Status of JUNO experiment

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on behalf of the JUNO collaboration

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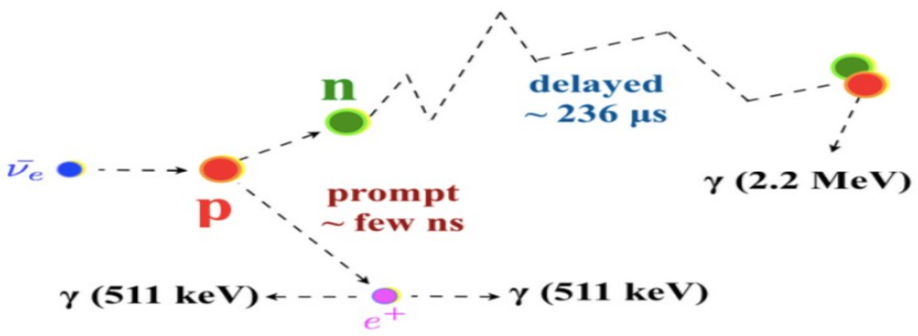
Reactor neutrinos

- Nuclear power plants are a pure and intense source of electron antineutrinos.
- Antineutrino detection through IBD (Inverse Beta Decay).

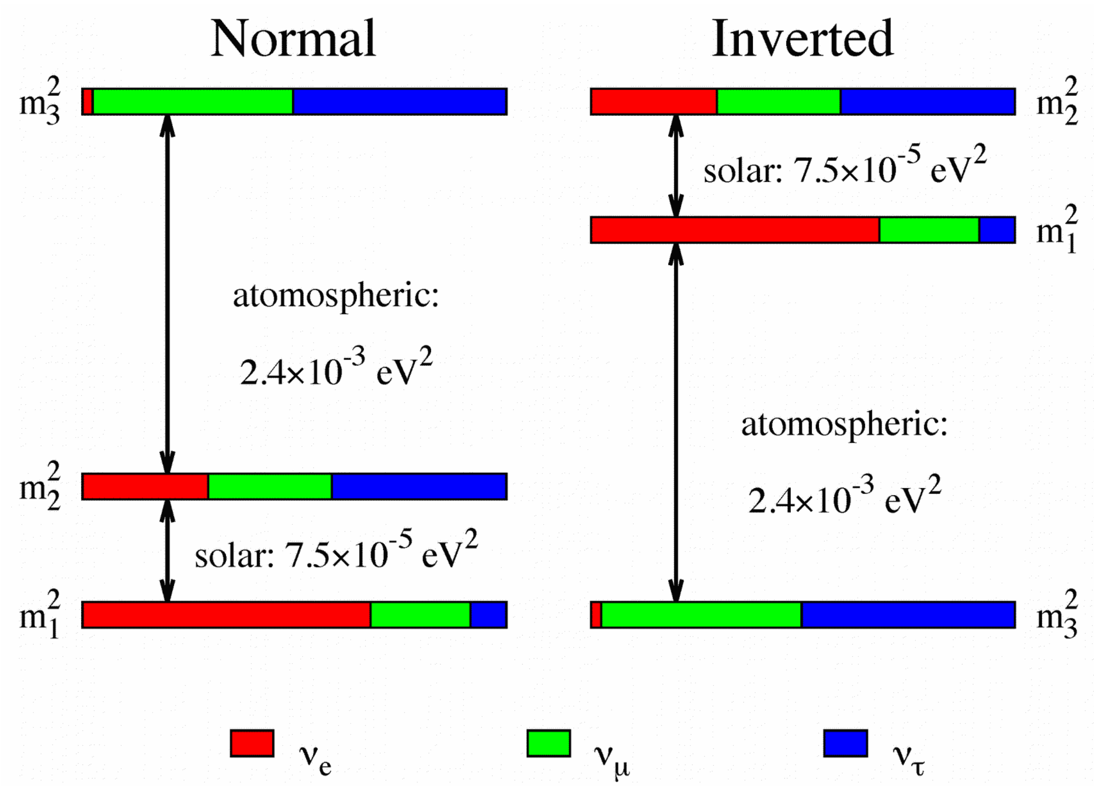


- Relatively large cross section
- Background rejection using coincidence between positron (prompt) and neutron (delayed) signals
- $E_{prompt}=E_\nu - 0.8$ MeV
- Disappearance probability independent from θ_{23} and CP violation.

History and perspectives of reactor neutrino physics:

- Neutrino discovery (Reines & Cowan, 1956)
- θ_{12} and Δm^2_{21} meaurement (KamLAND, 2003)
- Precision θ_{13} measurement (Daya Bay, RENO, Double Chooz)
- Neutrino mass hierarchy just around the corner (JUNO)

Open question: mass hierarchy



Two possible orderings.
Important consequences on neutrinoless double β decay.

Normal hierarchy slightly favored from present results (Nova, SK).
In the future, mass hierarchy determination with different methods:

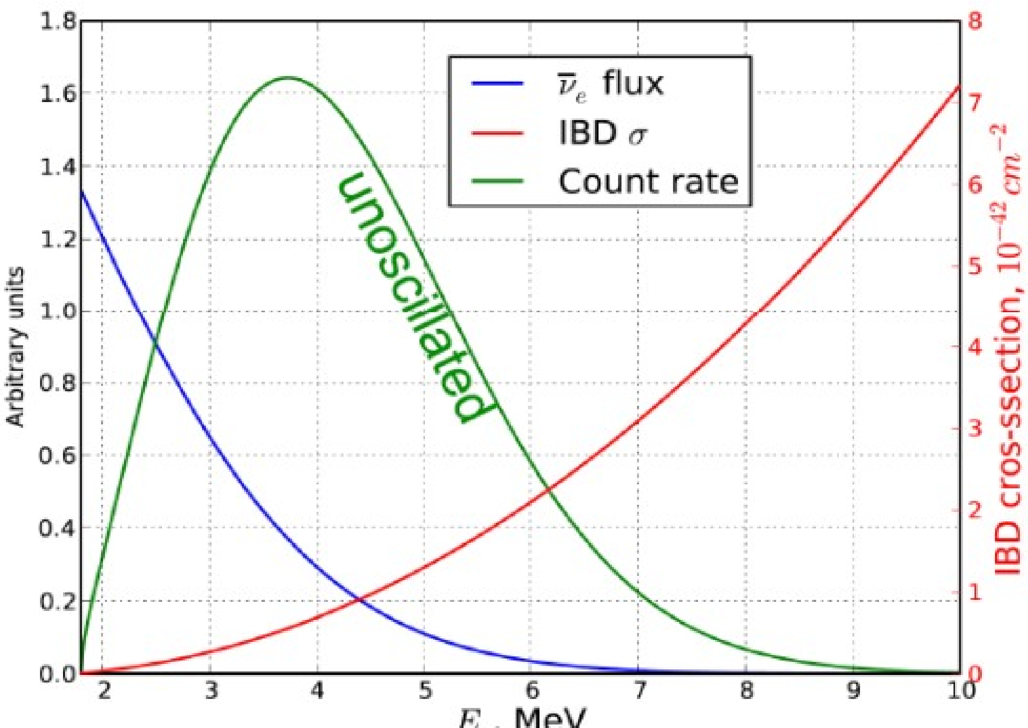
- Matter effect in Long Baseline neutrino beams (DUNE)
- Matter effect in atmospheric neutrinos (PINGU, ORCA)
- Spectrum modification of reactor antineutrinos induced by oscillations with solar-atmospheric parameters interference (JUNO)

Reactor antineutrino disappearance

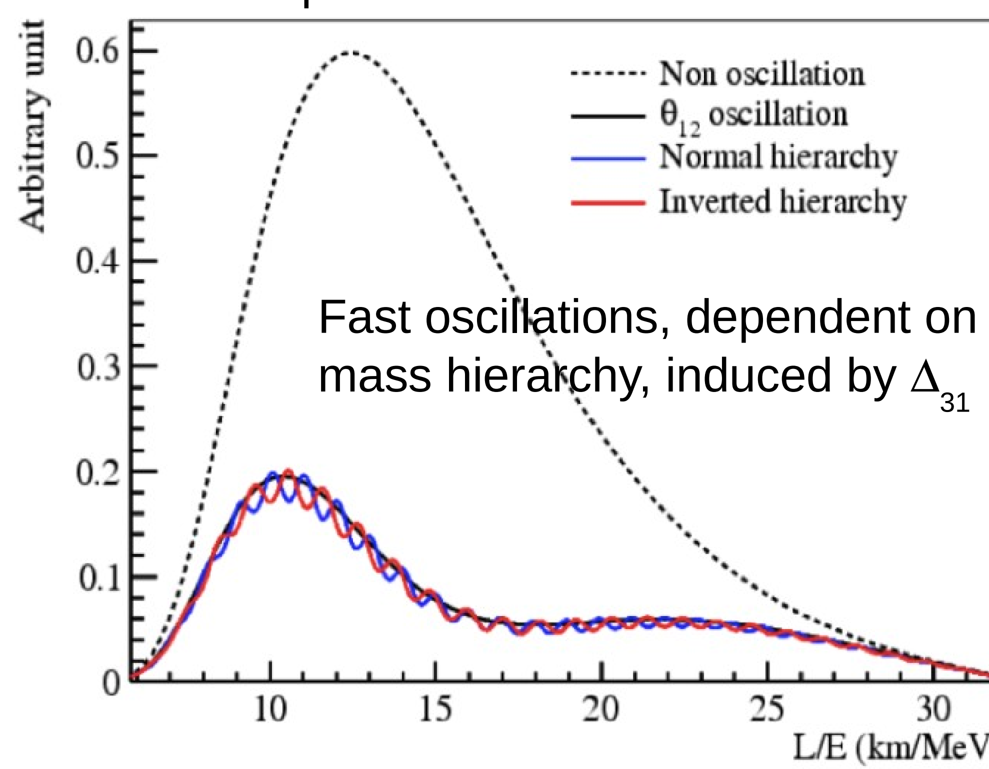
$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

$$
\begin{aligned}
\Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\
\mathrm{NH}: \; |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\
\mathrm{IH}: \; |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}|
\end{aligned}
$$

