Neutrino mass ordering: normal, abnormal and so what?

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- ♣ **Is abnormal OK?**
- ♣ **A new approach**
- ♣ **Some comments**

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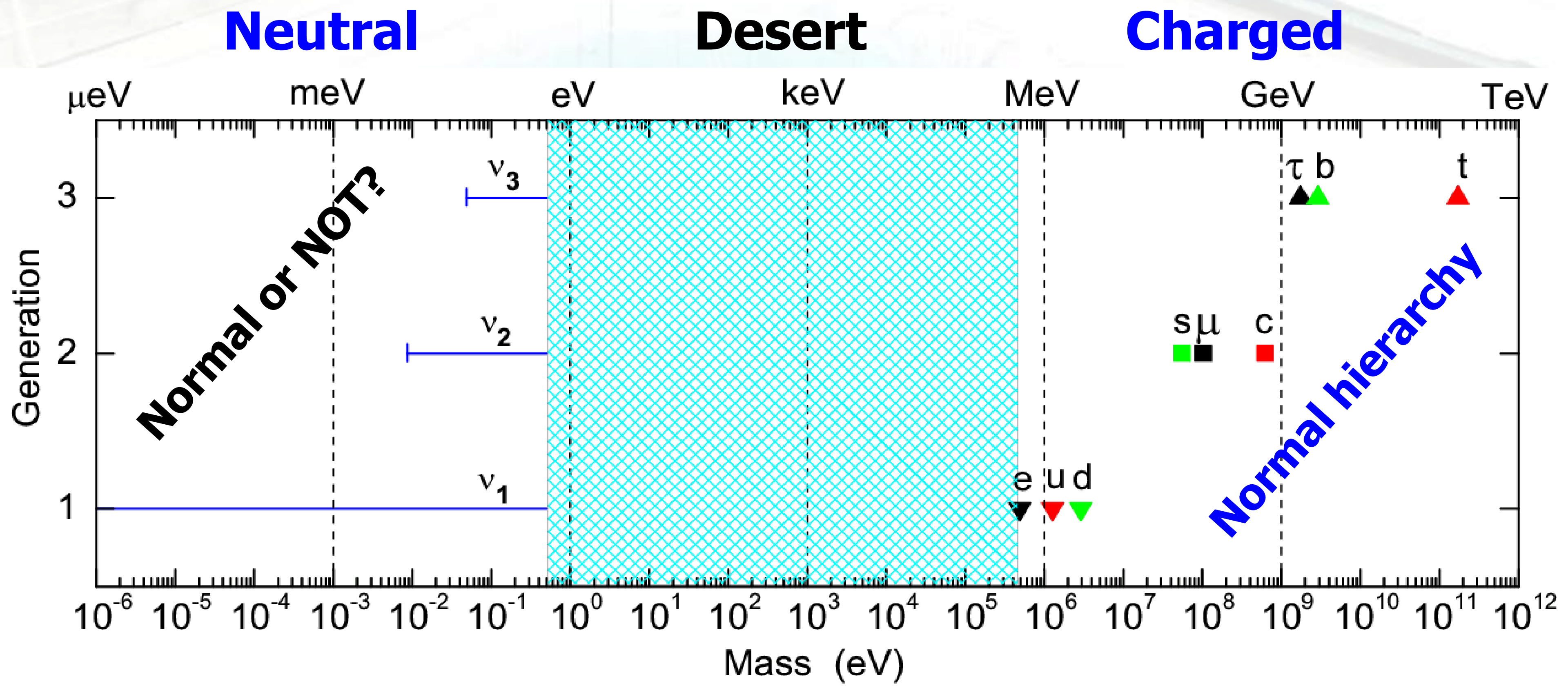
Mass ordering



Transforming the flavor basis to the mass basis, we arrive at the well-defined lepton and quark flavor mixing matrices:

$$-\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} \left[\overline{(e \quad \mu \quad \tau)_L} \, \gamma^\mu \, U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_L W^-_\mu + \overline{(u \quad c \quad t)_L} \, \gamma^\mu \, V \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L W^+_\mu \right] + \text{h.c.}$$

Is it a problem?

Neutrino mass ordering: 6 possibilities, but only 2 are allowed by data

$m_1 < m_2 < m_3$	**Normal, allowed**
$m_1 < m_3 < m_2$	**Abnormal, killed**
$m_2 < m_1 < m_3$	**Abnormal, killed**
$m_2 < m_3 < m_1$	**Abnormal, killed**
$m_3 < m_1 < m_2$	**Abnormal, allowed**
$m_3 < m_2 < m_1$	**Inverted, killed**

QUESTION:

If experiments tell us that Nature favors the abnormal mass ordering, shouldn't we theorists give a reason for it?

