Reactor-based Neutrino Results and θ_{13}

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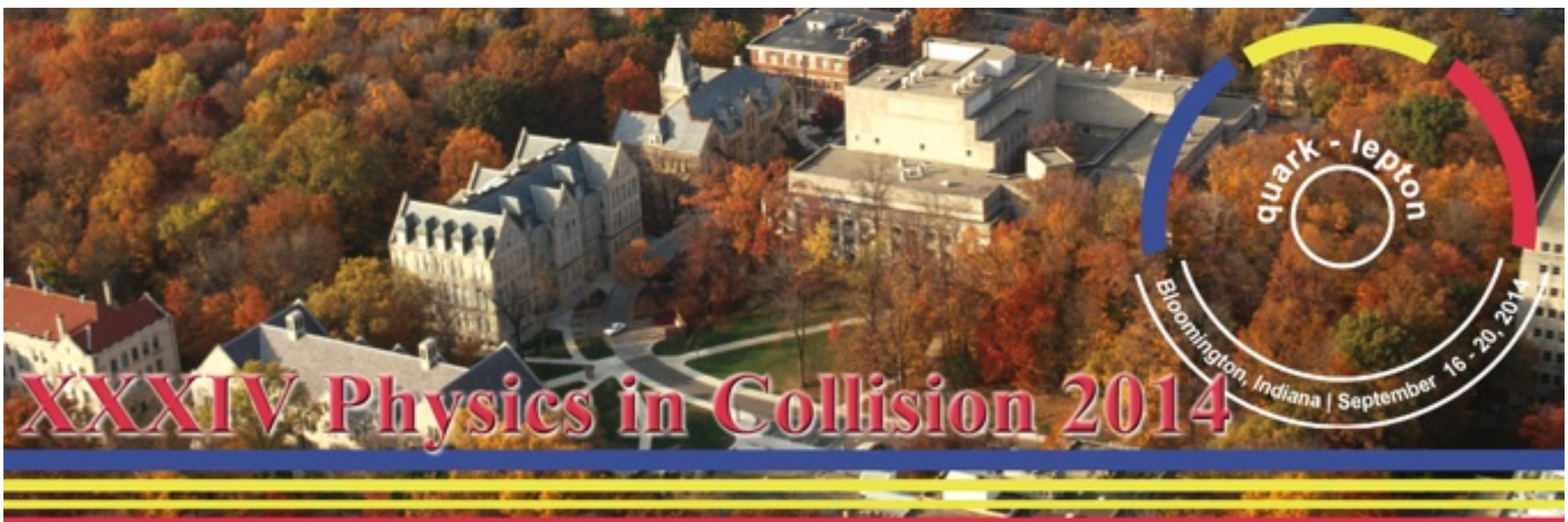
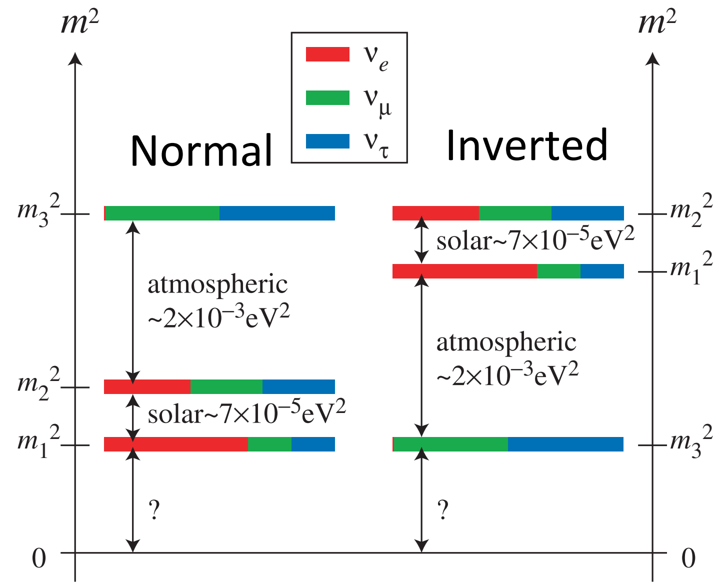
PIC 2014, Bloomington, Indiana, USA



Neutrino Mixing

Flavor Eigen state $|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i} |\nu_i\rangle$ Mass Eigen state



$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{-i\alpha_1/2} & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$

$s_{ij} \equiv \sin\theta_{ij}$

Atmospheric: $\theta_{23} \approx 45°$

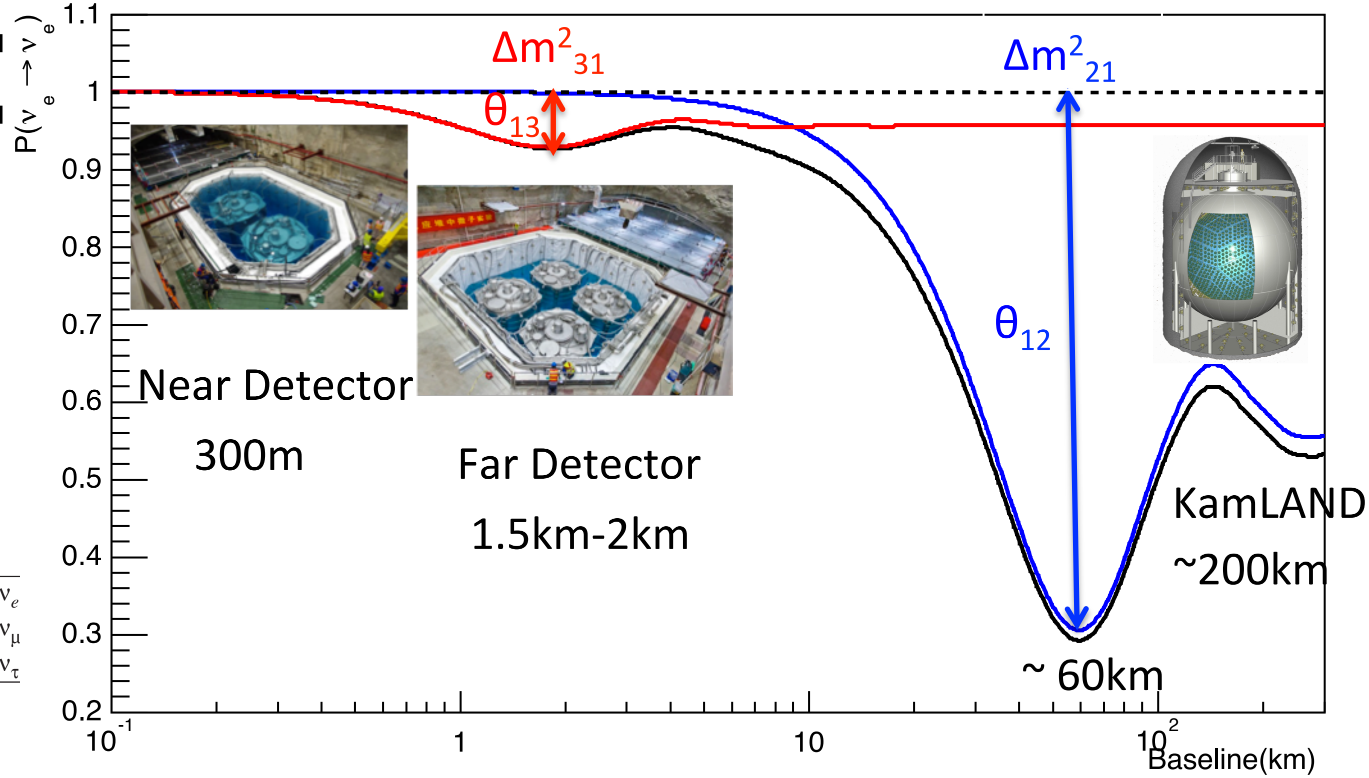
"CP" sector: θ_{13} =? δ = ?

Solar: $\theta_{12} \approx 34°$

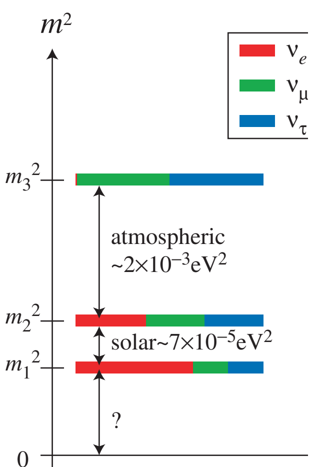
Majorana $0\nu\beta\beta$

Magnitude of θ_{13} is key to "sub-leading" effects: neutrino mass hierarchy and leptonic CP violation.

Reactor Neutrino Oscillation



$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{31} + \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

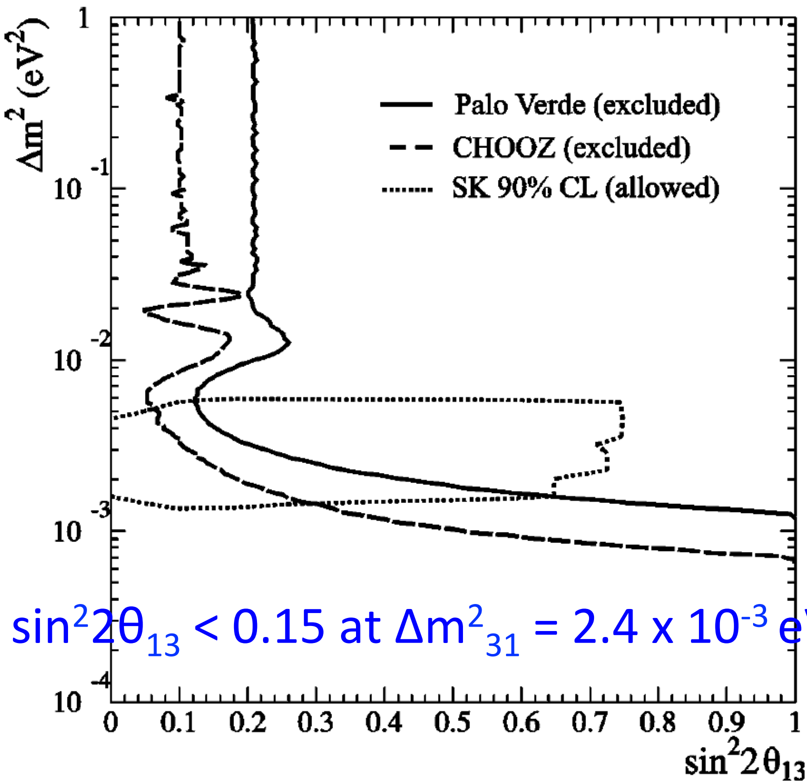


Two different oscillation length scale:

- $\Delta m^2_{31} \approx 2.4 \times 10^{-3}$ eV^2
- $\Delta m^2_{21} \approx 7.6 \times 10^{-5}$ eV^2

$$\Delta_{ij} = \Delta m^2_{ij} \frac{L}{4E}$$

Search for θ_{13} with Reactor Neutrinos



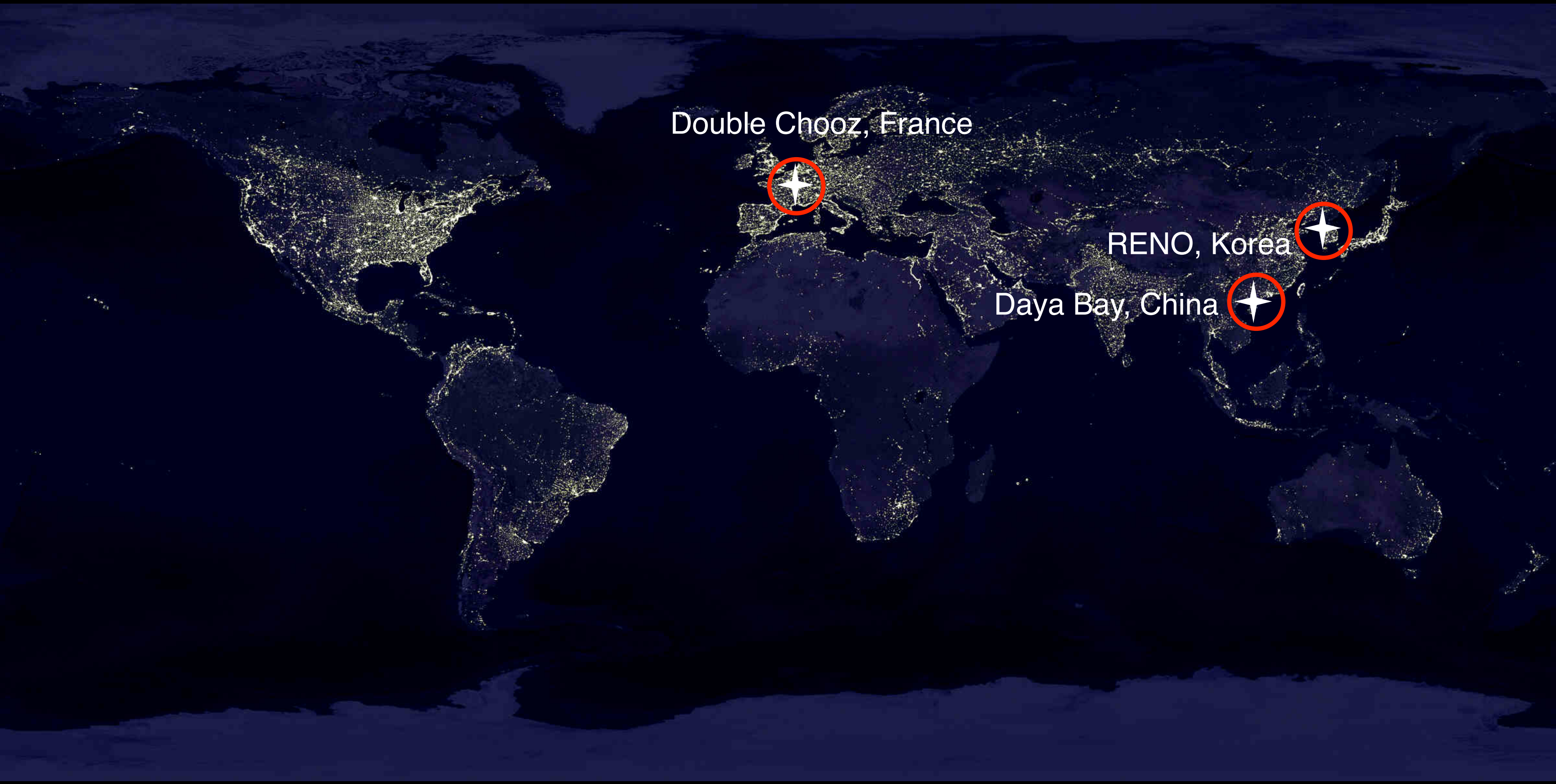
$\sin^2 2\theta_{13} < 0.15$ at $\Delta m^2_{31} = 2.4 \times 10^{-3}$ eV^2

