Status and Prospects of JUNO

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On behalf of the JUNO collaboration

Outline

- Experimental Goal
- JUNO sensitivity on Mass Hierarchy
- Experimental Progress
- Other Scientific Potential

Neutrino Physics and Exp. Goal

Six independent parameters give the behaviors of neutrino oscillations:

$$\left|\nu_\alpha\right\rangle = \sum_{i=1}^{3} U_{\alpha i}\left|\nu_i\right\rangle$$

Atmospheric, accelerator

Solar, reactor L~60km

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Reactor L~2km, accelerator

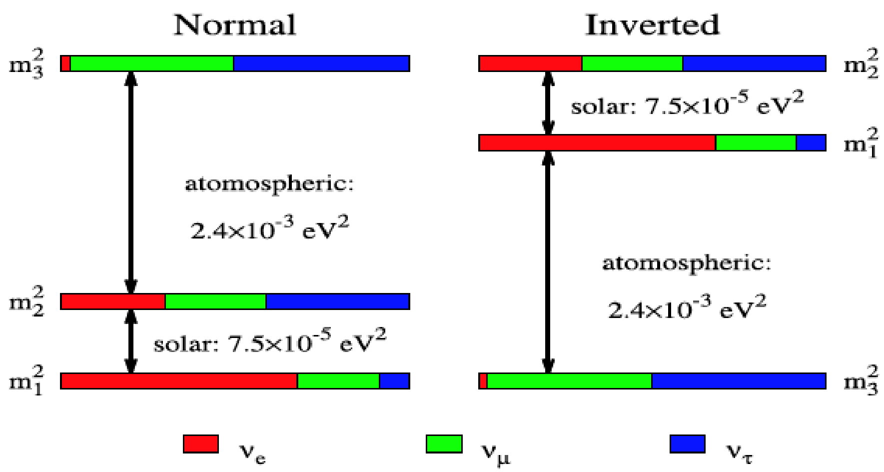
Current best estimations:

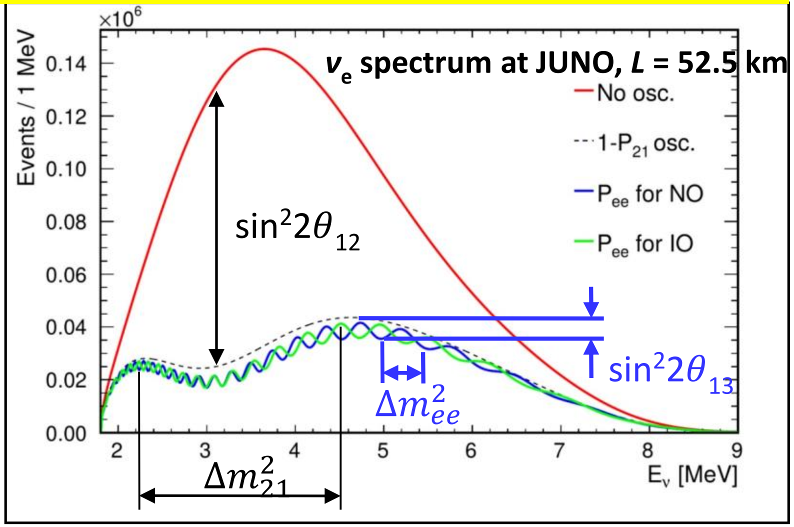
[F. Capozzi et al., arXiv: 1703.04471]

	Best Fit		Global 1 σ
	NO	IO	
Δm^2_{21} (eV^2)	7.37×10^{-5}		$\sim$ 2.3 %
Δm^2 (eV^2)	2.525×10^{-3}	2.505×10^{-3}	$\sim$ 1.6 %, sign is unknown
$sin^2\theta_{12}$	2.97×10^{-1}		$\sim$ 4-6%
$sin^2\theta_{13}$	2.15×10^{-2}	2.16×10^{-2}	4%
$sin^2\theta_{23}$	4.25×10^{-1}	5.89×10^{-1}	octant is unknown
δ/π	1.38	1.31	$\sim$ 50%

$$\Delta m^2 = \left|m_3^2 - (m_1^2 + m_2^2)/2\right|$$

Main Goal: Determine neutrino mass hierarchy(MH)





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δ/π	1.38	1.31	$\sim$ 50%

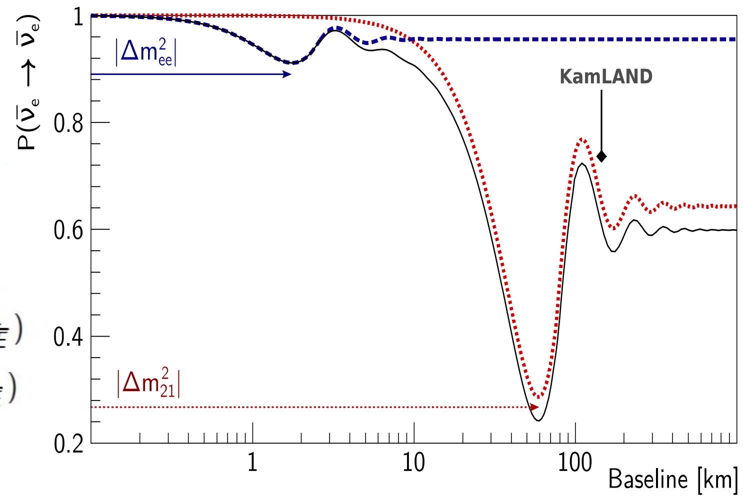
$$\Delta m^2 = \left|m_3^2 - (m_1^2 + m_2^2)/2\right|$$

2^{nd} Goal: Precision measurement of mass and mixing

Survival probability of electron antineutrino:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$

$$\sin^2(\Delta m^2_{ee} \tfrac{L}{4E}) \equiv \cos^2\theta_{12} \sin^2(\Delta m^2_{31} \tfrac{L}{4E}) + \sin^2\theta_{12} \sin^2(\Delta m^2_{32} \tfrac{L}{4E})$$



Current best estimations:

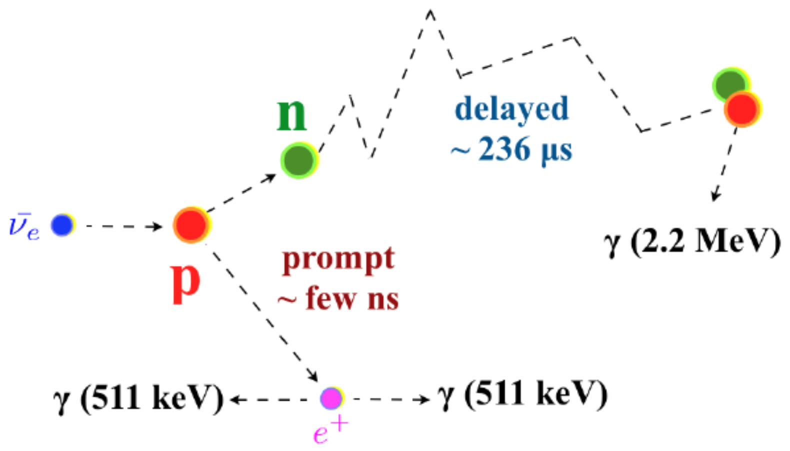
[F. Capozzi et al., arXiv: 1703.04471]

	Best Fit		Global 1 σ	
	NO	IO		
Δm^2_{21} (eV^2)	7.37×10^{-5}		$\sim 2.3\,\%$	<1%
Δm^2 (eV^2)	2.525×10^{-3}	2.505×10^{-3}	$\sim 1.6\,\%$, sign is unknown	
$sin^2\theta_{12}$	2.97×10^{-1}		$\sim$ 4-6%	<1%
$sin^2\theta_{13}$	2.15×10^{-2}	2.16×10^{-2}	4%	
$sin^2\theta_{23}$	4.25×10^{-1}	5.89×10^{-1}	octant is unknown	
δ/π	1.38	1.31	$\sim$ 50%	

