Neutrinos: an open window on Fundamental physics and the **Evolution** of the **Universe**

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MICE Collaboration Meeting
RAL

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Outline

1. Neutrino properties: questions for the future

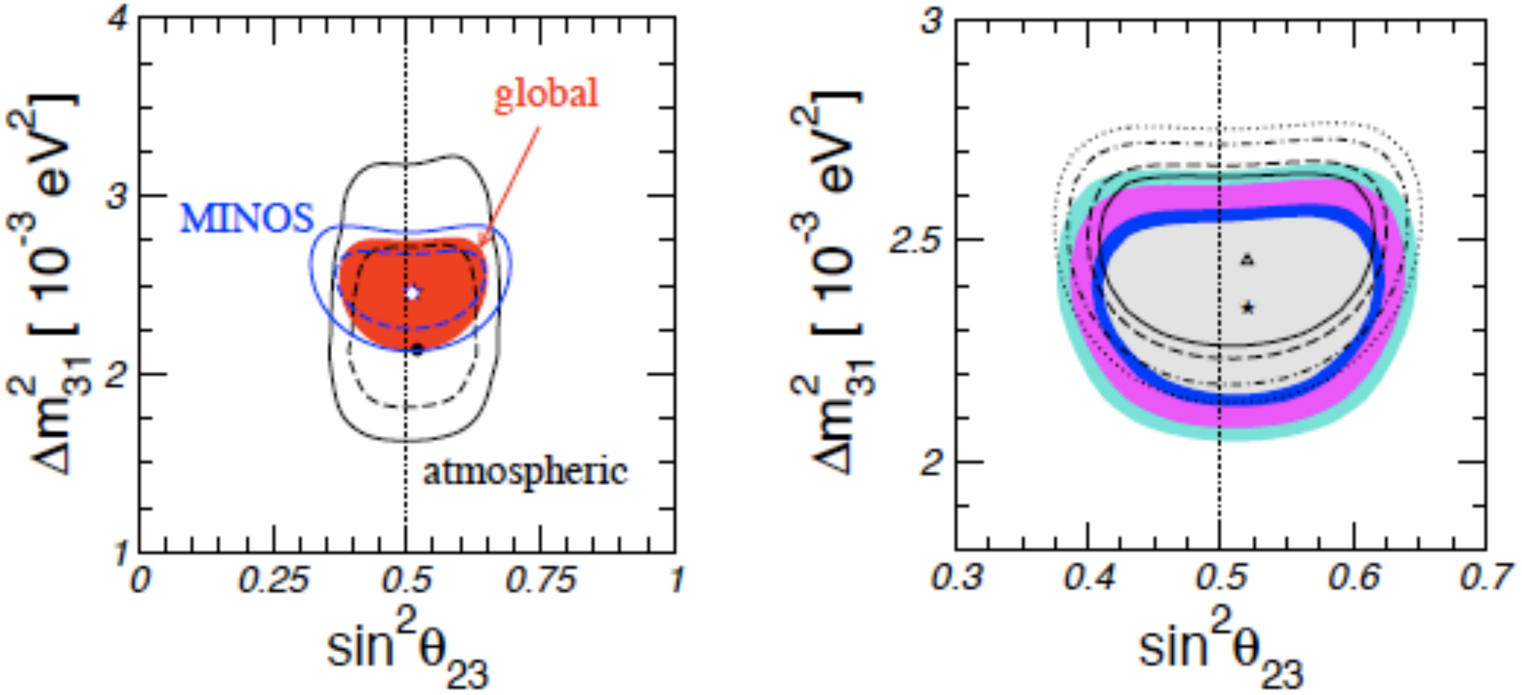
2. Measuring the parameters in LBL

3. Theory: the origin of neutrino masses and the problem of flavour

4. Conclusions and outlook

Neutrino oscillations measure mass squared differences and mixing angles.

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 \frac{\Delta m^2_{21} L}{4E}$$

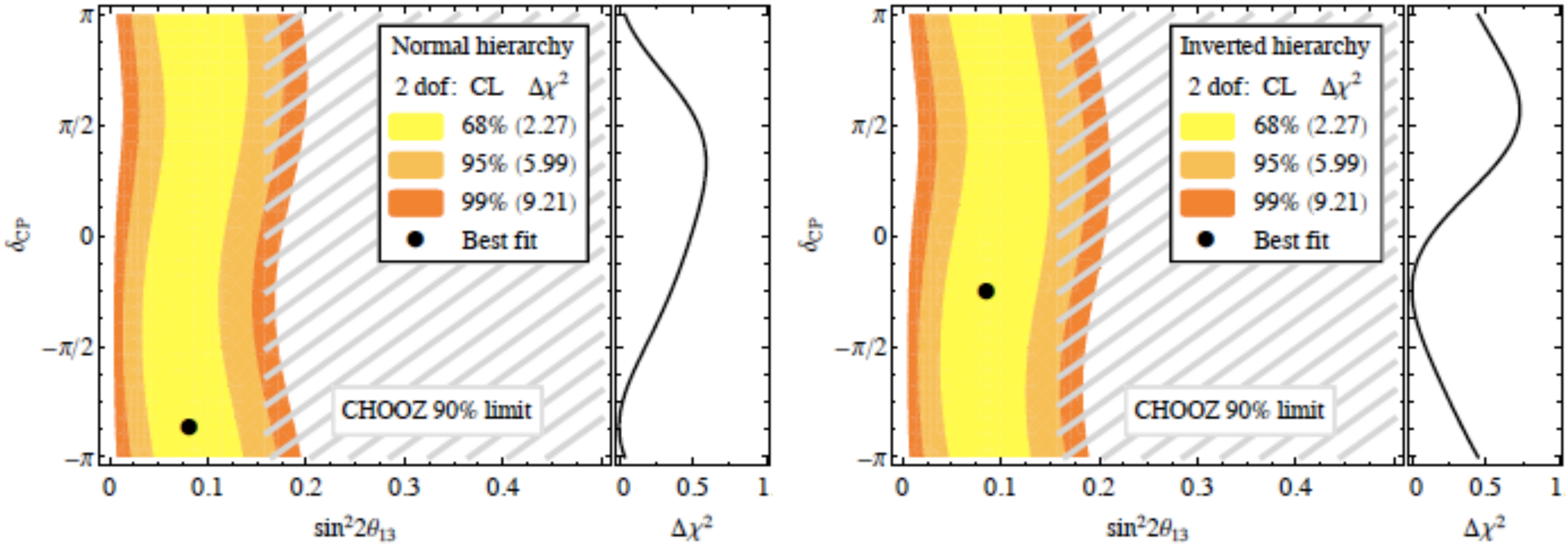


Schwetz et al., 1103.0734

Neutrino oscillations imply that neutrinos have mass and they mix!

First evidence of physics beyond the SM.

In 2011, the first hints of large θ_{13} were found in T2K, MINOS and DoubleCHOOZ.



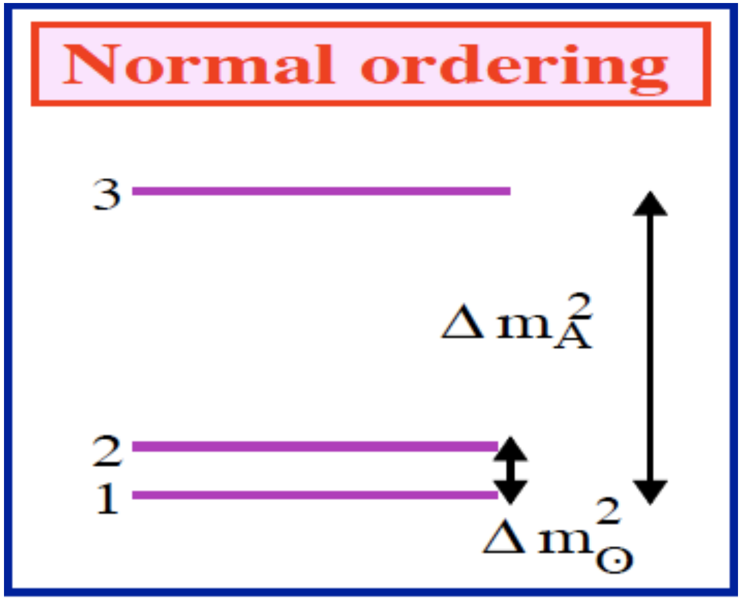
Machado et al., 1111.3330

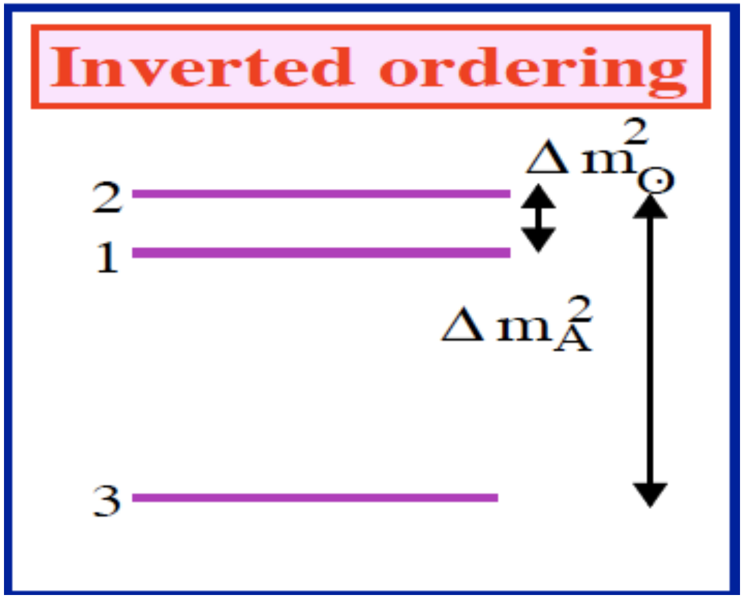
T2K, DoubleCHOOZ, RENO, Daya Bay will be able to confirm such hints very soon.

This will have important implications for experiments and theory.

Present status of (standard) neutrino physics

$\Delta m_s^2 \ll \Delta m_A^2$ implies at least 3 massive neutrinos.





$$m_1 = m_{\text{min}}$$
$$m_2 = \sqrt{m_{\text{min}}^2 + \Delta m_{\text{sol}}^2}$$
$$m_3 = \sqrt{m_{\text{min}}^2 + \Delta m_{\text{A}}^2}$$

$$m_3 = m_{\text{min}}$$
$$m_1 = \sqrt{m_{\text{min}}^2 + \Delta m_{\text{A}}^2 - \Delta m_{\text{sol}}^2}$$
$$m_2 = \sqrt{m_{\text{min}}^2 + \Delta m_{\text{A}}^2}$$

Measuring the masses requires: m_{min} and the ordering.

Mixing is described by a unitary mixing matrix.

$$U = \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar, reactor } \theta_\odot \sim 30^o} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atm, Acc. } \theta_A \sim 45^o}$$

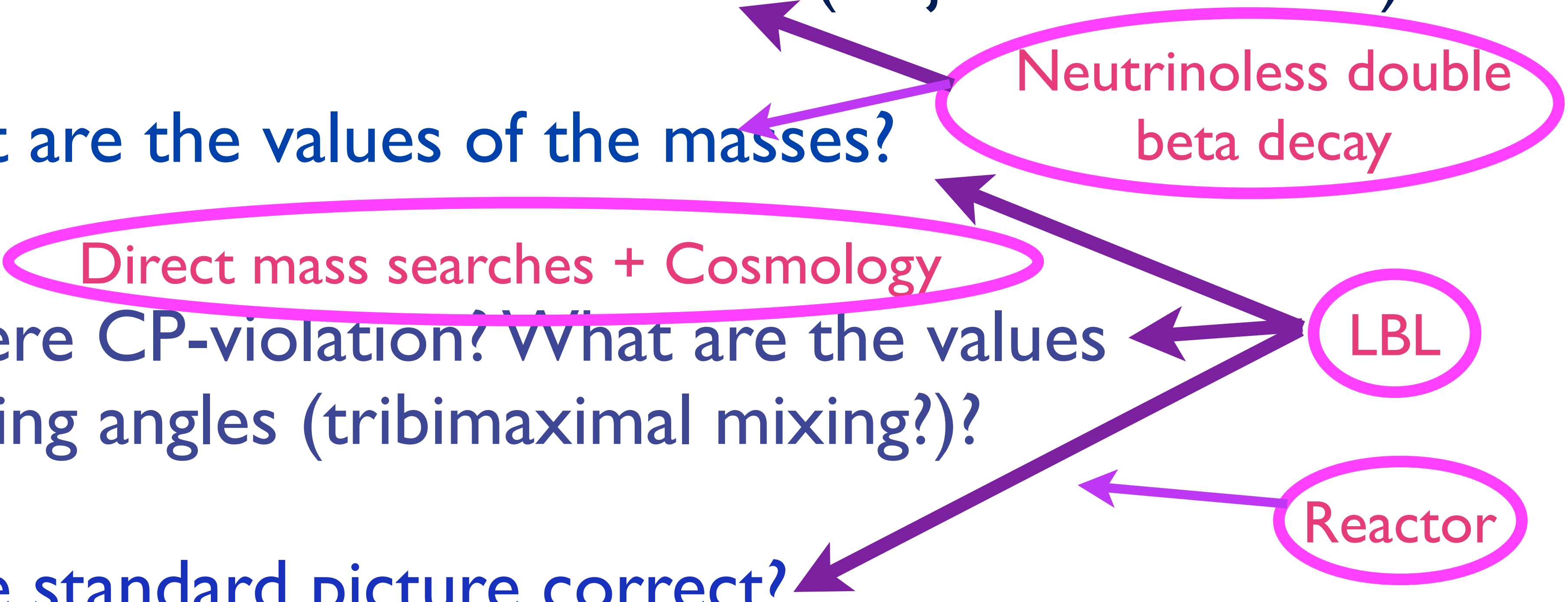
$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix}}_{\text{CPV phase}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor, Acc. } \theta < 12^o} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{-i\alpha_{31}/2+i\delta} \end{pmatrix}}_{\text{CPV Majorana phases}}$$

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

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

This is a fundamental question to answer and is related to leptogenesis and the possible origin of the baryon asymmetry of the Universe.

