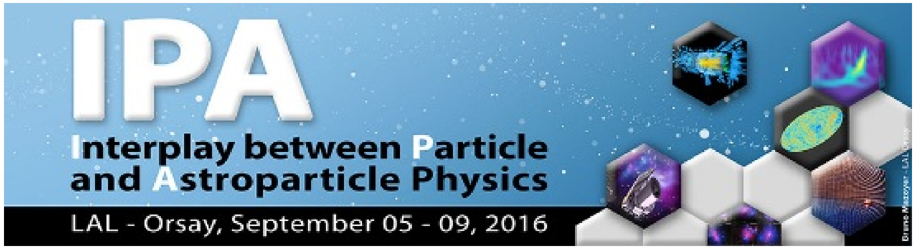

Physics, Design and Status of JUNO Experiment

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(On behalf of JUNO Collaboration)

School of Nuclear Science and Technology

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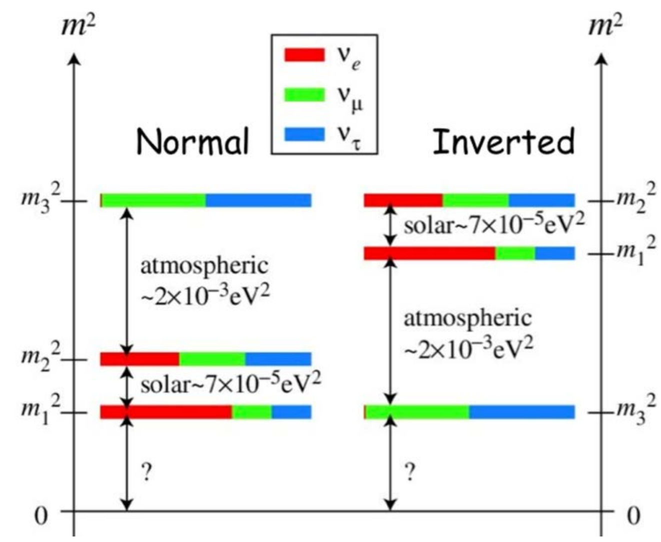
Sep. 5th, 2016

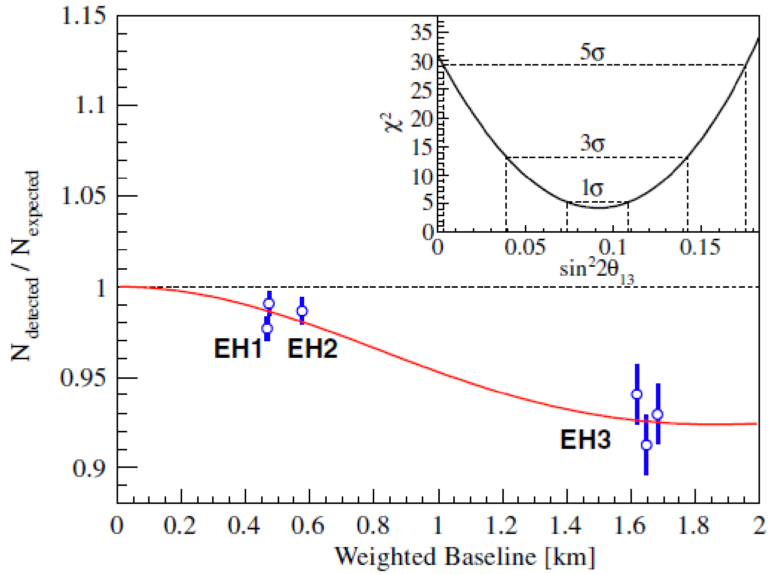
Outline

1. **JUNO Introduction**
2. **JUNO Physics Goals and Potentials**
3. **JUNO Design and Status**
   - ***3.1 Liquid Scintillator***
   - ***3.2 PMTs***
   - ***3.3 Central Detector Structure***
   - ***3.4 JUNO Detector Prototype***
   - ***3.5 Veto Detector***
   - ***3.6 Calibration system***
4. **Schedule**
5. **Summary**

1. JUNO Introduction

The Jiangmen Underground Neutrino Observatory (JUNO) is designed to primarily determine the neutrino **Mass Hierarchy** by detecting reactor anti-neutrinos via inversed beta decay.





$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat.}) \pm 0.005(\text{syst.})$$

PRL 108, 171803 (2012)

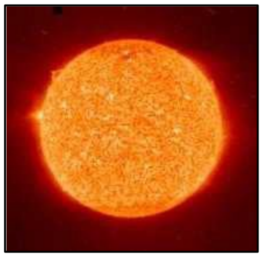
- ***Non-zero and large θ_{13} discovery opens a door to neutrino Mass Hierarchy.***
- ***JUNO was proposed in 2008, approved in 2013***

Location of JUNO

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

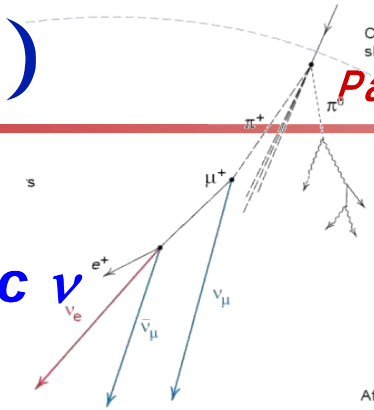
JUNO Event Rates（after selection）

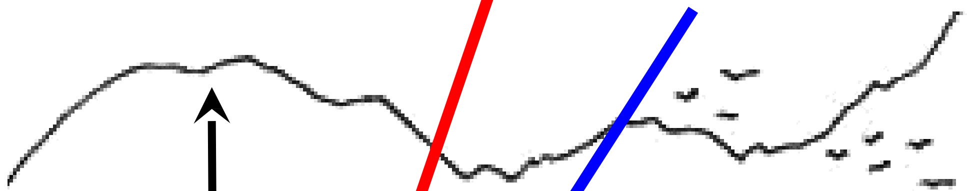
Supernova ν
5-7k in 10s for 10kpc



Solar ν
(10s-1000s)/day

Atmospheric ν
several/day

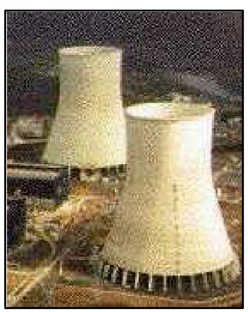




700 m

Cosmic muons
~ 250k/day

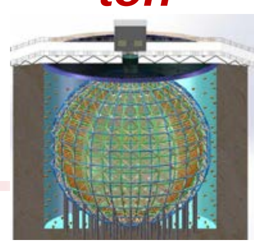
0.003 Hz/m²
215 GeV
10% multiple-muon



36 GW, 53 km

reactor ν, 60/day
Bkg: 3.8/day

20k ton



Geo-neutrinos
1.1/day

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

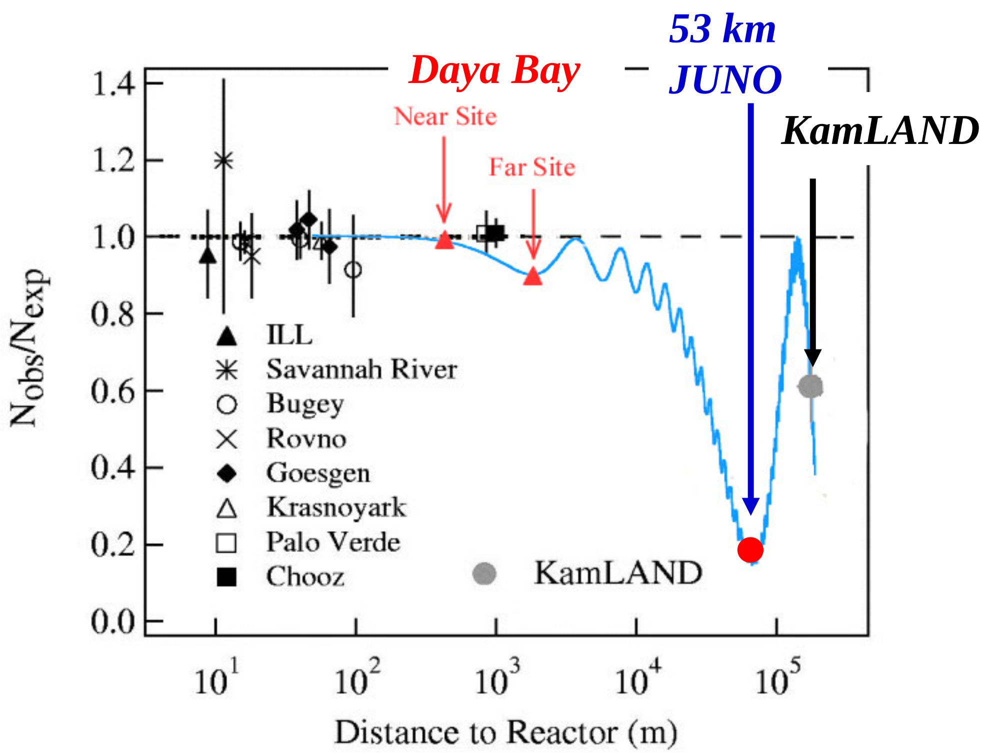
Now: 66 institutions
444 collaborators
8 observers

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


8th JUNO Collaboration Meeting
July 25-29, 2016, IHEP

2. JUNO Physics Goals and Potentials

- **27-36 GW reactor power, 20 kton LS detector**
- **3%/√E energy resolution, <1% energy non-linearity**



□ Rich physics possibilities

- □Neutrino MH using reactor neutrinos
- □Precision measurement of oscillation parameters
- □Supernova and Diffuse supernova neutrinos
- □Solar neutrinos, Geo-neutrinos, Sterile neutrinos
- □Atmospheric neutrinos and Dark matter searches
- □Nucleon decay and other exotic searches

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

2.1 Mass Hierarchy

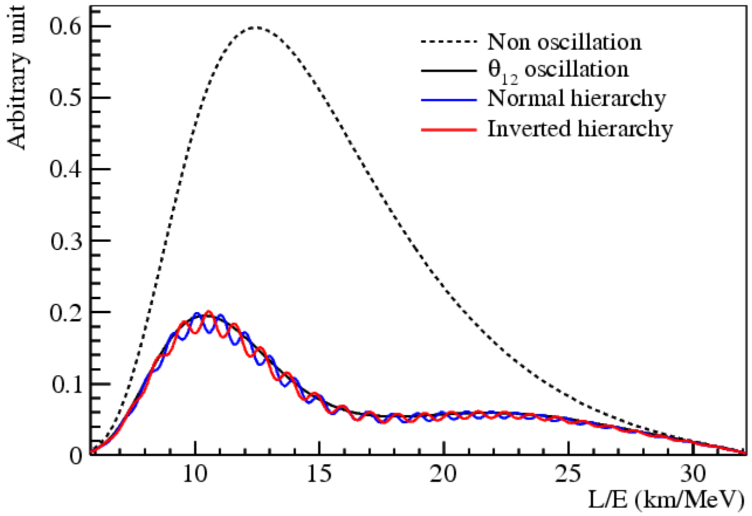
- Helps to define the goal of neutrino-less double beta decay (0νββ) search experiments, which aim to tell if neutrinos are Dirac or Majorana.
- A crucial factor for measuring lepton CP-violating phase, like Hyper-K.
- A key parameter of the neutrino astronomy and neutrino cosmology
- A critical parameter to understand the origin of neutrino masses and mixing.

Oscillation probability independent of CP phase and θ_{23} (Reactor neutrinos)

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

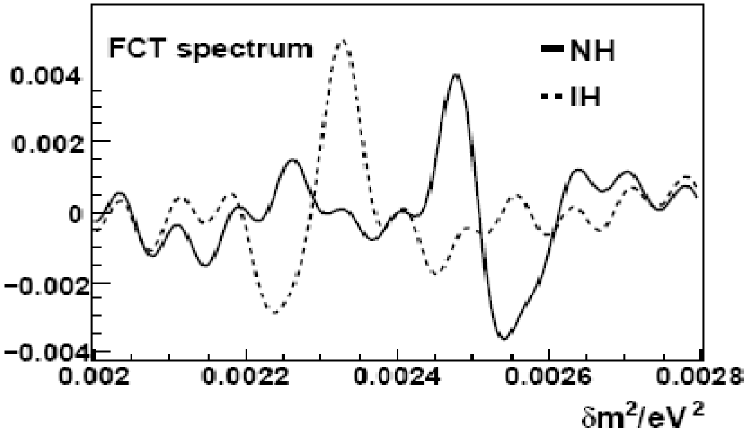
$$
\begin{aligned}
P_{ee} = 1 &- \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21}) \\
&- \sin^2 2\theta_{13}\sin^2(|\Delta_{31}|) \\
&- \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{21})\cos(2|\Delta_{31}|) \\
&\pm \frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|)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

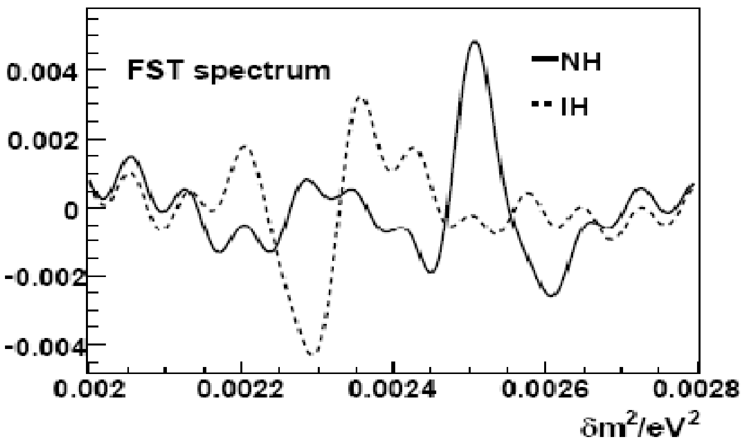
+ NH
- IH



- *The big suppression is the "solar" oscillation (Δm^2_{12}, $\sin^2\theta_{12}$)*
- *"Large" value of θ_{13} is crucial*