Neutrino Detection

The determination of the mass hierarchy relies on the identification on the positron spectrum of the "imprinting" of the anti-ν_e survival probability

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

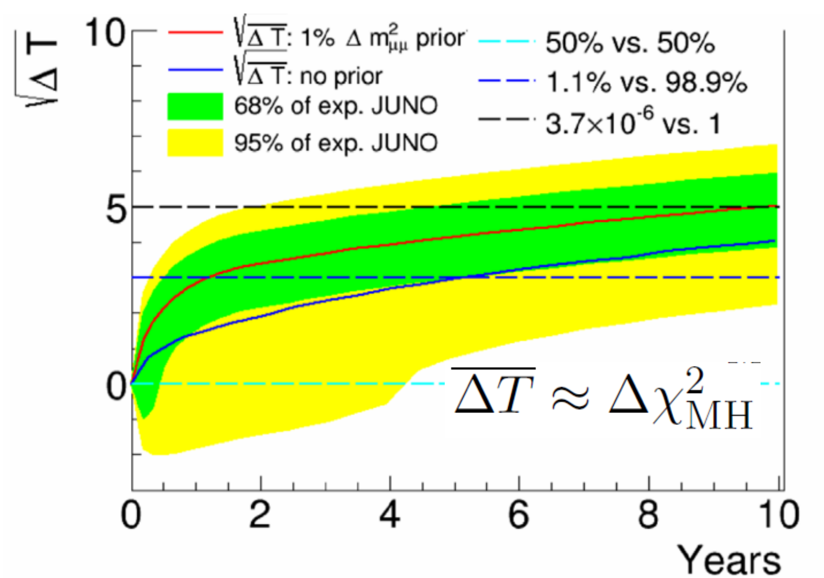


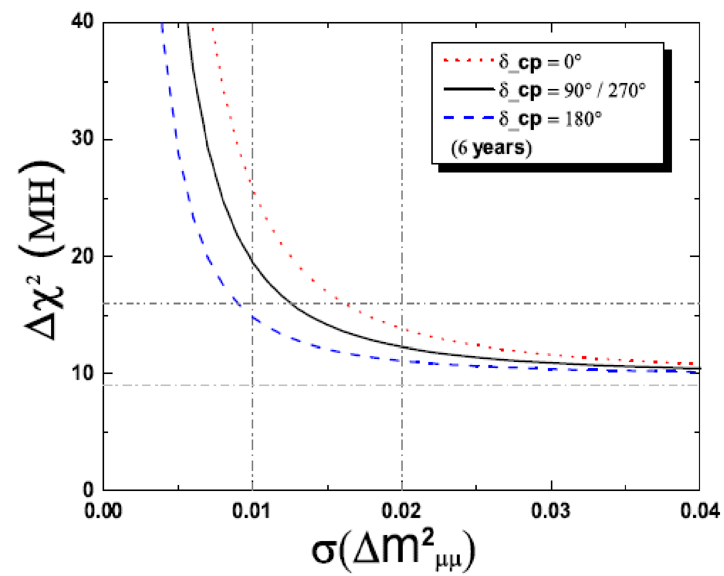
- Prompt signal: annihilation process
- Delayed signal: neutron capture
- Prompt + Delayed coincidence provides distinctive signature

JUNO sensitivity on MH

PRD 88, 013008 (2013)	Relative Meas.	w/ absolute Δm^2
Statistics only	4σ	5σ
Realistic case	3σ	4σ

JUNO **MH sensitivity with 6 years' data**





	Ideal	Core distr.	DYB & HZ	Shape	B/S (stat.)	B/S (shape)	$\lvert\Delta m^2_{\mu\mu}\rvert$
Size	52.5 km	Real	Real	1%	6.3%	0.4%	1%
$\Delta\chi^2_{\rm MH}$	16	- 3	-1.7	- 1	- 0.6	- 0.1	+ (4-12)

Keys to Precise Measurement

To achieve:

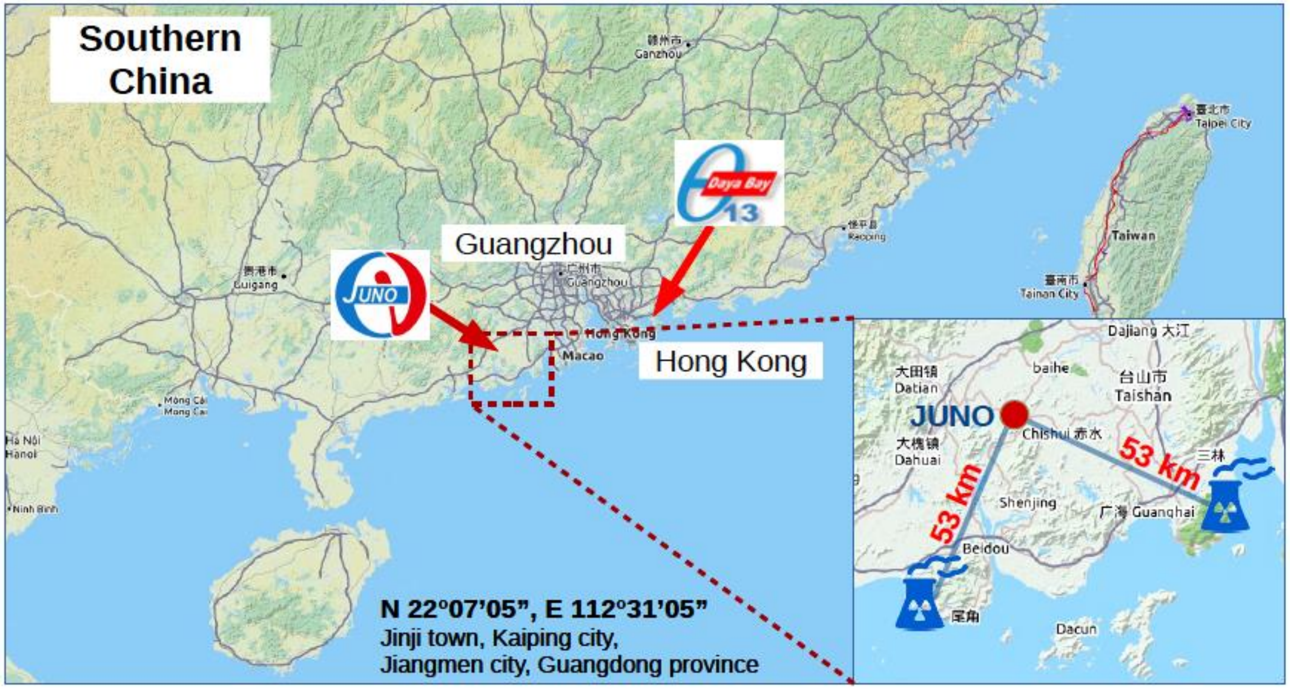
- **Baseline optimization**: $\mathbf{53 \pm 0.5}\ \boldsymbol{km}$
- **Excellent energy resolution: 3%/$\sqrt{E}$ [MeV]**

We should have

- ✓ **Powerful source**: 10 nuclear reactors (26.6 GWth in 2020, later 35.7 GWth)
- ✓ **Ideal baseline:** ~52.5 km (distance between target and reactor core)
- ✓ **Shielding**: 700 m underground → Muon event rate: ~3 /sec
- ✓ **Huge target mass**:
  Single 20 kt LS detector ~10^5 events in 6 years detected via IBD
- ✓ **Superb energy resolution**: 3%@1 MeV
  - High-yield scintillator
  - 75% photo coverage
- ✓ **Systematics suppression**:
  - Unique combination of two sets of PMTs: 17k 20-inch PMTs + 25k 3-inch PMTs

