# Measurements of Non-Accelerator Neutrinos

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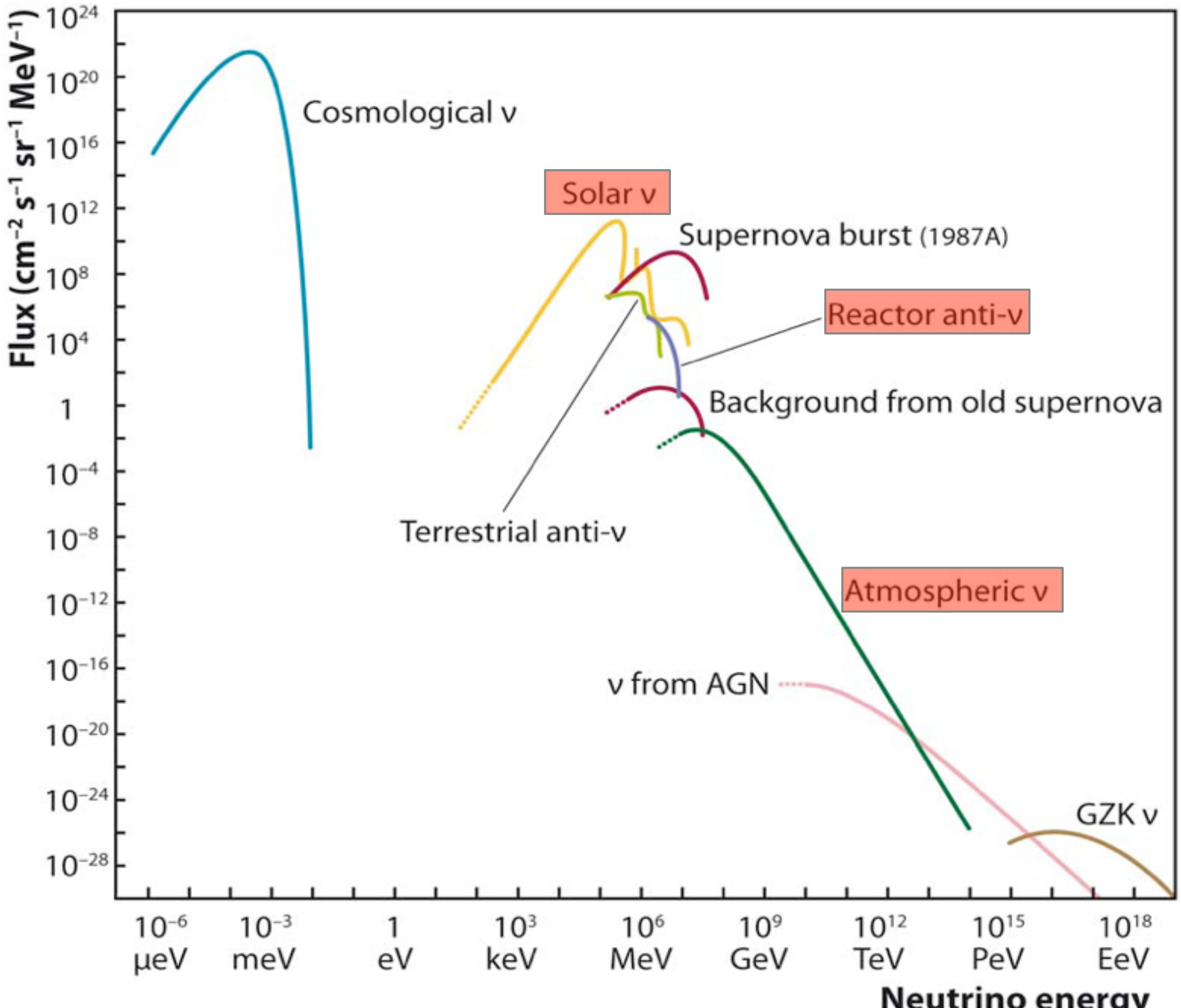
*NuFACT'16, Quy Nhon, Aug 22, 2016*

- *Discovery of Neutrino Oscillations and the Latest Measurements of Non-Accelerator Neutrinos*

# Disclaimers

- My audiences are experts in this field so I will simply try to entertain you with a story, focusing on Neutrino Oscillations and oscillation parameter measurements
- I will try to be complete but I must be biased due to personal experiences
- I apologise if I am missing your favourite experiments or results (Please speak to me offline so we could be more complete for the proceeding :)

# "Natural" Neutrino Sources Known to Us



# Discovery of Neutrino Oscillations and Nobel 2015

## The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

**Takaaki Kajita**

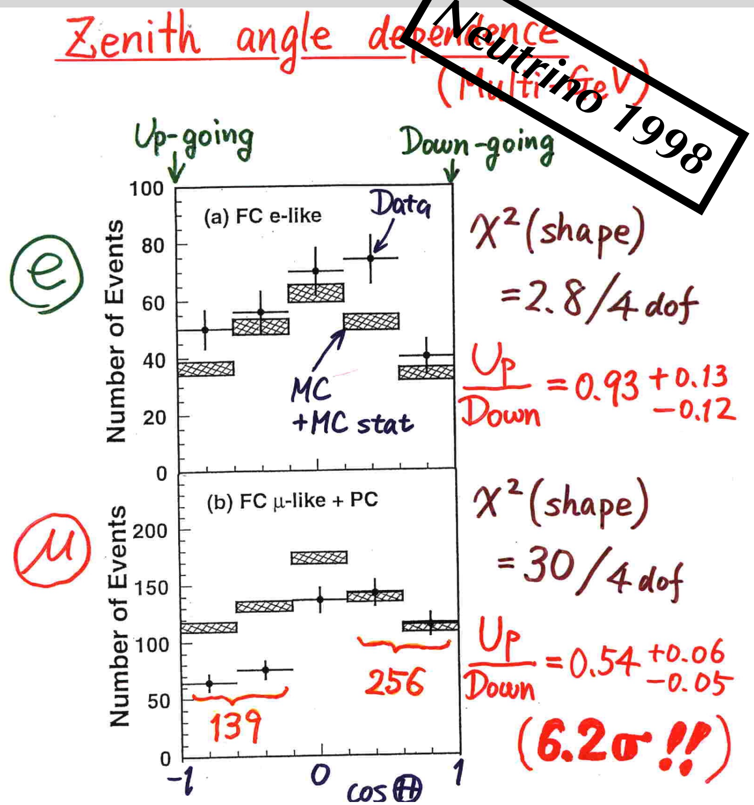
**Prize share:** 1/2

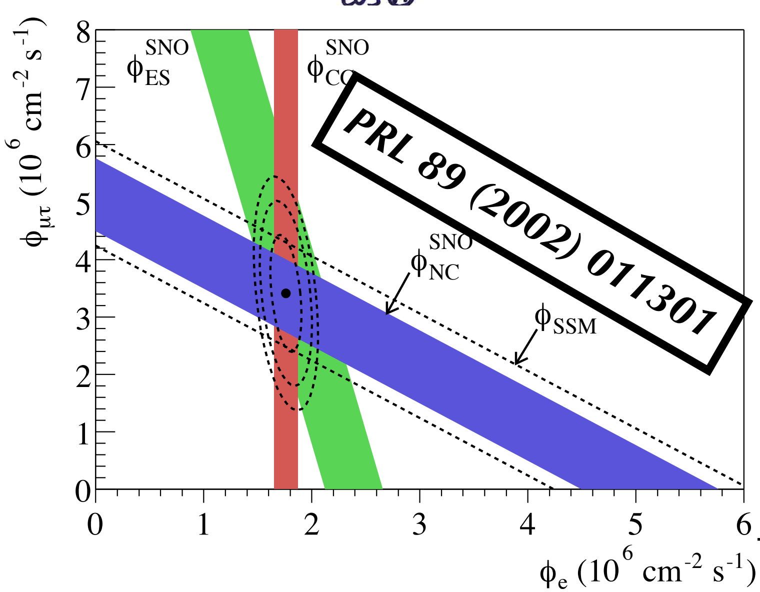
Photo: K. MacFarlane. Queen's University /SNOLAB

**Arthur B. McDonald**

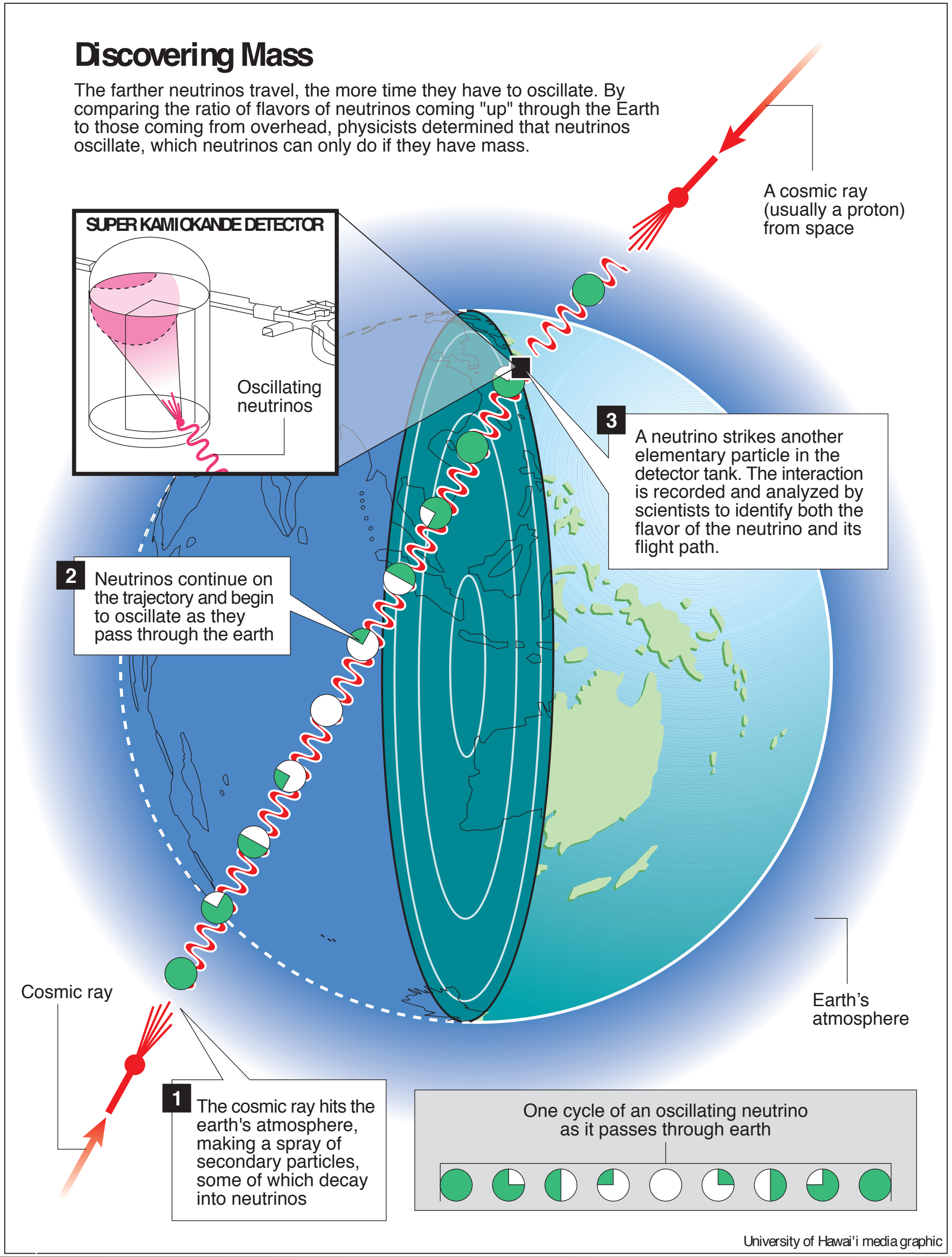
**Prize share:** 1/2

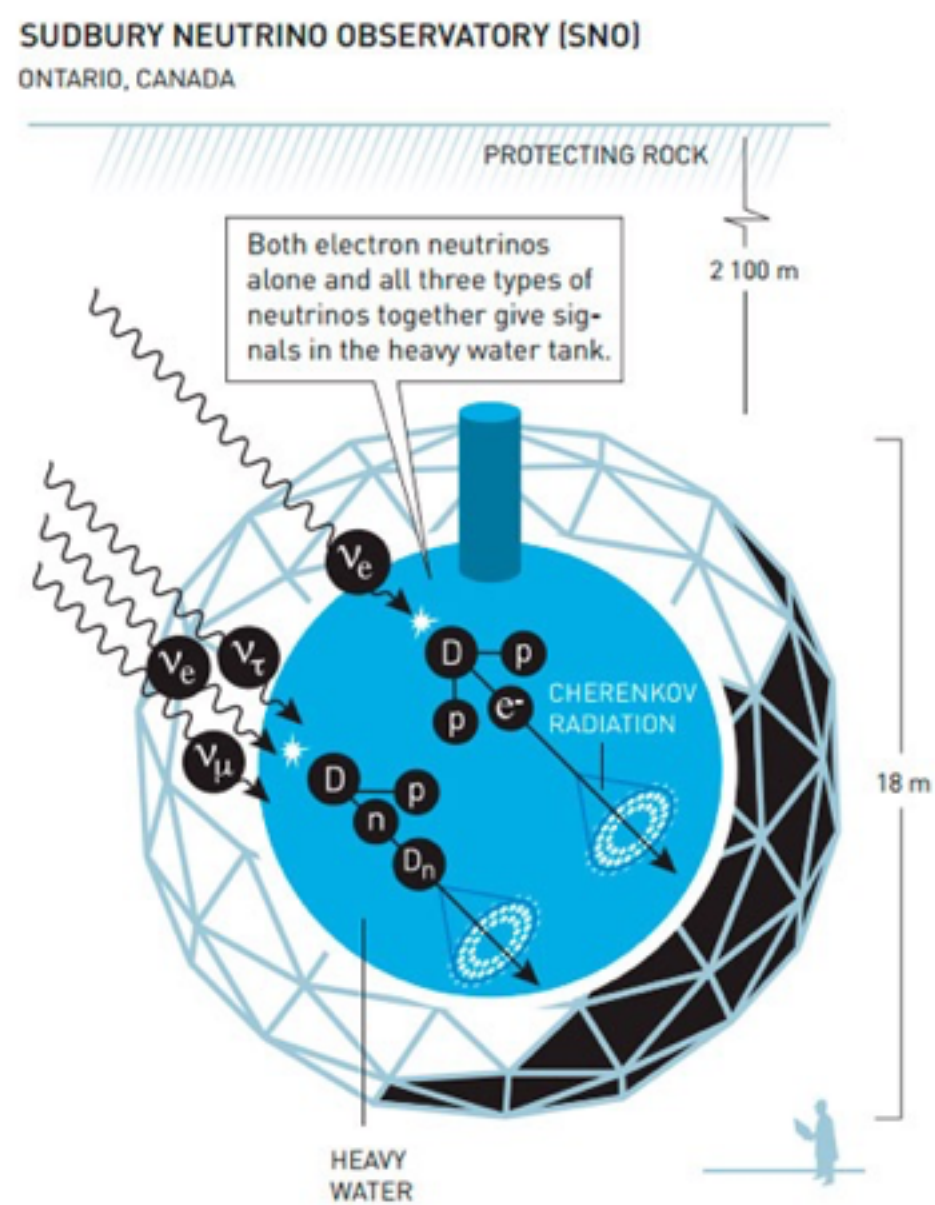
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*



# Super-Kamiokande and SNO Detectors



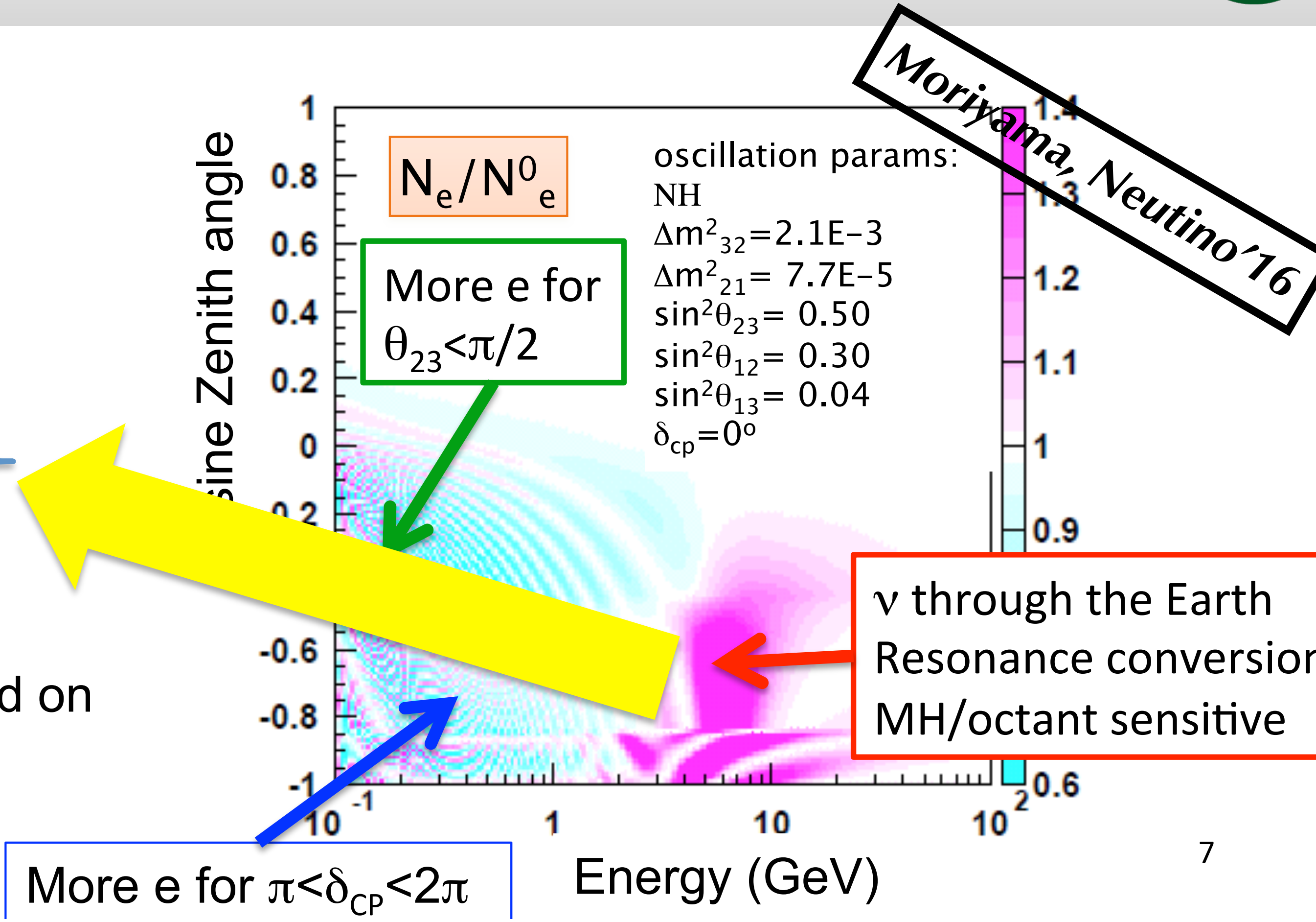
# Sensitivity to Various Parameters of Atmospheric Neutrinos

**$\nu_e$ sample**
Multi-GeV e-like ne
Multi-Ring e-like ne

**$\bar{\nu}_e$ sample**
Multi-GeV e-like ne
Multi-Ring e-like ne

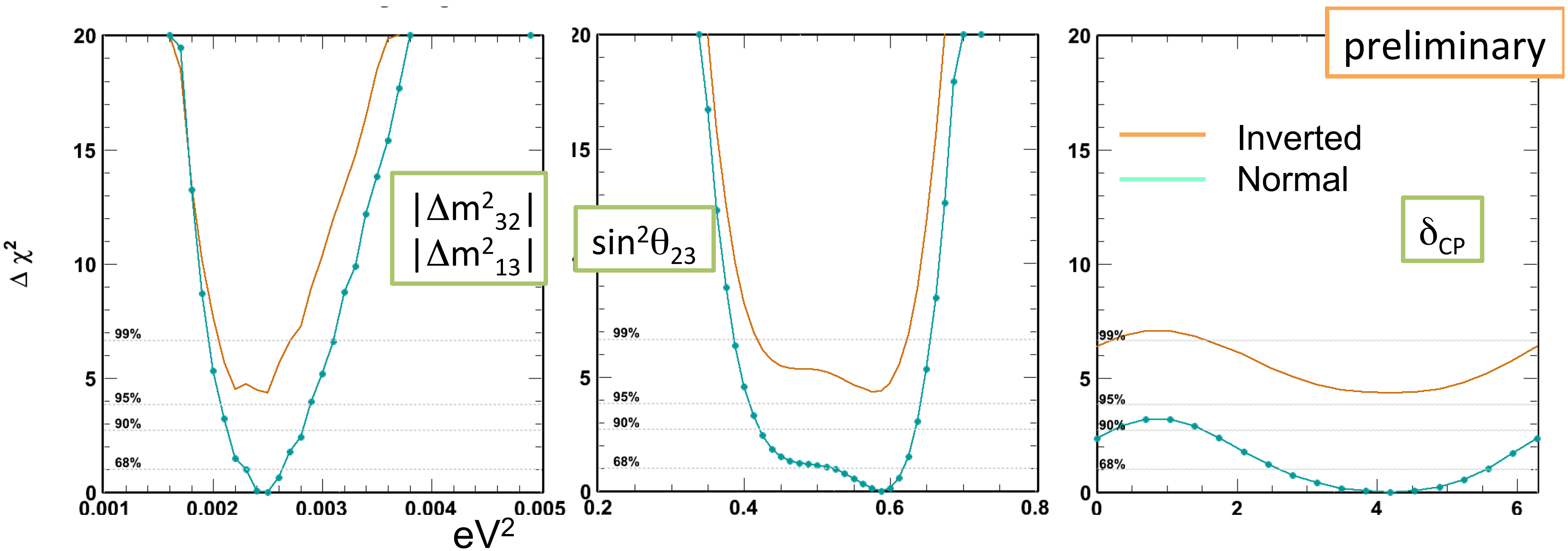
Multi-Ri **other**

statistical separation based on
- # of decay e
- # of rings
- transverse mom.




