# Exceptional Supersymmetric Standard Model

- Singlet SUSY models
- $E_6$SSM and TeV spectrum
- Unification
- Solving the flavour problem
- Constrained $E_6$SSM
- Dark matter from inert higgsinos/neutralinos
- Leptogenesis



UNIVERSITY OF Southampton
School of Physics and Astronomy

# Singlet SUSY Models

To solve the $\mu$ problem of the MSSM and reduce fine tuning led to consider: $W = \lambda S H_u H_d$ where singlet $\langle S \rangle \sim \mu$

But leads to weak scale axion due to global U(1) PQ symmetry

Need to remove axion somehow

In NMSSM we add $S^3$ to break U(1) PQ to $Z_3$

In USSM we gauge the U(1) PQ symmetry to eat the axion resulting in a massive Z' gauge boson – but not anomaly free

In $E_6$SSM the anomalies of the USSM are cancelled by three complete 27's of $E_6$ at the TeV scale with U(1) PQ $\in E_6$

# $E_6$SSM top-down

SFK, Moretti, Nevzorov

$$E_6 \to SO(10) \times U(1)_\psi \qquad SO(10) \to SU(5) \times U(1)_\chi$$

$E_6$ broken via SU(5) chain

Right handed neutrinos are neutral under: $U(1)_N = \frac{\sqrt{15}}{4} U(1)_\psi + \frac{1}{4} U(1)_\chi \longrightarrow Z'(N)$

$M_{GUT}$ — $E_6 \to SU(5)\times U(1)_N \to SM \times U(1)_N$

$$27_i \to (10,1)_i + (5^*,2)_i + (5^*,-3)_i + (5,-2)_i + (1,5)_i + (1,0)_i \qquad 27', \overline{27}'$$

- Quarks, leptons
- Triplets and Higgs
- Singlets and RHν s
- L',L'-bar ← Play role in unification and leptogenesis

RH ν masses: $M_3$, $M_2$, $M_1$

TeV — $U(1)_N$ broken, Z'(N) & triplets get mass, μ term generated

$M_W$ — $SU(2)_L \times U(1)_Y$ broken

# Matter content of $E_6$SSM at TeV

$$27_i \rightarrow 3\left[(Q_i,\, u_i^c,\, d_i^c,\, L_i,\, e_i^c)\right] + 3(D_i,\, \overline{D}_i) + 3(H_{2i}) + 3(H_{1i}) + 3(S_i) + 3(N_i^c)$$

Quarks and Leptons

D,D-bar fermions

Three families of Higgs
= one active family
+ 2 inert families (no VEV)

Singlets

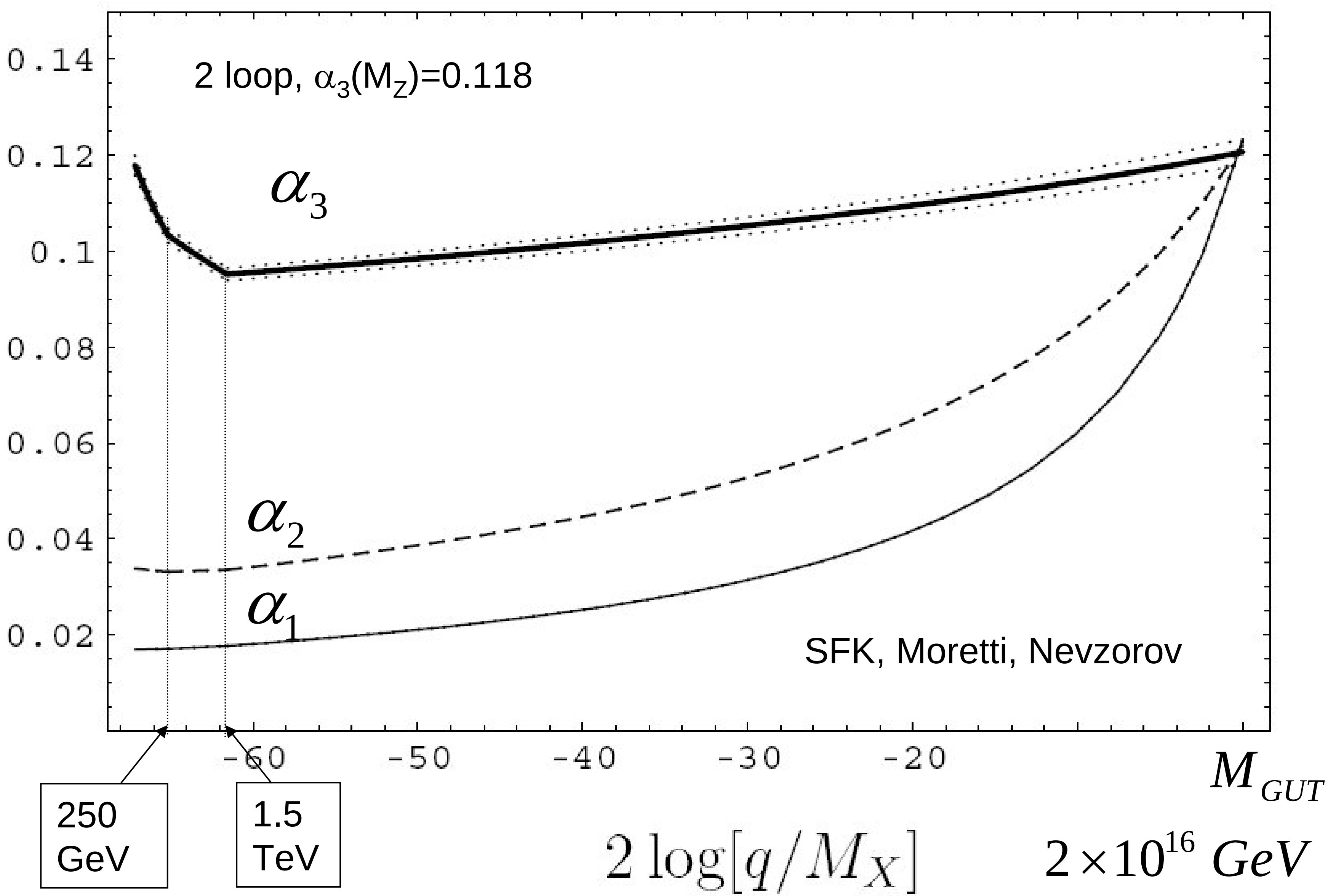
Right-handed neutrinos
(heavier than TeV)

