Present Status of Reactor Neutrino Experiments

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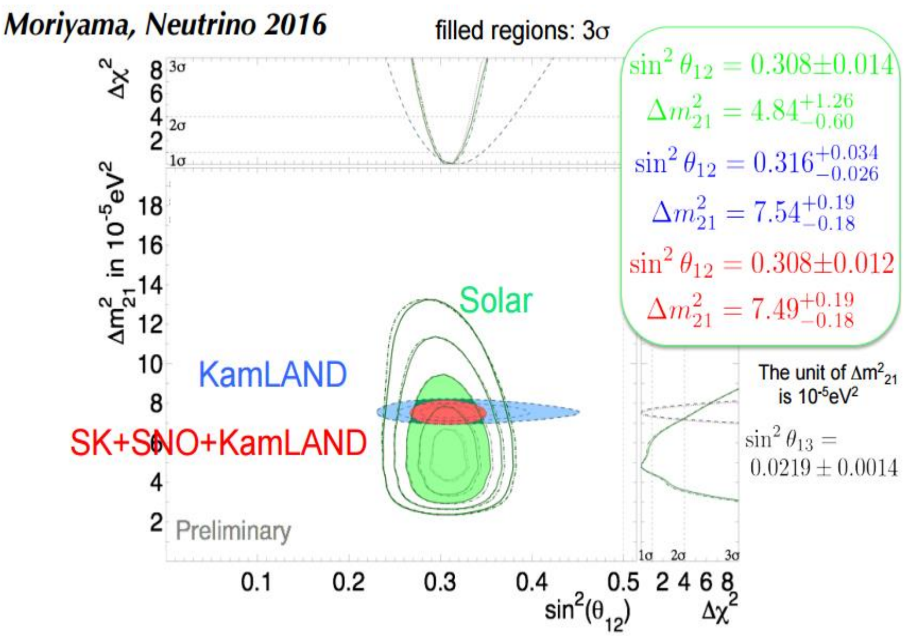
Outline

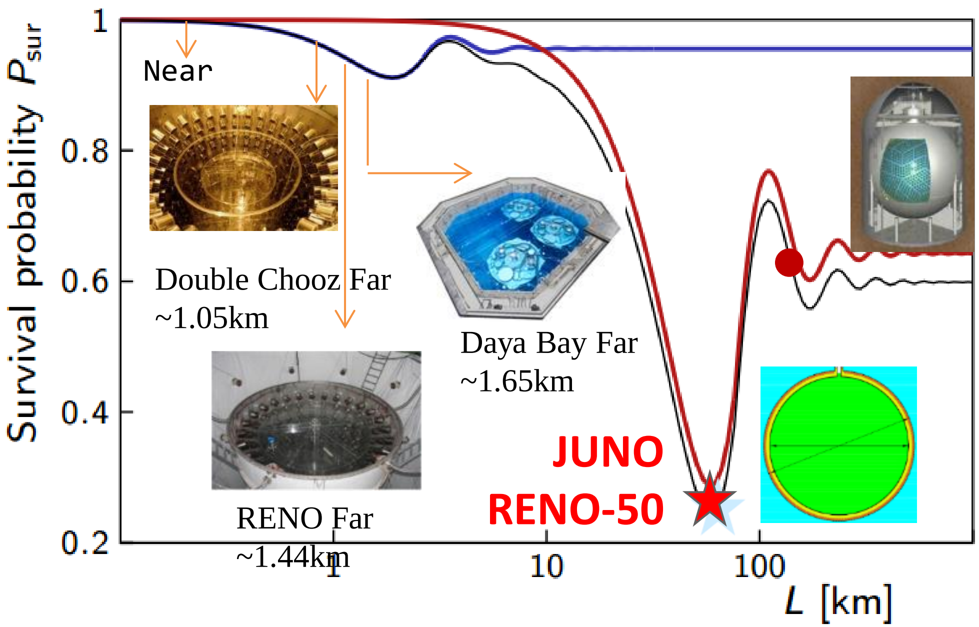
- **Very short baseline O(1m~10m) experiments will not be covered in this talk.**
- **A brief summary on short baseline (~1 to 2km) reactor neutrino experiments**
  - **Daya Bay, Double Chooz, RENO**
- **Focus on medium baseline (~50km) reactor neutrino experiments**
  - **JUNO**
  - **RENO-50**

Reactor ν: one of ways to understand ν nature

- **KamLAND+Solar provide the best measurement for θ_{12} and Δm^2_{21}.**
- **In 2012, the last unknown mixing angle θ_{13} was determined to be surprisingly large ~ 9° by the Daya Bay, as well as RENO and Double Chooz.**

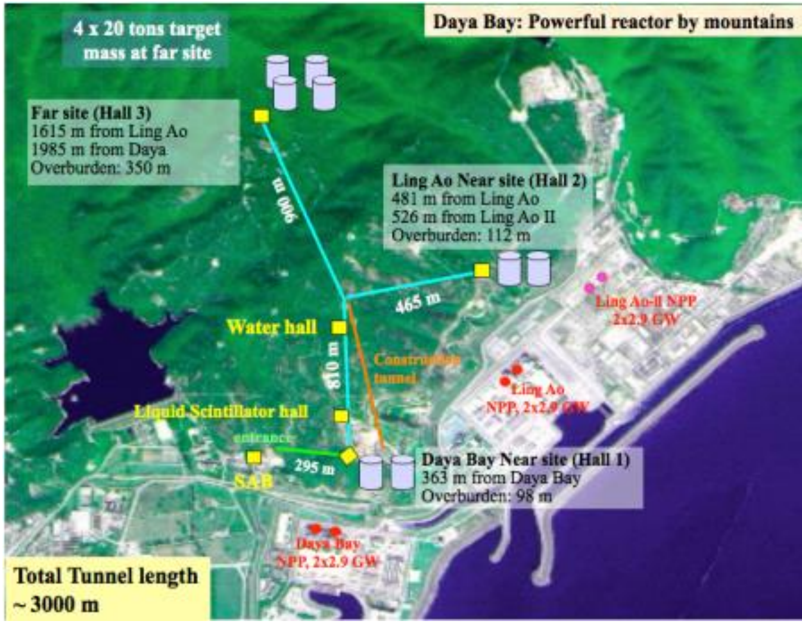


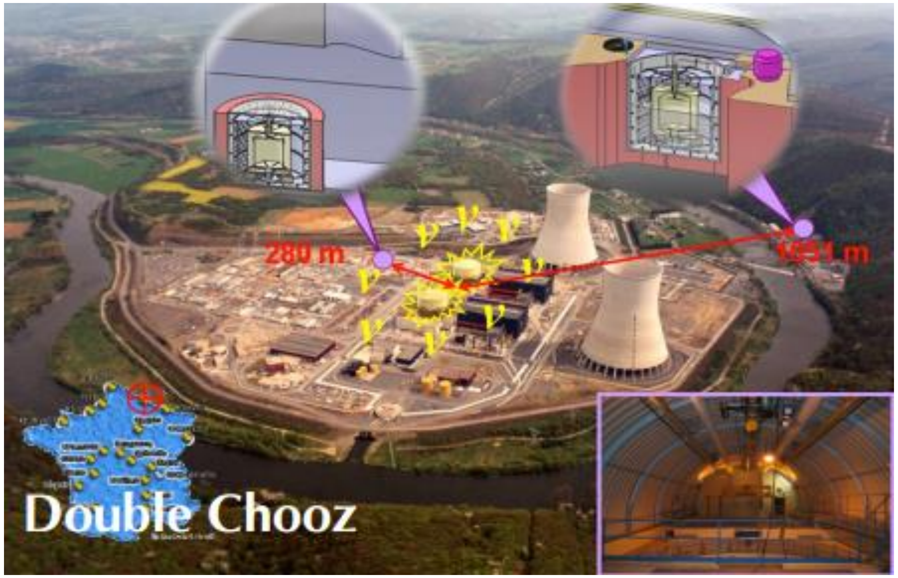
- **Determining Mass Hierarchy & precision measurement of θ_{12}, Δm^2_{21} and Δm^2_{31}**
  - **JUNO**
  - **RENO-50**



Keys in θ_{13} measurements

- **Powerful reactor complexes and large target mass** → large statistics.
- **Near-Far identically designed detectors** → reactor flux uncertainty cancellation.
- **Underground** → reduce backgrounds from cosmic rays.
- **Gd-doped liquid scintillator** → powerful radioactivity background rejection.





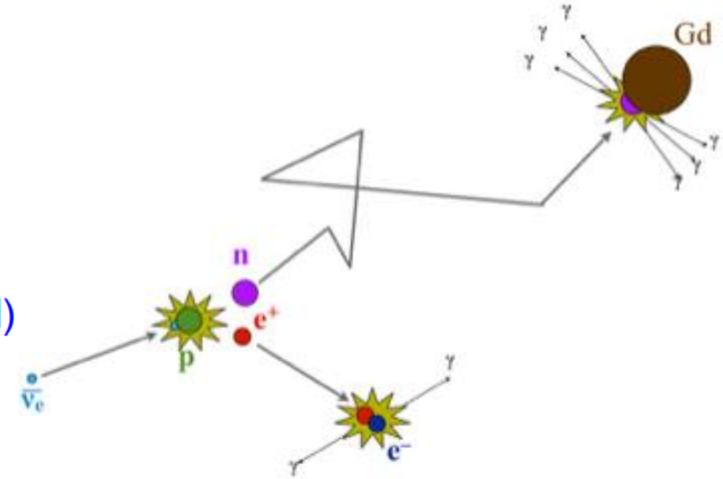
Antineutrinos are detected via the Inverse Beta Decay (IBD) reaction

$\overline{\nu}_e + p \rightarrow e^+ + n$ (prompt signal)

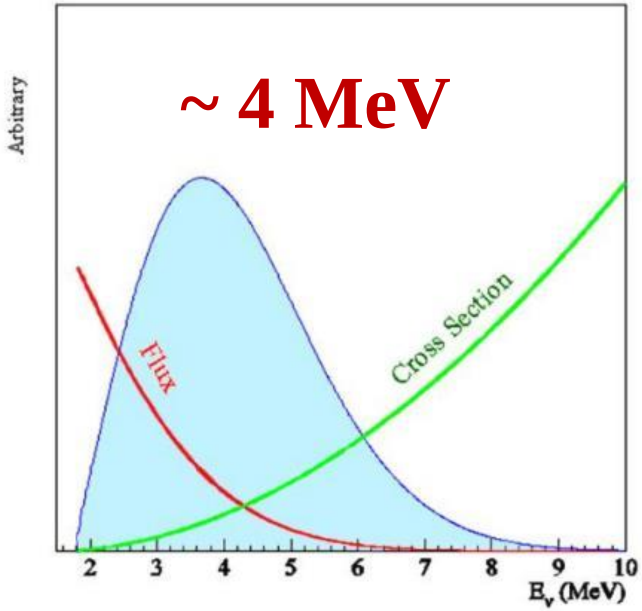
~200μs $\hookrightarrow + p \rightarrow D + \gamma$ (2.2 MeV) (delayed signal)

