Measuring the neutrino hierarchy with the JUNO reactor neutrinos experiment

Alberto Garfagnini
on behalf of the JUNO Collaboration

Università di Padova and INFN, Italy

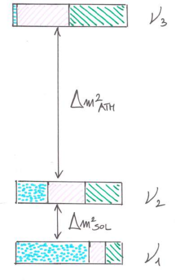
Beyond the Standard Model with Neutrinos and Nuclear Physics,
Solvay Workshop, Nov. 29 - Dec 1, Bruxelles, Belgium

Neutrino Mixing

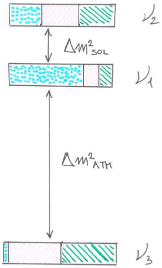
- three Flavour Eigenstates
- three Mass Eigenstates

$$|\nu_\alpha> = \sum_{i=0}^{3} U_{\alpha,i} |\nu_i>$$

- 3 Mixing Angles
- 1 CPV Dirac Phase
- 2 Independent Δm^2_{ij} (Δm^2_{12}, Δm^2_{23})



Normal Hierarchy



Inverted Hierarchy

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric

Reactor (L$\sim$ 1 km)

Solar

Current Neutrino Oscillation Knowledge

I. Esteban et al, arXiV 1611.01514

NuFIT 3.1 (2017)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 1.50$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.347$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.347$	$0.272 \to 0.347$
$\theta_{12}/^\circ$	$33.63^{+0.78}_{-0.75}$	$31.44 \to 36.07$	$33.63^{+0.78}_{-0.75}$	$31.44 \to 36.07$	$31.44 \to 36.07$
$\sin^2\theta_{23}$	$0.565^{+0.025}_{-0.120}$	$0.401 \to 0.628$	$0.572^{+0.021}_{-0.028}$	$0.419 \to 0.628$	$0.401 \to 0.628$
$\theta_{23}/^\circ$	$48.7^{+1.4}_{-6.9}$	$39.3 \to 52.4$	$49.1^{+1.2}_{-1.6}$	$40.3 \to 52.4$	$39.3 \to 52.4$
$\sin^2\theta_{13}$	$0.02195^{+0.00075}_{-0.00074}$	$0.01971 \to 0.02434$	$0.02212^{+0.00074}_{-0.00073}$	$0.01990 \to 0.02437$	$0.01971 \to 0.02434$
$\theta_{13}/^\circ$	$8.52^{+0.15}_{-0.15}$	$8.07 \to 8.98$	$8.55^{+0.14}_{-0.14}$	$8.11 \to 8.98$	$8.07 \to 8.98$
$\delta_{\rm CP}/^\circ$	228^{+51}_{-33}	$128 \to 390$	281^{+30}_{-33}	$182 \to 367$	$128 \to 390$
$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$6.80 \to 8.02$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$+2.515^{+0.035}_{-0.035}$	$+2.408 \to +2.621$	$-2.483^{+0.034}_{-0.035}$	$-2.589 \to -2.379$	$\begin{bmatrix} +2.408 \to +2.621 \\ -2.580 \to -2.389 \end{bmatrix}$

Three-flavor oscillation parameters from our fit to global data as of November 2017. The numbers in the 1st (2nd) column are obtained assuming NO (IO), i.e., relative to the respective local minimum, whereas in the 3rd column we minimize also with respect to the ordering. Note that $\Delta m^2_{3l} = \Delta m^2_{31} > 0$ for NO and $\Delta m^2_{3l} = \Delta m^2_{32} < 0$ for IO

Open questions in neutrino physics

- What is the correct mass hierarchy :

✓ Normal Hierarchy versus Inverted Hierarchy

- Is there a CP violation in the neutrino sector ? ($e^{-i\delta}$)

- Is there new physics beyond the three neutrino model ?

$$|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1 \text{ (PMNS Unitarity) ?}$$

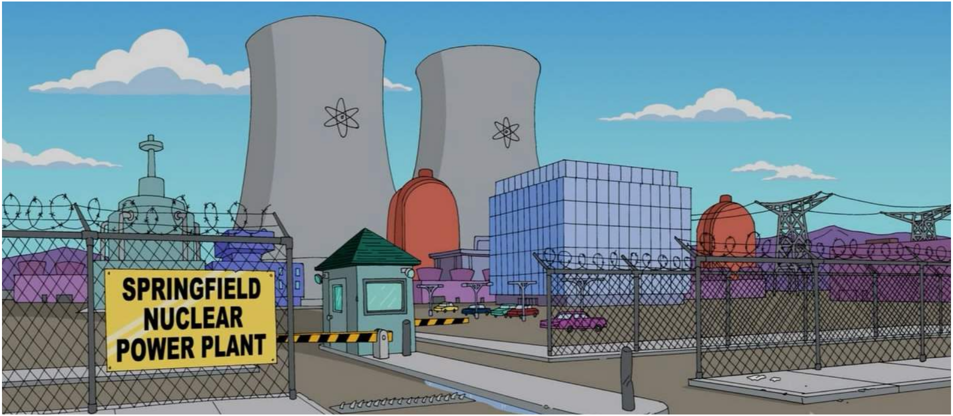
$$\Delta m^2_{13} + \Delta m^2_{21} + \Delta m^2_{32} = 0 \text{ ?}$$

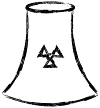
- Can we use neutrinos as messengers to understand our Universe ?

