Large detectors and neutrino physics

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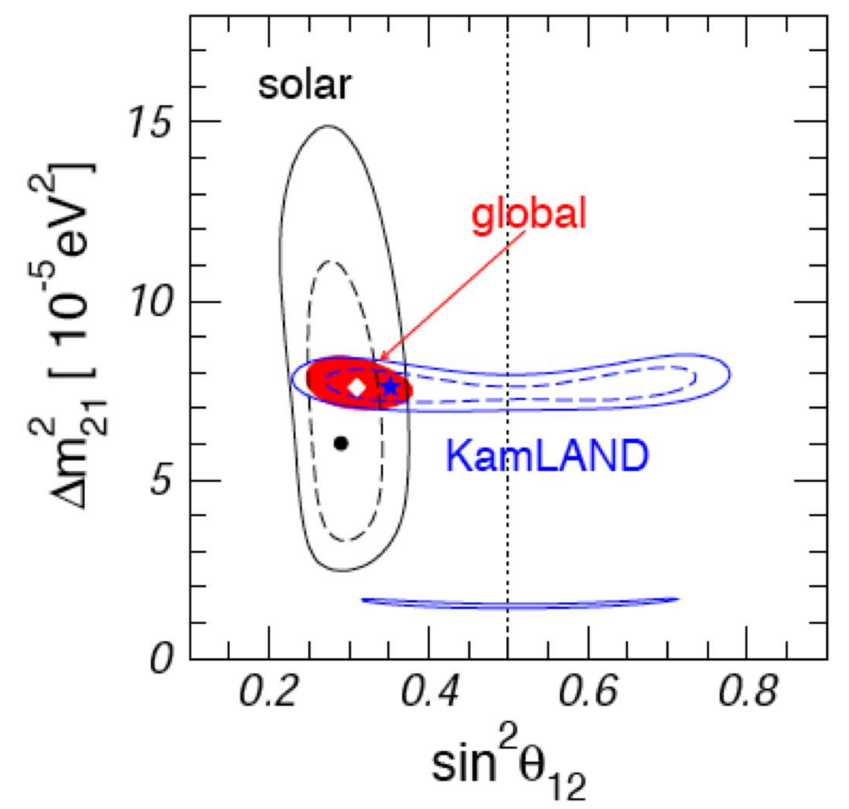
1 – Study of neutrino properties with Megaton-detectors

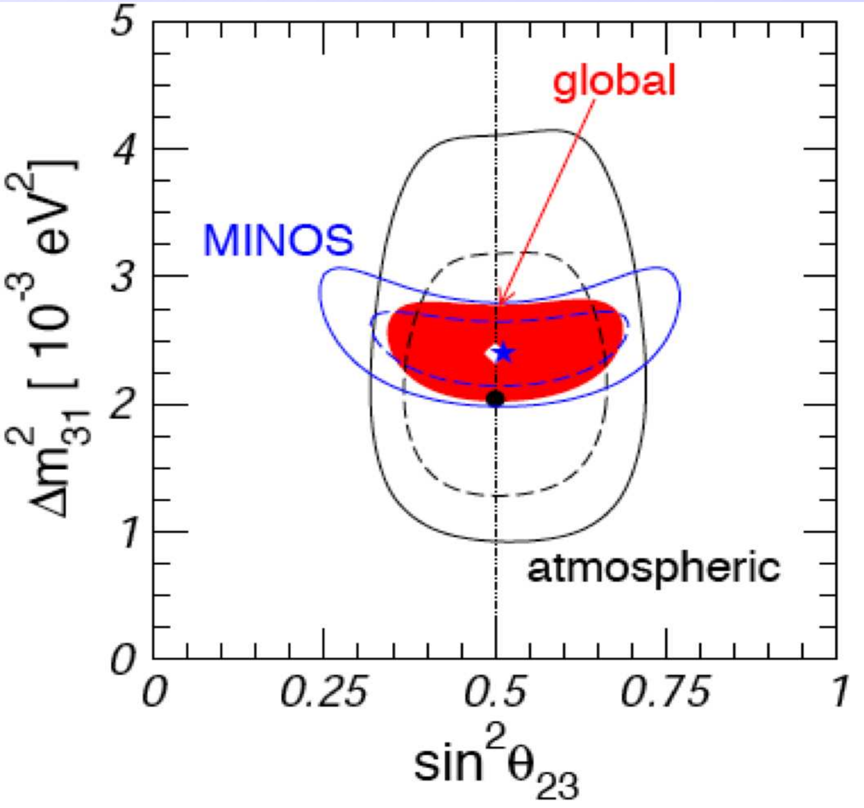
Megaton scale detectors allow to study neutrinos from terrestrial (accelerator, atmospheric, geoneutrinos) as well as astrophysical sources (Sun, Supernovae, dark matter annihilations).

Here I focus on the knowledge which can be obtained on **neutrino properties**.

- Atmospheric neutrinos
- Supernova neutrinos
- Long baseline neutrino experiments

- Solar neutrino and KamLAND experiments: $\Delta m^2_\odot$, θ_{12}
- Atmospheric neutrino, K2K, MINOS experiments: $\Delta m^2_{\rm atm}$, θ_{23}

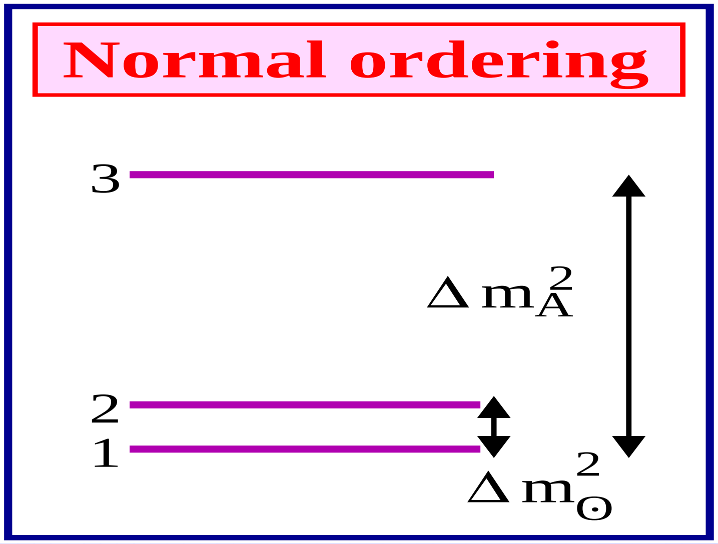


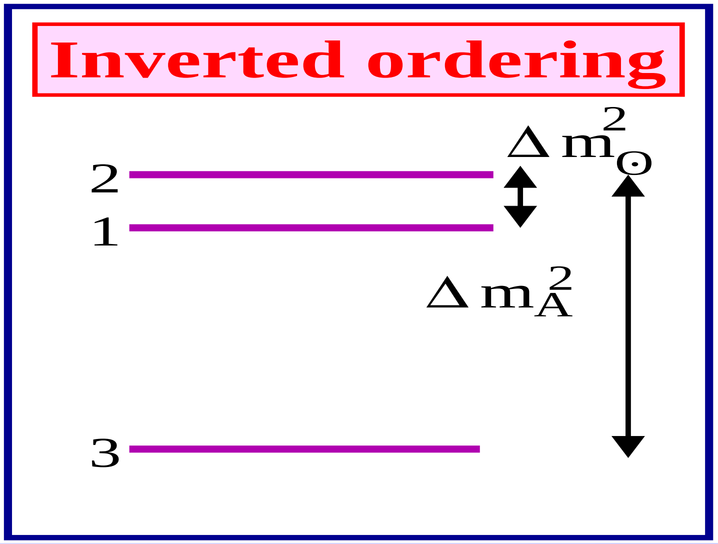


[Schwetz et al., NJP10]

$\sin^2\theta_{13} < 0.036\ (3\sigma)$. There is a recent hint of $\theta \neq 0$ at > 90%C.L.:

$$\sin^2\theta_{13} = 0.016 \pm 0.010$$ [Fogli et al., PRL101]





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

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

Measuring neutrino masses requires to know:

- m_{MIN}
- sign(Δm^2_{31}).

