Neutrinos Oscillation Experiments at Reactors

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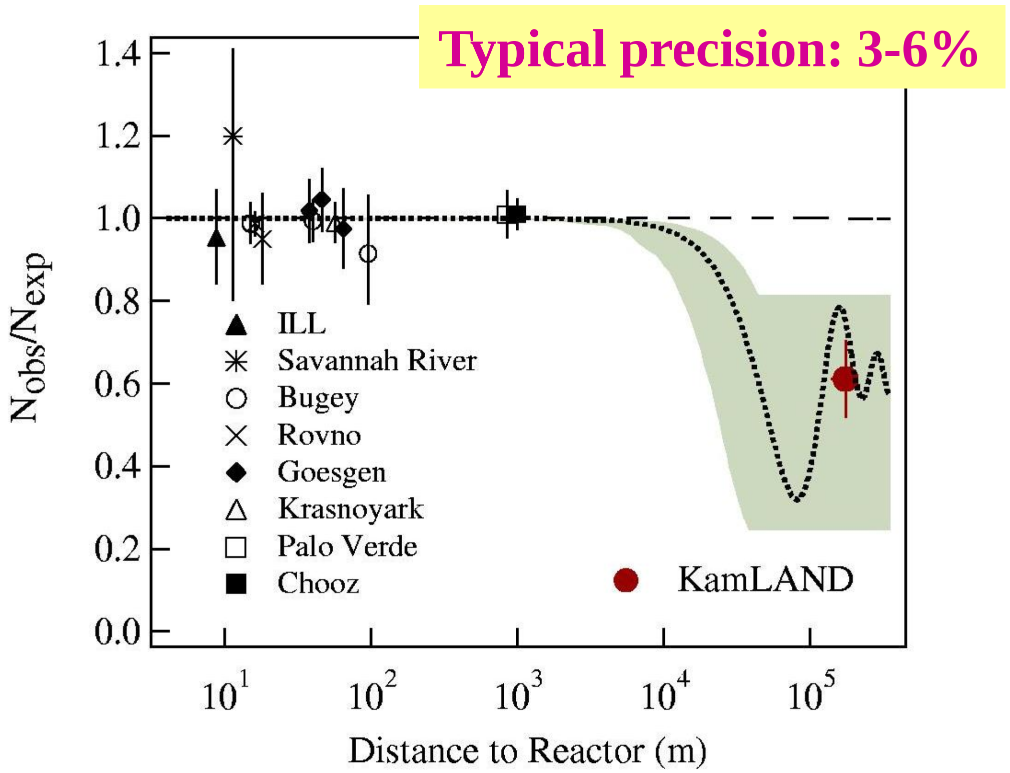
June 25, 2012

Reactor Experiment: comparing observed/expected neutrinos



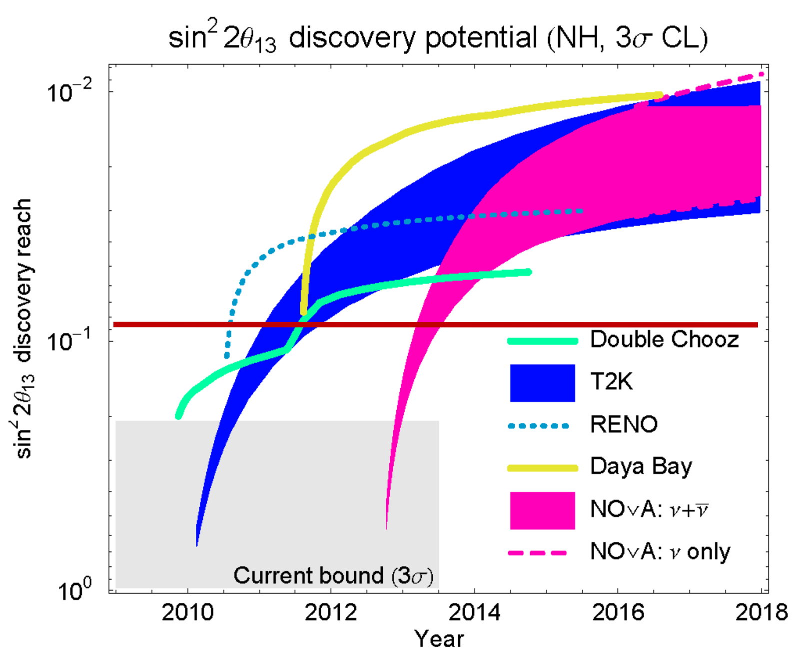
Precision of past exp.

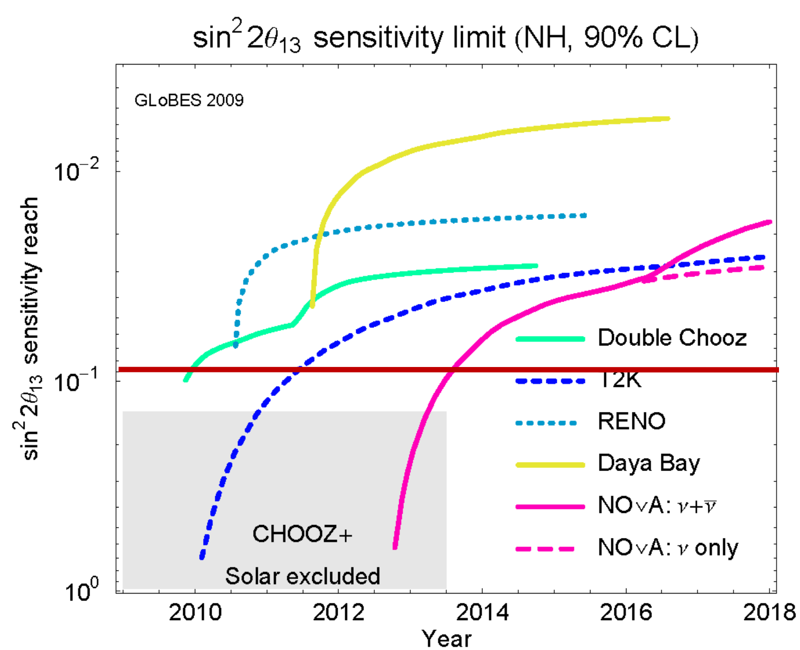
- **Reactor power: ~ 1%**
- **Spectrum: ~ 0.3%**
- **Fission rate: 2%**
- **Backgrounds: ~1-3%**
- **Target mass: ~1-2%**
- **Efficiency: ~ 2-3%**

