Neutrinos Experiments at Reactors

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A Long, Successful History

- Direct observation(50's): Reines
- Oscillation:
  - Early searches(70's-90's):
    - Reines, ILL, Bugey, … Palo Verde, Chooz
  - Determination of θ_{12}(90's-00's):
    - KamLAND
  - Discovery of θ_{13} (00's-10's): :
    - Daya Bay, Double Chooz，RENO
- Neutrino magnetic moments (90's-00's):
  - Texono, MUNU
- Mass hierarchy(10's-20's):
  - JUNO, RENO-50
- Sterile neutrinos(10's):
  - Nucifer, Stereo, Solid …

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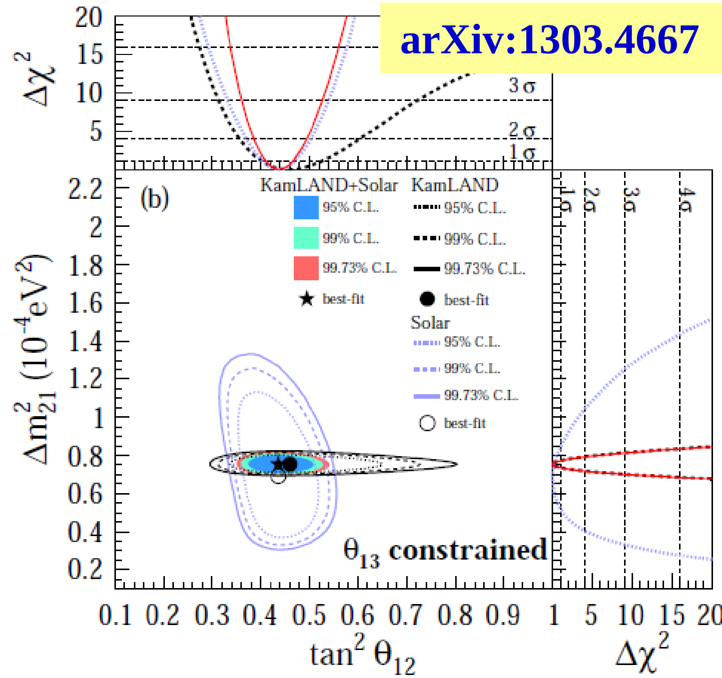
  - **JUNO, RENO-50**
- **Sterile neutrinos(10's):**
  - **Nucifer, Stereo, Solid …**

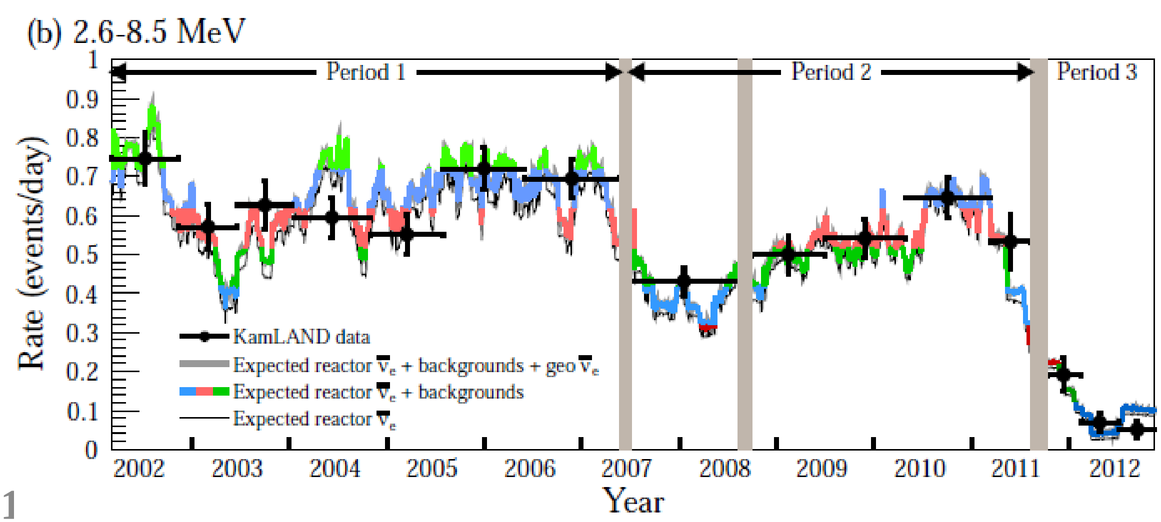
Latest KamLAND Results: θ_{12}

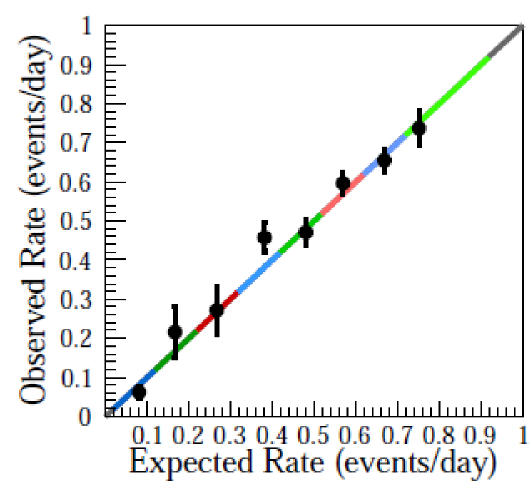
- **Reactors are all off in Japan since Mar. 2011:**
  - ⇨ A unique opportunity for precise measurement of backgrounds

Data combination	Δm^2_{21}	$\tan^2\theta_{12}$	$\sin^2\theta_{13}$
KamLAND	$7.54^{+0.19}_{-0.18}$	$0.481^{+0.092}_{-0.080}$	$0.010^{+0.033}_{-0.034}$
KamLAND + solar	$7.53^{+0.19}_{-0.18}$	$0.437^{+0.029}_{-0.026}$	$0.023^{+0.015}_{-0.015}$
KamLAND + solar + θ_{13}	$7.53^{+0.18}_{-0.18}$	$0.436^{+0.029}_{-0.025}$	$0.023^{+0.002}_{-0.002}$

arXiv:1303.4667



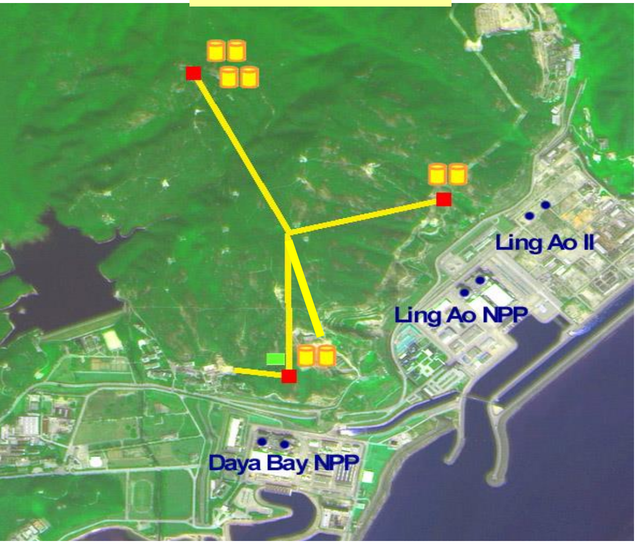




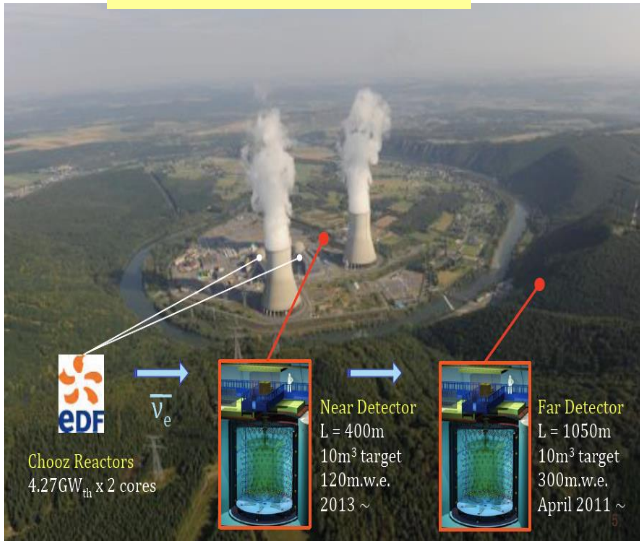
θ_{13}: Three on-going experiments

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

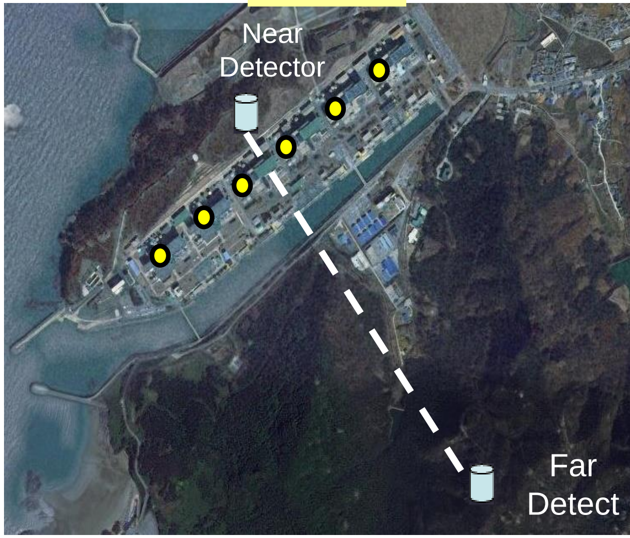
Daya Bay



Double Chooz

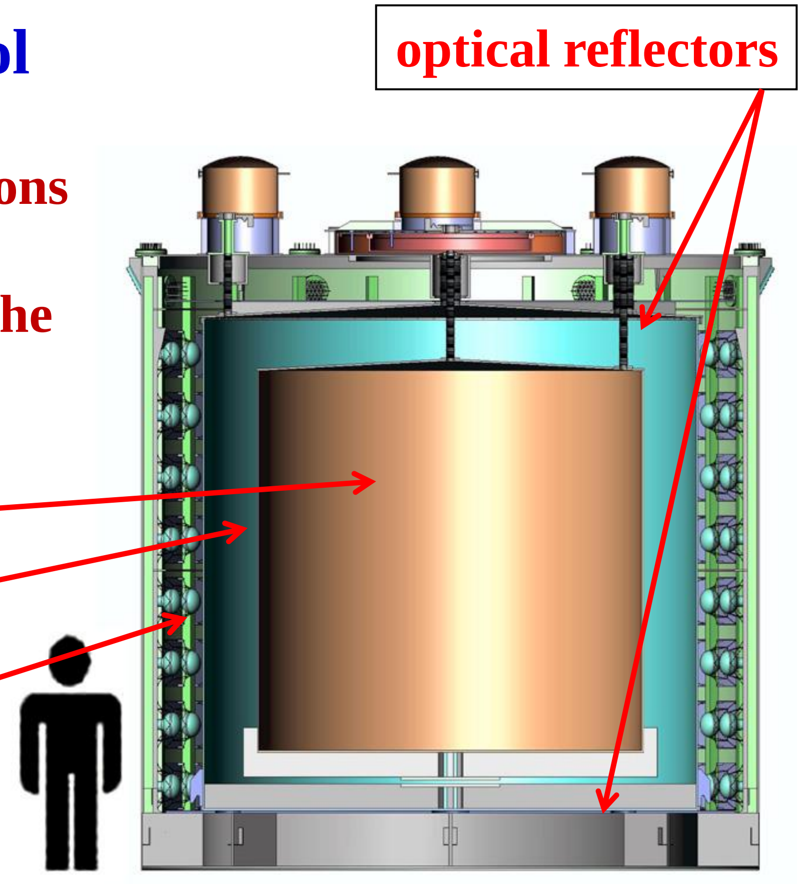


Reno



Detectors

- **Neutrino detector(s) in a water pool**
  - ⇨ Water for shielding backgrounds
  - ⇨ Water for stabilizing running conditions
  - ⇨ Water Cherenkov for muon veto
  - ⇨ RPC/plastic scintillator at the top of the water pool for muon veto
- **Three-zone 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

