SUSY Dark Matter Models

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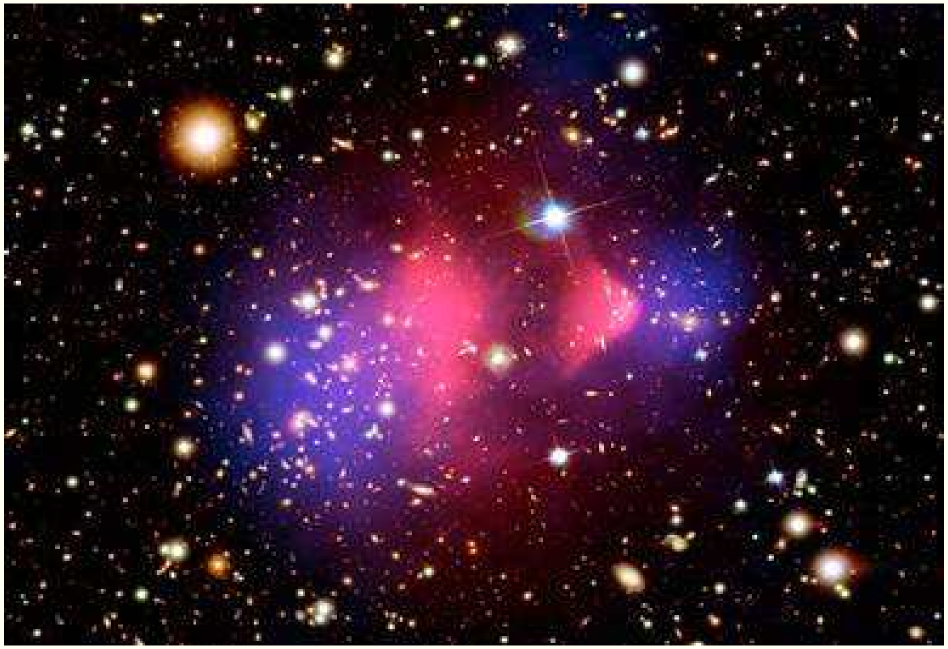
- ⋆ mSUGRA model
- ⋆ Normal scalar mass hierarchy
- ⋆ NUHM1
- ⋆ NUHM2
- ⋆ MWDM
- ⋆ BWCA
- ⋆ LM3DM (compressed SUSY)
- ⋆ mixed moduli-AMSB (KKLT)



Some successes of SUSY GUT theories

- ⋆ SUSY divergence cancellation maintains hierarchy between GUT scale $Q = 10^{16}$ GeV and weak scale $Q = 100$ GeV
- ⋆ gauge coupling unification!
- ⋆ Lightest Higgs mass $m_h \lesssim 130$ GeV as indicated by radiative corrections!
- ⋆ radiative breaking of EW symmetry if $m_t \sim 100 - 200$ GeV!
- ⋆ dark matter candidate: lightest neutralino $\tilde{Z}_1$
- ⋆ stable see-saw mechanism for neutrino mass
- ⋆ $SO(10)$ SUSY GUT: baryogenesis via leptogenesis

Our strategy:

★ Assume MSSM is valid effective theory between M_{weak} and M_{GUT}

- LSP is stable: good candidate for CDM

★ Stipulate SSB terms at $Q = M_{GUT}$ and evaluate SSB at M_{weak} via RG evolution

- EW symmetry broken radiatively by large m_t

★ Invoke

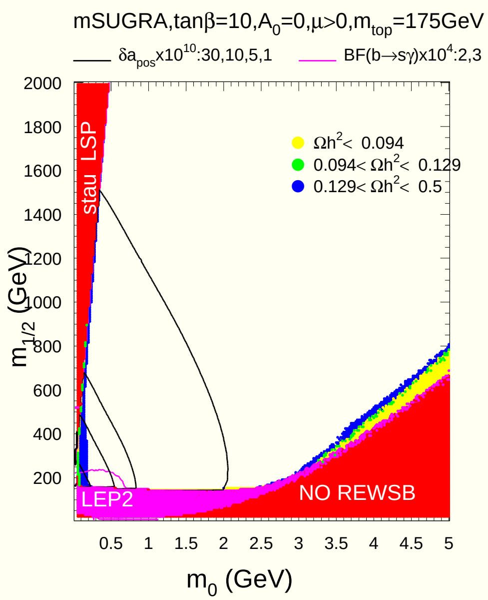
- minimal flavor violation
- ignore CP-viol. phases

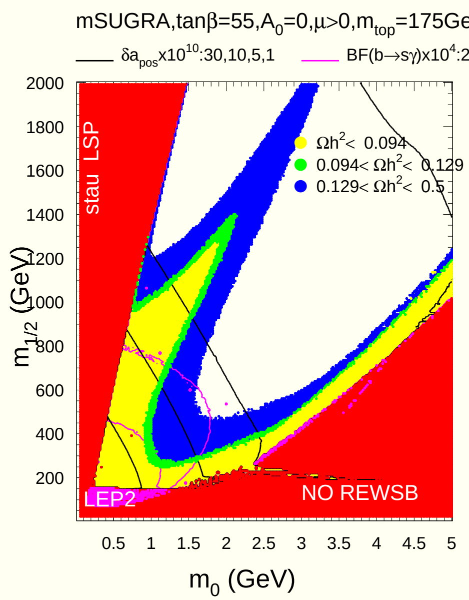
★ Spectra generated with Isajet/Isasugra

★ We will use the measured value $\Omega_{CDM}h^2 = 0.105 \pm 0.01$ as a guide to allowed phenomenology!

mSUGRA model; allowed parameter space

- ⋆ Case 1: paradigm mSUGRA model (thanks to Arnowitt, Nanopoulos, Weinberg, other pioneers· · ·)
  - $m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$





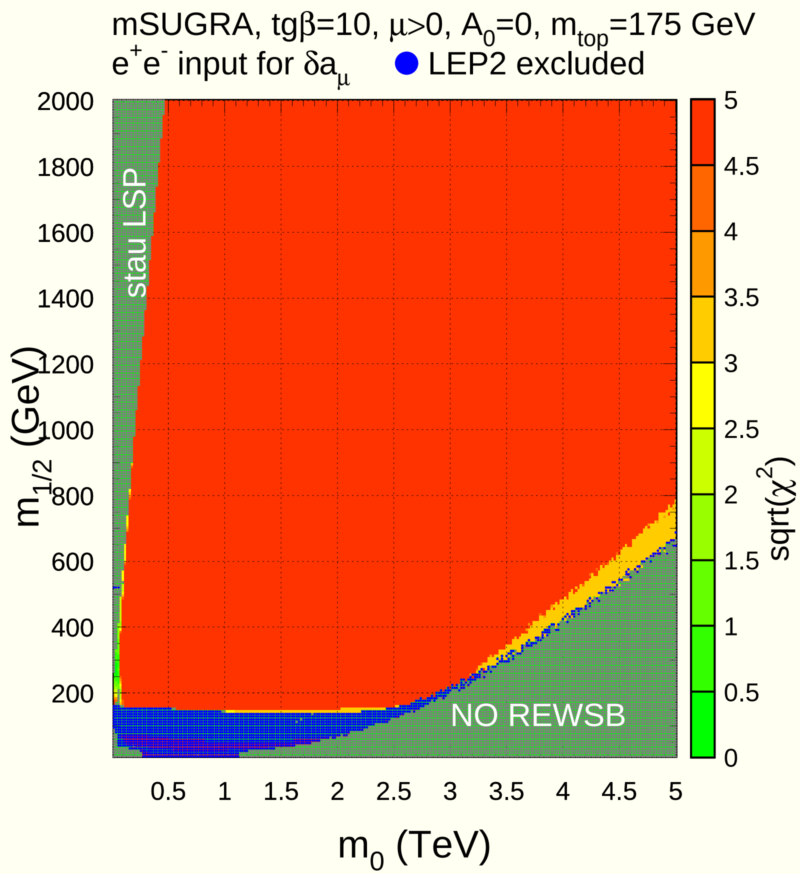
Main mSUGRA regions consistent with WMAP

