

Status and Perspectives of θ-13 Experimental Measurements

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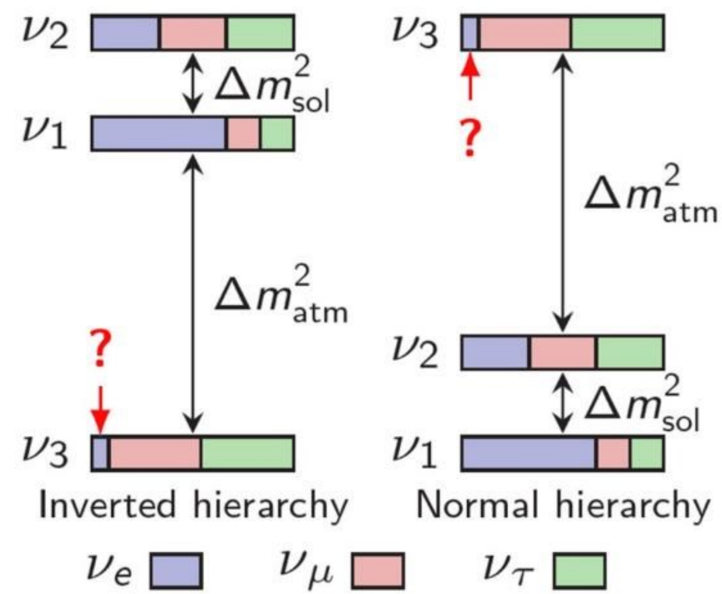
Neutrino Mixing

In a 3-ν framework

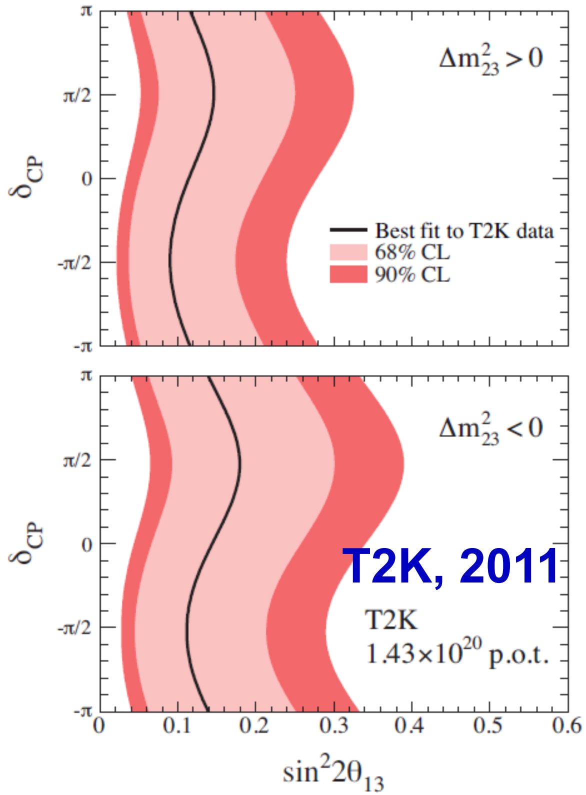
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \sim 45°$	**$\theta_{13} = ?$**	**$\theta_{23} \sim 34°$**	
Atmospheric	**Reactor**	**Solar**	**0νββ**
Accelerator	**Accelerator**	**Reactor**	

Measuring θ_{13}



Accelerator (appearance)

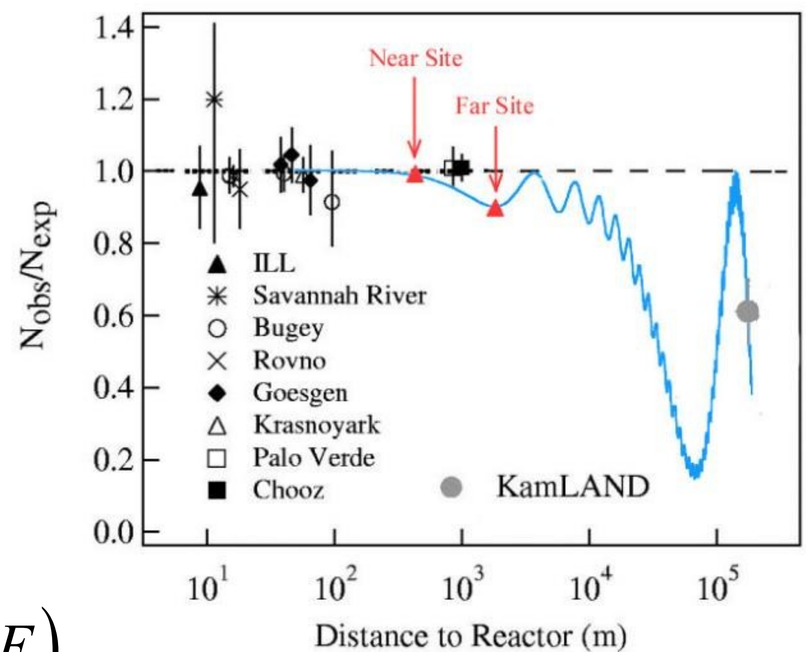
Related with CPV and matter effect

$$P_{\nu_\mu\to\nu_e} = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\Delta m^2_{31} L/4E\right) + (\text{CPV term}) + (\text{matter term}) + \cdots\cdots$$

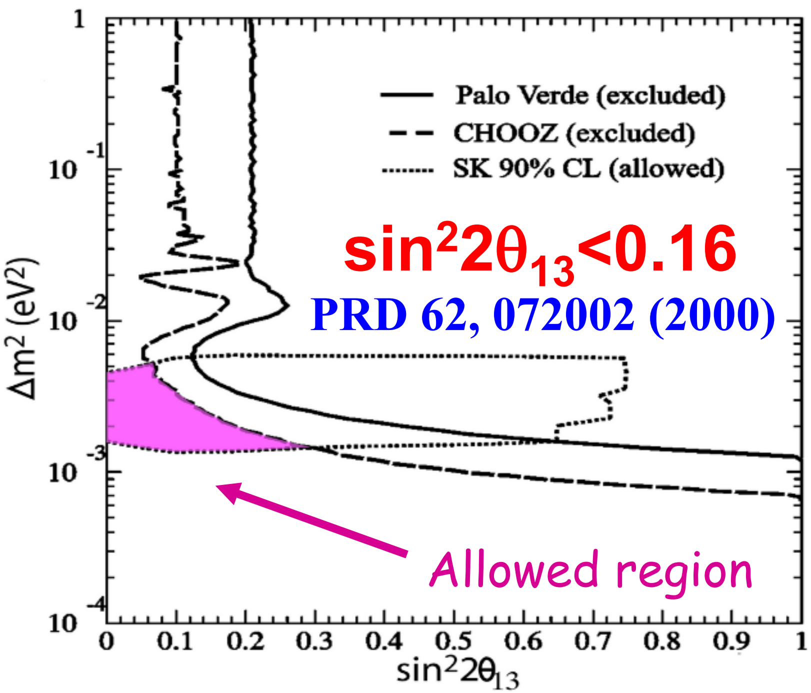
Reactor (disappearance)

Clean in physics, only related to θ_{13}
Large statistics, clean signal
Precision measurement

$$P_{\bar\nu_e\to\bar\nu_e} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{31} L/4E\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\Delta m^2_{21} L/4E\right)$$

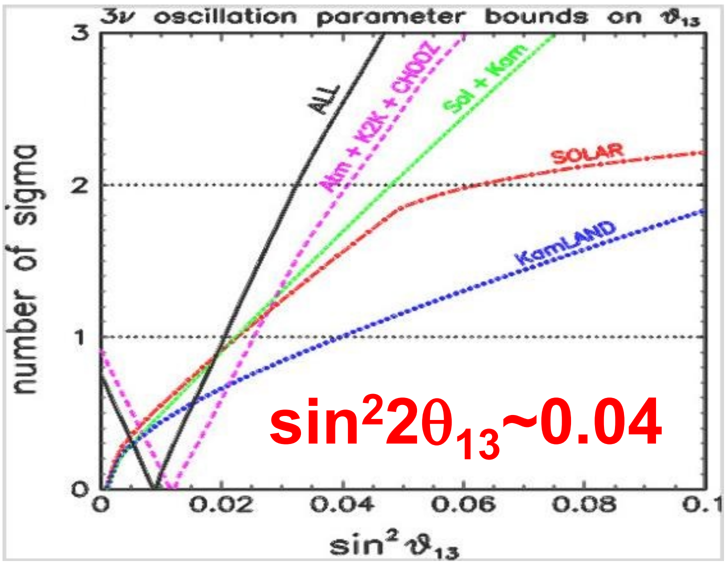


How large is θ_{13}?



$\sin^2 2\theta_{13} < 0.16$

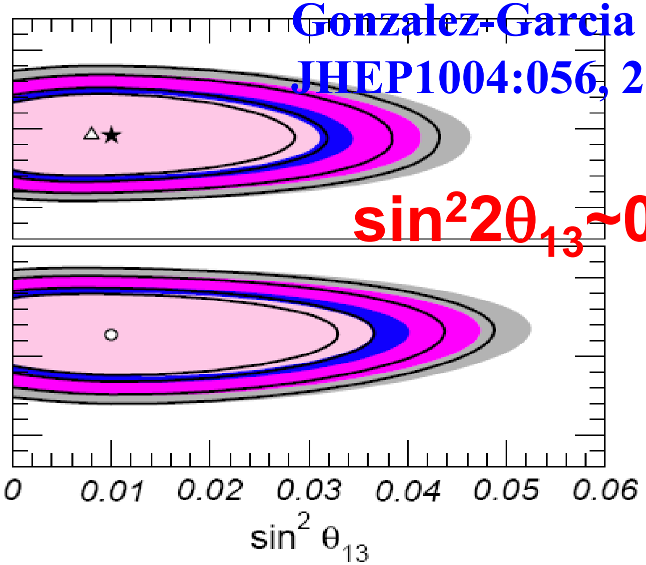
PRD 62, 072002 (2000)



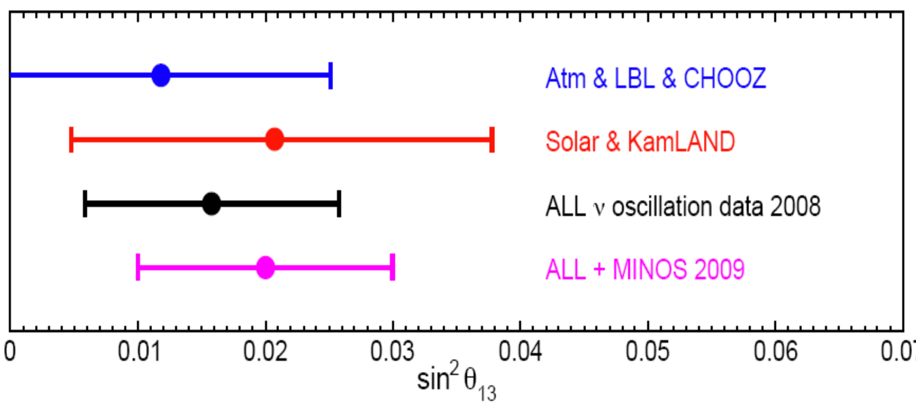
$\sin^2 2\theta_{13} \sim 0.04$

Fogli et al., hep-ph/0506307

Gonzalez-Garcia et al., JHEP1004:056, 2010



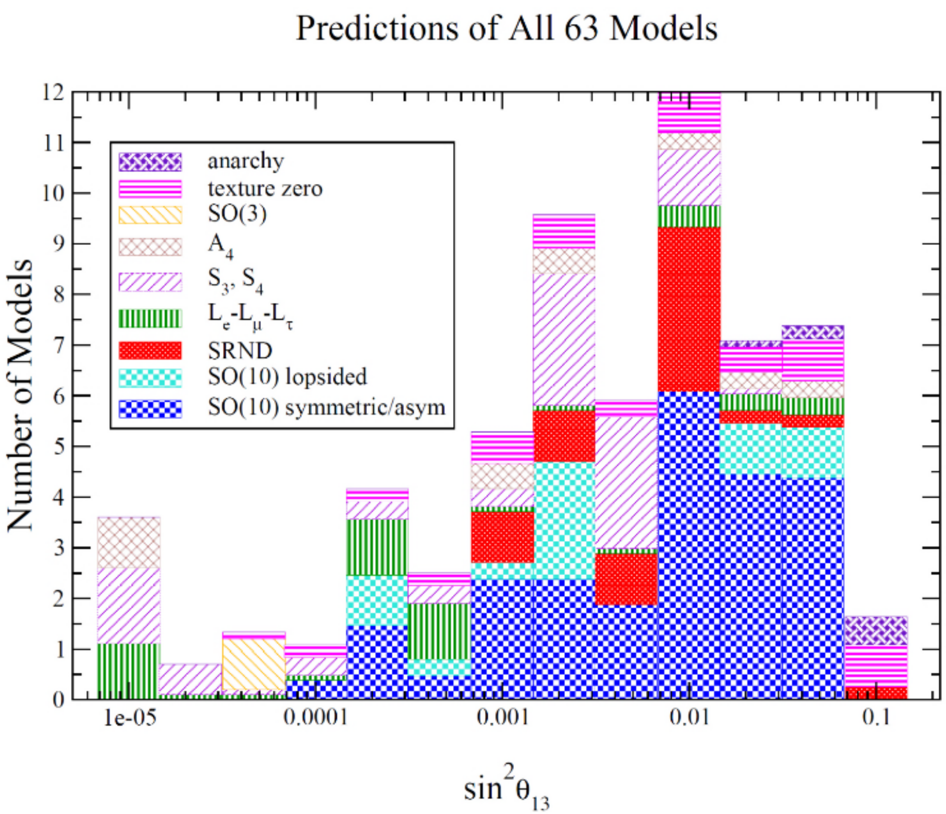
$\sin^2 2\theta_{13} \sim 0.04$



$\sin^2 2\theta_{13} \sim 0.08$, non-zero 2σ

Fogli et al., J.Phys.Conf.Ser.203:012103 (2010)

Measure $\sin^2 2\theta_{13}$ to 0.01



Phys. Rev. D74 (2006) 113006

Gateway to CP phase and Mass Hierarchy:

if $\sin^2 2\theta_{13}$ is too small (e.g. < 0.01), current accelerator technology can not measure CP and MH

→ Neutrino Factory, beta beam, …

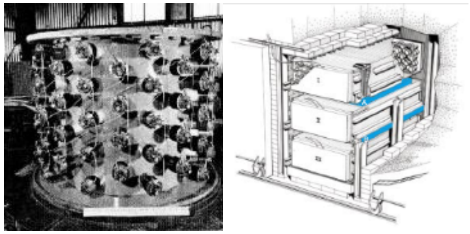
Uncertainty <0.6%

*"We recommend, as a high priority, …, An expeditiously deployed **multi-detector reactor experiment** with sensitivity to $\bar{\nu}_e$ disappearance down to $\sin^2 2\theta_{13}=0.01$"*

