UNIVERSITY OF Southampton
School of Physics and Astronomy

invisibles
neutrinos, dark matter & dark energy physics

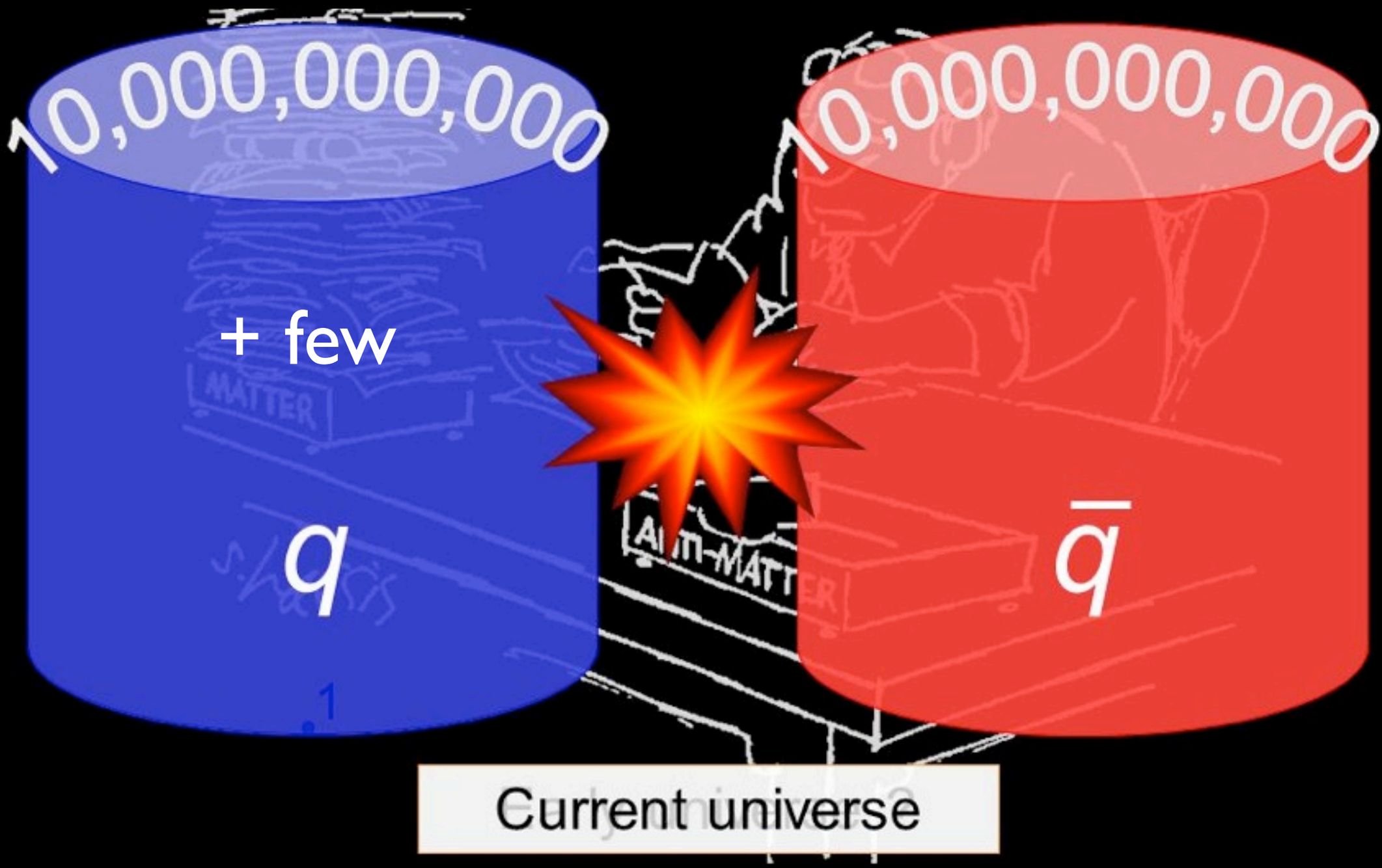
Leptogenesis and Flavour Models

Steve King

Warsaw, 2015

At the end of Inflation the Universe was empty, cold and bare...

After reheating a very slight excess of matter was somehow generated



Giving observed matter Universe

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = \frac{n_B}{n_\gamma} \approx 6 \times 10^{-10}$$

Sakharov conditions for generating a matter-antimatter asymmetry in the early Universe

- Baryon number B violation
- C and CP violation
- Departure from thermal equilibrium

Standard Model satisfies all three conditions in principle but fails in practice

⇒ need new physics -neutrino mass/mixing

Lepton Mixing Matrix

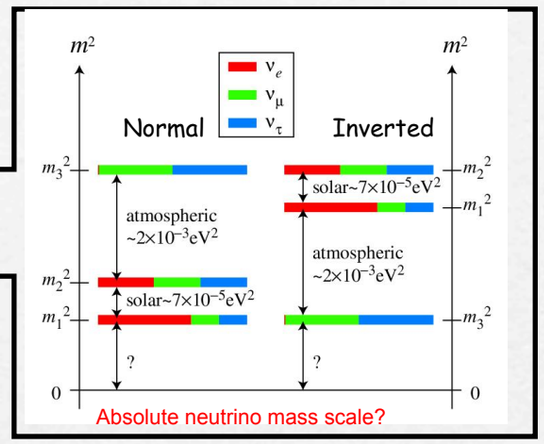
Standard Model states

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

PMNS matrix

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

Neutrino mass states



Pontecorvo
Maki
Nakagawa
Sakata

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23}^l & s_{23}^l \\ 0 & -s_{23}^l & c_{23}^l \end{pmatrix} \begin{pmatrix} c_{13}^l & 0 & s_{13}^l e^{-i\delta^l} \\ 0 & 1 & 0 \\ -s_{13}^l e^{i\delta^l} & 0 & c_{13}^l \end{pmatrix} \begin{pmatrix} c_{12}^l & s_{12}^l & 0 \\ -s_{12}^l & c_{12}^l & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{\alpha_{21}}{2} & 0 \\ 0 & 0 & \frac{\alpha_{31}}{2} \end{pmatrix}$$

$s_{ij}^l = \sin(\theta_{ij}^l)$

$c_{ij}^l = \cos(\theta_{ij}^l)$

Atmospheric | Reactor | Solar | Majorana

Oscillation phase δ^l

Majorana phases α_{21}, α_{31}

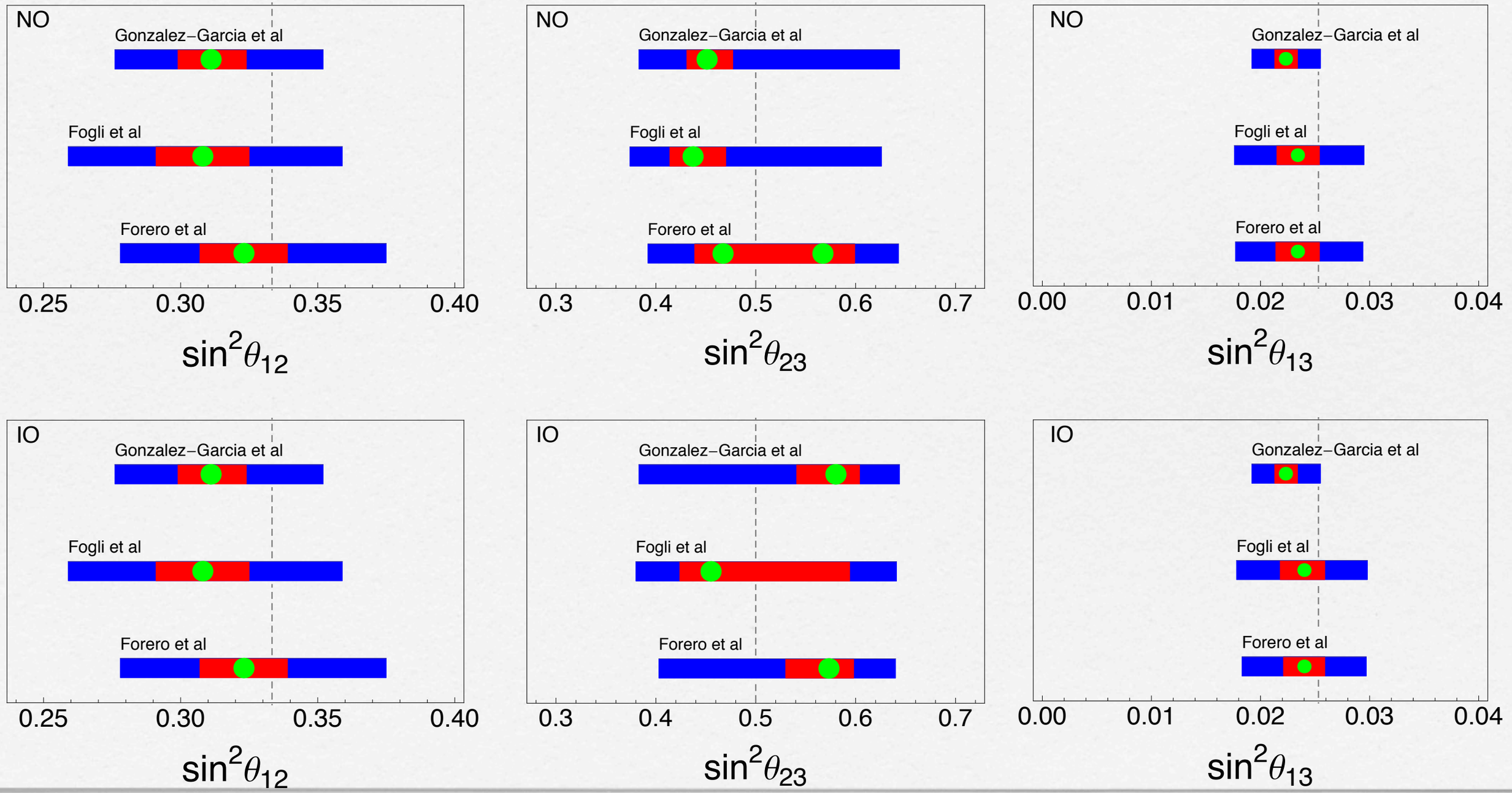
3 masses + 3 angles + 3 phases =
9 new parameters for SM

Gonzalez-Garcia et al = Gonzalez-Garcia, Maltoni, Salvado, Schwetz
Fogli et al = Capozzi, Fogli, Lisi, Marrone, Montanino, Palazzo
Forero et al = Forero, Tortola, Valle