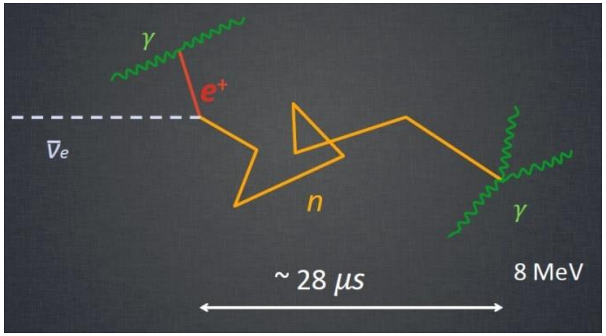


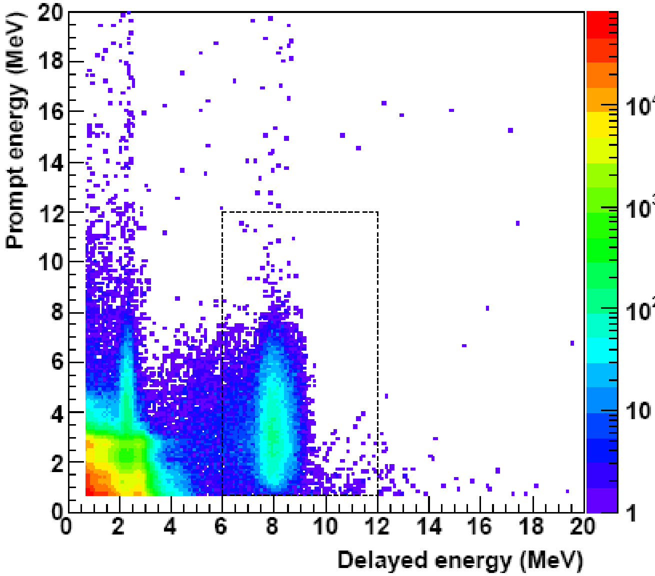
- **Light collection**

	PMT	Coverage	pe yield	pe yield/Coverage
Daya Bay	192 8"	~6%	163 pe/MeV	1.77
RENO	354 10"	~15%	230 pe/MeV	1
Double Chooz	390 10"	~16%	200 pe/MeV	0.81

Event Signature and Backgrounds

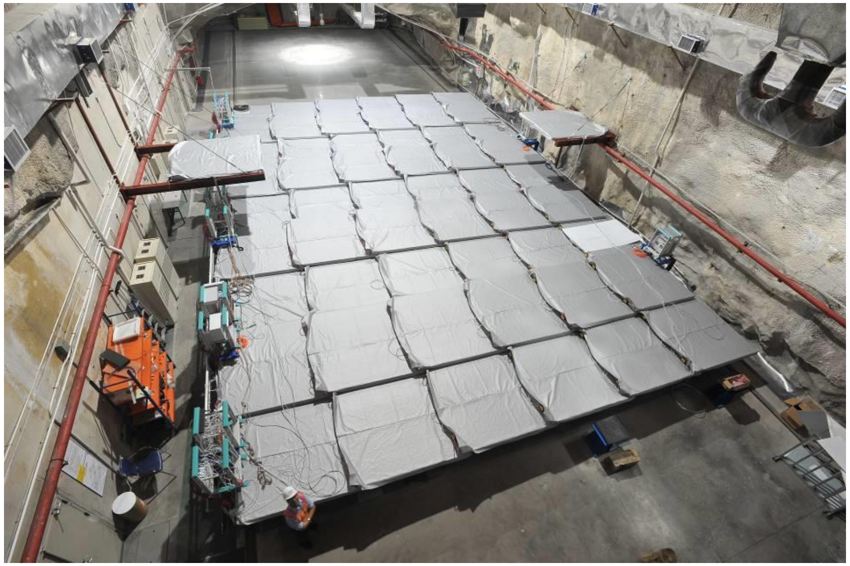
- **Signature:** $\bar{\nu}_e + p \rightarrow e^+ + n$
  - ⇨ **Prompt: e^+, 1-10 MeV,**
  - ⇨ **Delayed: n, 2.2 MeV@H, 8 MeV @ Gd**
  - ⇨ **Capture time: 28 μs in 0.1% Gd-LS**
- **Backgrounds**
  - ⇨ **Uncorrelated: random coincidence of γγ, γn or nn**
    - ✓ **γ from U/Th/K/Rn/Co… in LS, SS, PMT, Rock, …**
    - ✓ **n from α-n, μ-capture, μ-spallation in LS, water & rock**
  - ⇨ **Correlated:**
    - ✓ **Fast neutrons: n scattering - n capture**
    - ✓ **$^{8}He/^{9}Li$: β decay -n capture**
    - ✓ **Am-C source: γ rays - n capture**
    - ✓ **α-n: $^{13}C(\alpha,n)^{16}O$**

