Neutrino Experiments

Wei Wang / 王為, Sun Yat-Sen University
The 13th CosPA, Sydney, Australia, Nov 28, 2016

- *Discovery of Neutrino Oscillations*
- *Completion of mixing angles*
- *Unexpected and remaining questions*

Disclaimers

- This year is the 20th anniversary of the Super-K experiment: neutrino oscillation has been discovered for 18 years and physicists are quite familiar with most of the progresses
- Many people in audience are experts in this field so I will simply try to entertain you with my version of the story, focusing on neutrino oscillations and oscillation parameter measurements
- I try to be complete but I must be biased due to personal experiences
- I apologize if I am missing your favorite experiments or results


スーパーカミオカンデ観測20周年記念祝賀会
Super-Kamiokande 20th Anniversary Celebration
高級 清酒
満寿泉
芳醇

Discovery of Neutrino Oscillations and Nobel Prize

The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

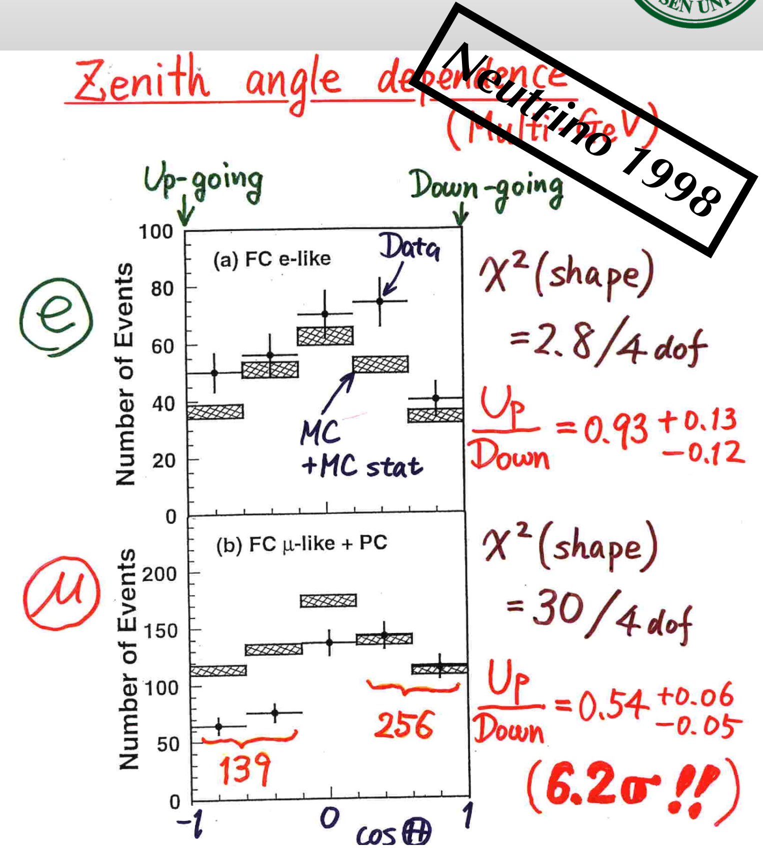
Prize share: 1/2

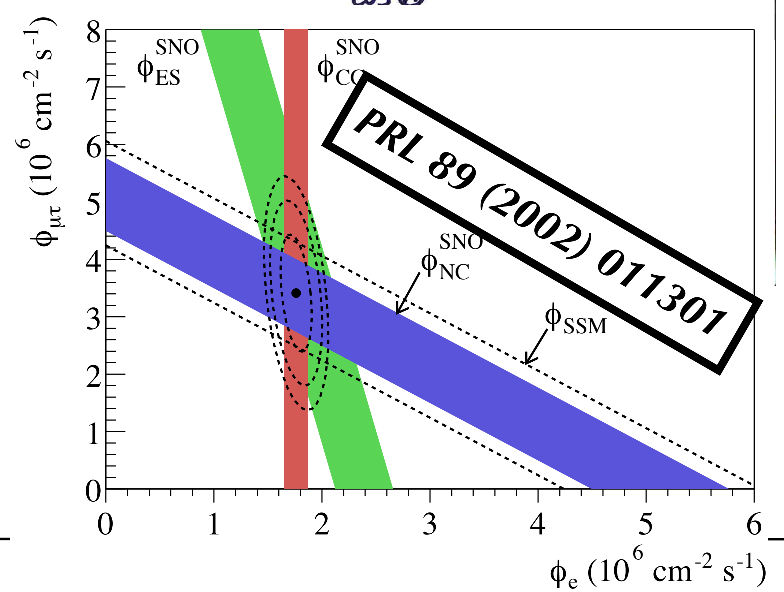
Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

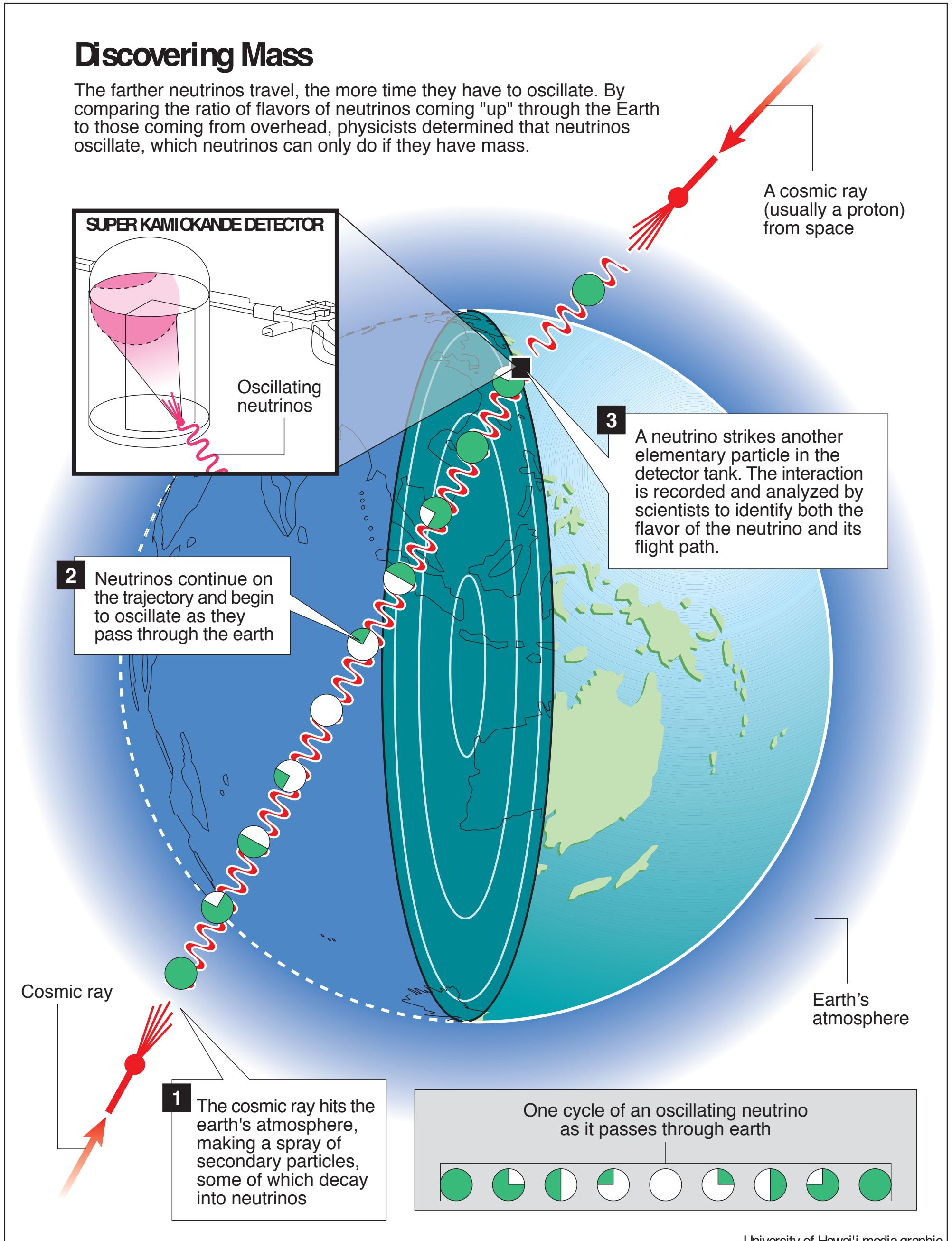
Prize share: 1/2

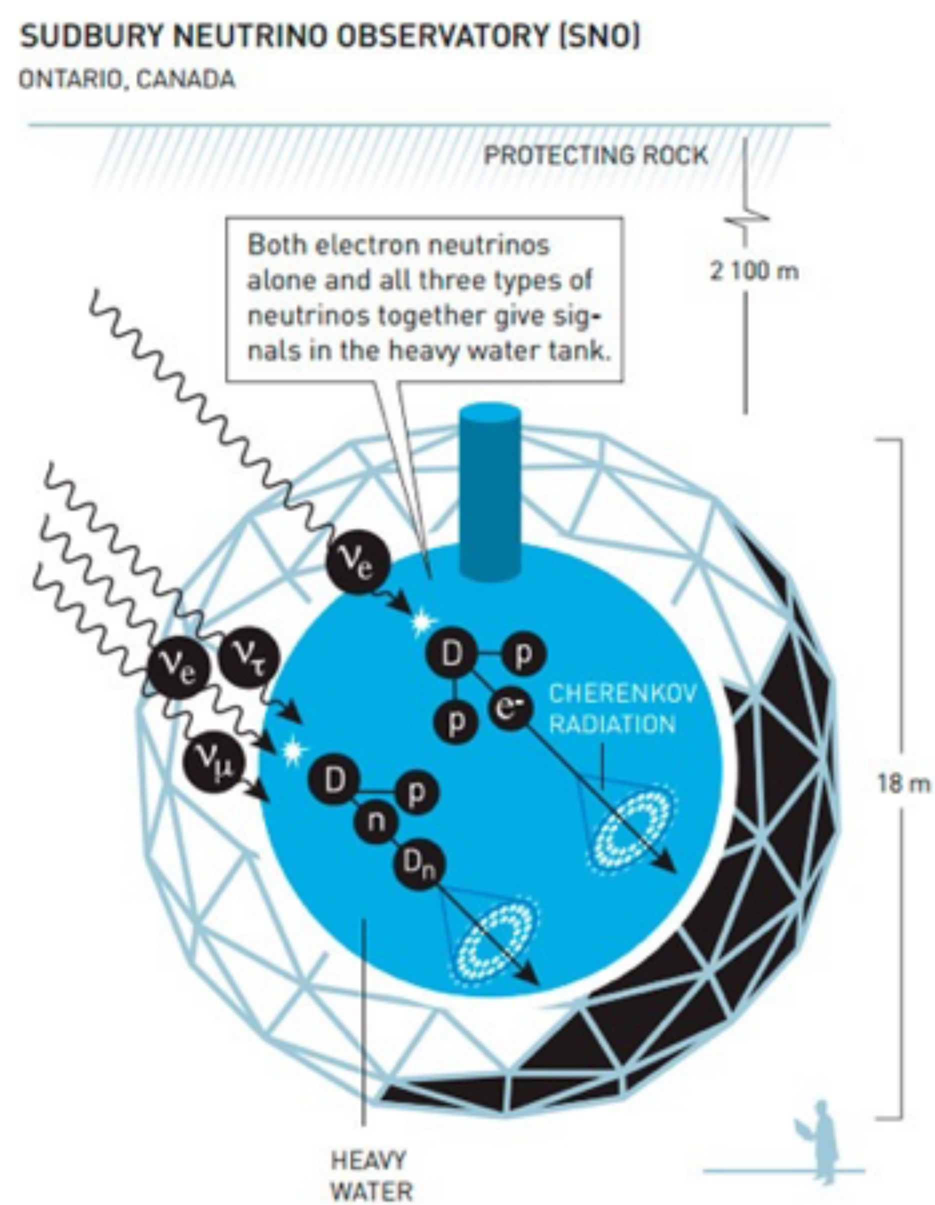
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*





Super-Kamiokande and SNO Detectors





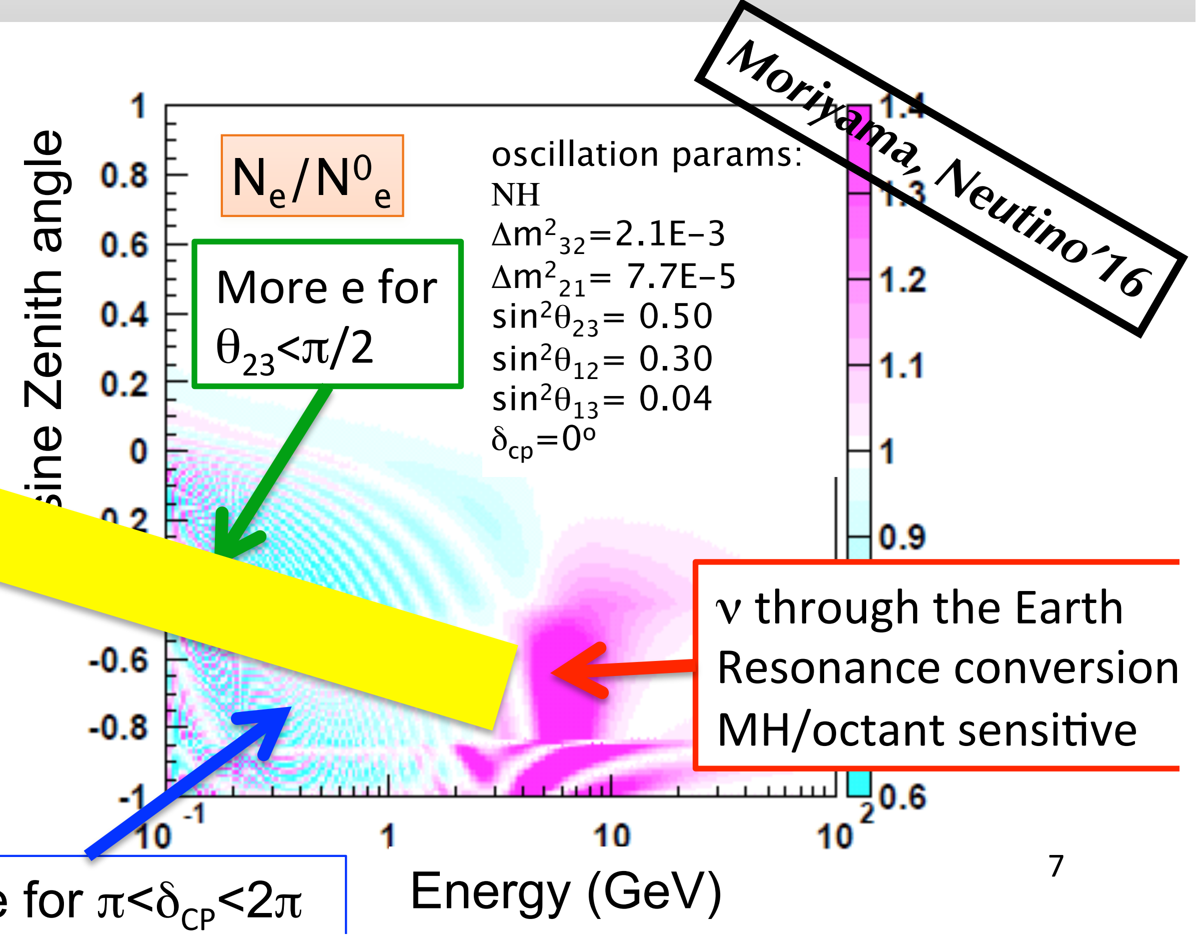
Sensitivity to Various Parameters of Atmospheric Neutrinos

ν_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

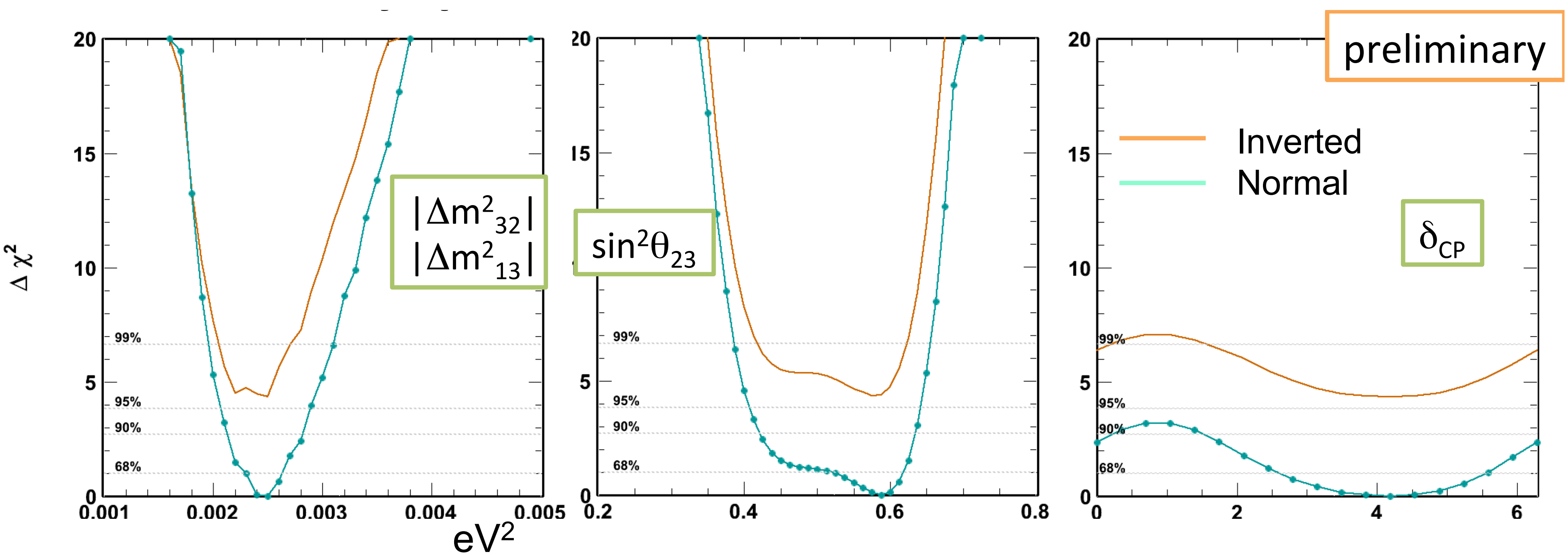
Multi-Ring other

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



- Matter effect can generate resonance conversion → Mass hierarchy
- Solar oscillation $\nu_\mu \Leftrightarrow \nu_e$ → octant sensitivity
- Interference between neutrino and antineutrino → CP phase sensitivity

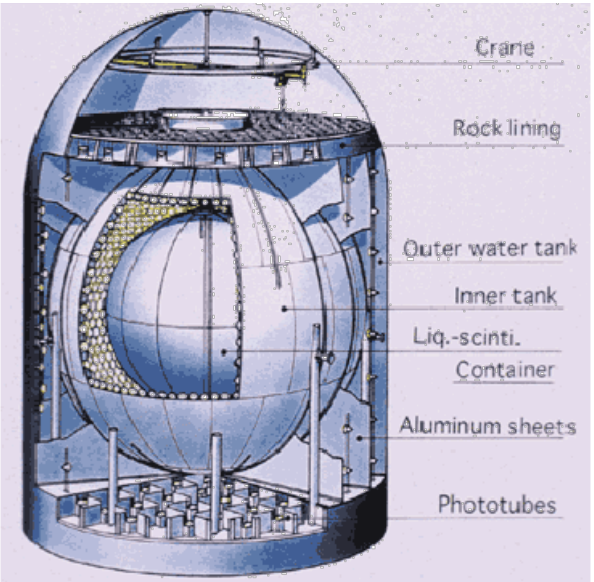
Super-K Atmospheric Neutrino Results

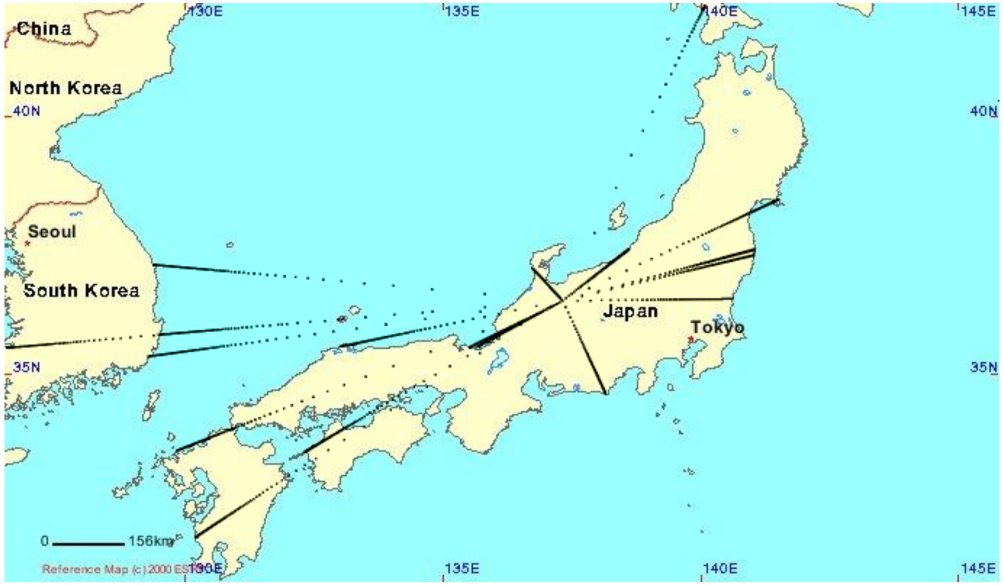


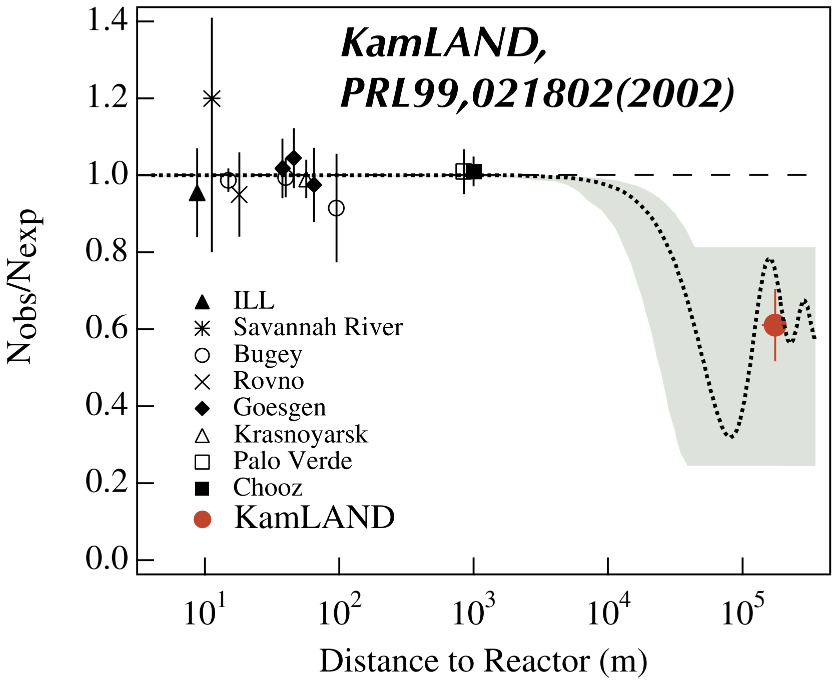
Fit (517 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32}\rvert$ eV^2
SK (IH)	576.08	0.0219 (fix)	4.189	0.575	2.5x10^{-3}
SK (NH)	571.74	0.0219 (fix)	4.189	0.587	2.5x10^{-3}

