Neutrino physics:

questions for the future

The main areas of research in Neutrino Physics are:

1. PHENOMENOLOGY: determining neutrino parameters (m_i, θ_i, δ, α_{ij}, N_ν, nature), by analysing the available data and the capabilities of different experimental setups.

2. THEORY: explaining the origin of neutrino masses and of the flavour structure, by considering see-saw models and alternative mechanisms of neutrino mass generation.

3. COSMOLOGY/ASTROPHYSICS: linking Neutrino Physics to Cosmology and Astrophysics in the Early Universe and in astrophysical objects as supernovae.

1 – Questions for the future in PHENOMENOLOGY

What are the fundamental questions for the present and the future?

1. Nature of neutrinos: Majorana vs Dirac?

2. Number of neutrinos: Are there sterile neutrinos?

3. Neutrino masses: NH, IH or QD?

4. CP-violation: $\delta \neq 0, \pi$ and/or $\alpha_{ij} \neq 0, \pi$?

   P.S. For being sensitive to CP violation (δ) and to matter effects in LBL or atmospheric neutrinos we need also to have a sizable $\sin^2\theta_{13}$.

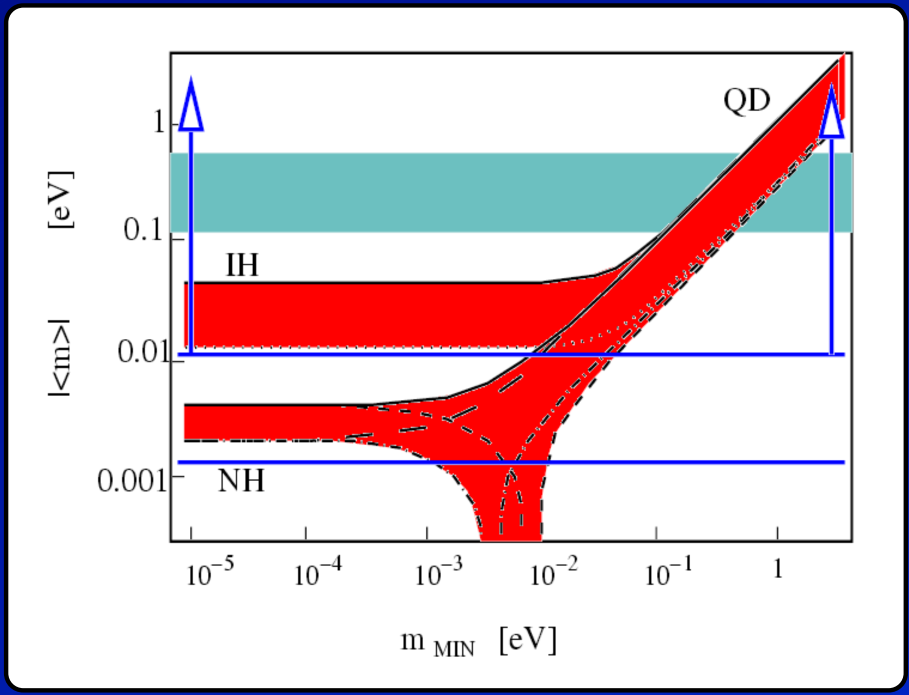
QUESTION 1: Nature of neutrinos.

Neutrino can be either

Dirac	or	Majorana
lepton number conserved		lepton number broken

- The **nature of neutrinos** is directly related to the **fundamental symmetries** of elementary particles interactions.
- It provides important information on the **origin of neutrino masses**: in the see-saw mechanism neutrinos are predicted to be Majorana particles.
- Lepton number violation is one of the key ingredients of **leptogenesis** as the mechanism for generating the baryon asymmetry of the Universe.

Neutrino oscillations are not sensitive to the nature of neutrinos. Processes which violate the lepton number by two units are required. The most sensitive of all is $(\beta\beta)_{0\nu}$-**decay** ($(A,Z) \to (A,Z+2) + 2e^-$).



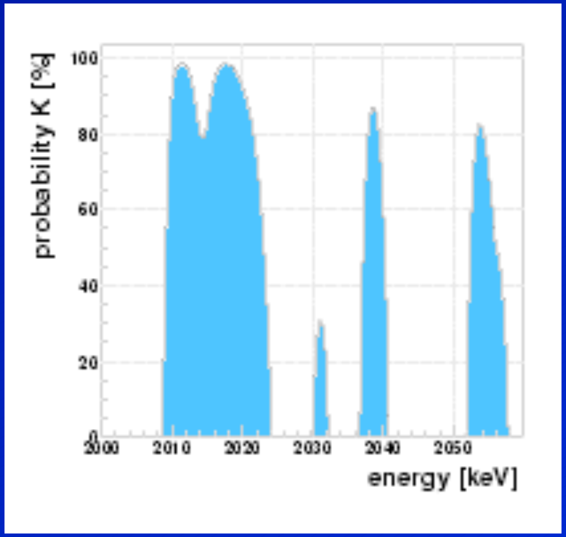
[S.T. Petcov, A. Yu. Smirnov, PLB 322 (1994) 109; S.M. Bilenky, S. P., S.T. Petcov, PRD 64 (2001) 053010; S.P., S.T. Petcov PLB 544 (2002) 239 and 580 (2004) 280; S.P., S.T. Petcov, T. Schwetz, in pub in PLB]

The present best limit on $|<m>|$ reads:

$|<m>| \; < (350 - 1050)$ meV	**Heidelberg-Moscow**
$|<m>| \; < (680 - 2800)$ meV	**NEMO3**
$|<m>| \; < (200 - 1050)$ meV	**CUORICINO**

Recently a claim of $(\beta\beta)_{0\nu}$decay discovery has been published [Klapdor-Kleingrothaus et al., PLB 586 (2004) 198]. It implies

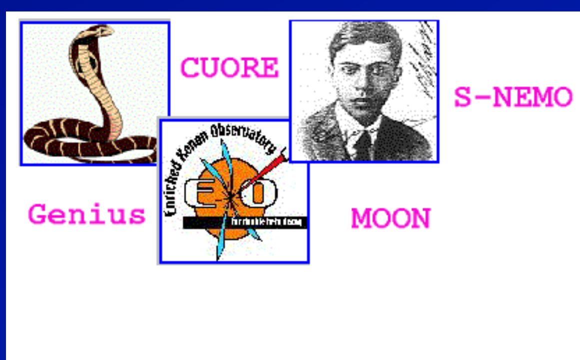
$$|<m>| \; \simeq 200 - 600 \text{ meV}$$



It is still a controversial even if very interesting result.

There are prospects to improve the present limit and test the discovery claim down to $|\langle m \rangle| \sim 200 - 300\,\mathrm{meV}$ in the present experiments NEMO3 and Cuoricino

and by one order of magnitude, $|\langle m \rangle| \sim 10 - 30\,\mathrm{meV}$, in the new generation of experiments which is now under R&D and construction (CUORE, GENIUS, Majorana, SuperNEMO, EXO, GERDA, COBRA).



All the allowed values for $|<m>|$

in the IH and QD spectra

are in the range of sensitivity

of present and/or upcoming $(\beta\beta)_{0\nu}$-decay experiments.

A positive signal in present or future exp would imply that

- the lepton number is not a conserved symmetry in nature,
- neutrinos are Majorana particles,

and it could give important information

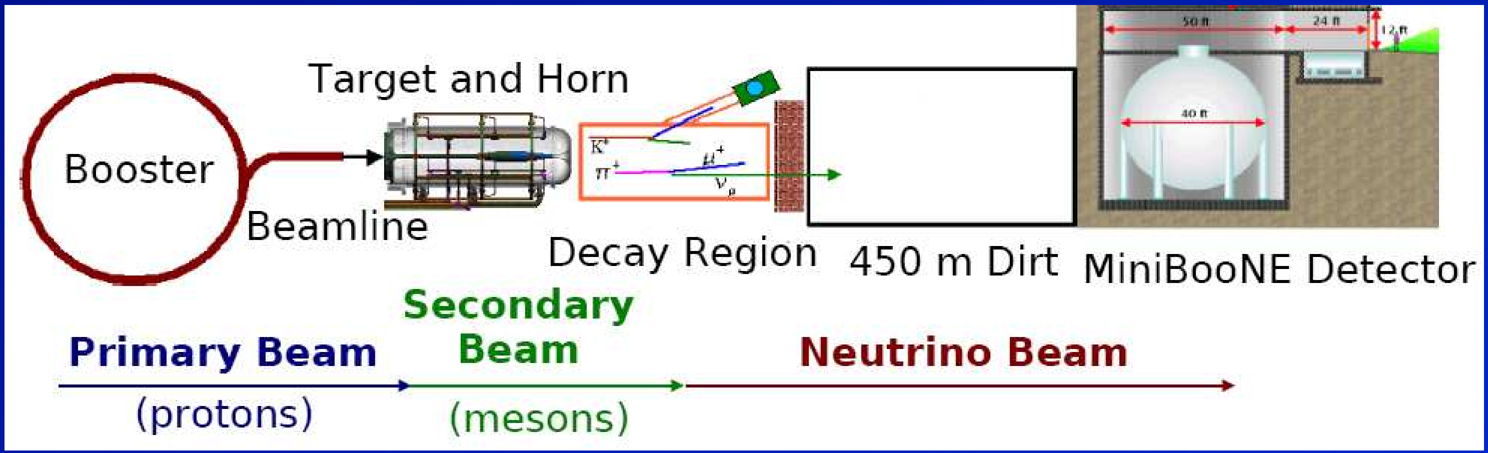
- on the neutrino mass spectrum
- and on the Majorana CP-V phases.

[S.P., S.T. Petcov, T. Schwetz, PLB]

QUESTION 2: Number of neutrinos.

The LSND signal requires the existence of sterile neutrinos and maybe new interactions.

It is currently checked by the **MiniBOONE** exp.



[http://www-boone.fnal.gov]

Results are expected soon (maybe). Stay tuned!!!!.

QUESTION 3: Neutrino masses.

m_1, m_2, m_3.

As we know only $\Delta m^2_\odot$ and $\Delta m^2_{\rm A}$, we need:

- the absolute mass scale ($m_{\rm MIN}$).
- the type of hierarchy ($sgn(\Delta m^2_{31})$).

Knowing the type of spectrum (NH, IH, QD) is crucial for understanding the origin of neutrino masses in the context of models Beyond the Standard Model.

Absolute mass scale

- Direct mass searches in **tritium beta decay** experiments. The present limit is $m_0 < 2.2$ eV (Troiztk and Mainz). KATRIN can reach a sensitivity to $m_0 \sim 0.2$ eV, covering all the QD spectrum.
- Cosmological observations. Exploiting the effects of massive neutrinos on structure formation in the Early Universe it is possible to constrain the sum of neutrino masses. Dependence on other parameters and degeneracies. Prospects for $\Sigma \sim 0.1$ eV.