$\Delta_{ij}=\Delta m^2_{ij}\, L / (4E)$



Antineutrino flux for L=53 km, maximum for solar parameters driven oscillations

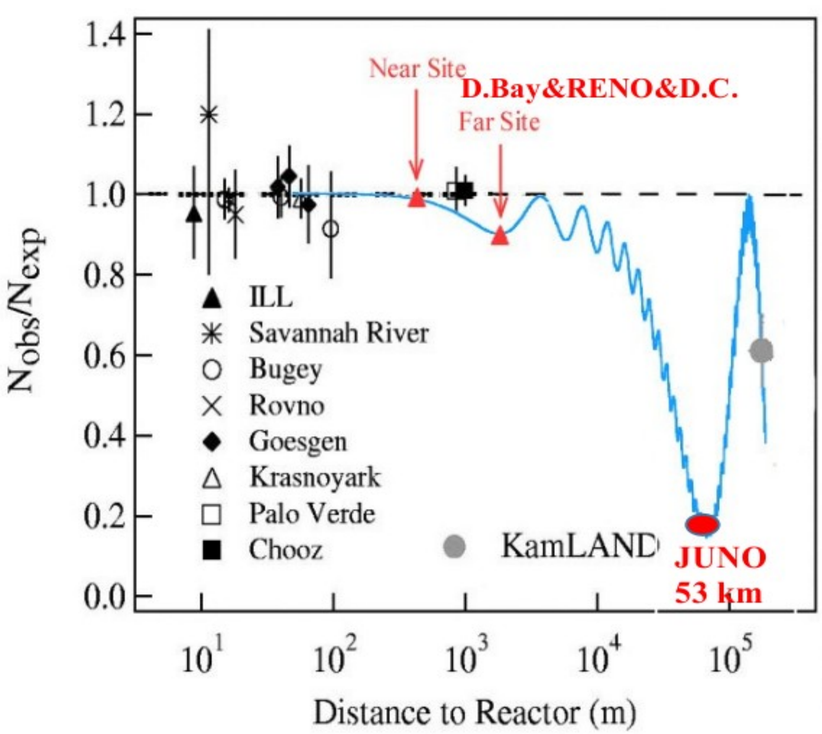


JUNO experiment location

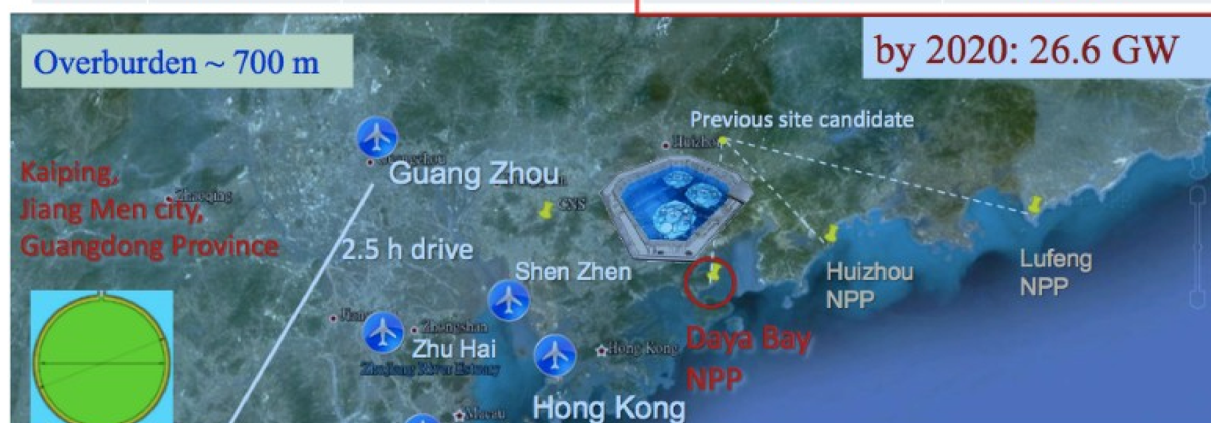
JUNO (Jiangmen Underground Neutrino Observatory) is a multipurpose anti-ν_e detector near Kaiping (South China).

Baseline (53 km) from Yangjian and Taishan reactors (10 cores) optimized in the region of maximum Δm^2_{21}-driven oscillations.

Expexted to start data taking in 2021.

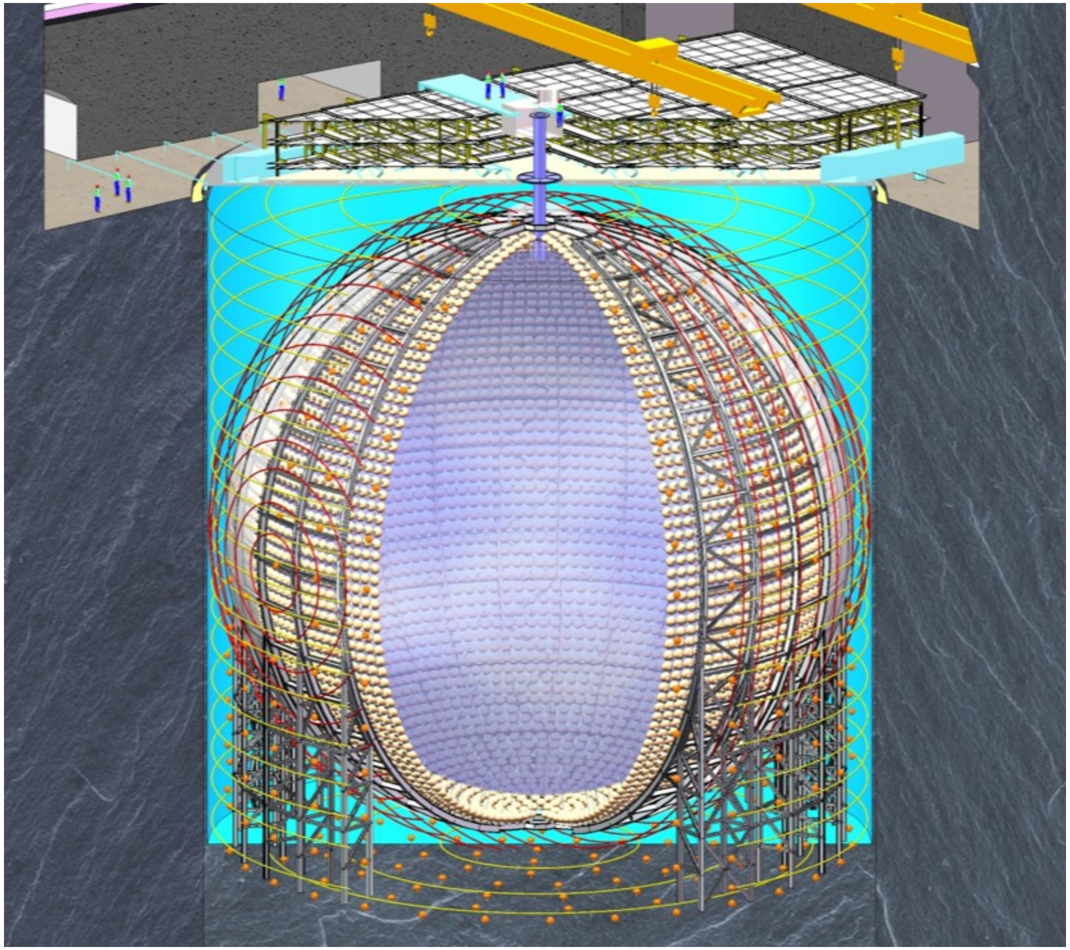


NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



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

JUNO experiment detector concept



10^5 events required in 6 years of data taking: 20 ktons of liquid scintillator in a sphere of about 35 m diameter.

Energy resolution 3%/√E(MeV):
- High liquid scintillator light yield and transparency.
- High photocatode coverage and photon detection efficiency.