~30μs for 0.1% Gd $\hookrightarrow + Gd \rightarrow Gd^*$

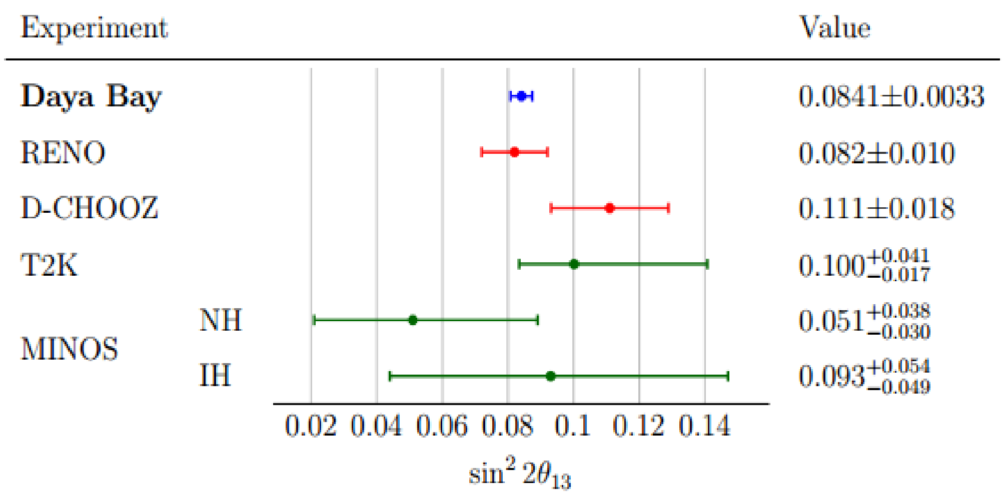
$\hookrightarrow Gd + \gamma$'s (8 MeV) (delayed signal)

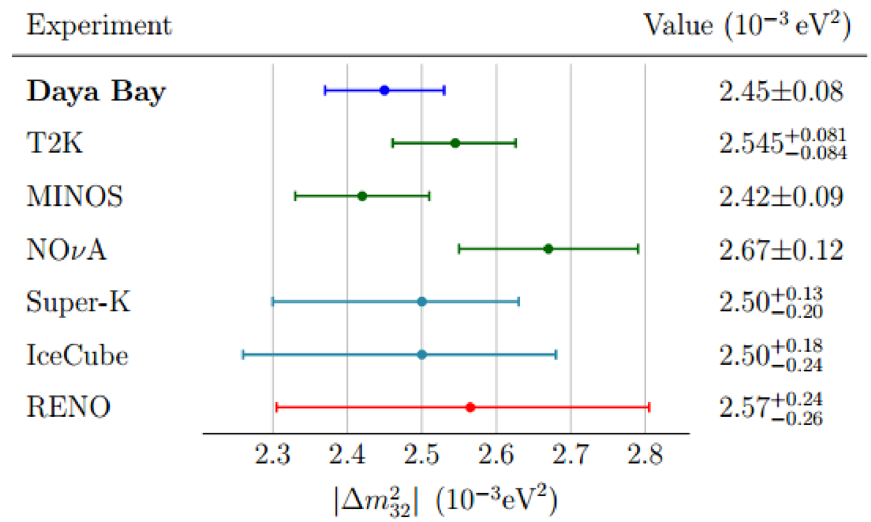


- **Gd-doped liquid scintillator**
  nGd + nH: Daya Bay, RENO, Double Chooz
- **Liquid scintillator**
  nH: JUNO, RENO-50



Results of θ_{13} and Δm^2_{ee}





- **Daya Bay**

  1230 days of data

  $\sin^2 2\theta_{13} = (8.41 \pm 0.27(\text{stat.}) \pm 0.19(\text{syst.})) \times 10^{-2}$

  $|\Delta m^2_{ee}| = (2.50 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})) \times 10^{-3}$ eV^2

  Neutrino 2016

- **RENO**

  500 days of data, the first measurement of Δm^2_{ee}

  $\sin^2 2\theta_{13} = (8.2 \pm 0.9(\text{stat.}) \pm 0.6(\text{syst.})) \times 10^{-2}$

  $|\Delta m^2_{ee}| = 2.62^{+0.21}_{-0.23}(\text{stat.})^{+0.12}_{-0.13}(\text{syst.})(\times 10^{-3}$ eV$^2)$

  PRL 116, 211801, 2016

- **Double Chooz**

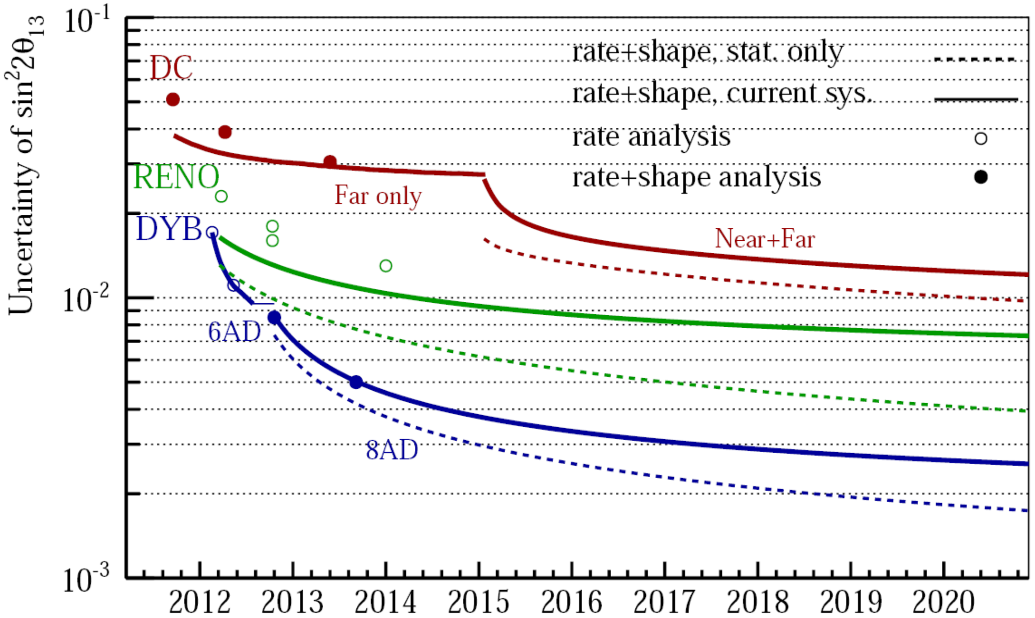
  270 days of data, first 2 detector result (since start of 2015).

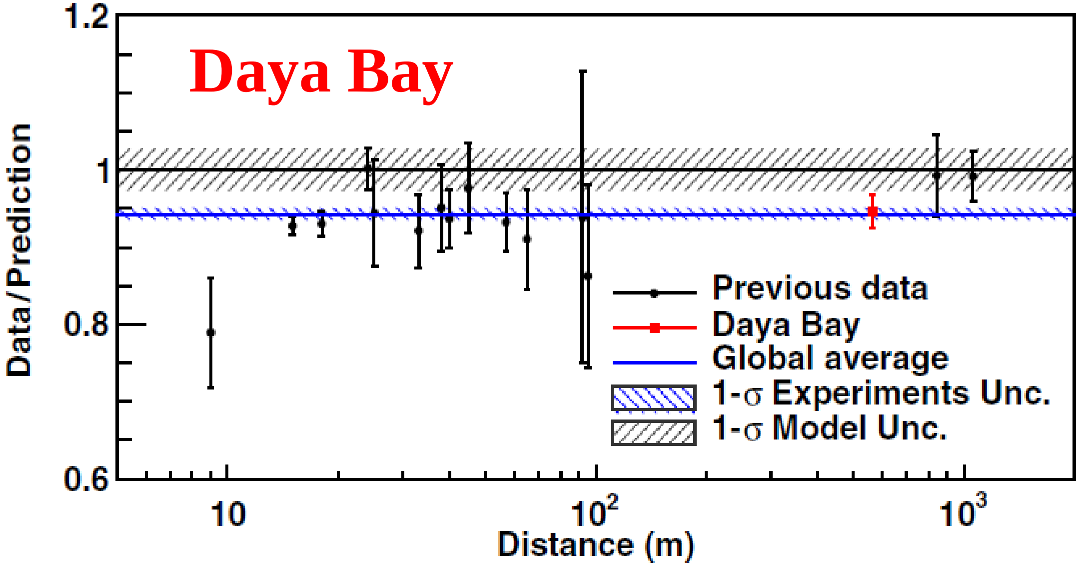
  $\sin^2 2\theta_{13} = (11.1 \pm 1.8(\text{stat.+syst.})) \times 10^{-2}$

  Moriond 2016

- **Daya Bay experiment**
  - **Is expected to continuously run until 2020.**
  - **The uncertainties of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$, from ~4% to ≤ 3%.**
- **RENO**
  - **Expected to take total 5 years of data.**
  - **The uncertainties of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$, from ~12% to ≤ 5%.**
- **Double Chooz**
  - **3 years near/far detector running.**
  - **The uncertainties of $\sin^2 2\theta_{13}$, from ~16% to ≤ 10%.**

The uncertainties can be further improved by combining Daya Bay, RENO and Double Chooz.