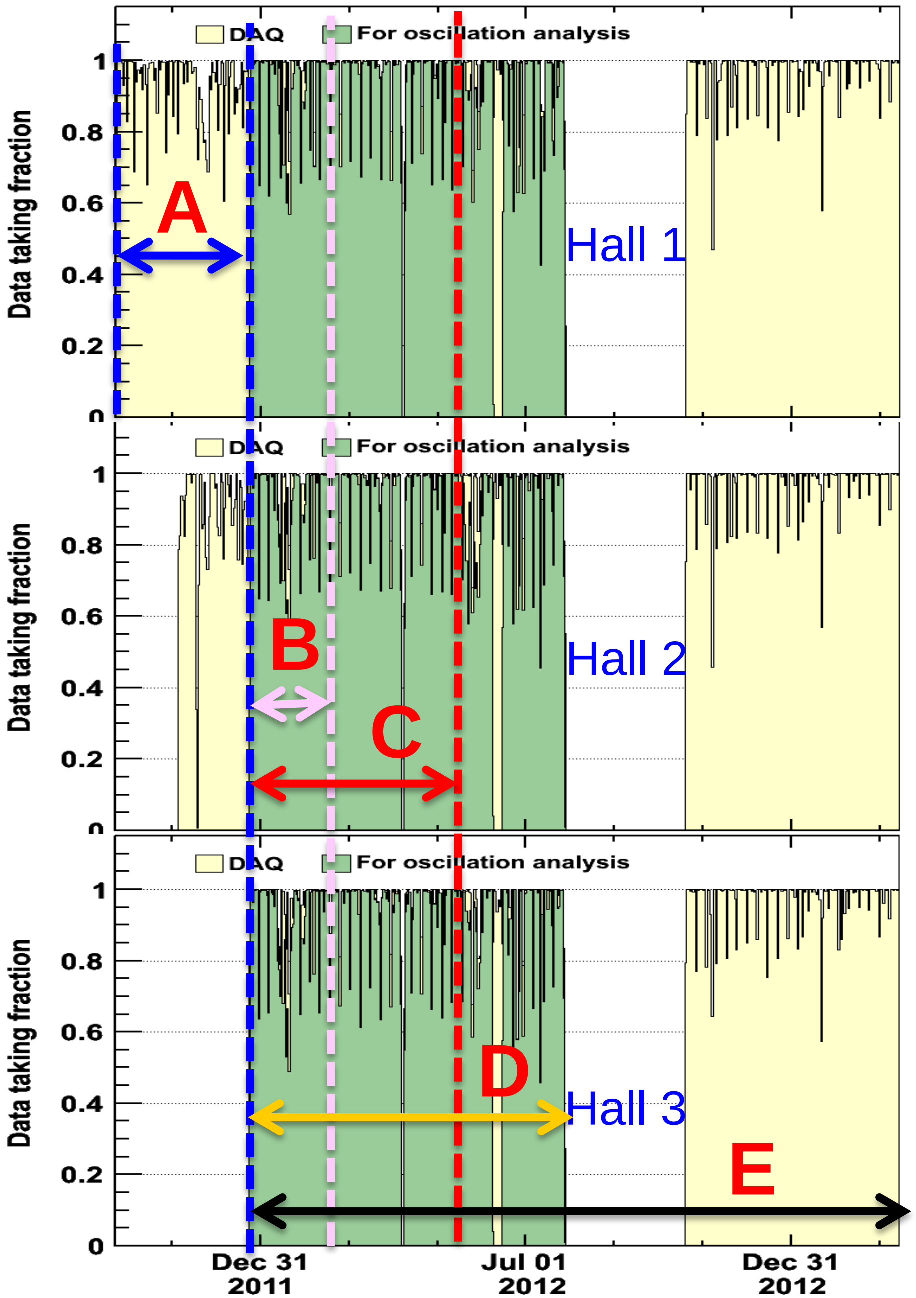




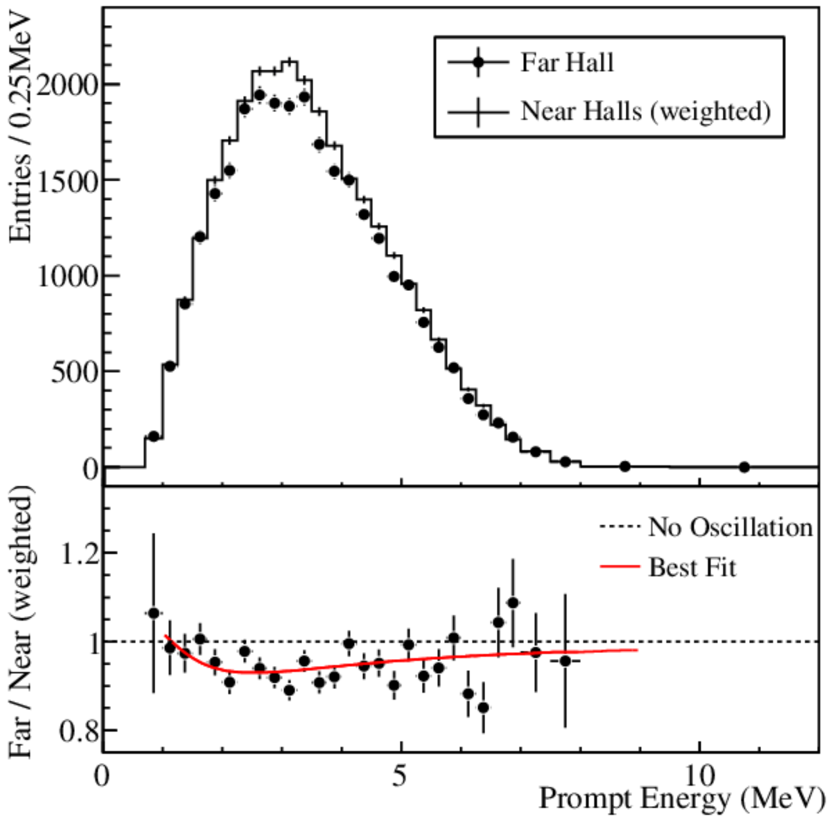
Daya Bay: Data taking & analysis status

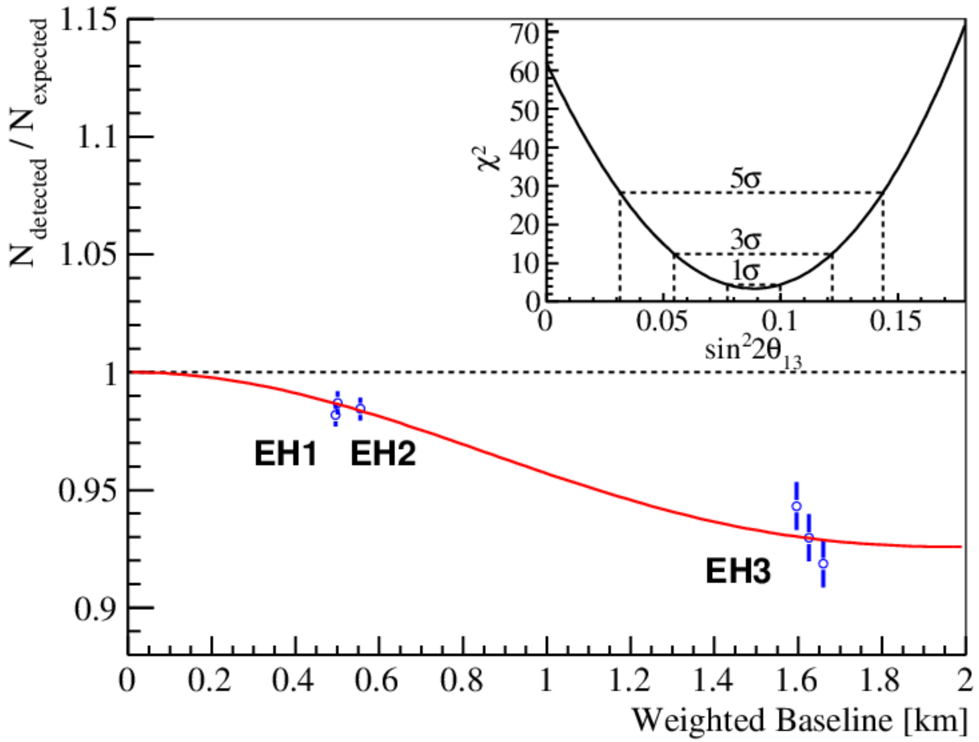
- **A→Two Detector Comparison:**
  Sep. 23, 2011 – Dec. 23, 2011
  NIM A 685 (2012), pp. 78-97
- **B→First Oscillation Result:**
  Dec. 24, 2011 – Feb. 17, 2012
  Phys. Rev. Lett. 108, 171803 (2012)
- **C→Updated analysis:**
  Dec. 24, 2011 – May 11, 2012
  Chinese Physics C37, 011001 (2013)





Daya Bay: Results(C)





F.P. An et al., Chin. Phys.C 37(2013) 011001

R = 0.944 ± 0.007 (stat) ± 0.003 (syst)

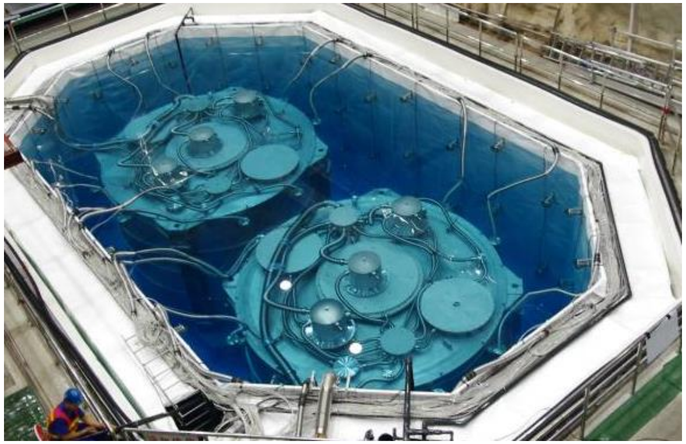
$\sin^2 2\theta_{13}$ = 0.089 ± 0.010(stat) ± 0.005(syst)

χ^2/NDF = 3.4/4, 7.7 σ for non-zero θ_{13}

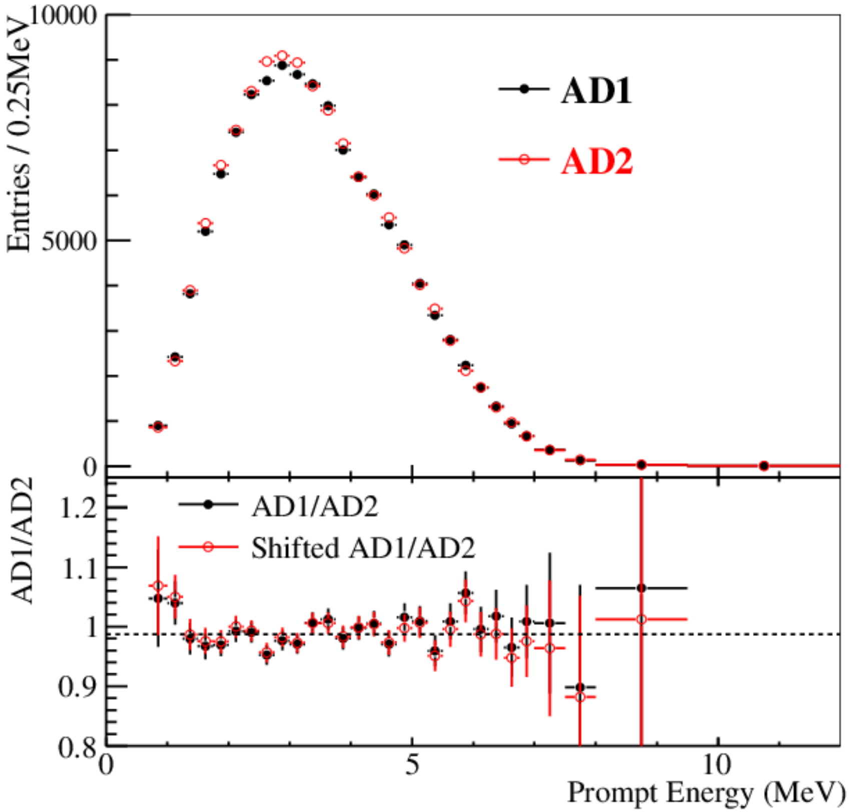
Sorry, D & E results will be released later

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

RENO Status

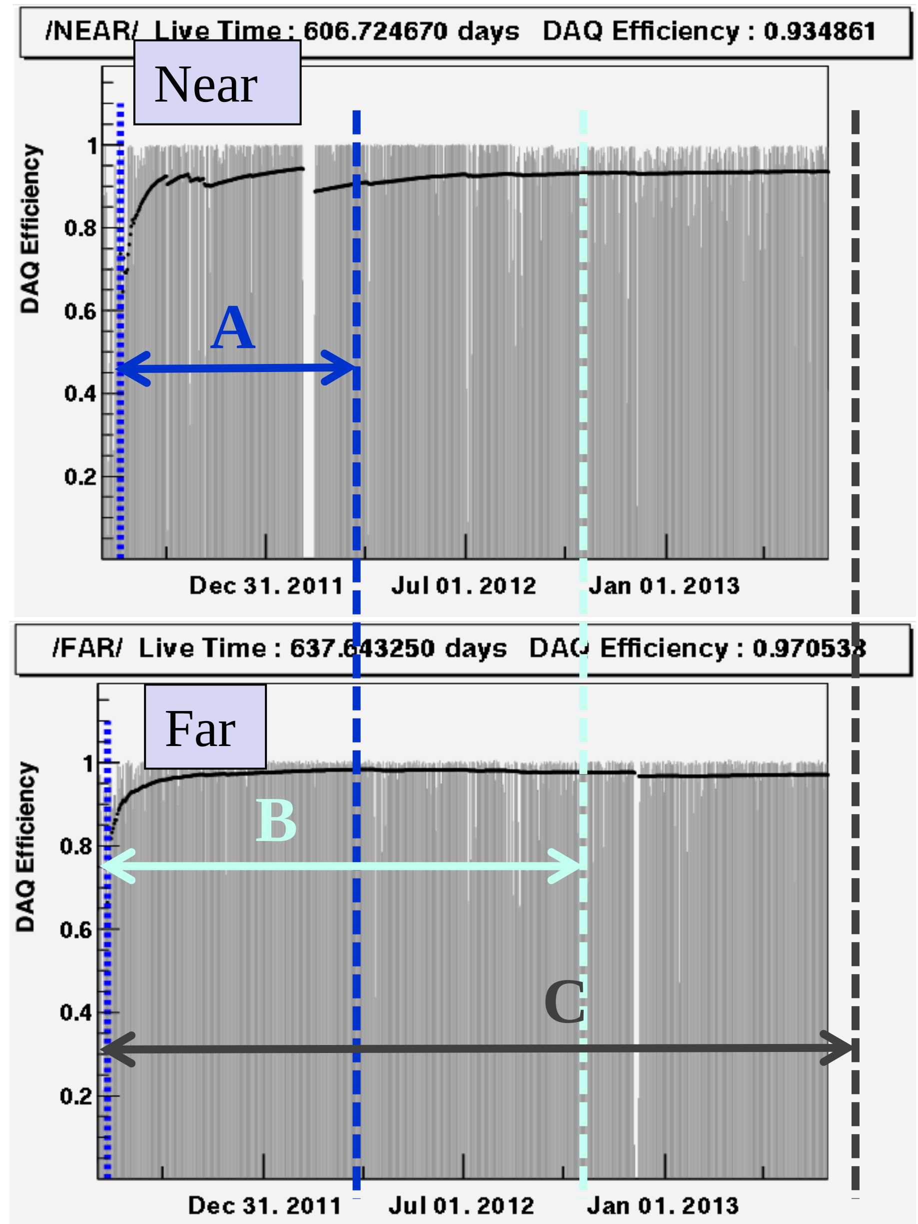
- Data taking began on Aug. 1, 2011 with both near and far detectors.
  (DAQ efficiency : ~95%)

- **A** (220 days) : **First q_{13} result**
  [11 Aug, 2011~26 Mar, 2012]
  PRL 108, 191802 (2012)

- **B** (403 days) : **Improved θ_{13} result**
  [11 Aug, 2011~13 Oct, 2012]
  NuTel 2013

- **C** (~700 days) : **Shape+rate analysis**
  (in progress)
  [11 Aug, 2011~31 Jul, 2013]

- Absolute reactor neutrino flux measurement in progress
  [reactor anomaly & sterile neutrinos]



From Soo-Bong Kim

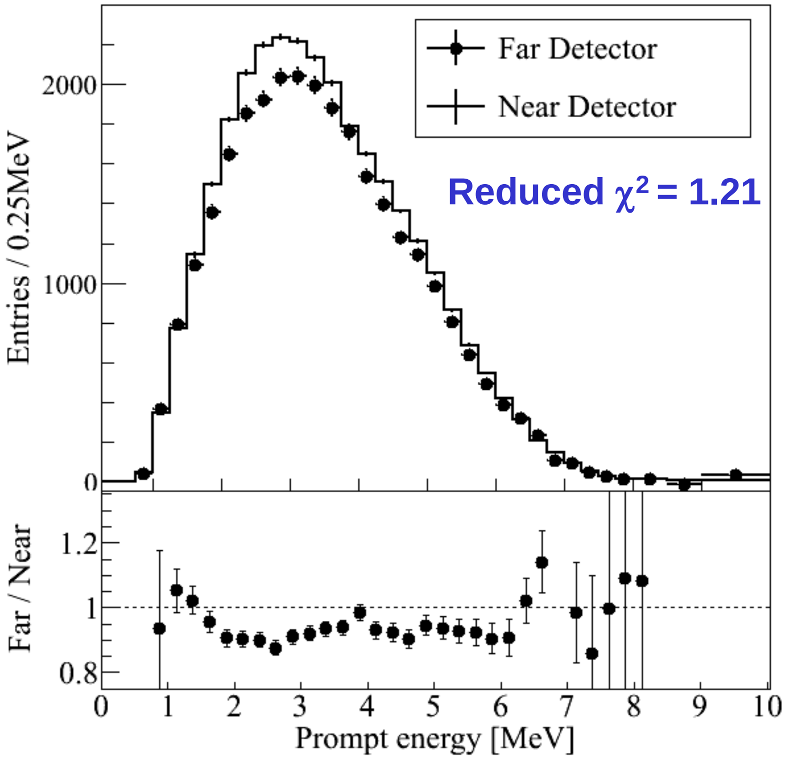
RENO Results

- First result in April 2, 2012.

