Neutrino oscillation:
non-accelerator experiments

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Outline

- Solar neutrinos
- Atmospheric neutrinos
- Reactor neutrinos
- Sterile neutrinos
- Summary

Neutrino Oscillation

- **If the neutrino mass eigenstate is different from that of the weak interaction, neutrinos can oscillate: from one type to another during the flight:**

$$\nu_e \longrightarrow \nu_\mu \longrightarrow \nu_e \longrightarrow \nu_\mu \longrightarrow$$

Oscillation probability:

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta)\,\sin^2(1.27\Delta m^2 L/E)$$

Oscillation amplitude — $\sin^2(2\theta)$

Oscillation frequency — Δm^2

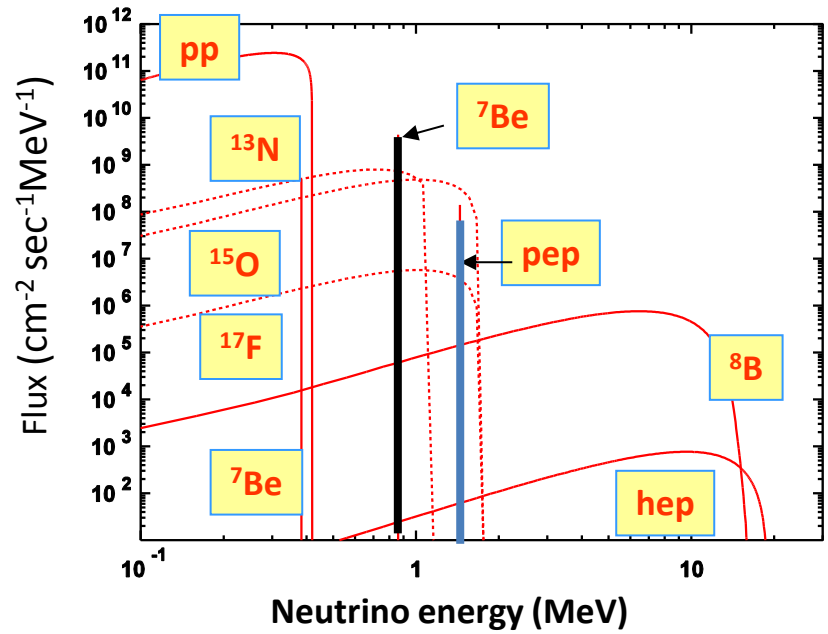
Oscillation matrix for 3 generations:

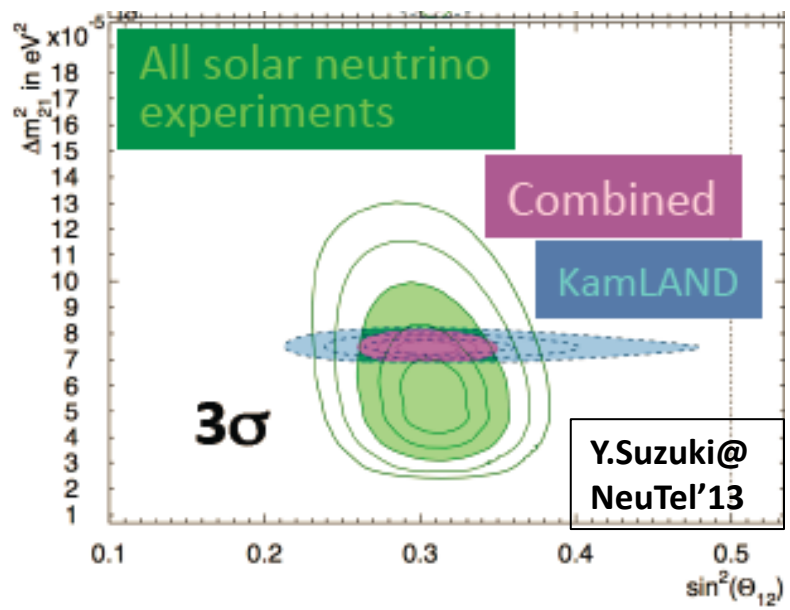
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- **Known parameters:** θ_{23}, θ_{12}, $|\Delta M^2_{23}|$, ΔM^2_{12},
- **Recent progress:** θ_{13}
- **Unknown parameters:** **mass hierarchy(ΔM^2_{23}), CP phase δ**

Solar neutrinos

- First indication of neutrino deficit by Homestake exp.(70's-90's)
- Confirmed by many Exp.s ➔ multiple solutions of θ_{12} & ΔM^2_{12}
- Solar neutrino oscillation established(00's):
  - SuperK: indication of LMA-MSW
  - SNO: missing ν_e appeared as $\nu_\mu+\nu_\tau$
  - KamLAND: θ_{12} & ΔM^2_{12}
  - Standard Solar Model established
- Current experiments:
  - Borexino
  - SuperKamiokande
- Main issues:
  - Solar related
- Future experiment:
  - SNO+, XMASS, LENA, JUNO…





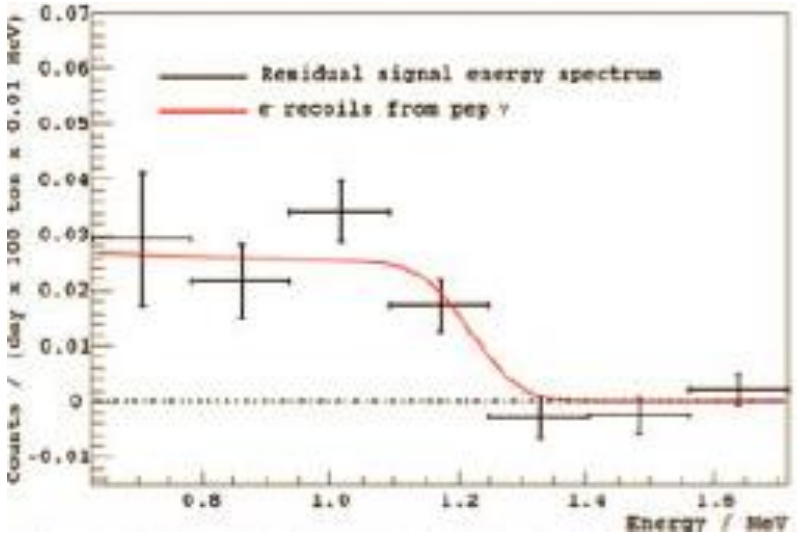
Borexino

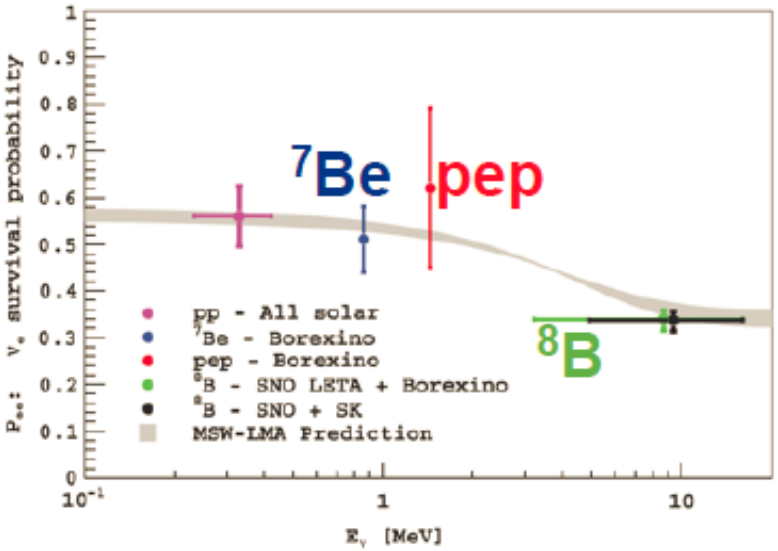
PRL 108(2012) 051302

- pep neutrinos are observed for the first time:

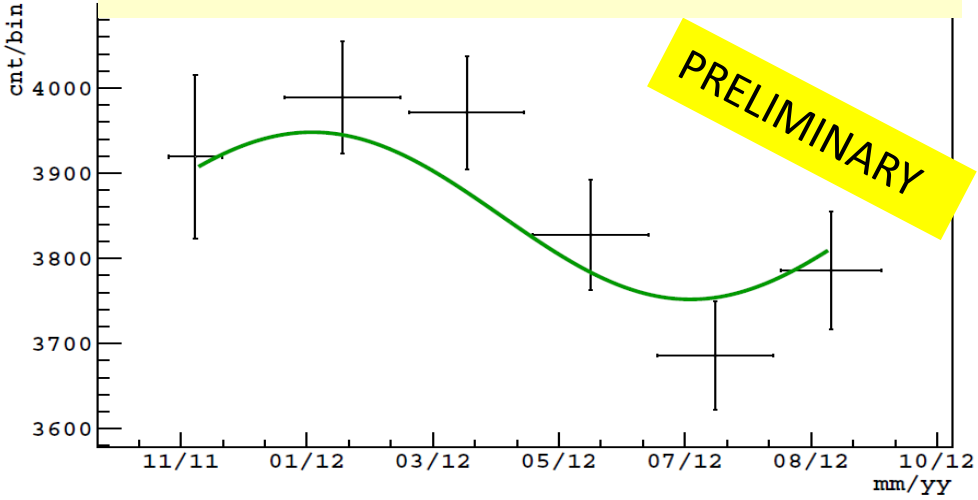
$$\Phi_{pep} = 1.6 \pm 0.3\ 10^{8}\ cm^{-2}\ s^{-1}$$

- Most of the solar ν_e components have been seen(except CNO): all in good agreement with SSM and the MSW-LMA solution
- Seasonal variation may be seen: an independent confirmation of solar ν_e observation





Results from Phase 2: Rate vs time



ranucci@EPS-HEP'13

Super-Kamiokande

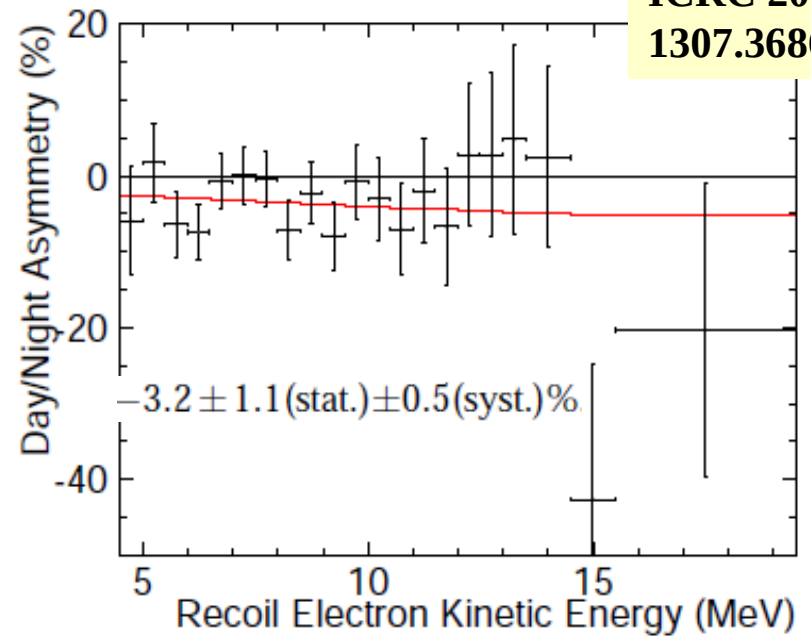
ICRC 2013
1307.3686

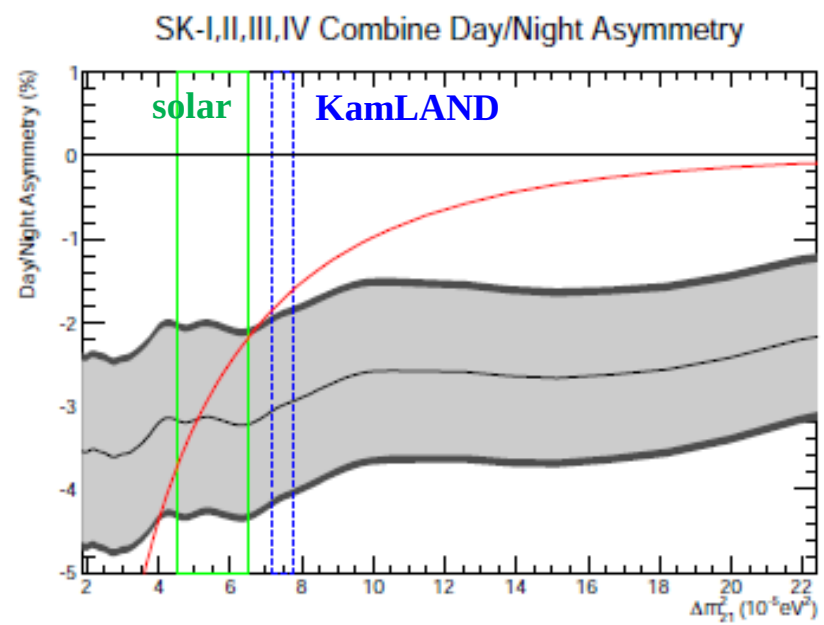
- Thanks to new electronics and tight FV cut, $E_{thresh} \sim 3.5$ MeV
- Improved θ_{12} & ΔM^2_{12} measurements in combination with other solar & KamLAND results:

$$\sin^2\theta_{12} = 0.304 \pm 0.013,$$

$$\Delta m^2_{21} = 7.45^{+0.20}_{-0.19} \times 10^{-5}\,\mathrm{eV}^2.$$

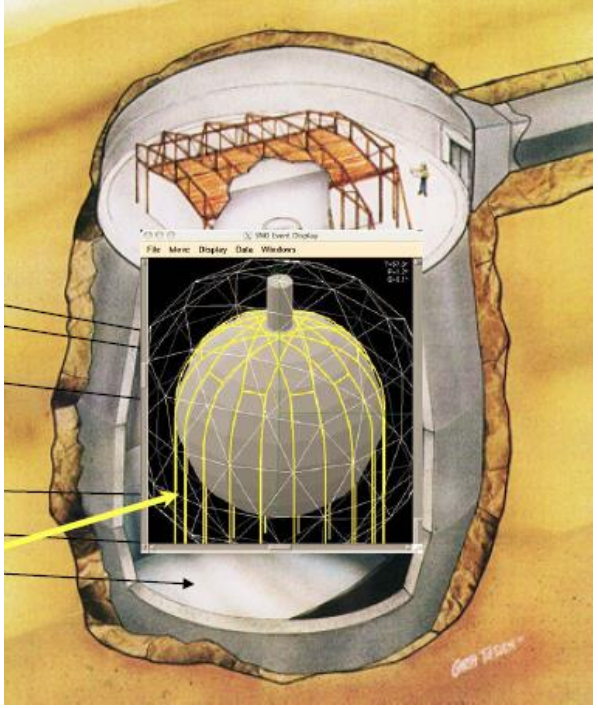
- A 2.7 σ Day-Night asymmetry is observed: indication of the regeneration of ν_e as they travel through earth matter
- In agreement with expectation (1 σ tension)