Key for a sensitive θ_{13} search

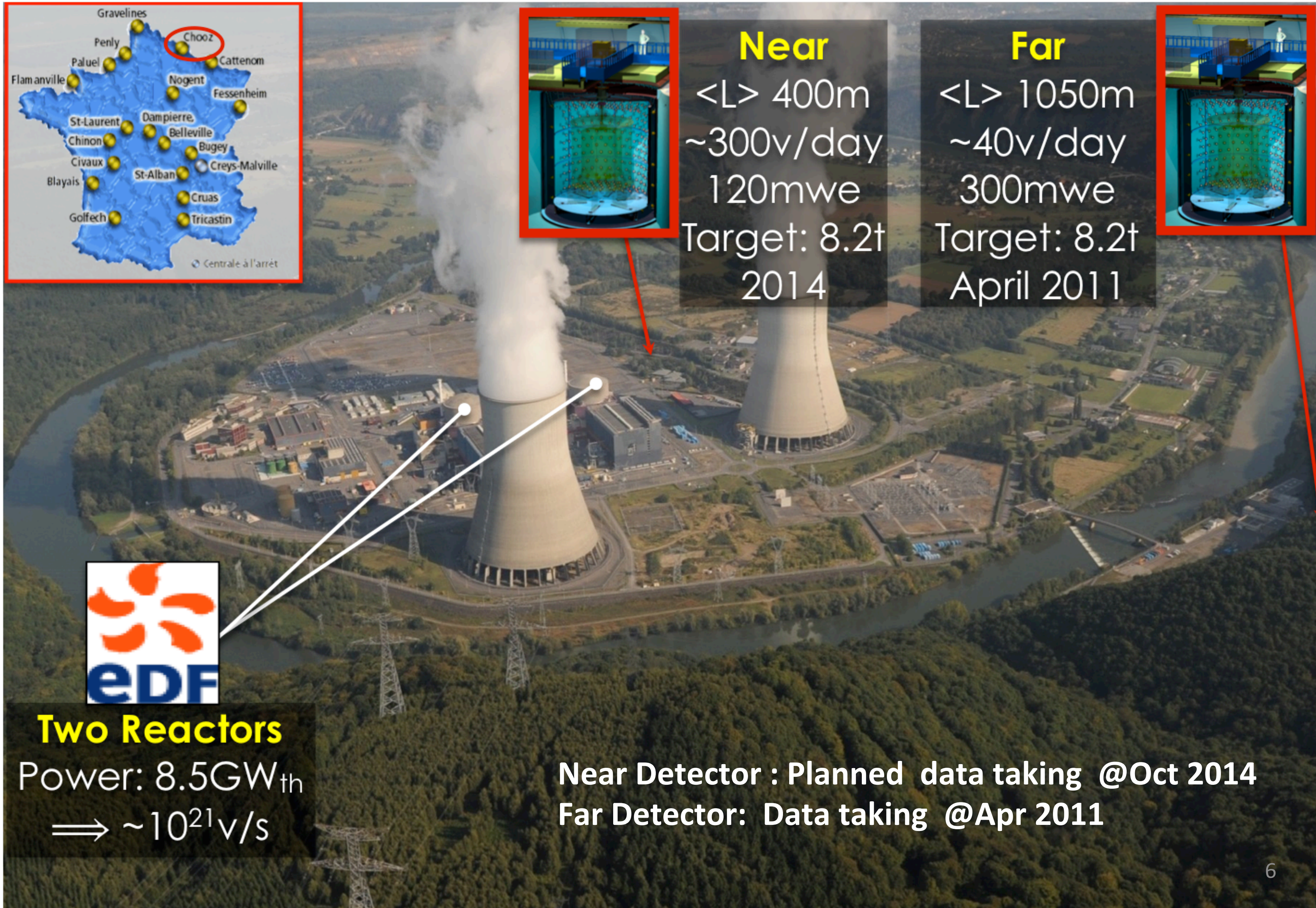
- **Large statistics**
  - Powerful reactor
  - Large target mass
- **Reducing reactor-related uncertainty**
  Far/Near cancellation
- **Reducing detector-related uncertainty**
  Multiple functional identical detectors
- **Reducing Background**
  Underground with large overburden
- **Optimize baseline** 1.5-2 km

	Reactor [GW_{th}]	Target [tons]	Depth [m.w.e]	Baseline [m]
CHOOZ	8.5	5	300	1115, 998
Palo Verde	11.6	12	32	890, 750

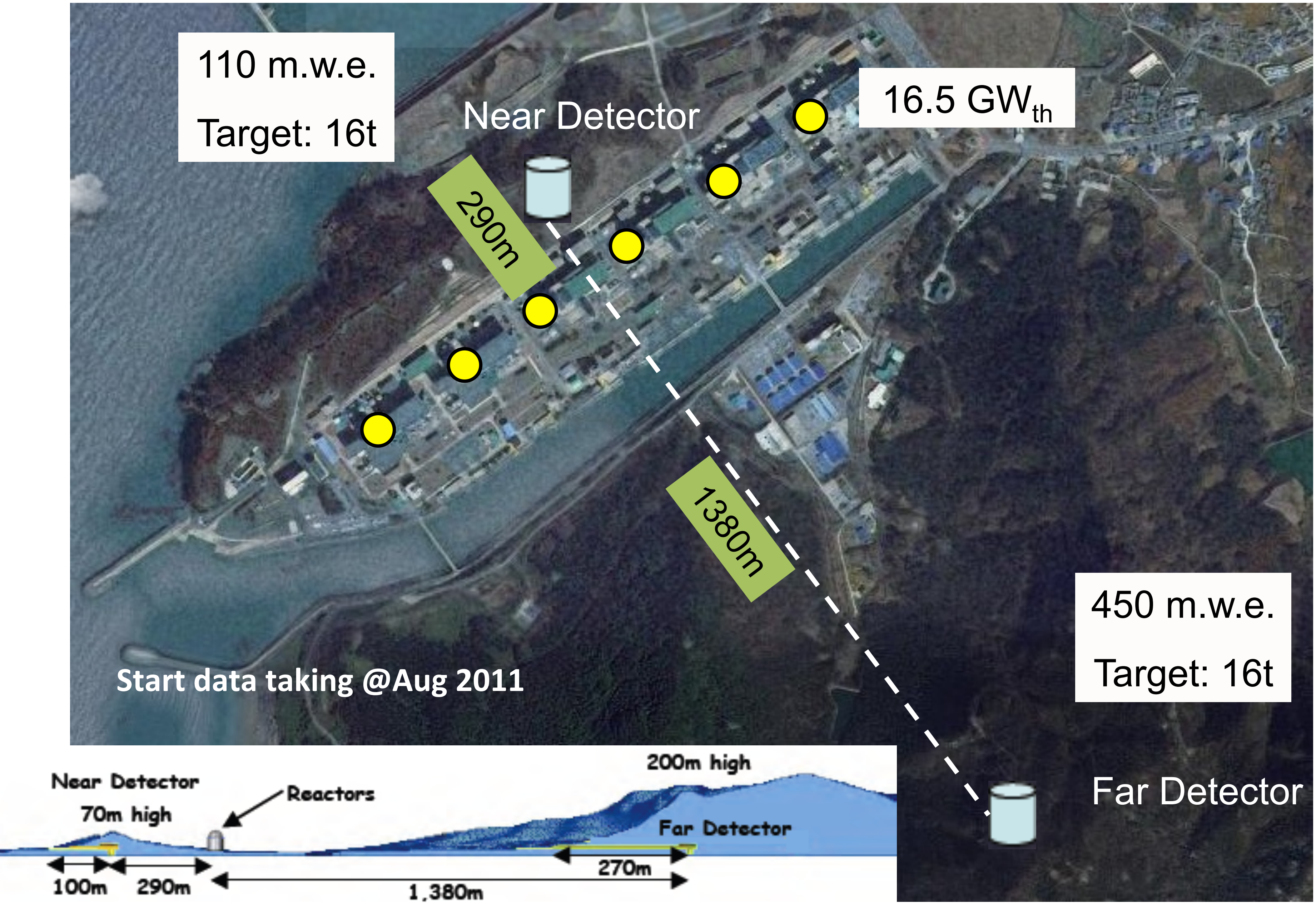
World Competing Reactor Neutrino Experiments for θ_{13}



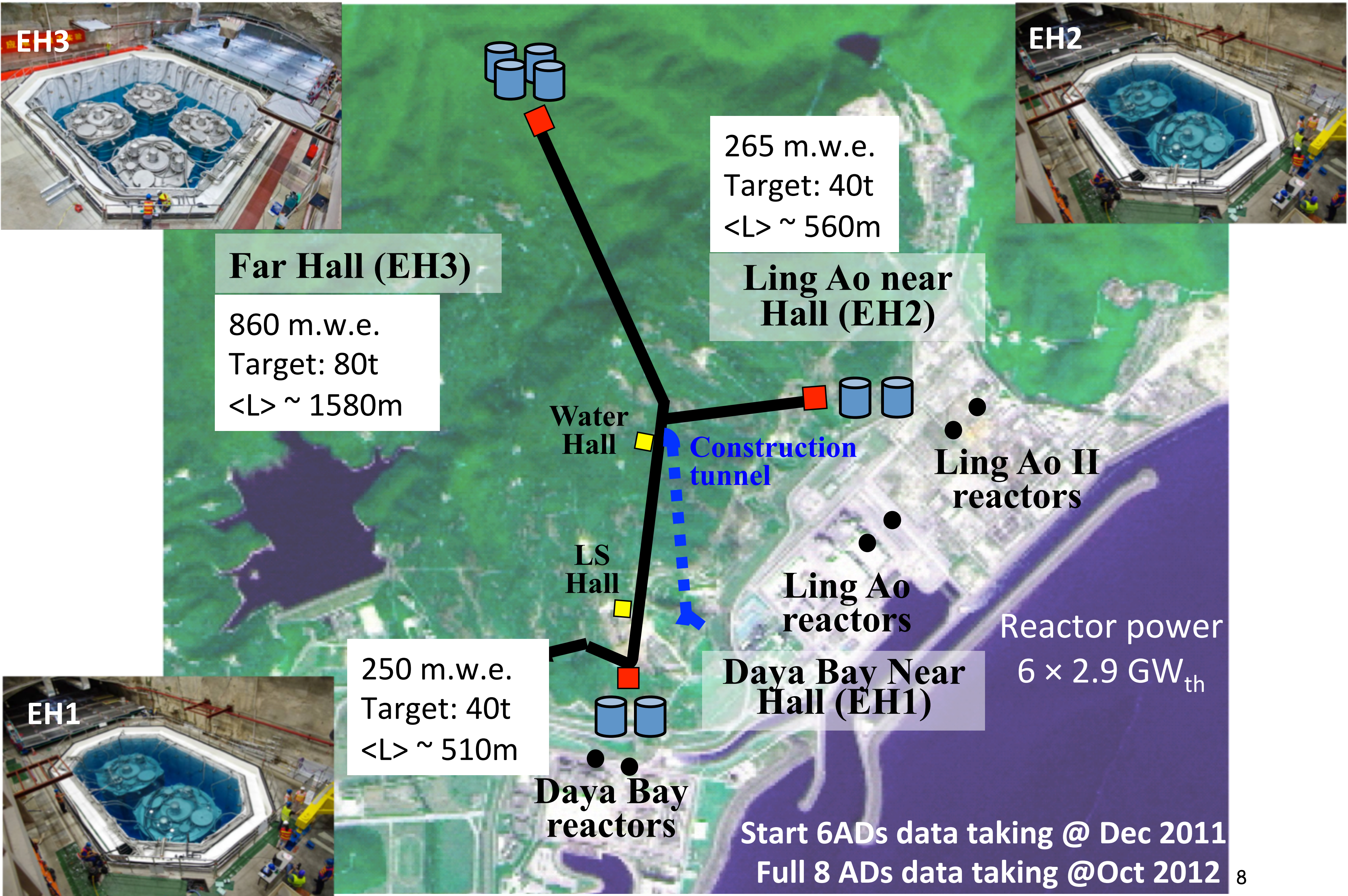
Double Chooz Experimental Setup



RENO Experimental Setup

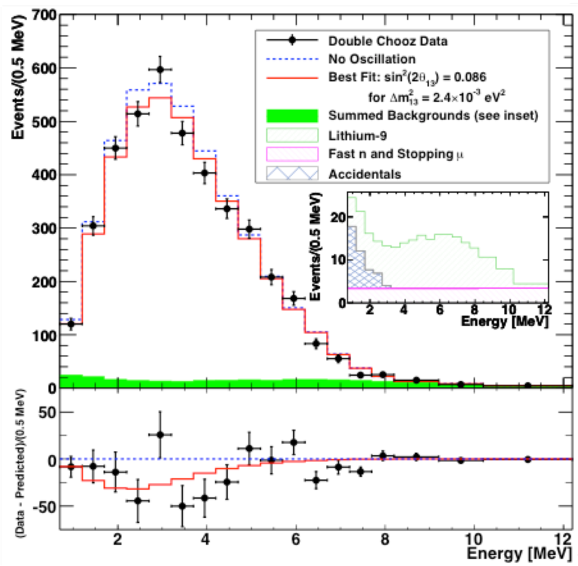


Daya Bay Experimental Setup

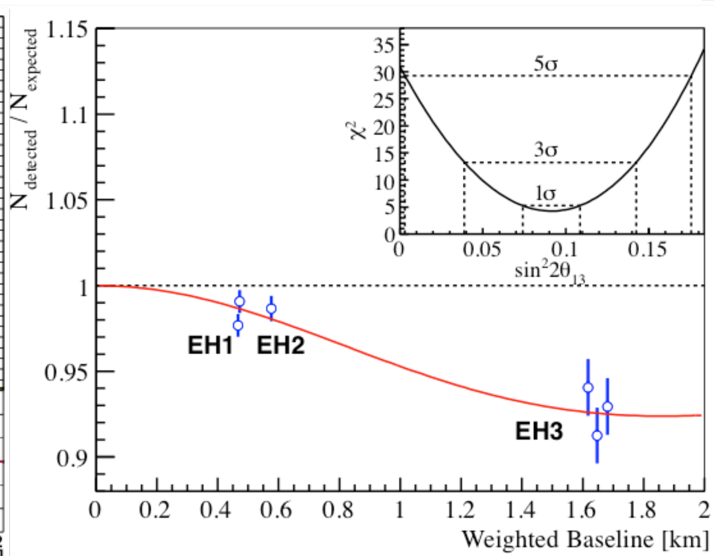


Discovery of θ_{13} from Reactor Exps.

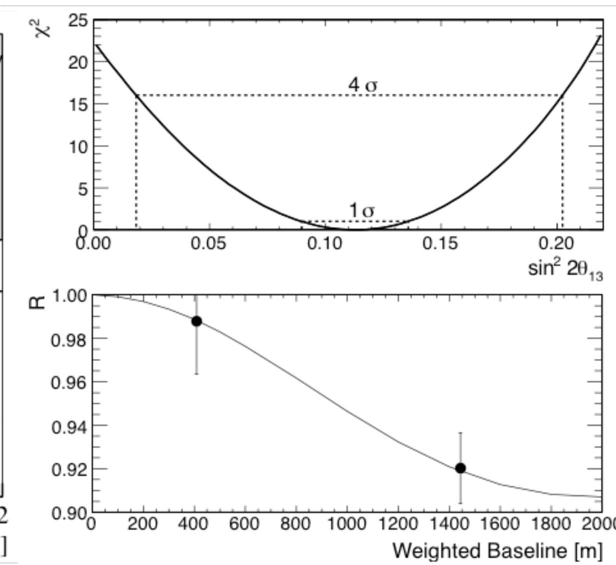
Double Chooz (Far + Bugey4)



Daya Bay (6ADs)



RENO (Near+Far)



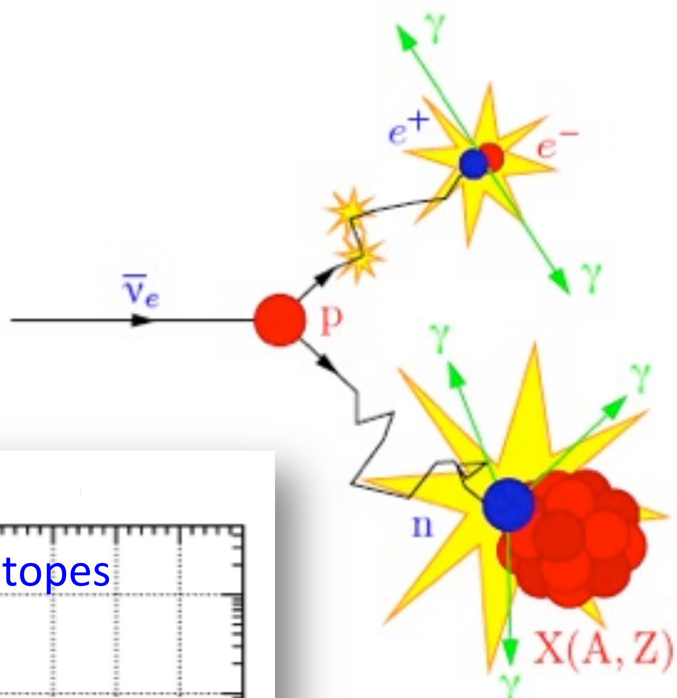
Nov/2011 Double Chooz: $\sin^2 2\theta_{13} = 0.086 \pm 0.041(\text{stat}) \pm 0.030(\text{syst})$ 1.7σ