Phenomenology questions for the future



- What is the nature of neutrinos (Majorana vs Dirac)?

- What are the values of the masses?

- Is there CP-violation? What are the values of mixing angles (tribimaximal mixing?)?

- Is the standard picture correct?

Neutrinoless double beta decay

Direct mass searches + Cosmology

LBL

Reactor

A wide experimental programme is under way or at the proposal stage. Other relevant searches are: solar (Borexino), atmospheric (megaton-scale detector, INO), supernova neutrinos, SBL exp for sterile neutrino searches such as the VLENF.

Long baseline neutrino oscillations

Long baseline neutrino oscillation experiments (T2K, LBNE, EU superbeams, neutrino factories and beta beams) will aim at studying the subdominant channels

$$\nu_{\mu,e} \longrightarrow \nu_{e,\mu} \quad \bar{\nu}_{\mu,e} \longrightarrow \bar{\nu}_{e,\mu}$$

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

for negligible matter and CPV effects.

in order to establish

1. **the mixing angles (θ_{13})**
2. **the mass hierarchy**
3. **Leptonic CPV**
4. **Non-standard effects.**

Matter effects

These oscillations take place in the Earth (e, p, n). A potential V in the Hamiltonian describes matter effects: $V = \sqrt{2} G_F (N_e - N_n/2)$

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

The mixing angle changes wrt vacuum

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

and the probability gets enhanced for neutrinos (antineutrinos) depending on the mass ordering.

CP-violation

A measure of CPV effects is given by

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

The full probability can be approximated as

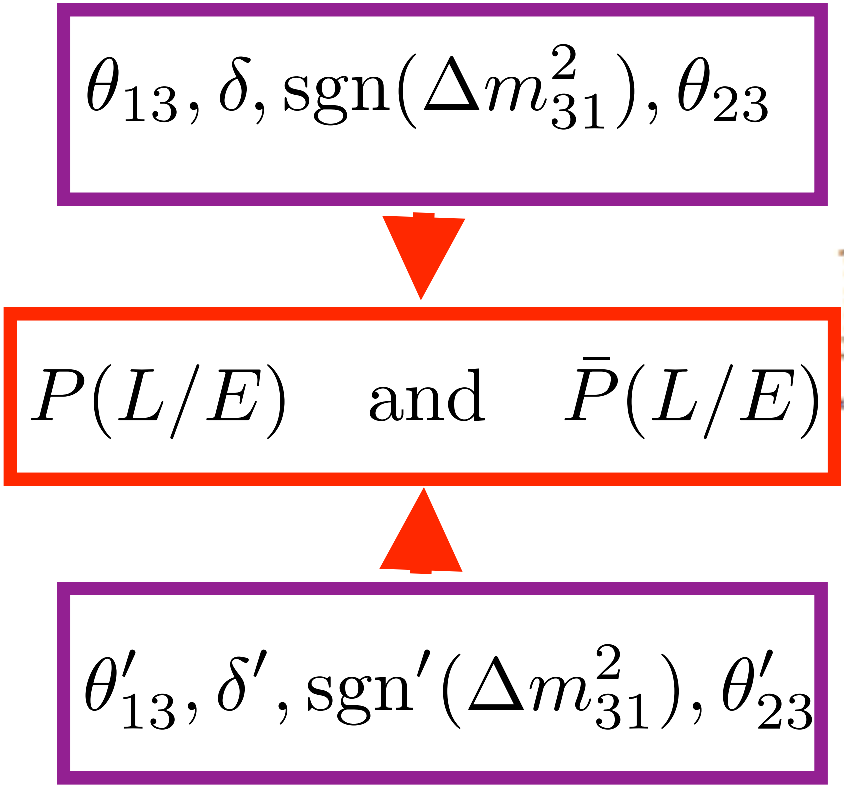
$$\begin{aligned} P(\bar{P}) \simeq \;& s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{A \mp \Delta_{13}}\right)^2 \sin^2 \frac{(A \mp \Delta_{13})L}{2} \\ & + \tilde{J} \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{A \mp \Delta_{13}} \sin \frac{AL}{2} \sin \frac{(A \mp \Delta_{13})L}{2} \cos\left(\mp\delta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

Matter effects

CP violation

Degeneracies

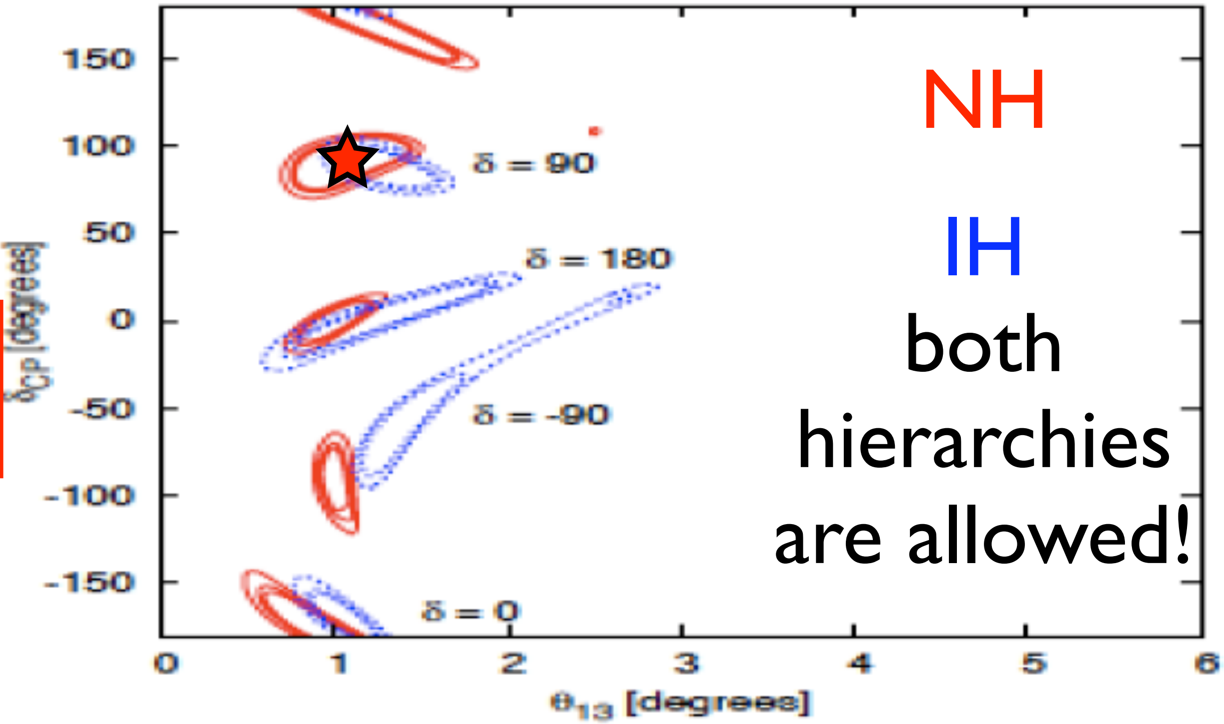
The determination of CPV and the mass ordering is complicated by the issue of **degeneracies**: different sets of parameters which provide an equally good fit to the data (eight-fold degeneracies).



$\theta_{13}, \delta, \mathrm{sgn}(\Delta m^2_{31}), \theta_{23}$

$P(L/E) \quad \text{and} \quad \bar{P}(L/E)$

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



NH

IH

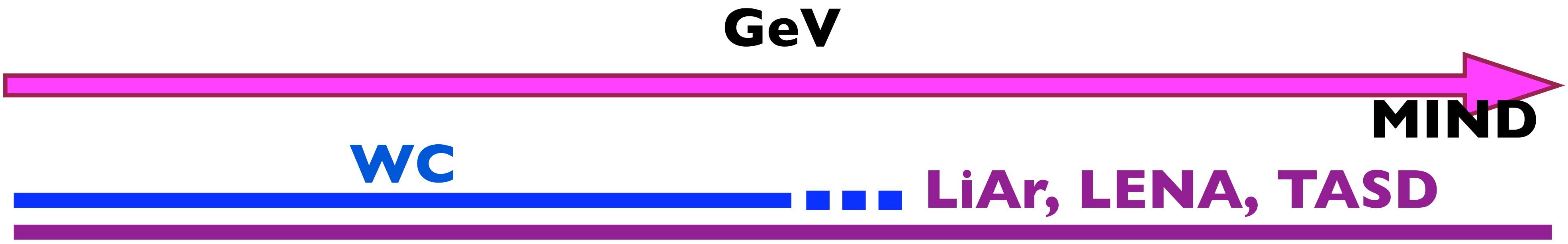
both hierarchies are allowed!

Future long baseline experiments

Different options are considered, depending of the neutrino production technique:

- **superbeams**
- **beta beams**
- **neutrino factory**

The baseline determines the energy of the beam and viceversa: exploit first oscillation maximum for best sensitivity. The energy and the oscillation channels impact on the type of detector used.



