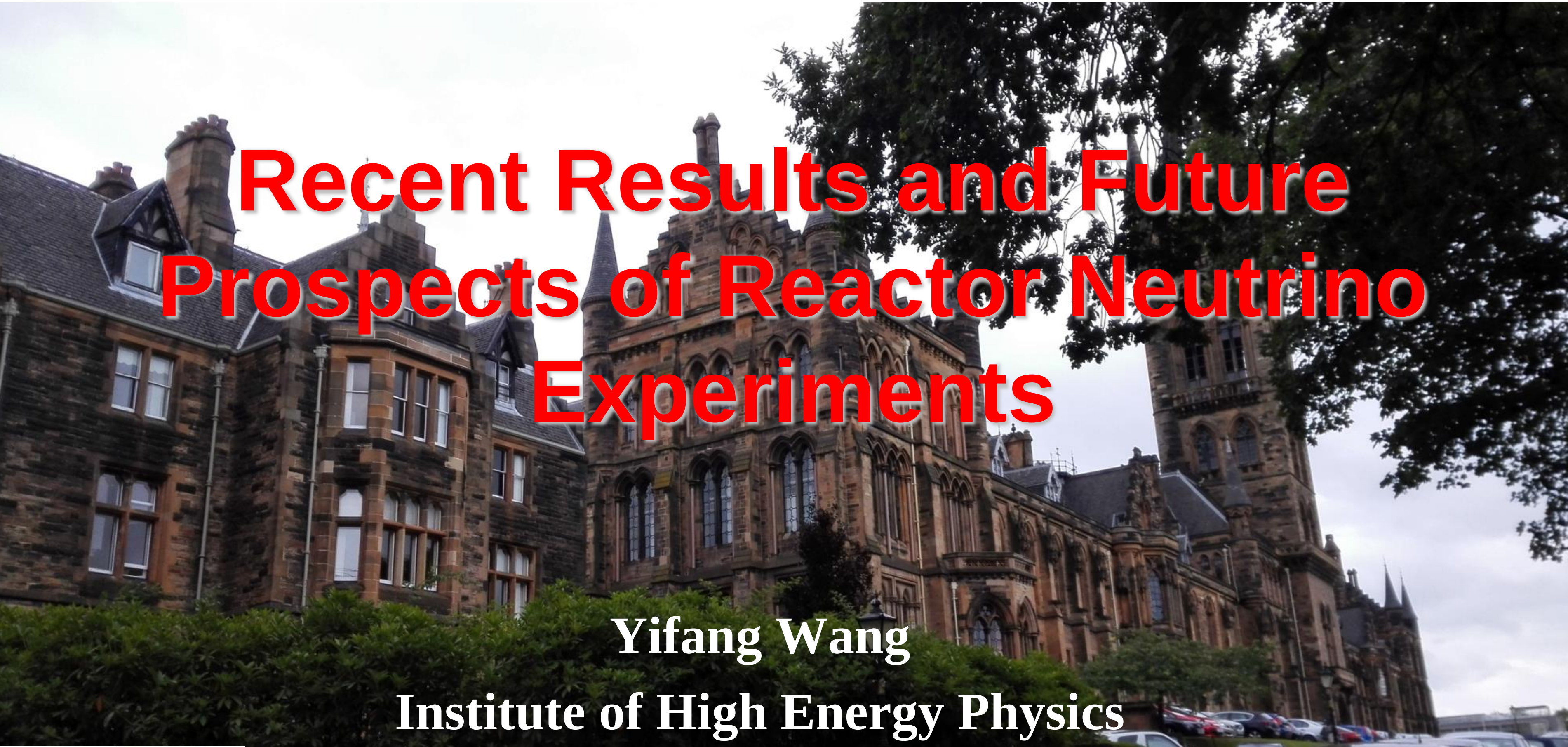
Recent Results and Future Prospects of Reactor Neutrino Experiments

Yifang Wang

Institute of High Energy Physics

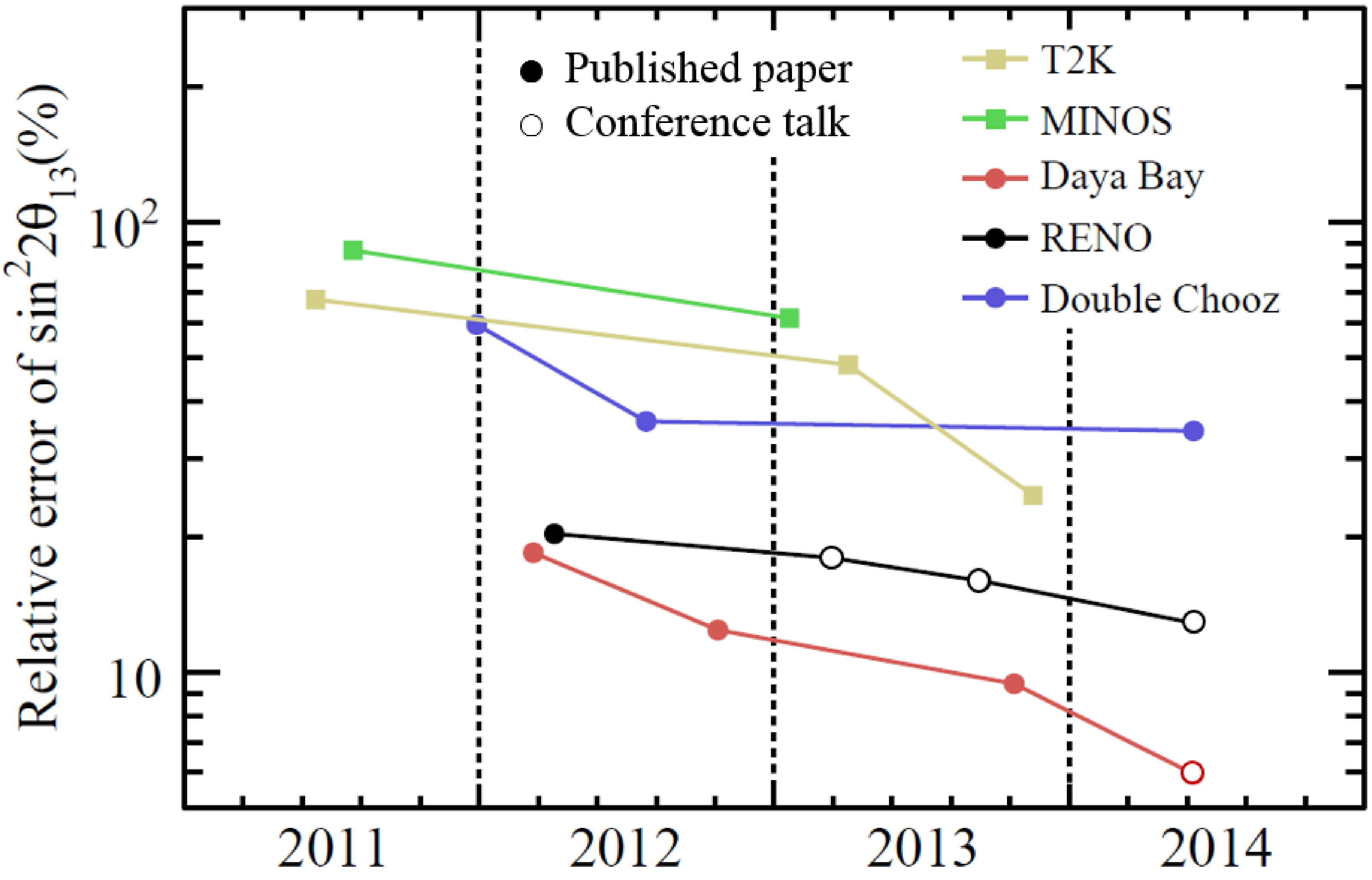
NuFACT 2014, Aug. 27, 2014, Glasgow



Outline

- **Latest results on θ_{13}**
  - **Daya Bay**
  - **Double Chooz**
  - **RENO**
- **Reactor neutrino flux and spectrum**
- **Search for sterile neutrinos**
- **Future experiments**
  - **JUNO**
  - **RENO-50**
- **Summary**

Remarkable Improvements on θ_{13}



Accelerator experiments assuming δ_{CP}=0, θ_{23}=45°

Reactor Results on θ_{13}

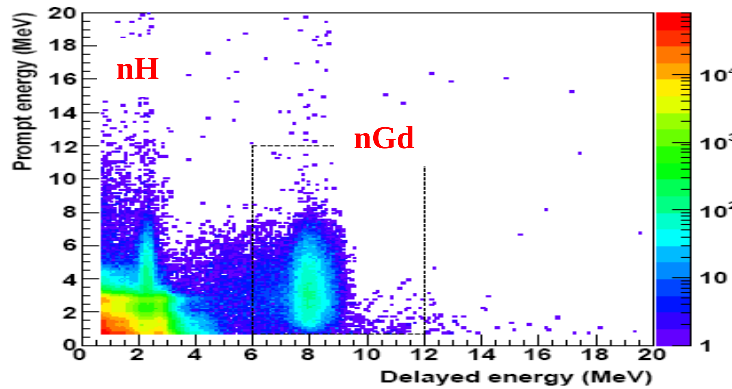
	Daya Bay	Double Chooz	RENO
nGd rate	PRL 108(2012) 171803 CPC 37(2013) 011001 PRL 112(2014) 061801	PRL 108(2012) 131801 PLB 735(2014)51 arXiv:1406.7763	PRL 108(2012) 191802 NeuTel 2013 TAUP/WIN 2013 Neutrino 2014
nGd spectrum	PRL 112(2014) 061801 Neutrino 2014	PRL 108(2011) 131801 PRD 86(2012) 052008 arXiv:1406.7763	×
nH rate	arXiv:1406.6468	PLB723(2013) 66	Neutrino 2014
nH spectrum	×	PLB723(2013) 66	×
Livetime	~564 days	468 days	~ 761 days