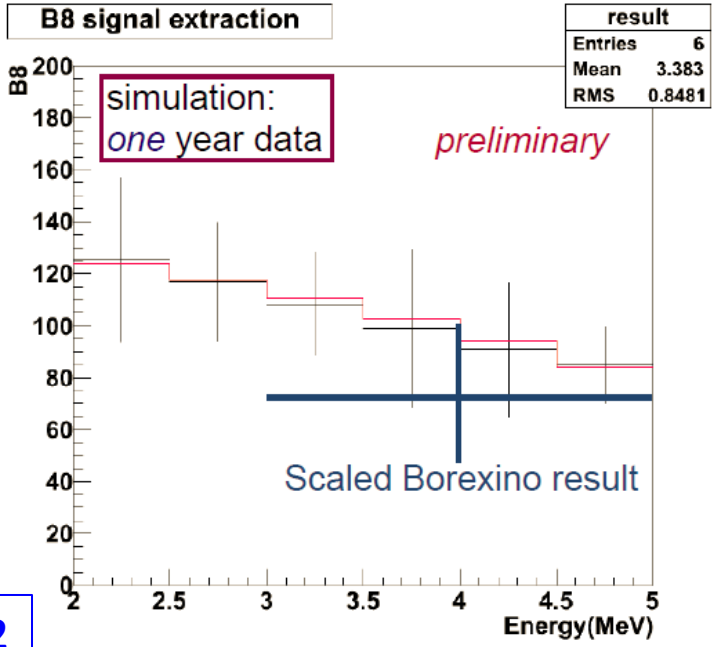




Future experiment: SNO+

- **Construction almost finished, to be operational next year**
  - 780t liquid scintillator(LAB)
  - 9500 PMTs
  - Water shielding
  - Hold down rope net on the 12 m diameter Acrylic vessel
- **Physics:**
  - Solar neutrinos
    - Better measurement of pep & ^{8}B neutrinos
    - Look for CNO neutrinos
  - Geoneutrinos
  - Supernova neutrinos
  - Double beta decays





McDonald@Neutrino'12

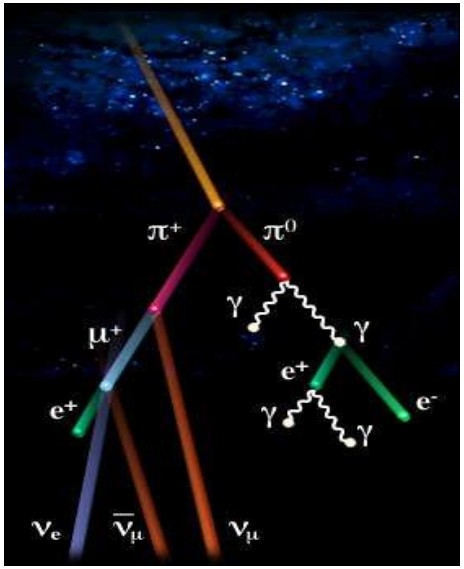
Future experiment: LENA

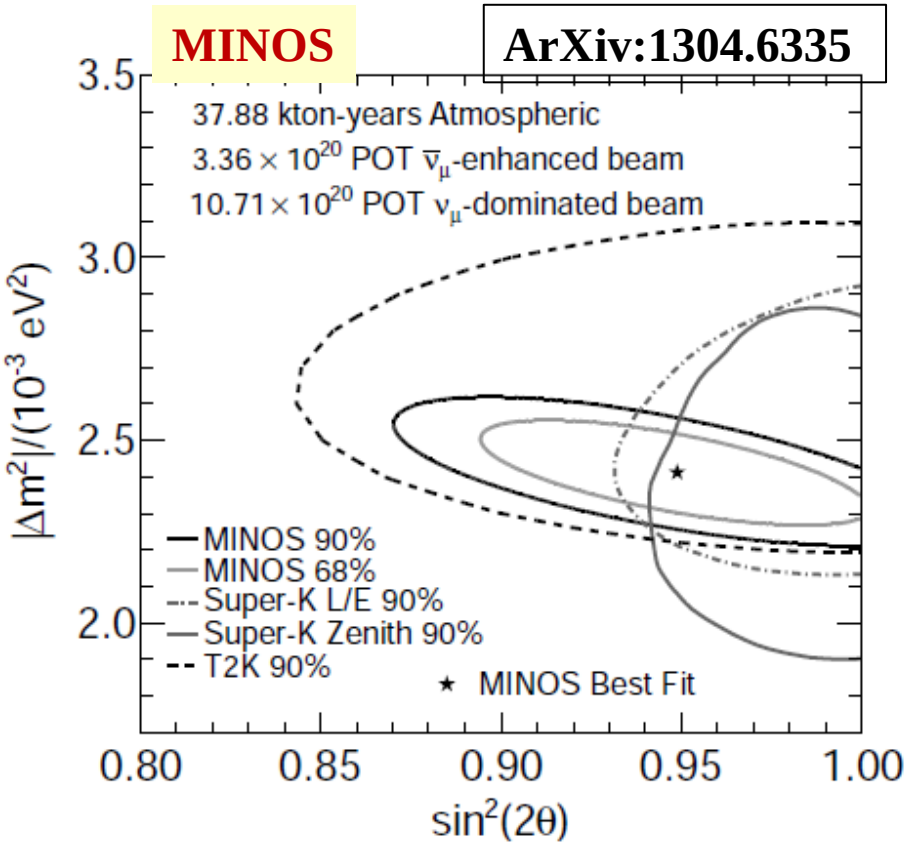
arXiv:1104.5620

- **The detector:**
  - 50 kt liquid scintillator(LAB)
  - 30,000 12” PMT with Winston cone, 30% coverage
  - Water Veto with 4000 8” PMT
- **Physics**
  - Solar neutrinos
    - CNO neutrinos for solar metallicity
  - Burst Supernova neutrinos
  - Diffused Supernova neutrinos
  - Geo-neutrinos
  - Short baseline neutrino oscillation experiment using radioactive sources: sterile neutrinos

Atmospheric neutrinos

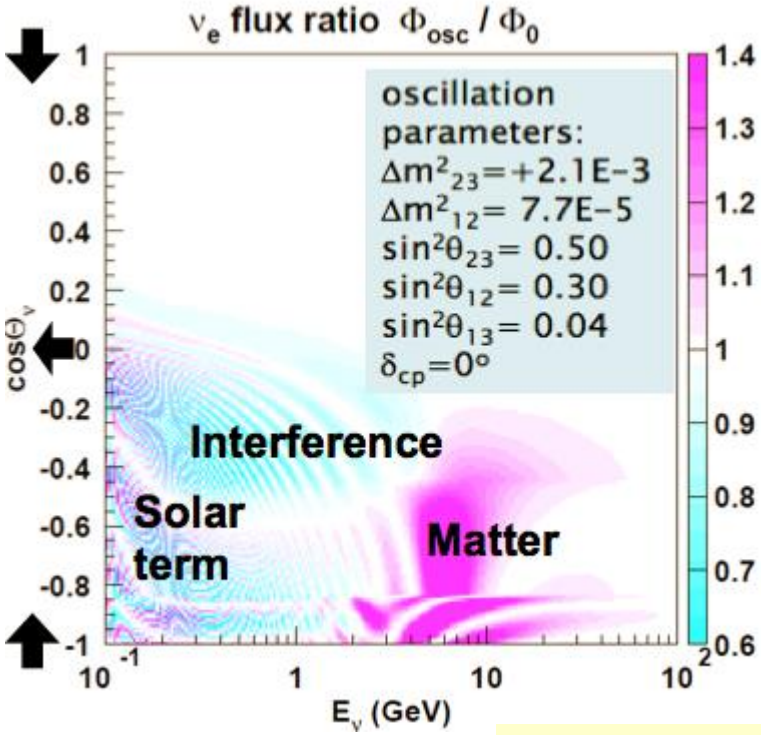
- Indications of anomaly (80's)
- Discovery of the neutrino oscillation by SuperK(98)
  - ⇨ Determination of θ_{23} & ΔM^2_{23}
  - ⇨ ν_μ oscillation: appearance of ν_τ
  - ⇨ Rejection of other explanations
- Current experiment:
  - ⇨ SuperK
- Main issues now:
  - ⇨ θ_{23} octant
  - ⇨ mass hierarchy
  - ⇨ CP phase
- Future experiments
  - ⇨ INO, PINGU, HyperK, …





Looking for sub-leading effects

- **Thanks to the huge statistics and large θ_{13}, we can look for:**
  - ⇨ **Mass hierarchy: enhanced high energy upward going ν_e due to the matter effect**
  - ⇨ **Octant of oscillation: enhanced low energy ν_e due to the solar term**
  - ⇨ **CP phase δ: interference between these two**



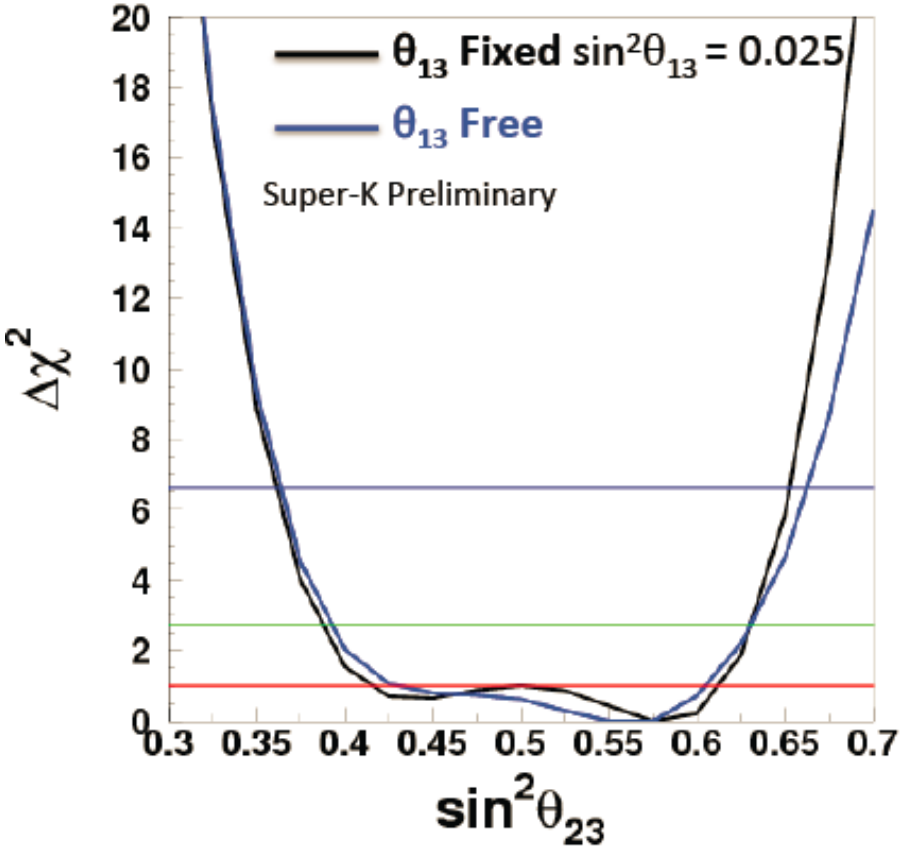
Walter@NeuTel'13

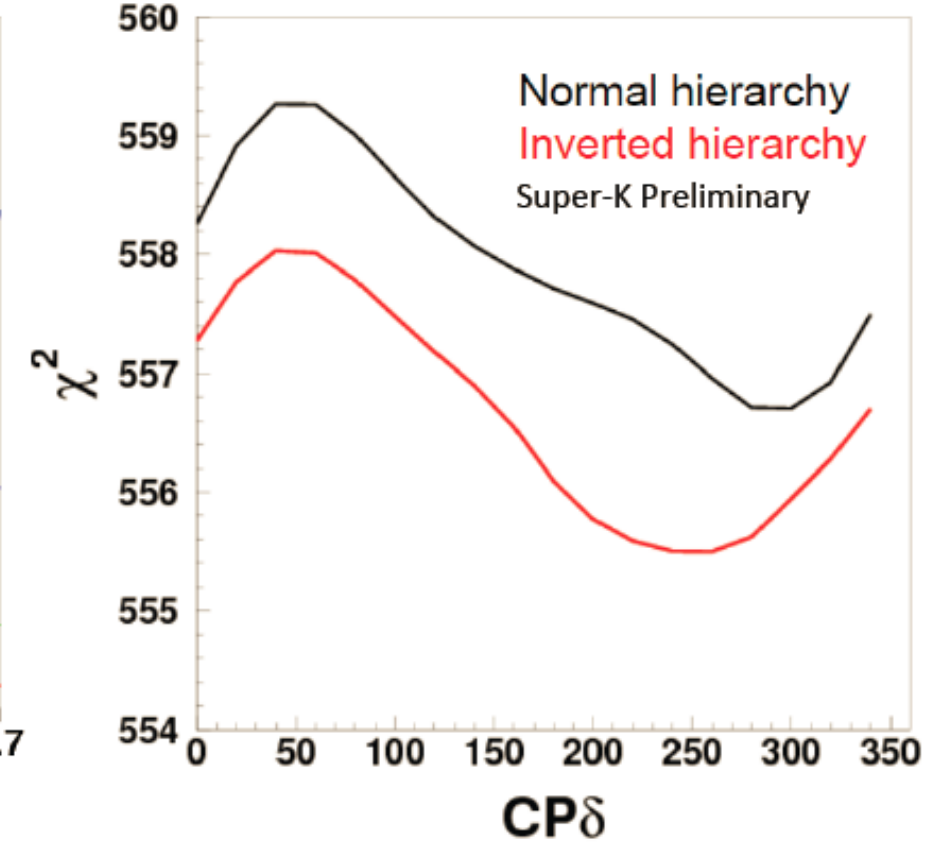
$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2 \cdot (r \cdot \cos^2\theta_{23} - 1)$$ **Solar term**

$$-r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin 2\theta_{23} \cdot (\cos\delta \cdot R_2 - \sin\delta \cdot I_2)$$ **interference**

$$+2\sin^2\tilde{\theta}_{13} \cdot (r \cdot \sin^2\theta_{23} - 1)$$ **Matter effect**

Recent Super-K results





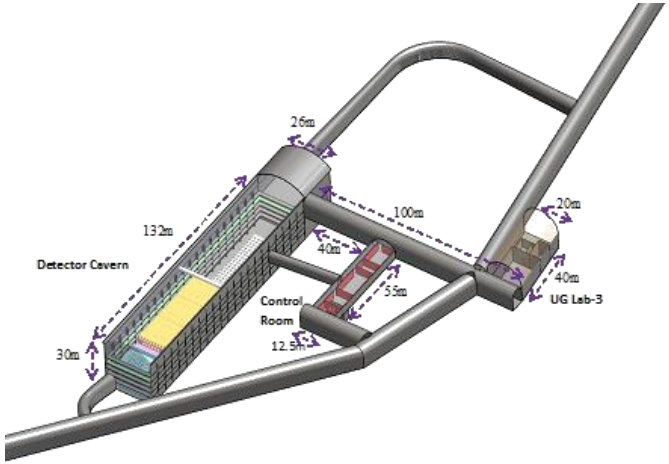
- Both free and constrained fits prefer 2nd octant
- 1.2σ preference for inverted hierarchy

