Motivations for neutrino accelerator experiments

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History of Neutrino Discoveries

- Atmospheric ν_μ are converted to ν_τ (SK) (98)
- Solar ν_e are converted to either ν_μ or ν_τ(SNO) (02)
- Only the LMA solution left for solar neutrinos (Homestake+Gallium+SK+SNO) (02)
- Reactor anti-ν_e disappear/reappear (KamLAND) (04)
- Accelerator ν_μ disappear (K2K 04 , MINOS 06)
- OPERA sees first tau appearance event (10)
- Message: many discoveries in neutrino physics

Impact of Neutrino Discoveries

- Lepton Flavor is not conserved
- Neutrinos have tiny masses, not very hierarchical
- Neutrinos mix a lot
- At least 7 new parameters for SM
- Quite unlike quark mass and mixing
- Of all fermions, neutrinos are least understood
- First new physics beyond the SM
- Message: most important discovery of last 20 years

Why Beyond Standard Model?

1. There are no right-handed neutrinos ν_R
2. There are only Higgs doublets of $SU(2)_L$
3. There are only renormalizable terms

Standard Model

In the Standard Model these conditions all apply so neutrinos are massless, with ν_e , ν_μ , ν_τ distinguished by separate lepton numbers L_e, L_μ, L_τ

Neutrinos and anti-neutrinos are distinguished by the total conserved lepton number $L=L_e+L_\mu+L_\tau$

To generate neutrino mass we must relax 1 and/or 2 and/or 3

Message: Neutrino Mass and Mixing is first physics BSM

Implications for PP and Cosmology

- Origin of tiny neutrino mass
  Extra dimensions, See-saw mechanism, SUSY
- Unification of matter, forces and flavour
  GUTs, Family Symmetry,…
- Did neutrinos play a role in our existence?
  Leptogenesis
- Did neutrinos play a role in forming galaxies?
  Hot/Warm Dark matter component
- Did neutrinos play a role in birth of the universe?
  Sneutrino inflation
- Can neutrinos shed light on dark energy? $\Lambda \sim m_\nu^4$

Particle Physics

Cosmology

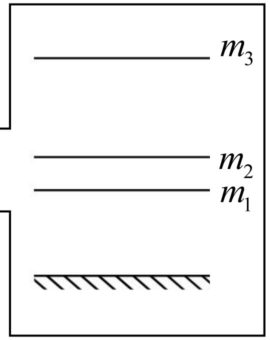
Message: many interesting implications for PP and Cosmology

Three Neutrino Mass and Mixing

$$\begin{pmatrix}\nu_e \\ e^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\mu \\ \mu^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\tau \\ \tau^-\end{pmatrix}_L$$

Standard Model states

Neutrino mass states



Pontecorvo
Maki
Nakagawa
Sakata

$$\begin{pmatrix}\nu_e \\ \nu_\mu \\ \nu_\tau\end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix} \begin{pmatrix}\nu_1 \\ \nu_2 \\ \nu_3\end{pmatrix}$$

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23}\end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1\end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1\end{pmatrix}$$

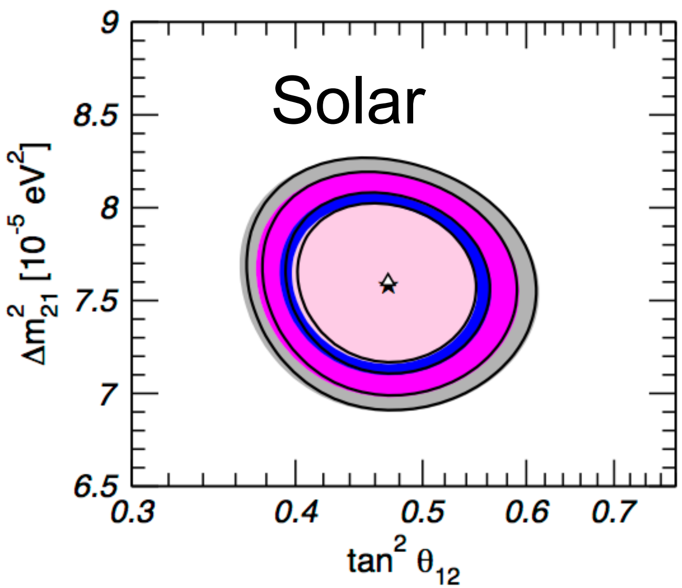
Atmospheric | Reactor | Solar | Majorana

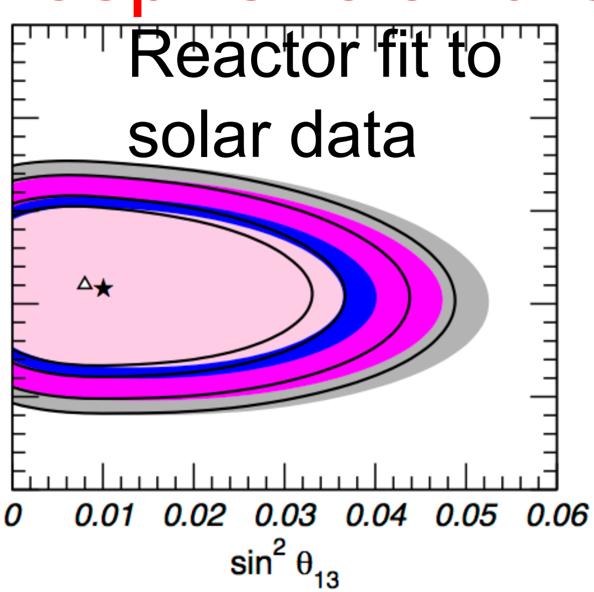
$s_{ij} = \sin\theta_{ij}$
$c_{ij} = \cos\theta_{ij}$

Oscillation phase δ
Majorana phases α_1, α_2

3 masses + 3 angles + 1(3) phase(s)
= 7(9) new parameters for SM

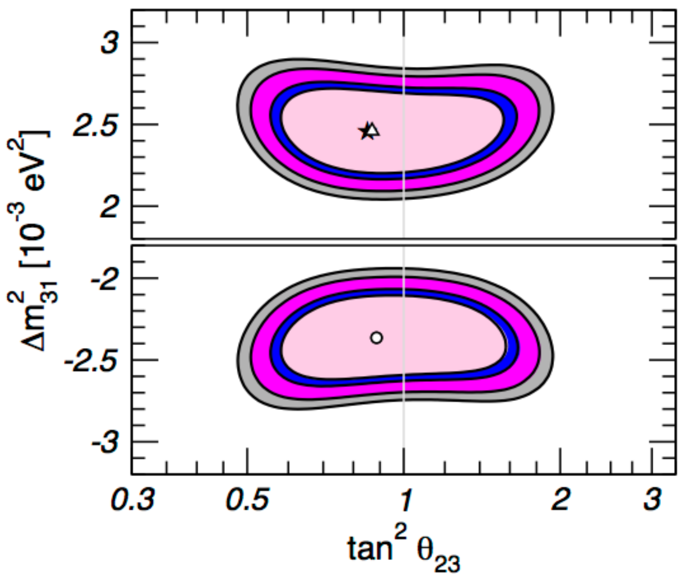
Global Fit to Atmospheric and Solar Data





