

Colliders and Cosmology

Dark Matter in variations of constrained
MSSM models:

A comparison between accelerator and
direct detection constraints

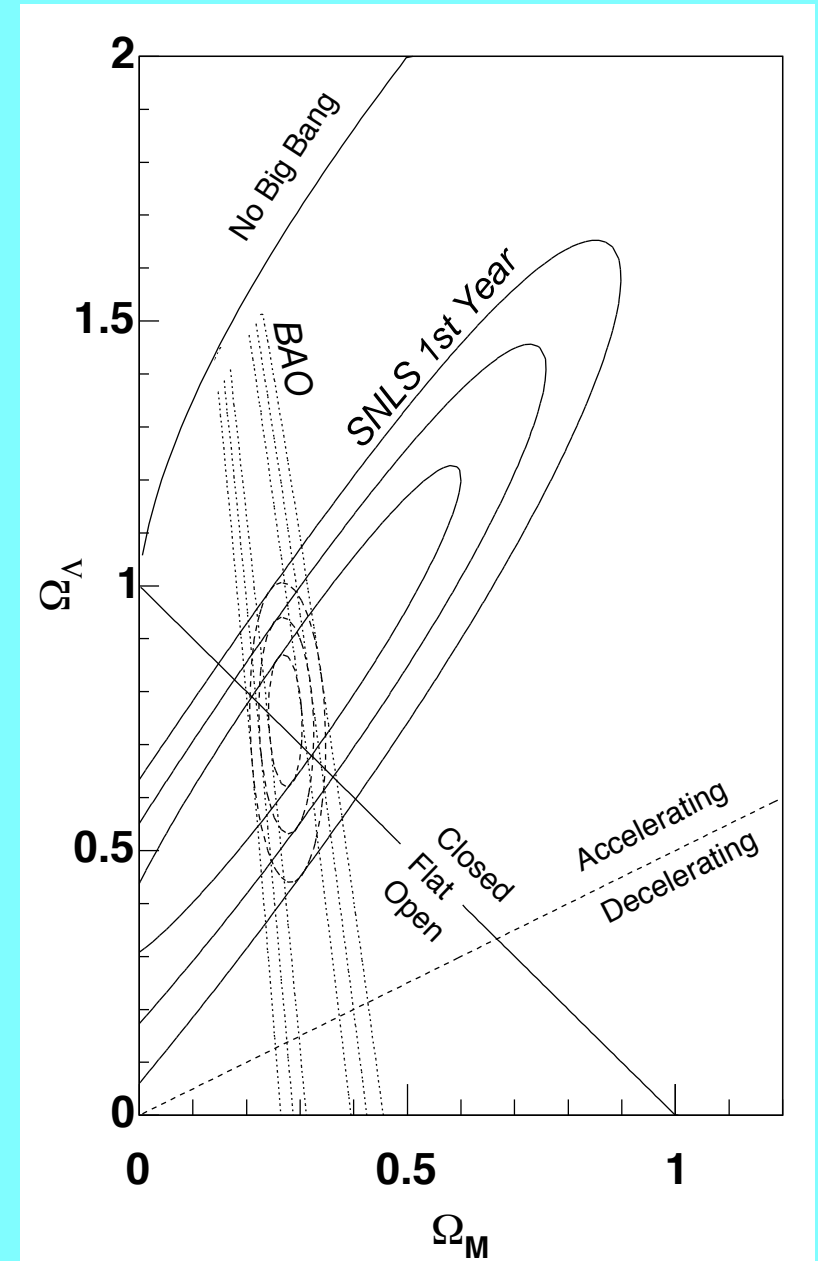
- CMSSM
- mSUGRA
- Sub-GUT
- NUHM

with: Ellis, Hahn, Heinemeyer, Sandick, Santoso, Spanos, Weber, Weiglein

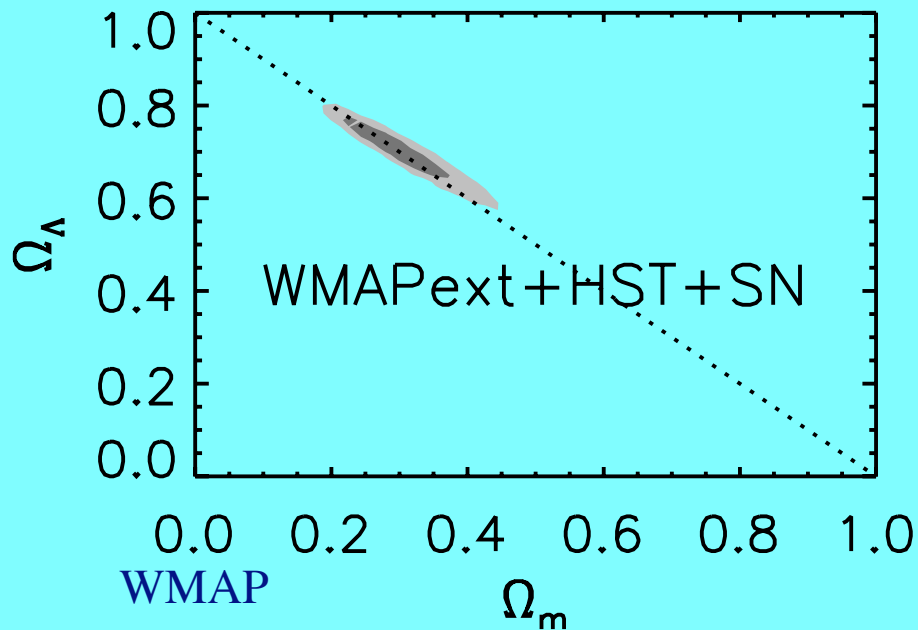
Evidence for Dark Matter



Clowe et al.



SNLS



WMAP

How Much Dark Matter

WMAP 3

Spergel et al

Precise bounds on matter content

How Much Dark Matter

WMAP 3

Spergel et al

Precise bounds on matter content

$$\Omega_m h^2 = 0.1265_{-0.0080}^{+0.0081} \quad \Omega_b h^2 = 0.0223 \pm 0.0007$$

$$\Omega_{\text{cdm}} h^2 = 0.1042_{-0.0080}^{+0.0081}$$

or

$$\Omega_{\text{cdm}} h^2 = 0.0882 - 0.1204 \quad (2 \sigma)$$

Unification Conditions

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

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mSugra Conditions

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predict $\mu, \tan \beta$

Direct Detection

- Elastic scattering cross sections for χp
- Dominant contribution to spin-independent scattering

$$\mathcal{L} = \alpha_{3i} \bar{\chi} \chi \bar{q}_i q_i,$$

Through light squark exchange

– Dominant for binos

Through Higgs exchange

– Requires some Higgsino component

Uncertainties from hadronic matrix elements

The scalar cross section

$$\sigma_3 = \frac{4m_r^2}{\pi} [Z f_p + (A - Z) f_n]^2$$

where

$$\frac{f_p}{m_p} = \sum_{q=u,d,s} f_{Tq}^{(p)} \frac{\alpha_{3q}}{m_q} + \frac{2}{27} f_{TG}^{(p)} \sum_{c,b,t} \frac{\alpha_{3q}}{m_q}$$

and

$$m_p f_{Tq}^{(p)} \equiv \langle p | m_q \bar{q} q | p \rangle \equiv m_q B_q$$

determined by

$$\sigma_{\pi N} \equiv \Sigma = \frac{1}{2} (m_u + m_d) (B_u + B_d)$$

The strangeness contribution to the proton mass

$$y = \frac{2B_s}{B_u + B_d} = \frac{(m_u + m_d) \langle p | s\bar{s} | p \rangle}{\Sigma}$$

$$= 1 - \frac{\sigma_0}{\Sigma}$$

$$\sigma_0 = 36 \pm 7 \text{ MeV}$$

Gasser, Leutwyler, Sanio
Knecht

For $\Sigma = 45 \text{ MeV}$, $y = 0.2$

$$f_{T_u} = 0.020 \quad f_{T_d} = 0.026 \quad f_{T_s} = 0.117$$

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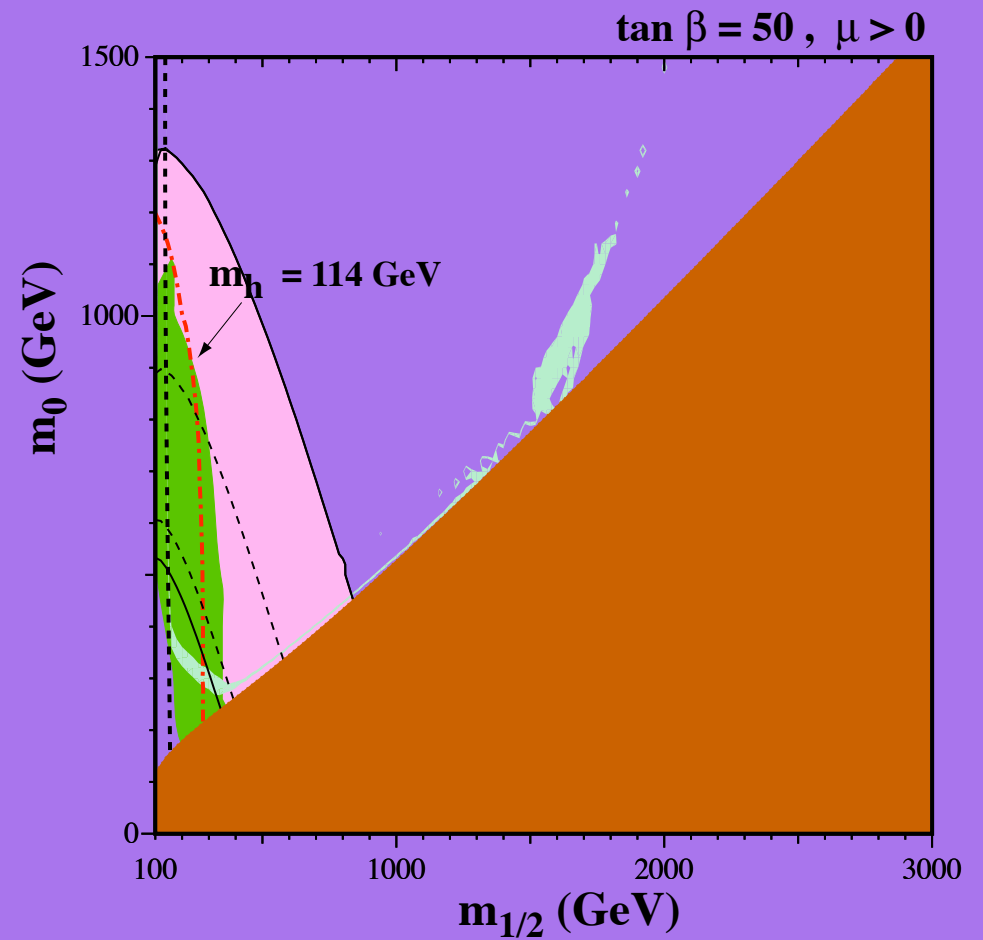
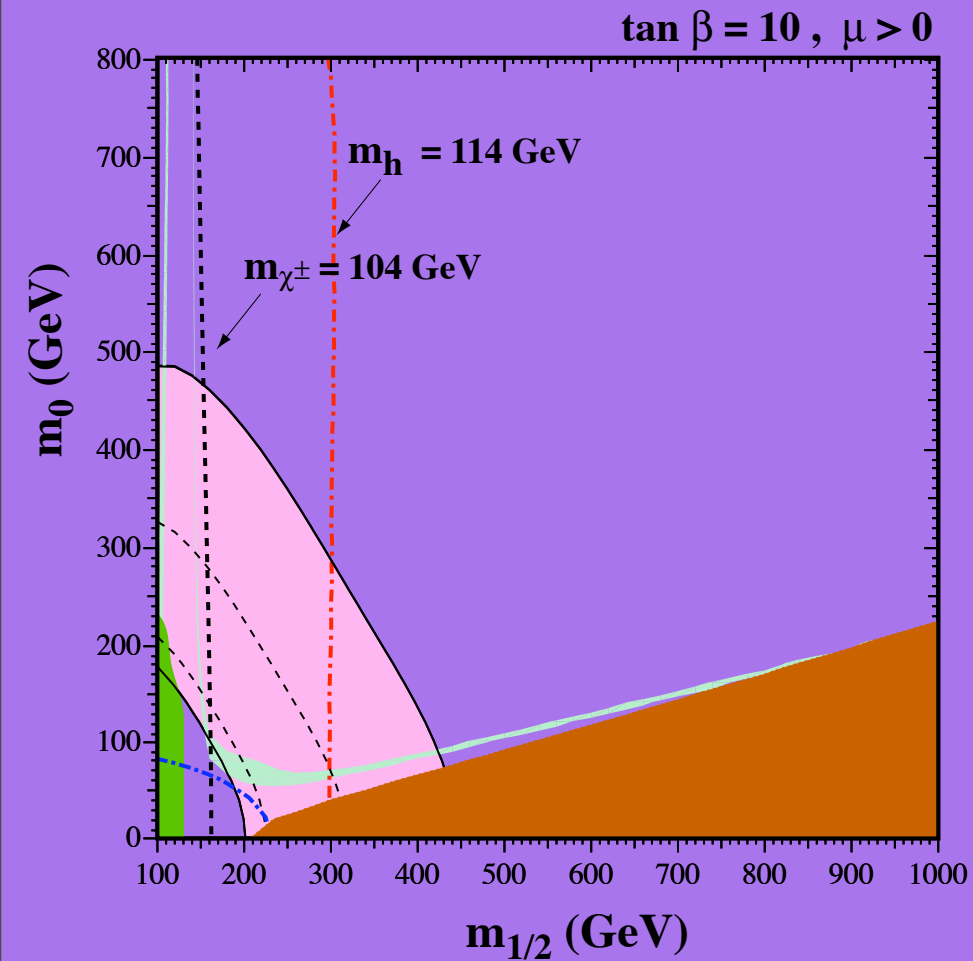
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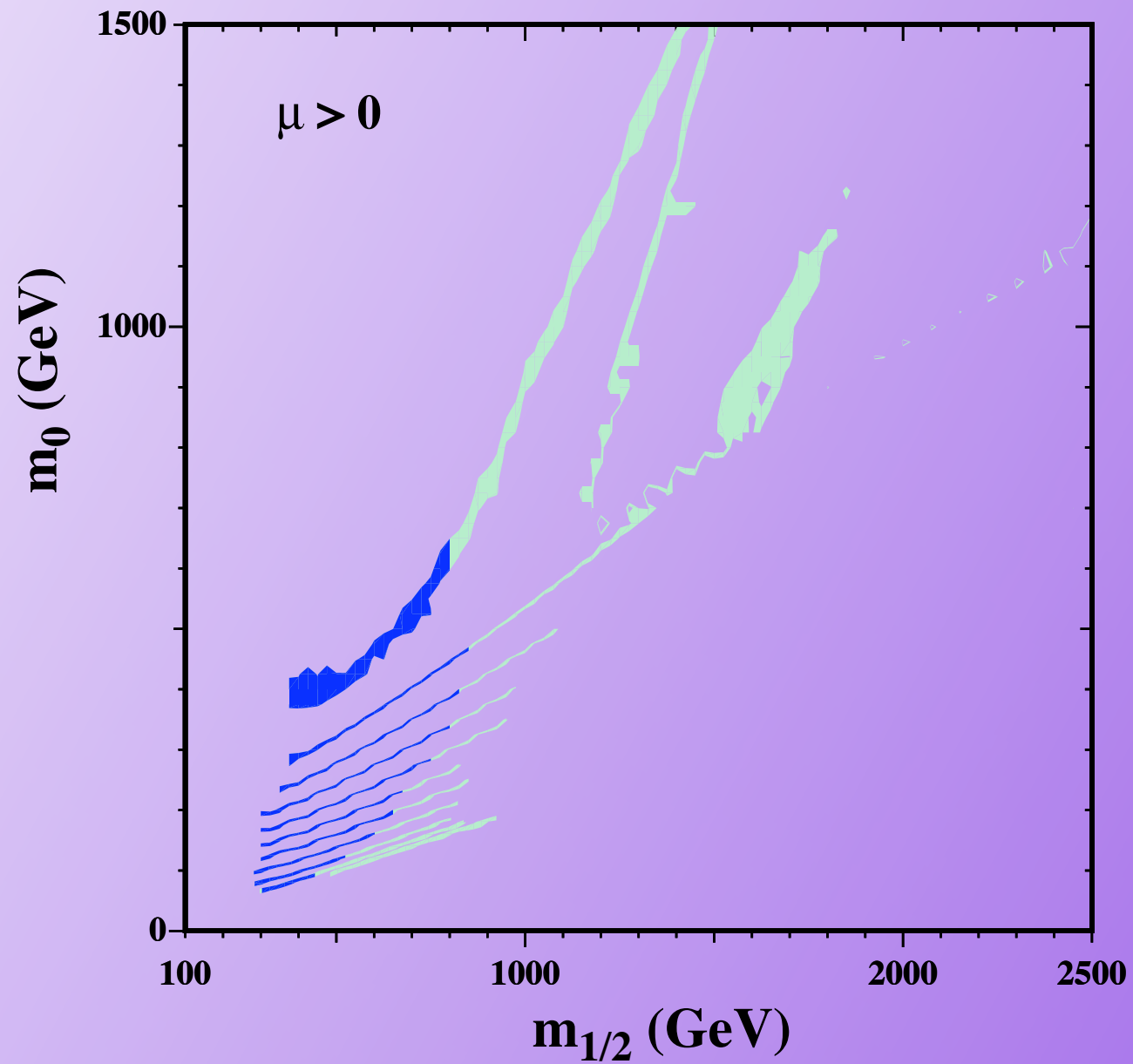
$$f_{T_u} = 0.016 \quad f_{T_d} = 0.020 \quad f_{T_s} = 0.$$

CMSSM



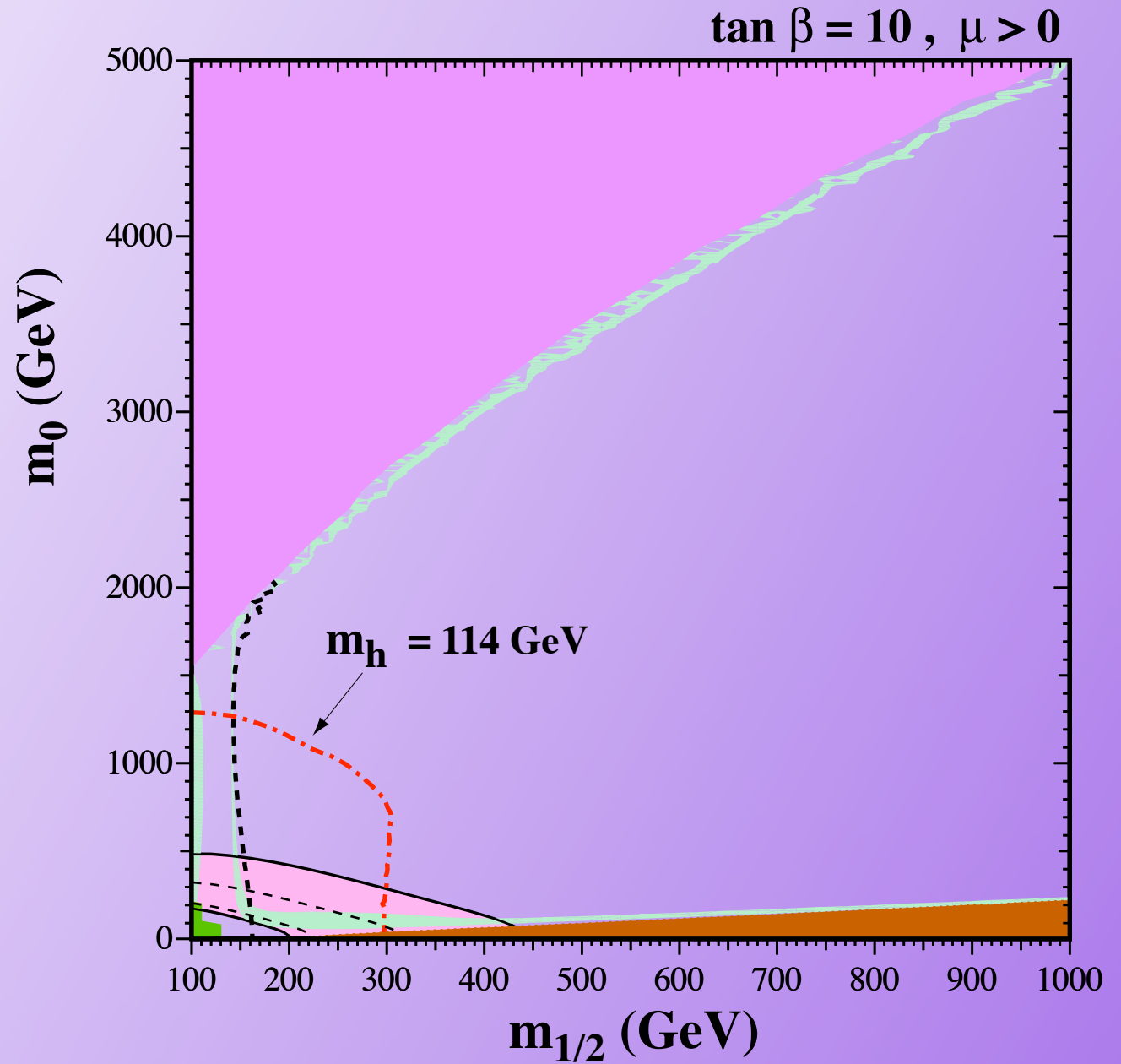
EOSS

Foliation in $\tan \beta$



Focus Point Region

As m_0 gets very large, RGE's force μ to 0, allowing neutralino to become Higgsino like with an acceptable relic density.

