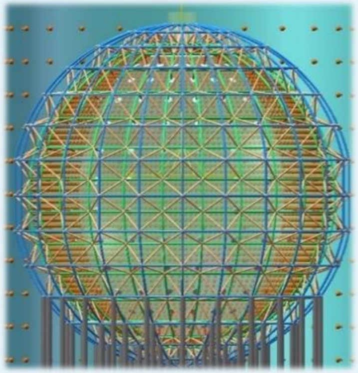


Neutrino Physics with Reactors

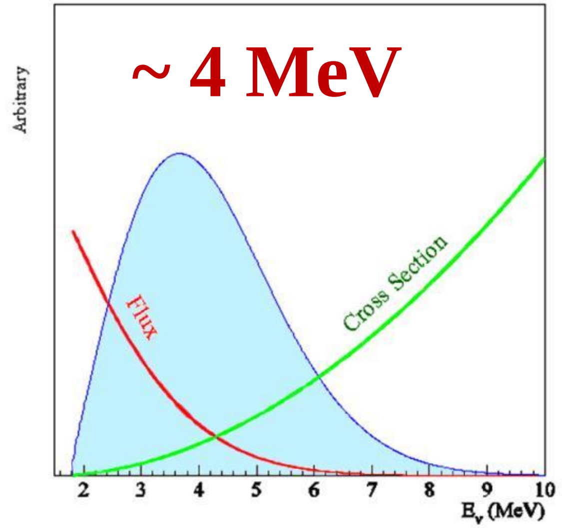
Jun Cao

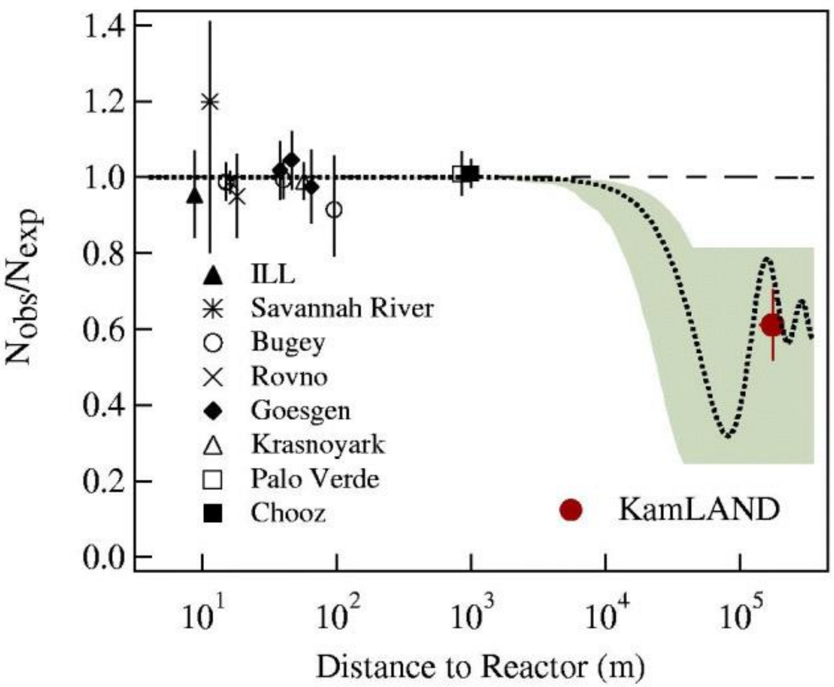
Institute of High Energy Physics

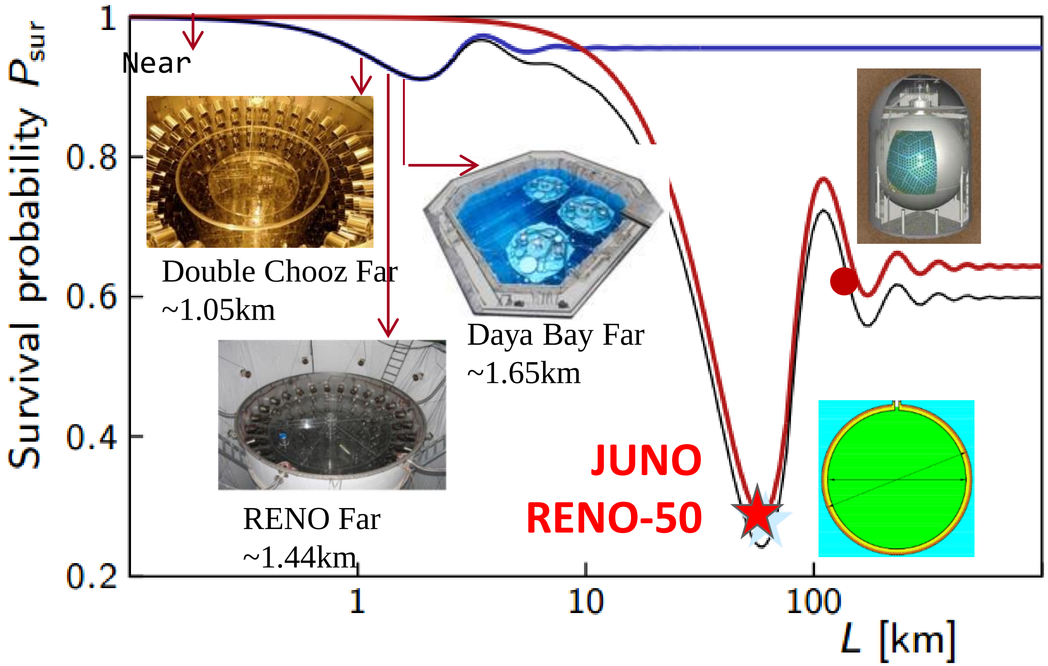
Workshop for Neutrino Programs with facilities in Japan, J-Parc, Aug. 5, 2015

Reactor Neutrinos

- Discovery of neutrino in 1956
- Small θ_{13} in 1990s
- limit on neutrino magnetic moment
- Observation of reactor $\overline{\nu_e}$ disappearance in 2003
- Discovery of non-zero θ_{13} in 2012
- Mass hierarchy and precision measurements
- Sterile neutrinos, Magnetic moment, …







Outline

- **Measuring θ_{13} and Δm^2_{ee}**
  - Daya Bay
  - Double Chooz
  - RENO
- **Determining Mass Hierarchy & precision measurement of θ_{12}, Δm^2_{21} and Δm^2_{31}**
  - JUNO
  - RENO-50
- **Search for sterile neutrinos**
- **Measuring reactor neutrino flux and spectrum**
- **Search for abnormal magnetic moment**
- **Summary**

Detecting Reactor Antineutrino

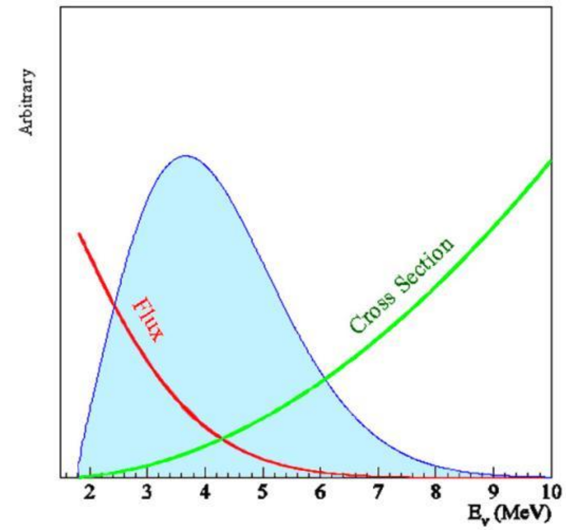
- ν-e scattering
- Inverse beta decay (IBD)

Prompt signal

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

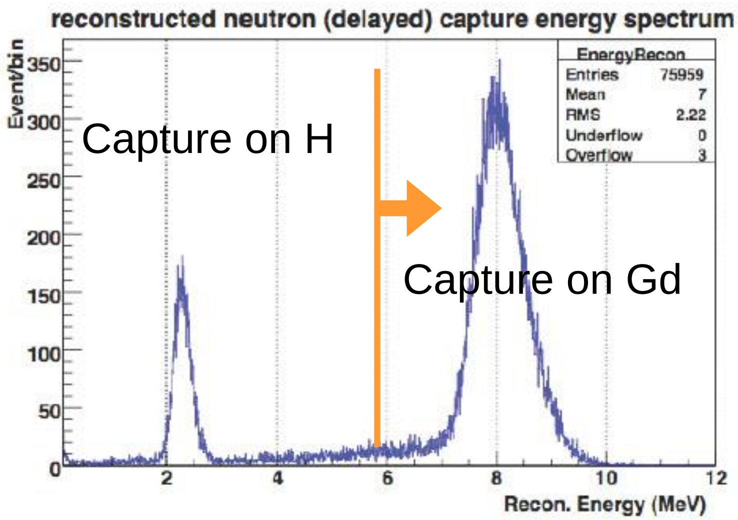
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

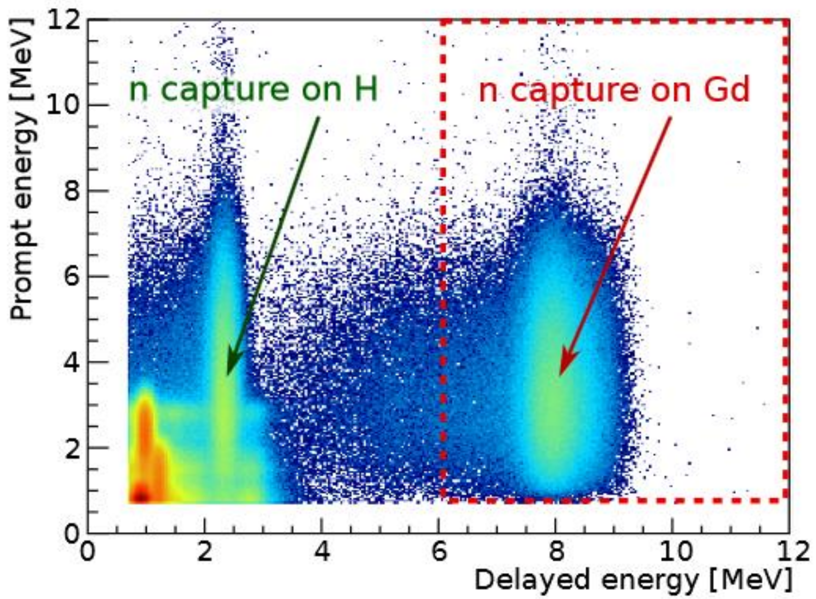
Delayed signal, Capture on H (2.2 MeV, ~180μs) or Gd (8 MeV, ~30μs)



Near site: ~thousands IBD/day
Far site: ~hundreds IBD/day

0.1% Gd by weight

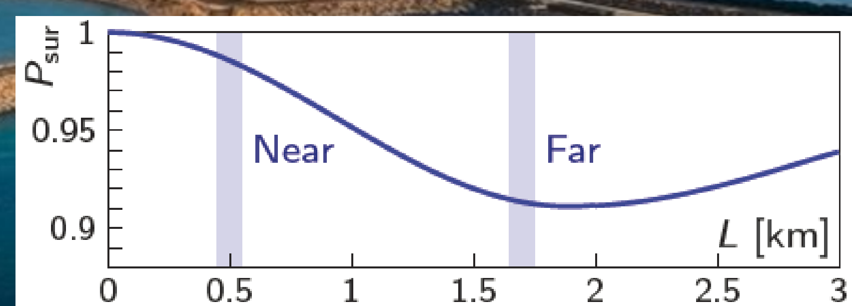




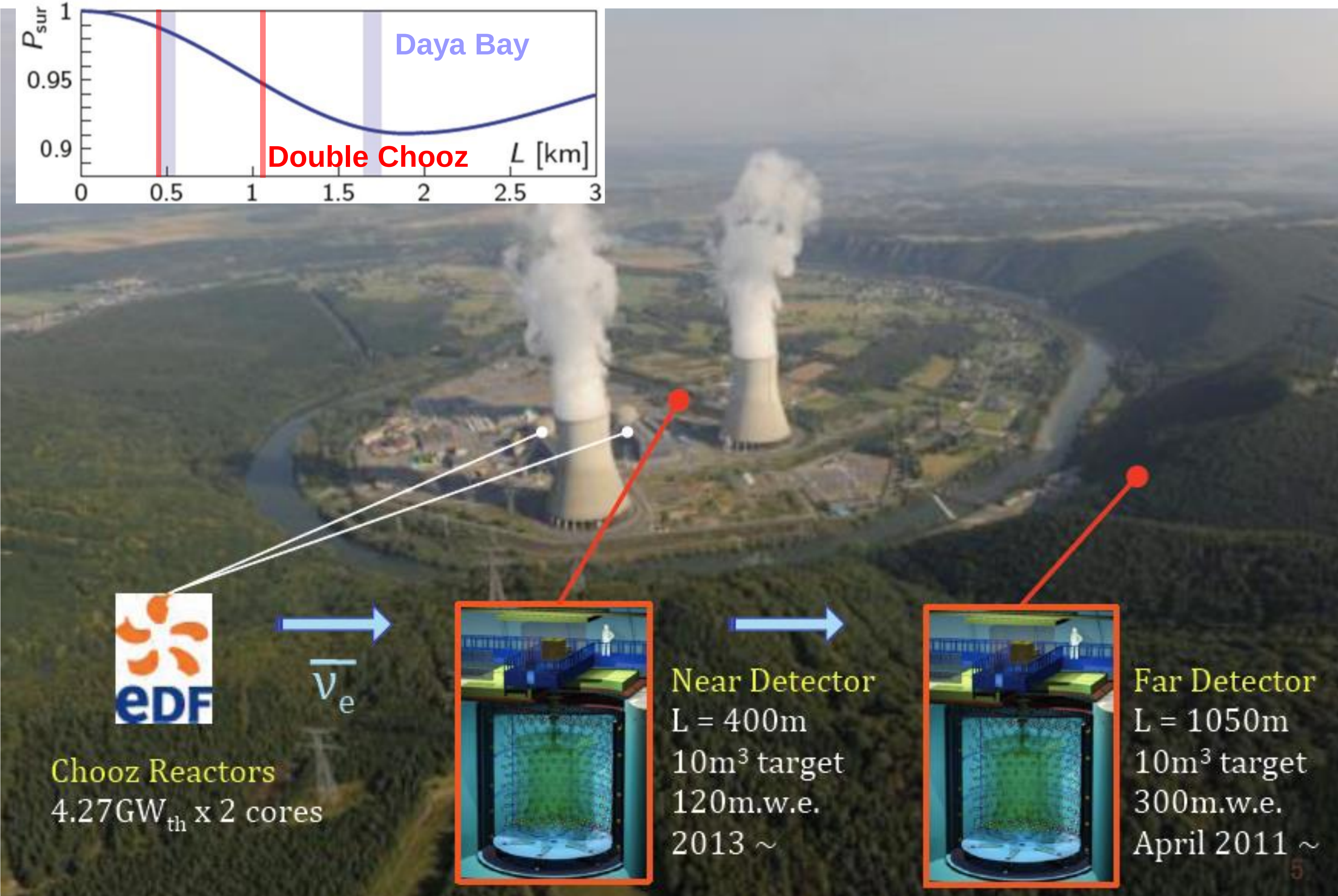
- **Measuring θ_{13} and Δm^2_{ee}**
  - **Daya Bay**
  - **Double Chooz**
  - **RENO**