- Matter effect can generate resonance conversion → Mass hierarchy
- Solar oscillation $\nu_\mu \Longleftrightarrow \nu_e$ → octant sensitivity
- Interference → CP phase sensitivity

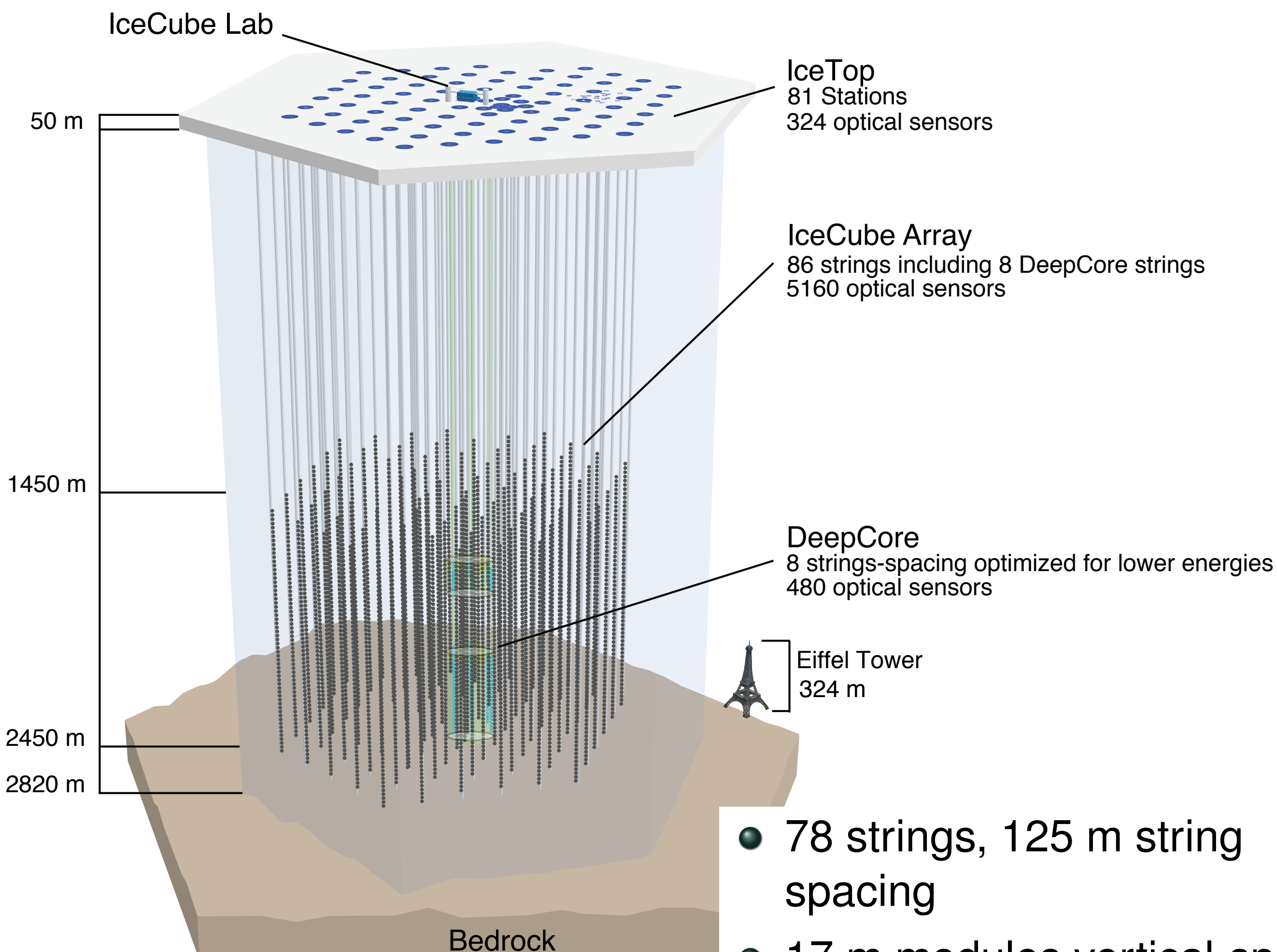
# Super-K Atmospheric Neutrino Results

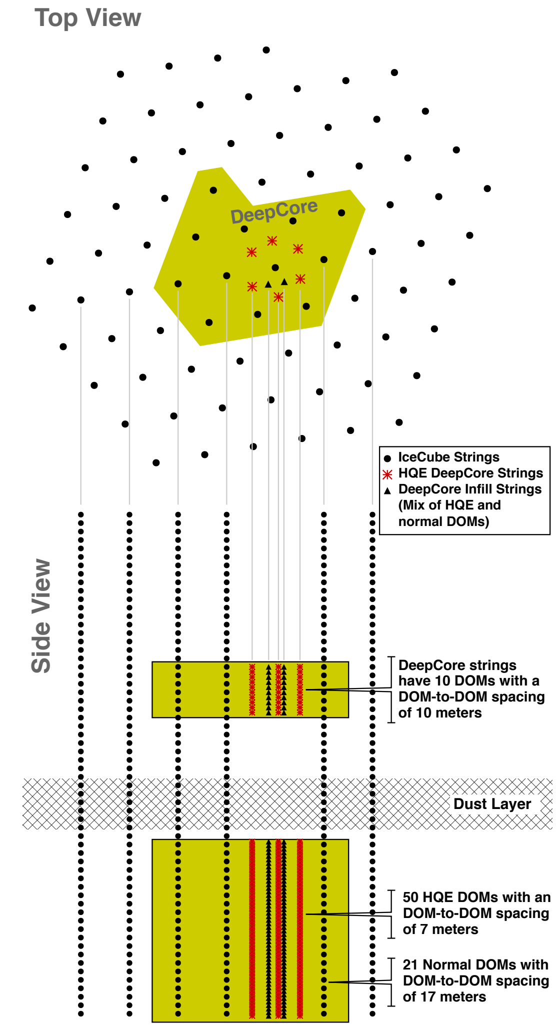



| Fit (517 dof) | $\chi^2$ | $\sin^2\theta_{13}$ | $\delta_{CP}$ | $\sin^2\theta_{23}$ | $\lvert\Delta m^2_{32}\rvert$ eV$^2$ |
|---|---|---|---|---|---|
| SK (IH) | 576.08 | 0.0219 (fix) | 4.189 | 0.575 | $2.5\times10^{-3}$ |
| SK (NH) | 571.74 | 0.0219 (fix) | 4.189 | 0.587 | $2.5\times10^{-3}$ |

- *$\Delta\chi^2$(NH-IH)=-4.3: Normal Mass Hierarchy is preferred by SK atm. data*
- *Weak CP and octant preferences*

# IceCube-DeepCore



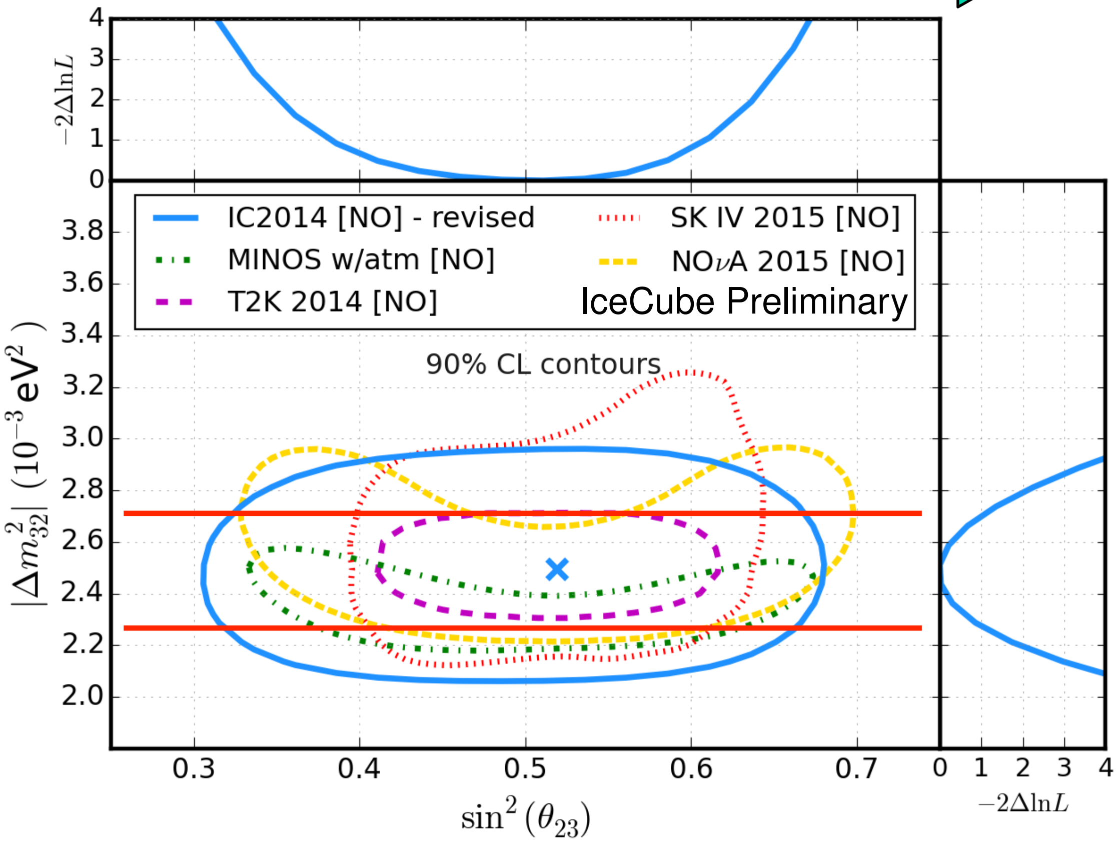

- 78 strings, 125 m string spacing
- 17 m modules vertical-spacing
- 8 strings, 40-75 m string spacing
- 7 m modules vertical-spacing

***Good for atmospheric oscillation parameters***

***Threshold energy too high for mass hierarchy***

# IceCube-DeepCore Results

PRD 91, 072004 (2015)




$$|\Delta m^2_{32}| = 2.50^{+0.18}_{-0.24} 10^{-3}\text{eV}^2$$

$$\sin^2(\theta_{23}) = 0.52^{+0.12}_{-0.10}$$

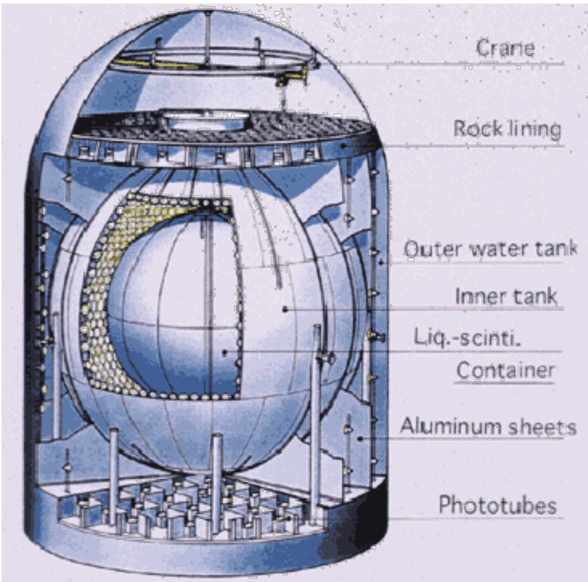
***Updates in 2016***

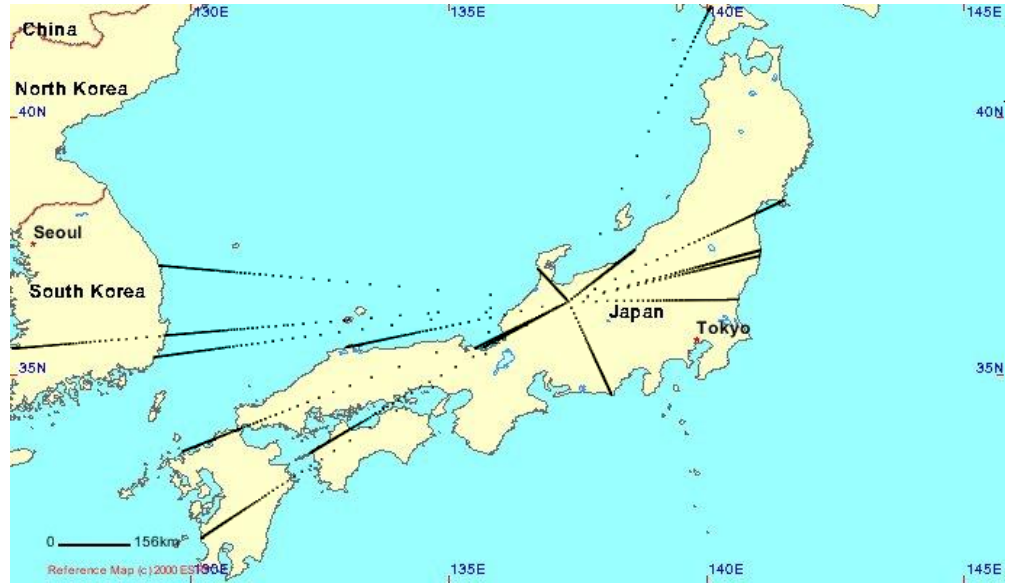
- Improved simulation, systematics, and MC/Data agreement results.
- Improved: detector noise model, tighter cut for atm. muon rejection, flux prediction, PE charge calibration, etc.

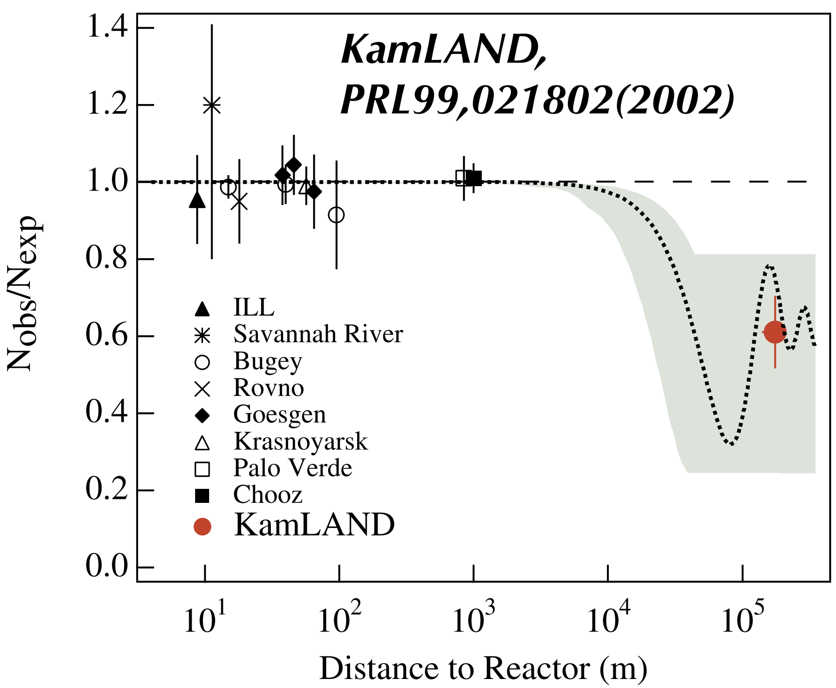
***Results competitive w/ SK***

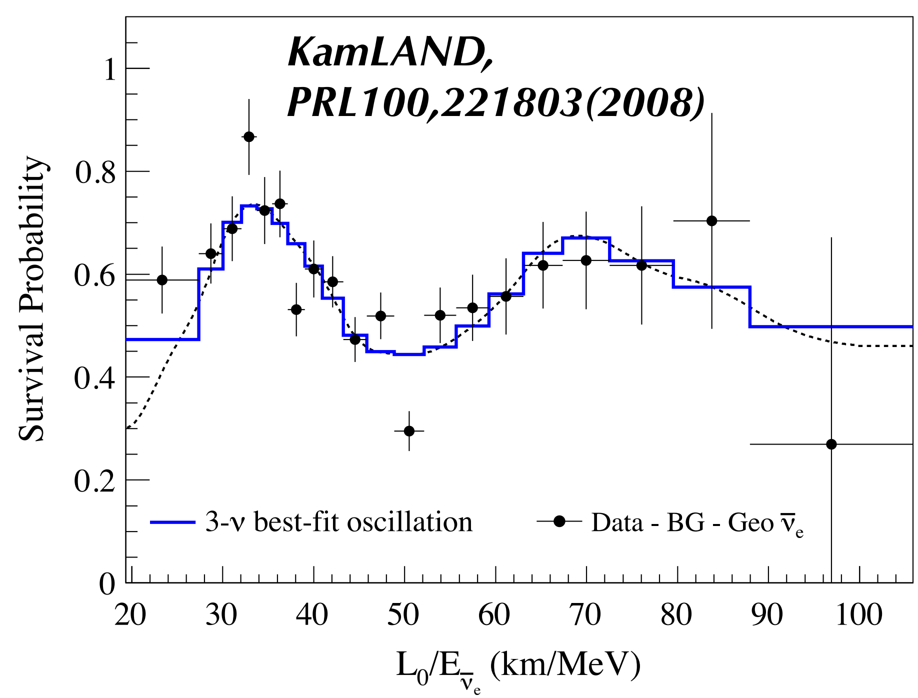
- Using only events with $E_{reco} < 56$ GeV
- Fitting to data done in 2D space $(E, \theta)$
  - $\chi^2/ndf = 52.4/56$
- Observed ≈5200 events in 953 days