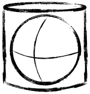
✓ look inside the core of a collapsing Supernova

✓ look at the earth's composition (Mantle & Core)

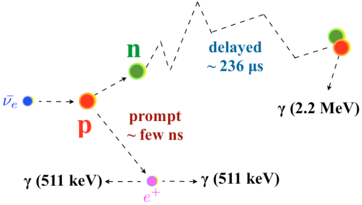
The JUNO approach: detect reactor $\overline{\nu}_e$







$\overline{\nu_e} + p \rightarrow e^+ + n$

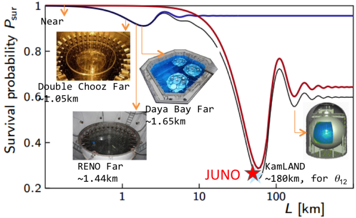


Reactor $\overline{\nu}_e$ Spectrum in JUNO

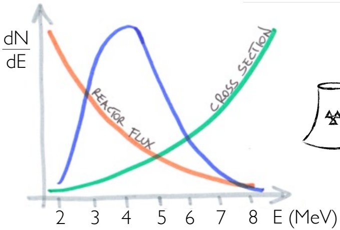
Survival Probability

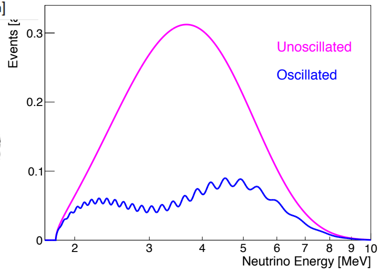
$$P\left(\overline{\nu}_e \rightarrow \overline{\nu}_e\right) = 1 - \sin^2 2\theta_{13} \cdot \left(\cos^2\theta_{12} \sin^2\Delta_{31} + \sin^2\theta_{12} \sin^2\Delta_{32}\right) \quad \text{FAST } \Delta m^2_{atm}$$

$$- \sin^2 2\theta_{12} \cdot \cos^4\theta_{13} \sin^2\Delta_{12} \quad \text{SLOW } \Delta m^2_{sol}$$



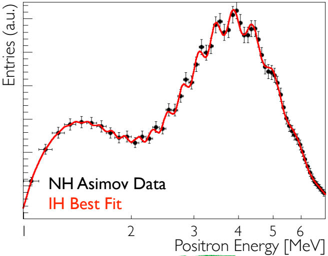
SPECTRUM AT EMISSION





JUNO Mass Hierarchy Sensitivity

Fit model against data



Many Experimental Caveats

Detection Systematics

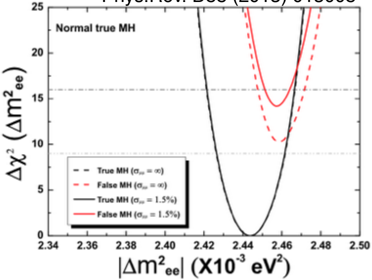
>>> we'll deal with them in a few slides

- Energy Resolution
- Energy Linearity

Background-related uncertainties

Spatial distribution of reactor cores

Phys.Rev. D88 (2013) 013008



Mass Hierarchy Sensitivity

100k signal events (20kt x 36GW x 6 years)

$\Delta\chi^2$: Fitting wrong model - Fitting correct one

Unconstrained (JUNO only) $\Delta\chi^2 \sim 10$

Using external $\Delta m_{\mu\mu}$ (1% precision) from long baseline exps: $\Delta\chi^2 \sim 14$

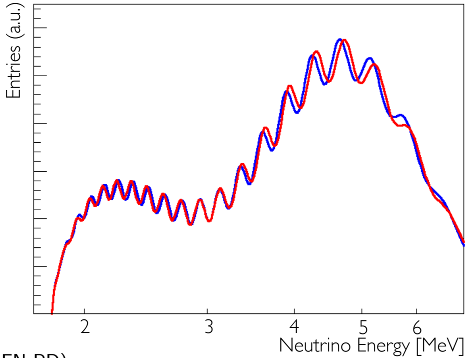
JUNO Oscillation Parameters Measurement

✓ Measuring the $\overline{\nu}_e$ spectrum allows to perform precise measurements of four oscillation parameters: θ_{13}, θ_{12}, Δm^2_{21} and $|\Delta m^2_{ee}|$

➜ $\sin^2 2\theta_{12}$, Δm^2_{21} and $|\Delta m^2_{ee}|$ can be measured with a precision $< 1\%$

Survival Probability

$$P\left(\overline{\nu}_e \rightarrow \overline{\nu}_e\right) = 1 \quad - \quad \sin^2 2\theta_{13} \cdot \left(\cos^2\theta_{12} sin^2\Delta_{31} + sin^2\theta_{12} sin^2\Delta_{32}\right)$$
$$- \quad sin^2 2\theta_{12} \cdot cos^4\theta_{13} \sin^2 \Delta_{12}$$



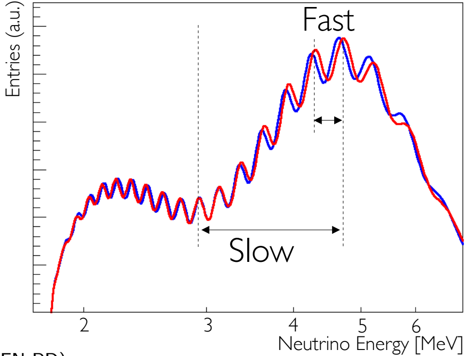
Oscillation Parameters : Mass Splittings