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

- A new result reported in March, 2013.

$$\sin^2 2\theta_{13} = 0.100 \pm 0.010(stat) \pm 0.015(syst)$$



$$R = \frac{\Phi^{Far}_{observed}}{\Phi^{Far}_{expected}} = 0.929 \pm 0.006(stat) \pm 0.009(syst)$$

<u>Statistics:</u>

-- about twice more data

<u>Systematics:</u>

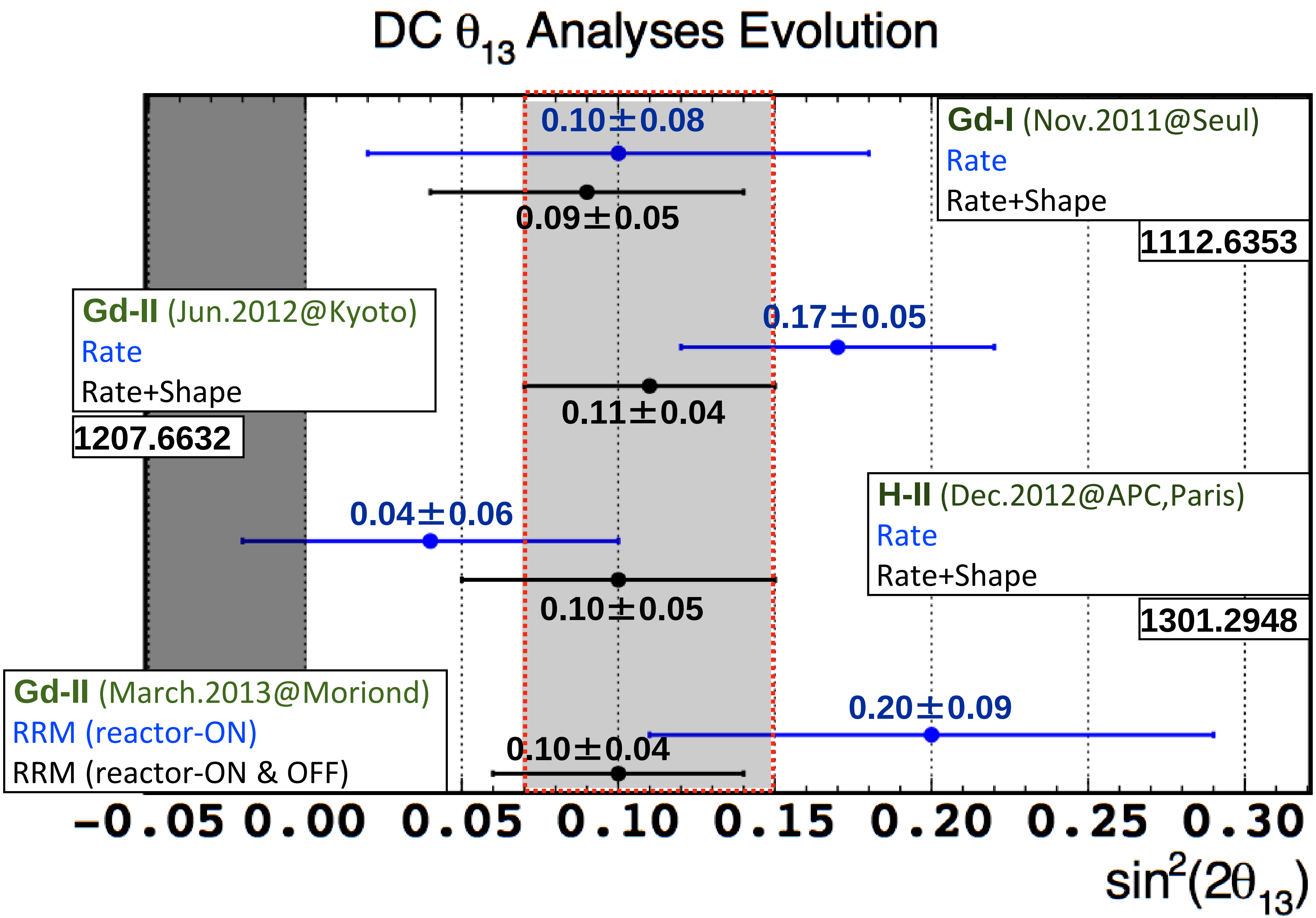
-- Improved background estimation/reduction

(Li/He background, fast N, flasher removal)

