Neutrino Physics:
general framework and open problems

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The purpose of this talk:

a short elementary introduction
(with apologies to the experts in the audience)
to set the stage for the following talks on experiments

- The general framework
- What has been learned so far
- Open questions in neutrino physics
- Some theoretical ideas

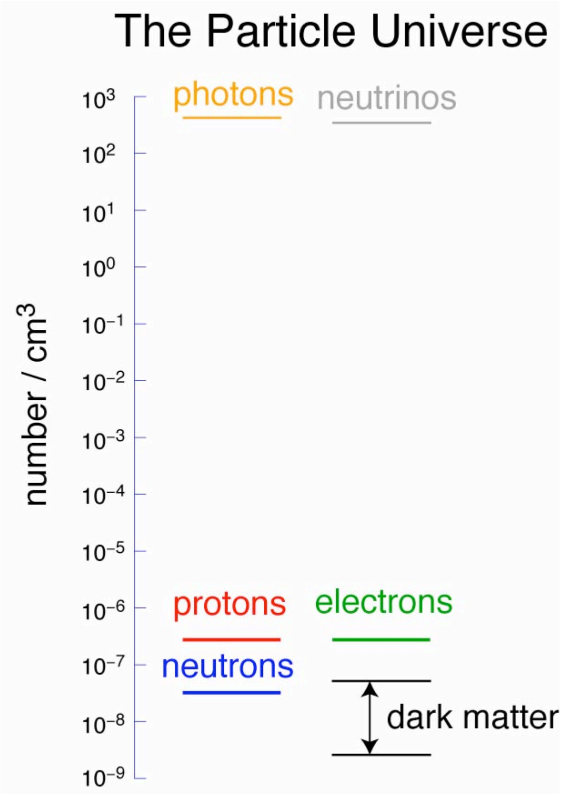
The importance of neutrinos

Cosmology and astrophysics:

Most abundant particles in the universe after the photons: ~ 300 neutrinos / cm^3 affect large scale structure and CMB

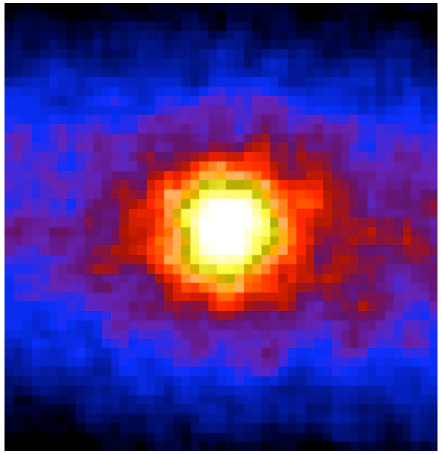
Copiously produced by stars

Weakly interacting and extremely light: can carry information over regions with large matter density and huge length scales e.g. they are probes of supernovae dynamics



Particle physics: a key to the flavour and unification problems

Tiny mass a possible window, via the see-saw mechanism, to extremely high energy scales, inaccessible directly to present lab experiments



SK picture of the sun

The "Nu" Standard Model

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \delta\mathcal{L}(m_\nu) + \ldots$$

$\mathcal{L}_{SM}$:

Renormalizable minimal SM Lagrangian
3 families with nu-left but no nu-right
$(B, L_e, L_{mu}, L_{tau})$ accidental global symmetries
[(B+L) anomalous]

$\delta\mathcal{L}(m_\nu)$:

Modification NEEDED to describe the observed breaking of lepton flavour in neutrino physics interpreted in terms of neutrino masses and mixing

" . . . " :

Possible additional operators (subleading effects)
no experimental evidence so far

$\delta\mathcal{L}(m_\nu)$ experimentally needed, but still undetermined

The crucial difference between the simple options:

B - L (~ L) : BROKEN or UNBROKEN

Dirac vs. Majorana neutrino masses

1. Dirac masses [Exact (B-L)]

•Yukawa couplings among L-left, nu-right and H
•Dirac masses and mixing as for other SM particles
•(B-L) conservation is now independent assumption

2. Majorana masses [Broken (B-L)]

$$\frac{1}{\Lambda}(H^\dagger L)^T Y (H^\dagger L) + h.c. \Rightarrow \frac{v^2}{\Lambda}\nu^T Y \nu + h.c. + \dots$$

Unique @ D=5

• $v \ll \Lambda \Rightarrow$ suppressed Majorana mass terms

•Heavy nu-R generate it by the see-saw mechanism:

$$(H^\dagger L)^T [y_\nu^T M^{-1} y_\nu] (H^\dagger L) + h.c.$$

•Possible role in the matter-antimatter asymmetry (baryogenesis through leptogenesis)

The leptonic mixing matrix U (often U_{PMNS})

Assume just three active massive neutrinos

interaction eigenstates

$\alpha = e, \mu, \tau$

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\, \nu_i$$

mass eigenstates

$i = 1, 2, 3$

Typical parametrization (last 2 phases only for Majorana):

$$U_{PMNS} = \begin{pmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{i\delta} \\ -s_{12} c_{23} - c_{12} s_{13} s_{23} e^{-i\delta} & c_{12} c_{23} - s_{12} s_{13} s_{23} e^{-i\delta} & c_{13} s_{23} \\ -c_{12} s_{13} c_{23} e^{-i\delta} + s_{12} s_{23} & -s_{12} s_{13} c_{23} e^{-i\delta} - c_{12} s_{23} & c_{13} c_{23} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

Three mixing angles θ_{12} θ_{13} θ_{23}

Three phases (in general) δ α β

(unphysical if Dirac and untestable by oscillations)

