Status and potentialities of the JUNO experiment

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On behalf of the JUNO Collaboration

XVII International Workshop on Neutrino Telescopes **Venice, 13-17 March '17**

The mass hierarchy

• From experiments

(see e.g. JHEP 1701 (2017) 087; arXiv: 1703.04471[hep-ph] and NPB 00 (2016) 1)

$\Delta m^2_{21} = (7.37 \pm 0.17) \times 10^{-5} eV^2$

(Solar + KL)

$|\Delta m^2_{31(32)} = (2.52 \pm 0.04) \times 10^{-3}|\ eV^2$

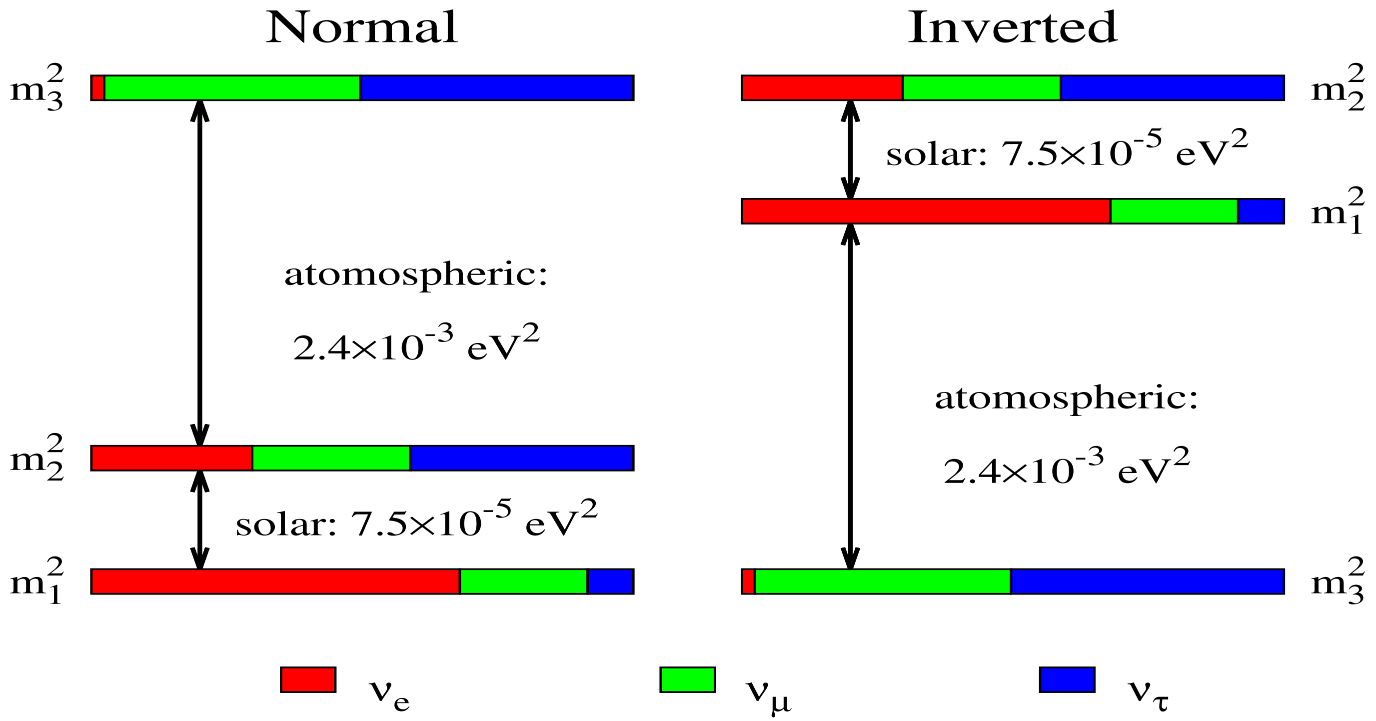
(Atmospheric + LBL)

• 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:

- Discrimination between different **models Beyond the Standard Model**
- Potential **discovery of experiments** (e.g $0\nu2\beta$, CP violation)

❑ Relatively large θ_{13} ($\sin^2(2\theta_{13} \cong 0.08\text{-}0.09)$)

$\Downarrow$

Study of **oscillation probability** corrections **dependent on MH "sign"**

Inverse β decay of $\overline{\nu}_e$ reactor with medium baseline

(Original idea by Choubey, Petcov, Piai (PRD68 (2003) 113006))

Mass hierarchy and reactor antineutrinos

- $\bar{\nu}_e$ survival probability: $\Delta m_{ij}^2 = m_i^2 - m_j^2$

$$P_{ee} = 1 - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \sin^2(2\theta_{13})\left(\cos^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \sin^2\theta_{12}\left(\frac{\Delta m^2_{32} L}{4E}\right)\right)$$

- **The last term (sensitive to the mass hierarchy)**, can be written as:

$$\frac{1}{2}\sin^2(2\theta_{13})\left\{1 - \left[1 - \sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)\right]^{1/2}\cos\left(2\left|\frac{\Delta m^2_{ee} L}{4E}\right| \pm \varphi\right)\right\},$$

$\Delta m^2_{ee} = (\cos^2(\theta_{12})\,\Delta m^2_{31} + \sin^2(\theta_{12})\,\Delta m^2_{32})$ and

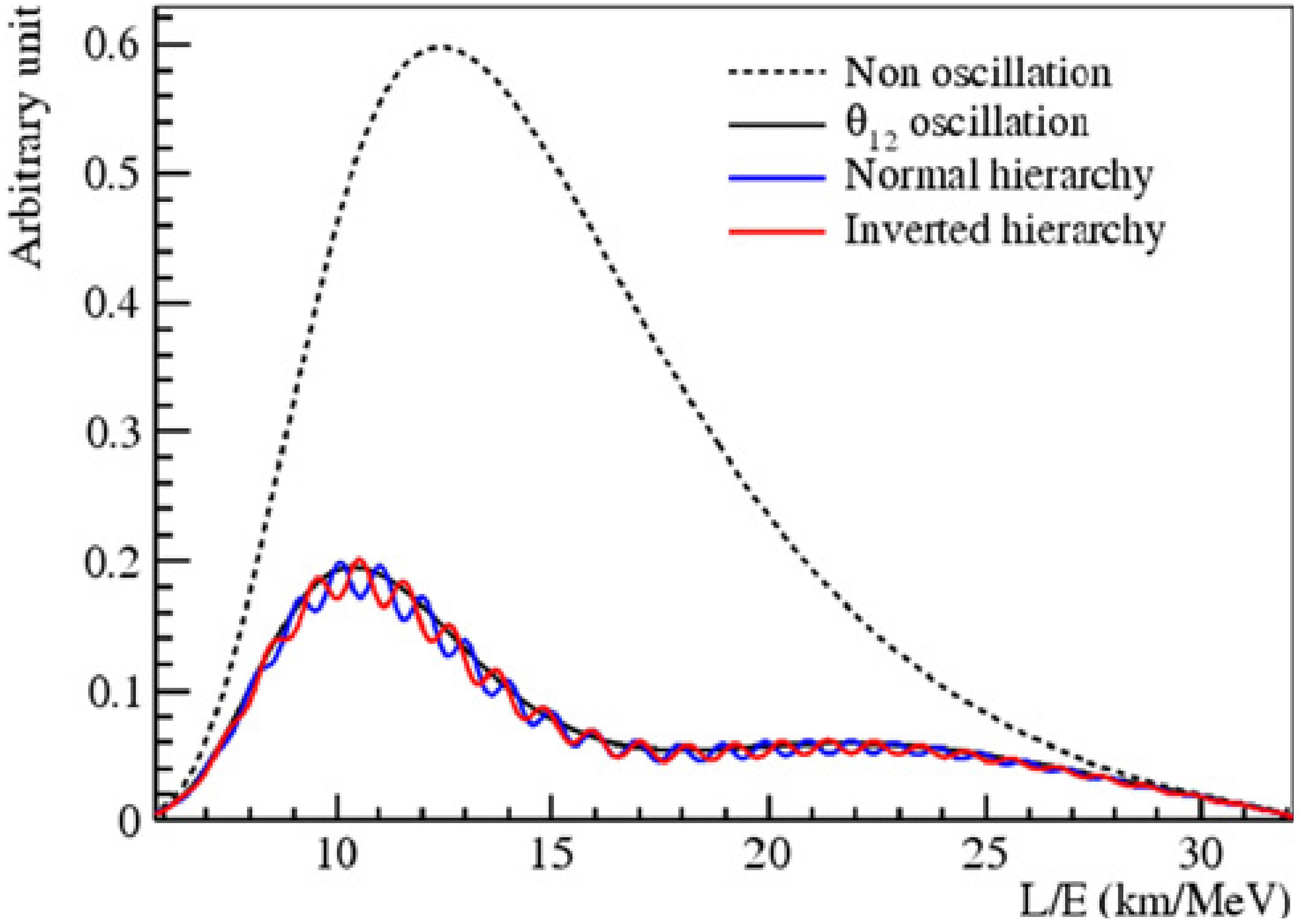
$\sin\varphi$ and $\cos\varphi$ denote combinations of mass and mixing parameters of the 1-2 sector.

