Neutrino physics:

questions for the future

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1 – Outline

- What are the questions to be addressed?
- Neutrinoless double beta decay
- Long baseline neutrino oscillation experiments
- Conclusions

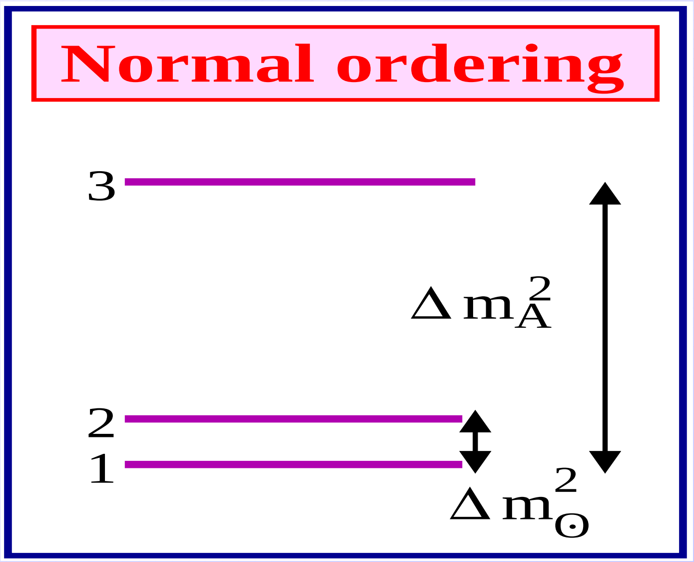
2 – Present status of neutrino physics

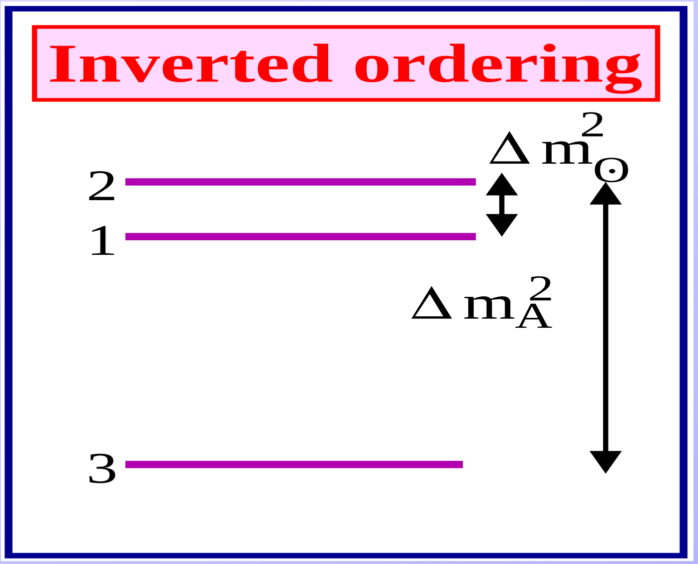
Neutrino oscillations are crucial in our understanding of neutrino physics as they imply that

NEUTRINOS ARE MASSIVE AND THEY MIX.

The explanation of neutrino masses requires physics beyond the Standard Model.

$$\Delta m^2_\odot = 8.0 \times 10^{-5}\,\mathrm{eV}^2 \ll \Delta m^2_{\mathrm{atm}} = 2.5 \times 10^{-3}\,\mathrm{eV}^2 \;\Rightarrow \mathbf{3}\ \nu.$$





$$m_1 = m_{\mathrm{MIN}}$$
$$m_2 = \sqrt{{m_{\mathrm{MIN}}}^2 + \Delta m^2_\odot}$$
$$m_3 = \sqrt{{m_{\mathrm{MIN}}}^2 + \Delta m^2_{\mathrm{atm}}}$$

$$m_3 = m_{\mathrm{MIN}}$$
$$m_1 = \sqrt{{m_{\mathrm{MIN}}}^2 + \Delta m^2_{\mathrm{atm}} - \Delta m^2_\odot}$$
$$m_2 = \sqrt{{m_{\mathrm{MIN}}}^2 + \Delta m^2_{\mathrm{atm}}}$$

Measuring neutrino masses requires to know m_{MIN} and sign(Δm^2_{31}).

Mixing is described by a unitary matrix:

$$|\nu_l\rangle = \sum_i U_{li} |\nu_i\rangle$$

U is the Pontecorvo-Maki-Nakagawa-Sakata matrix.

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

Solar, reactor $\theta_\odot \sim 30^o$ **Atm, Acc.** $\theta_A \sim 45^o$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{-i\alpha_{31}/2+i\delta} \end{pmatrix}$$

CPV phase **Reactor, Acc.** $\theta < 12^o$ **CPV Majorana phases**

If $U \neq U^*$, there is leptonic CP-violation.

3 – Questions for the future

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

1. 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. explaining the origin of neutrino masses and of the flavour structure, by considering see-saw models and alternative mechanisms of neutrino mass generation. [Note: ν mass $\ll m_e \sim 5 \times 10^5$ eV.]

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

In the remainder of the talk, I focus on neutrino phenomenology. The following issues need to be resolved:

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

These are the ingredients we need in order to understand the origin of neutrino masses in a theory beyond the SM.

Nature of neutrinos: Majorana vs Dirac?

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 mass spectrum: NH, IH or QD?

As we know only $\Delta m^2_\odot$ and $\Delta m^2_{\rm atm}$, 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.

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

If U is complex we have CP-violation:

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

- 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).

- Leptogenesis takes place in the context of see-saw models, which explain the origin of neutrino masses.

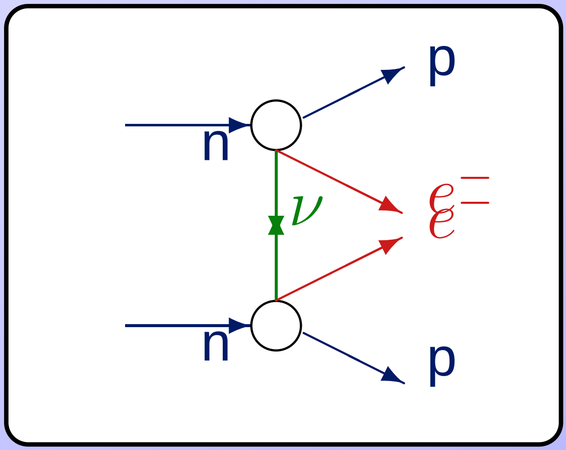
The observation of neutrinoless double beta decay (L violation) and of CPV in the lepton sector would be an indication, even if not a proof, of leptogenesis as the explanation for the observed baryon asymmetry of the Universe.

A wide experimental programme is under discussion for the future:

- reactor neutrino experiment: θ_{13}
- neutrinoless double beta decay: Nature of neutrinos, type of hierarchy, (CP-violation)
- long baseline neutrino experiments: type of hierarchy, CP-violation, matter effects, precision on known oscillation parameters

4 – Neutrinoless double beta decay

The nature of neutrinos can be tested only in processes which violate the lepton number by two units. The most sensitive of all is $(\beta\beta)_{0\nu}$**-decay** ($(A,Z) \to (A,Z+2) + 2e^-$). It can proceed through the exchange of light Majorana neutrinos:



The half-life time, $\mathrm{T}_{0\nu}^{1/2}$, of the $(\beta\beta)_{0\nu}$-decay depends on **the effective Majorana mass parameter,** $|{<}m{>}|$:

$$|{<}m{>}| \equiv \left| m_1|U_{\mathrm{e}1}|^2 + m_2|U_{\mathrm{e}2}|^2 e^{i\alpha_{21}} + m_3|U_{\mathrm{e}3}|^2 e^{i\alpha_{31}} \right| .$$

The predictions for $|{<}m{>}|$ depend strongly on the type of spectrum.

- NH: $$|{<}m{>}| \simeq \left|\sqrt{\Delta m^2_\odot}\cos^2\theta_{13}\sin^2\theta_\odot + \sqrt{\Delta m^2_{\rm atm}}\sin^2\theta_{13}e^{i\alpha_{32}}\right|$$

- IH:

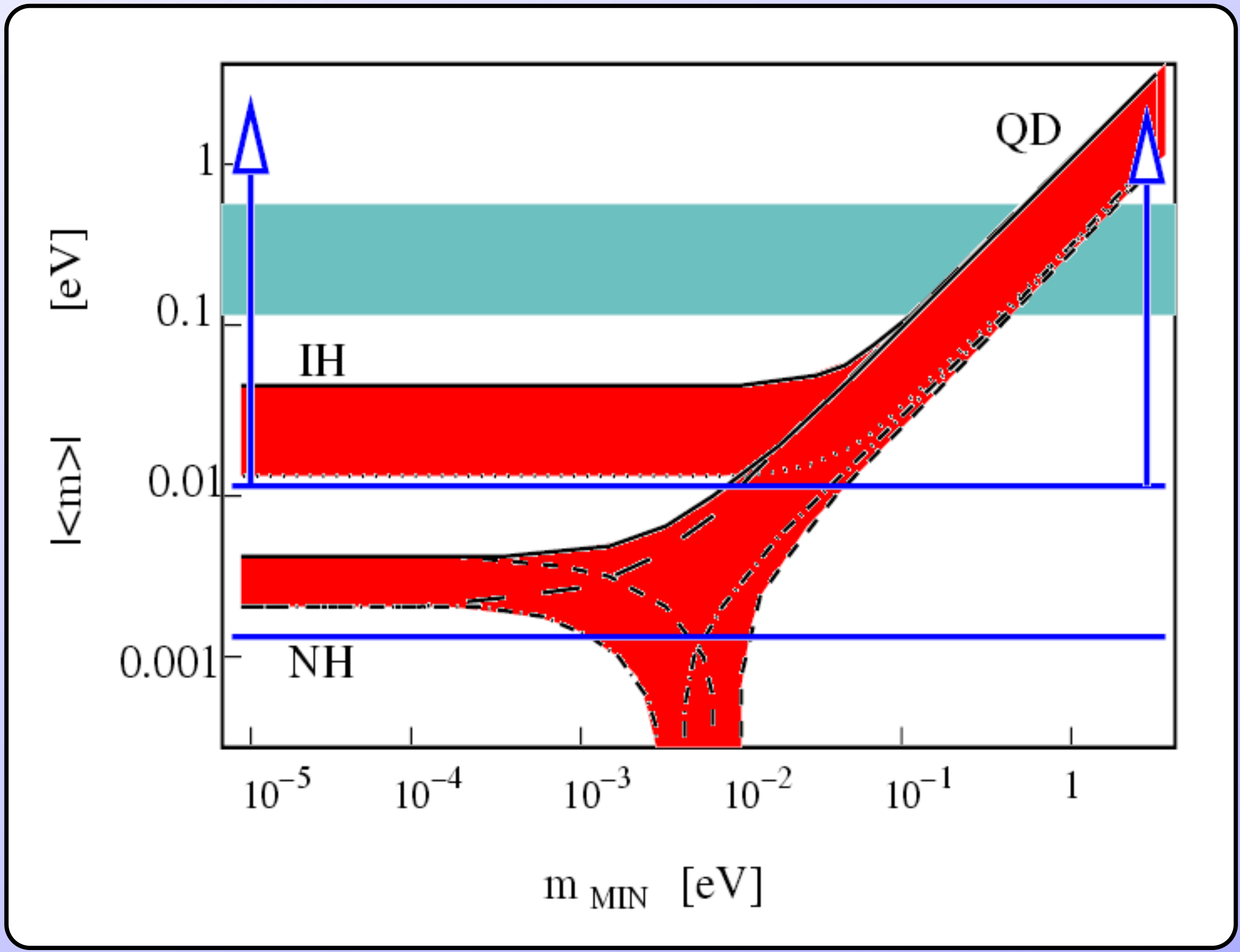
$$\sqrt{\Delta m^2_{\rm atm}}\cos 2\theta_\odot \leq |{<}m{>}| \simeq \sqrt{\left(1-\sin^2(2\theta_\odot)\sin^2\frac{\alpha_{21}}{2}\right)\Delta m^2_{\rm atm}} \leq \sqrt{\Delta m^2_{\rm atm}}$$

$|{<}m{>}|$ has a significant lower bound

$$0.01 \text{ eV} \lesssim |{<}m{>}| \lesssim 0.06 \text{ eV}$$

- QD: $$|{<}m{>}| \simeq m_{\bar\nu_e}\left|\left(\cos^2\theta_\odot + \sin^2\theta_\odot e^{i\alpha_{21}}\right)\cos^2\theta_{13} + \sin^2\theta_{13}e^{i\alpha_{31}}\right|$$

$$0.03 \text{ eV} \lesssim |{<}m{>}| \lesssim m_1$$



[S.T. Petcov, A. Yu. Smirnov, PLB 1994; S.M. Bilenky, S. P., S.T. Petcov, PRD 2001; S.P., S.T. Petcov, T. Schwetz, PLB 2004; S.P., S.T. Petcov PLB 2002, 2004, 2007]

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

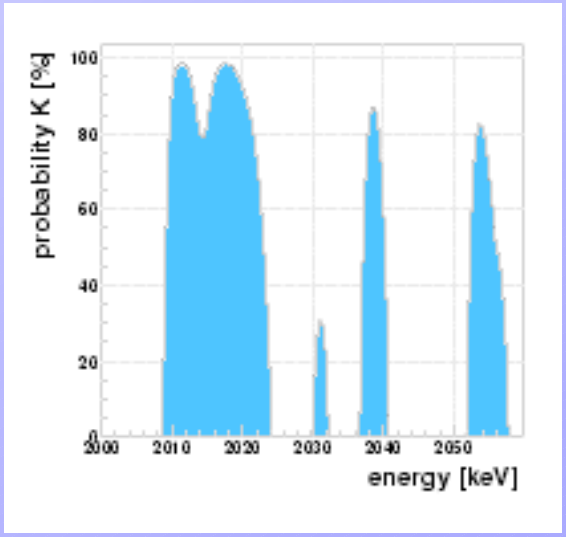
- on the neutrino mass spectrum
- and on the Majorana CP-V phases.

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

$|<m>| \ < (350 - 1050)\ \mathrm{meV}$	**Heidelberg-Moscow**
$|<m>| \ < (680 - 2800)\ \mathrm{meV}$	**NEMO3**
$|<m>| \ < (190 - 680)\ \mathrm{meV}$	**CUORICINO**

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

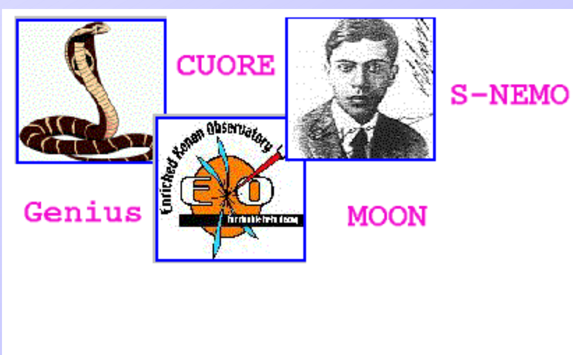
$$|<m>| \ \simeq 200 - 600\ \mathrm{meV}$$



It is still an unconfirmed even if very interesting result.

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

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



Experimental considerations

These experiments need to measure extremely rare events:

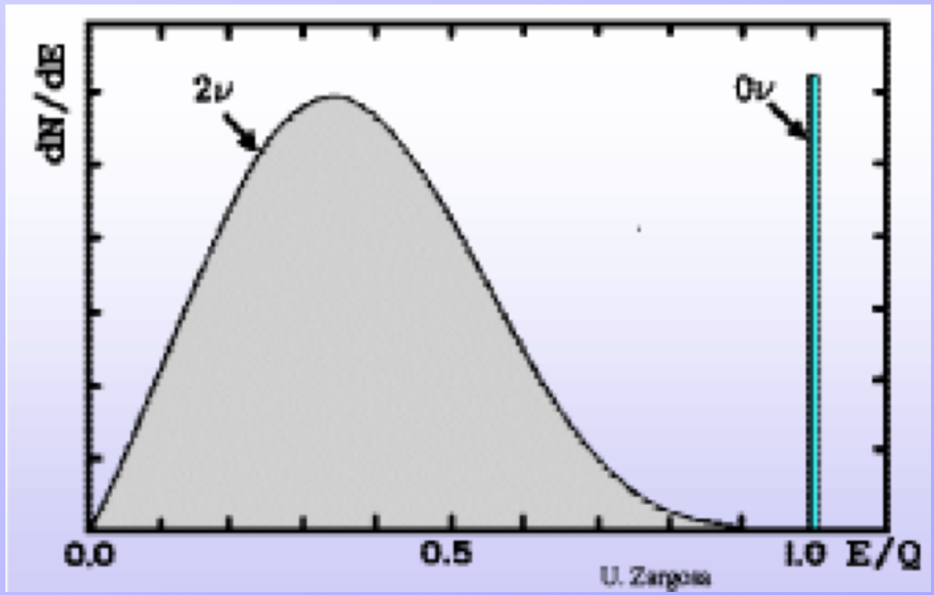
$T_{0\nu} \sim 10^{26}$–10^{27} years.

- Large source mass: few $\longrightarrow$ tens $\longrightarrow$ hundreds of Kg

- Low backgrounds:

deep underground (reduce external background)

very good energy resolution ($(\beta\beta)_{2\nu}$ background).



A wide experimental programme is under consideration.

It is important to have experiments which use different nuclei.

1. independent evidences
2. reduce the impact of nuclear matrix elements

$$(\mathrm{T}^{1/2}_{0\nu})^{-1} \propto M_{\mathrm{nuclear}}{}^2 |<m>|^{\,2}$$

M_{nuclear} are the limiting factor in extracting information on CP-violation from $(\beta\beta)_{0\nu}$-decay and affect the sensitivity to neutrino masses!

GERDA

The GERmanium Detector Array uses ^{76}Ge embodied in ultra-pure liquid argon.

- Phase I: 17.9 kg of existing ^{76}Ge with sensitivity to $\mathrm{T}_{0\nu}^{1/2} \sim 2 \times 10^{25}$ y for one year of data taking.
- Phase II: 40 kg of ^{76}Ge with suppressed background. Sensitivity to $|<m>| \sim 130$ meV for exposure 100 kg y.
- Phase III: 1 ton and further reduced background. Aims at the IH region.