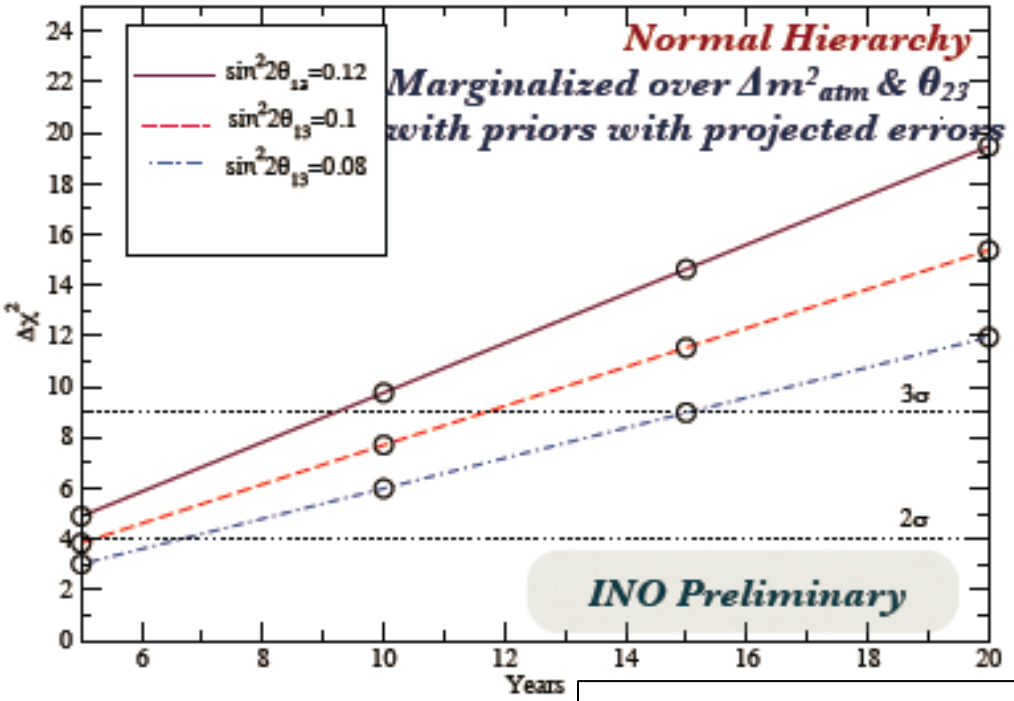
  sensitivity is 0.9σ

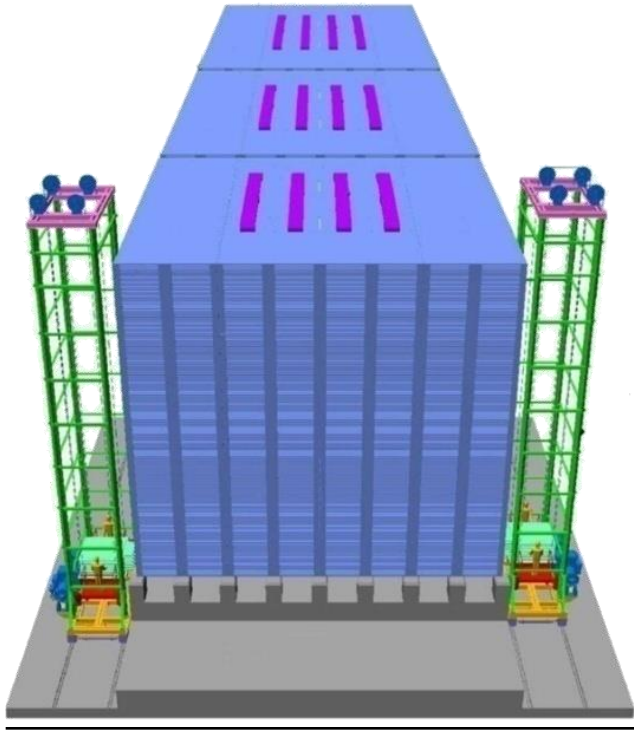
} Not significant!

Future experiment: INO

- INO(India-based Neutrino Observatory): 50kt magnetized iron plates interleaved with RPCs: Sign sensitive
- Construction started, operational: 2018
- Sensitivity to mass hierarchy: ~3σ after 10 years running



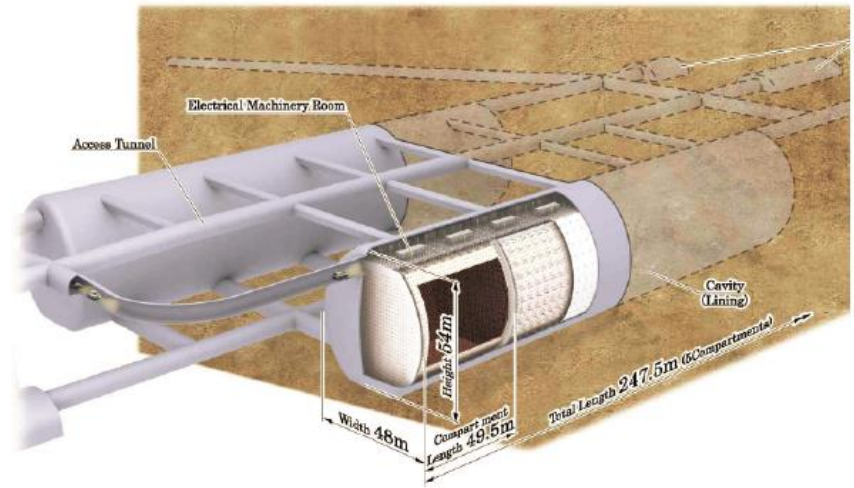


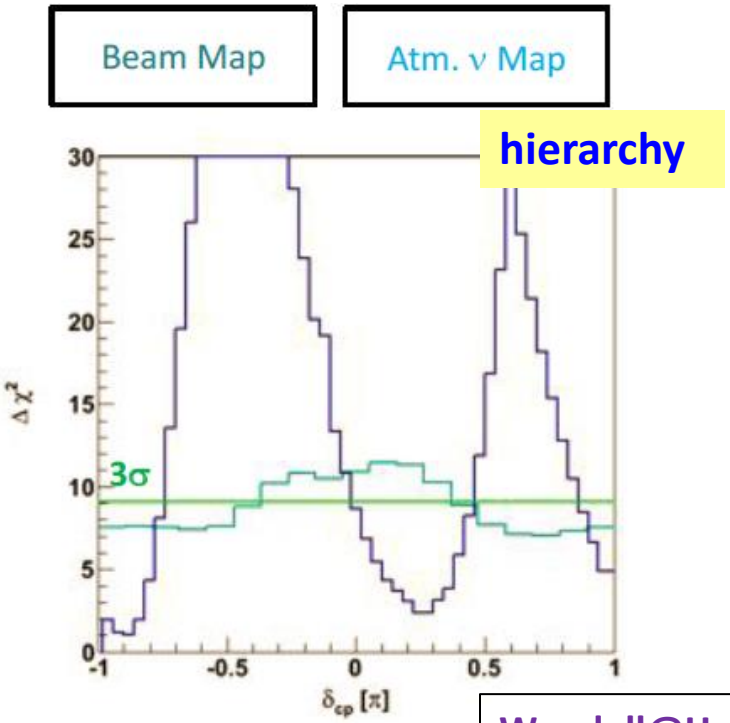


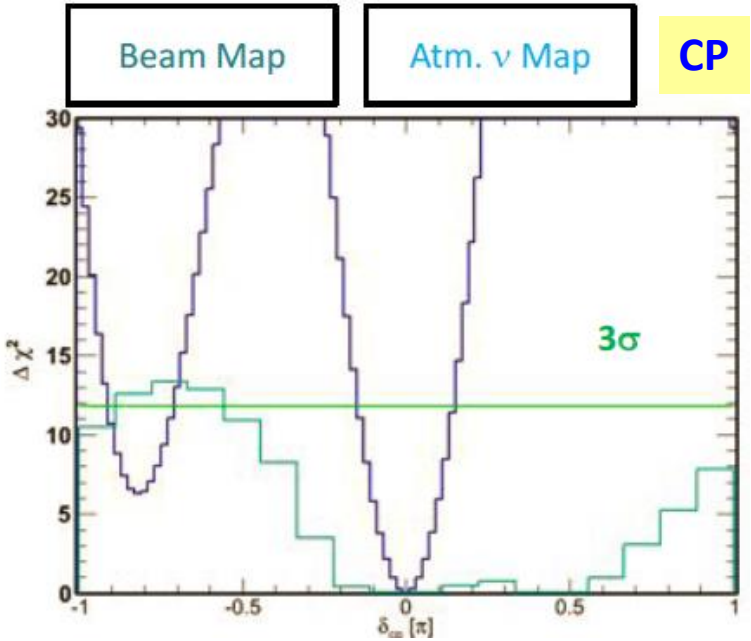
Choubey@neutrino'12

Future experiment: HyperK

- 1 Mt water Cerenkov detector
- 99000 20” PMT, 20% coverage
- Octant issue: $\Delta\sin^2\theta_{23} < 1\%$
- Mass hierarchy: complementary to T2HK
- CP: T2HK much better



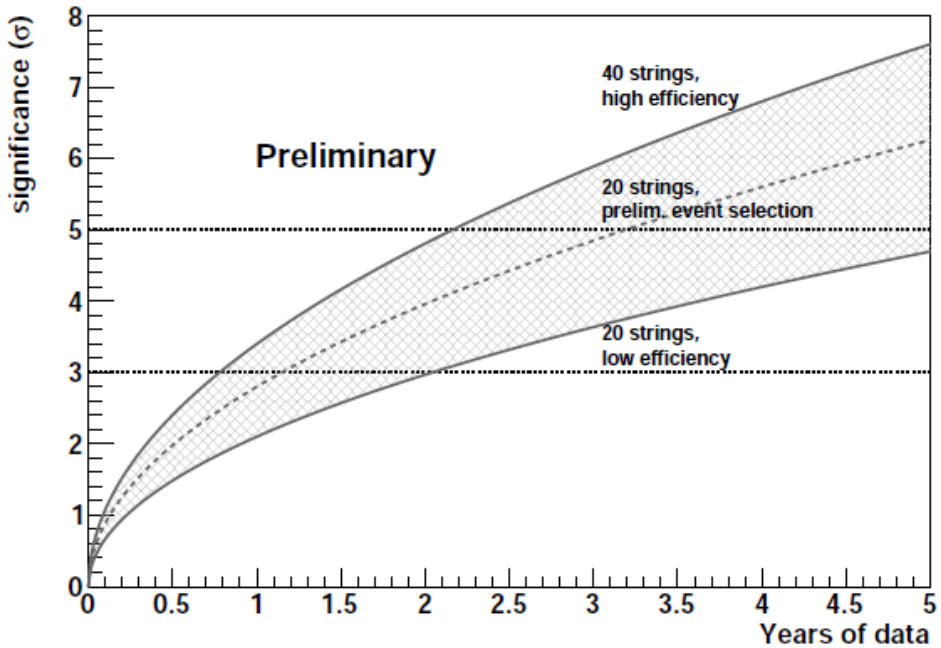


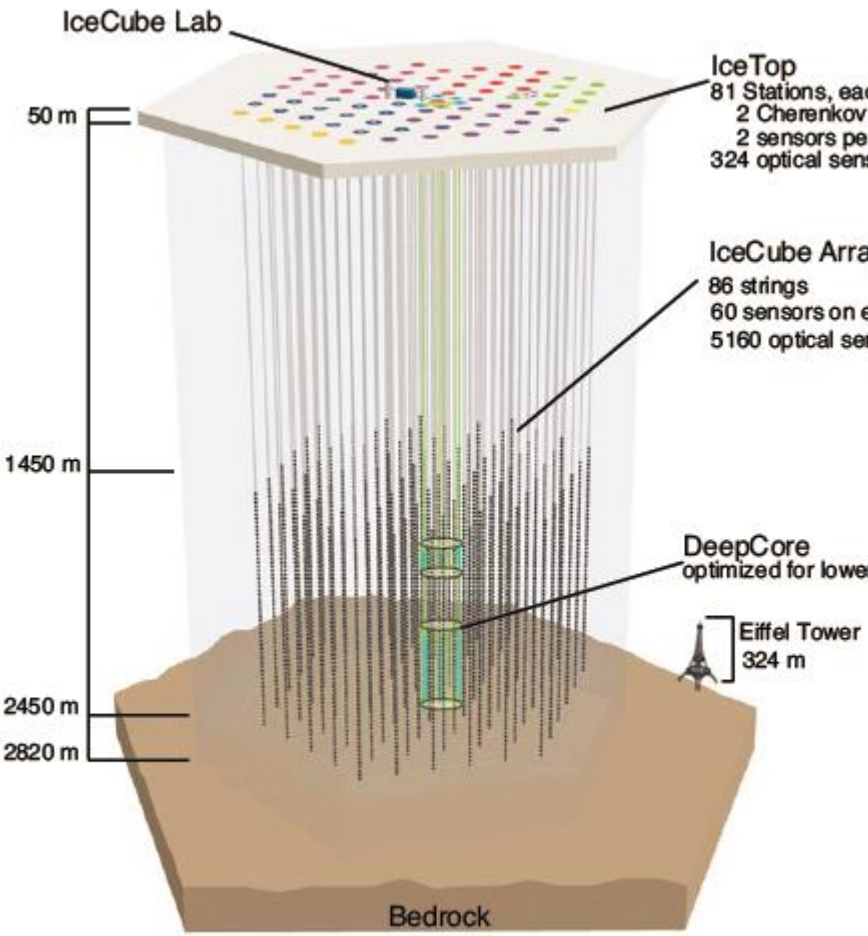


Wendell@HyperK open meeting 2012

Future experiment: PINGU

- A large ice Cerenkov detector with E_{thresh} ~ 1 GeV
  - ⇨ 20 strings with a spacing of 26 m
  - ⇨ Existing IceCube as the VETO
- Equivalent target mass: ~10 Mt
- Sensitivity: ~ 3σ in < 2 years (2020)