- The sign of **φ term** is **positive for NH** and **negative for IH** →

Fastly oscillating term, opposite for the 2 hierarchies, superimposed to the **general oscillation pattern**

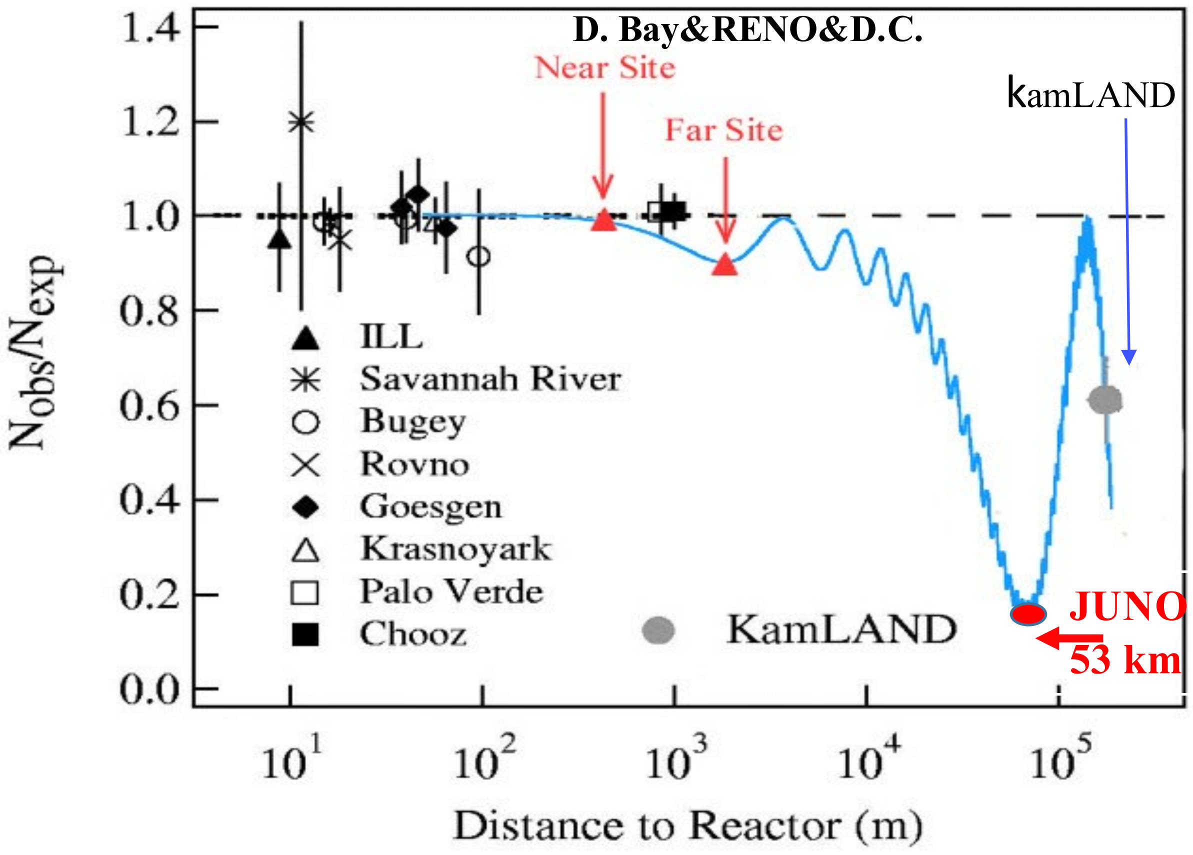
Spectrum dependence upon the Mass Hierarchy

Observed energy spectrum has a small dependence on the hierarchy
(in addition to other oscillation parameters).



The JUNO option

- **JUNO** (Jiangmen Underground Neutrino Observatory): **"multipurpose"** reactor $\overline{\nu_e}$ **experiment,** under construction near Kaiping (South China).
- **Baseline** from reactors (10 nuclear cores) to detector about 53 km: **optimized in the region of the maximum 1-2 oscillation**



Updated list of JUNO members

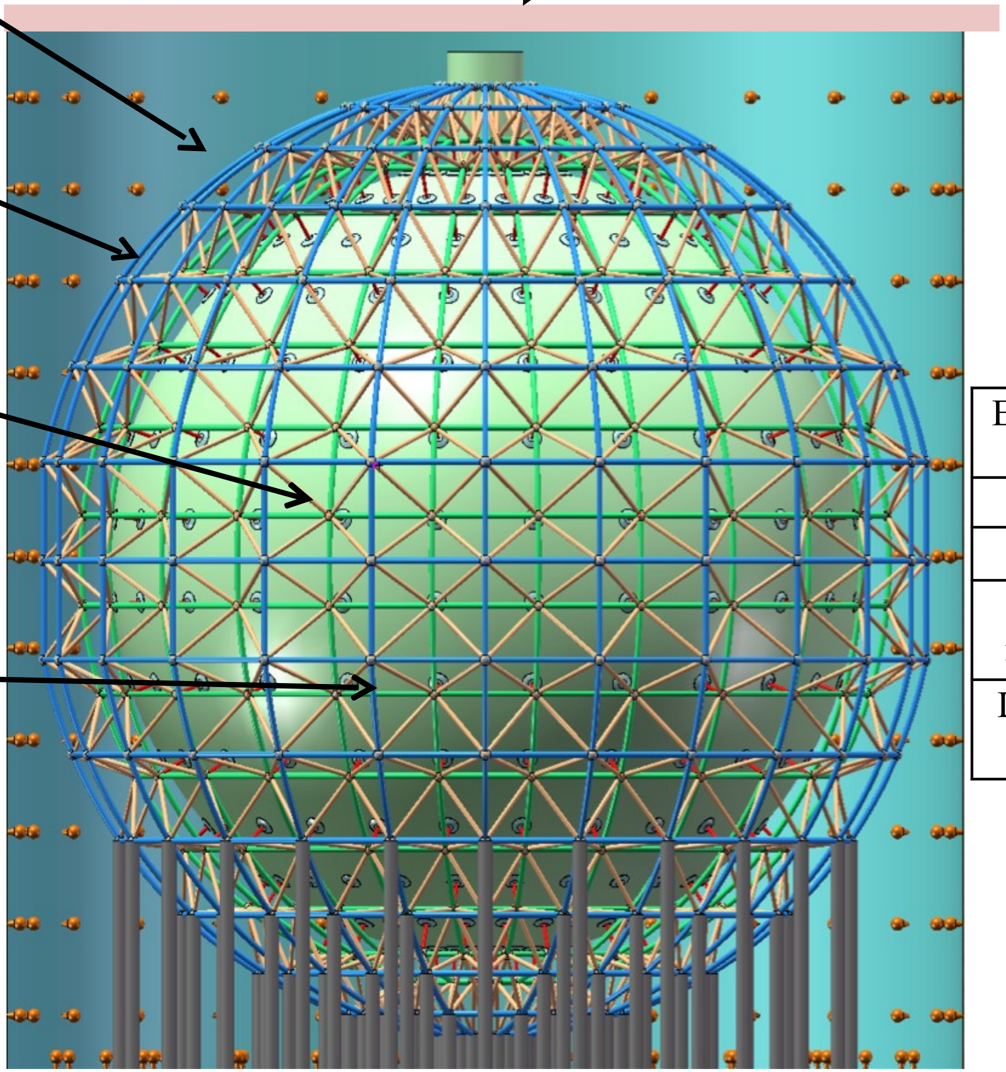
Country	Institute
Armenia	Yerevan Physics Institute
Belgium	Universite libre de Bruxelles
Brazil	PUC
Brazil	UEL
Chile	PCUC
Chile	UTFSM
China	BISEE
China	Beijing Normal U.
China	CAGS
China	ChongQing University
China	CIAE
China	DGUT
China	ECUST
China	Guangxi U.
China	Harbin Institute of Technology
China	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	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	Charles U.
Finland	University of Oulu
France	APC Paris
France	CENBG
France	CPPM Marseille
France	IPHC Strasbourg
France	LLR Palaiseau
France	Subatech Nantes
Germany	Forschungszentrum Julich ZEA2
Germany	RWTH Aachen U.
Germany	TUM
Germany	U. Hamburg
Germany	IKP FZJ
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	NARIT
Thailand	PPRLCU
Thailand	SUT
USA	UMD1
USA	UMD2