It should be operational in 2009.

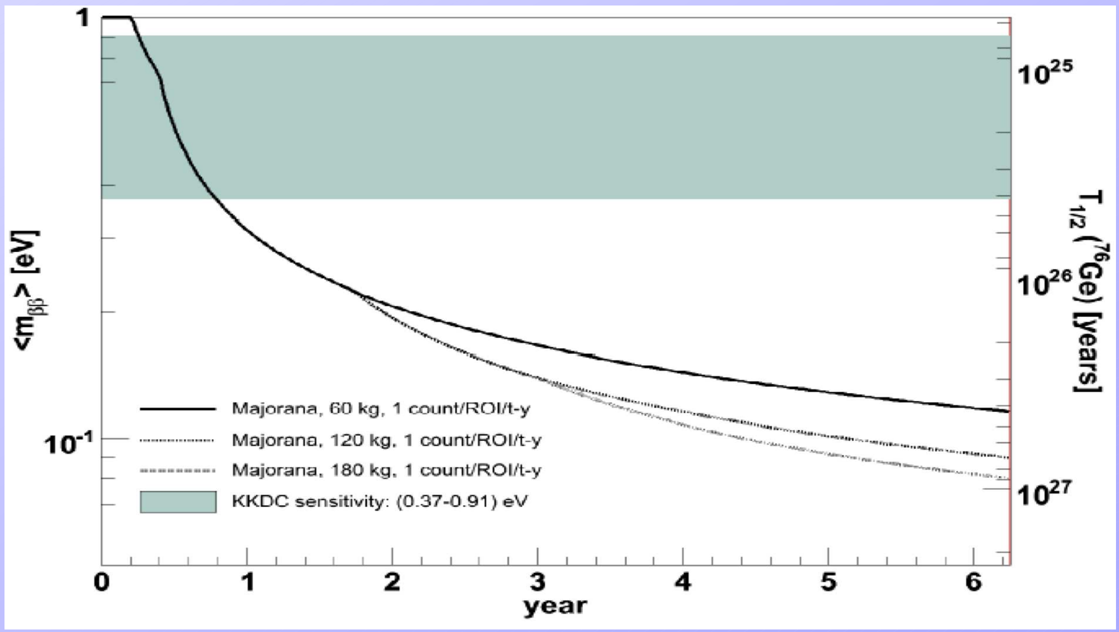
Majorana

Majorana uses ^{76}Ge in a modular structure.

Phase I: 1 Germanium crystals

Phase II: 14-18 crystals

Phase III: towards a 1 ton experiment, 210 crystals



SuperNEMO

SuperNEMO extrapolates NEMO3 experimental design: a thin source within two tracking volumes. Clearly identifies the decay processes $(\beta\beta)_{0\nu}$ and $(\beta\beta)_{2\nu}$.

- Isotopes: ^{82}Se or ^{150}Nd.

R&D program funded in UK, France and Spain. SuperNEMO has been recently included in the STFC UK medium-high priority list for particle physics experiments.

CUORE

CUORE (Cryogenic Underground Observatory for Rare Events) is the phase II of the running CUORICINO experiment.

It will use 988 750 g TeO_2 crystals for a total of 200 kg of ^{130}Te operated at very low temperatures.

- It aims at a sensitivity of $T_{0\nu}^{1/2} \sim 2.1 \times 10^{26}$ y in 5 years of operations, corresponding to $|<m>| \sim 20$–100 meV.
- With a subsequent reduction of background, it could reach $T_{0\nu}^{1/2} \sim 6.5 \times 10^{26}$ y.

EXO

The Enriched Xenon Observatory uses ^{136}Xe.

- Very good background control with Ba tagging.
- Active R&D program for a 10 ton Xe experiment aiming at a sensitivity to $\mathrm{T}_{0\nu}^{1/2} \sim 10^{28}$ y corresponding to $|<m>| \sim 10$ meV.

COBRA

COBRA uses CdZnTe semiconductors and is in the R&D phases. They have an exposure of 4.34 kg days.

Determining the nature of neutrinos

is one of the fundamental questions in particle physics.

Neutrinoless double beta decay will

search for the answer in the coming years.

A wide experimental programme

is in the R&D phase or under discussion.

5 – Long baseline neutrino experiments

LBL experiments search for neutrino oscillations with $L \sim$ 100s–1000s km.

- Disappearance probability, e.g. $P(\nu_\mu \to \nu_\mu)$: precise measurement of known oscillation parameters

- Appearance probability, e.g. $P(\nu_\mu \to \nu_e)$: controlled by θ_{13}: In vacuum and with no CPV the probability would be:

$$P_{\nu_\mu \to \nu_e} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta_{13}L}{2}$$

However, CP-violating and matter effects need to be taken into account.

Typically the experiments consider the oscillation probability in the neutrino and antineutrino channels.

The LBL oscillations take place in matter (Earth).

The Earth matter is not charge-symmetric as it is given only by e^-, p and n.
Matter effects in oscillations are not CP-invariant ($P \neq \bar{P}$).

Neutrinos travelling through the Earth are affected by matter and a potential V appears in the Hamiltonian ($V = \sqrt{2} G_F (N_e - N_n/2)$).

The probability can be approximated as:

$$P_{e\mu} = \sin^2\theta_{23} \sin^2 2\theta_{13}^m \sin^2 \frac{\Delta_{13}^m L}{2}$$

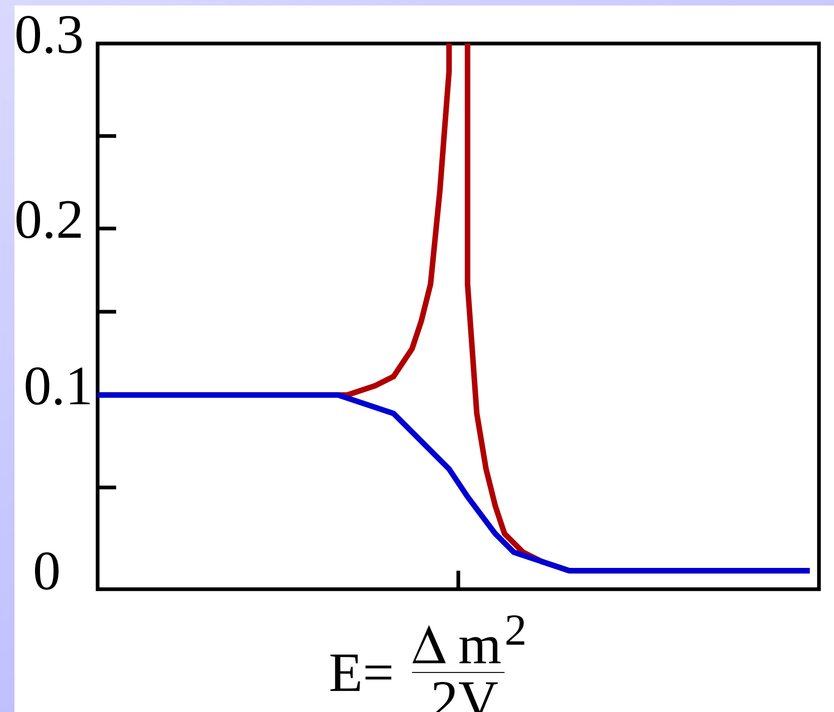
The mixing angle changes with respect to the vacuum case:

$$\sin 2\theta_m = \frac{(\Delta m^2/2E)\sin 2\theta}{\sqrt{\left(\frac{\Delta m^2}{2E}\sin 2\theta\right)^2 + \left(\frac{\Delta m^2}{2E}\cos 2\theta - V\right)^2}}$$

and $\Delta_{13}^m = \sqrt{\left(\frac{\Delta m^2}{2E}\sin 2\theta\right)^2 + \left(\frac{\Delta m^2}{2E}\cos 2\theta - V\right)^2}$.

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

For $\Delta m^2 < 0$, the opposite happens.



If U is complex ($\delta \neq 0, \pi$), we have CP-violation:

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

A measure of CP- violating effects is provided by:

$$A_{CP} = \frac{P(\nu_l \rightarrow \nu_{l'}) - P(\bar{\nu}_l \rightarrow \bar{\nu}_{l'})}{P(\nu_l \rightarrow \nu_{l'}) + P(\bar{\nu}_l \rightarrow \bar{\nu}_{l'})} \propto J_{CP} \propto \sin\theta_{13} \sin\delta$$

It is necessary to disentangle

true CP-V effects due to the δ phase

from the ones induced by matter:

degeneracies.