---- APS Neutrino Study, 2004

Reactor Neutrino Experiments

Discovery of ν

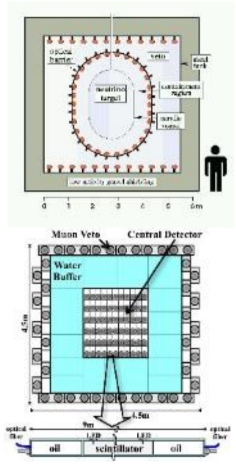


1953, Hanford, 0.3 ton
1956, Savannah River, 4.2 ton

Early searches for oscillation

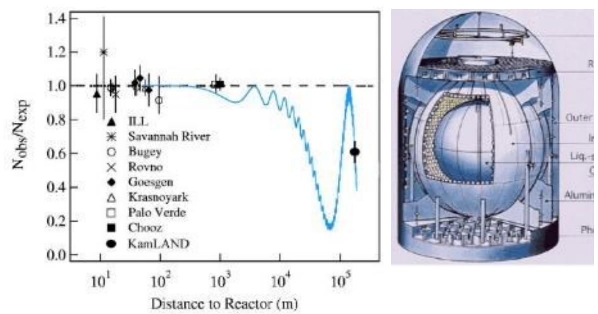
1980 Savannah, **YES**
1980 ILL, **NO**
1984 Bugey, **YES**
1986 Gosgen, **NO**
1995 Bugey-3, **NO**

Reactor ν spectra ~2%



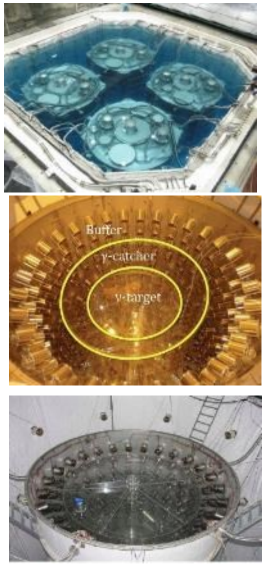
1997, CHOOZ, 8 ton
2000, Palo Verde, 12 ton

$\sin^2 2\theta_{13} < 0.15$



2002, KamLAND, **1000 ton**

Reactor ν oscillation (θ_{12})

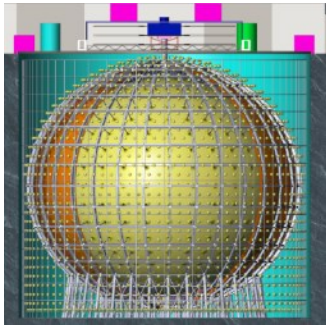


2012,
Daya Bay, 160 ton
Double Chooz, 16 ton
RENO, 32 ton

Non-zero θ_{13}

Mass Hierarchy,
Precision meas.

2020, JUNO, **20 000 ton**



Very short baseline exp. for sterile ν

Precision Measurement at Reactors

Major sources of uncertainties:

- Reactor related ~2%
- Detector related ~2%
- Background 1~3%

Lessons from past experience:

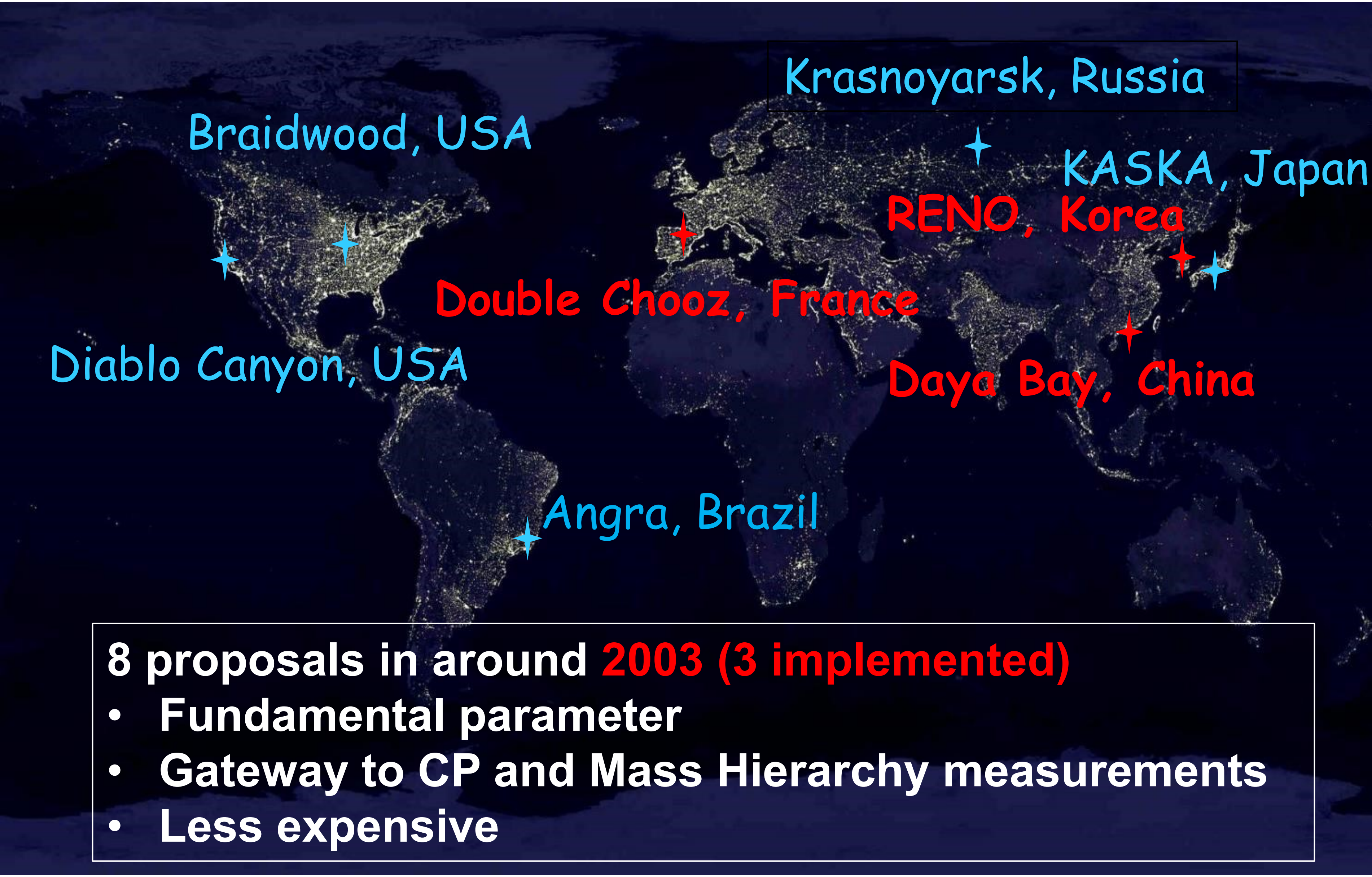
- Chooz: Good Gd-LS
- Palo Verde: Better shielding
- KamLAND: No fiducial cut

Near-far relative measurement

Mikaelyan and Sinev, hep-ex/9908047

	CHOOZ	Near-far	DYB
Reaction cross section	1.9 %	0	0
Energy released per fission	0.6 %	0	0
Reactor power	0.7 %	~0.1%	0.04%
Number of protons	0.8 %	<0.3%	0.03%
Detection efficiency	1.5 %	0.2~0.6%	0.2%→0.13%
Combined	2.7 %	< 0.6%	0.2%→**0.14%**

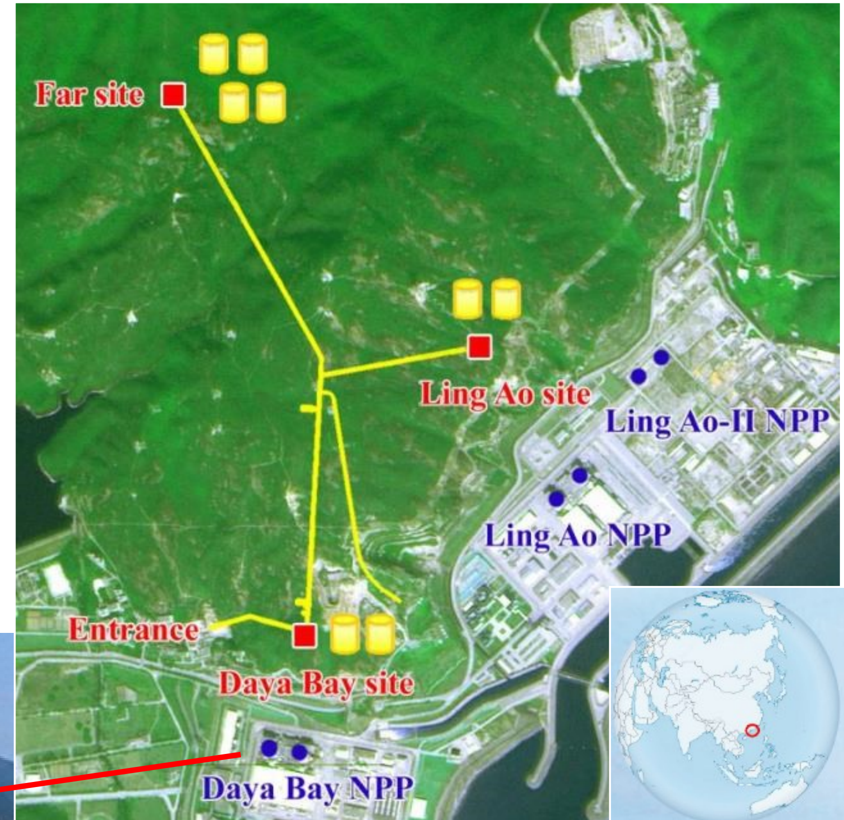
Proposed Reactor Experiments

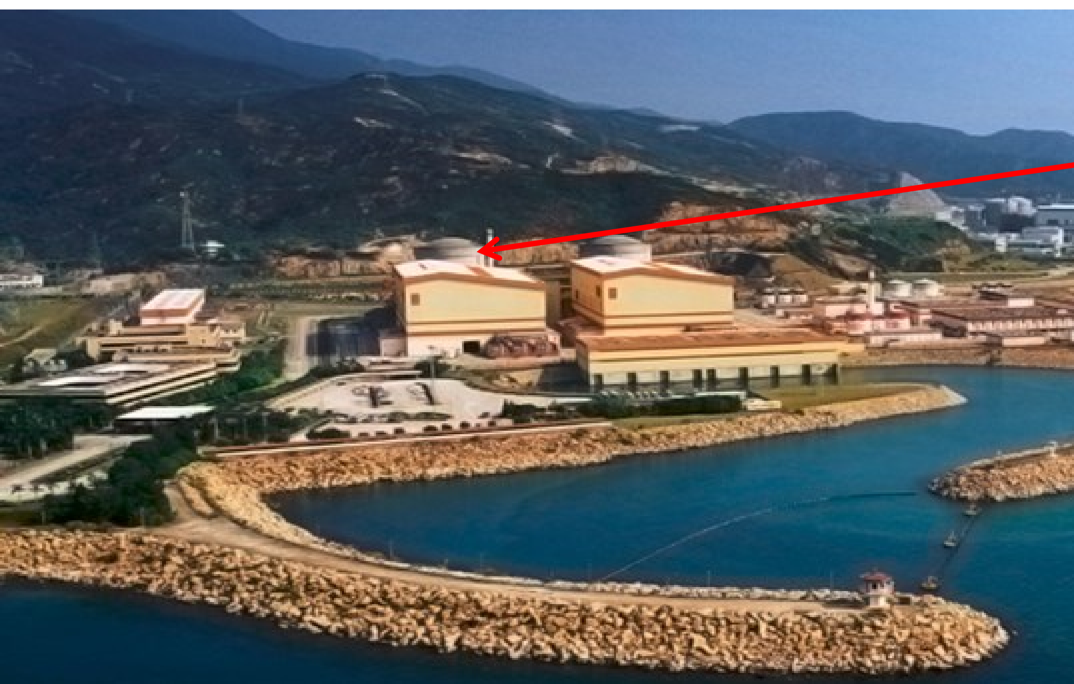


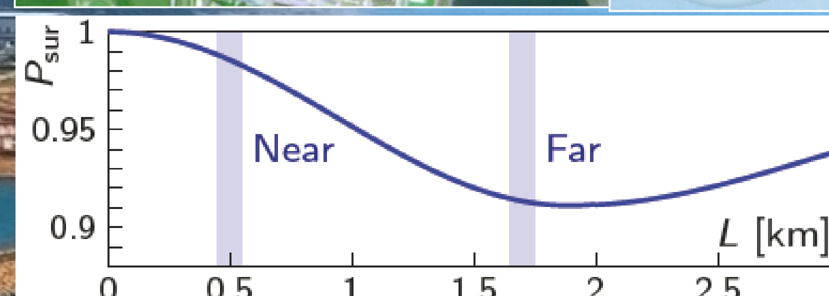
8 proposals in around 2003 (3 implemented)
- **Fundamental parameter**
- **Gateway to CP and Mass Hierarchy measurements**
- **Less expensive**

The Daya Bay Experiment

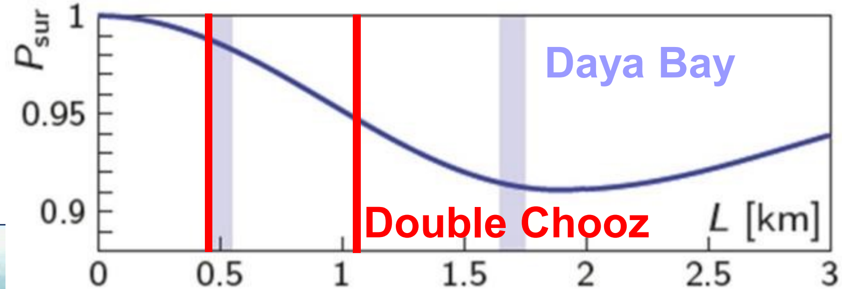
- 6 reactor cores, 17.4 GW_{th}
- Relative measurement
  - 2 near sites, 1 far site
- Multiple detector modules
- Good cosmic shielding
  - 250 m.w.e @ near sites
  - 860 m.w.e @ far site
- Redundancy