= 71 members

Observers

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

The JUNO detector



Underground detector: more than 700 m of rock overburden

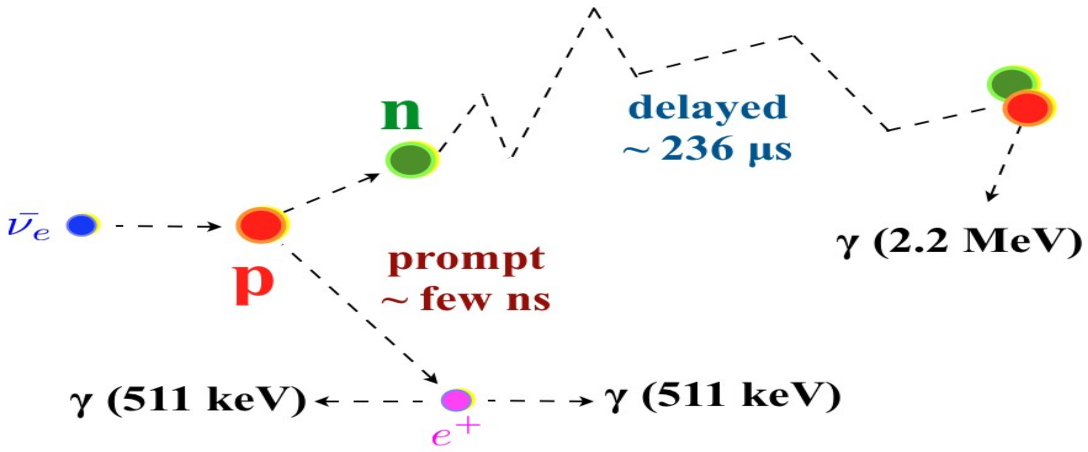
Experiment	**Daya Bay**	**BOREXINO**	**KamLAND**	**JUNO**
LS mass	20 ton	~ 300 ton	~ 1kton	**20 kton**
Coverage	~ 12%	~ 34%	~ 34%	~ 80%
Energy resolution	$7.5\%/\sqrt{E}$	$\sim 5\%/\sqrt{E}$	$\sim 6\%/\sqrt{E}$	$\sim 3\%/\sqrt{E}$
Light yield	~ 160 p.e./MeV	~ 500 p.e./MeV	~ 250 p.e./MeV	**~ 1200** p.e./MeV

The JUNO experiment

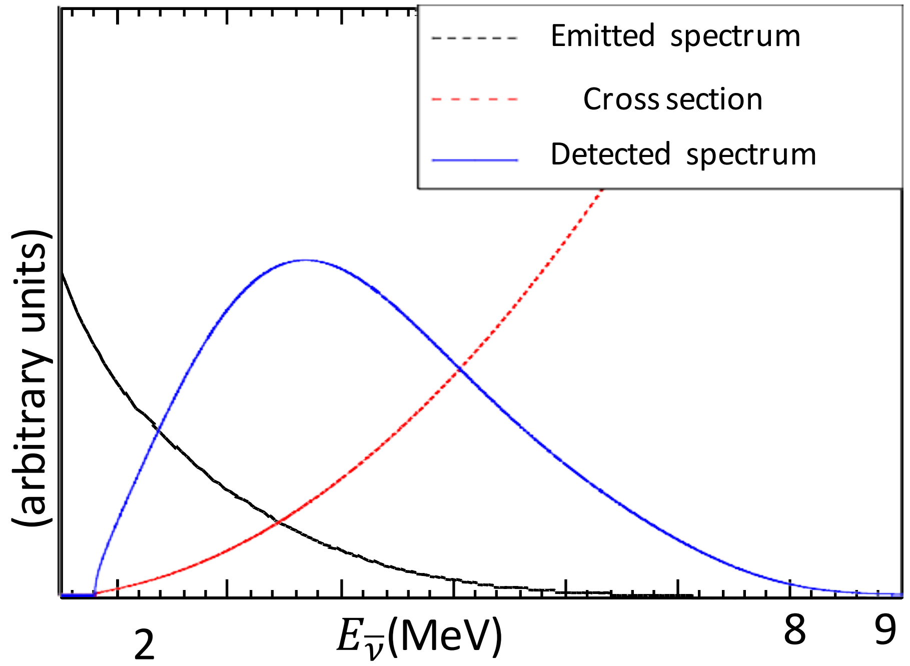
- Main reaction: $\overline{\nu_e} + p \rightarrow n + e^+$

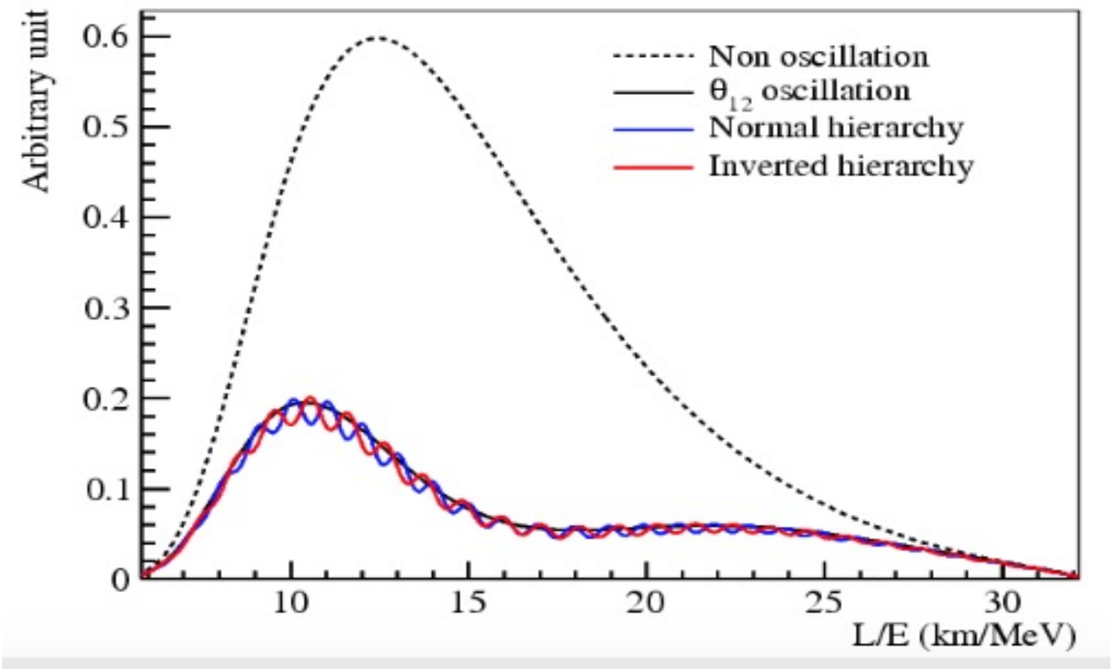
$E_{\overline{\nu}} \geq 1.8$ MeV

Time coincidence between e⁺ and 2.2 MeV γ from nuclear capture



Reactor $\overline{\nu_e}$: $E \leq 8$ MeV





JUNO main features

- Medium baseline (53 km); high statistics required

⇊

Large detector mass and proximity to several reactors

- Signature: position of the spectral wiggles in the spectrum

⇊

Very good E resolution $\left(\frac{\sigma(E)}{\sqrt{E}} \cong 3\%\right)$

Liquid scintillator (LAB+PPO+bis-MSB)

High photon yield

- Reduction of the cosmogenic background

⇊

Rock overburden about 720 m and a muon veto system

Milestones of the analysis

- **Discrimination** of **NH and DH** from **global fit and comparison of χ^2** of the best fit points for the 2 hierarchies.

