New Frontiers in Theoretical Physics
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and GGI 10th anniversary

The determination of neutrino mass pattern and neutrino properties

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IN QUESTO EDIFICIO,
TRA IL GENNAIO DEL 1925
E L'AUTUNNO DEL 1926,
TENNE IL SUO STUDIO
ENRICO FERMI
E IN ESSO REALIZZÒ
IL LAVORO SULLA STATISTICA
CHE PORTA IL SUO NOME.
I FISICI FIORENTINI POSANO
QUESTA LAPIDE IN RICORDO
DELL' UOMO
E DELLA SUA STRAORDINARIA
OPERA.

Abstract

- Historical and theoretical relevance of the determination of neutrino mass and oscillation pattern.
- The situation after 2002
- The mass hierarchy: status and perspectives.
- New scenarios opened by the ‘‘relatively large’’ value of θ_{13} .
- Studying the mass hierarchy (MH) through the analysis of MH dependent corrections in the spectrum of inverse β decay for electronic reactor antineutrinos in intermediate baseline experiments .
- The JUNO experiments and its potentialities.

The neutrino mass: a bit of history

- The detemination of neutrino mass is a long standing problem.
- **In** the **Standard Model** there's **no** room for **neutrino mass term**.
- In 2002, the **solar** neutrino experiment **SNO** (Neutral and Charged Current) and the **LBL reactor** experiment **KamLAND** definitely solved the "solar neutrino puzzle", confirming the proofs, obtained by the previous solar and atmospheric (mainly **SuperKamiokande** in '98) experiments, that neutrinos are massive and oscillating particles and there are at least 3 different mass eigenvalues.
- **Two possibilities**: neutrino is a **Majorana fermion or** there is a right handed **sterile neutrino**.
- Models beyond the Standard Model (S.M.) can accomodate a neutrino mass term and the oscillation and **mass patterns** are **essential to discriminate between different extensions of the S.M.**.

Experiments investigating neutrino mass continue to have a great impact on elementary particle physics, astrophysics and cosmology.

The oscillation pattern

- **Mixing matrix U_{PMNS}** connecting the neutrino flavor and mass eigenstates can be decomposed in the product of 3 matrices (containing the 3 mixing angles and the possible Dirac phase δ_{CP} and of a matrix containing the eventual Majorana phases $\alpha_{1,2}$):

