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JUNO: A Multipurpose Underground Precision Neutrino Detector

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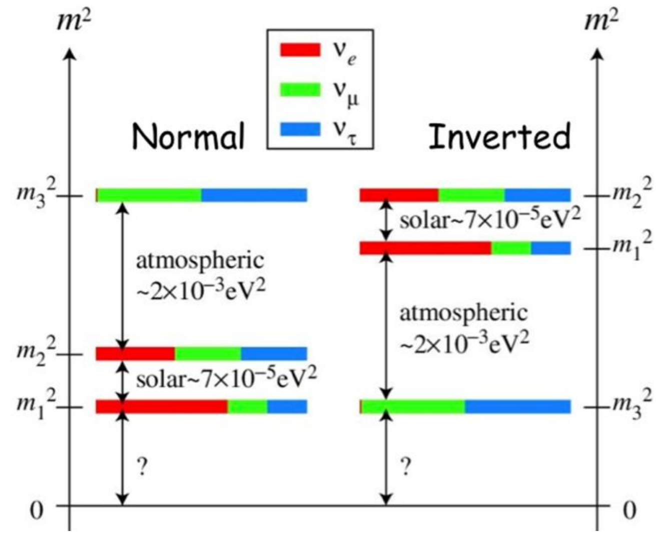
Jul. 5th, 2018

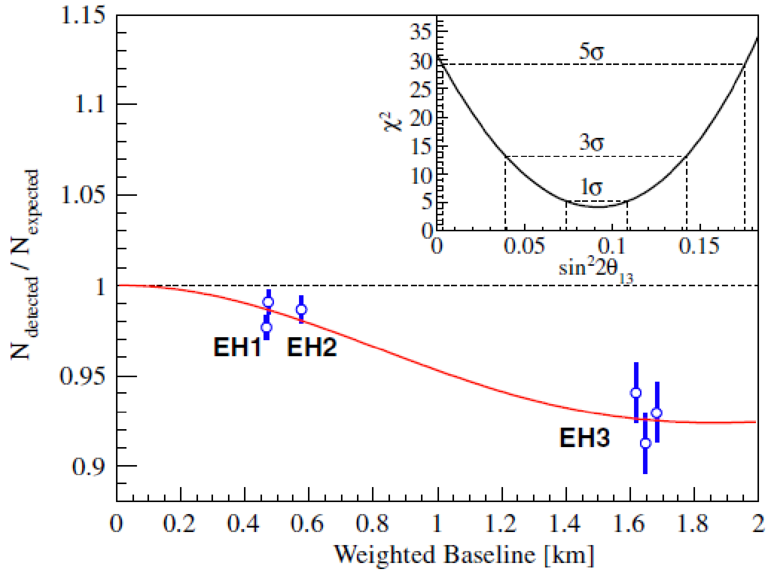
Outline

1. JUNO Introduction
2. JUNO Detector R&D
3. JUNO Physics Goals and Potentials
4. Milestones & 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.





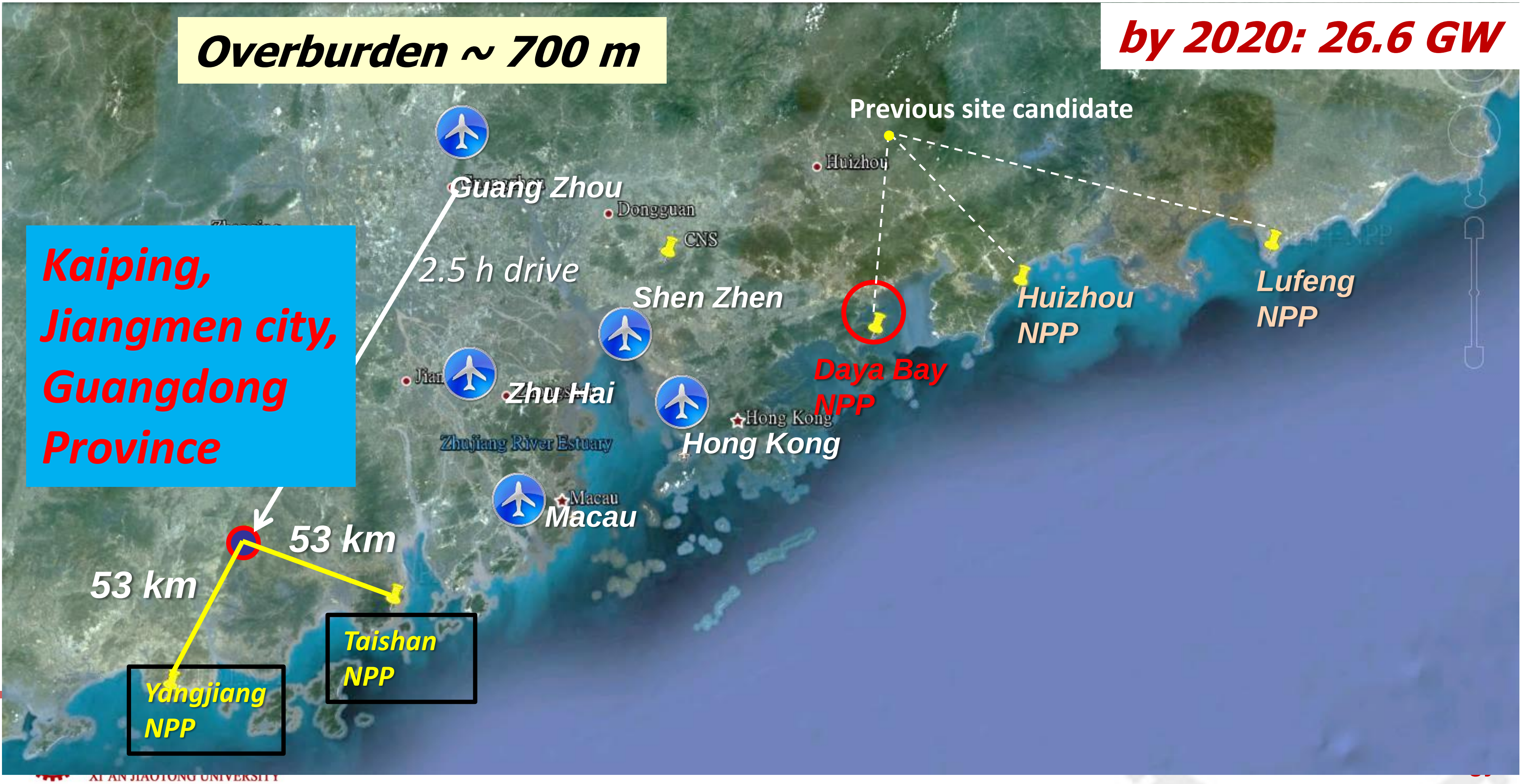
$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat.}) \pm 0.005(\text{syst.})$$

