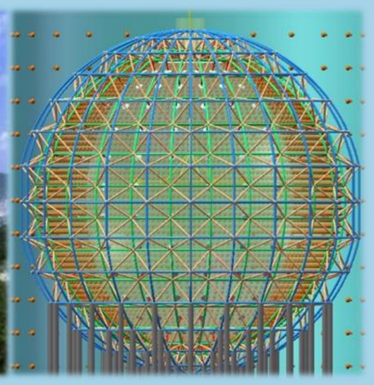


# Reactor Neutrino Experiments

**Jun Cao**

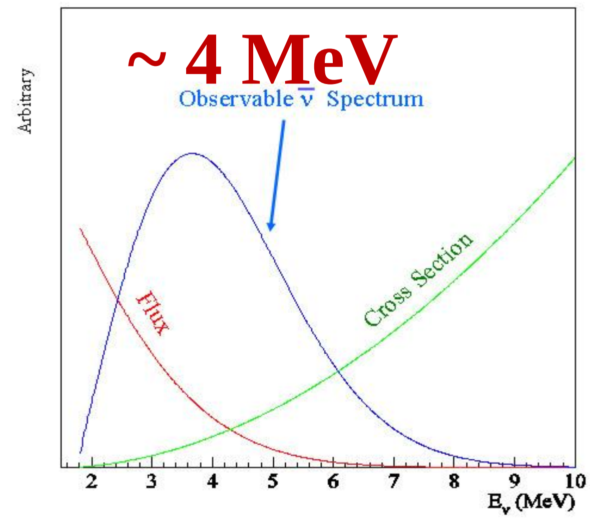
Institute of High Energy Physics

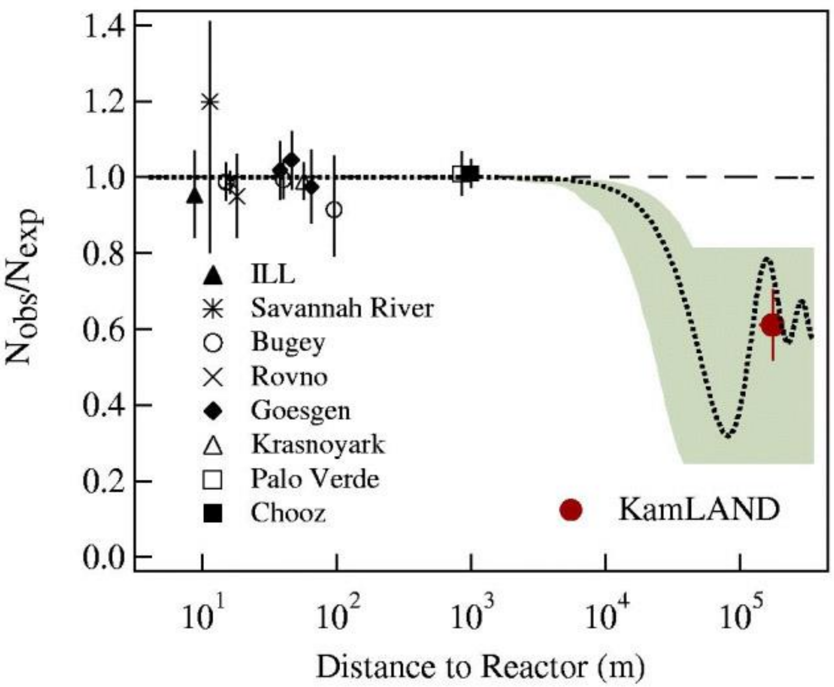
The 11th ICFA Seminar on Future Perspectives in High-Energy Physics

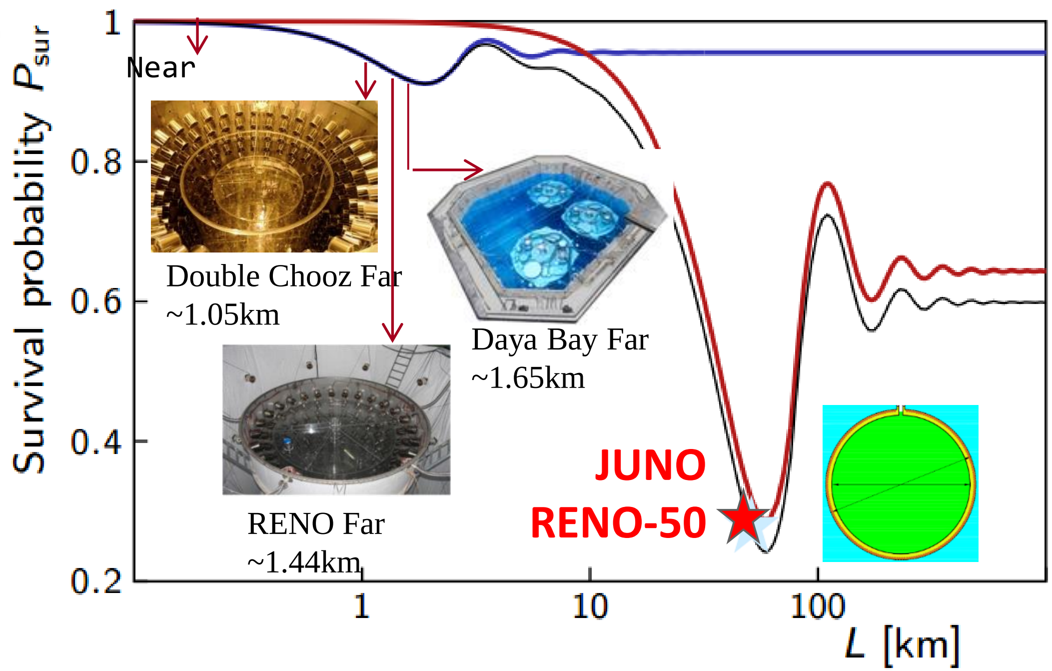
Institute of High Energy Physics, CAS, October 27-30, 2014

# Reactor Neutrinos

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



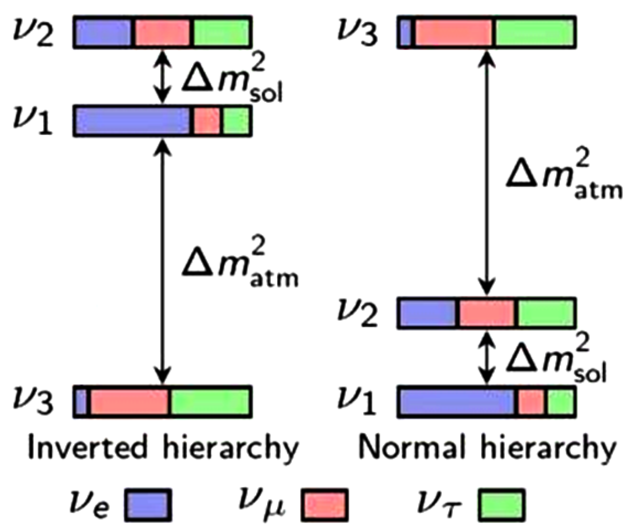
# Outline

- Latest results on $\theta_{13}$ and $\Delta m_{ee}$
  - ⇨ Daya Bay
  - ⇨ Double Chooz
  - ⇨ RENO
- Measuring reactor neutrino flux and spectrum
- Search for sterile neutrinos
- Future experiments
  - ⇨ JUNO
  - ⇨ RENO-50
  - ⇨ Short baseline experiments for sterile neutrinos
- Summary

# Neutrino Oscillation

**In a 3-ν framework**

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




$2.4 \cdot 10^{-3} \mathrm{eV}^2$

$7.5 \cdot 10^{-5} \mathrm{eV}^2$

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

**$\theta_{23} \sim 45°$**
**Atmospheric**
**Accelerator**

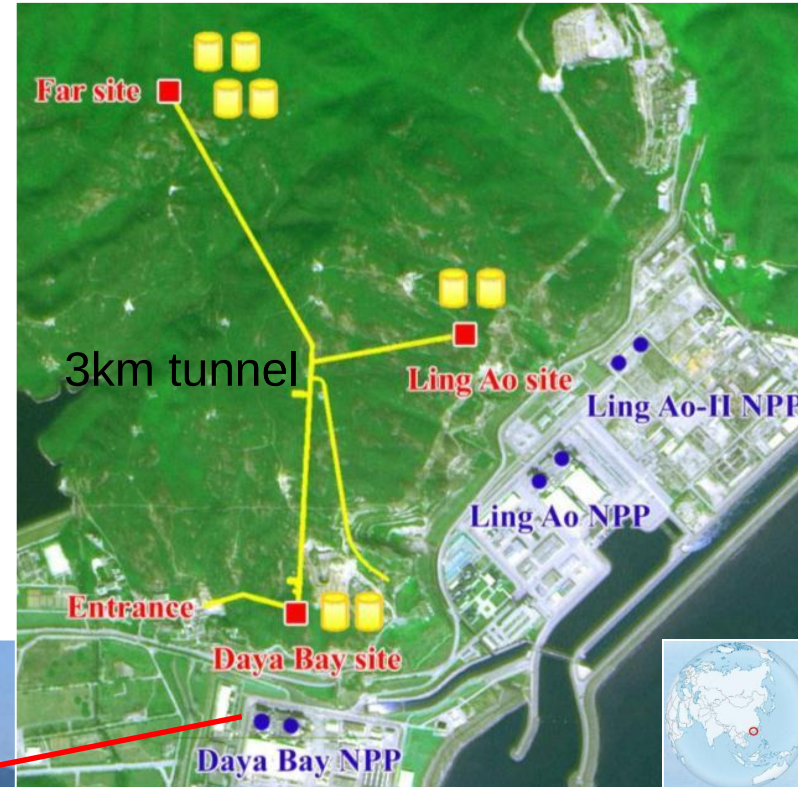
**$\theta_{13} \sim 9°$**
**Reactor**
**Accelerator**

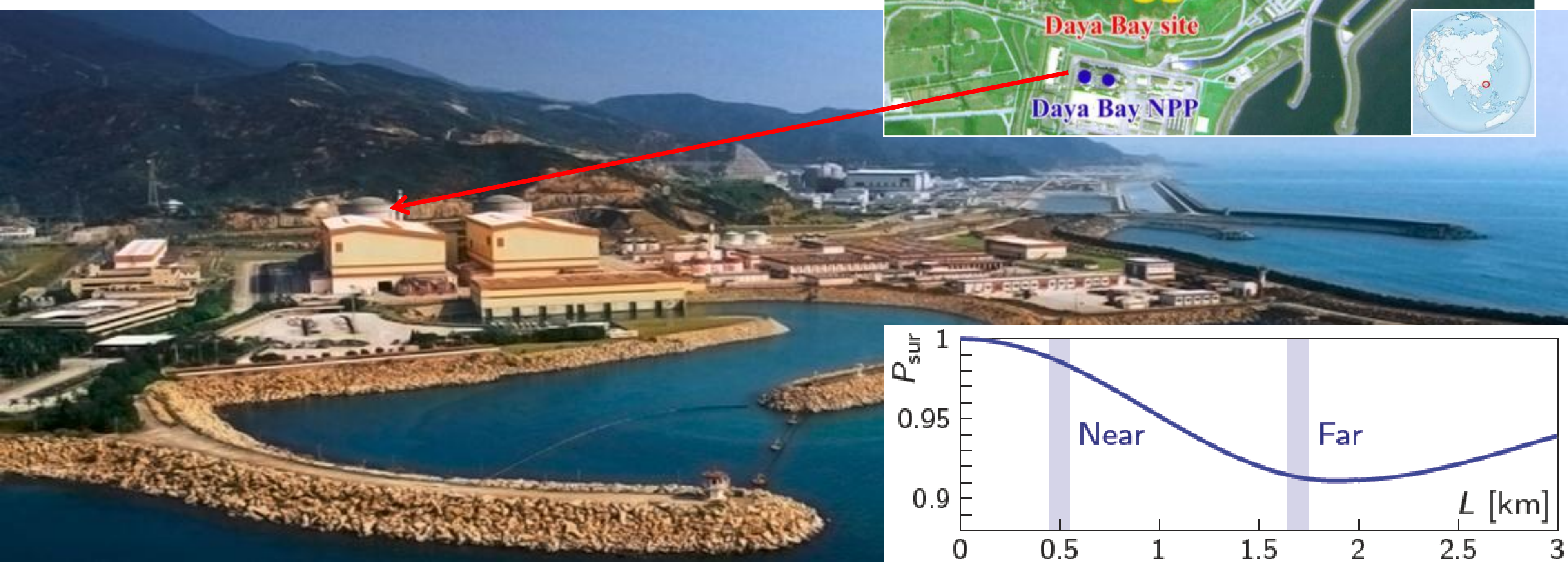
**$\theta_{12} \sim 34°$**
**Solar**
**Reactor**