❑ Crucial points

Sensitivity (**detector mass) and E resolution** to distinguish the right solution

For E resolution equal or better than 3%/√E: **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:

- ➢ JUNO looks at **vacuum oscillations** and, therefore, it **doesn't sufffer** from the **uncertainty** on **Earth density** profile **and** the ambiguity of **CP-violating phase**.
- ➢ It **does not depend on the θ_{13} value** (affecting only the amplitude of the corrections) **and** depends only mildly **on the 3-4 flavor pattern**.

The JUNO main goals

- ❑ **Mass hierarchy determination**
- ❑ **Mixing parameters precision measurement**
- ❑ **Supernova** burst & diffuse supernova **neutrinos**
- ❑ **Geoneutrinos**
- ❑ **Solar** & atmospheric **neutrino** studies
- ❑ Other measurements: search for sterile neutrinos and for nucleon decays; indirect dark matter searches; other exotic searches

Mass hierarchy sensitivity at JUNO

- The **MH sensitivity** is expressed in terms of:

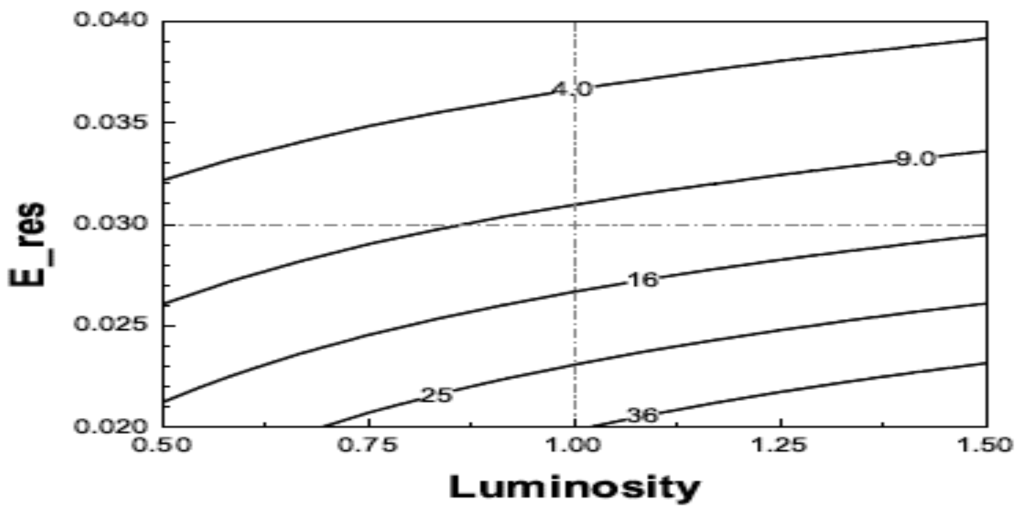
$$\Delta\chi^2_{MH} = \left|\, \chi^2_{MIN}\,(NH) - \chi^2_{MIN}\,(IH)\,\right|, \text{ with}$$

$$\chi^2_{Rea} = \sum_{i=1}^{N_{bins}} \frac{\left[M_i - T_i\left(1+\sum_k \alpha_{ik}\,\varepsilon_k\right)\right]^2}{M_i} + \sum_k \frac{\varepsilon_k^2}{\sigma_k^2},$$

M_i = measured ν events in the bin; T_i = no osc. predicted events; σ_k = syst. uncertainty;

ε_k = pull ; α_{ik} = fraction of event contribution of k^{th} pull to i^{th} bin

- **Results of the analysis**



	Ideal	Core distr.	Shape	B/S (stat.)	B/S (shape)	$\lvert\Delta m^2_{\mu\mu}\rvert$
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 measurements with JUNO

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

↓

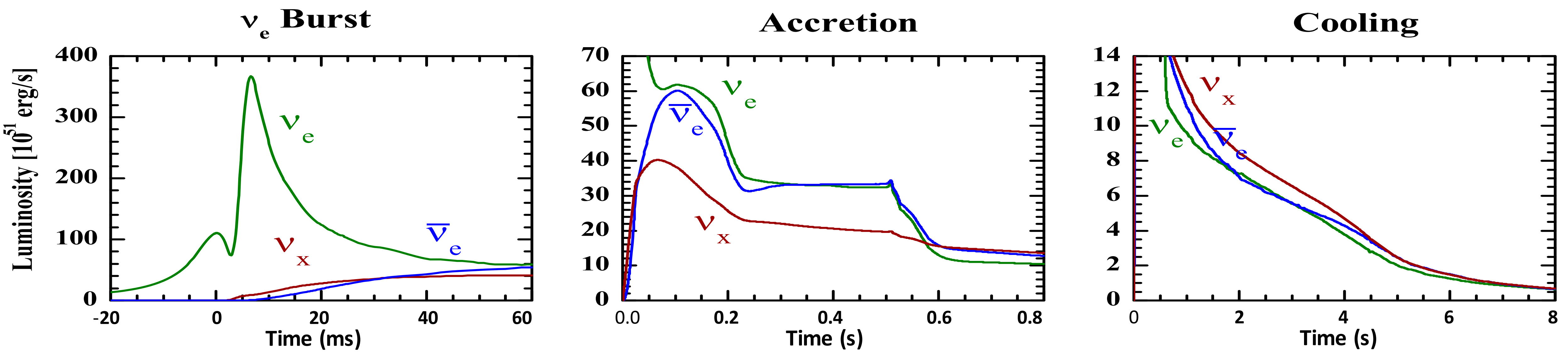
Precision measurement of mass and mixing

(at subpercent level for 3 oscillation parameters)

Oscillation Parameter	Current accuracy (global 1σ) **	Dominant experiment(s)	JUNO Potentiality
Δm^2_{21}	2.3%	KamLAND	0.59%
$\Delta m^2 = \lvert m_3^2 - \frac{1}{2}(m_1^2 + m_2^2)\rvert$	1.6%	MINOS, T2K	0.44%
$\sin^2(\theta_{12})$	~4-6%	SNO	0.67%

** See: Esteban et. al, JHEP 1701 (2017) 087 and F. Capozzi et al., arXiv: 1703.04471[hep-ph]

Supernova neutrino physics @ JUNO



- Huge amount of energy ($3x10^{53}$ erg) emitted in neutrinos (0.2 $M_\odot$) **over long time range**
- 3 phases equally important ▸ 3 experiments teaching us about astro- and particle-physics

Process	Type	Events ($< E_\nu >$ = 14 MeV)
$\bar{\nu}_e + p \rightarrow e^+ + n$	CC	5.0 x 10^3
$\nu + p \rightarrow \nu + p$	NC	1.2 x 10^3
$\nu + e \rightarrow \nu + e$	ES	3.6 x 10^2
$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$	NC	3.2 x 10^2
$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$	CC	0.9 x 10^2
$\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$	CC	1.1 x 10^2
N.B.: Other $<E_\nu>$ values	needed to be	considered for a 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