Fourier transform

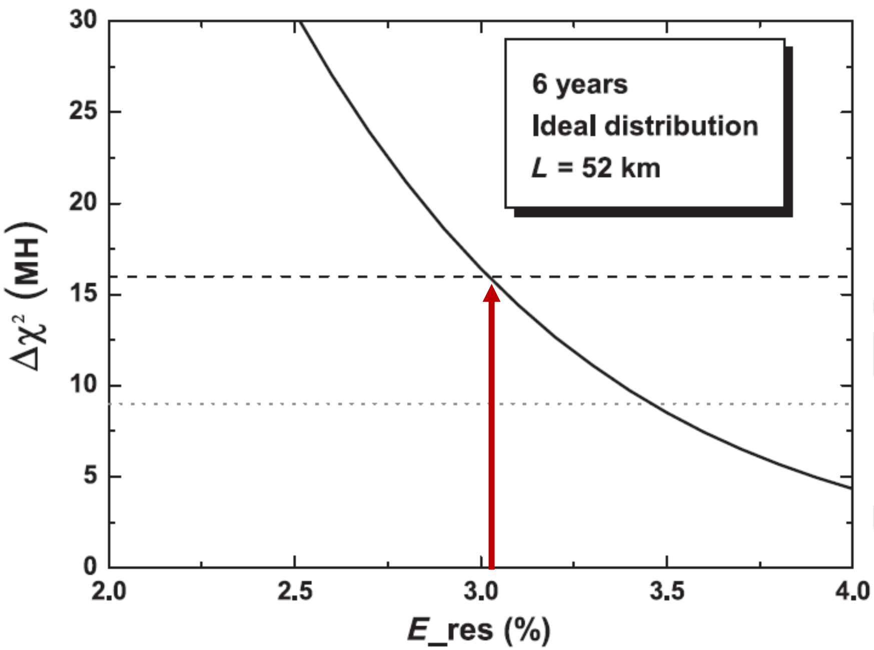




- **No pre-condition of Δm^2_{32}**
- **Only depends on shape but not absolute peak position**

- Key requirements on detector
  - PMT coverage: 75%
  - High Light yield: >=1200 p.e./MeV
  - LS attenuation length: >20 m

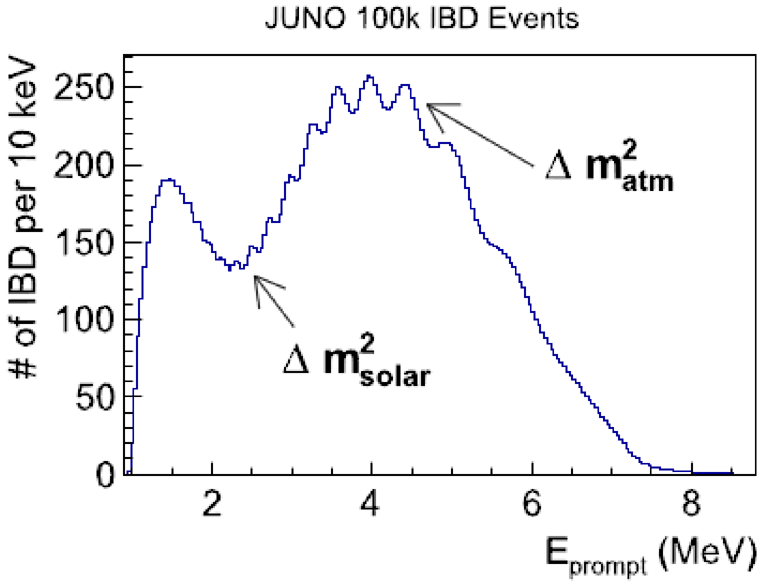
$$3\% / \sqrt{E}$$



2.2 Measurement of Oscillation Parameters

Due to good energy resolution and proper baseline, JUNO can help to:

- **Improve precisions of three parameters (Δm^2_{21}, Δm^2_{ee} and $\sin^2\theta_{12}$) to sub-percent level, several times improvement compared with current precision.**
- **Probe the unitarity of U_{PMNS} to ~1% level**



	Nominal	+B2B (1%)	+BG	+EL (1%)	+NL (1%)
$\sin^2\theta_{12}$	0.54%	0.60%	0.62%	0.64%	0.67%
Δm^2_{21}	0.24%	0.27%	0.29%	0.44%	0.59%
$\lvert\Delta m^2_{ee}\rvert$	0.27%	0.31%	0.31%	0.35%	0.44%

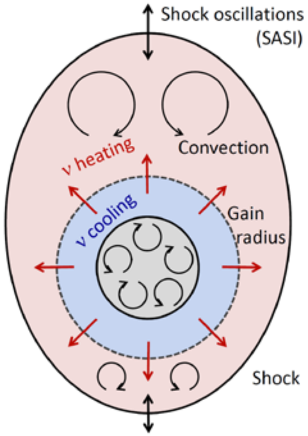
2.3 Supernova Neutrinos

- **SN detection is an ideal probe for astrophysics and particle physics.**
- **Largest LS detector of new generation → high statistics, good energy resolution and flavor information.**

- **Three Phases of Neutrino Emission**

1. Infall (Bounce and Shock Propagation, few tens of ms after bounce)
2. Accretion (Shock Stagnation, few tens to few hundreds of ms)
3. Neutron-star cooling (lasts until 10–20 s)

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	6.0×10^2	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	NC	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}C \to \nu + {}^{12}C^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}C \to e^- + {}^{12}N$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}C \to e^+ + {}^{12}B$	CC	6.0×10^1	1.1×10^2	1.6×10^2

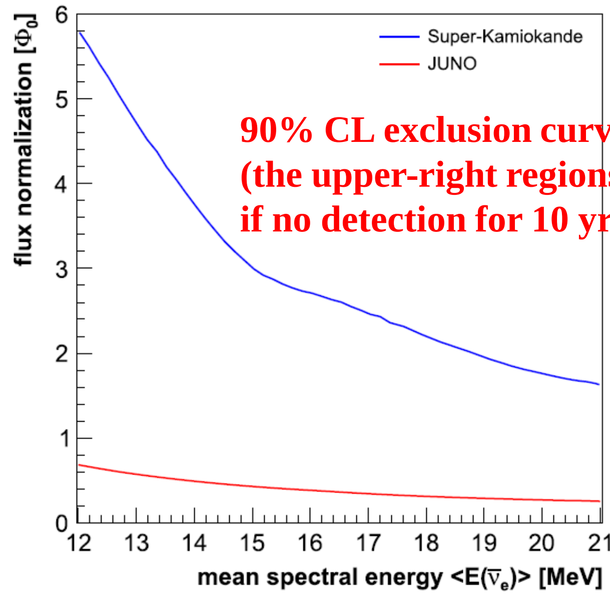


Advantage: Global analysis of all channels

- **Real-time meas. of three-phase ν signals**
- **Distinguish between different ν flavors**
- **Reconstruct ν energies and luminosities**
- **Almost background free due to time info**

2.4 Diffused SN Background

- About 10 core collapses/sec in the visible universe
  Emitted ν energy density is ~extra galactic background light and ~10% of CMB density
- Confirm star-formation rate
- Pushing frontiers of neutrino astronomy to cosmic distances



JUNO Advantages:

- **Excellent intrinsic capabilities of LS detectors for antineutrino tagging**
- **Excellent Background Rejection**

Observation window: 11 MeV < Eν< 30 MeV
PSD techniques for NC atmospheric ν (critical)
Fast neutrons: r < 16.8 m (equiv. 17 kt mass)

- **A positive signal @ 3σ level is conceivable for a 10-year measurement**
- **A non-detection would strongly improve current limits and exclude a significant range of DSNB parameter space.**

2.5 Solar neutrinos

JUNO advantages for solar ν detection

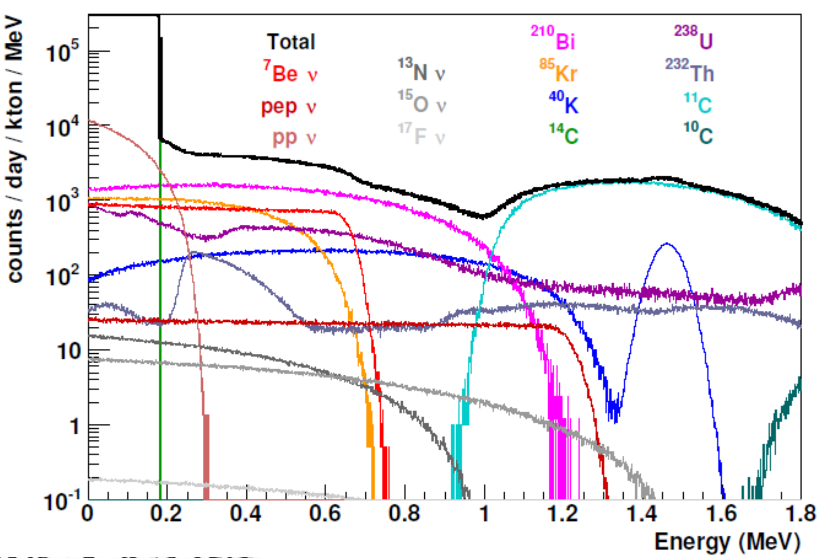
$$\nu_{e,\mu,\tau} + e^- \to \nu_{e,\mu,\tau} + e^- .$$

- ✓ large mass and lower E threshold → ^{7}Be and low tail of ^{8}B
- ✓ Expected σ(E) ≈ 3%/√E → can discriminate p-p from ^{14}C

Main challenges

- **Radio-purity similar to previous LS experiments**
- **Cosmogenic background, e.g. long--lived ^{11}C under ^{8}B**

Internal radiopurity requirements		
	baseline	ideal
^{210}Pb	5×10^{-24} [g/g]	1×10^{-24} [g/g]
^{85}Kr	500 [counts/day/kton]	100 [counts/day/kton]
^{238}U	1×10^{-16} [g/g]	1×10^{-17} [g/g]
^{232}Th	1×10^{-16} [g/g]	1×10^{-17} [g/g]
^{40}K	1×10^{-17} [g/g]	1×10^{-18} [g/g]
^{14}C	1×10^{-17} [g/g]	1×10^{-18} [g/g]
Cosmogenic background rates [counts/day/kton]		
^{11}C	1860	
^{10}C	35	
Solar neutrino signal rates [counts/day/kton]		
pp ν	1378	
^{7}Be ν	517	
pep ν	28	
^{8}B ν	4.5	
^{13}N/^{15}O/^{17}F ν	7.5/5.4/0.1	

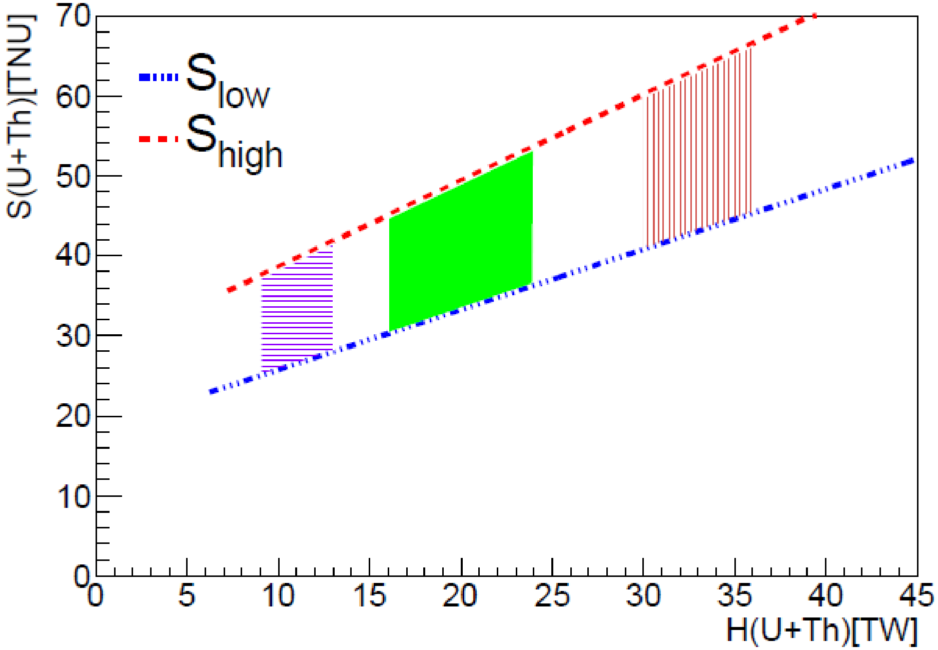


The expected singles spectra at JUNO with the "baseline" radiopurity requirements **(Assumed radio purity gives S:B≈1:3)**

2.6 Geo-neutrinos

- Anti-neutrinos from the Earth escape freely from the earth interior and bring the information about the U, Th and K abundances and their distributions inside the planet to earth surface
- Because of largest size of its LS detector, within the first year of running JUNO will record more geo-neutrino events than all other detectors will have accumulated until then.