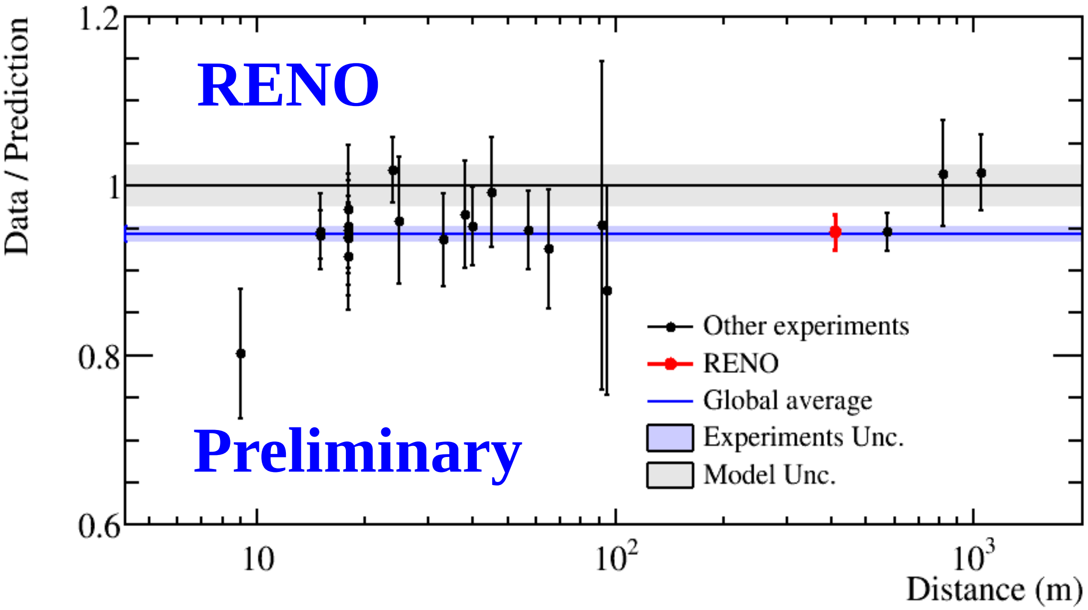


PRL 116, 061801 (2016)

Data/Prediction:

0.946±0.020 (Huber+Mueller)

0.992±0.021 (ILL+Vogel)

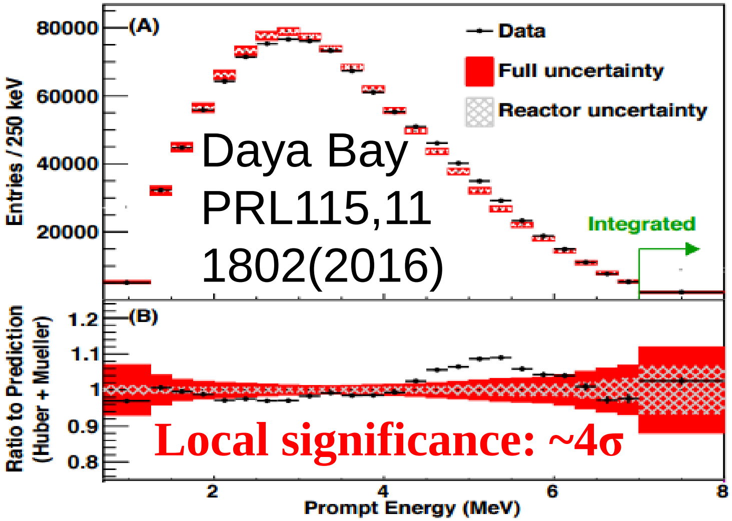


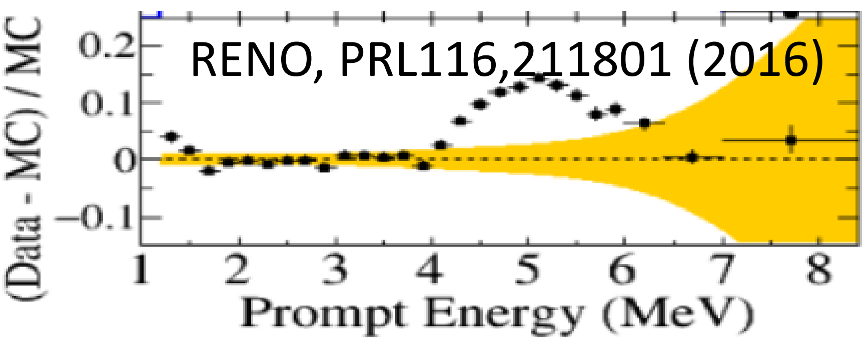
Preliminary

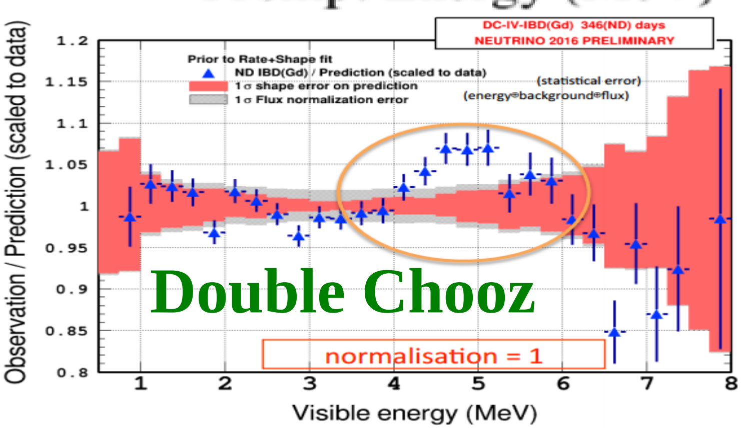
Data/Prediction:

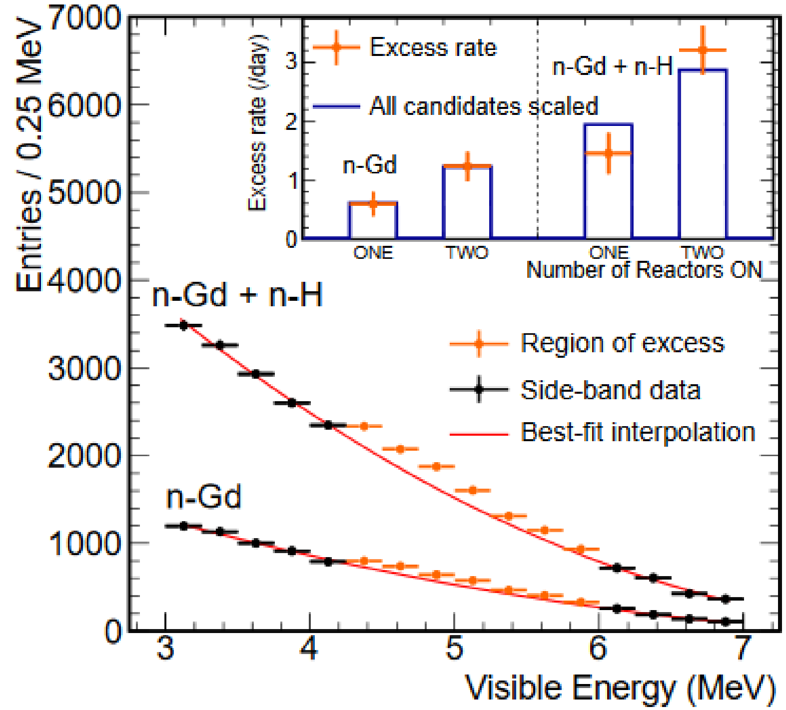
0.946±0.021 (Huber+Mueller)

Reactor flux spectrum distortion





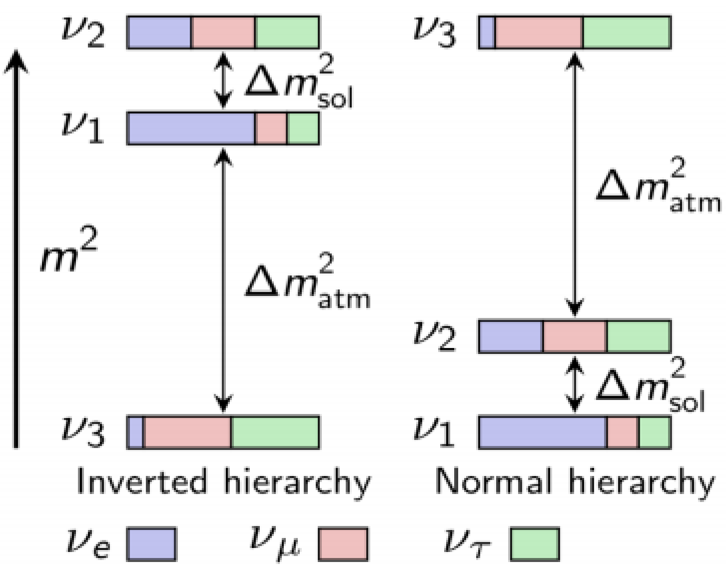


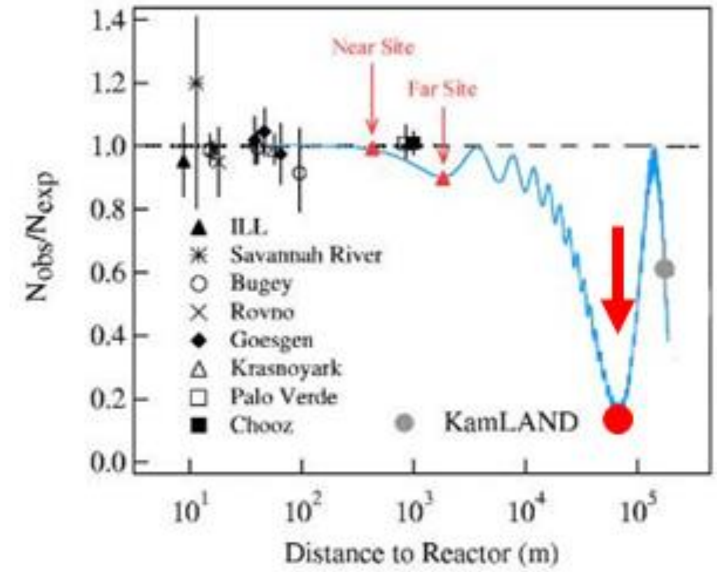


Double Chooz, JHEP 1601, 163 (2016)

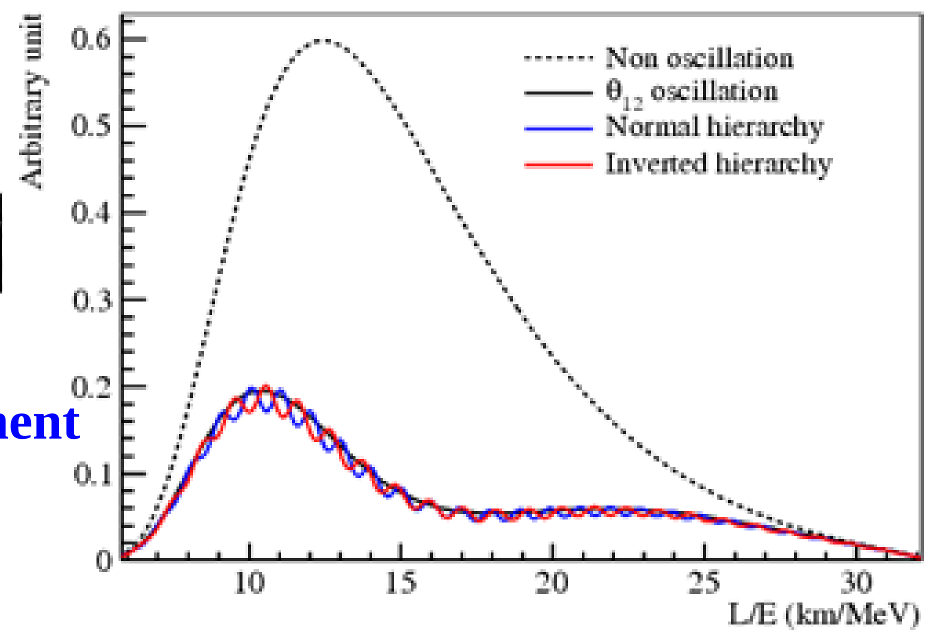
- All 3 experiments observed excess events in 4-6 MeV region.
- Excess events are correlated with reactor power.
- Excess does not appear in ^{12}B spectra.