Plus a TeV scale Z'(N)

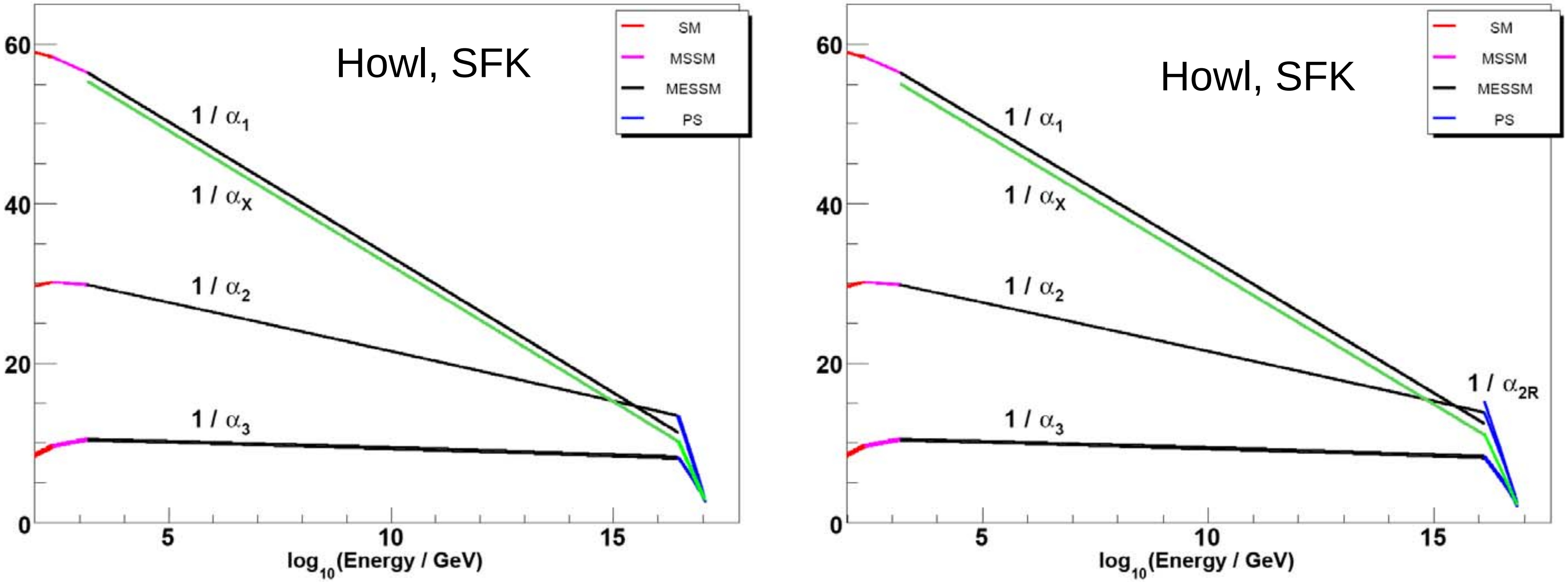
Plus all their SUSY superpartners

Message: $E_6$SSM predicts SUSY+ 3(5+5*+1) + Z' at LHC

# Unification in $E_6$SSM with L'



# Unification in $E_6$SSM without L'




Low energy (below $M_{GUT}$)
three complete families of 27's of $E_6$

High energy (above $M_{GUT} \sim 10^{16}$ GeV) this is embedded into a Pati-Salam model and additional heavy Higgs are added.