Type of hierarchy

- $(\beta\beta)_{0\nu}$decay: it can distinguish between different types of spectra (NH, IH, QD). The role of $\sin^2\theta_{13}$ is subdominant.

- atmospheric neutrino experiments: exploiting matter effects in magnetized or not detectors (Hyper-Kamiokande, INO).

- long baseline neutrino oscillation experiments exploiting matter effects. It depends crucially on the value of $\sin^2\theta_{13}$. Degeneracies arise with the CP-violating phase δ.

For $\Delta m^2 > 0$, mixing gets enhanced for neutrinos and suppressed for antineutrinos.
For $\Delta m^2 < 0$, the opposite happens.

QUESTION 4: CP-violation.

If U is complex we have CP-violation:

$$P(\nu_l \to \nu_{l'}) - P(\bar{\nu}_l \to \bar{\nu}_{l'})$$
$$= \frac{1}{2} \cos\theta_{13} \sin(2\theta_{12}) \sin(2\theta_{23}) \sin(2\theta_{13}) \sin\delta$$
$$\left(\sin\frac{\Delta m^2_{12} L}{2E} + \sin\frac{\Delta m^2_{23} L}{2E} + \sin\frac{\Delta m^2_{31} L}{2E} \right)$$

- Establishing leptonic CP-V is a fundamental and challenging task.
- There are:

1 Dirac phase (measurable in long base-line experiments)

and 2 Majorana phases (one might be determined in neutrinoless double beta decay).

Determining CP-V and the type of hierarchy in LBL exp

The CP-asymmetry and the type of hierarchy will be searched for in future long base-line experiments, looking for $\nu_\mu \longrightarrow \nu_e (\bar{\nu}_\mu \longrightarrow \bar{\nu}_e)$.

These oscillations take place in matter (Earth) which implies that

$$\boxed{P(\nu_l \rightarrow \nu_{l'}) \neq P(\bar{\nu}_l \rightarrow \bar{\nu}_{l'})}$$

If U is complex we have CP-violation:

$$\boxed{P(\nu_l \rightarrow \nu_{l'}) \neq P(\bar{\nu}_l \rightarrow \bar{\nu}_{l'})}$$

There are degenerate solutions:

$$\left.\begin{array}{l} \Delta m^2_{31}\ ,\ \theta_{13}\ ,\ \delta\ ,\ \theta_{23} \\ \Delta m^2_{31}{}',\ \theta_{13}',\ \delta',\ \theta_{23}' \end{array}\right\} \longrightarrow P, \bar{P}$$

In the range of energies ($E \sim 0.5 \div 4$ GeV) and length ($L \sim 200 \div 1000$ Km), of interest, the oscillation probability for $\nu_\mu \to \nu_e$, in 3-neutrino mixing case, is given by:

$$P(\bar{P}) \simeq \quad s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{A \mp \Delta_{13}}\right)^2 \sin^2 \frac{(A \mp \Delta_{13})L}{2}$$
$$+\tilde{J} \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{A \mp \Delta_{13}} \sin \frac{AL}{2} \sin \frac{(A \mp \Delta_{13})L}{2} \cos\left(\mp\delta + \frac{\Delta_{13} L}{2}\right)$$
$$+c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2 \frac{AL}{2}$$

with $\tilde{J} \equiv c_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12}$ and $\Delta_{13} \equiv \Delta m_{31}^2/(2E)$.
$A \equiv \sqrt{2} G_F \bar{n}_e$.

In the vacuum case, for simplicity, we identify 2-, 4- and 8- fold degeneracies [Barger, Marfatia, Whisnant]:

- (θ_{13}, δ) degeneracy [Koike, Ota, Sato; Burguet-Castell et al.] :

