Design, status and plans of JUNO & RENO-50 as a comprehensive neutrino program

Yuekun Heng
IHEP, Beijing, China
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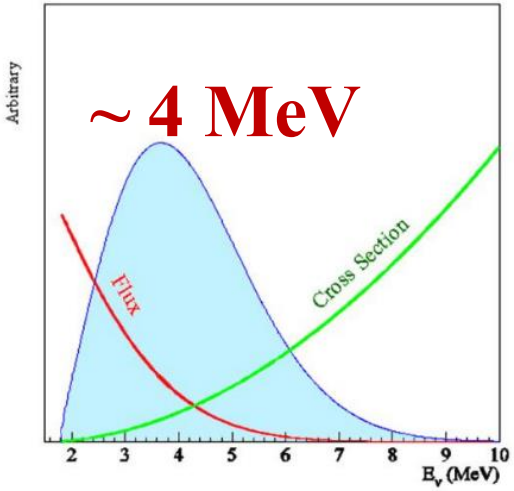
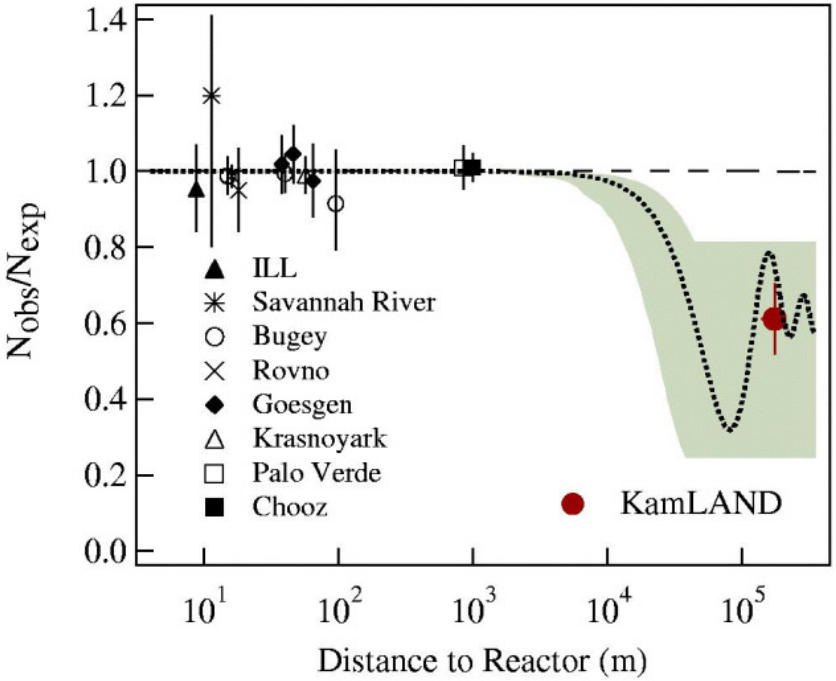
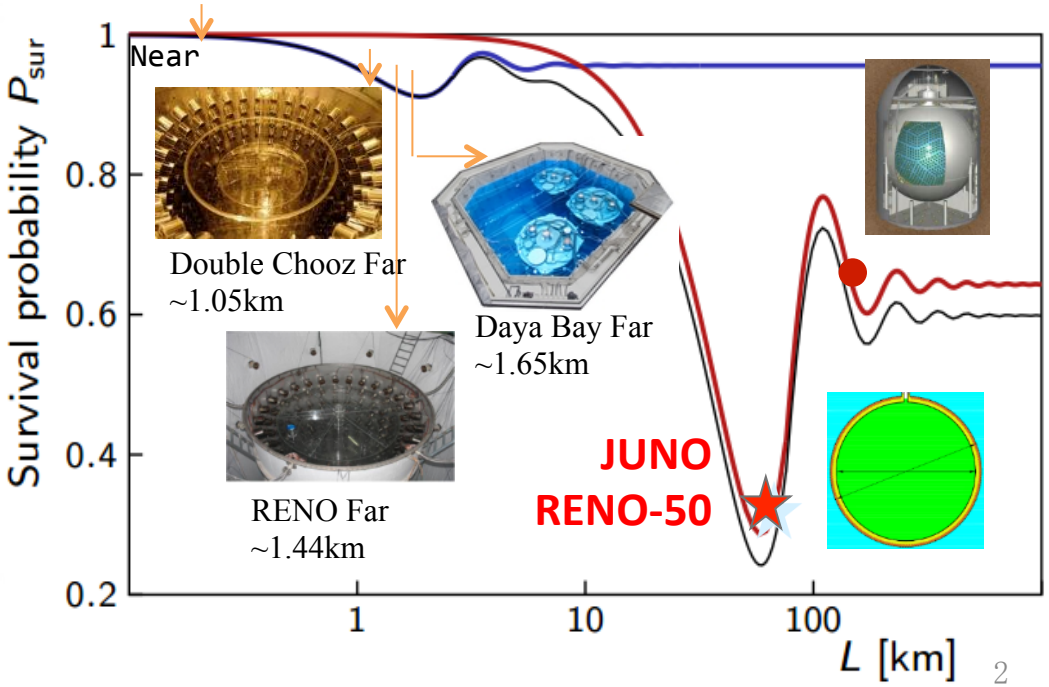
ICHEP2016
Chicago

Reactor Neutrinos

- Measuring θ_{13} and Δm^2_{ee}
  - Daya Bay, Double Chooz, RENO
  - Ultimate precision ~3%
- Determining Mass Hierarchy & precision measurement of θ_{12}, Δm^2_{21} and Δm^2_{31}
  - JUNO, RENO-50

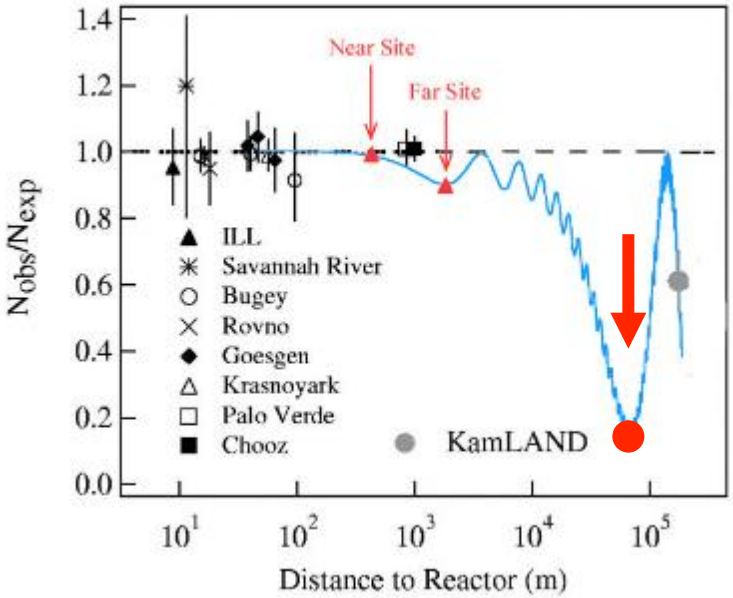


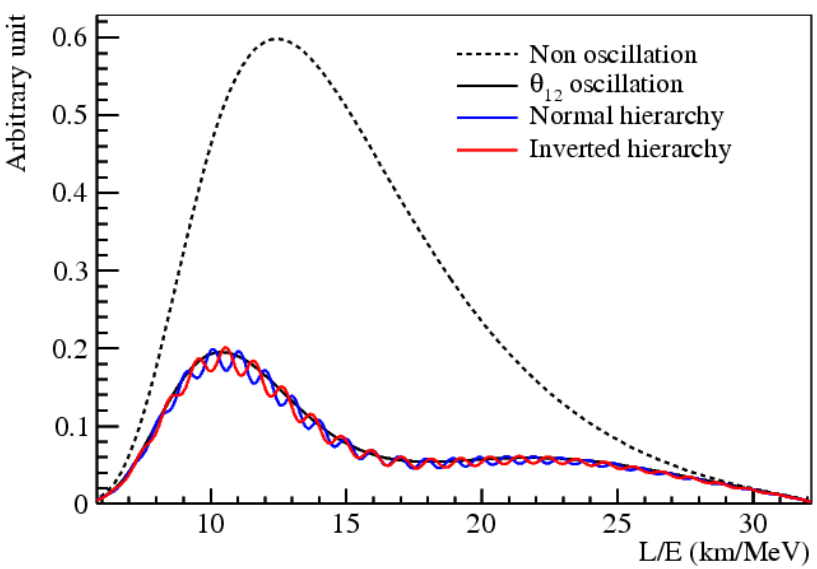




Determine MH with Reactors

Method from Petcov and Piai, Physics Letters B 553, 94-106 (2002)





Also refer to arXiv1210.8141

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

$$P_{ee} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21}) - \sin^2 2\theta_{13}\sin^2(|\Delta_{31}|) - \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{21})\cos(2|\Delta_{31}|) \pm \frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|)$$

