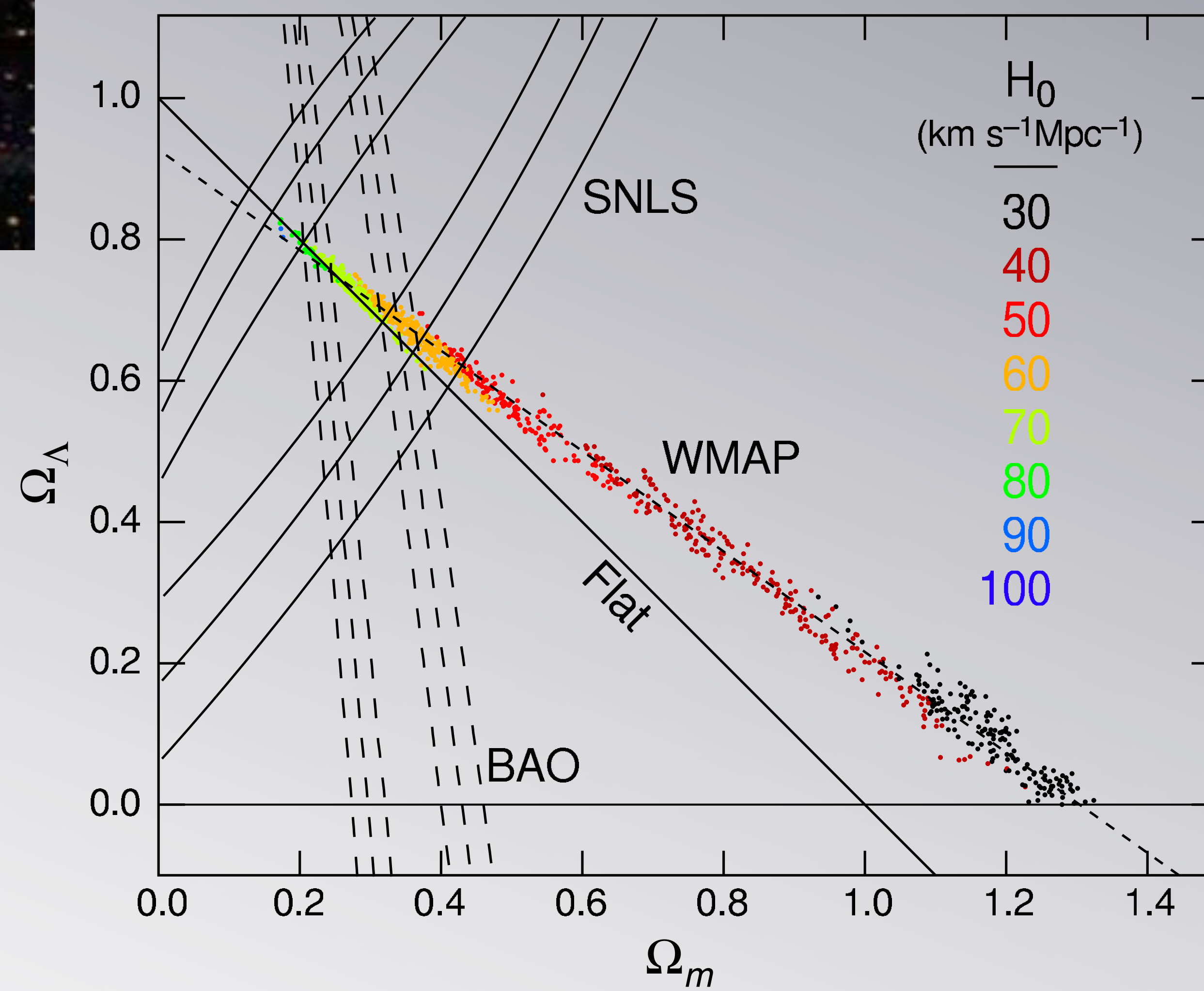
Supersymmetric Dark Matter and SuperGUT Unification Models

(Supersymmetric) Dark Matter



How Much Dark Matter

WMAP 7 Komatsu etal

Precise bounds on matter content

How Much Dark Matter

WMAP 7 Komatsu etal

Precise bounds on matter content

$\Omega_m h^2 = 0.1334 \pm 0.0056$ $\Omega_b h^2 = 0.0226 \pm 0.0006$

$$\Omega_{cdm} h^2 = 0.1109 \pm 0.0056$$

or

$$\Omega_{cdm}\, h^2 = 0.0997 - 0.1221 \quad (2\ \sigma)$$

SUSY Dark Matter

MSSM and R-Parity → Stable DM candidate

1) Neutralinos

$$\chi_i = \alpha_i \widetilde{B} + \beta_i \widetilde{W} + \gamma_i \widetilde{H}_1 + \delta_i \widetilde{H}_2$$

2) Sneutrino

Excluded (unless add L-violating terms)

3) Other:

Axinos, Gravitinos, etc

The Constrained and Very Constrained MSSM

- CMSSM - as a 4+ parameter theory
- VCMSSM models - 3+ parameter theory (mSUGRA)
- No-Scale models - 1+ parameter theory
- SuperGUT theories - unification at some input scale $M_{in} > M_{GUT}$ - plus GUT parameters.

SUSY Superpotential + Soft terms

$$
\begin{aligned}
W &= h_u H_2 Q u^c + h_d H_1 Q d^c + h_e H_1 L e^c + \mu H_2 H_1 \\
\mathcal{L}_{\text{soft}} &= -\frac{1}{2} M_\alpha \lambda^\alpha \lambda^\alpha - m_{ij}^2 \phi^{i*} \phi^j \\
&\quad -A_u h_u H_2 Q u^c - A_d h_d H_1 Q d^c - A_e h_e H_1 L e^c - B\mu H_2 H_1 + h.c.
\end{aligned}
$$

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\end{aligned}
$$

$$
\langle H_1 \rangle = \begin{pmatrix} v_1 \\ 0 \end{pmatrix} \qquad \langle H_2 \rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}
$$

$$
\tan\beta = \frac{v_2}{v_1}
$$

SUSY Superpotential + Soft terms

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$$

$$
\tan\beta = \frac{v_2}{v_1}
$$

R-parity conservation assumed ...... (sorry Herbie)

CMSSM Unification Conditions

- Gaugino masses: $M_i = m_{1/2}$
- Scalar masses: $m_i = m_0$ predict μ, B
- Trilinear terms: $A_i = A_0$

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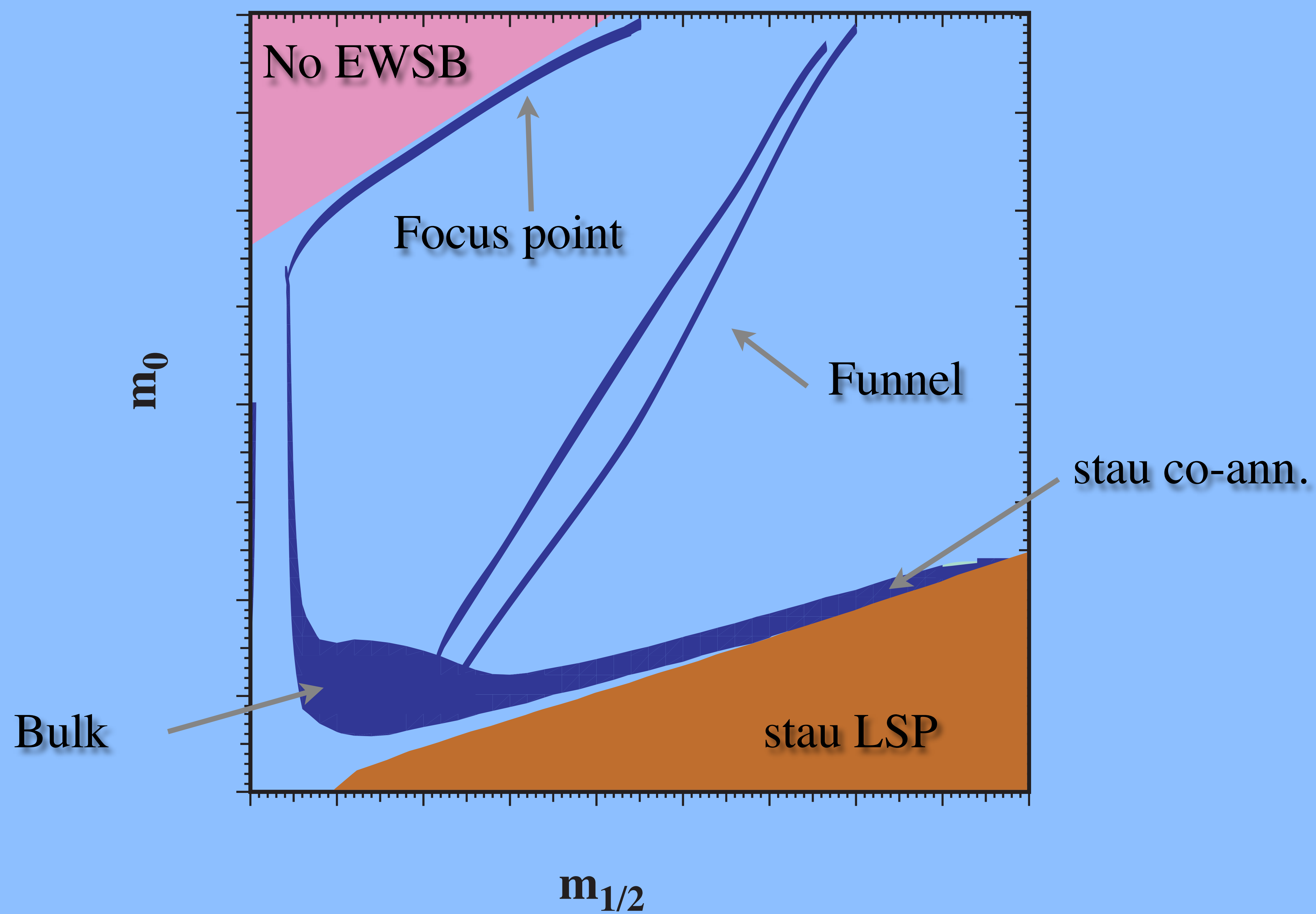
- Trilinear terms: $A_i = A_0$

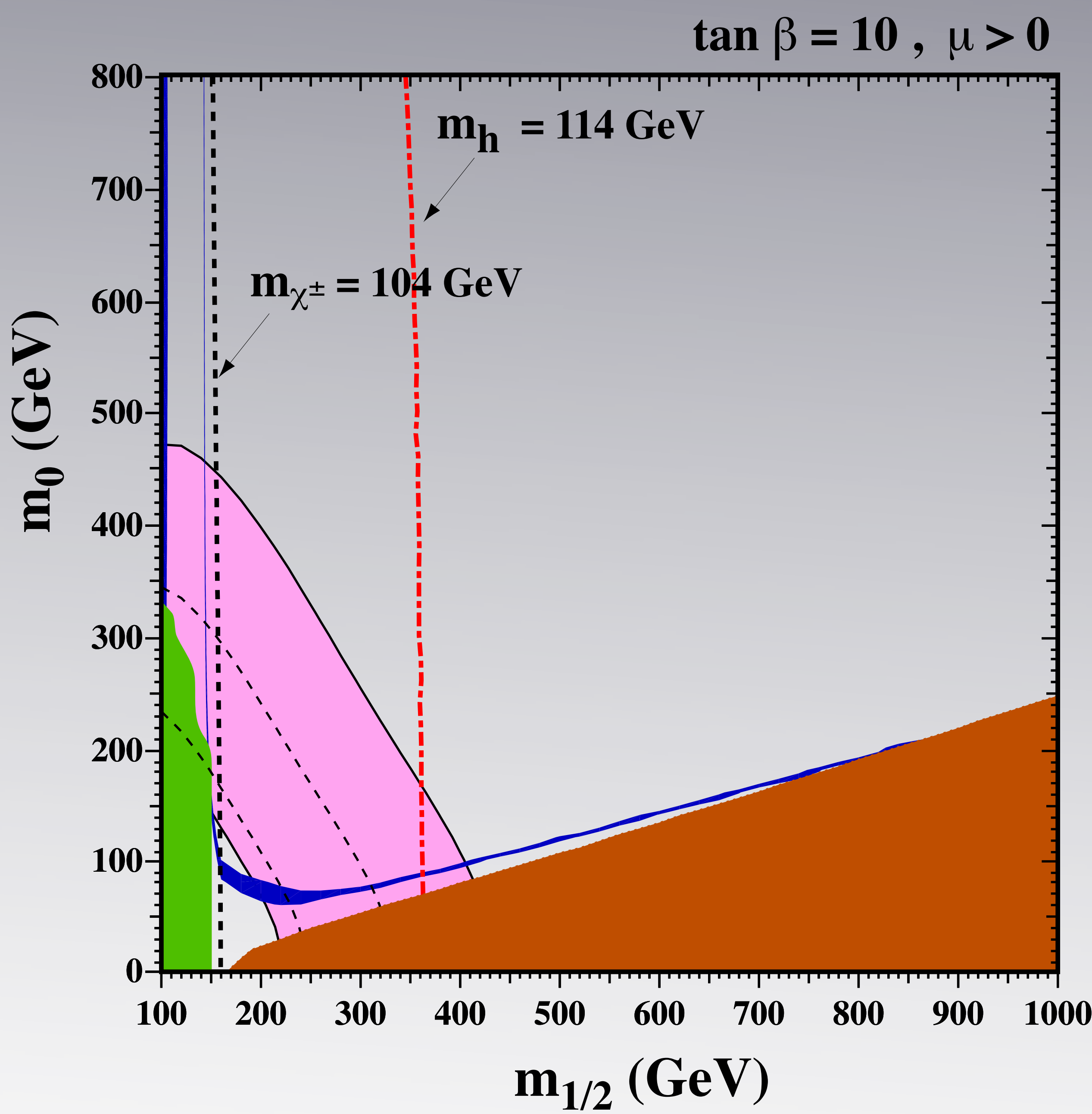
mSUGRA Unification Conditions

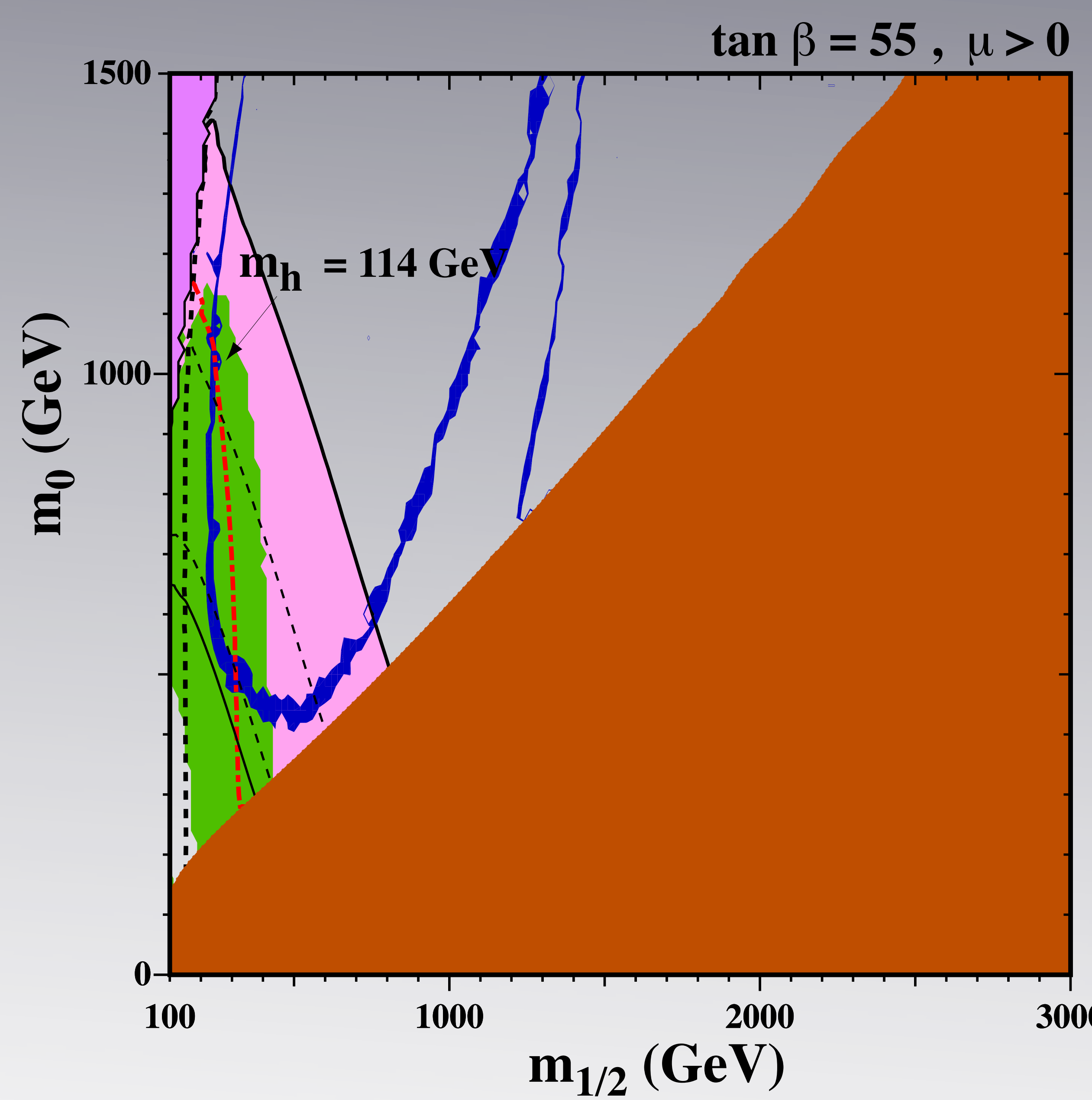
- Gravitino masses: $m_{3/2} = m_0$
- Bilinear term: $B_0 = A_0 - m_0$ predict μ, $\tan\beta$