There are degenerate solutions:

$$\Delta m^2_{31}\ ,\ \theta_{13}\ ,\ \delta\ ,\ \theta_{23}$$

$$\Delta m^2_{31}{}',\ \theta'_{13}\ ,\ \delta',\ \theta'_{23}$$

$$\rightarrow P, \overline{P}$$

In the range of energies ($E \sim 0.5 \div 4$ GeV) and length ($L \sim 200 \div 1500$ 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]:

$$\delta' \quad \pi - \delta$$

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

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

6 – Future LBL experiments

- Desirable characteristics:

  a) baseline > 800–1000 Km for significant matter effects

  b) detector with low energy threshold to fully exploit the oscillatory pattern of the signal (degeneracy resolution)

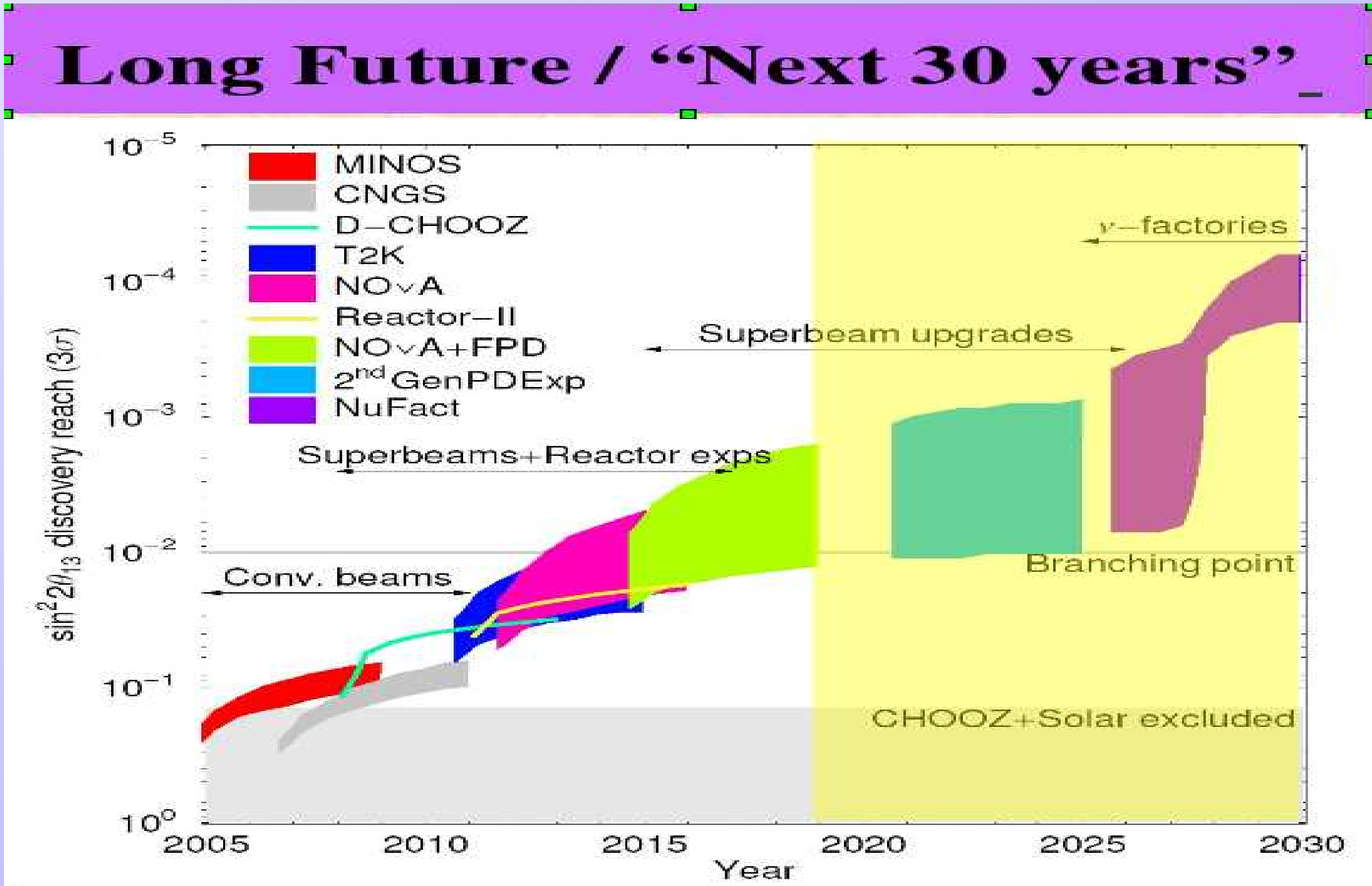
  c) wide beam to provide information at different energies

- The knowledge of θ_{13} (DCHOOZ, T2K) will play a crucial role in shaping the future LBL program.

1. **Superbeams**: a very intense ν_μ beam. Intrinsic ν_e background.

2. **Beta-beams**: ν_e beams given by the β-decays of high-gamma ions.

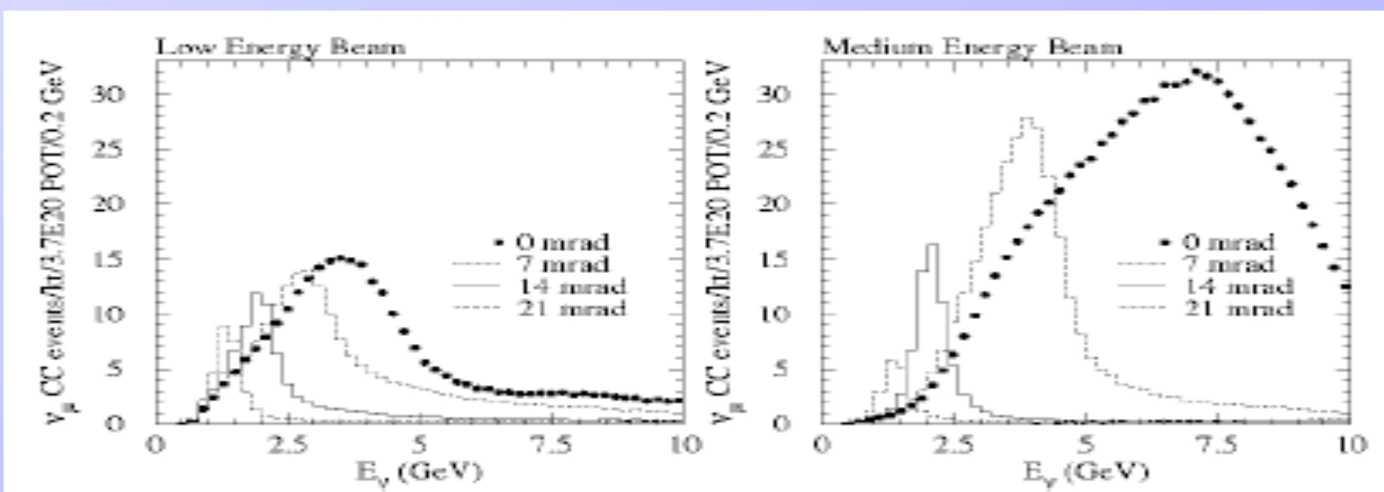
3. **Neutrino factories**: ν_μ-ν_e beam from high-γ muons (20 GeV - 50 GeV).



7 – Superbeam experiments

Superbeams use ν_μ beams from $\pi(K)$ decays and search for ν_e appearance.

- Phase I: T2K and NOνA to pin down θ_{13}. Off-axis experiments: the detector is located at a small angle with respect to the direction of the beam. It reduces the background and provides a beam spectrum very peaked.

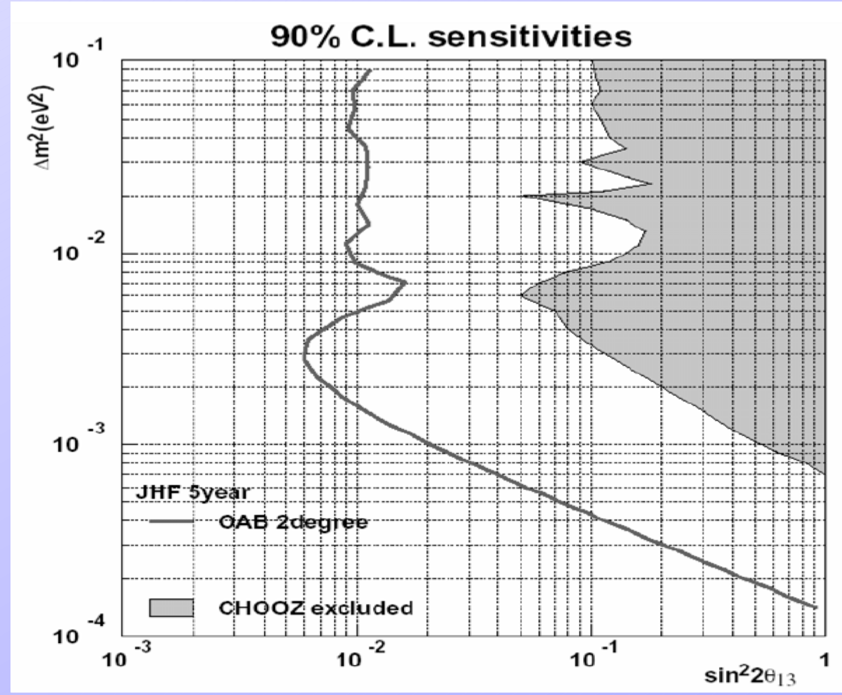


- Phase II: upgrade in flux and detector size.

T2K

Main goal is the determination of θ_{13}.

- Uses a beam from JPARC with $E = 750$ MeV.
- The detector is SuperKamiokande at $L = 295$ km.