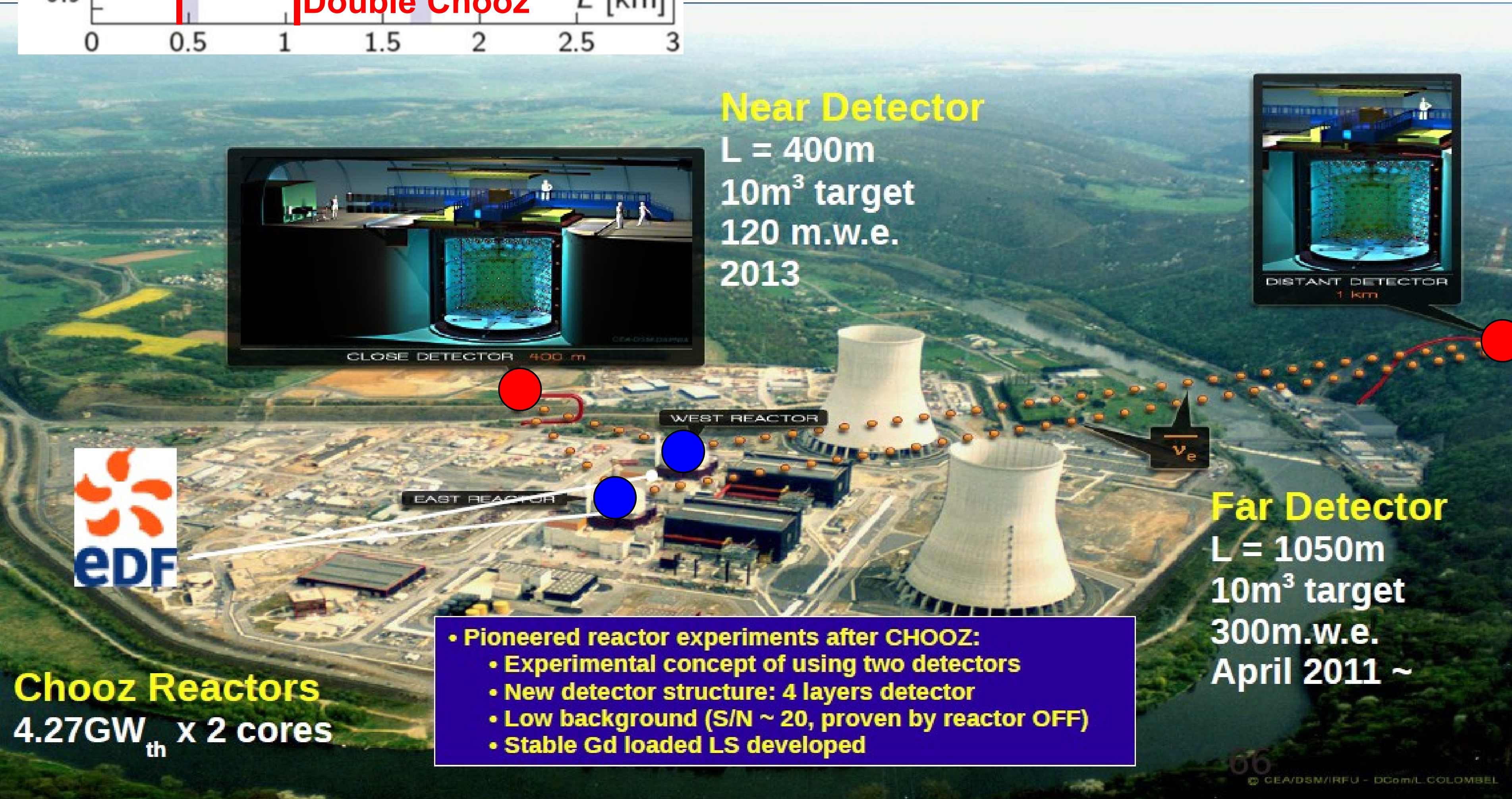






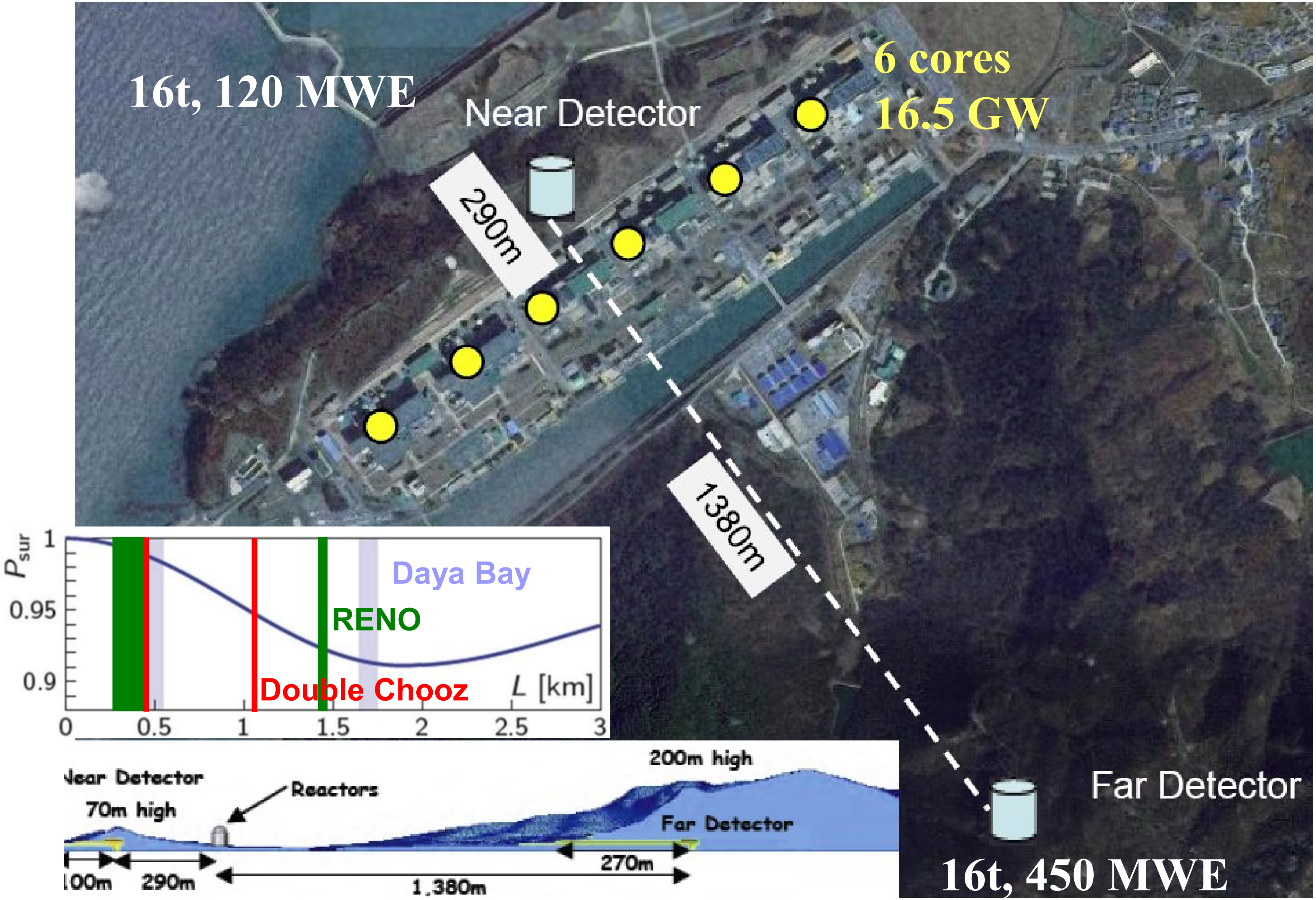
Double Chooz





- Pioneered reactor experiments after CHOOZ:
  - Experimental concept of using two detectors
  - New detector structure: 4 layers detector
  - Low background (S/N ~ 20, proven by reactor OFF)
  - Stable Gd loaded LS developed

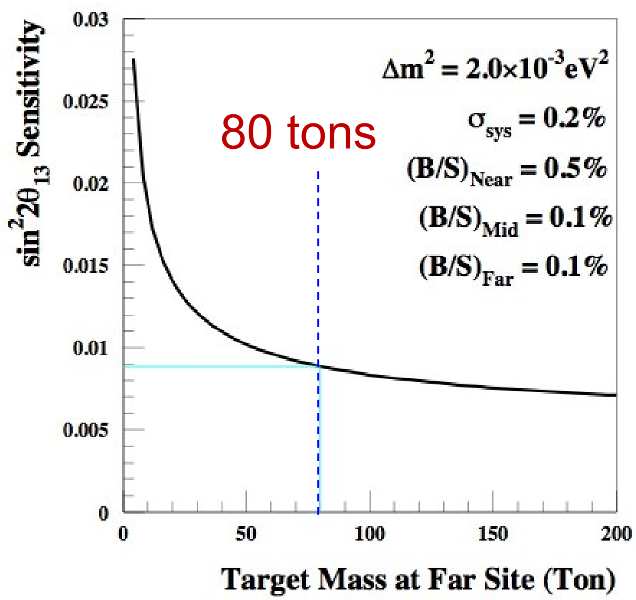
RENO



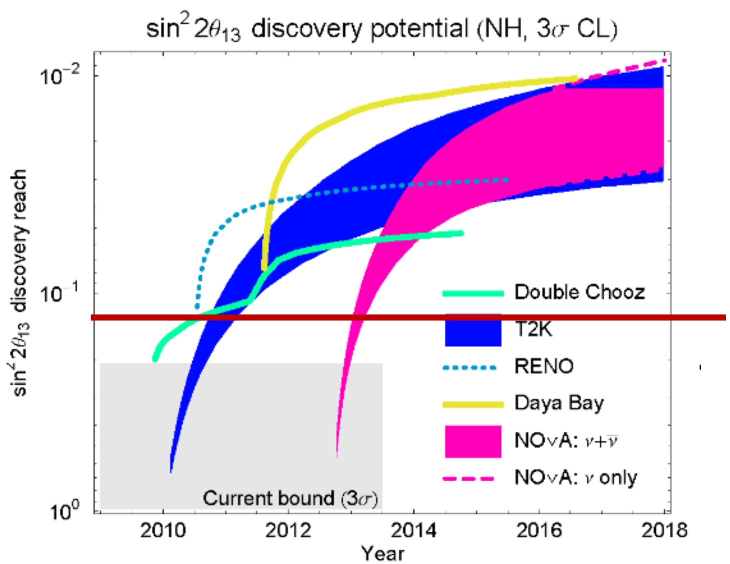
16t, 120 MWE
Near Detector
6 cores
16.5 GW
290m
1380m
Far Detector
16t, 450 MWE
P_{sur}
1
0.95
0.9
0
0.5
1
1.5
2
2.5
3
Daya Bay
RENO
Double Chooz
L [km]
Near Detector
70m high
Reactors
200m high
Far Detector
270m
100m
290m
1,380m

Three on-going experiments

Experiment	Power (GW)	Detector(t) Near/Far	Overburden (MWE) Near/Far	Sensitivity (90%CL)
Double Chooz	8.5	8 / 8	120 / 300	~ 0.03
Daya Bay	17.4	40 / 80	250 / 860	~ 0.008
RENO	16.5	16 / 16	120 / 450	~ 0.02



DYB CDR, sensitivity in 3 years



Huber et al. JHEP 0911:044, 2009

Detecting Reactor Antineutrino

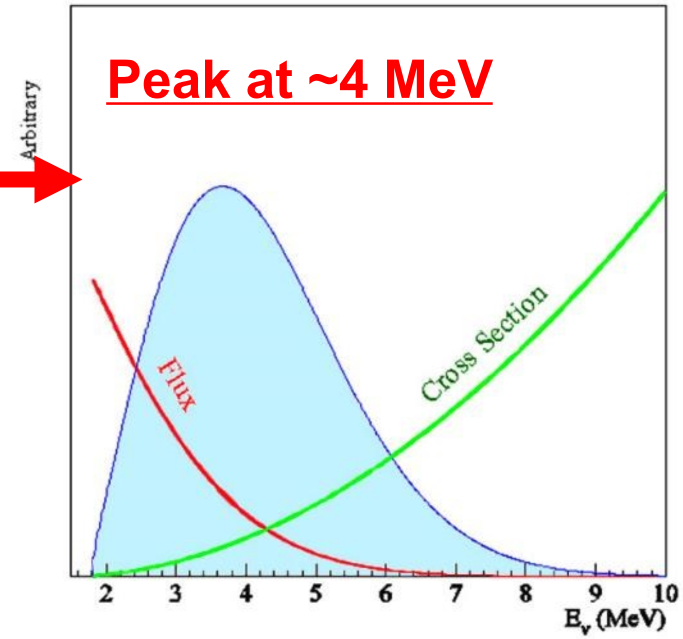
Inverse beta decay

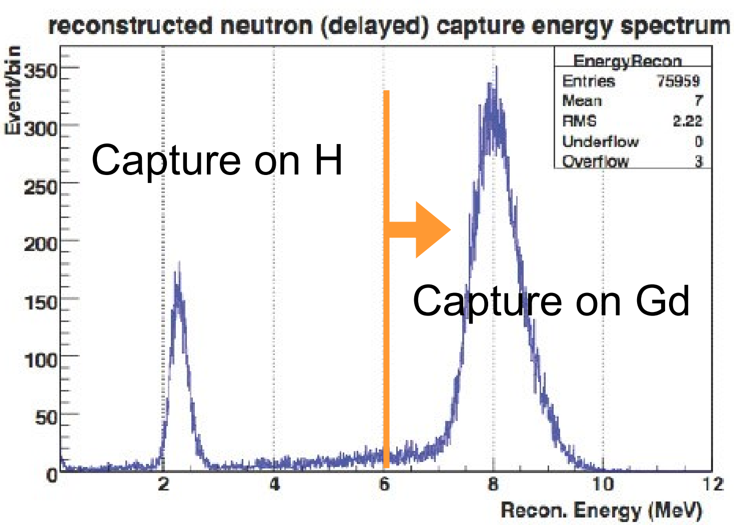
Prompt signal

$$e^{+} + e^{-} \rightarrow 2\gamma$$

$$\bar{\nu}_e + p \rightarrow e^{+} + n$$

Delayed signal, Capture on H (2.2 MeV) or Gd (8 MeV), ~30μs





$$E(\bar{\nu}_e) = E_{\text{prompt}} + Q - m_e$$
$$\sim E_{\text{prompt}} + 0.8\ \text{MeV}$$

Major backgrounds:

- ⇨ **fast neutron**
- ⇨ **$^{8}He/^{9}Li$**
- ⇨ **accidental coincidence**

Similar Detector Design

RPC or Plastic scintillator
⇨ **muon veto**

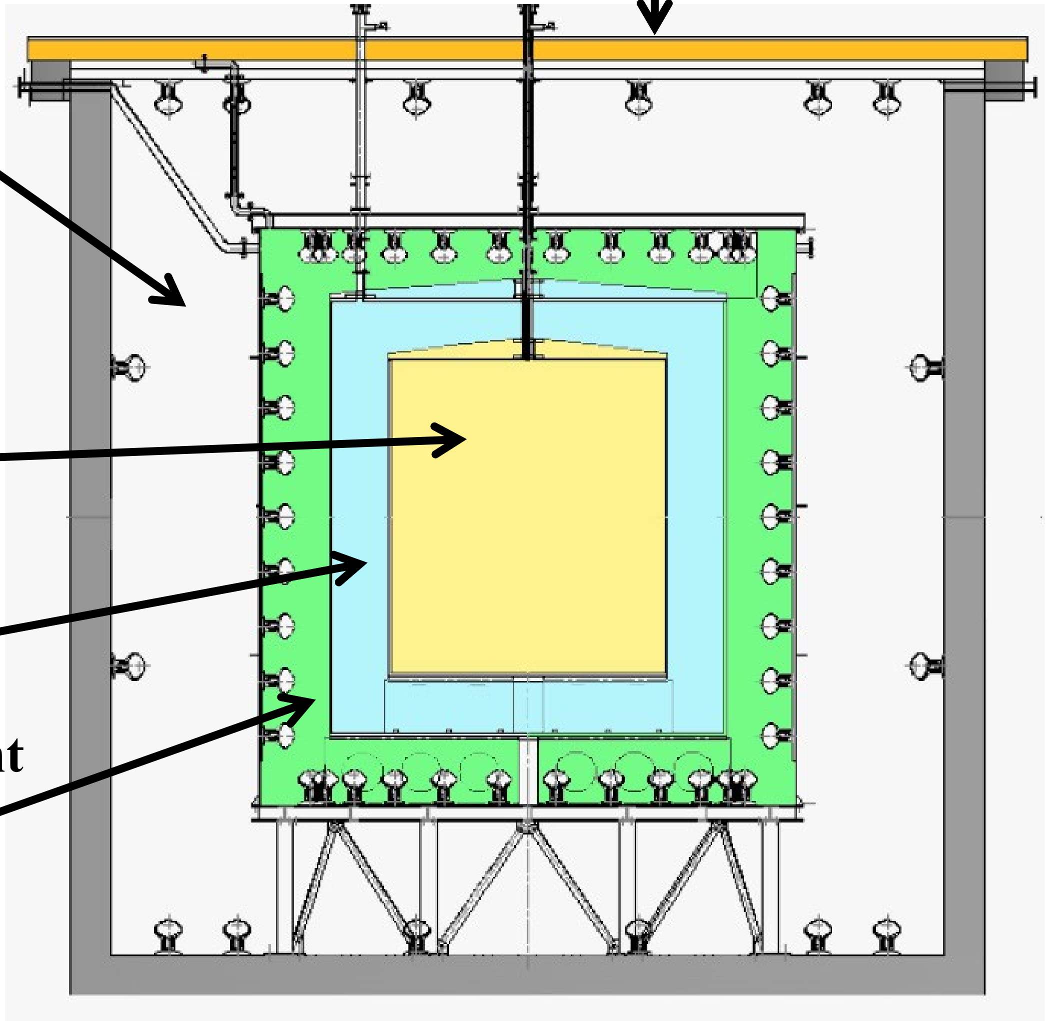
Water
- **Shield radioactivity and cosmogenic neutron**
- **Cherekov detector for muon**

Three-zone neutrino detector

⇨ **Target: Gd-loaded LS**
- **8-20 ton for neutrino**
- **Well defined target proton**

⇨ **γ-catcher: normal LS**
- **~ 10-20t for energy containment**

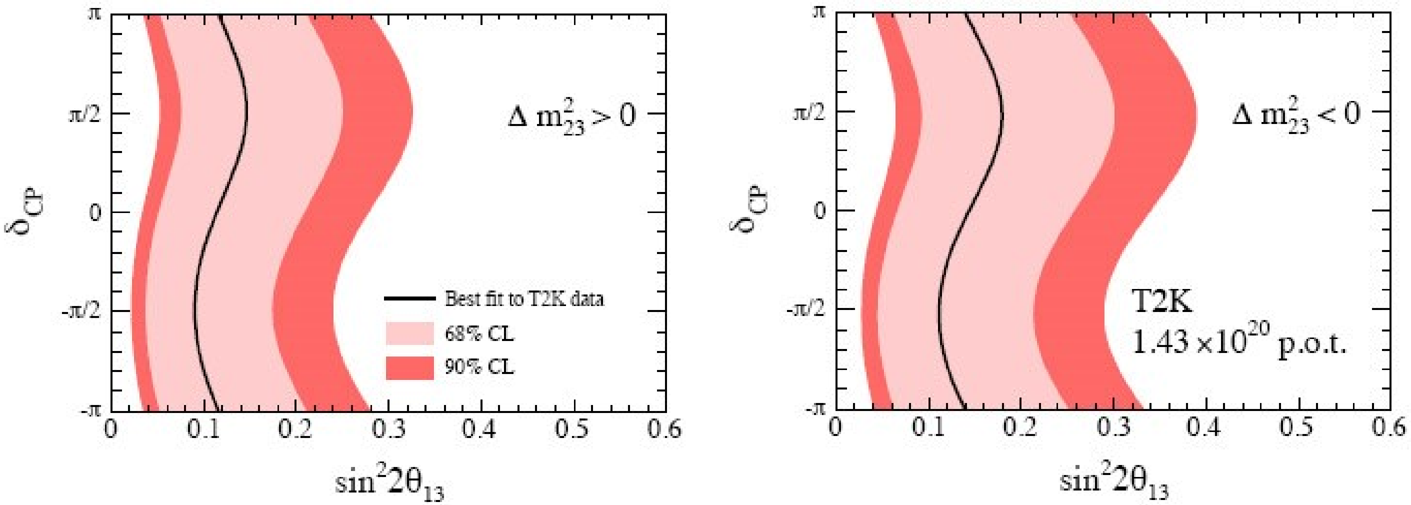
⇨ **Buffer shielding: oil**
- **~ 20-40t for shielding**



T2K Indication in 2011

- 6 ν_e events, 1.5±0.3 bkg expected. (1.43×10^{20} POT)
  - ⇨ θ_{13} non-zero probability 99.3% (2.5σ significance)

(assuming $\Delta m^2_{23}=2.4\times10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$)



90% C.L. interval & Best fit point (assuming $\Delta m^2_{23}=2.4\times10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$)

$0.03 < \sin^2 2\theta_{13} < 0.28$	$0.04 < \sin^2 2\theta_{13} < 0.34$
$\sin^2 2\theta_{13} = 0.11$	$\sin^2 2\theta_{13} = 0.14$

MINOS in 2011

Results on appearance of electron-neutrinos with 8.2×10^{20} POT

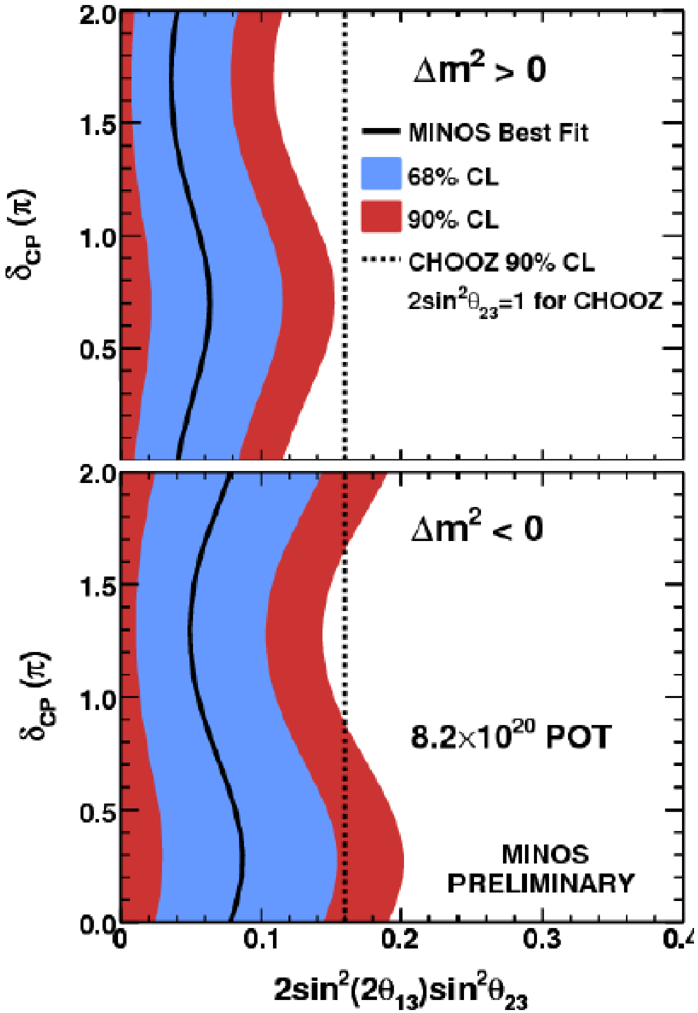
For $\delta_{CP} = 0$ the allowed values of $2\sin^2(2\theta_{13})\sin^2(\theta_{23})$ at 90% CL are:

0 to 0.12 (normal) central value: 0.04
0 to 0.19 (inverted) central value: 0.08

Expected background events:
49.5 ± 2.8 (syst) ± 7.0 (stat)

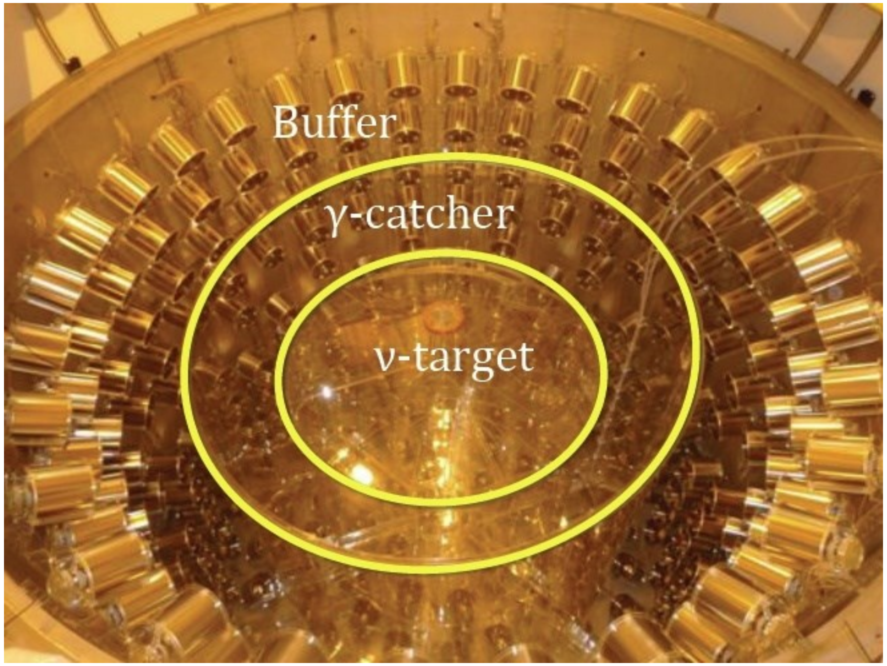
Observed events in FD data:
62

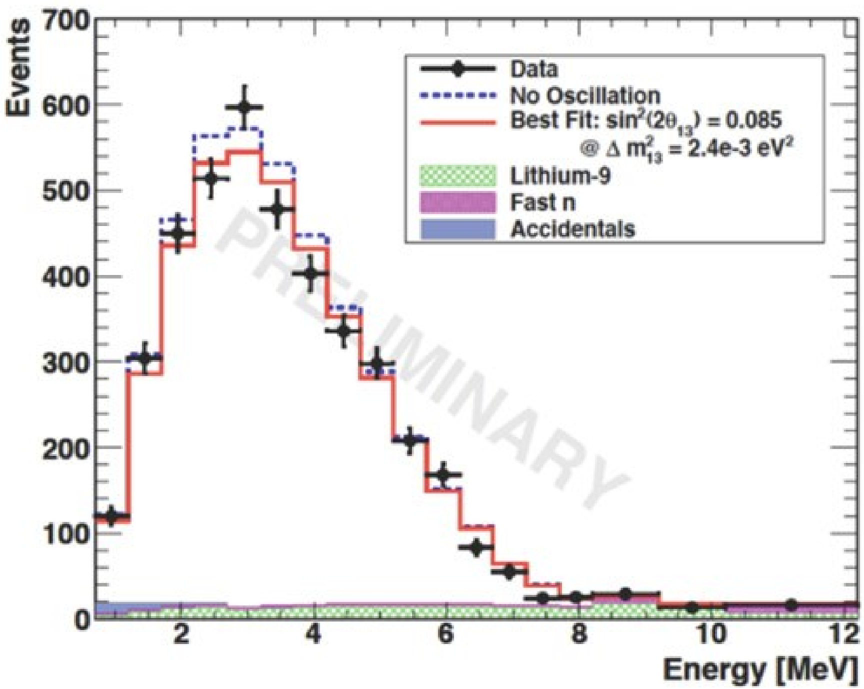
1.7σ excess above background



Exclusion limits based on the selected ν_e candidate event distribution.
Allowed values are in the colored regions

Double Chooz's 1st Results





- **Far detector starts data taking at the beginning of 2011**
- **First results in Nov. 2011 based on 85.6 days of data, at lowNu in Seoul.**

