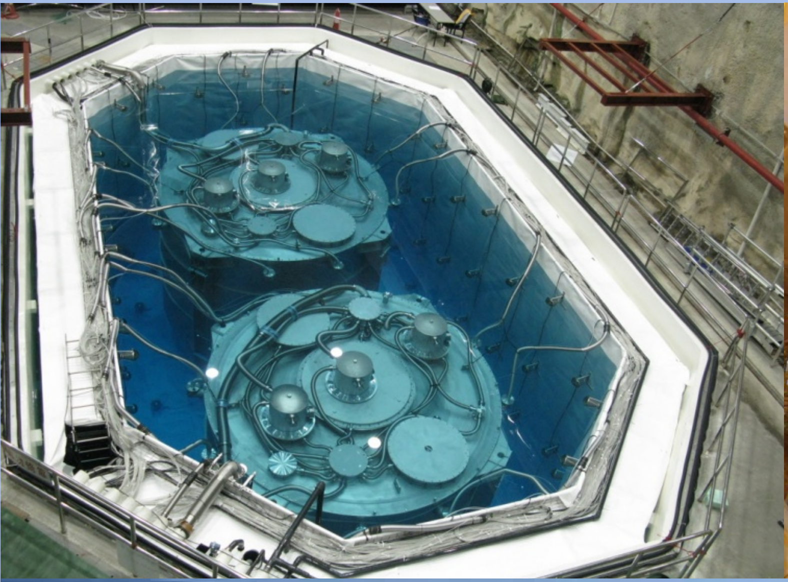
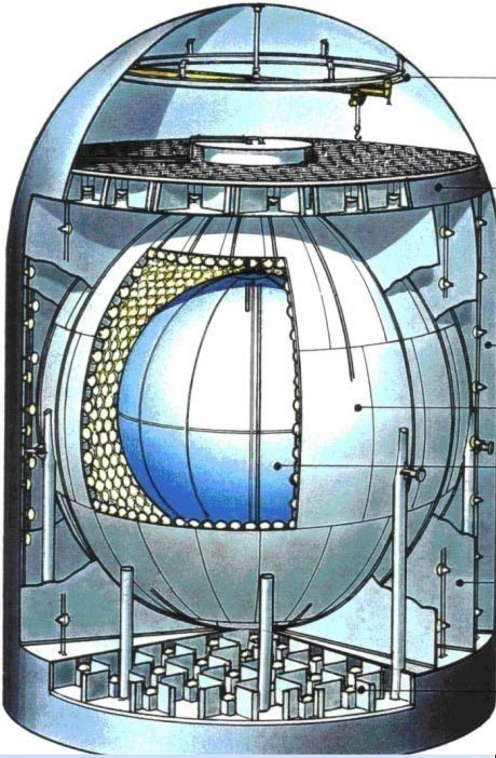
REACTOR NEUTRINO EXPERIMENTS





R. D. McKeown
Jefferson Lab, William & Mary

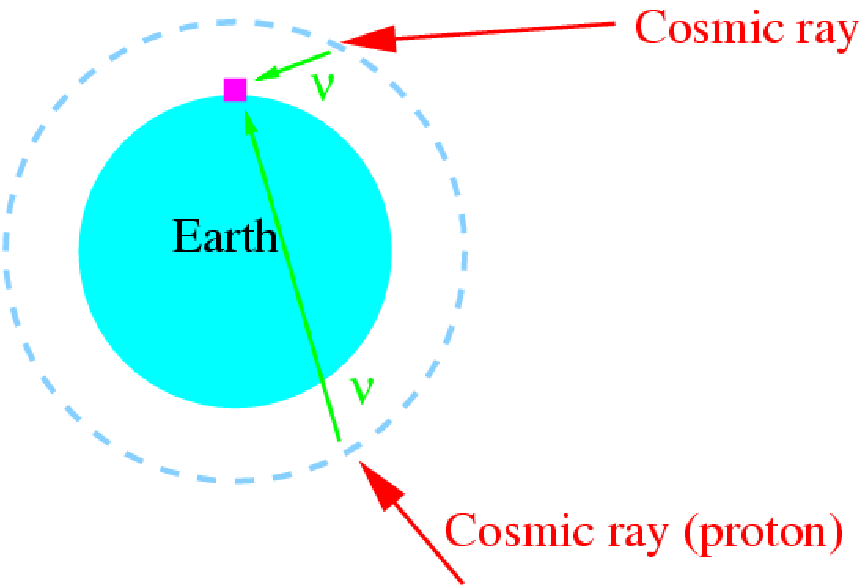
Elba Workshop
June 27, 2012

Outline

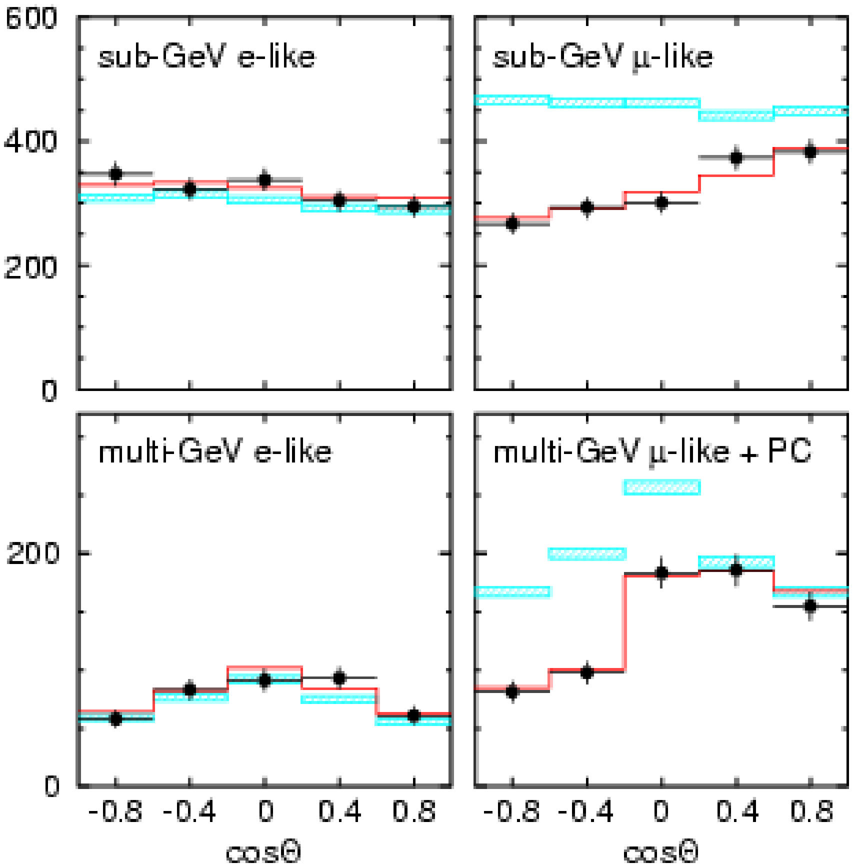
- Introduction to neutrinos and oscillations
- Reactor antineutrino experiments
- KamLAND
- θ_{13} experiments
- Outlook

Thanks to:
K. Heeger, W. Wang, X. Qian

Super-Kamiokande (1998)

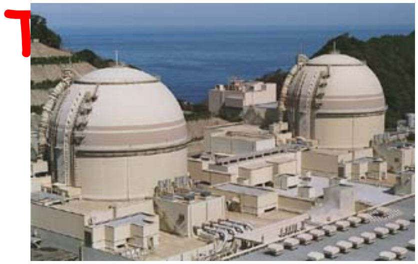


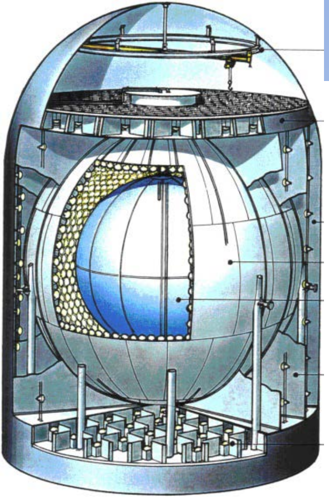
First evidence for neutrino oscillations!



Neutrino Mass and Mixing

T on Model





$$|\nu_e\rangle \xrightarrow{L} A_e\, |\nu_e\rangle + A_\mu\, |\nu_\mu\rangle$$

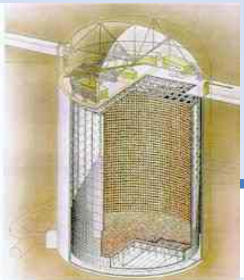
ν_1, ν_2 mass eigenstates m_1 , m_2

$$\boxed{|\nu_e\rangle = \cos\theta\, |\nu_1\rangle + \sin\theta\, |\nu_2\rangle}$$

$$\Delta m^2 = m_1^2 - m_2^2$$

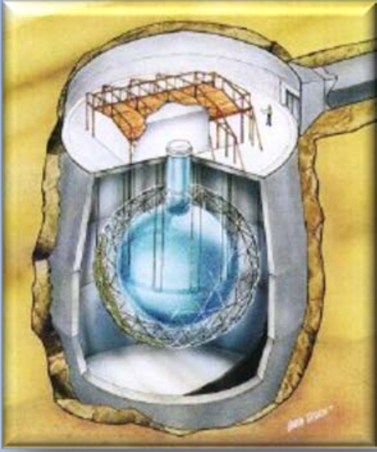
$$P_\mu = |A_\mu|^2 = \sin^2 2\theta \ \sin^2\left(\frac{\Delta m^2 L}{4 E_\nu}\right)$$

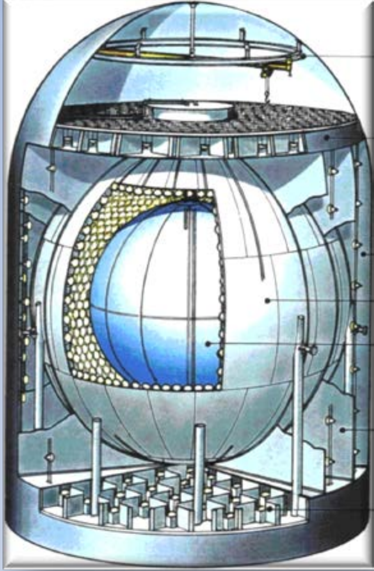
$$P_e = |A_e|^2 = 1 - \sin^2 2\theta \ \sin^2\left(\frac{\Delta m^2 L}{4 E_\nu}\right)$$

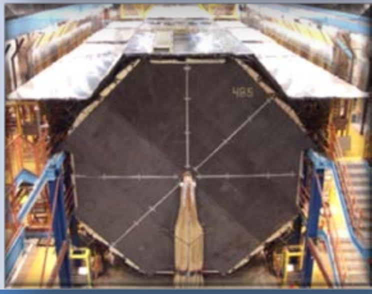


- **Neutrinos have mass!**
- **Substantial flavor mixing!**

Progress Since 2000







- Sudbury Neutrino Observatory (SNO)

  → flavor change responsible for solar ν_e deficit
- KamLAND

  → observes oscillation pattern, δm_{12}^2
- K2K & MINOS

  → precise determination of δm_{23}^2, θ_{23}
- Daya Bay (2012)

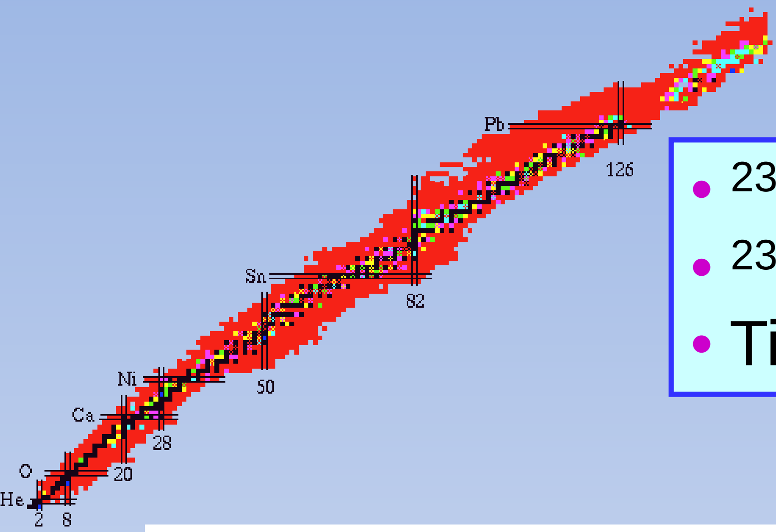
  → measurement of θ_{13}

KamLAND
Kamioka Liquid scintillator Anti-Neutrino Detector

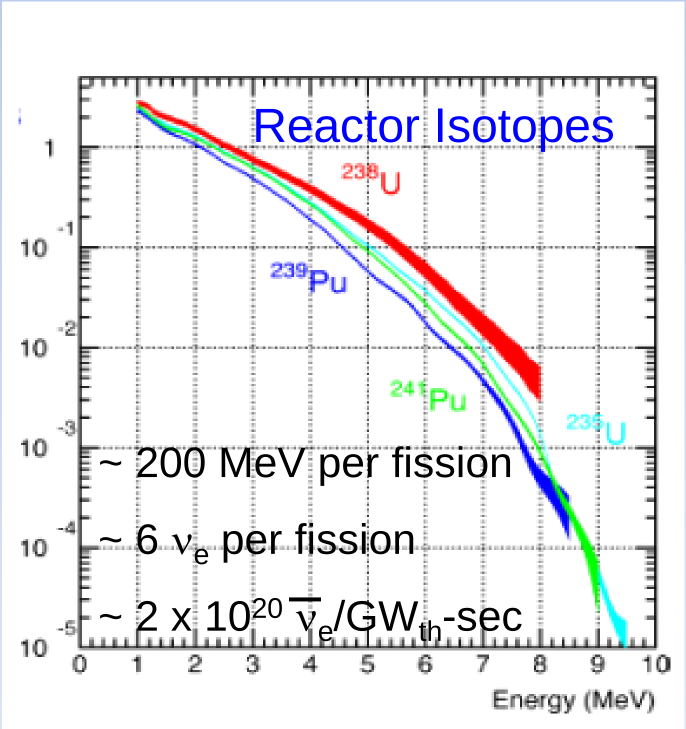

Kashiwazaki Nuclear Power Station : 25 GW

- $\bar{\nu}_e$ from n-rich fission products
- detection via inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$)
- Measure flux and <u>energy spectrum</u>

