Potentialities of JUNO and of SBL Reactor Neutrino Experiments

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On behalf of the JUNO Collaboration

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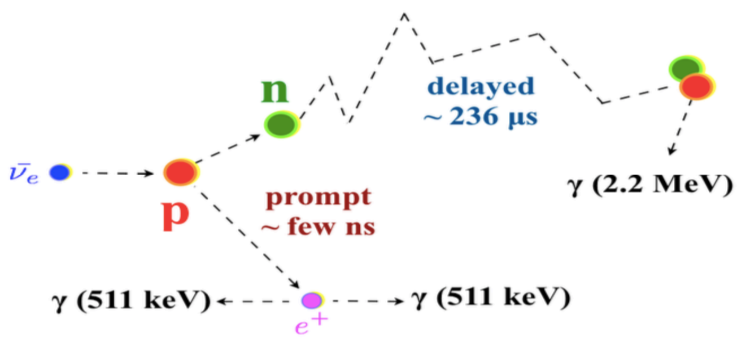
Reactor neutrino Physics

- **Nuclear** power plants **sources** of pure, intense and (generally) well-known **electron antineutrino beams** ($\bar{\nu}_e$). **Survival probability**:

$$P_{ee} = 1 - \cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2\Delta_{21} - \sin^2(2\theta_{13})[\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}]; \quad \Delta_{ij} = \frac{\Delta m^2_{ij} L}{4\,E_\nu} = \frac{(m_i^2 - m_j^2)\,L}{4\,E_\nu}$$

- Main analysis channel: **inverse β decay** (IBD): $\bar{\nu}_e + p \; -> e^+ + n$



- Relatively large cross section;
- Uncorrelated bckg rejection through time coincidence of positron and neutron signals
- $E_{vis}(e^+) = E_{\bar{\nu}}$ - 0.8 MeV
- Results **independent from θ_{23} and CP** violation

Successes and perspectives of reactor experiments

- Neutrino discoveries (Cowan & Reines '56)
- LBL exp.(**KamLAND;** '03): "solar" oscillation confirmation → θ_{12} and mainly Δm^2_{12}
- **SBL (Daya Bay, RENO and Double CHOOZ): $\theta_{13} \neq 0$** 1st measurements and θ_{13} and Δm^2_{32} determination
- **Medium baseline** ($\sim 50\,km$) **JUNO:** study of **neutrino mass hierarchy** and other topics

SBL reactor experiments

- 3 largest **SBL experiments**: **Daya Bay, RENO, Double CHOOZ**

◆ Common aspects

- Use of **Near and Far Detectors**
- **Nested structure** with: a) Internal Gd-LS $\bar{\upsilon}_e$ target; b) Pure liquid scintillator (better E measurement); c) Mineral Oil (radioactivity shield)
- Array of PMTs; External water pool (shield and cosmic ray detector)

◆ Specific aspects

Table 1. Comparison of some of the parameters of the Double CHOOZ, RENO and Daya Bay experiments. P_{th} stands for the total reactor thermal power.

	P_{th} [GW]	nGd target mass @ far site [tons]	Overburden (near/far) [mwe]	Data-taking (start-end)
Double Chooz	8.6	8.3	80/300	2011-2017
RENO	16.4	15.4	90/440	2011-2021
Daya Bay	17.4	80	270/950	2011-2020

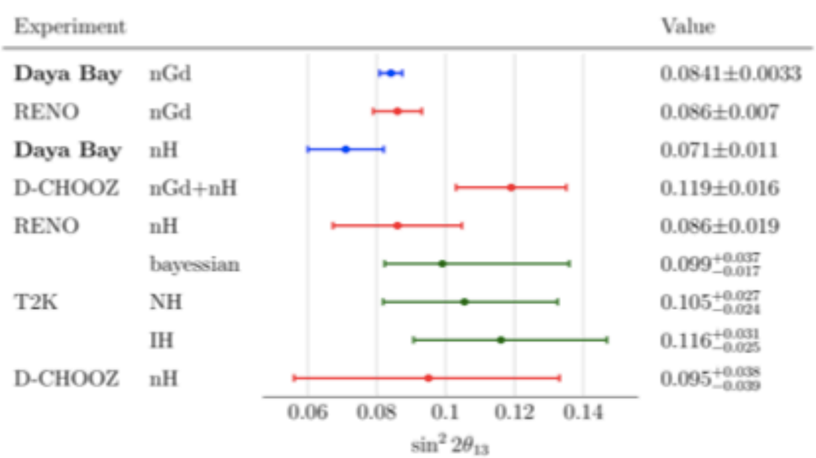
Table from: J. P. Ochoa-Ricoux, Int. J. Mod. Phys. Conf. Ser. 46 (2018) 18600001

