Precision measurements with JUNO: the next generation reactor neutrinos experiment

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on behalf of the JUNO Collaboration

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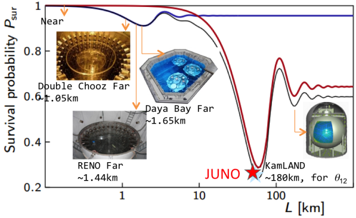
Reactor $\overline{\nu}_e$ Spectrum in JUNO

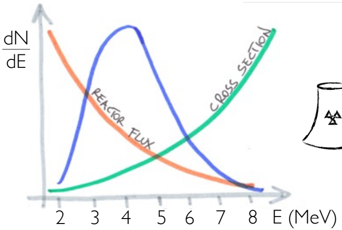
Survival Probability

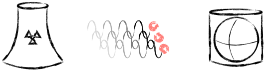
$$P\left(\overline{\nu}_e \rightarrow \overline{\nu}_e\right) = 1 - \sin^2 2\theta_{13} \cdot \left(\cos^2\theta_{12} \sin^2\Delta_{31} + \sin^2\theta_{12} \sin^2\Delta_{32}\right) \quad \text{FAST } \Delta m^2_{atm}$$

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

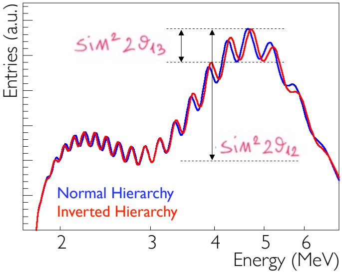


Spectrum at Emission

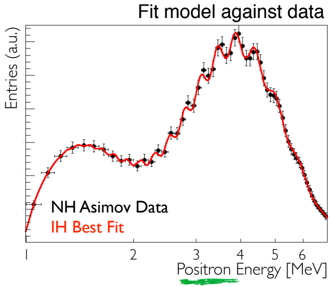




Spectrum at 50 Km



JUNO Mass Hierarchy Sensitivity



Many Experimental Caveats

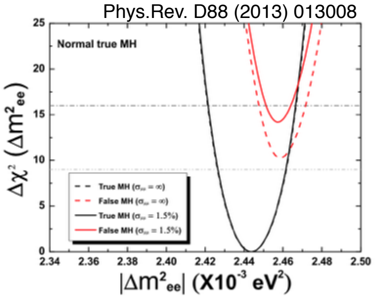
Detection Systematics

- Energy Resolution
- Energy Linearity

Background-related uncertainties

Spatial distribution of reactor cores

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



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: $\Delta\chi^2 \sim 14$

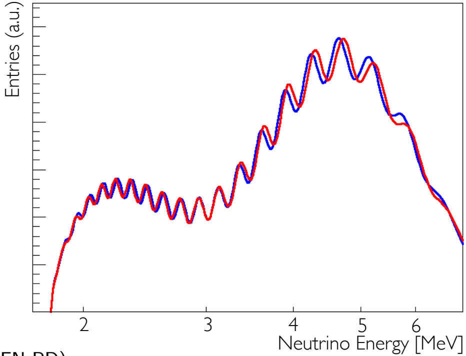
JUNO Oscillation Parameters Measurement

✓ 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

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



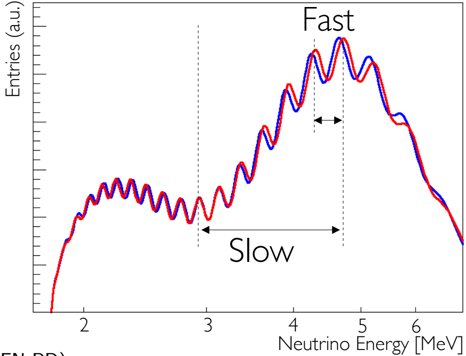
Oscillation Parameters : Mass Splittings

