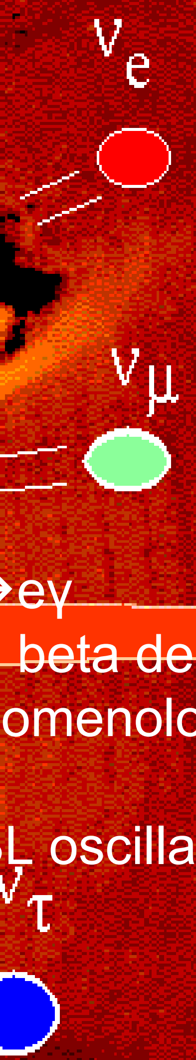
Neutrino Theory



1105-1130 **“Neutrino Theory” 20’ + 5’ discussion**

- Should include general broad overview for non-experts
- Topic to be addressed include:

o Neutrino physics and BSM at the TeV and GUT scale
o Connection with leptogenesis
o Relation to LFV processes such as $\mu \rightarrow e$ conversion and $\mu \rightarrow e\gamma$
o lepton flavour physics, θ_{13}, CP violation, neutrino-less double beta decay
o What are the important measurements and what are the phenomenological issues
(set the scene for the following experimental talks on reactor/LBL oscillation experiments/neutrinoless double beta decay/neutrino factory).
o target for 20 years

Executive Summary (now since I ***will*** run out of time)

- Neutrino physics has surprised us all
- We have witnessed a revolution in the past decade
- 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
- Play an essential role in the Universe $n_\nu \sim n_\gamma \gg n_e$
- Tiny neutrino mass indicates New Physics BSM

Impact on particle physics and cosmology

- Origin of tiny neutrino mass
  Extra dimensions, See-saw mechanism, SUSY
- Unification of matter, forces and flavour
  GUTs, Family Symmetry, Strings,…

Particle Physics

- Did neutrinos play a role in our existence?
  Leptogenesis
- Did neutrinos play a role in forming galaxies?
  Hot/Warm Dark matter component → limits
- Did neutrinos play a role in birth of the universe?
  Sneutrino inflation
- Can neutrinos shed light on dark energy? $\Lambda \sim m_\nu^4$

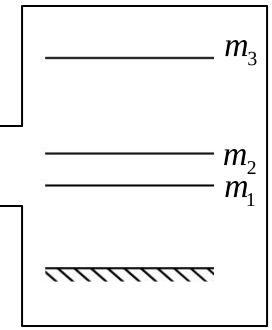
Cosmology

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

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

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\beta_1/2} & 0 & 0 \\ 0 & e^{i\beta_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

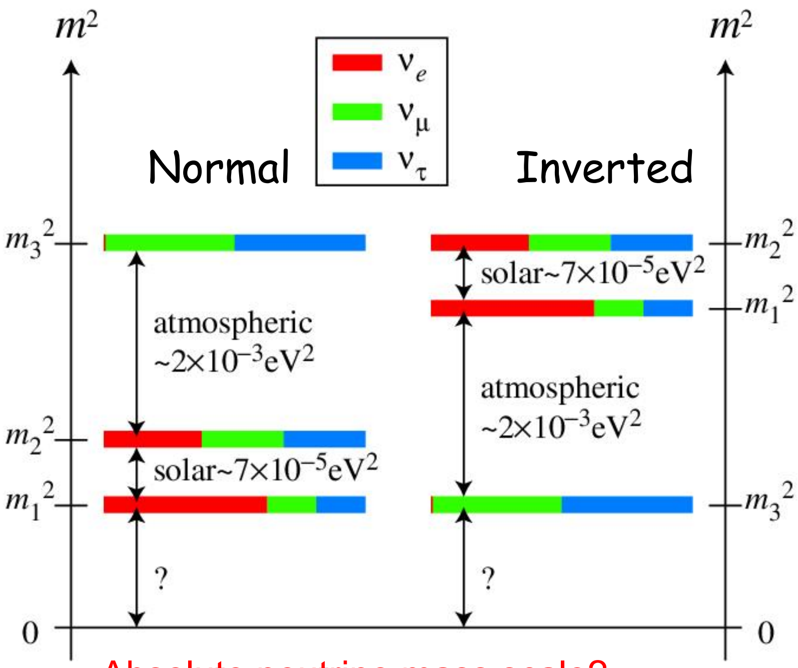
Atmospheric | Reactor | Solar | Majorana

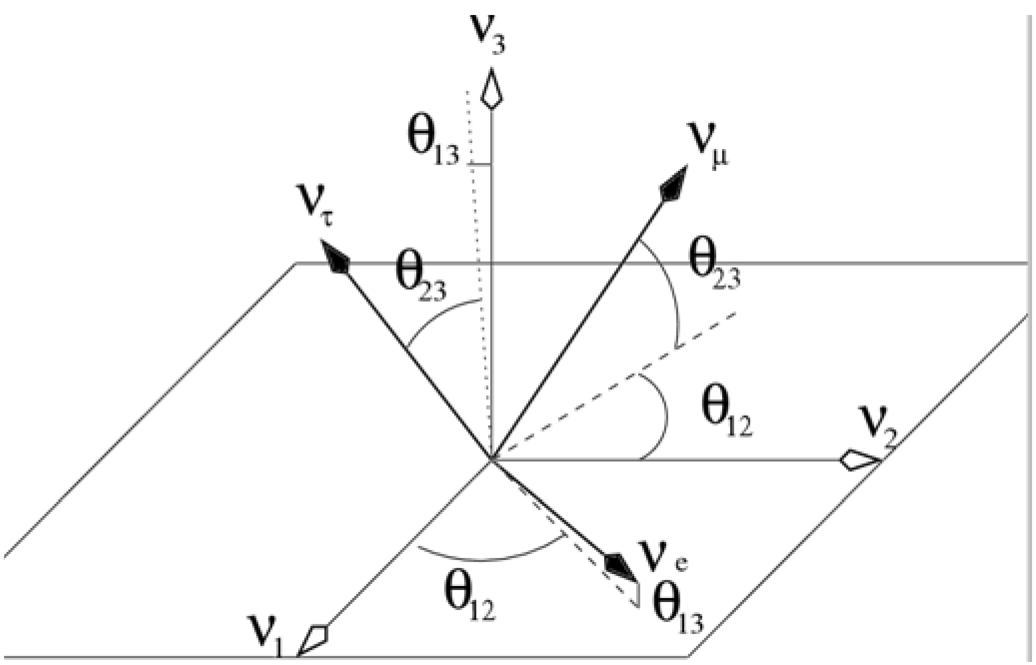
$s_{ij} = \sin\theta_{ij}$
$c_{ij} = \cos\theta_{ij}$

