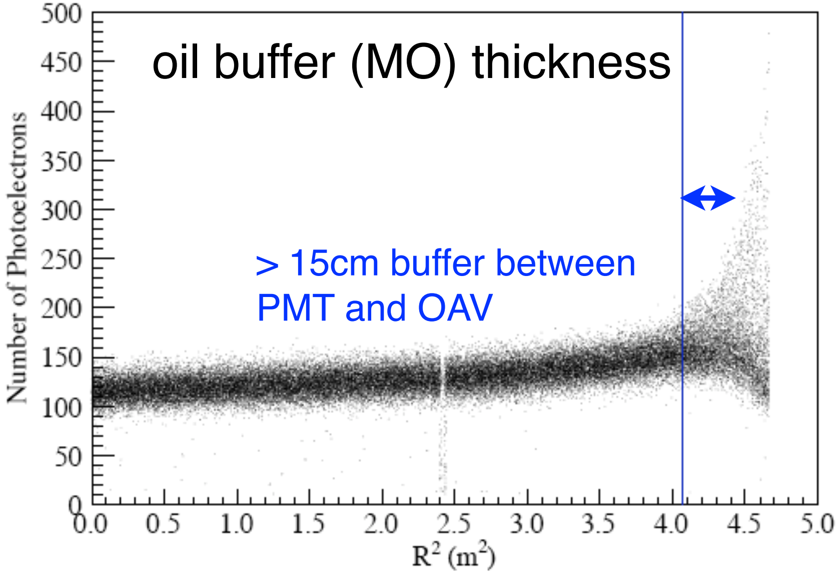
Daya Bay Antineutrino Detectors

3-Zone Design

no position reconstruction, no fiducial cut for event identification

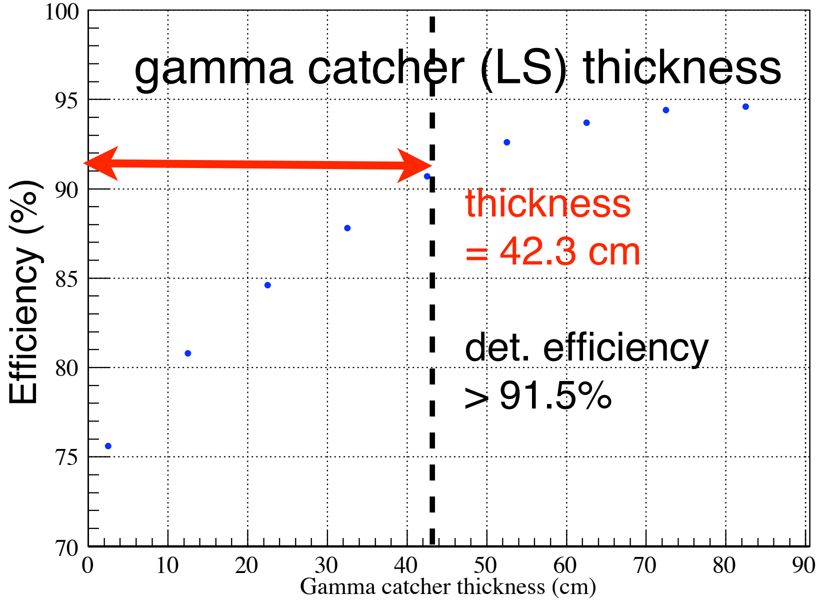


= 5m (tunnel limitations)



oil buffer (MO) thickness

> 15cm buffer between PMT and OAV

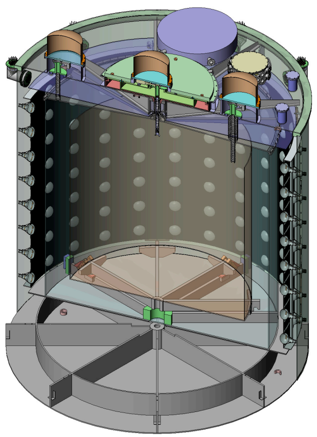


gamma catcher (LS) thickness

thickness = 42.3 cm

det. efficiency > 91.5%

Antineutrino Detection



Signal and Event Rates

Daya Bay near site	840
Ling Ao near site	740
Far site	90

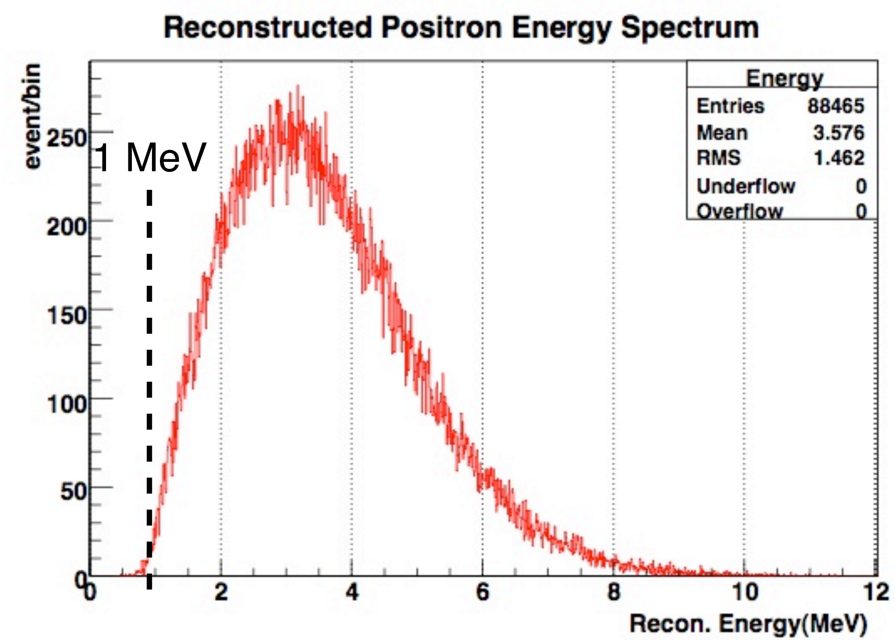
events/day per 20 ton module

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

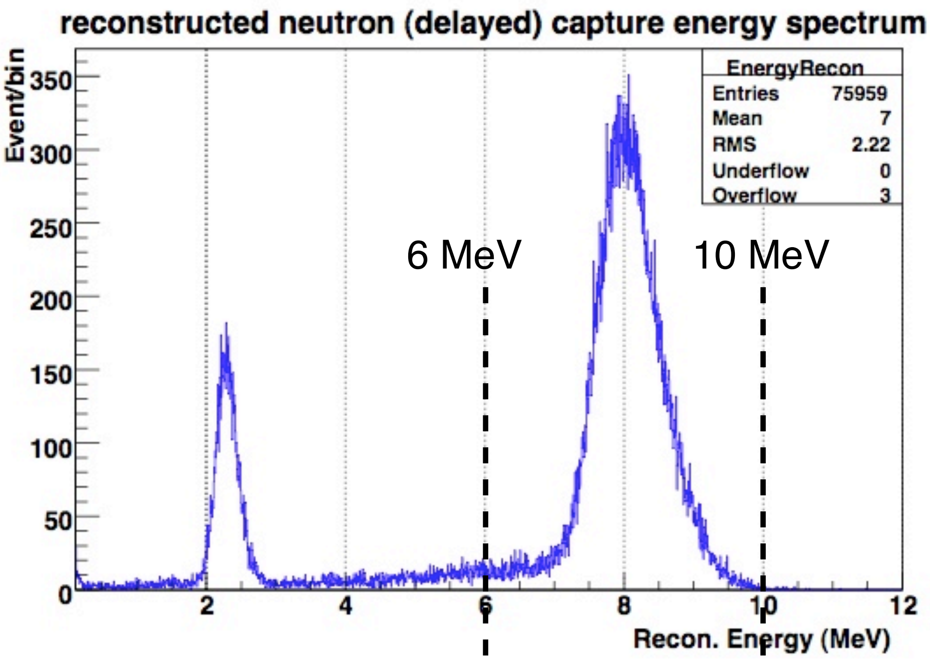
0.3 b $\mapsto + p \rightarrow D + \gamma$ (2.2 MeV) (delayed)