Questions for the future

- **What is the nature of neutrinos**?

Whether they Majorana ($\nu = \bar{\nu}$) or Dirac ($\nu \neq \bar{\nu}$). Majorana neutrinos violate the lepton number. $\boxed{\beta\beta_{0\nu} \text{ decay}}$

- **Absolute value of neutrino masses**?

Needed the type of hierarchy and the mass scale of the lightest neutrino:

$\beta\beta_{0\nu}$ **decay,** ^{3}**H** β **decay**

LBL oscillations, atmospheric neutrinos, supernova neutrinos

- **Leptonic CP-violation**?

$\delta \neq 0, \pi$ and/or $\alpha_{ij} \neq 0, \pi$. $\boxed{\textbf{LBL oscillations, } \beta\beta_{0\nu} \text{ decay}}$

- **Atmospheric neutrinos**: they could give information on the type of neutrino mass spectrum and on the values of the neutrino mixing angles. Having a magnetised detector would be useful as it allows to discriminate between neutrinos and antineutrinos and to have better sensitivity to matter effects.

- **Supernova neutrinos**: neutrinos produced in the core-collapse of a galactic supernova could provide information on θ_{13} and on the type of hierarchy.

- **Long baseline neutrino oscillation experiments**: subdominant neutrino oscillations are controlled by θ_{13} and are very sensitive to CPV and to matter effects. Various experimental setups are being considered in detail at present. I will give a short review.

2 – Atmospheric neutrinos

Once neutrinos have been produced in the atmosphere, they can travel through the Earth. The effective neutrino mass is changed due to the interaction with the background e^-, p and n and neutrino oscillations can get modified with respect to the case of vacuum.

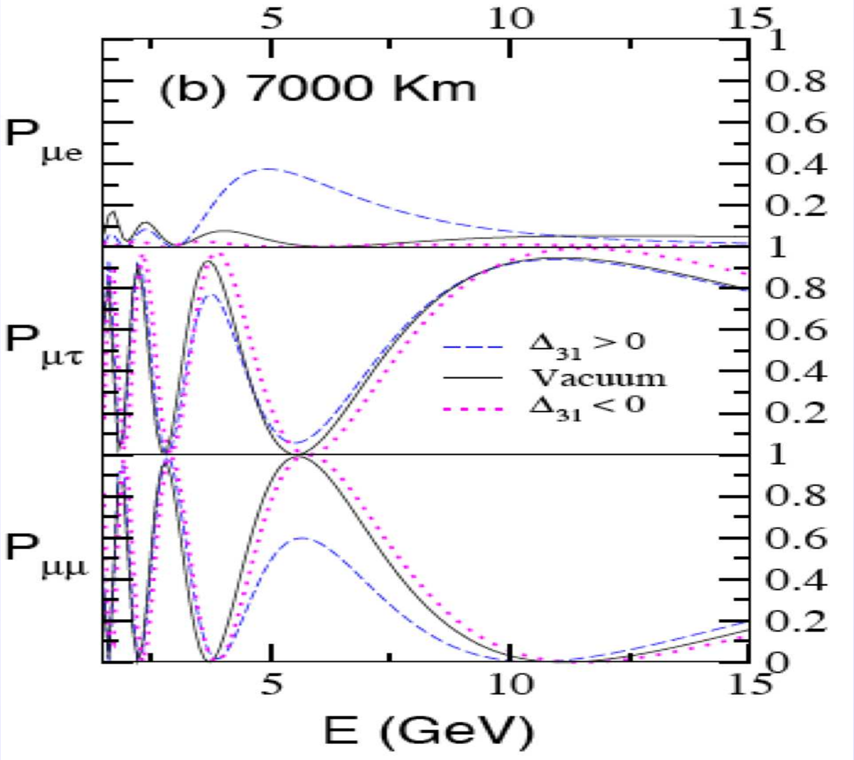
- Matter effects: A potential V in the Hamiltonian ($V = \sqrt{2} G_F (N_e - N_n/2)$) describes matter effects.

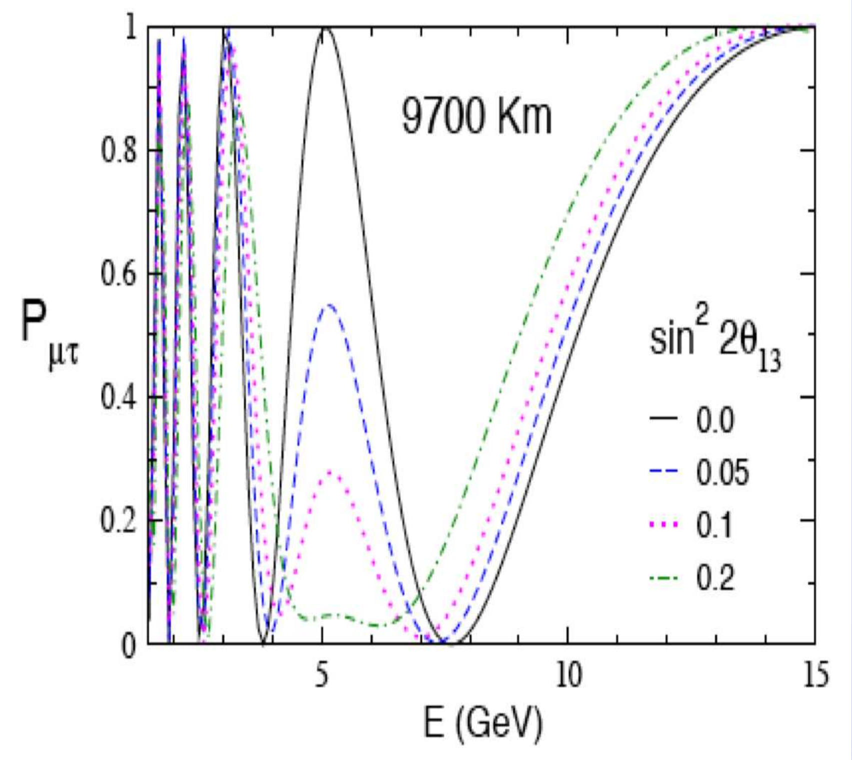
The mixing angle which controls the oscillations changes with respect to the vacuum case:

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

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

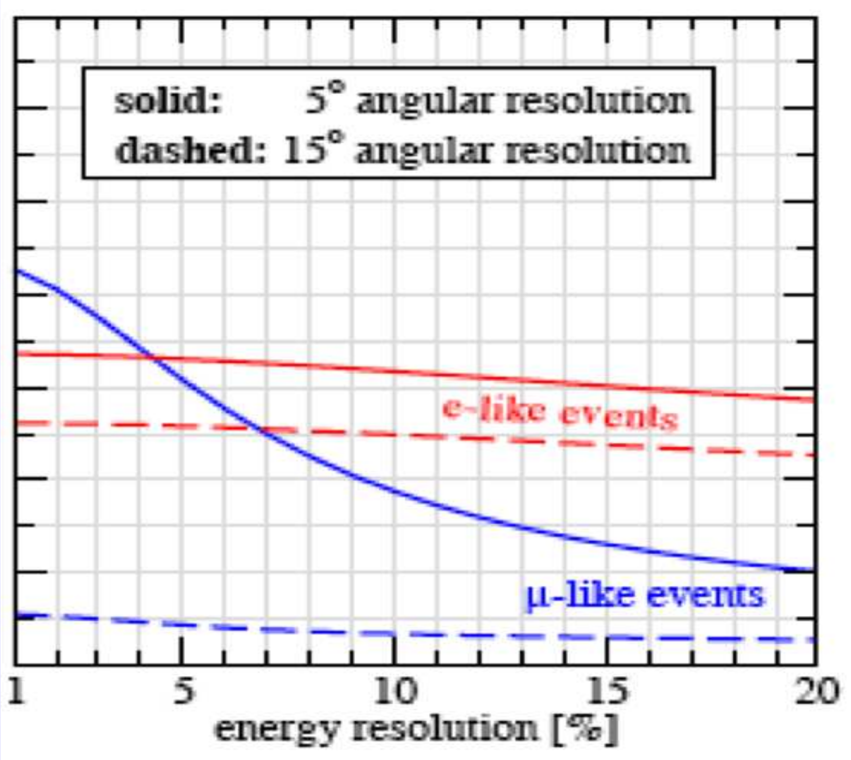
2 – Atmospheric neutrinos



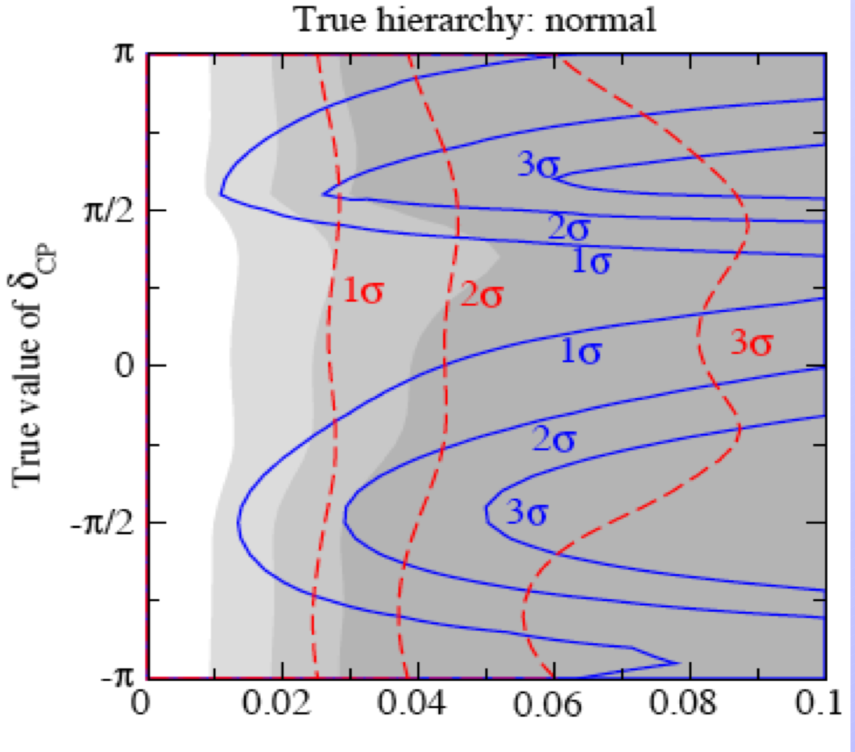


Gandhi et al., PRL94; Bernabeu; Maltoni; Palomares-Ruiz; Petcov; Schwetz et al.]

A large neutrino detector (possibly with charge discrimination) could resolve the type of neutrino mass hierarchy for $\sin^2 2\theta_{13} > 0.01$:



Petcov and Schwetz, NPB740



Huber, Maltoni, Schwetz, PRD71

3 – SuperNova neutrinos

In SN explosions neutrinos are produced in large amounts: $E \sim 10^{53}$ erg.

During the formation of the proto-neutron star, neutrinos are trapped in the core due to the high densities and are emitted from the neutrino-spheres in $\Delta t \sim 10$ s with a characteristic temperature: $E_{\nu_e} \sim 12$ MeV, $E_{\bar{\nu}_e} \sim 15$ MeV, $E_{\bar{\nu}_x} \sim 18\ (24)$MeV.

For a typical supernova, one expects:

	MEMPHYS	LENA	GLACIER
$\bar{\nu}_e$ IBD	2×10^5	9.0×10^3	
ν_e CC	1×10^4	80	2.5×10^4
$\bar{\nu}_e$ CC	1×10^4	500	540
ν_x eES	1×10^3	600	1×10^3
ν_x pES		7×10^3	
ν_x NC		3×10^3	3×10^4

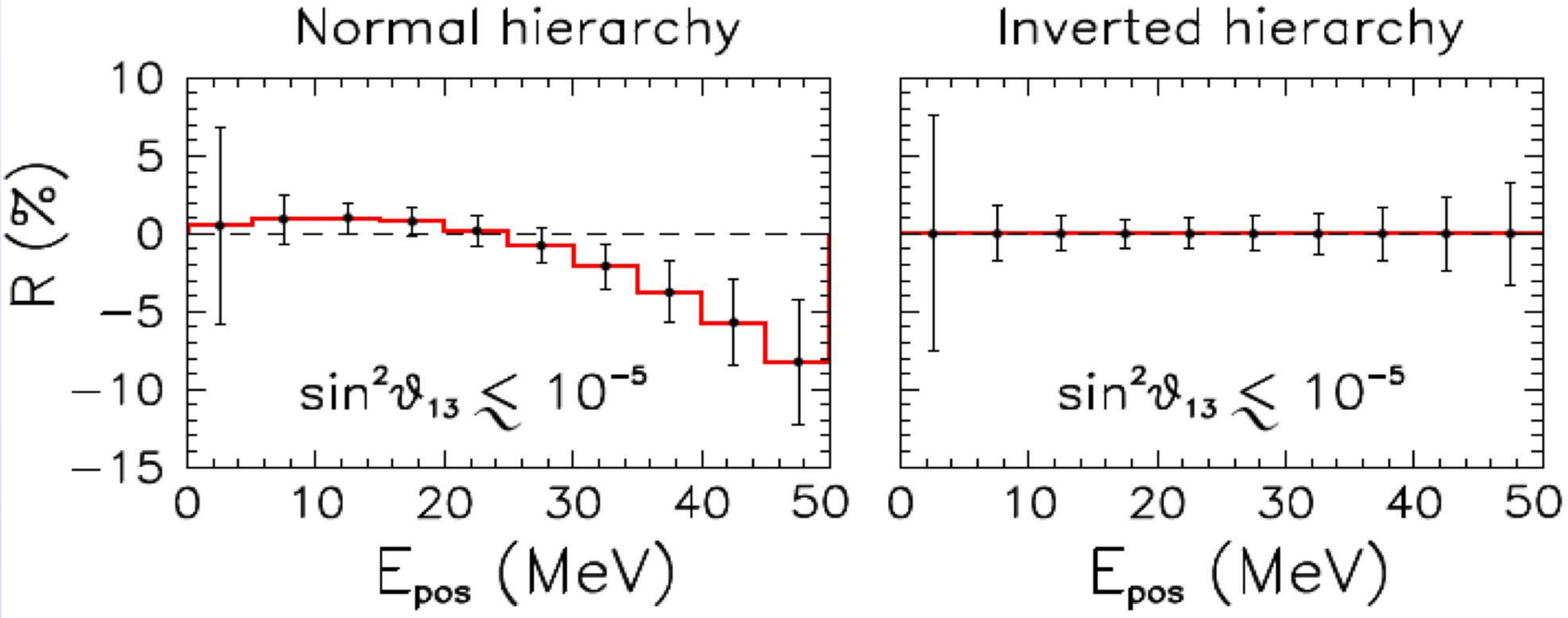
[Autiero et al., JCAP0711]

- Due to the very high densities, neutrinos have MSW and collective effects and convert from one flavour to another. The conversion depends on the type of hierarchy and on the energy.