Determine MH with Reactors





$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \boxed{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}}$$
$$-\boxed{\sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})}$$

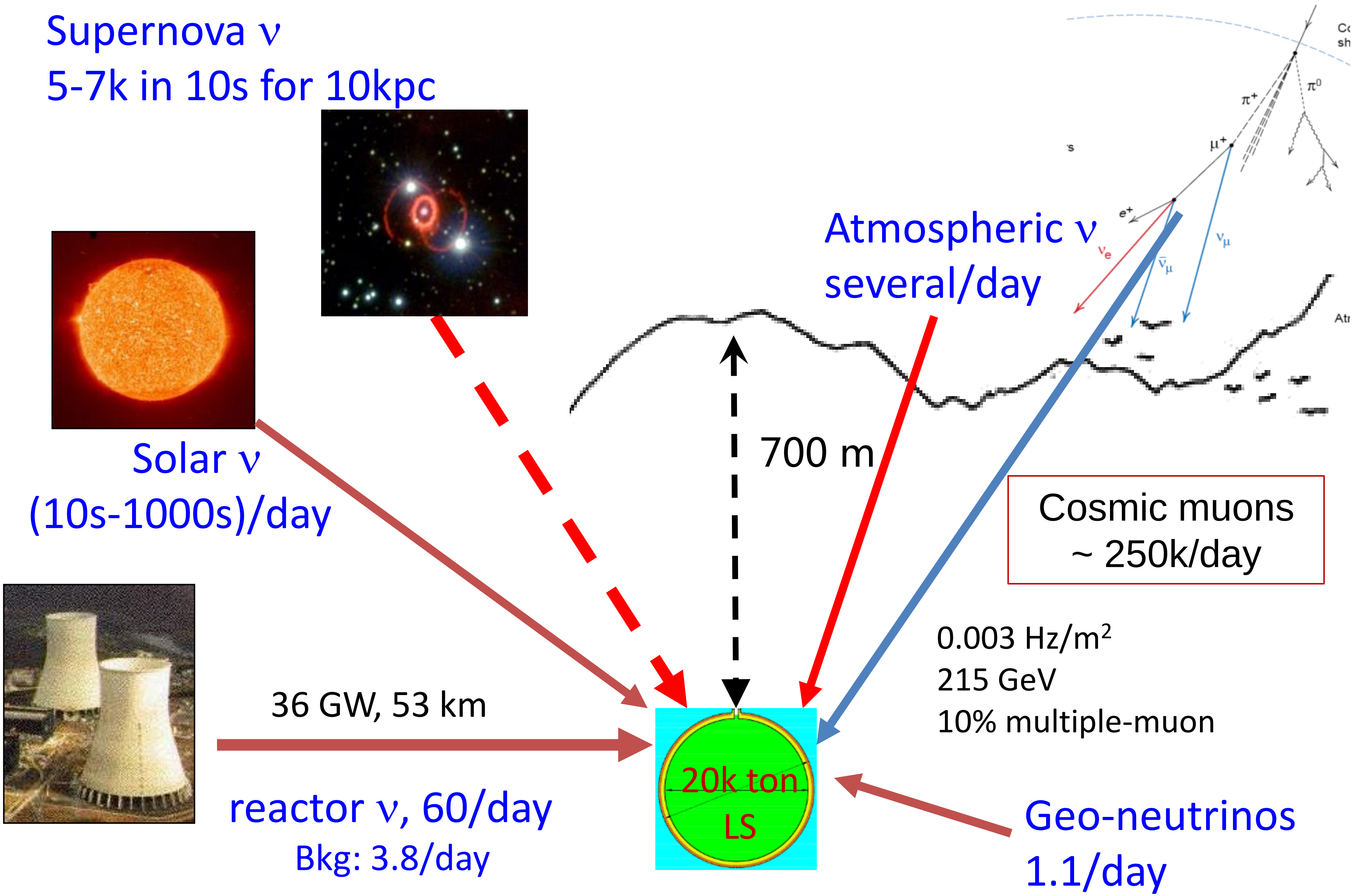


- **Precision energy spectrum measurement**
- **Independence of unknown CP phase**
- **Suitable baseline is ~50km**

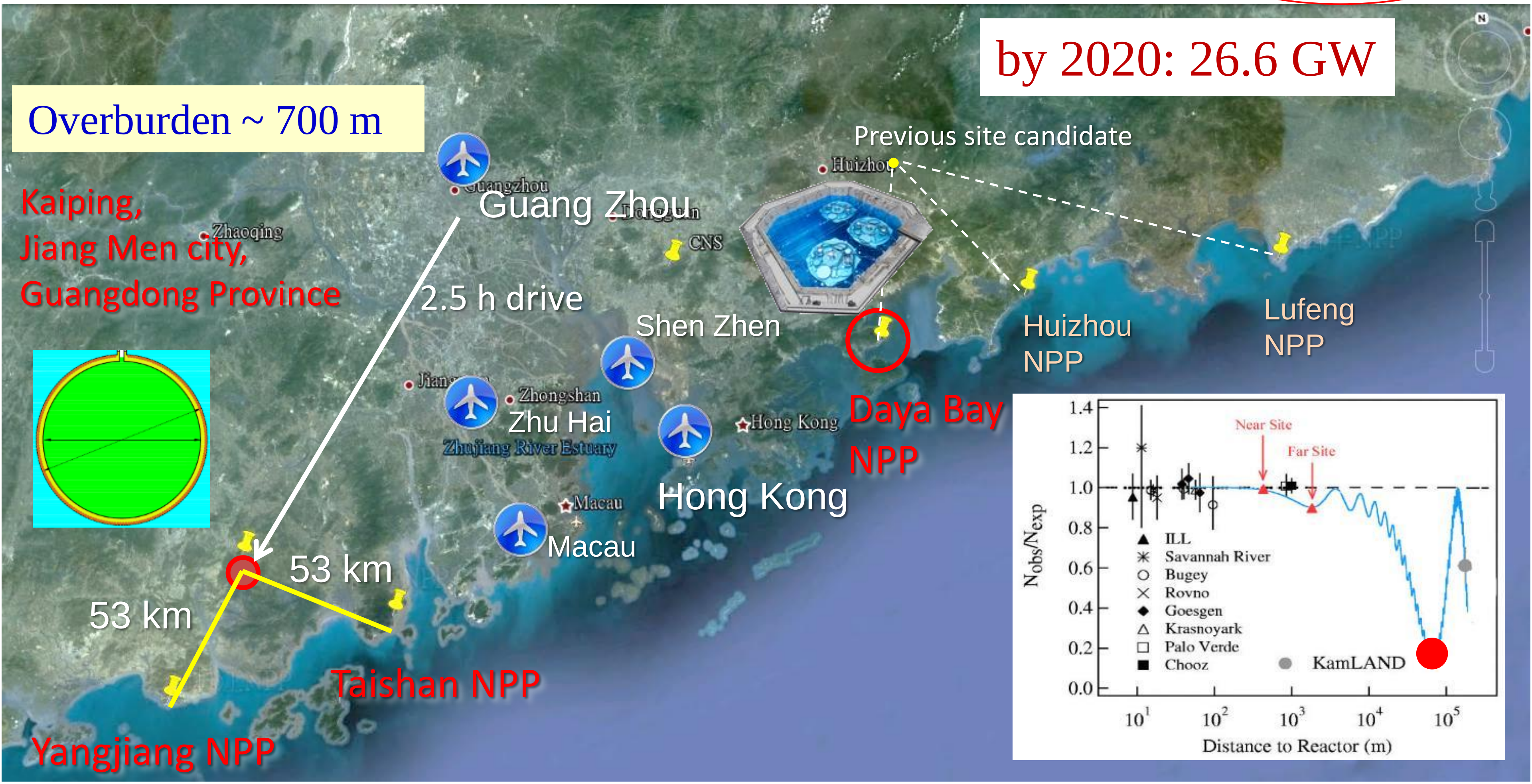
- **JUNO has been approved in Feb. 2013. ~ 300 M$.**
- **JUNO is a multi-purpose reactor neutrino experiment.**
  - **20 kton LS detector**
  - **3%/sqrt(E) energy resolution**
  - **700 m overburden**
  - **Rich physics**
    - ✓ **Reactor neutrino for MH and precision measurement of oscillation parameters**
    - ✓ **Supernovae neutrino**
    - ✓ **Geo-neutrino**
    - ✓ **Solar neutrino**
    - ✓ **Atmospheric neutrino**
    - ✓ **Exotic searching, such as proton decay, dark matter**

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

JUNO Event Rate (after selection)