The Reactor Neutrino Flux and Spectrum



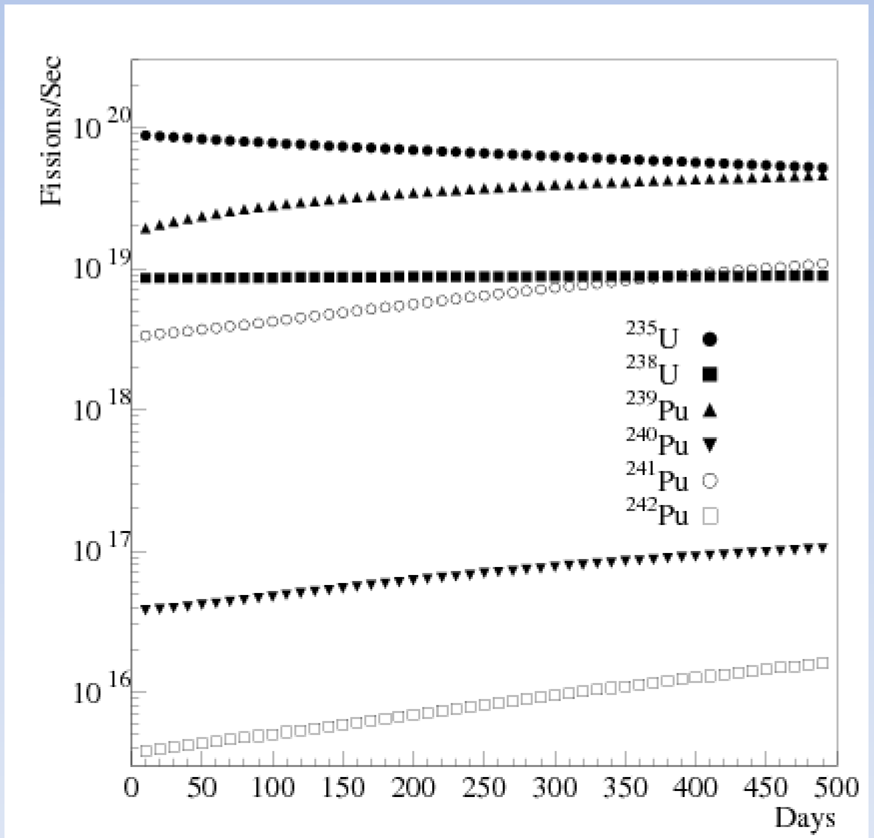
- ^{235}U, ^{239}Pu, ^{241}Pu from β *measurements*
- ^{238}U calculated
- Time dependence due to fuel cycle



~ 200 MeV per fission

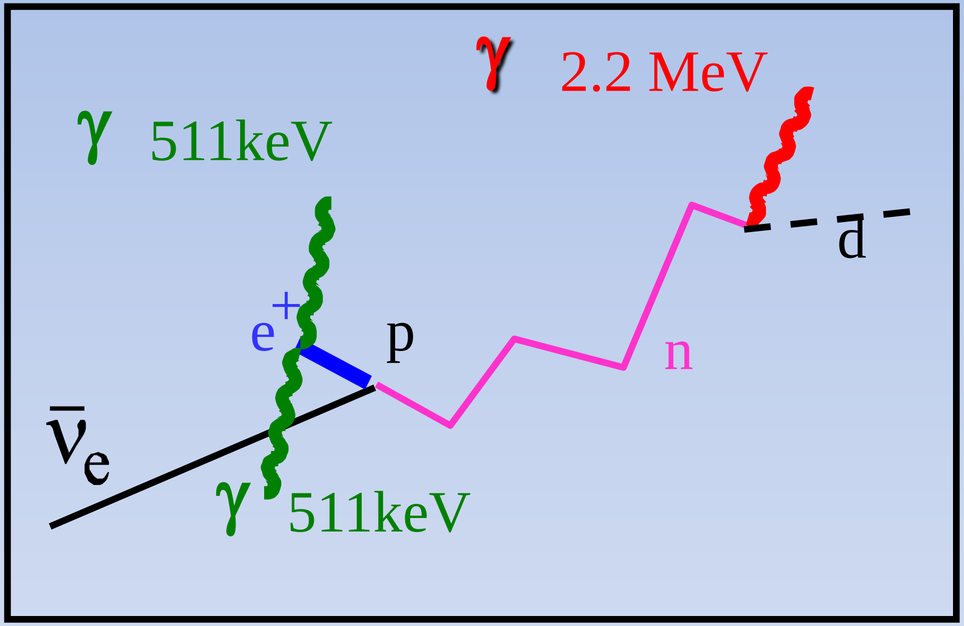
~ 6 ν_e per fission

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



Detection Signal

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

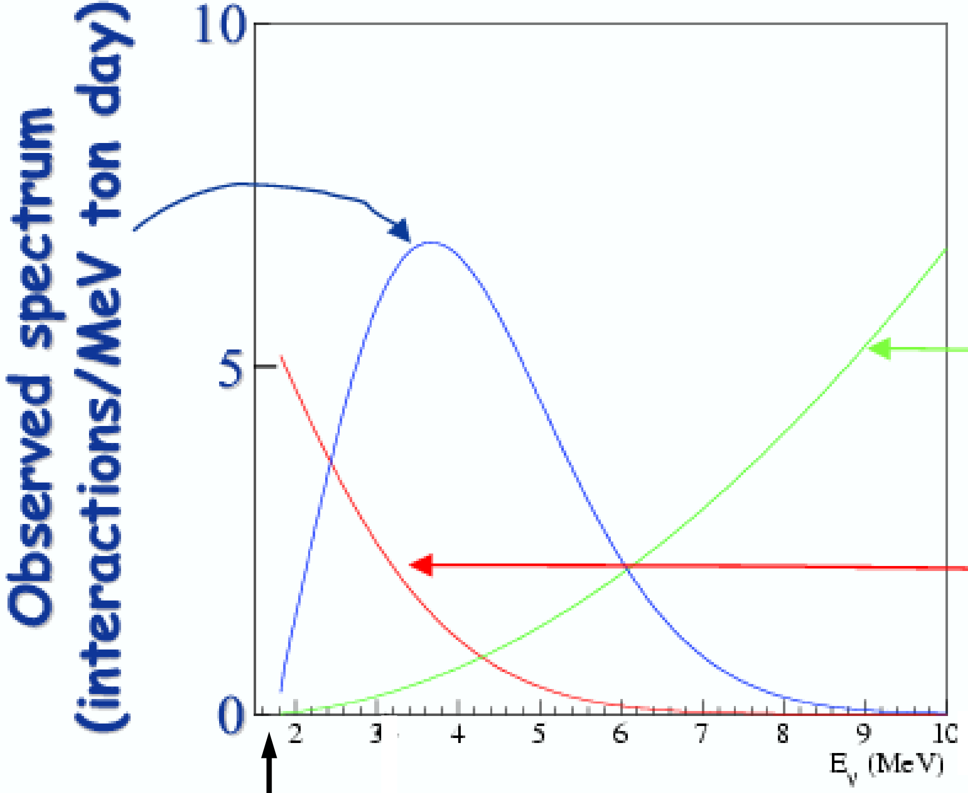


Coincidence signal:

- Prompt: e^+ annihilation → $E_\nu = E_{prompt} + \bar{E}_n + 0.8$ MeV
- Delayed: **n+p** 180 μs capture time, 2.2 MeV

  n+Gd 30 μs capture time, 8 MeV

The $\bar{\nu}_e$ energy spectrum



$\nu_e + p \rightarrow n + e^+$
cross section
($\sim 10^{-42}$ cm^2)

Calculated reactor
$\bar{\nu}_e$ spectrum

Neutrinos with E<1.8 MeV
are not detected

Precise Measurements

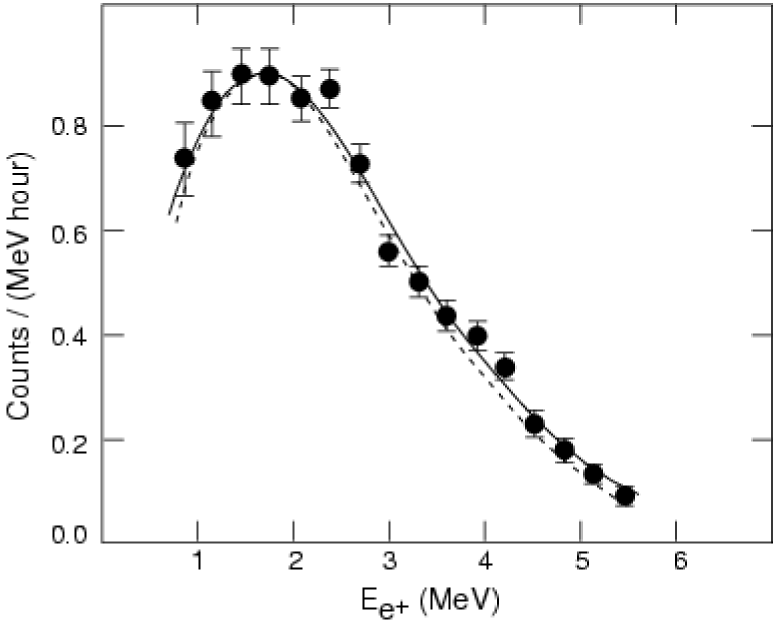
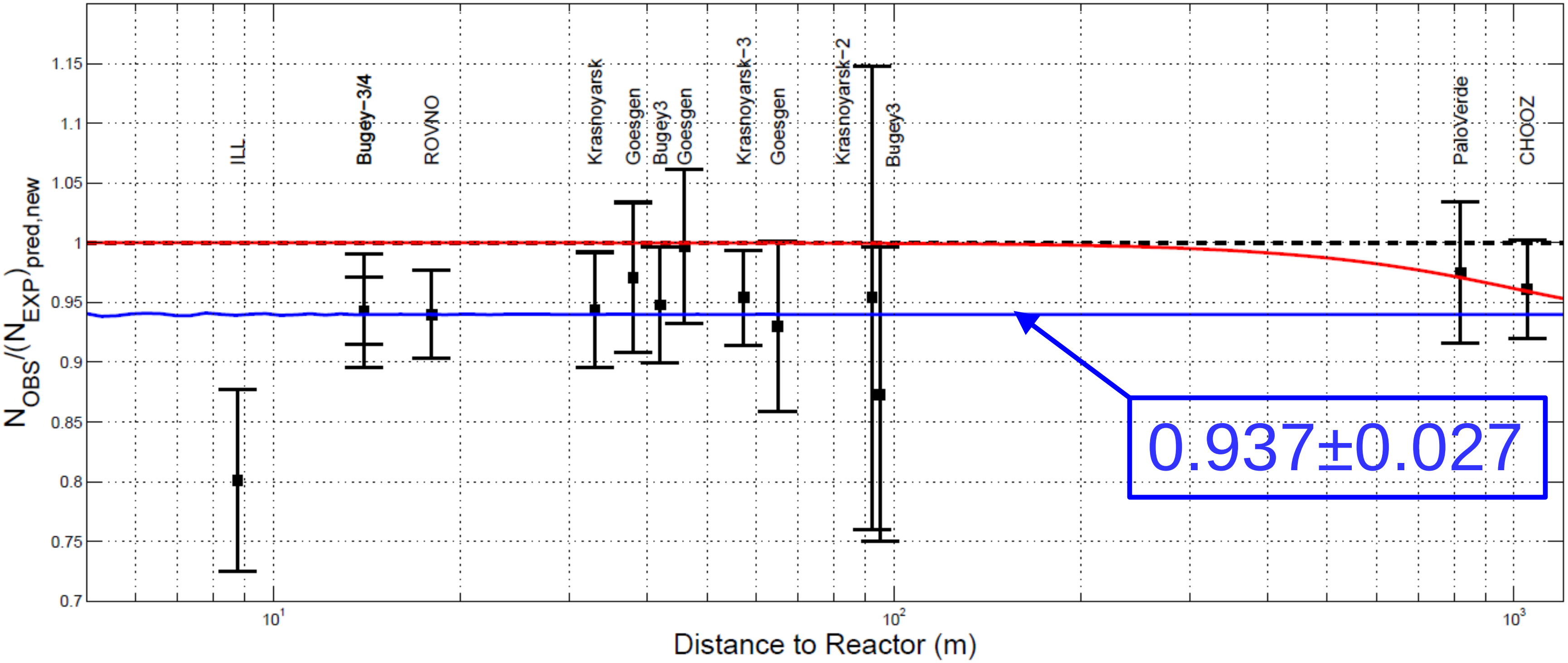


Figure 5: Positron spectrum measured at 45.9 m from the core of the Gösgen reactor [36]. Data points are obtained after background subtraction, errors are statistical only. The solid curve is a fit to the data assuming no oscillations. The dashed curve is derived independently by β-spectroscopy.

New Reactor Flux Analysis (2011)

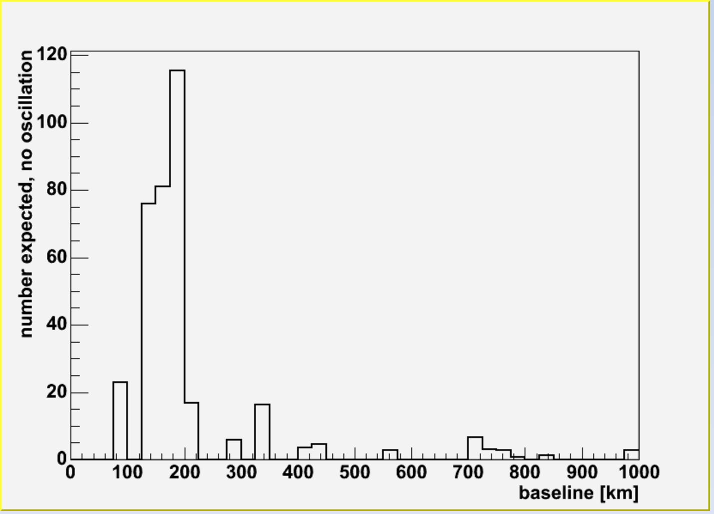


0.937±0.027

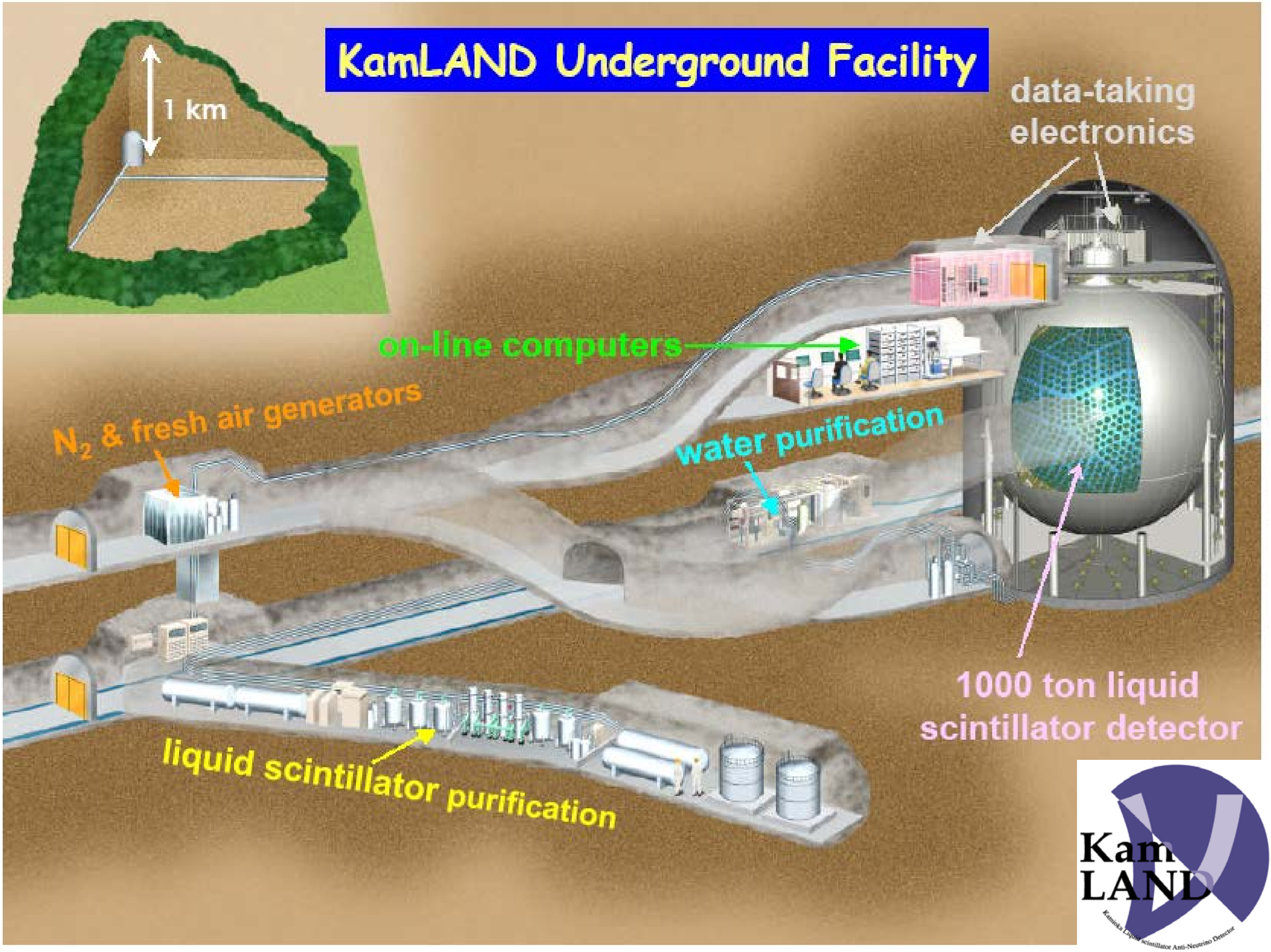
arXiv:1101.2755

KamLAND used the entire Japanese nuclear power industry as a longbaseline neutrino source