GeV

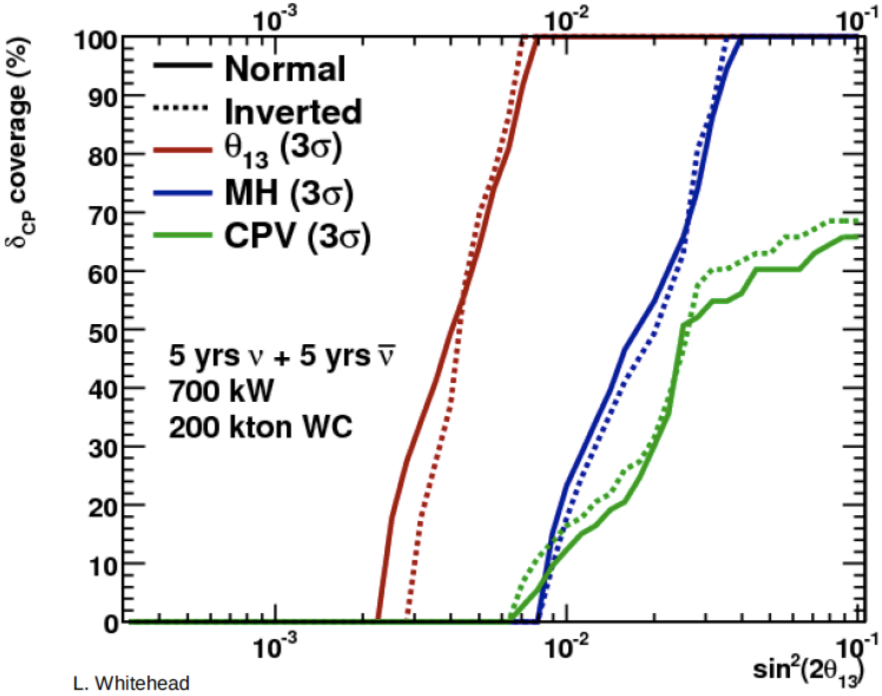
MIND

WC

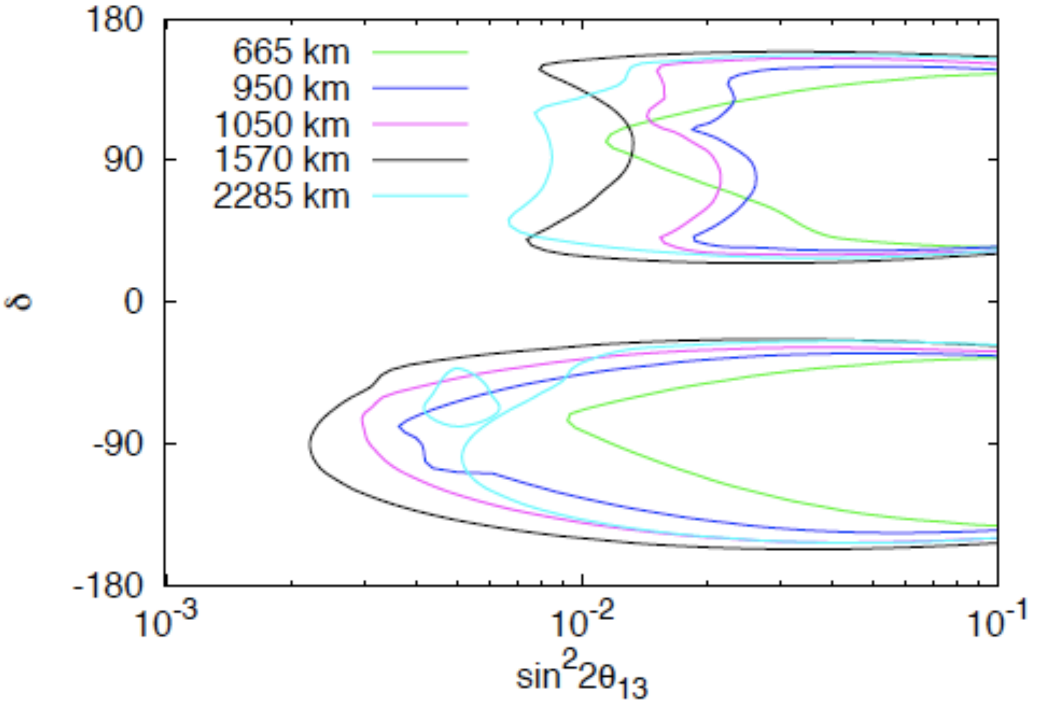
LiAr, LENA, TASD

Superbeams

Muon neutrinos come from pion decays with high fluxes and large detectors (T2K, NOvA, T2K-II, LBNE, SPL in EUROnu, LAGUNA-LBNO) at L~100-2000 km. Their sensitivity is ultimately limited by intrinsic background, systematics....



L. Whitehead

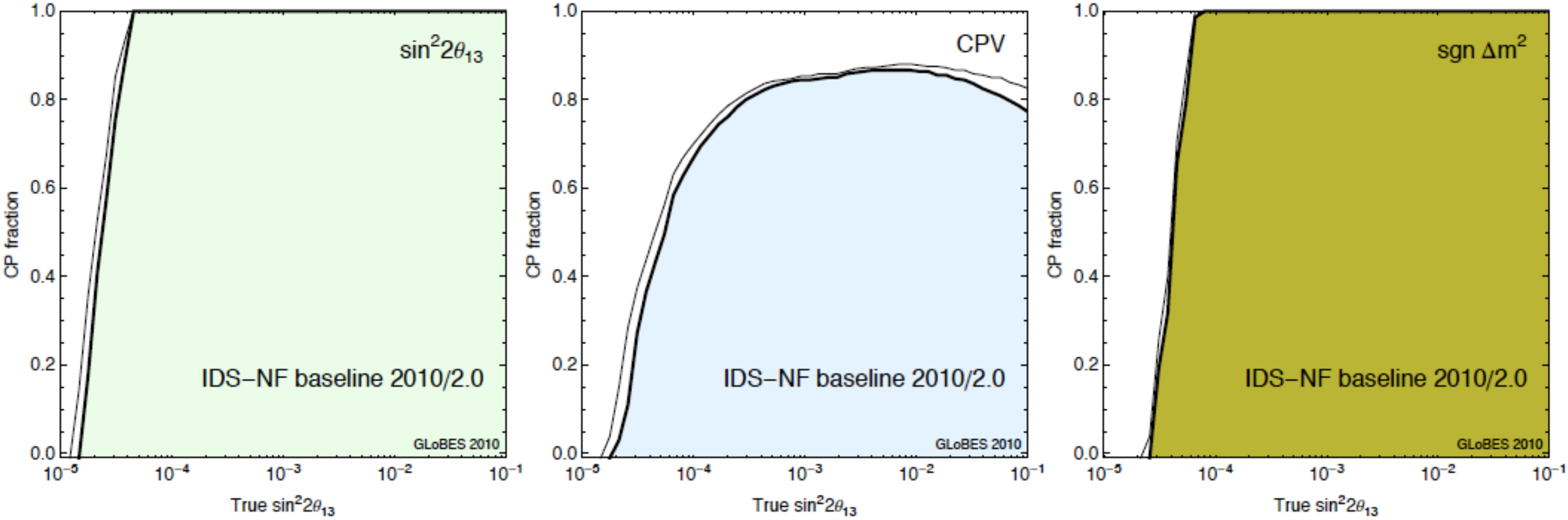


Coloma, SP, Li, in preparation

Neutrino factory

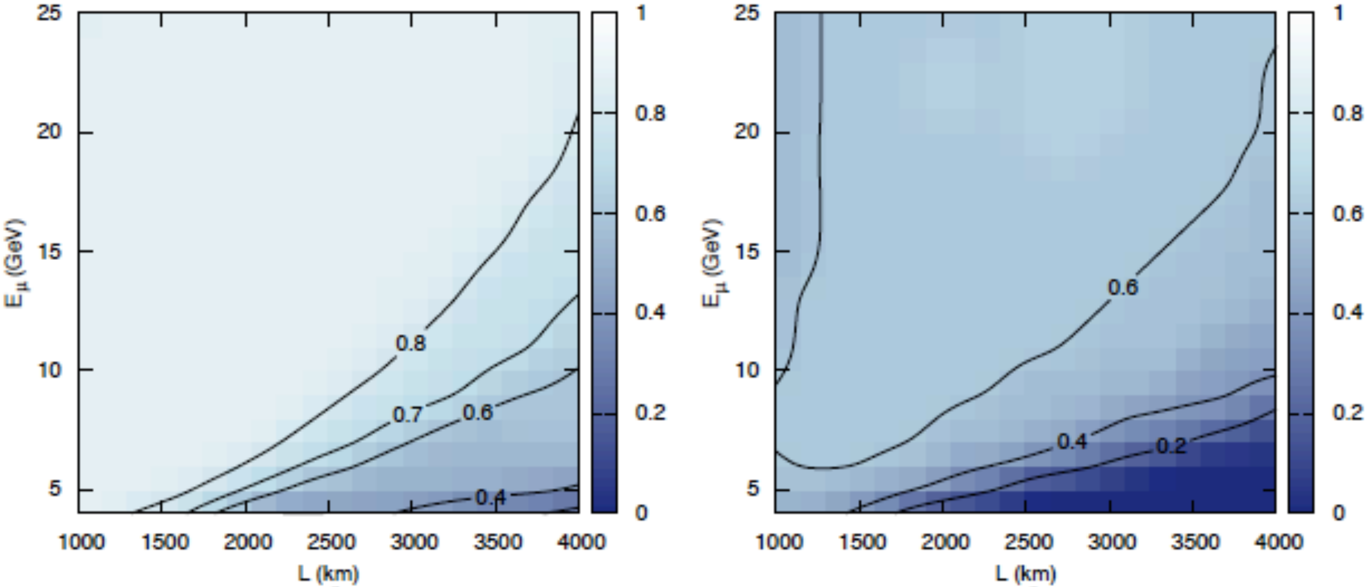
Neutrinos from muon decays at L~1500-7000 km. Pure beam and multiple oscillation channels but requires magnetised detector (MIND, LiAr).

See e.g. de Rujula, Gavela, Hernandez; Cervera et al.; Freund, Huber, Lindner; Rubbia ....

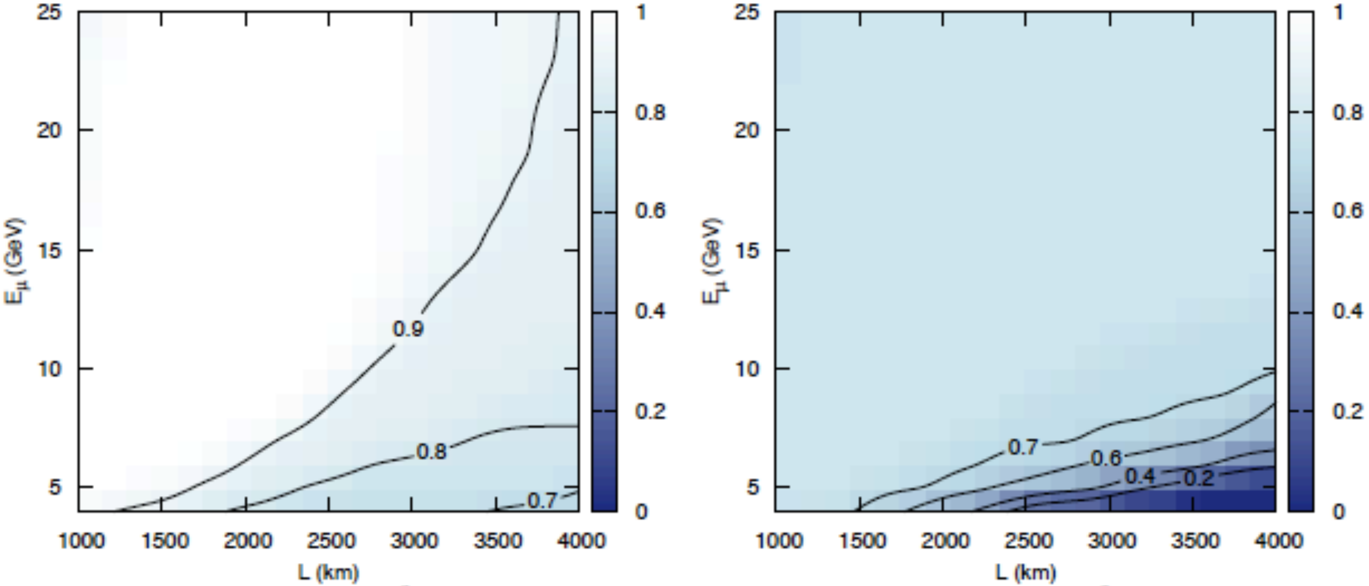


GLOBeS, Huber, Lindner, Winter and Huber, Kopp, Lindner, Rolinec, Winter; see IDS-NF

Neutrino factories (HENF, LENF) have excellent reach.