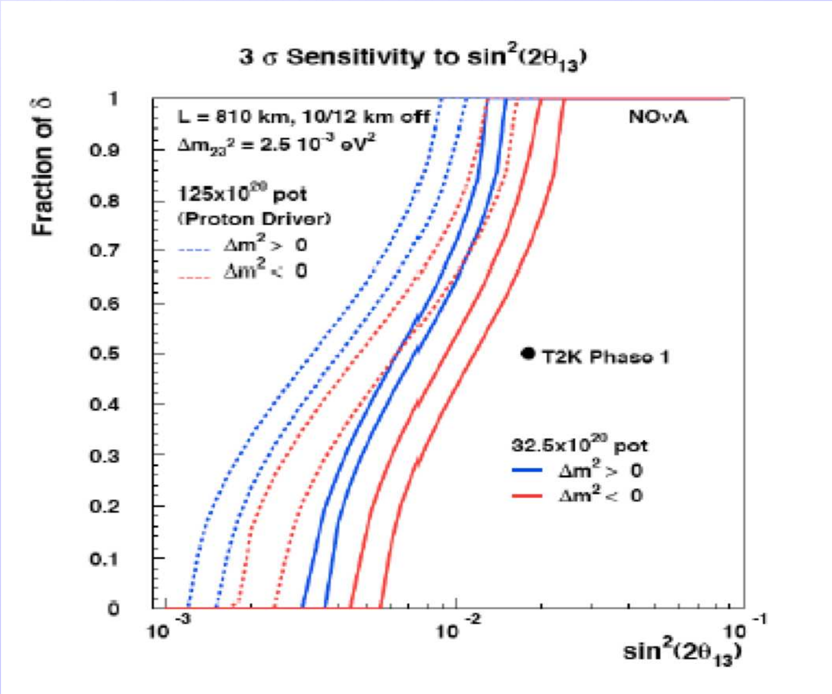


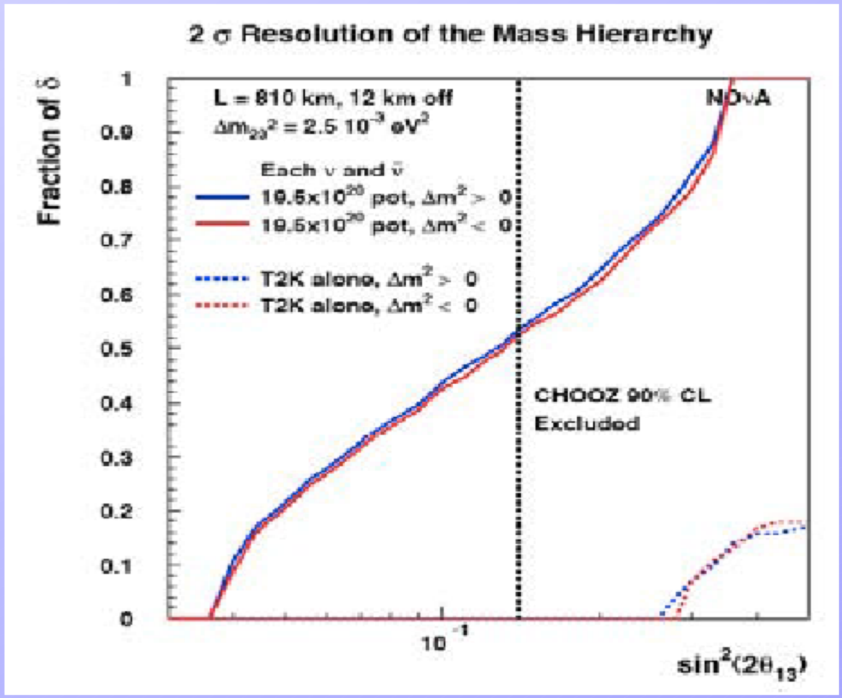
Expected start in 2009.

NOνA

Main goal is measuring θ_{13} but could have sensitivity to matter effects.

- Uses NU-MI beam sourced at Fermilab.
- Scintillator detector at 810 km distance and 12 km off-axis.

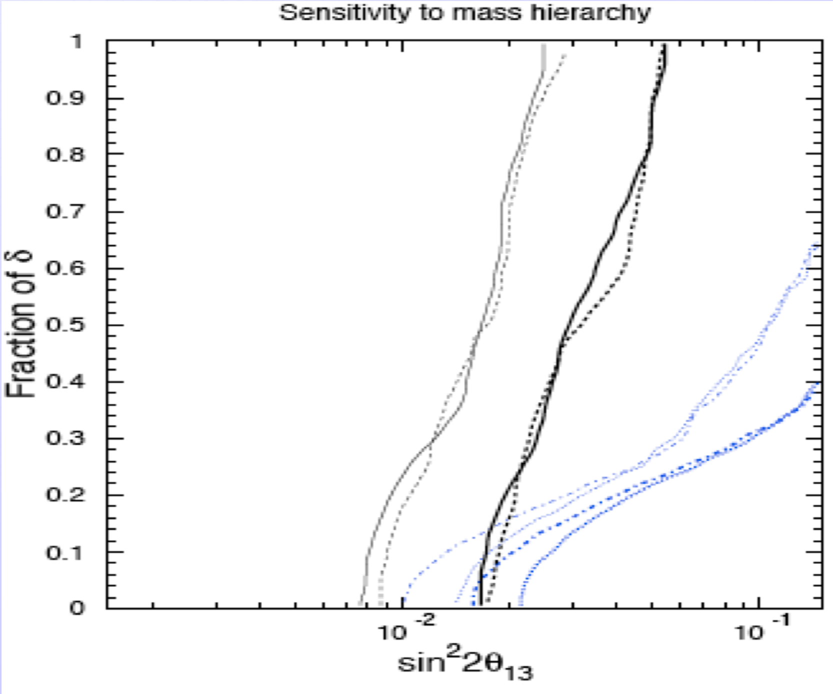


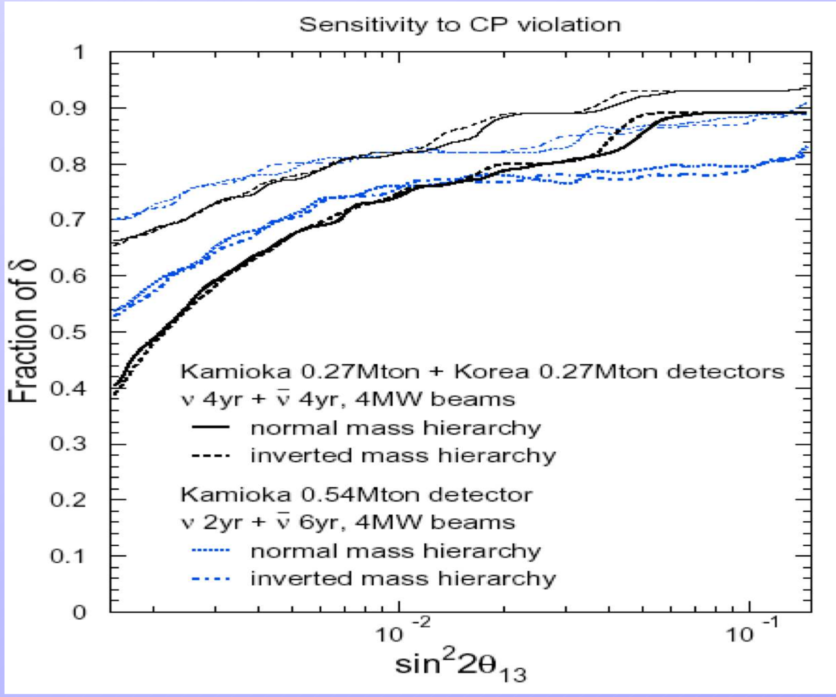


[NOνA proposal]

Future possible superbeam upgrades

- T2K-II: beam upgrade and Mton WĈ detector (or two, with one in Korea)



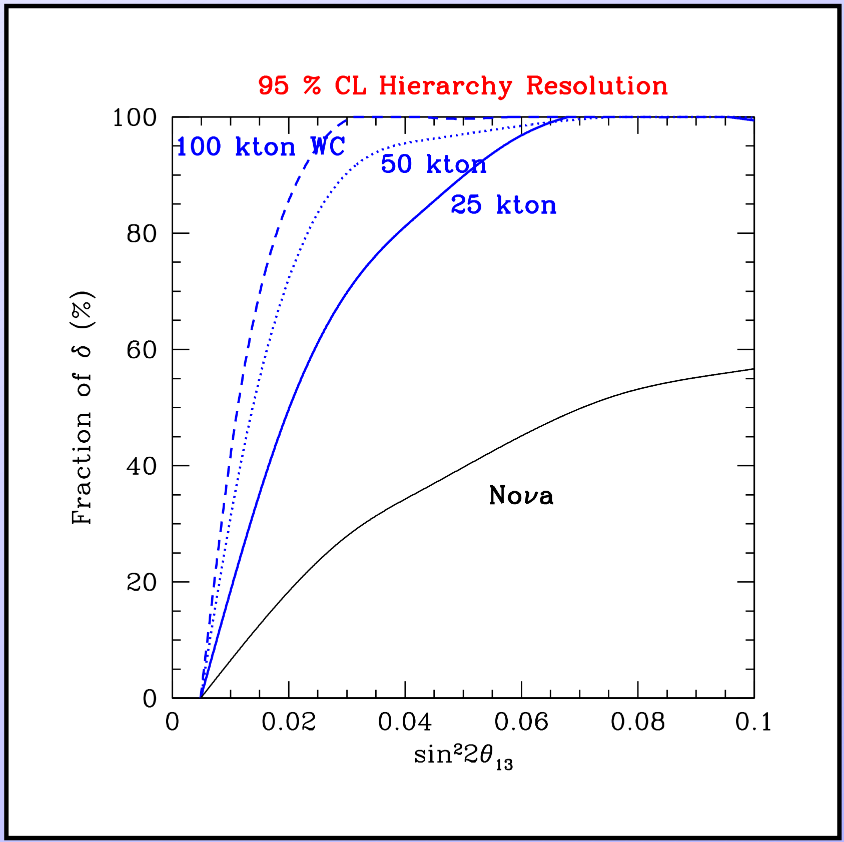


[Ishitsuka et al., PRD 2005, and subsequent works]