Kamioka Liquid Scintillator Anti-Neutrino Detector



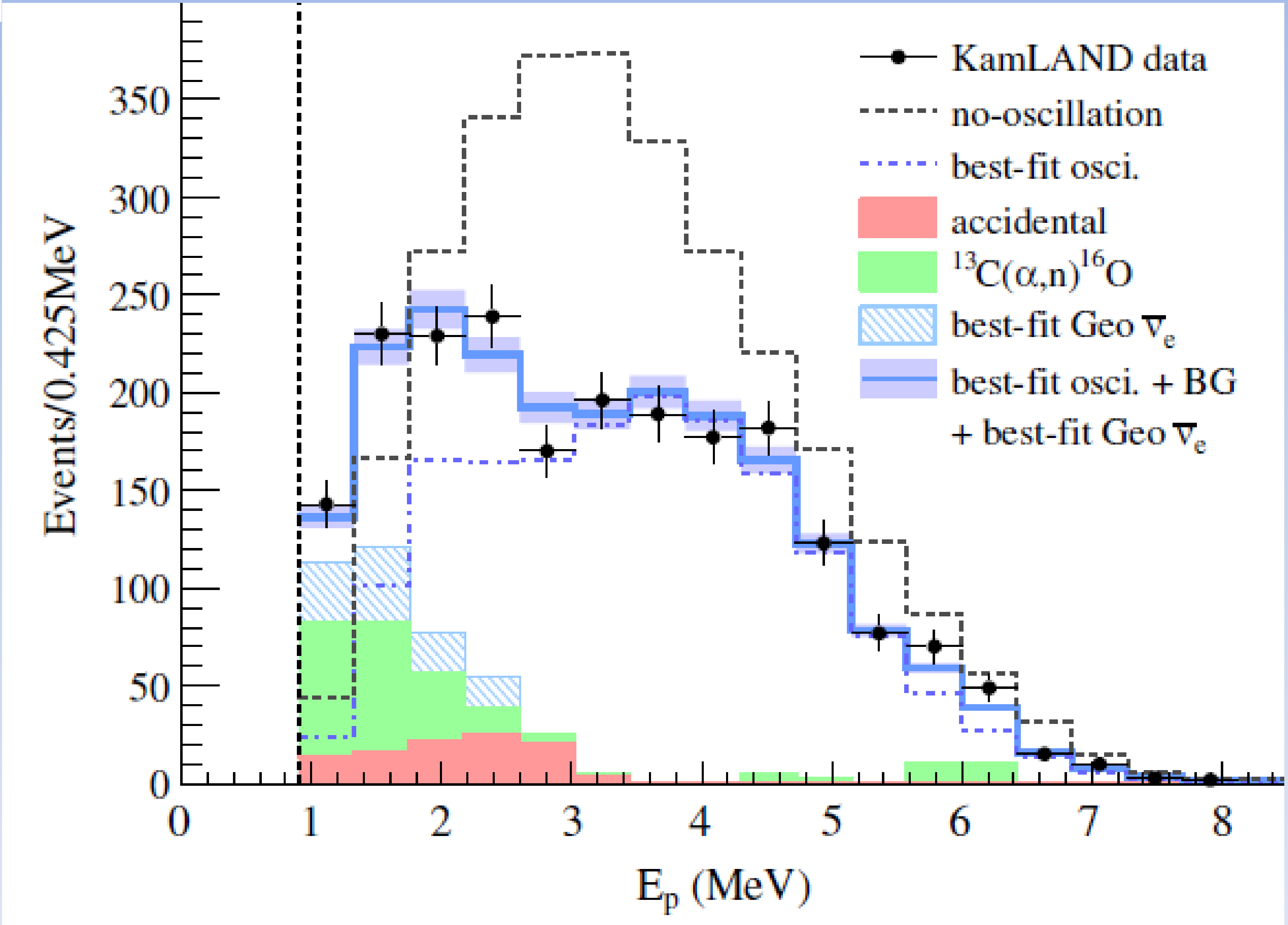
KamLAND Underground Facility



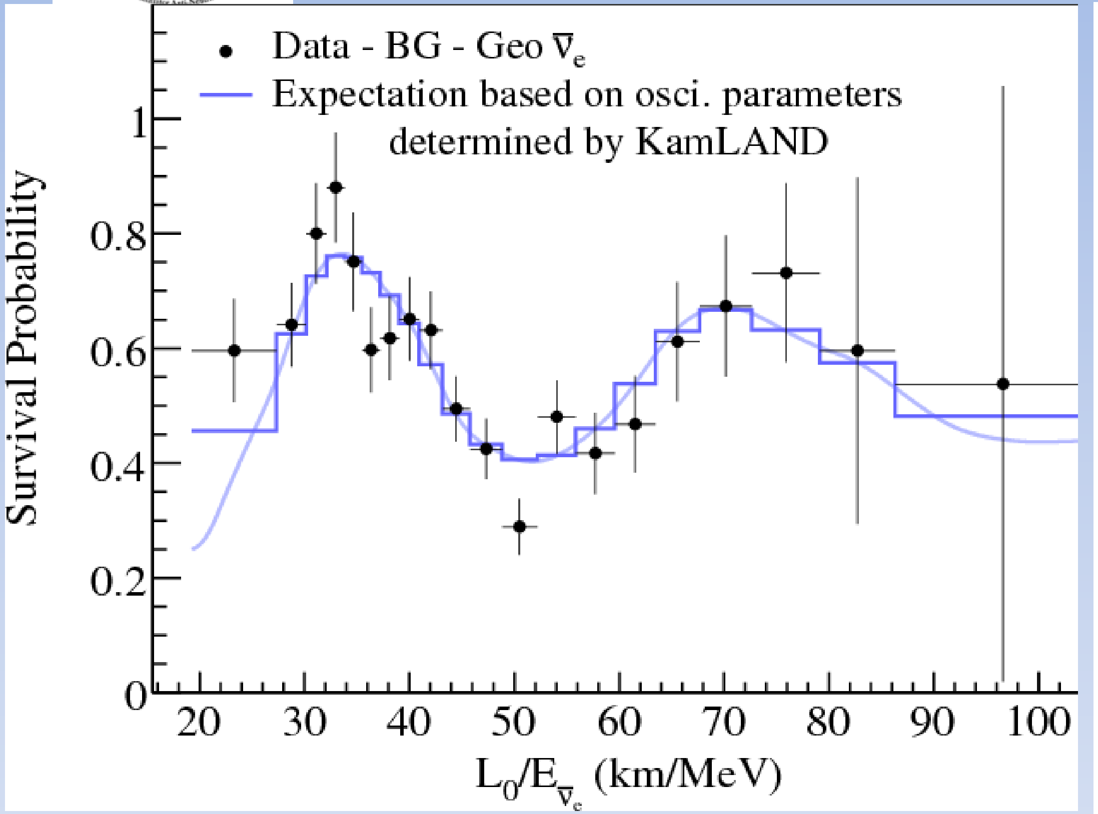
Kam LAND

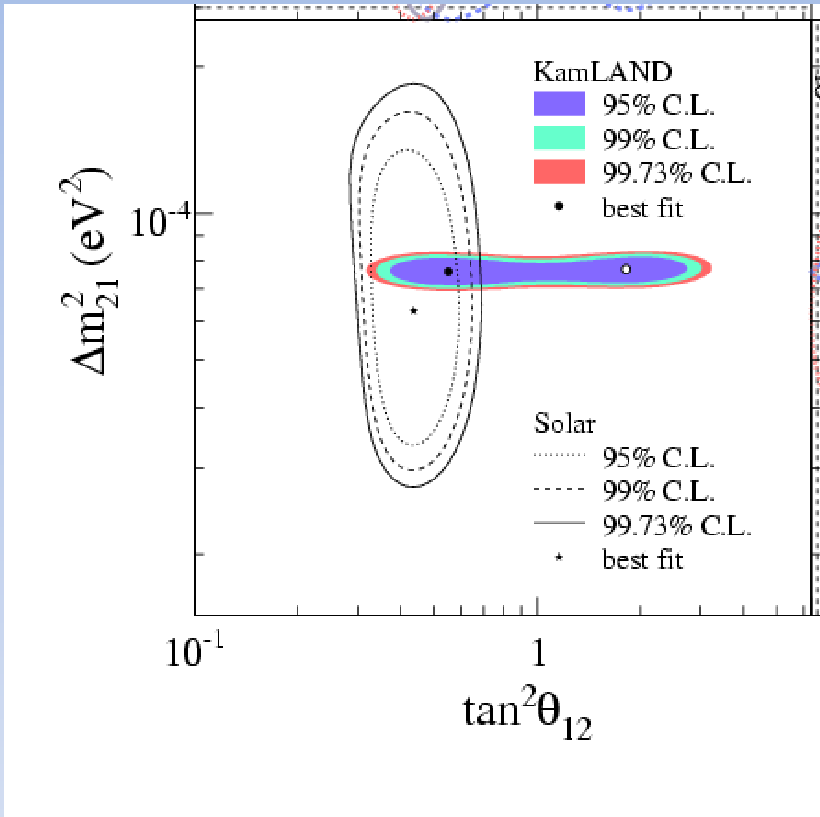
Kamioka Liquid scintillator Anti-Neutrino Detector

Energy Spectrum



KamLAND Result (2008)





PRL 100, 221803 (2008)

Best combined fit values:

$$\Delta m^2 = 7.59^{+0.21}_{-0.21} \times 10^{-5}\ eV^2$$

$$\tan^2\theta = 0.47^{+0.06}_{-0.05}$$

Pontecorvo Maki – Nakagawa – Sakata Matrix

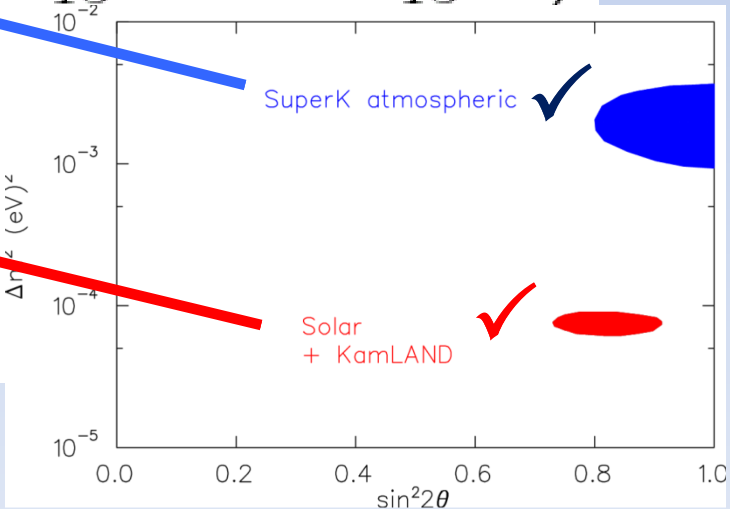
$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Gateway to CP Violation!