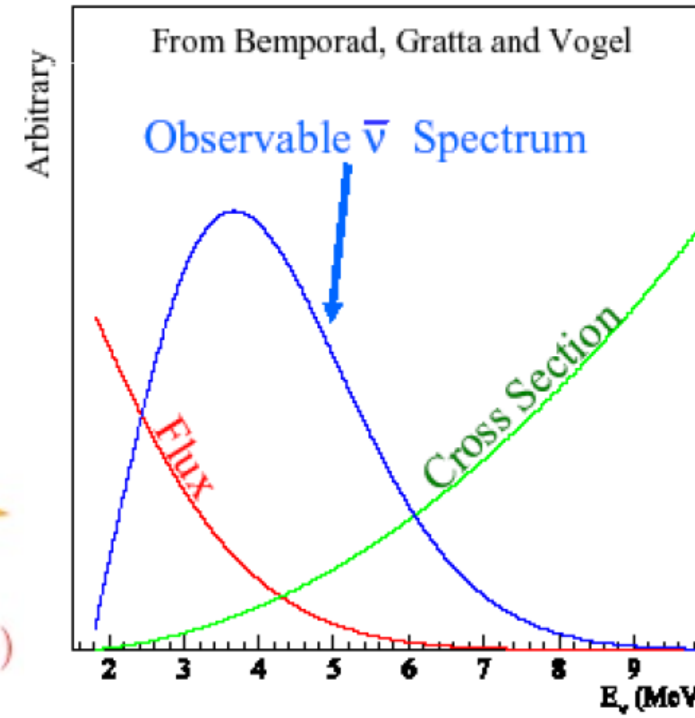
Mar/2012 Daya Bay: $\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$ 5.2σ

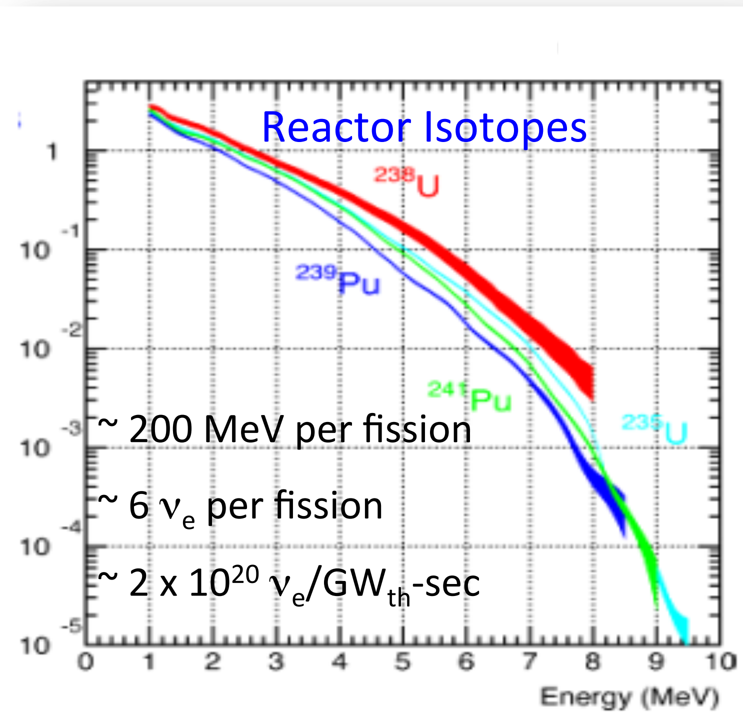
Apr/2012 RENO: $\sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat}) \pm 0.019(\text{syst})$ 4.9σ

First observation of ϑ_{13} after a decade of effort!

Reactor Neutrinos and Detection







~ 200 MeV per fission

~ 6 ν_e per fission

~ 2 x 10^{20} ν_e/GW_{th}-sec

- Source: Clean $\overline{\nu}_e$ signal
- Detection: Inverse beta decay (IBD)

Coincidence signal:

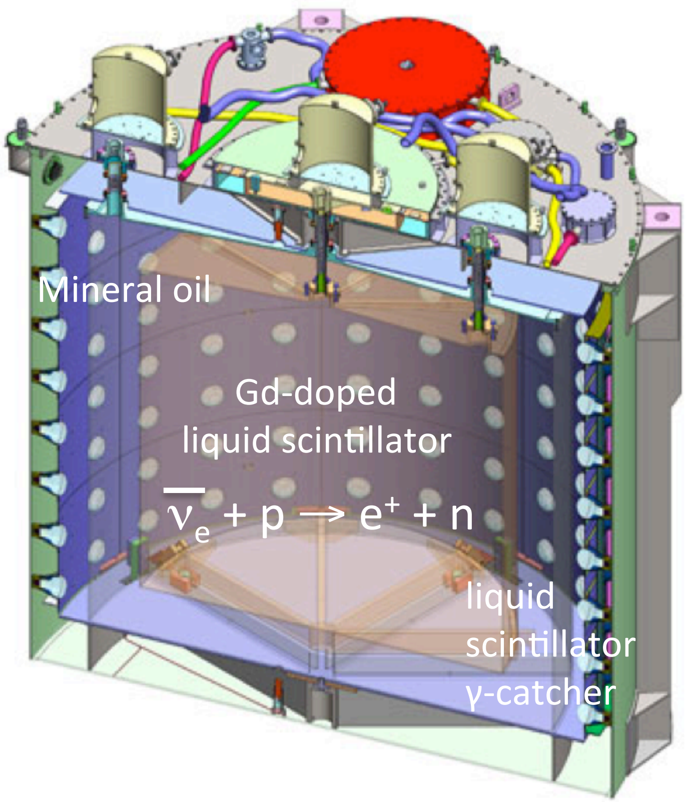
Prompt: e^+ annihilation $E_p \approx E_\nu - 0.8$ MeV

Delayed: n captured on H (2.2MeV) or Gd (8MeV)

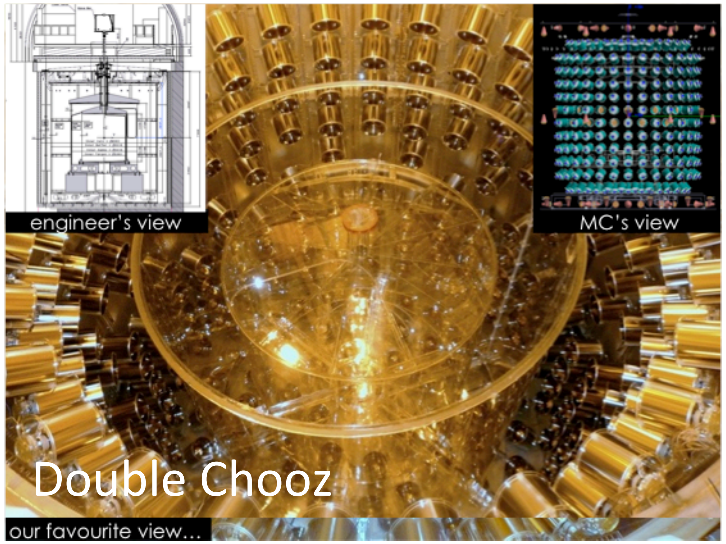
3-Zone Detector Design

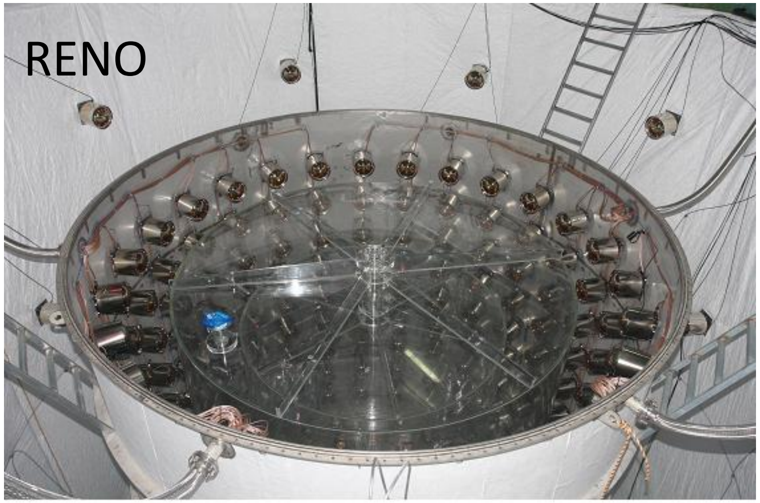
Daya Bay

- 8 "identical", 3-zone detectors
- no fiducial volume cut



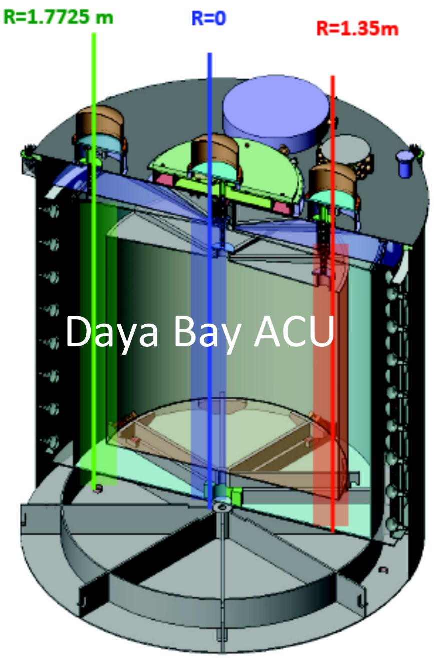
Target mass: 20t ± 3kg Gd-LS
Other mass: 20t LS+ 40t MO
Photo sensors: 192 8" PMTs

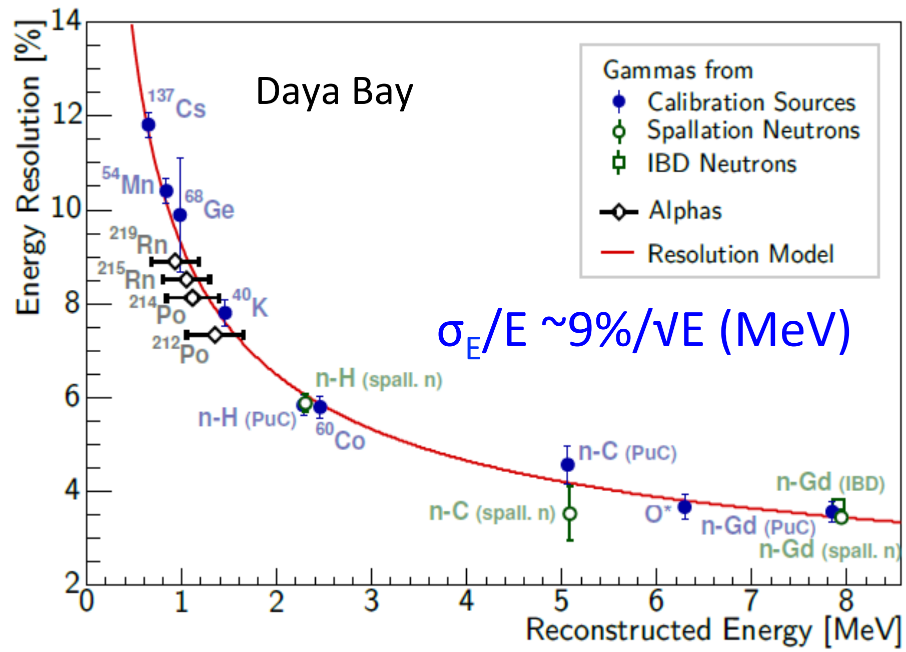




Detector Calibration

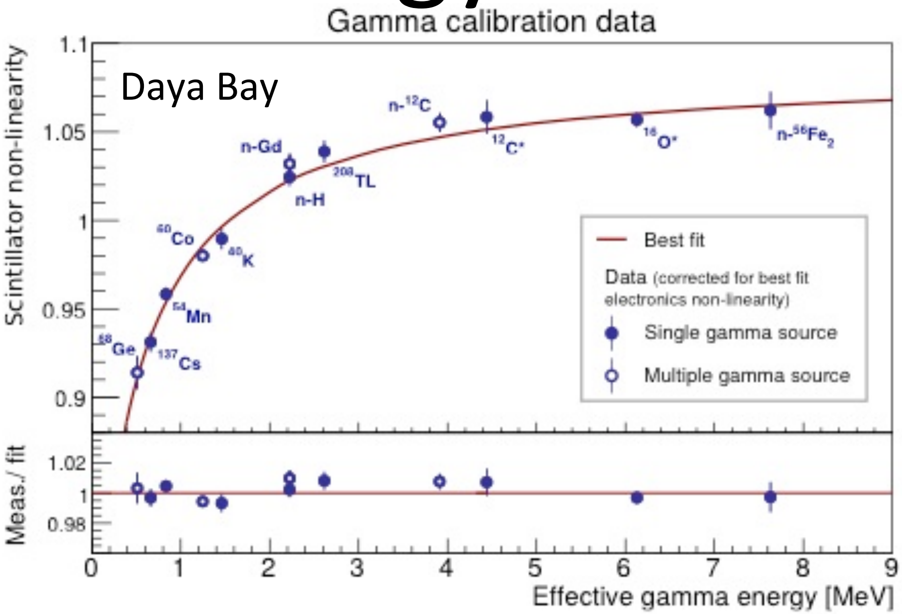
- Daya Bay Automatic Calibration Unit (ACU)
  - 3 sources for each 3 z axis on a turntable
  - ^{68}Ge, ^{41}Am^{13}C, ^{60}Co
  - LED diffuser ball
- Temporary special calibration sources
  - ^{137}Cs, ^{54}Mn, ^{241}Am^{9}Be, ^{239}Pu^{13}C
- Natural spallation neutrons
  - n-Gd, n-H, n-C capture
- Manual 4π calibration system

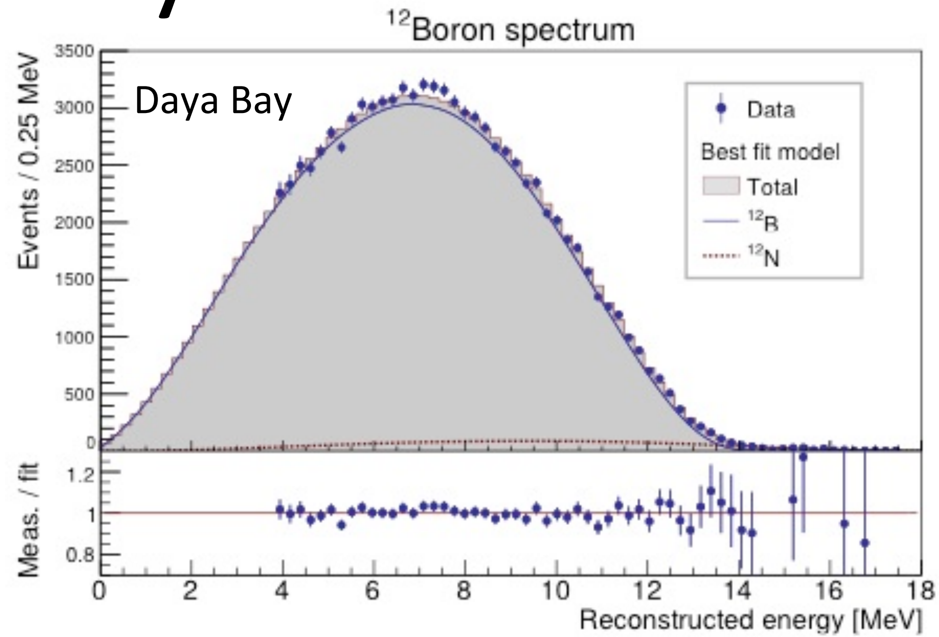


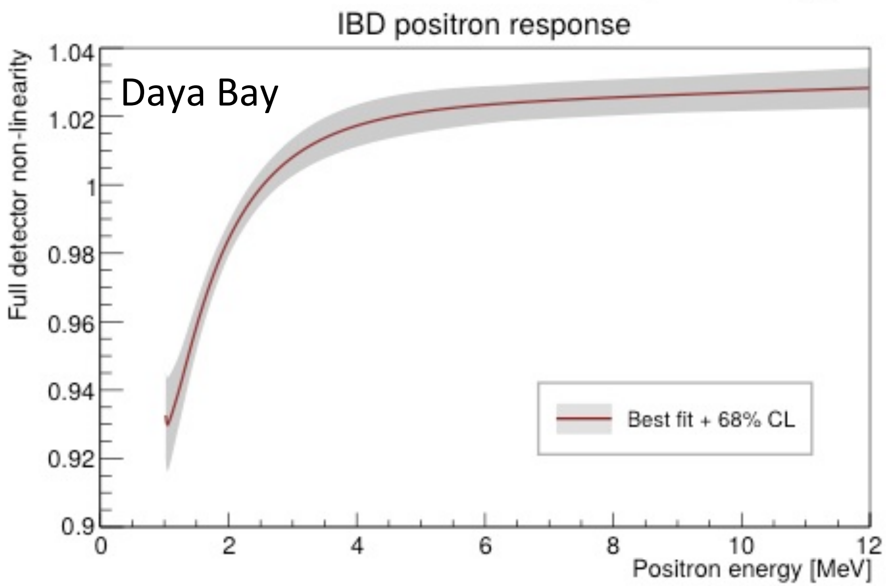


$\sigma_E/E \sim 9\%/\sqrt{E}$ (MeV)