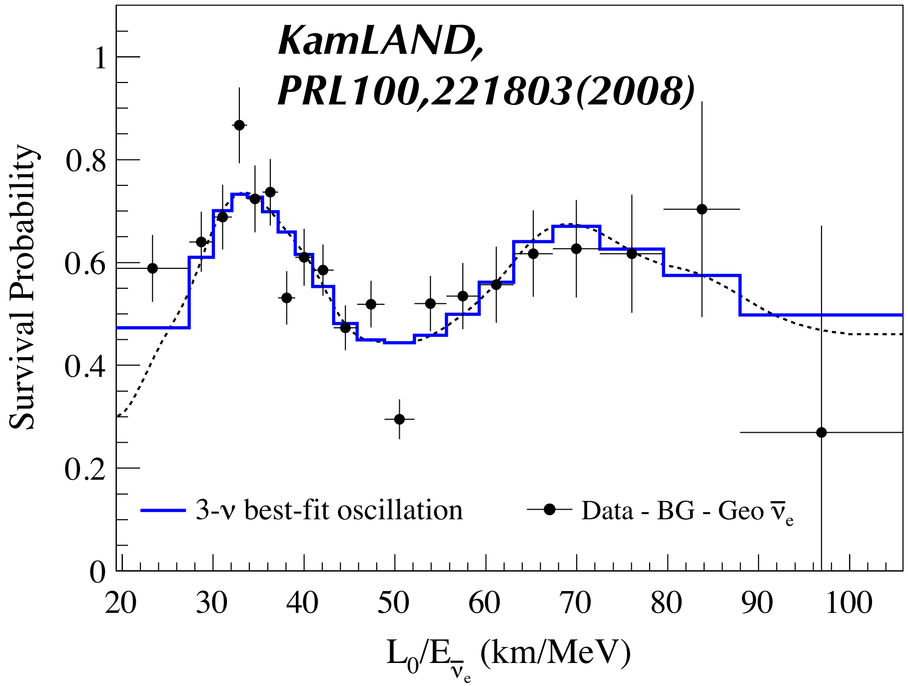
- *$\Delta\chi^2$(NH-IH)=-4.3: Normal Mass Hierarchy is preferred by SK atm. data*
- *Weak CP and octant preferences*

Solar Neutrino Oscillations using Reactor Neutrinos



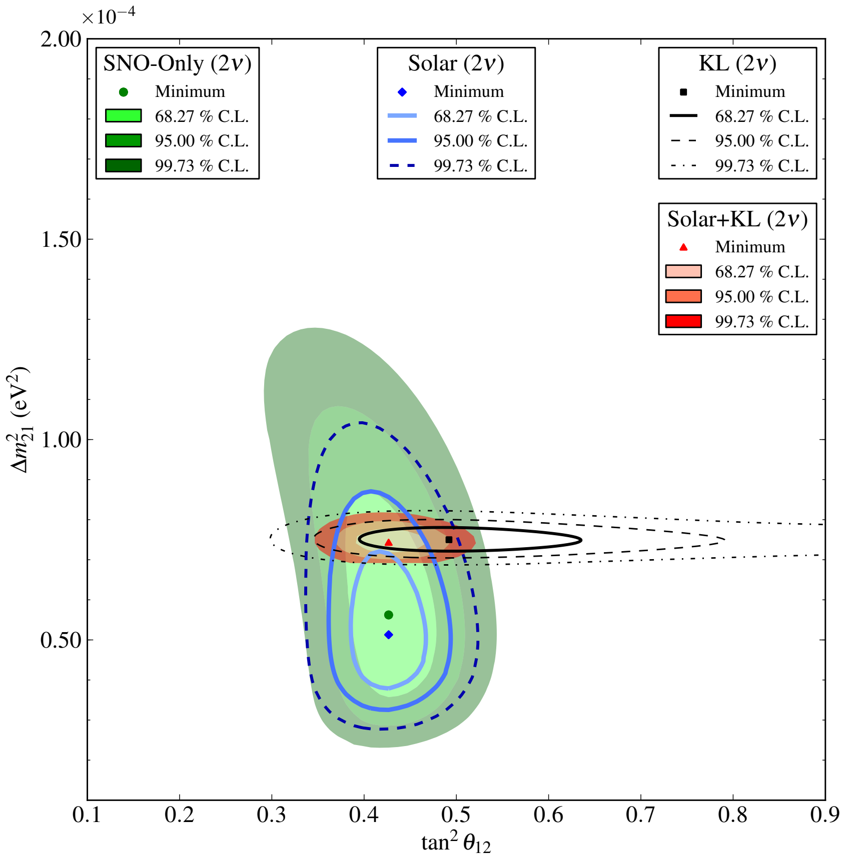




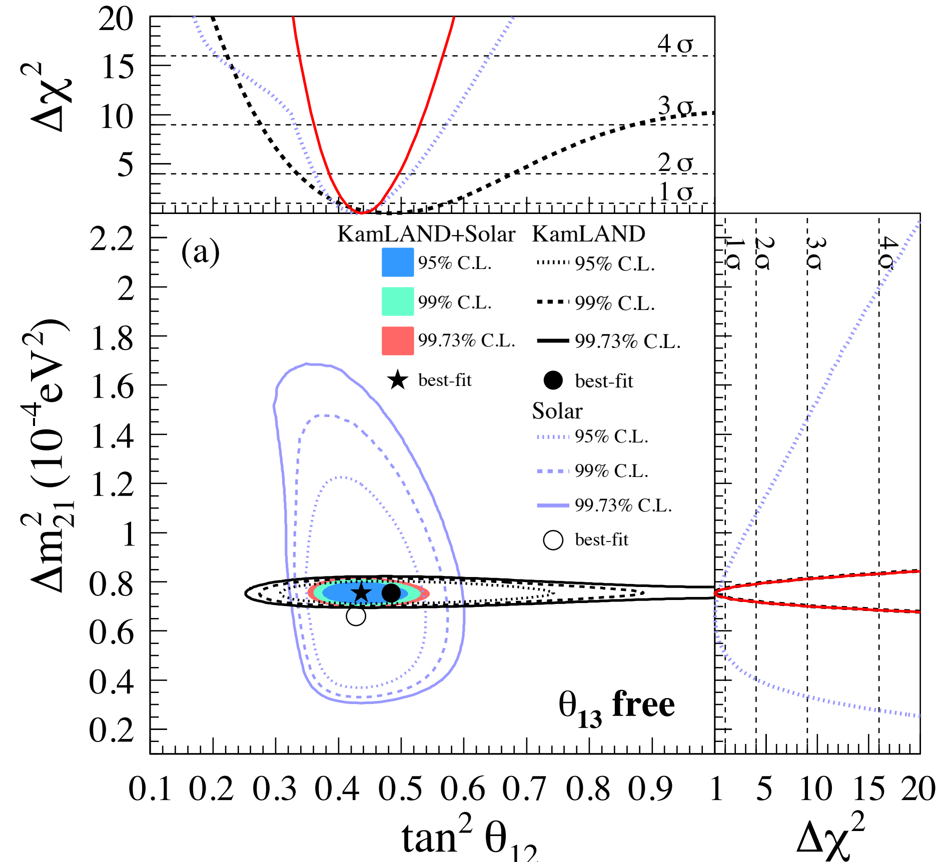


Combined Results from SNO and KamLAND

SNO, PRC88 (2013) 025501



KamLAND, PRD88 (2013) 033001

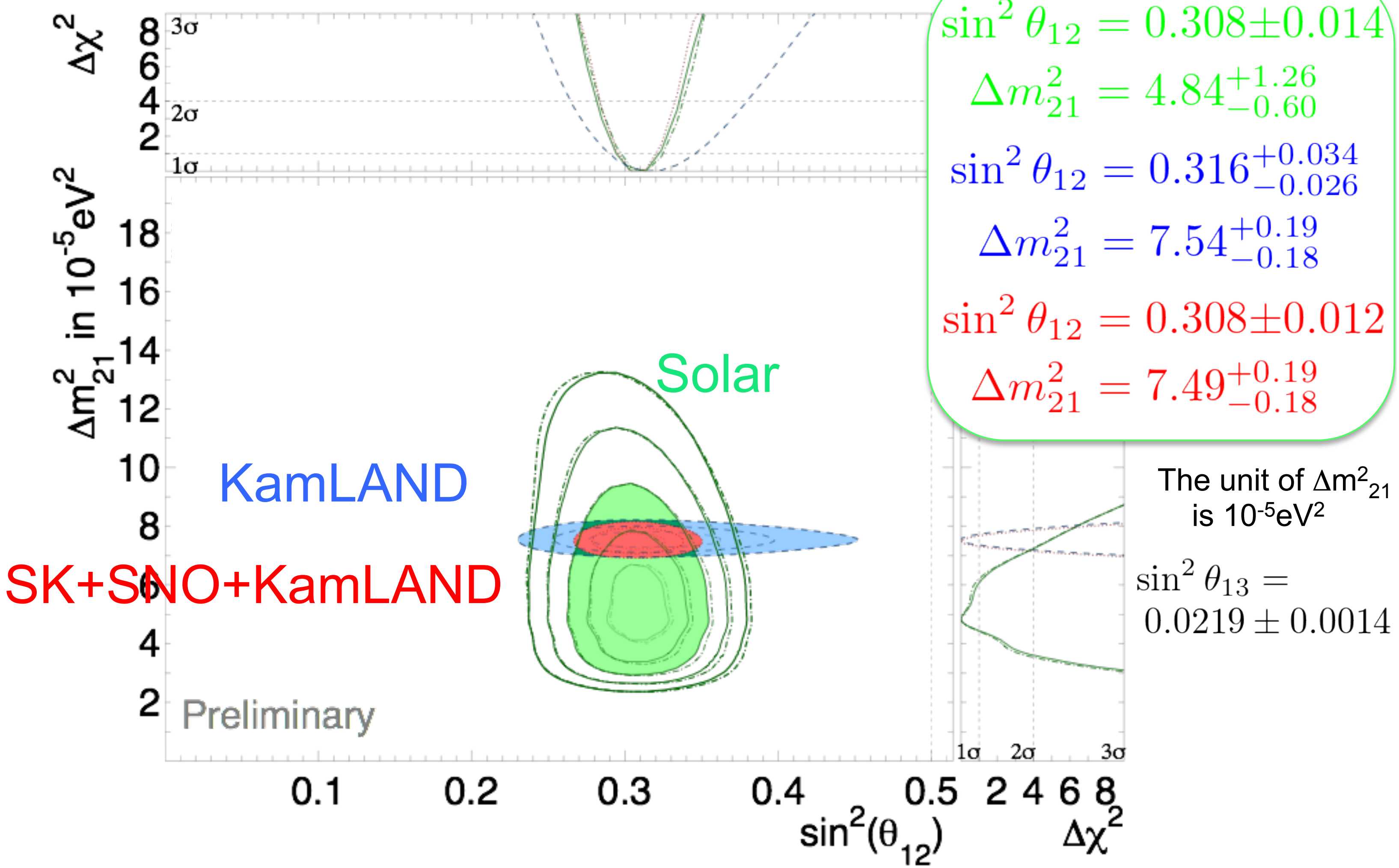


Global fits: arXiv:1507.05613

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

Adding the Super-K Solar Data till 2016

Moriyama, Neutrino 2016



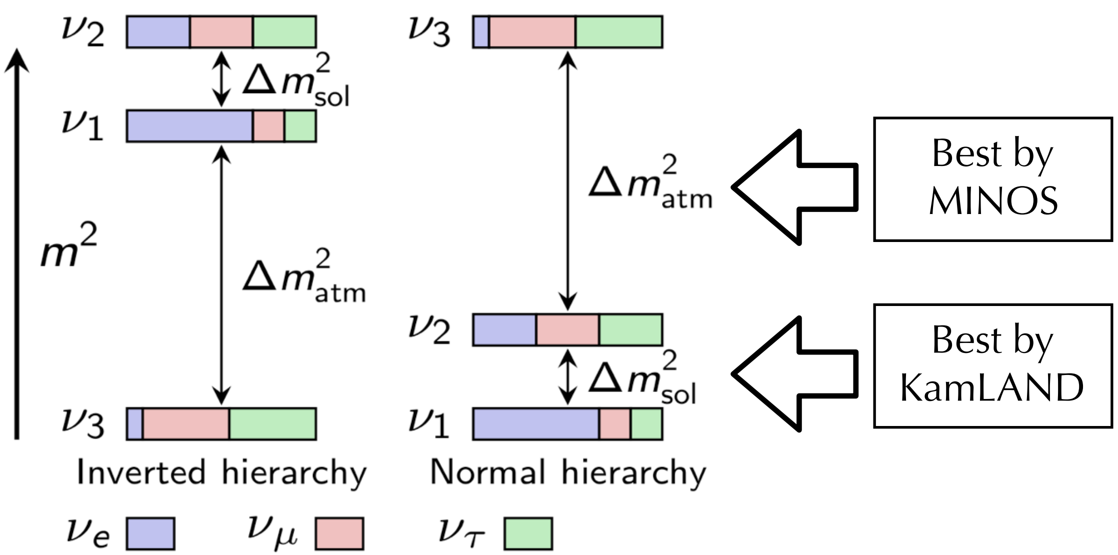
- SK data has increased the precision in solar mixing parameters significantly; SK spectrum and day/night data favor a lower Δm^2_{21} than KamLAND (2-sigma)
- SK has further lowered threshold to 2.5MeV, better chance to check the transition region

Picture of the Field for a Decade (2002-2012)

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric Sector:
SK, K2K, T2K, **MINOS**, etc

Solar Sector:
SNO, SK, KamLAND etc



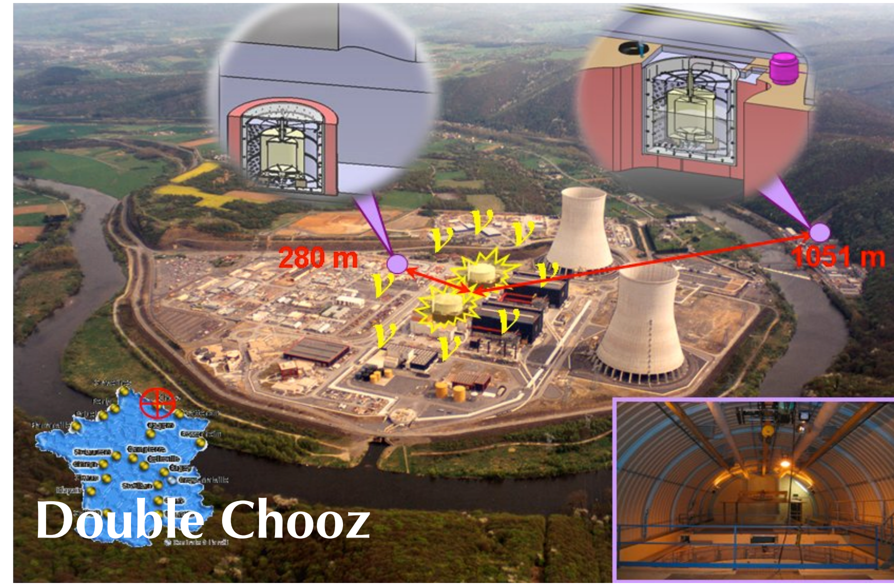
Invert ? Normal

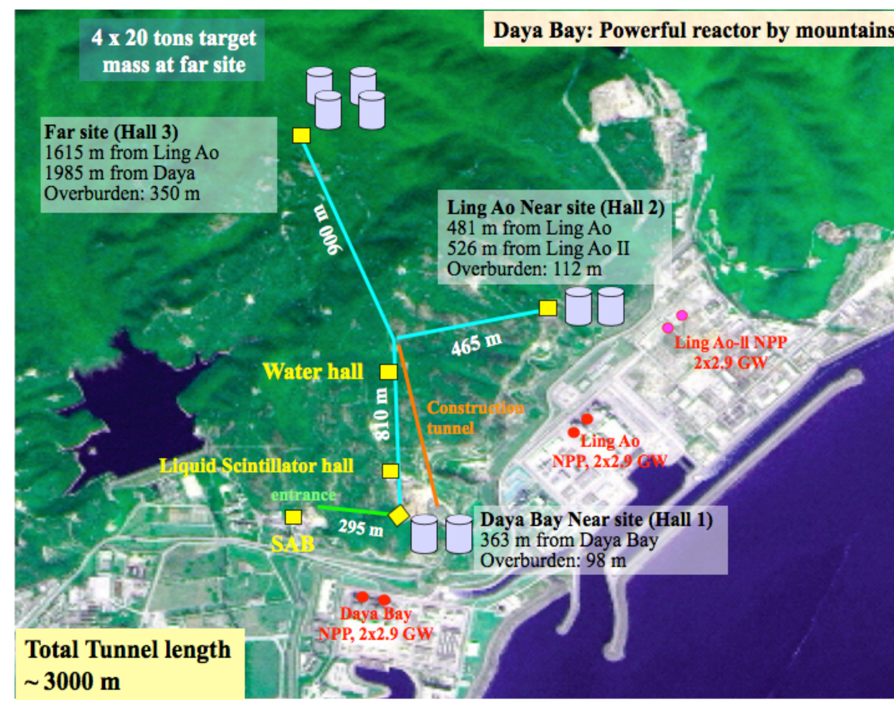
States m_1 and m_2 are differentiated by solar neutrino data (MSW effect)

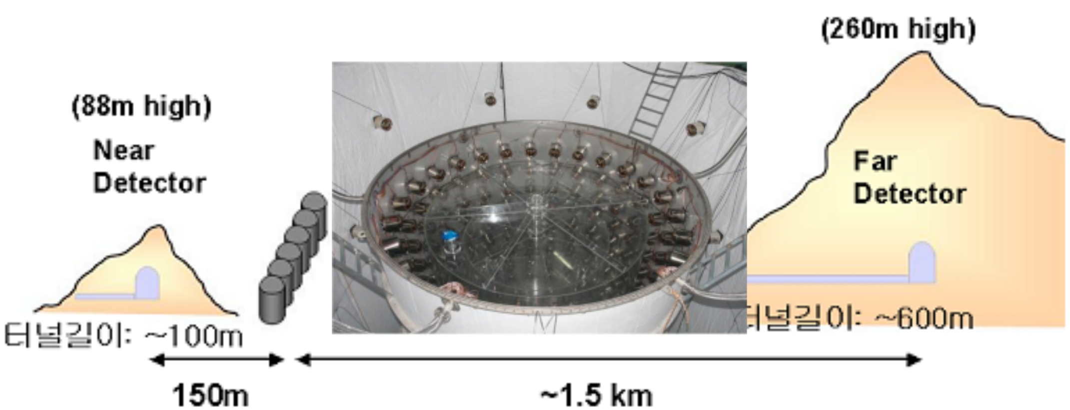
Glashow's Request of θ_{13} in 2003
(Photo by Kam-Biu Luk)

Dual Detector Short-Baseline Experiments Conceived

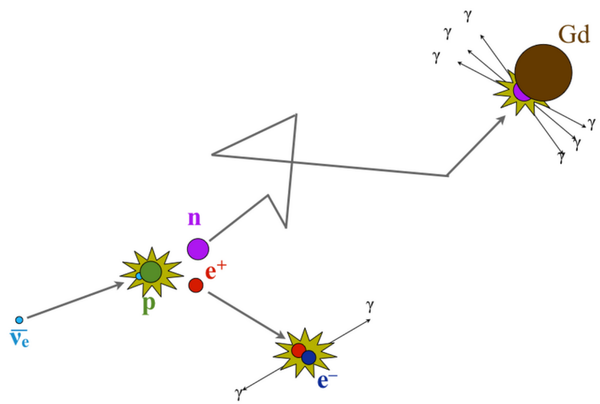
- Chooz and Palo Verde were not sensitive enough to get the lastly known mixing angle theta13: bad liquid scintillator is a factor but we blamed reactor neutrino flux uncertainty
  - Near-far reactor flux uncertainty **cancellation** proposed for Kr2Det in 2000
- Chooz ⟹ Double Chooz, Daya Bay and RENO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

