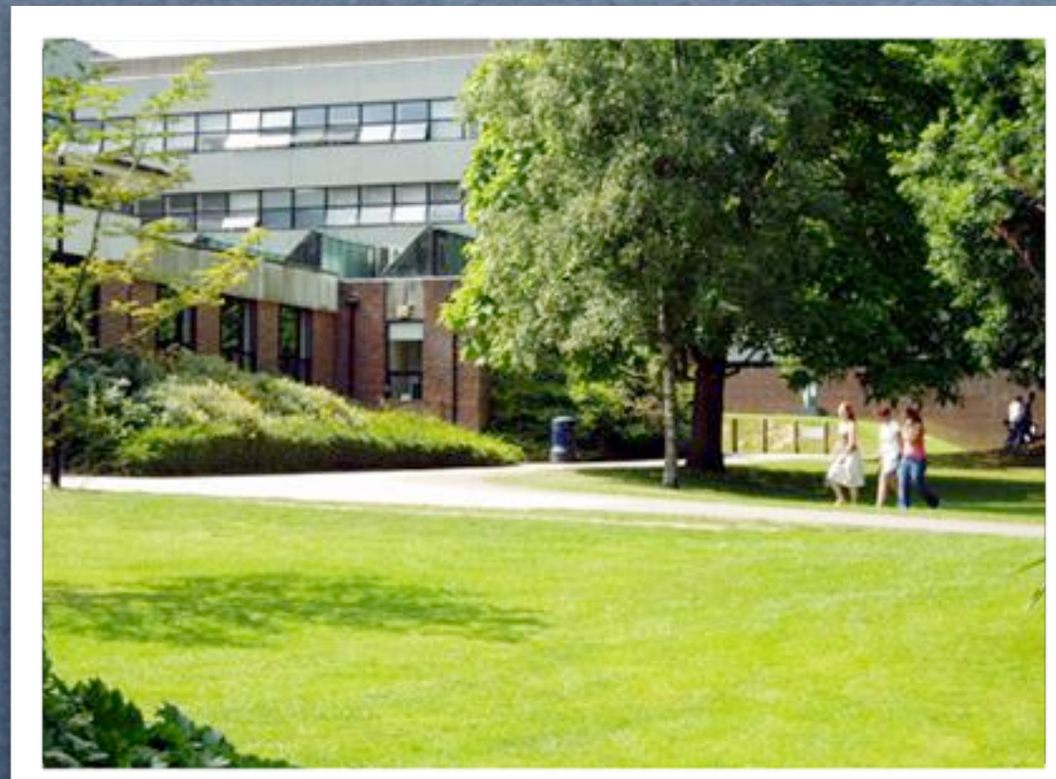
UNIVERSITY OF Southampton

School of Physics and Astronomy

Southampton Node



Steve King

Pre-meeting of Invisibles

Madrid, 29-30th March, 2012

Southampton High Energy Physics (SHEP) Theory


Elena Accomando


Ken Barnes (deceased)


Alexander Belyaev


Pasquale Di Bari


Nick Evans


Jonathan Flynn


Steve King


Stefano Moretti


Tim Morris


Douglas Ross


Chris Sachrajda


Roman Zwicky

SHEP is one of the largest theoretical particle physics groups in the UK: 11 Faculty

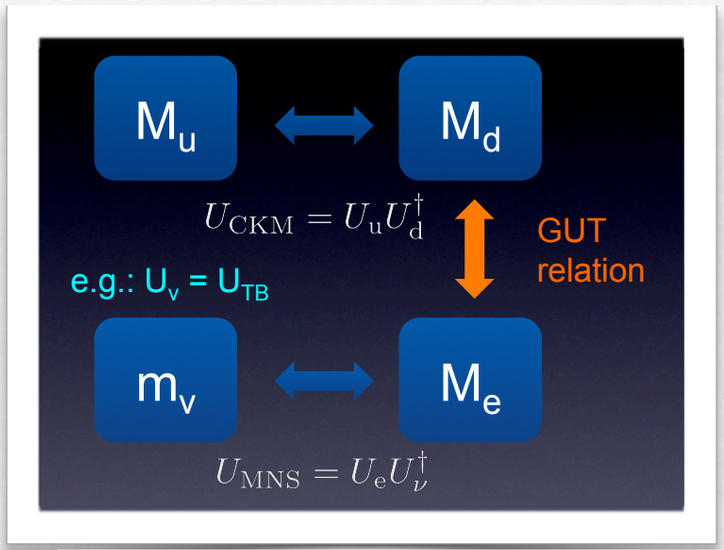
- **Profs.** Nick Evans, Jonathan Flynn, Steve King, Stefano Moretti, Tim Morris, Douglas Ross **FRS**, Chris Sachrajda **FRS** (Head of Group)
- **Drs.** Elena Accomando, Sacha Belyaev, Pasquale di Bari, Roman Zwicky
- 7 PDRAs (3 STFC, 2 MC, 1 ERC, 1 Self) and ~22 Ph.D.s (STFC, NExT, STAG, EU)

