CDM in Supersymmetric Models

Relic Density in the CMSSM

Phenomenological Constraints

Higgs masses, $b \rightarrow s\,\gamma$, g-2

Relaxing the CMSSM

Prospects for Detection

with: Ellis, Falk, Ferstl, Ganis, Santoso, Srednicki

SUSY Dark Matter

MSSM and R-Parity $\longrightarrow$

Stable DM candidate

1) Neutralinos

$$\tilde{\chi}_\iota = \alpha_\iota \tilde{B} + \beta_\iota \tilde{W} + \gamma_\iota \tilde{H}_1 + \delta_\iota \tilde{H}_2$$

2) Sneutrinos

Excluded (unless add L-violating terms)

3) Other:

Axinos, Gravitinos, etc

mass matrix

$$(\tilde{B}, \tilde{W}^3, \tilde{H}_1^0, \tilde{H}_2^0) \begin{pmatrix} M_1 & 0 & \frac{-g_1 v_1}{\sqrt{2}} & \frac{g_1 v_2}{\sqrt{2}} \\ 0 & M_2 & \frac{g_2 v_1}{\sqrt{2}} & \frac{-g_2 v_2}{\sqrt{2}} \\ \frac{-g_1 v_1}{\sqrt{2}} & \frac{g_2 v_1}{\sqrt{2}} & 0 & -\mu \\ \frac{g_1 v_2}{\sqrt{2}} & \frac{-g_2 v_2}{\sqrt{2}} & -\mu & 0 \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W}^3 \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix}$$

Depends on $M_{1/2}$, μ, and $\tan\beta$

Assume $M_1 = M_2 = M_3 = M_{1/2}$ @ GUT Scale

Also Relic Density Depends on m_0, m_A

Parameters

Higgs mixing mass: μ

Ratio of Higgs vevs: $\tan\beta$

Gaugino masses: M_i

Soft scalar masses: m_o

Bi and Trilinear Terms: B and A_i

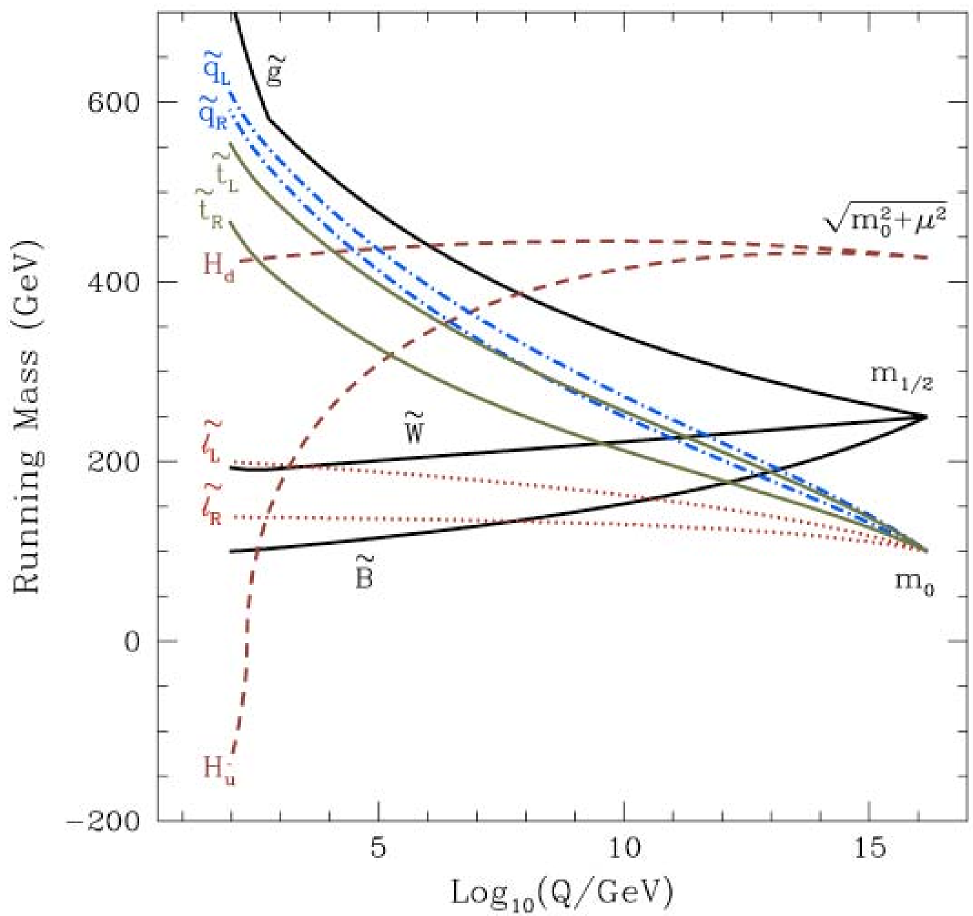
Phases: θ_μ, θ_A

Boundary conditions

- Input parameters: μ, m_1, m_2, B. predict M_Z, $\tan\beta$, m_A

CMSSM conditions

- Instead CMSSM:
  Input parameters: M_Z, m_1, m_2, $\tan\beta$ ($m_1 = m_2 = m_0$)
  predict μ, B, m_A



Falk

CMSSM Spectra

Unification to
rich spectrum
+
EWSB

The Relic Density

At high temperatures $T >> m_\chi$;

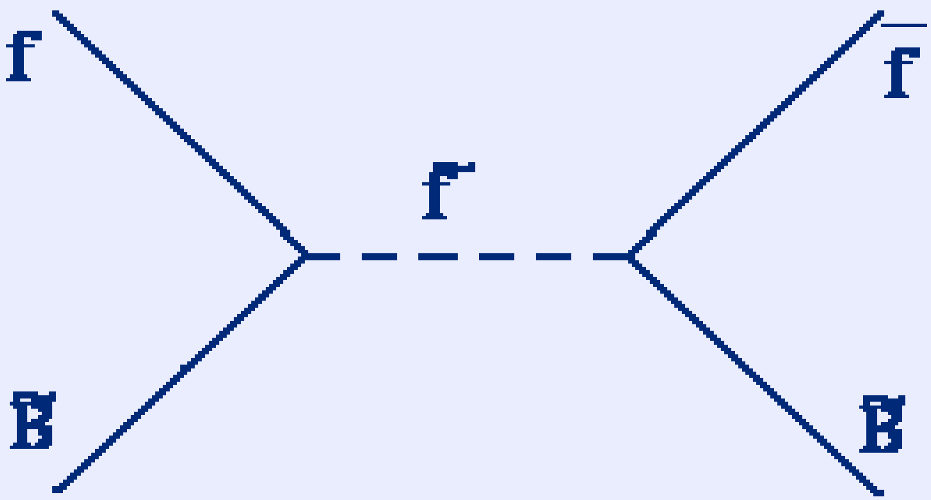
χ's in equilibrium $\Gamma > H$ $n_\chi \sim n_\gamma$

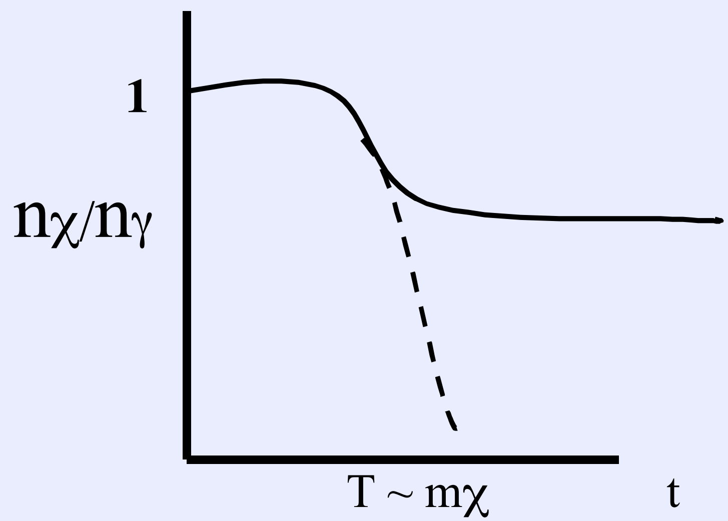
$\Gamma \sim n\sigma v \sim T^3\sigma v$; $HM_p \sim \sqrt{\rho} \sim T^2$

As $T < m_\chi$; annihilations drop n_χ

$n_\chi \sim e^{-m_\chi/T}\, n_\gamma$

Until freeze-out, $\Gamma < H$ $n_\chi/n_\gamma \sim$ constant





How Much Dark Matter

Upper limit to $\Omega\, h^2$

age of the Universe

($t > 12$ Gyr)