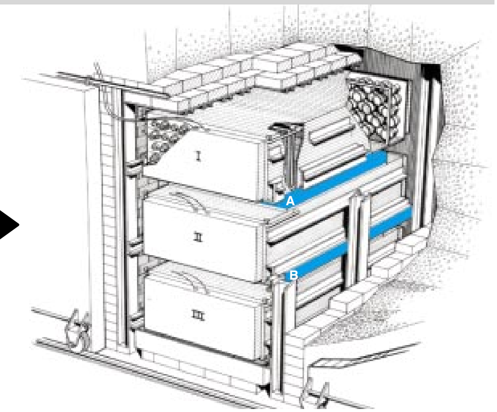


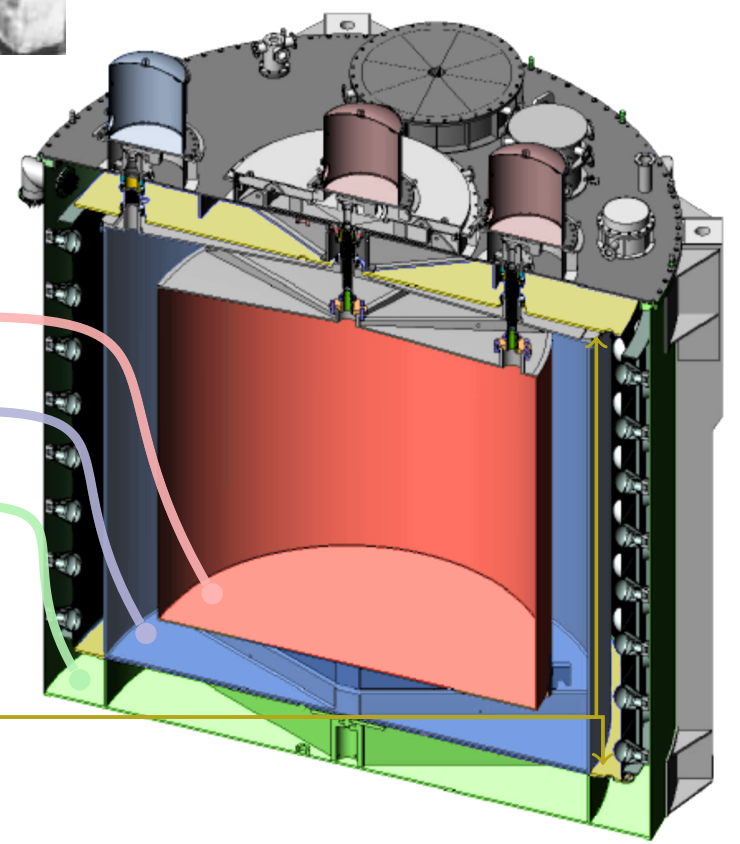




The Daya Bay Antineutrino Detector as an Example







- 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

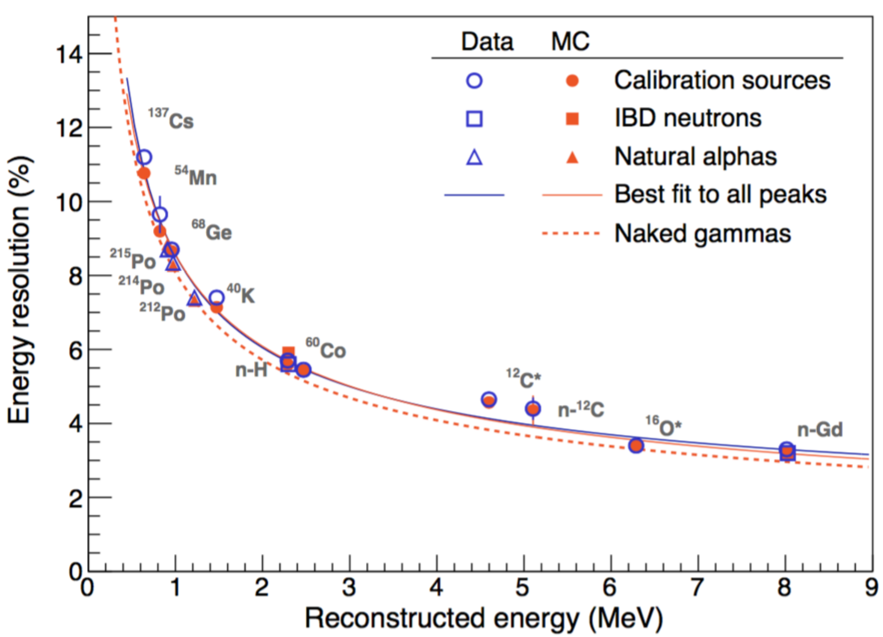
192 8 inch PMTs in each detector

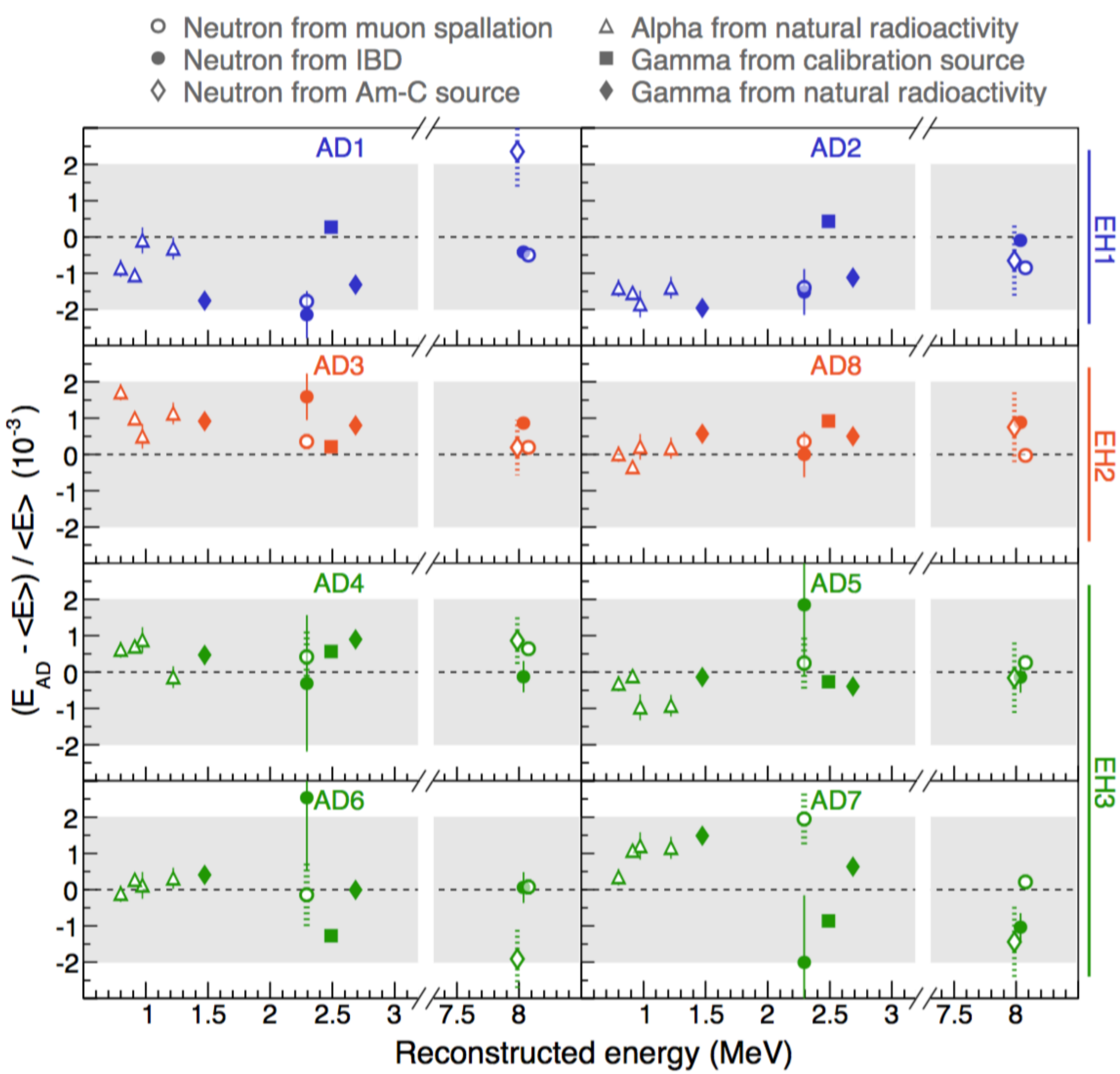
Top and bottom reflectors increase light yield and flatten detector response

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

The Daya Bay Detector Energy Responses

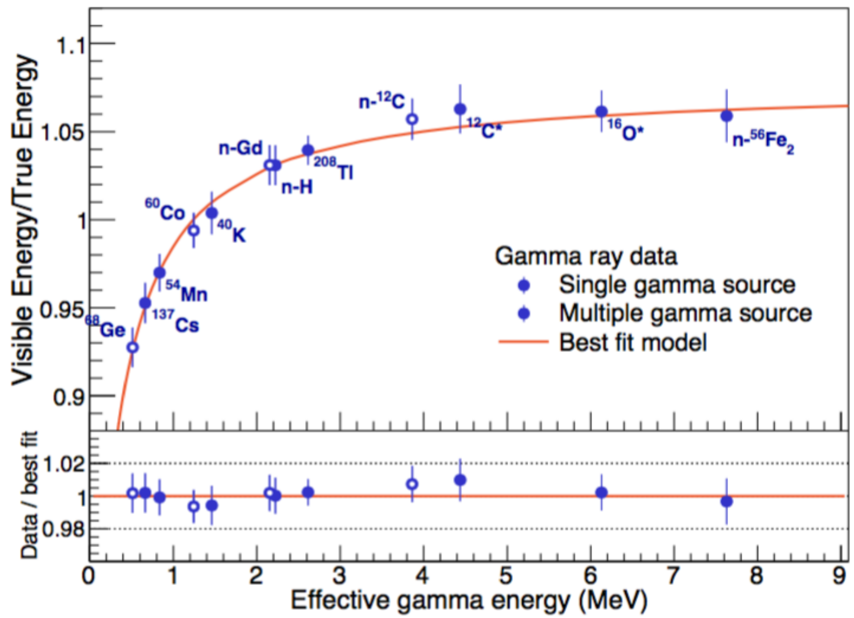
- Automatic weekly calibration
  - ^{68}Ge, ^{241}Am^{13}C, ^{60}Co
  - LED diffuser ball
- Spallation neutrons
- Natural radioactivities
- Special calibration campaign
  - ^{137}Cs, ^{54}Mn, ^{241}Am^{9}Be, ^{239}Pu^{13}C
- Manual 4π calibration

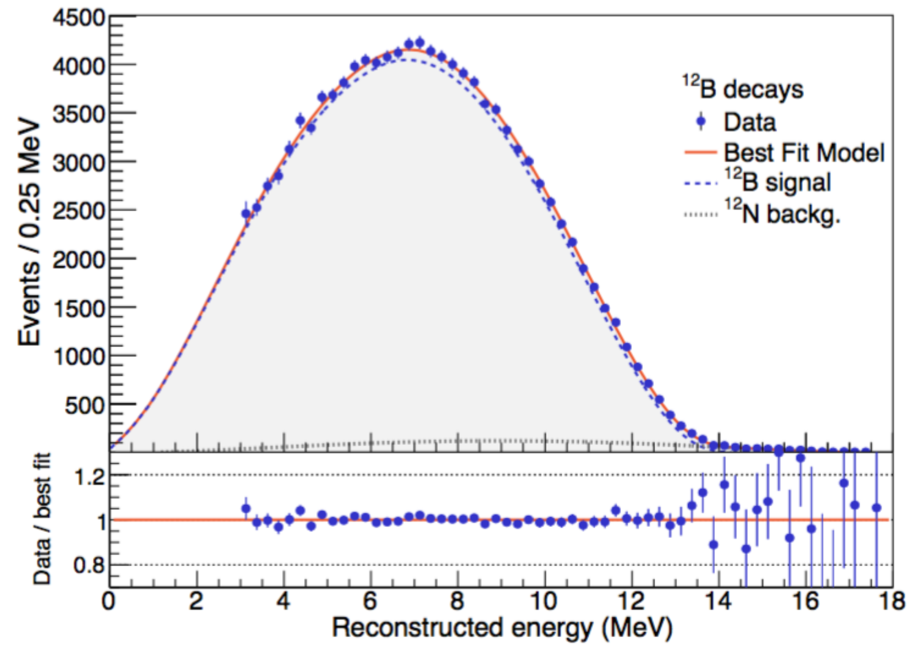


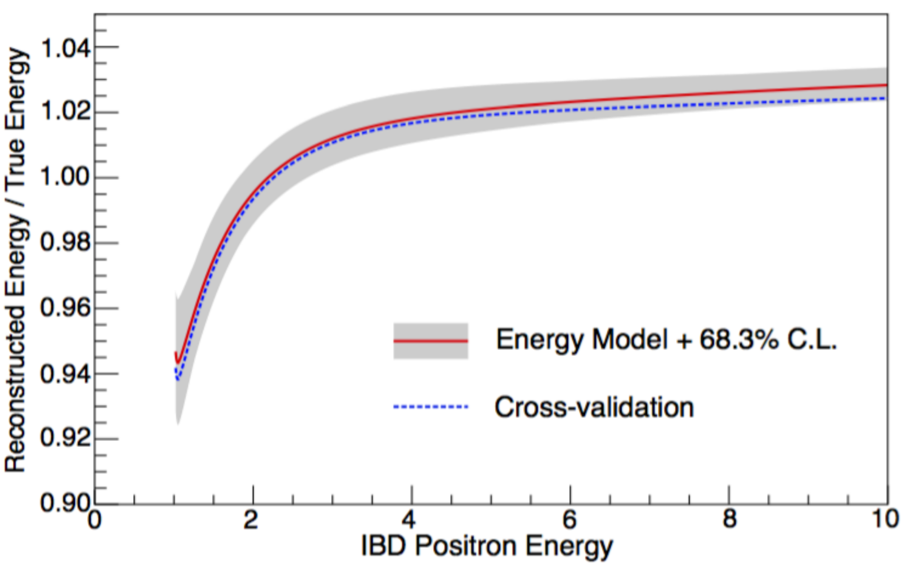


Relative detector energy scale < 0.2%

Energy Non-Linearity of Daya Bay





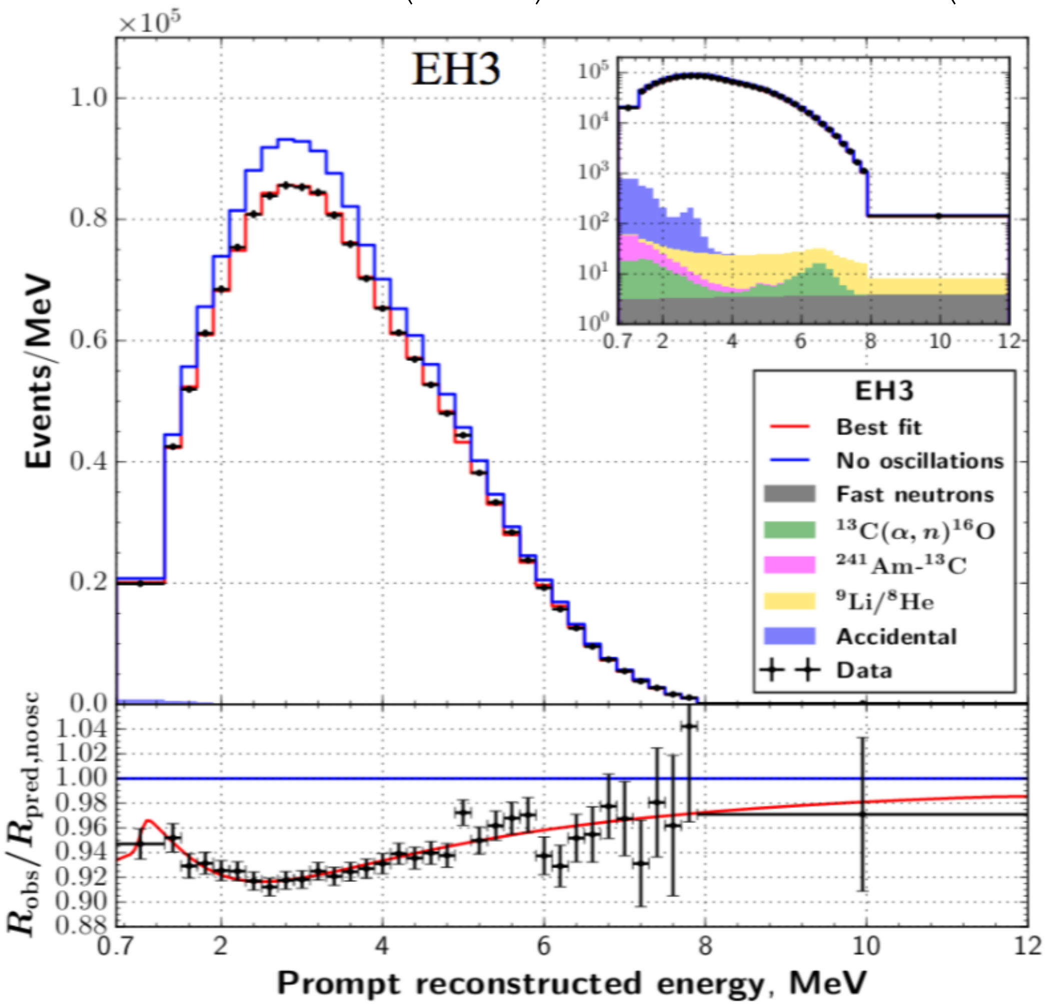


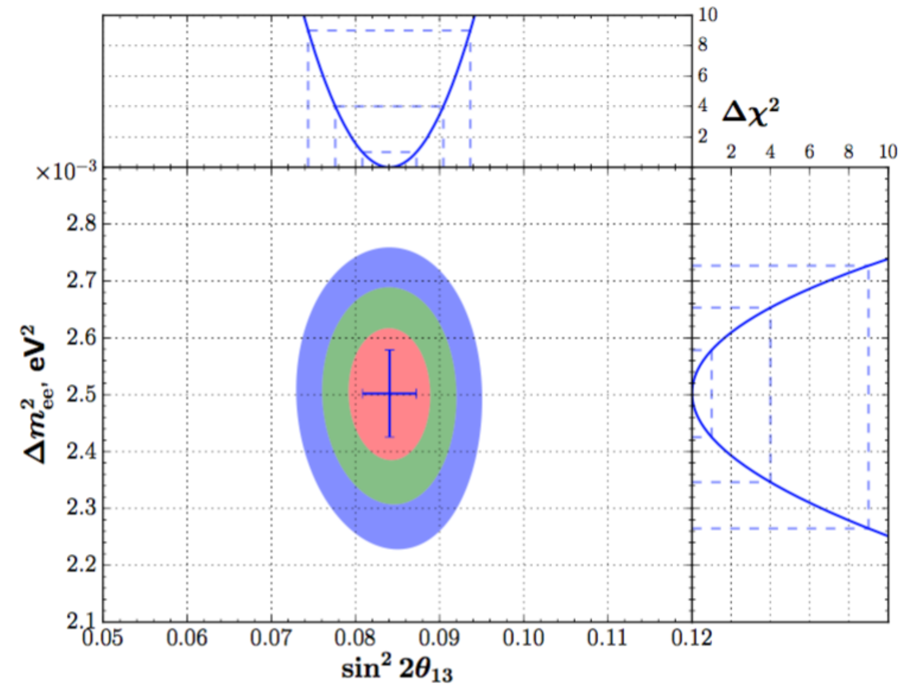
- Two major sources of non-linearity:
  - Scintillator response
  - Readout electronics
- Energy model for positron is derived from measured gamma and electron responses using simulation

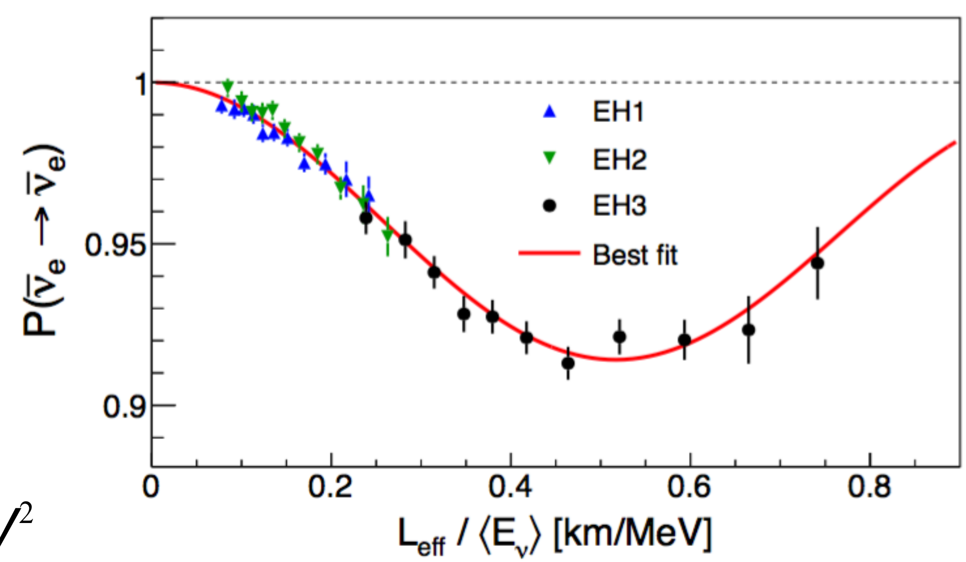
~1% uncertainty (correlated among detectors) — A Great Achievement!

Daya Bay: the Latest Results

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







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

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

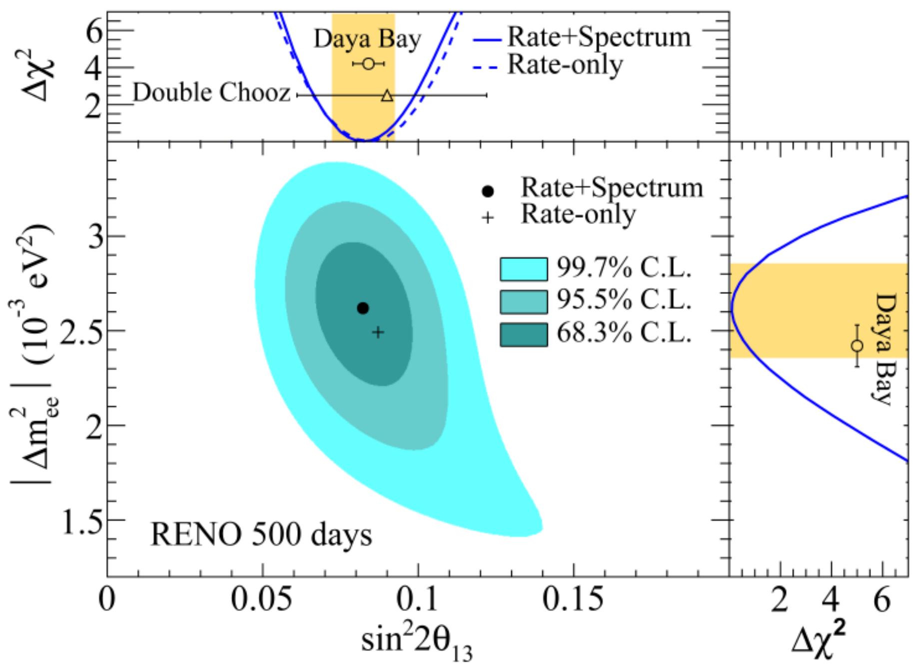
RENO: the Latest Results at ICHEP 2016

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



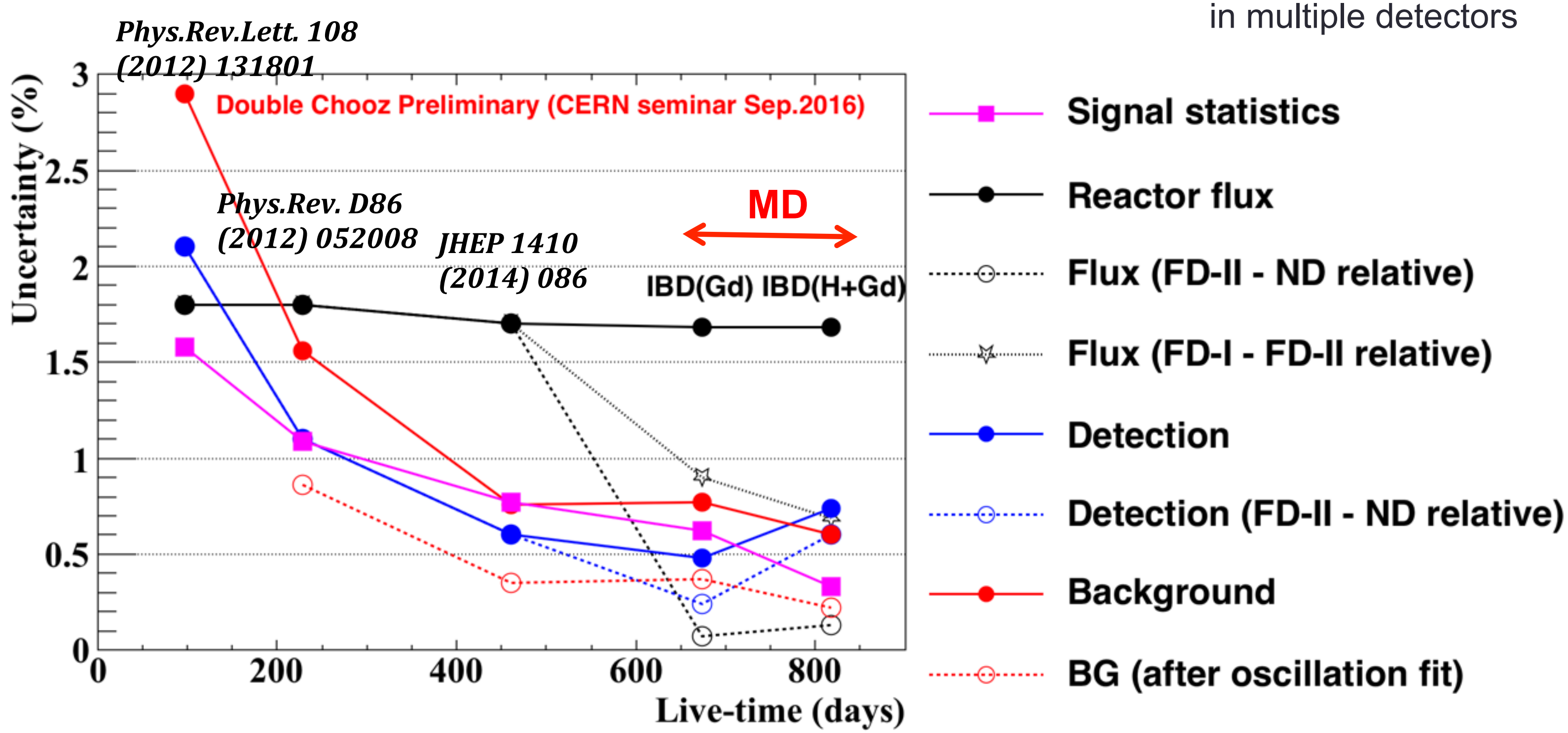
- arXiv:1511.05849.v2
- **PRL 116, 211801 (2016)**

- PRD to be submitted soon

Double Chooz: Double Detector Phase Started!