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***

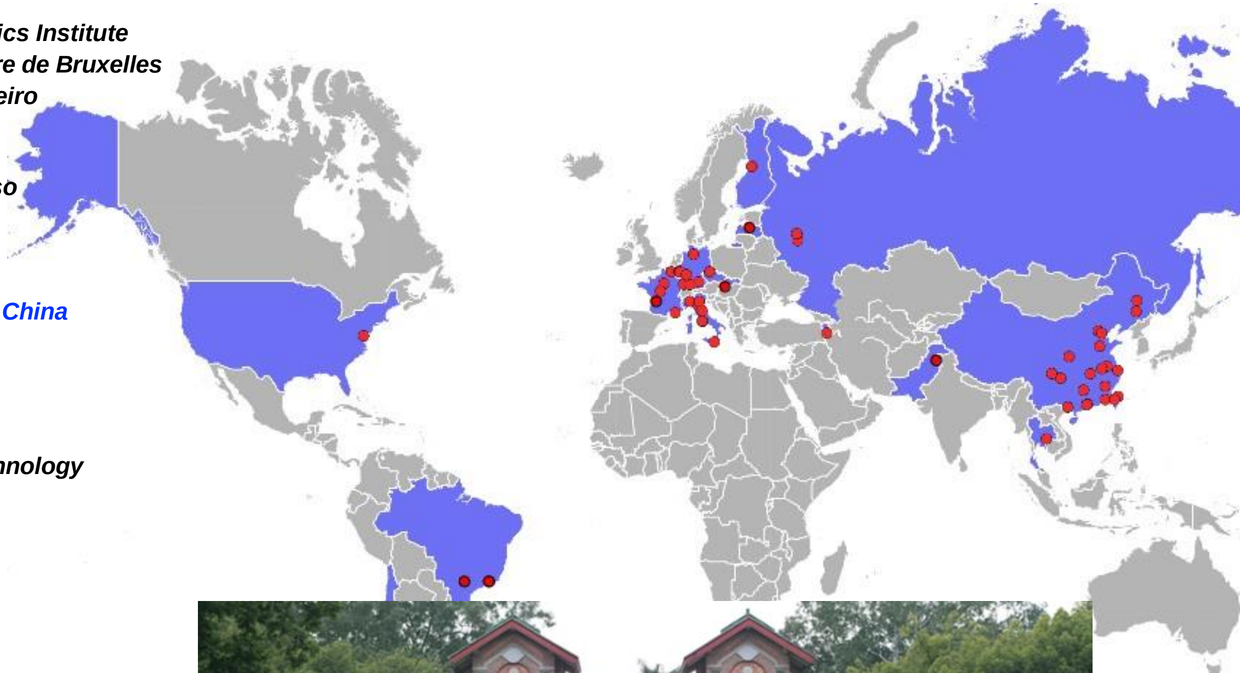
JUNO Location

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

Armenia Yerevan Physics Institute
Belgium Université libre de Bruxelles
Brazil PUC Rio de Janeiro
Brazil UE Londrina
Chile PCUC
Chile UTFSM Valparaiso
BISEE
Beijing Normal U.
CAGS
ChongQing University China
CIAE
DGUT
ECUST
Guangxi U.
Harbin Institute of Technology
IHEP
IMP-CAS
Jilin U.
Jinan U.
Nanjing U.
Nankai U.
NUDT
NCEPU
Pekin U.
Shandong U.
Shanghai JT U.
SYSU
Tsinghua U.
UCAS
USTC
U. of South China
Wu Yi U.
Wuhan U.
Xi'an JT U.
Xiamen University



Zhengzhou U.
Taiwan National Chiao-Tung U.
Taiwan National Taiwan U.
Taiwan National United U.
Czech R. Charles U. Prague
Finland U. Jyväskylä
France APC Paris
France CENBG Bordeaux
France CPPM Marseille France
IPHC Strasbourg France
Subatech Nantes
Germany ZEA FZ Julich
Germany RWTH Aachen U.
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Italy INFN Catania
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Italy INFN-Milano
Italy INFN-Milano Bicocca
Italy INFN-Padova
Italy INFN-Perugia
Italy INFN-Roma 3
Latvia IECS Riga
Pakistan PINSTECH Islamabad
Russia INR Moscow
Russia JINR
Russia MSU
Slovakia U. Bratislava FMPICU
Thailand NARIT
Thailand PPRLCU Bangkok
Thailand SUT
USA UMD1
USA UMD2

Collaboration established in July 2014
Now: 72 institutions, 593 collaborators

2. JUNO Detector R&D

Veto Detector

- ✓ ***Water Cherenkov detector:*** track muons and shield ambient radioactivity
- ✓ ***Top Trackers:*** independent muon tracking

Energy resolution: ~ 3%/√E

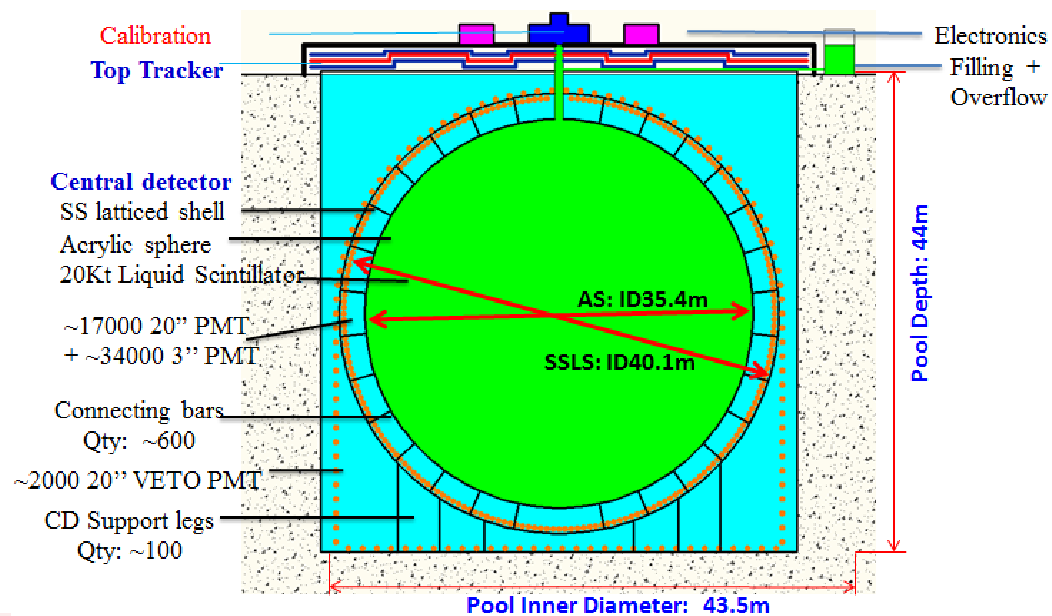
Energy Non-linearity : < 1%

Central Detector

- ✓ ***~20kt @ Φ35.4m (Largest LS detector) filled with LS.***
- ✓ ***Equipped with ~18k high QE 20" PMTs***
- ✓ ***25k 3" PMTs for better timing and higher saturation energy***

827. 3-inch PMT system of JUNO experiment
Jilei Xu (Institute of High Ene...)
06/07/2018, 18:30
Neutrino Physics | Poster | POSTER

Overburden of~700 m rock for cosmic-ray shielding



AS: Acrylic Sphere; SSLS: Stainless Steel Latticed Shell

Calibration system

- ✓ ***Multiple sources: e^+, γ, n***
- ✓ ***Full volume positioning***

2. 1 Liquid Scintillator

☐ Requirements for LS:

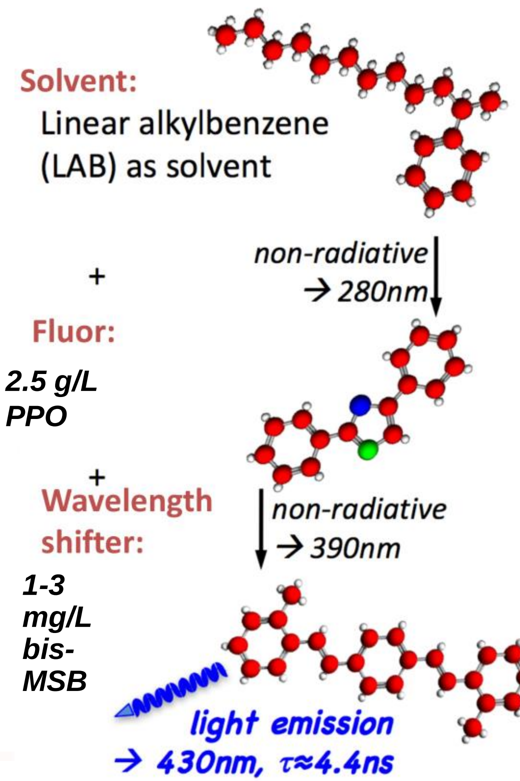
- ✓ ***High light-yield:*** *10^4 photons/MeV*
- ✓ ***High transparency:*** **Attenuation Length: >20m@430nm**
- ✓ ***Low background:*** **$^{238}U<10^{-15}g/g$, $^{232}Th<10^{-15}g/g$, $^{40}K<10^{-17}g/g$**

☐ LS Recipe

- ✓ **based on Daya bay**
- ✓ **Solvent: Linear Alkyl Benzene**
- ✓ **2.5g/L PPO**
- ✓ **1-4 mg/L bis-MSB**

☐ Purification pilot plant

- ✓ *Under operation at Daya Bay*
- ✓ *Distillation, Al_2O_3 column purification, water extraction and gas stripping*
- ✓ *> 23m A.L. after filling (w/o bis-MSB)*

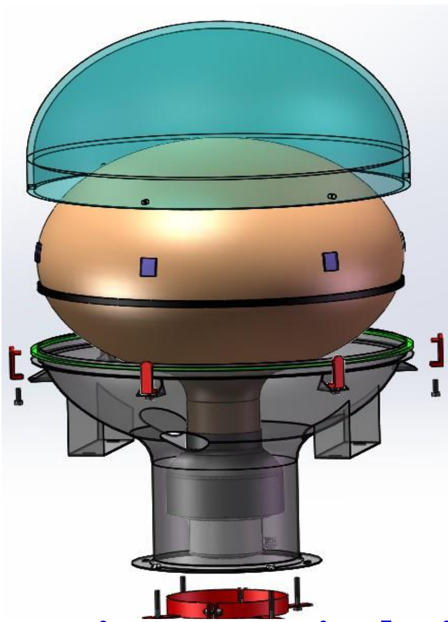


2.2 PMTs

20" PMTs with High QE

- ✓ **15k NNVT MCP-PMT:** newly developed by **North Night Vision Technology (NNVT)**, latest 300 PMTs' Detection efficiency is **> 30%**
- ✓ **5k Hamamatsu R12860**

654. the 20-inch PMT system for the JUNO experiment
Zhonghua Qin (Institute of High Ene...)
06/07/2018, 14:12
Detector: R&D for Present... | Parallel | Detector: R&D for Present...