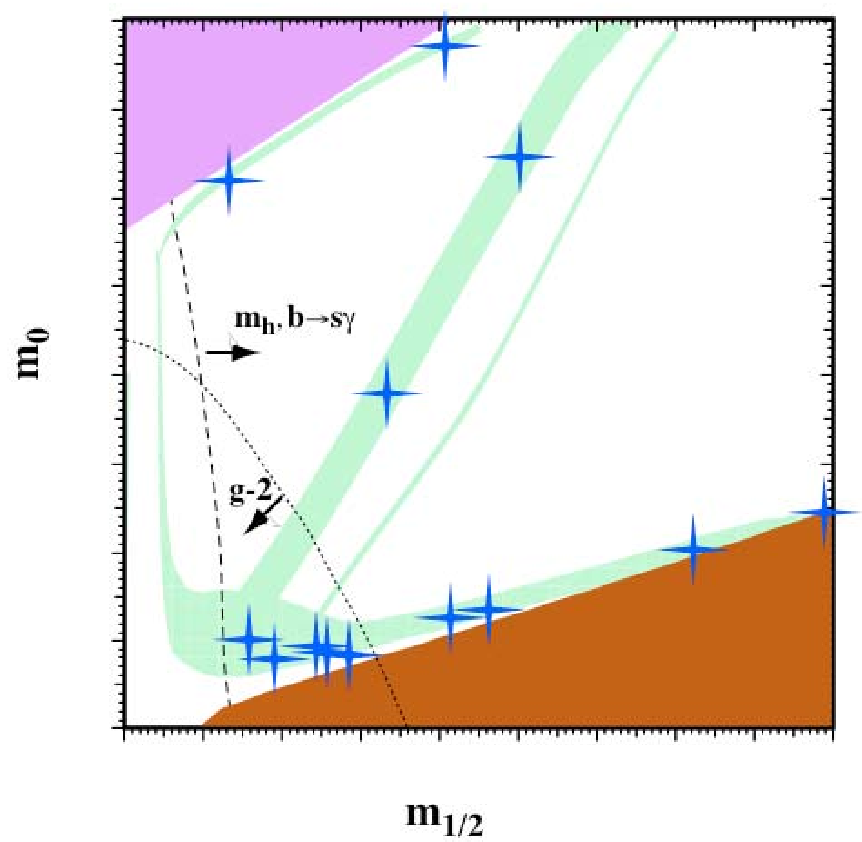
allows one to set an upper limit

$\Omega\, h^2 < 0.3$

Lower limit to $\Omega\, h^2$

Structure formation requires at least $\Omega\, h^2 > 0.1$ in dark matter

But this is not a strict constraint on SUSY dark matter

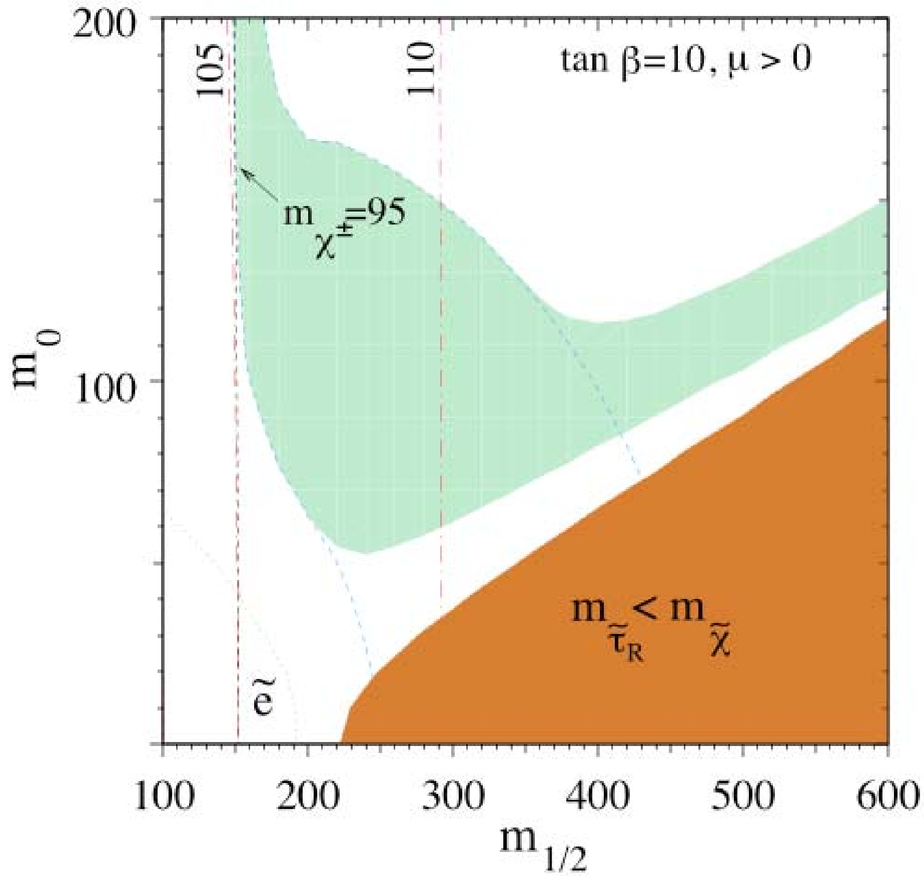


SUSY Benchmarks

No EWSB

Charged DM

Battaglia et al



$m_\chi \approx 0.4\ m_{1/2}$

Bulk Region of low $m_{1/2}$, m_0

Upper limit to $m_{1/2}$ ~ 450 GeV moved up to ~ 1400 GeV

Ellis, Falk, Olive, Srednicki

Co-annihilation

Often, the LSP is nearly degenerate with another SUSY sparticle.

$\chi, \chi', \chi^{\pm}$ nearly degenerate when $M_2 >> \mu$

Enhanced annihilation

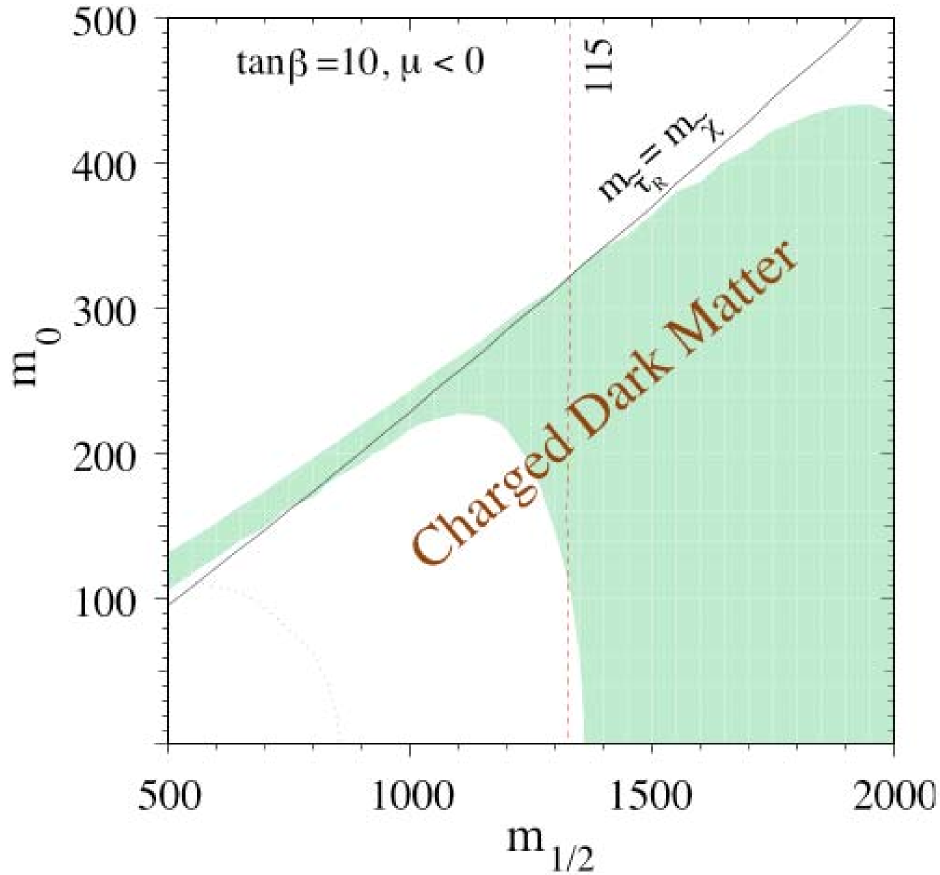
Greist + Seckel
Mizuta + Yamaguchi

$\longrightarrow$ lower Ωh^2

Also, in CMSSM, $\chi - \tilde{\tau}$ or $\chi - \tilde{t}$

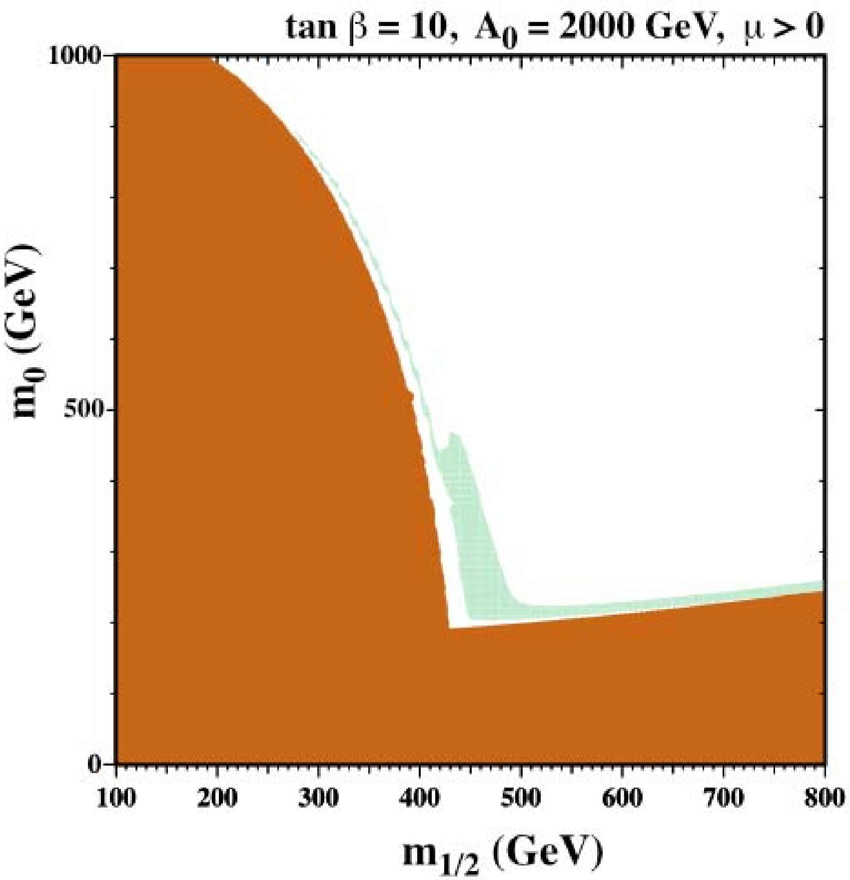
EFOS
Boehm, Djouadi, Drees
Ellis, Olive, Santoso

greatly affects upper limits to LSP.



Co-annihilation Region of high $m_{1/2}$, low m_0

Ellis, Falk, Olive, Srednicki



χ - $\tilde{t}$ co-annihilation

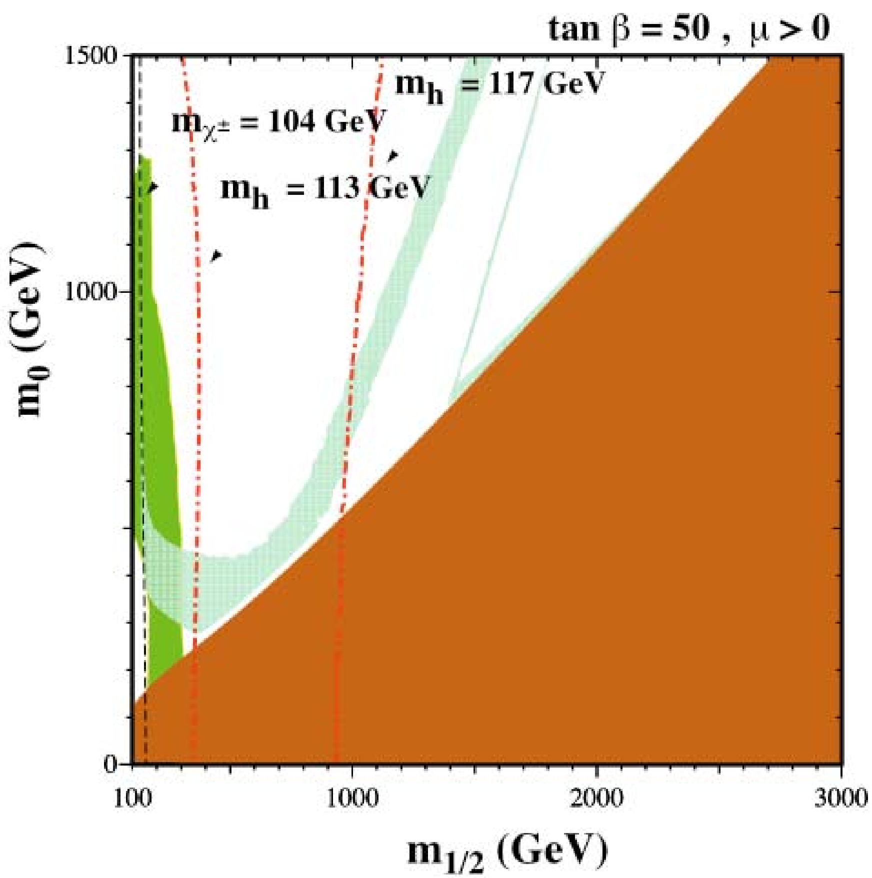
Region of high A_0

Ellis, Olive, Santoso

The CMSSM at large tan β

- Increased sensitivity to bottom quark mass - radiative corrections
- Rapid annihilation through s-channel A and H exchange due to:
  - $m_{\mathbf{A,H}}$ decreases as tan β increases
  - and $2m_{\chi} \sim m_{A,H}$ for a wide range in $m_{\mathbf{1/2}}$
  - b quark coupling enhanced by tan β