Energy Nonlinearity Calibration



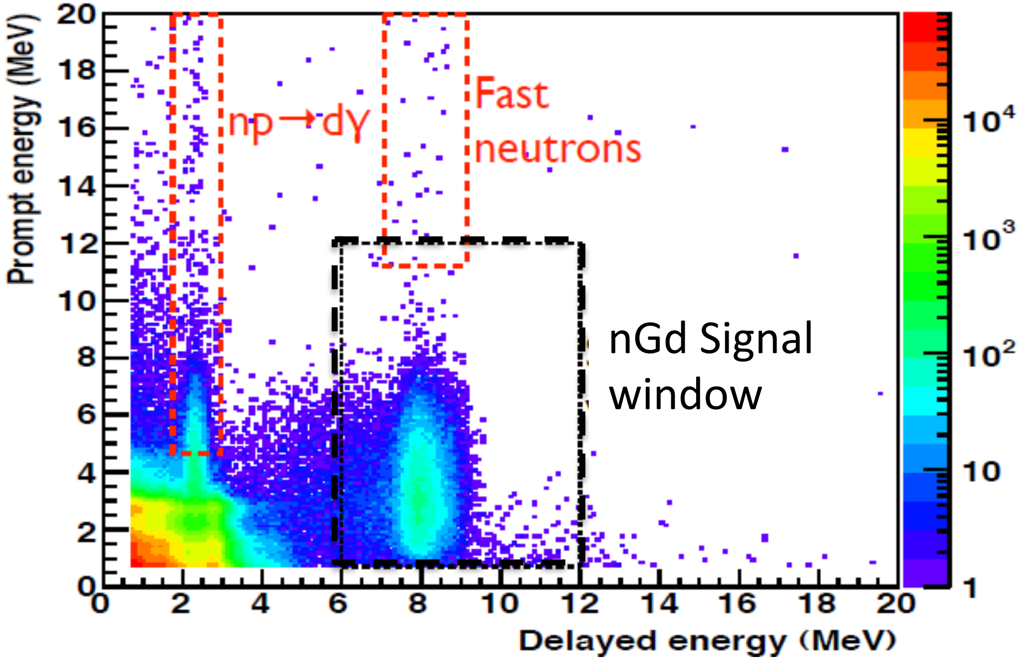


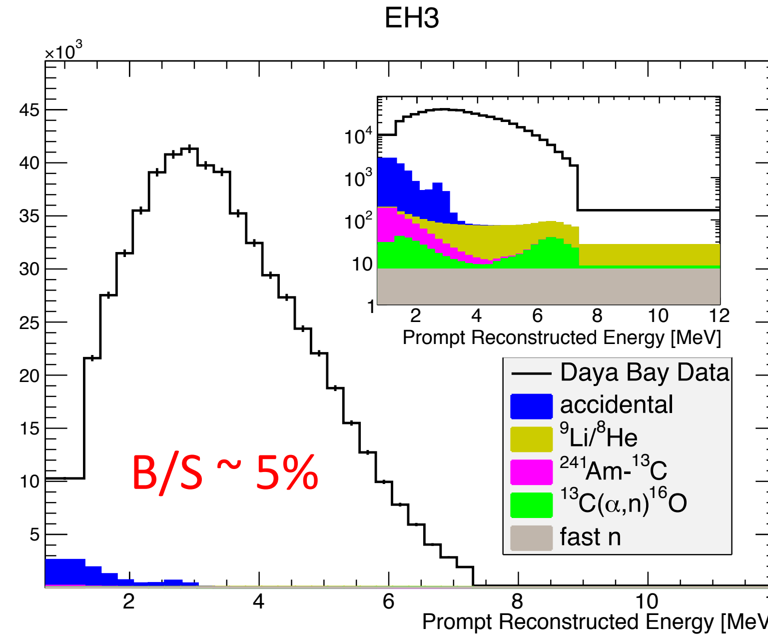


- Two major sources of energy non-linearity:
  - Scintillator response
  - Readout electronics
- Energy model is constrained with gamma and electron sources.

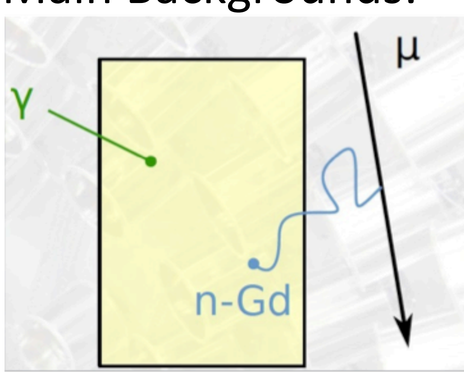
~1% uncertainty (correlated among detectors)

Coincidence IBD selection

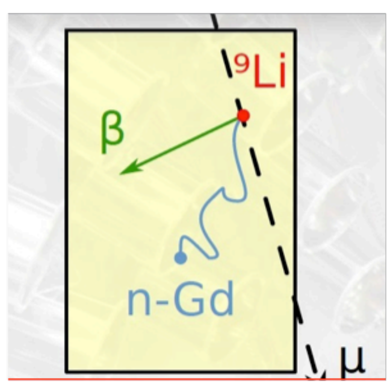




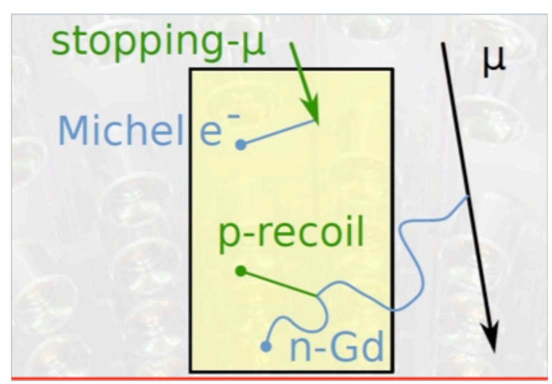
Main Backgrounds:



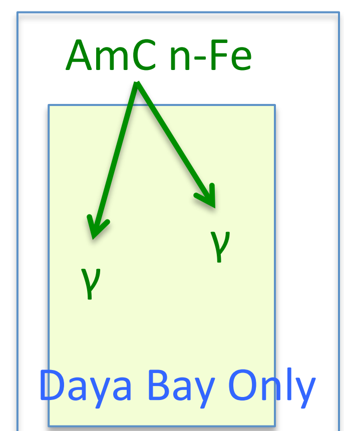
Accidental



β-n isotope



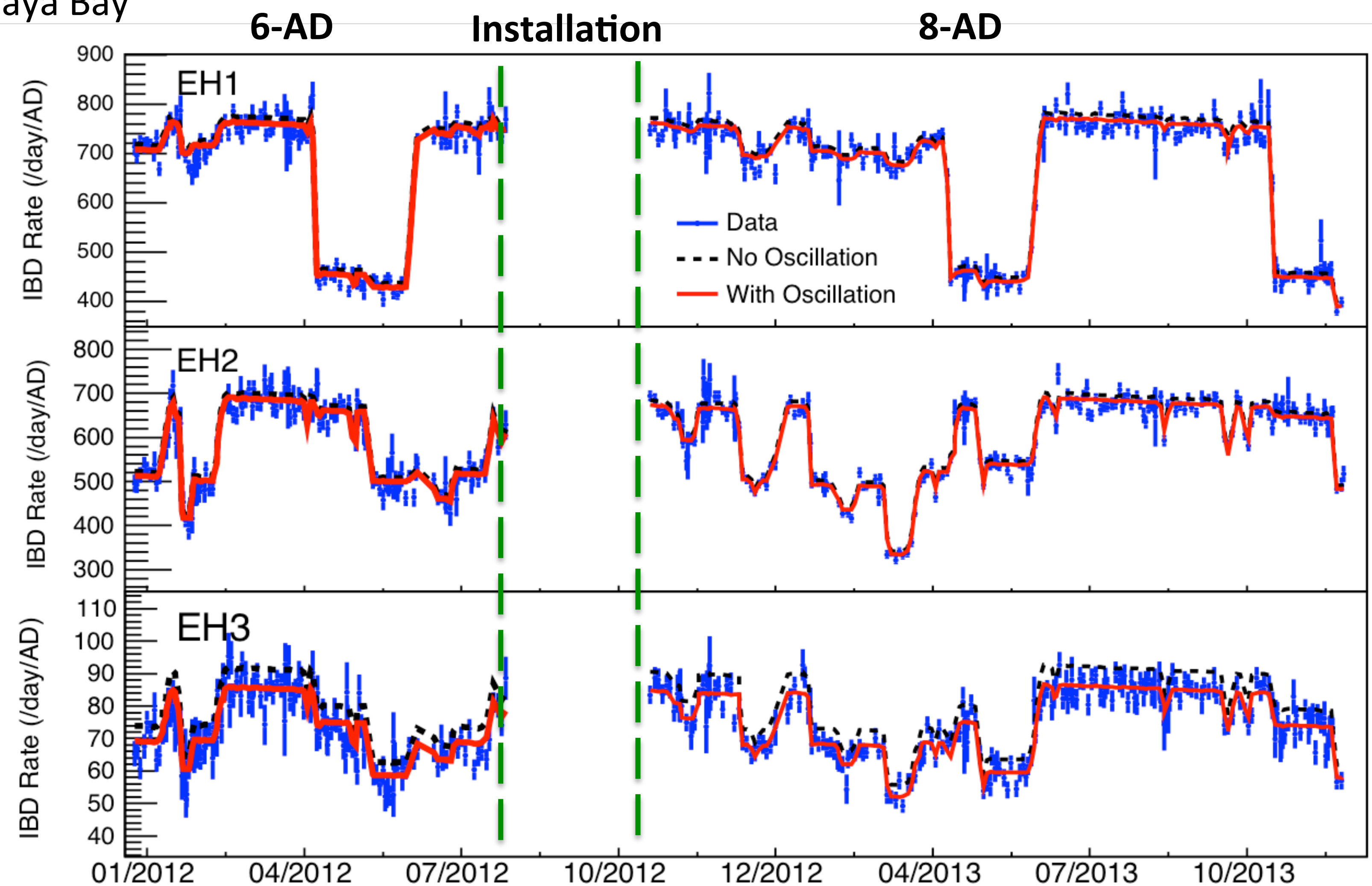
Fast neutron



neutron source

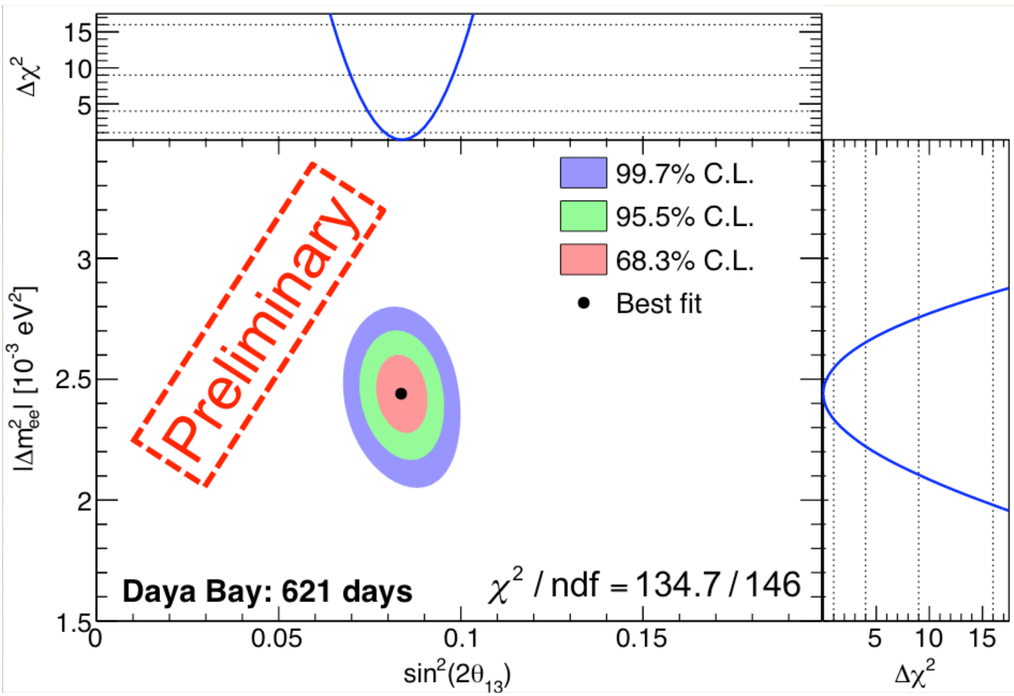
Antineutrino rate vs. Time

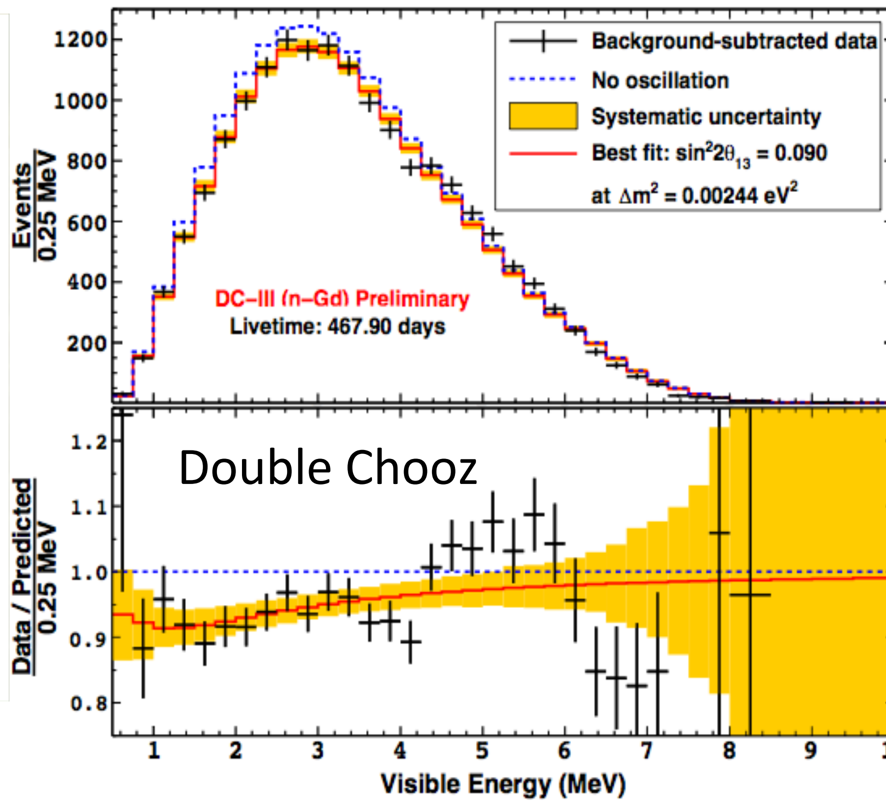
Daya Bay



IBD rate is strongly correlated with reactor flux expectations.

Spectra oscillation Analysis





Daya Bay (Neutrino 2014):

$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3} (eV^2)$$

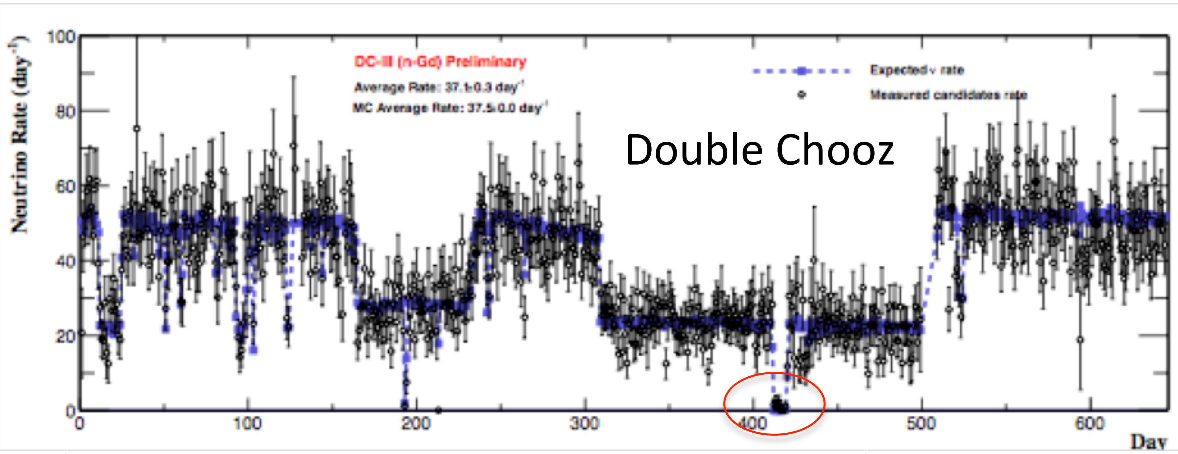
Most precise measurement of ϑ13!