SBL reactor experiments-Results

❑Main results

- **1st observation** (starting with Daya Bay '12) **of $\theta_{13} \neq 0$ at > 5 σ level**
- Thanks to rate and spectral shape analyses, **θ_{13}** and **Δm^2_{32} estimate**

		EXPERIMENT	
Parameter	Daya Bay	RENO	Double CHOOZ
$\sin^2(2\theta_{13})$	0.0856 ± 0.0029	0.0896 ± 0.0048 (stat) ± 0.0047(syst)	0.119 ± 0.016
$\|\Delta m^2_{32}\|$ (10^{-3} eV^2)	$2.471^{+0.068}_{-0.070}$ (NH) $2.575^{+0.068}_{-0.070}$ (IH)	2.68 ± 0.12 (stat) ± 0.07(syst) (Δm^2_{ee})	



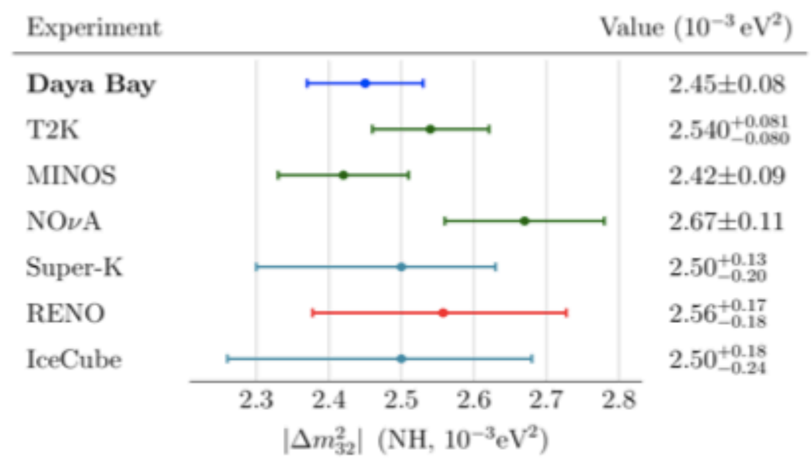


Table from: J.P.Ochoa-Ricoux, Int.J. Mod. Phys. Conf. Ser. 46 (2018) 18600001 and by courtesy of Gonchar, M

SBL reactor experiments – Results 2

- Looking for spectrum distortion and in combination with MINOS results: **search for sterile neutrino** and probe of LSND and MiniBoonE hints (**reduction of allowed regions**: Δm^2_{41}< 0.8 eV^2 excluded at 95% C.L.)

- **Hints confirmed by Daya Bay and RENO of**

A) $\bar{\nu}_e$ events deficit (already present in old SBL data): **reactor antineutrino anomaly.**

Hypothesis of explanation: **eV-scale sterile neutrino**

Under investigation by many experiments (STEREO, neutrino-4, PROSPECT, …). **First results reduce the eventual possible values to higher Δm^2**.

B) **Deviation from predicted spectrum in the region 4-6 MeV**

(seen also by Double CHOOZ and NEOS).

Under investigation; probably correlated with reactor power and fuel composition evolution (problems with ^{235}U).

Future of SBL experiments

❖**Double CHOOZ:** finished data taking last year, but possible new analyses.

❖**RENO:** possible extension until 2021 and 6% accuracy also for $sin^2\theta_{13}$ (already reached for Δm^2_{ee})

❖**Daya Bay:** by 2020 should reach **accuracy level ≤ 3%** on both parameters

❖ **Study of the different flux anomalies also** with other **new SBL**

Possible independent constraint on ^{235}U yield (important for the study of the "bump" in the 4-6 MeV region)

❖ **Use of movable and segmented detectors:** useful to **study** eventual oscillation to **eV-scale sterile neutrino** with different possible baselines.