Drees and Nojiri
Baer etal.
Ellis, Falk, Ganis, Olive, Srednicki



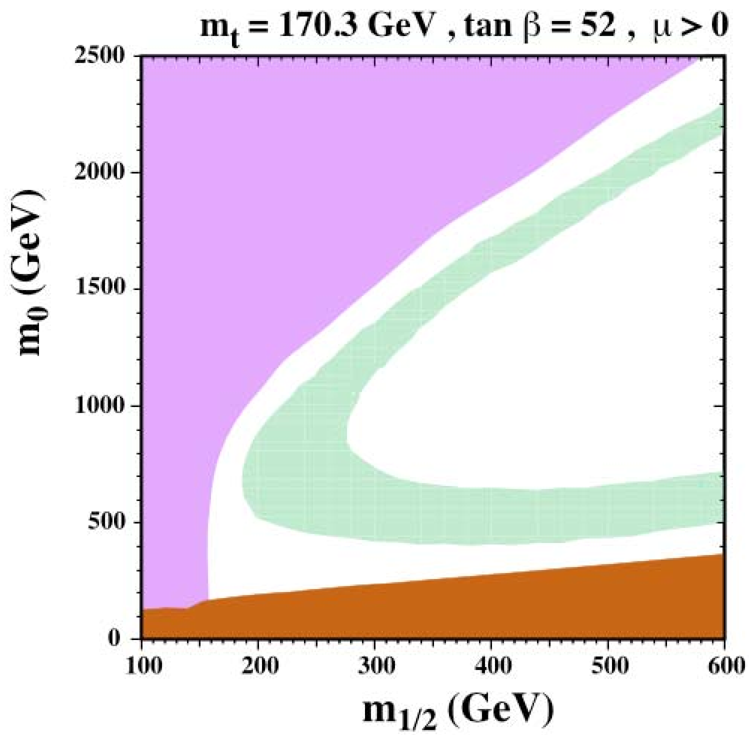
Funnel region at high tan β

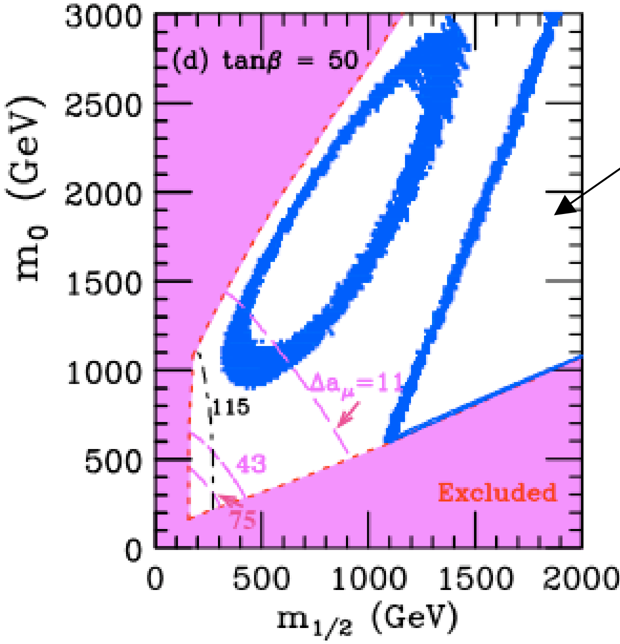
EFGOS

`Focus Point' Region

When $m_0 >> m_{1/2}$, the LSP becomes more Higgsino-like and rapid annihilation (through Z exchange)
drives the density down.