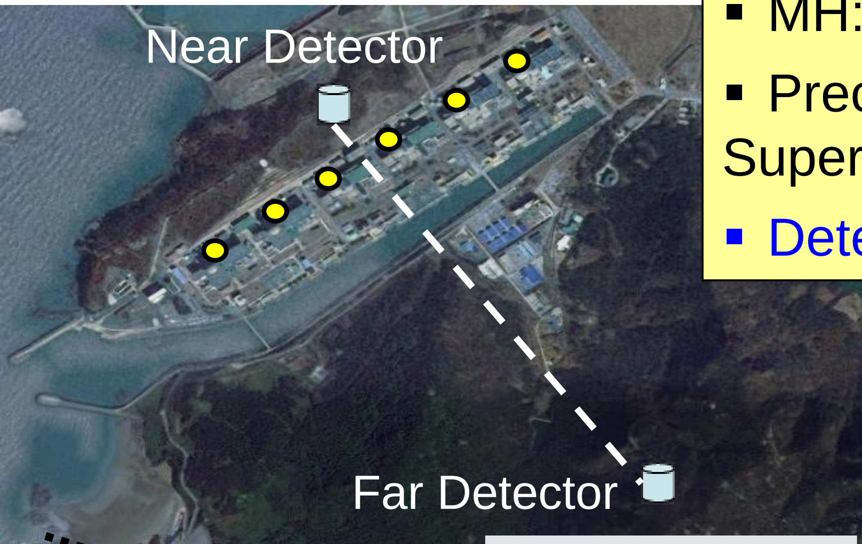


NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



RENO-50 Site

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



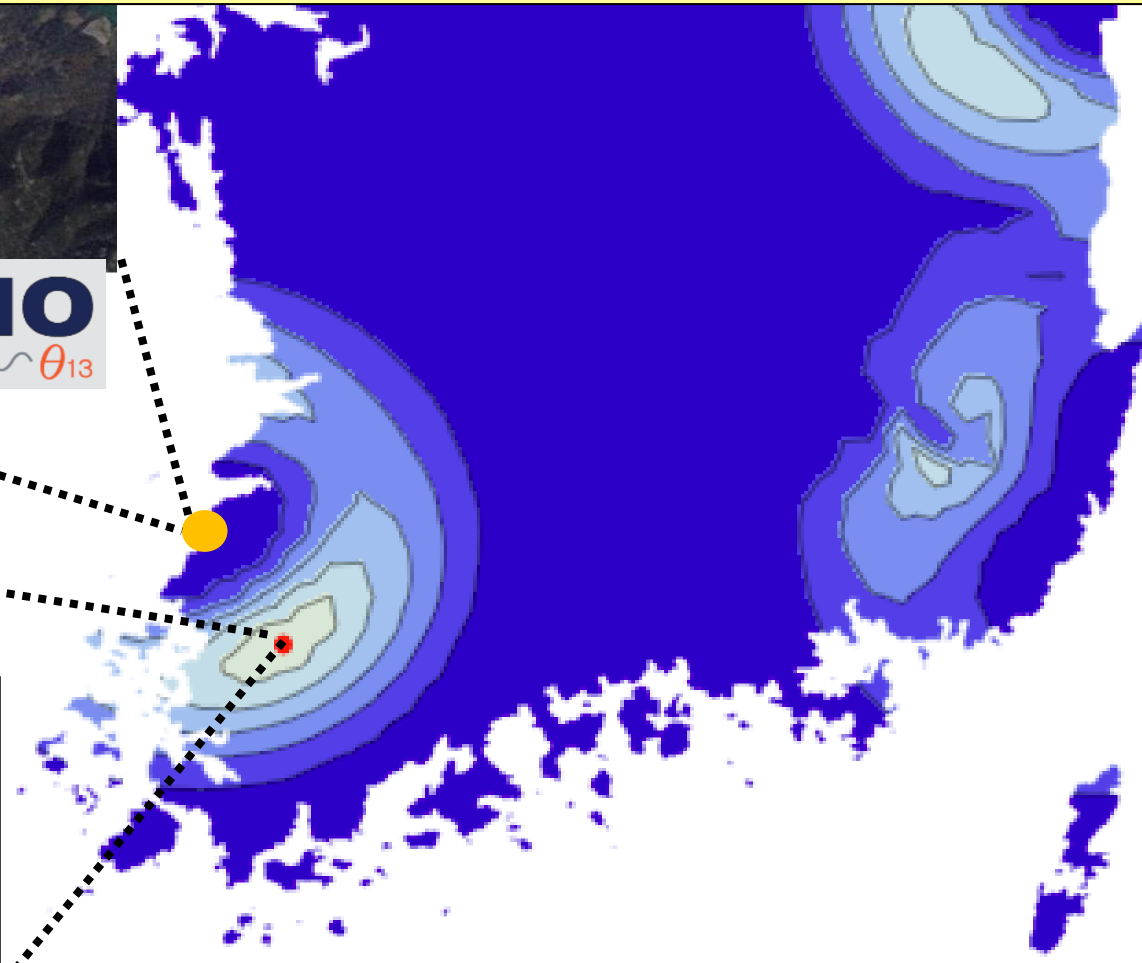
(NEAR Detector)

(FAR Detector)

RENO-50

18 kton LS Detector
~47 km from YG reactors

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

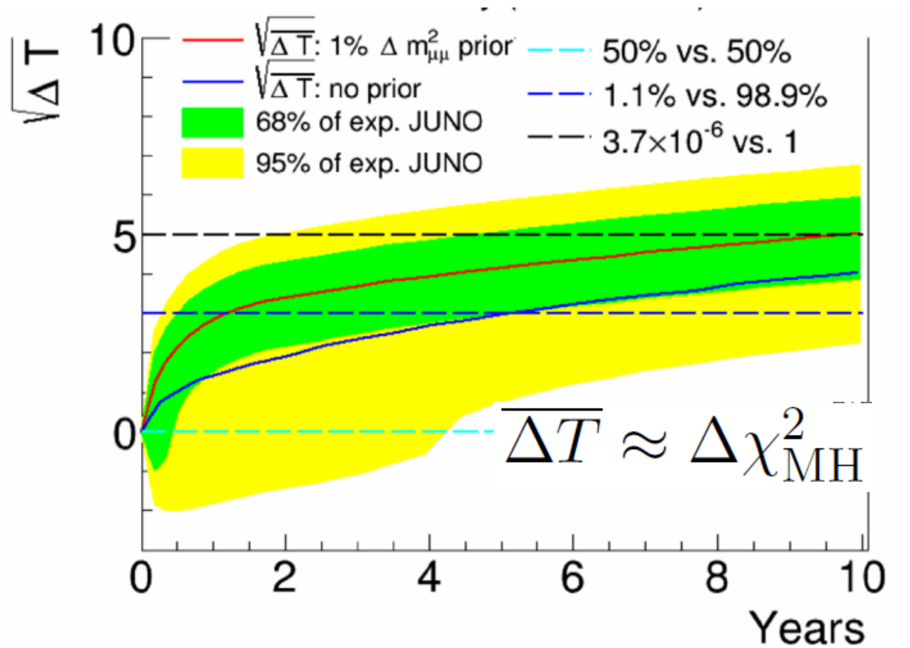


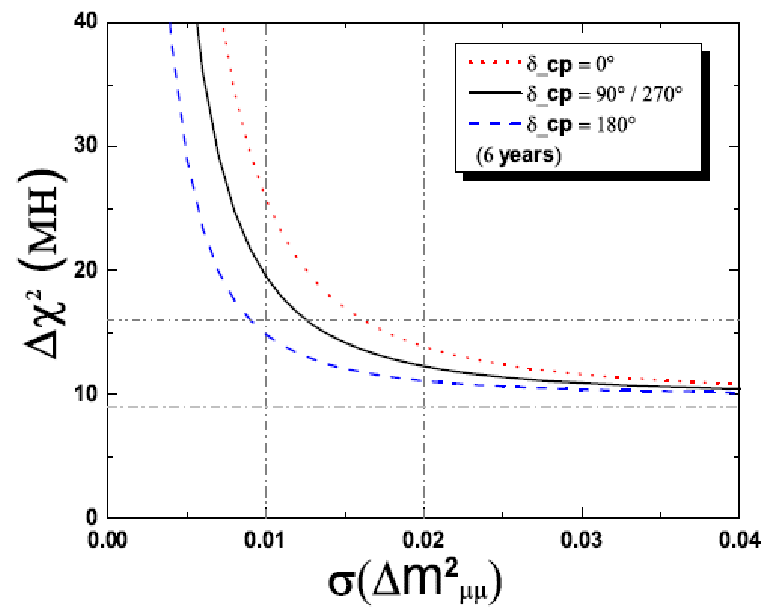
JUNO MH Sensitivity

PRD 88, 013008 (2013)	w/o $\Delta m^2_{\mu\mu}$	w/ $\Delta m^2_{\mu\mu}$ input (1%)
Statistics only	4σ	5σ
Realistic case	3σ	**4σ**

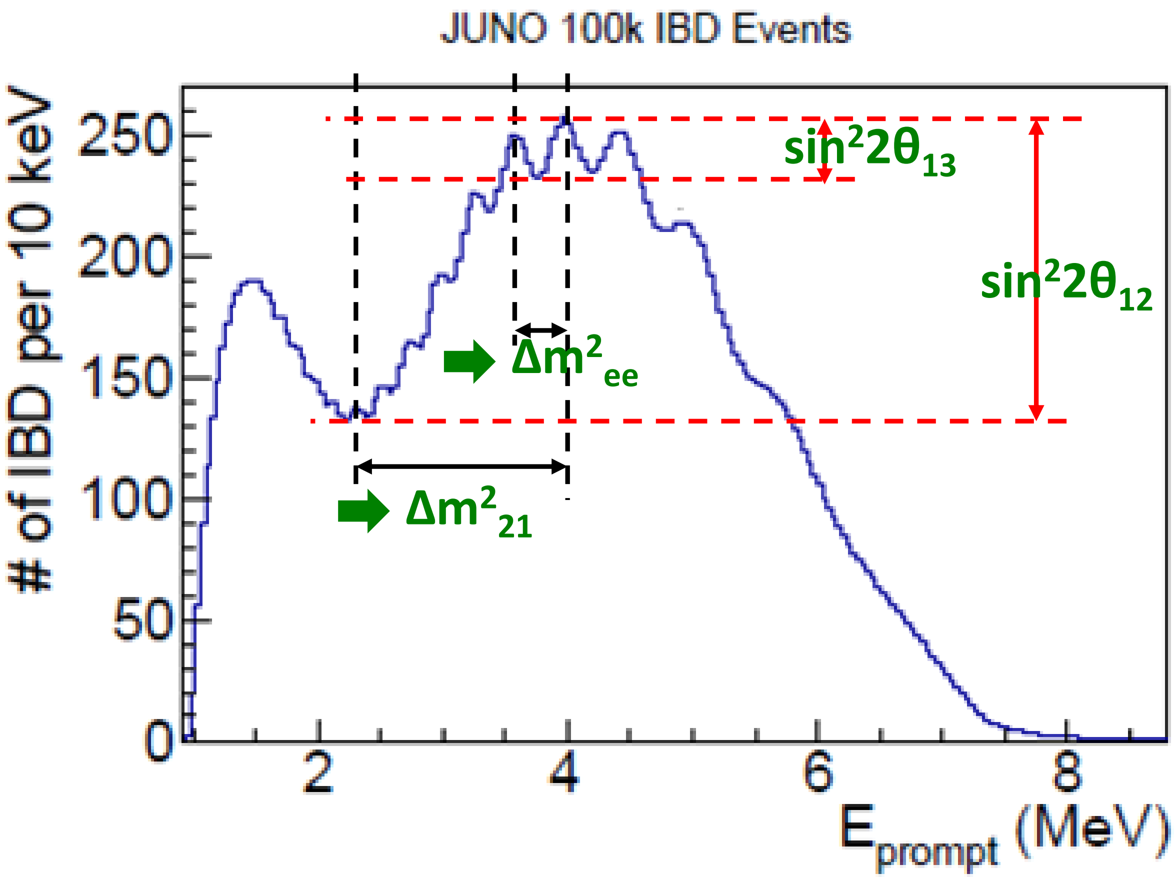
JUNO **MH sensitivity with 6 years' data:**

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





	Ideal	Core distr.	DYB & HZ	Shape	B/S (stat.)	B/S (shape)	$\lvert\Delta m^2_{\mu\mu}\rvert$
Size	52.5 km	Real	Real	1%	6.3%	0.4%	1%
$\Delta\chi^2_{MH}$	16	- 3	-1.7	- 1	- 0.6	- 0.1	+ (4-12)



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%

Challenges in JUNO

- **Energy resolution: $3\%/\sqrt{E}$**
  - **77% photocathode coverage**
  - **High PDE of PMTs: 35% at QE peak**
  - **Long attenuation length of LS: 20 m (abs. 60m + Rayl. Scatt. 30m)**
- **Reactor spectrum**
  - **Direct measurement of the spectrum to 1% by SBL reactor experiments.**
  - **Constraint from Daya Bay measurements, 1%.**