Or, one takes the normal mass ordering for granted, without any special reason?

If you frown on the abnormal case, you may reorder / renormalize it:

$$m_3 < m_1 < m_2 \quad \Downarrow \quad m'_1 < m'_2 < m'_3$$

$$(\nu_1, \nu_2, \nu_3) \to (\nu'_2, \nu'_3, \nu'_1)$$

$$-\mathcal{L}'_{\rm cc} = \frac{g}{\sqrt{2}} \left[\overline{(e \quad \mu \quad \tau)_{\rm L}} \ \gamma^\mu \ U' \begin{pmatrix} \nu'_1 \\ \nu'_2 \\ \nu'_3 \end{pmatrix}_{\rm L} W^-_\mu + \overline{(u \quad c \quad t)_{\rm L}} \ \gamma^\mu \ V \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\rm L} W^+_\mu \right] + {\rm h.c.}$$

Reordered PMNS

The PMNS matrix in the renormalized mass basis has a new structure:

$$|U| = \begin{pmatrix} 0.795 \to 0.846 & 0.513 \to 0.585 & 0.126 \to 0.178 \\ 0.205 \to 0.543 & 0.416 \to 0.730 & 0.579 \to 0.808 \\ 0.215 \to 0.548 & 0.409 \to 0.725 & 0.567 \to 0.800 \end{pmatrix}$$

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(Values based on M.C. Gonzalez-Garcia's talk at TAUP 13, September.)

The standard parametrization: $\delta \in [0^\circ, 360^\circ]$ and $\delta' \in [0^\circ, 360^\circ]$ **(3σ)**

$$\theta'_{12} = 77.8^\circ \to 81.3^\circ\ , \quad \theta'_{13} = 31.0^\circ \to 35.5^\circ\ , \quad \theta'_{23} = 30.5^\circ \to 57.5^\circ\ ;$$
$$\theta_{12} = 31.4^\circ \to 36.0^\circ\ , \quad \theta_{13} = 7.4^\circ \to 10.0^\circ\ , \quad \theta_{23} = 37.2^\circ \to 54.6^\circ\ .$$

CKM quark mixing

$$|V| = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

Dynamics → phenomenology

Flavor Symmetry

Texture zeros | **Element correlations** | **GUT relations**

They reduce the number of free parameters, leading to predictions for 3 mixing angles, in terms of either ν mass ratios or constant numbers.

Example (continuous symmetries)

$$M_{l,\nu} = \begin{pmatrix} 0 & \times & 0 \\ \times & 0 & \times \\ 0 & \times & \times \end{pmatrix}$$

Dependent on mass ratios

Example (discrete symmetries)

$$M_{\nu} = \begin{pmatrix} b+c & -b & -c \\ -b & a+b & -a \\ -c & -a & a+c \end{pmatrix}$$

Dependent on simple numbers

A → **PREDICTIONS** ← **B**

A is more relevant for our purpose, to establish a correlation between the neutrino mass spectrum and the lepton mixing pattern.

Basis choice

Let's try a new ansatz for the standard weak interactions, which don't involve any flavor-changing right-handed currents.

$$-\mathcal{L}_{\rm mass} = \overline{\mathbf{E}_{\rm L}} M_\ell \mathbf{E}_{\rm R} + \frac{1}{2}\overline{\mathbf{N}_{\rm L}} M_\nu \mathbf{N}^c_{\rm L} + \overline{\mathbf{U}_{\rm L}} M_{\rm u} \mathbf{U}_{\rm R} + \overline{\mathbf{D}_{\rm L}} M_{\rm d} \mathbf{D}_{\rm R} + {\rm h.c.}$$

Physics keeps unchanged for an arbitrary unitary transformation of the right-handed fields. We can

- ★ **make charged fermion mass matrices Hermitian;**
- ★ **get 3 zeros for quarks/leptons in a proper basis.**