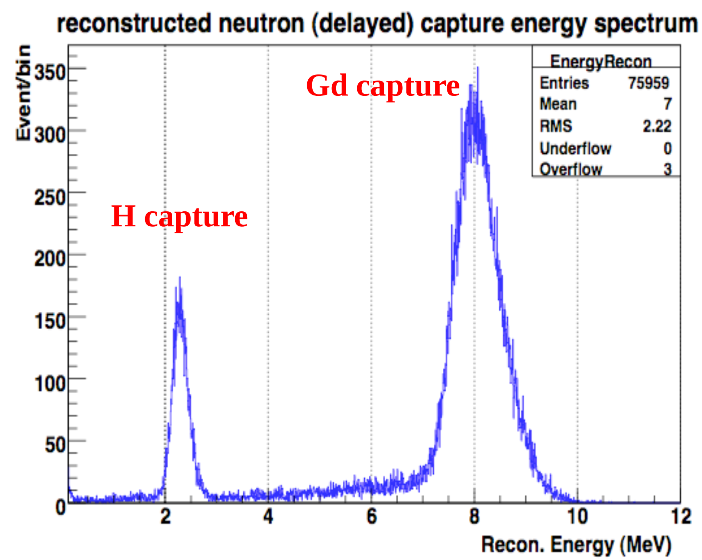
Event Selection

- **Reject PMT flashing events**
- **Reject muon-related events**
  - ⇨ Select a quiet time window between muons
  - ⇨ Wait substantial time if muons go through the target
- **Select events with right prompt-delayed time interval(~ 200 μs)**
  - ⇨ **Reject accidental background**
- **Select events in right energy window(nGd or nH)**
  - ⇨ **nGd ~ 85%, nH ~ 15%**

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

n + p → d + γ (2.2 MeV, ~ 180 μs)
n + Gd → Gd* + γ (8 MeV, 28 μs)





Double Chooz

- See the talk by Dr. M. Vivier *(CEA-Saclay)* on Friday
- Materials mainly from H. De Kerret's @ Neutrino 2014

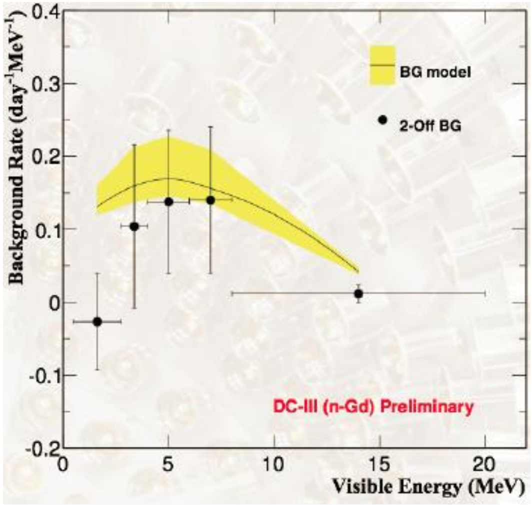
- Used Reactor-off method to directly measure backgrounds
- Used spectrum analysis for both nGd & nH events

- New analysis → less background and uncertainties, better flux prediction(^{238}U), better energy reconstruction, …

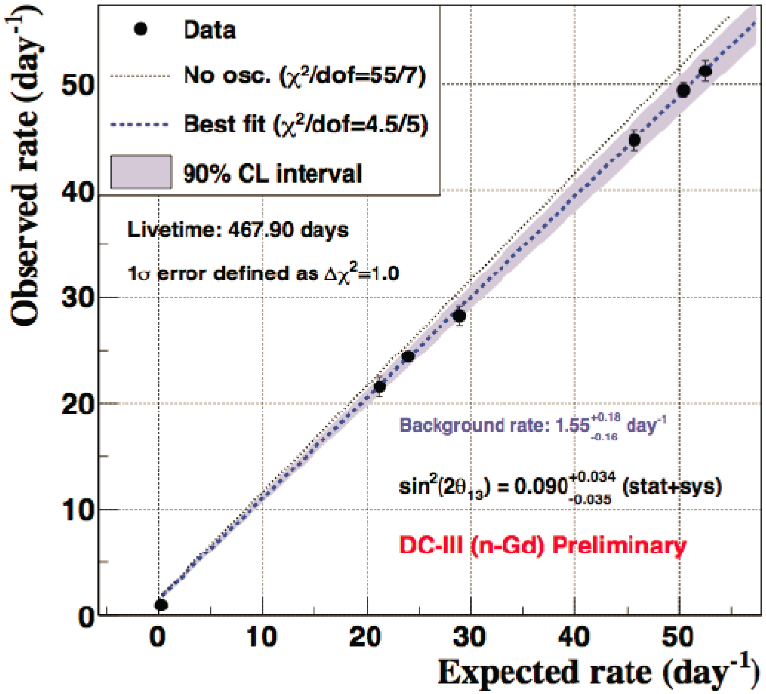
Gd-n analysis	Background		Theta 13
	input	output	
Rate + Shape (R+S)	BG model	background further constrained by shape	
Reactor Rate Modulation (RRM)	no	background independant teta 13 Measurement	
Reactor Rate Modulation (RRM)	full reactor off	no	Precision improved from this BG input
Rate Only (RO)	no	no	cross check
Rate Only (RO)	full reactor off	no	cross check

Reactor Rate Modulation

- **Direct measurement of backgrounds:**
  - ⇨ 7 events in 7.238 days
  - ⇨ 13.4 expected
  - ⇨ Tension @ ~ 2σ ➔ no room for unknown backgrounds
- **Good θ_{13} results:**



ON ⊕ OFF ⊕ background model

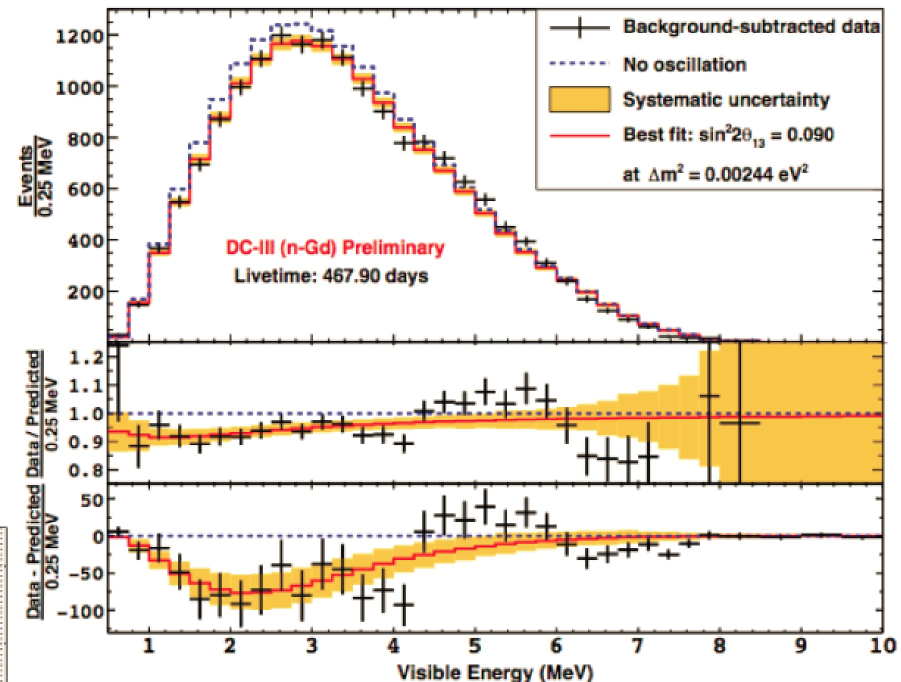


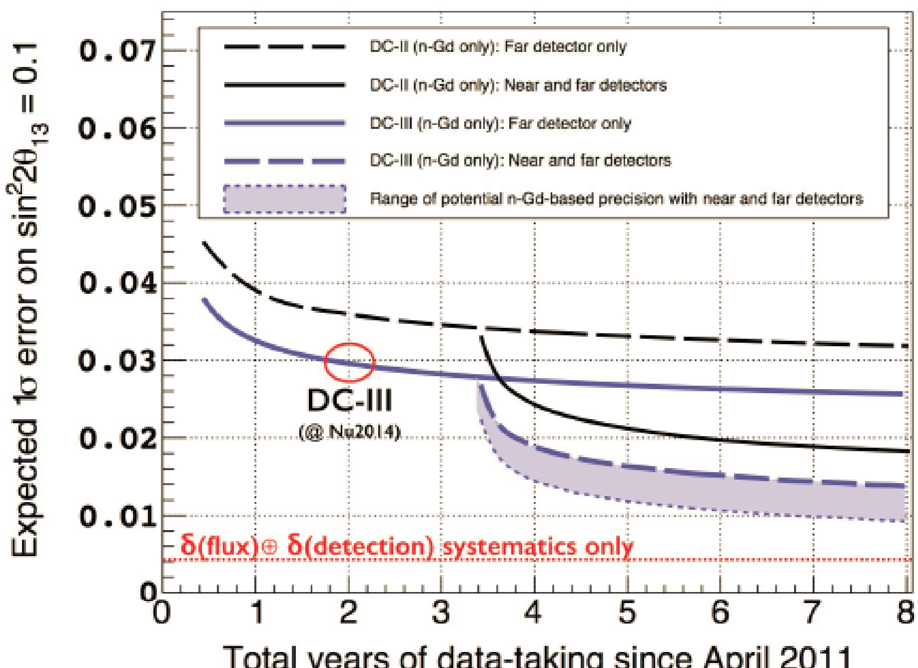
Recent Results and Future Prospect

- nGd rate+shape analysis for far detector only

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

$(\chi^2/n.d.f. = 51.4/40)$





- Near detector ready soon: fill this summer, neutrinos in Sep./Oct.
- Expected final precision on $\sin^2 2\theta_{13}$: ~ 10-15%