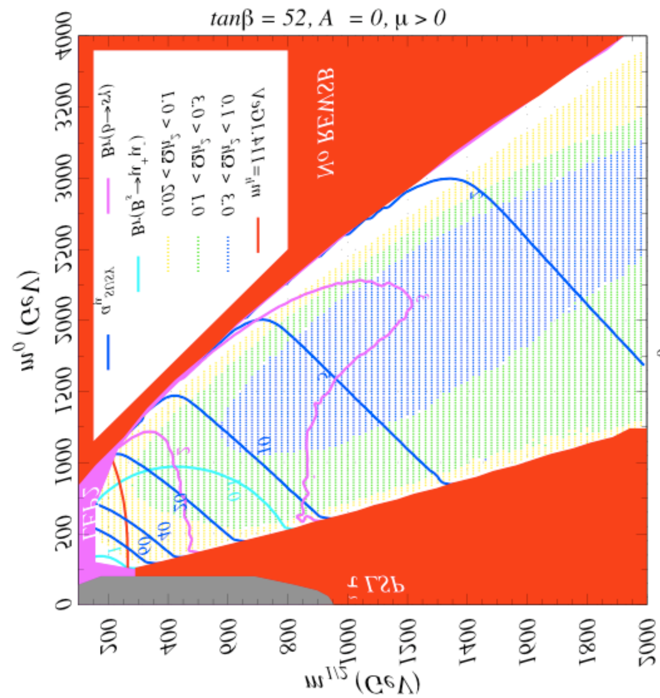
Feng, Matchev, Wilczek

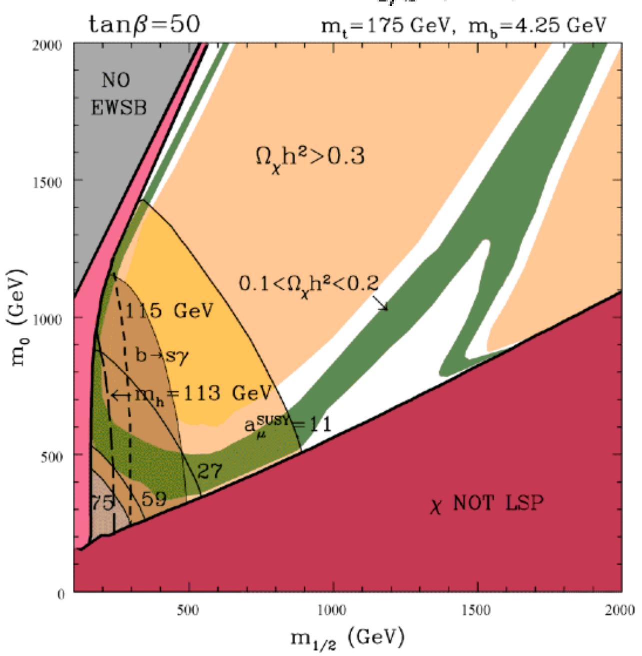




Barger & Kao

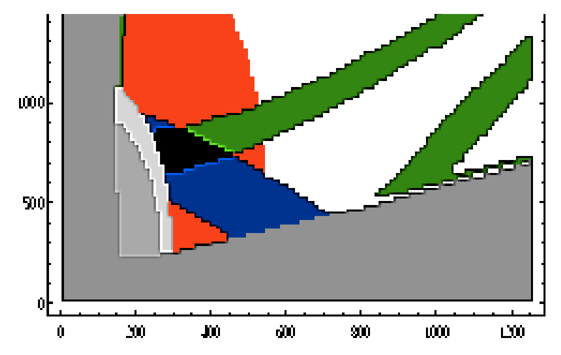
Baer etal





Nihei etal

Drees etal



See also

Lahanas & Spanos

Constraints

- Chargino mass limit

$M_{\chi^\pm} \geq 104$ GeV

Constrains (M_2 and μ)/ $m_{1/2}$

- Higgs mass limit

$M_H \geq 114$ GeV

Constrains (m_A, M_2, A)/ $m_{1/2}$

particularly at low tan β

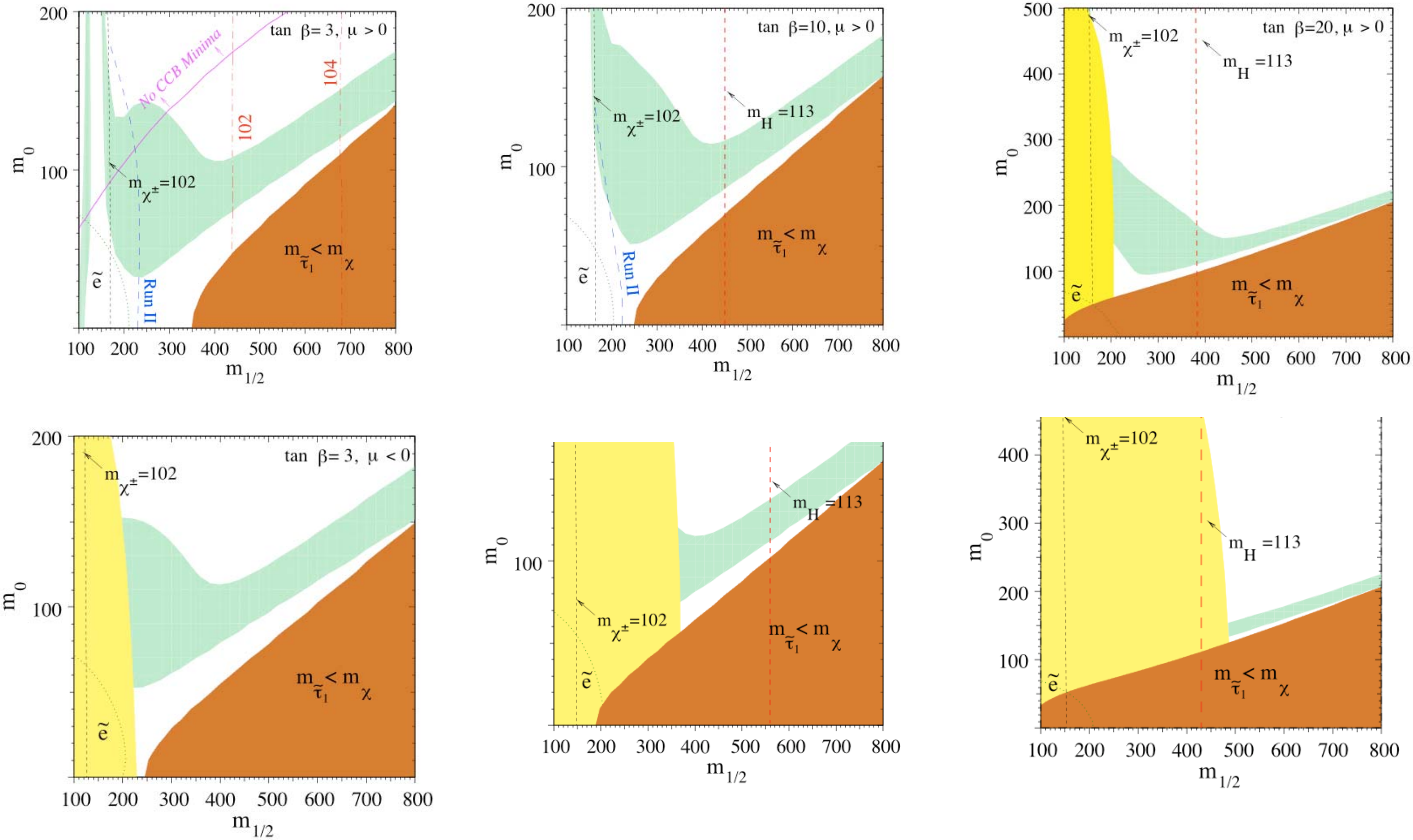
- b to s γ

Constrains (m_A)/ $m_{1/2}$ at high tan β and $\mu < 0$

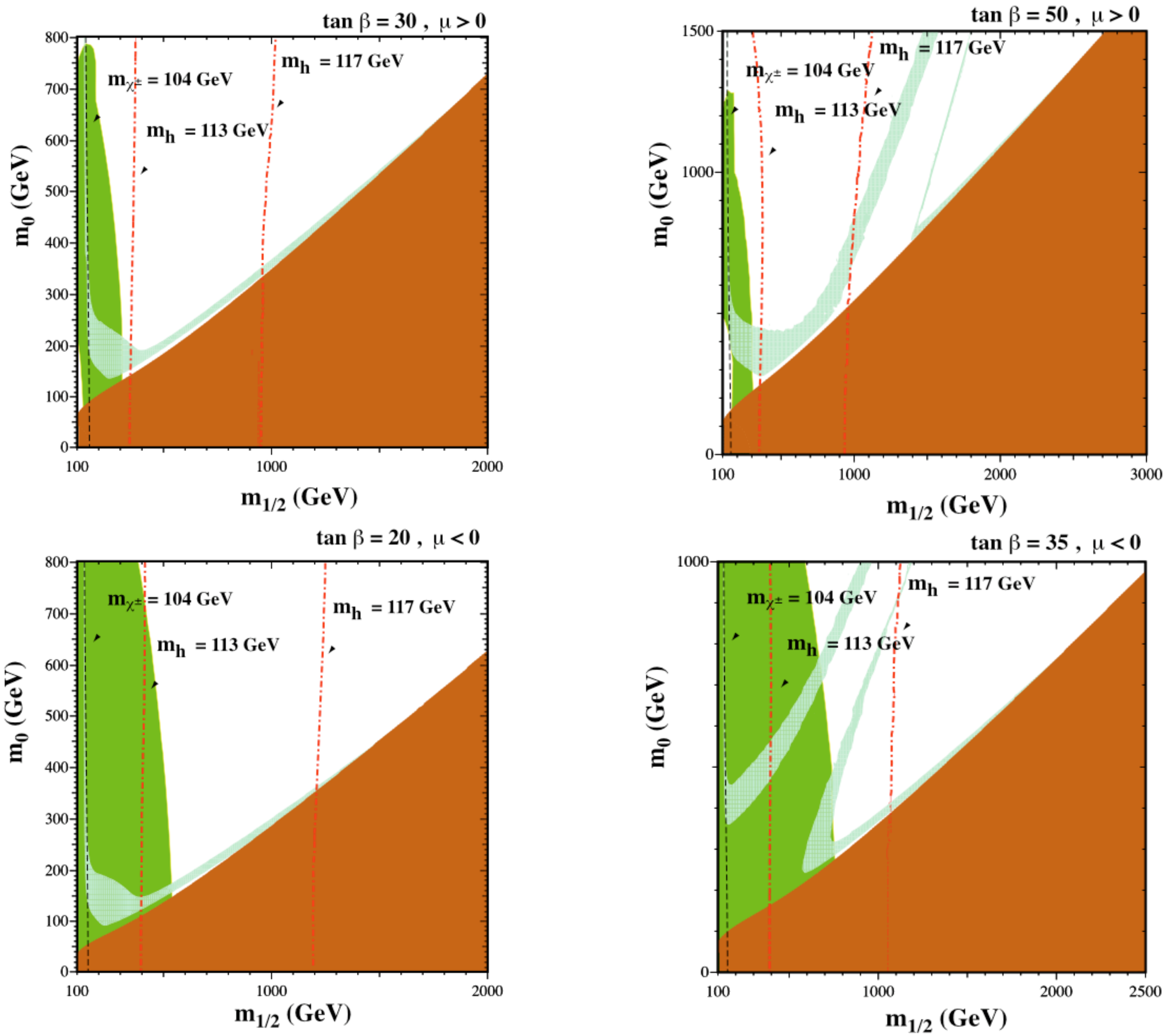
- Also sfermion mass limits from LEP and CDF

$m_f \geq 99$ GeV (roughly)

χ is the LSP

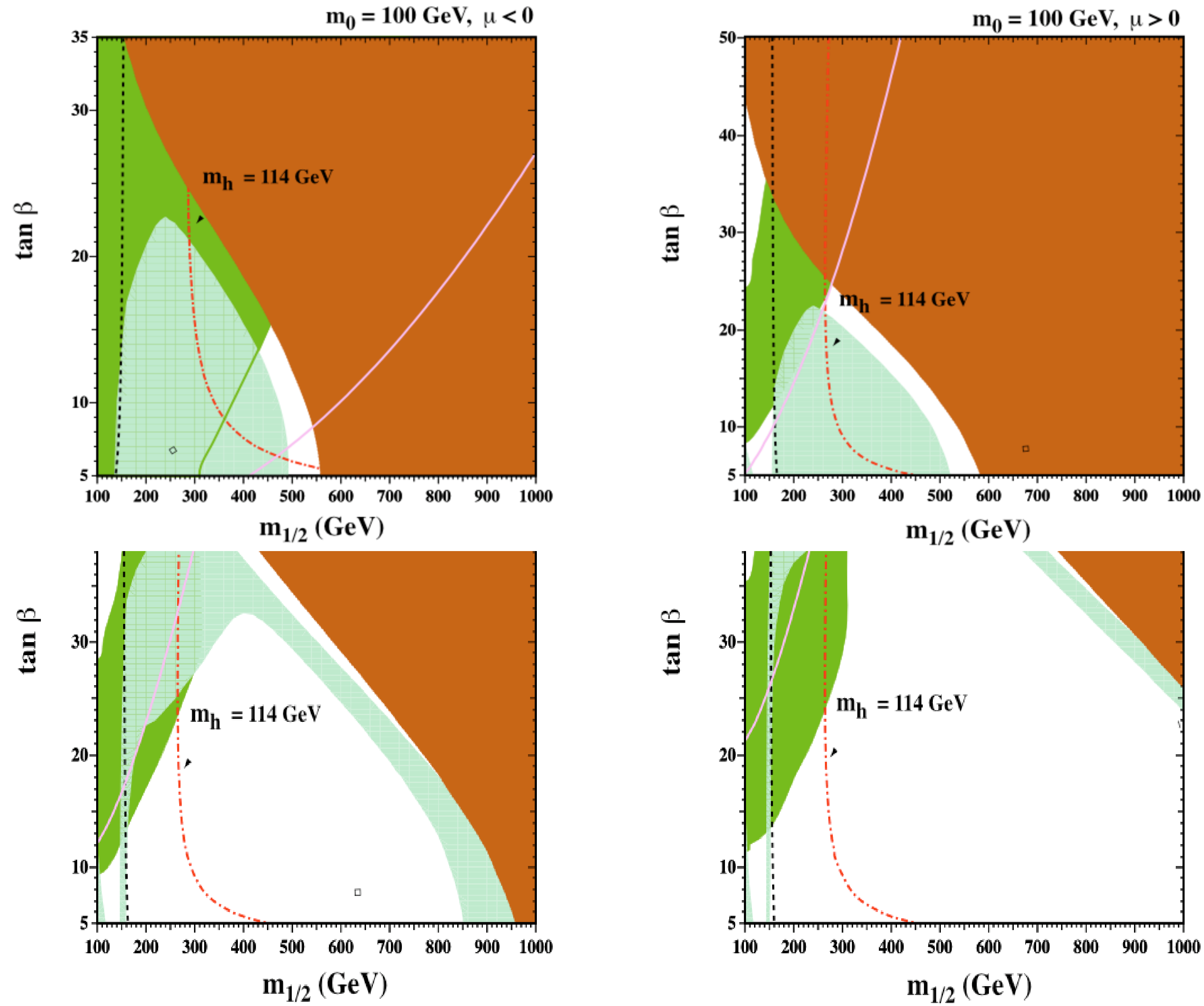


tan β= 3, μ > 0
No CCB Minima
102
104
m χ±=102
m τ̃1 < m χ
ẽ
Run II
m0
m1/2
tan β=10, μ > 0
m χ±=102
m H =113
m τ̃1 < m χ
ẽ
Run II
m0
m1/2
tan β=20, μ > 0
m χ±=102
m H =113
m τ̃1 < m χ
ẽ
m0
m1/2
tan β= 3, μ < 0
m χ±=102
m τ̃1 < m χ
ẽ
m0
m1/2
m H =113
m χ±=102
m τ̃1 < m χ
ẽ
m0
m1/2
m χ±=102
m H =113
m τ̃1 < m χ
ẽ
m0
m1/2



The plane at high tan β and the appearance of funnels.

Another view



Boundary conditions

- Input parameters: μ, m_1, m_2, B. predict M_Z, $\tan\beta$, m_A

CMSSM conditions

- Instead CMSSM:

  Input parameters: M_Z, m_1, m_2, $\tan\beta$ ($m_1 = m_2 = m_0$)

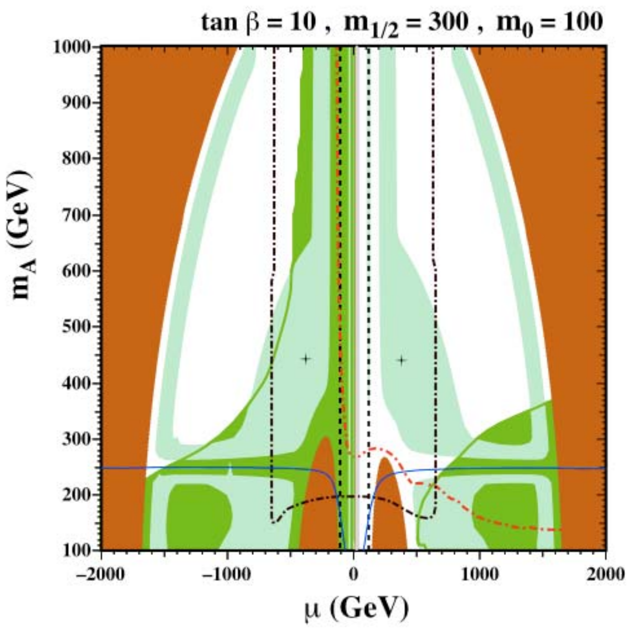
  predict μ, B, m_A

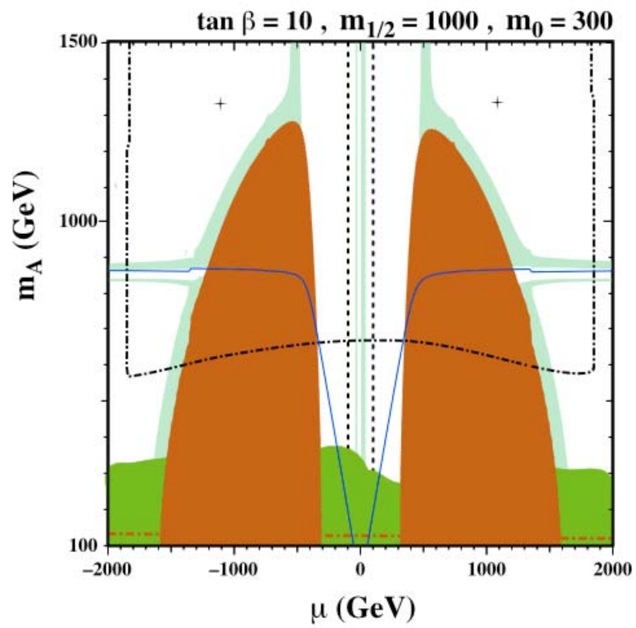
Relaxing CMSSM conditions

- Or instead NUHM:

  Input parameters: M_Z, μ, m_A, $\tan\beta$ predict m_1, m_2, B

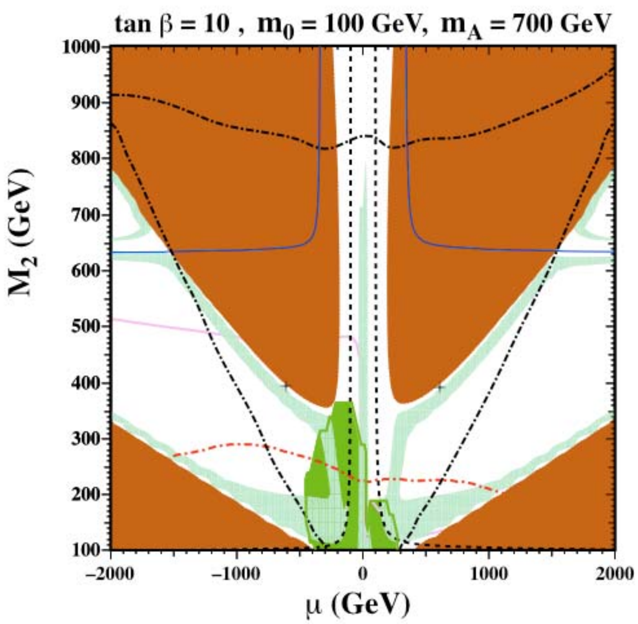
Ellis, KO, Santoso

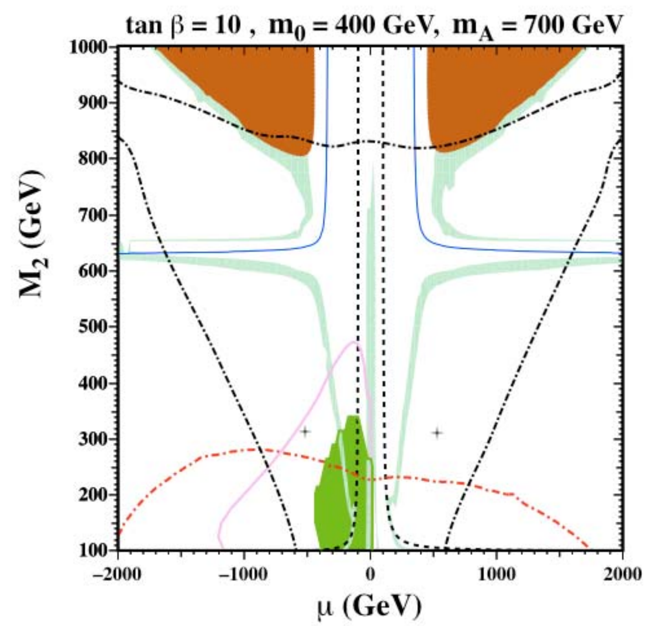




The m_A– μ plane

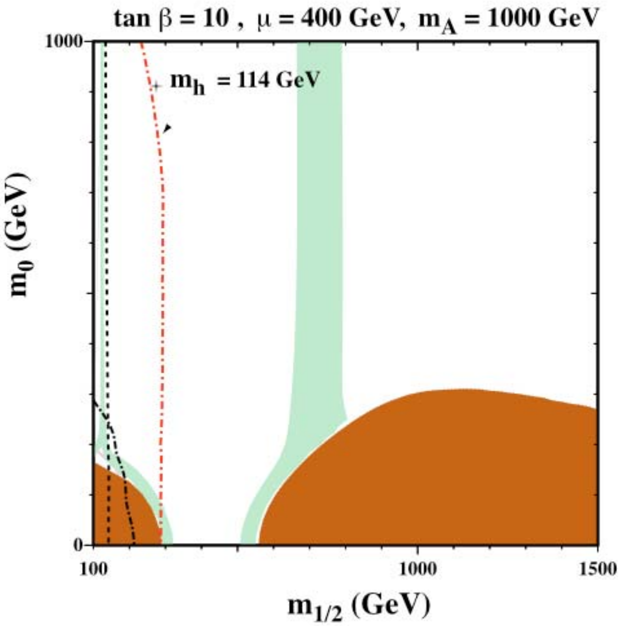
+ CMSSM value

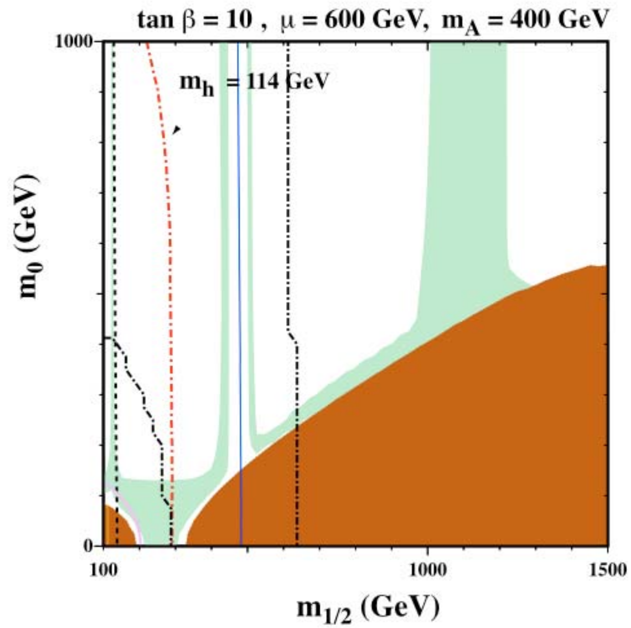




The M_2– μ plane

+ CMSSM value





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

+ CMSSM value

Have future accelerators been saved by g-2?

- Original results from Recent BNL E821

$$\delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 43 \pm 16 \times 10^{-10}$$

- Strong correlations between a_μ and μ

  $\mu < 0$ excluded.