Masses and mass hierarchies

Three physical mass[2] eigenvalues $m_1^2 \quad m_2^2 \quad m_3^2$

Oscillations probe only differences $\Delta m_{ij}^2 = m_j^2 - m_i^2$

$$|\Delta m_{13}^2|, |\Delta m_{23}^2| > \Delta m_{12}^2 > 0$$

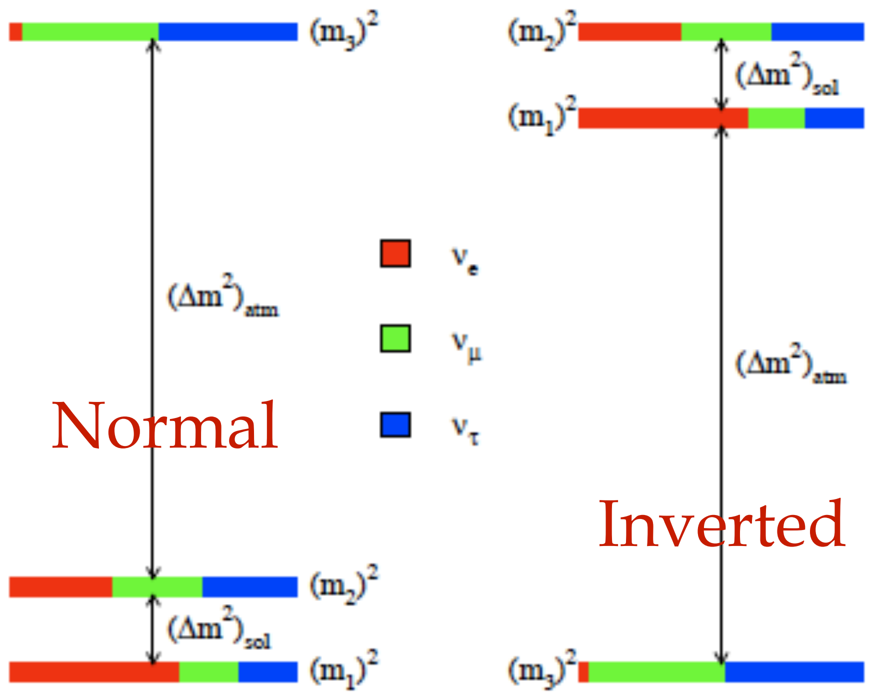
`atmospheric' `solar'

Hierarchies:

Normal $\Delta m_{13}^2 > 0$

Inverted $\Delta m_{13}^2 < 0$

Degenerate $m_i^2 \gg |\Delta m_{ij}^2|$



Present non-oscillation knowledge

End-point in tritium beta decay

$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$

$$m_\nu^2 \simeq \sum_i |U_{ei}|^2 m_i^2$$

$$m_\nu < 2.2\, eV$$

Cosmological bounds (dependence on model and data set)

$$\sum_i m_i < 0.2 \div 2 \quad eV$$

Cosmic Microwave Background
Large Scale Structure
…

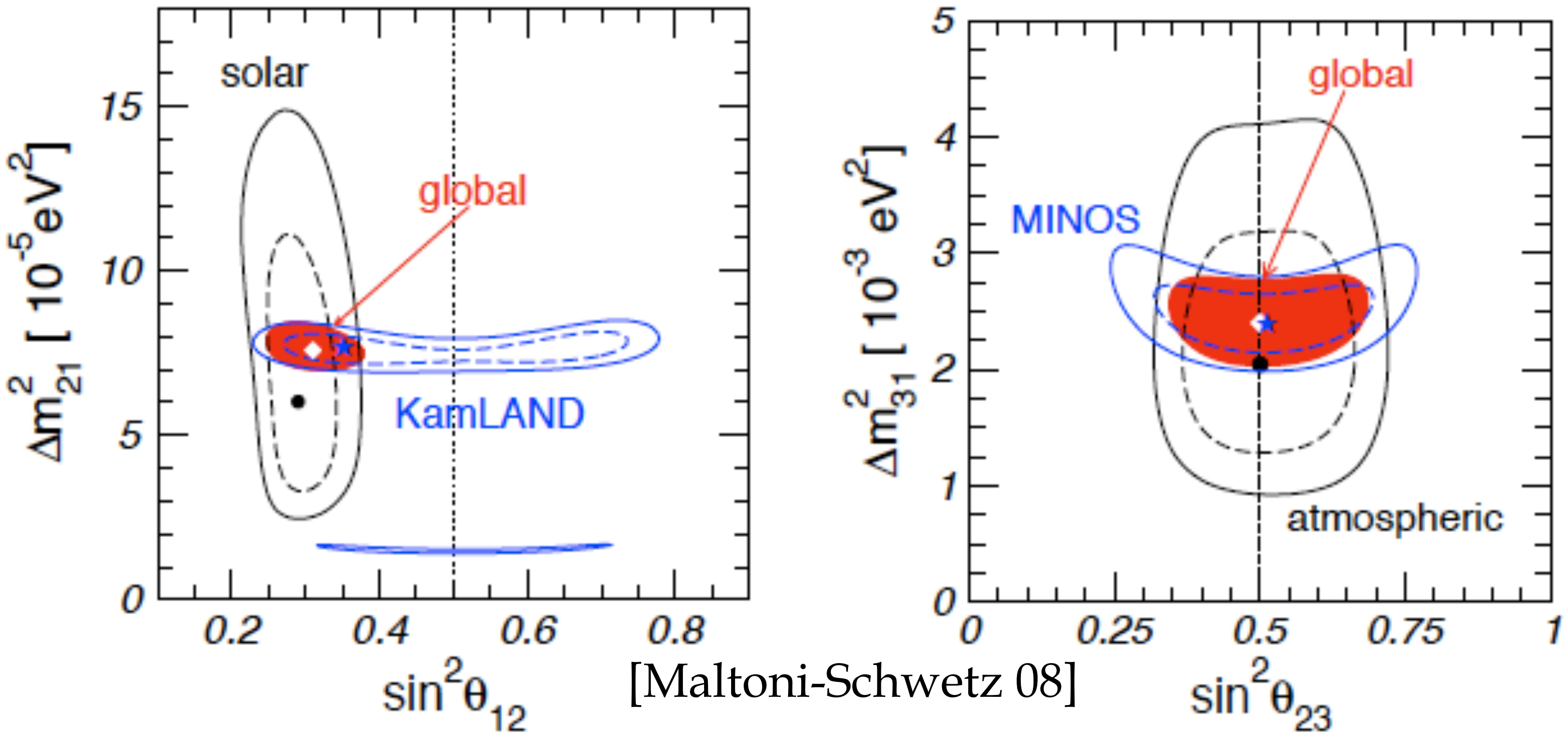
Neutrinoless double beta decay (A,Z) ➔ (A,Z+2)+2e (0nu)