Gonzalez-Garcia,
Maltoni, Salvado

arXiv:1001.4524



$$\Delta m^2_{21} = 7.59 \pm 0.20 \; \left({}^{+0.61}_{-0.69}\right) \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2_{31} = \begin{cases} -2.36 \pm 0.11 \; (\pm 0.37) \times 10^{-3}\ \mathrm{eV}^2 \\ +2.46 \pm 0.12 \; (\pm 0.37) \times 10^{-3}\ \mathrm{eV}^2 \end{cases}$$

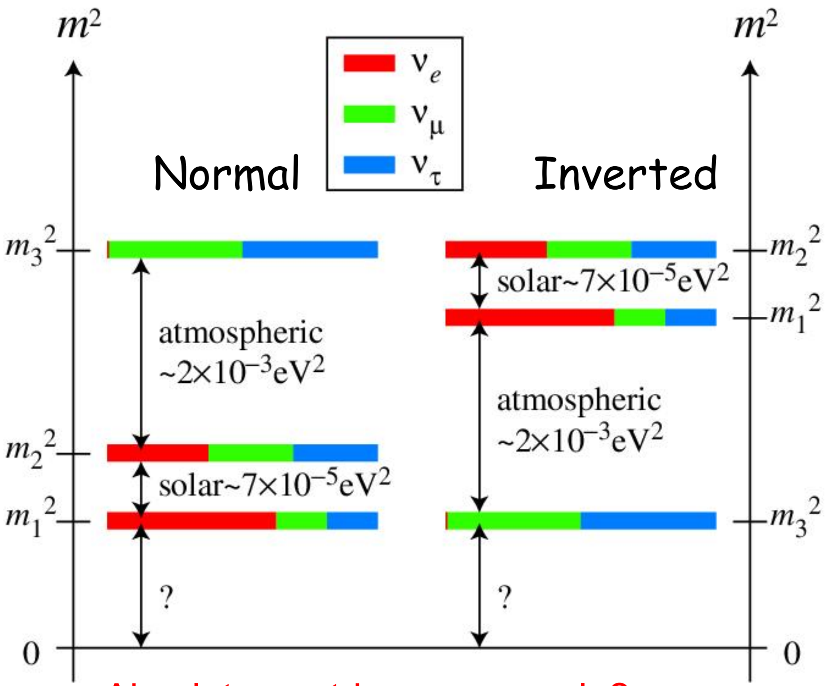
$$\theta_{12} = 34.4 \pm 1.0 \; \left({}^{+3.2}_{-2.9}\right)^\circ$$

$$\theta_{23} = 42.8\,{}^{+4.7}_{-2.9} \; \left({}^{+10.7}_{-7.3}\right)^\circ$$

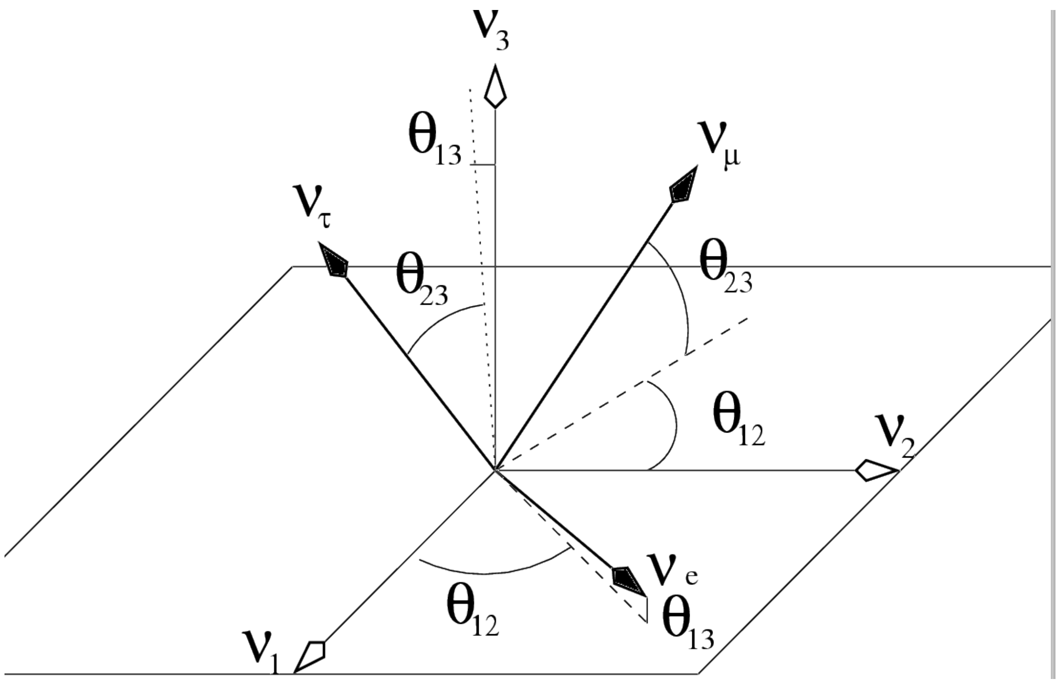
$$\theta_{13} = 5.6\,{}^{+3.0}_{-2.7} \; (\leq 12.5)^\circ$$

Atmospheric

Three Neutrino Mass and Mixing at a glance



Absolute neutrino mass scale?



Message: the neutrino mass ordering and mass scale are not yet measured, nor is the reactor mixing angle or CP phase

Tri-bimaximal Mixing

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

Harrison, Perkins, Scott

Including deviations from TB mixing

$$\theta_{13} = \Delta_{13}^{TB}, \quad \theta_{12} = 35^o + \Delta_{12}^{TB}, \quad \theta_{23} = 45^o + \Delta_{23}^{TB}.$$

c.f. data

$$\theta_{13} = 5.6^{+3.0}_{-2.7} \quad \theta_{12} = 34.4 \pm 1.0 \quad \theta_{23} = 42.8^{+4.7}_{-2.9}$$

Message: neutrino mixing is consistent with the remarkably simple TB mixing pattern, hinting at an underlying symmetry

Tri-bimaximal Parametrisation

SFK **arXiv:0710.0530**

$$s_{13} = \frac{r}{\sqrt{2}}, \quad s_{12} = \frac{1}{\sqrt{3}}(1+s), \quad s_{23} = \frac{1}{\sqrt{2}}(1+a)$$

$$0.07 < r < 0.21, \quad -0.05 < s < 0.003, \quad -0.09 < a < 0.04$$

r = reactor   s = solar   a = atmospheric

$$U \approx \begin{pmatrix} \sqrt{\frac{2}{3}}(1-\frac{1}{2}s) & \frac{1}{\sqrt{3}}(1+s) & \frac{1}{\sqrt{2}}re^{-i\delta} \\ -\frac{1}{\sqrt{6}}(1+s-a+re^{i\delta}) & \frac{1}{\sqrt{3}}(1-\frac{1}{2}s-a-\frac{1}{2}re^{i\delta}) & \frac{1}{\sqrt{2}}(1+a) \\ \frac{1}{\sqrt{6}}(1+s+a-re^{i\delta}) & -\frac{1}{\sqrt{3}}(1-\frac{1}{2}s+a+\frac{1}{2}re^{i\delta}) & \frac{1}{\sqrt{2}}(1-a) \end{pmatrix}$$