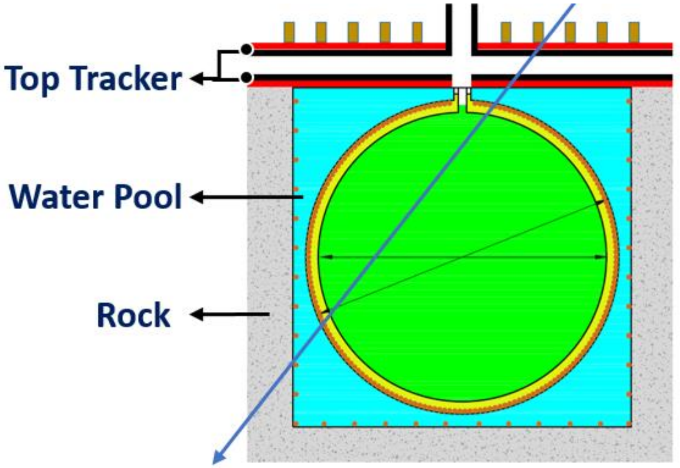
Characteristics	MCP-PMT	R12860
Detection Eff. (QE×CE*area) (%)	27%, >24%	27%, >24%
P/V of SPE	3.5, >2.8	3,>2.5
TTS on the top point (ns)	*~12,<15*	***2.7,<3.5***
Rise time/Fall time(ns)	R~5; F~12	R~5,<7; F~9,<12
Anode Dark count(Hz)	20k,<30k	10k,<50k
After Pulse (%)	1,<2	10,<15
Glass Radioactivity (ppb)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

Protection cover is designed to prevent chain implosion reaction

878. Implosion protection and waterproof potting for the JUNO 20-inch PMTs
Mrs meihang xu (IHEP)
06/07/2018, 18:30
Beyond the Standard Mo... | Poster | POSTER

2.3 Veto system

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



Water Cherenkov detector

- *20-30 kton ultrapure water is supplied and maintained by circulation system(<0.2 Bq/m³)*
- *~2400 20" PMTs*
- *Detection efficiency >95%*

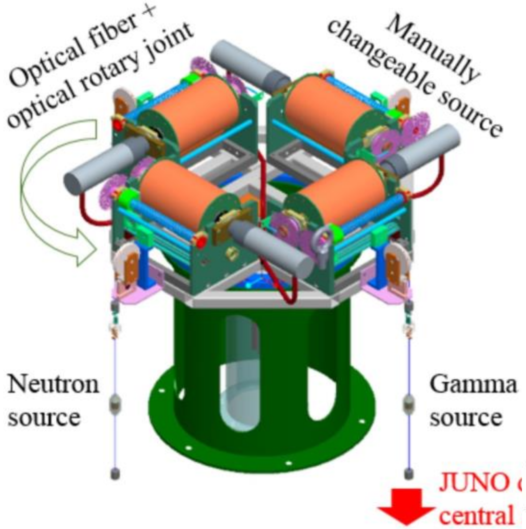
Top Tracker

879. The Top Tracker detector of the JUNO experiment
Yuri Gornushkin (Joint Institute for N...)
06/07/2018, 18:30
Poster POSTER

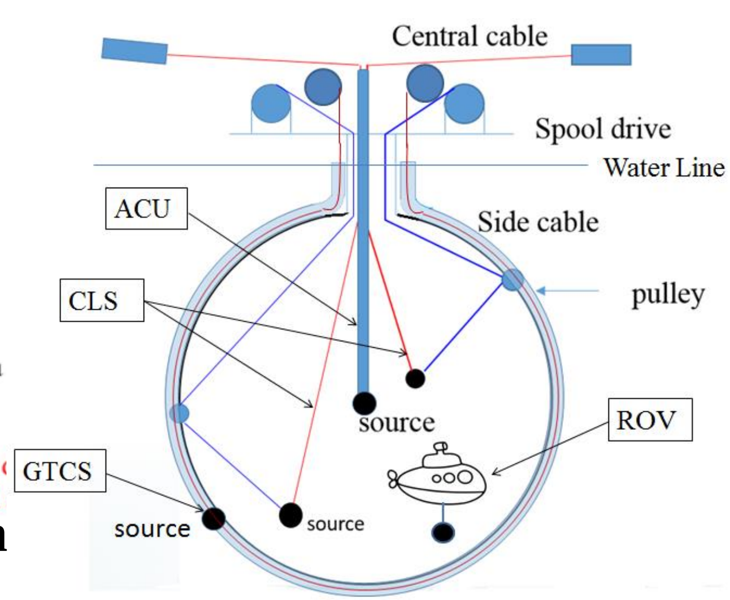
- *Reuse plastic scintillator from OPERA*
- *3 layers to cover 1/2 on top.*
- *Each module are readout at both ends by multi anode photomultipliers.*

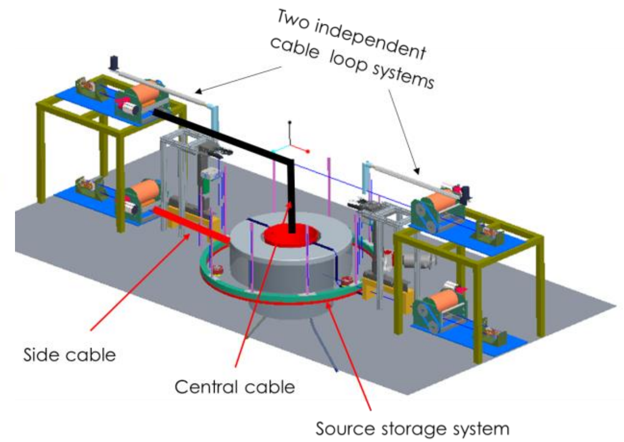
2.4Calibration System

Automatic Calibration Unit (ACU)



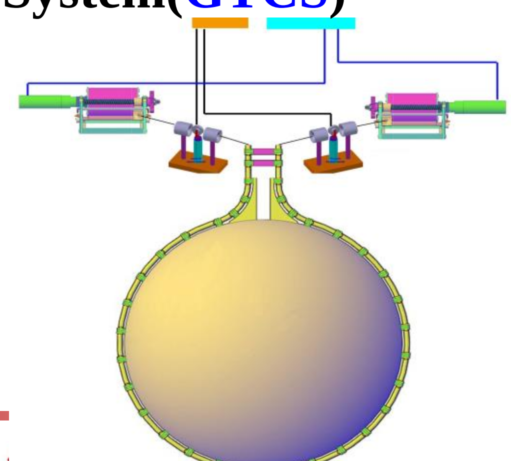
Cable Loop System (CLS)



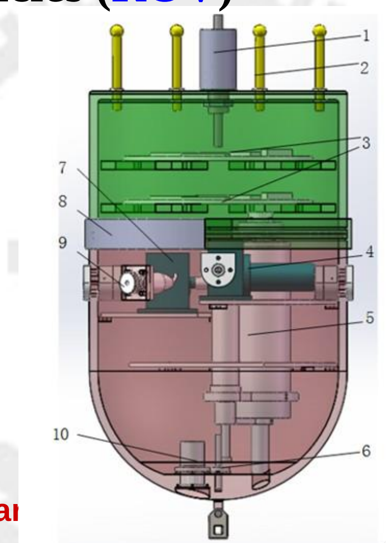


Remotely Operated under-liquid-scintillator Vehicles (ROV)

Guide Tube Calibration System(GTCS)

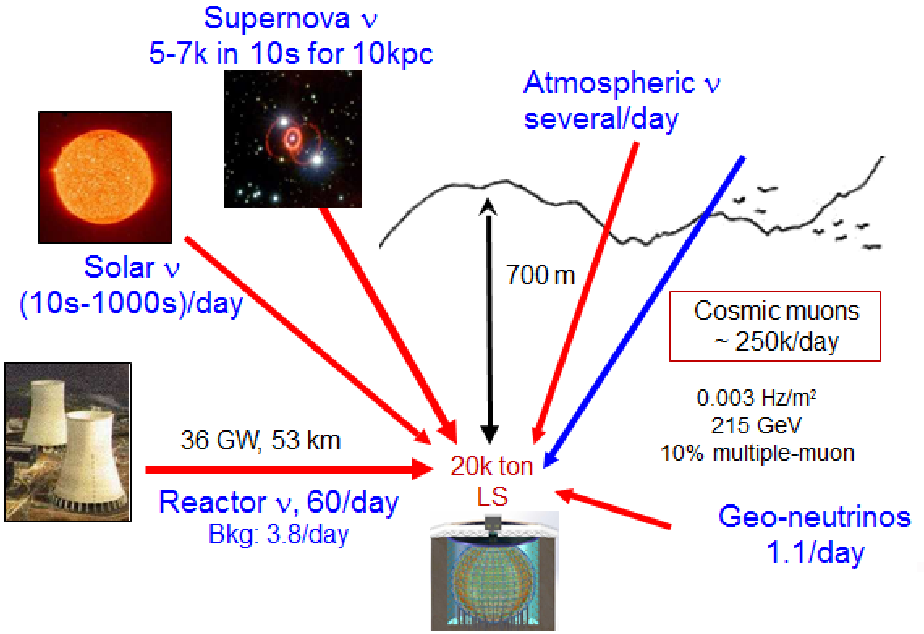


- **Complementary for covering entire energy range of reactor neutrinos and full-volume position coverage inside JUNO central detector**



3. JUNO Physics Goals and Potentials

	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%**	**~78%**
Energy Resolution	~7.5%/√E	**~5%/√E**	~6%/√E	**<3%/√E**
Energy Non-linearity	~1.5%	**~1%**	~2%	**<1%**



Due to its large scale and best performance, JUNO will be an exceptional detector and it has rich physics potentials.