Global Fits 2014/15

$$\theta_{13} = \frac{\theta_C}{\sqrt{2}} \rightarrow 9.2^\circ$$

35° 45°

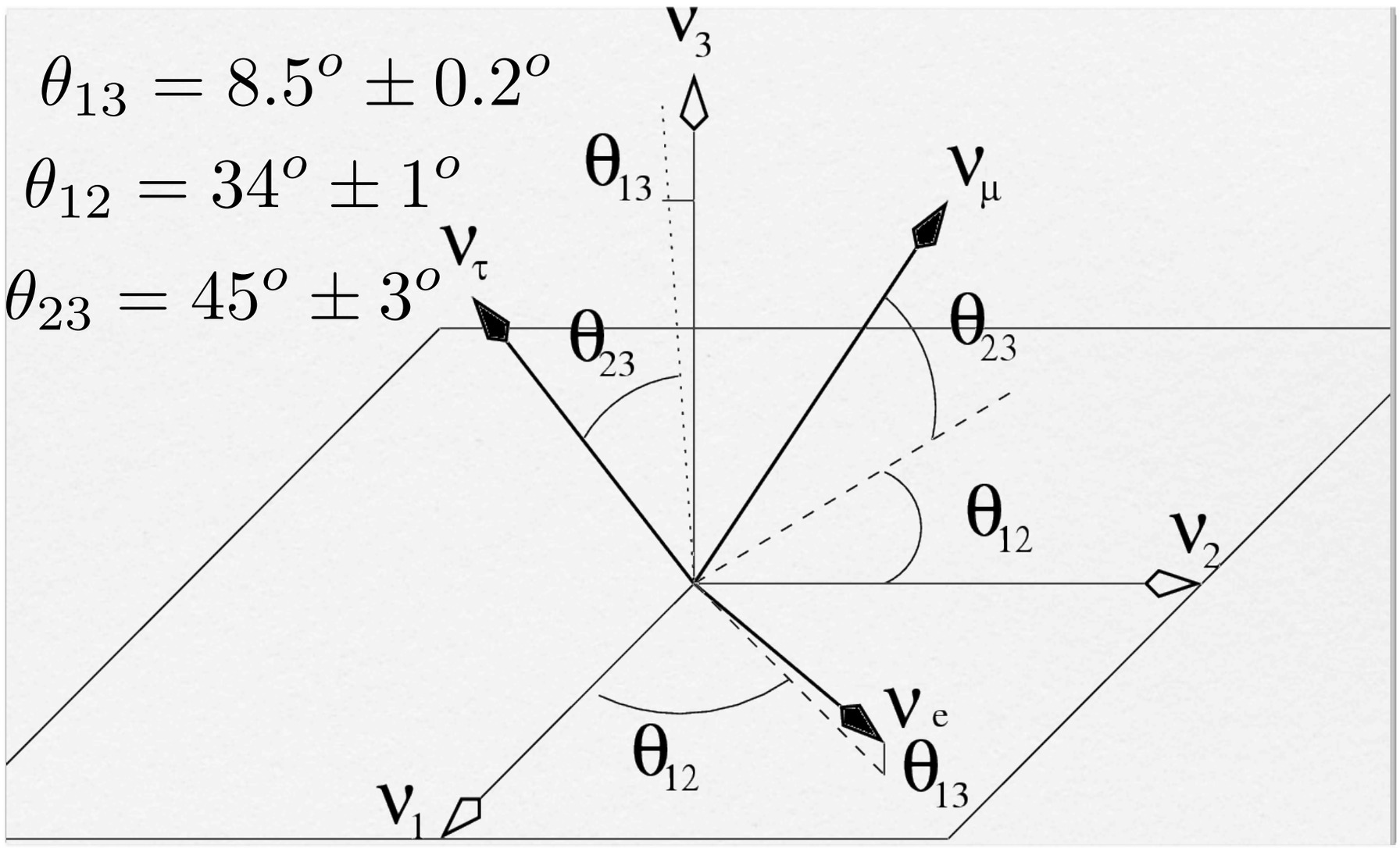


Lepton Mixing Angles (approx.)

$$\theta_{13} = 8.5^o \pm 0.2^o$$

$$\theta_{12} = 34^o \pm 1^o$$

$$\theta_{23} = 45^o \pm 3^o$$

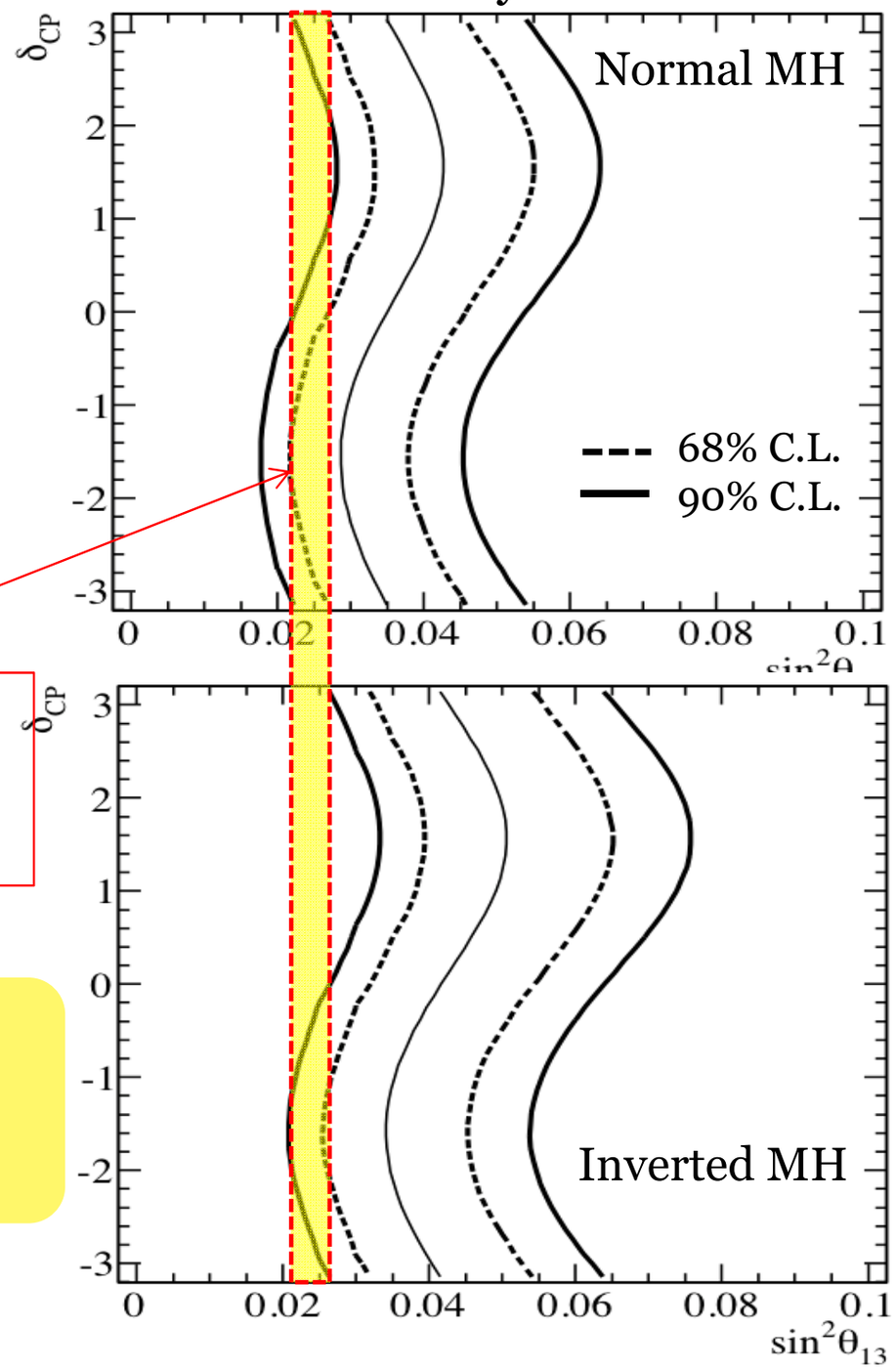


Hint for CP phase

T2K Run1-4 data
(data till 2013)
Preliminary

Fit ν_μ sample and ν_e sample simultaneously by $\sin^2\theta_{23}$, $\sin^2\theta_{13}$, δ and Δm^2

Now uncertainty of $\sin 2\theta_{23}$ is included.



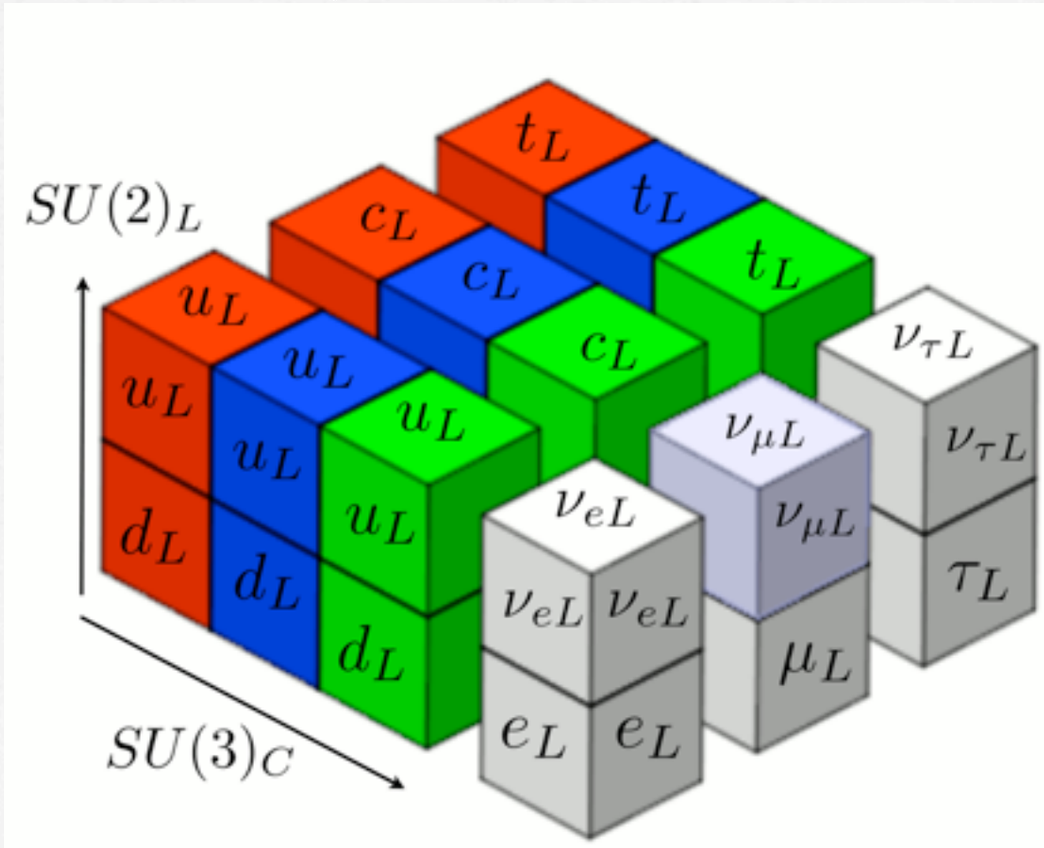
68% allowed region from reactor measurement (PDG2013)