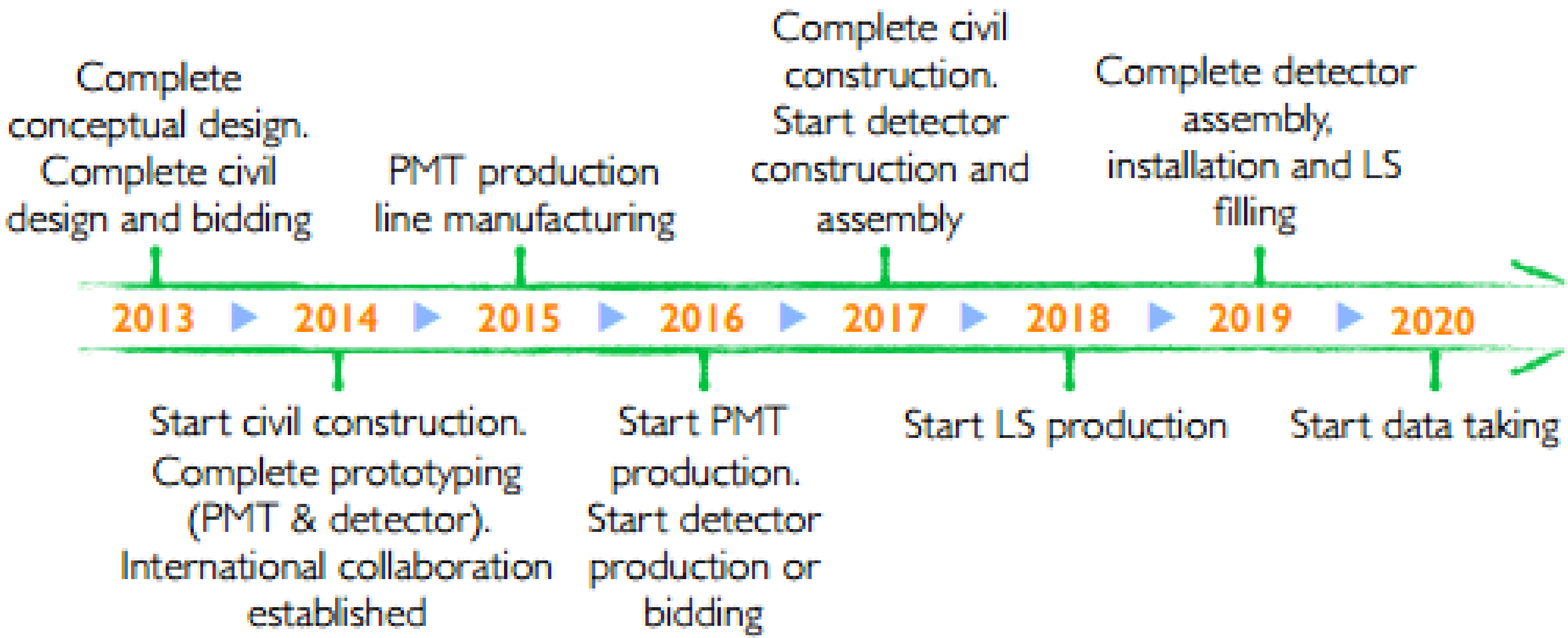
	Daya Bay	KamLAND	BOREXINO	JUNO
LS mass	0.042 kt	1 kt	0.5 kt	20 kt
Energy Resolution	$7.5\%/\sqrt{E}$	$6\%/\sqrt{E}$	$5\%/\sqrt{E}$	$3\%/\sqrt{E}$
Light yield	~160 p.e./MeV	250 p.e./MeV	511 p.e./MeV	1200 p.e./MeV
Photo-Cathode Coverage	~12%	~34%	~34%	77%

JUNO Collaboration

Country	Institute
Armenia	Yerevan Physics Institute
Belgium	Universite libre de Bruxelles
Brazil	PUC
Brazil	UEL
Chile	PCUC
Chile	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	IMP-CAS
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
China	NUDT
Czech	Charles U.
Finland	University of Oulu
France	APC Paris
France	CPPM Marseille
France	IPHC Strasbourg
France	LLR Palaiseau
France	Subatech Nantes
Germany	Forschungszentrum Julich
Germany	RWTH Aachen U.
Germany	TUM
Germany	U. Hamburg
Germany	IKP FZI 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
Pakistan	PINSTECH
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

Collaboration established in July 2015
Now: 66 institutions
444 collaborators
8 obervers

JUNO Schedule



- **Future Plans**
  - **Run for 20-30 years**
  - **Likely, double beta decay experiment in 2030**

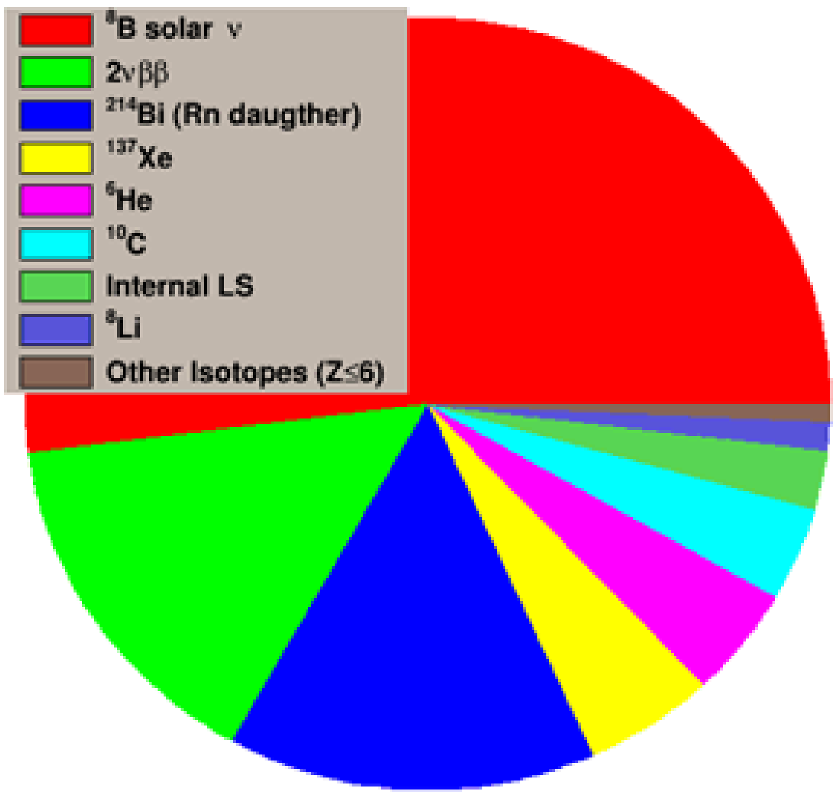
By dissolving Xe/Te to LS, we can make JUNO to be a DBD experiment.

Take Xenon as an example.

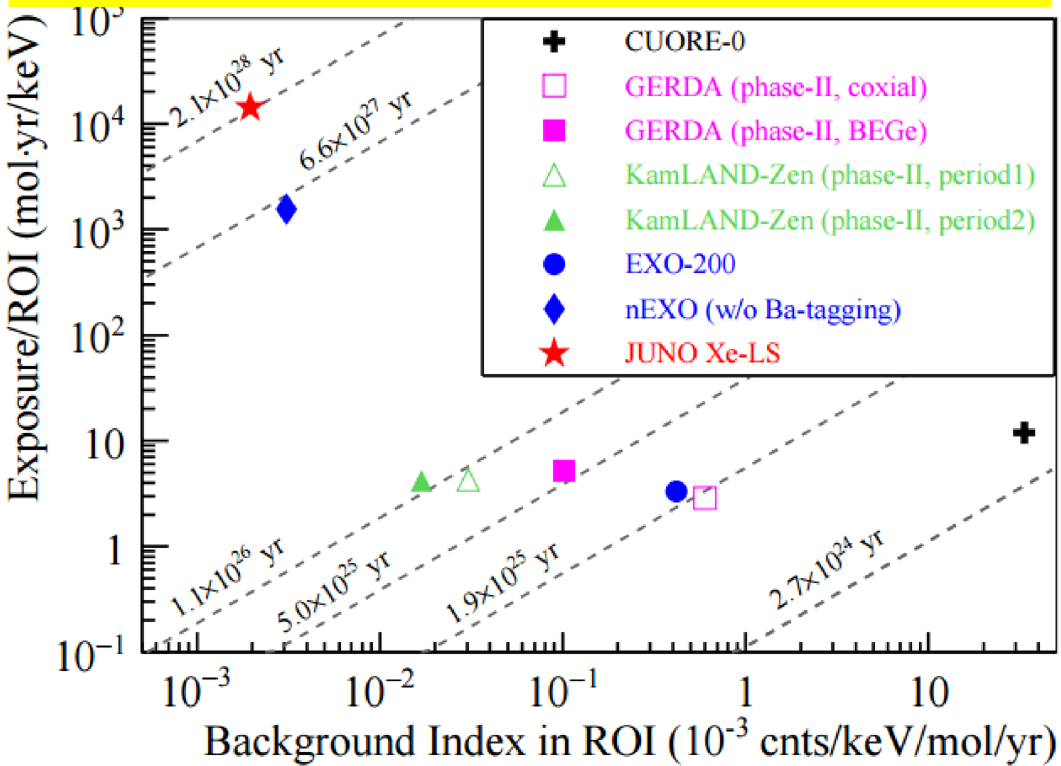
arXiv:1610.07143

	KamLAND-Zen	JUNO Xe-LS
Energy resolution	$6.6\%/\sqrt{E}$ [6] $7.3\%/\sqrt{E}$ [12]	$3\%/\sqrt{E}$
Xe-doping	2.5% (phase I [6]) 2.9% (phase II [12])	5%
^{136}Xe enrichment	~91% [6, 12]	80%
$0\nu\beta\beta$ ROI	(2.3, 2.7) MeV [12]	(2403, 2513) keV
$\varepsilon_{0\nu\beta\beta}$ in ROI	72.2%[a]	90.5%