Need high precision experiments

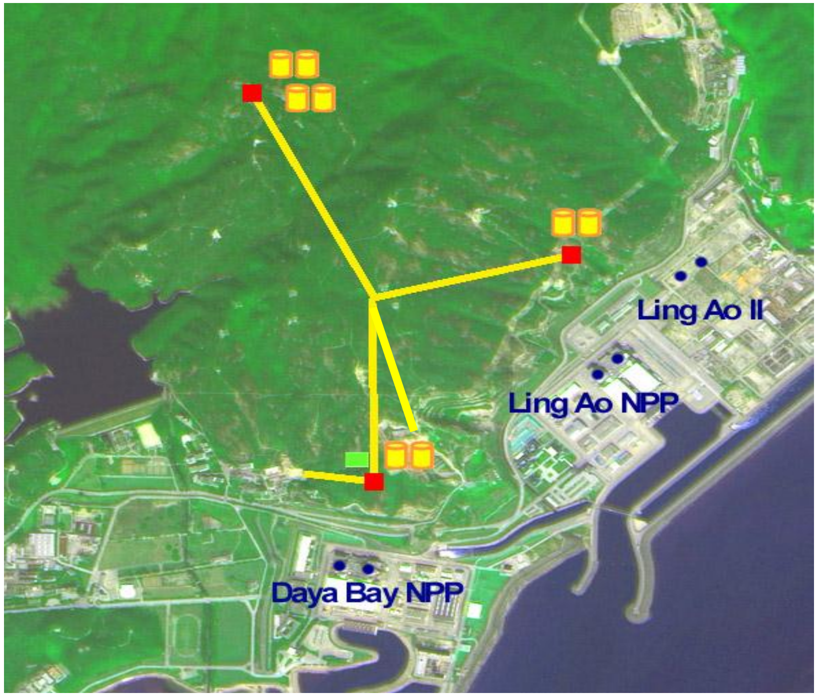
Three on-going experiments

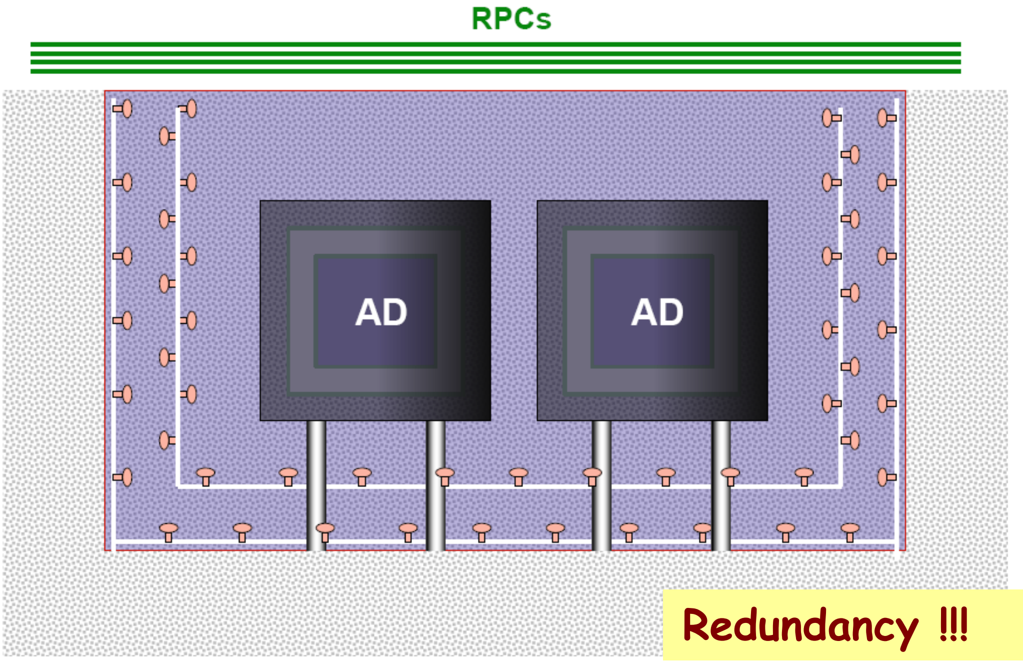
Experiment	Power (GW)	Baseline(m) Near/Far	Detector(t) Near/Far	Overburden (MWE) Near/Far	Sensitivity (90%CL)
Double Chooz	8.5	400/1050	8.2/8.2	120/300	~ 0.03
Daya Bay	17.4	470/576/1650	40//40/80	250/265/860	~ 0.008
Reno	16.5	409/1444	16/16	120/450	~ 0.02





Three experiments: Daya Bay



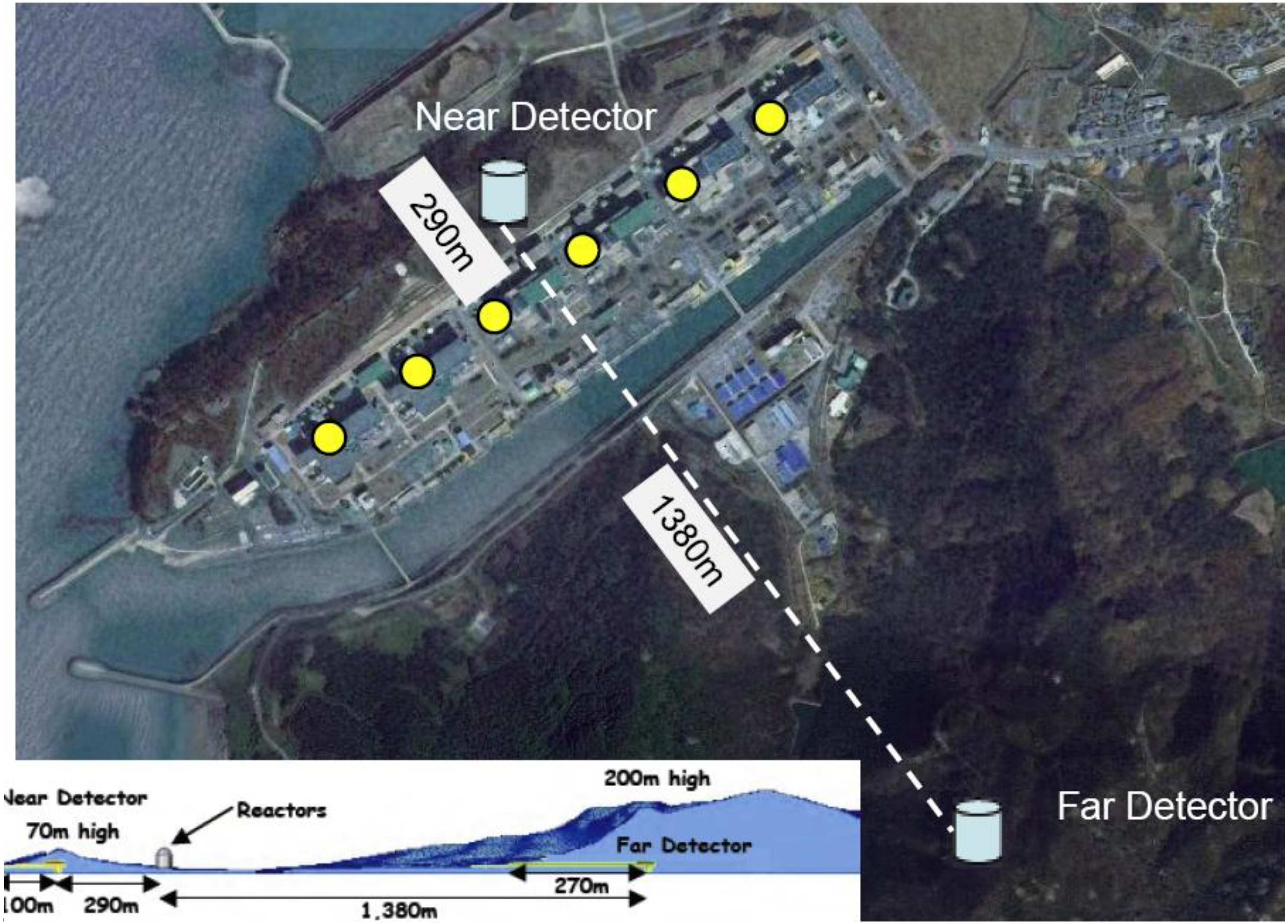


- Relative measurement to cancel Corr. Syst. Err.
  - ⇨ 2 near sites, 1 far site
- Multiple AD modules at each site to reduce Uncorr. Syst. Err.
  - ⇨ Far: 4 modules， near: 2 modules

Cross check; Reduce errors by 1/√N

- Multiple muon detectors to reduce veto eff. uncertainties
  - ⇨ Water Cherenkov： 2 layers
  - ⇨ RPC： 4 layers at the top + telescopes