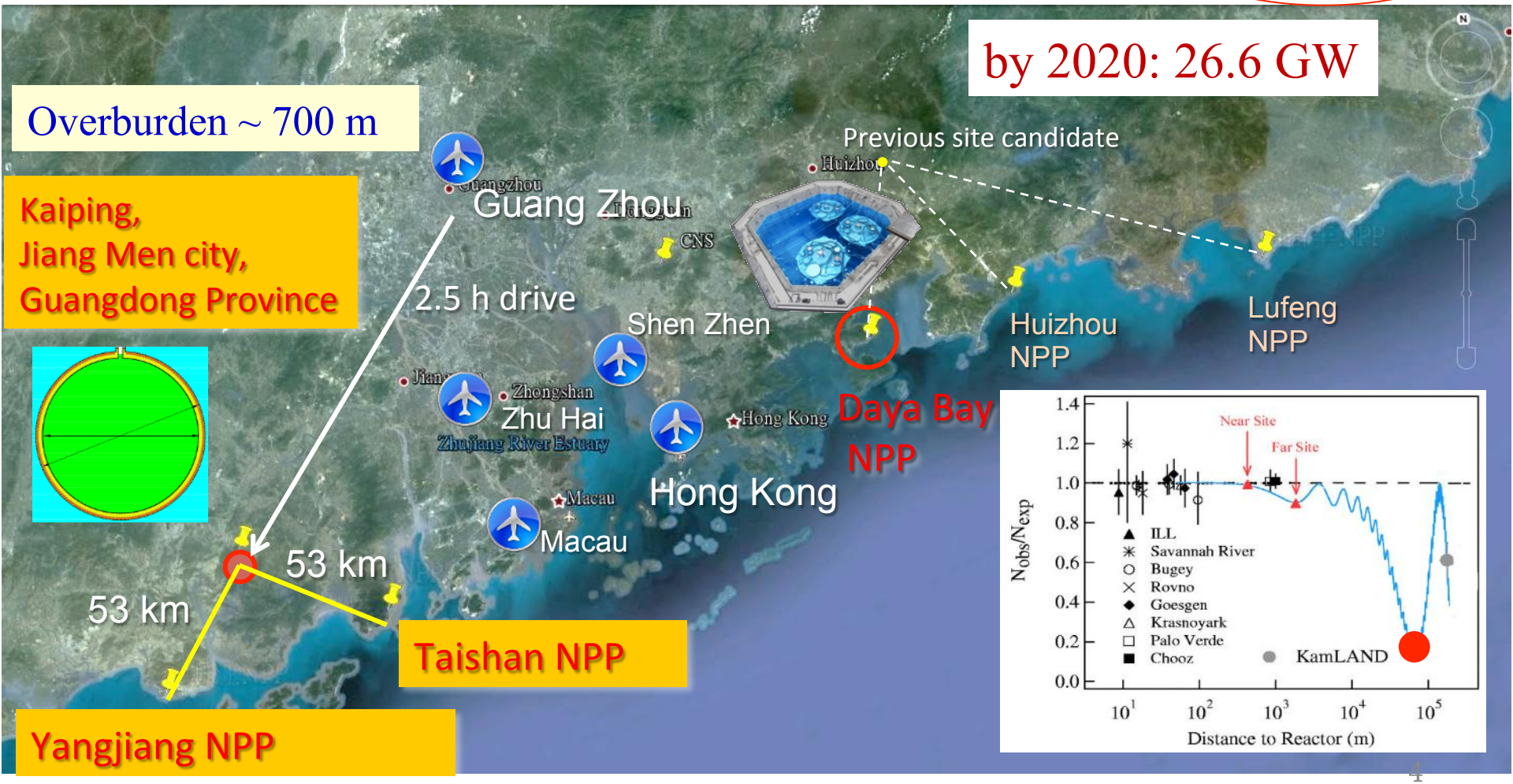
+ NH
- IH

- The big suppression is the "solar" oscillation → Δm^2_{21} , $\sin^2\theta_{12}$
- **"Large" value of θ_{13} crucial**
- **The NH or IH can be seen if the neutrino spectrum is as precise as 3% @ 1MeV**

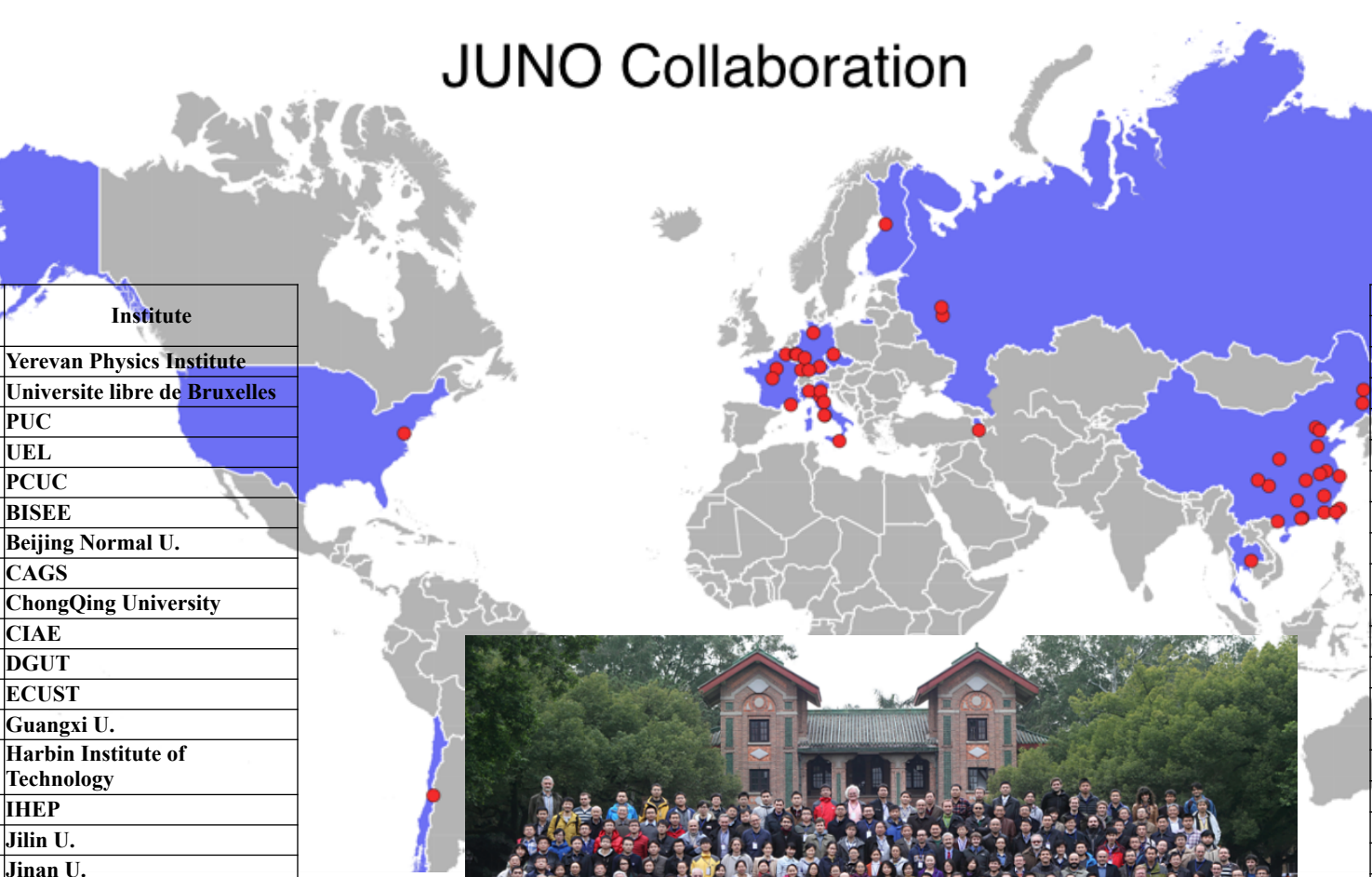
JUNO Site

JUNO has been approved in Feb. 2013. ~ 300 M$ by China

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



JUNO Collaboration

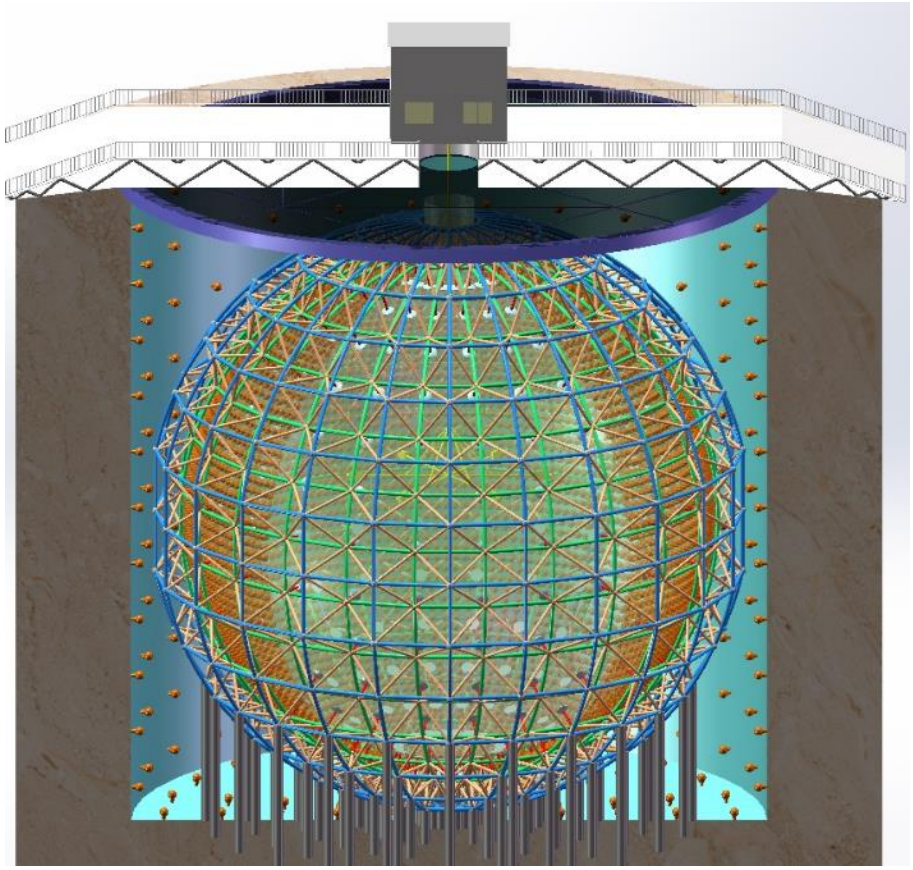


Institute
Yerevan Physics Institute
Universite libre de Bruxelles
PUC
UEL
PCUC
BISEE
Beijing Normal U.
CAGS
ChongQing University
CIAE
DGUT
ECUST
Guangxi U.
Harbin Institute of Technology
IHEP
Jilin U.
Jinan U.
Nanjing U.
Nankai U.
NCEPU
Pekin U.
Shandong U.
Shanghai JT U.
IMP-CAS
SYSU
Tsinghua U.
UCAS
USTC
U. of South China
Wu Yi U.
Wuhan U.
Xi'an JT U.