Generic $m_{1/2}$ - m_0 plane



$m_{1/2}$ - m_0 planes





- CMSSM

Ellis, Olive, Santoso, Spanos

MCMC Analysis

Long list of observables to constrain CMSSM parameter space

Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Paradisi, Ronga, Weiglein

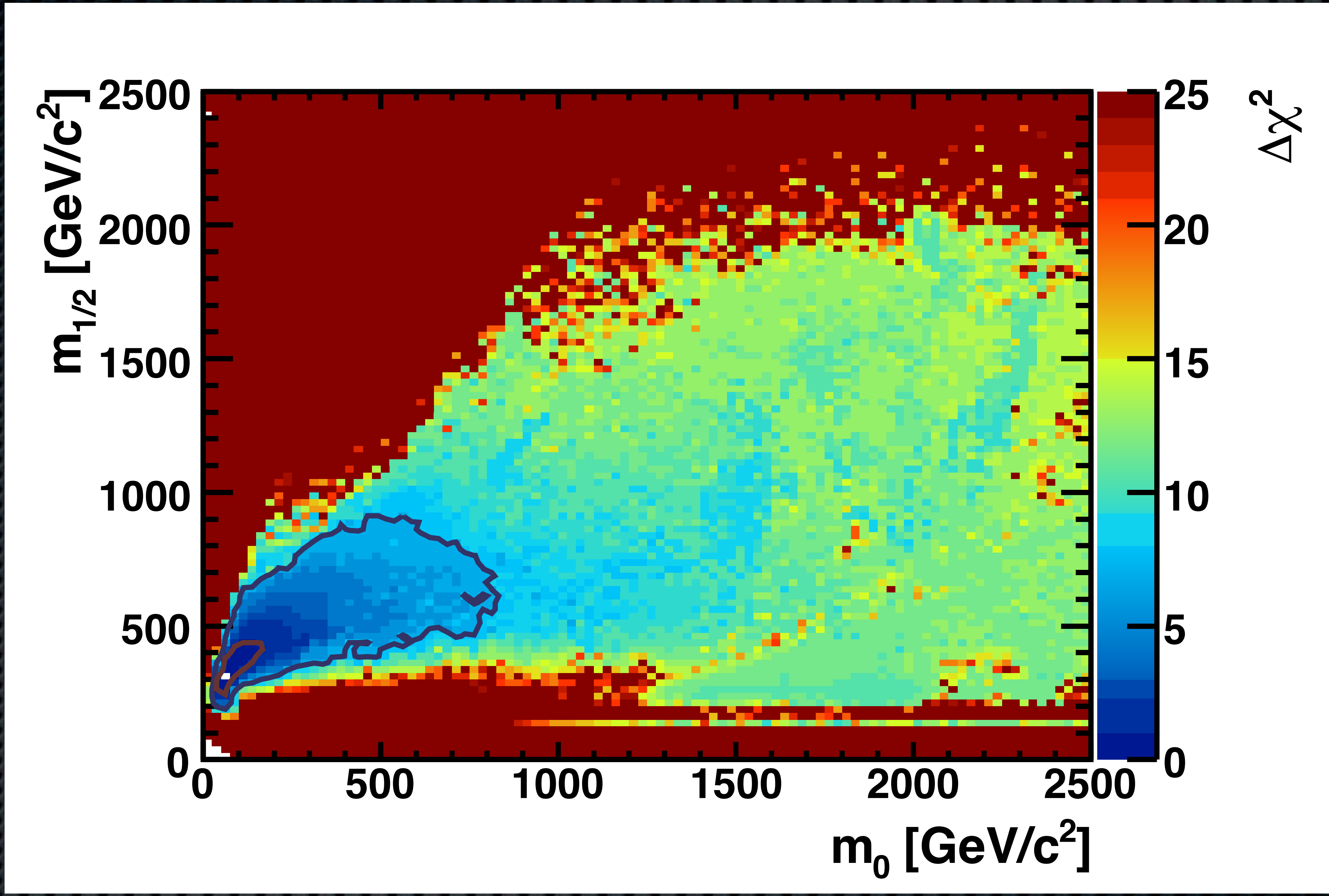
$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2}$$
$$+ \chi^2(M_h) + \chi^2(\mathrm{BR}(B_s \to \mu\mu))$$
$$+ \chi^2(\text{SUSY search limits})$$
$$+ \sum_i^M \frac{(f^{\mathrm{obs}}_{\mathrm{SM}_i} - f^{\mathrm{fit}}_{\mathrm{SM}_i})^2}{\sigma(f_{\mathrm{SM}_i})^2}$$

Observable
$\Delta\alpha^{(5)}_{\mathrm{had}}(m_Z)$
m_Z [GeV/c^2]
Γ_Z [GeV/c^2]
σ^0_{had} [nb]
R_l
$A_{\mathrm{fb}}(\ell)$
$A_\ell(P_\tau)$
R_{b}
R_{c}
$A_{\mathrm{fb}}(\mathrm{b})$
$A_{\mathrm{fb}}(\mathrm{c})$
A_{b}
A_{c}
$A_\ell(\mathrm{SLD})$
$\sin^2\theta^\ell_{\mathrm{w}}(Q_{\mathrm{fb}})$

Observable
m_W [GeV/c^2]
$a^{\mathrm{exp}}_\mu - a^{\mathrm{SM}}_\mu$
m_h [GeV/c^2]
$\mathrm{BR}^{\mathrm{exp}}_{b\to s\gamma}/\mathrm{BR}^{\mathrm{SM}}_{b\to s\gamma}$
m_t [GeV/c^2]
$\Omega_{\mathrm{CDM}}h^2$
$\mathrm{BR}(B_s \to \mu^+\mu^-)$
$\mathrm{BR}^{\mathrm{exp}}_{B\to\tau\nu}/\mathrm{BR}^{\mathrm{SM}}_{B\to\tau\nu}$
$\mathrm{BR}^{\mathrm{exp}}_{B_d\to\ell\ell}/\mathrm{BR}^{\mathrm{SM}}_{B_d\to\ell\ell}$
$\mathrm{BR}^{\mathrm{exp}}_{B\to X_s\ell\ell}/\mathrm{BR}^{\mathrm{SM}}_{B\to X_s\ell\ell}$
$\mathrm{BR}^{\mathrm{exp}}_{K\to\mu\nu}/\mathrm{BR}^{\mathrm{SM}}_{K\to\mu\nu}$
$\mathrm{BR}^{\mathrm{exp}}_{K\to\pi\nu\bar\nu}/\mathrm{BR}^{\mathrm{SM}}_{K\to\pi\nu\bar\nu}$
$\Delta m^{\mathrm{exp}}_s/\Delta m^{\mathrm{SM}}_s$
$\frac{(\Delta m^{\mathrm{exp}}_s/\Delta m^{\mathrm{SM}}_s)}{(\Delta m^{\mathrm{exp}}_d/\Delta m^{\mathrm{SM}}_d)}$
$\Delta m^{\mathrm{exp}}_K/\Delta m^{\mathrm{SM}}_K$

$\Delta\chi^2$ map of m_0 - $m_{1/2}$ plane

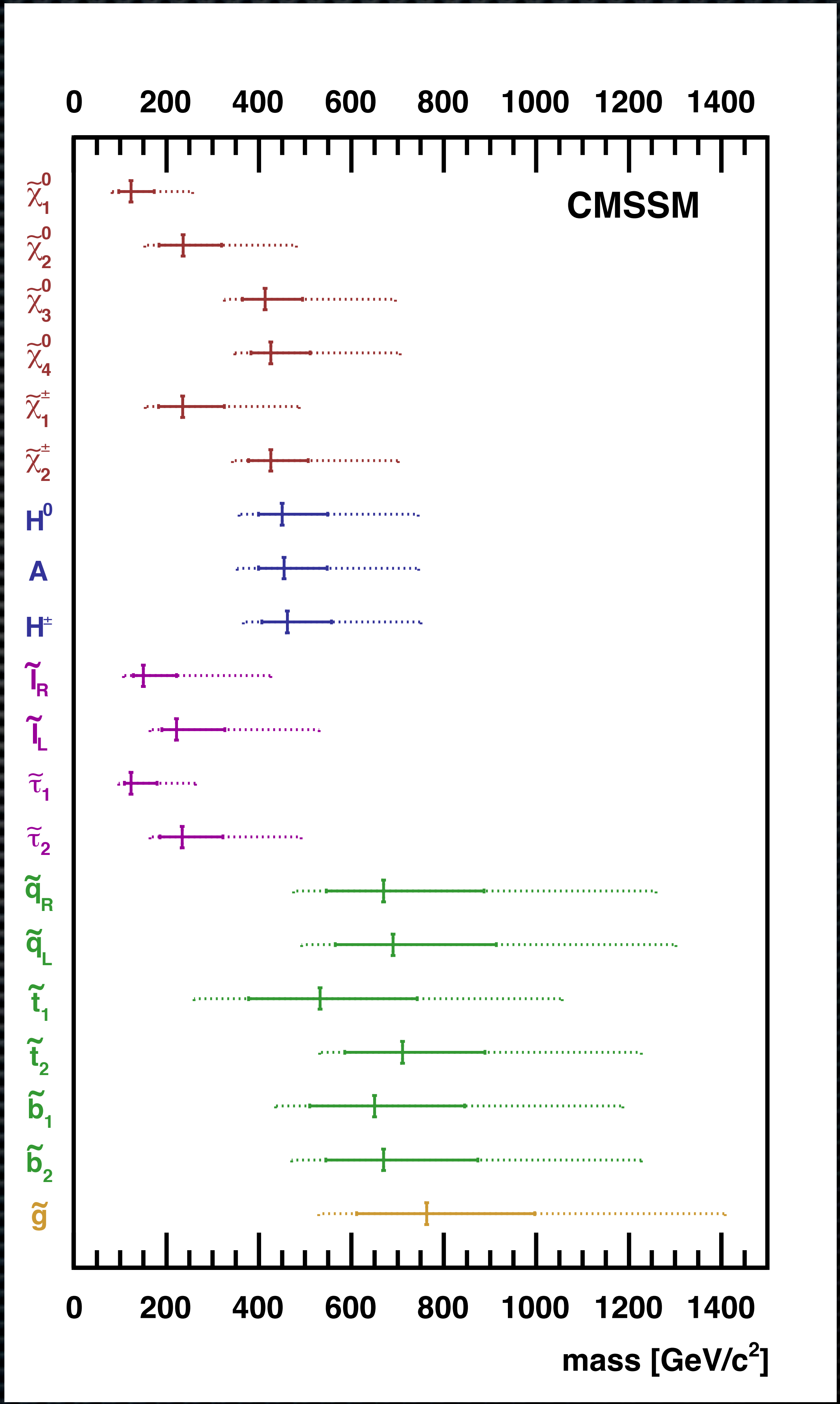
Mastercode



Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Ronga, Weiglein

- CMSSM

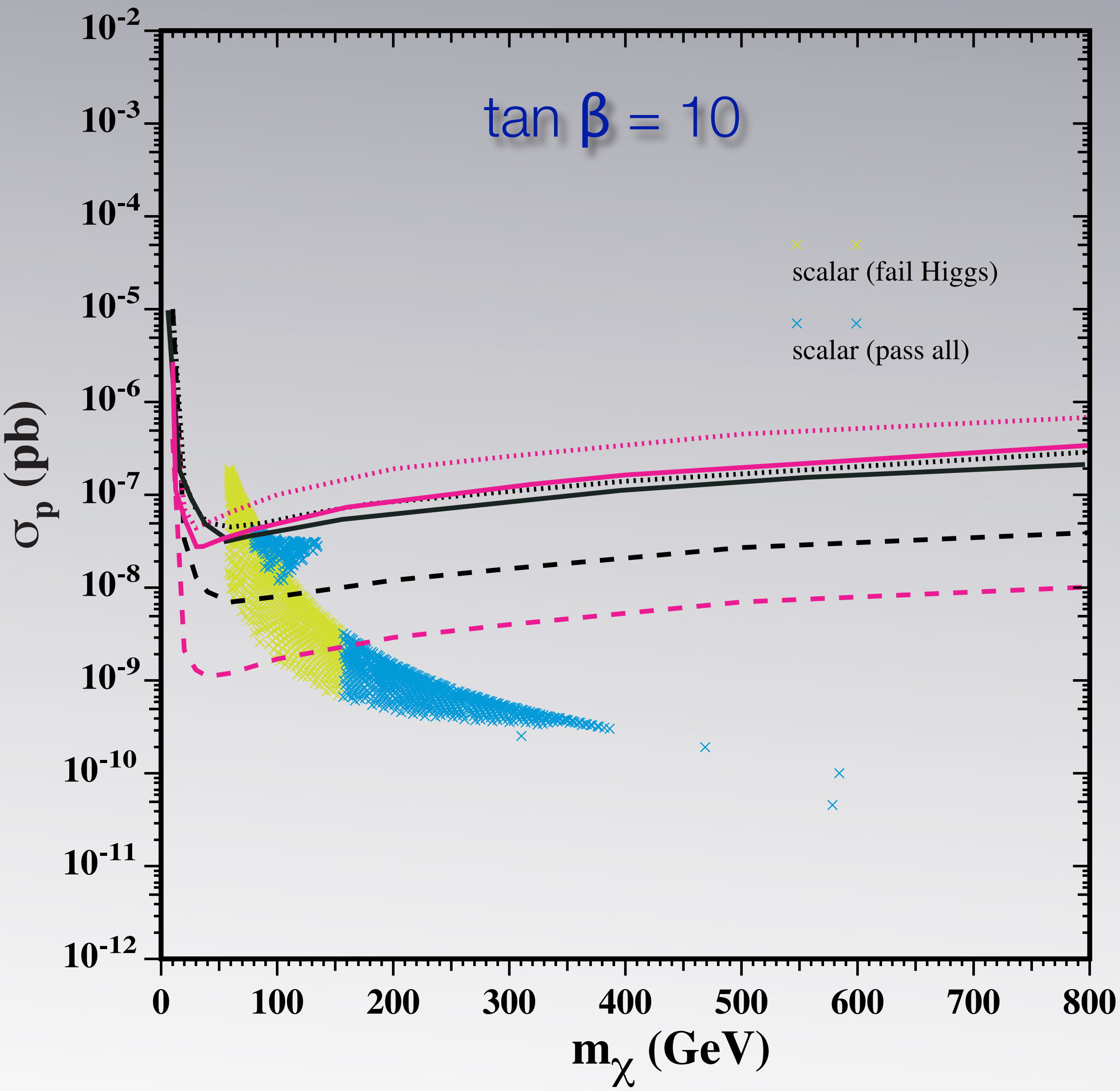
- Mass spectrum of best fit point is relatively light