For details see J. Phys. G 43 (2016) no.3, 030401

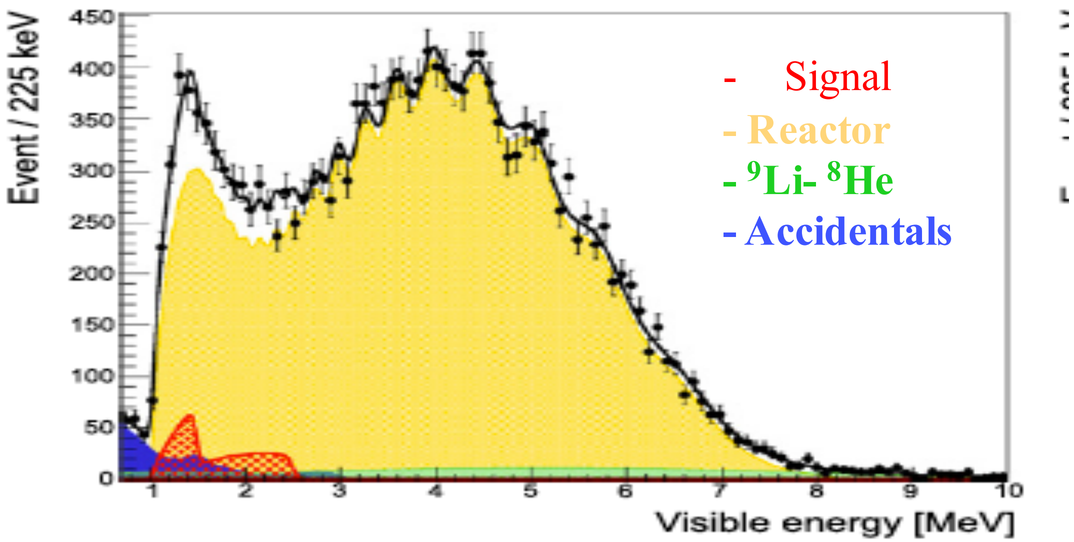
Geo-neutrino physics @ JUNO (Geology ⟷ Physics)

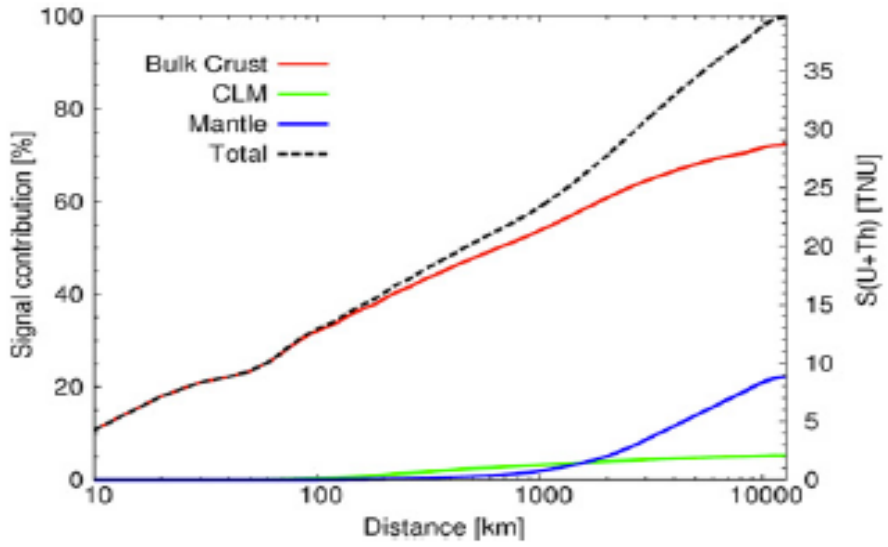
- ❑ Estimation **of radiogenic contribution to** the total **heat** power **of the Earth** (46±3 TW)
- ❑ Measuring **ν from ^{238}U and ^{232}Th** radioactive decay chains and testing **Th/U rate**

⬇

- •**Earth composition** (abundance of radioactve elements) ⟶ Earth's **models**
- • **Structure** of the **mantle** and nature of mantle **convection**
- • **Radioactive content** of the continental **crust** (Euranian plate)

- ❑ **JUNO advantages**: Size; Depth; Radiopurity.
- ❑ Signal:$\bar{\nu}_e$ IBD (E > 1.806 MeV); 1 year of JUNO (~300 – 500 geo-n events) > (KL+BX+ Sno+)