- These effects are present both at large θ_{13} but also for $10^{-10} < \sin^2\theta_{13} < 10^{-5}$ due to collective effects in the supernova. In the normal hierarchy the ν spectra remain unchanged, while for inverted hierarchy the antineutrino spectra are completely swapped and the neutrino ones as well for sufficiently high energy. In the envelope, MSW effects are efficient for antineutrinos and large θ_{13}.

- Studying the neutrinos coming from a SN explosions would allow to get information on the neutrino properties, e.g. determining the type of neutrino mass spectrum.

- Shock wave effects
- Spectral split in ν_e
- Earth matter effects if 2 detectors in different locations



[Dasgupta et al., PRL101]

4 – Long baseline neutrino experiments

δ and the sign of Δm^2_{31} can be measured in long baseline appearance ν-oscillation experiments: they use a manmade flux of neutrinos with detectors located at 100s-1000s of km away.

These accelerator neutrino experiments search for $\nu_\mu \longrightarrow \nu_e$ appearance:

$$\boxed{P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31} L}{4E}}$$

for subdominant matter effects and CPV.

- CP-violating and matter effects are **controlled by the angle θ_{13}**.

- Matter effects: for constant density, the probability can be approximated as (for no CPV)

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

For $\Delta m^2 > 0$, the probability gets enhanced for neutrinos and suppressed for antineutrinos. Viceversa, for $\Delta m^2 < 0$. Matter effects imply that

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

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

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

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 $\nu_\mu \longrightarrow \nu_e$, in 3-neutrino mixing case, is given by:

$$\boxed{\begin{aligned} P(\bar{P}) \simeq \quad & s^2_{23} \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{A \mp \Delta_{13}}\right)^2 \sin^2 \frac{(A \mp \Delta_{13})L}{2} \\ & + \tilde{J} \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{A \mp \Delta_{13}} \sin \frac{AL}{2} \ \sin \frac{(A \mp \Delta_{13})L}{2} \cos\left(\mp\delta + \frac{\Delta_{13}L}{2}\right) \\ & + c^2_{23} \ \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2 \frac{AL}{2} \end{aligned}}$$

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

It is necessary to disentangle

true CP-V effects due to the δ phase

from the ones induced by matter:

degeneracies.

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.] :

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

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

$$\begin{aligned} &\delta' && \pi - \delta \\ &\mathrm{sign}'(\Delta m^2_{13}) && -\mathrm{sign}(\Delta m^2_{13}) \end{aligned}$$

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

5 – Synergy between Megaton detectors and long baseline oscillations

- Desirable characteristics for a long baseline experiment:

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

b) this implies a small flux and a very large (megaton scale) detector

c) detector with low energy threshold (100s of MeV) to fully exploit the oscillatory pattern of the signal (necessary for degeneracy resolution)

The synergy is two-fold:

- **detectors**
- **location of the underground laboratory which defines the baseline.**

Future LBL experiments:

1. **Superbeams**: a very intense ν_μ beam. Intrinsic ν_e background. Typical energies: 100 MeV to few GeV $\longrightarrow$ WC, LiAr or scintillator detector.
2. **Beta-beams**: ν_e beams given by the β-decays of high-gamma ions. Same energy and type of detector as for superbeams.
3. **Neutrino factories**: ν_μ-ν_e beam from high-γ muons (20 GeV - 50 GeV). The detector needs to be magnetised to distinguish the signal from the background. A new concept for a **neutrino factory** uses muons at low energy (GeV) and requires a magnetised detector with a threshold below 1 GeV, as a Liquid Argon Detector or a Scintillator detector.

Detector

- It is critical to perform detailed simulations of these detectors. The sensitivity of these experiments depends very much on the properties of the detector (backgrounds, energy resolution, size).

- The energy resolution and the threshold determine the ability to exploit the rich oscillatory pattern and therefore resolve degeneracies.
- The size and efficiency determine the statistics which can be reached, this is very critical for betabeams.
- Systematics errors might be the future limiting factors.
- Superbeams and betabeams do not need magnetisation which is instead necessary for neutrino factory.

Baseline

- The study of specific sites for an underground laboratory will provide the choice of baselines (from CERN or RAL-UK or Germany) which affects significantly the physics reach.
- The longer the baseline the stronger matter effects in the oscillations. This implies an increased sensitivity to the type of neutrino mass spectrum.
- The longer the baseline the smaller the flux, which can be compensated with a larger detector or higher intensity.
- The longer the baseline the higher the energy as the experiments try to increase the sensitivity by having the average energy at first oscillation maximum. Higher energy typically implies higher cross section but also impacts on the type of detector used (WC versus LiAr vs scintillator vs iron magnetised).

The choice of baseline has a very strong effect on the physics reach of the setup.

6 – Superbeam experiments

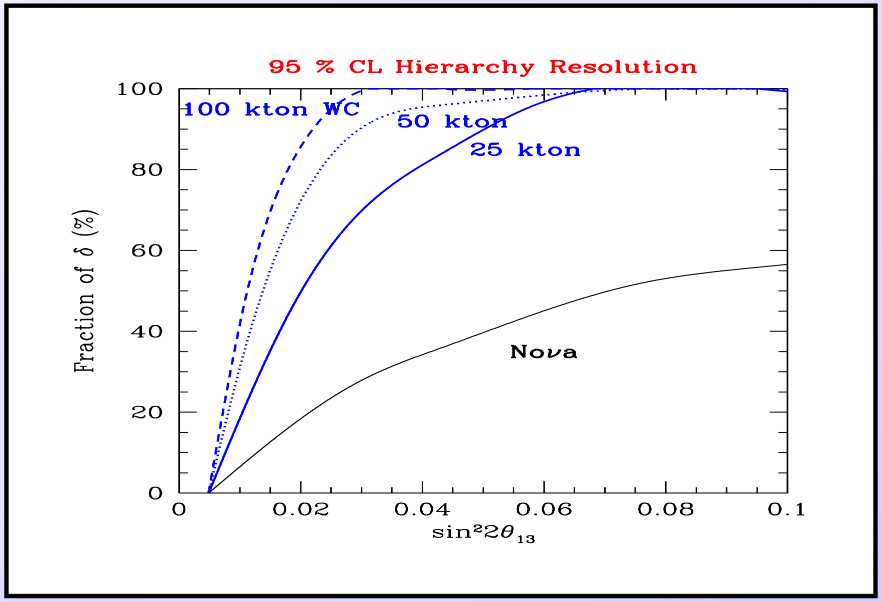
Superbeams use ν_μ beams from $\pi(K)$ decays and search for ν_e appearance.