Location

- ➢ Civil construction for underground site started early 2015
- ✓ **Powerful source**: 10 nuclear reactors (26.6 GWth in 2020, later 35.7 GWth)
- ✓ **Ideal baseline**: 52.5 km
- ✓ **Shielding**: 700 m underground → Muon event rate: ~3 /sec



JUNO Collaboration

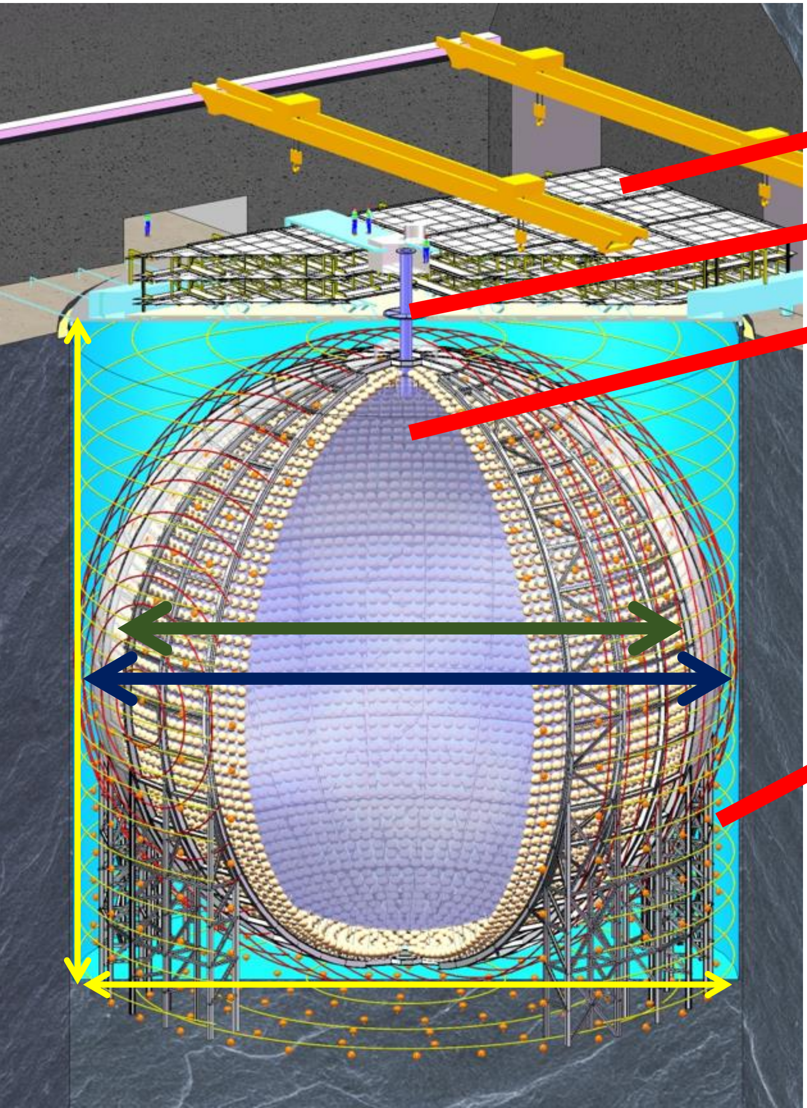
71 institutions, 571 collaborators

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	LLR Palaiseau
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

Observers

1. Department of Physics, Jyvaskyla University, Finland
2. Institute of Electronics and Computer Science, Riga, Latvia

Experimental Layout



Top tracker (solid scintillator)

Calibration system, chimney

Central detector (CD)

- Optical separation: *Acrylic sphere*
- Stainless Steel Latticed Shell
- 20 kton *Liquid Scintillator*
- *PMTs*: 17k 20'' PMTs + 25k 3'' PMTs
- Ultra-pure water buffer (2 m)

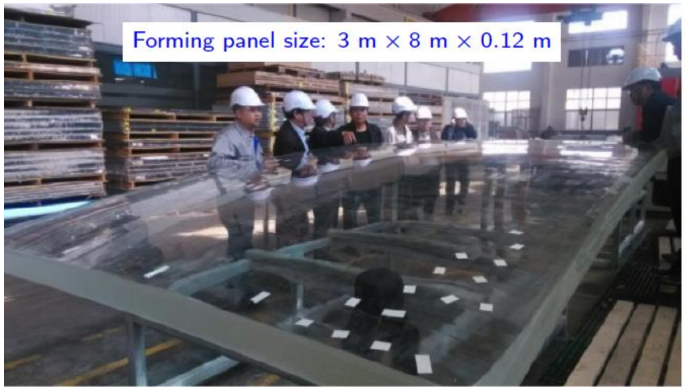
Water Cherenkov veto pool

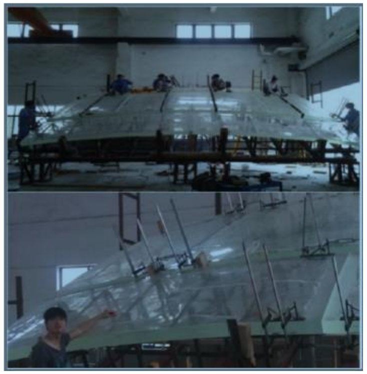
- 20” PMTs
- 35 kton pure water
- Earth Magnetic Field shielding coils

Central detector (CD)

➢ Acrylic Sphere and Stainless Steel truss

- ✓ safety was given a priority
- ✓ 260 acrylic panels of 12 cm thickness
- ✓ Total weight: ~600 t of acrylic and ~600 t of steel



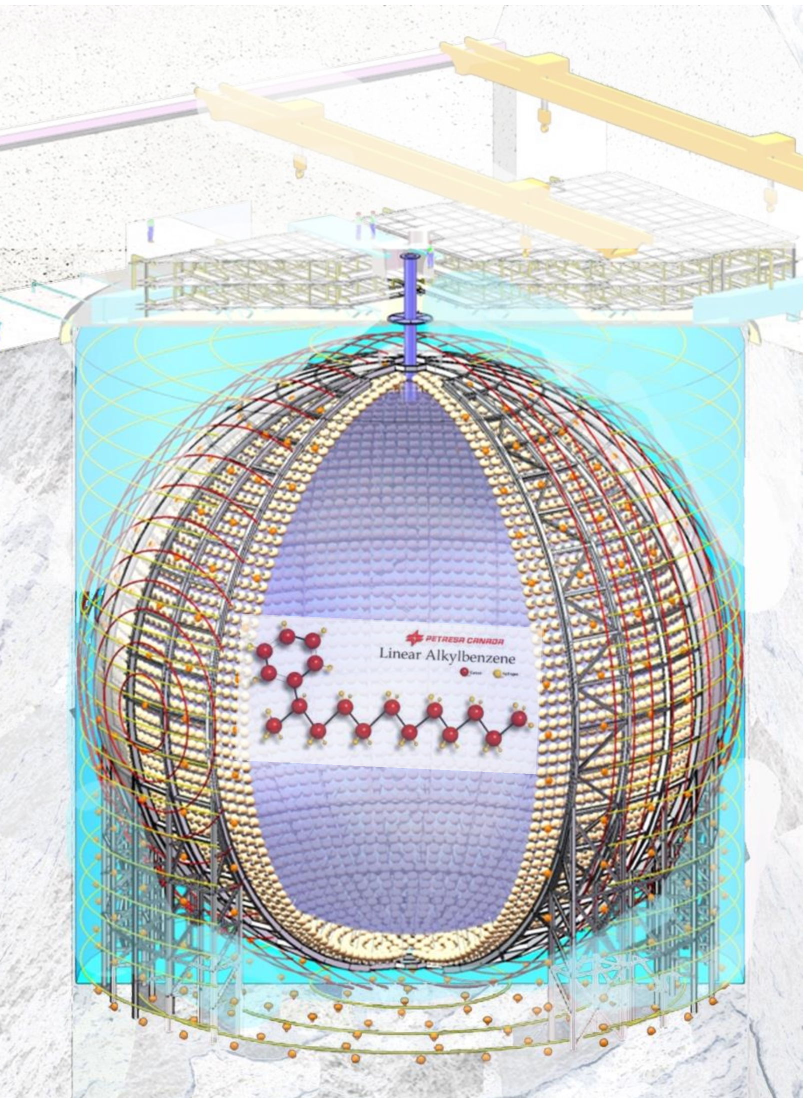


Central detector (CD)

➢ LS in acrylic vessel (35.4 m diam.)