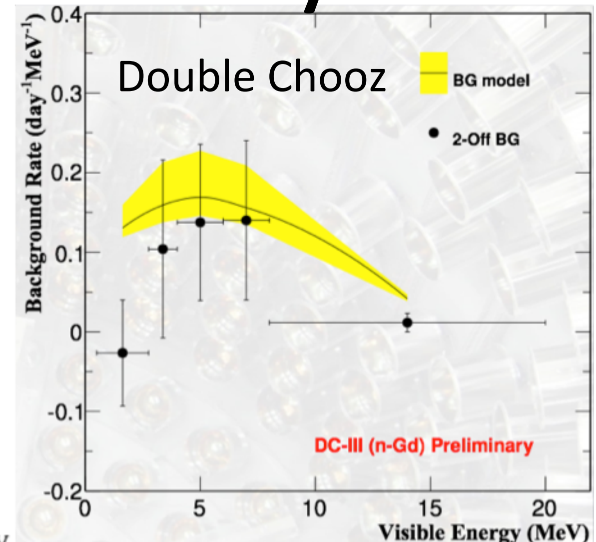
Double Chooz (arXiv:1406.7763):

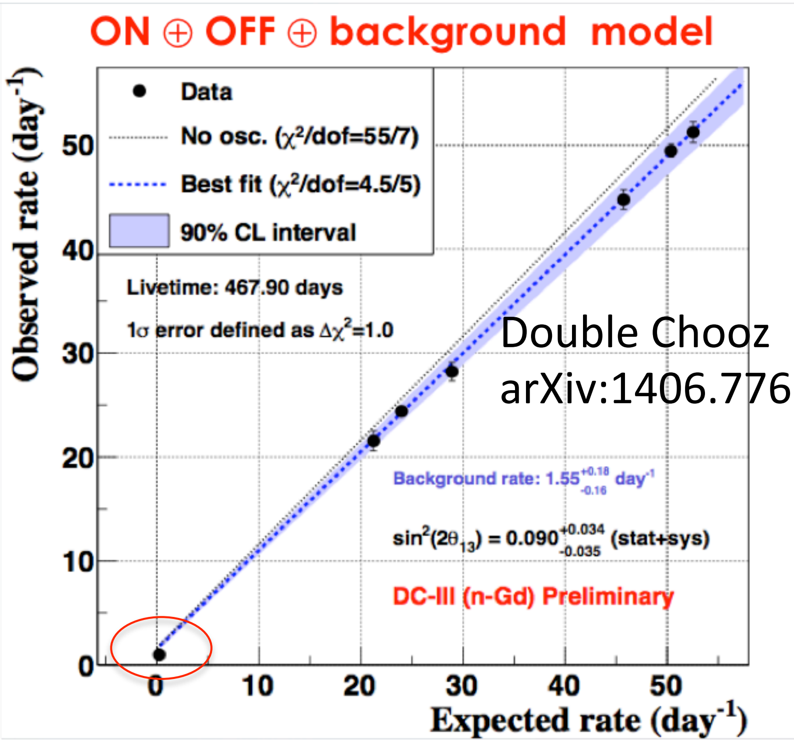
$$\sin^2 2\theta_{13} = 0.09 \pm 0.03 \quad (3\sigma)$$

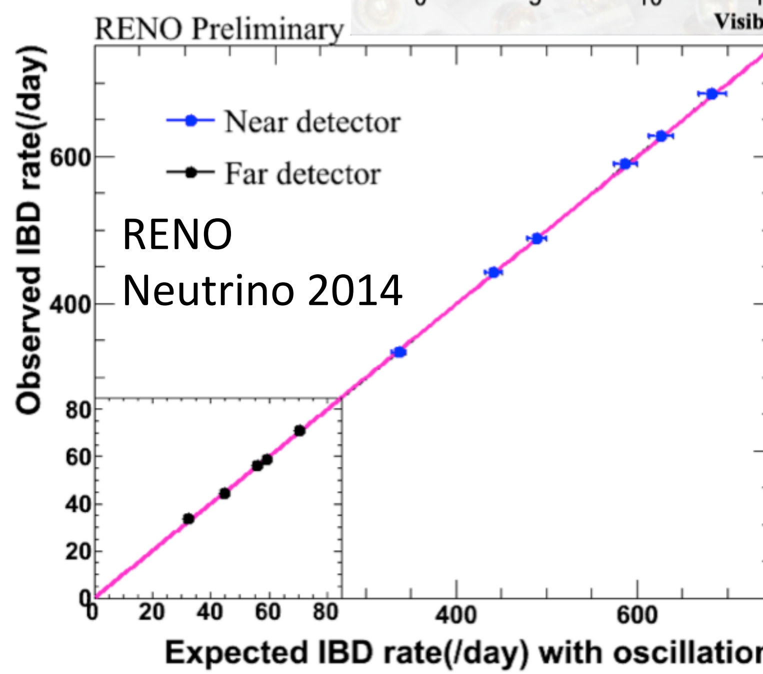
$|\Delta m^2_{ee}| \sim |\Delta m^2_{32}| \sim |\Delta m^2_{32}|$

Reactor Rate Modulation Analysis









$\sin^2 2\theta_{13}$ = 0.090± 0.034(5)

Rate Only: $\sin^2 2\theta_{13}$ = 0.101± 0.013 (7.8σ)

Validation with nH Analysis

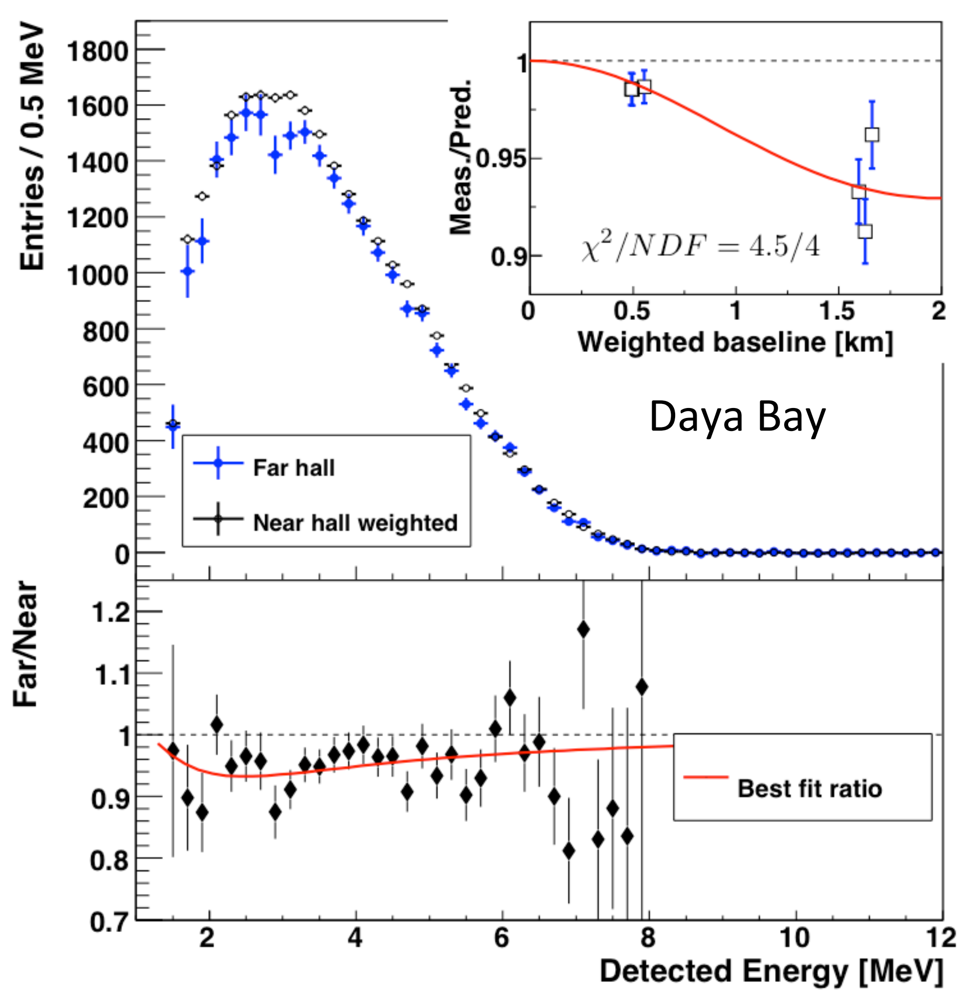
Largely Independent θ_{13} measurement

- Capture time: 30μs (nGd) -> 200μs(nH)
- Delayed E: 8MeV (nGd) -> 2.2 MeV (nH)
- More Energy leakage at boundary

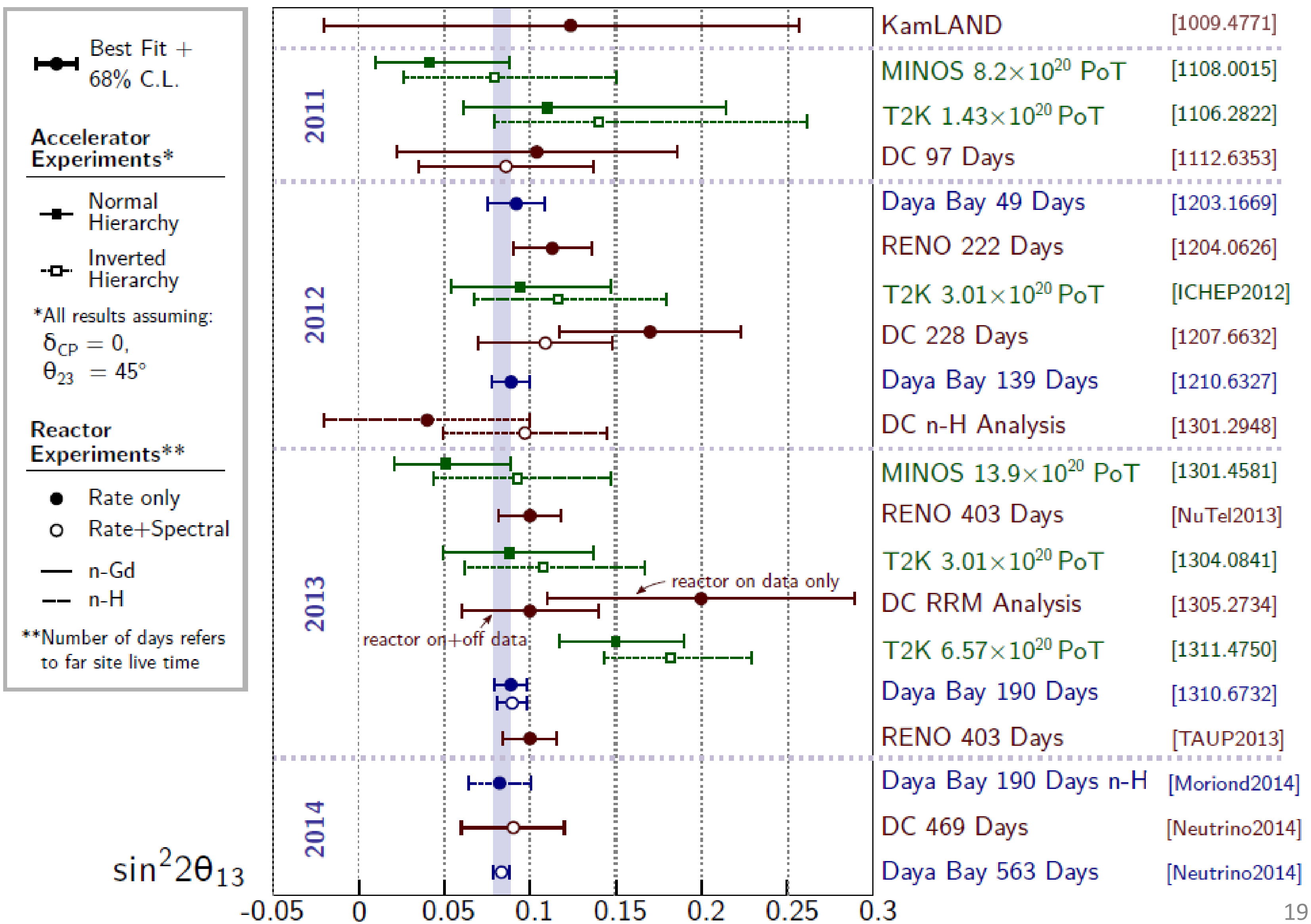
Double Chooz (Rate+Spectra):
$\sin^2 2\theta_{13} = 0.097 \pm 0.034(\text{stat}) \pm 0.034\ (\text{syst})$
Phys. Lett. B723 (2013) 66-70

Daya Bay (Rate Only) :
$\sin^2 2\theta_{13} = 0.083 \pm 0.018$
arXiv: 1406.6468

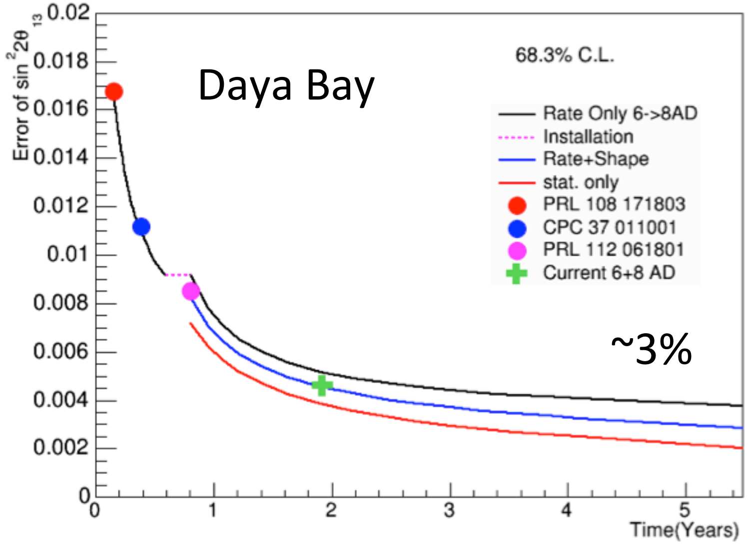
RENO (Rate Only) :
$\sin^2 2\theta_{13} = 0.095 \pm 0.015(\text{stat}) \pm 0.025\ (\text{syst})$
Neutrino 2014