**0νββ**

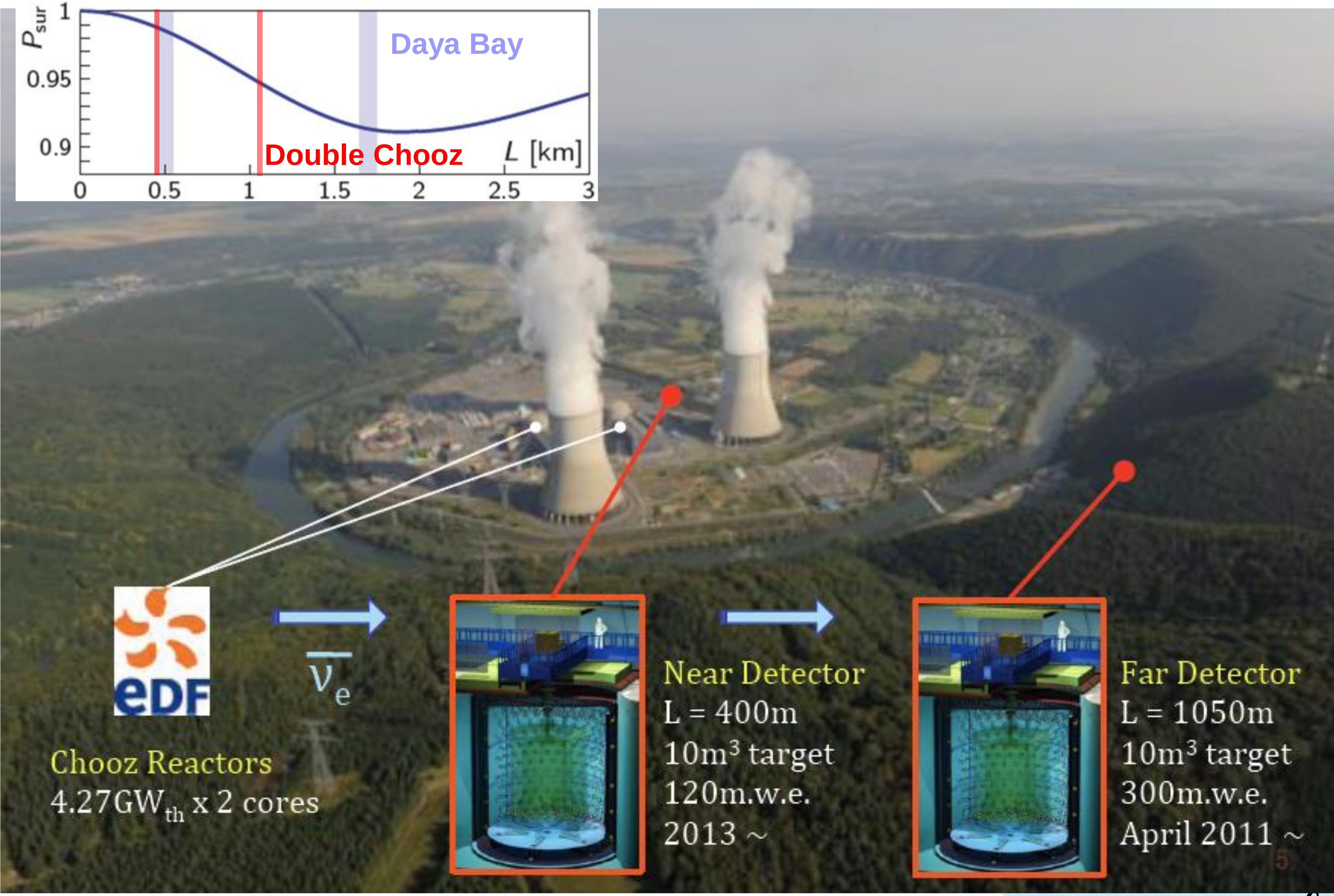
# The Daya Bay Experiment

- 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

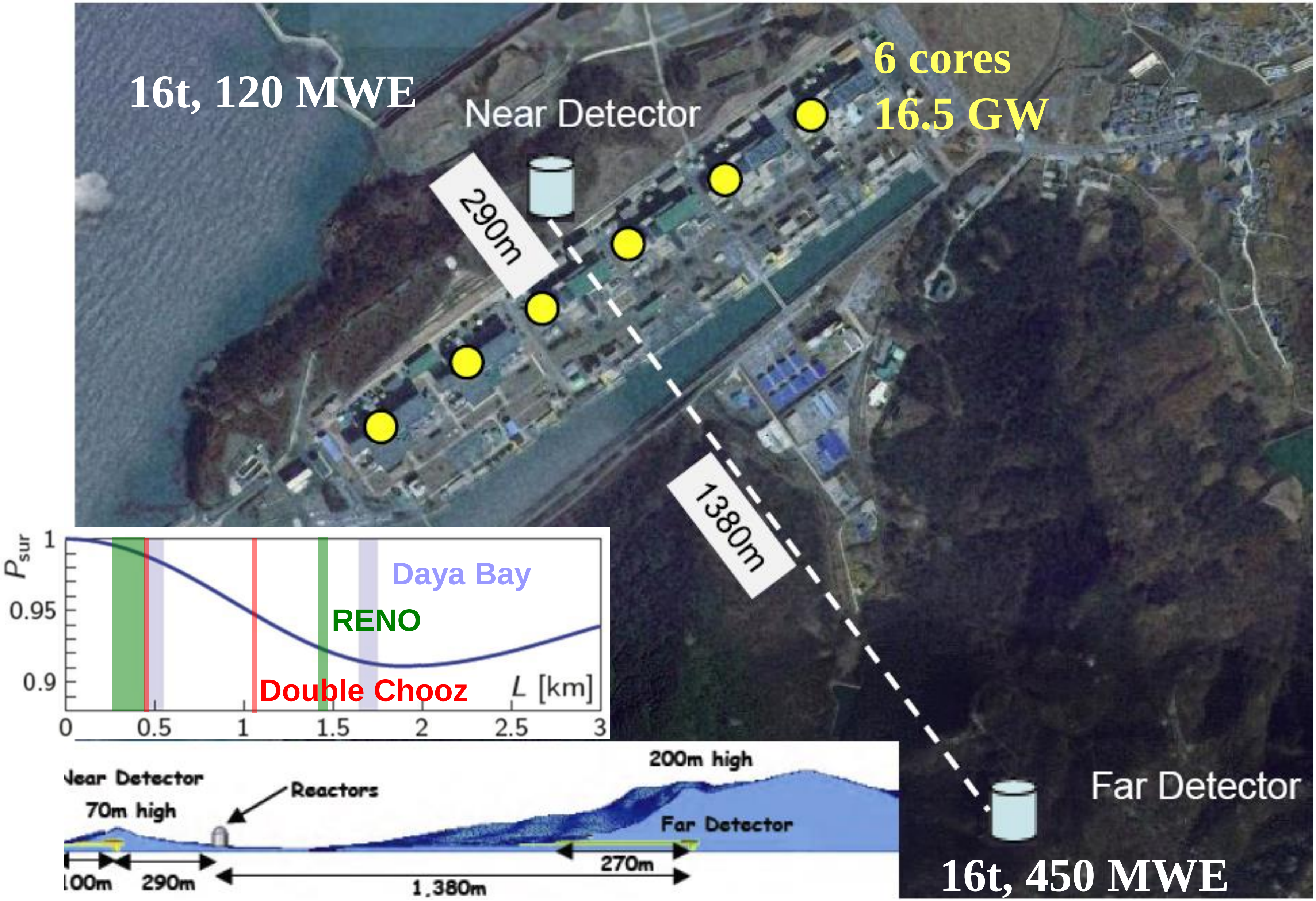


# Double Chooz



# 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]
200m high
Near Detector
70m high
Reactors
Far Detector
100m
290m
270m
1,380m

# Detecting Reactor Antineutrino

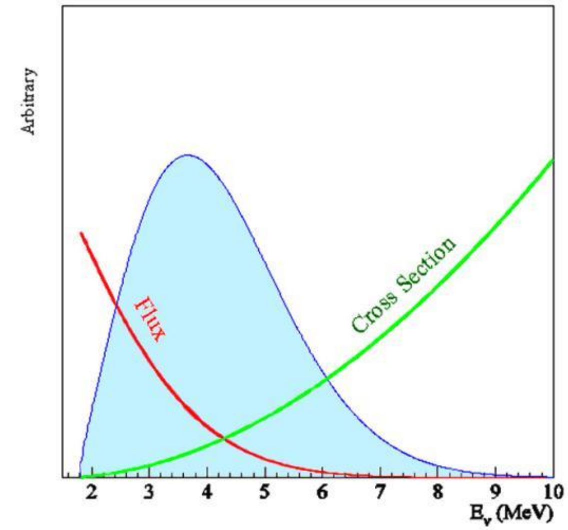
Inverse beta decay

Prompt signal

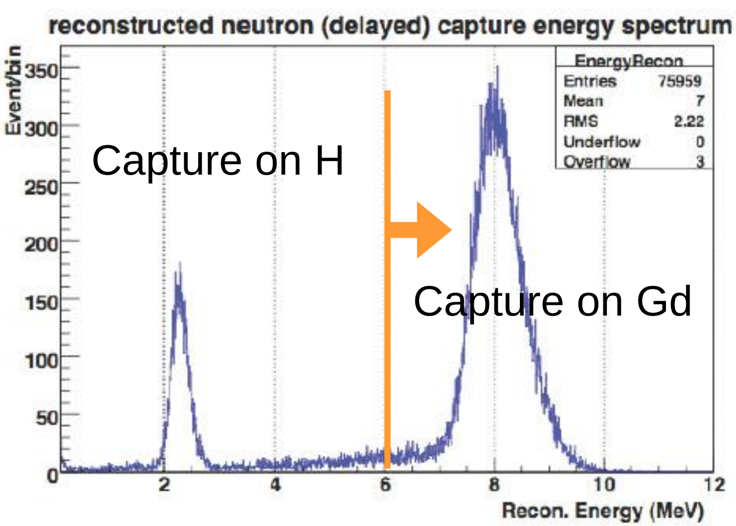
$$e^{+} + e^{-} \rightarrow 2\gamma$$

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

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

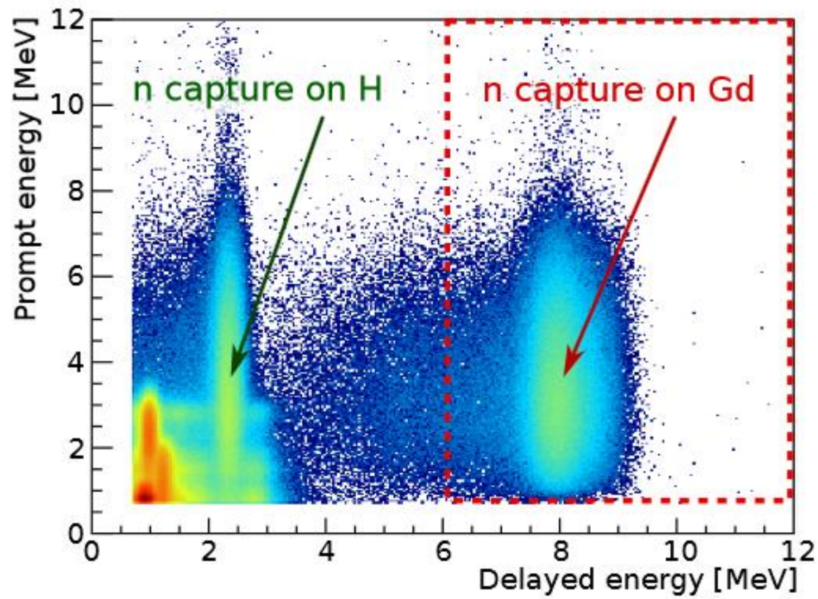



0.1% Gd by weight



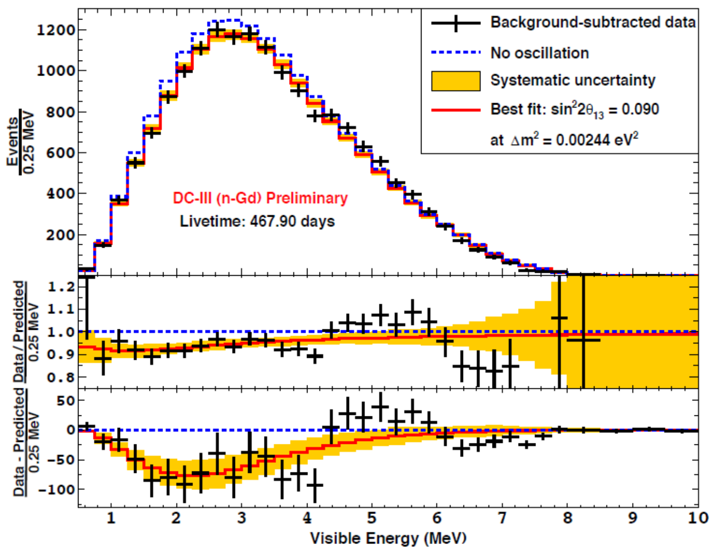

Near site: ~thousands IBD/day

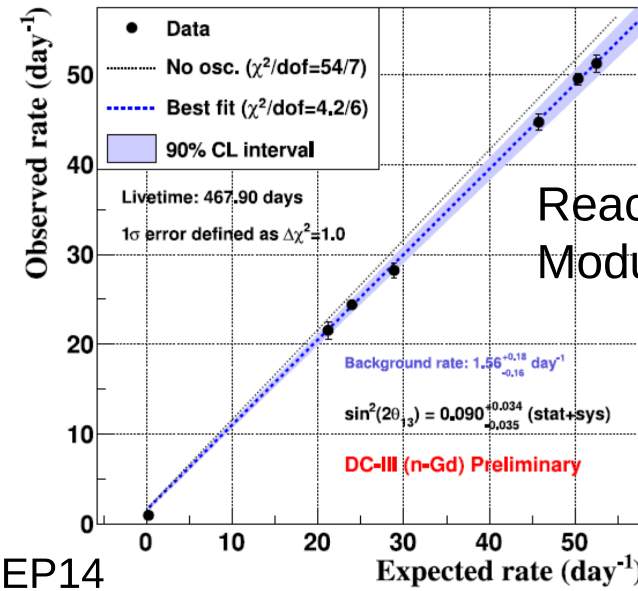
Far site: ~hundreds IBD/day



# 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, …**




Haser, ICHEP14

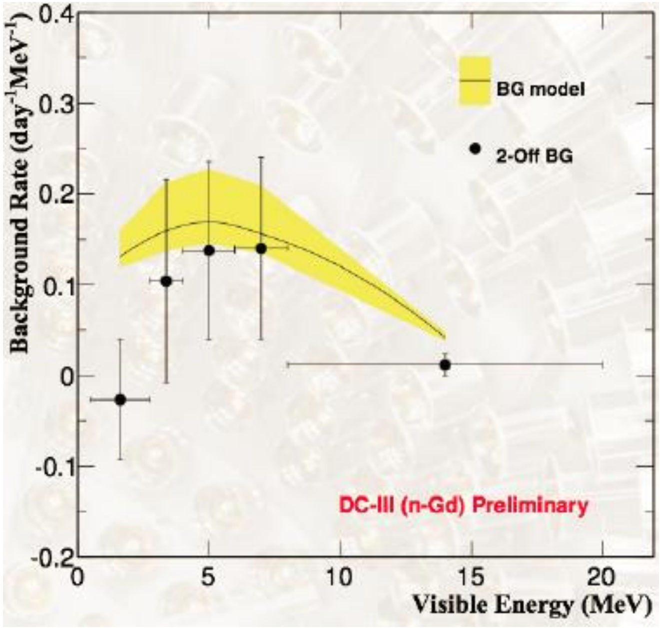
R+S: $\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$, BG rate: $1.38 \pm 0.14$ day$^{-1}$