Oscillation phase δ
Majorana phases β_1, β_2

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

Neutrino mass squared splittings and angles

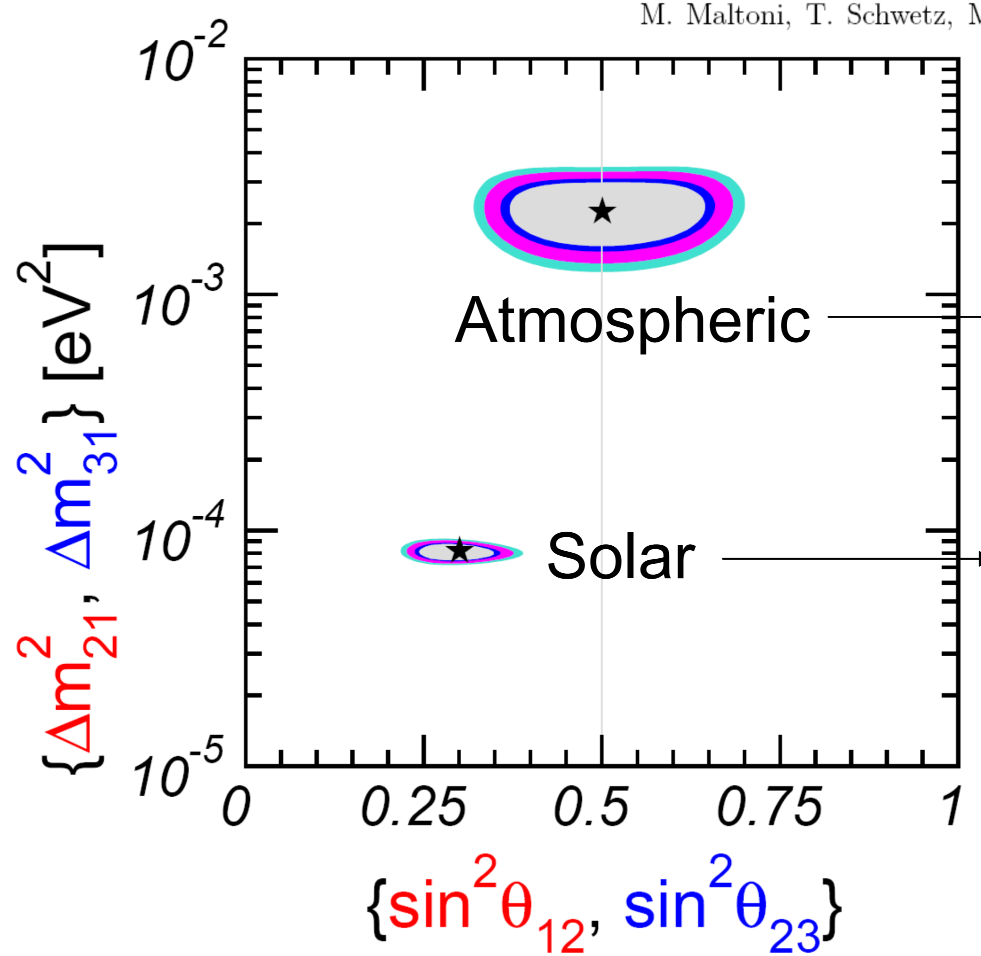




Absolute neutrino mass scale?

Global Fit to Atmospheric and Solar Data

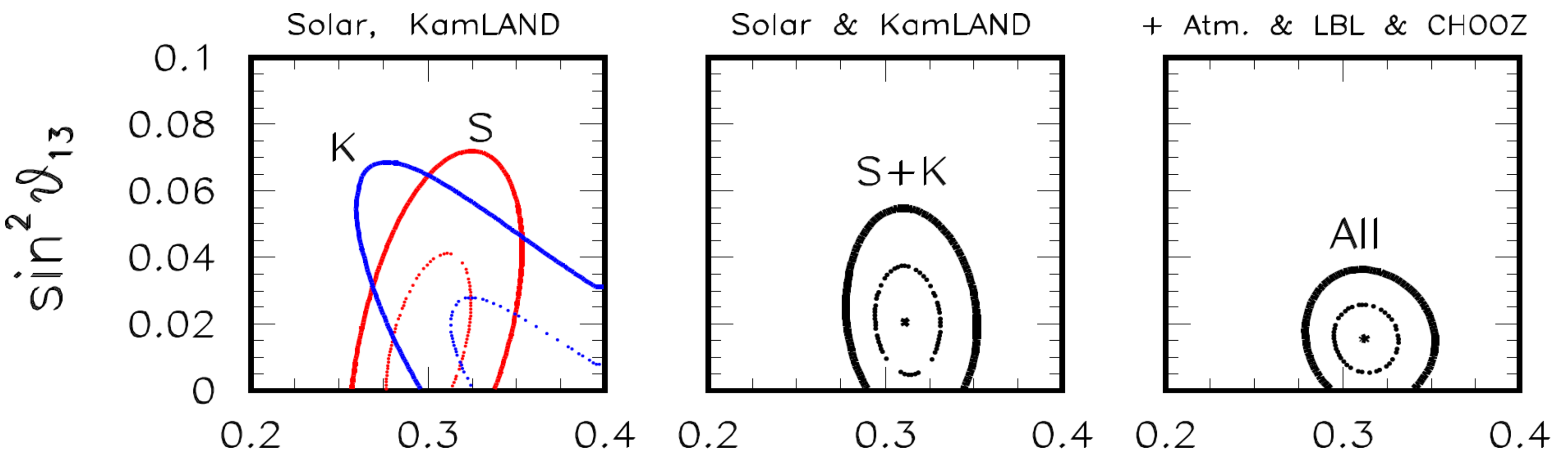
M. Maltoni, T. Schwetz, M. A. Tortola and J. W. F. Valle,