We work in 4 overlapping areas (STFC Funded):

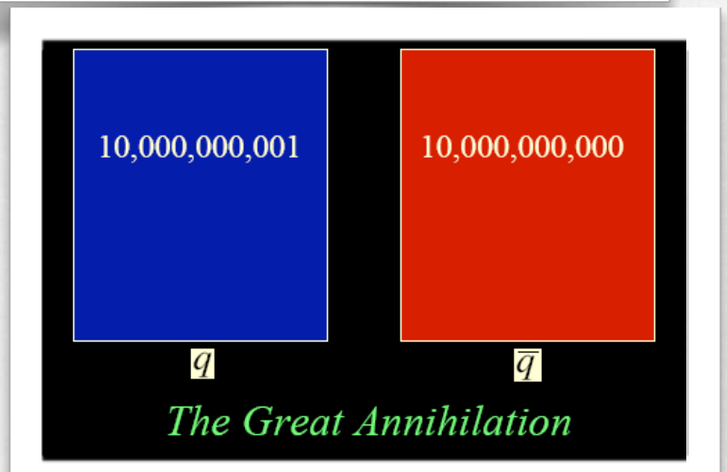
- **Collider phenomenology**: NExT Inst. Founded RAL/SHEP led by SHEP (SEPnet)
- **Beyond Standard Model, ν & Flavour, Cosmology**: EU FP7 "Invisibles"
- **Lattice Quantum Chromodynamics (QCD)**: UKQCD, ERC Starter (Dr. A Juttner)
- **Strongly Coupled Gauge Theory & AdS/CFT**: Holograv ESF Net

Invisibles staff interests

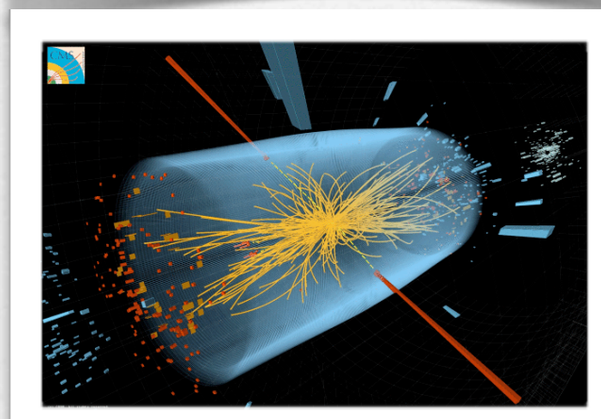
- Steve King: Neutrinos and Flavour Models, GUTs and Strings, Cosmology, SUSY Models