✓ 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

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



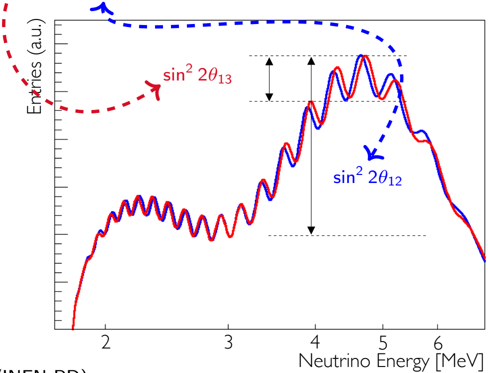
Oscillation Parameters : Mixing Angles

✓ 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

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



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

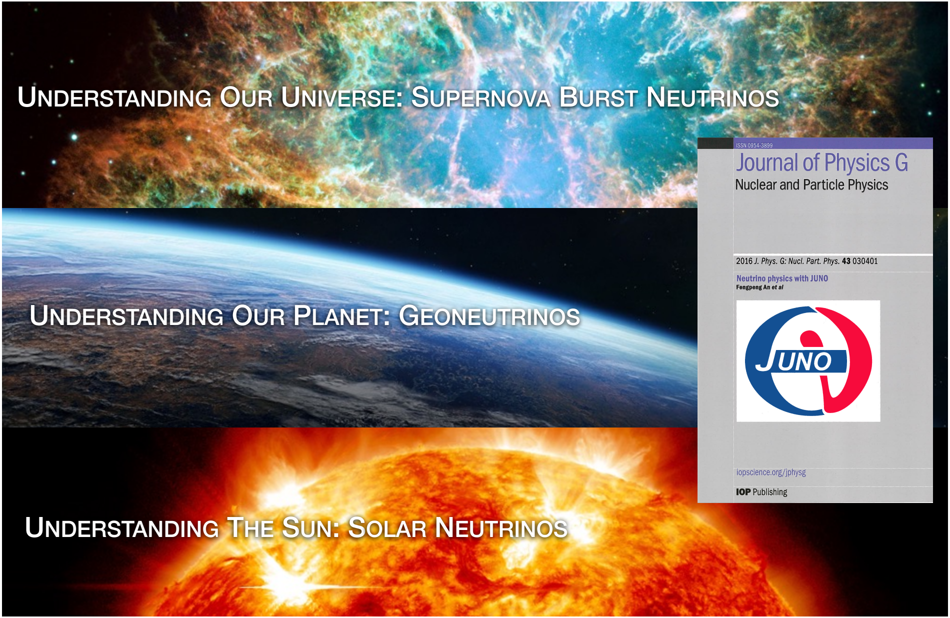
$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{13} \cdot (\cos^2\theta_{12} sin^2\Delta_{31} + sin^2\theta_{12} sin^2\Delta_{32}) - sin^2 2\theta_{12} \cdot cos^4\theta_{13} \sin^2\Delta_{12}$$

Cosmogenic Bkg (3% Norm + 10% Shape)
Bin-to-bin uncorrelated uncertainty

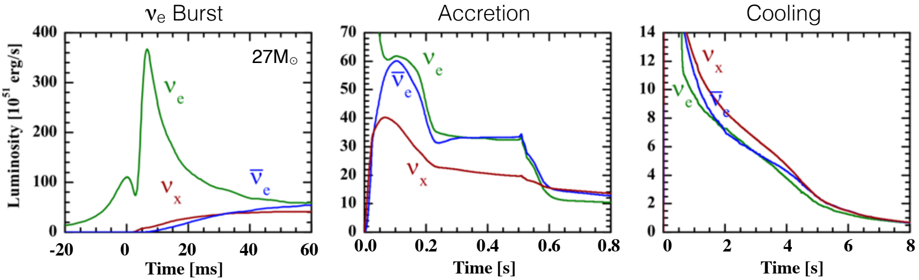
Energy scale uncertainty
Energy non-linear uncertainty

	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%
$\lvert\Delta m^2_{ee}\rvert$	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⊙) over long time range
- 3 phases equally important ▶ 3 experiments teaching us about astro- and particle-physics

Process	Type	Events ⟨E_ν⟩=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 ⟨E_ν⟩ 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

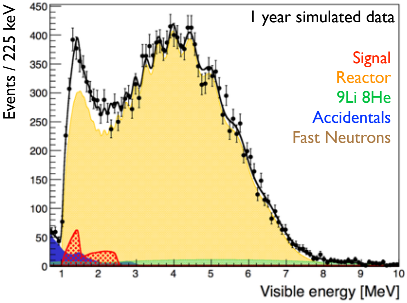
JUNO Geo Neutrino Physics

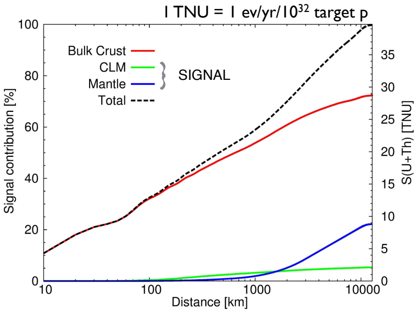
Earth's surface heat flow 46±3 TW. What fraction due to **primordial vs radioactive** sources?

