Supersymmetry: looking beyond mSUGRA

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Minimal Supersymmetric Standard Model (MSSM)

- Gauge symmetry: $SU(3)_c \times SU(2)_L \times U(1)_Y$
- Fields ➡ superfields
  - fermions $\Longrightarrow$ (left) chiral scalar superfields
  - gauge fields $\Longrightarrow$ gauge vector superfields
  - *two* Higgs doublets are necessary
- Add all admissible soft SUSY-breaking terms

$$\mathcal{L}_{soft} = b_{ij} S_i S_j + a_{ijk} S_i S_j S_k - S_i^\dagger m_{ij}^2 S_j - \frac{1}{2} M_{A\alpha} \lambda_{A\alpha} \lambda_{A\alpha}$$

- *R*-parity conserving model has 178 arbitrary parameters
  ➡ INTRACTABLE PHENOMENOLOGY
- Need to resort to models

Minimal Supergravity model (mSUGRA)

- SUSY breaking communicated to visible sector via gravity
- Weak-scale MSSM values constructed via RGE evolution, assuming:
  - Universality of SSB terms at GUT scale $\simeq 2 \times 10^{16}\ GeV$
  - Radiative EW symmetry breaking due to large m_t
  - Alignment of quark and squark matrices
  - Massless neutrinos
- Independent parameters:
  - $m_{H_u} = m_{H_d} = m_{\tilde{f}} \equiv m_0$ -- universal scalar mass
  - $M_1 = M_2 = M_3 \equiv m_{1/2}$ -- universal gaugino mass
  - $A_u = A_d = A_e \equiv A_0$ -- universal trilinear parameter
  - $\tan\beta$ -- replacement of bilinear SSB parameter *B*
  - $sign(\mu)$

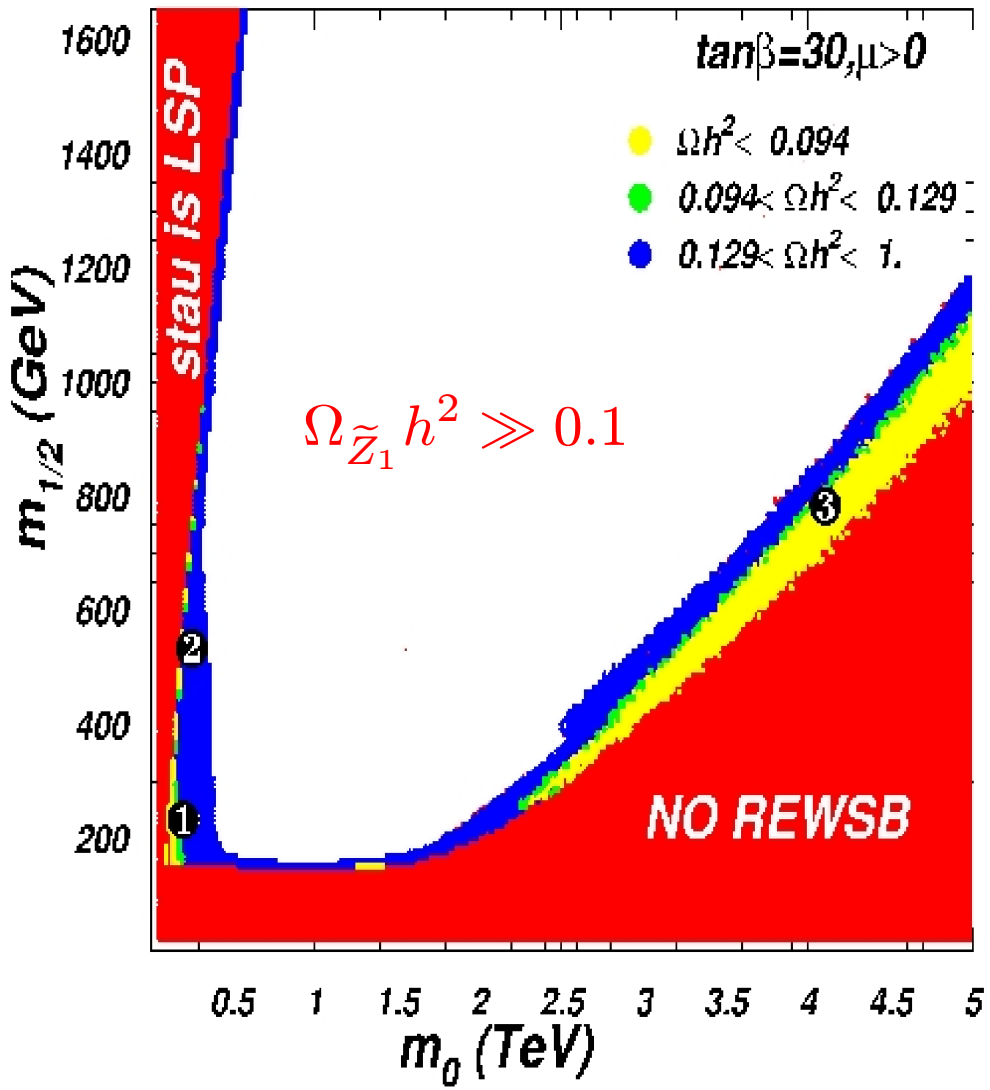
RD in mSUGRA

- Lightest neutralino is LSP over most of para space – DM candidate

$$\widetilde{Z}_1 = N_1 \widetilde{H}_u^0 + N_2 \widetilde{H}_d^0 + N_3 \lambda_3 + N_4 \lambda_0$$

- Most of para space ruled out due to too high Relic Density
- Special RD-allowed regions:
  1) bulk region
  2) stau co-annih. $(m_{\widetilde{Z}_1} \simeq m_{\widetilde{\tau}_1})$
  3) HB/FP region (small $|\mu|$)

Baer, Belyaev, Balazs '02



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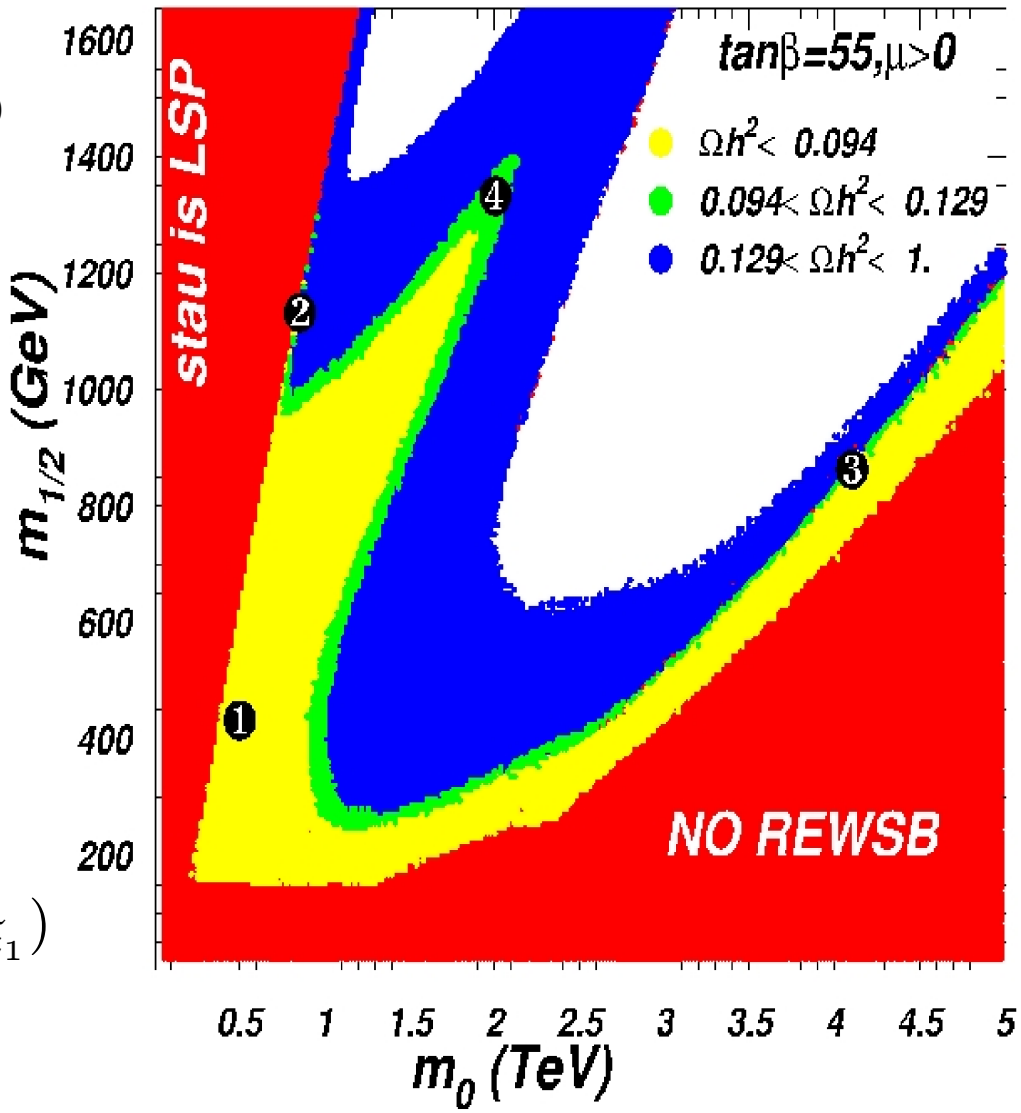
  3) HB/FP region (small $|\mu|$)
  4) *A*-funnel $(2m_{\widetilde{Z}_1} \simeq m_A)$
     - *h* corridor $(2m_{\widetilde{Z}_1} \simeq m_h)$
     - stop co-annihilation $(m_{\widetilde{Z}_1} \simeq m_{\tilde{t}_1})$