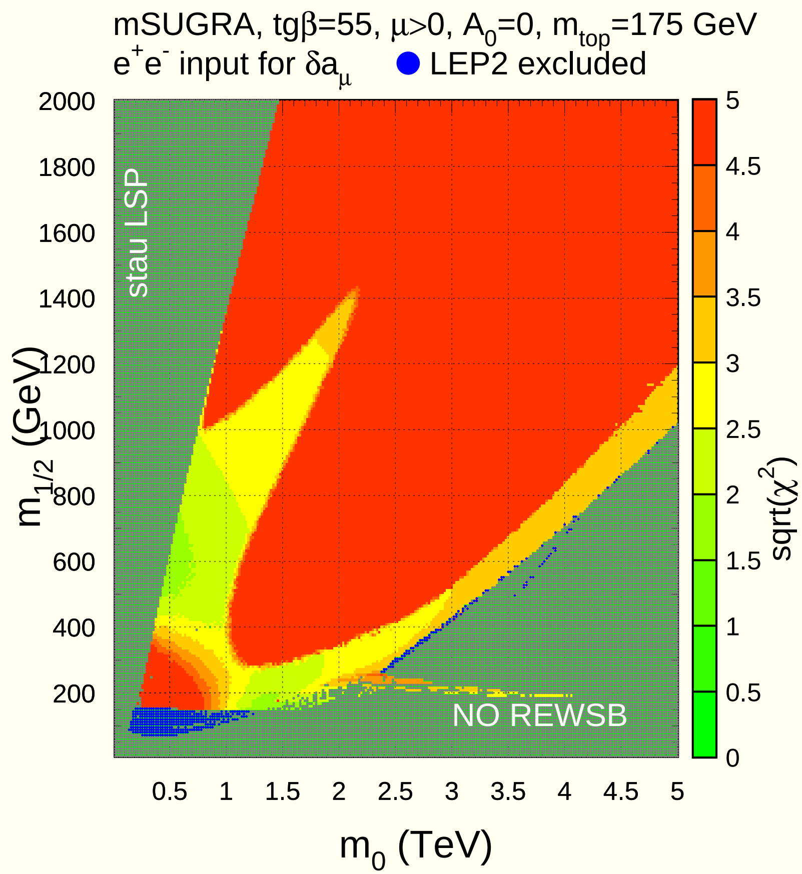
⋆ most of parameter space excluded: $\Omega_{CDM}h^2$ too big!

⋆ Exceptions:

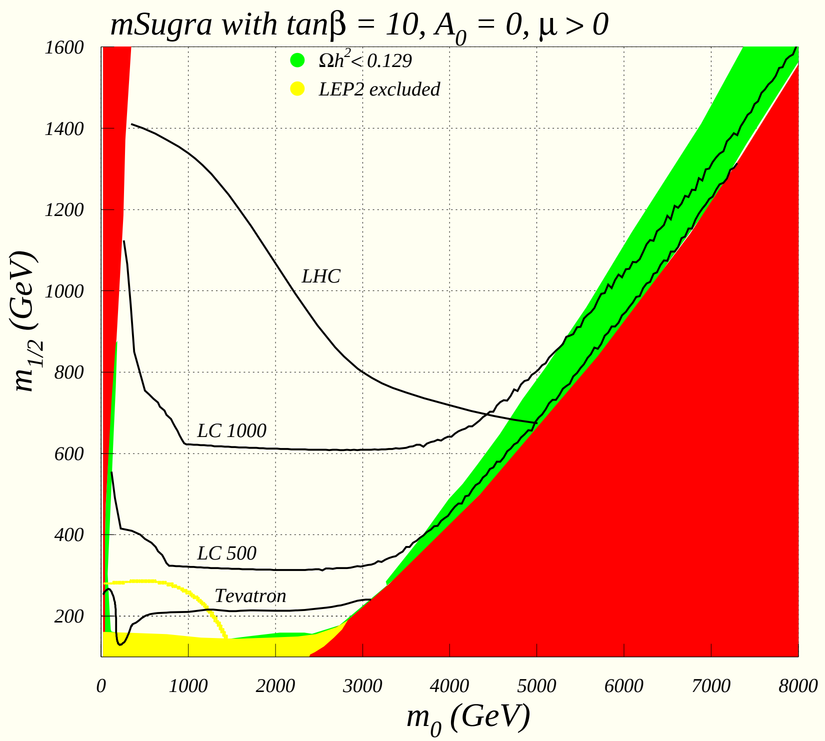
- bulk region (low m_0, low $m_{1/2}$)
- stau co-annihilation region ($m_{\tilde{\tau}_1} \simeq m_{\widetilde{Z}_1}$)
- HB/FP region (large m_0 where $|\mu| \to small$)
- A-funnel ($2m_{\widetilde{Z}_1} \simeq m_A,\ m_H$)
- h corridor ($2m_{\widetilde{Z}_1} \simeq m_h$)
- stop co-annihilation region (particular A_0 values $m_{\tilde{t}_1} \simeq m_{\widetilde{Z}_1}$)