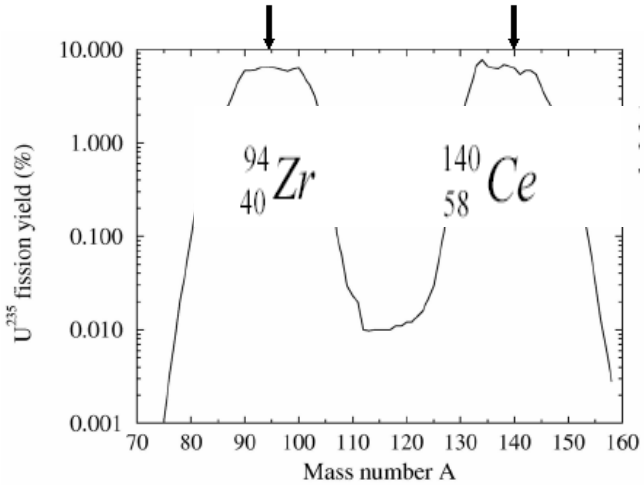


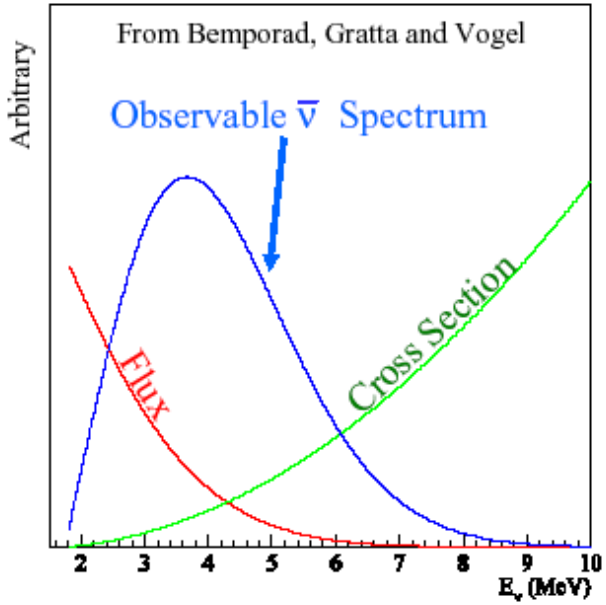
arXiv:1306.5846

Reactor neutrinos

- Direct detection of neutrinos(50's)
- 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
- Magnetic moments(90's-00's):
  - ⇨ Texono, MUNU,…
- Mass hierarchy(10's-20's):
  - ⇨ JUNO, RENO-50
- Sterile neutrinos(10's):
  - ⇨ Nucifer, Stereo, Solid …

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$

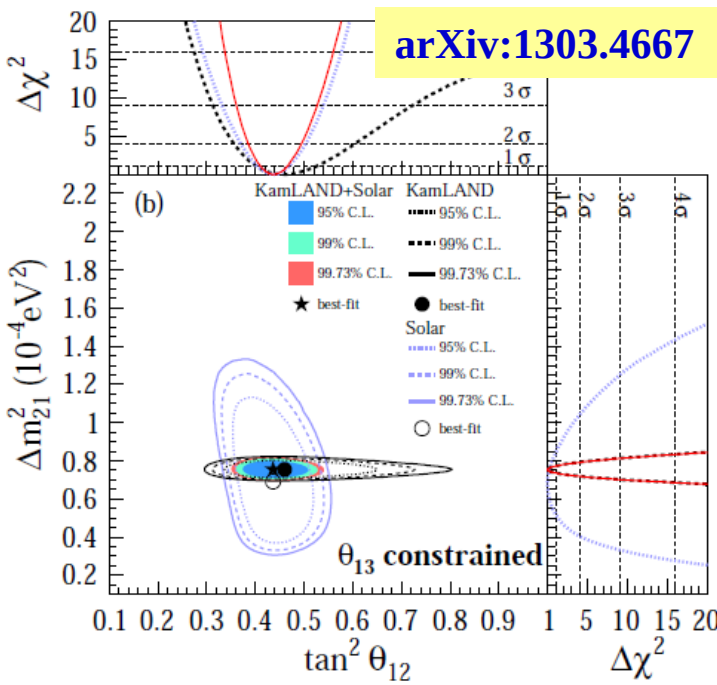


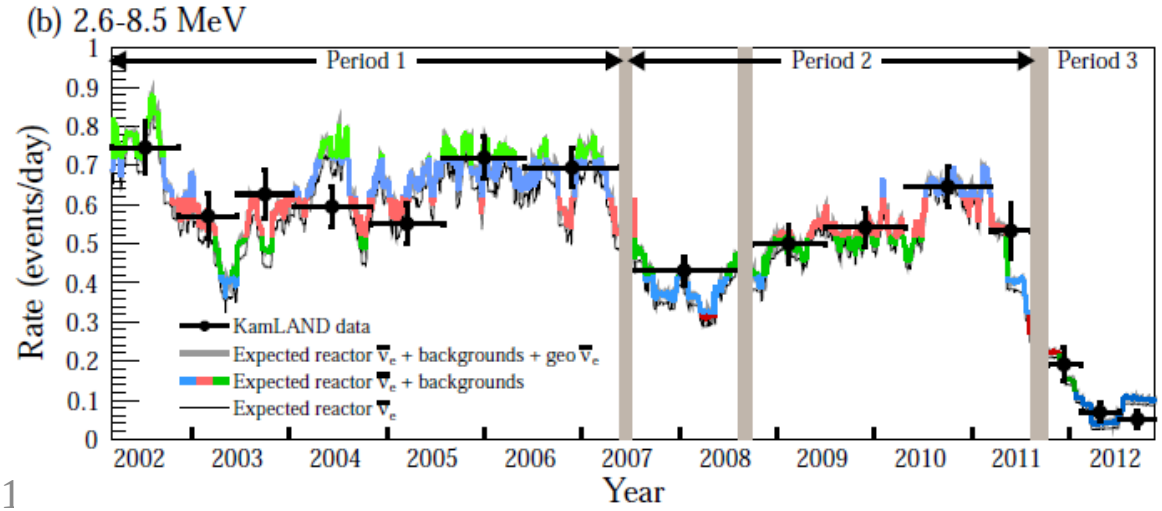


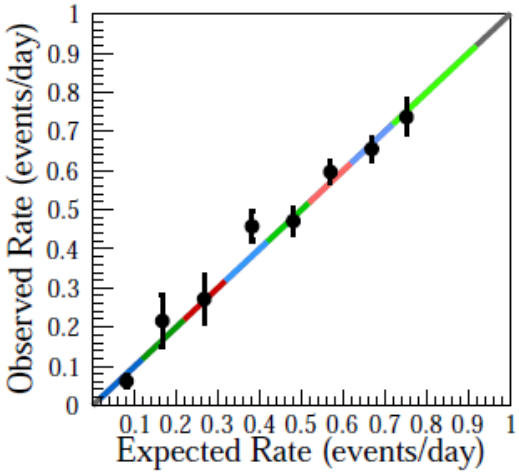
Latest KamLAND Results: θ_{12} & ΔM^2_{12}

- **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}	$7.53^{+0.18}_{-0.18}$	$0.436^{+0.029}_{-0.025}$	$0.023^{+0.002}_{-0.002}$