➢ Benchmark points for colliders

Baer, Belyaev, Balazs '02



mSUGRA prejudices

- Relic-density-consistent “bulk region” ➡ many light sparticles
- Higgs-funnel occurs only for large $\tan\beta$ values
- MHDM occurs only if scalars are essentially decoupled at LHC
- Lighter $\tilde{b}_1 \simeq \tilde{b}_L$, lighter $\tilde{\tau}_1 \simeq \tilde{\tau}_R$
- Lightest Higgs boson is SM-like and should be heavier than ~114 GeV
- The wino content of LSP is never large
- Neutrino masses do not affect DM and collider signatures
- No-scale solution is ruled out

Each of these statements is false in simple extensions of mSUGRA

Non-Universal SSB parameters

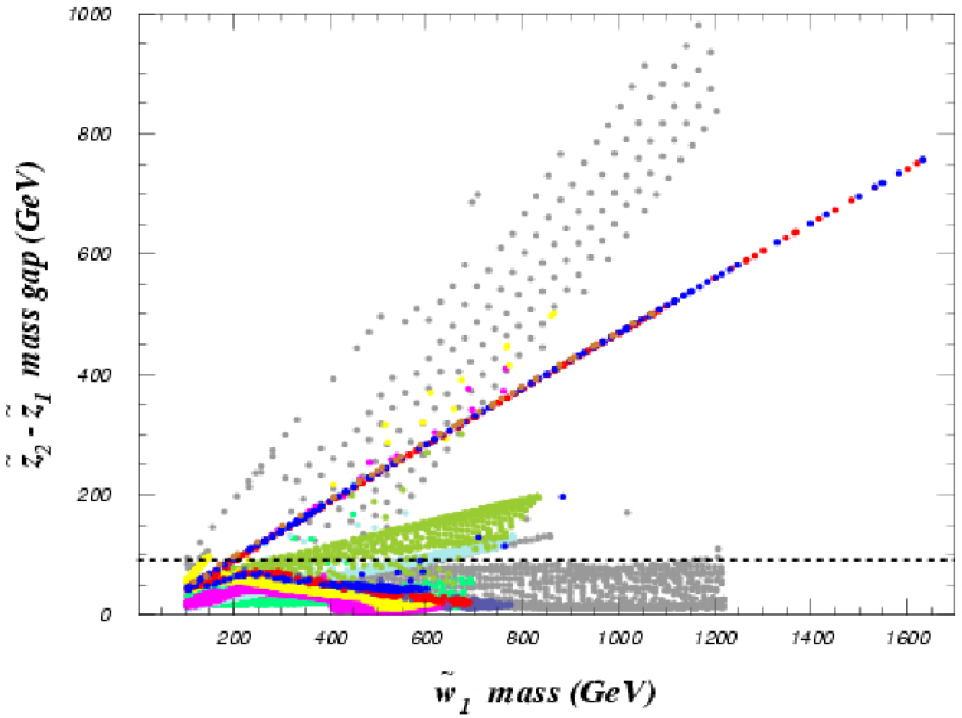
Baer, AM, Park, Tata

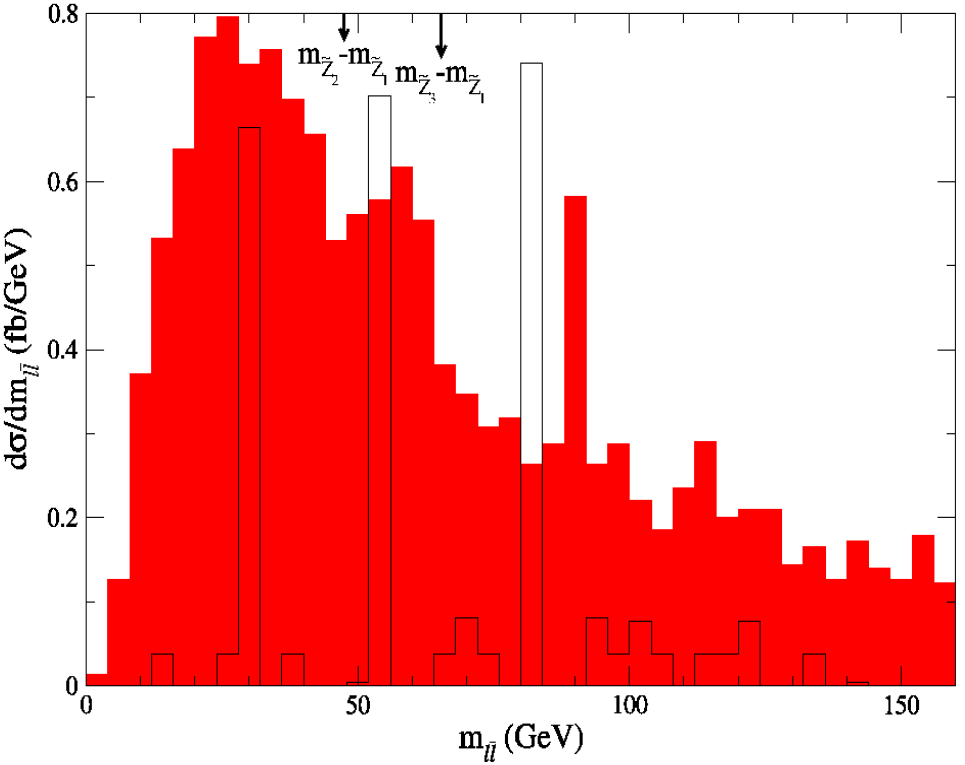
- Non-universal Higgs mass parameters: $m^2_{H_u,H_d} \neq m_0^2$
  - Co-annih. via very light $\tilde{u}_R/\tilde{c}_R$ or light $\tilde{\tau}_1 \simeq \tilde{\tau}_L$ (with other scalars heavy)
  - Higgs funnel for all values of $\tan\beta$
  - MHDM for small values of scalar masses
  - Lightest Higgs can be as light as ~50 GeV
- Non-universal gaugino mass parameters:
  - $M_1(weak) \simeq M_2(weak) \Longrightarrow$ mixed wino DM (MWDM)
  - $M_1(weak) \simeq -M_2(weak) \Longrightarrow$ bino-wino co-annihilation (BWCA)
  - Large $M_2 \Longrightarrow$ low $|\mu|$, so mixed higgsino DM (MHDM)
  - Low $|M_3| \Longrightarrow$ MHDM; enhanced radiative decays of gluino

By adjusting one additional parameter, all points in mSUGRA para plane become RD-allowed!