Huge systematic improvements

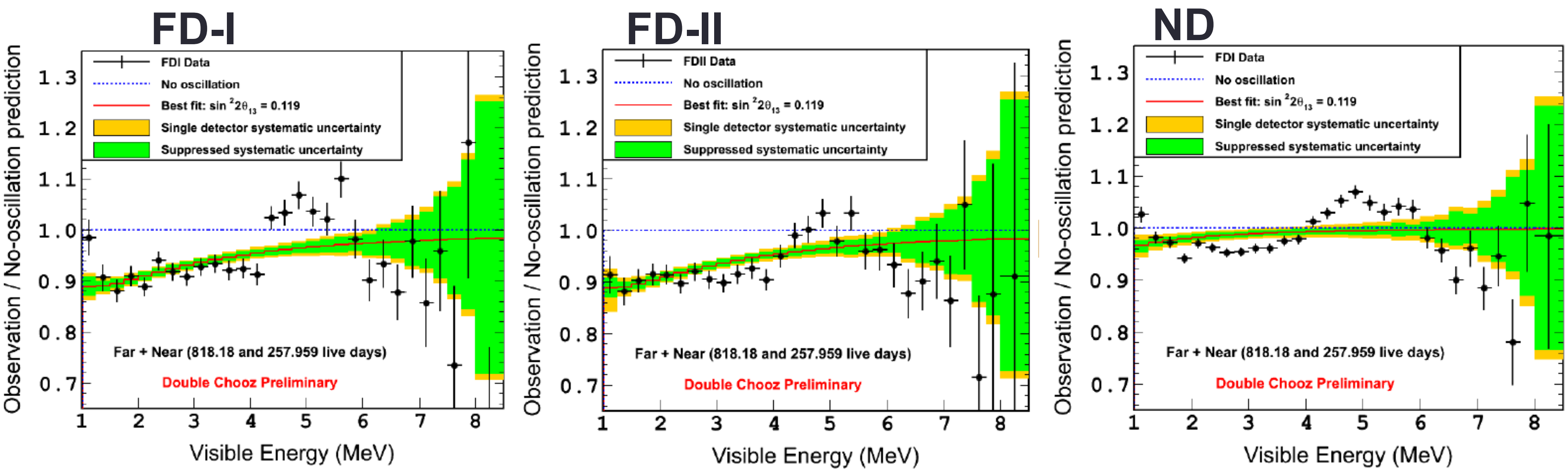
SD: single detector
MD: relative uncertainties
in multiple detectors



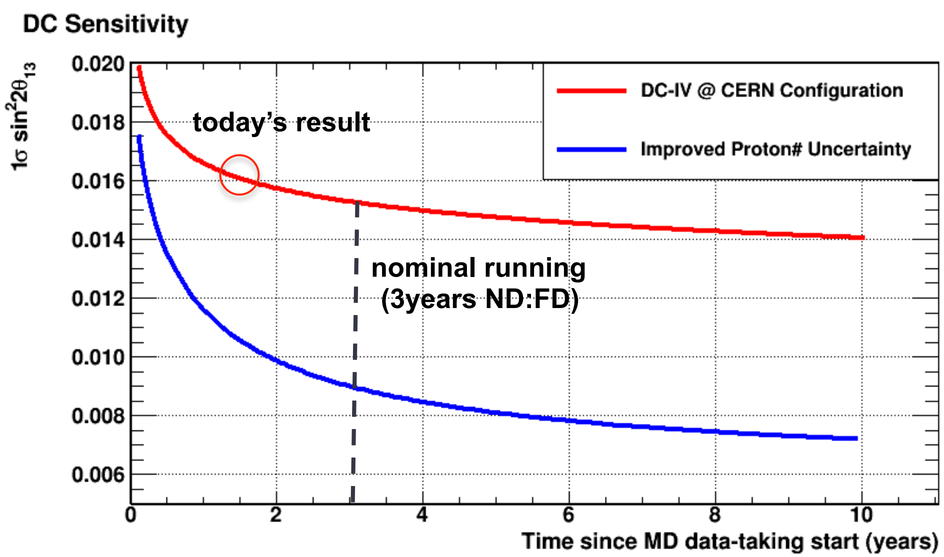
C. Palomares
NNN'16

- 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

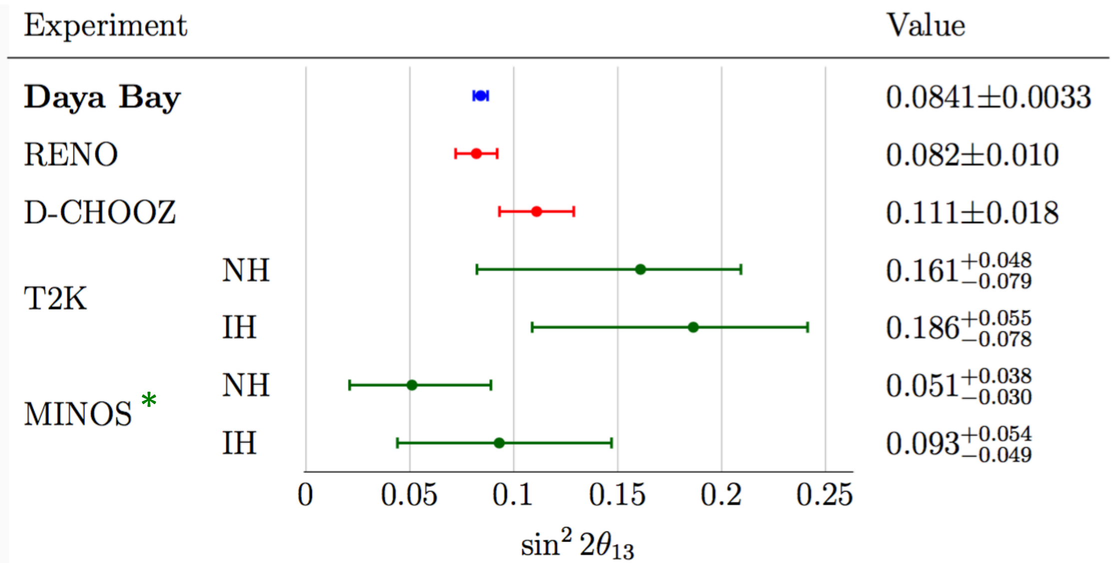


$\sin^2(2\theta_{13}) = 0.119 \pm 0.016$ (stat.+syst.) (χ^2/dof = 236.2/114)



- Still statistics dominated
  - ➡ Will include nH captures
  - ➡ Improvements are expected in systematics
- ***Aiming at 3-year MD data taking***

Global Results of $\sin^2 2\theta_{13}$ and Atmospheric Δm^2



Daya Bay holds the best results:

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

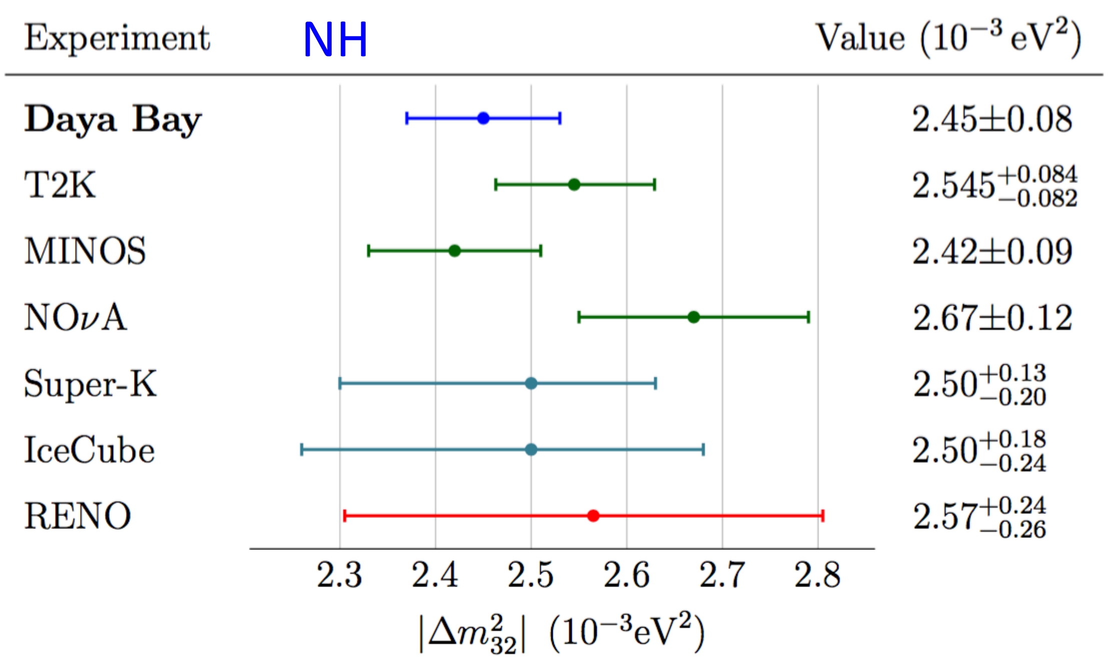
A join workshop has been held for the 3 collaborations in Seoul in Oct, 2016

Daya Bay:

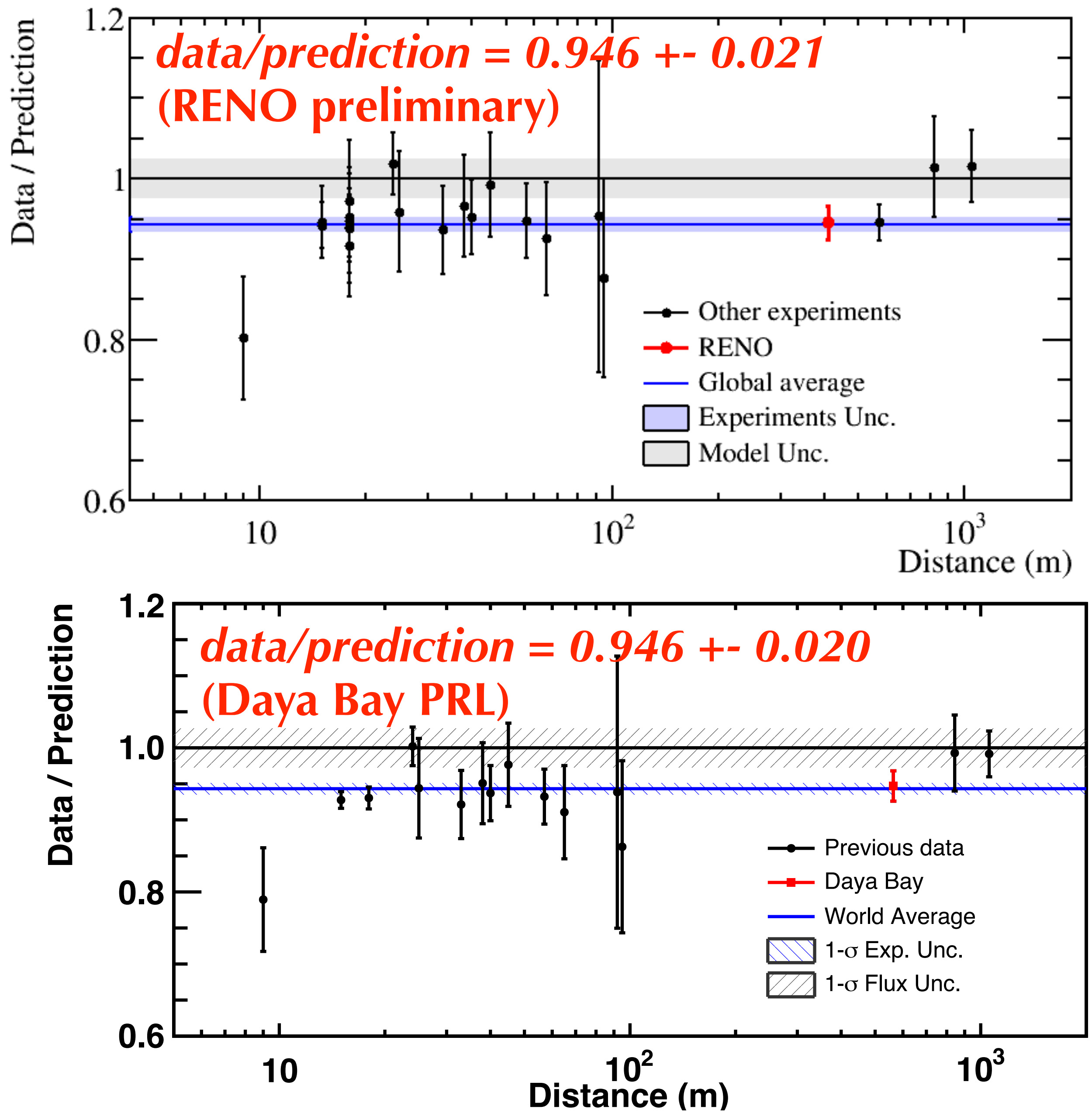
$|\Delta m^2_{ee}| \approx |\Delta m^2_{32}| \pm 0.05 \times 10^{-3}\ \mathrm{eV}^2$

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

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



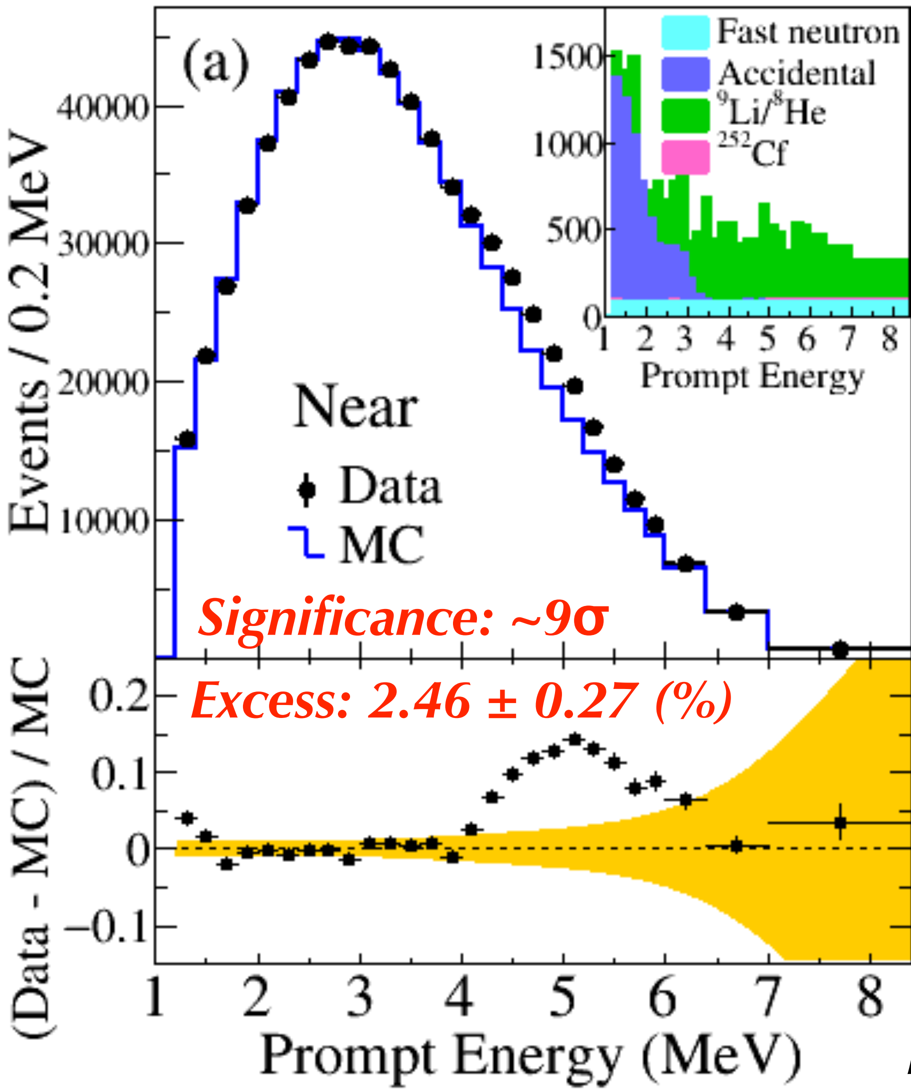
The Reactor Flux Anomaly



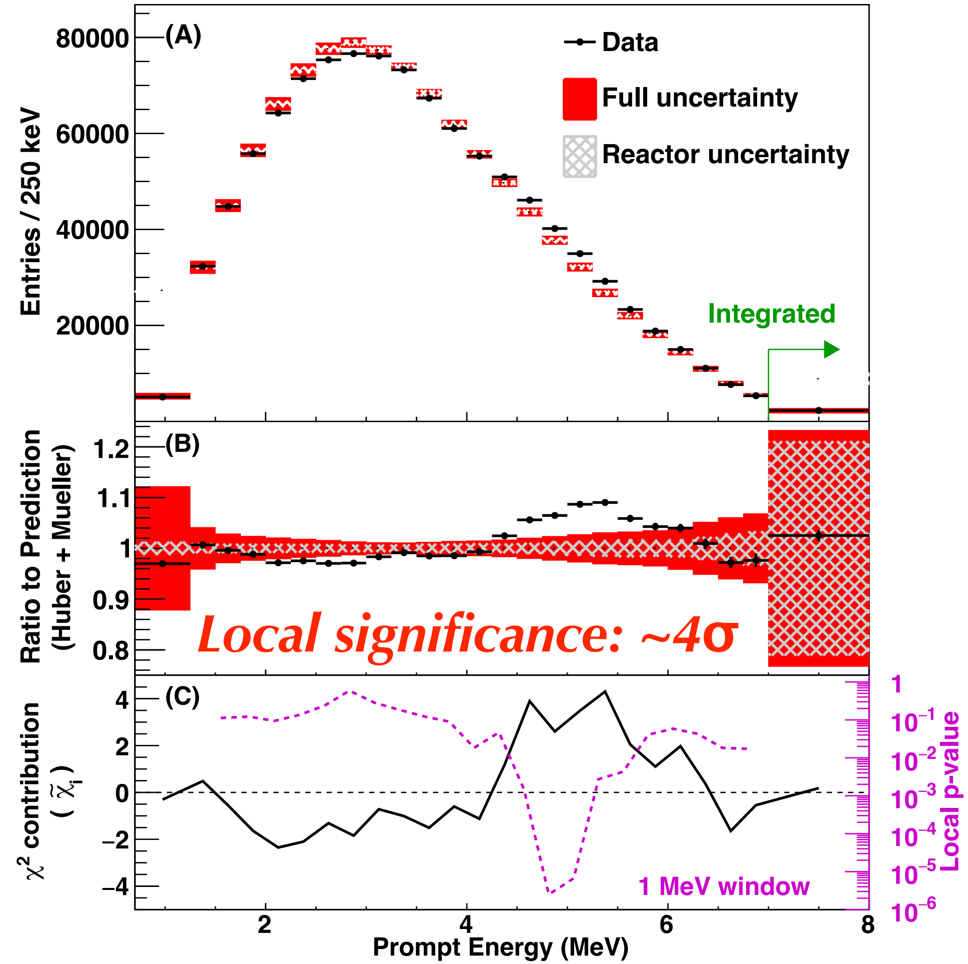
- Huber re-evaluation of the ILL data for ^{235}U, ^{239}Pu, ^{241}Pu
- Muller *et al ab initio* ^{238}U
- Various detector-side checks carried out but no smoking gun
- Both RENO and Daya Bay confirm this is correlated with reactor power

The Reactor Flux Spectrum Discrepancy

RENO preliminary



Daya Bay CPC



Blaming fission isotope beta decay calculation/data?