- **~1.1/day @JUNO after IBD Selection**
- **The expected geo-neutrino signal at JUNO as a function of radiogenic heat due to U and Th in the Earth, H(U+Th).**



2.7 light sterile neutrino searches

- Sterile neutrinos at the eV or sub-eV scale are well motivated by the short-baseline neutrino oscillation anomalies.
- Without an additional near detector, reactor antineutrino oscillations cannot search for eV-scale sterile neutrinos. However, the diameter of the JUNO central detector (~35 m) enables source-based method because of both purity of their source and the possibility to probe the baseline dependence

Radioactive Source Selection Requirement

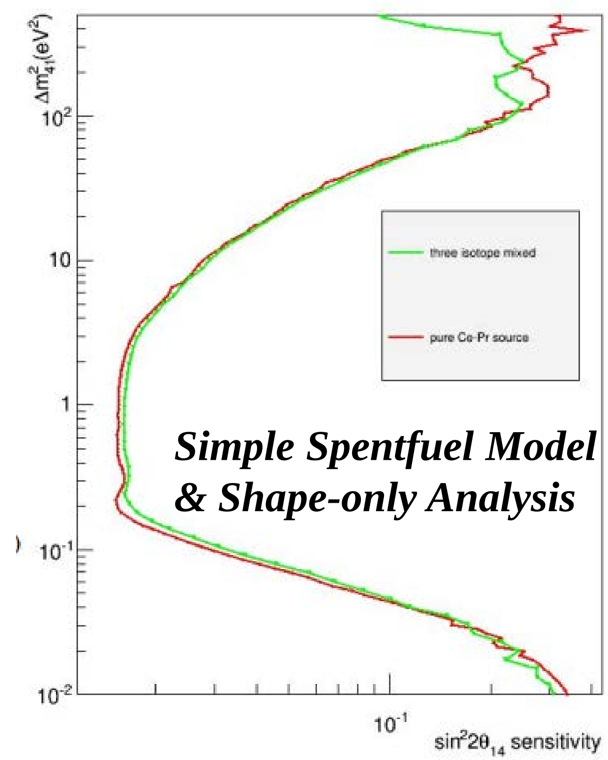
✓ ***A pair parent and daughter nucleus:***

- ***Parent nucleus:** Low-Q , Long life: Easy to transport and storage*
- ***Daughter nucleus:** High Q, Short life:produce antineutrinos with energy above 1.8MeV (IBD threshold)*

✓ ***Spent fuel of reactors is preferred because it's easy to and cheap to obtain.***

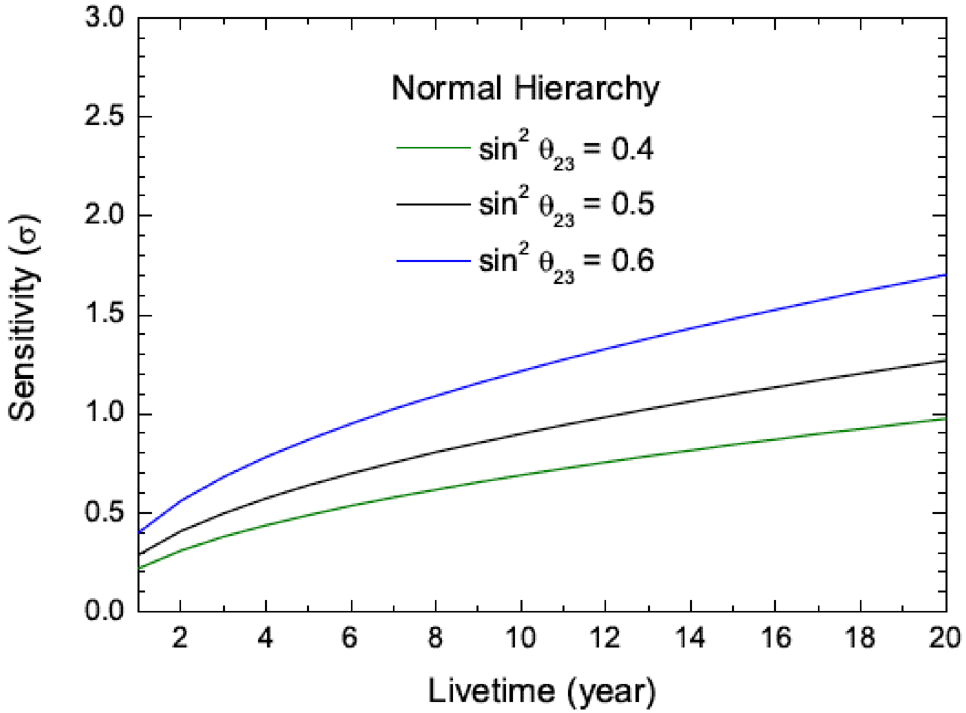
^{144}Ce-^{144}Pr is favorable

^{144}Ce-^{144}Pr, with Q_β(Pr)=2.996 MeV and $\tau_{1/2}$(Ce)=285 d.



2.8 Atmospheric neutrinos

- Our focus on JUNO atmospheric neutrinos is to make a complementary mass hierarchy measurement.
- For the upward atmospheric neutrinos, the oscillation probabilities $P(\nu_\mu \rightarrow \nu_\mu)$ and $P(\nu_e \rightarrow \nu_\mu)$ in the NH and IH cases have obvious differences due to the MSW resonance effect.



Here we only consider ν_μ and $\bar{\nu}_\mu$ charged current (CC) events. $\mu^\pm$ tracks are required to have a length $L_\mu > 5$ m

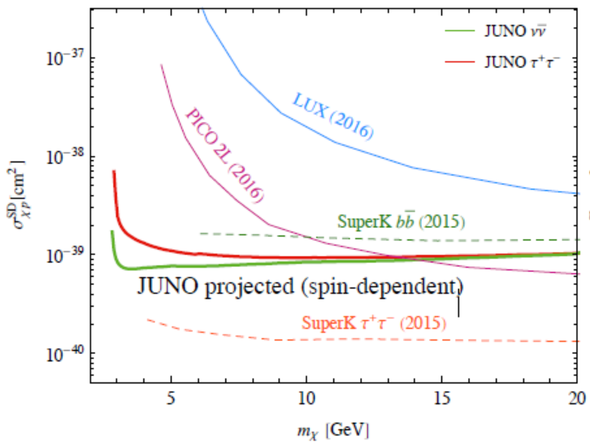
- **JUNO's MH sensitivity can reach 0.9 σ for a 200 kton-years exposure and $\sin^2\theta_{23} = 0.5$, which is complementary to the JUNO reactor neutrino results.**

2.9 Indirect Detection of Dark Matter

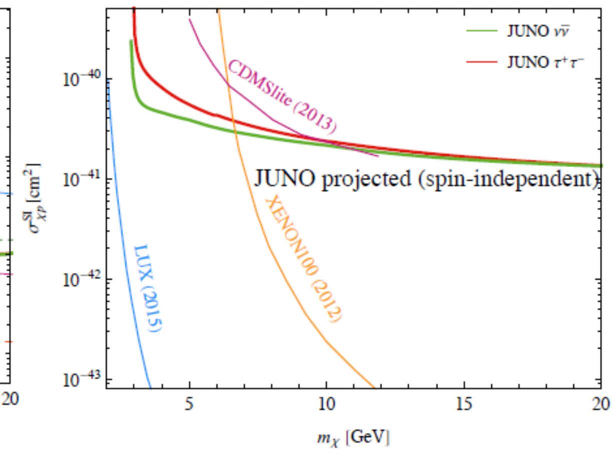
- Dark matter (DM) can be trapped in the Galactic halo, the Sun or the Earth
- Annihilation or decays of trapped DM particles χ can be detected indirectly by looking for their neutrino signature → direction information needed (muon neutrino events preferred)
- Expected neutrino fluxes resulting from DM annihilation or decays can be established based on different models

To estimate JUNO sensitivity, we focus on

- ✓ **muon type events above 1 GeV coming from a 30-degree solid angle range surrounding the direction of the Sun,**
- ✓ $\chi\chi \rightarrow \tau^+\tau^-$ **and** $\chi\chi \rightarrow \nu\bar{\nu}$ **are considered as a bench mark;**
- ✓ **Assuming** $B_\chi^{\tau\nu} = 1$



The JUNO 2σ sensitivity in 5 years to the spin-dependent cross section $\sigma^{SD}_{\chi p}$ in 5 years. The constraints from the direct detection experiments are also shown for comparison.



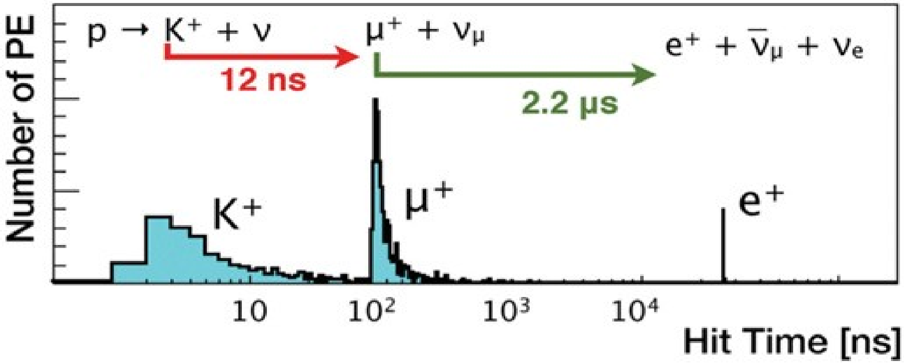
The JUNO 2σ sensitivity in 5 years to the spin-independent cross section $\sigma^{SI}_{\chi p}$. The recent constraints from the direct detection experiments are also shown for comparison.

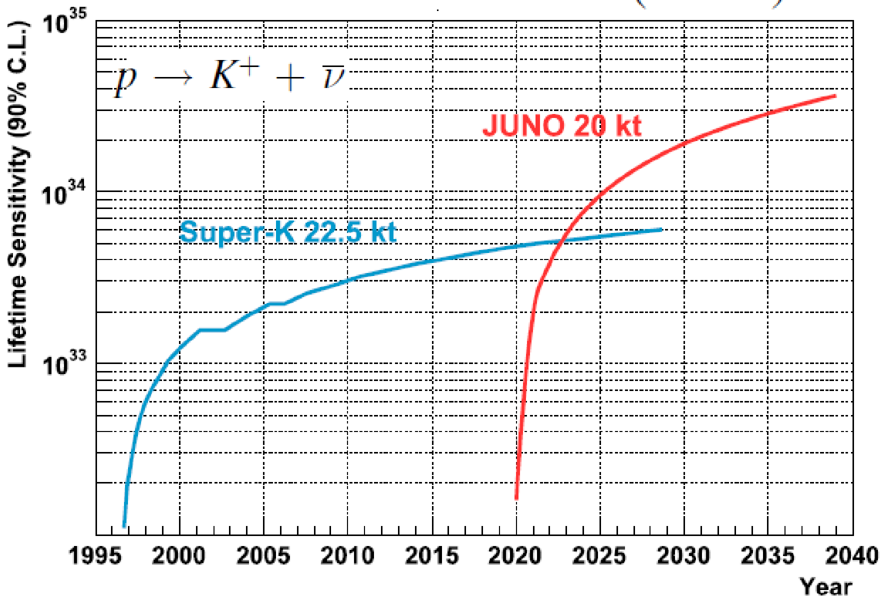
2.10 Opportunity in Proton Decay

- The prompt signal K^+ overlaps with its decay-to-muon signal → one prompt signal → two-pulse events
- Main background comes from one-pulse atmospheric neutrino interactions

$$p \to K^+ + \overline{\nu}$$

- $K^+ \to \mu^+\nu_\mu$ (63.43%),
- $K^+ \to \pi^+\pi^0$ (21.13%),
- $K^+ \to \pi^+\pi^+\pi^-$ (5.58%),
- $K^+ \to \pi^0 e^+\nu_e$ (4.87%),
- $K^+ \to \pi^+\pi^0\pi^0$ (1.73%).





- Pulse shape discrimination of the combined prompt signal is the key to distinguish the signal from atmospheric neutrino background
- Time span between 15% and 85% of the maximum pulse height greater than 7 ns can retain 65% signal while rejecting almost all muon neutrino backgrounds $\Delta T_{15\%-85\%} > 7$ ns

Note: In comparison, Super-K's sensitivity is projected to the year of 2028.