$$m_{ee} = \left| \sum_i U_{ei}^2 m_i \right|$$

$$m_{ee} < 0.2 - 1\, eV$$

(large uncertainties in the nuclear matrix elements)

The `solar' and `atmospheric' parameters



[Maltoni-Schwetz 08]

$$\Delta m^2_{sol} \sim 7.7 \times 10^{-5}$$

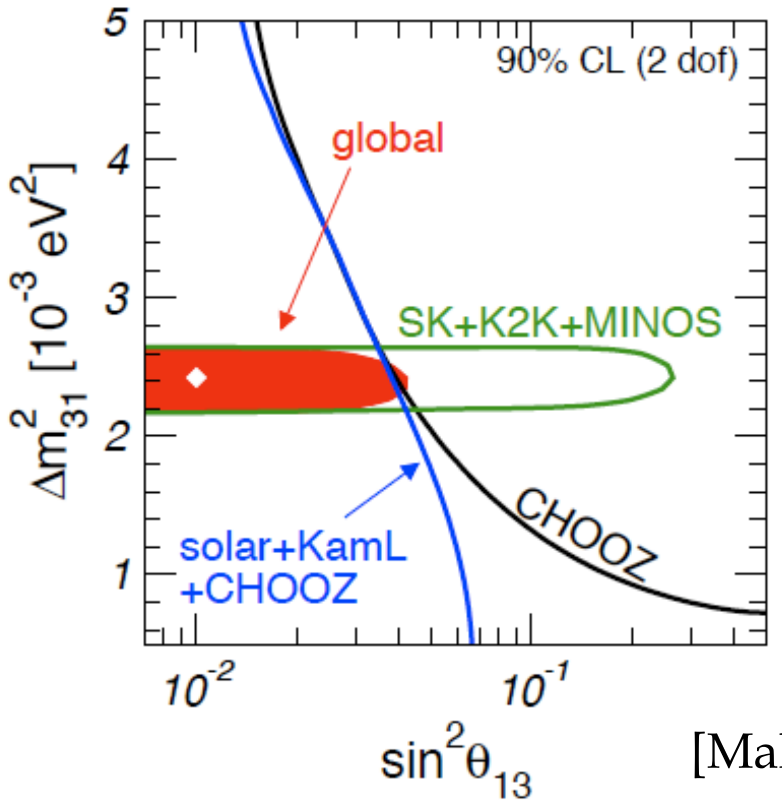
$$\Delta m^2_{atm} \sim 2.5 \times 10^{-3}$$

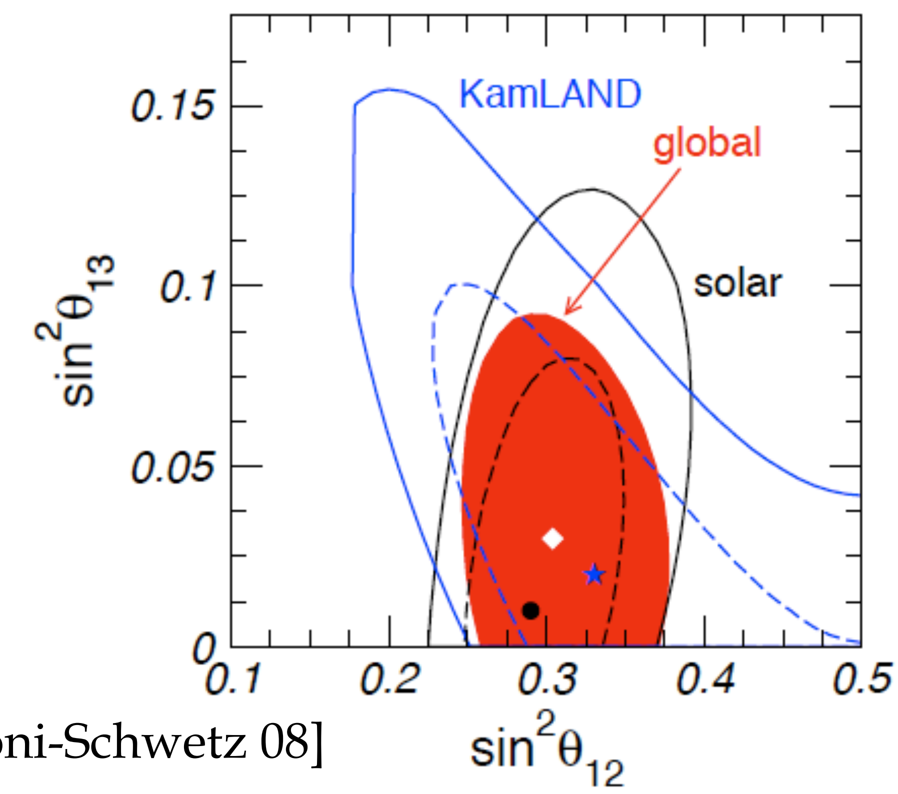
$$\theta_{sol} \sim 35^o$$

$$\theta_{atm} \sim 45^o$$

parameter	best fit$\pm 1\sigma$	3σ interval
Δm^2_{21} [10^{-5}eV^2]	$7.67^{+0.22}_{-0.21}$	7.07–8.34
Δm^2_{31} [10^{-3}eV^2]	-2.39 ± 0.12 $+2.49 \pm 0.12$	$-(2.02$–$2.79)$ $+(2.13$–$2.88)$
$\sin^2\theta_{12}$	$0.321^{+0.023}_{-0.022}$	0.26–0.40
$\sin^2\theta_{23}$	$0.47^{+0.07}_{-0.06}$	0.33–0.64

