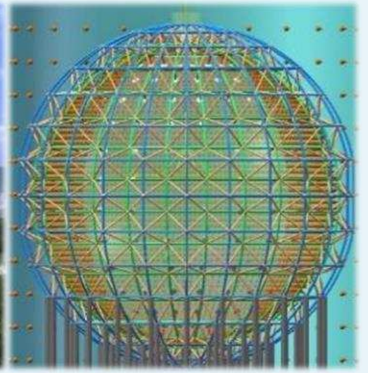
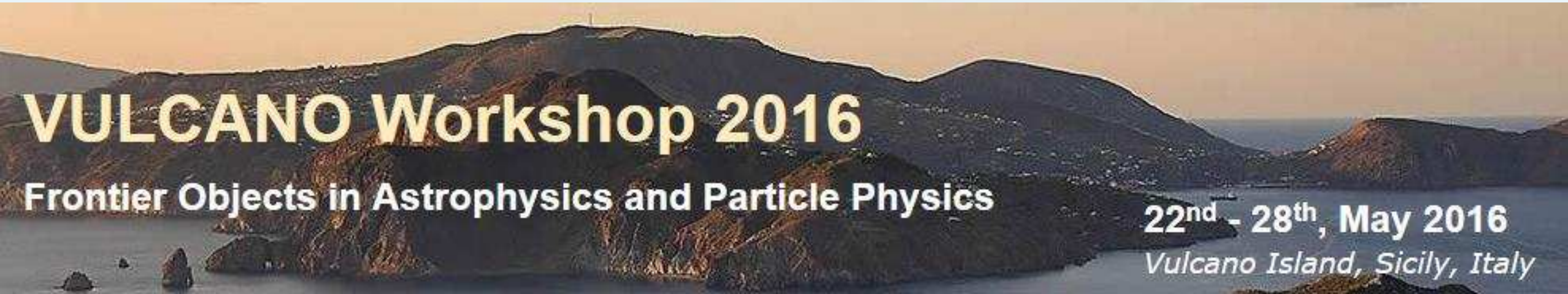


Reactor Neutrinos and Mass Hierarchy

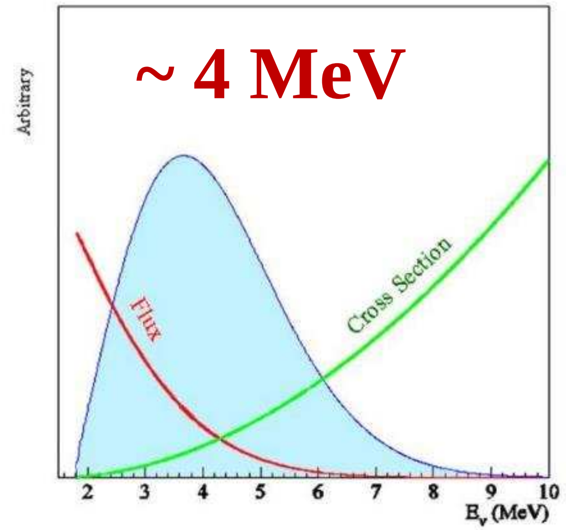
Jun Cao

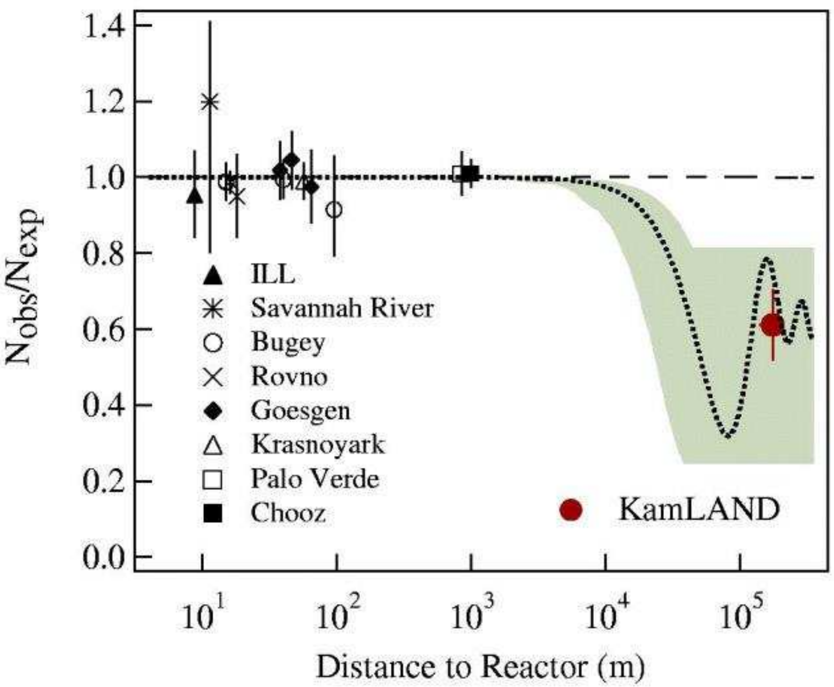
Institute of High Energy Physics, Beijing

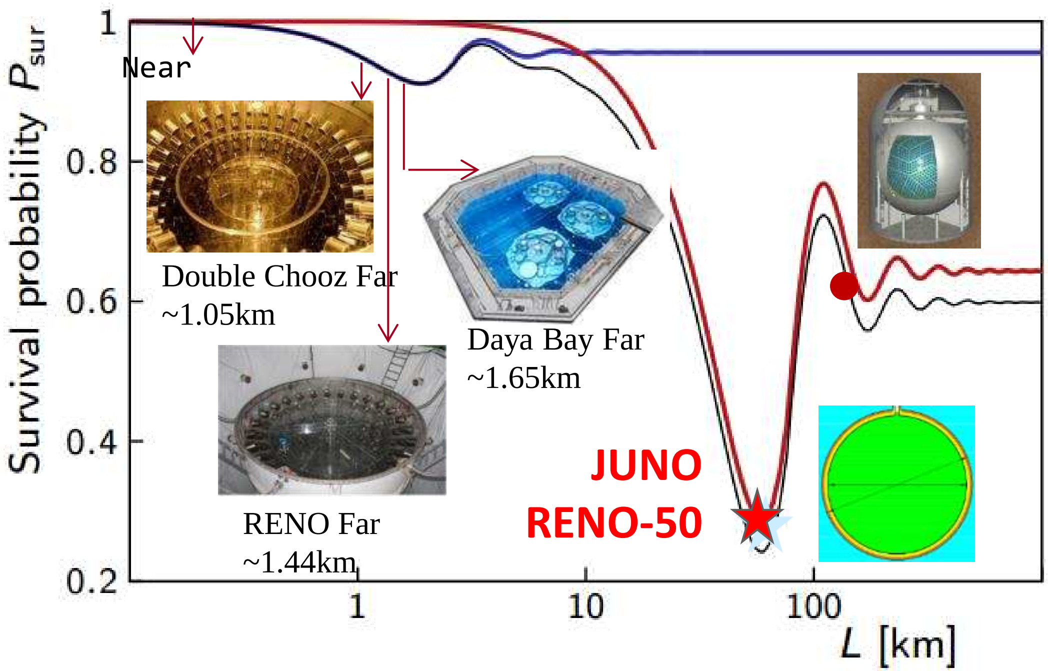


Reactor Neutrinos

- **Measuring θ_{13} and Δm^2_{ee}**
  - ⇨ **Daya Bay, Double Chooz, RENO**
- **Rate and Spectrum**
- **Determining Mass Hierarchy & precision measurement of θ_{12}, Δm^2_{21} and Δm^2_{31}**
  - ⇨ **JUNO, RENO-50**







Detecting Reactor Antineutrino

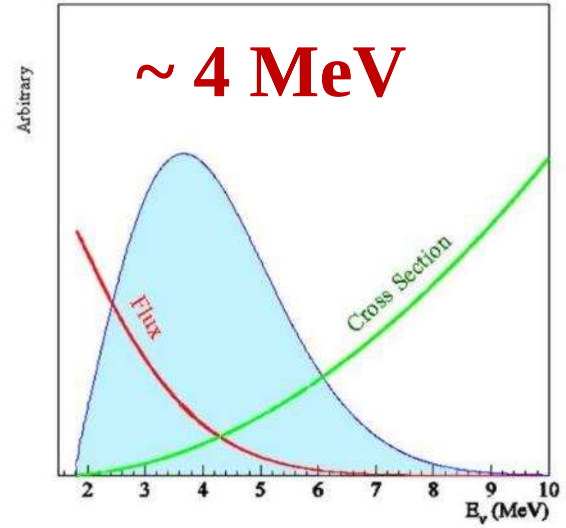
- ν-e scattering
- Inverse beta decay (IBD)

Prompt signal

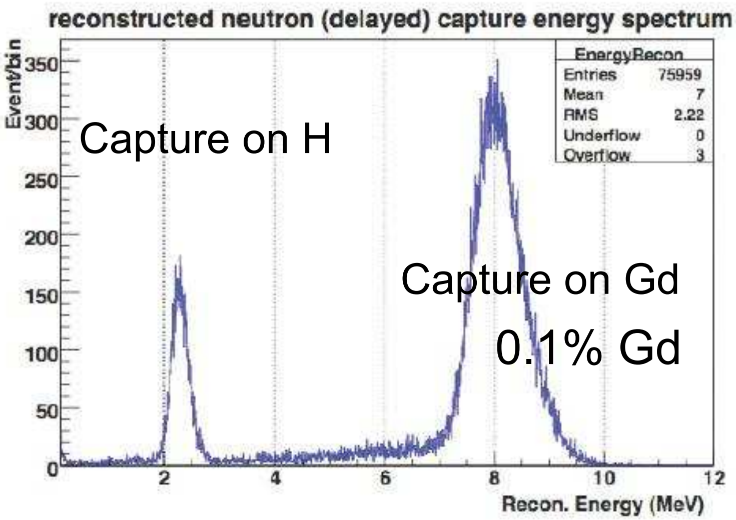
$$e^+ + e^- \to 2\gamma$$

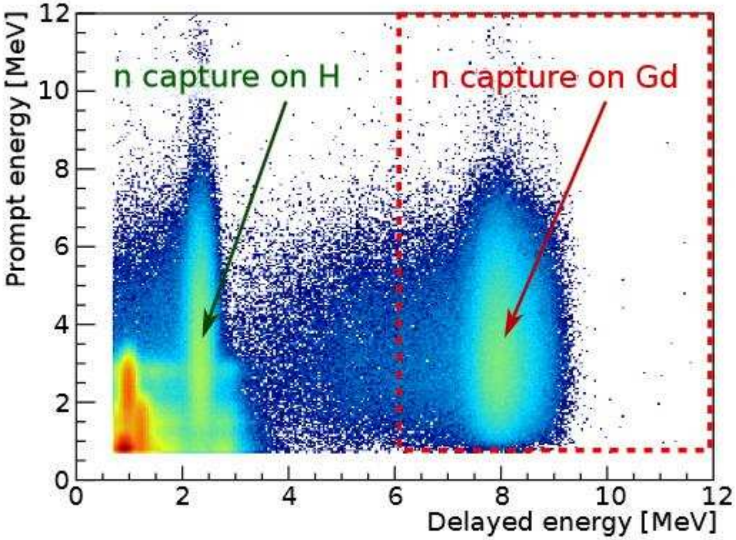
$$\bar{\nu}_e + p \to e^+ + n$$

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

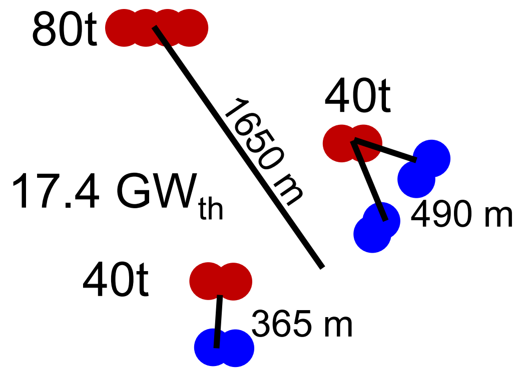


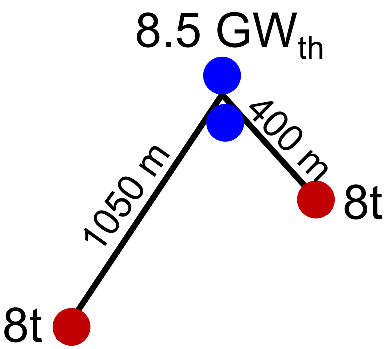
$$E(\bar{\nu}_e) = E_{\rm prompt} + Q - m_e \sim E_{\rm prompt} + 0.8\ \text{MeV}$$