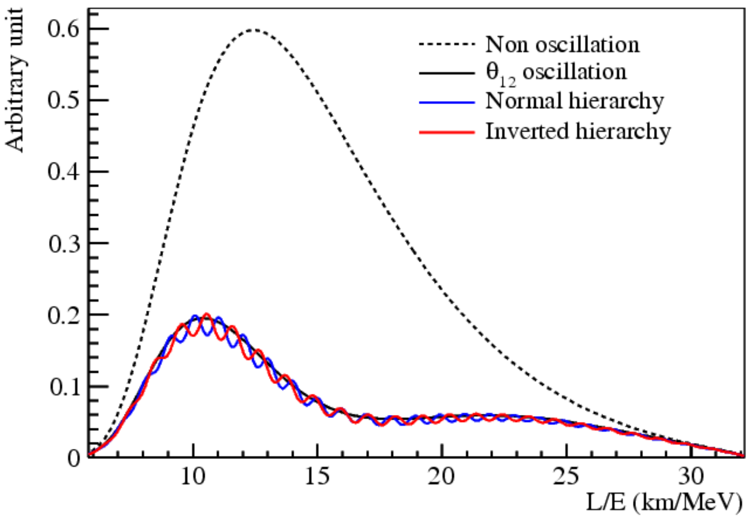
3.1 Mass Hierarchy

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

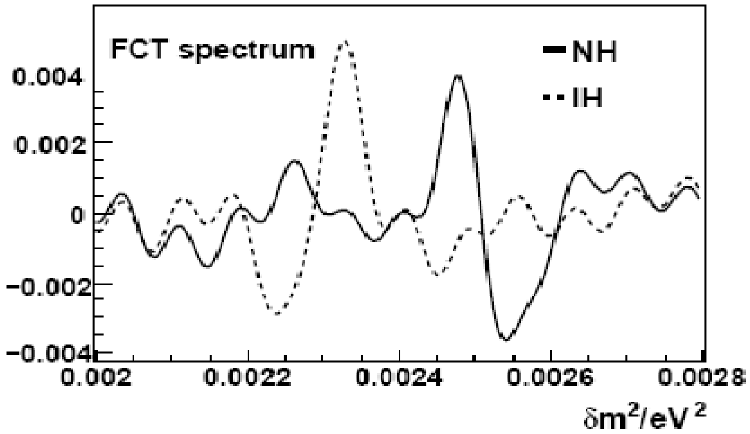
$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$
$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$

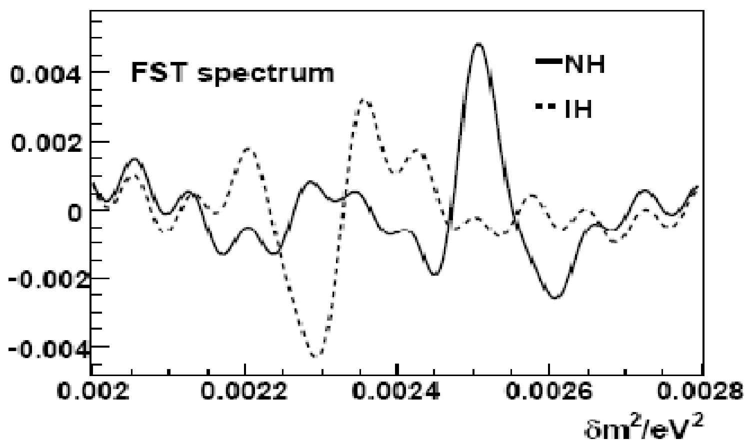
$$P_{ee} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21}) - \sin^2 2\theta_{13}\sin^2(|\Delta_{31}|) - \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{21})\cos(2|\Delta_{31}|) \pm \frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|)$$

+ NH
- IH

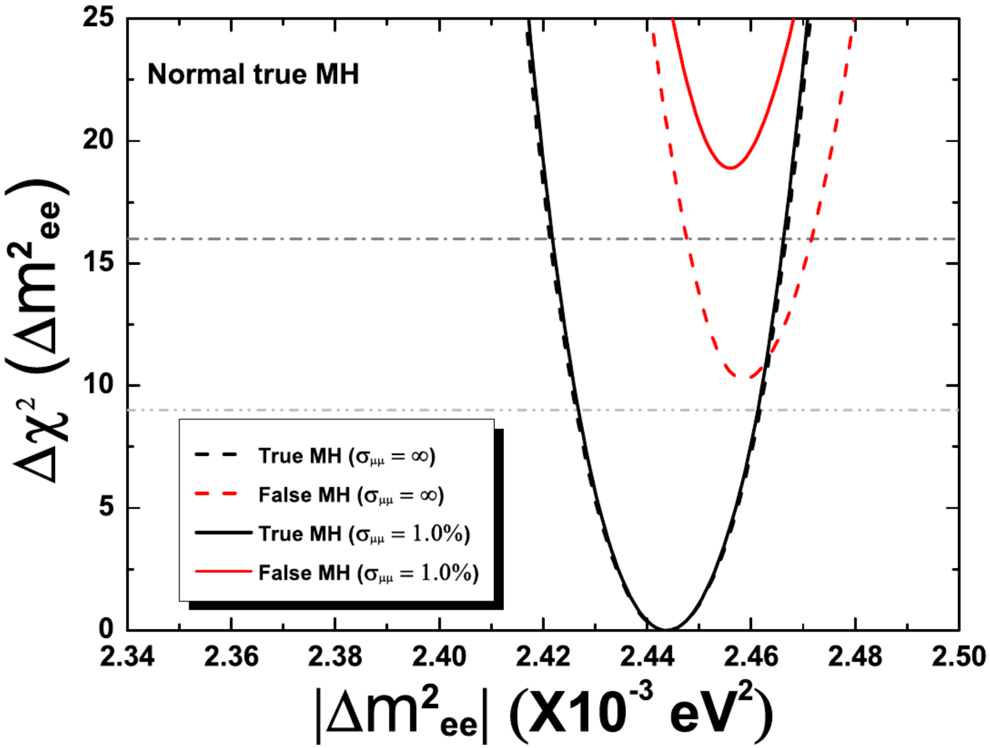


- ***The big suppression is the "solar" oscillation (Δm^2_{12}, $\sin^2\theta_{12}$)***
- ***"Large" value of θ_{13} is crucial***





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



Sensitivity with 100k events (~6 yrs)

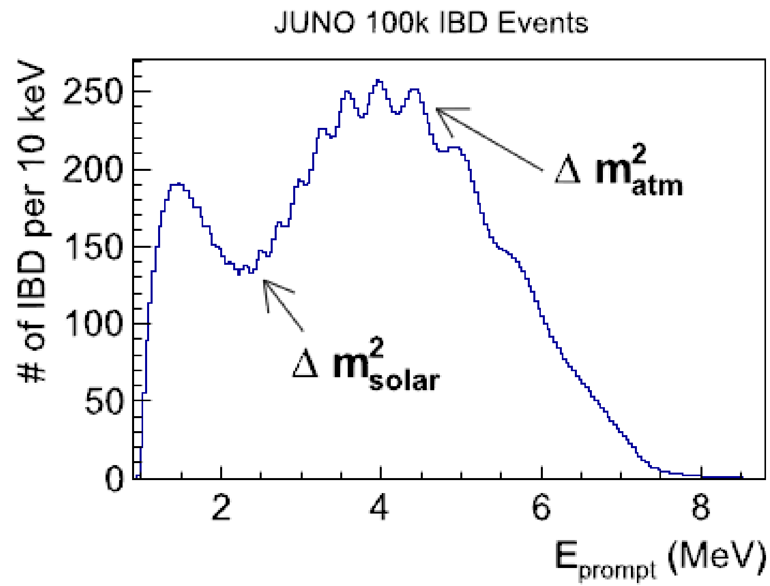
✓ No constraint: $\overline{\Delta\chi^2} > 9$