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

Prompt Energy Signal



Delayed Energy Signal



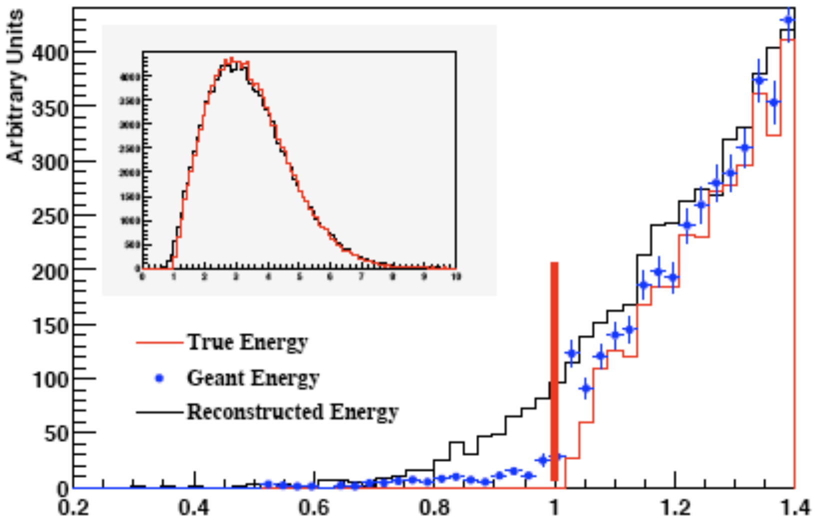
Antineutrino Detector Performance

Detection Efficiencies

Geant4-based simulations

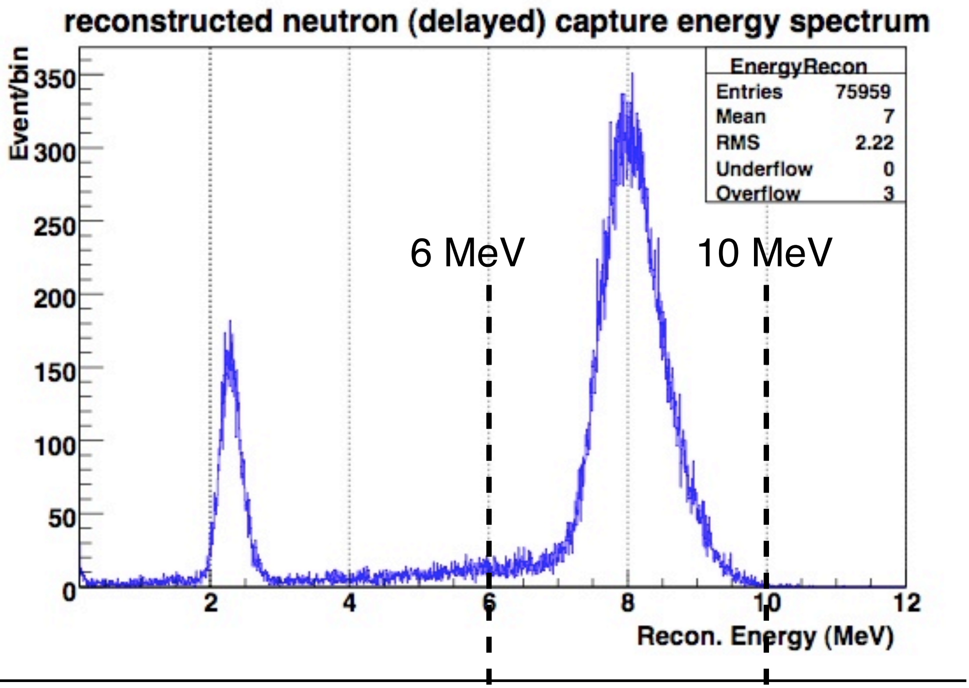
Prompt e^+ Signal

1 MeV cut for prompt positrons: >99%, uncertainty negligible



Delayed n Signal

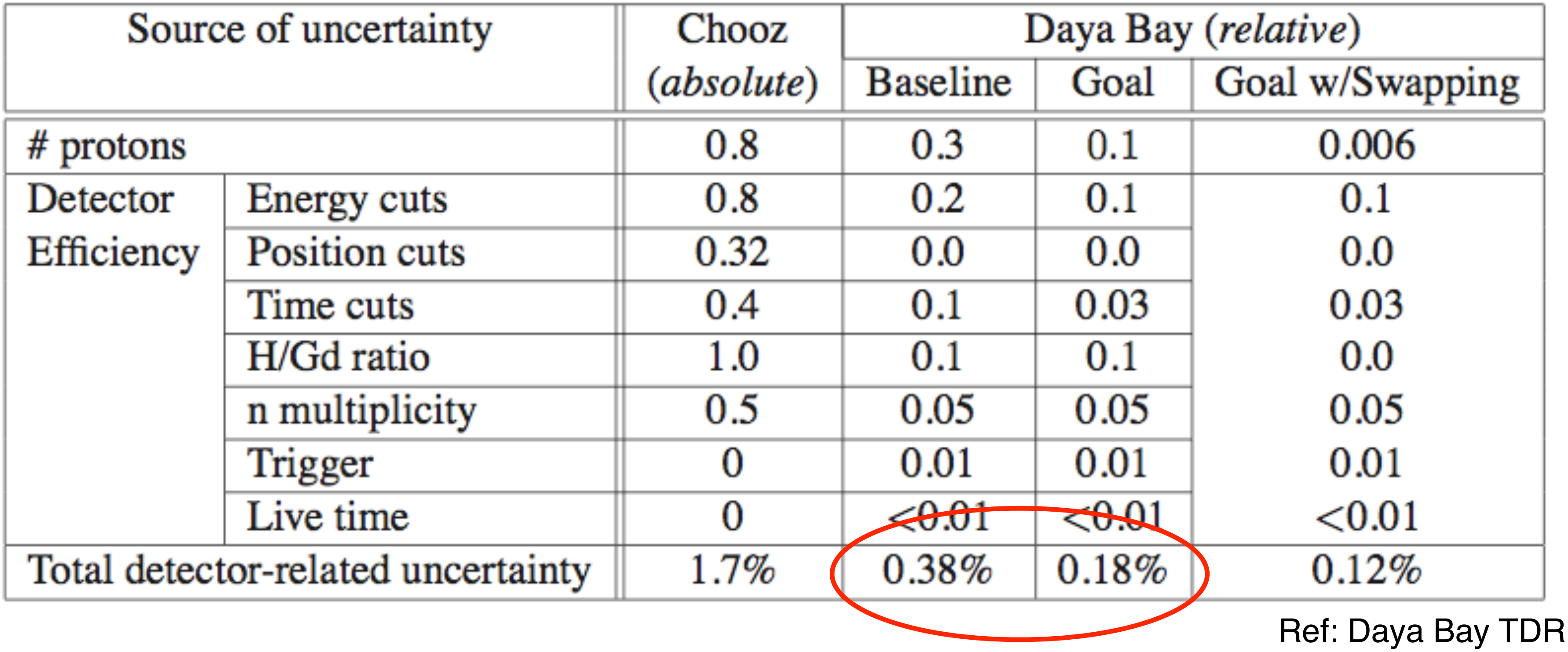
6 MeV cut for delayed neutrons: 91.5%, uncertainty 0.22% assuming 1% energy uncertainty



Systematic Uncertainties

Detector-Related Uncertainties

Absolute measurement **Relative measurement**



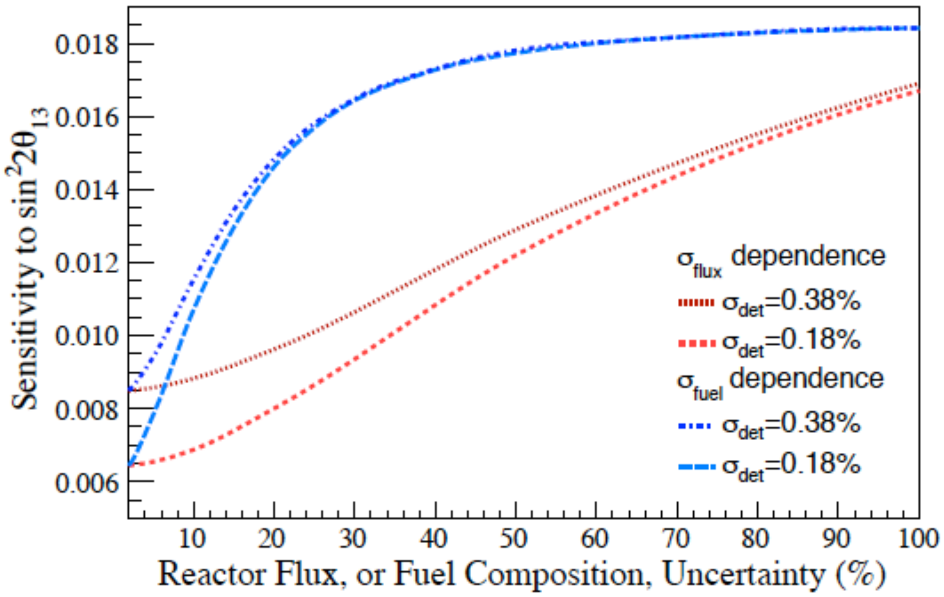
Source of uncertainty		Chooz (*absolute*)	Daya Bay (*relative*)		
			Baseline	Goal	Goal w/Swapping
# protons		0.8	0.3	0.1	0.006
Detector Efficiency	Energy cuts	0.8	0.2	0.1	0.1
	Position cuts	0.32	0.0	0.0	0.0
	Time cuts	0.4	0.1	0.03	0.03
	H/Gd ratio	1.0	0.1	0.1	0.0
	n multiplicity	0.5	0.05	0.05	0.05
	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

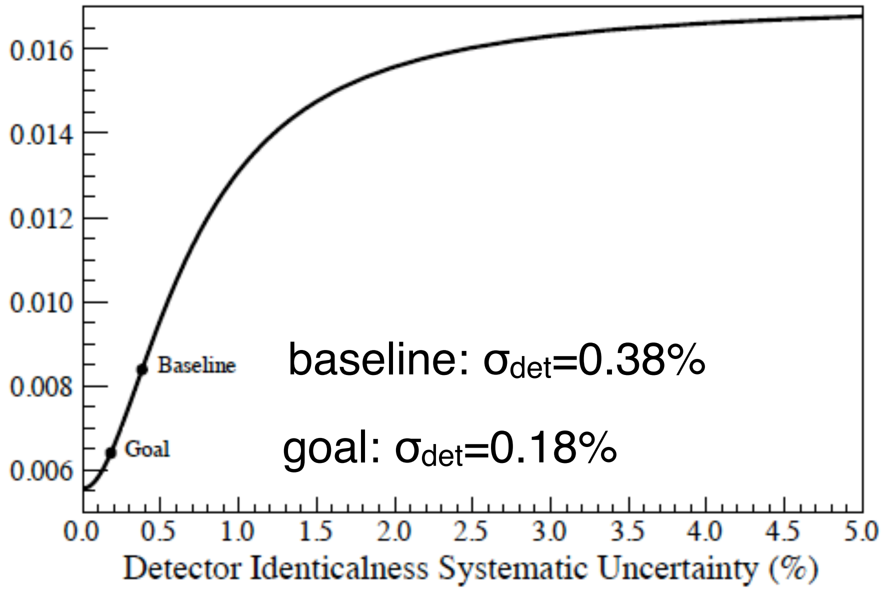
O(0.2-0.3%) precision for relative measurement between detectors at near and far sites

Sensitivity and Systematics

Reactor and $\overline{\nu}_e$ Source



Detector



baseline: σ_{det}=0.38%

goal: σ_{det}=0.18%

Ref: GLOBES
McFarlane, Wisconsin

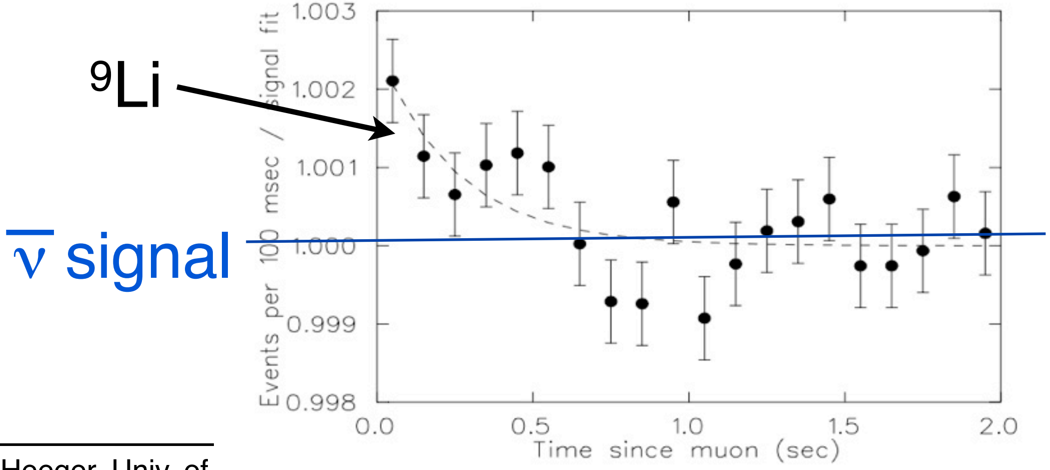
- near-far detector concept largely cancels source and detector systematics
- knowledge of reactor source is still helpful

