- What is the origin of neutrino masses?
- Is it possible to uncover the neutrino mass generation mechanism from low energy data?
- Is neutrino mass generated at a low or an high scale?

In the context of GUT scale seesaw:

- Flavor symmetry explaining quarks and leptons at same time?
- Are flavor symmetries with a GUT compatible? In which context?
- Which are interesting symmetries? ($G \rtimes Z_3$ with G abelian)
- How is the flavor symmetry broken?
- Flavon potential (VEV alignment, Are hierarchies possible?)

# Lepton Flavor Symmetries - GUT Scale Seesaw

Type I Seesaw mechanism $m_\nu \approx -m_D M_{NN}^{-1} m_D^T$ enables

- to have a different flavor structure
- But in SO(10): $m_D \sim m_u \Rightarrow$ Quadratic hierarchy in neutrino masses
- Cancellation of hierarchies needed in neutrino mass matrix

attempts to combine GUT and discrete flavor symmetry:

- King, Malinsky (2006): 5d SO(10), matter fields localized on PS brane $\rightarrow$ LH and RH fields do not transform in the same way
- Altarelli, Feruglio, Hagedorn (2008): SU(5) $\rightarrow m_D \not\sim m_u$ due to different origin
- Morisi, Picariello, Torrente-Lujan, Bazzocchi, Frigerio (2008): matter in (16,3), contribution to $m_\nu$ from type I and type II seesaw, type I seesaw contribution alone difficult
- Hagedorn, Schmidt, Smirnov (2009): additional SO(10) singlets, double seesaw mechanism, cancellation by symmetry
- Bazzocchi, de Medeiros Varzielas (2009): additional SO(10) singlets, cancellation of hierarchy by VEV alignment

# Setup within SO(10)

| Field | $\underline{\mathbf{16}}_i$ | $S_i$ | $\mathbf{H}$ | $\Delta$ | $\chi_i$ |
|---|---|---|---|---|---|
| $SO(10)$ | $\underline{\mathbf{16}}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{10}}$ | $\overline{\underline{\mathbf{16}}}$ | $\underline{\mathbf{1}}$ |

# Setup within SO(10)

| Field | $\underline{\mathbf{16}}_i$ | $S_i$ | $\mathbf{H}$ | $\Delta$ | $\chi_i$ |
|---|---|---|---|---|---|
| $SO(10)$ | $\underline{\mathbf{16}}$ | $\underline{\mathbf{1}}$ | $\underline{\mathbf{10}}$ | $\underline{\overline{\mathbf{16}}}$ | $\underline{\mathbf{1}}$ |
| $\Sigma(81)$ | $\underline{\mathbf{3}}_{\mathbf{1}}$ | $\underline{\mathbf{1}}_{\mathbf{i}}$ | $\underline{\mathbf{1}}_{\mathbf{1}}$ | $\underline{\mathbf{1}}_{\mathbf{1}}$ | $\underline{\mathbf{3}}_{\mathbf{2}} \cong \underline{\mathbf{3}}^\star_{\mathbf{1}}$ |

$$\frac{\alpha_{ij}}{\Lambda}\underline{\mathbf{16}}_i\ \underline{\mathbf{16}}_j\ H\chi^{(\star)} + \frac{\beta_{ij}}{\Lambda}\underline{\mathbf{16}}_i\ \Delta\ S_j\chi + (M_{SS})_{ij}\, S_i S_j\ ,$$

$$\mathcal{M} = \begin{pmatrix} 0 & \alpha\,\langle H\rangle\,\frac{\langle\chi\rangle}{\Lambda} & \beta\,\langle\Delta\rangle_\nu\,\frac{\langle\chi\rangle}{\Lambda} \\ . & 0 & \beta\,\langle\Delta\rangle_N\,\frac{\langle\chi\rangle}{\Lambda} \\ . & . & M_{SS} \end{pmatrix} \Rightarrow m_\nu^{DS} \approx m_D M_{NS}^{-1\,T} M_{SS} M_{NS}^{-1} m_D^T$$

**Which flavor symmetry?**

- Explain number of generations: $\underline{\mathbf{16}}_i \sim \underline{\mathbf{3}}$
- Explain difference in CKM and MNS matrix (in lowest order)
- Complex $\underline{\mathbf{3}} \Rightarrow A_4$ not possible, but: $T_7$ [Luhn,Nasri,Ramond], $\Sigma(81)$ [Ma], ...

# Mass Matrices

$$m_D = \frac{\alpha \, \langle \mathbf{H} \rangle}{\Lambda} \begin{pmatrix} \langle \chi_1 \rangle^* & 0 & 0 \\ 0 & \langle \chi_2 \rangle^* & 0 \\ 0 & 0 & \langle \chi_3 \rangle^* \end{pmatrix}$$

$$M_{NS} = \frac{\langle \Delta \rangle_N}{\Lambda} \begin{pmatrix} \langle \chi_1 \rangle & 0 & 0 \\ 0 & \langle \chi_2 \rangle & 0 \\ 0 & 0 & \langle \chi_3 \rangle \end{pmatrix} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega & \omega^2 \\ 1 & \omega^2 & \omega \end{pmatrix} \begin{pmatrix} \beta_1 & 0 & 0 \\ 0 & \beta_2 & 0 \\ 0 & 0 & \beta_3 \end{pmatrix}$$

$$M_{SS} = \begin{pmatrix} A & 0 & 0 \\ \cdot & 0 & B \\ \cdot & \cdot & 0 \end{pmatrix}$$

## Some Lessons

- Large top suggests that it has a different origin
- Scenarios with type I seesaw is strongly constrained due to $m_u \sim m_D$ $\rightarrow$ relation between $m_D$ and $M_{NN}$ needed to cancel hierarchy (additional singlets or VEV alignment)
- Simple picture (all matter from 16) is not so easy to implement
- VEV alignment is difficult

## Some Questions

- Are there other symmetries which implement this type of cancellation?
- Can neutrino mass originate from one source in the GUT context?
- Is there an effect of many singlets besides scaling the effective seesaw scale?
- What is the best way to achieve the required VEV alignment?