✓ With 1% constraint: $\overline{\Delta\chi^2} > 16$

3.2 Measurement of Oscillation Parameters

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

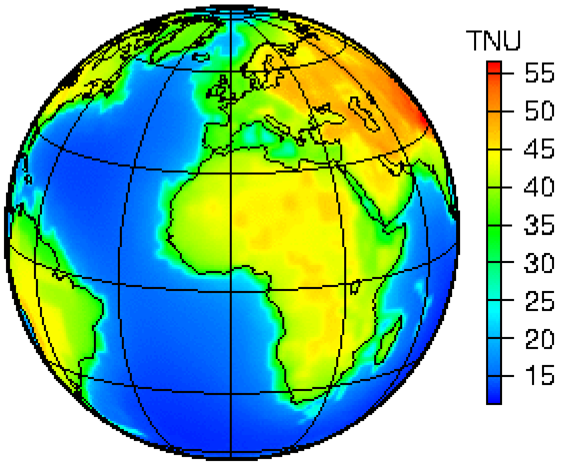
- **Improve precisions of three parameters (Δm^2_{21}, Δm^2_{ee} and $\sin^2\theta_{12}$) to sub-percent level, several times improvement compared with current precision.**
- **Probe the unitarity of U_{PMNS} to ~1% level**



	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%

3.3 Neutrino Astrophysics and Others

- Neutrinos from the Earth escape freely and bring the information about U, Th and K abundances and their distributions
- Due to its largest LS size, the expected geo-neutrino rate in JUNO is ~1.1/day.
- Within the 1st year, JUNO will record more geo-neutrino events than all other detectors



➢ ***JUNO will be the most precise experiment for geo-neutrino study. In the meanwhile, JUNO is also attractive for other neutrino astrophysics, such as supernova neutrinos, diffuse supernova neutrinos, solar neutrinos and atmospheric neutrinos.***

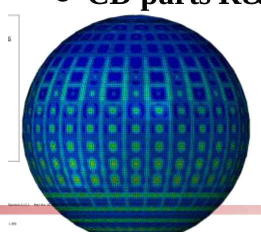
Beside these, additional physics is also rich in JUNO

- Sterile neutrinos
- Dark matter searches
- Proton decay
- Other exotic searches

4. Milestones & Schedule

2014:

- International collaboration established
- Start civil construction

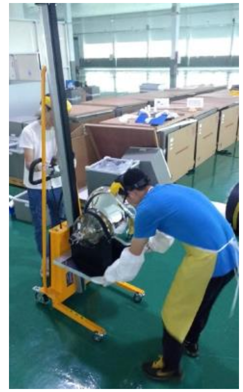


2015:

- PMT production line setup
- CD parts R&D

2016:

- Start PMT production
- Start CD parts production



2017:

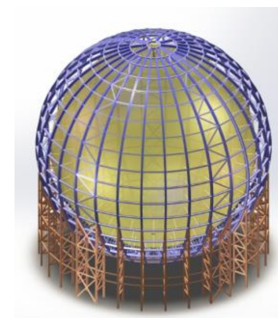
- Start PMT testing
- TT arrived

2018:

- PMT potting
- starts Delivery of surface buildings
- Start production of acrylic sphere

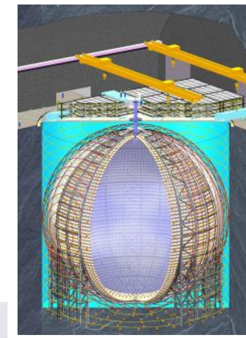
2019-2020:

- Electronics production starts
- Civil work and lab preparation Completed
- Detector constructing



2021:

- Detector ready for Data taking!



5. Summary

- **JUNO is a multipurpose underground precision neutrino detector, which is a very active R&D program and will achieve design goals.**
- **JUNO will measure Mass hierarchy (3-4 σ in 2027) and 3 oscillation parameters to <1% level, with other rich physics potentials, such as supernova, geo-neutrino, solar neutrino, sterile neutrino.**
- **JUNO detector R&D and fabrication are progressing smoothly, aiming at data-taking in 2021.**

Thanks for your attention!

Backup Slides

JUNO Requirements

☐ Reactor baseline variation: < 0.5 km
- ✓ JUNO site meets this requirement

☐ Energy resolution: ~ $3\%/\sqrt{E}$
- The crucial parameter

☐ Energy Non-linearity : < 1%
- ✓ Large non-linearity could lead to wrong answer

☐ Statistics: 100k events in 6 yrs
- ✓ 26.6-35.7 GW reactor power
- ✓ 20 kton detector (→ ~60 evts/day)

☐ Background minimization
- ✓ Deep underground
- ✓ Precision muon tracking to maximize exposure
- ✓ Minimization of Material Radioactivity

Comparisons

JUNO will be an exceptional detector

	Daya Bay	BOREXINO	KamLAND	JUNO
Target Mass	~20 t	~300 t	**~1 kt**	**~20 kt**
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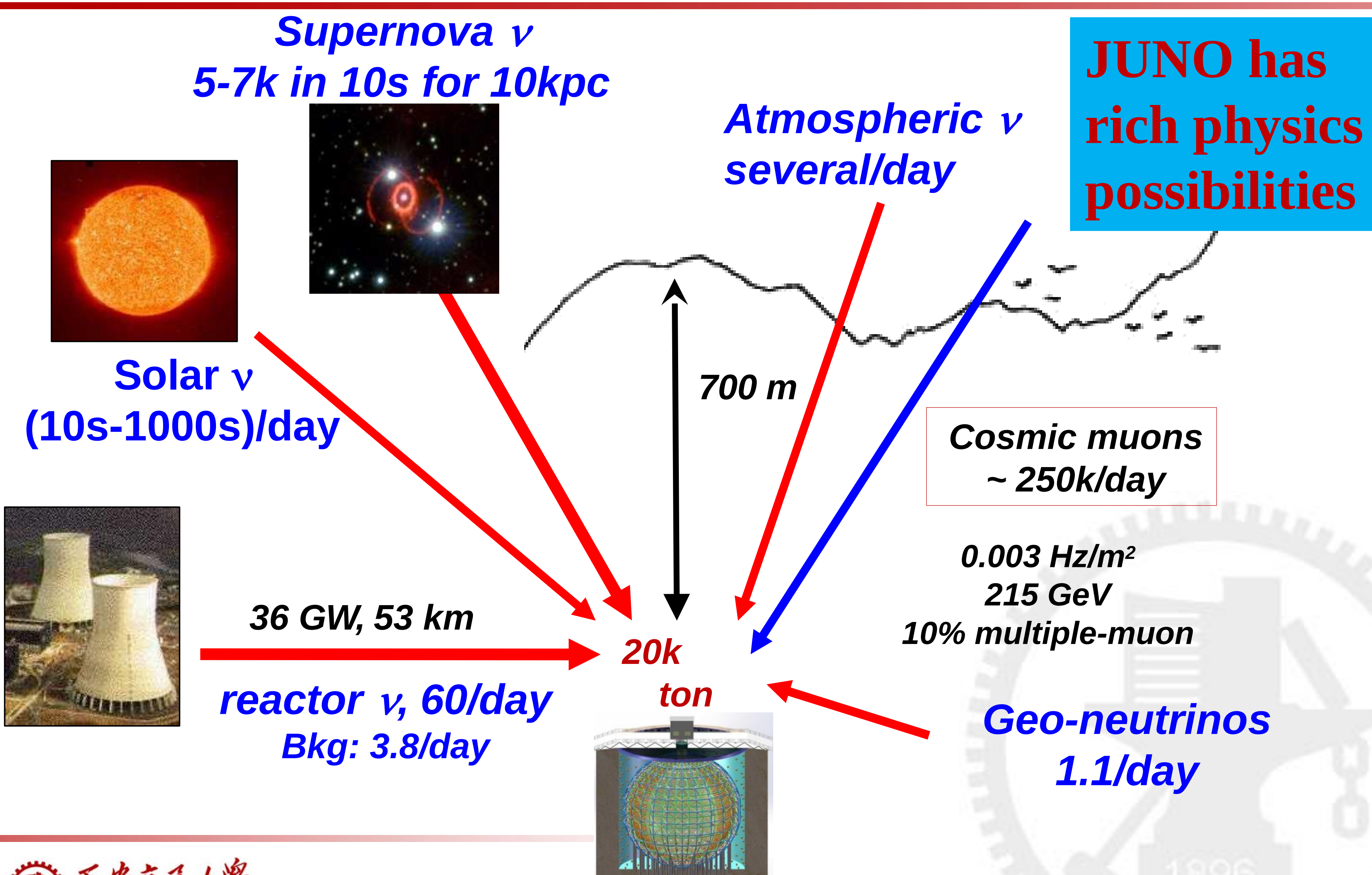
JUNO Physics Goals and Potentials



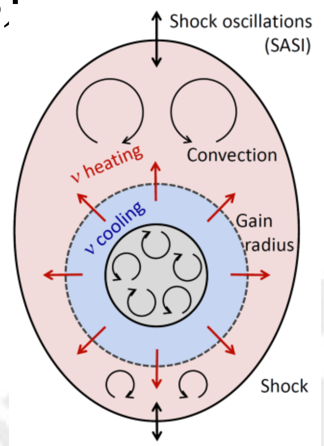
Supernova Neutrinos

- 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
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	CC	6.0×10^1	1.1×10^2	1.6×10^2