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

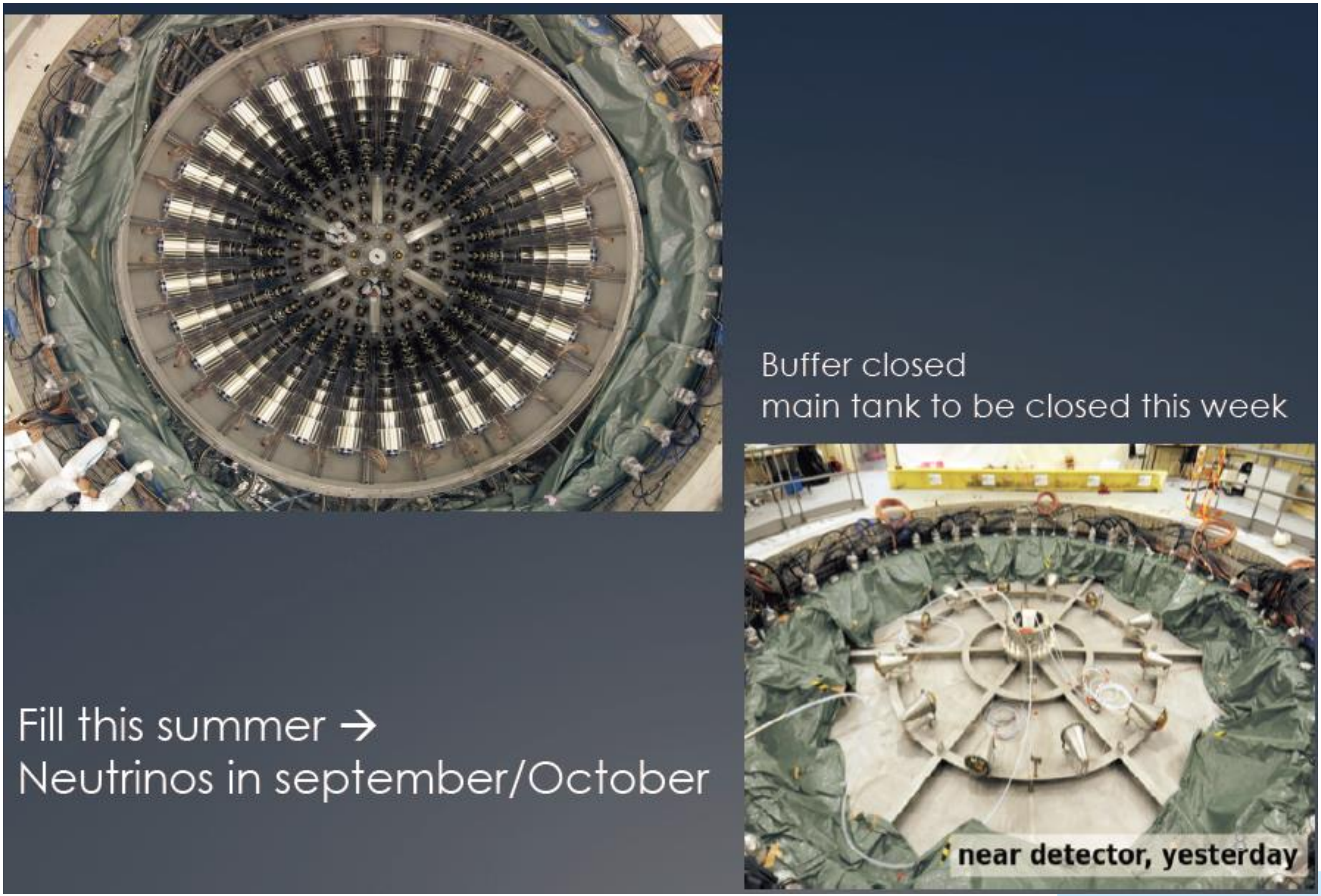


Double Chooz

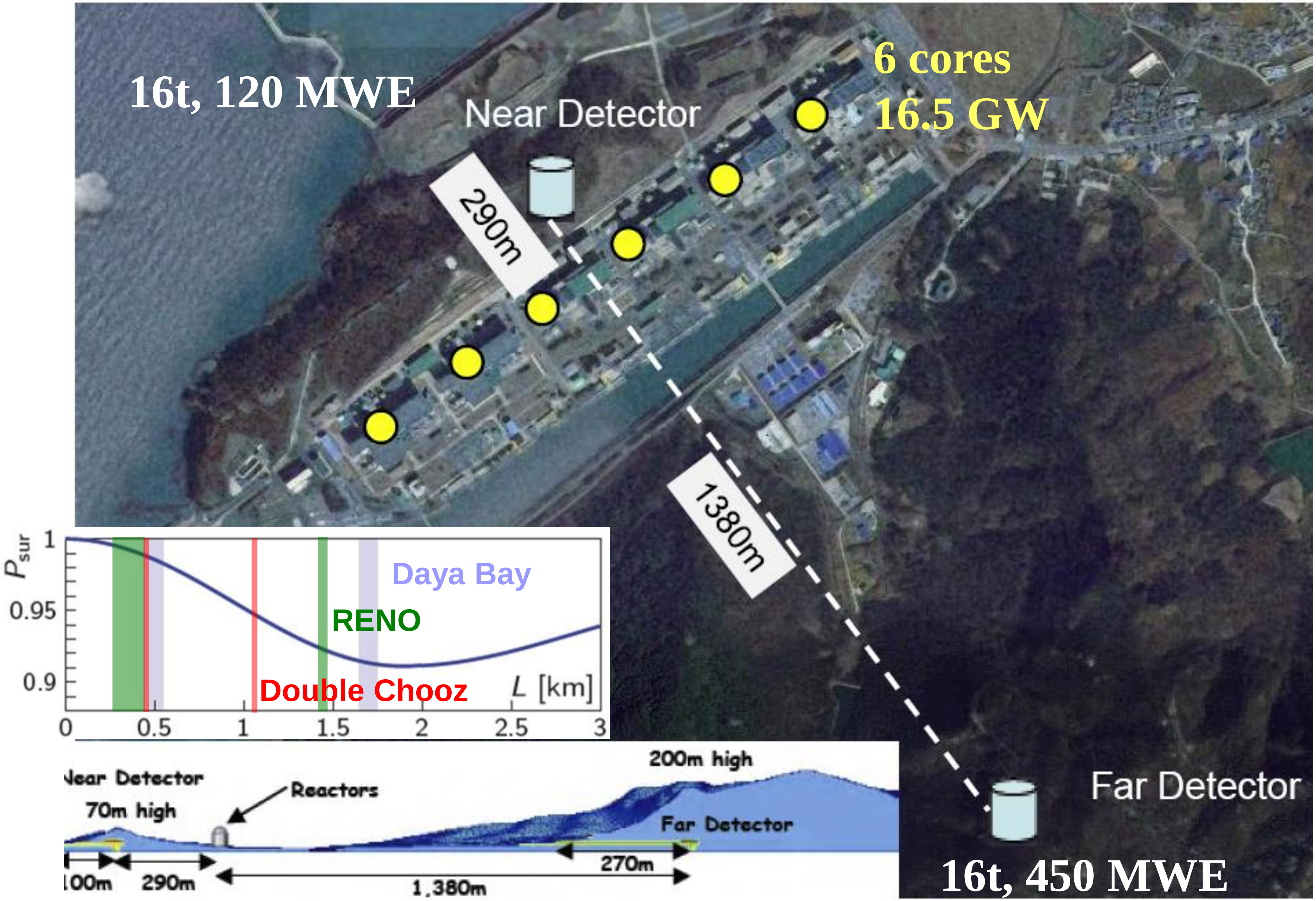


Double Chooz Near Site

- **the second detector was inaugurated on September 25, 2014**



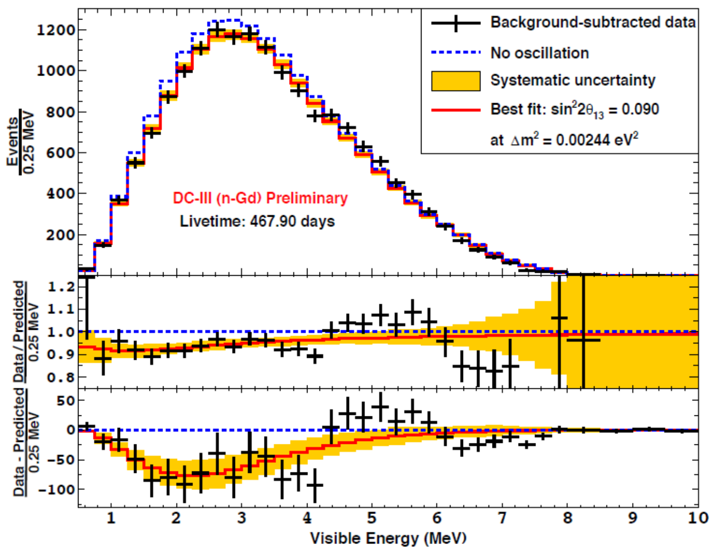
RENO

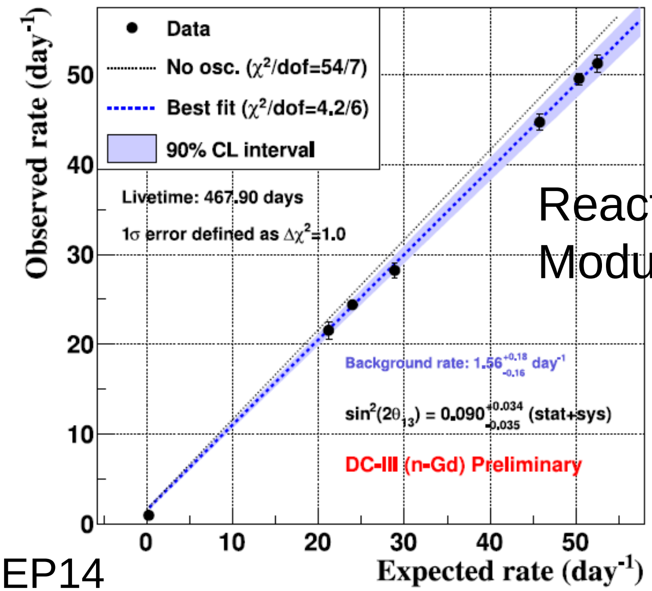


16t, 120 MWE
Near Detector
6 cores
16.5 GW
290m
1380m
Far Detector
16t, 450 MWE
P_{sur}
1
0.95
0.9
Daya Bay
RENO
Double Chooz
L [km]
0
0.5
1
1.5
2
2.5
3
Near Detector
70m high
Reactors
200m high
Far Detector
100m
290m
270m
1,380m

Double Chooz

- **2011.4-2013.1 (460 days). No near site data until 2014.9**
- **Used spectrum analysis for both nGd & nH events**
- **Used Reactor-off data to directly measure backgrounds**
- **New analysis → less background and uncertainties, better flux prediction(^{238}U), better energy reconstruction, …**





Reactor Rate Modulation

Haser, ICHEP14

R+S: $\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$, BG rate: 1.38 ± 0.14 day^{-1}

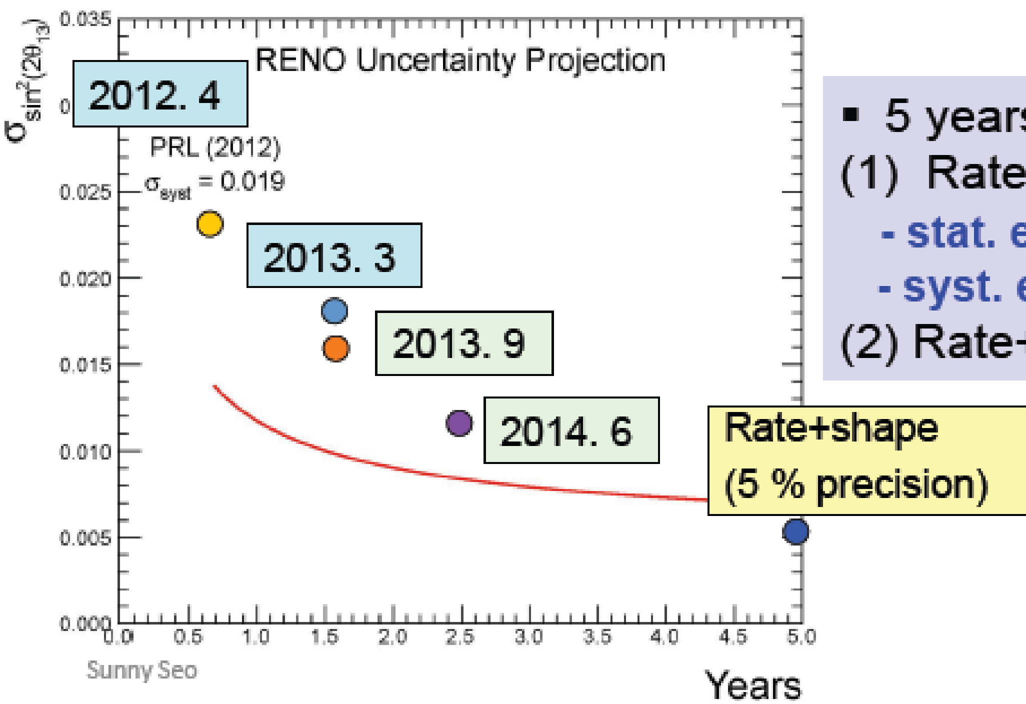
RRM: $\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035}$, BG rate: 1.56 ± 0.17 day^{-1}

RRM (no BG constraint): $\sin^2 2\theta_{13} = 0.060 \pm 0.039$, BG rate: 0.93 ± 0.40 day^{-1}

RENO

- 2011.8-2013.12 (800 days)
- Also reactor rate modulation analysis
- Shape analysis is on the way
- Reduced systematics but worsened by ^{252}Cf contamination

Singapore 2015 $\sin^2 2\theta_{13} = 0.090 \pm 0.008(stat.) \pm 0.008(syst.)$



- 5 years of data :

(1) Rate-only: ±7%

- stat. error : ±0.008 → ±0.005
- syst. error : ±0.010 → ±0.005

(2) Rate+shape: ±5%

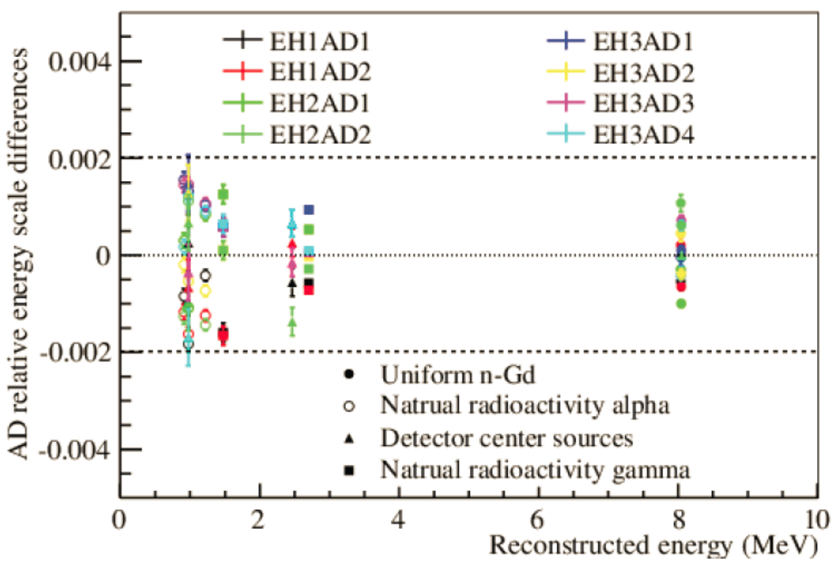
31

Daya Bay

- 2011.12-2013.11 (621 days)
- Detailed and precise corrections for E non-linearity
- Continue to improve: reduced backgrounds and systematics
- Rate + Shape analysis for nGd events
- Rate analysis for nH events