Chattopadhyay, Nath

Ellis, Nanopoulos, KO

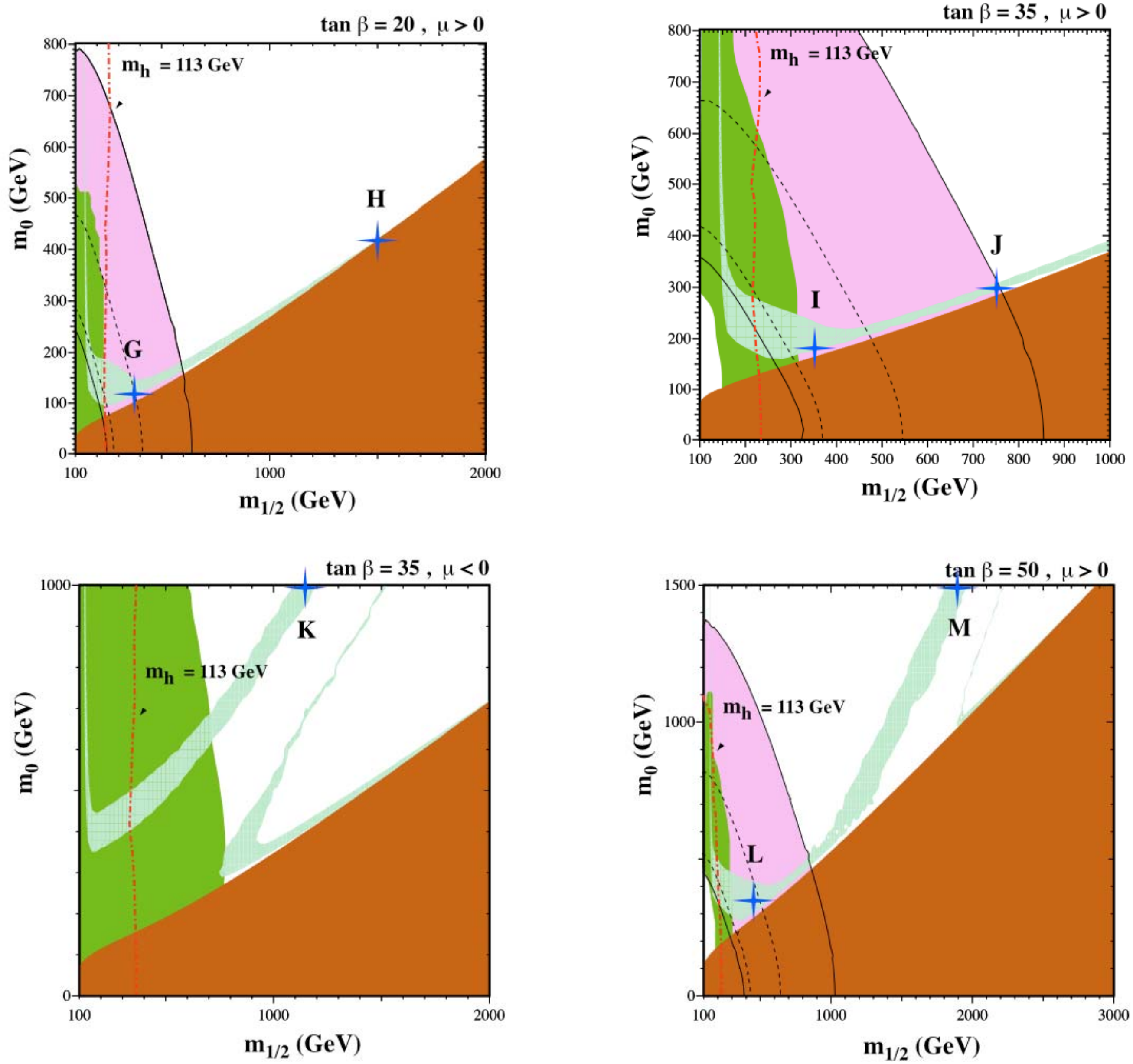
- Theoretical corrections

$$\delta a_\mu = 26 \pm 16 \times 10^{-10}$$

– $\mu > 0$ strongly favored

– Small m_0 $m_{1/2}$ excluded

Ellis, KO, Santoso



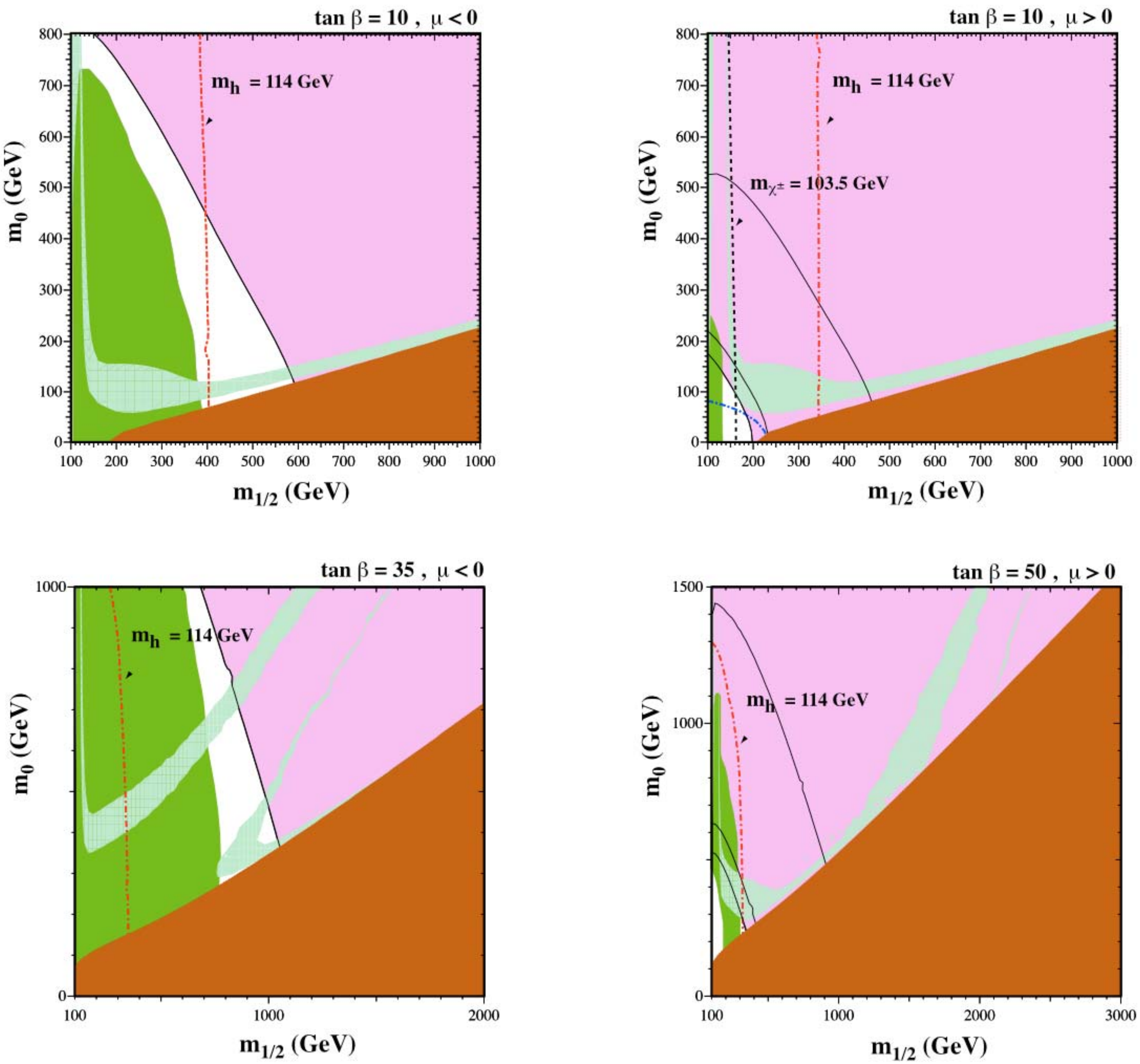
Effects of g-2

Note: $\mu < 0$ excluded

Large $m_{1/2}$, m_0 excluded

Labels show benchmark points

From: Battaglia etal



Effects of weaker g-2

Note: μ < 0 still Strongly constrained

Ellis, KAO, Santoso

Direct Detection

Eastic scattering cross sections

for χ p

Use only parameters which satify accelerator bounds and relic denisty

Results: low cross sections

$< 10^{-3}$ pb spin

$< 10^{-7}$ pb scalar

MSSM allows higher cross sections at higher m_χ

$$+ \quad \alpha_{3i}\, \bar{\chi}\, \chi\, \bar{q}_i\, q_i + \alpha_{4i}\, \bar{\chi}\, \gamma^5\, \chi\, \bar{q}_i\, \gamma^5\, q_i$$

$$+ \quad \alpha_{5i}\, \bar{\chi}\, \chi\, \bar{q}_i\, \gamma^5\, q_i + \alpha_{6i}\, \bar{\chi}\, \gamma^5\, \chi\, \bar{q}_i\, q_i$$

The terms involving α_{1i}, α_{4i}, α_{5i}, and α_{6i} lead to velocity dependent elastic cross sections.

Remaining terms are:

the spin dependent coefficient

$$\alpha_{2i}$$

and scalar coefficient

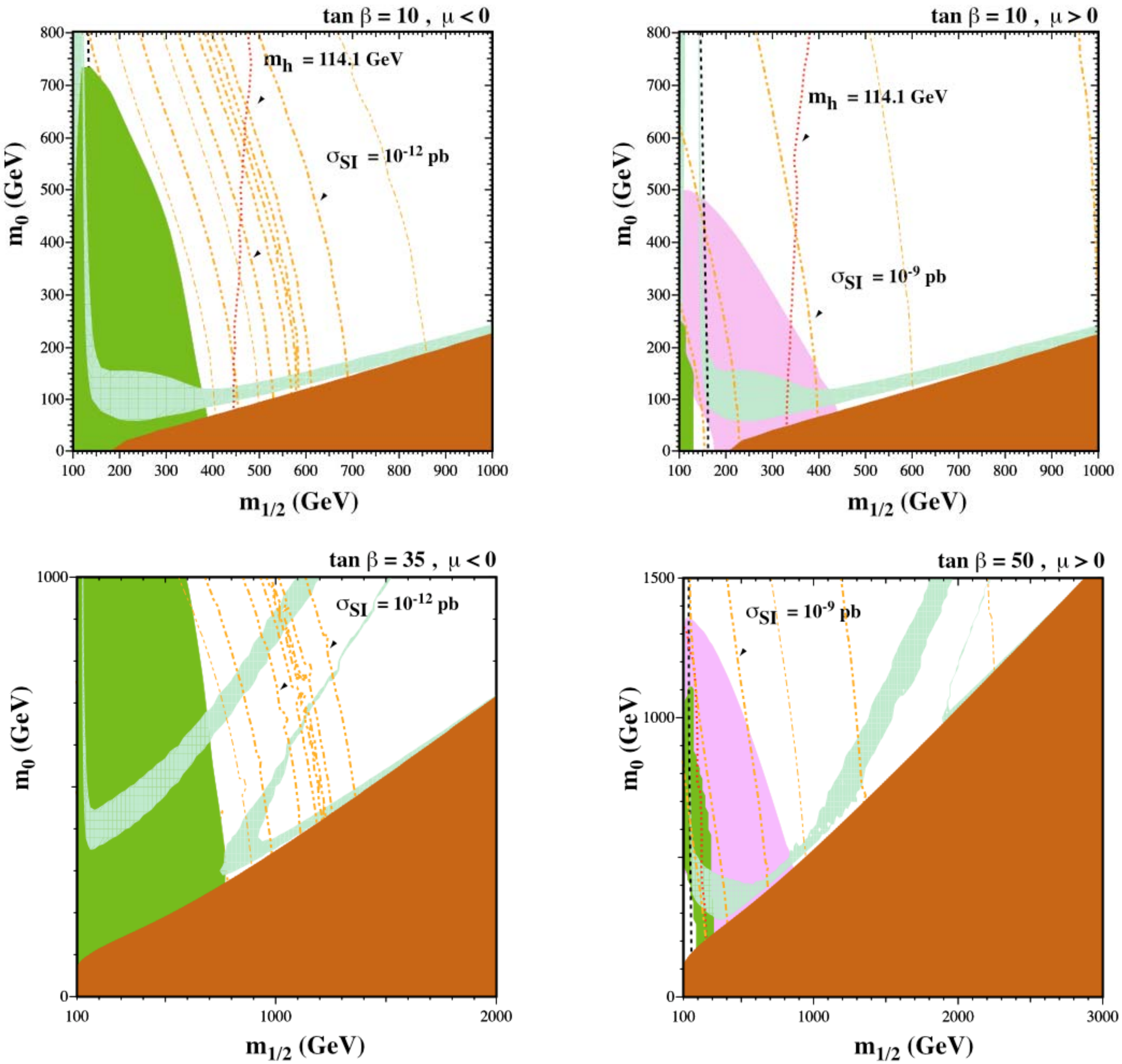
$$\alpha_{3i}$$

Contributions to α_2: Spin-Dependent cross-section

- Through light squark exchange
  - Dominant for binos
- Through Z exchange
  - Requires a strong Higgsino component

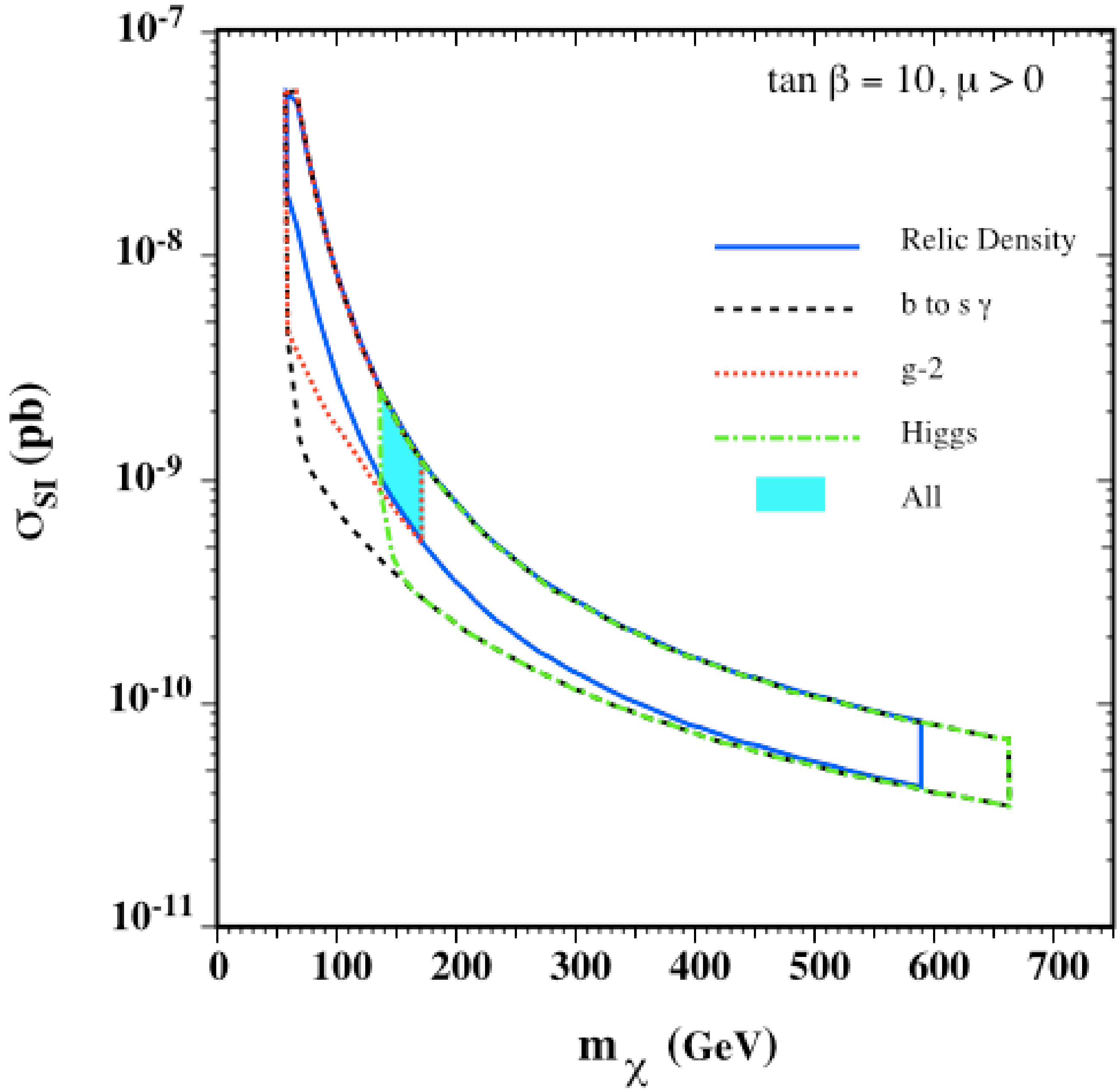
Contributions to α_3: Spin-Independent cross-section