Open question: the mass hierarchy

- **From the experiments**

(See e.g. F. Capozzi *et. al.* Progr.Part.Nucl.Phys.102 (2018) 48 or I. Esteban *et al.* JHEP 1701 (2017) 087)

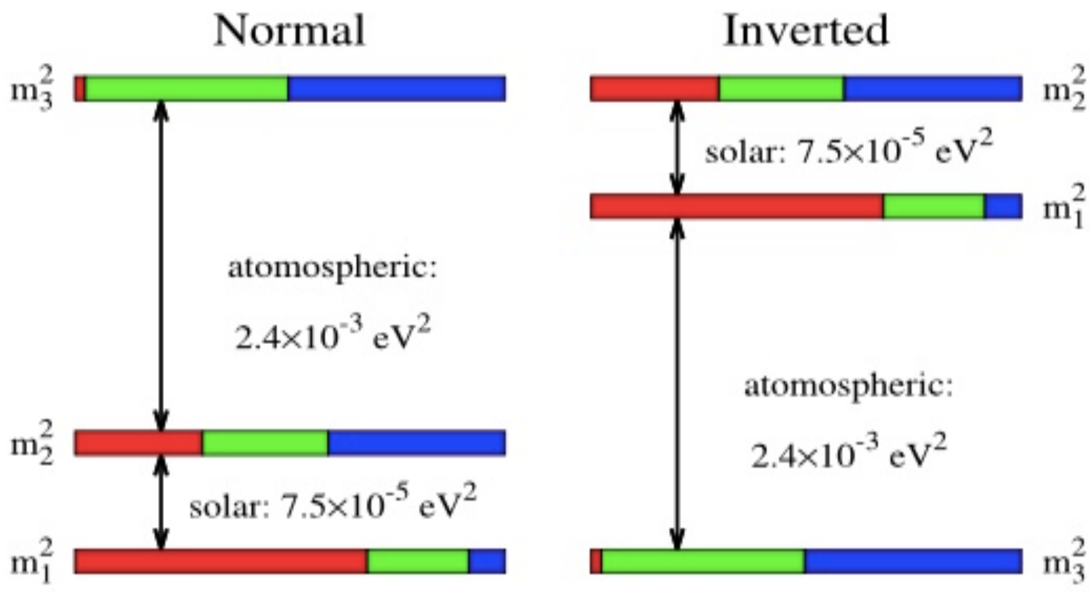
$\Delta m^2_{21} = (7.4 \pm 0.2) \times 10^{-5}\, eV^2$ (Solar+KL) $\Delta m^2_{31(32)} = (2.42 \pm 0.04) \times 10^{-3}\, eV^2$ (Atmospheric+LBL)

- **Two possible scenarios**

NH

$|\Delta m^2_{31}| = |\Delta m^2_{32}| + \Delta m^2_{21}$

$|\Delta m^2_{31}| > |\Delta m^2_{32}|$



IH

$|\Delta m^2_{31}| = |\Delta m^2_{32}| - \Delta m^2_{21}$

$|\Delta m^2_{31}| < |\Delta m^2_{32}|$

The mass hierarchy determination

❑ Mass Hierarchy (**MH**) **important for**

➢ **Potential discoveries** of experiments ($0\nu2\beta$; CP violation)

➢ Discrimination between different **extensions of Standard Model** ➔ important also for **high energy physics strategies**

❑ Accelerator LBL (T2K and mainly NOνA), compared with reactors, favors NH but no final conclusions at the moment

❑ In **future dedicated experiments** with beams from:

➢ **Accelerator LBL** (DUNE) (see talk by)

➢ **Atmospheric** (PINGU, ORCA) (see talk by)

➢ **Reactors**: **JUNO** ready for data taking in 2021

Relatively large $\sin^2(\theta_{13})$ (≅0,08-0,09) ➔

Study of oscillation probability **corrections** dependent on **MH "sign"** through analysis of **medium baseline reactor $\overline{\nu}_e$ inverse β decay.**

(Original idea by Choubey, Petcov, Piai, PRD 68 (2003) 113006)

