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The neutrino mass ordering and the JUNO experiment

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Abstract

- The **neutrino mass eigenvalues ordering (Normal or Inverted Hierarchy)** is one of the main open issues of neutrino physics, with a significant **impact** both **on model building and on the potentialities of** present and future **experiments** (like the ones looking for neutrinoless double betha decays).
- A possibility of investigating this problem is offered by the **study of the mass hierarchy dependent corrections** in the antineutrino inverse β decays **in medium baseline reactor experiments**.
- This idea is at the basis of the research project of **JUNO**, a multipurpose underground **neutrino experiment,** that will soon become operative **in the South of China**. The JUNO main characteristic are discussed, together with its rich physics program and the status and perspectives of the experiment.

The neutrino mass hierarchy

- **From oscillation experiments**

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

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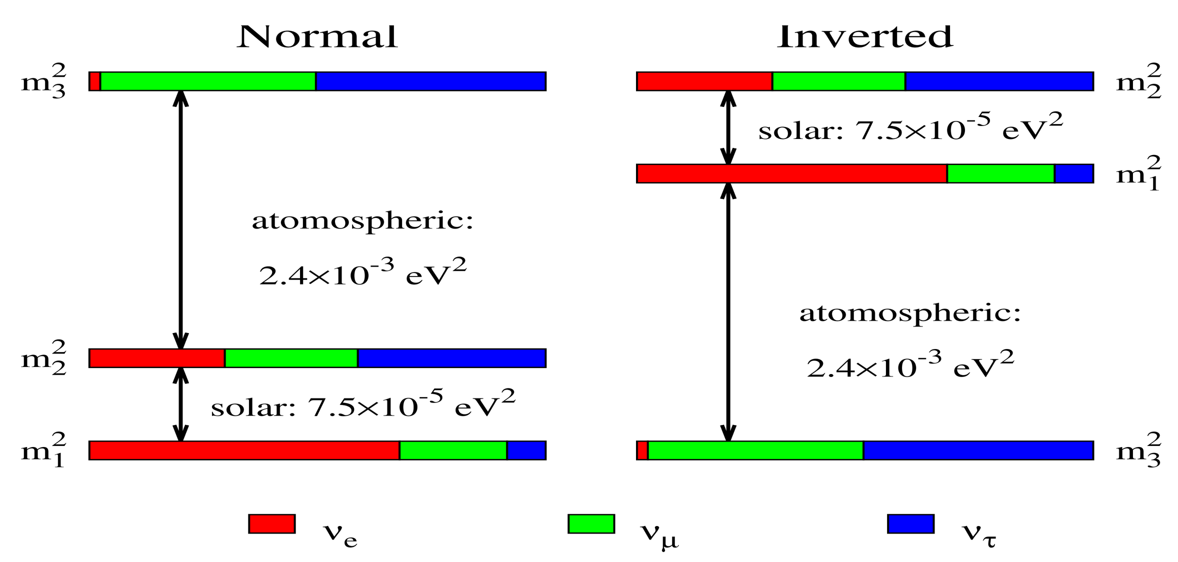
Differences of the squared mass eigenvalues ($\Delta m^2_{ij} = m_i^2 - m_j^2$)

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

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

- **Two possible scenarios**



Normal Hierarchy (NH): $|\Delta m^2_{31}| = |\Delta m^2_{32}| + \Delta m^2_{21}$, $|\Delta m^2_{31}| > |\Delta m^2_{32}|$

Inverted Hierarchy (IH): $|\Delta m^2_{31}| = |\Delta m^2_{32}| - \Delta m^2_{21}$, $|\Delta m^2_{31}| < |\Delta m^2_{32}|$

- **The neutrino mass hierarchy is important for:**
- ➢ **Discrimination** of different **models** Beyond Standard Model
- ➢ **Discovery potential** of **experiments** ($0\nu 2\beta$, CP violation)

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

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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

$\overline{\nu_e}$ survival probability ($\Delta m^2_{ij} = m_i^2 - m_j^2$)

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

The last **term** (**sensitive to** mass **hierarchy**), can be put as:

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

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

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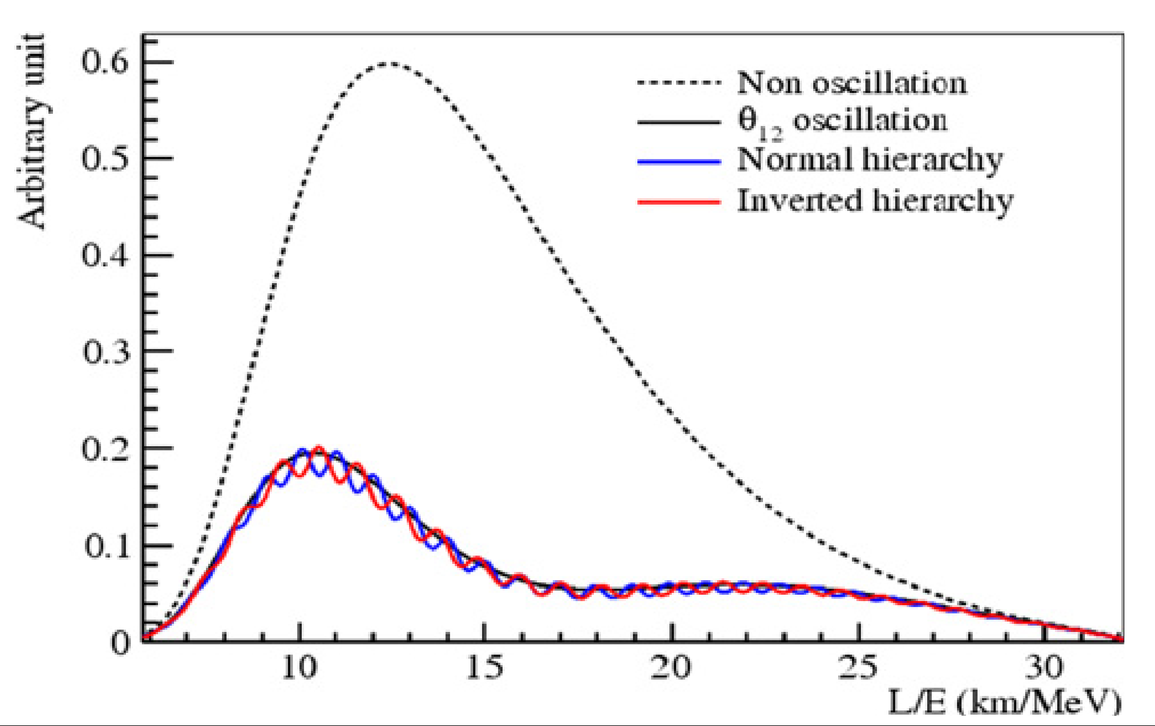
Fastly oscillating term, opposite for the 2 hierarchies, superimposed to the **general oscillation pattern**