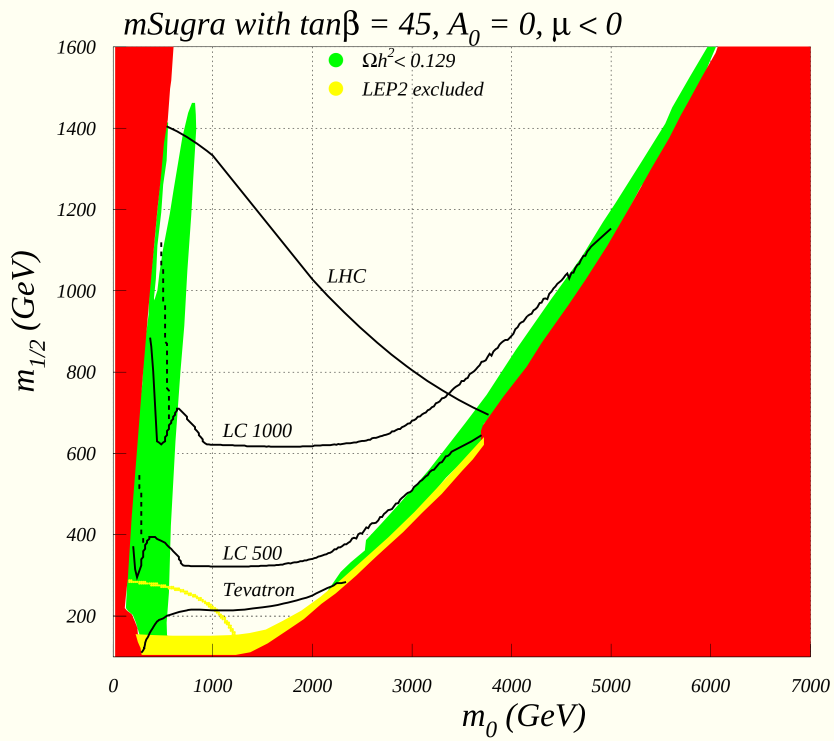
Constraints as χ^2 on mSUGRA model





Sparticle reach of all colliders and relic density

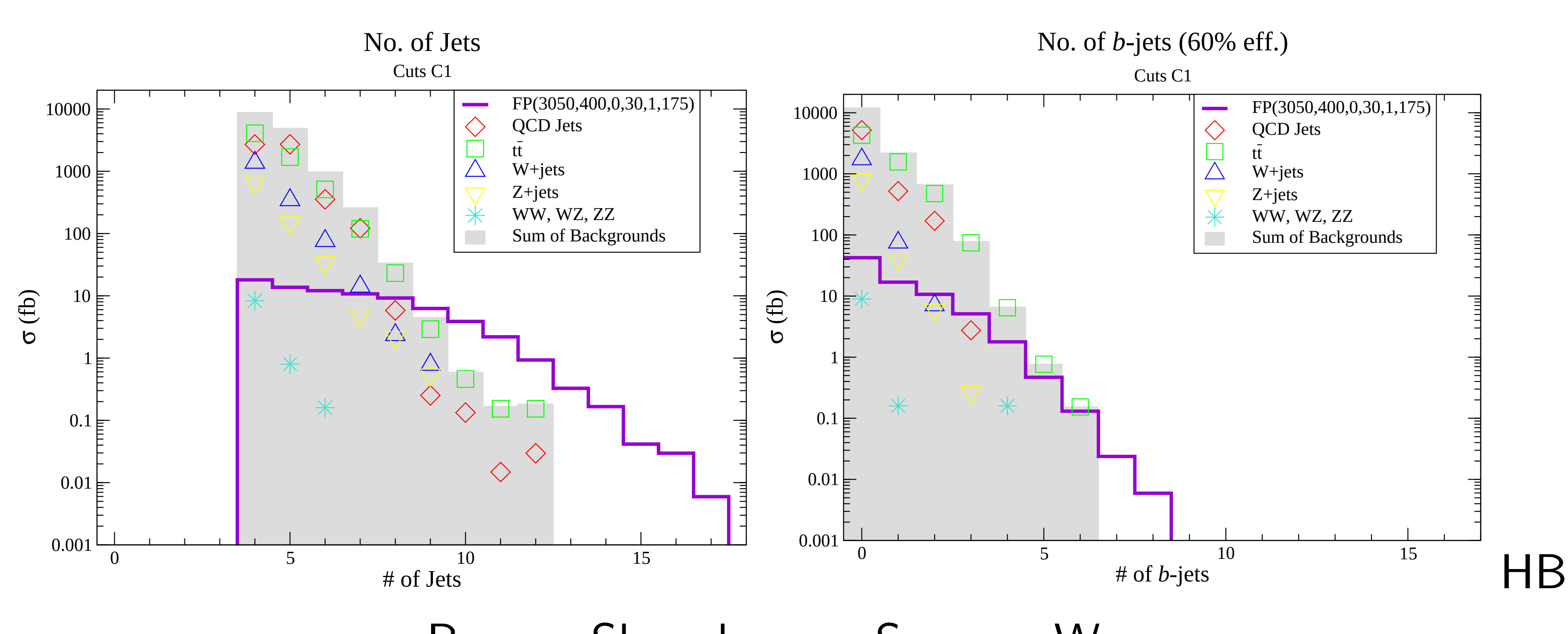




HB, Belyaev, Krupovnickas, Tata

HB/FP region: absolute measure of $m_{\tilde{g}}$ at LHC!

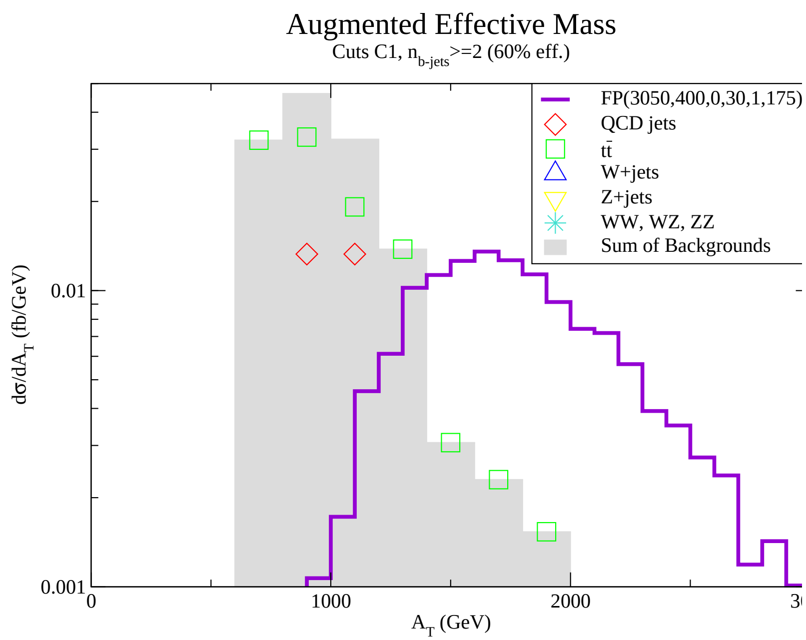
- LHC events characterized by high jet, b-jet, isol. lepton multiplicity

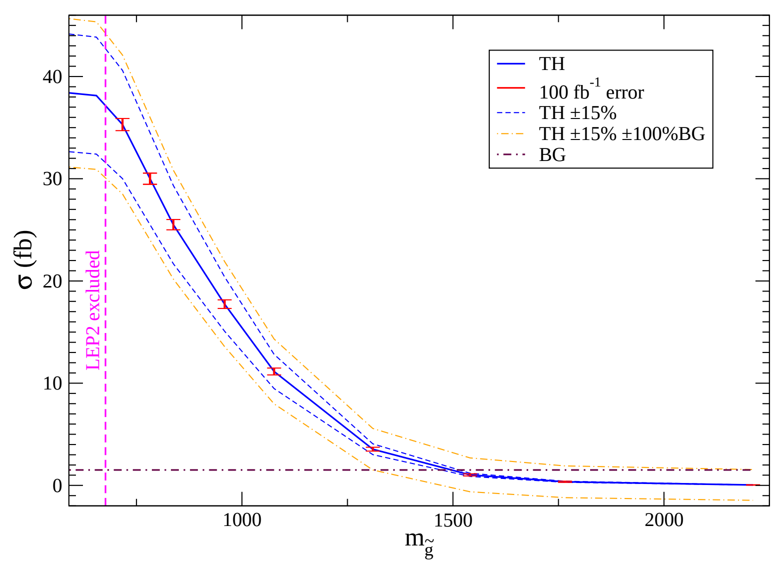


HB, Barger, Shaughnessy, Summy, Wang

Measure $m_{\tilde{g}}$ in HB/FP region via total rate to $\sim 8\%$

- require cuts C1 plus $n_(j) \geq 7$, $n(b-j) \geq 2$, $M_{eff} \geq 1400$ GeV





HB,

Barger, Shaugnessy, Summy, Wang

Direct detection of SUSY DM

scan over mSUGRA space ($\Omega_{CDM}h^2 \sim 0.11$) :