(a)TASD: $\sin^2 2\theta_{13} = 10^{-2}$ (b)TASD: $\sin^2 2\theta_{13} = 10^{-3}$



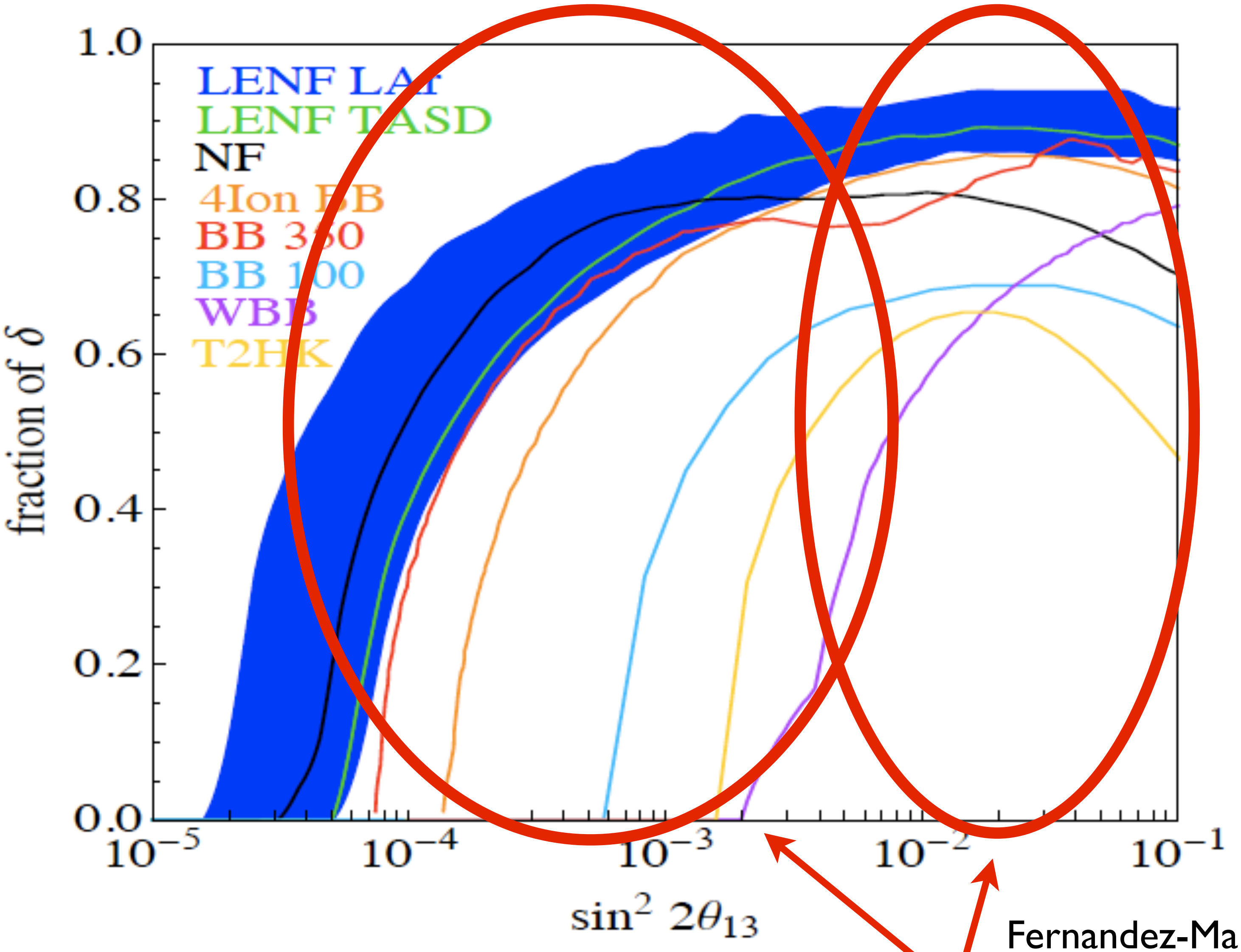
(c)LAr (optimistic): $\sin^2 2\theta_{13} = 10^{-2}$ (d)LAr (optimistic): $\sin^2 2\theta_{13} = 10^{-3}$

Sensitivity to CP-violation.

Lines show the fraction of delta for which CPV can be determined.

Excellent sensitivity for large θ_{13} rather independent from L and E and increase in sensitivity with energy for small θ_{13}

Ballett, SP



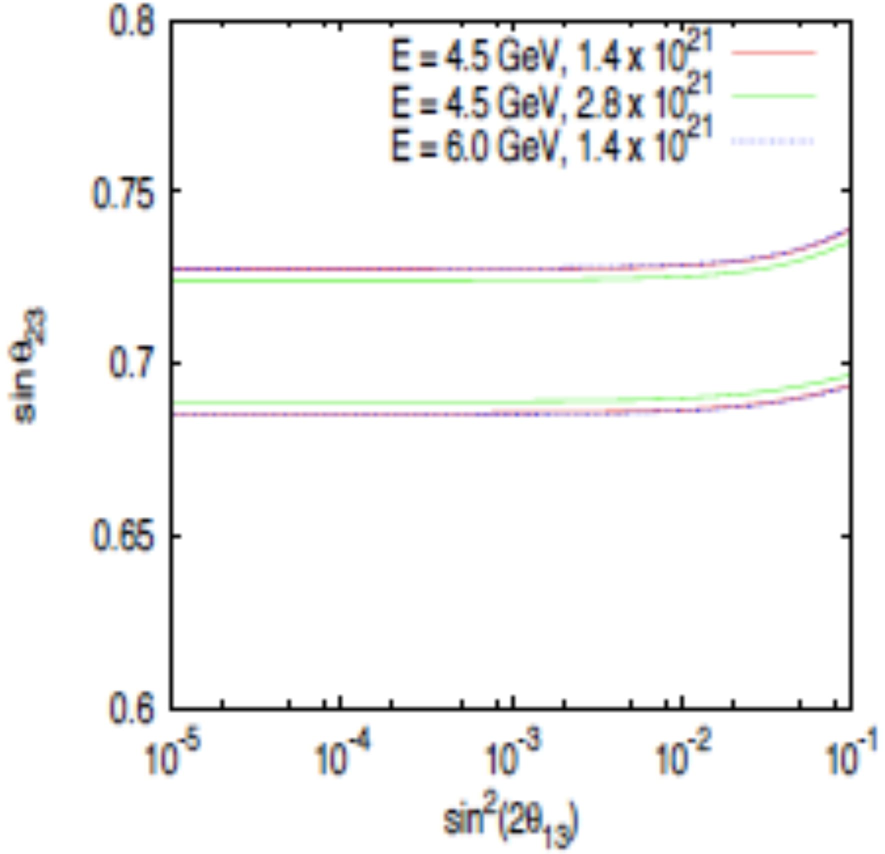
The best reach in CPV!

Fernandez-Martinez et al., 0911.3776

Depending on the values of θ_{13} and on the precision required, **different experimental setups and optimisations are required.**

Standard scenario: precision measurements

In order to discriminate models of flavour, it is important to measure with great precision the angles.



Fernandez-Martinez et al., 0911.3776

In particular, deviations from 45 of θ_{23} from 0 of θ_{13} and the value of θ_{12}

Testing the standard scenario

A plethora of hints of physics beyond 3 neutrino mixing and SM interactions is present.

LSND appearance experiment

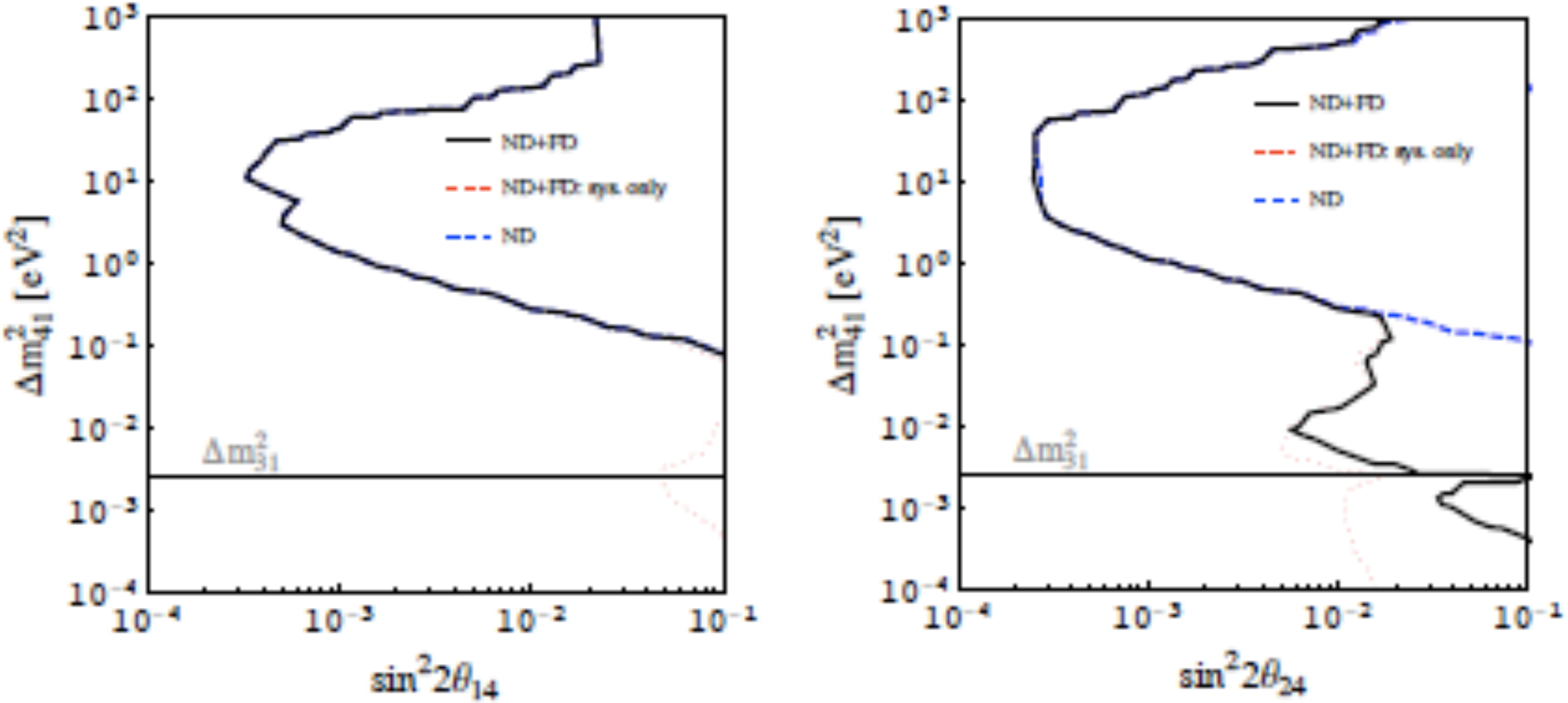
MiniBooNE neutrino and antineutrino results

Reactor anomaly

If confirmed, it would lead to a radical shift in our understanding of neutrino and physics BSM and would require a reanalysis of the reach of future neutrino oscillation experiments.

Sterile neutrinos

Sterile neutrinos could be present in extensions of the SM with masses from sub-eV to GUT scale. Of phenomenological interest for oscillations are those with sub-eV to multi-eV masses (LSND, MiniBooNE). New angles and CPV phases appear.



See e.g. Meloni, Tang, Winter, 1007.2419. Also, Donini et al., Antusch et al., Tang and Winter...

NSI

NSI appear as additional effects in the H:

$$\hat{H}^{fl} = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{pmatrix} U^\dagger \pm A \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

NSI can arise in extensions of the SM. For instance D=6 operators typically lead to

$$\mathcal{O}^6 = \frac{1}{\Lambda^2} \left(L_\square \, \gamma^\square \, L_\square \right) \left(L_\square \, \gamma_\square \, L_\square \right) \quad \longleftrightarrow \quad \epsilon \sim g^2 M_W^2 / (g_{NSI}^2 M_{NSI}^2)$$

Strong bounds arise from oscillations, pion decay, CKM unitarity..., typically <0.001, 0.1, and at the loop-level, if charged current processes cannot be avoided.