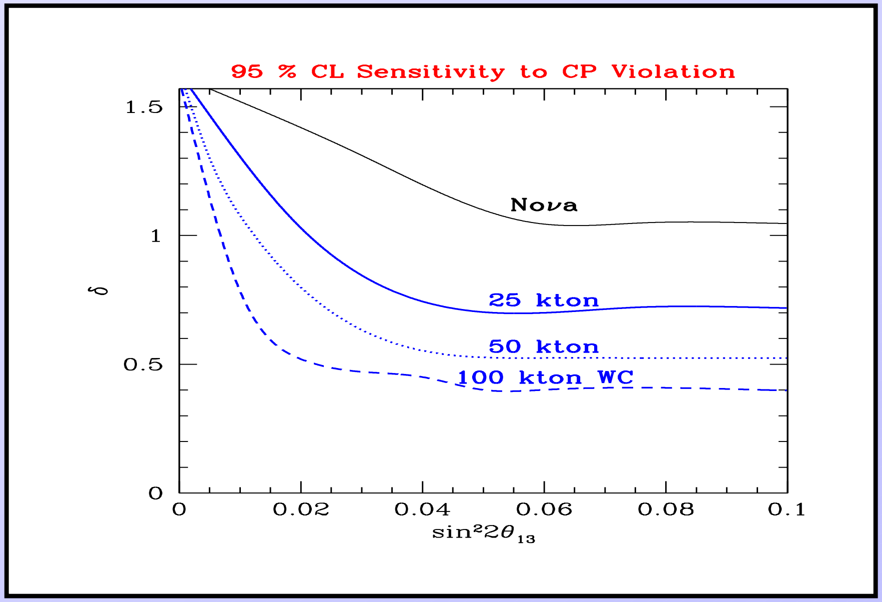
- In 2009, T2K will start: uses a baseline of 295 km and SK as a detector. Its main goal is to discover θ_{13}.

- NOνA is in preparation: uses the NuMI beam from Fermilab to a TASD detector located 800 km away. It has sensitivity to CP-violation and possibly the type of hierarchy (due to the longer baseline).

hierarchy

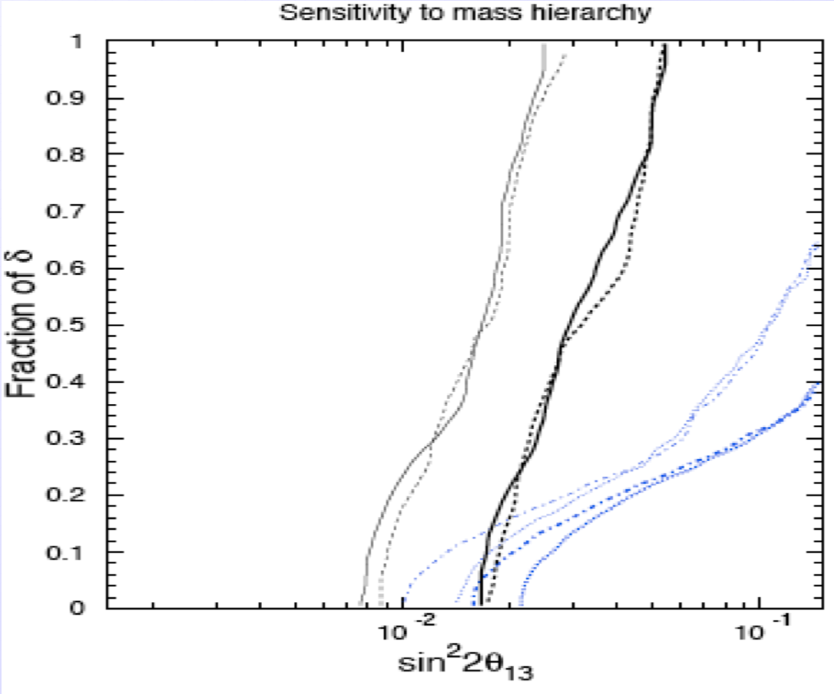
CP-violation



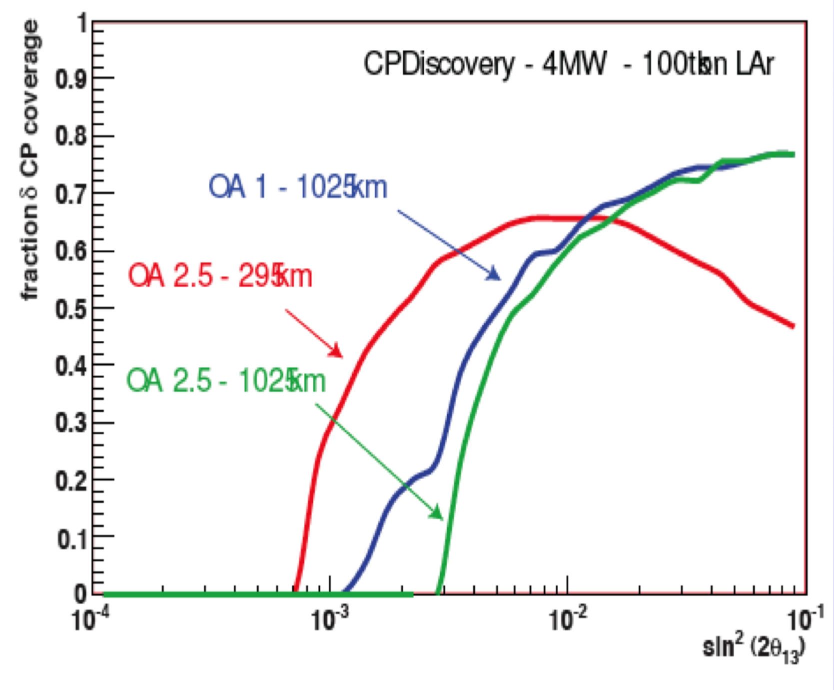


[Mena et al., see also NOvA proposal]

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



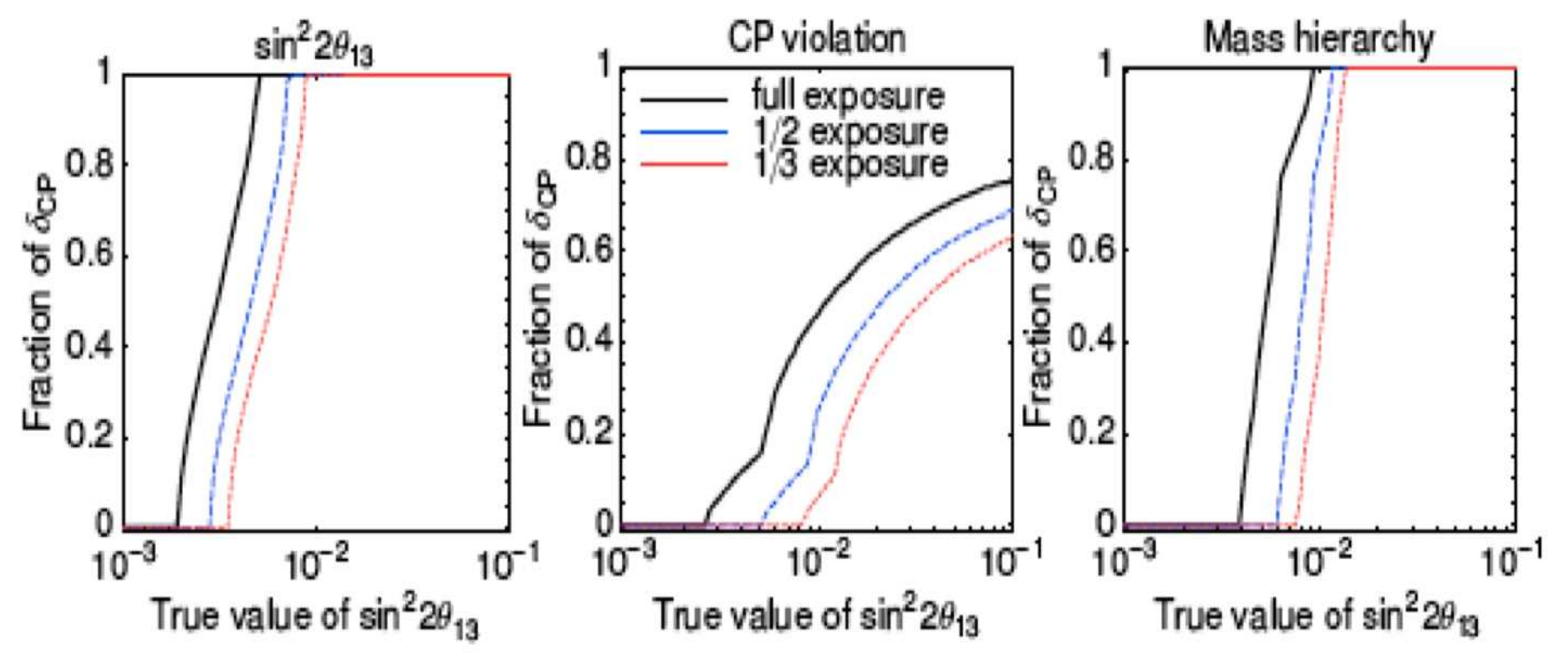
[Ishitsuka et al., PRD72 and subsequent works]