★ Stage 1:

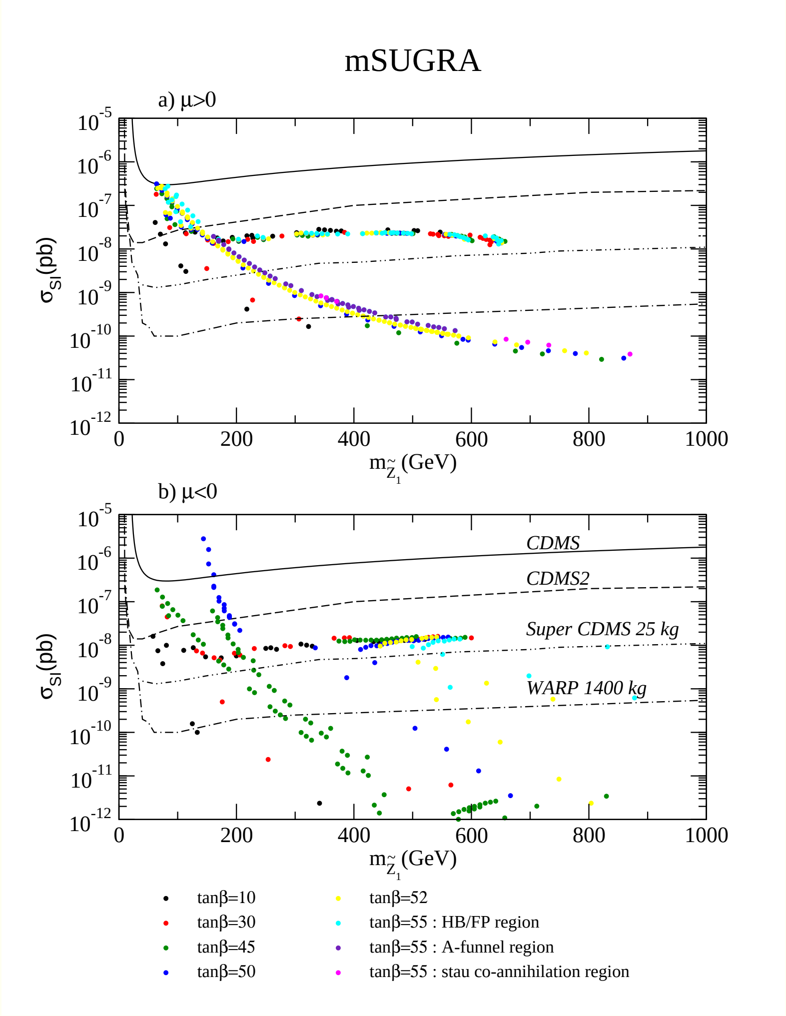
- CDMS1, Edelweiss, Zeplin1

★ Stage 2:

- CDMS2, CRESST2, Edelweiss2
- Zeplin2, Xenon-10

★ Stage 3:

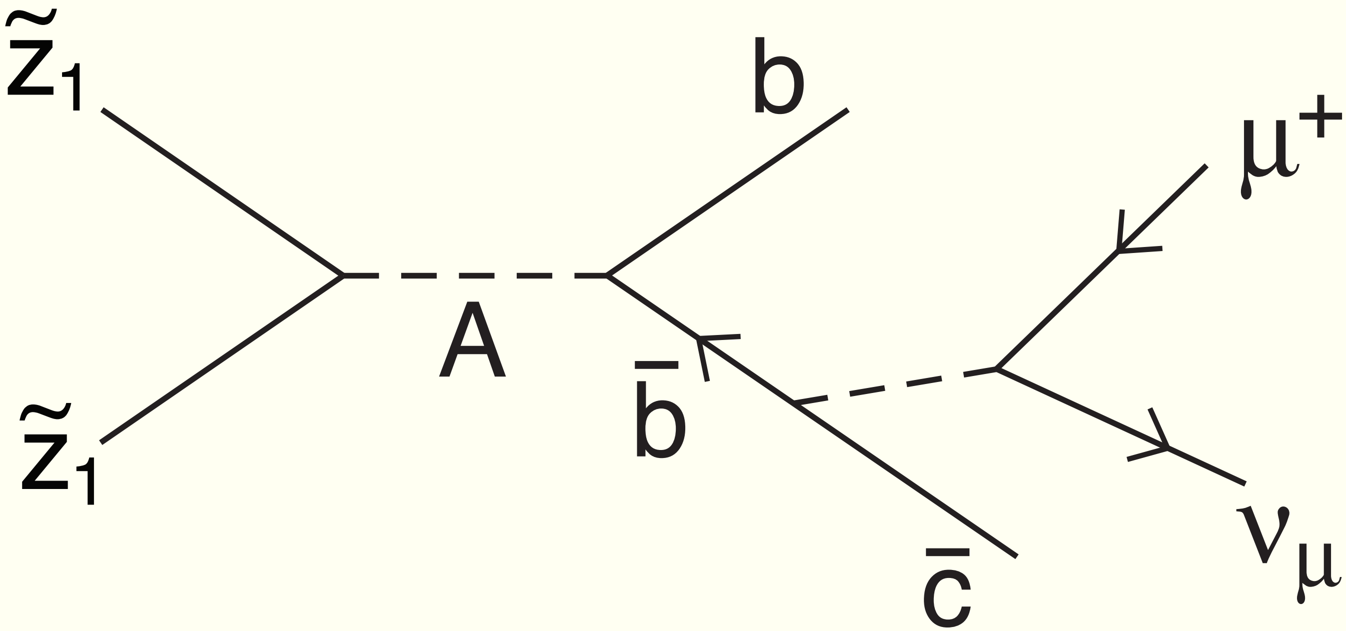
- SuperCDMS, LUX, (mini)CLEAN
- WARP, ArDM



Indirect detection (ID) of SUSY DM: ν-telescopes

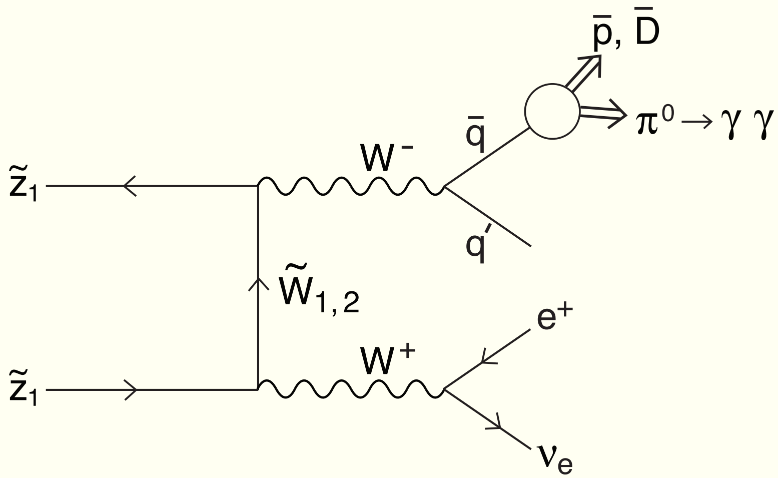
★ $\tilde{Z}_1\tilde{Z}_1 \to b\bar{b}, etc.$ in core of sun (or earth): $\Rightarrow \nu_\mu \to \mu$ in ν telescopes