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

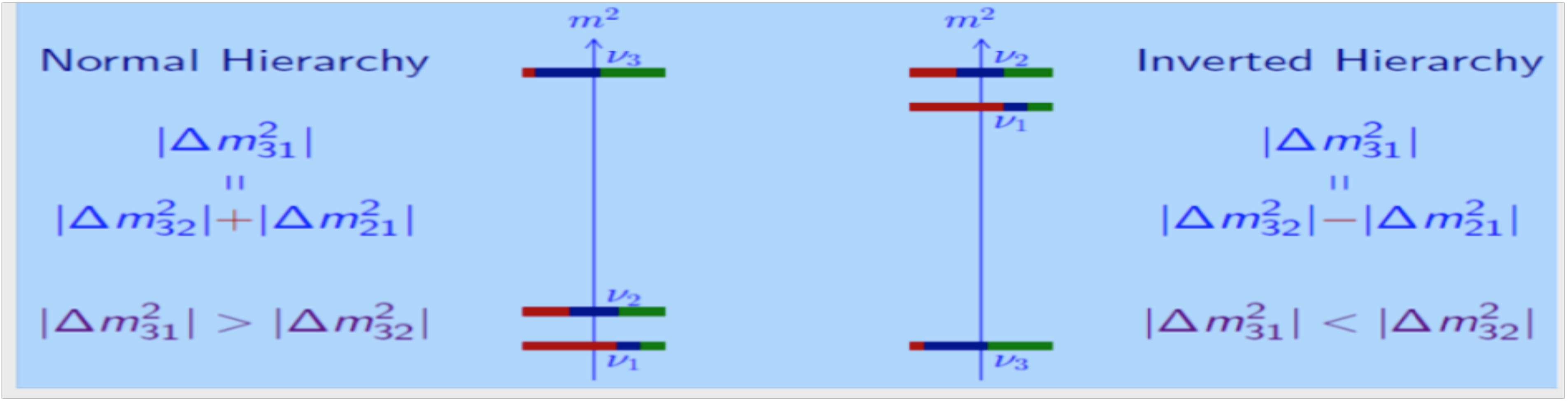
Neutrino mass and oscillation post 2002

- Main question in oscillation pattern after '02: **θ_{13} determination.**
- **In 2012** the results of **3 SBL** reactor antineutrino experiments (**Daya Bay**, **RENO** and **Double CHOOZ**) proved that **θ_{13} is ≠ 0 and "relatively large"** ($\sin^2(2\theta_{13}) \cong 0.085$) , confirming the hints coming from different LBL accelerator (**K2K** and mainly **T2K** and **MINOS**) and from global phenomenoligical fits.

This opened the way to the **possibility of** present and future experiments looking for **CP violation** in the leptonic sector (proportional to $\sin^2(\theta_{13})$) **and for the mass hierarchy determination.**

The mass hierarchy puzzle

- The ν **absolute mass scale and its** real **nature** (Majorana or Dirac) **still unknown** (results from the search for neutrinoless double β decays or the study of rare β decays end point or other future elementary particle or cosmological experiments), **but we know quite well the differences of the squared mass eigenvalues.**
- However, **2 different patterns for the mass eigenstates are still compatible** with the data, in the 3 flavor scheme: the **Normal Hierarchy (NH)** and the **Inverted Hierarchy (IH),**



Status of the mixing parameters

From a global 3 flavor analysis (including solar, atmospheric, reactor and accelerator neutrino experiments and with the addition of IceCube, Deep Core)
(taken from F. Capozzi, E. Lisi, Marrone, Montanino, Palazzo, **NPB 00** (2016), 1.)

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 ⊕ 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			

$\delta m^2 = m_2^2 - m_1^2$; $\Delta m^2 = m_3^2 - \frac{1}{2}(m_1^2 + m_2^2)$ with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH

The mass hierarchy

- **Mass hierarchy determination** essential for:
- discrimination between different S.M. extensions;
- estimation of the discovery potential of future experiments, like $0\nu2\beta$ decays.
- The "**relatively large**" value of θ_{13} makes possible the **study** of the **mass hierarchy**, by investigating the corrections to the **oscillation probability depending on** the sign of the **MH**, which are proportional to $\sin^2(2\theta_{13})$.
- Possibility of performing this study by looking at the spectrum of inverse β decay for electronic reactor antineutrinos in intermediate baseline experiments.

Idea originally proposed by Choubey, Petcov, Piai (Phys.Rev. D68 (2003) 113006) .

The status of mass hierarchy determination

- **Present data, mainly from** the LBL accelerator experiment **NOνA, seem to favor the Normal Hierarchy (NH) solution.**

– NOνA (August 2015): evidence of ν_e appearance and analysis of this channel, compared with the ν_μ disappearance study. In the analysis the significance on MH has been computed separately for NH and IH taking the "distance" from solution corresponding to the reactor measurements of θ_{13}.

The inverted hierarchy solution is disfavored at ≈ 3 σ in the range $0 < \delta_{CP} < 0.9\,\pi$.

- **In next** 6 **years** a significant **increase in NOνA exposure** (about 13 times larger) is foreseen.
- However, the **NH preference would dissapear in presence of a sterile neutrino** at ≈ 1 eV scale in the 3+1 flavor scheme.

The future of mass hierarchy studies

- In the near future:
- inputs from future LBL accelerator data (T2K and NOνA)
- new analyses of atmospheric data (SK)
- future global fits

- However, **the final answer will probably come by future dedicated experiments,** with neutrinos from :
  - reactors (JUNO, RENO50)
  - LBL accelerators (DUNE)
  - atmsopheric (PINGU and ORCA) .