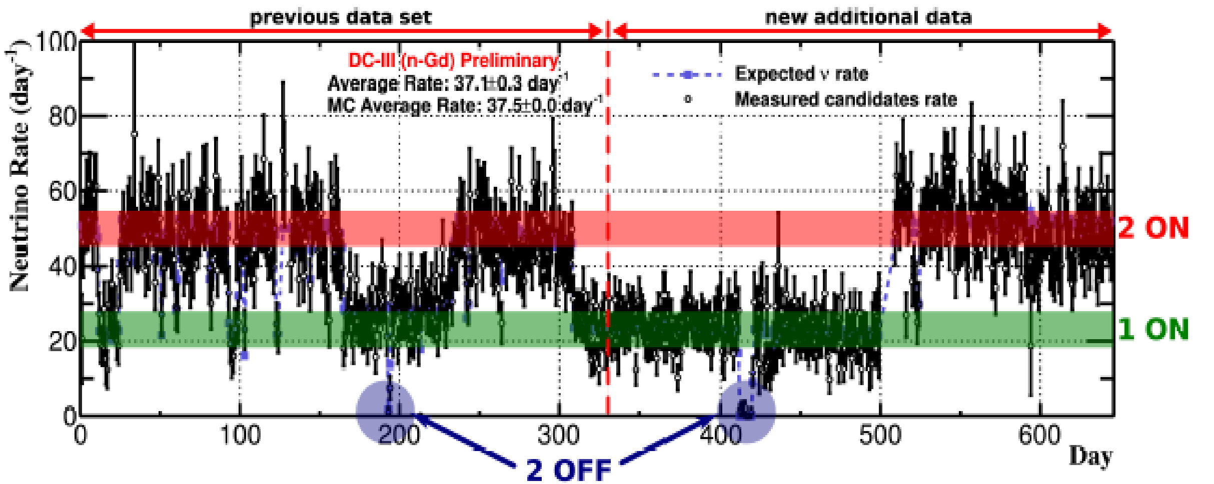
RRM: $\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035}$, BG rate: $1.56 \pm 0.17$ day$^{-1}$

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

# 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
  - $12.9^{+3.1}_{-1.4}$ expected
  - Tension @ ~ 2σ ➔ no room for unknown backgrounds

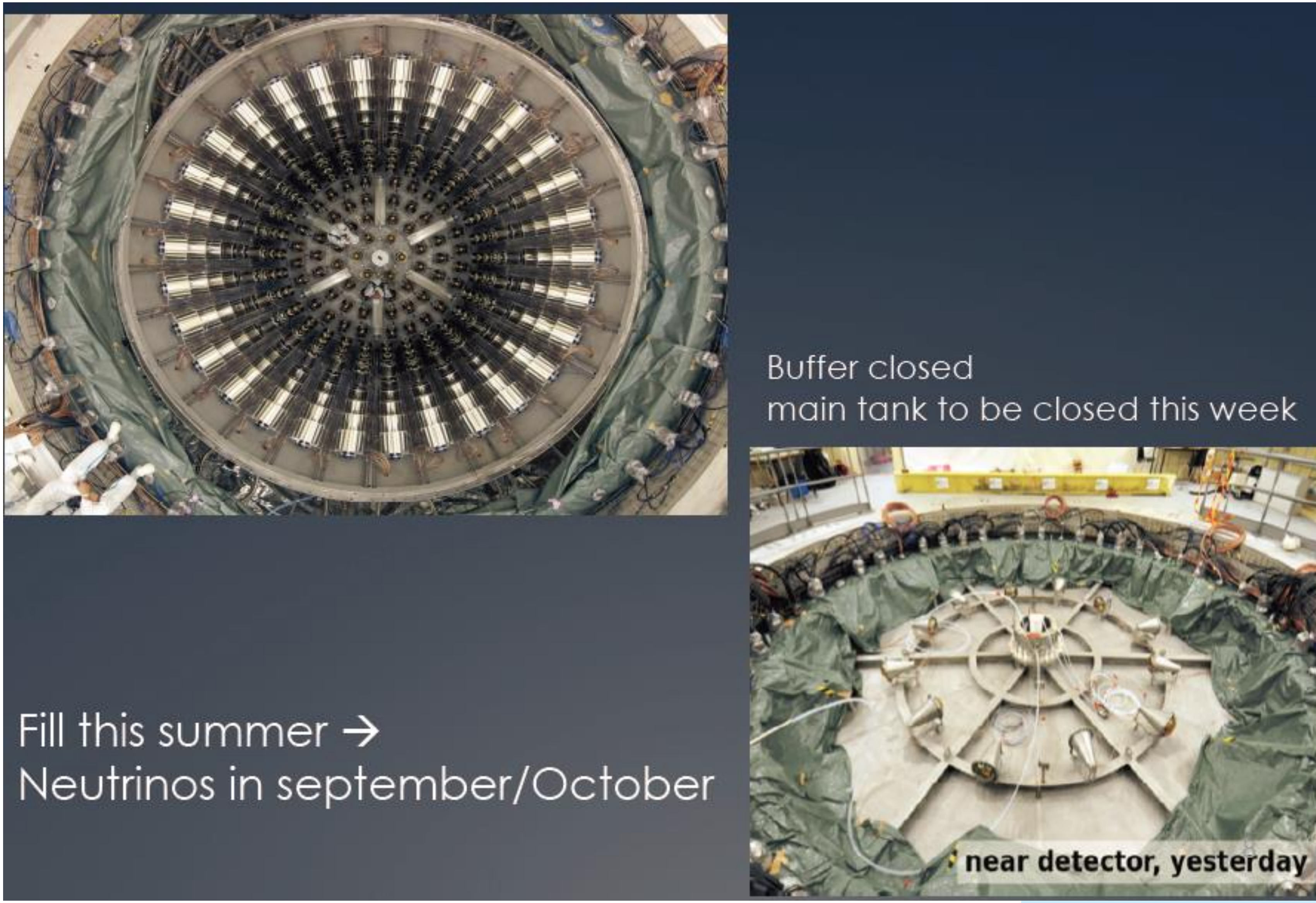



Haser, ICHEP14

# DC Near Site

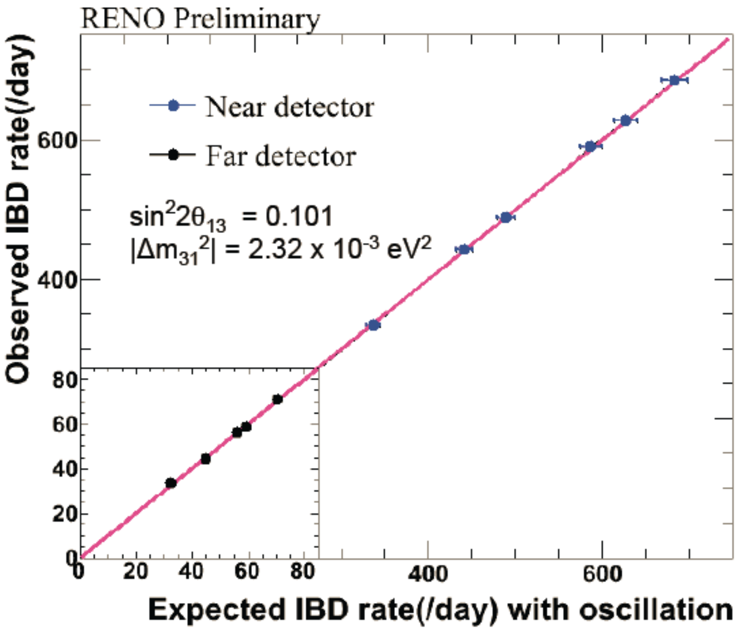
- the second detector was inaugurated on September 25, 2014

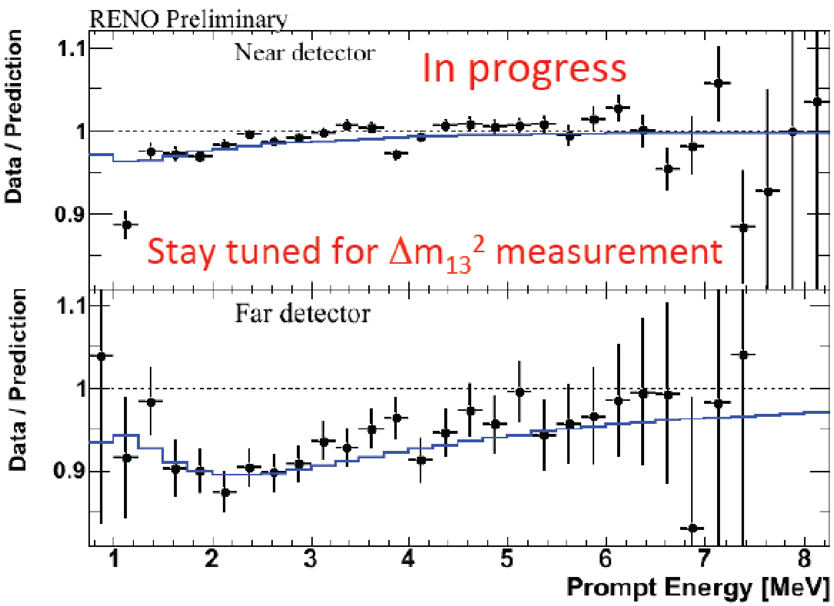


# RENO

- 2011.8-2013.12 (800 days)
- Also reactor rate modulation analysis
- Shape analysis is on the way
- Reduced systematics butworsened by $^{252}Cf$ contamination
  - Data before contamination 0.012 (sys) → 0.007 (sys)
  - Data after contamination → 0.018 (sys)

Seo, Neutrino14



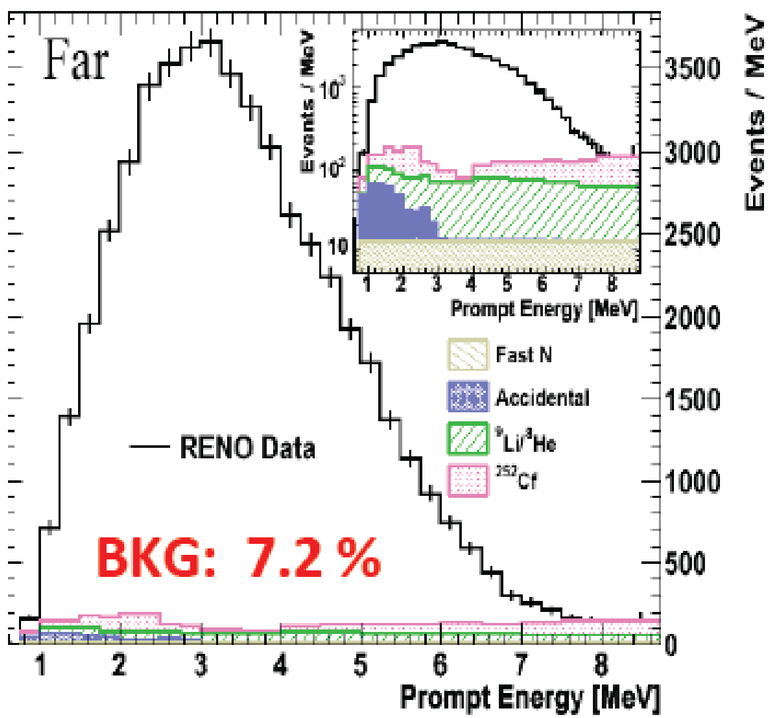
# RENO results

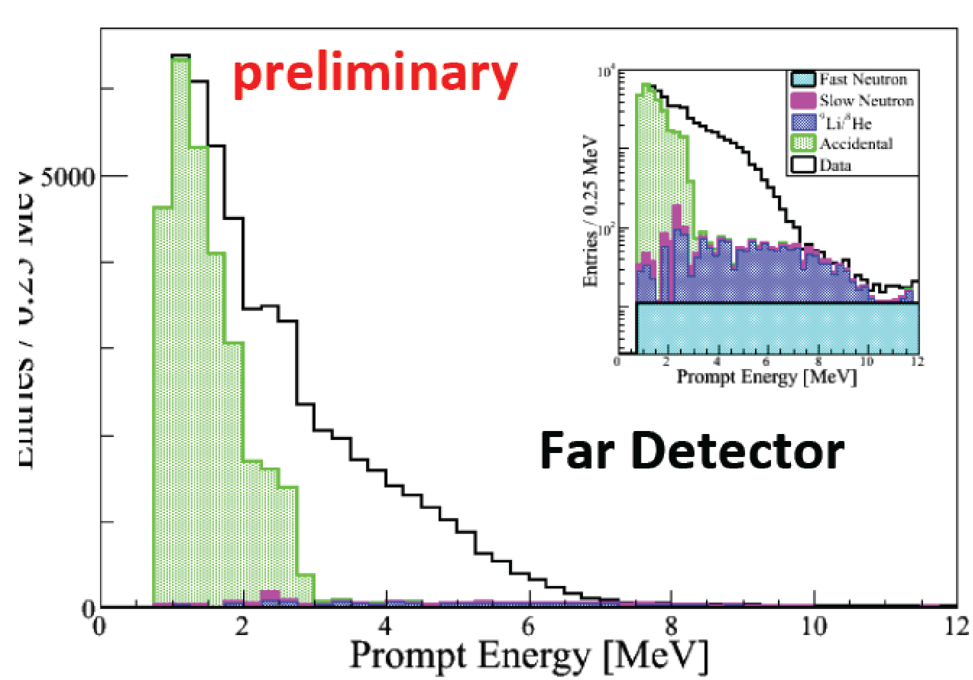
- Rate analysis result: preliminary

$\sin^2(2\theta_{13}) = 0.101 \pm 0.008\ (\text{stat.}) \pm 0.010\ (\text{sys.})$