# Solar Neutrino Oscillations using Reactor Neutrinos



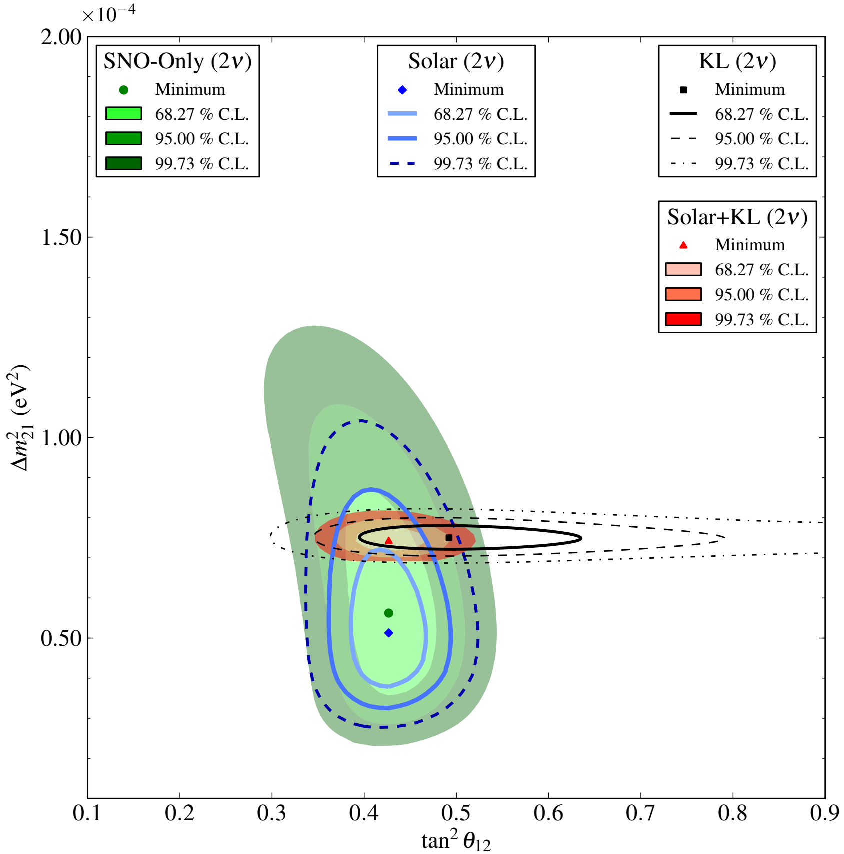



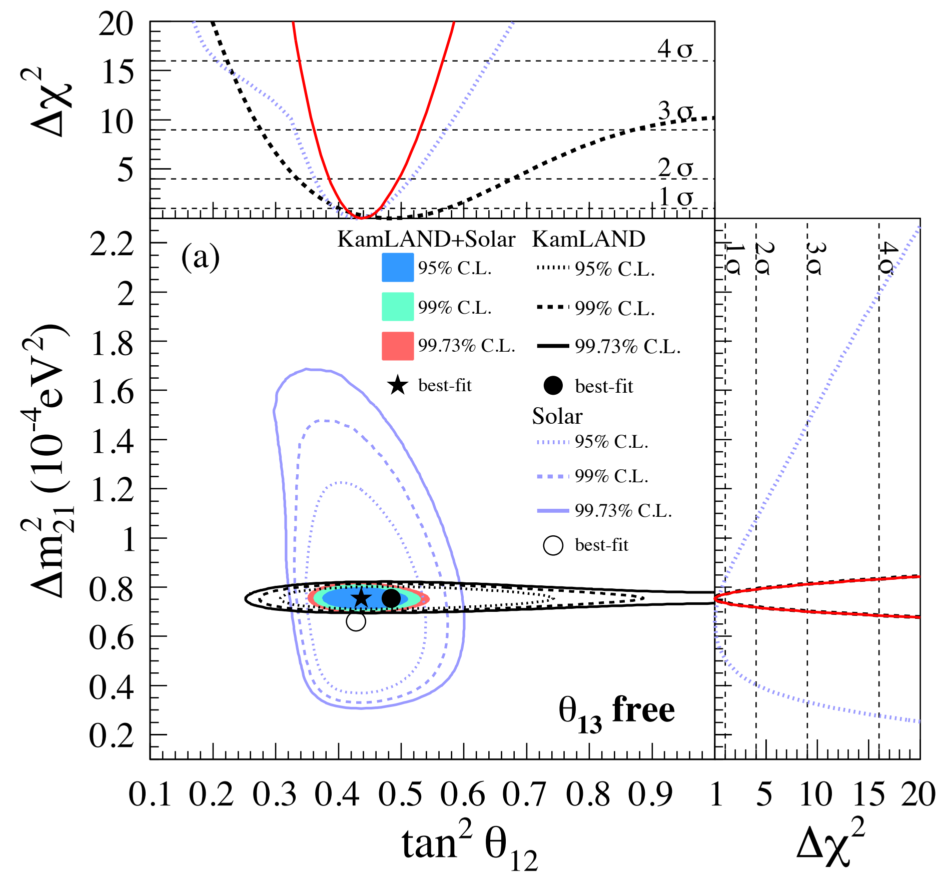



# Combined Results from SNO and KamLAND

***SNO, PRC88 (2013) 025501***



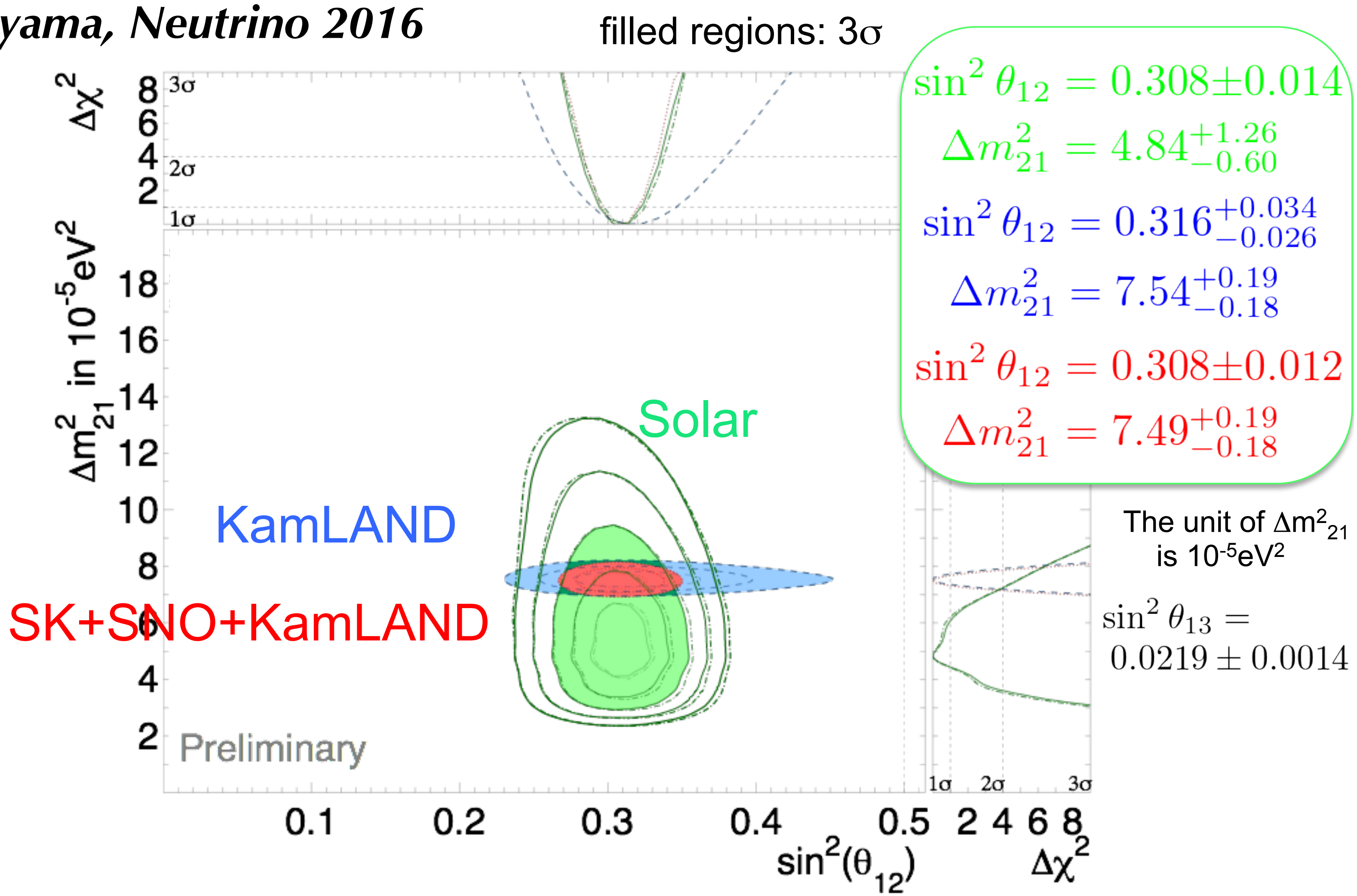

***KamLAND, PRD88 (2013) 033001***




- The combined results of SNO and KamLAND provide the best measurement for the solar mixing parameters: $\theta_{12}$ and $\Delta m^2{}_{21}$
- And they won't be (significantly) improved for a long time …….
  ***to be continued***

# Adding the Super-K Solar Data till 2016

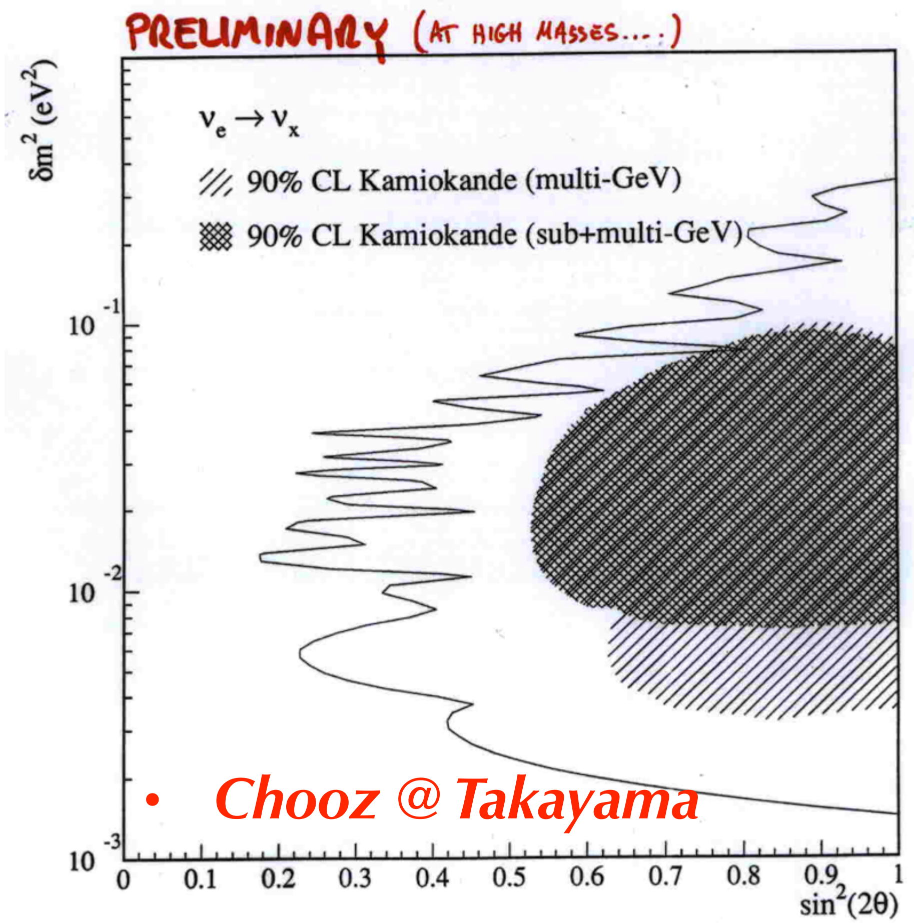
***Moriyama, Neutrino 2016***

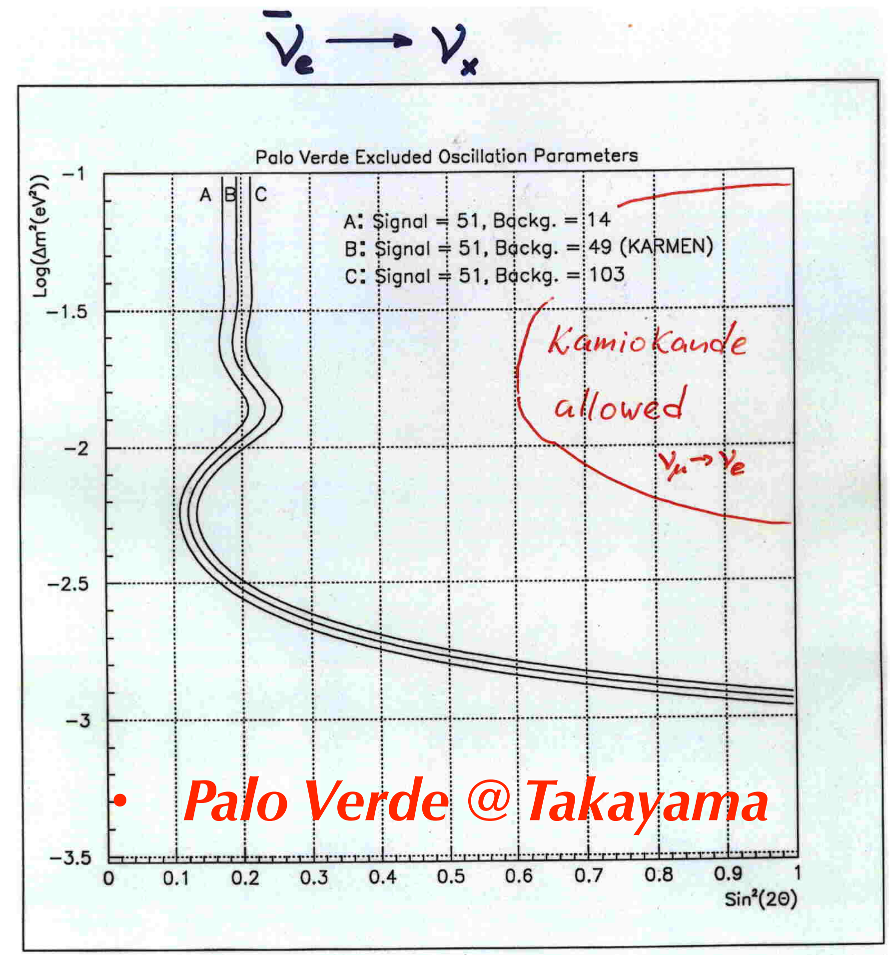



- SK spectrum and day/night data favor a lower $\Delta m^2_{21}$ than KamLAND (2-sigma)
- SK has further lowered threshold to 2.5MeV, better chance to check the transition region

# Also at Neutrino'98 in Takayama

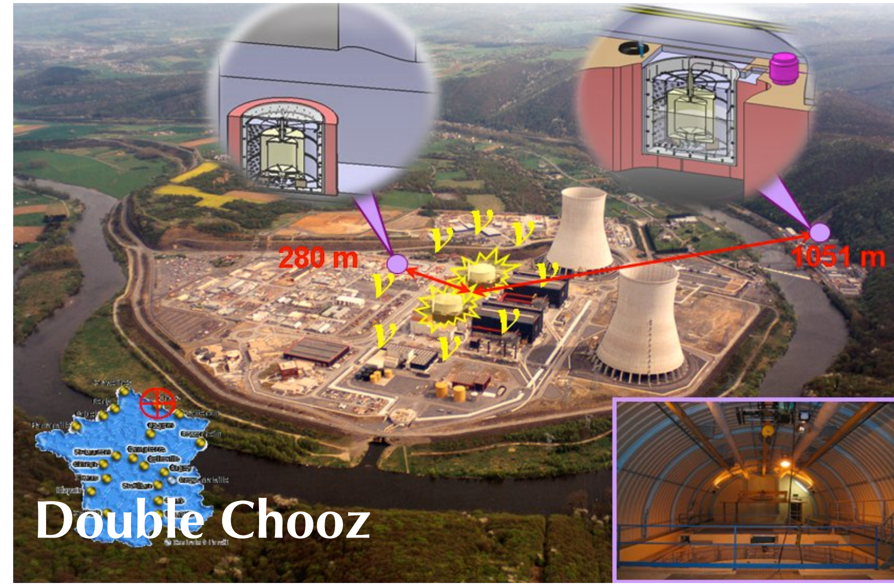
- Chooz and Palo Verde did not find oscillation at the distance hinted by the atmospheric data
- Which is why we were so certain that $\nu_\mu \rightarrow \nu_\tau$

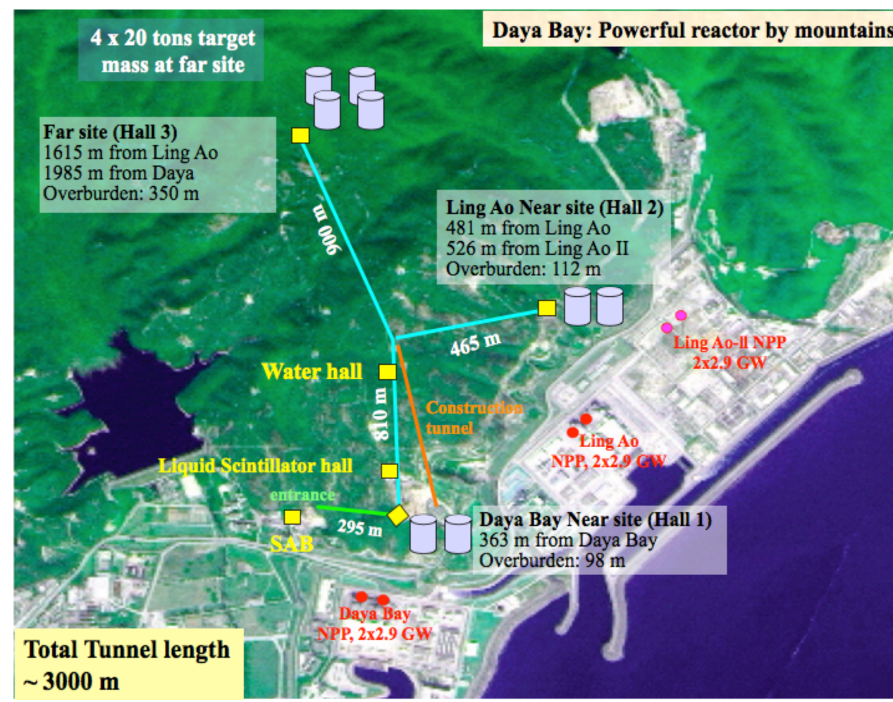


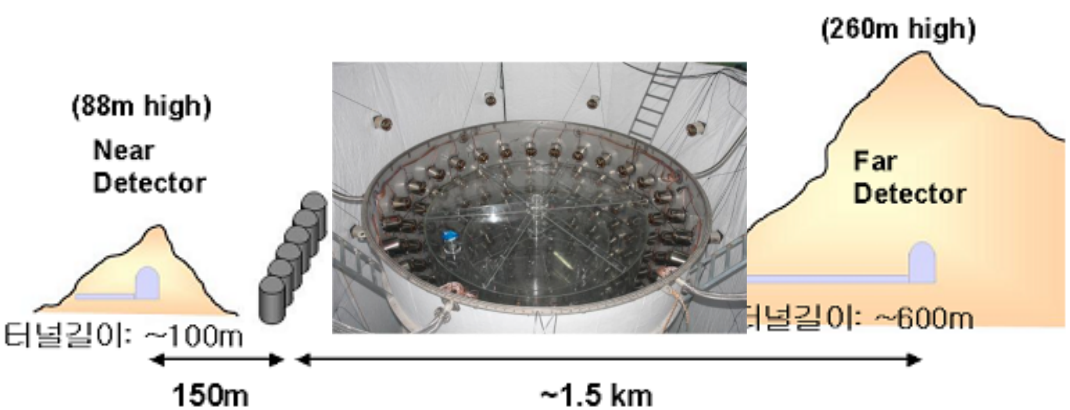



# Dual Detector Short-Baseline Experiments Conceived

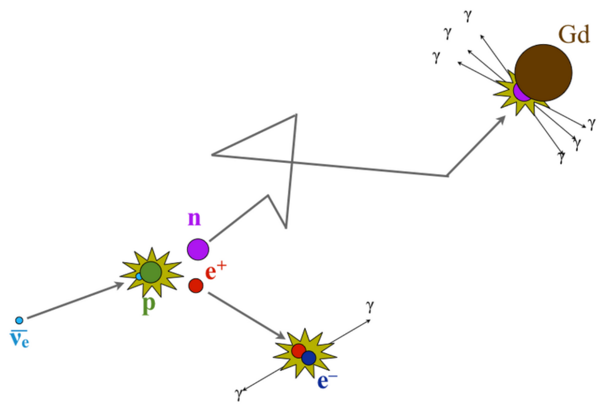
- Chooz and Palo Verde were not sensitive enough to get the lastly known mixing angle theta13: bad liquid scintillator is a factor but we blamed reactor neutrino flux uncertainty
  - Near-far reactor flux uncertainty **cancellation** proposed for Kr2Det in 2000
- Chooz ⟹ Double Chooz, Daya Bay and RENO entered the competition of measuring theta13

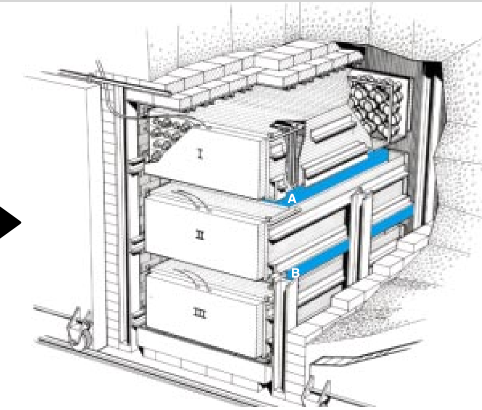


# The Daya Bay Antineutrino Detector as an Example




- Correlation of prompt and delayed signals

➡ ***Fashion comes and goes :)***

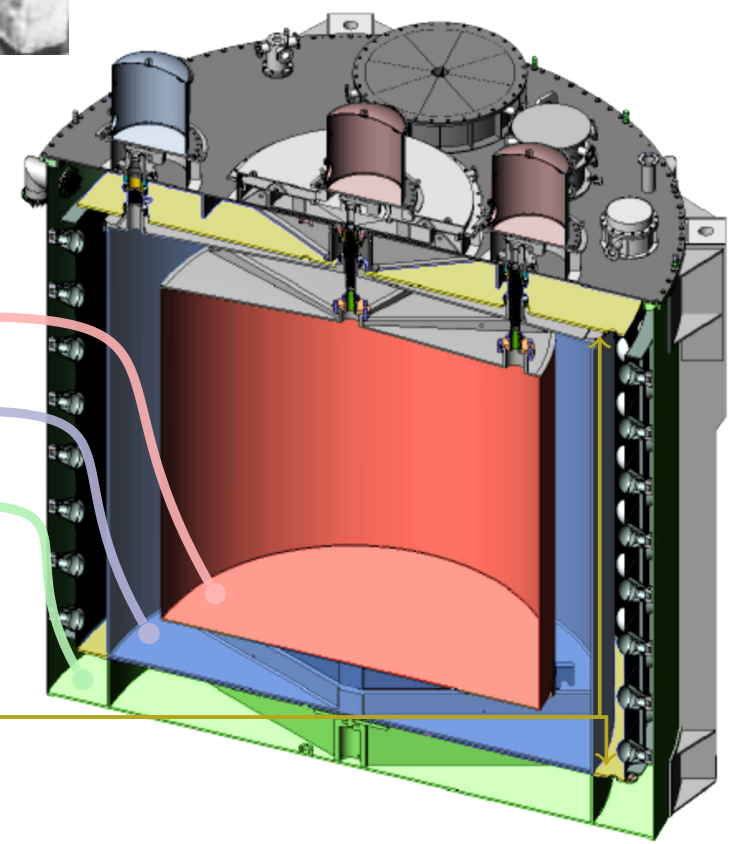
**3 zone cylindrical vessels**

| | Liquid | Mass | Function |
|---|---|---|---|
| Inner acrylic | Gd-doped liquid scint. | 20 t | Antineutrino target |
| Outer acrylic | Liquid scintillator | 20 t | Gamma catcher |
| Stainless steel | Mineral oil | 40 t | Radiation shielding |