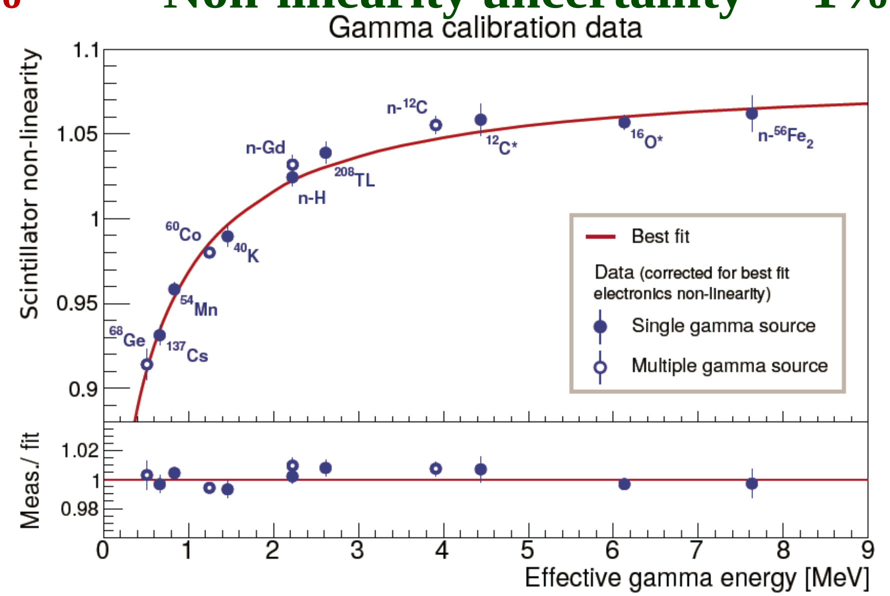
0.5%

Relative energy scale difference: <0.2%



2%

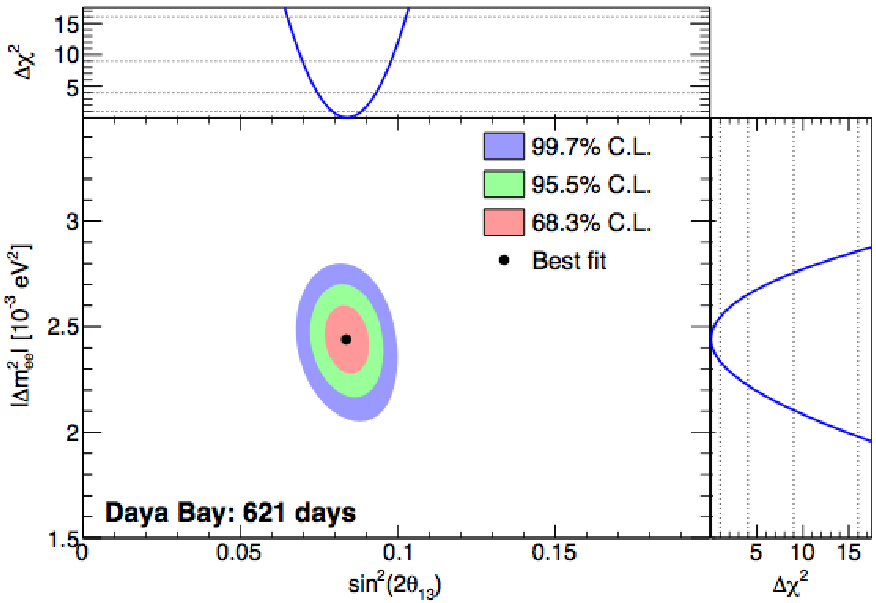
Non-linearity uncertainty 1%



C.Zhang, Neutrino14 & W.Wang, ICHEP14

Daya Bay Results

nGd rate+shape



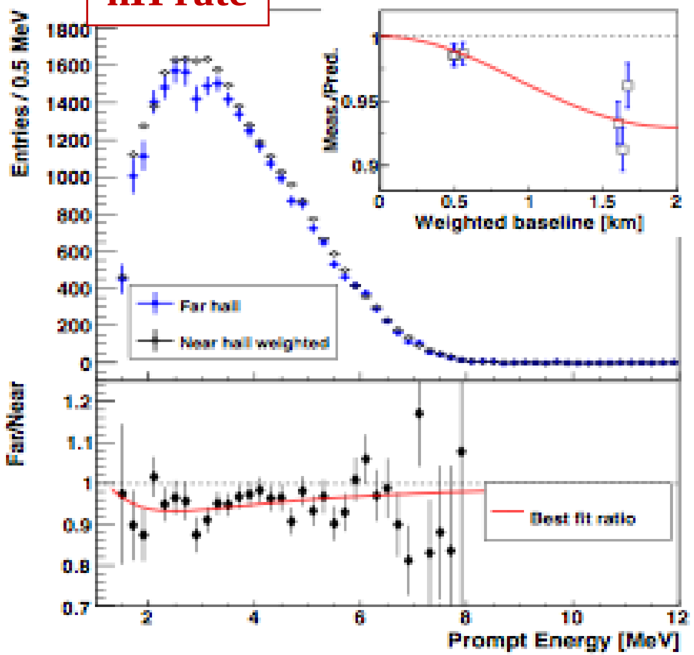
$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

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

$$\chi^2/NDF = 134.7/146$$

arXiv: 1505.03456

nH rate

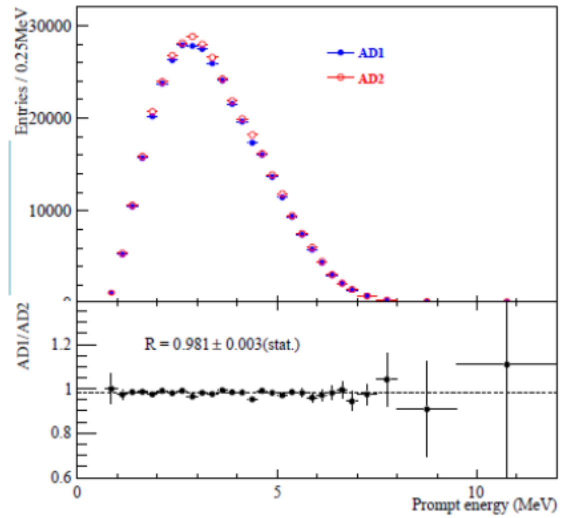


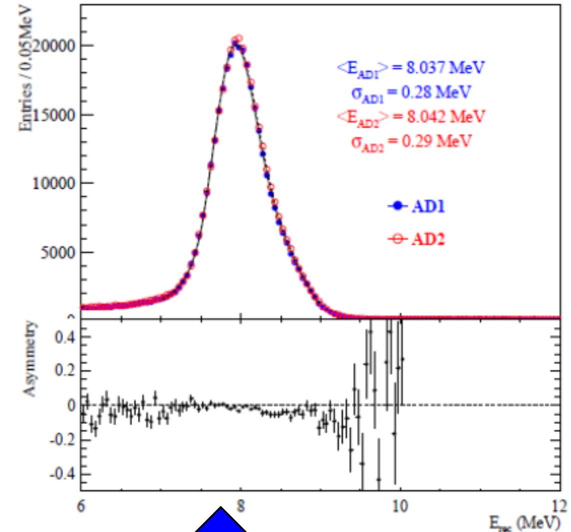
$\sin^2 2\theta_{13} = 0.083$ +- 0.018

- $\Delta(\sin^2 2\theta_{13})/\sin^2 2\theta_{13} \sim 6\%$
  - ⇨ best among all mixing angles
- $\Delta(\Delta m^2_{ee})/\Delta m^2_{ee} \sim 5\%$
  - ⇨ similar to that of MINOS

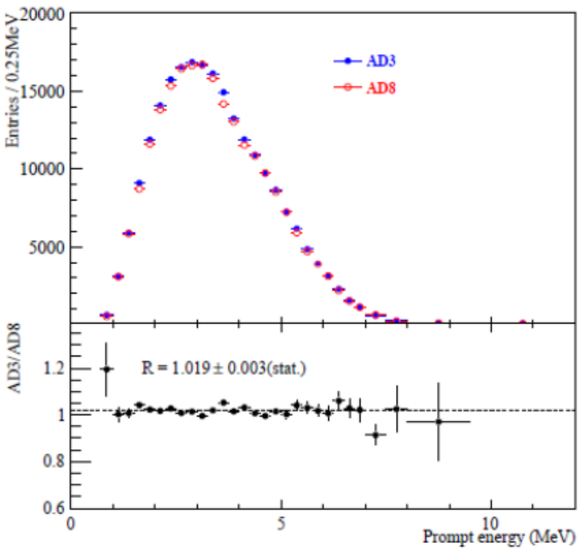
Systematics at Daya Bay

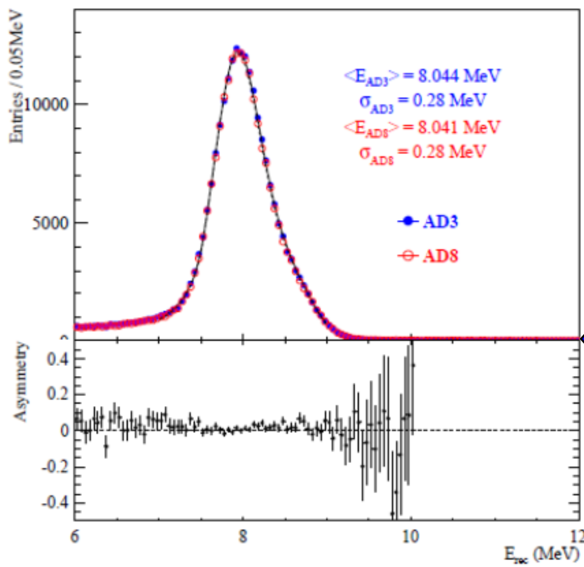
- **Side-by-side calibration: Multiple detectors at near sites**





AD1/AD2 (6+8AD data)
Expected: 0.982
Measured: 0.981 $\pm$ 0.004



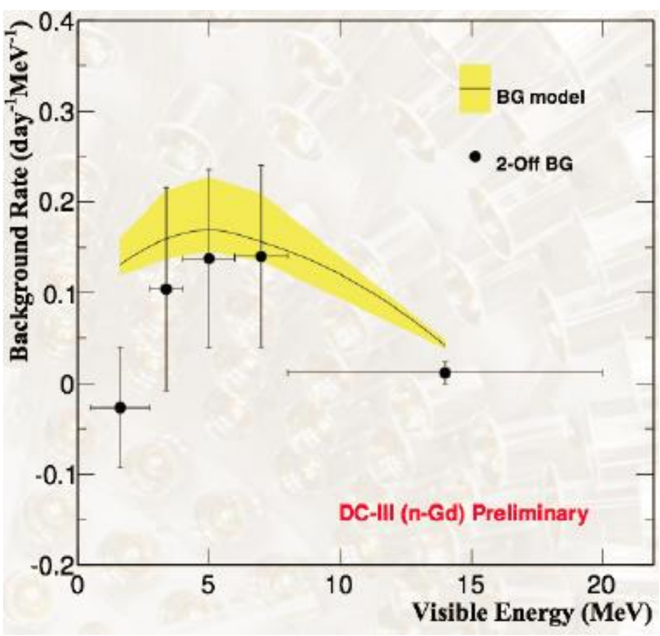


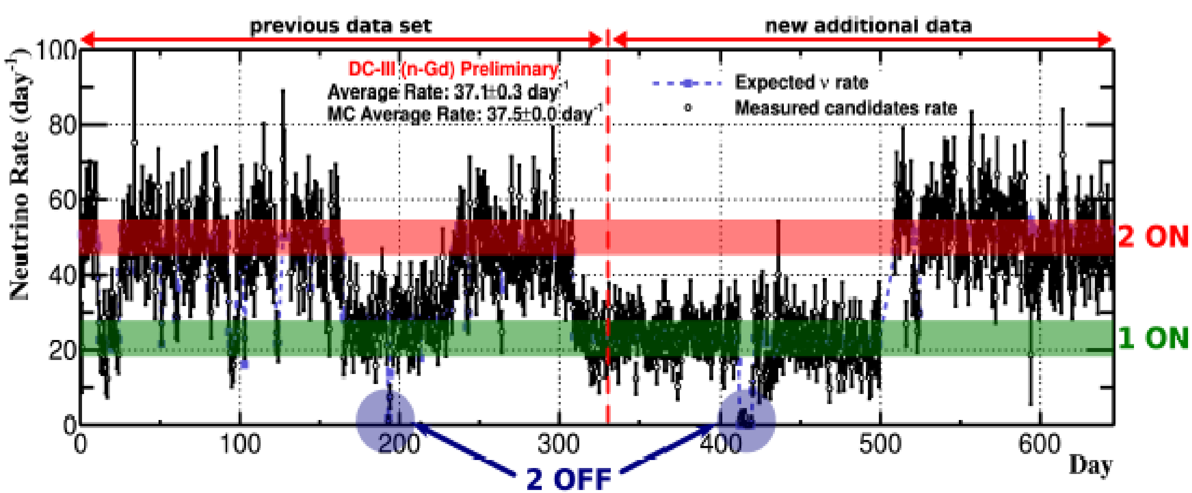
AD3/AD8 (8AD data)
Expected: 1.012
Measured: 1.019 $\pm$ 0.004

J.Zhao, Nufact14

Backgrounds at DC

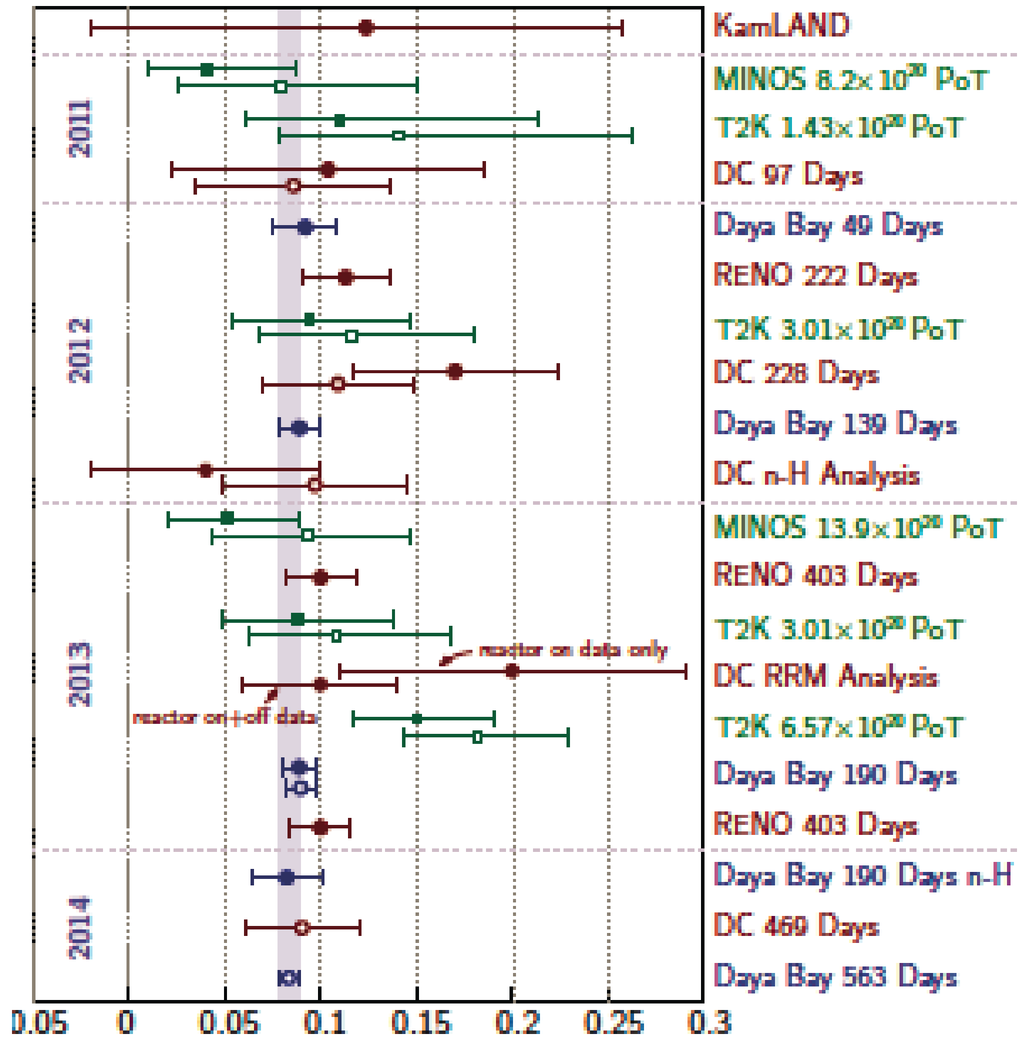
- **Major backgrounds for reactor exp.**
  - ⇨ **Cosmogenic neutron/isotopes: ^{8}He/^{9}Li and fast neutron**
  - ⇨ **Ambient radioactivity: accidental coincidence**
- **Direct measurement of backgrounds:**
  - ⇨ **7 events in 7.24 days**
  - ⇨ $\mathbf{12.9^{+3.1}_{-1.4}}$ **expected**
  - ⇨ **Tension @ ~ 2σ ➔ no room for unknown backgrounds**