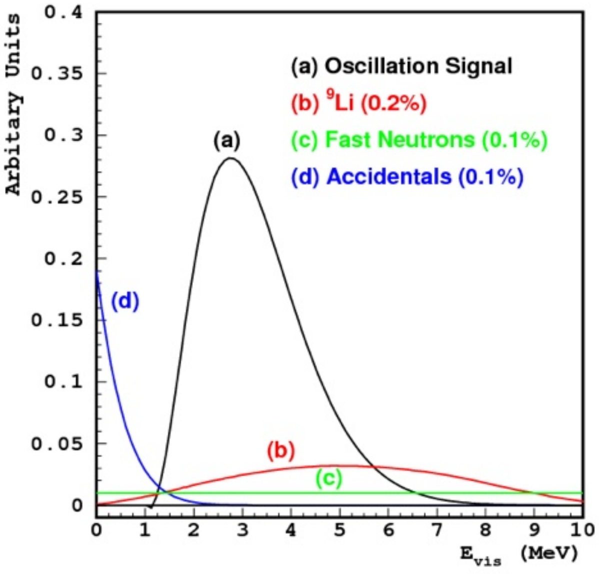
and what about backgrounds....?

Daya Bay Background Summary

	DYB site	LA site	far site
Antineutrino rate (/day/module)	840	760	90
Natural radiation (Hz)	<50	<50	<50
Single neutron (/day/module)	18	12	1.5
β-emission isotopes (/day/module)	210	141	14.6
Accidental/Signal	<0.2%	<0.2%	<0.1%
Fast neutron/Signal	0.1%	0.1%	0.1%
^{8}He^{9}Li/Signal	0.3%	0.2%	0.2%

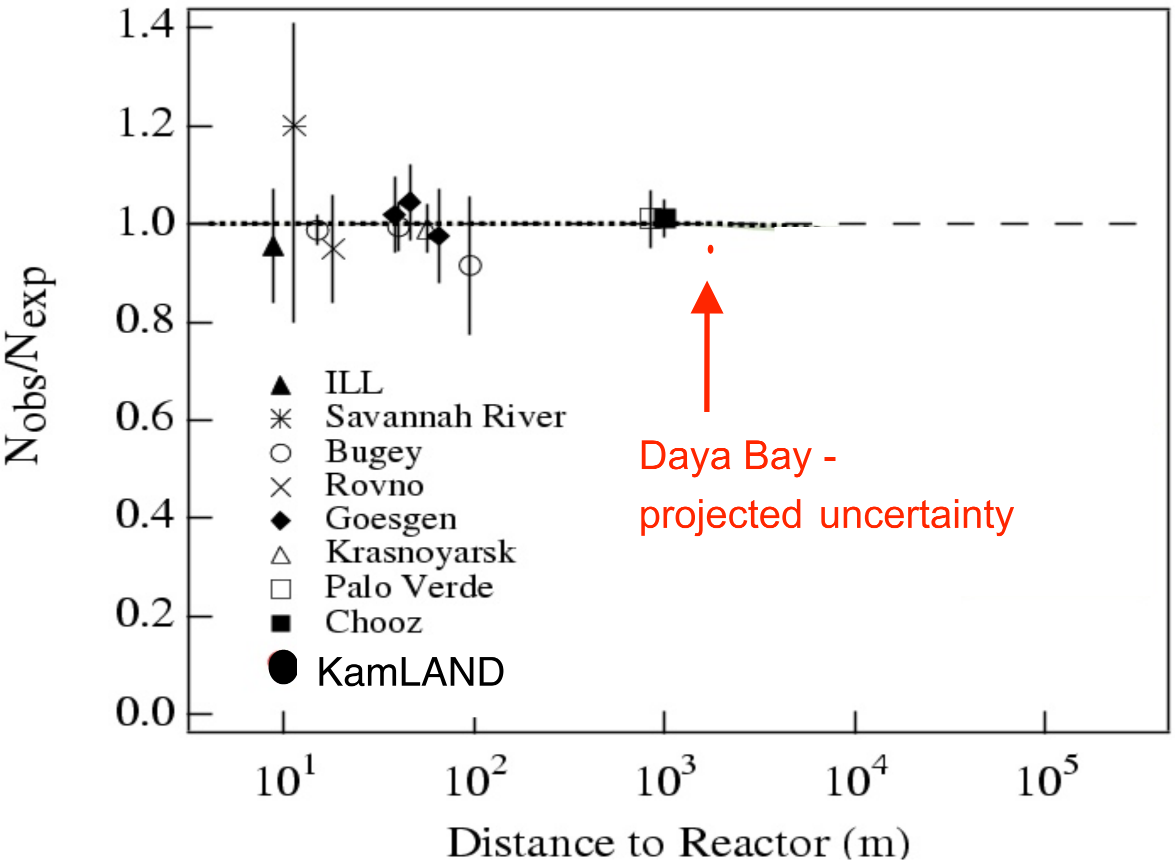
backgrounds from beta-delayed neutron emission isotopes ^{8}He and ^{9}Li will have to be measured and subtracted