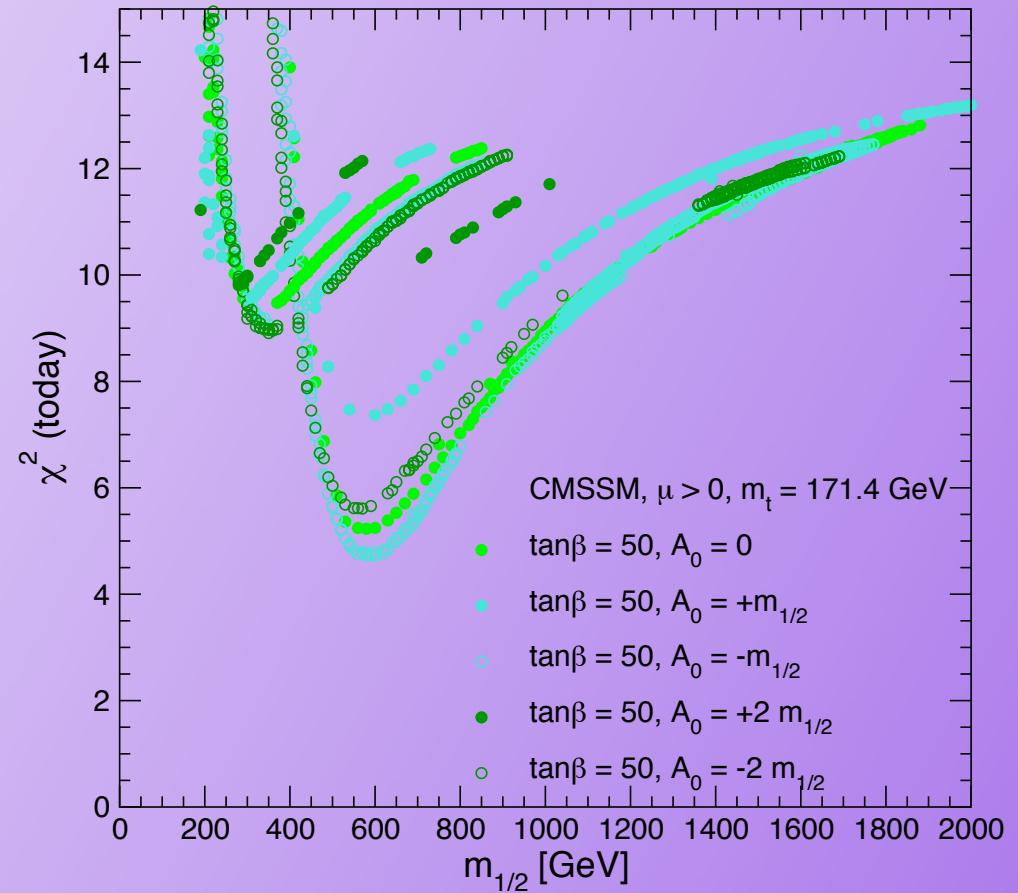
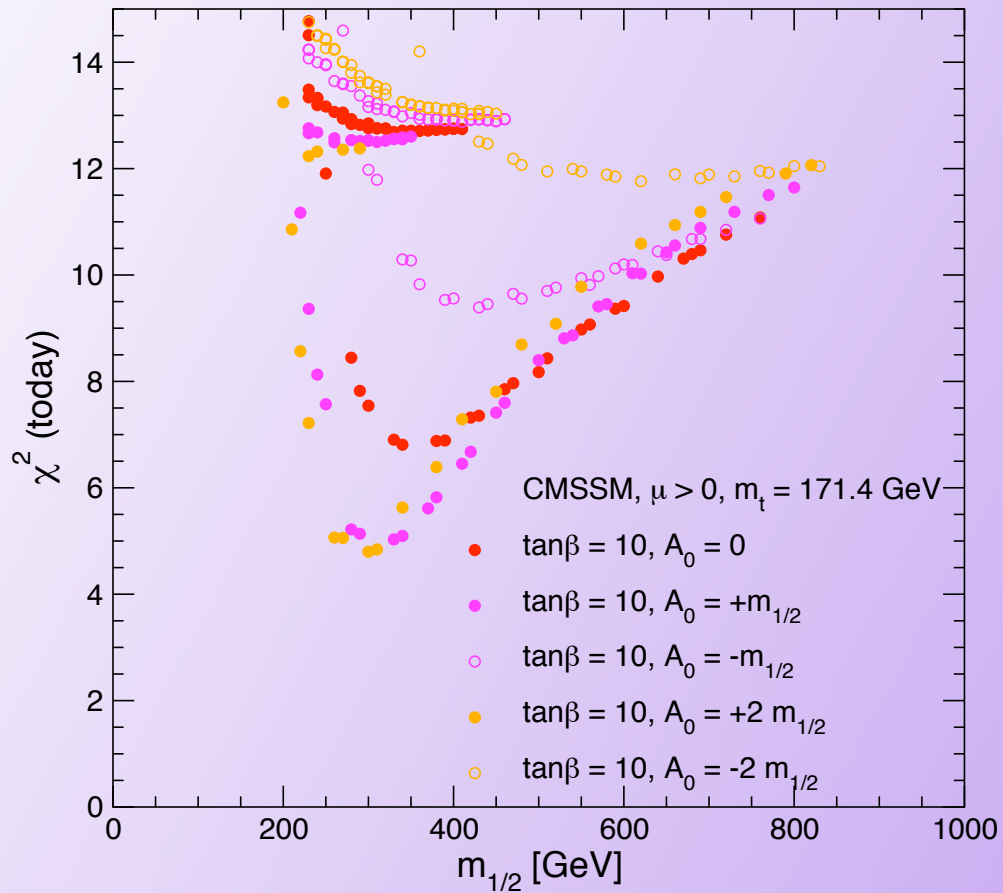


Indirect Sensitivities

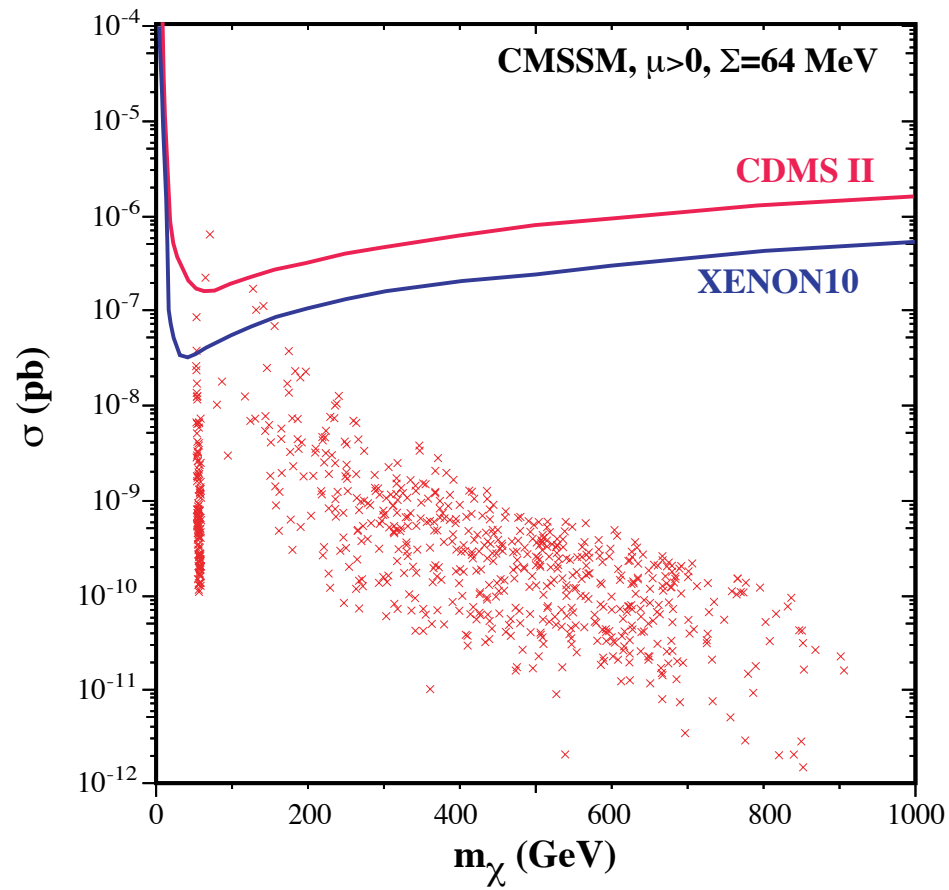
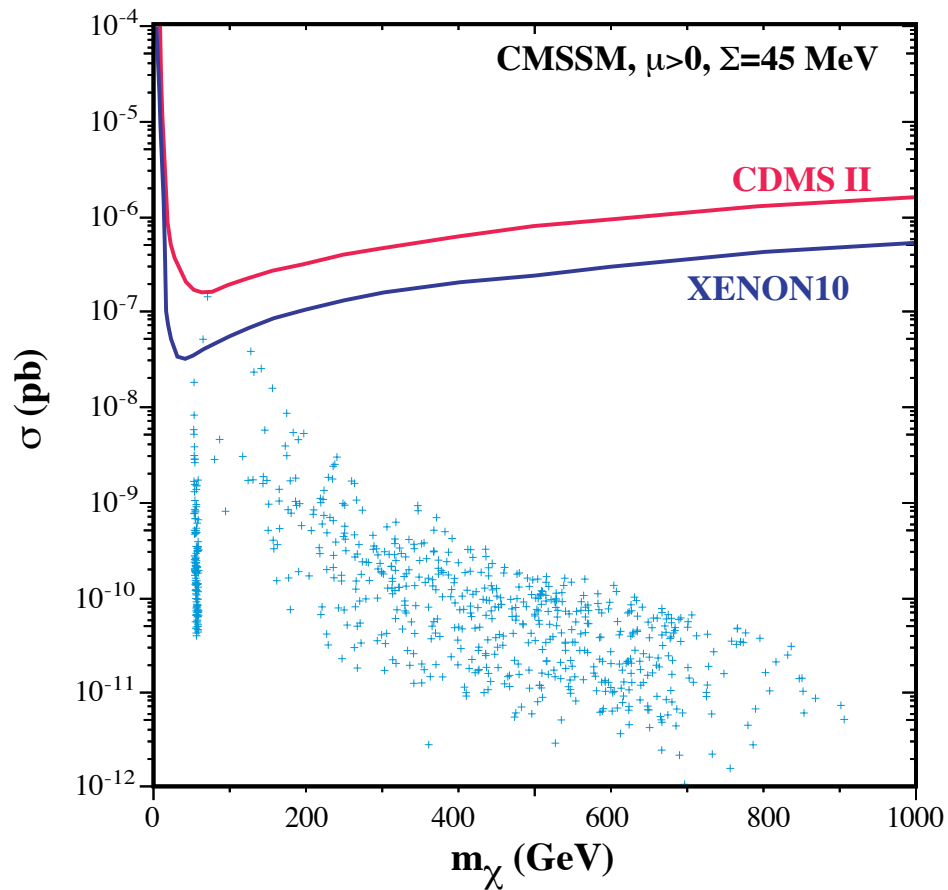
- M_W
- $\sin^2 \theta$
- Γ_Z
- $(g-2)_\mu$
- $\text{BR}(b \rightarrow s \gamma)$
- $\text{BR}(B_u \rightarrow \tau \nu_\tau)$
- ΔM_{B_s}
- M_h
- $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$

$$\chi^2 \equiv \sum_{n=1}^4 \left(\frac{R_n^{\text{exp}} - R_n^{\text{theo}}}{\sigma_n} \right)^2 + \chi_{M_h}^2$$

Indirect Sensitivities to CMSSM models



Direct Detection in the CMSSM



Sub-GUT models

Why assume that the supersymmetry breaking scale is M_{GUT} ?

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Flavor-blind supersymmetry breaking \rightarrow universality

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Gauge coupling unification maintained (at the GUT scale)

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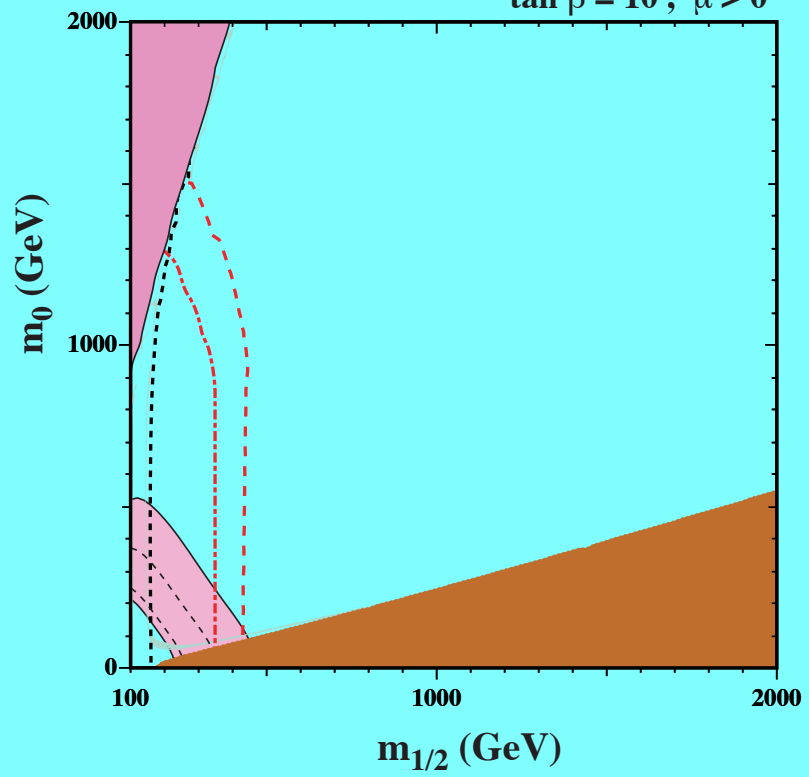
Why assume that the supersymmetry breaking scale is M_{GUT} ?