Spectrum dependence upon the Mass Hierarchy

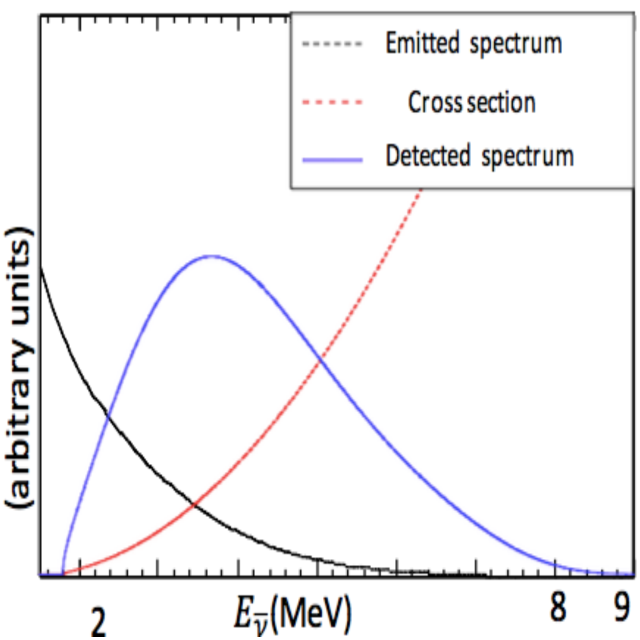
Electron antineutrino survival probability depends on the mass hierarchy (**NH or IH**).

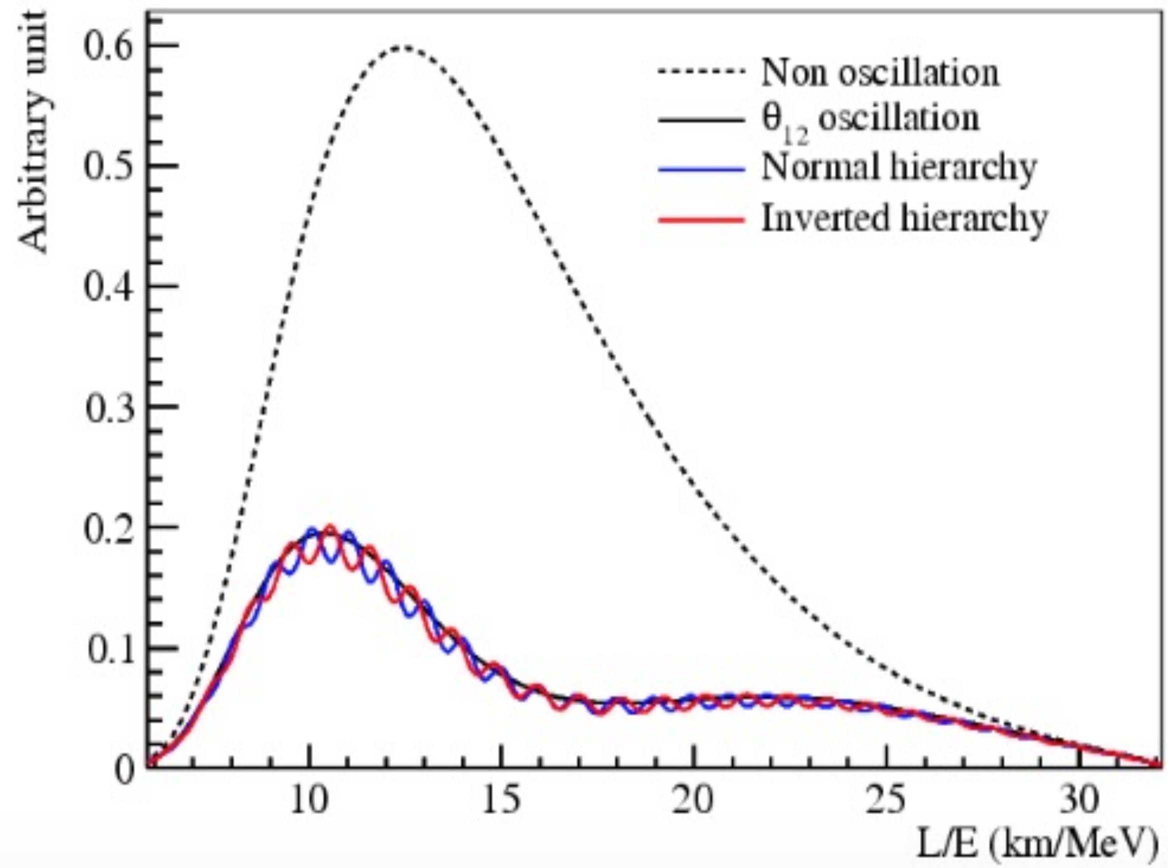
$$P_{ee} = 1 - cos^4\theta_{13}\, sin^2(2\,\theta_{12}) sin^2\Delta_{21} - sin^2(2\theta_{13})(cos^2\theta_{12} sin^2\Delta_{31} + sin^2\theta_{12} sin^2\Delta_{32}) =$$
$$1 - cos^4\theta_{13}\, sin^2(2\,\theta_{12}) sin^2\Delta_{21} - \frac{1}{2} sin^2(2\theta_{13})[1 - \sqrt{1 - sin^2(2\theta_{12}) sin^2\Delta_{21}}\ \cos(2\Delta_{ee} \pm \varphi)]$$