✓ Measuring the $\overline{\nu}_e$ spectrum allows to perform precise measurements of four oscillation parameters:

$$\sin^2 2\theta_{13}, \quad \sin^2 2\theta_{12}, \quad \Delta m^2_{21} \quad \text{and} \quad |\Delta m^2_{ee}|$$

Survival Probability

$$P\left(\overline{\nu}_e \to \overline{\nu}_e\right) = 1 \quad - \quad \sin^2 2\theta_{13} \cdot \left(\overbrace{cos^2\,\theta_{12} sin^2\Delta_{31} + sin^2\theta_{12} sin^2\Delta_{32}}\right)$$
$$- \quad sin^2 2\theta_{12} \cdot cos^4\theta_{13}\,\sin^2 \Delta_{12}$$



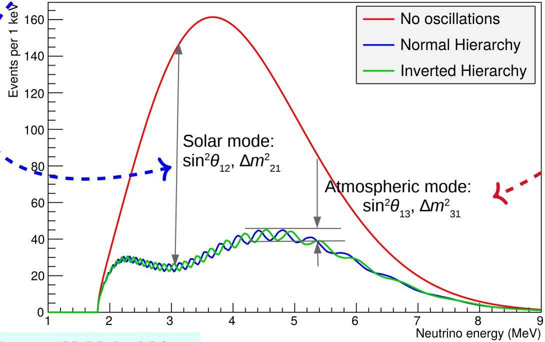
Oscillation Parameters : Mixing Angles

✓ Measuring the $\overline{\nu}_e$ spectrum allows to perform precise measurements of four oscillation parameters:

$$\sin^2 2\theta_{13}, \quad \sin^2 2\theta_{12}, \quad \Delta m^2_{21} \quad \text{and} \quad |\Delta m^2_{ee}|$$

Survival Probability

$$P\left(\overline{\nu}_e \to \overline{\nu}_e\right) = 1 \quad - \quad \sin^2 2\theta_{13} \cdot \left(\cos^2\theta_{12} sin^2\Delta_{31} + sin^2\theta_{12} sin^2\Delta_{32}\right)$$
$$- \; sin^2 2\theta_{12} \cdot cos^4\theta_{13} \sin^2 \Delta_{12}$$



Courtesy **Y. Malyshkin**

Oscillation Parameters : precision and systematics

✓ Measuring the $\overline{\nu}_e$ spectrum allows to perform precise measurements of four oscillation parameters:

$$\sin^2 2\theta_{13}, \quad \sin^2 2\theta_{12}, \quad \Delta m^2_{21} \quad \text{and} \quad |\Delta m^2_{ee}|$$

Survival Probability

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta_{13} \cdot \left(\cos^2\theta_{12} sin^2\Delta_{31} + sin^2\theta_{12} sin^2\Delta_{32}\right) - sin^2 2\theta_{12} \cdot cos^4\theta_{13} \sin^2\Delta_{12}$$

Cosmogenic Bkg (3% Norm + 10% Shape)

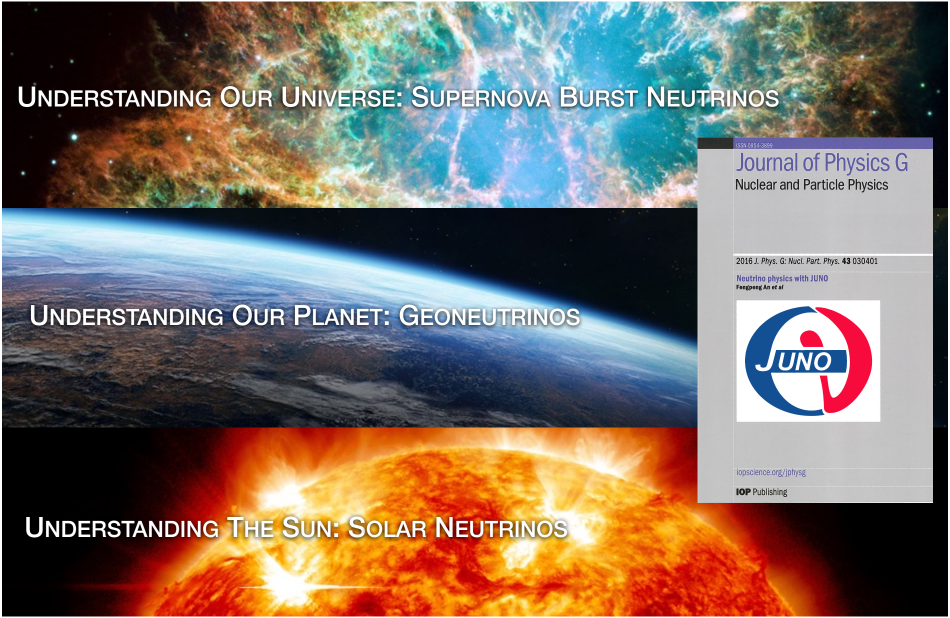
Bin-to-bin uncorrelated uncertainty

Energy scale uncertainty

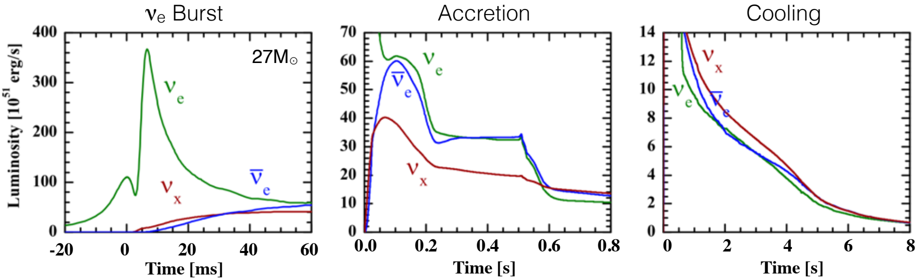
Energy non-linear uncertainty

	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%
$\|\Delta m^2_{ee}\|$	0.27%	0.31%	0.31%	0.35%	0.44%