Strati et al., Progress in Earth and Planetary Science (2015) 2:5

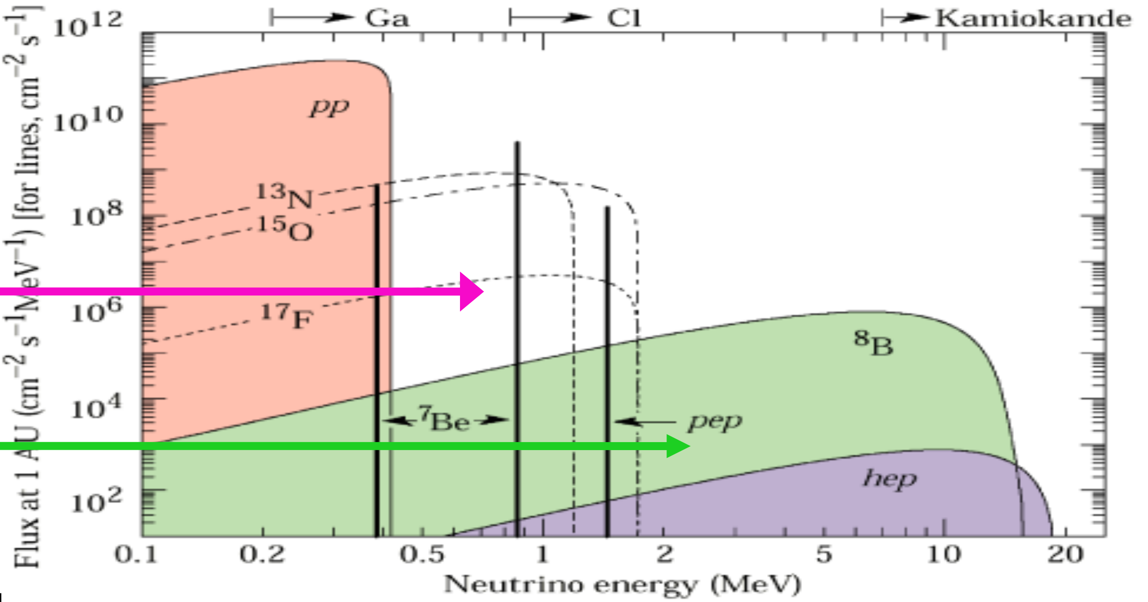
Solar neutrinos with JUNO

❑ **JUNO advantages:** LS high mass; E resolution ; Radiopurity

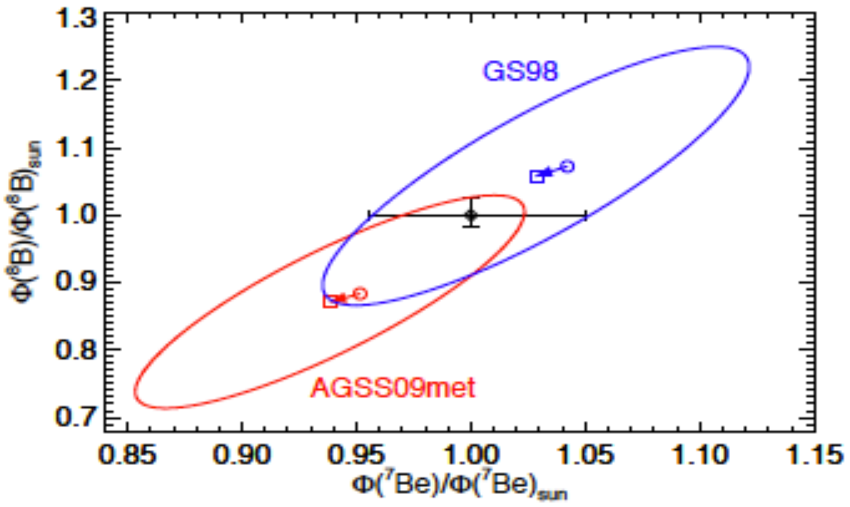
❑ ν_e elastic scattering ➡

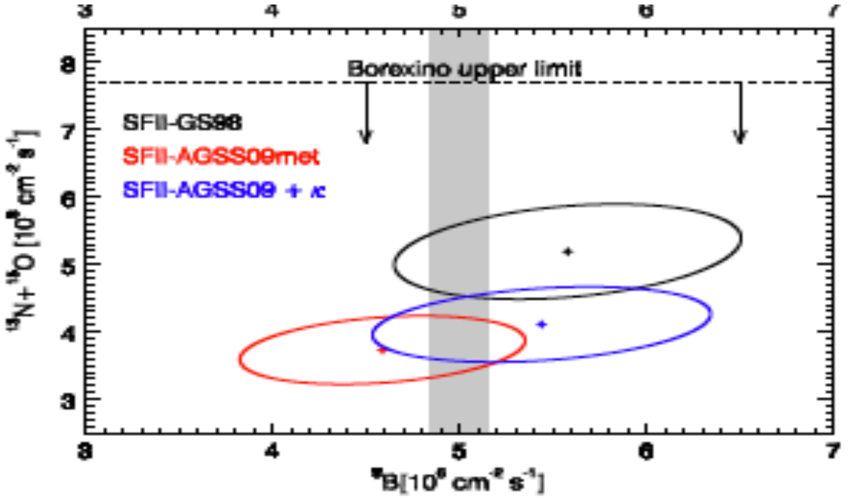
Study of part of the pp solar fusion chain

- **^{7}Be neutrinos:**
  sub-MeV part of spectrum
- **^{8}B neutrinos**
  Test of **MSW** oscillation **pattern.**

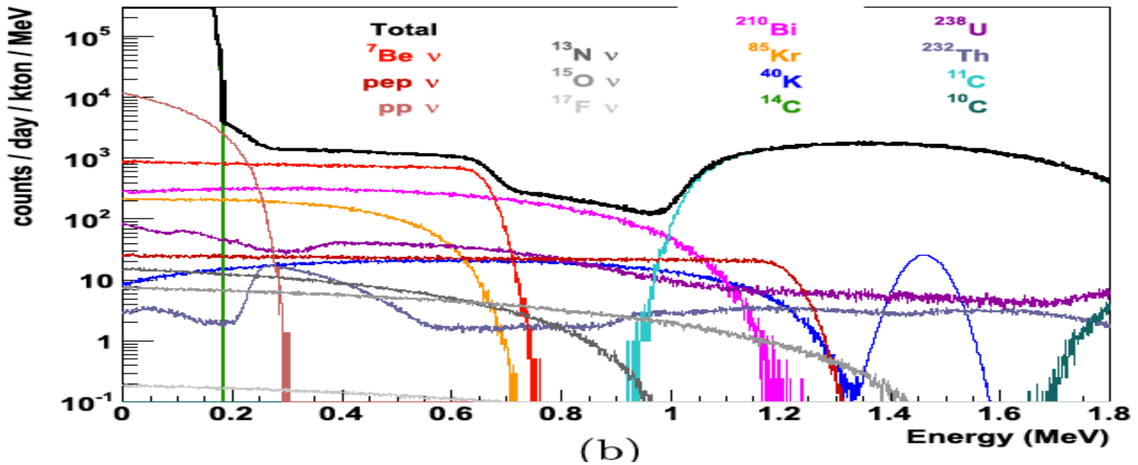


❑ Impact on **Solar Models**. Metallicity probem





^{7}Be neutrinos @JUNO



(b)

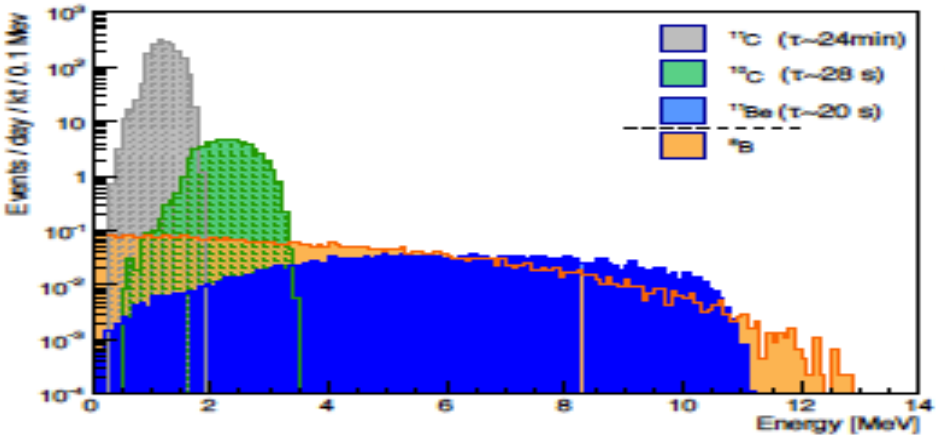
Expected spectra at JUNO for ideal radiopurity

- Required **high radiopurity** levels
- Main bckg: **^{210}Bi, ^{85}Kr**, ^{238}U, ^{40}K

^{8}B neutrinos @JUNO

❑ High p.e. yield ⟶ **low E threshold , Good E resolution.**

- Internal, external, reactor **bckg under control .**
- Main problem: long lived spallation radioisotopes. Most dangerous ^{11}Be



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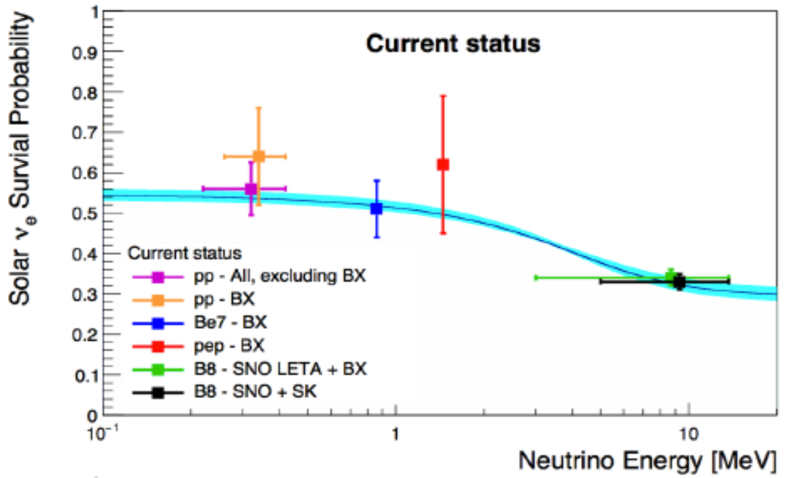


arXiv 1602.01733

❑ **MSW oscillation pattern**

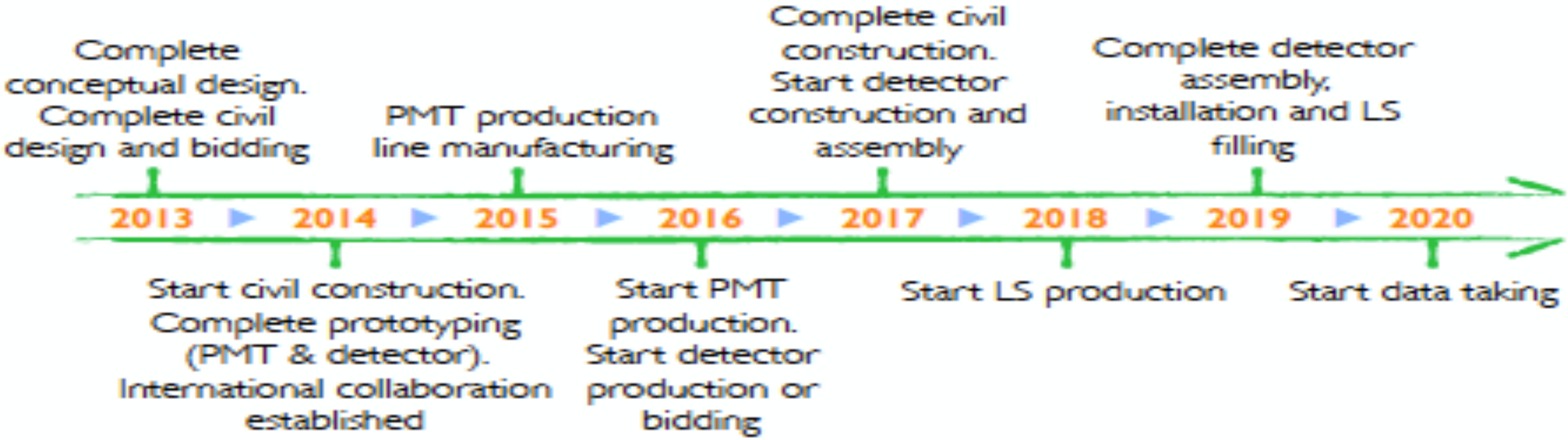
Search **for upturn in transition** between vacuum and matter enhanced **regions.**