$\theta_{23} = 43.1^{o}{}^{+4.4^o}_{-3.5^o}$

$\theta_{12} = 34.5^o \pm 1.4^o$

There is a 2σ hint for θ_{13} being non-zero



$$\sin^2\theta_{13} = 0.016 \pm 0.010$$ Fogli et al '08

$$\sin^2\theta_{13} = 0.02 \pm 0.01$$ Fogli et al '09

The 2009 estimate includes the MINOS results which show a 1.5σ excess of events in the electron appearance channel

Tri-bimaximal (TB) mixing

Harrison, Perkins, Scott

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

TB angles $\theta_{12} = 35^\circ,\quad \theta_{23} = 45^\circ,\quad \theta_{13} = 0^\circ.$

c.f. data $\theta_{12} = 34.5^\circ \pm 1.4^\circ, \theta_{23} = 43.1^\circ \pm 4^o,\ \theta_{13} = 8^\circ \pm 2^o$

Current data is consistent with TB mixing
(ignoring the 2σ hint for θ_{13})

Useful to parametrize the PMNS mixing matrix in terms of deviations from TBM

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

SFK '07

$$0.14 < r < 0.24, \ -0.05 < s < 0.02, \ -0.04 < a < 0.10$$

r = reactor | s = solar | a = atmospheric

e.g. **r≠ 0, s=0, a=0** gives Tri-bimaximal-reactor (TBR) mixing

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

SFK '09

TBR not as simple as TB but is required if $\theta_{13} \neq 0$

Oscillation formulae in terms of r,s,a,δ

$$\boxed{P_{\alpha\beta} = P(\nu_\alpha \to \nu_\beta)} \qquad \boxed{\Delta_{ij} = 1.27\Delta m^2_{ij} L/E}$$

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

See talks by E.Falk, D.Wark

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

For formulae including matter effects see SFK **arXiv:0710.0530**

Important measurements (experiments)

2009

Time (provocative)

#1. Count the number of neutrinos (MiniBoone)

#2. Measure the neutrino mass scale m_1 ($0\beta\beta$)

#3. Determine the nature of neutrino mass ($0\beta\beta$)

#4. Determine the sign of the mass ordering (LBL)

mass

#5. Measure θ_{13} (Reactor, LBL)

#6. Measure deviation of θ_{23} from bimaximal (LBL)

#7. Measure deviation of θ_{12} from trimaximal (Reactor)

mixing

#8. Measure δ (LBL)

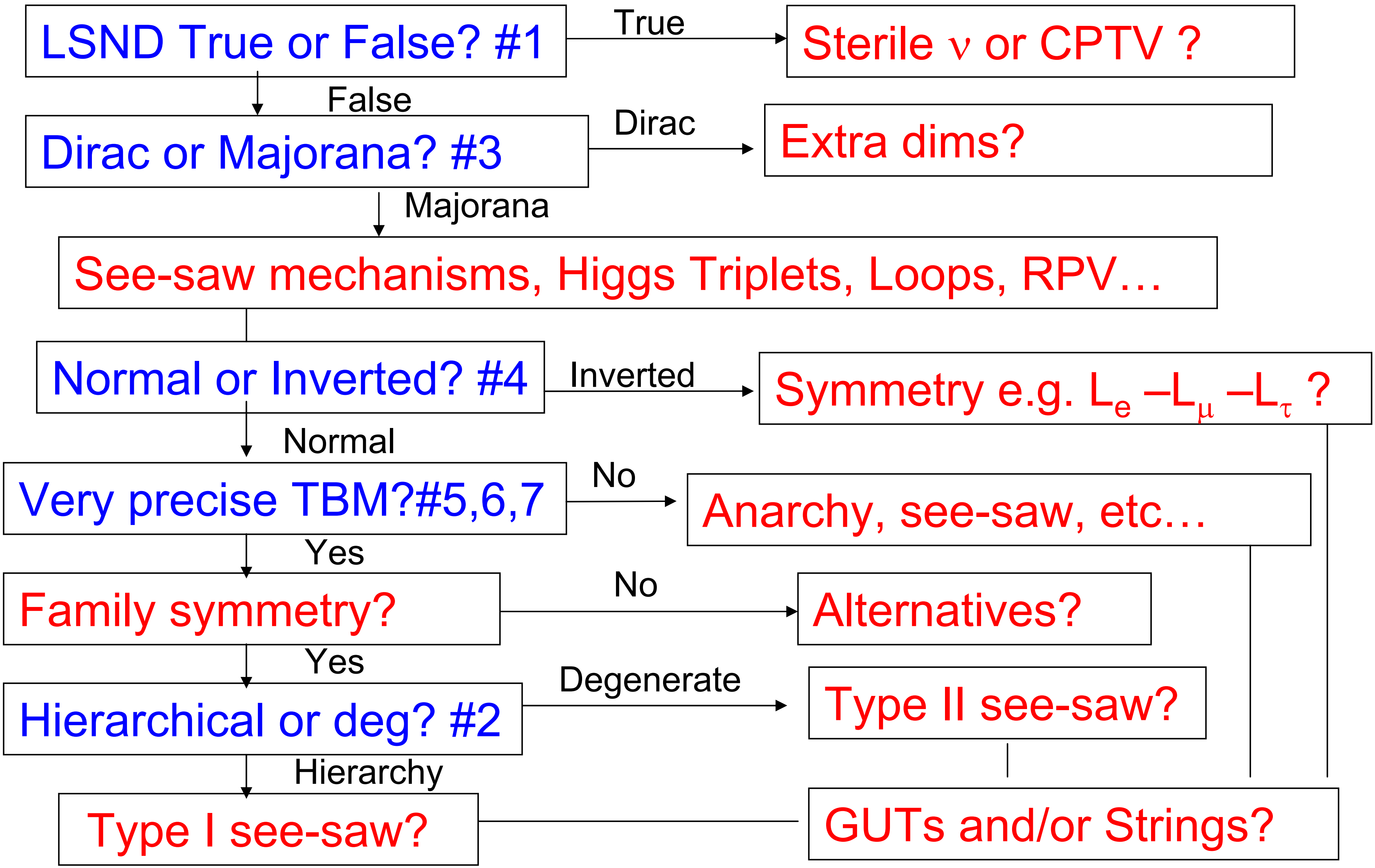
#9. Measure β_2 ($0\beta\beta$)