- Very preliminary result on n-H IBD analysis: Very preliminary Rate analysis

$\sin^2(2\theta_{13}) = 0.095 \pm 0.015\ (\text{stat.}) \pm 0.025\ (\text{sys.})$




nGd

Seo, Neutrino14

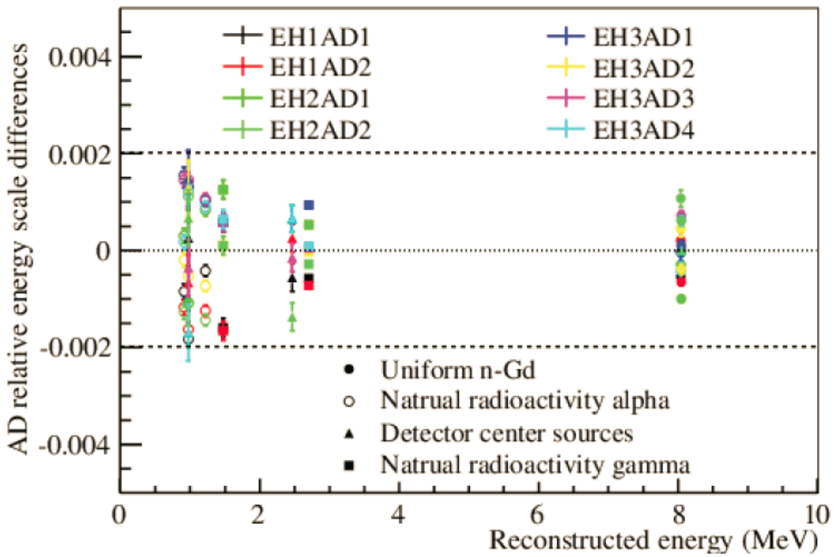
nH

# 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

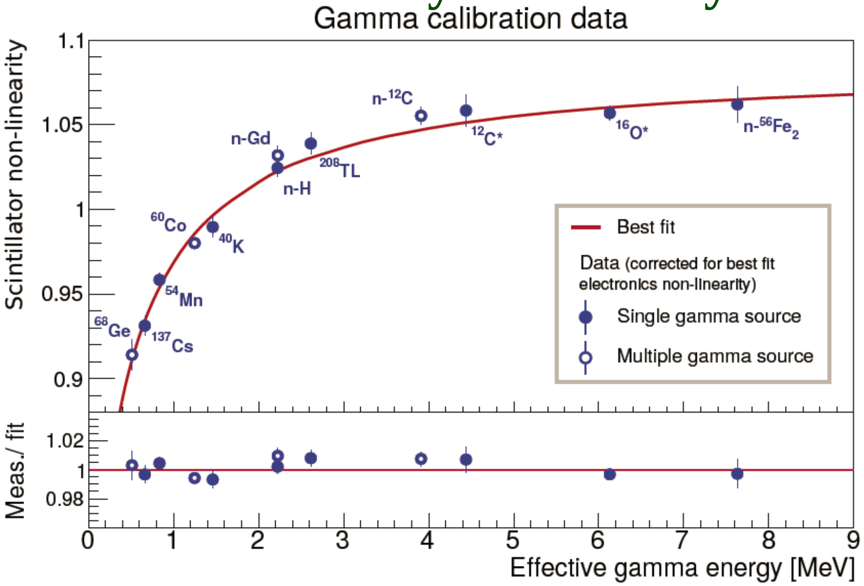
0.5%

Relative energy scale difference: <0.2%




2%

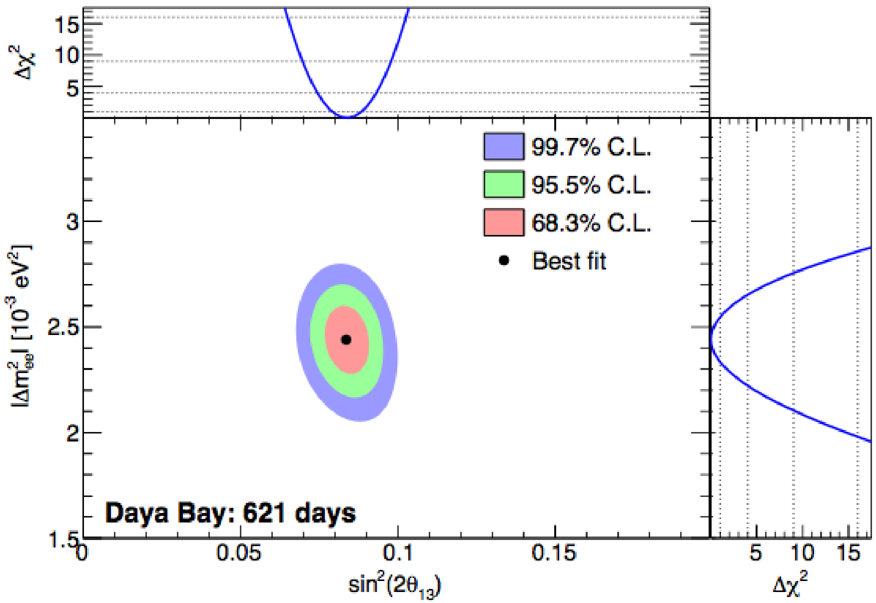
Non-linearity uncertainty < 1%




C.Zhang, Neutrino14 & W.Wang, ICHEP14

# Daya Bay Results

nGd rate+shape

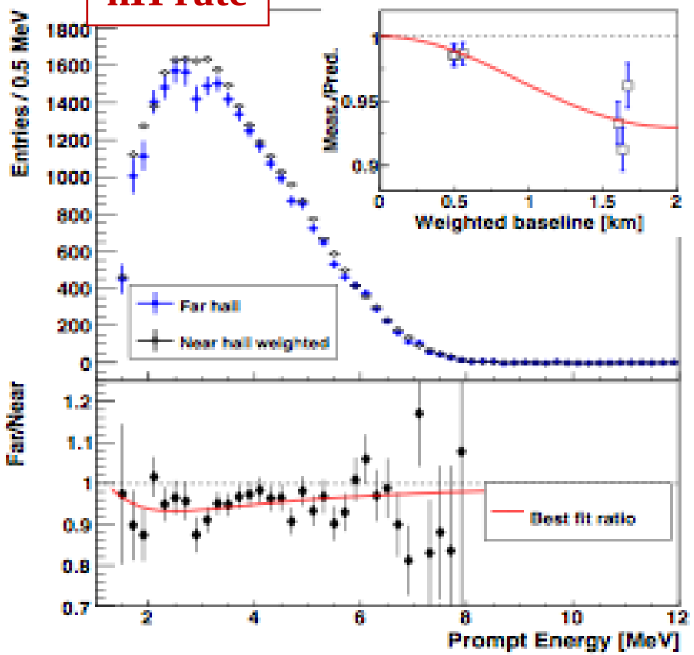



$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

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

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

nH rate



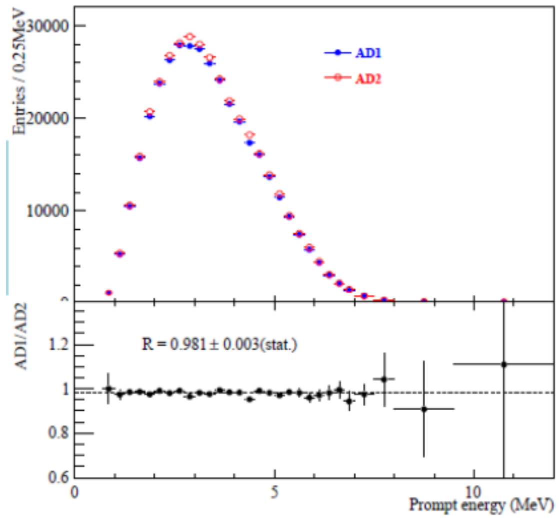

$\sin^2 2\theta_{13} = 0.083$ +- $0.018$

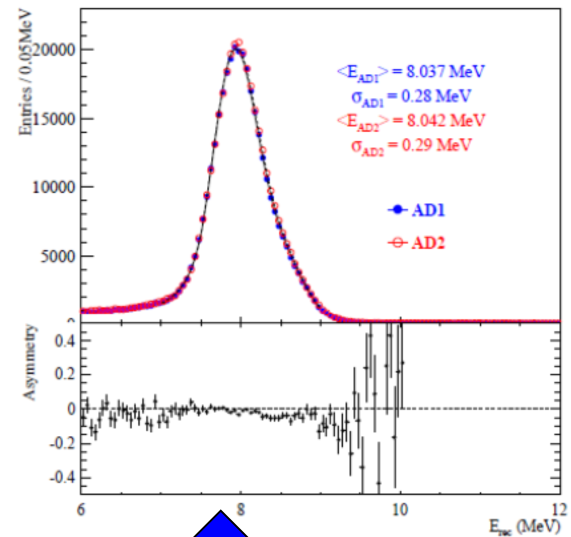
- **$\Delta(\sin^2 2\theta_{13})/\sin^2 2\theta_{13}$ ~ 6%, the best among all mixing angles**
- **$\Delta(\Delta m^2_{ee})/\Delta m^2_{ee}$ ~ 5%, similar to that of MINOS**
- **nH results ~4.5σ, independent check**