Fritzsch texture

$$M_{\rm u} = \begin{pmatrix} E_{\rm u} & C_{\rm u} & F_{\rm u} \\ C^*_{\rm u} & D_{\rm u} & B_{\rm u} \\ F^*_{\rm u} & B^*_{\rm u} & A_{\rm u} \end{pmatrix} , \quad M_{\rm d} = \begin{pmatrix} 0 & C_{\rm d} & 0 \\ C^*_{\rm d} & 0 & B_{\rm d} \\ 0 & B^*_{\rm d} & A_{\rm d} \end{pmatrix}$$

$$M_\ell = \begin{pmatrix} E_\ell & C_\ell & F_\ell \\ C^*_\ell & D_\ell & B_\ell \\ F^*_\ell & B^*_\ell & A_\ell \end{pmatrix} , \quad M_\nu = \begin{pmatrix} 0 & C_\nu & 0 \\ C_\nu & 0 & B_\nu \\ 0 & B_\nu & A_\nu \end{pmatrix}$$

$$O^\dagger_{\rm u} M_{\rm u} M^\dagger_{\rm u} O_{\rm u} = {\rm Diag}\{m^2_u, m^2_c, m^2_t\}$$
$$O^\dagger_{\rm d} M_{\rm d} M^\dagger_{\rm d} O_{\rm d} = {\rm Diag}\{m^2_d, m^2_s, m^2_b\}$$
$$O^\dagger_\ell M_\ell M^\dagger_\ell O_\ell = {\rm Diag}\{m^2_e, m^2_\mu, m^2_\tau\}$$
$$O^\dagger_\nu M_\nu O^*_\nu = {\rm Diag}\{m_1, m_2, m_3\}$$

How to deal with? **Exactly calculable!**

MNS: $U = O^\dagger_\ell O_\nu$

CKM: $V = O^\dagger_{\rm u} O_{\rm d}$

Dynamics = assumptions?

How to deal with mass matrices of up-type quarks & charged leptons?

the large top / tau mass limit

$$\lim_{m_t\to\infty}\left(M_{\rm u}M_{\rm u}^\dagger\right) \propto \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \infty \end{pmatrix} , \qquad \lim_{m_t\to\infty} O_{\rm u} \propto \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\lim_{m_\tau\to\infty}\left(M_\ell M_\ell^\dagger\right) \propto \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \infty \end{pmatrix} , \qquad \lim_{m_\tau\to\infty} O_\ell \propto \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

MNS → $$U_{\alpha i} = \sum_{k=1}^{3} (O_\ell)^*_{k\alpha} (O_\nu)_{ki} \; , \qquad V_{\alpha i} = \sum_{k=1}^{3} (O_{\rm u})^*_{k\alpha} (O_{\rm d})_{ki}$$ ← **CKM**

In this approach we obtain a successful result for quark flavor mixing:

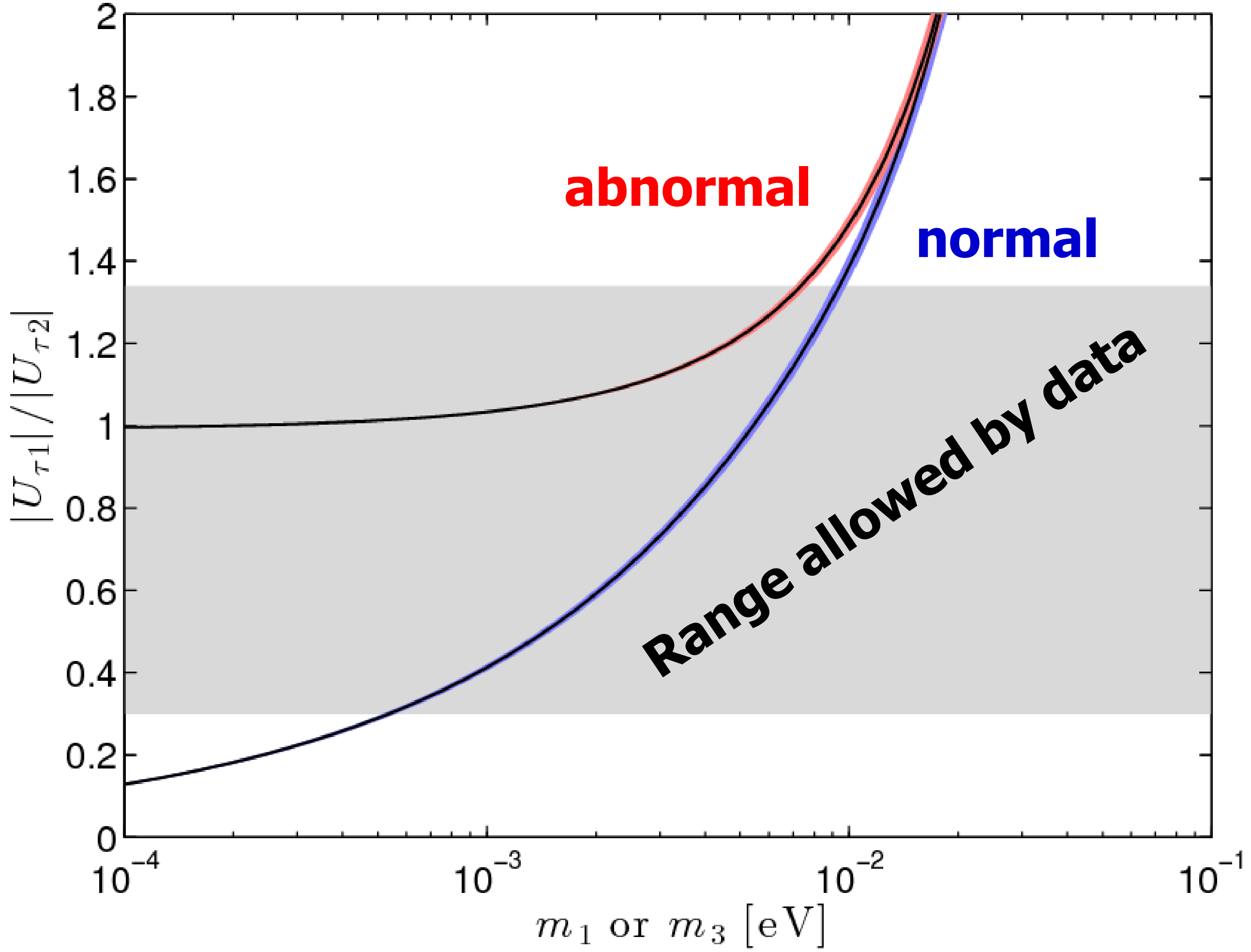
$$\lim_{m_t\to\infty}\left|\frac{V_{td}}{V_{ts}}\right| = \left|\frac{(O_{\rm d})_{3d}}{(O_{\rm d})_{3s}}\right| = \sqrt{\frac{m_d}{m_s}\cdot\frac{m_b+m_d}{m_b-m_d}\cdot\frac{m_b+m_s}{m_b-m_s}}$$

Numerical prediction: $|V_{td}|/|V_{ts}| = 0.227$ **;** **Data:** $|V_{td}|/|V_{ts}| = 0.215^{+0.010}_{-0.013}$ **.**

How about leptons?

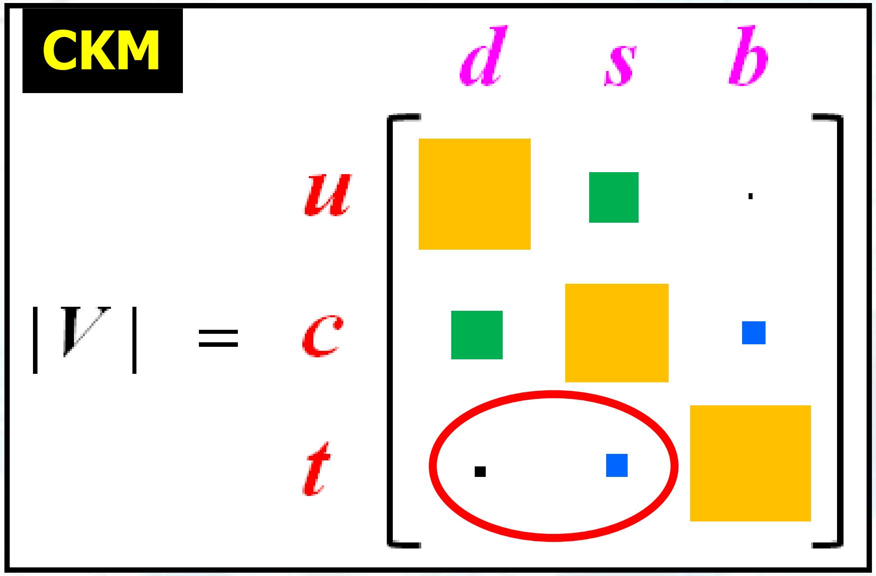
In a similar way we arrive at the prediction for lepton flavor mixing:

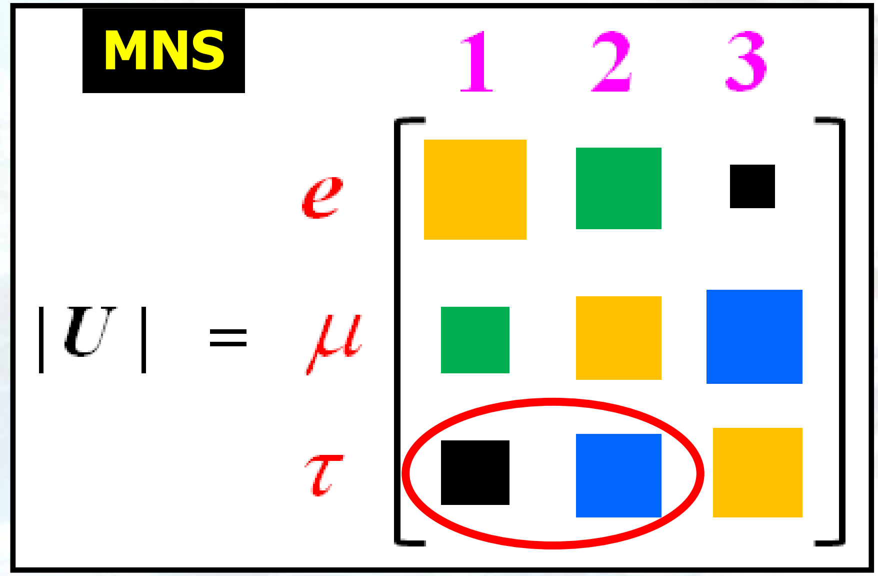
$$\lim_{m_\tau \to \infty} \left| \frac{U_{\tau 1}}{U_{\tau 2}} \right| = \left| \frac{(O_\nu)_{31}}{(O_\nu)_{32}} \right| = \sqrt{\frac{m_1}{m_2} \cdot \frac{m_3 + m_1}{m_3 - m_1} \cdot \frac{m_3 + m_2}{m_3 - m_2}}$$



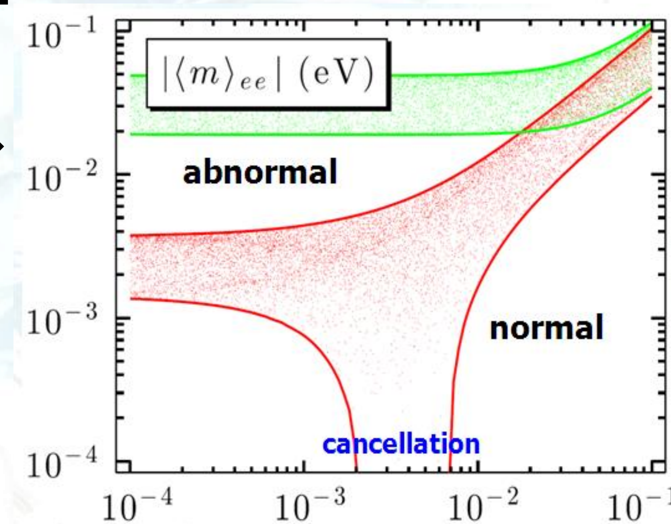
My bet is ……

The neutrino mass spectrum should be normal.



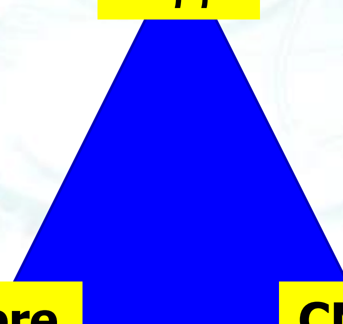


The large top/tau mass limit may at least help understand the bottom left corner of the CKM/MNS matrix.



Many experimentalists favor abnormal/nearly degenerate mass ordering, as they want to see a signature of 0νββ or of cosmology earlier.