192 8 inch PMTs in each detector

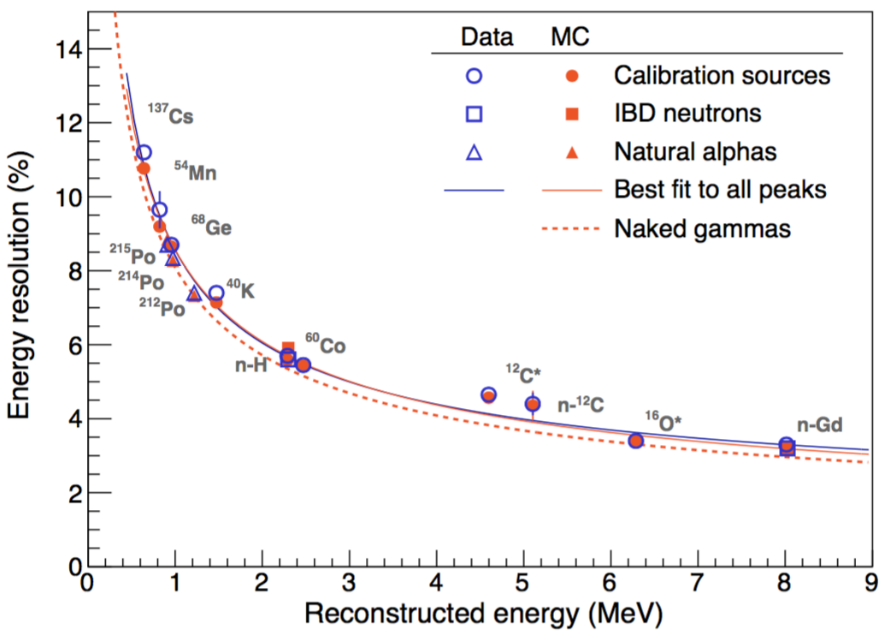
Top and bottom reflectors increase light yield and flatten detector response

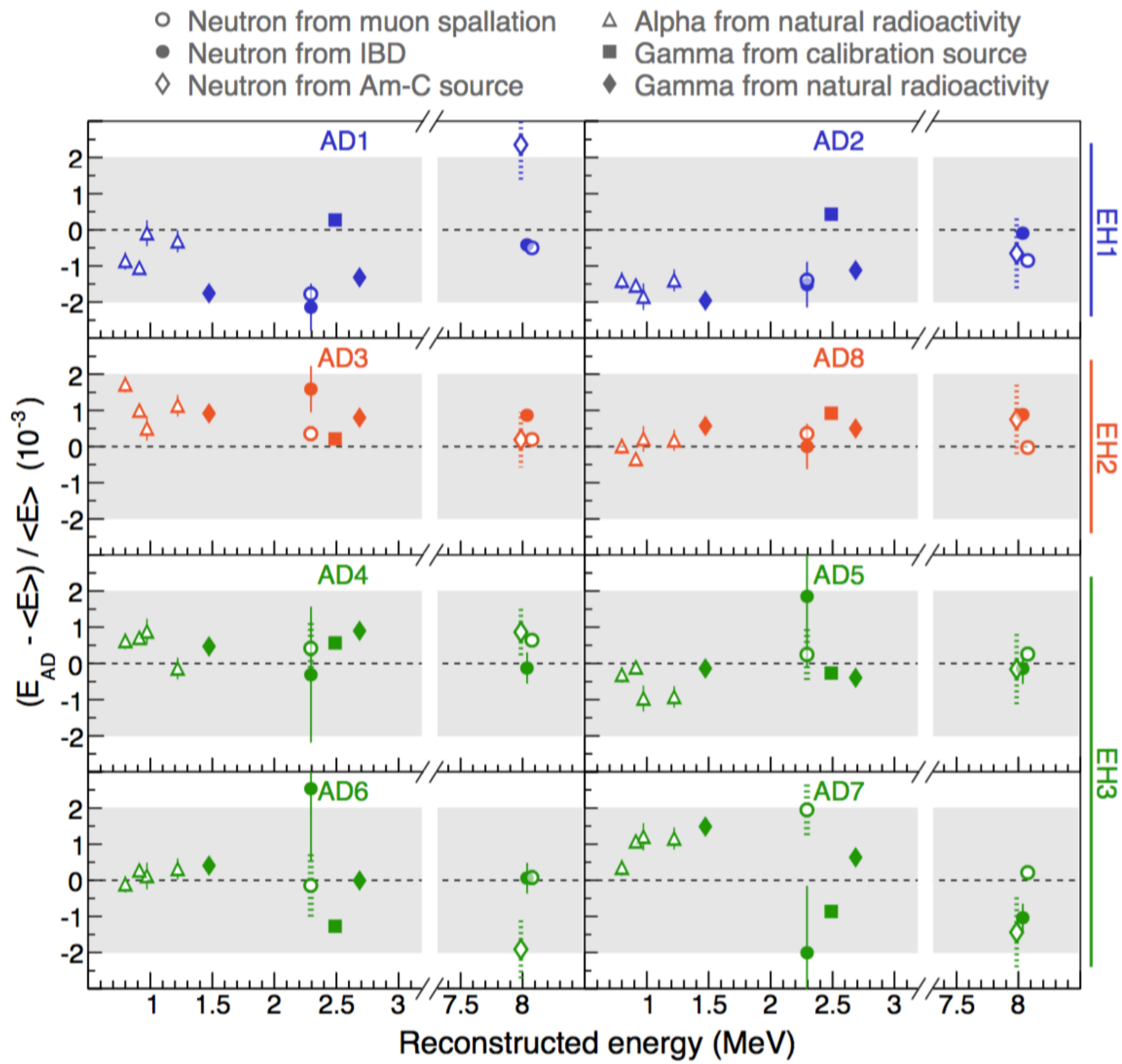
$(\frac{7.5}{\sqrt{E}} + 0.9)\%$ energy resolution



# The Daya Bay Detector Energy Responses

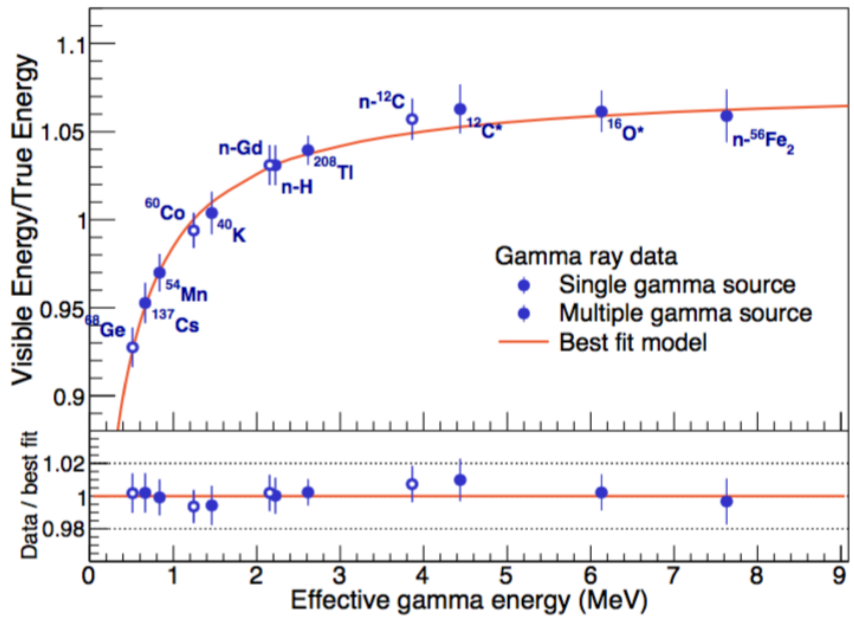
- Automatic weekly calibration
  - $^{68}$Ge, $^{241}$Am$^{13}$C, $^{60}$Co
  - LED diffuser ball
- Spallation neutrons
- Natural radioactivities
- Special calibration campaign
  - $^{137}$Cs, $^{54}$Mn, $^{241}$Am$^{9}$Be, $^{239}$Pu$^{13}$C
- Manual 4π calibration

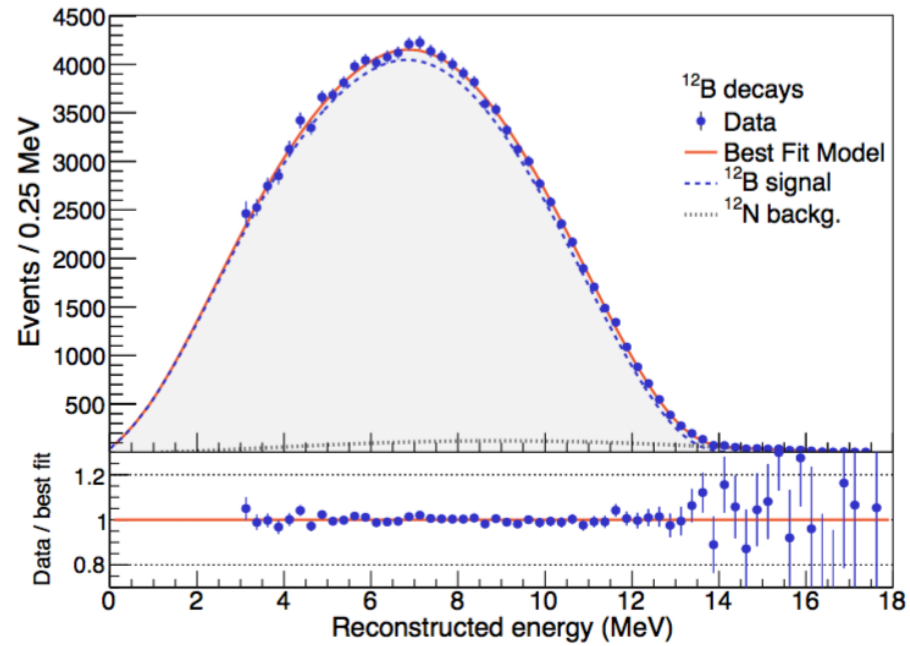


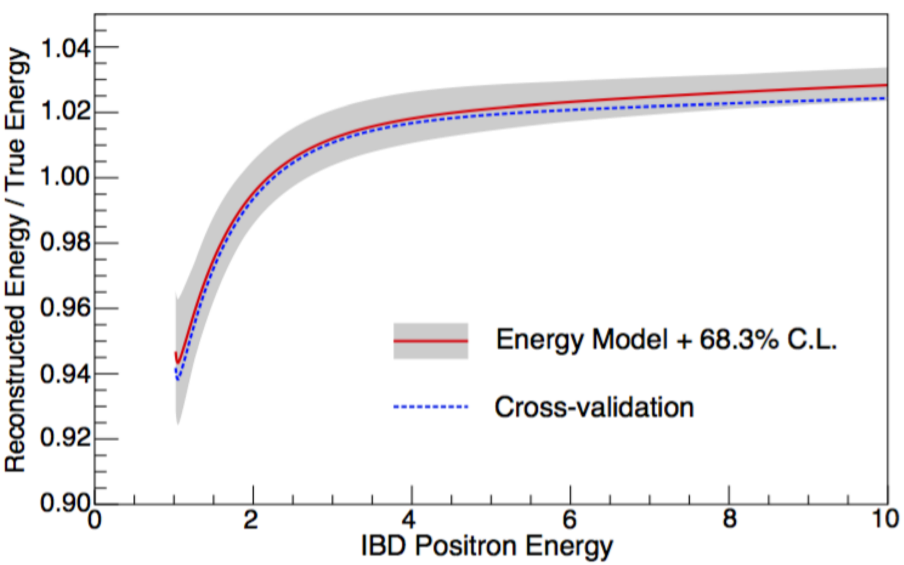




***Relative detector energy scale < 0.2%***

# Energy Non-Linearity of Daya Bay



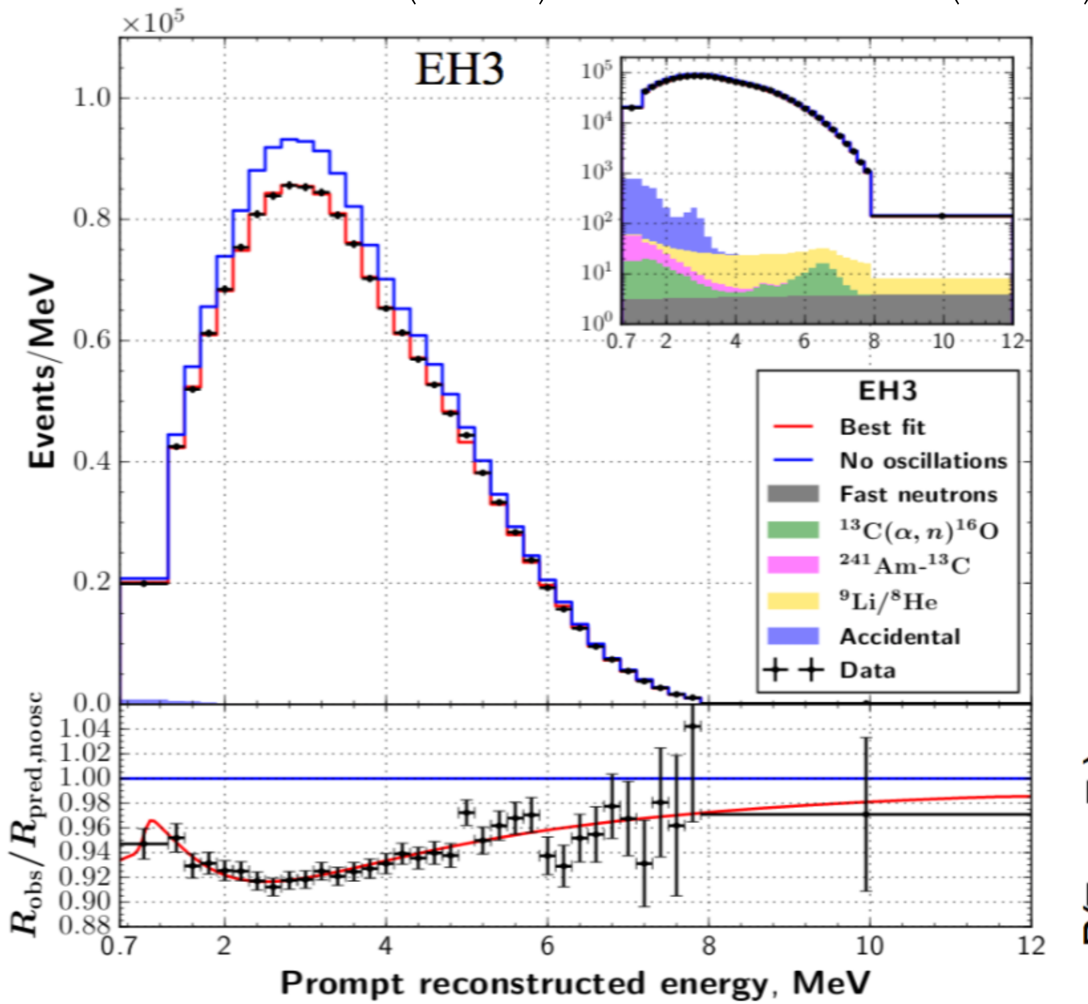



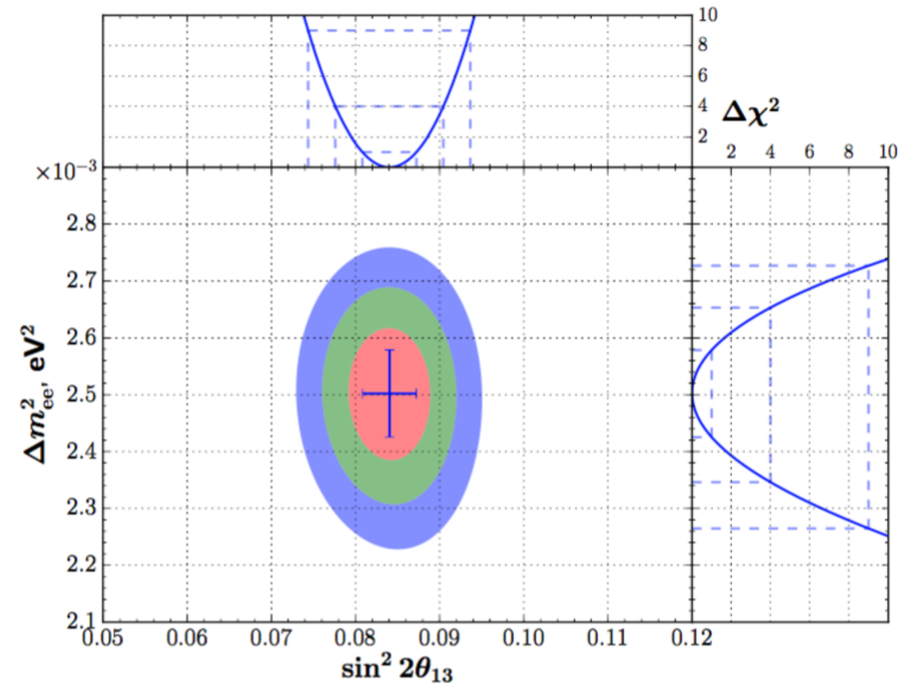

- Two major sources of non-linearity:
  - Scintillator response
  - Readout electronics
- Energy model for positron is derived from measured gamma and electron responses using simulation

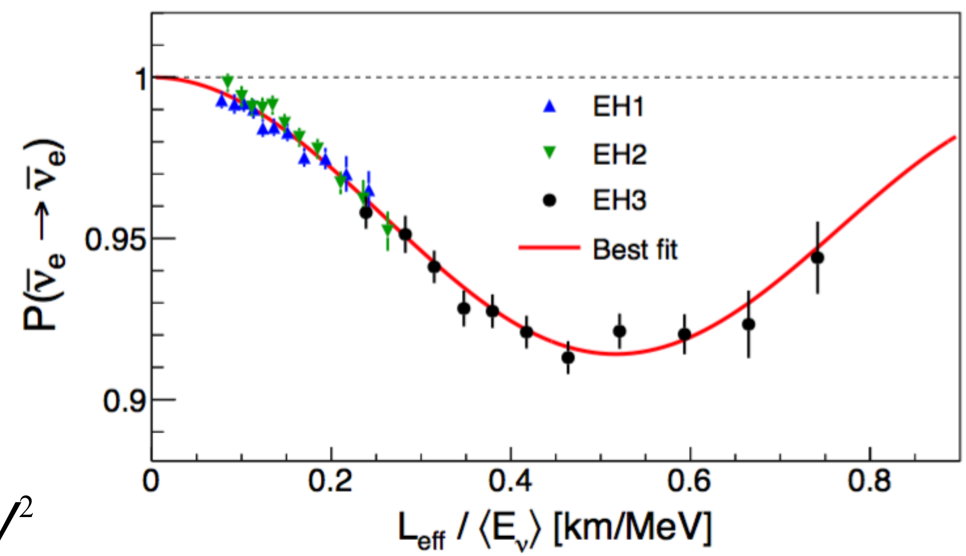
***~1% uncertainty (correlated among detectors) — A Great Achievement!***

# Daya Bay: the Latest Results

$$P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$




$$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(stat.) \pm 0.0019(syst.)$$

$$|\Delta m^2_{ee}| = [2.50 \pm 0.06(stat.) \pm 0.06(syst.)] \times 10^{-3}\, eV^2$$

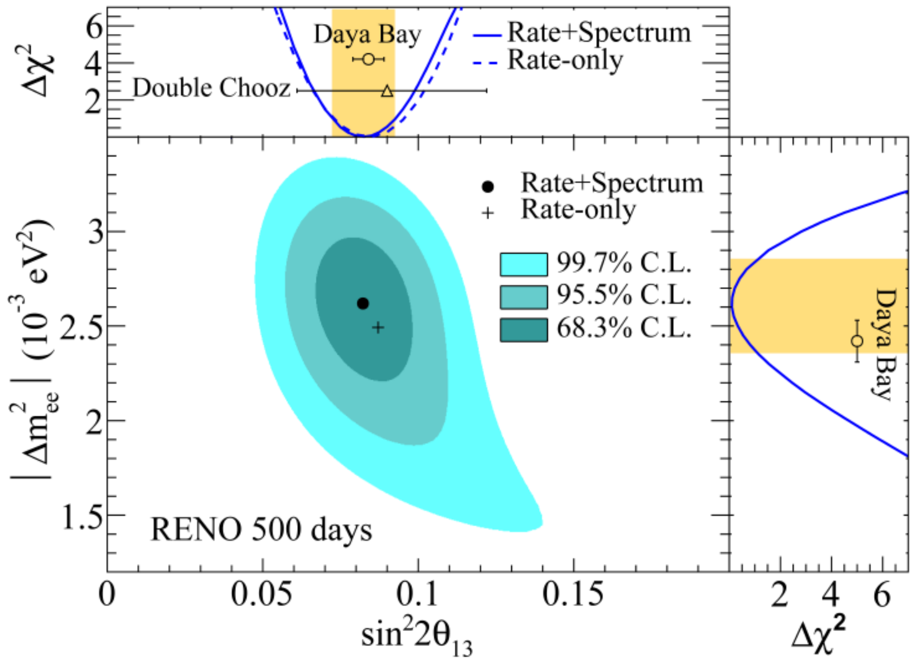
# RENO: the Latest Results at ICHEP 2016

**Rate Only** $\sin^2 2\theta_{13} = 0.087 \pm 0.009(\text{stat.}) \pm 0.007(\text{syst.})$ $\pm 0.011(\text{total})$

**Rate + Shape**

$|\Delta m^2_{ee}| = 2.62^{+0.21}_{-0.23}(\text{stat.})^{+0.12}_{-0.13}(\text{syst.})\ (\times 10^{-3}\, eV^2)$ $\pm 0.26\ (\text{total})$ 10 % precision