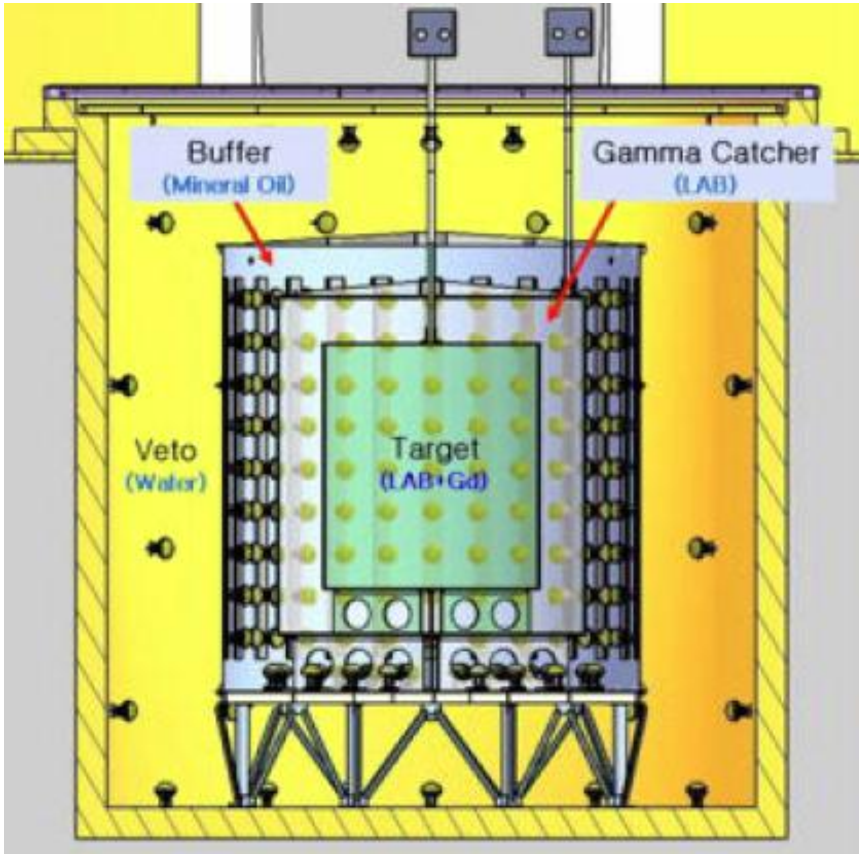
Three Experiments: RENO



Three experiments: Double Chooz

Detector

- Neutrino detector(s) in a water pool
  - ⇨ Water for shielding backgrounds
  - ⇨ Water Cherenkov for muon veto
  - ⇨ RPC/plastic scintillator at the top for muon veto
- Three zones neutrino detector:
  - ⇨ Target: Gd-loaded LS
    - ✓ ~ 10-20t for neutrino
  - ⇨ γ-catcher: normal LS
    - ✓ ~ 10-20t for energy containment
  - ⇨ Buffer shielding: oil
    - ✓ ~ 20-40t for shielding



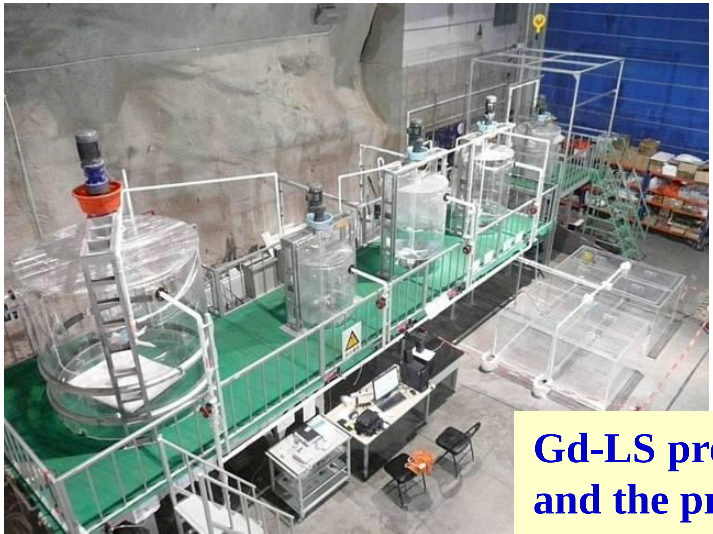
- Light collection
  - Daya Bay: 192 8"PMT for 163 PE/MeV
  - RENO: 354 10"PMT for 250 PE/MeV
  - Double Chooz: 390 10"PMT 200 PE/MeV

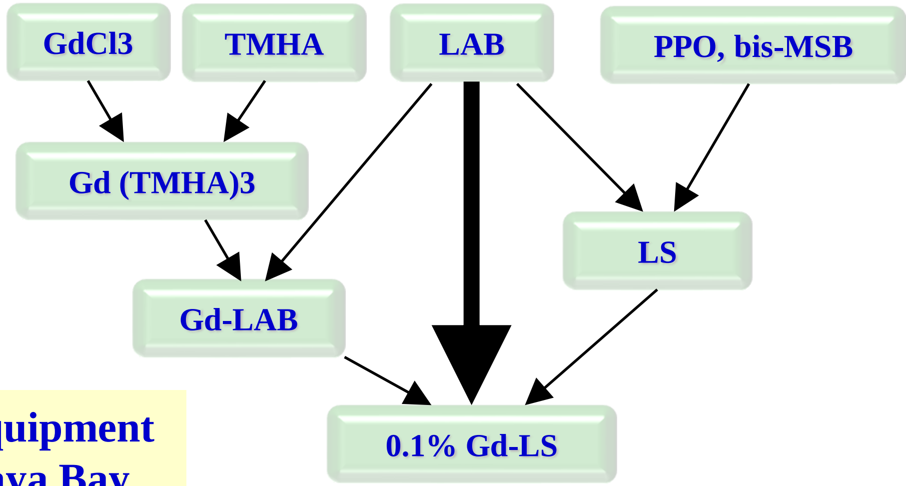
Gd-Loaded Liquid Scintillator: a challenge

- **Issue: transparency, aging, …**

Currently produced Gd-loaded liquid scintillators

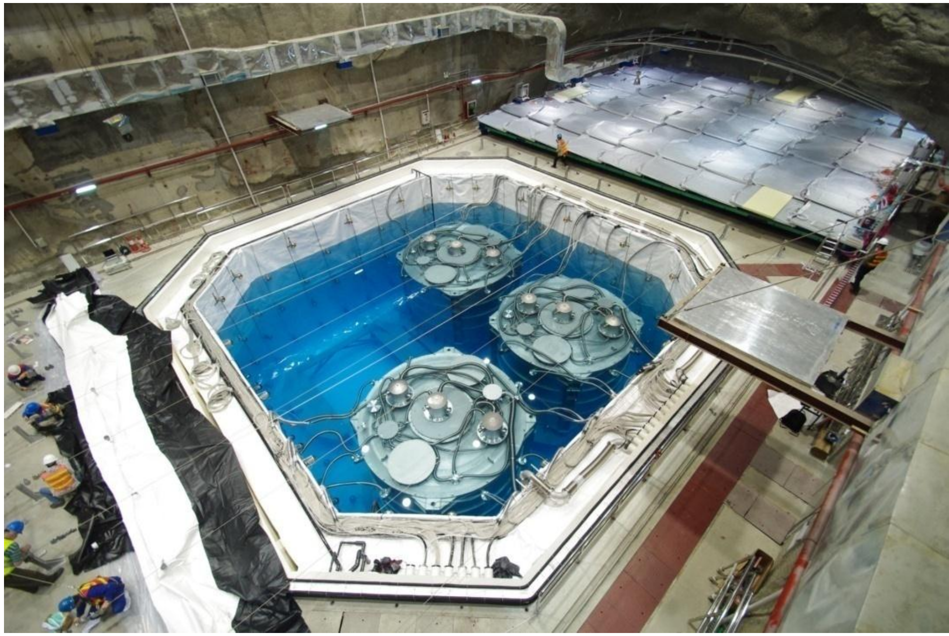
Groups	Solvent	Complexant for Gd compound	Quantity(t)
Chooz	IPB	alcohol	5
Palo Verde	PC+MO	EHA	12
Double Chooz	PXE+dodecane	Beta-Dikotonates	8
Reno	LAB	TMHA	40
Daya Bay	LAB	TMHA	185





Gd-LS production Equipment and the process by Daya Bay

Daya Bay



- Hall 1(2 ADs) started the operation on Aug. 15, 2011
- Hall 2(1 AD) physics data taking on Nov.5, 2011
- Hall 3(3 ADs) started physics data taking on Dec.24, 2011
- First physics results based on 55 days of data taking on March 8, 2012

$Sin^2 2\theta_{13} = 0.092 \pm 0.016(stat) \pm 0.005(syst)$, 5.2 σ for non-zero θ_{13}