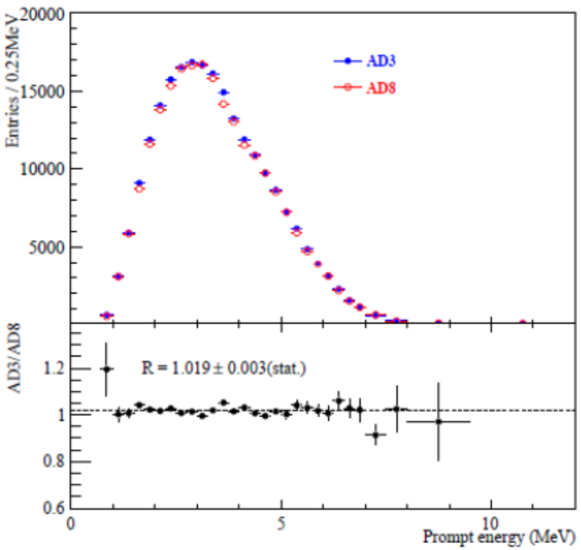
C.Zhang, Neutrino14 & W.Wang, ICHEP14

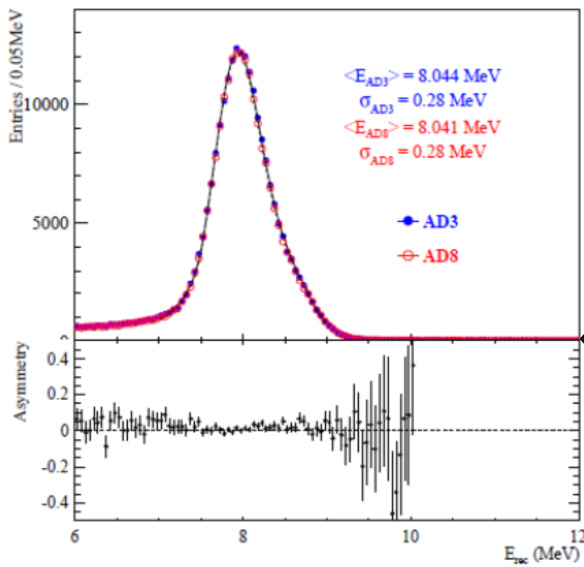
# Systematics at Daya Bay

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



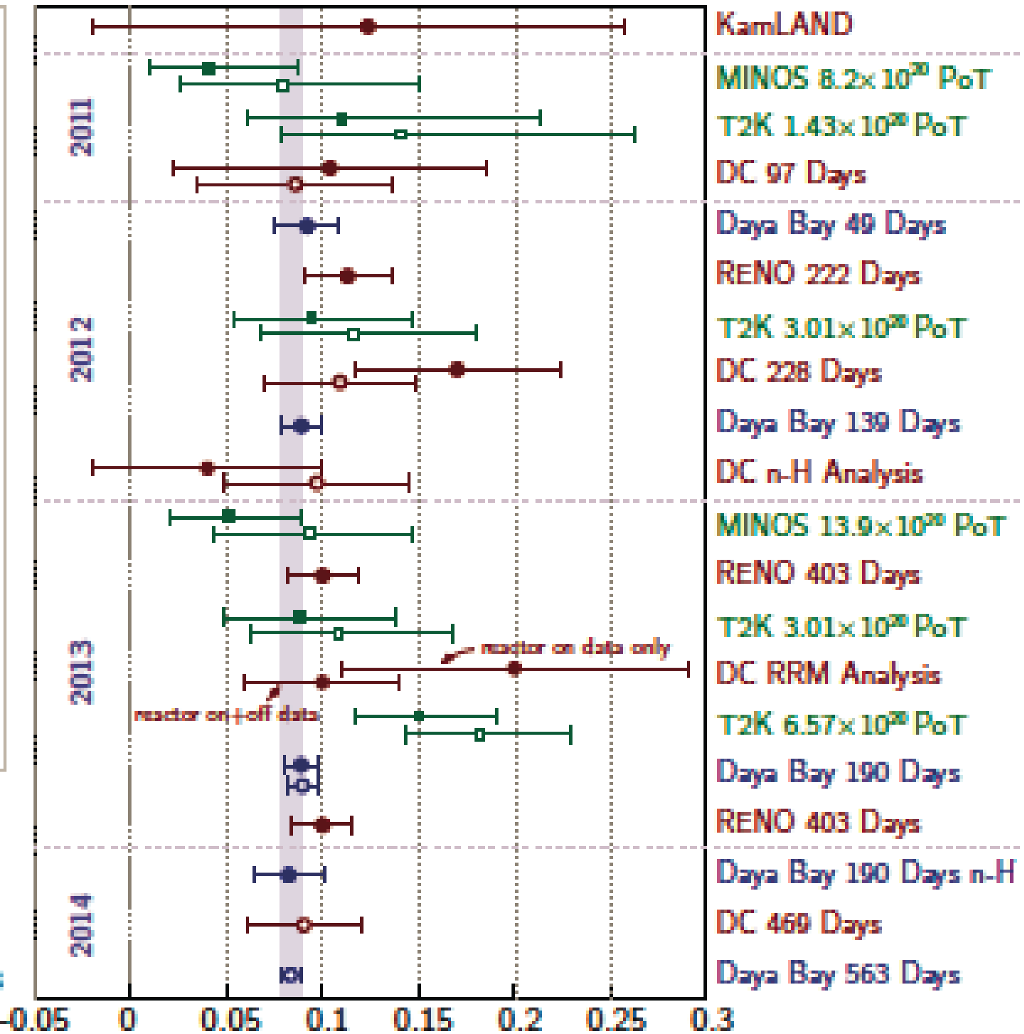




AD1/AD2 (6+8AD data)
Expected: 0.982
Measured: 0.981 ± 0.004

AD3/AD8 (8AD data)
Expected: 1.012
Measured: 1.019 ± 0.004

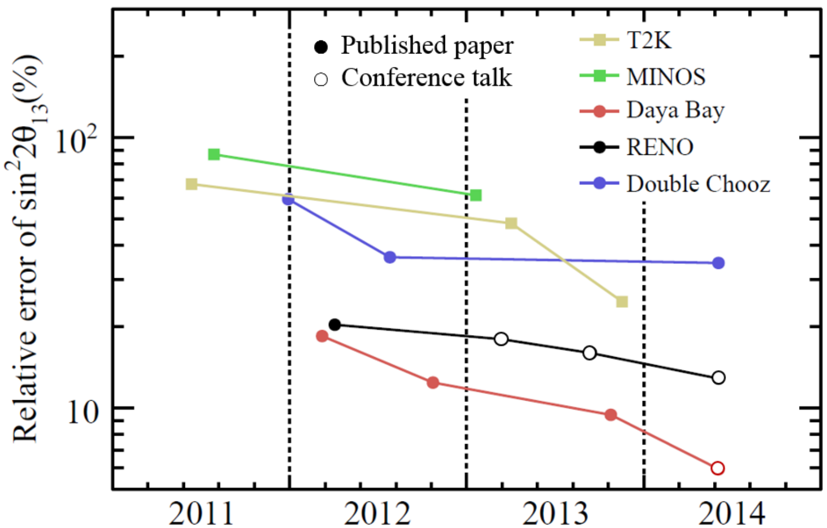
J.Zhao, Nufact14

# Remarkable Improvements on $\theta_{13}$




Jetter, Tau2014

Y.F.Wang, Nufact2014



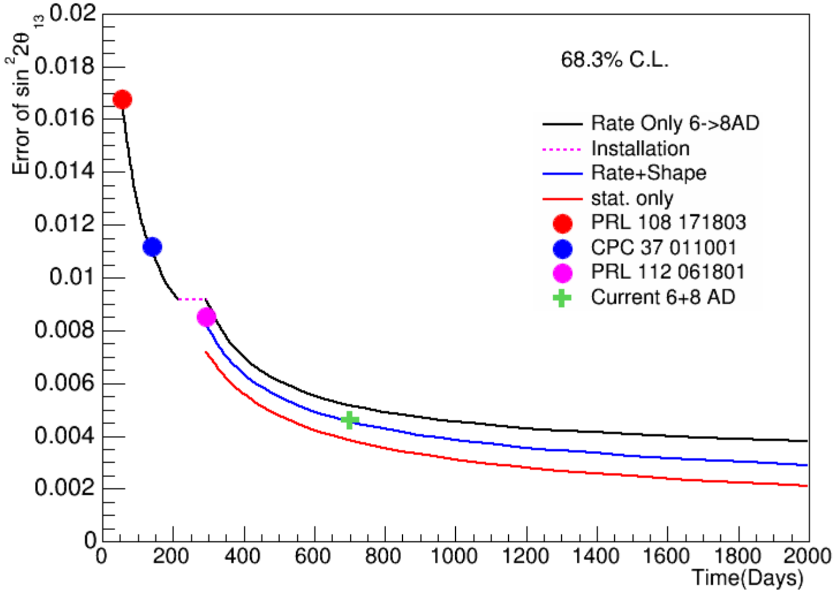

For accelerator experiments assuming $\delta_{CP}=0$, $\theta_{23}=45^o$

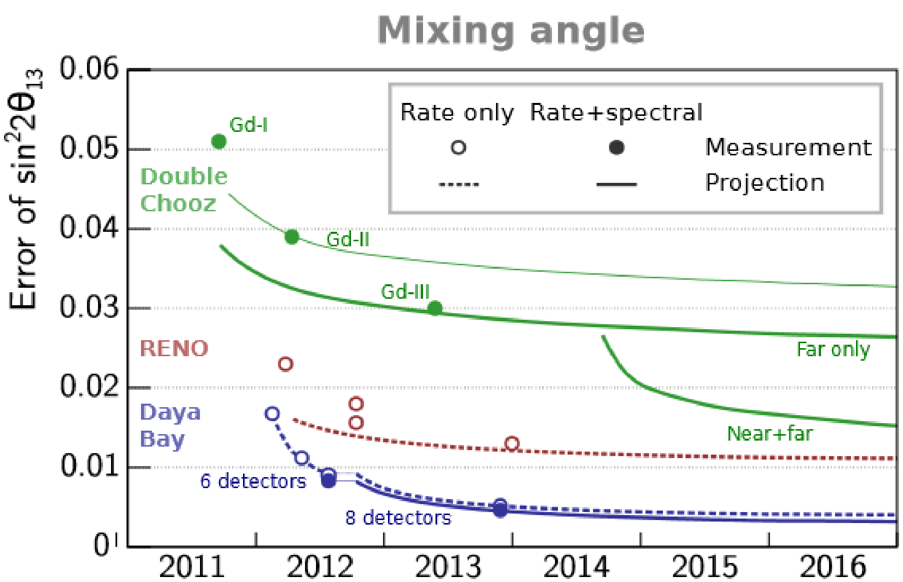
**Uncertainty reduced significantly → now 6%, will be 3% in 2017.**

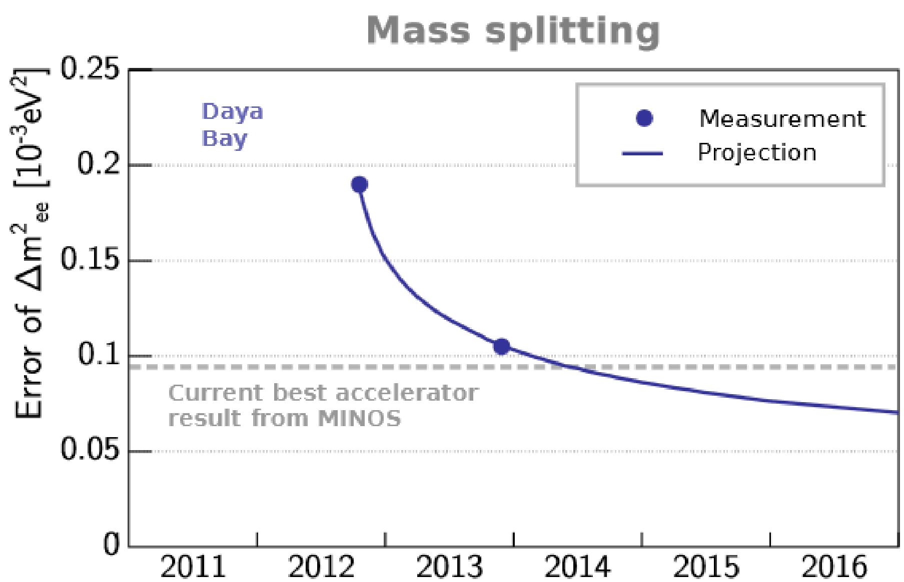
**The most precise ν mixing parameter.**

# Future Prospects

- Precision still dominated by statistics (Daya Bay)
- Continue to improve systematics
- Daya Bay data taking until 2017
- Precision expected:
  - $\Delta(\sin^2 2\theta_{13}) \sim 0.003$ ➔ ~ 3%
  - $\Delta(\Delta m^2_{ee}) \sim 0.07$ ➔ ~3%



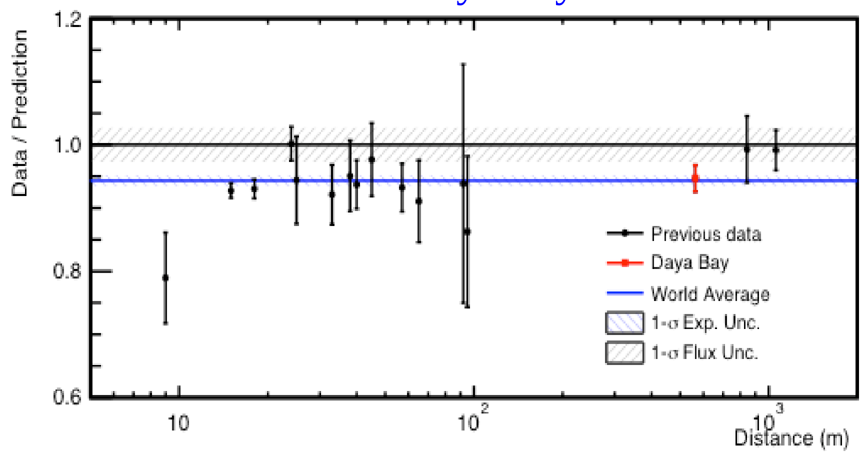



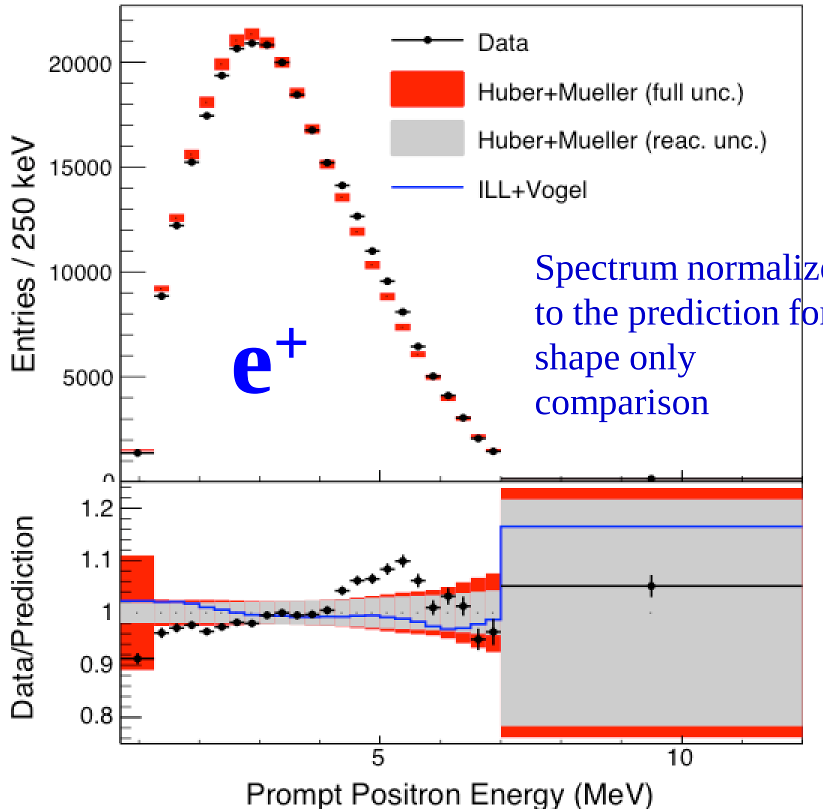

Jetter, Tau2014

# Absolute Reactor Flux and Spectrum

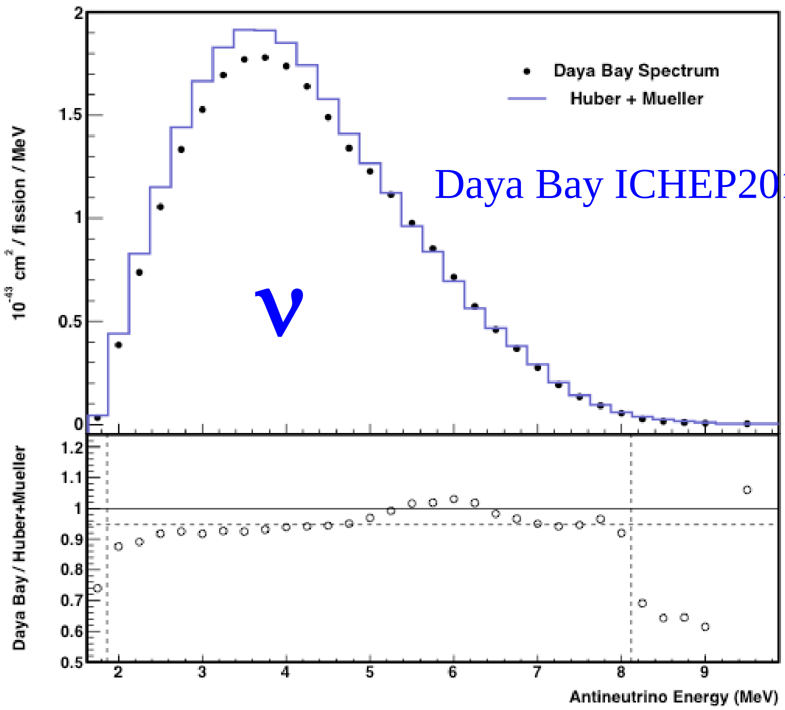
- **Absolute Flux**
  - ⇨ **Data/(Huber+Mueller): 0.947±0.022**
  - ⇨ **Data/(ILL+Vogel): 0.992 ± 0.023**
  - ⇨ **Consistent with others**
- **Absolute neutrino spectrum:**
  - ⇨ **After non-linearity correction**