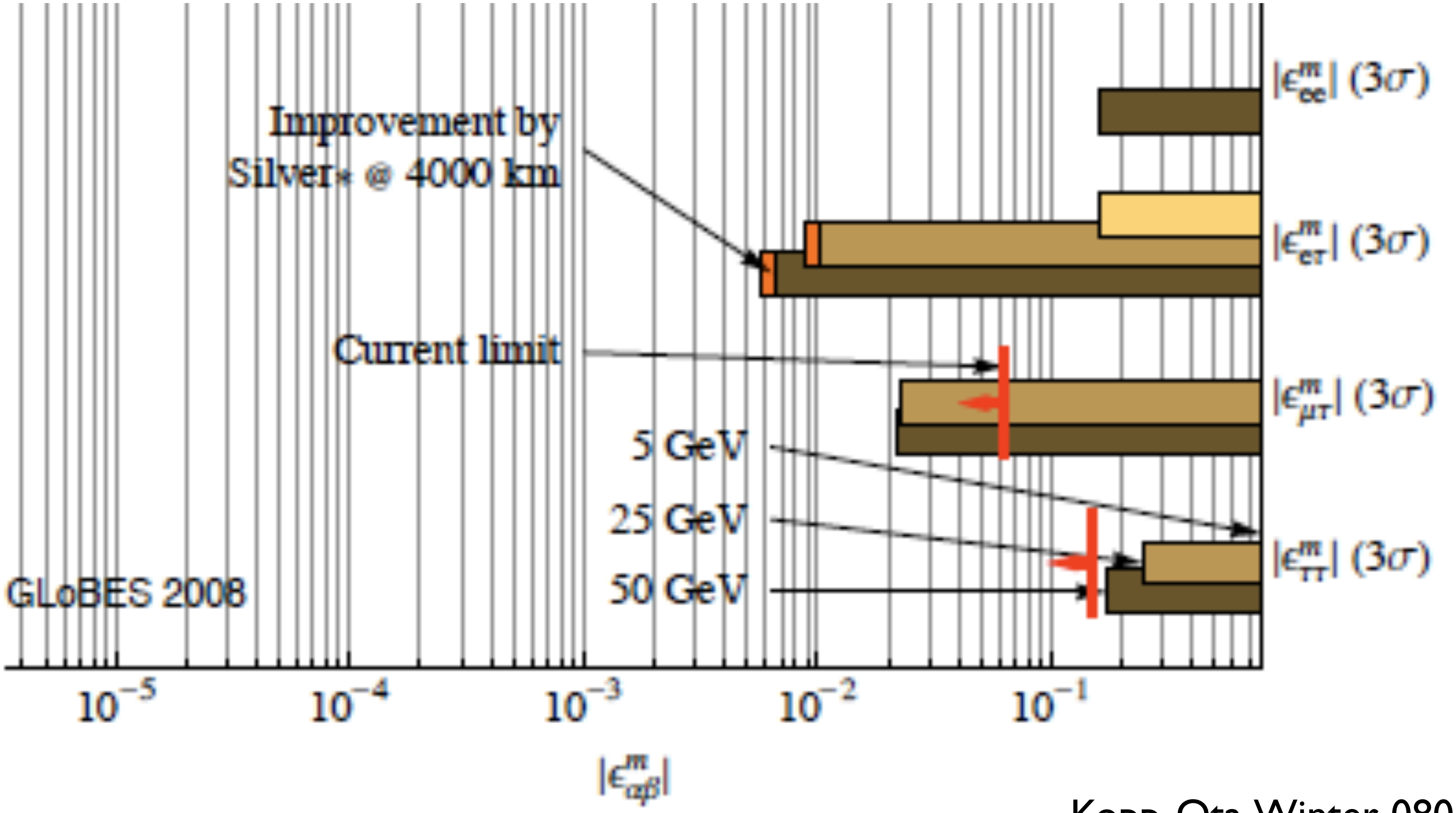
LBL experiments are also sensitive to NSI at source, propagation and detection (Grossman, 95):

matter effects

$$\begin{aligned}
P_{\nu_e\to\nu_\mu} \simeq\; & \frac{s_{213}^2 s_{23}^2}{\left(1-\frac{A}{\Delta_{31}}\right)^2} \\
& + \frac{s_{213}c_{13}s_{212}s_{223}}{1-\frac{A}{\Delta_{31}}}\frac{\Delta_{21}}{A}\sin\left(\frac{AL}{2}\right)\cos\left(\frac{\pi+AL}{2}-\delta\right) \\
& \boxed{-\,4\varepsilon_{e\mu}}\frac{s_{213}c_{23}s_{23}^2}{1-\frac{A}{\Delta_{31}}}\sin\left(\frac{AL}{2}\right)\cos\left(\frac{\pi+AL}{2}-\delta+\phi_{e\mu}\right) \\
& \boxed{-\,4\varepsilon_{e\tau}}\frac{s_{213}c_{23}s_{23}^2}{1-\frac{A}{\Delta_{31}}}\sin\left(\frac{AL}{2}\right)\cos\left(\frac{\pi+AL}{2}-\delta+\phi_{e\tau}\right)
\end{aligned}$$

The longer baseline (higher energy), the better the physics reach as NSI effects become more important.

The HENF provides the best sensitivity to NSI:



Kopp, Ota, Winter, 0804.2261

This analysis assumes two MIND detectors and therefore the reach for E=5 GeV is very limited.

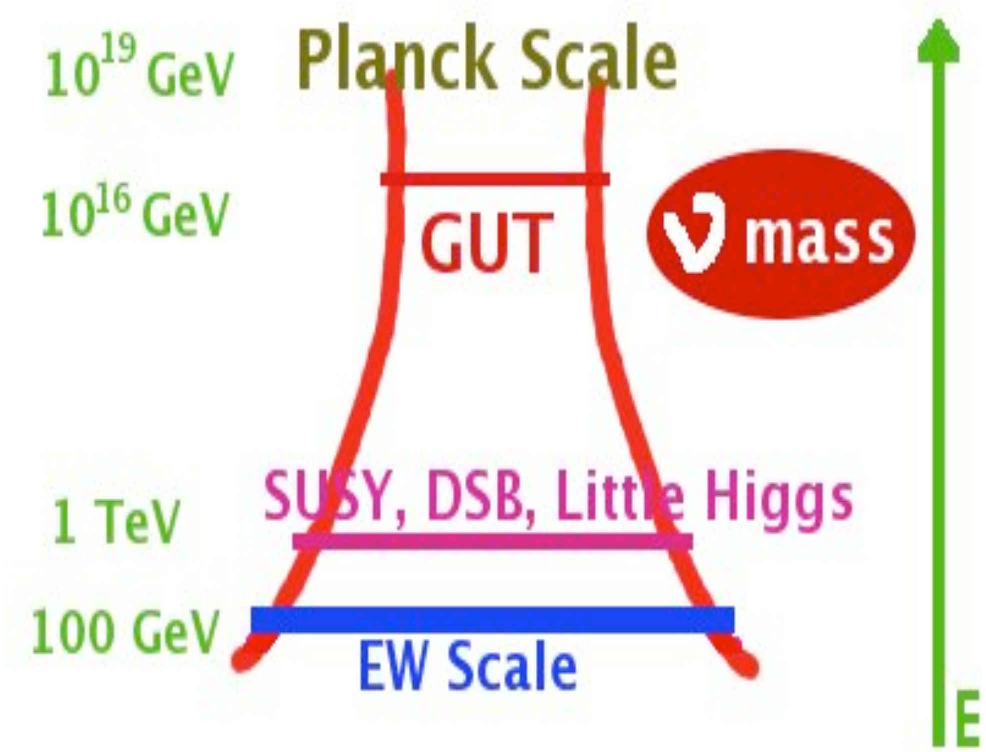
Neutrino Physics provides information on the fundamental laws of Nature and on the evolution of the Universe.

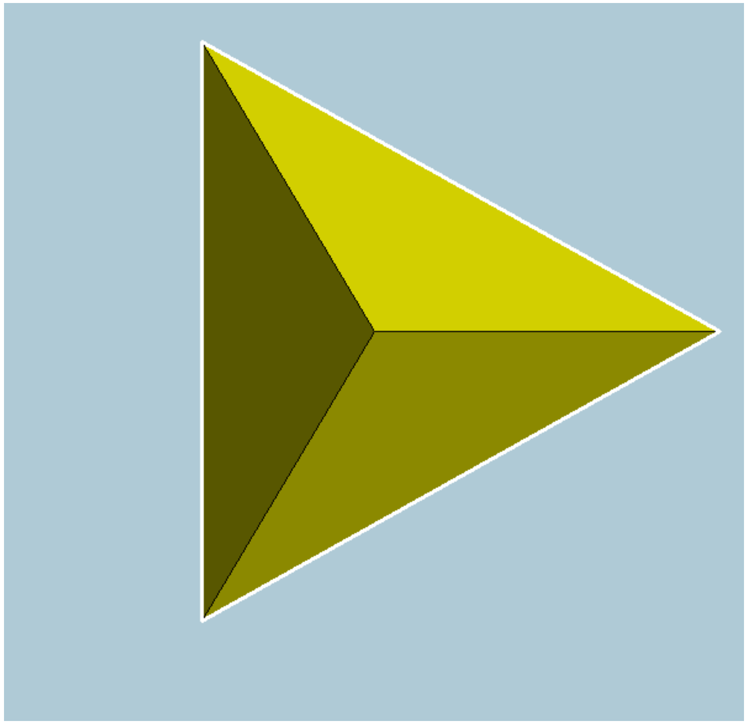
Open window on the Physics beyond the SM at scales, possibly not otherwise reachable.

Neutrinos are messengers from the Early Universe and from Extreme Astrophysical Environments.

Open window on Physics beyond the SM

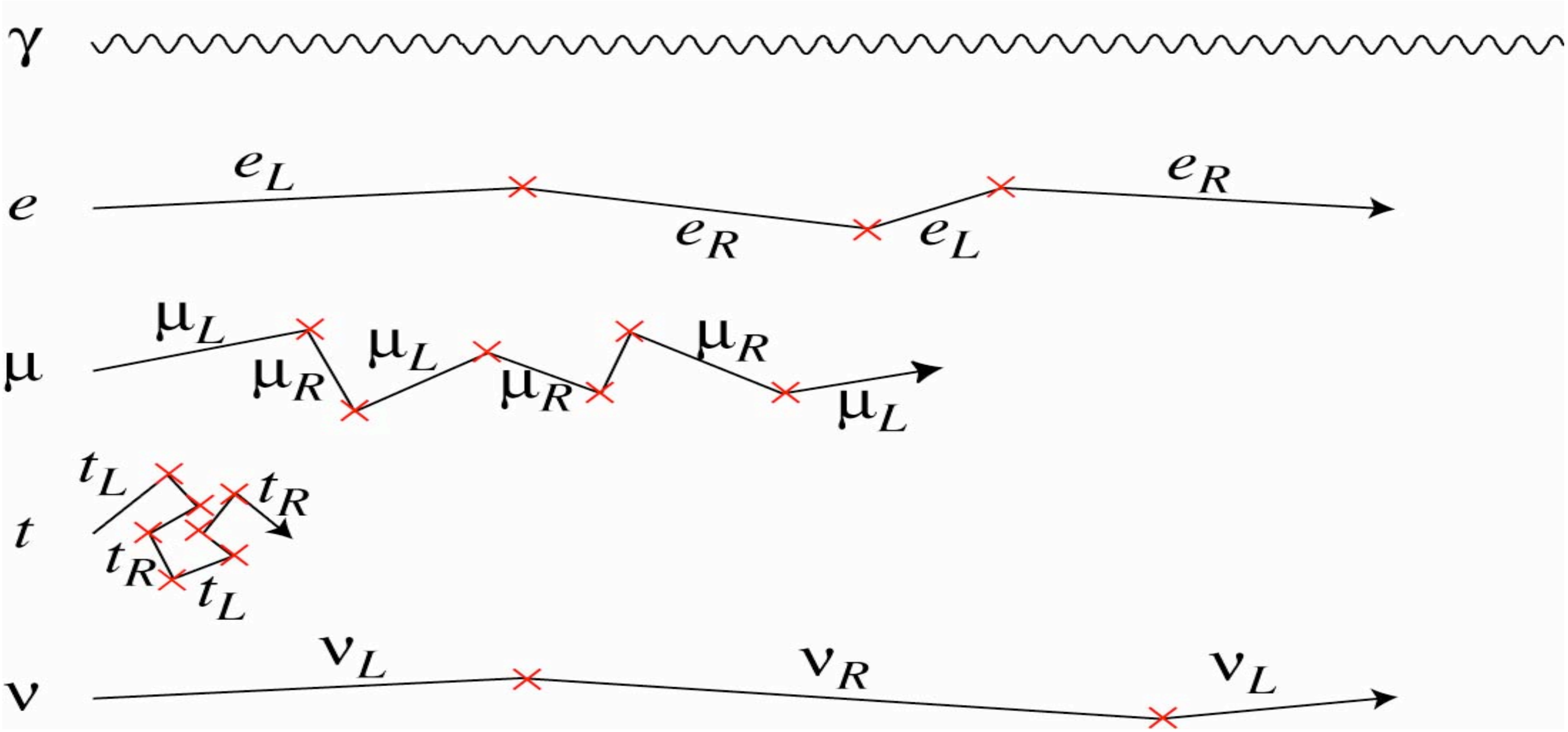
Neutrino physics gives a new perspective on physics BSM.





This information is **complementary** with the one which comes from flavour physics experiments and from colliders.

Neutrino masses in the sub-eV range cannot be explained naturally within the SM.