- Amanda, Icecube, Antares

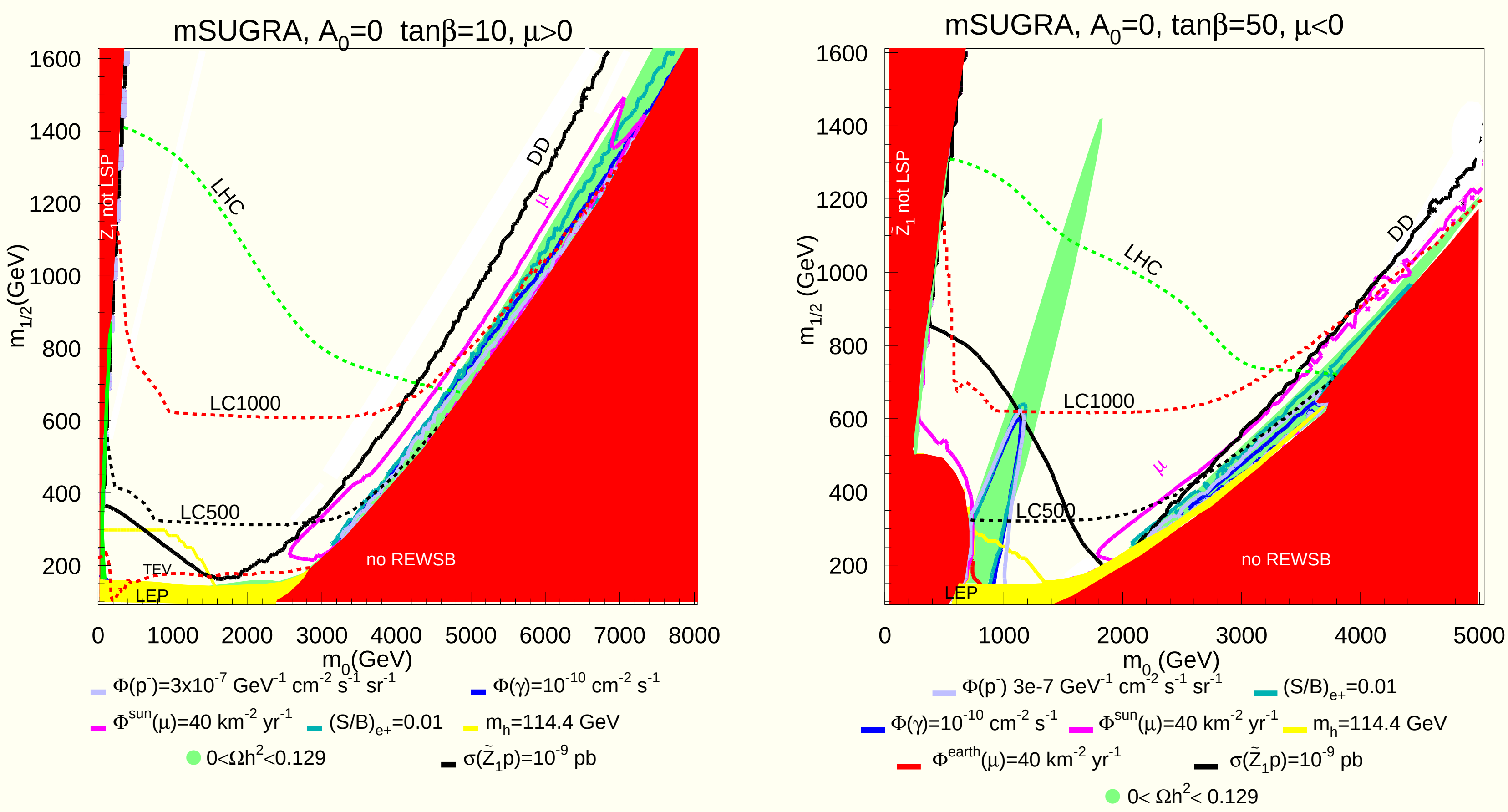


ID of SUSY DM: γ and anti-matter searches

- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \gamma$ in galactic core or halo
- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to e^+$ in galactic halo
- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \bar{p}$ in galactic halo
- $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \bar{D}$ in galactic halo



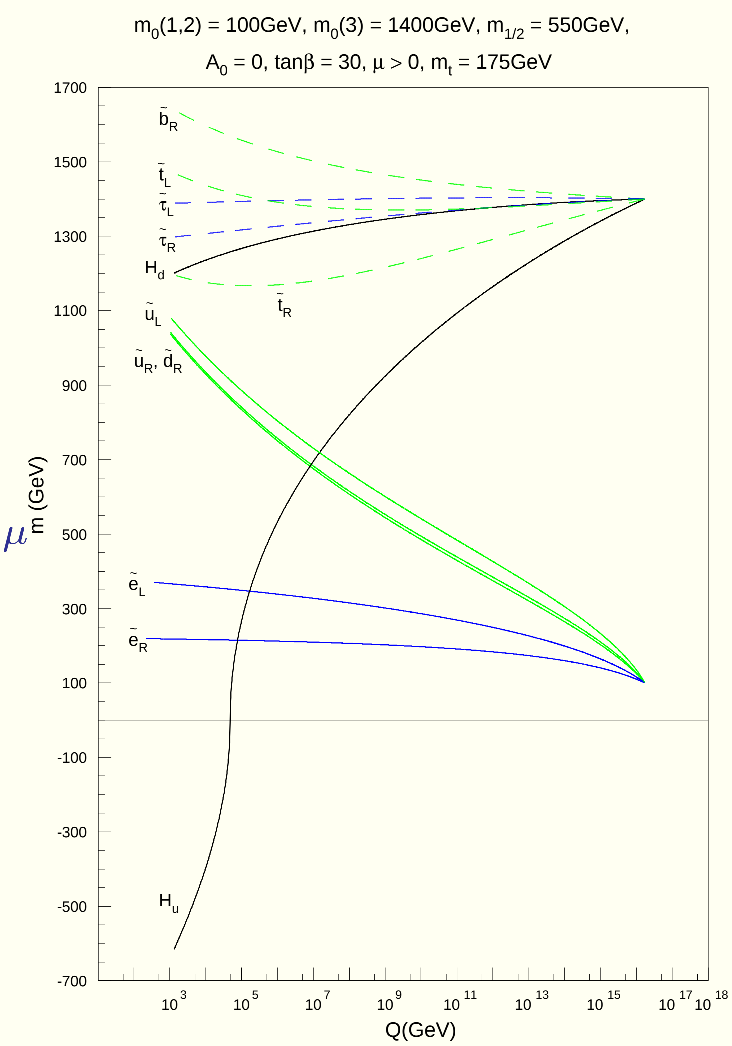
Direct and indirect detection of neutralino DM