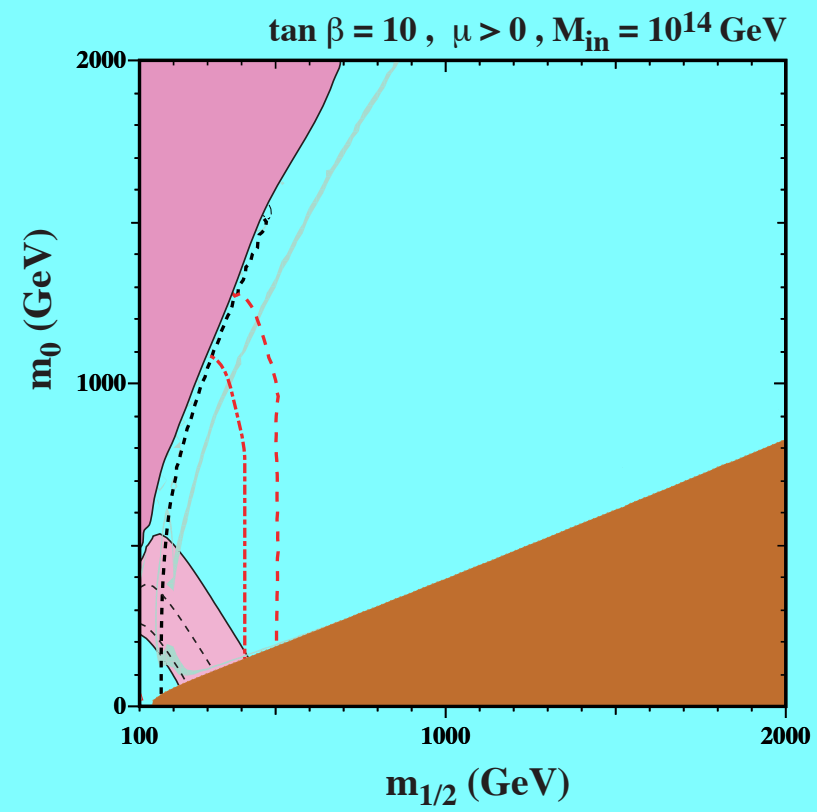
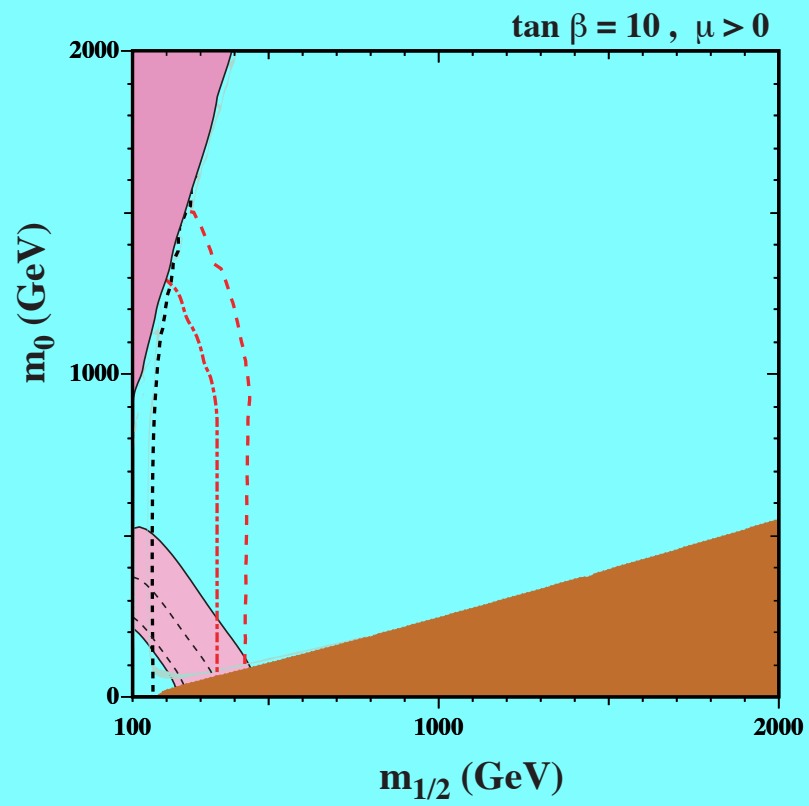
Flavor-blind supersymmetry breaking \rightarrow universality
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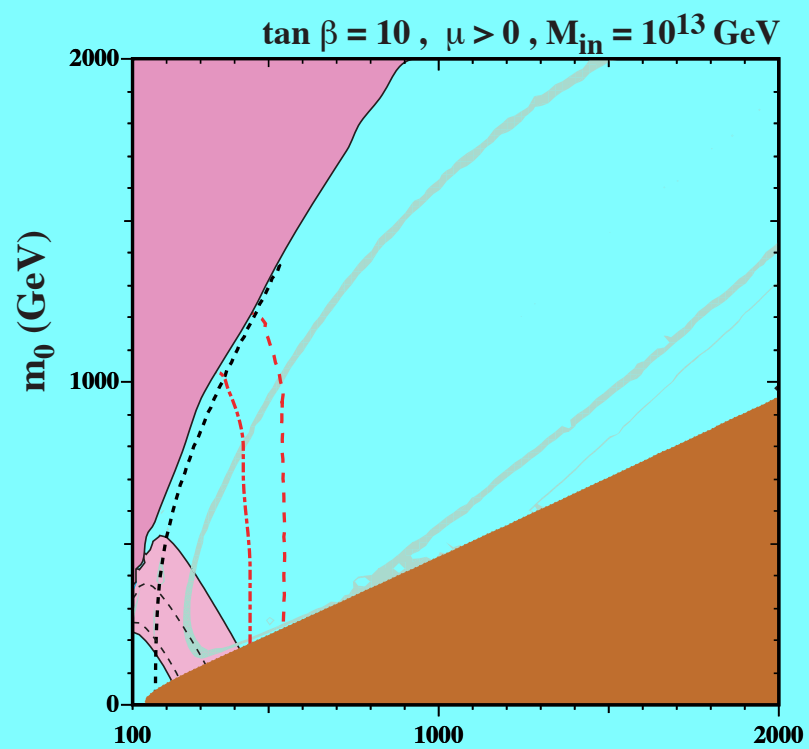
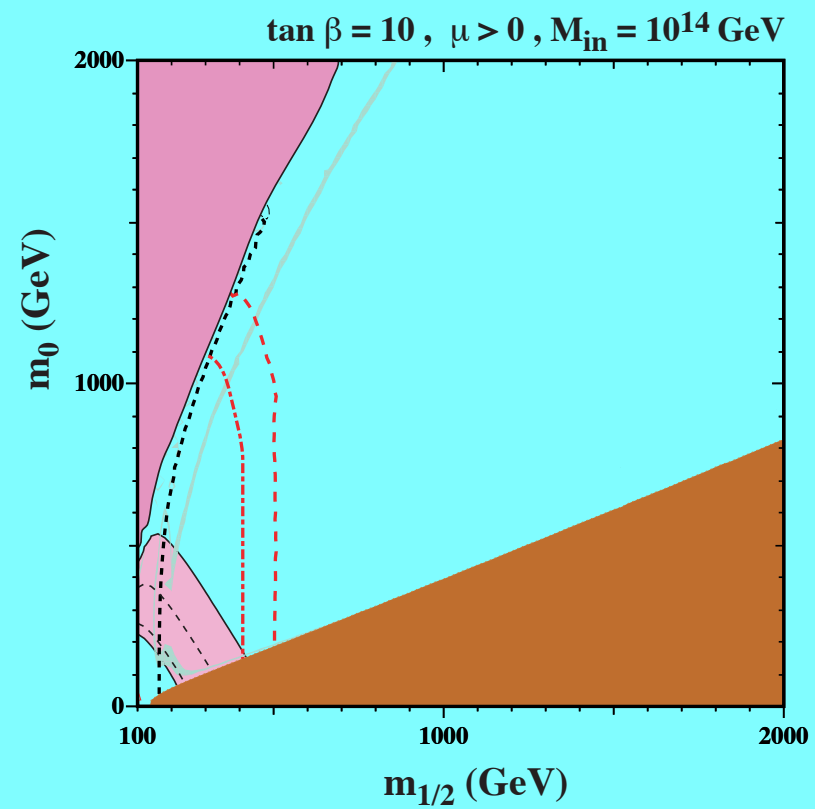
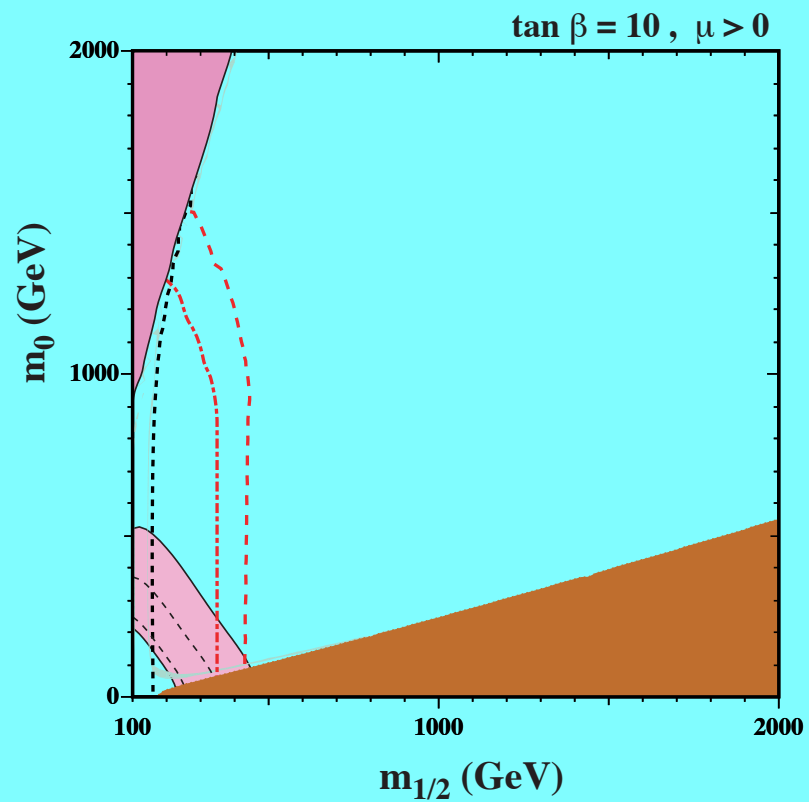
Gauge coupling unification maintained (at the GUT scale)

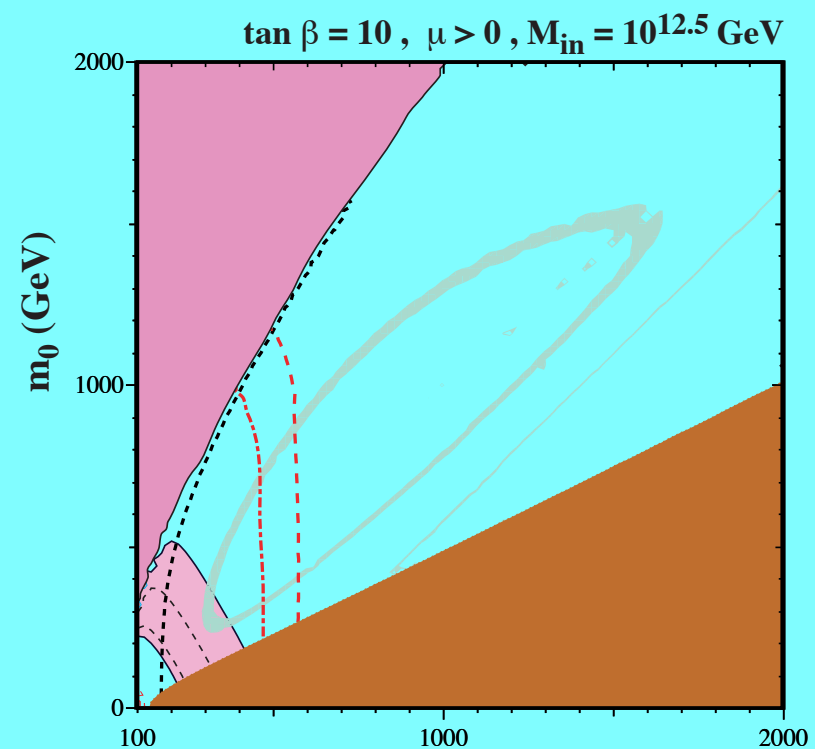
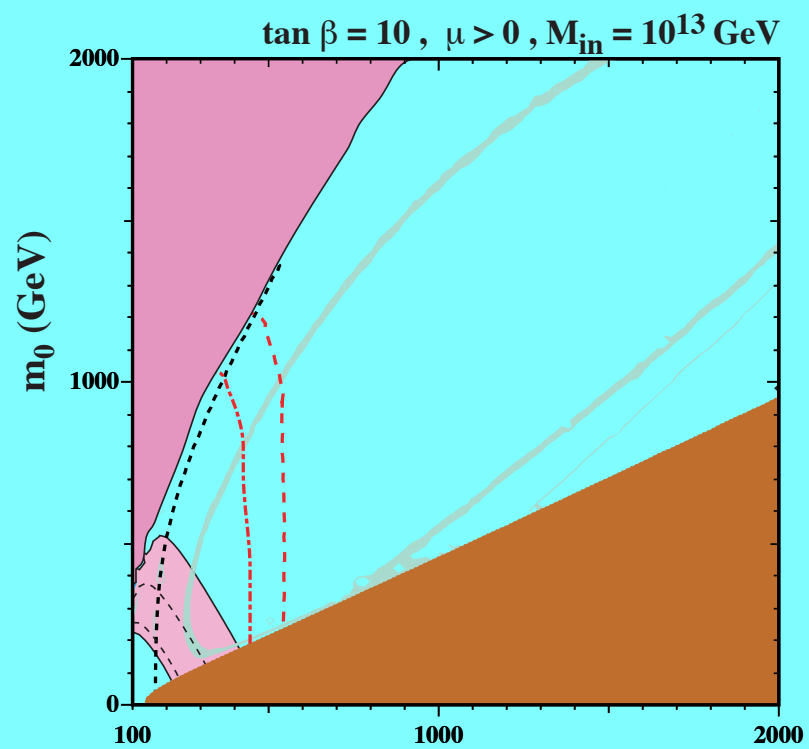
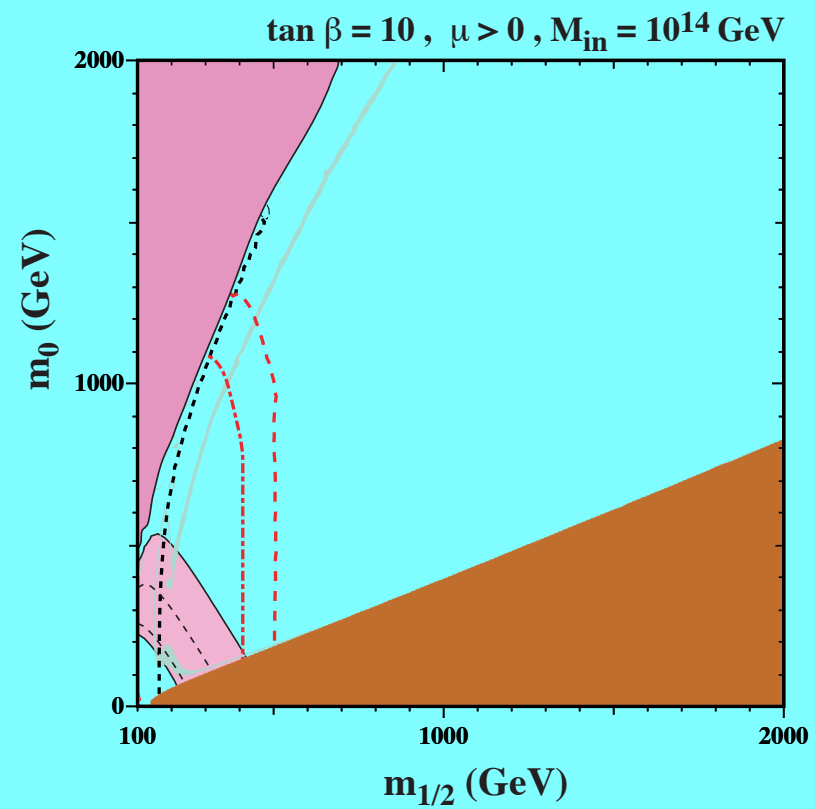
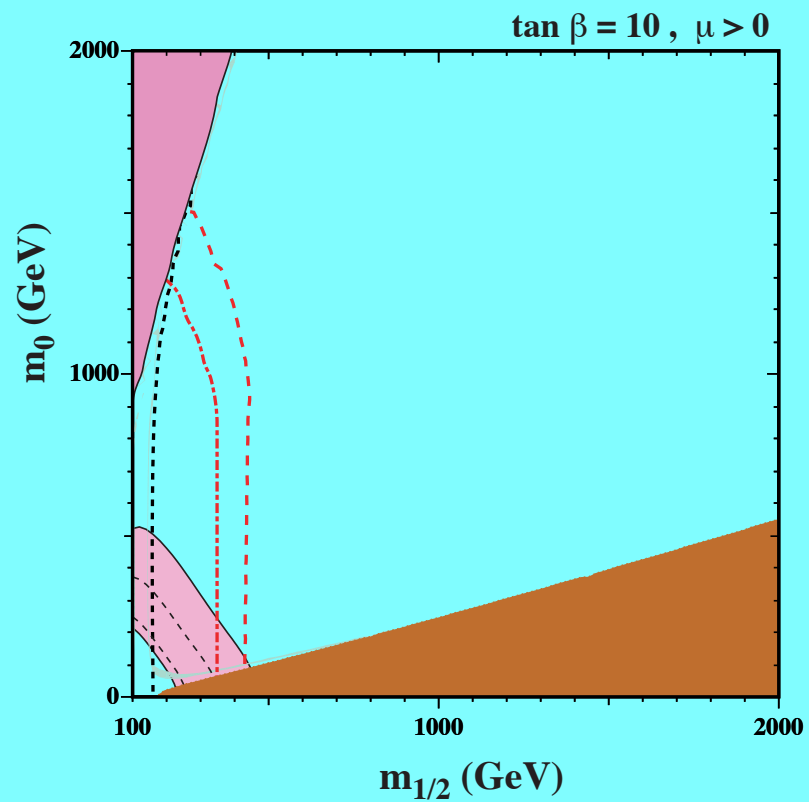
Gaugino and scalar masses unified at some scale $M_{\text{in}} < M_{\text{GUT}}$

$\tan \beta = 10, \mu > 0$

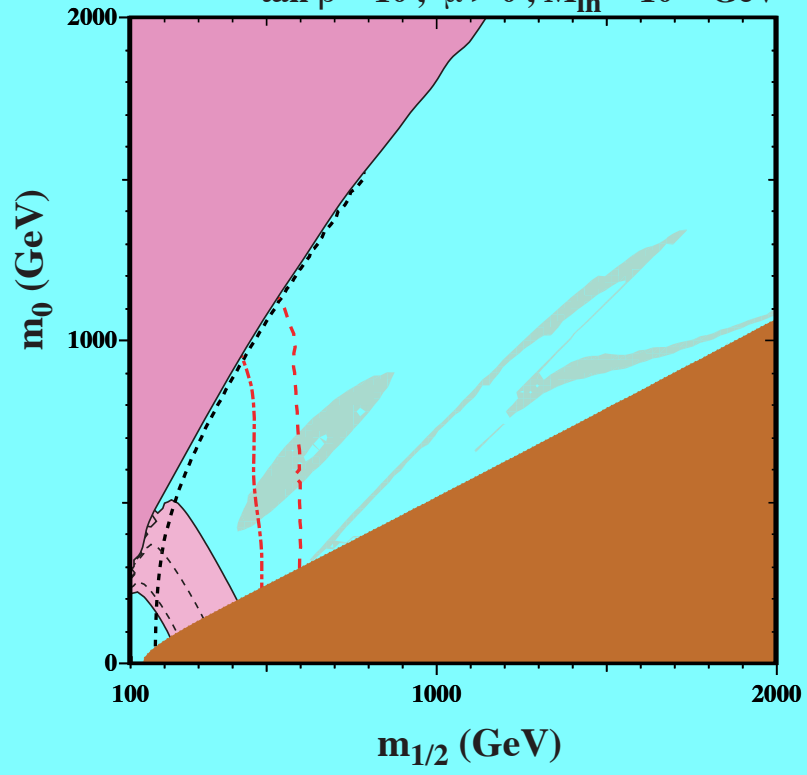




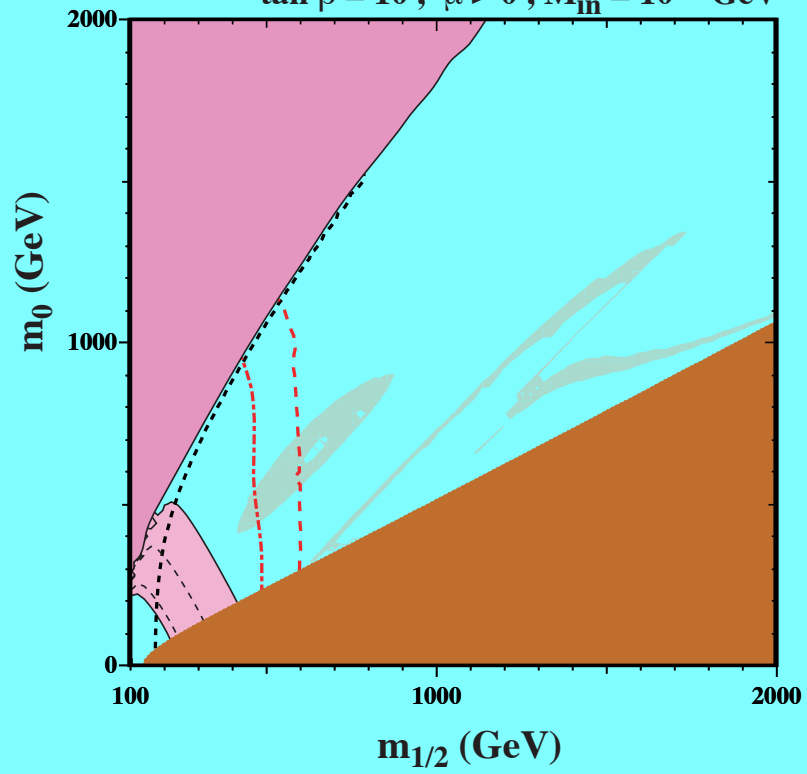




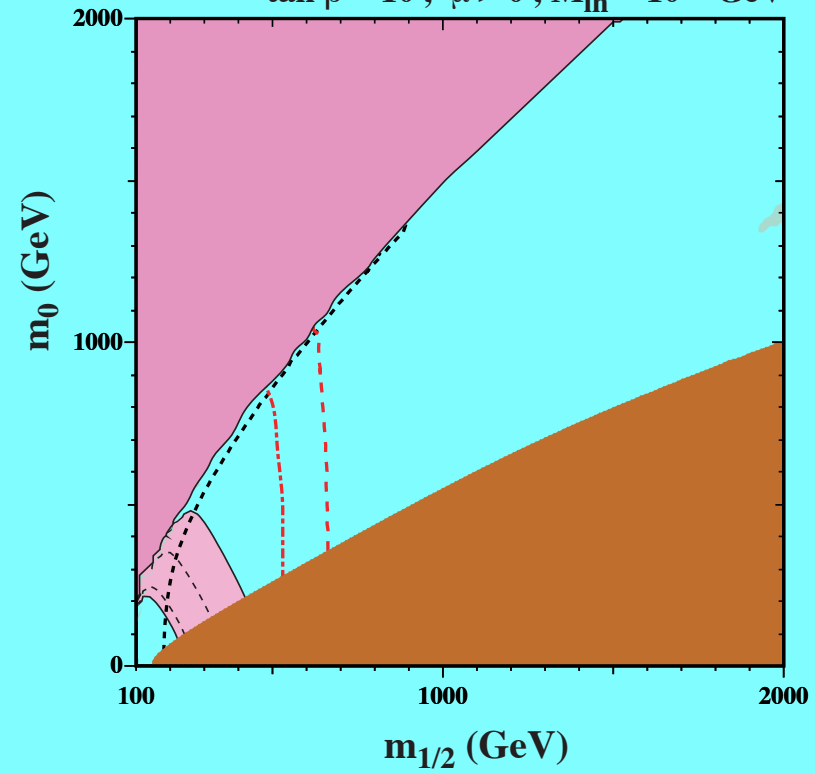
$\tan \beta = 10, \mu > 0, M_{\text{in}} = 10^{12} \text{ GeV}$