#10. Measure β_1 ($0\beta\beta$)

CP violation

2029

Implications of mass/mixing measurements



Dirac or Majorana? #3

Majorana masses

CP conjugate

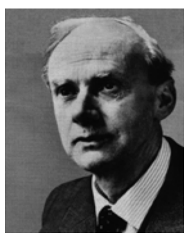
$$\boxed{m_{LL}\overline{\nu}_L \nu_L^c}$$

$$\boxed{M_{RR}\overline{\nu}_R \nu_R^c}$$

Violates L

Violates L_e, L_μ, L_τ

Neutrino=antineutrino



$$\boxed{m_{LR}\overline{\nu}_L \nu_R}$$

Conserves L

Violates L_e, L_μ, L_τ

Neutrino $\neq$ antineutrino

Dirac mass

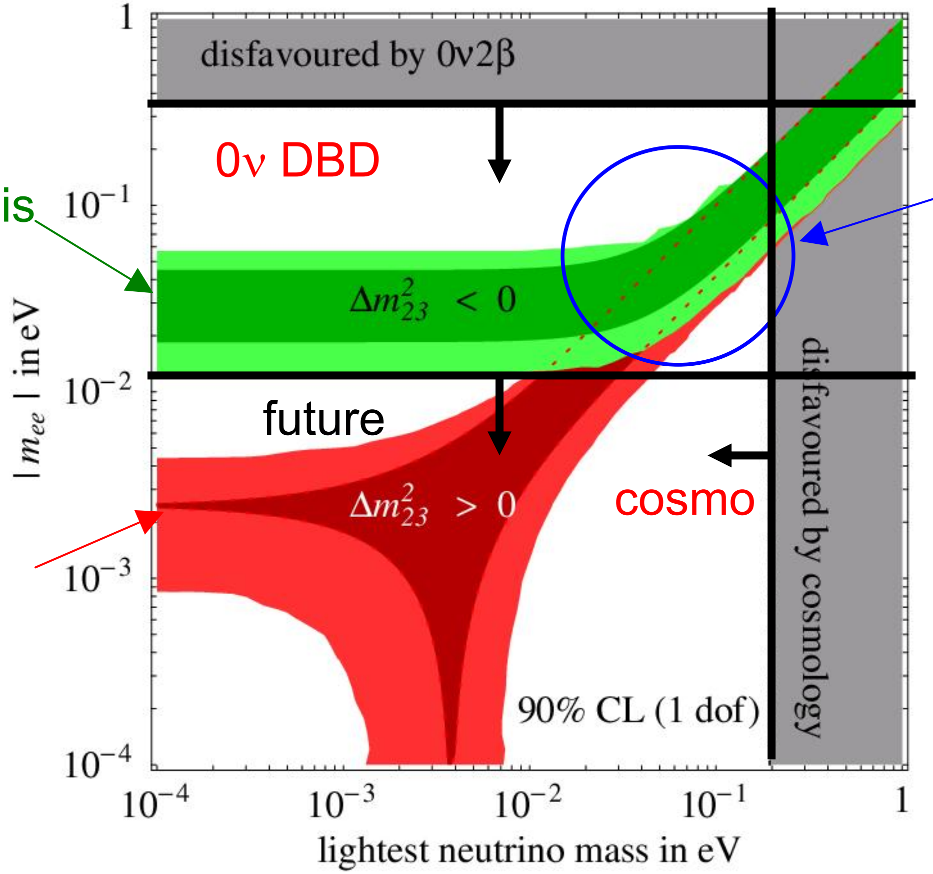
0νββ experiments will decide

See talk by Y. Ramachers

Cosmology and 0νββ experiments are complementary

Inverted hierarchy is TESTABLE

Normal hierarchy is NOT TESTABLE

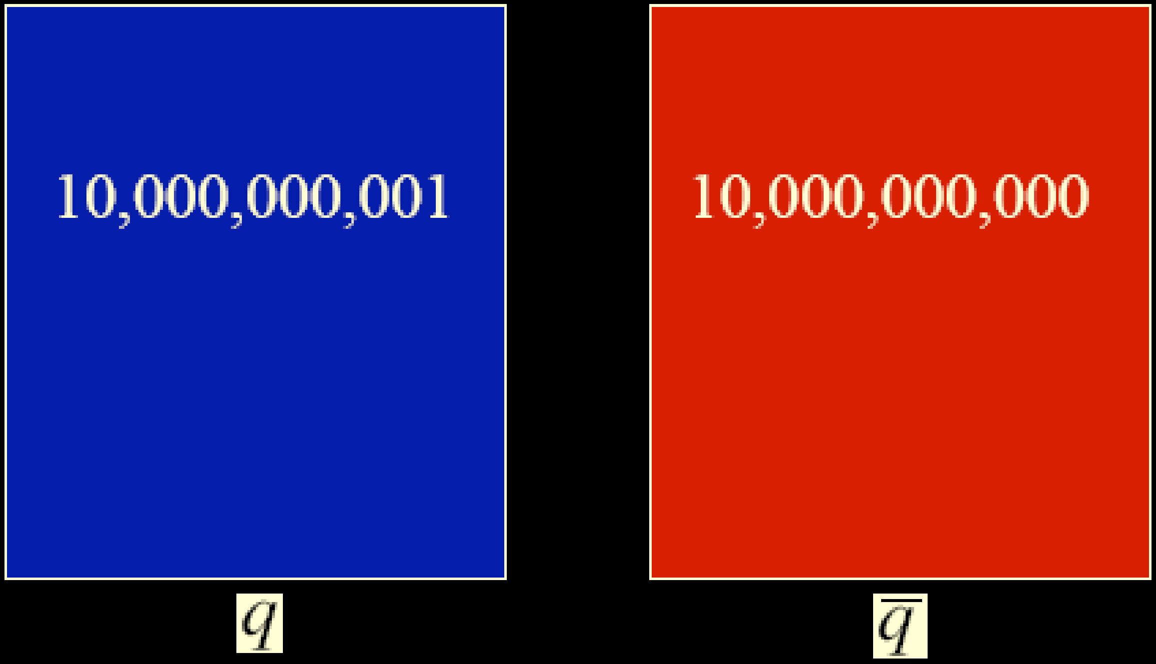


Approx. degeneracy is TESTABLE

Feruglio, Strumia, Vissani, Pascoli, Petcov