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

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

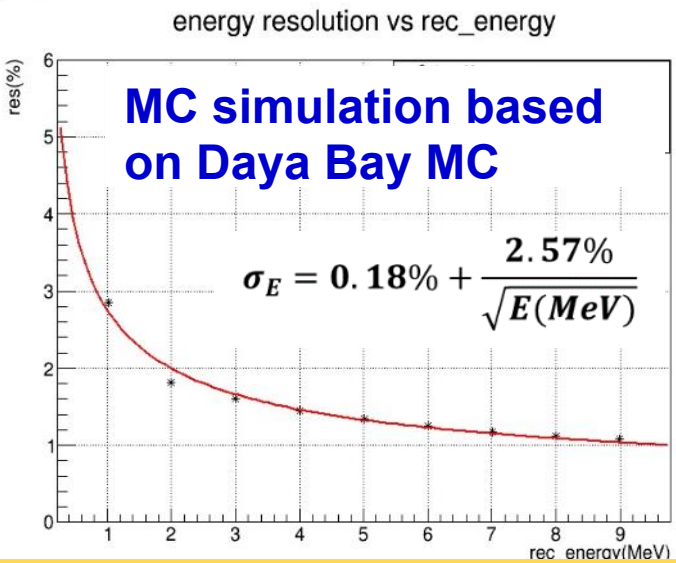
Rich Physics Program with Huge and precise LS Detector



- **20 kton LS detector**
- **3% energy resolution**
- **700 m underground**
- **Rich physics possibilities**
  - **Reactor neutrino for Mass hierarchy**
  - **Precision measurement of oscillation parameters**
  - **Supernovae neutrino**
  - **Geoneutrino**
  - **Solar neutrino**
  - **Atmospheric neutrino**
  - **Exotic searches** including proton decay, dark matter

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

Main Challenges

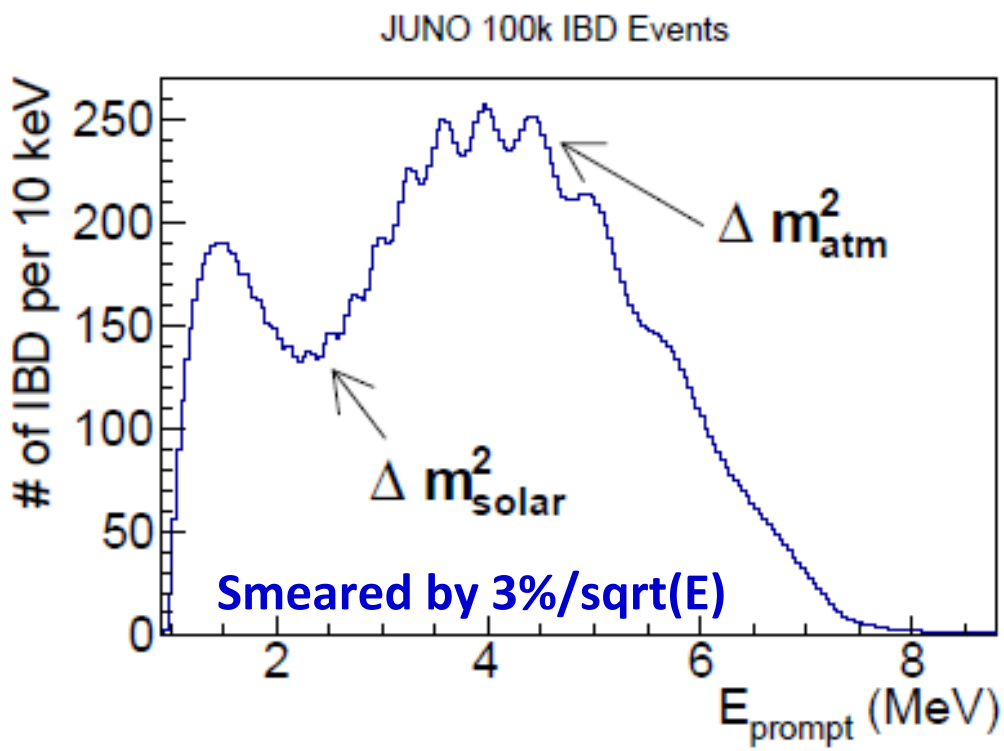


- 75% photocathode coverage
- PMT peak QE: 35%
- Attenuation length of 20 m
  → abs. 60 m + Rayl. scatt. 30m

- 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% @ 1MeV	5% @ 1MeV	3% @ 1MeV
Light yield	250 p.e./MeV	511 p.e./MeV	1200 p.e./MeV

Precision Measurements



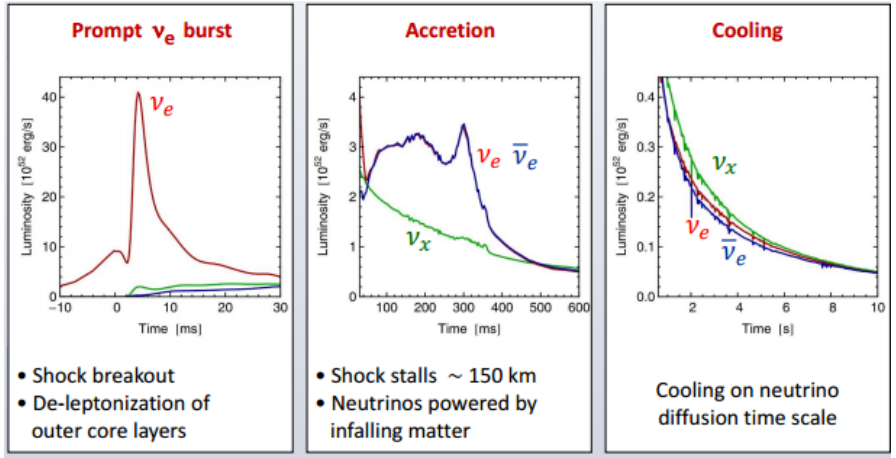
Probing the unitarity of U_{PMNS} to ~1%
more precise than CKM matrix elements !

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

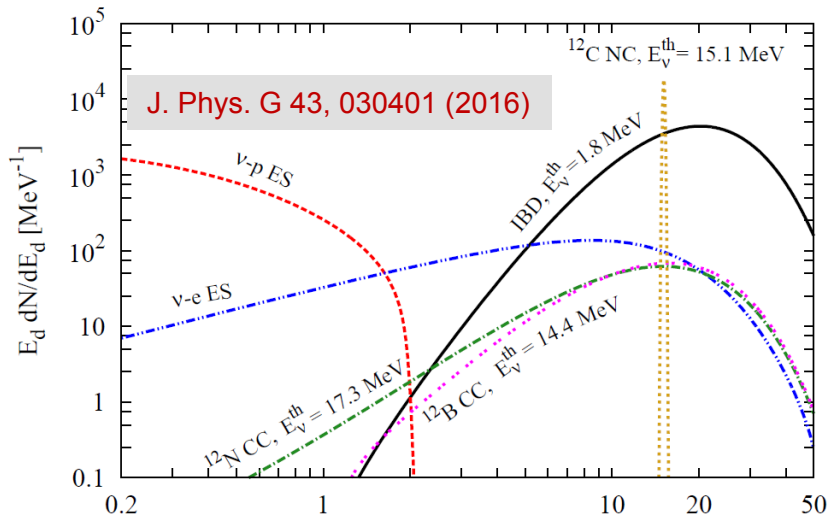
$$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

	Statistics	Systematics considering: 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%

Supernova Detection



Three phases of supernova, Fischer et al. (Basel group), A&A 517:A80, 2010 [arxiv:0908.1871]



The neutrino event spectra with respect to the visible energy *E*d in the JUNO detector for a SN at 10 kpc

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \rightarrow e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \rightarrow \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \rightarrow \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\mathrm{C} \rightarrow \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}$	CC	0.5×10^2	0.9×10^2	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}$	CC	0.6×10^2	1.1×10^2	1.6×10^2

Table. JUNO can detect the quantity of neutrino from a galactic SN @ 10 kpc Special trigger and buffer memory are designed.

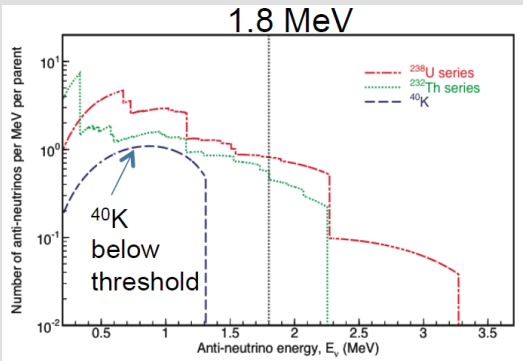
Roughly: one time / 22 years in our galaxy, SN 1987a, Kamiokande II, ~10 ν

JUNO can do

- Big quantity with distinguished different ν flavors
- Reconstruct ν energies and luminosities
- Almost background free due to time information
- Study the explosion mechanism
- Together with gravitational wave / optical observation

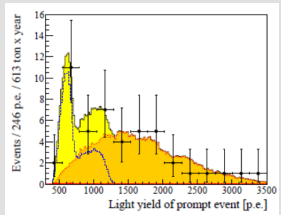
Geoneutrino detection

- **Geoneutrino: antineutrino from the decay of ^{238}U, ^{232}Th, ^{40}K in the Earth, occupying 99% radiogenic heat in the earth. Nature. 310 (5974): 191–198**



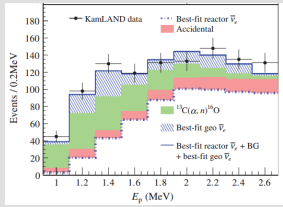
- **Results from Kamland:**
  - PRD 88 (2013) 033001
  - 2002-2012 data: geoneu.