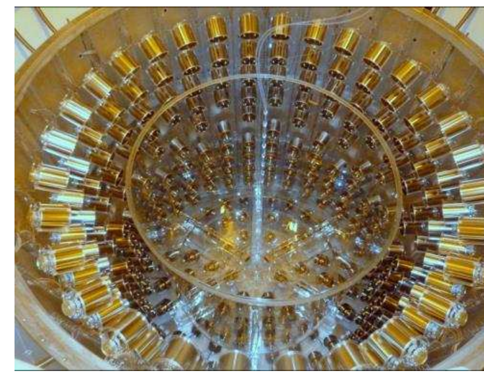


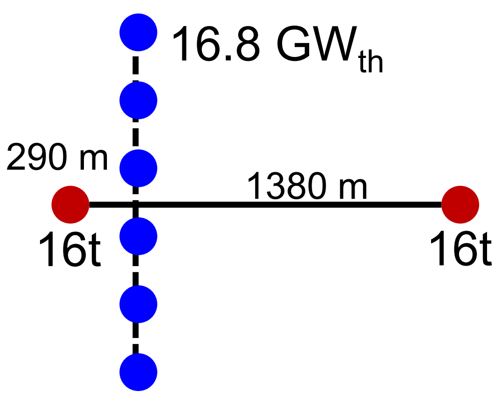


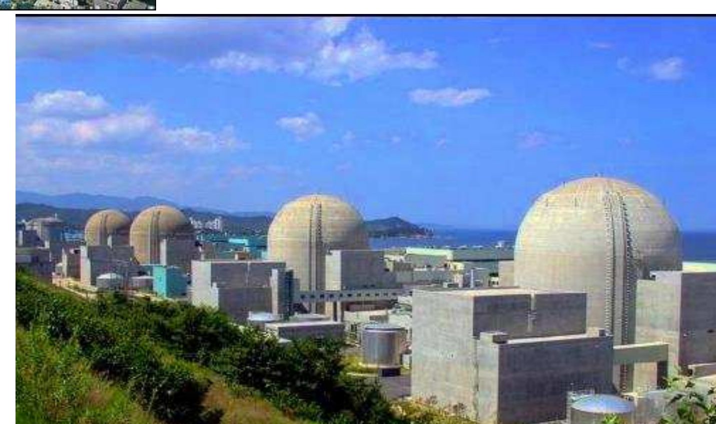
Daya Bay, Double Chooz, RENO for θ_{13}



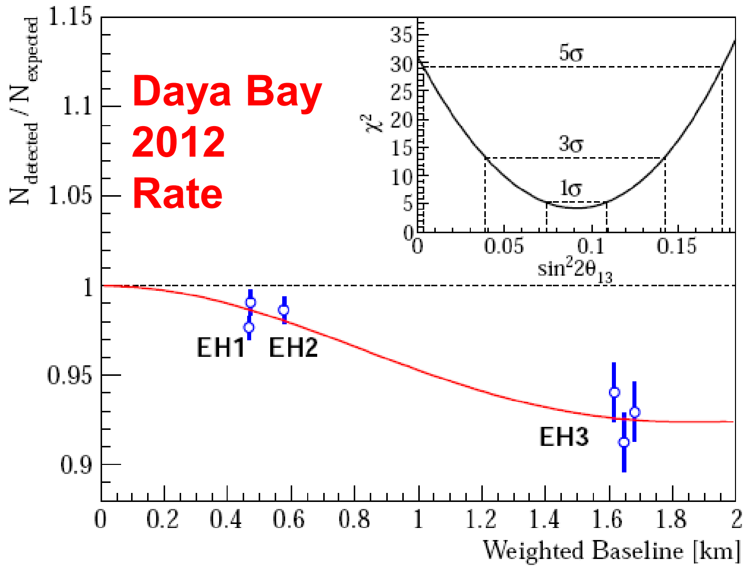


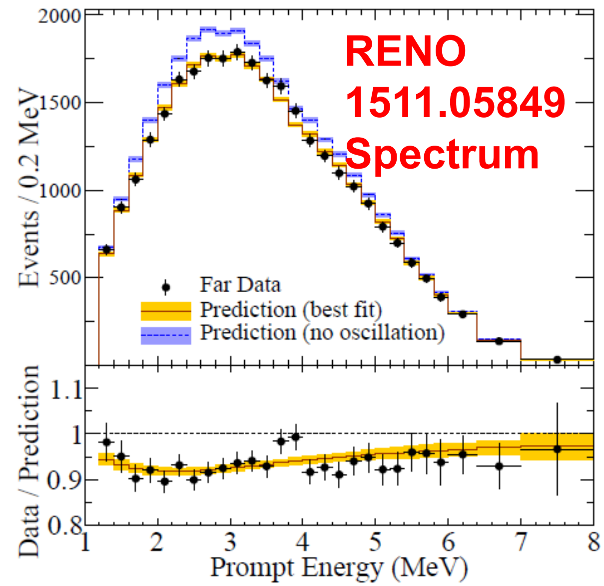


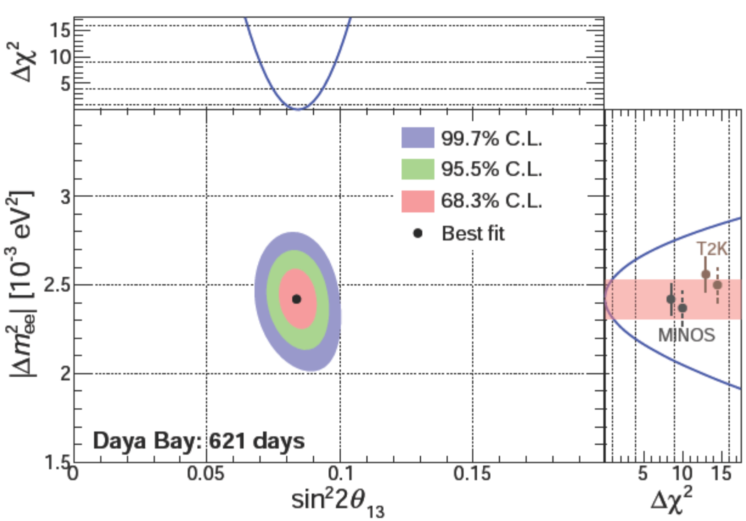




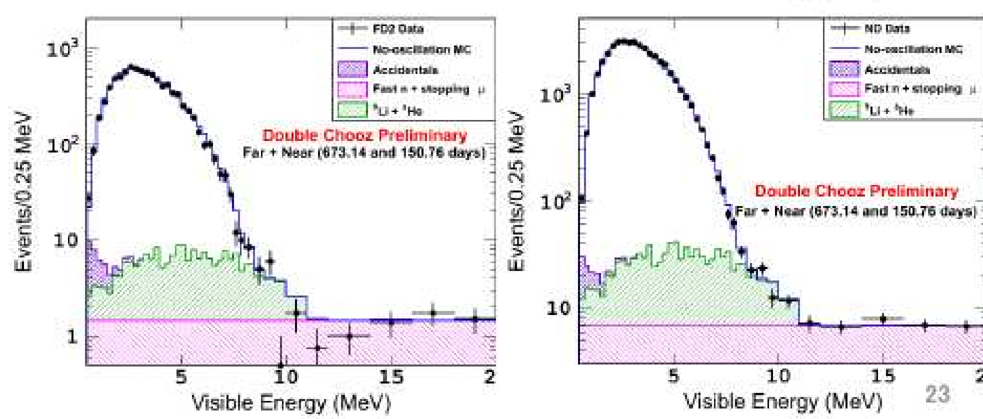
Measuring θ_{13}





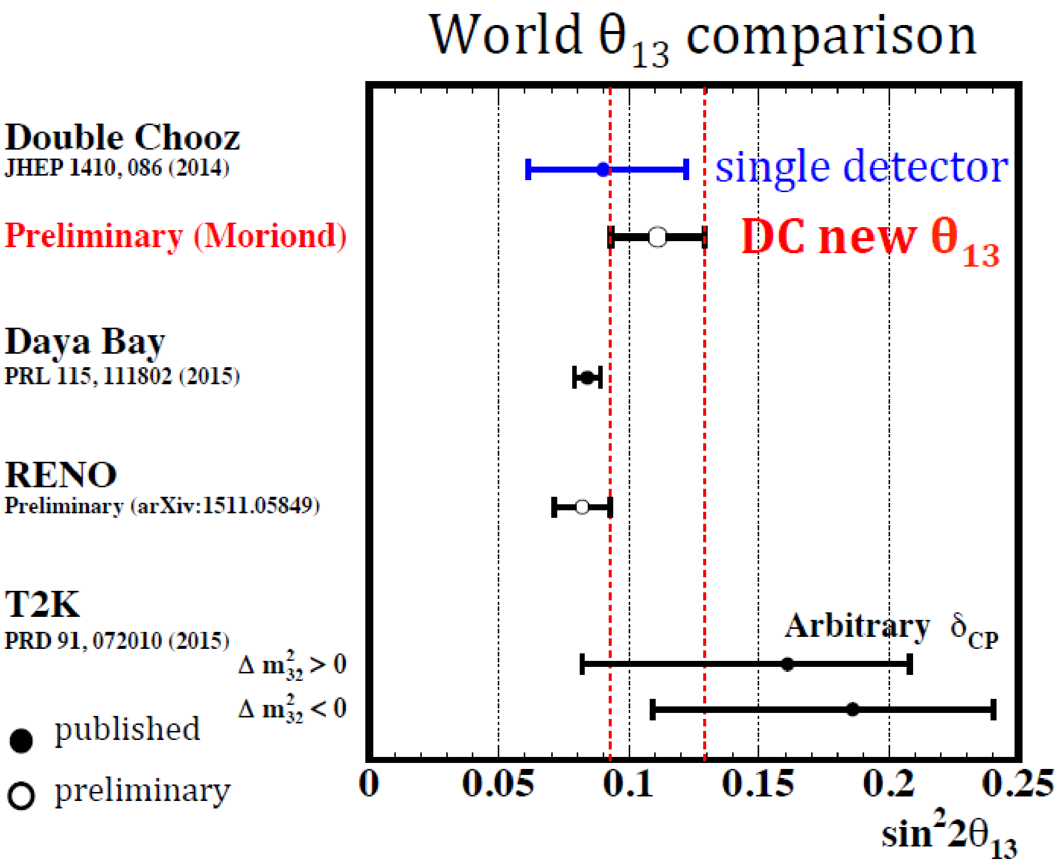


Double Chooz, Moriond 2016, bkg

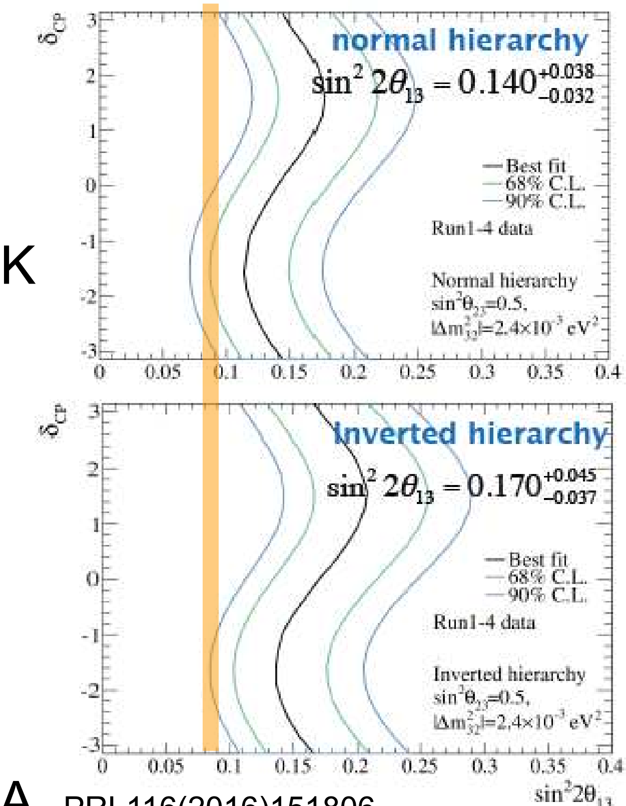


Results for θ_{13}

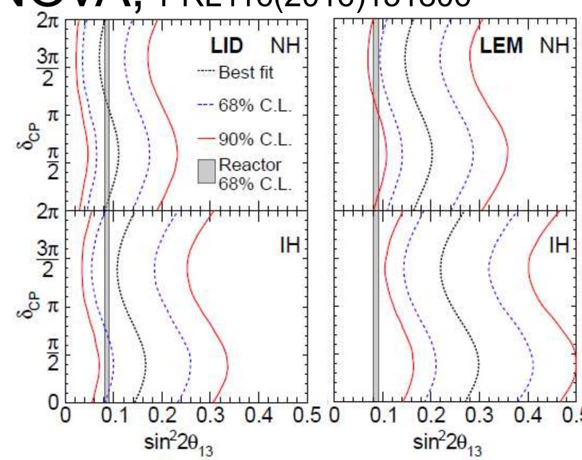
- More than 10 releases from the 3 experiments
- Tension with T2K and NOvA indicating maximum CP violation



T2K



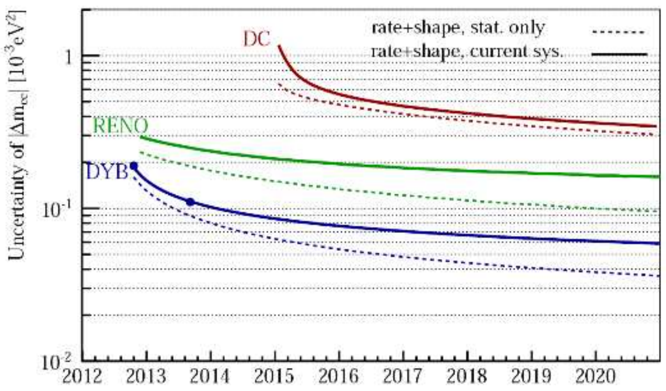
NOvA, PRL116(2016)151806

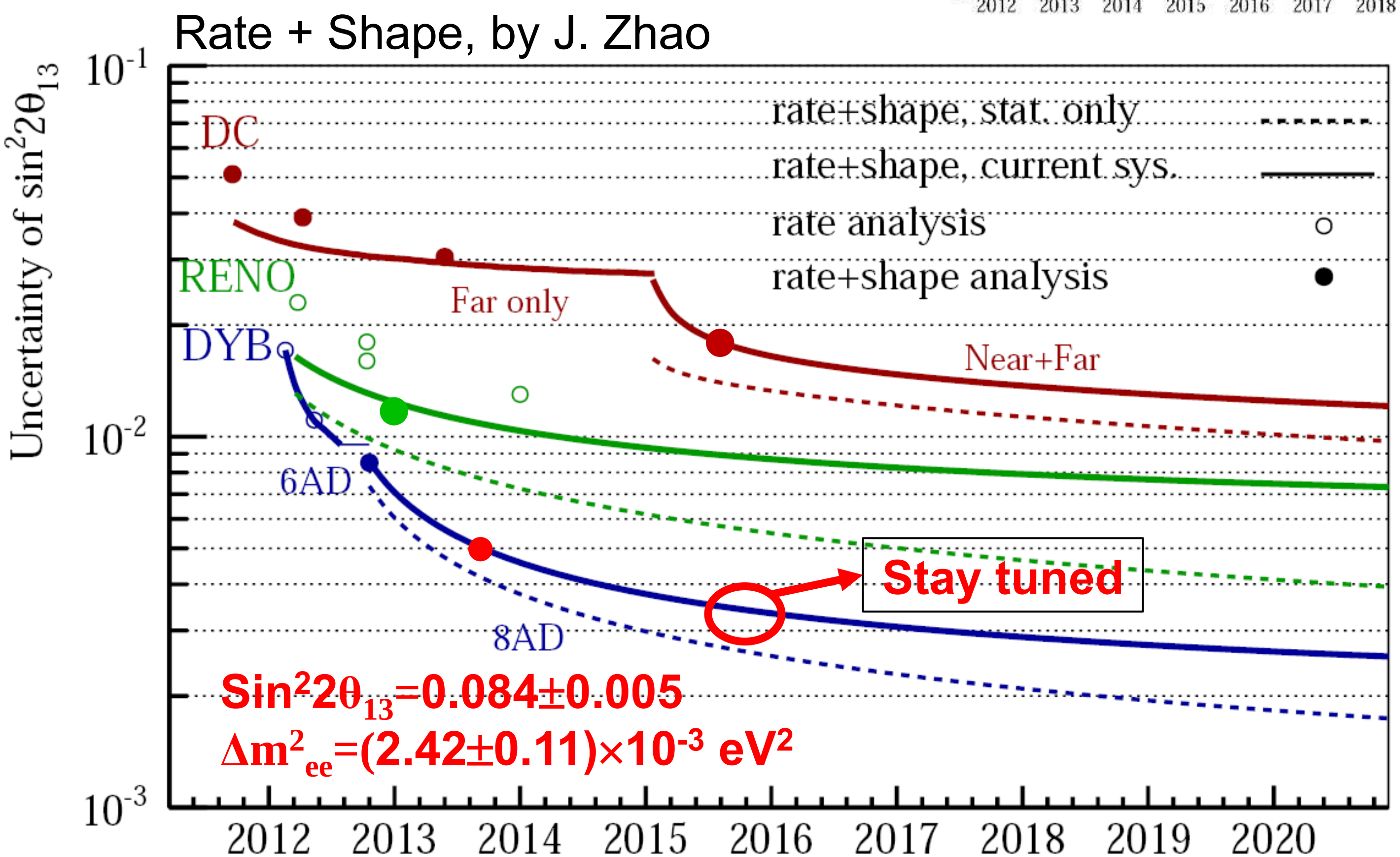


M. Ishitsuka@Moriond for DC

Future Prospects

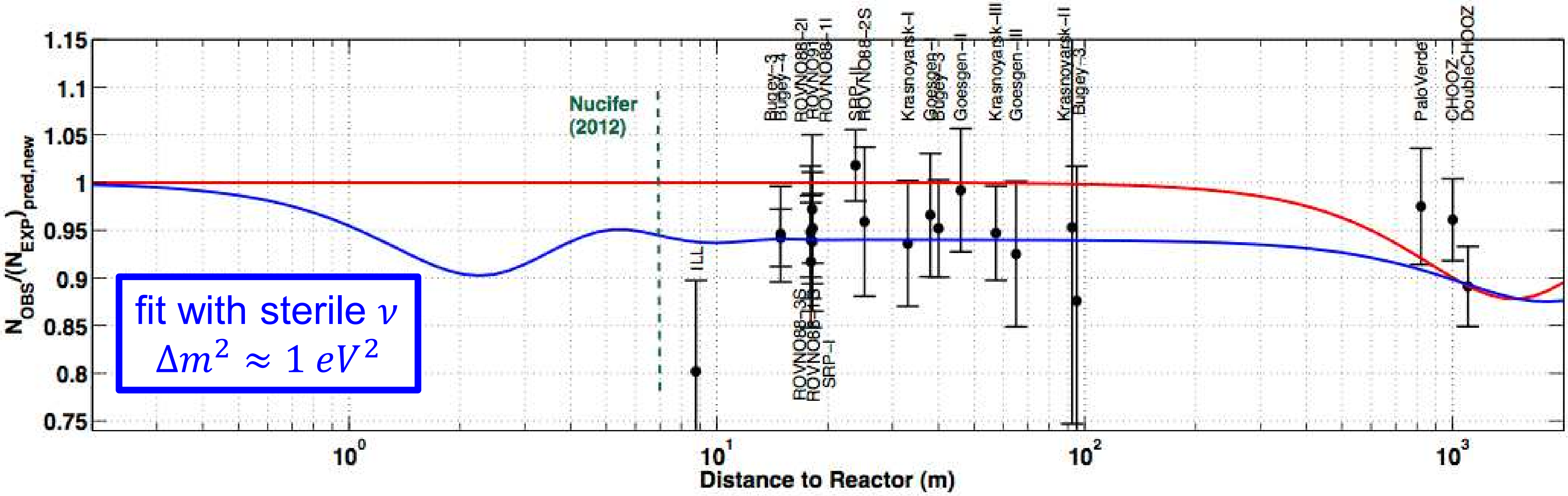
- Daya Bay:
  - $\Delta(\sin^2 2\theta_{13}) \sim 0.003 \rightarrow \sim 3\%$
  - $\Delta(\Delta m^2_{ee}) \sim 0.07 \rightarrow \sim 3\%$
- RENO: ~5%
- Double Chooz: ~10%