NEAR DETECTOR : READY SOON

Buffer closed
main tank to be closed this week

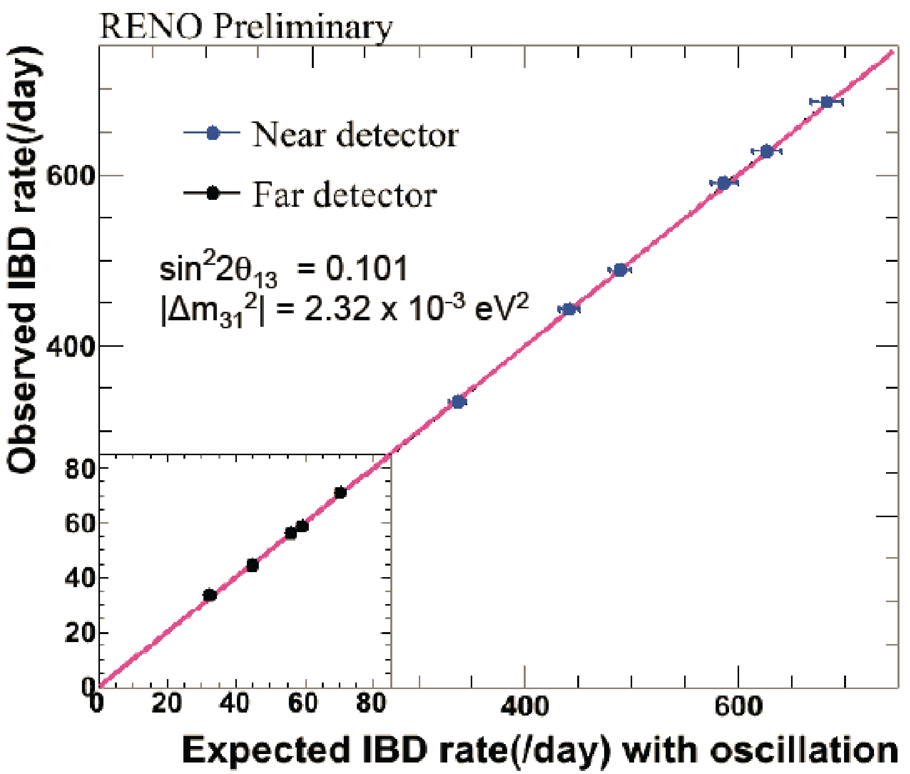
Fill this summer →
Neutrinos in september/October

From Herve de Kerret

RENO

- See talk by Dr. Hyunkwan Seo*(Sungkyunkwan University)* on Friday
- Materials mainly from Dr. Seon-Hee Seo's @Neutrino 2014

- Also reactor rate modulation analysis
- New results on nGd & nH rate analysis
- Shape analysis is on the way
- Reduced systematics but ^{252}Cf contamination worsened the uncertainty



Results and Future Prospects

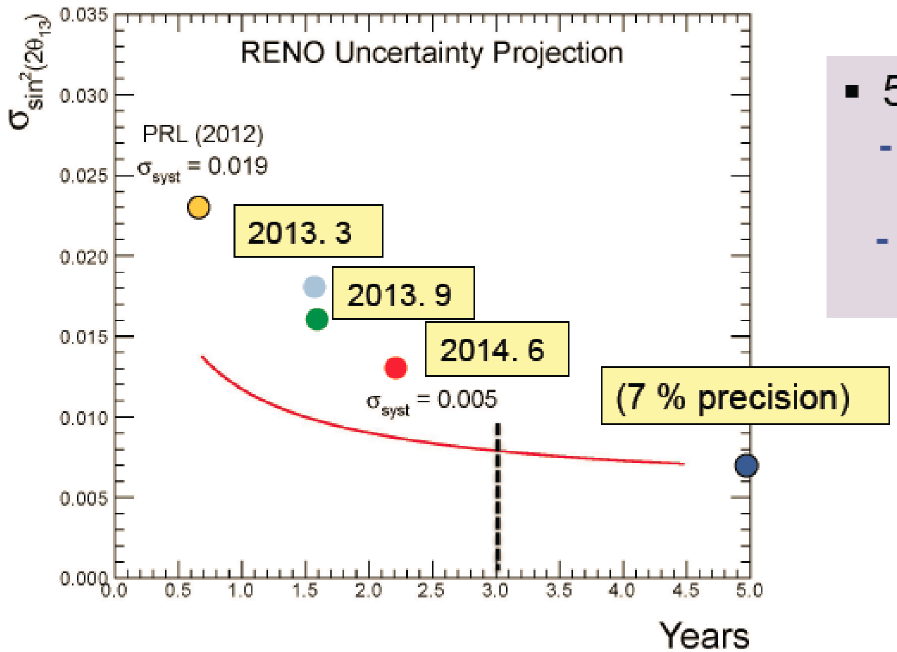
- **nGd rate analysis**

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

- Data before ^{252}Cf contamination: previous **0.012 (sys.)** → **0.007 (sys.)**
- Data after ^{252}Cf contamination: → **0.018 (sys.)**

- **nH rate analysis**

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



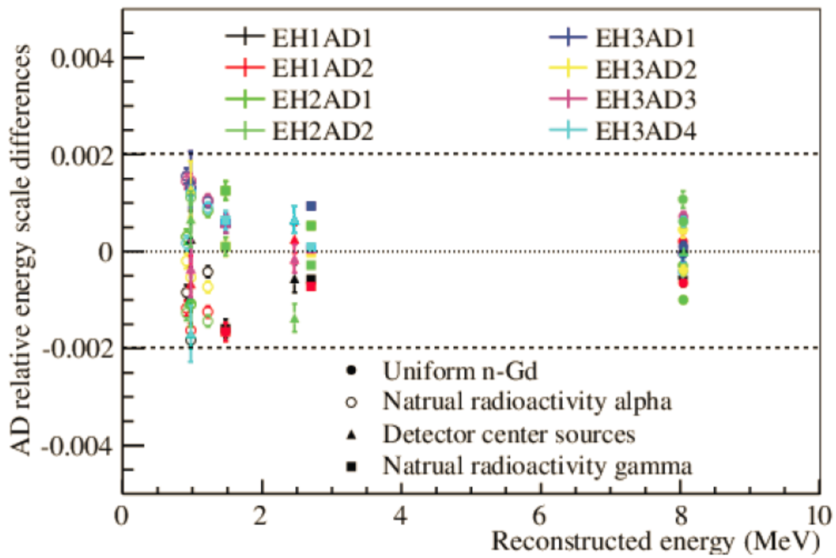
- 5 years of data : 7 %
  - stat. error : $\pm$0.008 → $\pm$0.005
  - sys. error : $\pm$0.010 → $\pm$0.005

Daya Bay

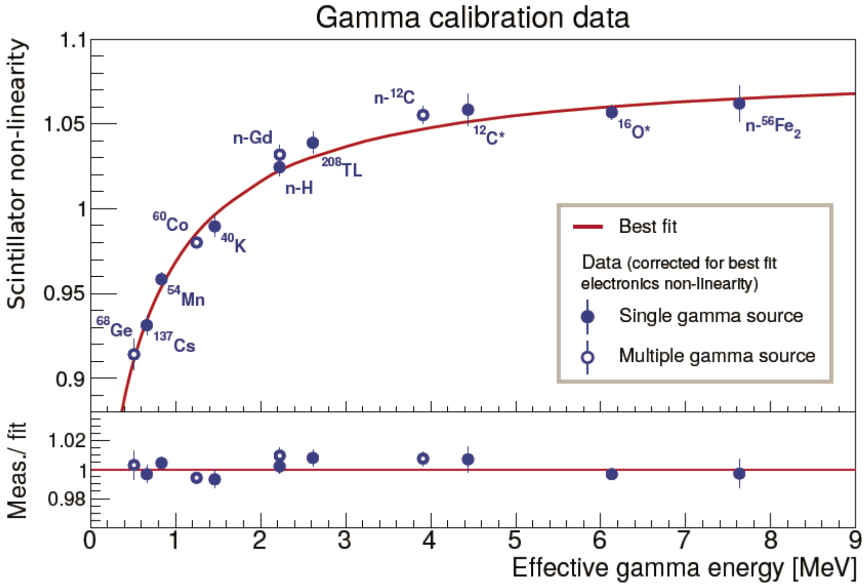
- See talk by Ms. Jie Zhao *(IHEP） on Friday*

- Detailed and precise corrections for non-linearity
- Continue to improve: reduced backgrounds and systematics
- Rate + Shape analysis for nGd events
- Rate analysis for nH events