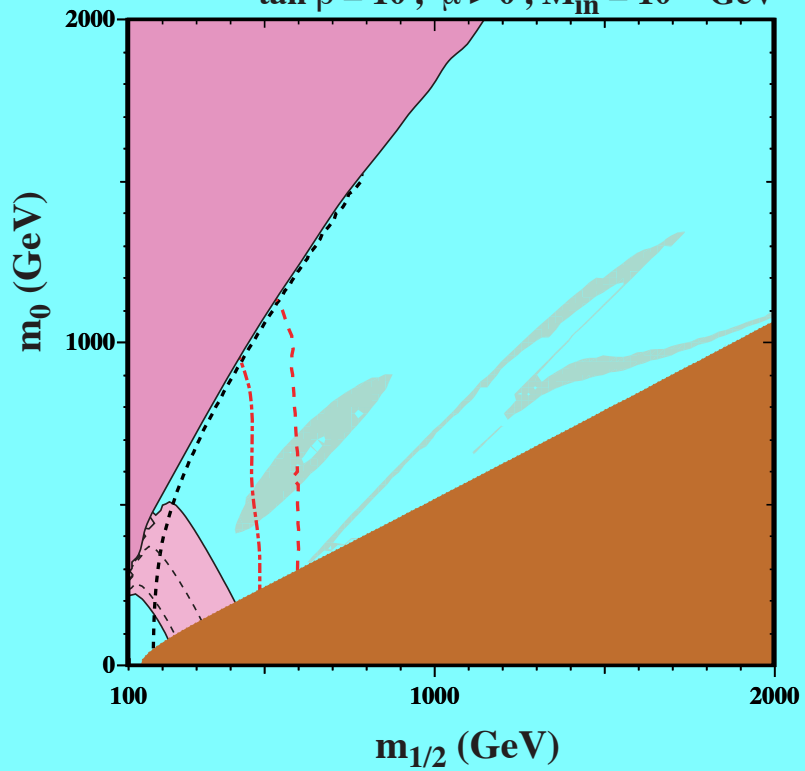
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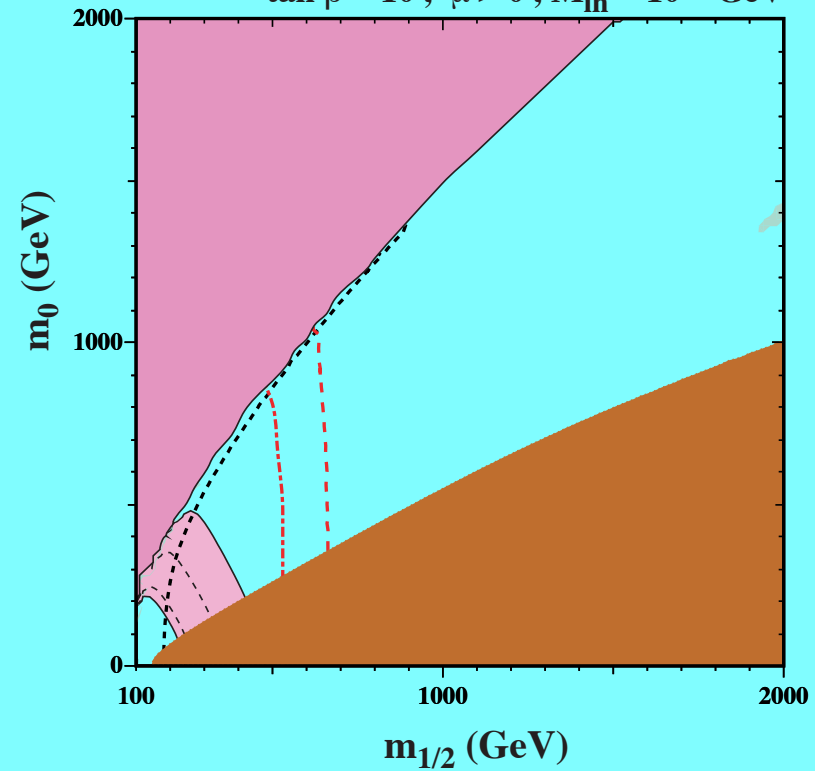
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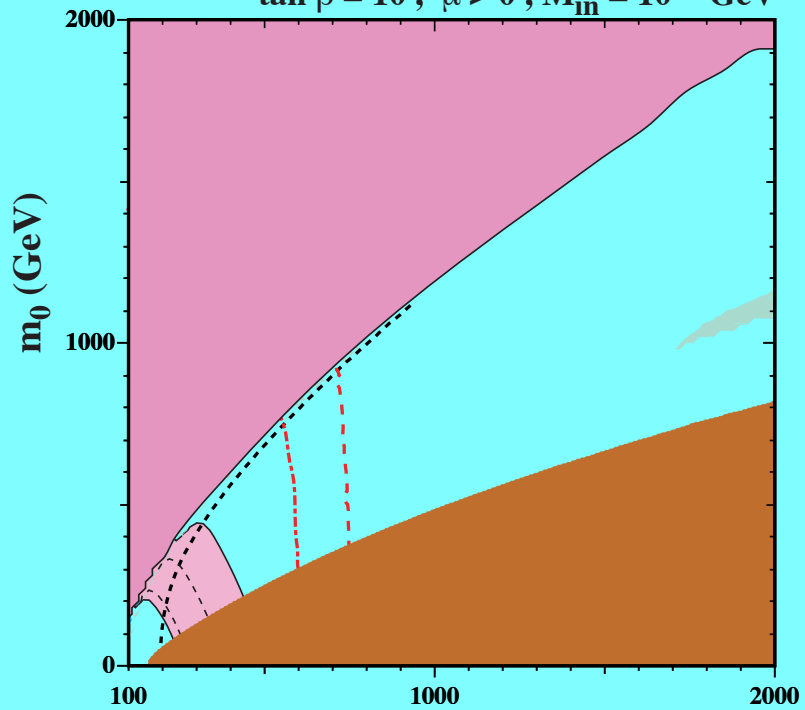
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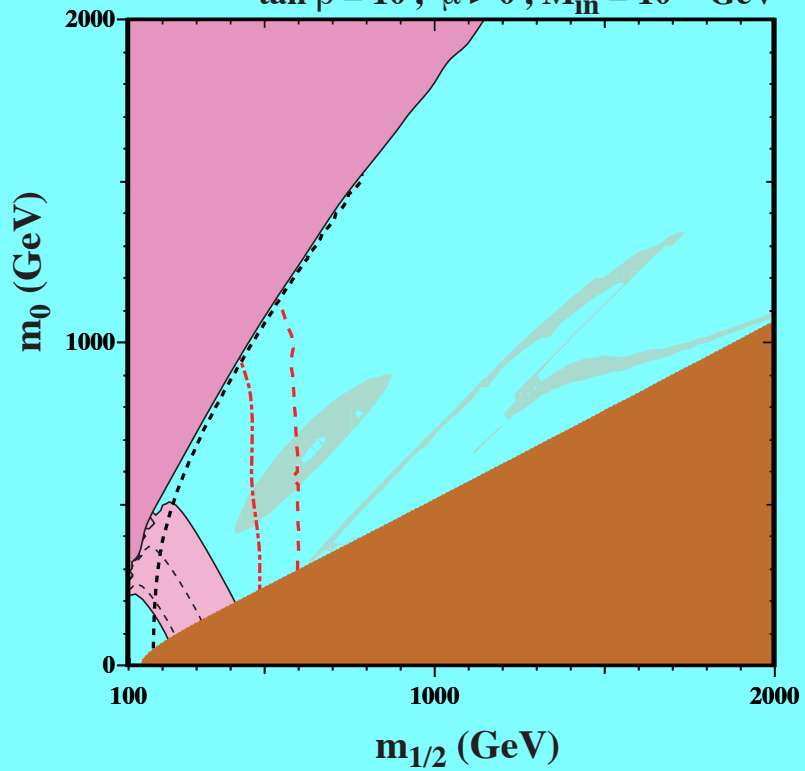
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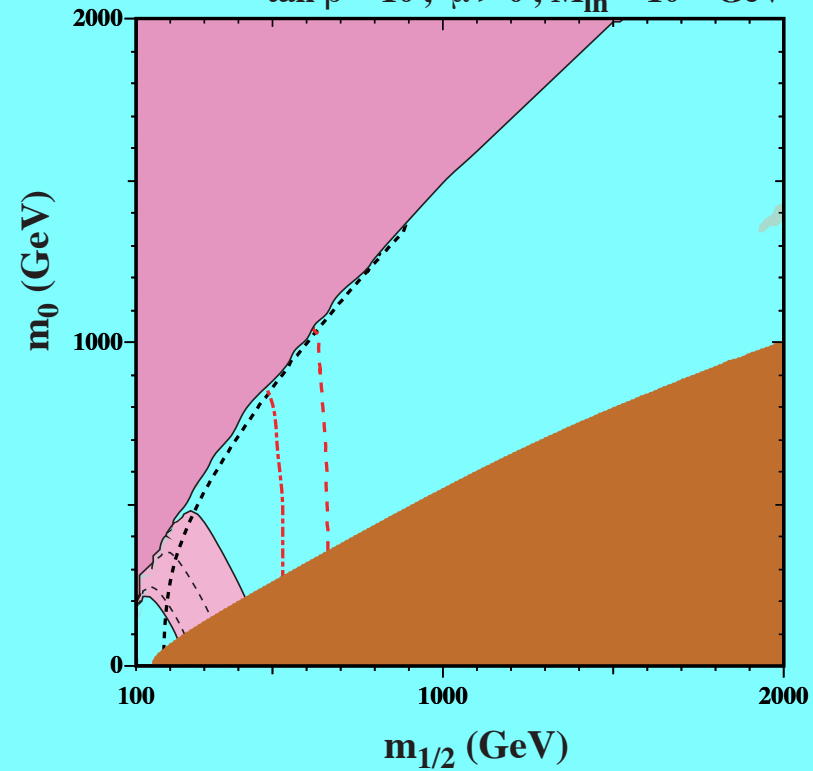
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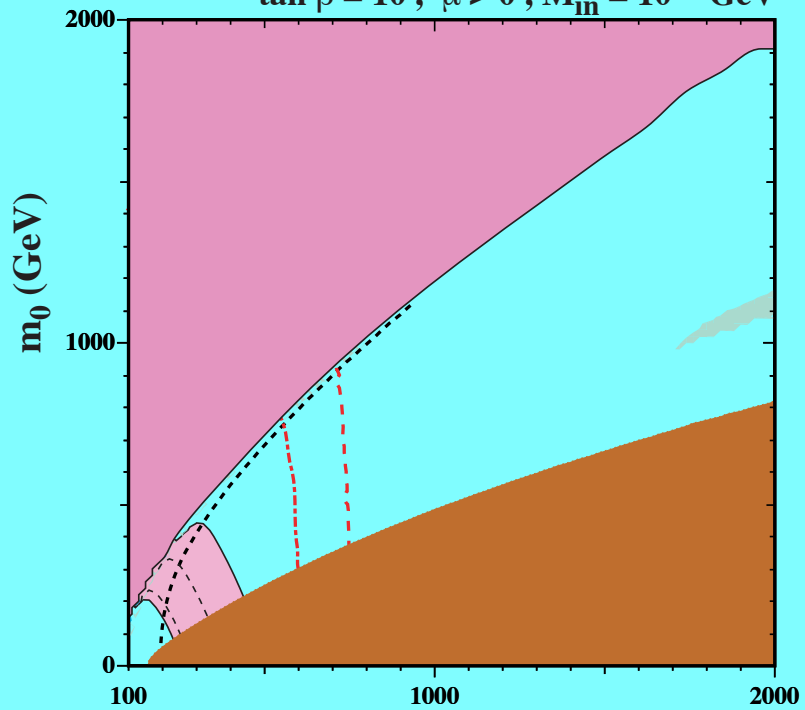
$\tan \beta = 10, \mu > 0, M_{\text{in}} = 10^{12} \text{ GeV}$



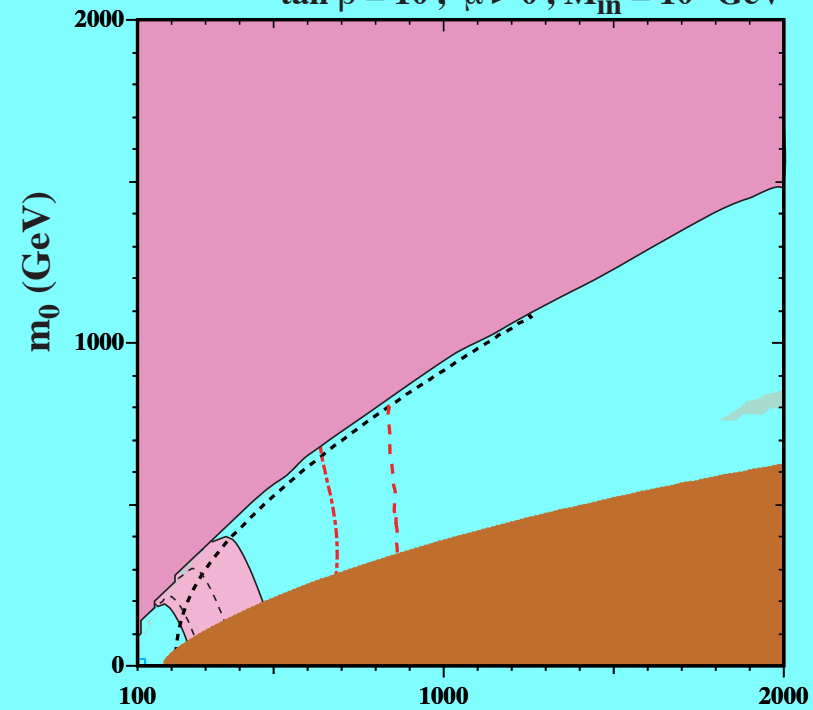
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$\tan \beta = 10, \mu > 0, M_{\text{in}} = 10^{10} \text{ GeV}$

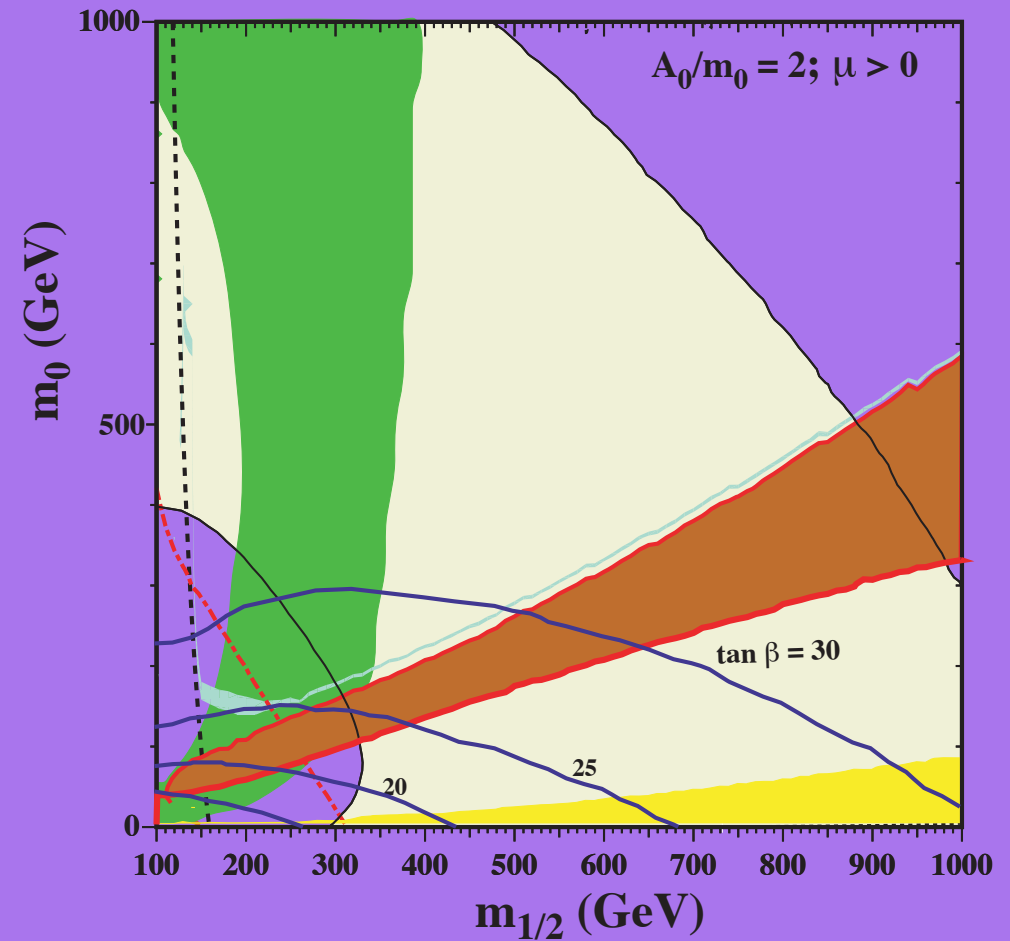
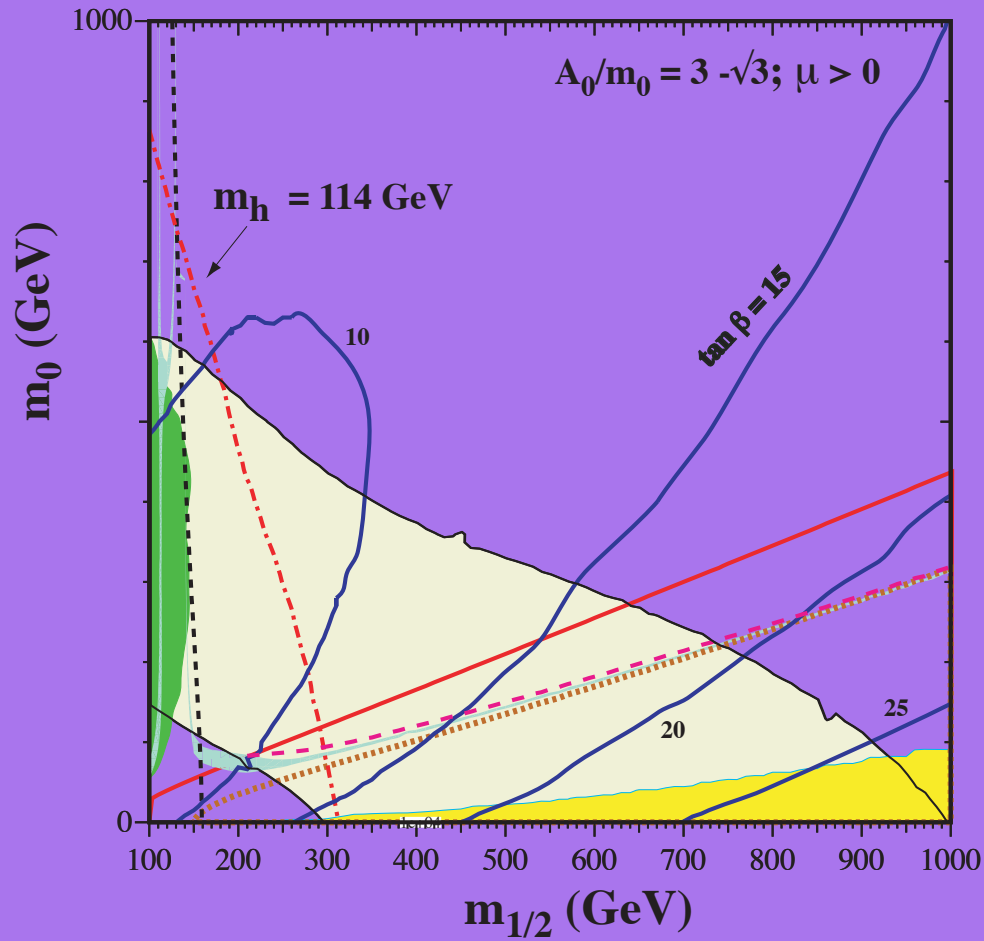