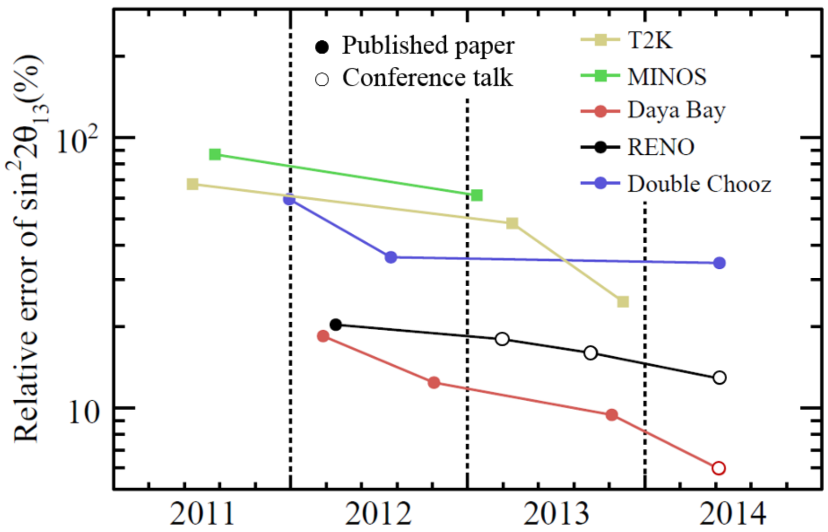
Haser, ICHEP14

Remarkable Improvements on θ_{13}



Jetter, Tau2014

Y.F.Wang, Nufact2014

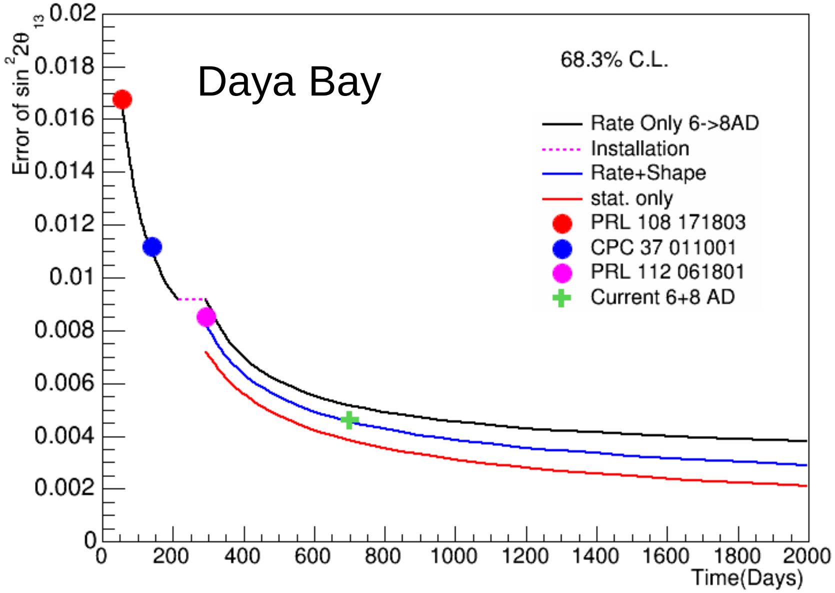


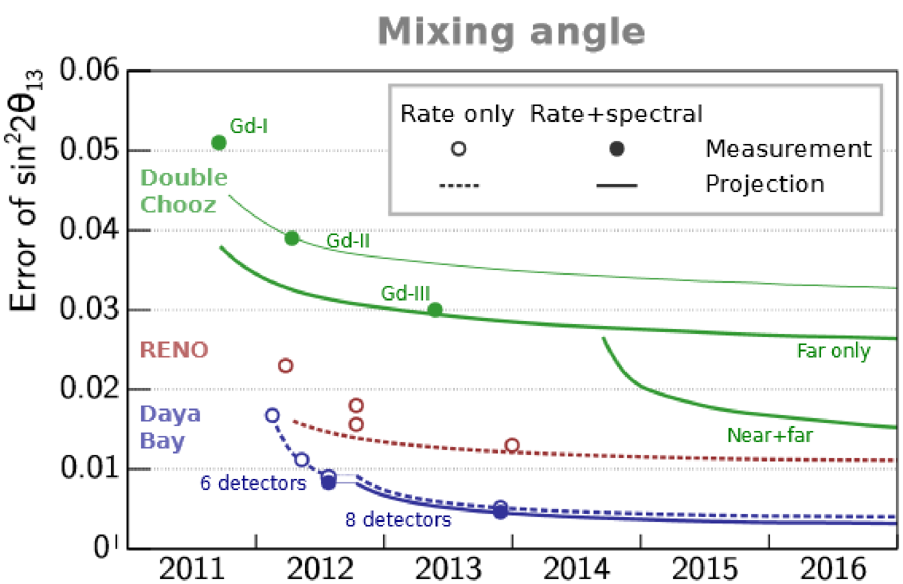
For accelerator experiments assuming $\delta_{CP}=0$, $\theta_{23}=45^{o}$

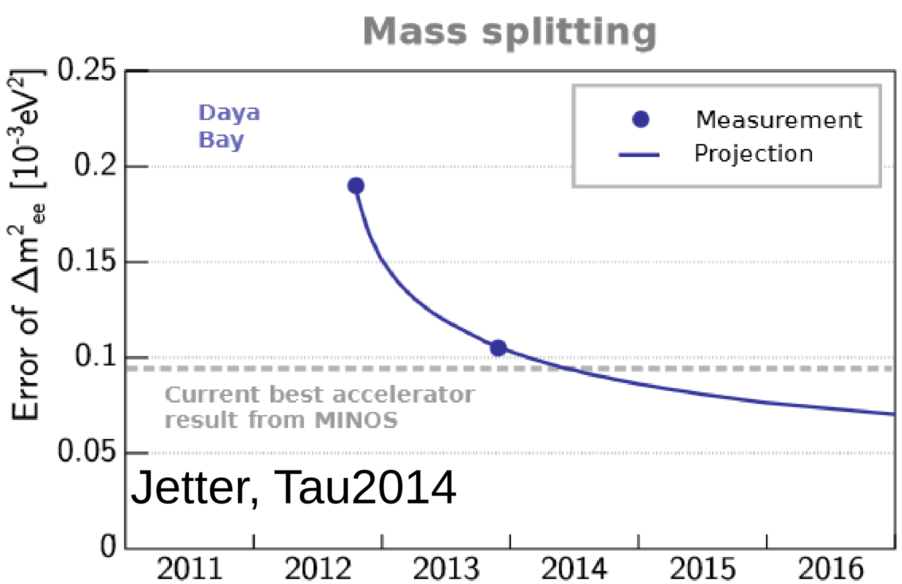
Uncertainty reduced significantly → now 6%, will be 3% in 2017.

Future Prospects

- **Precision still dominated by statistics**
- **Continue to improve systematics**
- **Precision expected:**
  - **Daya Bay:**
    - $\Delta(\sin^2 2\theta_{13}) \sim 0.003 \rightarrow \sim 3\%$
    - $\Delta(\Delta m^2_{ee}) \sim 0.07 \rightarrow \sim 3\%$
  - **RENO: ~5%**
  - **Double Chooz: ~10%**

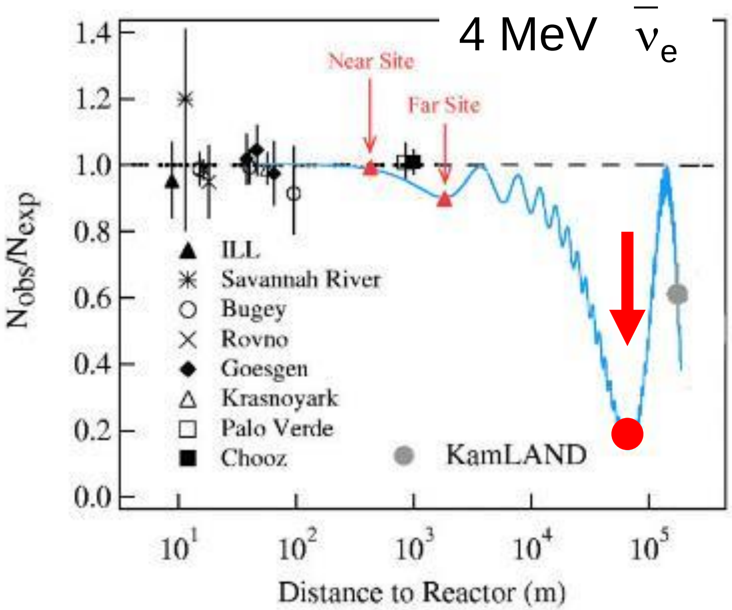






- **Determining Mass Hierarchy**
- **Precision measurement of θ_{12}, Δm^2_{21} and Δm^2_{31}**
  - ⇨ **JUNO**
  - ⇨ **RENO-50**

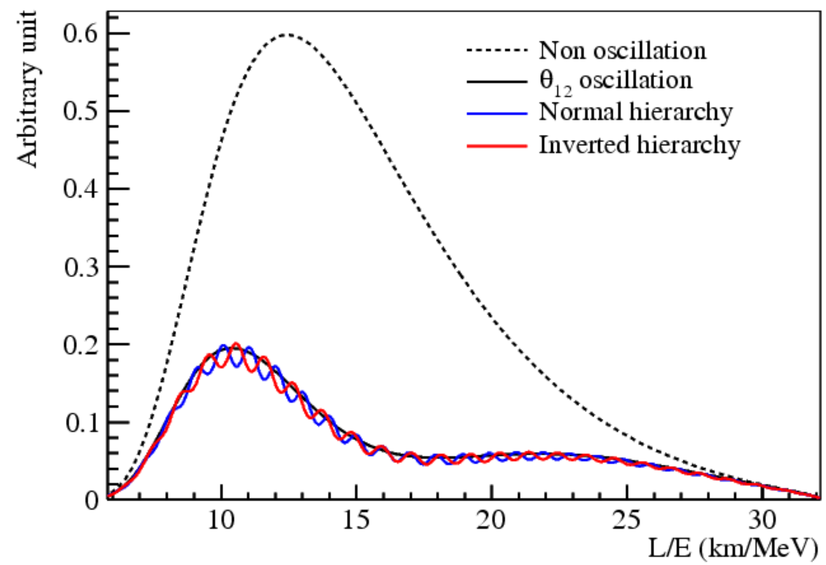
Determine MH with Reactors



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

$$\frac{1}{2}\sin^2 2\theta_{13}\left[1 - \sqrt{1 - \sin^2 2\theta_{12}\sin^2\Delta_{21}}\,\boxed{\cos(2|\Delta_{ee}| \pm \phi)}\right.$$

- A fixed definition Δm^2_{ee}
- And an energy related phase shift ϕ

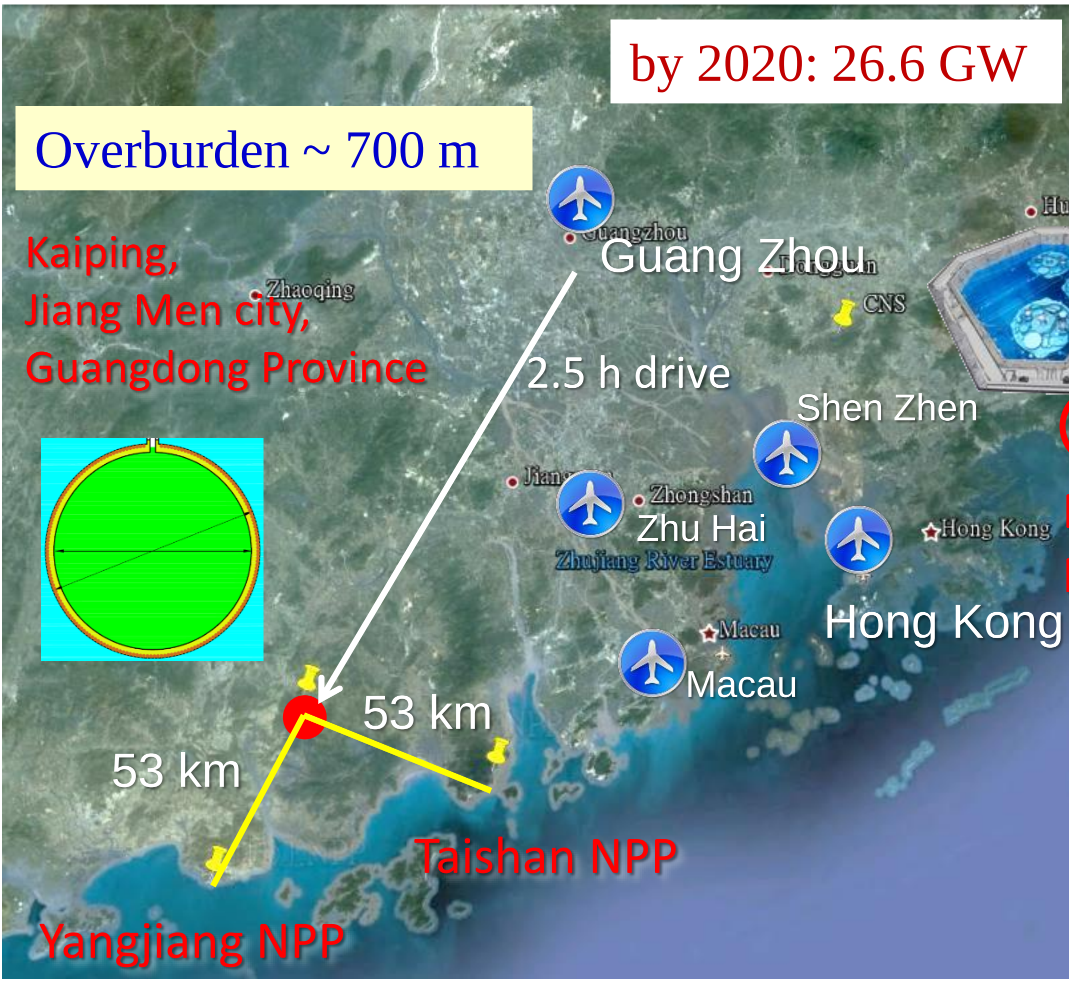


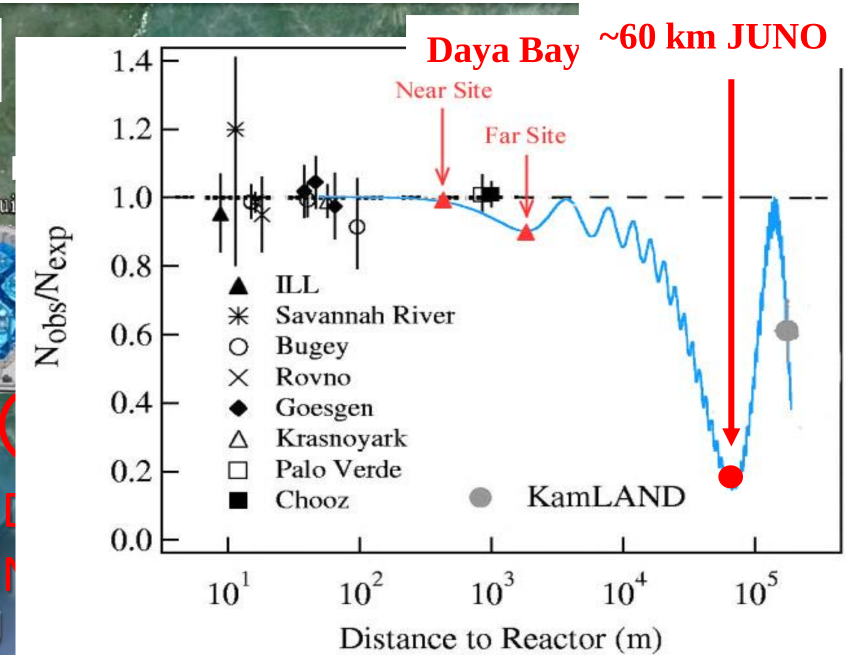
Precision energy spectrum measurement interference between P_{31} and P_{32}
→ ϕ: Relative measurement