Hint for $\delta_{CP} \approx -90°$

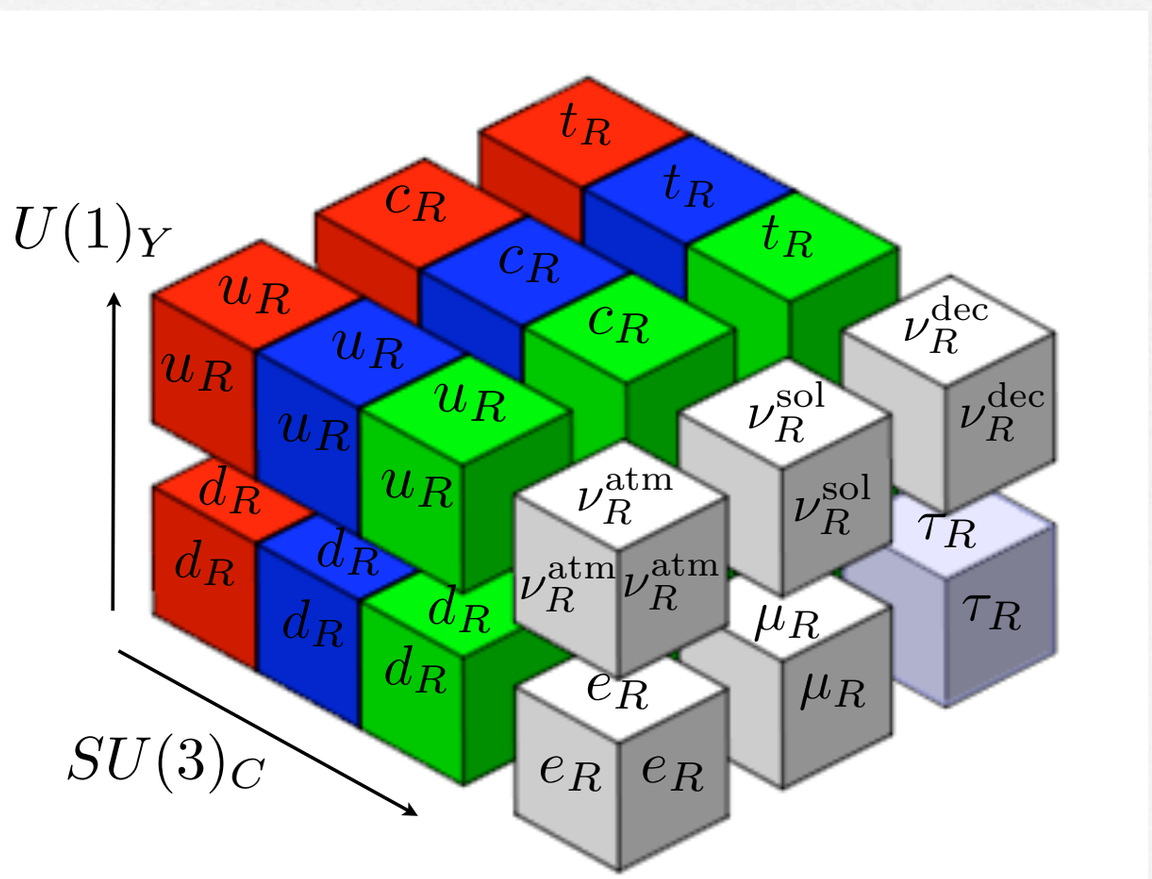
Neutrino mass motivates Standard Model with right-handed neutrinos

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

Left-handed quarks and leptons (active neutrinos)



Right-handed quarks and leptons (sterile neutrinos)



The RH neutrino Spectrum

$M_{\rm GUT}$ ↑ M_R

Classic See-Saw (Leptogenesis)

Minkowski...

TeV

Low Scale See-Saw (LHC)

GeV

Asaka-Shaposhnikov

Nu-MSM

BAU (resonant lepto)

MeV

Pilaftsis et al

keV

WDM King and Merle

eV

LSND, Reactor Anomaly,...

meV

Extra radiation (Planck)

low energy nu mass matrix

$$m^\nu = -m_D \frac{1}{M_R} m_D^T$$

Leptogenesis from neutrinos

Fukugita, Yanagida (1986)

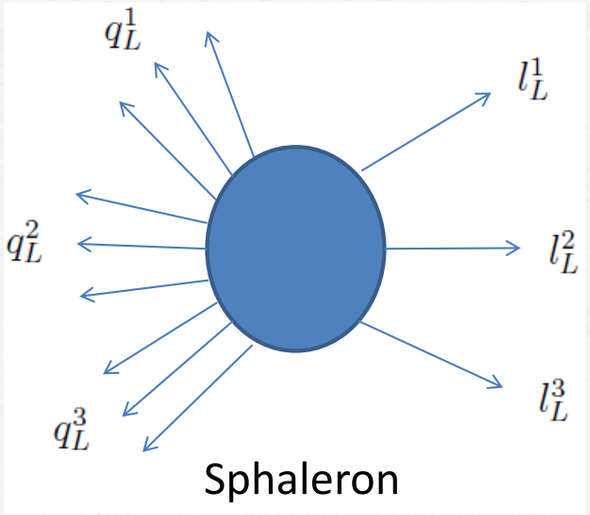
✓ RH neutrinos are produced in early universe and decay out of equilibrium giving net lepton numbers L_e, L_μ, L_τ

✓ CP violation from complex Yukawa couplings λ^ν

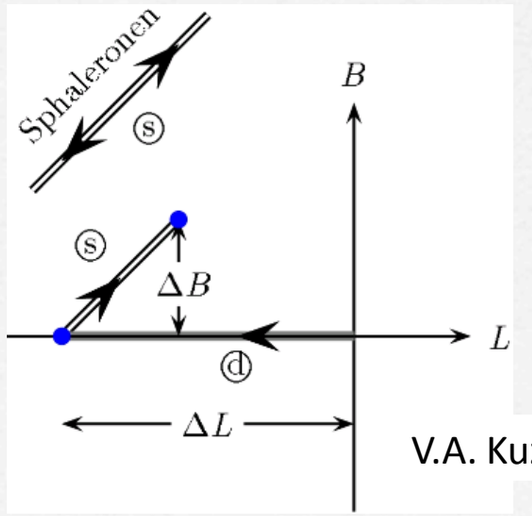
✓ Out of equilibrium Boltzmann eqs give partial washouts

✓ ΔL processed into ΔB via B-L conserving sphalerons

$$-\Delta L = \Delta(B-L) \to \frac{1}{3}\Delta B - \frac{2}{3}\Delta L$$



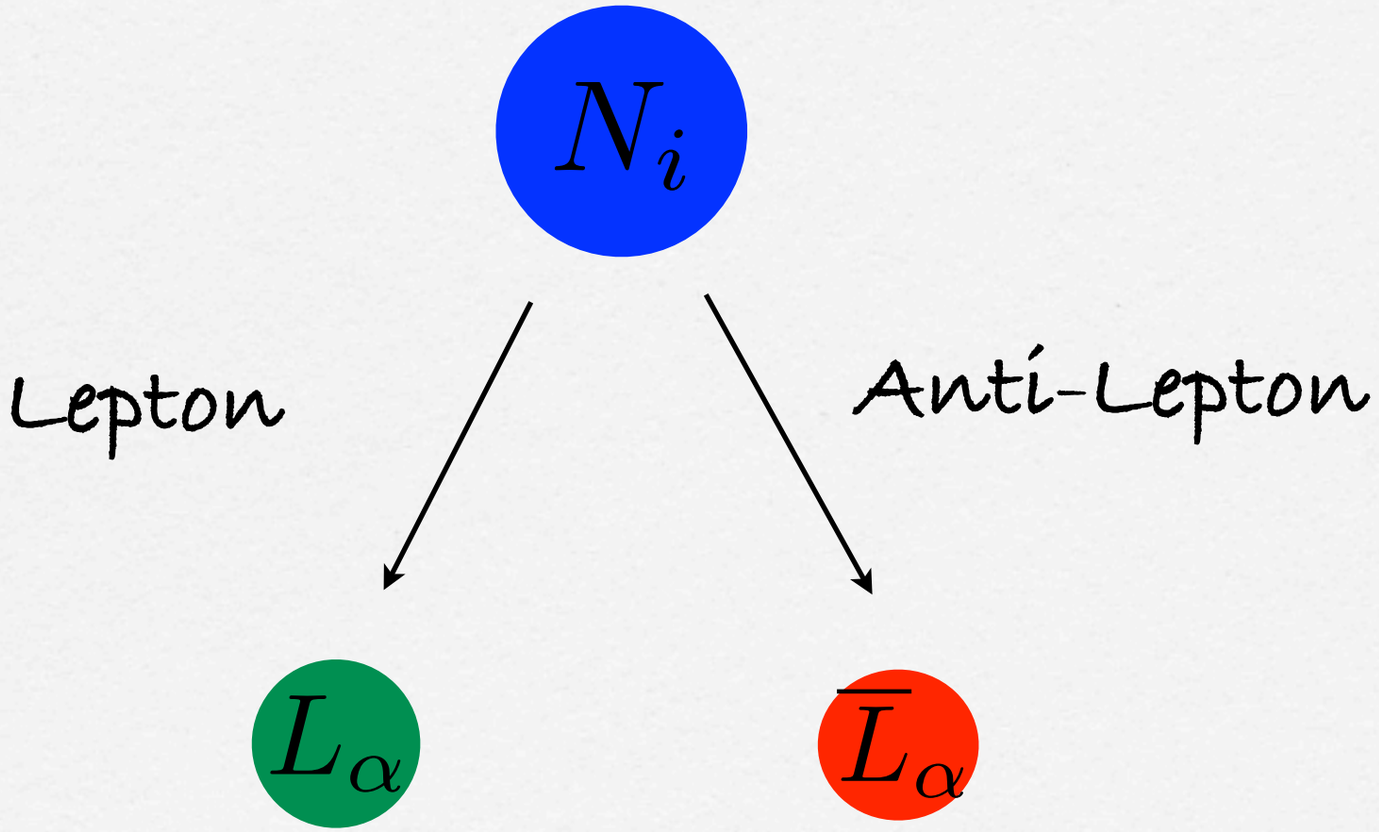
Sphaleron



V.A. Kuzmin, V.A. Rubakov, M.E. Shaposhnikov (1985)