-- Improved energy scale calibration

For details, see Seon-Hee Seo's talk at NeuTel 2013

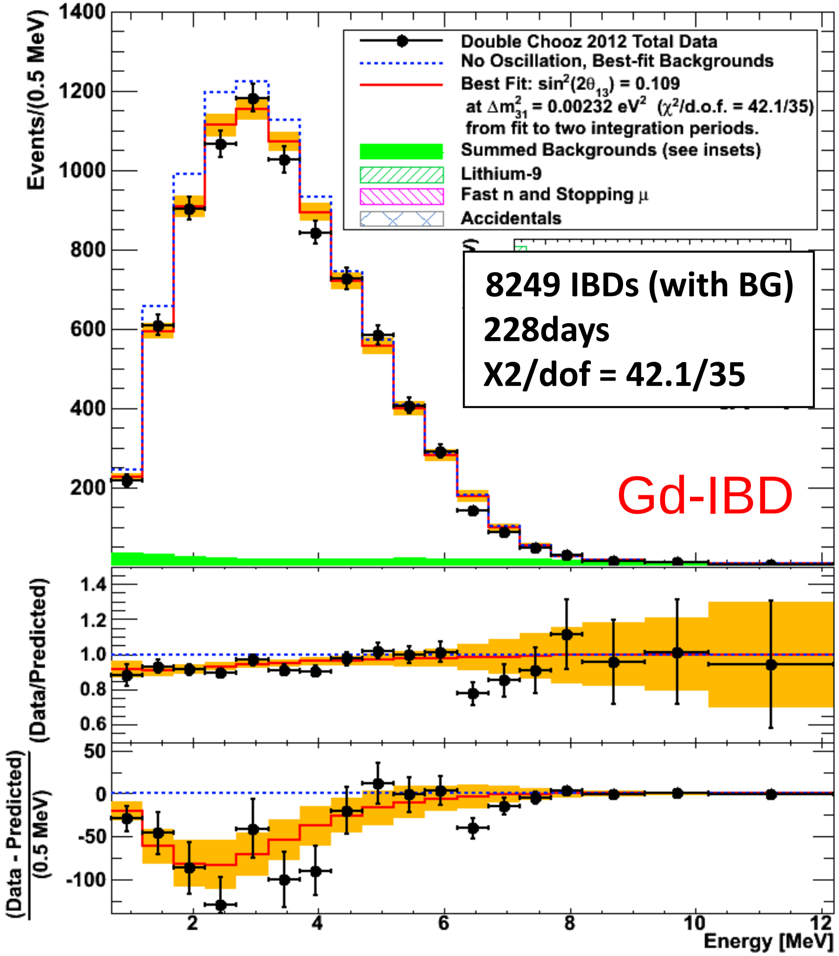
Double Chooz: many results



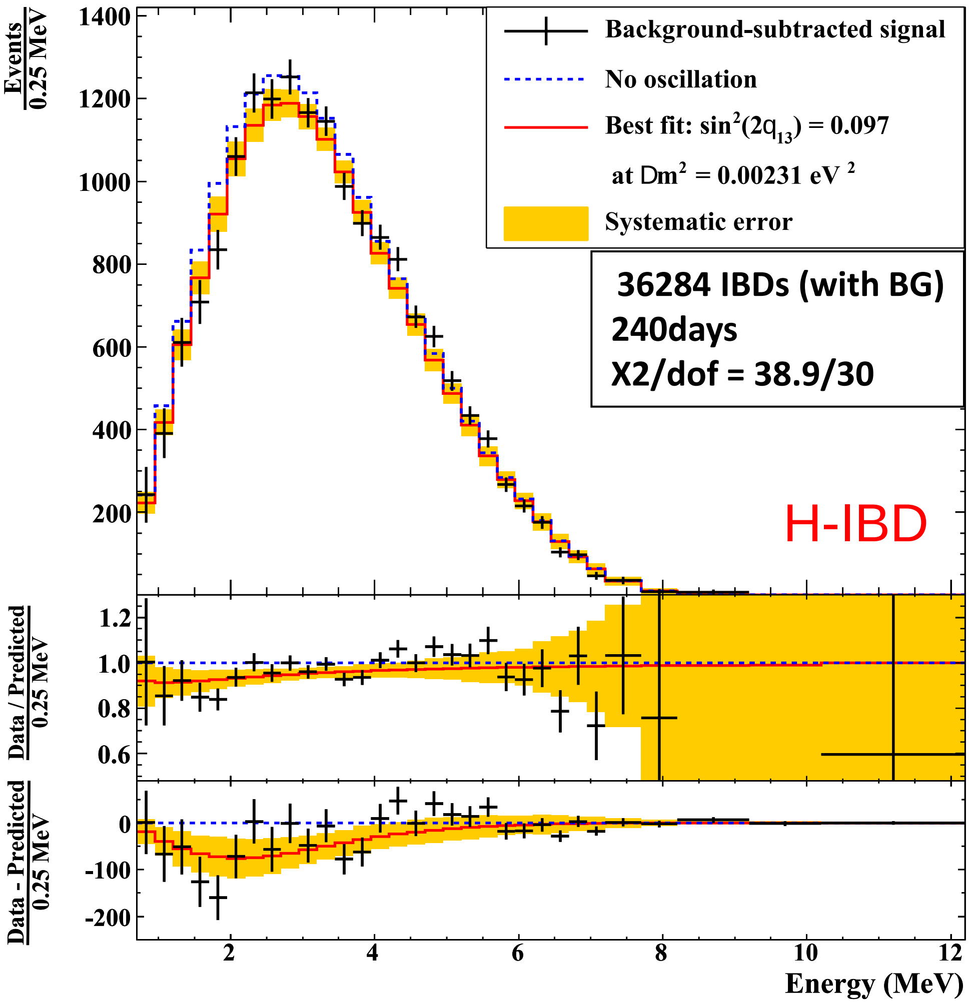
From Herve de Kerret

Two independent measurements

Phys. Rev. D86 (2012) 052008



Phys. Lett. B723 (2013) 66-70



Rate+shape analysis→ clear θ_{13} E/L pattern & BG constrains

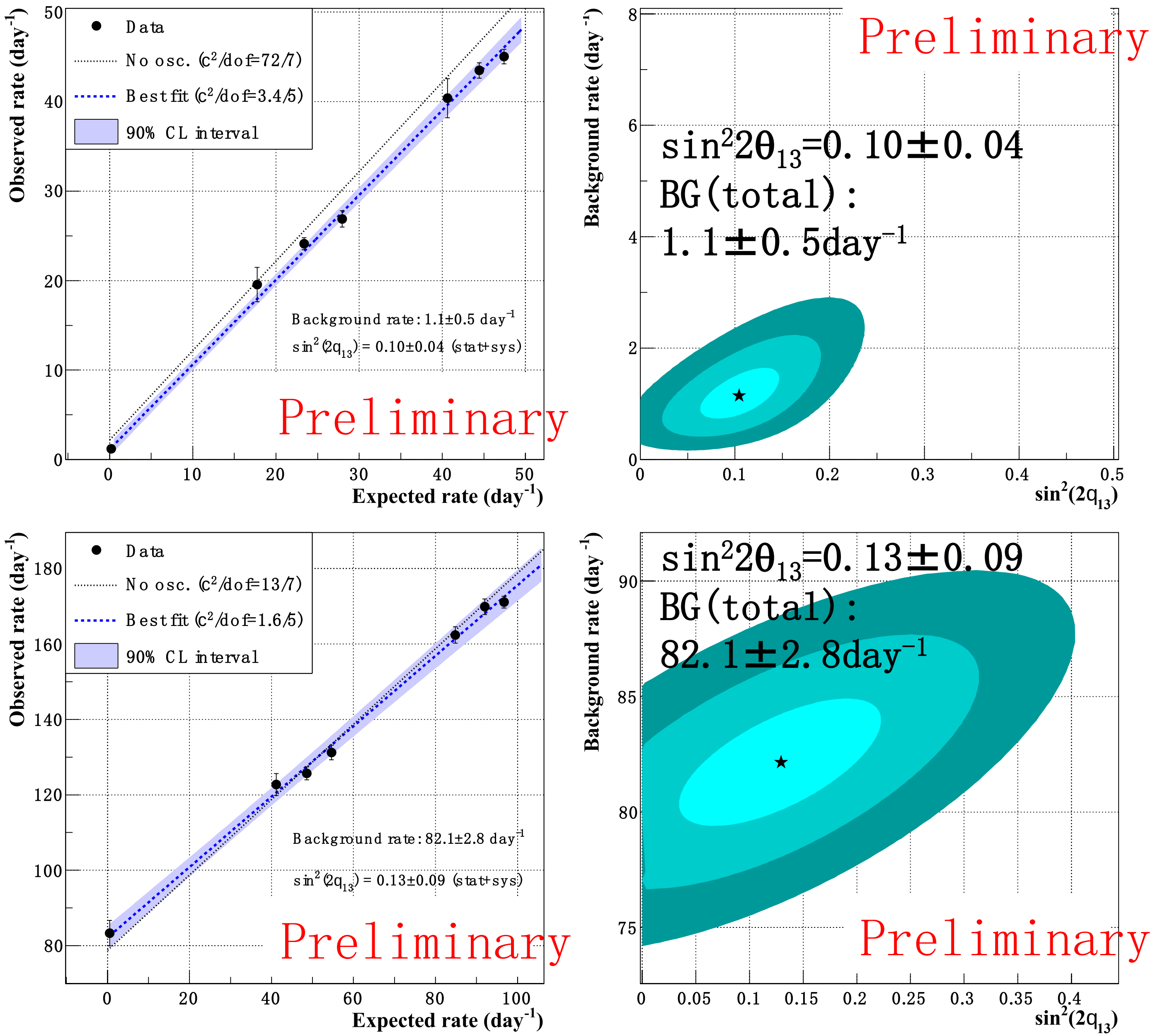
DC-II(Gd): $\sin^2(2\theta_{13})=0.109\pm0.04$ $[0.030^{stat}\pm0.025^{syst}]$

DC-II(H): $\sin^2(2\theta_{13})=0.097\pm0.05$ $[0.034^{stat}\pm0.034^{syst}]$

Well controlled background: Reactor-off

Gd-IBD data
(S/N~40)

H-IBD data
(S/N~1)



From Herve de Kerret

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%**

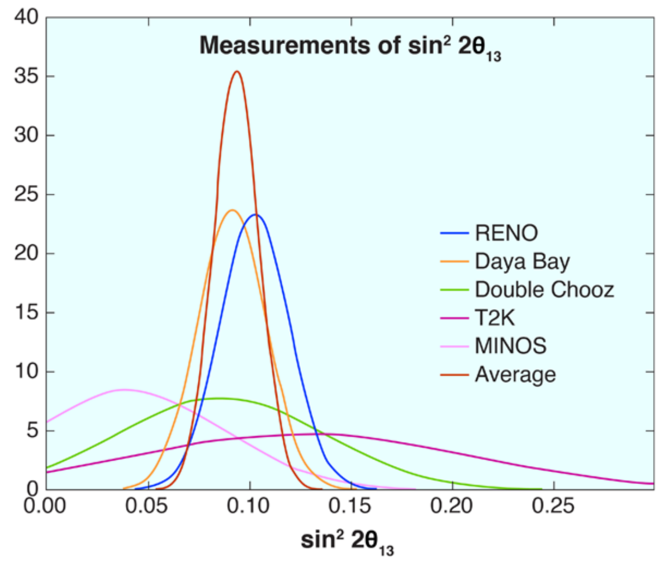
Reactor flux estimate

	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%

Summary of latest results

- **Daya Bay**
  - ⇨ **Gd: $\sin^2 2\theta_{13} = 0.089 \pm 0.010^{stat} \pm 0.005^{syst}$**
- **Double Chooz**
  - ⇨ **Gd: $\sin^2(2\theta_{13}) = 0.109 \pm 0.030^{stat} \pm 0.025^{syst}$**
  - ⇨ **H: $\sin^2(2\theta_{13}) = 0.097 \pm 0.034^{stat} \pm 0.034^{syst}$**
- **RENO**
  - ⇨ **Gd: $\sin^2 2\theta_{13} = 0.113 \pm 0.013^{stat} \pm 0.019^{syst}$**
- **Can we take their weighted average ?**

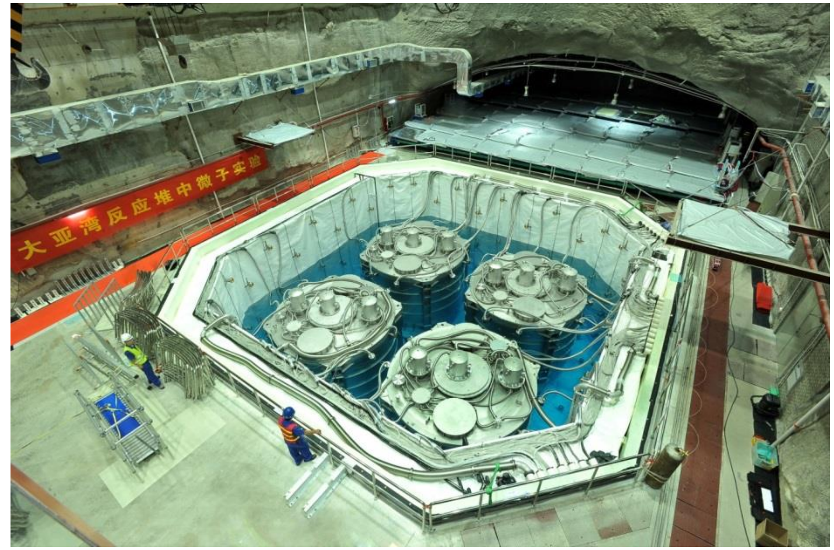
  Yes, if following issues are properly dealt:
  - ⇨ **Correlated errors between experiments**
  - ⇨ **Errors are estimated in a unified way**

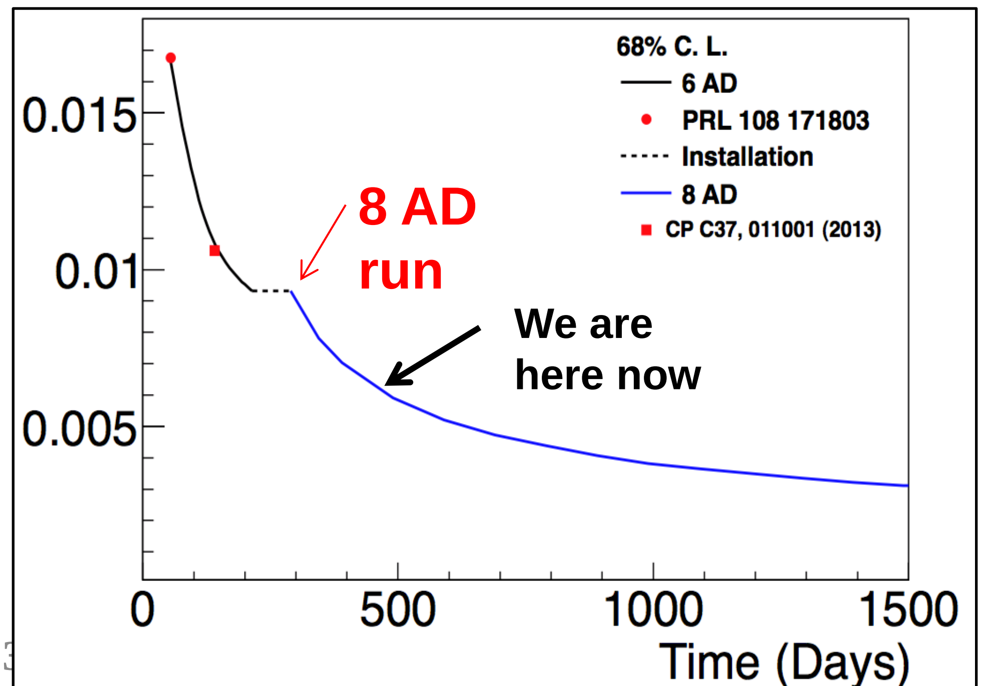


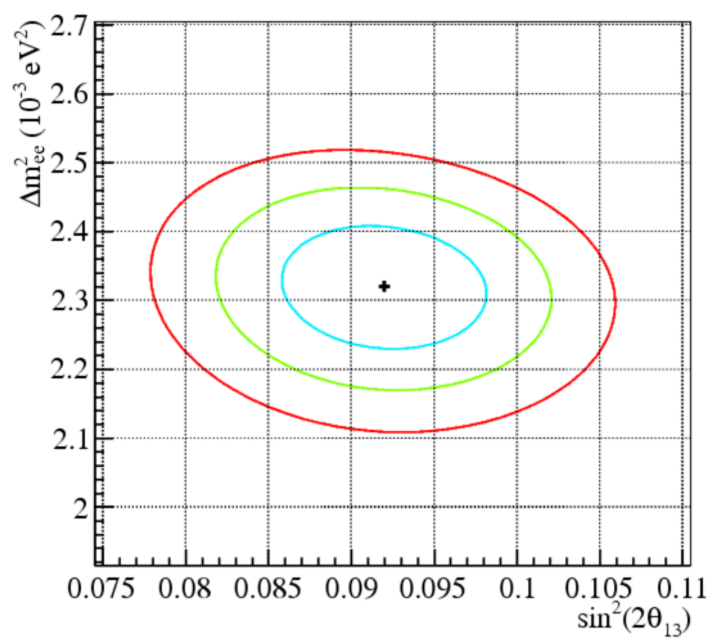
Be careful !!!