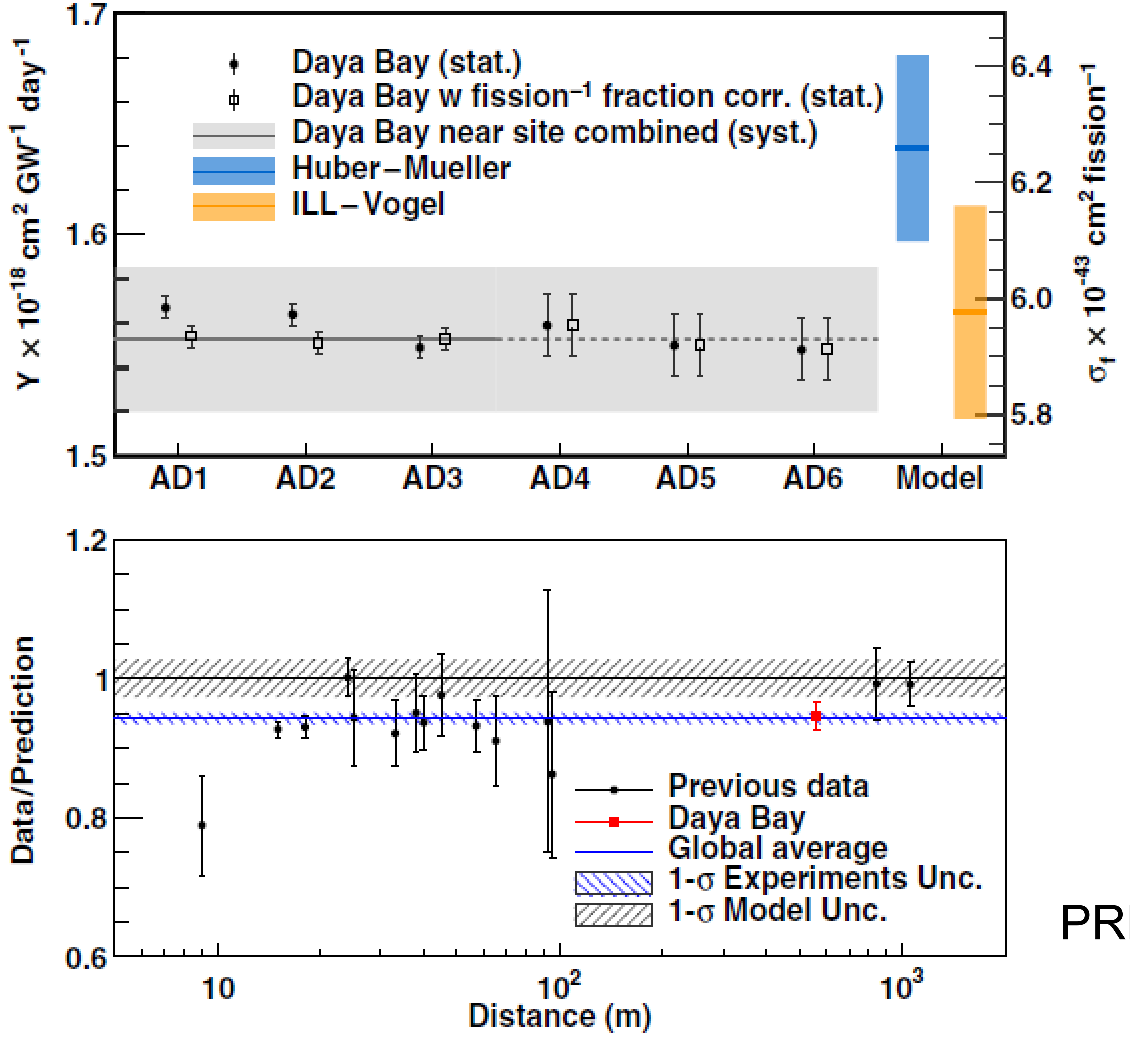
Reactor Anomaly (Rate)

- **ILL spectra agree w/ data**
- **Mueller-Huber spectra higher than data**
- **Sterile neutrino?**



G. Mention et al.
Phys.Rev. D83 (2011) 073006

Daya Bay Absolute Rate Measurement

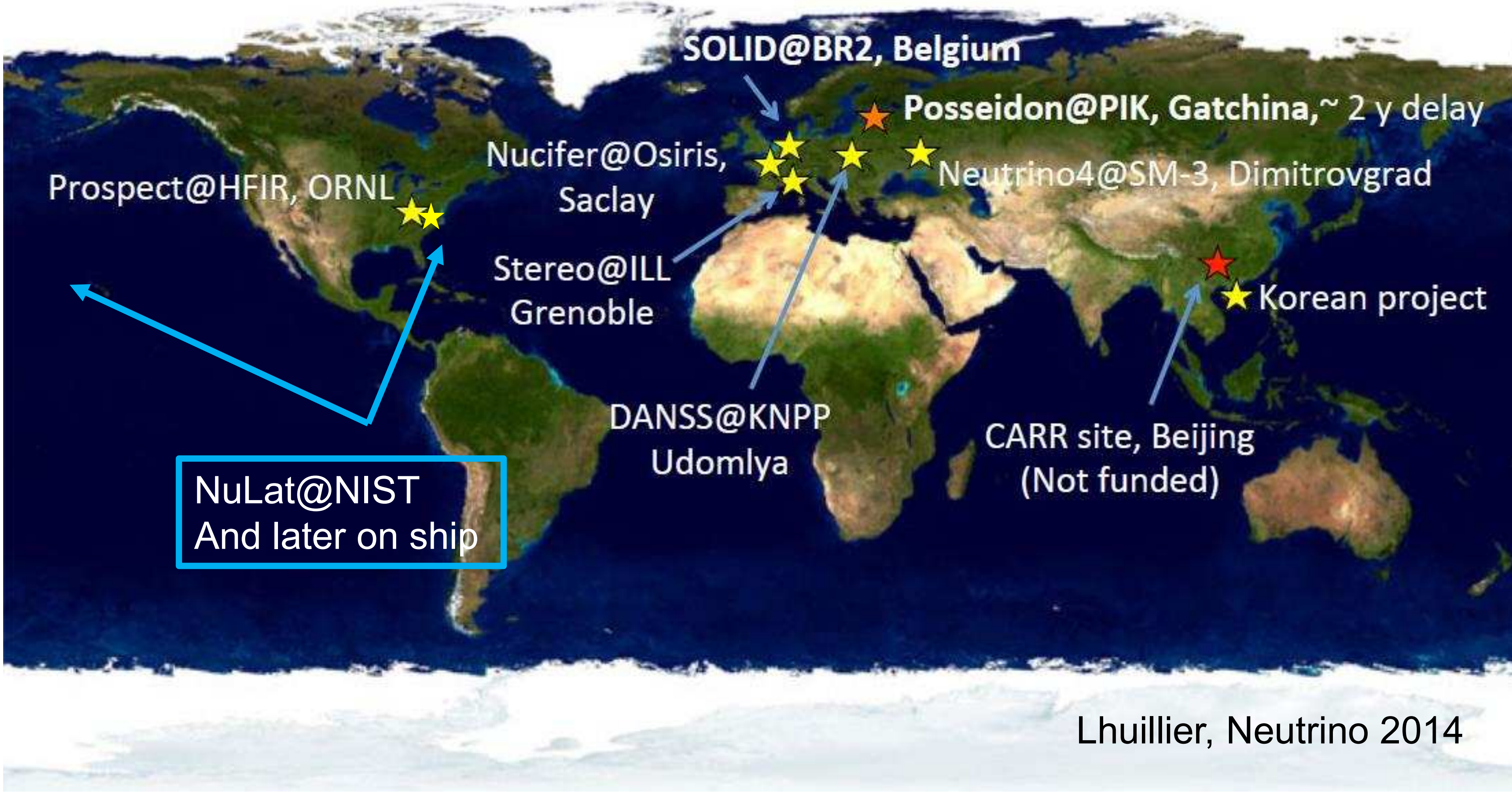


PRL 116, 061801 (2016)

- **Daya Bay measurement of absolute Flux**
  - ⇨ **Data/(Huber+Mueller): 0.946±0.022**
  - ⇨ **Data/(ILL+Vogel): 0.991 ± 0.023**

Reactor Exp. for Sterile Neutrino

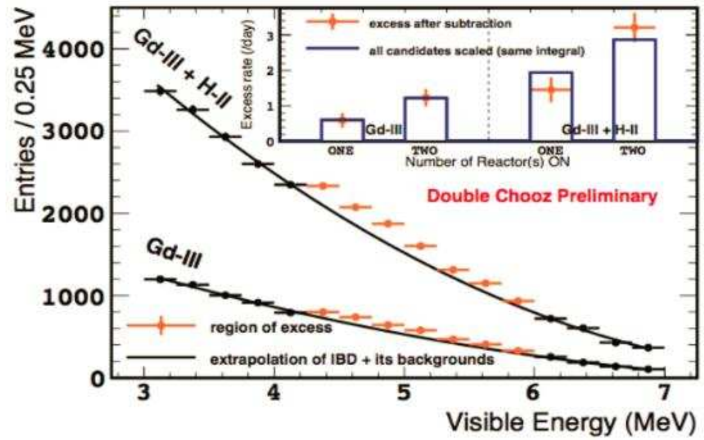
- **Different technologies: (Gd, Li, B) (seg.)(movable)(2 det.)**
- **Most have sensitivity 0.02~0.03 @Δm~1eV^2 @90%CL**



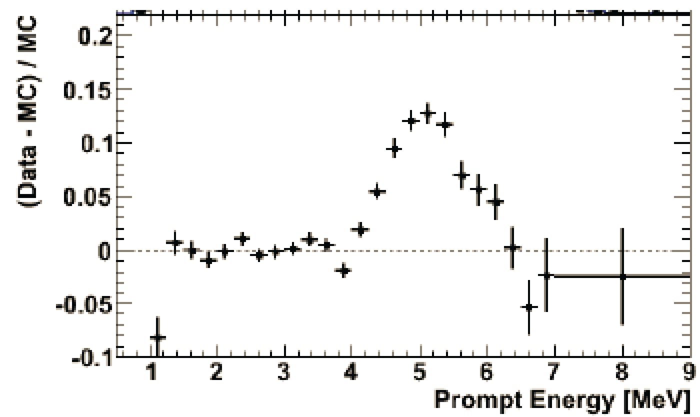
5 MeV Bump on Reactor Spectrum

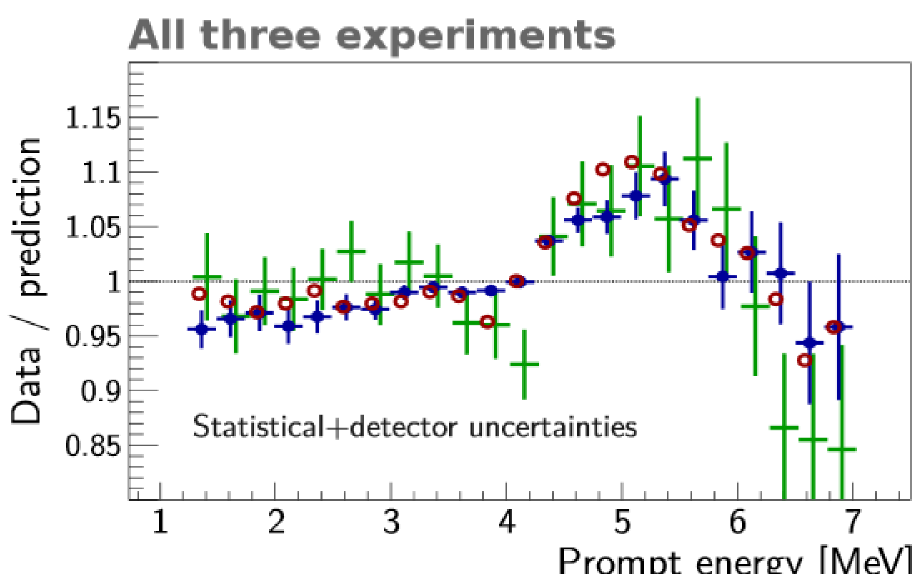
- Events are reactor power related & time independent
- Events are IBD-like:
  - ⇨ Disfavors unexpected backgrounds
- **No effect to θ_{13} at DYB, RENO; under control at DC**
- Possibly due to forbidden decays (PRL112: 2021501; PRL114:012502)

DC, Neutrino 2014



RENO, Neutrino 2014



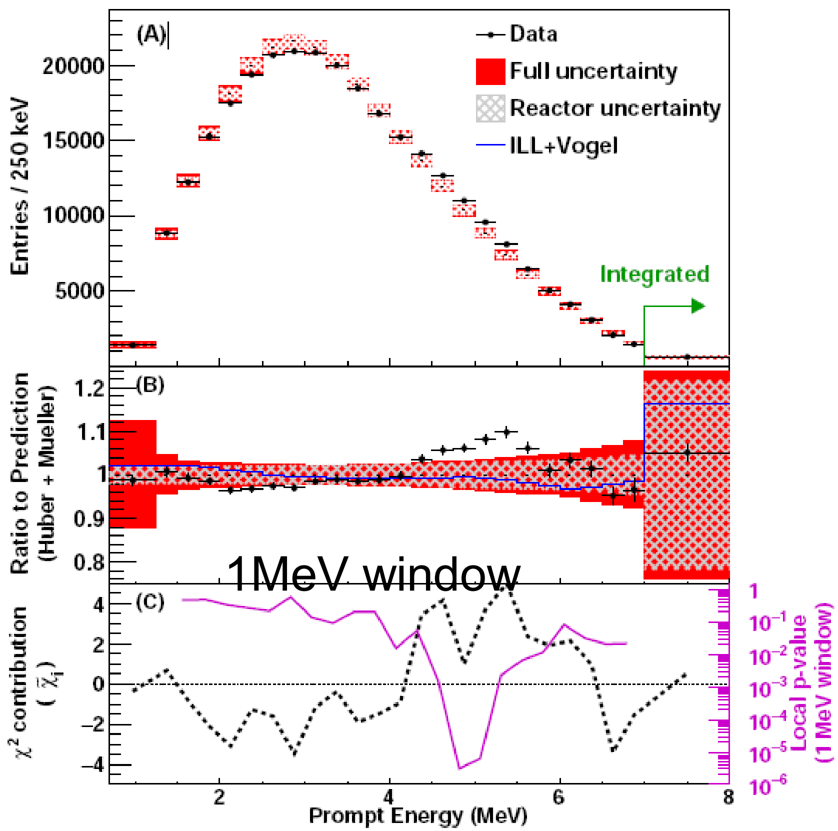


Jetter, Tau2014

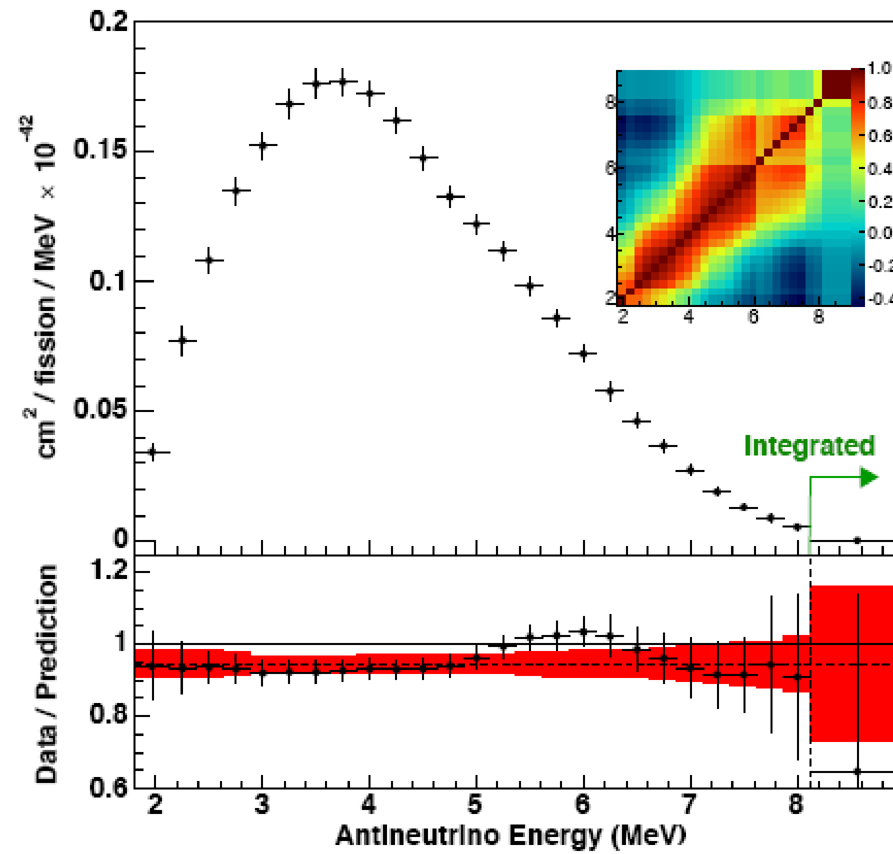
Measuring the spectrum

- Bump local significance ~ 4σ
- Unfolding the reactor neutrino spectrum
  - ⇨ Between 1.5 and 7MeV, it ranges from 1.0% at 3.5 MeV to 6.7% at 7 MeV, and above 7 MeV it is larger than 10%.