JUNO progress and schedule

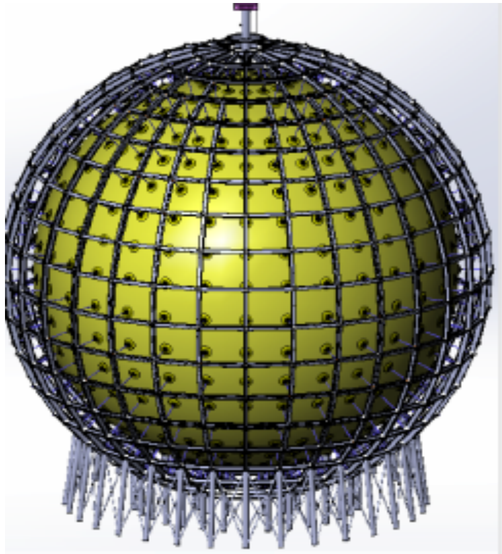
- ❑ Experimental **hall overburden: 720 m** (1900 mwe)

- ❑ Vertical shaft progress: 513 m out of 630 m

- ❑ Slope tunnel progress: 1055 m out of 1340 m



Juno central detector structure: acrylic sphere and stainless steel truss



- Acrylic thickness: 120 mm
- Acrylic panels: ~ 260 pieces
- Total weight: ~ 600 t of acrylic and ~ 600 t of steel

Forming panel size: 3m x 8m x 120mm

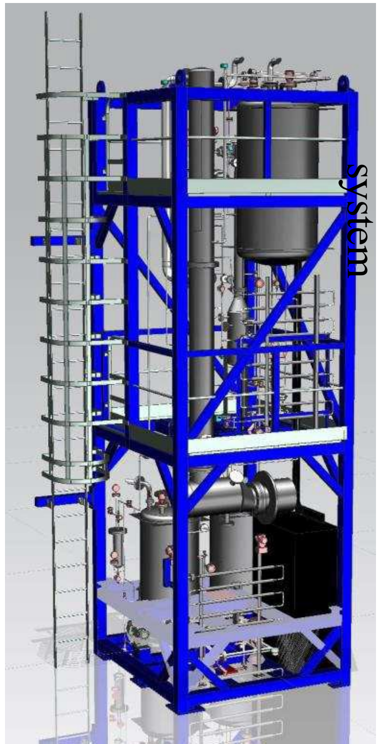
- The problems of shrinkage and shape variation were resolved.
- The radioactivity level of panels checked and under control.

Highlights: LS Pilot plant

- Purify 20 ton LAB to test the overall design of purification system at Daya Bay. Replace the target LS in one detector
- Quantify the effectivities of subsystems
  - ⇨ Optical : >20m A.L@430nm?
  - ⇨ Radio-purity: 10^{-15} g/g (U, Th) ?
- Determine the performances of sub-systems
  - ⇨ Al_2O_3 column, distillation, gas striping, water extraction

Distillation and steam stripping system

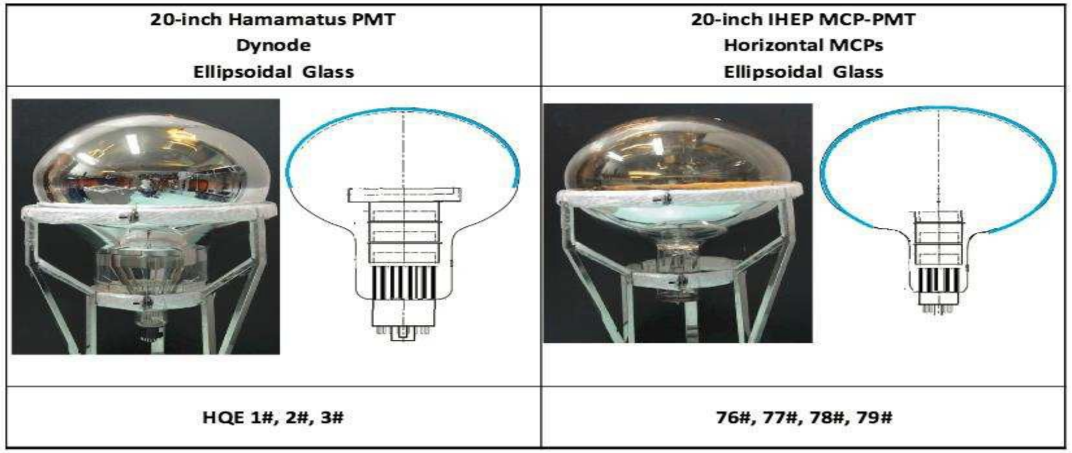
Installed at Daya Bay



Al_2O_3 column pilot plant installed in Daya Bay LS hall

Recent milestone: choice of PMT types

2 Large PMT producers selected: **North Night Vision Technology (NNVT)** and **Hamamatsu**



Characteristics	unit	MCP PMT (NNCV - IHEP)	R12860 (Hamamatsu)	Note
Electron Multiplier		Micro Channel Plate	Dynode	
Photocathode Mode		Reflection + Transmission	Transmission	
Quantum Efficiency (400nm)	%	26(T), 30 (T+R)	30 (T)	En Resolution
Relative Detection Efficiency	%	110	100	En Resolution
Single Photo-electron P/V		3+	3+	Reconstruction
Transient Time Spread	ns	12	3	Vertex
Rise Time / Fall Time	ns	R~2, F~10	R~7, F~17	
Anode Dark Count	Hz	~30 k	~30 k	Trigger
After Pulse Time Distribution	μs	4.5	4, 17	
After Pulse Rate	%	3	10	
Glass		Low-Potassium Glass	Hario-32	Background

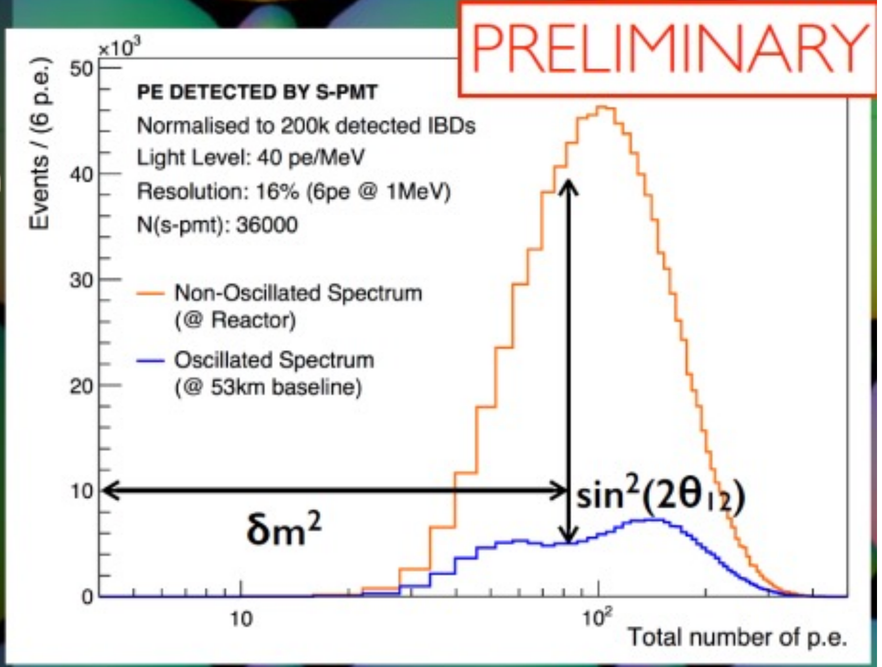
JUNO's Double Calorimetry System…

Additional readout system (36000 3" PMTs): 2 independent readouts embedded within same detector (systematics control)