[Kajita, Kim, Rubbia, 2008]

- Wide band beam with 100kton size detector

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



[Barger et al.; Huber et al.]

7 – β-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.]

- low energy option: $\gamma \sim 100$ with ^{6}He and ^{18}Ne and $L = 130$ km (CERN-Frejus). No sensitivity to matter effects.

- high energy: $\gamma \sim 400$ with longer distances. Improved sensitivity.

- high Q-value: use of ^{8}B and ^{8}Li for a high neutrino energy.

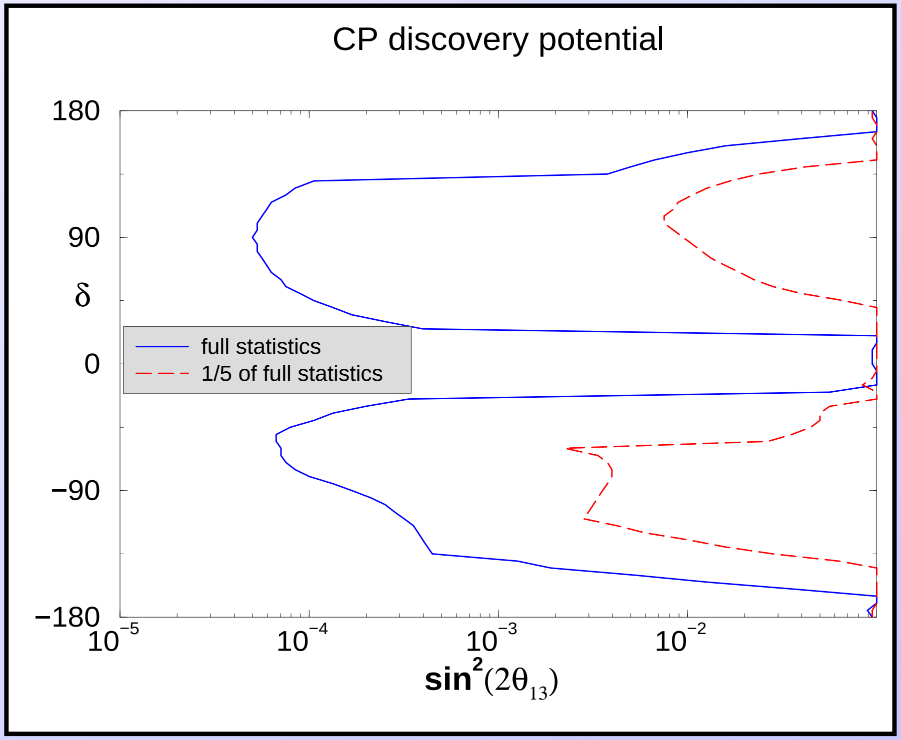
7 – β-beams

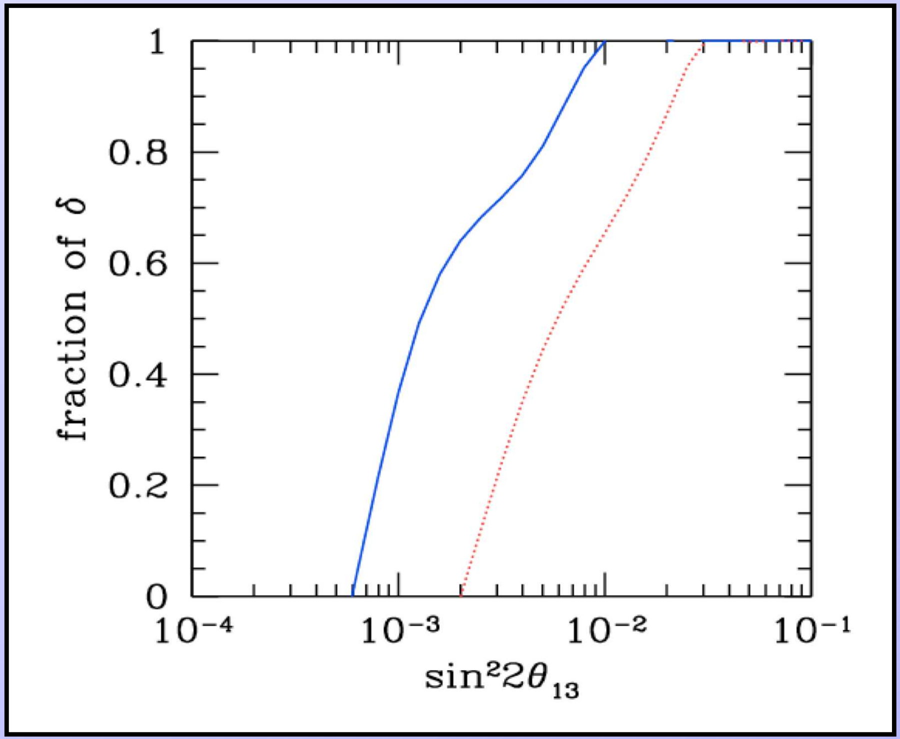
		Current SPS			Upgraded SPS		
Isotope	E_P (MeV)	γ	E_ν (GeV)	L_{max} (km)	γ	E_ν (GeV)	L_{max} (km)
^{18}Ne	1.86	250	0.93	460	592	2.20	1090
^{6}He	1.94	150	0.58	288	355	1.38	682
^{8}B	7.37	281	4.15	2051	666	9.82	4859
^{8}Li	6.72	169	2.27	1122	400	5.37	2658

Consider a betabeam with intermediate γ and long baseline in Europe.

- $\gamma = 450$ for ^{18}Ne with 5×10^{21} ions-kton-years.