$$\delta' = \pi - \delta$$

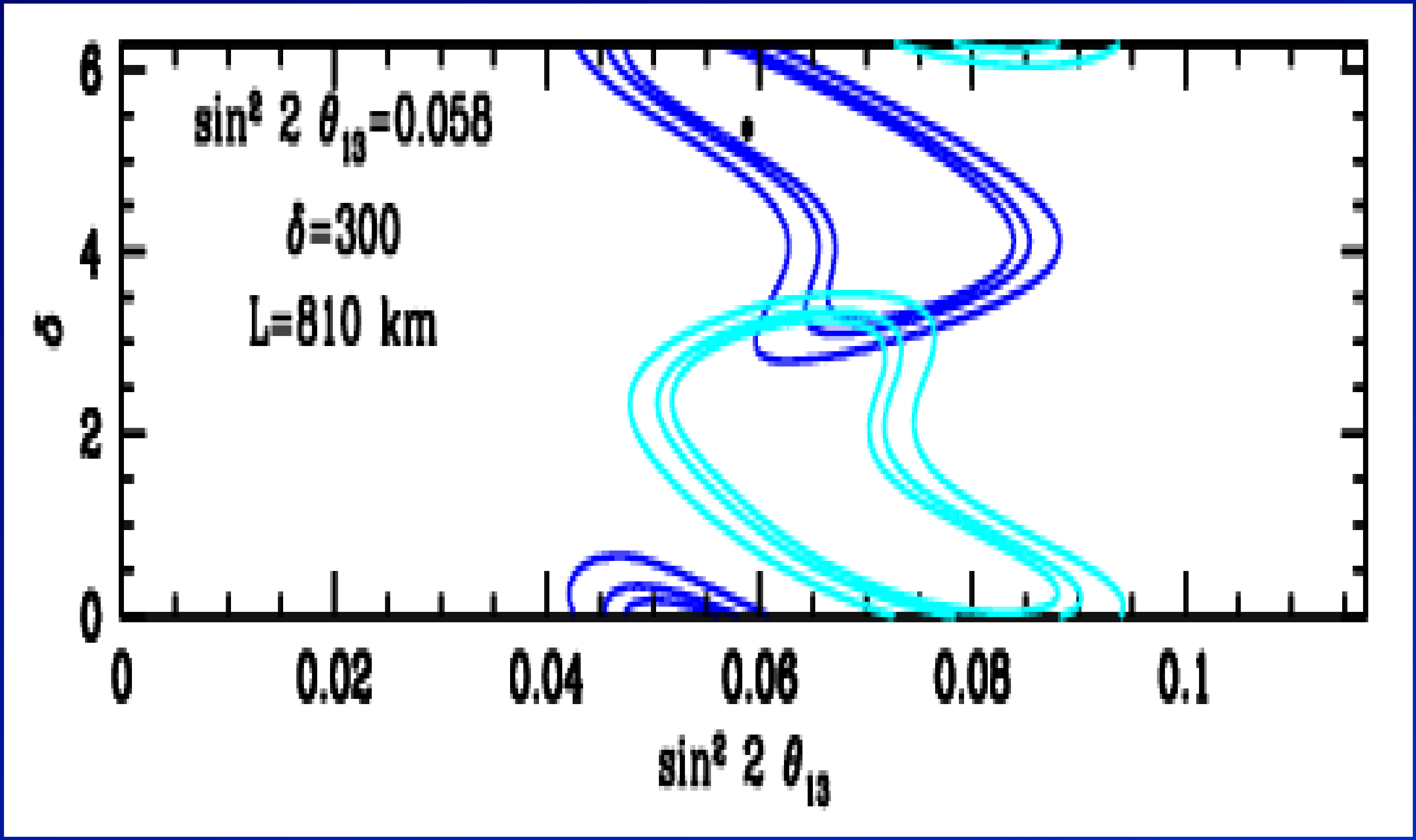
$$\theta'_{13} = \theta_{13} + \cos\delta \sin 2\theta_{12} \frac{\Delta m^2_{12} L}{4E} \cot\theta_{23} \cot \frac{\Delta m^2_{13} L}{4E}$$

- $(\mathrm{sign}(\Delta m^2_{13}), \delta)$ degeneracy [Minakata, Nunokawa]:

$$\delta' \qquad \pi - \delta$$

$$\mathrm{sign}'(\Delta m^2_{13}) \qquad -\mathrm{sign}(\Delta m^2_{13})$$

- $\theta_{23}, \pi/2 - \theta_{23}$ degeneracy [Fogli, Lisi].

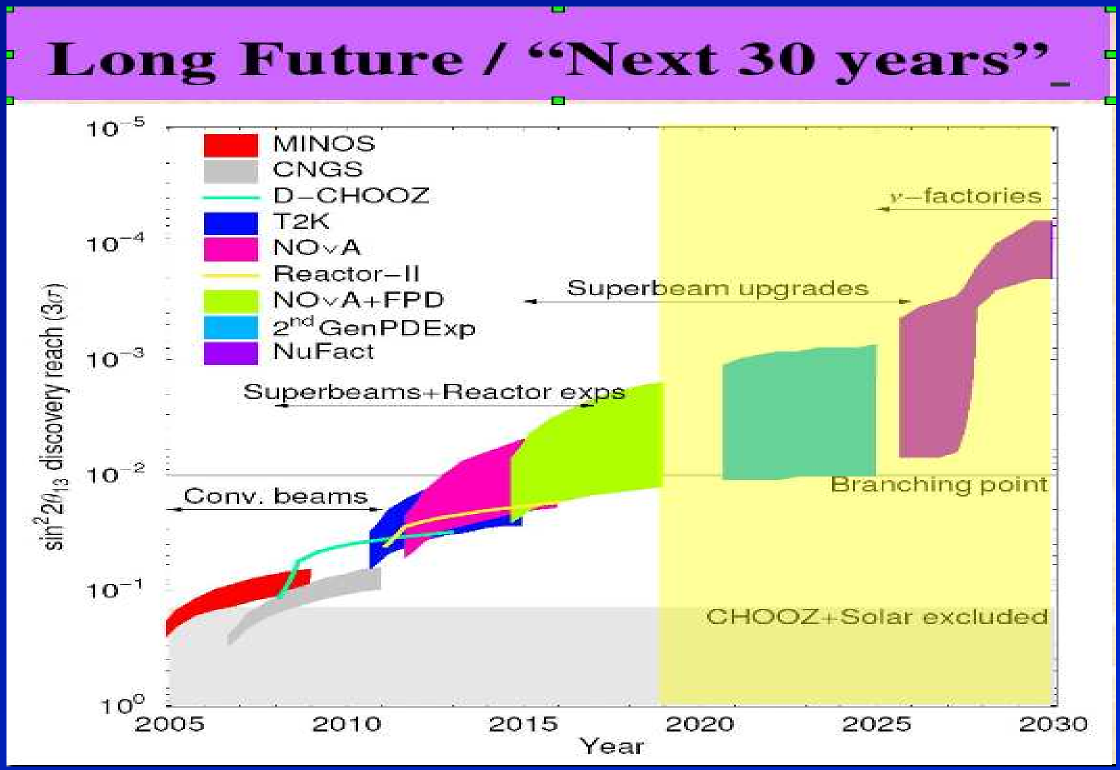


[from O. Mena, S. Palomares-Ruiz, S.P.]