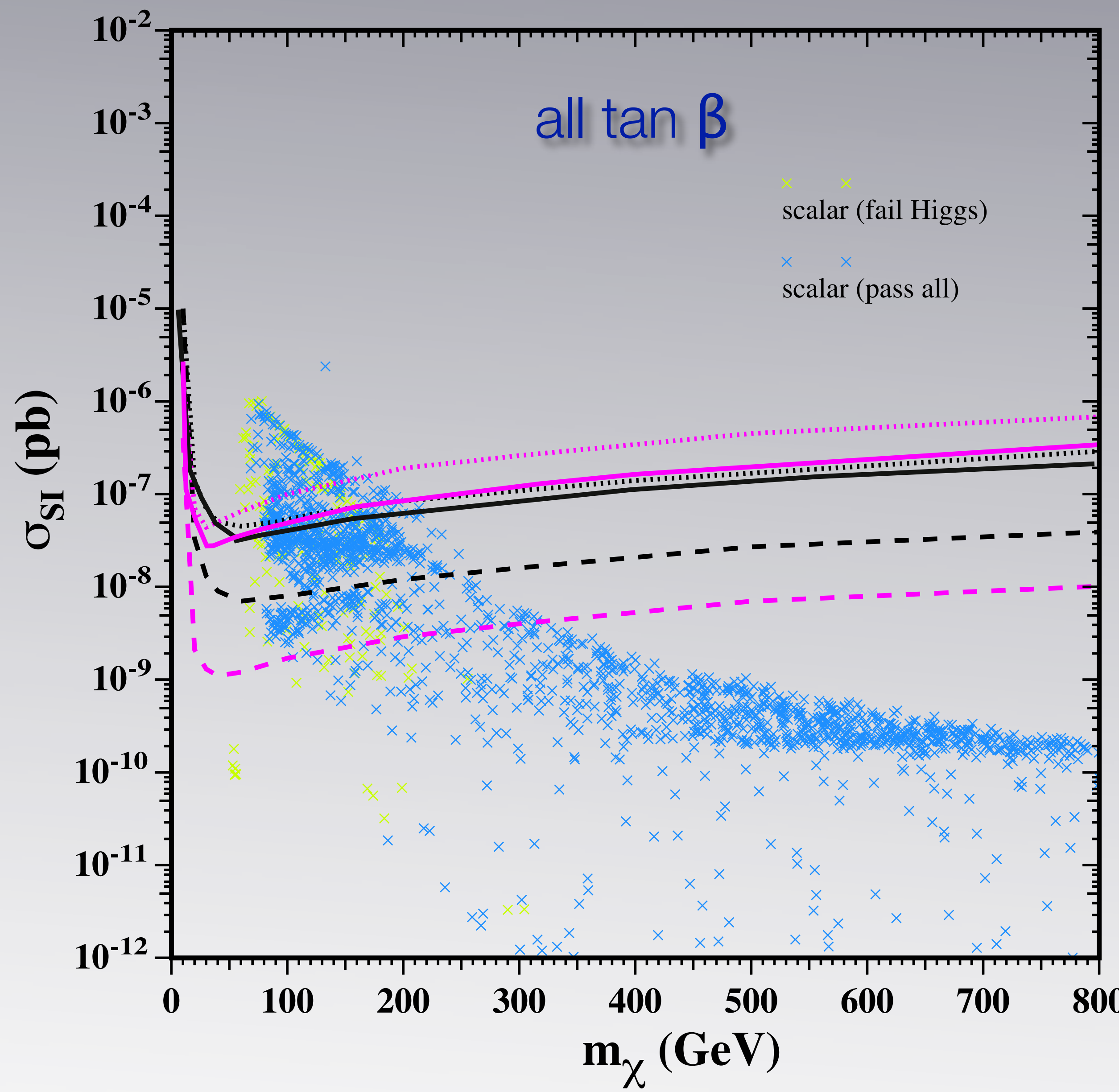


Mastercode

Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Ronga, Weiglein

Elastic cross section for direct detection

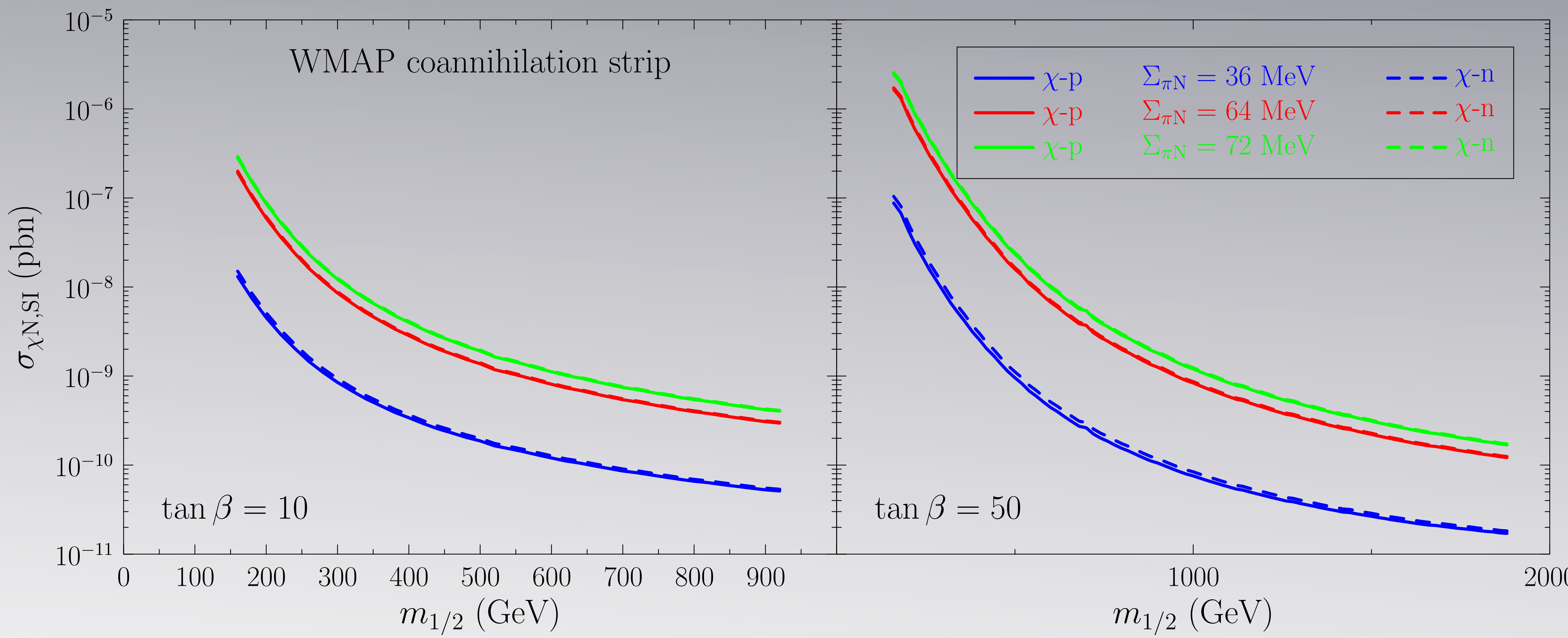




- CMSSM

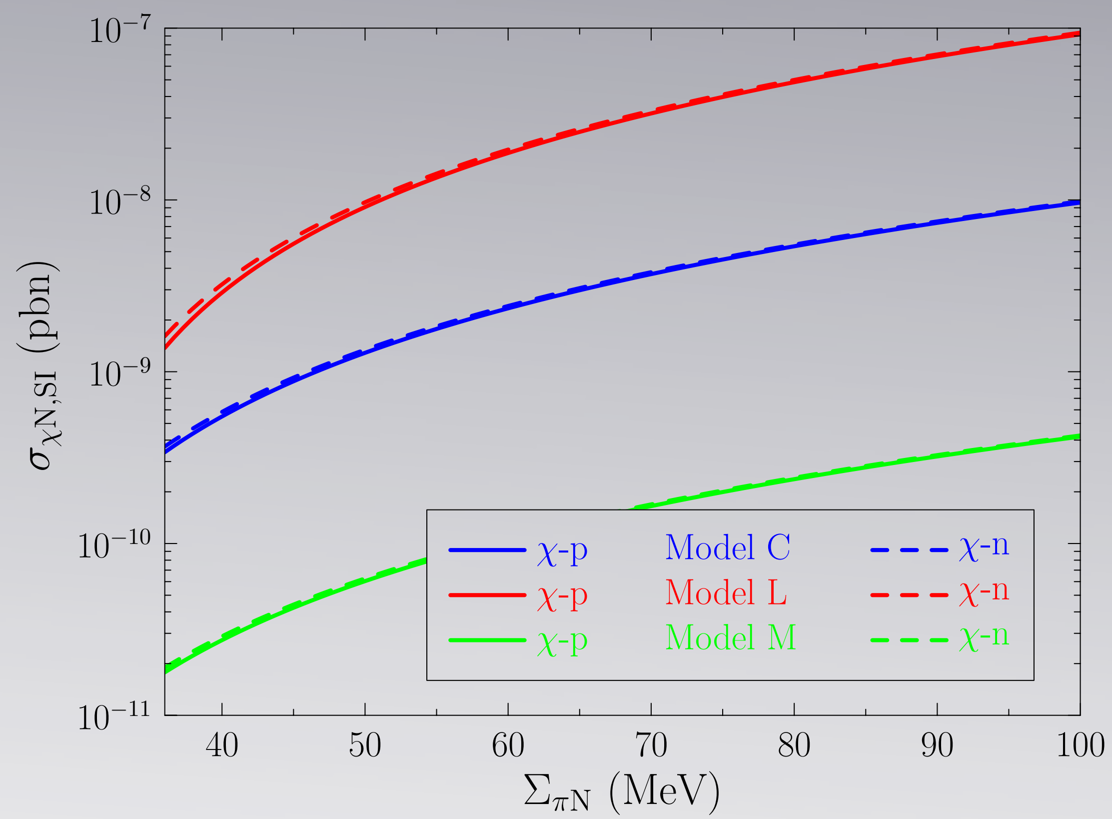
Ellis, Olive, Sandick

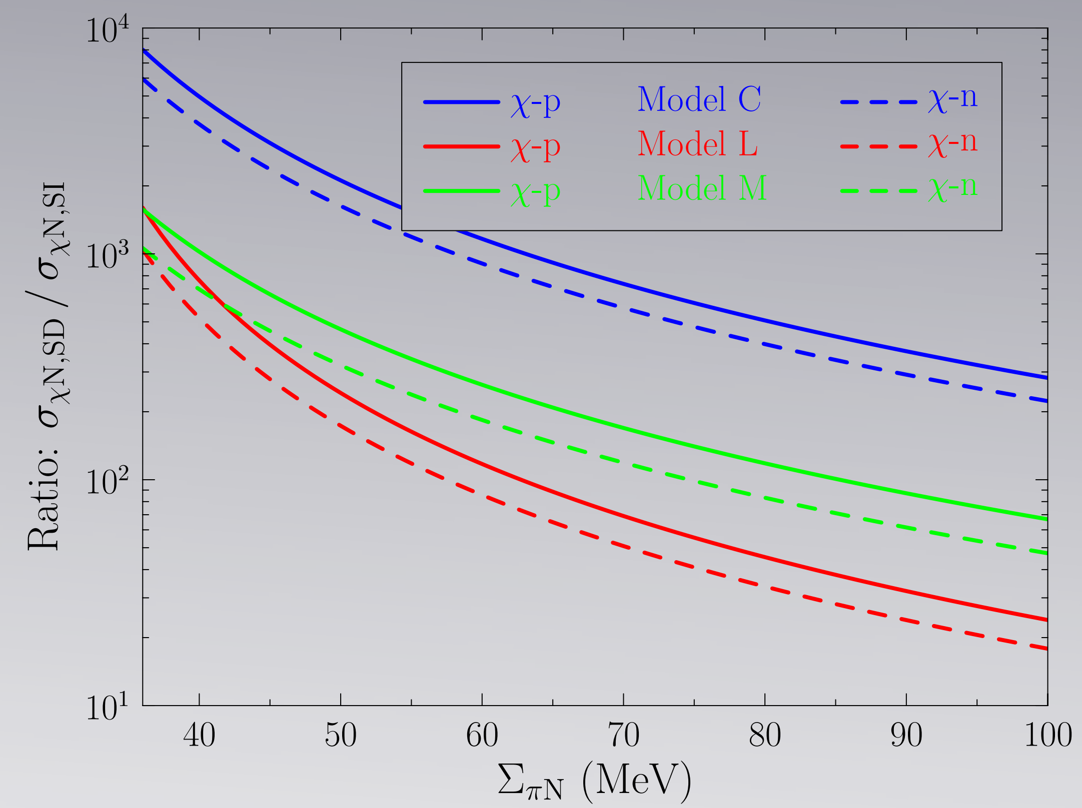
Uncertainties due to $\Sigma_{\pi N}$



Ellis, Olive, and Savage

Benchmarks as a function of $\Sigma_{\pi N}$

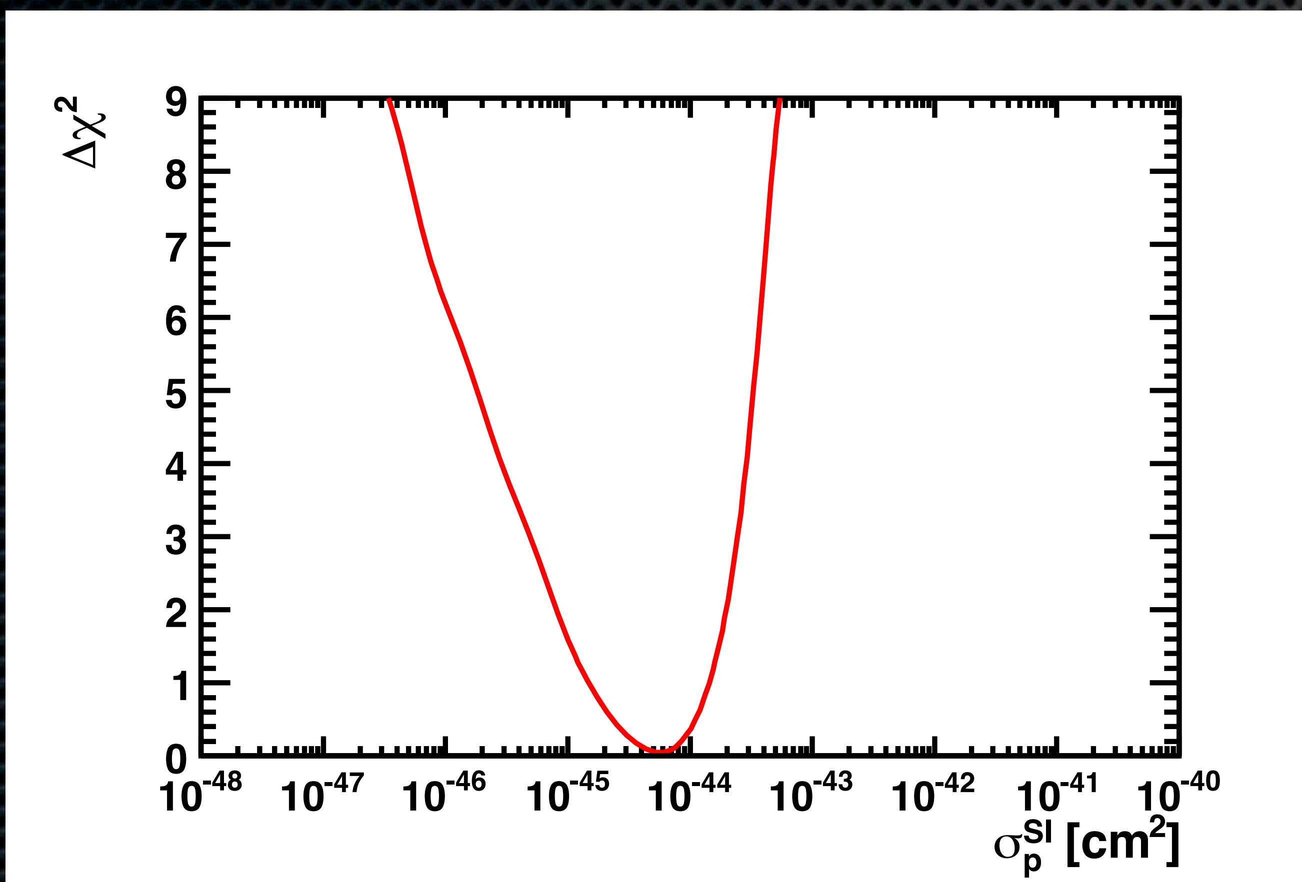


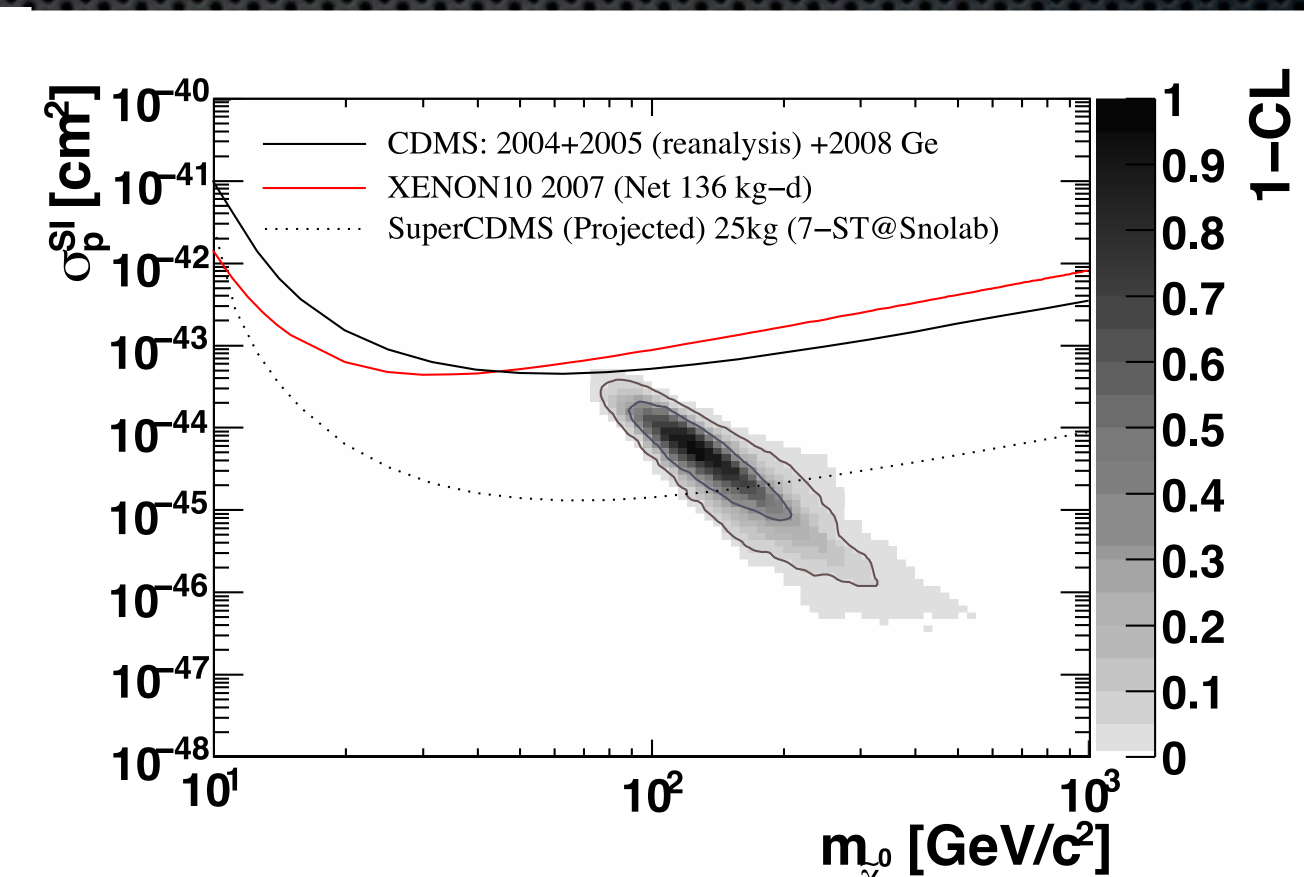


Ellis, Olive, Savage, and Spanos

Elastic cross section from MCMC analysis

Mastercode

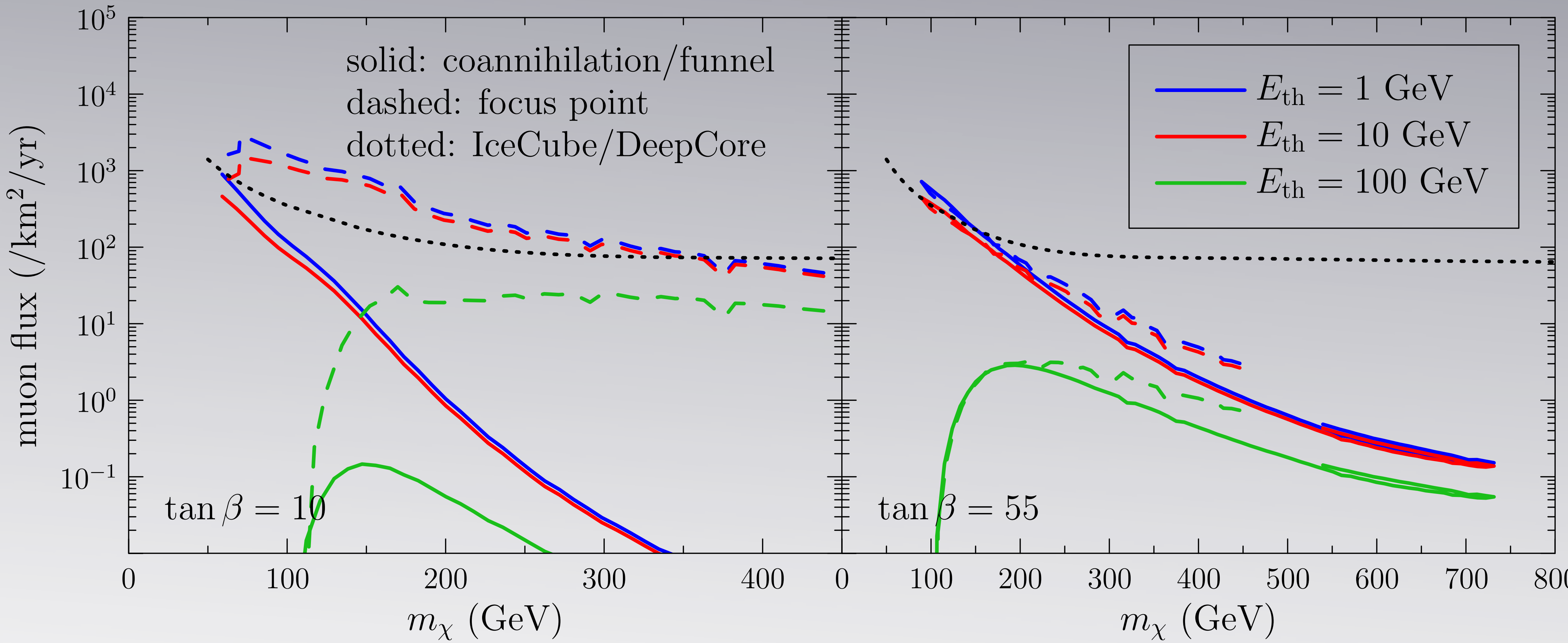




- CMSSM

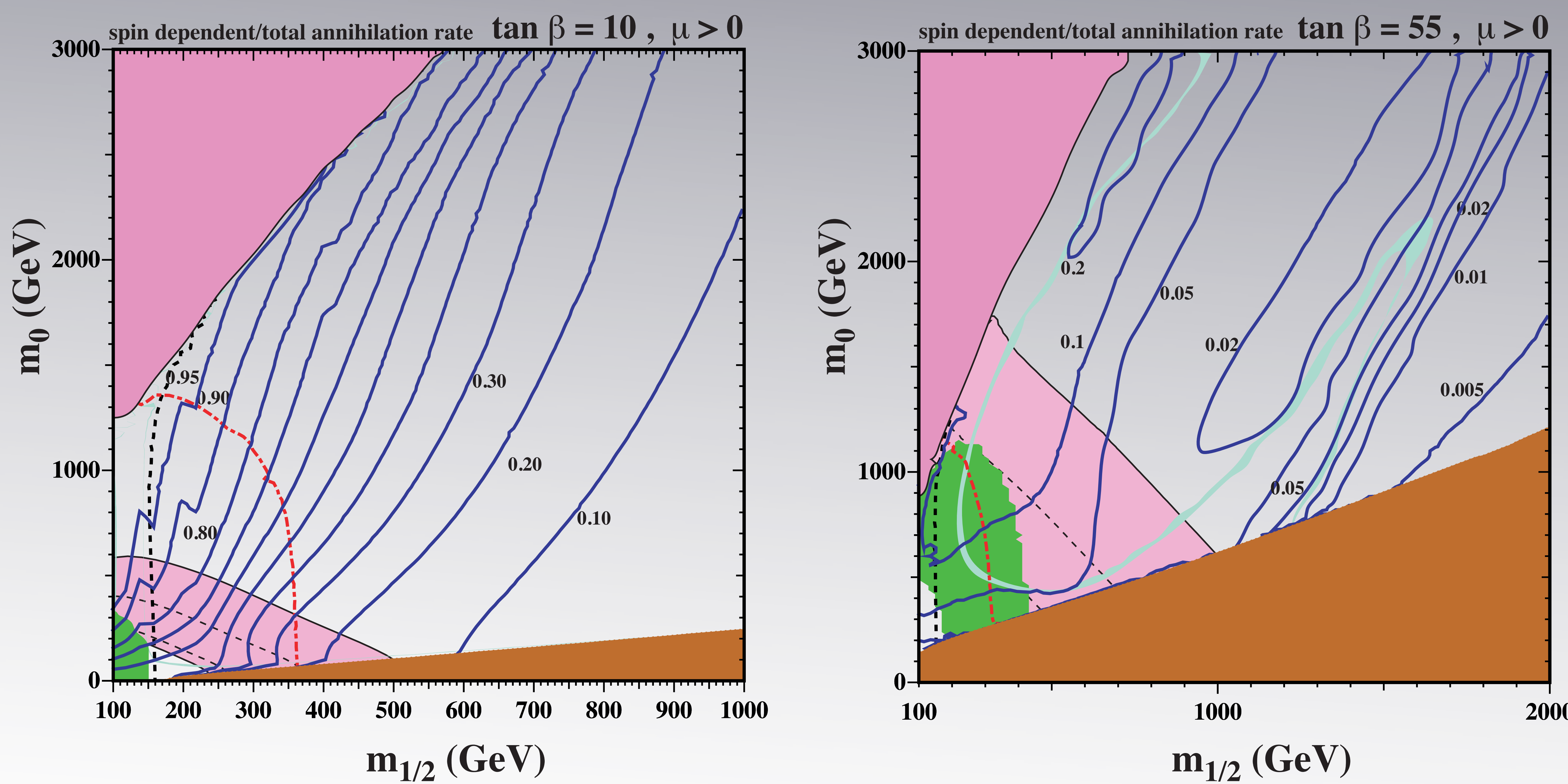
Buchmueller, Cavanaugh, De Roeck, Ellis, Flacher, Heinemeyer, Isidori, Olive, Ronga, Weiglein