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}$$

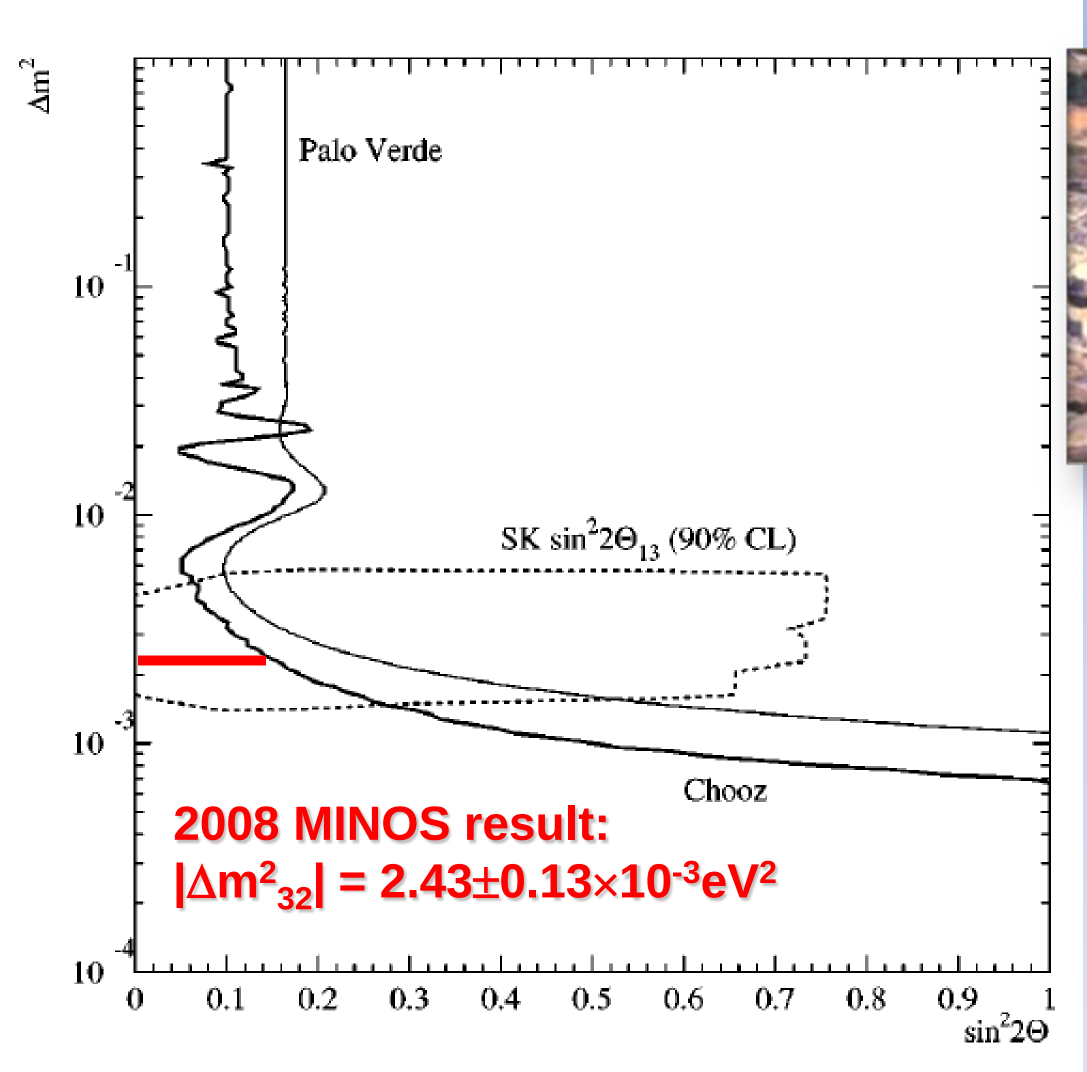
CP violation

$$\times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} .$$

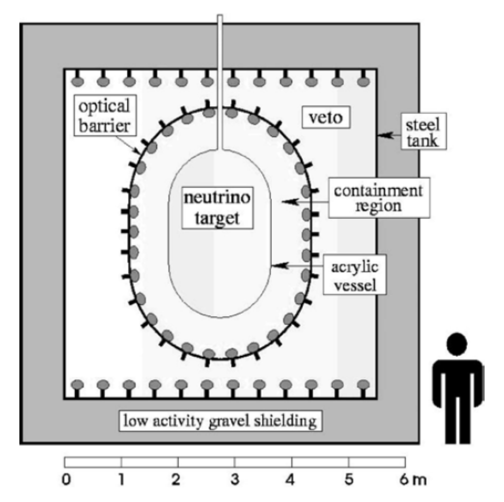


CHOOZ/Palo Verde limits for θ_{13}

(2001-3)



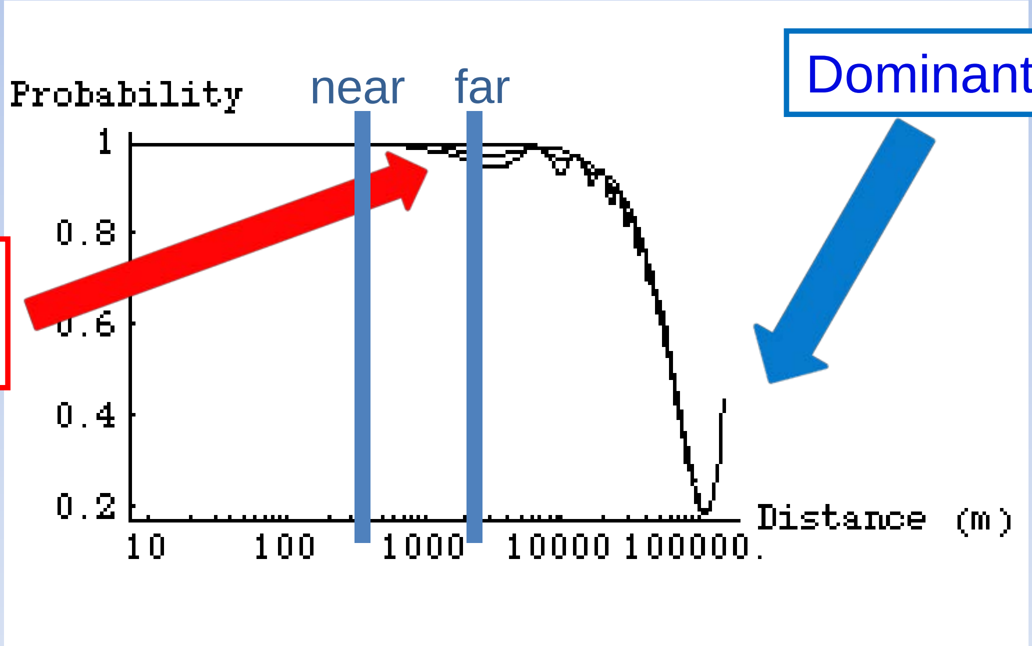
2008 MINOS result:
$|\Delta m^2_{32}| = 2.43 \pm 0.13 \times 10^{-3} \mathrm{eV}^2$



$\sin^2 2\theta_{13} < 0.15$ (90% CL)

$\bar{\nu}_e$ Survival Probability (3 generations)

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

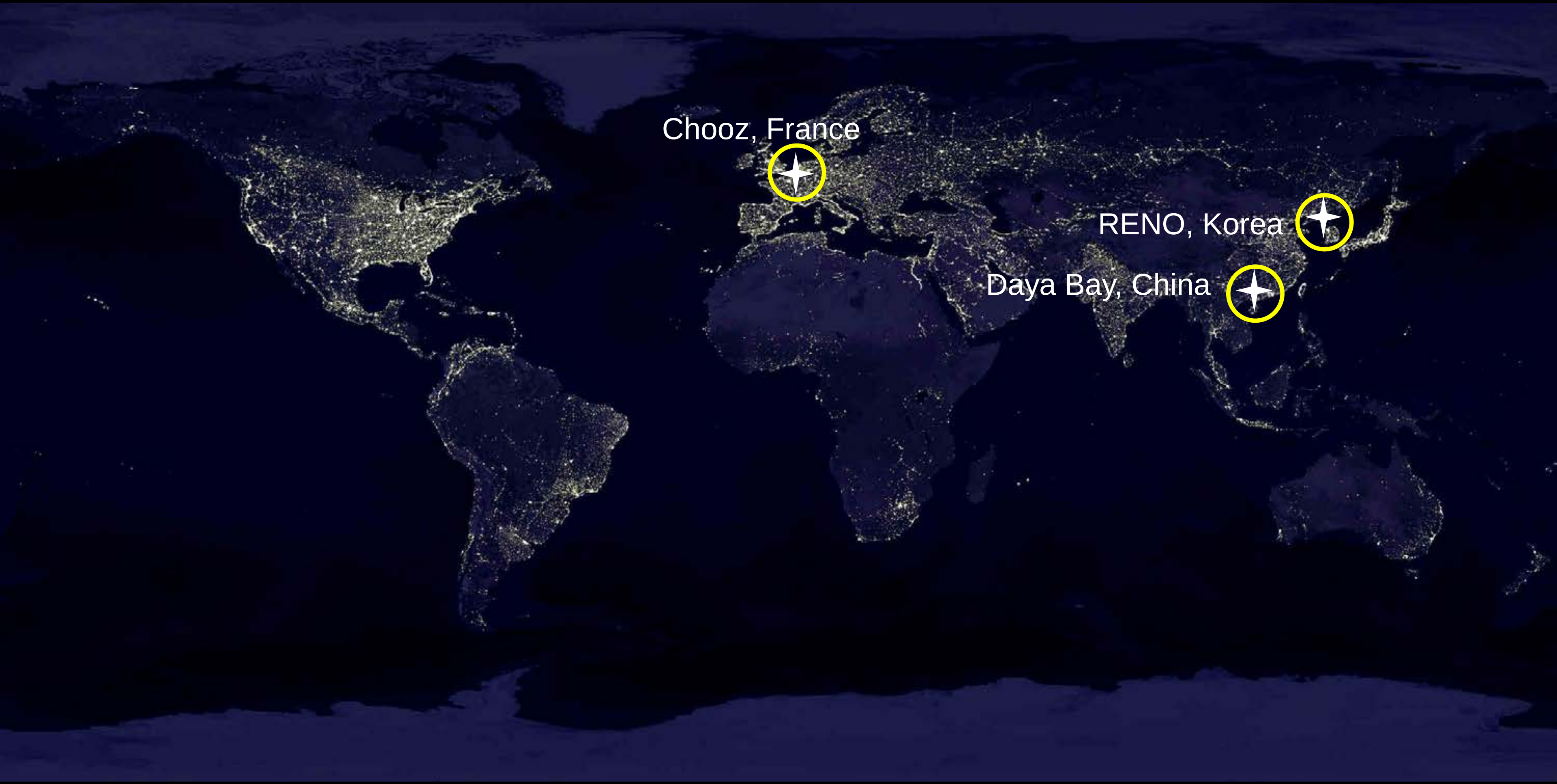


Subdominant θ_{13} Oscillation

Dominant θ_{12} Oscillation

- "Clean" measurements of θ, Δm^2
- Use 2 detector sites

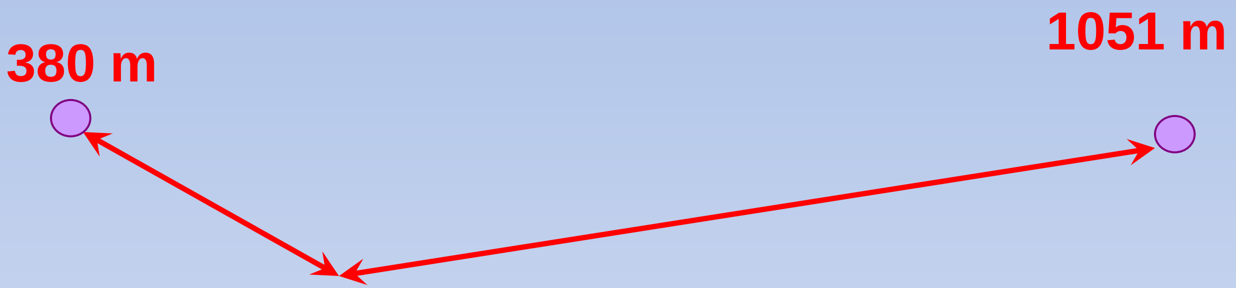
New Reactor θ_{13} Neutrino Experiments

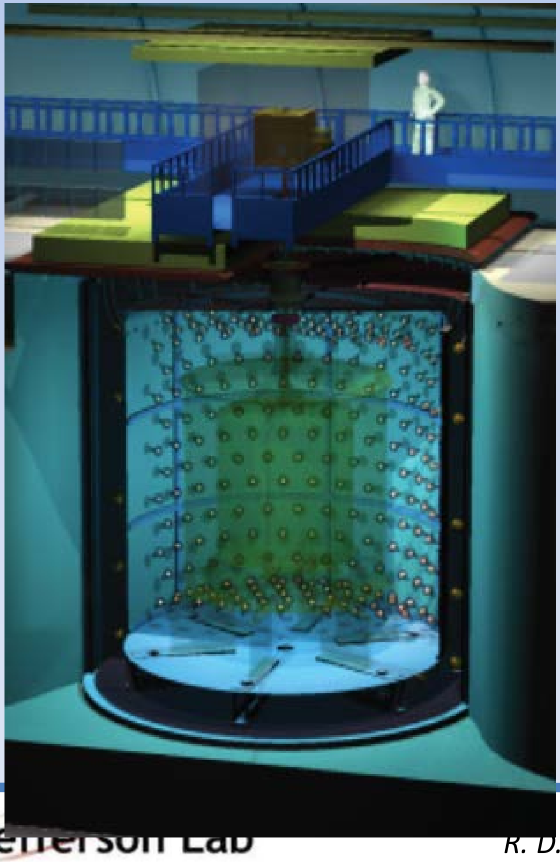


Two identical detectors:10 tons each.

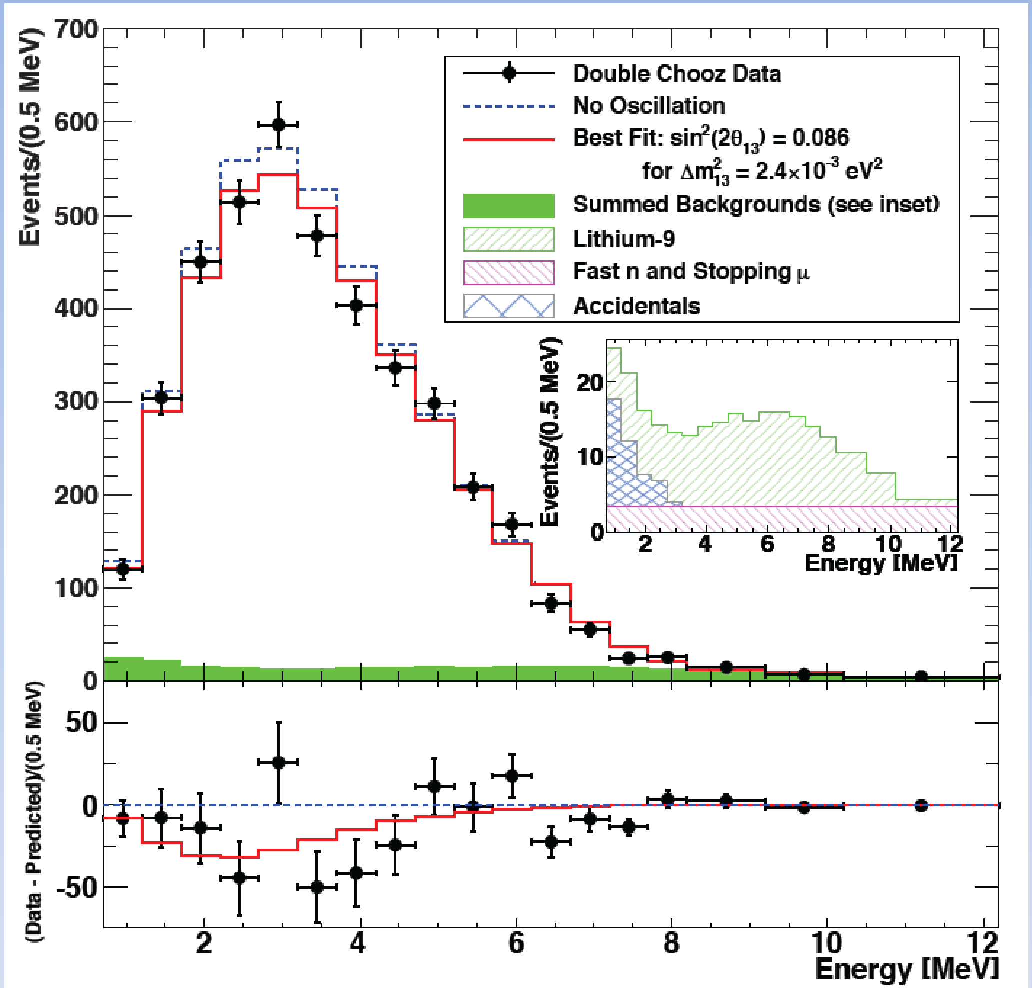
Phase 1 (2010-12): Far Detector in existing lab.

Phase 2 (2013): running with Near detector in new lab.