$\sin^2 2\theta_{13}$=0.086±0.041(Stat)±0.030(Syst), 1.7σ for non-zero θ_{13}

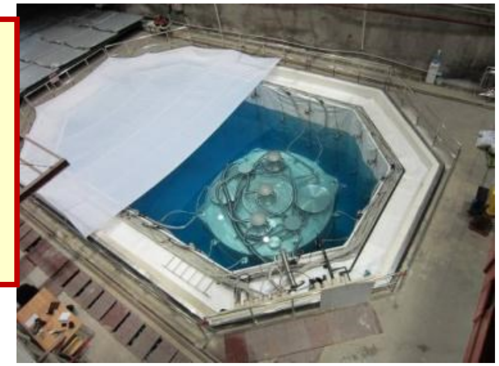
Daya Bay Results

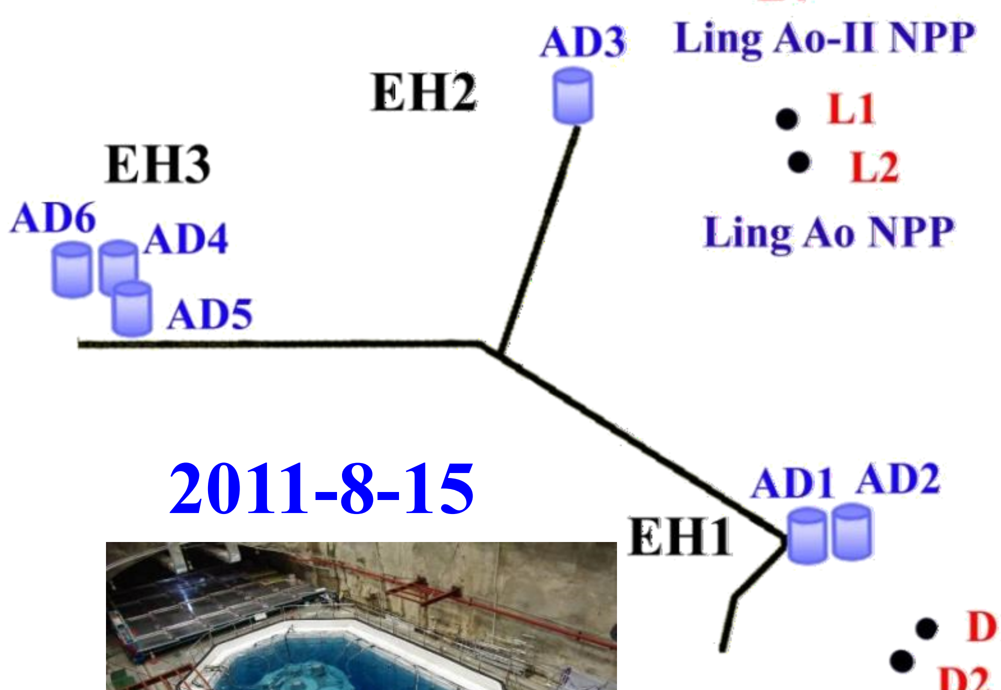
Mar. 8, 2012, with 55 day data

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

5.2σ for non-zero θ_{13}

2011-11-5





2011-12-24

2011-8-15

Blind Strategy:

Baselines, reactor power, target mass

RENO

- **Data taking started on Aug. 11, 2011**
- **First physics results based on 228 days data taking (up to Mar. 25, 2012) released on April 3, 2012, revised on April 8, 2012, published on May 11, 2012:**

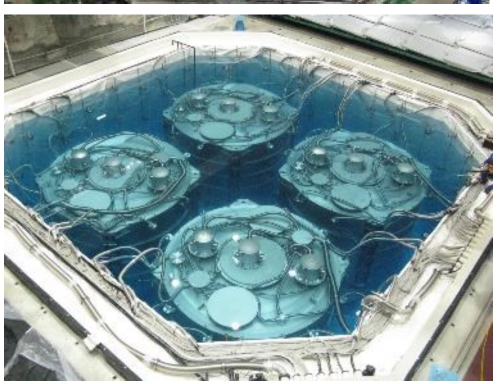
$\sin^2 2\theta_{13} = 0.113 \pm 0.013(\mathrm{Stat}) \pm 0.019(\mathrm{Syst})$, 4.9σ for non-zero θ_{13}

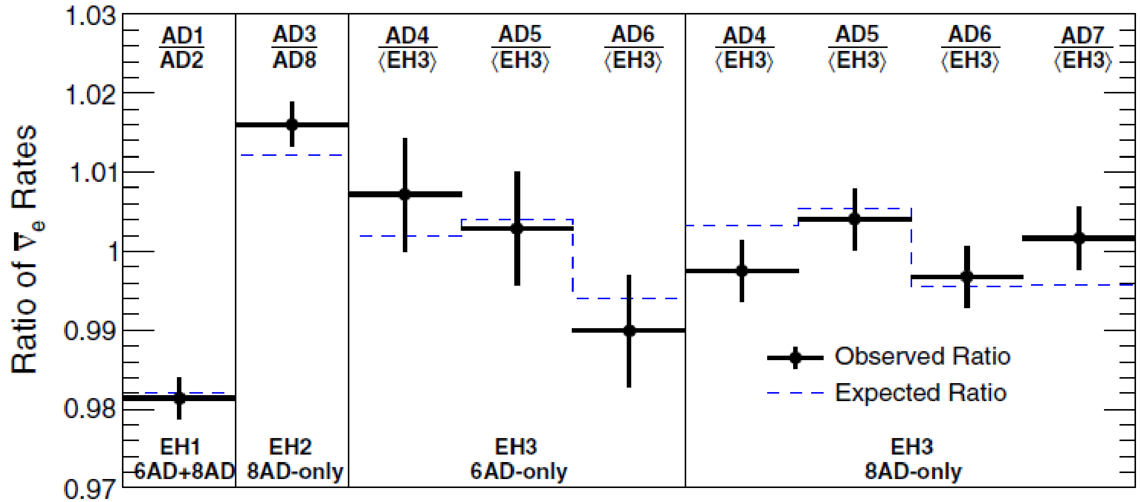
Three Uncertainty Sources (DYB/RENO)

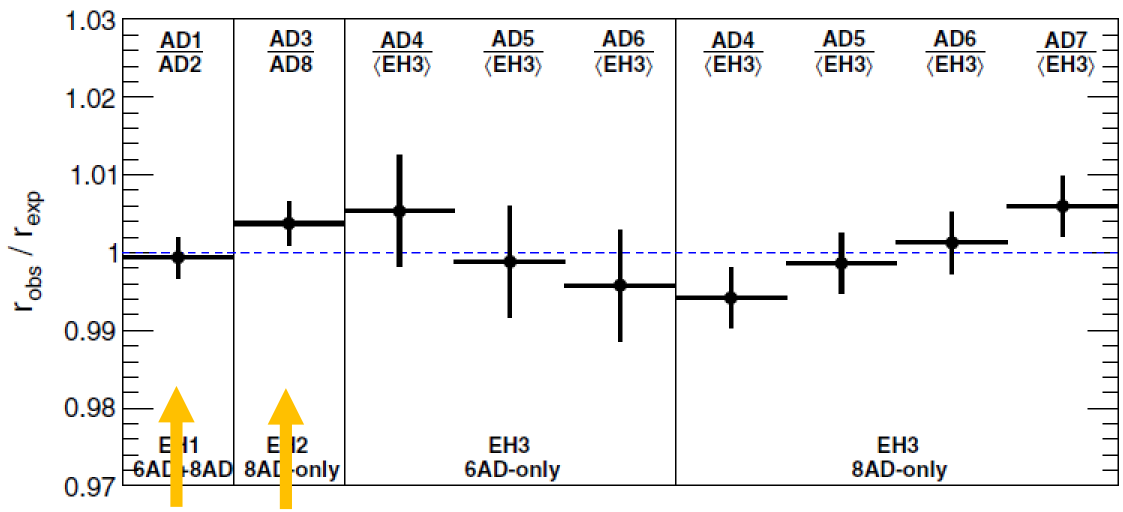
- **1. Reactor**
  - Power ⊕ Fission Fraction, a single core: $\sigma_r \sim 0.8\%$
  - DC: imperfect location of the near site, cancel to 11% of σ_r
  - DYB: 2 near sites for 6 reactors, cancel to 5% of σ_r, i.e. 0.04%
  - RENO: 1 near site for 6 reactors, cancel to 23% of σ_r, i.e. 0.2%
- **2. Detector (DYB side-by-side calibration)**
  - DYB: single detector: 0.2%, statistical cancellation w/ multiple detectors, actual uncertainty: ~0.1%
  - RENO: 0.2%
- **3. Backgrounds (DC constraint from reactor-off)**
  - DYB: 0.2% (N), 0.35% (F)
  - RENO: 0.8% (N)
- **Statistics**
  - DYB: 1% for 55 days (0.18% in 2015, and 0.11% in 2020)
  - RENO: 0.8%
- **DC was not a near/far experiment until 2015.**

"Measuring" Systematics at DYB

If the detector systematics was estimated correctly, detectors at the same site should have the consistent event rates (share the same backgrounds and flux)



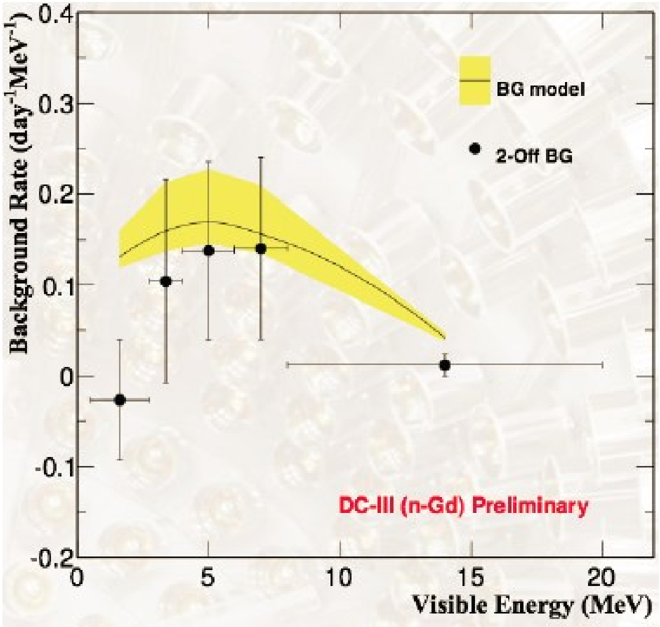


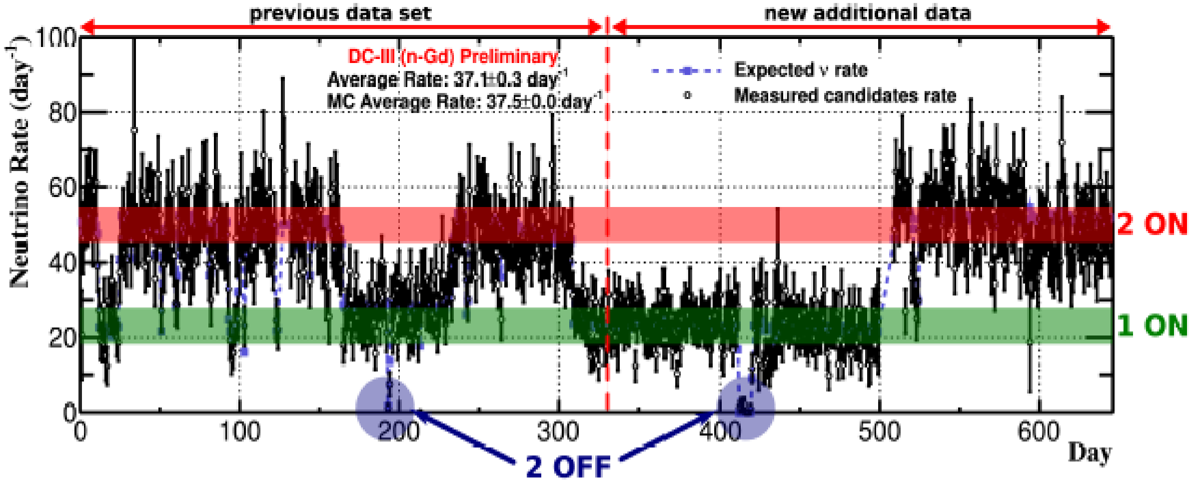


<0.2% **<0.4%** **DYB proposal 0.38%**

Backgrounds at DC

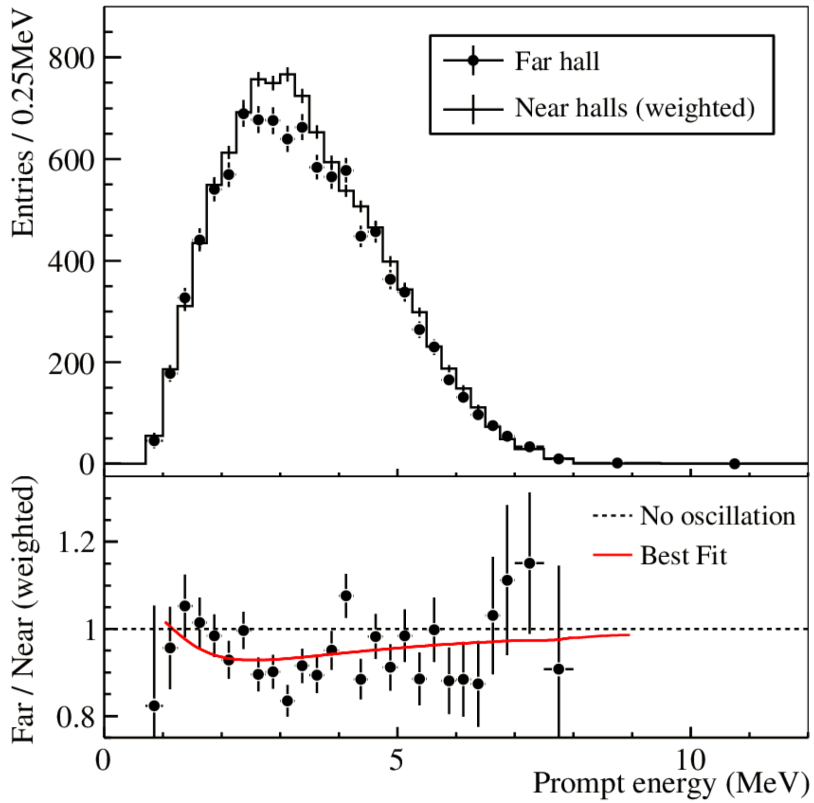
- **Direct measurement of backgrounds:**
  - 7 events in 7.24 days
  - $12.9^{+3.1}_{-1.4}$ expected
  - Tension @ ~ 2σ ➔ no room for unknown backgrounds