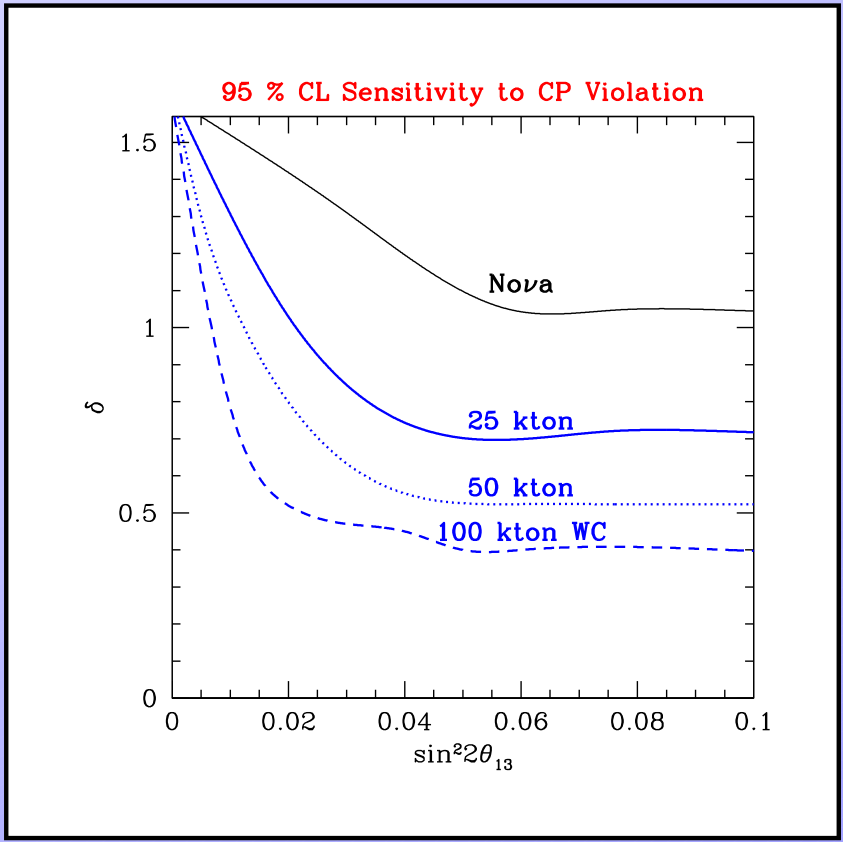
- Super-NOνA: upgrade of NOνA with a second detector at 200 km off-axis (same L/E).

The type of hierarchy can be determined with very weak impact from the unknown value of the δ-phase.

hierarchy



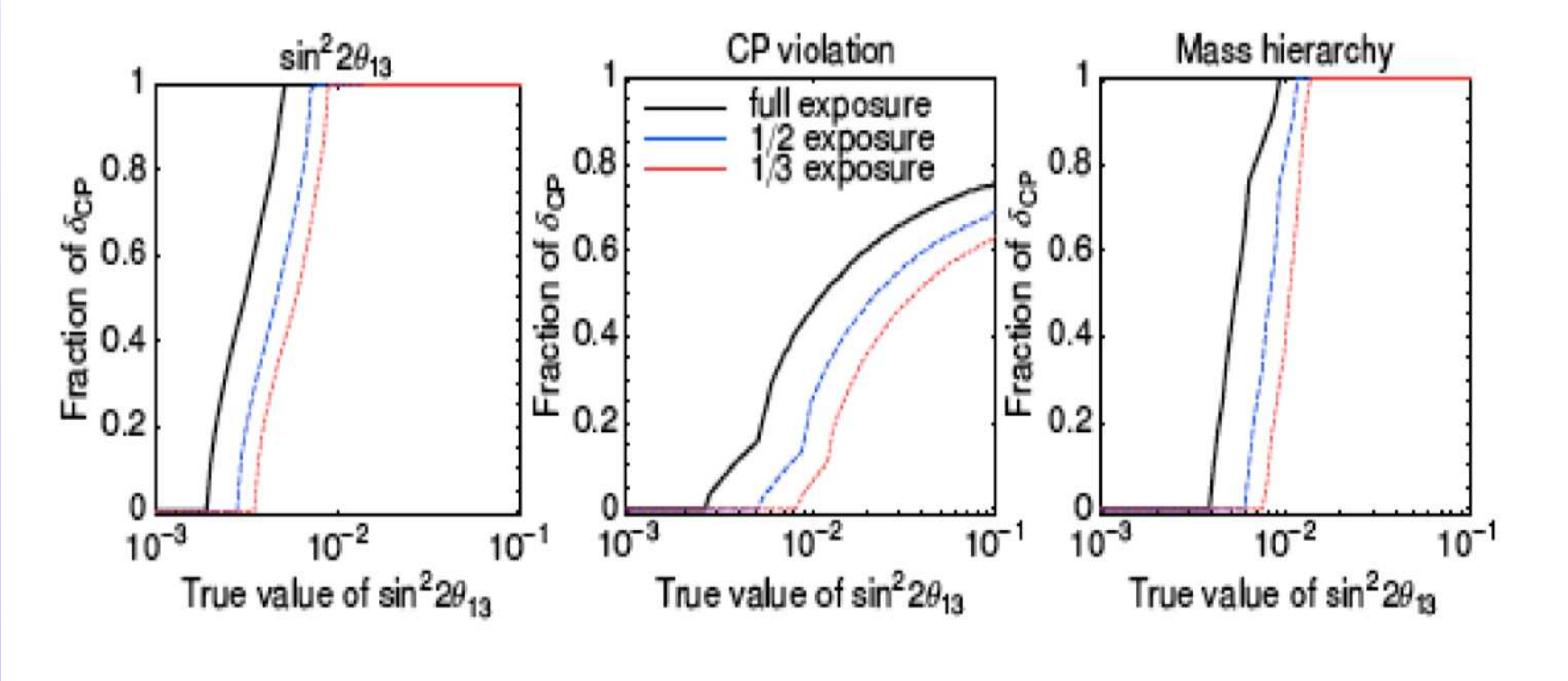
CP-violation



[O. Mena, S.Palomares-Ruiz, S.P., PRD 2005 and PRD 2006]

- Wide band beam with 100 kton size detector

Exploits the energy resolutions and the wide spectrum to resolve degeneracies and determine CP-violation.



[Barger et al.; Huber et al.]

8 – Beta beams

In betabeams ions are accelerated to high gamma and then stored in a decay ring. From their beta decays a pure beam of ν_e is produced with a well known spectrum. [Zucchelli; Mezzetto; Huber et al.; Donini et al.; Bouchet et al.; Campagne et al.; Agarwalla et al.; Rubbia et al.; Cervera et al.]

- Ions: low Q ^{6}He, ^{18}Ne, high Q ^{8}B and ^{8}Li.
- Achievable γ ($E_\nu = E_0 2\gamma$):

CERN SPS: $\gamma_{He} = 150$ and $\gamma_{Ne} = 250$

Upgraded SPS (or Tevatron): $\gamma_{He} = 350$ and $\gamma_{Ne} = 580$

LHC: $\gamma_{He} \sim 2500$ and $\gamma_{Ne} \sim 4000$

- Detector at suitable distance for ν_μ appearance.