Expected Precision and Sensitivity of Daya Bay

Expected Precision to $\overline{\nu}_e$ Flux

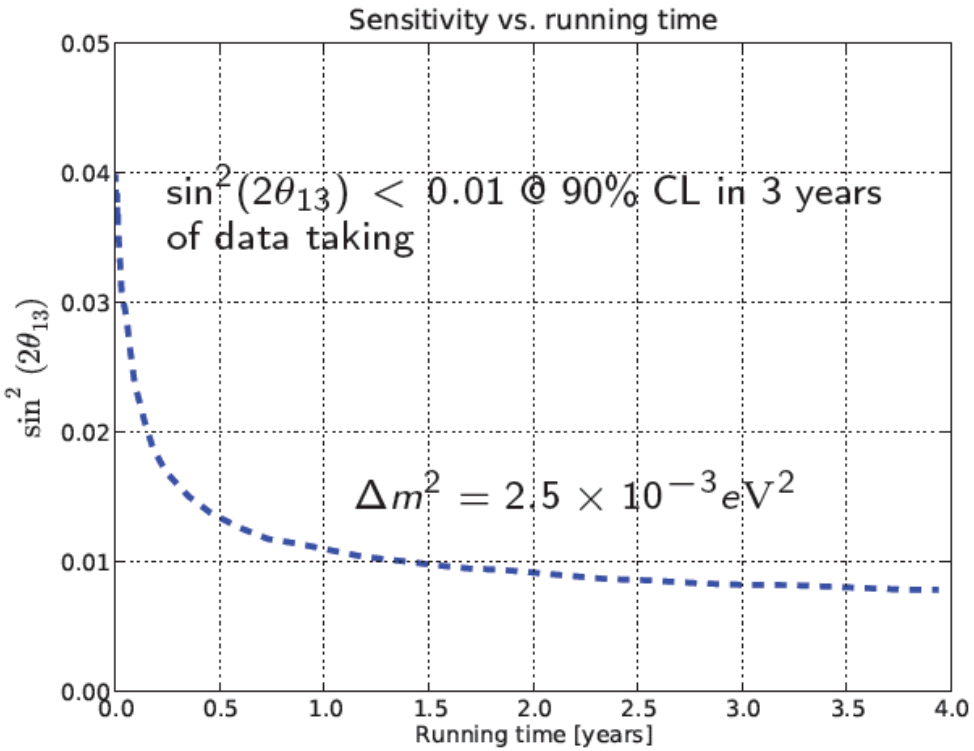


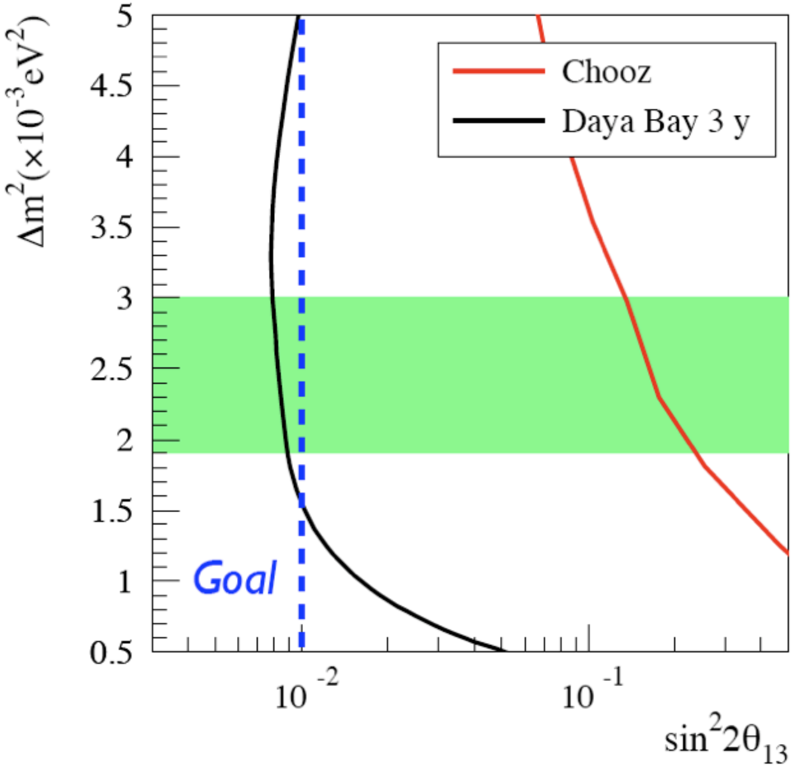
Daya Bay -
projected uncertainty

past reactor experiments
= 1 detector

next generation of experiments
> 2 detectors

Expected Precision and Sensitivity of Daya Bay



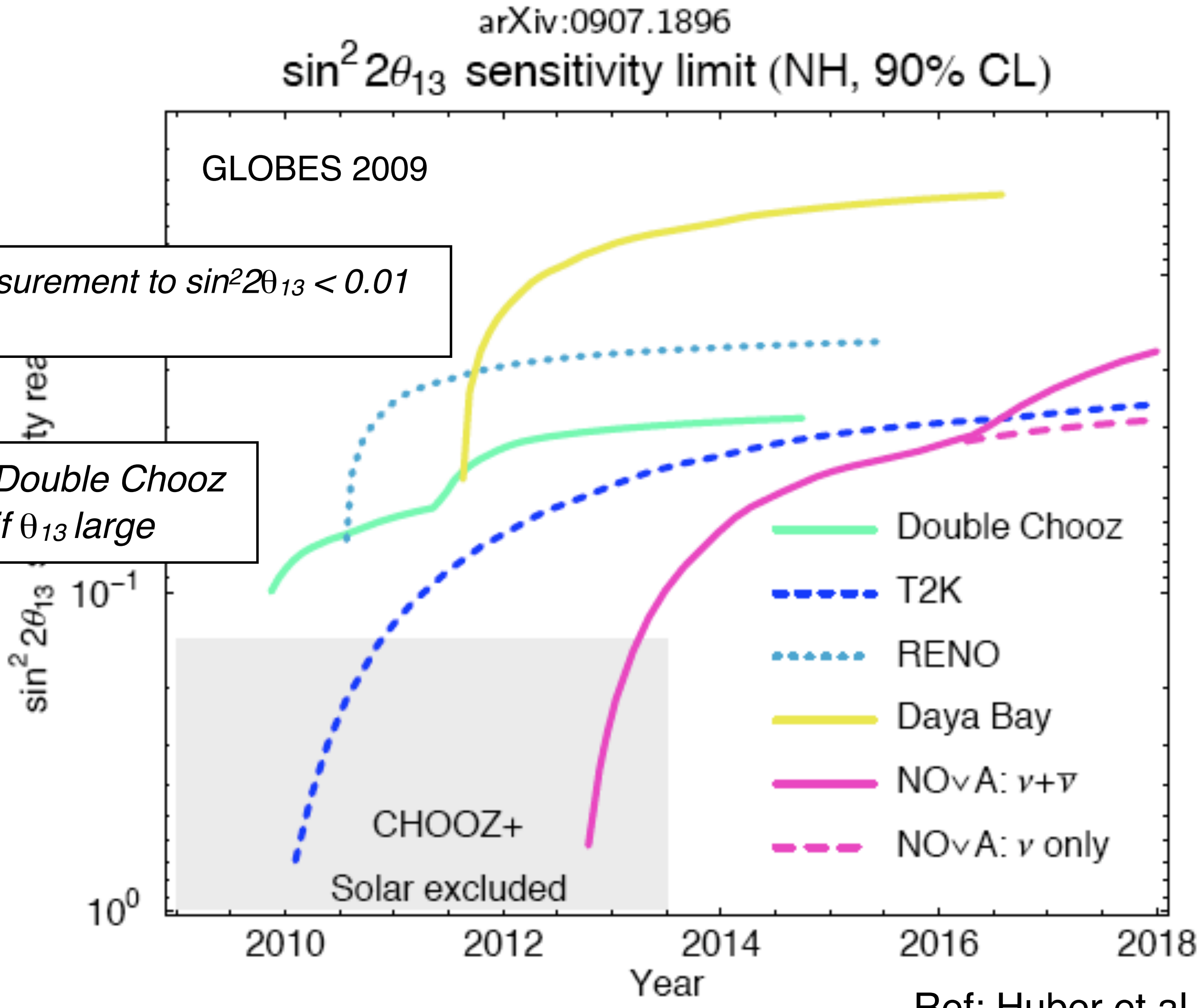


Daya Bay Sensitivity to $\sin^2 2\theta_{13}$

$\sin^2 2\theta_{13}$ < 0.01 @ 90% CL
in 3 years of data taking

2011 start data taking with near site
2012 start data taking with full experiment

Summary and Outlook



precision measurement to $\sin^2 2\theta_{13} < 0.01$ *by Daya Bay*

first hint of θ_{13} *by Double Chooz and T2K possible if* θ_{13} *large*

Ref: Huber et al.

Summary and Outlook

precision measurement of θ_{13} for unambiguous discovery and combined analysis with T2K and NOvA

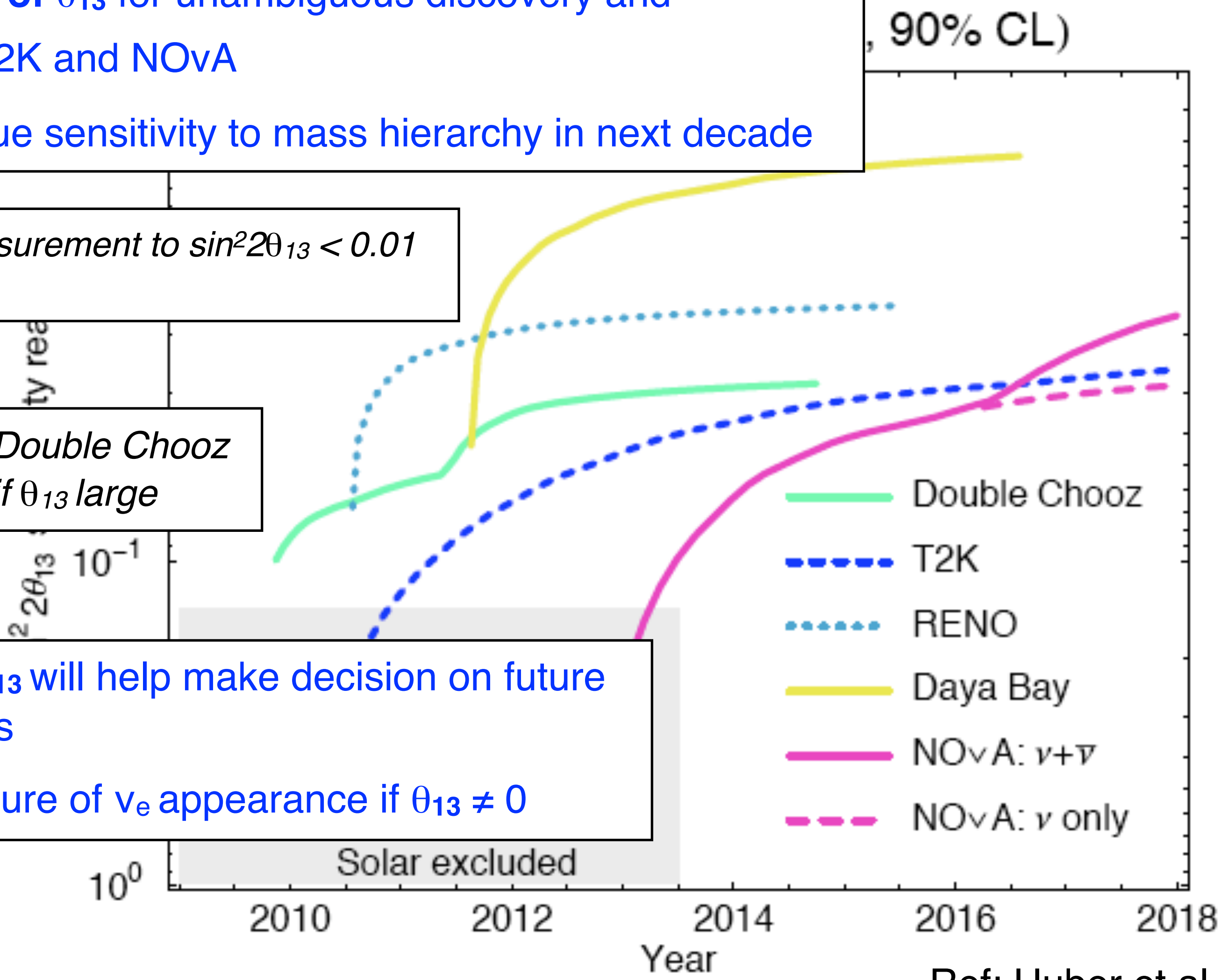
NoVA could provide unique sensitivity to mass hierarchy in next decade

precision measurement to $\sin^2 2\theta_{13} < 0.01$ by Daya Bay

first hint of θ_{13} by Double Chooz and T2K possible if θ_{13} large

early measurement of θ_{13} will help make decision on future long-baseline experiments

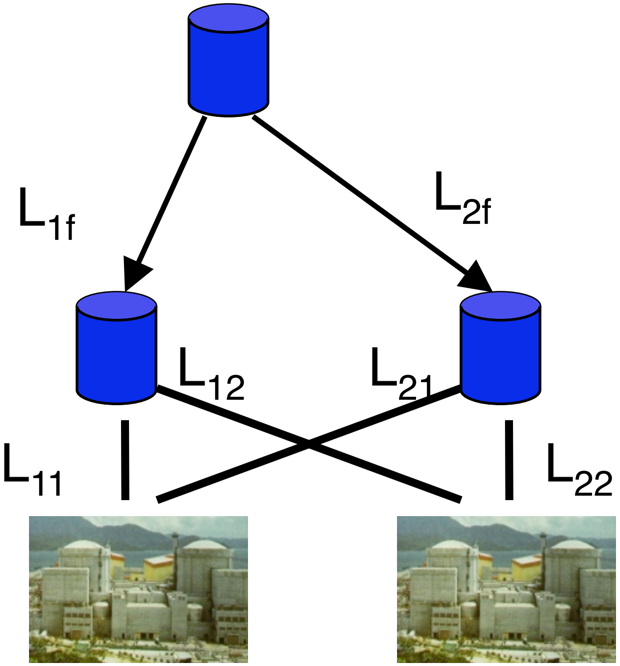
T2K may see early signature of ν_e appearance if $\theta_{13} \neq 0$



Ref: Huber et al.