Daya Bay Neutrino 2014




Spectrum normalized to the prediction for shape only comparison

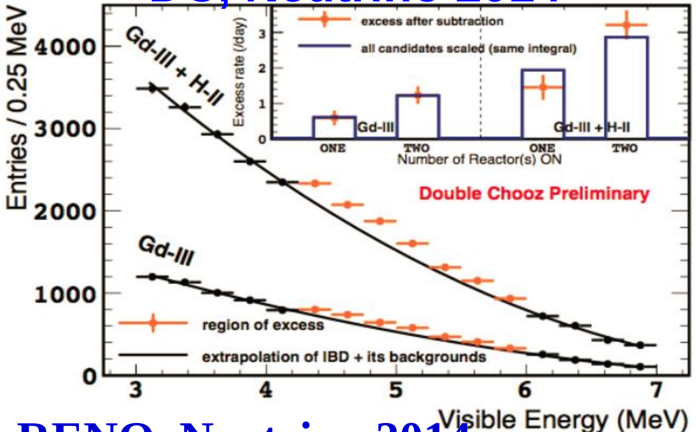



Daya Bay ICHEP2014

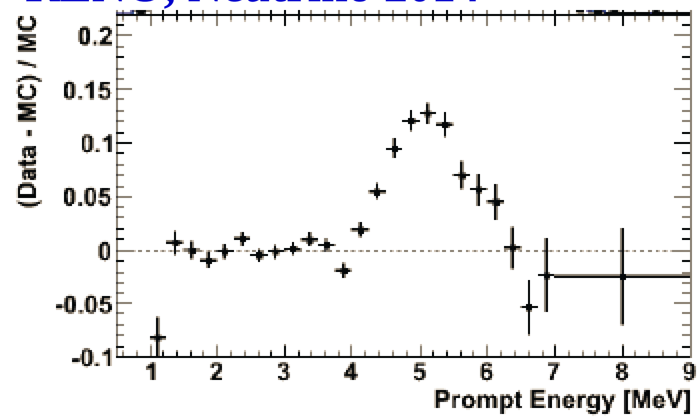
# 5 MeV Bump on Reactor Spectrum

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

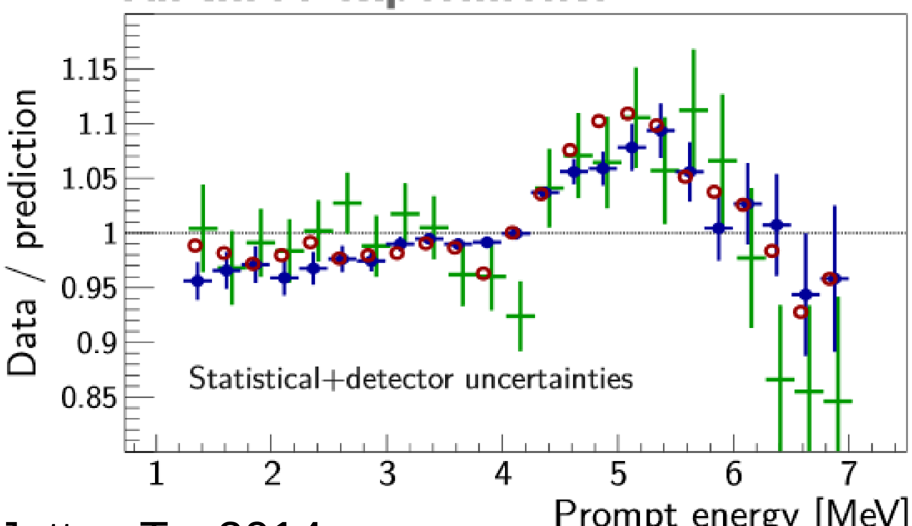
DC, Neutrino 2014



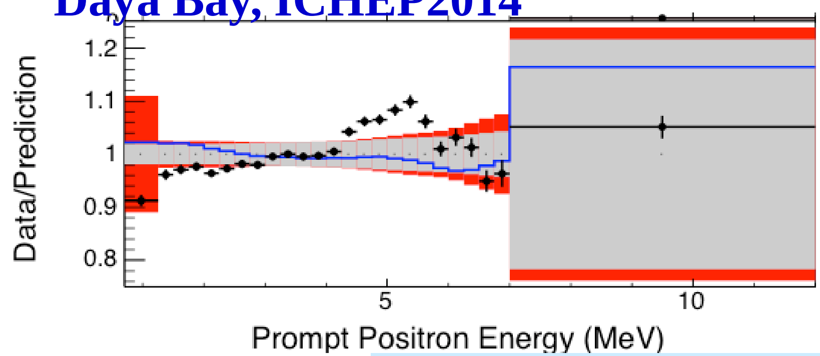

RENO, Neutrino 2014




All three experiments




Daya Bay, ICHEP2014



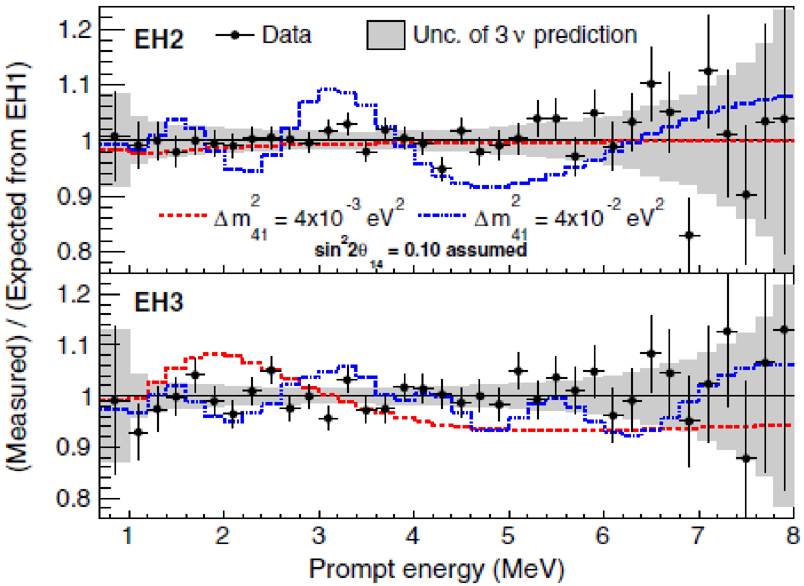

Jetter, Tau2014

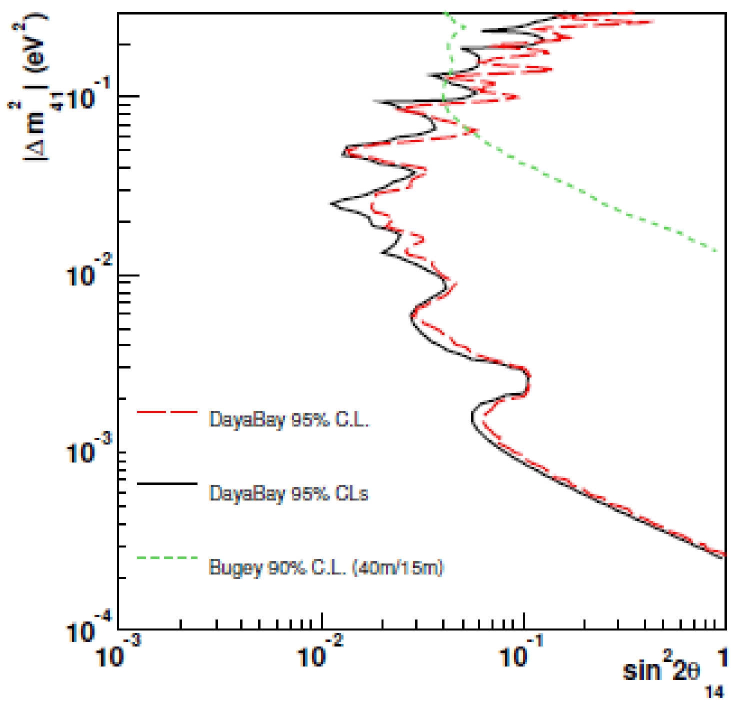
# Search for Sterile Neutrinos

- Precise reactor neutrino spectrum from Daya Bay near site can test the sterile neutrino hypothesis
- But ~400 m baseline is not ideal for the reactor anomaly
- In addition to accelerator and radioactive source experiment for sterile neutrinos, we also need experiments very close to the reactor (exp.) for sterile neutrinos:
  - ✓ Proposals around → Next page

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

Daya Bay: PRL113, 141802, 2014




Measurement by shape distortion

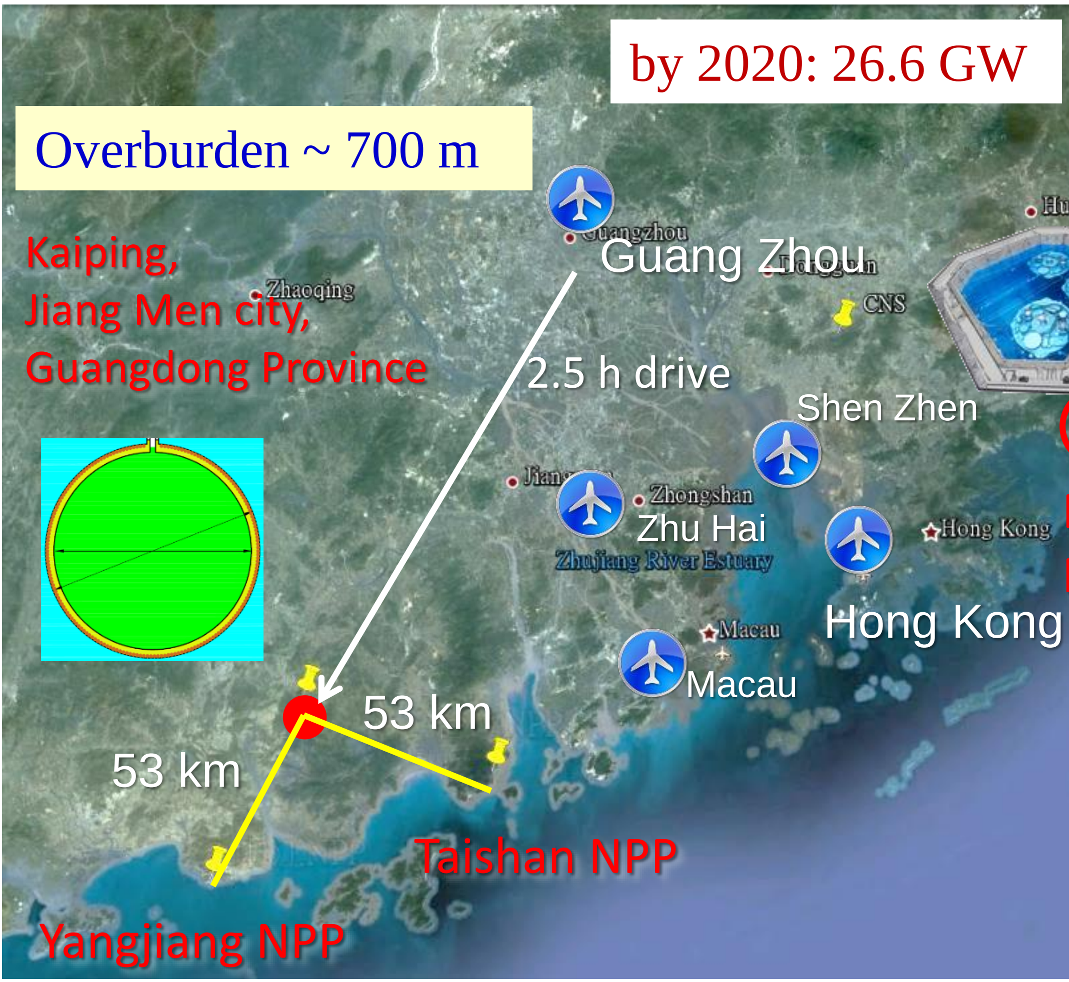
# Future Reactor Exp. for Sterile Neutrino

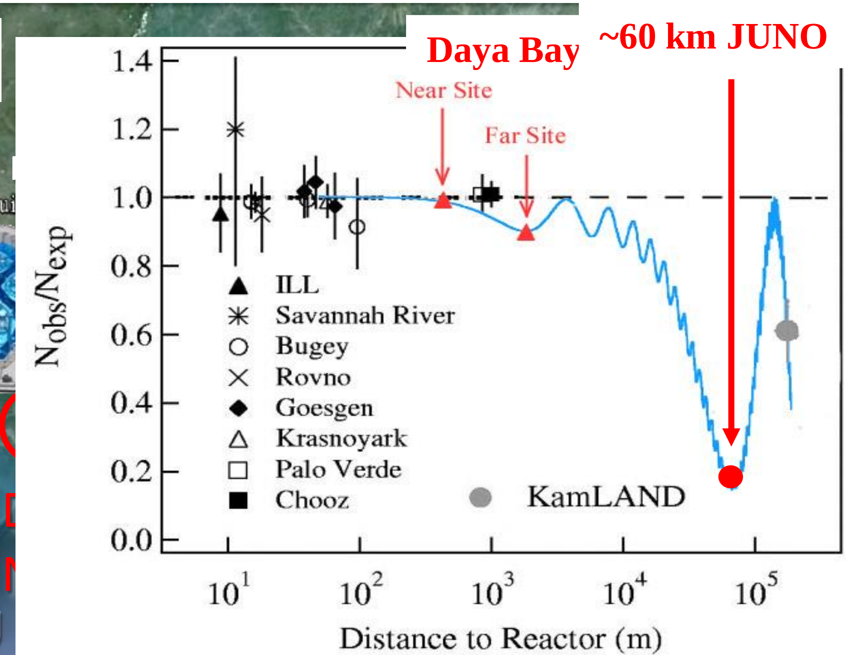
- **Different technologies: (Gd, Li, B) (seg.)(movable)(2 det.)**
- **Most have sensitivity 0.02~0.03 @$\Delta m \sim 1eV^2$ @90%CL**


