Results and Prospects of Reactor Neutrino Experiments

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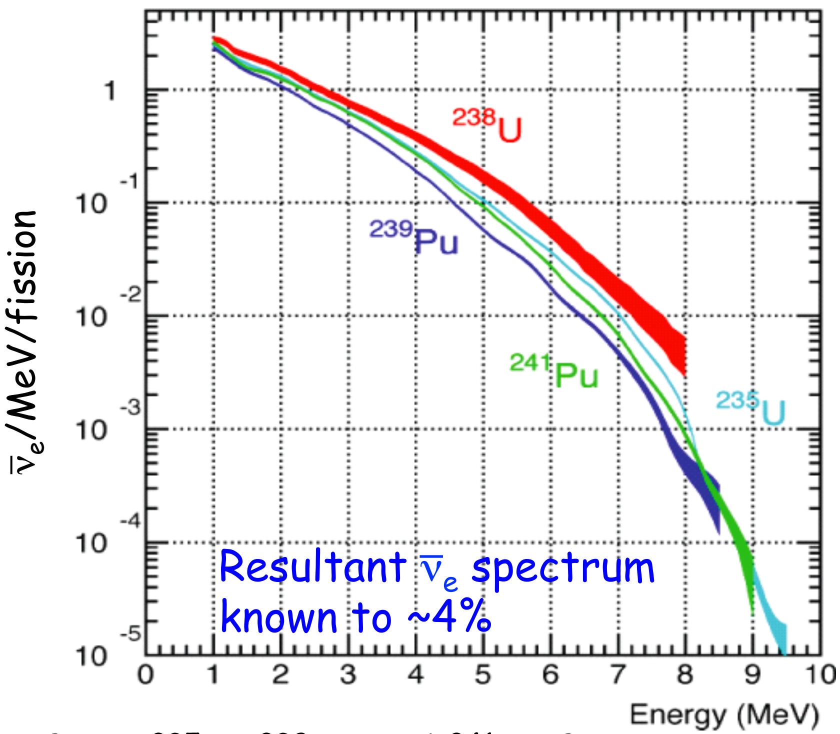
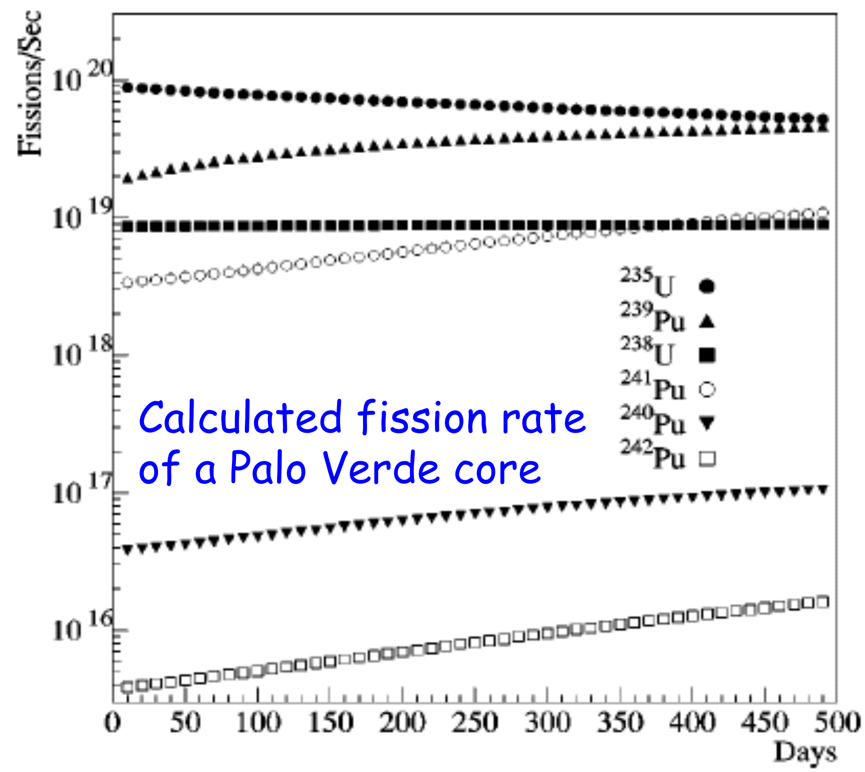
Yield And Energy Spectrum Of Reactor $\overline{\nu}_e$

- Fission processes in nuclear reactors produce a huge number of low-energy $\overline{\nu}_e$:

3 GW_{th} generates 6×10^{20} $\overline{\nu}_e$ per sec

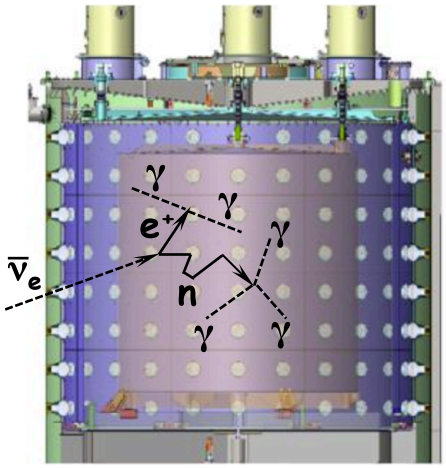




- $\overline{\nu}_e$ from ^{235}U, ^{239}U, and ^{241}Pu fission:
  - measure β spectrum using thermal neutron induced fission on the isotope
  - convert β spectrum to $\overline{\nu}_e$ spectrum
- $\overline{\nu}_e$ from ^{238}U fission:
  - $\overline{\nu}_e$ spectrum based on calculation & a measurement

- Uncertainty in $\overline{\nu}_e$ yield, ~2%, due to
  - Thermal power (<1%)
  - Sampling of fuel
  - Analysis of fractions of isotopes in samples

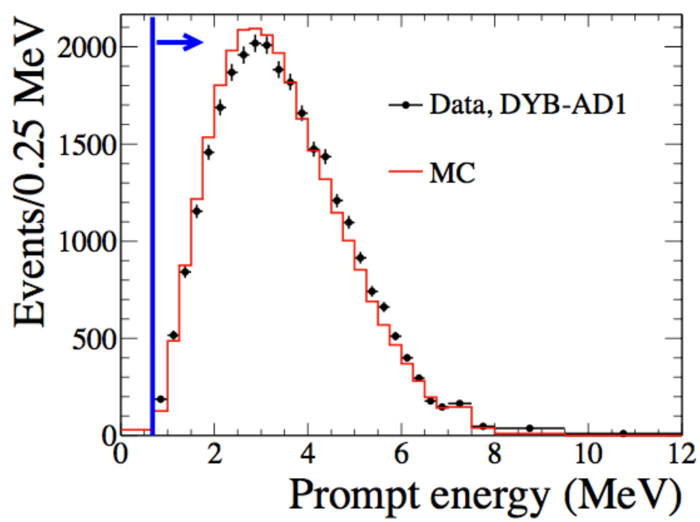
Detecting $\overline{\nu}_e$ With Liquid Scintillator

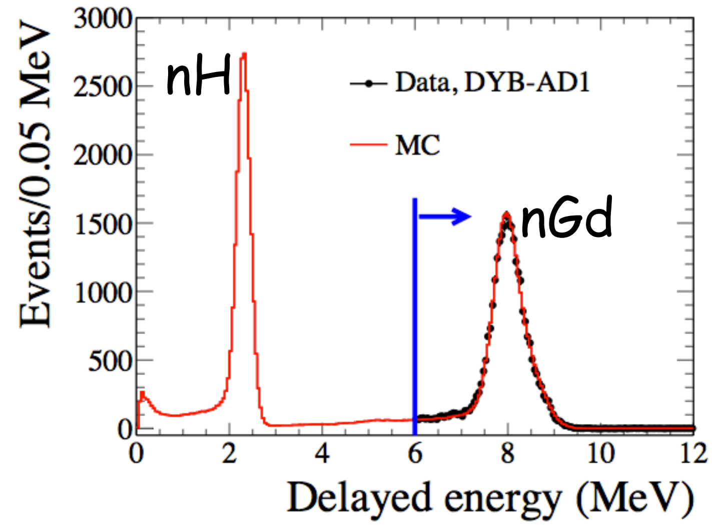


Inverse β-decay reaction in (doped) liquid scintillator:

$\overline{\nu}_e + p \rightarrow e^+ + n$ (prompt)

- 180 μs → $+ p \rightarrow D + \gamma(2.2\ \mathrm{MeV})$ (delayed)
- 30 μs, 0.1% Gd → $+ Gd \rightarrow Gd^*$
  - → $Gd + \gamma\text{'s}(8\ \mathrm{MeV})$ (delayed)



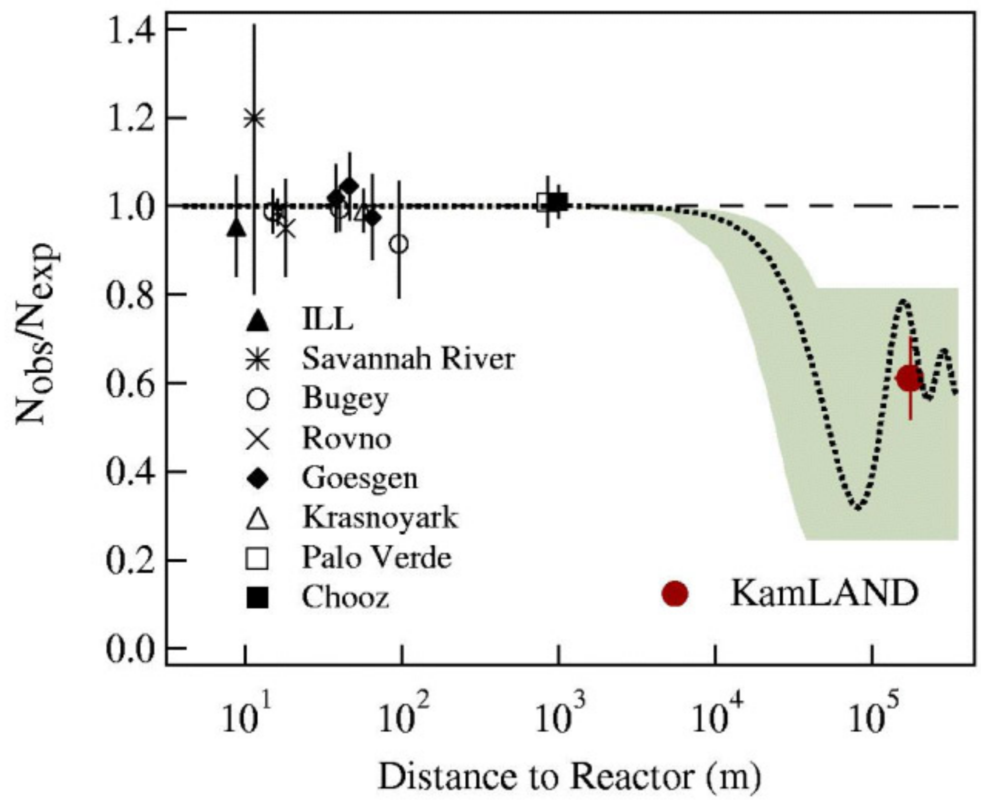


- Time- and energy-tagged signal is a good tool to suppress background.
- Energy of $\overline{\nu}_e$ is given by:

$$E_\nu \approx T_{e+} + T_n + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8\ \mathrm{MeV}$$

Overview

- Reactor anti-neutrino experiments have significant impacts on neutrino physics:
  - First observation of (anti)neutrino in 1956
  - Low-energy antineutrino interaction
    - Look for ν magnetic moment
  - Investigation of neutrino oscillation
    - The first observation of disappearance of $\overline{\nu}_e$
    - Determination of θ_{13}
    - Resolving ν mass hierarchy
    - Search for sterile neutrinos



Neutrino Mixing

Weak eigenstates are not the same as mass eigenstates

Neutrinos have mass → Physics beyond SM ?

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix

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

Weak eigenstates

ν_e ν_μ ν_τ

Described by

θ_{12} θ_{23} θ_{13}

δ

Mass eigenstates

m_1 m_2 m_3

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

$$\Delta m_{31}^2 = \Delta m_{32}^2 + \Delta m_{21}^2$$

Neutrino Oscillation

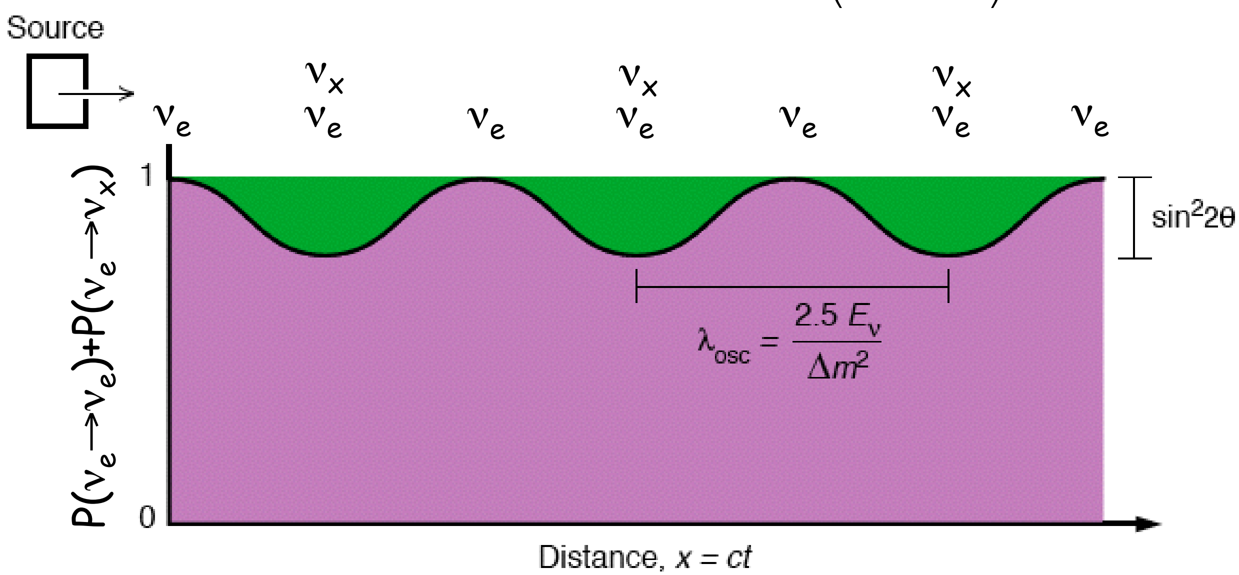
- Factorize the mixing matrix as:

$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

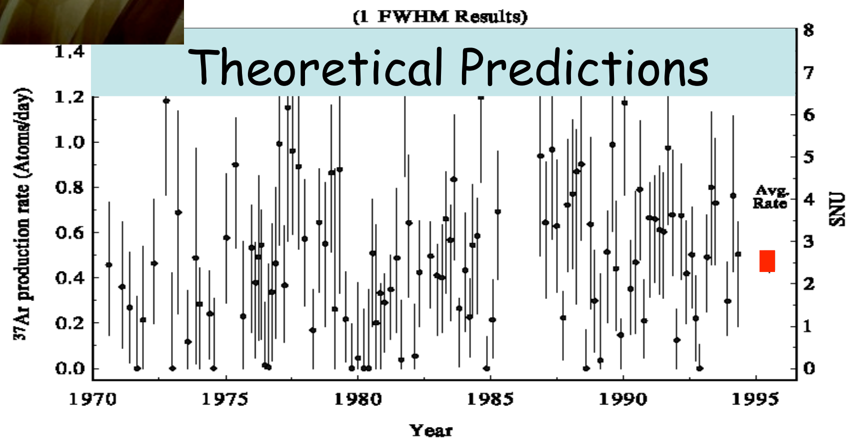
solar ν reactor $\bar{\nu}$	reactor $\bar{\nu}$ accelerator ν	atmospheric ν accelerator ν

- The survival probability of $\nu_e \rightarrow \nu_e$ is:

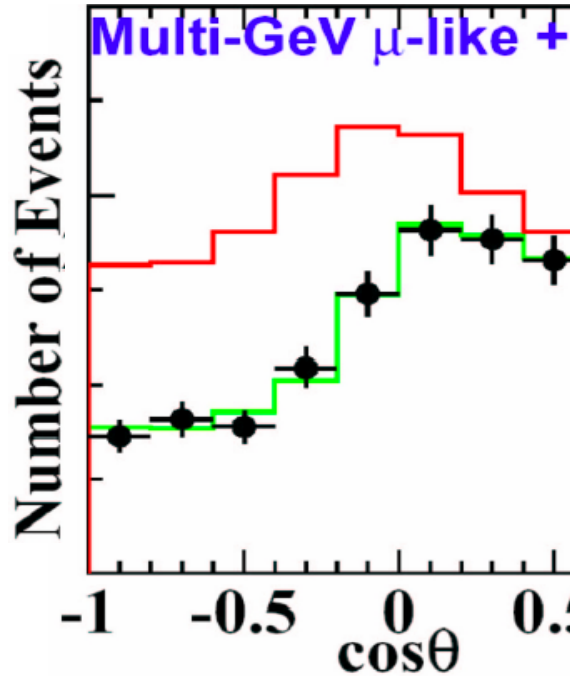
$$P(\nu_e \rightarrow \nu_e) \sim 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

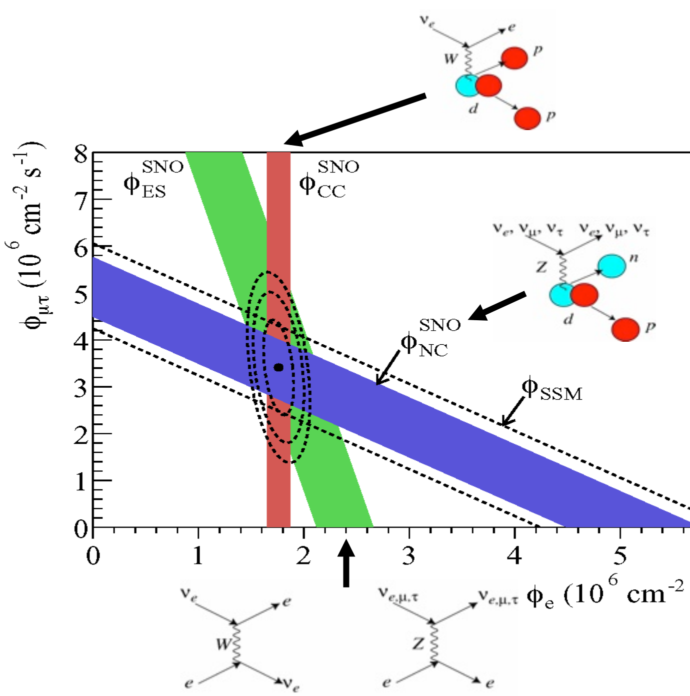


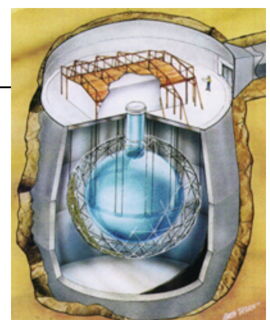
Discoveries of Neutrino Oscillation

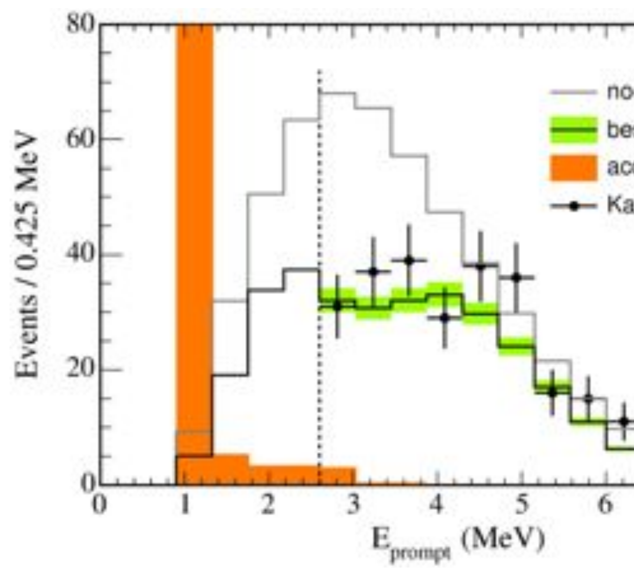


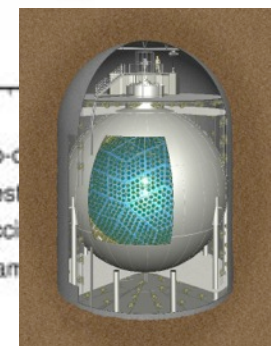
1 SNU = 10^{-36} interaction/atom/s





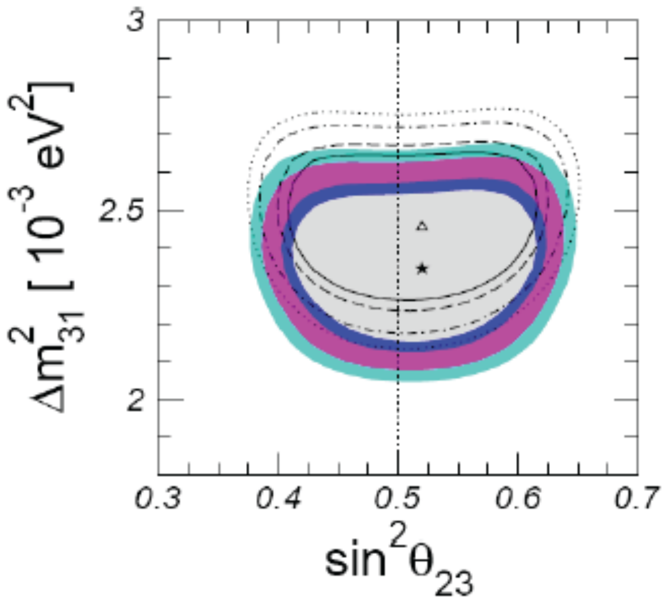






Where Did We Stand Circa 2011 ?