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





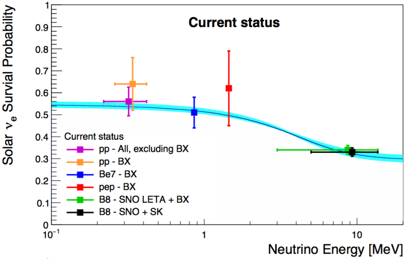
JUNO Solar Neutrino Physics

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

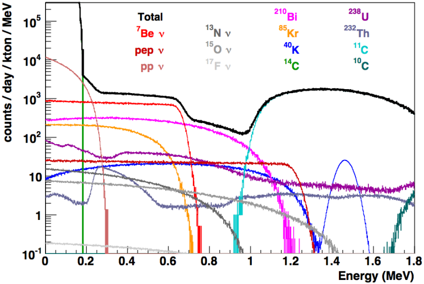
JUNO: neutrinos from **^{7}Be and ^{8}B** chains

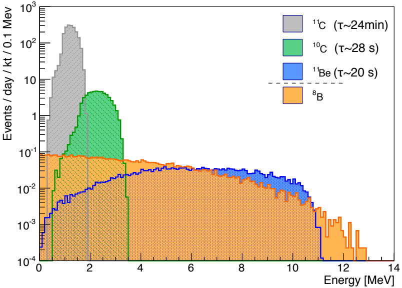
Investigate **MSW effect**: Transition between vacuum and matter dominated regimes