- long baseline $L = 1050$ km (CERN-Boulby): new possibility to build large caverns at Boulby to host 10-kton detectors

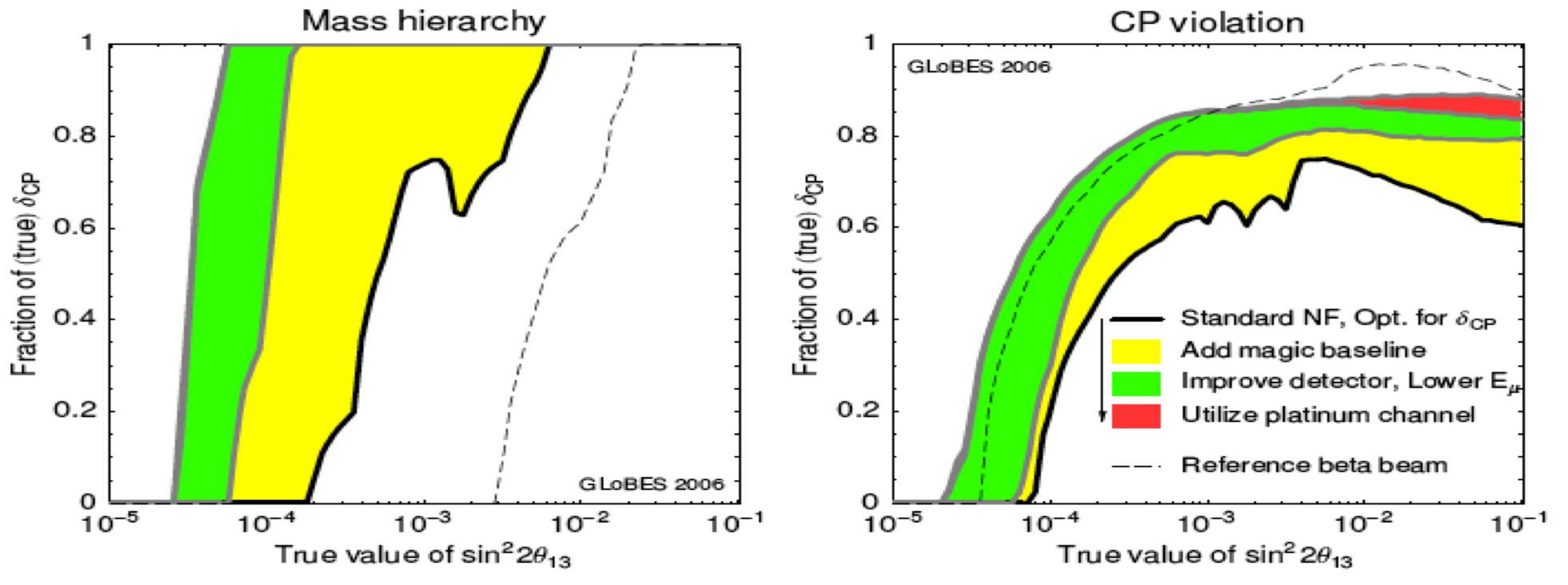




[Meloni, Mena, Orme, Palomares-Ruiz, SP, JHEP]

8 – A neutrino factory

- For detectors with few GeV thresholds for measuring wrong-sign muons with adequate background rejection, a high energy neutrino factory ($E_\mu \sim 20 - 50$ GeV) is necessary.
- The baseline detector is a 50 kton iron magnetized detector located at 3000 km and 7000 km (magic baseline).



[Huber et al, PRD74]

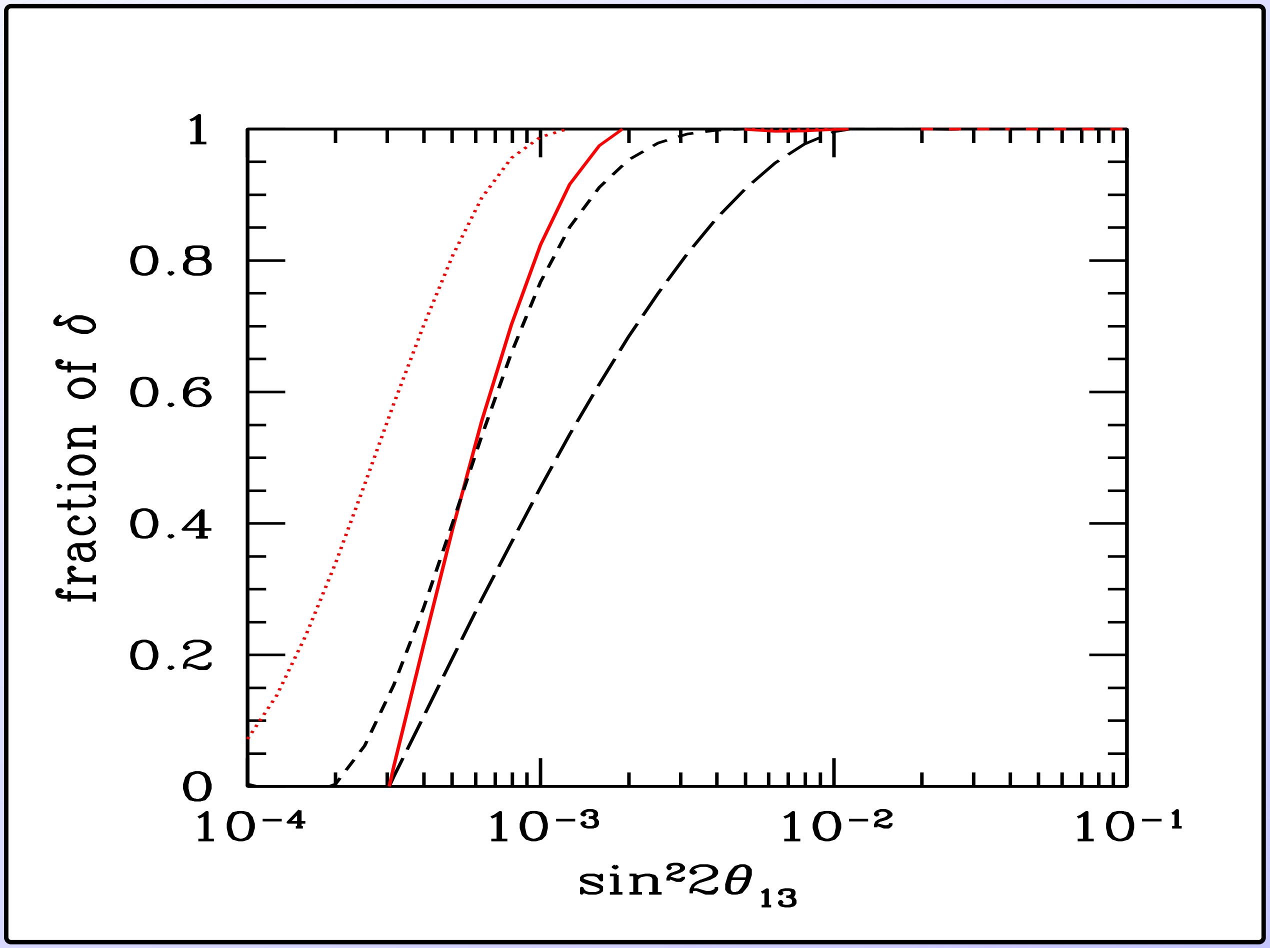
- For lower thresholds, it is possible to reduce the energy of the muons (streamlining the acceleration steps) and correspondingly the distance:

low-energy neutrino factory concept.