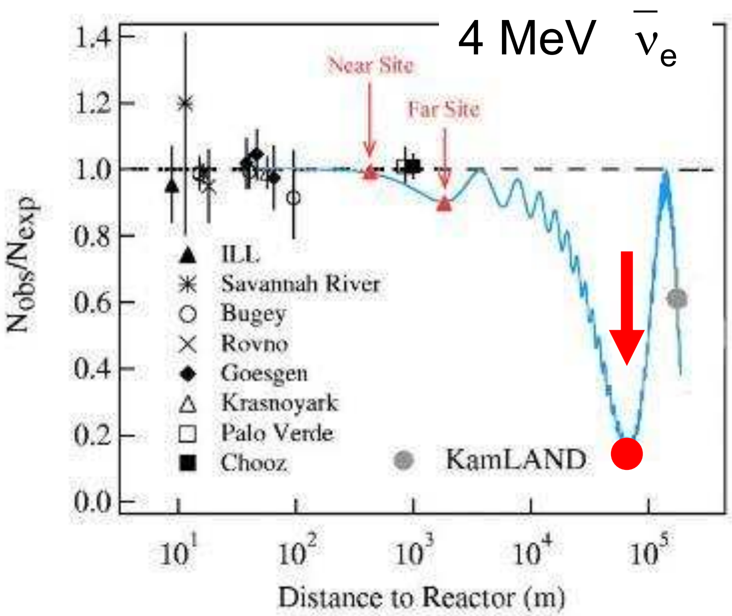
PRL 116, 061801 (2016)



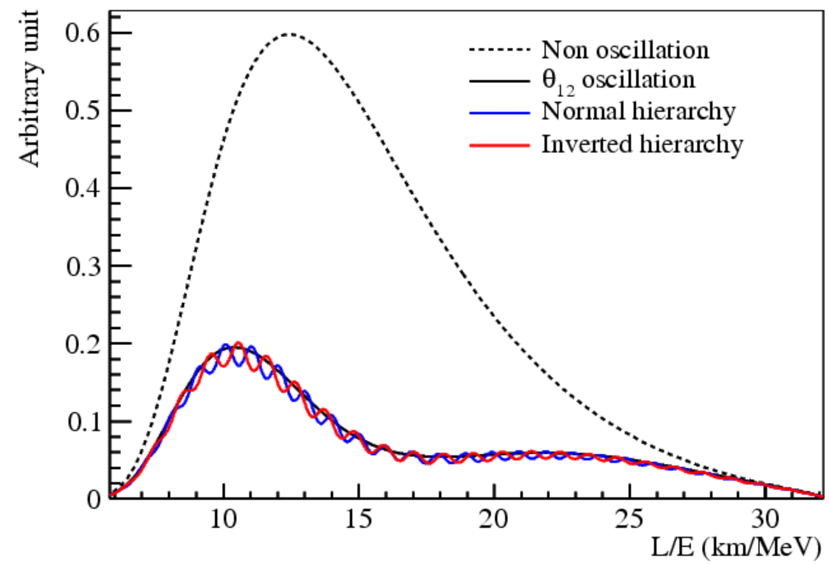
$^{235}U : ^{238}U : ^{239}Pu : ^{241}Pu \mid 0.586 : 0.076 : 0.288 : 0.050$



Determine MH with Reactors



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



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**

Δm^2_{31} and Δm^2_{32} Interference (ϕ)	Δm^2_{ee} and $\Delta m^2_{\mu\mu}$ difference	Matter Effect

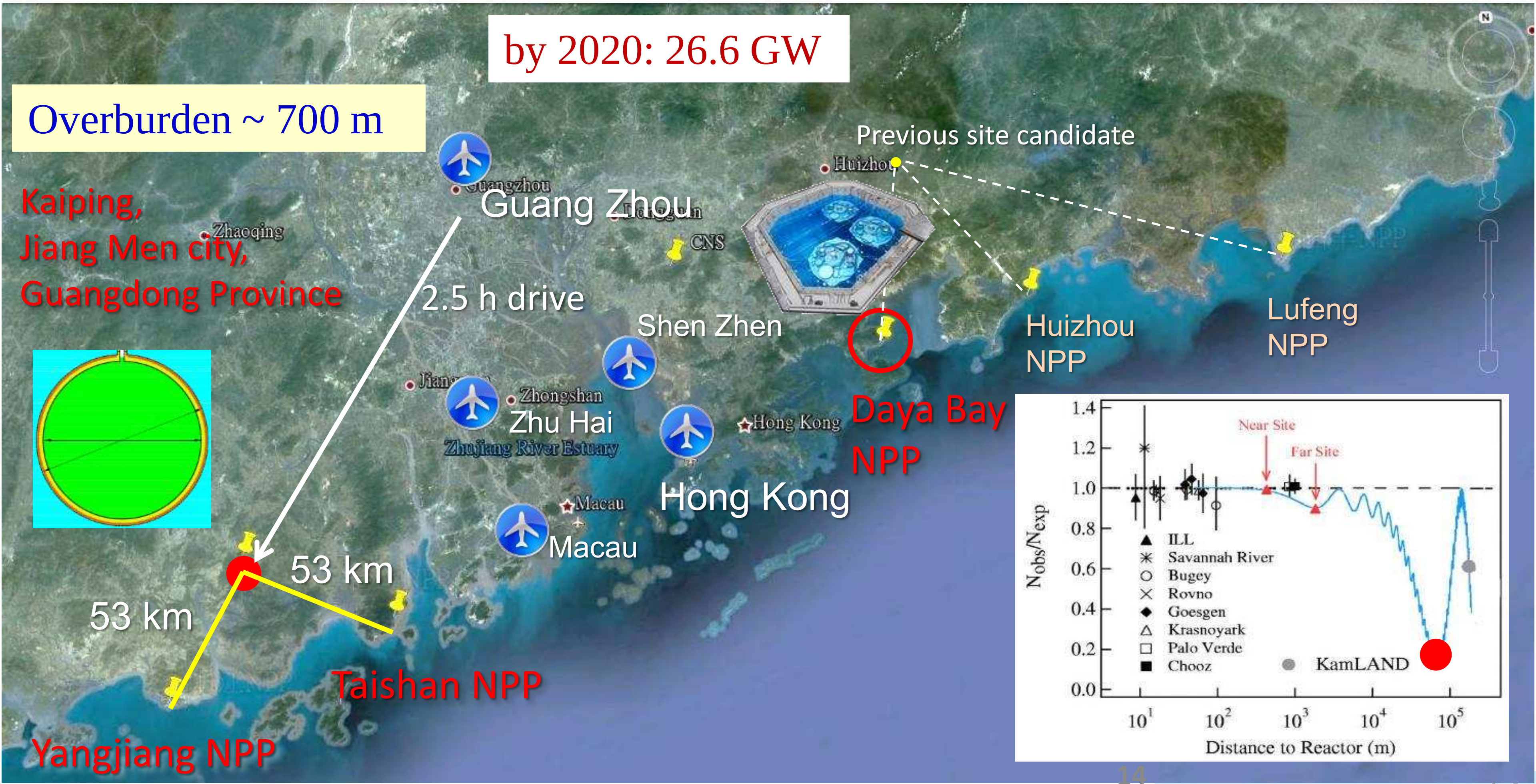
Reactor

atmospheric

Accelerator

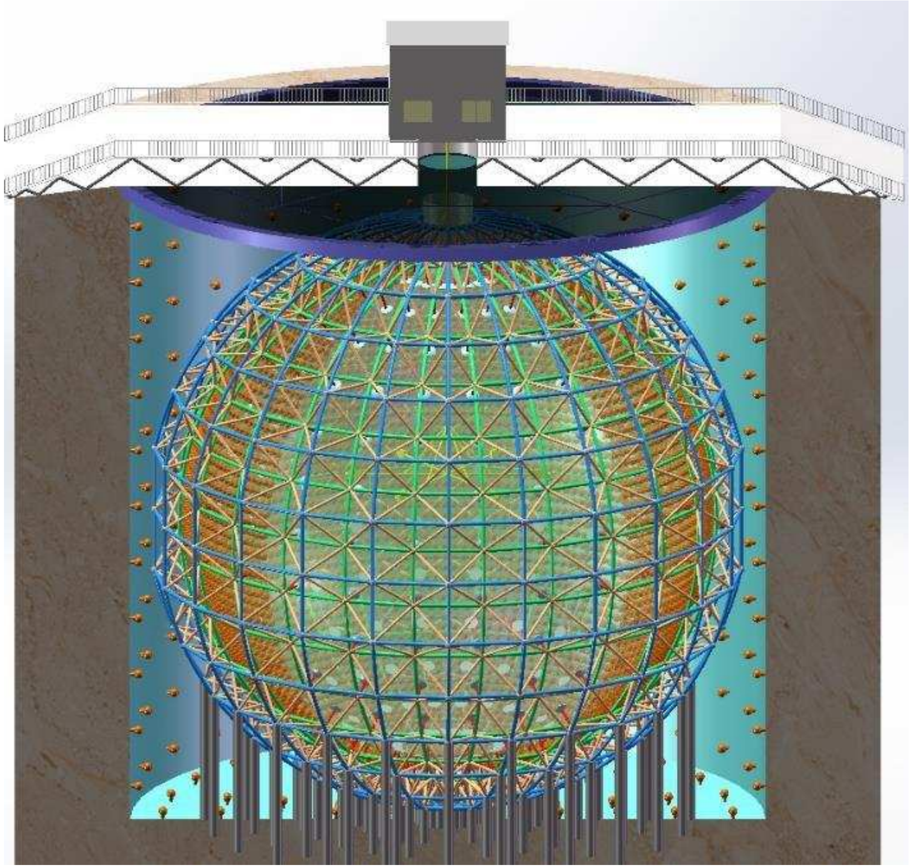
JUNO for Mass Hierarchy

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



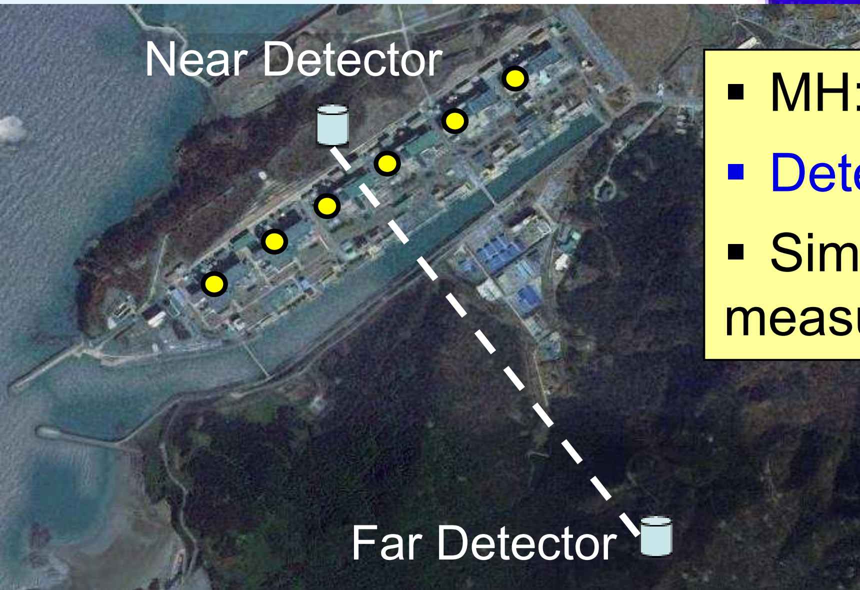
Rich Physics Program

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

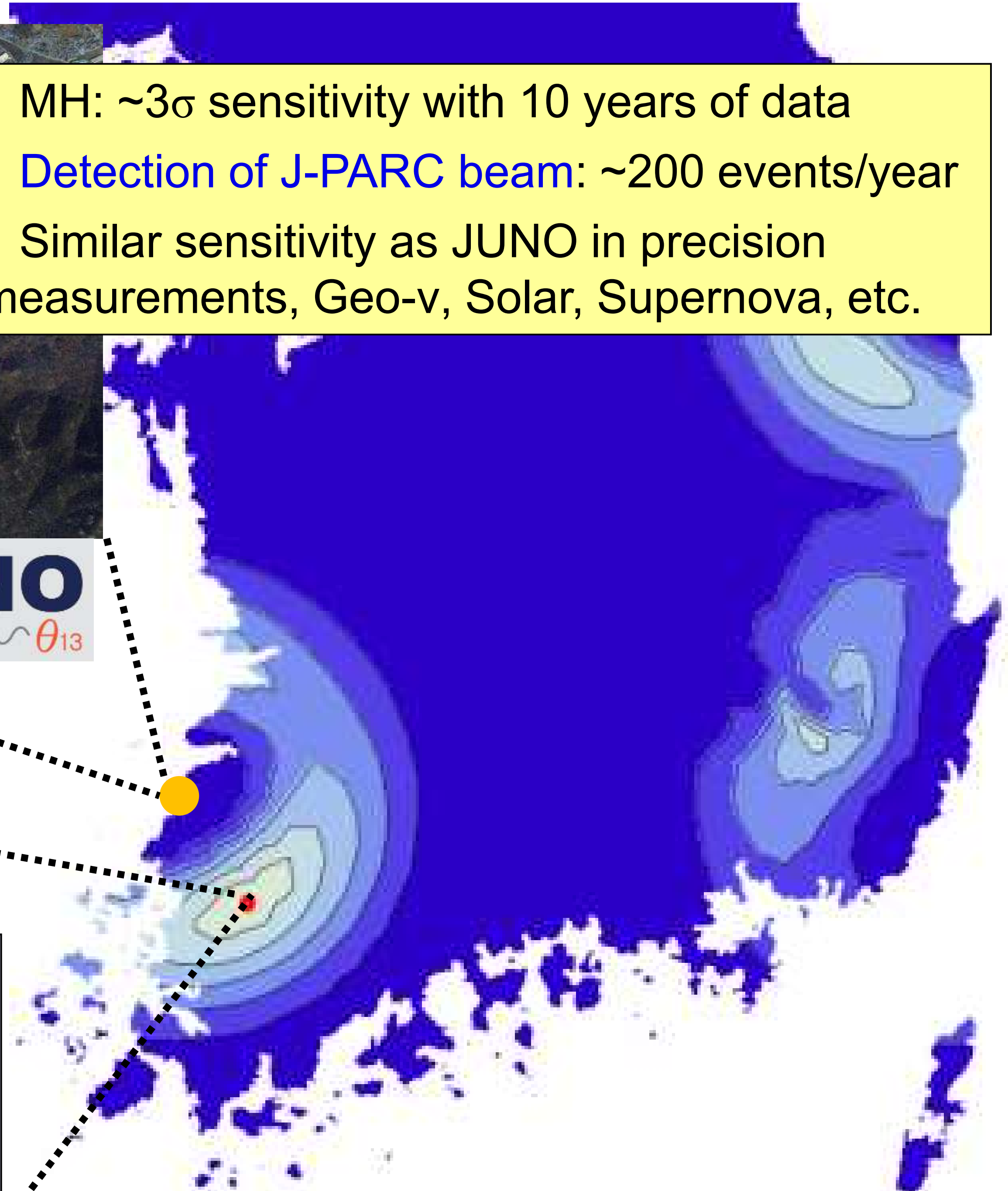


- **20 kton LS detector**
- **3% energy resolution**
- **700 m underground**
- **Rich physics possibilities**
  - **Reactor neutrino for Mass hierarchy and precision measurement of oscillation parameters**
  - **Supernovae neutrino**
  - **Geoneutrino**
  - **Solar neutrino**
  - **Atmospheric neutrino**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

Neutrino Physics with JUNO, J. Phys. G 43, 030401 (2016)



- MH: ~3σ sensitivity with 10 years of data
- Detection of J-PARC beam: ~200 events/year
- Similar sensitivity as JUNO in precision measurements, Geo-ν, Solar, Supernova, etc.