$\Delta_{ij} = \frac{\Delta m^2_{ij}\, L}{4\, E}$ and **the phase factor φ** is defined in such a way that its sin and cos are **combinations of 1-2 mass and mixing parameters ; $+\varphi = NH$; $-\varphi = IH$**

Fastly oscillating MH dependent correction superimposed to general oscillation

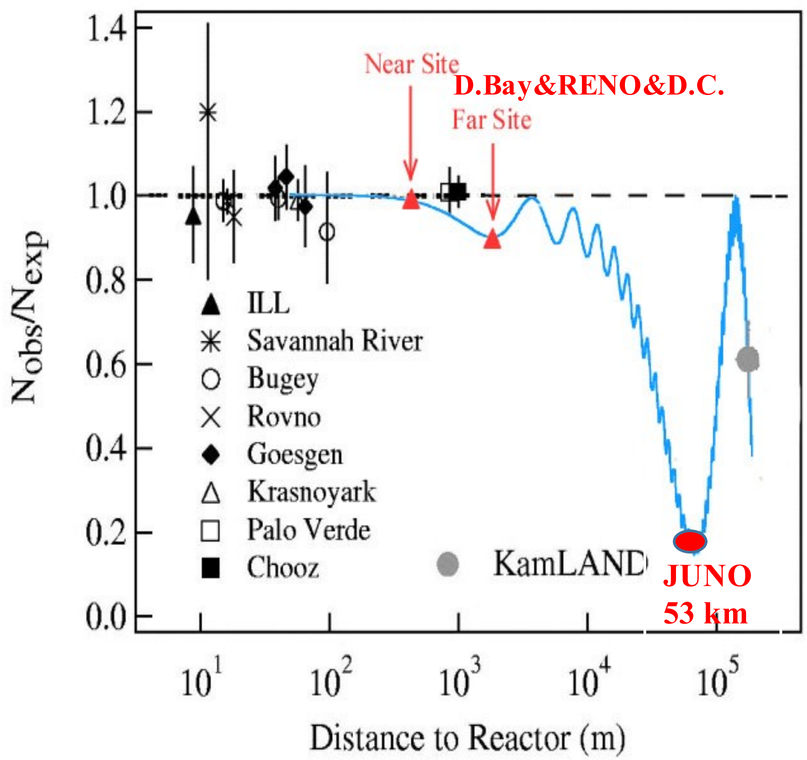
Expected number of events



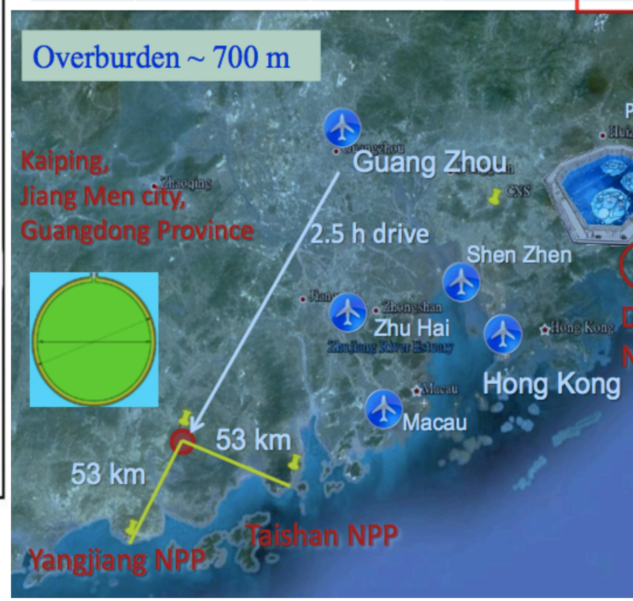


The JUNO experiment

- **JUNO** (Jiangmen Underground Neutrino Observatory): multipurpose **reactor $\bar{\nu}_e$** under construction near Kaiping(South China).**Ready for data taking in 2021**
  - **Baseline** from reactors (10 cores) to detector about 53 km: optimized in the region of the maximum 1-2 oscillation.