Relative energy scale difference: <0.2%

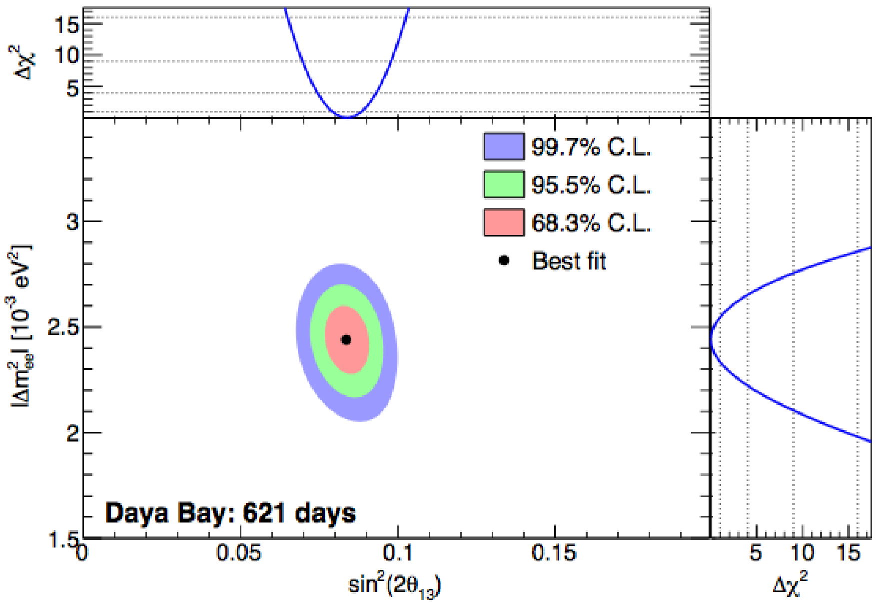


Non-linearity uncertainty < 1%

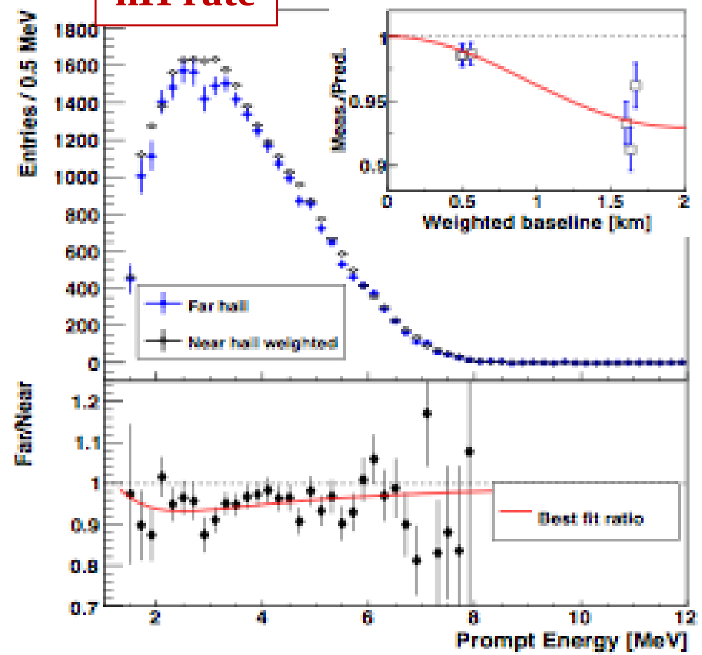


Recent Results

nGd rate+shape



nH rate



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

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

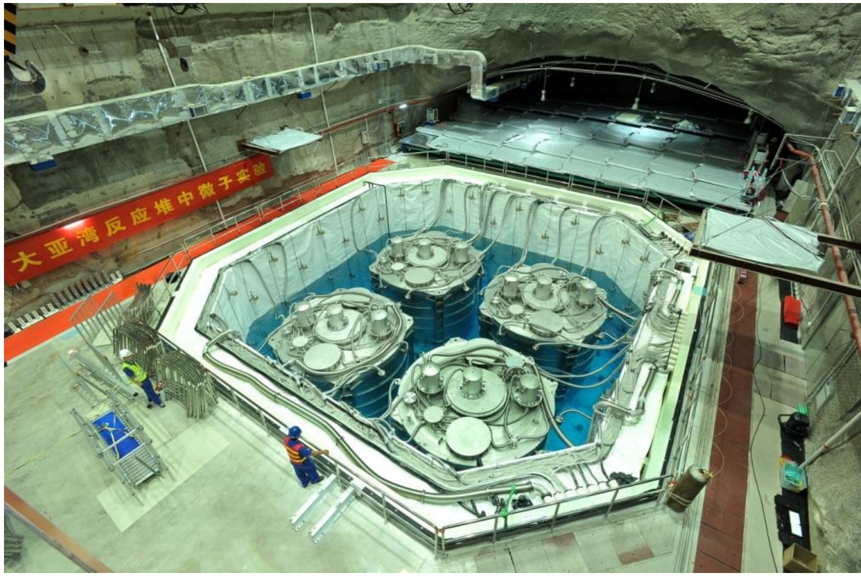
$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\mathrm{eV}^2$$

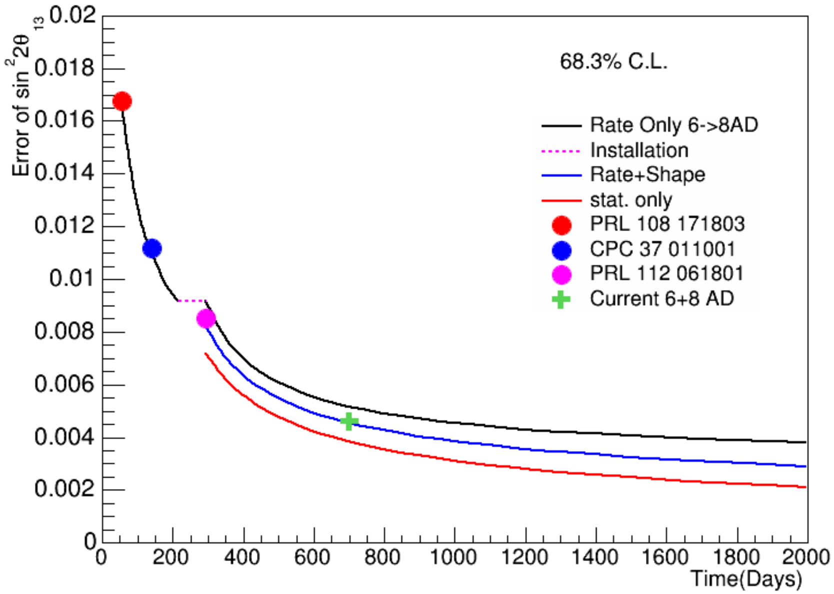
$$\chi^2/NDF = 134.7/146$$

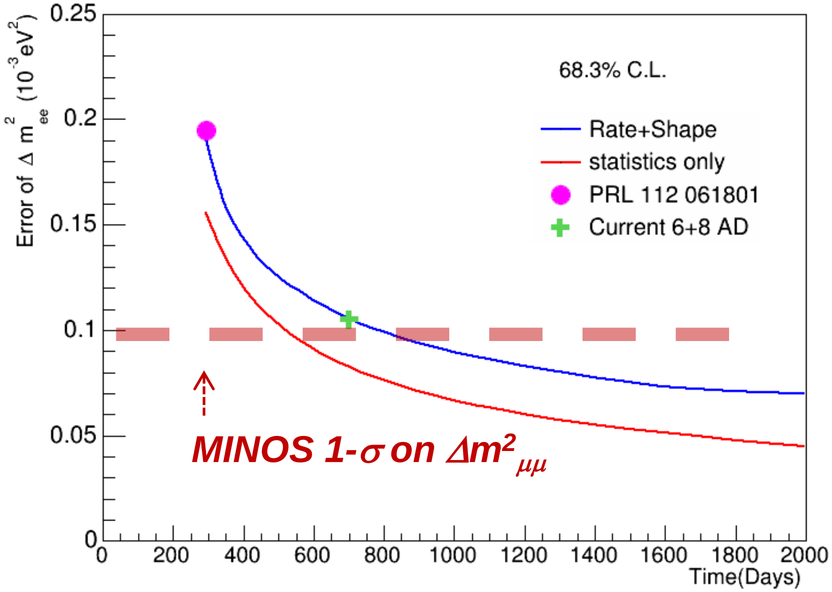
- **$\Delta(\sin^2 2\theta_{13})/\sin^2 2\theta_{13} \sim 6\%$, the best among all mixing angles**
- **$\Delta(\Delta M^2_{ee})/\Delta M^2_{ee} \sim 5\%$, similar to that of MINOS**
- **nH results ~4.5σ, independent check**

Future Prospects

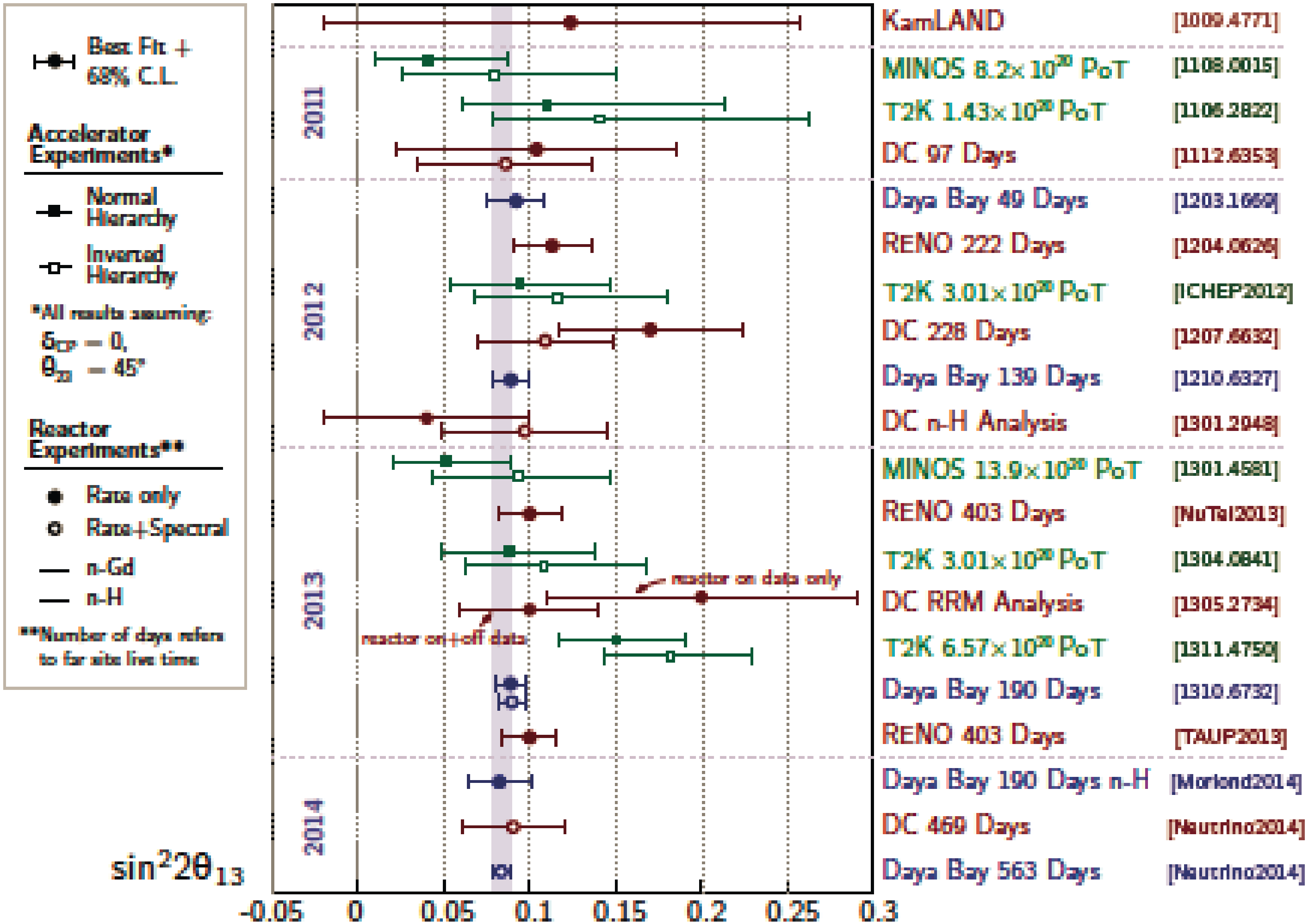
- Precision still dominated by statistics
- Continue to improve systematics
- Data taking until 2017
- Precision expected:
  - $\Delta(\sin^2 2\theta_{13}) \sim 0.003 \rightarrow \sim 3\%$
  - $\Delta(\Delta M^2_{ee}) \sim 0.07 \rightarrow \sim 3\%$