Reactor Related Systematic Uncertainty

*For multi cores, **reweight oversampled** cores to maximize near/far cancellation of the reactor power fluctuation.*



$$\alpha = \frac{\frac{1}{L_{22}^2 L_{1f}^2} - \frac{1}{L_{21}^2 L_{2f}^2}}{\frac{1}{L_{11}^2 L_{2f}^2} - \frac{1}{L_{12}^2 L_{1f}^2}}$$

$$\frac{\mathrm{Near}}{\mathrm{Far}} = \alpha \frac{\mathrm{Near1}}{\mathrm{Far}} + \frac{\mathrm{Near2}}{\mathrm{Far}}$$

Assuming 30 cm precision in core position

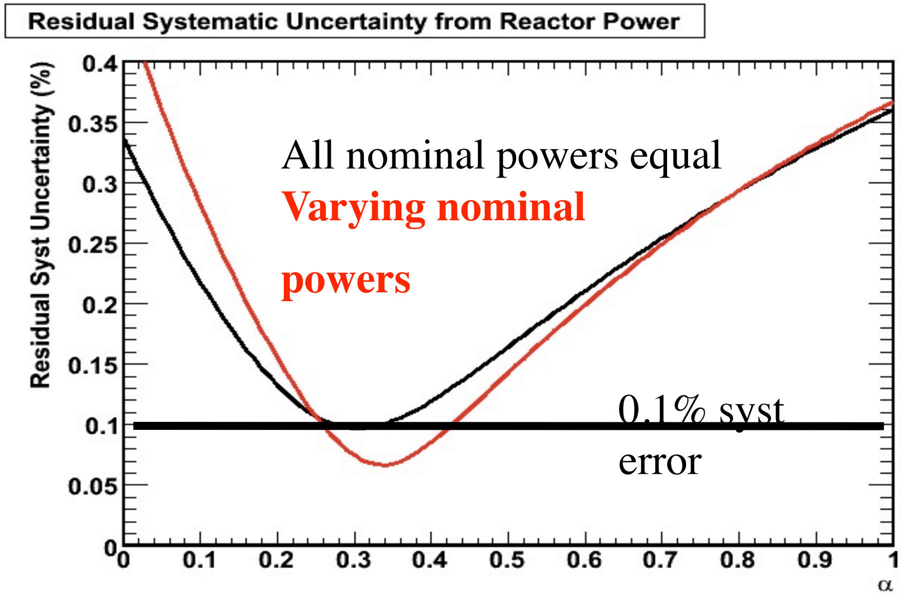
Number of cores	α	σ_ρ(power)	σ_ρ(location)	σ_ρ(total)
4	0.338	0.035%	0.08%	0.087%
6	0.392	0.097%	0.08%	0.126%

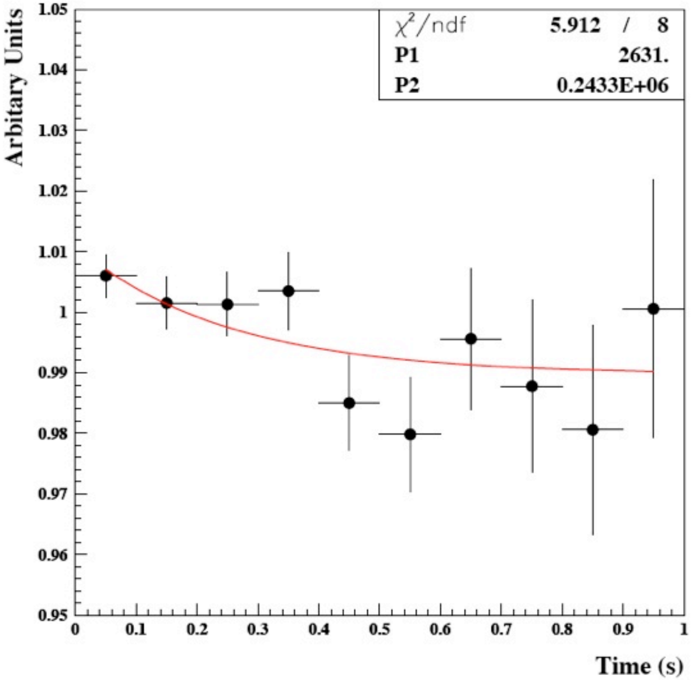
Systematic Errors from the Reactor Site

Reactor Power Fluctuation in Multiple Reactor Cores

$$\frac{\alpha\,(\text{Daya Bay near}) + \text{Ling Ao near}}{\text{Far}}$$

2% uncertainty per core in reactor power → residual systematic uncertainty is < 0.1%





Cosmogenic Backgrounds

Using Monte Carlo estimate how well background can be estimated from data using only time since last muon.

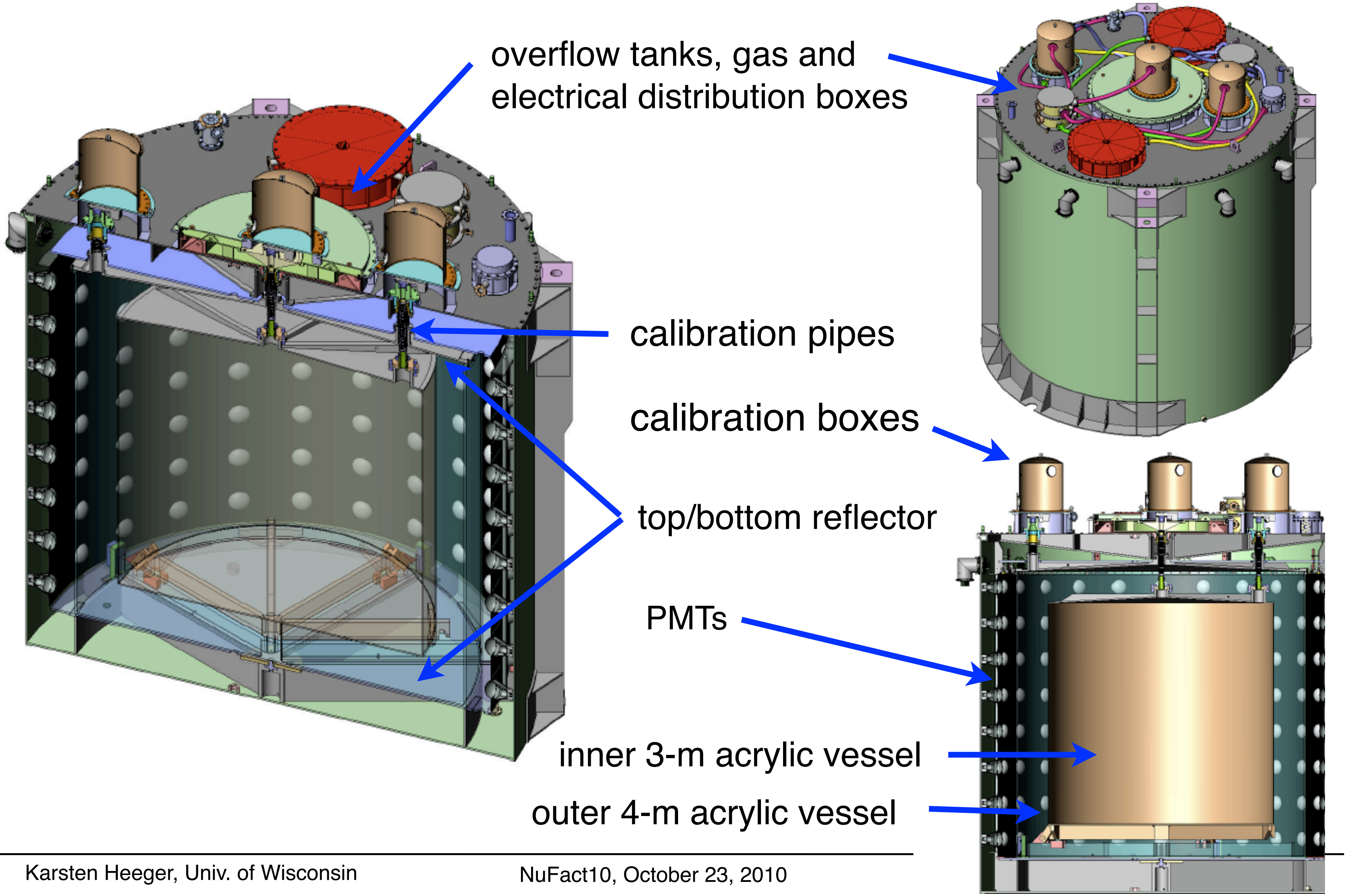
^{8}He/^{9}Li $\sigma < 0.2\%$

Calculate muon rate underground using surface distributions and MUSIC simulations.

Using measured cross section for production of ^{9}Li and ^{8}He at 190 GeV and scaling with $\sigma \sim E^{0.73}$, obtain an estimated production rate.