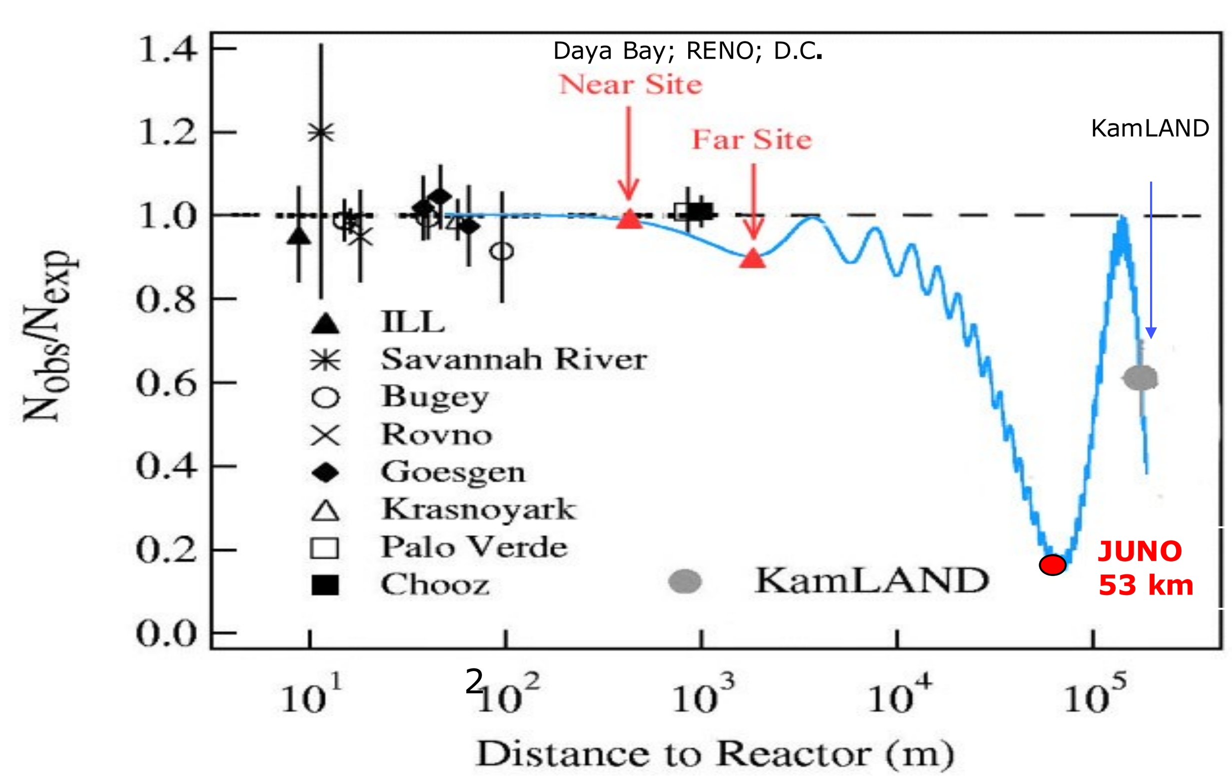
Spectrum dependence upon the mass hierarchy