3. JUNO detector

Overburden of~700 m rock for cosmic-ray shielding

□ *Veto Detector*

Water Cherenkov detector: tracks muons and shields ambient radioactivity

Top Trackers: independent muon tracking

□ *Central Detector*

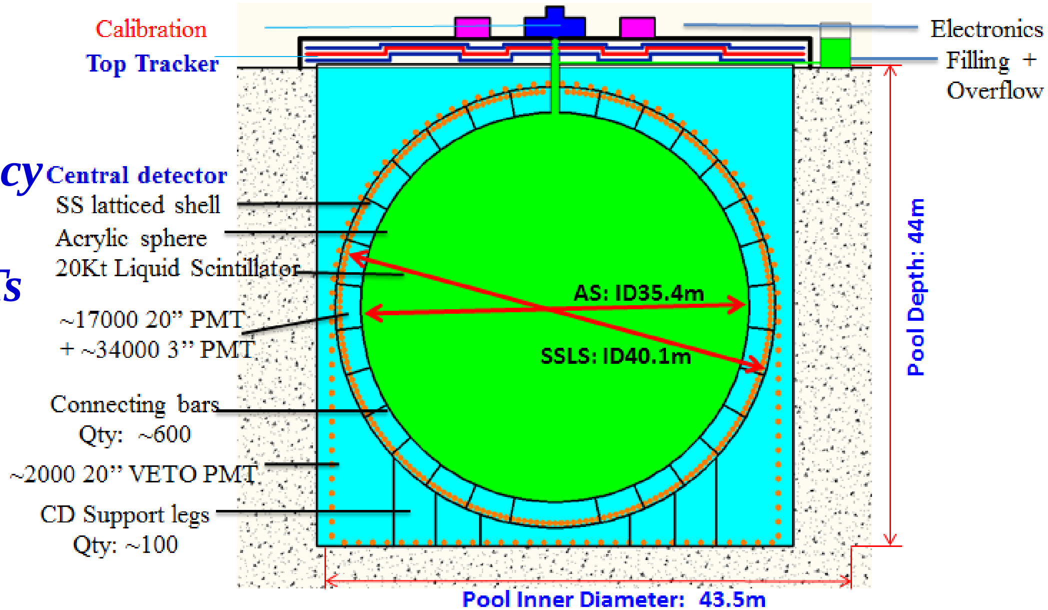
- *~20kt @ Φ35.4m (Largest LS detector)*
- *Filled with LS of high light yield(>=1200p.e./MeV) and transparency > 20m@430nm*
- *Equipped with ~17k high QE 20" PMTs*
- *Dual calorimetry using ~34 k 3" PMTs for better timing and higher saturation energy*

□ *Calibration system*

- *Multiple sources: e+, γ, n*
- *Full volume + positioning:*
  1D: ACU
  2D: CLS + GTCS
  3D: ROV

A multi-purpose neutrino observatory

- ***Energy resolution: <3%@1MeV***
- ***Energy linearity: <1%***



AS: Acrylic Sphere; SSLS: Stainless Steel Latticed Shell

➢ ***1GHz sampling waveform readout electronics for better energy understanding and more possibilities***

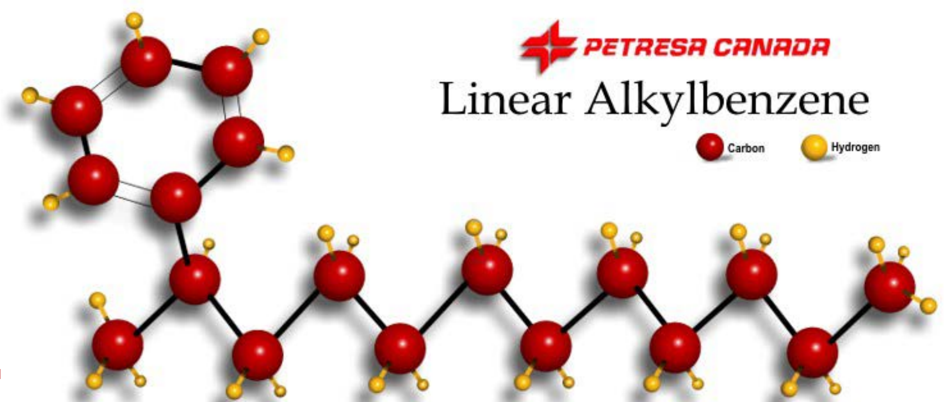
3. 1 Liquid Scintillator

Requirements for LS:

- ✓ Long Attenuation Length: >20m@430nm
- ✓ Low background: $^{238}U < 10^{-15}$g/g
  $^{232}Th < 10^{-15}$g/g
  $^{40}K < 10^{-17}$g/g

LS Recipe (based on Daya bay)

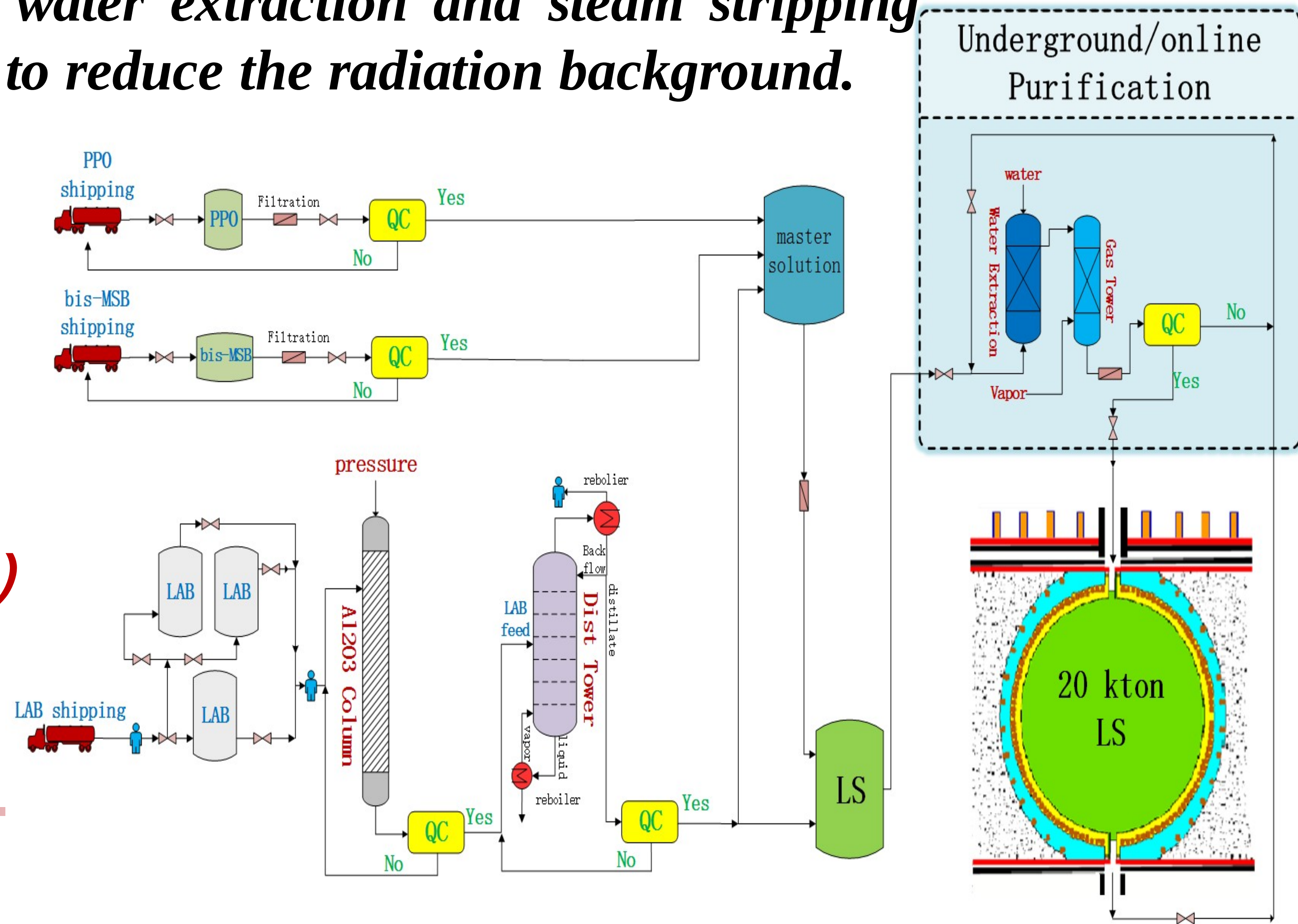
- ✓ Solvent: Linear Alkyl Benzene
- ✓ 3g/L PPO (purity>=99.5%)
- ✓ 15mg/L bis-MSB

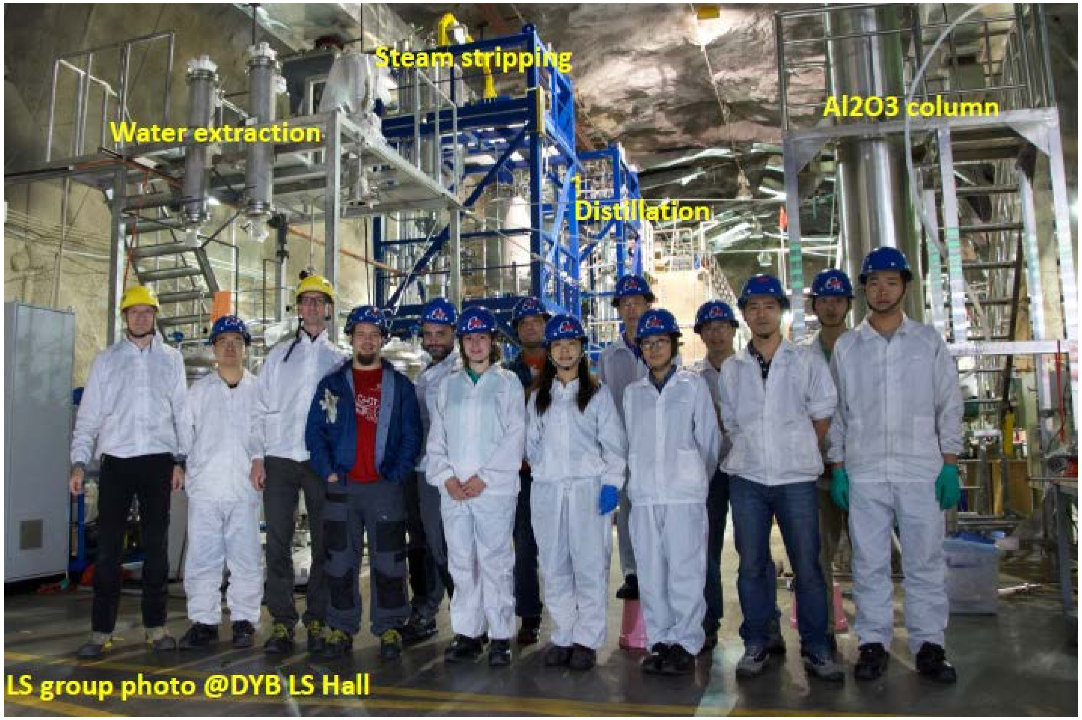


Purification for 20 kton LS

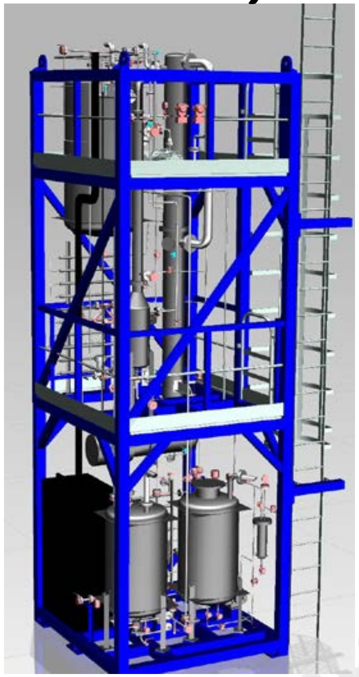
- ✓ LS A.L. is increased by Al_2O_3 column
- ✓ Distillation, water extraction and steam stripping will be used to reduce the radiation background.

JUNO –LS mass production flow chart (Preliminary)

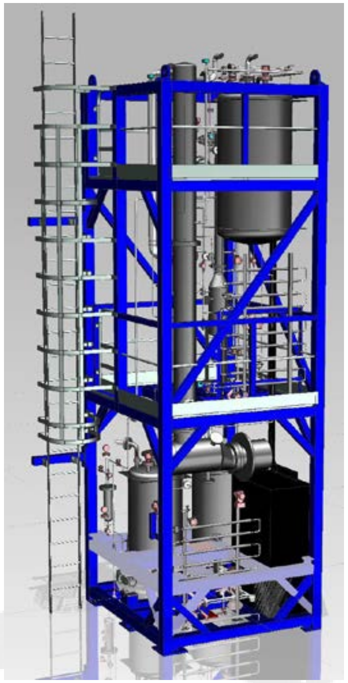




Distillation system

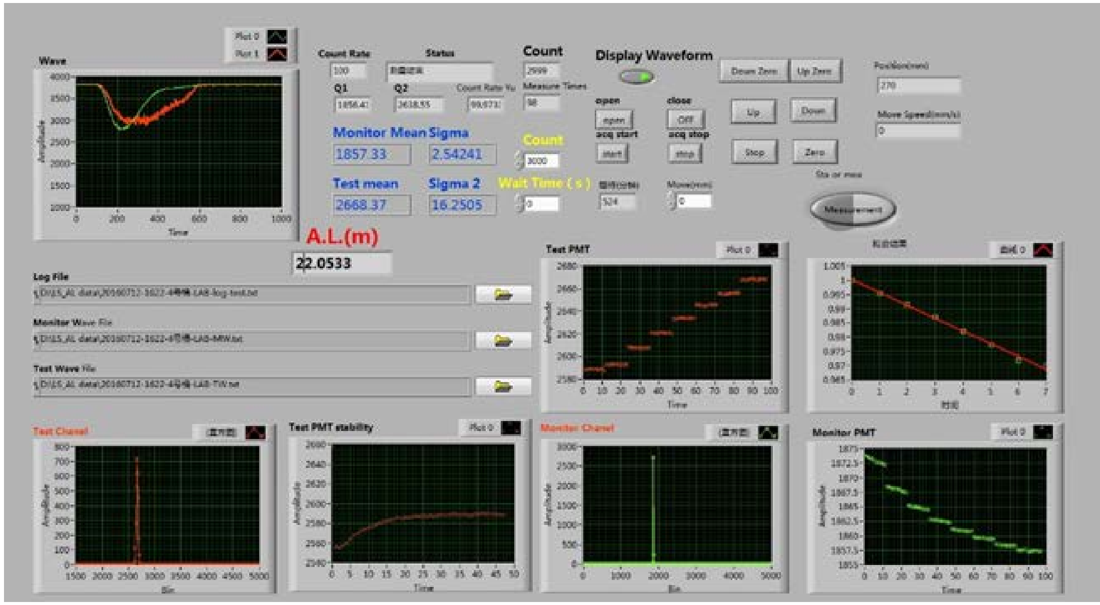


Steam stripping



- **Purify 20 ton LAB(one AD in Hall #1) to test the overall design of purification system at Daya Bay.**
- **4 main LS pilot plants have been installed in DYB LS Hall and Joint commissioning will take place this Oct.**

- A set of Attenuation length measurement system is ready at DYB
- The sample of distillation pilot plant and steam stripping pilot plant have been measured.