$\tan \beta = 10, \mu > 0, M_{\text{in}} = 10^9 \text{ GeV}$



mSugra models

- $\tan \beta$ fixed by boundary conditions ($B_0 = A_0 - m_0$)
- “planes” determined by A_0/m_0
- Gravitino often the LSP ($m_{3/2} = m_0$)



The Very CMSSM (mSUGRA):

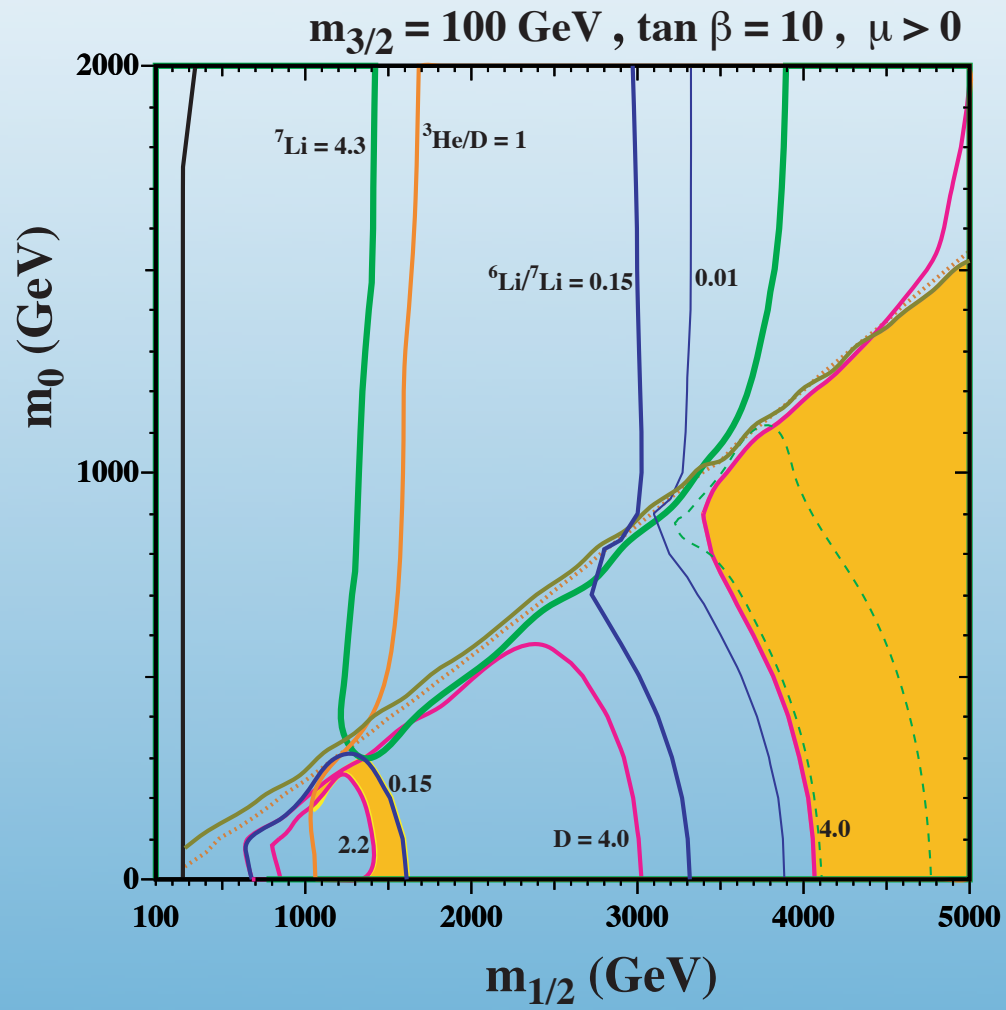
- Add $B_0 = A_0 - m_0$: Select $\tan \beta$

Ellis, Olive, Santoso, Spanos

Limits on Unstable particles due to Photo-Destruction and -Production of Nuclei

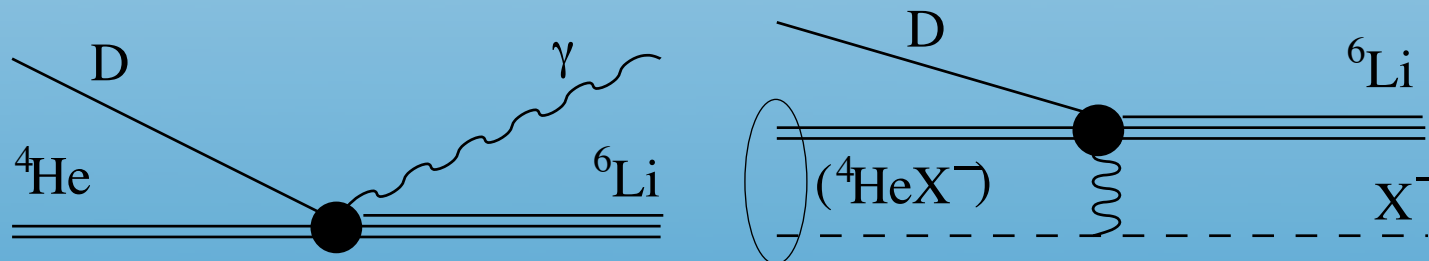
2 key parameters

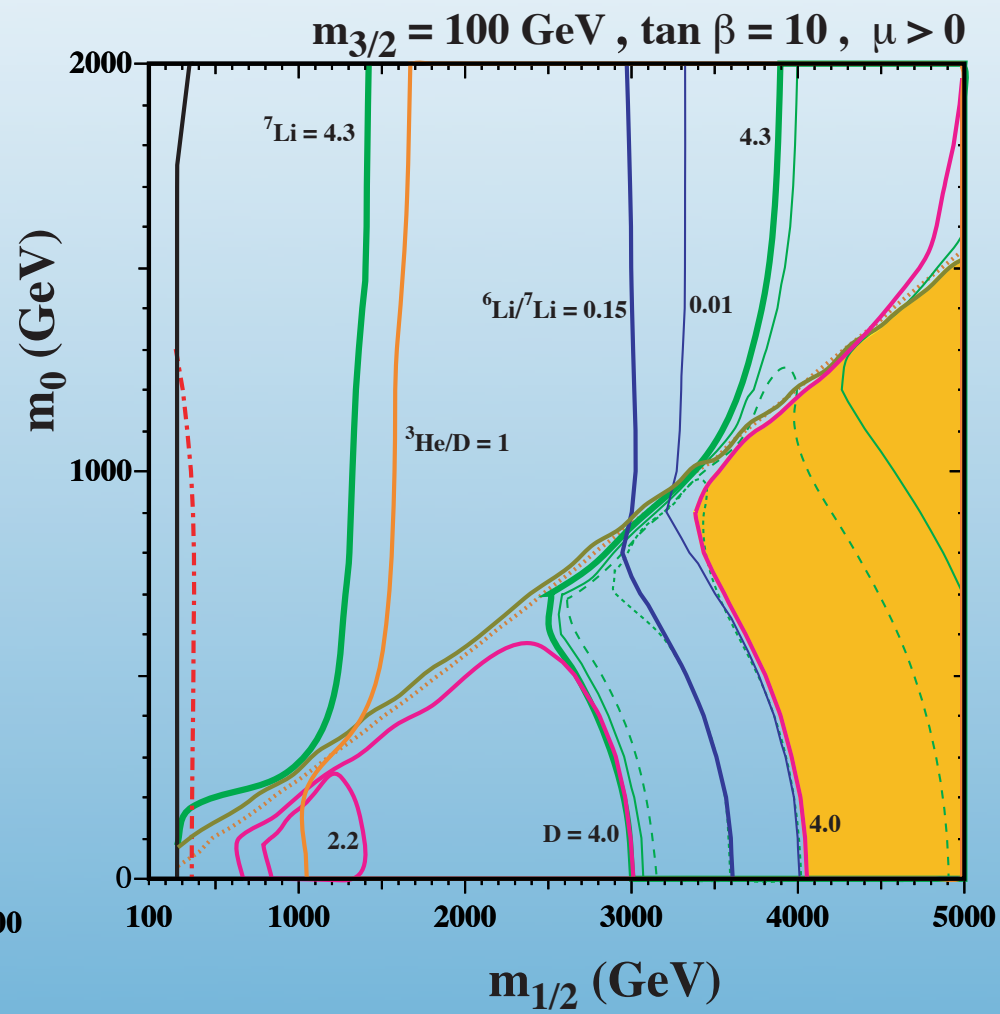
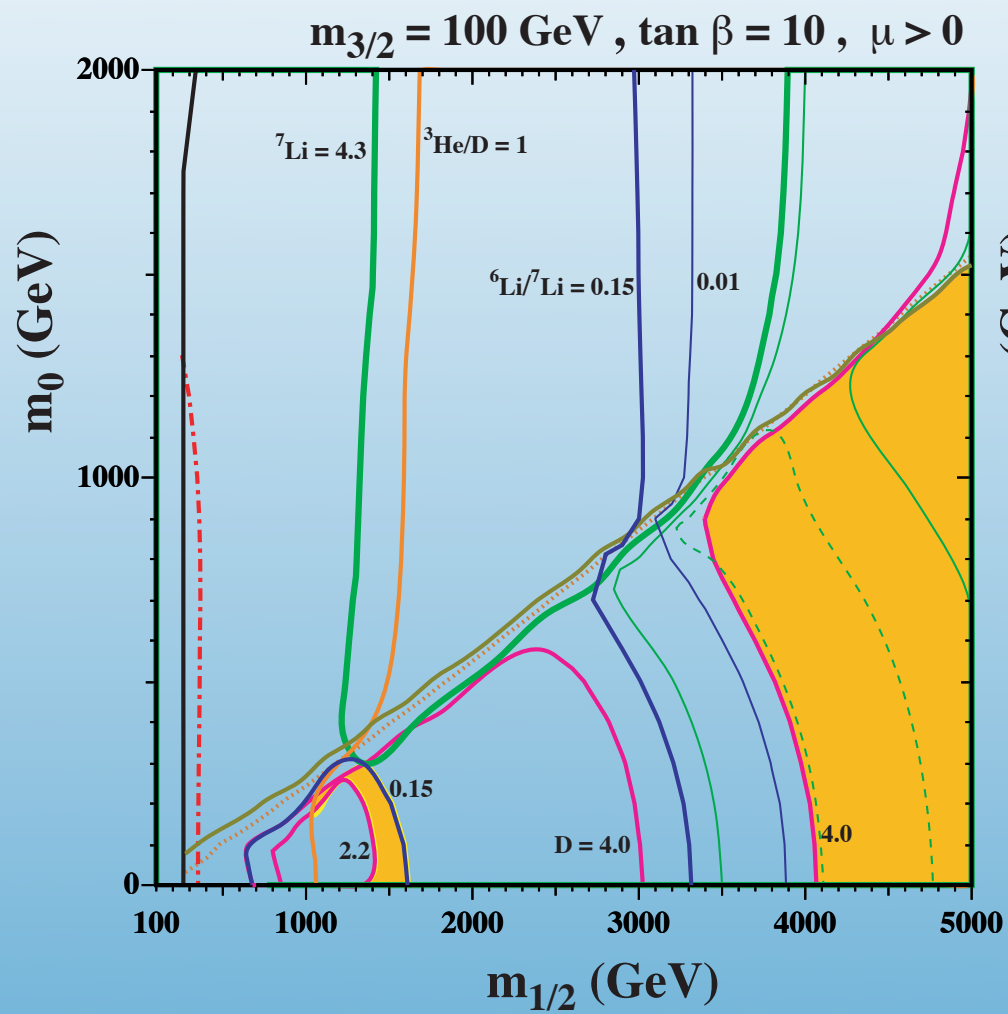
$$\zeta_X \equiv \frac{n_X^0}{n_\gamma^0} M_X = r M_X = 2r E_0, \quad \text{and} \quad \tau_X$$

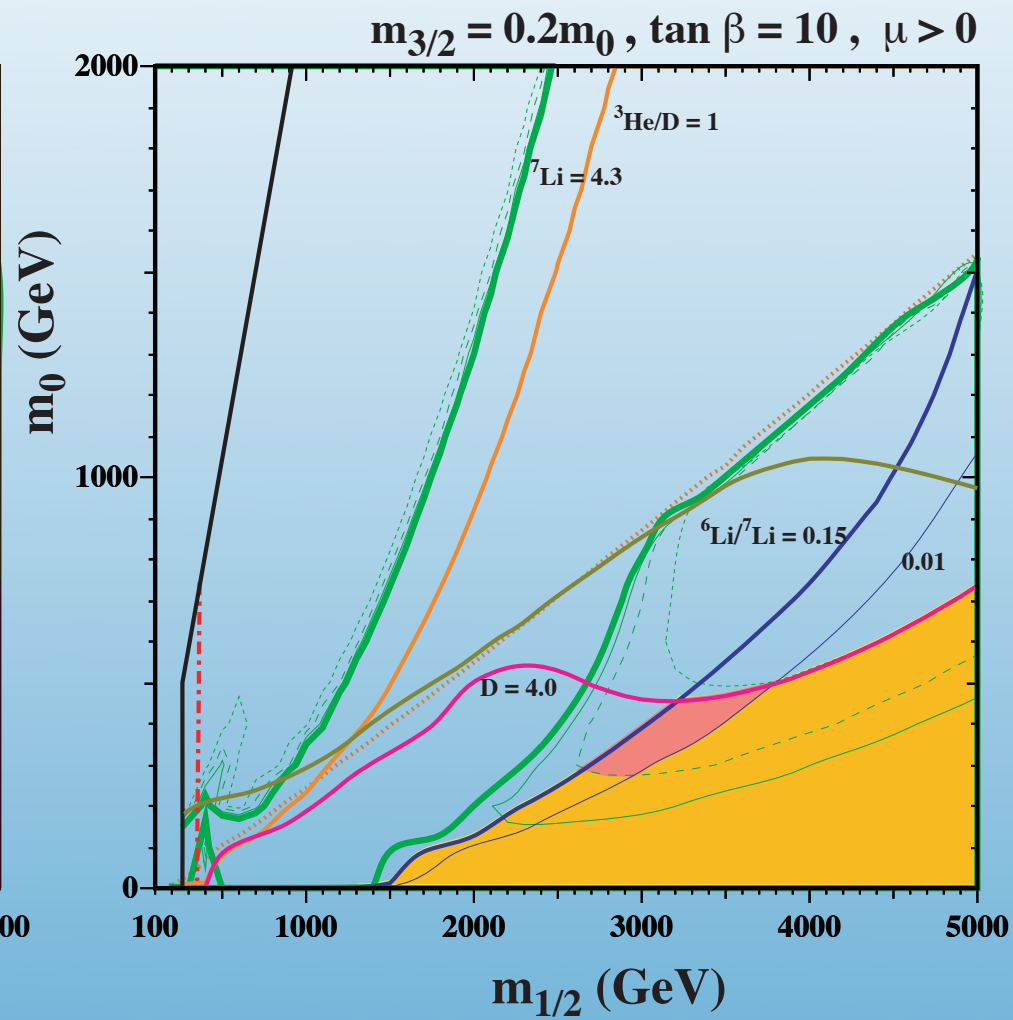
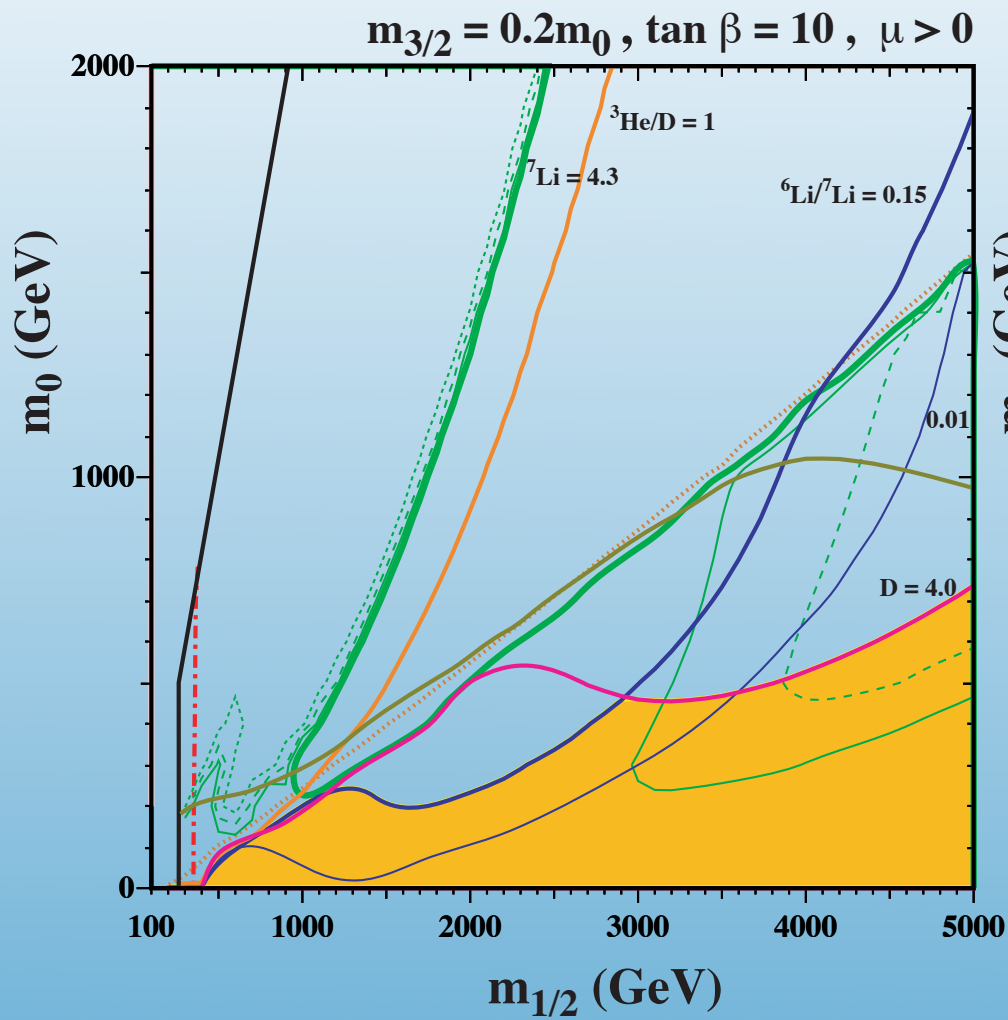


Effects of Bound States

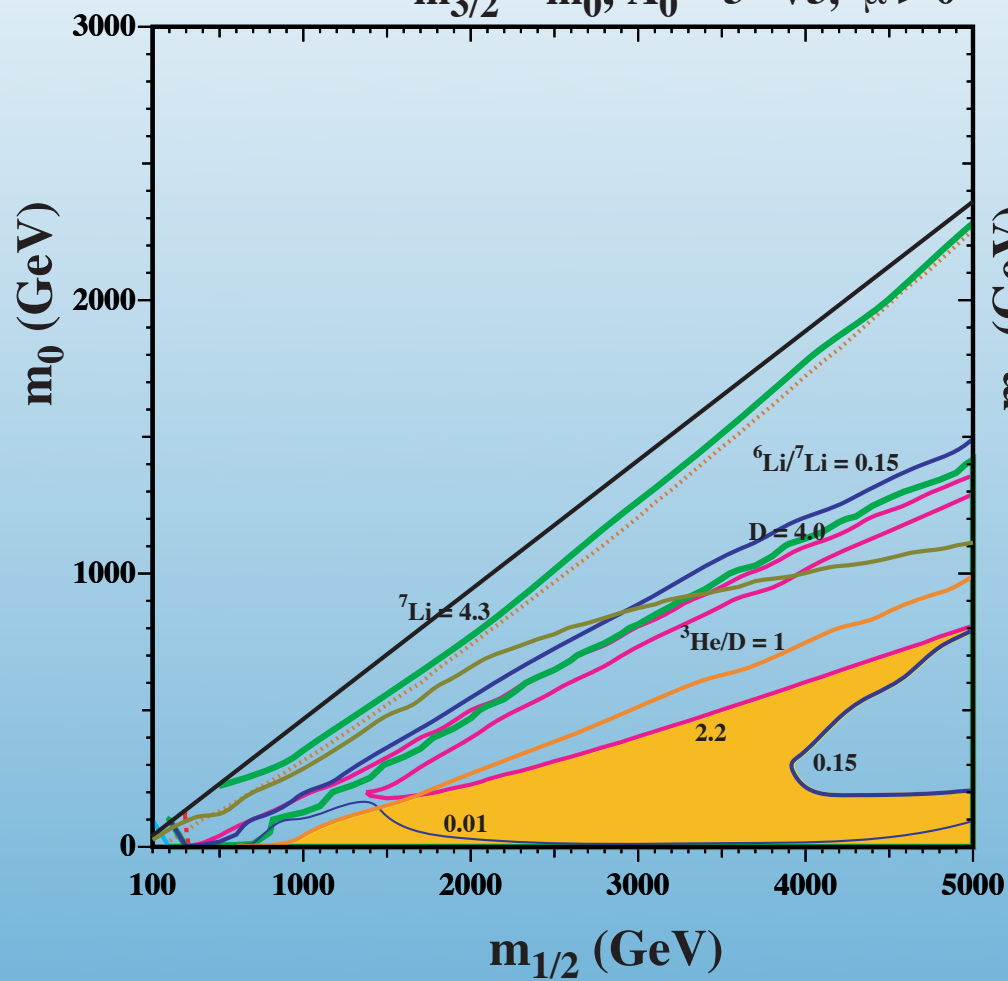
- In SUSY models with a $\tilde{\tau}$ NLSP, bound states form between ${}^4\text{He}$ and $\tilde{\tau}$
- The ${}^4\text{He} (D, \gamma) {}^6\text{Li}$ reaction is normally highly suppressed (production of low energy γ)
- Bound state reaction is not suppressed