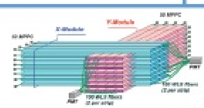
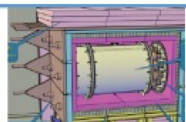
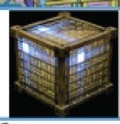
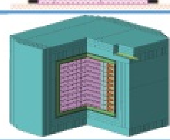
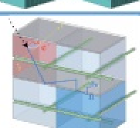
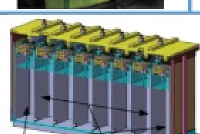
For example, see: Dwyer & Langford, PRL114 (2015)012502; Hayes et al, PRL112 (2014) 202501

Haunting Neutrino Questions

- Are there sterile neutrinos?
- Neutrino mass hierarchy?
- θ_{23} octant?
- CP violation in the lepton sector?
- Majorana or Dirac?
- Absolute neutrino mass scale?
- ……

Booming of the Very Short-Baseline Experiments

N. Bowden, Neutrino'16

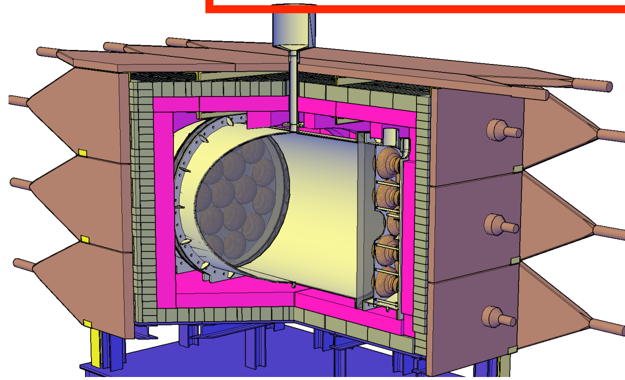
Experiment		Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia)		3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea)		2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double 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

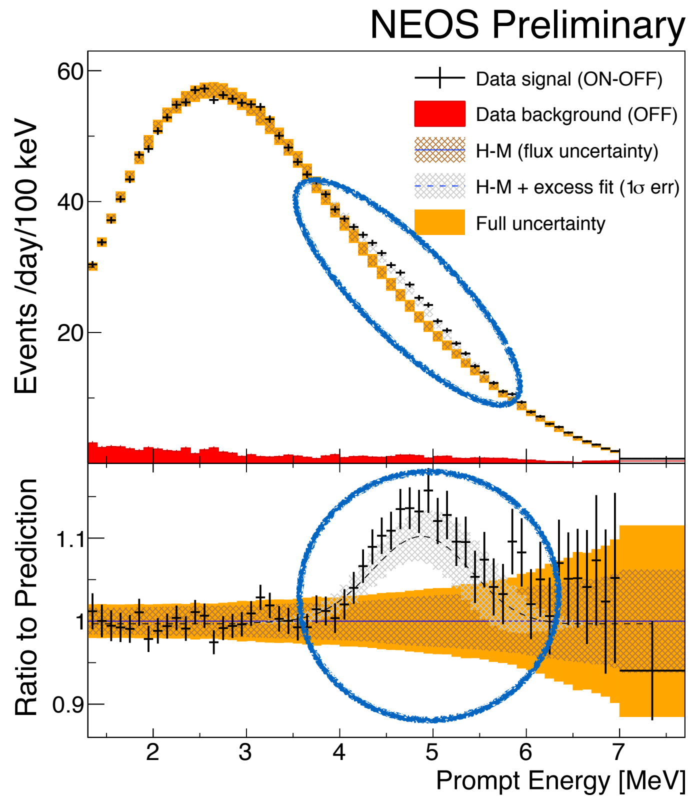
Highlights from the Very Short-Baseline Experiments

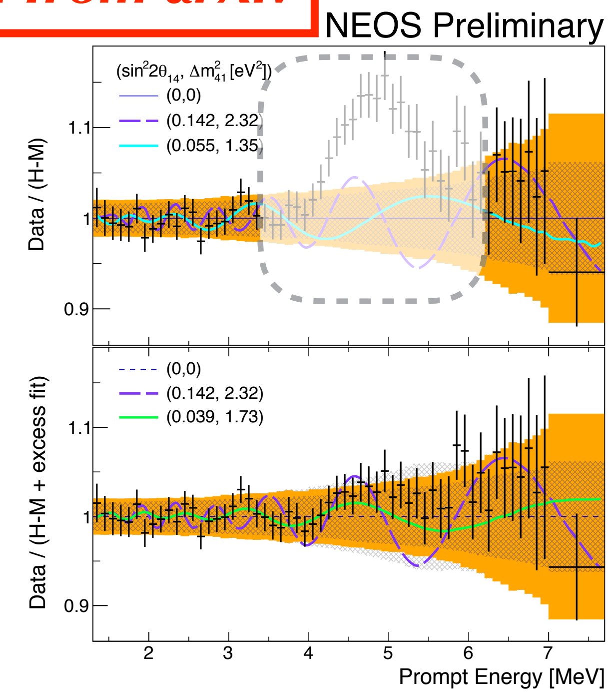
Paper Withdrawn from arXiv

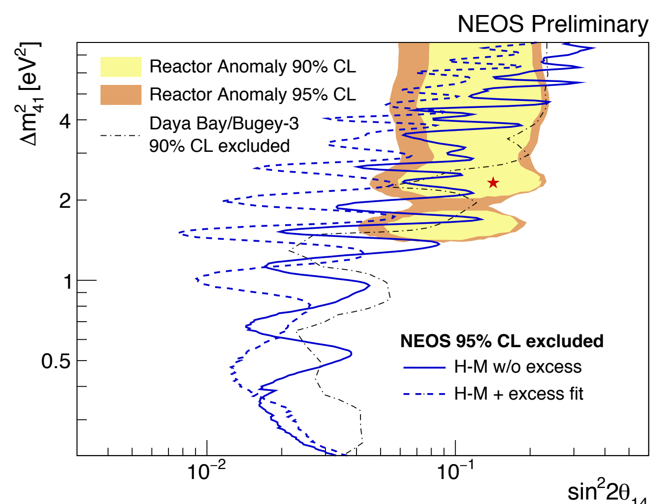
NEOS @ ICHEP 2016

- 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





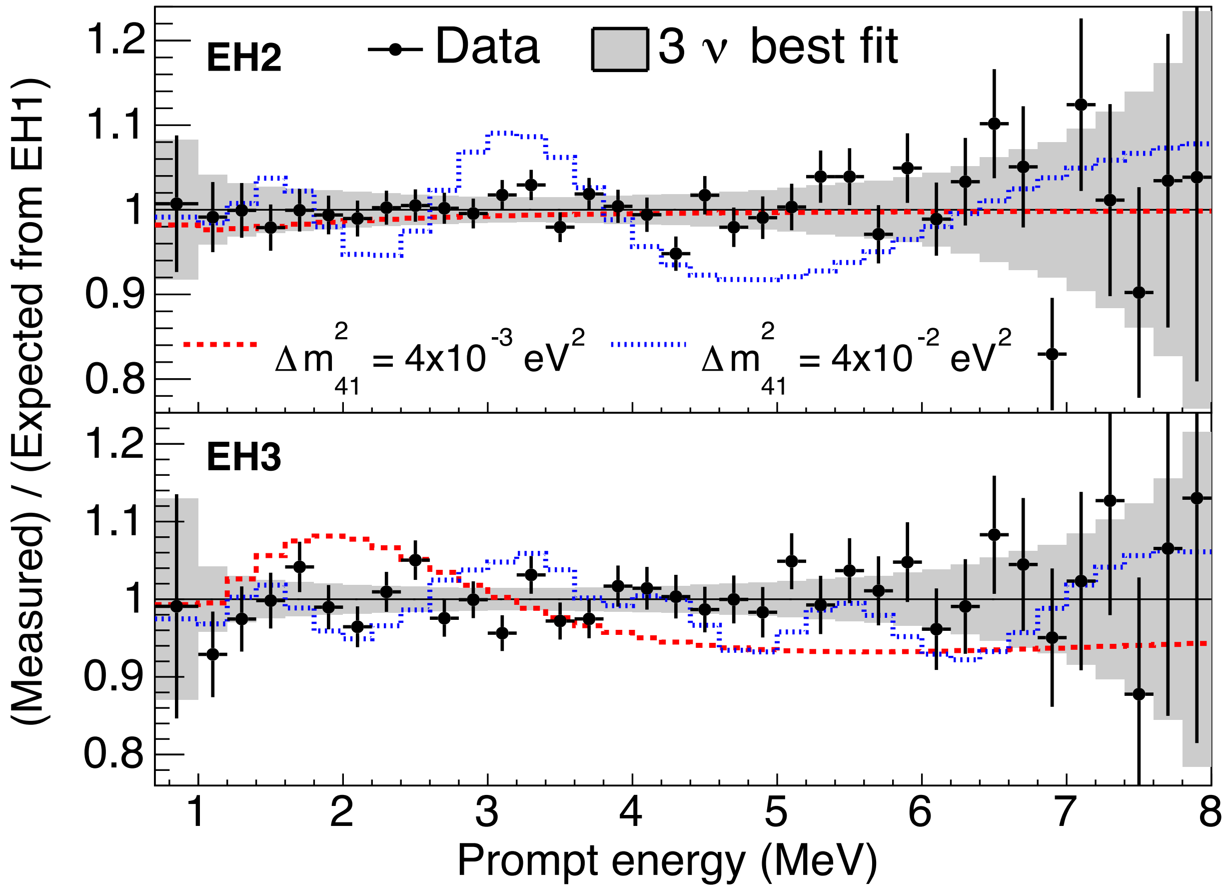




What about Sterile Neutrinos?

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

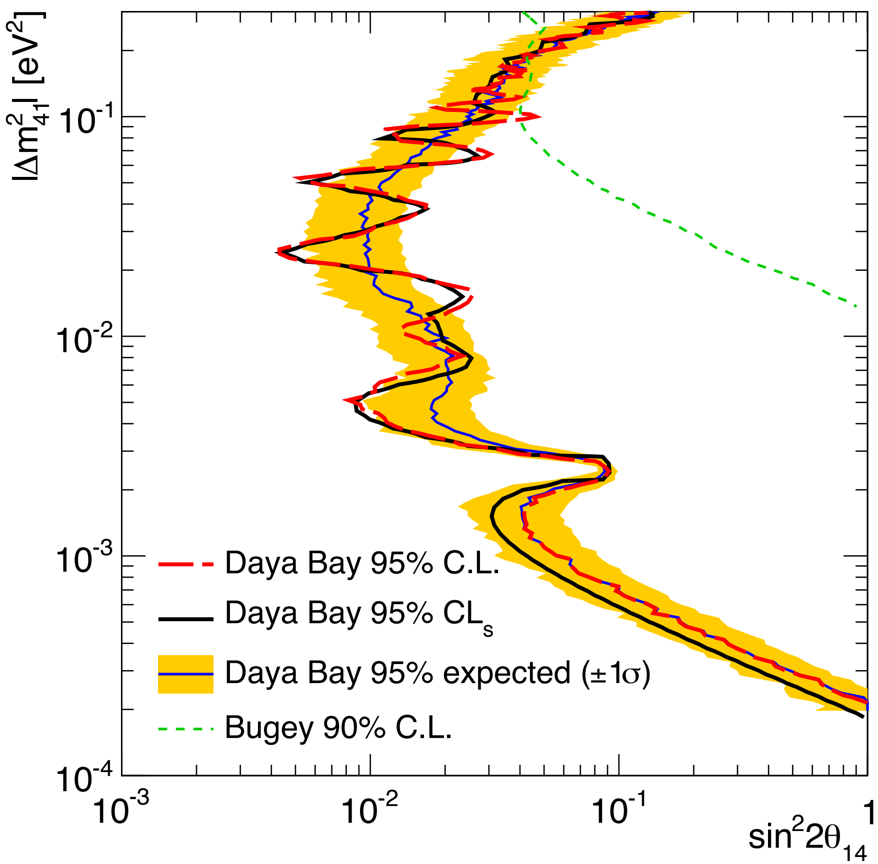
- Daya Bay baselines >350m ⇒ not as sensitive to mass-squared splittings greater than or around 1eV^2



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

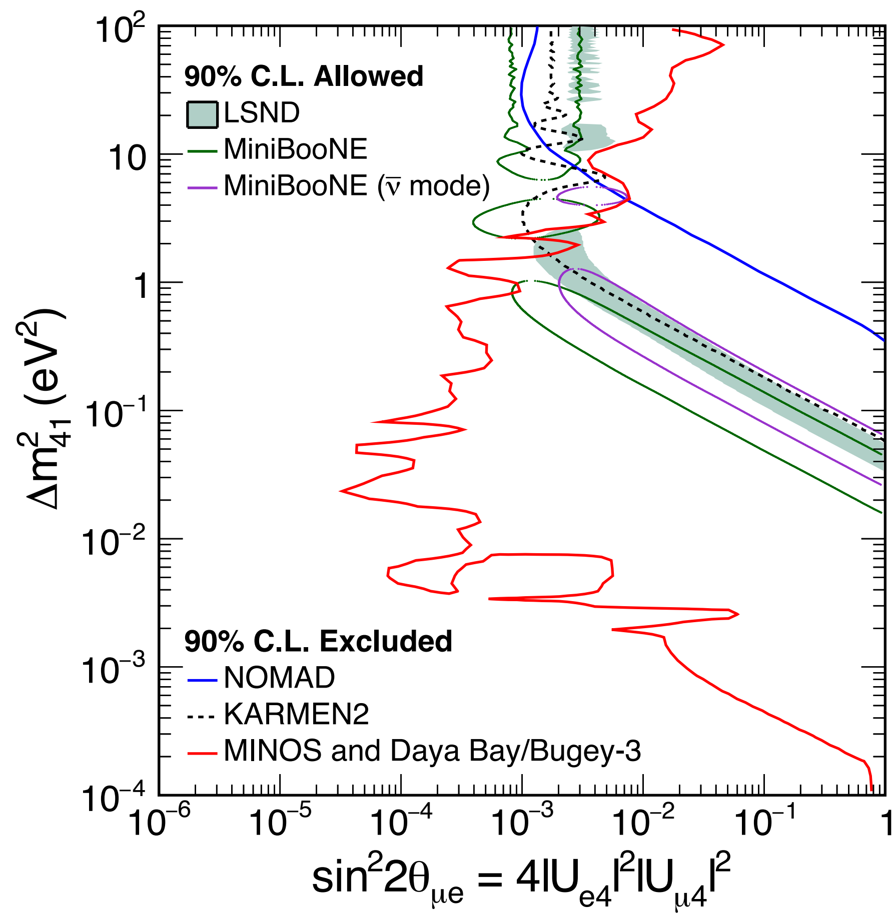
Sterile Neutrino Searches at Daya Bay and Elsewhere

- Daya Bay alone



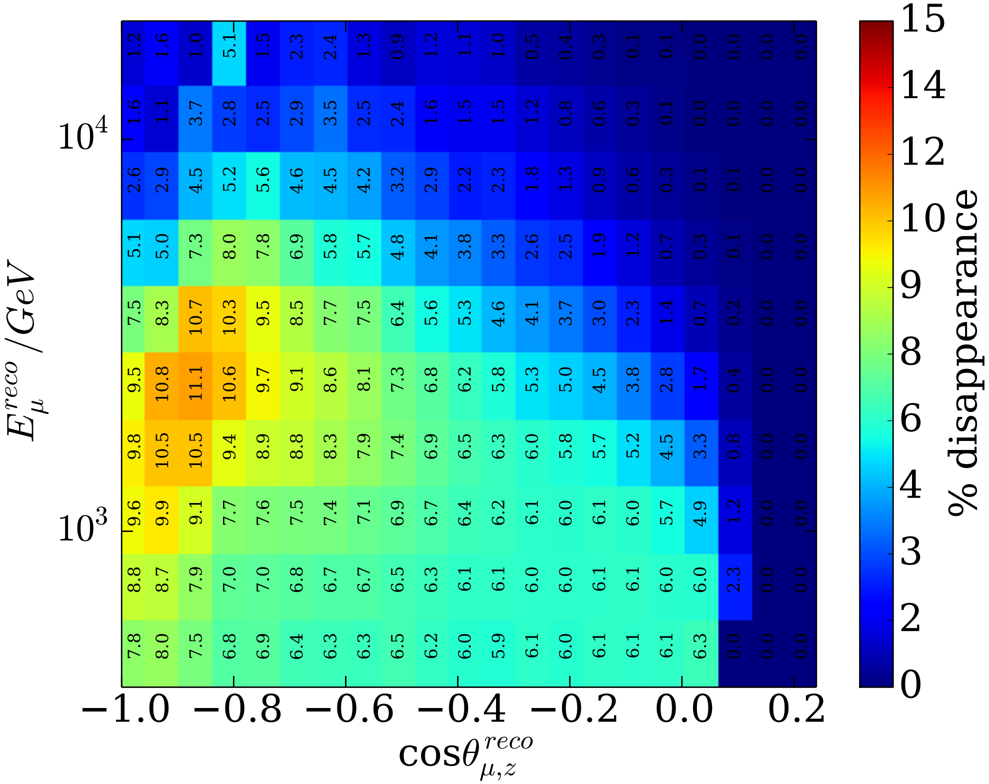
Daya Bay arXiv: 1607.01174

- Daya Bay, MINOS and Bugey-3

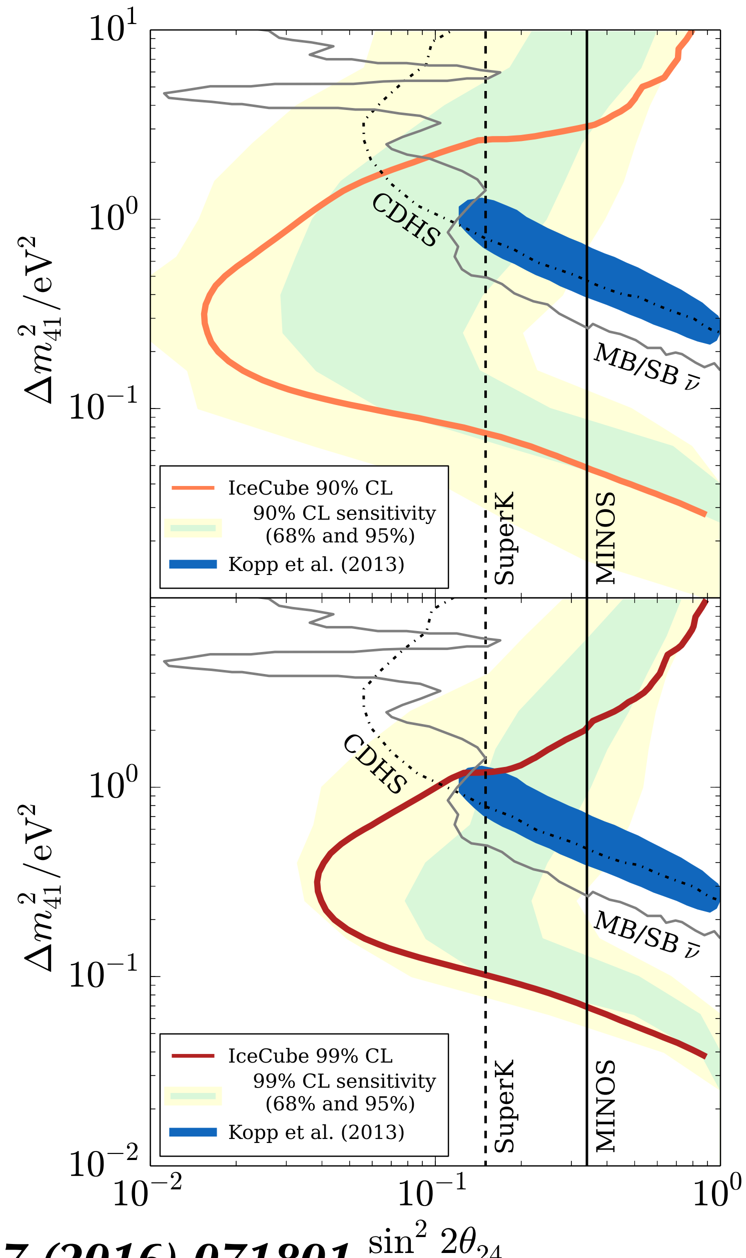


Daya Bay+MINOS, arXiv:1607.01177

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



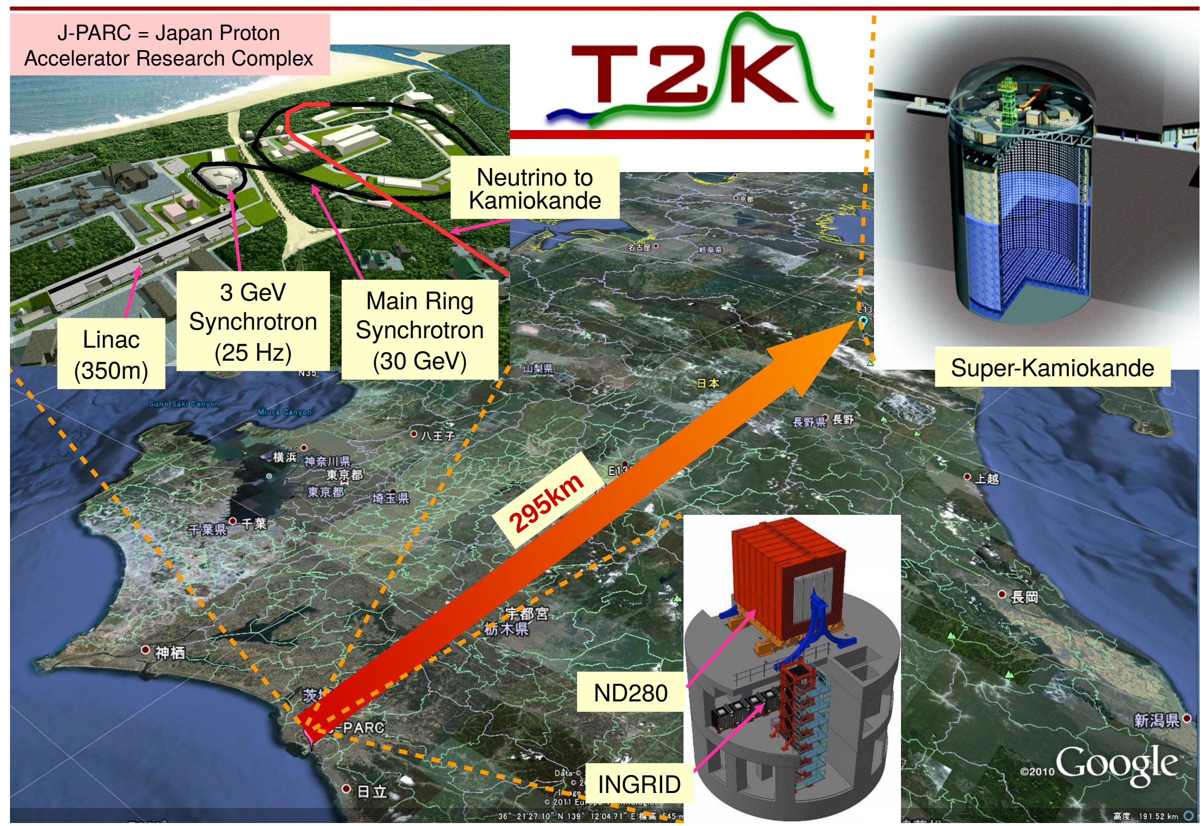
Matter effect causes oscillation resonants for certain sterile neutrino parameters — distinctive signature