Non-Universal SSB parameters

Baer, AM, Park, Tata





- In many models $\widetilde{Z}_2$ decays via 3-body mode
  ➡ location of dilepton mass edge at $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1}$ may be possible at LHC
- In MHDM models, $\widetilde{Z}_3$ may also be light ➡ multiple mass edges

Seesaw mechanism

- Observed neutrino oscillations ➡ massive neutrinos

$$\Delta m^2_{21} = (7.65^{+0.69}_{-0.60}) \times 10^{-5} eV \qquad \sin^2\theta_{12} = 0.304^{+0.066}_{-0.054}$$
$$|\Delta m^2_{31}| = (2.40^{+0.35}_{-0.33}) \times 10^{-3} eV \qquad \sin^2\theta_{23} = 0.50^{+0.17}_{-0.14}$$
$$\sin^2\theta_{13} < 0.056$$

- Mass scale $\sum m_\nu \lesssim 1\,\mathrm{eV}$
- Seesaw mechanism (type-I): add 3 singlet right-handed neutrinos N_i

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \Longrightarrow \begin{pmatrix} m_D M_N^{-1} m_D^T & 0 \\ 0 & M_N \end{pmatrix}$$

3 *light Majorana* neutrinos

$$m_{\nu_i} \lesssim 0.3\ eV$$

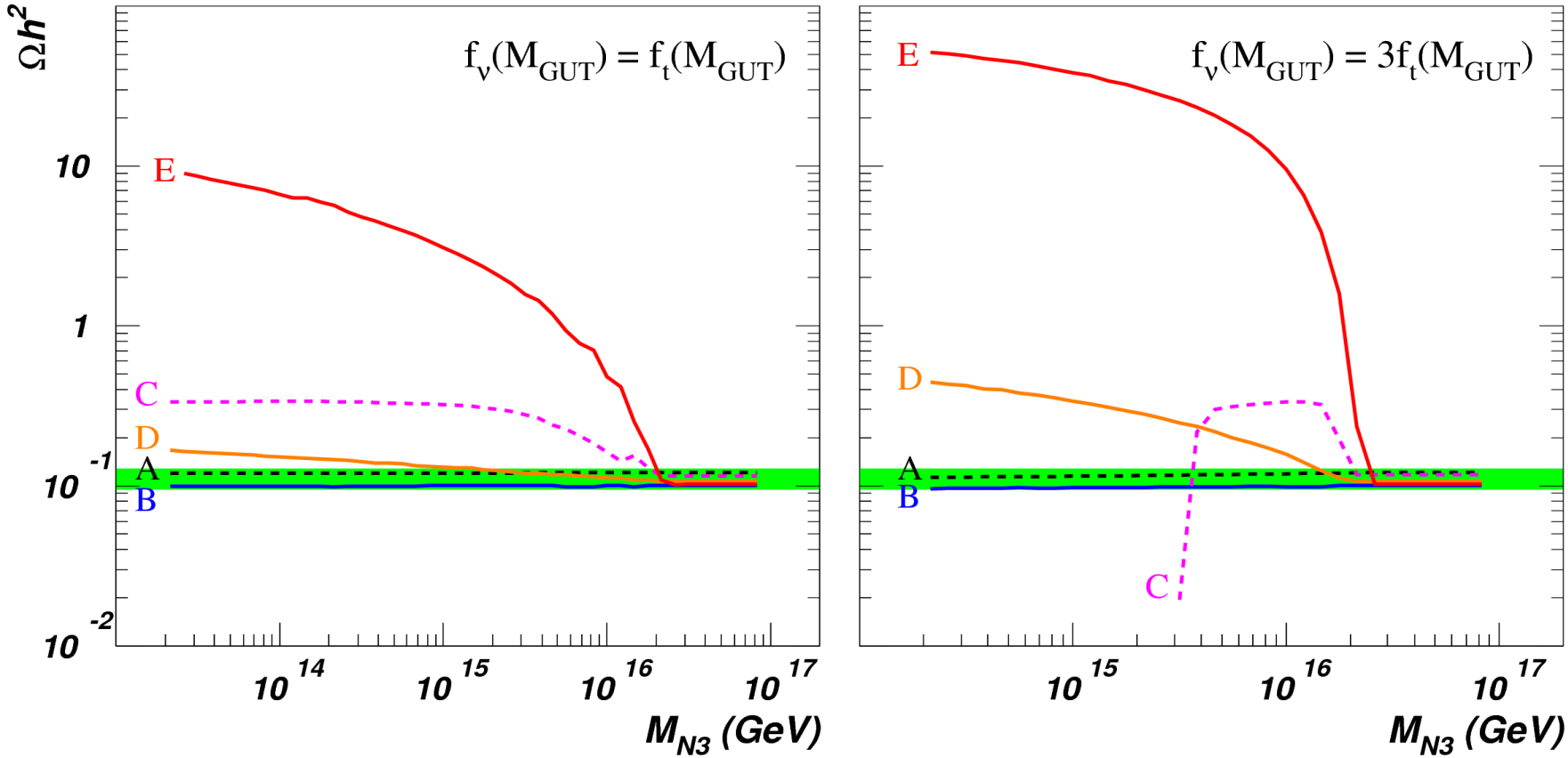
3 *heavy Majorana* neutrinos

$$M_{N_i} \sim (10^{10} - 10^{16})\ GeV$$

RHN effects in mSUGRA

Barger, AM, Marfatia '08

- Neutrino Yukawas from SO(10): $\mathsf{f}_\nu = R_{\nu u}\,\mathsf{f}_u$
- Significant impact on RD ➡ allowed regions shift in para space



A=bulk, B=stau co-annih., C=stop co-annih., D=Higgs funnel, E=HB/FP

RHN effects in mSUGRA

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- Neutrino Yukawas from *SO(10)*: $\mathsf{f}_\nu = R_{\nu u}\,\mathsf{f}_u$
- Significant impact on RD ➡ allowed regions shift in para space
- Sparticle masses and composition can be modified:
  e.g. $\tilde{\tau}_1 \simeq \tilde{\tau}_L$ for large A_0
- New sneutrino co-annihilation mechanism possible
- Most prominent effects when SSB slepton mass and/or trilinear couplings are large

SSB unification scale

- Limits on flavor violation in hadron and lepton sectors and Grand Unified Theories suggest universality of SSB terms:

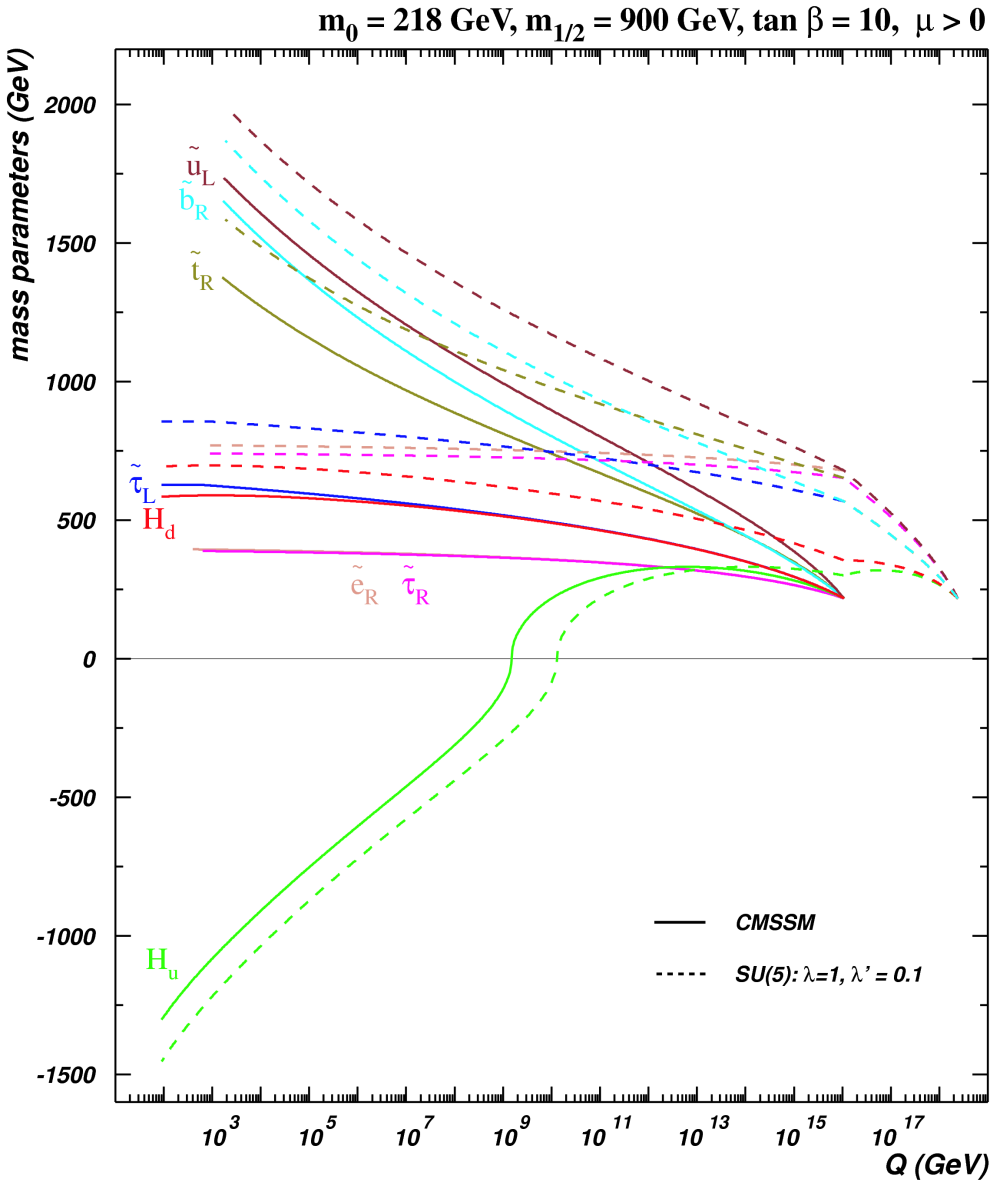
  $m_{\tilde{f}} \equiv m_0, \; M_{A\alpha} \equiv m_{1/2}, \; A_i \equiv A_0$ at scale M_{in}