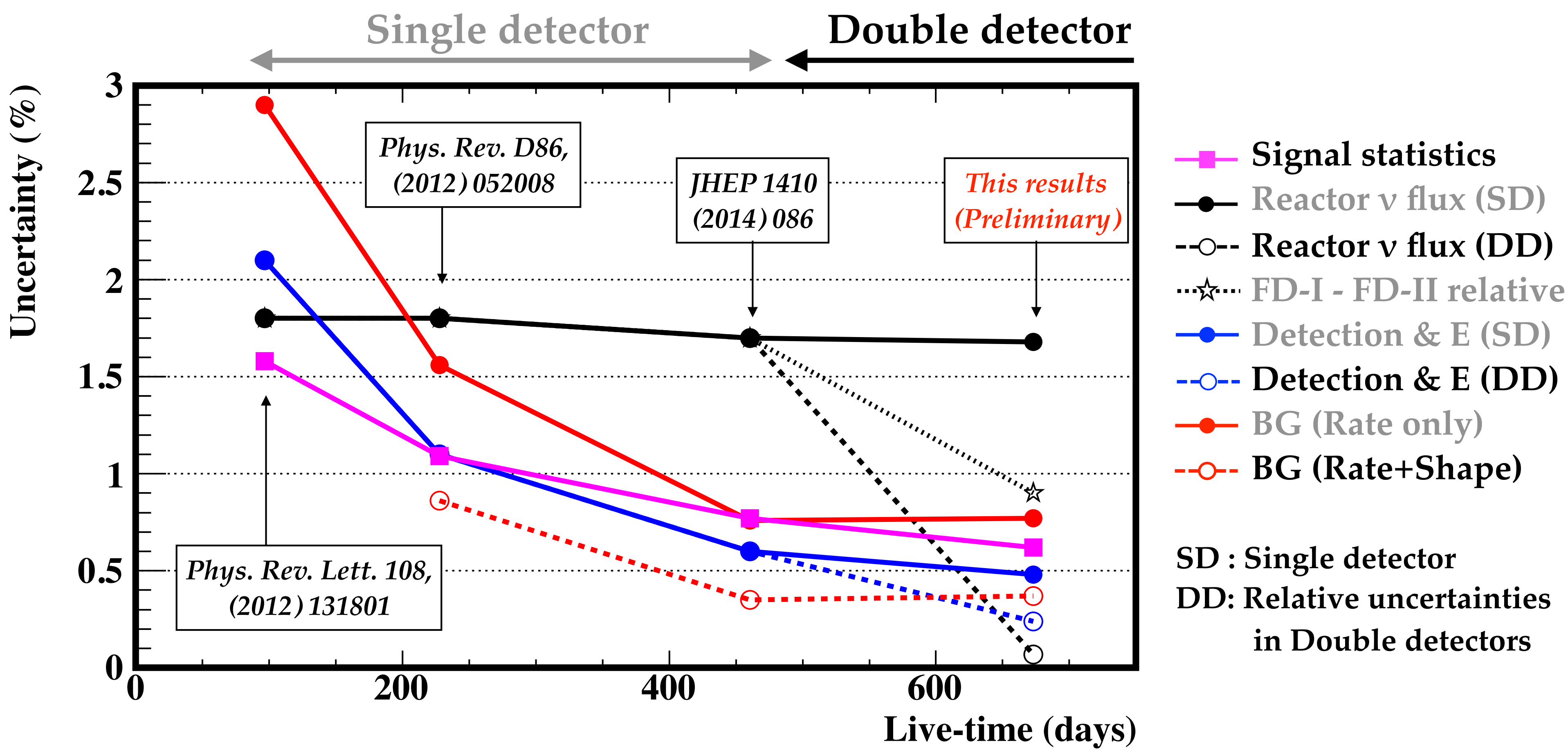
$\sin^2 2\theta_{13} = 0.082 \pm 0.009(\text{stat.}) \pm 0.006(\text{syst.})$ $\pm 0.010(\text{total})$ 12 % precision




- arXiv:1511.05849.v2
- PRL 116, 211801 (2016)

- PRD to be submitted soon

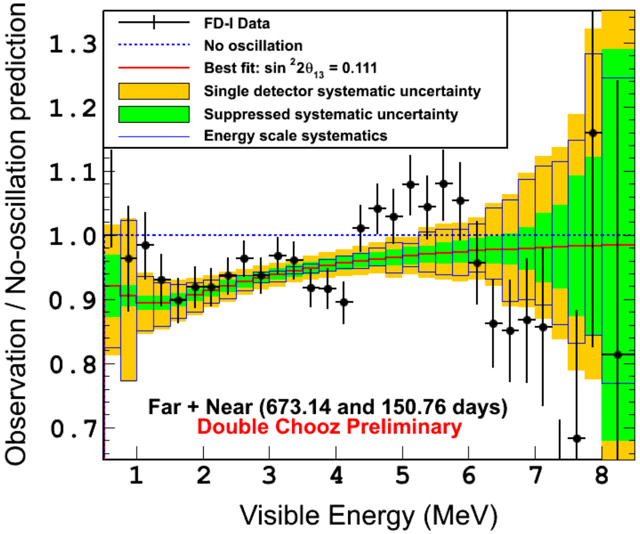
# Double Chooz: Double Detector Phase Started!



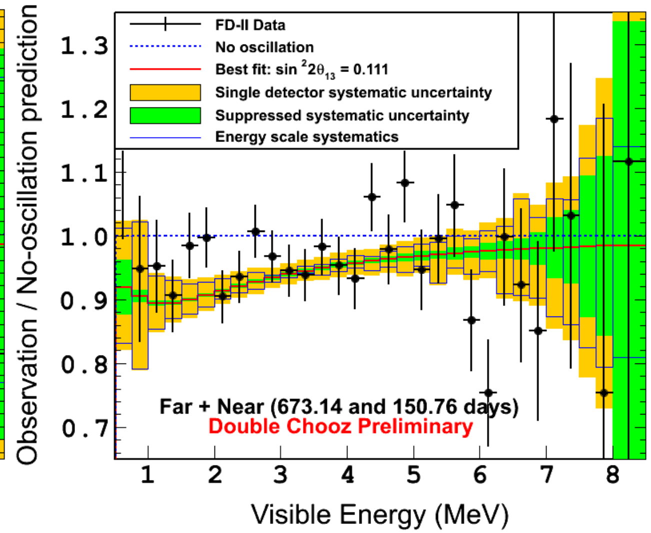

- Far detector (FD) started data taking since 2011; A unique opportunity of reactor-off data for better background constrain
  - Bugey as the flux constrain
- Near detector (ND) started data taking since 2015

# Double Chooz: the Latest Results

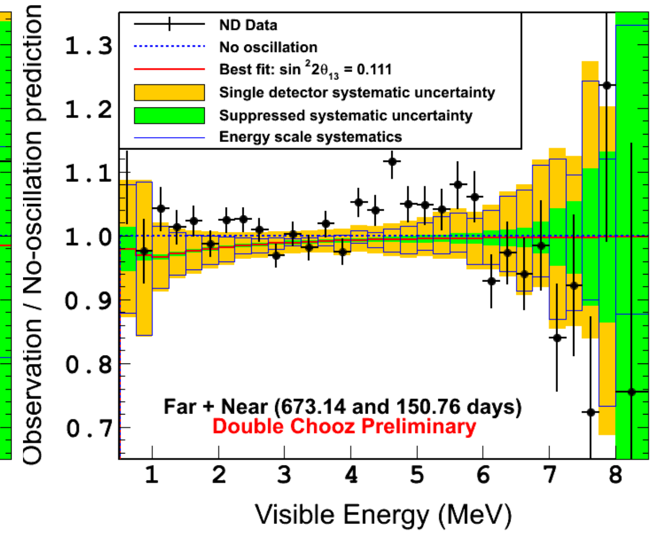
FD-I




FD-II

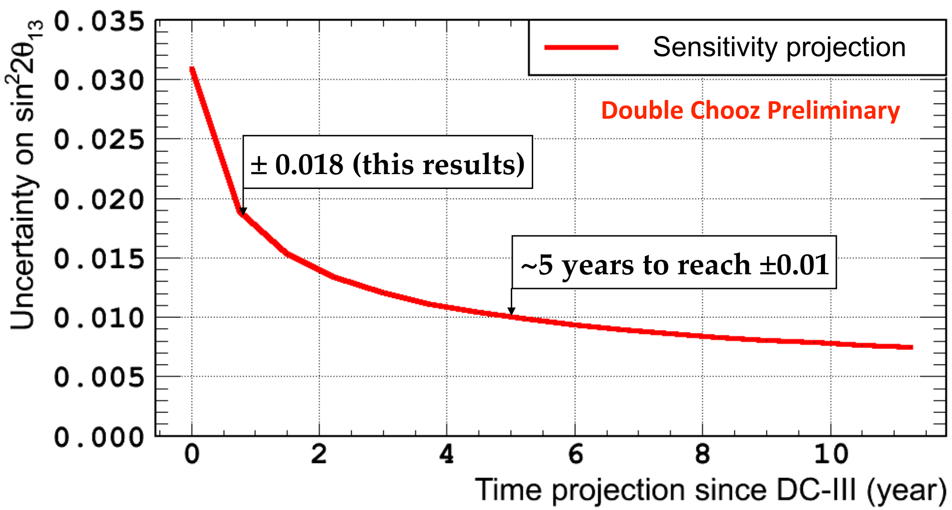



ND



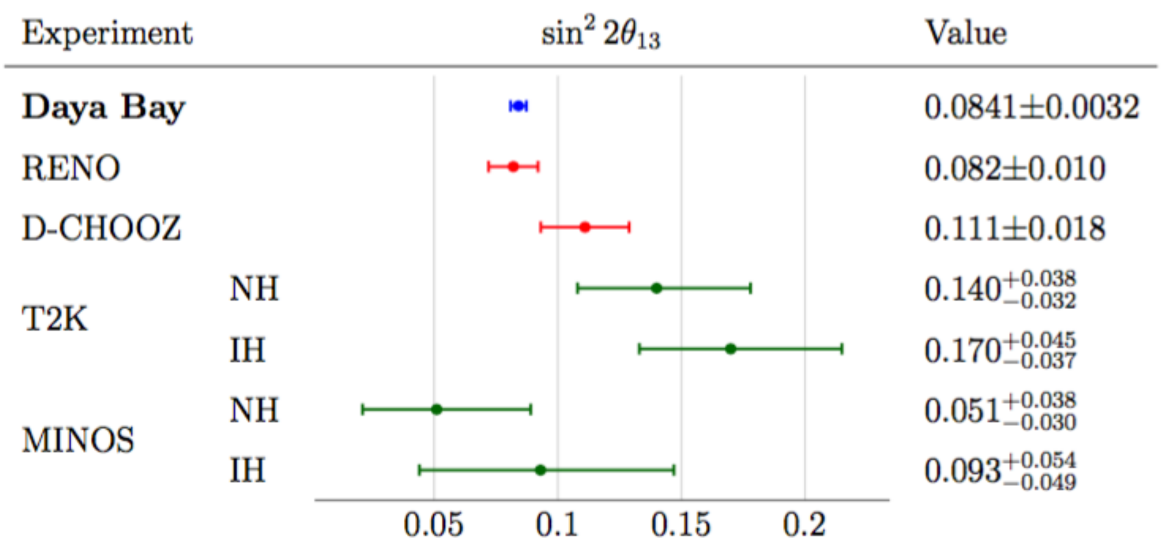

**Best-fit: $\sin^2 2\theta_{13} = 0.111 \pm 0.018$ ($\chi^2$/dof = 128.8/120)**
**Non-zero $\theta_{13}$ observation at 5.8 σ C.L.**

**Double Chooz Preliminary**




- Still statistics dominated
  - ➡ Will include nH captures
  - ➡ Improvements are expected in systematics
- ***Aiming at new results on Sep 20 at CERN Seminar***

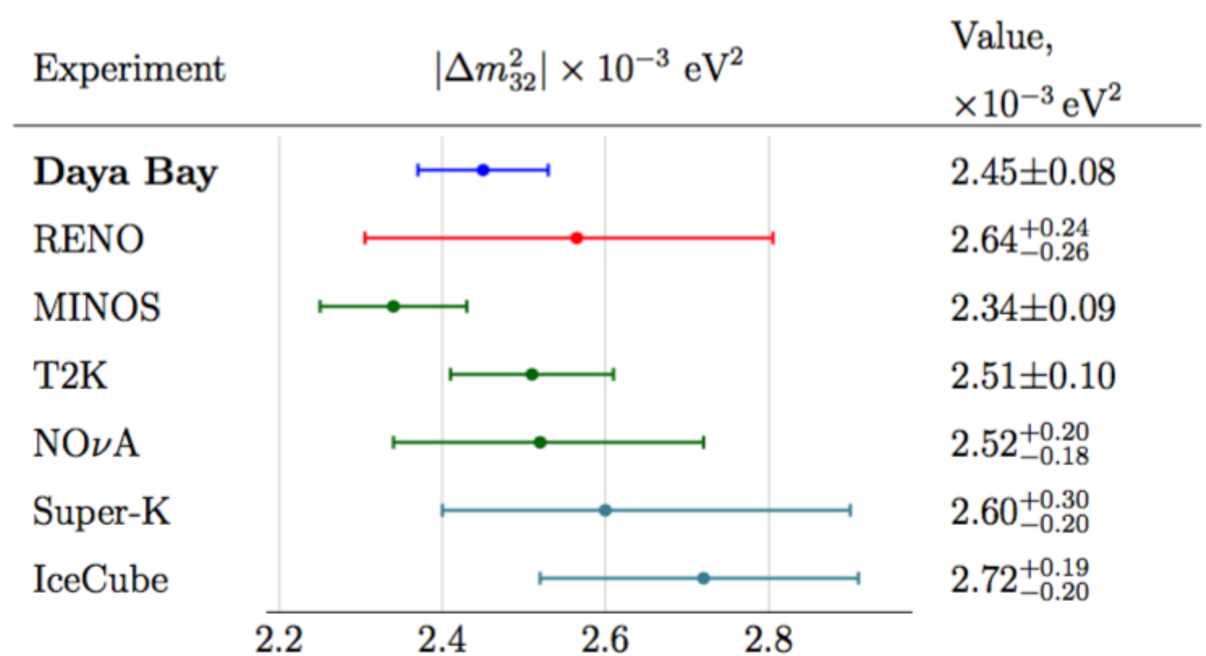
# Global Results of $\sin^2 2\theta_{13}$ and Atmospheric $\Delta m^2$




Daya Bay holds the best results:

- $\sin^2 2\theta_{13}$ uncertainty: 3.9%
- $|\Delta m^2_{32}|$ uncertainty: 3.4%

***A join workshop will be held for the 3 collaborations in upcoming October***



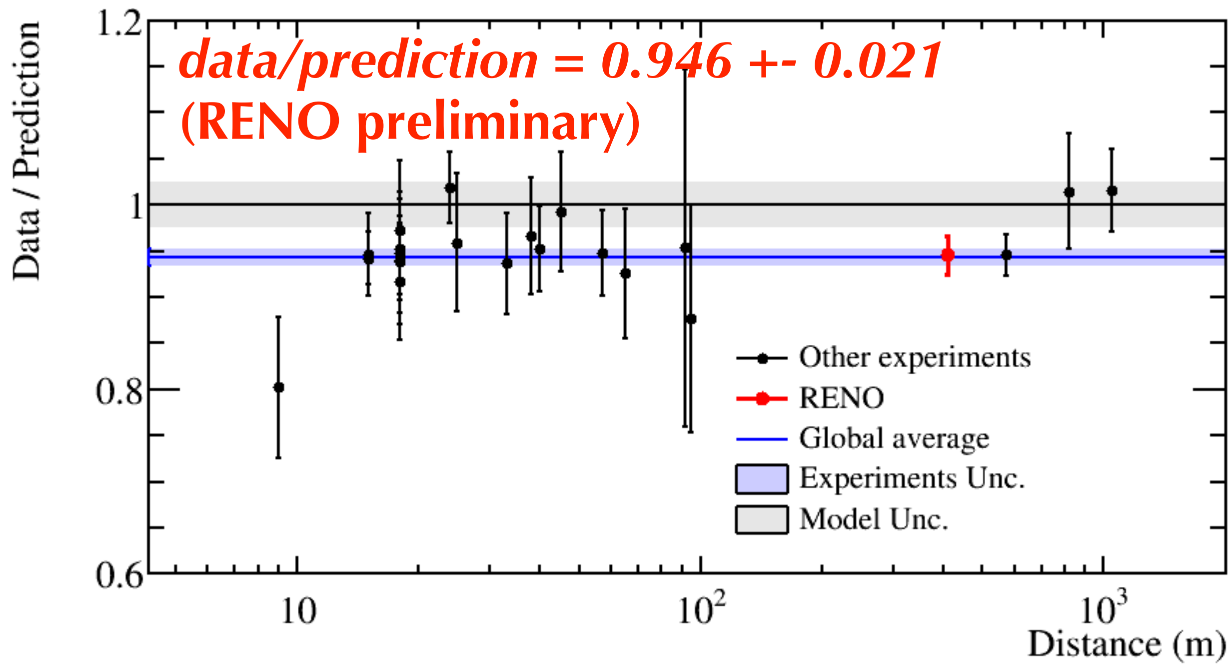

Daya Bay:

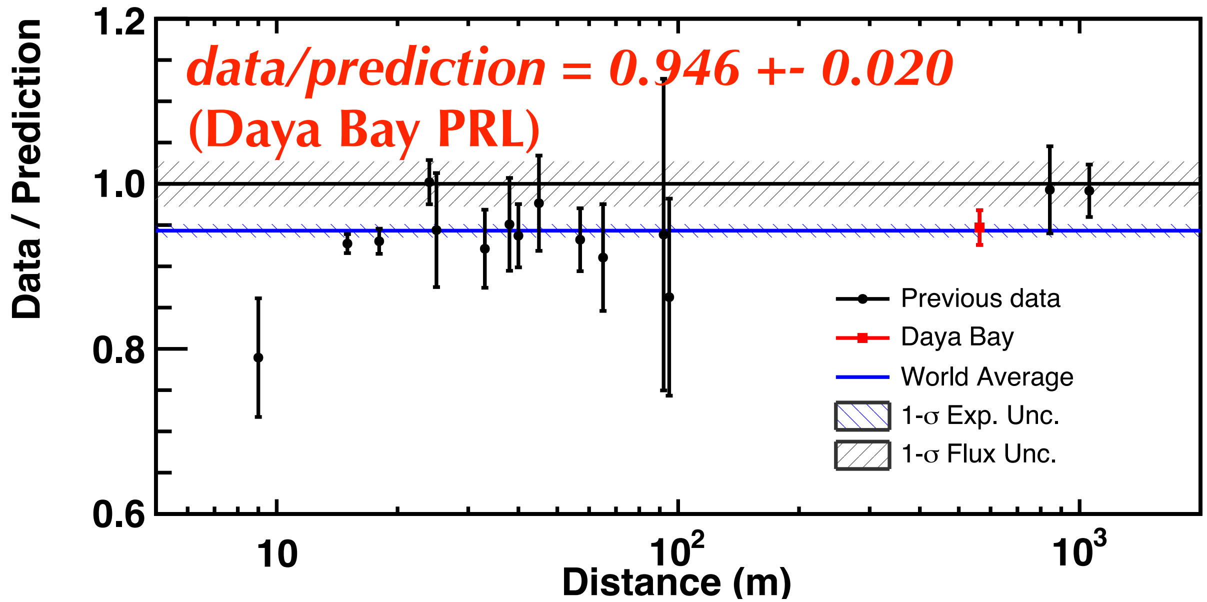
$|\Delta m^2_{ee}| \approx |\Delta m^2_{32}| \pm 0.05 \times 10^{-3}\ \text{eV}^2$