Indirect Detection in the CMSSM



Ellis, Olive, Savage, and Spanos

Spin-Independent contibution to capture in the sun



Ellis, Olive, Savage, and Spanos

mSUGRA Models

- tan β fixed by boundary conditions ($B_0 = A_0 - m_0$)
- ``planes'' determined by A_0/m_0
- Gravitino often the LSP ($m_{3/2} = m_0$)
- No Funnels
- No Focus Point

Minimal Supergravity Models

e.g. Barbieri, Ferrara, Savoy

Nilles, Srednicki, Wyler

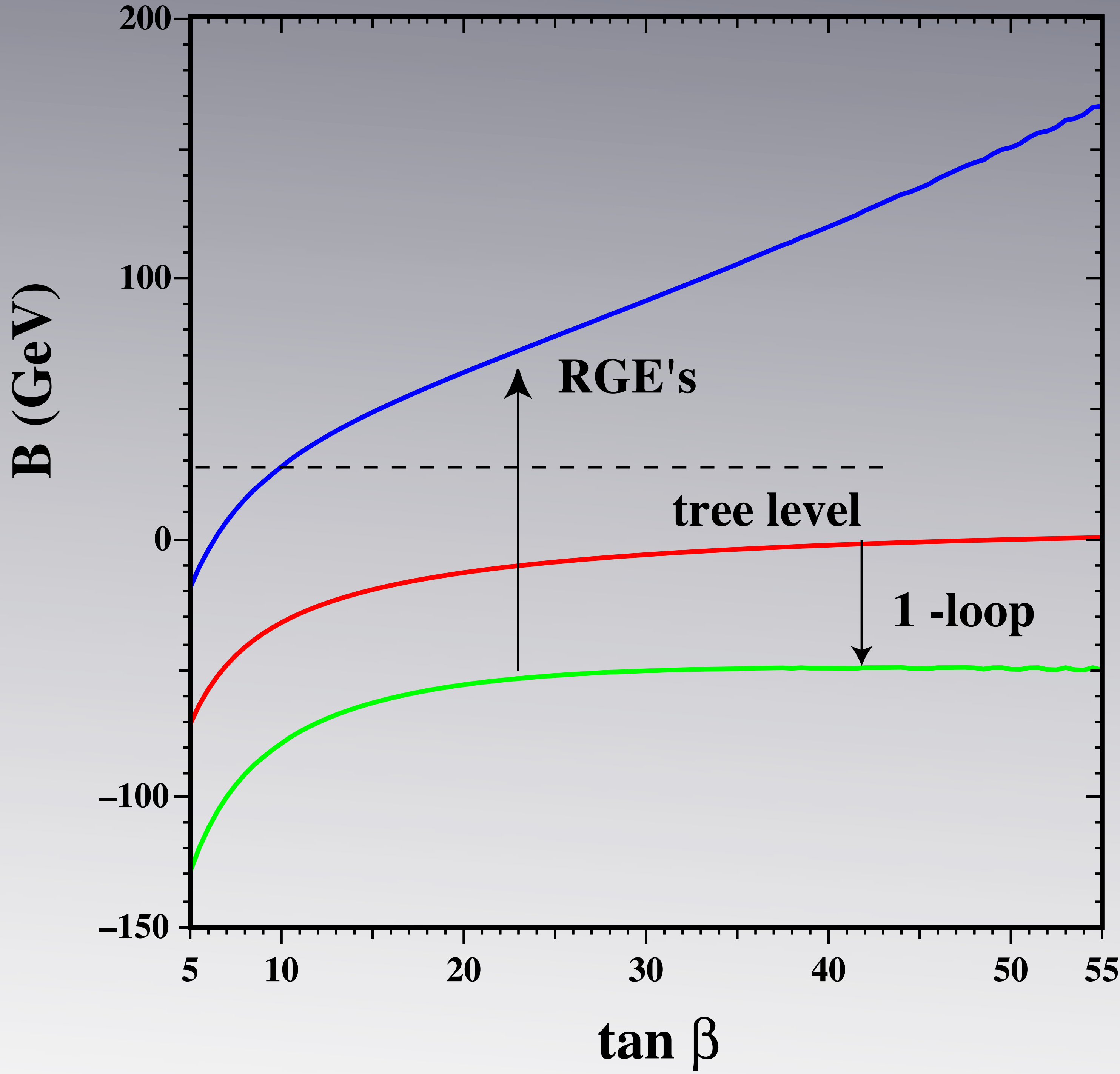
$G = \varphi\,\varphi^* + z\,z^* + \ln|W|^2;\;\; W = f(z) + g(\varphi)$

$$V = \left|\frac{\partial g}{\partial \varphi}\right|^2 + m_{3/2}\left(\varphi\frac{\partial g}{\partial \varphi} + \left(\sqrt{3}\langle z\rangle - 3\right)g + h.c.\right) + m_{3/2}{}^2\varphi\varphi^*$$

3g for trilinear terms
2g for bilinear terms

For Polonyi models $\langle z\rangle = \sqrt{3} - 1$, and

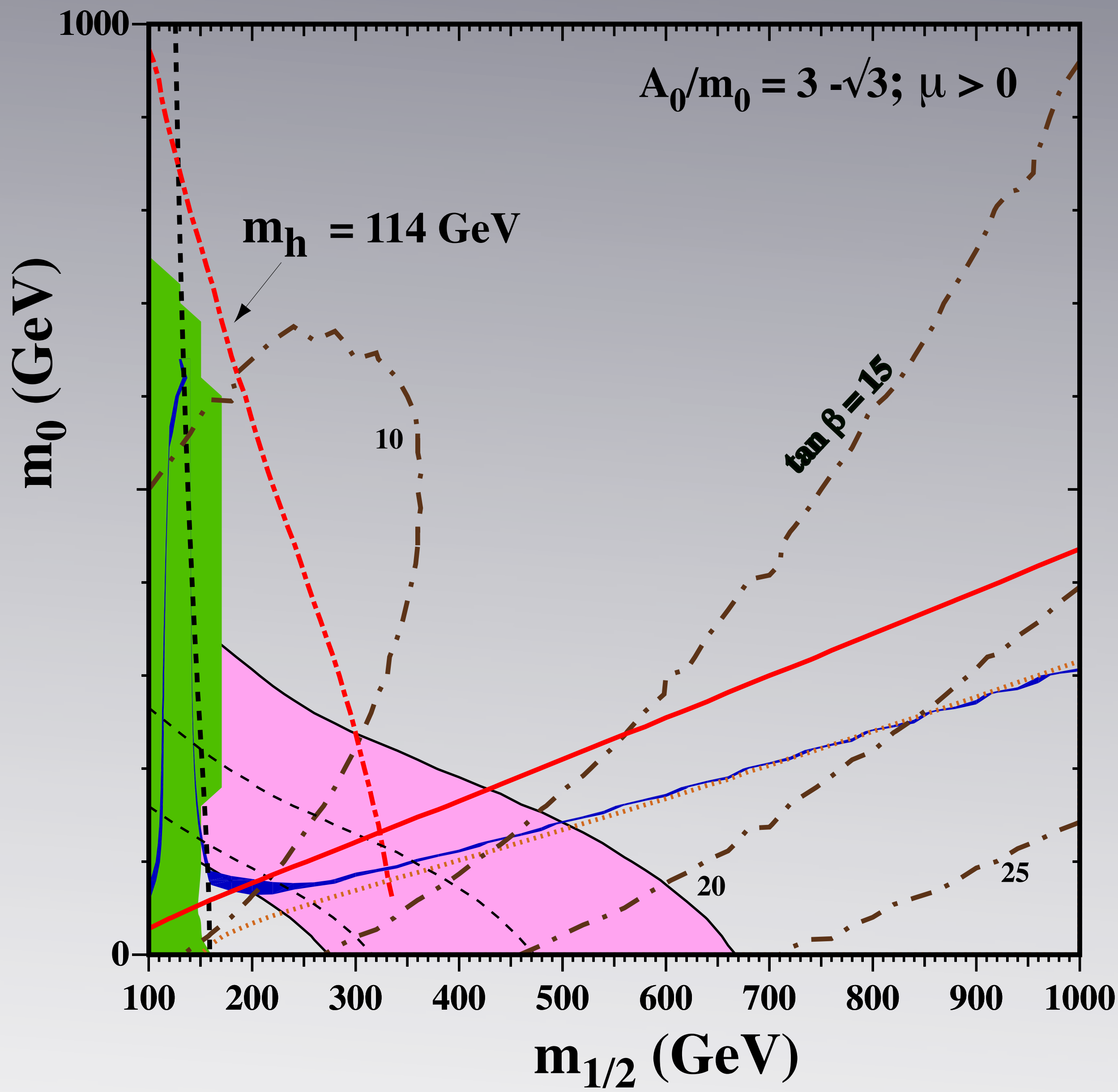
$\longrightarrow$ $m_0 = m_{3/2}$; $A_0 = (3 - \sqrt{3})\, m_0$; $B_0 = A_0 - m_0$

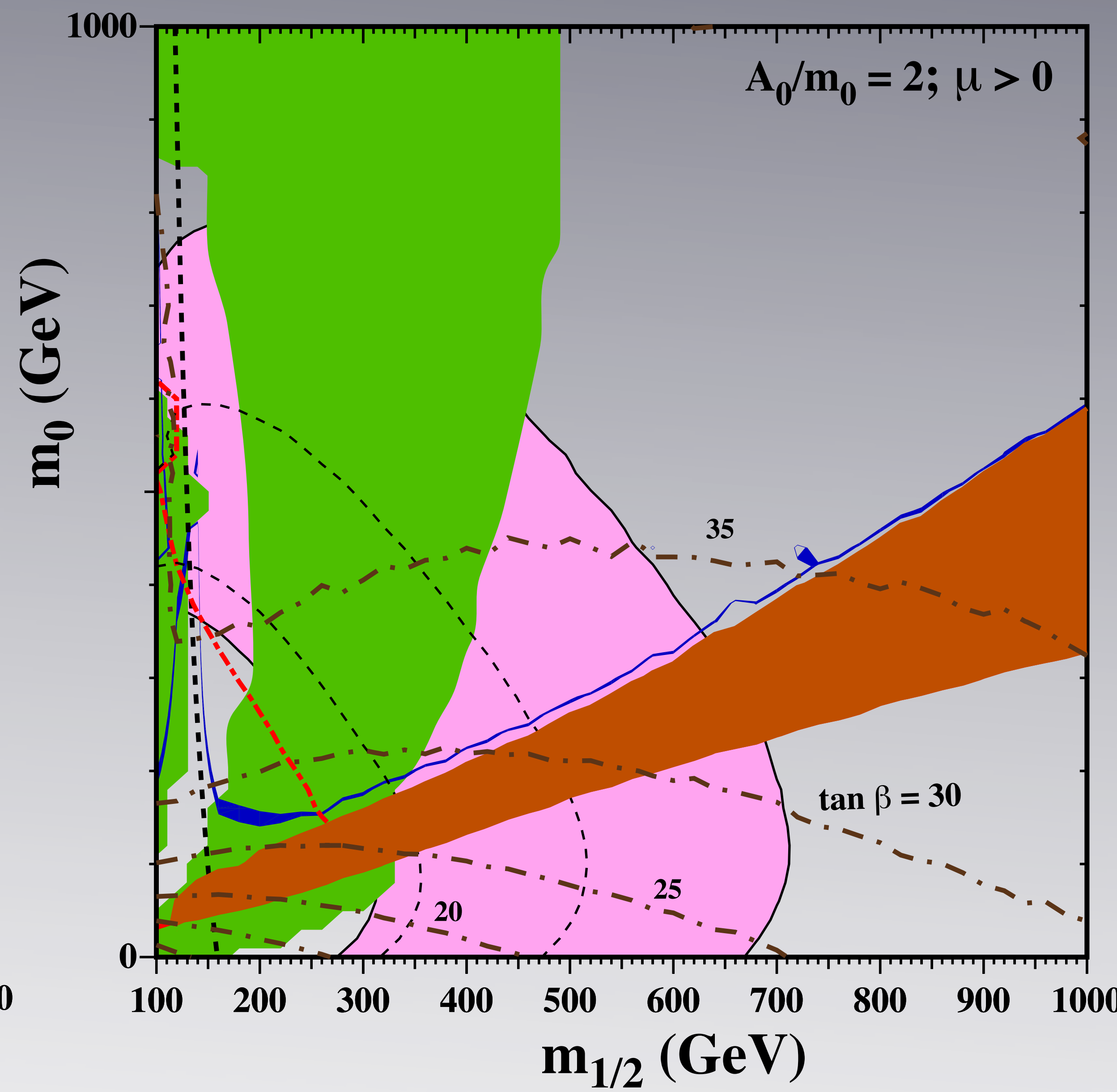


In the CMSSM, any choice of B/tan β is allowed.

The condition
$B_0 = A_0 - m_0$ restricts
tan β to a specific value.

$m_{1/2}$ - m_0 planes

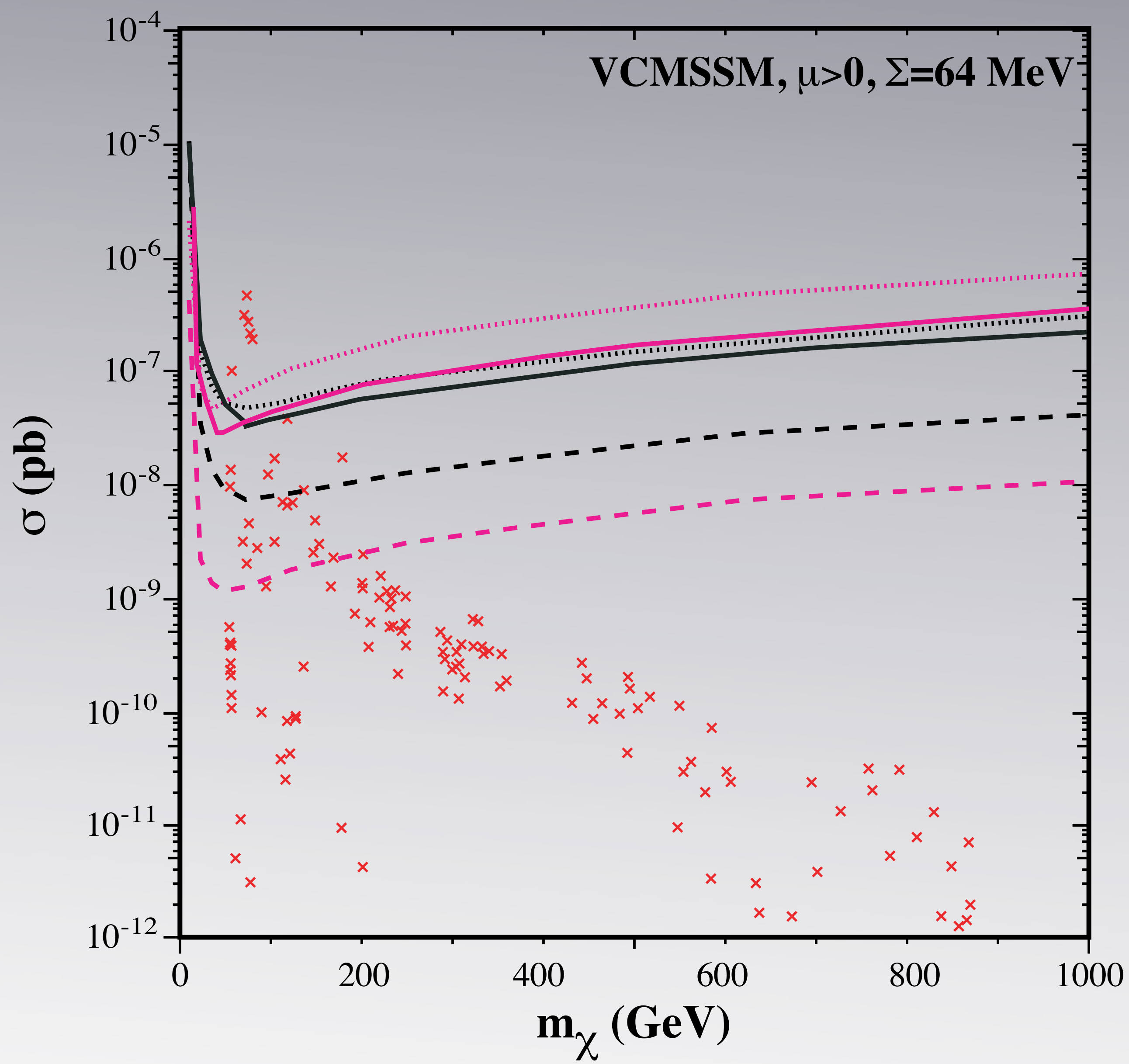




- VCMSSM (mSUGRA)

Ellis, Olive, Santoso, Spanos

Elastic cross section for direct detection



- VCMSSM (mSUGRA)