Present data is consistent with r,s,a=0 →tri-bimaximal so need to measure r,s,a,δ

Oscillation formulae in terms of r,s,a

$$P_{\alpha\beta} = P(\nu_\alpha \to \nu_\beta)$$

$$\Delta_{ij} = 1.27\Delta m_{ij}^2 L/E$$

reactor

$$\left\{ P_{ee} = 1 - 2r^2 \sin^2 \Delta_{31} - \frac{8}{9}\Delta_{21}^2 \right.$$

Only sensitive to the reactor parameter r

LBL

$$\left\{ \begin{aligned} P_{\mu e} &= r^2 \sin^2 \Delta_{31} + \frac{4}{9}\Delta_{21}^2 + \frac{4}{3} r \Delta_{21} \sin\Delta_{31} \cos(\Delta_{31} + \delta) \\ P_{\mu\mu} &= 1 - (1 - 4a^2)\sin^2 \Delta_{31} - \frac{2}{9}(1 + 3\cos 2\Delta_{31})\Delta_{21}^2 \\ &+ \frac{2}{3}(1 - s - r\cos\delta)\Delta_{21} \sin 2\Delta_{31}. \end{aligned} \right.$$

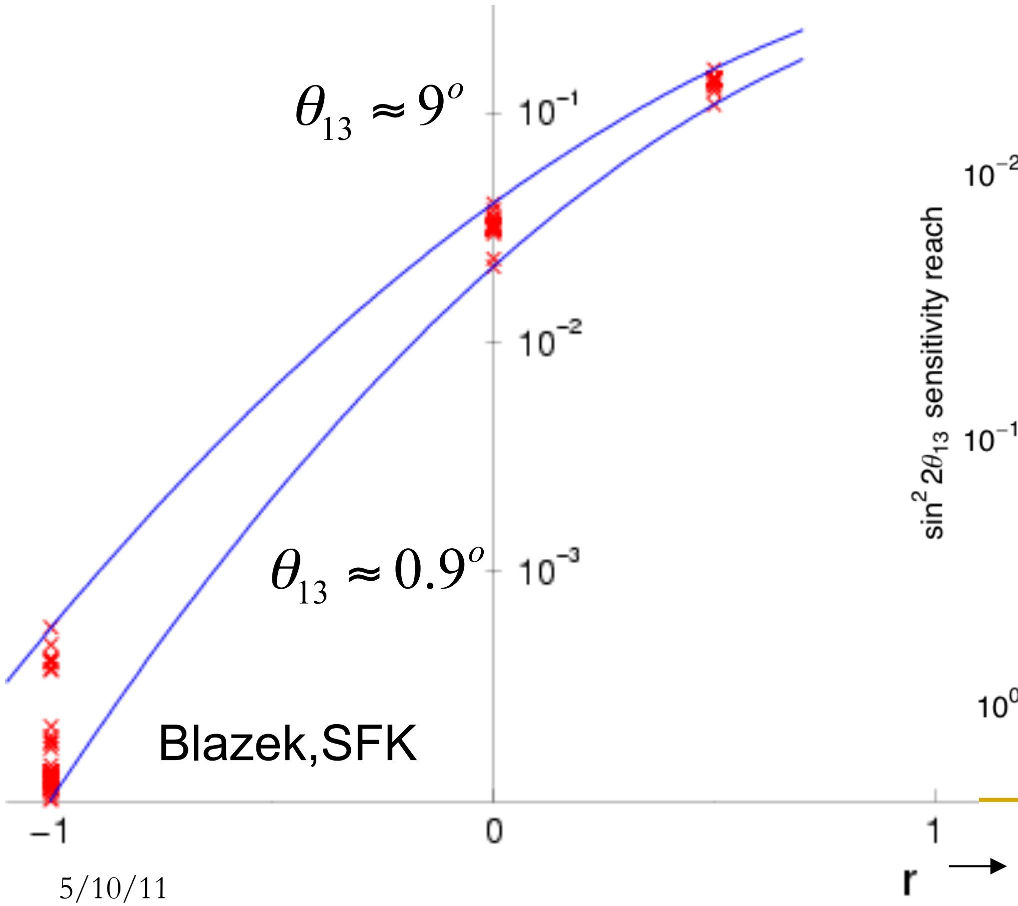
Sensitive to r,s,a

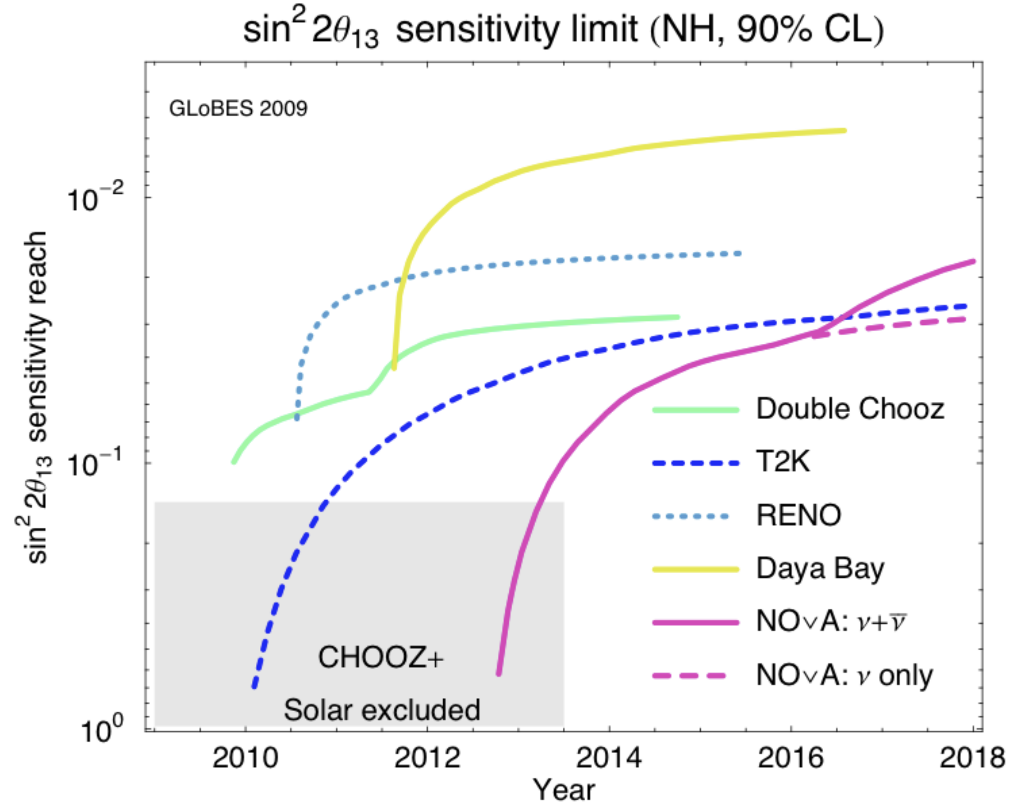
For a list of formulae including matter effects see SFK **arXiv:0710.0530**