Sample	Attenuation length（m）
Standard sample	16.08
LAB in 4# tank of daya bay	23.2 (Average)
LAB in 4# of daya bay-distillation & filtered	28.62 (Average, better)
LAB in 5# tank of dayabay	25.5(Average)
LAB in 5# of daya bay striped & filtered	23.83 (similar with the raw LAB)

3.2 PMTs

□ *20" PMTs with High QE*

- ✓ **15k NNVT MCP-PMT:** **newly developed by North Night Vision Technology (NNVT), used for central detector and veto detector.**
- ✓ **5k Hamamatsu R12860:** **used for central detector**

Characteristics	MCP-PMT (NNVT)	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~5; F~12	R~5,<7; F~9,<12
Anode Dark count(Hz)	20k,<30k	10k,<50k
After Pulse Percentage(%)	1,<2	10,<15
Glass Radioactivity(ppb)	^{238}U:50 ^{232}Th:50 ^{40}K:20	^{238}U:400 ^{232}Th:400 ^{40}K:40

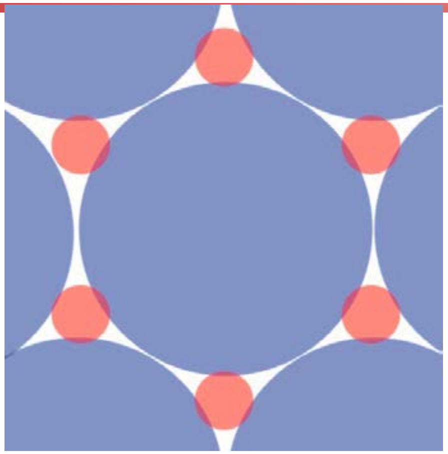
NNVT MCP-PMT

Hamamatsu R12860

□ 34,000 3” PMTs: an vital “aider” to 20” PMTs

Small size → no saturation and better linearity in JUNO situation

→Can serve as a standalone calorimeter

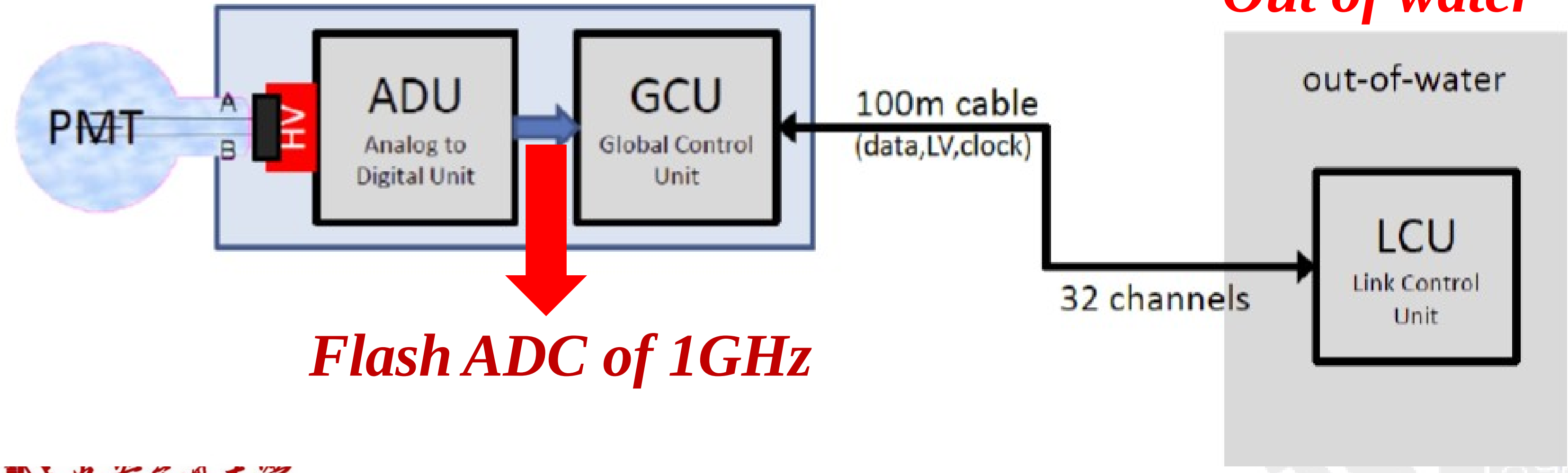


Mixture of 20” and 3” PMTs

□ PMT Readout

Front part under-water

Out of water

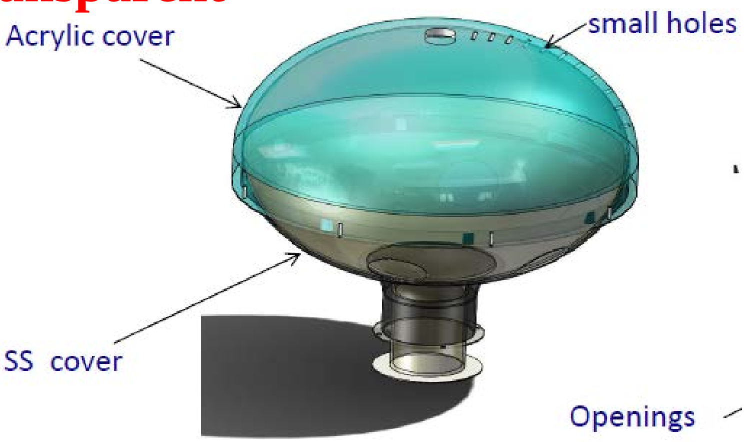


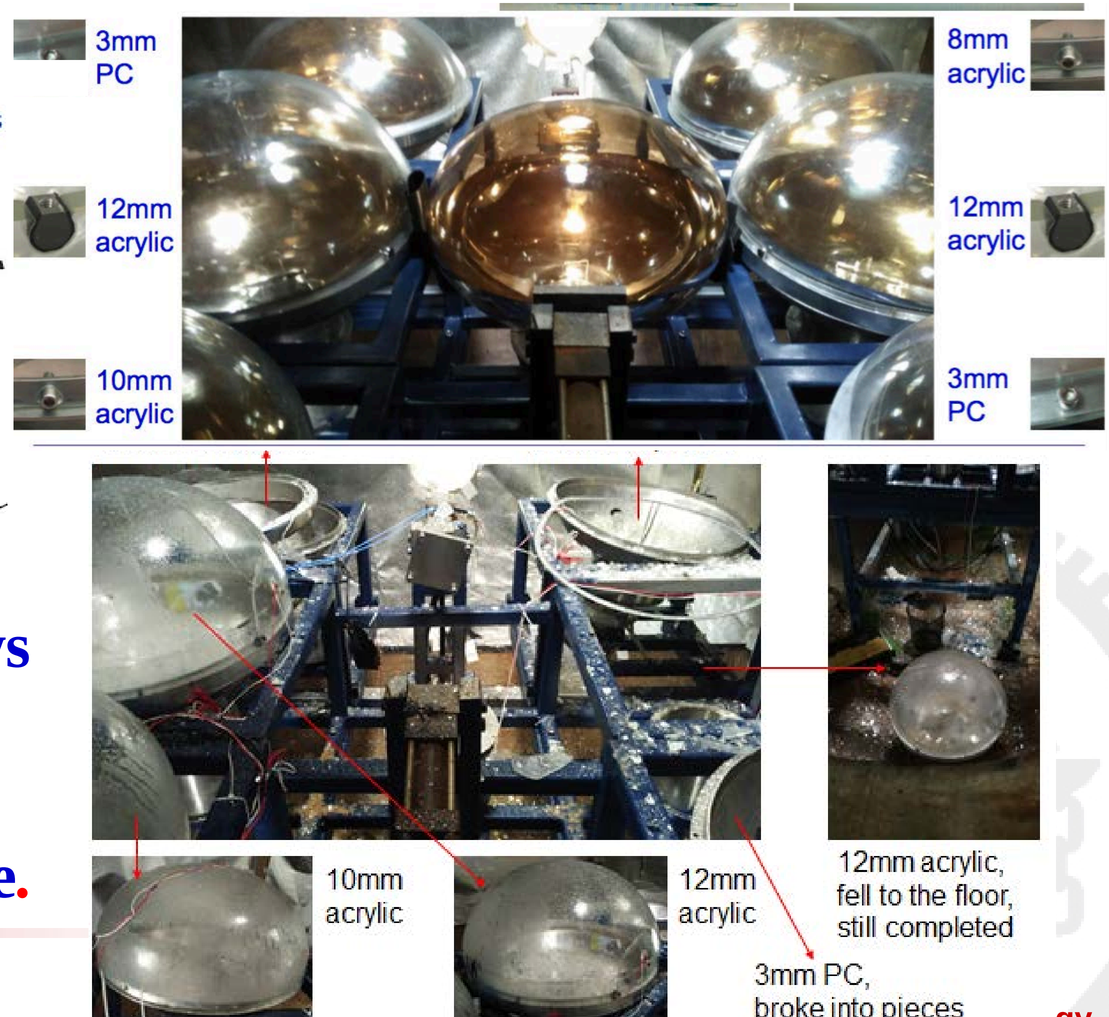
Flash ADC of 1GHz

PMT protection

- PMT protection is designed to prevent chain reaction due to shockwave from PMT implosion

transparent





- **Two implosion tests shows All four 12mm acrylic cover survived and is reliable to be our baseline.**

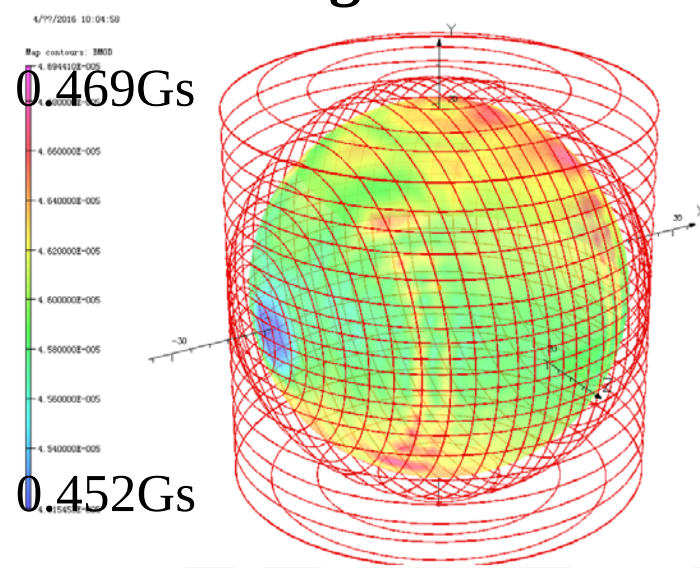
EMF shielding

Compensation coils system is chosen for earth magnetic field shielding in JUNO

Prototype of compensation coils

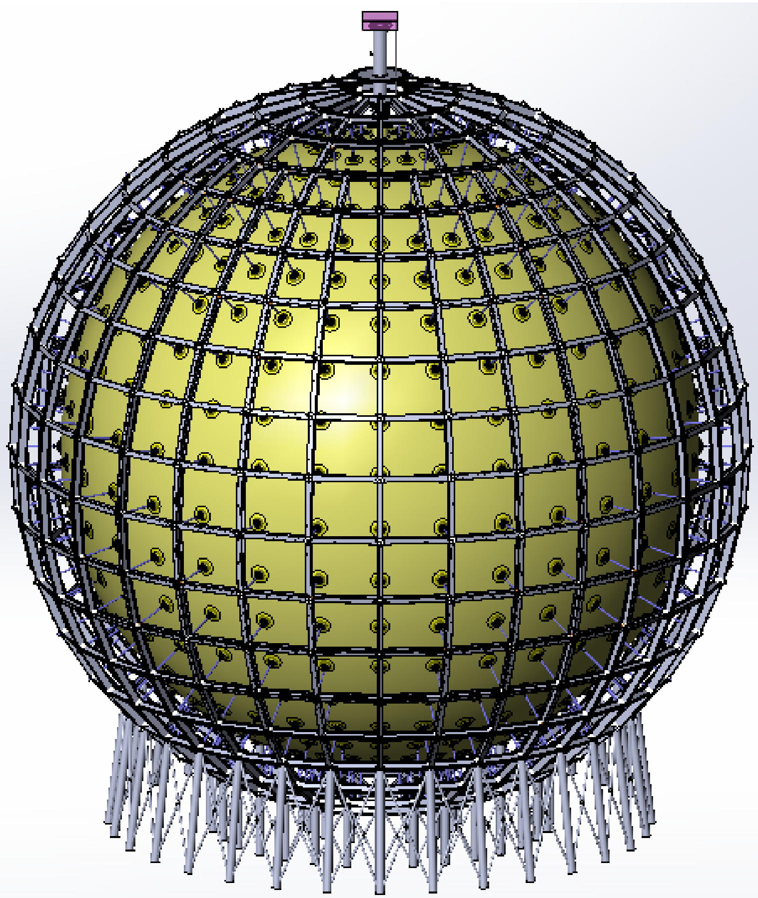
- **Φ1.25m with accuracy~5mm;**
- **residual intensity(Φ0.8m diameter)<0.05Gs**
- **Good validation about the compensation coils design**