No-Scale Supergravity

$$
\begin{aligned}
G &= \frac{K}{M_P^2} + F\left(\phi^i\right) + F^\dagger\left(\phi_i^*\right) \\
K &= -3\,M_P^2 \ln\left[\frac{z+z^*}{M_P} - \frac{\phi^i\,\phi_i^*}{3\,M_P^2}\right]
\end{aligned}
$$

$$V = e^{G - \frac{1}{3}K} |F_i|^2$$

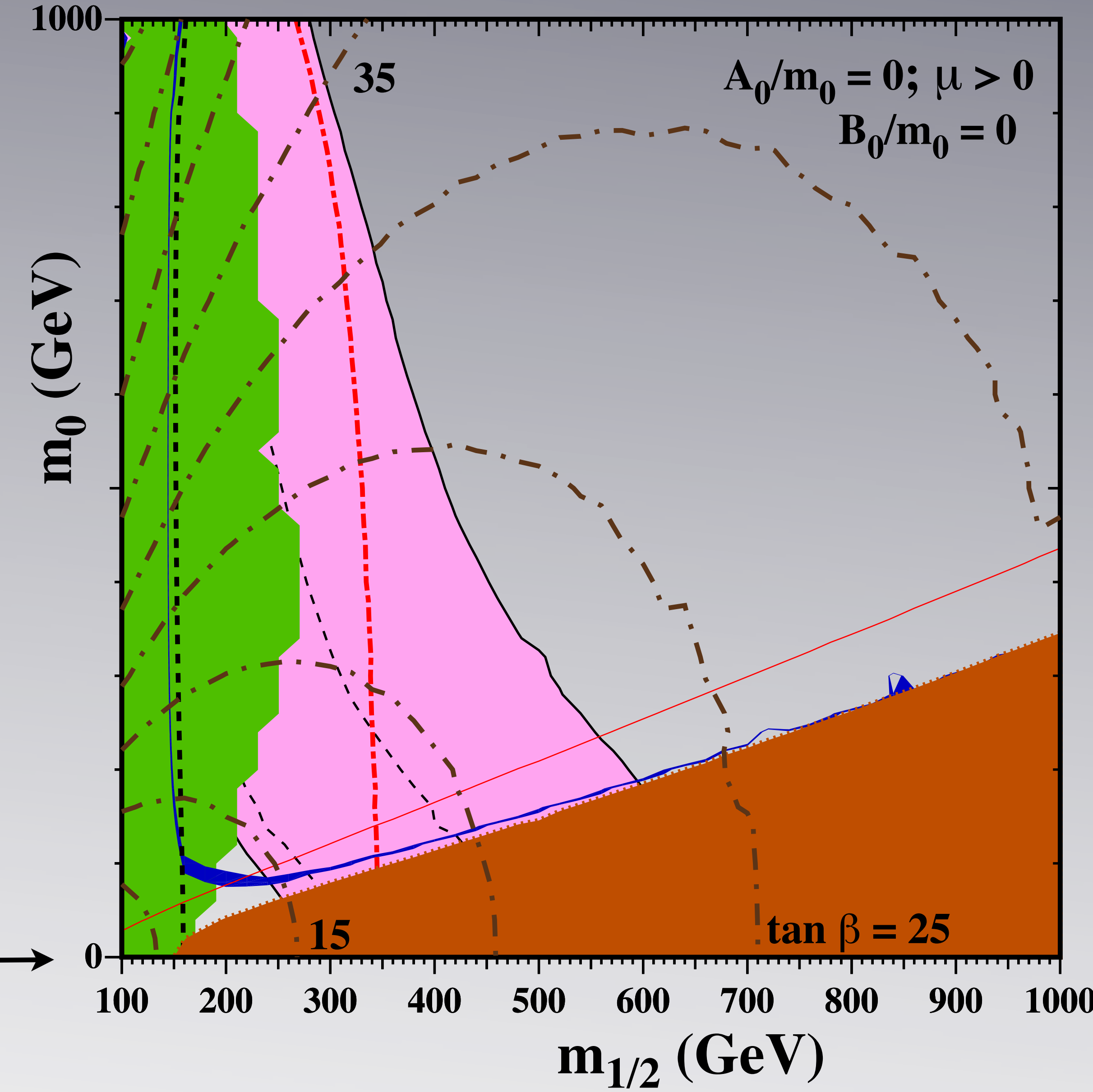
gauge kinetic function

$$m_\lambda = \frac{1}{2} m_{3/2}^{1/3} \frac{h_{,z}}{Reh}$$

Gravitino mass set independently from $m_{1/2}$ and m_0

$m_{1/2}$ - m_0 planes with $A_0 = B_0 = 0$

No-Scale



- VCMSSM (incl. no-scale supergravity)

Super GUT Models

Ellis, Mustafayev, Olive
also: Polonsky + Pomerol;
Calibbi, Mambrini, Vempati;
Carquin, Ellis, Gomez, Lola,
Rodriguez-Quintero

- What if the input scale for supersymmetry breaking, M_{in}, is $> M_{GUT}$?
- Additional RGE running (between M_{in} and M_{GUT}) implies more splitting between sparticle masses
- co-annihilation region squeezed to lower $m_{1/2}$ - (due to increased splitting at high M_{in})
- focus point region shifts to higher m_0 - (due to increased running of soft Higgs masses at high M_{in})
- funnel region persist to low m_0 and may remain consistent with g-2

GUTSuperpotential

$$W_5 = \mu_\Sigma \,\mathrm{Tr}\,\hat\Sigma^2 + \frac{1}{6}\lambda' \,\mathrm{Tr}\,\hat\Sigma^3 + \mu_H \hat{\mathcal{H}}_{1\alpha}\hat{\mathcal{H}}_2^\alpha + \lambda \hat{\mathcal{H}}_{1\alpha}\hat\Sigma^\alpha_\beta \hat{\mathcal{H}}_2^\beta$$
$$+(\mathbf{h_{10}})_{ij}\epsilon_{\alpha\beta\gamma\delta\zeta}\hat\psi_i^{\alpha\beta}\hat\psi_j^{\gamma\delta}\hat{\mathcal{H}}_2^\zeta + (\mathbf{h_{\overline{5}}})_{ij}\hat\psi_i^{\alpha\beta}\hat\phi_{j\alpha}\hat{\mathcal{H}}_{1\beta}$$

New couplings: λ and λ'

λ affects running of soft Higgs masses, adjoint and Yukawas ; λ' affects only the adjoint

New soft masses and μ terms

GUTSuperpotential

$$\begin{aligned} W_5 &= \mu_\Sigma \operatorname{Tr}\hat{\Sigma}^2 + \frac{1}{6}\lambda' \operatorname{Tr}\hat{\Sigma}^3 + \mu_H \hat{\mathcal{H}}_{1\alpha}\hat{\mathcal{H}}_2^\alpha + \lambda \hat{\mathcal{H}}_{1\alpha}\hat{\Sigma}^\alpha_\beta \hat{\mathcal{H}}_2^\beta \\ &\quad + (\mathbf{h_{10}})_{ij}\epsilon_{\alpha\beta\gamma\delta\zeta}\hat{\psi}_i^{\alpha\beta}\hat{\psi}_j^{\gamma\delta}\hat{\mathcal{H}}_2^\zeta + (\mathbf{h_{\overline{5}}})_{ij}\hat{\psi}_i^{\alpha\beta}\hat{\phi}_{j\alpha}\hat{\mathcal{H}}_{1\beta} \end{aligned}$$

New couplings: λ and λ'

λ affects running of soft Higgs masses, adjoint and Yukawas ; λ' affects only the adjoint

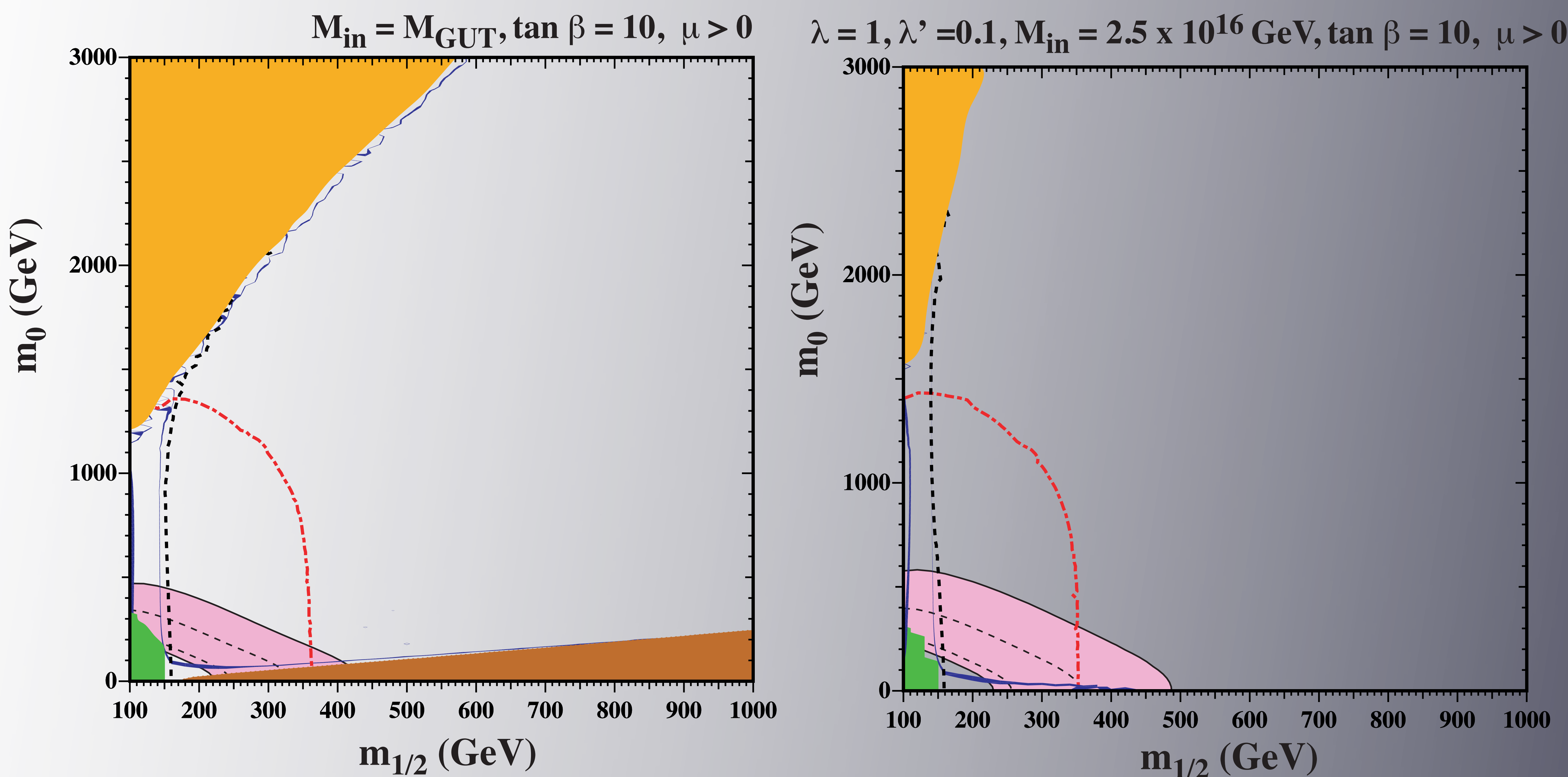
New soft masses and μ terms

Model Specified by 7+ parameters

$$m_0,\ m_{1/2},\ A_0,\ M_{in},\ \lambda,\ \lambda',\ \tan\beta,\ sgn(\mu)$$

$$\begin{aligned} m_{\overline{\mathbf{5}},1} = m_{\mathbf{10},1} = m_{\overline{\mathbf{5}}} = m_{\mathbf{10}} = m_{\mathcal{H}_1} = m_{\mathcal{H}_2} = m_\Sigma &\equiv m_0, \\ A_{\overline{\mathbf{5}}} = A_{\mathbf{10}} = A_\lambda = A_{\lambda'} &\equiv A_0, \\ M_5 &\equiv m_{1/2}. \end{aligned}$$