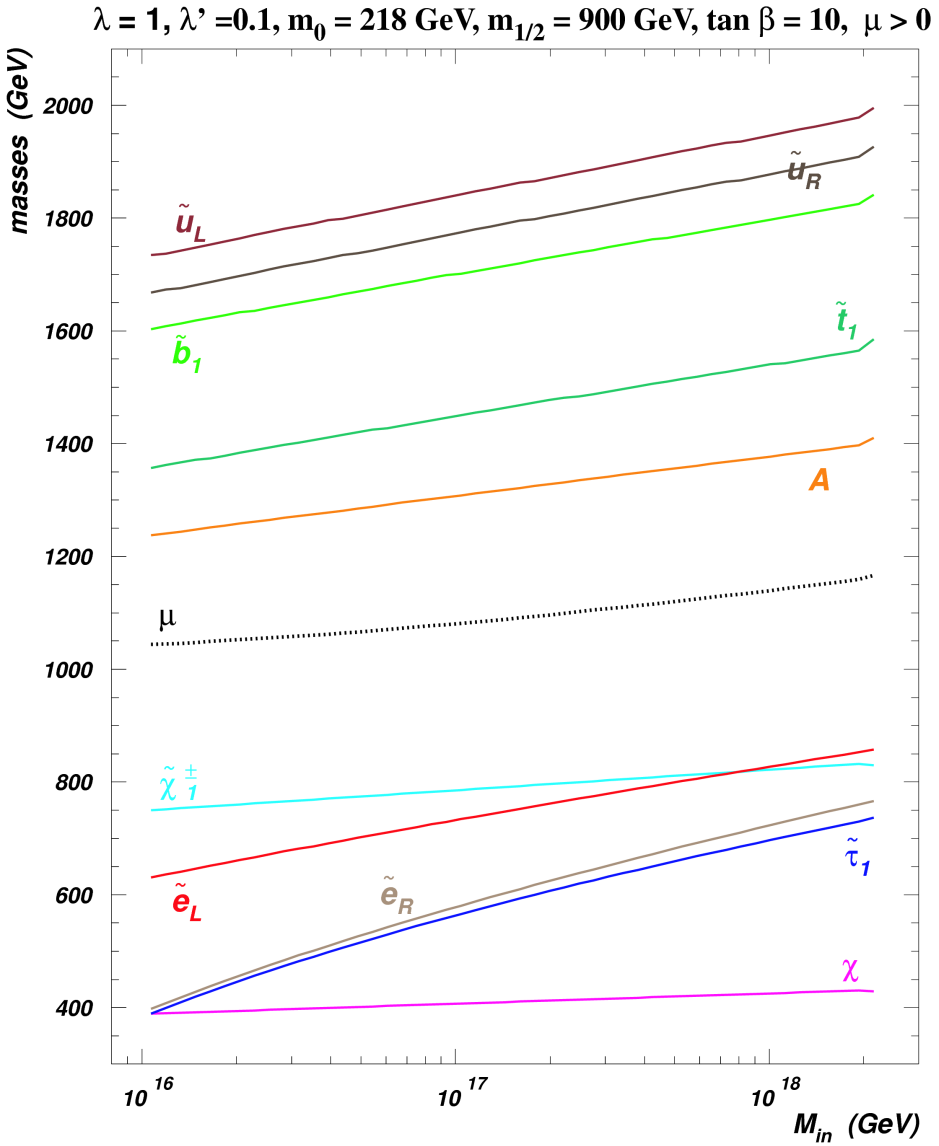
- How large is M_{in}?
  - $M_{in} = M_{GUT} \simeq 2 \times 10^{16}\, GeV \implies$ mSUGRA
  - $M_{in} < M_{GUT} \implies$ "GUT-less" models *Ellis,Olive,Sandick '06-'08*
  - $M_{in} > M_{GUT}$
- Need to assume particular GUT model