JUNO Extended Physics Programme



JUNO SuperNova Neutrino Physics



- Huge amount of energy (3×10^{53}erg) emitted in neutrinos (~$0.2M_\odot$) over **long time range**
- 3 phases equally important ▸ 3 experiments teaching us about astro- and particle-physics

Process	Type	Events $\langle E_\nu \rangle$=14MeV
$\bar{\nu}_e + p \rightarrow e^+ + n$	CC	5.0×10^3
$\nu + p \rightarrow \nu + p$	NC	1.2×10^3
$\nu + e \rightarrow \nu + e$	ES	3.6×10^2
$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$	NC	3.2×10^2
$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$	CC	0.9×10^2
$\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$	CC	1.1×10^2
NB Other $\langle E_\nu \rangle$ values need to be considered to get complete picture.		

Expected events in JUNO for a typical SN **distance of 10kpc**

We try to be able to handle Betelgeuse (d~0.2kpc) resulting in ~10MHz trigger rate

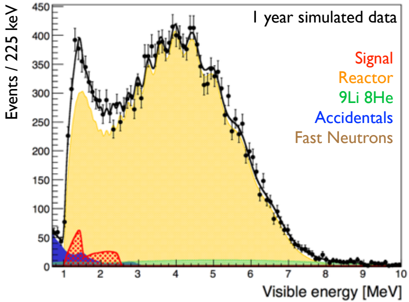
J.Phys. G43 (2016) no.3, 030401

JUNO Geo Neutrino Physics

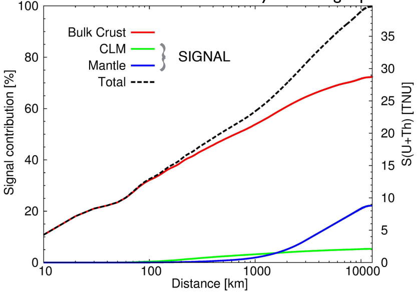
Earth's surface heat flow 46±3 TW. What fraction due to **primordial vs radioactive** sources?
Understanding of:

- **composition** of the Earth : abundance of radioactive elements
- chemical layering in the mantle and the nature of **mantle convection**
- energy needed to drive **plate tectonics**
- understand how the geodynamo, which powers the magnetosphere, works

Detect **electron antineutrinos from the ^{238}U and ^{232}Th** decay chains



I TNU = I ev/yr/10^{32} target p



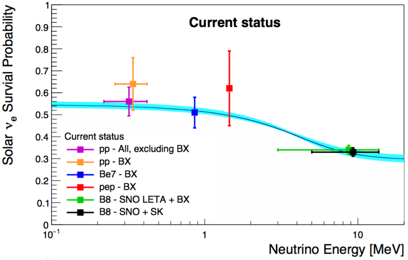
JUNO Solar Neutrino Physics

Fusion reactions in solar core: powerful source of electron neutrinos O(1 MeV)

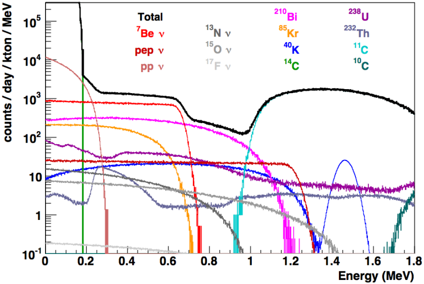
JUNO: neutrinos from **^{7}Be and ^{8}B** chains

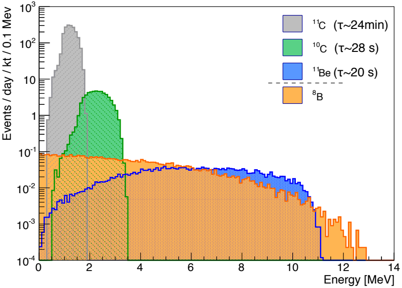
Investigate **MSW effect**: Transition between vacuum and matter dominated regimes

Constrain **Solar Metallicity** Problem: Neutrinos as proxy for Sun composition



arXiv 1602.01733





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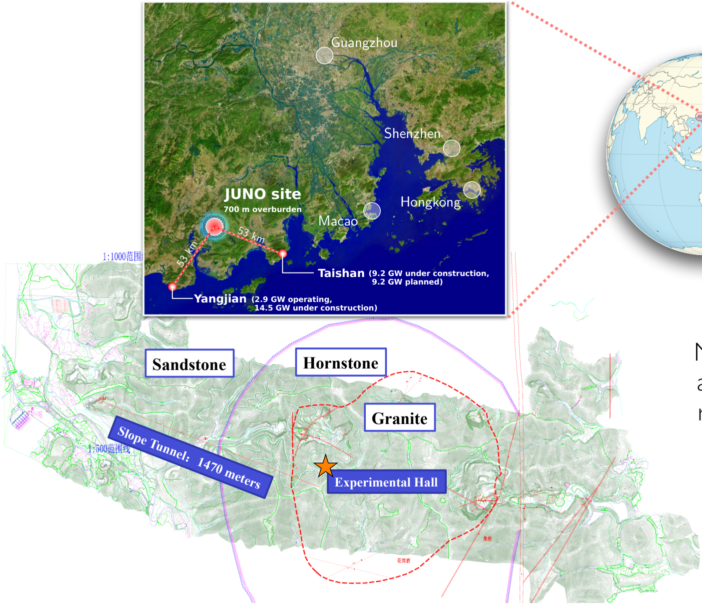
The JUNO Collaboration