Degeneracies impact strongly the sensitivity to future experiments and need to be resolved!

Many future long base-line neutrino oscillation experiments will do precision studies of neutrino oscillations.

1. Superbeams.
2. Neutrino factories.
3. Beta-beams.



Superbeams (NOνA, T2K, BNL):

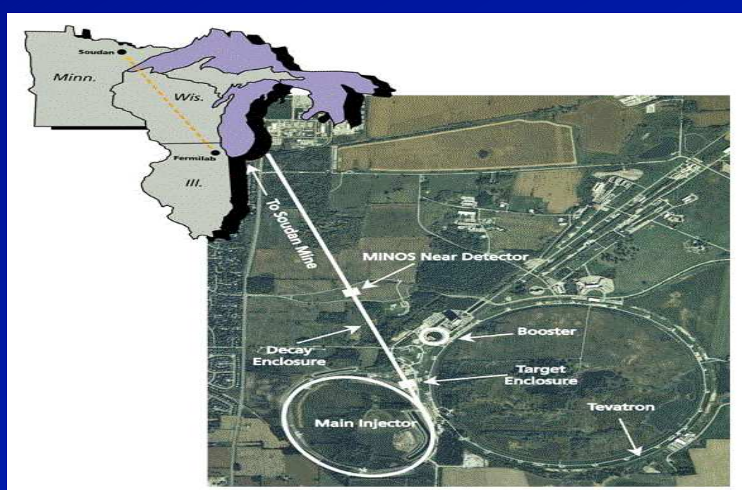
a very intense ν_μ beam produced in $\pi^\pm, K^\pm$ decays to search for ν_μ disappearance, ν_e appearance and ν_τ appearance.

Off-axis detector to achieve a narrow energy beam.

Energy of hundred of MeV to few GeV.

Distance 700–1000 Km.

NOνA



[http://www-nova.fnal.gov]

T2K

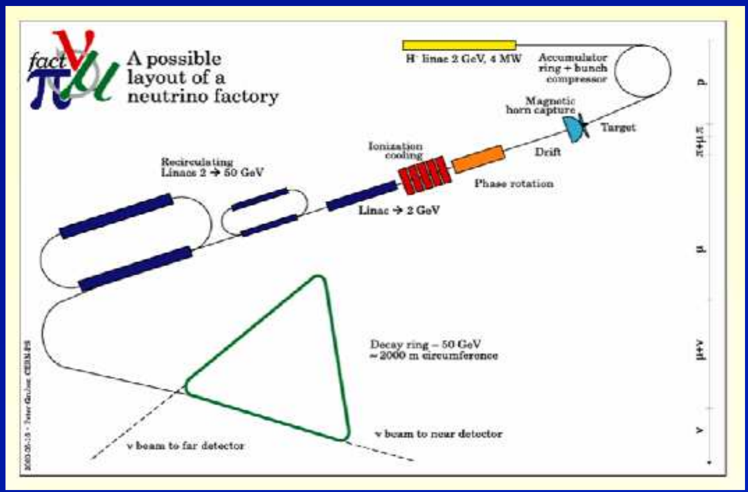
[http://neutrino.kek.jp/jhfnu/]

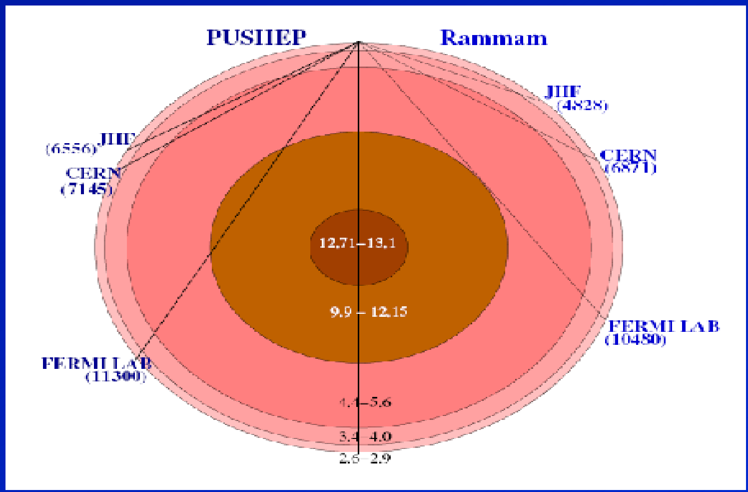
Neutrino factories:

ν_μ and ν_e are produced in very relativistic muon decays.

Energies of 20–50 GeV.

Distance 3000–7000 Km.