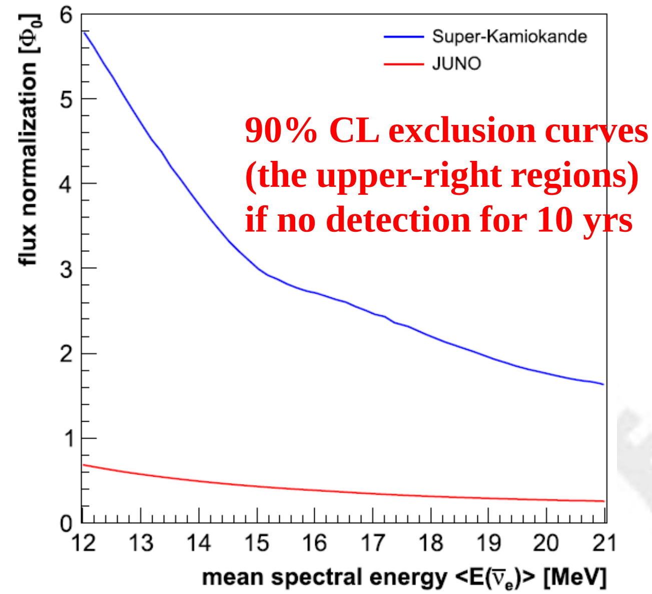


Advantage: Global analysis of all channels

- 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

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.**

Solar neutrinos

JUNO advantages for solar ν detection

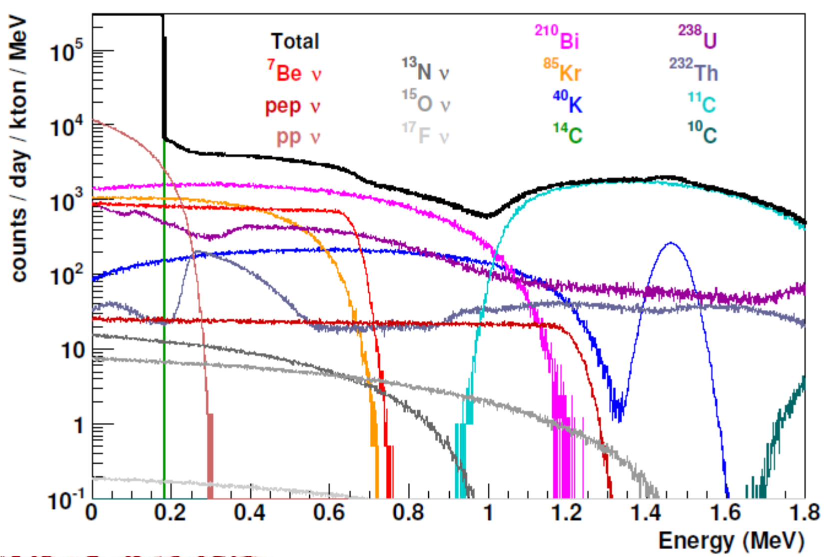
$$\nu_{e,\mu,\tau} + e^- \to \nu_{e,\mu,\tau} + e^-.$$

- ✓ 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	



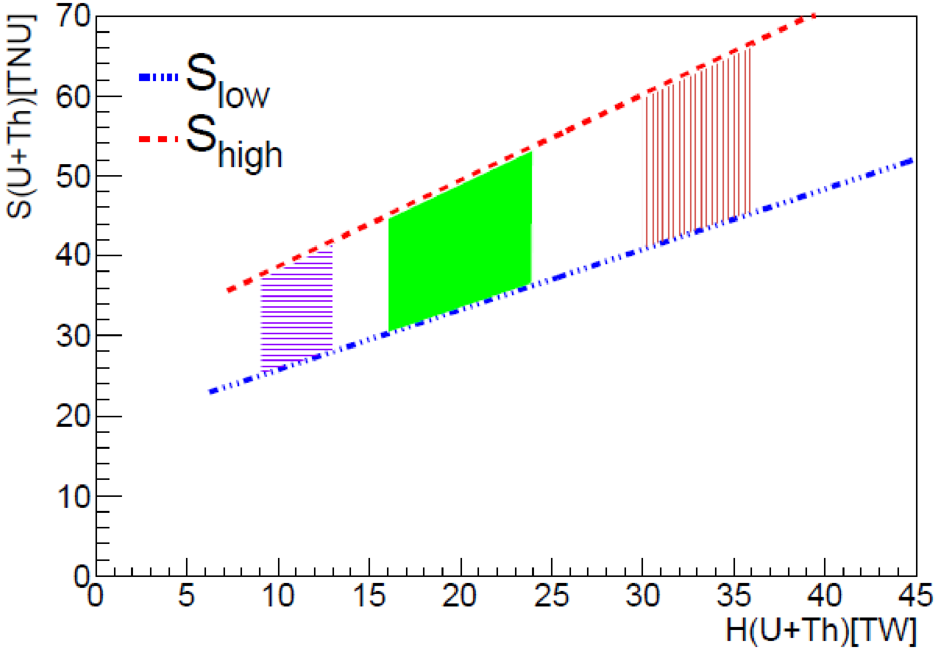
The expected singles spectra at JUNO with the "baseline" radiopurity requirements **(Assumed radio purity gives S:B≈1:3)**

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).**



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

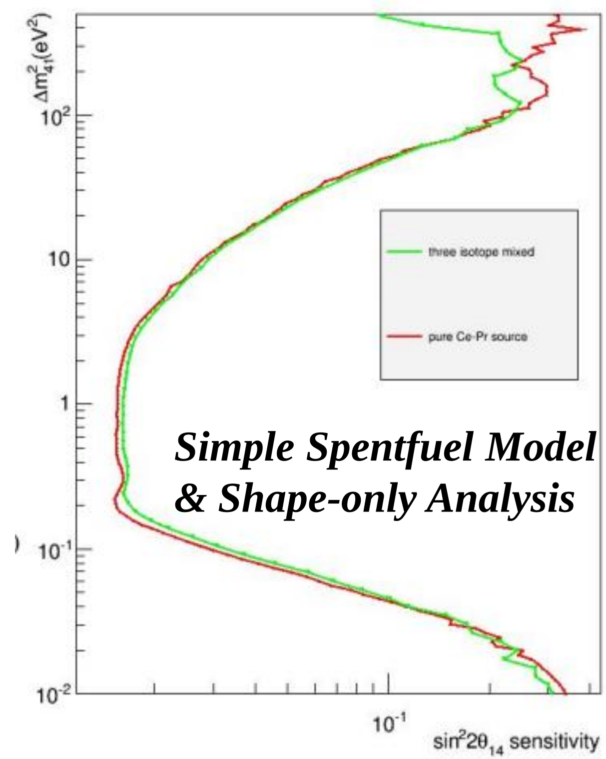
✓ ***A pair parent and daughter nucleus:***