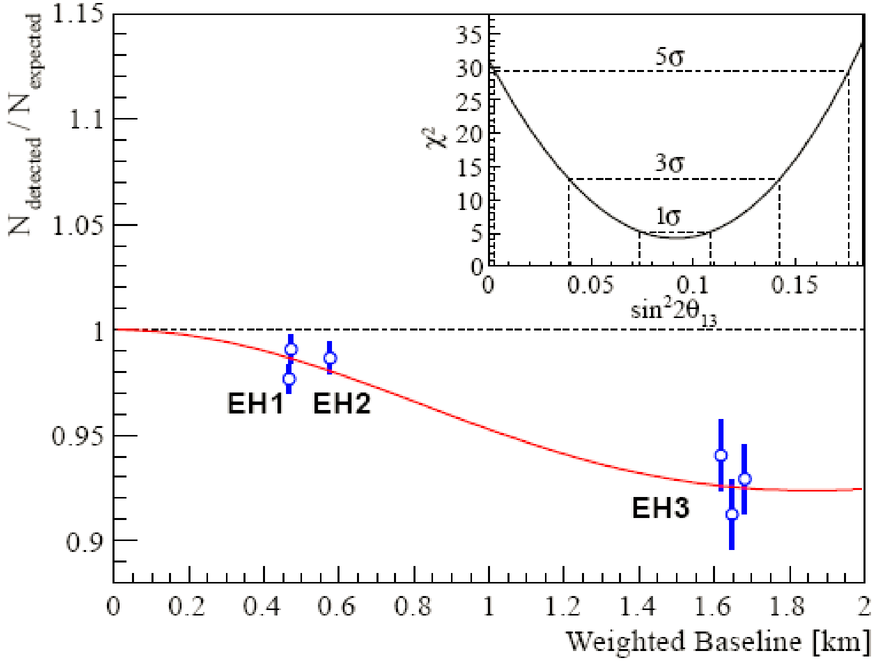


Haser, ICHEP14

First measurement at Daya Bay



20% precision in $\sin^2 2\theta_{13}$

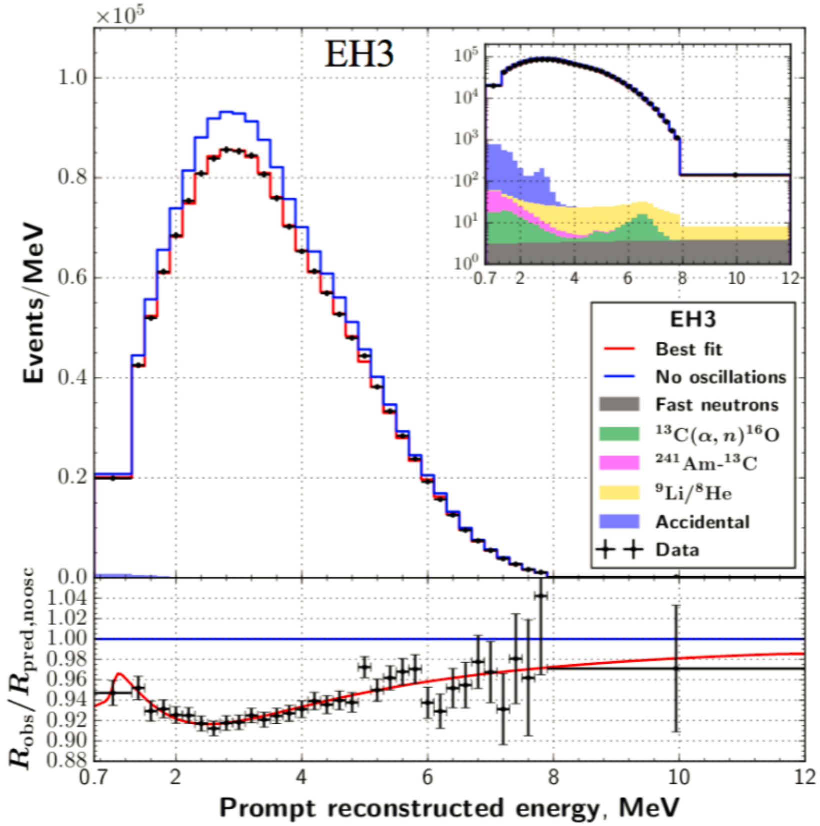


R = 0.940 ± 0.011 (stat) ± 0.004 (syst)

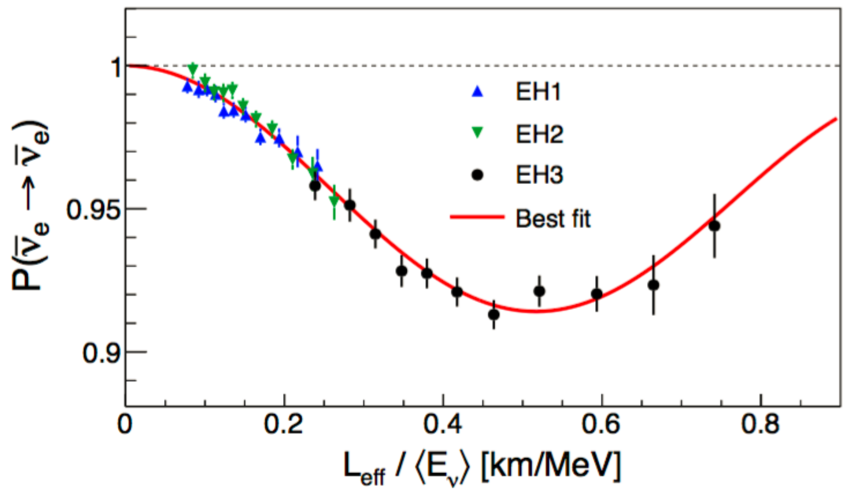
$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$

A clear observation of far site deficit with the first 55 days' data.
5.2 σ for non-zero value of θ_{13}
Spectral distortion consistent with oscillation.

Latest Measurement at Daya Bay



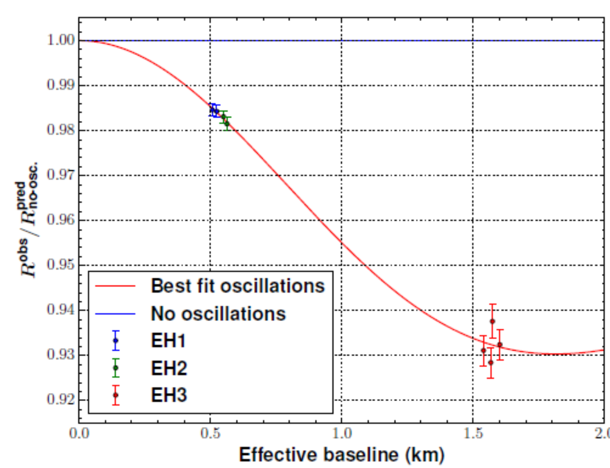
4% precision in $\sin^2 2\theta_{13}$



$\sin^2 2\theta_{13} = [8.41 \pm 0.33] \times 10^{-2}$

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

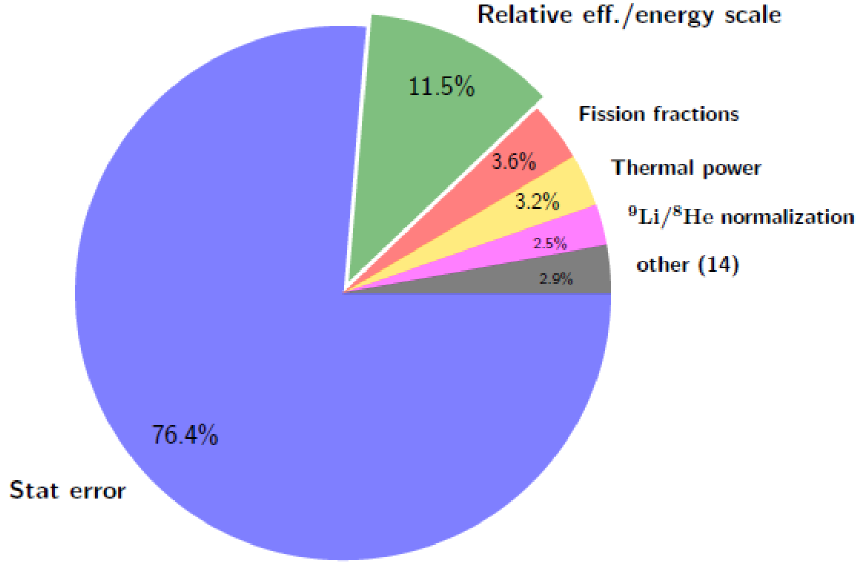
IH: $\Delta m^2_{32} = [-2.55 \pm 0.08] \times 10^{-3}\ eV^2$



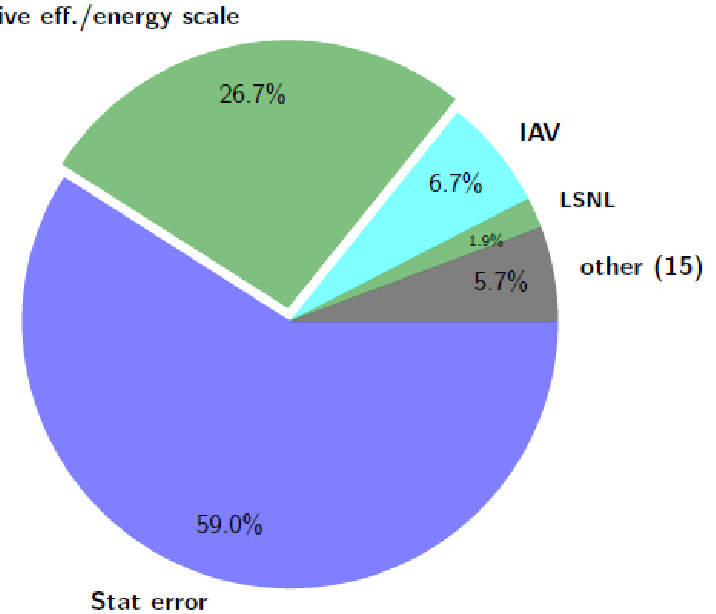
1230 days

PRD 95, 072006 (2017)

Current DYB Error Budget

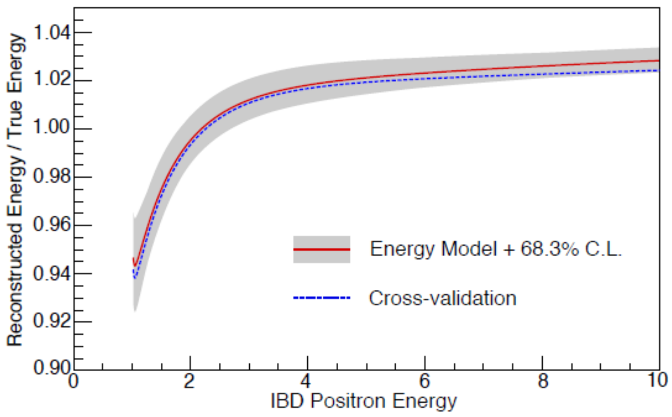


$\sin^2 2\theta_{13}$

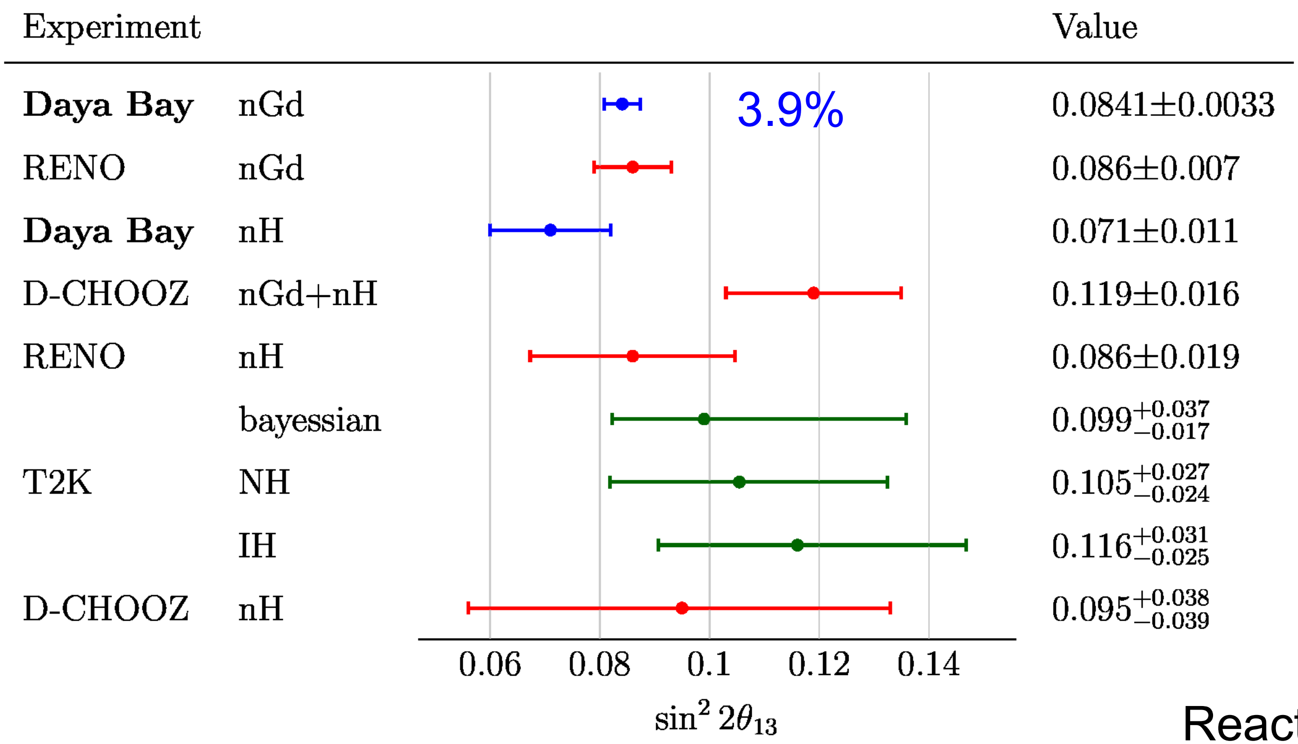


Δm^2_{32}

Statistics	0.18%	
Efficiency	~0.1%	Single det. 0.14%
Background	0.13%	Spectrum constraint
Reactor	0.04%	
Non-linearity	~1%	Less important