- **Requirements for JUNO LS**
  - Lower background for physics: $^{238}U<10^{-15}$g/g, $^{232}Th<10^{-15}$g/g, $^{40}K<10^{-17}$g/g
  - High light yield: ~10 k ph./MeV
    concentration of flour need to be optimized
  - Long attenuation length: >20m@430nm

- **Preliminary LS recipe** (based on DYB experiment)
  20 kt LS : 3g/l PPO +15 mg/l bis-MSB in LAB
  - PPO: 2,5-Diphenyloxazole
  - Bis-MSB: 1,4-di-(2-methylstyryl)benzene, p-bis(o-methylstyryl)benzene
  - LAB: linear alkyl benzene

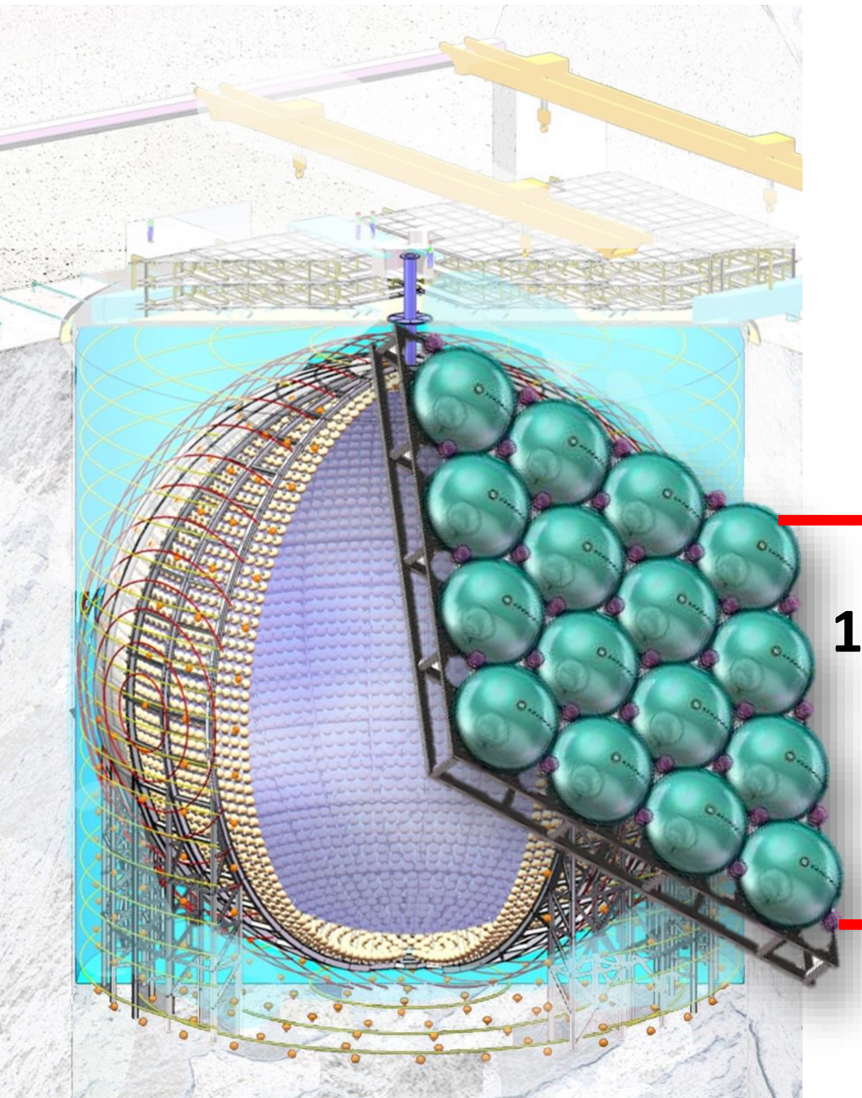


Overall LAB5 view at Daya Bay

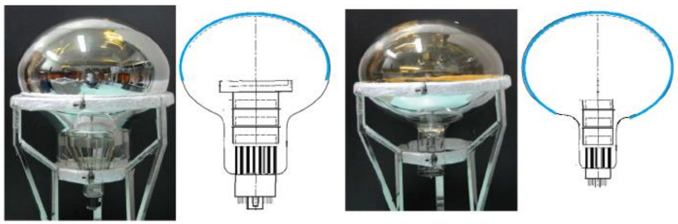
Central detector (CD)

➢ Double Calorimetry System

- >75% photo coverage
- 2 independent PMT systems
- LPMT: energy resolution 3% @ 1MeV
- sPMT: control of systematics
- LPMT+sPMT: huge dynamical range



17k 20'' PMTs
+
25k 3'' PMTs

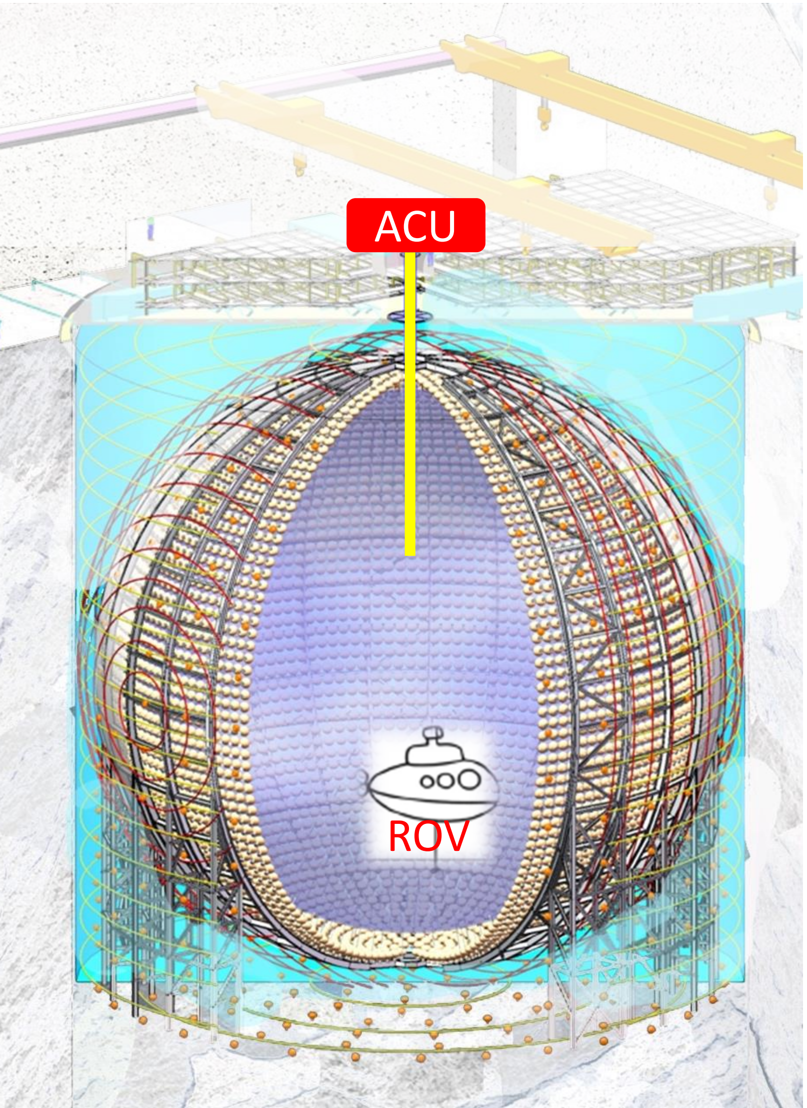


Dynode PMT MCP-PMT

$QE \times CE = 35\%$

Central detector (CD)