HB, Belyaev, Krupovnickas, O'Farrill

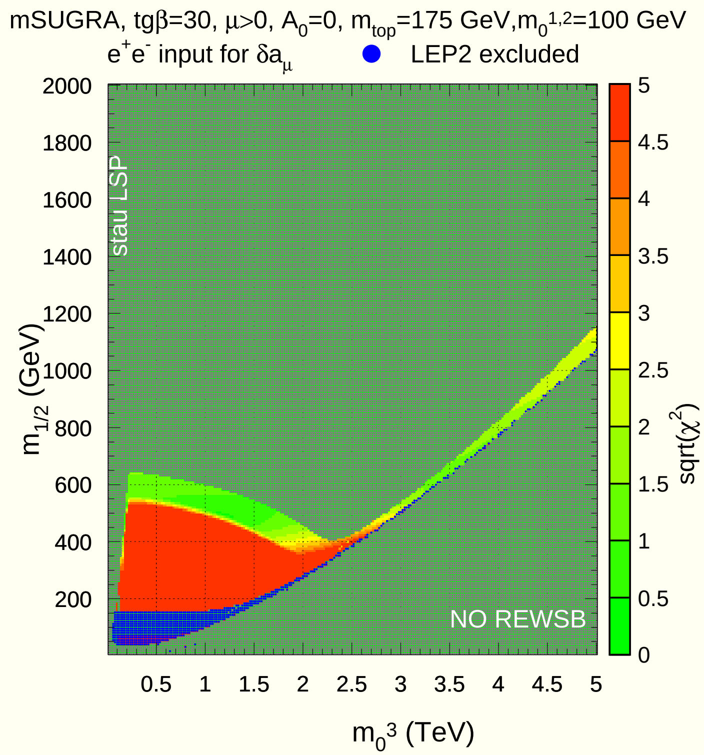
SUGRA models with non-universal scalars

- Normal scalar mass hierarchy (NMH):
- $BF(b \to s\gamma)$ prefers heavy 3rd gen. squarks
- $(g-2)_\mu$ prefers light 2nd gen. sleptons
- $m_0(1) \simeq m_0(2) \ll m_0(3)$
  - (preserve FCNC bounds)
- motivation: reconcile $BF(b \to s\gamma)$ with $(g-2)_\mu$
  - HB, Belyaev, Krupovnickas, Mustafayev
  - JHEP 0406, 044 (2004)



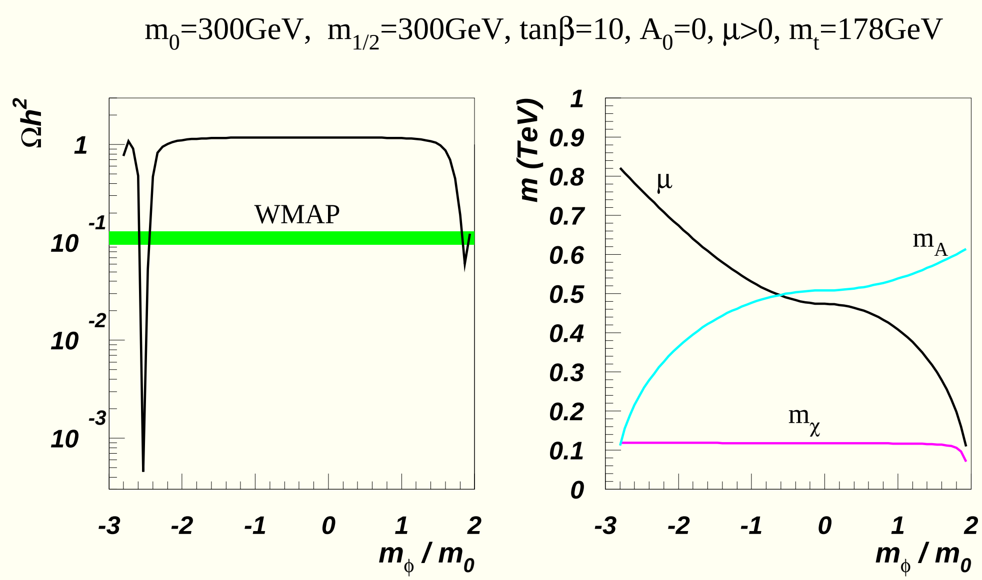
Normal scalar mass hierarchy: parameter space

- $m_0(1) \simeq m_0(2) \ll m_0(3)$
- LHC: light sleptons, enhanced leptonic cascade decays
- ILC: first two gen. sleptons likely accessible; squarks/staus heavy



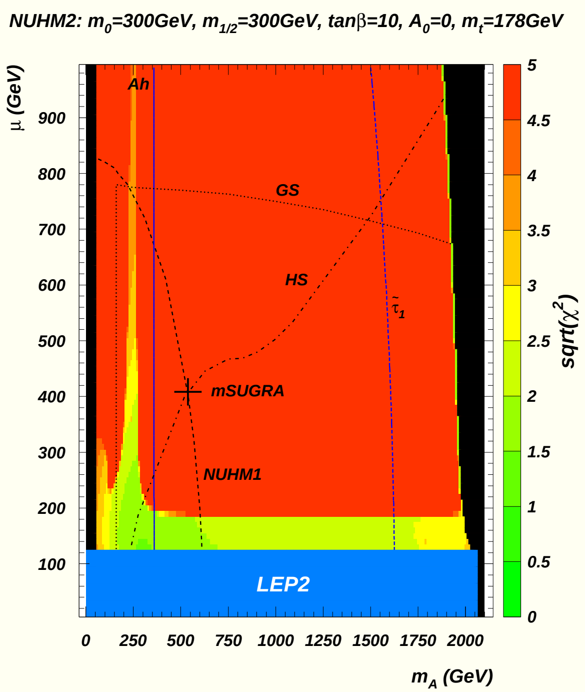
SUGRA models with non-universal Higgs mass (NUHM1)

- $m_{H_u}^2 = m_{H_d}^2 \equiv m_\phi^2 \neq m_0$: Drees; HB, Belyaev, Mustafayev, Profumo, Tata
- motivation: $SO(10)$ SUSYGUTs where $\hat{H}_{u,d} \in \phi(10)$ while matter $\in \psi(16)$
- $m_\phi^2 \gg m_0 \Rightarrow$higgsino DM for any $m_0,\ m_{1/2}$
- $m_\phi^2 < 0 \Rightarrow$ can have A-funnel for any $\tan\beta$



NUHM2 (2-parameter case)

- $m_{H_u}^2 \neq m_{H_d}^2 \neq m_0$: HB, Belyaev, Mustafayev, Profumo, Tata
- motivation: $SU(5)$ SUSYGUTs where $\hat{H}_u \in \phi(5)$, $\hat{H}_d \in \phi(\bar{5})$
- can re-parametrize $m_{H_u}^2,\ m_{H_d}^2 \leftrightarrow \mu,\ m_A$ (Ellis, Olive, Santoso)
- large S term in RGEs $\Rightarrow$ light $\tilde{u}_R,\ \tilde{c}_R$ squarks, $m_{\tilde{e}_L} < m_{\tilde{e}_R}$