Minimal SU(5) GUT

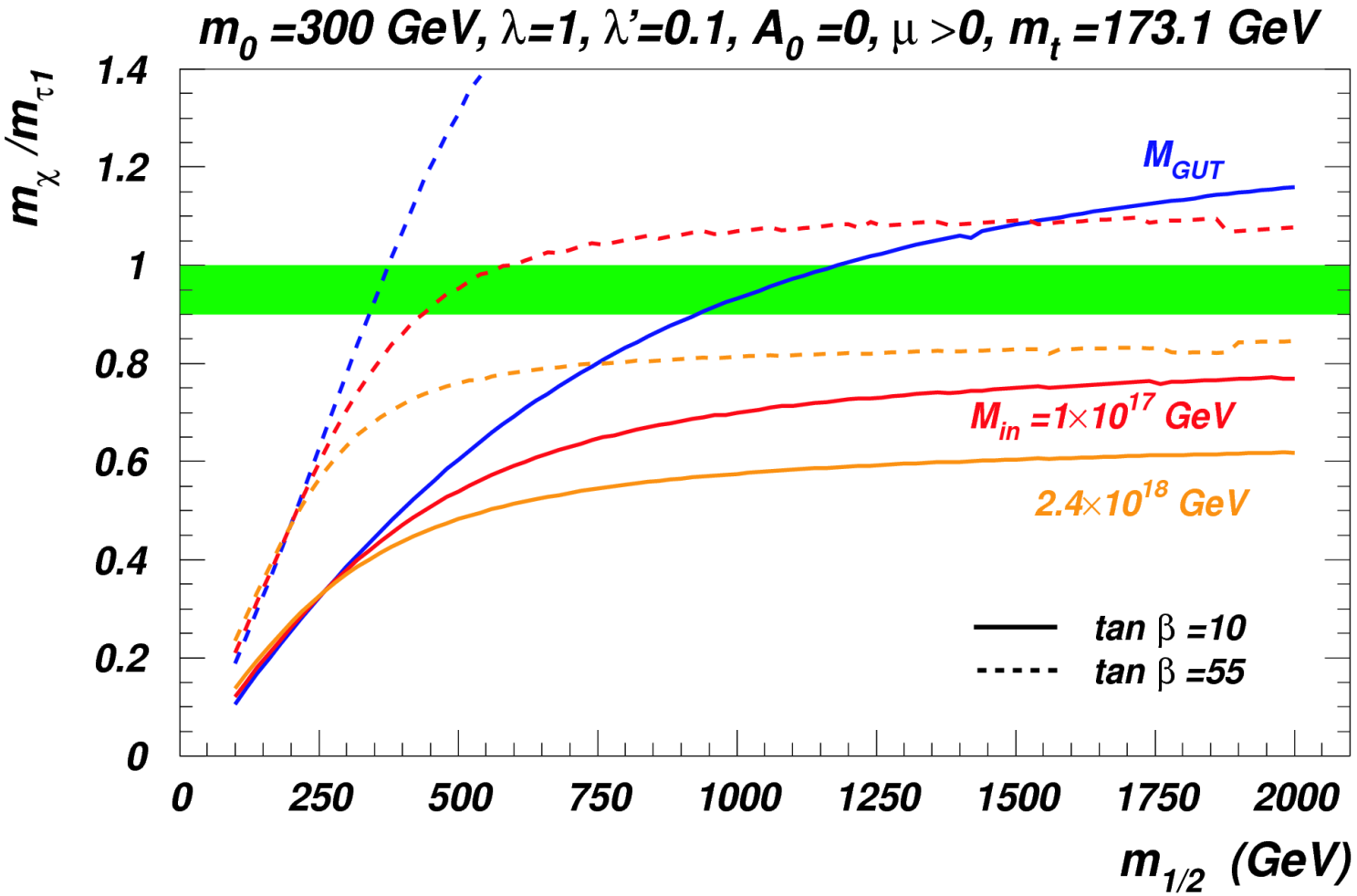
- Field content:
  $\phi \in \{D^c, L\},\ \psi \in \{Q, U^c, E^c\},\ \mathcal{H}_1 \in \{H_d, H_d^C\},\ \mathcal{H}_2 \in \{H_u, H_u^C\},\ \Sigma$
- Superpotential
  $$\mathcal{W}_5 = \mu_\Sigma \Sigma^2 + \lambda' \Sigma^3 + \mu_H \mathcal{H}_1 \mathcal{H}_2 + \lambda \mathcal{H}_1 \Sigma \mathcal{H}_2 + h_{10} \psi \psi \mathcal{H}_2 + h_5 \psi \phi \mathcal{H}_1$$
- Parameter space:
  $$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu),\ \lambda,\ \lambda',\ M_{in}$$
- SSB matching of SU(5) to MSSM
  $$A_t = A_{10}\,, \qquad A_b = A_\tau = A_5\,,$$
  $$m^2_{D_3} = m^2_{L_3} = m^2_5\,, \qquad m^2_{Q_3} = m^2_{U_3} = m^2_{E_3} = m^2_{10}\,,$$
  $$m^2_{H_d} = m^2_{\mathcal{H}_1}\,, \qquad m^2_{H_u} = m^2_{\mathcal{H}_2}$$
- Previous works: Polonski and Pomarol '94, Baer et al '00, Blair, Porod and Zerwas '03, ...

RGEs and sparticle spectrum

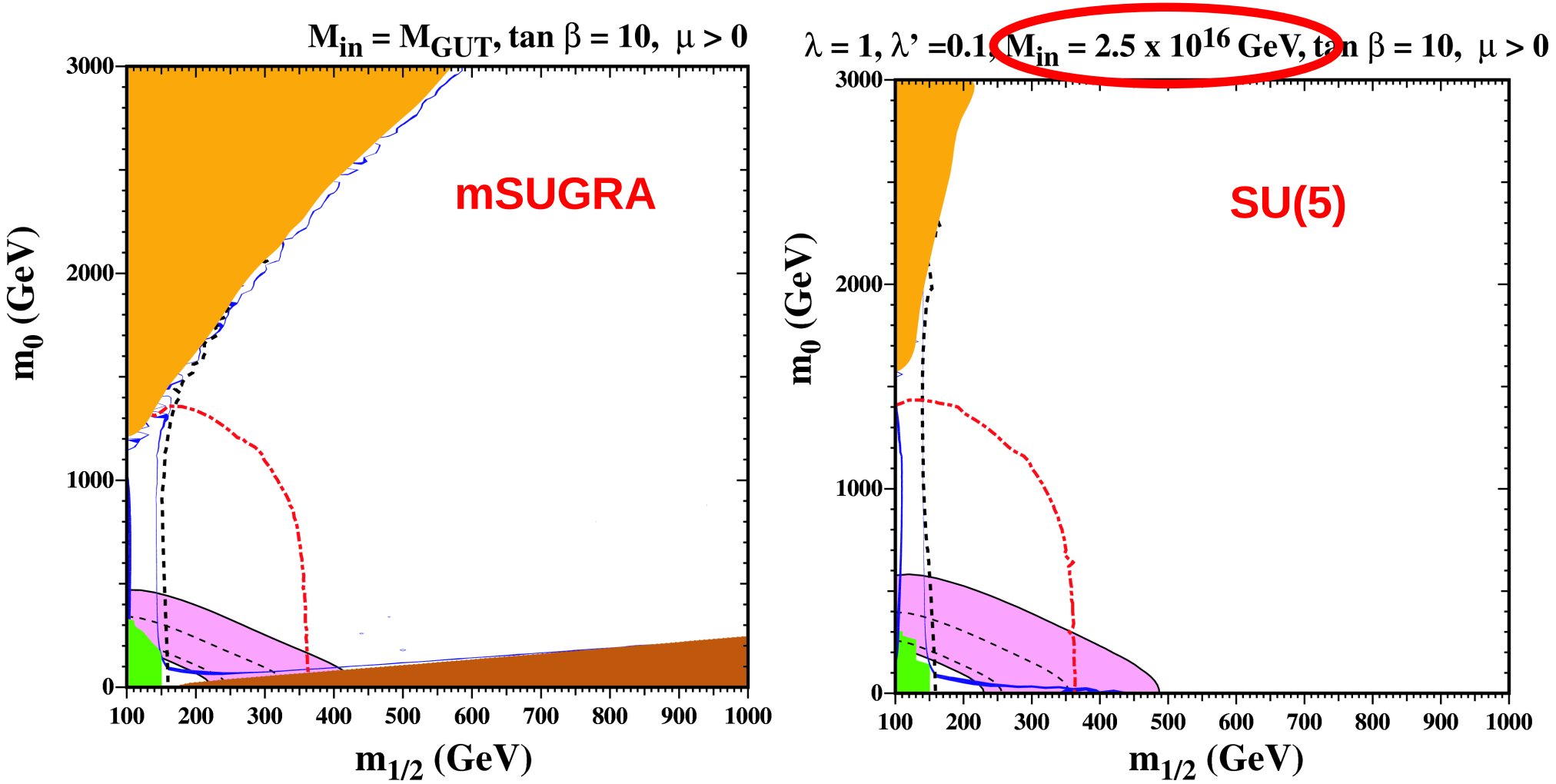




RD mechanisms in SU(5)