Further improvement with $\Delta m^2_{\mu\mu}$ measurement from accelerator exp.
→ Δm^2_{ee}: **Absolute measurement**

JUNO for Mass Hierarchy

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW

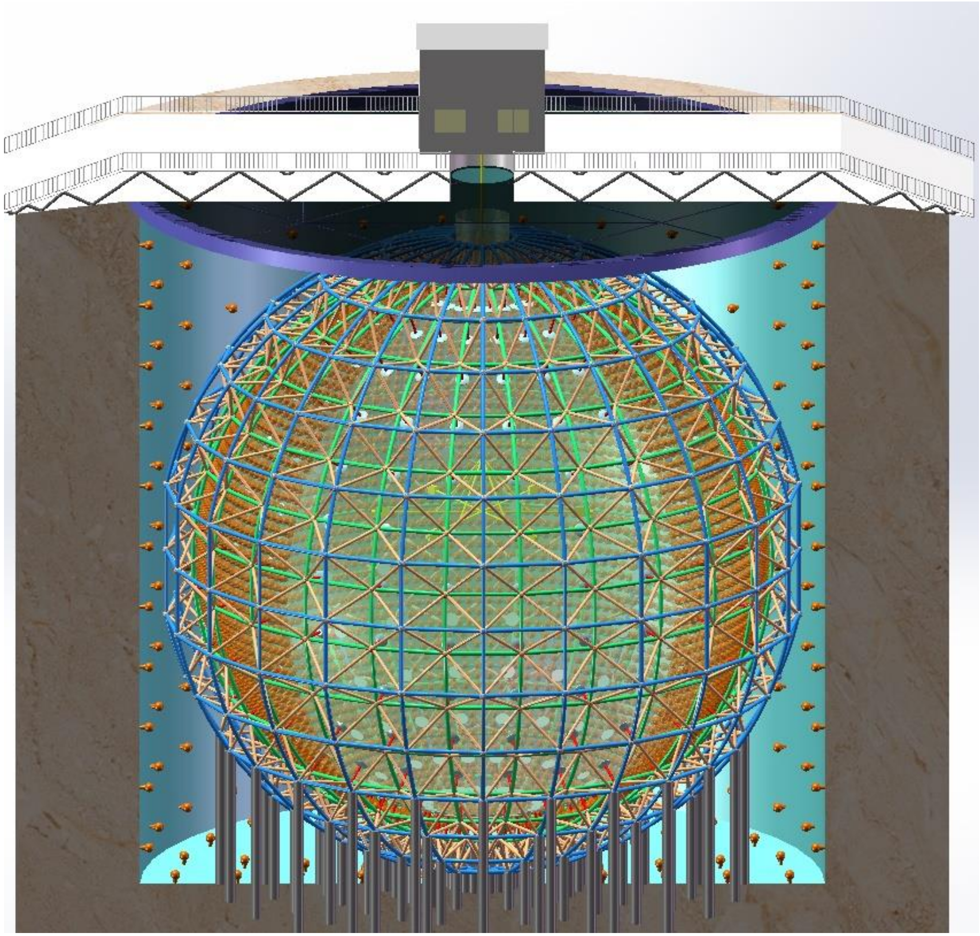




Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

JUNO Physics

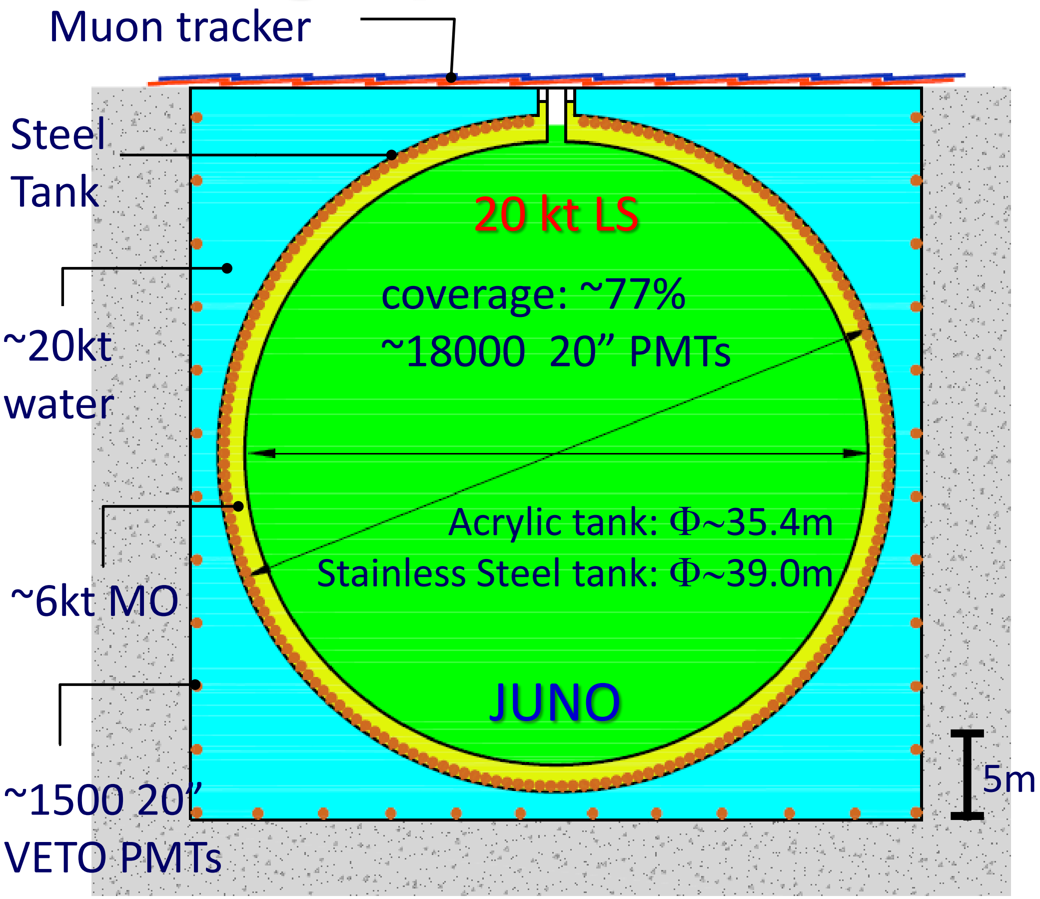
- JUNO has been approved in Feb. 2013. ~ 300 M$.
- is a multiple-purpose neutrino experiment

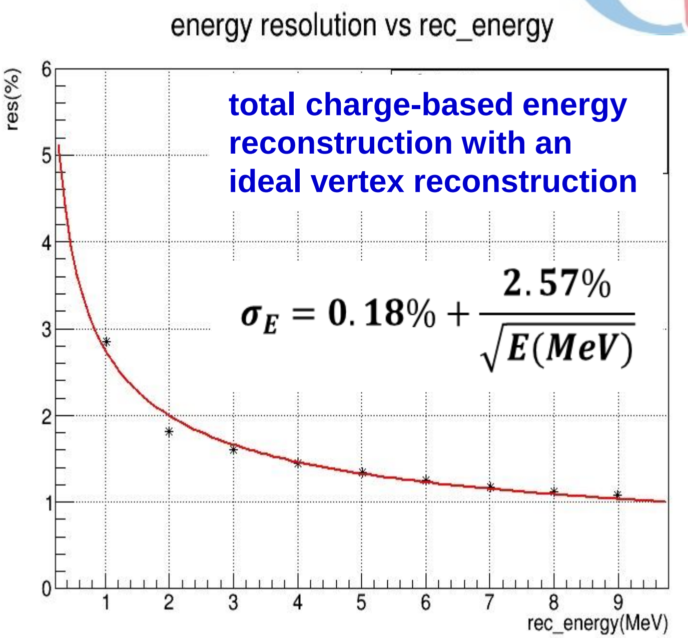


- 20 kton LS detector
- 3% energy resolution
- 700 m underground
- Rich physics possibilities
  - Reactor neutrino for Mass hierarchy and precision measurement of oscillation parameters
  - Supernovae neutrino
  - Geoneutrino
  - Solar neutrino
  - Atmospheric neutrino
  - Exotic searches

Neutrino Physics at JUNO, arXiv:1507.05613

High-precision, Giant LS detector





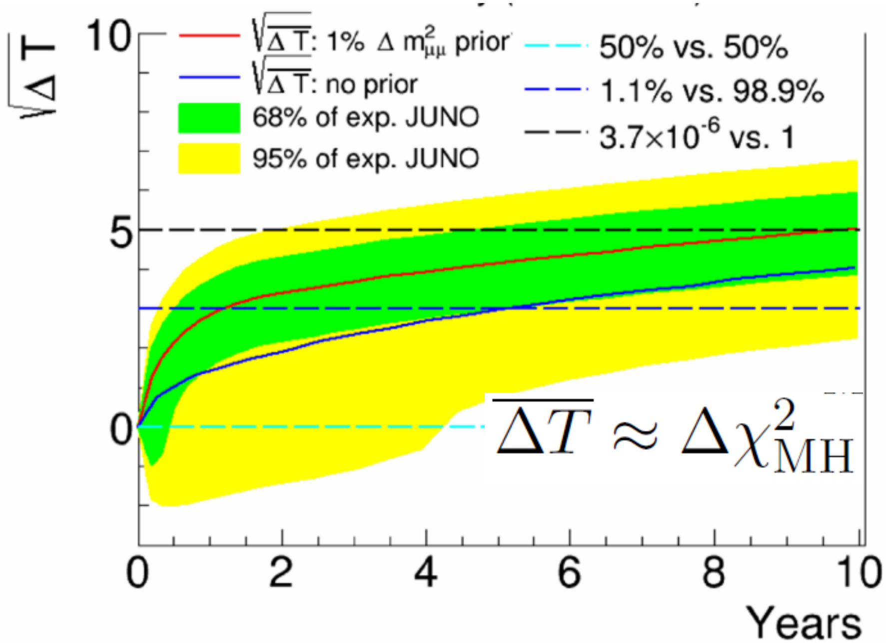
- **77% photocathode coverage**
- **PMT QE from 35%**
- **Attenuation length of 20 m**
  ➔ abs. 60 m + Rayl. scatt. 30m

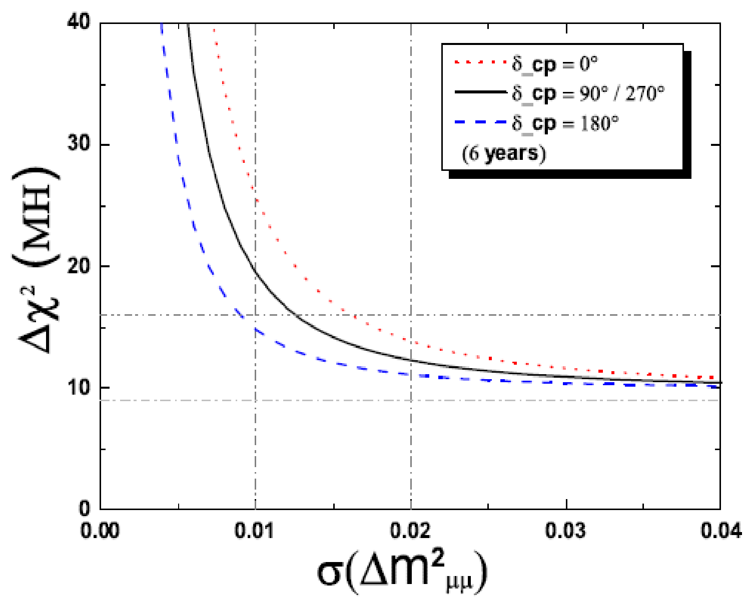
	KamLAND	BOREXINO	JUNO
LS mass	1 kt	0.5 kt	20 kt
Energy Resolution	$6\%/\sqrt{E}$	$5\%/\sqrt{E}$	$3\%/\sqrt{E}$
Light yield	250 p.e./MeV	511 p.e./MeV	1200 p.e./MeV

Sensitivity on MH

PRD 88, 013008 (2013)	Relative Meas.	Use absolute Δm^2
Statistics only	4σ	5σ
Realistic case	3σ	4σ

***JUNO* MH sensitivity with 6 years' data:**

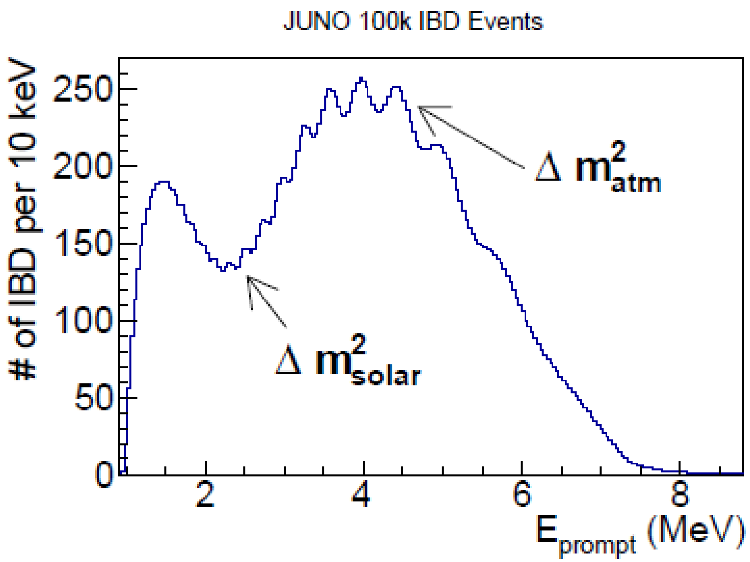




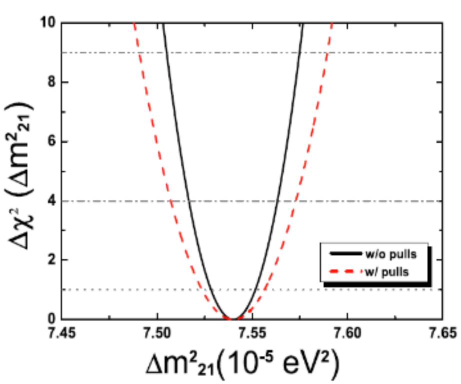
	Ideal	Core distr.	Shape	B/S (stat.)	B/S (shape)	$\lvert\Delta m^2_{\mu\mu}\rvert$
Size	52.5 km	Real	1%	4.5%	0.3%	1%
$\Delta\chi^2_{\rm MH}$	+16	−4	−1	−0.5	−0.1	+8

Precision Measurements

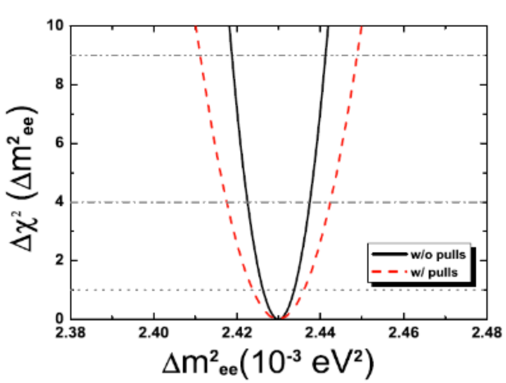
Probing the unitarity of U_{PMNS} to ~1%
more precise than CKM matrix elements !