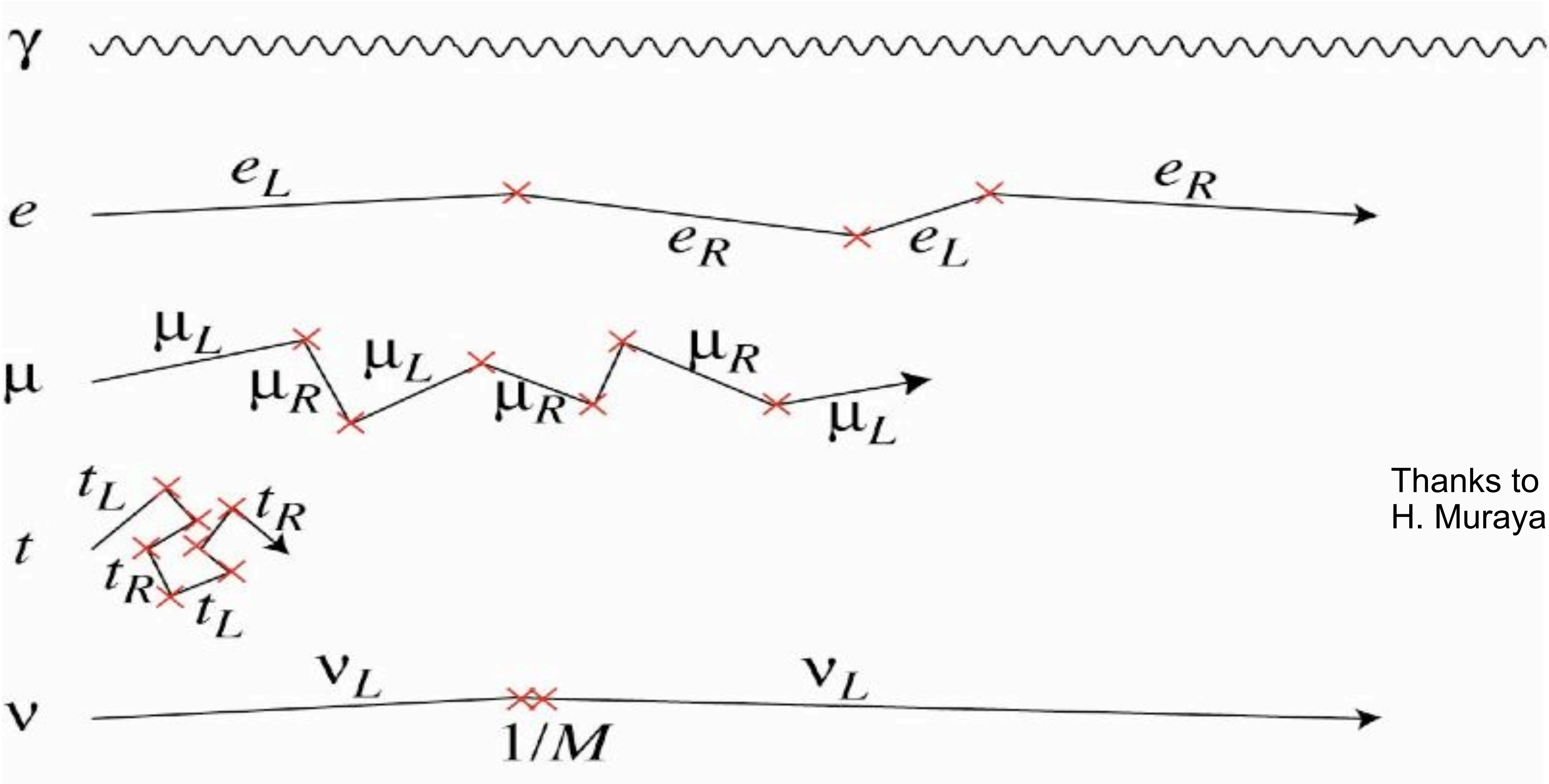


Thanks to
H. Murayama

$$y_\nu = \frac{m_\nu}{v} = \frac{0.1\,\mathrm{eV}}{250\,\mathrm{GeV}} = 4 \times 10^{-13}$$

Many theorists consider this explanation of neutrino masses unnatural.

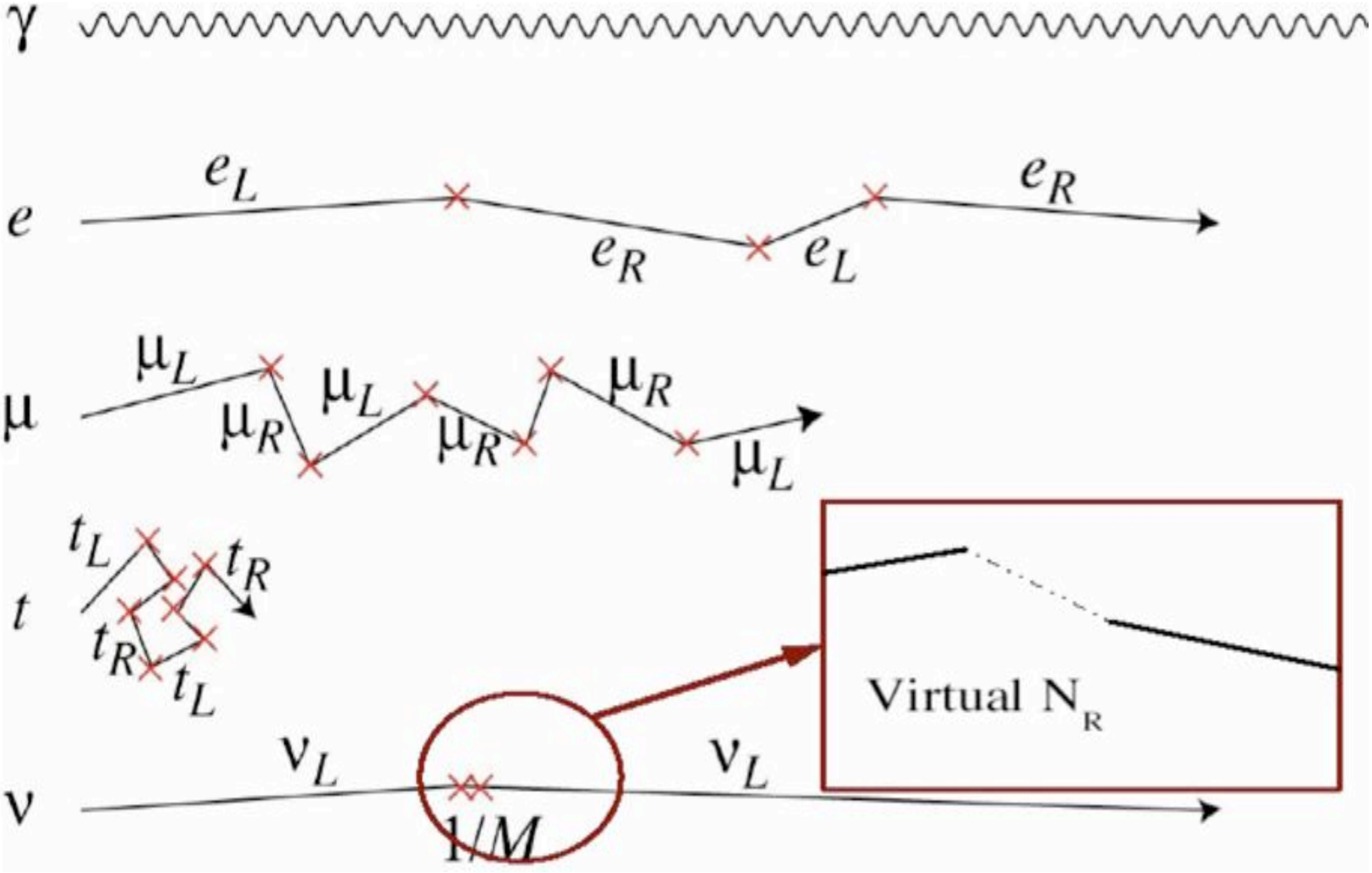
If neutrino are Majorana particles (neutrinos and antineutrinos are indistinguishable), a different type of neutrino mass can be generated (**Majorana mass**):



Thanks to
H. Murayama

$$-\mathcal{L} = \lambda \frac{\nu_L H \, \nu_L H}{M} = \frac{\lambda v^2}{M} \nu_L^T C \nu_L$$

The Majorana mass term can arise as the **low energy realisation of a higher energy theory**.

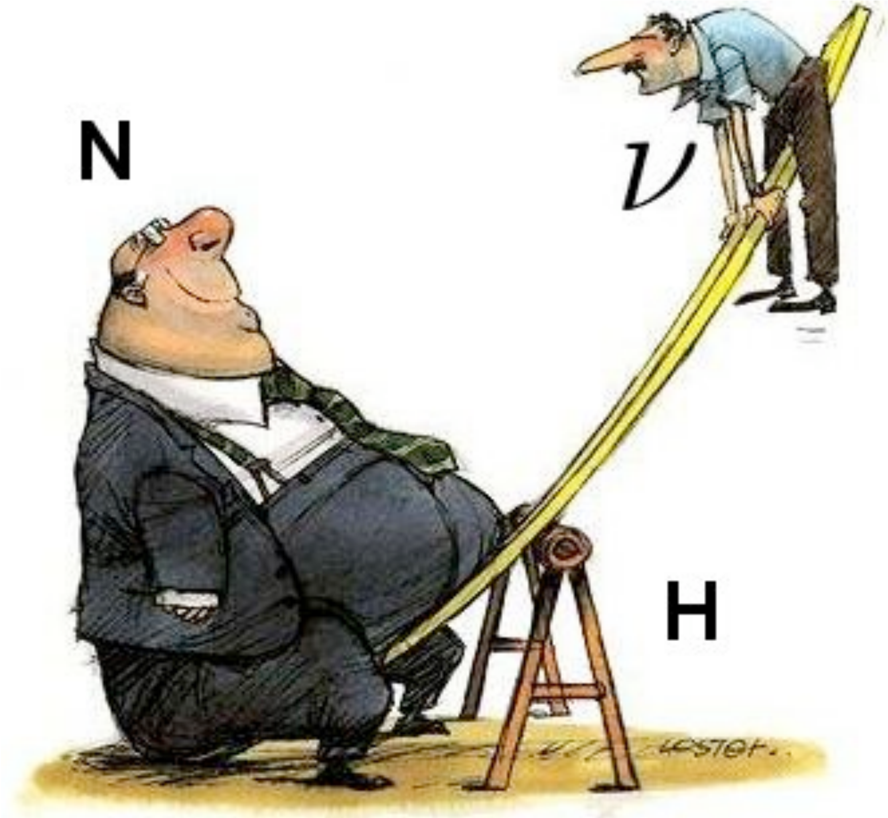


Thanks to
H. Murayama

$$m_\nu = \frac{\lambda^2 v^2}{M} \rightarrow M \sim 10^{14}\ \mathrm{GeV}$$

The see saw mechanism

In the **see-saw mechanism**, neutrinos acquire a very small mass due to their interactions. Minkowski; Yanagida; Gell-Mann, Ramond, Slansky.



- Introduce a right handed neutrino **N**
- Couple it to the Higgs and left handed neutrinos

$$m_{light} \simeq \frac{m_D^2}{M_R} \sim \frac{100\ \mathrm{GeV}^2}{10^{14}\ \mathrm{GeV}} \sim 0.1\ \mathrm{eV}$$

Other models have new particles at TeV scale, testable a the LHC.