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



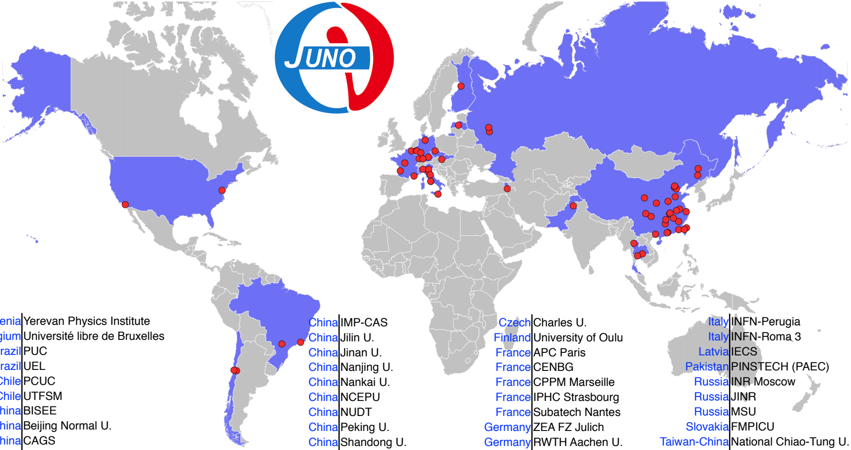
arXiv 1602.01733





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

The JUNO Collaboration



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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	CUG
China	DGUT
China	ECUST
China	ECUT
China	Guangxi U.
China	Harbin Institute of Technology
China	IGG
China	IGGCAS
China	IHEP
China	IMP-CAS
China	Jilin U.
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China	Nanjing U.
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China	NCEPU
China	NUDT
China	Peking U.
China	Shandong U.
China	Shanghai JT U.
China	SYSU
China	Tsinghua U.
China	UCAS
China	USTC
China	U. of South China
China	Wu Yi U.
China	Wuhan U.
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Germany	U. Hamburg
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Italy	INFN-Perugia
Italy	INFN-Roma 3
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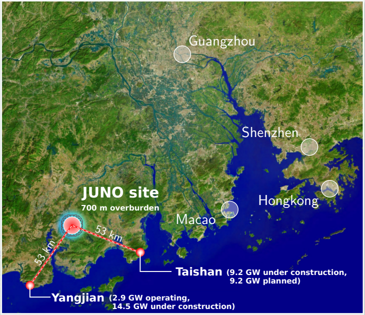
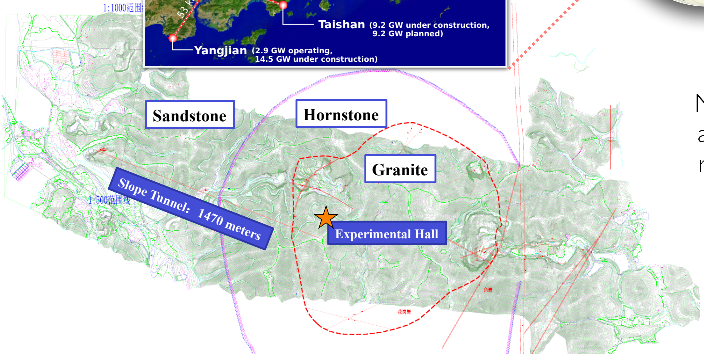
Pakistan	PINSTECH (PAEC)
Russia	INR Moscow
Russia	JINR
Russia	MSU
Slovakia	FMPICU
Taiwan-China	National Chiao-Tung U.
Taiwan-China	National Taiwan U.
Taiwan-China	National United U.
Thailand	NARIT
Thailand	PPRLCU
Thailand	SUT
USA	UMD1
USA	UMD2
USA	UCI

The JUNO Experiment

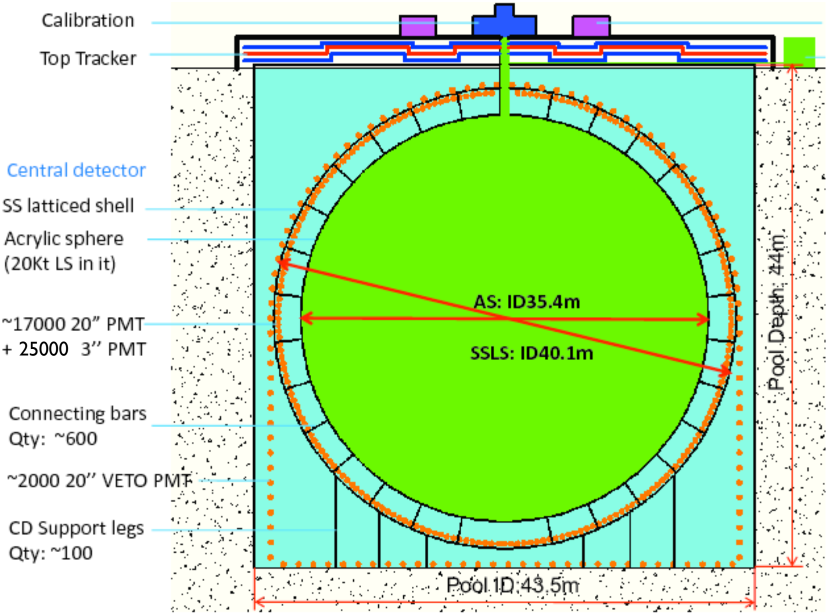




Nice granite structure at right distance from reactors (very lucky!)