J. Learned

# 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 |

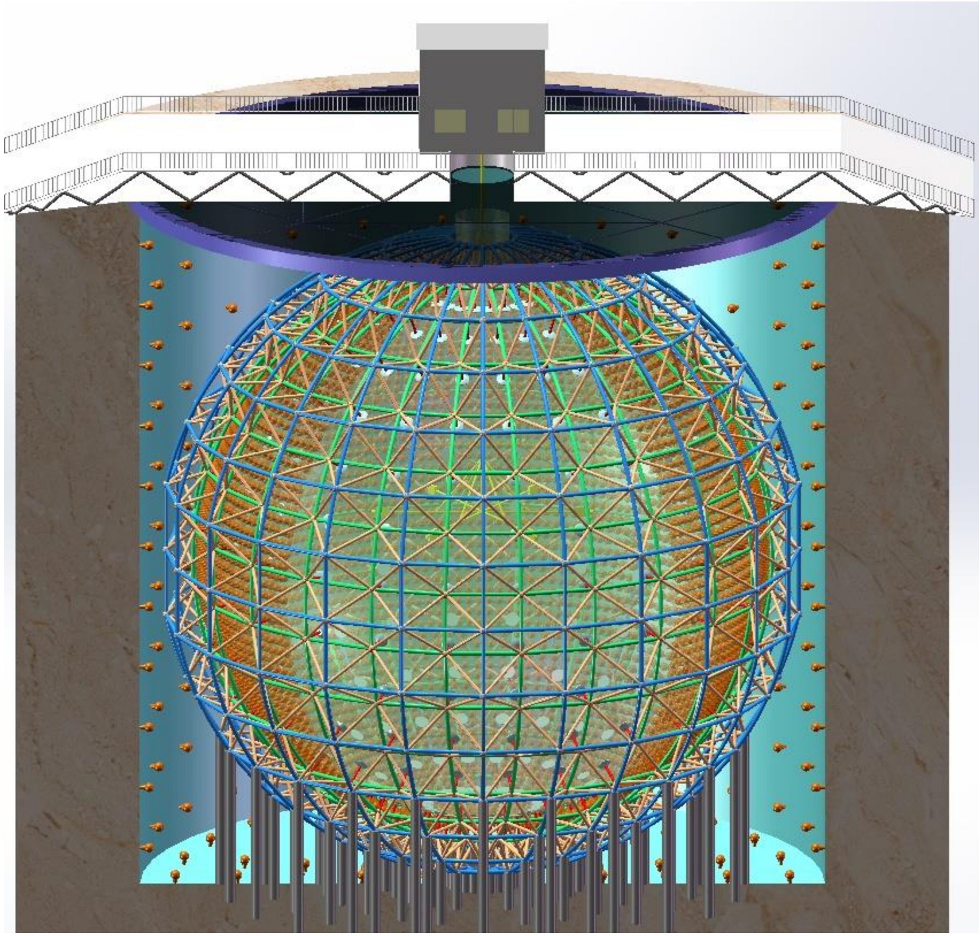



| Cores | YJ-C1 | YJ-C2 | YJ-C3 | YJ-C4 | YJ-C5 | YJ-C6 |
|---|---|---|---|---|---|---|
| Power (GW) | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 |
| Baseline (km) | 52.75 | 52.84 | 52.42 | 52.51 | 52.12 | 52.21 |
| Cores | TS-C1 | TS-C2 | TS-C3 | TS-C4 | DYB | HZ |
| Power (GW) | 4.6 | 4.6 | 4.6 | 4.6 | 17.4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

# The JUNO Experiment

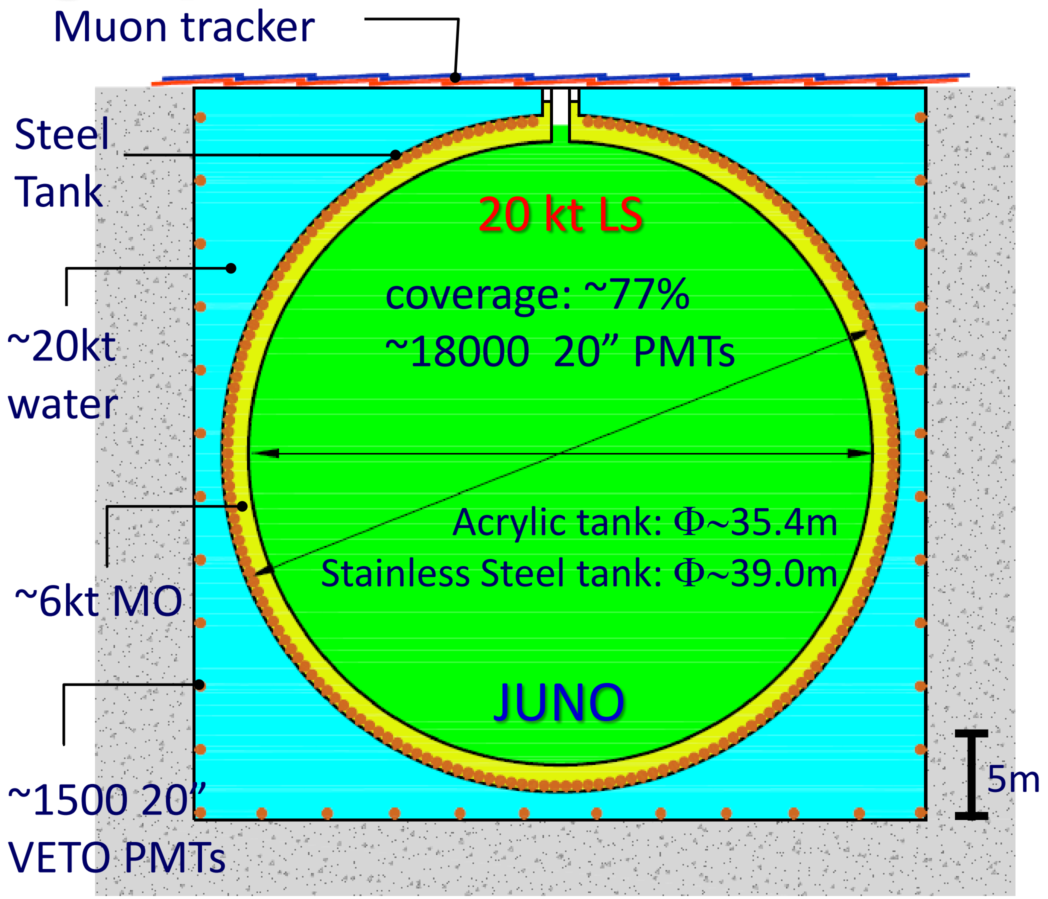
- Jiangmen Underground Neutrino Observatory, a multiple-purpose neutrino experiment, approved in Feb. 2013. ~ 300 M$.



- 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

**Talk by Y.F. Wang at ICFA seminar 2008**, Neutel 2011; by J. Cao at Nutel 2009, NuTurn 2012 ;
Paper by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen, PRD78:111103, 2008; PRD79:073007,2009

# High-precision, Giant LS detector




| | 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 |

# Signals & Backgrounds

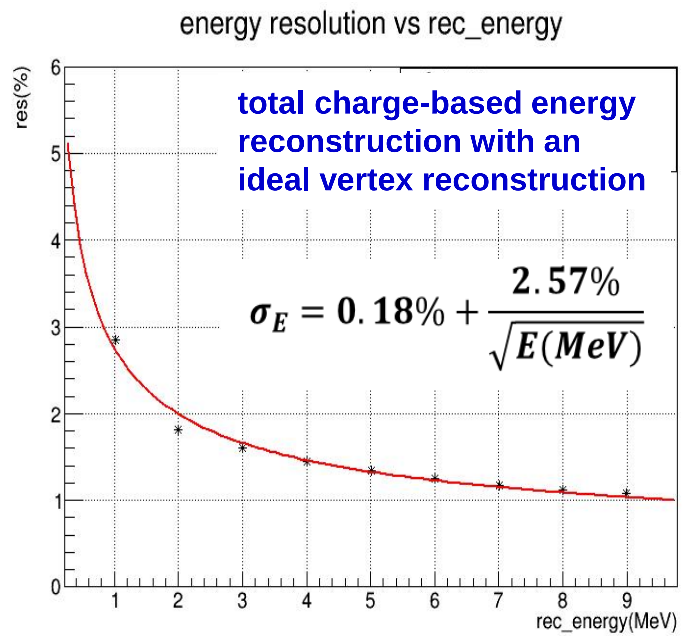
- Estimated IBD signal event rate: ~60/day
- Overburden 700m: Eμ ~ 211 GeV, Rμ ~ 0.003 Hz/$m^2$
  - ⇨ Muon efficiency > 99.5% (Daya Bay > 99.8%)
- Liquid Scintillator without Gd-loading (τ~200 μs) for
  - ⇨ Better attenuation length ➔ better resolution
  - ⇨ Lower irreducible accidental backgrounds from LS
  - ⇨ Singles: 5 Hz by LS and 5 Hz by PMT
- Backgrounds:

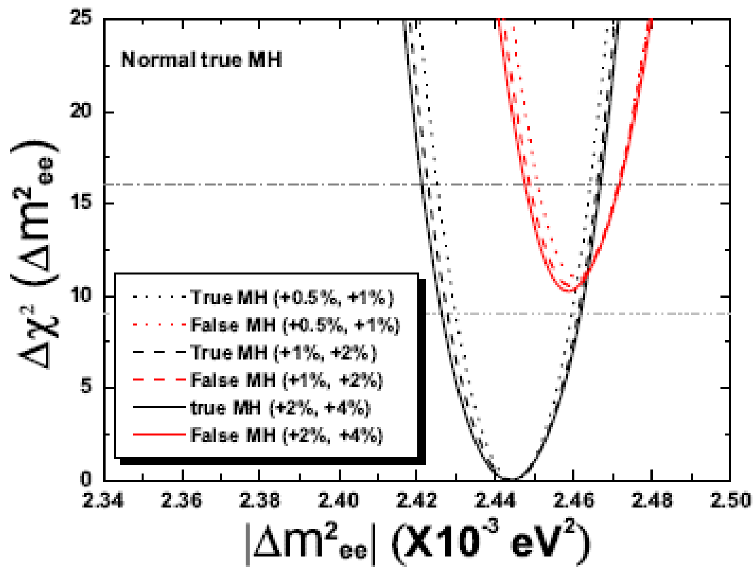
| Event Type | Raw rate | Reduction |
|---|---|---|
| Accidentals | ~410/day | → 1.1 /day w/ prompt-delayed distance $R_{p\text{-}d}$ < 1.5m. Negligible. |
| Fast neutron | 0.01/day | 0.01/day (σ=100%) |
| $^{9}$Li/$^{8}$He | 80/day | 1.8/day after muon veto (σ=20%) |
| (a, n) | 3.8/day (acrylic)<br>0.2/day (balloon) | →0.05 /day (acrylic), FV cut (σ=50%)<br>→ negligible (balloon), FV cut |

# MC Study：Energy Scale & Resolution

- **Resolution: based on DYB MC:**
  - ⇨ **JUNO Geometry**
  - ⇨ **80% photocathode coverage**
  - ⇨ **PMT QE from 25% ➔ 35%**
  - ⇨ **Attenuation length of 20 m ➔**
    **abs. 60 m + Rayleigh scatt. 30m**
- **Energy non-linearity**
  - ⇨ **By introduce a self-calibration (based on $\Delta m^2_{ee}$ periodic peaks), effects can be corrected and sensitivity is un-affected**

    **Y.F. Li et al., arXiv:1303.6733**
  - ⇨ **Application of this method: Relatively insensitive to continuous backgrounds, non-periodic structures. Assumed 2% uncer. ➔**
  - ⇨ **DYB non-linearity ~ 1%**



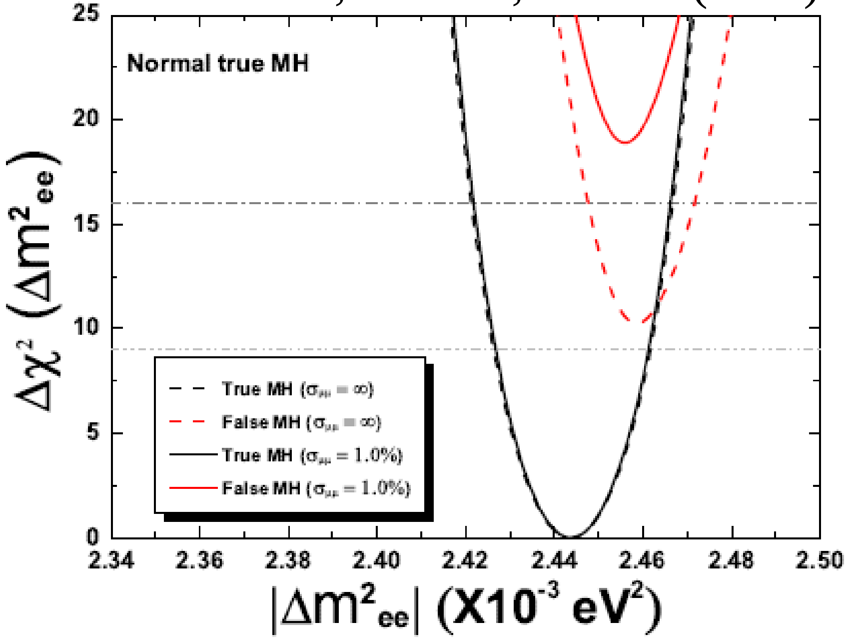
# Physics Reach

## Thanks to a large $\theta_{13}$

- Mass hierarchy
- Precision measurement of mixing parameters
- Supernova neutrinos
- Geoneutrinos
- Solar & atmospheric neutrinos
- Sterile neutrinos

| | Current | JUNO |
|---|---|---|
| $\Delta m^2_{12}$ | 4% | 0.6% |
| $\Delta m^2_{23}$ | 5% | 0.6% |
| $\sin^2\theta_{12}$ | 5% | 0.7% |
| $\sin^2\theta_{23}$ | 10% | N/A |
| $\sin^2\theta_{13}$ | 6% ➔ 3% | ~ 15% |

Y.F. Li et al, PRD 88, 013008 (2013)

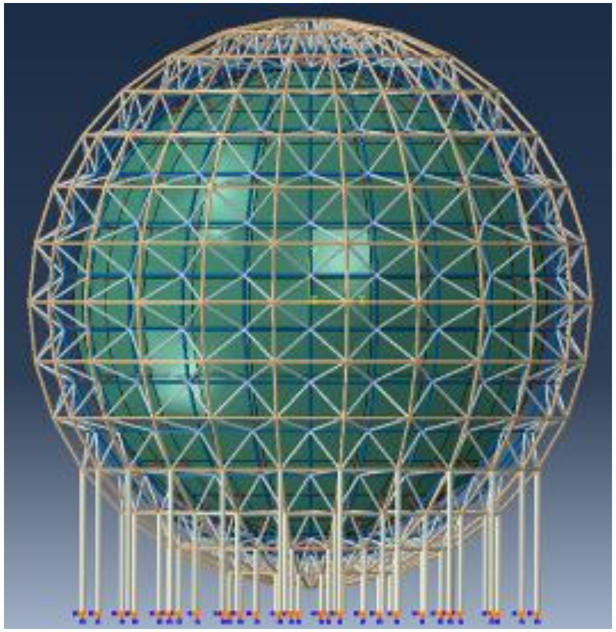


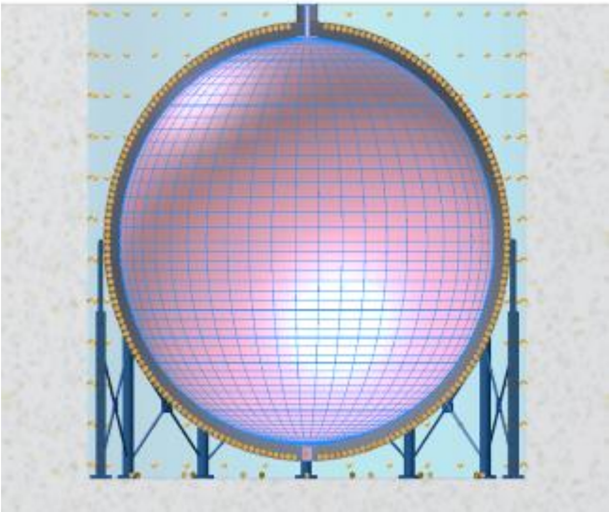

For 6 years, mass hierarchy can be determined at $4\sigma$ level, if $\Delta m^2_{\mu\mu}$ can be determined at 1% level