NH: $\Delta m^2_{32} = [2.45 \pm 0.08] \times 10^{-3}\ \text{eV}^2$

IH: $\Delta m^2_{32} = [-2.55 \pm 0.08] \times 10^{-3}\ \text{eV}^2$

# The Reactor Flux Anomaly

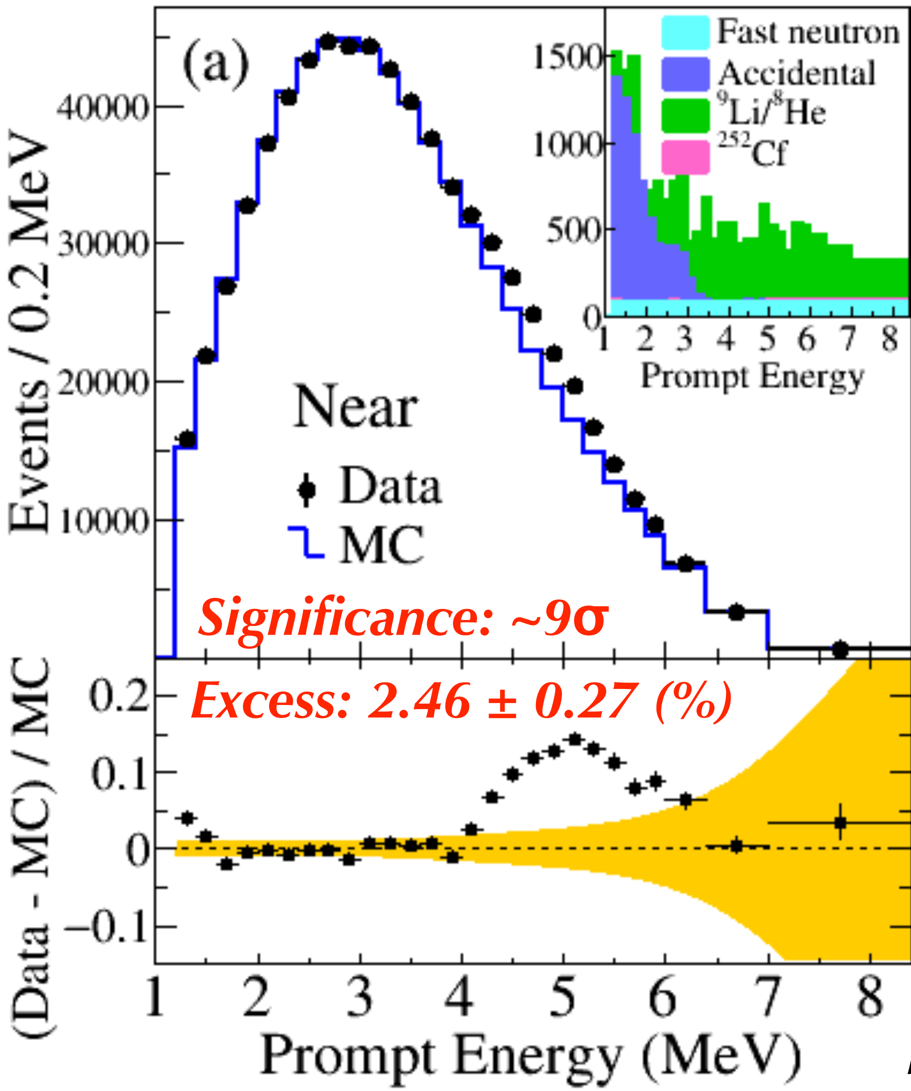


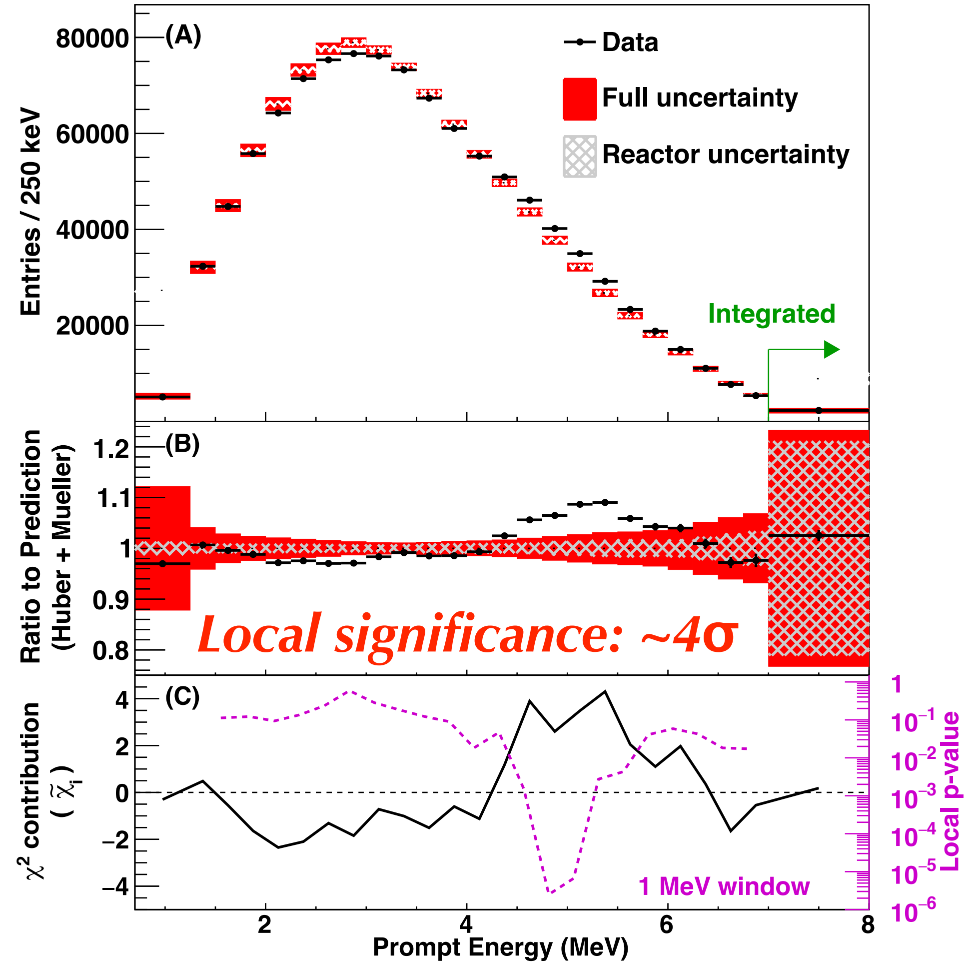

- Huber re-evaluation of the ILL data for $^{235}U$, $^{239}Pu$, $^{241}Pu$
- Muller *et al ab initio* $^{238}U$
- Various detector-side checks carried out but no smoking gun
- Both RENO and Daya Bay confirm this is correlated with reactor power

# The Reactor Flux Spectrum Discrepancy

## RENO preliminary




## Daya Bay CPC



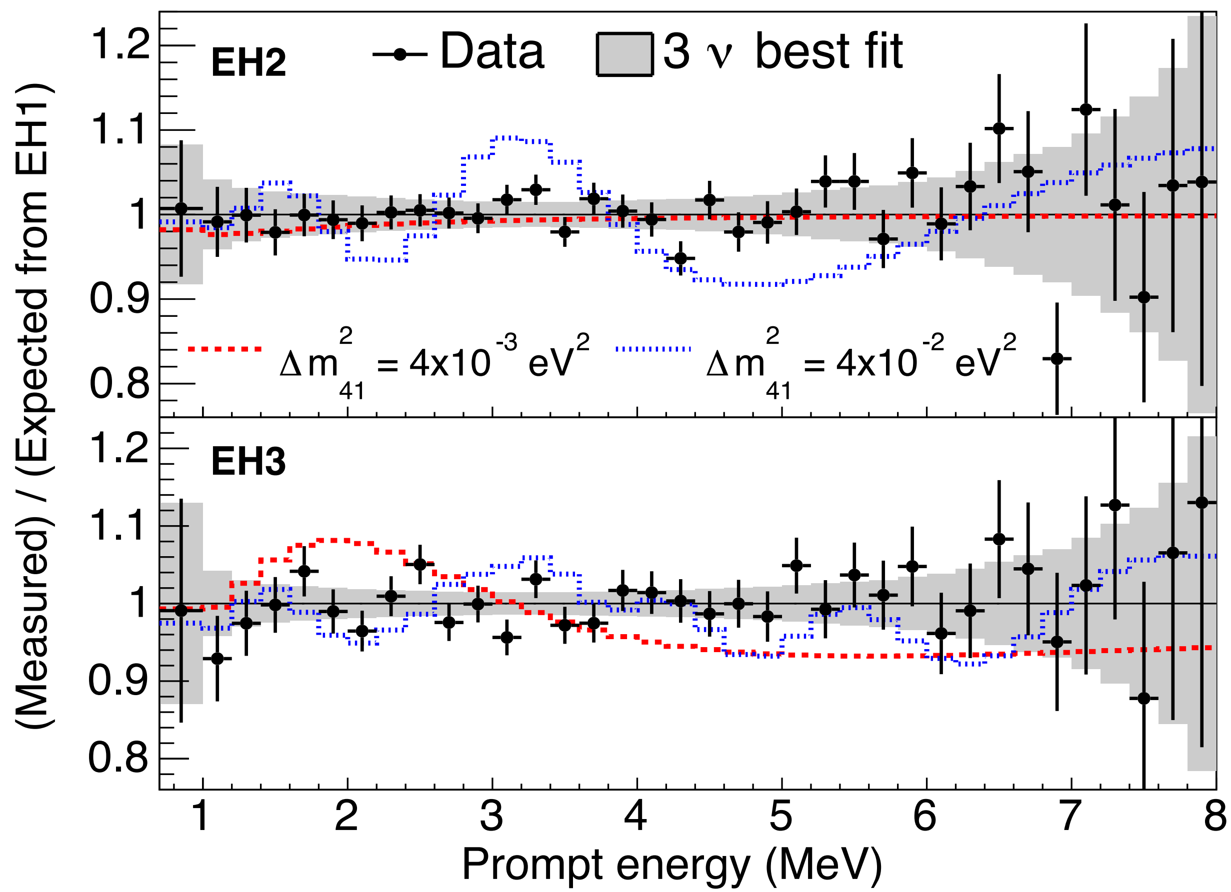

***Blaming fission isotope beta decay calculation/data?***

***For example, see: Dwyer & Langford, PRL114 (2015)012502; Hayes et al, PRL112 (2014) 202501***

# What about Sterile Neutrinos?

$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee}L}{4E_\nu}\right) - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41}L}{4E_\nu}\right)$$

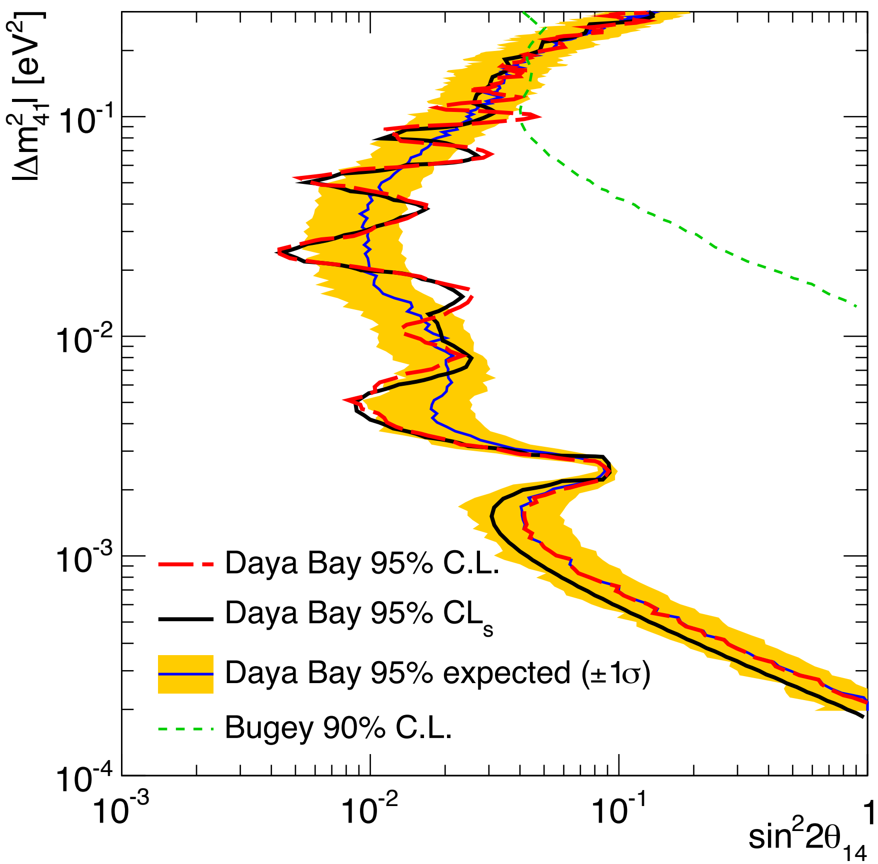
- Daya Bay baselines >350m ⇒ not as sensitive to mass-squared splittings greater than or around 1eV$^2$




*dashed curves assumes $\sin^2 2\theta_{14} = 0.1$*

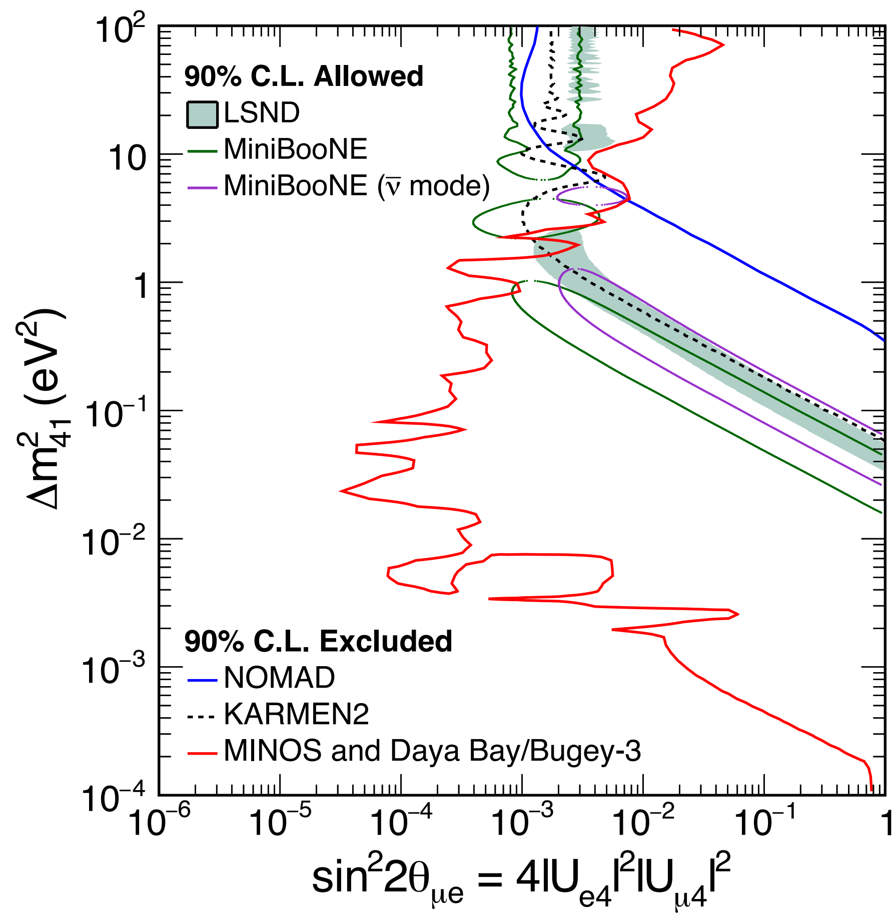
# Sterile Neutrino Searches at Daya Bay and Elsewhere

- Daya Bay alone




***Daya Bay arXiv: 1607.01174***

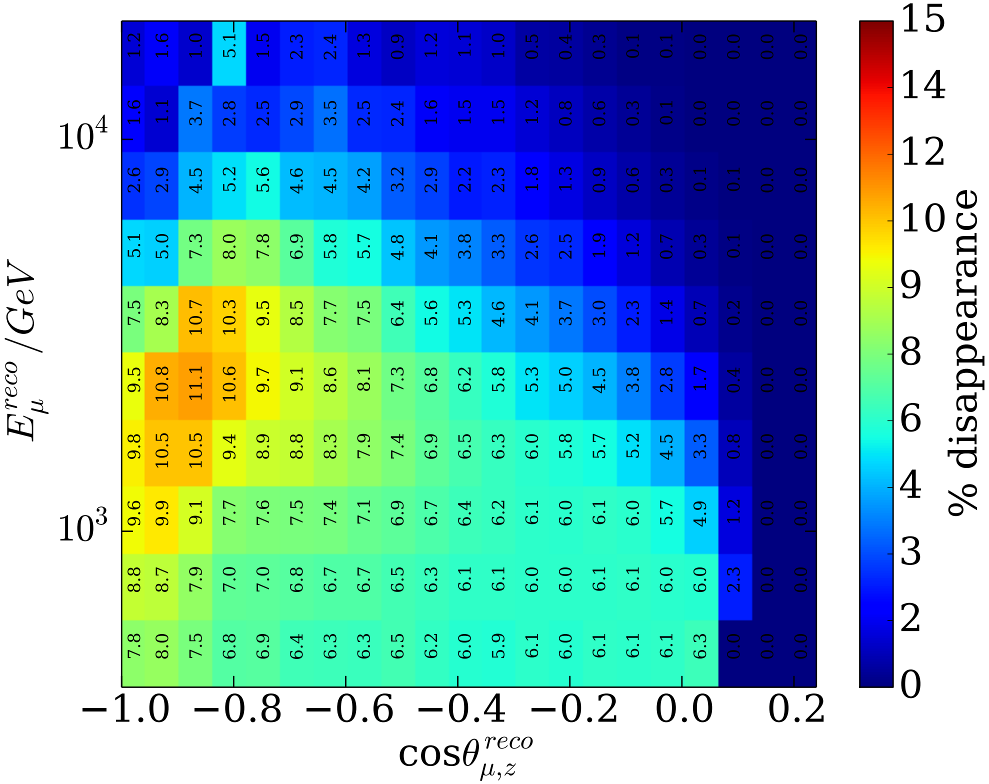
- Daya Bay, MINOS and Bugey-3

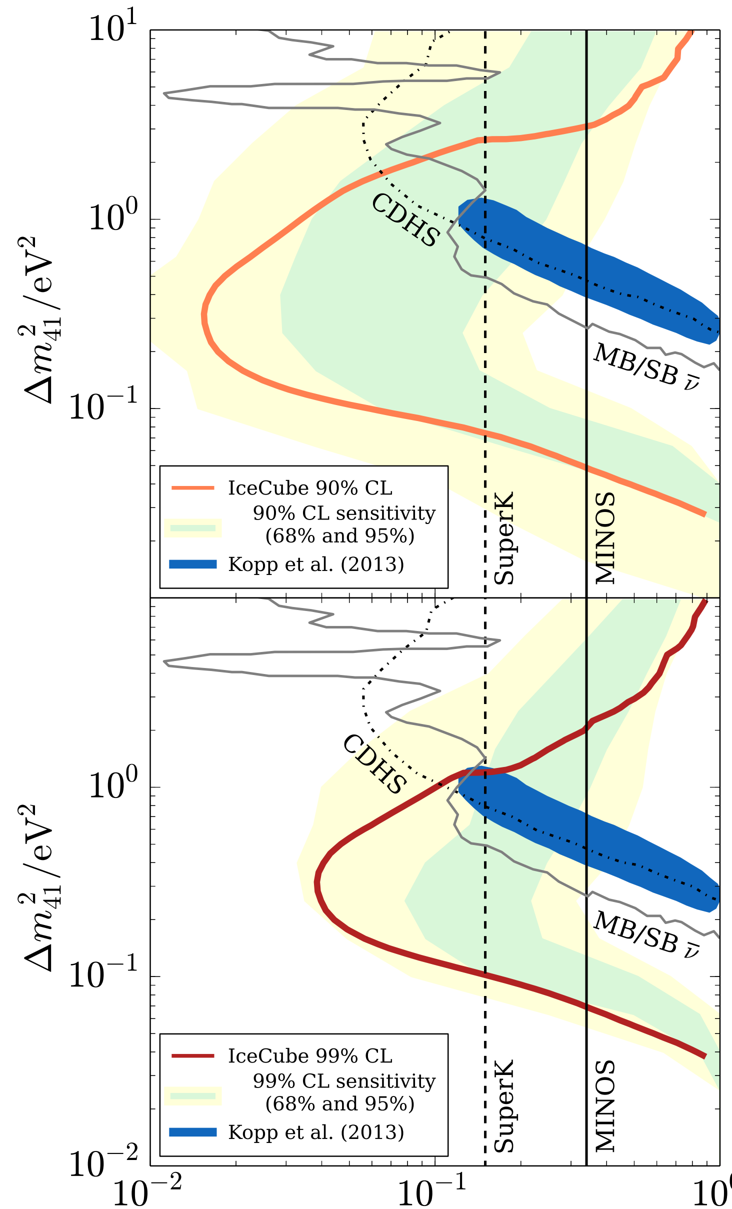



***Daya Bay+MINOS, arXiv:1607.01177***

# Searches for Sterile Neutrinos by IceCUBE

***Nature, Aug 6, 2016, "Icy telescope throws cold water on sterile neutrino theory"***



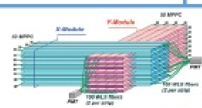
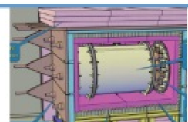
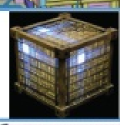
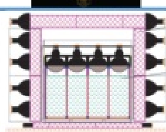
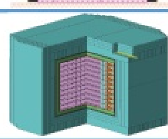
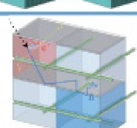




Matter effect causes oscillation resonants for certain sterile neutrino parameters — distinctive signature