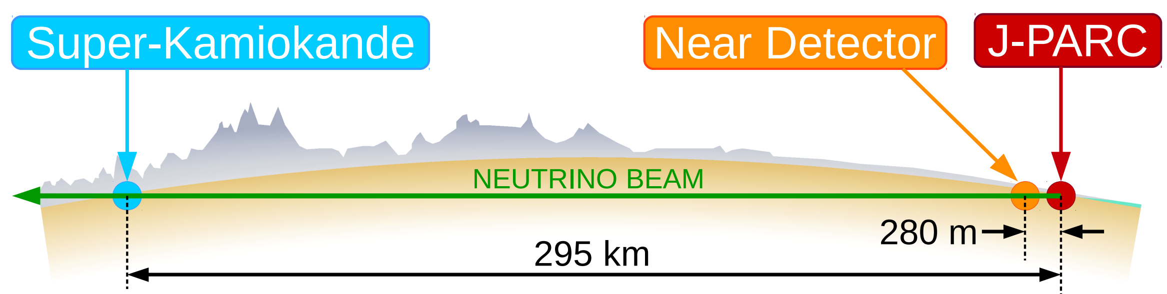


IceCube, PRL117 (2016) 071801

Long-Baseline Neutrino Experiments in Japan

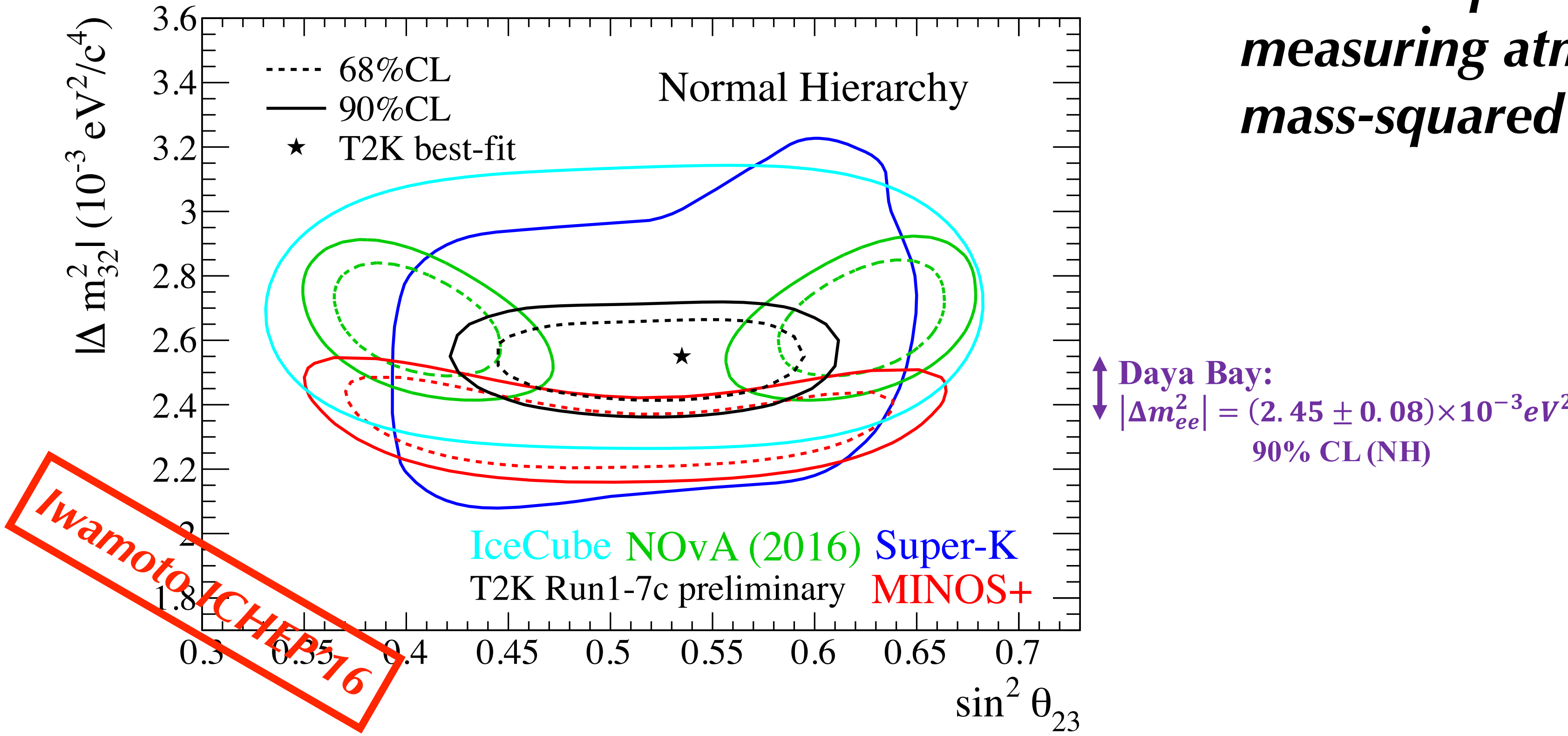
- KEK to Super-K (K2K) was the first long-baseline neutrino experiment confirmed the Super-K result in 2002
- Tokai to Super-K (T2K) is the upgraded version: a completely new neutrino beam from J-PARC and a completely new near detector complex
- Aiming at observing electron neutrino appearance to measure theta13 and the CP phase





θ_{23} and Δm^2_{32}

- Consistent with maximal mixing



Off-axis beam experiments are more precise in measuring atmospheric mass-squared splitting

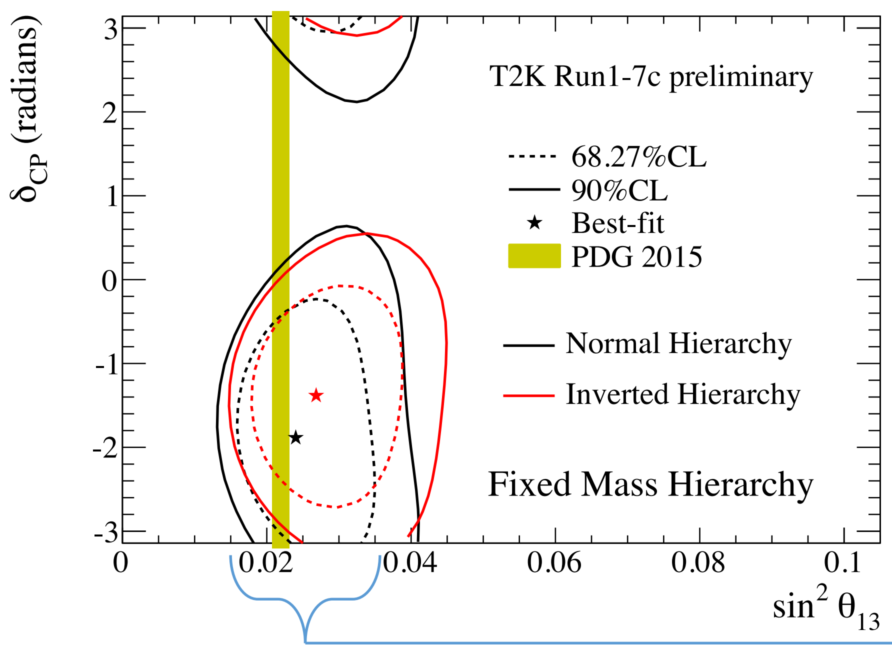
	NH	IH
$\sin^2\theta_{23}$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.066}$
$\lvert\Delta m^2_{32}\rvert[10^{-3}\text{eV}^2]$	$2.545^{+0.081}_{-0.084}$	$2.510^{+0.081}_{-0.083}$

Combining Reactor Results

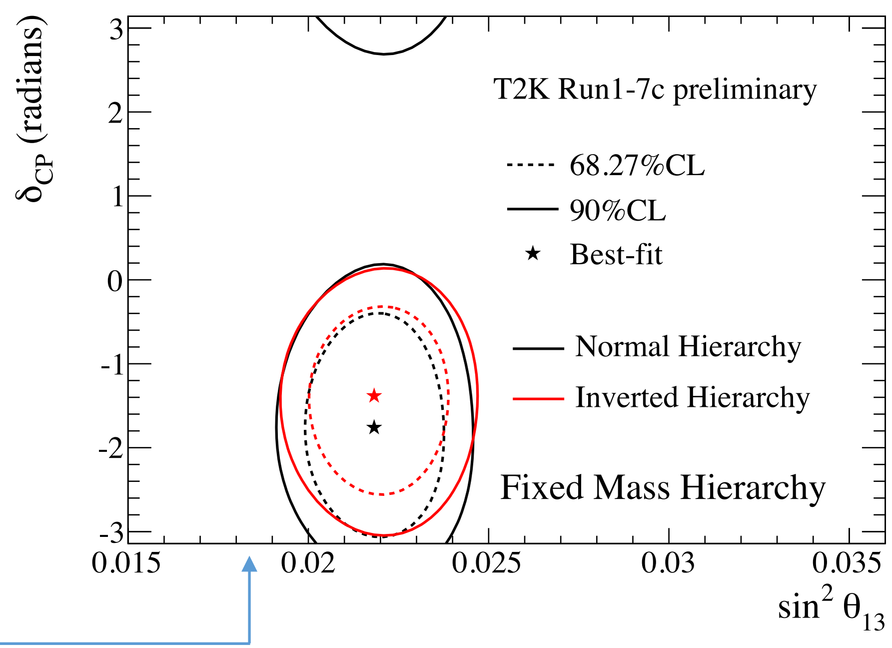
θ_{13} and δ_{cp}

Iwamoto ICHEP'16

T2K-Only



T2K Result with Reactor Constraint
($sin^2 2\theta_{13} = 0.085 \pm 0.005$)



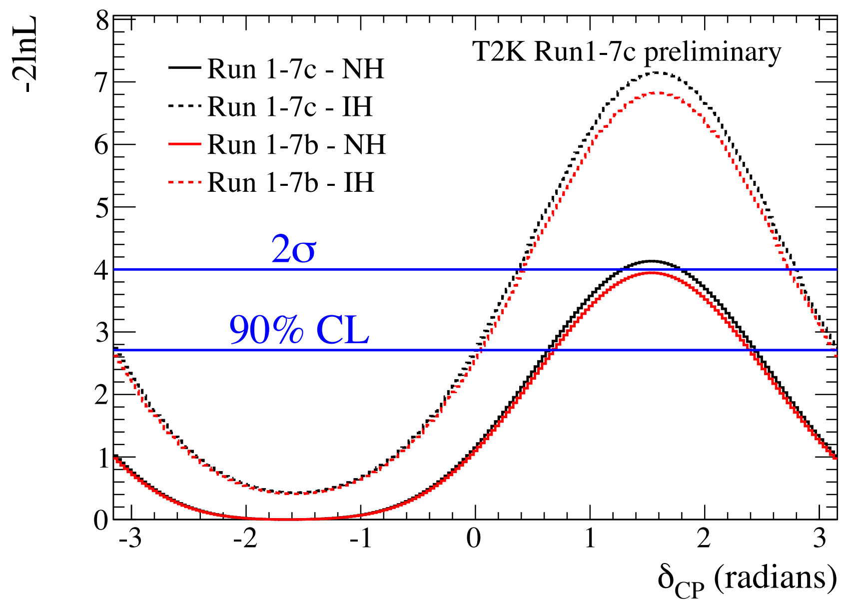
- T2K-only result consistent with the reactor measurement
- Favors the $\delta_{cp} \sim -\frac{\pi}{2}$ region

θ_{13} and δ_{cp}

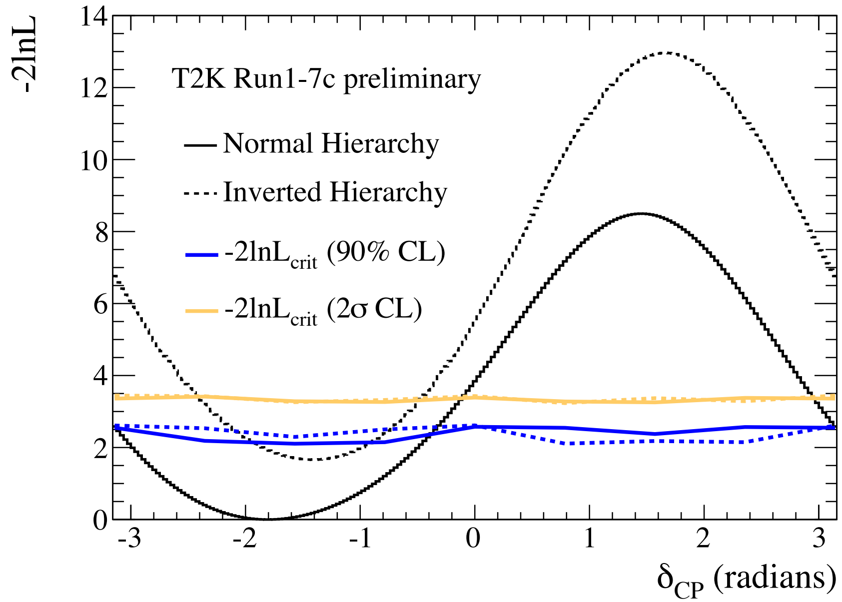
Iwamoto ICHEP'16

- T2K result with reactor constraint ($\sin^2 2\theta_{13} = 0.085 \pm 0.005$)

Sensitivity (Simulation)



Measurement (Data)



$\delta_{cp} = [-3.13, -0.39](NH), [-2.09, -0.74]\ (IH)$ at 90% CL

Long-Baseline Neutrino Experiments in U.S.A.

NOνA

Oscillation channels:

$\nu_\mu \rightarrow \nu_e$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

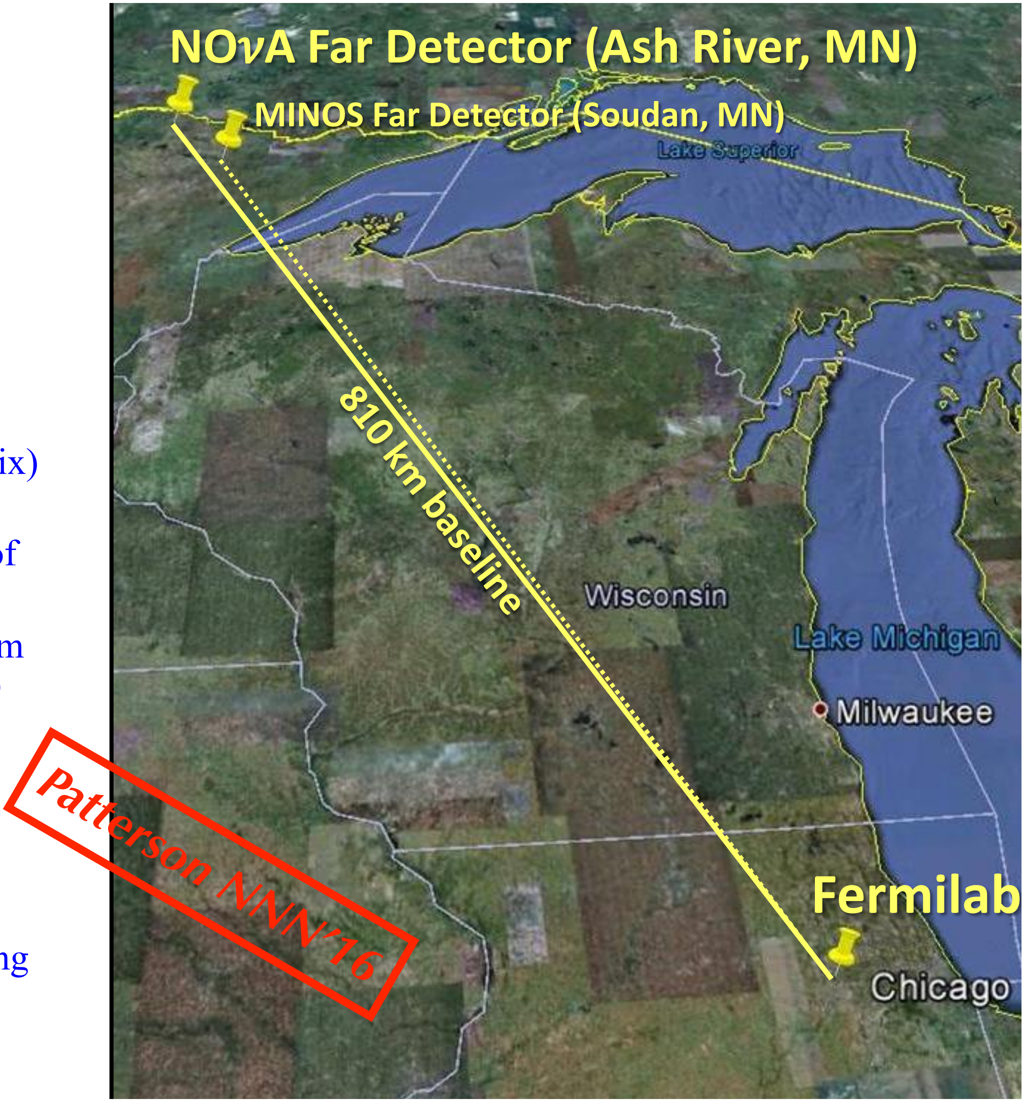
$\nu_\mu \rightarrow \nu_\mu$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

- **ν mass hierarchy ?**
- **θ_{23} octant ?** (ν_3 flavor mix)
- Allowed range of δ_{CP} **?**
- Precision measurements of $\sin^2\theta_{23}$ and Δm^2_{32} .
- **Over-constrain** the system (*Deviations from νSM ?*)

Also ...

- Sterile neutrinos, *CPT*v, NSI, and other exotica
- Supernova neutrinos
- Neutrino-nucleus scattering at Near Detector

Ryan Patterson, Caltech

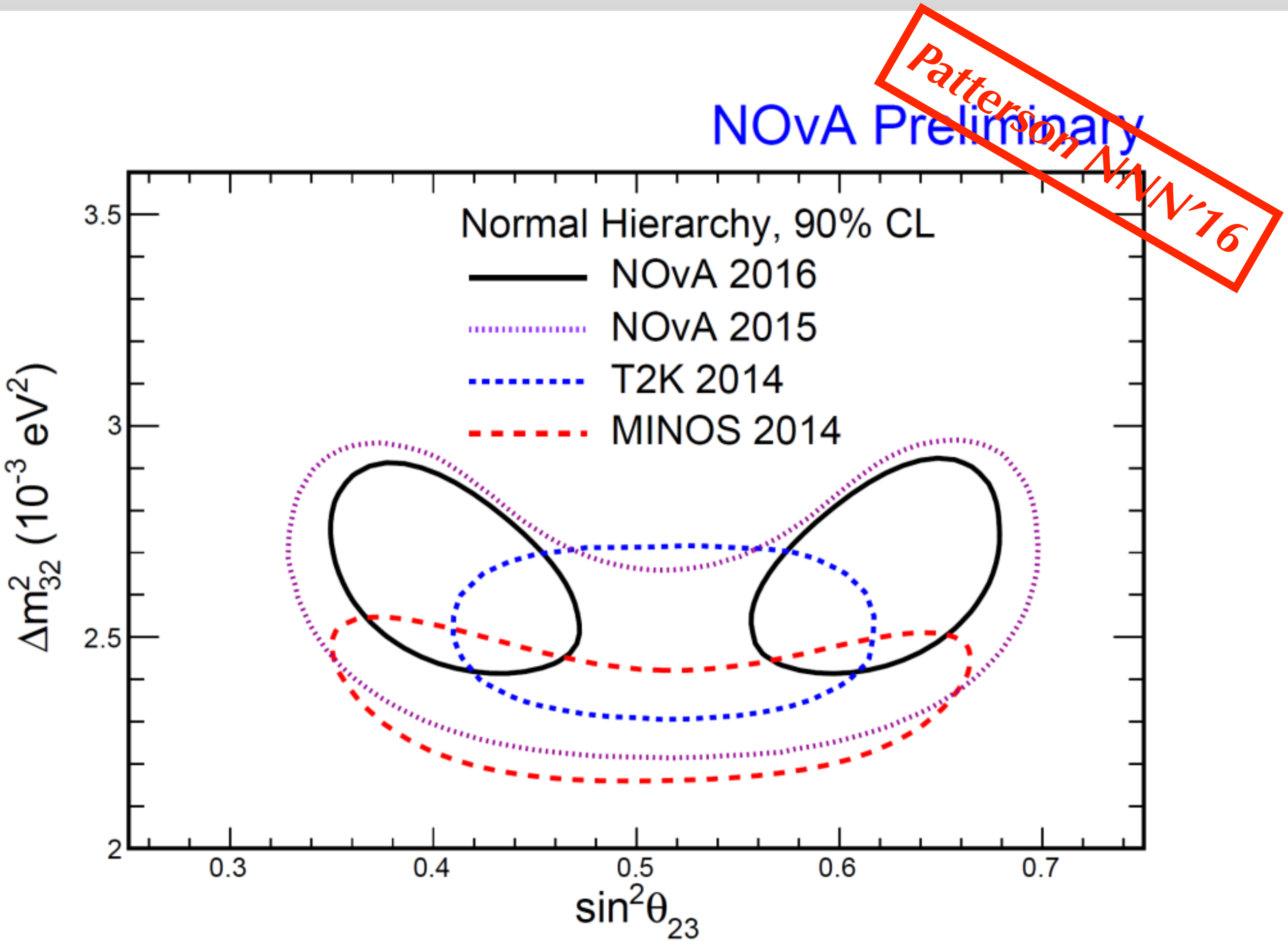


- MINOS is the first long-baseline neutrino experiment is MINOS in the U.S.A.
  - MINOS provided the best mass-squared splitting measurement before NOvA
- NOvA is an upgraded long-baseline experiment
  - NuMI's off-axis beam
  - Segmented liquid scintillator detectors: 3kt near detector and 14kt far detector

Disappearance Channel of NOvA

Allowed regions compatible with MINOS, T2K, and 2015 NOvA *(shown at right)*

Non-maximal mixing favored at 2.5σ C.L.