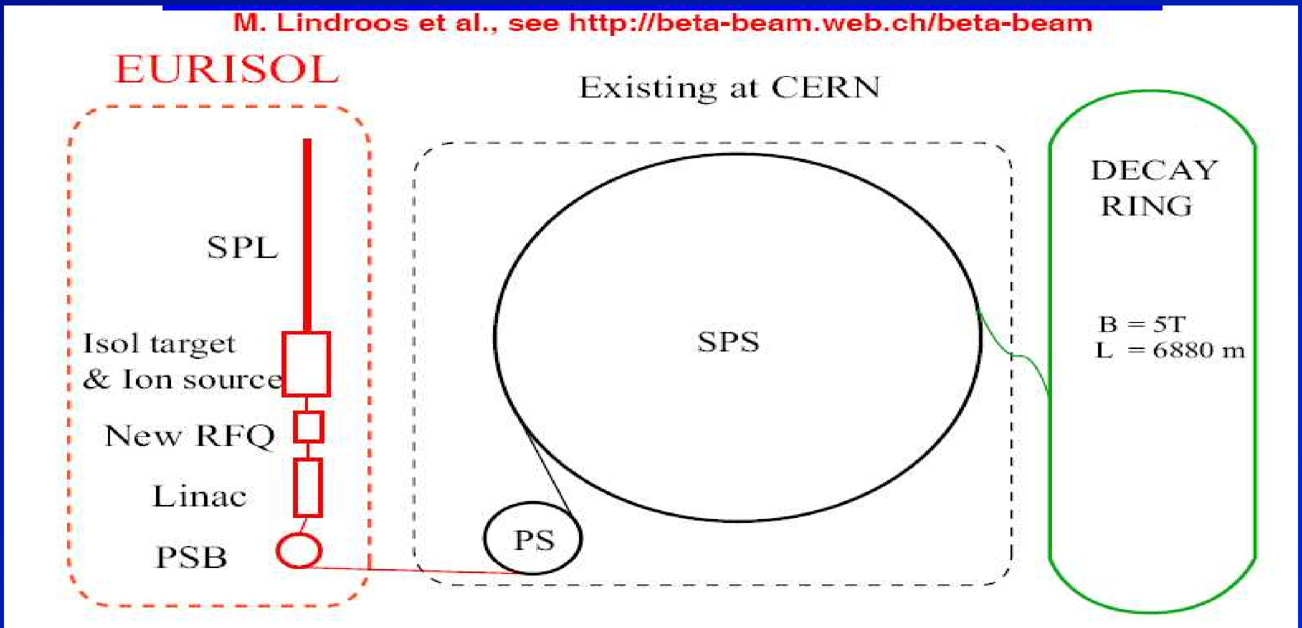
[INO proposal]

Beta-beams:

ν_e are produced by beta decay of accelerated ions.

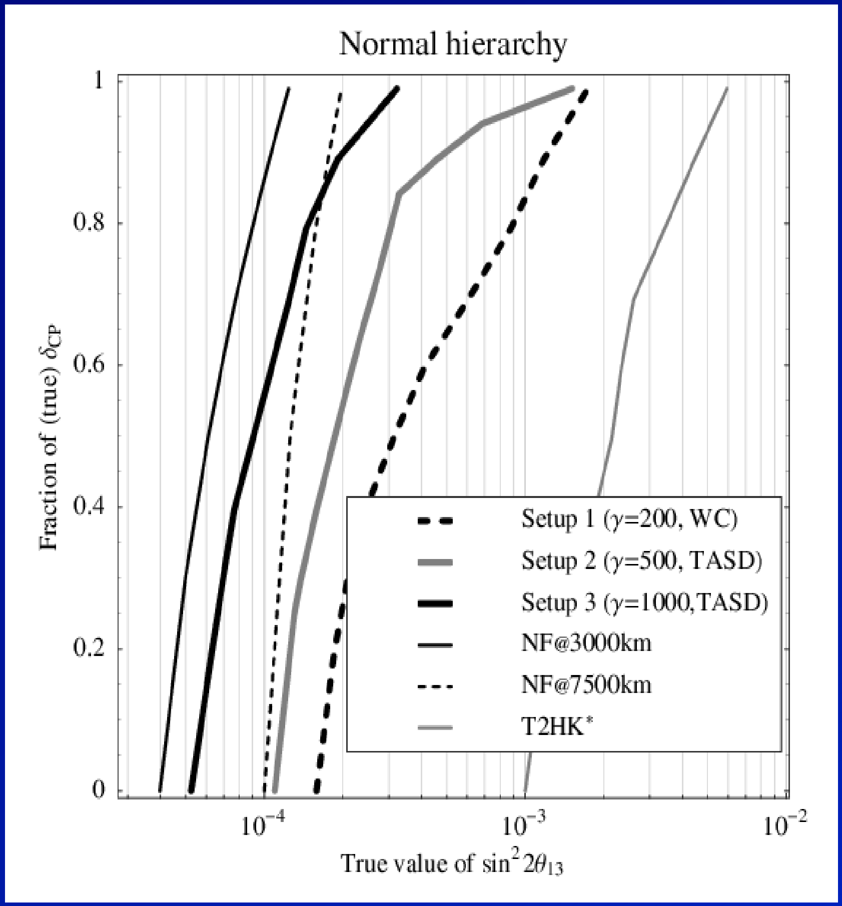
Energies 200-2000 MeV.

Distance 100-1000 Km.