- Pasquale Di Bari: Leptogenesis, Neutrinos, GUTs



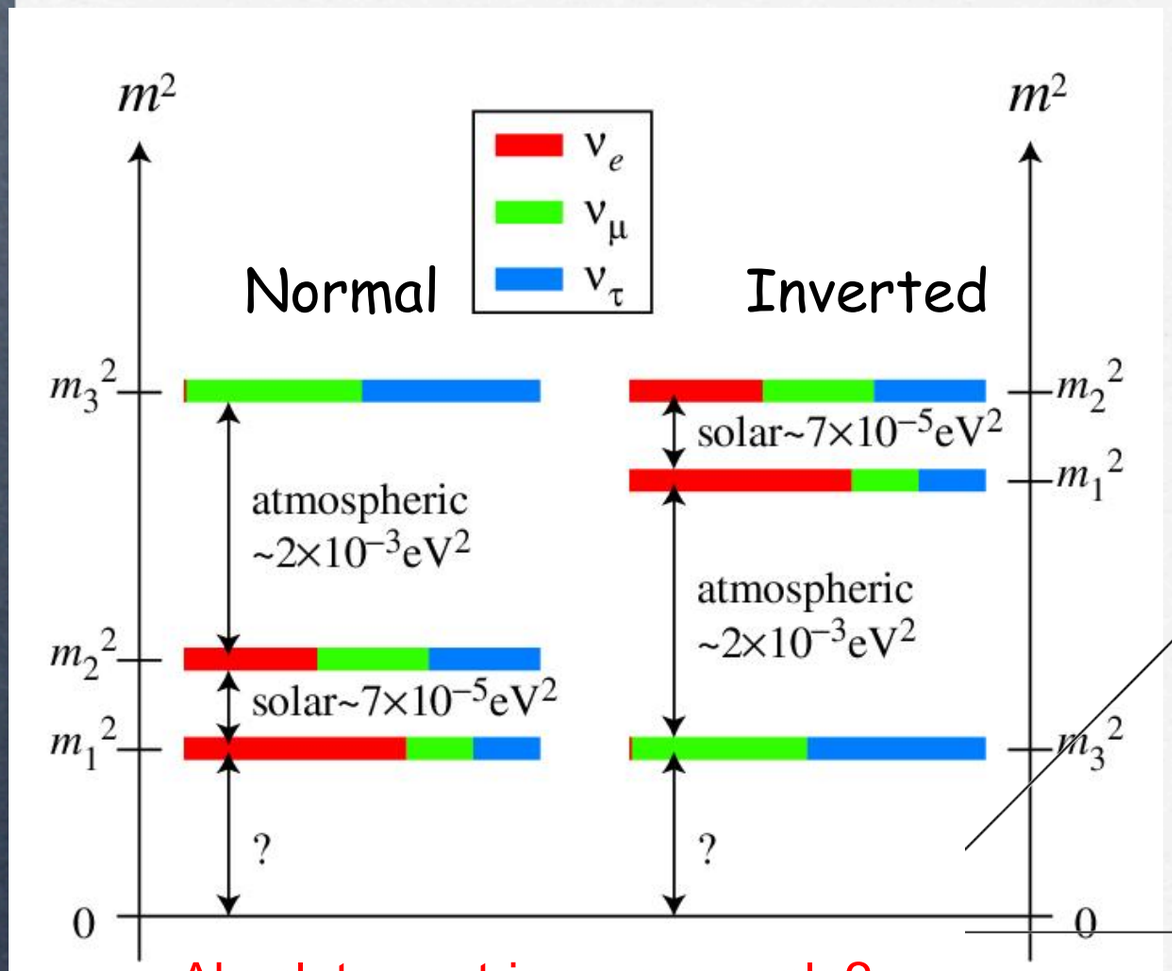
- Sasha Belyaev (CMS): BSM, Collider Phenomenology