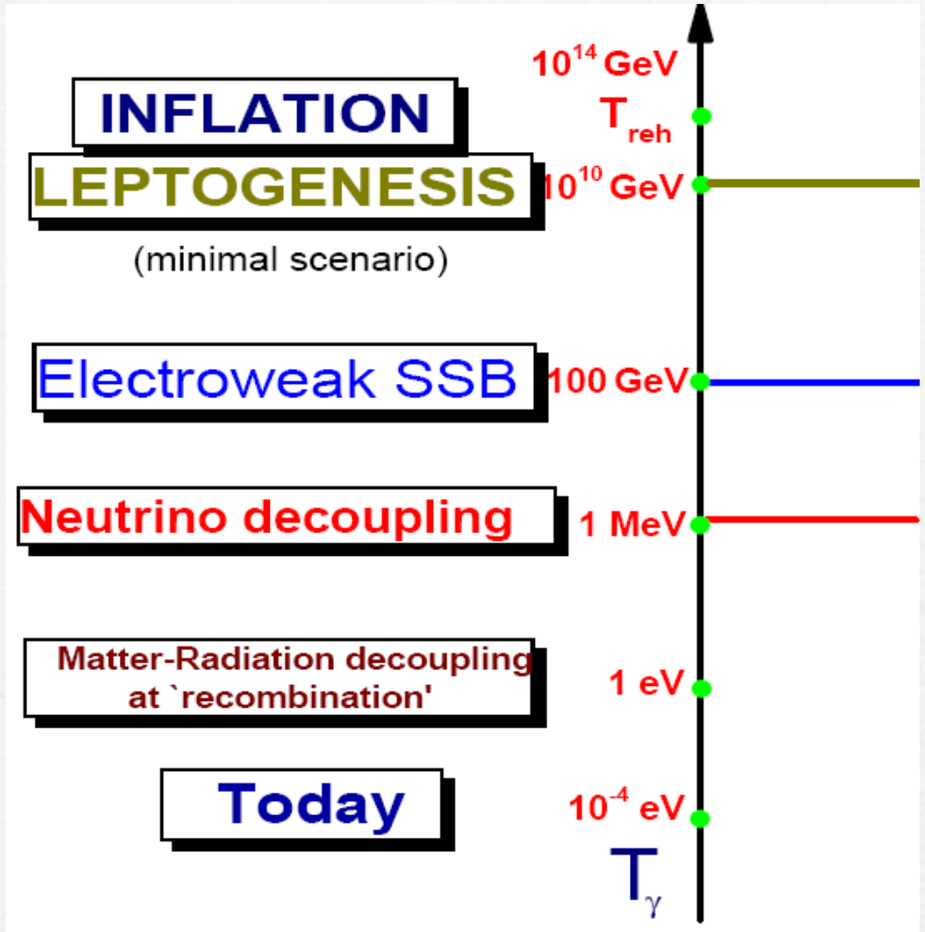
Leptogenesis

Right-handed neutrino with Majorana mass

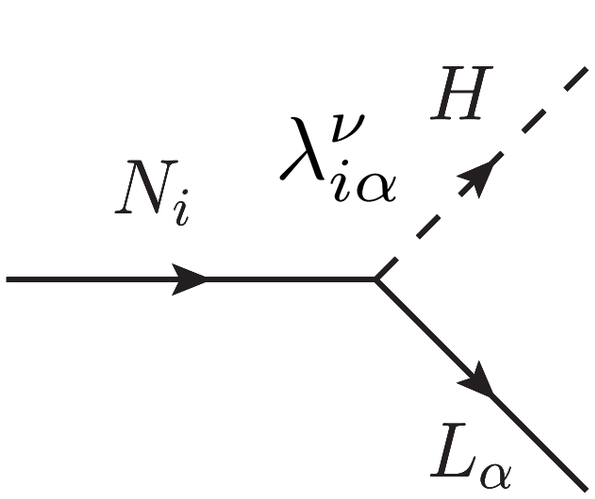


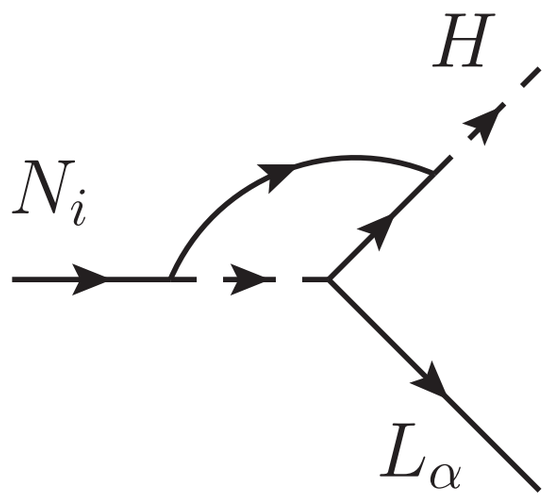
Lepton Asymmetry

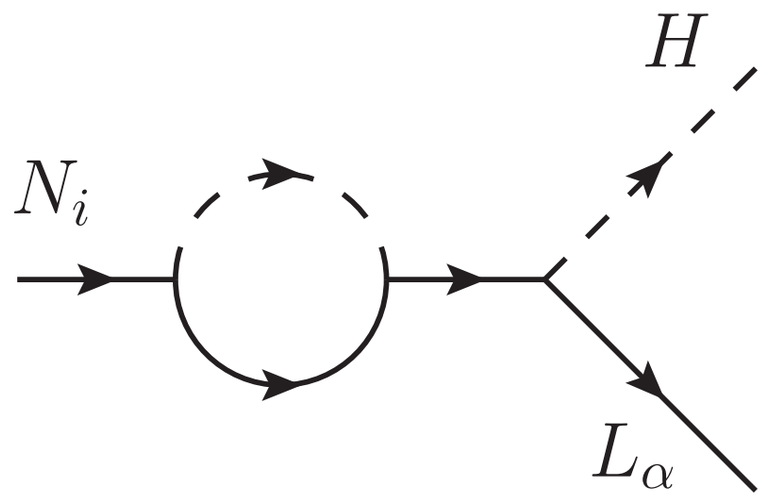
$$\varepsilon_{i\alpha} \equiv \frac{\Gamma_{i\alpha} - \overline{\Gamma}_{i\alpha}}{\Gamma_i + \overline{\Gamma}_i}$$



(Flanz,Paschos,Sarkar'95; Covi,Roulet,Vissani'96; Buchmüller,Plümacher'98)







(Nardi,Nir,Roulet,Racker '06;Abada,Davidson,Losada,Josse-Michaux,Riotto'06)

Lepton Asymmetry

$$\varepsilon_{i\alpha} \equiv \frac{\Gamma_{i\alpha} - \overline{\Gamma}_{i\alpha}}{\Gamma_i + \bar{\Gamma}_i}$$

Calculated from tree-level x 1-loop interference

sum over i includes N1, N2, ... leptogenesis
sum over α includes flavour-dependent effects

B-L Asymmetry

$$\Delta(B-L) = \sum_i \sum_\alpha \varepsilon_{i,\alpha} \times \kappa_{i,\alpha}$$