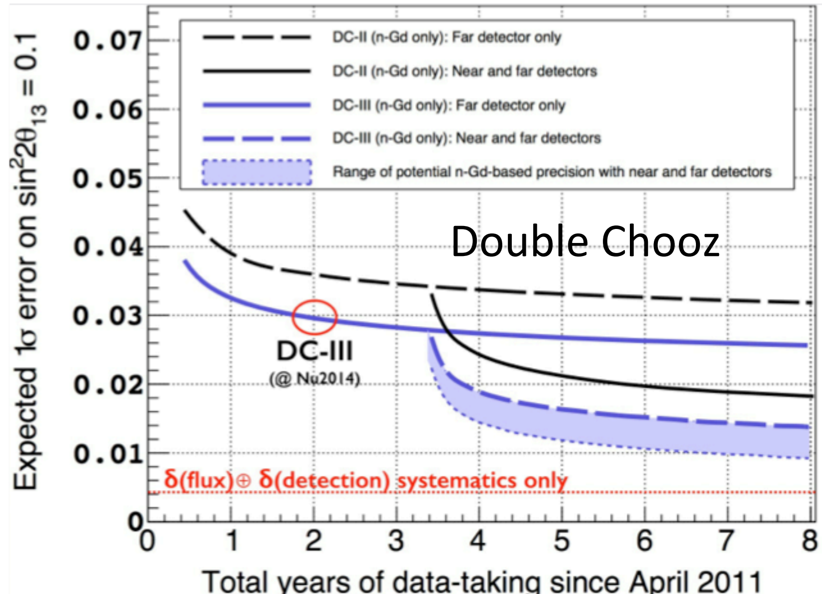


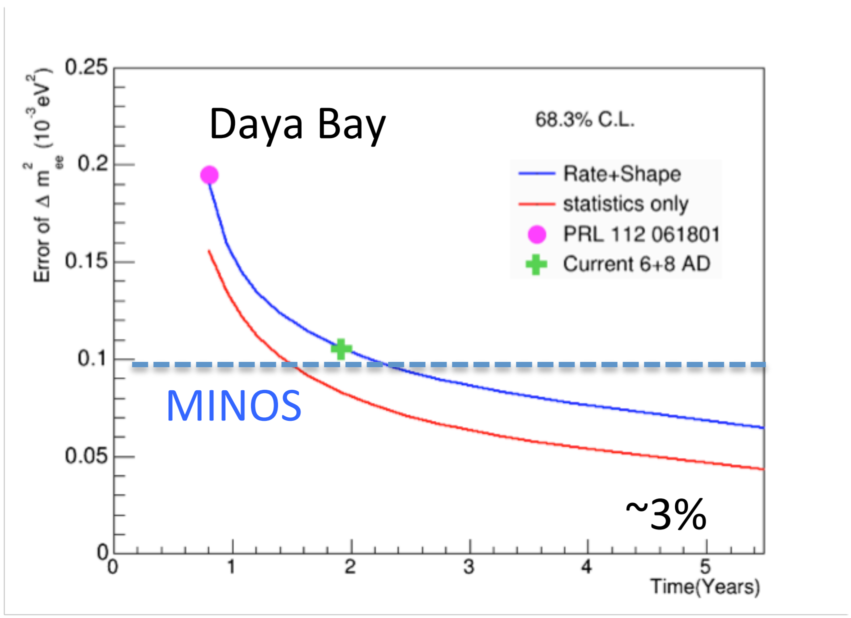
List of Recent θ13 Measurements

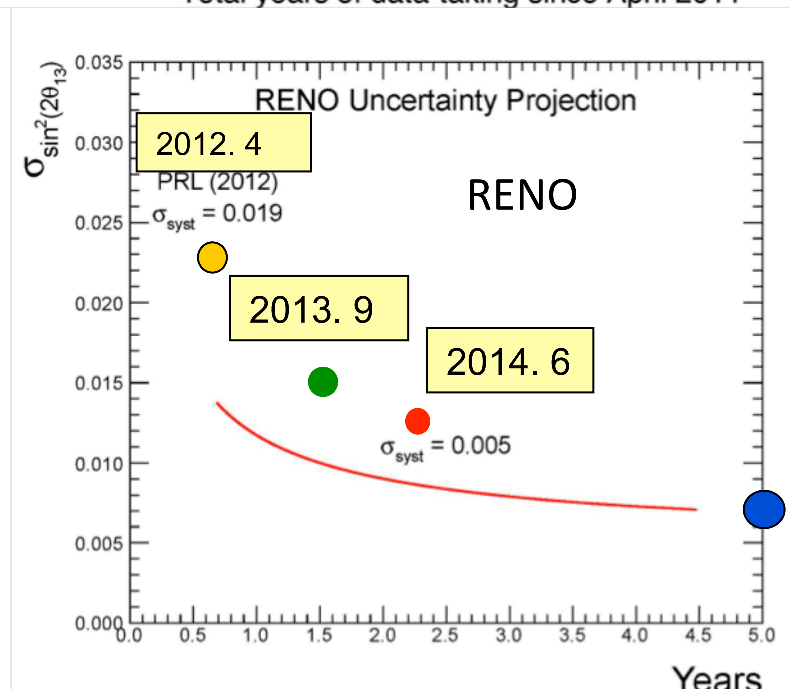


θ_{13} and Δm^2 Sensitivities

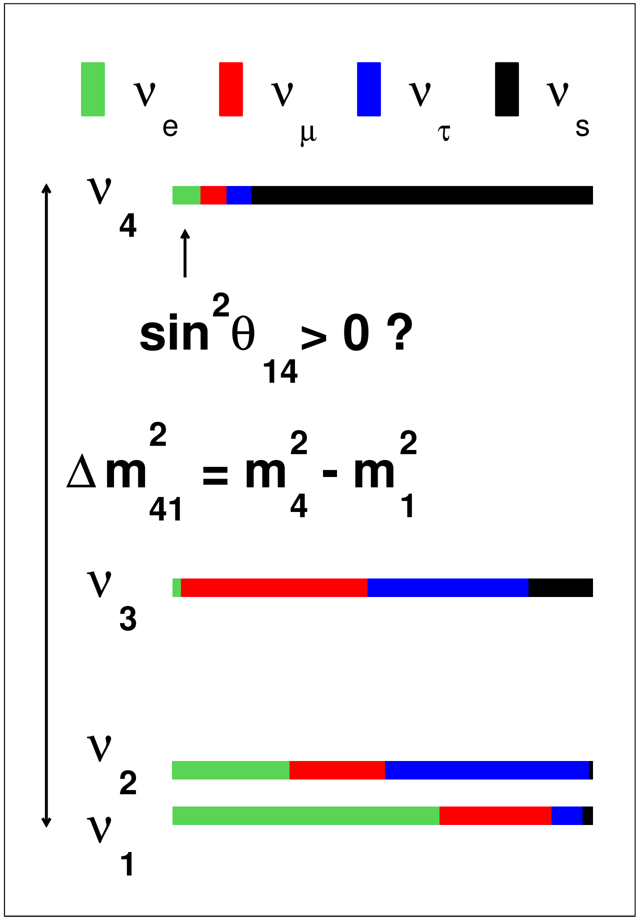


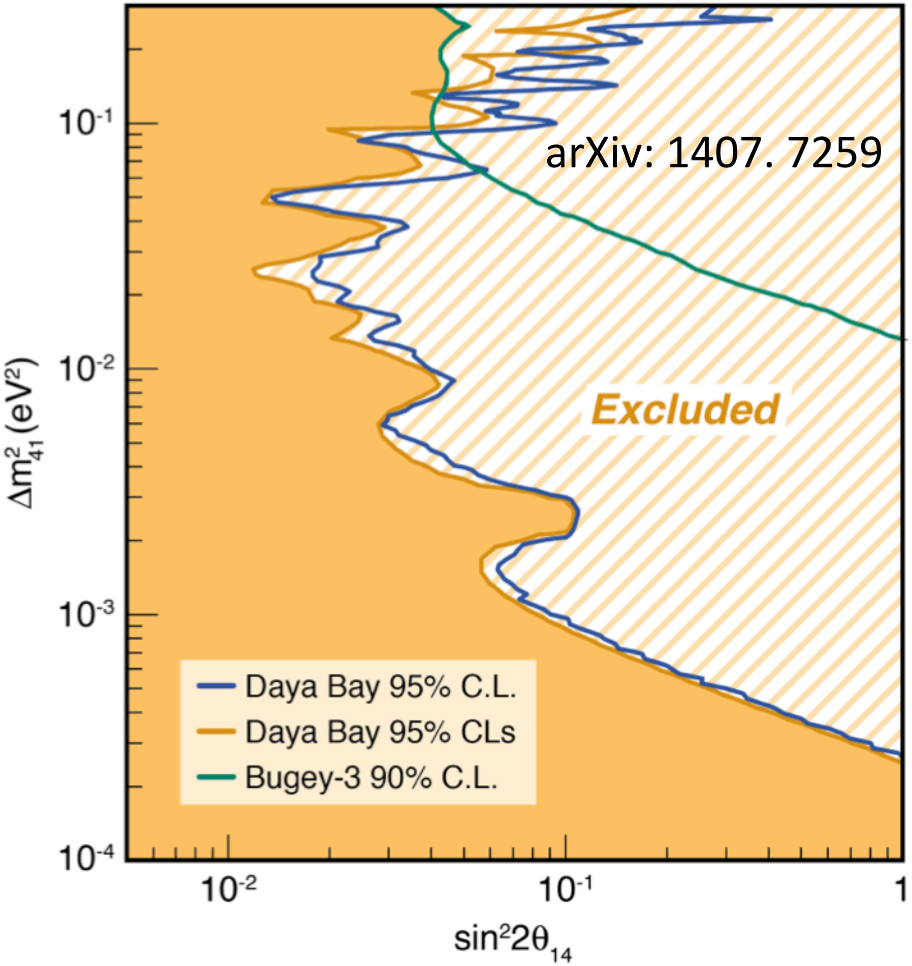






Light Sterile Neutrino Search

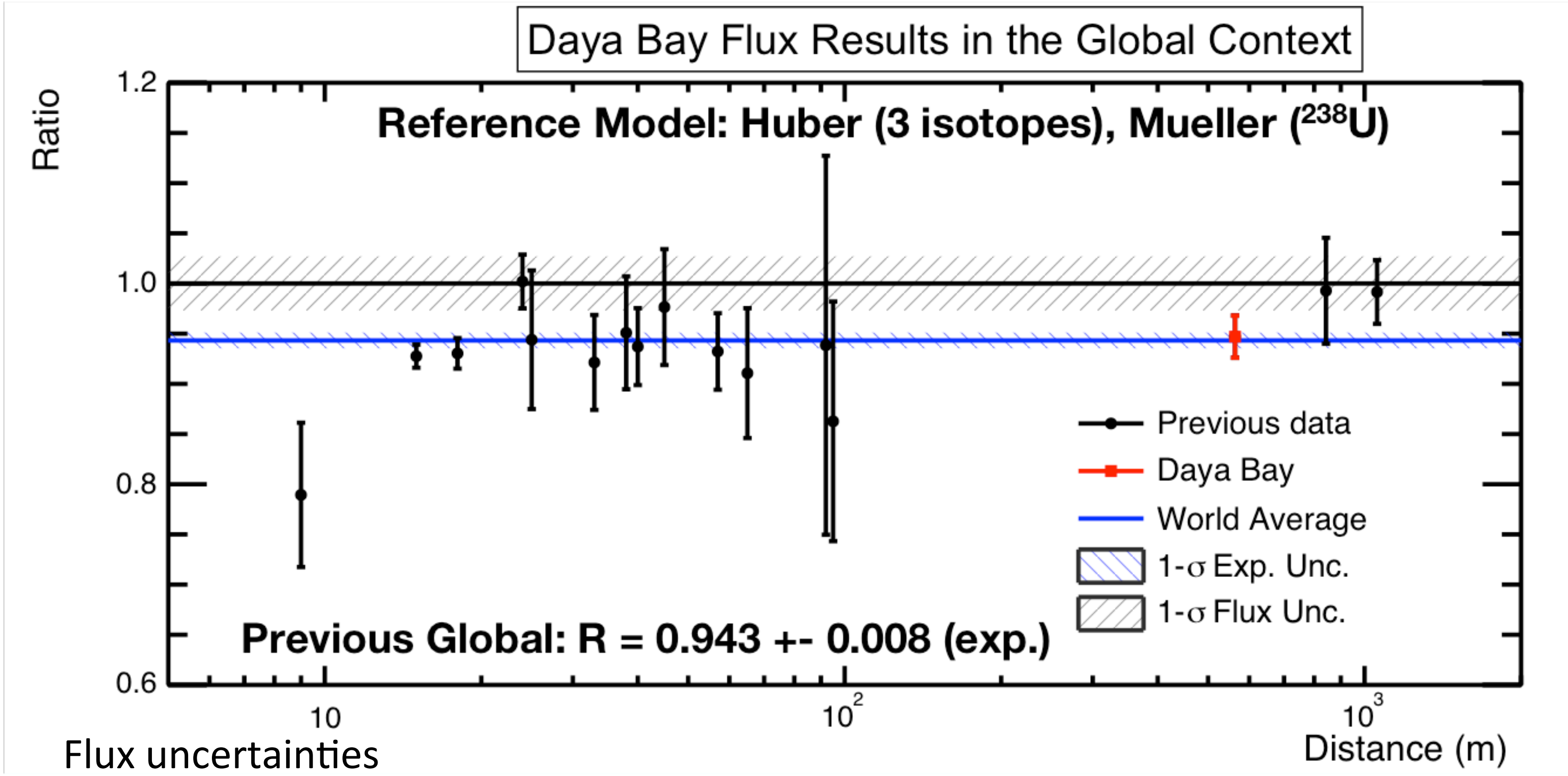




Search for an active light sterile neutrino with 3+1 model

- Search for a higher frequency oscillation pattern besides $|\Delta m^2_{31}|$
- Excluded a large region of sterile neutrino with $|\Delta m^2_{41}| < 0.3 eV^2$

Absolute Reactor Antineutrino Flux



Flux uncertainties

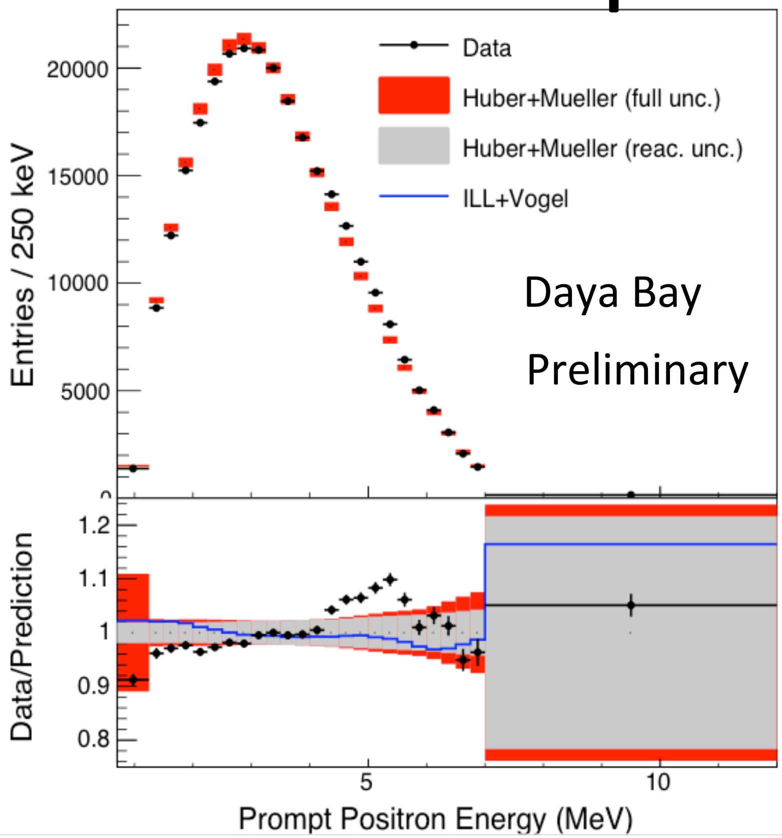
Detector related	2.1%
Reactor related	0.8%
θ_{13}	0.2%
Statistics	0.2%
Total	**2.3%**

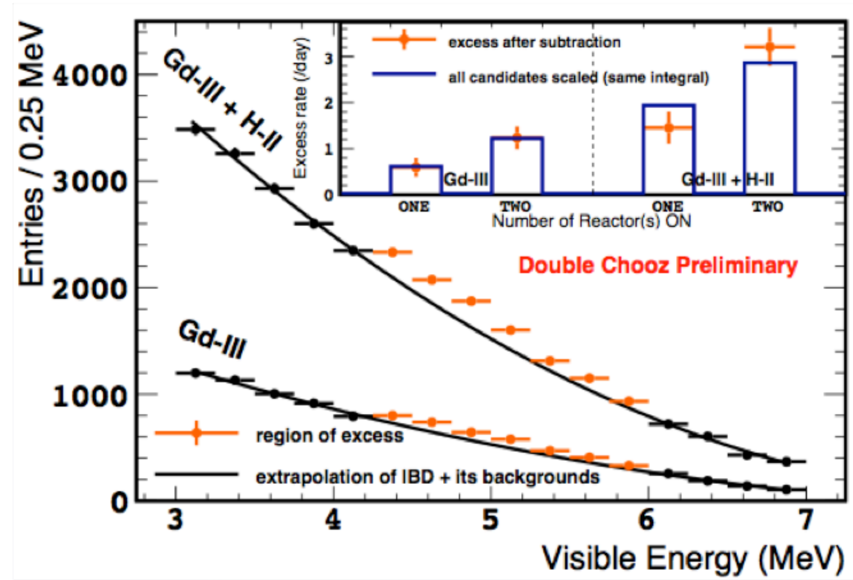
Data/Prediction (Huber+Mueller)

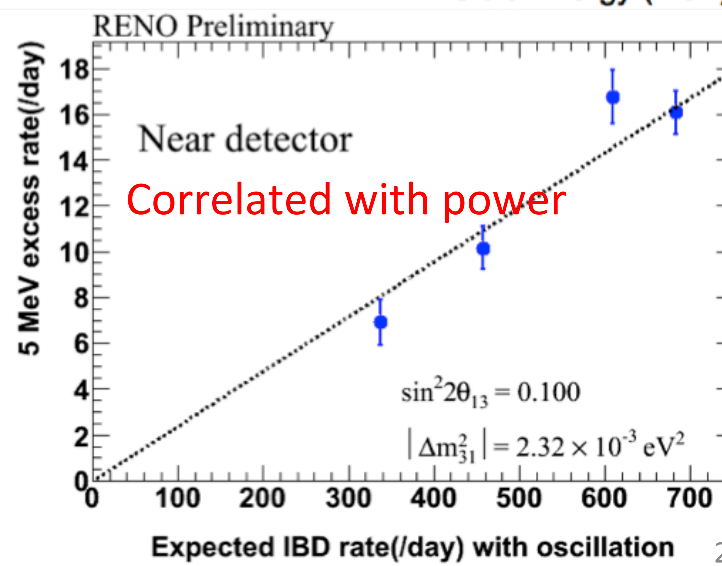
R = 0.947 ± 0.022

Daya Bay's reactor flux measurement is consistent with previous short baseline experiments.