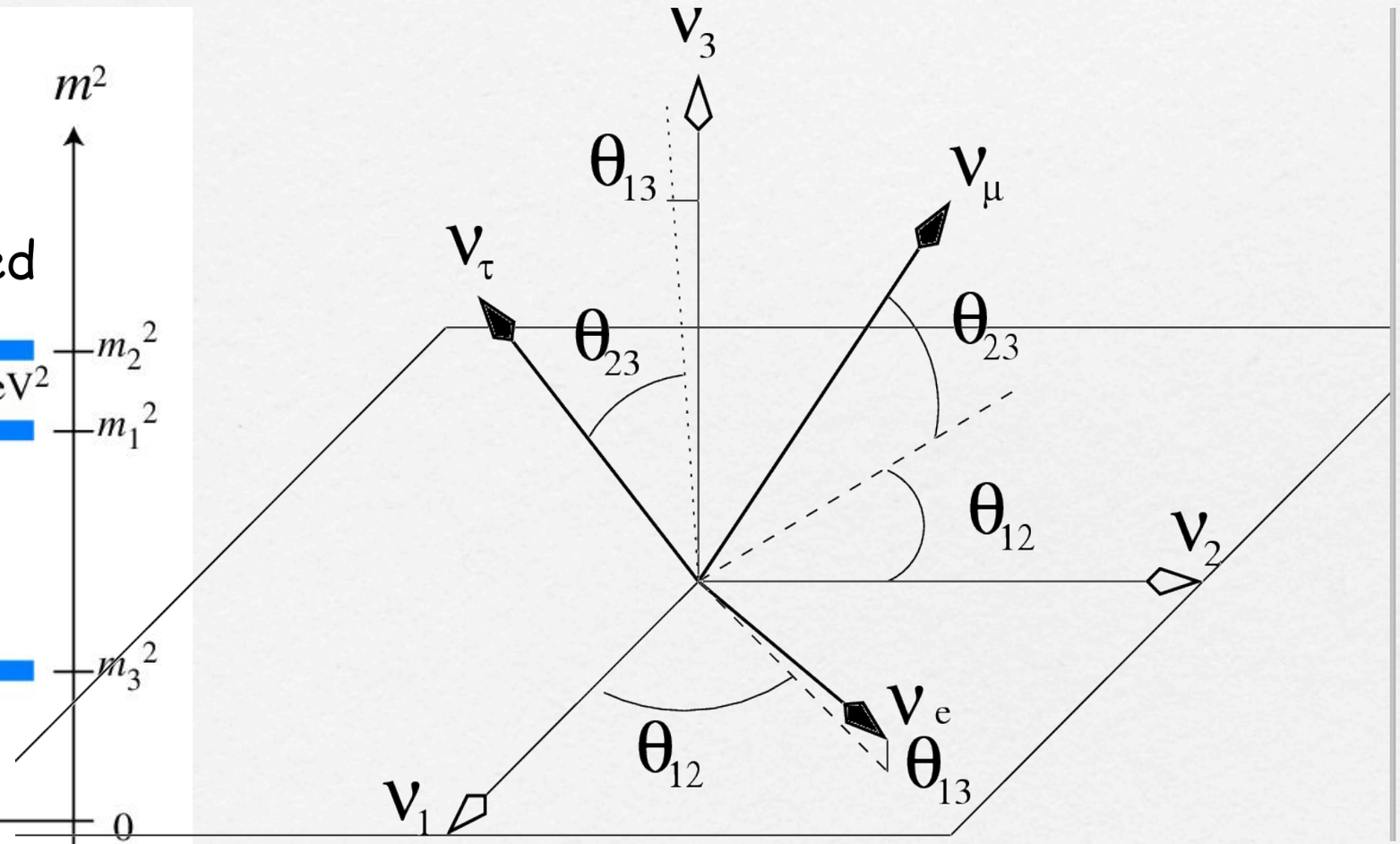
2 Postdocs, 8 students in Invisibles areas

- Alex Stuart (Postdoc): Neutrinos and Family Symmetry Models, GUTs
- Iain Cooper (Student) Neutrinos and Family Symmetry Models, GUTs
- David Jones (Student) Neutrinos and Leptogenesis
- Plus 5 other students: Leptogenesis, BSM, Collider
- Alex Merle (MC Postdoc, starts 1st June): Neutrinos, Family Symmetry and Cosmology
- Thomas Neder (Invisibles Junior ESR PhD student)

Neutrino Mass and Mixing



Absolute neutrino mass scale?



A fascinating puzzle...

Neutrino Tri-Mixing Patterns

s = solar a = atmospheric r = reactor

- **General Mixing**

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

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

- **Tri-bimaximal**

$$s = a = r = 0$$

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

Excluded by Daya Bay

- **Tri-bimaximal-reactor** $s = a = 0,\ r \neq 0$

$$U_{TBR} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}}re^{-i\delta} \\ -\frac{1}{\sqrt{6}}(1+re^{i\delta}) & \frac{1}{\sqrt{3}}(1-\frac{1}{2}re^{i\delta}) & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}}(1-re^{i\delta}) & -\frac{1}{\sqrt{3}}(1+\frac{1}{2}re^{i\delta}) & \frac{1}{\sqrt{2}} \end{pmatrix} P$$