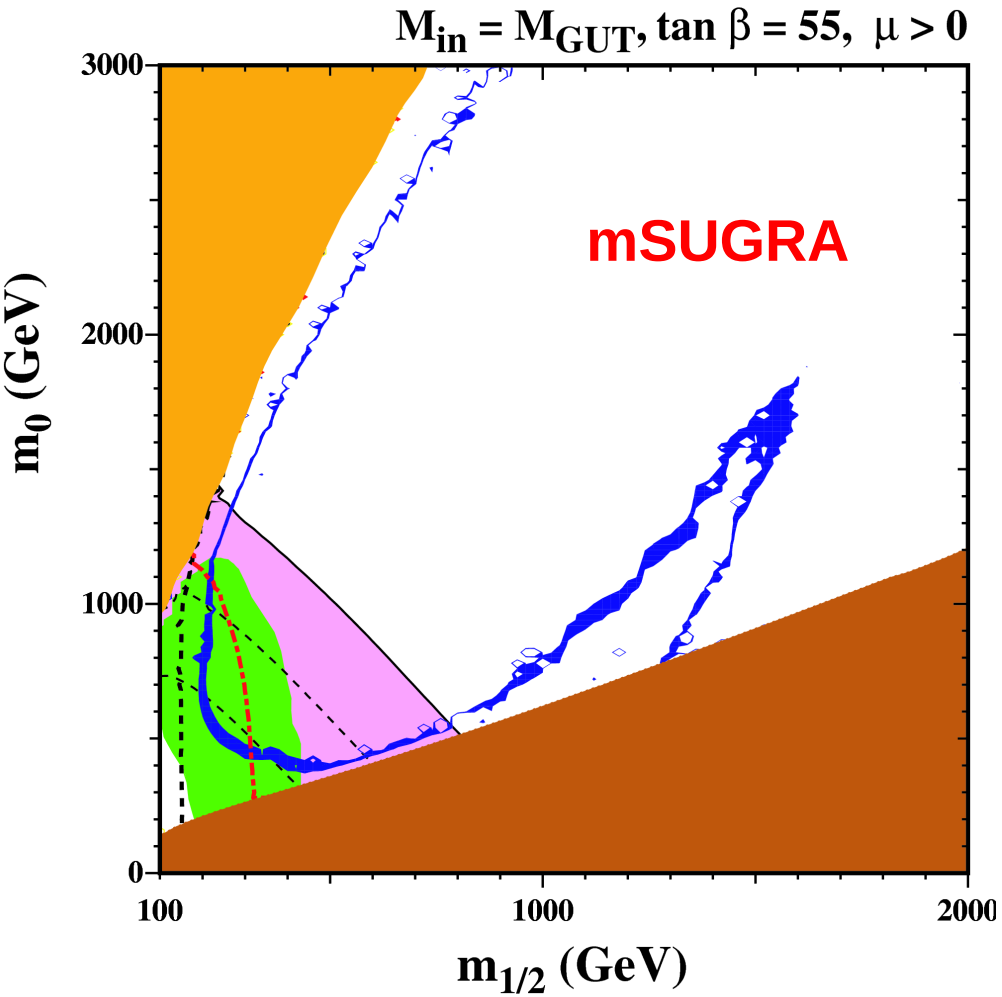


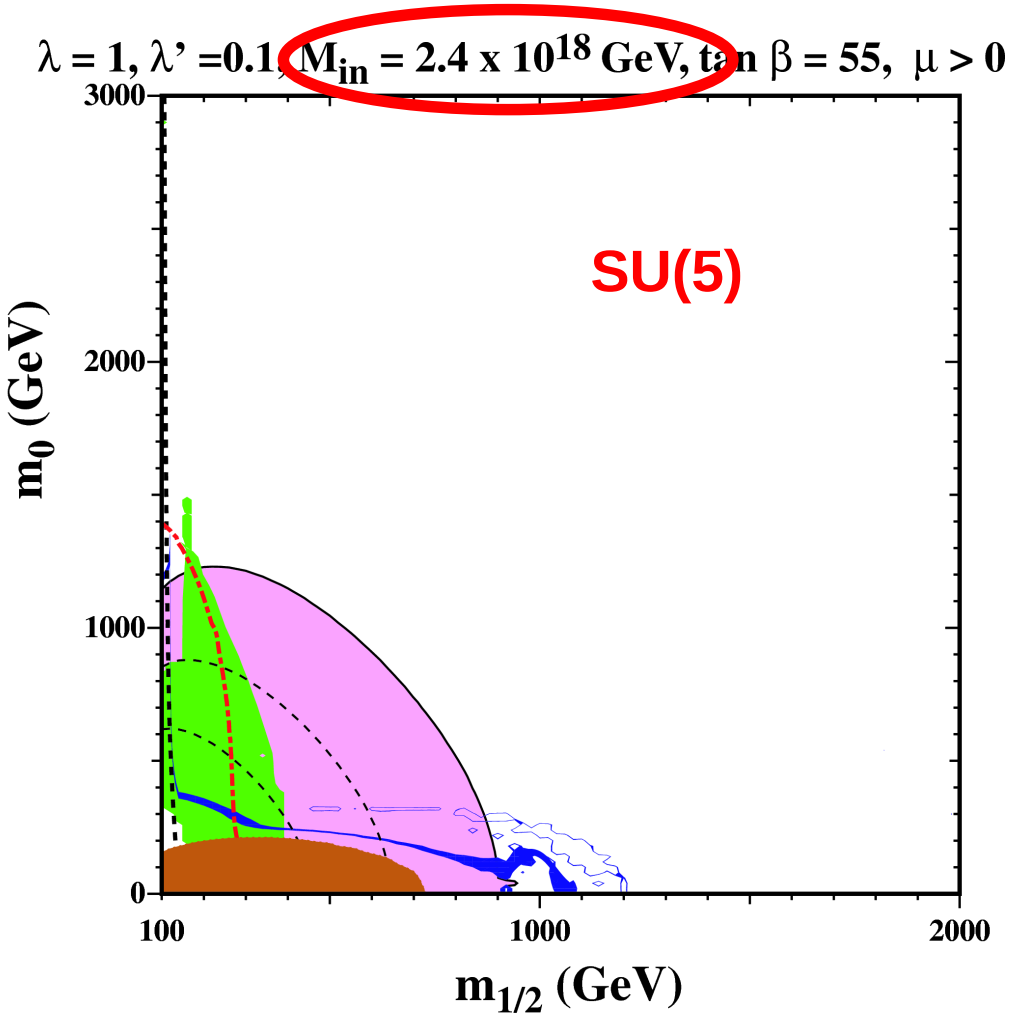
$(m_0,\ m_{1/2})$ plane



Ellis, AM, Olive

$(m_0,\ m_{1/2})$ plane at large $\tan\beta$



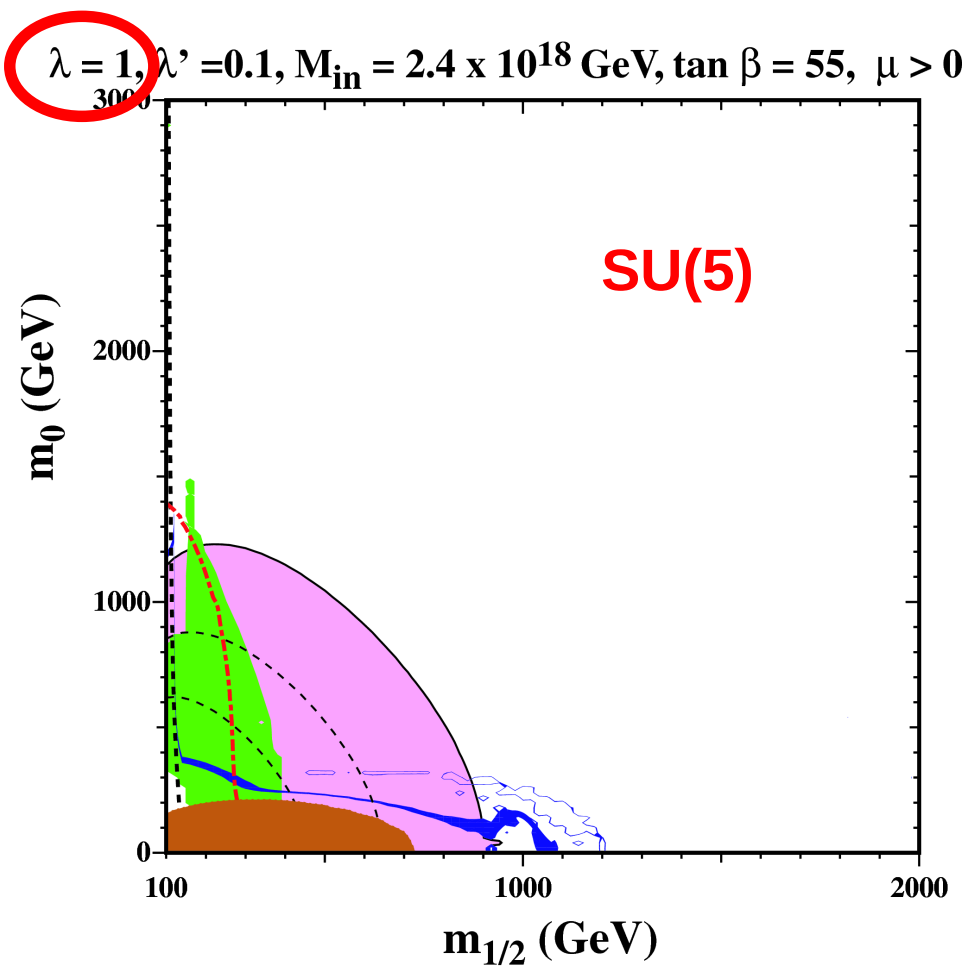


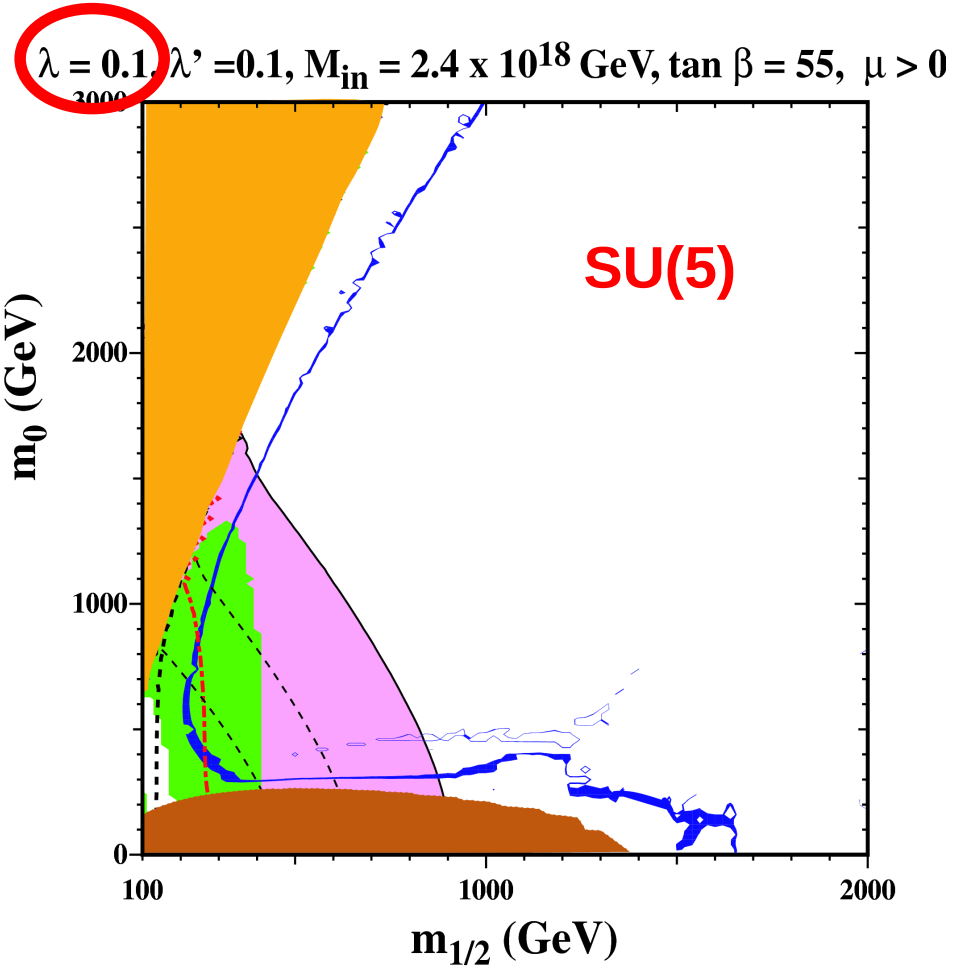
Effect of coupling λ

- Matching of SU(5) and MSSM couplings at M_{GUT}

$$
\begin{aligned}
g_5 &\Longleftrightarrow g_1,\ g_2,\ g_3 \\
f_{10} &\Longleftrightarrow f_t \\
f_5 &\Longleftrightarrow f_b,\ \ f_\tau \\
\lambda &\Longleftrightarrow \\
\lambda' &\Longleftrightarrow