B.G. rate: ~1.34/ROI/(ton ^{136}Xe)/yr



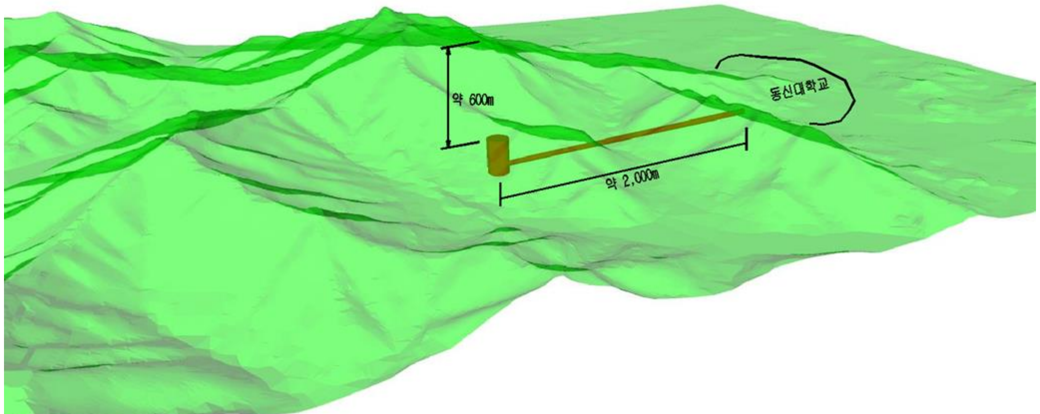
★: 50 tons of target, 5 years exposure



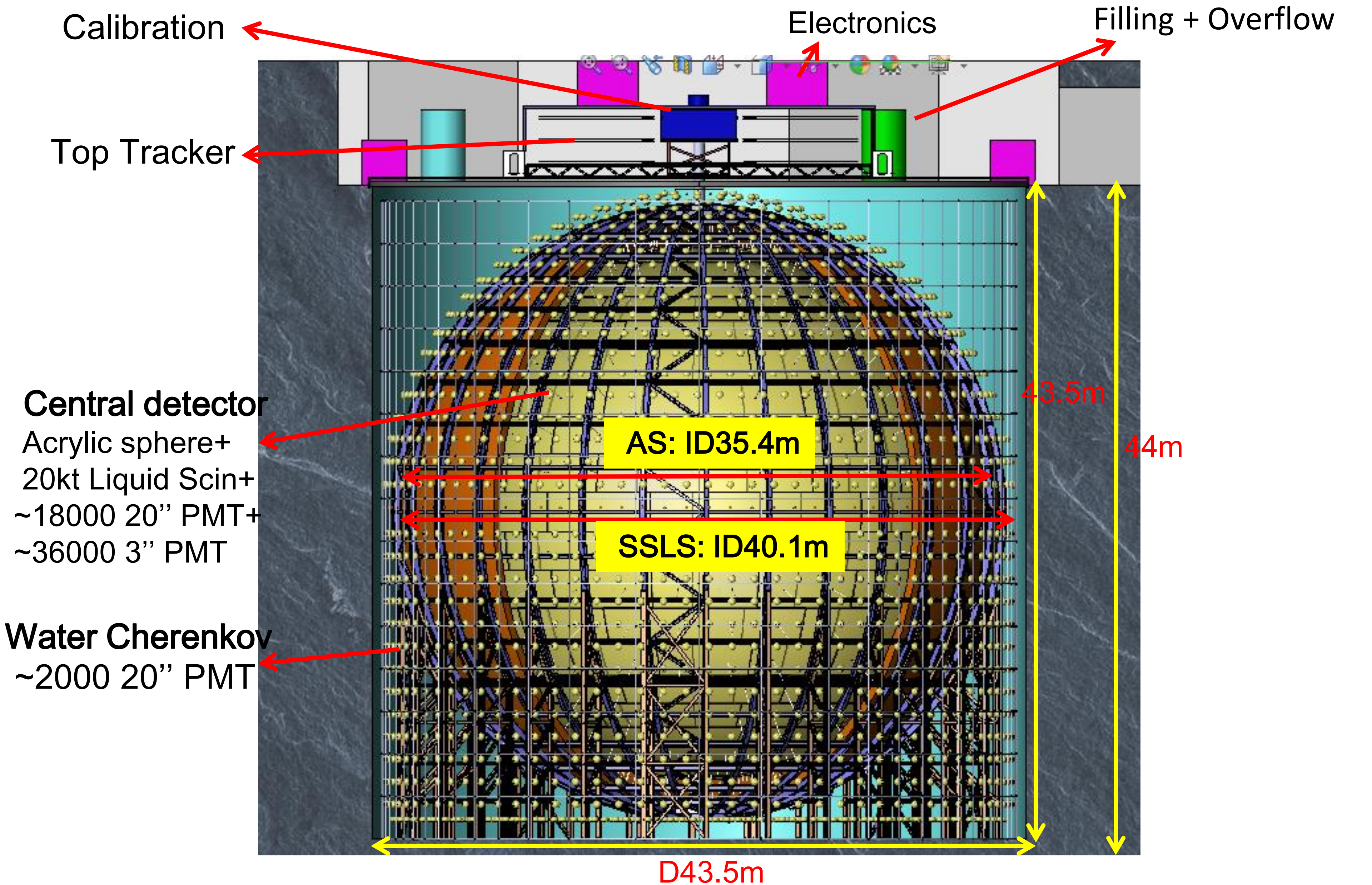
RENO-50 Schedule

- ❄ **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**



JUNO Detector

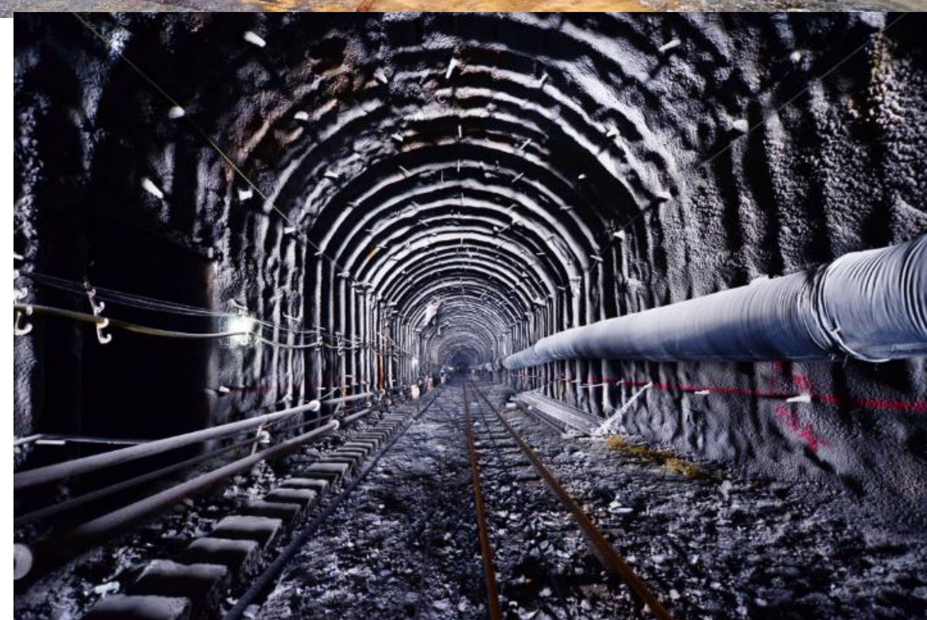


AS: Acrylic sphere; SSLS: stainless steel latticed shell

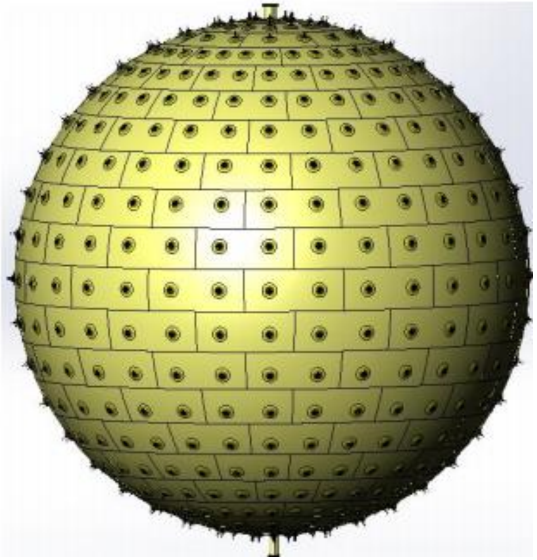
Civil Progress

Ground breaking in Jan. 2015

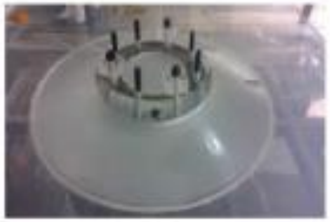
- **1020 m** slope tunnel excavated out of 1340 m
- **485 m** vertical shaft excavated out of 611 m



Acrylic Sphere R&D

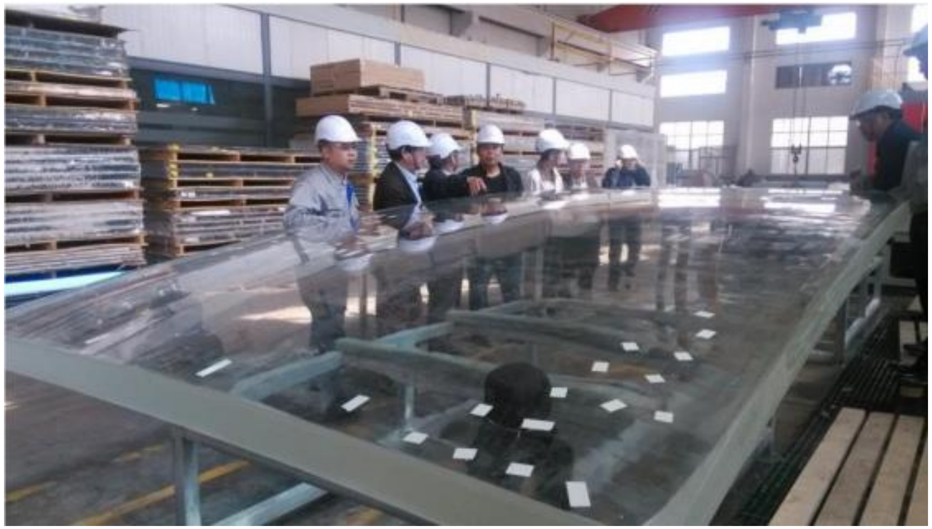


Acrylic divided into 200+ panels



The problems of shrinkage and shape variation were resolved.

Three companies had good practices.