***IceCube, PRL117 (2016) 071801***

# Booming of the Very Short-Baseline Experiments

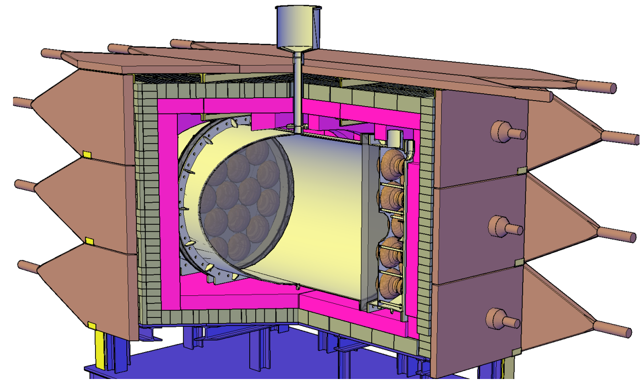
*N. Bowden, Neutino'16*

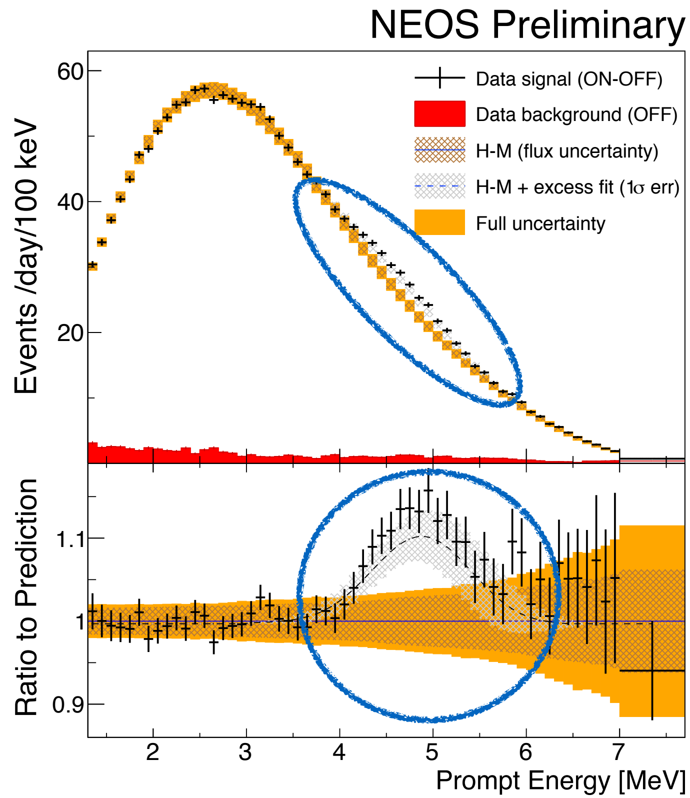
| Experiment | | Reactor Power/Fuel | Overburden (mwe) | Detection Material | Segmentation | Optical Readout | Particle ID Capability |
|---|---|---|---|---|---|---|---|
| DANSS (Russia) |  | 3000 MW LEU fuel | ~50 | Inhomogeneous PS & Gd sheets | 2D, ~5mm | WLS fibers. | Topology only |
| NEOS (South Korea) |  | 2800 MW LEU fuel | ~20 | Homogeneous Gd-doped LS | none | Direct double ended PMT | recoil PSD only |
| nuLat (USA) |  | 40 MW $^{235}$U fuel | few | Homogeneous $^{6}$Li doped PS | Quasi-3D, 5cm, 3-axis Opt. Latt | Direct PMT | Topology, recoil & capture PSD |
| Neutrino4 (Russia) |  | 100 MW $^{235}$U fuel | ~10 | Homogeneous Gd-doped LS | 2D, ~10cm | Direct single ended PMT | Topology only |
| PROSPECT (USA) |  | 85 MW $^{235}$U fuel | few | Homogeneous $^{6}$Li-doped LS | 2D, 15cm | Direct double ended PMT | Topology, recoil & capture PSD |
| SoLid (UK Fr Bel US) |  | 72 MW $^{235}$U fuel | ~10 | Inhomogeneous $^{6}$LiZnS & PS | Quasi-3D, 5cm multiplex | WLS fibers | topology, capture PSD |
| Chandler (USA) |  | 72 MW $^{235}$U fuel | ~10 | Inhomogeneous $^{6}$LiZnS & PS | Quasi-3D, 5cm, 2-axis Opt. Latt | Direct PMT/ WLS Scint. | topology, capture PSD |
| Stereo (France) |  | 57 MW $^{235}$U fuel | ~15 | Homogeneous Gd-doped LS | 1D, 25cm | Direct single ended PMT | recoil PSD |

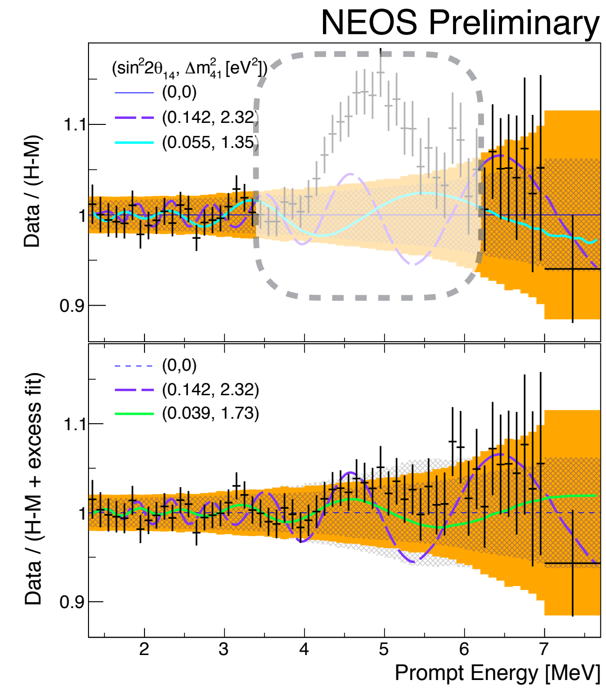
# Highlights from the Very Short-Baseline Experiments

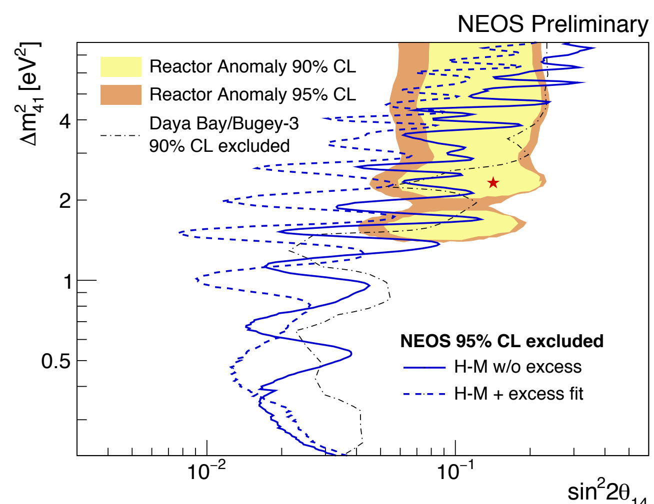
## *NEOS @ ICHEP 2016*

- 2.8 GWt commercial reactor
  — Hanbit NPP in Yeonggwang, Korea
  — core size: 3.1 m (ϕ), 3.8 m (H)
  — LEU fuel.
- Tendon Gallery
  — 24 m baseline
  — overburden > 20 mwe
- Homogeneous LS detector
  — 5% energy resolution @ 1 MeV
  — PSD capability
- Spectral shape analysis with a single detector/baseline measurement
  — dependence on reference spectrum
- Shieldings
  — 10 cm B-PE, 10 cm Pb
  — muon counter

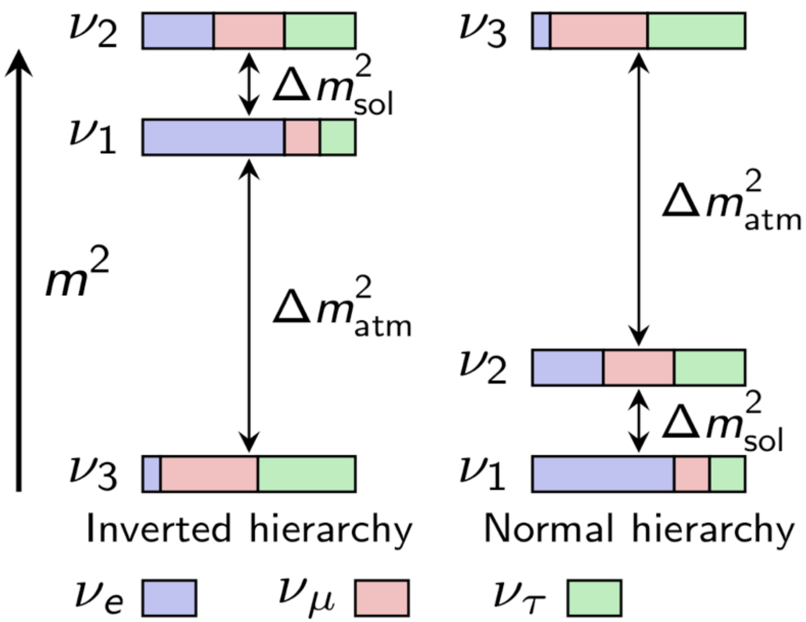


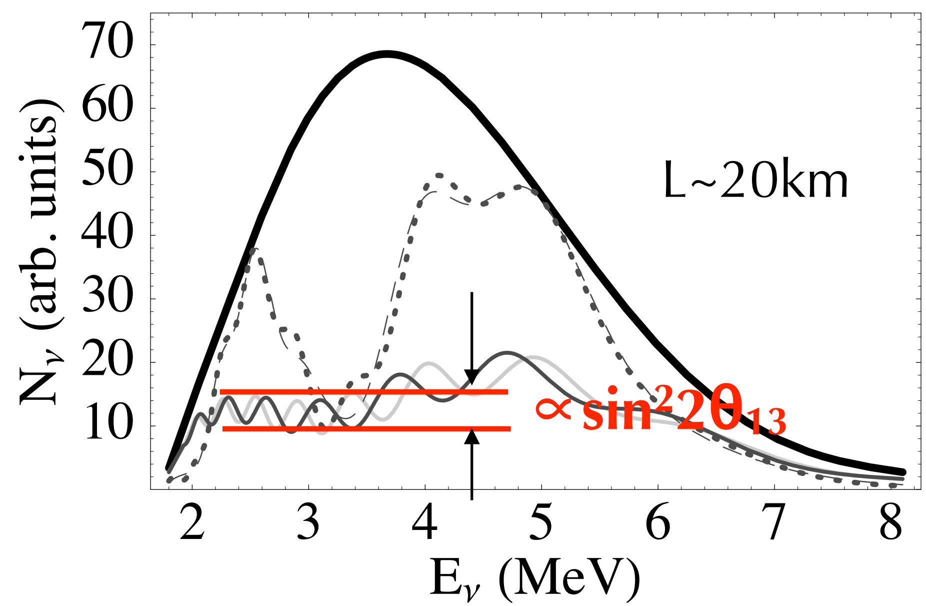


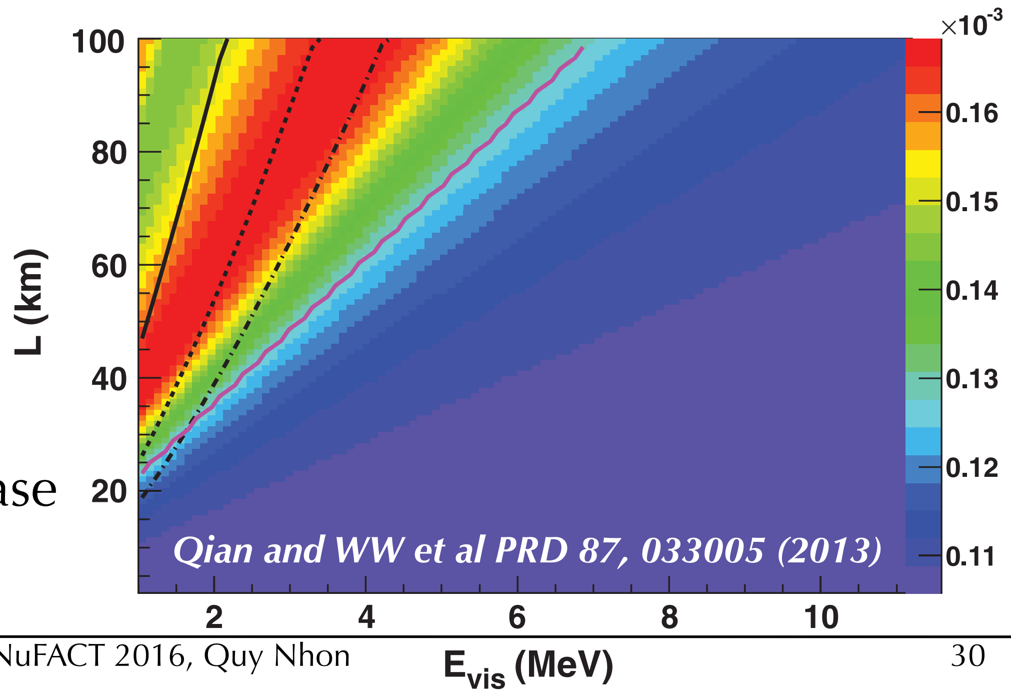
# Known θ13 Enables Neutrino Mass Hierarchy at Reactors



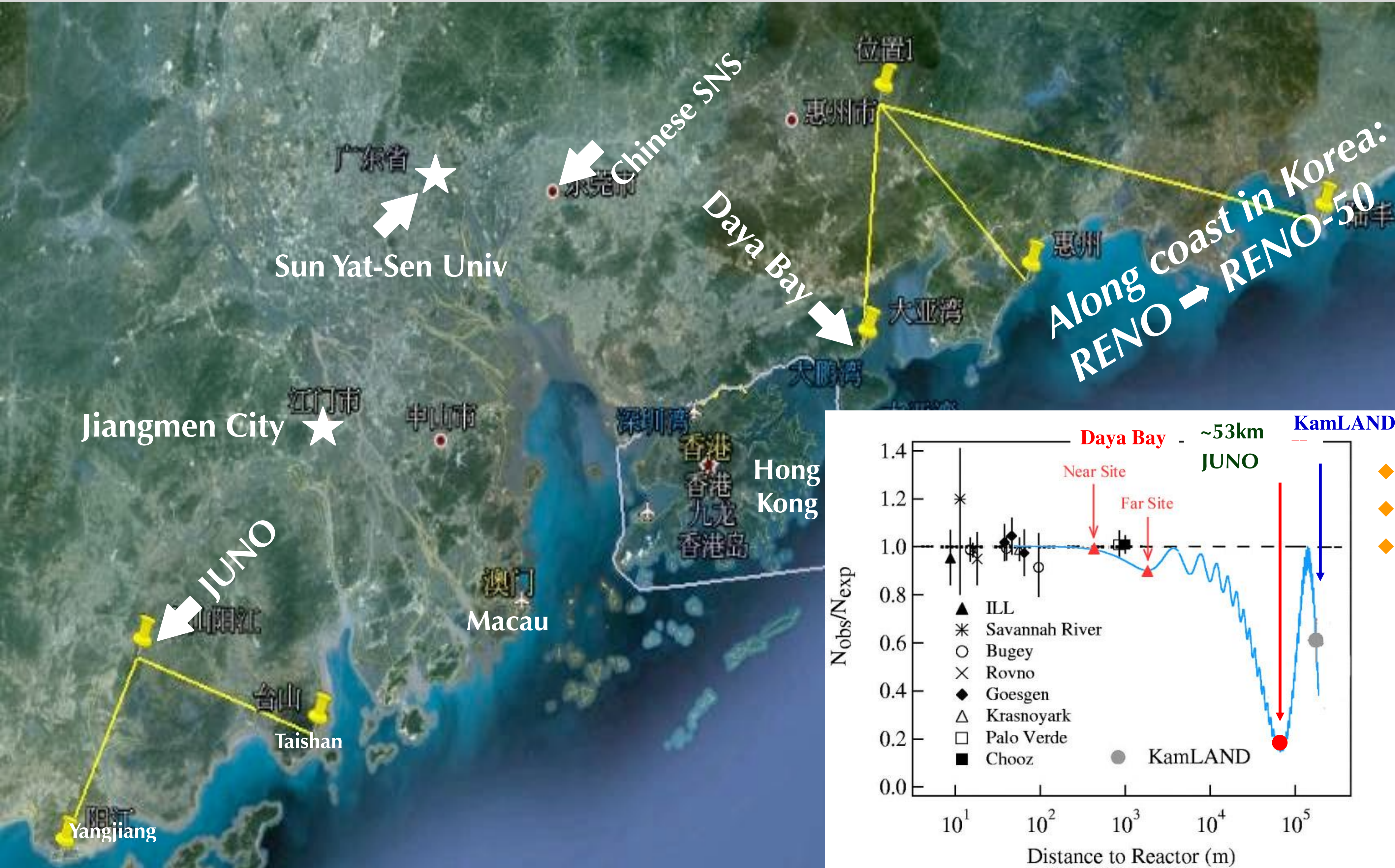

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$- \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$




- ✓ Mass hierarchy is reflected in the spectrum
- ✓ Signal independent of the unknown CP phase
- ✓ Suitable baseline is ~60km

# Jiangmen Underground Neutrino Observatory as an Example

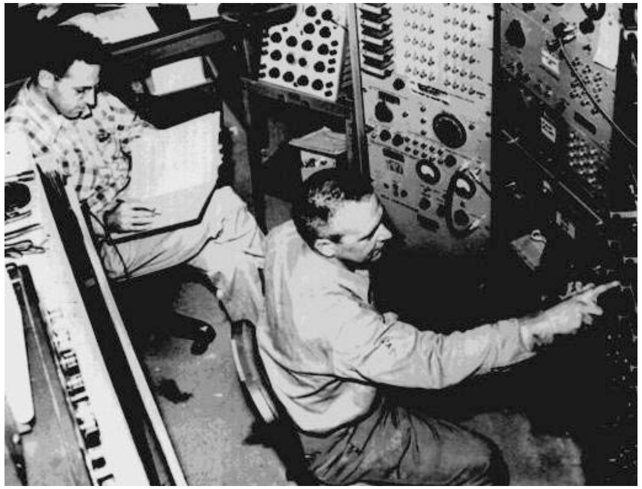


# Summary

- Direct detection of (anti)neutrinos started with reactor neutrinos; Neutrino oscillations were first discovered in atmospheric neutrino data
- Reactor neutrinos are providing some of the most precise oscillation parameter measurements
- Non-accelerator neutrinos provide great potential in resolving the neutrino mass hierarchy
- Non-accelerator neutrinos will continue to excel in search of sterile neutrinos and other exotic new physics: let's expect unexpected!

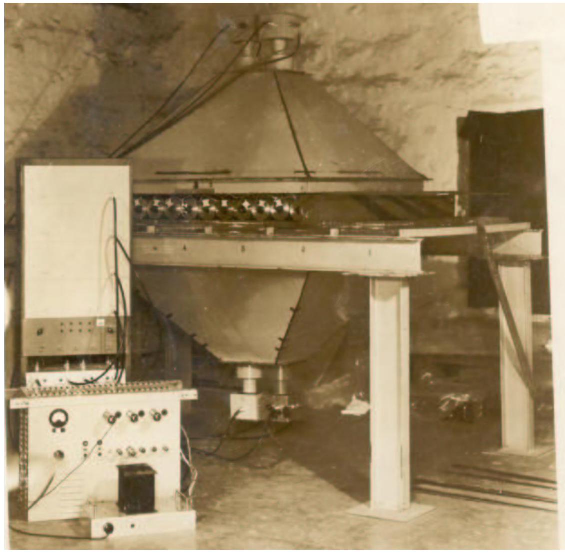
*What I have skipped: BOREXINO, SOX, exotic New Physics searches, Katrin, Ultra-high energy neutrinos, neutrinoless double beta decay experiments……*

# Non-Accelerator Neutrino Milestones



- First neutrino detection: the Savannah River Plant, Reines and Cowan in 1956

➡ Generations of reactor experiments



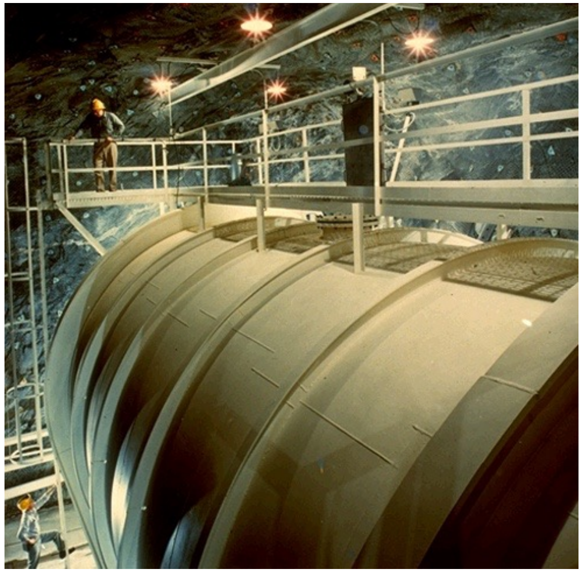
- First atmospheric neutrino detection: Kolar Gold Fields (KGF), 1965