Reactor Angle: Theory vs Experiment

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

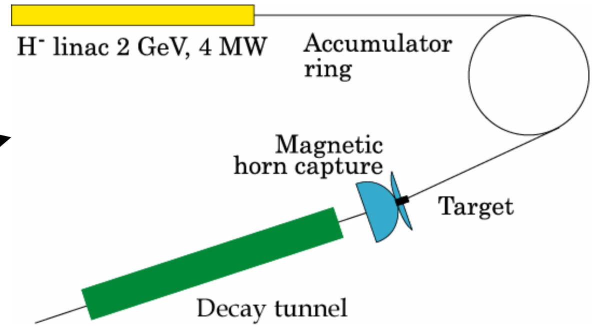
Reactor angle in Abelian Family Symmetry Models vs Experimental Prospects

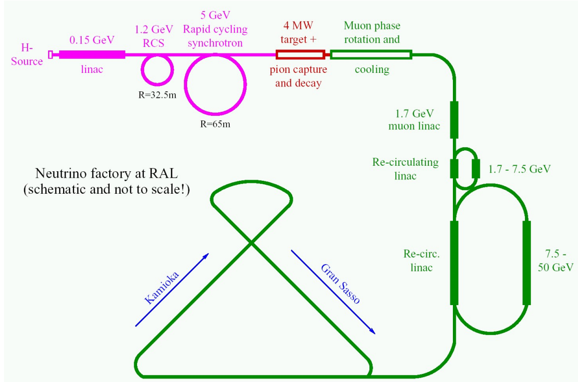


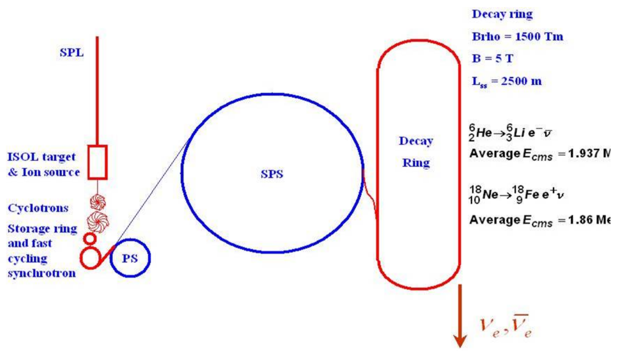


Future LBL Options:

- Second generation super-beam: CERN, LBNE (WBB), T2HK
- Neutrino Factory
- Beta-beam

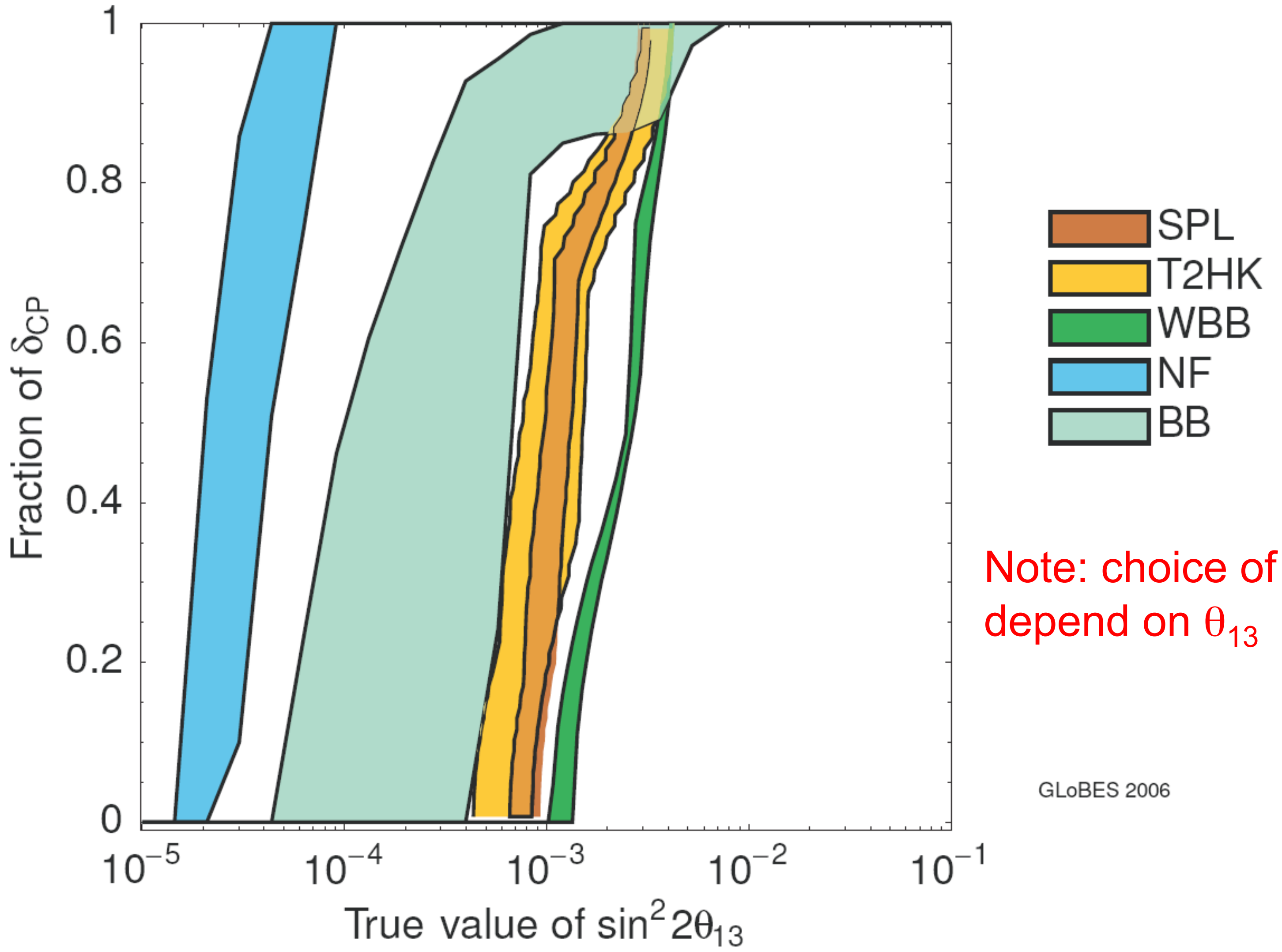






Prospects to measure θ_{13}

Physics at a future Neutrino Factory and super-beam facility. By ISS Physics Working Group
Rept.Prog.Phys.72:106201,2009
arXiv:0710.4947 [hep-ph]