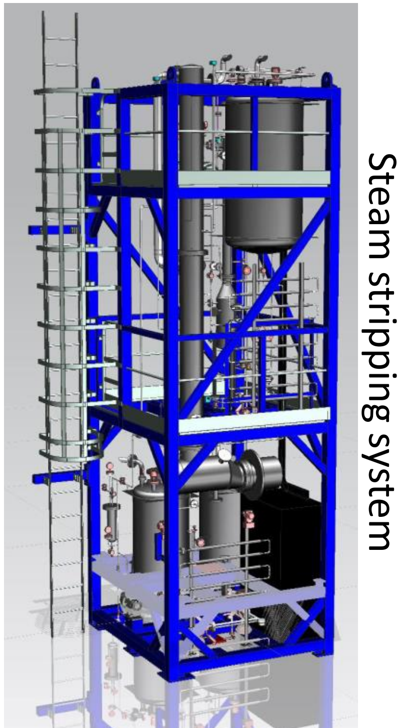
Forming panel size: 3m x 8m x 120mm

LS Pilot Plant

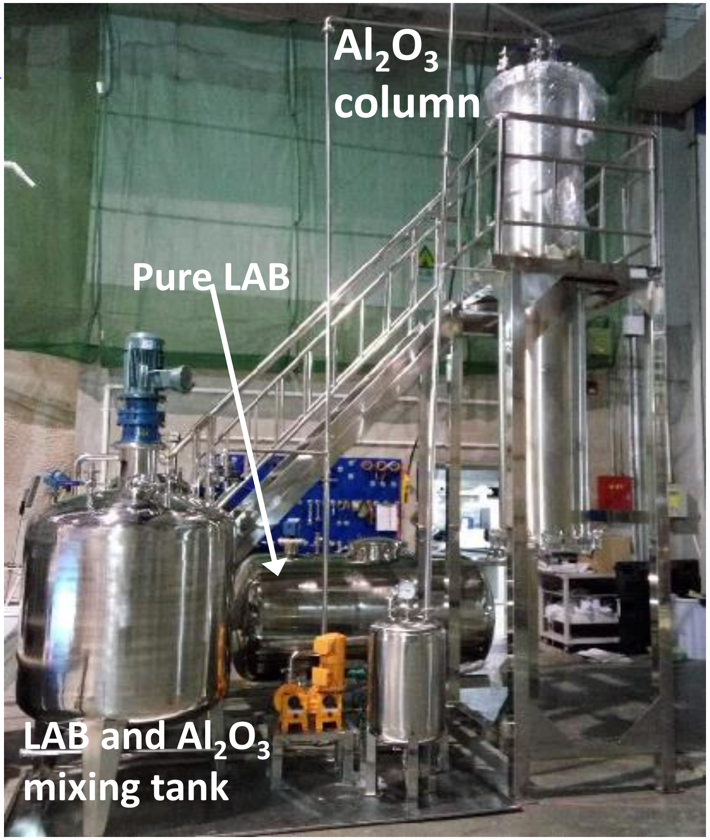
- **LS requirement**
  - **Optical : >20m A.L @430nm**
  - **Radio-purity: < 10^{-15} g/g (U, Th)**
- **Purification**
  - **Purify 20 ton LAB to test the overall design of purification system at Daya Bay. Plan to replace the target LS in one detector.**
- **Determine the choice of sub-systems**
  -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

Distillation and steam stripping

Installed at Daya Bay



Al_2O_3 column pilot plant installed in Daya Bay LS hall



Finished 20” PMT bidding at the end of 2015:

- -- 15,000 MCP-PMT (NNVT, China)
- -- 5,000 Dynode-PMT (Hamamatsu, Japan)

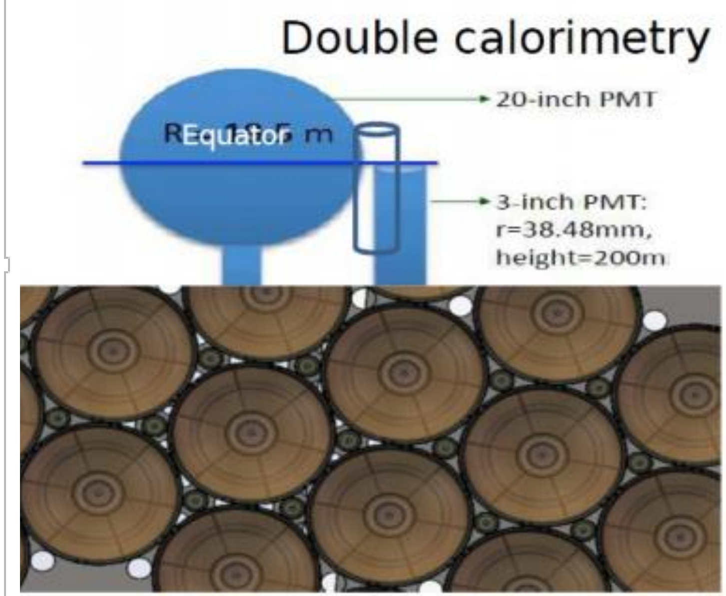
Double calorimetry

- -- ~36,000 3” PMT
- -- MELZ(RU), HZC(CH), ETL(UK), Hamamatsu(JP)

MCP-PMT

Dynode-PMT

Characteristics	unit	MCP-PMT（NNVC）	R12860（Hamamatsu）
Detection Eff.(QE*CE*area)	%	27%, > 24%	27%, > 24%
P/V of SPE		3.5, > 2.8	3, > 2.5
TTS on the top point	ns	~12, < 15	2.7, < 3.5
Rise time/ Fall time	ns	R~2 , F~12	R~5, <7; F~9, <12
Anode Dark Count	Hz	20K, < 30K	10K, < 50K
After Pulse Rate	%	1, <2	10, < 15
Radioactivity of glass	ppb	238U:50 232Th:50 40K: 20	238U:400 232Th:400 40K: 40



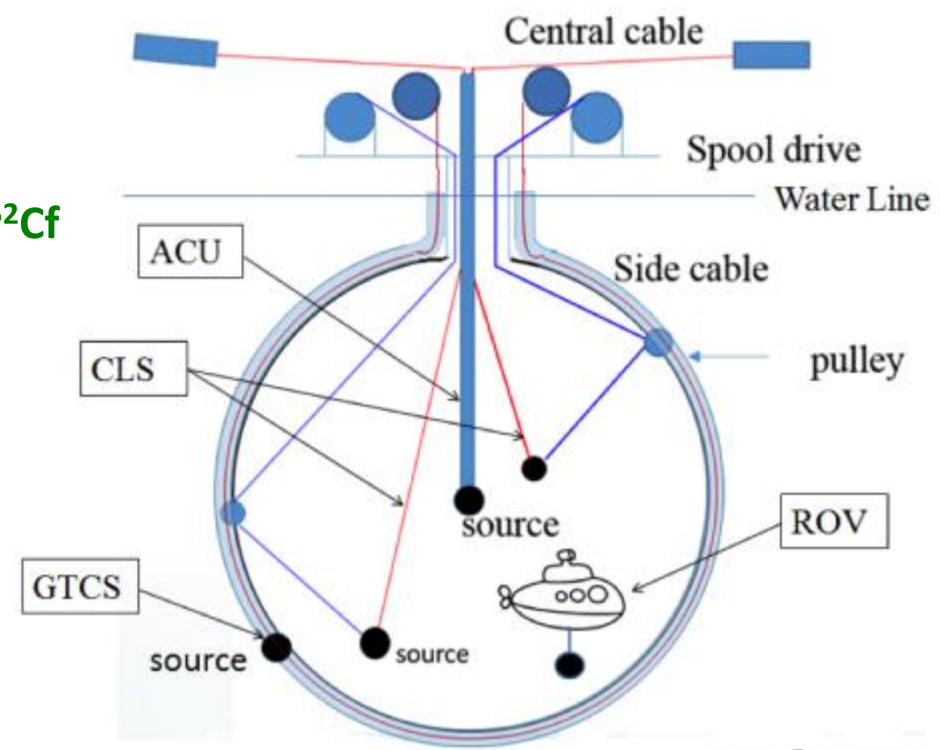
Calibration System

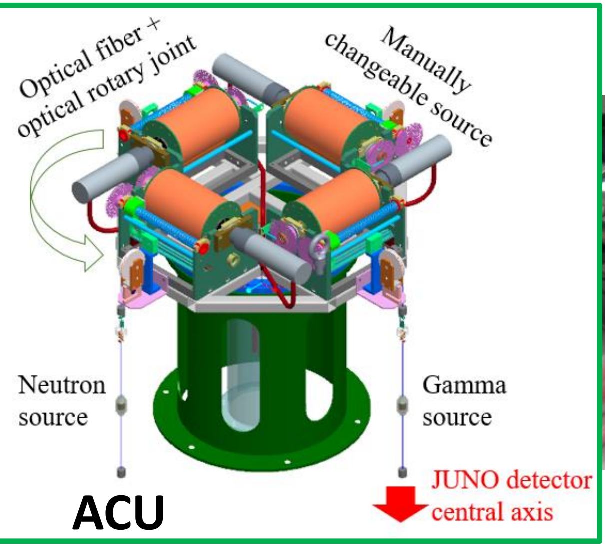
Radioactive sources

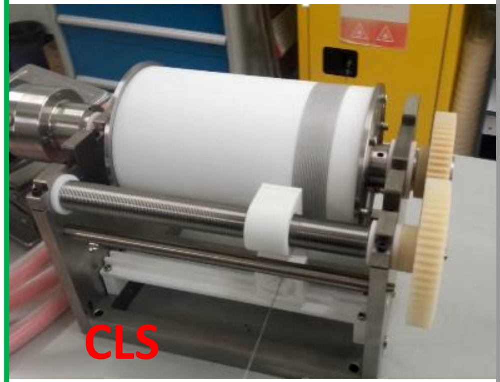
- gamma: ^{40}K, ^{54}Mn, ^{60}Co, ^{137}Cs
- positrons: ^{22}Na, ^{68}Ge
- neutrons: ^{241}Am-Be, ^{241}Am-^{13}C, ^{241}Pu-^{13}C, ^{252}Cf

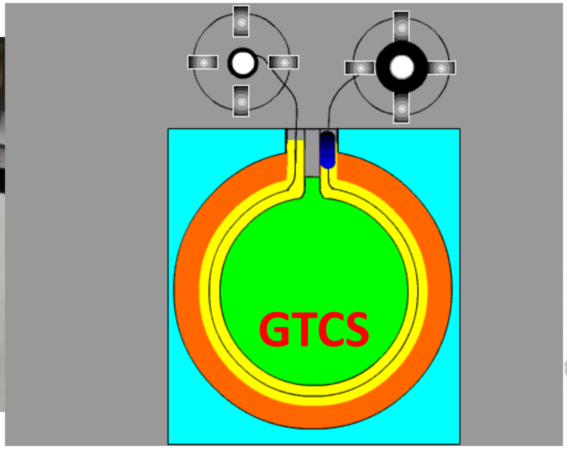
Four calibration systems

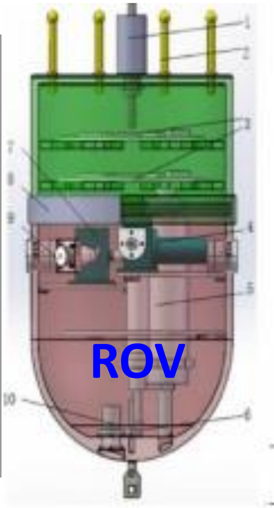
- 1D: Automatic Calibration Unit -- ACU
- 2D: Cable Loop System – CLS
  Guide Tube Calibration System -- GTCS
- 3D: Remotely Operated under-liquid-scintillator Vehicles -- ROV











RENO-50 R&D Status

(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

- **θ_{13} has been well measured by Daya Bay, RENO and Double Chooz experiments. The ultimate precision will reach ~3%.**

- **JUNO and RENO-50 have been designed to determine MH with 3-4 σ in 2026 and precisely measure oscillation parameters to $< 1\%$.**

- **JUNO is a fully funded project and construction/R&D are rapidly progressing.**
  - **PMT system, LS, Acrylic sphere, Calibration, readout, …**
  - **Aiming to take data in 2020.**

- **RENO-50 has R&D funding and various R&D are in progress.**
  - **Working for full funding**
  - **Aiming to take data in 2022.**

Thanks for your attention!