Comparison of all θ_{13} Measurements



Reactor Flux and Spectrum

- **See talk by Dr. Fengpeng AN *(East China University of Science and Technology)* on Friday**

- **Daya Bay measured the flux and energy spectrum:**
  - ⇨ **Absolute flux**
  - ⇨ **Absolute e^+ energy spectrum**
  - ⇨ **Unfolded absolute ν energy spectrum**

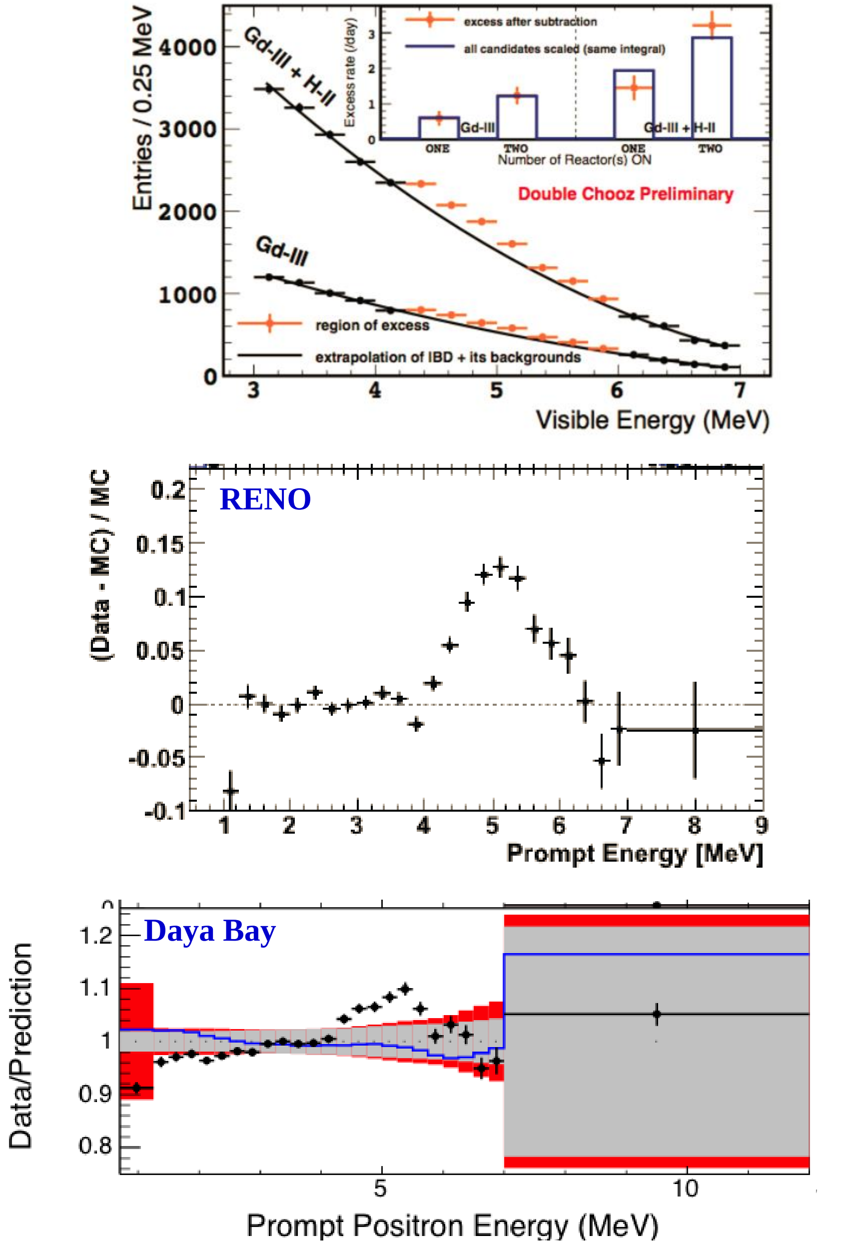
Reactor anomaly？

- **All three experiments, Daya Bay, Double Chooz and RENO, observed a "bump" at ~5 MeV**
  - ⇨ **No effect to θ_{13} if near-far configuration applied(Daya Bay & RENO)**
  - ⇨ **Under control even if only far detector is used(Double Chooz)**
  - ⇨ **Not large enough to explain the reactor anomaly**

Excess in [4,6] MeV Region

- Significance ~ 4 σ
- Events are reactor power related & time independent
- Events are IBD-like:
  - ⇨ Disfavors unexpected backgrounds
- A single β-branch or mono-energetic line cannot simulate the bump
- A possible explanation:
  - ⇨ Decays of prominent fission daughter isotopes (~ 42% rate from ^{96}Y, ^{92}Rb, ^{142}Cs, ^{97}Y, ^{93}Rb, ^{100}Nb, ^{140}Cs, ^{95}Sr)