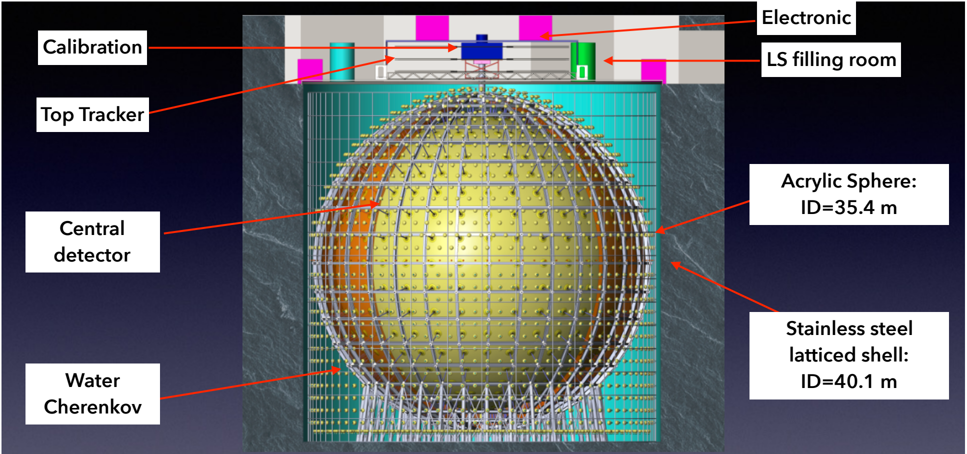
Jiangmen City
Guandong province

JUNO Detector Design



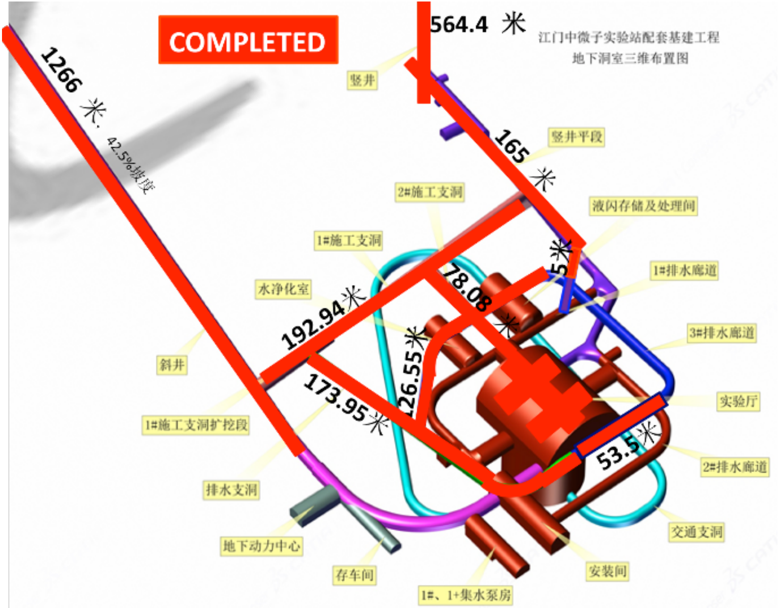
AS: Acrylic sphere; SSLS: stainless steel latticed shell

JUNO Detector Challenges

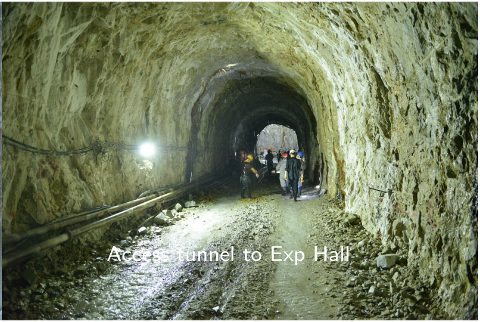


Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	20 ton	~300 ton	**~1 kton**	**20 kton**
Coverage	~12%	**~34%**	**~34%**	**~80%**
Energy resolution	~7.5%/√E	**~5%/√E**	~6%/√E	**~3%/√E**
Light yield	~ 160 p.e. / MeV	**~ 500 p.e. / MeV**	~ 250 p.e. / MeV	**~ 1200 p.e. / MeV**

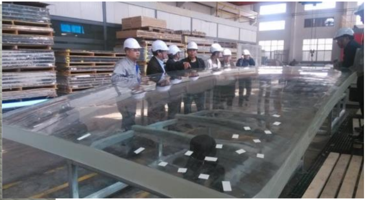
JUNO Civil Construction (summer 2018)



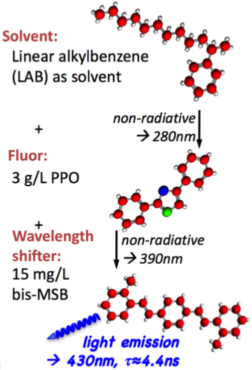
JUNO Civil Construction (summer 2018)



JUNO Central Detector Prototype



JUNO Liquid Scintillator



Requirements for $E_{res} = 3\%/\sqrt{E}$

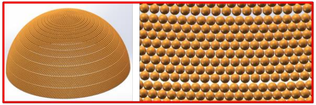
- high light yield: $\sim 10^4$ photons/MeV
- high transparency: att. length > 25 m @ 430 nm