\end{aligned}
$$

Effect of coupling λ





No-scale SU(5)

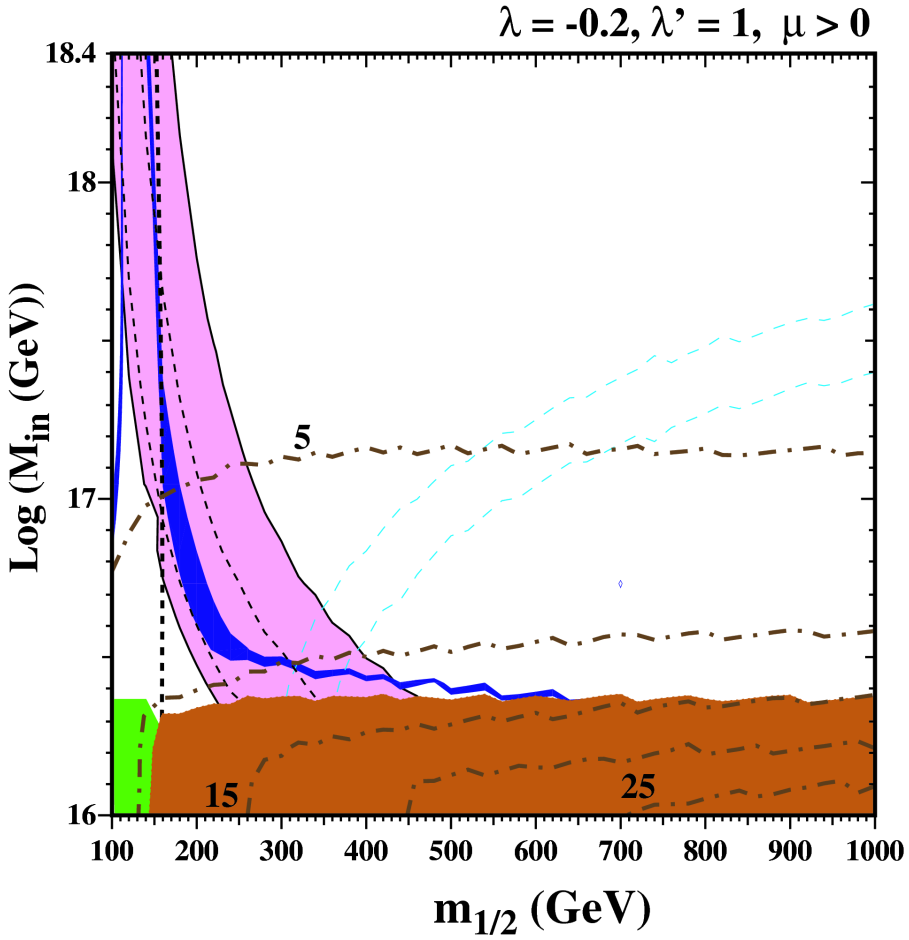
- No-scale $m_0 = A_0 = B_0 = 0$ provides solution to SUSY flavor problem
- Appears in supergravity and gaugino mediation
- Ruled out for $M_{in} = M_{GUT}$ $\longleftarrow$ stau LSP
- No-scale SU(5) para space: $m_{1/2}, \lambda, \lambda', M_{in}$
- Additional matching condition

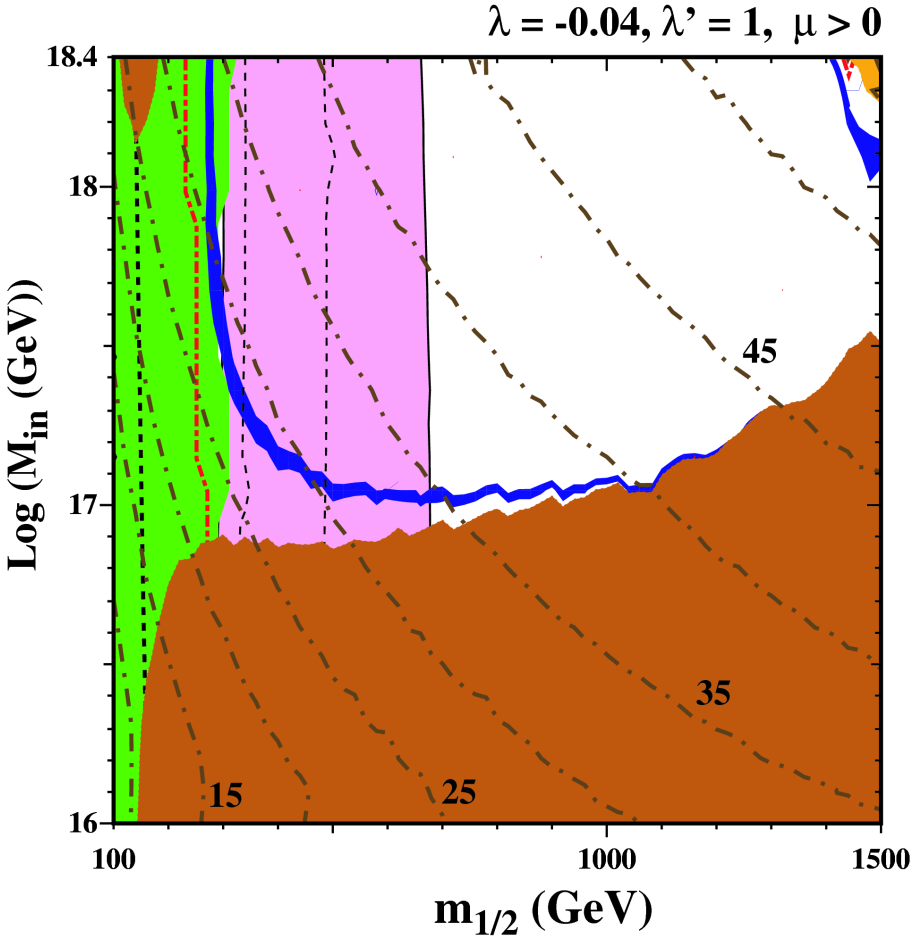
$$B = B_H - \frac{6\lambda}{\mu\lambda'}\left[(B_\Sigma - A_{\lambda'})(2B_\Sigma - A_{\lambda'}) + m_\Sigma^2\right]$$