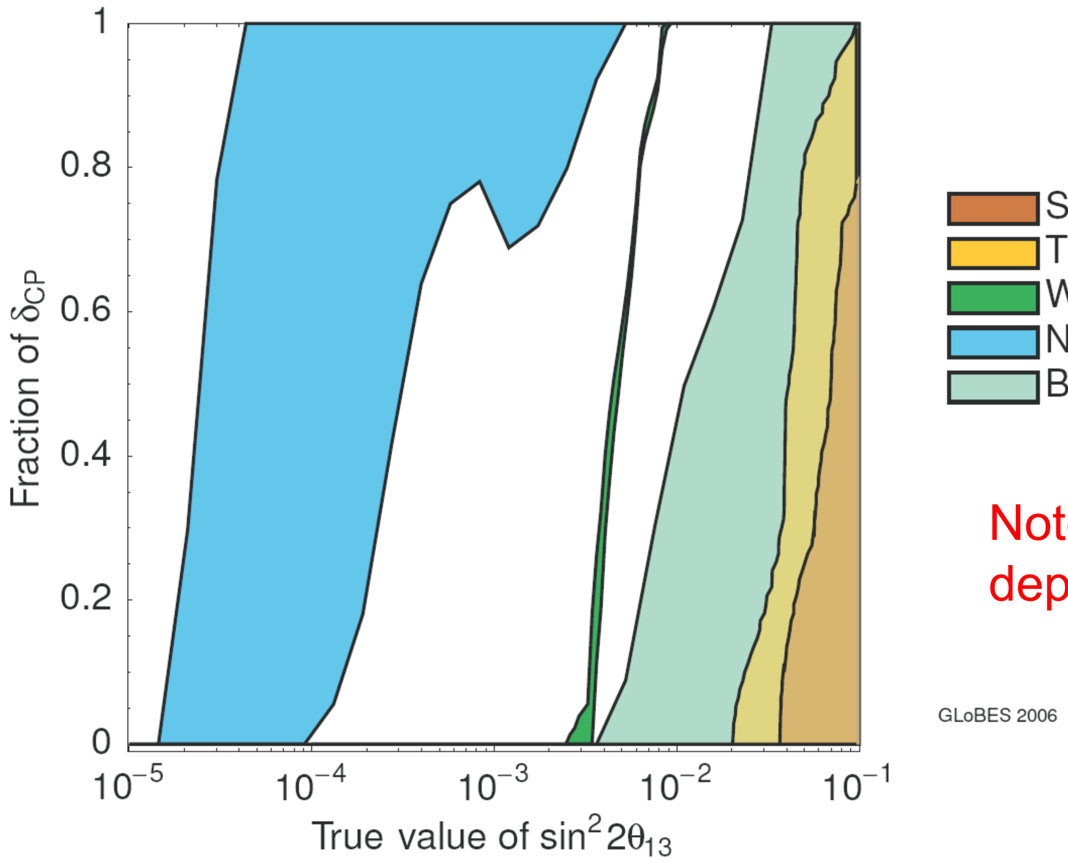


Note: choice of facility will depend on θ_{13}

Prospects to measure the pattern of ν masses

Sensitivity to the Sign of Δm_{23}^2

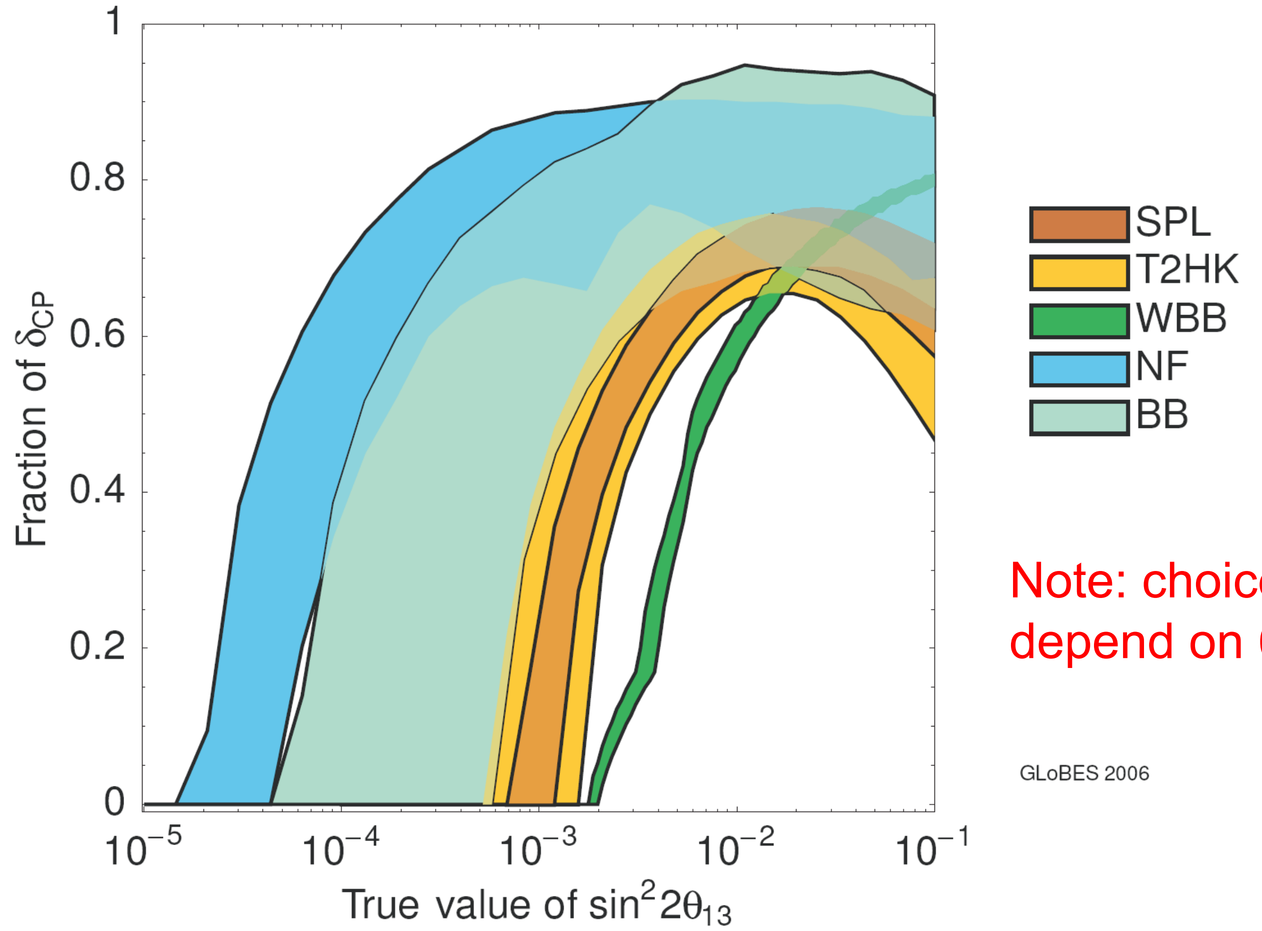
Physics at a future Neutrino Factory and super-beam facility. By ISS Physics Working Group
Rept.Prog.Phys.72:106201,2009
arXiv:0710.4947 [hep-ph]