Present knowledge on theta13



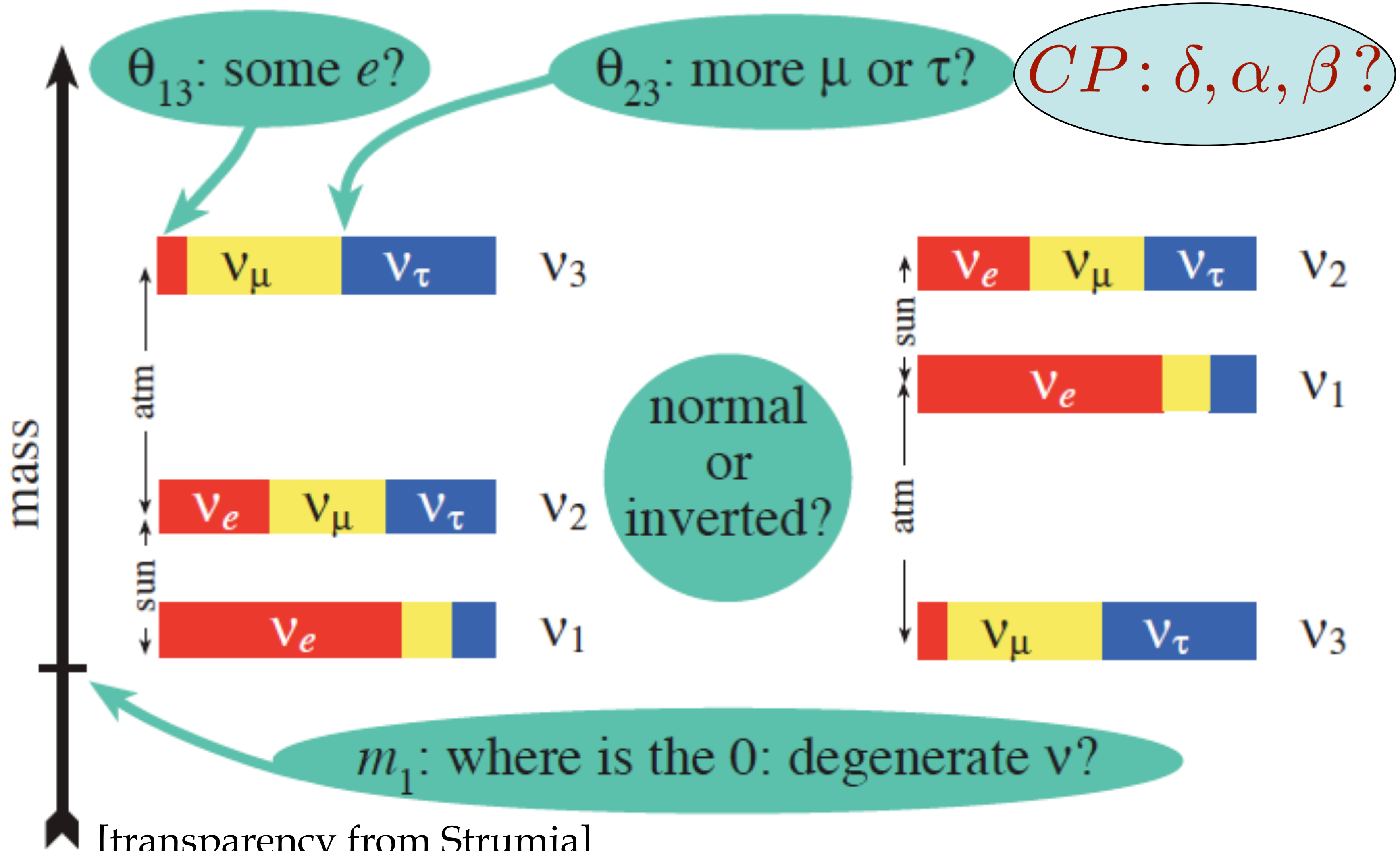


[Maltoni-Schwetz 08]

parameter	Ref. [1] best fit$\pm 1\sigma$	Ref. [1] 3σ interval
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.056

Known unknowns

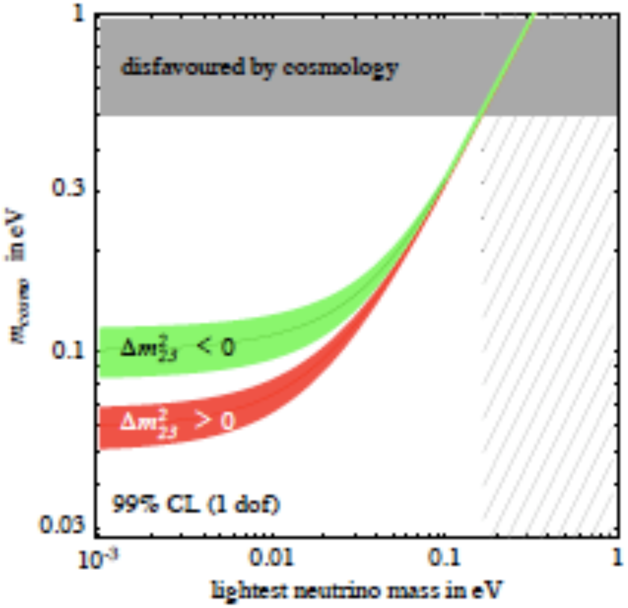
Is L violated?