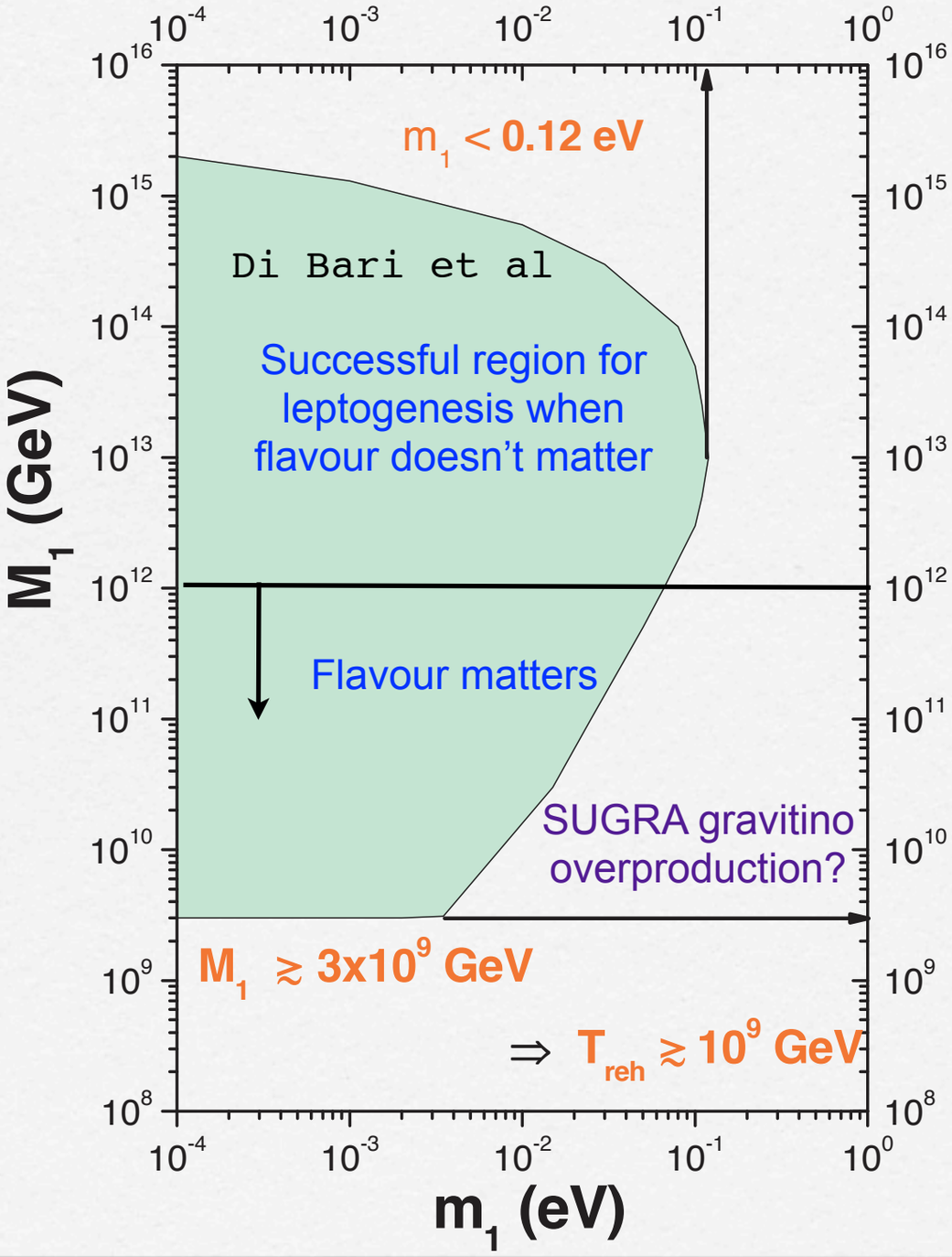
efficiency factors include washouts

Baryon Asymmetry

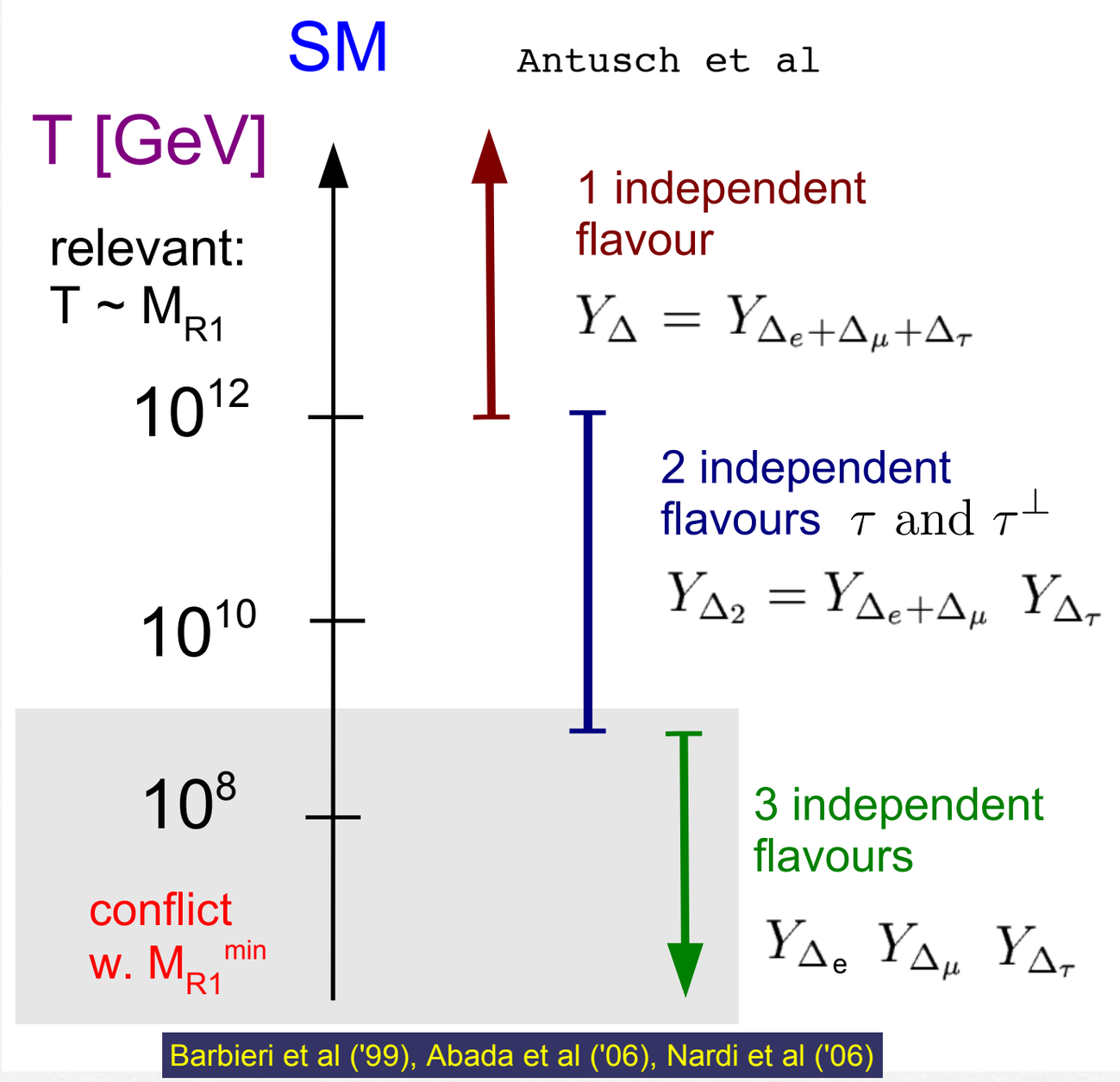
$$\eta_B \approx a_{sph} \frac{\Delta(B-L)}{n_\gamma}$$

$$a_{sph} \approx 1/3$$

When flavour doesn't matter

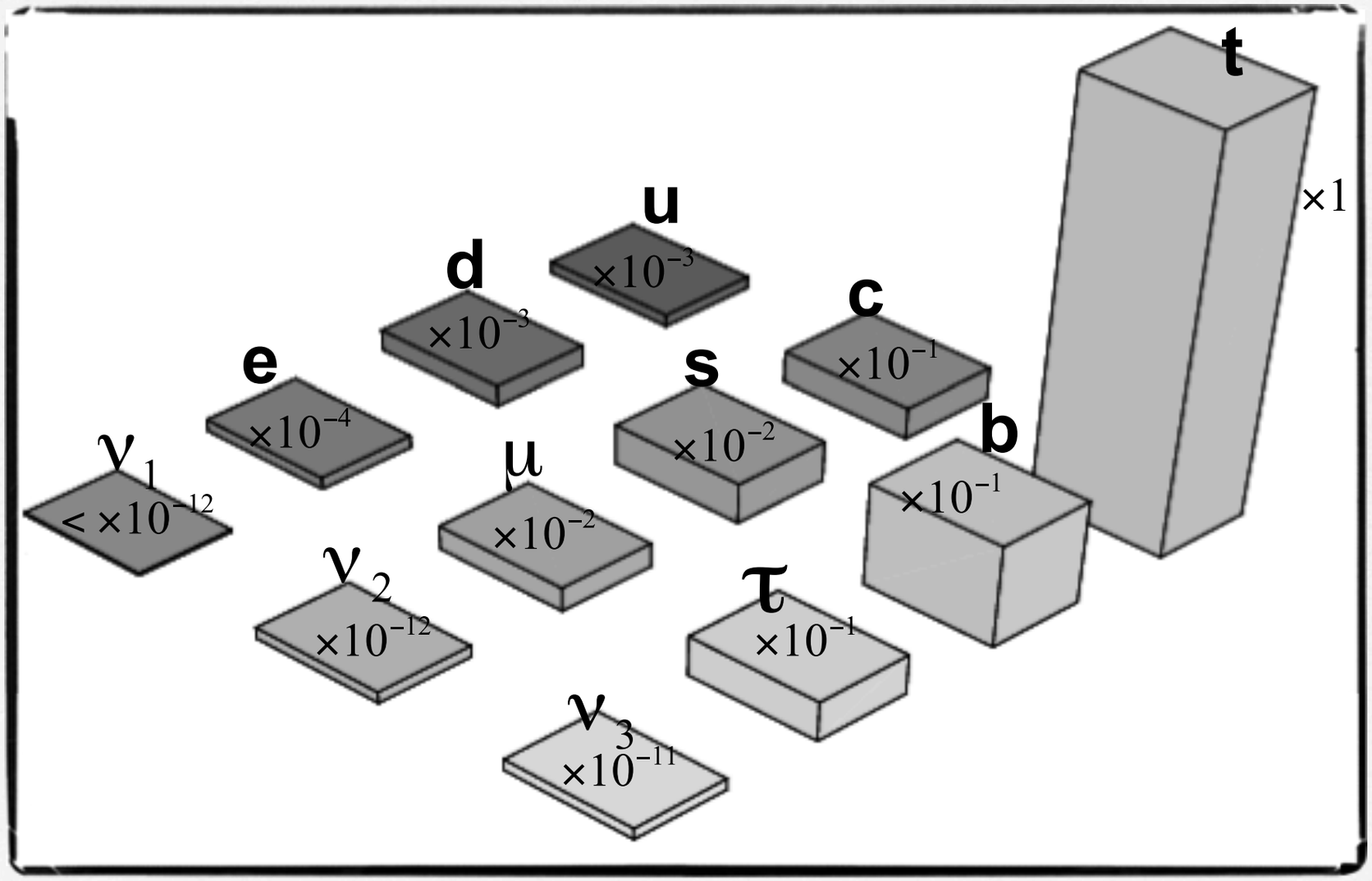


When flavour matters

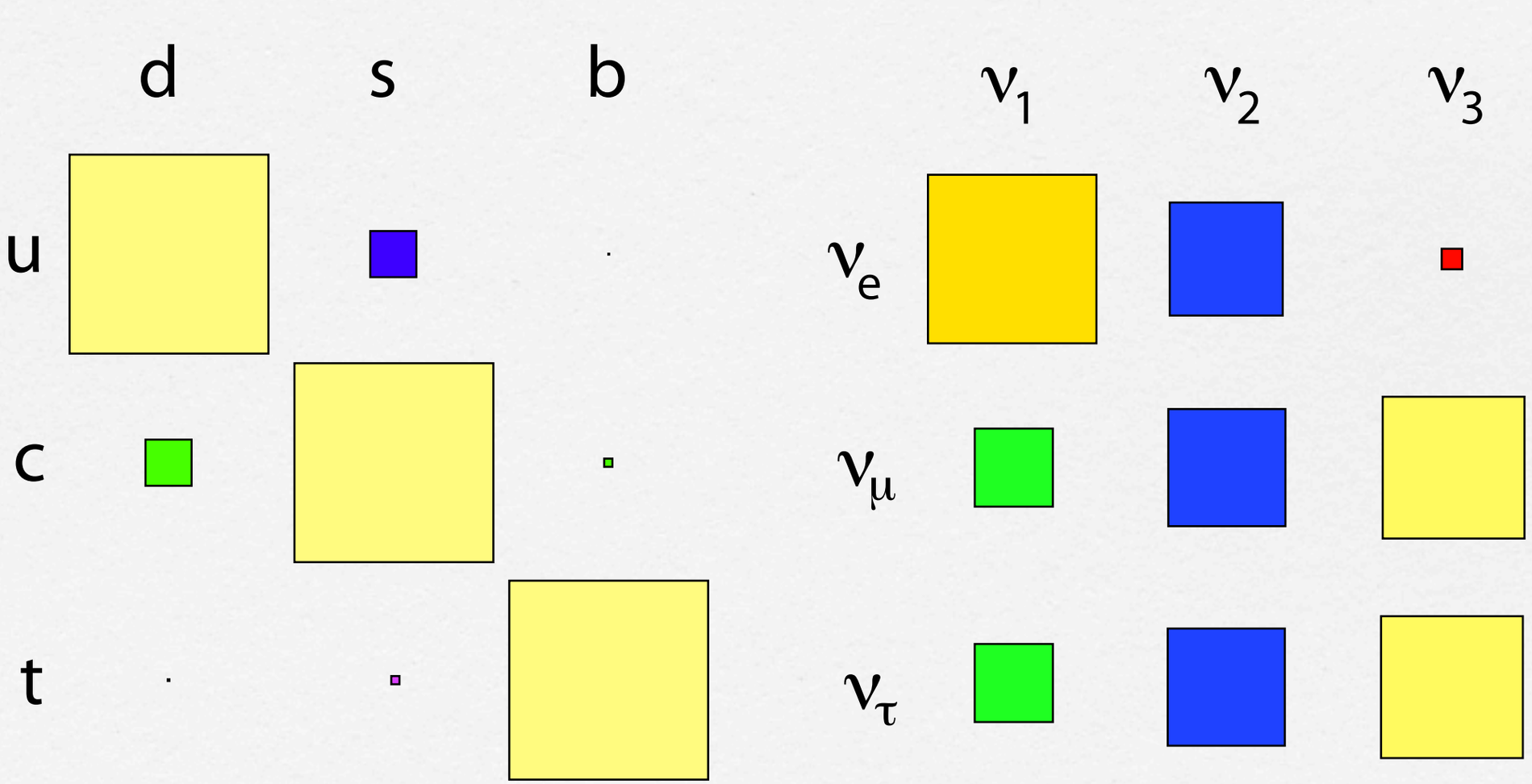


Barbieri et al ('99), Abada et al ('06), Nardi et al ('06)