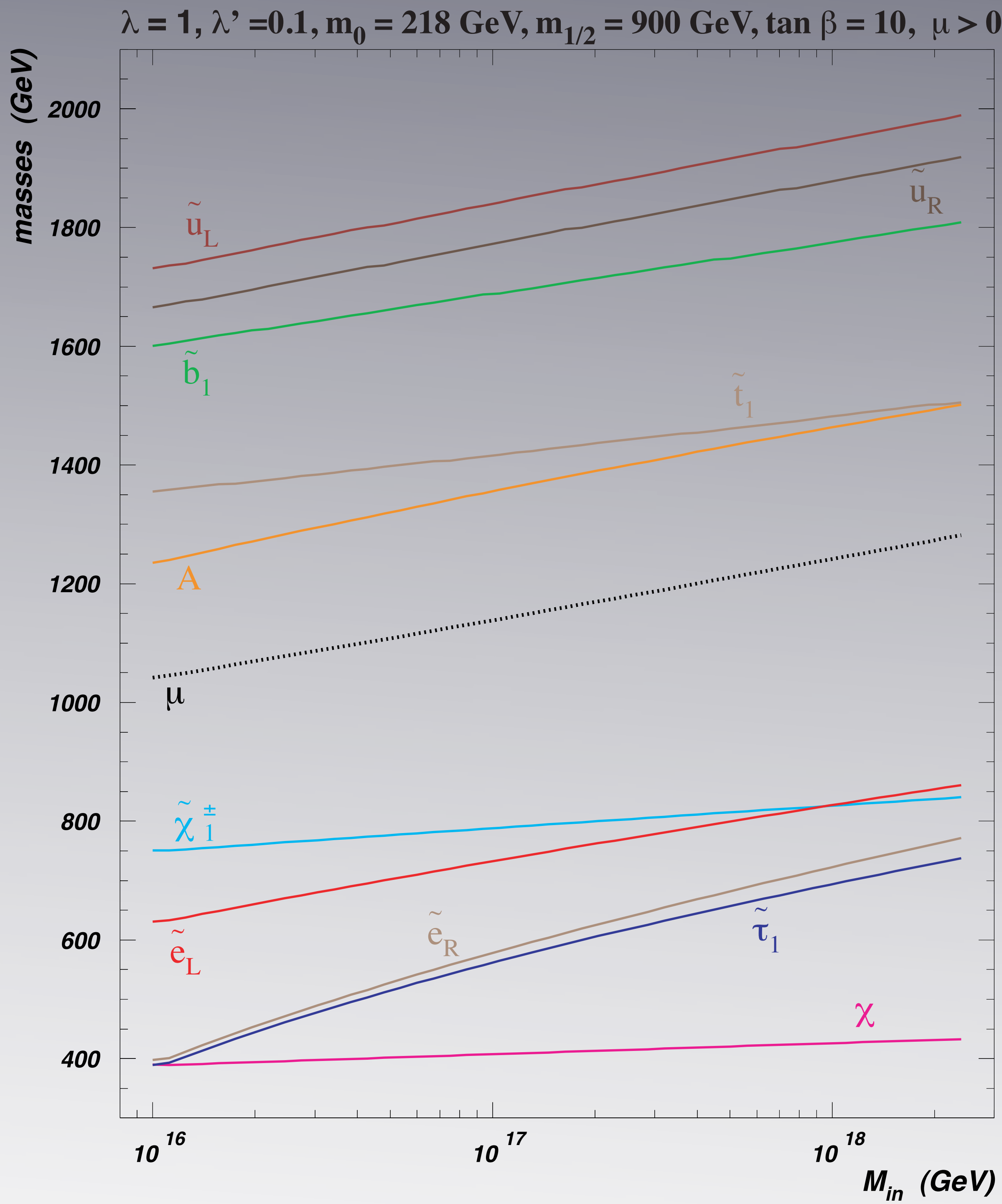
$m_{1/2}$ - m_0 planes

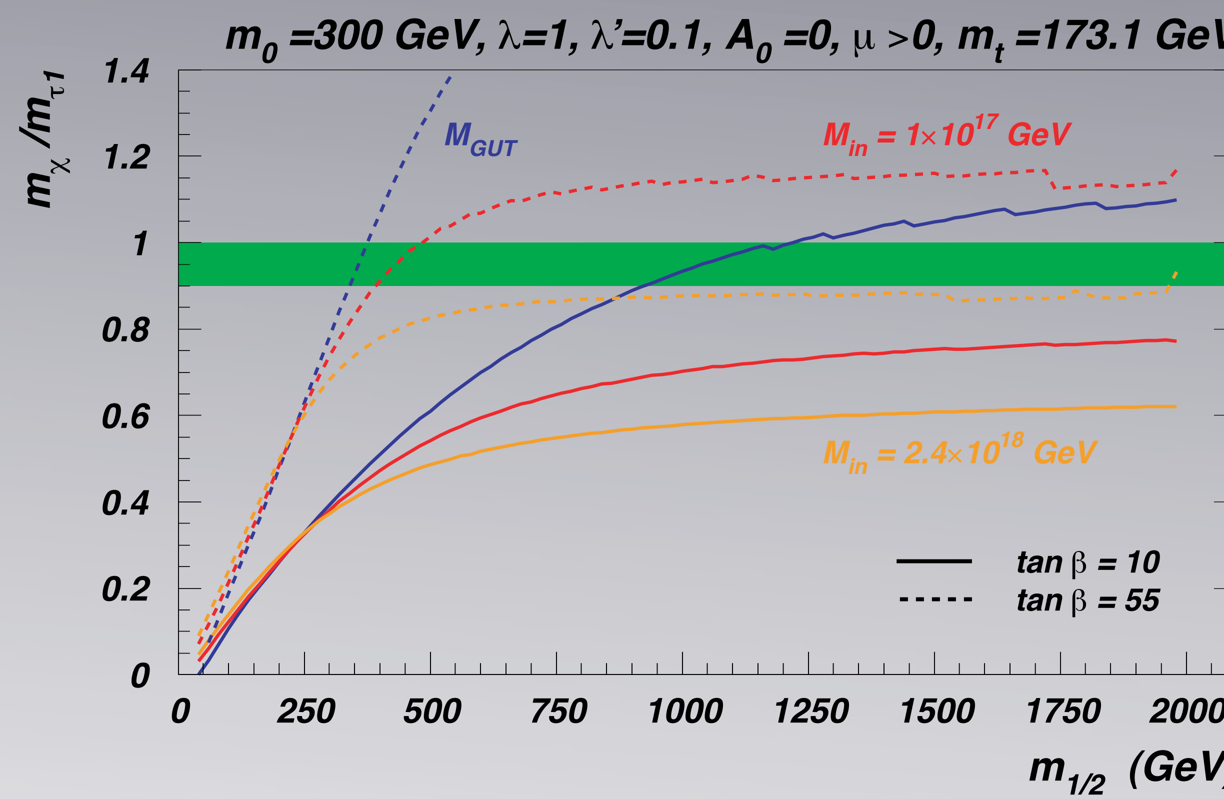


- SuperGUT CMSSM

Ellis, Mustafayev, Olive

Evolution of mass parameters near coannihilation region

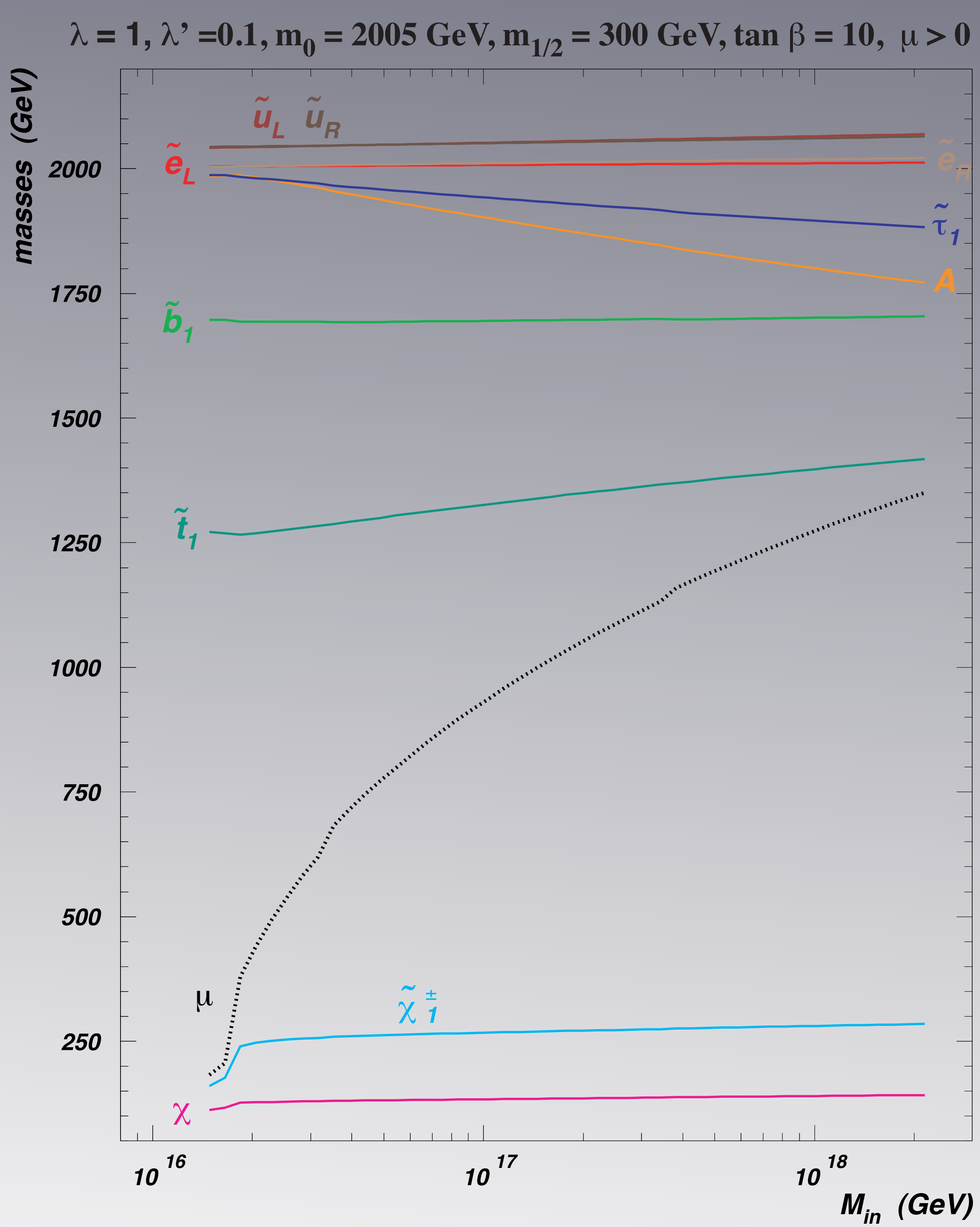


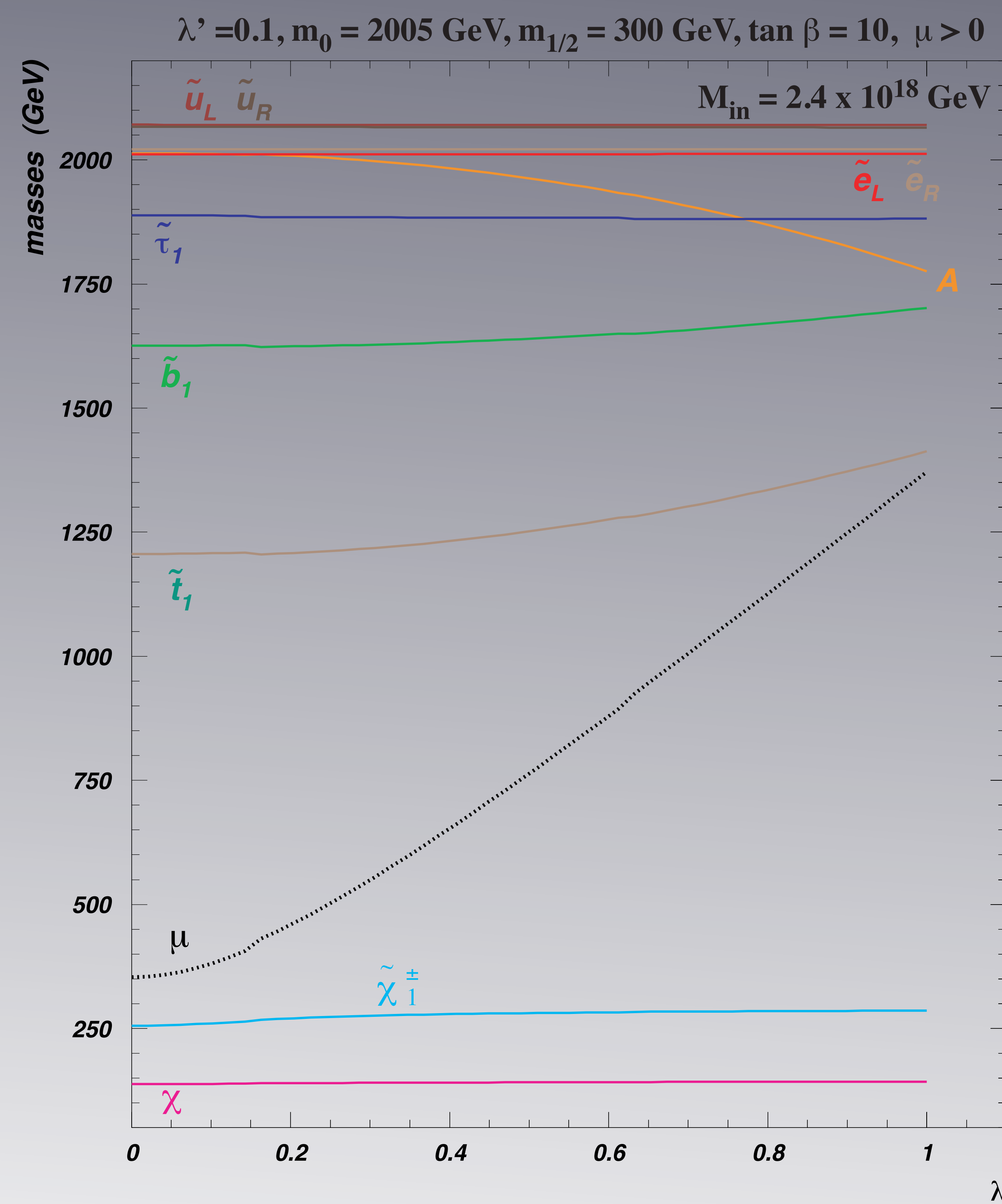


- SuperGUT CMSSM

Ellis, Mustafayev, Olive

Evolution of mass parameters near focus point

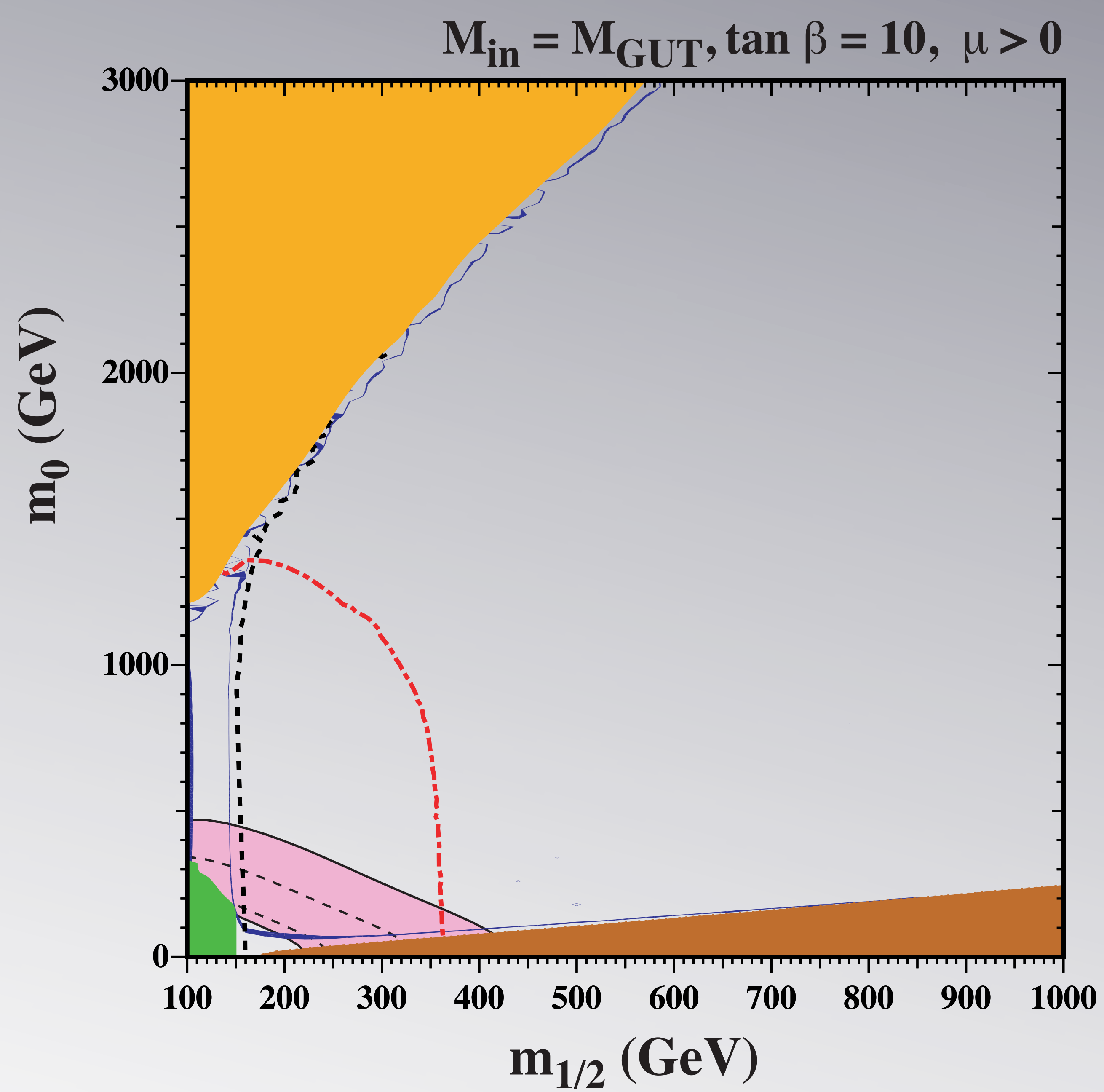


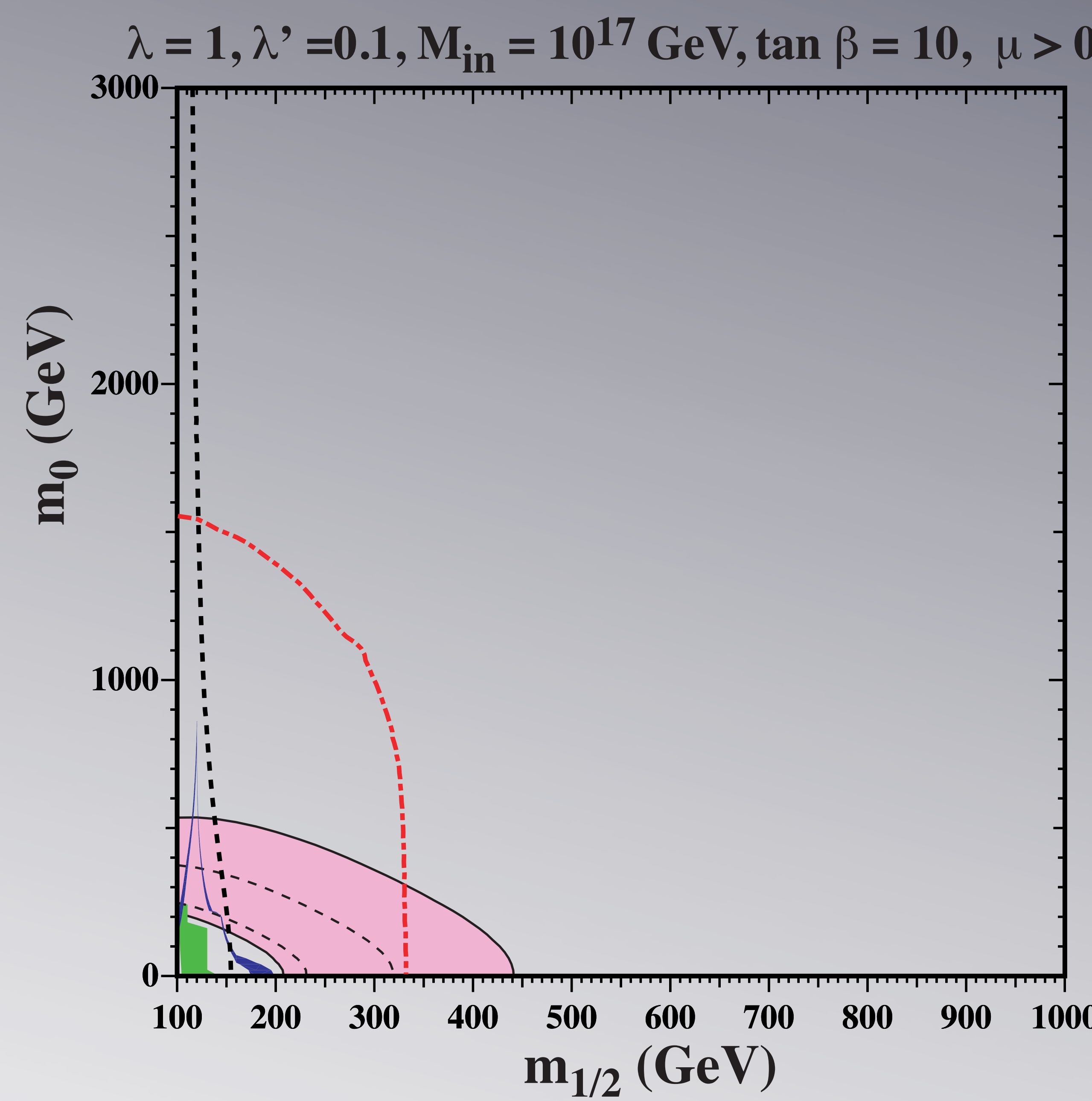


- SuperGUT CMSSM

Ellis, Mustafayev, Olive

$m_{1/2}$ - m_0 planes

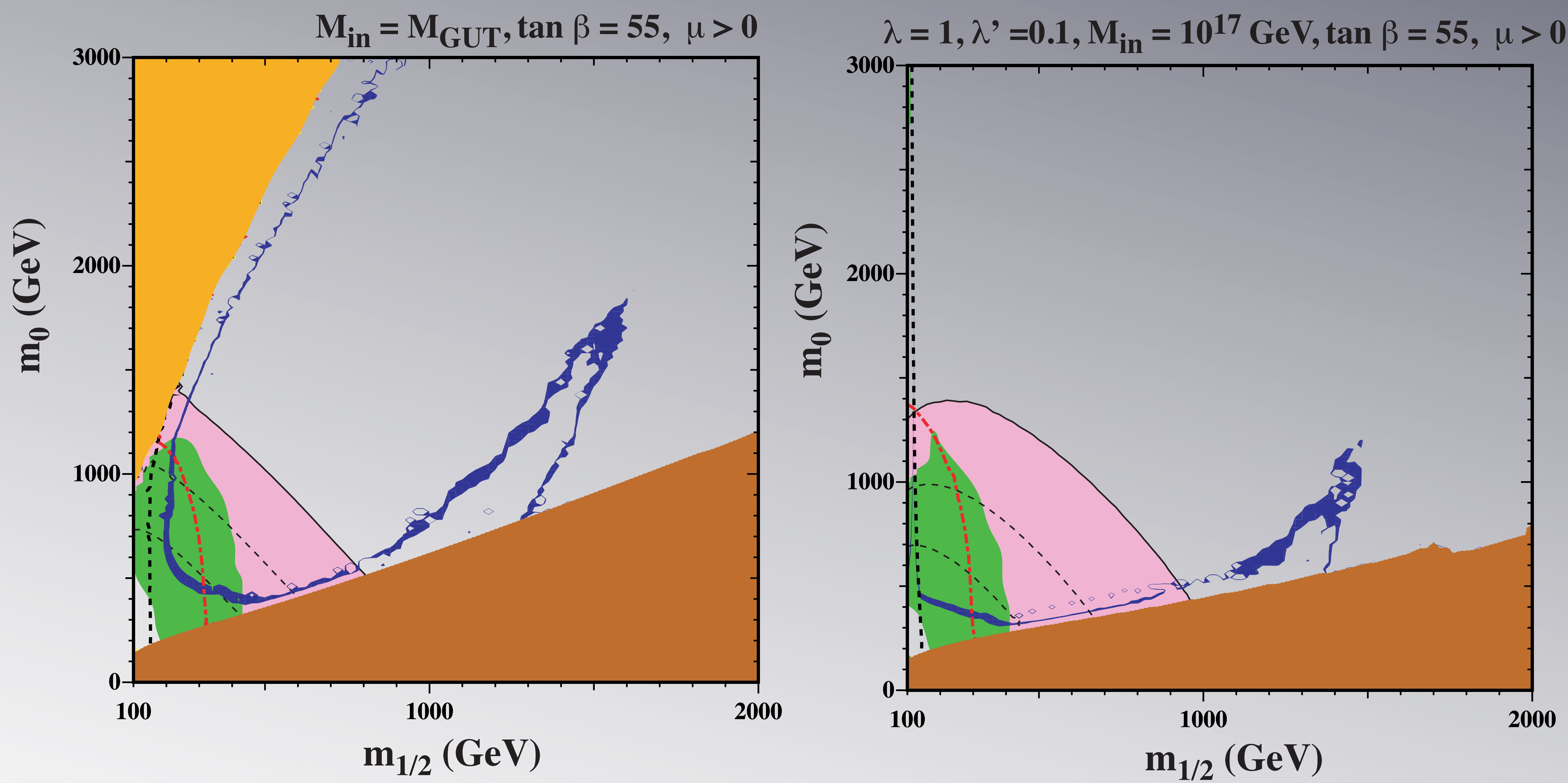




- SuperGUT CMSSM

Ellis, Mustafayev, Olive

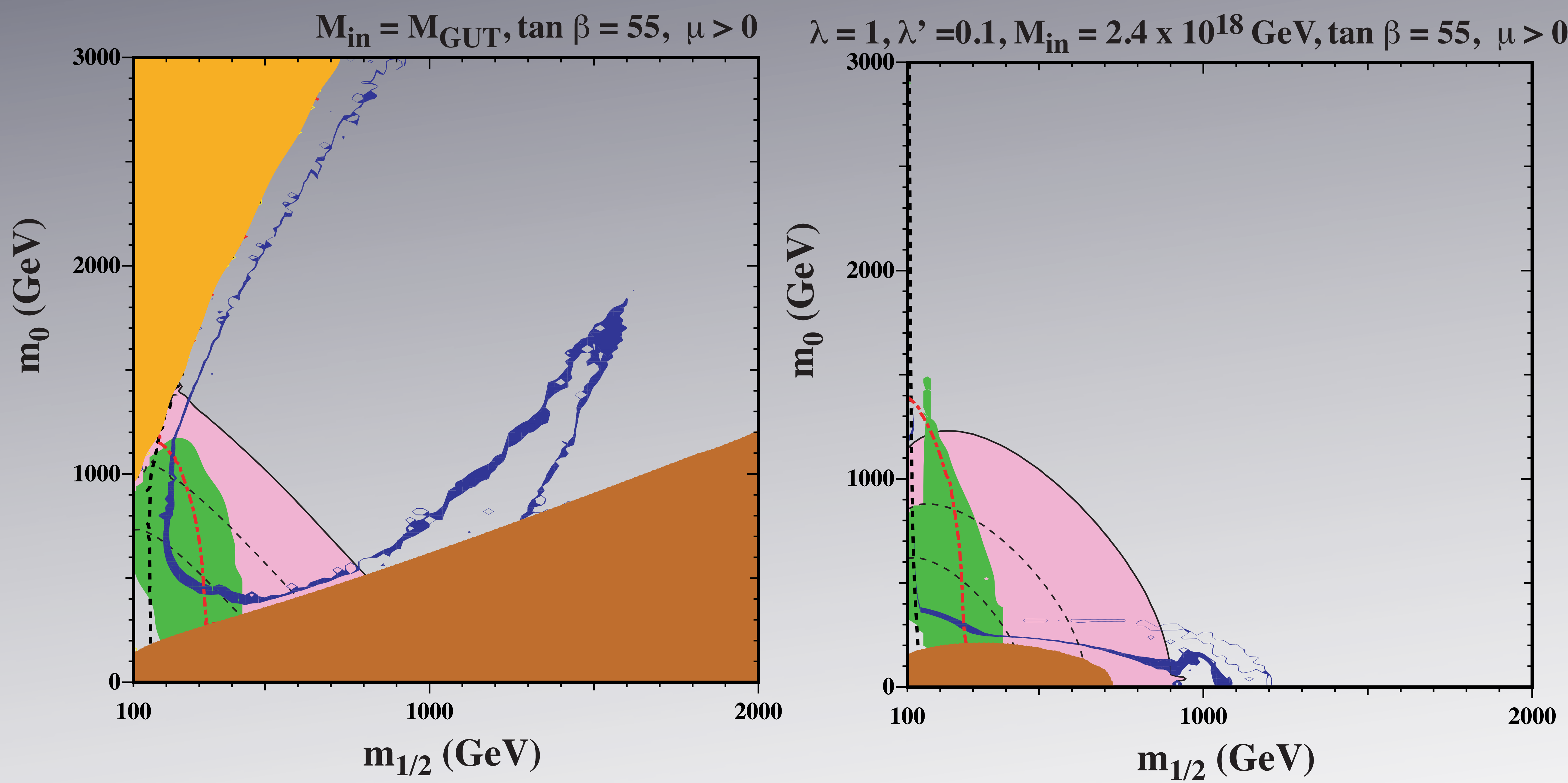
$m_{1/2}$ - m_0 planes



- SuperGUT CMSSM

Ellis, Mustafayev, Olive

$m_{1/2}$ - m_0 planes



- SuperGUT CMSSM

Ellis, Mustafayev, Olive

No-Scale Supergravity Models

Ellis, Mustafayev, Olive

- Phenomenologically viable only if the input scale for supersymmetry breaking, M_{in}, is > M_{GUT}
- co-annihilation region responsible for relic density
- focus point no longer defined ($m_0 = 0$)
- funnel region not present with neutralino LSP
- Gravitino mass not determined

Same GUT Superpotential

$$
\begin{aligned}
W_5 \;=\; & \mu_\Sigma \,\mathrm{Tr}\,\hat{\Sigma}^2 + \frac{1}{6}\lambda' \,\mathrm{Tr}\,\hat{\Sigma}^3 + \mu_H \hat{\mathcal{H}}_{1\alpha}\hat{\mathcal{H}}_2^\alpha + \lambda \hat{\mathcal{H}}_{1\alpha}\hat{\Sigma}^\alpha_\beta \hat{\mathcal{H}}_2^\beta \\
& + (\mathbf{h_{10}})_{ij}\epsilon_{\alpha\beta\gamma\delta\zeta}\hat{\psi}_i^{\alpha\beta}\hat{\psi}_j^{\gamma\delta}\hat{\mathcal{H}}_2^\zeta + (\mathbf{h_{\bar{5}}})_{ij}\hat{\psi}_i^{\alpha\beta}\hat{\phi}_{j\alpha}\hat{\mathcal{H}}_{1\beta}
\end{aligned}
$$

No-Scale models require $m_0 = A_0 = B_0 = 0$

$$
\begin{aligned}
m_{\bar{\mathbf{5}},1} = m_{\mathbf{10},1} = m_{\bar{\mathbf{5}}} = m_{\mathbf{10}} = m_{\mathcal{H}_1} = m_{\mathcal{H}_2} = m_\Sigma &\equiv m_0 = 0, \\