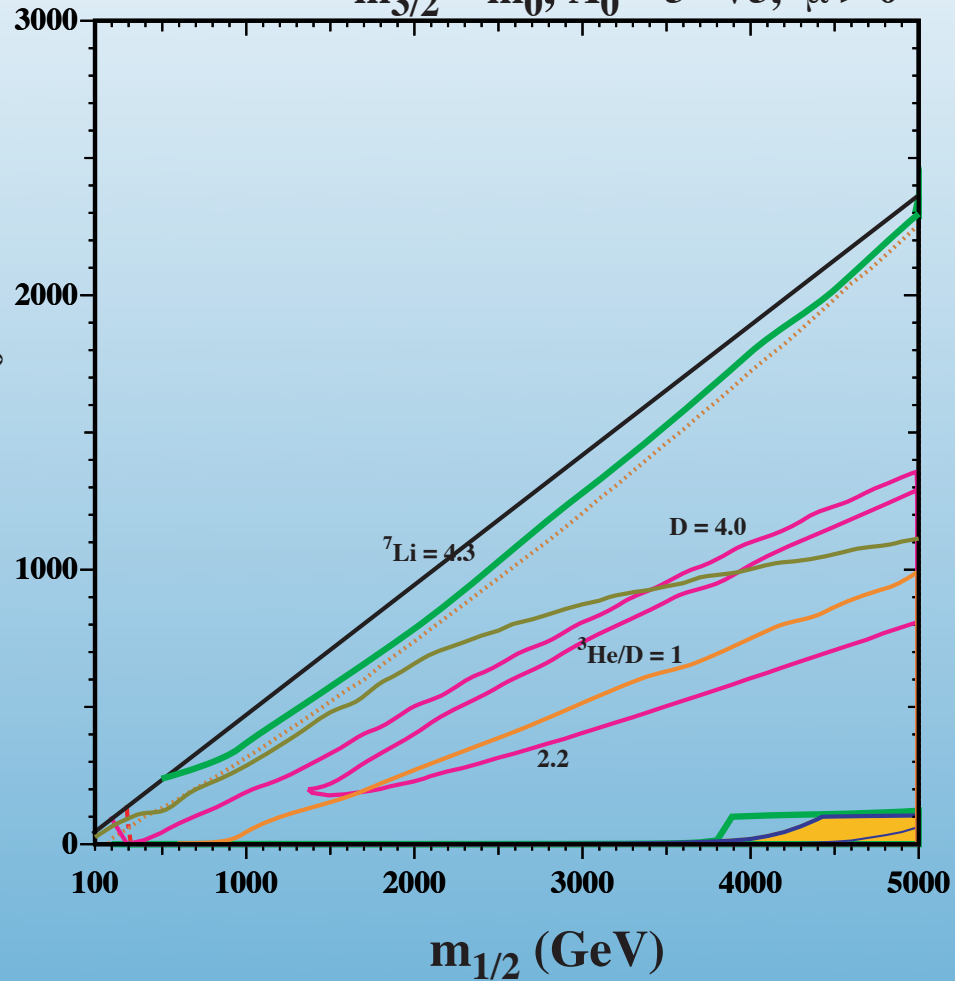




$m_{3/2} = m_0, A_0 = 3 - \sqrt{3}, \mu > 0$



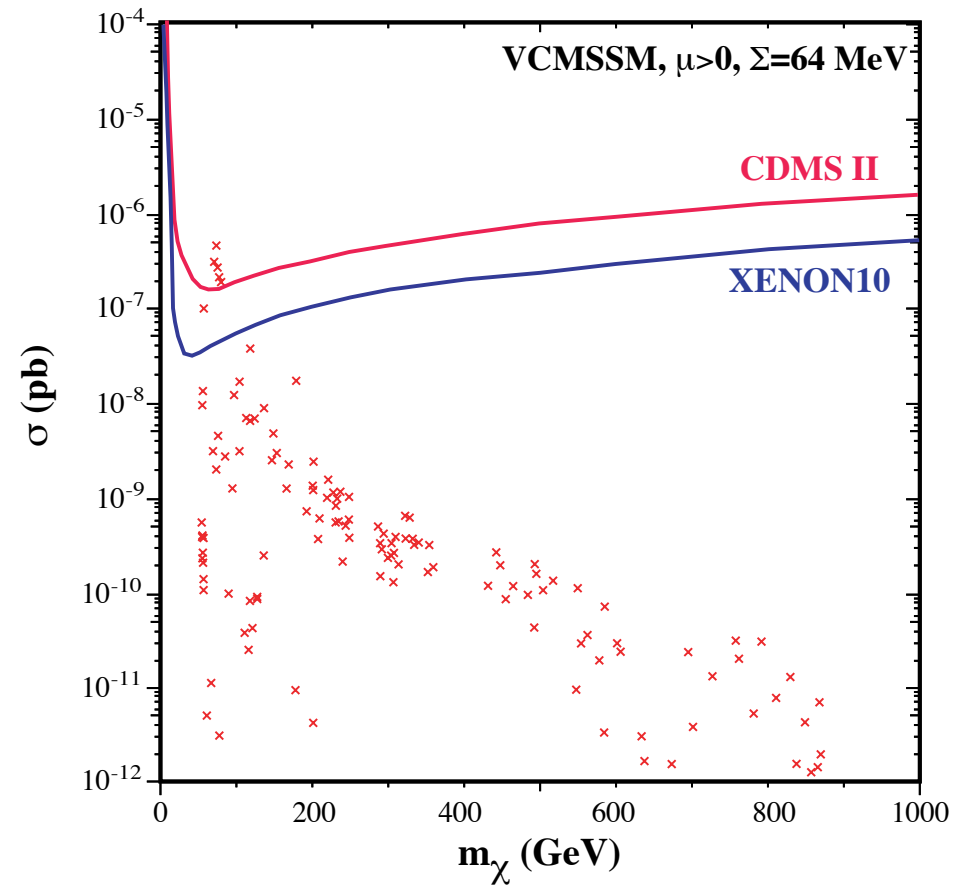
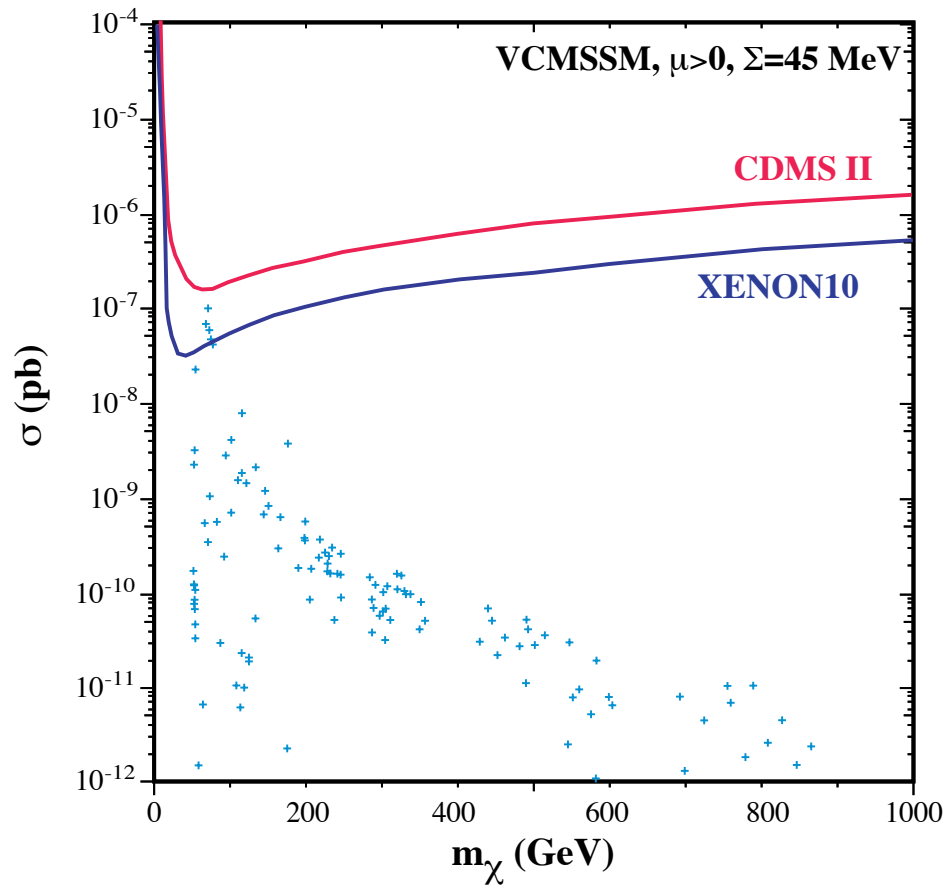
$m_{3/2} = m_0, A_0 = 3 - \sqrt{3}, \mu > 0$



mSugra models

- $\tan \beta$ 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 Funnel
- No Focus Point

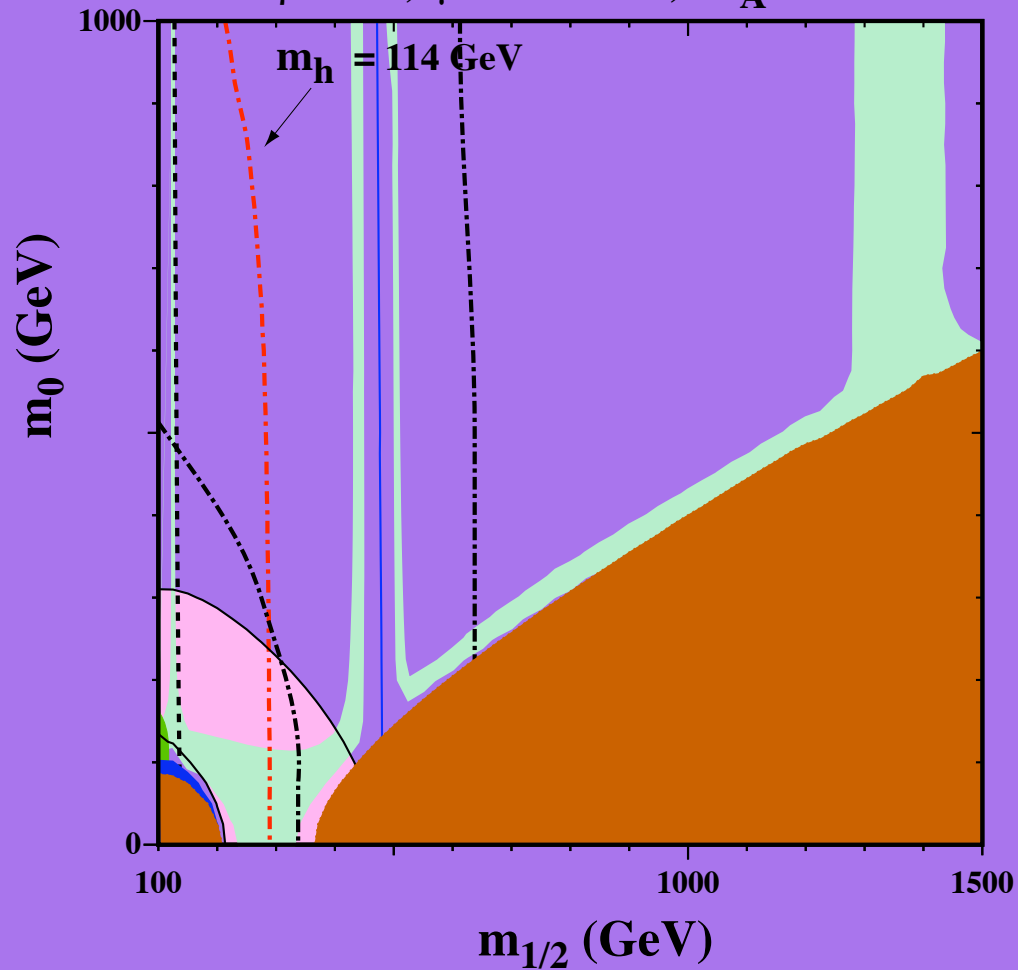
Direct Detection of NDM in the mSugra models



NUHM

- Drop unification of scalar masses
- All Higgs soft masses, m_1 and m_2 , to be chosen independently of m_0
- Allows μ and m_A to be free parameters