Energy scale uncertainty < 1%:
- Calibration systems
- Stereo-calorimetry

JUNO will be the largest scintillator detector ever built !

Experiment	Daya Bay	Borexino	KamLAND	JUNO
LS mass (tons)	20 /detector	~300	~1,000	20,000
Nb of collected p.e. per MeV	~160	~500	~250	~1200
Energy resolution @ 1 MeV	~7.5%	~5%	~6%	~3%

JUNO signal and background

Daily event rate after selection cuts.

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		77	0.1	0.05
Energy cut	97.8%			410			
Time cut	99.1%	73	1.3		71		
Vertex cut	98.7%			1.1			
Muon veto	83%	60	1.1	0.9	1.6		
Combined	73%	60*	3.8				

* At a nominal power of 36 GWth (26.6 GWh in 2020)

R<17.2 m

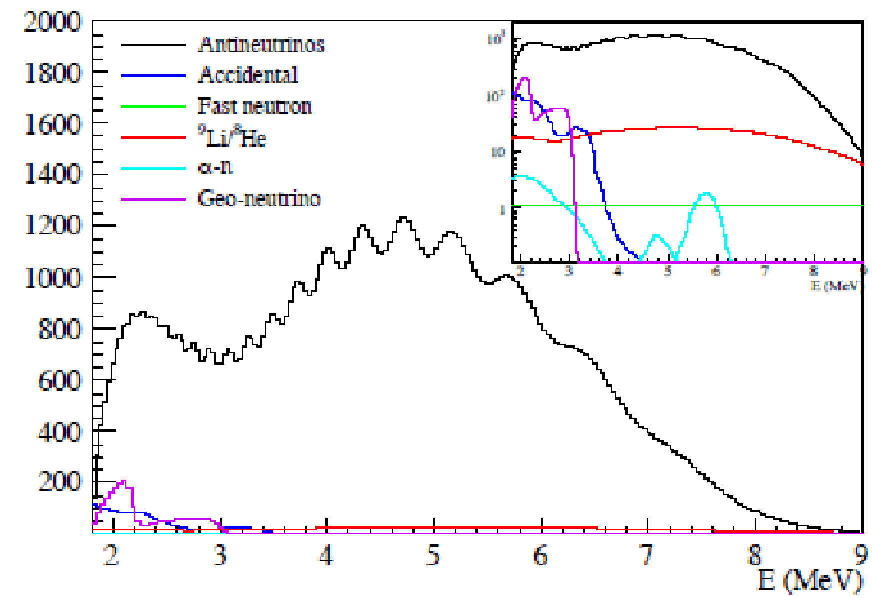
$\Delta T < 1$ ms

$\Delta R < 1.5$ m

Veto system

0.7 MeV < E_{promt} < 12 MeV

1.9 MeV < $E_{delayed}$ < 2.5 MeV



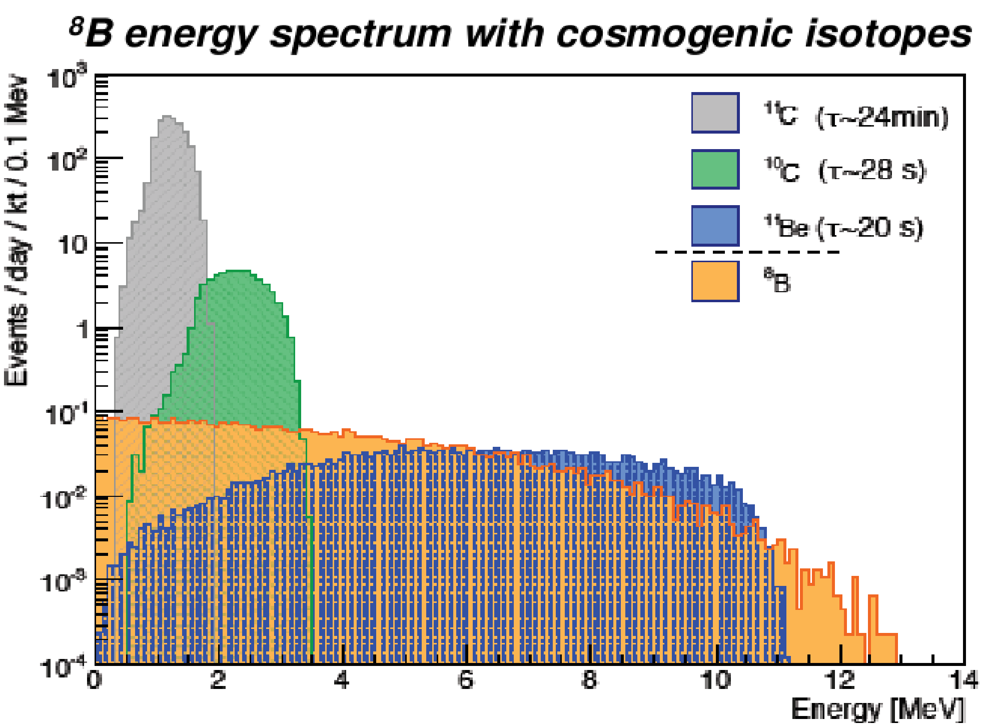
Careful treatment of cosmogenic ^{9}Li/^{8}He background.
After selection cuts:
60 IBD and 3.8 bkg events/day.

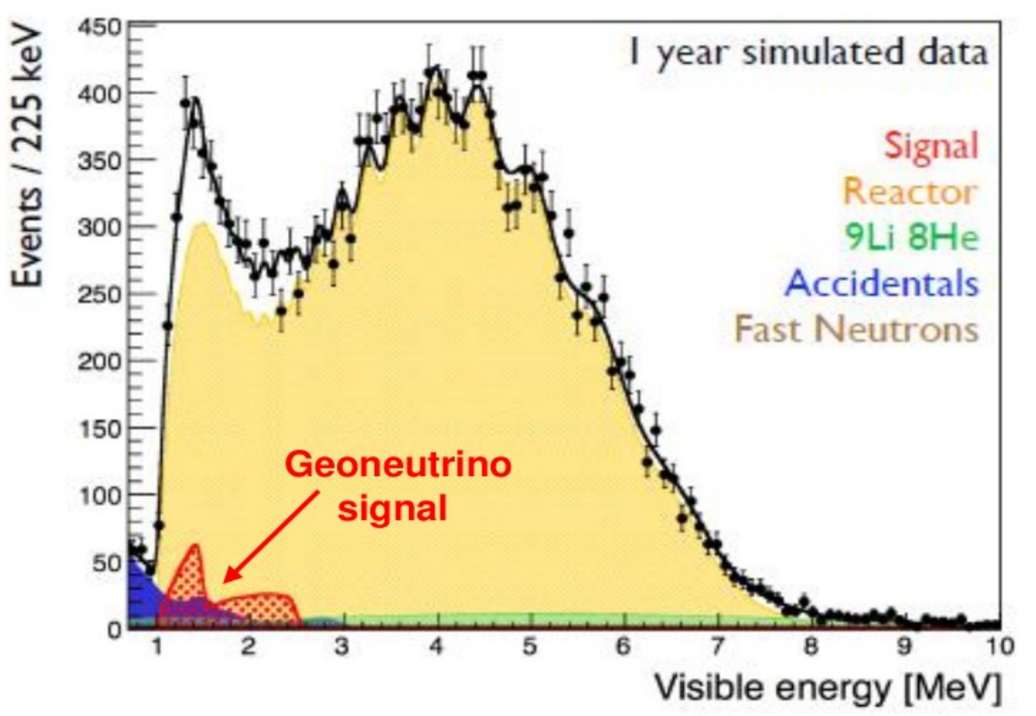
JUNO Physics reach

JUNO designed to reach 3-4 σ precision on MH determination (with 100000 events). But also other measurements possible:

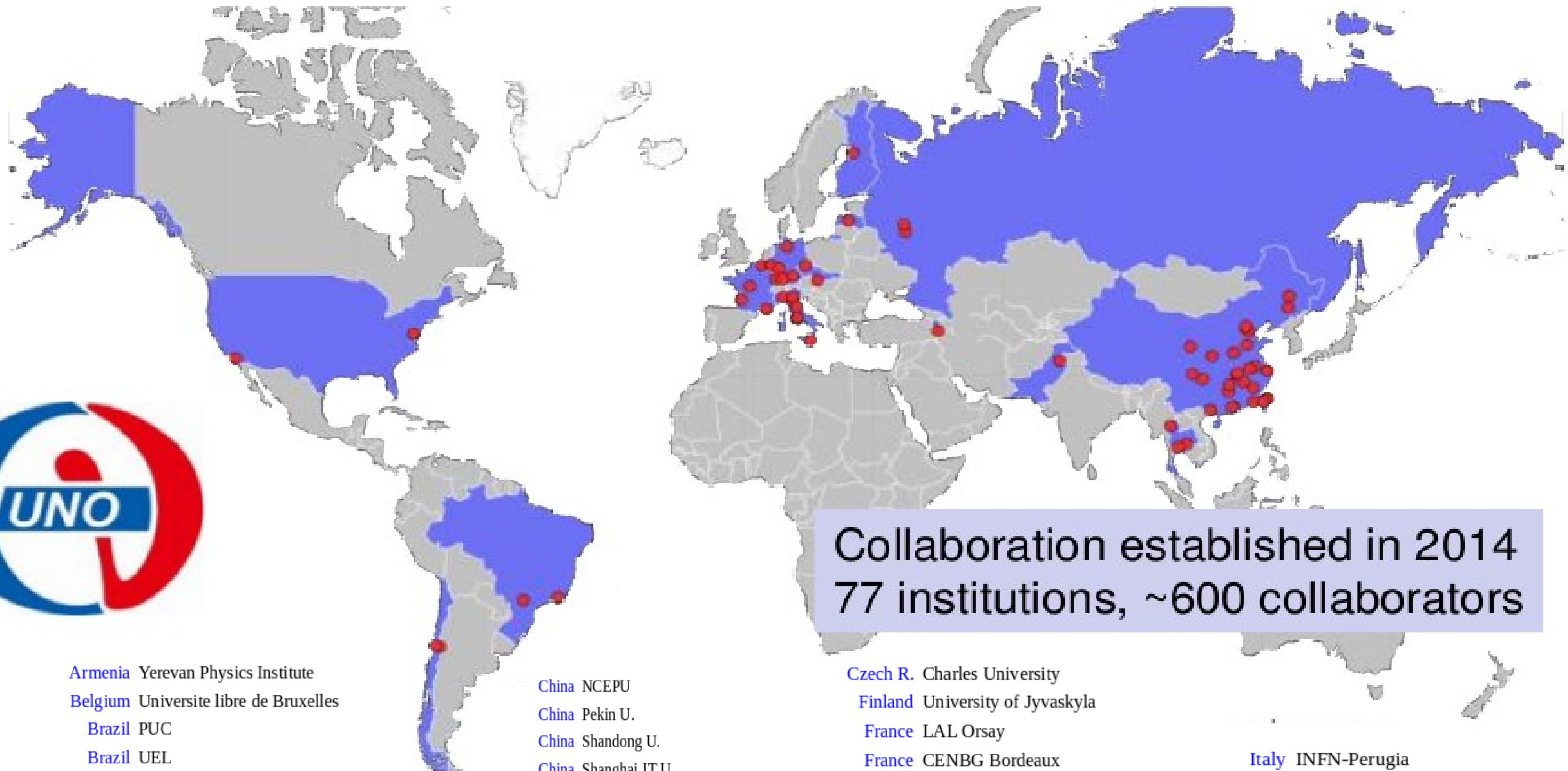
- Oscillation parameters determination (θ_{12}, Δm^2_{21}, Δm^2_{31}) at sub-% level.
- Neutrino observation from natural sources (solar, atmospheric, Supernova burst, diffuse Supernova neutrinos, geoneutrinos).
- Exotic searches (Lorentz-Invariance-Violation, Proton decay).

More details in J. Phys. G43 (2016) n.3, 030401





JUNO Collaboration

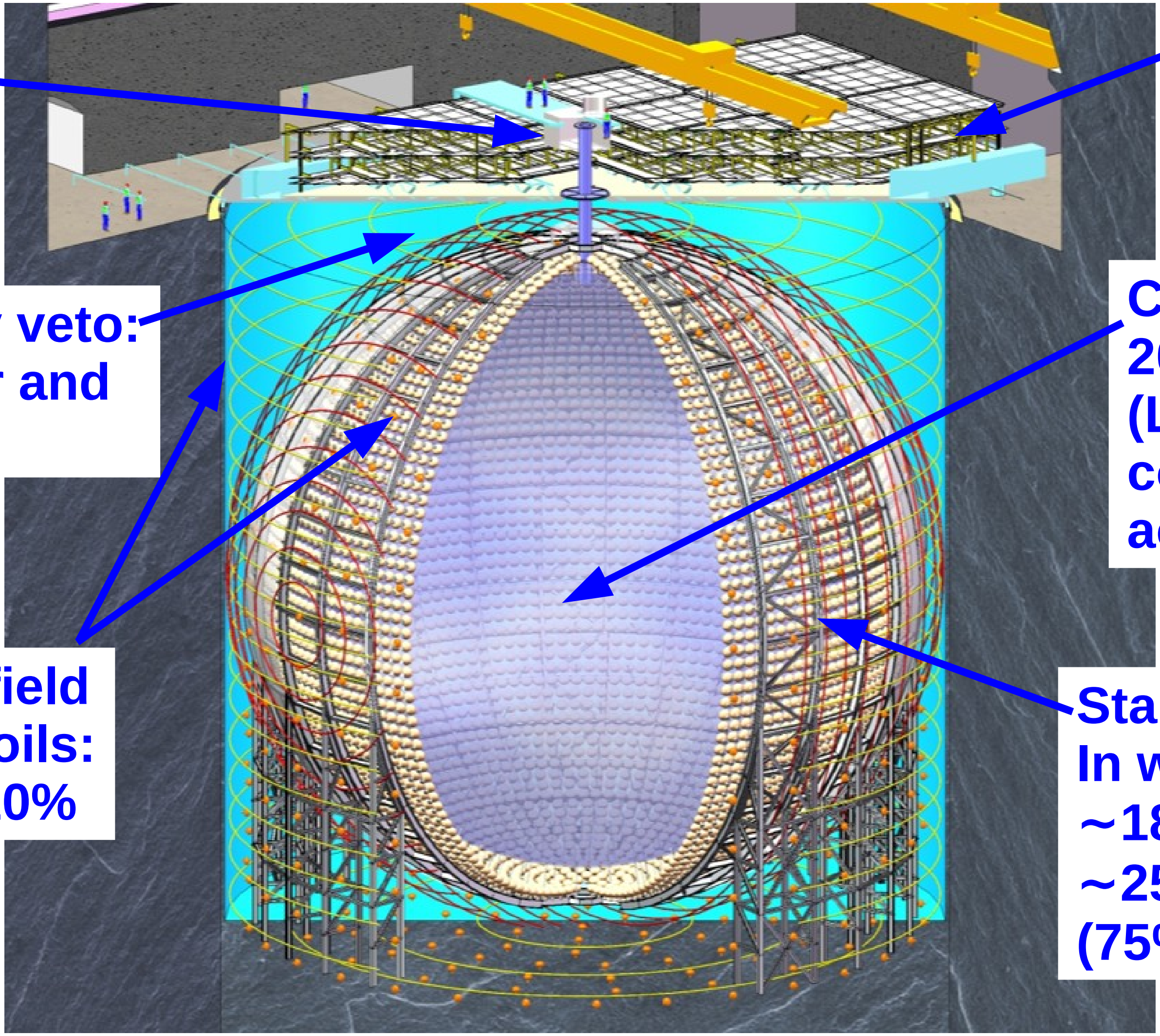


Collaboration established in 2014
77 institutions, ~600 collaborators

Armenia Yerevan Physics Institute
Belgium Universite libre de Bruxelles
Brazil PUC
Brazil UEL
Chile PCUC
Chile UTFSM
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 IGG-Beijing
China IGG-Wuhan
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 Zhengzhou U.
China NUDT
China CUG-Beijing
China ECUT-Nanchang City
Czech R. Charles University
Finland University of Jyvaskyla
France LAL Orsay
France CENBG Bordeaux
France CPPM Marseille
France IPHC Strasbourg
France Subatech Nantes
Germany FZJ-ZEA
Germany RWTH Aachen U.
Germany TUM
Germany U. Hamburg
Germany FZJ-IKP
Germany U. Mainz
Germany U. Tuebingen
Italy INFN-Catania
Italy INFN-Frascati
Italy INFN-Ferrara
Italy INFN-Milano
Italy INFN-Milano Bicocca
Italy INFN-Padova
Italy INFN-Perugia
Italy INFN-Roma3
Latvia IECS
Pakistan PINSTECH (PAEC)
Russia INR Moscow
Russia JINR
Russia MSU
Slovakia FMPICU
Taiwan-China National Chiao-Tung U.
Taiwan-China National Taiwan U.
Taiwan-China National United U.
Thailand NARIT
Thailand PPRLCU
Thailand SUT
USA UMD1
USA UMD2
USA UC Irvine

JUNO Experiment

700 m overburden.