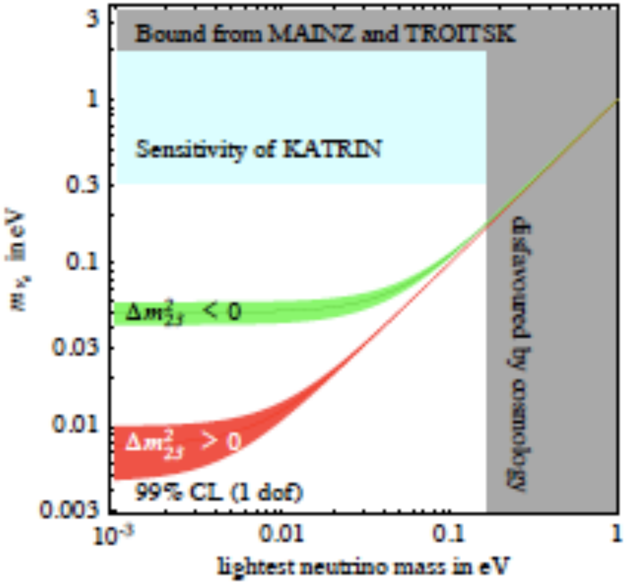


[transparency from Strumia]

Prospects for non-oscillation parameters

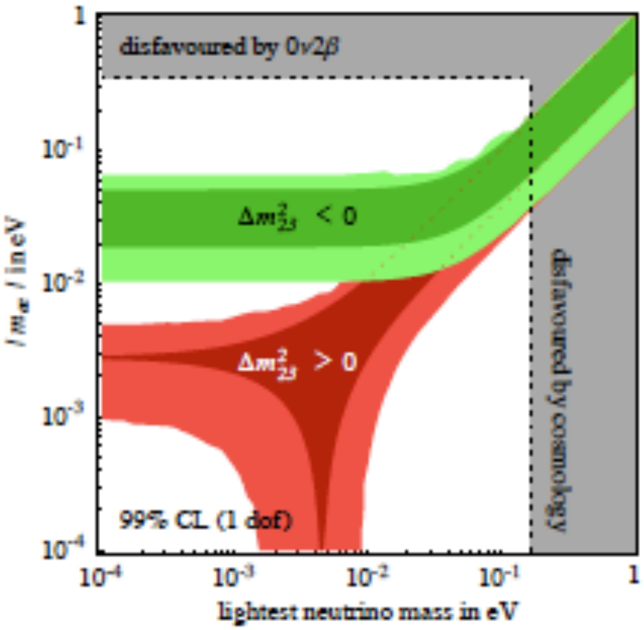
$\sum_i m_i$





m_ν

m_{ee}



Planck: $\sum_i m_i \sim 0.03\, eV$

Katrin: $m_\nu \sim 0.2\, eV$

Gerda,SuperNemo,EXO200,Cuore:

$m_{ee} \sim 0.04\, eV$

Oscillation parameters

θ_{13}

- Only an upper bound so far (hints?)
- Size may shed light on flavour breaking
- Size is crucial for other questions below

$\left(\theta_{23} - \frac{\pi}{4}\right)$

- Size may shed light on flavour breaking

$sign(\Delta m^2_{13})$

- Inverted hierarchy may point to a symmetry

$\delta\ (CPV)$

- Unconstrained at the moment in [0,2pi]
- The leptonic counterpart of the KM phase!

To probe CPV, need θ_{13} non-zero and large enough

In general, same goals as experiments on quark flavour:

overconstrain the 3-standard-neutrino paradigm

Sensitivity to theta13

Reactors (nubar-e disappearence)

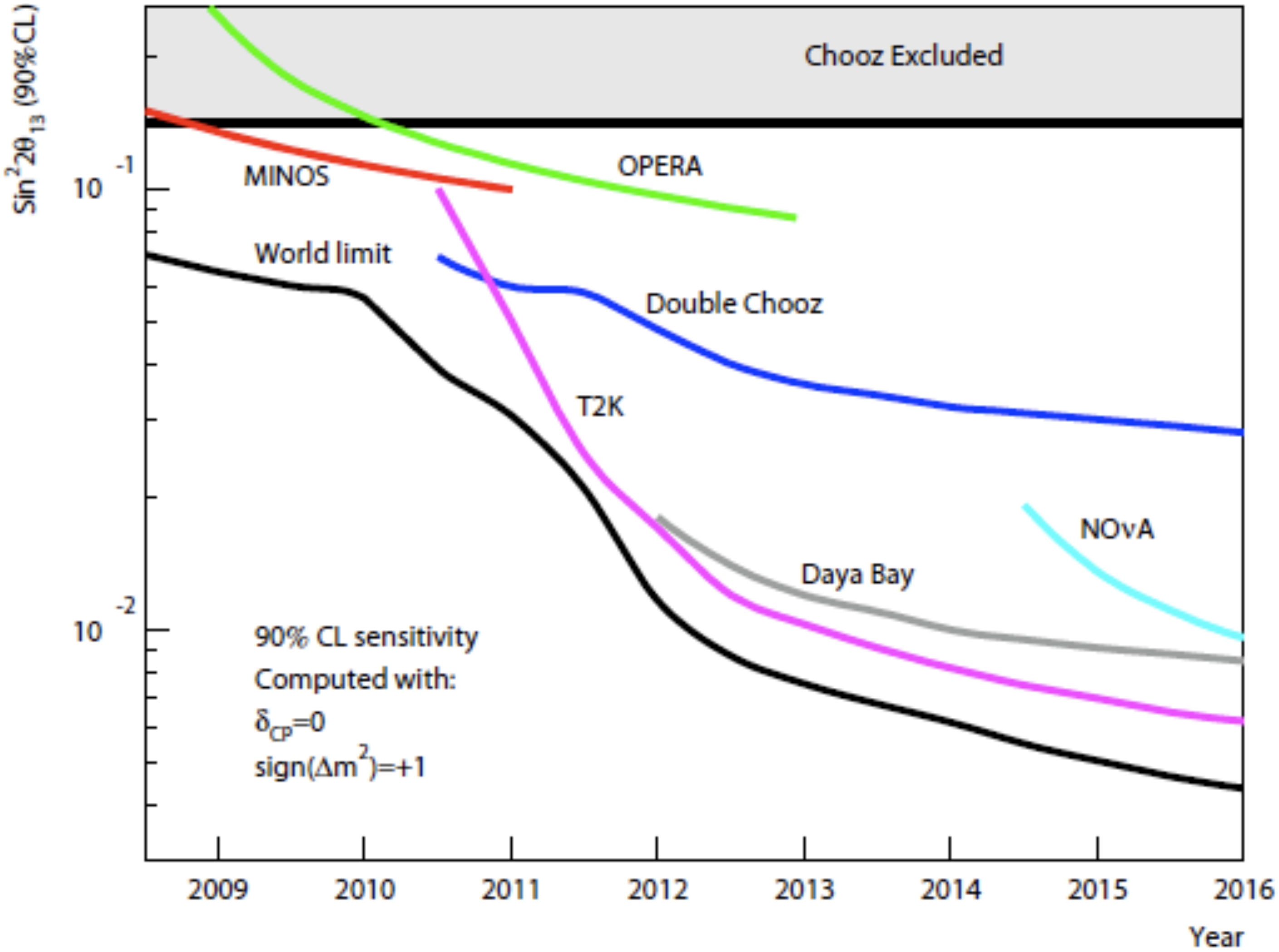
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