(NEAR Detector)

(FAR Detector)

RENO-50

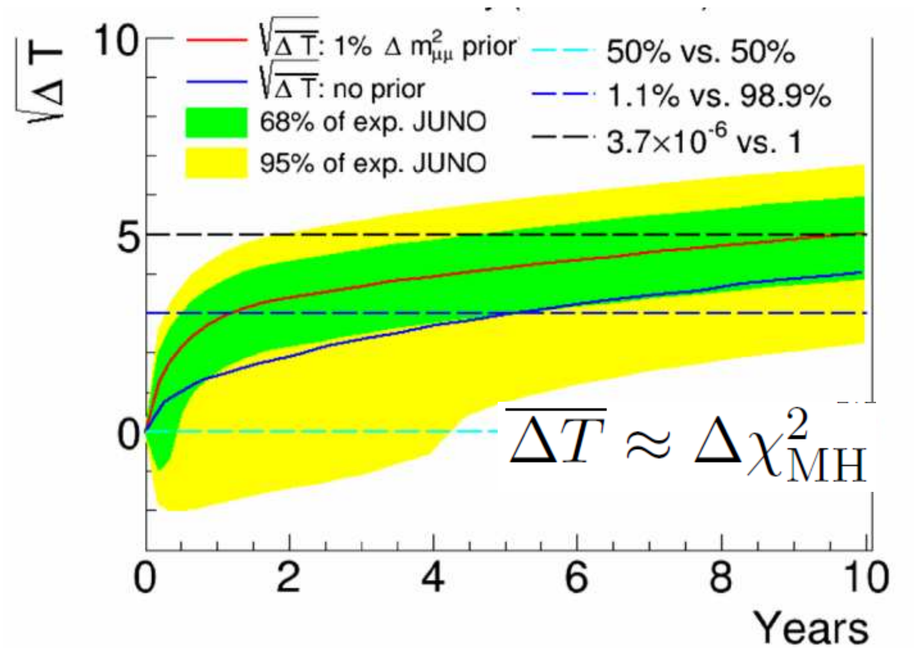
18 kton LS Detector
~47 km from YG reactors

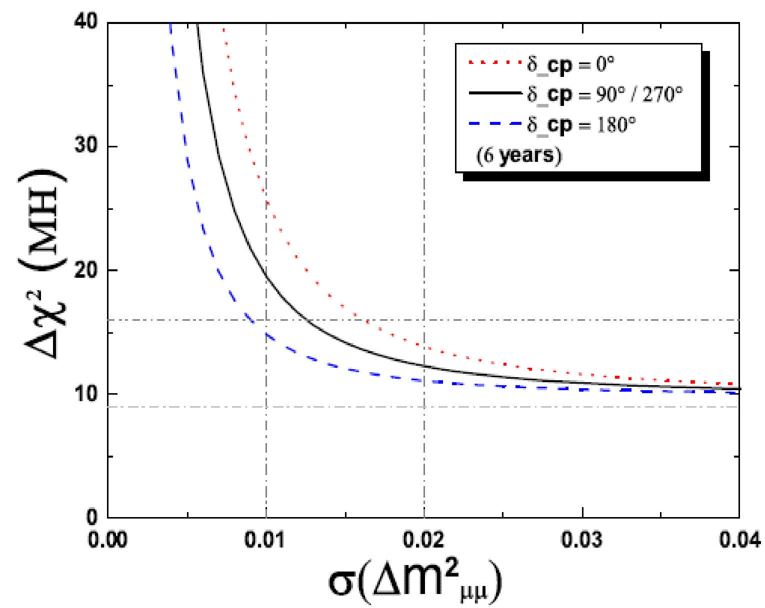
Mt. Guemseong (450 m)
~900 m.w.e. overburden

Sensitivity on MH

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

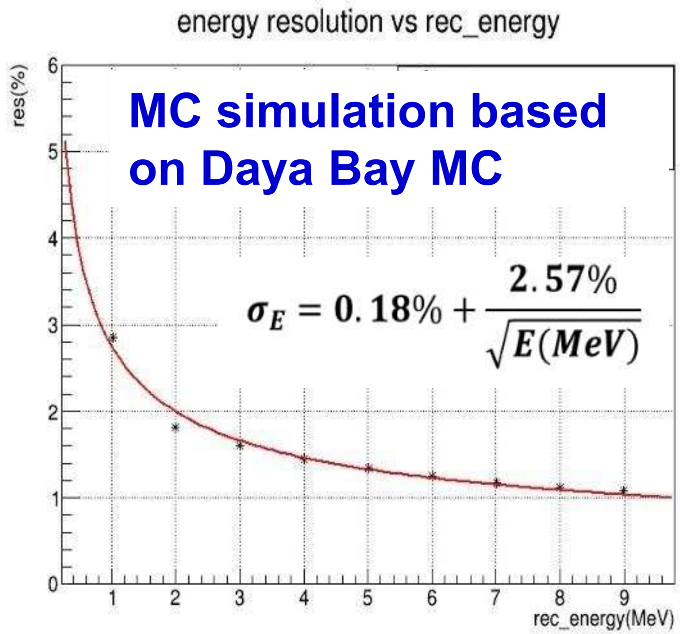
JUNO **MH sensitivity with 6 years' data:**





	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%
$\Delta\chi^2_{\mathrm{MH}}$	+16	−4	−1	−0.5	−0.1	+8

Challenges



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

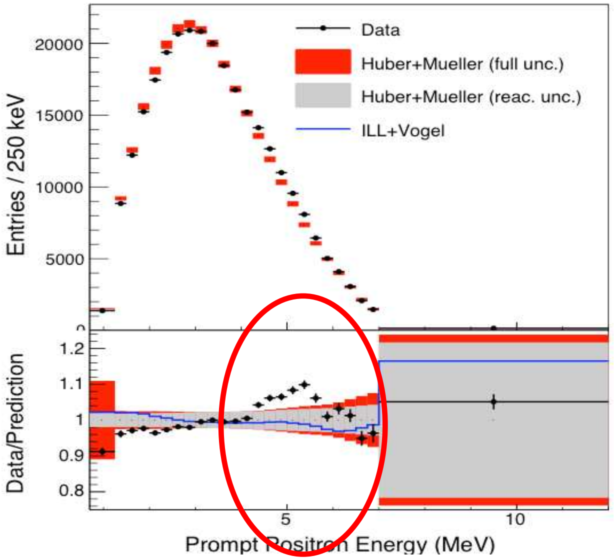
- Two Challenges:
  - ⇨ How good is the energy resolution
  - ⇨ How well we know the reactor spectrum
- Model prediction (2-10%) + energy nonlinearity (1-3%) from LS and electronics/readout
- Two approaches to mitigate the spectrum uncertainties
  - ⇨ Direct measurement of the spectrum to 1% by SBL reactor exp.
  - ⇨ Constraint from Daya Bay measurements, independent of models, similar LS and similar electronics → 1%

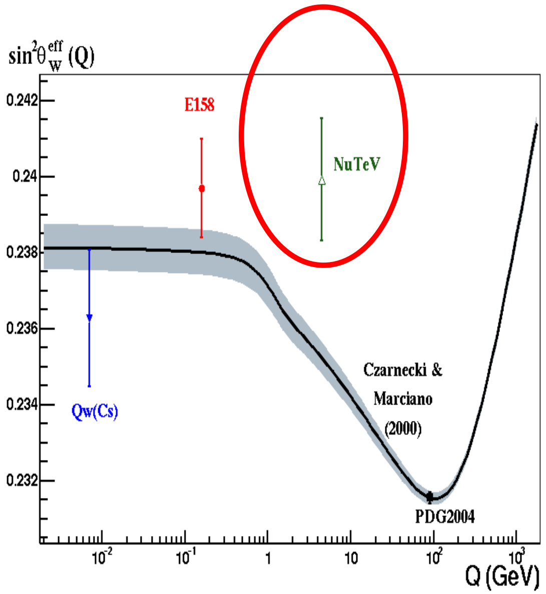
	KamLAND	BOREXINO	JUNO
LS mass	1 kt	0.5 kt	20 kt
Energy Resolution	$6\%/\sqrt{E}$	$5\%/\sqrt{E}$	$3\%/\sqrt{E}$
Light yield	250 p.e./MeV	511 p.e./MeV	1200 p.e./MeV

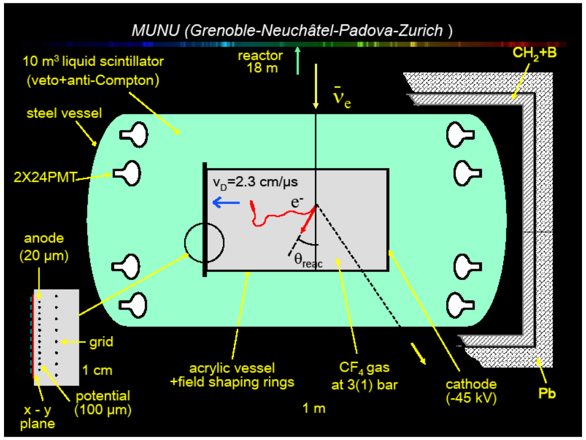
Short Baseline Exp. with Gas TPC

- Gas TPC detector at ~20 m from a reactor
  - ⇨ ν-e scattering
  - ⇨ High energy precision (<3%/sqrt(E))
- Major motivation: high precision reactor spectrum to 1%
  - ⇨ Input for JUNO. Daya Bay energy resolution 8%, JUNO 3%
- Other motivations:
  - ⇨ The weak mixing angle θw
  - ⇨ Abnormal magnetic moment
  - ⇨ Sterile neutrino

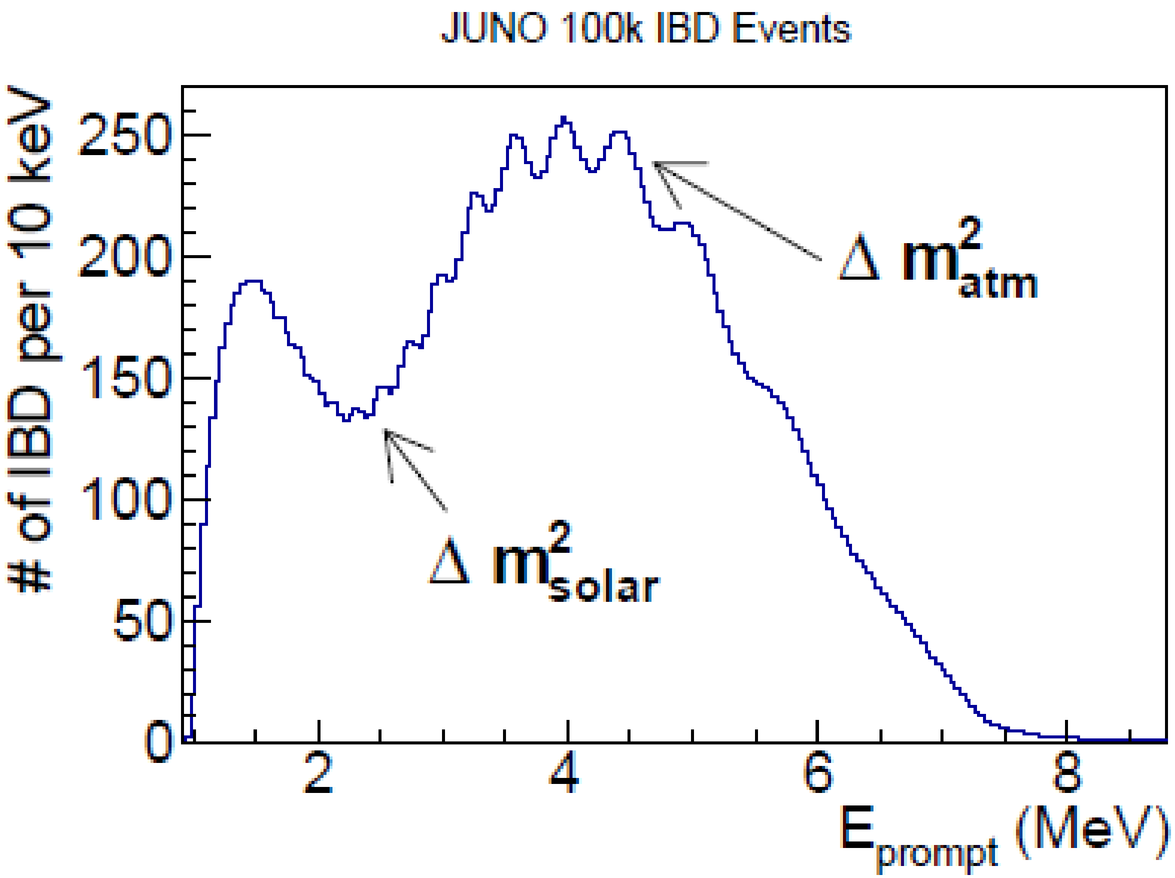
MUNU exp:
$\mu_\nu < 0.9 \times 10^{-10}\ \mu_B$
CF_4 , T > 700 keV
PLB 615(2005)153







Precision Measurements



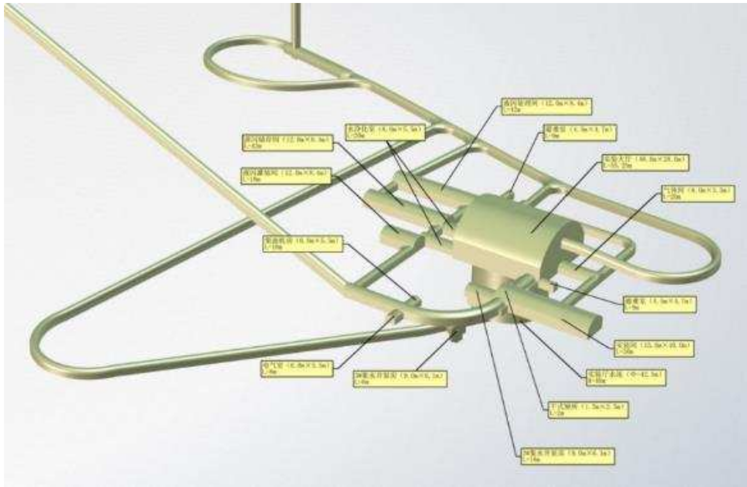
Smeared by 3%/sqrt(E)

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

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

JUNO Progress and Schedule

- **Ground breaking in Jan. 2015**
  - ⇨ **900 m slope tunnel excavated out of 1340 m**
  - ⇨ **330 m vertical shaft excavated out of 611 m**