# Solving the flavour problem in the $E_6$SSM

1) Usual flavour problem of SM: why three families with the observed fermion (including neutrino) masses and mixings?

2) Additional flavour problem of MSSM: why are FCNCs and CP violating processes (esp. EDMs) so small?

3) Further problem of $E_6$SSM: why do three families of Higgs give small FCNCs?

In MSSM 1),2) solved by $\Delta_{27}$ Varzielas, SFK, Ross; Antusch, Malinsky et al

In $E_6$SSM also 3) solved by $\Delta_{27}$ SFK, Howl

e.g. matter in (3,27) of $\Delta_{27}$ x $E_6$
→ TB mixing, 2 degenerate LSPs, 2 degenerate D-fermions

Resulting model resembles constrained $E_6$SSM

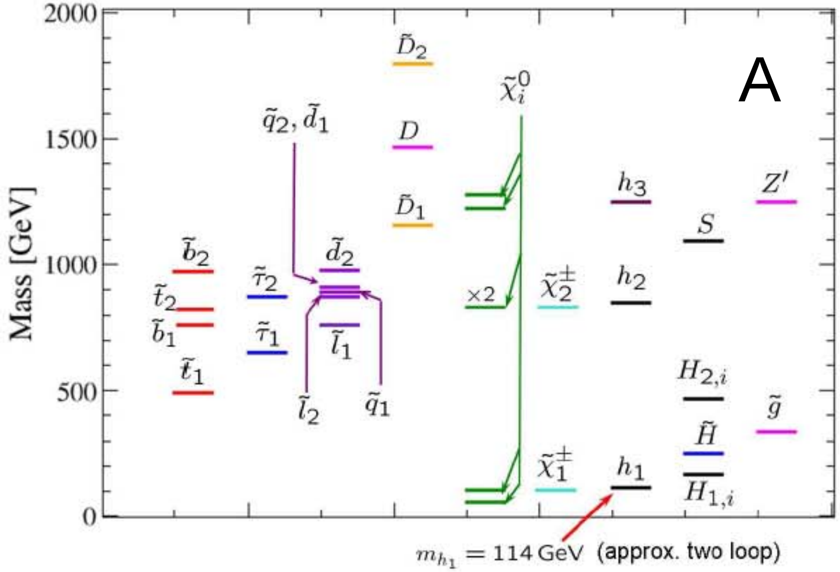
Athron, SFK, Miller, Moretti, Nevzorov

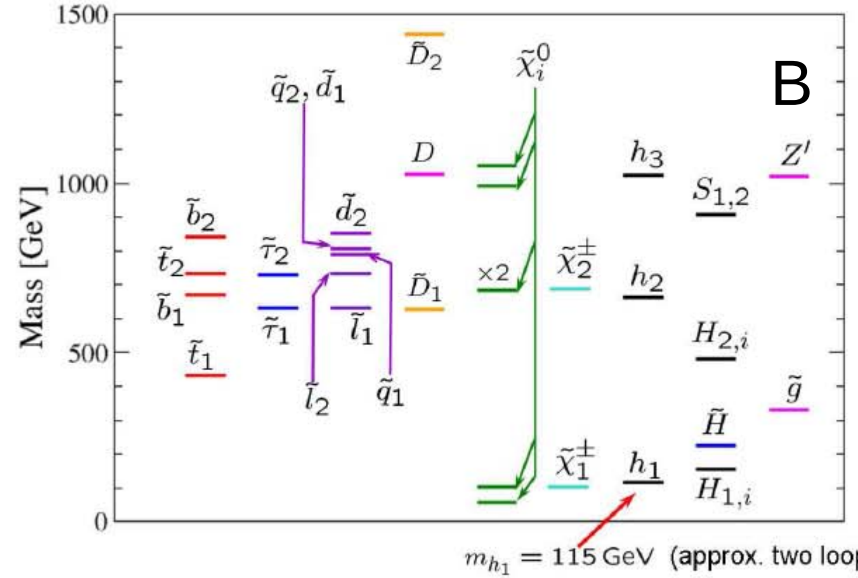
# The Constrained $E_6$SSM

$$W \approx \lambda_i S H_{u,i} H_{d,i} + \kappa_i S D_i \bar{D}_i$$

EWSB, LEP, 2-loop RGE

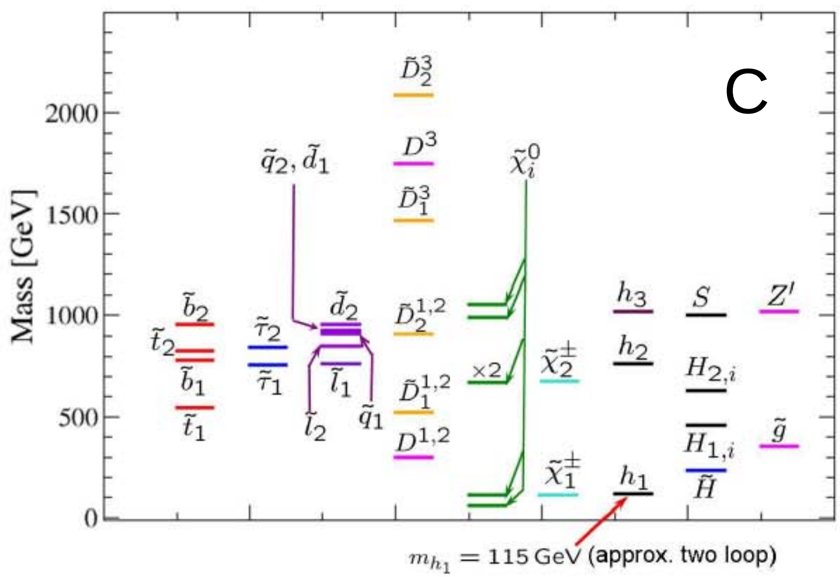
| Low Mass Benchmark Points | A | B | C | D |
|---|---|---|---|---|
| $\tan\beta$ | 3 | 10 | 10 | 10 |
| $\lambda_3(M_X)$ | -0.465 | -0.37 | -0.378 | -0.395 |
| $\lambda_{1,2}(M_X)$ | 0.1 | 0.1 | 0.1 | 0.1 |
| $\kappa_3(M_X)$ | 0.3 | 0.2 | 0.42 | 0.43 |