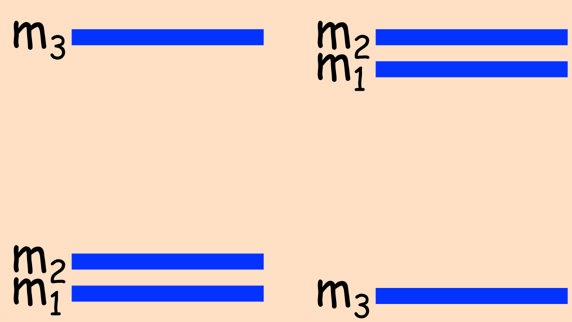
$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



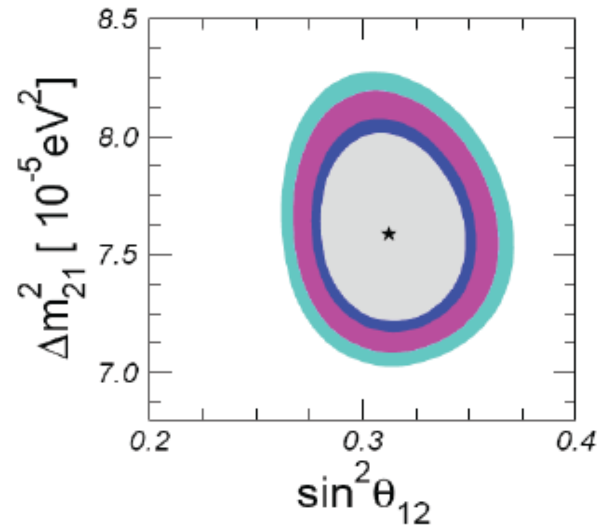
$\theta_{23} \sim 45°$

θ_{13} ?

δ ?



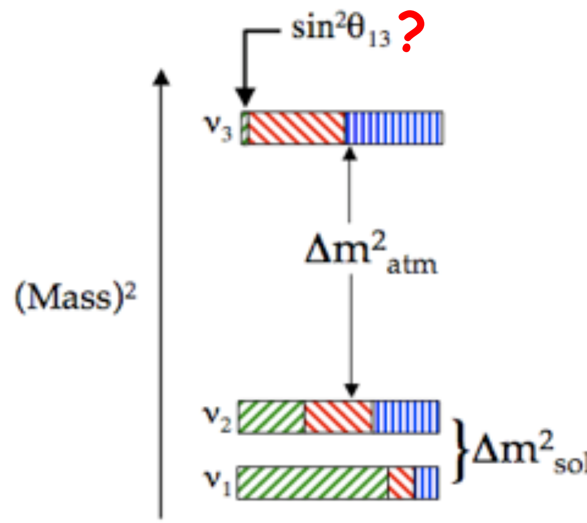
Normal or Inverted mass hierarchy ?



$\theta_{12} \sim 34°$

Importance of θ_{13}

- It is one of the key parameters in determining the leptonic mixing matrix.
- What is ν_e fraction of ν_3?



- Enables new opportunities to resolve the mass hierarchy.
- It is the gateway to CP violation in the neutrino sector:

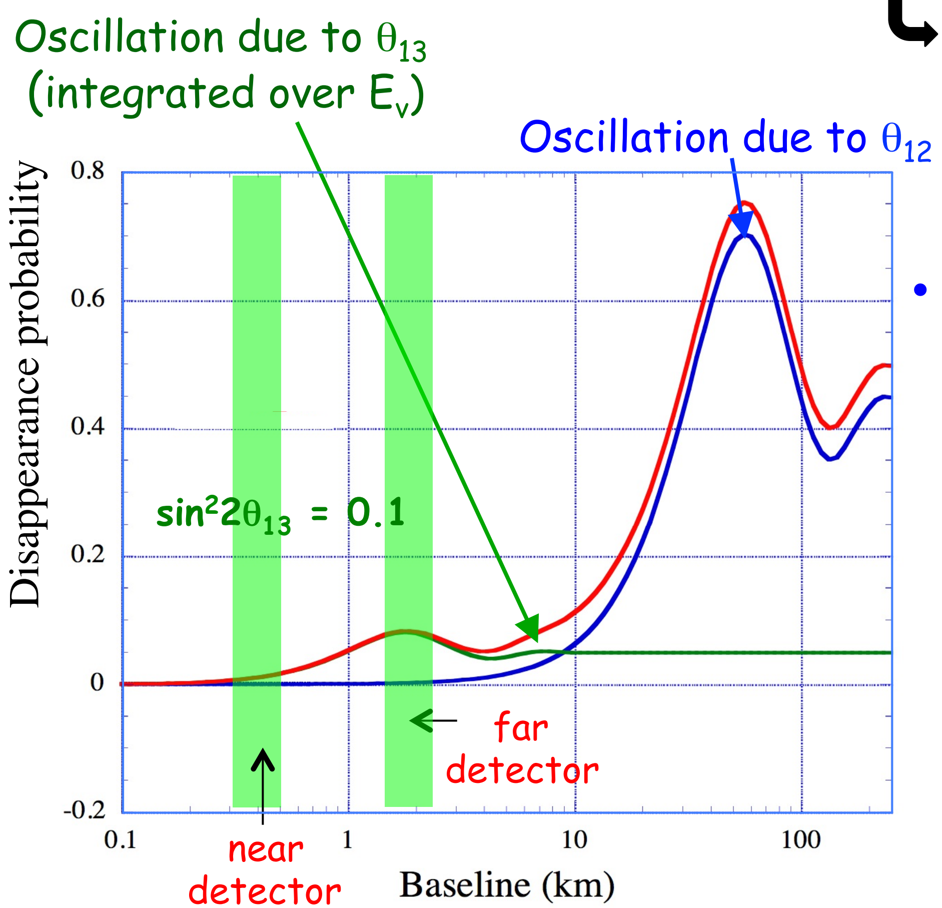
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) \propto \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta$$

Determining θ_{13} With Reactor $\bar{\nu}_e$

- Look for disappearance of reactor $\bar{\nu}_e$:

$$P(\bar{\nu}_e \rightarrow x) \approx \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{ee}^2 L}{4E_\nu}\right) + \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

$$\Delta m_{ee}^2 \cong \Delta m_{31}^2 \cos^2\theta_{12} + \Delta m_{32}^2 \sin^2\theta_{12}$$



- Perform relative measurement, for a given E_ν [PAN63, 1002 (2000)]:

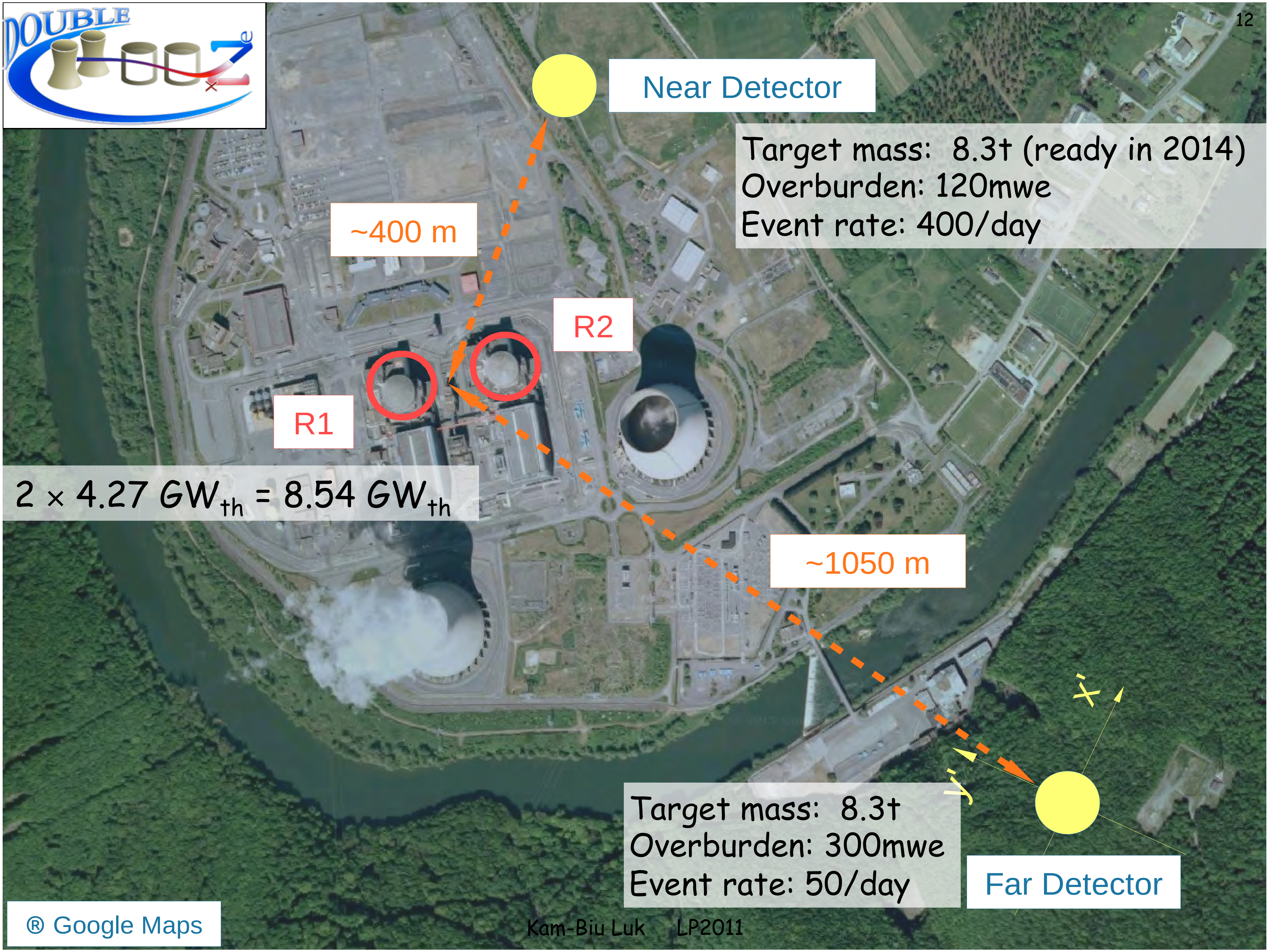
$$\frac{R_{Far}}{R_{Near}} = \left(\frac{L_{Near}}{L_{Far}}\right)^2 \left(\frac{N_{Far}}{N_{Near}}\right)\left(\frac{\varepsilon_{Far}}{\varepsilon_{Near}}\right)\left(\frac{1-P_{Far}}{1-P_{Near}}\right)$$

$\bar{\nu}_e$ rate	$1/r^2$	number of protons	detection efficiency	Yield $\sin^2 2\theta_{13}$ & Δm^2_{ee}

All correlated errors cancelled and enables precise measurements.

Reactor-based θ_{13} Experiments

Experiment	Reactor Power (GW_{th})	Flux-weighted Baseline (m) Near/Far	Target mass (t) Near/Far	Overburden (mwe) Near/Far
Daya Bay	17.4	(470,576)/1650	(40,40)/80	(250,265)/860
Double Chooz	8.5	400/1050	8.3/8.3	120/300
RENO	16.5	409/1444	16.5/16.5	120/450


Near Detector
Target mass: 8.3t (ready in 2014)
Overburden: 120mwe
Event rate: 400/day
~400 m
R2
R1
$2 \times 4.27\ GW_{th} = 8.54\ GW_{th}$
~1050 m
x'
y'
Target mass: 8.3t
Overburden: 300mwe
Event rate: 50/day
Far Detector
® Google Maps

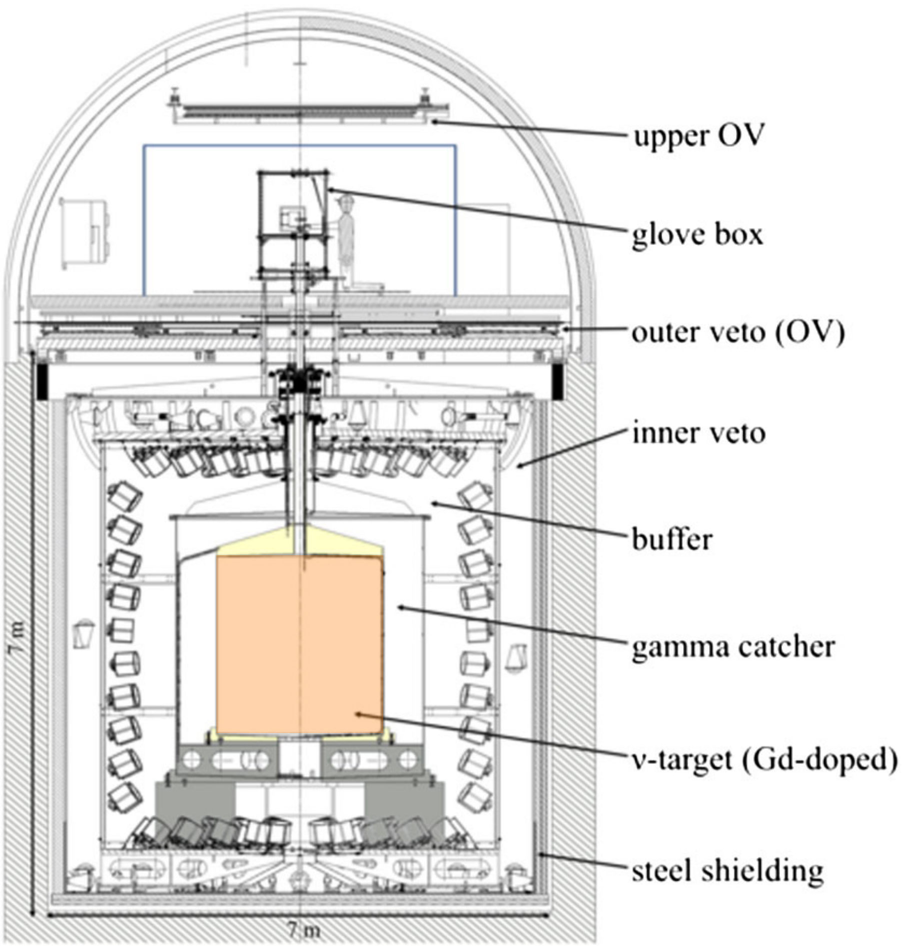
Double Chooz Collaboration

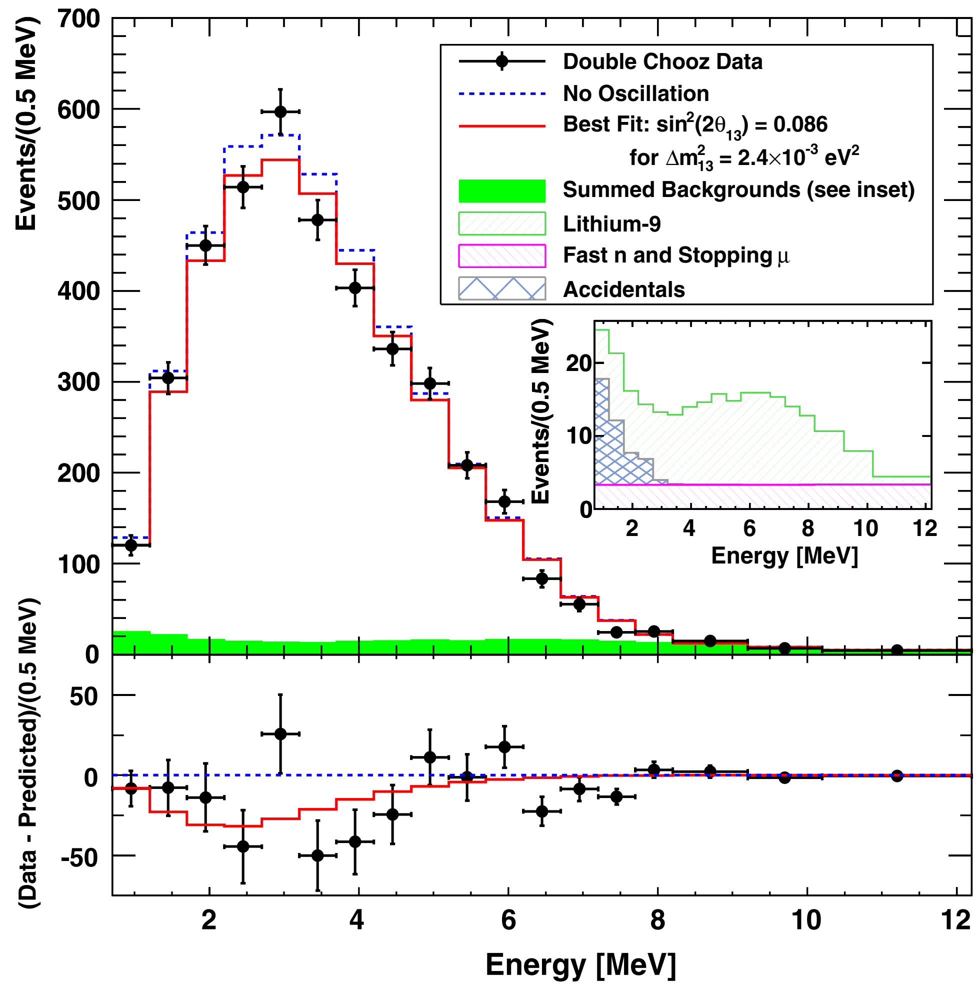
Brazil	France	Germany	Japan	Russia	Spain	USA
CBPF	APC	EKU	Tohoku U.	INR RAS	CIEMAT-Madrid	U. Alabama
UNICAMP	CEA/DSM/IRFU:	Tübingen	Tokyo Inst. Tech.	IPC RAS		ANL,U. Chicago
UFABC	SPP, SPhN	MPIK Heidelberg	Tokyo Metro. U.	RRC Kurchatov		Columbia U.
	SEDI, SIS	RWTH Aachen	Niigata U.			UC Davis
	SENAC	TU München	Kobe U.			Drexel U.
	CNRS/IN2P3:		Tohoku Gakuin U.			IIT, KSU, MIT,
	Subatech		Hiroshima Inst. Tech.			U. Notre Dame
	IPHC					U. Tennessee
						Virginia Tech