- ***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.***

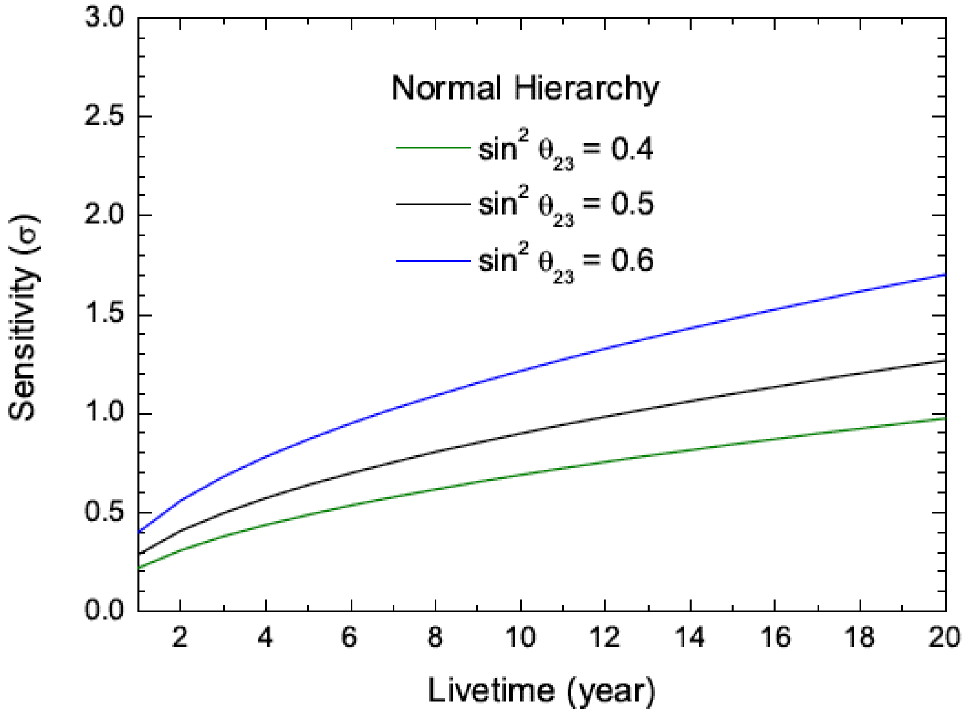
^{144}Ce-^{144}Pr is favorable

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



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

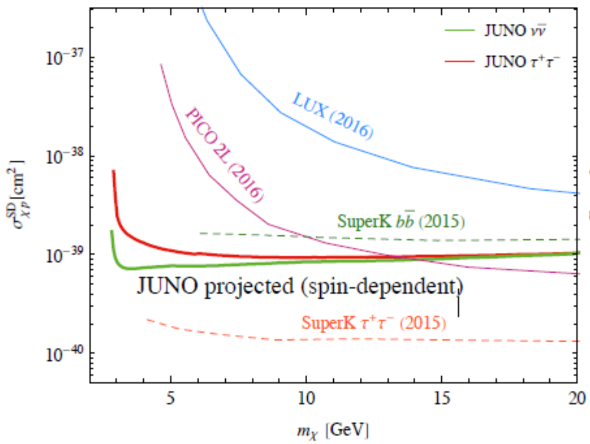
- **JUNO's MH sensitivity can reach 0.9 σ for a 200 kton-years exposure and $\sin^2\theta_{23} = 0.5$, which is complementary to the JUNO reactor neutrino results.**

Indirect Detection of Dark Matter

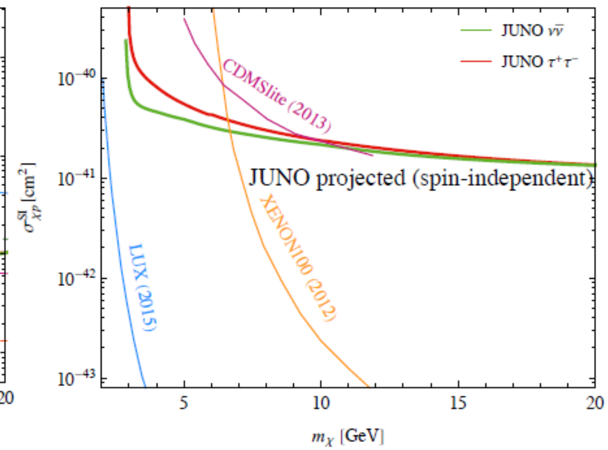
- Dark matter (DM) can be trapped in the Galactic halo, the Sun or the Earth
- Annihilation or decays of trapped DM particles χ can be detected indirectly by looking for their neutrino signature → direction information needed (muon neutrino events preferred)
- Expected neutrino fluxes resulting from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



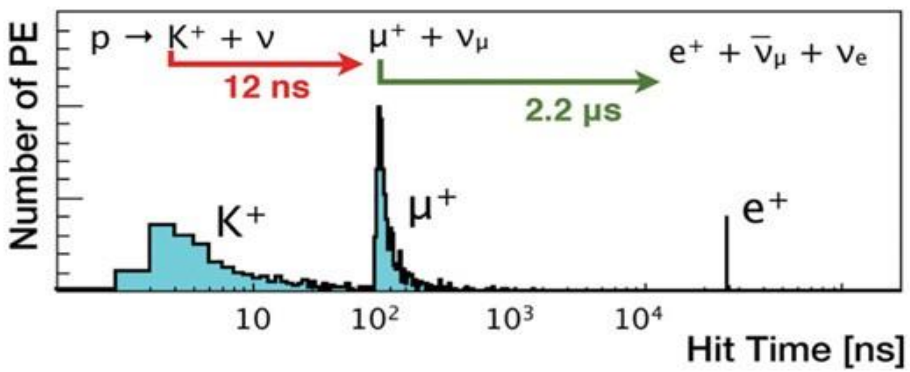
The JUNO 2σ sensitivity in 5 years to the spin-independent cross section $\sigma^{SI}_{\chi p}$. The recent constraints from the direct detection experiments are also shown for comparison.