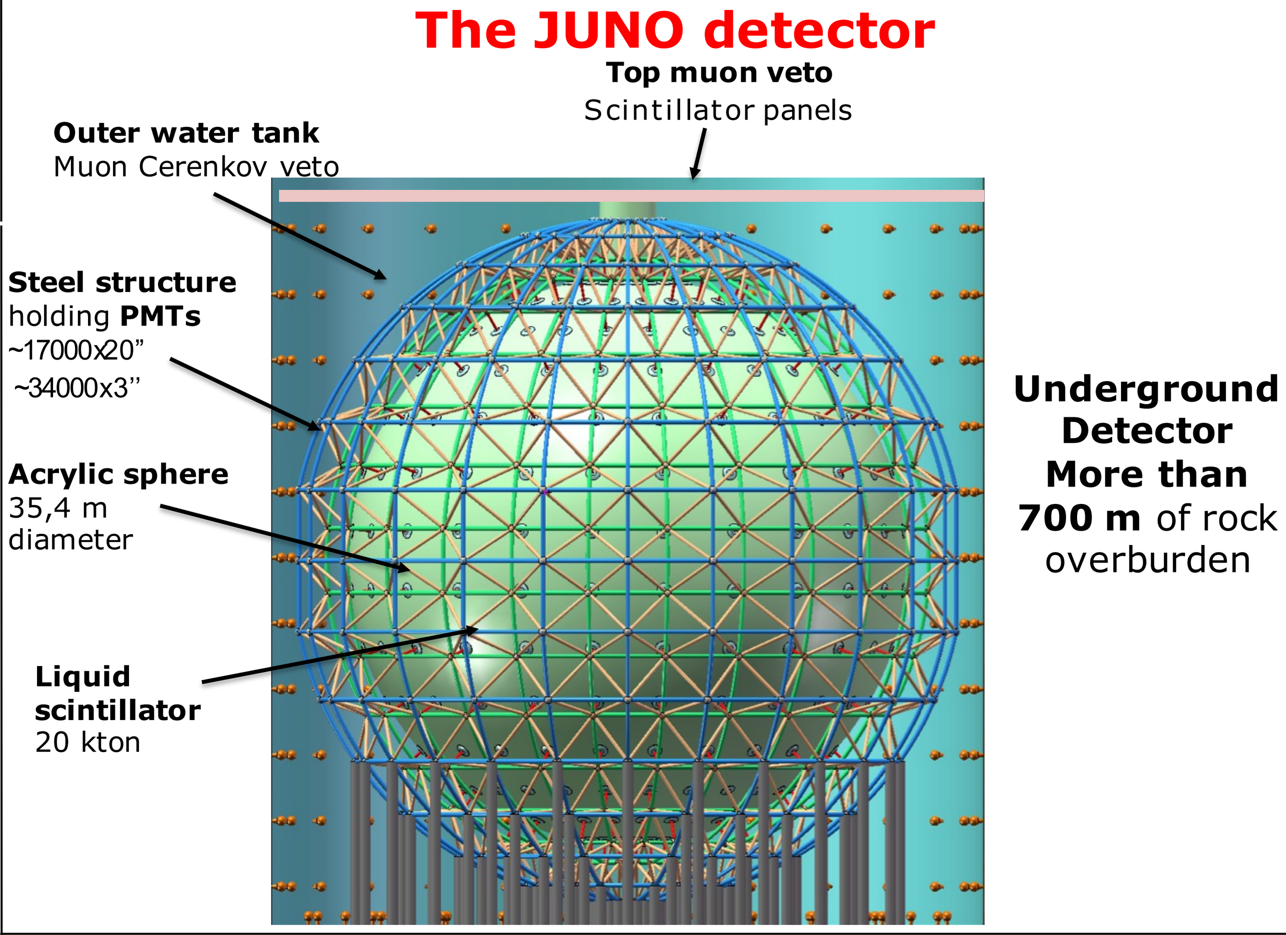
The JUNO option

JUNO (Jiangmen Underground Neutrino Observatory): **multi-purpose** reactor $\overline{\nu_e}$ **experiment,** under construction near Kaiping (South China). JUNO collaboration includes more than 70 instutions spread all over 3 continents.

Baseline reactors-detector about 53 km: **optimized in the region of the maximum 1-2 oscillation**



The JUNO detector

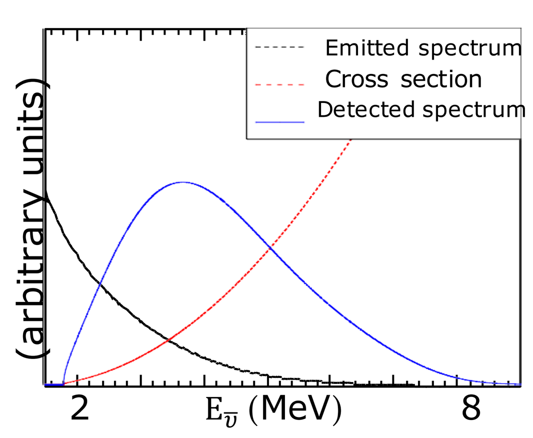


The JUNO experiment

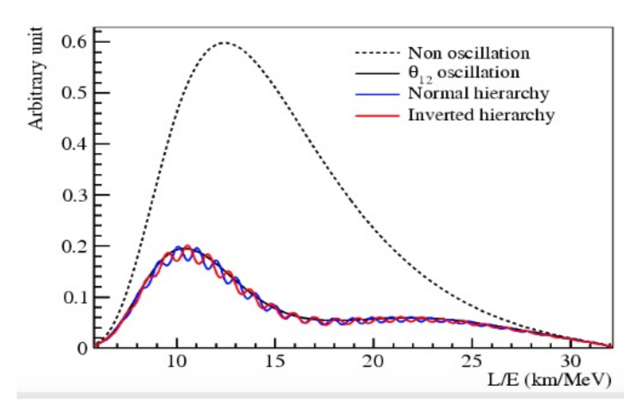
- Main reaction: $\overline{\nu_e} + p \rightarrow n + e^+$ $E_{\bar{\nu}} \geq 1.8$ MeV

Time coincidence between e^+ signal and 2.2 MeV γ emission from nuclear capture.