Double Chooz Repeated CHOOZ (2012)

Absolute measurement with only the Far Detector

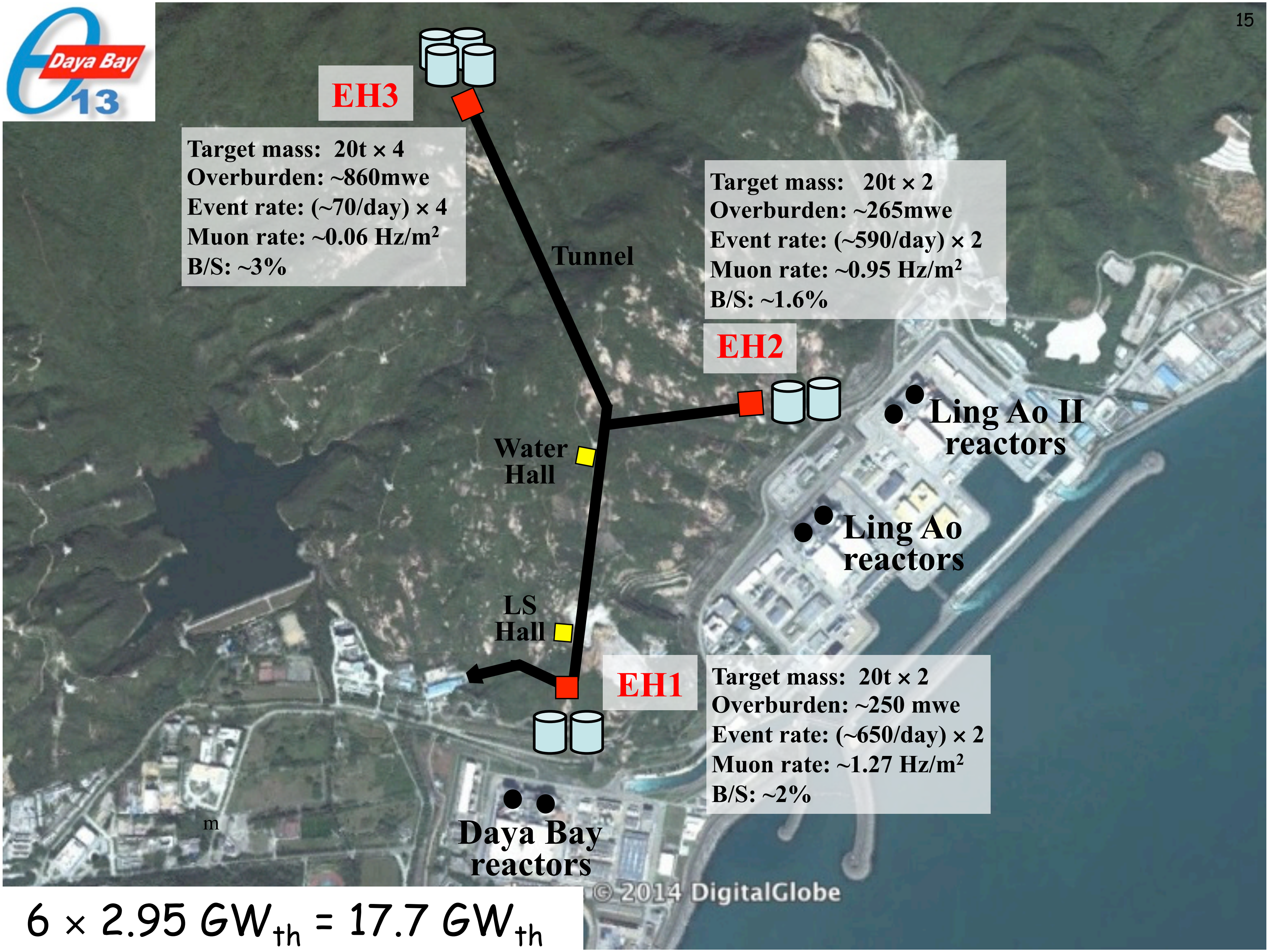
$R = N_{obs}/N_{pred} = 0.944 \pm 0.016\ (stat) \pm 0.040\ (syst)$





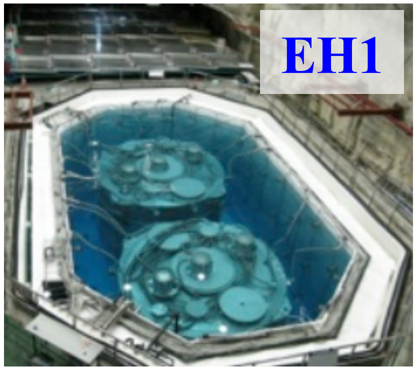
PRL **108**, 131801 (2012)

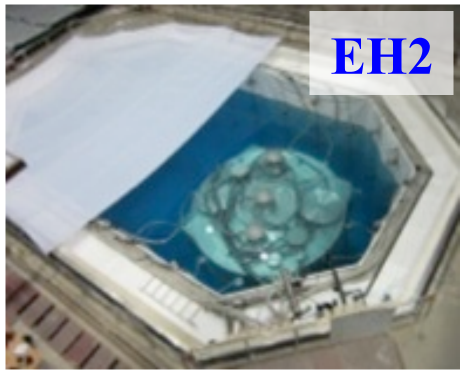
$\sin^2 2\theta_{13} = 0.086 \pm 0.041\ (stat) \pm 0.030\ (syst)$

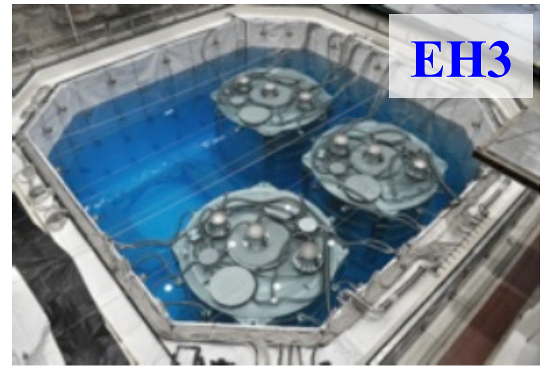


$6 \times 2.95\ GW_{th} = 17.7\ GW_{th}$

Daya Bay : Definitive Results on θ_{13} (2012)

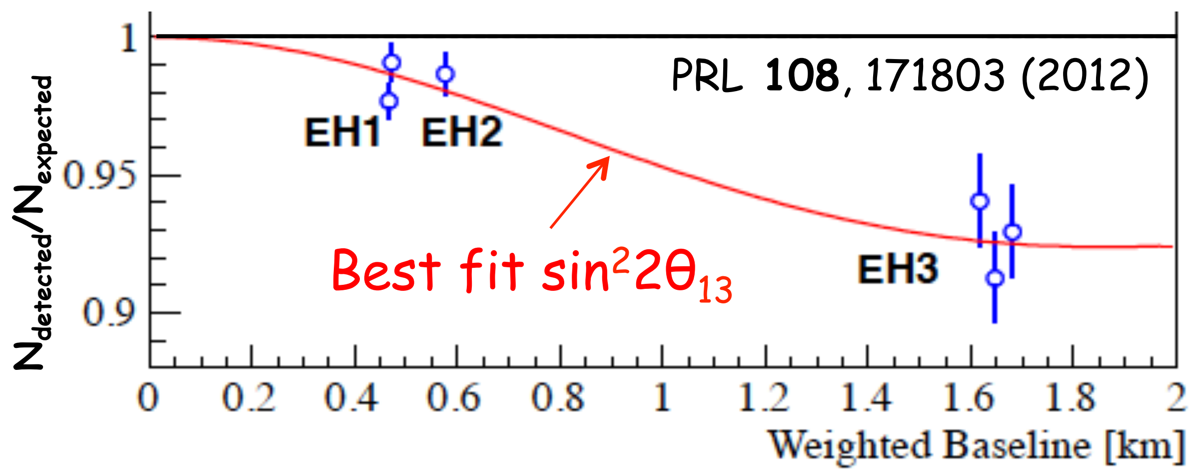




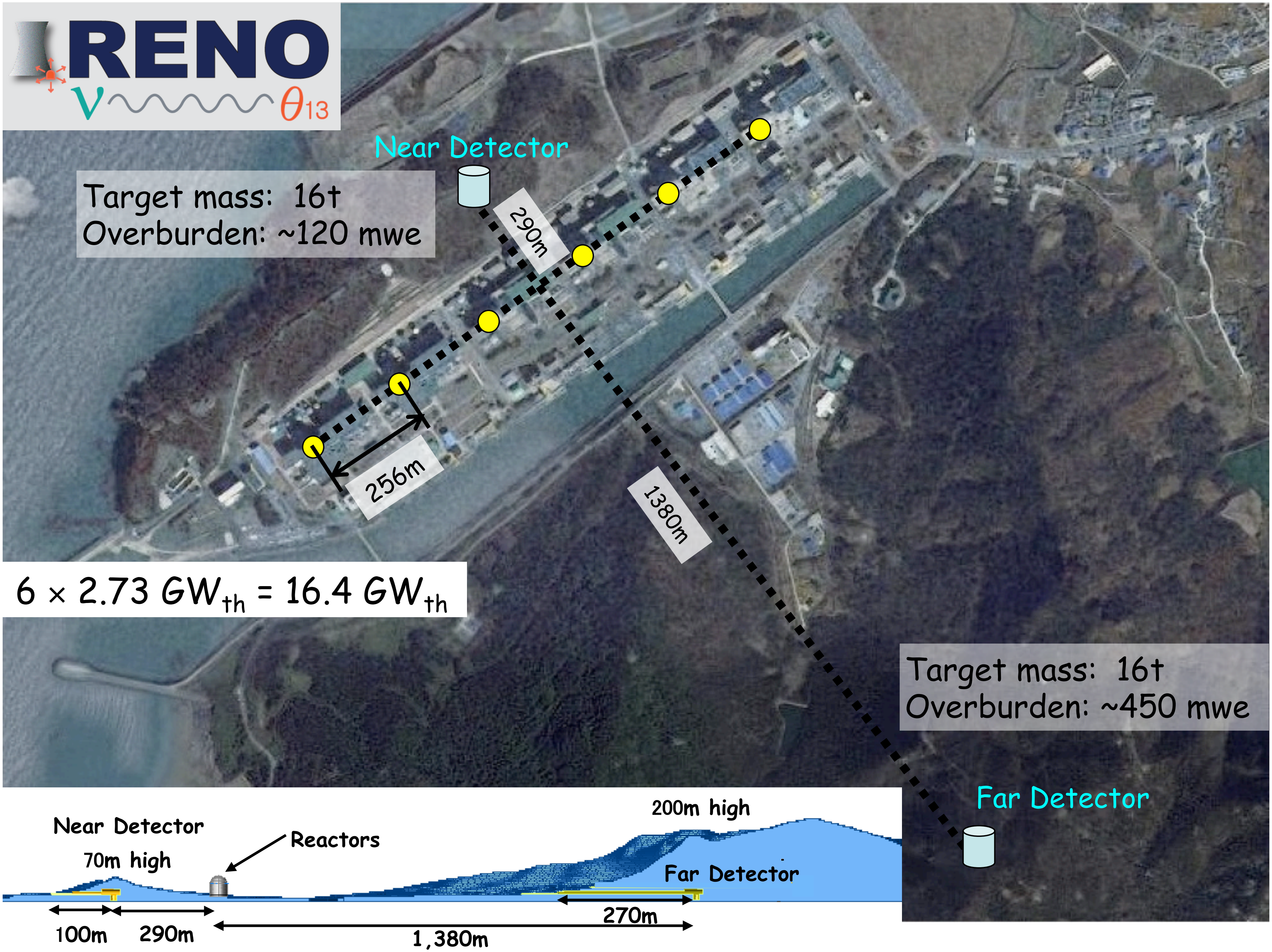


With 55 days of data, discovered disappearance of reactor $\bar{\nu}_e$ at short baseline in March 2012:

$R = 0.940 \pm 0.011\ (\text{stat}) \pm 0.004\ (\text{syst})$

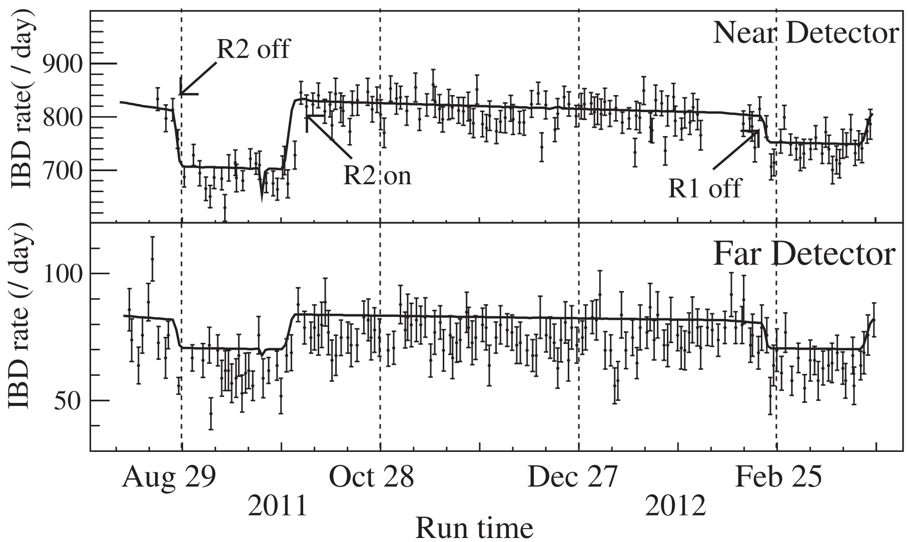


$\sin^2 2\theta_{13} = 0.092 \pm 0.016\ (\text{stat}) \pm 0.005\ (\text{syst})$

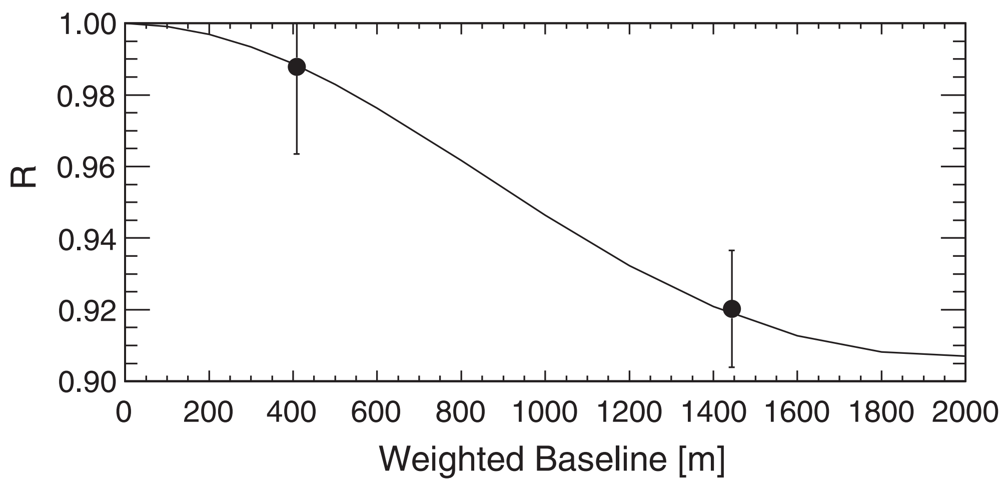

RENO
ν θ13
Near Detector
Target mass: 16t
Overburden: ~120 mwe
290m
256m
1380m
6 × 2.73 GWth = 16.4 GWth
Target mass: 16t
Overburden: ~450 mwe
Far Detector
Near Detector
70m high
Reactors
200m high
Far Detector
100m
290m
1,380m
270m

RENO

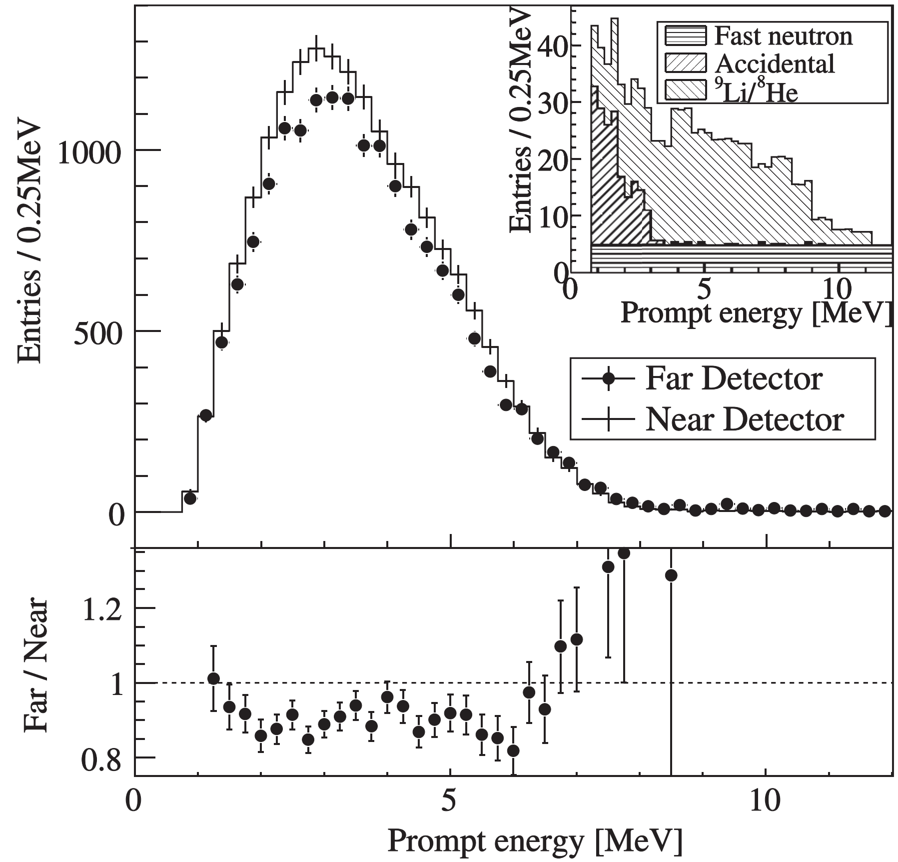
Confirmation of Non-zero θ_{13}



R = 0.920 ± 0.009 (stat) ± 0.014 (syst)