How did we survive the great annihilation?

Want to understand $\eta = \dfrac{n_b - n_{\bar{b}}}{n_\gamma} = \left(6.1 \pm 0.2\right) \times 10^{-10}$



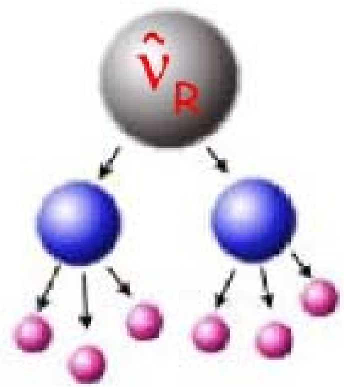
Murayama

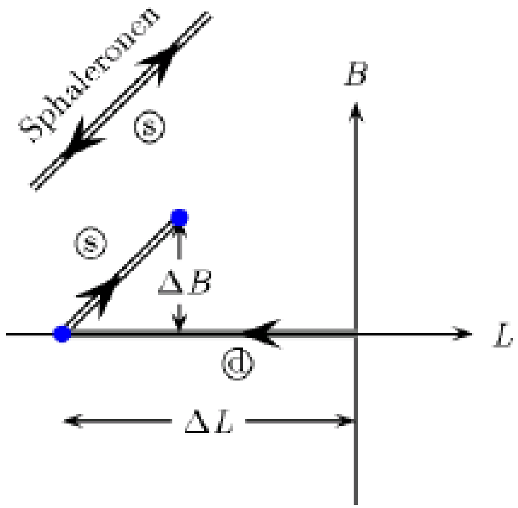
The Great Annihilation

Leptogenesis

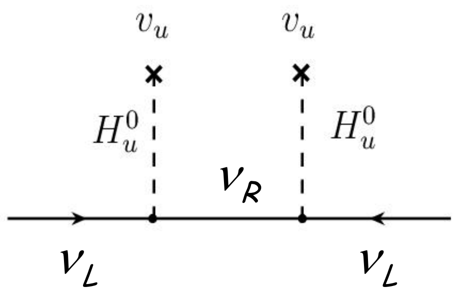
Fukugita,Yanagida

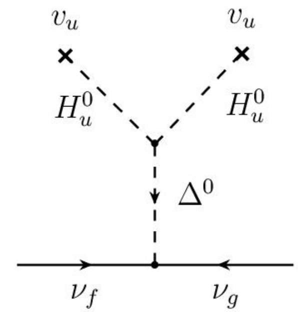
- Right-handed neutrinos are produced in early universe and decay out of equilibrium giving net lepton numbers L_e , L_μ , L_τ
- CP violation from complex Yukawa couplings
- Out of equilibrium Boltzmann eqs lead to L_e , L_μ , L_τ partial washouts
- Surviving L_e, L_μ , L_τ are processed into B via B-L conserving sphalerons





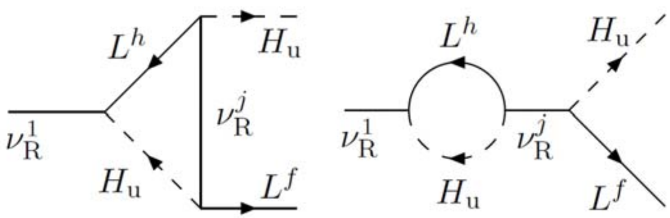
Can leptogenesis be linked to the 3 PMNS phases?