- Through light squark exchange
  - Dominant for binos
- Through Higgs exchange
  - Requires some Higgsino component

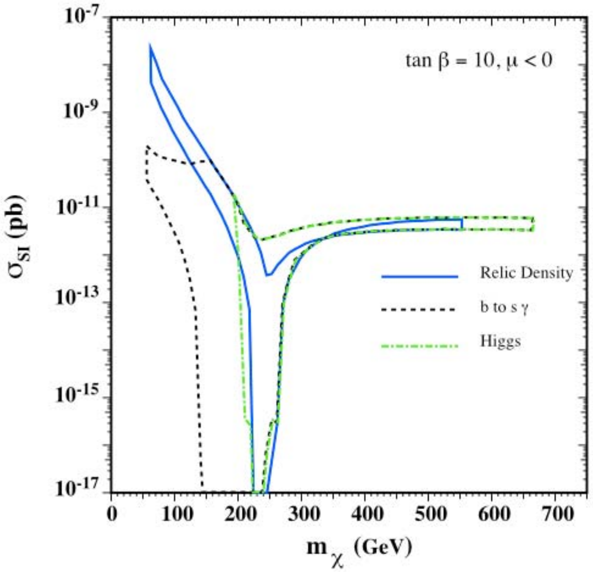


The Spin-independent Elastic cross-section

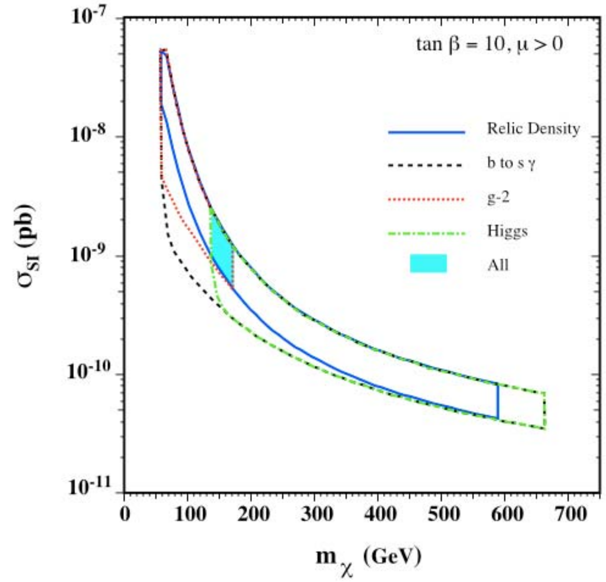
Note cancellation When $\mu < 0$



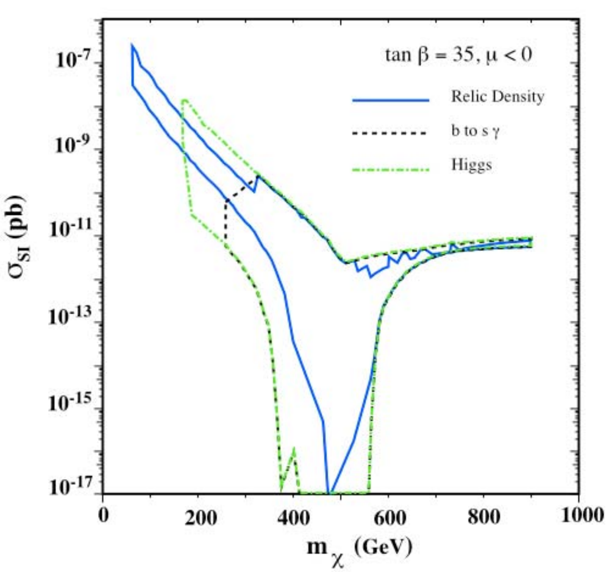
Ellis Ferstl, KO



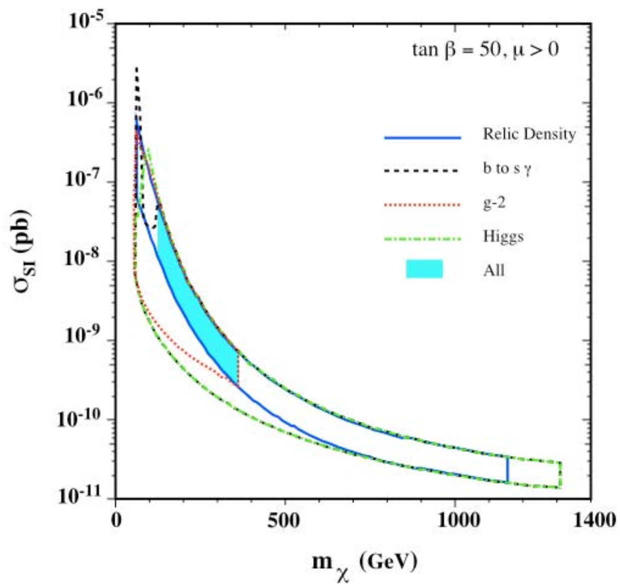
tan β = 10, μ < 0
Relic Density
b to s γ
Higgs
σSI (pb)
mχ (GeV)



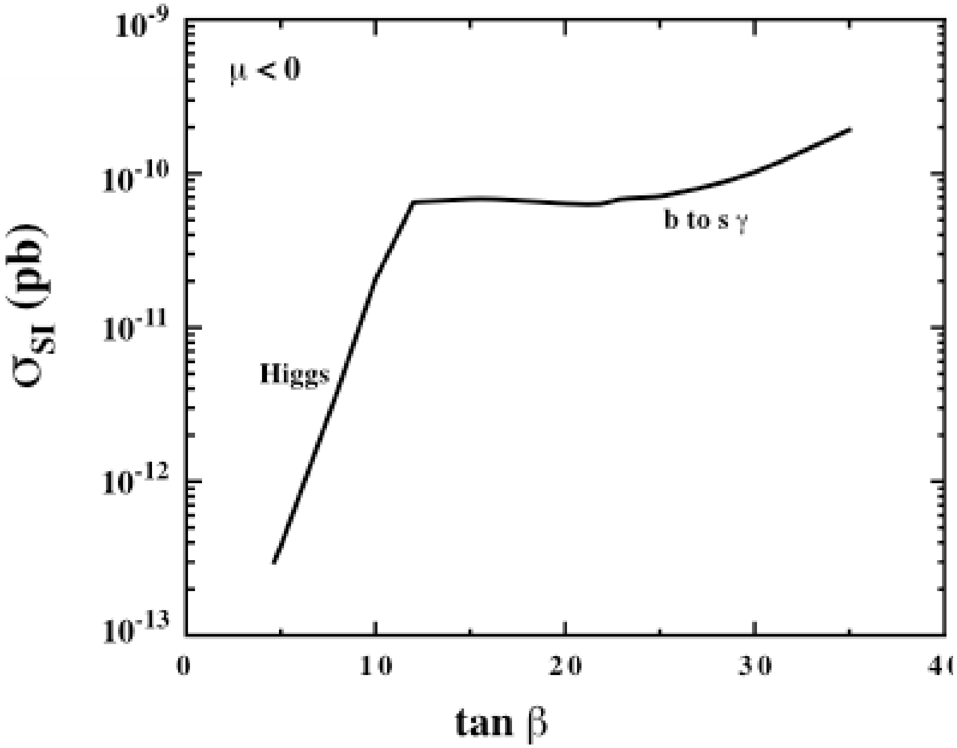
tan β = 10, μ > 0
Relic Density
b to s γ
g-2
Higgs
All
σSI (pb)
mχ (GeV)



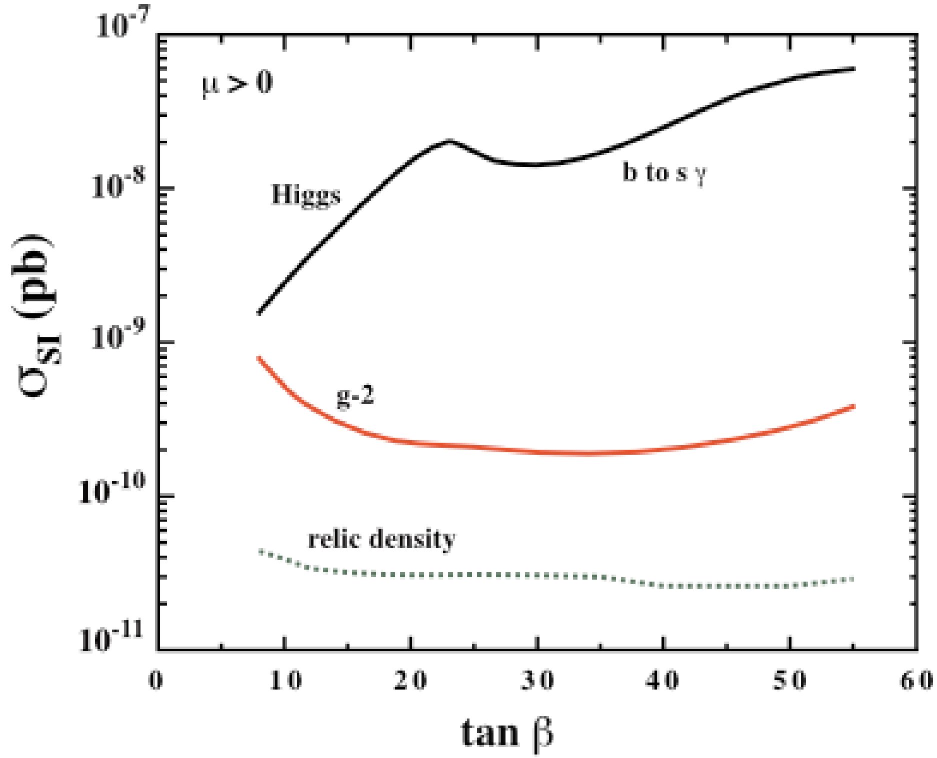
tan β = 35, μ < 0
Relic Density
b to s γ
Higgs
σSI (pb)
mχ (GeV)