- **Tri-maximal 1**

$$s = 0 \qquad a = r\cos\delta$$

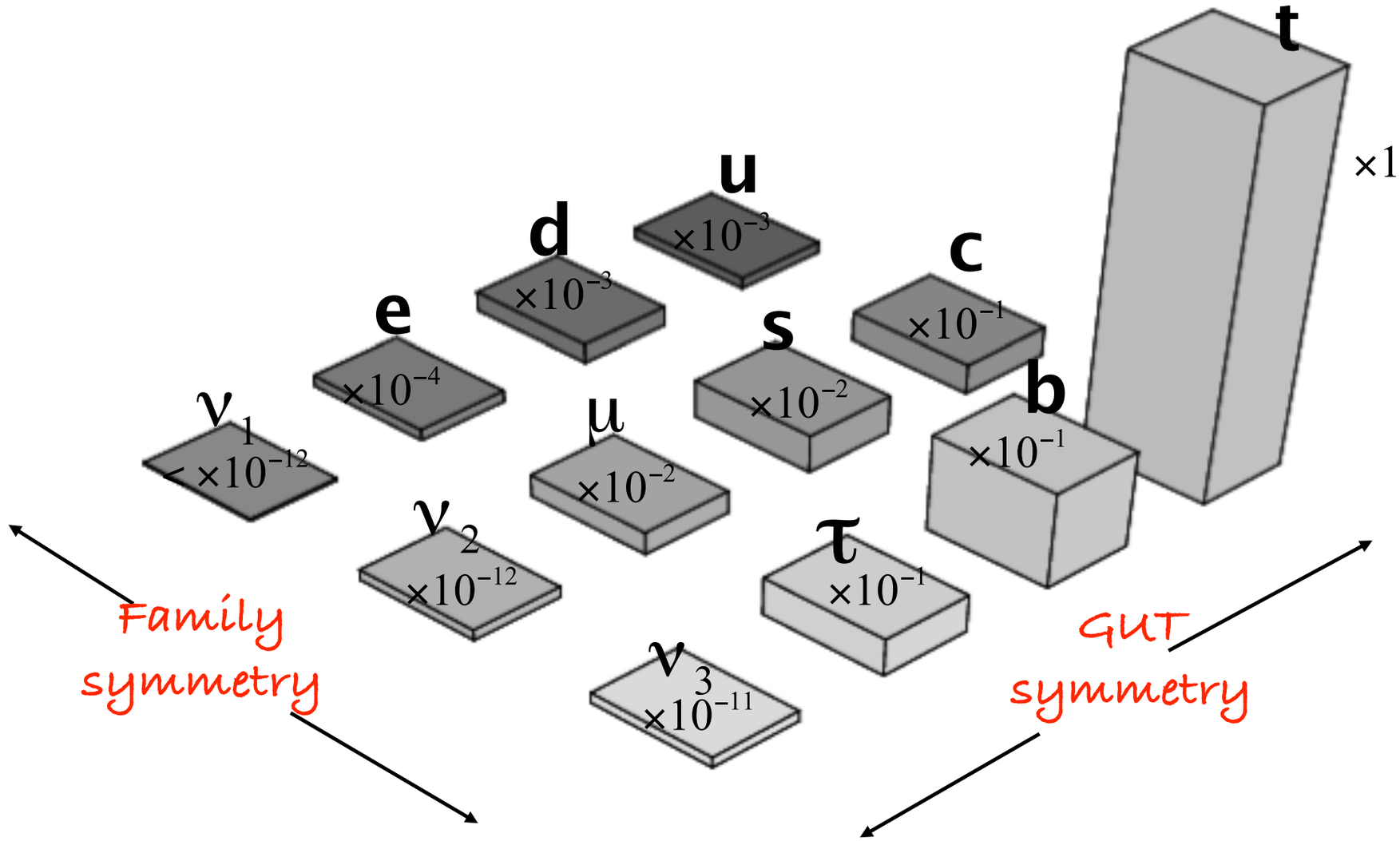
$$U_{\rm TM_1} = P' \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}}re^{-i\delta} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}}(1-\frac{3}{2}re^{i\delta}) & \frac{1}{\sqrt{2}}(1+re^{-i\delta}) \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}}(1+\frac{3}{2}re^{i\delta}) & -\frac{1}{\sqrt{2}}(1-re^{-i\delta}) \end{pmatrix} P$$