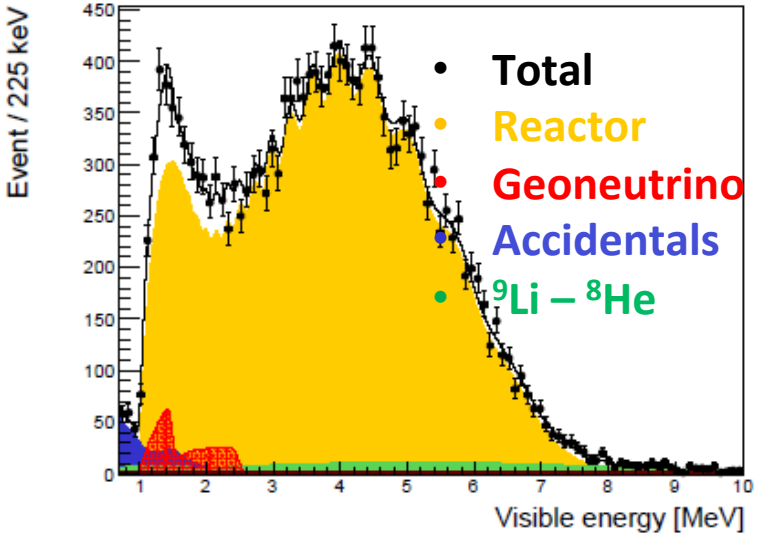
116± $^{27}_{28}$



- **Results from Borexino:**
  - PLB 722 (2013) 295
  - 2007-2012 data: geoneu.

14.3±4.4

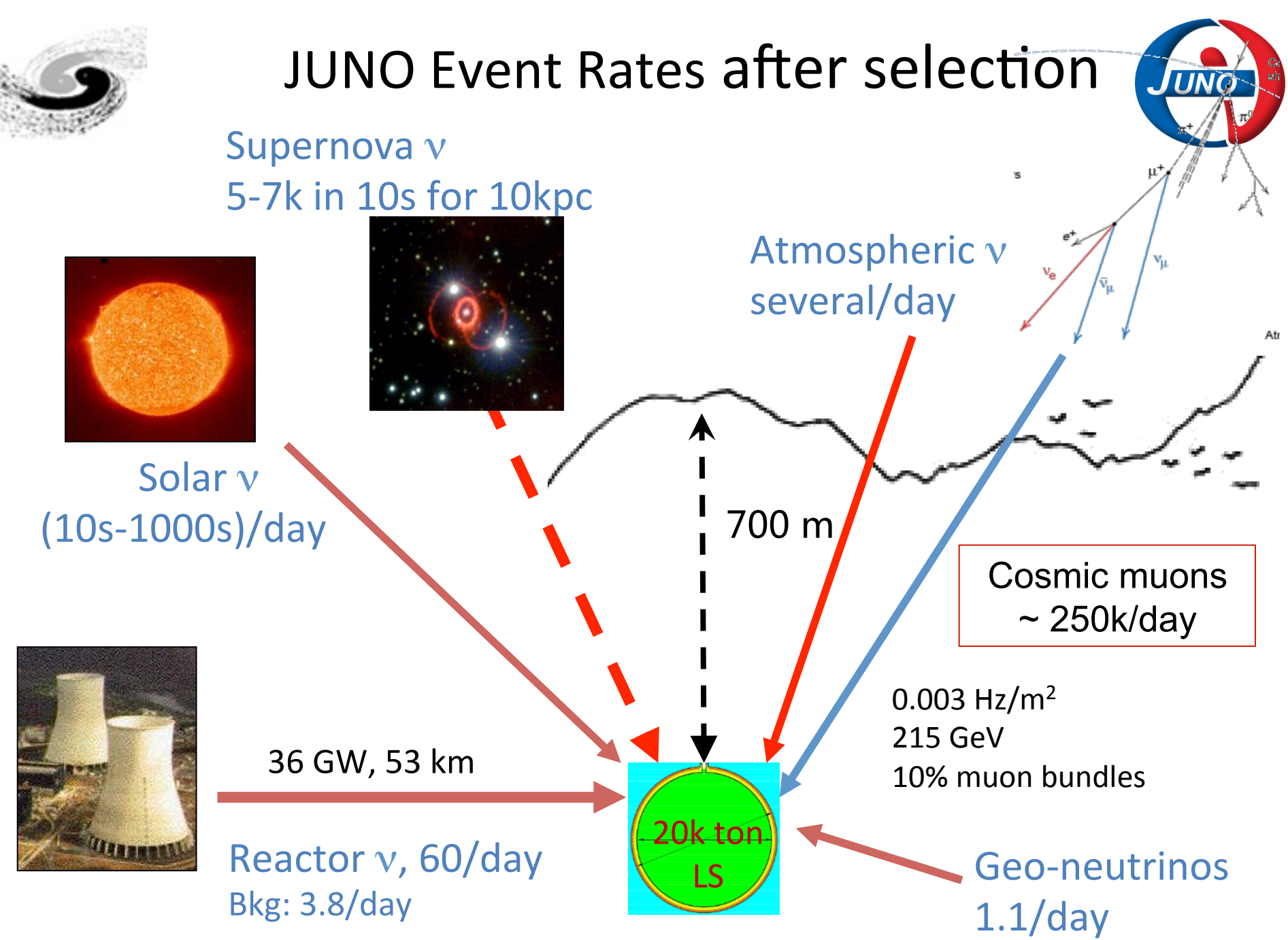




Result of a single toy Monte Carlo for 1-year measurement of JUNO
- FV 18.35 kton (17.2 m radial cut)
- 80% detection efficiency;
- 3% @ 1 MeV energy resolution

- JUNO's unprecedented size and sensitivity allows for the recording of ~400 geoneutrinos per year. 6 months JUNO would match the present world sample of recorded geoneutrinos in the world.
- Earth's surface heat: 46 ± 3 TW, debating it is from primordial or radioactive sources.

JUNO Event Rates after selection

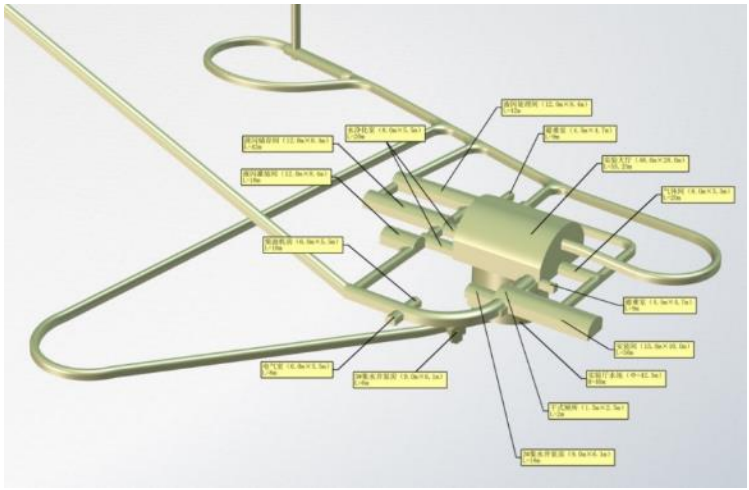


Next about JUNO Project Progress

JUNO Schedule and Progresses

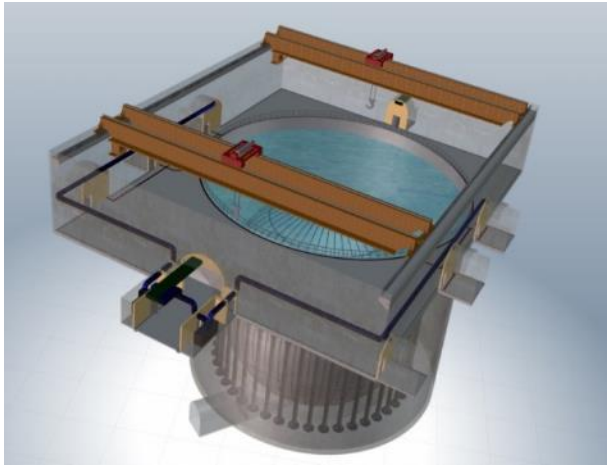
Ground breaking in Jan. 2015

- 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：2014-2018
- Detector component production：2016-2017
- Detector assembly & installation：2018-2019
- Filling & data taking：2020