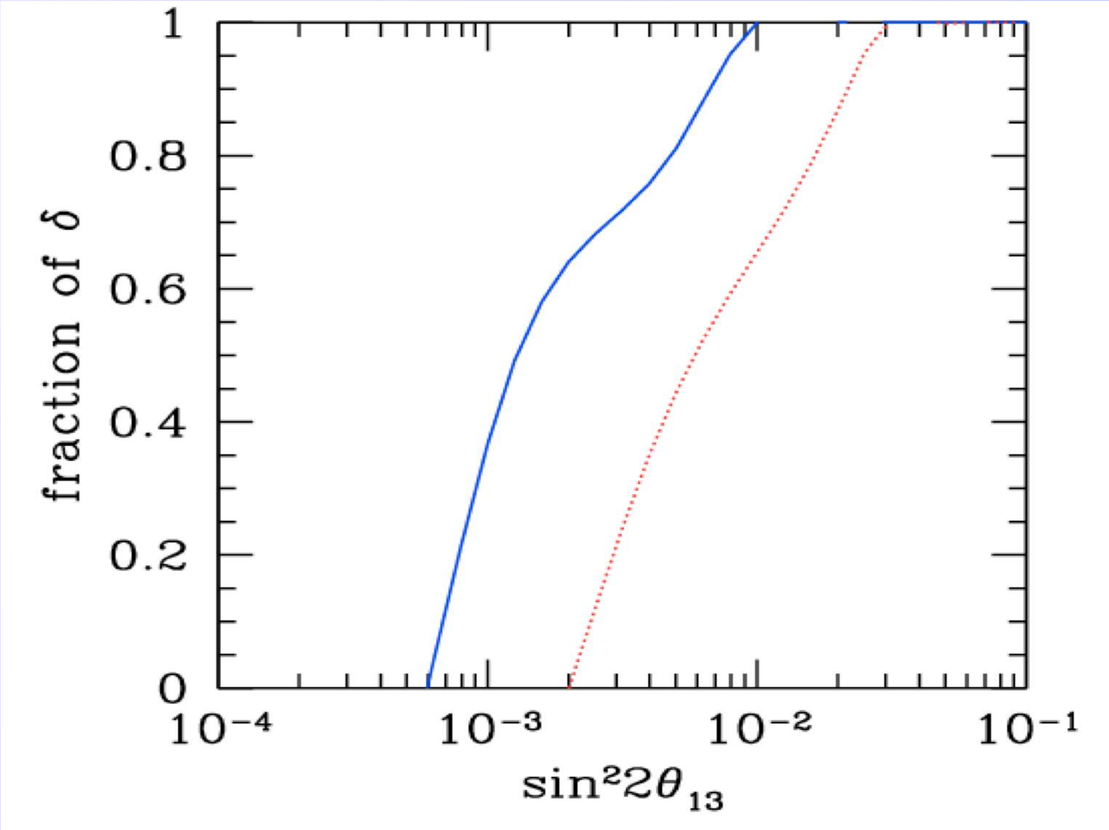
- Low energy β-beam: CERN-Frejus option with $E_\nu \sim 200$ MeV and $L = 130$ km. Good sensitivity to CP-violation. No matter effects.

- Intermediate γ betabeam with $E_\nu \sim 2$ GeV and $L = 1000$ km. This is due to a new possibility to build large caverns at Boulby to host 10-kton detectors.

[Meloni, Mena, Orme, Palomares-Ruiz, SP, arXiv:0802.0255]

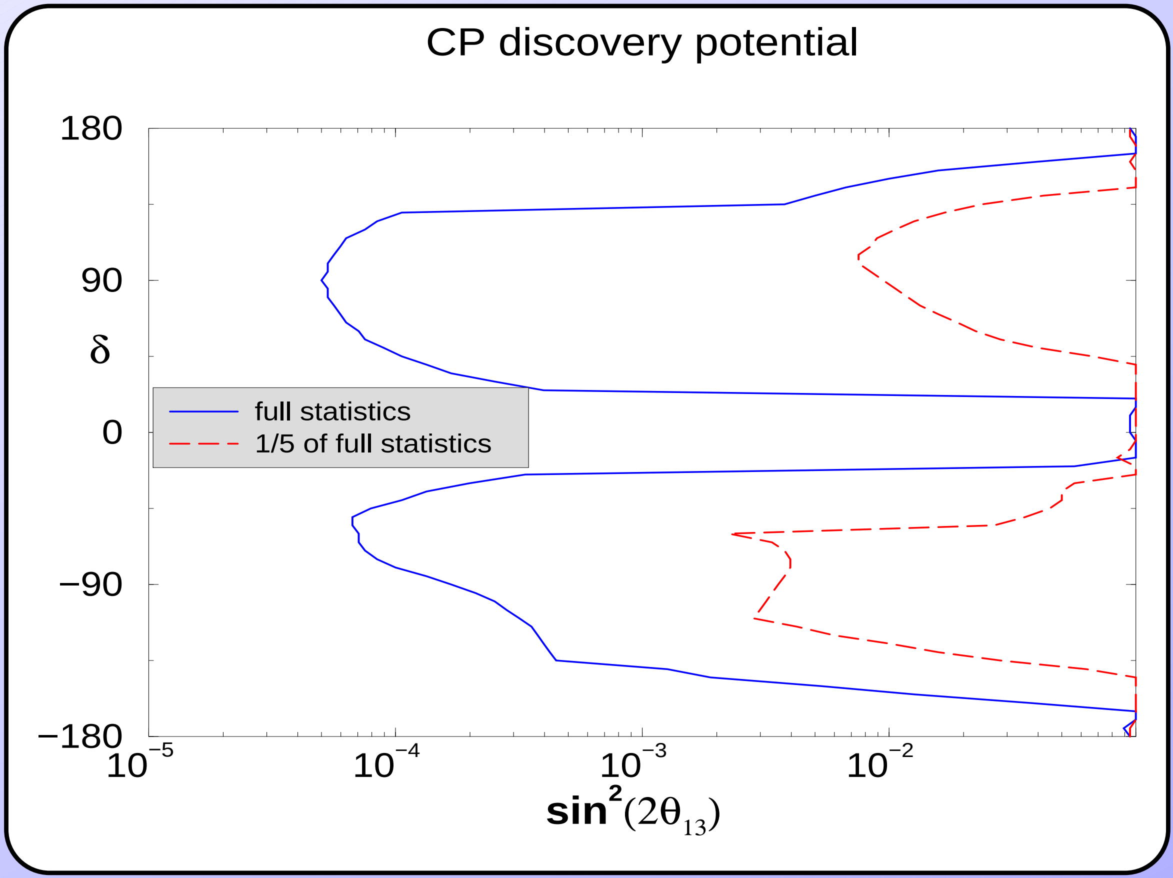
- High energy betabeam.

Hierarchy resolution at 99%CL.



The hierarchy can be resolved for 50% of values of δ for $\sin^2 2\theta_{13} > 0.001\ (0.005)$.

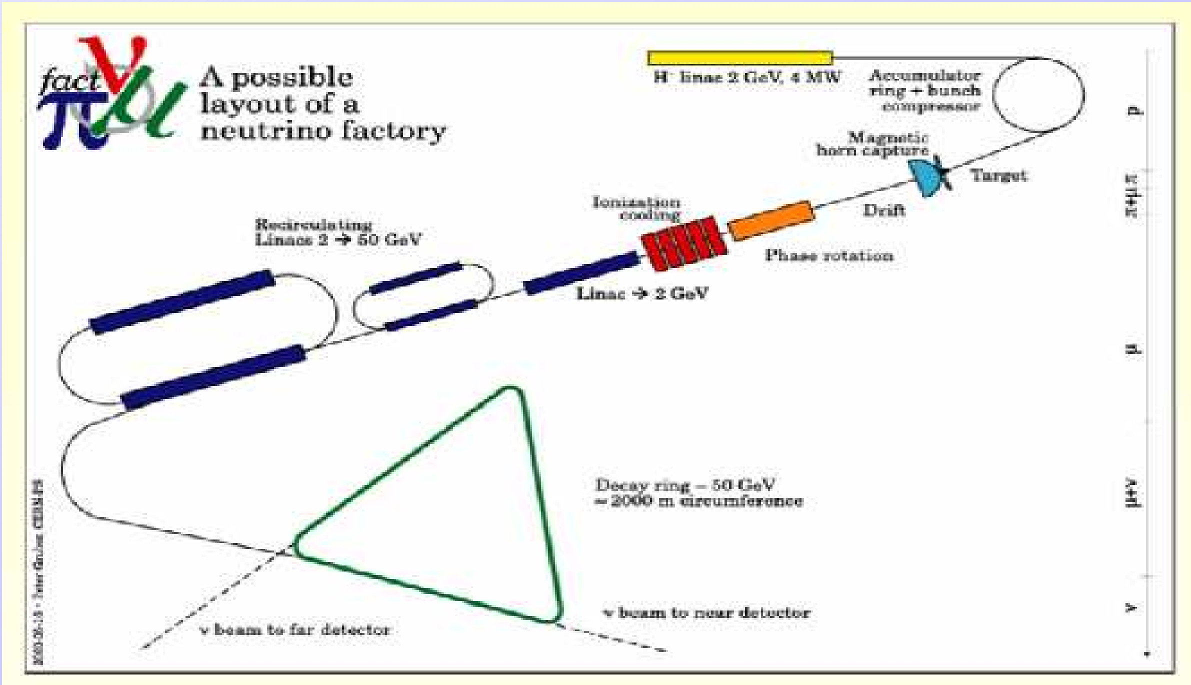
CP-violation discovery at 99%CL.



CP-violation can be found for values as small as $\sin^2 2\theta_{13} > 10^{-4}$ (few $\times\, 10^{-3}$).

9 – Neutrino factory

The beam is sourced by high γ muon decays: $\mu^- \longrightarrow e^- \nu_\mu \bar{\nu}_e$.



The signal is given by $\bar{\nu}_e \longrightarrow \bar{\nu}_\mu$, which needs to be distinguished from the dominant ν_μ flux. This implies the use of magnetised detectors.