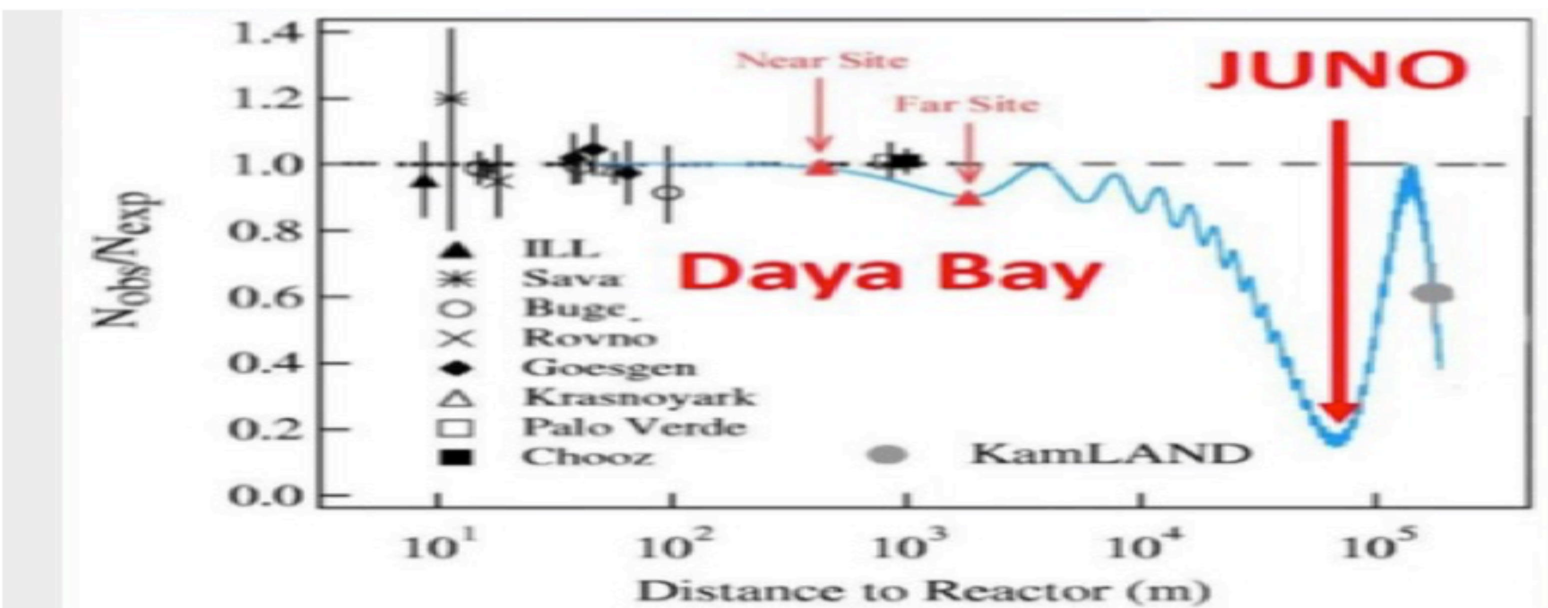
Here we focus the attention on JUNO experiment that should start data taking in 2020.

The JUNO experiment

- **JUNO** (Jiangmen Underground Neutrino Observatory): **multipurpose neutrino reactor experiment,** under construction close to Kaiping, in the South of China.
- Detector: **huge (20 kt) liquid scintillator** (Linear Alkyl-Benzene), **underground**, with over 700 m overburden

- **Reactor antineutrinos**: mainly from 2 different nuclear power plants, with a total of 10 cores (in the original project).

- Average distance reactor-detector ≈ 53 km; medium **baseline optimized to be region of maximum of oscillation in 2-1 sector.**



JUNO main goals

For more details see the JUNO Yellow Book (F. An, G. An, Qi An, V. Antonelli et al. [JUNO collaboration], J.Phys. G43 (2016) no.3, 030401)