- Updated results reported on June 4, 2012 at Neutrino 2012

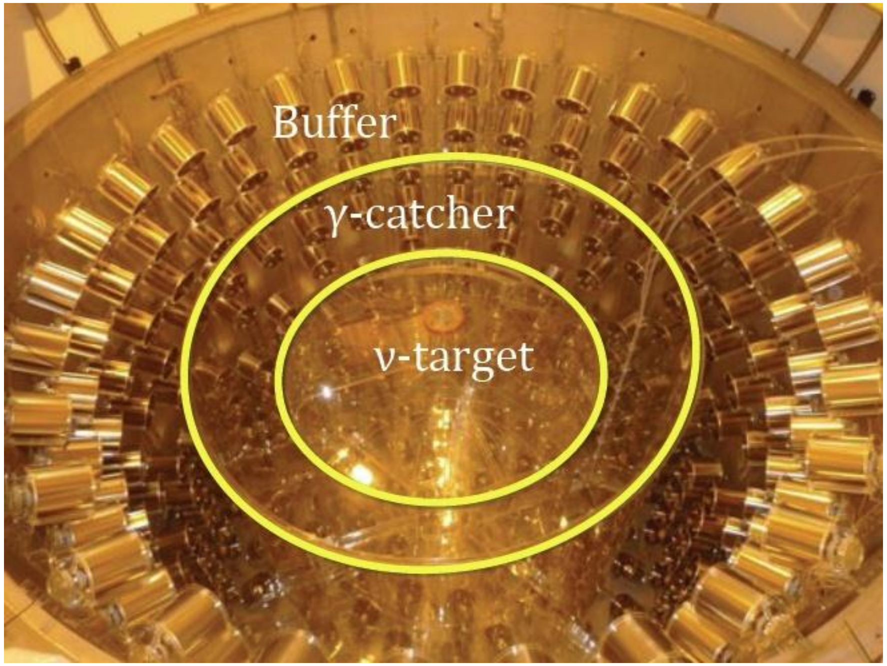
$Sin^2 2\theta_{13} = 0.089 \pm 0.011(stat) \pm 0.005(syst)$, 7.7 σ for non-zero θ_{13}

Reno

- Data taking started on Aug. 11, 2011
- First physics results based on 228 days data taking(up to Mar. 25, 2012) released on April 3, 2012, revised on April 8, 2012, published on May 11, 2012:

$\sin^2 2\theta_{13}=0.113\pm0.013(\mathrm{Stat})\pm0.019(\mathrm{Syst})$, 4. 9σ for non-zero θ_{13}

Double Chooz



- **Far detector starts data taking at the beginning of 2011**
- **First results based on 85.6 days of data taking reported in Nov. 2012**

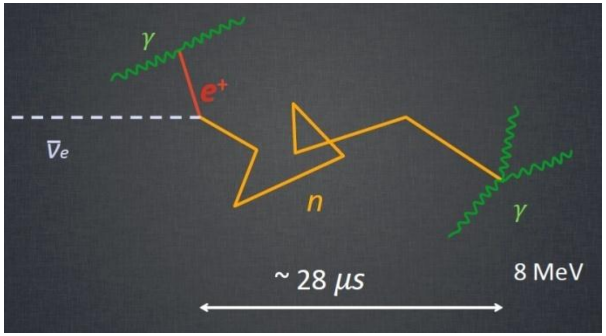
$\sin^2 2\theta_{13}=0.086\pm0.041(\text{Stat})\pm0.030(\text{Syst})$, 1.7σ for non-zero θ_{13}

- **Updated results based on 228 days of data taking reported on June 4, 2012 at Neutrino 2012**

$\sin^2 2\theta_{13}=0.109\pm0.030(\text{Stat})\pm0.025(\text{Syst})$, 3.1σ for non-zero θ_{13}

Event Signature and Backgrounds

- **Signature:** $\bar{\nu}_e + p \rightarrow e^+ + n$
  - ⇨ **Prompt: e^+, 1-10 MeV,**
  - ⇨ **Delayed: n, 2.2 MeV@H, 8 MeV @ Gd**
  - ⇨ **Capture time: 28 μs in 0.1% Gd-LS**



- **Backgrounds**
  - ⇨ **Uncorrelated: random coincidence of γγ, γn or nn**
    - ✓ **γ from U/Th/K/Rn/Co… in LS, SS, PMT, Rock, …**
    - ✓ **n from α-n, μ-capture, μ-spallation in LS, water & rock**
  - ⇨ **Correlated:**
    - ✓ **Fast neutrons: prompt—n scattering, delayed—n capture**
    - ✓ **^{8}He/^{9}Li: prompt—β decay, delayed—n capture**
    - ✓ **Am-C source: prompt—γ rays, delayed—n capture**
    - ✓ **α-n: ^{13}C(α,n)^{16}O**

Backgrounds & uncertainties

	Daya Bay		Reno		Double Chooz
	Near	Far	Near	Far	Far
Accidentals (B/S)	1.4%	4.0%	0.56%	0.93%	0.6%
Uncertainty(ΔB/B)	1.0%	1.4%	1.4%	4.4%	0.8%
Fast neutrons(B/S)	0.1%	0.06%	0.64%	1.3%	1.6%
Uncertainty(ΔB/B)	31%	40%	2.6%	6.2%	30%
^{8}He/^{9}Li (B/S)	0.4%	0.3%	1.6%	3.6%	2.8%
Uncertainty (ΔB/B)	52%	55%	48%	29%	50%
α-n(B/S)	0.01%	0.05%	-	-	-
Uncertainty(ΔB/B)	50%	50%	-	-	-
Am-C(B/S)	0.03%	0.3%	-	-	-
Uncertainty (ΔB/B)	100%	100%	-	-	-
Total backgrounds(B/S)	1.9%	4.7%	2.8%	5.8%	5.0%
Total Uncertainties (Δ(B/S))	0.2%	0.35%	0.8%	1.1%	1.5%