- **Tri-maximal 2**

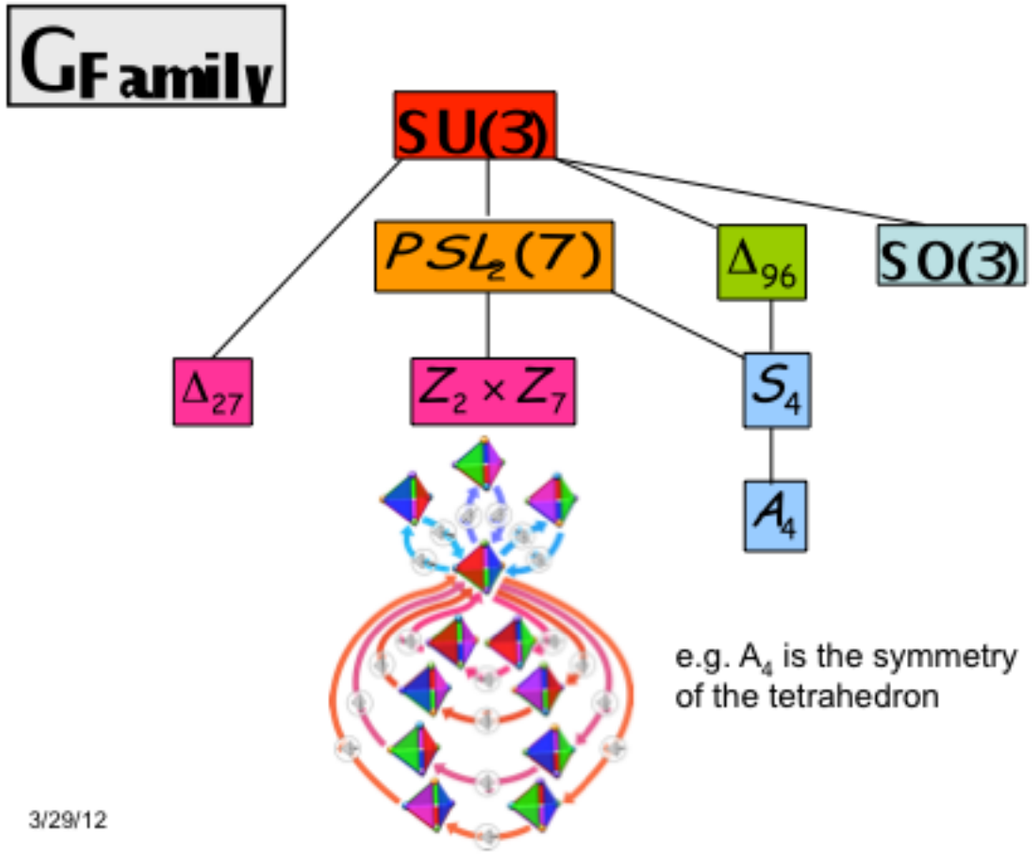
$$s = 0 \qquad a = -\frac{1}{2}r\cos\delta$$

$$U_{\rm TM_2} = P' \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}}re^{-i\delta} \\ -\frac{1}{\sqrt{6}}(1+\frac{3}{2}re^{i\delta}) & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}}(1-\frac{1}{2}re^{-i\delta}) \\ -\frac{1}{\sqrt{6}}(1-\frac{3}{2}re^{i\delta}) & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}}(1+\frac{1}{2}re^{-i\delta}) \end{pmatrix} P$$