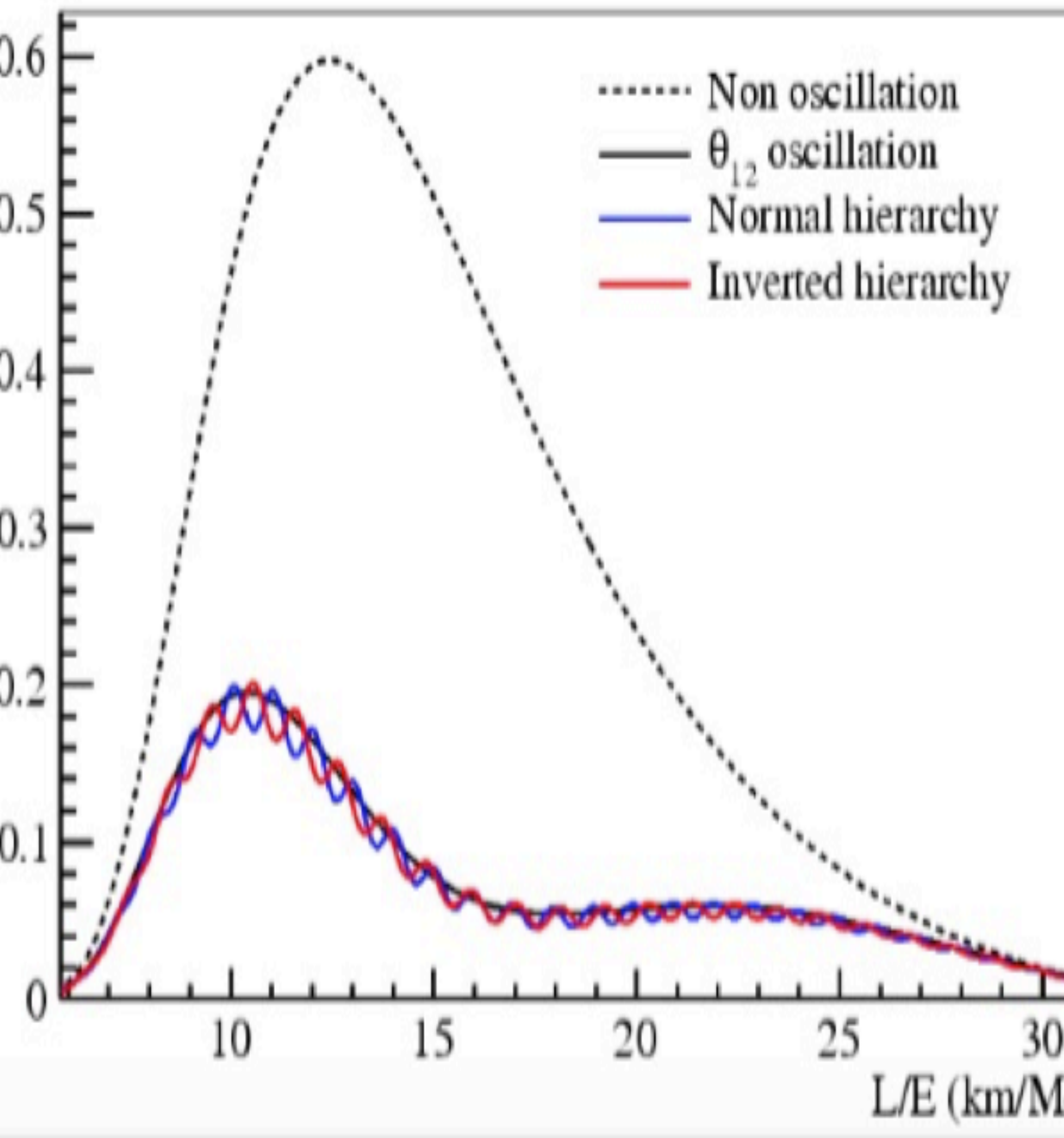
- **Main goal: determination of mass hierarchy,** but also other important measurements:

- 1%, or subpercent, level measurement of some **mass and mixing** oscillation parameters.

	Current accuracy	**JUNO potentiality**
Δm^2_{12}	4%	0.6%
$\vert\Delta m^2_{23}\vert$	5%	0.6%
$\sin^2\theta_{12}$	5%	0.7%

- **Geoneutrinos** and neutrinos from extraterrestrial sources (**Supernovae and solar neutrinos**)

Studying the mass hierarchy with JUNO



- **Region** (E ≅ few MeV; baselines≈50km) of **maximum sensitivity to the higher order corrections** to the oscillation parameters **depending upon the mass hierarchy.**

The mass hierarchy determination at JUNO

- **Electronic antineutrino survival probability**, can be written

$$P_{ee} = 1 - (c_{13})^4 \sin^2(2\theta_{12}) \times \sin^2[(\Delta m_{21}^2 \times L)/(4E)] - \sin^2(2\theta_{13}) \times \sin^2(\Delta_{ee})$$

$$\sin^2(\Delta_{ee}) = (c_{12})^2 \times \sin^2[(\Delta m_{31}^2 \times L)/(4E)] + (s_{12})^2 \times \sin^2[(\Delta m_{32}^2 \times L)/(4E)],$$

where: $c_{ij} = \cos(\theta_{ij})$; $s_{ij} = \sin(\theta_{ij})$; $\Delta m_{ij}^2 = m_i^2 - m_j^2$