| $\kappa_{1,2}(M_X)$ | 0.3 | 0.2 | 0.06 | 0.08 |
| $s$[TeV] | 3.3 | 2.7 | 2.7 | 2.7 |
| $M_{1/2}$[GeV] | 365 | 363 | 388 | 358 |
| $m_0$ [GeV] | 640 | 537 | 681 | 623 |
| $A_0$[GeV] | 798 | 711 | 645 | 757 |

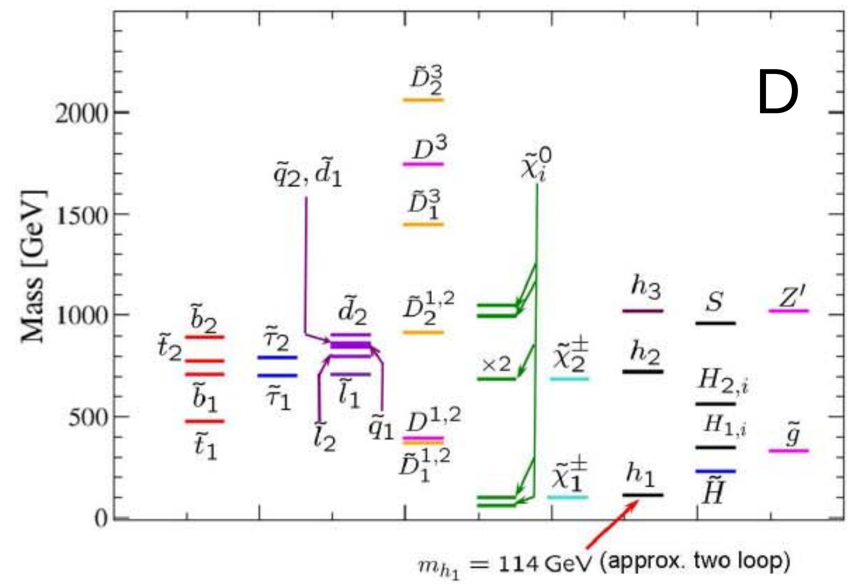



# $cE_6SSM$ Low Mass Benchmarks

Athron, SFK, Miller, Moretti, Nevzorov



SFK, Hall

# Dark Matter from Inert Higgsinos/singlinos

3 families of Higgs = 1 MSSM family $H_u$, $H_d$ + 2 inert families $H_{u1}$, $H_{d1}$, $H_{u2}$, $H_{d2}$

3 families of Singlets = 1 NMSSM singlet S + 2 inert singlets $S_1$, $S_2$

The full neutralino mass matrix

$$\tilde{\chi}^0_{\rm int} = \Big( \underbrace{\tilde{B} \quad \tilde{W}^3 \quad \tilde{H}^0_d \quad \tilde{H}^0_u}_{\text{MSSM}} \;\Big|\; \underbrace{\tilde{S} \quad \tilde{B}'}_{\text{USSM}} \;\Big|\; \underbrace{\tilde{H}^0_{d2} \quad \tilde{H}^0_{u2} \quad \tilde{S}_2}_{E_6\text{SSM}} \;\Big|\; \underbrace{\tilde{H}^0_{d1} \quad \tilde{H}^0_{u1} \quad \tilde{S}_1}_{E_6\text{SSM}} \Big)^{\rm T}$$

$$\begin{pmatrix} M^n_{\rm USSM} & B_2 & B_1 \\ B_2^{\rm T} & A_{22} & A_{21} \\ B_1^{\rm T} & A_{21}^{\rm T} & A_{11} \end{pmatrix}$$