Calibration box

Top Tracker:
3 layers of plastic scintillator strips (from OPERA)

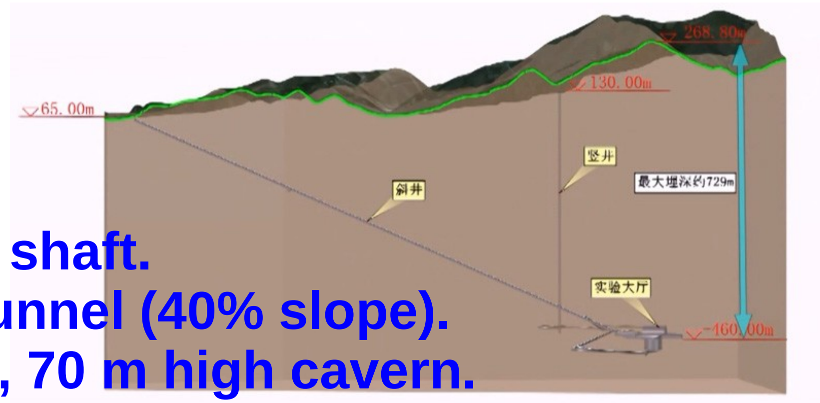
Water Cerenkov veto:
35 kton of water and 2000 20” PMTs

Central detector:
20 kton of LS (LAB/PPO/bisMSB) contained inside an acrylic sphere.

Earth magnetic field compensating coils:
residual field < 10%

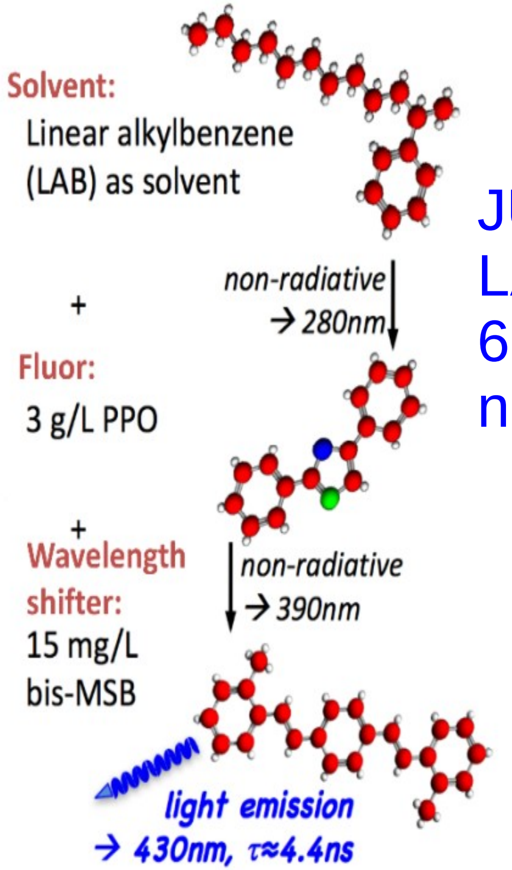
Stainless Steel Truss:
In water, holding
~18000 20” PMTs
~25000 3” PMTs
(75% photo-coverage)

Civil engineering



- 564 m vertical shaft.
- 1266 m long tunnel (40% slope).
- 50 m diameter, 70 m high cavern.

Liquid scintillator



JUNO liquid scintillator composition:
LAB + PPO (2.5 g/l) + bis-MSB (1-3 mg/l)
60 ton of PPO and 24-72 kg of bis_MSB needed in total.

Requirements from energy resolution:
High light yield (10^4 γ/MeV)
Attenuation length: > 20 m @ 430 nm
Good radiopurity: ^{238}U/^{232}Th < 10^{-15} g/g, ^{40}K < 10^{-16} g/g.

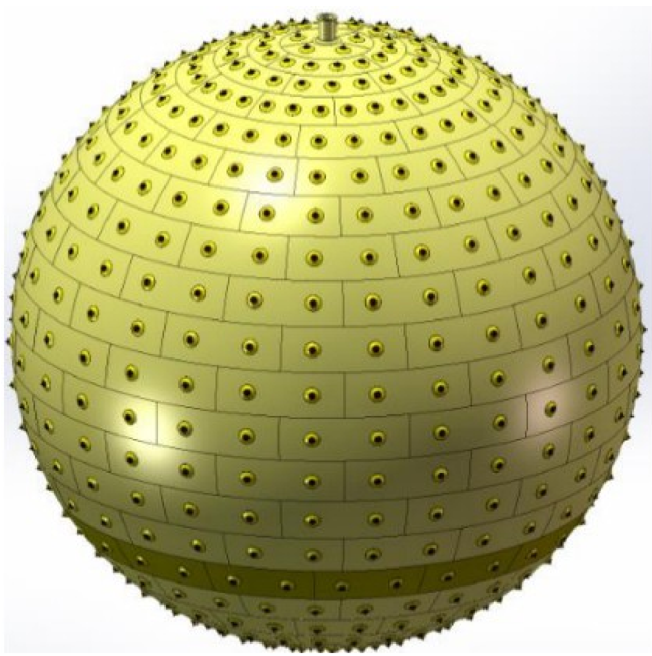
Liquid scintillator purification pilot plant undet test @ Daya Bay:

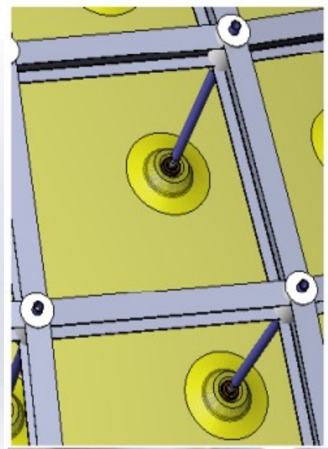
- Distillation, Al_2O_3 column purification, filtration, water extraction, gas stripping.
- Measured attenuation length of purified LAB > 25 m.
- Ongoing studies on radio-impurities.

OSIRIS detector design study for monitoring LS radio-purity at 10^{-16} g/g level (solar neutrinos specifications) during JUNO filling.

Central detector

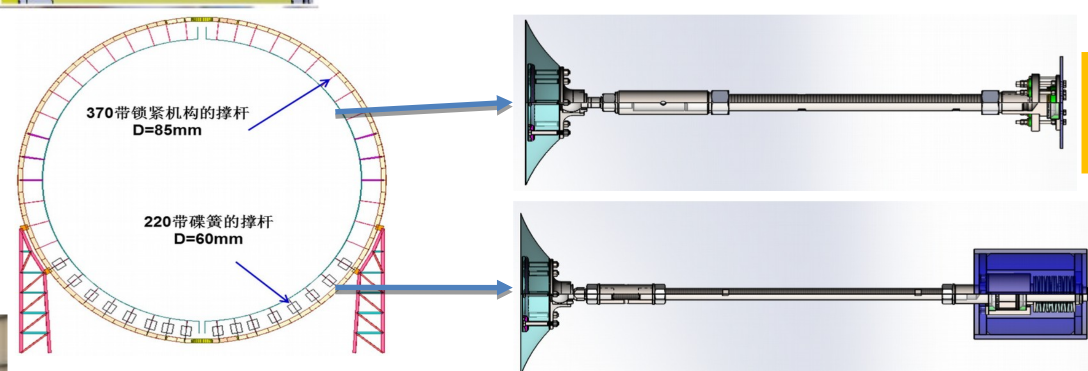
The central detector will be built with acrylic panels of 12 cm thickness: about 260 panels for a total weigth around 600 tons.
The Stainless Steel main structure is connected to the acrylic sphere.





Acrylic requirements:

- Max stress control on acrylic < 3.5 Mpa
- Max pulling load for acrylic node ~ 8 tons
- Break at load for acrylic node ~ 100 tons
- Radiopurity 10^{-12} g/g for ^{40}K, ^{238}U, ^{232}Th



370 half fixing structures

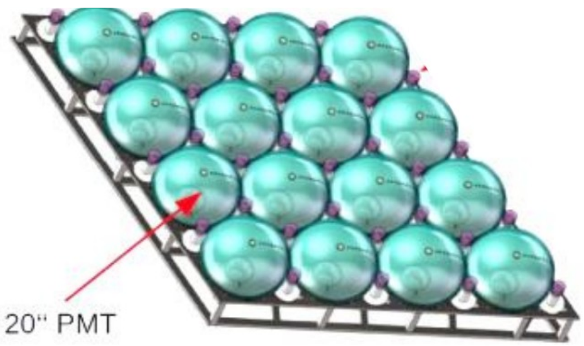
220 spring structures

JUNO CD prototype 1:12 built @ IHEP, complete of FOC (Filling/Overflow/Circulation) systems for testing.

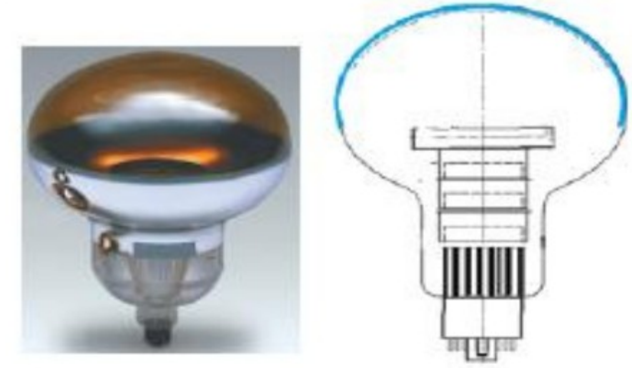
Large PMT system

JUNO will use 20” Photomultipliers as its main photodetection system.