- ***No obvious efficiency lose when Magnetic field <0.15Gs.***
- **The residual intensity<0.05Gs in central detector PMT region after shielding**



3. 3 CD structure

Acrylic sphere + SS truss



AS: Φ35.4m

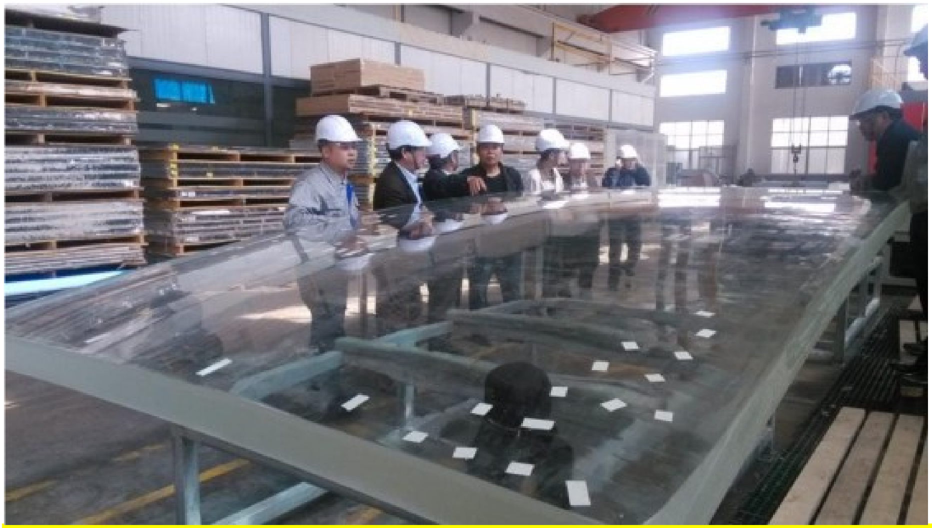
SSLS: Φ 40.1m

□ *Key features*

- ✓ ***Thickness of Acrylic: 120mm***
- ✓ ***Acrylic panels(21/23 layers + top chimney+ bottom flange): ~260 piece***
- ✓ ***Connecting nodes: ~590***
- ✓ ***Total Weight: 600 tons of acrylic and 600 tons of steel***

FEA shows maximum stress of acrylic < 3.5Mpa (as required) when tensile load < 8.2 ton.

- ***Temperature control:*** *1°C → 20m^3 LS volume change*
- ***Seismic load:*** ***still need more test to understand the liquid case.***



Forming panel size: 3m × 8m 120mm

Prototype of spherical panel

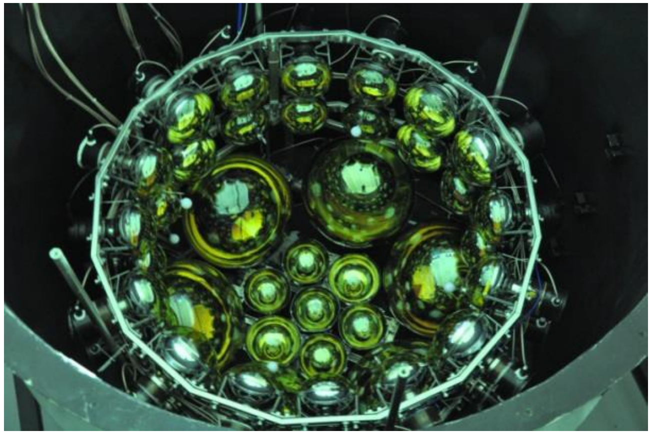
Acrylic connection nodes

The problems of shrinkage and shape variation were resolved.

bonding machine @SYSU

3.4 JUNO Detector Prototype

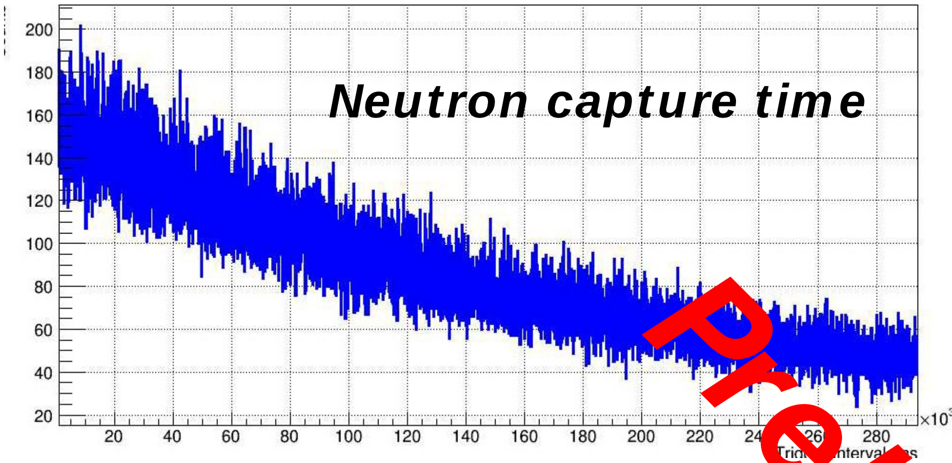
- **Check company parameters**
- **Prepare for PMT mass testing,**
- **Obtain experiences on:**
  - **Large PMT mounting & installation**
  - **Water proof PMT potting**
  - **PMT performance in LS detector**
  - **Calibration testing**

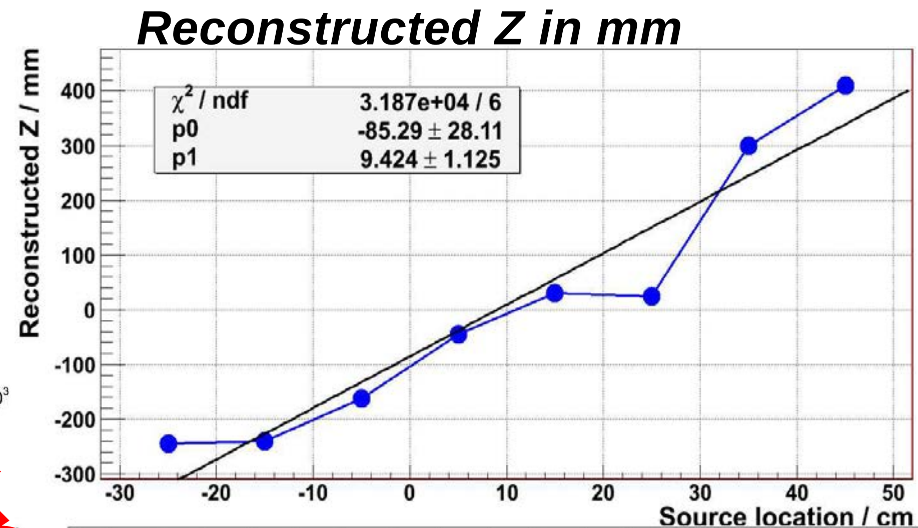


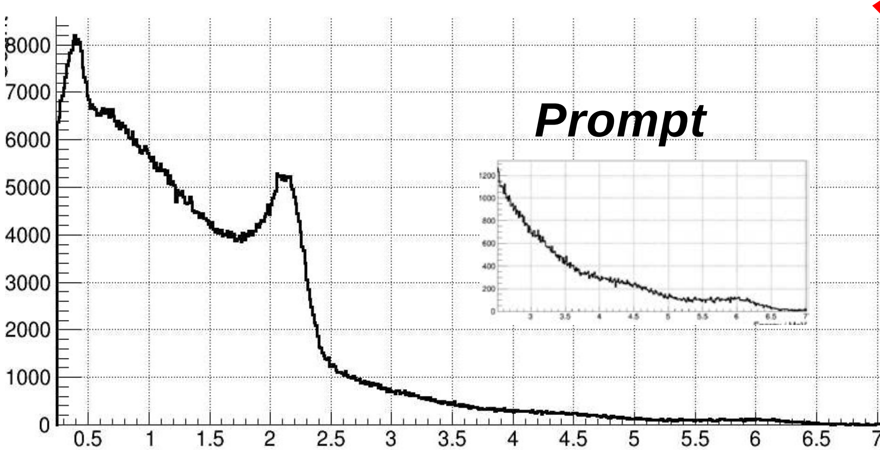
- ***Finished at the end of 2015***
- ***Preliminary analysis shows:***

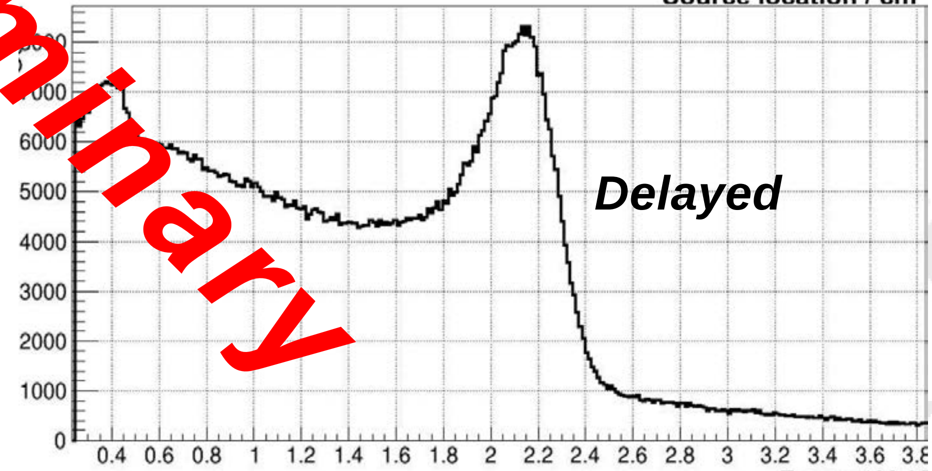
– All sub-system reached designed Goal
– PMT water potting working well
– Need more tests and further understanding

PuC neutron source loaded in JUNO prototype





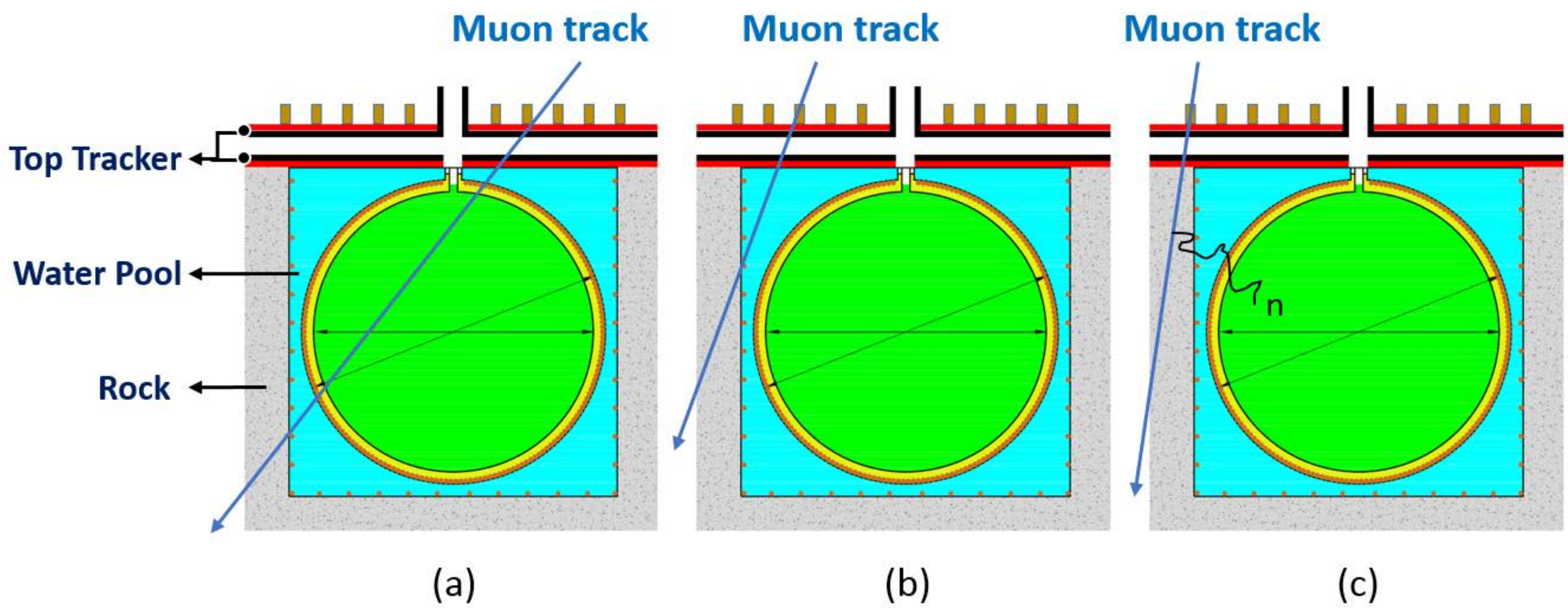




3.5 Veto system

- Cosmogenic isotopes reduction ($^{9}Li/^{8}He$) → precise muon track
- Fast neutrons background rejection → passive shielding and possible tagging
- Radioactivity from rock → passive shielding by water