Far site only result (2011)



PRL108, 131801(2012) arXiv:1112.6353v1

$\sin^2 2\theta_{13}$=0.086±0.041(stat)±0.030(sys)

Systematic Uncertainties

- Detector: 2.1%
- Reactor: 1.8% (mostly Bugey-4)
- Background: 2.94% (mostly ^{9}Li)

Daya Bay - A Powerful Neutrino Source

Ling Ao NPP
2 × 2.9 GW_{th}

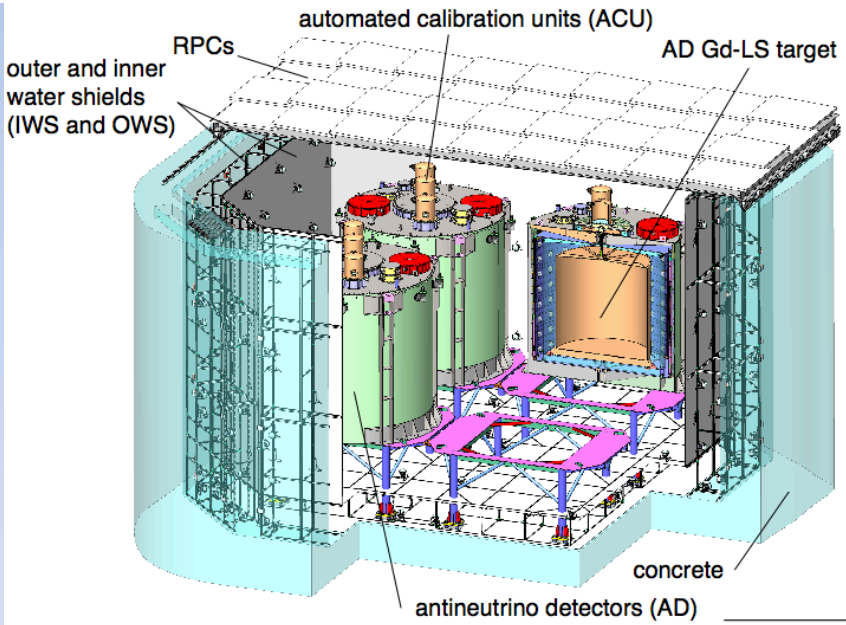
Ling Ao II NPP
2 × 2.9 GW_{th}

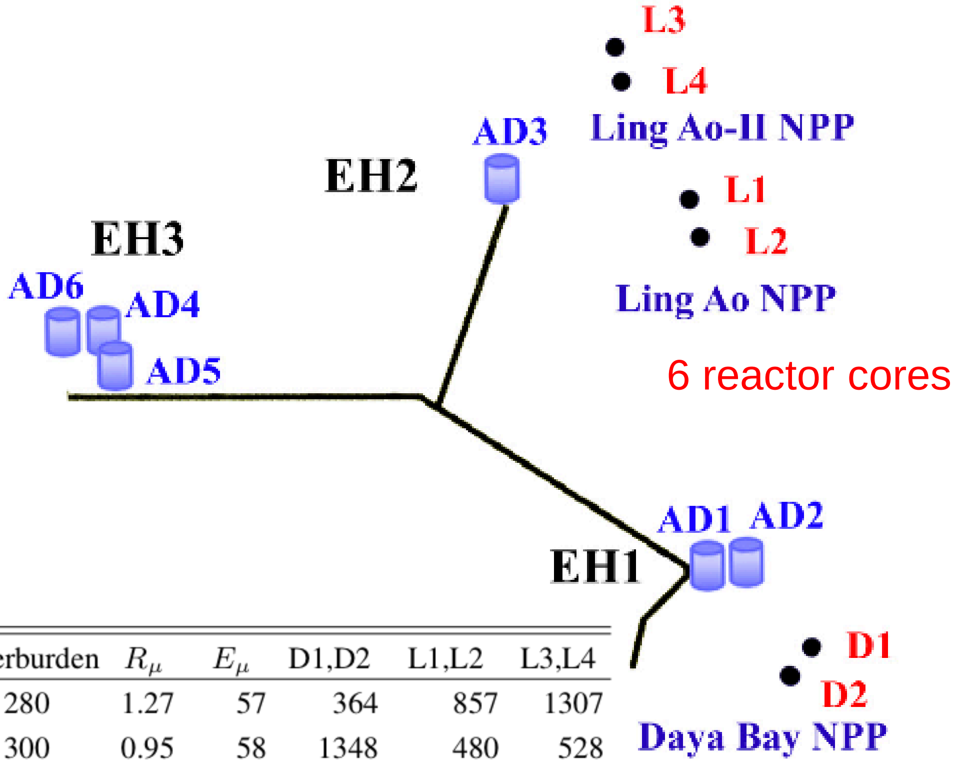
Daya Bay NPP
2 × 2.9 GW_{th}

- Among the top 5 most powerful reactor complexes in the world, producing 17.4 GW_{th} (6 x 2.95 GW_{th})
- All 6 reactors are in commercial operation
- Adjacent to mountains; convenient to construct tunnels and underground labs with sufficient overburden to suppress cosmic rays

Reactors produce ~2×10^{20} antineutrinos/sec/GW

Daya Bay Experiment Layout

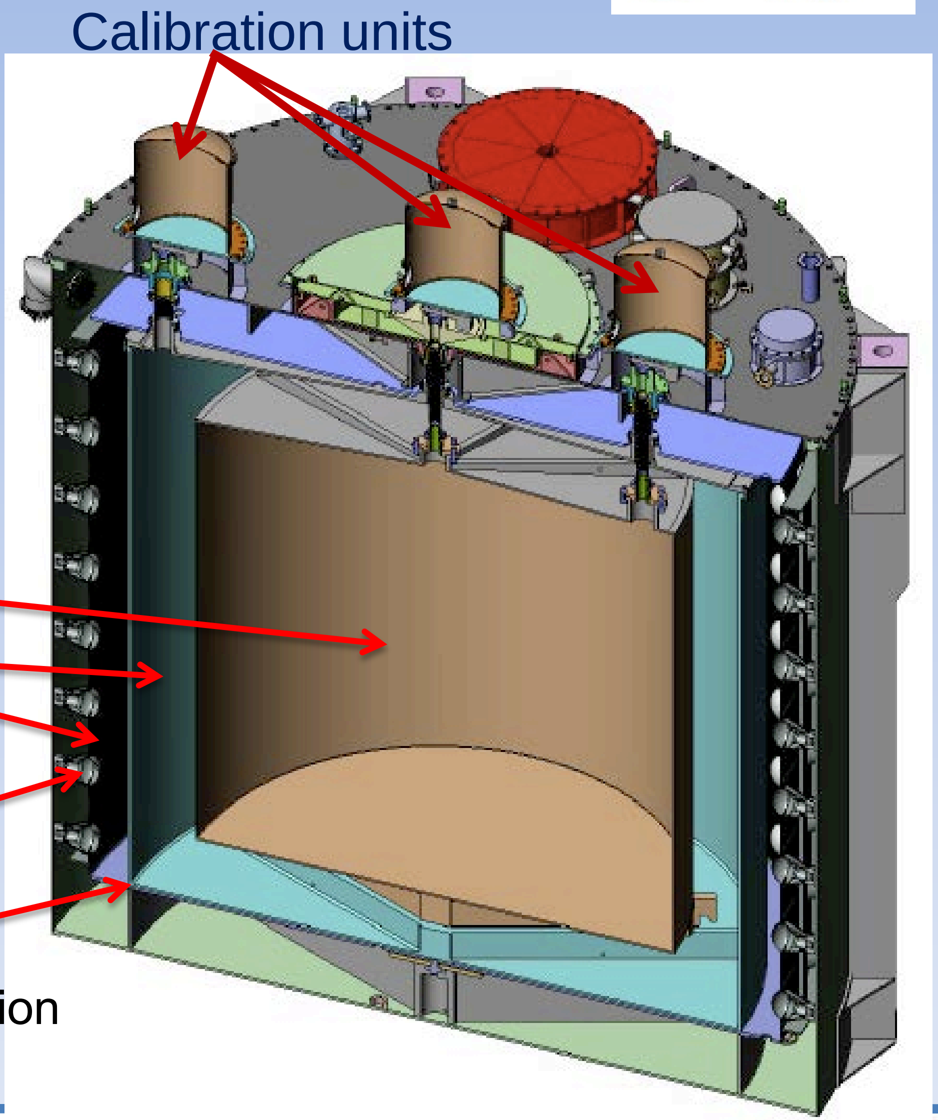




	Overburden	R_μ	E_μ	D1,D2	L1,L2	L3,L4
EH1	280	1.27	57	364	857	1307
EH2	300	0.95	58	1348	480	528
EH3	880	0.056	137	1912	1540	1548

6 antineutrino detectors in 3 underground experimental halls

Antineutrino Detectors



6 ‘functionally identical’ detectors:

Reduce systematic uncertainties

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

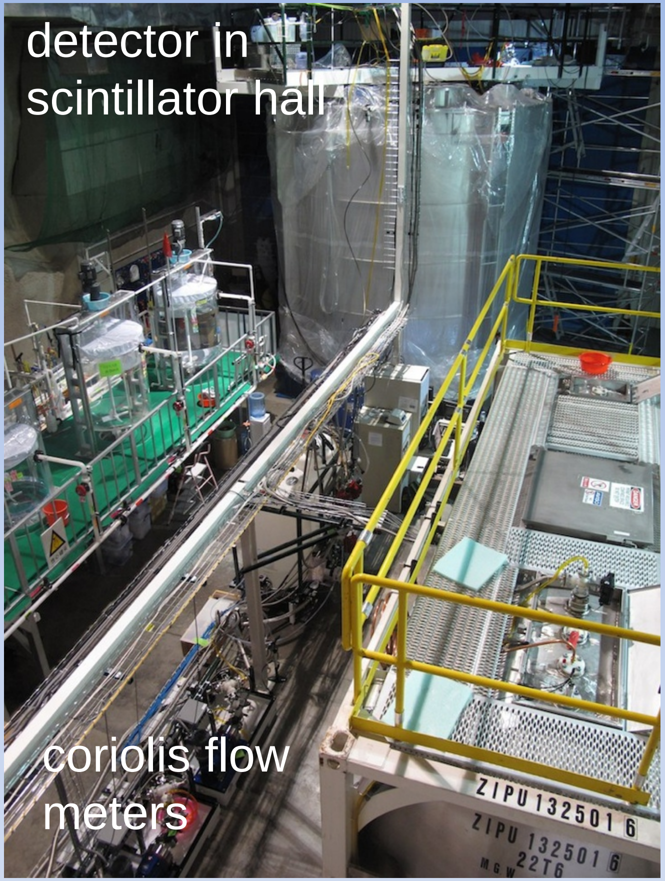
3 nested cylinders:

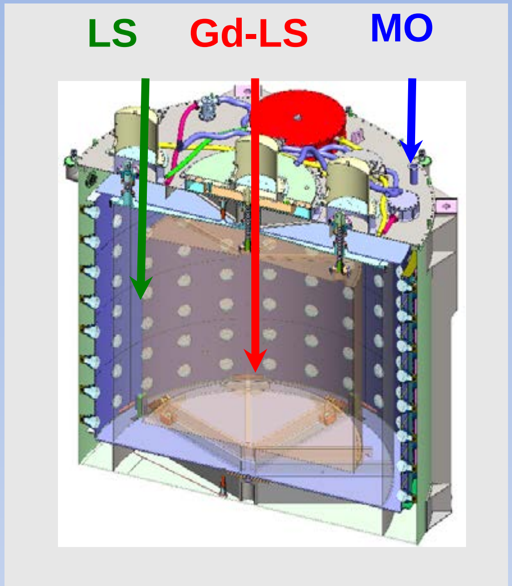
Inner: 20 tons Gd-doped LS (d=3.1m)
Mid: 20 tons LS (d=4m)
Outer: 40 tons mineral oil buffer (d=5m)

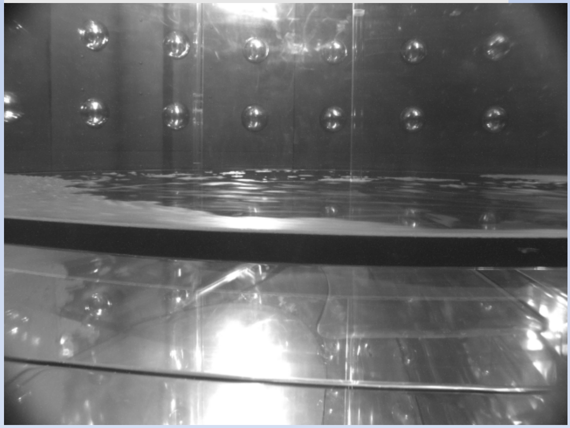
Each detector:

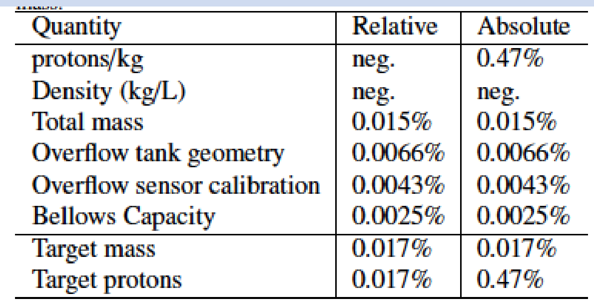
192 8-inch Photomultipliers
Reflectors at top/bottom of cylinder
Provides (7.5 / √E + 0.9)% energy resolution