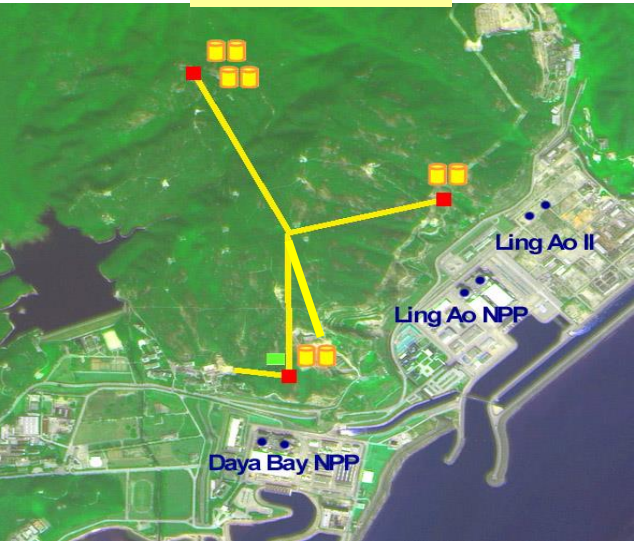




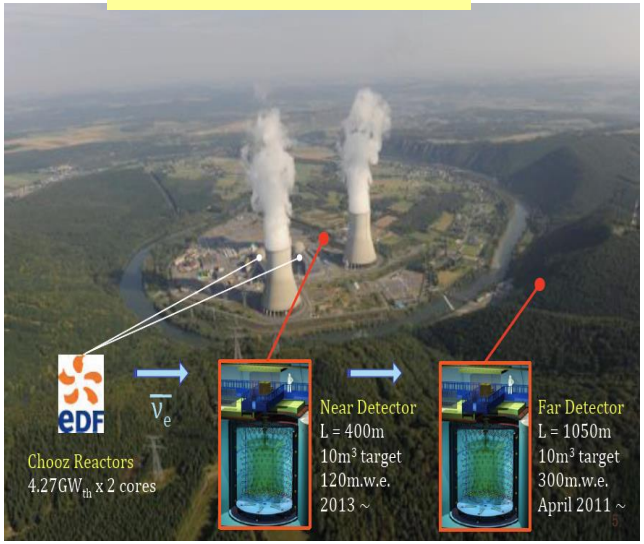
θ_{13}: Three on-going experiments

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

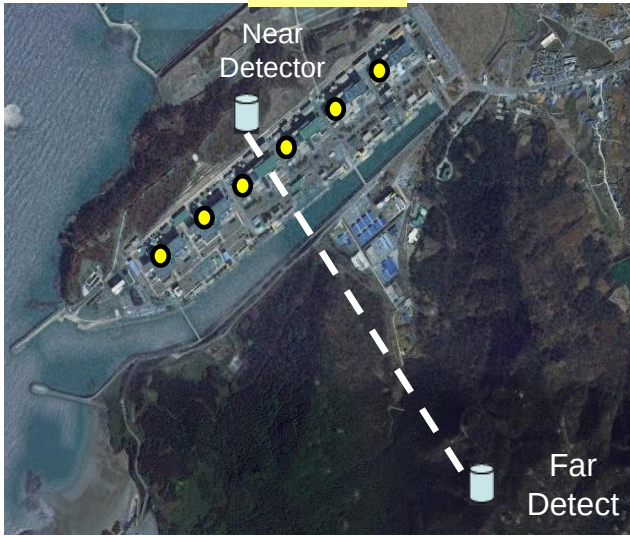
Daya Bay



Double Chooz

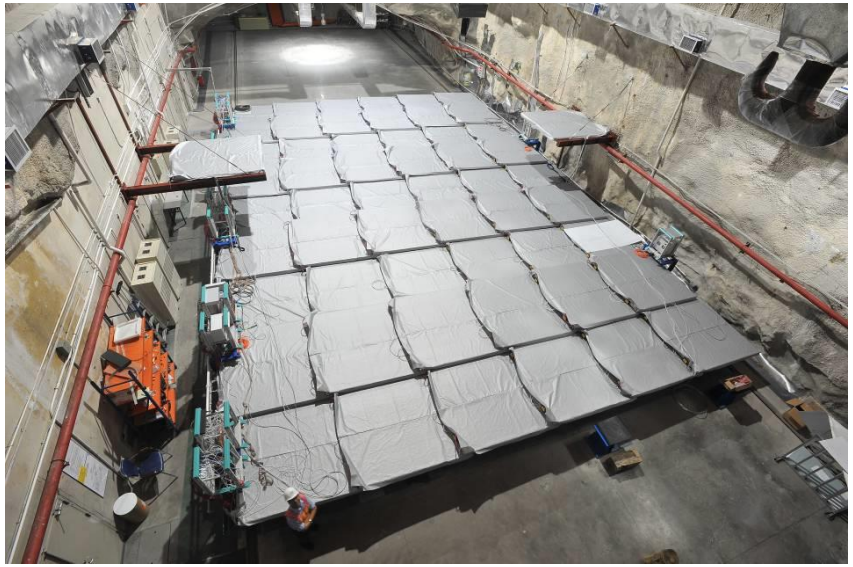


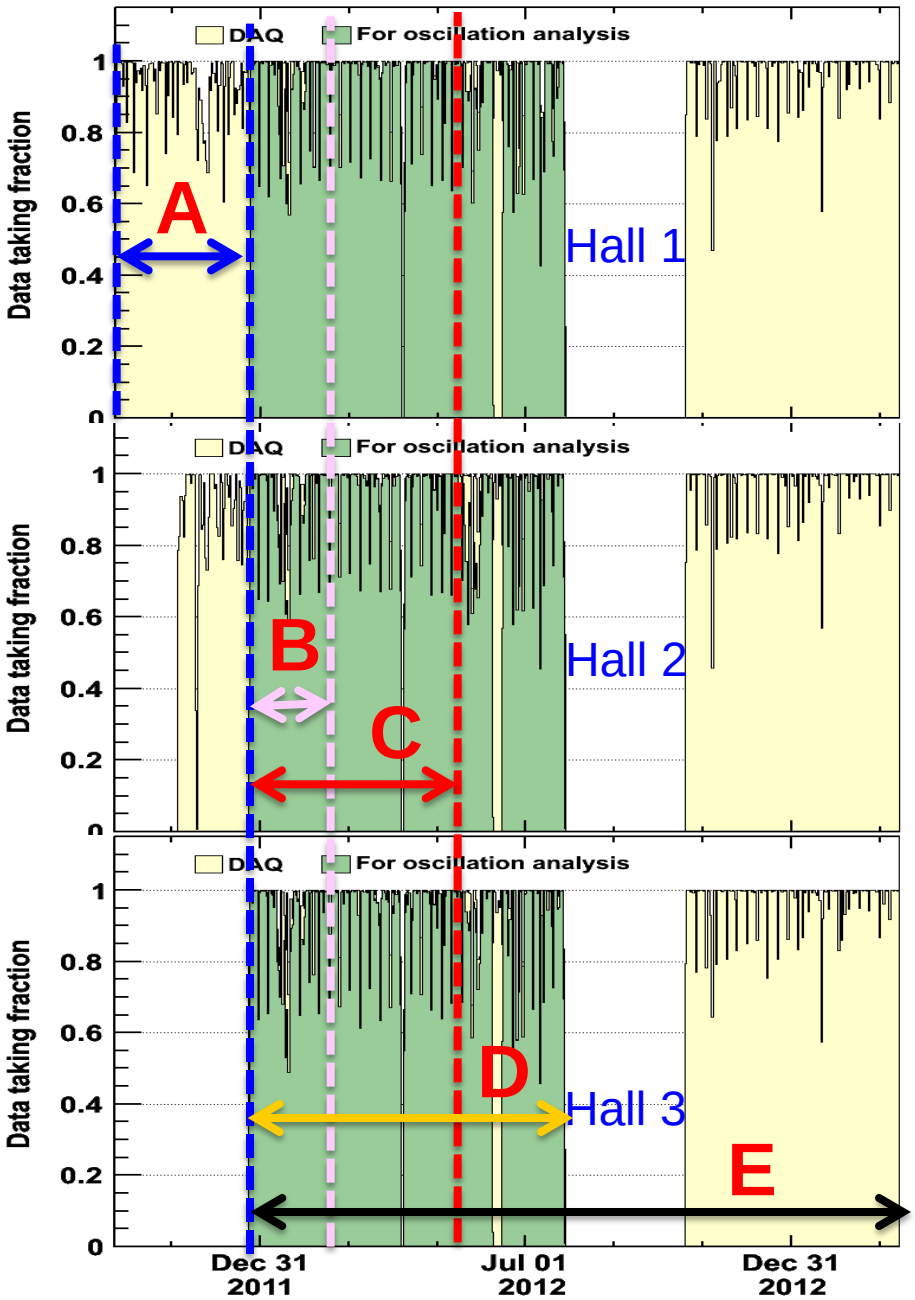
Reno



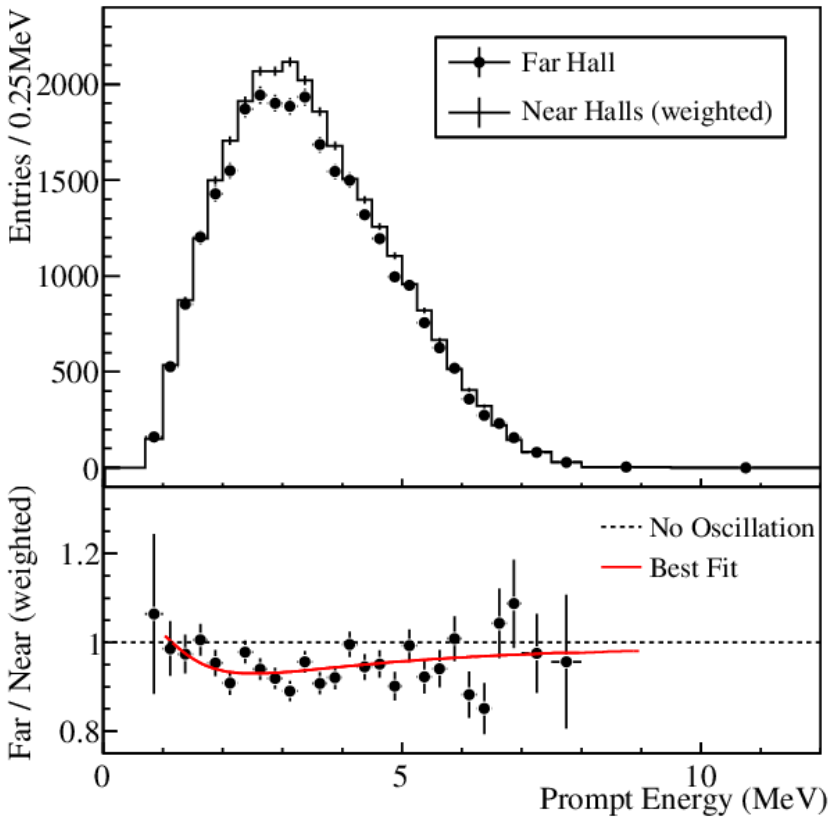
Daya Bay：Data taking & analysis status

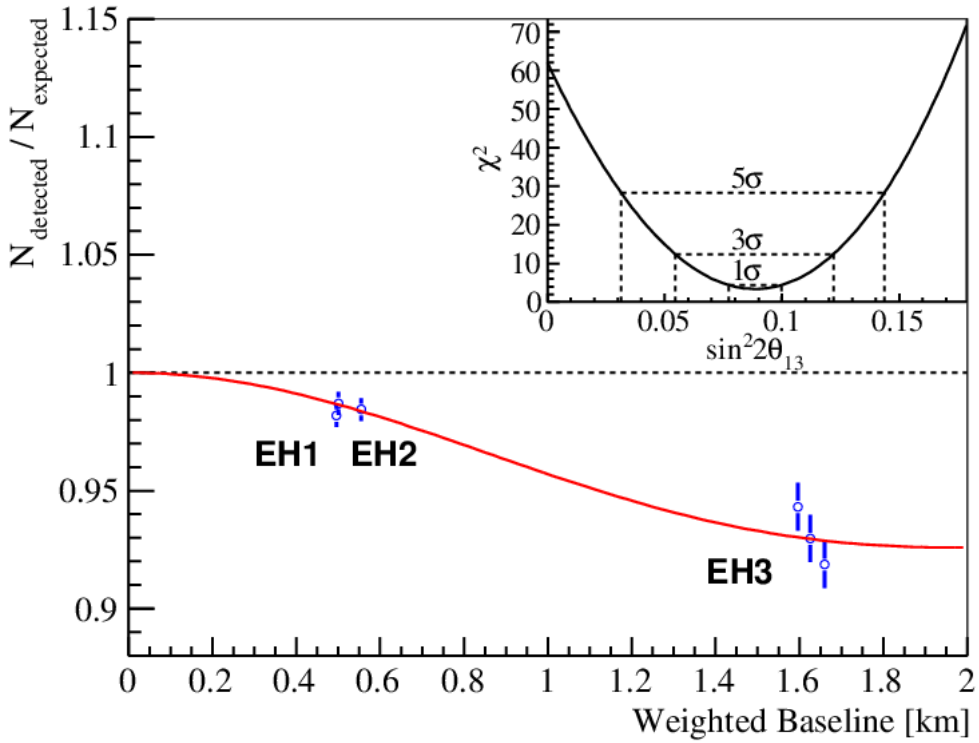
- A→Two Detector Comparison:
  Sep. 23, 2011 – Dec. 23, 2011
  NIM A 685 (2012), pp. 78-97
- B→First Oscillation Result:
  Dec. 24, 2011 – Feb. 17, 2012
  Phys. Rev. Lett. 108, 171803 (2012)
- C→Updated analysis:
  Dec. 24, 2011 – May 11, 2012
  Chinese Physics C37, 011001 (2013)





Daya Bay：Results(C)





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

R = 0.944 ±0.007 (stat) ±0.003 (syst)

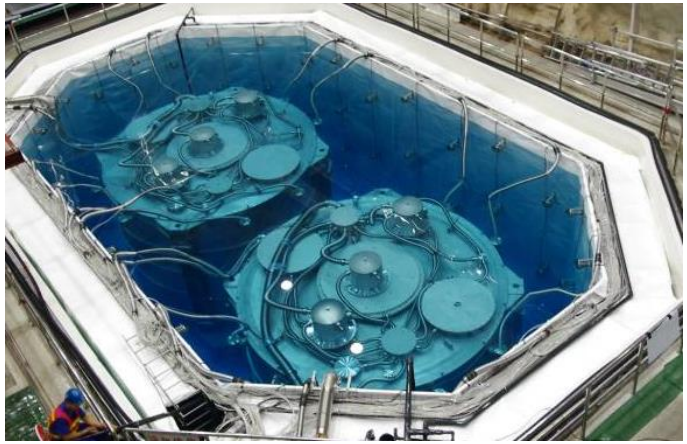
$\sin^2 2\theta_{13}$ = 0.089 ± 0.010(stat) ± 0.005(syst)

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

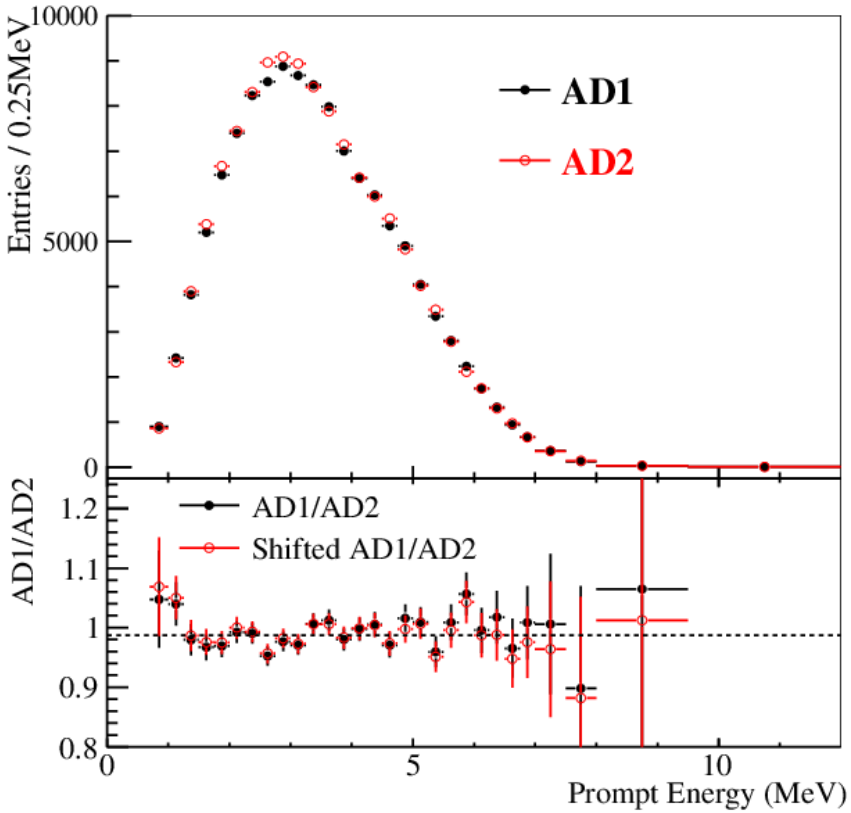
Rate+Shape analysis for (D) will be announced at NuFact in Aug. at IHEP

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

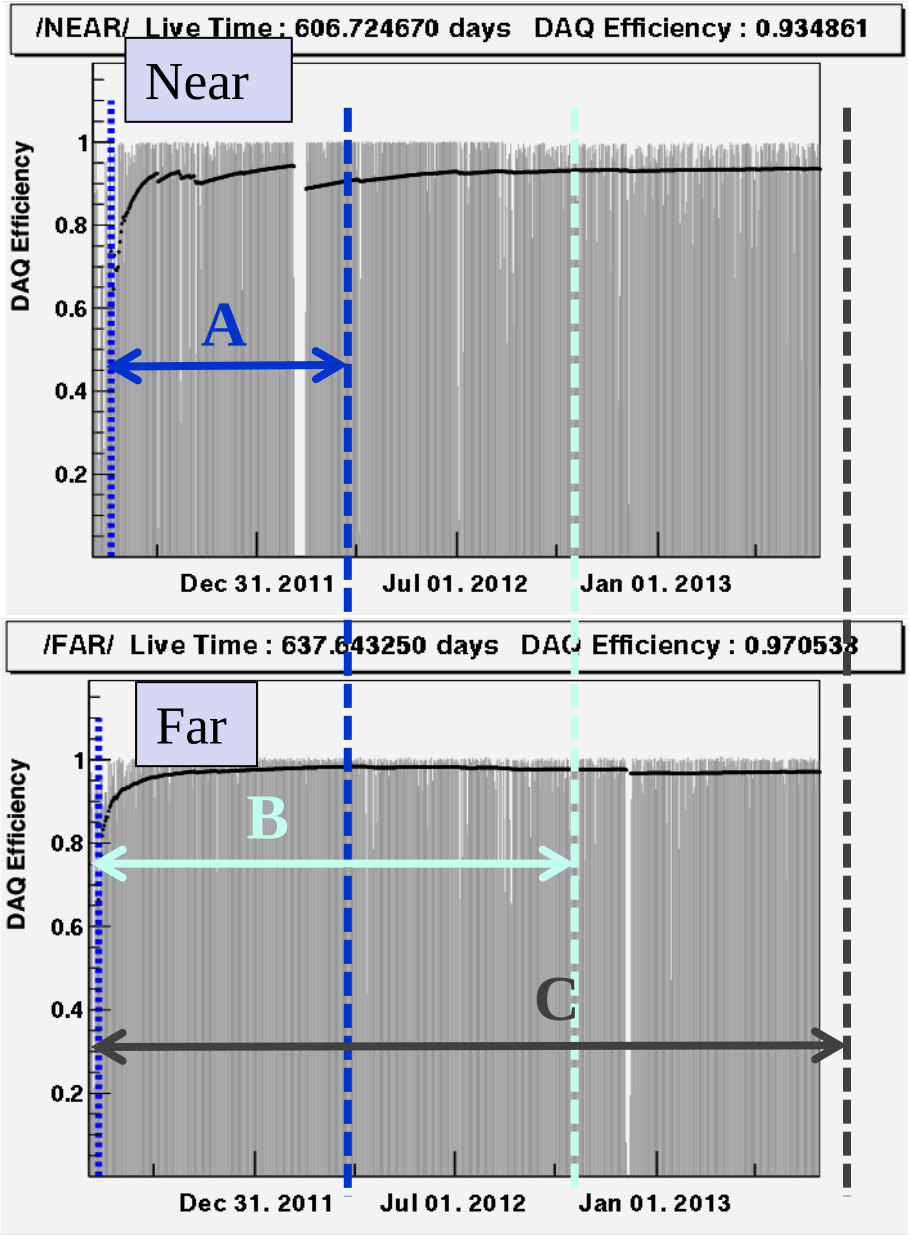
- Data taking began on Aug. 1, 2011 with both near and far detectors.
  (DAQ efficiency : ~95%)

- **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

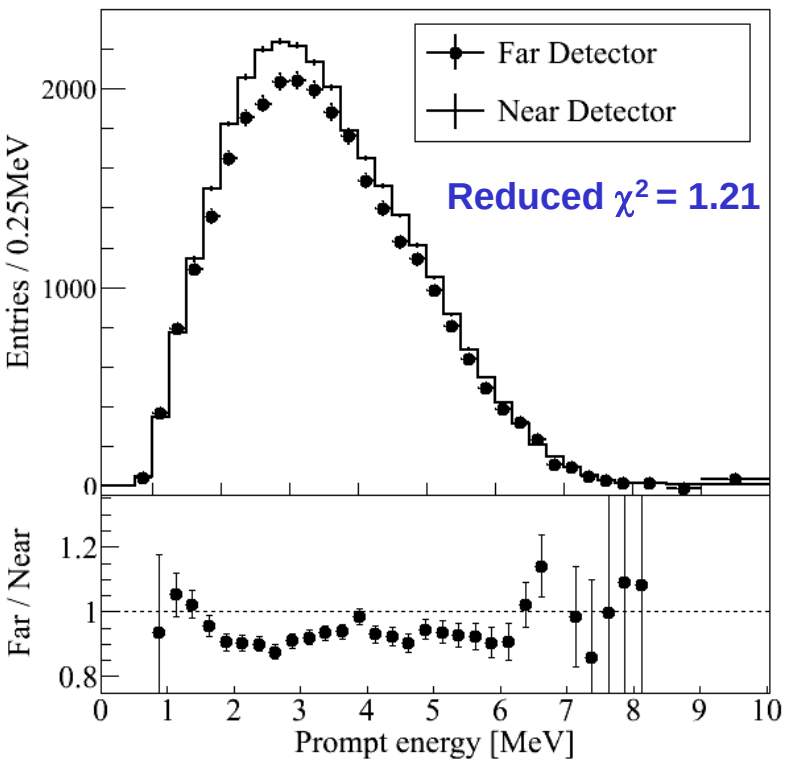
RENO Results

- 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.