➡ INO


- Atmospheric neutrinos as backgrounds to proton decays

➡ First supernova neutrino detection: Kamiokande, 1987

➡ Super-Kamiokande discovered atmospheric neutrino oscillations 1998

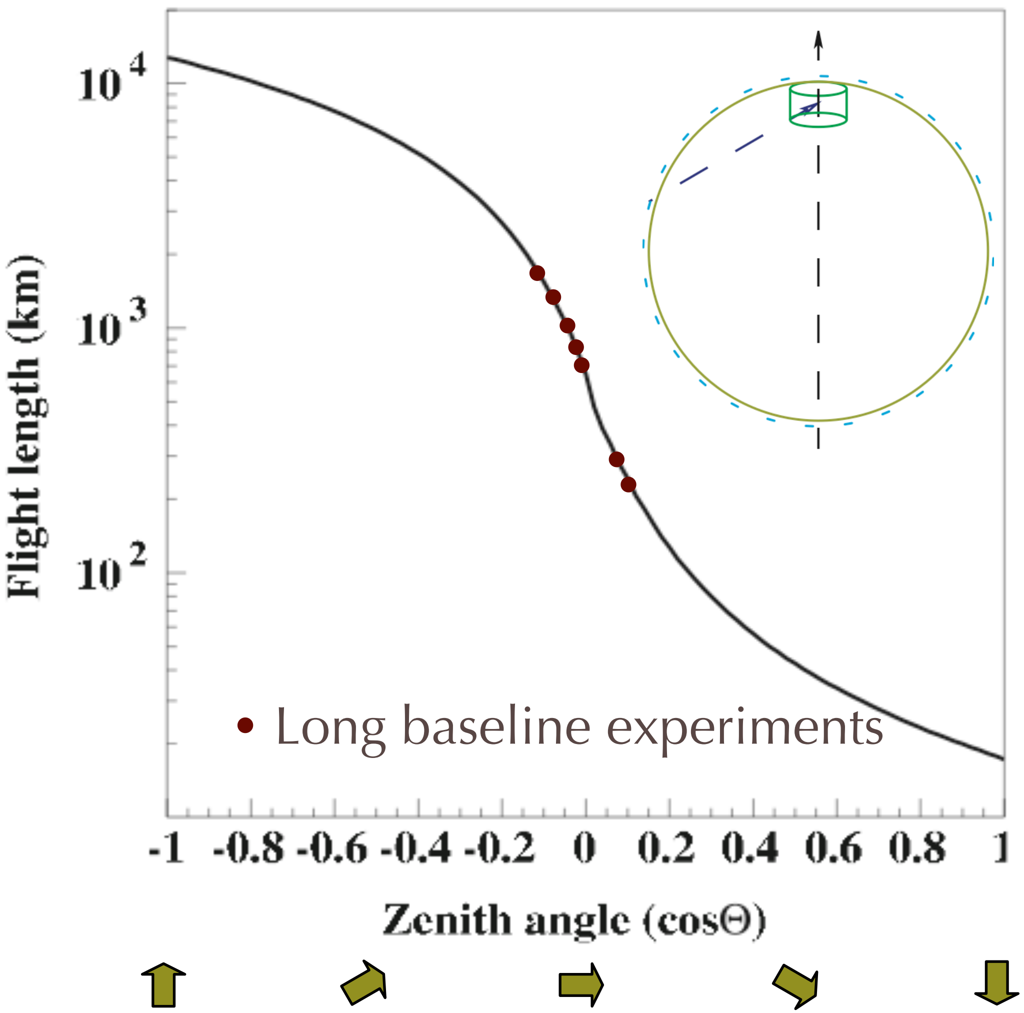


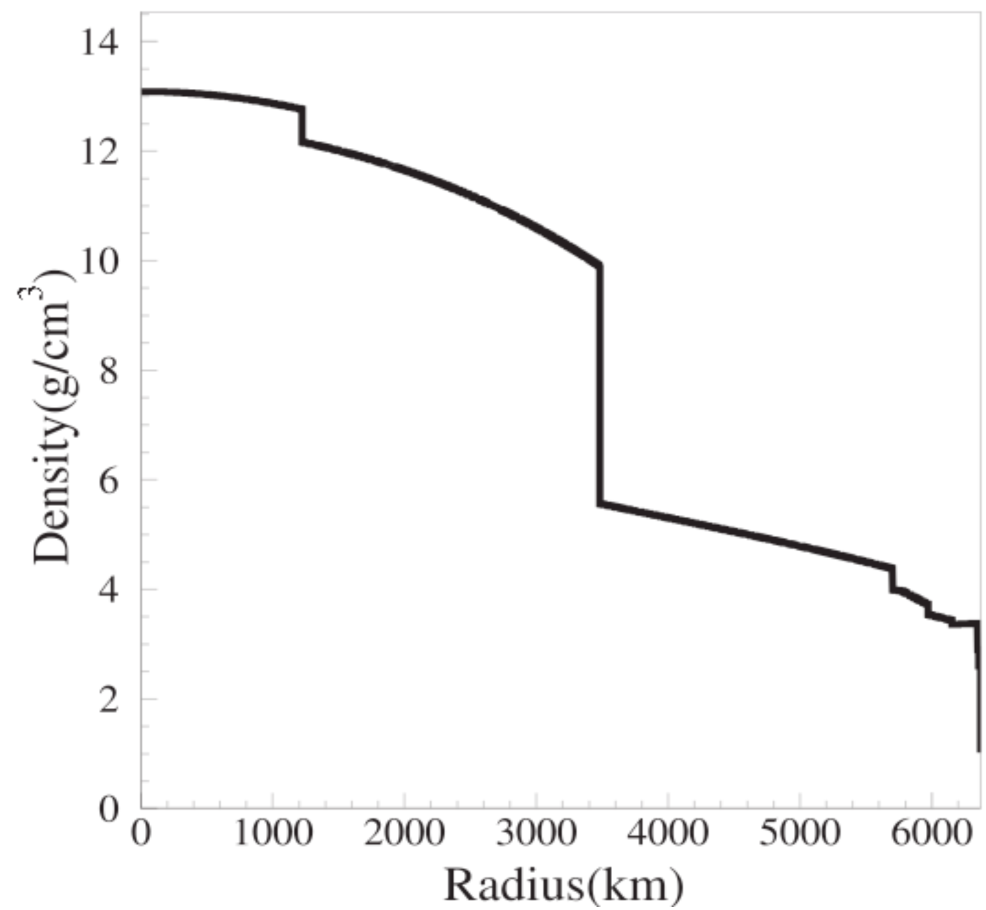
- First solar neutrino detection: R. Davis, Homestake, 1970's - 1990's

➡ SNO resolving the solar neutrino problem 2002

➡ Am I missing anything? Don't complain yet.

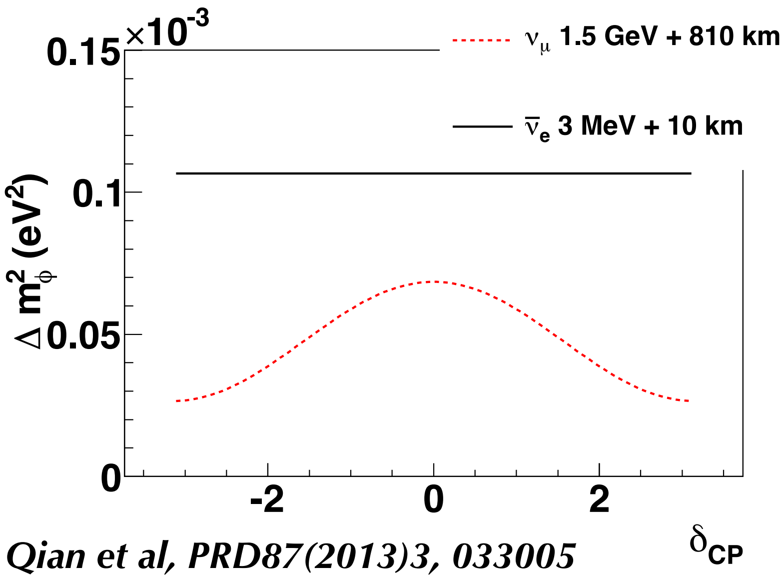
# Looking into Atmospheric Neutrinos More




- Great advantages in energy, baseline and matter density coverage
- Super-Kamiokande: Liquid Water Cherenkov; IceCube/DeepCore: Frozen Water Cherenkov; MINOS/MINOS+: Plastic Scintillator

# Why is the $\Delta m^2_{ee}$ Measurement Interesting?




***Qian et al, PRD87(2013)3, 033005***

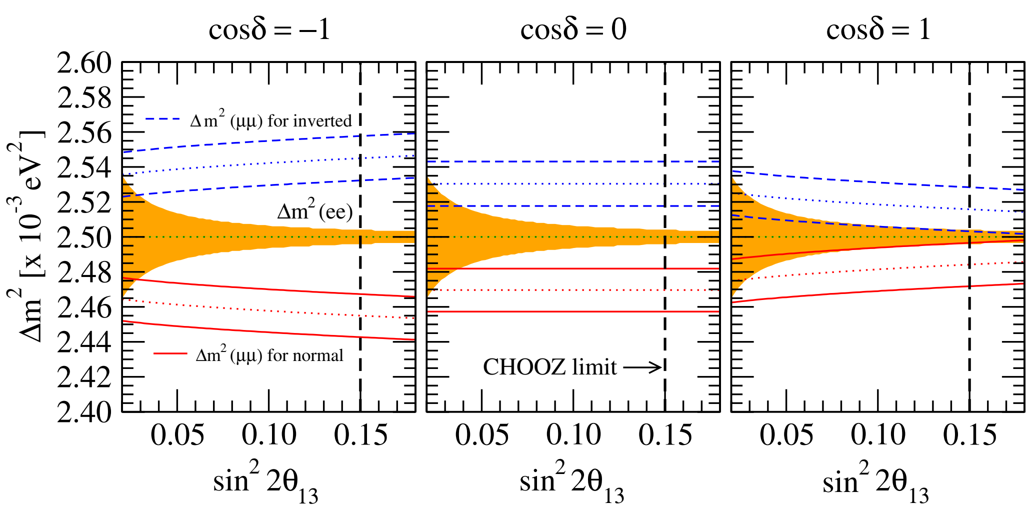
FIG. 6: The dependence of effective mass-squared difference $\Delta m^2_{ee\phi}$ (solid line) and $\Delta m^2_{\mu\mu\phi}$ (dotted line) w.r.t. the value of $\delta_{CP}$ for $\bar{\nu}_e$ and $\nu_\mu$ disappearance measurements, respectively.

$$\begin{aligned} P(\bar{\nu}_e \to \bar{\nu}_e) &= 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ &= 1 - 2s^2_{13}c^2_{13} - 4c^4_{13}s^2_{12}c^2_{12}\sin^2\Delta_{21} + 2s^2_{13}c^2_{13}\sqrt{1-4s^2_{12}c^2_{12}\sin^2\Delta_{21}}\cos(2\Delta_{32}\pm\phi) \end{aligned}$$

$$P_{\nu_\mu\to\nu_\mu} = 1 - P^\mu_{21} - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\frac{(\Delta m^2_{32}\pm\phi)L}{4E}$$

***Because it could, potentially, tell MH!***

***But it is too hard of a job from this approach.***




***Minakata et al PRD74(2006), 053008***

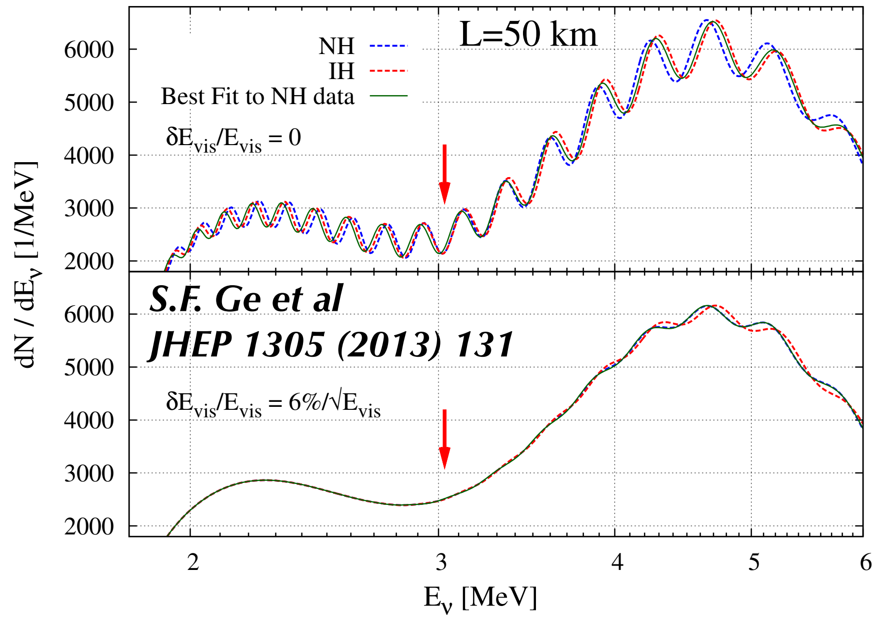
TABLE II: Simple fitting for mass splitting $\Delta m^2_{32}$ and $\Delta m^2_{31}$ using Eqs. (11), (12), (16), and (19) in NH (or (20) in IH) as constraints. The corresponding 2-tailed p-values increase from that in Table I. Here the slight preference for normal hierarchy remains.

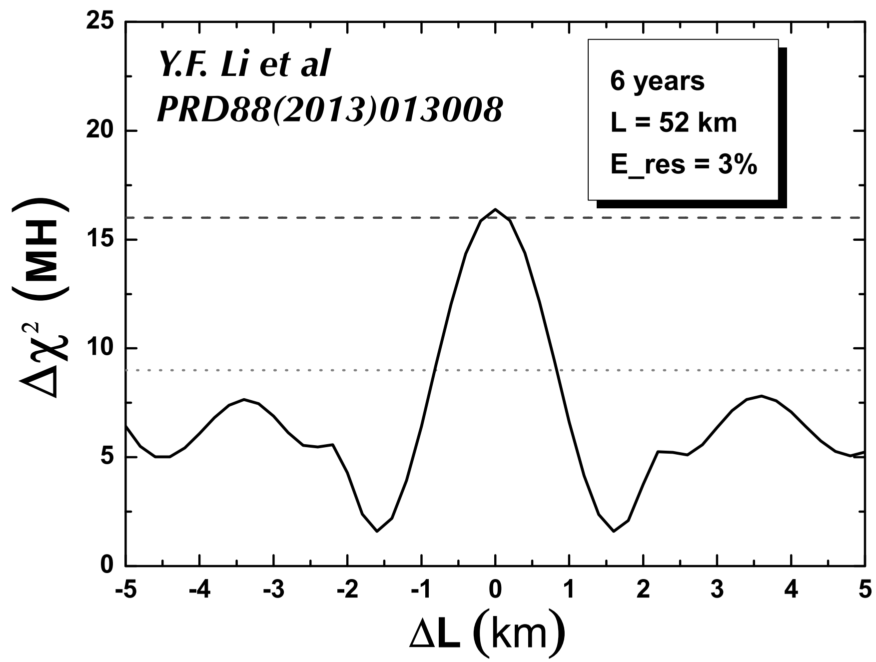
| | Fit in normal hierarchy | Fit in inverted hierarchy |
|---|---|---|
| $\Delta m^2_{32}$ | $(2.46 \pm 0.07)\times 10^{-3}$ eV$^2$ | $-(2.51 \pm 0.07)\times 10^{-3}$ eV$^2$ |
| $\Delta m^2_{31}$ | $(2.53 \pm 0.07)\times 10^{-3}$ eV$^2$ | $-(2.44 \pm 0.07)\times 10^{-3}$ eV$^2$ |
| $\chi^2$/DoF | 0.96/2 | 1.21/2 |
| p-value | 62% | 55% |

***Zhang&Ma, arXiv:1310.4443***

# Challenges in Resolving MH using Reactor Sources

- Energy resolution: ~3%/sqrt(E)
  - Bad resolution leads to smeared spectrum and the MH signal practically disappears
- Energy scale uncertainty: <1%
  - Bad control of energy scale could lead to no answer, or even worse, a wrong answer
- Statistics (who doesn't like it?)
  - ~36GW thermal power, a 20kt detector plus precise muon tracking to get the best statistics
- Reactor distribution: <~0.5km
  - If too spread out, the signal could go away due to cancellation of different baselines
  - JUNO baseline differences are within half kilometer.



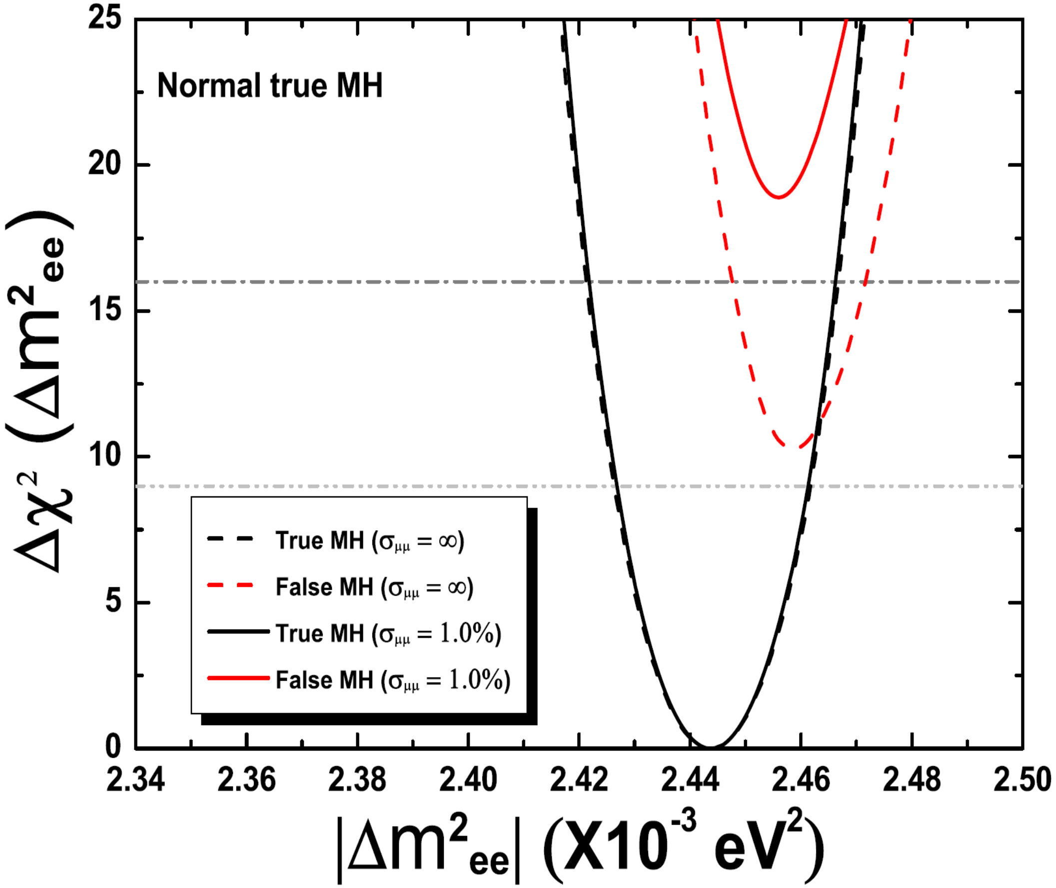



# The Detector Performance Goals

| | Daya Bay | BOREXINO | KamLAND | JUNO |
|---|---|---|---|---|
| Target Mass | 20t | ~300t | **~1kt** | **~20kt** |
| PE Collected | ~160 PE/MeV | **~500 PE/MeV** | ~250 PE/MeV | **~1200 PE/MeV** |
| Photocathode Coverage | ~12% | **~34%** | **~34%** | **~80%** |
| Energy Resolution | ~7.5%/√E | **~5%/√E** | ~6%/√E | **3%/√E** |
| Energy Calibration | ~1.5% | **~1%** | ~2% | **<1%** |

➡ **An unprecedented LS detector is under development for the JUNO project —> a great step in detector technology**

# Expected Significance to Mass Hierarchy




- ~3-sigma if only a relative spectral measurement without external atmospheric mass-squared splitting
- ~4-sigma with an external $\Delta m^2$ measured to ~1% level in $\nu_\mu$ beam oscillation experiments
  - ~1% in $\Delta m^2$ is reachable based on the combined T2K+NOvA analysis by S.K. Agarwalla, S. Prakash, WW, arXiv:1312.1477

✓Realistic reactor distributions considered

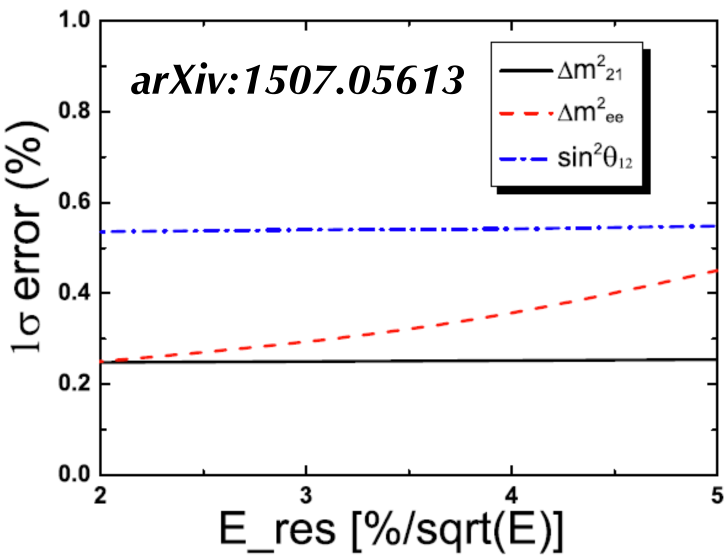
✓20kt valid target mass, 36GW reactor power, 6-year running

✓3% energy resolution and 1% energy scale uncertainty assumed

# JUNO Precision Measurements Warranted

Global now
arXiv:1507.05613

| | $\Delta m^2_{21}$ | $\lvert\Delta m^2_{31}\rvert$ | $\sin^2\theta_{12}$ | $\sin^2\theta_{13}$ | $\sin^2\theta_{23}$ |
|---|---|---|---|---|---|
| Dominant Exps. | KamLAND | MINOS | SNO | Daya Bay | SK/T2K |
| Individual $1\sigma$ | 2.7% [121] | 4.1% [123] | 6.7% [109] | 6% [122] | 14% [124, 125] |
| Global $1\sigma$ | 2.6% | 2.7% | 4.1% | 5.0% | 11% |




***Consistent conclusion from an independent study by A.B. Balantekin et al, Snowmass'13, arXiv:1307.7419***

- Precision <1% measurements are warranted in a experiment like JUNO
  - Enable a future ~1% level PMNS unitarity test
  - Neutrinoless double beta decay needs precise $\theta_{12}$

| | Nominal | + B2B (1%) | + BG | + EL (1%) | + NL (1%) |
|---|---|---|---|---|---|
| $\sin^2\theta_{12}$ | 0.54% | 0.60% | 0.62% | 0.64% | 0.67% |
| $\Delta m^2_{21}$ | 0.24% | 0.27% | 0.29% | 0.44% | 0.59% |
| $\lvert\Delta m^2_{ee}\rvert$ | 0.27% | 0.31% | 0.31% | 0.35% | 0.44% |

JUNO: 100k evts
arXiv:1507.05613