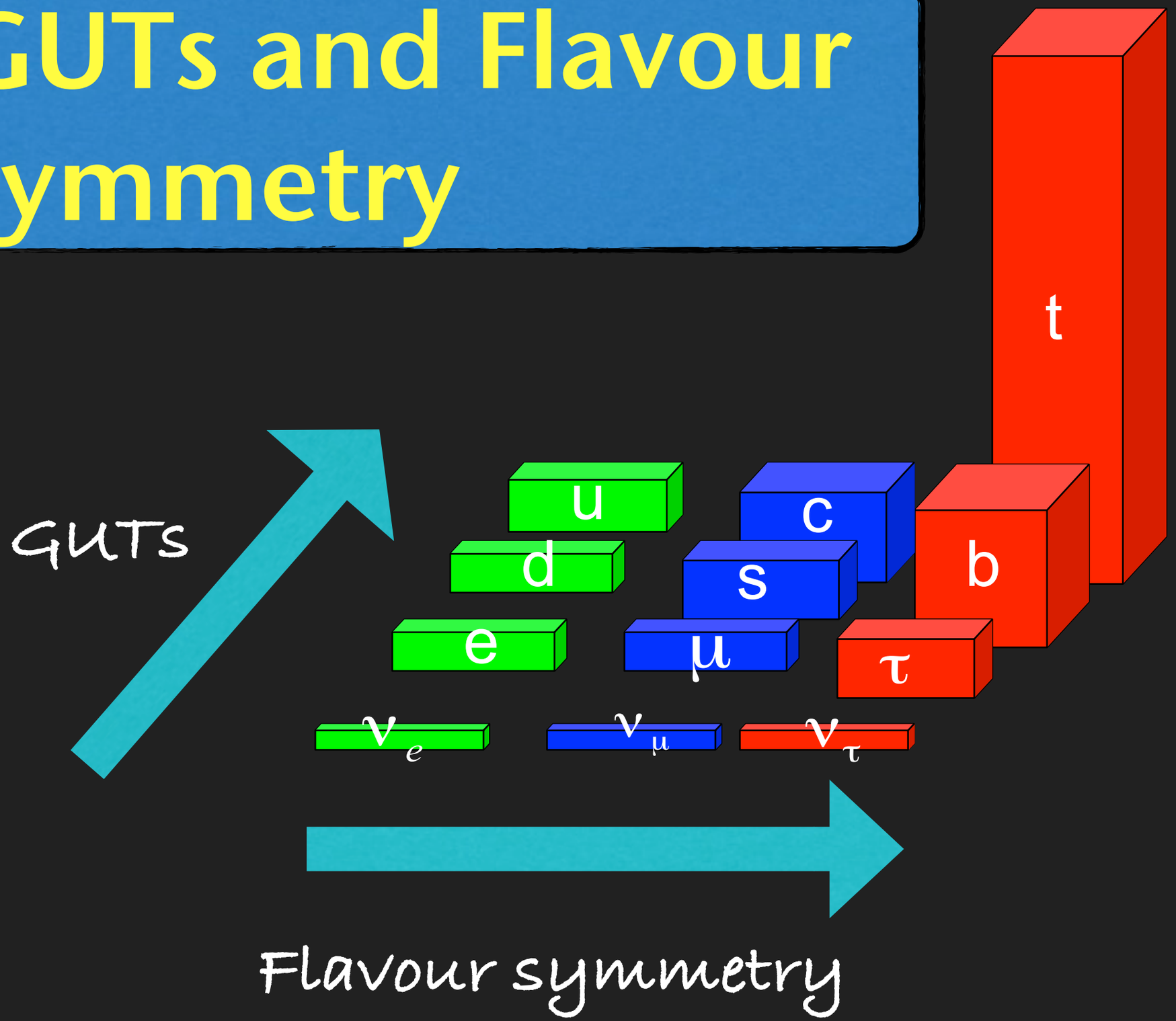
What is the origin of Quark and Lepton Masses?



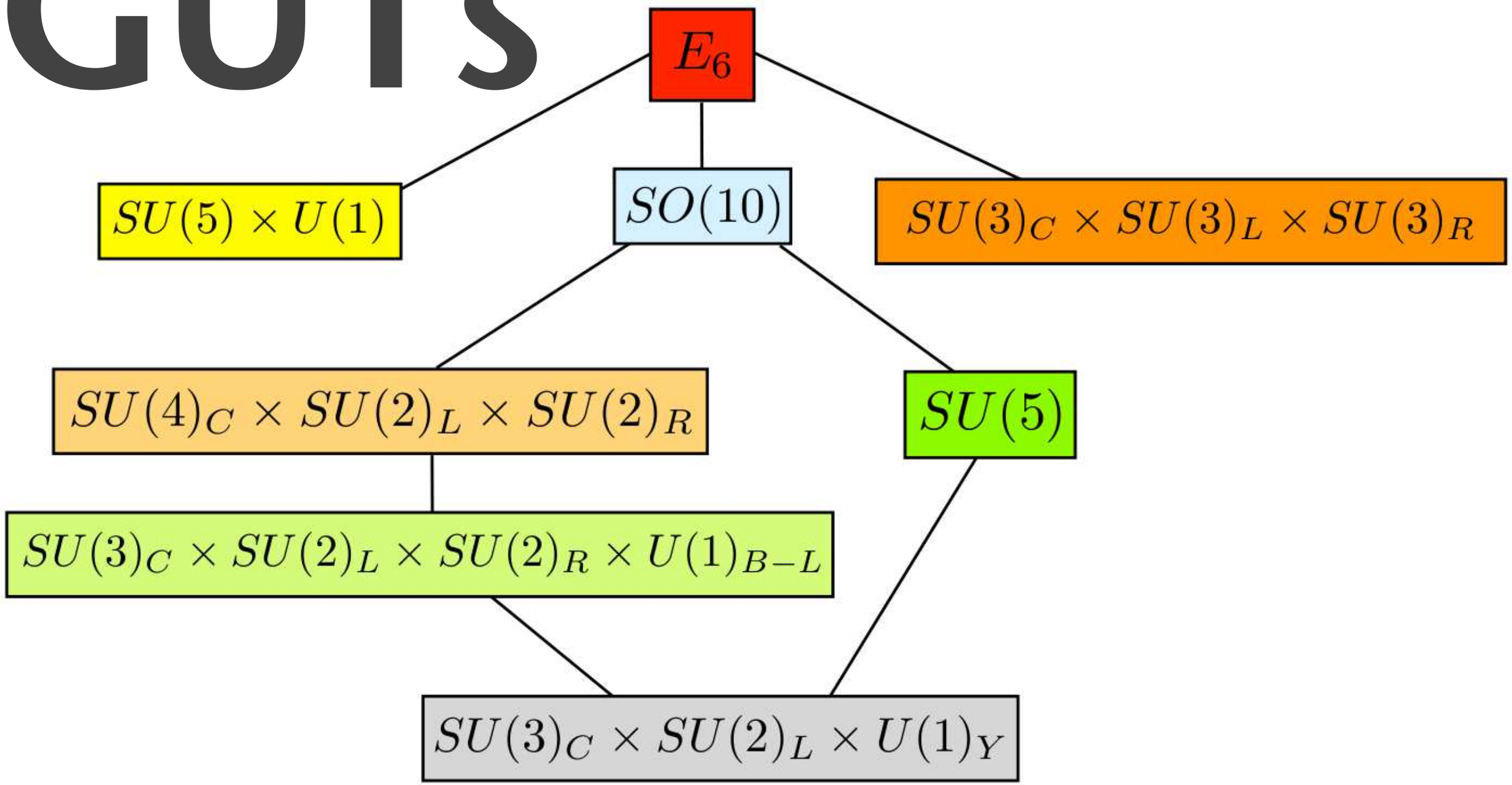
What is the origin of Quark and Lepton Mixing?



GUTs and Flavour symmetry



GUTs

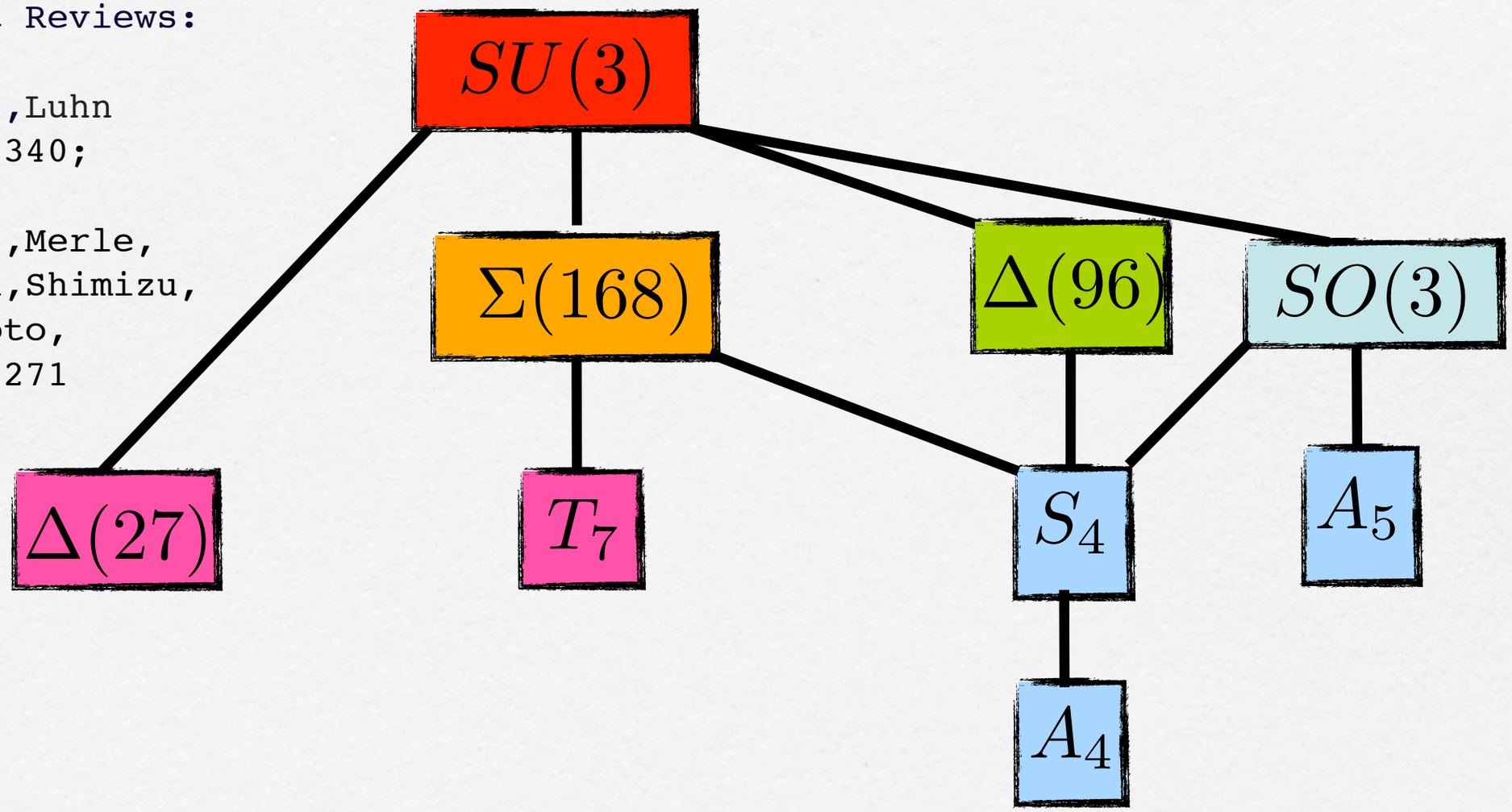

E_6
$SU(5) \times U(1)$
$SO(10)$
$SU(3)_C \times SU(3)_L \times SU(3)_R$
$SU(4)_C \times SU(2)_L \times SU(2)_R$
$SU(5)$
$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
$SU(3)_C \times SU(2)_L \times U(1)_Y$