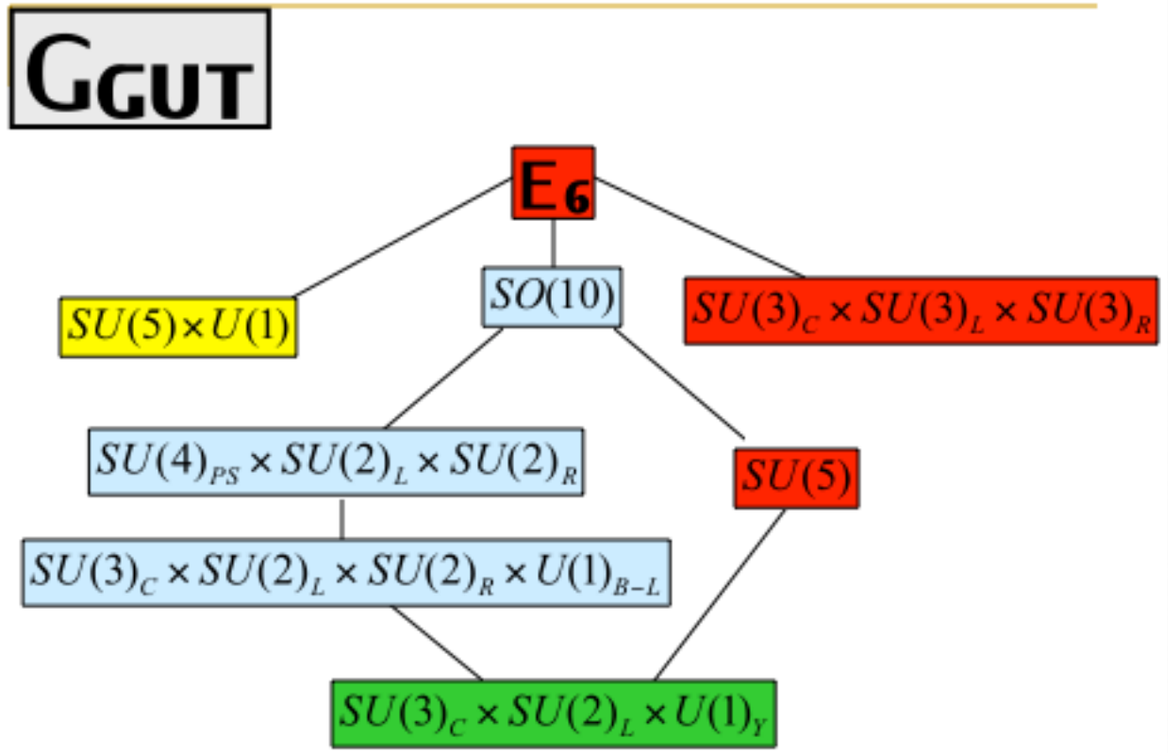
Family Symmetry × GUTs



Family Symmetry and GUTs



e.g. A_4 is the symmetry of the tetrahedron



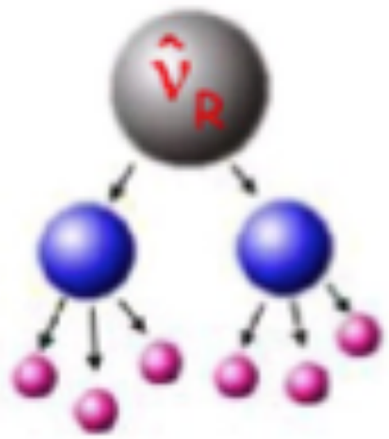
Neutrinos and Flavour Models

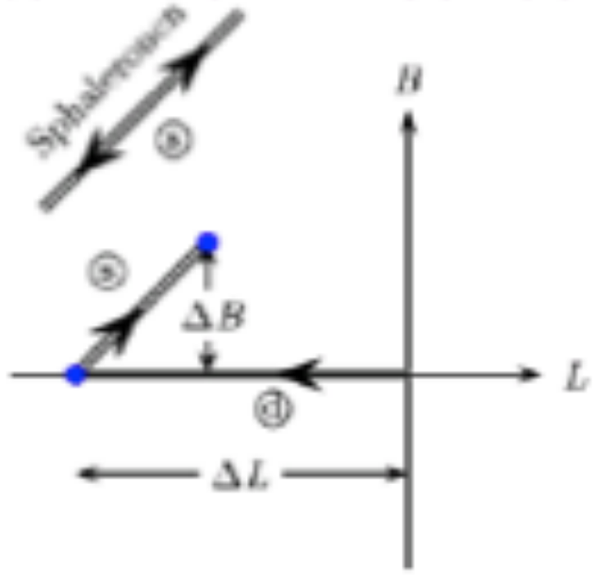
- At Southampton we have worked on models all of these mixing patterns, plus the Golden Ratio, using discrete family symmetries A4, A5, S4, Δ27, Δ96, PSL(2,7),..
- Type I see-saw models may be formulated in diagonal right-handed neutrino basis using different types of sequential dominance, or in the symmetry basis where subgroups are preserved in neutrino sector
- We have also considered type II and III see-saw models
- We have integrated these patterns of neutrino mixing into GUT models based on SU(5), SO(10), E6,...
- Typically the mixing patterns apply to the neutrino sector and lepton mixing involves (small) charged lepton corrections as well as (small) RG and CN corrections

Leptogenesis

Fukugita, Yanagida

- Right-handed 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
- Out of equilibrium Boltzmann eqs lead to L_e , L_μ , L_τ partial washouts
- Surviving L_e, L_μ , L_τ are processed into B via B-L conserving sphalerons