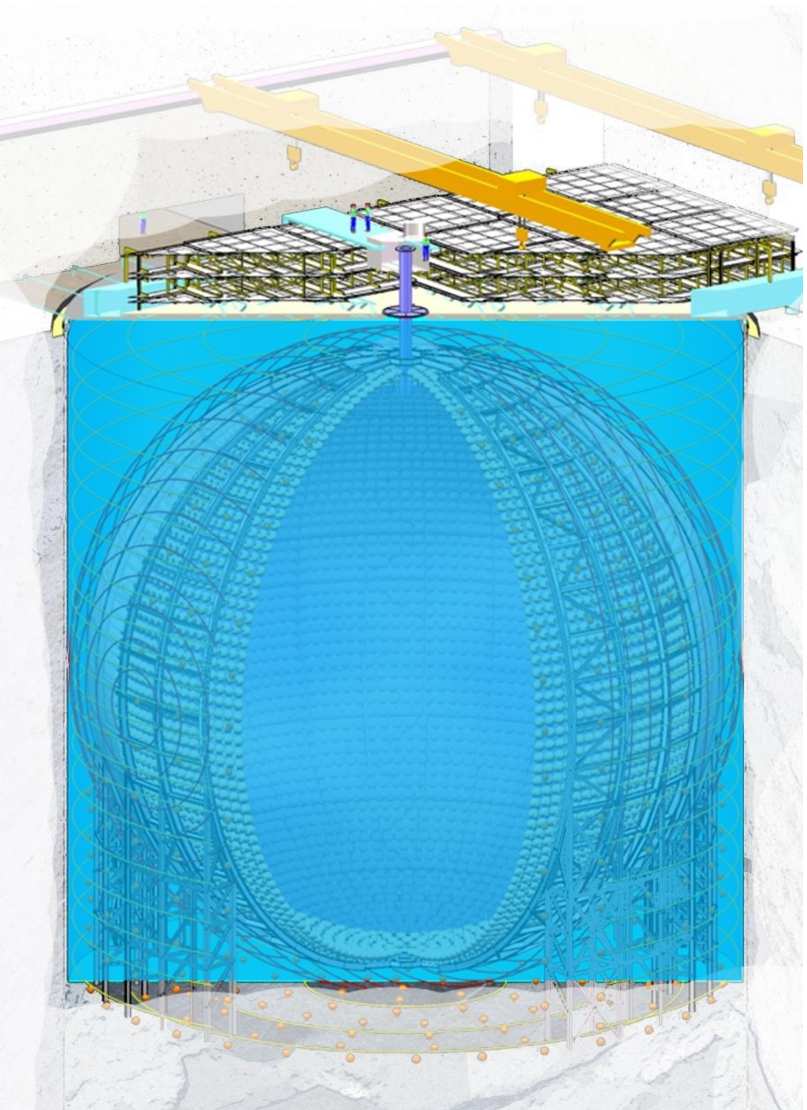
➢ Calibration system



- **The challenge:**
  - overall energy resolution: ≤ 3% $/\sqrt{E}$
  - energy scale uncertainty: <1%

- **Four complementary calibration systems**
  - **1D**: Automatic Calibration Unit (ACU)
    → central axis scan
  - **2D**: Cable Loop System (CLS)
    → scan vertical planes
    Guide Tube Calibration System (GTCS)
    → CD outer surface scan
  - **3D**: Remotely Operated under-LS Vehicle (ROV)
    → whole detector scan

Veto System



➢Goals of veto

- Fast neutron background rejection
- Help muon tracking and cosmogenic isotopes study
- Gamma background passive shielding
- Earth magnetic field shielding

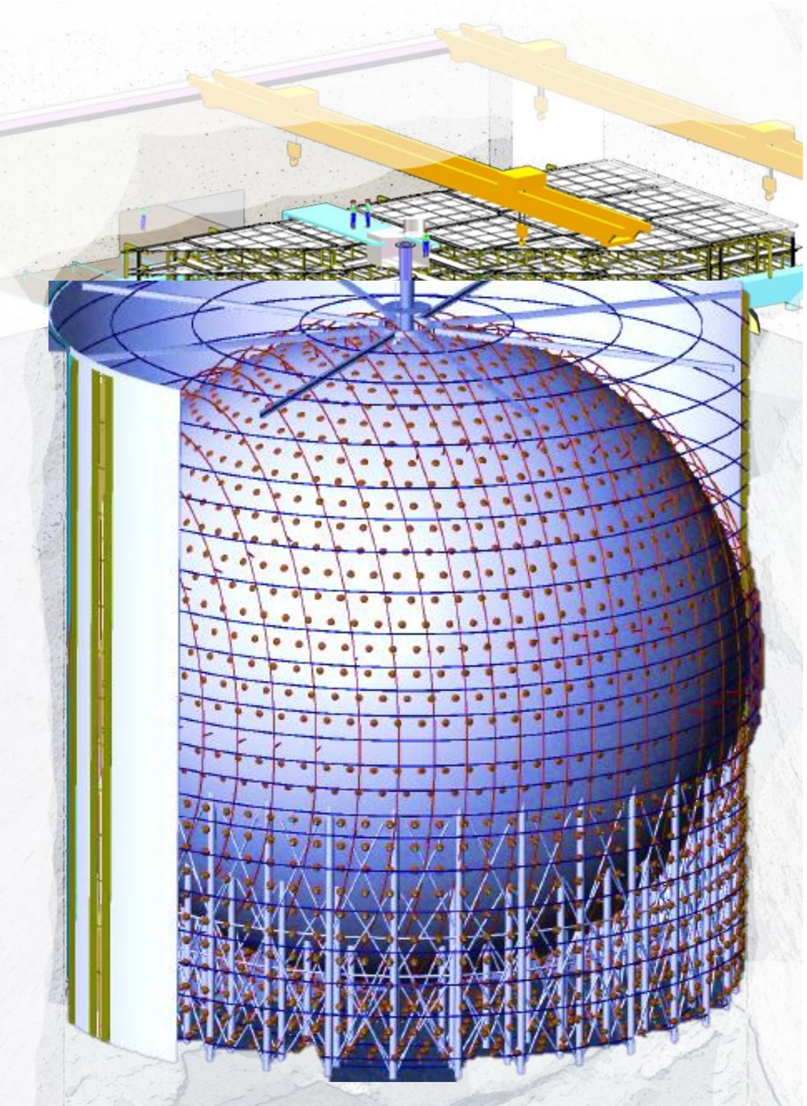
➢Top tracker

- Re-using the **OPERA's** Target Tracker
  (plastic scintillator, 49m^2/module)
- Cover half of the top area

➢Water cherenkov detector

- ~2000 20" PMT
- 35 kton ultrapure water with a circulation system
- Detector efficiency is expected to be > 95%
- Fast neutron background ~0.1/day.

Water Cherenkov detector



- Mechanical structure
  - A “bird cage” structure was designed for support veto PMTs, tyvek films, cables and water pipes.
- Earth magnetic field (EMF) shielding system
  - Use double coils system for EMF shielding。
  - The theoretical calculation and prototype data are consist with each other. It’s a good validation for compensation coils design of JUNO.