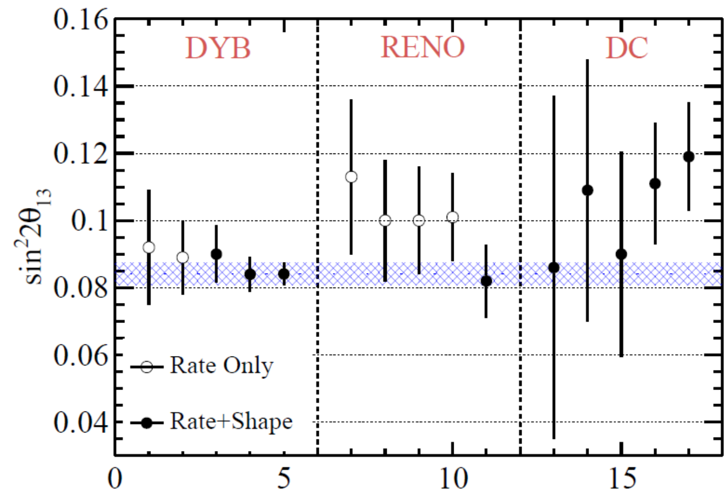


Global Status in θ_{13}



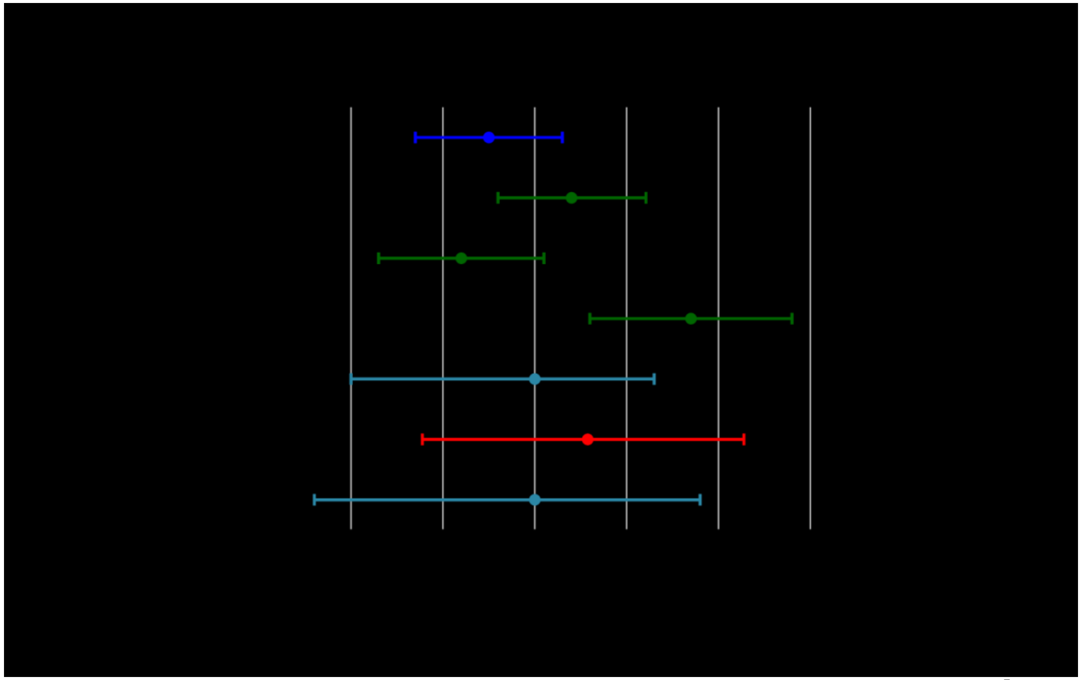
By Maxim Gonchar

Reactor release history

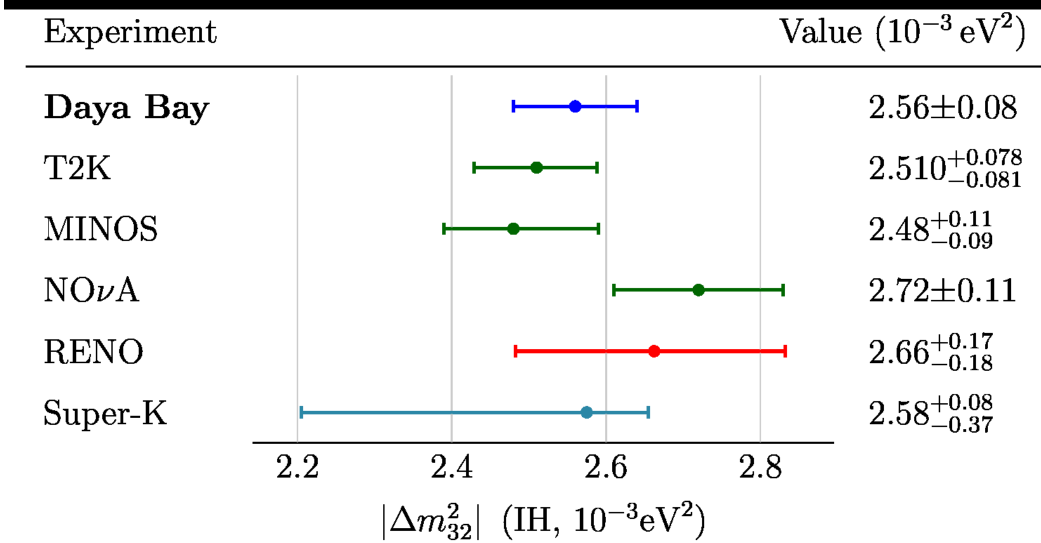


By Jie Zhao

Global Status in Mass Split

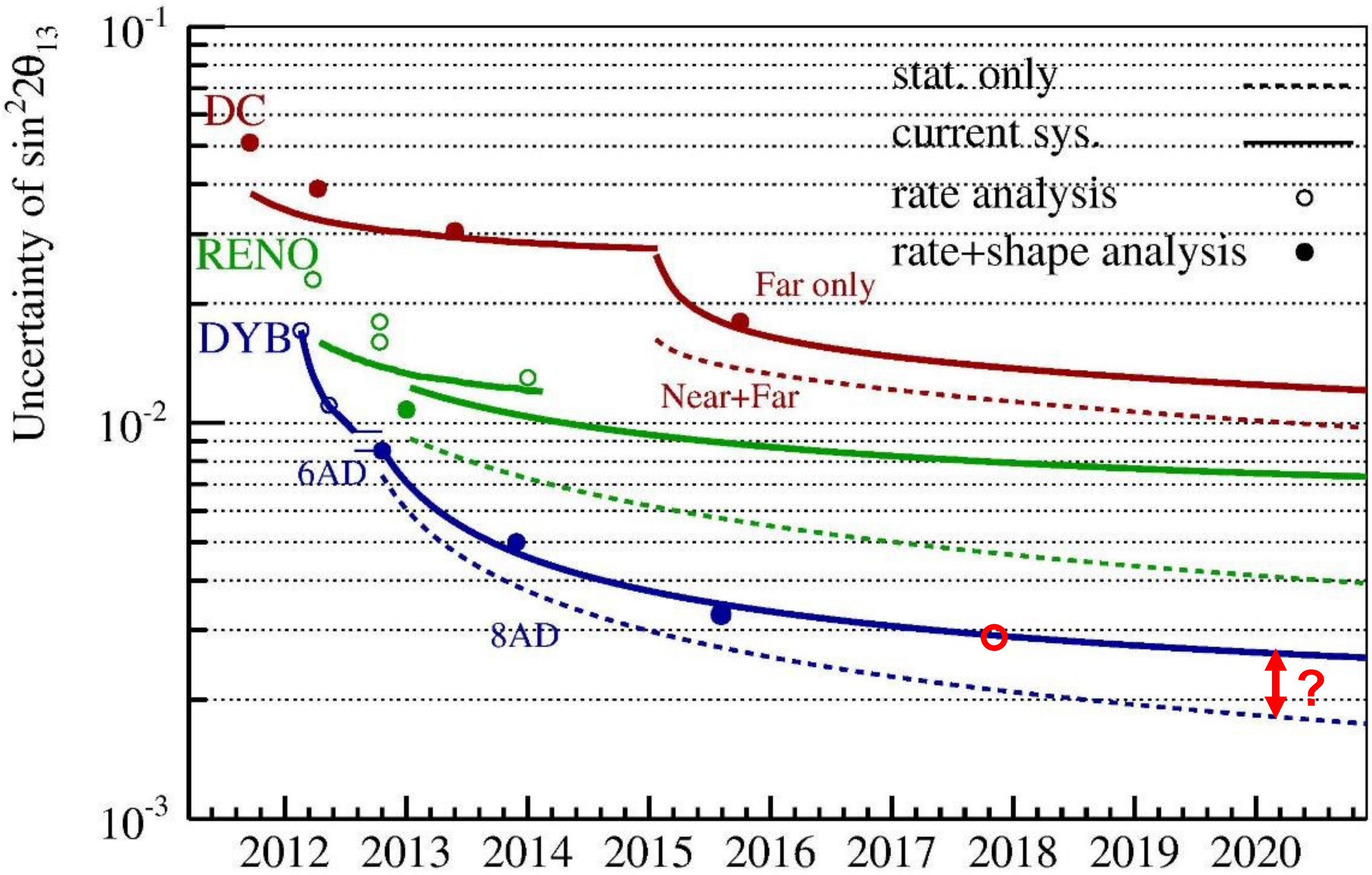


3.2%



By Maxim Gonchar

Future Sensitivity



By Jie Zhao

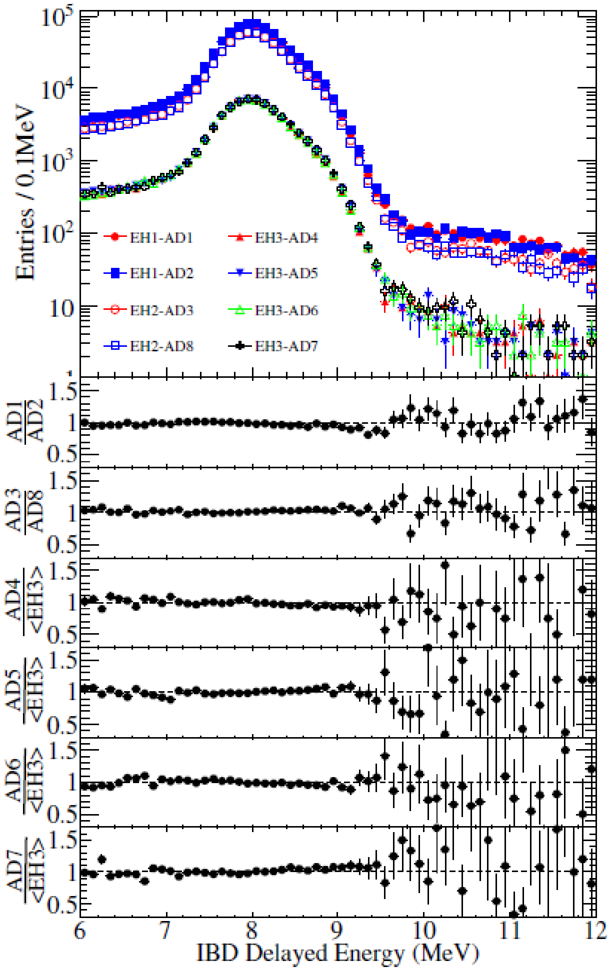
3% or 2%

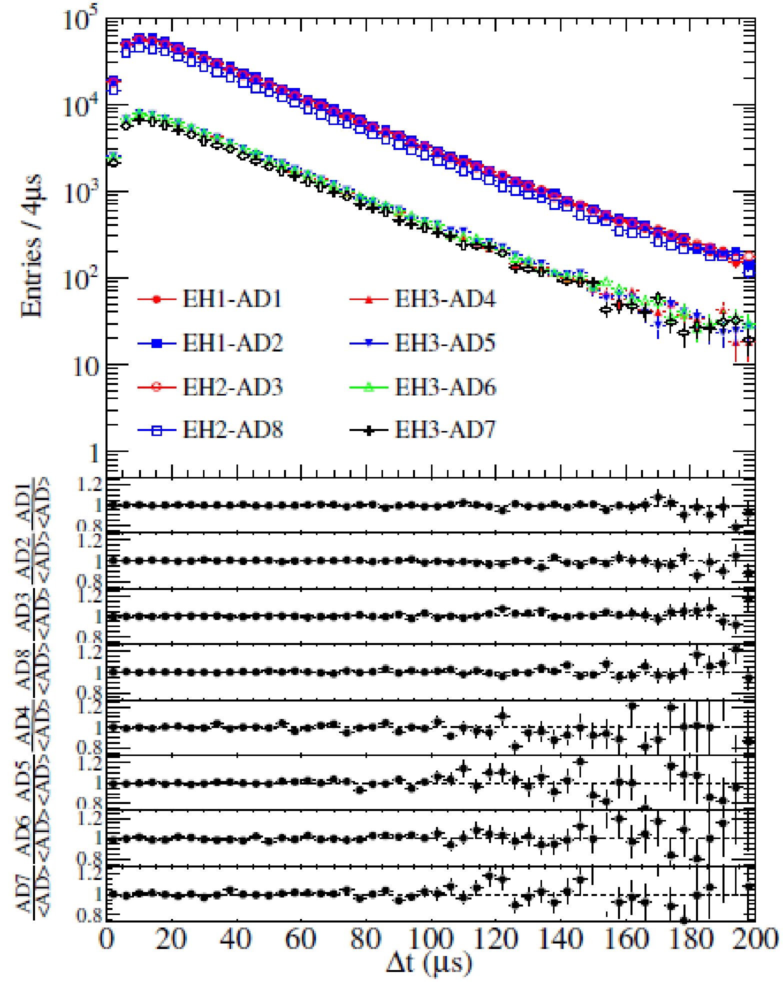
- DYB: running to 2020, 3% precision (1.5x stat. in 2018 summer)
- RENO: operation funding secured until 2019.2
- Double Chooz: at least Jan. 2018

Efficiencies and Systematics

	Daya Bay 2012		Daya Bay Now	
	Corr.	Uncorr.	Corr.	Uncorr.
Target proton	0.47%	0.03%	0.92%	0.03%
Flasher cut	0.01%	0.01%	0.01%	0.01%
Delayed energy cut	0.6%	0.12%	0.97%	0.08%
Prompt energy cut	0.1%	0.01%	0.10%	0.01%
Multiplicity cut	0.02%	<0.01%	0.02%	0.01%
Capture time cut	0.12%	0.01%	0.12%	0.01%
Gd capture fraction	0.8%	<0.1%	0.95%	<0.10%
Spill-in	1.5%	0.02%	1.0%	0.02%
livetime	0.002%	<0.01%	0.002%	0.01%
Total	1.9%	0.2%	1.93%	0.13%

Efficiency Uncertainty





- **Delayed energy cut: energy scale uncert. 0.2% (designed 1%, first 0.5%)**
- **Neutron capture time (Gd concentration difference): showed IBD here, studied w/ IBD, spallation n, Am-C, Am-Be, Pu-C sources, likely improved w/ more data.**

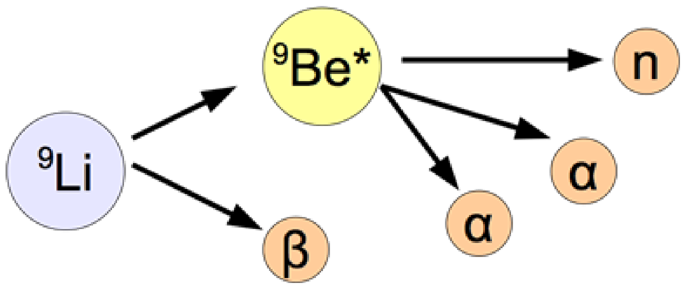
Backgrounds & Uncertainties

	Daya Bay 2012		Daya Bay Now	
	Near	Far	Near	Far
Accidentals (B/S)	1.4%	4.0%	1.3%	1.6%
ΔB/S	0.01%	0.06%	0%	0%
Fast neutrons (B/S)	0.1%	0.06%	0.13%	0.06%
ΔB/S	0.03%	0.02%	0.01%	0.01%
^{8}He/^{9}Li (B/S)	0.4%	0.3%	0.4%	0.3%
ΔB/S	0.2%	0.16%	0.12%	0.10%
α-n (B/S)	0.01%	0.05%	0.01%	0.07%
ΔB/S	0.005%	0.025%	0.005%	0.04%
Am-C (B/S)	0.03%	0.3%	0.02%	0.05%
ΔB/S	0.03%	0.3%	0.01%	0.03%
Total backgrounds(B/S)	1.9%	4.7%	1.8%	2%
Total Uncertainties Δ(B/S)	0.2%	0.35%	0.13%	0.10%