Armenia	Yerevan Physics Institute
Belgium	Université 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	Sichuan U.
China	IMP-CAS
China	SYSU
China	Tsinghua U.
China	UCAS
China	USTC
China	U. of South China
China	Wu Yi U.
China	Wuhan U.
China	Xi'an JT U.
China	Xiamen University
China	NUDT
Czech	R. Charles U. Prague
Finland	University of Oulu
France	APC Paris
France	CENBG Bordeaux
France	CPPM Marseille
France	IPHC Strasbourg
France	Subatech Nantes
Germany	ZEA FZ Julich
Germany	RWTH Aachen U.
Germany	TUM
Germany	U. Hamburg
Germany	IKP FZ 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 (PAEC)
Russia	INR Moscow
Russia	JINR
Russia	MSU
Slovakia	FMPICU
Taiwan	National Chiao-Tung U.
Taiwan	National Taiwan U.
Taiwan	National United U.
Thailand	SUT
Thailand	NARIT
Thailand	PPRLCU
USA	UMD1
USA	UMD2

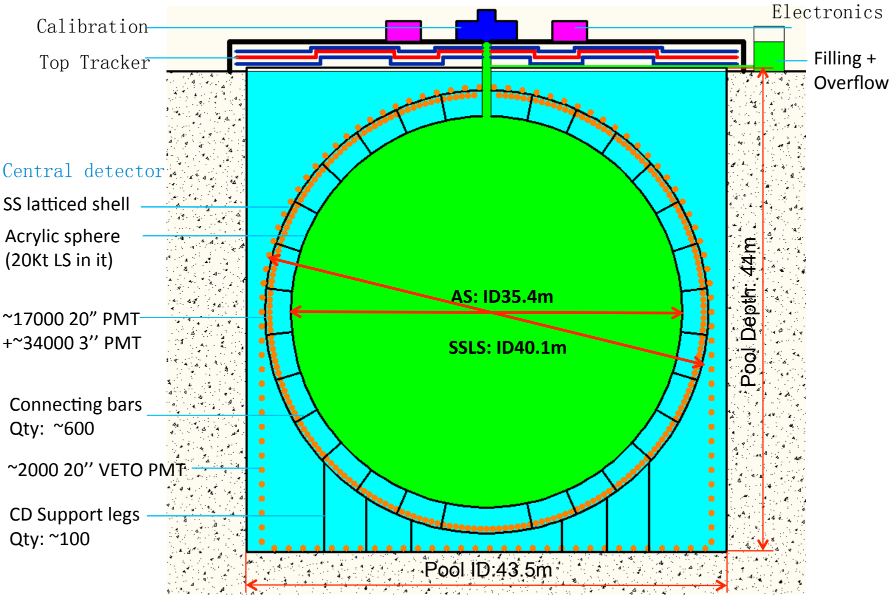
The JUNO Experiment



Nice granite structure at right distance from reactors (very lucky!)

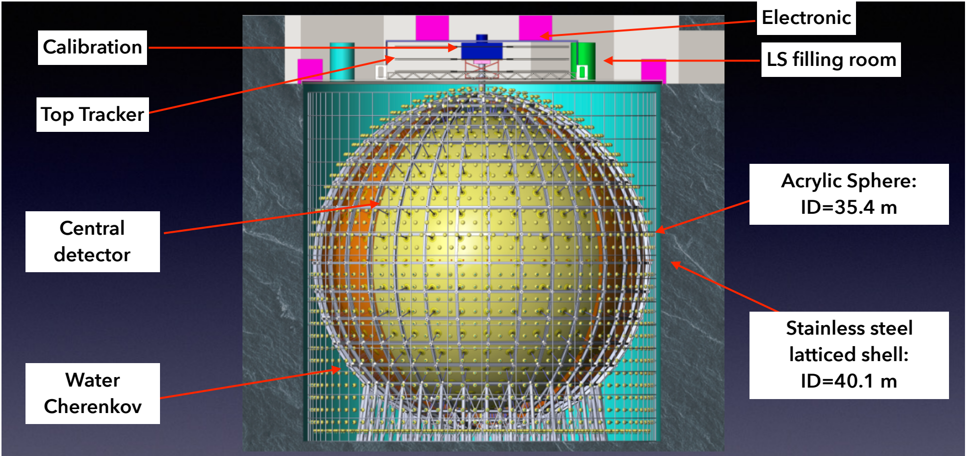
Jiangmen City
Guandong province

JUNO Detector Design



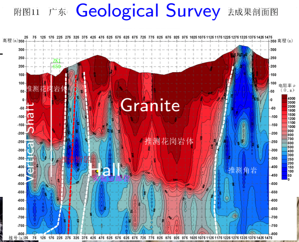
AS: Acrylic sphere; SSLS: stainless steel latticed shell