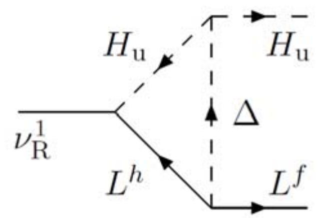




Covi,Roulet,Vissani **Type I** **Type II** Antusch,SFK

Leptogenesis diagrams



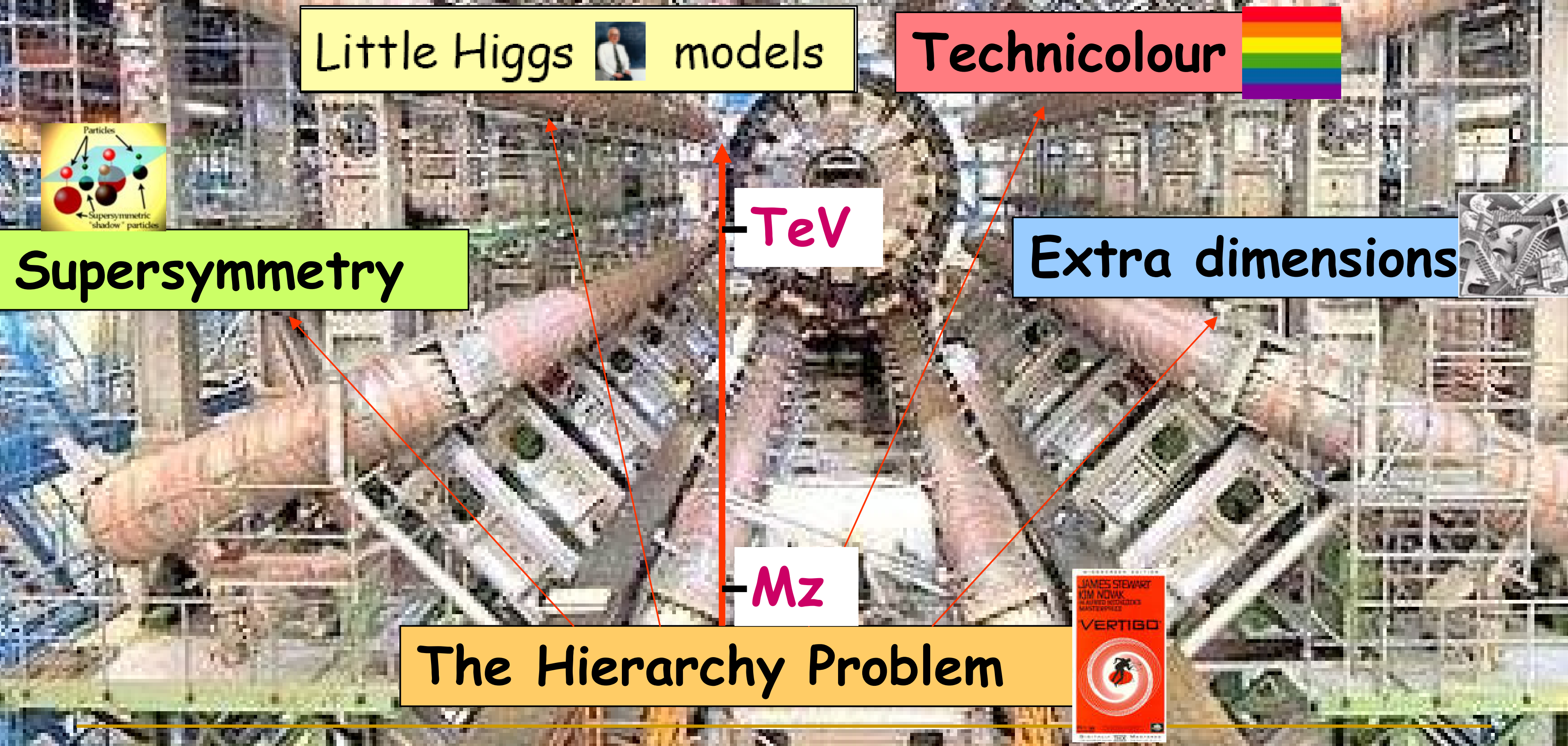


Clearly no link in general since 3x3 Yukawa matrix involves 9→6 phases

However in particular models the number of Yukawa phases may be reduced e.g. sequential dominance decouples a RH neutrino→ 3 phases, and a texture zero removes another→ 2 phases, then can show $|\phi_{\mathrm{COSMO}}| = |\phi_{\beta\beta0\nu}|$ SFK

Other interesting examples in flavour dependent LG: Antusch, SFK, Riotto; Pascoli, Petcov, Riotto