Expect couplings of inert - active sector to be small ∼ 1% →

Expect almost decoupled inert sector→ good dark matter candidate

$\Delta_{27}$ predicts $A_{11}=A_{22}=0$

→ 2 degenerate LSPs

# Leptogenesis in the $E_6$SSM

SFK, Luo, Miller, Nevzorov

Right-handed neutrinos

$$W_N = h^N_{kxj}(H^u_k L_x)N^c_j + g^N_{kij} D_k d^c_i N^c_j + \frac{1}{2} M_{ij} N^c_i N^c_j$$

Three families of Higgs — Four families of Leptons — Three families of Leptoquarks

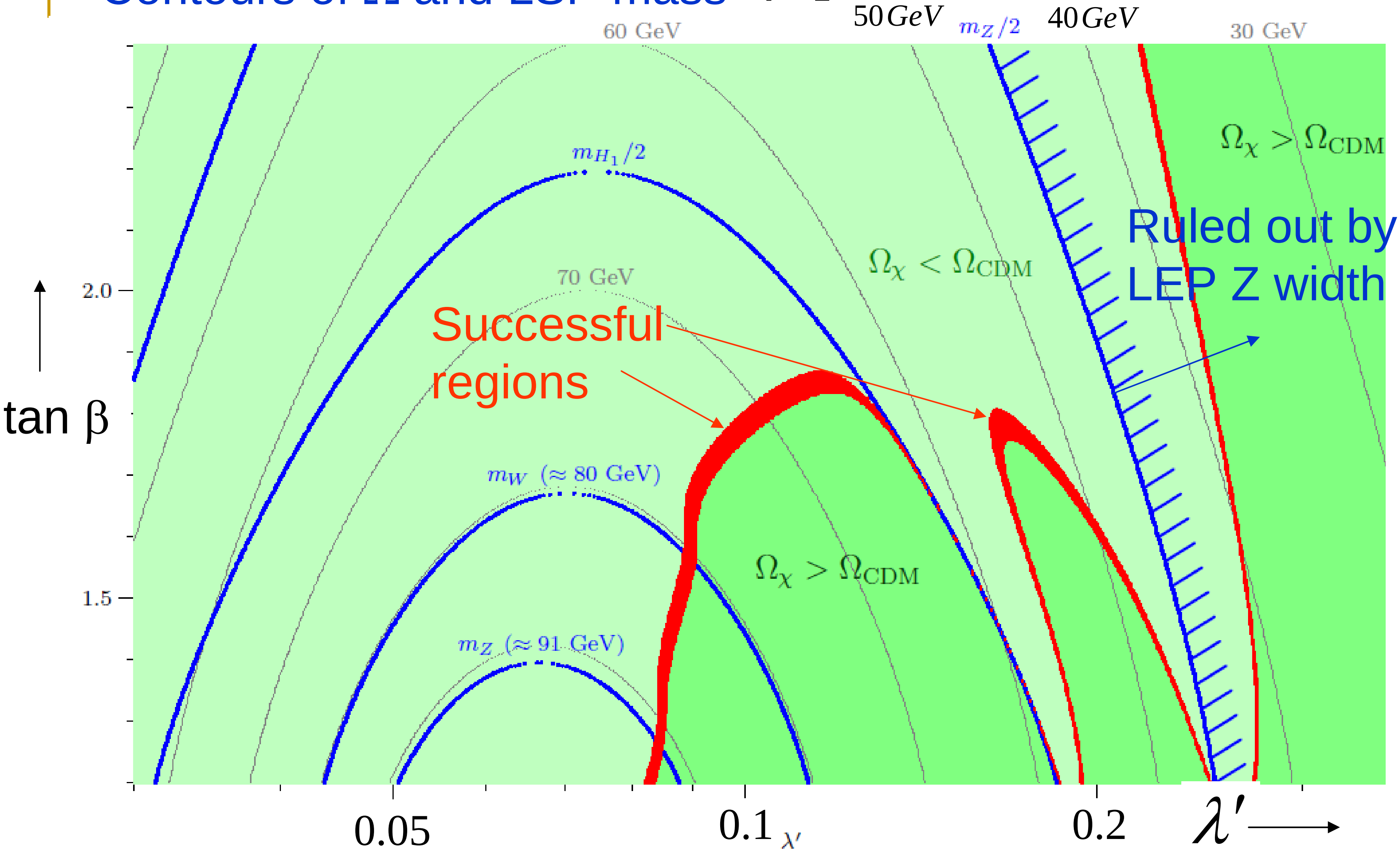
- $L_4$ is vector like $M_4 L_4 \overline{L}_4$ $M_4 \sim$ few TeV for GUT unification
- $L_4$ , $H^u_{1,2}$,$D_k$ contribute to leptogenesis but not neutrino mass
- Can get very large asymmetries, hence constraint $M_1 > 10^8$ GeV from leptogenesis is relaxed
- e.g. leptogenesis in $E_6$SSM allows e.g. $M_1 = 100$ TeV
→ no gravitino problem