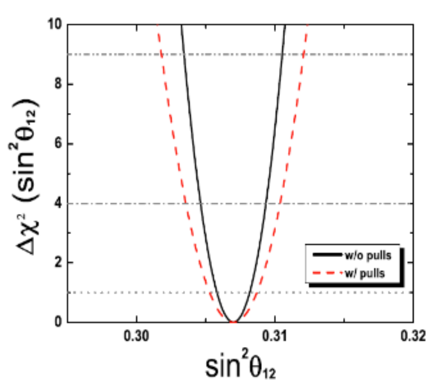
	Statistics	+BG +1% b2b +1% EScale +1% EnonL
$\sin^2\theta_{12}$	0.54%	0.67%
Δm^2_{21}	0.24%	0.59%
Δm^2_{ee}	0.27%	0.44%



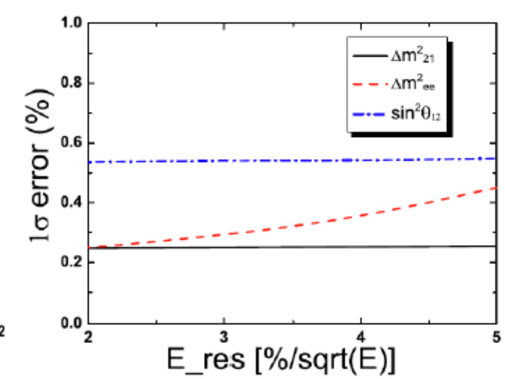
0.16%→0.24%



0.16%→0.27%



0.39%→0.54%

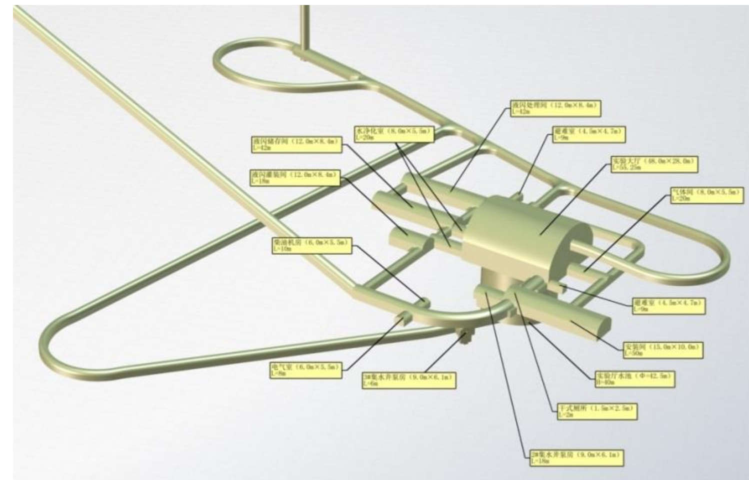


Correlation among parameters

E resolution

Current Status & Brief Schedule

- **Ground breaking in Jan. 2015**
  - ⇨ **500 m slope tunnel excavated out of 1340 m**
  - ⇨ **75 m vertical shaft excavated out of 611 m**
- **Central detector using acrylic**
- **International Collaboration formed w/ 380 members from 55 institutions in 12 countries/regions**



Schedule:

Civil preparation：2013-2014

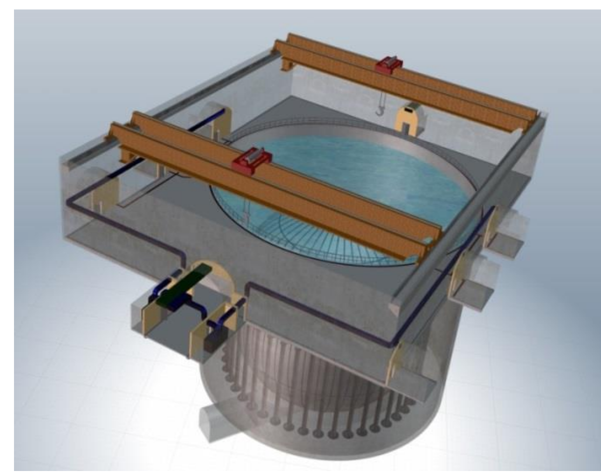
Civil construction：2014-2017

Detector component production：2016-2017

PMT production：2016-2019

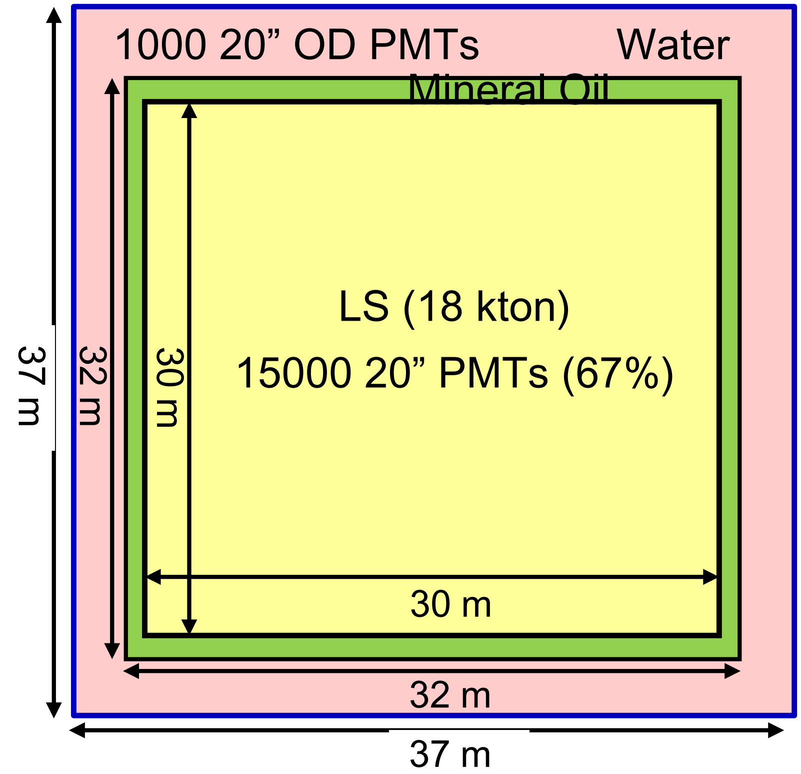
Detector assembly & installation：2018-2019

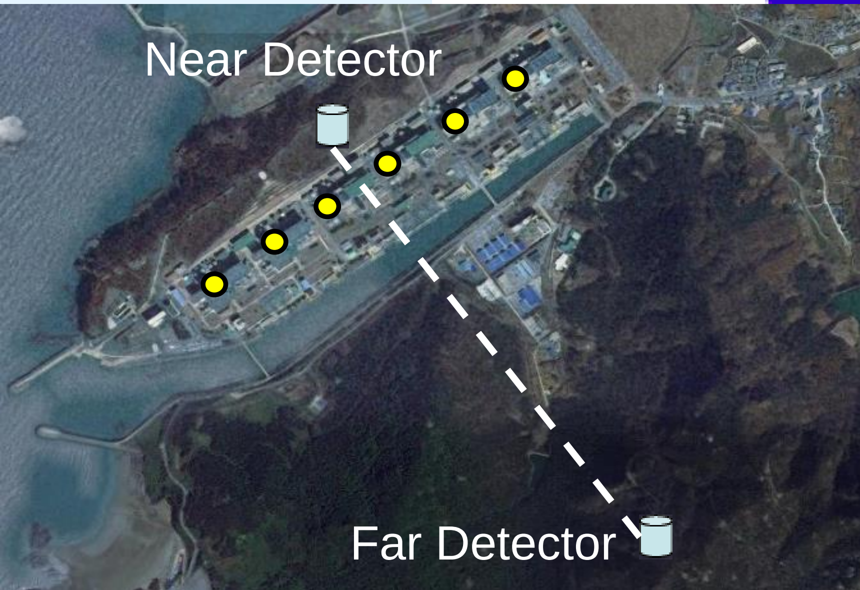
Filling & data taking：2020



RENO-50

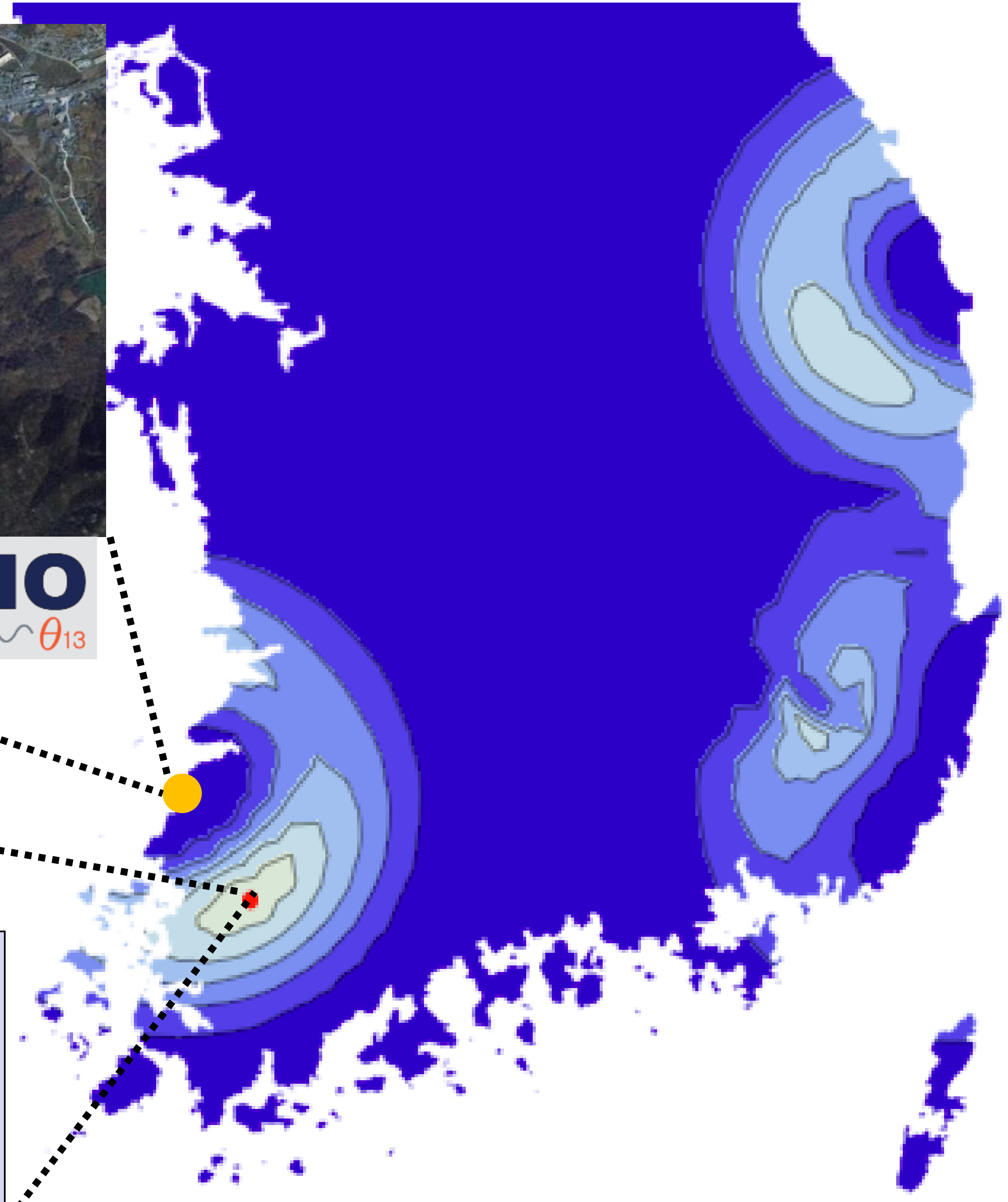
- An underground detector consisting of 18 kton ultra- low-radioactivity liquid scintillator & 15,000 20" PMTs, at 50 km away from the Hanbit (Yonggwang) nuclear power plant
- Goals :
  - ⇨ Precision meas. of θ_{12} and Δm^2_{21}
  - ⇨ Determination of mass hierarchy
  - ⇨ Study neutrinos from reactors, (the Sun), the Earth, Supernova, and any possible stellar objects
- Budget : $ 100M for 6 year(Civil engineering: $ 15M, Detector: $ 85M)
- Schedule
  - ⇨ 2014-2019: Facility and detector construction
  - ⇨ 2020~ Operation





(NEAR Detector)

(FAR Detector)



RENO-50

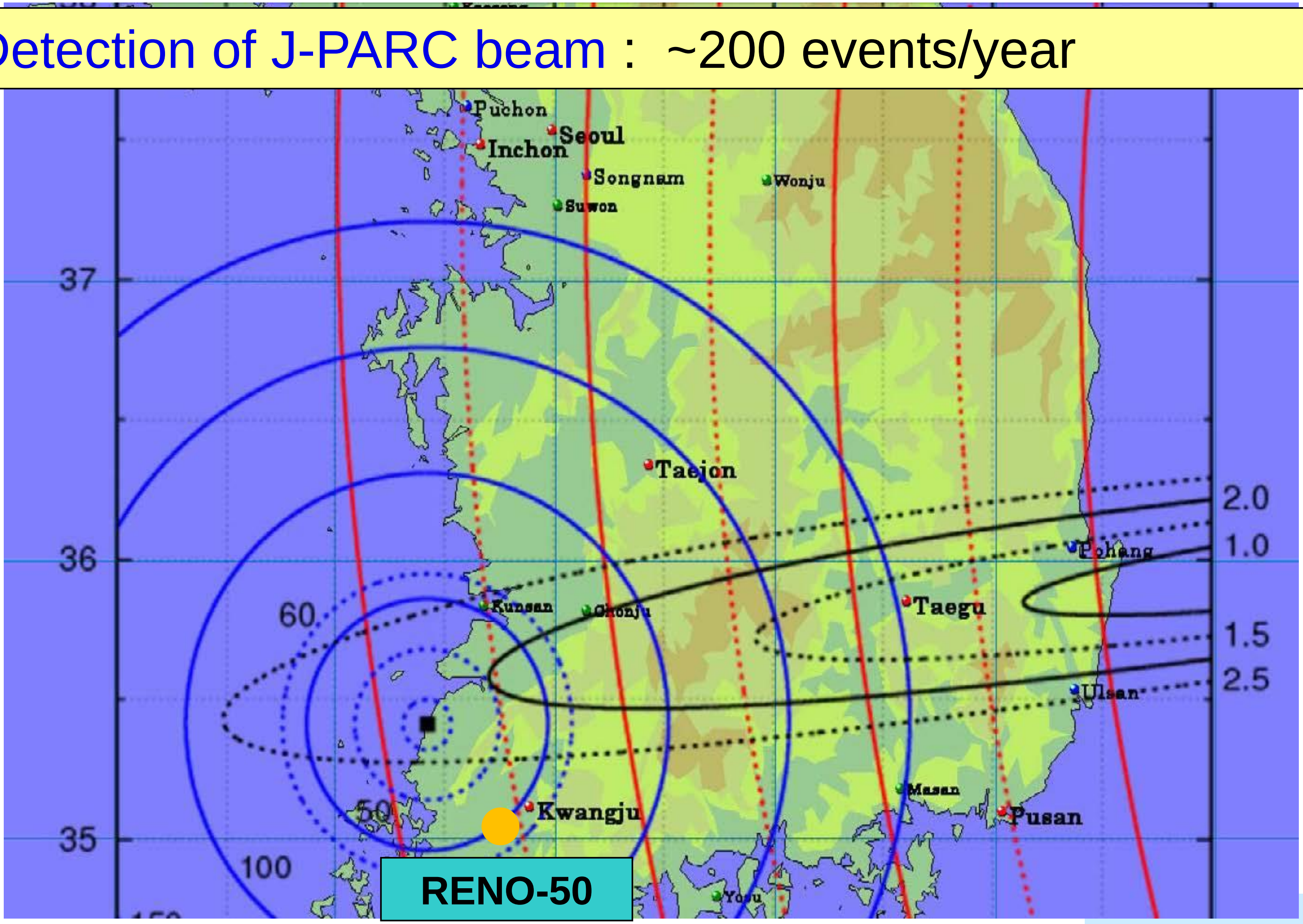
18 kton LS Detector
~47 km from YG reactors