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



Spectrum including oscill. effects



JUNO main features

❖ Medium baseline (53 km); high statistics required

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Large detector mass and proximity to several reactors

❖ Signature: position of the spectral wiggles in the spectrum

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

Liquid scintillator (LAB+PPO+bis-MSB)

High photon yield

❖ Reduction of the cosmogenic background

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Rock overburden about 720 m and a muon veto system

Comparison with other experiments

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

❑ Milestones of the analysis

- **Global fit** and **comparison** of χ^2 best fit points **for NH and DH solutions**
- For E resolution equal or better than 3%/√E: **hierarchy discrimination at 3-4 σ C.L.**

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

❑ Main advantages

➢ JUNO looks at **vacuum oscillations;** hence it **doesn't sufffer** the **uncertainty** on **Earth density** profile **and** the ambiguity of **CP-violating phase**.

➢ Mass hierarchy solution **doesn't depend on θ_{13} value** (affecting only the amplitude of the corrections) **and** depend mildly **on the 3-4** neutrino **flavor** scheme.

Mass hierarchy determination at JUNO

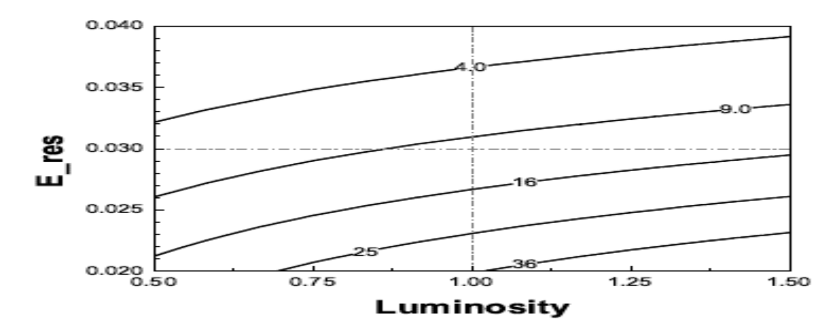
Mass hierarchy sensitivity is expressed in terms of:

$$\Delta\chi^2_{MH} = \left|\chi^2_{MIN}(NH) - \chi^2_{MIN}(IH)\right|; \quad \chi^2_{Reactor} = \sum_{i=1}^{N_{bins}} \frac{[M_i - T_i(1 + \sum_k \alpha_{ik}\varepsilon_k)]^2}{M_i} + \sum_k \frac{\varepsilon_k^2}{\sigma_k^2}$$

with: M_i=measured ν events in the bin; T_i =no oscillation predicted events; σ_k =systematic uncertainty; ε_k =pull factor; α_{ik} =fraction of event contribution of k^{th} pull to i^{th} bin

Results of the analysis

Iso-$\Delta\chi^2_{MH}$countour lines represent the $\Delta\chi^2_{MH}$ value as a function of luminosity (L=1 corresponds to n. of events after 6 years of JUNO data taking with nominal reactor $\overline{\nu_e}$flux and 80% efficiency) and of the resolution.



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 determination at JUNO

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

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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%

Other JUNO physics goals

In addition to the mass hierarchy discrimination and oscillation parameters determination, JUNO will look for:

❑ **Supernova** burst & diffuse supernova **neutrinos**

❑ **Geoneutrinos**

❑ **Solar** & atmospheric **neutrino** studies

❑ **Other measurements**:search for sterile υ and nucleon decays; indirect dark matter searches; other exotic searches

For more details about all of these topics **see the JUNO Yellow Book** (Phys. G: Nucl. Part. Phys. 43 (2016) 030401) **and the V. Antonelli talk at the recent Neutrino Telescopes** Workshop (Venice March 2017)

Progress and status of the experiment

- **Excavation works almost finished** (vertical shaft 513 out of 630 m and slope tunnel 1030 out of 1340 m)
- **Detector construction and assembly going on**:
- Central detector (huge and very thick acrylic sphere): problems of shrinkage and shape variations were resolved; radioactivity levels are under control;
- Various purification techniques successfully tested at a Liquid Scintillator Pilot Plant at Daya Bay;
- 2 different kinds of **20'' photomultipliers** (from Hamamatsu and from a Chinese company NNVT): **very good performances**, mainly for quantum and relative detection efficiency ⟹ very good E resolution;
- Presence of a double calorimetry systems, made up with small (3'') PMTs ⟹ systematics control, internal redundancuy and better osc. parameters determination.

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