# Conclusion

- **$E_6$SSM well motivated by FT and $\mu$ problems**
- **Predicts matter in three 27 families at TeV scale + Z'**
- **Unification is preserved**
- **Flavour problems solved by non-Abelian family symmetry → model resembles c$E_6$SSM**
- **c$E_6$SSM predicts rich phenomenology at LHC e.g. 2 degenerate D-fermions, Z', light gauginos**
- **Two degenerate LSPs from inert Higgsinos/singlinos provide novel WIMP candidates**
- **Leptogenesis significantly enhanced by extra states such as Higgs, L' leptons and D leptoquarks which allows light right-handed neutrinos e.g. 100 TeV**

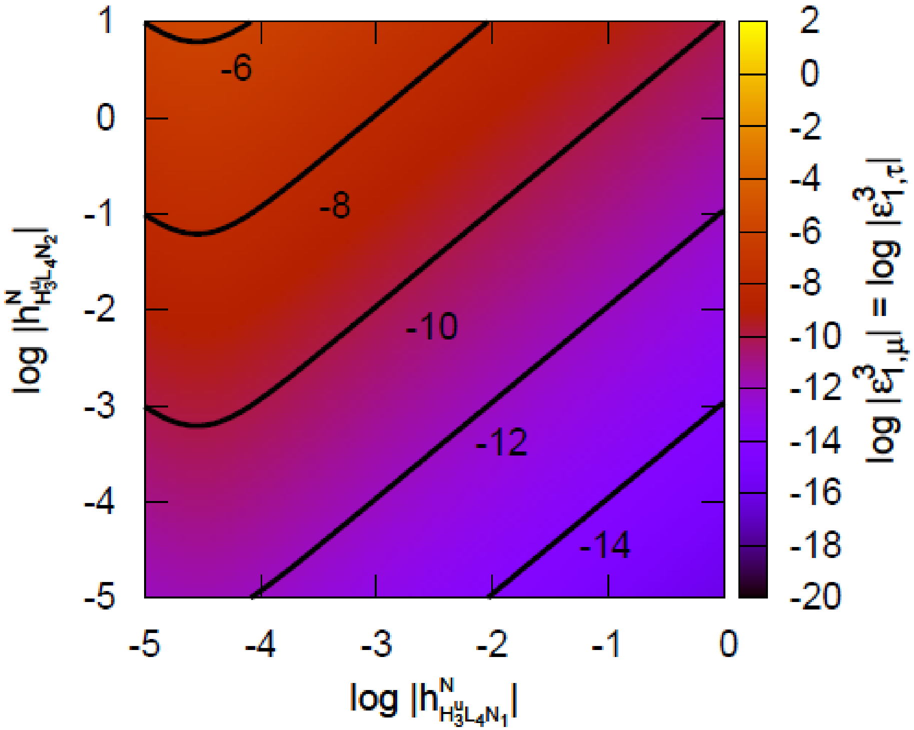
# Contours of Ω and LSP mass

SFK, Hall

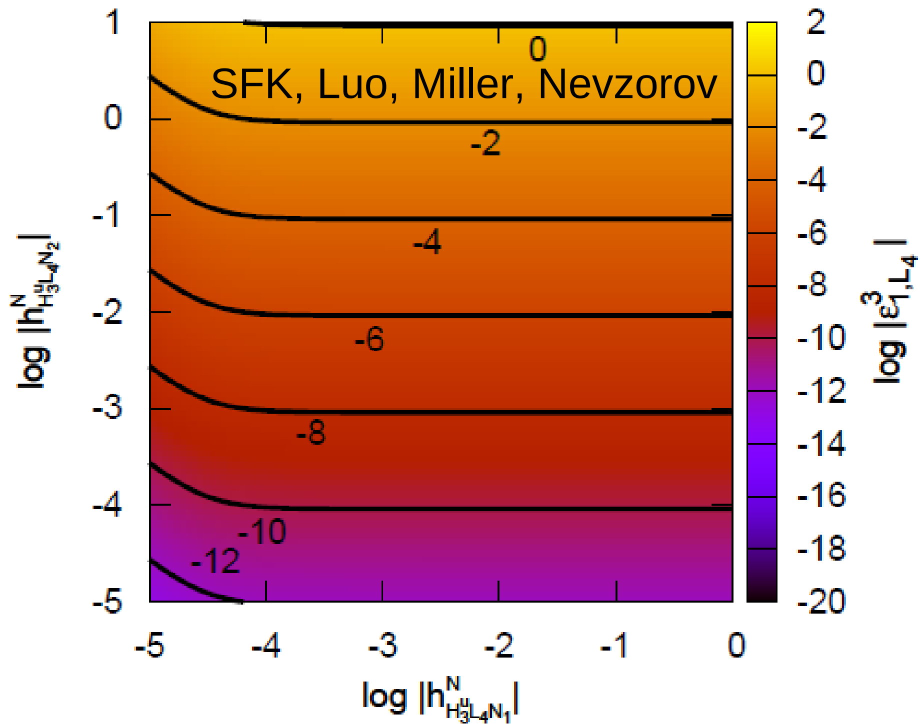


# Scenario 1: Effect of extra leptons $L_4$ alone (extra Higgs and leptoquark couplings set to zero)

$\mu = \tau$ lepton asymmetry contours for $M_1 = 10^6$ GeV



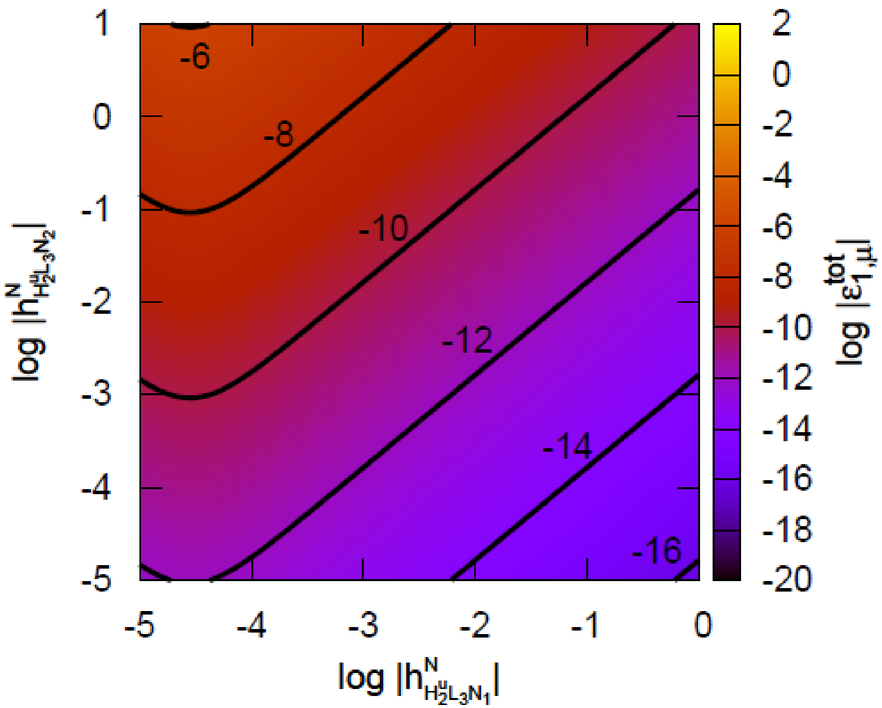

$L_4$ lepton asymmetry contours for $M_1 = 10^6$ GeV



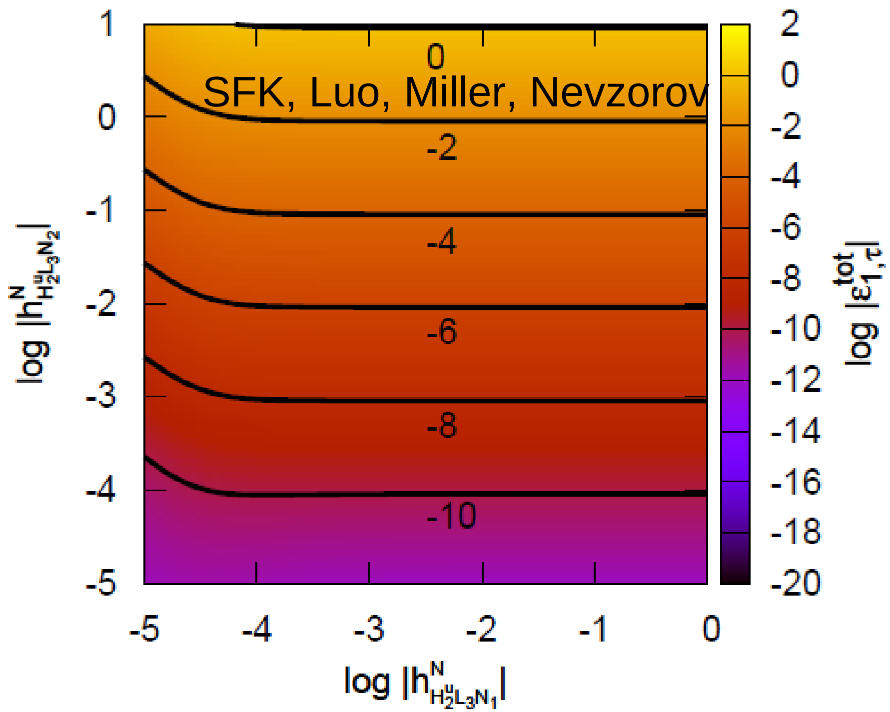

Both plots are in plane of $H^u{}_3 L_4 N_{1,2}$ Yukawa couplings