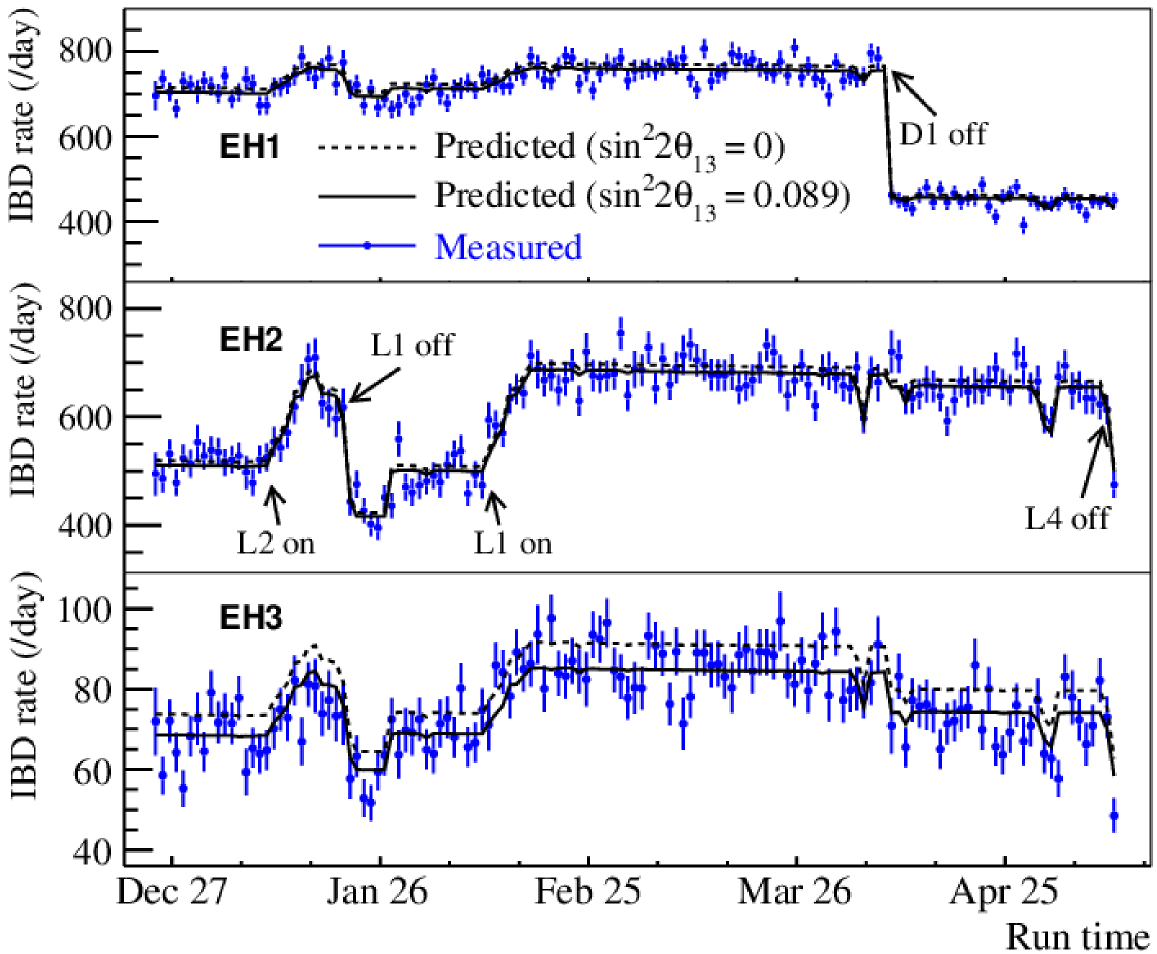
Efficiencies and Systematics

	Daya Bay		Reno		Double Chooz
	Corr.	Uncorr.	Corr.	Uncorr.	Corr/Uncorr.
Target proton	0.47%	0.03%	0.5%	0.1%	0.3%
Flasher cut	0.01%	0.01%	0.1%	0.01%	-
Delayed energy cut	0.6%	0.12%	0.5%	0.1%	0.7%
Prompt energy cut	0.1%	0.01%	0.1%	0.01%	-
Energy response	-	-	-	-	0.3%
Trigger efficiency					<0.1%
Multiplicity cut	0.02%	<0.01%	0.06%	0.04%	-
Capture time cut	0.12%	0.01%	0.5%	0.01%	0.5%
Gd capture ratio	0.8%	<0.1%	0.7%	0.1%	0.3%
Spill-in	1.5%	0.02%	1.0%	0.03%	0.3%
livetime	0.002%	<0.01%			-
Muon veto cut	-	-	0.06%	0.04%	-
Total	1.9%	0.2%	1.5%	0.2%	1.0%

Reactor flux estimate

	Daya Bay		Reno		Double Chooz
	Corr.	Uncorr.	Corr.	Uncorr.	Corr./Uncorr.
Thermal power		0.5%		0.5%	0.5%
Fission fraction/Fuel composition		0.6%		0.7%	0.9%
Fission cross section /Bugey 4 measurement	3%		1.9%		1.4%
Reference spectra			0.5%		0.5%
IBD cross section			0.2%		0.2%
Energy per fission	0.2%		0.2%		0.2%
Baseline	0.02%		-		0.2%
Spent fuel		0.3%			
Total	3%	0.8%	2.0%	0.9%	1.8%

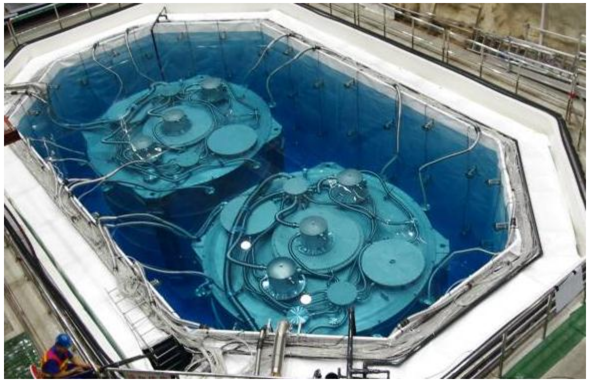
Daily Rate: Evidence of Deficit



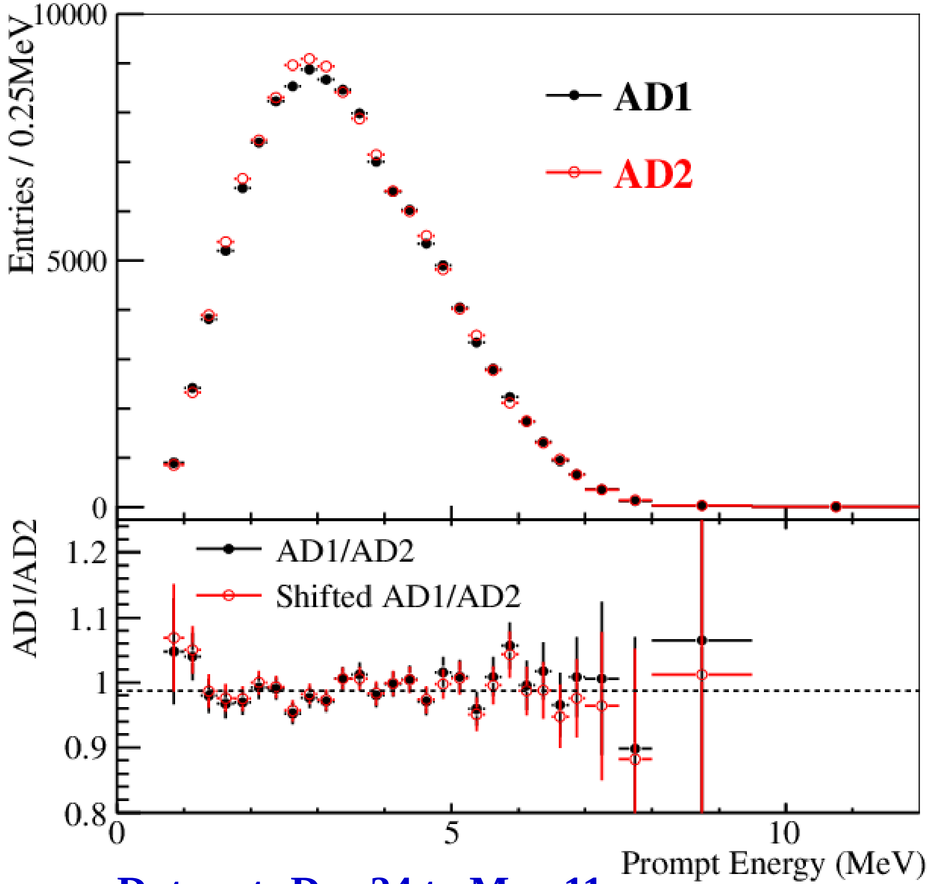
Predictions are absolute, multiplied by one normalization factor from the fitting

Systematic Errors at Daya Bay: Side-by-Side Comparison

- **Expected ratio of neutrino events: R(AD1/AD2) = 0.982**
  - ⇨ The ratio is not 1 because of target mass, baseline, etc.
- **Measured ratio: 0.987 ± 0.004(stat) ± 0.003(syst)**



This check will determine finally the systematic error

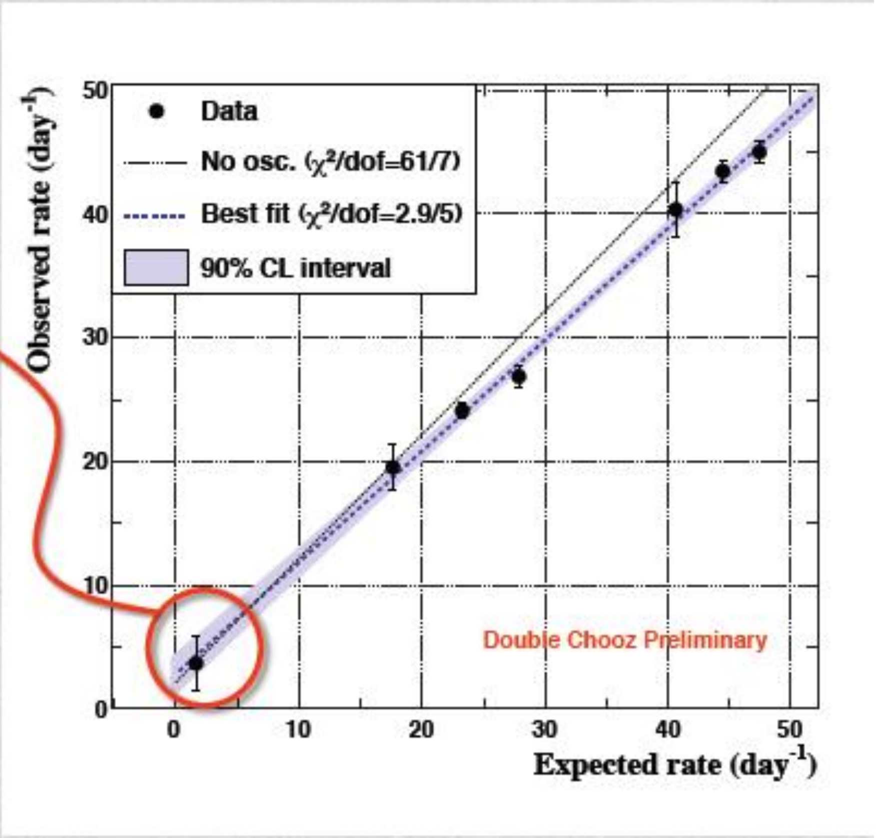


Data set: Dec 24 to May 11

Backgrounds at Double Chooz: Reactor-off

2 events observed in 0.84 days live-time with **both reactors off** (= 2.2 event/day)