# Most Promising Insights from Experimental Constraints

### Question

What is the most important parameter to be be determined experimentally (in the neutrino sector) to exclude large classes of flavour models?

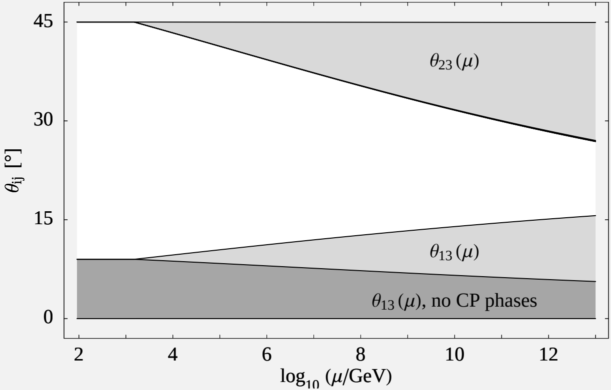
### Strong Indications for a Flavour Symmetry

- (Almost) vanishing $\theta_{13}$
- (Almost) maximal $\theta_{23}$
- Inverted mass hierarchy "requires" explanation by symmetry

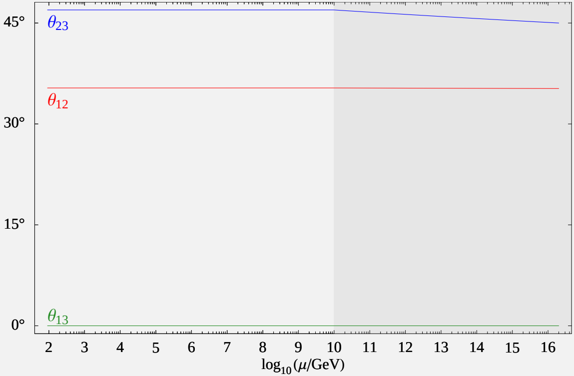
### What is the required precision?

- Corrections from higher dimensional operators model dependent (but usually at next order in expansion)
- Renormalization group running might give an hint on the size (Size strongly dependent on absolute mass scale)

# RG evolution

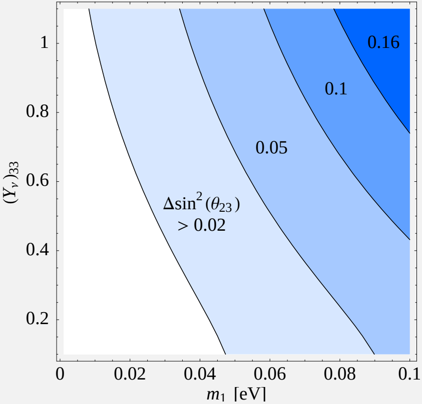


# Strong Normal Hierarchy




$$\Delta\theta_{ij} \approx -\frac{D_\Delta}{2}\frac{\Delta m_{ji}^2}{v_\Delta^2}\sin 2\theta_{ij}\ln\frac{\Lambda}{M_\Delta}$$

# $\theta_{23}$



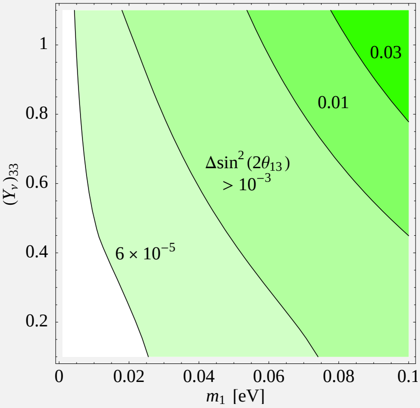

- $|0.5 - \sin^2\theta_{23}| \leq 0.16$
- small deviations from maximal mixing
- running above see–saw scales
- suppression by phases possible

$\tan\beta = 20$, $\delta = \varphi_1 = \varphi_2 = 0$, analytic estimate

| Current | Beams | T2K+NuMI | JPARC-HK | NuFact-II |
|---|---|---|---|---|
| 0.16 | 0.1 | 0.050 | 0.020 | 0.055 |

[P. Huber, M. Lindner, M. Rolinec, T. Schwetz, W. Winter [hep-ph/0403068]]

# $\theta_{13}$




$\tan\beta = 20$, $\delta = \varphi_1 = 0$, $\varphi_2 = \pi$, analytic estimate

- $\sin^2 2\theta_{13} \leq 0.16$
- $\theta_{13} = 0$ at GUT scale only preserved if $m_3 = 0$
- suppression by phases possible

| Current | Beams | D-CHOOZ | T2K+NuMI | JPARC-HK | NuFact-II |
|---|---|---|---|---|---|
| 0.16 | 0.061 | 0.032 | 0.023 | $10^{-3}$ | $6 \times 10^{-5}$ |

[P. Huber, M. Lindner, M. Rolinec, T. Schwetz, W. Winter ('04)]