PRL **108**, 191802 (2012)

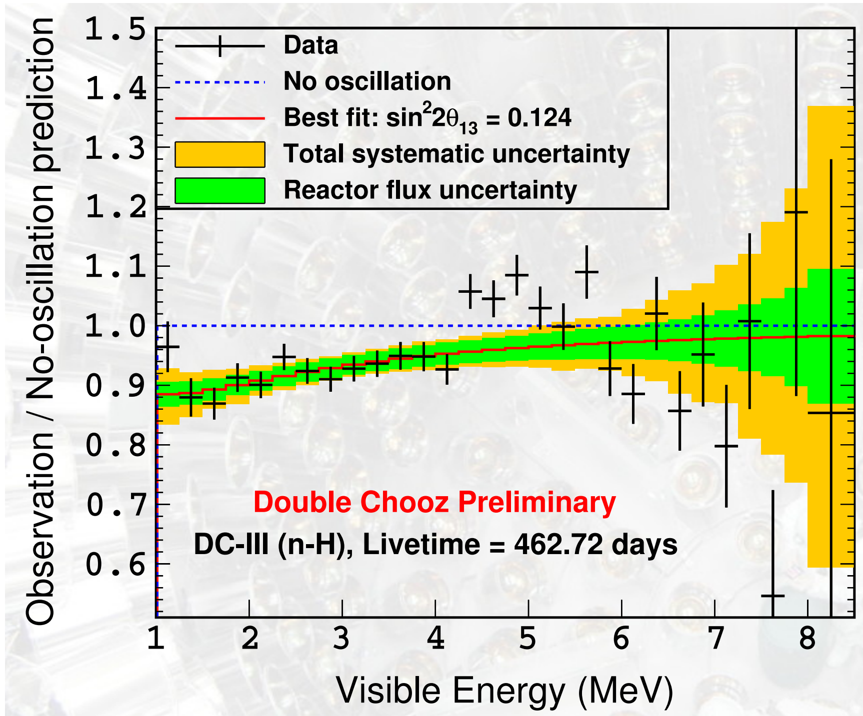


$\sin^2 2\theta_{13}$ = 0.113 ± 0.013 (stat) ± 0.019 (syst)

Latest Result on θ_{13} From n-H Data

- Provided an independent measurement of θ_{13}
  - Improved analysis & reduced systematic uncertainties
  - Based on 463 days of data with only far detector
  - Rate + shape analysis

Source	Uncertainty [%]	
Reactor flux	1.8	1.7
Statistics	1.1	0.6
Accidental background	0.2	0.02
Cosmogenic isotope background	1.6	+0.86/-0.50
Fast neutrons	0.6	0.23
Light noise	0.1	
Energy scale	0.3	
Efficiency	1.6	1.0
Total	3.1	+2.3/-2.2
	old	EPS2015



EPS 2015: $\sin^2 2\theta_{13} = 0.124^{+0.030}_{-0.039}$

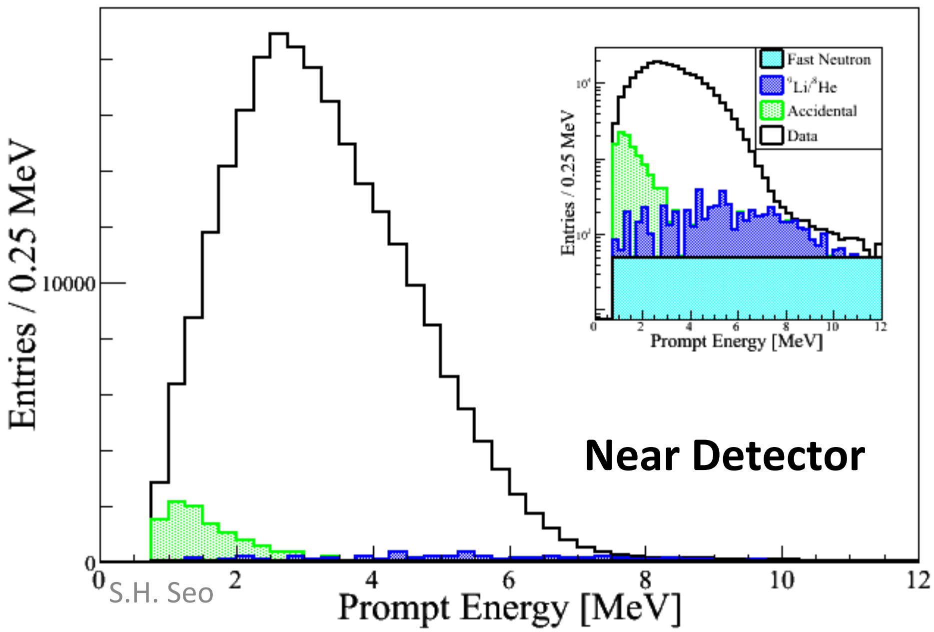
Old: $\sin^2 2\theta_{13} = 0.097 \pm 0.048$ PL B723(2013)66

Preliminary n-H Results on θ_{13}

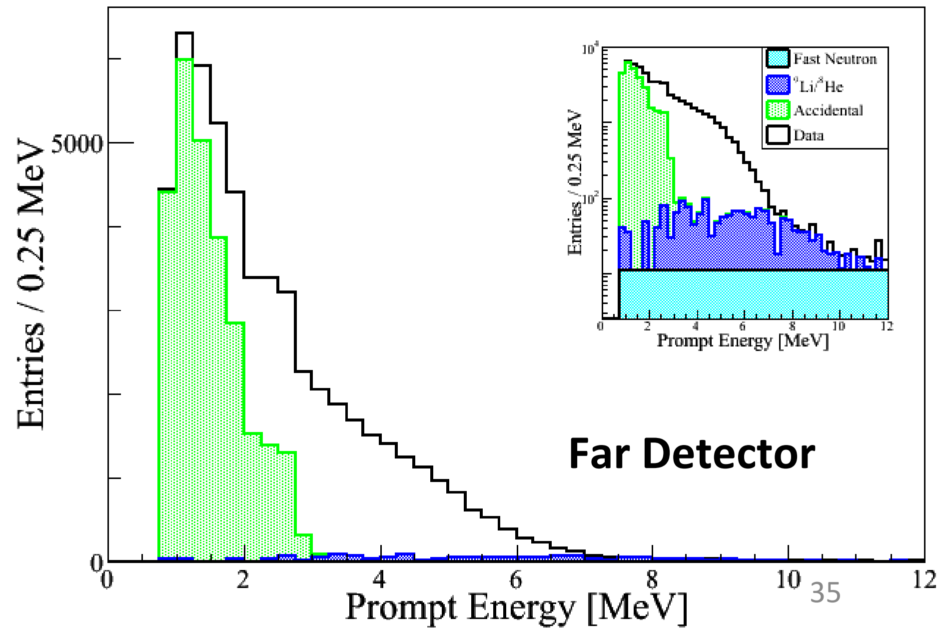
With ~400 days of data based on n-H capture

- Perform a rate-only analysis on ~54k events (far detector)
- Need to control the accidental background well

preliminary



preliminary

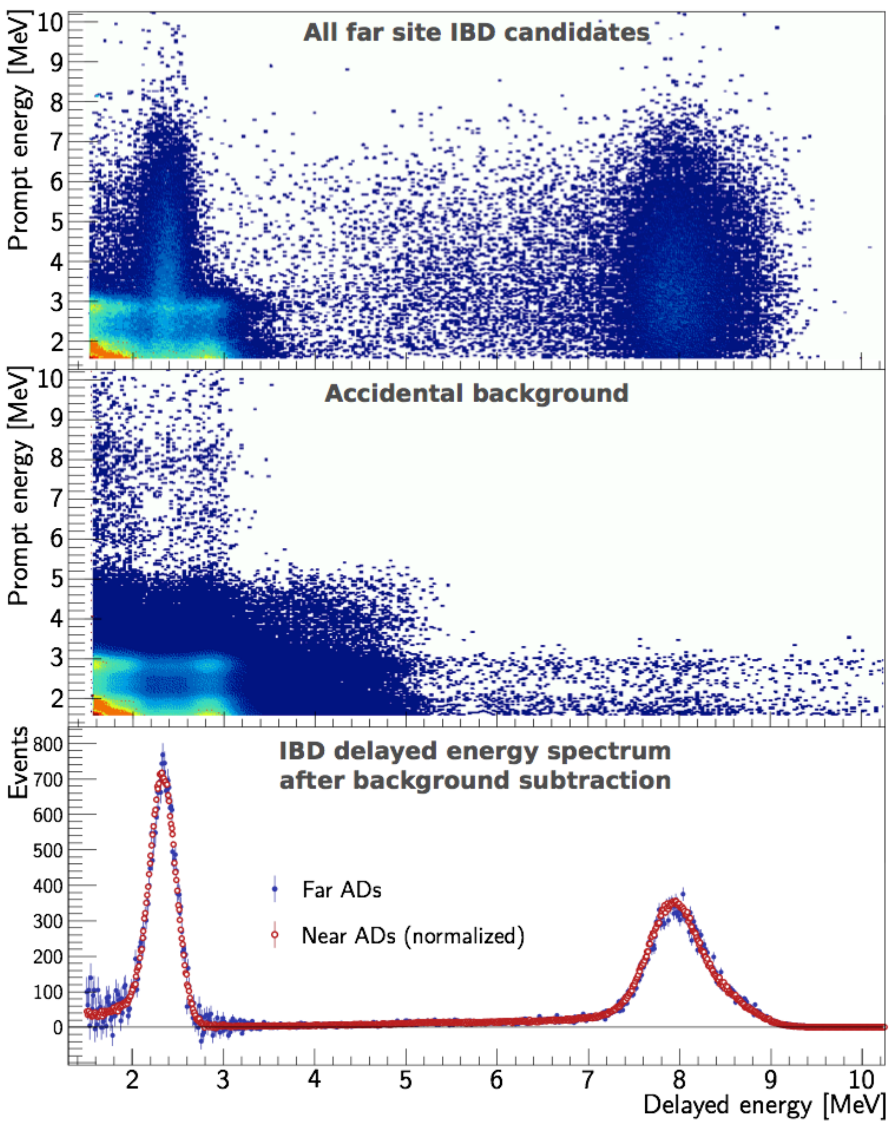


$\sin^2 2\theta_{13}$ = 0.103 ± 0.014 (stat) ± 0.014 (syst)

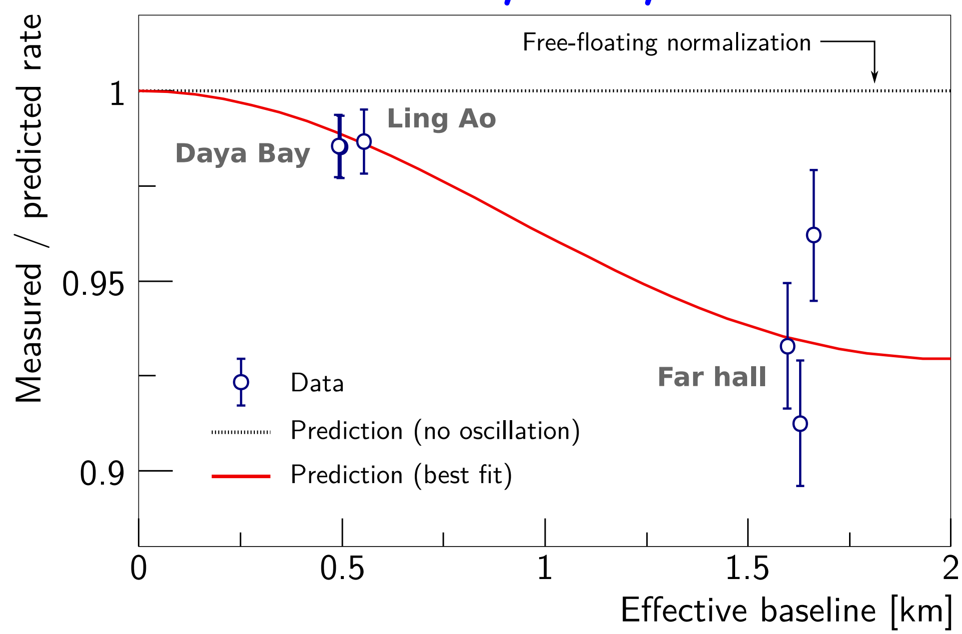
Relative measurement is crucial !

Measurement of $\sin^2\theta_{13}$ with n-H Data

neutron-capture on hydrogen: 217 days of data with 6 ADs



Rate-only analysis



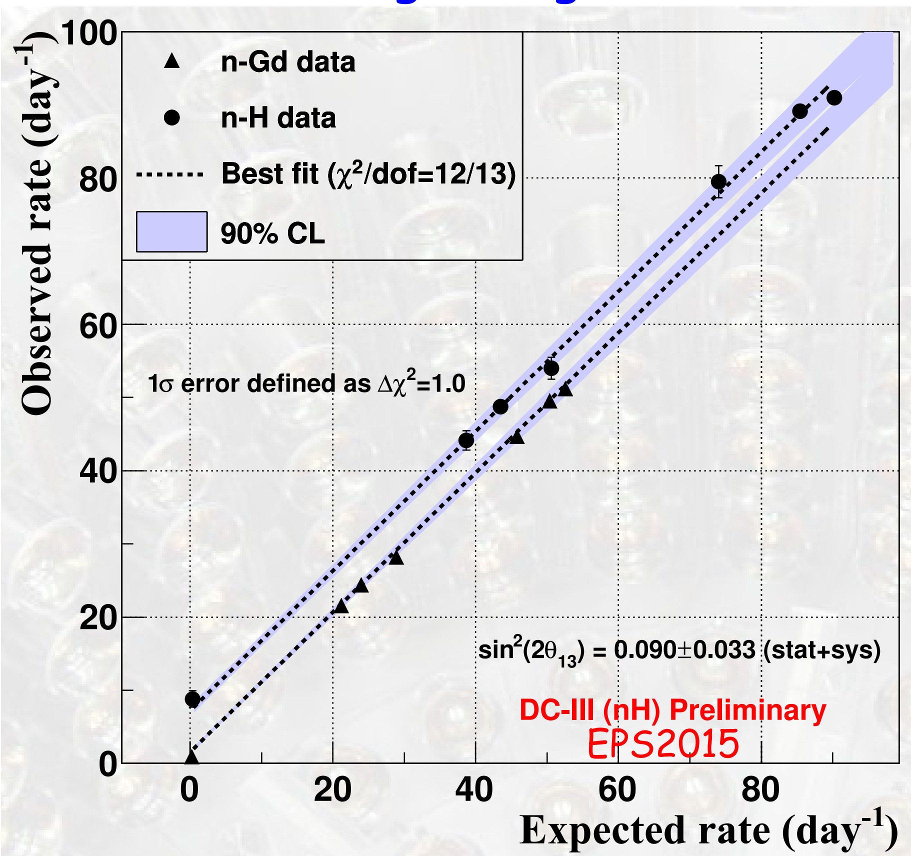
$$\sin^2 2\theta_{13} = 0.083 \pm 0.018$$
$$\chi^2/N_{\mathrm{DoF}} = 4.5/4$$

PRD **90**, 071101(R) (2014).

Double Chooz: Latest n-Gd Results

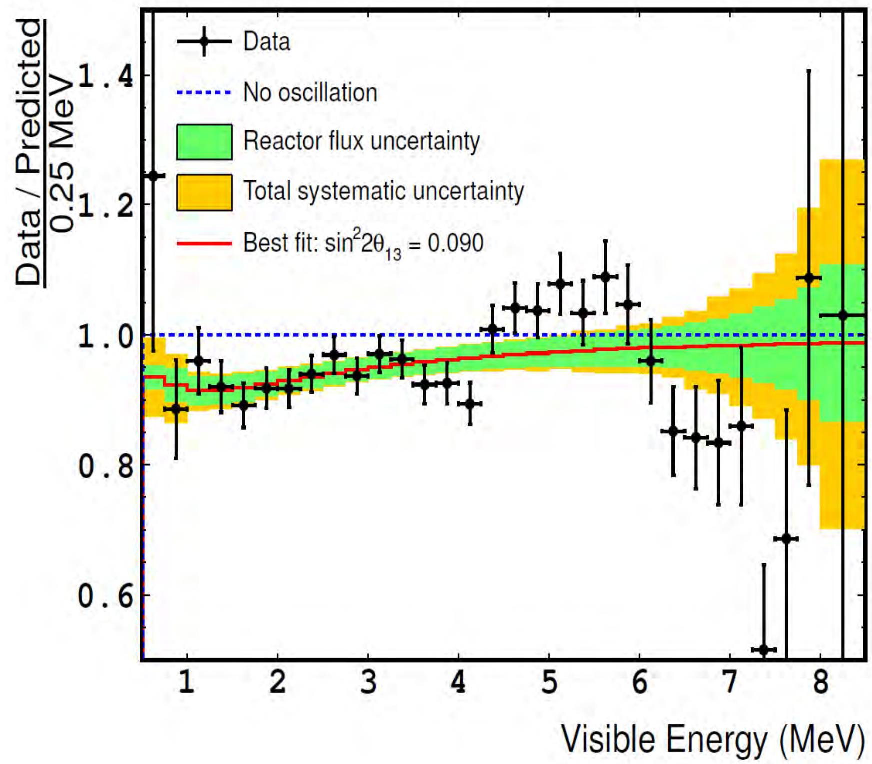
467.9 live days of n-Gd events collected at the far site