Note: choice of facility will depend on θ_{13}

Prospects to measure CP Violation

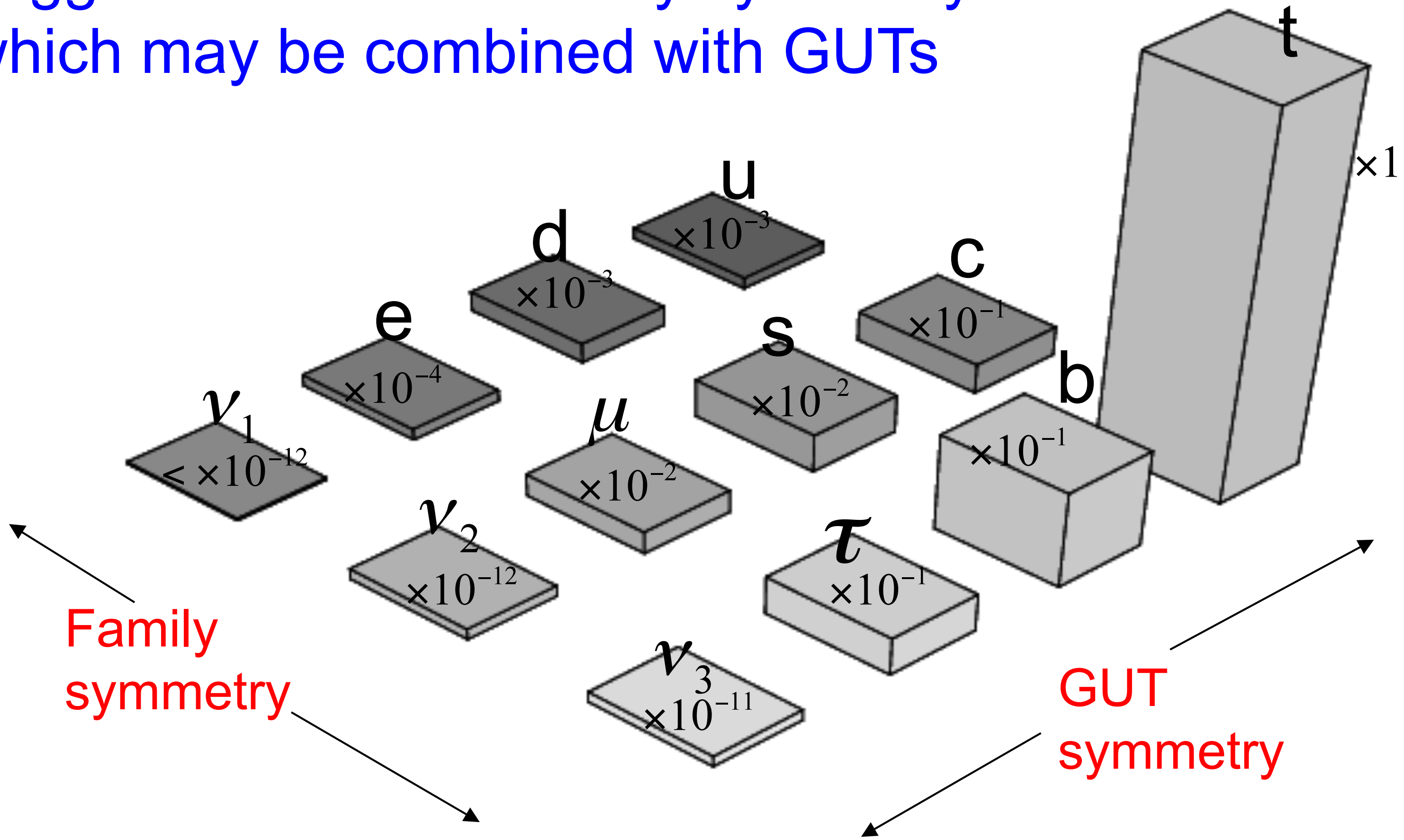
Physics at a future Neutrino Factory and super-beam facility. By ISS Physics Working Group
Rept.Prog.Phys.72:106201,2009
arXiv:0710.4947 [hep-ph]



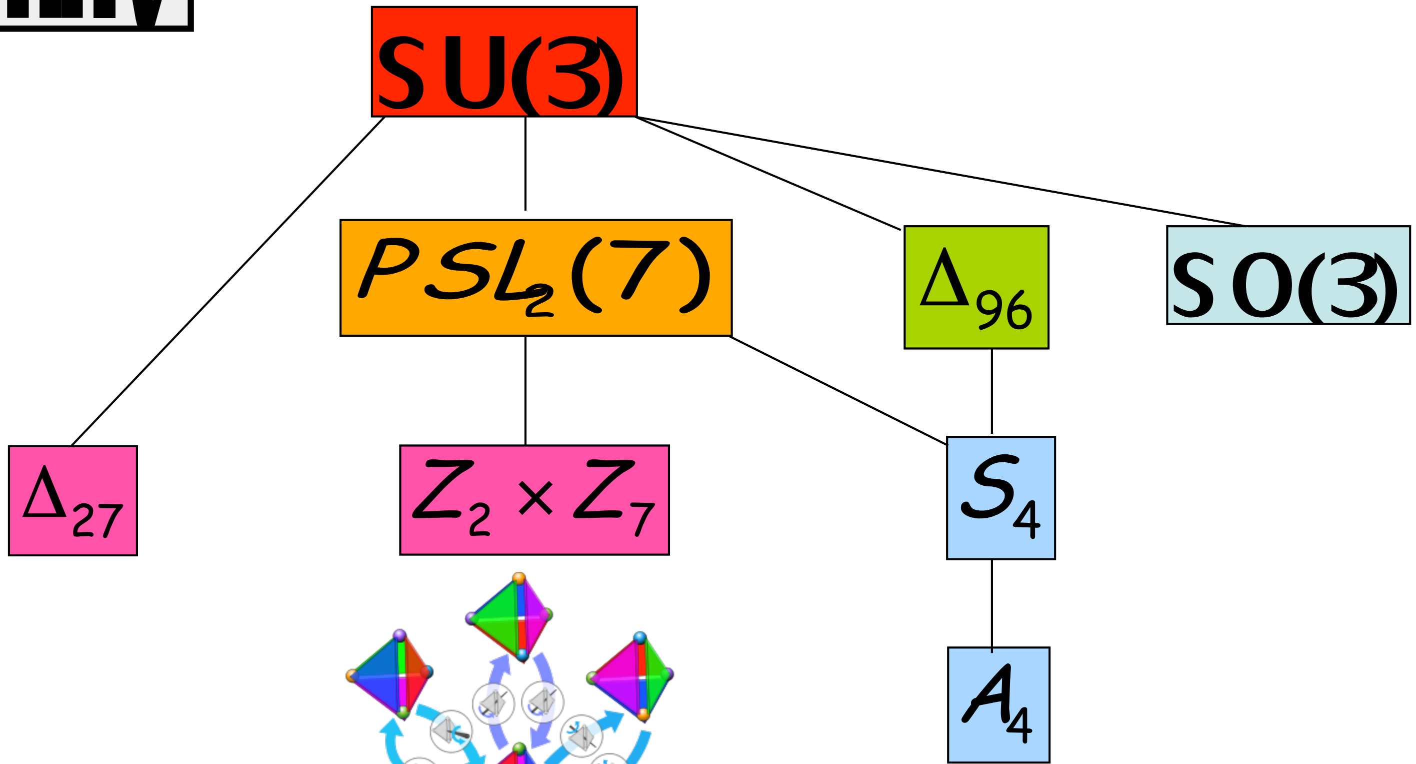
Note: choice of facility will depend on θ_{13}