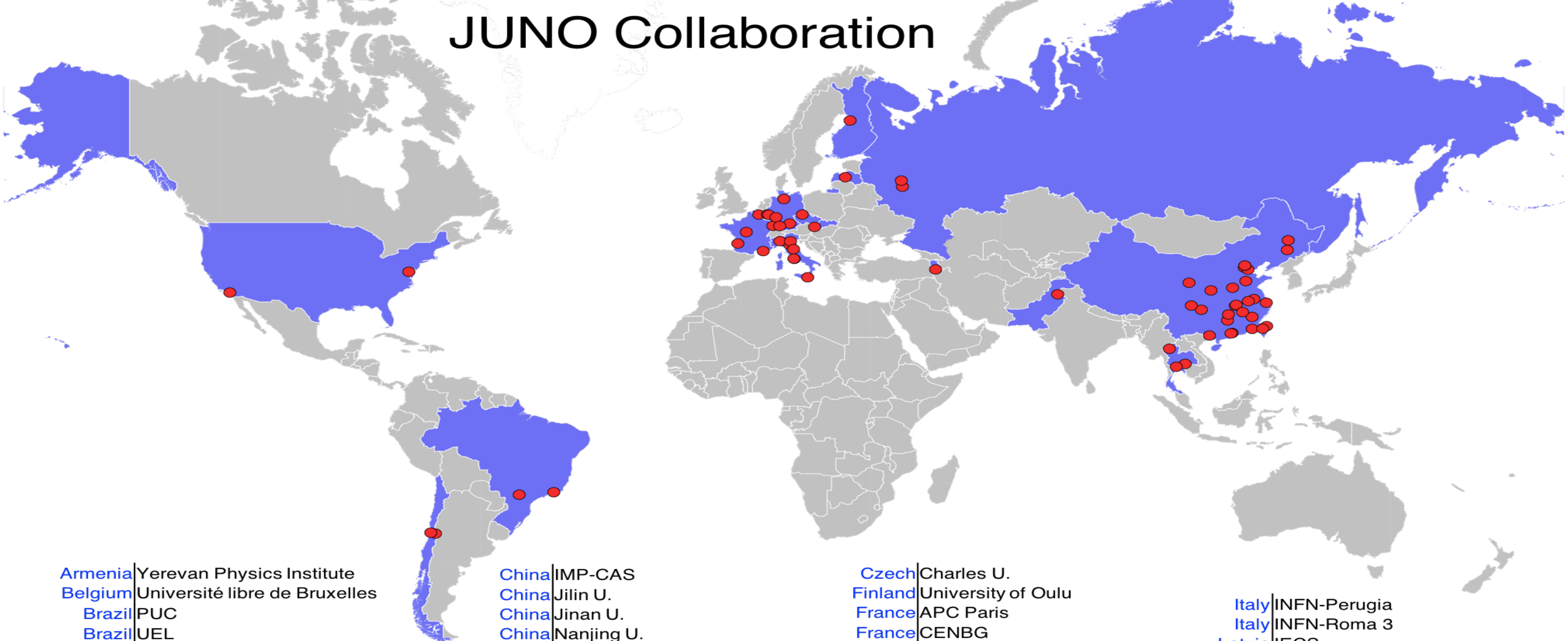


NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

JUNO Collaboration



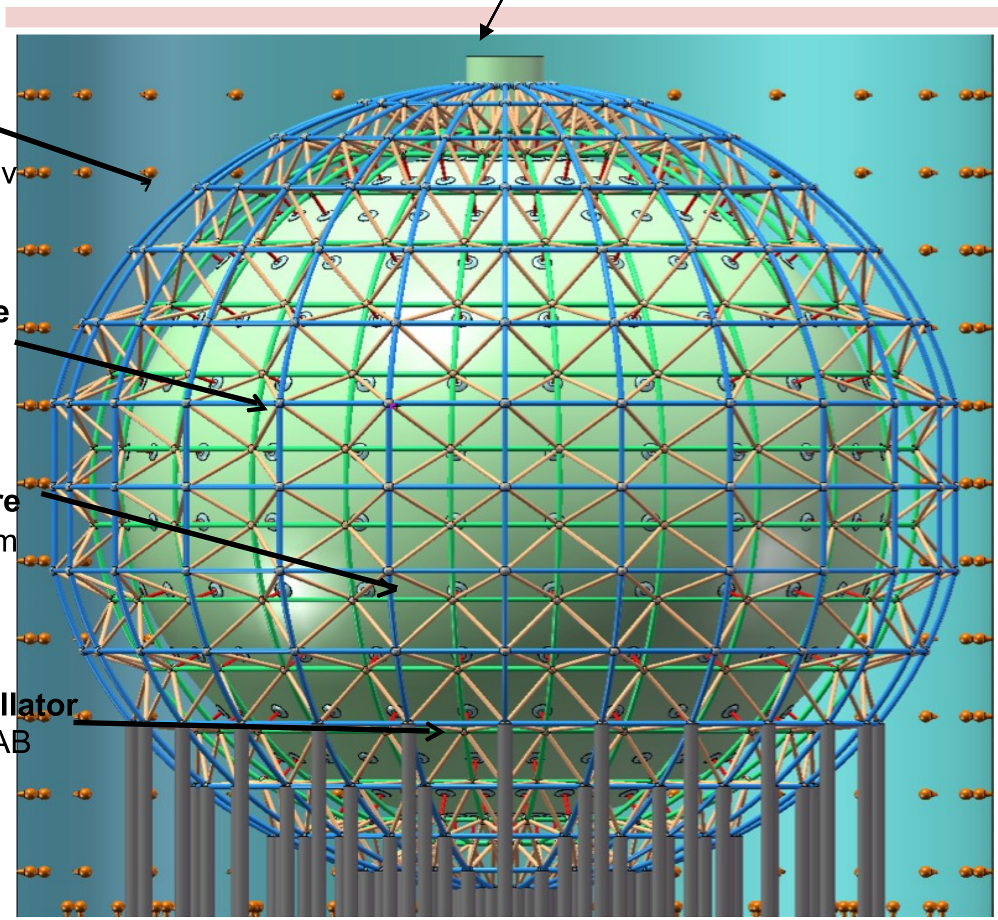
Armenia	Yerevan Physics Institute
Belgium	Université libre de Bruxelles
Brazil	PUC
Brazil	UEL
Chile	PCUC
Chile	UTFSM
China	BISEE
China	Beijing Normal U.
China	CAGS
China	ChongQing University
China	CIAE
China	CUG
China	DGUT
China	ECUST
China	ECUT
China	Guangxi U.
China	Harbin Institute of Technology
China	IGG
China	IGGCAS
China	IHEP
China	IMP-CAS
China	Jilin U.
China	Jinan U.
China	Nanjing U.
China	Nankai U.
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.
China	Xi'an JT U.
China	Xiamen University
China	Zhengzhou U.
Czech	Charles U.
Finland	University of Oulu
France	APC Paris
France	CENBG
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
Latvia	IECS
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	NARIT
Thailand	PPRLCU
Thailand	SUT
USA	UMD1
USA	UMD2
USA	UCI

Collaboration established on July ’14

Now 77 institutions

~600 collaborators

The JUNO detector



Underground detector: more than 700 m of rock overburden.

20 kton Liquid scintillator (LAB+PPO+BisMB)

Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	20 ton	~ 300 ton	~ 1 kton	**20 kton**
Coverage	12%	~ 34%	~ 34%	**> 75%**