JUNO Detector Challenges

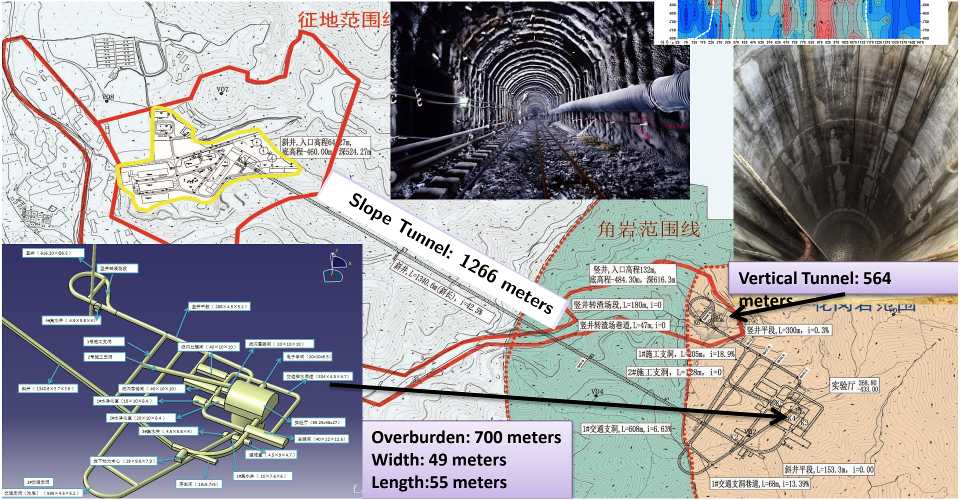


Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	20 ton	~300 ton	~1 kton	20 kton
Coverage	~12%	~34%	~34%	~80%
Energy resolution	~7.5%/√E	~5%/√E	~6%/√E	~3%/√E
Light yield	~ 160 p.e. / MeV	~ 500 p.e. / MeV	~ 250 p.e. / MeV	~ 1200 p.e. / MeV

JUNO Civil Construction

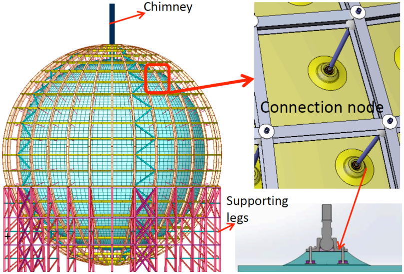


- ✓ Experimental Hall overburden: 700 m (1900 mwe)
- ✓ Two access to experimental Hall
- ➜ Vertical shaft : 564 m, completed
- ➜ Slope tunnel : 1266 m, completed

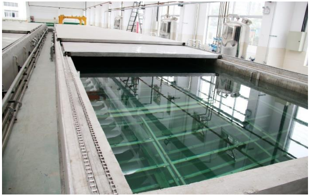


JUNO Central Detector Structure

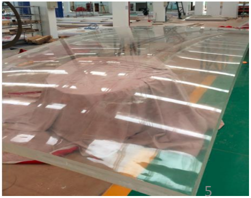
- Acrylic sphere and Stainless Steel truss
- ✓ all immersed in water
- ✓ Acrylic thickness : 120 mm
- ✓ Acrylic panels : 256 pieces (3×8 m^2, 12 cm thick)
- ✓ Total weight : $\sim$ 600 t of acrylic and $\sim$ 600 t of steel
- ✓ bidding completed, acrylic in production, construction will start in 2019
- ✓ Acrylic sheet mass production under preparation



MMA storage tank



water pool for acrylic polimerization



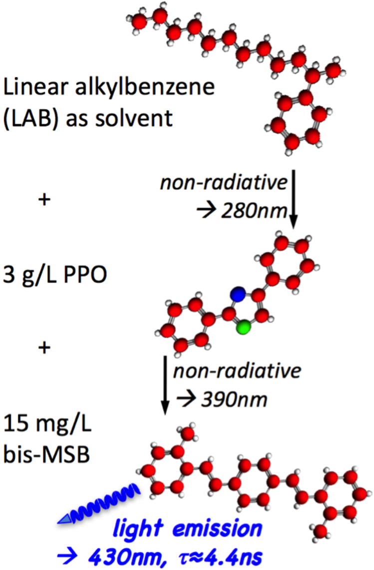
spherical shape, termal bending

JUNO Liquid Scintillator

- high light yield to reduce σ_E from statistical fluctuations: $\sim 10^4$ scintillation γs/MeV
- pure organic solvent (LAB)
- high fluor (PPO) concentration
- high transparency: > 20 m
- add wavelength shifter (bisMSB)

Requirements

- long attenuation length > 20 m 430 nm
- no doping, Al_2O_3 column purification
- high light-yield:
- no addition of paraffin
- large fluor concentration
- good radiopurity:
- $< 10 - 15$ g/g in U/Th
- $< 10 - 16$ g/g in K
- vacuum distillation



JUNO Liquid Scintillator Pilot Plant

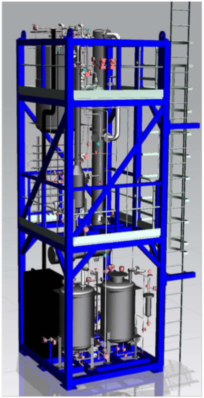
Goals

- ✓ Purify 20 t LAB to test the overall design and operation at Daya Bay.
  Replace the target LS in one detector.