Other Physics

Core-collapse supernovae

5000 IBD/10 s @10kpc

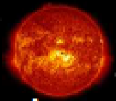
- Probe SN explosion mechanism

DSNB

1-2 evts/year

Up to 3 sigma detection level for standard parameters

- Probe transition region of MSW paradigm
- Study solar metallicity

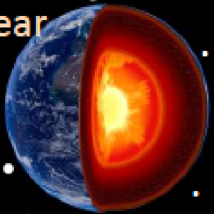


Solar ν

tens of ^{8}B-ν/day

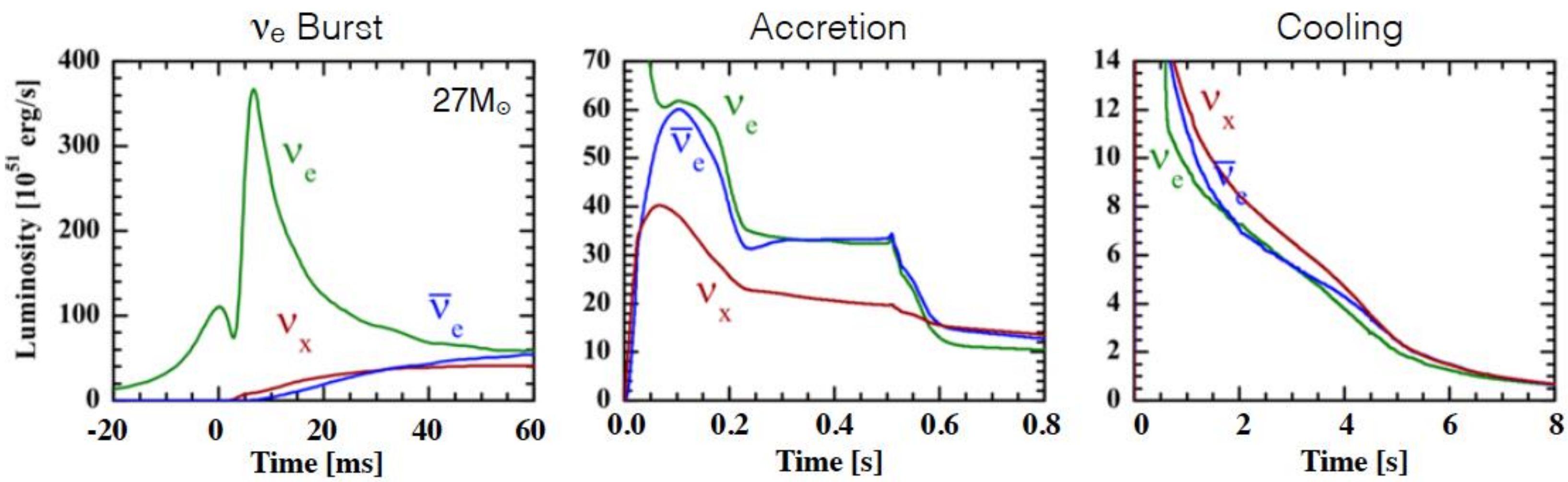
Geo $\bar{\nu}$

400 evts/year



Precise knowledge on backgrounds needed

Supernova (SN) burst neutrinos



- Huge amount of energy (3×10^{53}erg) emitted in neutrinos (~$0.2M_\odot$) over long time range
- 3 phases equally important

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 10 kpc**

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

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Diffuse SN neutrino background

Problem: NC atmospheric neutrino events with prompt energy deposition + neutron knock-out from ^{12}C mimic IBD events

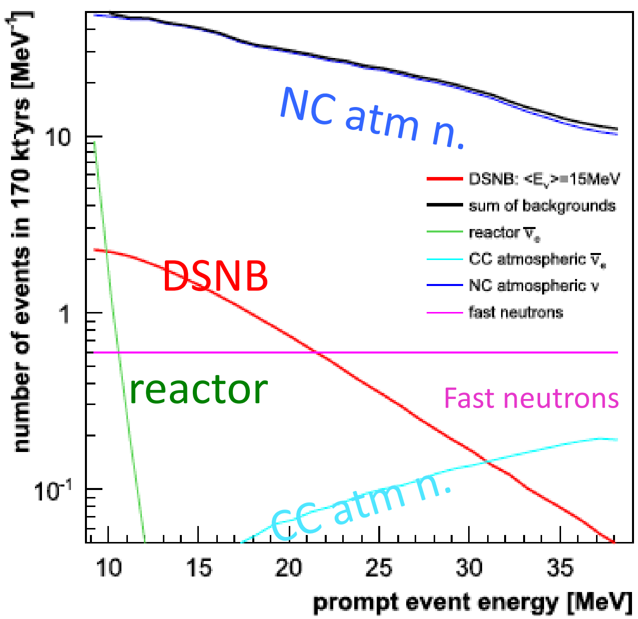
Possible solution: NC atmospheric neutrino background can be suppressed by the **pulse shape discrimination**!

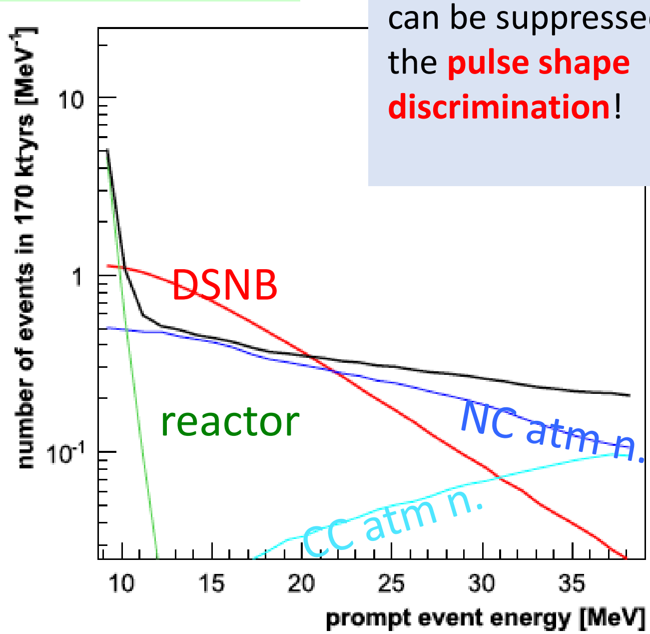
10^8SN per year average flux

DSNB spectrum

averaged SN spectrum redshifted by cosmic expansion

$\bar{\nu}_e$ flux: 20 $cm^{-2}s^{-1}$





Never observed yet!

10 Years' sensitivity

Syst. uncertainty BG	5 %		20 %	
$\langle E_{\bar{\nu}_e} \rangle$	rate only	spectral fit	rate only	spectral fit
12 MeV	$1.7\,\sigma$	$1.9\,\sigma$	$1.5\,\sigma$	$1.7\,\sigma$
15 MeV	$3.3\,\sigma$	$3.5\,\sigma$	$3.0\,\sigma$	$3.2\,\sigma$
18 MeV	$5.1\,\sigma$	$5.4\,\sigma$	$4.6\,\sigma$	$4.7\,\sigma$
21 MeV	$6.9\,\sigma$	$7.3\,\sigma$	$6.2\,\sigma$	$6.4\,\sigma$

Geoneutrino

Big advantage:

- ✓ Big volume and thus high statistics!