Water Cherenkov detector + Top Tracker



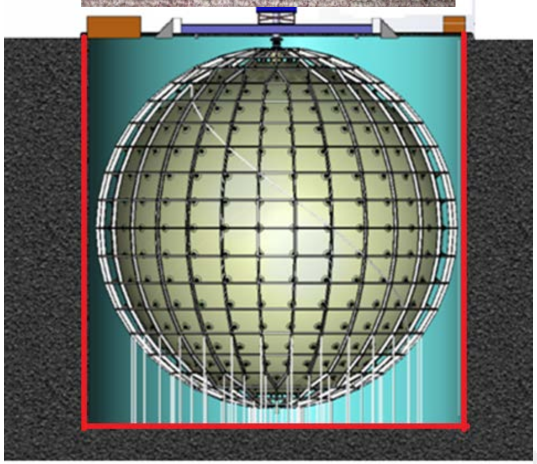
Water Cherenkov detector

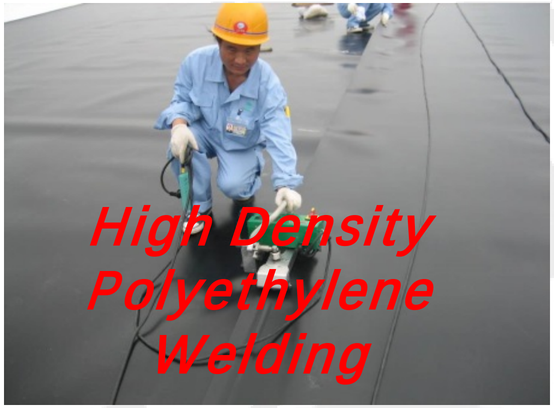
- ***20-30 kton ultrapure water is supplied and maintained by circulation system***
- ***~2k 20” PMTs***
- ***Detection efficiency >95%***

✓ ***Fast neutron background ~0.1/day***

✓ ***Water buffer is 3.2m from rock to central detector***

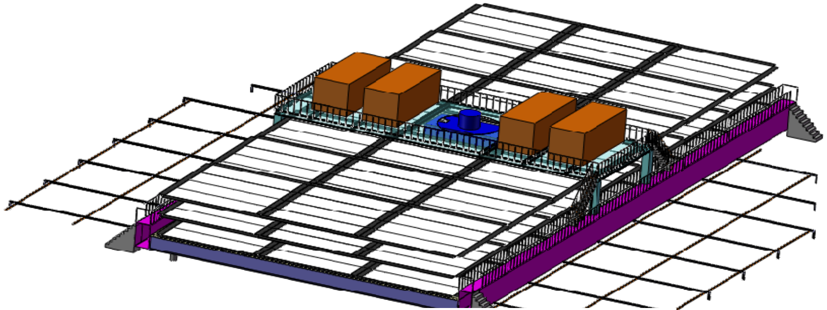
✓ ***Radioactive background from rock is 7.4 Hz @3.2m water buffer***





Top Tracker

- **Complementary**
- **Reuse Target Tracker of OPERA experiment (plastic scintillator)**
- **Arranged in 3 horizontal layers spaced by 1m to cover half of the top area.**
- **All the 64 WLS fibers of one module are read at both ends by two 64 channels multi anode photomultipliers (MaPMT).**



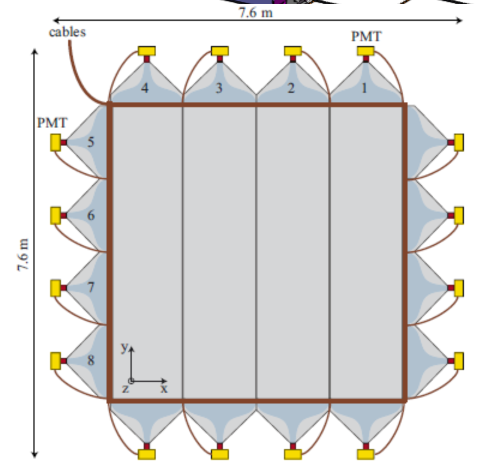


Fig. 3. Schematic view of a plastic scintillator strip wall.

Select "gold" muons for radioactive events reduction

- ***Ensure good muon tracking***
- ***Perform a precise muon tracking and provide valuable information for cosmic muon-induced $^{9}Li/^{8}He$ study.***

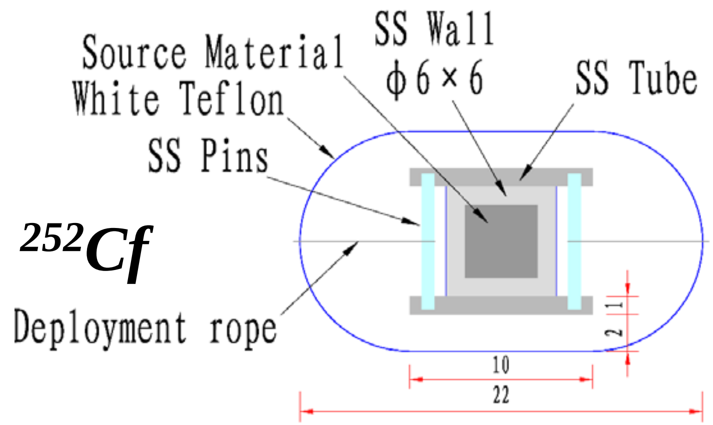
3.6 Calibration System

- ***Radioactive sources***

  γ: ^{40}K, ^{54}Mn, ^{60}Co, ^{137}Cs

  e^+: ^{22}Na, ^{68}Ge

  n: ^{241}Am-Be, ^{241}Am- ^{13}C or ^{241}Pu- ^{13}C, ^{252}Cf

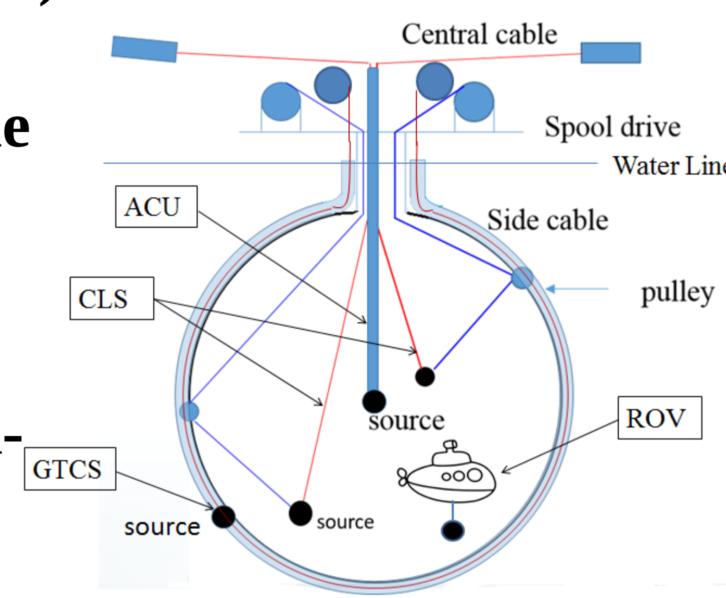


- ***Position Control***

  1-D: Automatic Calibration Unit (ACU) for central axis scan

  2-D: Cable Loop System (CLS) for one vertical plane scan + Guide Tube Calibration System(GTCS) for CD outer surface

  3-D: Remotely Operated under-liquid-scintillator Vehicles (ROV) for whole CD scan

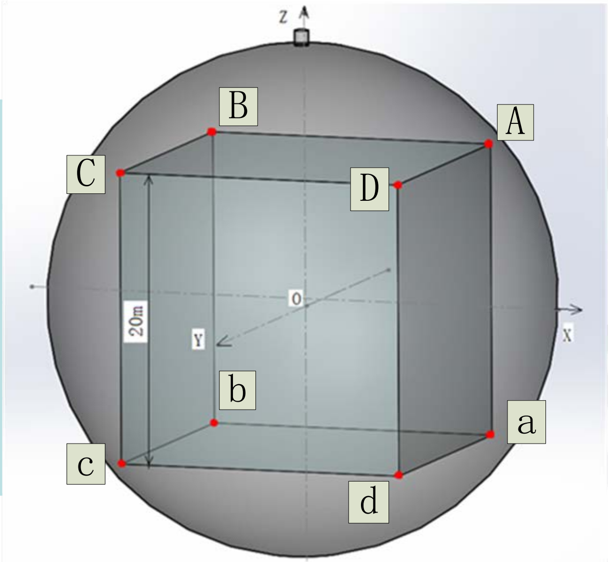


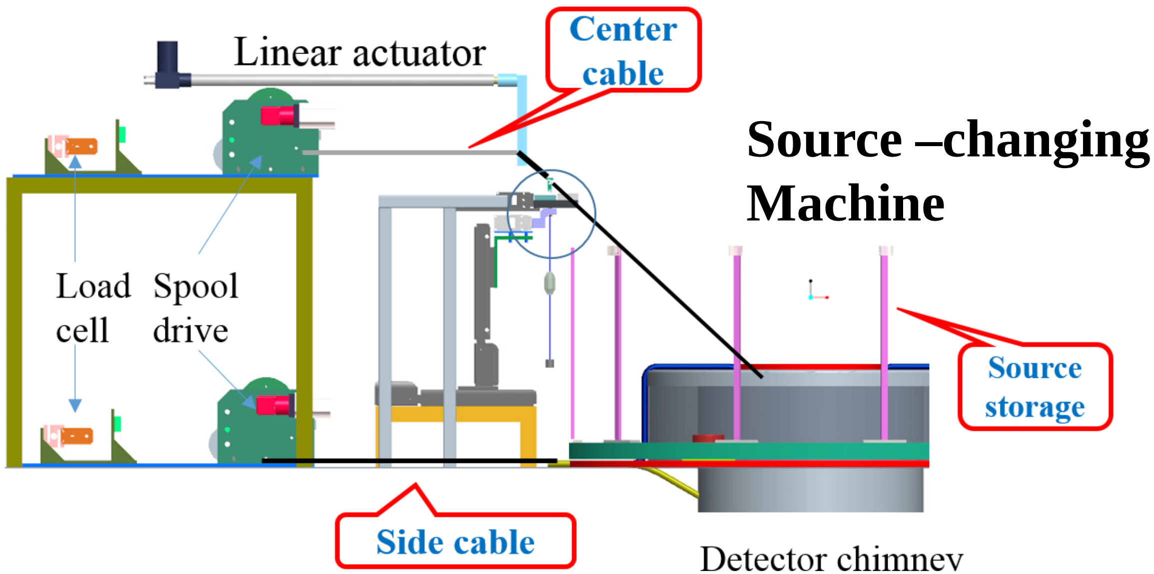
System	Position Control	Source change	Others
ACU	Spool drive (steel wire coated with Teflon Φ1.0) +Tension Control	Manual	All critical, have to be combined
CLS		Automatic	
GTCS		Manual	
ROV	Remotely Operated Vehicle	Manual	Insurance

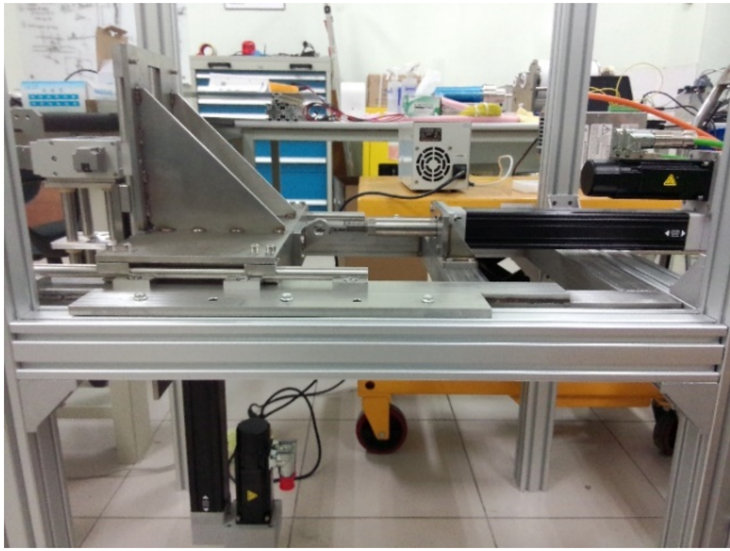
◆ *Positioning*

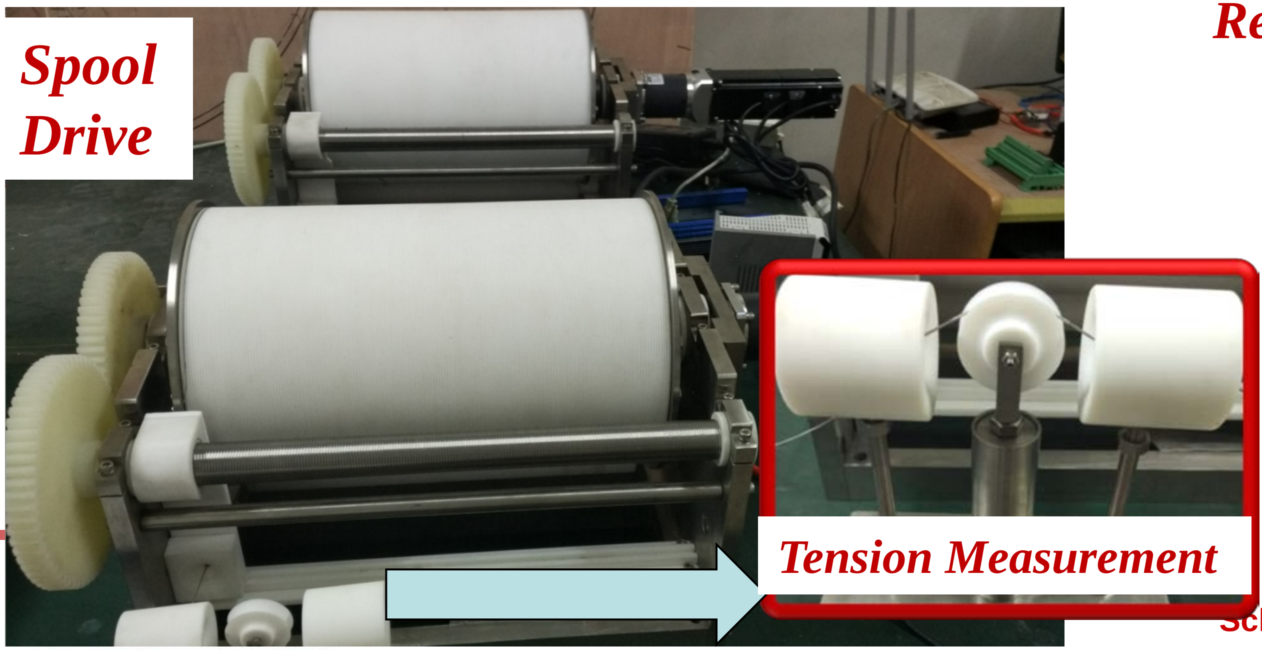
Method	System
Rope Length Calculation	CLS, ACU and GTCS
Ultrasonic receiver	ROV, CLS
CCD(Independent)	ROV, CLS