$\tan \beta = 10, \mu = 700 \text{ GeV}, m_A = 400 \text{ GeV}$

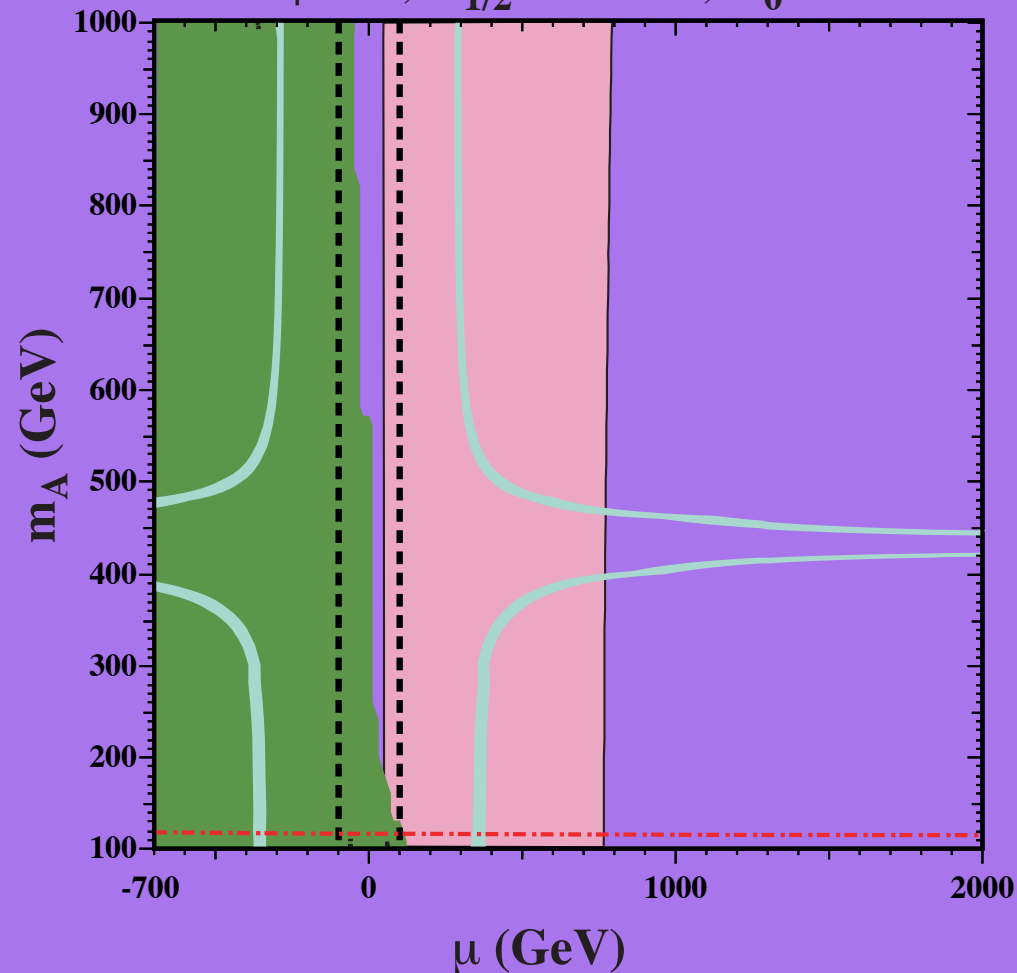


The $m_0 - m_{1/2}$ plane

+ CMSSM value

Ellis, Falk, Olive, Santoso

$\tan \beta = 35, m_{1/2} = 500 \text{ GeV}, m_0 = 1000 \text{ GeV}$

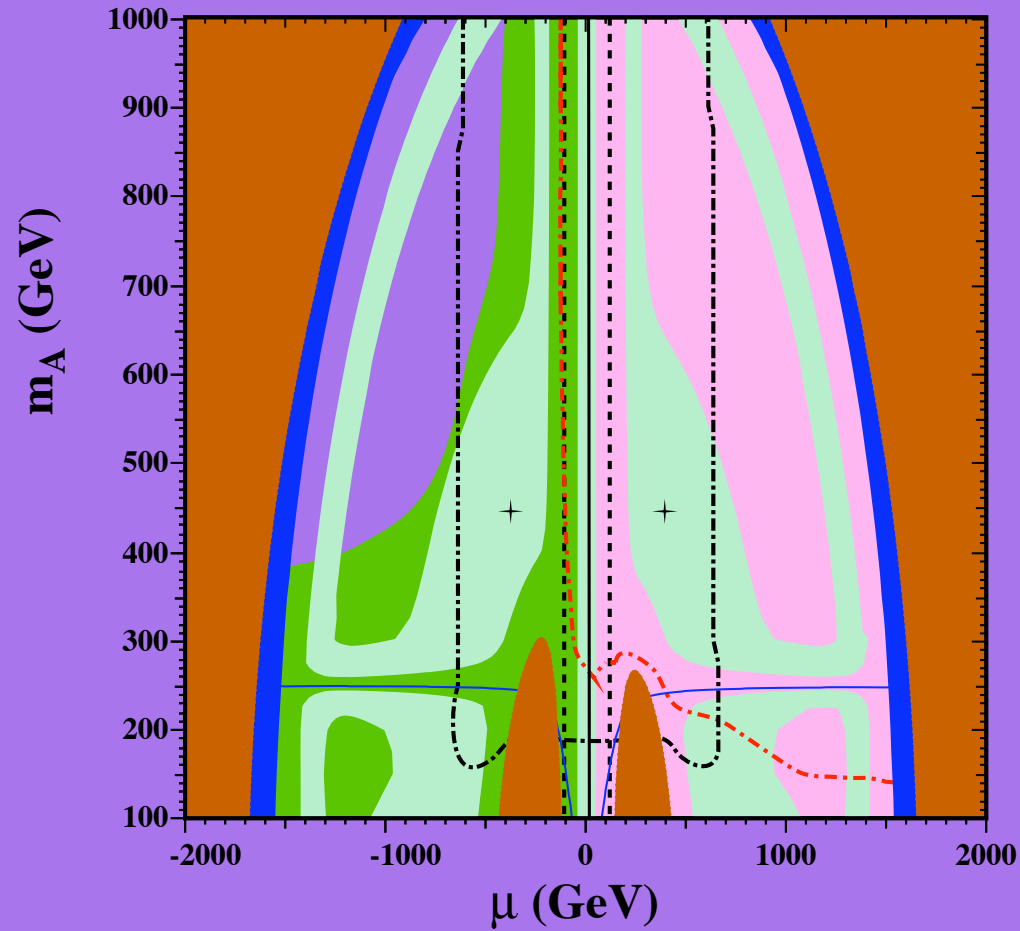


The $m_A - \mu$ plane

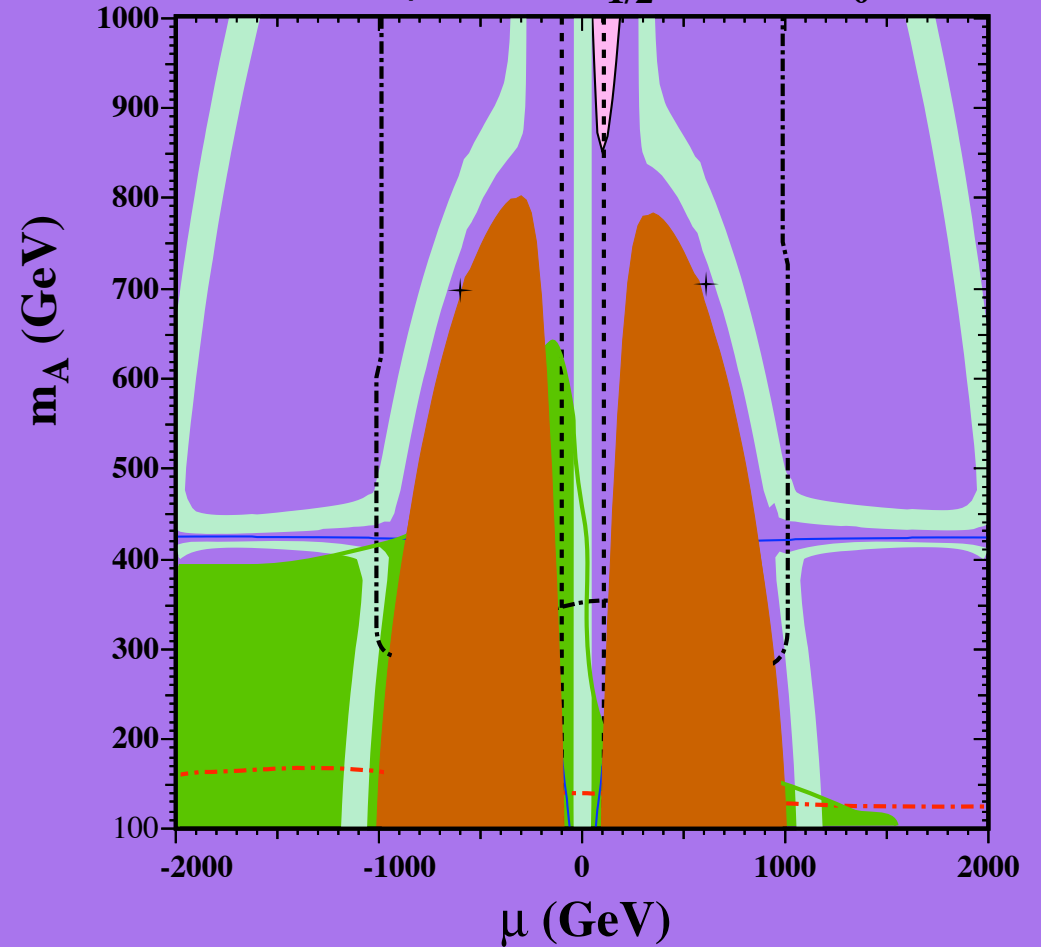
+ CMSSM value

Ellis, Olive, Santoso, Spanos

$\tan \beta = 10, m_{1/2} = 300, m_0 = 100$



$\tan \beta = 10, m_{1/2} = 500, m_0 = 100$

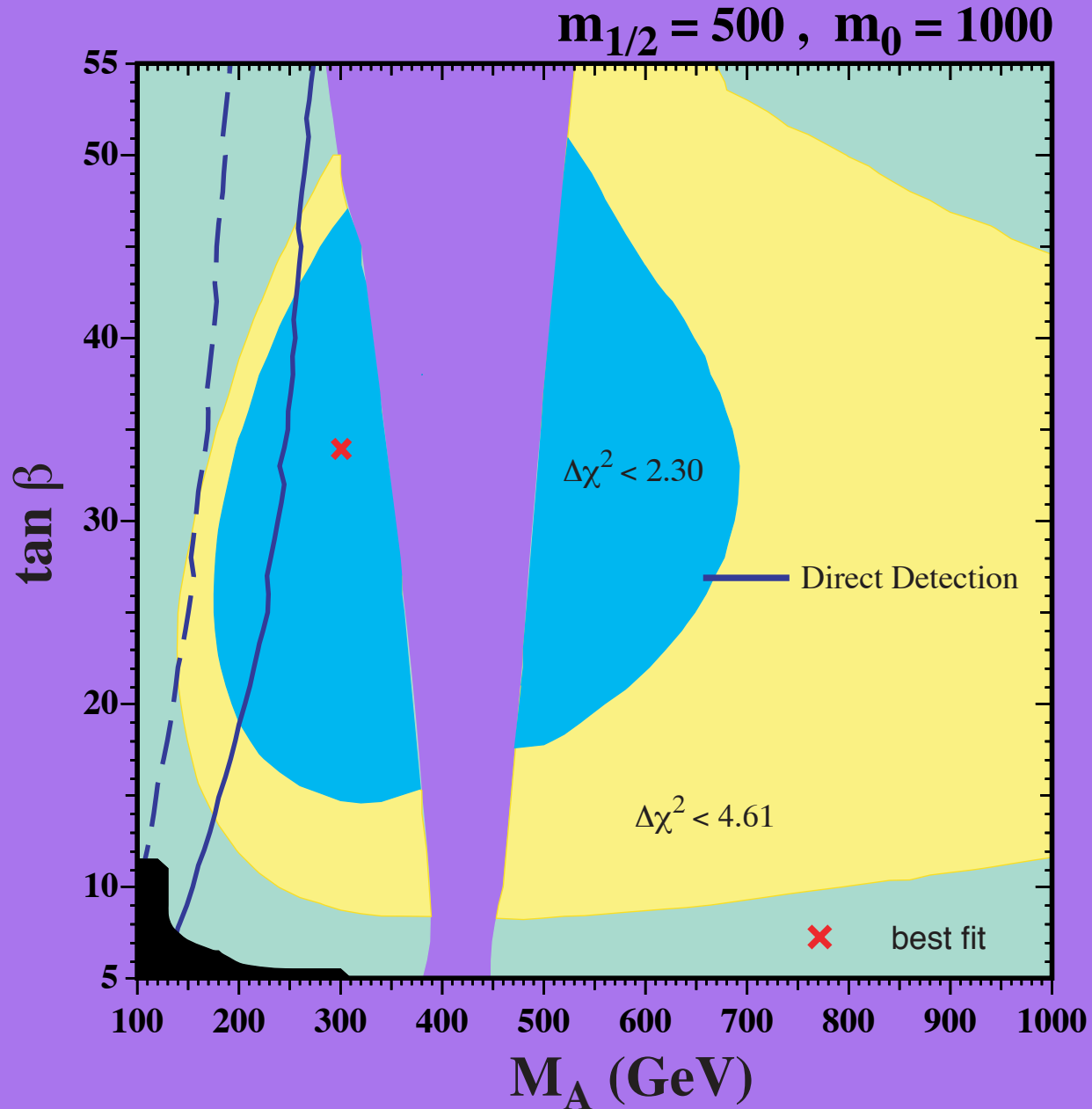


The $m_A - \mu$ plane

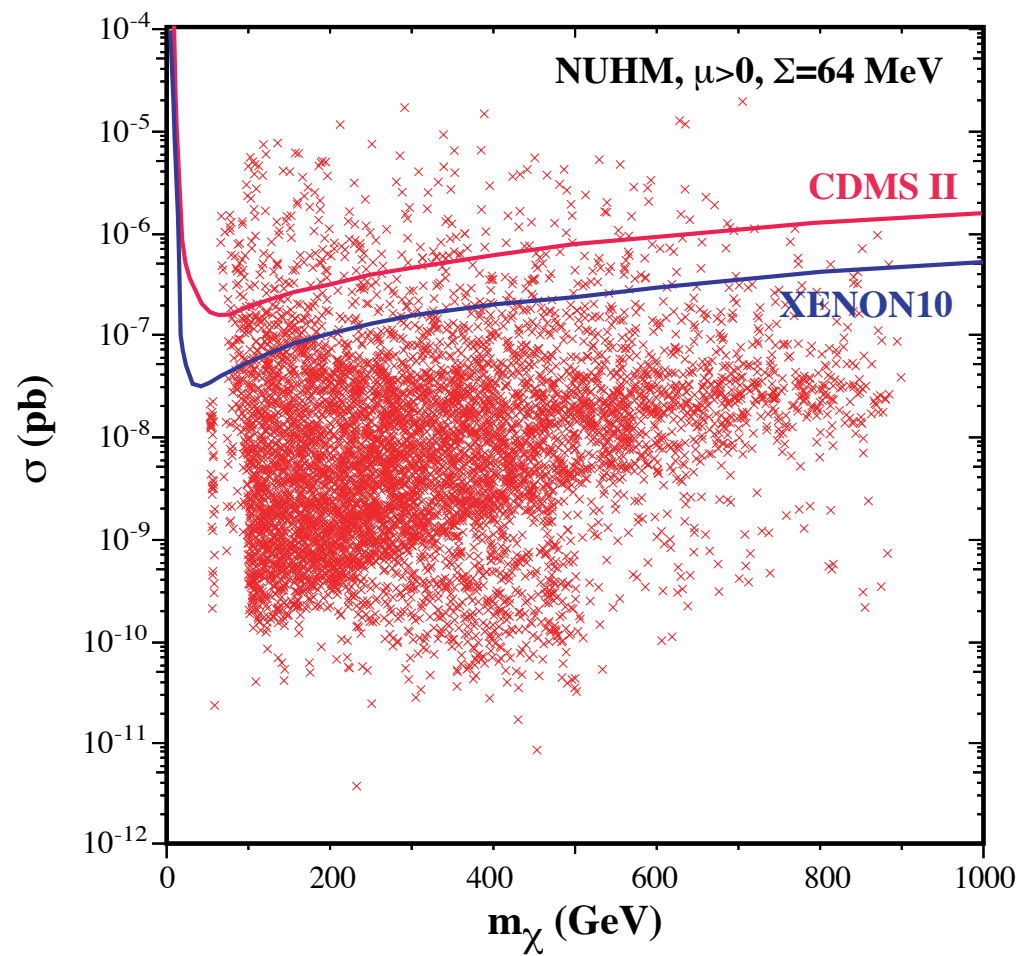
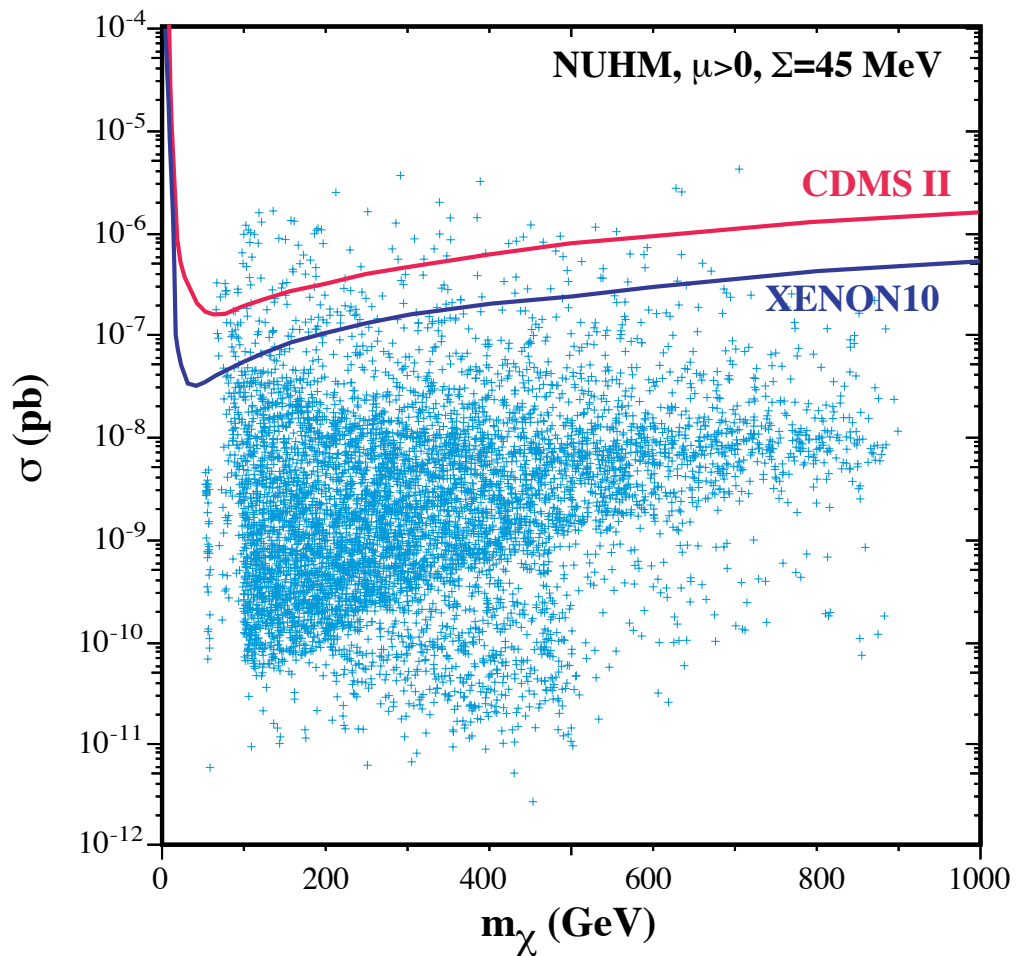
+ CMSSM value

Ellis, Olive, Santoso

CDM-consistent M_A - $\tan \beta$ planes

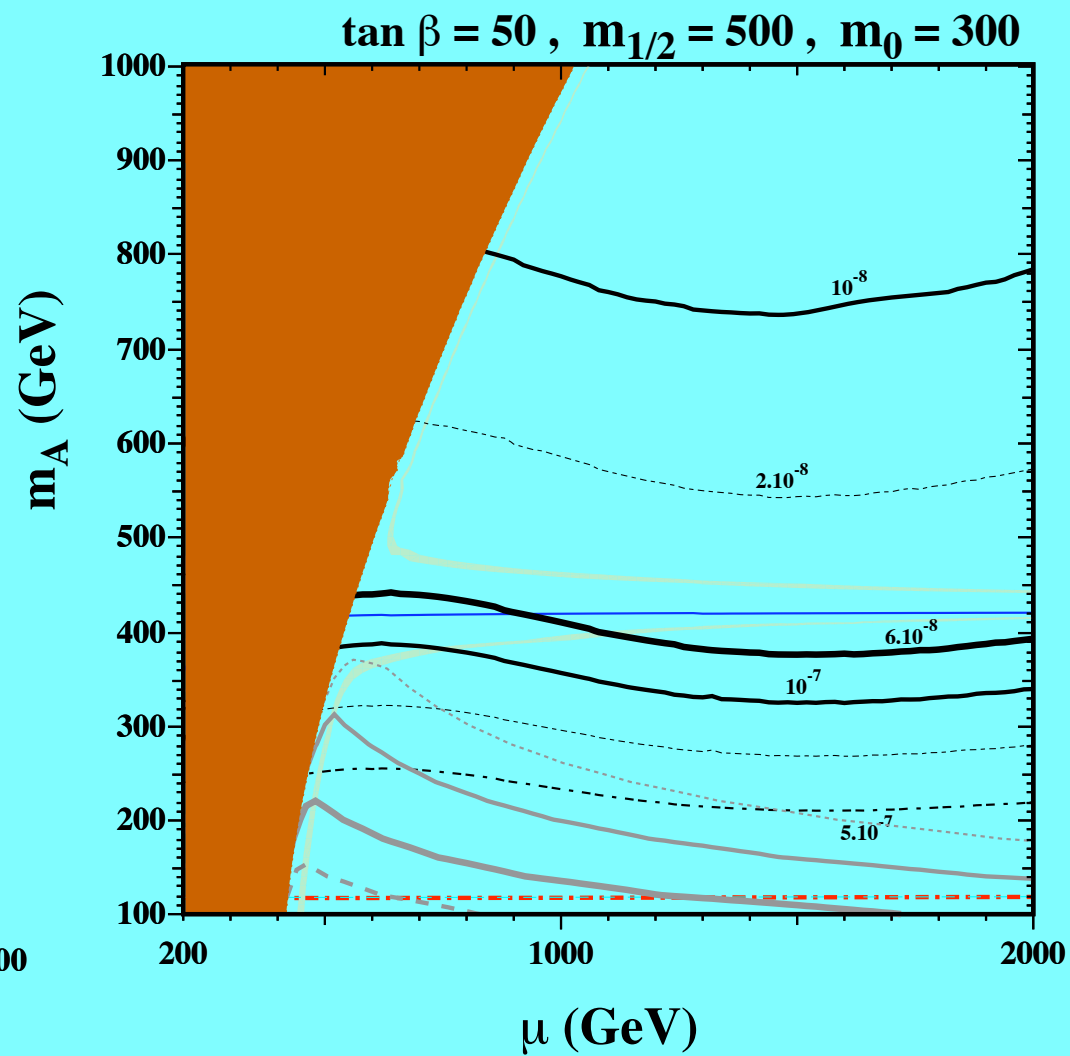
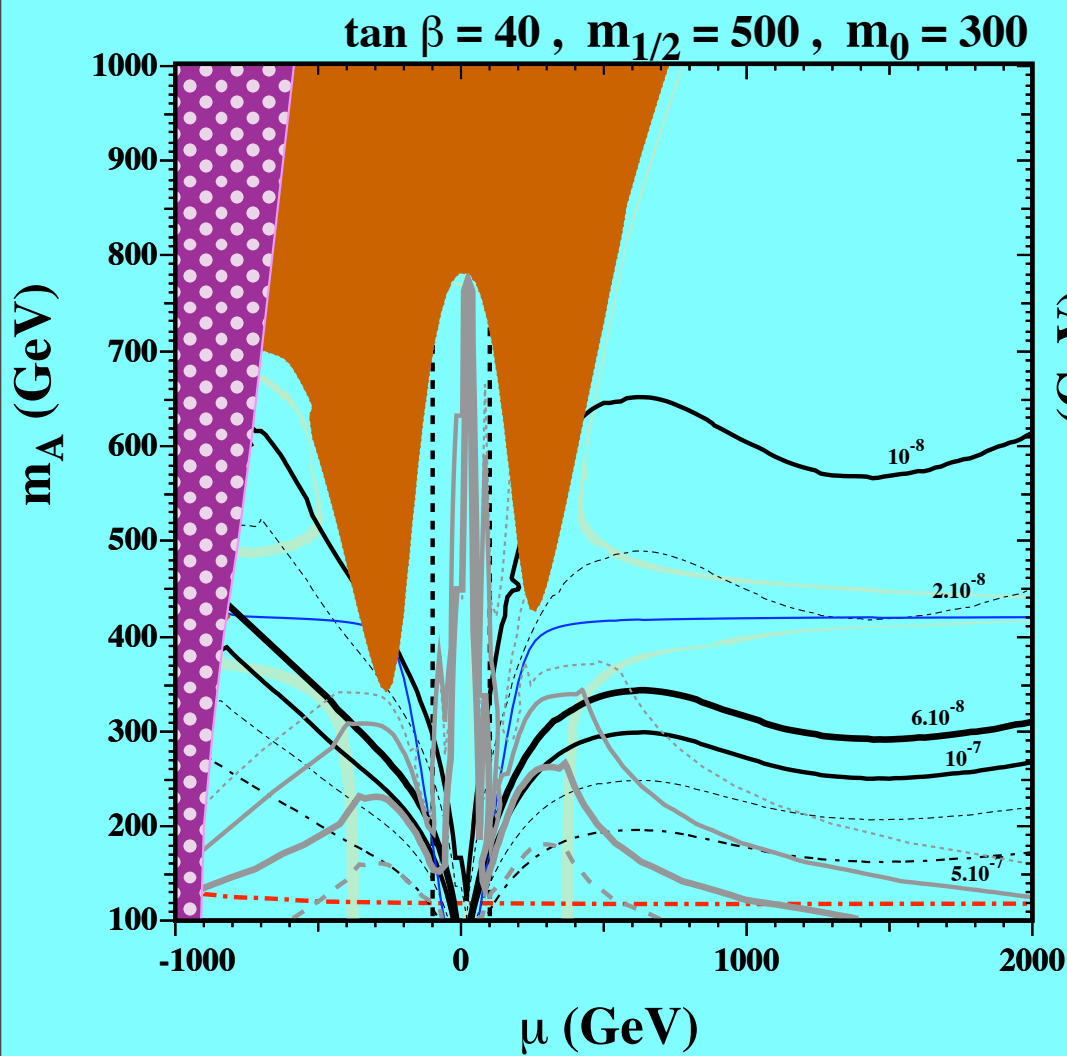