# Scenario 2: Effect of extra Higgs $H^u_2$ alone (extra lepton and leptoquark couplings set to zero)

$\mu$ lepton asymmetry contours for $M_1 = 10^6$ GeV



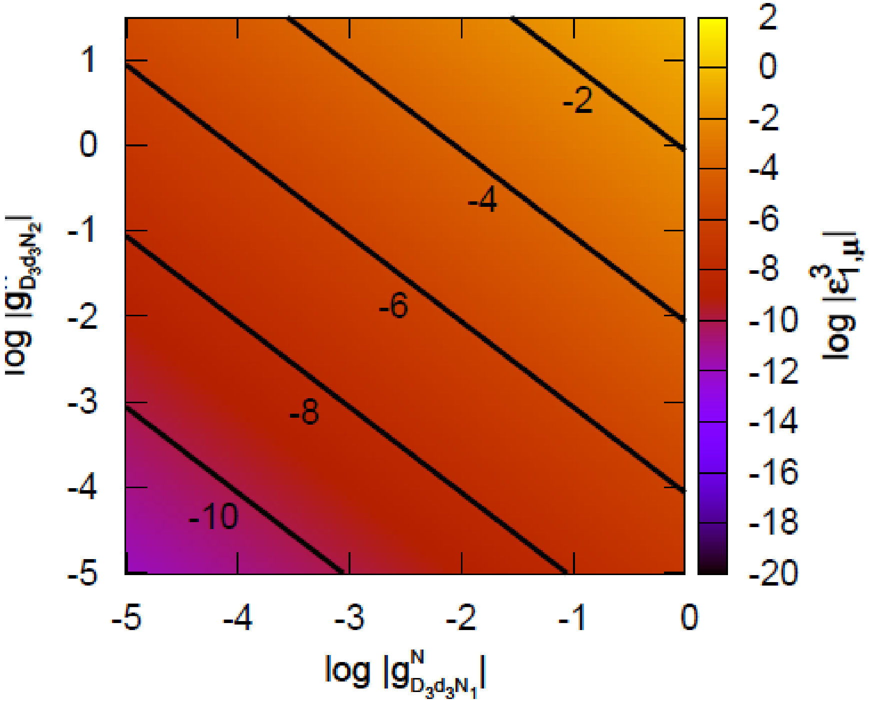

$\tau$ lepton asymmetry contours for $M_1 = 10^6$ GeV



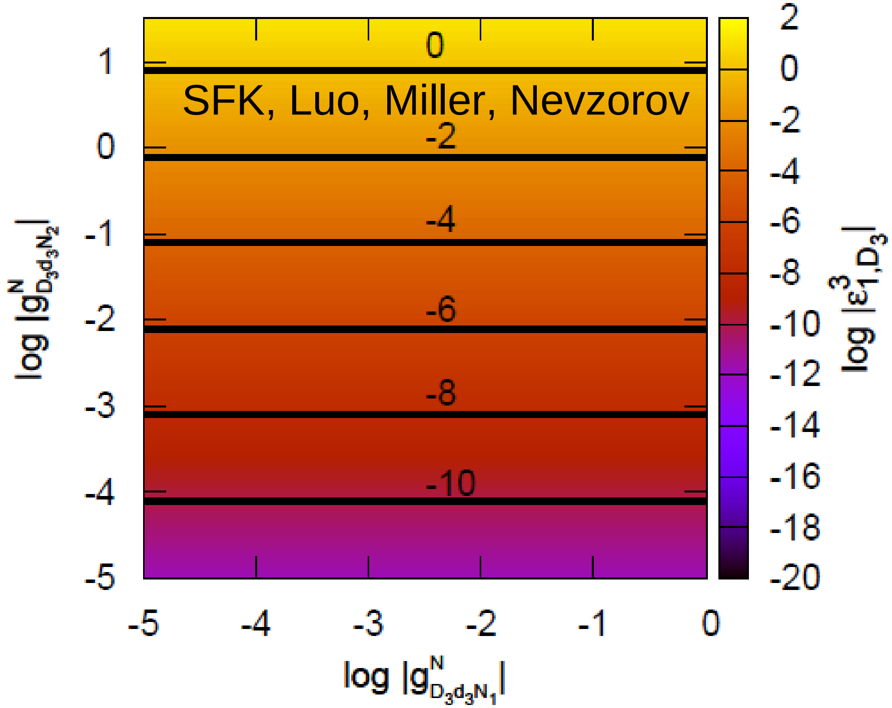

Both plots are in plane of $H^u_2 L_3 N_{1,2}$ Yukawa couplings

# Scenario 3: Effect of extra leptoquarks $D_k$ alone (extra Higgs and lepton couplings set to zero)

$\mu = \tau$ lepton asymmetry contours for $M_2 = 10\ M_1$




$D_3$ lepton asymmetry contours for $M_2 = 10\ M_1$




Both plots are in plane of $D_3d_3N_{1,2}$ Yukawa couplings