Tight arrangement with a photocoverage of ~ 75%



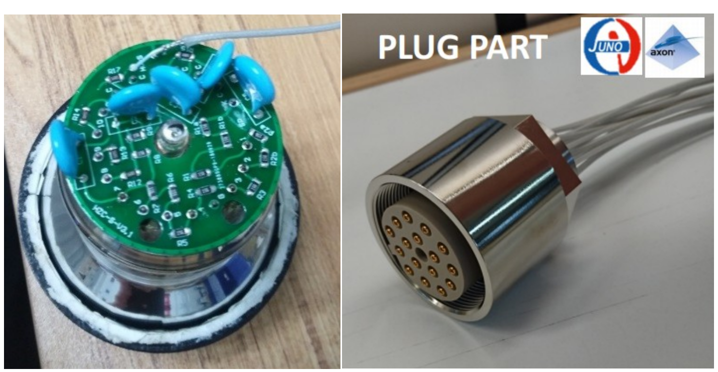
Microchannel plate MCP-PMTs



Dynode-PMTs

Two complementary technologies:

- 15000 MCP-PMTs from NNVT
- 5000 dynode PMTs from Hamamatsu

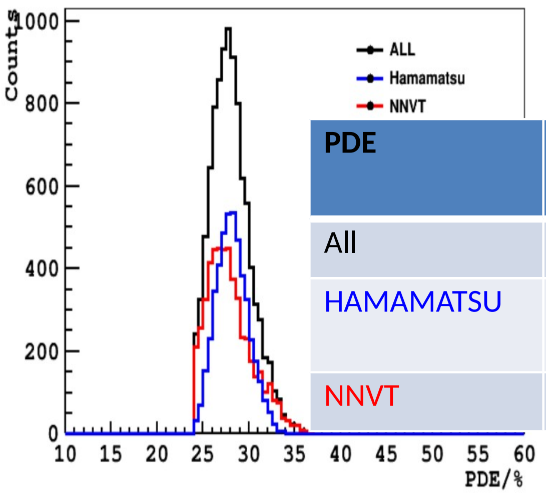


Characteristics	unit	MCP-PMT (NNVT)	R12860 (Hamamatsu)
Detection efficiency (QE*CE)	%	27 (increased to 30)	27
P/V of SPE		3.5, >2.8	3, >2.5
TTS on top point	ns	~12, <15	2.7, <3.5
Rise time/Fall time	ns	R~2, F~12	R~5, F~9
After pulse rate	%	1, <2	10, <15
Glas radioactivity	ppb	238U : 50 232Th : 50 40K : 20	238U : 400 232Th : 400 40K : 40

Large PMT testing

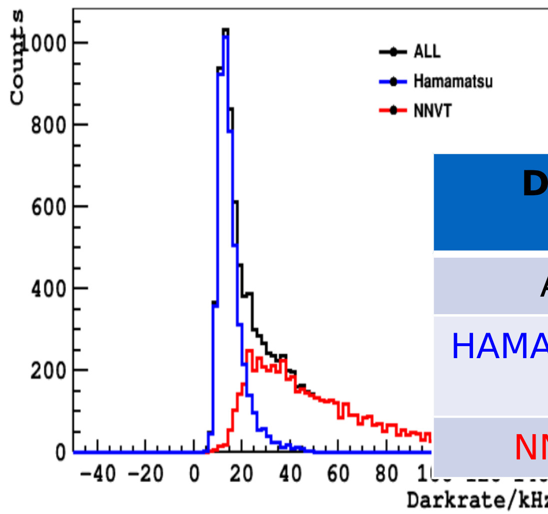
Large PMT production started in 2016.
Dedicated facility for testing @PanAsia warehouse, Zhongshan: visual inspection followed by performance test using 2 containers (batch test) and 2 scanning stations (sampling test).

PDE of all tested PMTS

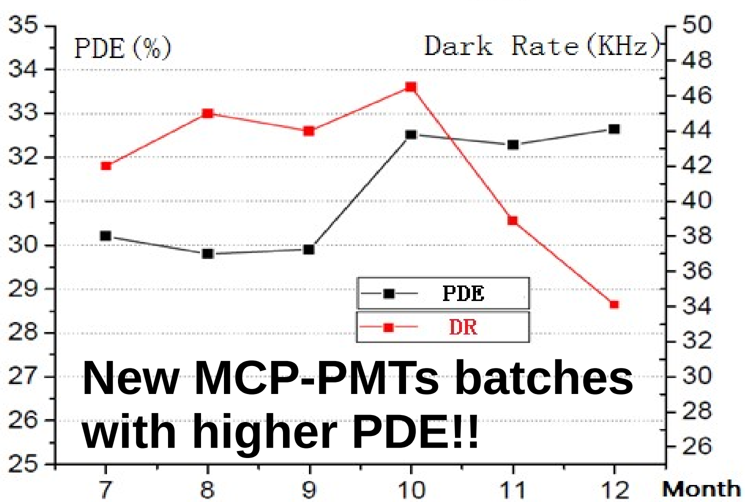


PDE	Mean(%)
All	28.0
HAMAMATSU	28.1
NNVT	27.9

Darkrate of all tested PMTS



DCR	Mean(KHz)
All	31.5
HAMAMATSU	15.5
NNVT	46.1

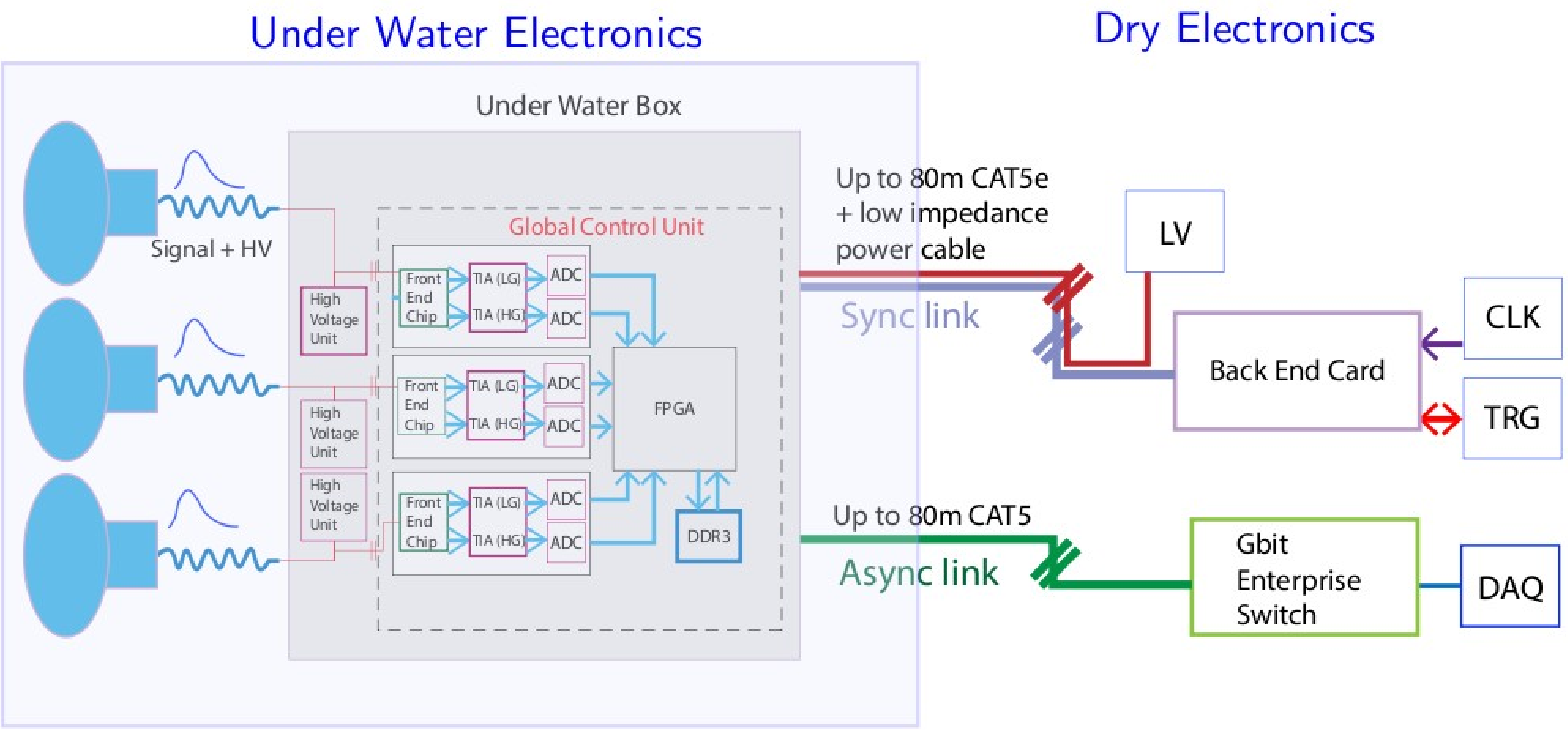


5000 dynode and 8000 MCP PMTS delivered.
11000 PMTs tested in the containers and 1500 in the scanning stations.