Detector Filling and Target Mass Measurement









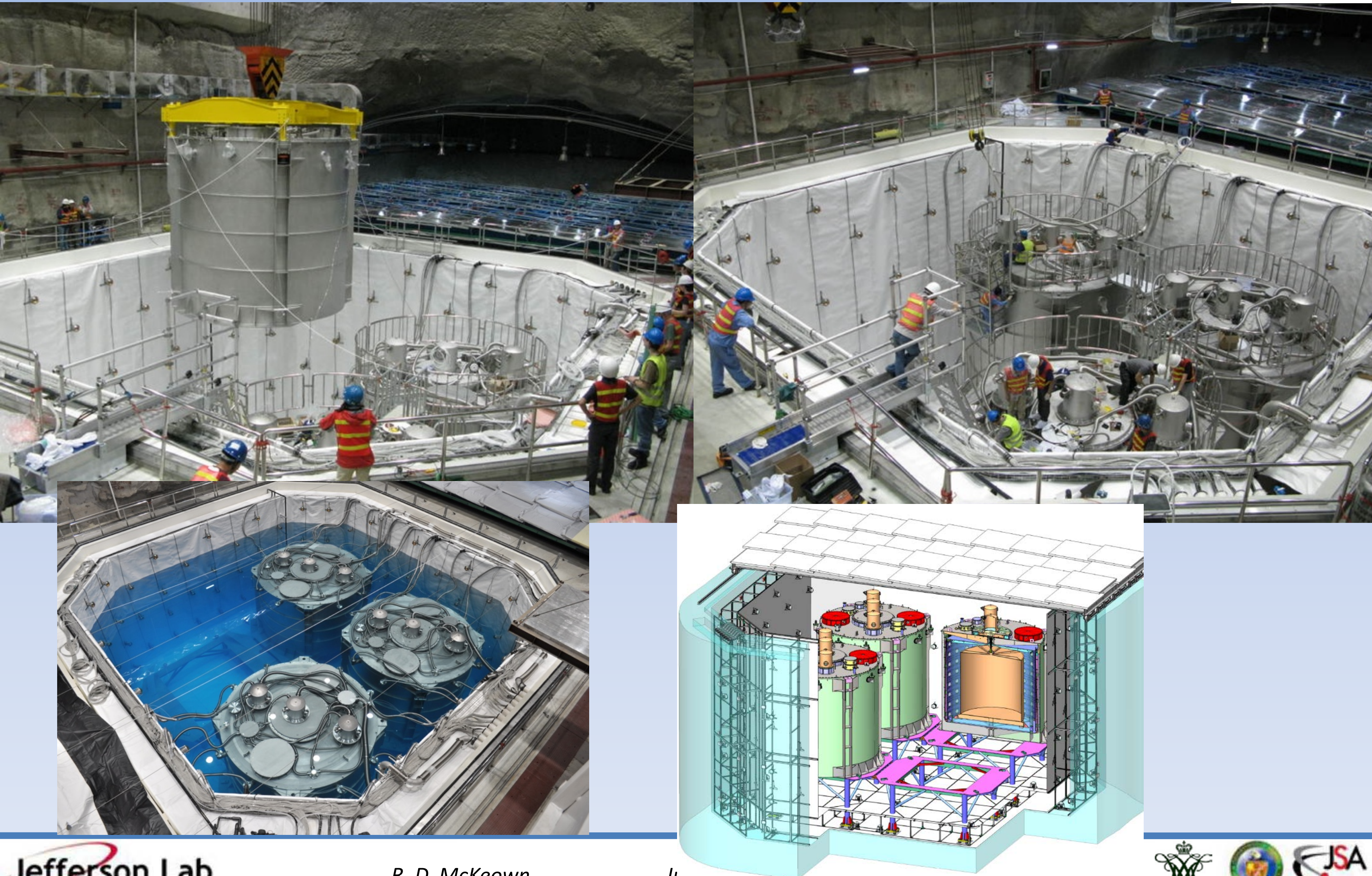
Quantity	Relative	Absolute
protons/kg	neg.	0.47%
Density (kg/L)	neg.	neg.
Total mass	0.015%	0.015%
Overflow tank geometry	0.0066%	0.0066%
Overflow sensor calibration	0.0043%	0.0043%
Bellows Capacity	0.0025%	0.0025%
Target mass	0.017%	0.017%
Target protons	0.017%	0.47%

Target mass determination error ± 3kg out of 20,000

<0.03% during data taking period

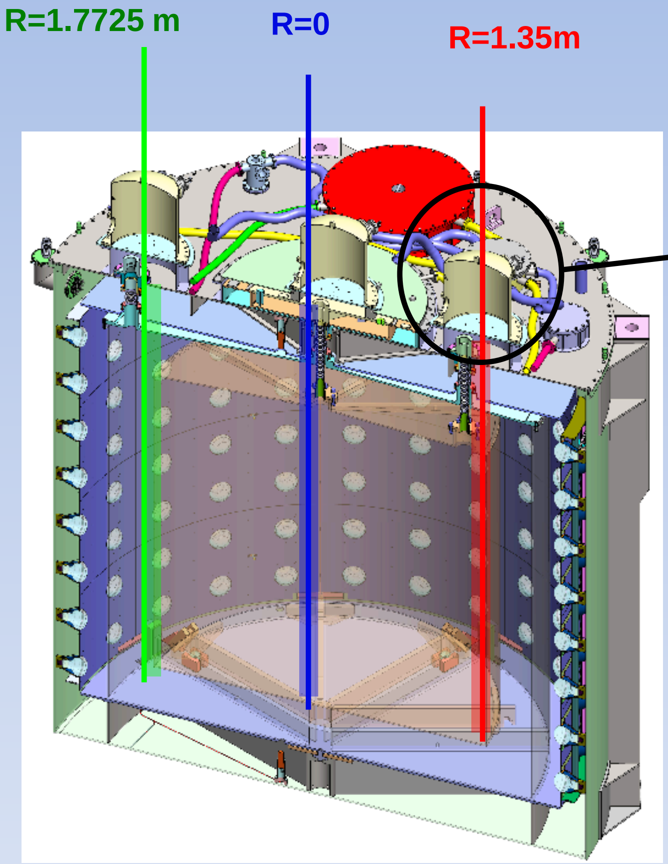
Detectors are filled from same reservoirs *"in-pairs"* within < 2 weeks.

Antineutrino Detector Installation - Far Hall

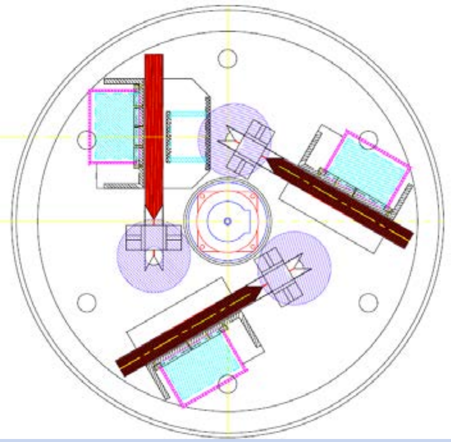


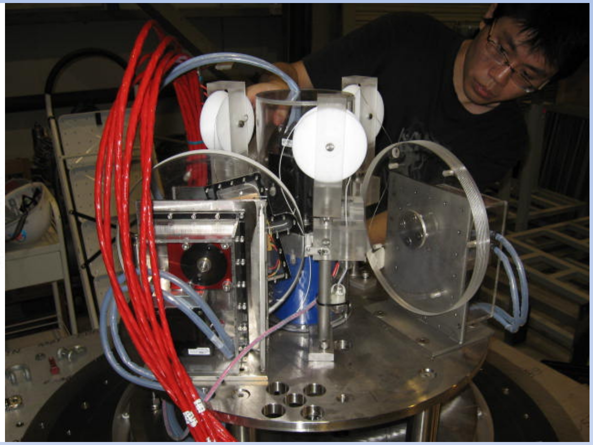
Automated Calibration System

3 Automatic calibration units (ACUs) on each detector



Top view



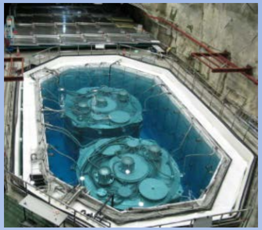


3 sources for each z axis on a turntable (position accuracy < 5 mm):

- 10 Hz ^{68}Ge (0 KE e^+ = 2×0.511 MeV γ's)
- 0.5 Hz ^{241}Am-^{13}C neutron source (3.5 MeV n without γ) + 100 Hz ^{60}Co gamma source (1.173+1.332 MeV γ)
- LED diffuser ball (500 Hz) for T_0 and gain

Three axes: center, edge of target, middle of gamma catcher

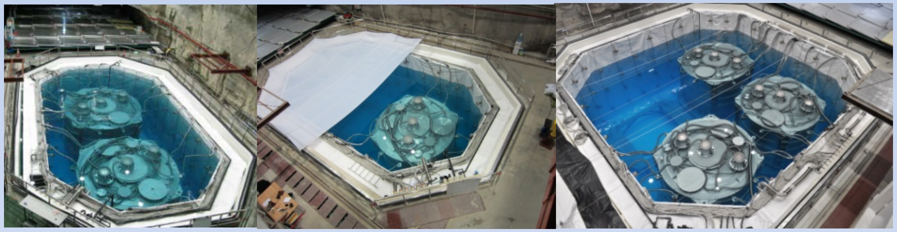
Data Period



Two Detector Comparison

- Sep. 23, 2011 – Dec. 23, 2011
- Side-by-side comparison of 2 detectors
- Demonstrated detector systematics better than requirements.

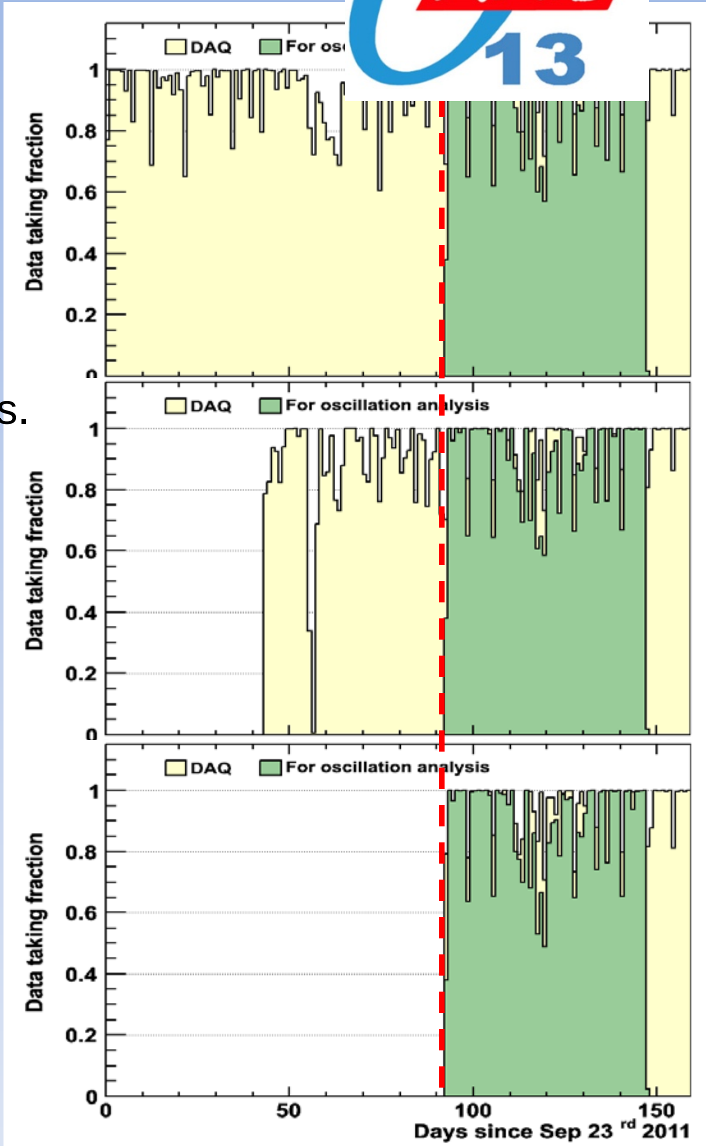
Daya Bay Collab.
arXiv:1202:6181 (2012)



Current Oscillation Analysis

- Dec. 24, 2011 – Feb. 17, 2012
- All 3 halls (6 ADs) operating
- DAQ uptime: >97%
- Antineutrino data: ~89%

Daya Bay Collab.
arXiv: 1203.1669 (2012)



Antineutrino (IBD) Selection

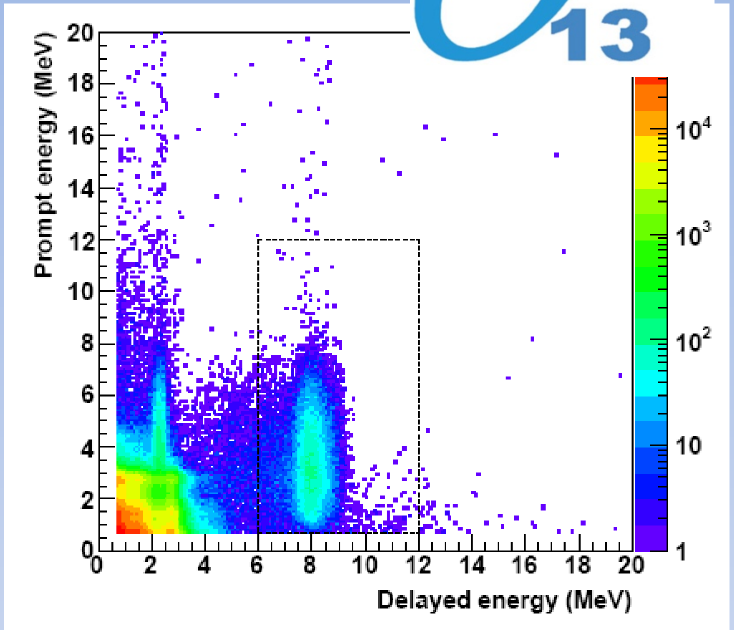
Selection of Prompt + Delayed

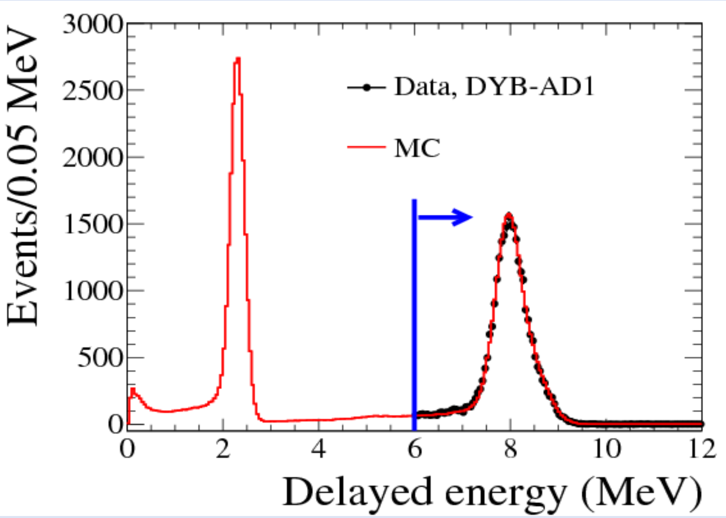
- Reject Flashers
- Prompt Positron: 0.7 MeV < E_p < 12 MeV
- Delayed Neutron: 6.0 MeV < E_d < 12 MeV
- Capture time: 1 μs < Δt < 200 μs
- Muon Veto:
  - Pool Muon: Reject 0.6ms
  - AD Muon (>20 MeV): Reject 1ms
  - AD Shower Muon (>2.5GeV): Reject 1s
- Multiplicity:
  - No other signal > 0.7 MeV
  - in -200 μs to 200 μs of IBD.