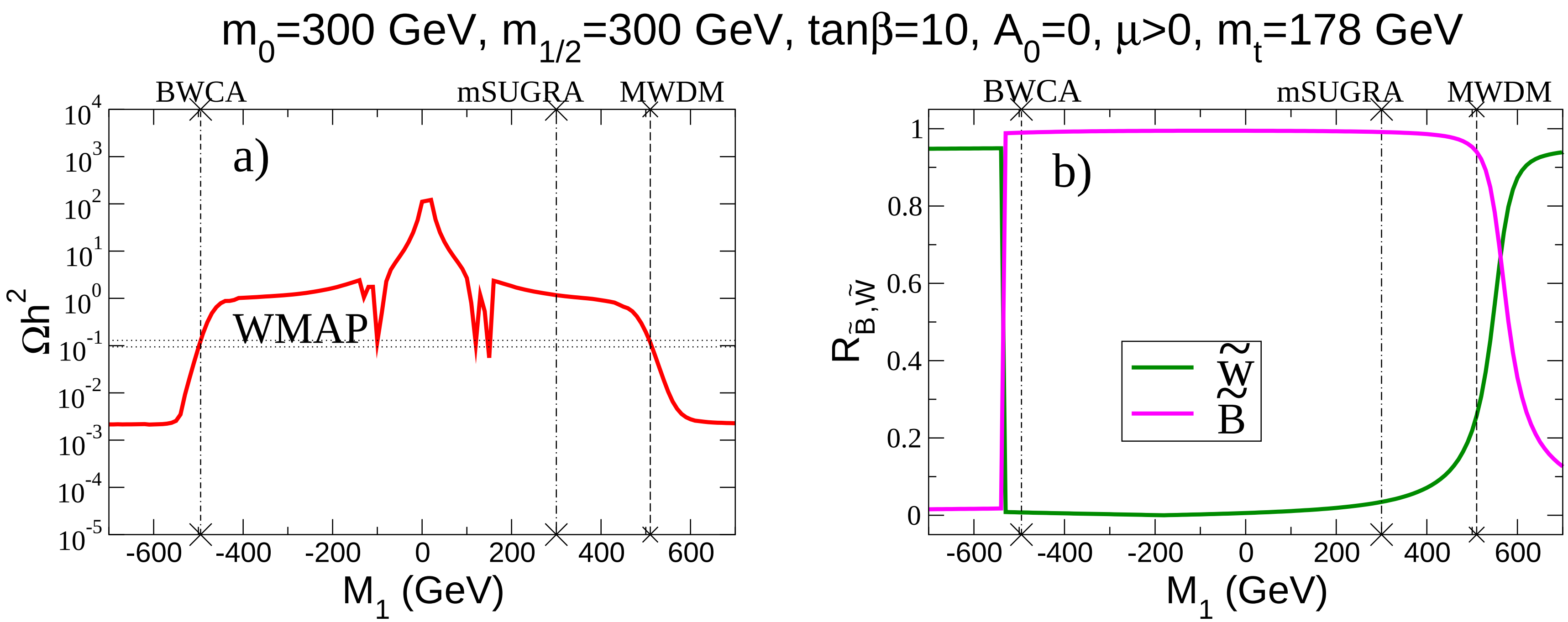
Non-universal gaugino masses

- ⋆ SUGRA models where GKF transforms non-trivially (Snowmass '96)
- ⋆ Heterotic superstring models with orbifold compactification: SUSY breaking dominated by the moduli field
- ⋆ KKLT model of type IIB string compactification with fluxes
- ⋆ Extra-dimensional SUSY GUT models where SUSY breaking is communicated from the SUSY breaking brane to the visible brane via gaugino mediation (e.g. Dermisek-Mafi model)
- ⋆ ...
- ⋆ Here we adopt a phenomenological approach of independent M_1, M_2, M_3 but require consistency with WMAP
  - MWDM: HB, Mustafayev, Park, Profumo, JHEP**0507**, 046 (2005)
  - BWCA DM: HB, Krupovnickas, Mustafayev, Park, Profumo, Tata, JHEP**0512** (2005) 011.

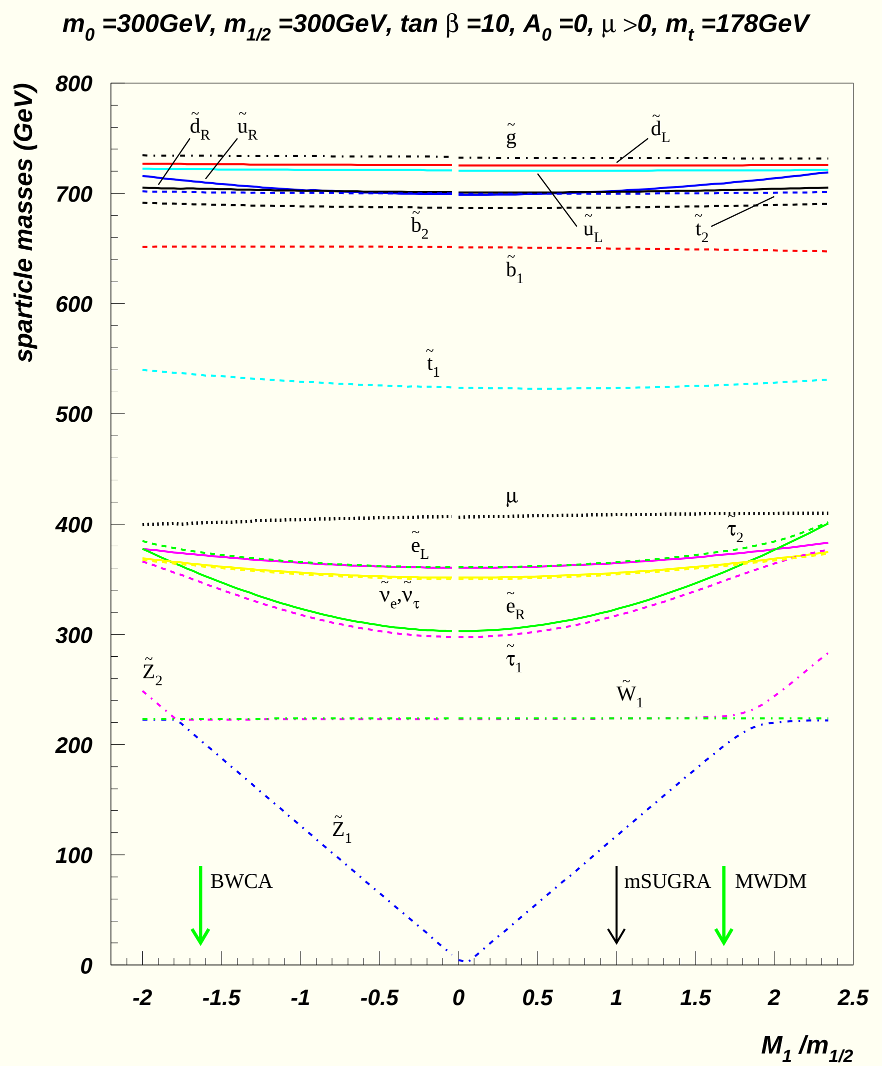
– LM3DM: HB, Mustafayev, Park, Profumo, Tata, JHEP**0604** (2006) 041.