PMT potting facility assembled.

Large PMT electronics

The Large PMTs are read-out with full waveform digitization and operated (HV setting) independently.
The signal is digitized near the voltage divider.

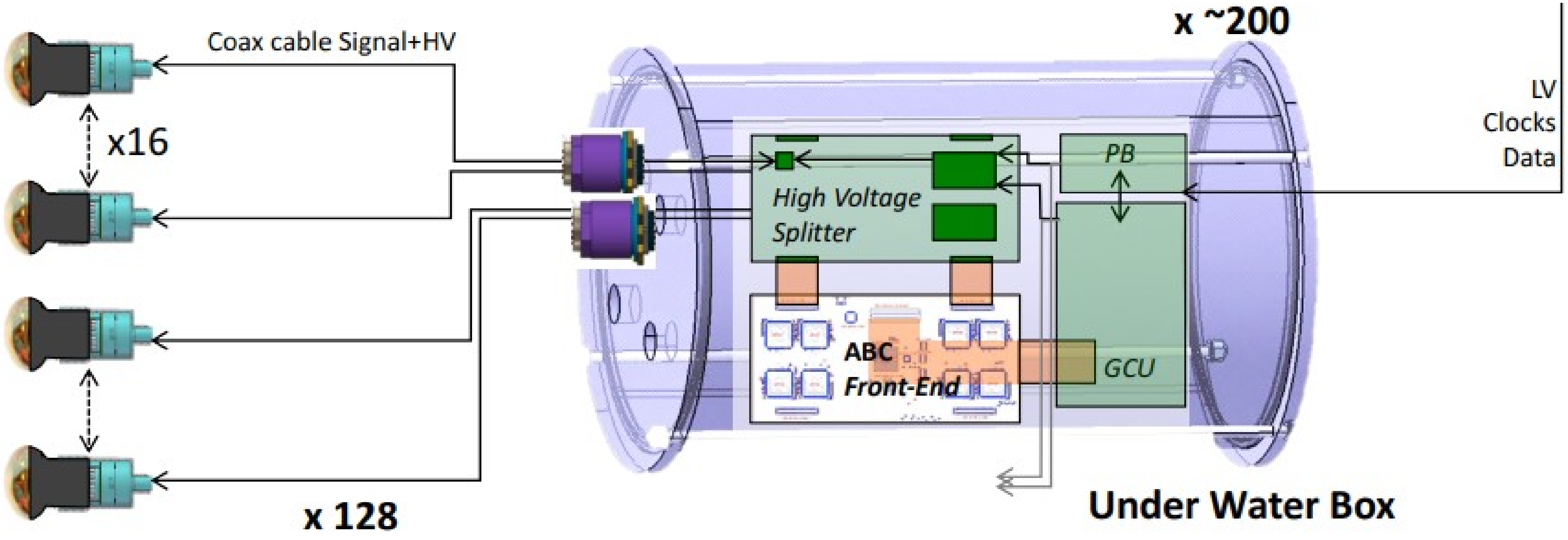


Small PMT system

JUNO will use also 3-inch PMTs as a complementary photo-detection system in order to improve the control of systematics and increase the dynamic range in photon-counting mode.

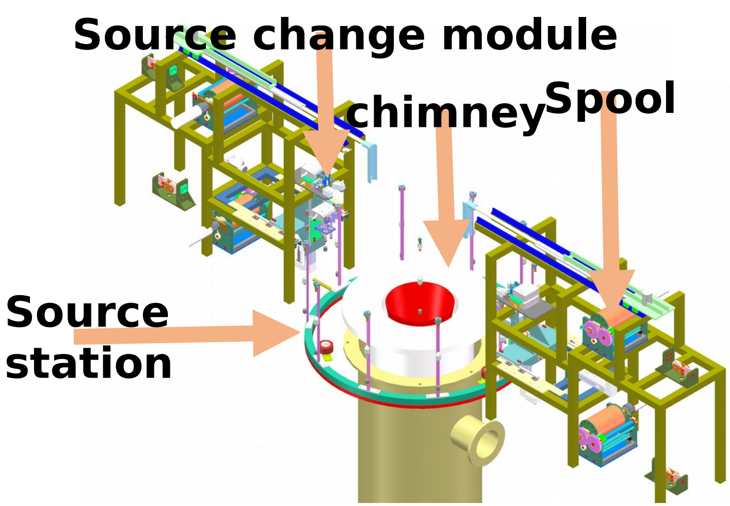
25600 PMTs from HZC company.
12000 already produced and in great part tested.

128 PMTs connected to one underwater box, to reduce the electronics channel number.

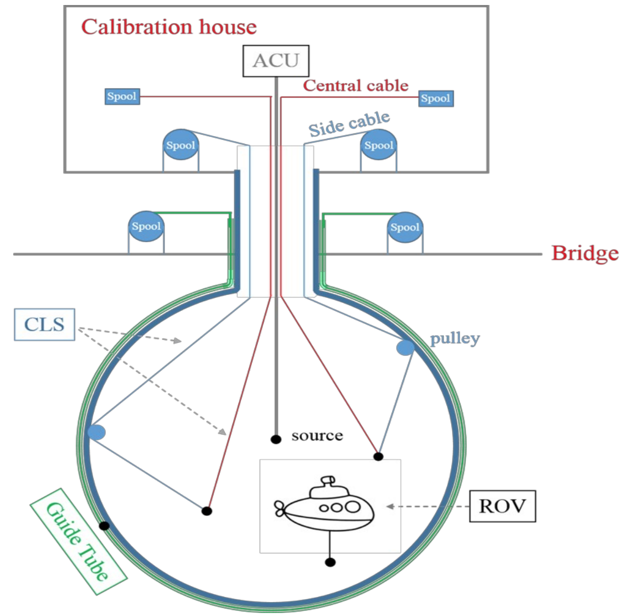


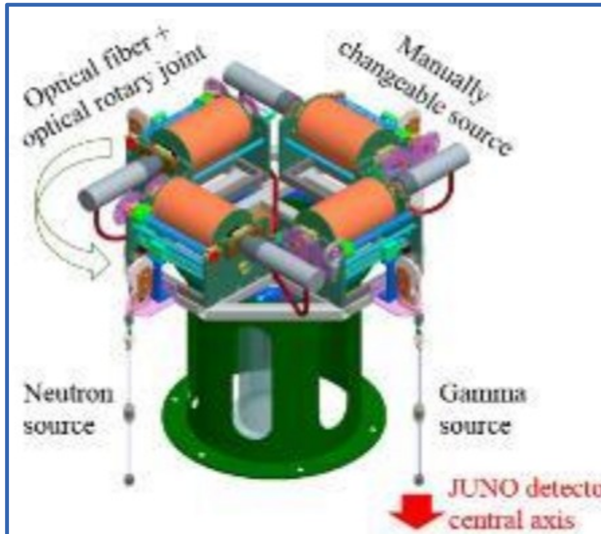
Calibration system

To keep energy scale uncertainty below 1%, four calibration systems under development, using e-, e+, γ and n sources.

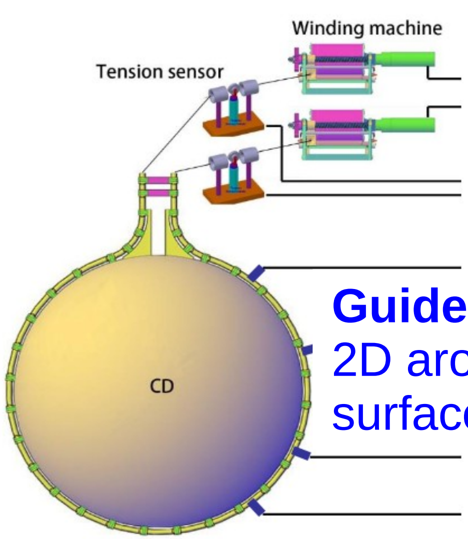


Cable loop system (CLS)
2D plane inside vessel.





Automatic calibration unit (ACU)
1D along detector z-axis



Guide tube (GT)
2D around outer surface vessel

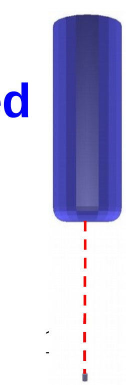
And in addition to this......

2 source positioning systems:
- USS (ultrasonic sensor system);
- CCD system.

266 nm laser system to monitor PMT gains.

Temperature monitoring of CD.