Selection driven by uncertainty in relative detector efficiency

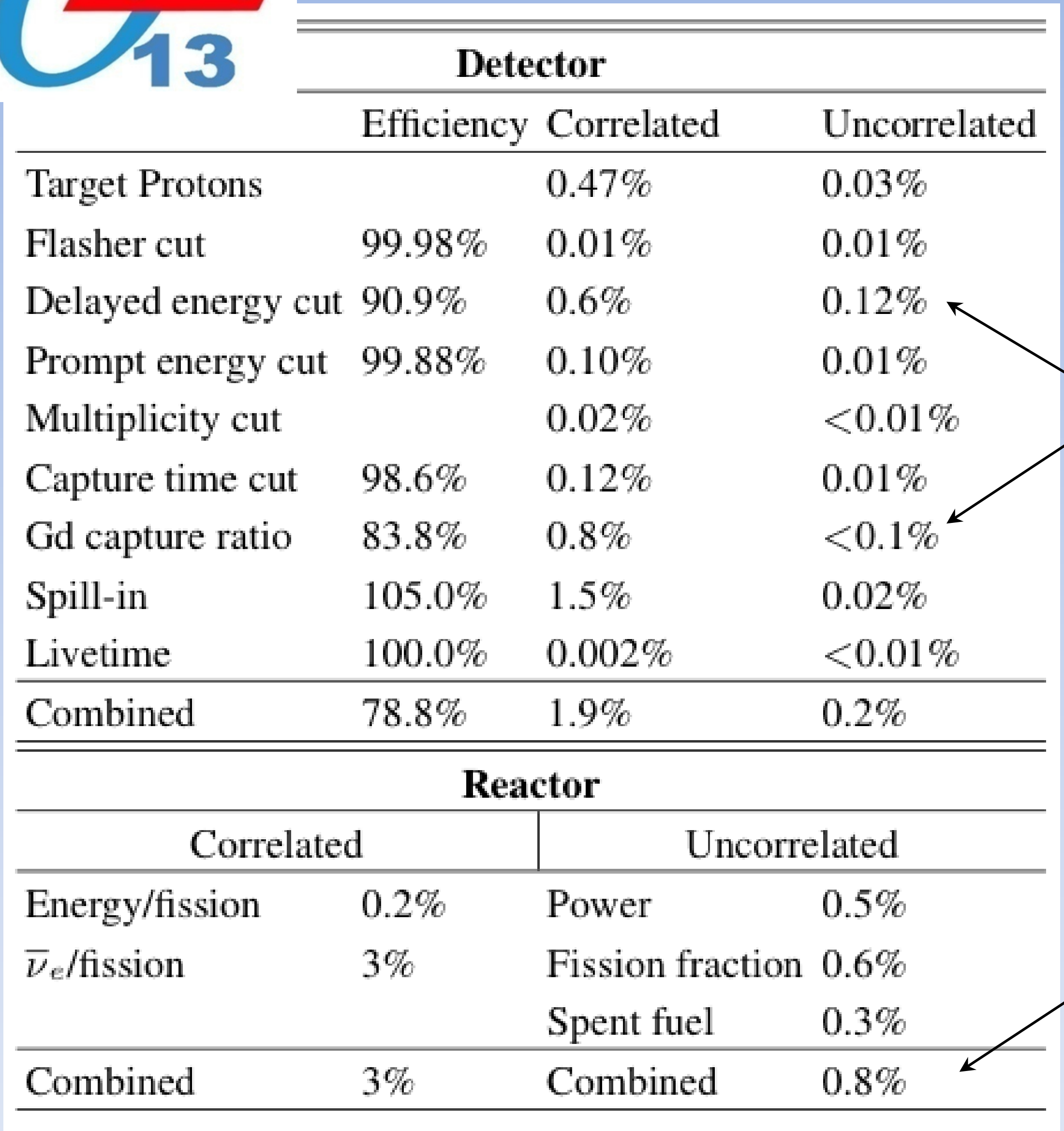
$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2 \boxed{\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)} \left[\frac{P_{\rm sur}(E, L_{\rm f})}{P_{\rm sur}(E, L_{\rm n})}\right]$$

Uncertainty in relative E_d efficiency (0.12%) between detectors is largest systematic.





Uncertainty Summary



Detector

	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

Reactor

Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

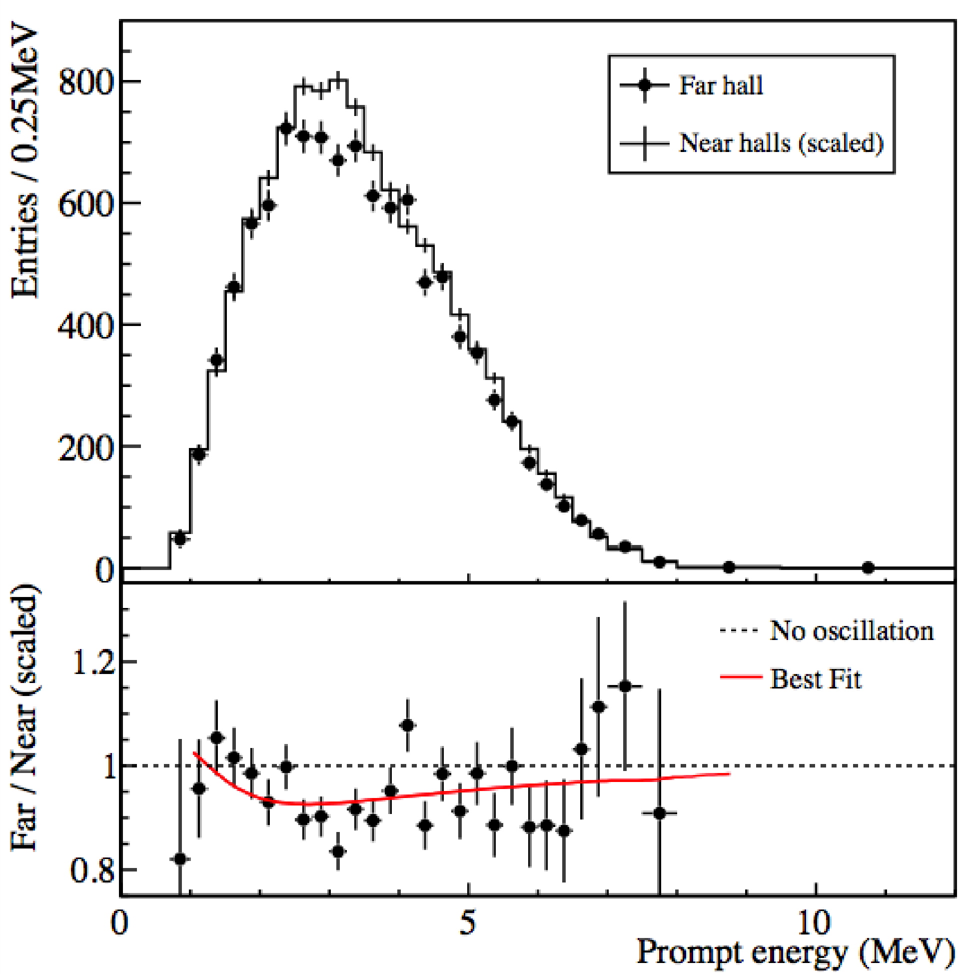
For near/far oscillation,
only uncorrelated uncertainties
are used.

Largest systematics are
smaller
than far site statistics (~1%)

Influence of uncorrelated
reactor
systematics reduced (~1/20)
by far vs. near measurement.

Far vs. Near Comparison

Compare measured rates and spectra



$$R = \frac{Far_{measured}}{Far_{expected}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6}(\alpha_i(M_1 + M_2) + \beta_i M_3)}$$

M_n are the measured rates in each detector. Weights α_i, β_i are determined from baselines and reactor fluxes.

R = 0.940 ± 0.011 (stat) ± 0.004 (syst)

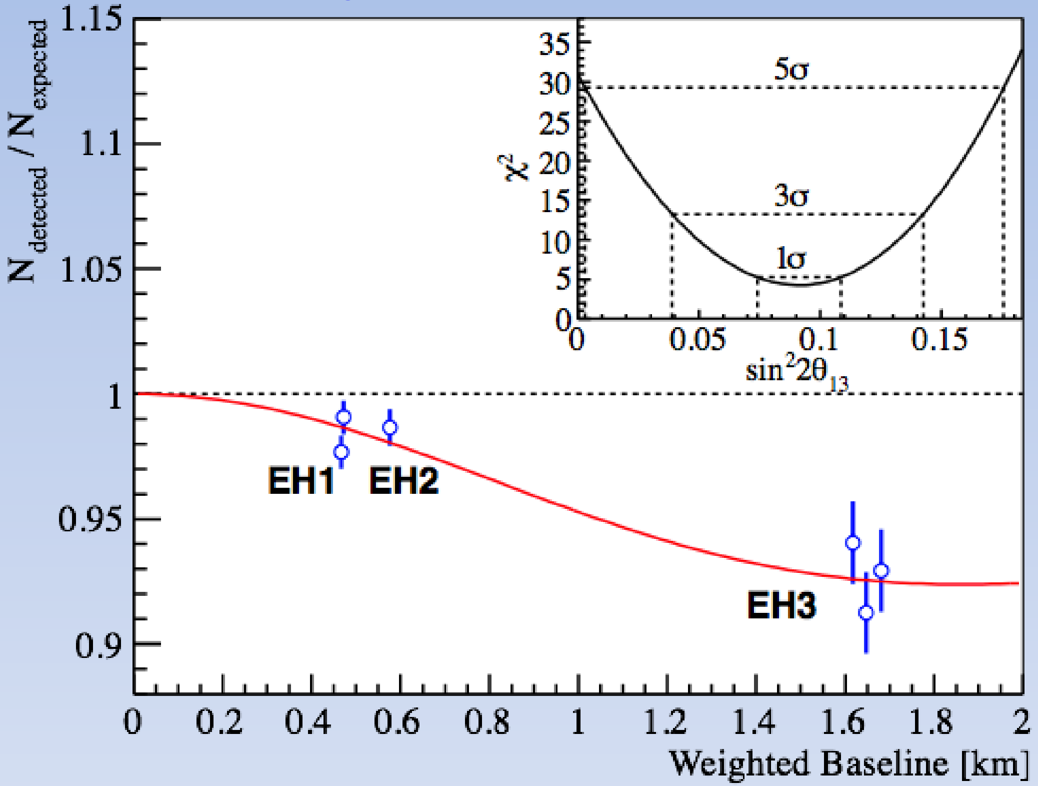
Clear observation of far site deficit.

Spectral distortion consistent with oscillation.*

* Caveat: Spectral systematics not fully studied; θ_{13} value from shape analysis is not recommended.

Rate Analysis

Estimate θ_{13} using measured rates in each detector.



Uses standard χ^2 approach.

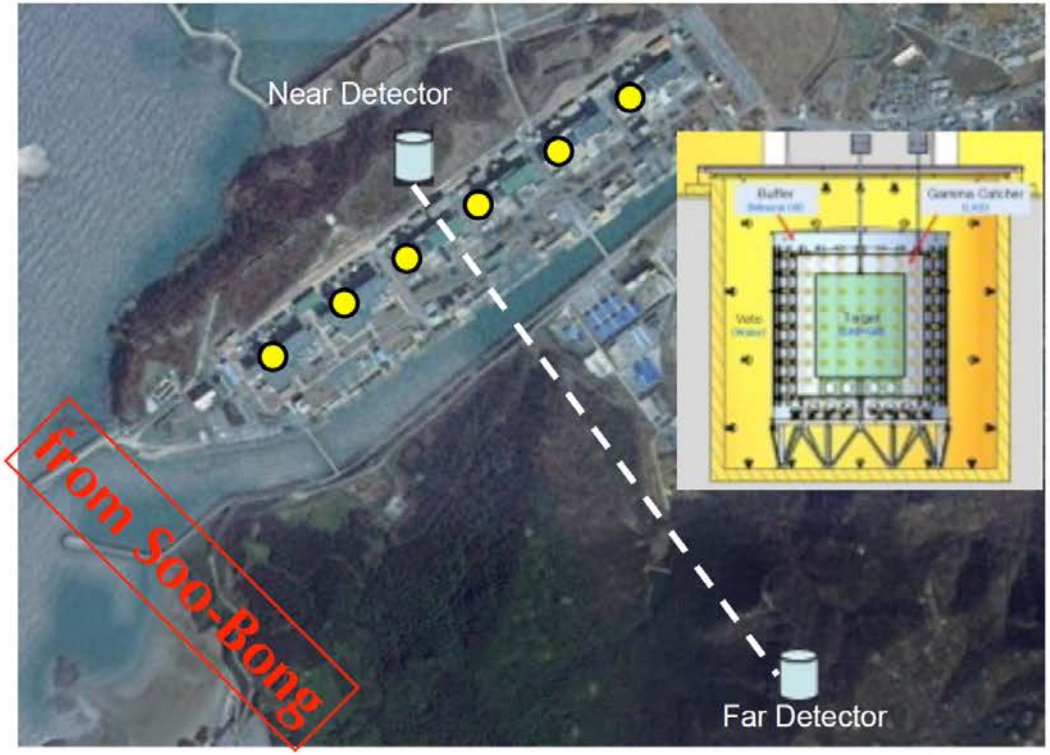
Far vs. near relative measurement.
[Absolute rate is not constrained.]

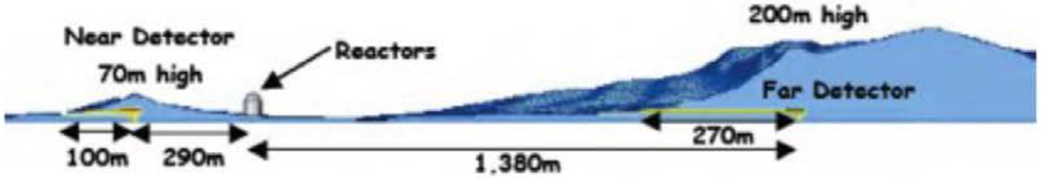
Consistent results obtained by independent analyses, different reactor flux models.

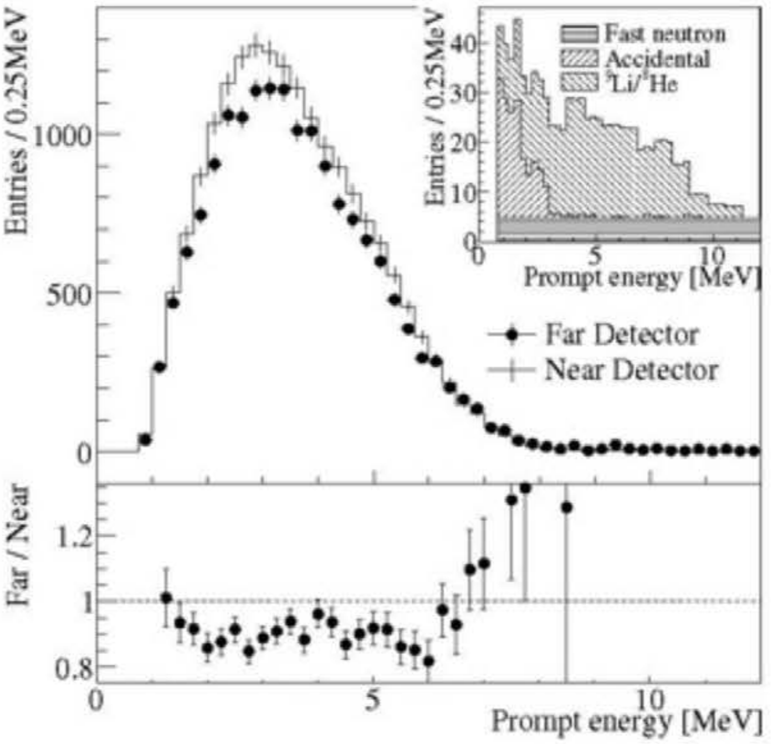
$\sin^2 2\theta_{13} = 0.092 \pm 0.016\ (\text{stat}) \pm 0.005\ (\text{syst})$