Flavour Symmetry

Recent Reviews:

S.F.K.,Luhn
1301.1340;

S.F.K.,Merle,
Morisi,Shimizu,
Tanimoto,
1402.4271



Björkeroth, de Anda, de Medieoros Varzielas and S.F.K. 1503.03306

Towards a complete A_4xSU(5) SUSY GUT

- Renormalisable at GUT scale, SU(5) breaking potential, spontaneously broken CP.
- The MSSM is reproduced with R-parity emerging from a discrete Z_4^R .
- Doublet-triplet splitting is achieved through the Missing Partner mechanism.
- mu term is generated at the correct scale.
- Proton decay is sufficiently suppressed.
- It solves the strong CP problem through the Nelson-Barr mechanism .
- Explains quark mass hierarchies, mixing angles and the CP phase.
- Two right-handed neutrinos, lighter one dominantly giving atmospheric neutrino mass.
- Z_9 flavour symmetry fixes the phase η to be one of ninth roots of unity, choose 2pi/3
- **Gives minimal predictive seesaw model see next slide**

Björkeroth, de Anda, de Medeiros Varzielas and S.F.K. 1505.05504

Leptogenesis in minimal predictive seesaw

$$\lambda^\nu = \begin{pmatrix} 0 & b \\ a & 3b \\ a & b \end{pmatrix}, \quad M^c = \begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix},$$

2RHN Seesaw matrices from A4xSU(5)

$$\epsilon_{1,\alpha} \approx -\frac{3}{8\pi}\frac{M_1}{M_2}\frac{\mathrm{Im}\left[(\lambda_\nu^\dagger)_{1\alpha}(\lambda_\nu^\dagger\lambda_\nu)_{12}(\lambda_\nu^T)_{2\alpha}\right]}{(\lambda_\nu^\dagger\lambda_\nu)_{11}}$$

$$\epsilon_{1,e} = 0$$

Asymmetries

$$\epsilon_{1,\mu} = 3\epsilon_{1,\tau} = \frac{9}{4\pi}\frac{M_1 m_b}{v^2 \sin^2\beta}\sin\eta$$

$$\approx 6.01 \times 10^{-7}\left[\frac{M_1}{10^{10}\ \mathrm{GeV}}\right]$$

Washout parameters

$$\tilde{m}_{1,e} = 0, \qquad \tilde{m}_{1,\mu} = \tilde{m}_{1,\tau} = |a|^2\frac{v^2\sin^2\beta}{M_1}.$$

optimal values $\sim 10^{-3}$ eV

$$Y_B = \frac{2700}{31\pi^5 g_*}\frac{M_1}{M_2}\eta_{1,\mu}|b|^2\sin\eta$$

$$\eta \equiv -\arg[a^{*2}b^2]$$

Baryon asymmetry of the Universe (BAU)

Björkeroth, de Anda, de Medeiros Varzielas and S.F.K. 1505.05504

Leptogenesis in minimal predictive seesaw

m_a (meV)	m_b (meV)	η (rad)	θ_{12} (°)	θ_{13} (°)	θ_{23} (°)	$\delta_{\rm CP}$ (°)	m_2 (meV)	m_3 (meV)
26.57	2.684	$\frac{2\pi}{3}$	34.3	8.67	45.8	-86.7	8.59	49.8

Excellent fit to oscillation data!

low energy nu mass matrix

$$m^\nu = m_a \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} + m_b e^{i\eta} \begin{pmatrix} 1 & 3 & 1 \\ 3 & 9 & 3 \\ 1 & 3 & 1 \end{pmatrix} \qquad m_a = \frac{|a|^2 v^2}{M_1}, \quad m_b = \frac{|b|^2 v^2}{M_2}$$

same phase

BAU

$$Y_B \approx 2.5 \times 10^{-11} \sin\eta \left[\frac{M_1}{10^{10}\ \text{GeV}}\right]$$

$$\eta \equiv -\arg[a^{*2} b^2]$$

Leptogenesis - PMNS link

$$\eta = \frac{2\pi}{3} \ \leftrightarrow \ \delta_{CP} \sim -\frac{\pi}{2}$$

✳The phase eta is the only source of CP violation in neutrino oscillations and leptogenesis

✳Positive eta is associated with positive baryon asymmetry and negative oscillation phase