Energy resolution	7.5%/√E	~ 5%/√E	~ 6%/√E	~ 3%/√E
Light yield (p.e./MeV)	~160	~ 500	~ 250	**~ 1200**

JUNO main features and milestones of the analysis

- Medium baseline (53 km) and high statistic required → **Large detector mass**
- Signature: position of the spectral wiggles in the spectrum

→ **Very good E resolution:** $\sigma(E)/\sqrt{E} \cong 3\%$

- Reduction of the cosmogenic background → **Rock overburden ~ 700 m**
- **Near detector** (**Gd-LS** with 1800 mm diameter; 2.63 ton at ~30 m from the core, with 30 times the JUNO event rate and resolution ≤ 1.7%. Use of **criogenic Si-PM**) **to know exactly the reactor flux shape** and avoid potential effect of eventual spectral distorsions
- **Hierarchy discrimination** from **global fit and comparison of** χ^2 of the minum for the 2 hierarchies.

For resolution ≥ 3% : **hierarchy discrimination at 3-4 σ** C.L.

(see the JUNO Yellow Book:, J. of Phys. G: Nucl. Part. Phys. 43 (2016) 030401)

Main advantages:

- Looking at **vacuum oscillations** JUNO **doesn't suffer** from **uncertainty** on **Earth density** profile **and** on **CP-violating phase ambiguity**.
- **No dependence on** θ_{13} **value** (affecting only the corrections amplitude); only mild dependence **on the 3-4 flavor pattern**.