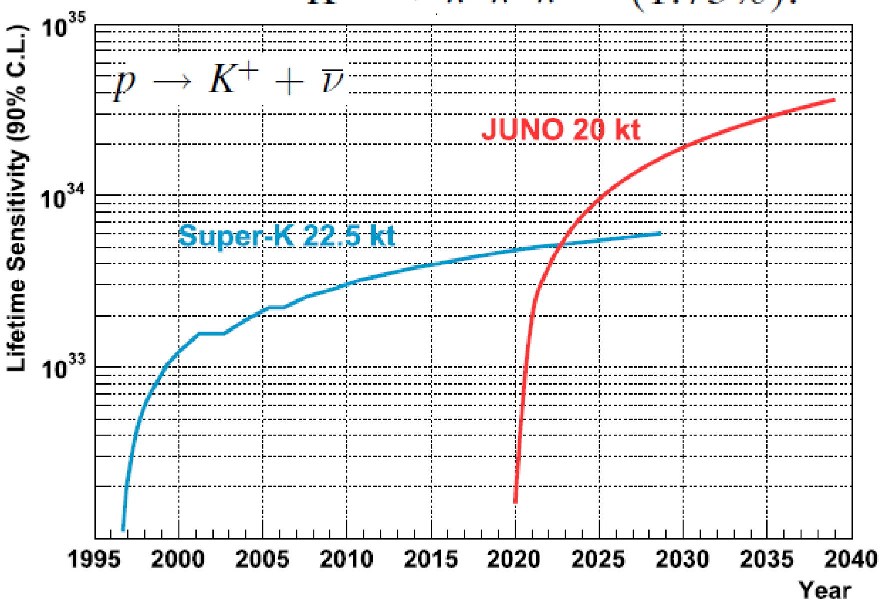
Opportunity in Proton Decay

- 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

$$\Delta T_{15\%-85\%} > 7 \text{ ns}$$

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

JUNO Detectors

Yellow: CD

Blue: Veto

Calibration

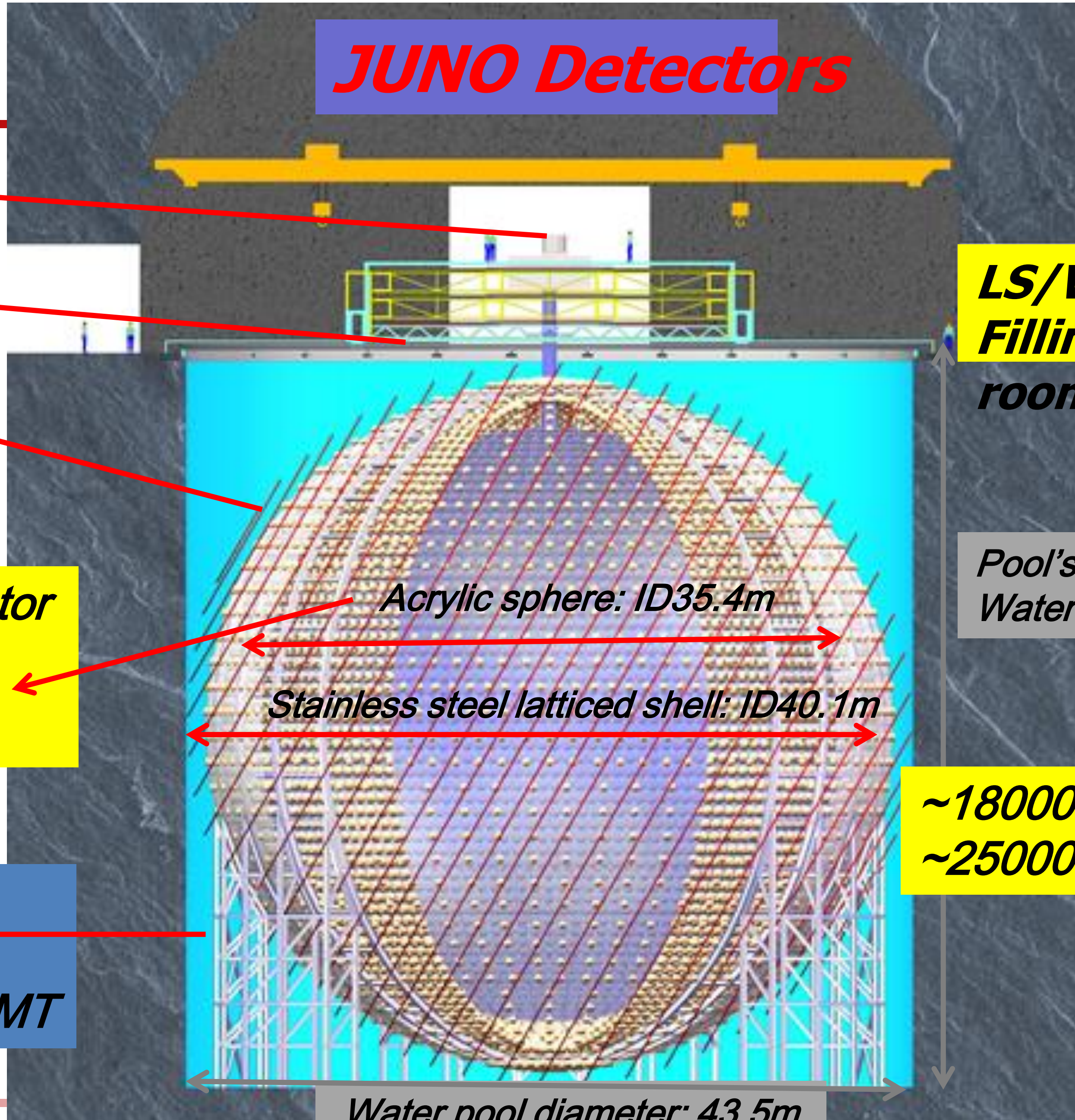
Top Tracker

Earth Magnetic Field shielding coils

Central detector
Steel Structure +
Acrylic sphere +
20kt Liquid Scin

Water Cherenkov
~2400 20" PMT

LS/Water Filling room



Pool's height 44m
Water depth 43.5m

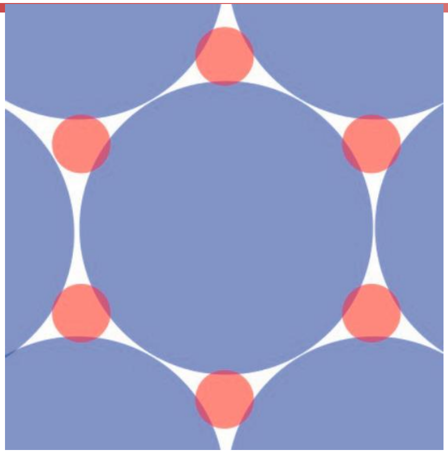
~18000 20" PMT+
~25000 3" PMT

3" PMTs

- 25,000 3" PMTs contracted with HZC: an vital "aider" to 20" PMTs

Small size → no saturation and better linearity in JUNO situation

→Can serve as a standalone calorimeter



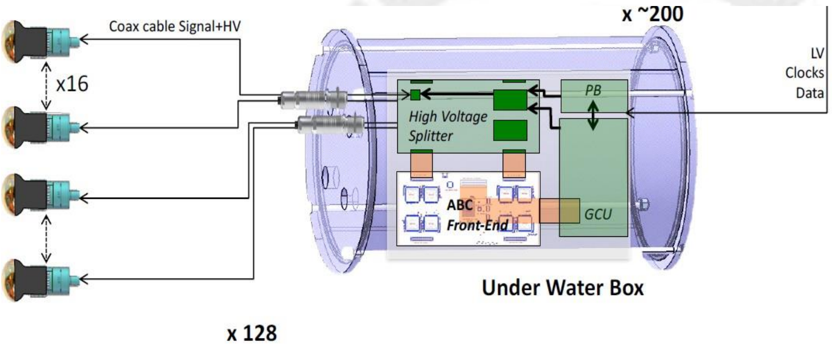
Mixture of 20" and 3" PMTs

- 4000 produced, 3000 tested at HZC

200 boxes × 128 PMTs

JUNO custom design: XP72B22

- ✓ *QE 24% , P/V 3.0*
- ✓ *SPE resolution 30%*
- ✓ *TTS 2-5 ns*



Prototype already built

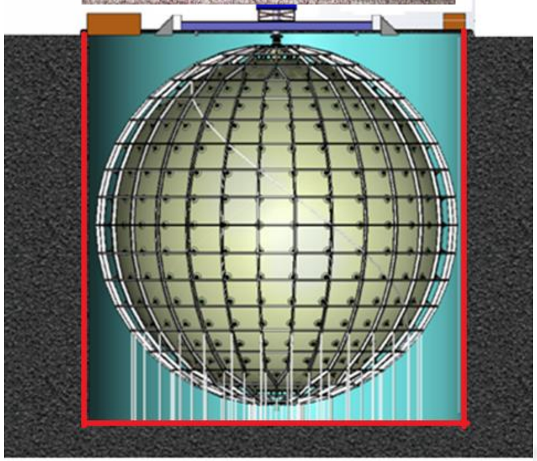
Water Cherenkov detector

- *20-30 kton ultrapure water is supplied and maintained by circulation system(<0.2 Bq/m^3)*
- *~2.4k 20" PMTs*
- *Detection efficiency >95%*

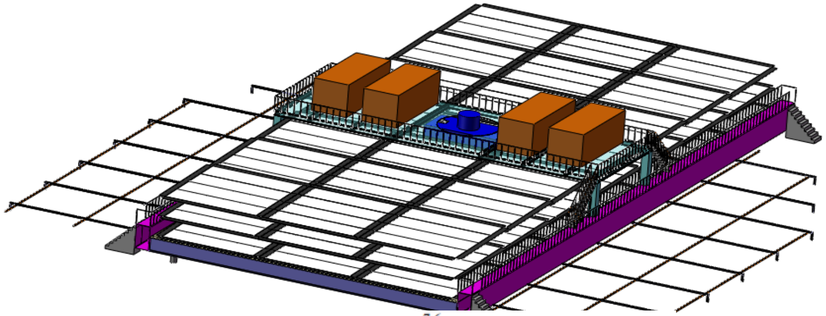
✓ *Fast neutron background ~0.1/day*

✓ *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).**

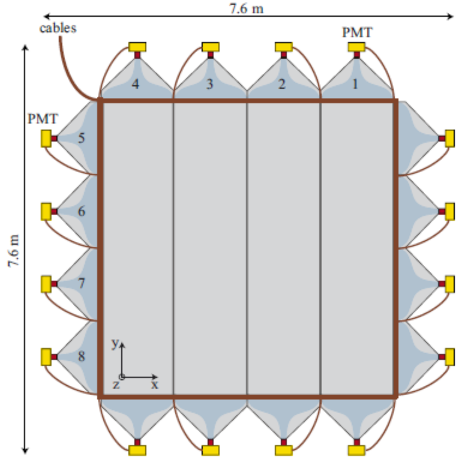


Fig. 3. Schematic view of a plastic scintillator strip wall.

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.*

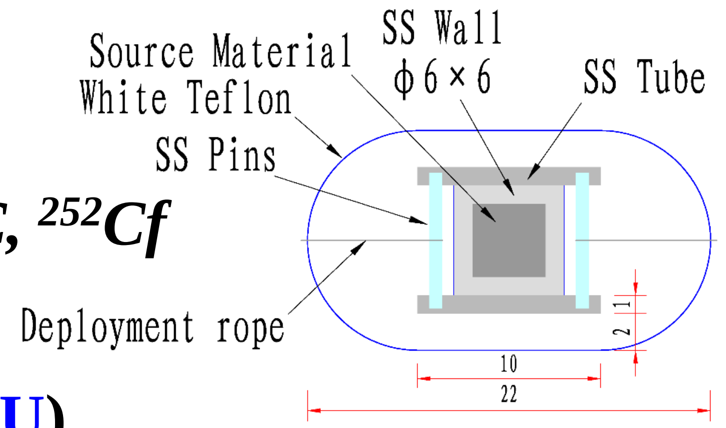
Calibration System

◆ *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**

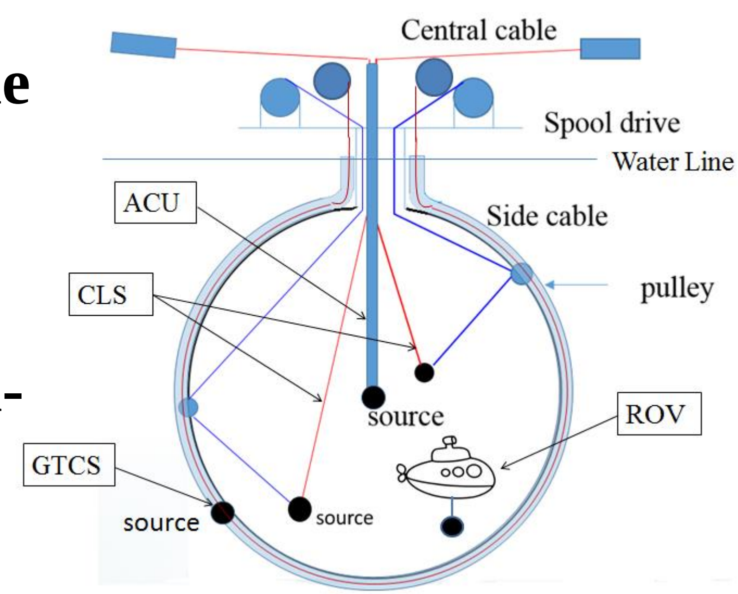


◆ *Position Control*

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



- **These 4 calibration systems are complimentary for covering entire energy range of reactor neutrinos and achieving full-volume position coverage inside JUNO central detector.**

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