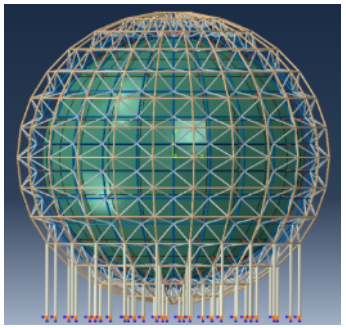
Future Plan

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

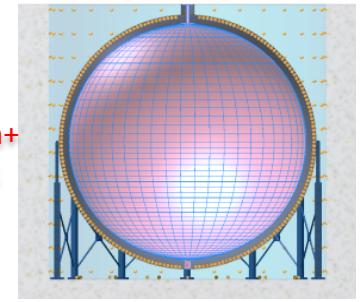
Civil Progress

Highlights: Central Detector

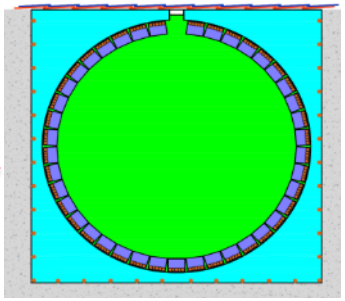
Acrylic sphere+ SS truss



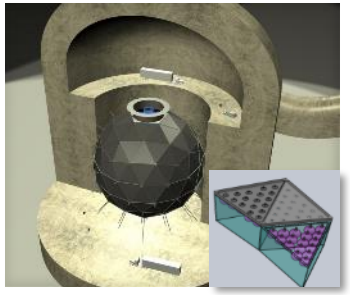
Balloon+ SS tank



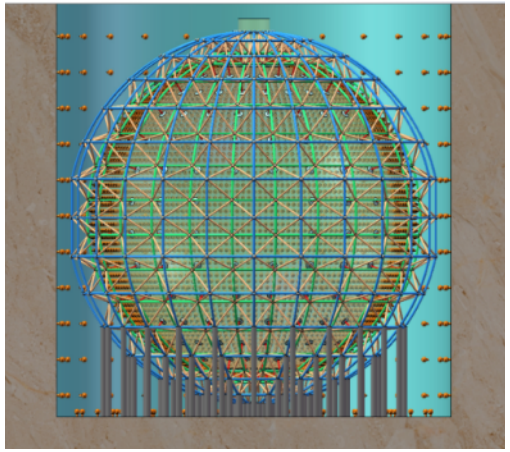
Acrylic module+ SS tank



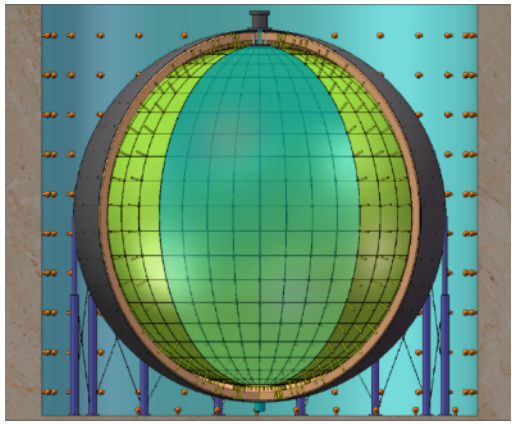
Acrylic sphere+ SS tank



March, 2014

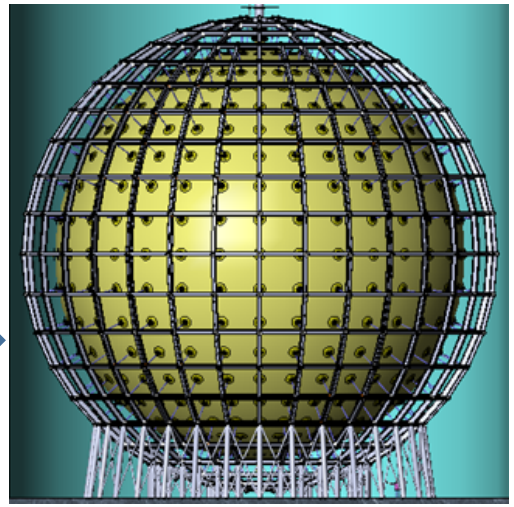


SS truss+ Acrylic sphere



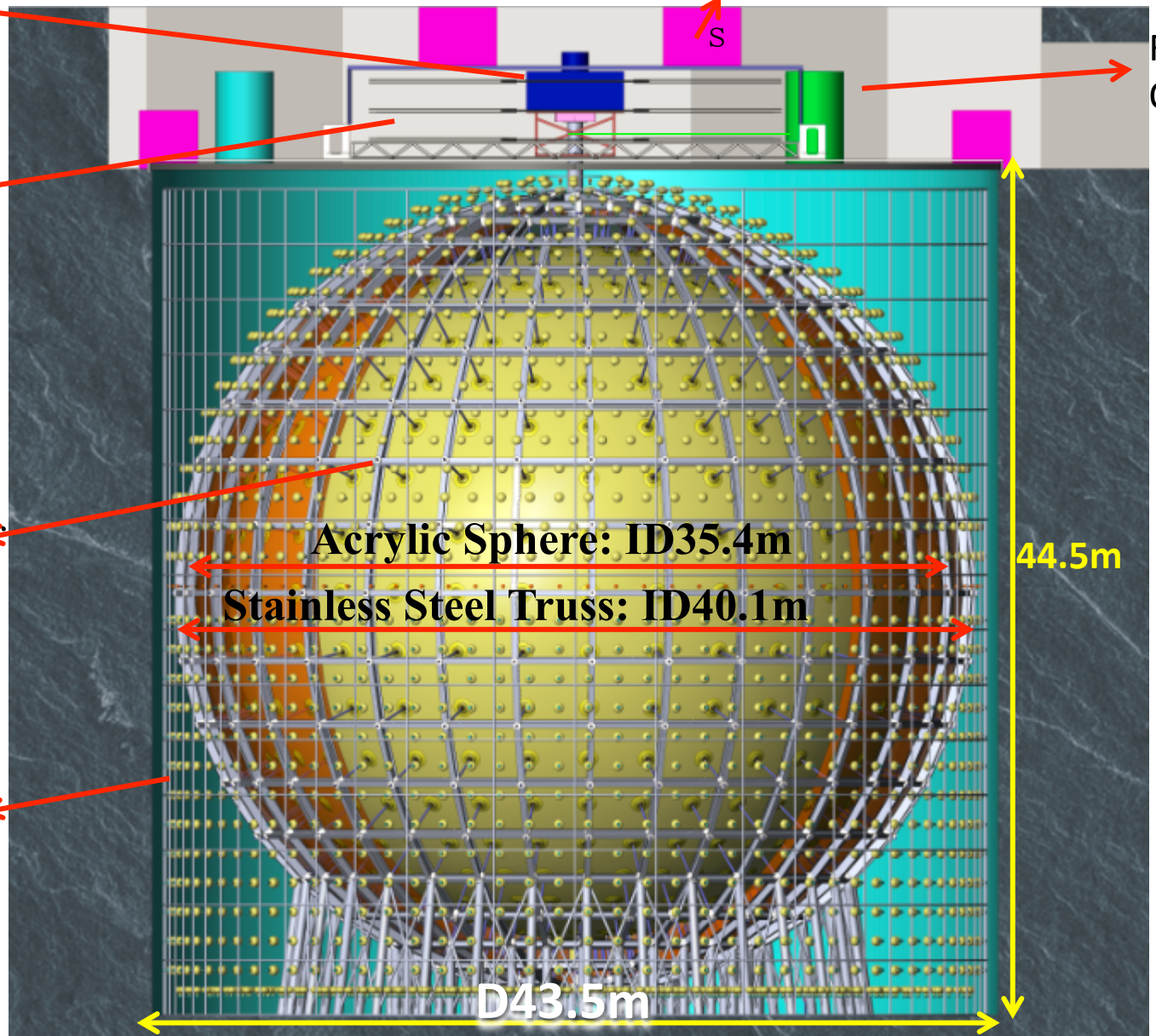
Balloon + Acrylic support+ SS tank

July, 2015



Final decision:
Acrylic sphere + SS truss

Highlights: Detector Dimension



Calibration

Electronics

Filling + Overflow

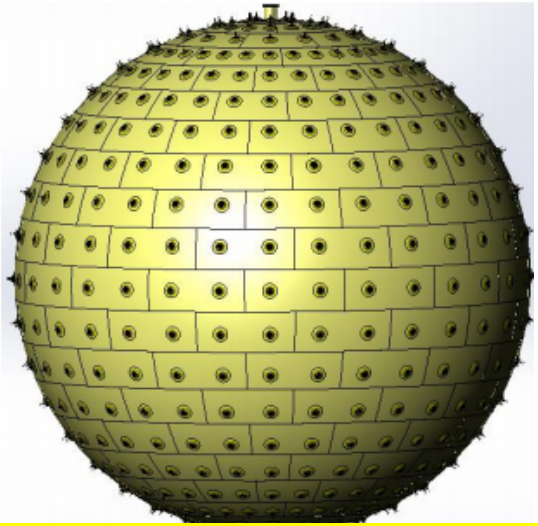
Top Tracker

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

Acrylic connection nodes

The problems of shrinkage and shape variation were resolved.

How to make the acrylic safe?

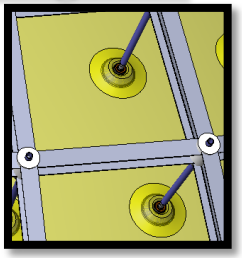
Acrylic stress is a critical issue for engineering design

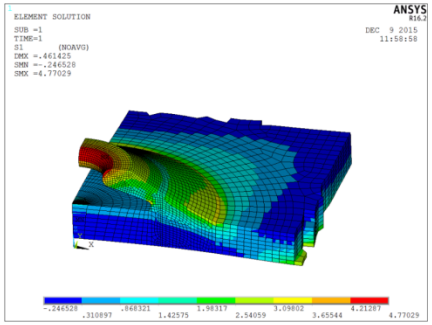
The maximum stress of acrylic is concentrated at connecting node

How to reduce the stress on acrylic node?

a. Lower the load on connecting bar

b. Improve the design of connecting node





Worst case: running, the total vertical load is ~2600t ↑

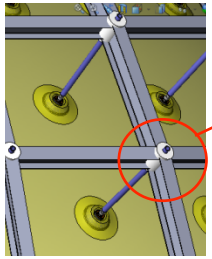
~560 connecting nodes will carry this load

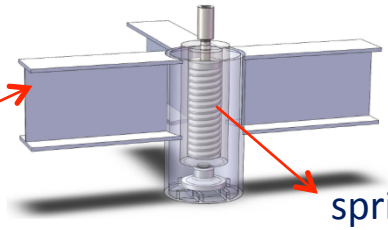
a. How to lower the max load on connecting bar?

- Add the quantity of bar ⟶ Add light block X
- Improve the load distribution on bars ✓

How to improve the load distribution on bars?