Ultrasonic Receiver Array

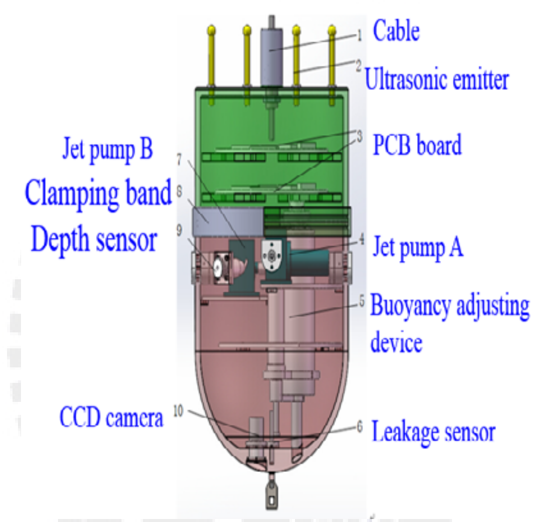


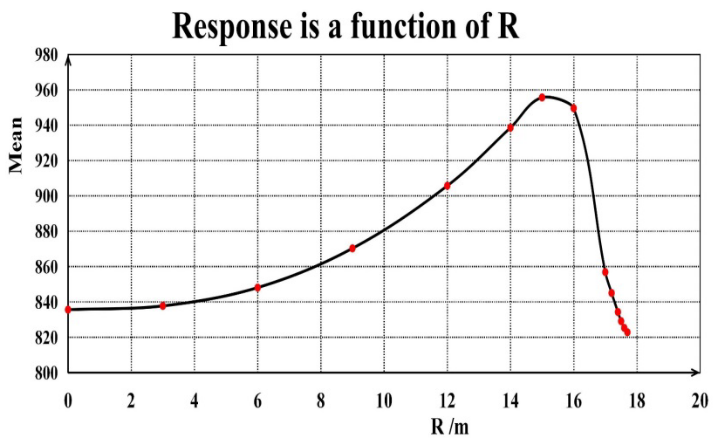






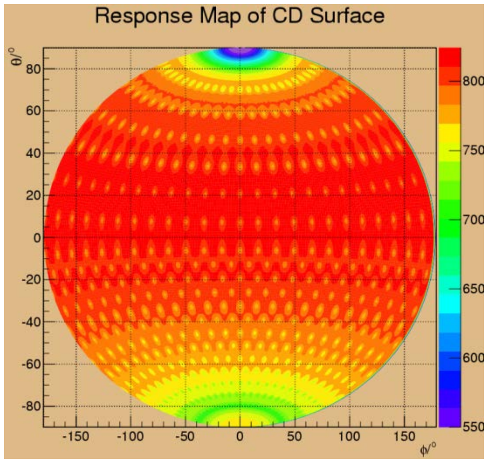
Remotely Operated Vehicles

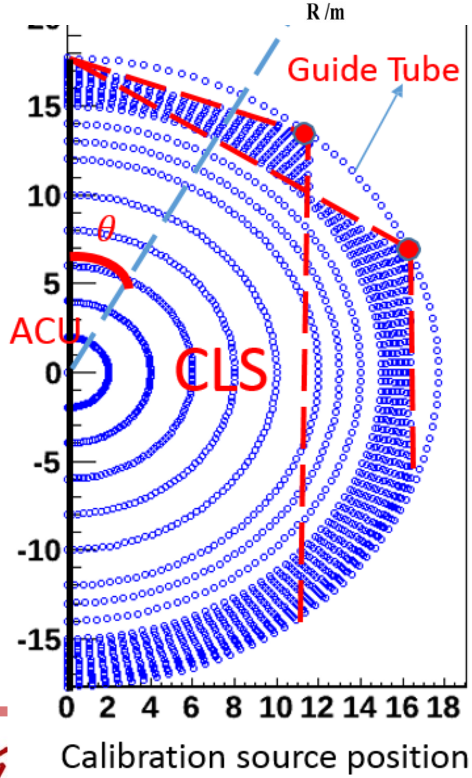




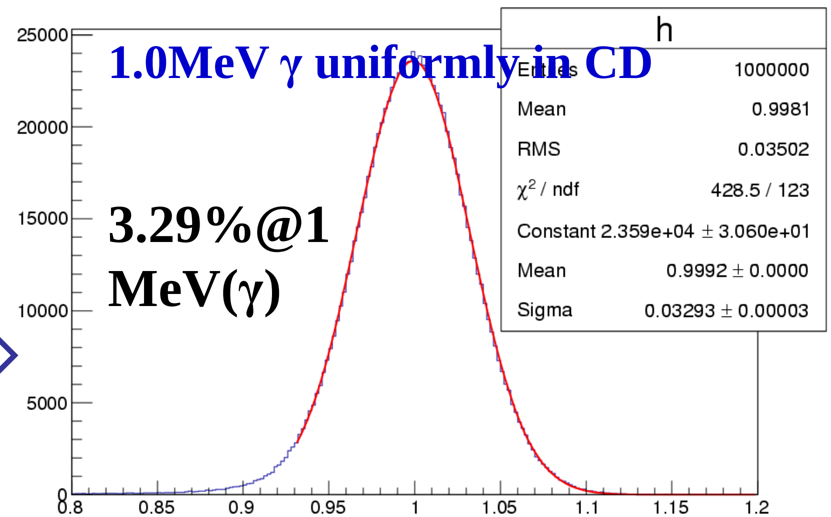
□ *Boundary Effect Sources*

- ✓ *Chimney*
- ✓ *Fasteners*
- ✓ *PMT Distribution*



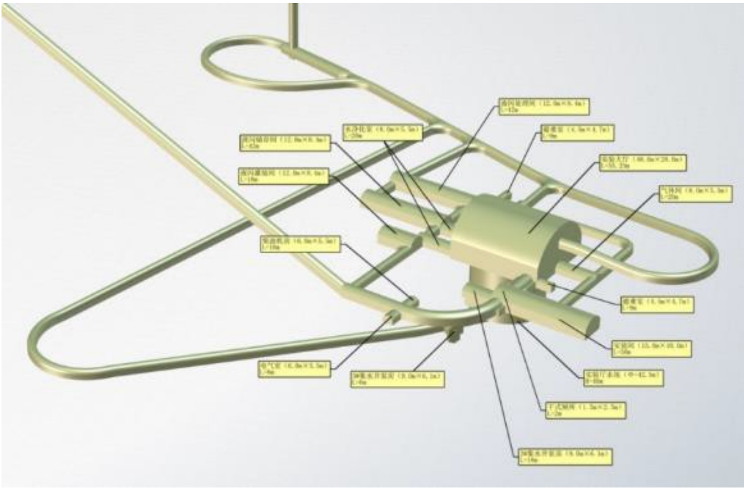


Ratio of (R,θ) to center f(R,θ) from calibration used for correction



□ Need further improvements and more work

4. Schedule

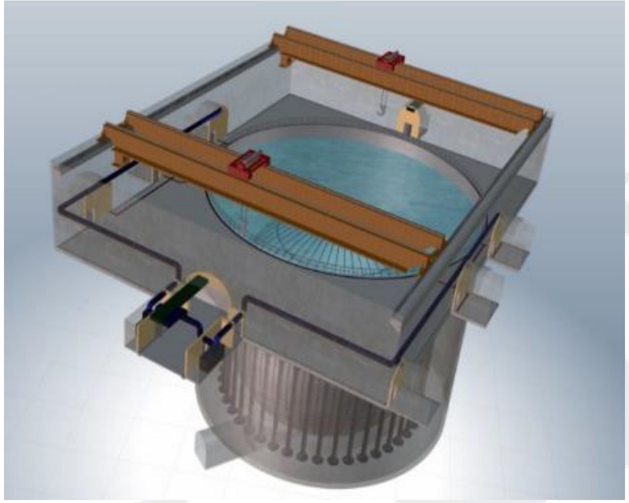


Ground breaking in Jan. 2015

- *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： 2014-2018**
- **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**

5. Summary

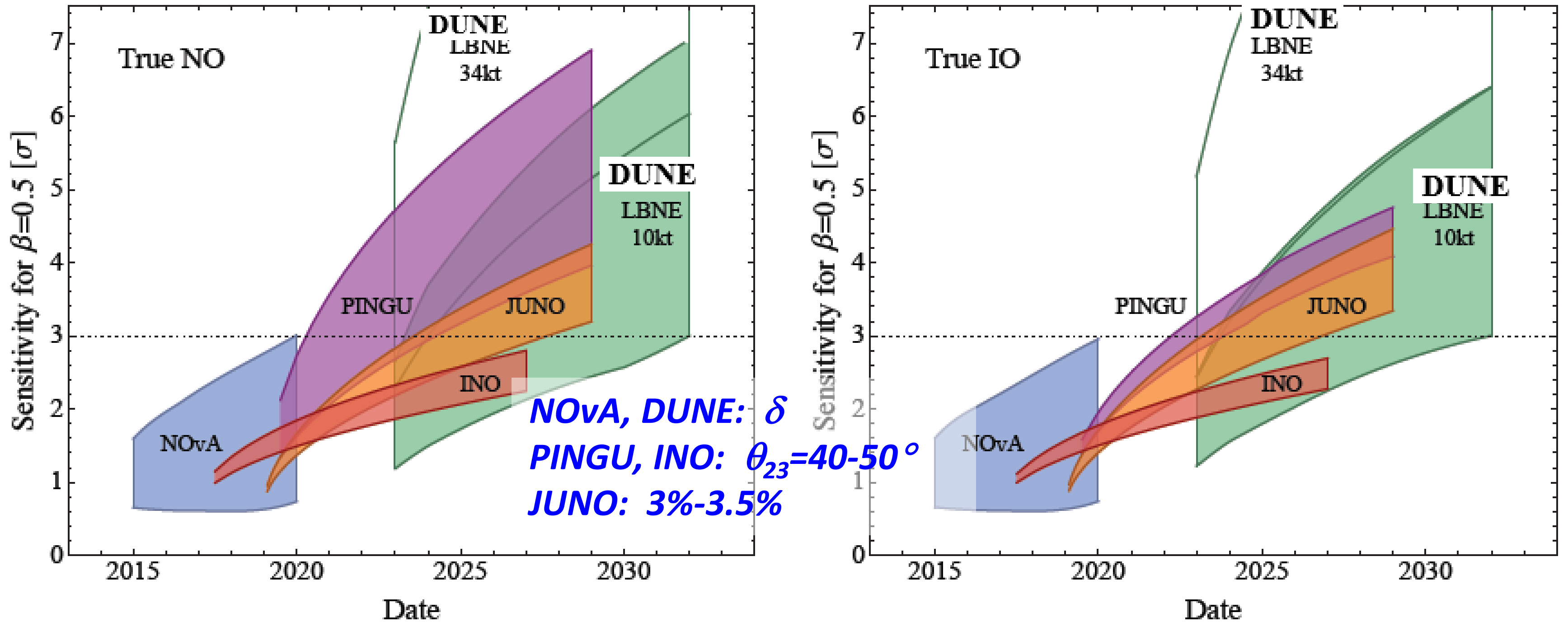
- JUNO is a fully funded project and progressing in fast track.
- JUNO will measure Mass hierarchy (3－4 σ in 2026) and 3 oscillation parameters to <1% level, with other rich physics potentials, such as supernova, geo-neutrino, solar neutrino, sterile neutrino.
- JUNO construction and R&D are on schedule, aiming at data taking in 2020.

Thanks for your attention!

Back up

Comparison with Other Experiments

M. Blennow et al., JHEP 1403 (2014) 028



NOvA, DUNE: δ
PINGU, INO: θ_{23}=40-50°
JUNO: 3%-3.5%

- JUNO is unique for measuring MH using reactor neutrinos
  - Independent of the CP phase and free from the matter effect: complementary to accelerator-based experiments
  - competitive in time
  - Many other science goals

	Daya Bay	BOREXINO	KamLAND	JUNO
Target Mass	~20 t	~300 t	**~1 kt**	**~20 kt**
Photoelectron Yield (PE/MeV)	~160	**~500**	~250	**~1200**
Photocathode Coverage	~12%	**~34%**	**~34%**	**~80%**
Energy Resolution	~7.5%/√E	**~5%/√E**	~6%/√E	**<3%/√E**
Energy Non-linearity	~1.5%	**~1%**	~2%	**<1%**

F.P. An et al, J. Phys. G 43 (2016) 030401 [arXiv:1507.05613]