Future prospects: Daya Bay

- Calibration & maintenance completed last summer.
- Full detector operational since Oct. 2012
- Precision measurements in the next 3-5 years

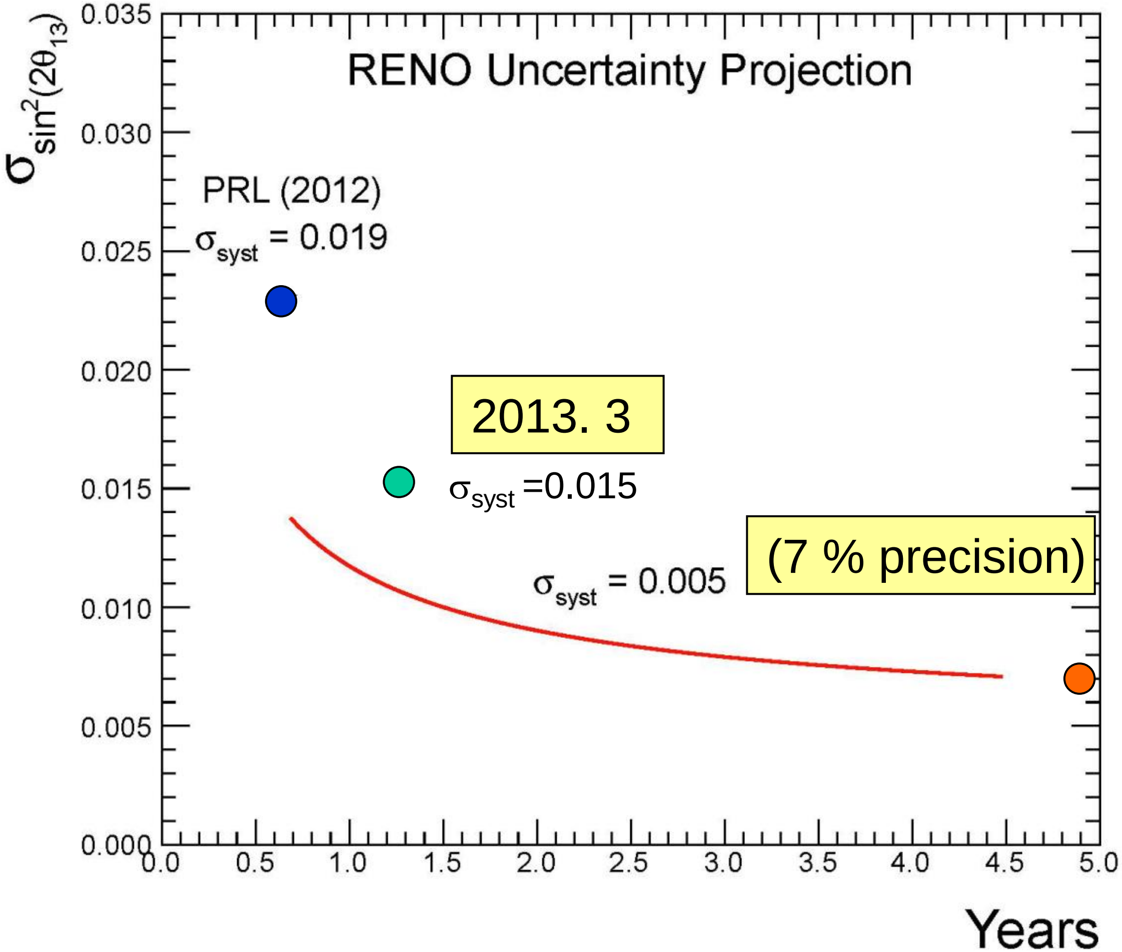






RENO's Projected Sensitivity of θ_{13}

$$\sin^2 2\theta_{13} = 0.100 \pm 0.010(stat.) \pm 0.015(syst.)$$



- **Goals**
  - $\sin^2 2\theta_{13}$ to **7%** precision
  - direct measurement of Δm^2_{31}
  - precise measurement of **reactor neutrino flux and spectrum**
  - study for reactor anomaly and sterile neutrinos

From Soo-Bong Kim

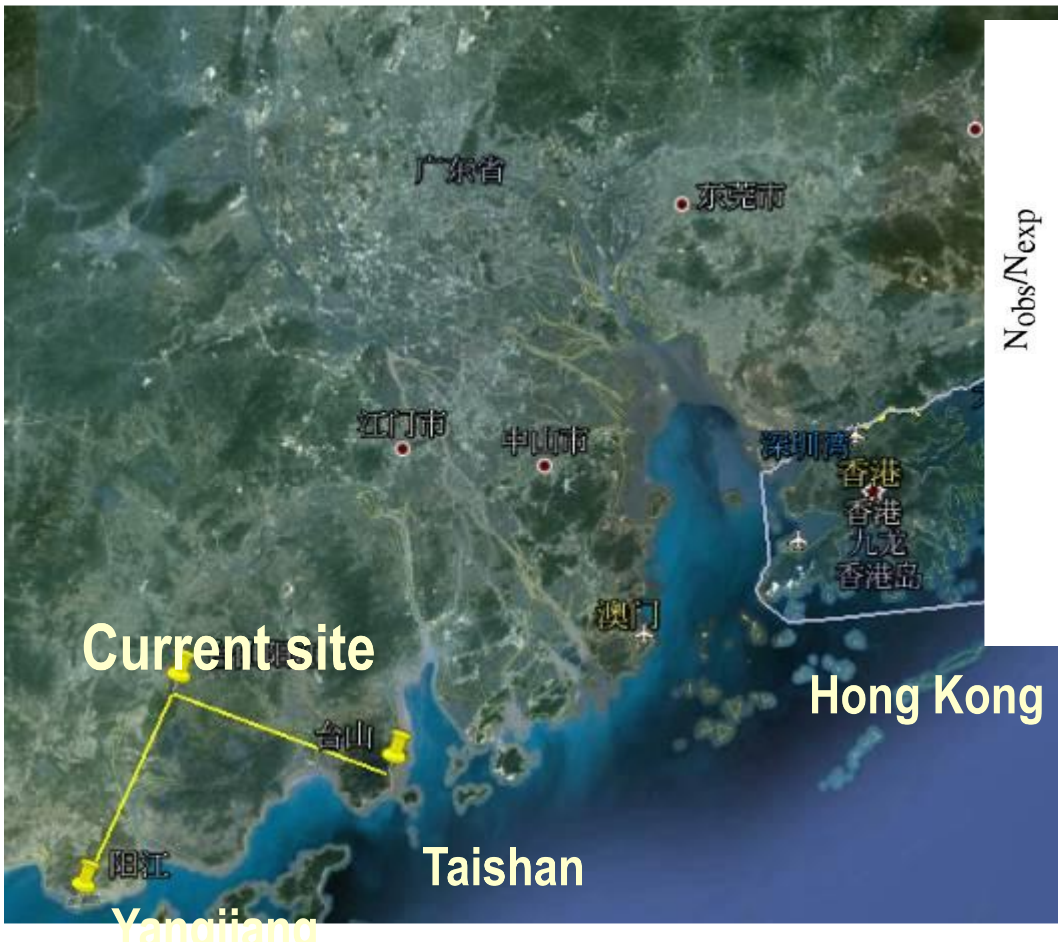
Double Chooz

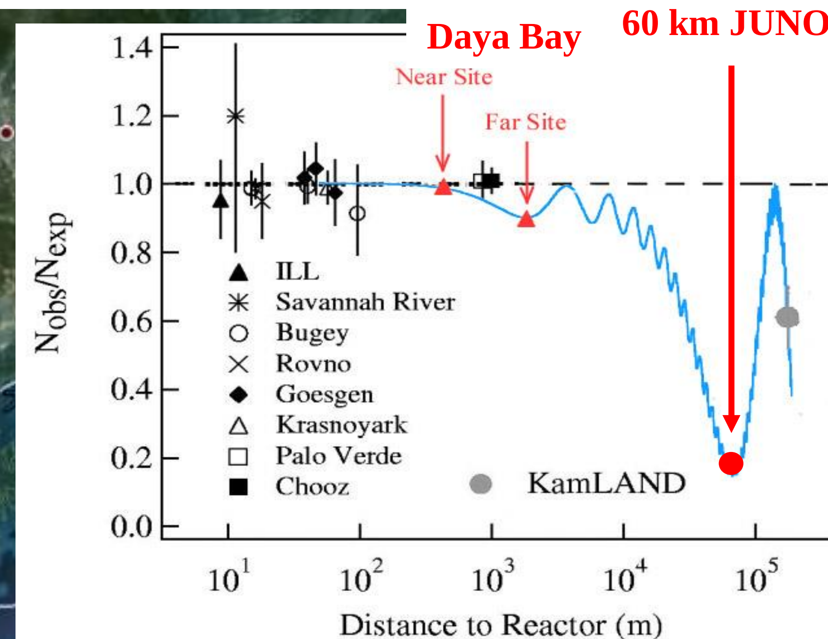
- Near detector in construction till Spring 2014.
- The first result of the full experiment will be available at the end of 2014, towards a final precision of 10%.

From Herve de Kerret

Next Step: Mass Hierarchy

	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	running	planned	approved	Construction	construction
power/GW	17.4	17.4	17.4	17.4	18.4



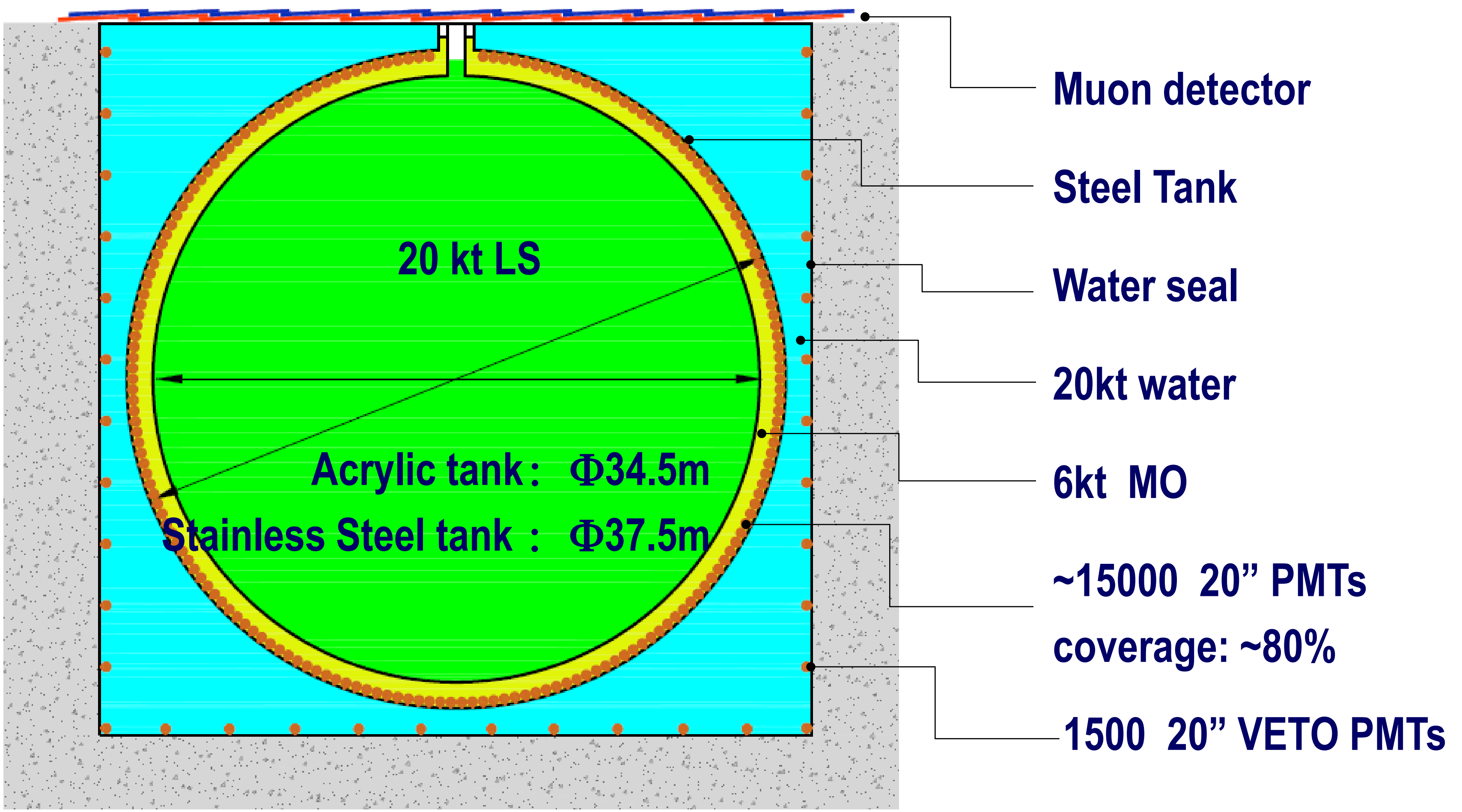


Talk by YFW at ICFA seminar 2008, Neutel 2011; by J. Cao at NuTurn 2012 ;