Neutrino Spectrum Comparison



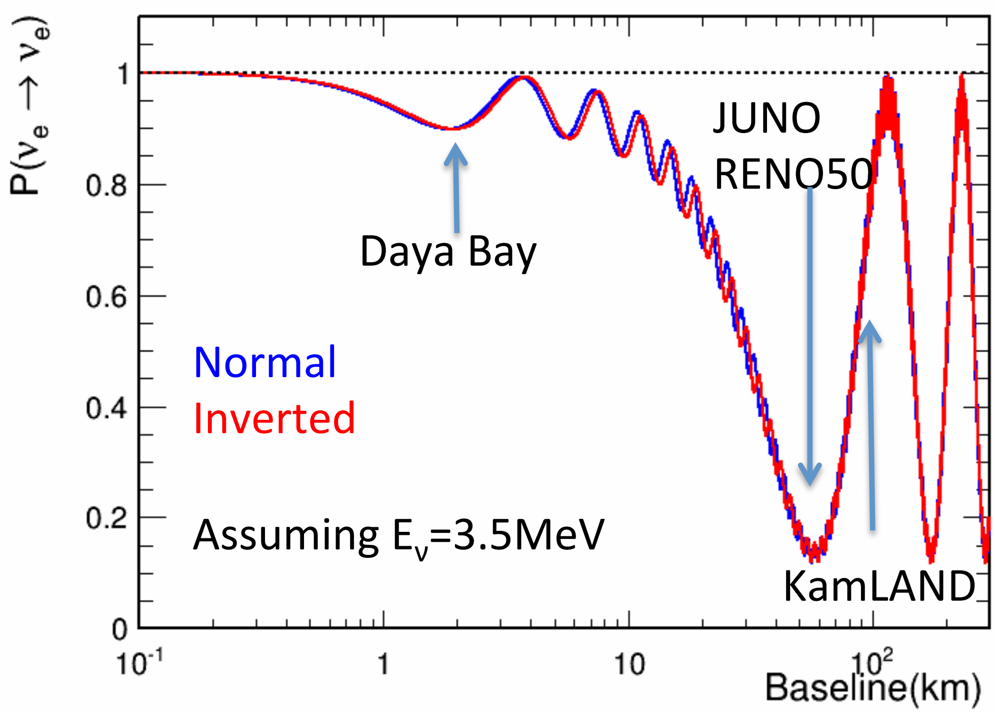


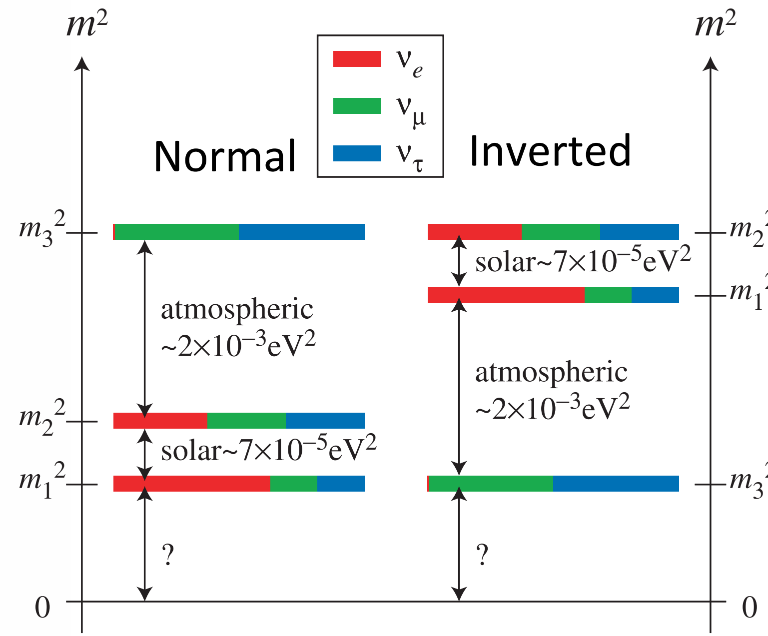


- Data/prediction shows a significant deviation at 4-6 MeV region (3.9σ)
- Recent *ab initio* calculation provides a possible explanation involving decays from some prominent fission daughter isotopes. (arXiv:1407.1281)

Next Generation Reactor Neutrino Experiments: JUNO and RENO50

Thanks to the "large" ϑ_{13}





Normal : $|\Delta m^2_{31}| = |\Delta m^2_{32}| + \Delta m^2_{21}$

Inverted: $|\Delta m^2_{31}| = |\Delta m^2_{32}| - \Delta m^2_{21}$

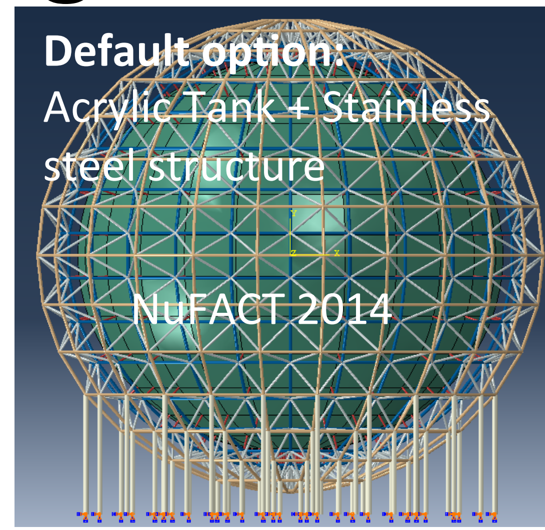
$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\boxed{\sin^2(\Delta_{31})} \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\boxed{\sin^2(\Delta_{32})}
\end{aligned}
$$

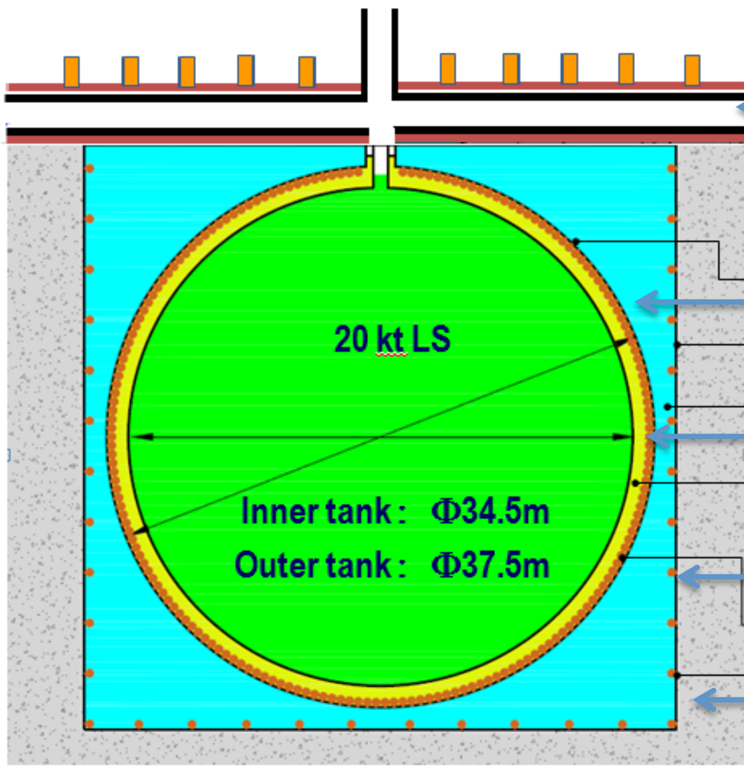
JUNO and RENO50

- 20 kton LS detector
- 53 km baseline
- <3% energy resolution

JUNO Detector Design

	KamLAND	JUNO
LS mass	1kt	20kt
Energy resolution	6%/√E	3%/√E
Light yield	250 P.E./MeV	1200 P.E./MeV
PMT coverage	34%	80%





Muon veto
(Opera target tracker)

Water System

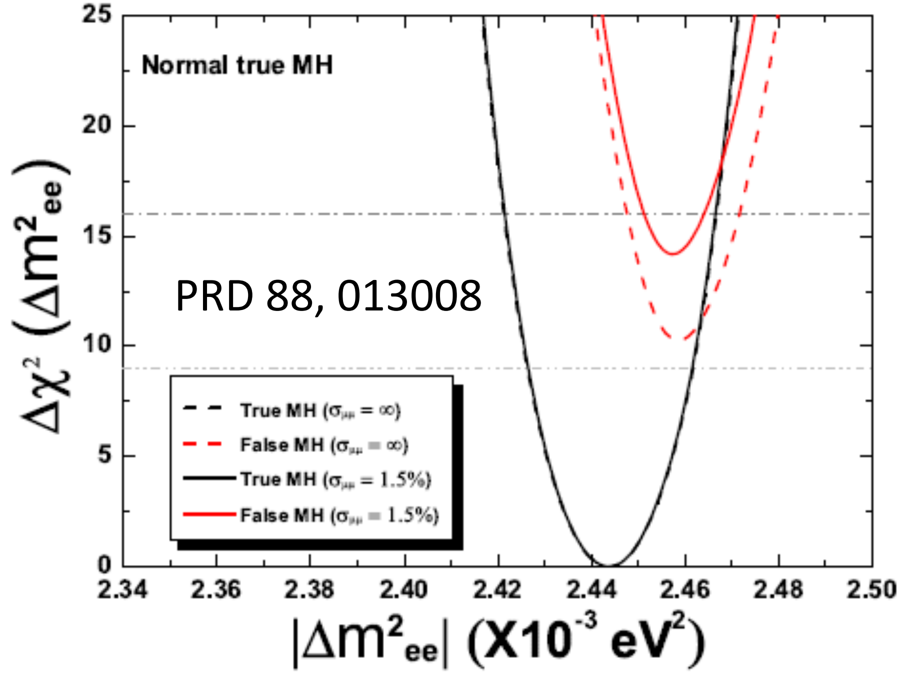
15000 20” PMT

2000 20” Veto PMT

Magnet shielding

JUNO Sensitivity

- With 6 years of data taking, assuming 3% energy resolution, 2% energy nonlinearity assuming known curve shape and with external T2K/NovA $\Delta m^2_{\mu\mu}$ of 1.5%, JUNO can achieve $\Delta\chi^2=14$



Precision measurement

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

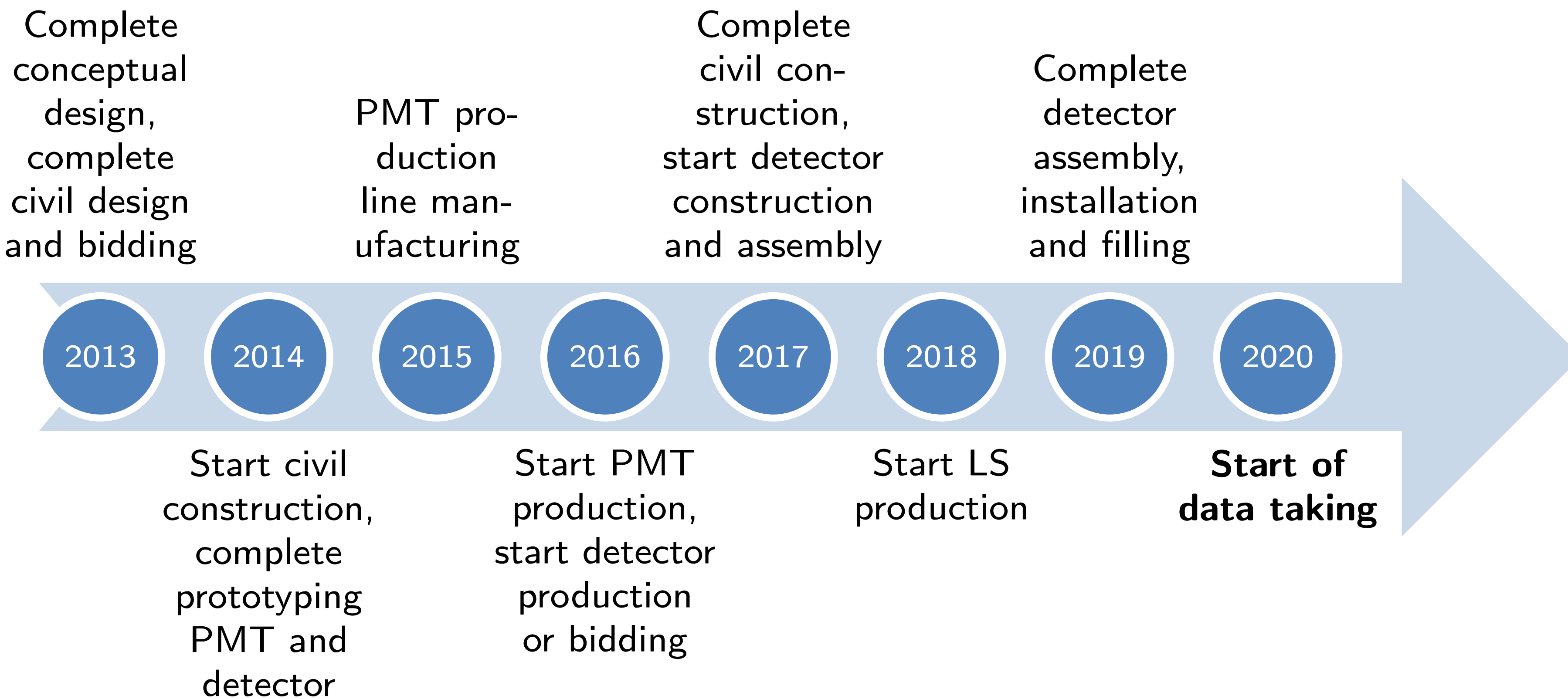
- Sub-percent precision measurement of oscillation parameters

Summary

- Recent reactor neutrino experiments have successfully discovered the "large" value of $\theta_{13} \sim 8.4°$.
  - Neutrino physics has entered a precision era.
- Rapid progress has been made for the precision measurement of oscillation parameters and neutrino spectrum.
  - The ultimate precision on $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ can reach ~3% by Daya Bay in 2017.
  - Precision measurement of the neutrino spectrum will also help future reactor neutrino experiments.
- Next generation of reactor neutrino experiments (JUNO and RENO50) are focusing on solving neutrino mass hierarchy and precision measurement of neutrino mixing matrix in next decade.
- Stay tuned with reactor neutrino experiments.