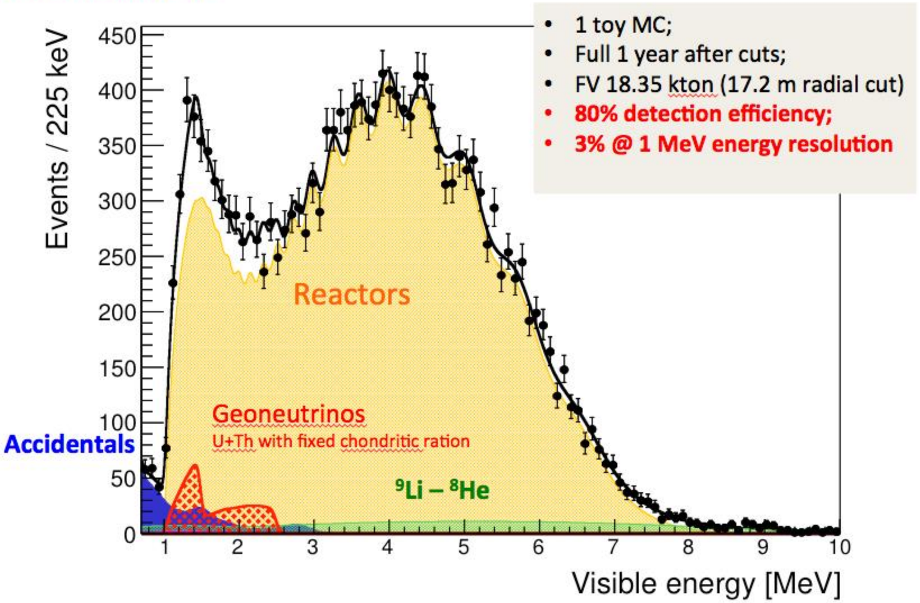
Main limitations:

- ✓ Huge reactor neutrino background;
- ✓ Relatively shallow depth – cosmogenic background;

Critical:

- ✓ Keep other backgrounds (^{210}Po contamination!) at low level and under control;

Simulated JUNO antineutrino spectrum (prompt energy) and the best fit

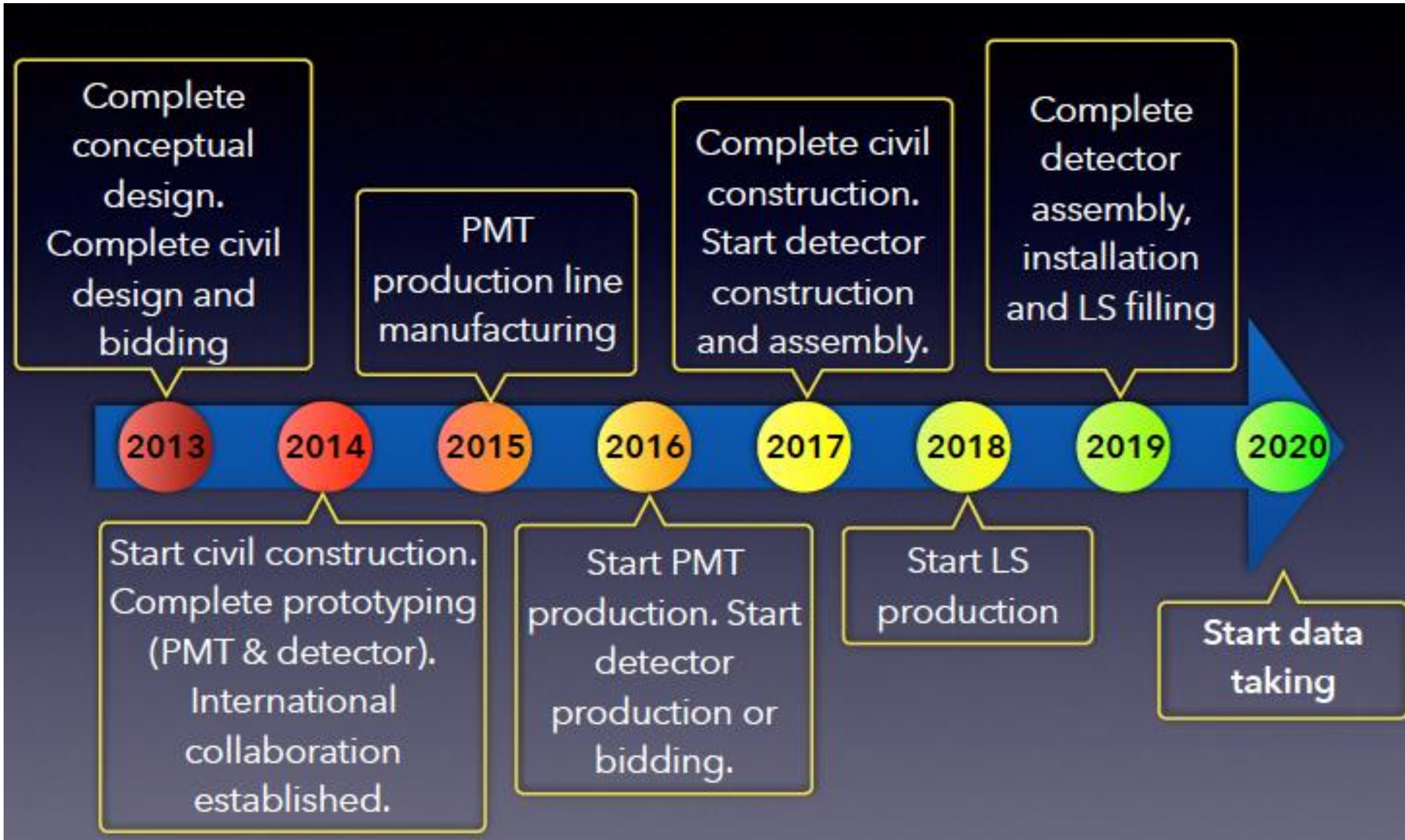


Source	Events/year
Geoneutrinos	408 ± 60
U chain	311 ± 55
Th chain	92 ± 37
Reactors	16100 ± 900
Fast neutrons	3.65 ± 3.65
^{9}Li - ^{8}He	657 ± 130
$^{13}C(\alpha, n)^{16}O$	18.2 ± 9.1
Accidental coincidences	401 ± 4

[arXiv:1510.01523]

- Current (KamLAND and Borexino) precision on geoneutrino flux is ~17-25%
- JUNO can reach 17% precision within the first year and 6% after 10 years
- Geological study of the local crust: separate mantle contribution
- Join efforts of other future experiments: SNO+, Jinping, HANOHANO, ...

JUNO Schedule



Summary

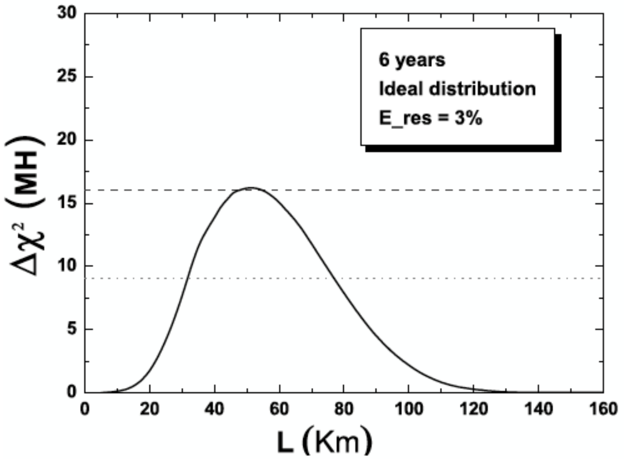
- JUNO is a multipurpose medium baseline (52.5 km) reactor neutrino experiment under construction in China
- The mass hierarchy determination on 3σ after 6 years (or even better: 4.4σ with 1% constrain on $|\Delta m^2_{\mu\mu}|$)
- Significant improvement of the uncertainty of $\sin^2 2\theta_{12}$, Δm^2_{12} and Δm^2_{ee}
- Data for other investigations: SN, solar, atmospheric and geo-neutrinos, proton decay, ...
- Start of data taking in 2020