See poster by C. Jillings

Antineutrino Detector Overview



overflow tanks, gas and electrical distribution boxes

calibration pipes

calibration boxes

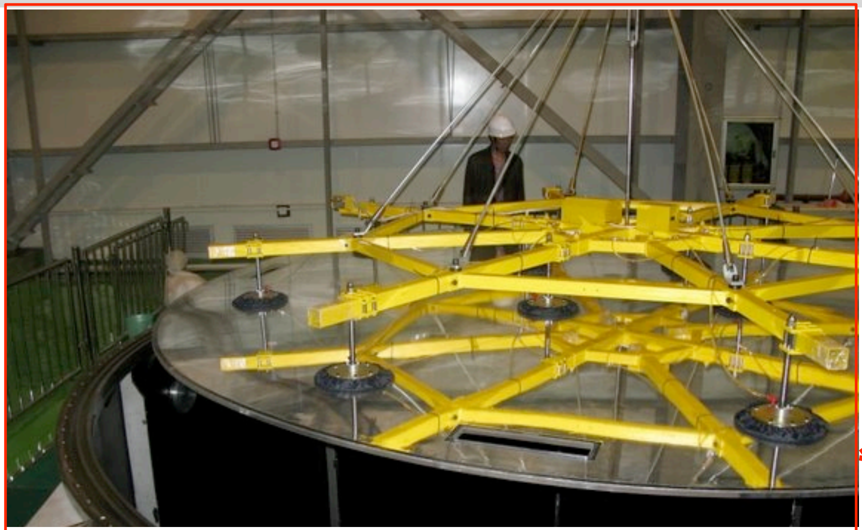
top/bottom reflector

PMTs

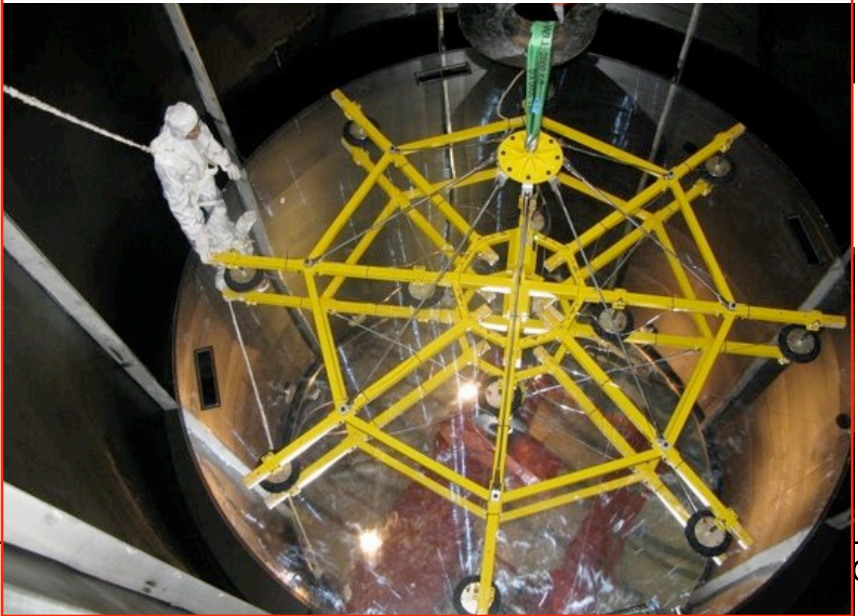
inner 3-m acrylic vessel

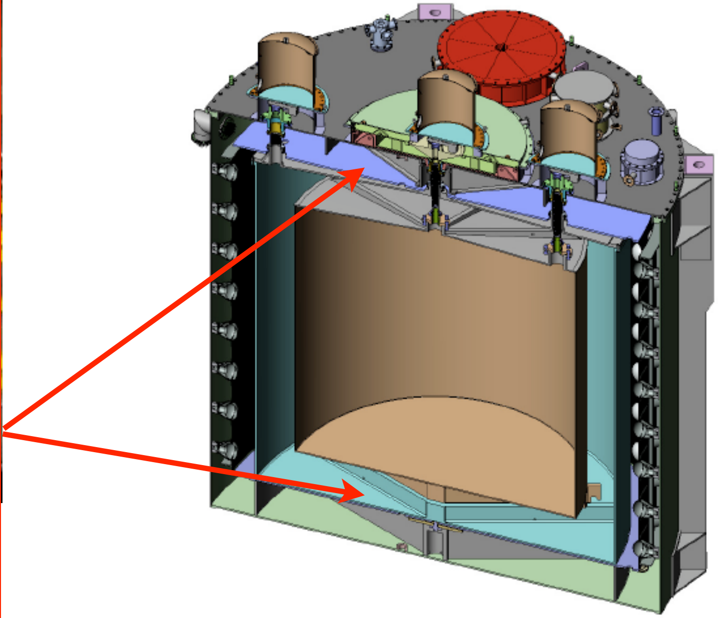
outer 4-m acrylic vessel

Detector Top/Bottom Reflectors

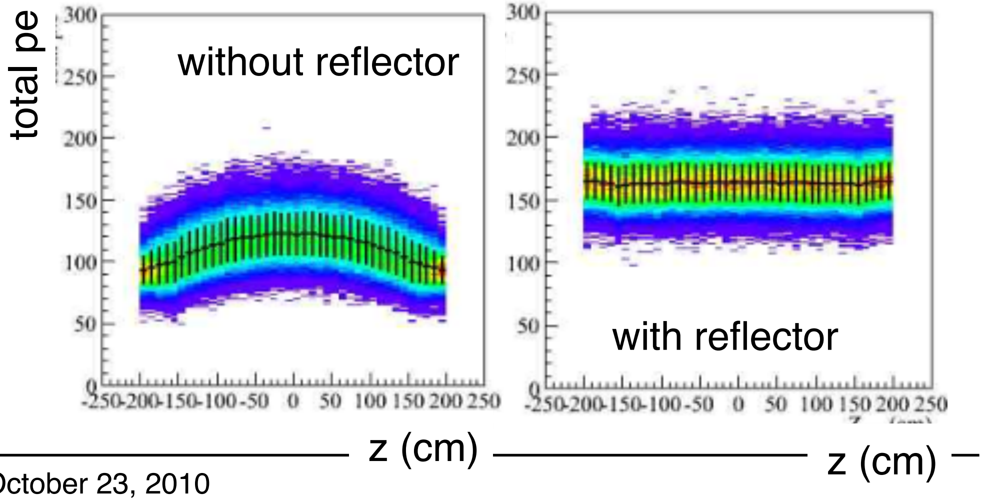


specular reflectors consist of ESR® high reflectivity film on acrylic panels

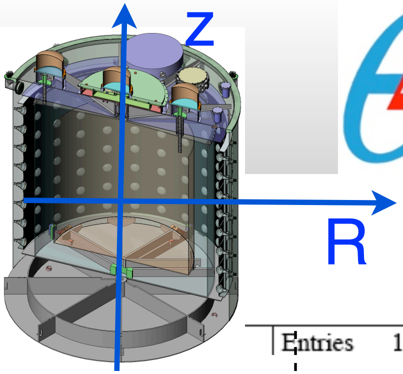




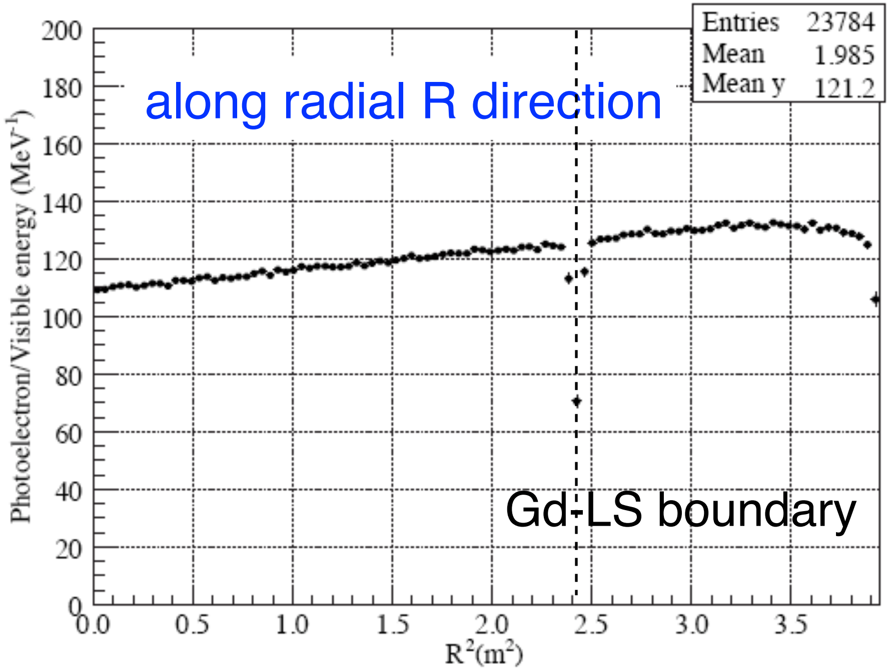
reflector flattens detector response



Antineutrino Detector Response

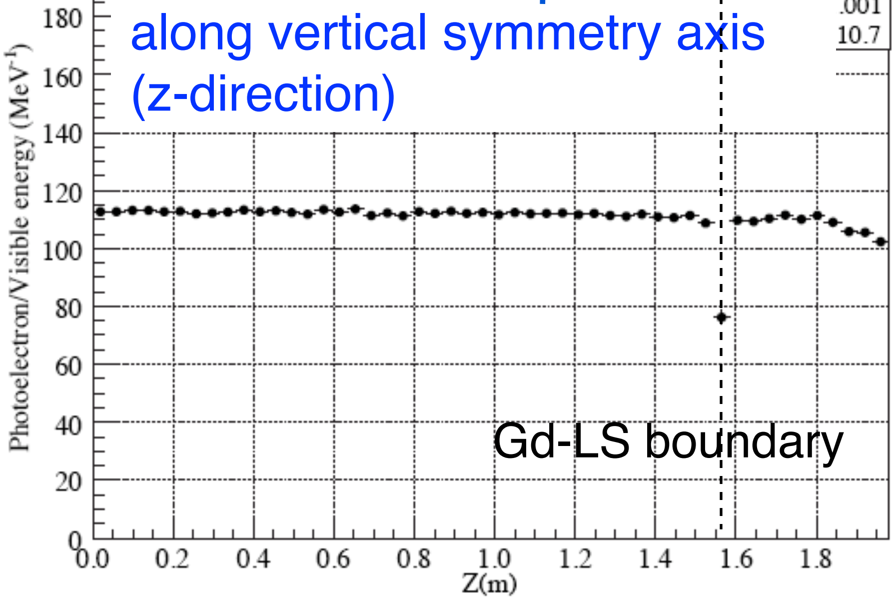


Detector Uniformity



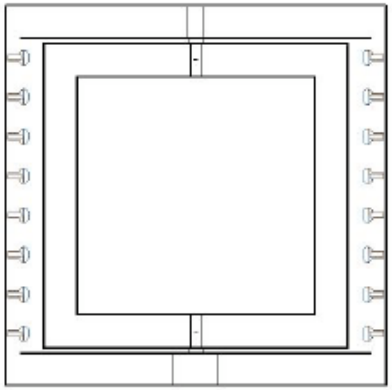
along radial R direction

Gd-LS boundary

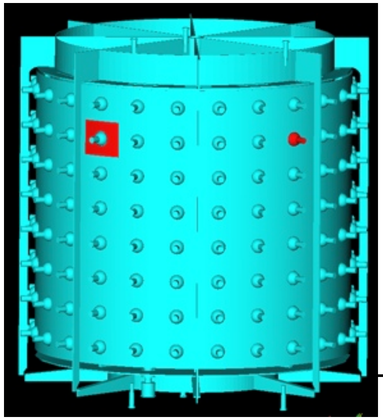


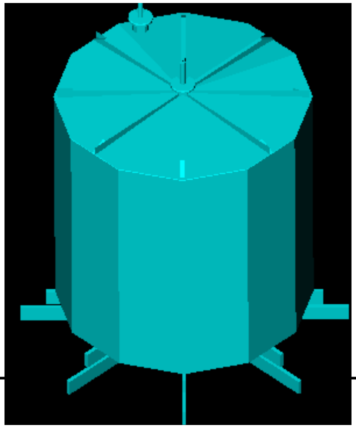
along vertical symmetry axis (z-direction)