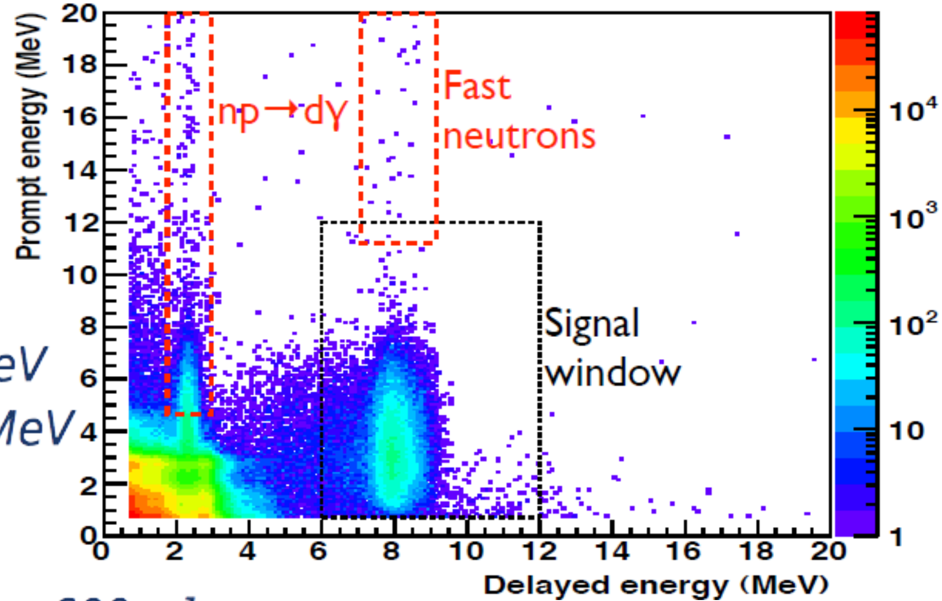
Backup slides

JUNO Schedule



Antineutrino (IBD) selection

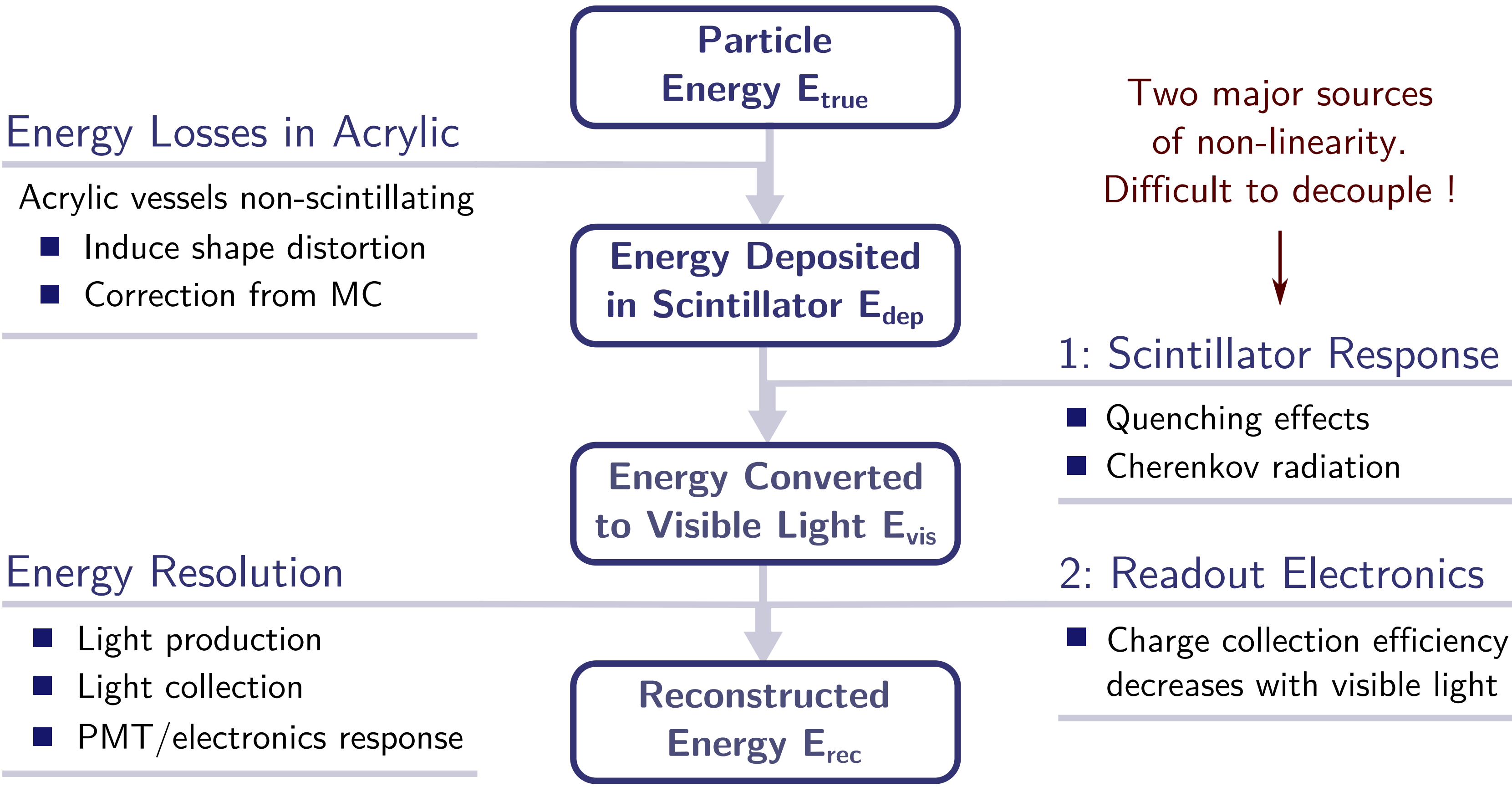
Coincidence IBD selection



Selection:

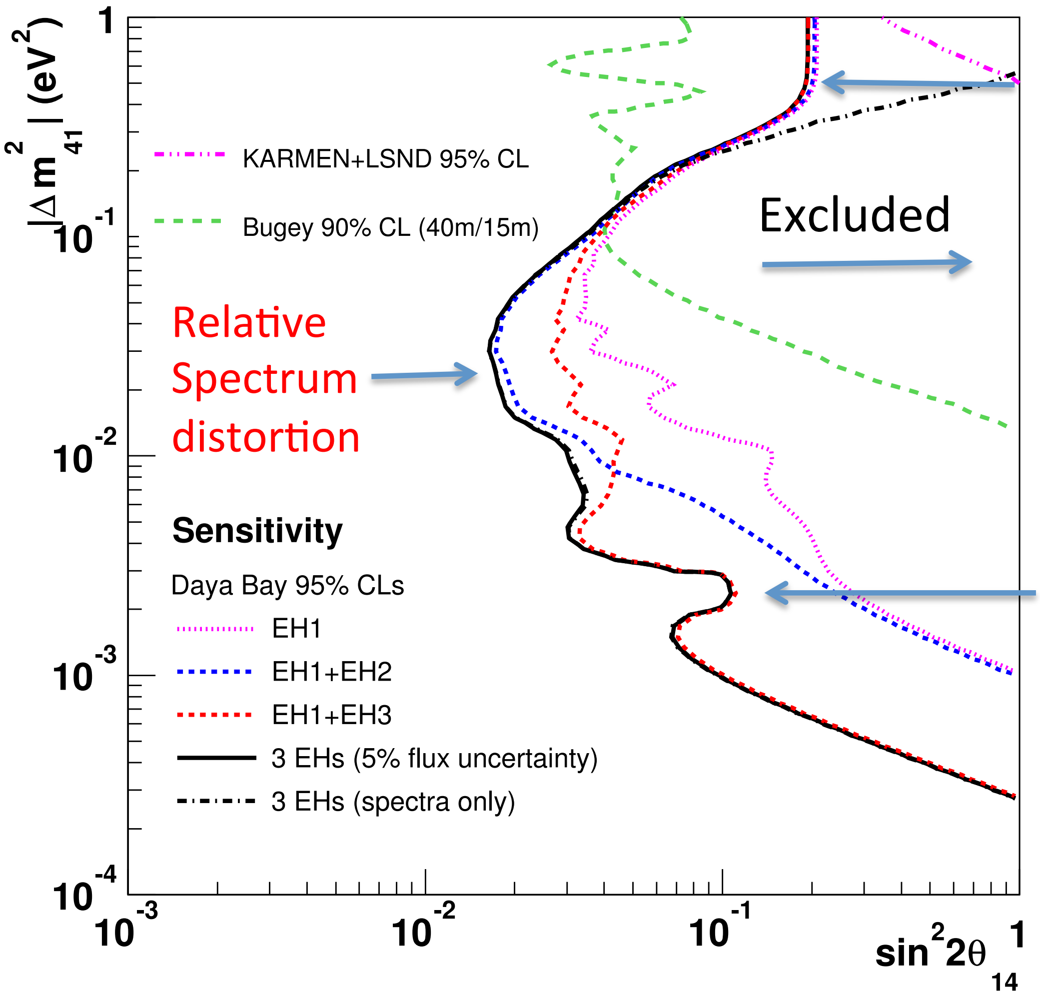
- Reject PMT Flashers
- Prompt Positron: *0.7 MeV < Ep < 12 MeV*
- Delayed Neutron: *6.0 MeV < Ed < 12 MeV*
- Capture time: *1 μs < Δt < 200 μs*
- Muon Veto for delay neutron:
  - Water Pool Muon (nHit>12): *Reject [-2μs, 600μs]*
  - AD Muon (>3000PE): *Reject [-2μs, 1400μs]*
  - AD Shower Muon (>3 x 10^5 PE): *Reject [-2μs, 0.4s]*
- Multiplicity:
  No additional prompt-like signal in 400μs before the delayed signal, and no delayed-like signal in 200μs after the delayed signal

Overview of the Energy Response Model



Model maps true energy E_{true} to reconstructed kinetic energy E_{rec}

6-AD Light Sterile Neutrino Sensitivity



Absolute rate deficit

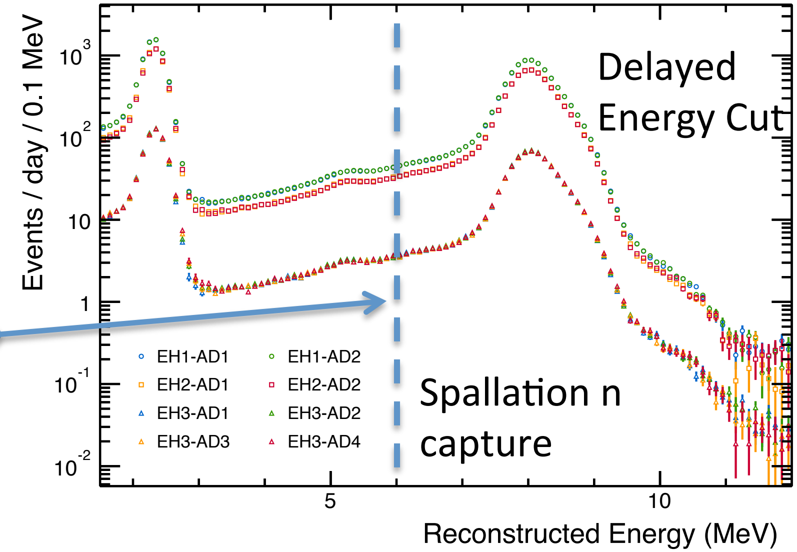
- Multiple baseline of Daya Bay Experimental Halls
- Can probe largely unexplored region at $|\Delta m^2_{41}| < 0.1$ eV^2

$|\Delta m^2_{41}|=|\Delta m^2_{31}|$. Degeneracy region of $\sin^2 2\theta_{14}$ and $\sin^2 2\theta_{13}$

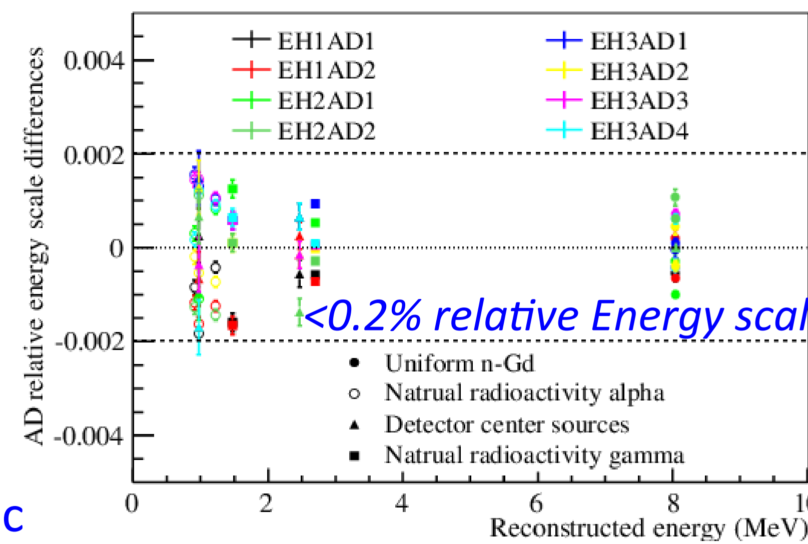
Assuming $\sin^2 2\theta_{13} = 0.089$ and $\sin^2 2\theta_{14}=0$, W/O stat. or syst. fluctuation

Summary of systematics

Detector			
	Efficiency	Uncertainty	
		Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed Energy cut	92.7%	0.97%	0.12%
Prompt Energy cut	99.81%	0.10%	0.01%
Capture time cut	98.70%	0.12%	0.01%
Gd capture ratio	84.2%	0.95%	0.10%
Spill-in correction	104.9%	1.50%	0.02%
Combined	80.6%	2.1%	0.2%

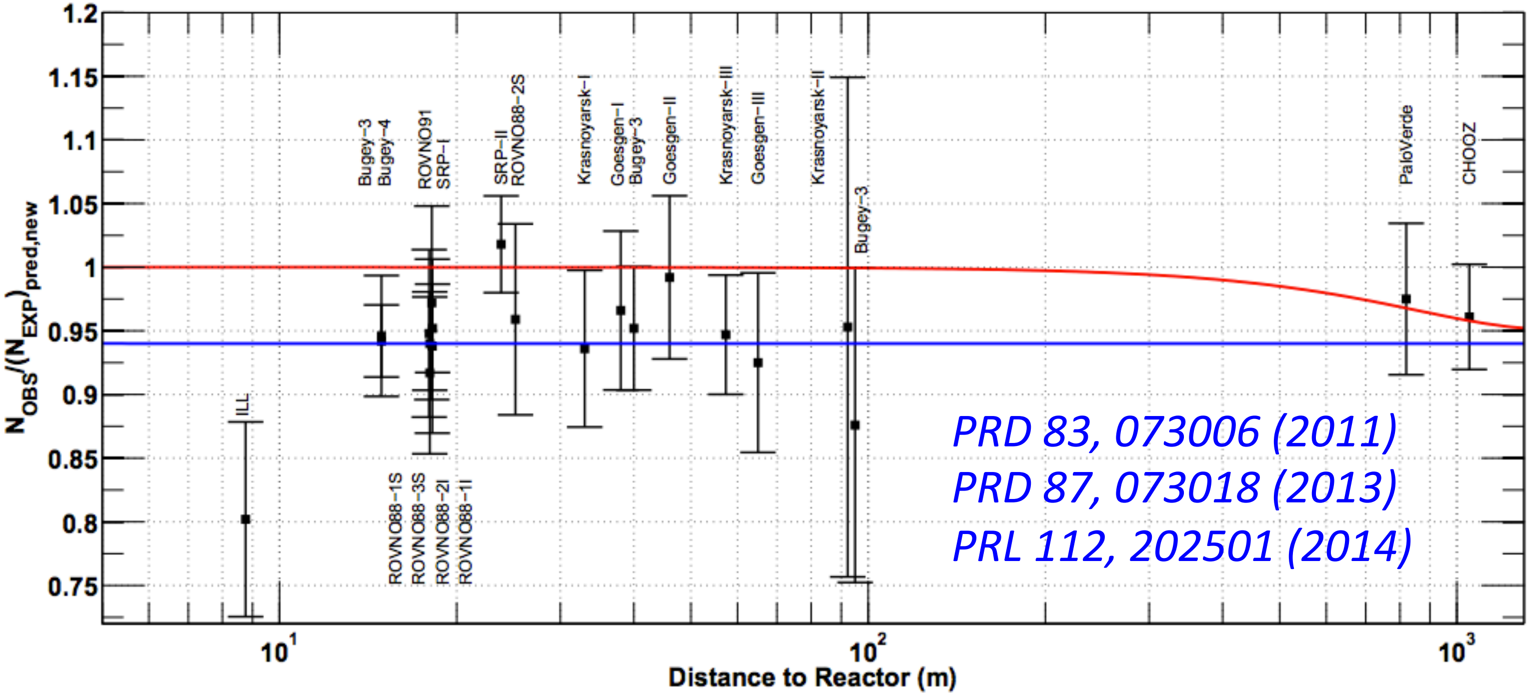


Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%



Relative uncertainty is still smaller than statistic uncertainty at Far Site (0.26%)

"Reactor Anomaly"



- New reactor antineutrino flux increased 3% relative to the previous calculation
- Neutron lifetime becomes smaller -> IBD xsec increased 3%
- R = 0.943 ± 0.023