Schedule:

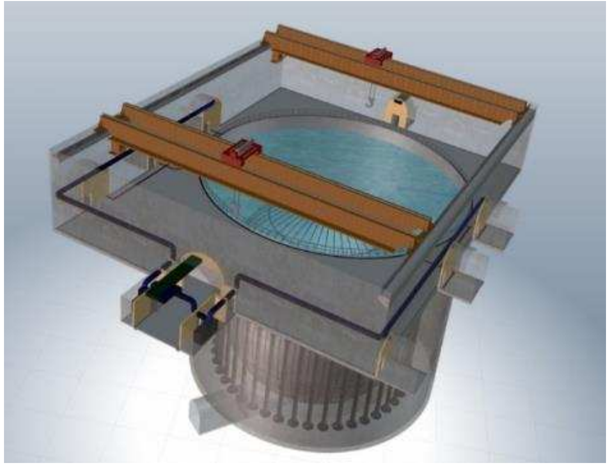
Civil preparation： 2013-2014

Civil construction： 2014-2017

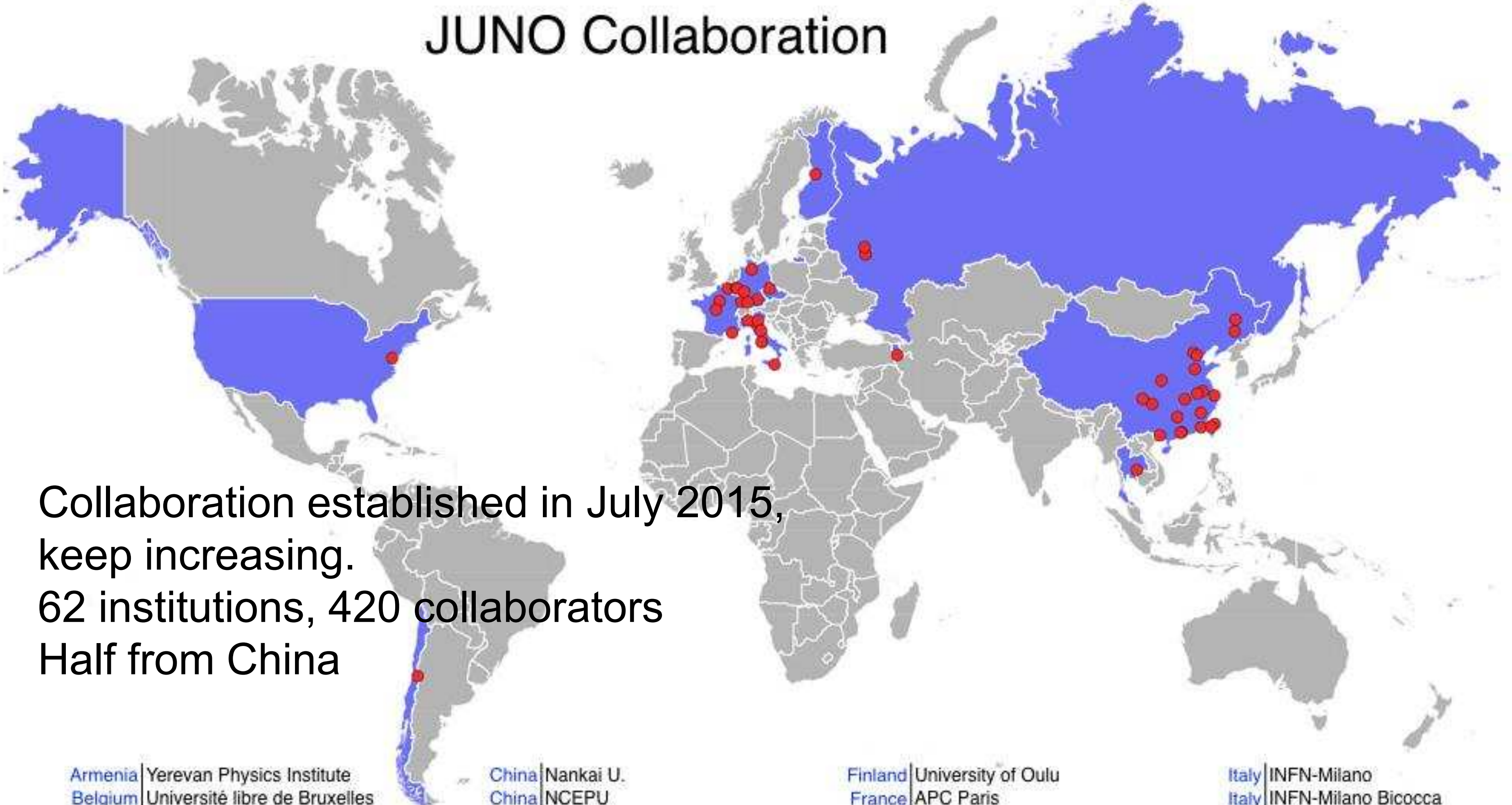
Detector component production： 2016-2017

Detector assembly & installation： 2018-2019

Filling & data taking： 2020



JUNO Collaboration

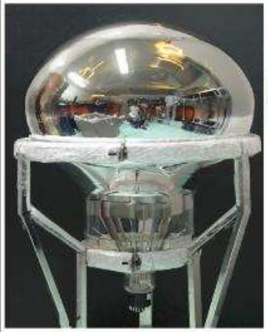
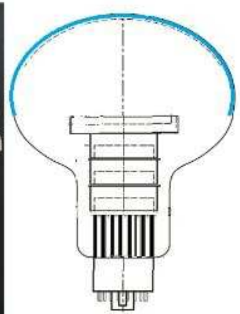
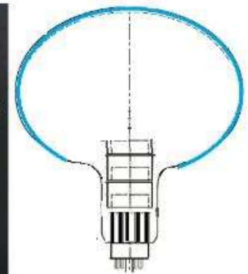


Collaboration established in July 2015,
keep increasing.
62 institutions, 420 collaborators
Half from China

Armenia	Yerevan Physics Institute
Belgium	Université libre de Bruxelles
Chile	PCUC
China	BISEE
China	Beijing Normal U.
China	CAGS
China	ChongQing University
China	CIAE
China	DGUT
China	ECUST
China	Guangxi U.
China	Harbin Institute of Technology
China	IHEP
China	Jilin U.
China	Jinan U.
China	Nanjing U.
China	Nankai U.
China	NCEPU
China	Pekin U.
China	Shandong U.
China	Shanghai JT U.
China	Sichuan U.
China	SYSU
China	Tsinghua U.
China	UCAS
China	USTC
China	U. of South China
China	Wu Yi U.
China	Wuhan U.
China	Xi'an JT U.
China	Xiamen University
Czech	R. Charles U. Prague
Finland	University of Oulu
France	APC Paris
France	CPPM Marseille
France	IPHC Strasbourg
France	LLR Palaiseau
France	Subatech Nantes
Germany	ZEA FZ Julich
Germany	RWTH Aachen U.
Germany	TUM
Germany	U. Hamburg
Germany	IKP FZ Jülich
Germany	U. Mainz
Germany	U. Tuebingen
Italy	INFN Catania
Italy	INFN di Frascati
Italy	INFN-Ferrara
Italy	INFN-Milano
Italy	INFN-Milano Bicocca
Italy	INFN-Padova
Italy	INFN-Perugia
Italy	INFN-Roma 3
Russia	INR Moscow
Russia	JINR
Russia	MSU
Taiwan	National Chiao-Tung U.
Taiwan	National Taiwan U.
Taiwan	National United U.
Thailand	SUT
USA	UMD1
USA	UMD2

Civil Progress

Highlights: 20” PMT bidding

20-inch Hamamatus PMT Dynode Ellipsoidal Glass	20-inch IHEP MCP-PMT Horizontal MCPs Ellipsoidal Glass
 	 
HQE 1#, 2#, 3#	76#, 77#, 78#, 79#

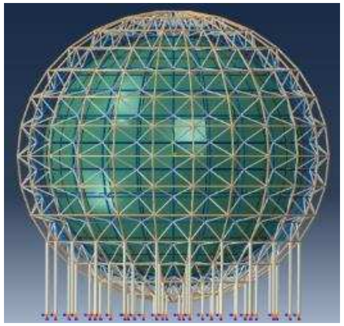
Evaluate both the PMT characteristics’ impacts on MH hierarchy and the cost.

Finished 20” PMT bidding at end of 2015:
-- 15000 MCP-PMT (NNVT)
-- 5000 Dynode-PMT (Hamamatsu)

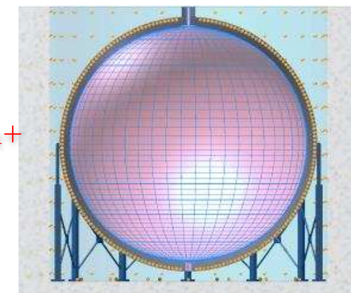
	unit	MCP-PMT（IHEP）	R12860 （Hamamatsu）
Electron Multiplier	--	MCP	Dynode
Photocathode mode	--	reflection+ transmission	transmission
Quantum Efficiency（400nm）	%	26 (T), 30 (T+R)	30(T)
Relativity Detection Efficiency	%	~ 110%	~ 100%
P/V of SPE		＞3	＞3
TTS on the top point	ns	~12	~3
Rise time/ Fall time	ns	R~2 , F~10	R~7 , F~17
Anode Dark Count	Hz	~30K	~30K
After Pulse Time distribution	us	4.5	4, 17
After Pulse Rate	%	3	10
Glass	--	Low-Potassium Glass	HARIO-32

Highlights: Central Detector Design

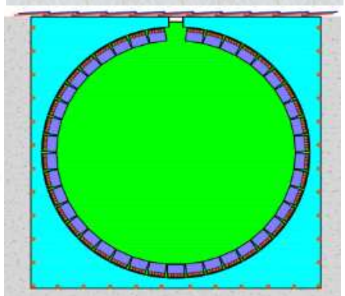
Acrylic sphere+ SS truss



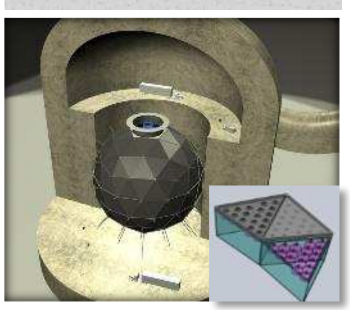
Balloon+ SS tank



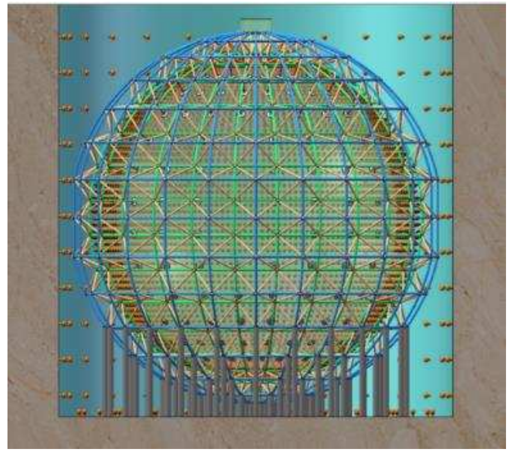
Acrylic module+ SS tank



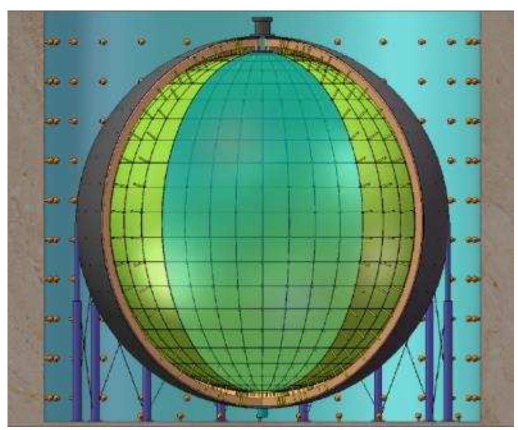
Acrylic sphere+ SS tank



March, 2014

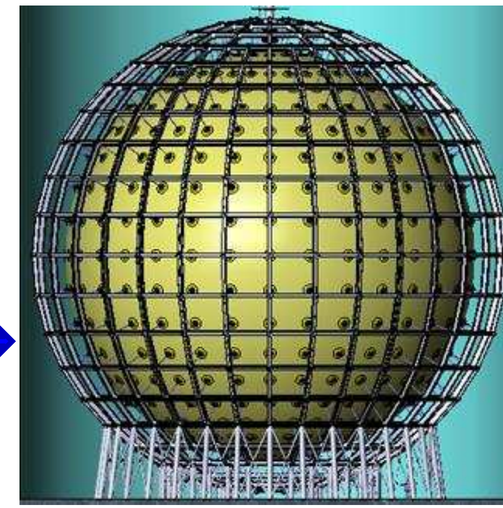


SS truss+ Acrylic sphere



Balloon + Acrylic support+ SS tank

July, 2015



Final decision:
Acrylic sphere + SS truss

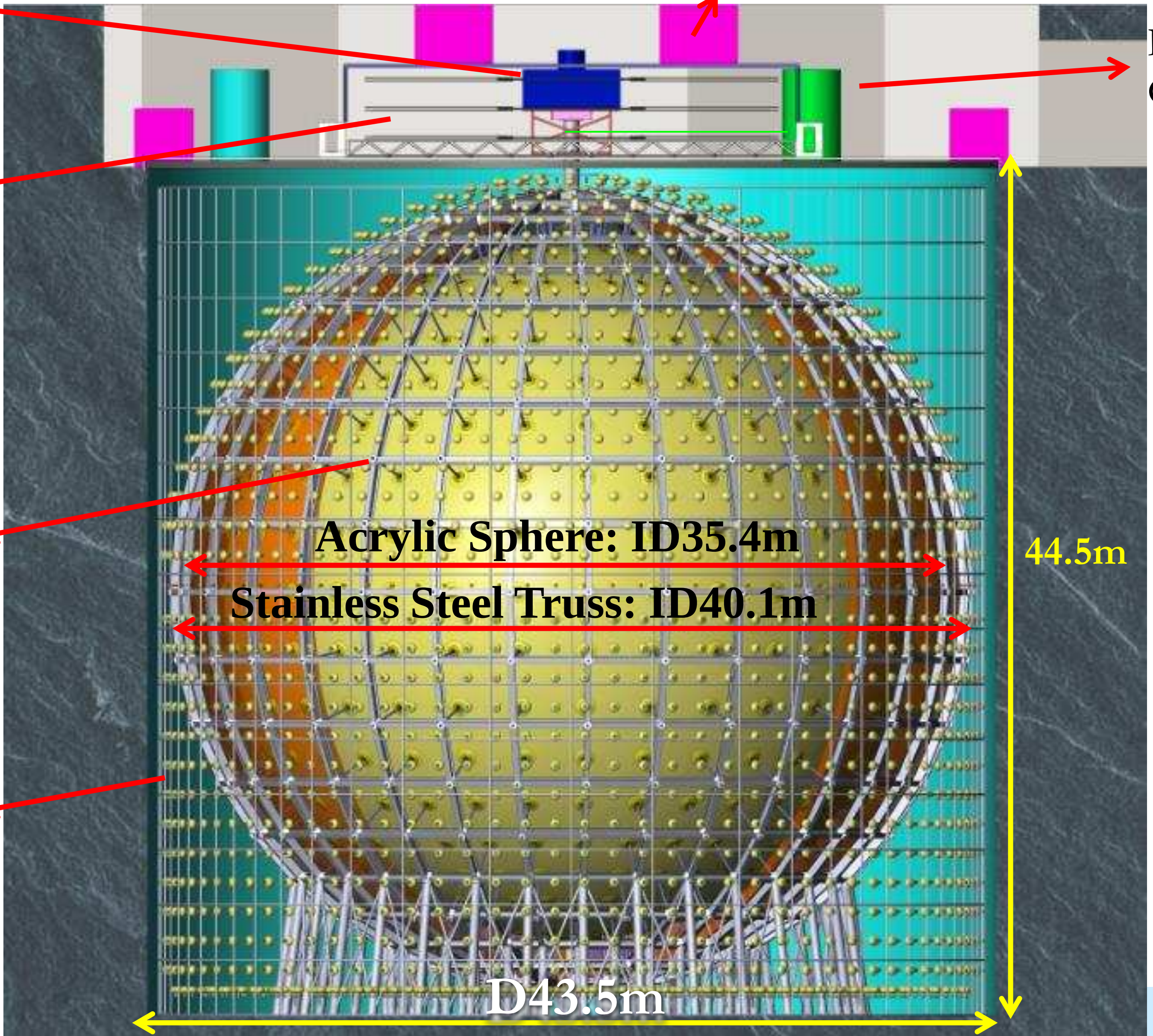
Highlights: Finalizing Detector Dimension