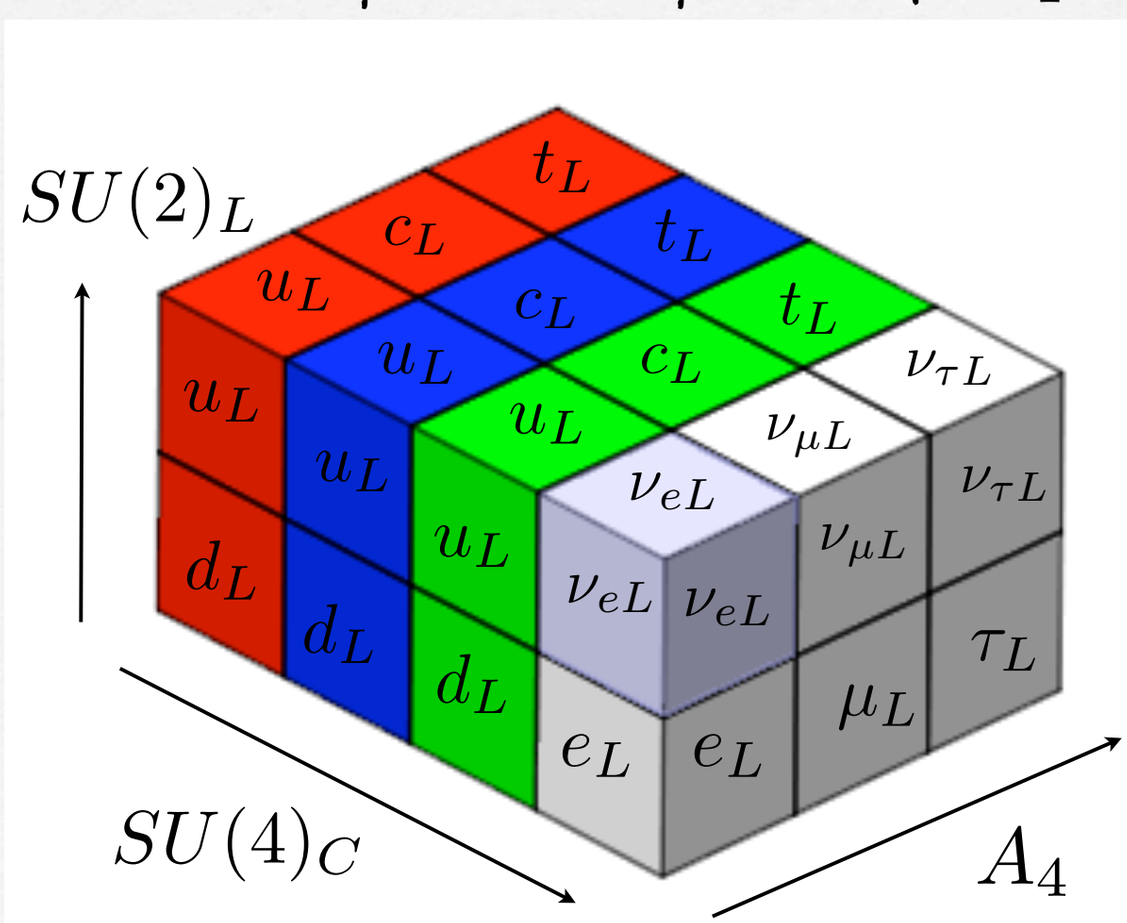
S.F.K. 1406.7005

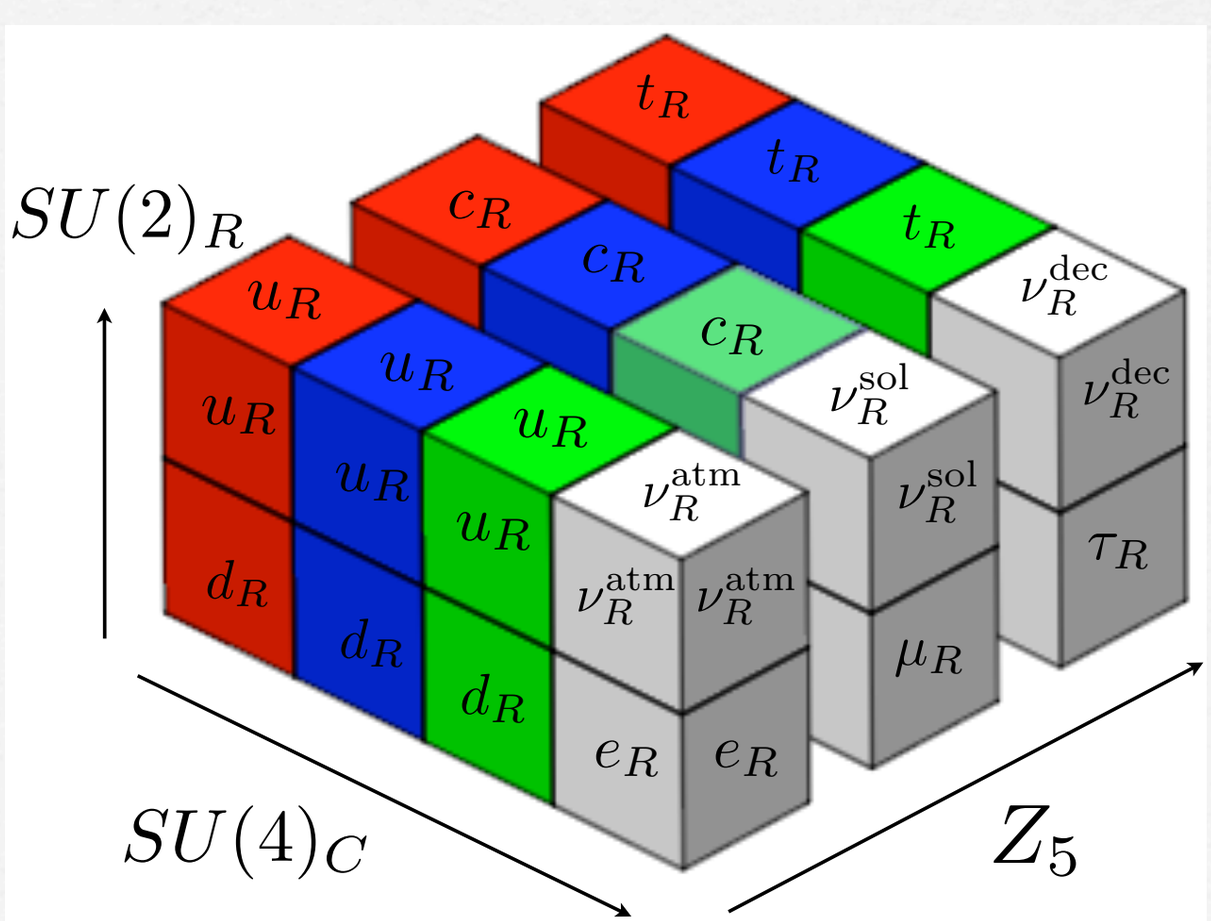
A to Z of Flavour with Pati-Salam

$$A_4 \times Z_5 \times SU(4)_C \times SU(2)_L \times SU(2)_R$$

Left-handed quarks and leptons triplets of A_4

Right-handed quarks and leptons distinguished by Z_5





Yukawa matrices in A to Z model

Theory basis

$$Y^u = \begin{pmatrix} 0 & be^{-i3\pi/5} & 0 \\ ae^{-i3\pi/5} & 4be^{-i3\pi/5} & 0 \\ ae^{-i3\pi/5} & 2be^{-i3\pi/5} & c\,e^{i\phi} \end{pmatrix} \qquad Y^d \sim Y^e \sim \begin{pmatrix} y_d^0 & 0 & 0 \\ 0 & y_s^0 & 0 \\ 0 & 0 & y_b^0 \end{pmatrix}$$

Equal

$$Y'^{\nu} = \begin{pmatrix} 0 & be^{-i3\pi/5} & 0 \\ ae^{-i3\pi/5} & 4be^{-i3\pi/5} & 0 \\ ae^{-i3\pi/5} & 2be^{-i3\pi/5} & ce^{i\phi} \end{pmatrix}, \quad M'_R = \begin{pmatrix} M'_{11}\,e^{2i\xi} & 0 & M'_{13}\,e^{i\xi} \\ 0 & M'_{22}\,e^{i\xi} & 0 \\ M'_{13}\,e^{i\xi} & 0 & M'_{33} \end{pmatrix}$$

Flavour basis

$$\xi = +4\pi/5$$

$$Y^{\nu} \approx \begin{pmatrix} 0 & be^{-i\,(\xi/2+3\pi/5)} & 0 \\ a\,e^{-i(\xi+3\pi/5)} & 4be^{-i\,(\xi/2+3\pi/5)} & a\,R_{13}\,e^{-i(\xi+3\pi/5)} \\ a\,e^{-i\,(\xi+3\pi/5)}(1-\gamma) & 2be^{-i(\xi/2+3\pi/5)} & c\,e^{i\phi} \end{pmatrix} \qquad M_R = \begin{pmatrix} M_1 & 0 & 0 \\ 0 & M_2 & 0 \\ 0 & 0 & M_3 \end{pmatrix}$$

$$\gamma \approx (c/a)R_{13}e^{i(\phi+\xi+3\pi/5)} \qquad R_{13} \approx \frac{M'_{13}}{M'_{33}}$$

P.Di Bari and S.F.King 1507.06431

Leptogenesis in A to Z model

A to Z model has typical SO(10) relation

$$m_{\nu 1}^D = m_{\rm up}, \quad m_{\nu 2}^D = m_{\rm charm}, \quad m_{\nu 3}^D = m_{\rm top}$$

SO(10) inspired N1 leptogenesis: W. Buchmuller and M. Plumacher, [hep-ph/9608308]; E. Nezri and J. Orlo, [hep-ph/0004227]; F. Buccella, D. Falcone and F. Tramontano, [hep-ph/0108172]; G. C. Branco, R. Gonzalez Felipe, F. R. Joaquim and M. N. Rebelo, [hep-ph/0202030]; E. K. Akhmedov, M. Frigerio and A. Y. Smirnov,[hep- ph/0305322].

Type I seesaw gives a strong RH mass hierarchy

$$M_1 : M_2 : M_3 \sim m_{\rm up}^2 : m_{\rm charm}^2 : m_{\rm top}^2$$

with N_1 is too light for leptogenesis

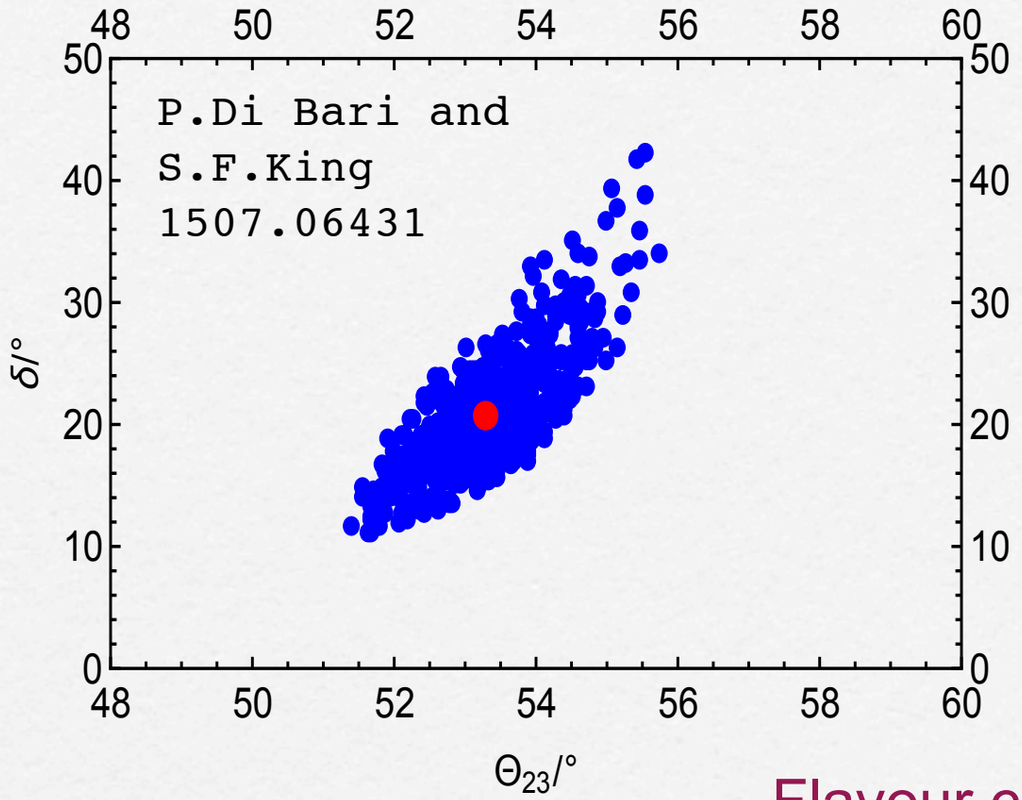
$$M_1 : M_2 : M_3 \sim 10^5 {\rm GeV} : 10^{10} {\rm GeV} : 10^{15} {\rm GeV}$$

SO(10) inspired N2 leptogenesis: P. Di Bari and A. Riotto, 0809.2285,1012.2343; P. Di Bari, L. Marzola and M. Re Fiorentin, 1411.5478 [hep-ph]].

What about N_2 leptogenesis?

P.Di Bari '05-'15

(Vives '05; Blanchet, PDB '06; Nardi,Nir '07; Blanchet, PDB '08)



N2 Leptogenesis

$\chi^2_{\rm min}$	5.15
$M'_{11}/10^6{\rm GeV}$	1.30
$M'_{22}/10^{10}{\rm GeV}$	0.48
$M'_{33}/10^{12}{\rm GeV}$	2.16
$M'_{13}/10^{10}{\rm GeV}$	1.81
M'_{13}/M'_{22}	3.75
ϕ/π	0.795
$M_1/10^7{\rm GeV}$	15
$M_2/10^{10}{\rm GeV}$	0.483
$M_3/10^{12}\,{\rm GeV}$	2.16
$\lvert\gamma\rvert$	203
$m_1/{\rm meV}$	2.3
$m_2/{\rm meV}$ $(p_{\Delta m^2_{12}})$	8.93 (-0.22)
$m_3/{\rm meV}$ $(p_{\Delta m^2_{13}})$	49.7 (+0.17)
$\sum_i m_i/{\rm meV}$	61
$m_{ee}/{\rm meV}$	1.95
$\theta_{12}/^\circ$ $(p_{\theta_{12}})$	33.0 (-0.58)
$\theta_{13}/^\circ$ $(p_{\theta_{13}})$	8.40 (-0.47)
$\theta_{23}/^\circ$ $(p_{\theta_{23}})$	53.3 (+2.1)
$\delta/^\circ$	20.8
$\beta_1/^\circ$	118
$\beta_2/^\circ$	281
$\alpha_{21}/^\circ$	163
$\alpha_{31}/^\circ$	242
$\rho/^\circ$	279
$\sigma/^\circ$	220

Flavour coupling

Washout at N1 scale

$$\eta_B^{(\mu)} \approx -0.01\ \varepsilon_{2\tau}\kappa(K_{2\tau})\frac{K_{2\mu}}{K_{2e}+K_{2\mu}}C^{(2)}_{\tau^\perp\tau}e^{-\frac{3\pi}{8}K_{1\mu}}$$

Muon asymmetry survives washout

Tau asymmetry produced at N2 scale

successful value

$\eta_B/10^{-10}$ (p_{η_B})	6.101 (+0.01)
$\varepsilon_{2\tau}$	-8.1×10^{-6}
$K_{1\mu}$	0.11
$K_{1\tau}$	4341
$K_{2\tau}$	7.3
$K_{2\mu}$	29.2
K_{2e}	1.8

"Flavour swap" scenario: tau asym→muon asym

Conclusions

- Leptogenesis is a leading candidate for BAU
- GUT x Discrete Family Symmetry gives predictive candidate theories of flavour: we considered two examples
- A4xSU(5) SUSY GUT gives minimal predictive seesaw, with successful N1 leptogenesis including a link to low energy CP violation in oscillations
- A to Z Pati-Salam unifies RH neutrinos with quarks and leptons, explains Cabibbo angle, gives successful N2 leptogenesis