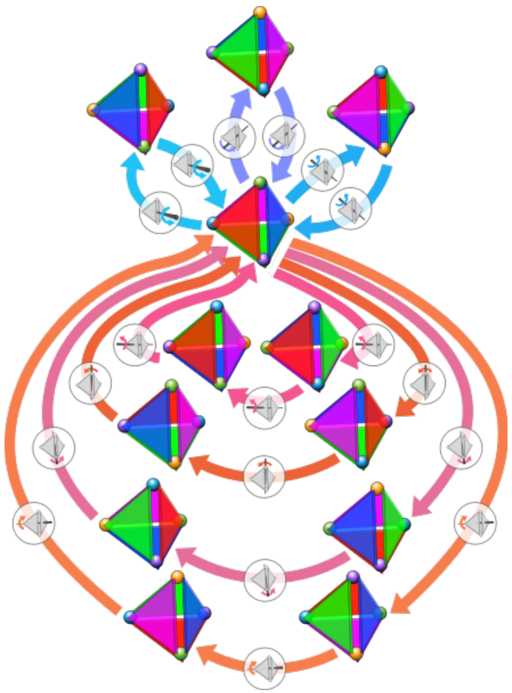
Tri-bimaximal Mixing×GUTs

Message: Tri-bimaximal mixing suggests a discrete family symmetry which may be combined with GUTs