Possible also combined analyses with data from future neutrino telescopes, to further increase the statistical discrimination power of both.

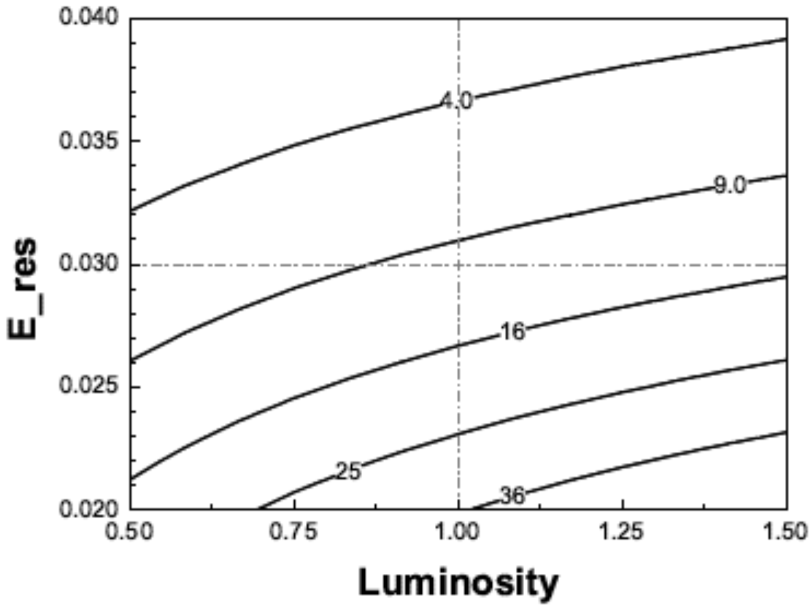
Mass hierarchy sensitivity at JUNO

- **MH sensitivity** expressed in terms of: $\Delta\chi^2_{MH} = |\chi^2_{Min}(NH)-\chi^2_{Min}(IH)|$

Interpretation of the result statistical significance is not unique.

In a frequentist framework $\sqrt{\Delta\chi^2}\sigma$ indicates the hierarchy "sensitivity level"

Iso-$\Delta\chi^2$ contour plot as function of E resolution and luminosity L (L=1 means 6 years of data taking with nominal luminosity).



Main contributions affecting the mass hierarchy sensitivity

	Ideal	Core distr.	Shape	B/S (stat.)	B/S (shape)	$\|\Delta m^2_{\mu\mu}\|$
Size	52.5 km	Real	1%	4.5%	0.3%	1%
$\Delta\chi^2_{MH}$	+16	−4	−1	−0.5	−0.1	+8

PRD 88, 013008 (2013)	Hierarchy discrimination power	With info on $\Delta m^2_{\mu\mu}$ from LBL expts
Statistics only	4σ	5σ
Realistic case	3σ	4σ

Mass and mixing parameters with JUNO

Very **high statistics** and very **good E resolution**

↓

Precision measurement of mass and mixing

(at subpercent level for 3 oscillation parameters)

Oscillation Parameter	Current accuracy (global 1σ)	Dominant experiment(s)	JUNO Potentiality
Δm^2_{21}	2.2%	KamLAND	0.6%
$\lvert \Delta m^2_{ee} = \cos^2\theta_{12}\,\Delta m^2_{31} + \sin^2\theta_{12}\,\Delta m^2_{32} \rvert$	2.4%	MINOS	0.4-0.5%
$\sin^2\theta_{12}$	5.4	SNO	0.7%

Other nutrino physics topics with JUNO

❑ Solar neutrinos

JUNO's **advantages: large mass, very good E resolution**, radiopurity.
Main caveats: cosmogenic and radioactive bckg.
Studies of: ^{7}**Be** (interesting for solar metallicity); ^{8}**B** (solar metallicity; test of LMA pattern and search for Non Standard Interactions); **hep** ν

❑ Supernova burst & diffuse Supernova neutrinos

❑ Geoneutrinos

Estimation of radiogenic contribution to Earth heat power and test of Earth's geochemical models.

JUNO's **advantages: size**, radiopurity, depth.

1 year of JUNO data > KL + BX + SNO+

❑ Atmospheric neutrinos

Difficult, but not impossible task

❑ Exotic searches

Search of isotropic and non isotropic **Lorentz Invariance Violation**; **Proton decay** (mainly Susy inspired channel); etc.