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

J-PARC neutrino beam

Dr. Okamura & Prof. Hagiwara

- Detection of J-PARC beam : ~200 events/year



Complementary MH Determination

Δm^2_{31} and Δm^2_{32} Interference (ϕ)

Δm^2_{ee} and $\Delta m^2_{\mu\mu}$ difference

Matter Effect

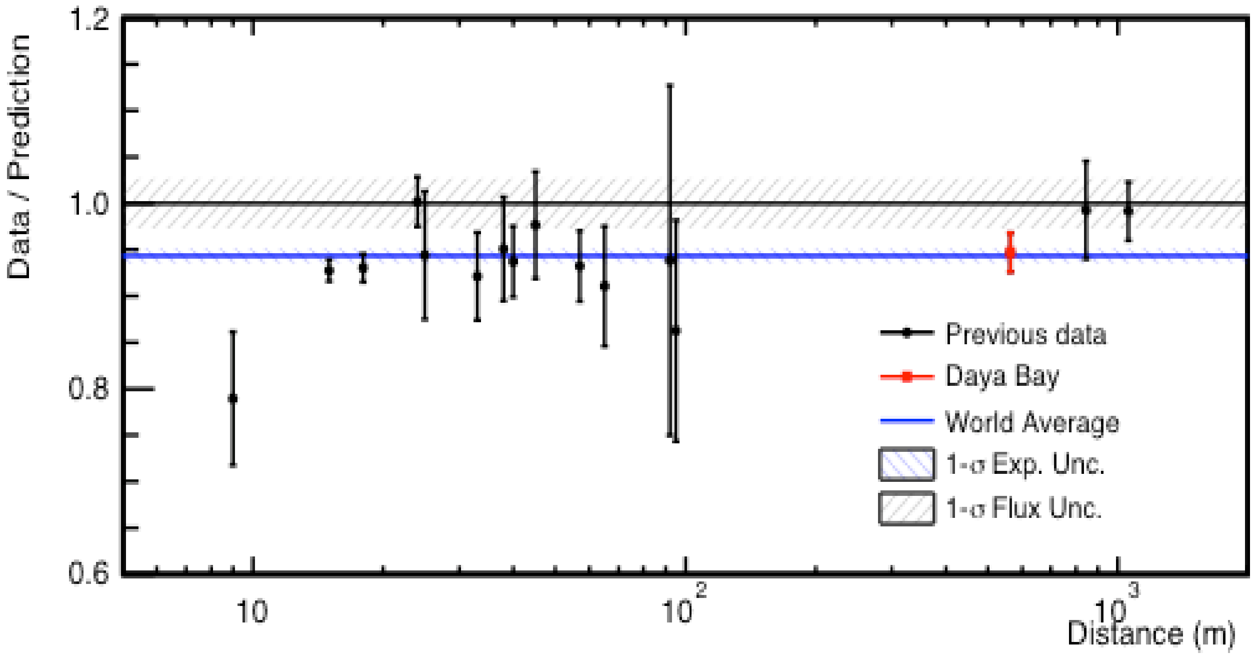
Reactor

atmospheric

Accelerator

- **Reactors**
  - **JUNO: approved, data in 2020, 3-4σ in 6 years.**
  - **RENO-50: R&D**
- **Atmospheric**
  - **INO: approved, data in 2019-2020, 3σ in 10 years**
  - **PINGU: planned, data in 2021, 3σ in 4 years**
  - **ORCA: planned, data in 2020, 3σ in 4 years**
  - **Hyper-K: planned, data in 2025?**
- **Accelerator**
  - **NOvA: operation, 1/3 chance at 95% CL**
  - **DUNE: 10 kton from 2024, 40 kton from 2027, >5σ for all CPs**

Reactor Anomaly



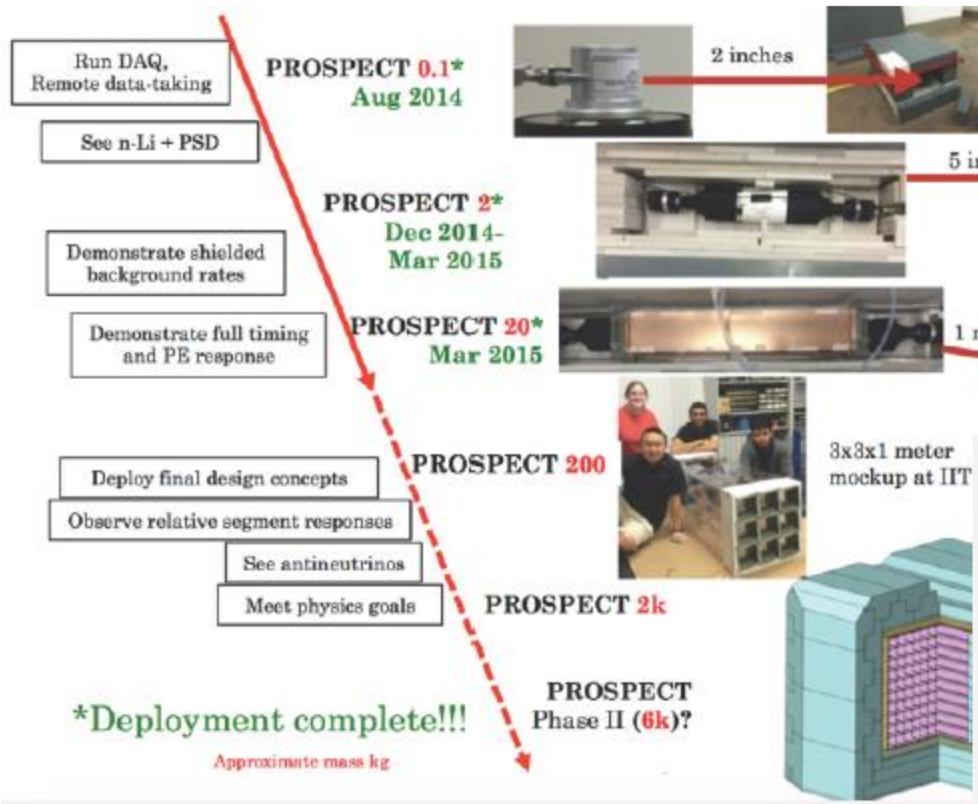
- **Short baseline experiment observed deficit comparing to an improved flux model (Huber+Mueller) (Mention et al.)**
- **Daya Bay measurement of absolute Flux**
  - ⇨ **Data/(Huber+Mueller): 0.947±0.022**
  - ⇨ **Data/(ILL+Vogel): 0.992 ± 0.023**
  - ⇨ **Consistent with others**

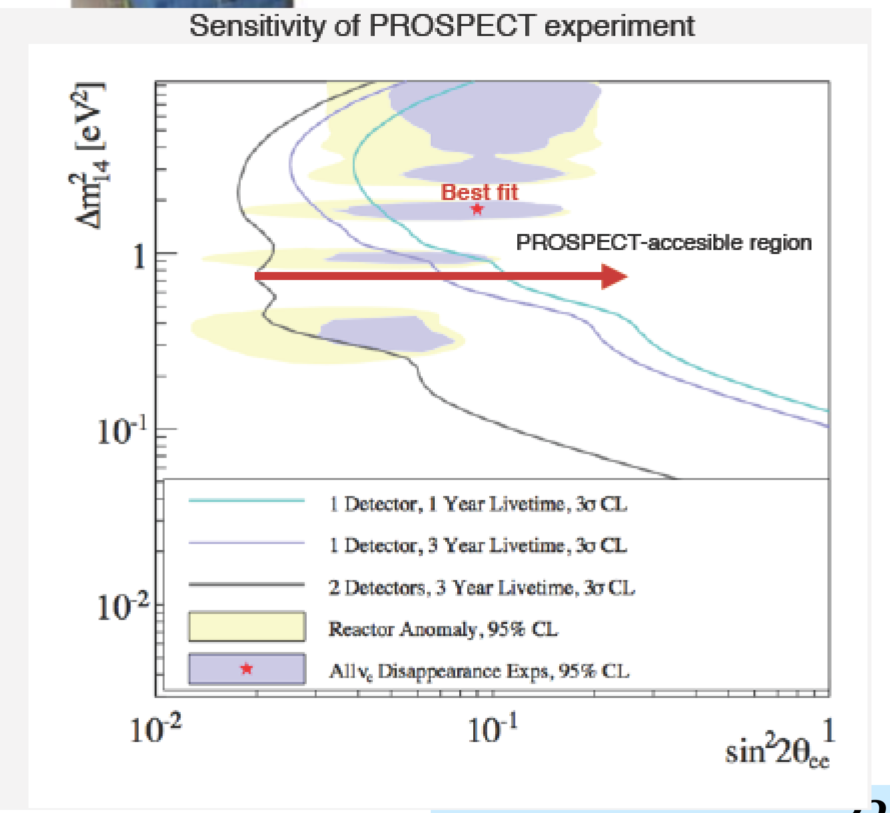
Future Reactor Exp. for Sterile Neutrino

- **Different technologies: (Gd, Li, B) (seg.)(movable)(2 det.)**
- **Most have sensitivity 0.02~0.03 @Δm~1eV^2 @90%CL**

J. Learned

Example: PROSPECT

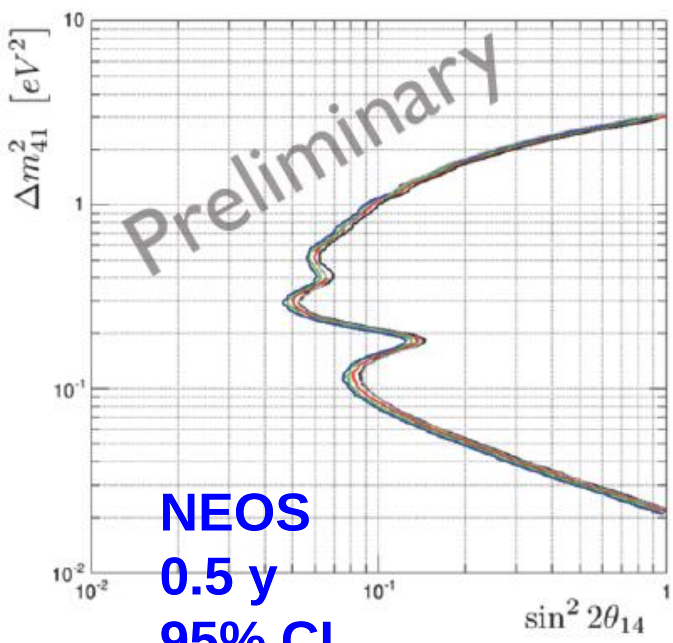


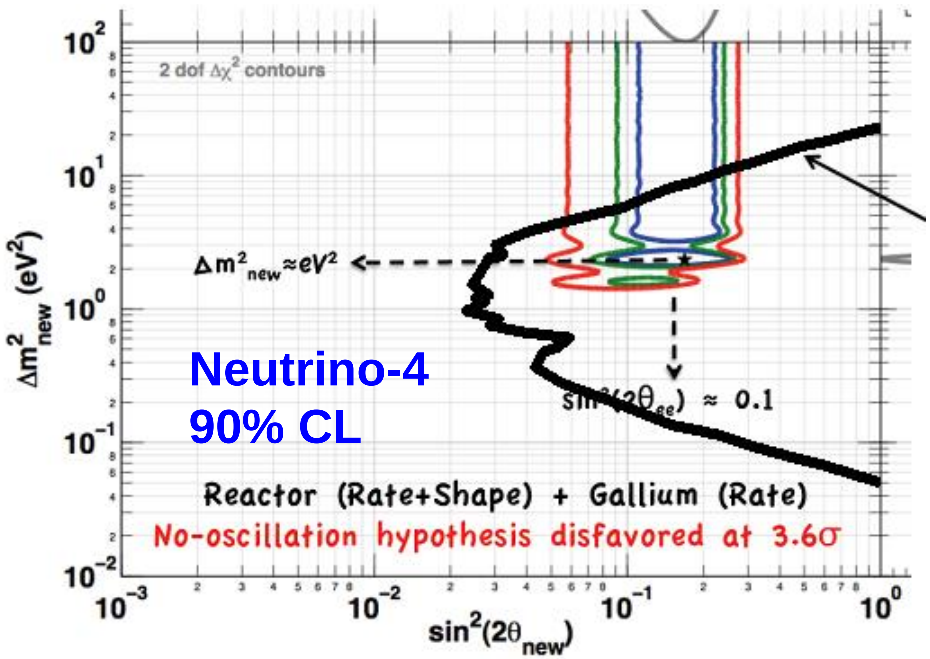


- Li-LS
- 4-5% energy resolution
- U-235 spectrum

More Examples: NEOS, Neutrino-4

~Jul 2015	Aug~Sep 2015	Oct 2015~Mar 2016 ~ …
Detector Construction & Commissioning & Installation on site	Reactor Overhaul Maintanance	Reactor On
	Reactor Off data	Reactor On Data