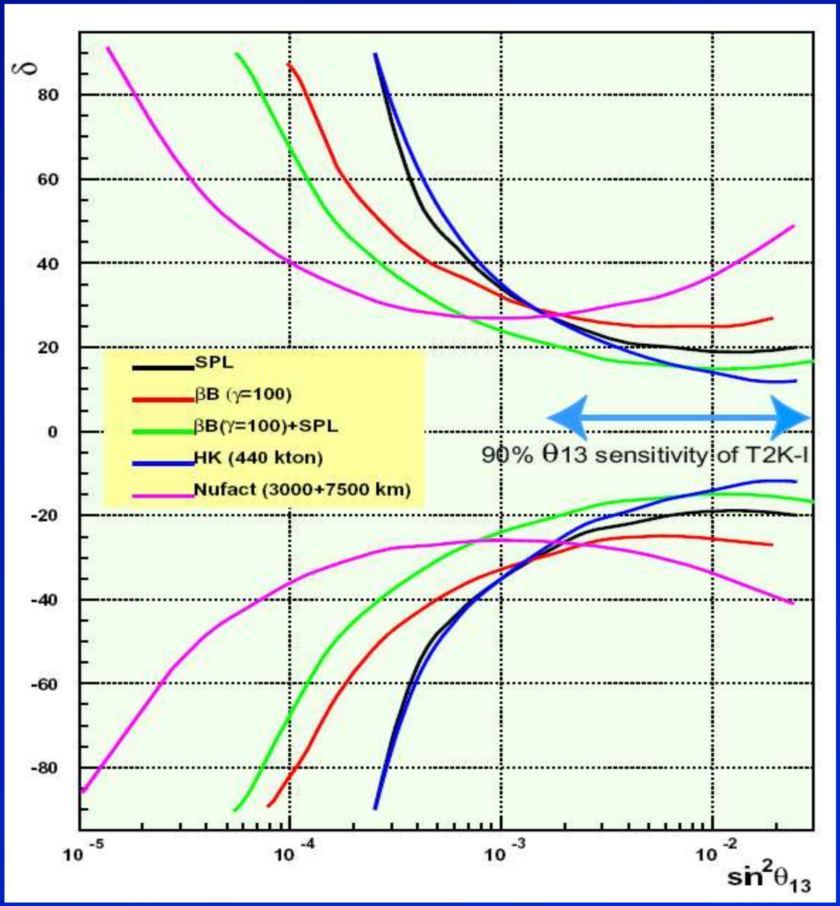
Ultimate sensitivity in neutrino factories or beta-beams:

mass hierarchy



[Huber et al., hep-ph/0506237]

CP-violation



[Mezzetto @ taup 2005]

Atmospheric neutrinos

By exploiting matter effects in large detectors (INO, HK?, Atlas?) it is possible to obtain information on the type of hierarchy from atmospheric neutrinos.

Either a Mton WC detector and > 10 years of data taking is required or a 100kton iron magnetized detector (charge identification!!!) by looking at the difference between $P(\nu_\mu \rightarrow \nu_\mu)$ and $P(\bar{(}\nu)_\mu \rightarrow \bar{(}\nu)_\mu)$.

INO proposal for an magnetic iron detector in India.

2 – Questions for the future in THEORY

What are the fundamental questions for the present and the future?

- The two crucial questions are smallness of neutrino mass and mixing pattern.

- Understand the mechanism at the origin of neutrino masses.

See-saw type I	heavy N_R
See-saw type II	triplet
Extra-dimensions	branes+bulk
Technicolor	extended models
low-energy models	scalar or fermion singlets

Bottom-up analysis

Look for features of the neutrino mass matrix (equalities, zeros, hierarchy) which could suggest a symmetry.

- Bi-maximal mixing:

$$U_{bm} = \frac{1}{2}\begin{pmatrix} \sqrt{2} & \sqrt{2} & 0 \\ -1 & 1 & \sqrt{2} \\ 1 & -1 & \sqrt{2} \end{pmatrix} \qquad (1)$$

This is not compatible with $\theta_\odot$ but it can be the dominant structure with corrections coming from the charged lepton sector.

- Tri-bimaximal mixing:

$$U_{tbm} = \frac{1}{\sqrt{6}} \begin{pmatrix} 2 & \sqrt{2} & 0 \\ -1 & \sqrt{2} & \sqrt{3} \\ 1 & -\sqrt{2} & \sqrt{3} \end{pmatrix} \tag{2}$$

This is in good agreement with data.

- Horizontal symmetries

$L_e - L_\mu - L_\tau$

Discrete symmetry (A_4, S_3, Z_4,....)

$U(1)$ in order to explain the hierarchy of elements.

$SU(2)$, $SO(3)$, $SU(3)$

Top-down analysis

Within the context of a specific mechanism, for ex. see-saw, impose symmetries or features of the Dirac mass and Majorana masses.

There need to be at least two N_R (for having at least 2 masses $\neq 0$). Ex.

Choose:

Dirac mass matrix $\begin{pmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & ? \end{pmatrix}$

Heavy Majorana mass $\begin{pmatrix} M1 & 0 & 0 \\ 0 & M2 & 0 \\ 0 & 0 & M3 \end{pmatrix}$

- Embed in GUT theory
- Link with leptogenesis
- Link with LFV charged lepton decays (if SUSY).

3 – Questions for the future in COSMOLOGY and ASTROPHYSICS

What are the fundamental questions for the present and the future?

- Leptogenesis: is there a link between the low energy and high energy parameters? See yesterday's lecture.
- neutrinos as Dark matter
- neutrinos and BBN
- Sterile neutrinos and WDM

Neutrinos and dark matter

Neutrinos contribute to the dark matter of the Universe. They freeze-out at the MeV temperature (hot relic) when weak interactions get out of equilibrium ($\Gamma \sim H$).