Reactor Rate Modulation analysis
for constraining background model



Combined : $\sin^2 2\theta_{13} = 0.090 \pm 0.033$

Rate + shape analysis



$\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$

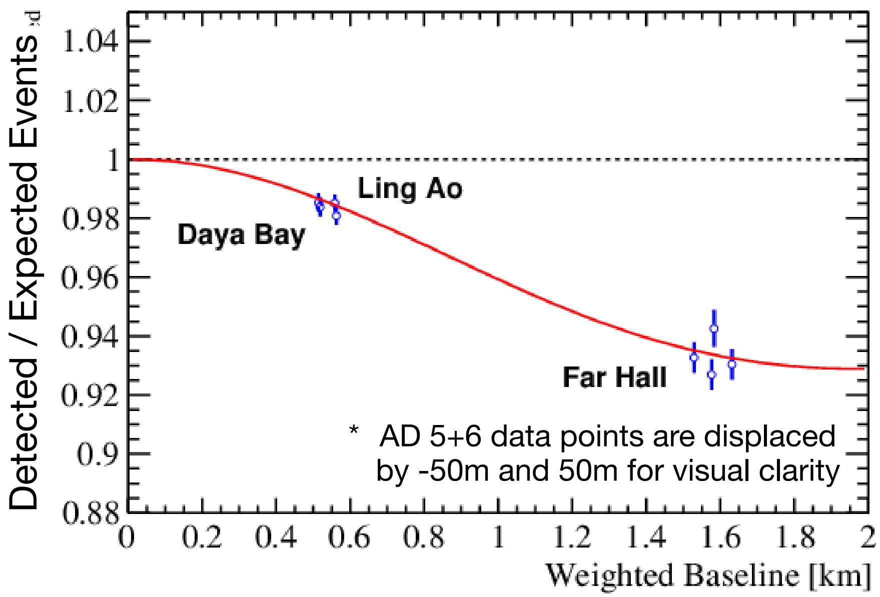
JHEP 10(2014)086

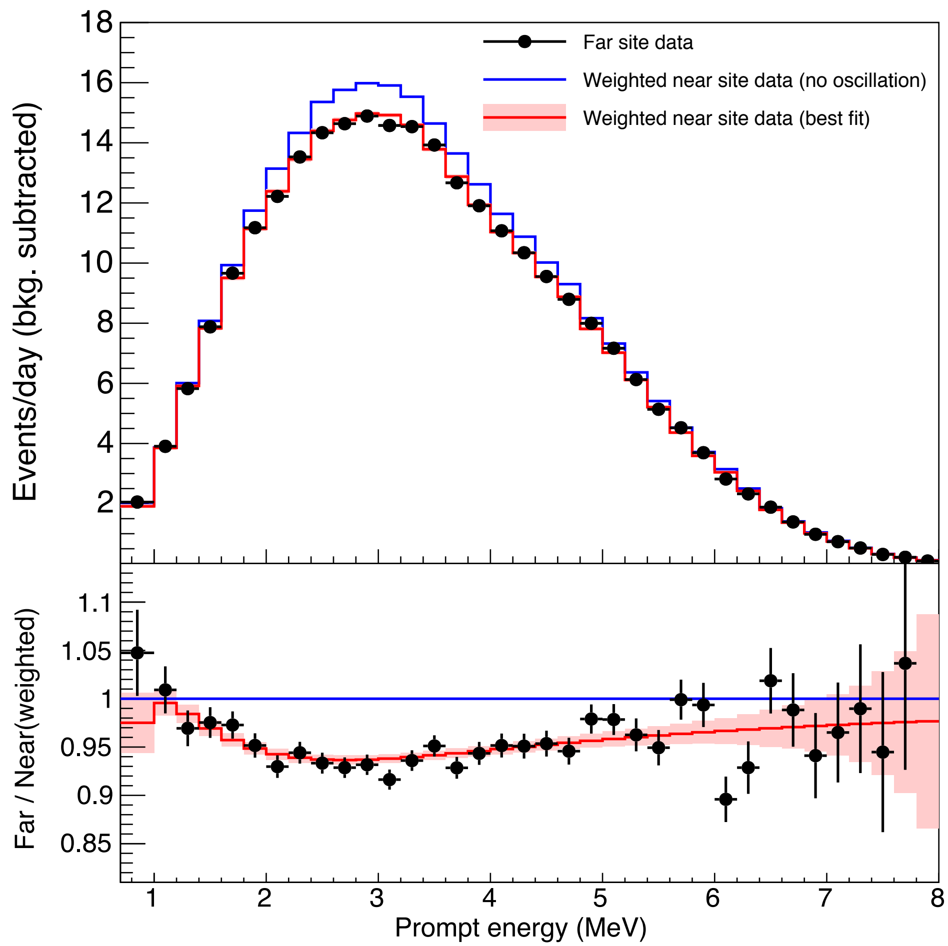
Rate+Spectral Analysis (2015)

Collected >10^6 $\bar{\nu}_e$ reactions using n-Gd capture with 6 & 8 ADs

- Over 150,000 IBD events at the far hall

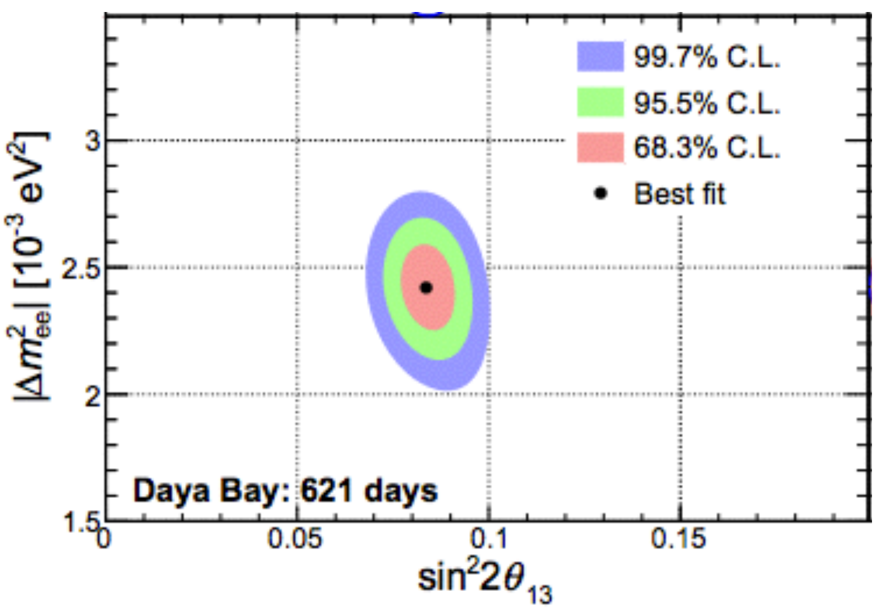
- Detected relative deficit in rate and relative distortion in the spectrum are in excellent agreement with oscillation

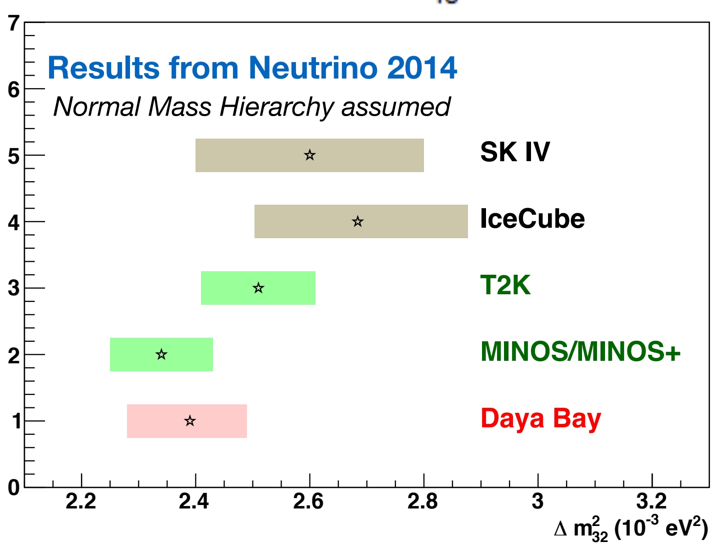




Latest Results on Oscillation Parameters

arXiv: 1505.03456, accepted by PRL





- Most precise $\sin^2 2\theta_{13}$:

  $\sin^2 2\theta_{13} = 0.084 \pm 0.005$

  (Statistics: ~70% of total error)

- Most precise $|\Delta m^2_{ee}|$:

  $|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3}$ eV^2

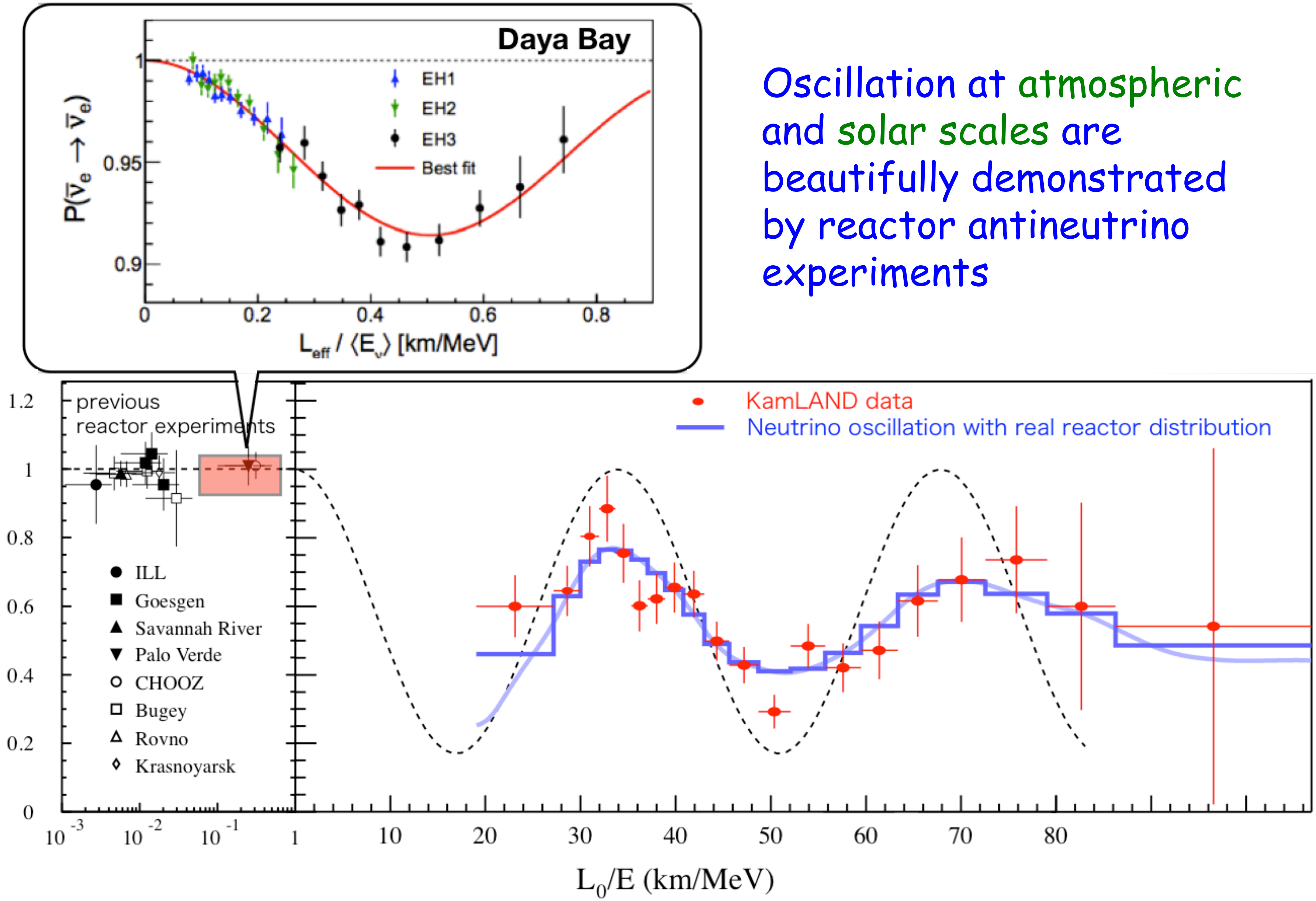
  (Statistics: ~60% of total error)

  $\chi^2/ndf = 135/146$

- $|\Delta m^2_{ee}|$ vs $|\Delta m^2|$
  - Consistent
  - Similar precision

- Support 3-flavor paradigm

Unambiguous Oscillation Pattern



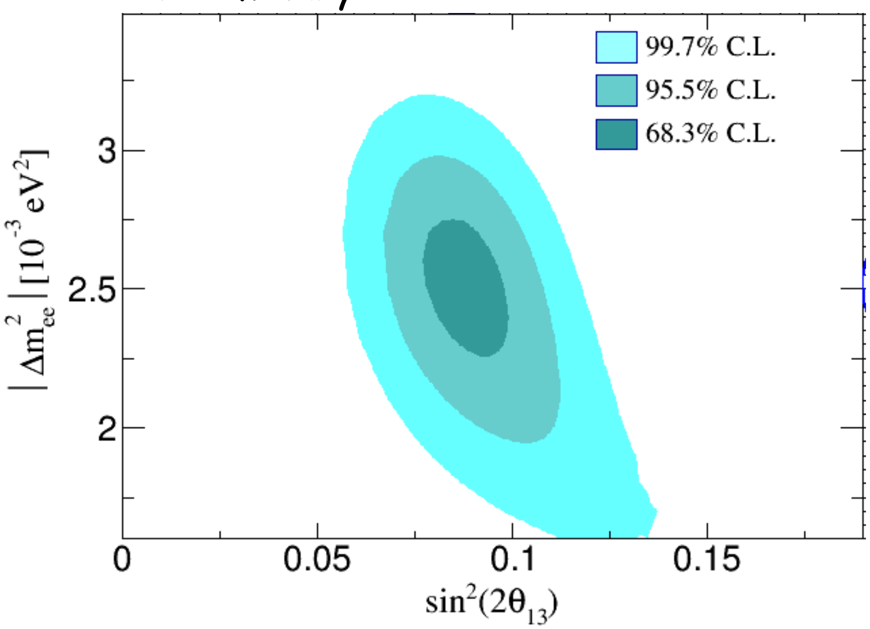
Oscillation at atmospheric and solar scales are beautifully demonstrated by reactor antineutrino experiments

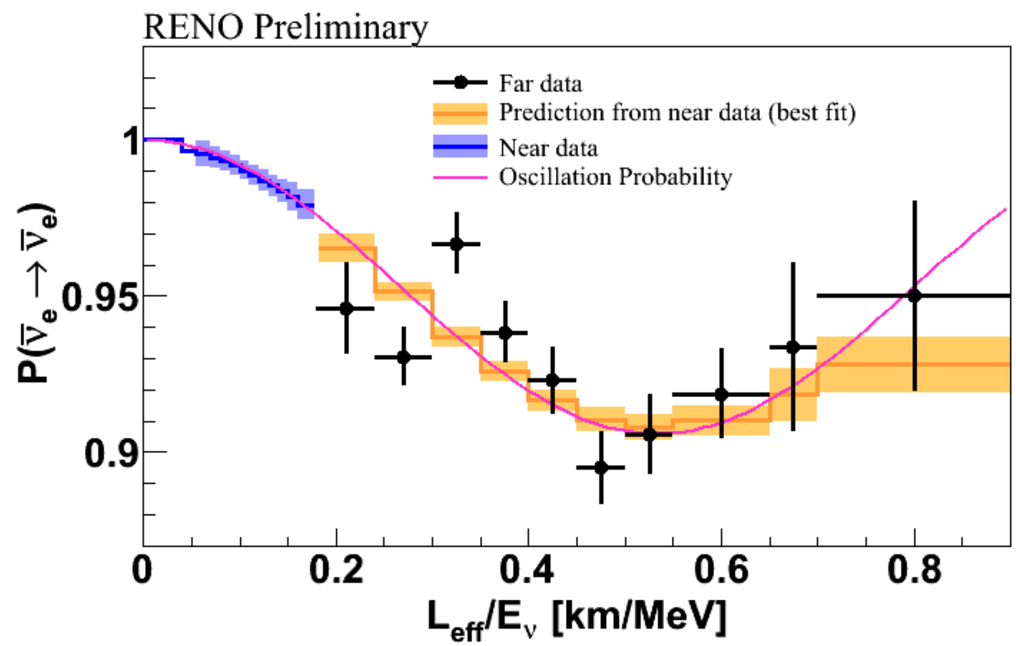
Latest n-Gd Results on Oscillation

Based on ~800 days of IBD events with n-Gd capture

- 470k events (6% bkgd) in near site & ~52k (12% bkgd) in the far hall
- Rate + spectral analysis

Preliminary

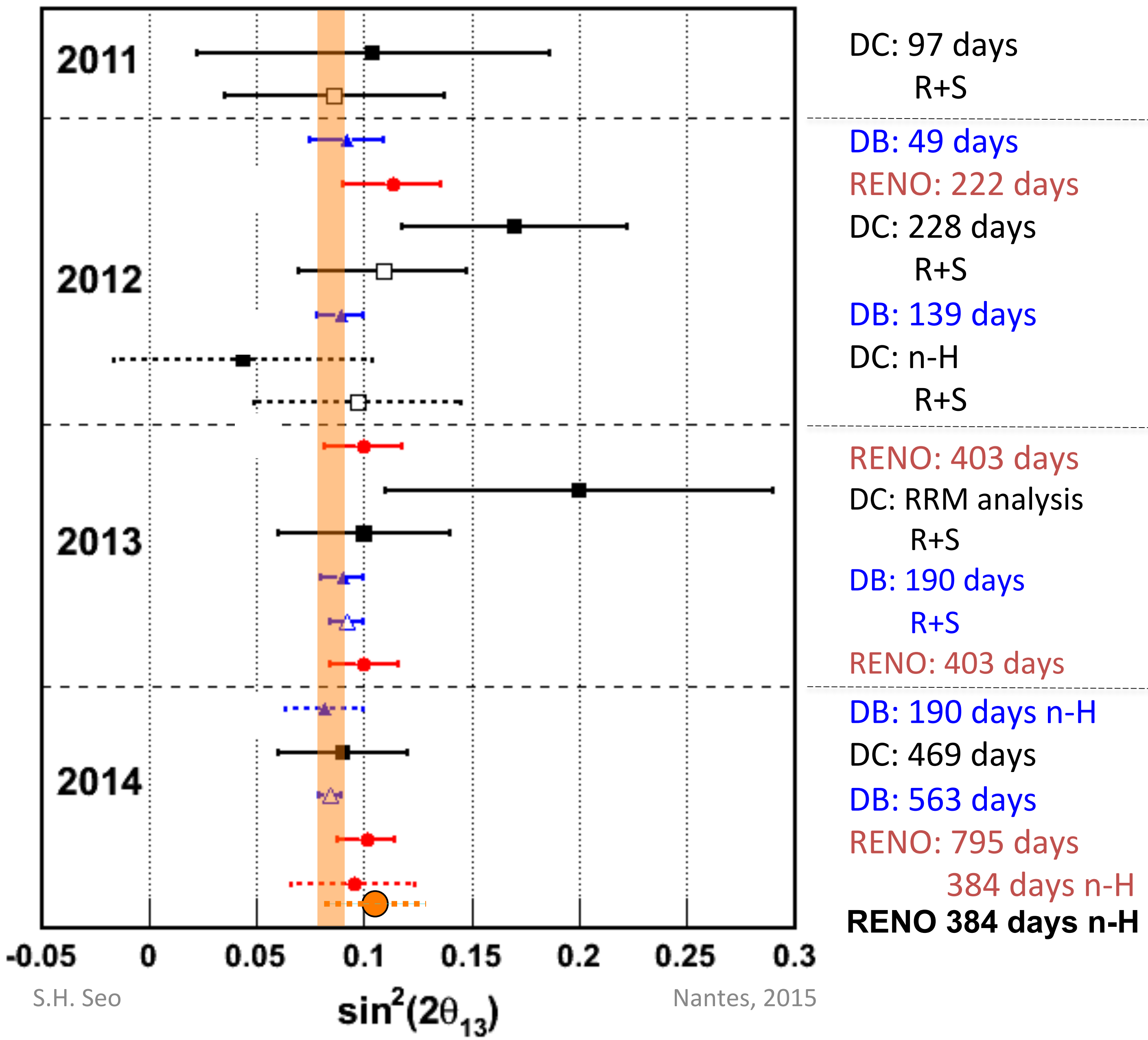




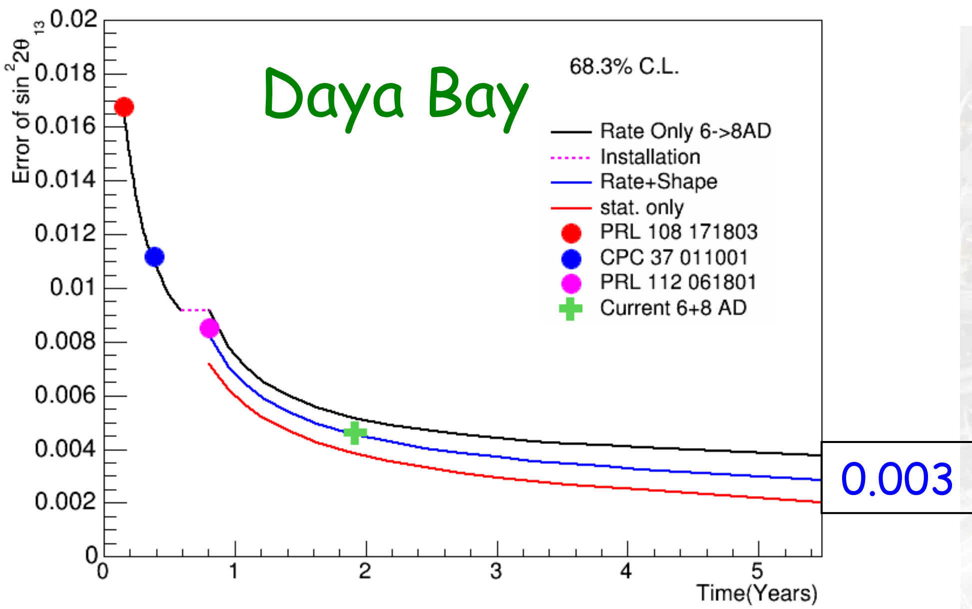
$\sin^2 2\theta_{13}$ = 0.088 ± 0.008 (stat) ± 0.007 (syst)