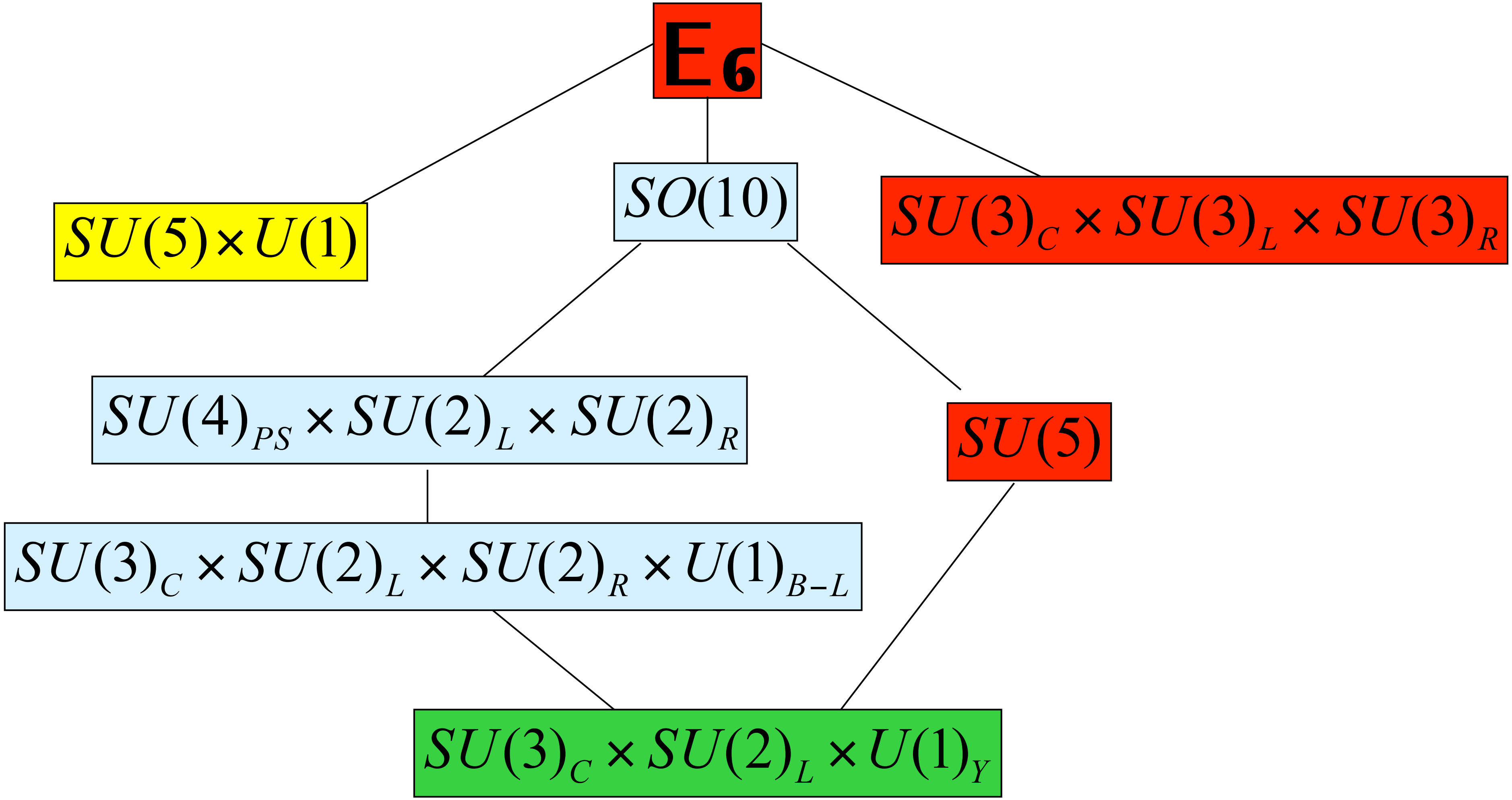
G_F Family



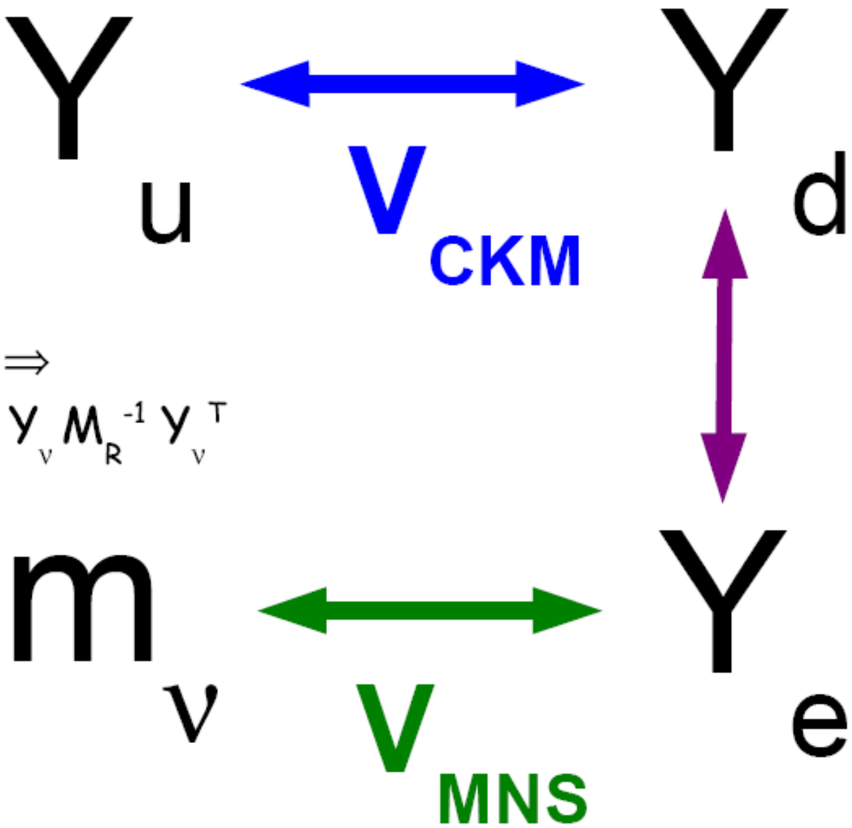


e.g. A_4 is the symmetry of the tetrahedron

G_{GUT}


E_6
$SU(5)\times U(1)$
$SO(10)$
$SU(3)_C\times SU(3)_L\times SU(3)_R$
$SU(4)_{PS}\times SU(2)_L\times SU(2)_R$
$SU(5)$
$SU(3)_C\times SU(2)_L\times SU(2)_R\times U(1)_{B-L}$
$SU(3)_C\times SU(2)_L\times U(1)_Y$

TB Mixing×GUT Predictions



Class of models: $\theta_{12}^{d} \gg \theta_{12}^{u}$

$\theta_{12}^{d} \approx \theta_C$

See-saw ⇒

$m_\nu = v_{EW}^2 Y_\nu M_R^{-1} Y_\nu^T$

$$\theta_{13} \approx \frac{\theta_{12}^{e}}{\sqrt{2}} \approx \frac{\theta_C}{3\sqrt{2}} \approx 3^\circ,$$

$$\rightarrow \sin^2 2\theta_{13} \approx 10^{-2}$$

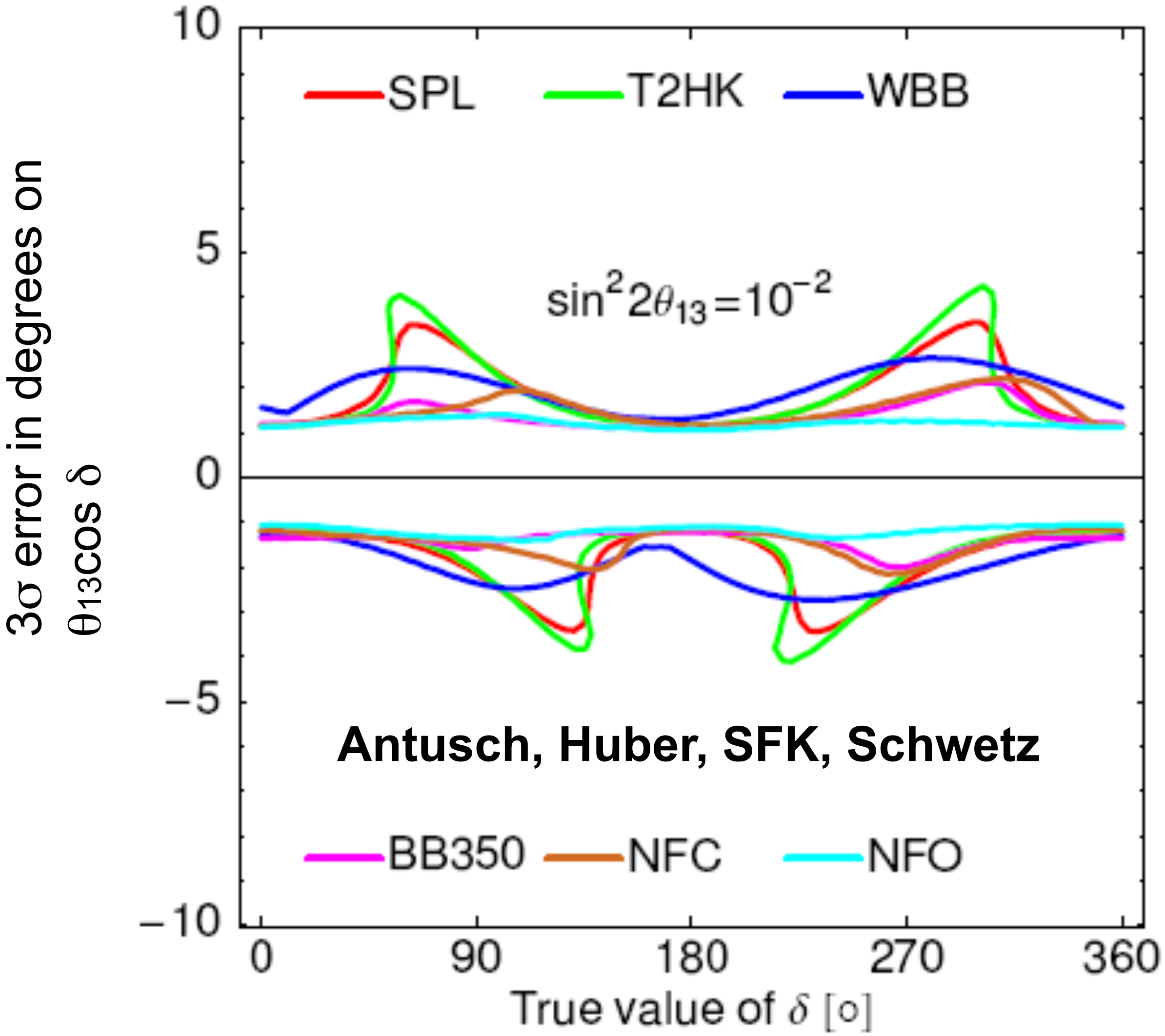
$$\theta_{12} \approx 35.3^o + \theta_{13}\cos\delta$$

Sum Rule

SFK, Antusch, Masina

Message: TB mixing can never be exact in GUT models

Prospects to measure sum rule combination $\theta_{13} \cos \delta$



Summary

- We have witnessed a revolution in neutrino physics
- Yet still do not understand origin of neutrino mass and mixing
- Current data consistent with tri-bimaximal mixing
- Realistic models predict deviations from tri-bimaximal mixing

Benchmark Model	θ_{13}	$\lvert\theta_{23} - 45^o\rvert$	$\lvert\theta_{12} - 35^o\rvert$	δ
TBM $\otimes$ GUT [9]	$\frac{\theta_C}{3\sqrt{2}} = 3^o$	$\leq 1^o$	$\leq 1^o$	$90^o, 270^o$
QLC [10]	$\theta_C = 13^o$	$\leq 1^o$	large	180^o
Abelian [4]	Fig.7	large	large	any

- In order to discriminate between these models to test GUTs of Flavour against Abelian Models or QLC…
- Need to measure the deviations of the reactor, atmospheric and solar angles from their TB values, and also measure δ