Calibration

Electronics

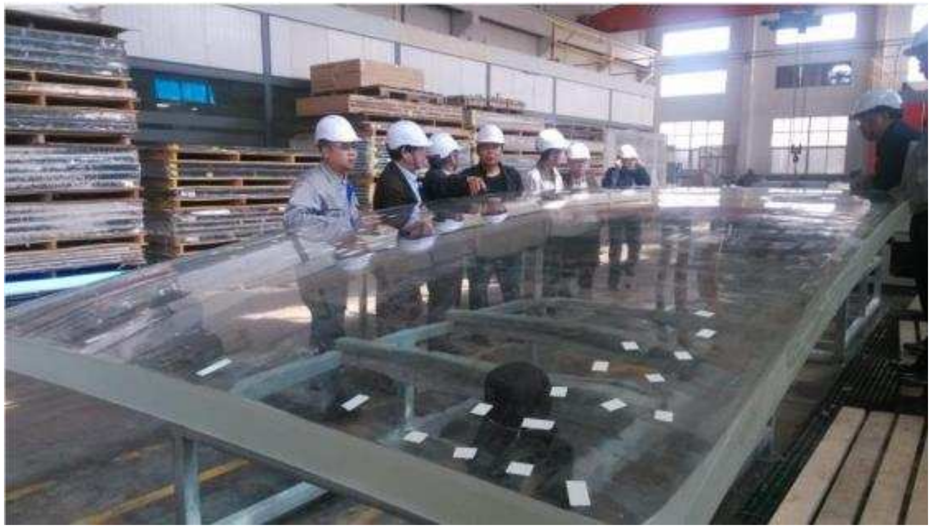
Filling +
Overflow

Top Tracker

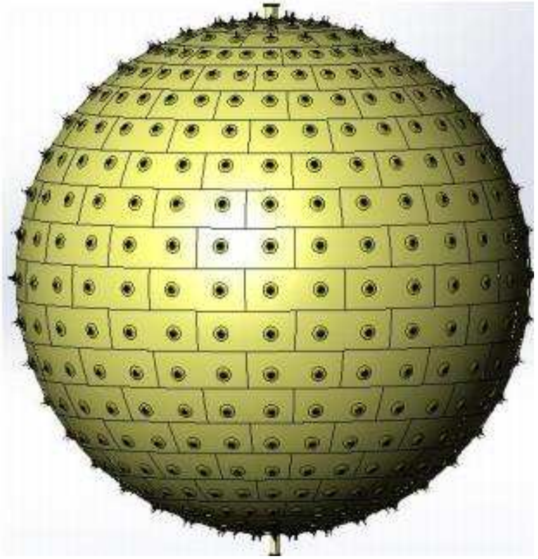


Central detector
Acrylic sphere+
20kt Liquid Scin+
~17000 20" PMT+
~34000 3" PMT
Water Cherenkov
~2000 20" PMT

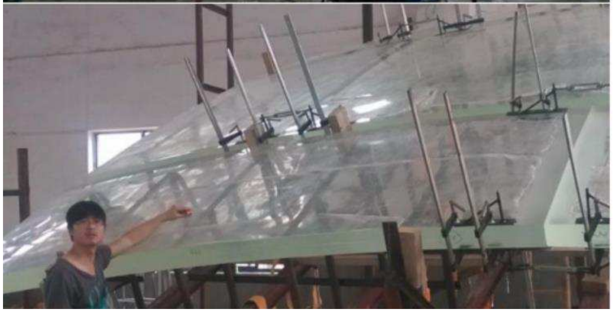
Highlights: Acrylic Sphere R&D



Forming panel size: 3m x 8m x 120mm



Acrylic divided into 200+ panels



Prototype of spherical panel

The problems of shrinkage and shape variation were resolved.

Three companies had good practices.

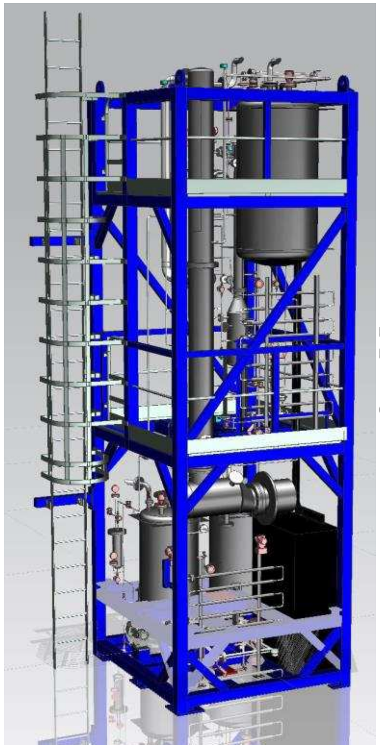
Highlights: LS Pilot plant

- Purify 20 ton LAB to test the overall design of purification system at Daya Bay. Replace the target LS in one detector
- Quantify the effectivities of subsystems
  - Optical : >20m A.L @430nm?
  - Radio-purity: 10^{-15} g/g (U, Th) ?
- Determine the choice of sub-systems
  - Al_2O_3 column, distillation, gas striping, water extraction

Distillation and steam stripping system (by Italian group).

Installed at Daya Bay

Distillation system



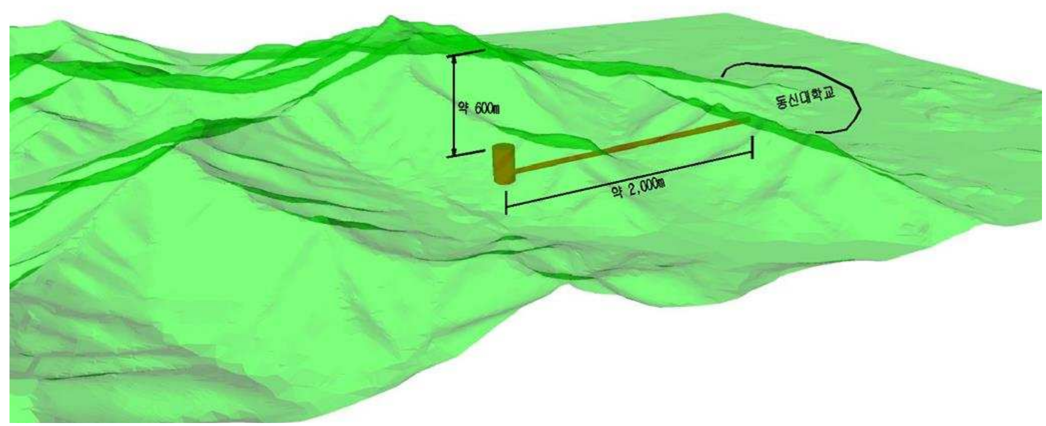
Steam stripping system

Al_2O_3 column pilot plant installed in Daya Bay LS hall

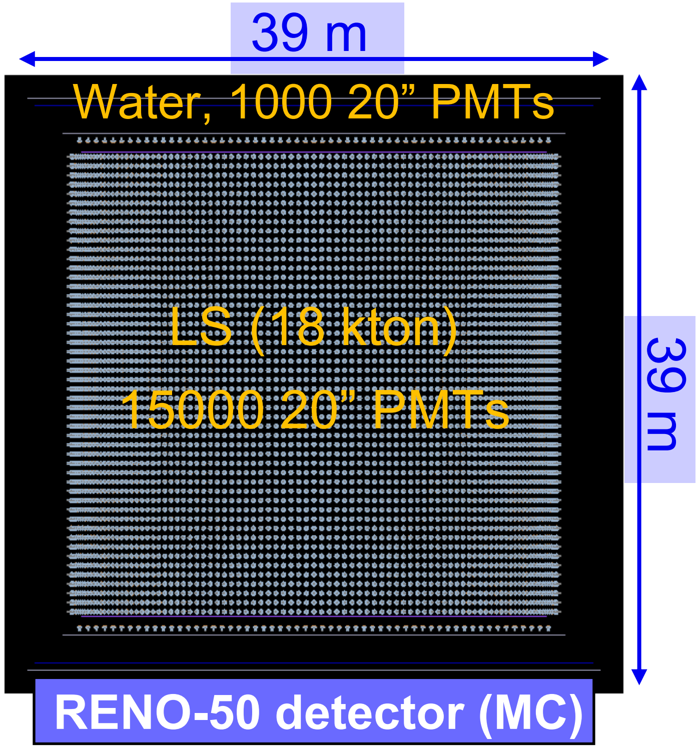
RENO-50 Schedule

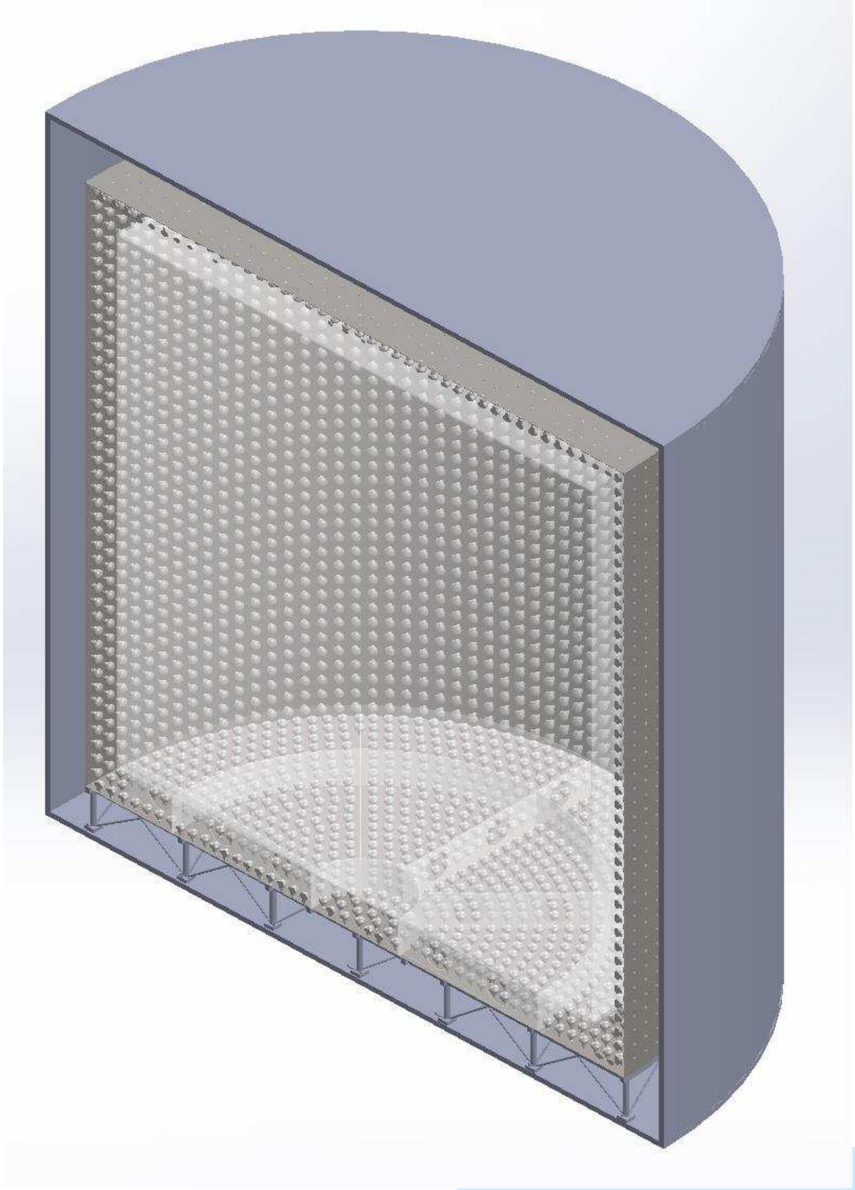
- **Budget : $ 100M for 6 year (Civil engineering: $ 15M, Detector: $ 85M)**
- **R&D supported by Samsung (2M$ for 2015-2017)**
- **Efforts on obtaining a full construction fund**
- **Schedule**
  - ⇨ **2016-2021: Facility and detector construction**
  - ⇨ **2022~ Operation**

- Geological survey for design of tunnel and experimental hall
- Cost estimation to be obtained soon



Conceptual Design of RENO-50 Detector





RENO R&D

(1) Development of DAQ electronics

- Specification for *dead time free, high sensitivity and high speed signal processing.* Prototype boards to be tested

(2) Develop techniques of LS purification

- Reduction of LS radioactivity to 10^{-16} g/g of U and Th
- Removal of LS impurities for attenuation length of ~25 m

(3) Mechanical design of detector

- Detailed drawing of mechanical parts in progress

(4) Measurement of radioactivity for the detector materials

- Evaluate radioactivity of detector parts using HPGe

(5) Measurement device for absolute LS attenuation length

- Developed a long pipe device with a laser source and a PMT

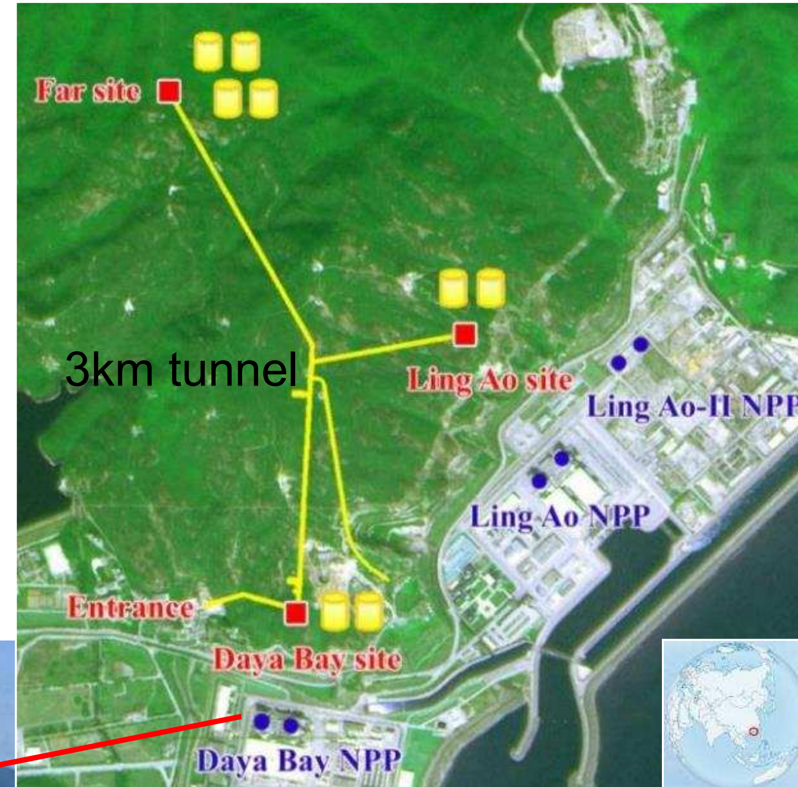
Summary

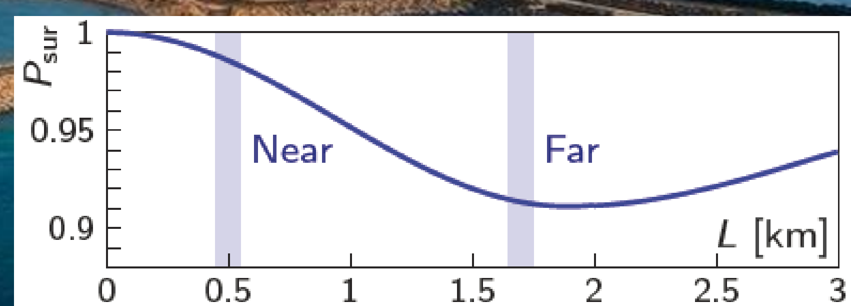
- Significant improvement on $\sin^2 2\theta_{13}$ precision from the Daya Bay, Double Chooz and RENO experiments. Ultimate precision will reach ~3%.
- Precision measurement of the absolute neutrino flux and spectrum.
- JUNO and RENO-50 will measure Mass hierarchy (3-4 σ in 2026) and 3 mixing parameters up to < ~1% level.
- JUNO construction and R&D are on schedule, aiming at data taking in 2020.
  - Many R&D accomplishments such as PMT bidding, detector design and R&D, LS pilot, Electronics, etc.
- RENO-50 has R&D funding and works for full funding, aiming at data taking in 2022.