Adjust the stiffness of some connecting bars , to get a better distribution of load on whole sphere

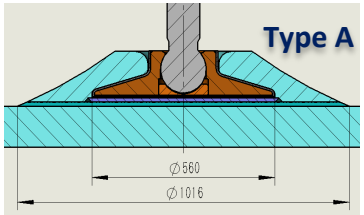




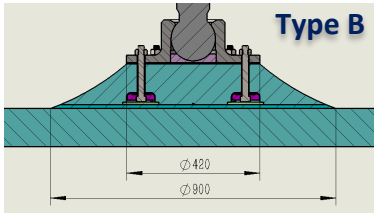
spring

b. How to improve the node design

- Optimize the structure of node
- Two kinds of node for compressive area or tensile area

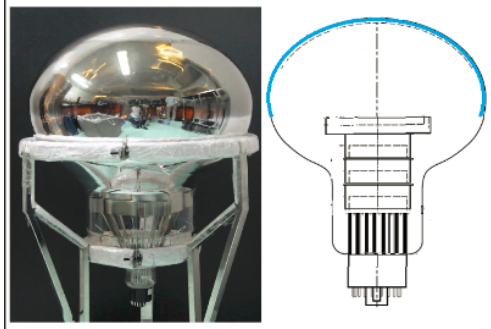
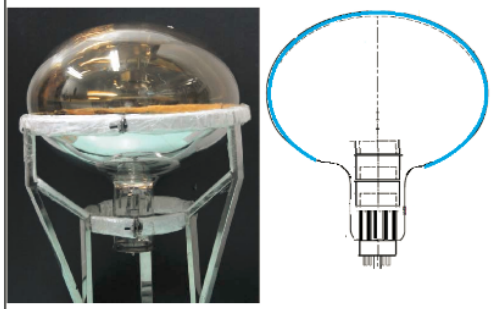


High tensile strength



High compressive strength

Highlights: 20” PMT bidding

20-inch Hamamatus PMT Dynode Ellipsoidal Glass	20-inch IHEP MCP-PMT Horizontal MCPs Ellipsoidal Glass
	

Many prototypes of MCP-PMTs
by the Chinese R&D group
First in the world for large size MCP-PMT

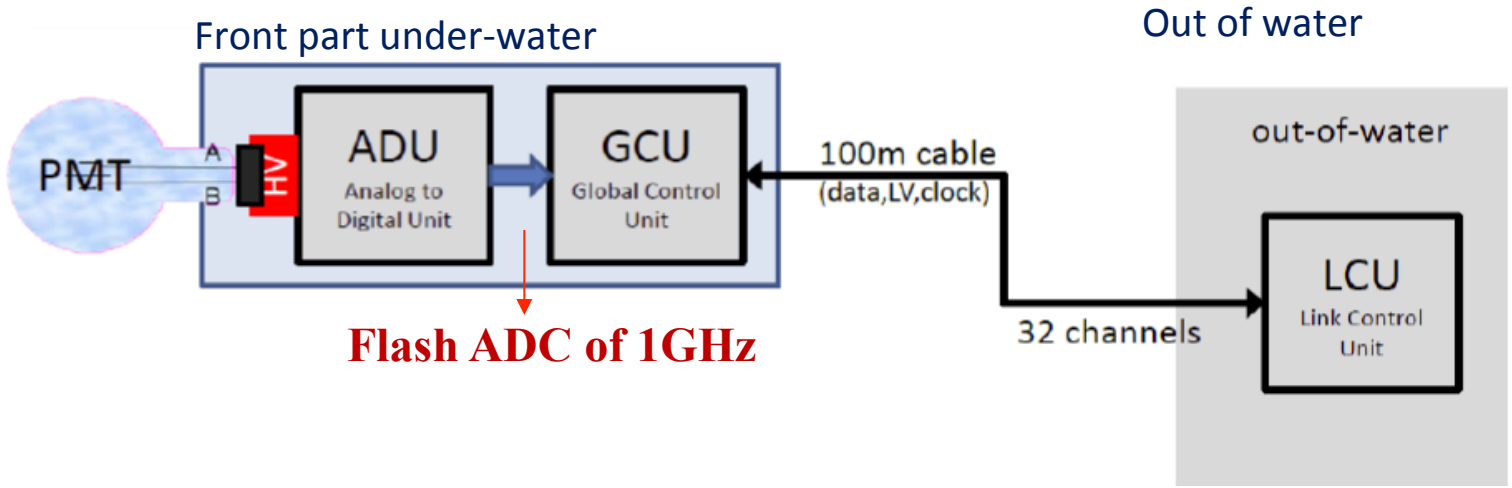
Characteristics	unit	MCP-PMT（NNVC）	R12860 （Hamamatsu）
Detection Eff.(QE*CE*area)	%	27%, > 24%	27%, > 24%
P/V of SPE		3.5, > 2.8	3, > 2.5
TTS on the top point	ns	~12, < 15	2.7, < 3.5
Rise time/ Fall time	ns	R~2 , F~12	R~5, <7; F~9, <12
Anode Dark Count	Hz	20K, < 30K	10K, < 50K
After Pulse Rate	%	1, <2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

Evaluate the impact of the PMT characteristics on the MH as well as the cost → Finished 20” PMT bidding at the end of 2015:

-- 15,000 MCP-PMT (NNVT)

-- 5,000 Dynode-PMT (Hamamatsu)

Highlights: PMT Readout



- Put most of electronics underwater and sealed with BASE, HV together.
- Use a **CAT5+ cable** to transfer data, hit, clock, power and trigger

- Needs to consider the integration and potting structure with PMT
- Replacement under water is almost impossible, need high reliability of potting, electronics and HV

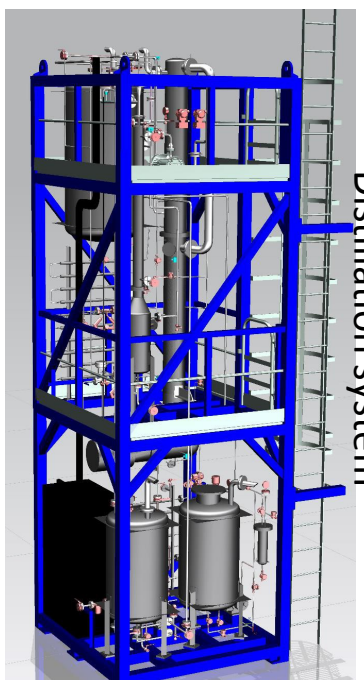
Highlights: LS Pilot plant

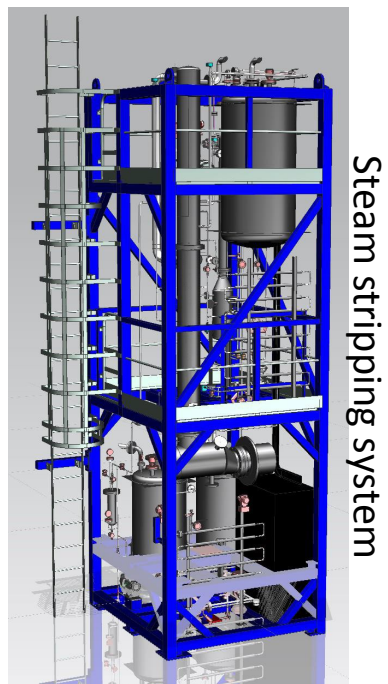
- Purify 20 ton LAB to test the overall design of purification system at Daya Bay. Plan to replace the target LS in one detector.

- Quantify the effectiveness of subsystems
  - Transparency : >20m A.L @430nm
  - Radio-purity: < 10^{-15} g/g (U, Th)
- Determine the choice of sub-systems
  - Al_2O_3, distillation, gas striping, water extraction