Purification pilot plant

- Check purification effectiveness on U/Th/K and radioactive gases
- Targeted at least 10^{-15} g/g
- Under operation at Daya Bay
- Distillation Al_2O_3, column purification, water extraction and gas stripping
- > 25 m A.L. after filling (measured)
- optimizing LS recipe, studying radio-purity
- same plants scaled for JUNO

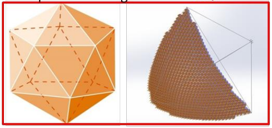
JUNO 20” and 3” PMTs system

Supper layer arrangement method 77.8%



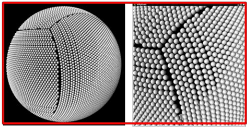
Spherical triangle method 72%

2



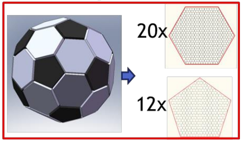
Volleyball arrangement method 75.96%

3



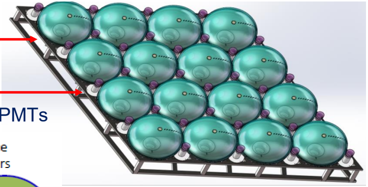
Football arrangement method 74.08%

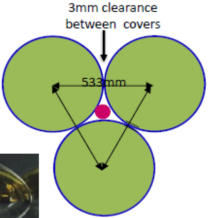
4



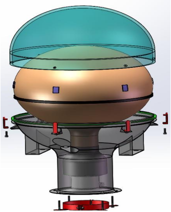
20” PMT(~18000)

3”sPMT(~25000)
Arranged between 20”PMTs





XP72B22
by HZC/Photonis

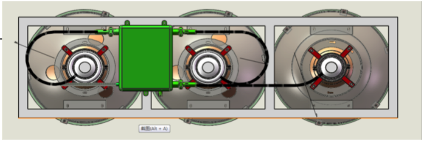


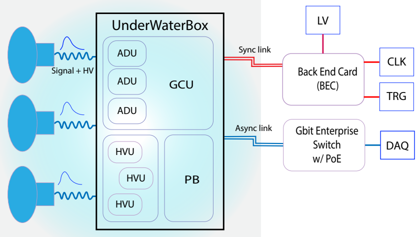
20” PMTs from NNVT and Hamamatsu

JUNO Readout electronics

20" PMT system

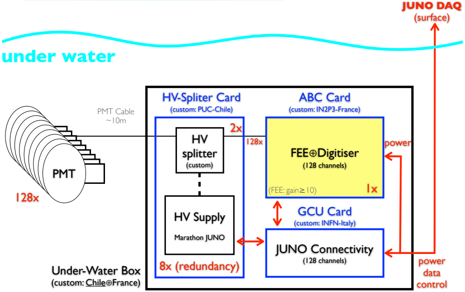
- waveform sampled at 1 GHz and digitized close to source
- 3 PMTs readout and digitally processed by one Global Control Unit Board (GCU)
- digital signal trasferred above water using Gbit Ethernet link
- run in global trigger or auto-trigger mode
- local DDR memory available for Super Nova events





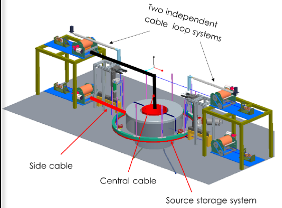
3" PMT system

- 128 PMTs are readout and digitized underwater. Digitization performed with CatiROC chip.
- system works in photon counting mode (1 hit = 1 p.e.)
- no dead time up to 200 kHz
- excellent time resolution ($\sim$ 50 ps) and linearity ($<$ 400 p.e.)