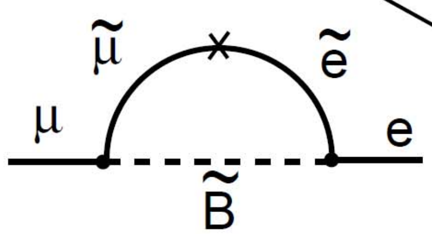
New Physics at the TeV Scale



If SUSY is found then LFV and EDMs are inevitable

The only question is the origin of the slepton mass matrix

$\mu \to e$

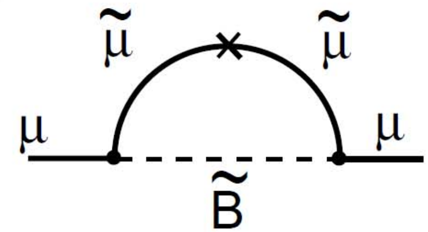


Slepton mass matrix

$$\begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

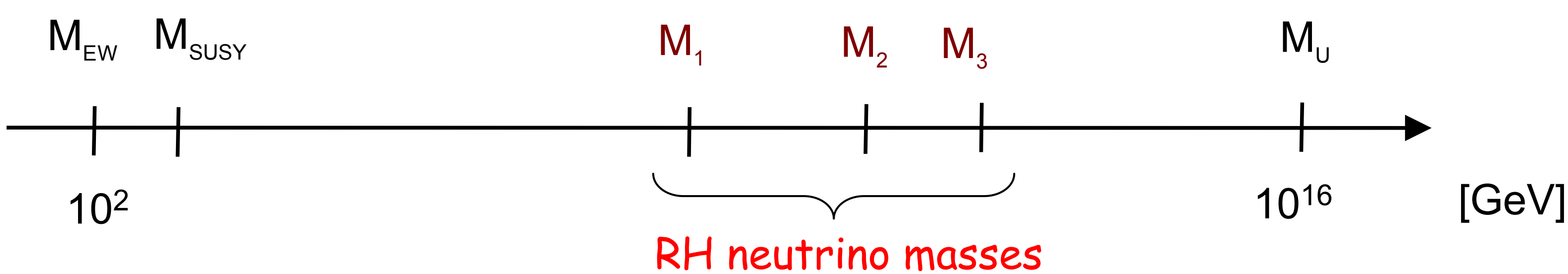
MDM

EDM



mSUGRA prediction at M_U

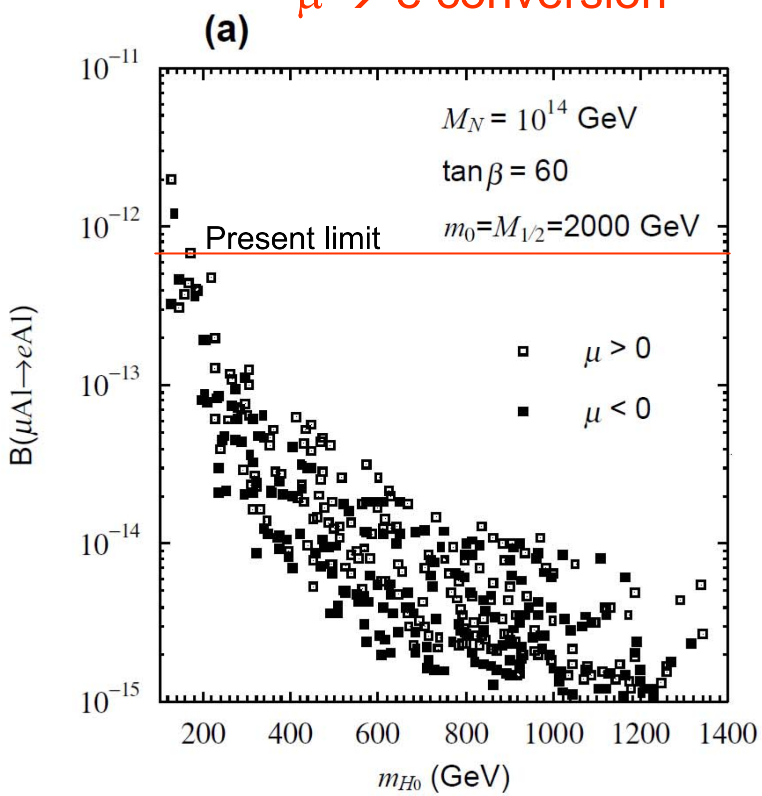
$$m^2_{\tilde{L}_{ij}} = m_0^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \Delta m^2_{\tilde{L}_{ij}} \xleftarrow{\text{RG running}} m^2_{\tilde{L}_{ij}} = m_0^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



Lepton Flavour Violation in mSUGRA

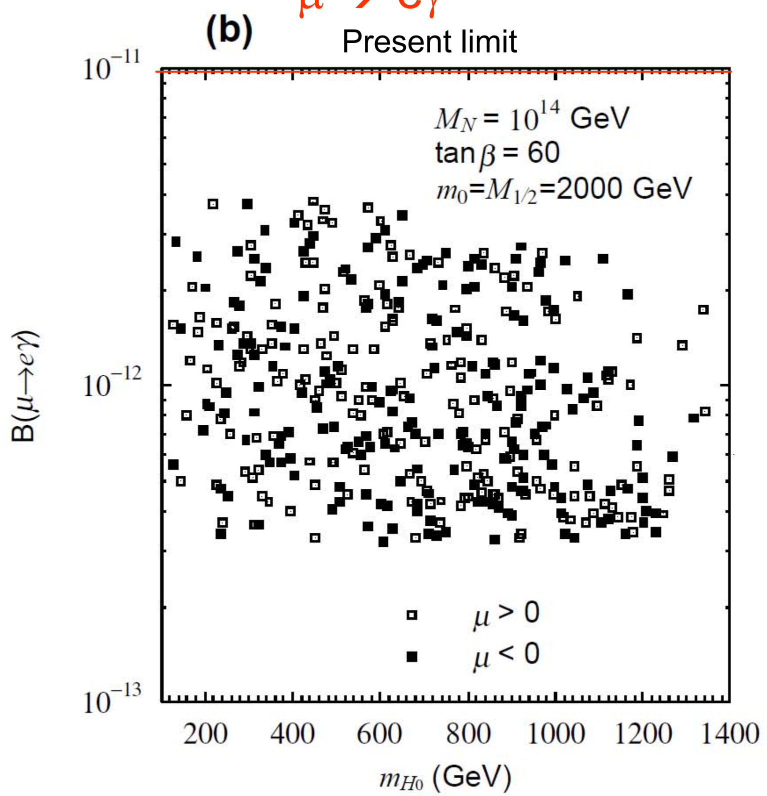
Typically $\frac{\sigma(\mu^- Ti \to e^- Ti)}{\sigma(\mu^- Ti \to capture)} \sim 4 \times 10^{-3} B(\mu \to e\gamma)$ but enhanced for large tan β