The flavour problem

Mixing is compatible with tri-bi-maximal pattern.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} -\frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Harrison, Perkins, Scott

This can arise from specific forms of the neutrino mass matrix with flavour symmetries (e.g. A4).

$$(M^\nu_{eff})^{TBM} = \begin{pmatrix} a & b & b \\ . & d & (a+b-d) \\ . & . & d \end{pmatrix}$$

Low, Volkas

Determining the deviations from TBM is important to understand the underlying flavour theory. Typically the deviations will be related together. For ex.

$$\sin^2\theta_{13} = \frac{1}{3}\sin^2\bar{\theta}, \qquad \sin^2\theta_{12} = \frac{\cos^2\bar{\theta}}{3-\sin^2\bar{\theta}}, \qquad \sin^2\theta_{23} = \frac{3}{2}\frac{\left|\cos\bar{\theta} - \sqrt{\frac{2}{3}}e^{i\gamma}\sin\bar{\theta}\right|^2}{3-\sin^2\bar{\theta}}$$

Ballett, King, Lhun, SP, Schmidt

In other models, e.g. GUTs, other connections between the values of the mixing angles can be found. For ex.

$$\theta_{12}^{o} = 35^{o} + \theta_{13}^{o}\cos\delta$$

King; Antusch, King; Masina

Neutrinos are messengers from the Universe

Supernovae

Dark Matter annihilations

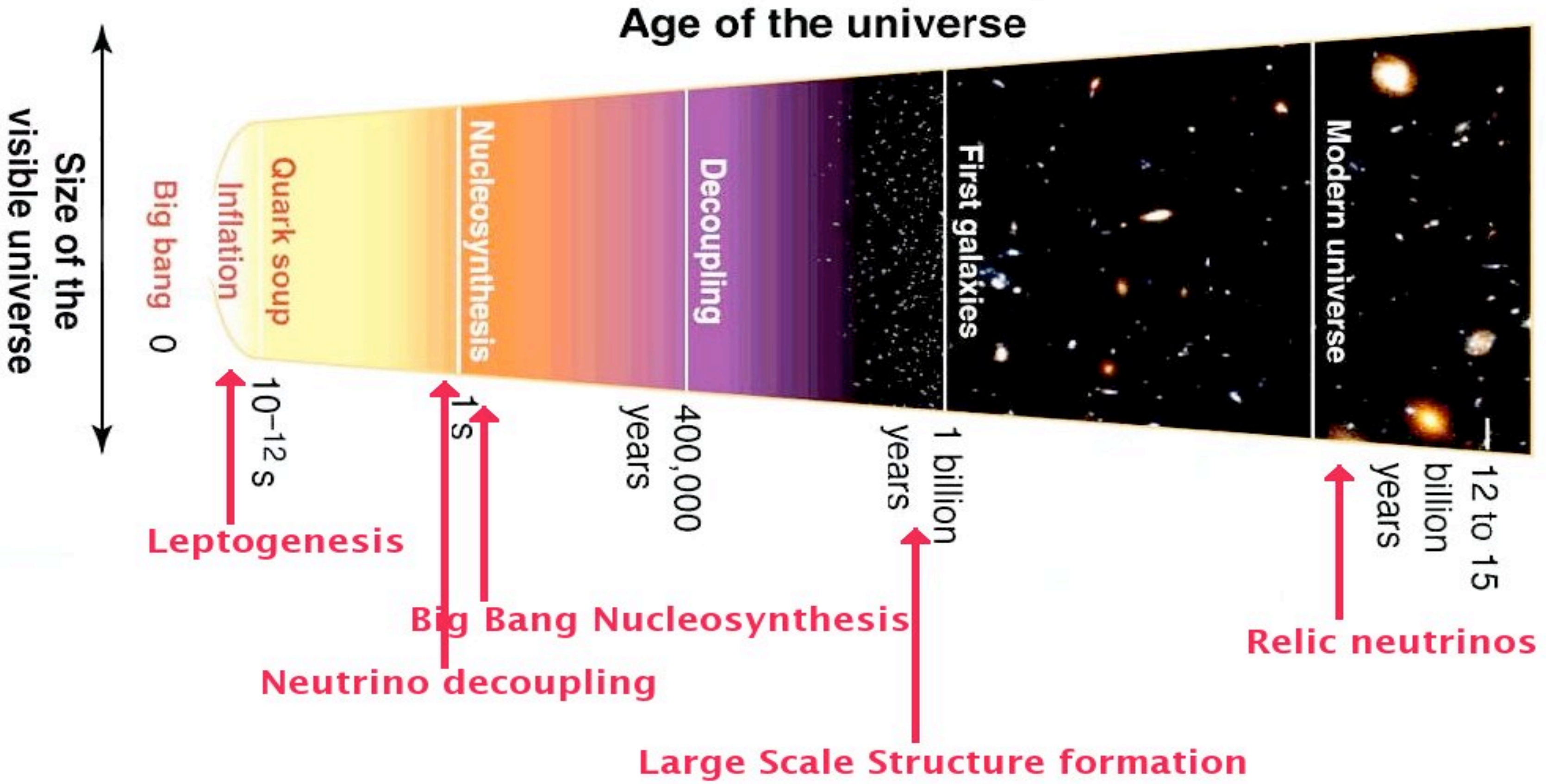
Leptogenesis

Relic neutrinos

Sterile Neutrinos as Dark Matter

Big Bang Nucleosynthesis

HDM and structure formation



Neutrinos constitute a **hot dark matter** component and affect the formation of clusters of galaxies.

Sterile neutrinos with m~eV behave as HDM and are severely constrained by cosmology.

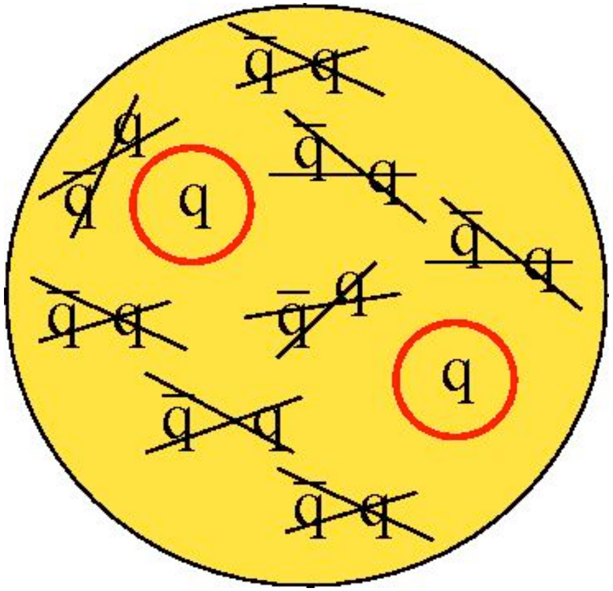
Sterile neutrinos with m~keV are WDM.

Leptogenesis and the Baryon Asymmetry

10000000001 quarks

In the Early Universe

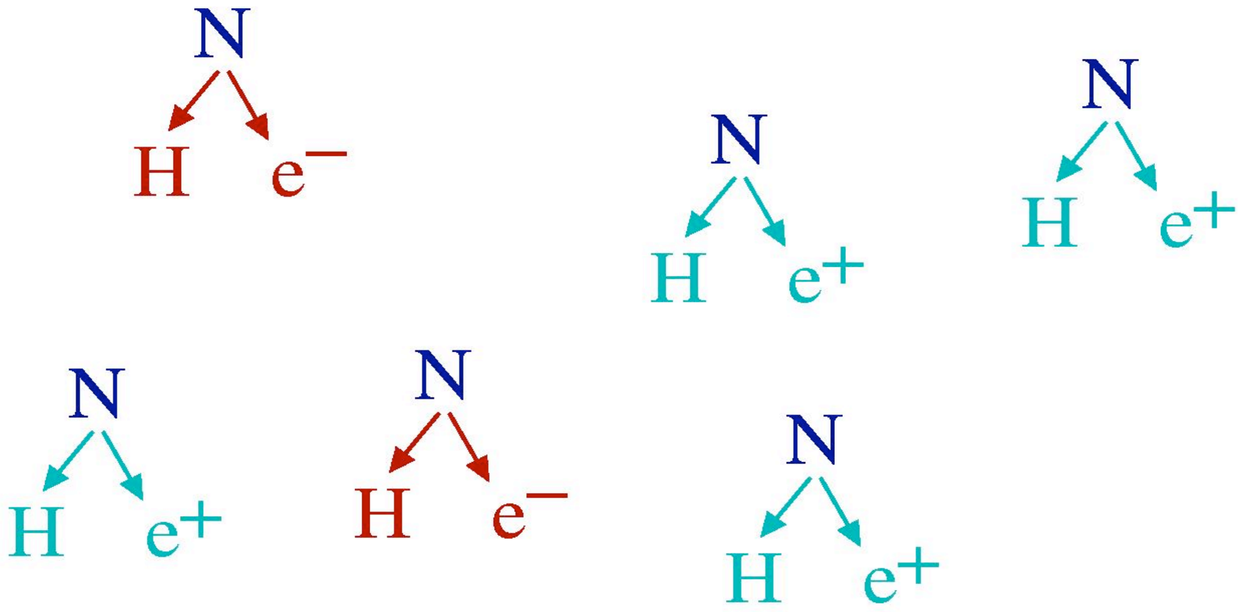
10000000000 antiquarks



As the temperature drops, only quarks are left:

$$Y_B = \frac{n_B}{n_\gamma} = (6.0 \pm 0.2) \times 10^{-10}$$

The excess of quarks can be explained by **Leptogenesis** (Fukugita, Yanagida): the heavy N responsible for neutrino masses generate a lepton asymmetry.



Excess of $e^+ \longrightarrow$ excess of q over $\bar{q}$

This requires **L violation, CP-violation** and **non-equilibrium** (expansion of the EU).
The lepton asymmetry is then converted into the baryon asymmetry.

The **see-saw mechanism** (type I) might be responsible for **neutrino masses** and the **baryon asymmetry**.

Is there a **connection** between the two**?**

- In general, there are more parameters at high energy (where leptogenesis happens) w.r.t. the ones we can measure in experiments at low energy.

- Due to **flavour effects**, if we **observe CPV at low energy** we know that generically a **baryon asymmetry** was generated.

- **Observing L violation and CPV** would constitute a **strong hint in favour of leptogenesis as the origin of the baryon asymmetry**.

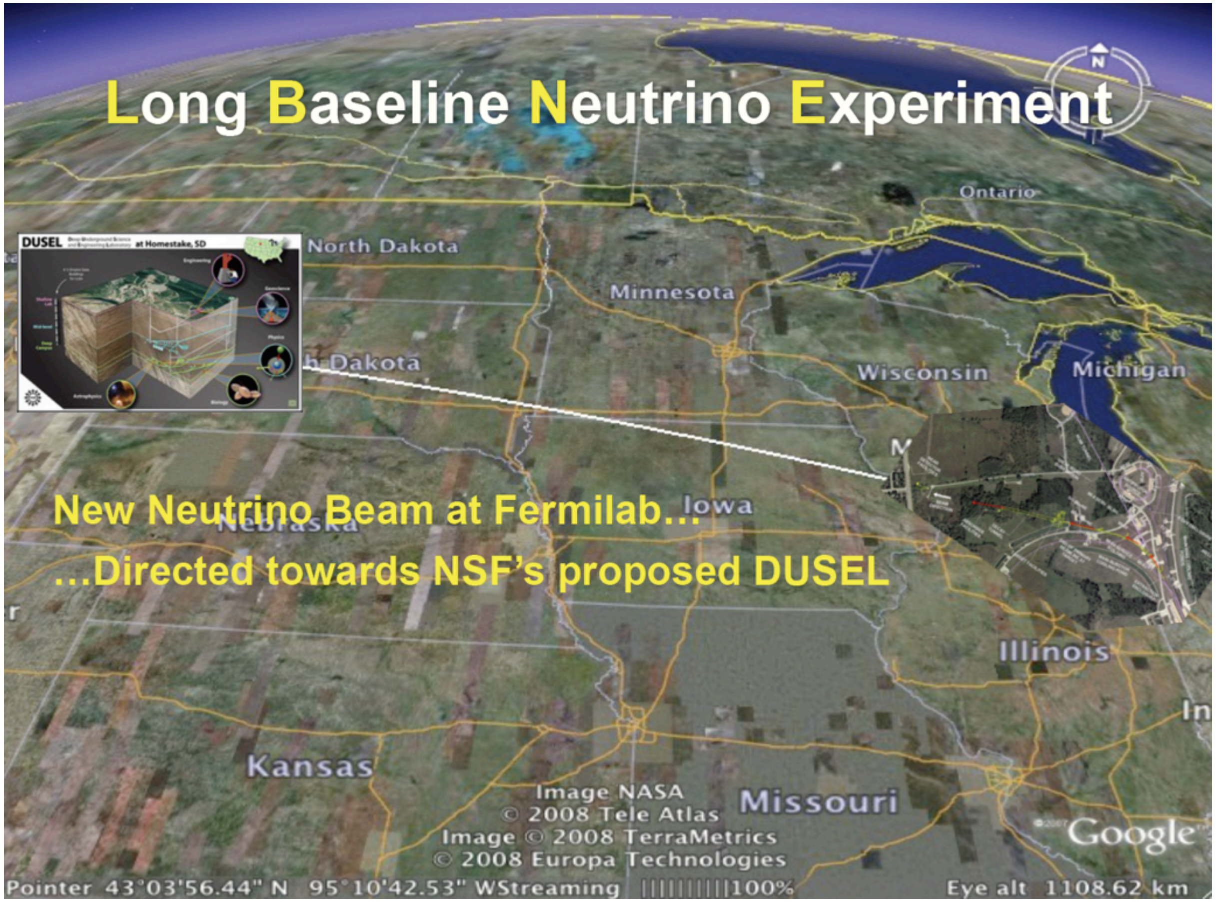
Conclusions

- In the past few years, the neutrino oscillation parameters have been measured with good precision. The (near) present experiments are going to improve the precision and possibly discover θ_{13} .