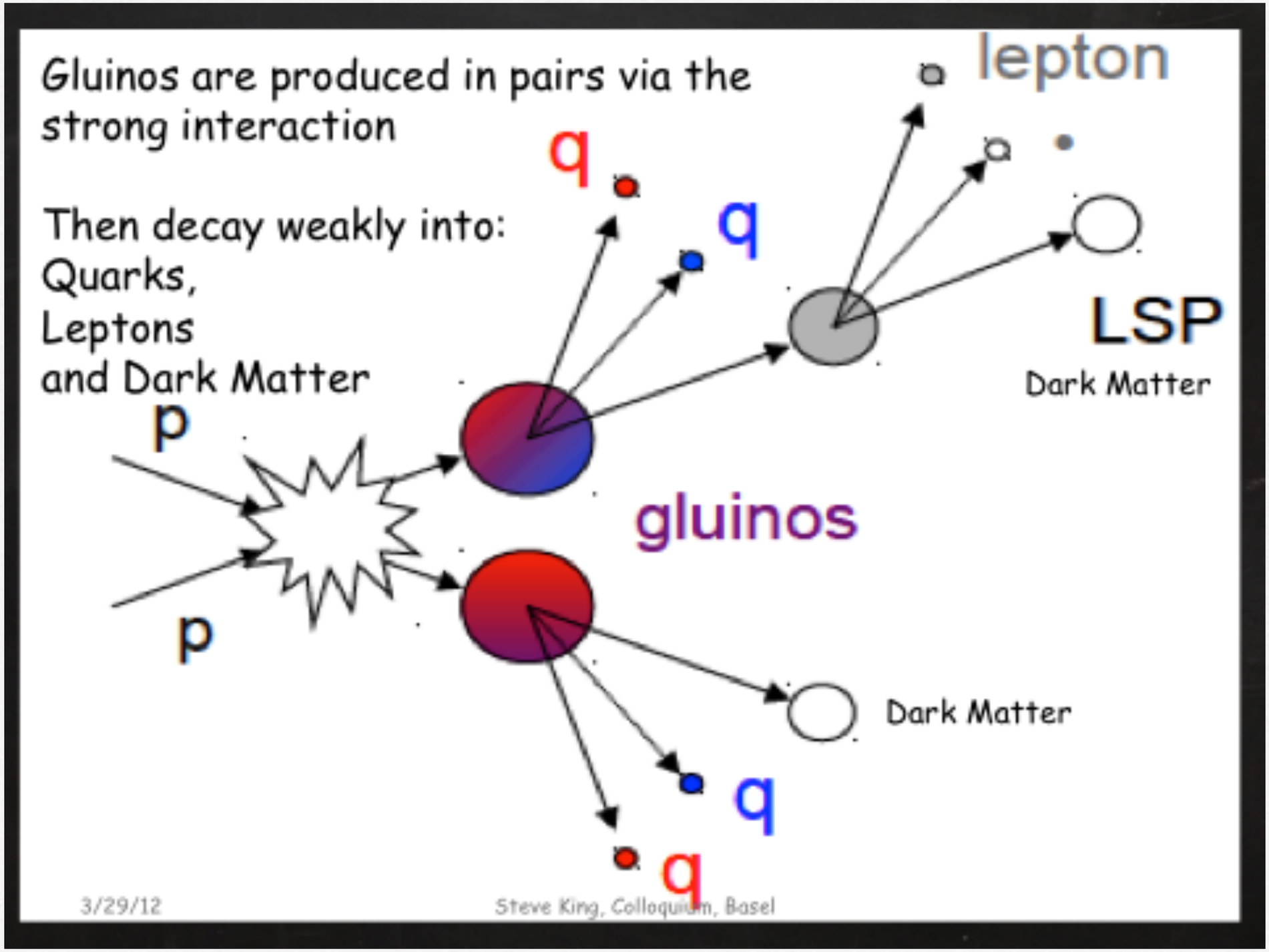




Leptogenesis

- We have shown that in flavour models with form dominance leptogenesis is exactly zero at leading order due to form dominance, but may be switched on by HO or RG corrections
- We are amongst the first to study flavour dependent thermal Leptogenesis which is dominated by the second right-handed neutrino N2
- For example, the two right-handed neutrino model has regions where N2 dominates, corresponding to sequential dominance
- In SO(10) inspired models we showed that N2 domination plays crucial role
- For non-zero initial abundance, under certain conditions we showed that the washout may be particularly ineffective: phantom leptogenesis
- We showed that the density matrix is useful formalism for describing such effects
- In SUSY leptogenesis, the reheating temperature may be lowered by such effects

Dark Matter at Colliders



Dark Matter at Colliders

- We have studied usual CMSSM paradigm
- As well as MSSM with non-universal Higgs, third family sparticles and non-universal gauginos
- We studied USSM with an extra gauged U(1)'
- We studied the E6SSM where Wimp may be either a Bino (as in MSSM) or a new inert singlino/Higgsino combination
- We showed that if WIMP is an inert singlino/Higgsino then the Higgs may decay into it (bad)
- But the gluino may also decay into inert singlino/Higgsino (good) giving distinctive signatures in gluino decay (longer cascade decay chains, more leptons, less missing energy)

Conclusion

- Southampton has interest in three invisibles areas: Neutrinos and Flavour Models, Leptogenesis, Dark Matter at Colliders

- Southampton is part of the UK NExT Collaboration

- Experiment-Theory Collaboration
- We provide a full program of PhD training lectures

"Invisibles" are welcome!