A_{\bar{\mathbf{5}}} = A_{\mathbf{10}} = A_\lambda = A_{\lambda'} &\equiv A_0 = 0, \\
B_\Sigma = B_H &\equiv B_0 = 0, \\
M_5 &\equiv m_{1/2}\ .
\end{aligned}
$$

Model Specified by 4+ parameters

$$
m_{1/2},\ M_{in},\ \lambda,\ \lambda',\ sgn(\mu)
$$

Same GUT Superpotential

$$W_5 = \mu_\Sigma \operatorname{Tr} \hat{\Sigma}^2 + \frac{1}{6}\lambda' \operatorname{Tr} \hat{\Sigma}^3 + \mu_H \hat{\mathcal{H}}_{1\alpha} \hat{\mathcal{H}}_2^\alpha + \lambda \hat{\mathcal{H}}_{1\alpha} \hat{\Sigma}^\alpha_\beta \hat{\mathcal{H}}_2^\beta$$
$$+ (\mathbf{h_{10}})_{ij} \epsilon_{\alpha\beta\gamma\delta\zeta} \hat{\psi}_i^{\alpha\beta} \hat{\psi}_j^{\gamma\delta} \hat{\mathcal{H}}_2^\zeta + (\mathbf{h_{\bar{5}}})_{ij} \hat{\psi}_i^{\alpha\beta} \hat{\phi}_{j\alpha} \hat{\mathcal{H}}_{1\beta}$$

No-Scale models require $m_0 = A_0 = B_0 = 0$

$$\begin{aligned} m_{\mathbf{\bar{5}},1} = m_{\mathbf{10},1} = m_{\mathbf{\bar{5}}} = m_{\mathbf{10}} = m_{\mathcal{H}_1} = m_{\mathcal{H}_2} = m_\Sigma &\equiv m_0 = 0, \\ A_{\mathbf{\bar{5}}} = A_{\mathbf{10}} = A_\lambda = A_{\lambda'} &\equiv A_0 = 0, \\ B_\Sigma = B_H &\equiv B_0 = 0, \\ M_5 &\equiv m_{1/2} \ . \end{aligned}$$

But really,

Model Specified by 3+ parameters

$$m_{1/2}, \ M_{in}, \ \lambda/\lambda', \ sgn(\mu)$$

Model Specified by 3+ parameters

$$m_{1/2},\ M_{in},\ \lambda/\lambda',\ sgn(\mu)$$

As in mSUGRA models, tanβ determined (now from $B_0 = 0$)

But $B_0 = 0$ is a condition applied at M_{in}

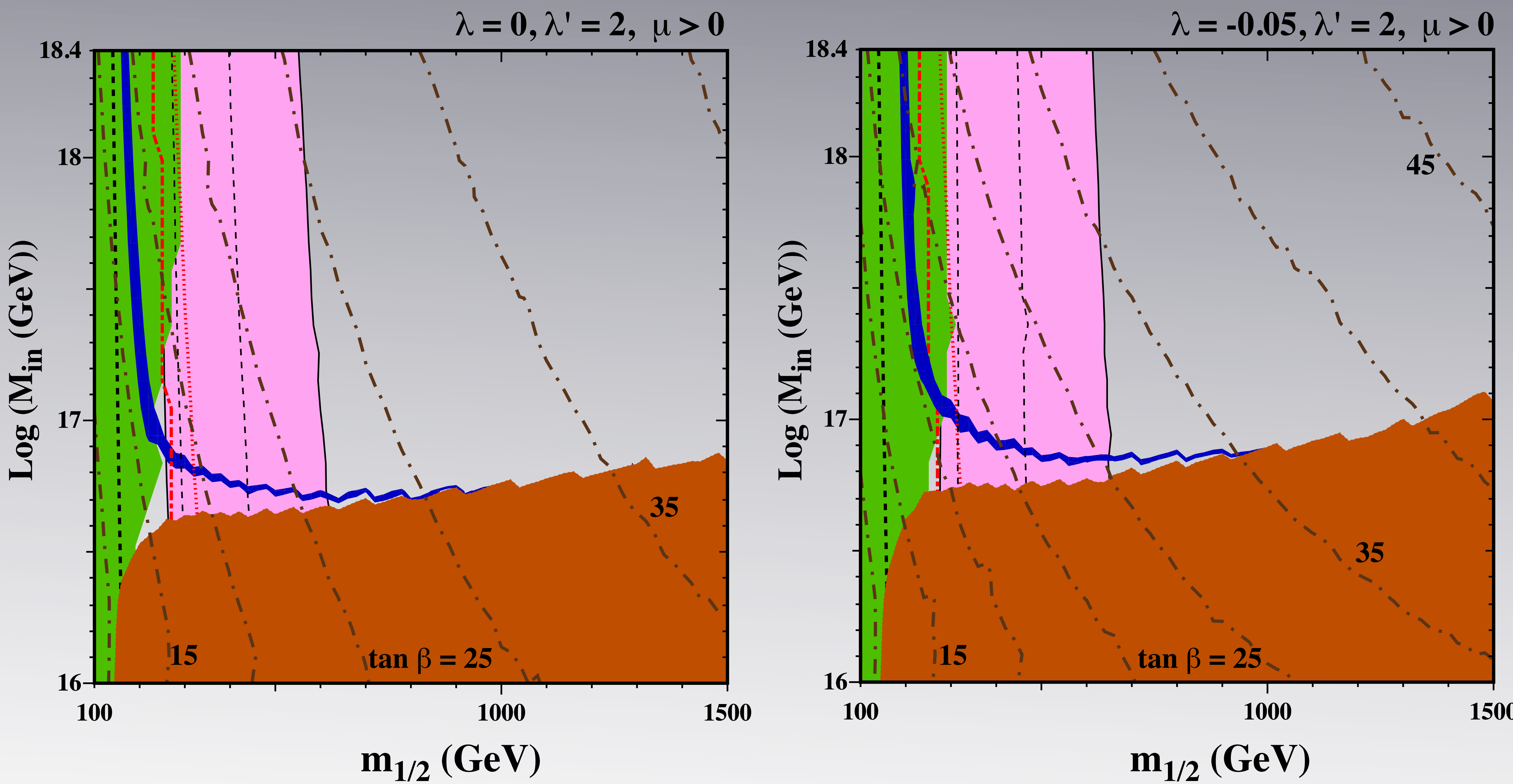
MSSM B parameter must now be matched to GUT B parameters

$$B_\Sigma,\ B_H$$

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

Borzumati + Takahashi

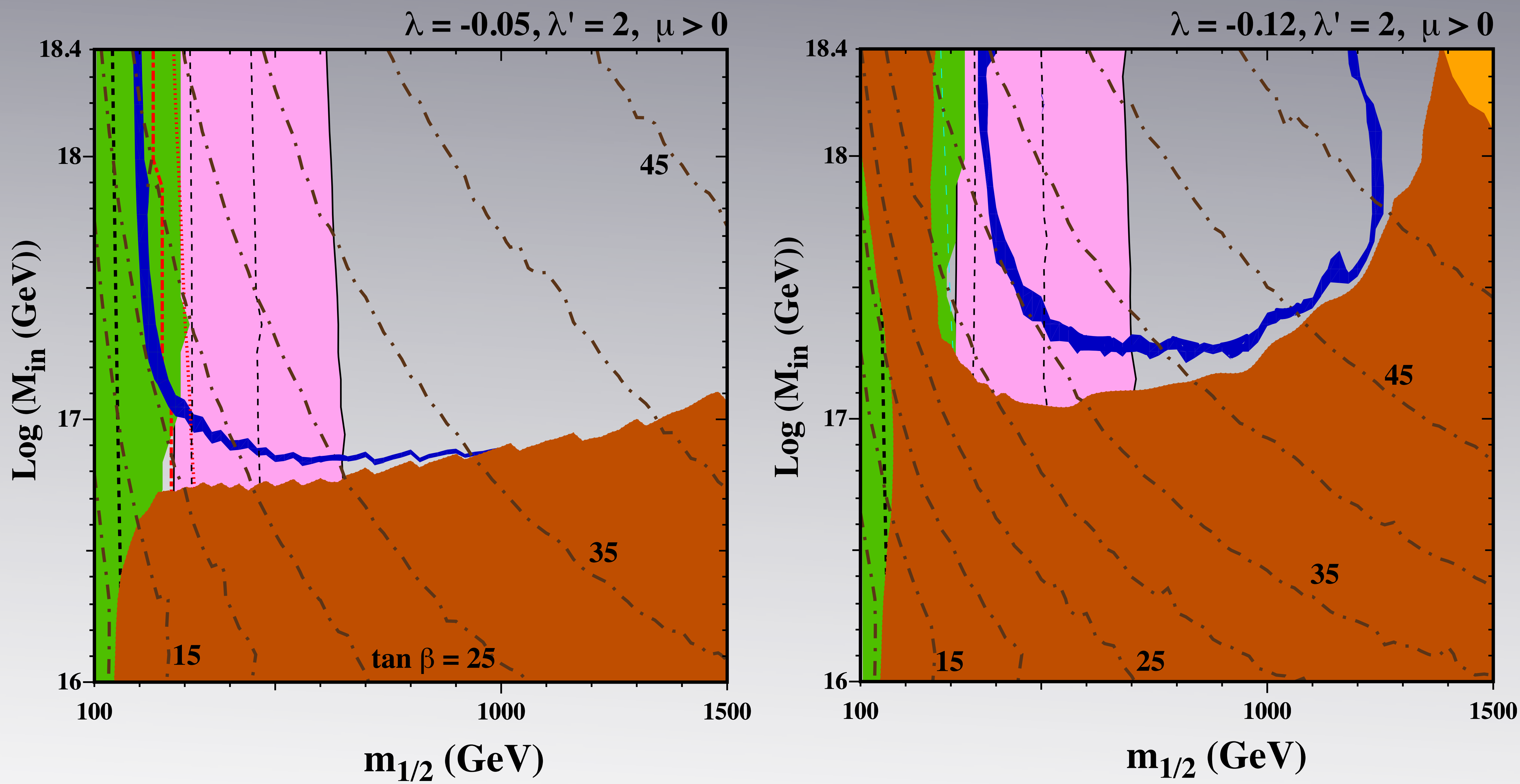
$m_{1/2}$ - M_{in} planes
($m_0 = A_0 = B_0 = 0$)



- No-Scale Supergravity

Ellis, Mustafayev, Olive

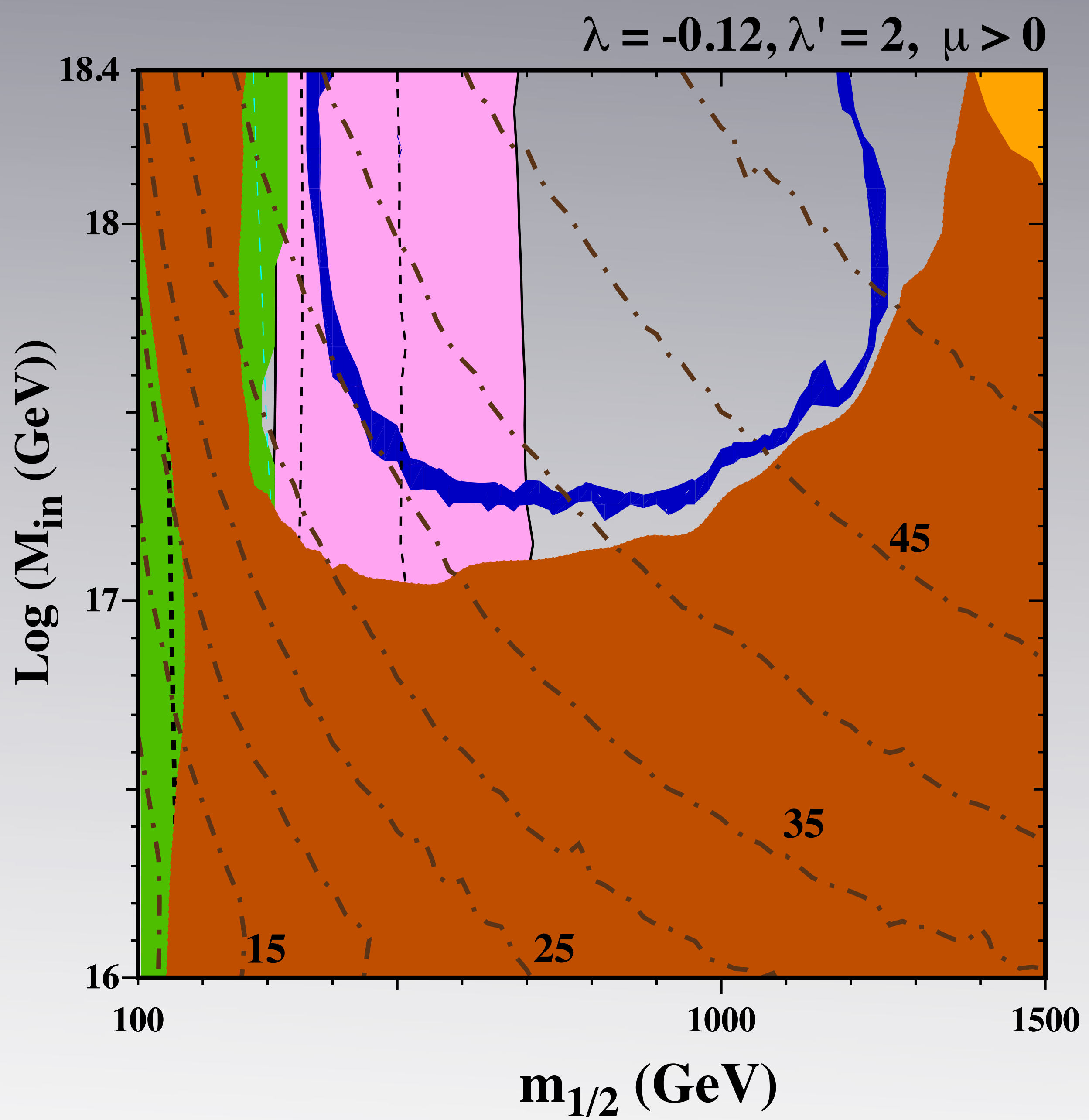
$m_{1/2}$ - M_{in} planes ($m_0 = A_0 = B_0 = 0$)