Paper by L. Zhan, YFW, J. Cao, L.J. Wen, PRD78:111103,2008; PRD79:073007,2009

The plan: a large LS detector

- LS volume: × 20➔ for more mass & statistics
- light(PE) × 5➔ for resolution

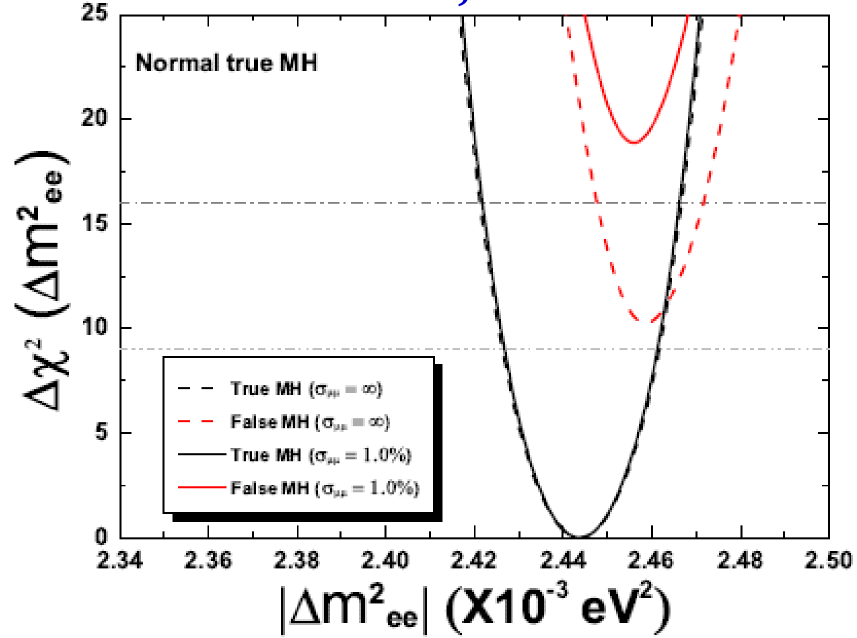


Physics Reach

Thanks to a large θ_{13}

- Mass hierarchy
- Precision measurement of mixing parameters
- Supernova neutrinos
- Geoneutrinos
- Sterile neutrinos
- ……

Y.F. Li et al., arXiv:1303.6733



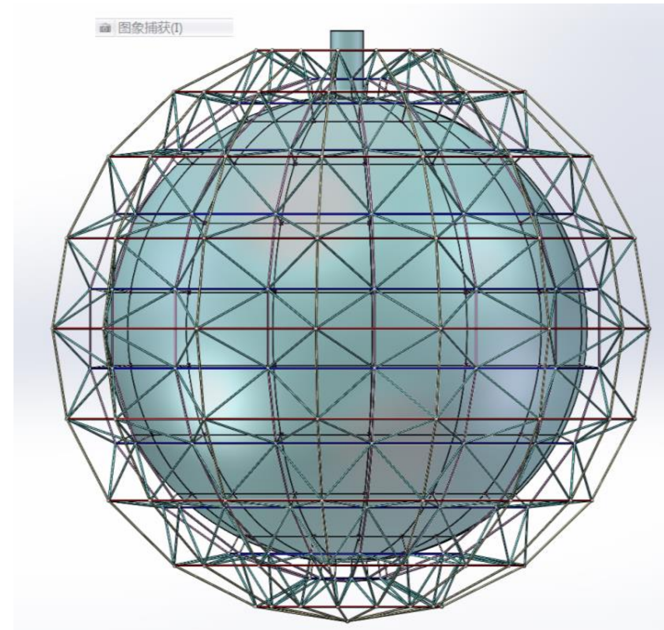
	Current	Daya Bay II
Δm^2_{12}	3%	0.6%
Δm^2_{23}	5%	0.6%
$\sin^2\theta_{12}$	6%	0.7%
$\sin^2\theta_{23}$	20%	N/A
$\sin^2\theta_{13}$	14% → 4%	~ 15%

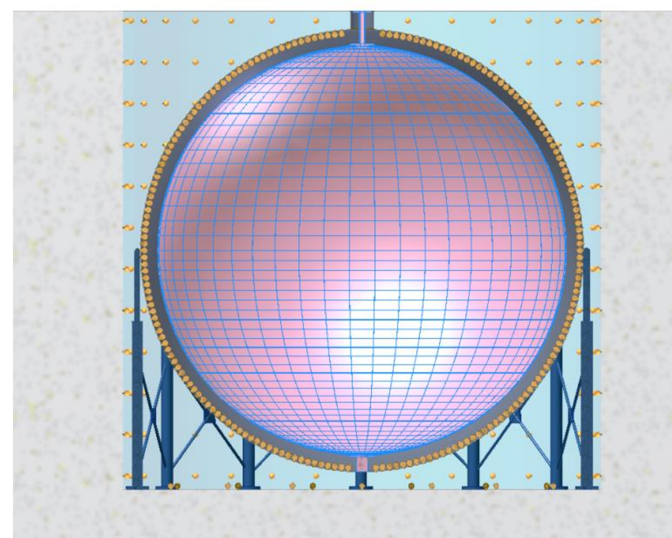
For 6 years, mass hierarchy cab be determined at 4σ level, if $\Delta m^2_{\mu\mu}$ can be determined at 1% level

Detector size: 20kt
Energy resolution: 3%/√E
Thermal power: 36 GW

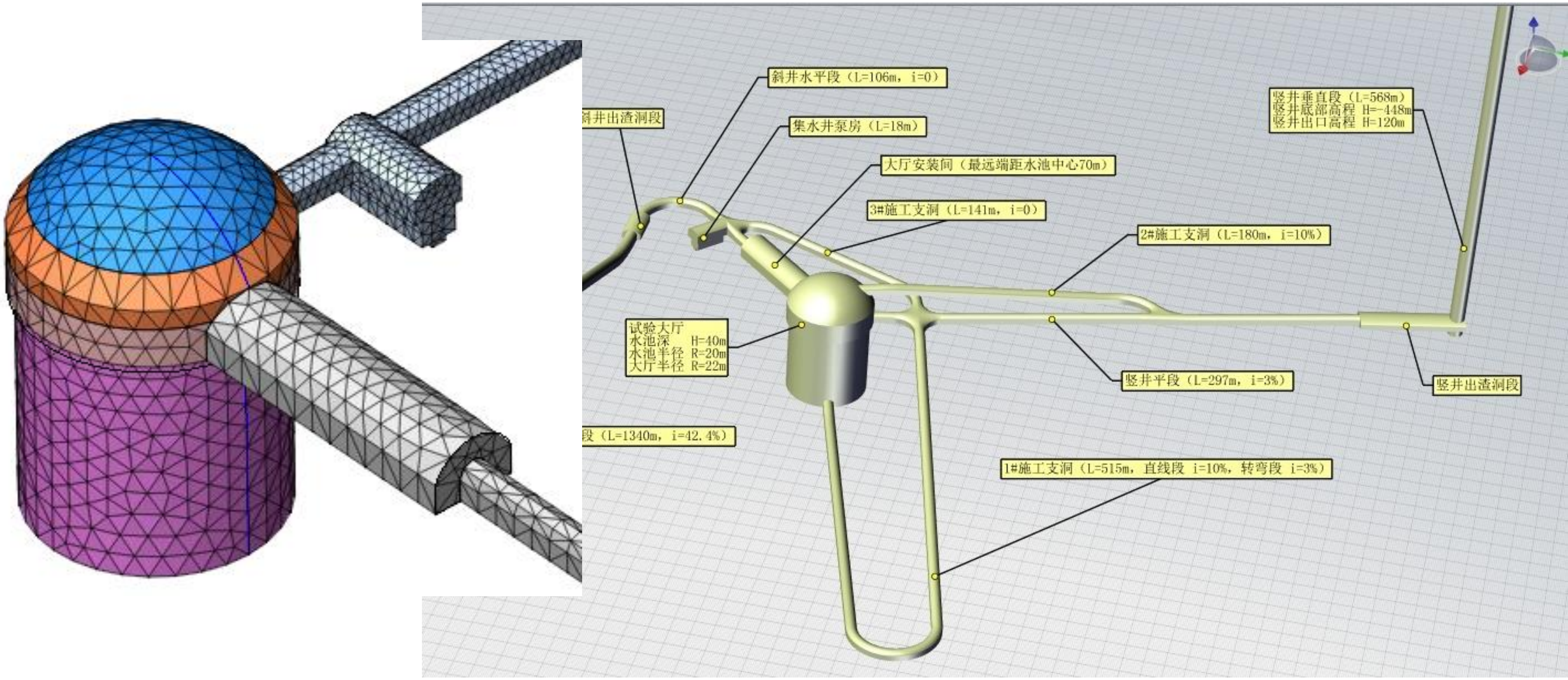
Detector design

- **LS detector in the water pool: No Gd-loading**
- **Estimated signal event rate: 40/day**
- **Backgrounds:**
  - **Accidentals(~10%), $^{9}Li/^{8}He$(<1%), fast neutros(<1%)**
- **Several detector options:**
  - **Acrylic ball + unistruct for PMT**
  - **Steel ball + acrylic blocks**
  - **Steel ball + acrylic walls + Balloon**
  - **…**
- **Design is underway**
- **Prototype will be started by the end of year**
- **Final decision: 2014-2015**





Experimental hall



- **Preliminary study shows that:**
  - **Stability of the hall is not a problem**
  - **Total time needed for the civil construction is 3 years**

Proposal for RENO-50

Soo-Bong Kim (KNRC, Seoul National University)

"International Workshop on RENO-50, June 13-14, 2013"