Direct Detection in the NUHM



EOSS

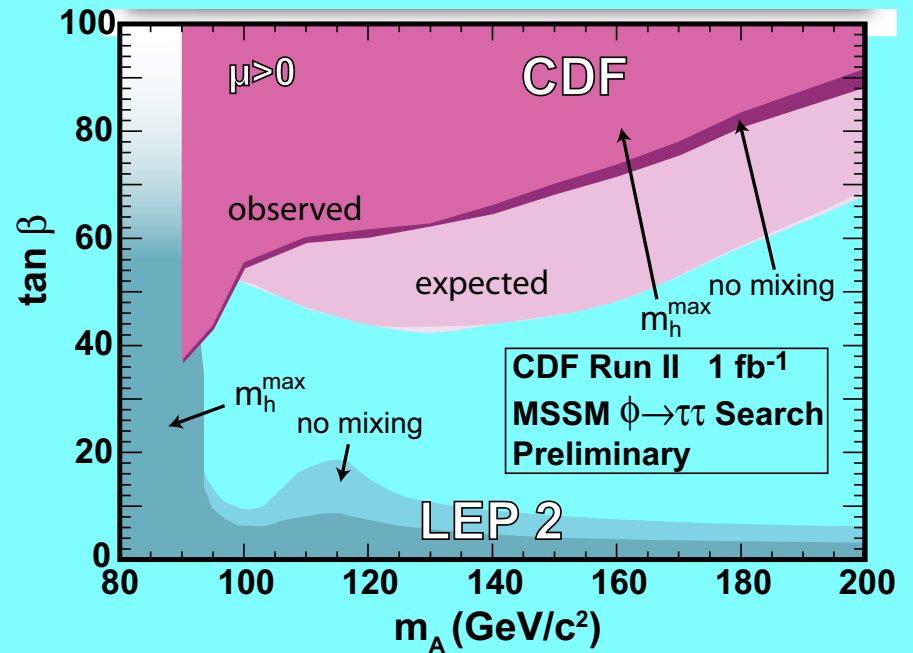
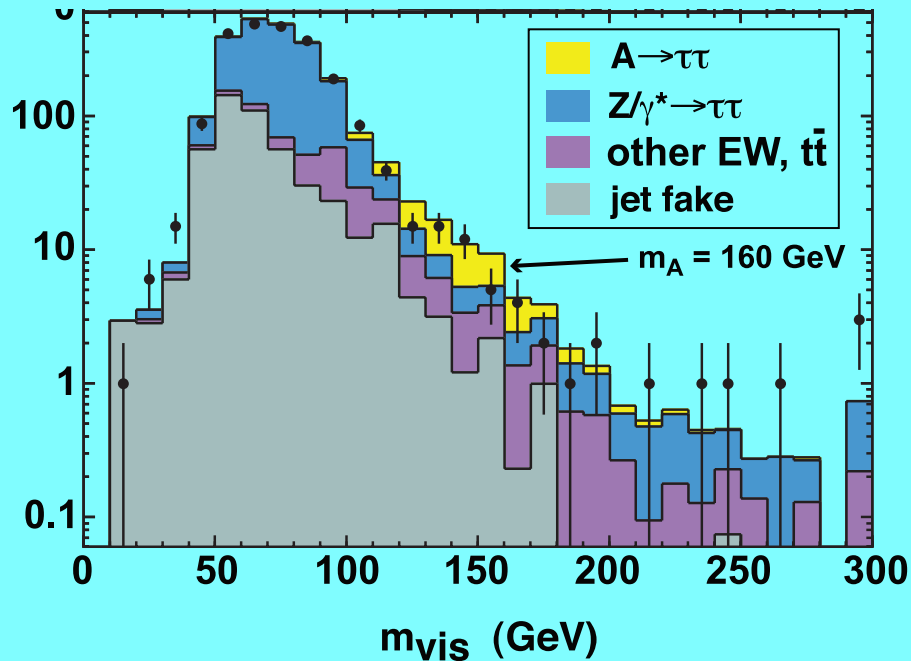
Competition between Direct Detection and $B \rightarrow \mu^+ \mu^-$



EOSS

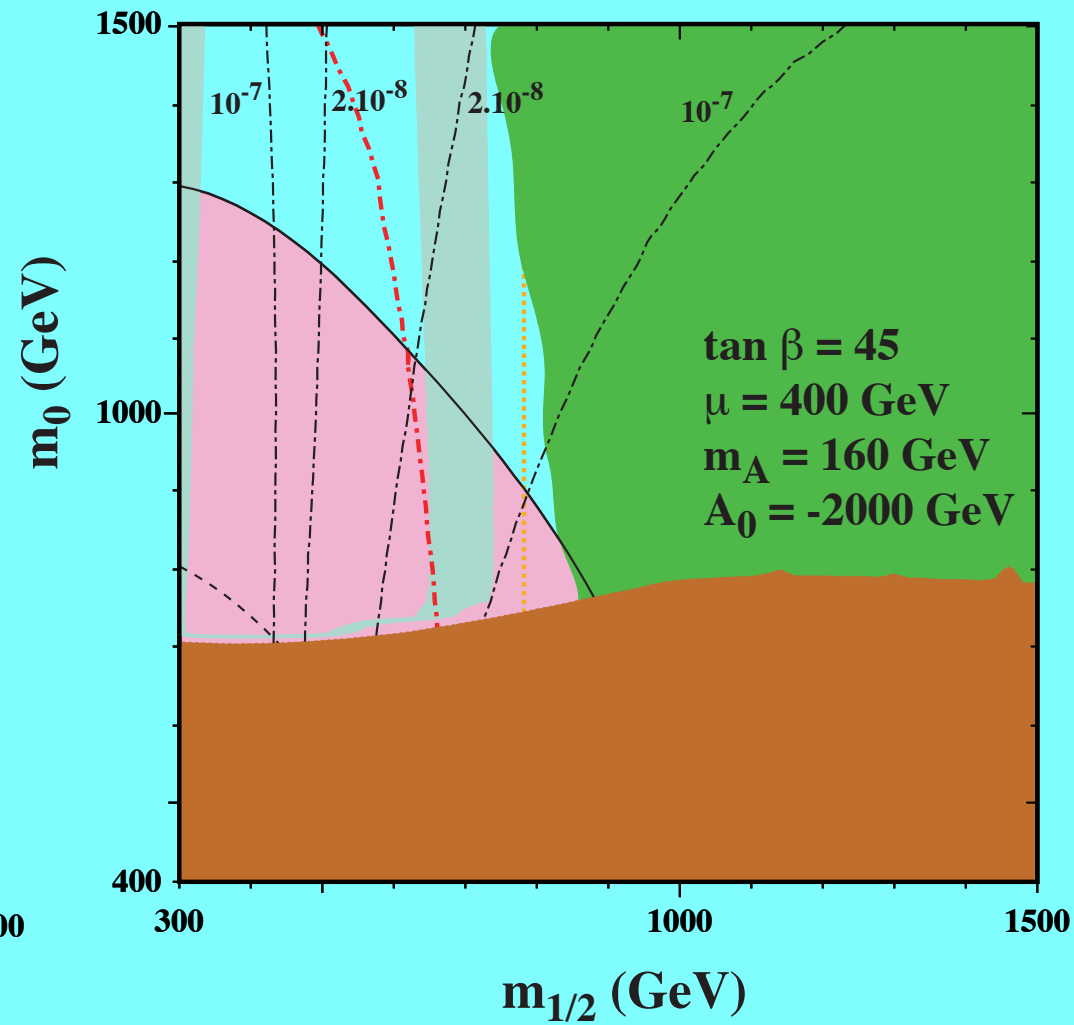
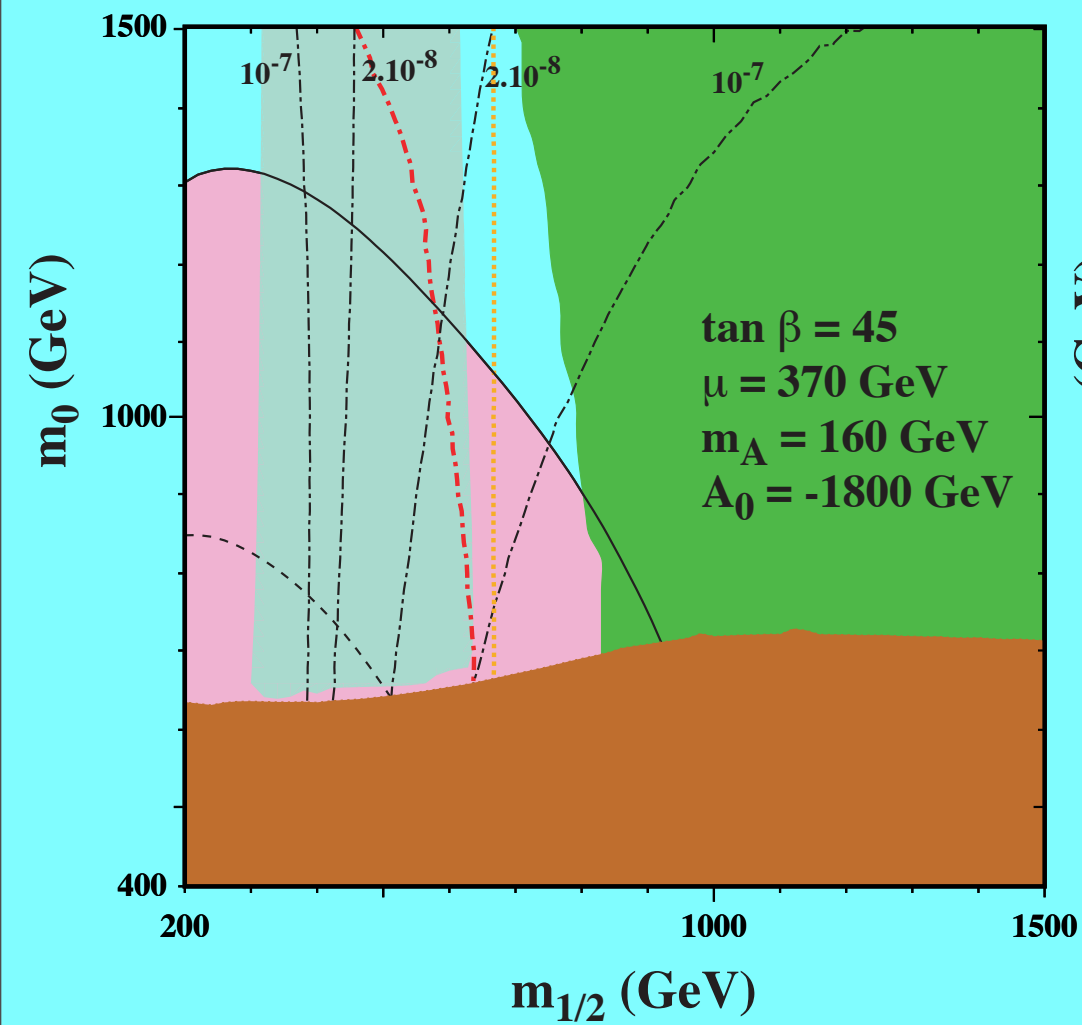
Hint of Higgs?

CDF

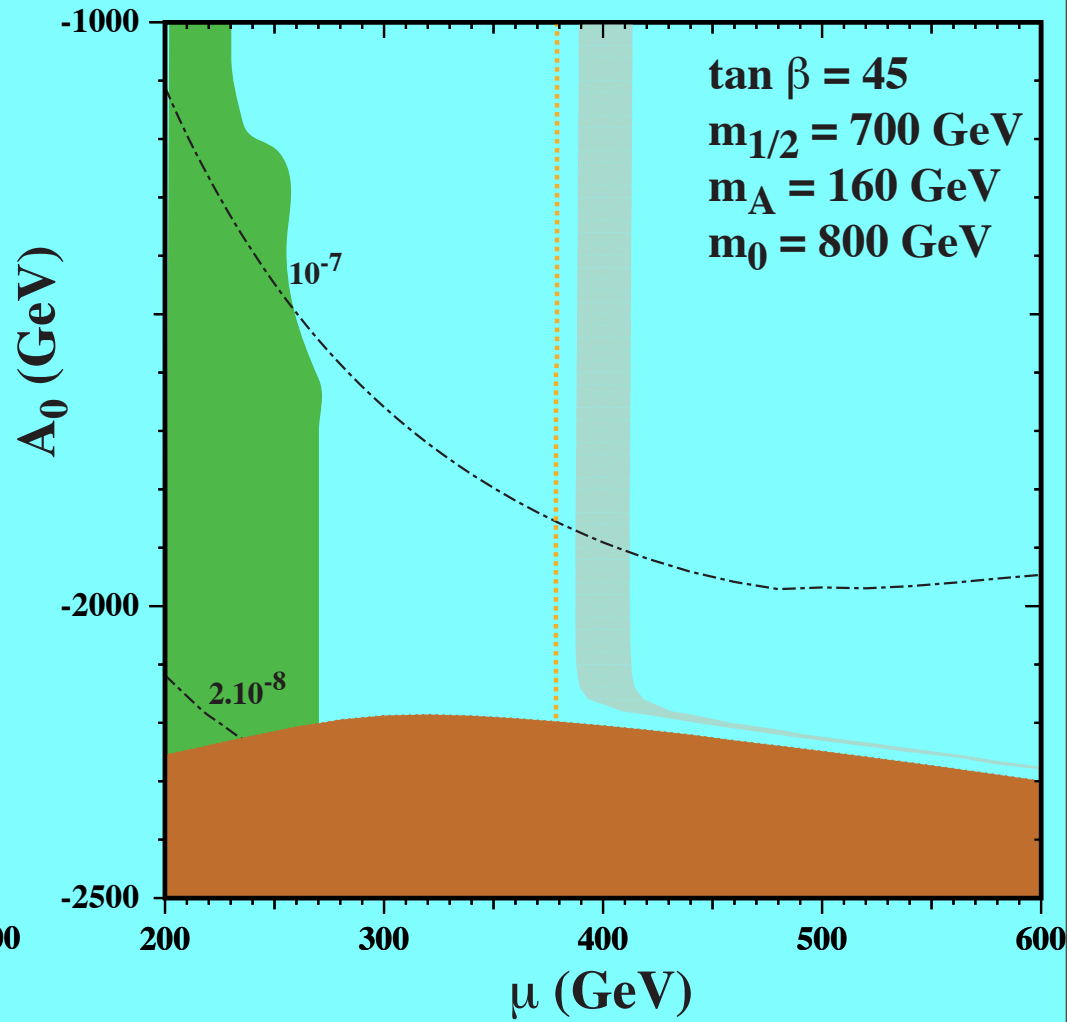
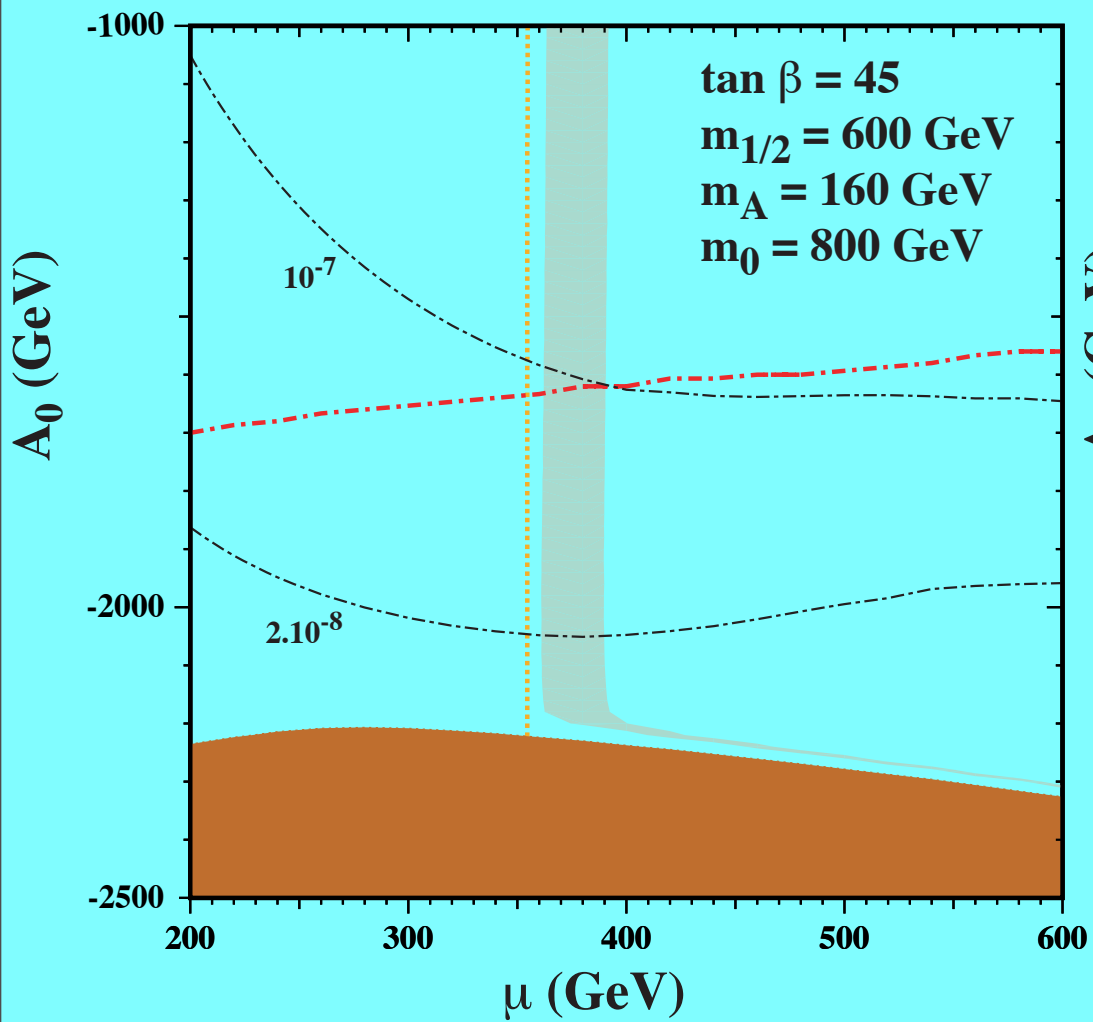


Not possible in CMSSM (light Higgs)
but barely possible in NUHM

NUHM Planes



EHOW



EHOW

Hint of Higgs?

- Small M_A and large $\tan \beta$ possible but very constrained in the NUHM (not possible in the CMSSM)
- $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$ should be detected soon
- $\text{BR}(b \rightarrow s \gamma)$ should show deviations from SM
- Dark Matter should be detected by CDMS and XENON10

Summary

- mSugra models most difficult to access experimental esp. if GDM
- Good indication from indirect sensitivities for 'low' energy signal for SUSY.
- Good prospect for Direct detection and $B \rightarrow \mu^+ \mu^-$ particularly in non CMSSM models (unless GDM)
- Hint of Higgs should be accompanied by many deviations from the SM