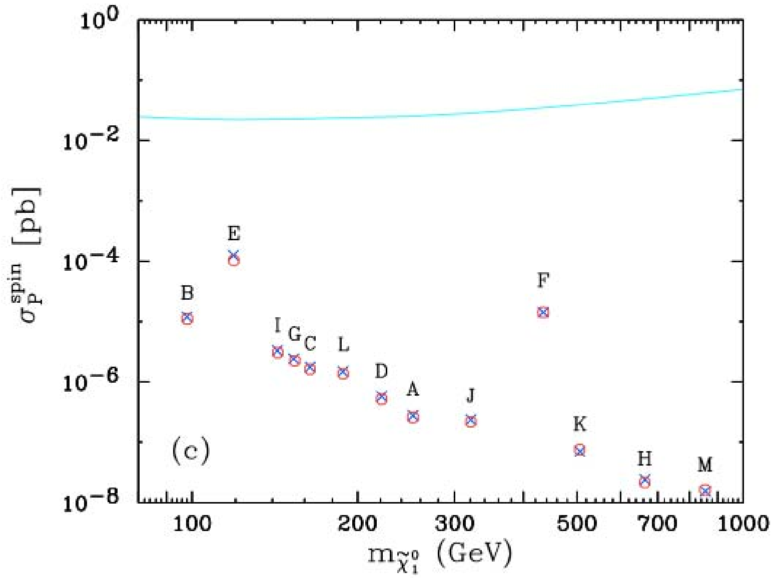
tan β = 50, μ > 0
Relic Density
b to s γ
g-2
Higgs
All
σSI (pb)
mχ (GeV)

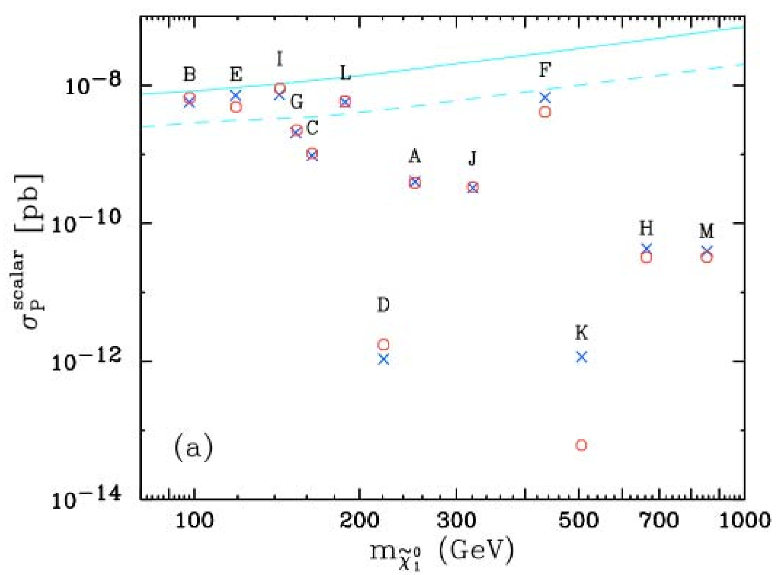


Ellis, Ferstl, KAO



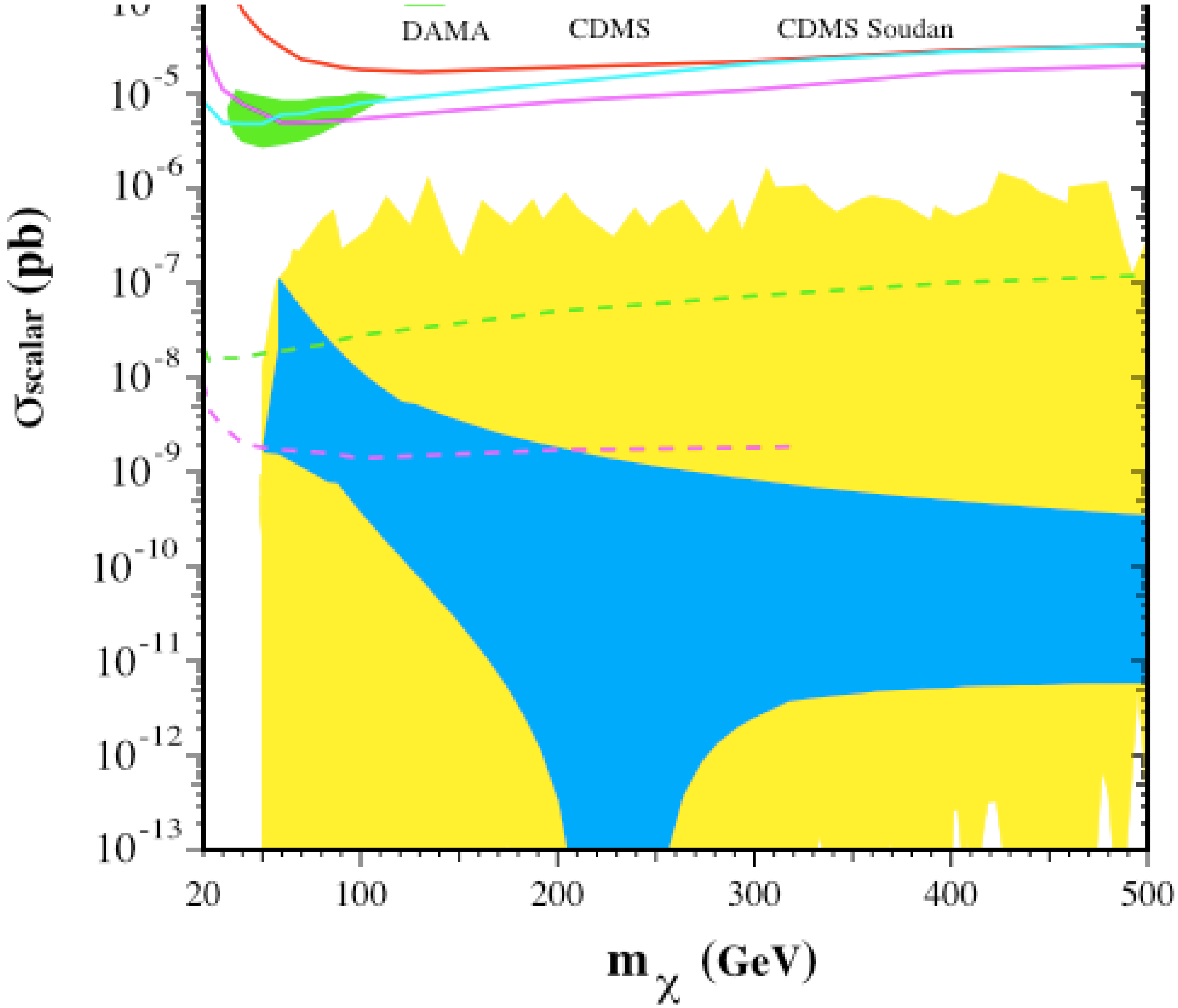
Upper and lower limit to σ

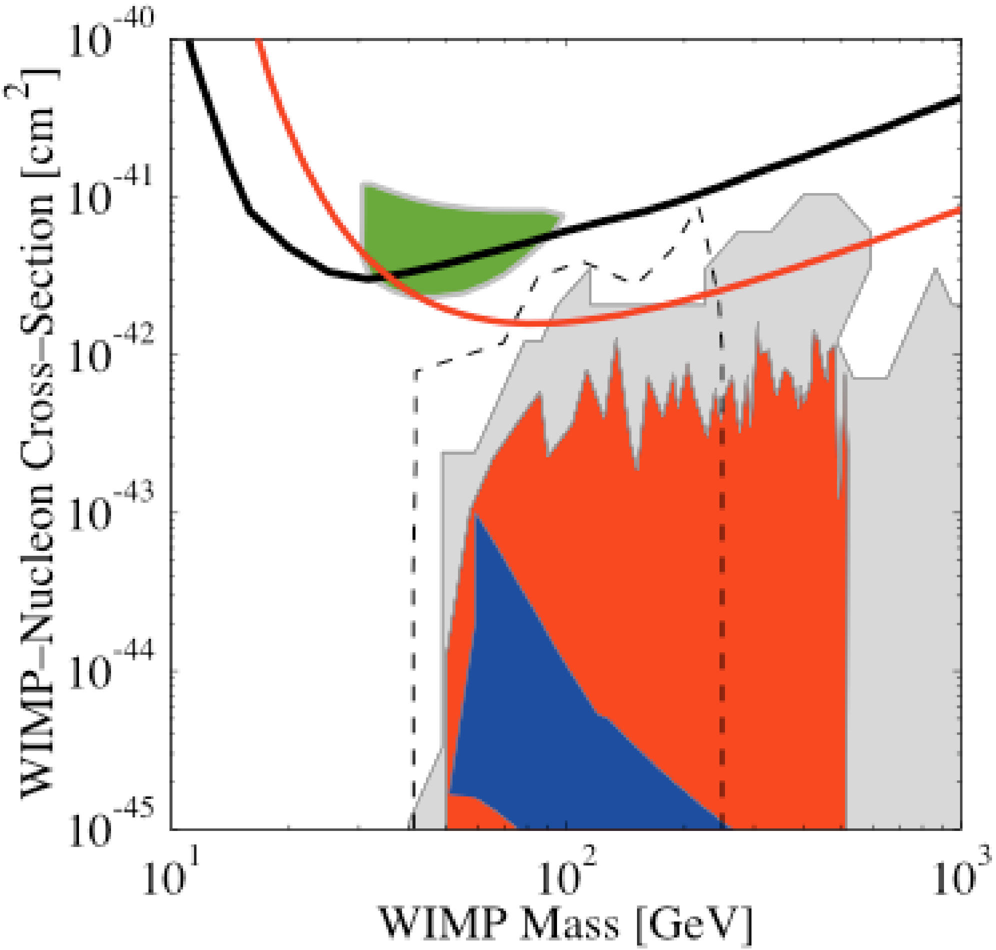




Detectability of Benchmark points

Feng etal


DAMA
CDMS
CDMS Soudan
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
σ_{scalar} (pb)
20
100
200
300
400
500
m_χ (GeV)



CDMS: Abrams etal
astro-ph/0203500

EDELWEISS: Benoit etal
astro-ph/0206271

Summary

- Accelerator Constraints:

Push towards larger values of m_χ. (Trend may be halted by future g-2 results.)

CMSSM

- Spin-Dependent cross sections:

$\sigma_2 < 10^{-5}$ pb (>3 x 10^{-7} pb if g-2) *

  – But this is far below current sensitivites.

- Scalar cross sections:

$\sigma_3 < 10^{-7}$ pb (> 10^{-9} pb if g-2) *

  – Perhaps within experimental reach.

* Old g-2

MSSM

- While higher cross-sections are possible (with suitable choices of mass scales),
  (up to a few x 10^{-7} pb for scalar cross sections - maybe up to 10^{-6} pb with nuclear uncertainties)
  much lower cross sections are also possible.

Indirect Detection

- Great for ν's, (perhaps also for exotic relics), but remains a challenge for neutralinos in the CMSSM