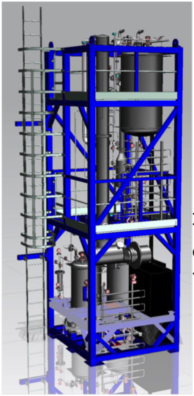
- ✓ Quantify the subsystems effectiveness:
  - ➜ optical : $>$ 20 m at 430 nm
  - ➜ radio-purity : 10^{-15} g/g (U, Th)

- ✓ Allow to select the best sub-system
  - ➜ Al_2O_3 column, distillation, gas stripping, water extraction

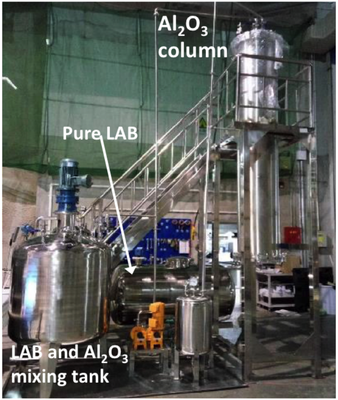
Distillation and steam stripping
Installed at Daya Bay



Distillation system

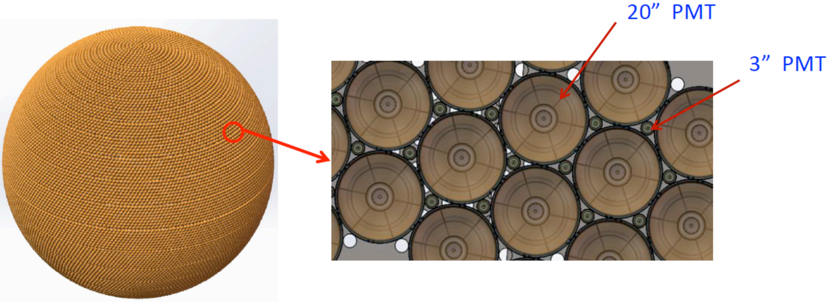


Steam stripping system



JUNO PMT system: the detector's eyes

✓ Two independent systems: large PMTs (20") and small PMTs (3")



✓ 20000 large PMTs:

- measure energy via charge integration, increase photon statistics
- 18000 for central detector, optical coverage $> 75\%$

✓ 25000 small PMTs:

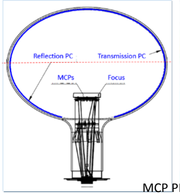
- measure energy via photon counting, reduce/control possible large PMTs non linearities and the systematics non-stochastic effect
- 25000 for central detector, 2.5% additional optical coverage

JUNO Large PMTs

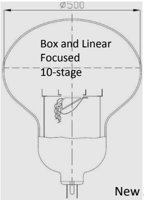
✓ 20” PMT JUNO bidding completed :

∼ 15k MCP-PMT (NNVT)

∼ 5k Dynode-PMT (Hamamatsu)



MCP PMT

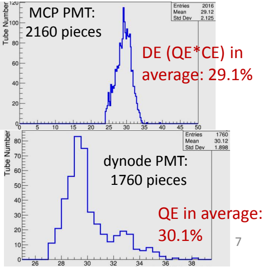


New 20-inch PMT R12860

- the key parameters

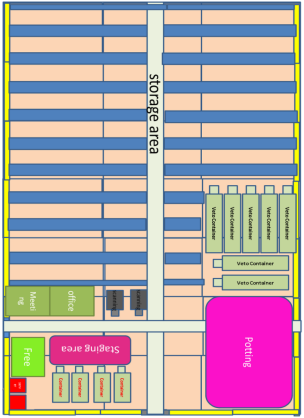
Characteristics	unit	MCP-PMT (NNVT)	R12860 (Hamamatsu)
Detection Efficiency (QE*CE)	%	27%	27%
P/V of SPE		3.5, > 2.8	3, > 2.5
TTS on the top point	ns	~12, < 15	2.7, < 3.5
Rise time/ Fall time	ns	R~2, F~12	R~5,F~9
Anode Dark Count	Hz	20K, < 30K	10K, < 50K
After Pulse Rate	%	1, <2	10, < 15
Radioactivity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

- Measurement from the vendors



JUNO PMTs testing program

- an extensive test program has been developed to certify each produced PMT
- so far about 3000 NNVT PMTs and 2000 Hamamatsu PMTs have been qualified
- the test facility is located close to the experimental site and will host all the PMT instrumentation tasks (i.e. potting and assembly)

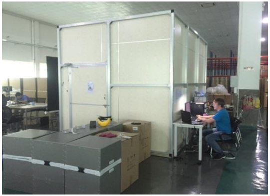


the test and potting station


Storage of received PMTs


PMT visual inspection


Batch test of 36 PMTs
within a container


scanning test of PMT
within a dark room

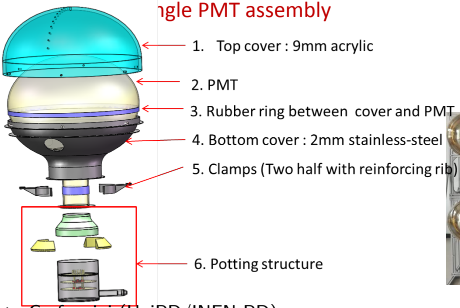
JUNO PMTs instrumentation

- Waterproof potting: Designed as multiple waterproof layers: putty tape + glue+ moisture prevention, to reach failure rate < 0.5% for the first 6 years;
- Implosion protection: acrylic + stainless steel protection covers; 50 prototypes and many implosion tests done.; thickness optimized;
- Single PMT assembly: parts integration;
- Installation: designed to achieve 75% coverage; Installation in parallel to acrylic sphere construction;