Gd-LS boundary

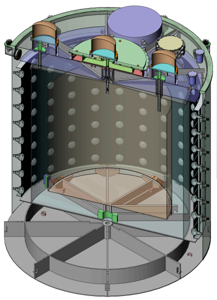


- GEANT4-based simulations
- idealized 3-zone detector plus reflectors
- developing realistic geometry in simulations



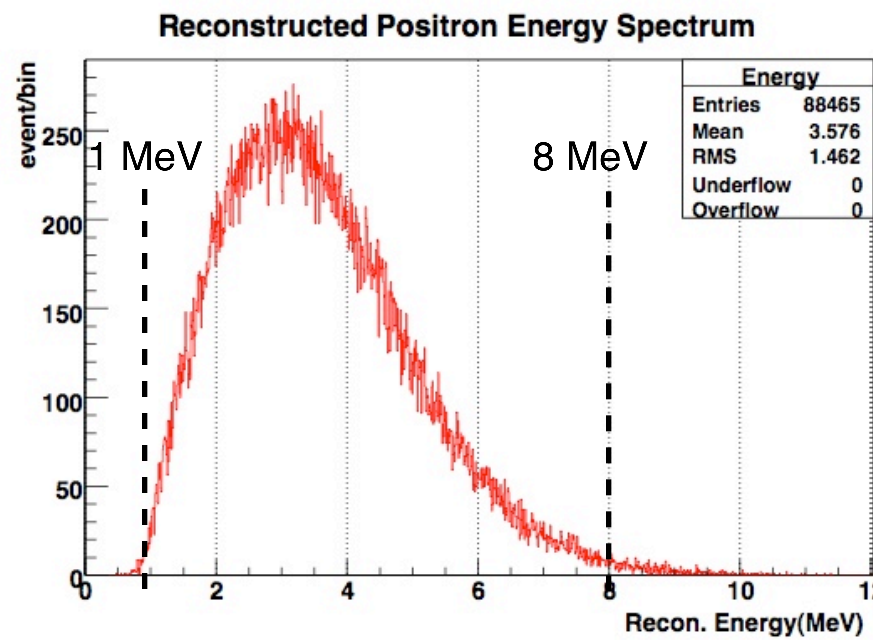


Energy Calibration and Efficiencies



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

Prompt Energy Signal

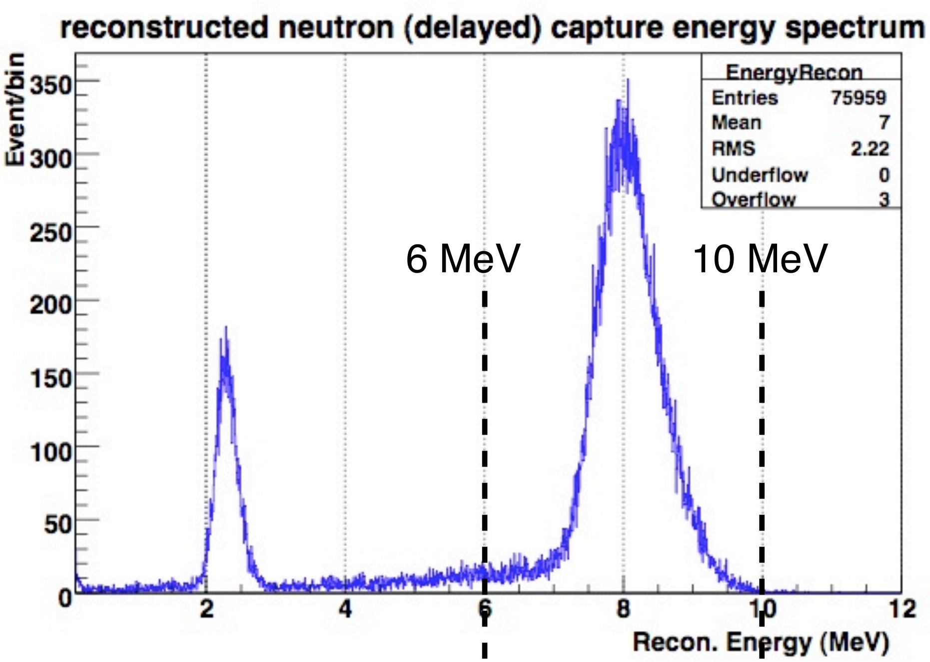


e⁺ threshold: stopped positron signal using ^{68}Ge source (2x0.511 MeV)

e⁺ energy scale: 2.2 MeV neutron capture signal (n source, spallation)

1 MeV cut for prompt positrons: >99%, uncertainty negligible

Delayed Energy Signal

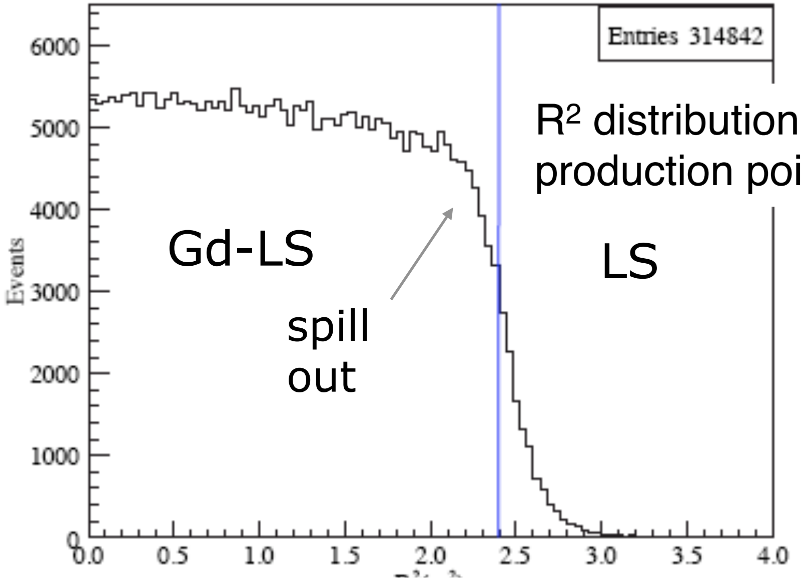


6 MeV threshold: n capture signals at 8 and 2.2 MeV (n source, spallation)

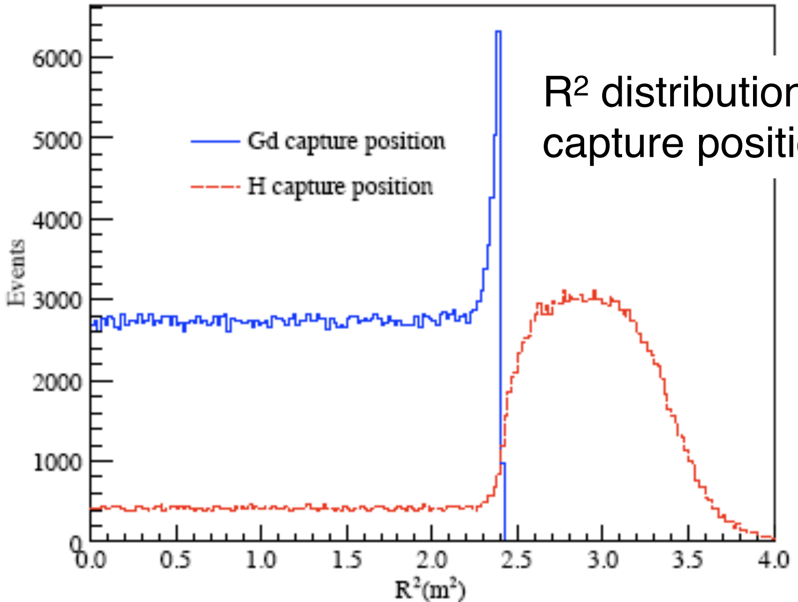
6 MeV cut for delayed neutrons: 91.5%, uncertainty 0.22% assuming 1% energy uncertainty