Accelerators (nu-e appearance)

Dependence on CP-phase, mass hierarchy, matter effects

$$\begin{aligned}
P(\nu_\mu \to \nu_e) = & \; 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \\
& + 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin\Delta_{31} [\cos\Delta_{32}\cos\delta - \sin\Delta_{32}\sin\delta] \sin\Delta_{21} \\
& - 8c_{13}^2 s_{13}^2 s_{23}^2 s_{12}^2 \cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} \\
& + 4c_{13}^2 s_{12}^2 [c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta] \sin^2\Delta_{21} \\
& - 8c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2) \frac{aL}{4E_\nu} \sin\Delta_{31}\left[\cos\Delta_{32} - \frac{\sin\Delta_{31}}{\Delta_{31}}\right] .
\end{aligned}$$

Near future prospects on theta13



also Reno

Year?

[Mezzetto arXiv:0905.2842]

More speculative unknowns

Going beyond `known unknowns', there may be other observable manifestations of lepton flavour breaking

•Measurable LFV in the charged lepton sector?

$\mu \longrightarrow e\,\gamma$ mu-e conversion in nuclei $\mu \longrightarrow eee$ Rare tau decays EDM, AMM

Possible but need new physics not too far from TeV scale
If so, any relation between LFV and new physics @ LHC?

•The simple 3-neutrino picture may be possibly ruled out (unitarity tests,…: is there room for sterile neutrinos?)

•Many other increasingly speculative possibilities…

Some theoretical ideas

There is no theory of flavour in the quark sector,
and the same holds true also in the lepton sector.
But some interesting pattern is worth noticing…

Tri-bimaximal mixing [Harrison-Perkins-Scott 2002] :

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

by unitarity

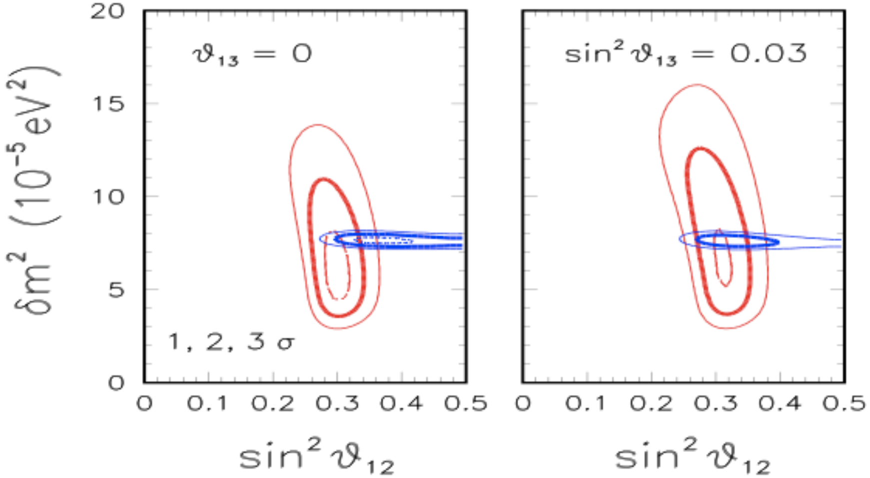
$$\theta_{13} = 0, \quad \sin^2 2\theta_{23} = 1, \quad \tan^2 \theta_{12} = 1/2.$$

Can be justified by discrete non-Abelian symmetries
e.g. A_4 (even permutations of 4 objects: "tetrahedral")
However:
-not so easy to extend to quarks, especially in GUTs
-likely broken at some level, but how and how much?