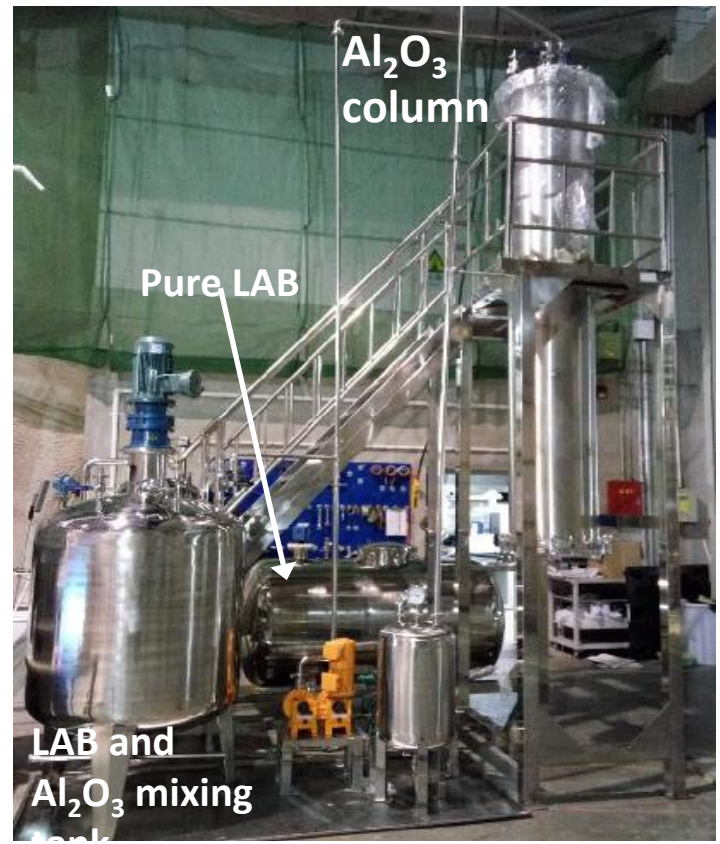
Distillation and steam stripping

Installed at Daya Bay



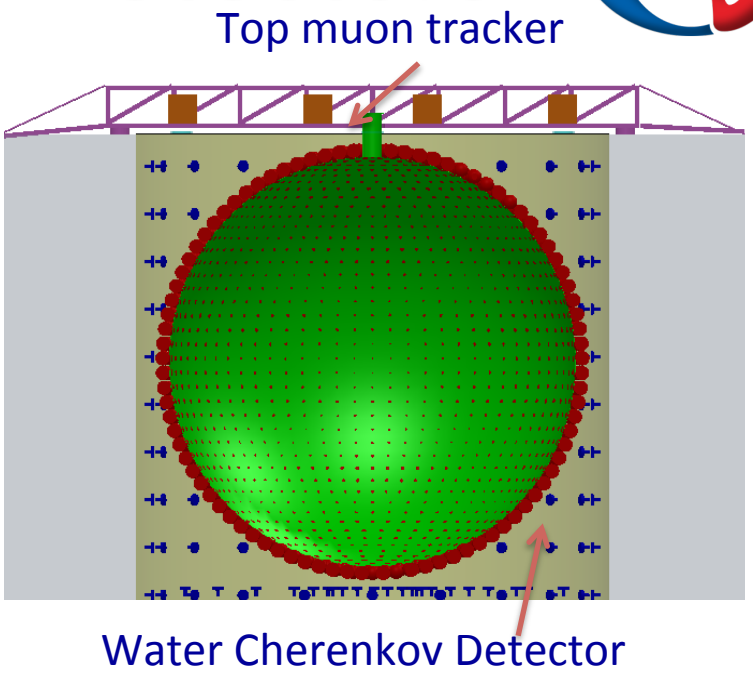


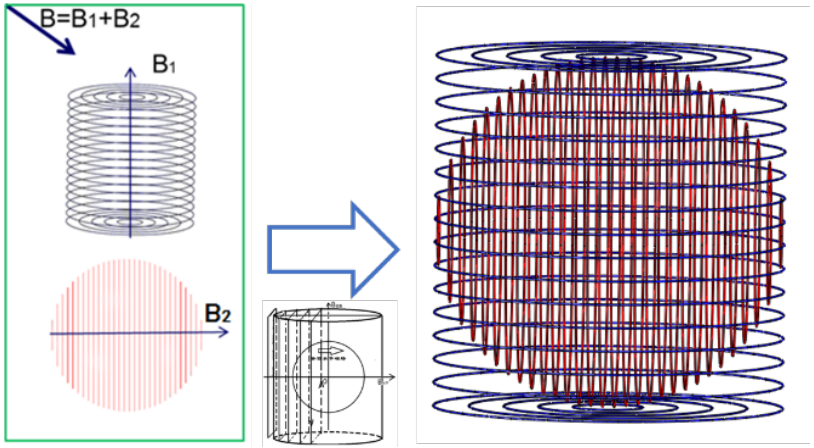
Al_2O_3 column pilot plant installed in Daya Bay LS hall



Highlights: Veto Detectors

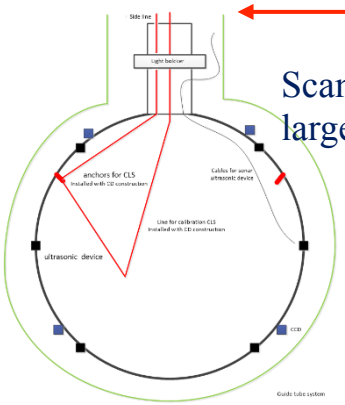
- Cosmic muon flux
  - Overburden：~700 m
  - Muon rate：0.0031 Hz/m^2
    - Hit on CD: ~several Hz
  - Average energy：214 GeV
- Water Cherenkov Detector
  - > 3.9 m water shielding, Radon: <0.2 Bq/m^3
  - ~2000 20”PMTs
  - 40 kton pure water, HDPE lining
  - Similar technology as Daya Bay (99.8% efficiency)
- Compensation Coil for EMF shield
- Top muon tracker
  - Decommissioned OPERA plastic scintillator



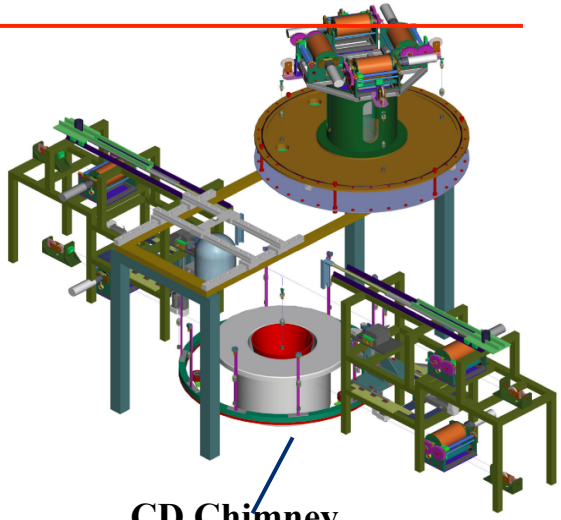


Highlights: Calibration system

Cable Loop System (CLS)



Scan the position at large



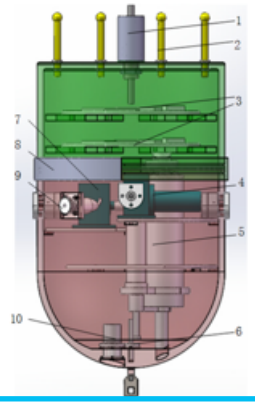
CD Chimney

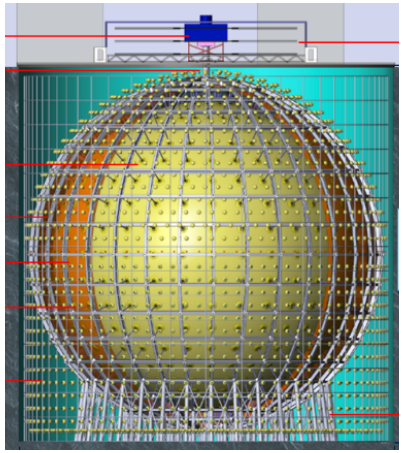
Key: automatically take source from the storage and guide it into the electronic hands.

Four methods

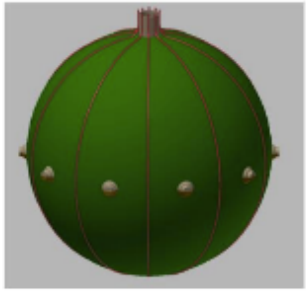
1. ACU： center line
2. Cable loop system:
3. ROV: “submarine”
4. Surface guide tube

Remotely Operated Vehicle(ROV)





•Regular deployment (every week)
• Deployment of radioactive and **Guide Tube (GT)**

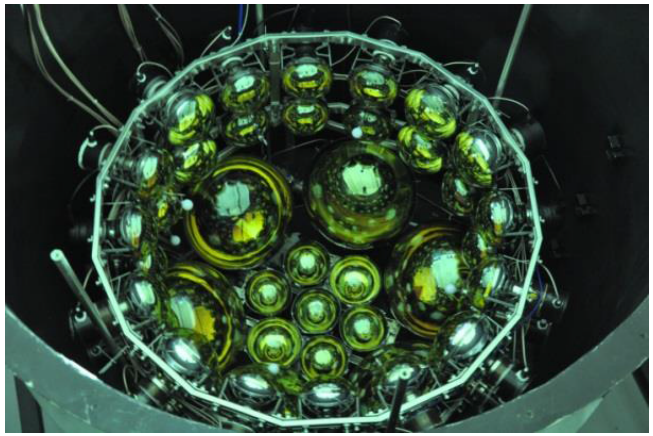


Scan outer surface of CD

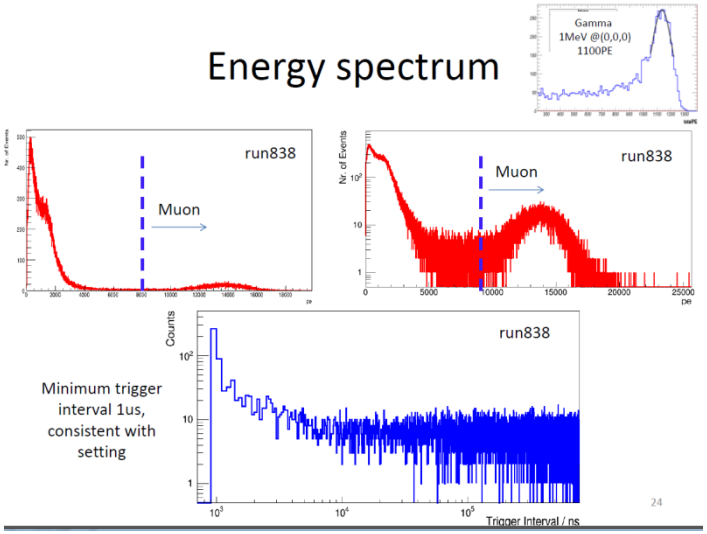
The radiation source is driven with rope pulled by step motors

Highlights: JUNO Prototype

Whole picture of the prototype



Inside picture of the prototype



- The end of 2015, finished construction/ filling, start data taking
- Preliminary analysis shows:
  - –all sub-system reached designed goal: detector\ electronics\water system
  - –PMT water potting working well
- More tests and understanding are doing…

Next about RENO-50

The contents provided by Prof. Soo-Bong Kim

Overview of RENO-50

- **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** : - Determination of neutrino mass hierarchy
- High-precision measurement of θ_{12}, Δm^2_{21} and Δm^2_{ee} - Supernova neutrino, Geo-neutrino and solar neutrino

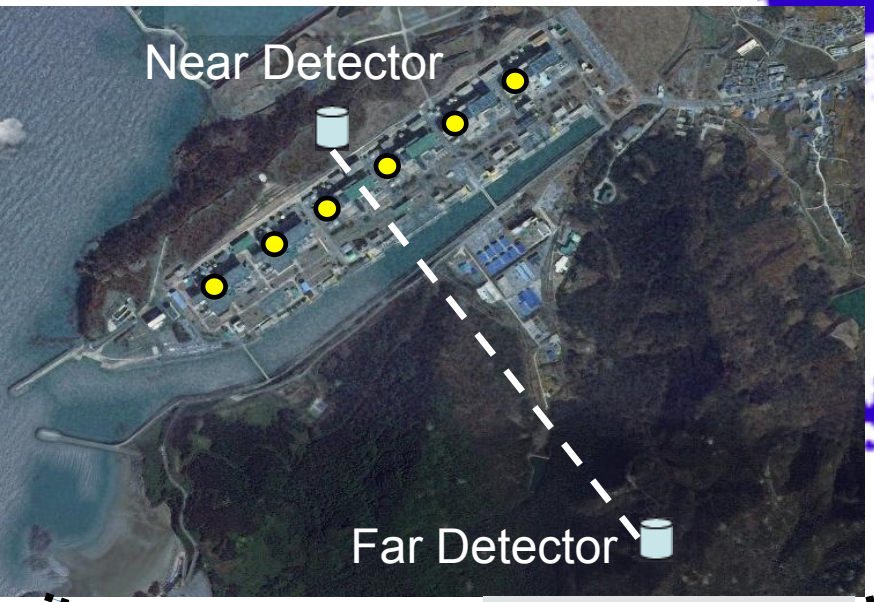
- **Budget** : $ 100M for 6 year construction
(Civil engineering: $ 15M, Detector: $ 85M)