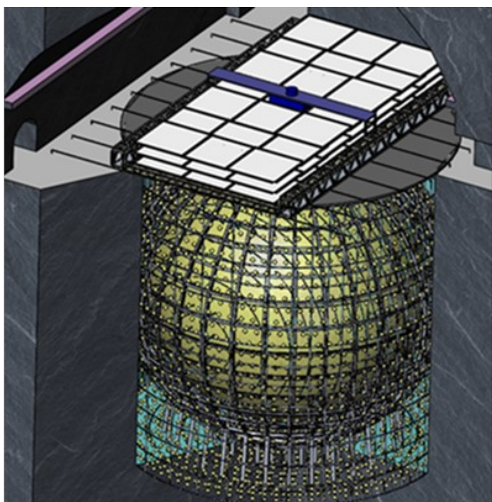
Remotely operated vehicle (ROV)
3D anywhere inside vessel

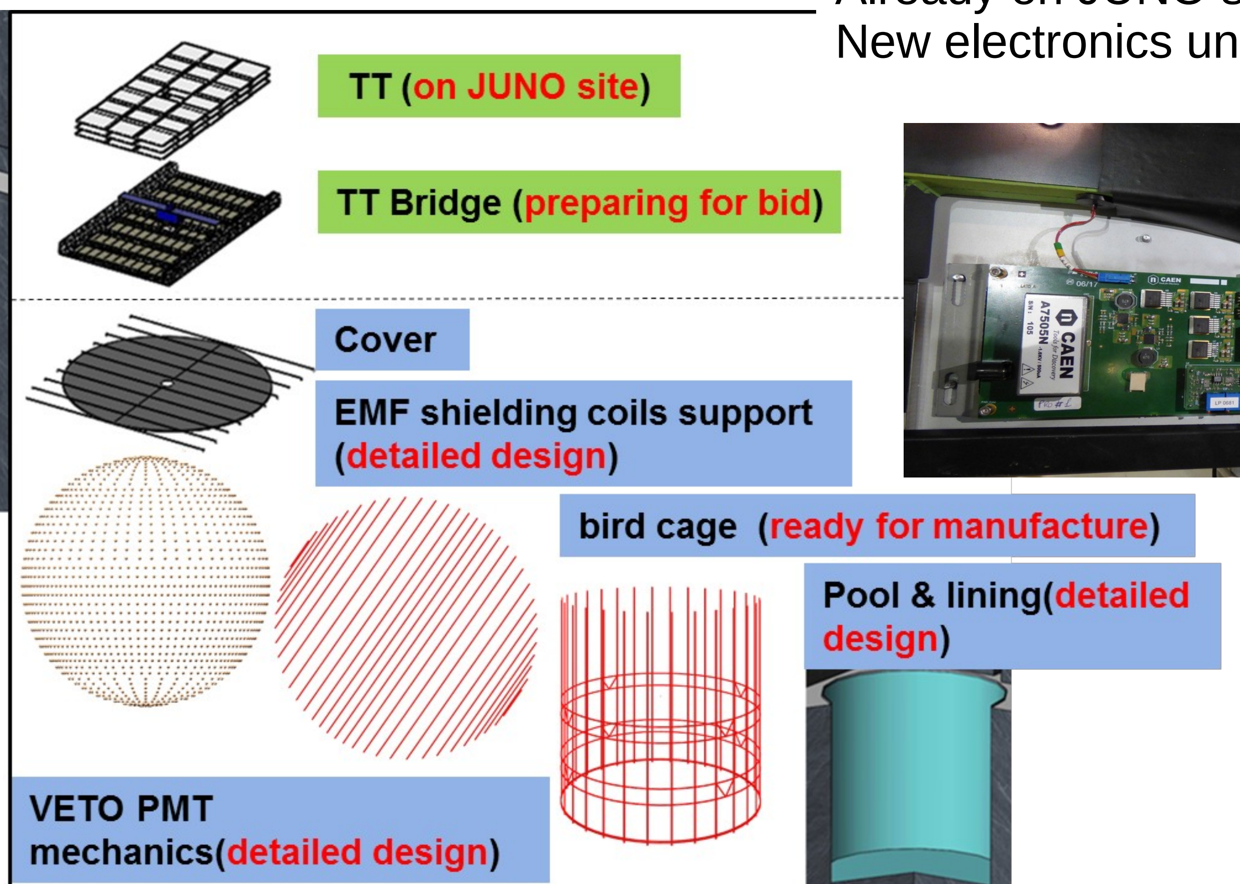


Veto system

To handle the cosmogenic background, the experiment is endowed with a VETO system, made by a **water Cerenkov** with 2000 LPMTs and a **Top Tracker**. **Earth magnetic shielding coils** are also part of the system.

Top Tracker made of scintillator strips refurbished from OPERA.
Already on JUNO site.
New electronics under development.





Water temperature:
T=21±1 °C

Radon concentration
< 0.2 Bq/m³.

TAO
(Taishan Anti-neutrino Observatory)

Measure anti-neutrino spectrum at % level to provide:
- **a model-independent reference spectrum for JUNO**
- **a benchmark for investigation of the nuclear database**

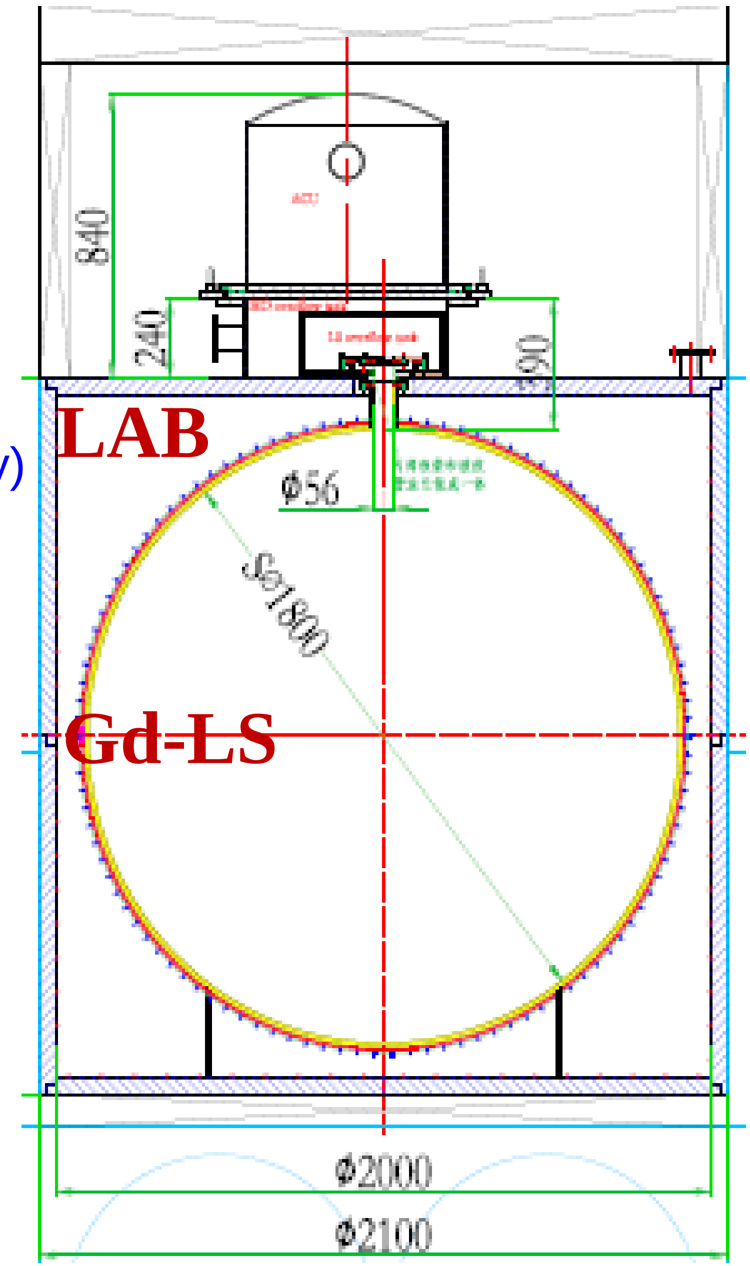
Ton-scale detector at 30 m from reactor core with higher energy resolution.

Detector characteristics:
2.6 t Liquid scinitllator detector (1 t FV=4000 interactions/day)
Full coverage SiPM read-out (50% PDE)
Operation of liquid scintillator and electronics at -50 ^{o}C.
Expected resolution of $\sim$1.5 %/$\sqrt{\mathrm{E}}$.

Detector description from inner to outside:
- Liquid scintillator with Gd @-50 ^{o}C;
- SiPM and support;
- Cryogenic vessel;
- 1-1.5 m water or High Density PolyEthylene shielding;
- Muon detector.

Planned to be operative since 2020.

Welcome collaborators.....



Summary and Conclusions

JUNO is a next generation experiment in neutrino physics and astrophysics.

With its large mass (20 kton of liquid scintillator) and its unprecedented energy resolution (3% @ E=1 MeV), JUNO will address several physics items:

- **Neutrino mass hierarchty measurement at 3-4 σ level;**
- **Sub-% precision measurement of oscillation parameters (θ_{12}, Δm^2_{21}, Δm^2_{31});**
- **Solar, supernova, and geoneutrino measurements.**

Precise understanding of detector performance with:

- **Two independent photo-detection systems (Large and Small Photomultipliers)**
- **A calibration system with many ancillary sub-systems**
- **TAO reference detector looking for the fine structure of reactor energy spectrum.**

Expected to start data taking in two years from now, during 2021.