Backgrounds: $^9Li/^8He$

- **Cosmic μ produced $^9Li/^8He$ in LS**

  β-decay + neutron emitter

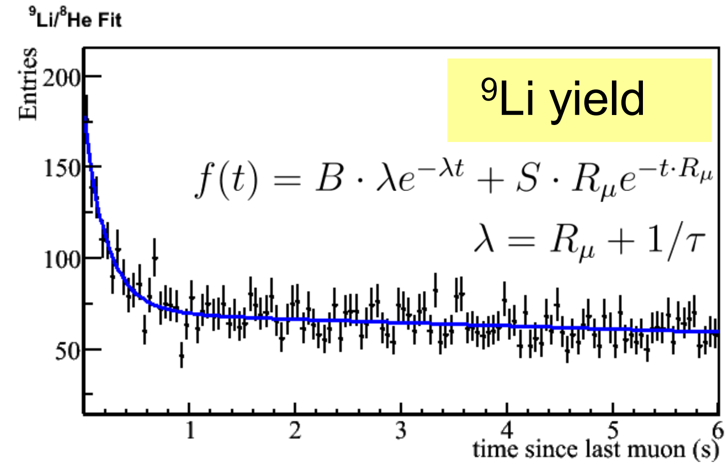


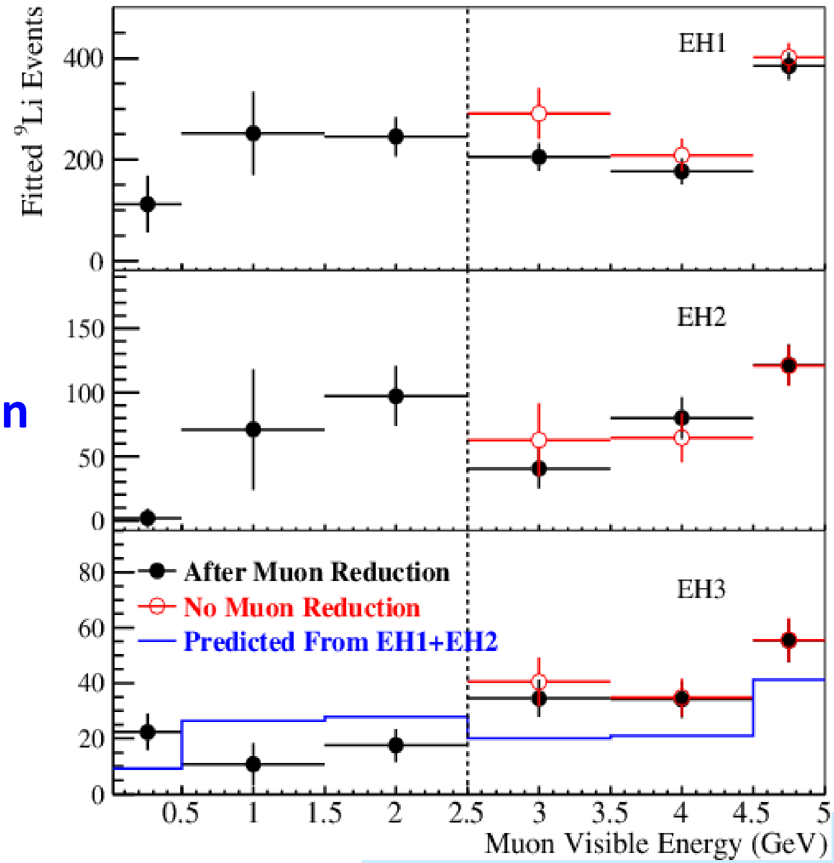
- **Measurement:**
  - Time-since-last-muon fit method

B/S uncertainty: $\sigma_b = \frac{1}{\sqrt{N}} \cdot \sqrt{(1+\tau R_\mu)^2 - 1}$

  - Improve the precision by preparing muon samples w/ and w/o followed neutrons
  - Muons with small visible energy also produce $^9Li/^8He$

ΔB/B ~ 50% from assigned systematics





Summary

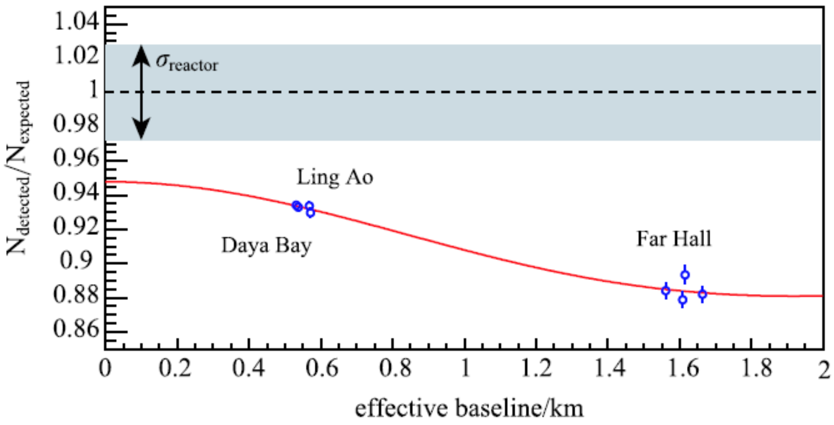
- **Daya Bay plan to operate until 2020, RENO to 2019, Double Chooz to Jan. 2018**
- **Daya Bay ultimate precision of $\sin^2 2\theta_{13}$ will reach ~3% (statistical precision 0.2%), with likely improvements in efficiency and background uncertainty.**

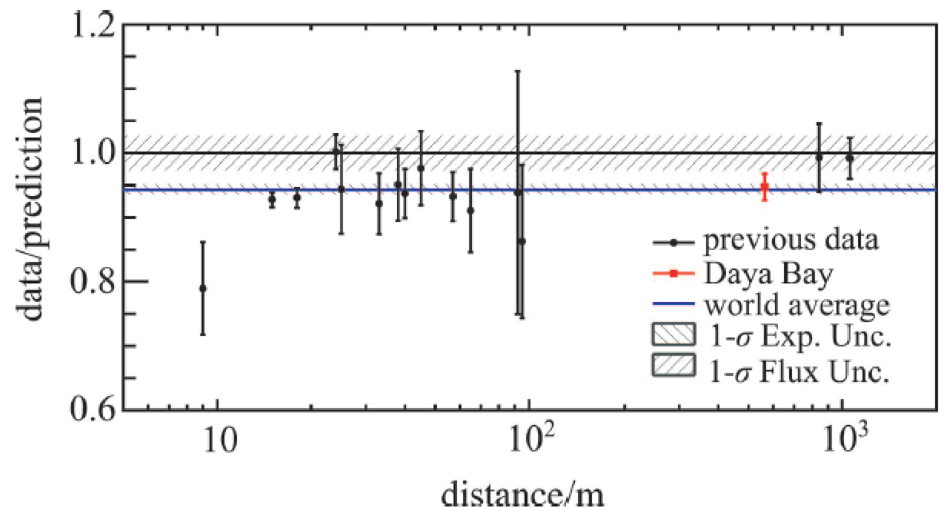
Statistics	Efficiency	Background	Reactor
0.11%	~0.1%	0.13%	0.04%

- **One DYB near detector was used for JUNO technology studies since Jan. 2017 (light yield optimization, scintillator optical purification, low background), no impact to θ_{13}**
- **Flux and spectrum anomalies and Sterile neutrino studies**

Thanks !

Daya Bay Absolute Rate Measurement





Chin. Phys. C41, 013002 (2017)

- ⇨ **Data/(Huber+Mueller): 0.946±0.020**
- ⇨ **Past global average: 0.942±0.009**
- ⇨ **Data/(ILL+Vogel): 0.992±0.021**

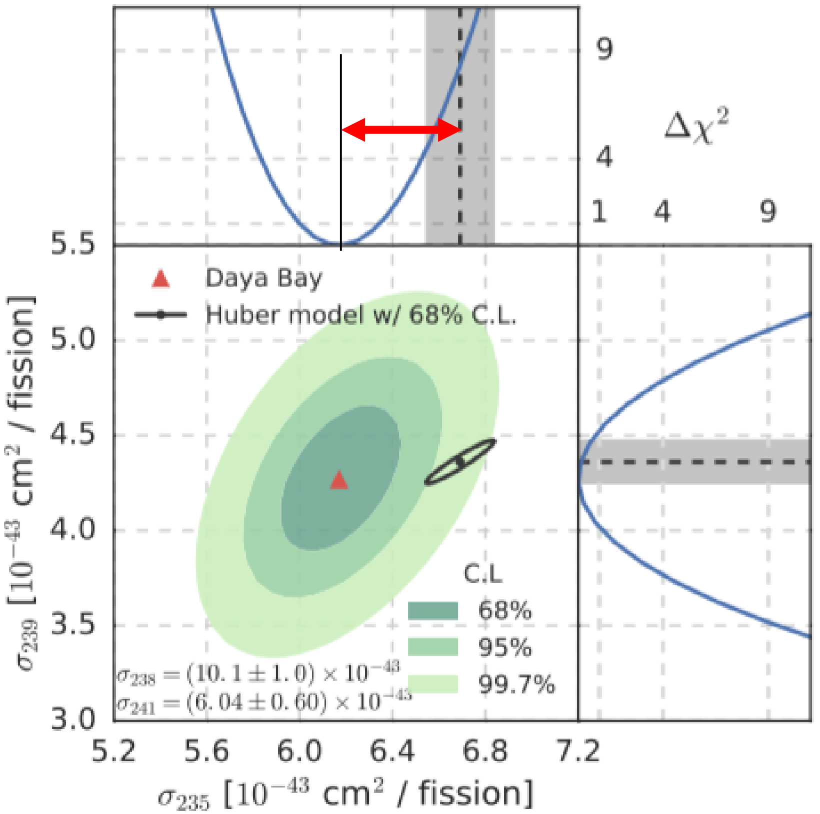
contribution	uncertainty
statistics	0.1%
oscillation	0.1%
reactor	0.9%
detection efficiency	1.93%
total	2.1%

Special calibration in Jan. 2017

Stay tuned

Daya Bay Fuel Evolution

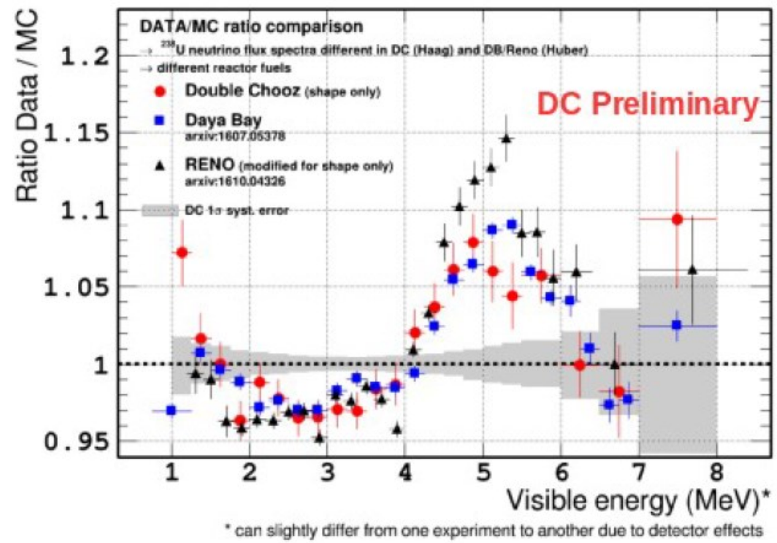
- Combined fit for major fission isotopes ^{235}U and ^{239}Pu
- σ235 is 7.8% lower than Huber-Mueller model (2.7% meas. uncertainty)
- σ239 is consistent with the prediction (6% meas. uncertainty)
- 2.8σ disfavor equal deficit (H-M model & sterile hypothesis)

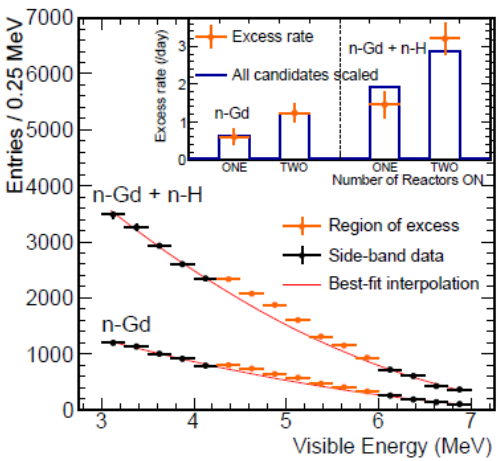


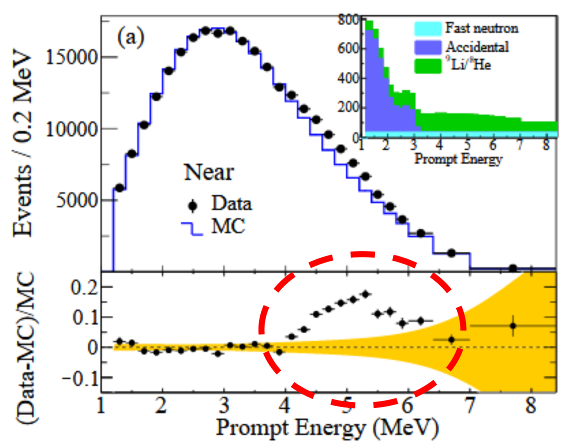
PRL118, 251801 (2017)

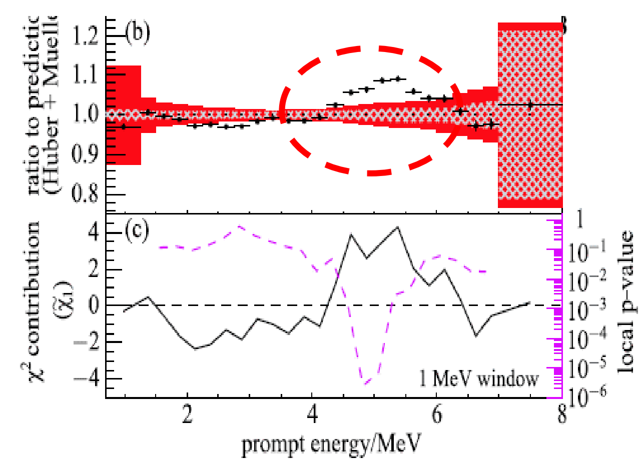
Reactor Anomaly (Spectrum)

- 5 MeV Bump
- Not due to energy non-linearity
- Not due to sterile ν
- Possibly due to forbidden decays (PRL112: 2021501; PRL114:012502)









DC, JHEP 1410 (2014) 086 **RENO:arXiv:1610.04326** **Chin. Phys. C41, 013002 (2017)**