Thanks !

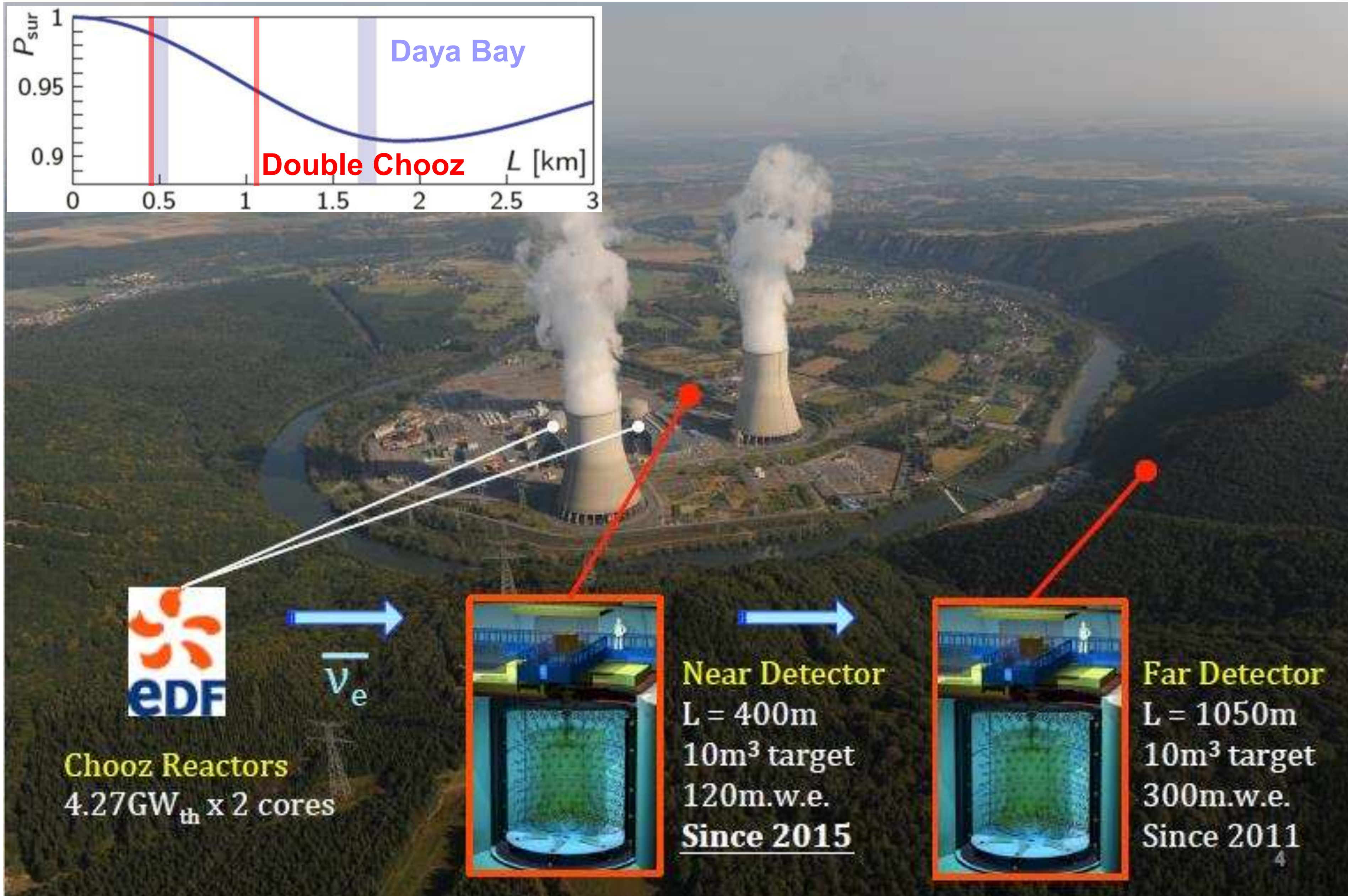
The Daya Bay Experiment

- 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

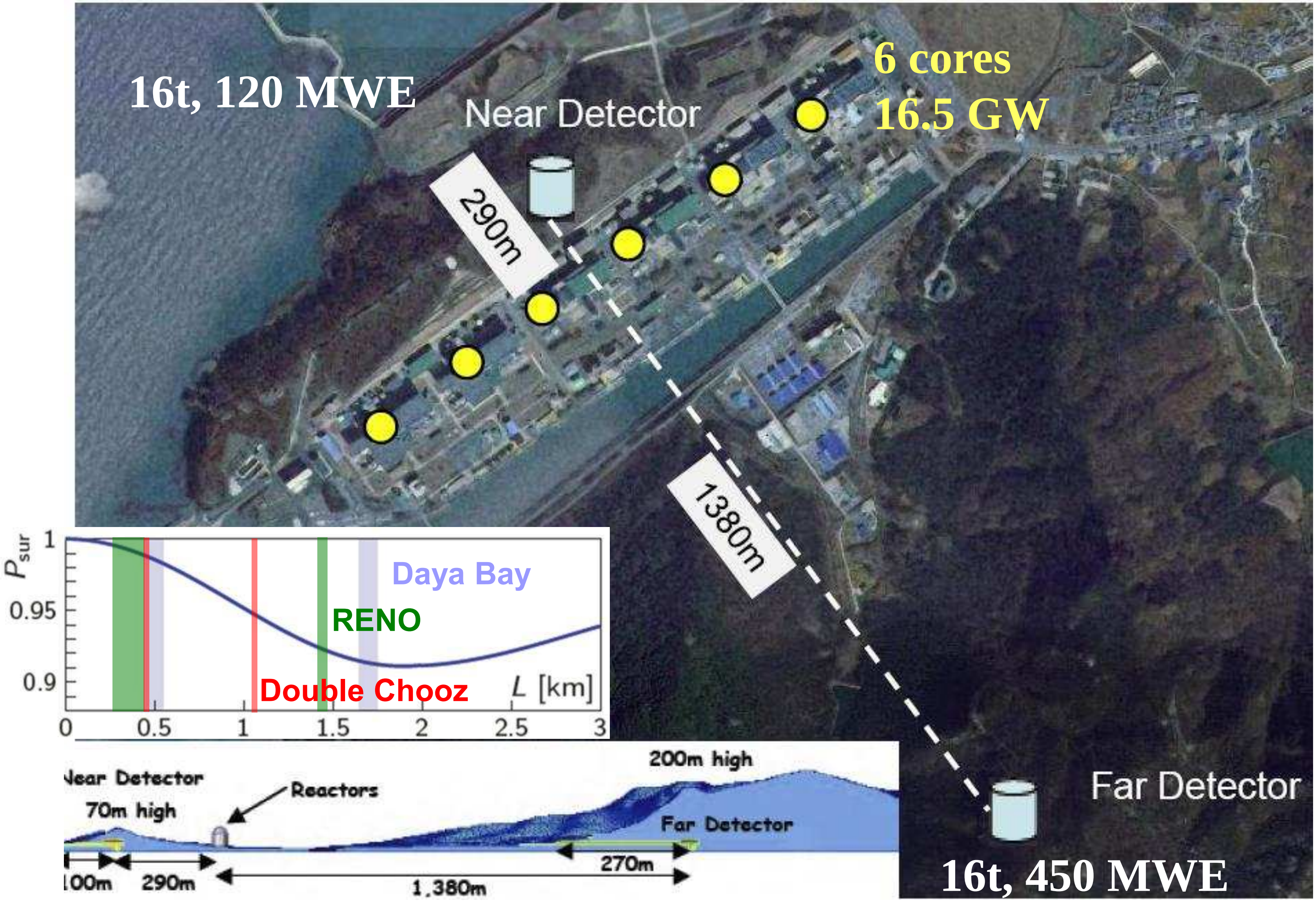




Double Chooz



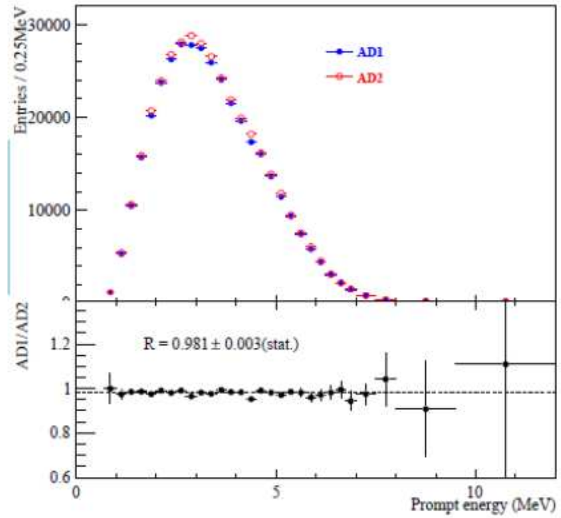
RENO

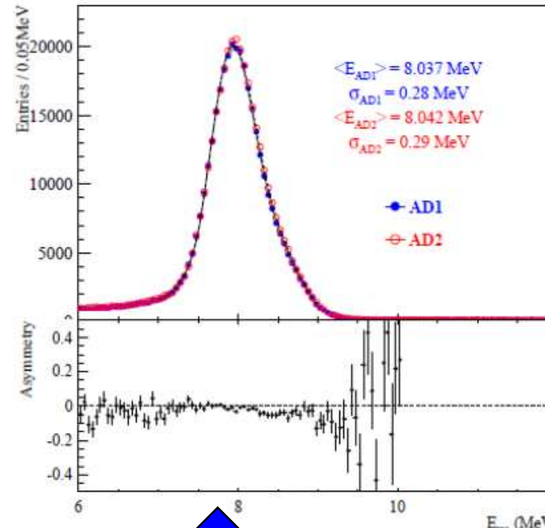


16t, 120 MWE
Near Detector
6 cores
16.5 GW
290m
1380m
Far Detector
16t, 450 MWE
P_{sur}
1
0.95
0.9
0
0.5
1
1.5
2
2.5
3
Daya Bay
RENO
Double Chooz
L [km]
Detector
70m high
Reactors
200m high
Far Detector
100m
290m
270m
1,380m

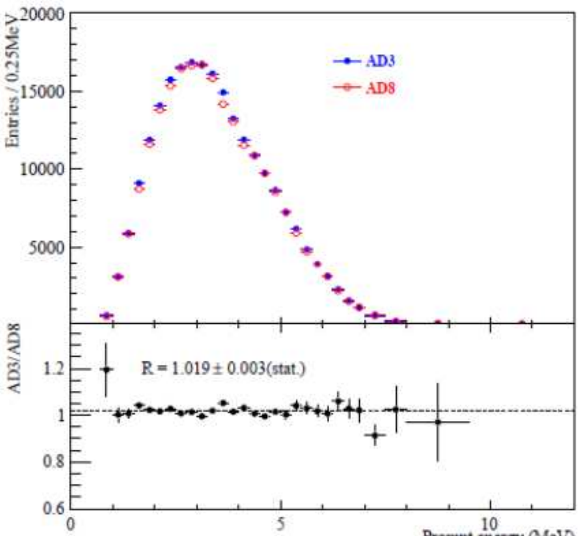
Systematics at Daya Bay

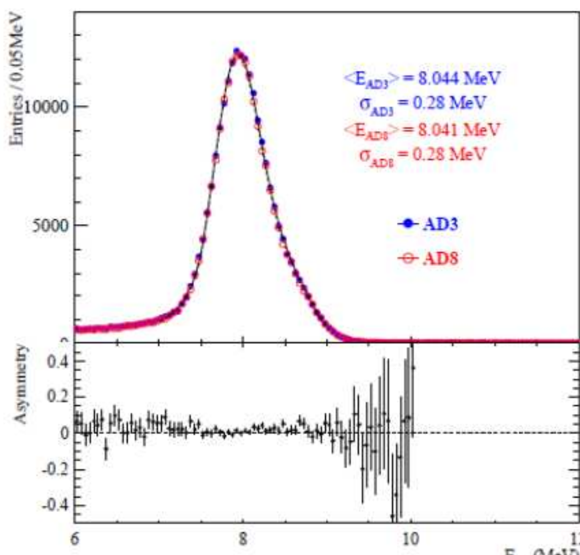
- **Side-by-side calibration: Multiple detectors at near sites**





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

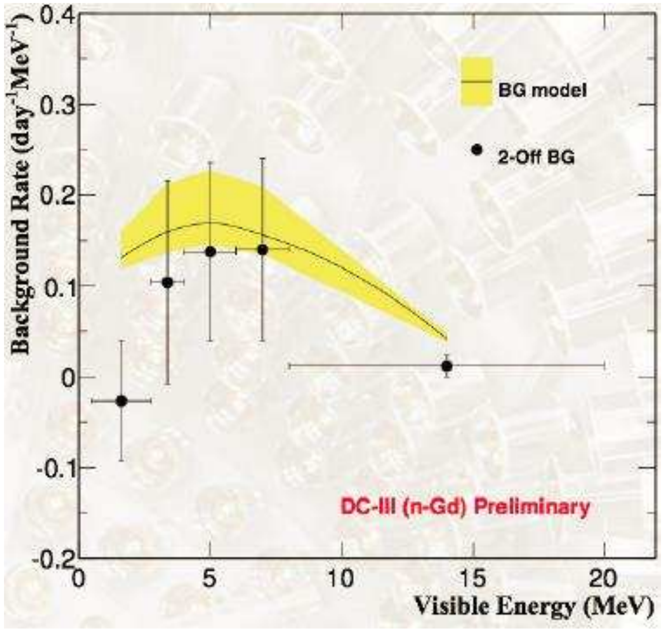


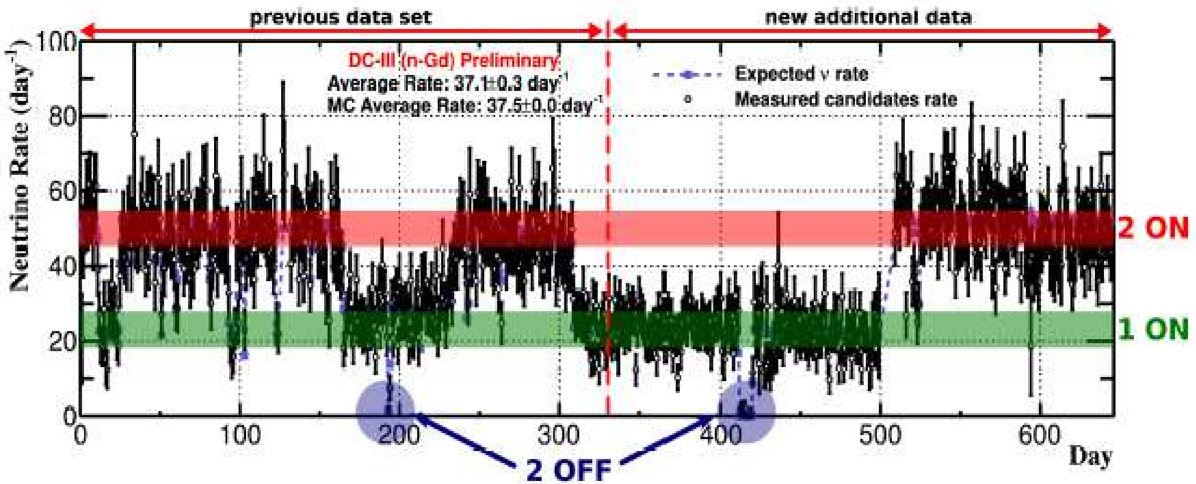


AD3/AD8 (8AD data)
Expected: 1.012
Measured: 1.019 ± 0.004

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