Antineutrino Detector Event Distributions

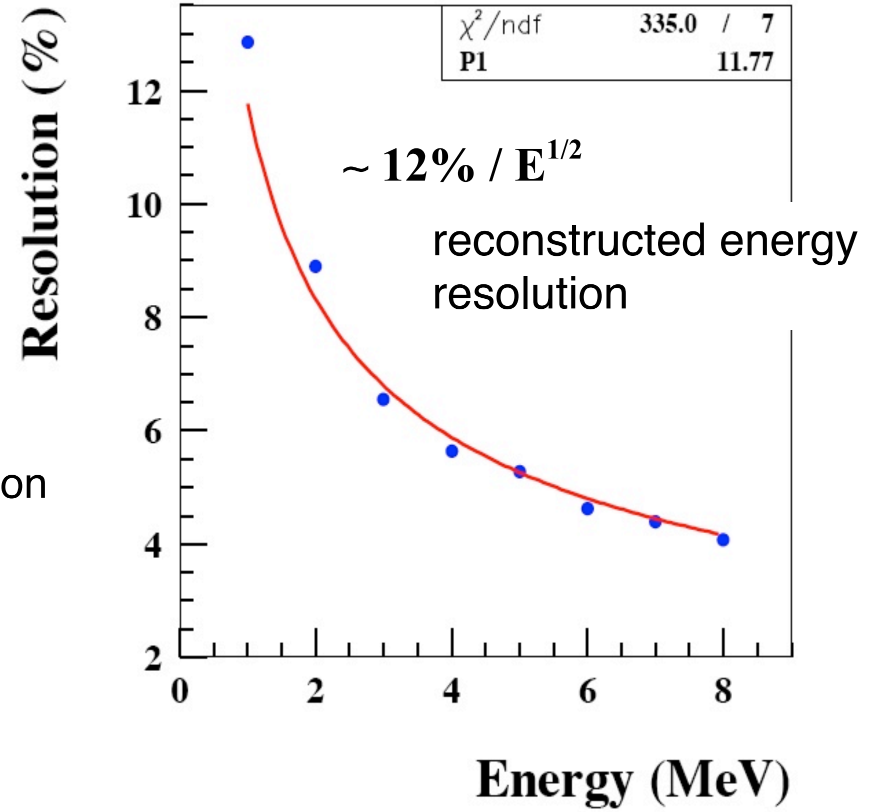
Geant4-based simulations



R² distribution of neutron production point



R² distribution of neutron capture position



reconstructed energy resolution

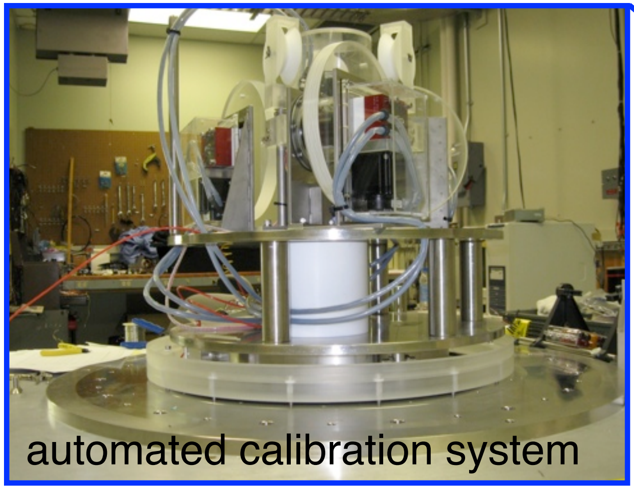
Detector Calibration

automated calibration system
→ routine weekly deployment of sources

LED light sources
→ monitoring optical properties

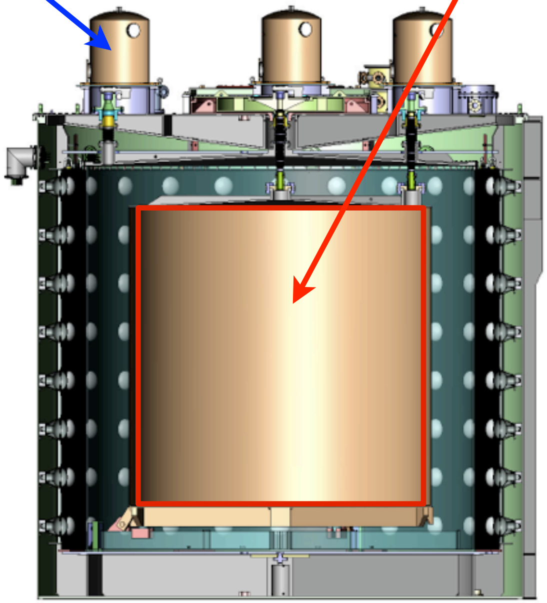
e^+ and n radioactive sources (=fixed energy)
→ energy calibration

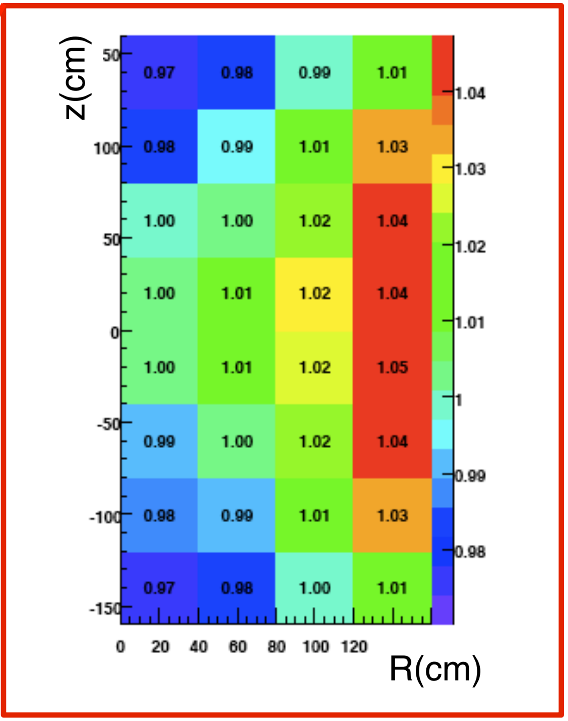
tagged cosmogenic background (free)
→ fixed energy and time



automated calibration system

^{68}Ge source
Am-C + ^{60}Co source
LED diffuser ball

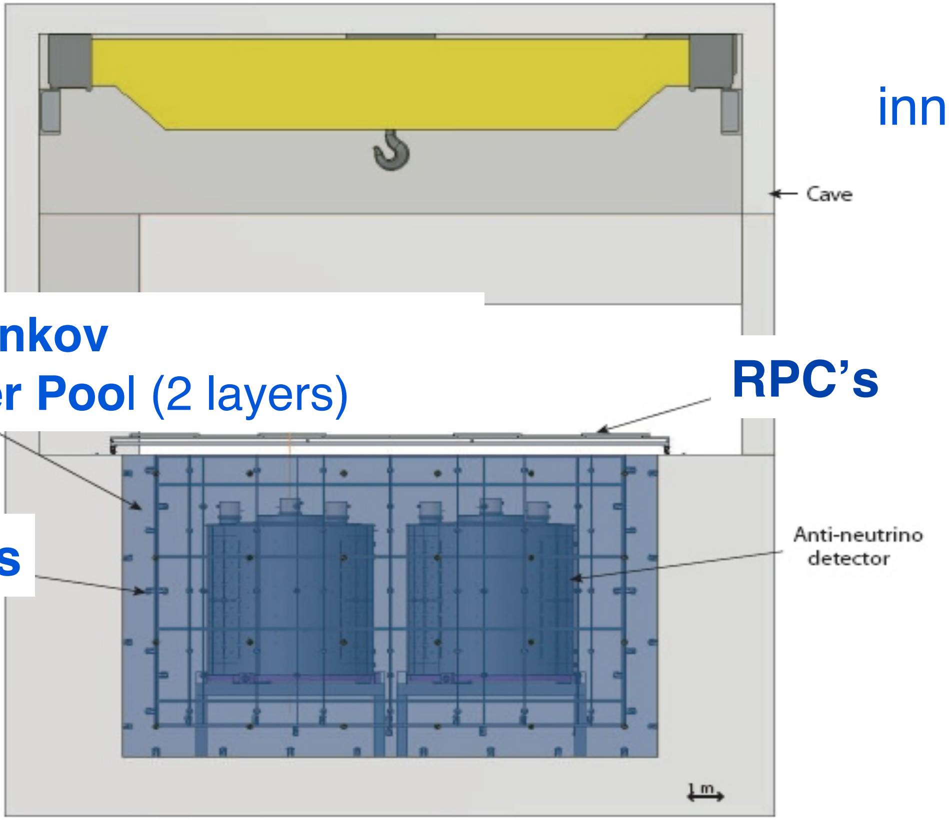




0.97	0.98	0.99	1.01
0.98	0.99	1.01	1.03
1.00	1.00	1.02	1.04
1.00	1.01	1.02	1.04
1.00	1.01	1.02	1.05
0.99	1.00	1.02	1.04
0.98	0.99	1.01	1.03
0.97	0.98	1.00	1.01

σ/E = 0.5% per pixel requires:
1 day (near), 10 days (far)

Muon Veto System



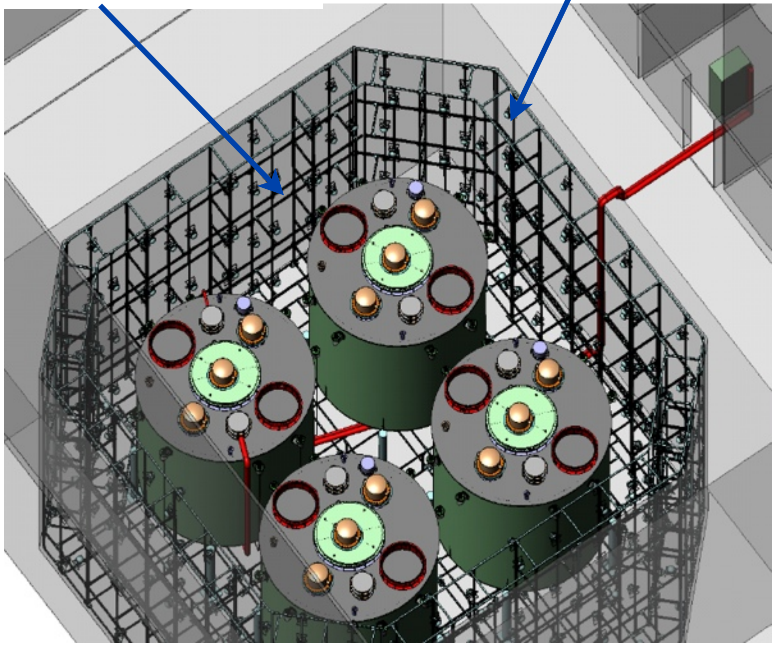
Cerenkov Water Pool (2 layers)

RPC's

PMTs

1m outer water shield

inner water veto



RPCs: muon detect efficiency 98.6% and ~0.5m spatial resolution.
Two-layer water pool: 962 PMTs, >2.5m water shield for neutron background, ~0.5m spatial resolution

Daya Bay veto system provides a combined muon detection efficiency > 99.5%.

KamLAND 2008: Systematics and Backgrounds

Systematic Uncertainties

	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

fiducial volume systematics reduced from 4.7% → 1.8%

total systematics: 4.1%

Estimated Backgrounds

TABLE II: Estimated backgrounds after selection efficiencies.

Background	Contribution
Accidentals	80.5 ± 0.1
^{9}Li/^{8}He	13.6 ± 1.0
Fast neutron & Atmospheric ν	<9.0
^{13}C(α,n)^{16}O G.S.	157.2 ± 17.3
^{13}C(α,n)^{16}O ^{12}C(n,nγ)^{12}C (4.4 MeV γ)	6.1 ± 0.7
^{13}C(α,n)^{16}O 1st exc. state (6.05 MeV e^+e^-)	15.2 ± 3.5
^{13}C(α,n)^{16}O 2nd exc. state (6.13 MeV γ)	3.5 ± 0.2
Total	276.1 ± 23.5

significantly reduced

(number of events)