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



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

Statistics:

-- about twice more data

Systematics:

-- Improved background estimation/reduction

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

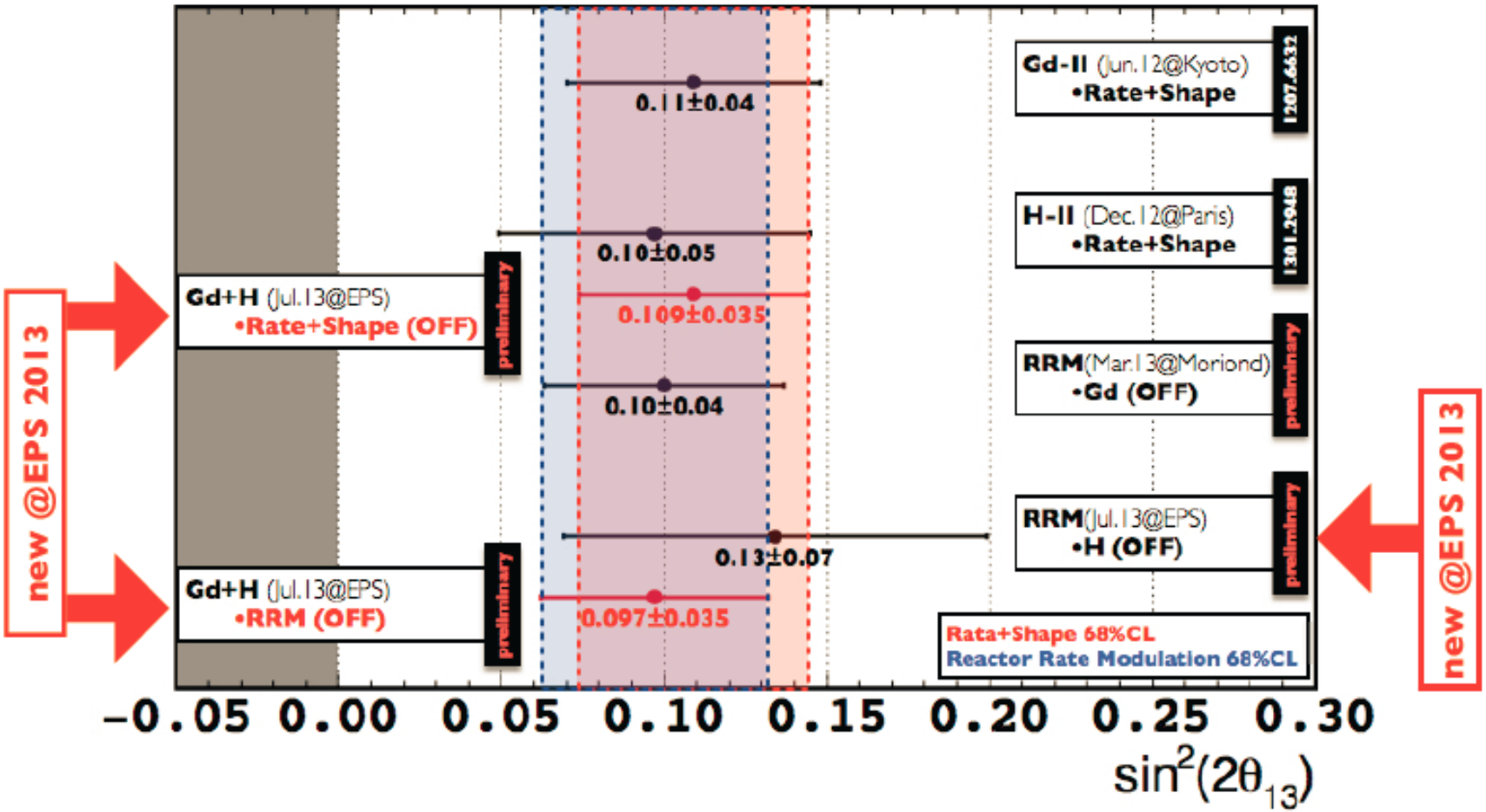
-- Improved energy scale calibration

For details, see Seon-Hee Seo's talk at NeuTel'13

Double Chooz: many results

4 measurements→ 2 combined (*Gd & H*) measurements

[**preliminary** correlations matrix→detector + flux + BG]



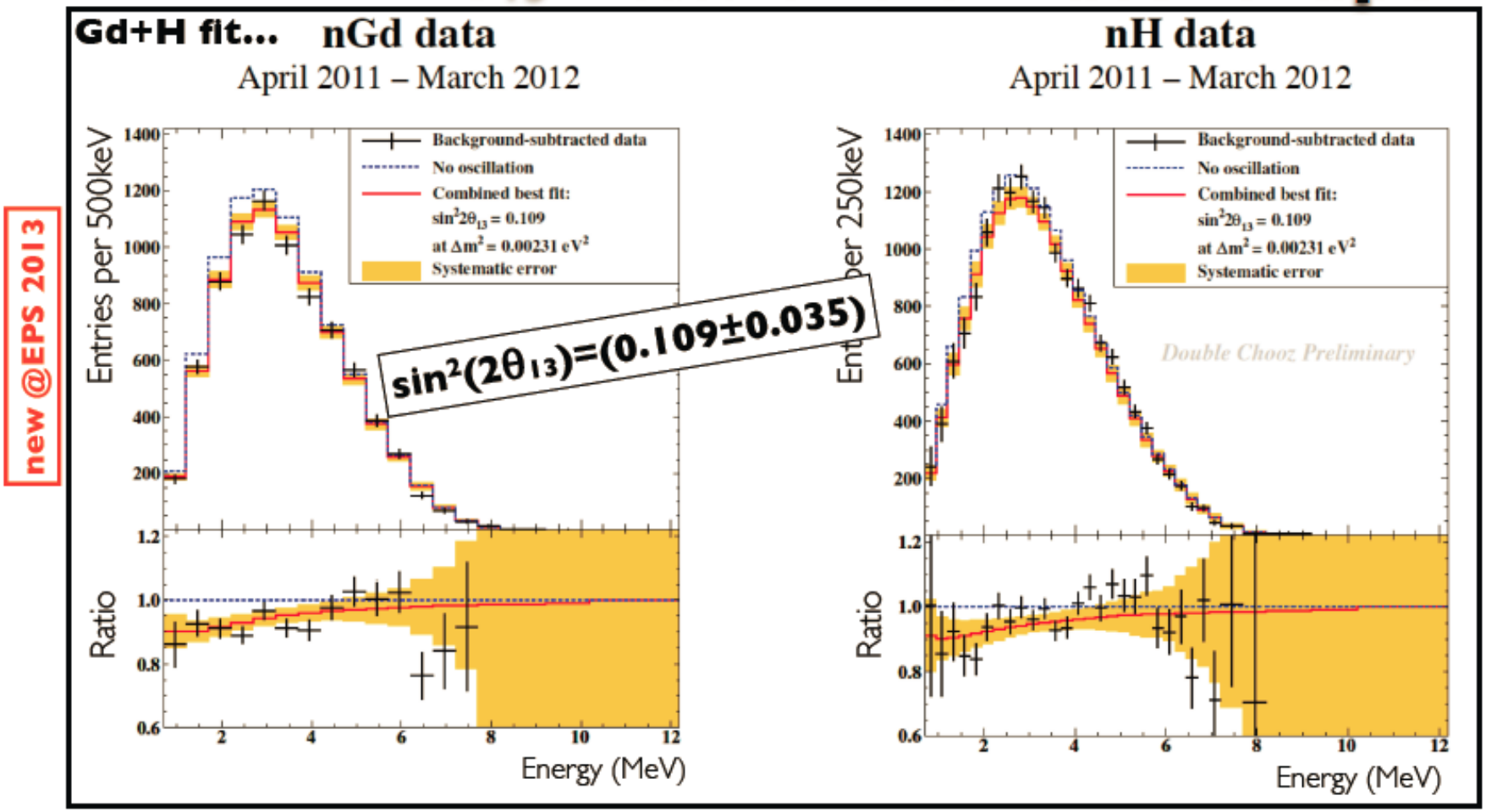
remarkable agreement (R+S & RRM) both Gd and H sample→**accuracy validation**

combined Gd & H individual measurements→**higher precision**

[DC internal validation cross-checks→(future) compare against Daya Bay & RENO]

Anatael Cabrera (CNRS-IN2P3 & APC)

θ_{13} measurement→**rate+shape**...

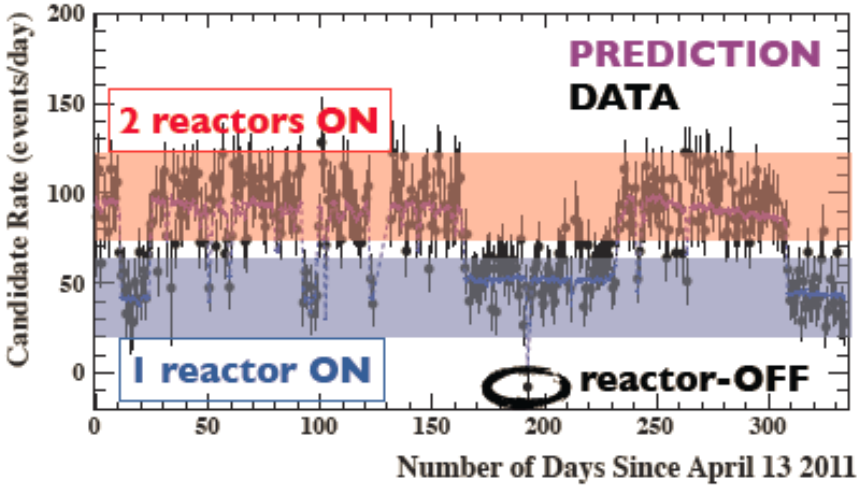


$\sin^2(2\theta_{13})$ measured via spectral distortion & rate deficit (disappearance) [**only DC**]

- **signal:** includes consistency against oscillation E/L distortion (≥6MeV ~irrelevant)
- **BG:** full spectral info for every BG (→what if missing any BG?)
- **detector:** ~1% precision energy reconstruction [data/MC→non-linearities, etc.]

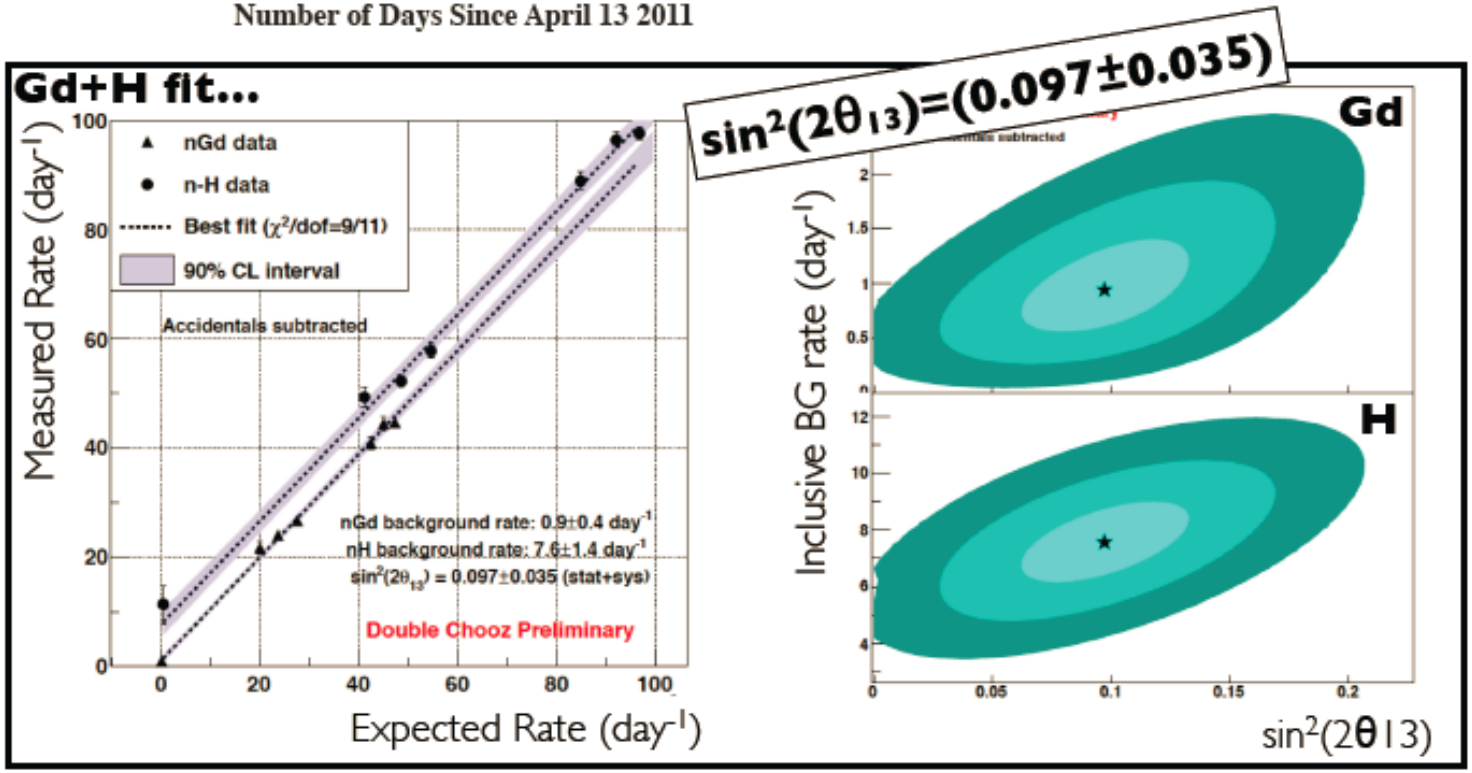
Anatael Cabrera (CNRS-IN2P3 & APC)

Reactor Rate Modulation(RRM) method



- **DC simple site:** 2 powerful reactors
  - → 100% flux modulation (→reactor-OFF)
- **reactor-OFF:** naked BG (inclusively)
- **reactor-ON:** IBDs+BG
- **RRM analysis** [**only DC**]
  - → slope[**$\sin^2(2\theta_{13})$**] & intercept[**BG rate**]
  - → combined Gd+H samples (more precise)

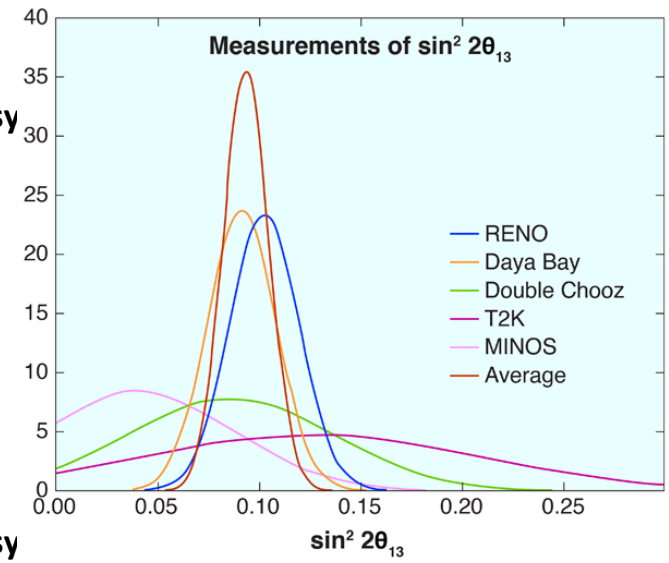
new @EPS 2013



Anatael Cabrera (CNRS-IN2P3 & APC)

Summary of latest reactor results

- **Daya Bay**
  - ⇨ Gd rate: $\sin^2 2\theta_{13} = 0.089 \pm 0.010^{stat} \pm 0.005^{sy}$
- **Double Chooz**
  - ⇨ Rate+Shape: $\sin^2(2\theta_{13}) = 0.109 \pm 0.035$
  - ⇨ RRM: $\sin^2(2\theta_{13}) = 0.097 \pm 0.035$
- **RENO**
  - ⇨ Gd rate: $\sin^2 2\theta_{13} = 0.113 \pm 0.013^{stat} \pm 0.019^{sy}$