- A wide future neutrino programme is planned: neutrinoless double beta decay and long baseline neutrino oscillation experiments.

- They will give crucial information on neutrino properties in order to understand the **origin of neutrino masses** and the **problem of flavour**. **Precision measurements** will be crucial.

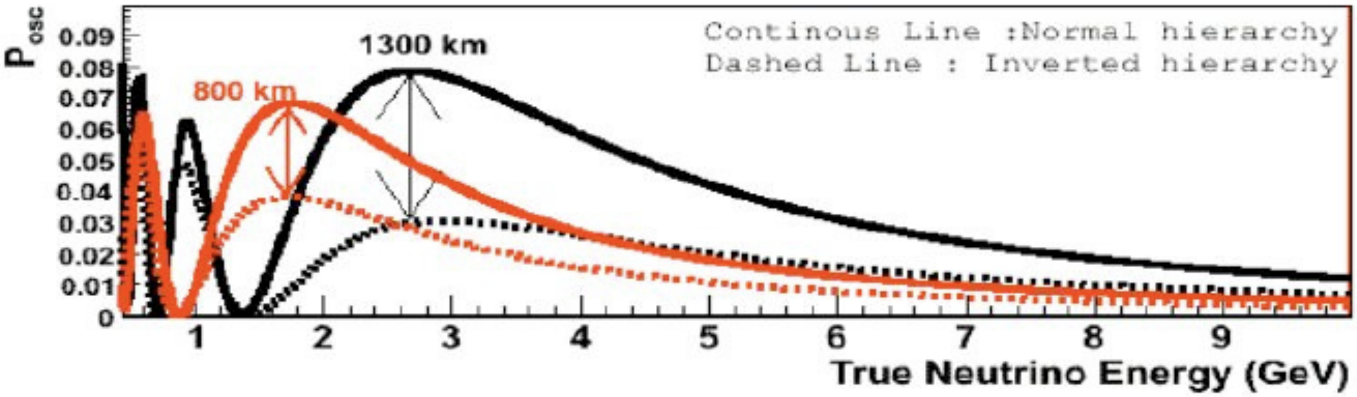
LBNE



Wideband beam which exploits the rich oscillatory pattern.

With Project X (from 700 kW to 2 MW), even better sensitivities could be obtained.

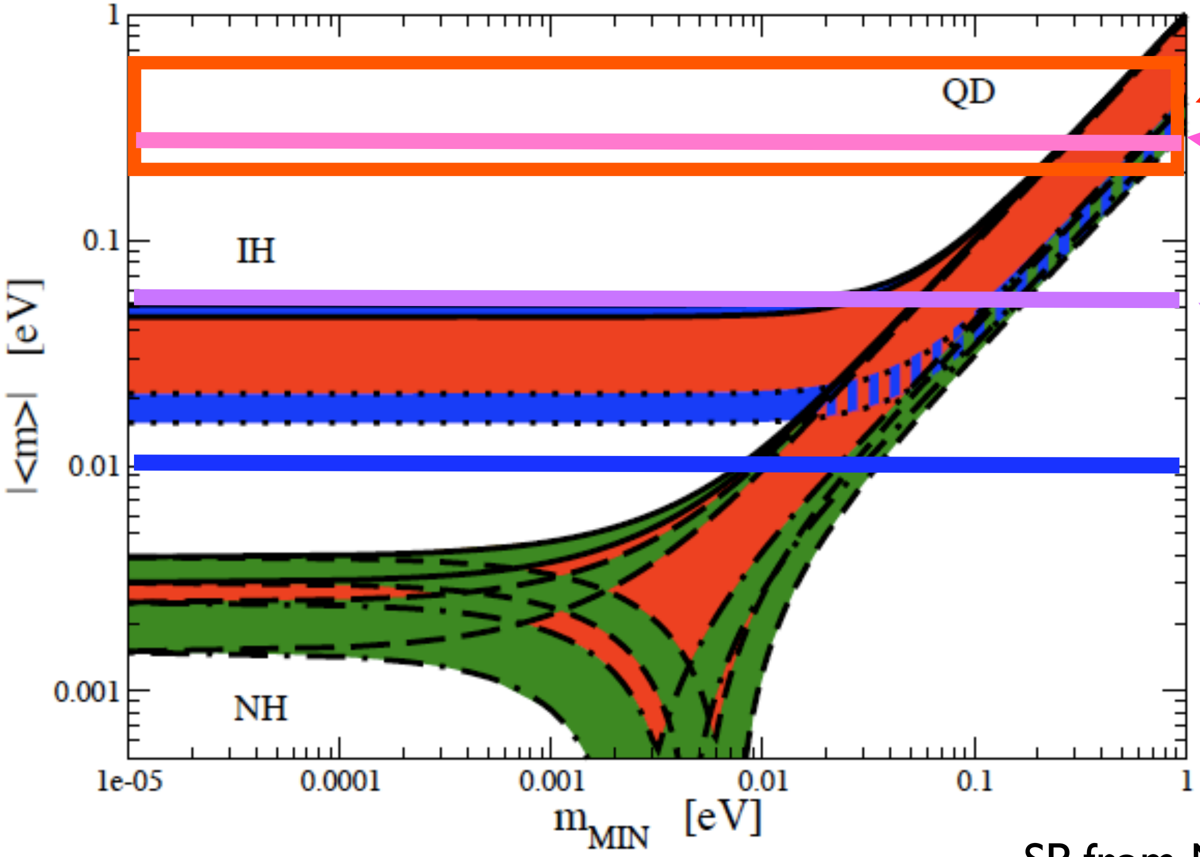
Presented by S. Parke at NeuTel 2011



Neutrinoless double beta decay

The half-life depends on neutrino properties through

$$|\langle m\rangle| \sim |m_1 \cos^2\theta_{12} + m_2 \sin^2\theta_{12} e^{i\alpha_{21}} + m_3 \sin^2\theta_{13} e^{i\alpha_{31}}|$$



Klapdor-Kleingrothaus claim 2002 and 2006

Present bounds: Heidelberg-Moscow, IGEX, Cuoricino and NEMO3

Next generation: GERDA, EXO, CUORE, SuperNEMO, SNO+, Majorana, COBRA...

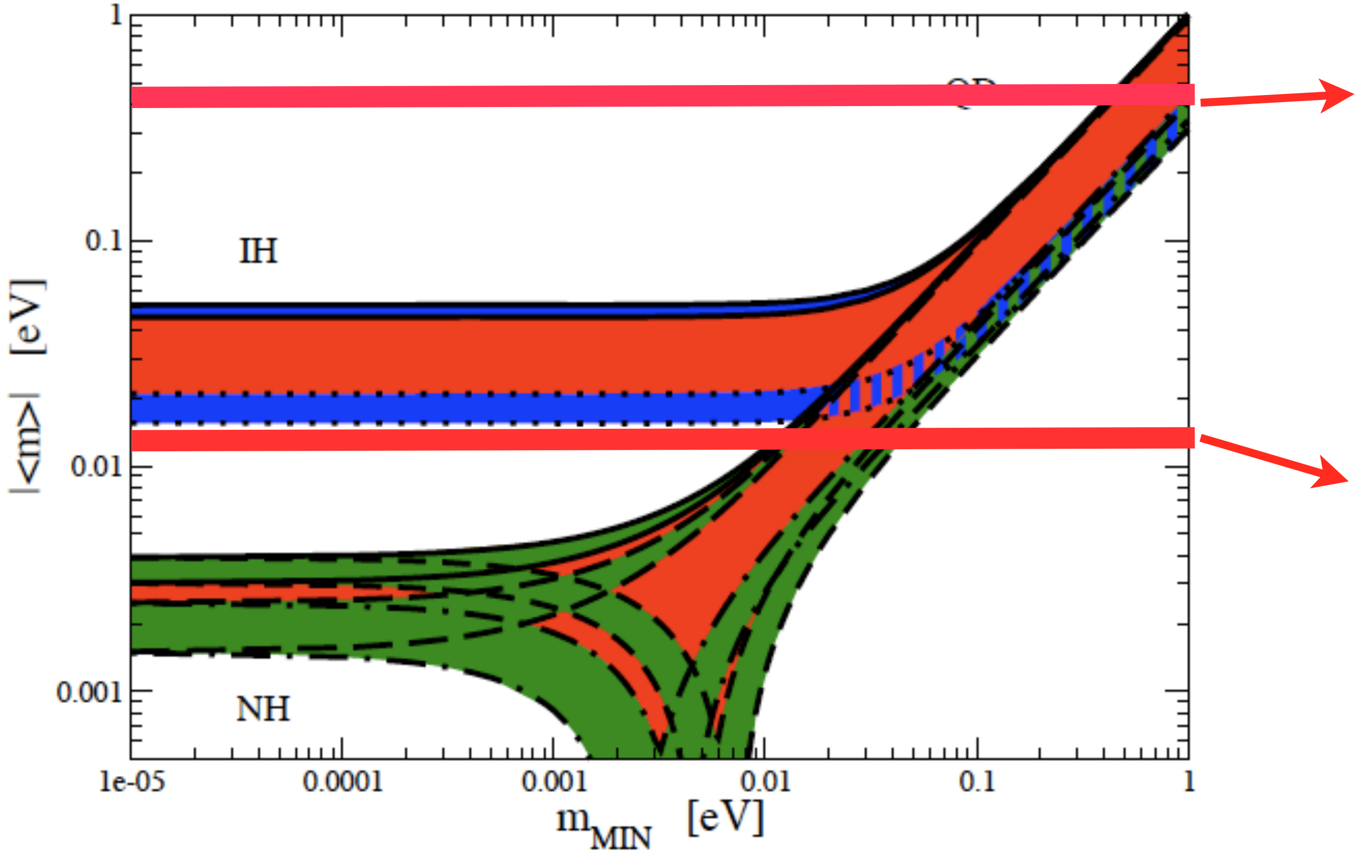
Future experiments: ~1 ton

SP from Nakamura, Petcov review in PDG

Wide experimental program for the future:

a positive signal would indicate that L is violated!

It might give information on neutrino masses (and CPV).



It would imply QD spectrum for neutrinos.

It would imply that inverted ordering is excluded.

It will be critical to establish the origin of the signal (light or heavy Majorana neutrinos, RV SUSY,...).

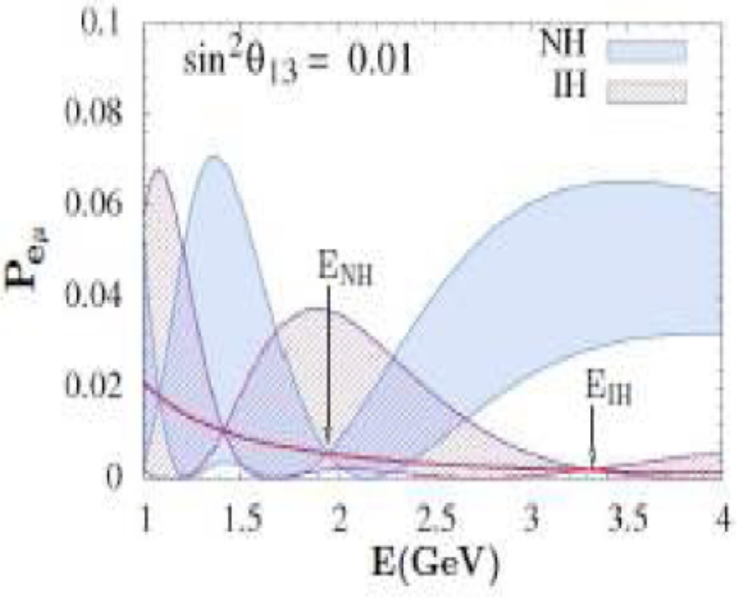
- (θ_{13}, δ) degeneracy (Koike, Ota, Sato; Burguet-Castell et al.)

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

Having information at different L/E can resolve this.

- sign(Δm^2_{31}) vs CPV (matter effects). In vacuum:

$$\delta' \to \pi - \delta \qquad \text{sign}'(\Delta m^2_{13}) \to -\text{sign}(\Delta m^2_{13})$$



This degeneracy is broken by matter effects.

For ex. Bimagic baseline at L=2540 km
Excellent sensitivity to the hierarchy
A. Dighe et al., 1009.1093; Raut et al. 0908.3741; Joglekar et al. 1011.1146

- the octant of θ_{23} (low E data) (Fogli, Lisi)