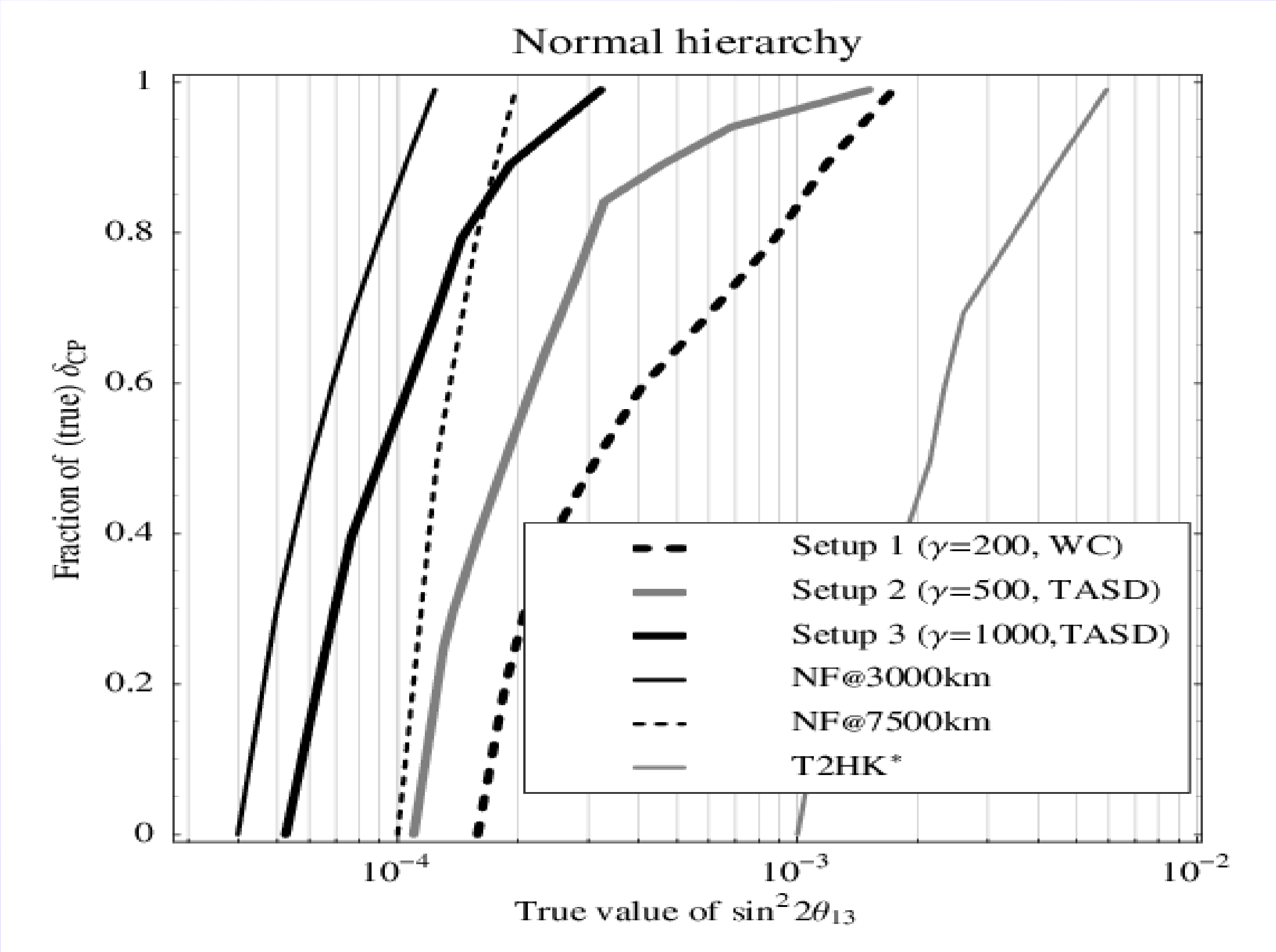
The baseline setup considers:

- Iron magnetised detectors with few GeV thresholds for measuring wrong-sign muons with adequate background rejection

- Muon energy $E_\mu \sim 20 - 50$ GeV and corresponding distances $L \sim 3000$–7000 km.

- For lower thresholds, it is possible to reduce the energy of the muons (streamlining the acceleration steps) and correspondingly the distance: low-energy neutrino factory concept.

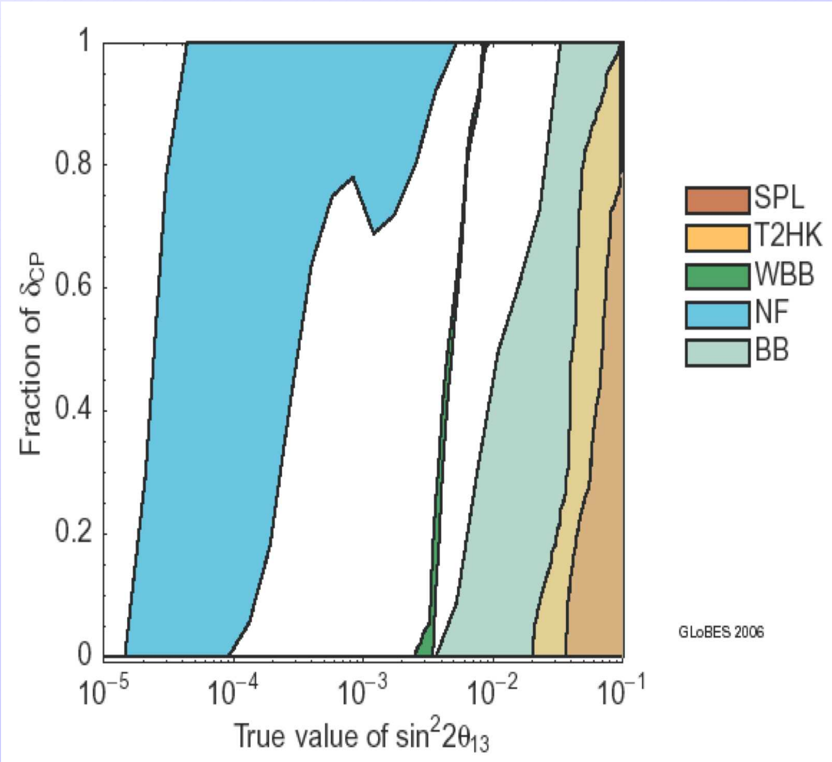
Ultimate sensitivity in neutrino factories or beta-beams:

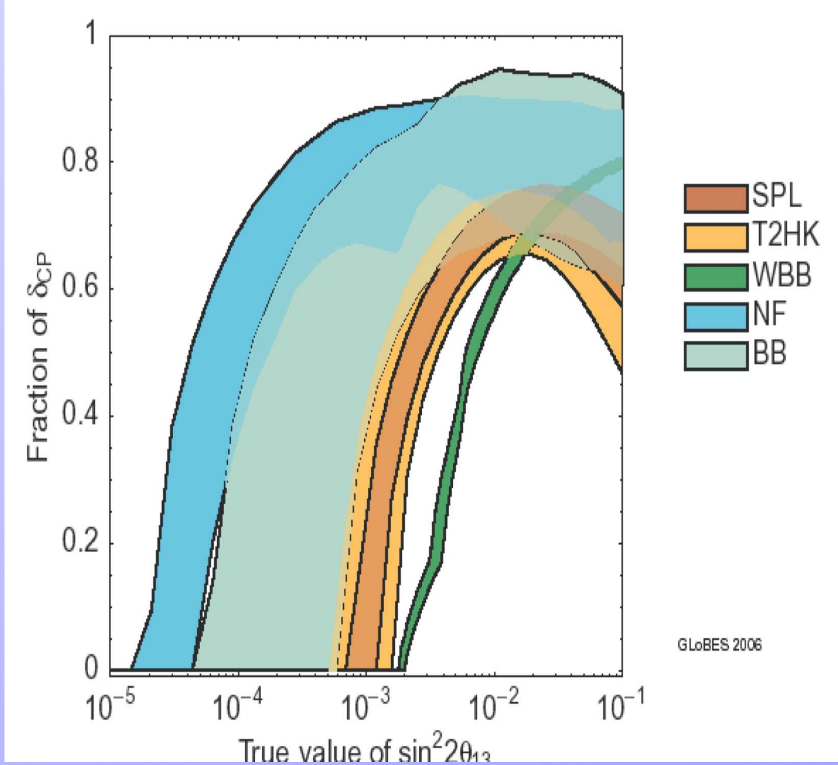


[Huber et al., PRD 2005]

10 – Experiment comparison

- The sensitivity of a setup depends critically on experimental parameters (flux, energy resolution, detector threshold, fiducial volume, systematics).





[ISS report, arXiv:07104947]

This is a very important time for understanding which neutrino LBL experiment.

- A FP7 Design study is in the negotiating phases: EUROnu. It will focus on superbeams, betabeams and neutrino factory.
- The International Design study on a neutrino factory is an effort which includes US, Europe and Asia and focuses on neutrino factory from the physics, accelerator and detector points of view.
- A FP7 Design study LAGUNA is also in the negotiating phases. It is devoted to underground laboratories and megaton-scale neutrino detectors.

11 – 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.

1. Nature of neutrinos: Dirac vs Majorana
2. Neutrino masses
3. CP-violation in the leptonic sector.

- A wide experimental program is going to address these questions in the next future: reactor and tritium beta decay, $(\beta\beta)_{0\nu}$-decay, LBL experiments.