0νββ →



Accelerator/Reactor/Atmosphere

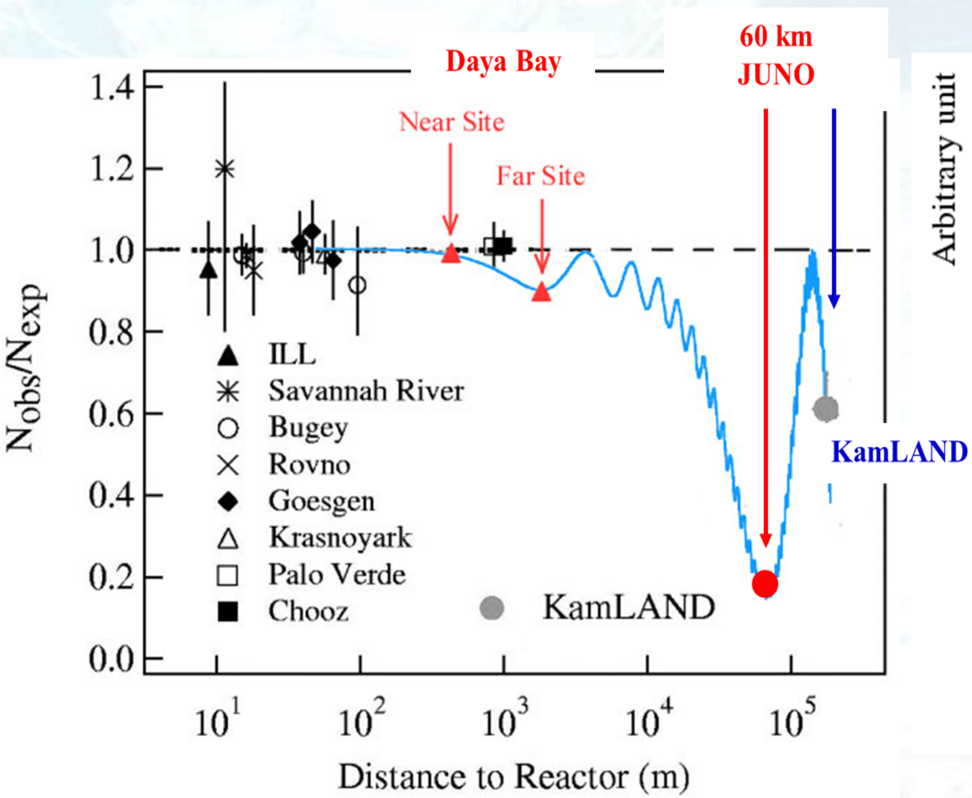
CMB

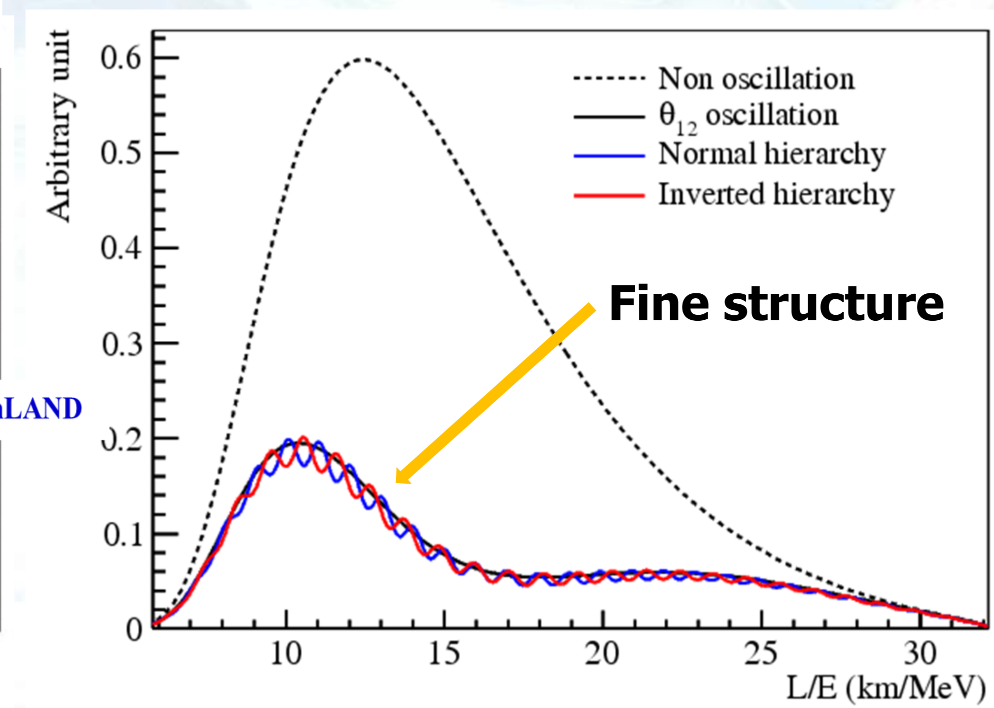
JUNO experiment

Accelerator/atmospheric: matter effects

$$\Delta m^2_{31} + 2\sqrt{2} G_F N_e E$$

Reactor (JUNO): Optimum baseline at the minimum of Δm^2_{21} oscillations, corrected by the fine structure of Δm^2_{31} oscillations.





Concluding remarks