→ Background rate consistent with estimation (2.2 ±0.6 event/day)



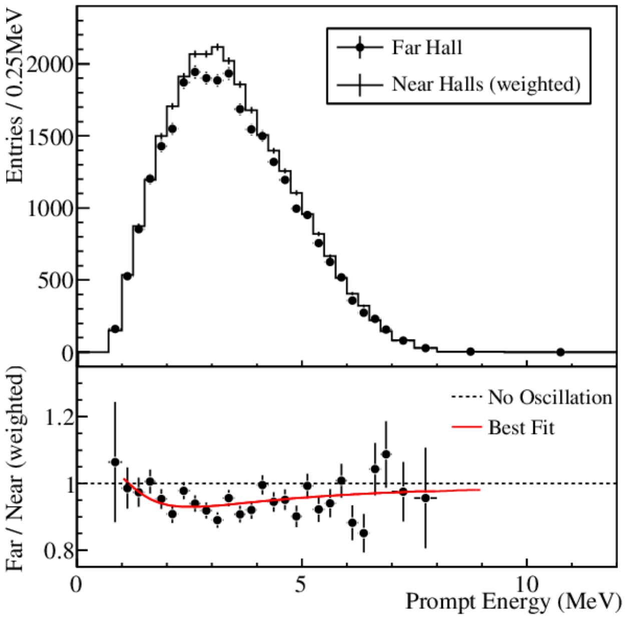
Best fit to expected rate:

$\sin^2 2\theta_{13}$ = 0.19 ± 0.06

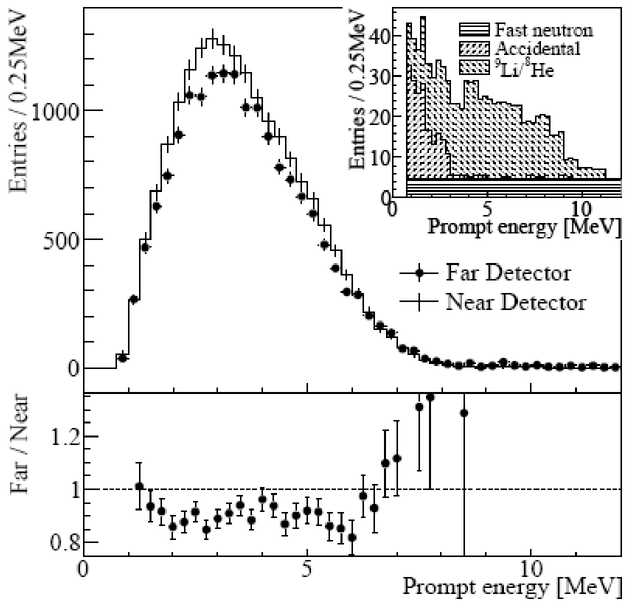
BG rate = 2.9 ± 1.1 event/day

Electron Anti-neutrino Disappearence: Latest results

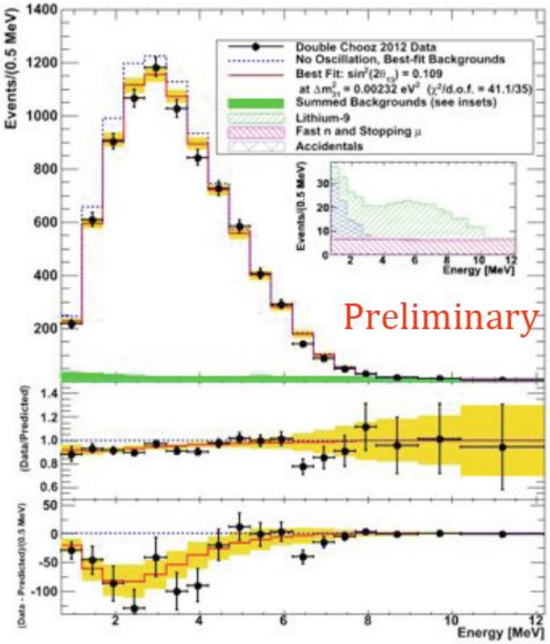
Daya Bay



Reno



Double Chooz



R=0.944±0.007 ±0.003

R= 0.920±0.009±0.014

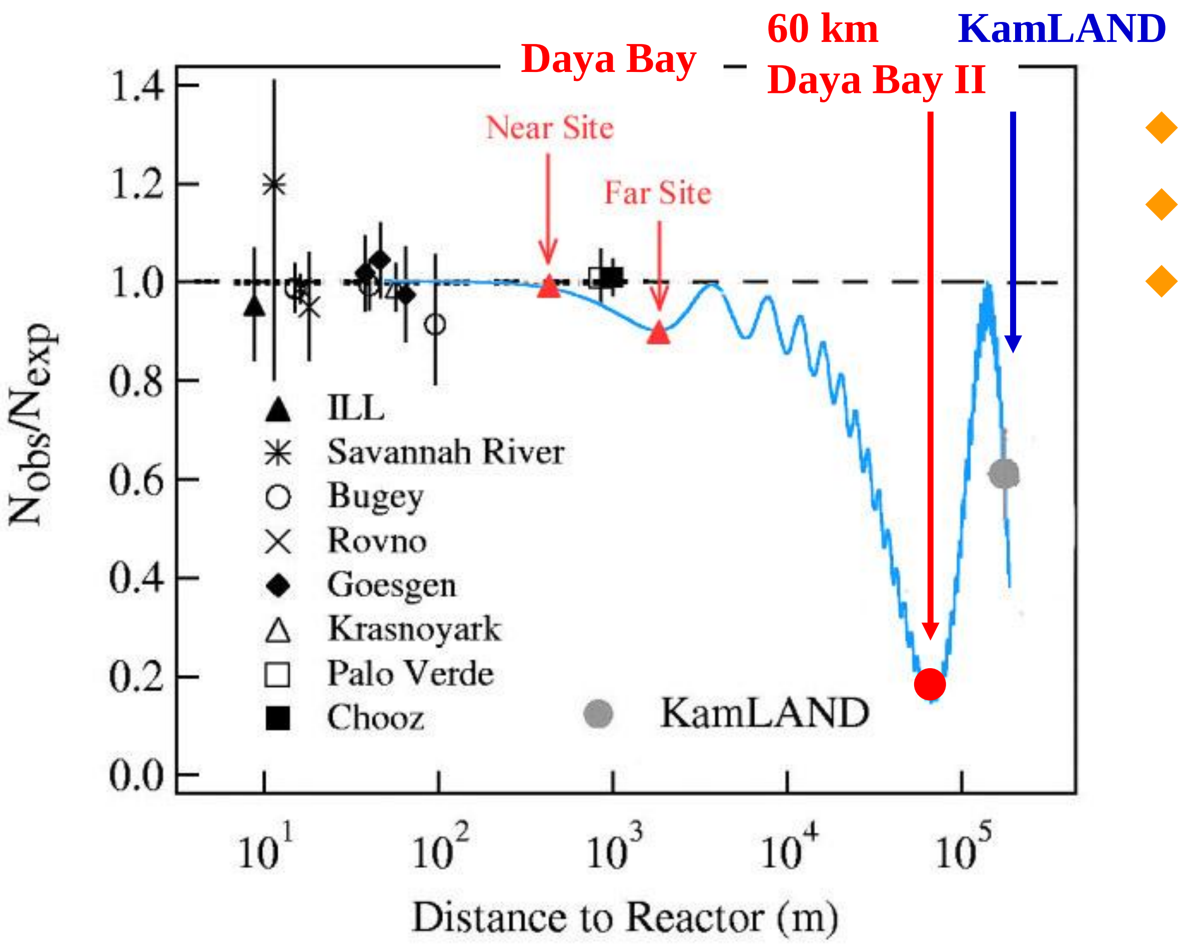
$\sin^2 2\theta_{13}$=0.170±0.035±0.040

Daya Bay	Reno	Double Chooz
$\sin^2 2\theta_{13}$=0.089±0.010±0.005	$\sin^2 2\theta_{13}$=0.113±0.013±0.019	$\sin^2 2\theta_{13}$=0.109±0.030±0.025
7.7 σ for non-zero θ_{13}	4. 9σ for non-zero θ_{13}	3.1 σ for non-zero θ_{13}