Ellis, AM, Olive

$(m_{1/2}, M_{in})$ plane of no-scale SU(5)

- Case $\lambda/\lambda' > 0$ (also Schmaltz and Skiba '00) $\Longrightarrow \tan\beta \lesssim 30$
- Case $\lambda/\lambda' < 0 \Longrightarrow$ large $\tan\beta$





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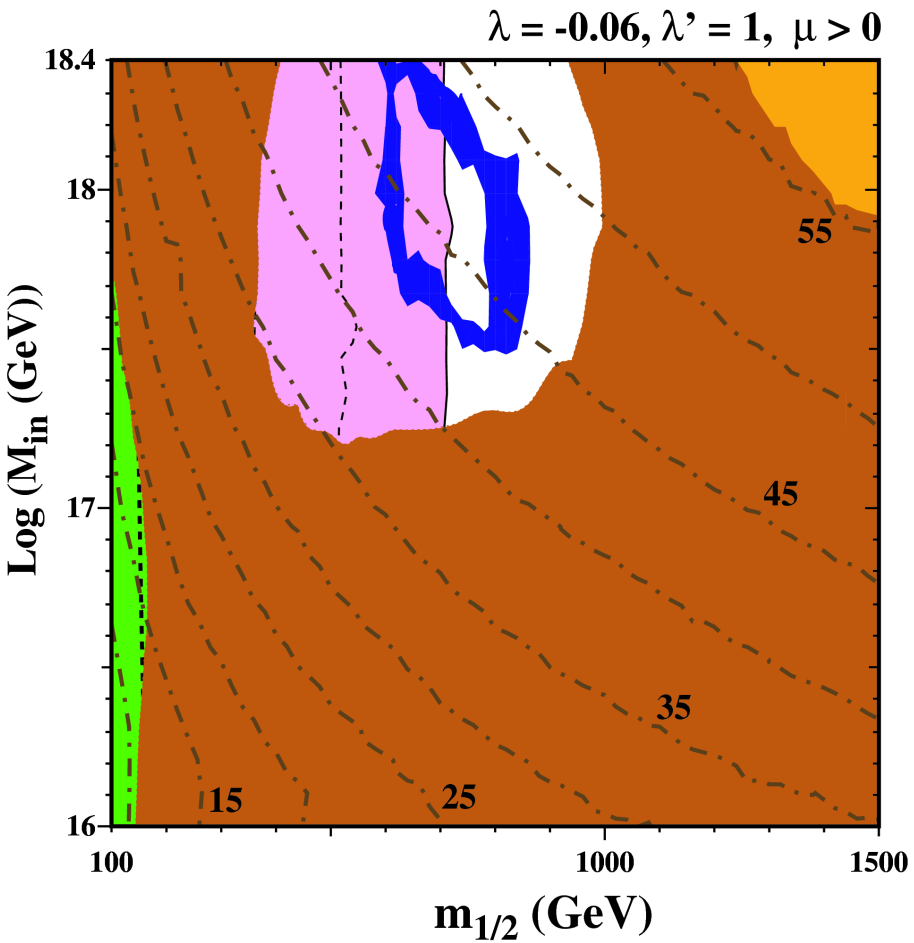

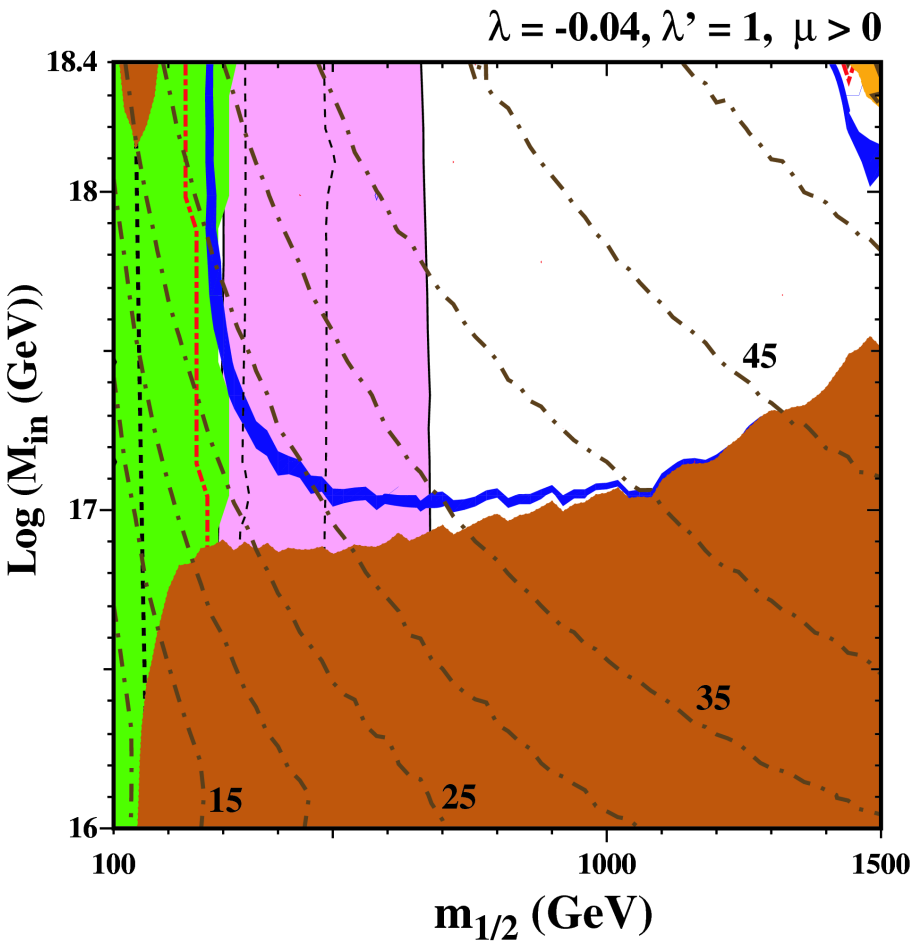

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- Case $\lambda/\lambda' > 0$ (also Schmaltz and Skiba '00) $\Longrightarrow$ $\tan\beta \lesssim 30$
- Case $\lambda/\lambda' < 0$ $\Longrightarrow$ large $\tan\beta$
- Increasing M_{in} increases splitting between sparticle masses
- No-scale SU(5) is constrained to $m_{1/2} \lesssim 1\,TeV\,(1.5\,TeV)$

  ➡ light sparticle spectrum fully testable at LHC with $10\,(100)\,fb^{-1}$

Conclusions

- SUSY is very compelling BSM theory.
  It has a 'little' problem – it hasn't been found yet.
- Although many SUSY searches utilize mSUGRA, it is *not* typical scenario: simple modifications of mSUGRA assumptions can solve many of its tensions and may significantly change expected phenomenology
- LHS is running and early data and simulations agree amazingly well, so we might soon be able to finally hunt down the EW-scale supersymmetry!

HB/FP in minimal SU(5)