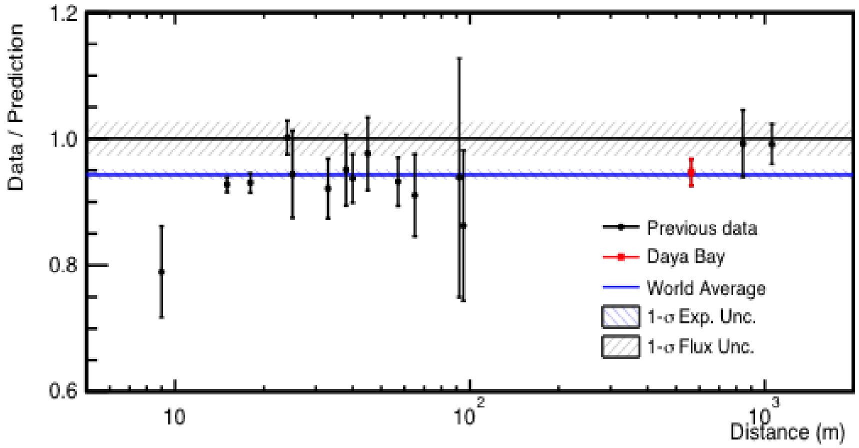
arXiv:1407.1281

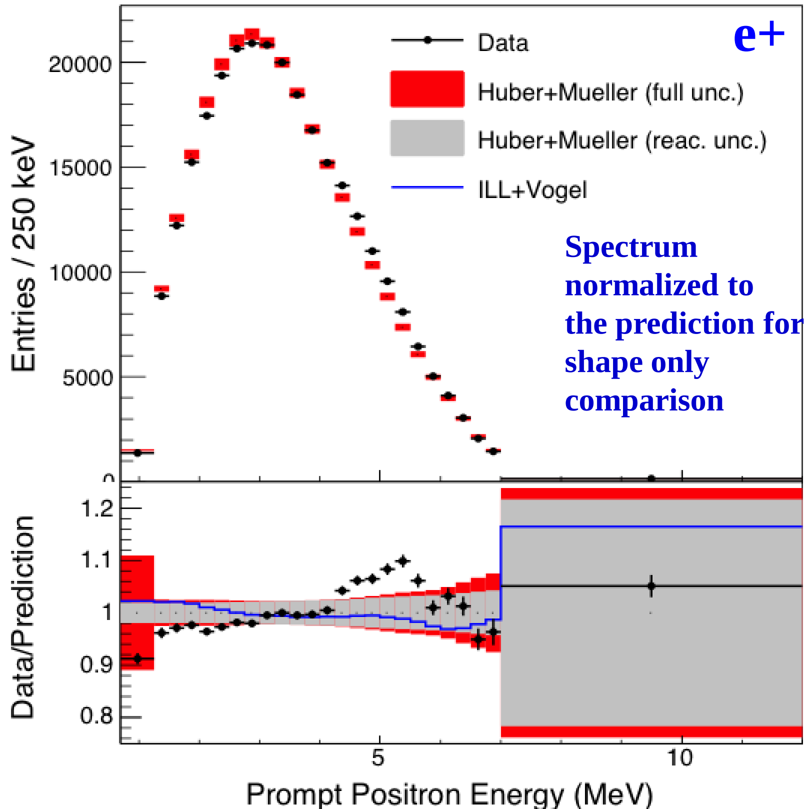


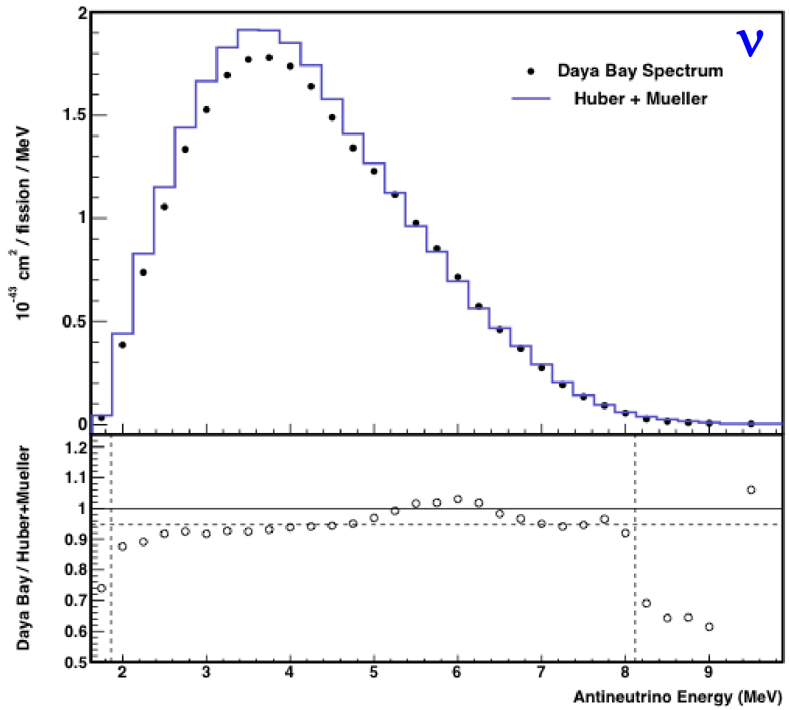
Absolute Flux and Spectrum

Daya Bay preliminary

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





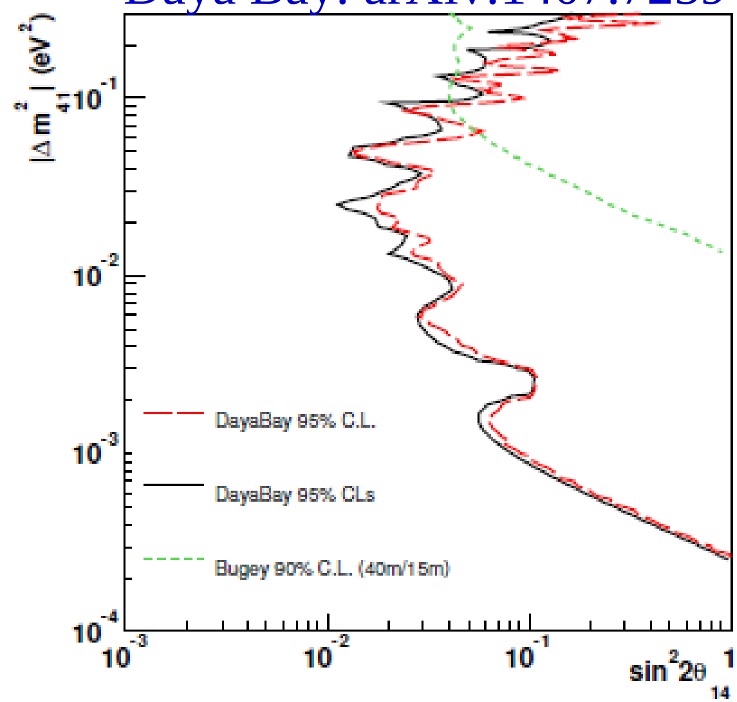


Search for Sterile Neutrinos

- 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 for sterile neutrinos AND JUNO type of experiments:
  - High precision reactor spectrum measurement(statistics ~ 1-10 M events, energy resolution ~ 1-2%, event vertex ~ 10 cm, …)
  - Proposals around: Nucifer, Stereo, Prospect, Solid, …

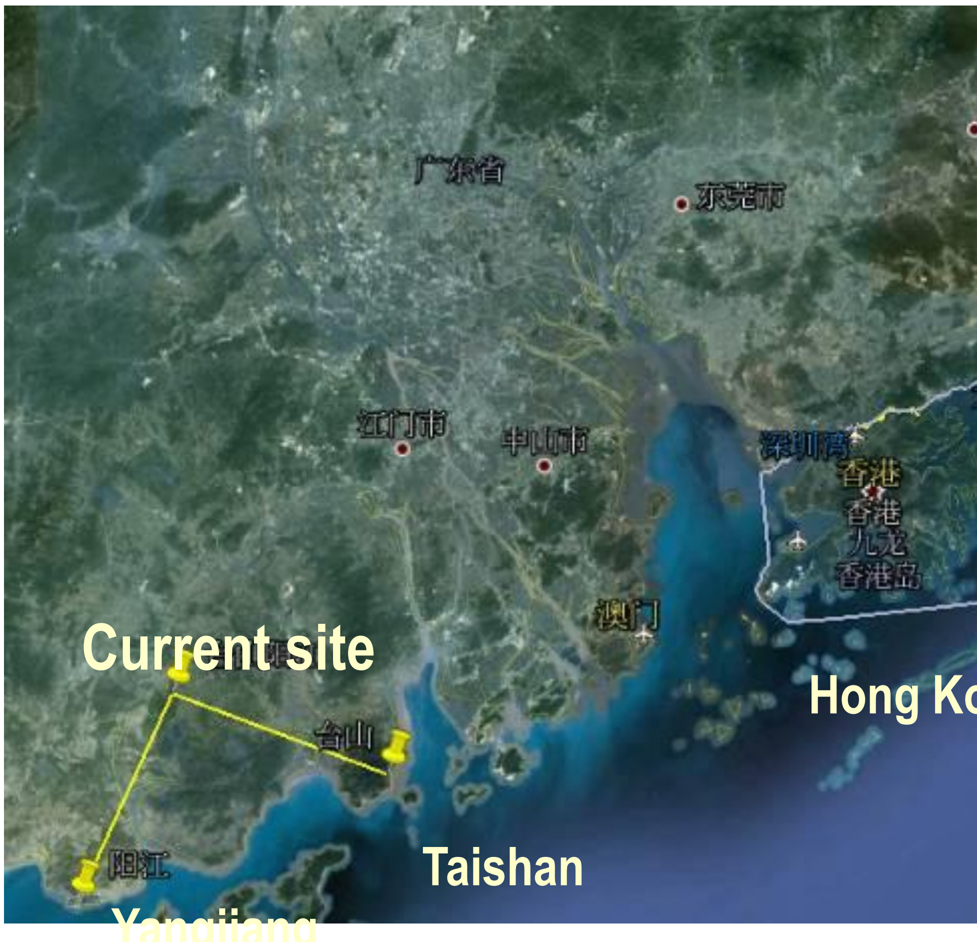
$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee}L}{4E_\nu}\right) - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41}L}{4E_\nu}\right)$$

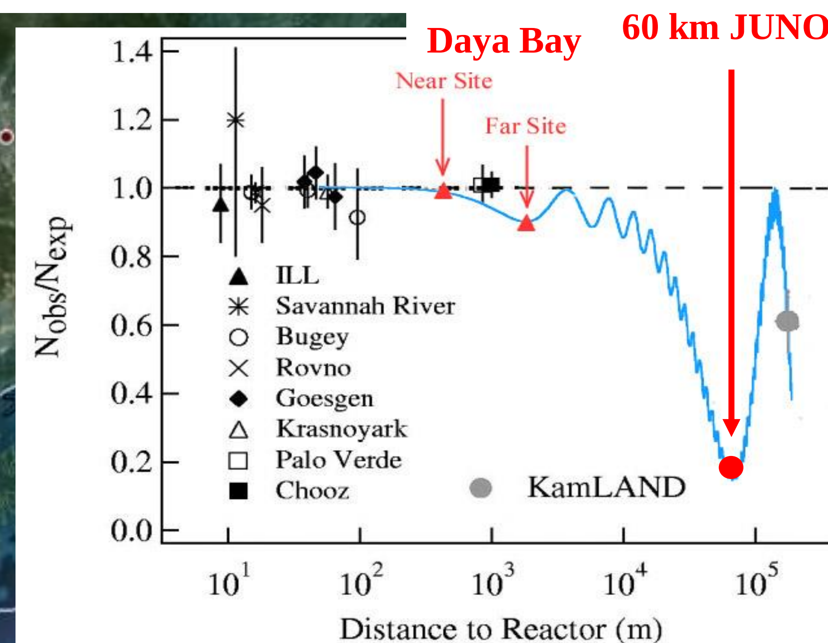
Daya Bay: arXiv:1407.7259



Next Step: Mass Hierarchy

	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	running	planned	approved	Construction	construction
power/GW	17.4	17.4	17.4	17.4	18.4



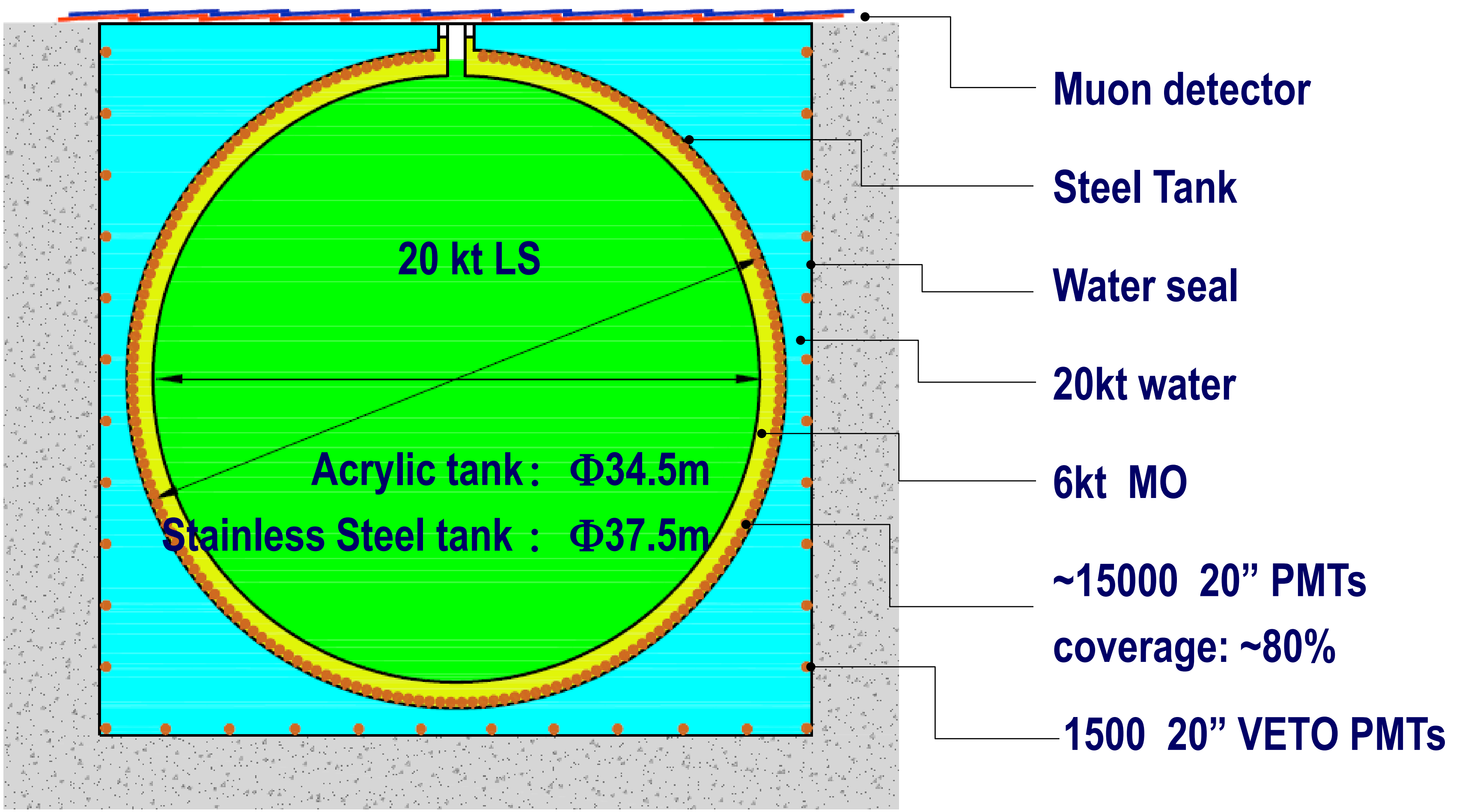


Before 2020：

Yangjiang 17.4GW + Taishan19.9 GW = 27.3 GW

The Plan: a Large LS Detector

- LS volume: × 20➔ for more mass & statistics
- light(PE) × 5➔ for resolution



Signals & Backgrounds

- **Estimated IBD signal event rate: ~40/day**
- **LS without Gd-loading for**
  - Better attenuation length ➔ better resolution
  - Lower irreducible accidental backgrounds from LS, important for a larger detector:
    - ✓ With Gd: ~ 10^{-12} g/g ➔ 50,000 Hz
    - ✓ Without Gd: ~ 10^{-16} g/g ➔ 5 Hz
- **Backgrounds**