μ → e conversion



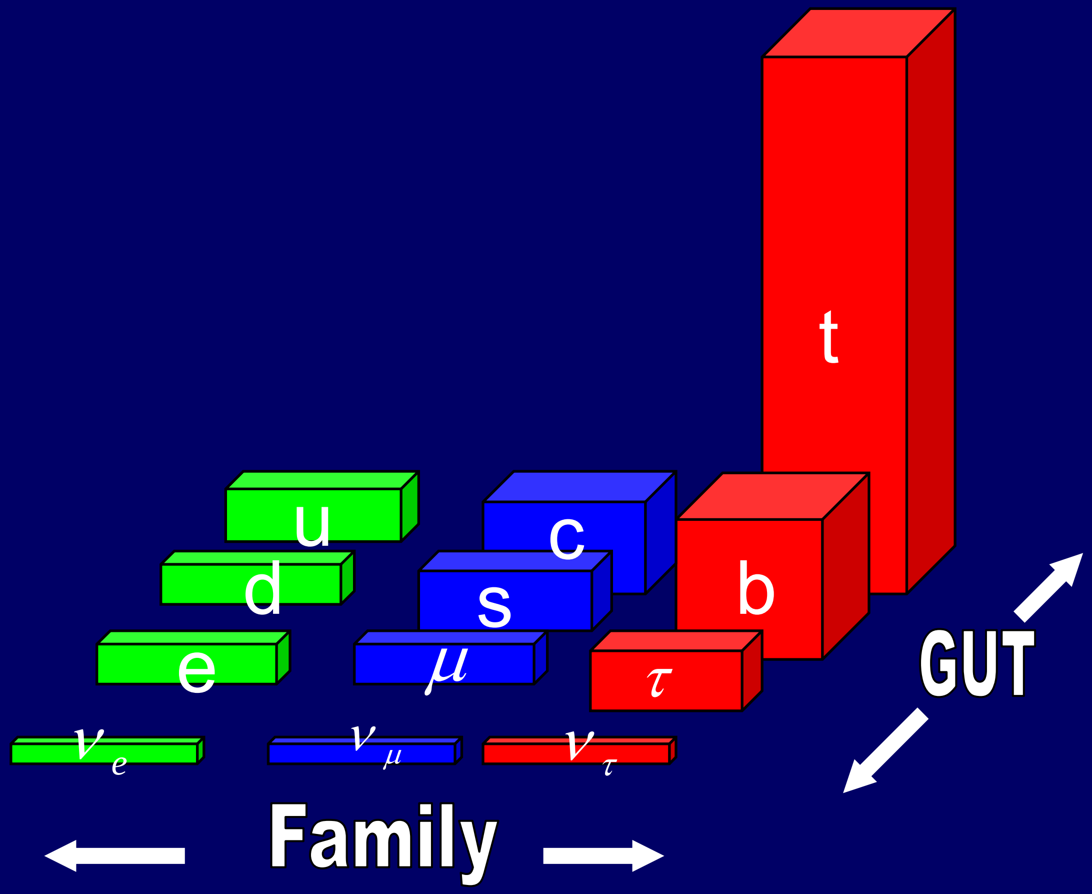
COMET/PRISM can improve the limits by $10^4/10^6$

μ → eγ



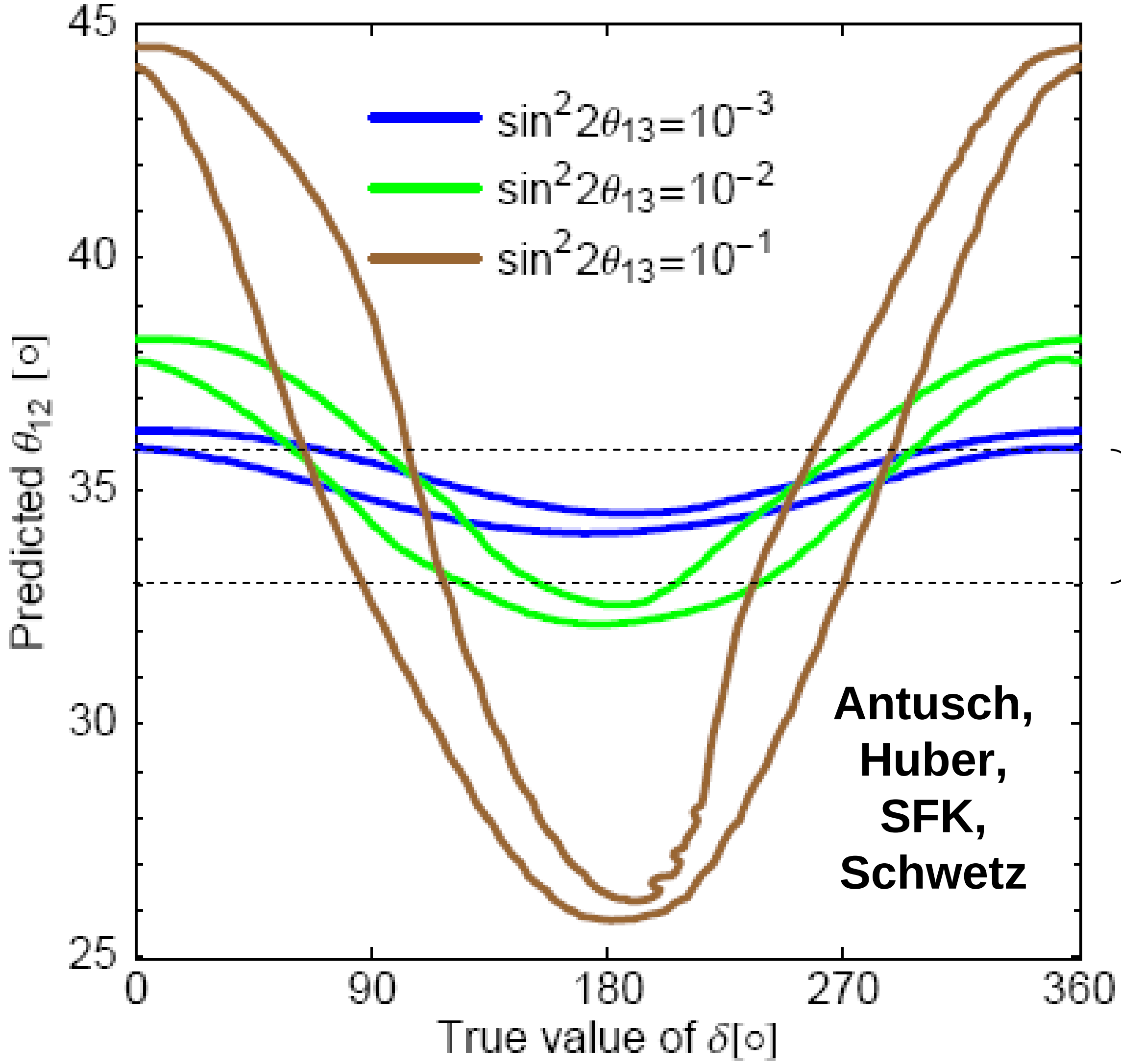
MEG can improve the limits by 10^2

New Physics at the GUT scale



Tri-bimaximal mixing suggests a family symmetry (c.f. quark colour)

GUT x Family symmetry→ $\theta_{12} \approx 35.3^o + \theta_{13}\cos\delta$



Sum Rule

Bands show 3σ error for optimized neutrino factory determination of $\theta_{13}\cos\delta$

$\theta_{12}=34.5^o \pm 1.4^o$

(current value)