- **Last term**, **sensitive to the mass hierarchy**, can be rewritten in the form:

$$\tfrac{1}{2} \times \sin^2(2\theta_{13}) \{1 - [1 - \sin^2(2\theta_{12}) \times \sin^2(\Delta_{21})]^{1/2} \cos(2|\Delta_{ee}| \pm \phi)\},$$

where: $\Delta_{ij} = (m^2_{ij} \times L)/(4E)$; $\Delta m^2_{ee} = (\cos^2\theta_{12} \times \Delta m_{31}^2 + \sin^2\theta_{12} \times \Delta m_{32}^2)$

and the angle ϕ defined so that $\sin(\phi)$ and $\cos(\phi)$ denote combinations of mass and mixing parameters of the sector 1-2 (θ_{12} and Δ_{21}).

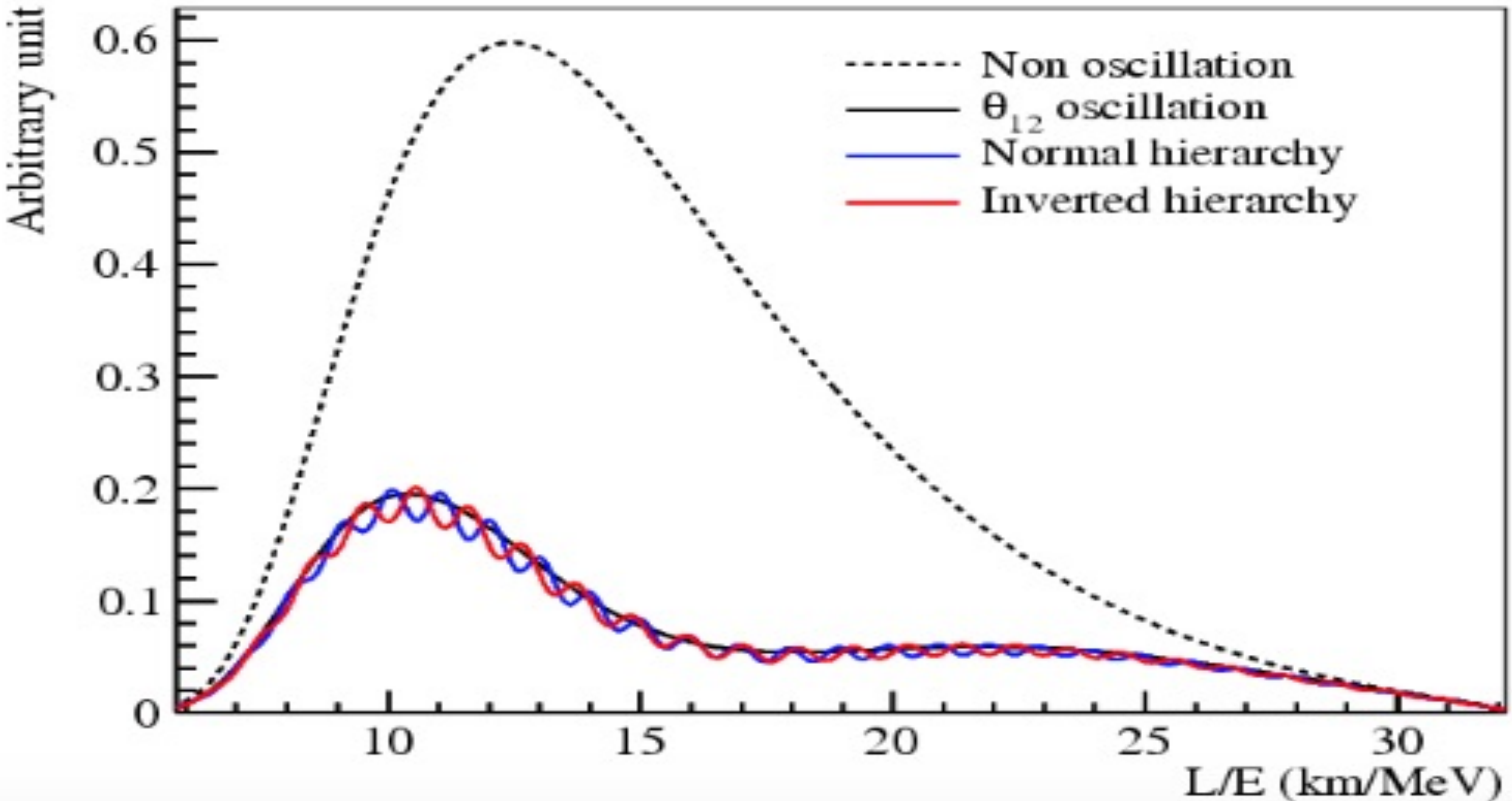
Sign in front of ϕ, changes according to the **mass hierarchy**:

+1 for **NH** and **-1** in case of **IH**.

Fastly oscillating term, superimposed to the general oscillation pattern, **leads to a contribution of opposite sign in the 2 cases of NH and IH.**

Spectrum dependence upon the Mass Hierarchy

Fastly oscillating term, superimposed to general oscillation pattern, leads to a contribution of opposite sign in the 2 cases of NH and IH. Number of detected events depend upon the mass hierarchy (in addition to the mass and oscillation parameters).



Milestones of the analysis

- **By fitting the data** as function of oscillation parameters (including other ν experiments) **and comparing χ^2** obtained for the best fit points in normal and inverted hierarchy cases, possible to **discriminate between the 2 hierarchies.**
- **Crucial points:**

very big **detector sensitive mass and** very good **energy resolution**.

- If resolution is not enough a solution with the wrong mass hierarchy is indistinguishable from the right hierarchy solution.

For energy resolution equal or better than 3%/√E, it should be possible to discriminate the 2 hierarchies at 3-4 σ C.L. (See the JUNO Yellow Book: An

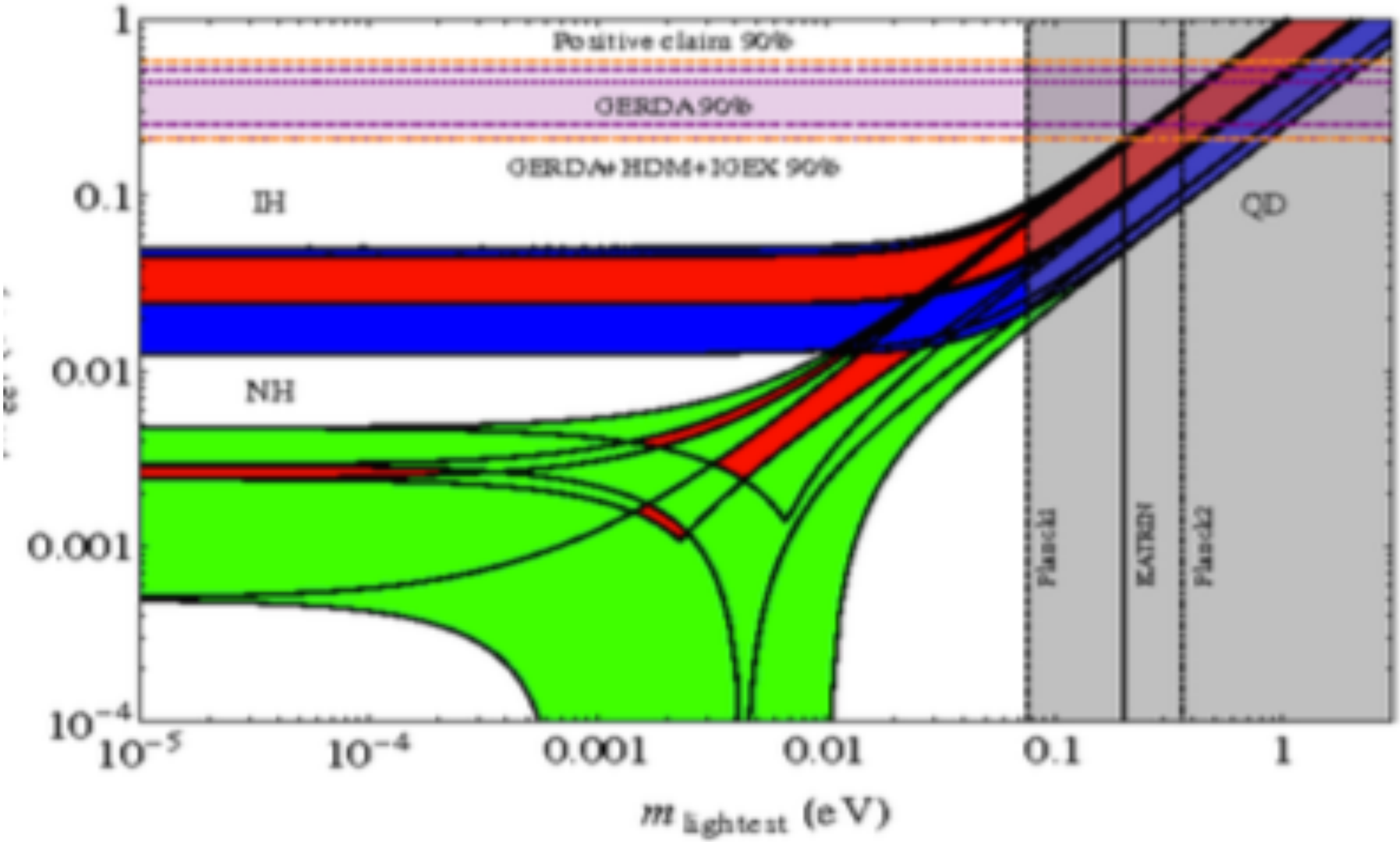
- Differently from LBL ν experiments looking for MH , **JUNO and RENO50** look at vacuum (instead of matter induced) oscillations and, therefore, they **don't sufffer** from the **uncertainty** on Earth density profile and the ambiguity of the CP-violating phase. **Moreover they do not depend on the value of θ_{13}** (which affects only the amplitude of the corrections they are looking for) **and depend only mildly on the 3-4 flavor pattern**.