Future

- **Daya Bay**
  - **Installation of AD7 and AD8 this summer**
  - **Full data taking this fall**
  - **Final precision of $\sin^2 2\theta_{13}$: ~5%**
- **RENO**
  - **Continue data taking**
  - **Final precision of $\sin^2 2\theta_{13}$: ~10%**
- **Double Chooz**
  - **Near site detector installation underway**
  - **Full data taking(by the end of) next year**
  - **Final precision of $\sin^2 2\theta_{13}$: ~15%**

Next Step: Daya Bay-II Experiment

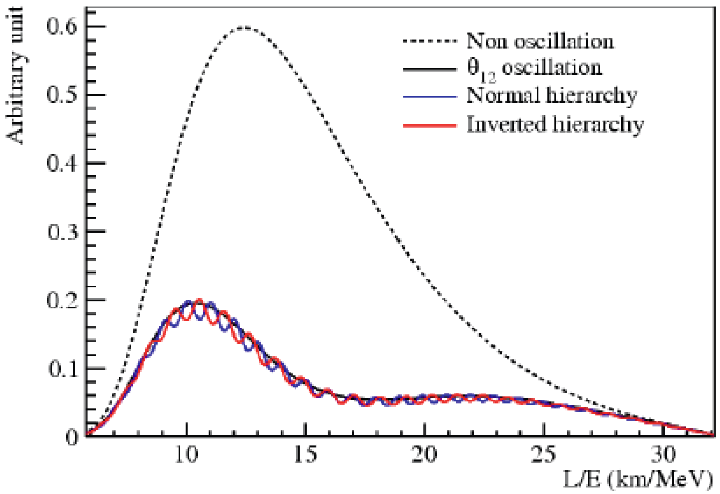


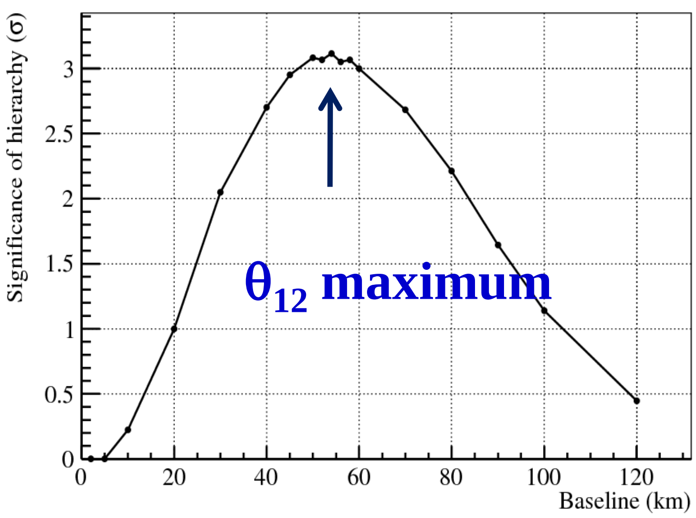
- **20 kton LS detector**
- **3% energy resolution**
- Rich physics possibilities
  - **Mass hierarchy**
  - **Precision measurement of 4 mixing parameters**
  - **Supernovae neutrino**
  - **Geoneutrino**
  - **Sterile neutrino**
  - **Atmospheric neutrinos**
  - **Exotic searches**

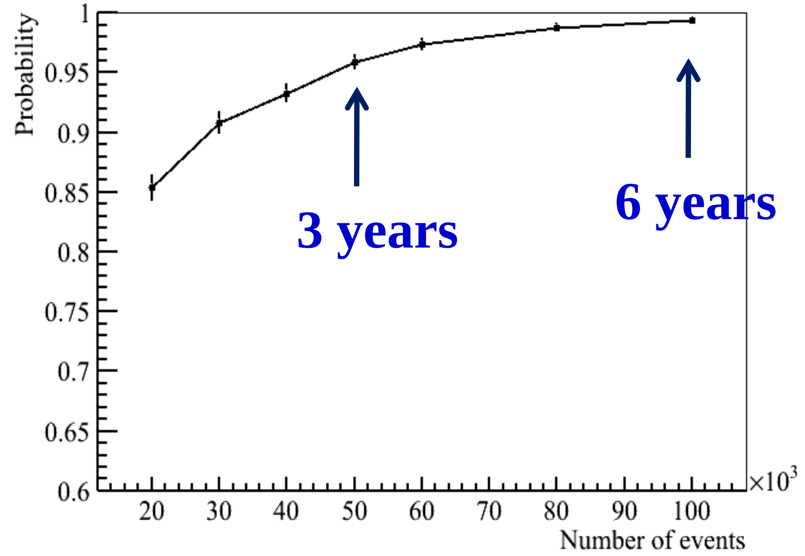
Talk by YFW at ICFA seminar 2008, Neutel 2011; by J. Cao at NuTurn 2012 ;
Paper by L. Zhan, YFW, J. Cao, L.J. Wen, PRD78:111103,2008; PRD79:073007,2009

Mass Hierarchy: 20kt, 3% detector @36 GW

- Distortion of energy spectrum due to mass hierarchy
- Enhance signature in frequency regime ➔ using Fourier transformation formalism