$\tau \sim 200\ \mu s$

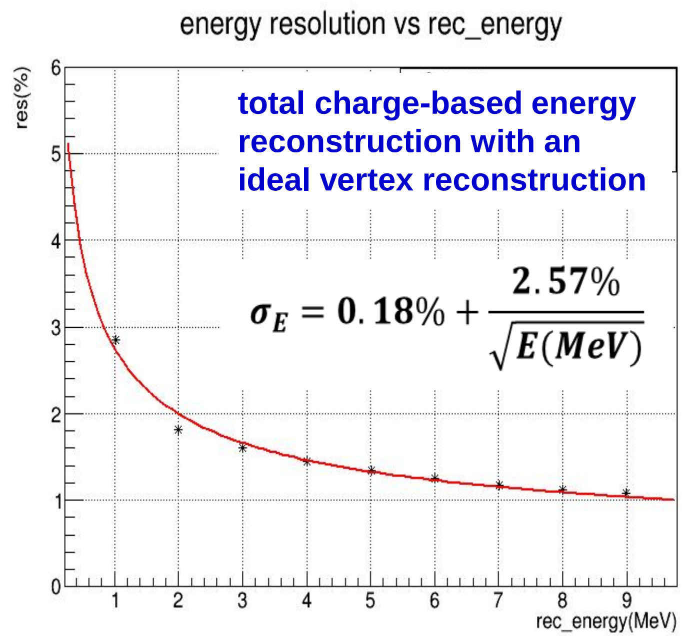
Overburden 700m:
E_μ ~ 211 GeV, R_μ ~ 3.8 Hz
Single rates:
5 Hz by LS and 5Hz by PMT
muon efficiency ~ 99.5%

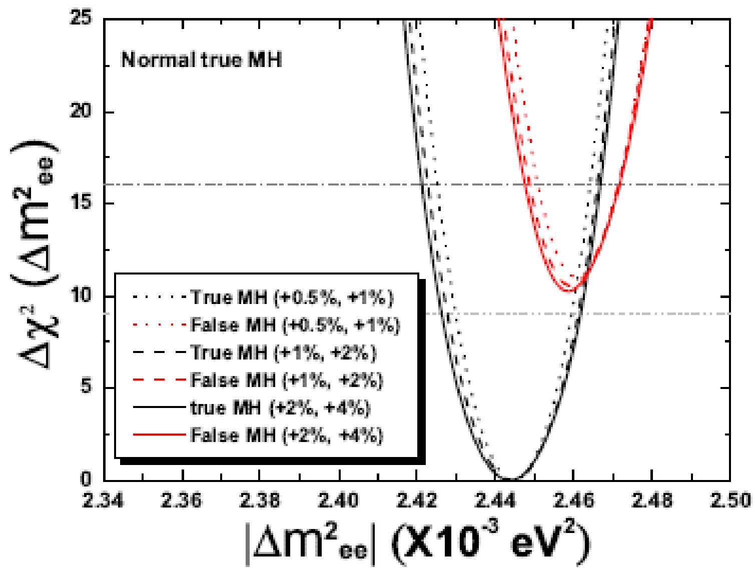
	B/S @ DYB EH1	B/S @ JUNO	Techniques to be used by JUNO
Accidentals	~1.4%	~10%	Low PMT radioactivity; LS purification; prompt-delayed distance cut
Fast neutron	~0.1%	~0.4%	High muon detection efficiency (similar as DYB)
$^{9}Li/^{8}He$	~0.4%	~0.8%	Muon tracking; If good track, distance to muon track <5m and veto 2s; If shower muon, full volume veto 2s

MC Study：Energy Scale & Resolution

- **Resolution: based on DYB with:**
  - JUNO Geometry
  - 80% photocathode coverage
  - PMT QE from 25% ➔ 35%
  - Attenuation length of 20 m ➔ abs. 60 m + Rayleigh scatt. 30m
- **Energy scale**
  - By introduce a self-calibration (based on ΔM^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



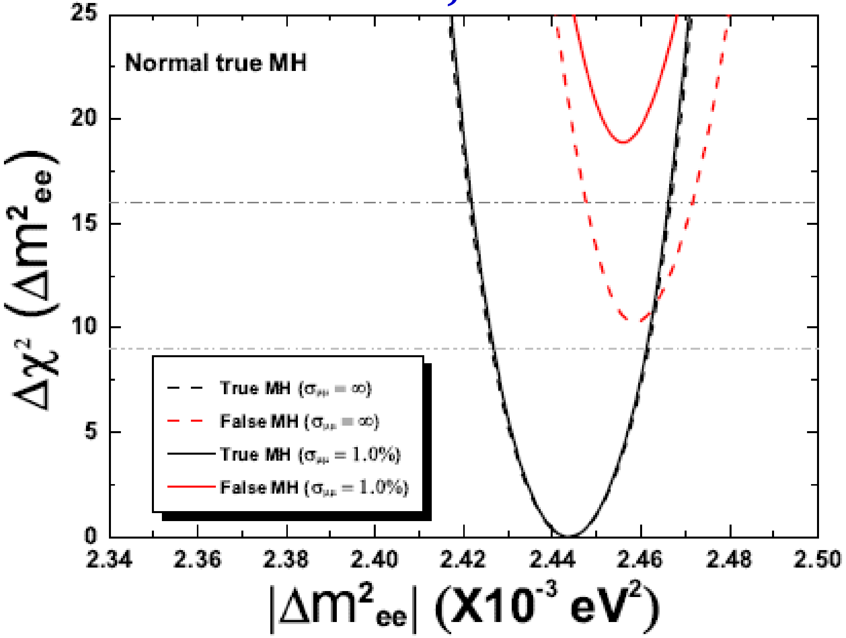


Physics Reach

Thanks to a large θ_{13}

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

Y.F. Li et al., arXiv:1303.6733



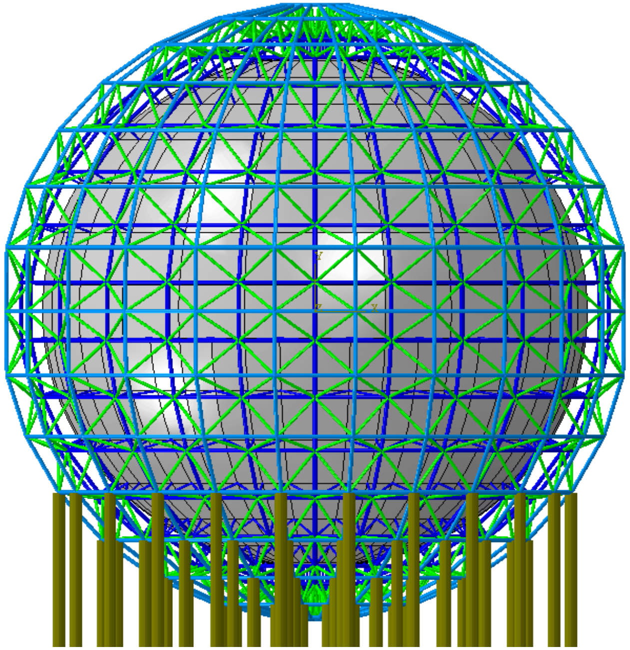
	Current	JUNO
Δm^2_{12}	4%	0.6%
Δm^2_{23}	5%	0.6%
$\sin^2\theta_{12}$	5%	0.7%
$\sin^2\theta_{23}$	10%	N/A
$\sin^2\theta_{13}$	6% ➔ 3%	~ 15%

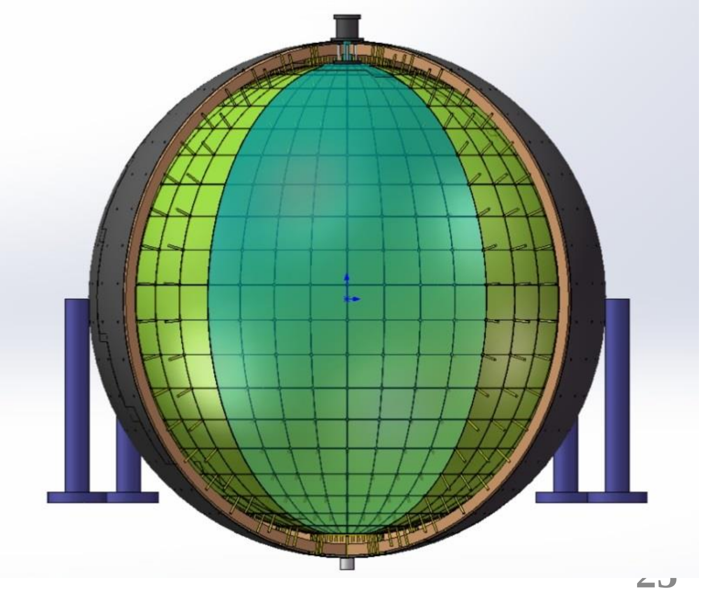
For 6 years, mass hierarchy cab be determined at 4σ level, if $\Delta m^2_{\mu\mu}$ can be determined at 1% level