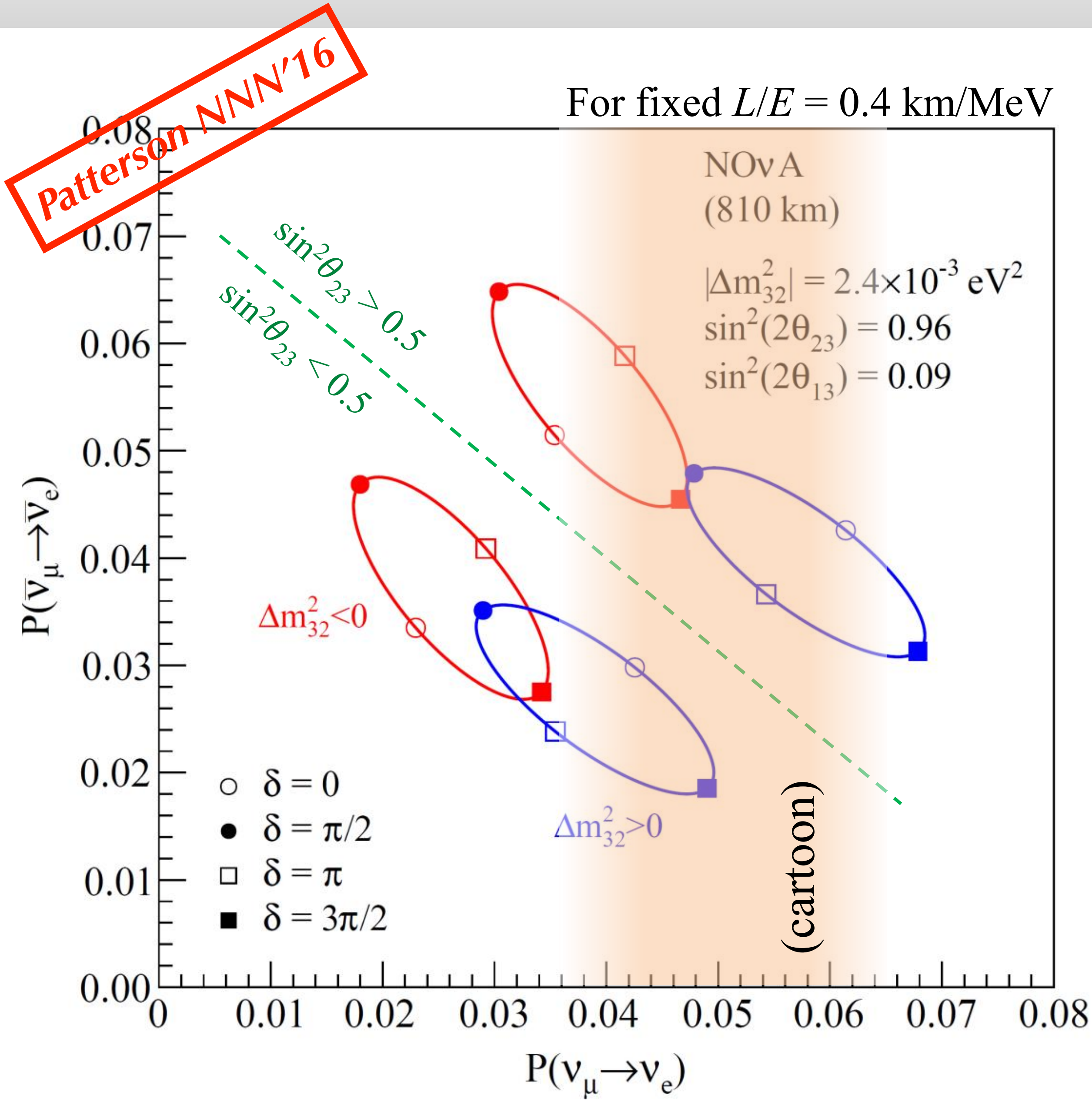
[NH case]

$\Delta m^2_{32} = (2.67 \pm 0.12) \times 10^{-3}\ eV^2$

already 4.5% uncertainty (MINOS closed at 3.8%)

$\sin^2(\theta_{23}) = 0.40^{+0.03}_{-0.02} \quad (0.63^{+0.02}_{-0.03})$

Appearance Signals of NOvA



$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ vs. $P(\nu_\mu \to \nu_e)$

plotted for a single neutrino energy and baseline

→ Strong dependence on δ and **ν mass hierarchy**

→ $P \propto \sin^2\theta_{23}$ *[approx.]*

Total prediction:

~17 to 42 ν_e candidates
(depending on osc. pars.)

Includes **8.2** background
(~independent of osc. pars.)

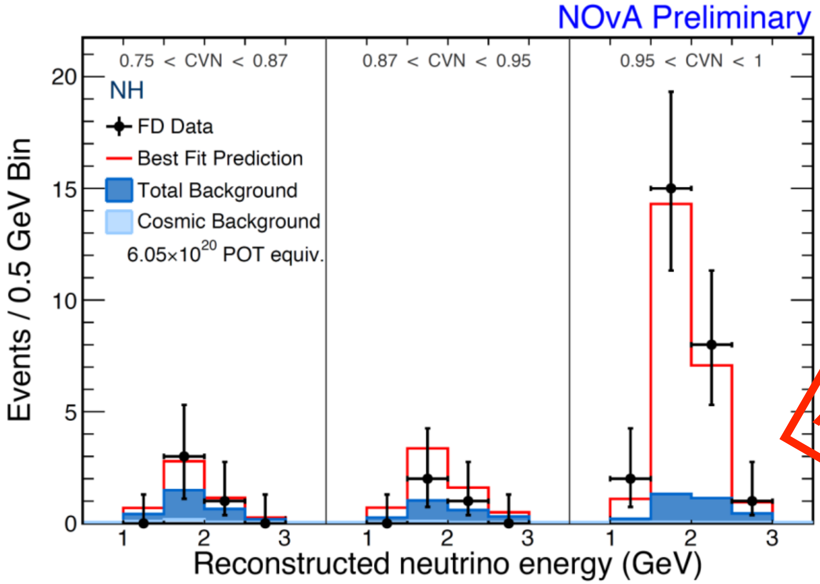
Syst. uncertainty:
±5% signal
±10% background

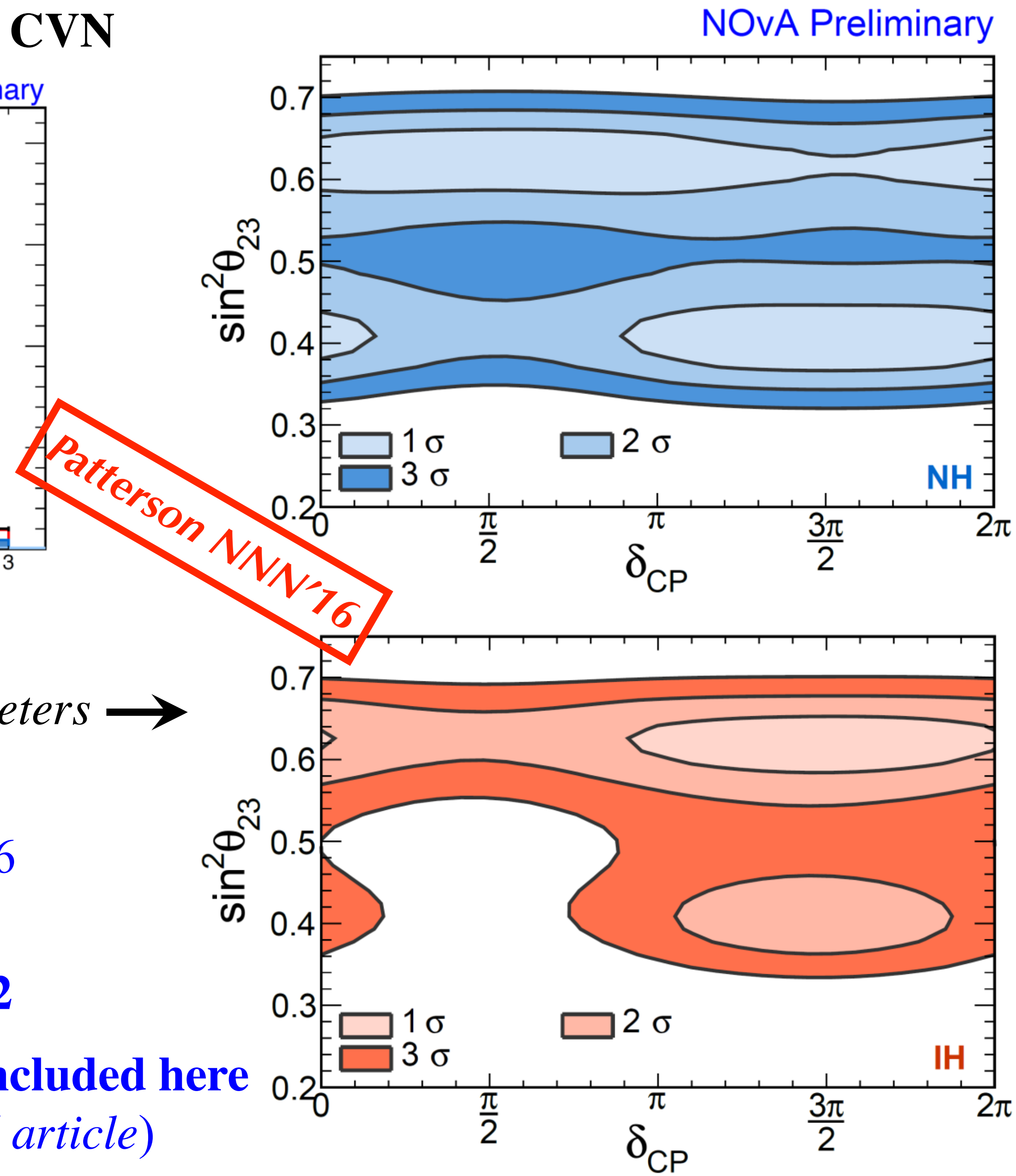
Observed in FD data:
33 ν_e candidates

>8σ observation of ν_e appearance

NOvA Preliminary Tries of MH, CP and Octant

Measure signal in 2D bins of E_ν × CVN





In terms of allowed physical parameters →

NH preference not signif.: $\Delta\chi^2$=0.46

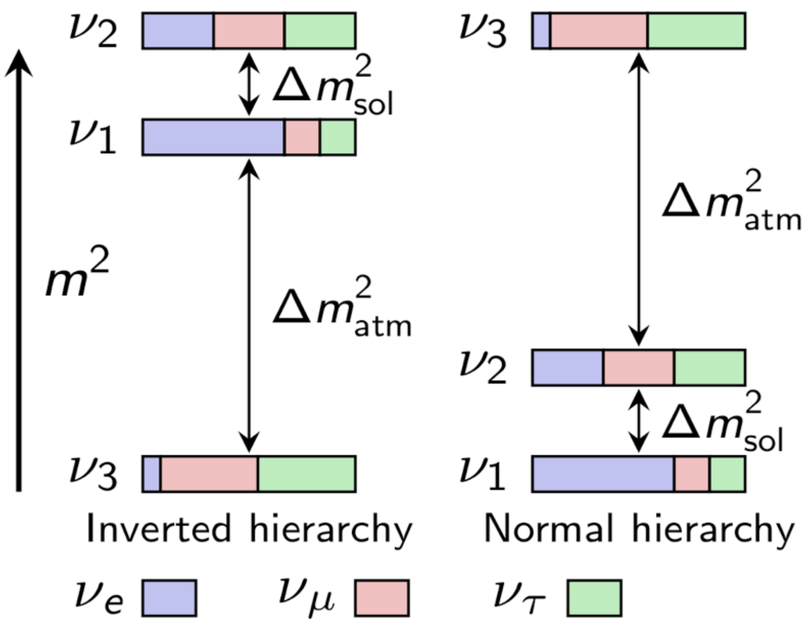
>3σ exclusion of region in

IH, lower octant, around $\delta=\pi/2$

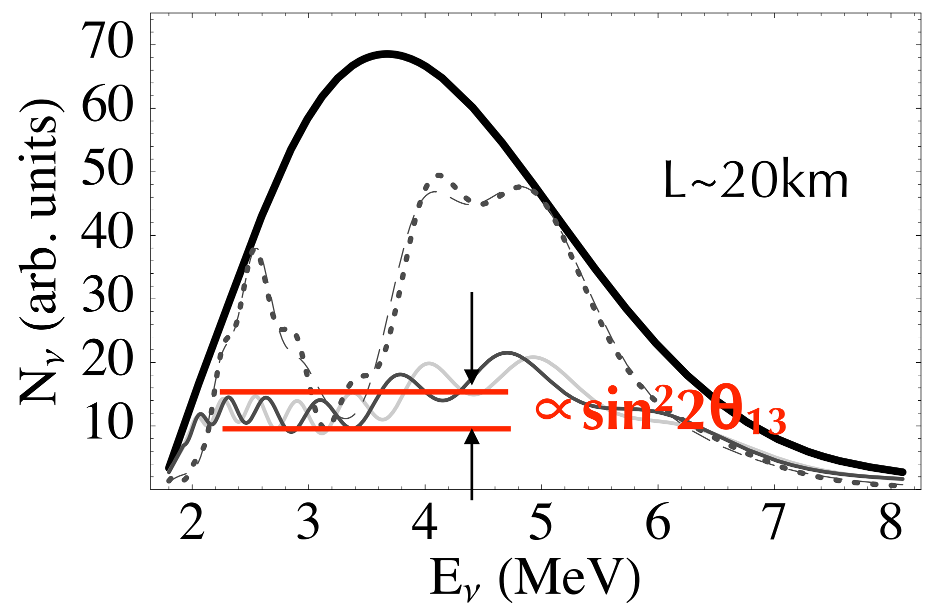
Feldman-Cousins corrections **not included here**

(*will appear in forthcoming journal article*)

Known θ13 Enables Neutrino Mass Hierarchy at Reactors

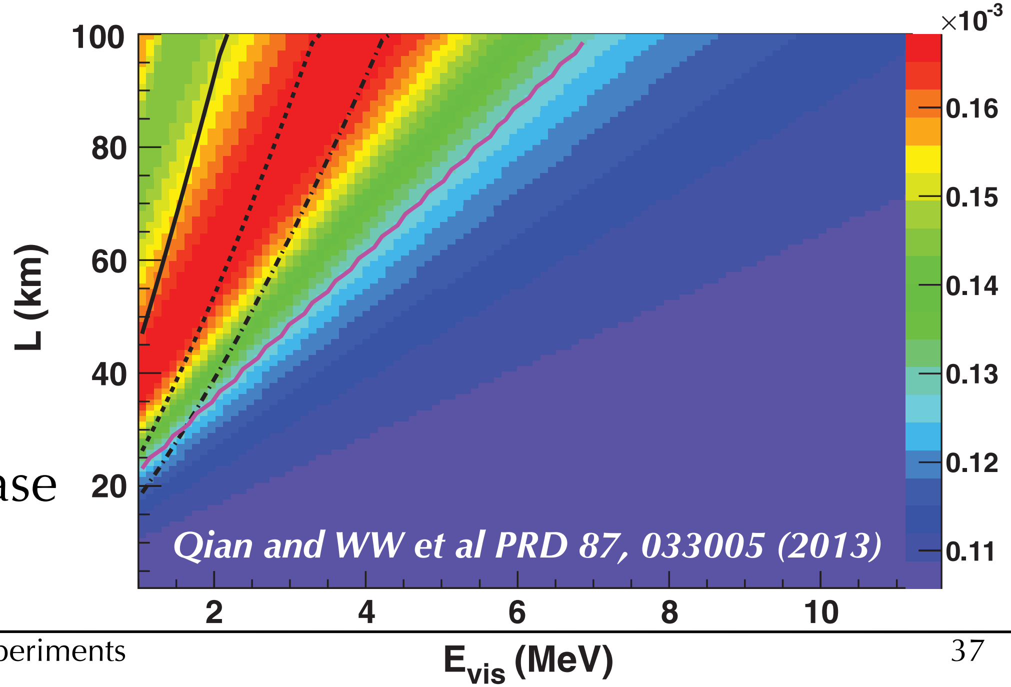


Petcov&Piai, Phys. Lett. B533 (2002) 94-106



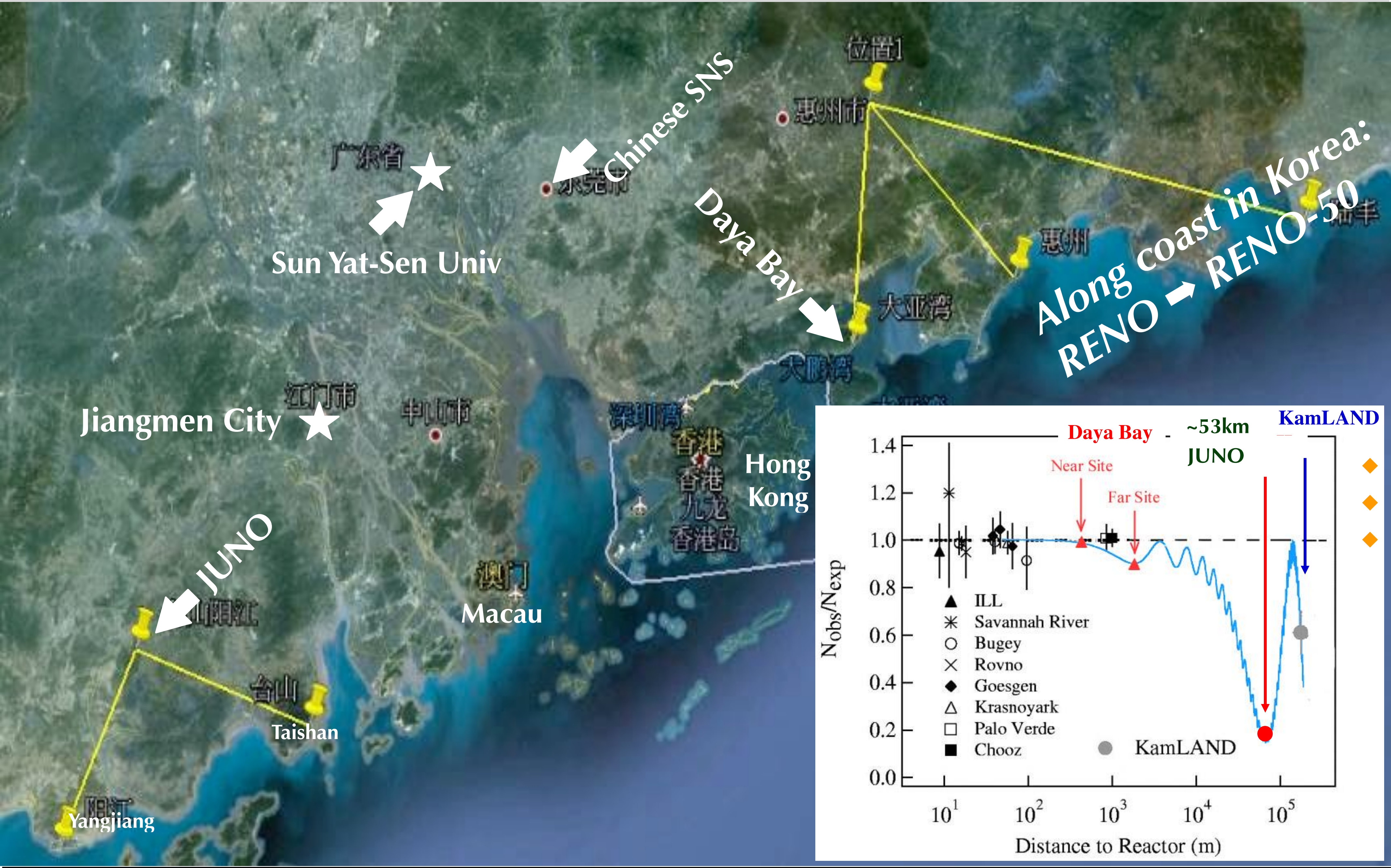
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

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

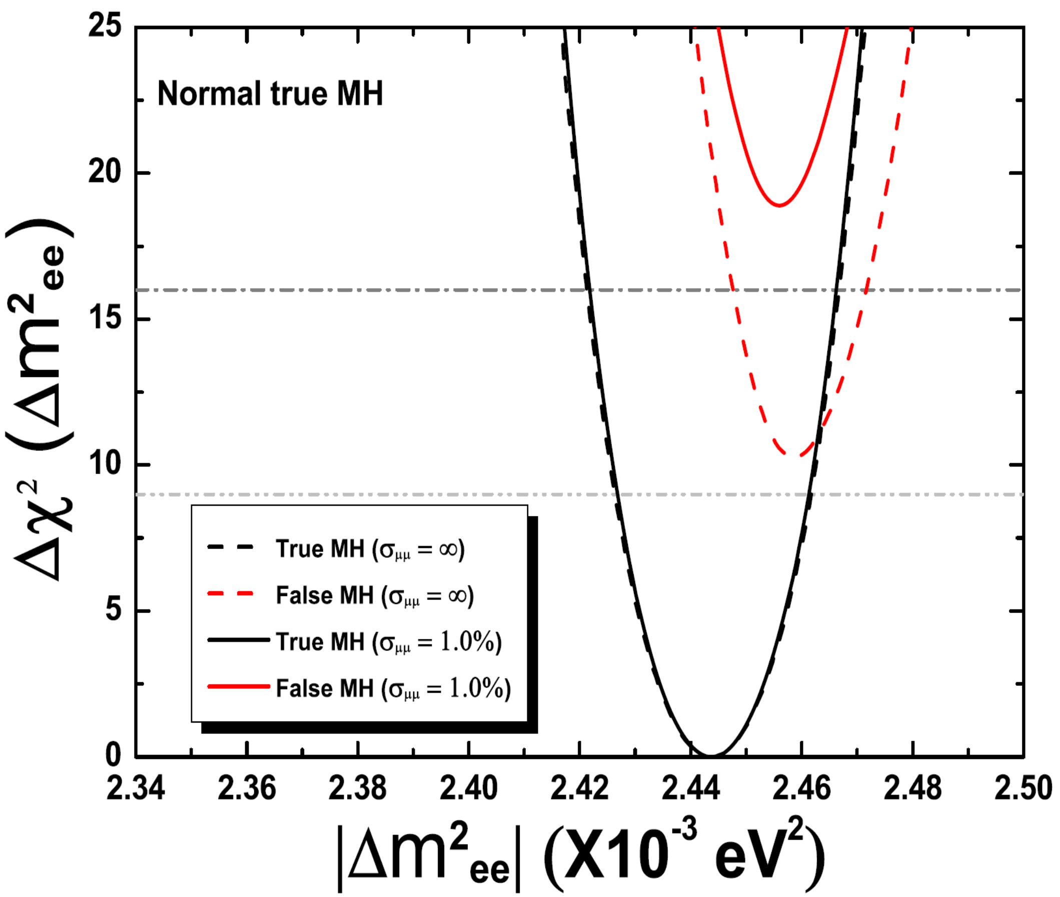


- ✓ Mass hierarchy is reflected in the spectrum
- ✓ Signal independent of the unknown CP phase
- ✓ Suitable baseline is ~60km