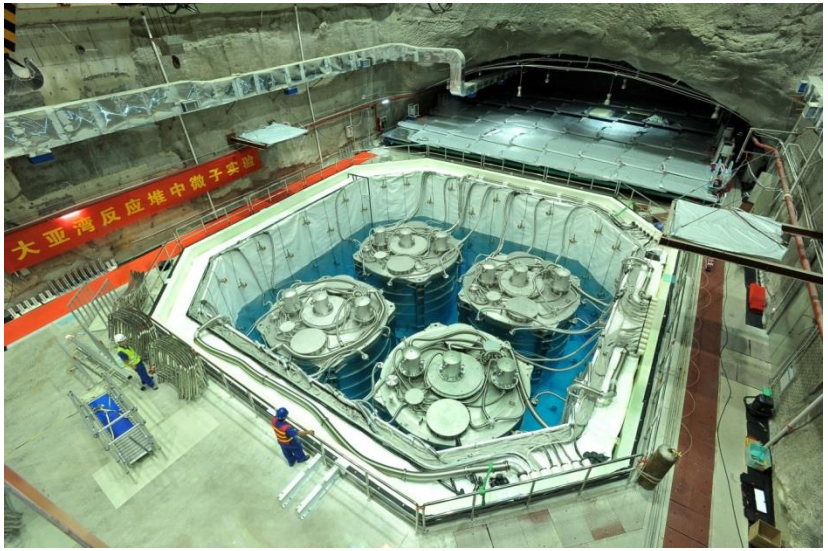
- **Can we take their weighted average ?**

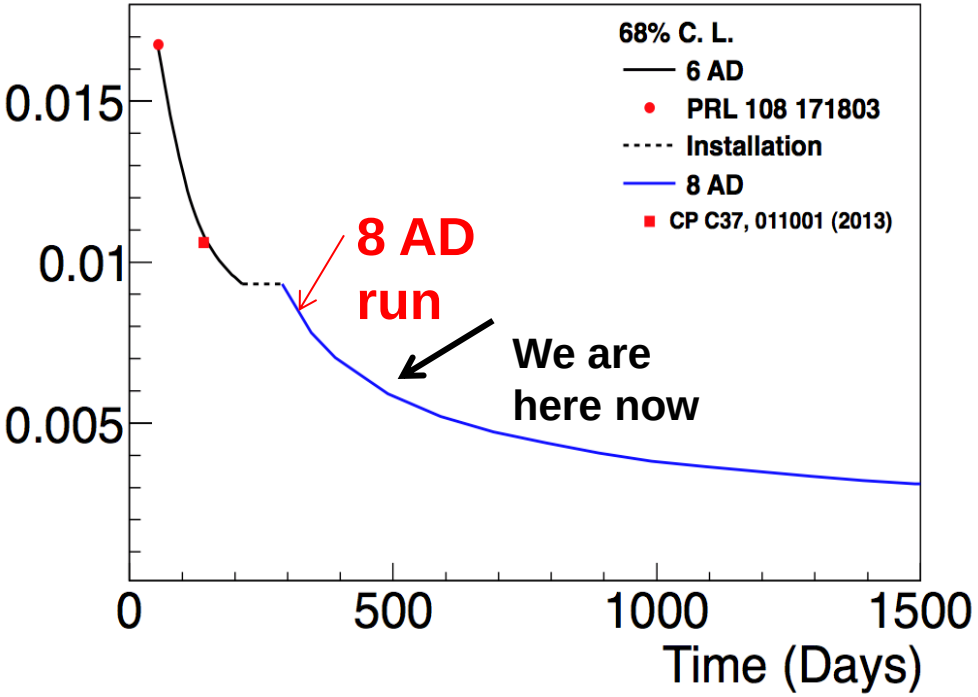
  Yes, if following issues are properly dealt:
  - ⇨ Correlated errors between experiments
  - ⇨ Errors are estimated in a unified way

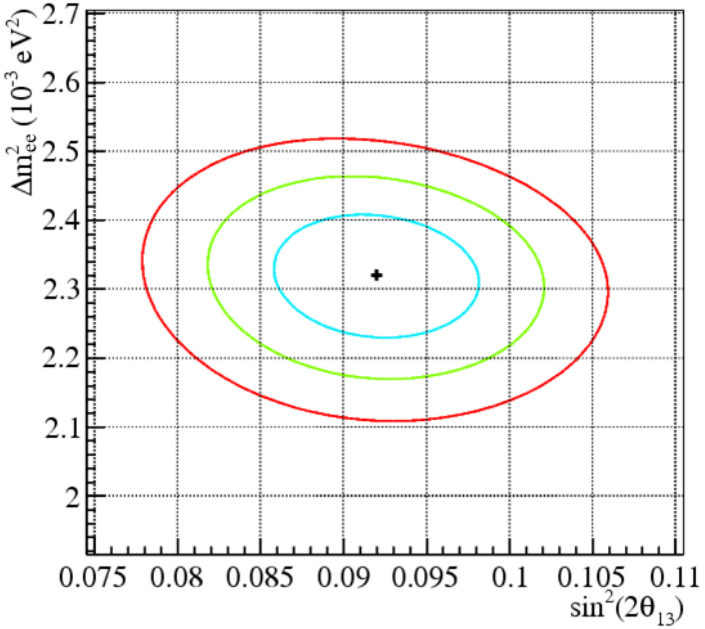
The three experiments will work together to report results in a coherent way, and probably can report a combined result.

Future prospects: Daya Bay

- Calibration & maintenance completed last summer.
- Full detector operational since Oct. 2012
- Precision in 3-5 years: ~4%

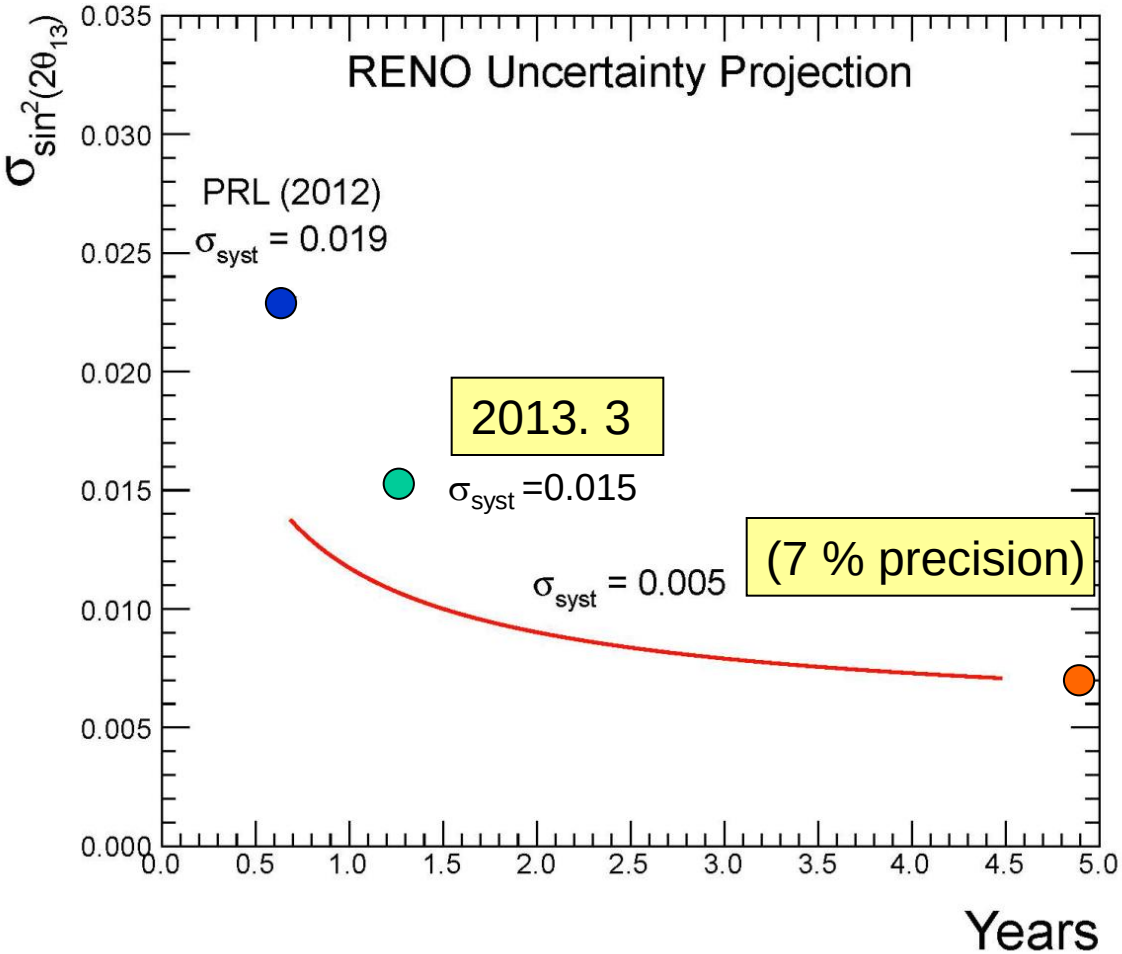






RENO's Projected Sensitivity of θ_{13}

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



- **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

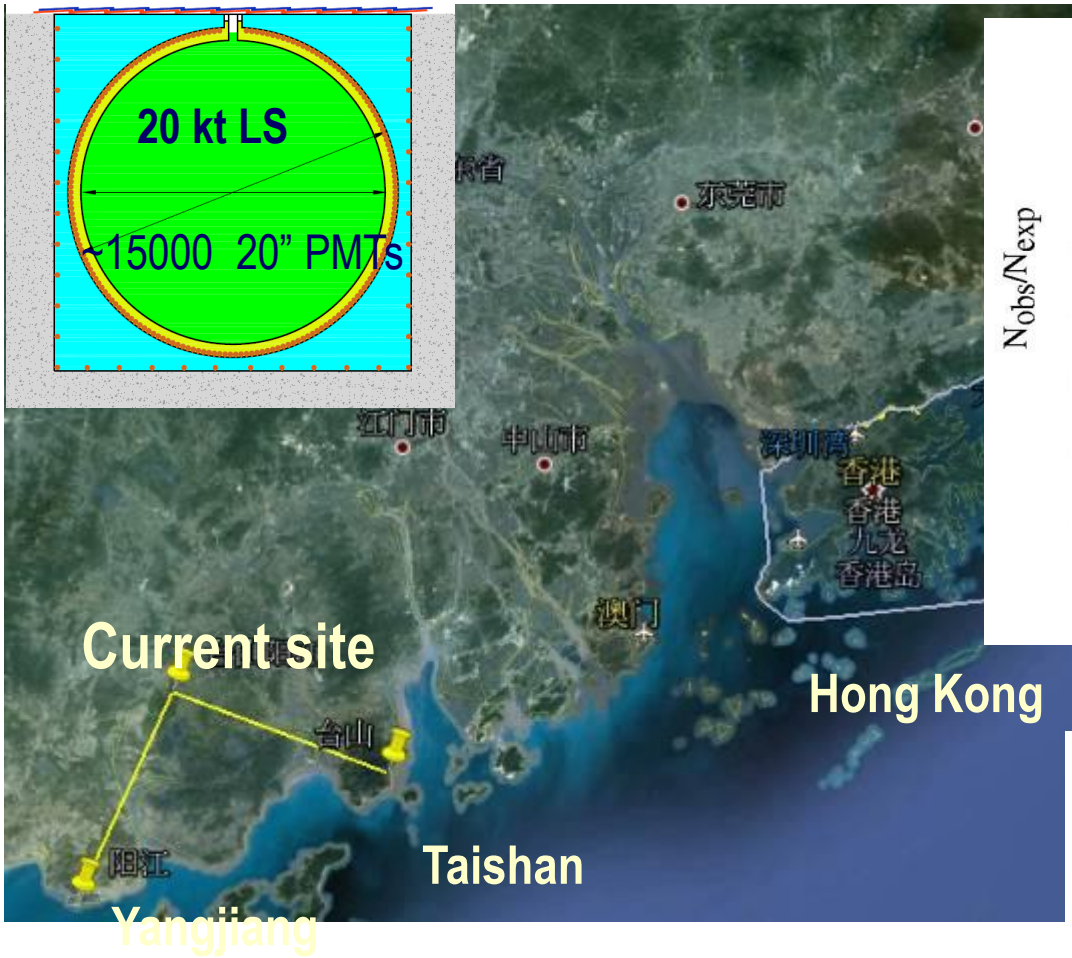
Double Chooz

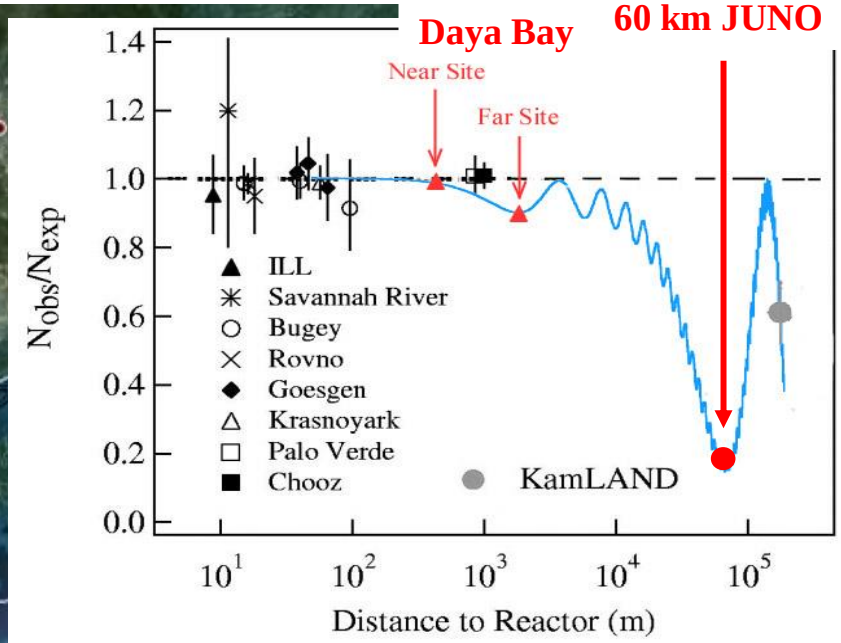
- **Near detector in construction till Spring 2014.**
- **The first result of the full experiment will be available at the end of 2014, towards a final precision of 10%.**