Conclusions

- The neutrino mass pattern is still an open problem.
- From the oscillation experiments one gets the $\Delta m^2 = m_i^2 - m_j^2$, but two different hierarchies (the direct and the inverse one) are still compatible with the data
- Determination of the right hierarchy is an important issue, not only for neutrino physics and model building, but also for all elementary particle physics and astrophysics.
- Main recent results in this field have been discussed, together with the most significant aspects of the theoretical analysis and the future perspectives.
- Possibility of studying mass hierarchies by means of future reactor antineutrino experiments with intermediate baselines
- Discussion on the potentiality of the JUNO experiment, that will start the data taking in very few years from now.

Backup slides

Impact of the mass hierarchy on the sensitivity of 0ν2β decay experiments



Appearance experiments

- From 2002 to 2012, both **LBL accelerator** ν (K2K, T2K and MINOS) and **SBL reactor anti-ν** (Daya Bay, Double CHOOZ and RENO) experiments, together with global phenomenological fits, proved that θ_{13} is **different from 0.**
- Starting with the CERN-Gran Sasso (**CNGS**) **beam,** a **series of appearance signals** confirmed directly the flavor oscillation using neutrinos by artificial sources (accelerators and reactors).

- **OPERA** ('08 - '12): 5 candidate ν_τ events in ν_μ beam, corresponding to a significance of oscillation and ν_τ appearance larger than 5 σ .

- **T2K**: ν_e appearance in a high intensity ν_μ beam (produced at J-PARC and studied at SuperK (L=295 Km)); 7.3 σ significance. Similar results by **MINOS** (735 km LBL, studying ν_μ and anti-$\nu\mu$ from Fermilab NuMI beamline).

T2K Foreseen exposure, in the next 5 years, 20 times larger than the present one: superbeam. Antineutrino channel under investigation.

- Since 2014: **NOνA** (superbeam in USA; L ≈ 810 km) studying ν_μ –> ν_e and antineutrino channel

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$$- \sin^2(2\theta_{13}) \times \{(c_{12})^2 \times \sin^2[(\Delta m_{31}^2 \times L)/(4E)] + (s_{12})^2 \times \sin^2[(\Delta m_{32}^2 \times L)/(4E)]\},$$

where: $c_{ij} = \cos(\theta_{ij})$; $s_{ij} = \sin(\theta_{ij})$; $\Delta m_{ij}^2 = m_i^2 - m_j^2$

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