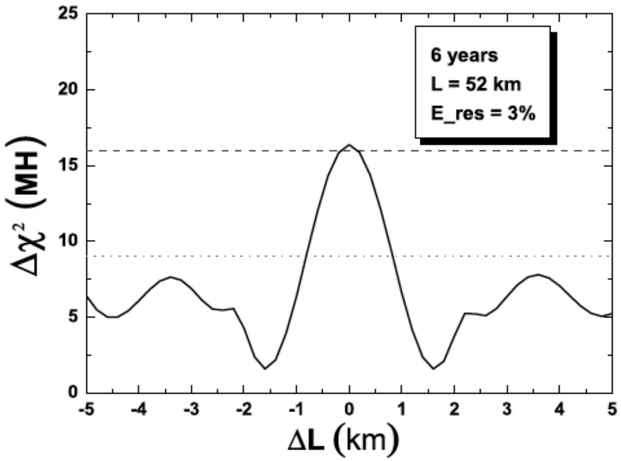
Backup slides

JUNO sensitivity on MH

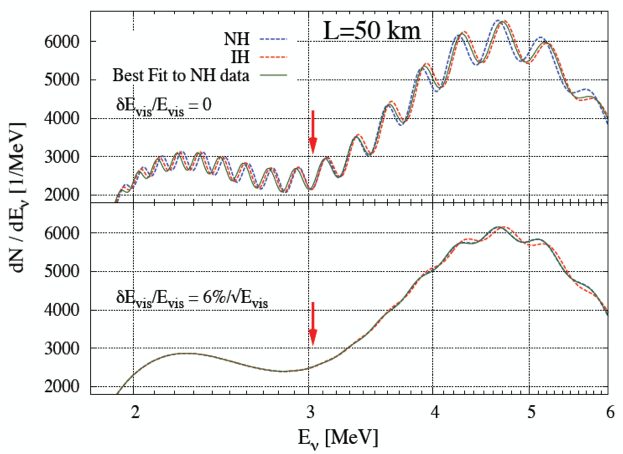
$$\Delta\chi^2_{MH} = [\chi^2_{MIN}(NH) - \chi^2_{MIN}(IH)]$$

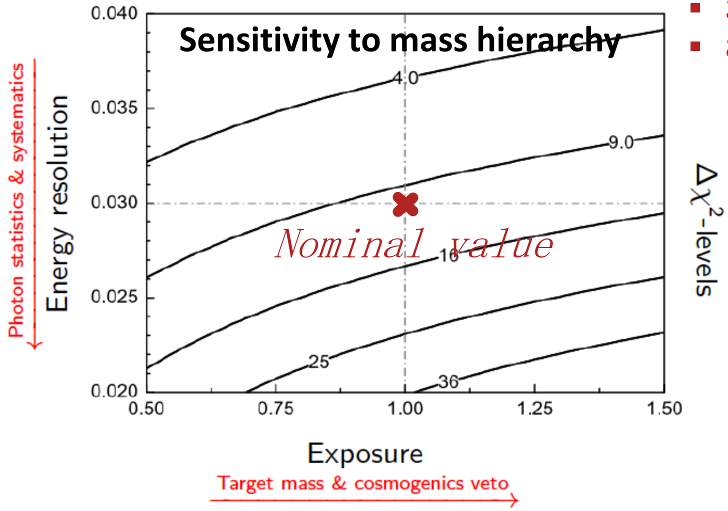
- **Baseline optimization: $53 \pm 0.5\ km$**





- **Excellent energy resolution: $3\%/\sqrt{E}$ [MeV]**





nominal exposure

- 36 GW x 6 years x 20 kt
- 80% detection efficiency

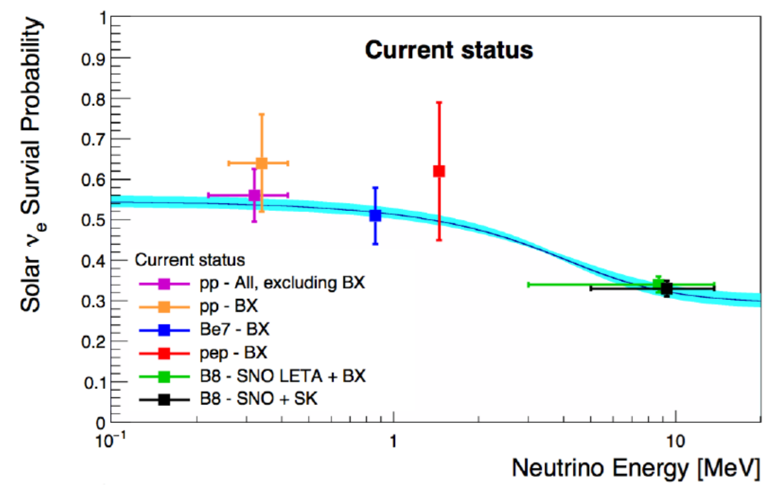
Solar neutrinos

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

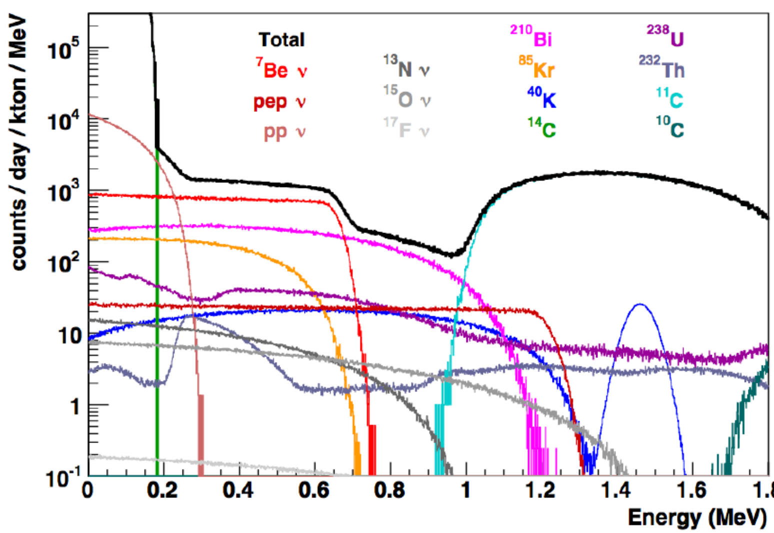
JUNO: neutrinos from **^{7}Be and ^{8}B** chains

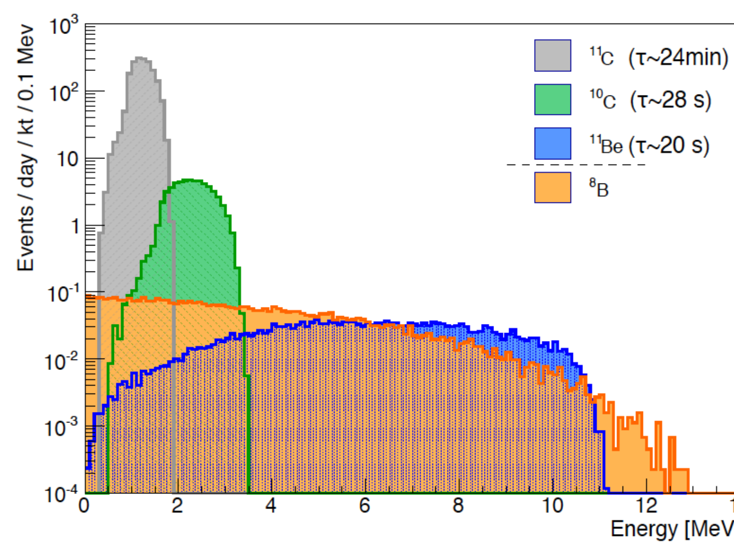
Investigate **MSW effect**: Transition between vacuum and matter dominated regimes

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



arXiv 1602.01733





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