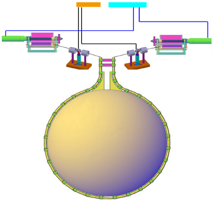


JUNO Calibration System

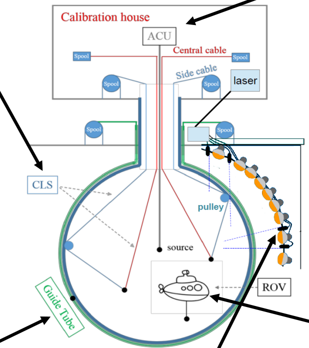
5 complementary system under development with good progress results



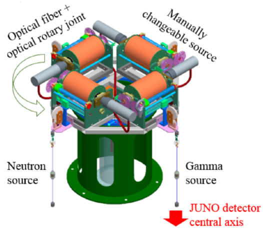
Cable Loop System (CLS)
2D, plane inside the vessel



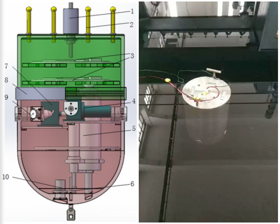
Guide Tube (GT)
2D around outer surface of vessel



Laser fiber system
1D-like, fixed positions



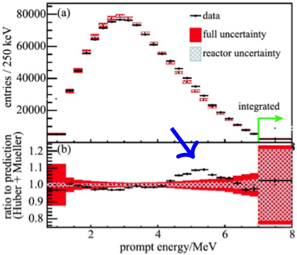
Automatic calibration unit (ADU)
1D along detector z-axis



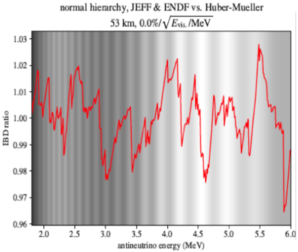
Remotely Operated Vehicle (ROV)
3D anywhere in the vessel

JUNO-TAO

- Taishan Antineutirno Observatory (TAO), a ton-level, high energy resolution LS detector at 30 m from the core, a satellite experiment for JUNO
- measure the reactor neutrino spectrum with sub-percent E resolution
  - ➜ provide model-independent reference spectrum for JUNO
  - ➜ provide a benchmark for investigation of the nuclear database
- full coverage of SiPM with 50% PDE (-50°C) + LS ➜ 4500 pe/MeV
  - ➜ $1.5\%/\sqrt{E}$ photon statistical resolution
  - ➜ $< 1\%$ energy resolution at > 3 MeV

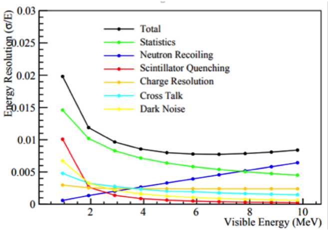


5 MeV bump



possible fine structure

arXiv: 1808.03276

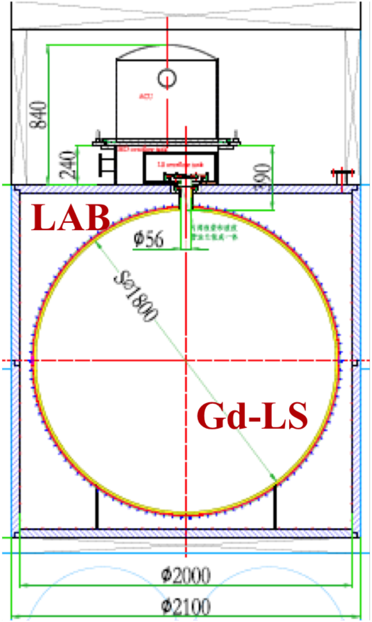


energy resolution

TAO detector structure

- 3 t of Gd-LS in a spherical vessel
  ➜ 1 t FV: event rates: 30 × JUNO
- 10 m^2 SiPM with 50% PDE, operated at $-50°$C
- Cryogenic vessel, HDPE shielding, muon veto, calibration system
- laboratory in a basement at -10 m, about 30-35 m from the Taishan-1 reactor core (4.5 GW)
  ➜ fast neutron bkg well controlled with 1 m HDPE shielding
- plan to be online in 2020

Welcome new collaborators!



Conclusions

- The JUNO experiment provides vast physics opportunities with its large mass and unprecedented energy resolution
- Aim at Neutrino Mass Ordering sensitivity 3σ in 6 yrs
- Sub-percent measurement of $\sin^2\theta_{12}$, Δm^2_{12} and Δm^2_{ee}
- many other physics topics can be accessed (geo-neutrinos, solar neutrinos, supernova neutrinos, proton decay, ...)
- need a precise understanding of the detector response and of the energy scale
- a reference detector, TAO, is planned for precise reactor spectrum measurements close to the Taishan core
- project well along the realization path
- expected data taking to start in 2021