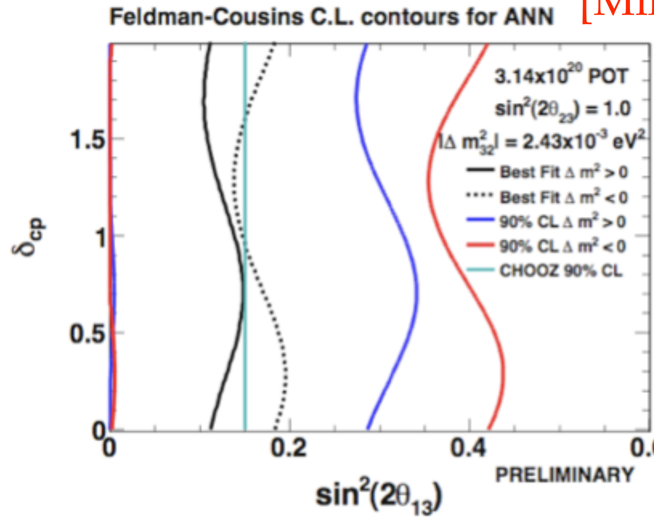
Backup Slides

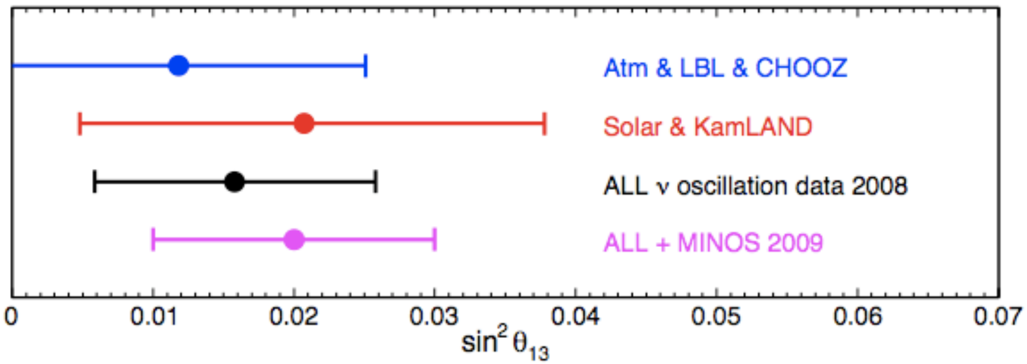
Hints of theta13 ≠ 0 ?

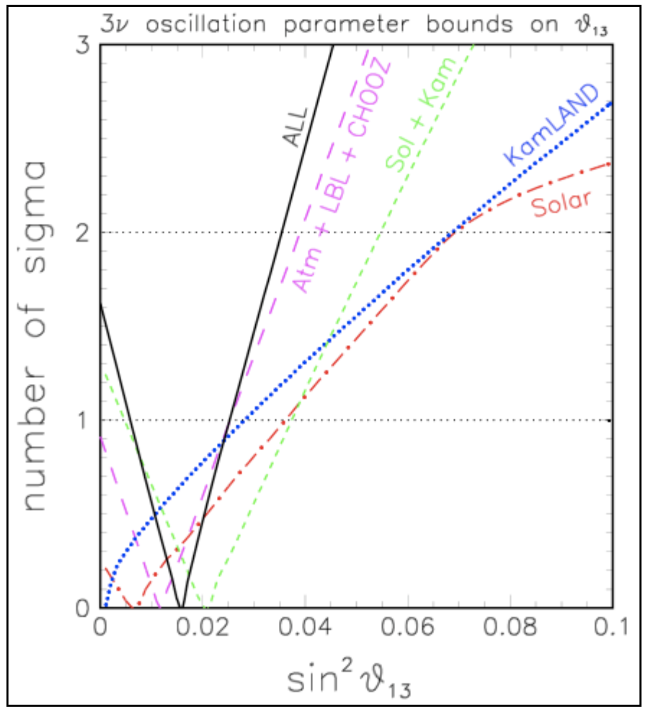
[Solar + KamLand]



[Minos 2009]