Detector size: 20kt
Energy resolution: 3%/√E
Thermal power: 36 GW

# JUNO Central Detector

- **Detector**
  - Target: 20 kt LS
  - Backgrounds/reactor signal: Accidentals (~10%), $^{9}Li/^{8}He$ (<1%), fast neutrons (<1%)
- **A huge detector in a water pool:**
  - Default option: acrylic tank (D~35m) + SS truss (D~39m)
  - Alternative option: SS tank (D~39m) + acrylic structure + balloon (D~35m)
- **Challenges:**
  - Engineering: mechanics, safety, lifetime, …
  - LS: high transparency, low background
  - PMT: high QE, high coverage
- **Design & prototyping underway**



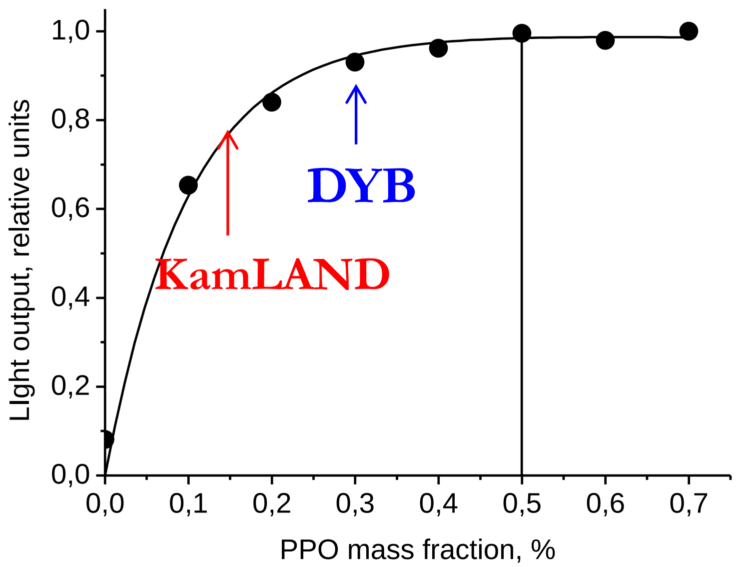


# Liquid Scintillator in JUNO

- **Recipe**

  **LAB+PPO+bisMSB (no Gd-loading)**

- **Increase light yield**
  - ⇨ **Optimization of fluors concentration**
- **Increase transparency**
  - ⇨ **Good raw solvent LAB**
    - Improve production processes: cutting of components, using Dodecane instead of MO, improving catalyst, etc
  - ⇨ **Online handling/purification**
    - Distillation, Filtration, Water extraction, Nitrogen stripping, …
- **Reduce radioactivity**
  - ⇨ **Less risk, since no Gd**
  - ⇨ **Instrinsic singles < 3Hz (above 0.7MeV), if $^{40}K/U/Th < 10^{-15}$ g/g (TCF)**

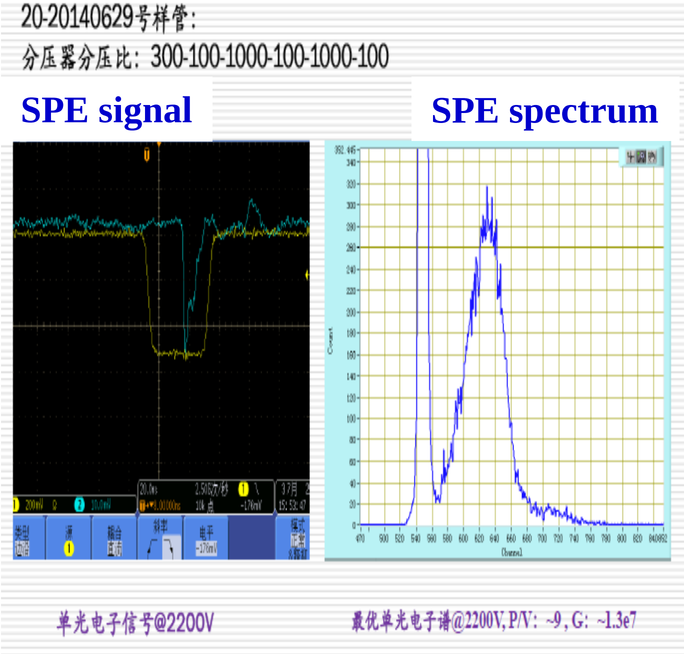



| Linear Alky Benzene (LAB) | Atte. Length @ 430 nm |
|---|---|
| RAW | 14.2 m |
| Vacuum distillation | 19.5 m |
| $SiO_2$ coloum | 18.6 m |
| $Al_2O_3$ coloum | 22.3 m |
| LAB from Nanjing, Raw | 20 m |
| $Al_2O_3$ coloum | 25 m |

# High QE PMT

- **20" PMTs under discussion:**
  - MCP-PMT with Chinese Industry
  - Photonics-type PMT: 8"➔ 12" ➔ 20"
  - Hammamatzu R5912-100 (SBA)
- **MCP-PMT development:**
  - Technical issues mostly resolved
  - Successful 8" prototypes
  - A few 20" prototypes

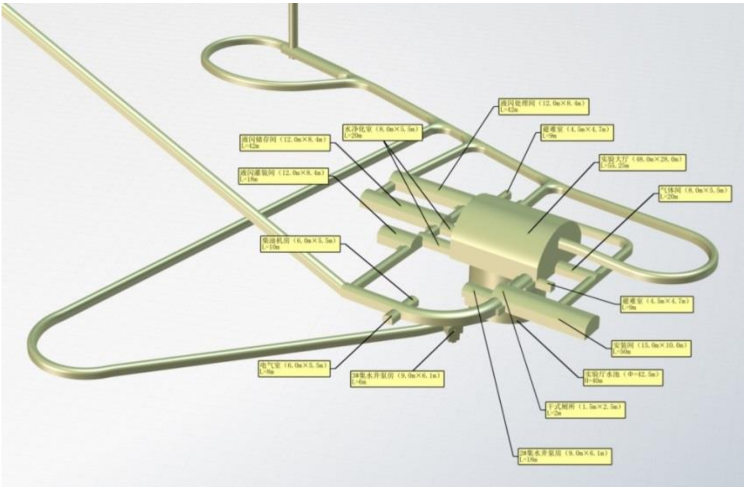
20" PMT




| | R5912 | R5912-100 | MCP-PMT |
|---|---|---|---|
| QE@410nm | 25% | >30% | ~ 30% |
| Rise time | 3 ns | 3.4ns | 5ns |
| SPE Amp. | 17mV | 18mV | 17mV |
| P/V of SPE | >2.5 | >2.5 | > 2.5 |
| TTS | 5.5ns | 1.5 ns | 3.5 ns |

# Current Status & Brief Schedule

- Project approved by CAS for R&D and design
- Geological survey completed
  - ⇨ Granite rock, tem. ~ 31 $^{o}$C, little water
- EPC contract signed:
  - ⇨ Engineering design by Aug.
- Paper work towards the construction:
  - ⇨ Land, environment, safety, …
- Ground breaking in Jan. 2015



**Schedule:**

Civil preparation： 2013-2014

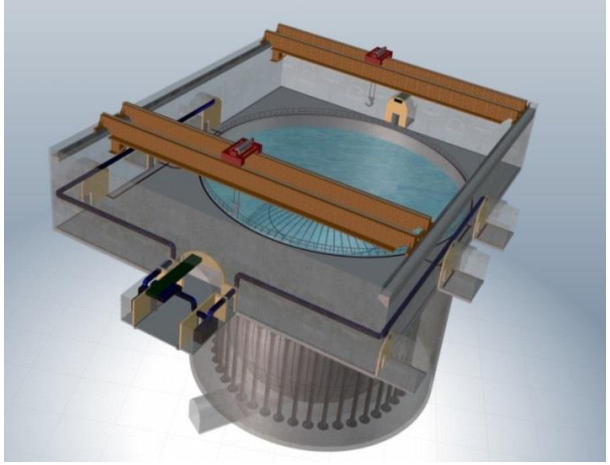
Civil construction： 2014-2017

Detector component production： 2016-2017

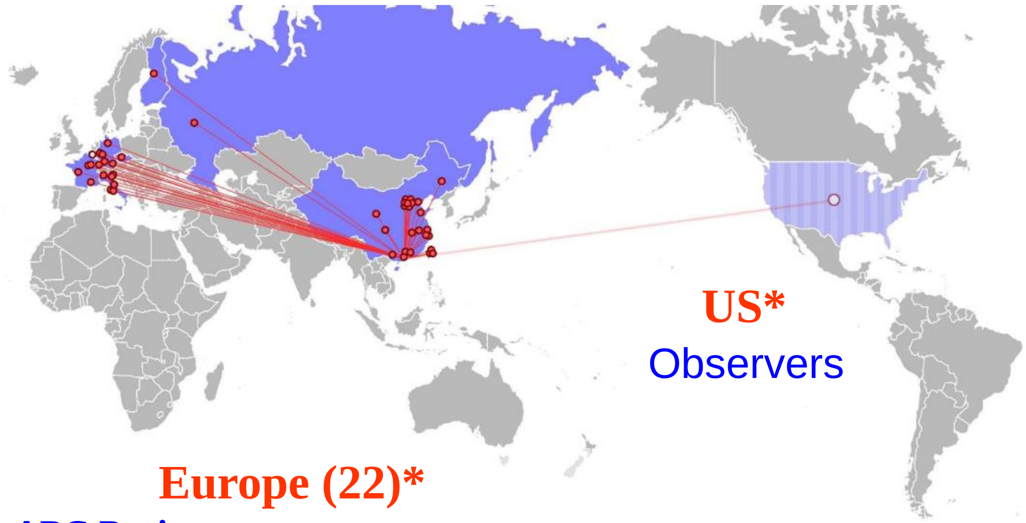
PMT production： 2016-2019

Detector assembly & installation： 2018-2019

Filling & data taking： 2020



# Collaboration Established



US*
Observers

## Asia (25)

| | | |
|---|---|---|
| Nankai U. | BNU | SYSU |
| Natl. Chiao-Tung U. | CAGS, | Tsinghua U. |
| Natl. Taiwan U. | CIAE | UCAS |
| Natl. United U. | DGUT | USTC |
| NCEPU | ECUST | Wuhan U. |
| Pekin U. | Guangxi U. | Wuyi U. |
| Shandong U. | IHEP | Xi'an JT U. |
| Shanghai JT U. | Jilin U. | |
| Sichuan U. | Nanjing U. | |

## Europe (22)*

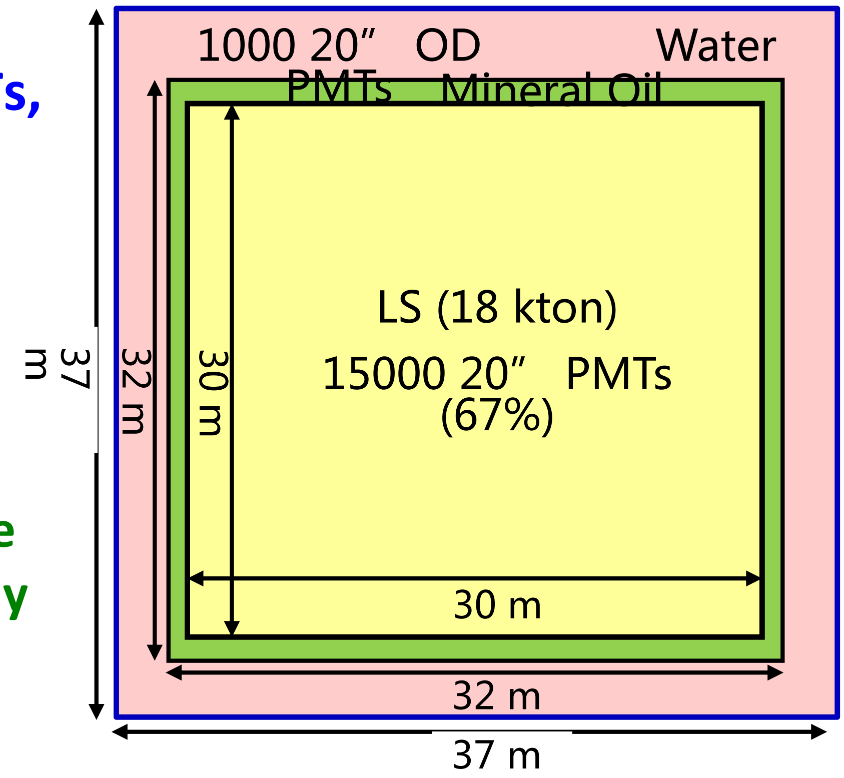
| | |
|---|---|
| APC Paris | IPHC Strasbourg |
| Charles U. | JINR |
| CPPM Marseille | LLR Paris |
| FZ Julich | RWTH Aachen U. |
| INFN-Frascati | Subatech Nantes |
| INFN-Ferrara | TUM |
| INFN-Milano | U.Hamburg |
| INFN-Padova | U.Mainz |
| INFN-Perugia | U.Oulu |
| INFN-Roma 3 | U.Tuebingen |

U. libre de Bruxelles (Observer)
HEPHY (Observer)

*** Some subject to funding agency approval**

# 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 $\theta_{12}$ and $\Delta m^2_{21}$
  - ⇨ 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)



# Summary

- Significant improvement on $\sin^2 2\theta_{13}$ precision from the Daya Bay, Double Chooz and RENO experiments.
- Ultimate precision of $\sin^2 2\theta_{13}$ 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.
- Sterile neutrinos have been studied by Daya Bay.
- 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 !**