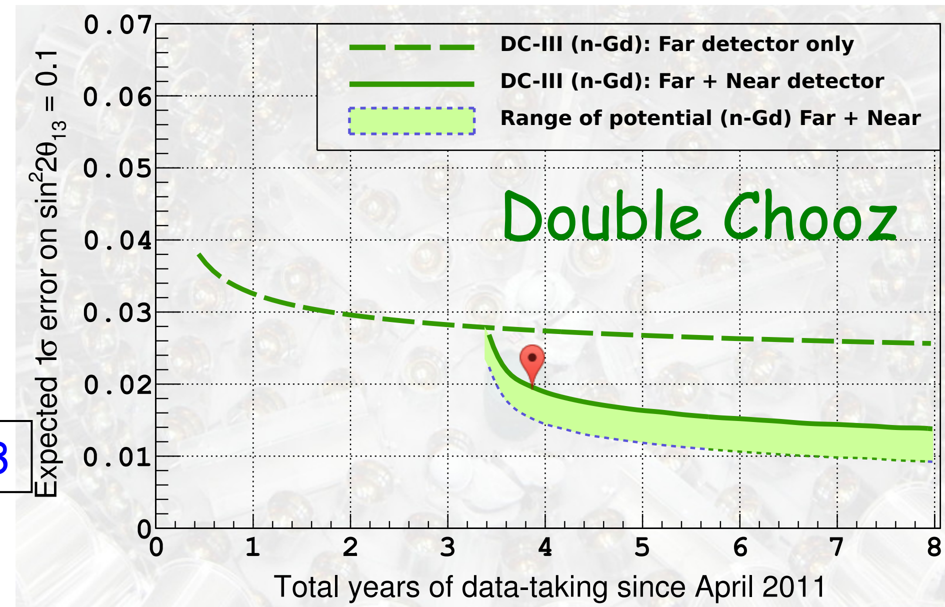
$|\Delta m^2_{ee}|$ = [2.52 ± 0.19 (stat) ± 0.17 (syst)] × 10^{-3} eV^2

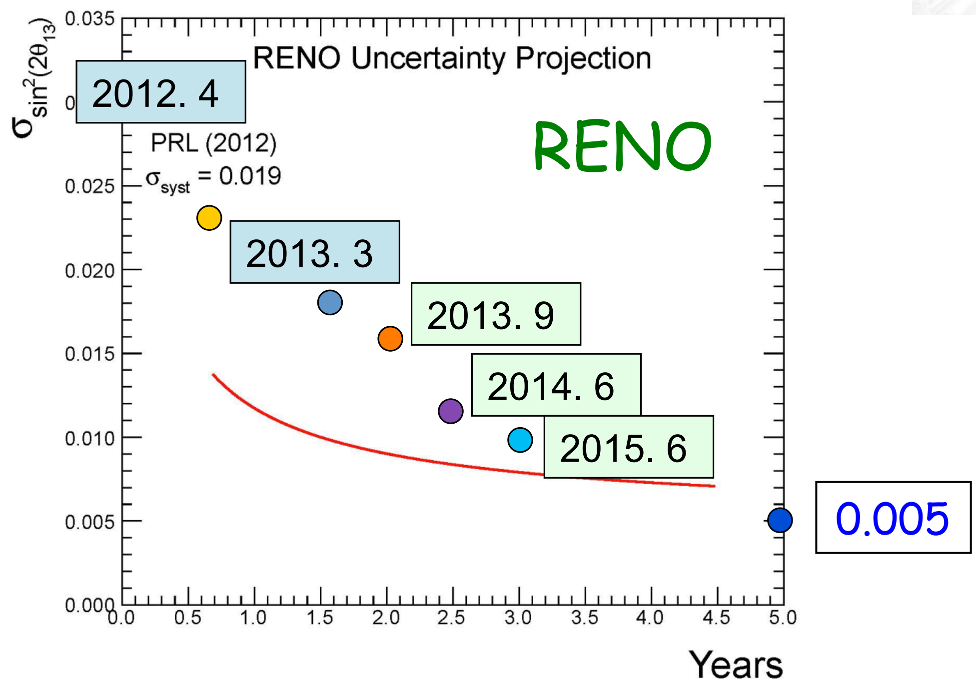
Global Landscape of $\sin^2 2\theta_{13}$



θ_{13} : What Lies Ahead ?

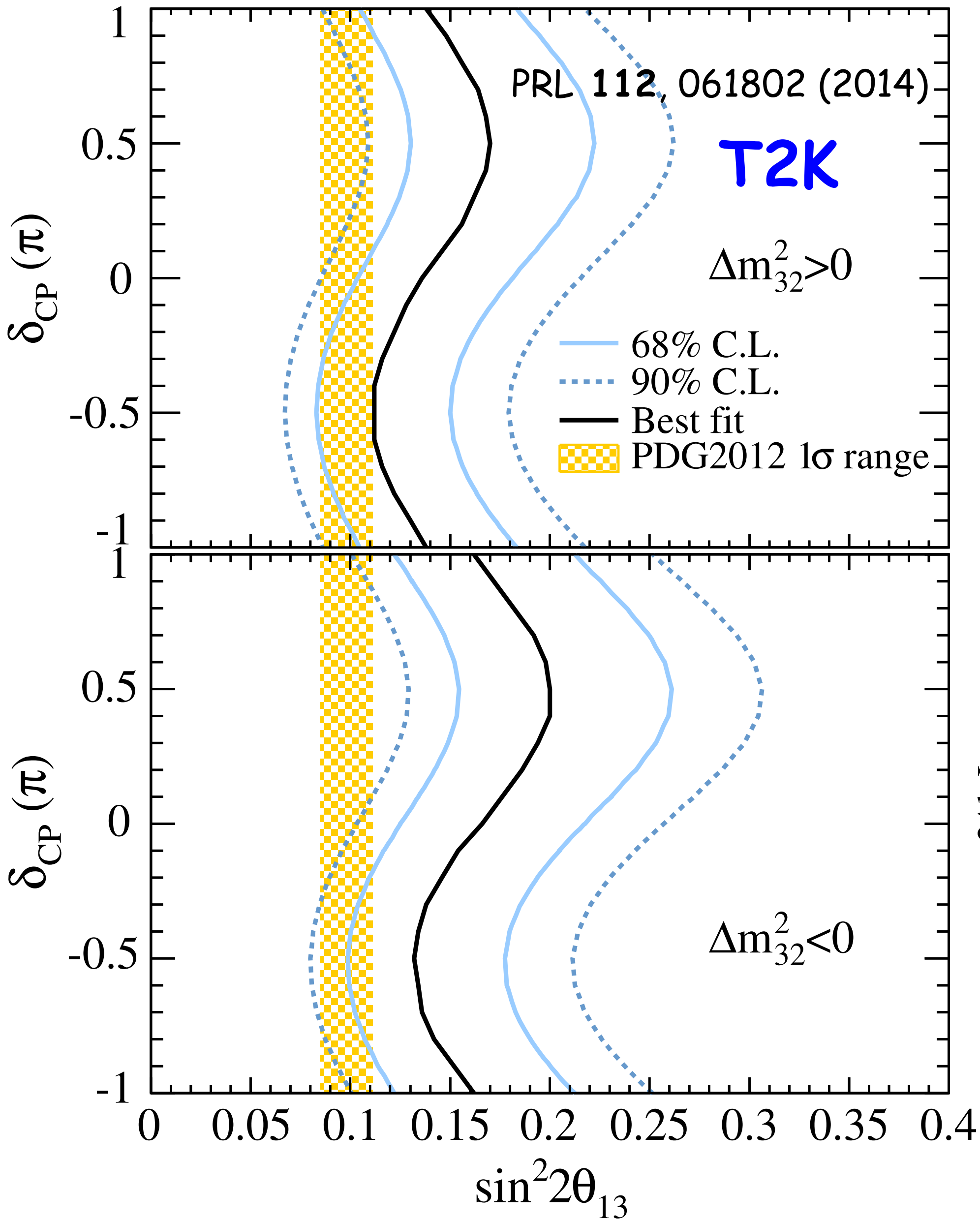




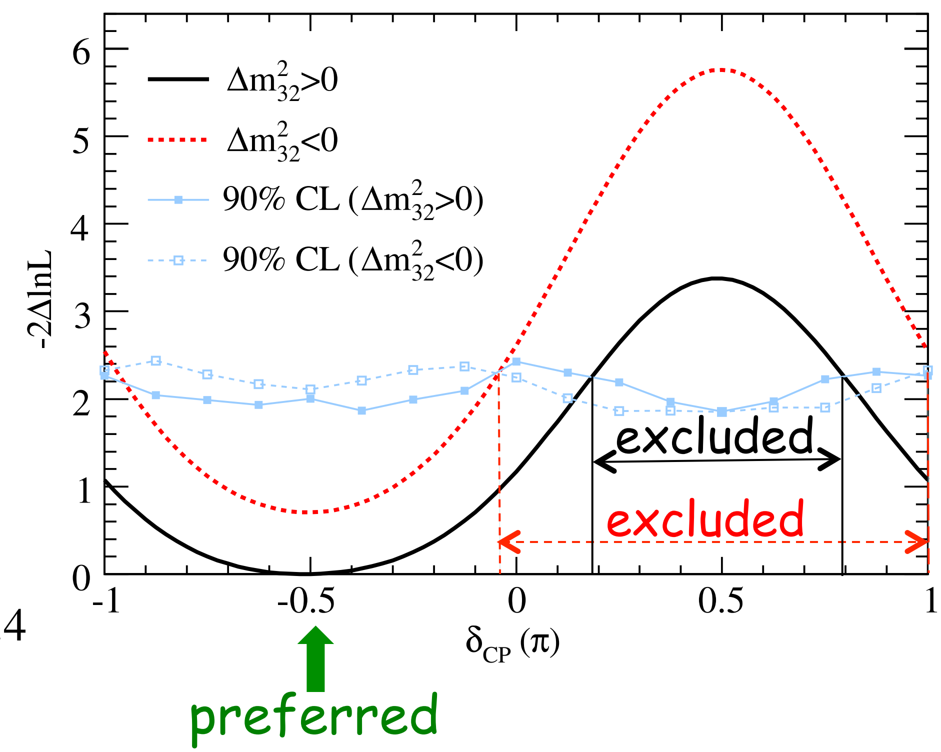


- Daya Bay will
  - provide the most precise value of θ_{13} in the foreseeable future
  - still be limited by statistics by the end of 2017

Synergy Between Accelerator & Reactor Expts



- Observed 28 ν_e events
  - expected ~5 if θ_{13} = 0
  - unambiguous observation of ν_e appearance (>7 s.d.)
- Used $\sin^2 2\theta_{13} = 0.098 \pm 0.013$ (PDG 2012) to constrain δ_{CP} :

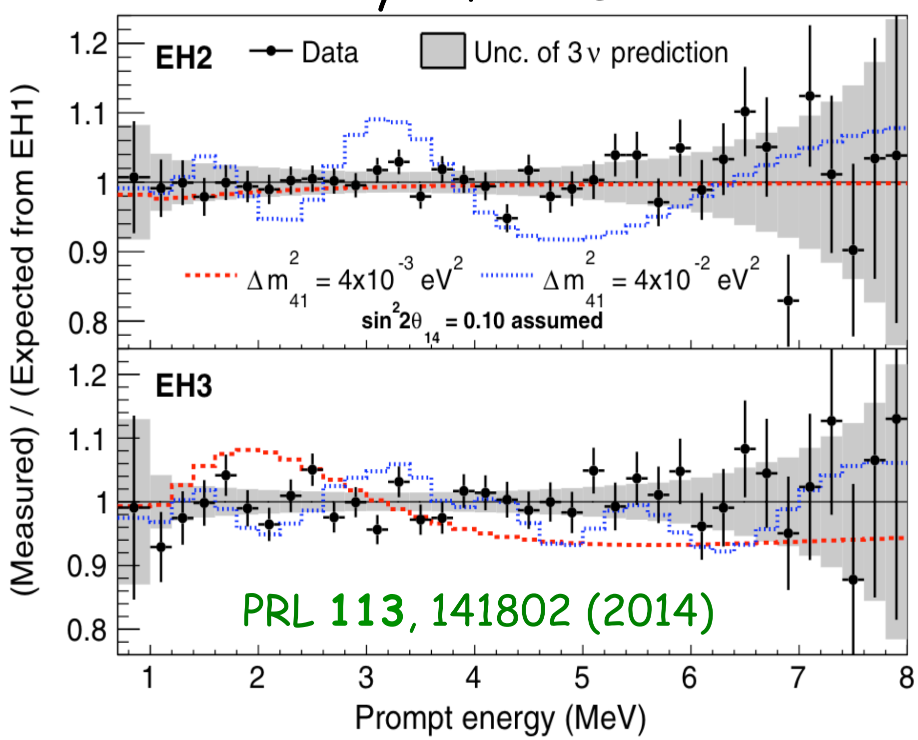


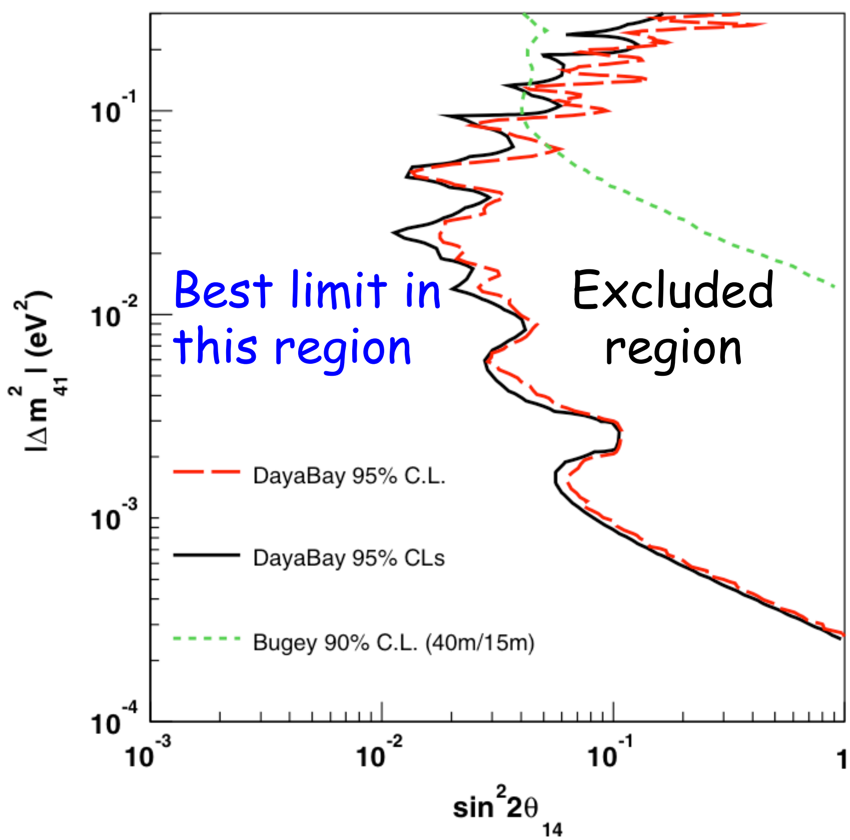
Search For Light Sterile Neutrino

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

- Multiple baselines and detectors
  - cover a broad mass range to search for sterile neutrino
  - relative measurement of energy spectra reduces systematic errors

217 days of 6-AD data





Tackling Mass Hierarchy With Reactor $\overline{\nu}_e$

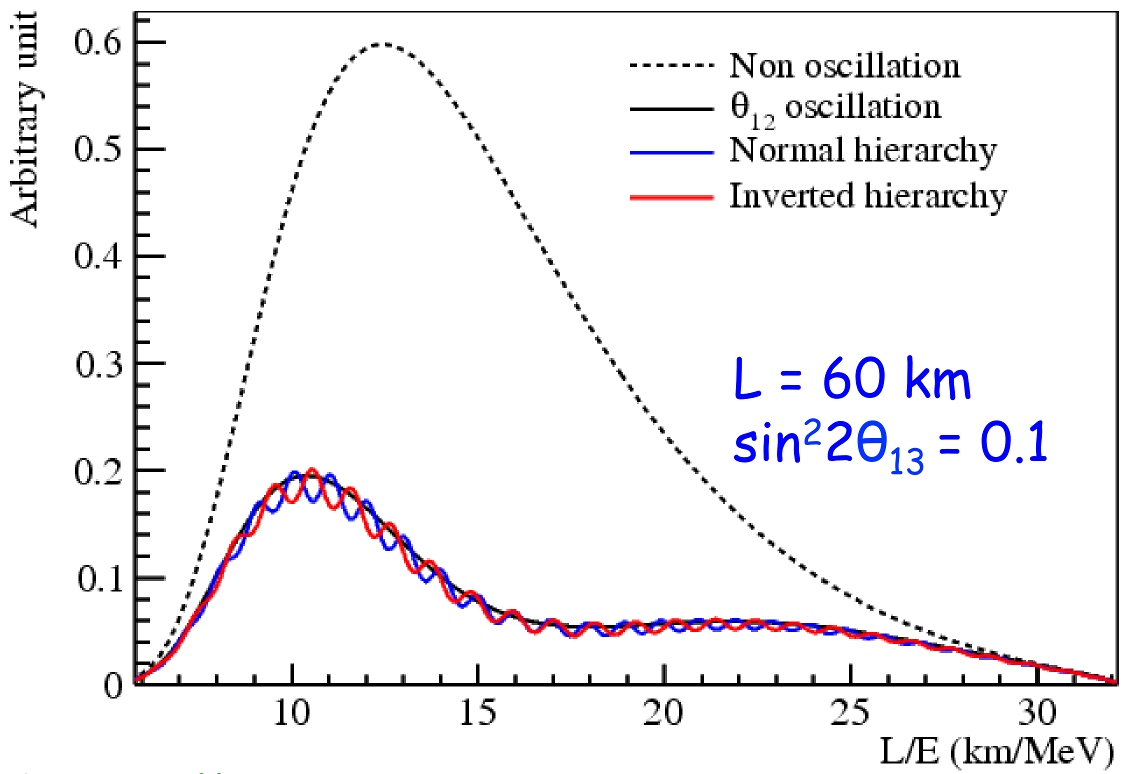
- Survival probability of $\overline{\nu}_e$ is given by:

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - P_{21} - P_{31} - P_{32}$$

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

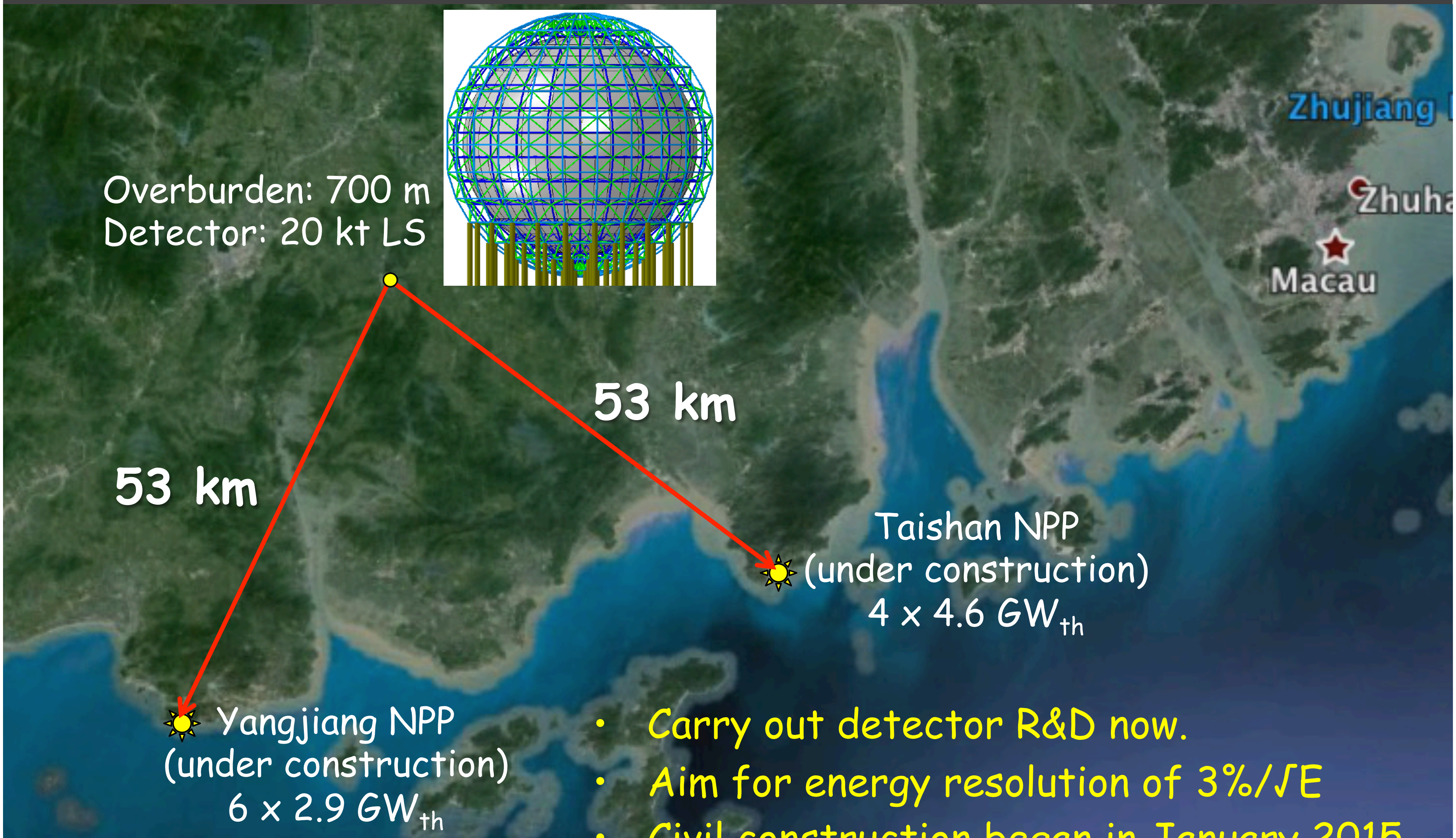
$$P_{31} = \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) \qquad P_{32} = \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)$$

- Large θ_{13} enables determination of mass hierarchy with reactors

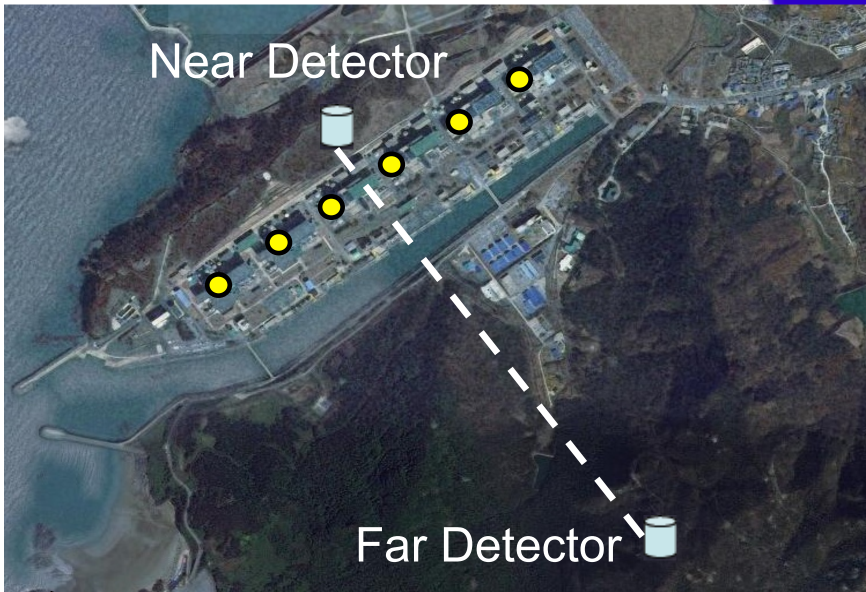


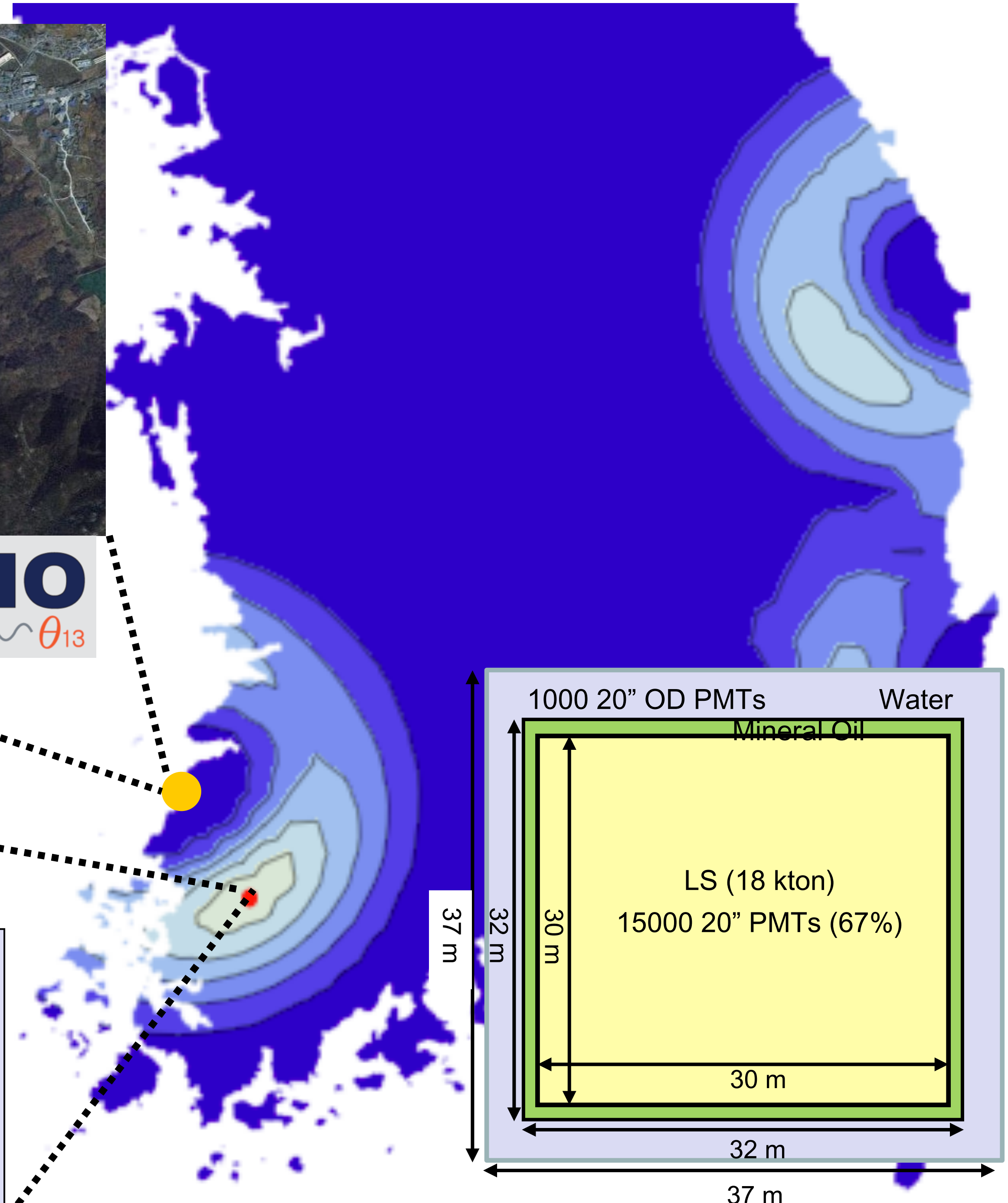
- Need high statistics and excellent energy measurement.

JUNO in China



- Carry out detector R&D now.
- Aim for energy resolution of 3%/√E
- Civil construction began in January 2015.
- Begin data taking in 2020.





RENO-50

18 kton LS Detector
~47 km from YG reactors

Mt. Guemseong (450 m)
~900 m.w.e. overburden

Scientific Potential of JUNO/RENO-50

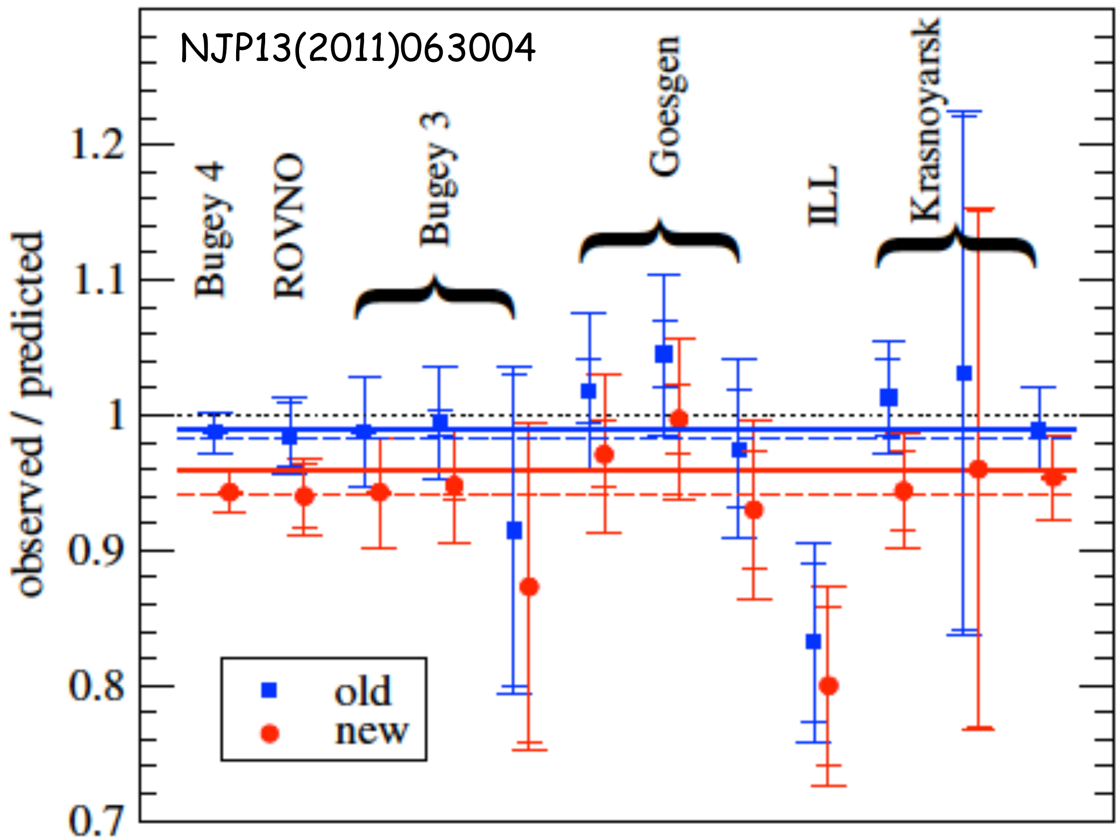
- Resolve the mass hierarchy
  - ~4 standard-deviation discrimination in 6 years
- Precision determination of neutrino-mixing parameters

	Current fractional precision	JUNO/ RENO-50
$\sin^2 2\theta_{12}$	3%	0.7%
Δm^2_{21}	3%	0.6%
Δm^2_{31}	2.5%	0.6%

- Search for supernova neutrinos
  - ~5000 events for supernovae occur at 8 kpc
- Study geo-neutrinos

Reactor Antineutrino Anomaly

- Reactor antineutrino flux at short distance is ~5% smaller
  - New calculations yielded 3% more flux
    - Mention etal., PRD**83**(2011)054615 and update (2012)
    - Huber PRC**84**(2011)024617
  - Included contributions from long-lived isotopes
  - Measured neutron lifetime has decreased, leading to larger σ(IBD).

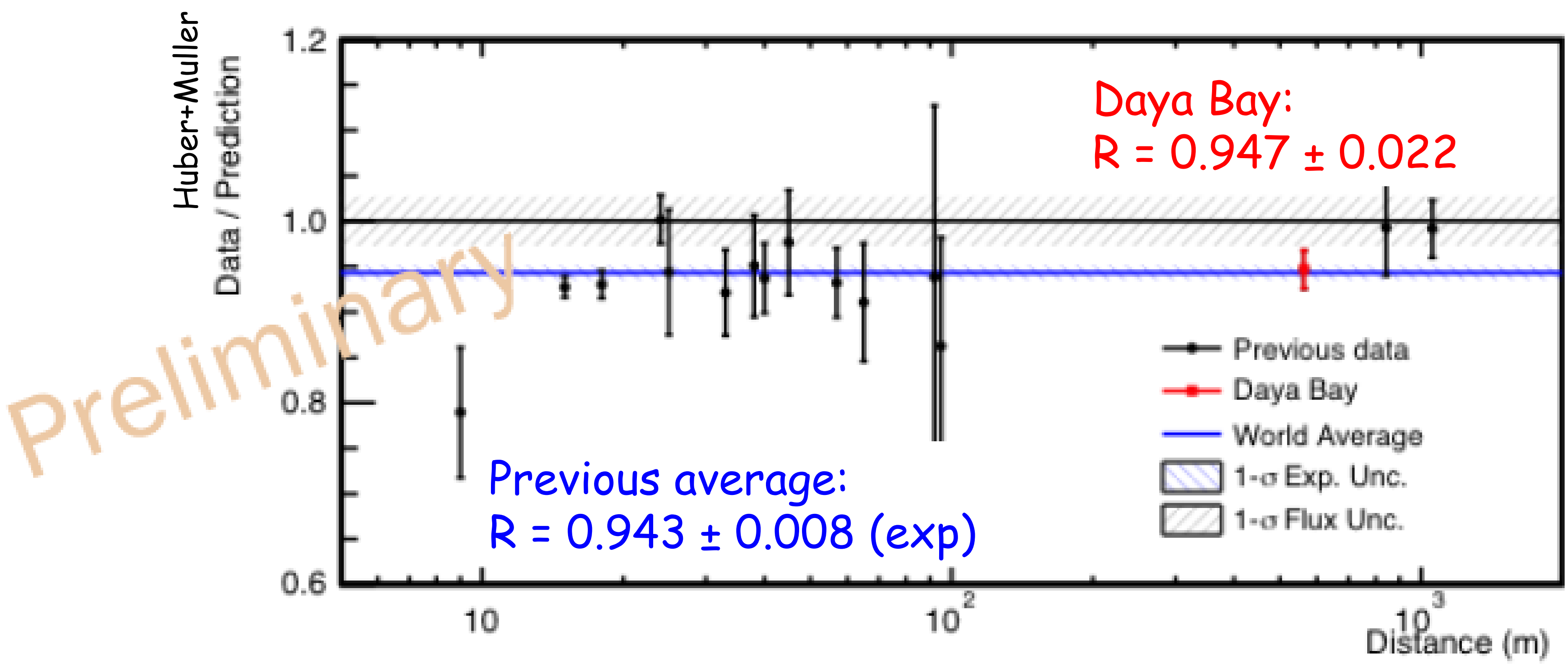


Absolute $\overline{\nu}_e$ Flux

- Flux-weighted baseline of 3 detectors in near halls = 573 m
- Mean fission fractions of data set:

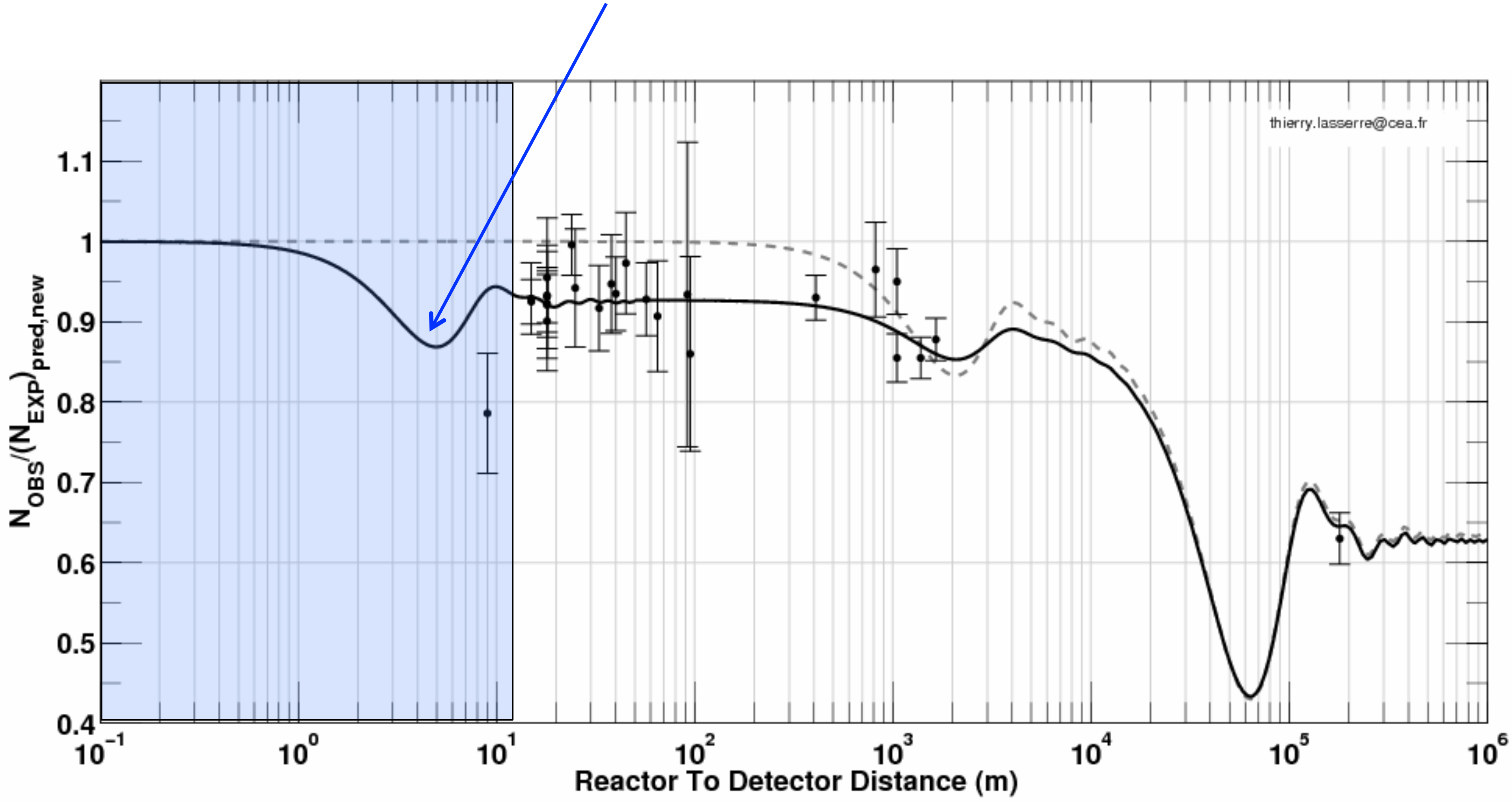
  $^{235}U : ^{238}U : ^{239}Pu : ^{241}Pu = 0.586 : 0.076 : 0.288 : 0.050$

- Daya Bay's result is consistent with those obtained at very short baselines:



Sterile Neutrino As A Solution

Reactor anti-neutrino anomaly may be due to sterile-active neutrino oscillation with $\Delta m^2 \sim 1$ eV^2:



Reactor-based Initiatives

- Very short-baseline reactor neutrino experiments & proposals to look for $\bar{\nu}_e$ disappearance

Project	Gd	^{6}Li	Segmented	Move	Det.	Dist. (m)	Power (MW)	Mass (ton)	Depth (m)
DANNS	yes	no	yes	no	1	9.7-12.2	3000	0.9	50
Hanaro	yes	yes	yes	yes	1	6	30-2800	1	few
Neutrino-4	yes	no	no	yes	1	6-12	100	1.5	~10
Nucifer	yes	no	no	no	1	7	70	0.8	13
Poseidon	yes	no	no	no	1	5-8	100	~3	~15
Prospect	yes	yes	yes	no	2	7-18	85	1 - 10	few
Solid	no	yes	yes	no	1	6-8	45-80	2.9	10
Stéréo	yes	no	no	yes	1	8.8-11.2	57	1.75	18

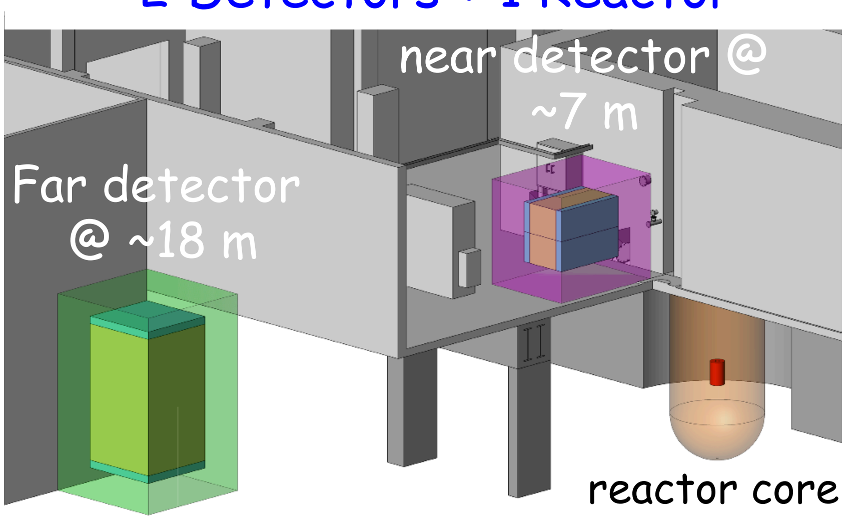
M. Pallavicini

- Challenge: beat down background from reactor & cosmic ray

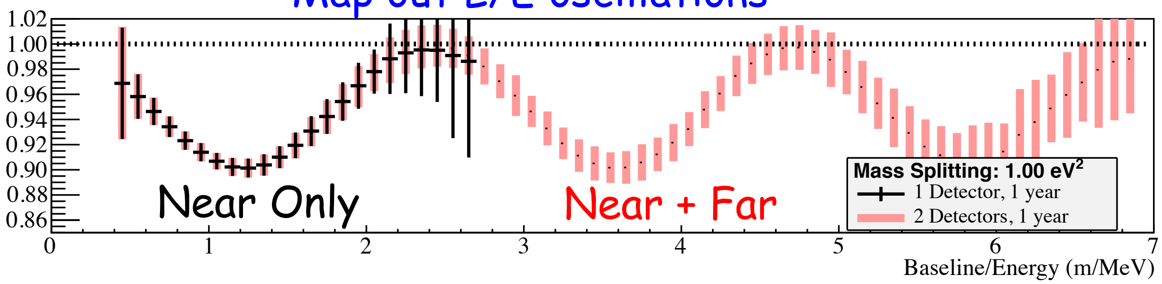
PROSPECT

- **2015**: Measurement with near detector
- **2016-18**: Definitive measurement (5σ) with near+far detectors

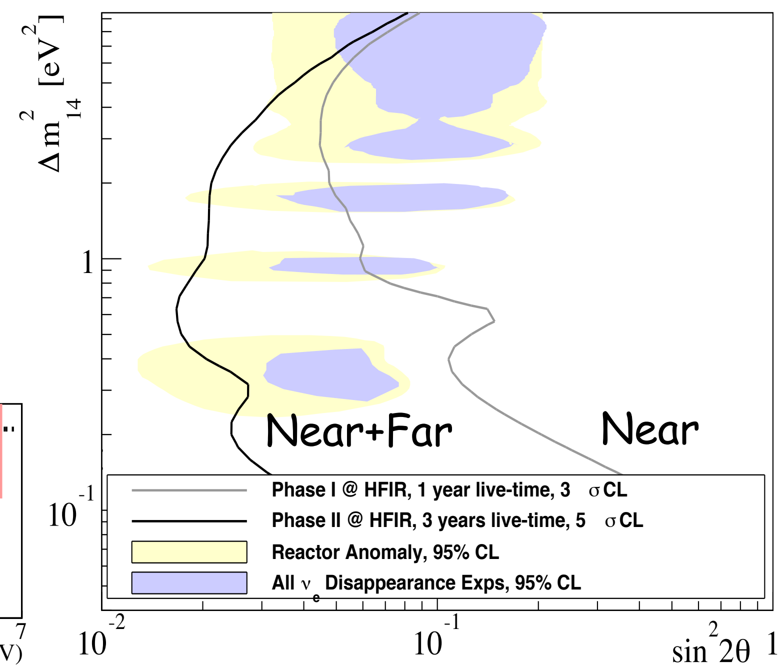
2 Detectors + 1 Reactor



Map out L/E oscillations



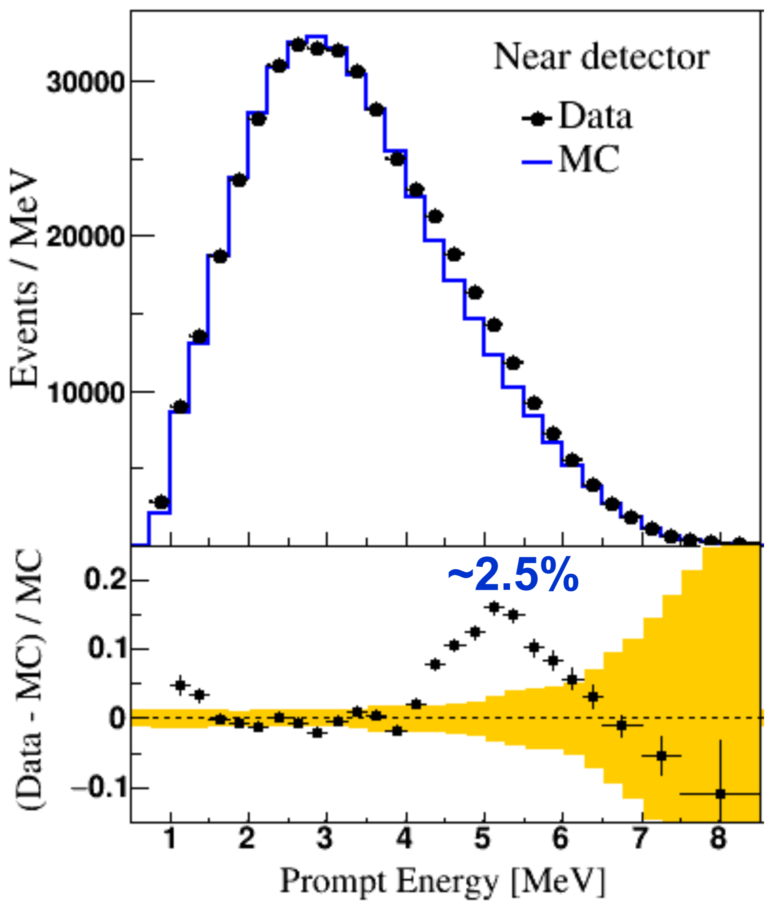
arXiv:1309.7647



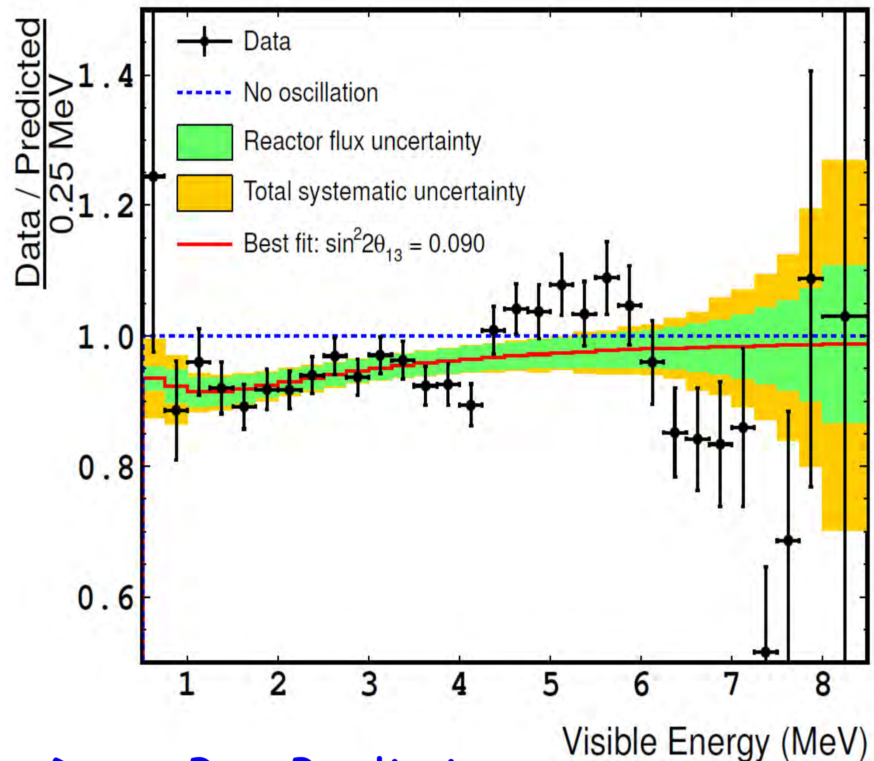
Unexpected Excess Near 5 MeV in Spectrum

Prediction: Huber+Mueller

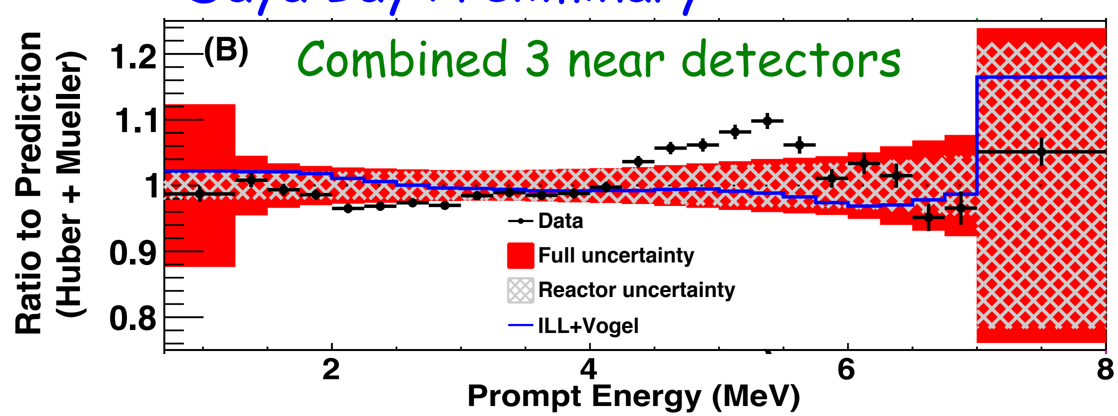
RENO Preliminary



Double Chooz



Daya Bay Preliminary

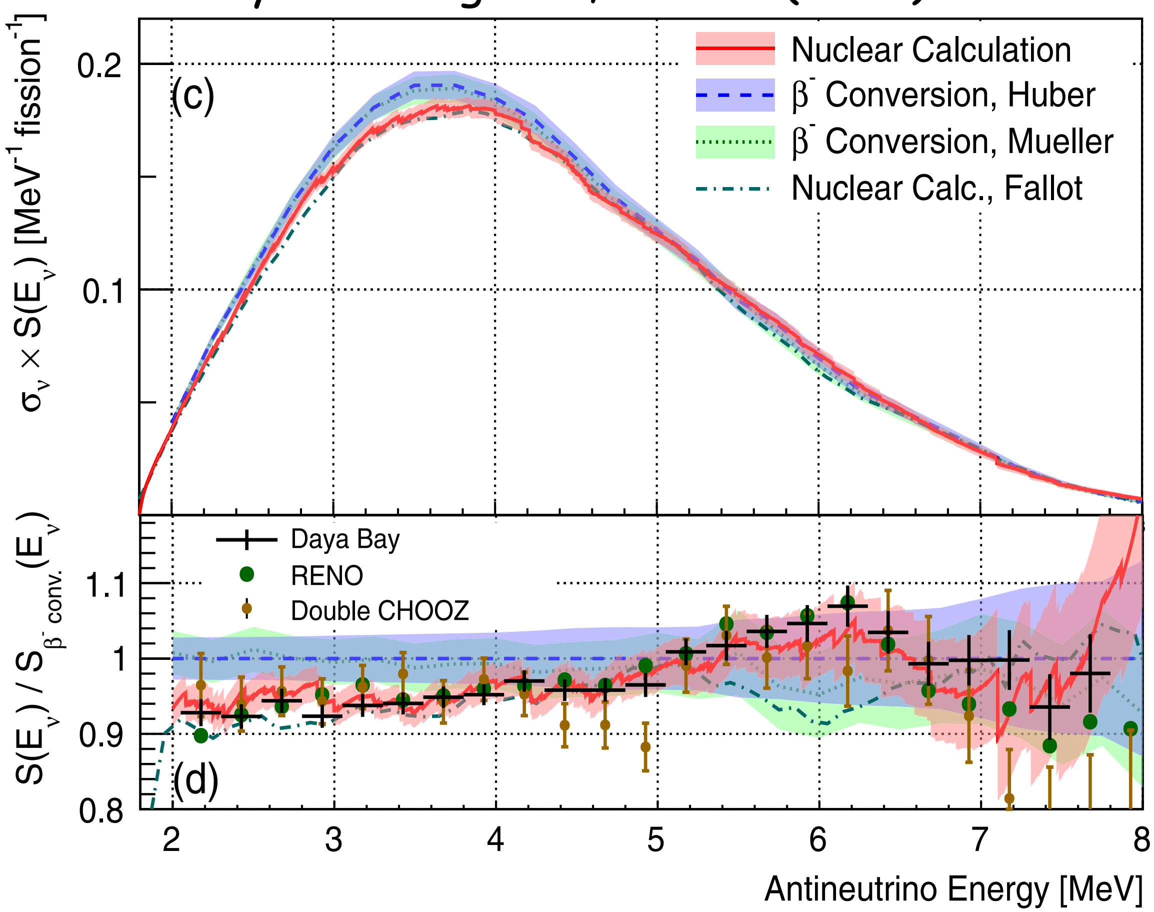


Possible Explanation of Excess of $\bar{\nu}_e$ Events

Direct calculation of $\bar{\nu}_e$ spectrum based on nuclear databases

- combine $\bar{\nu}_e$ spectra of >6000 beta decays of >1000 daughter isotopes in the fission processes

Dwyer & Langford, PRL 114(2015)012502



- Excess of $\bar{\nu}_e$ events come from:
  ^{96}Y, ^{92}Rb. ^{342}Cs, ^{97}Y, ^{93}Rb, ^{100}Nb, ^{140}Cs, ^{95}Sr
- Predicts many fine spectral structures due to Coulomb correction of β-decay that most parametrizations miss

Summary

- Nuclear reactors continue to be excellent tools and have played a key role for studying neutrino physics.

- Reactor antineutrino experiments are essential for
  - Determination of the mixing angle θ_{12}, θ_{13}, and Δm^2
  - Search for light sterile neutrinos
  - Address the neutrino mass hierarchy problem

- There are still unresolved details in nuclear physics for understanding the flux and spectrum of reactor antineutrinos.

- Future of reactor antineutrino experiment is bright!