Waterproof potting

Implosion test

ıgle PMT assembly

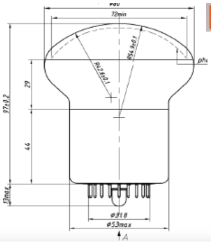


PMT module design and installation

JUNO small PMTs

- Bidding is finished and contract has been signed with HZC company
  JUNO custom design: XP72B22
  - Upgrade of XP72B20
  - Dedicated R&D of better timing with JUNO input

  Start production from the beginning of 2018;



海南展创光电技术有限公司 HZC PHOTONICS

XP72B22

- XP72B22 performance requirements

Parameters	HZC's response
QE×CE @ 420 nm	24% (>22%)
TTS(FWHM) of SPE	<5ns
P/V ratio of SPE	3 (>2)
SPE signal width (sigma)	35% (<45%)
Dark rate @ ¼ PE	1kHz (<1.8kHz)
QE uniformity	<30% in Φ60mm
Pre/after pulse ratio	<5%, < 15%
Nonlinearity	<10%@1-100PE
Radioactivity	238U: <400ppb, 232Th: <400ppb, 40K: <200ppb

- Test results of XP72B22 samples

- QE: 23.5% - 26%; P/V: 3;
- SPE resolution: <30%; TTS: 2-5ns

No.	Resolution	P-V Ratio	Gain@1350V	TTS(ns)
70195	0.231	4.889	2.5e+07	2.2
70197	0.276	6.818	2.3e+07	2.3
70215	0.245	2.832	0.4e+07	2.0
70218	0.251	5.239	1.0e+07	2.7
70219	0.279	4.592	0.6e+07	3.2
70222	0.269	6.657	1.5e+07	2.6
70226	0.239	7.800	2.3e+07	5.0
70236	0.249	6.440	2.2e+07	4.4

JUNO Calibration System

Goals

- ✓ Overall energy resolution : $3\%/\sqrt{E}$
- ✓ Energy scale, non linearities : $< 1\%$

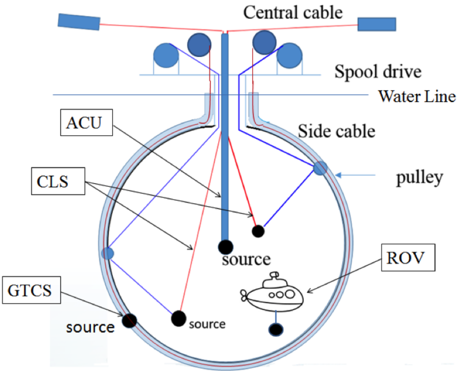
Four Complementary Systems

- ✓ 1D : Automatic Calibration Unit ACU
  for central axis scan
- ✓ 2D : Cable Loop System CLS
  for vertical planes scan and
  Guide Tube Calibration System GTCS
  for CD outer surface
- ✓ 3D : Remotely Operated
  under-liquid-scintillator Vehicles ROV
  for whole CD scan

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

Radioactive Sources

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



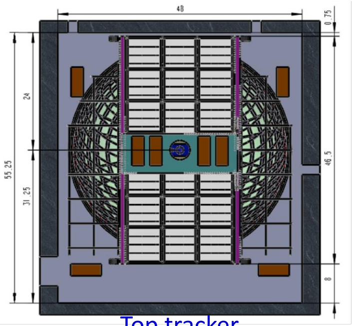
JUNO VETO System

Top Tracker

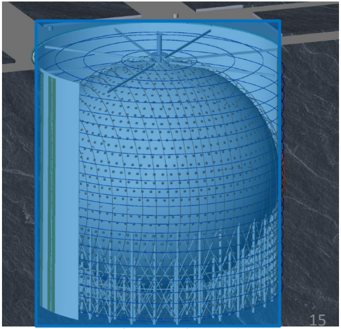
- ✓ implemented reusing the OPERAs Target Tracker
  - 62 walls to be rearranged in three layers spaced by 1 m
  - will covering half of the top area

Water Cherenkov

- ✓ 2000 20" PMTs and 35 ktons ultrapure water
- ✓ detector efficiency expected to be $> 95\%$
  - Fast neutron background 0.1/day
  - radon control less than 0.2 Bq/m3
  - Earth magnetic field (EMF) compensation coil: residual EMF will be less than 10%



Top tracker



water Cherenkov detector

JUNO Schedule

Complete conceptual design. Complete civil design and bidding

PMT production line manufacturing

Complete civil construction. Start detector construction and assembly

Complete detector assembly, installation and LS filling

2013 ▶ 2014 ▶ 2015 ▶ 2016 ▶ 2017 ▶ 2018 ▶ 2019 ▶ 2020

Start civil construction. Complete prototyping (PMT & detector). International collaboration established

Start PMT production. Start detector production or bidding

Start LS production

Start data taking

Conclusions

- The JUNO as a Next Generation underground liquid scintillator detectors has a vast potential physics reach : Mass Hierarchy determination, and beyond
- Following this line, JUNO has been designed to mark significant breakthroughs on the ultimate quests of neutrino properties
- the JUNO Collaboration is rapidly progressing toward finalizing the design and start the detector construction: all important design decision have been taken and the prototyping phase makes important step forwards for all the subsystems
- the year 2020 will open a new horizion on neutrino physics measurements and JUNO will help to to shed light on some of the most intriguing and hidden questions of neutrino physics