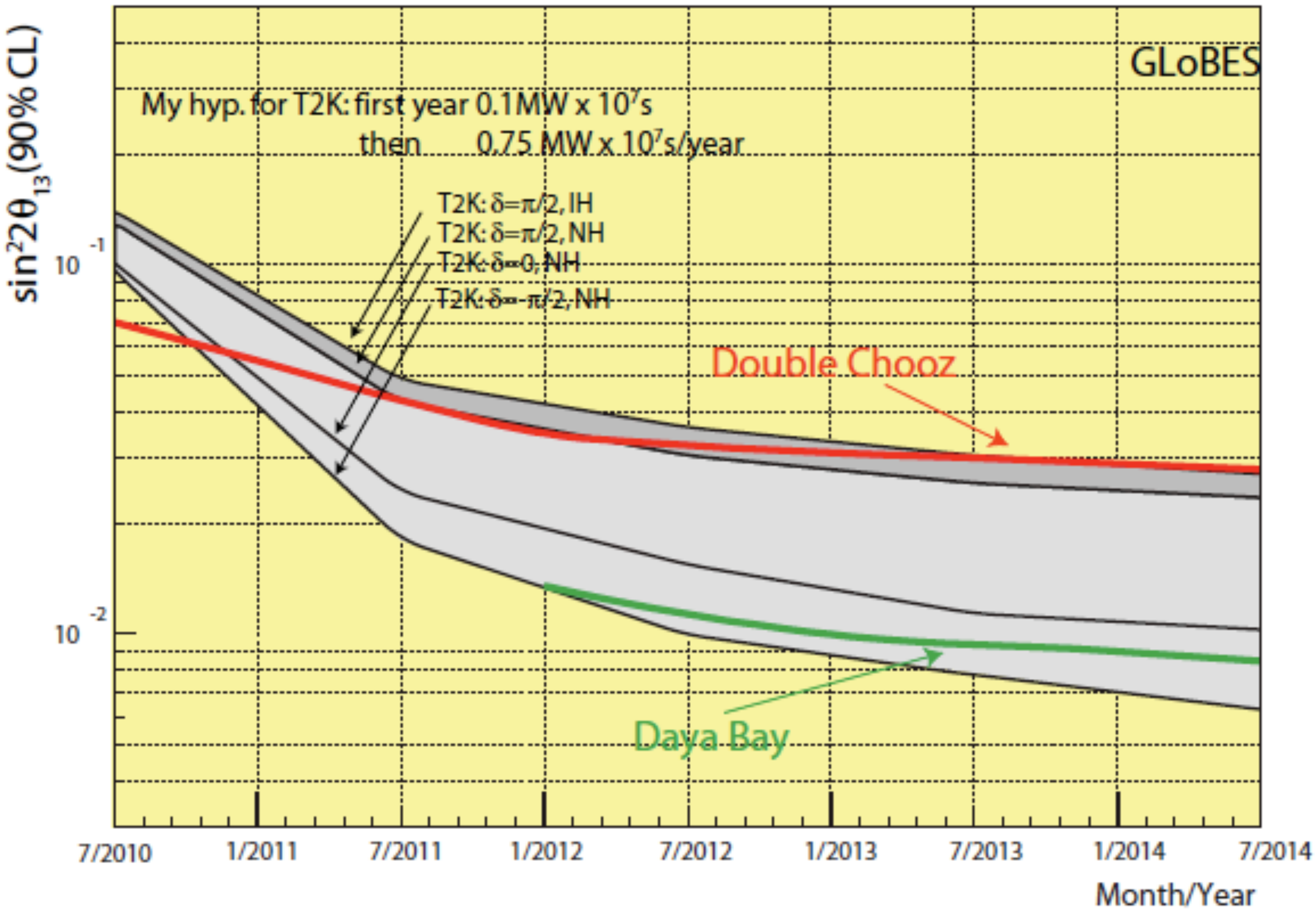






[Fogli-Lisi-Marrone-Palazzo-Rotunno 2009]

More on theta13 in the near future



[transparency from Mezzetto]

The θ_{13} Fork.

$\sin^2 2\theta_{13} > 0.01$

$\sin^2 2\theta_{13} < 0.01$

$\sin^2 2\theta_{13} \approx 0.01$

- If $\sin^2 2\theta_{13} \geq \sim 0.01$ there are sufficient events for conventional beams to potentially observe CP violation.
- They are hampered by the impure nature of such beams.

- If $\sin^2 2\theta_{13}$ is smaller, then the fractional CP effect is larger, but conventional beams have no events left.
- Must build a βB or a NF.

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Imperial College/RAL

More theory: leptogenesis & CP violation

Effective theory with the 3 (mostly LH) light neutrinos only:

9 parameters: 3 masses, 3 mixing angles, 3 CPV phases

9 more parameters with the 3 heavy (mostly RH) neutrinos:

3 more masses, 3 more mixing angles, 3 more CPV phases

Leptogenesis:

Out-of equilibrium, CP-violating decays of heavy right-handed neutrinos in the early universe generate a net lepton-antilepton asymmetry, converted into baryon asymmetry by SM interactions

12 parameters contribute, but not the low-energy phase δ

Some more theory on tri-bimaximal (TB) mixing

Why $$U_{PMNS} \approx U_{TB} \equiv \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$ **?**

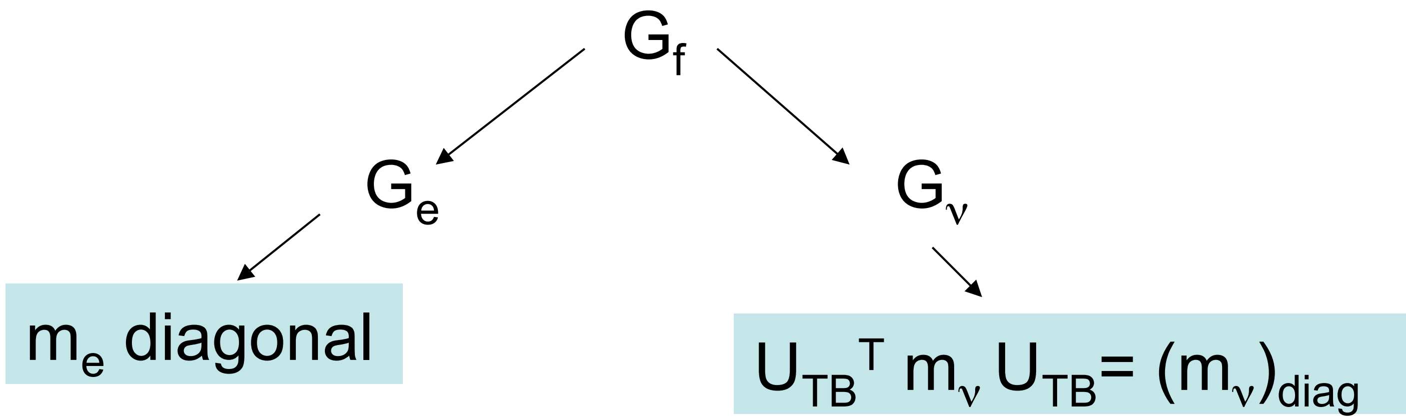
$$U_{PMNS} = U_e^+ U_\nu$$

Flavour symmetry G_f broken into:

G_e in the charged lepton sector (m_e invariant under G_e)

G_ν in the neutrino sector (m_ν invariant under G_ν)

Choosing G_e and G_ν we can predict the observed U_{PMNS}.



Simplest example based on the discrete group $G_f = A_4$
[the subgroup of SO(3) leaving a regular tetrahedron invariant]
All elements of A_4 can be generated from two, S and T, such that:

$$S^2 = T^3 = (ST)^3 = 1$$

S generates a subgroup Z_2 of A_4
T generates a subgroup Z_3 of A_4

simple models have been constructed where $G_e = Z_3$, $G_\nu = Z_2$ and lepton mixing matrix $U_{PMNS} = U_{TB}$ at leading order in SB parameters
small corrections induced by higher order terms

generic predictions:
θ_{13} and $(\theta_{23} - \pi/4)$ are very small
testable in a not-so-far future