We performed an analysis of a low energy neutrino factory:

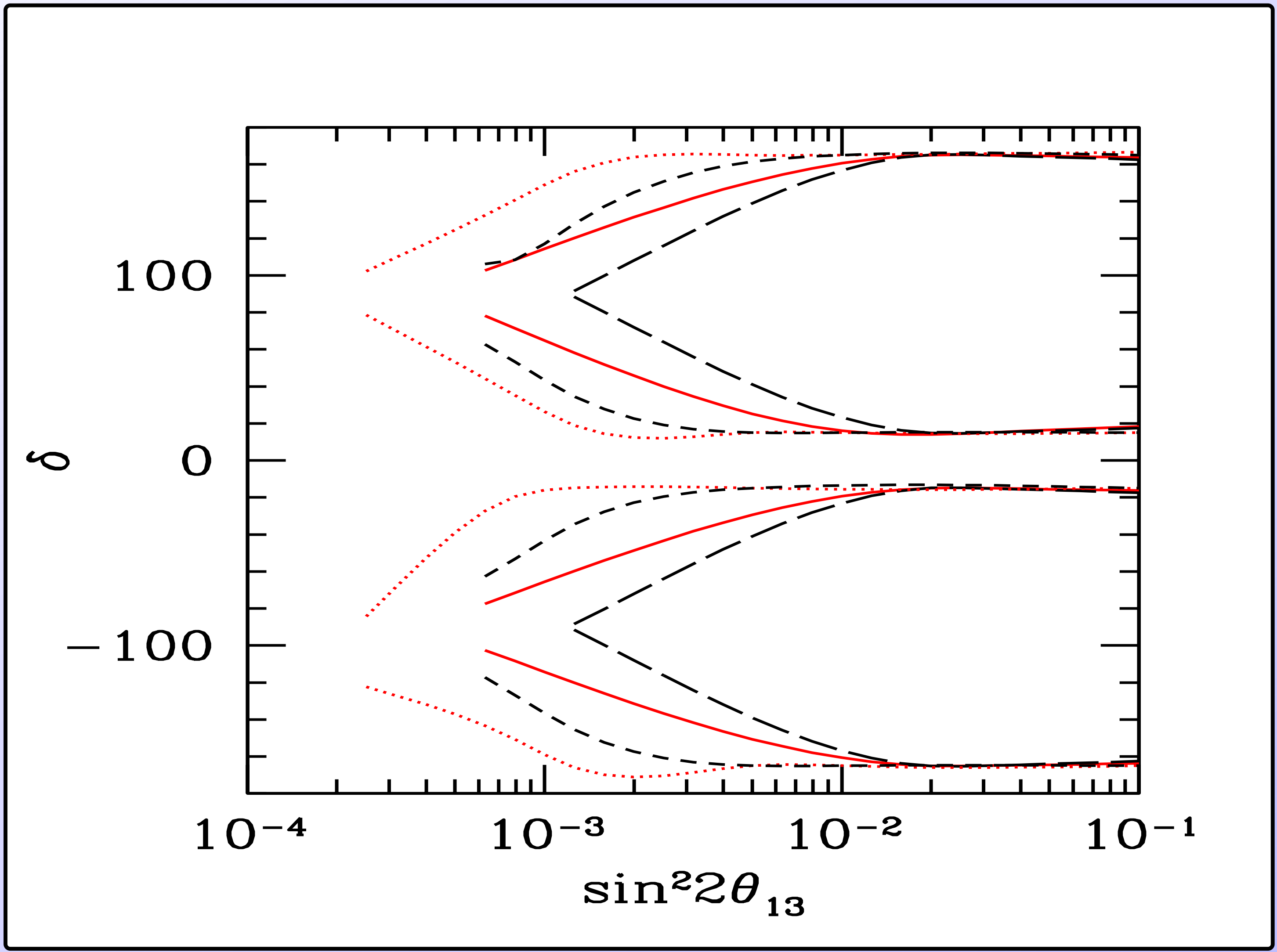
- short baseline, $L =$1480 km;
- fine grained magnetized detector TASD (efficiency: 73%; see P. Kyberd's talk).
- low energy threshold: 0.5 GeV and $dE/E = 30\%$
- Setup A: 1×10^{23} kton-decays; Setup B: 3×10^{23} kton-decays

The exclusion plots for the type of hierarchy.



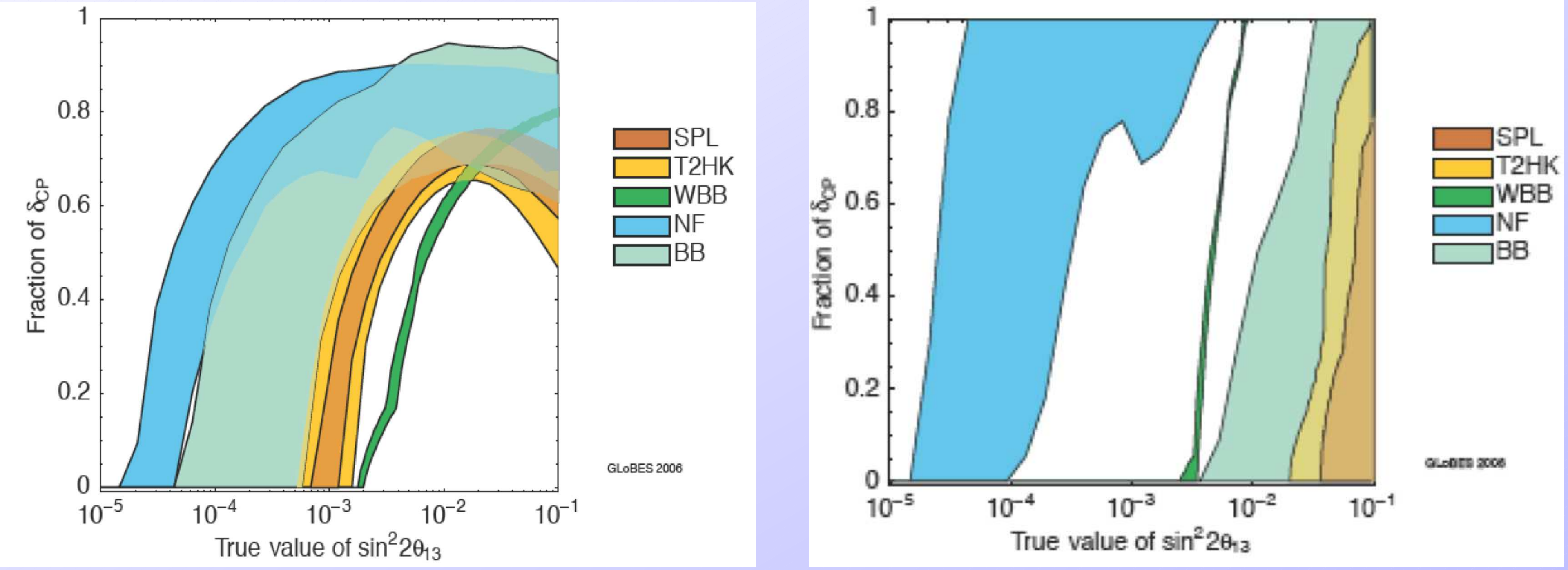
For values of $\sin^2\theta_{13}$ as small as 0.003 (for Setup A, background $\ll 10^{-3}$) and 9×10^{-4} (for Setup B, background $\ll 10^{-3}$), it can be established independently from the δ phase!

CP-violation reach:



Sensitivity to CPV for $\sin^2\theta_{13}$ down to few $\times 10^{-4}$.

A summary of the sensitivity of some studied setups:



Sensitivity to CPV and the type of neutrino mass hierarchy [from the ISS study]

Neutrinos can also be used to study properties of astrophysical objects, dark matter and the Universe.

- Diffuse neutrino background
- Geoneutrinos
- Solar neutrinos
- Neutrinos from dark matter annihilations:

from WIMP annihilations in the Sun

from light DM annihilations in the galaxy.

Their detection allows to reconstruct DM properties (mass and interactions) and compare with the knowledge from LHC and future colliders as well as direct and indirect DM searches.

10 – Conclusions

Megaton scale detectors have a wide physics reach.

- Studies of solar and atmospheric neutrinos, reactor and geoneutrinos
- Detection of supernova neutrinos: both for a future SN and for the diffuse SN neutrino background.
- Long baseline neutrino oscillations. The choice and size of the detector combined with the baseline (determined by the location of the underground laboratory) is critical in defining the sensitivity of the experiment.
- Indirect detection of dark matter in neutrino detectors will provide useful information on dark matter and its properties. In the next few years, this information needs to be combined with the LHC and direct searches.