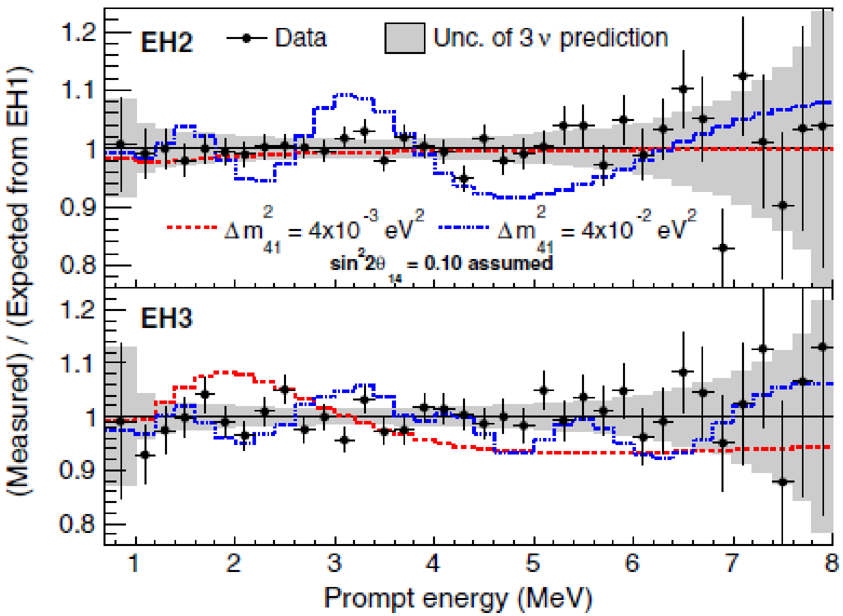
- Neutrino-4, waiting for filling

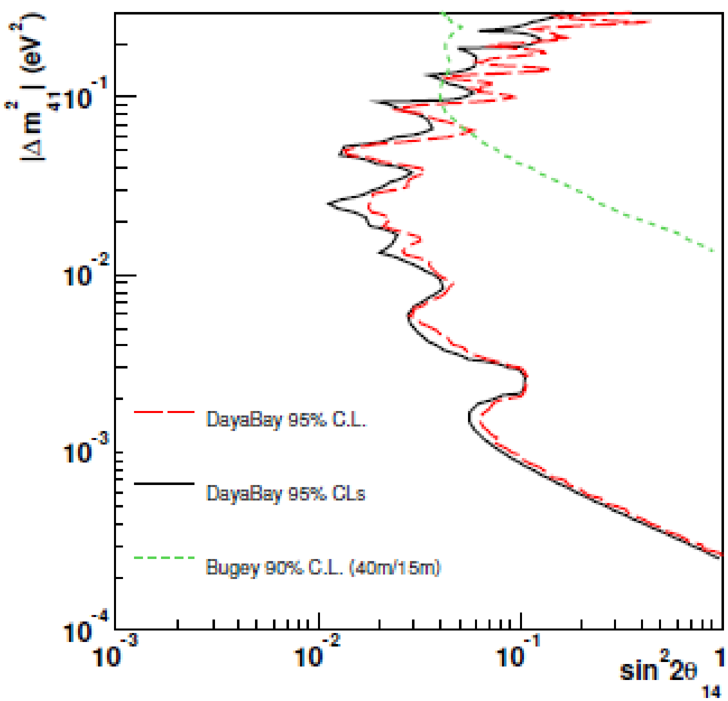
Search for Light Sterile Neutrinos

- Precise reactor neutrino spectrum from Daya Bay near site can test the sterile neutrino hypothesis
- ~400 m baseline is not ideal for the reactor anomaly → much better exclusion in 0.001-0.1 eV^2 region

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

Daya Bay: PRL113, 141802, 2014



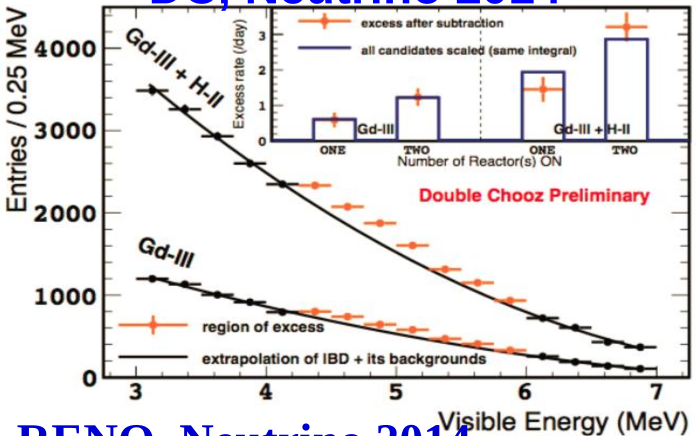


Measurement by shape distortion

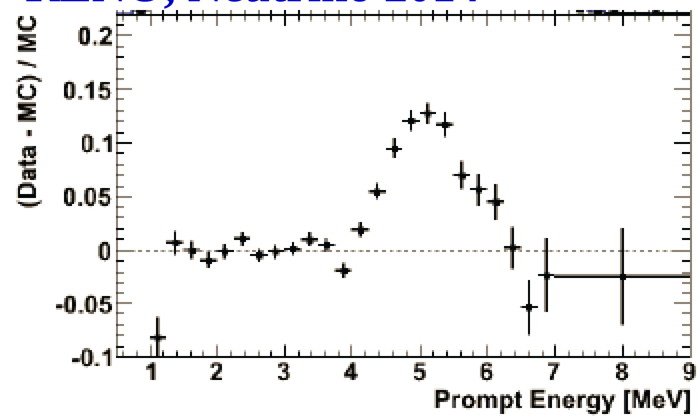
5 MeV Bump on Reactor Spectrum

- Significance ~ 4 σ
- Events are reactor power related & time independent
- Events are IBD-like:
  - ⇨ Disfavors unexpected backgrounds
- **No effect to θ_{13} at DYB, RENO; under control at DC**
- Possibly due to forbidden decays (PRL112, 2021501, 2014, arXiv:1407.1281)

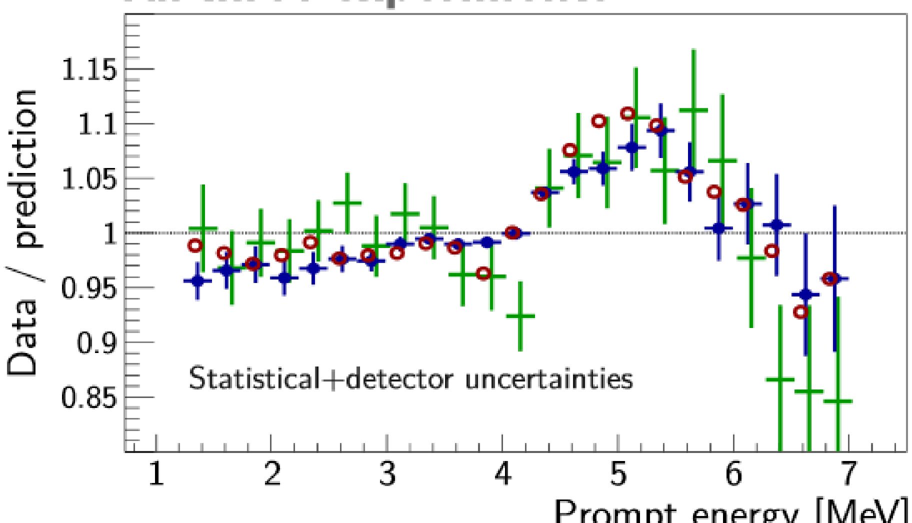
DC, Neutrino 2014



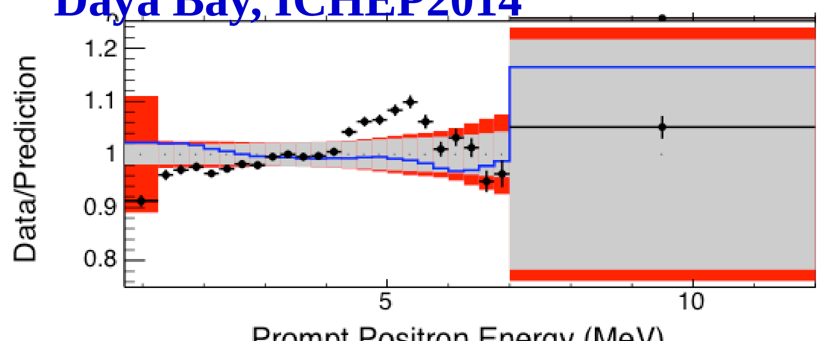
RENO, Neutrino 2014



All three experiments



Daya Bay, ICHEP2014

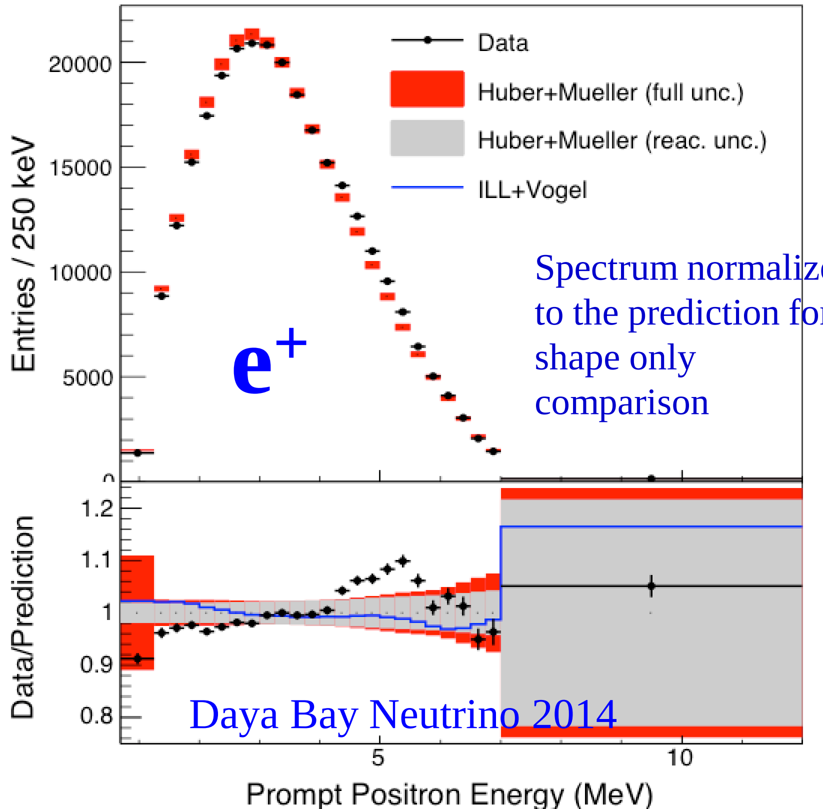


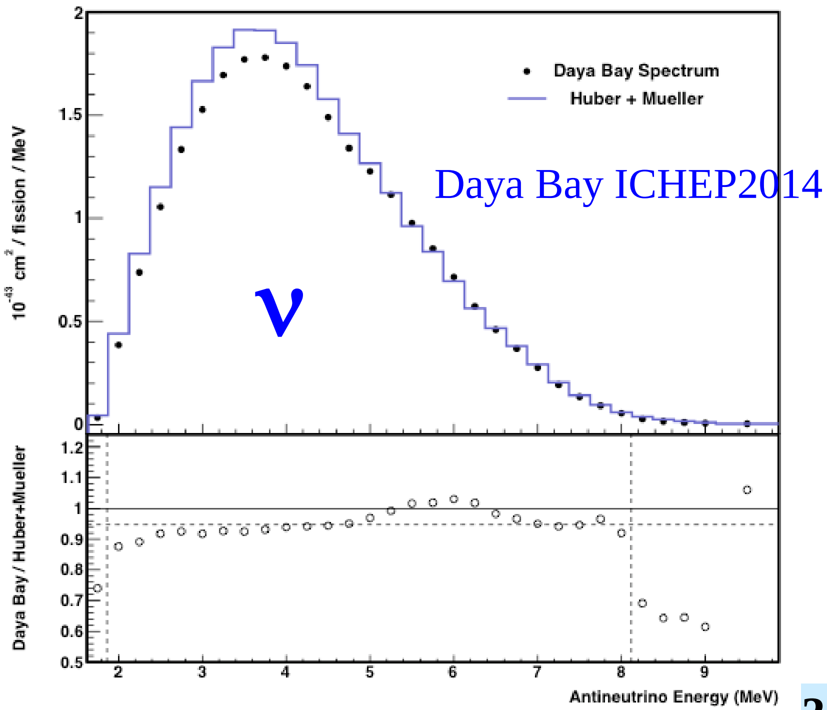
Jetter, Tau2014

Absolute Reactor Flux and Spectrum

- **Absolute neutrino spectrum**
  - **Unfolded from the positron spectrum after non-linearity correction. Most precise reactor spectrum.**
  - **Unfolding bias 0.5% between 2.2-6.5 MeV**

e+ spectrum uncertainty 0.9% @3.5 MeV

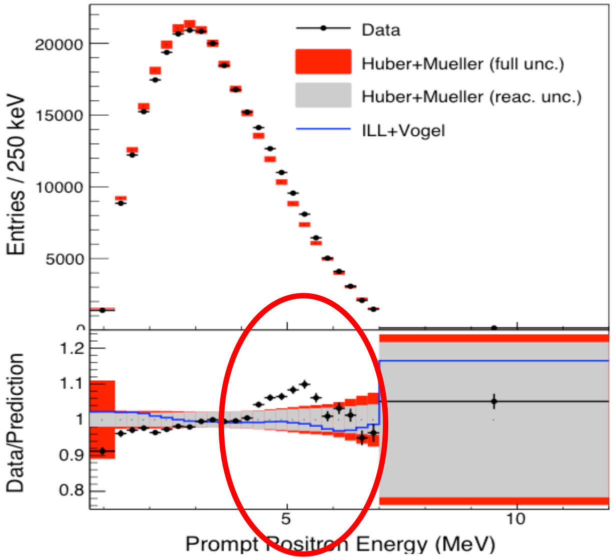


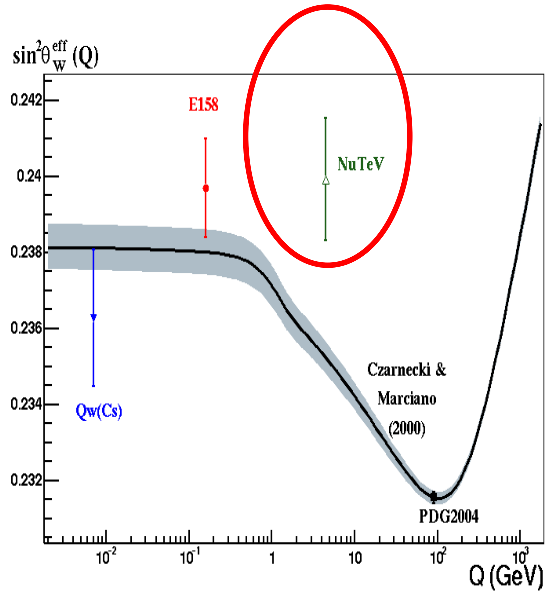


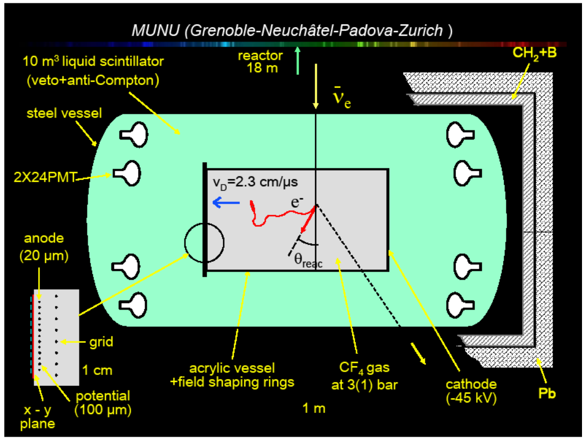
Short Baseline Exp. with Gas TPC

- Gas TPC detector at ~20 m from a reactor (J. Cao, L.J. Wen)
  - ⇨ ν-e scattering
  - ⇨ High energy precision (<3%/sqrt(E))
- Major motivation: high precision reactor neutrino spectrum
  - ⇨ Input for JUNO. Daya Bay energy resolution 8%, JUNO 3%
- Other motivations:
  - ⇨ The weak mixing angle θw
  - ⇨ Abnormal magnetic moment
  - ⇨ Sterile neutrino

MUNU exp:
$\mu_\nu < 0.9 \times 10^{-10}\ \mu_B$
CF_4 , T > 700 keV
PLB 615(2005)153







Summary

- Significant improvement on $\mathrm{Sin}^2 2\theta_{13}$ precision from the Daya Bay, Double Chooz and RENO experiments.
- Ultimate precision of $\mathrm{Sin}^2 2\theta_{13}$ will reach ~ 3-4%
- A precision measurement of the absolute neutrino flux and spectrum from Daya Bay.
- A bump around 5 MeV observed by all three experiments.
- Reactor Anomaly may have a definite answer before 2020.
- Reactor neutrinos will play important roles on:
  - ⇨ Mass hierarchy
  - ⇨ Precision measurement of 3/6 mixing parameters up to < ~1% level ➔ unitarity test of the mixing matrix
  - ⇨ Sterile neutrinos
  - ⇨ Other Neutrino properties

Thanks !