Their contribution to the relic mass density:

$$\Omega_\nu h^2 = 7.83 \times 10^{-2} \left[g_{eff}/g_{*S}\right] (m_\nu/\mathrm{eV})$$

At large scale structure formation, $T \sim$ keV, they are relativistic. Their effect is to smooth out the matter density perturbations reducing the formation of structure. They are therefore a Hot Dark matter component.

This implies bounds on their mass.

$$\Sigma \equiv \sum_i m_{\nu i} < \mathcal{O}(1-2)\,\mathrm{eV}$$

Future experiments might be able to reach $\Sigma \sim 0.1$ eV.

Neutrinos as BBN

Big Bang Nucleosynthesis takes place at $T \sim 100$ keV–1 MeV. The density of p and n freezes out when the inverse beta decay becomes inefficient. Subsequently deuterium, ^{4}He, and the other light elements are produced. Their abundance depends on:

$$\frac{n}{p} = e^{-(m_n - m_p)/T + (\mu_e - \mu_\nu)/T}$$

The number of relativistic degrees of freedom at BBN modifies $\frac{n}{p}$. The ^{4}He abundance can be used to constrain the number of light neutrinos in equilibrium at BBN.

$$N_\nu < 4.5$$

Sterile neutrinos as WDM

Sterile neutrinos with small mixing and masses $\sim$ keV have been proposed as warm dark matter. They are produced in the Early Universe, e.g. via oscillations:

$$\frac{d}{dt} f_s(p,t) - Hp\frac{d}{dp} f_s(p,t) \simeq \Gamma(\nu_a \to \nu_s; p,t)(f_a(p,t) - f_s(p,t))$$

The resulting density of relic sterile neutrinos:

$$\Omega_{\nu_2} \sim 0.3 \left(\frac{\sin^2 2\theta}{10^{-8}}\right) \left(\frac{m_s}{\mathbf{keV}}\right)^2$$

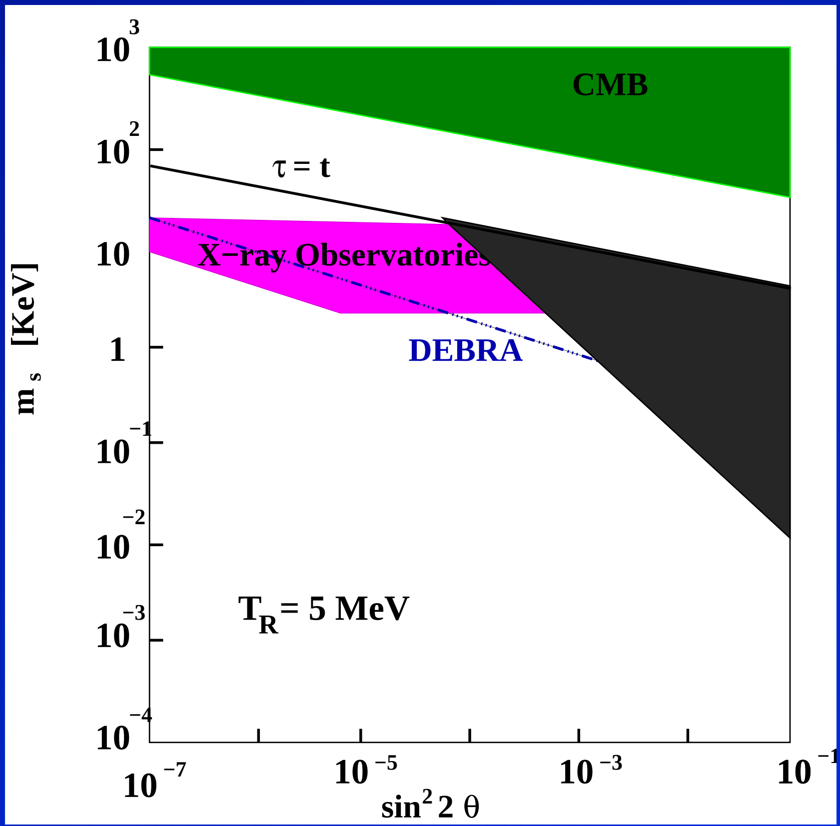
Dodelson, Widrow; Dolgov, Hansen; Fuller, Shi; Abazajian, Fuller, Patel

For masses in the keV range, this is a warm dark matter candidate.

They decay in $\nu_s \to 3\nu_a$ and $\nu_s \to \nu_a\,\gamma$ (BR $\sim$ 0.01), with decay rate

$$\Gamma_{e\nu} \simeq \frac{G_F^2}{768\pi^3} \sin^2 2\theta \, m_s^5$$

- The photons produced in the decays of DM ν_s would contribute to the DEBRA.
- Neutrinos can lead to a X-ray signal from clusters of galaxies.



Still viable?????

4 – Conclusions

- We have strong evidence for neutrino oscillations. They imply that Neutrinos are massive ($\Delta m^2 \neq 0$) and that they mix ($\sin\theta \neq 0$).

Neutrino masses and mixing requires new physics beyond the SM.

- Questions for the future:

1. Nature of neutrinos: Majorana vs Dirac?
2. Number of neutrinos: Are there sterile neutrinos?
3. Neutrino masses: NH, IH or QD?
4. CP-violation: $\delta \neq 0, \pi$ and/or $\alpha_{ij} \neq 0, \pi$?

- A wide experimental program is going to address these questions in the next future: $(\beta\beta)_{0\nu}$-decay, LBL, atmospheric neutrino, β-decay exp....

STAY TUNED!!!!!