$\sin^2 2\theta_{13} = 0$ excluded at 5.2σ

RENO Measurement in South Korea





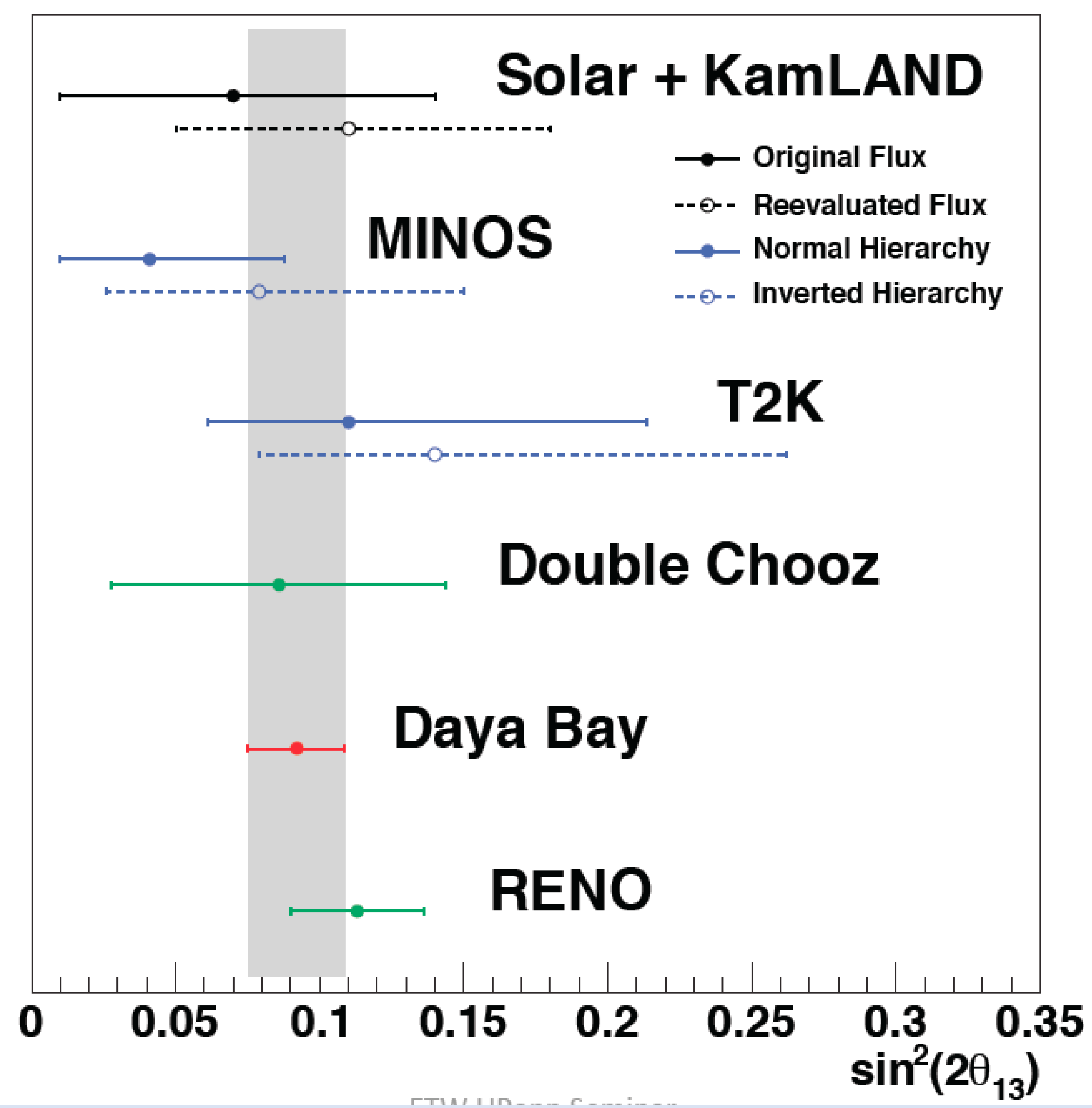


- Same strategy; Similar detector design; Similar Analysis; Consistent result

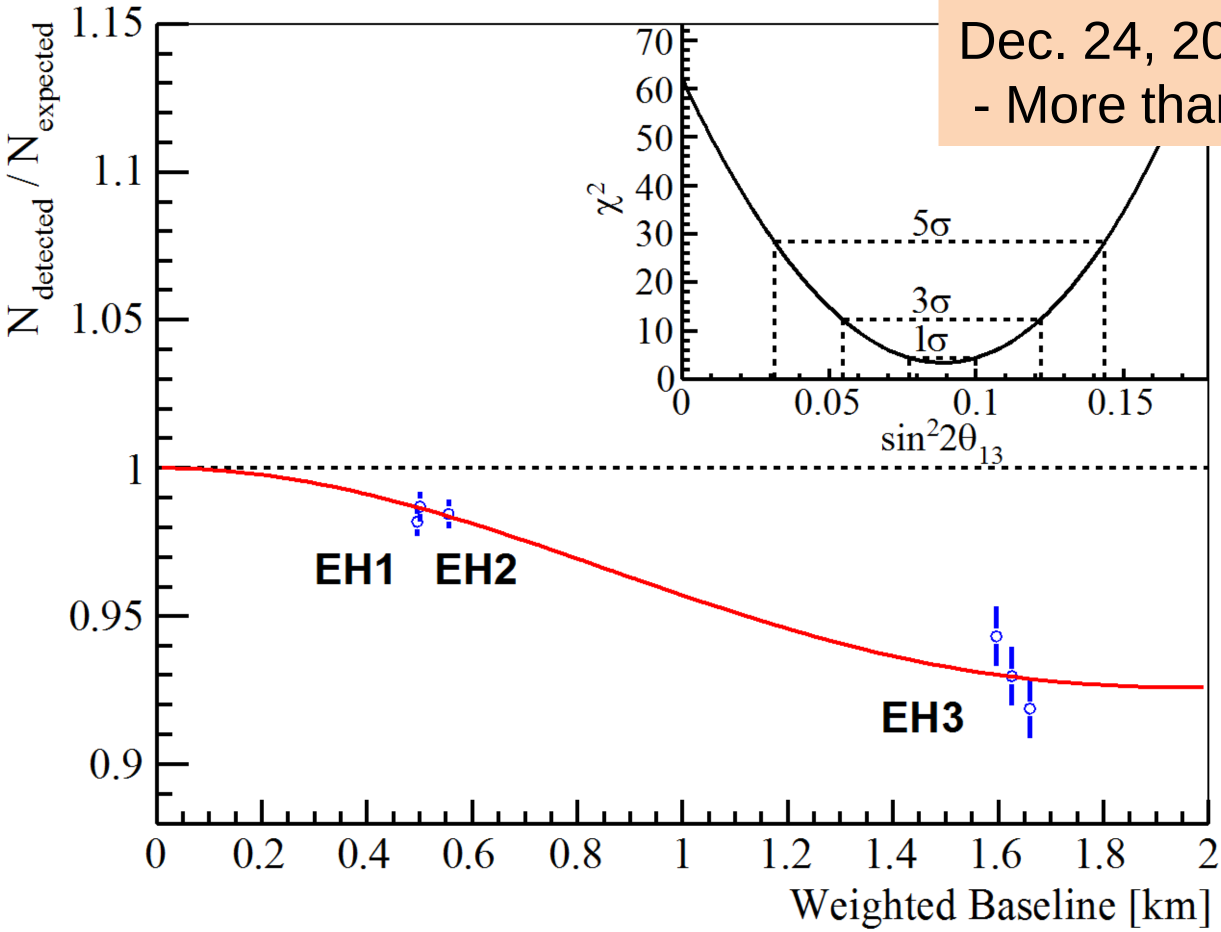
$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat.) \pm 0.019(syst.)$$

arXiv:1204.0626v2

Summary of θ_{13} Measurements



Updated Rate Analysis (June 2012)



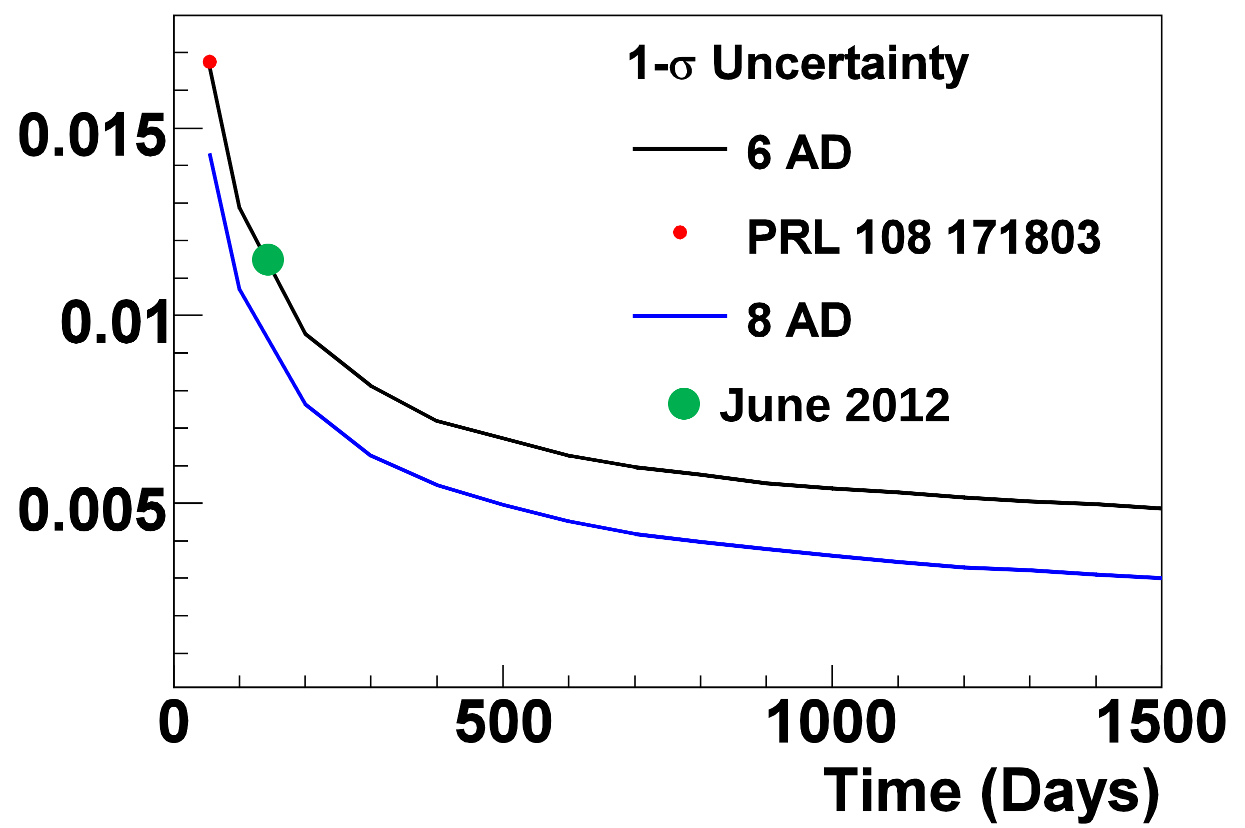
Dec. 24, 2011 – May 11, 2012

- More than 2.5x the previous data set

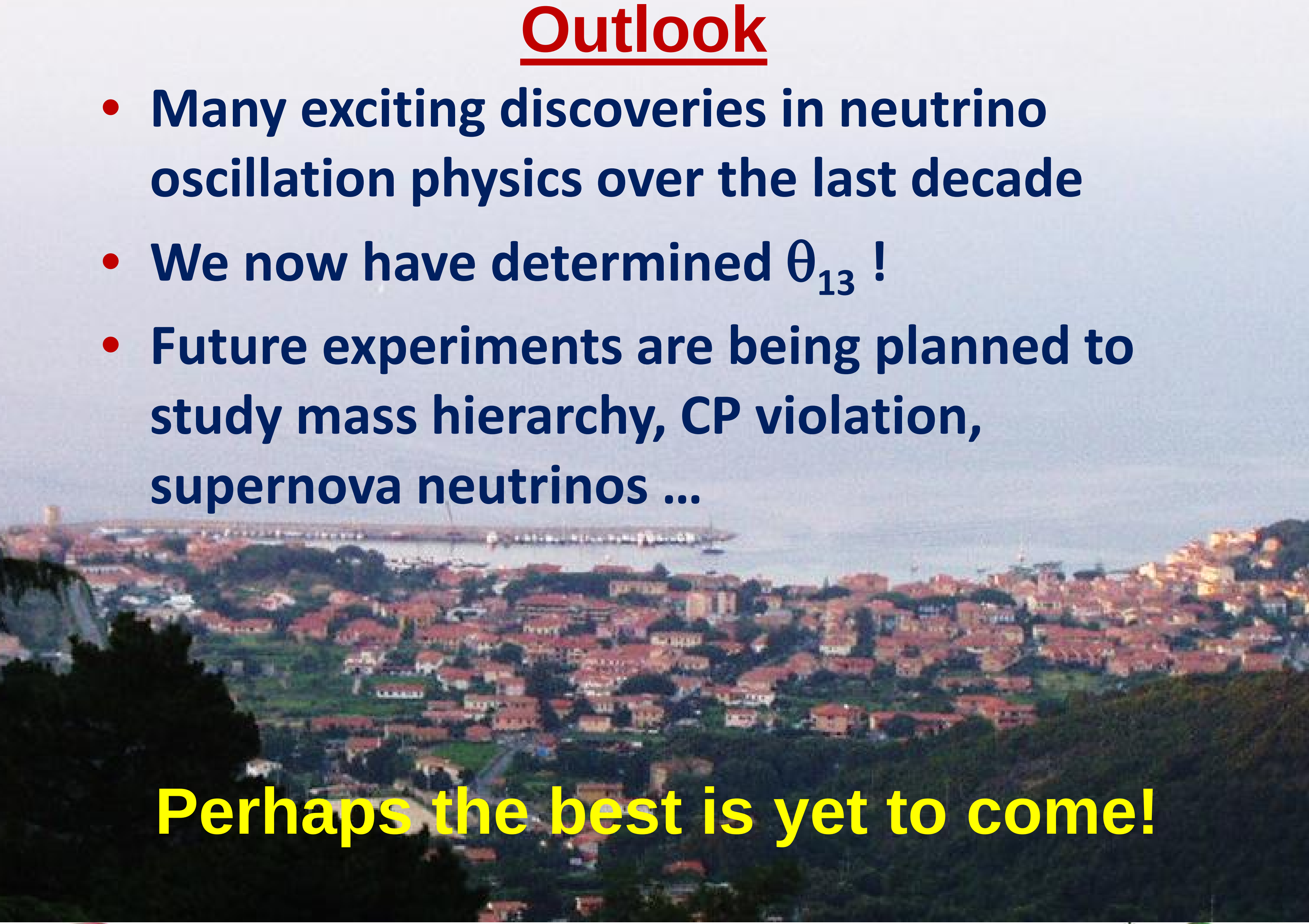
Most precise measurement of $\sin^2 2\theta_{13}$ to date.

$\sin^2 2\theta_{13} = 0.089 \pm 0.010 \text{ (stat)} \pm 0.005 \text{ (syst)}$

Future Sensitivity to $\sin^2 2\theta_{13}$



Outlook



- Many exciting discoveries in neutrino oscillation physics over the last decade
- We now have determined θ_{13} !
- Future experiments are being planned to study mass hierarchy, CP violation, supernova neutrinos …

Perhaps the best is yet to come!