From Herve de Kerret

Future Experiment: JUNO

	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

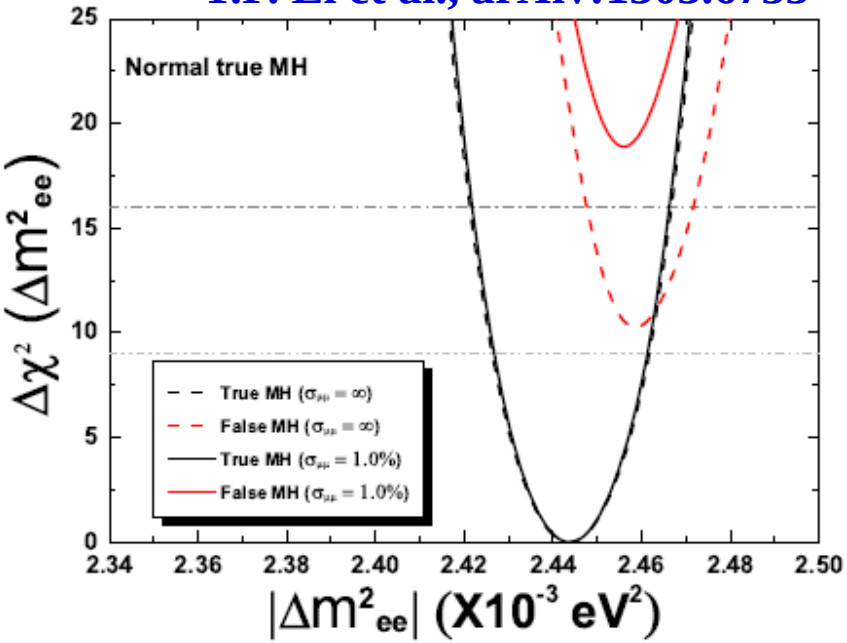
Physics Reach

Thanks to a large θ_{13}

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

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

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

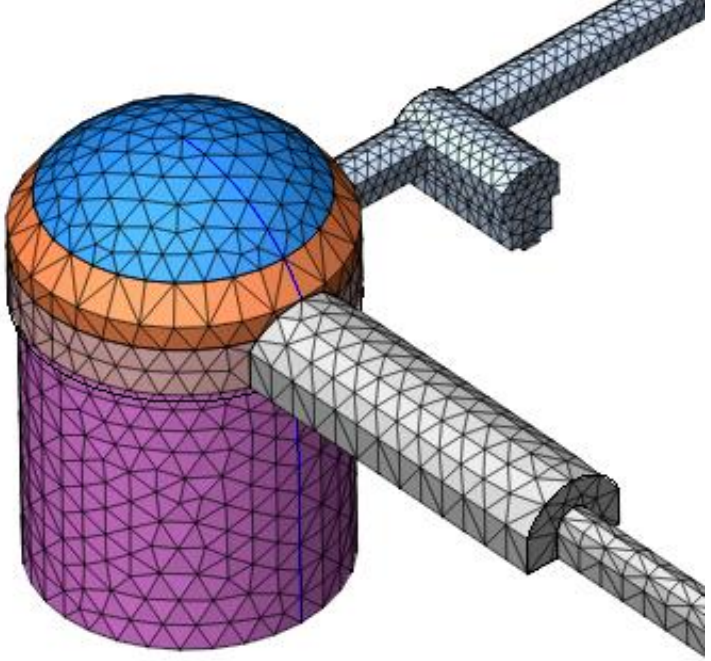


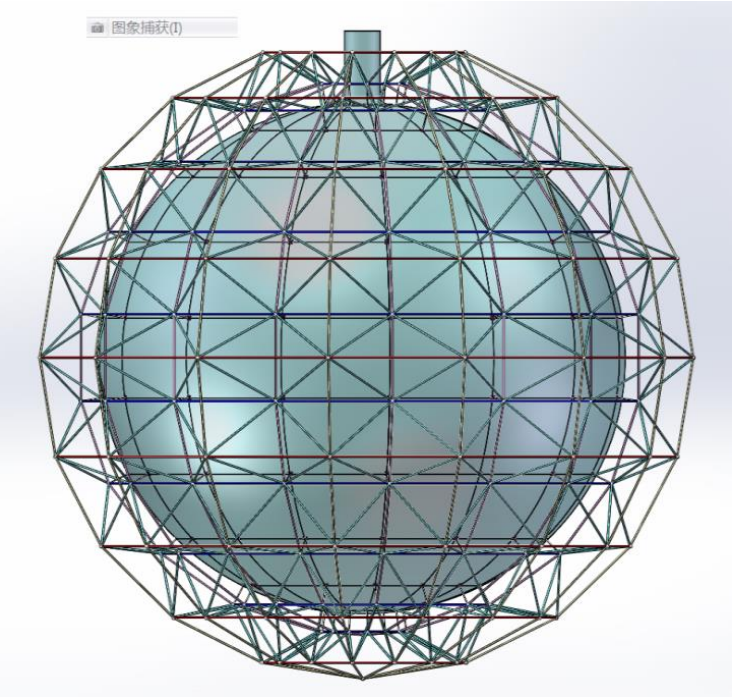
	Current	Daya Bay II
Δm^2_{12}	3%	0.6%
Δm^2_{23}	5%	0.6%
$\sin^2\theta_{12}$	5%	0.7%
$\sin^2\theta_{23}$	5%	N/A
$\sin^2\theta_{13}$	14% ➔ 4%	~ 15%

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

Status of JUNO

- Conceptual design & R&D plan approved in China
- Site determined, geological survey will be completed in 2 months
- Detailed civil design underway
- Detector design underway
- R&D started:
  - ⇨ Detector prototyping
  - ⇨ LAB-based Liquid scintillators
  - ⇨ Photo-detectors(PMTs)
  - ⇨ Readout electronics
- Collaboration will be established by the end of this year

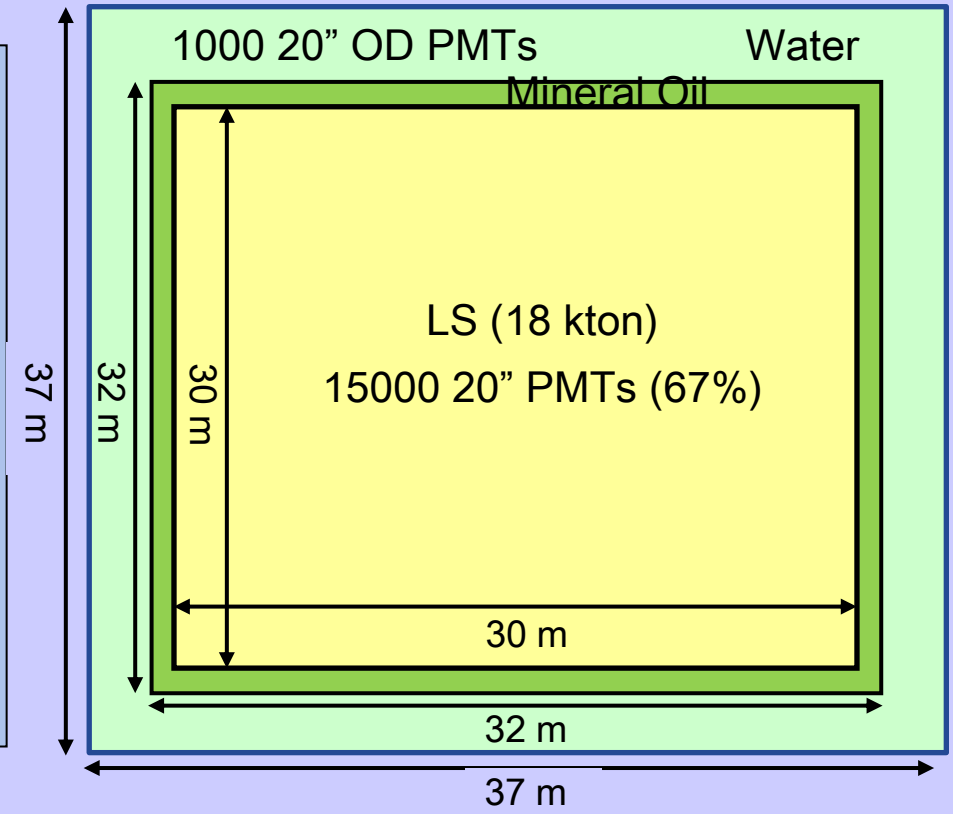




RENO-50

- **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

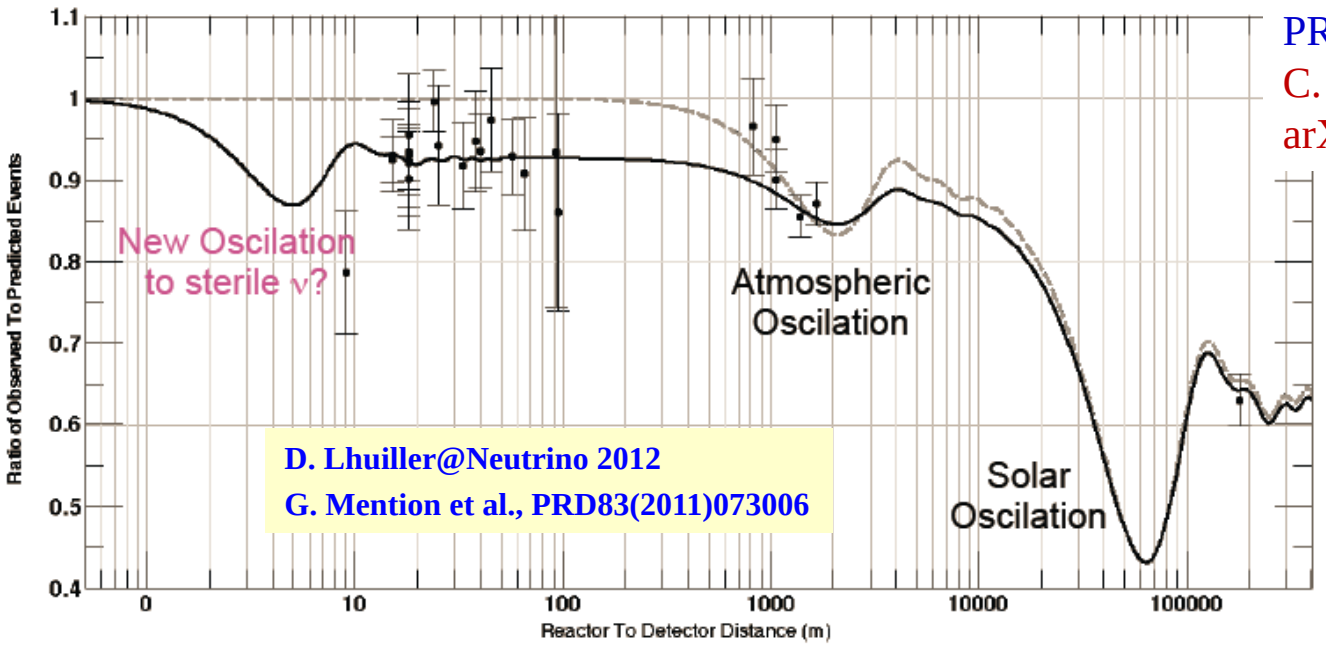


From Soo-Bong Kim

Reactor neutrino anomaly

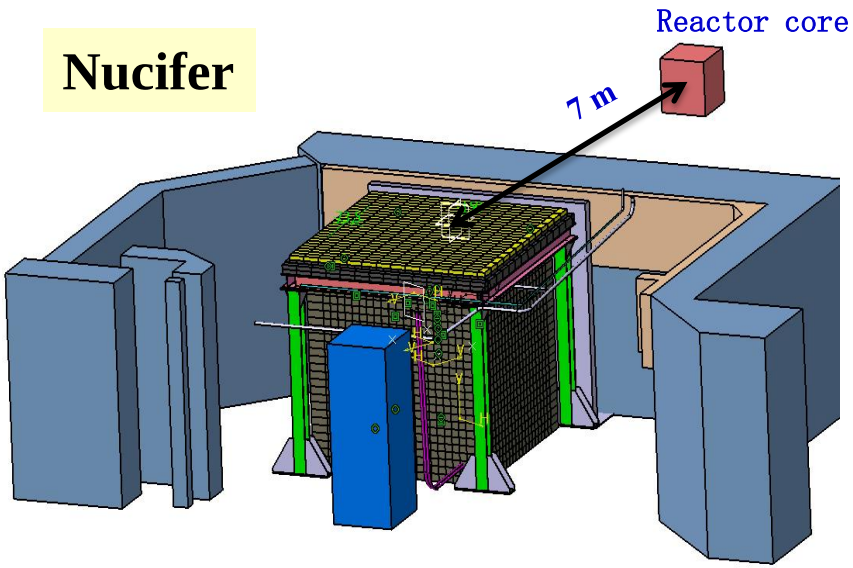
- By a new flux calculation, there may exist a reactor neutrino flux deficit: 0.943±0.023. A 3σ effect ?
- Later confirm by other calculations
- Oscillation with sterile neutrinos ?
  - Other experimental "hints": LSND, MiniBooNE, Gallex…
  - Global fit of all "hints": severe tensions
  - Cosmological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

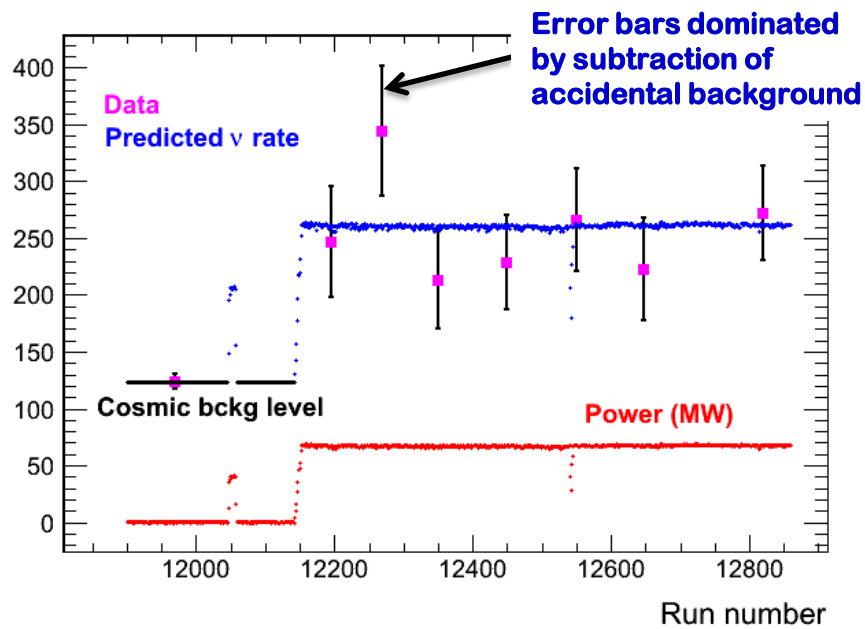
T.A. Mueller et al., PRC83:054615,2011
P. Huber et al., PRC84:024617,2011.
C. Zhang et al., arXiv: 1303.0900



Solution: experiments

- **Radioactive sources: CeLAND(^{144}Ce in KamLAND), SoX(^{51}Cr in Borexino),…**
- **Accelerator beams: IsoDAR, Icarus/Nessie, nuSTORM…**
- **Reactors: Nucifer, Stereo, Solid, SCARR, …**
  - ⇨ **Backgrounds near by reactors**
  - ⇨ **Precision better than 1%**
- **New measurements of β-spectrum from U & Pu(Munich)**





Figures from T. Lasserre

Will be upgraded to reduce backgrounds

Summary

- Solar neutrinos continue to provide improved measurements of θ_{12} & ΔM^2_{12}; solar-related and other astrophysics issues require much larger detectors.
- Atmospheric neutrinos can improve the precision of θ_{23} & ΔM^2_{23}; sub-leading effects can be used to determine the **mass hierarchy & CP phase**.
- Reactor neutrinos provided precise measurements of θ_{13} & ΔM^2_{13}; next generation experiments can measure precisely θ_{12} & ΔM^2_{12} & ΔM^2_{23}, determine the **mass hierarchy,** and study many astrophysics issues.
- Sterile neutrino issues will be settled by experiments at reactors and/or using radioactive sources & accelerators, sooner or later.

Mass hierarchy and **CP phase** will be known in a not too far future