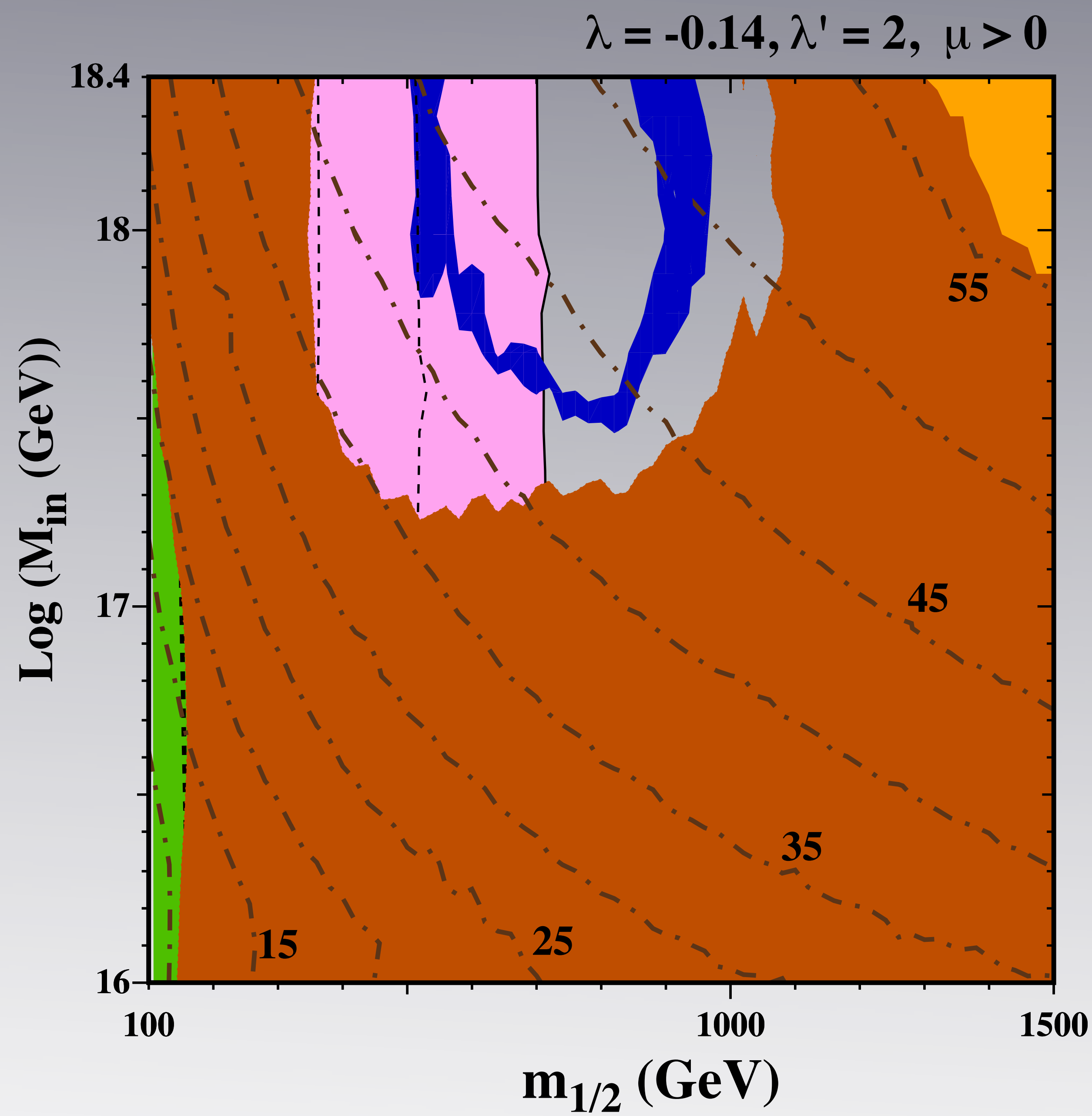


- No-Scale Supergravity

Ellis, Mustafayev, Olive

$m_{1/2}$ - M_{in} planes
($m_0 = A_0 = B_0 = 0$)

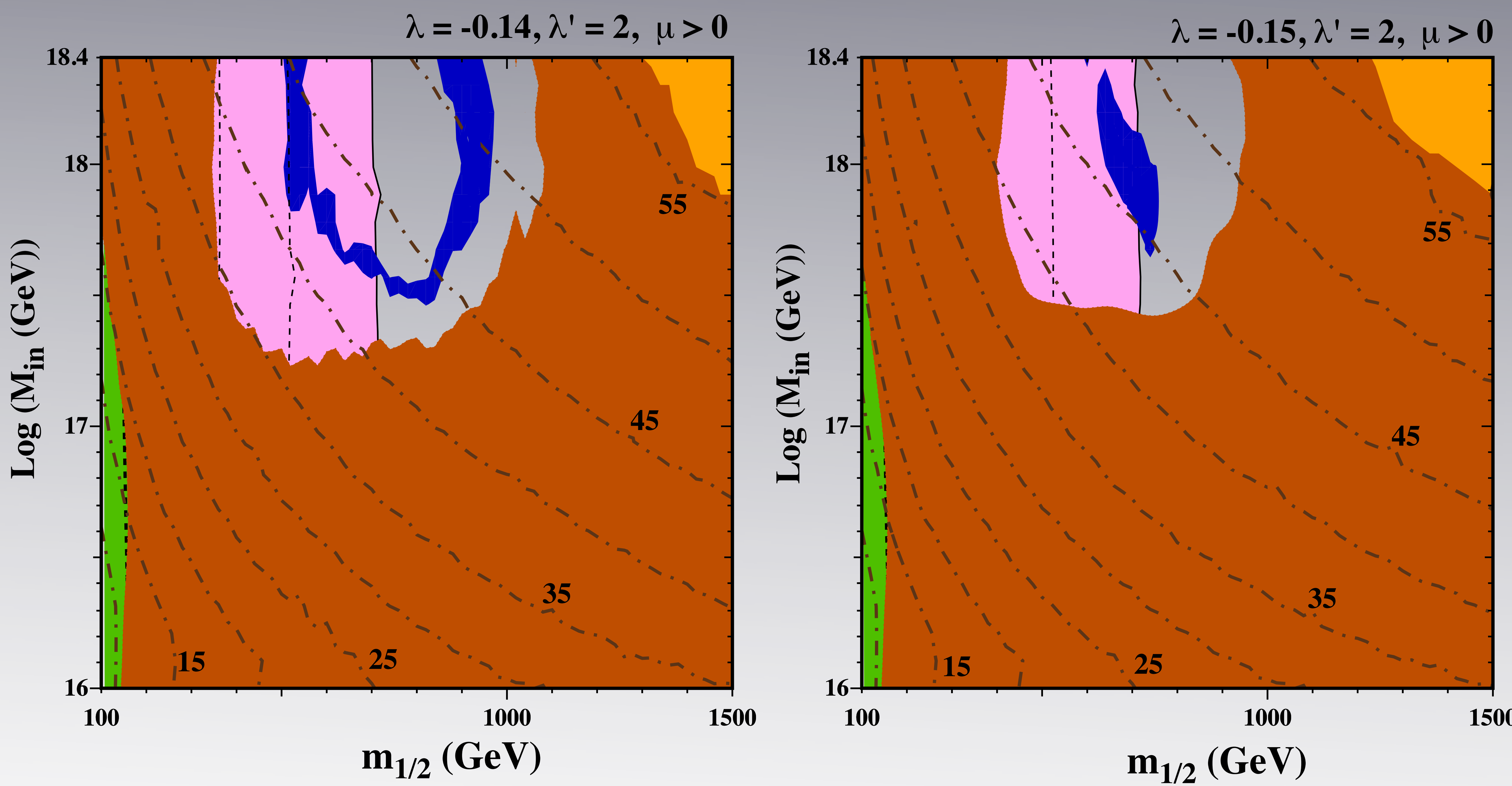




- No-Scale Supergravity

Ellis, Mustafayev, Olive

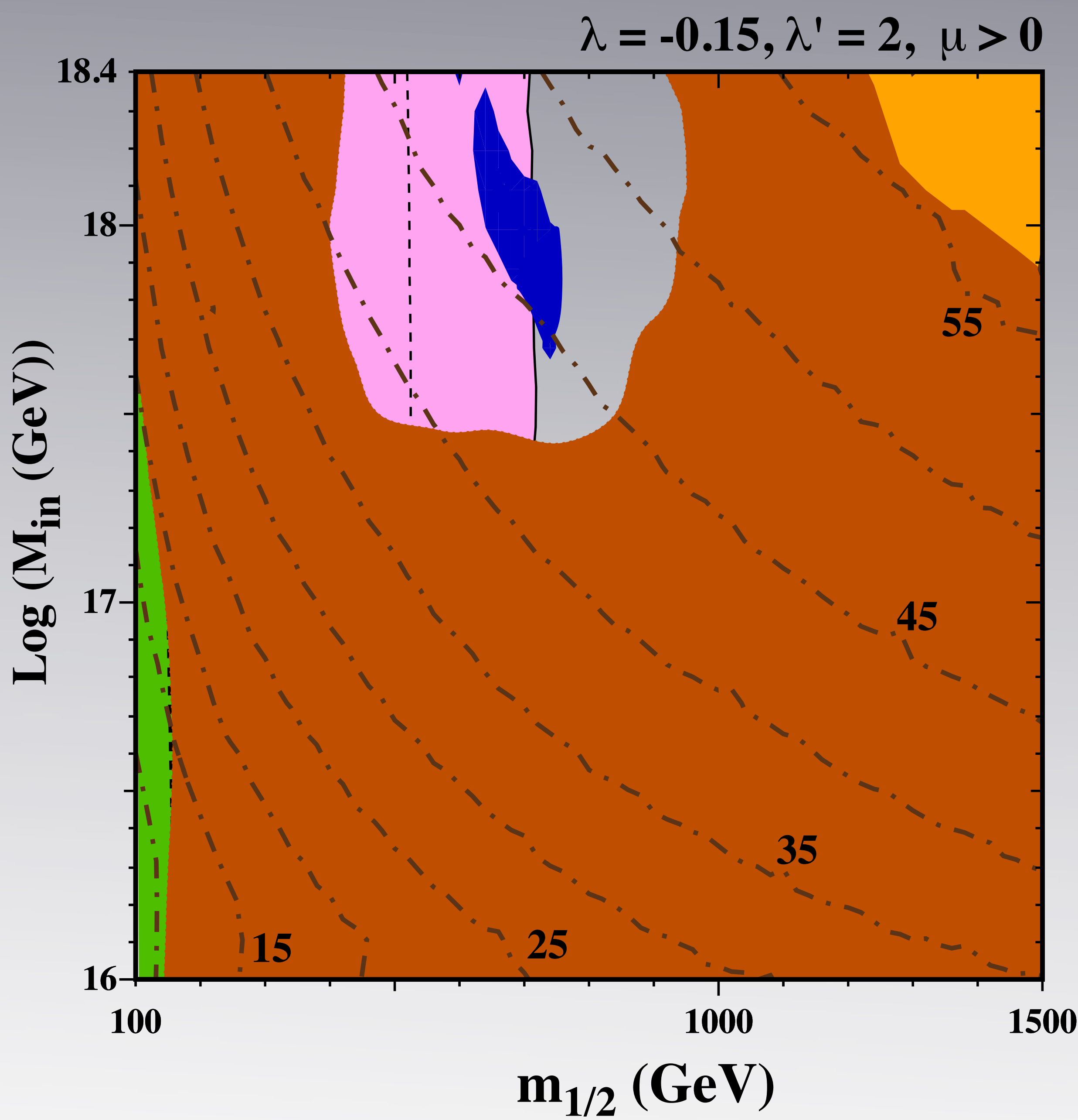
$m_{1/2}$ - M_{in} planes ($m_0 = A_0 = B_0 = 0$)

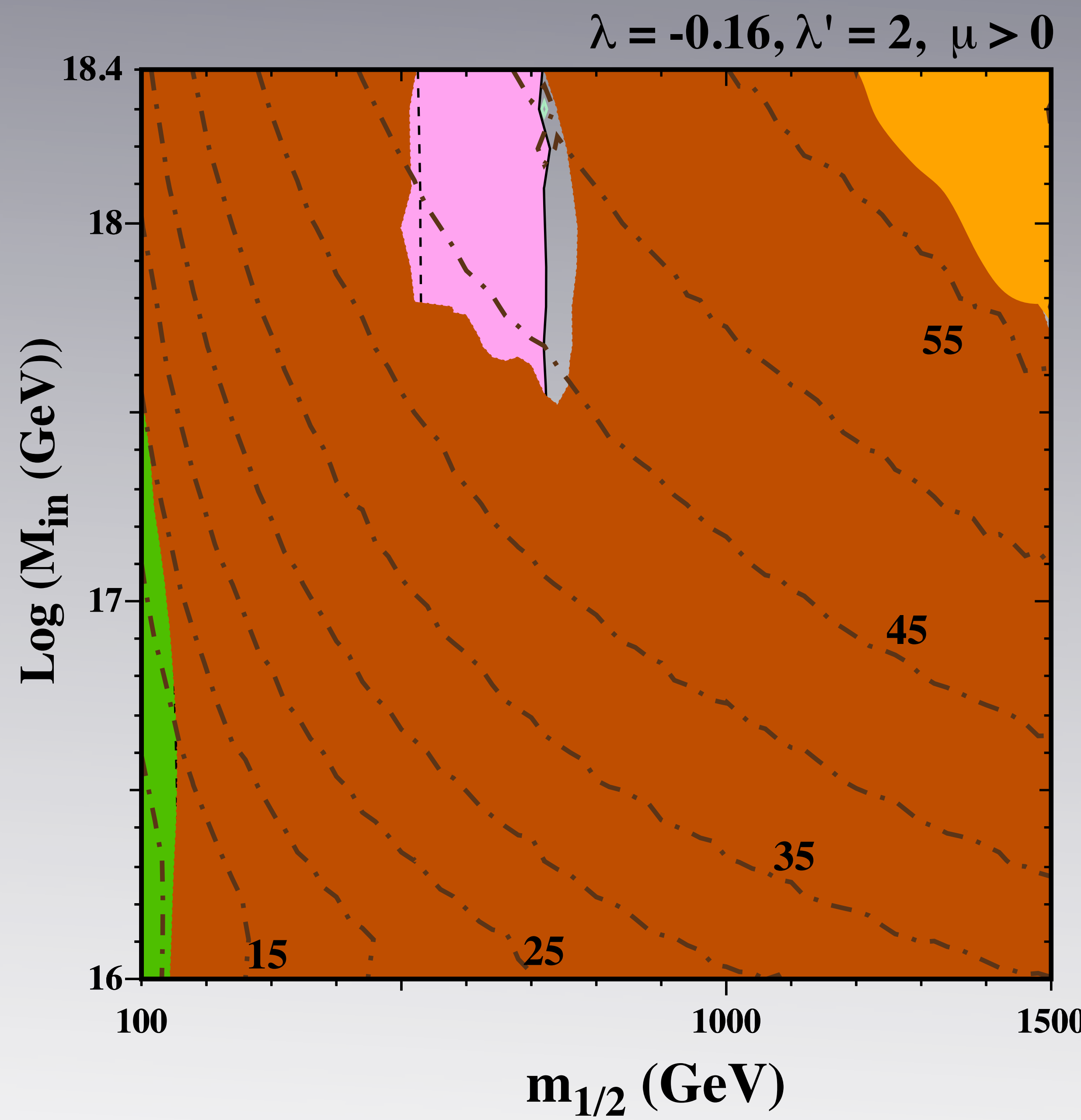


- No-Scale Supergravity

Ellis, Mustafayev, Olive

$m_{1/2}$ - M_{in} planes
$(m_0 = A_0 = B_0 = 0)$





- No-Scale Supergravity

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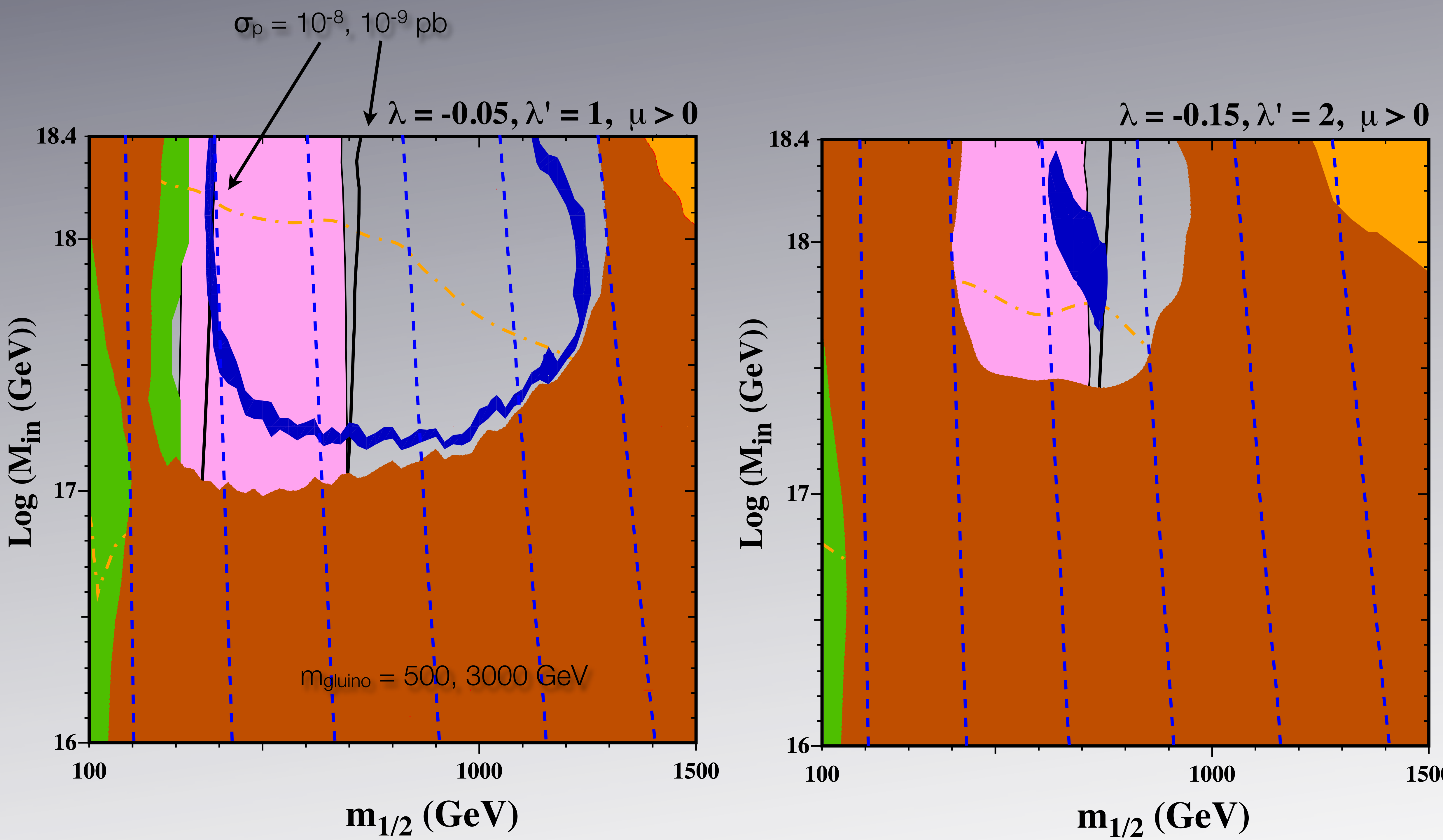
Detection prospects



- No-Scale Supergravity

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Summary

- CMSSM-mSUGRA - different theories
- focus point/funnels absent in mSUGRA
- Gravitino often the LSP in mSUGRA
- No real reason for $M_{in} = M_{GUT}$
- $M_{in} > M_{GUT}$ can restore the phenomenological viability of No-Scale Supergravity models
- Differentiating between these will be a challenge