  - An R&D funding (US $2M for 3 years of 2015-2017) is given by the Samsung Science & Technology Foundation.
  - Efforts on obtaining a full construction fund

- **Schedule** : 2016 ~ 2021 : Facility and detector construction
  2022 ~ : Operation and experiment

Physics Potential of RENO-50

- Determination of neutrino mass ordering
  - 3σ sensitivity with 10 years of data
- Precise (~0.5%) measurement of θ_{12}, Δm^2_{21} and Δm^2_{ee}
  - An interesting test for unitarity & essential for the future discoveries
- Neutrino burst from a Supernova in our Galaxy
  - ~5,600 events (@8 kpc)
  - Study the core collapsing mechanism with neutrino cooling
- Geo-neutrinos : ~ 1,500 geo-neutrinos for 5 years
  - Study the heat generation mechanism inside the Earth
- Solar neutrinos
  - MSW effect on neutrino oscillation
- Sterile neutrino search : reactor / radioactive sources / IsoDAR
- Detection of J-PARC beam : ~200 events/year



(NEAR Detector)

RENO

ν θ_{13}

(FAR Detector)

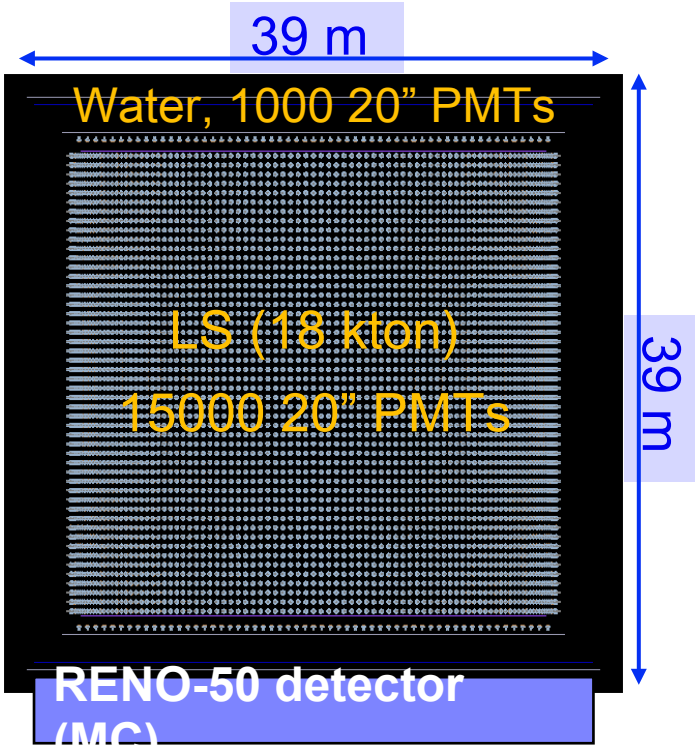
RENO-50

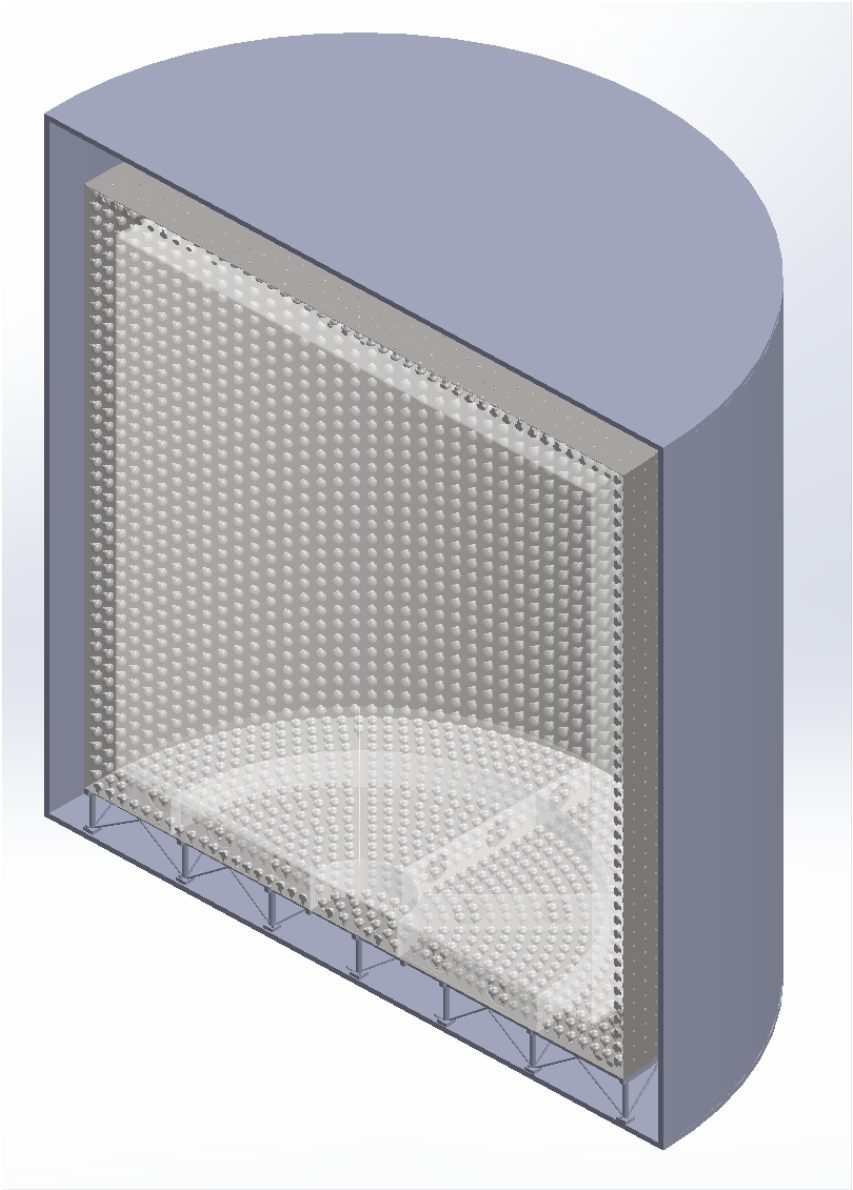
18 kton LS Detector
~47 km from YG reactors

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

RENO-50 Candidate Site

Conceptual Design of RENO-50 Detector





R&D in Progress

(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
- Several methods applied for investigation and evaluation
- Efforts on high sensitive measurement of radioactive concentration and optical parameters in LS

(3) Mechanical design of detector

- Detailed drawing of mechanical parts in progress
- MC simulation to estimate the performance

R&D in Progress

(4) Measurement of radioactivity for the detector materials

- Evaluate radioactive contamination of detector parts using a high purity Ge detector
- Estimate event rate contribution of those contaminations

(5) Measurement device for absolute LS attenuation length

- Developed a long pipe device with a laser source and a PMT
- Upgrade of the device in progress

SAMSUNG 삼성미래기술육성재단

- An R&D funding (US $2M for 3 years of 2015-2017) is given by the Samsung Science & Technology Foundation.

- Efforts on obtaining a full construction fund

Summary

- JUNO and RENO-50 will measure Mass hierarchy (3-4 σ in 2026) and 3 oscillation parameters to <1% level. And many other topics like supernova, geo -neutrino, solar neutrino, sterile neutrino, etc
- 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.

Thank you for your attention!

backup

Selection	IBD efficiency	IBD	Geo-νs	Accidental	^{9}Li/^{8}He	Fast n	(α, n)
-	-	83	1.5	$\sim 5.7 \times 10^4$	84	-	-
Fiducial volume	91.8%	76	1.4	410	77	0.1	0.05
Energy cut	97.8%	73	1.3		71		
Time cut	99.1%						
Vertex cut	98.7%			1.1			
Muon veto	83%	60	1.1	0.9	1.6		
Combined	73%	60	3.8				

Table 2-1: The efficiencies of antineutrino selection cuts, signal and backgrounds rates.

Detector material	^{238}U	^{238}Th	^{40}K	^{60}Co
PMT glass	22 ppb	20 ppb	3.54 ppb	-
Acrylic	10 ppt	10 ppt	10 ppt	-
Polymer film	2 ppt	4 ppt	1 ppt	-
Steel	0.096 ppb	1.975 ppb	0.049 ppb	0.002 Bq/kg
Copper	1.23 mBq/kg	0.405 mBq/kg	0.0377 mBq/kg	-

Table 13-10: The estimated radioactivity of JUNO detector construction materials

LS	^{238}U	^{238}Th	^{40}K	^{210}Pb	^{85}Kr	^{39}Ar
No distillation	10^{-15} g/g	10^{-15} g/g	10^{-16} g/g	$1.4 \cdot 10^{-22}$ g/g	50 μBq/m^3	50 μBq/m^3
After distillation	10^{-17} g/g	10^{-17} g/g	10^{-18} g/g	10^{-24} g/g	1 μBq/m^3	-

Table 13-11: The estimated radioactivity of JUNO LS

Fiducial Cut	LS (Hz)	PMT (Hz)	Acrylic (Hz)	Strut (Hz)	Fastener (Hz)	Sum (Hz)
R<17.7 m	2.39	2.43	69.23	0.89	0.82	75.75
R<17.6 m	2.35	1.91	41.27	0.66	0.55	46.74
R<17.5 m	2.31	1.03	21.82	0.28	0.32	25.75
R<17.4 m	2.27	0.75	12.23	0.22	0.19	15.66
R<17.3 m	2.24	0.39	6.47	0.13	0.12	9.33
R<17.2 m	2.20	0.33	3.61	0.083	0.087	6.31
R<17.1 m	2.16	0.23	1.96	0.060	0.060	4.47
R<17.0 m	2.12	0.15	0.97	0.009	0.031	3.28