- (high precision calorimetry for $\pm\Delta m^2$) response aid to 20" PMTs for non-stochastic systematics ($\lesssim$3% @ 1MeV)
- ($\theta_{12} \oplus \delta m^2$) internal redundancy oscillation parameter measurement: internal cross-check (<1% precision)
- (^{9}Li background) enhanced μ-tracking for cosmogenic ion production tagging/vetoing on C ($^{12}B/^{9}Li/^{8}He$)
- (supernova readout complementarity) double-readout to ensure unbiassed both energy and rate measurement
- (readout$\oplus$trigger complementarity) complementary time resolution, dynamic range & trigger (position) information → powerful event reconstruction

3" PMT

(several options)
- MELZ (RU)
- HZC (CH)
- ETL (UK)
- Hamamatsu(JP)



complementary (θ_{12},δm^2) measurement

Many other ongoing tasks

- Read out **electronics**
- Electronics, cable, box, etc.
- **Radioactivity measurements and screening**
- **Calibration**
- Slow control:
  PMT, water, environmental monitoring & control
- **DAQ**
- Offline farm, data storage/data center, software, …
- Development of MC and **analysis tools**
- Installation strategy
- **PMT testing**

Conclusions

- ❑ **MH determination**: important open issue of neutrino physics
  impact on **model building** and **experiments**.
- ❑ Possibility of **determining MH**, by studying **IBD of $\bar{\nu}_e$ with medium baselines**

The JUNO option

- ❑ **JUNO** experiment: main **features and potentialities**
- ❑ **Mass Hierarchy** determination at **JUNO**
- ❑ **SN neutrino** physics at JUNO
- ❑ **Geoneutrinos** at JUNO
- ❑ **Solar neutrinos** at JUNO (**^{7}Be** and **^{8}B** neutrinos)
- ❑ JUNO **schedule and progress**: excavation works, central detector, LS purification and testing, PMT (double calorimetry system), …

Backup slides

Mass hierarchy study at JUNO

- **Parameters:** m = 20 kt LS ; Thermal power = 36 GW ; Exposure time = 6 y (i.e. 2000 d)

Crucial point: energy resolution

$$\frac{\sigma_E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2} \cong \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{1.6\ b}{\sqrt{E}}\right)^2 + \left(\frac{c}{1.6\ \sqrt{E}}\right)^2}$$

Statistics (a term) — Non stochastic (b and c terms)

Requirement:

$$\frac{\sigma_E}{\sqrt{E}} \leq 3\% \quad \Longrightarrow \quad \sqrt{a^2 + (1.6\ b)^2 + \left(\frac{c}{1.6}\right)^2} \leq 3\%$$

Overall LAB5 view at Daya Bay

Values of the mixing parameters from global fits with 3 flavors

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \to 0.640$	$0.385 \to 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \to 53.1$	$38.4 \to 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \to 0.02408$	$0.01934 \to 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \to 8.93$	$7.99 \to 8.91$
$\delta_{CP}/^\circ$	261^{+51}_{-59}	$0 \to 360$	277^{+40}_{-46}	$145 \to 391$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix} +2.407 \to +2.643 \\ -2.629 \to -2.405 \end{bmatrix}$

Table 1. Three-flavor oscillation parameters from our fit to global data after the NOW 2016 and ICHEP-2016 conference. 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 $\Delta m^2_{3\ell} \equiv \Delta m^2_{31} > 0$ for NO and $\Delta m^2_{3\ell} \equiv \Delta m^2_{32} < 0$ for IO.

Taken from Esteban et al. **JHEP 1701 (2017) 087**

TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values for the mass-mixing parameters and associated $n\sigma$ ranges ($n = 1, 2, 3$), defined by $\chi^2 - \chi^2_{min} = n^2$ with respect to the separate minima in each mass ordering (NO, IO) and to the absolute minimum in any ordering. (Note that the fit to the δm^2 and $\sin^2\theta_{12}$ parameters is basically insensitive to the mass ordering.) We recall that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, and that δ is taken in the (cyclic) interval $\delta/\pi \in [0, 2]$.

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}\ \mathrm{eV}^2$	NO, IO, Any	7.37	7.21 – 7.54	7.07 – 7.73	6.93 – 7.96
$\sin^2\theta_{12}/10^{-1}$	NO, IO, Any	2.97	2.81 – 3.14	2.65 – 3.34	2.50 – 3.54
$\lvert\Delta m^2\rvert/10^{-3}\ \mathrm{eV}^2$	NO	2.525	2.495 – 2.567	2.454 – 2.606	2.411 – 2.646
	IO	2.505	2.473 – 2.539	2.430 – 2.582	2.390 – 2.624
	Any	2.525	2.495 – 2.567	2.454 – 2.606	2.411 – 2.646
$\sin^2\theta_{13}/10^{-2}$	NO	2.15	2.08 – 2.22	1.99 – 2.31	1.90 – 2.40
	IO	2.16	2.07 – 2.24	1.98 – 2.33	1.90 – 2.42
	Any	2.15	2.08 – 2.22	1.99 – 2.31	1.90 – 2.40
$\sin^2\theta_{23}/10^{-1}$	NO	4.25	4.10 – 4.46	3.95 – 4.70	3.81 – 6.15
	IO	5.89	4.17 – 4.48 ⊕ 5.67 – 6.05	3.99 – 4.83 ⊕ 5.33 – 6.21	3.84 – 6.36
	Any	4.25	4.10 – 4.46	3.95 – 4.70 ⊕ 5.75 – 6.00	3.81 – 6.26
δ/π	NO	1.38	1.18 – 1.61	1.00 – 1.90	0 – 0.17 ⊕ 0.76 – 2
	IO	1.31	1.12 – 1.62	0.92 – 1.88	0 – 0.15 ⊕ 0.69 – 2
	Any	1.38	1.18 – 1.61	1.00 – 1.90	0 – 0.17 ⊕ 0.76 – 2

Taken from F. Capozzi et al. **arXiv: 1703.04471[hep-ph]**

Results of the old (201 6) fit from the Bari group

Table 1: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. See also Fig. 1 for a graphical representation of the results. We recall that Δm^2 is defined as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH. The CP violating phase is taken in the (cyclic) interval $\delta/\pi \in [0, 2]$. The last row reports the (statistically insignificant) overall χ^2 difference between IH and NH.

Parameter	Hierarchy	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2	NH or IH	7.37	7.21 – 7.54	7.07 – 7.73	6.93 – 7.97
$\sin^2\theta_{12}/10^{-1}$	NH or IH	2.97	2.81 – 3.14	2.65 – 3.34	2.50 – 3.54
$\Delta m^2/10^{-3}$ eV^2	NH	2.50	2.46 – 2.54	2.41 – 2.58	2.37 – 2.63
$\Delta m^2/10^{-3}$ eV^2	IH	2.46	2.42 – 2.51	2.38 – 2.55	2.33 – 2.60
$\sin^2\theta_{13}/10^{-2}$	NH	2.14	2.05 – 2.25	1.95 – 2.36	1.85 – 2.46
$\sin^2\theta_{13}/10^{-2}$	IH	2.18	2.06 – 2.27	1.96 – 2.38	1.86 – 2.48
$\sin^2\theta_{23}/10^{-1}$	NH	4.37	4.17 – 4.70	3.97 – 5.63	3.79 – 6.16
$\sin^2\theta_{23}/10^{-1}$	IH	5.69	4.28 – 4.91 $\oplus$ 5.18 – 5.97	4.04 – 6.18	3.83 – 6.37
δ/π	NH	1.35	1.13 – 1.64	0.92 – 1.99	0 – 2
δ/π	IH	1.32	1.07 – 1.67	0.83 – 1.99	0 – 2
$\Delta\chi^2_{\text{I-N}}$	IH–NH	+0.98			

Taken from Capozzi et al, **NPB 00 (2016) 1**