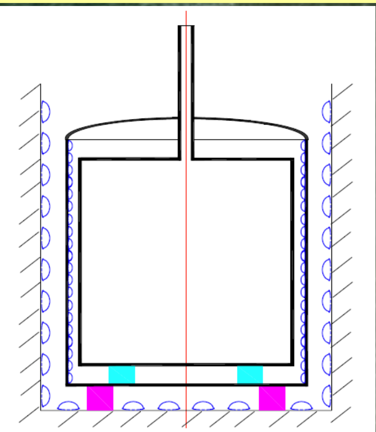


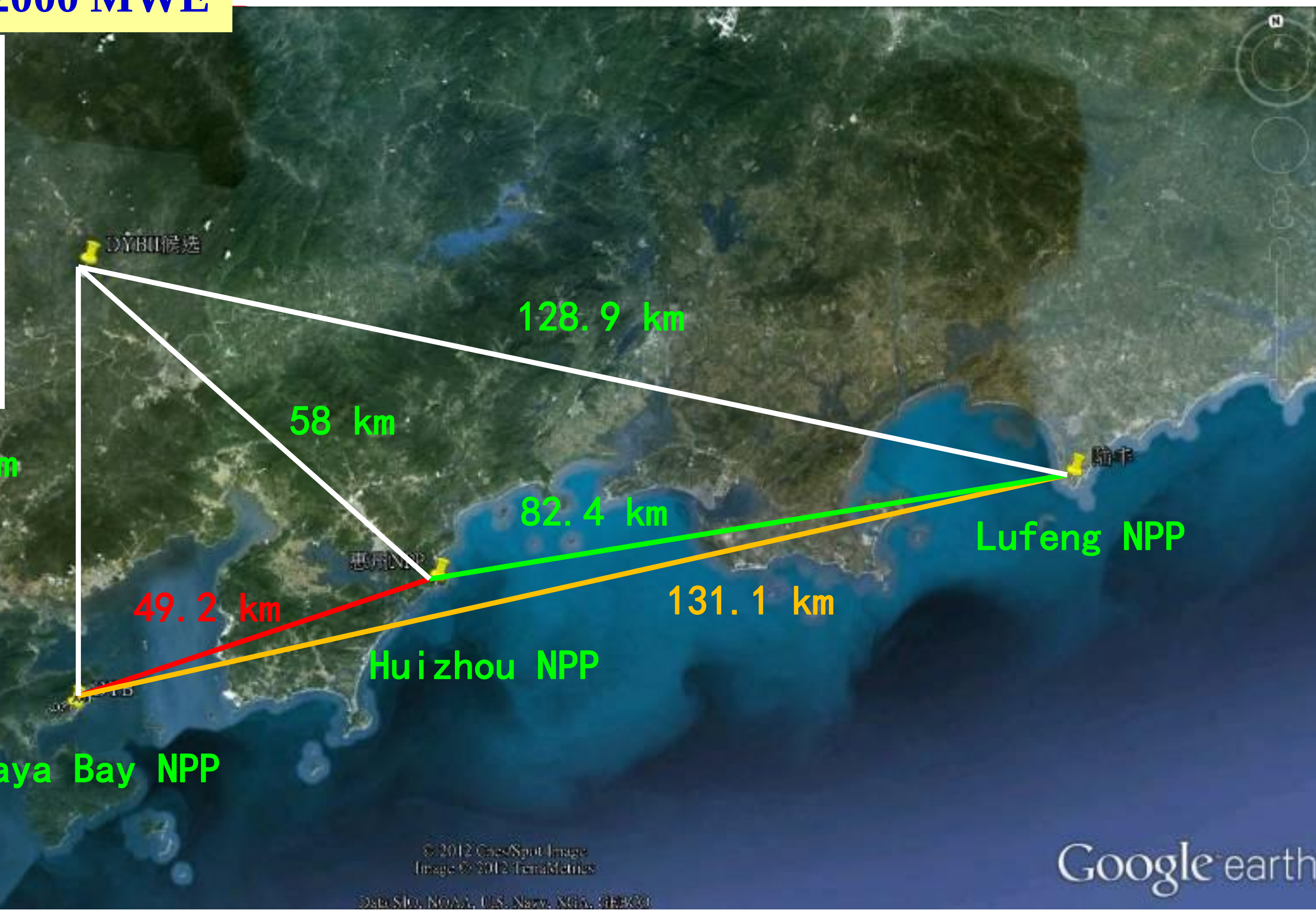


An Ideal Location

Thermal power > 36 GW

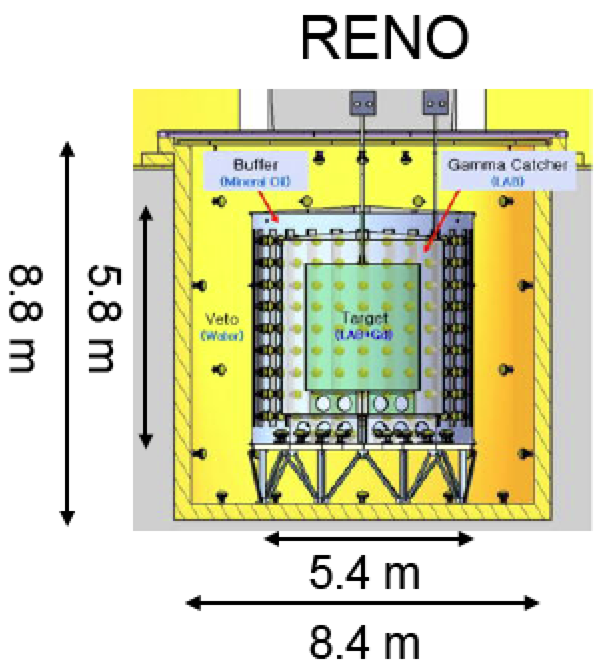
Overburden ~ 2000 MWE

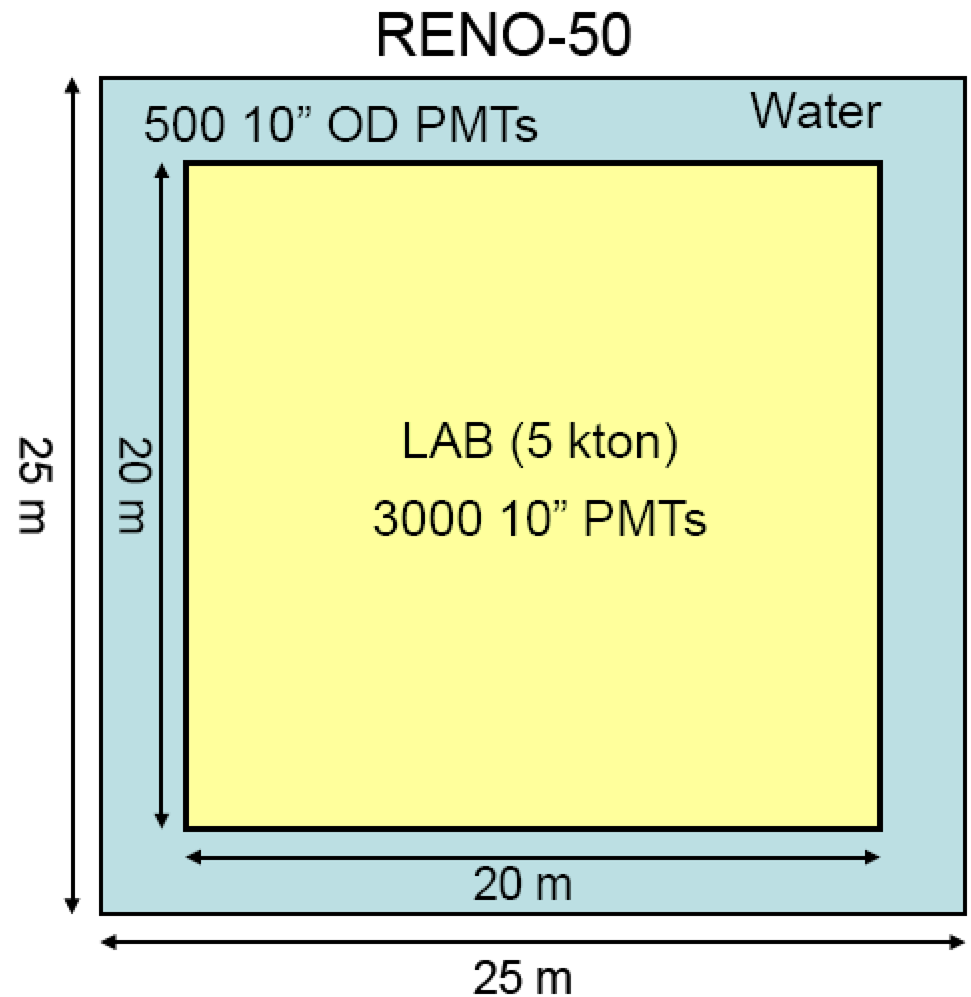




RENO-50

- 5000 tons ultra-low-radioactivity Liquid Scintillation Detector





S.B. Kim, talk at Neutrino 2012

Physics with RENO-50

- Precise measurement of θ_{12}

  $$\frac{\delta \sin^2\theta_{12}}{\sin^2\theta_{12}} \sim 1.0\%(1\sigma)$$ in a year ← current accuracy : 5.4%

- Determination of mass hierarchy Δm^2_{13}

- Neutrino burst from a Supernova in our Galaxy :

  ~1500 events (@8 kpc)

- Geo-neutrinos : ~ 300 geo-neutrinos for 5 years

- Solar neutrinos : with ultra low radioacitivity

- Reactor physics : non-proliferation

- Detection of T2K beam : ~120 events/year

- Test of non-standard physics : sterile/mass varying neutrinos

Summary

- **Daya Bay experiment discovered the new oscillation and provided the most precise measurement of θ_{13}**
- **Precision on $Sin^2 2\theta_{13}$ will be improved in the next few years, up to ~ 5%**
- **As the most powerful man-made neutrino source, reactor neutrinos will continue to play an important role:**
  - **Mass hierarchy**
  - **Precision measurement of mixing parameters up to < 1% level ➔ unitarity test of the mixing matrix**
  - **Sterile neutrinos**
  - **Neutrino magnetic moments**

Reference

- **Daya Bay**
  - F.P. An et al., Daya Bay Coll., " A side-by-side comparison of Daya Bay anti-neutrino detectors", arXiv: 1202.6181[physics.ins-det], Nucl. Inst. and Meth. A 685 (2012), pp. 78-97
  - F.P. An et al., Daya Bay Coll., "Observation of electron anti-neutrino disappearance at Daya Bay", arXiv: 1203.1669[hep-ex], Phys. Rev. Lett. 108, 171803 (2012)
  - D. Dwyer, Talk at Neutrino 2012, Kyoto, June 4, 2012
- **Double Chooz**
  - Y. Abe et al., Double Chooz Collaboration , "Indication for the disappearance of reactor electron antineutrinos in the Double Chooz experiment.", Phys.Rev.Lett. 108 (2012) 131801
  - M. Ishitsuka, Talk at Neutrino 2012, Kyoto, June 4, 2012
- **RENO**
  - J.K. Ahn et al., Reno Collaboration, "Observation of Reactor Electron Anti-Neutrino Disappearance in the RENO Experiment",
    Phys.Rev.Lett. 108 (2012) 191802