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

Central Detector

- **A D~35m detector in the water pool:**
  - **Mechanics， optics, chemistry, cleanness， assembly, …**
- **Current design:**
  - **Default: acrylic tank(D~35m) + SS structure**
    - ✓ **Acrylic bonding, creeping， stress, steel support at acrylic, deformation, event reconstruction with total refection, …**
  - **Backup: SS tank(D~38m) + acrylic panel + balloon**
    - ✓ **Balloon materials, cleanness, leaks, deployment, …**
- **Two teams working on the design and R&D.**
- **Prototyping soon**

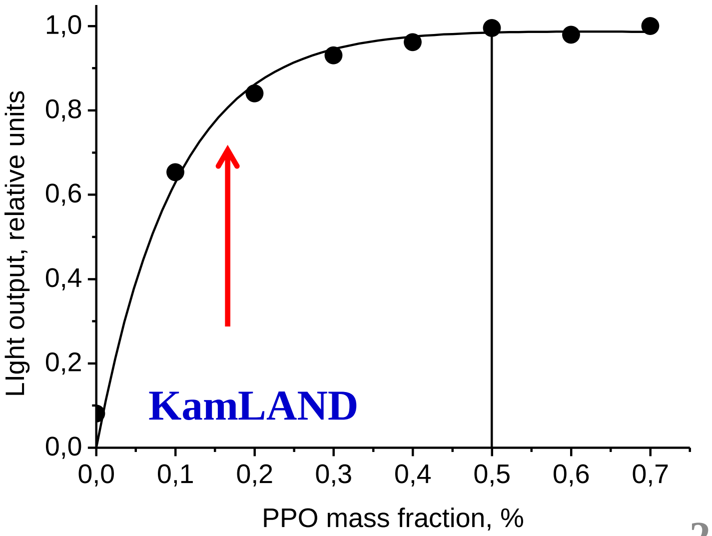




Liquid Scintillator

- **Our choice: LAB+PPO+BisMSB**
  - **At Daya Bay: 15 m**
  - **Our target: ~30 m**
- **R&D efforts:**
  - ⇨ **Improve raw materials**
  - ⇨ **Improve the production process**
  - ⇨ **Purification**
    - ✓ **Distillation, Filtration, Water extraction, Nitrogen stripping…**
  - ⇨ **Optimization of flour concentration**
- **Other issues:**
  - ⇨ **Rayleigh scattering length**
  - ⇨ **Energy non-linearity**
  - ⇨ **Aging**
  - ⇨ **Material selection: BKG & purity**
  - ⇨ **Engineering for 20kt**
    - ✓ **Transportation, storage, transfer line, mixing and purification equipment, safety, interface with civil, …**

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

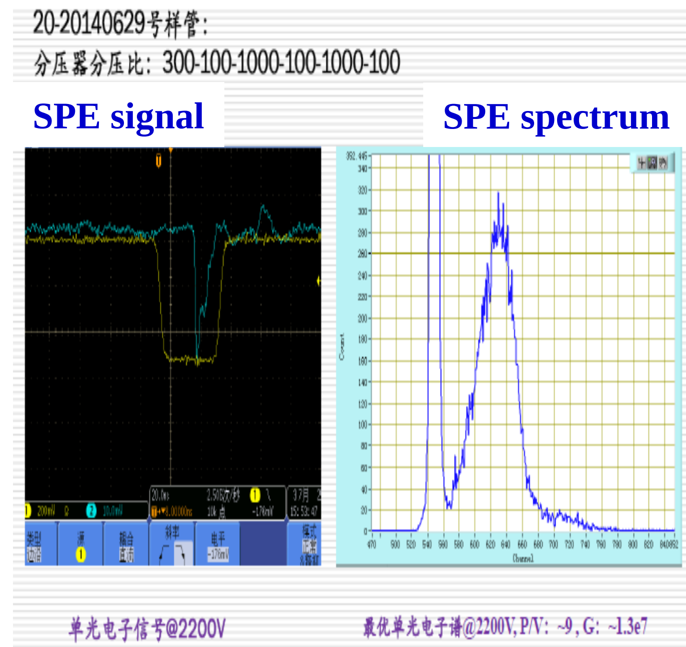


High QE PMT

- **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

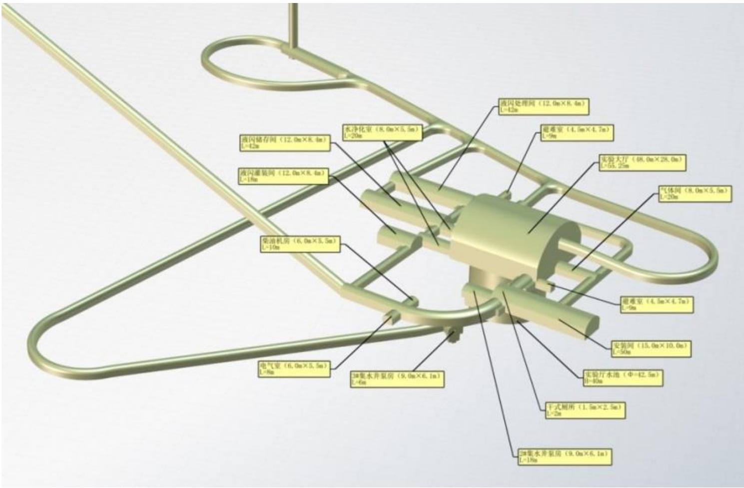
	R5912	R5912-100	MCP-PMT
QE@410nm	25%	>30%	~ 30%
Rise time	3 ns	3.4ns	5ns
SPE Amp.	17mV	18mV	17mV
P/V of SPE	>2.5	>2.5	> 2.5
TTS	5.5ns	1.5 ns	3.5 ns

20” PMT



Current Status & Brief Schedule

- **Project approved by CAS for R&D and design**
- **Geological survey completed**
  - ⇨ Granite rock, tem. ~ 31 °C, little water
- **EPC contract signed:**
  - ⇨ **Engineering design by Aug.**
  - ⇨ **Construction work by Nov. ?**
- **Paper work towards the construction:**
  - ⇨ **Land, environment, safety, …**



Schedule:

Civil preparation：2013-2014

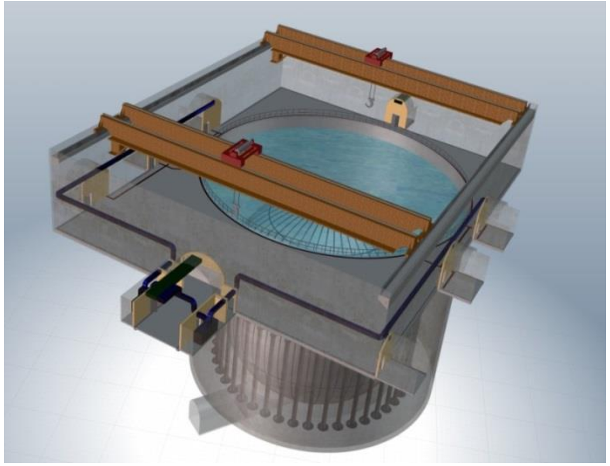
Civil construction：2014-2017

Detector component production：2016-2017

PMT production：2016-2019

Detector assembly & installation：2018-2019

Filling & data taking：2020



Collaboration Established

Political Map of the World, June 1999

Europe (20)*

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

US*

BNL, UIUC, Houston
Observers on behalf of US institutions

Asia (25)

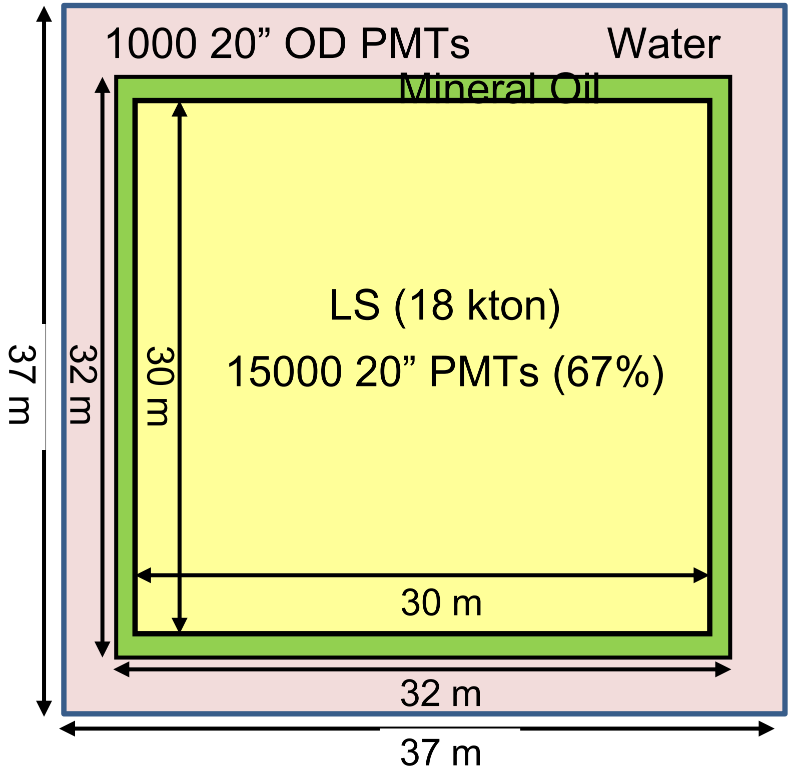
Beijing Normal U.
CAGS,
CIAE
DGUT
ECUST
Guangxi U.
IHEP
Jilin U.
Nanjing U.
Nankai U.
Natl. Chiao-Tung U.
Natl. Taiwan U.
Natl. United U.
NCEPU
Pekin U.
Shandong U.
Shanghai JT U.
Sichuan U.
SYSU
Tsinghua U.
UCAS
USTC
Wuhan U.
Wuyi U.
Xi'an JT U.

*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 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 :

  2013 ~ 2018 : Facility and detector construction
  2019 ~ : Operation and experiment



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.
- Sterile neutrinos have been studied by Daya Bay. Future experiments are desired.
- A bump around 5 MeV observed by all three experiments. A possible explanation is decays of prominent fission isotopes
- 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
  - ⇨ Neutrino properties: magnetic moments, coherent scattering (not covered in this talk)…