Jiangmen Underground Neutrino Observatory as an Example



Expected Significance to Mass Hierarchy



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

✓Realistic reactor distributions considered

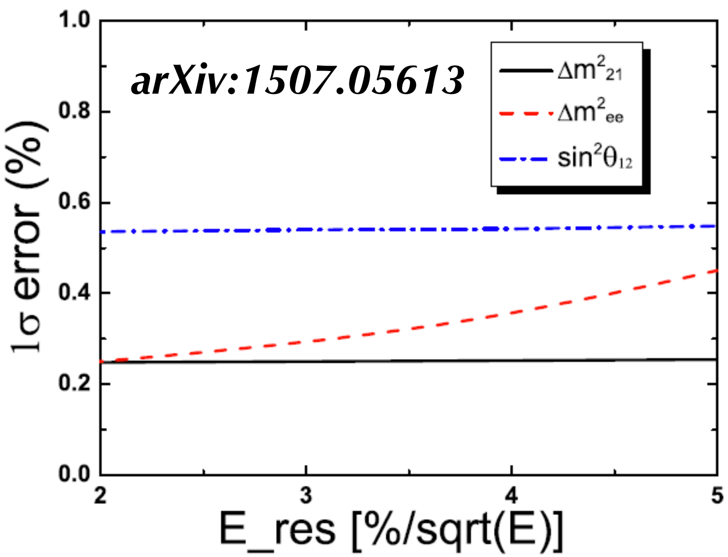
✓20kt valid target mass, 36GW reactor power, 6-year running

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

JUNO Precision Measurements Warranted

Global
arXiv:1507.05613

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



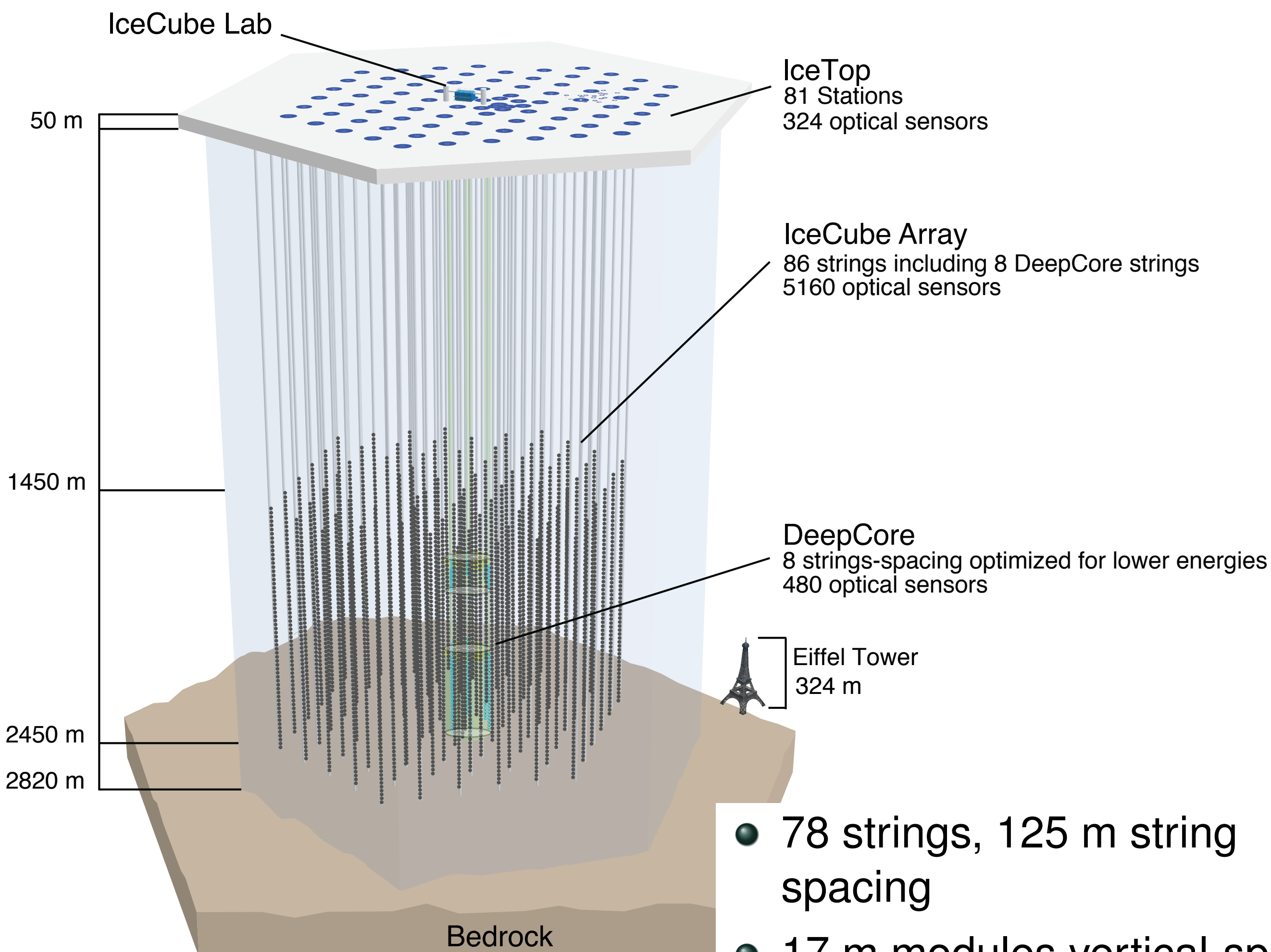
Consistent conclusion from an independent study by A.B. Balantekin et al, Snowmass'13, arXiv:1307.7419

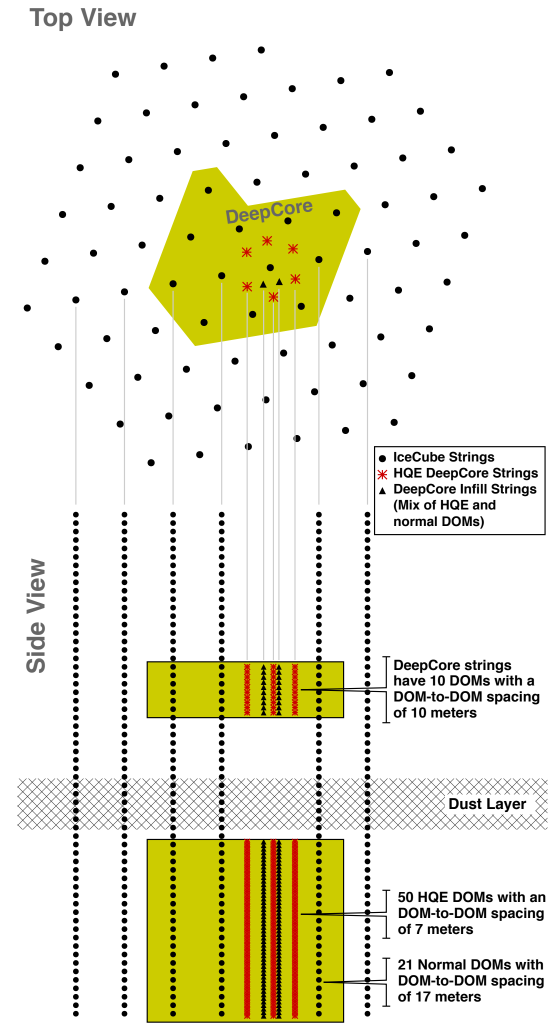
- Precision <1% measurements are warranted in a experiment like JUNO
  - Enable a future ~1% level PMNS unitarity test
  - Neutrinoless double beta decay needs precise θ_{12}

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

JUNO: 100k evts
arXiv:1507.05613

IceCube-DeepCore





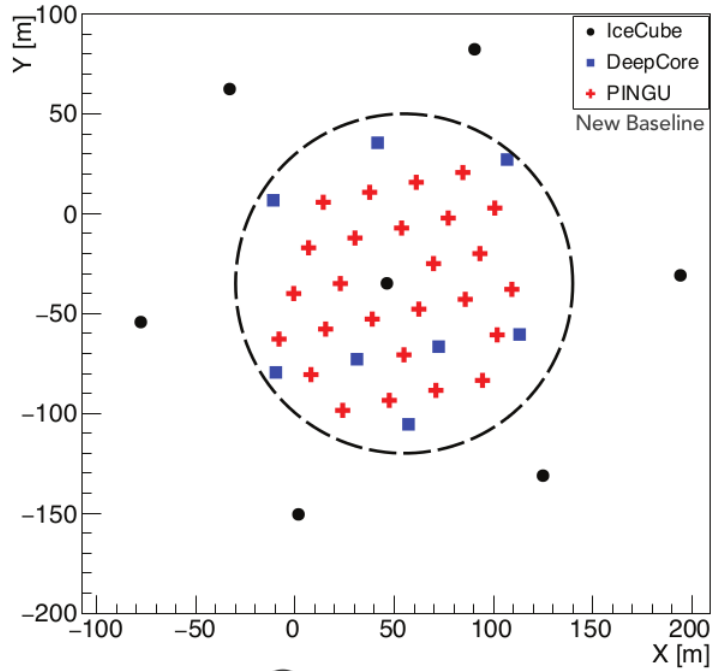
- 78 strings, 125 m string spacing
- 17 m modules vertical-spacing
- 8 strings, 40-75 m string spacing
- 7 m modules vertical-spacing

Good for atmospheric oscillation parameters

Threshold energy too high for mass hierarchy

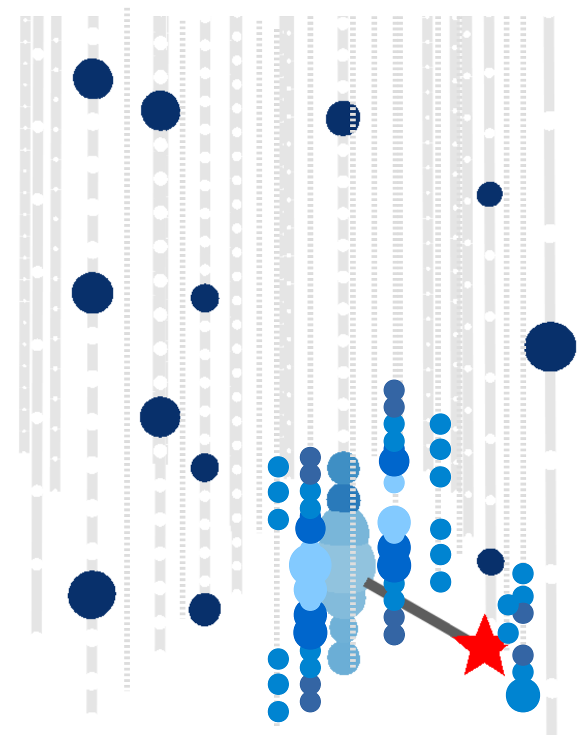
IceCube-Gen2/PINGU

- Resonance oscillation due to MSW effect for atmospheric mass-squared splitting happens in Earth for few GeV neutrinos
- Under different mass hierarchies, the resonance energies differ ⟹ event differences tell mass hierarchy



Current

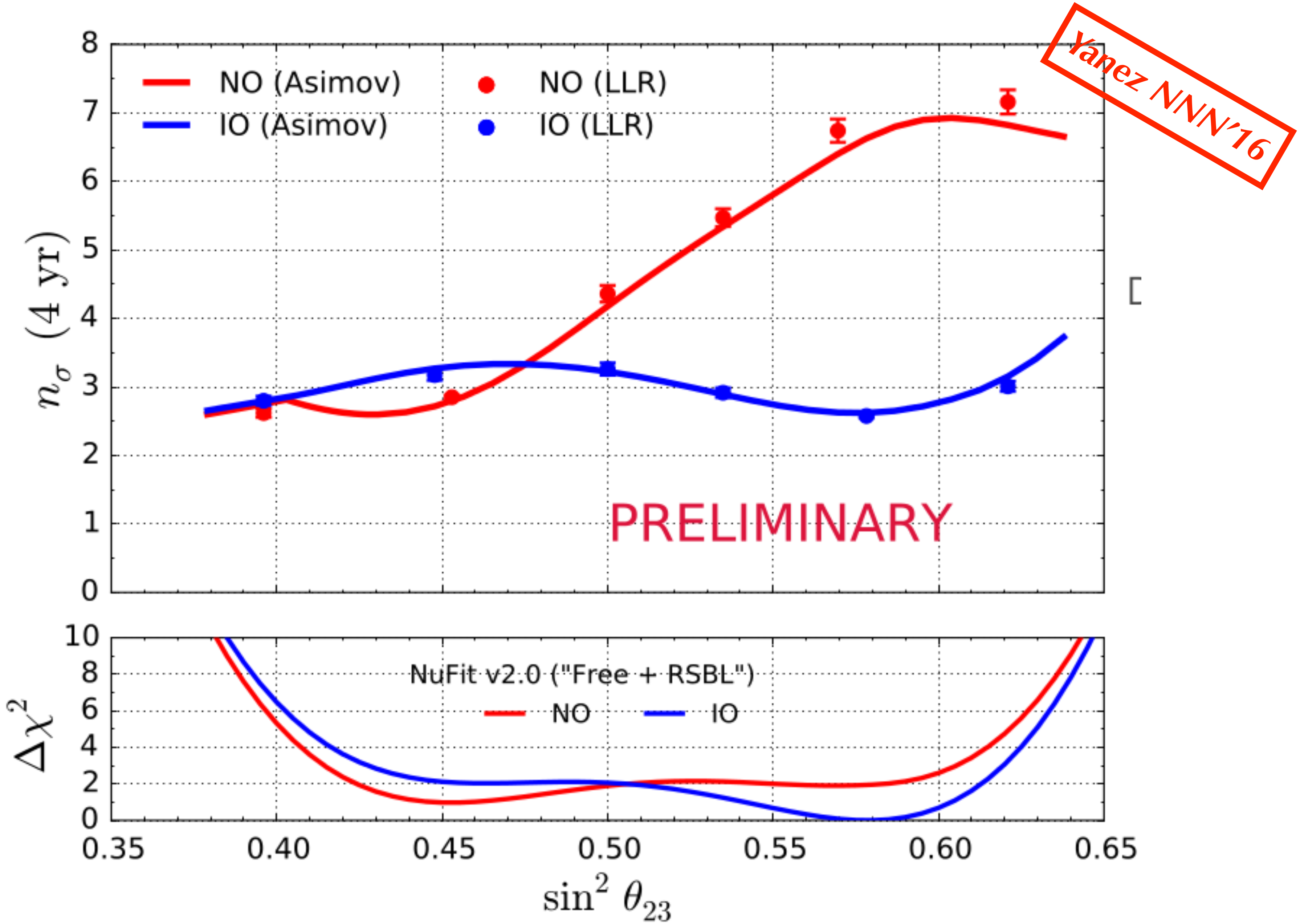
26 strings
192 DOMs/string
1.5 m DOM-DOM spacing



➡ Need large statistics ⟹ IceCube

➡ Need to lower the energy threshold ⟹ IceCube-Gen2/PINGU

IceCube-Gen2/PINGU Sensitivity to MH and Octant



Summary

- Exciting and steady progresses have been made in the past 20 years in neutrino experiments since Super-K turned on — ***New physics beyond the Standard Model***

- ***The current generation Long-baseline neutrino experiments are showing potential in measuring CP and mass hierarchy***: expecting more data from beam upgrades and planning more data taking

- ***Non-accelerator neutrinos provide great potential in resolving the neutrino mass hierarchy***: JUNO, RENO-50, IceCube-Gen2/PINGU

- ***Unanswered questions in neutrino sector*** might hold the keys to many profound questions — S***tay tuned and expect unexpected!***

What I have skipped: MiniBooNe, MicroBooNe, OPERA, ICARUS, BOREXINO/SOX, RENO-50, Hyper-K, ORCA/KM3NET, DUNE, Katrin, ……, exotic New Physics searches, Ultra-high energy neutrinos, and neutrinoless double beta decay experiments……

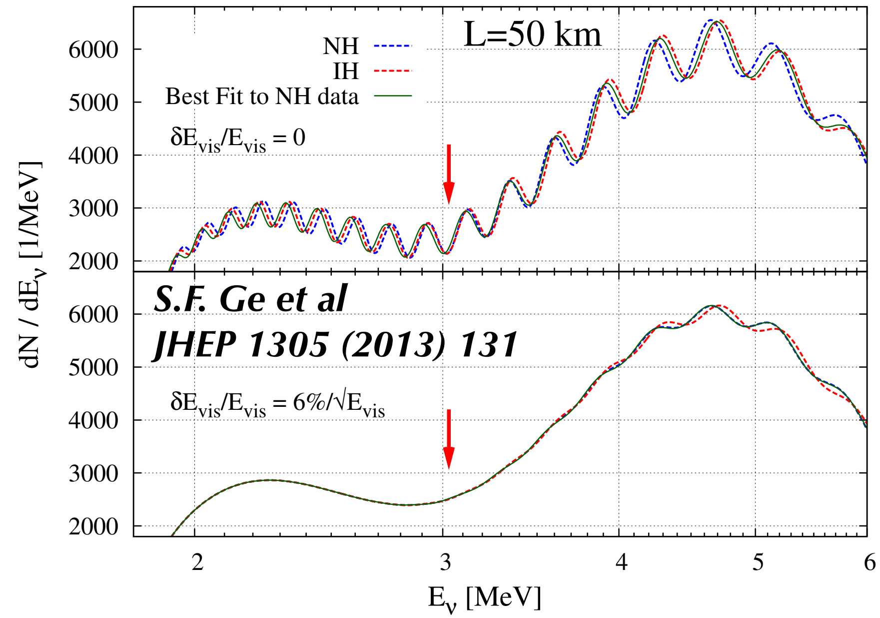
The Detector Performance Goals

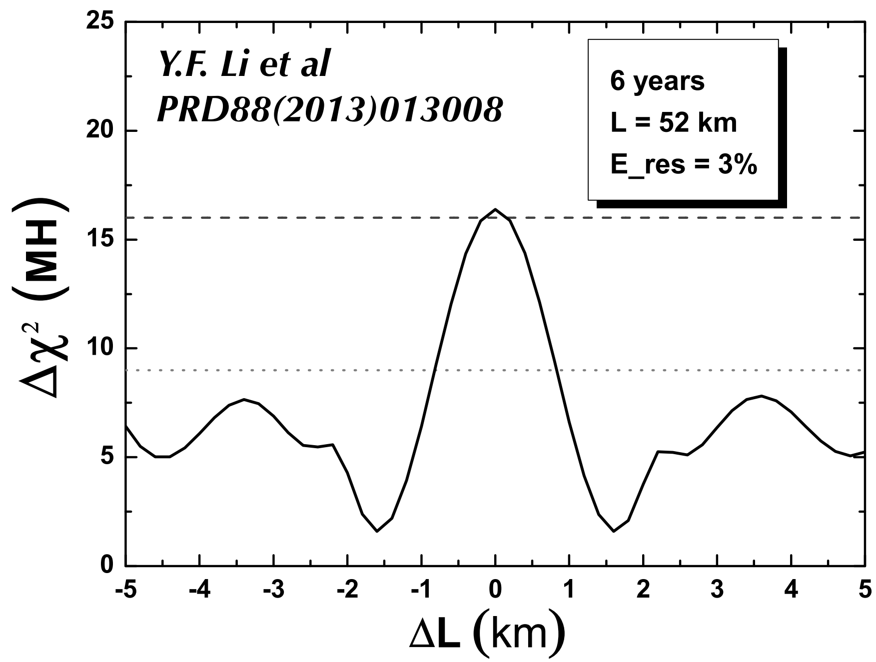
	Daya Bay	BOREXINO	KamLAND	JUNO
Target Mass	20t	~300t	**~1kt**	**~20kt**
PE Collected	~160 PE/MeV	**~500 PE/MeV**	~250 PE/MeV	**~1200 PE/MeV**
Photocathode Coverage	~12%	**~34%**	**~34%**	**~80%**
Energy Resolution	~7.5%/√E	**~5%/√E**	~6%/√E	**3%/√E**
Energy Calibration	~1.5%	**~1%**	~2%	**<1%**

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

Challenges in Resolving MH using Reactor Sources

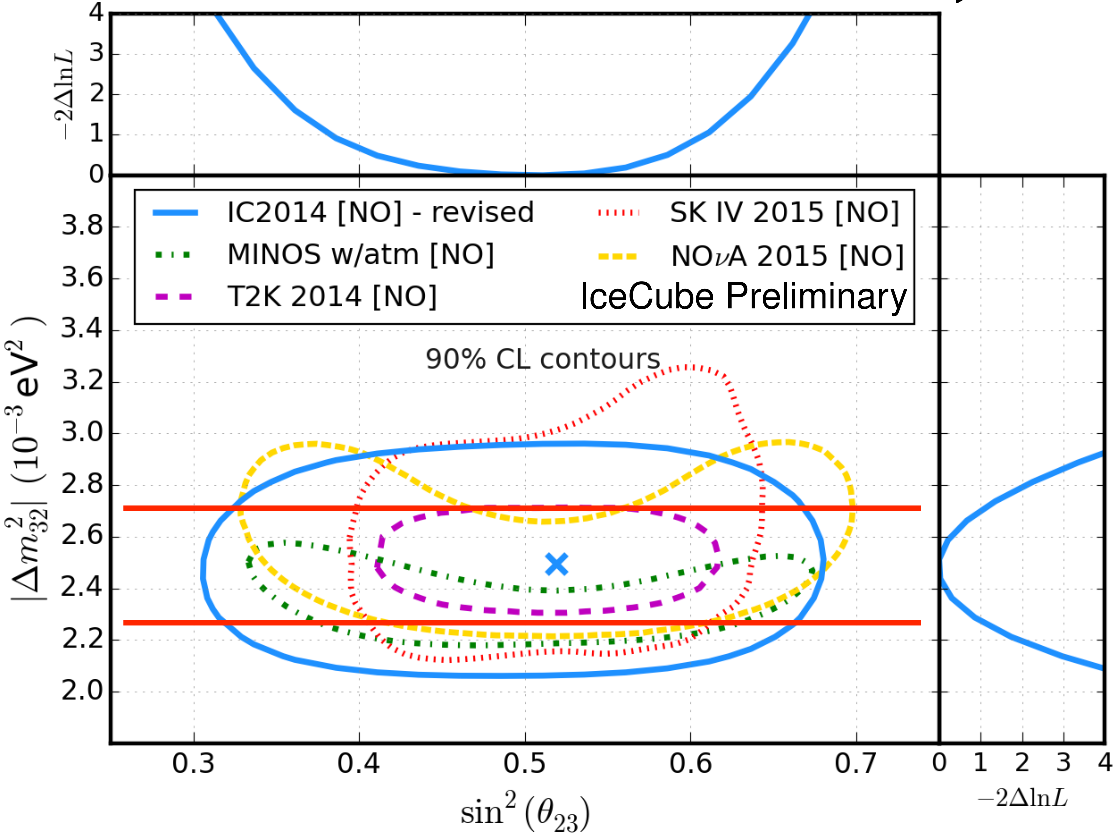
- Energy resolution: ~3%/sqrt(E)
  - Bad resolution leads to smeared spectrum and the MH signal practically disappears
- Energy scale uncertainty: <1%
  - Bad control of energy scale could lead to no answer, or even worse, a wrong answer
- Statistics (who doesn't like it?)
  - ~36GW thermal power, a 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.





PRD 91, 072004 (2015)

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

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

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

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