KNRC
Korea Neutrino Research Center

Overview of RENO-50

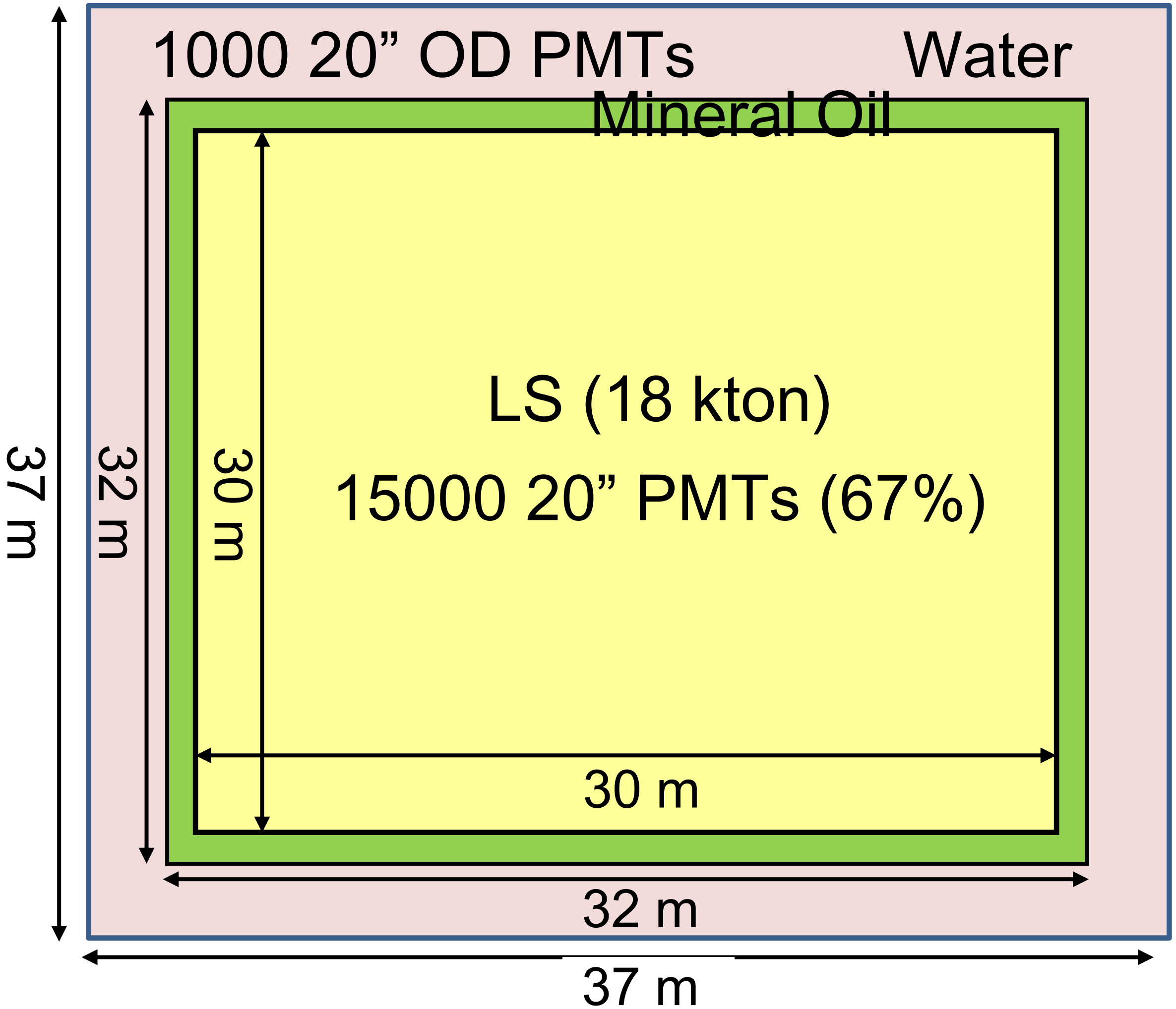
- **RENO-50** : An underground detector consisting of 18 kton ultra-low-radioactivity liquid scintillator & 15,000 20” PMTs, at 50 km away from the Hanbit(Yonggwang) nuclear power plant

- **Goals** : - High-precision measurement of θ_{12} and Δm^2_{21}
  - Determination of neutrino mass hierarchy
  - Study neutrinos from reactors, (the Sun), the Earth, Supernova, and any possible stellar objects

- **Budget** : $ 100M for 6 year construction
  (Civil engineering: $ 15M, Detector: $ 85M)

- **Schedule** : 2013 ~ 2018 : Facility and detector construction
  2019 ~ : Operation and experiment

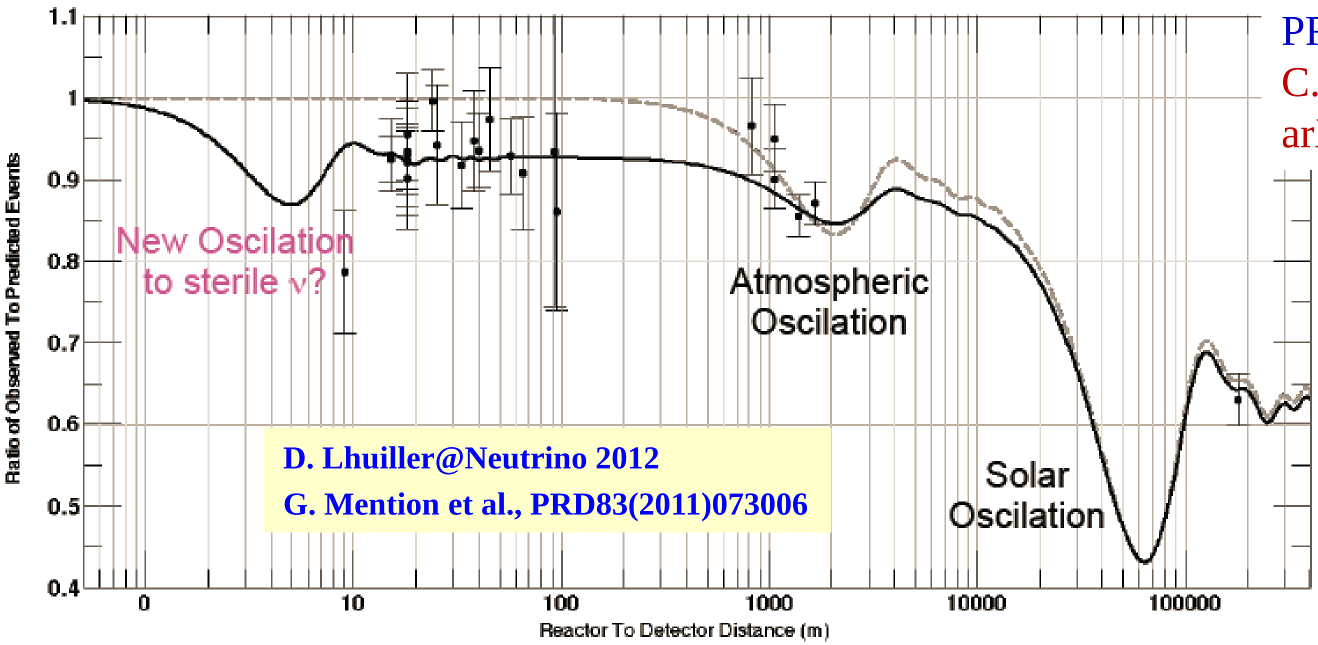
Conceptual Design of RENO-50



Reactor neutrino anomaly

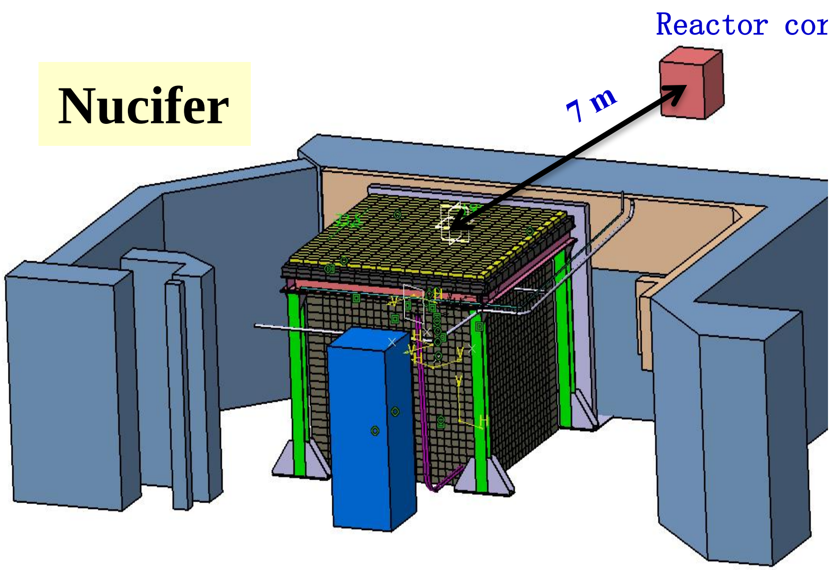
- By a new flux calculation, there may exist a reactor neutrino flux deficit: 0.943±0.023. A 3σ effect ?
- Later confirm by other calculations
- Oscillation with sterile neutrinos ?
  - Other experimental "hints": LSND, MiniBooNE, Gallex…
  - Global fit of all "hints": severe tensions
  - Cosmological bounds: not so favored
- New analysis: different opinions

T.A. Mueller et al., PRC83:054615,2011
P. Huber et al., PRC84:024617,2011.
C. Zhang et al., arXiv: 1303.0900

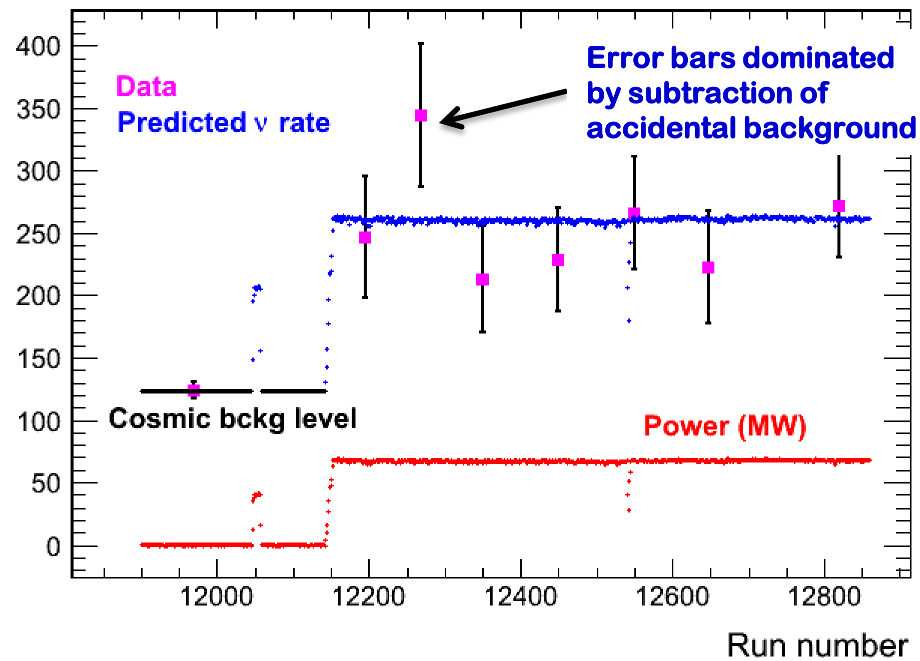


Solution: experiments

- **Radioactive sources: CeLAND(^{144}Ce in KamLAND), SoX(^{51}Cr in Borexino),…**
- **Accelerator beams: IsoDAR, Icarus/Nessie, nuSTORM…**
- **Reactors: Nucifer, Stereo, Solid,…**
- **New measurements of β-spectrum from U & Pu(Munich)**



Figures from T. Lasserre



Will be upgraded to reduce backgrounds

Summary

- Reactor neutrinos are powerful and well understood
- Recently very successful on θ_{12}, θ_{13}, …
- Precision on $Sin^2 2\theta_{13}$ will be significantly improved in the next few years, up to ~ 4%
- Will play important roles on:
  - ⇨ Mass hierarchy
  - ⇨ Precision measurement of 3/6 mixing parameters up to < ~1% level ➔ unitarity test of the mixing matrix
  - ⇨ Sterile neutrinos
  - ⇨ Neutrino properties: magnetic moments, coherent scattering, …