★ Related work: Corsetti and Nath; Birkedal-Hansen and Nelson; Bertin, Nezri and Orloff; Bottino, Donato, Fornengo, Scopel; Belanger, Boudjema, Cottrant, Pukhov, Semenov; Mambrini, Munoz and Cerdeno; Auto, HB, Belyaev, Krupovnickas; Masiero, Profumo, Ullio

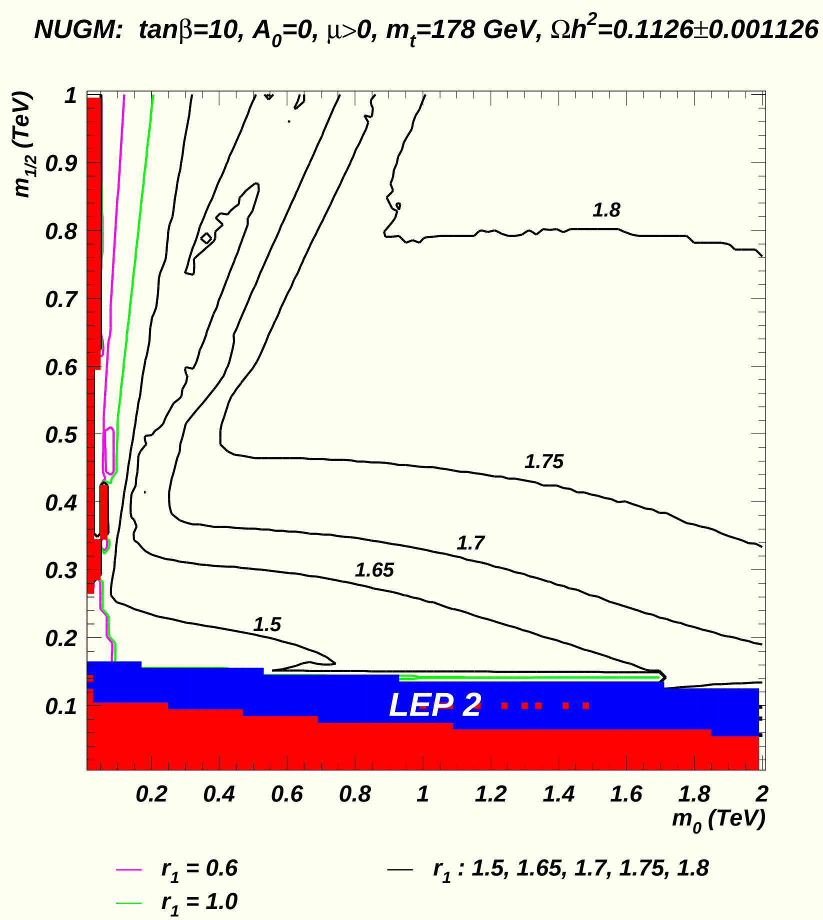
$\Omega_{\widetilde{Z}_1} h^2$ **vs.** M_1



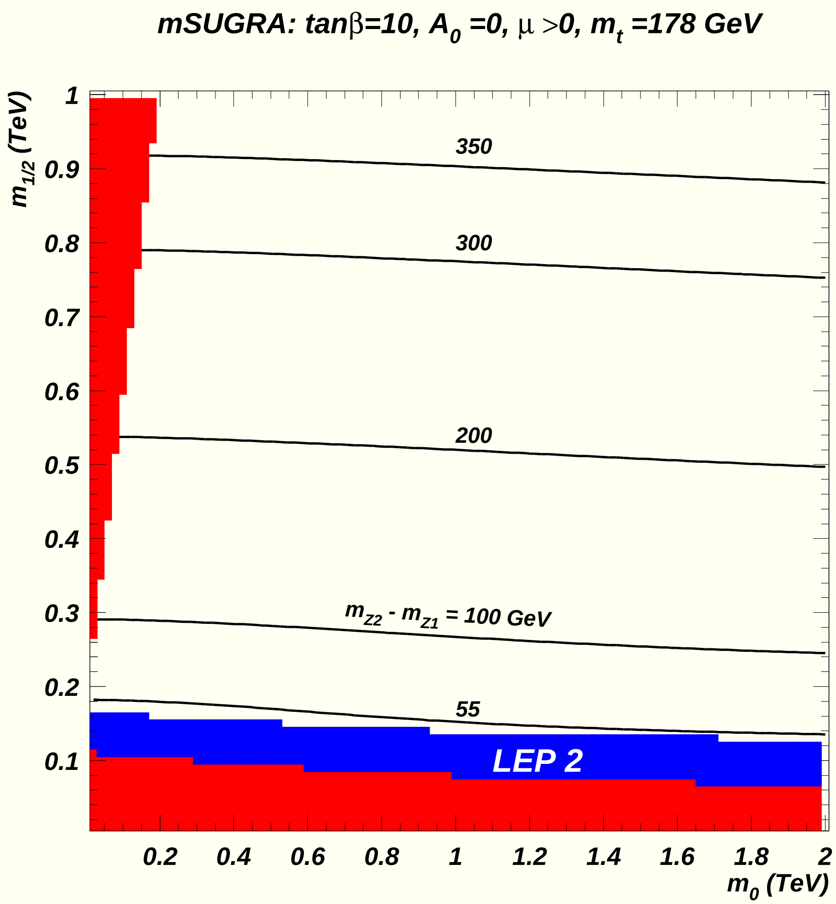
Sparticle mass spectra vs M_1

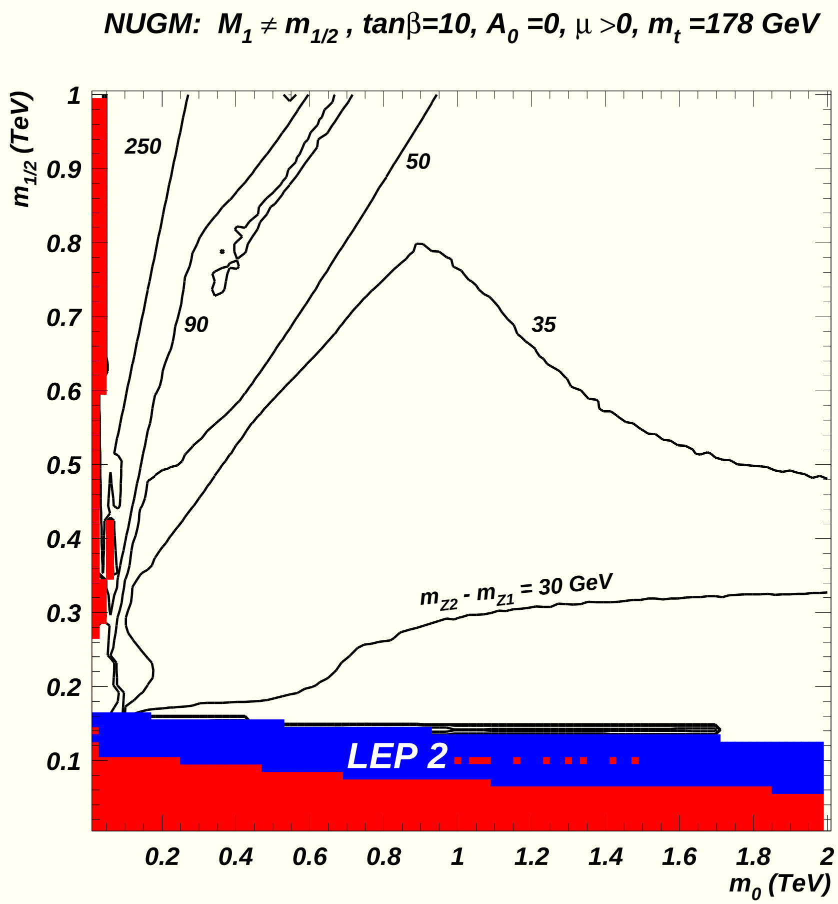


MWDM: plot $r_1 \equiv M_1/M_2$ (at M_{GUT} which gives $\Omega_{CDM}h^2 \simeq 0.11$

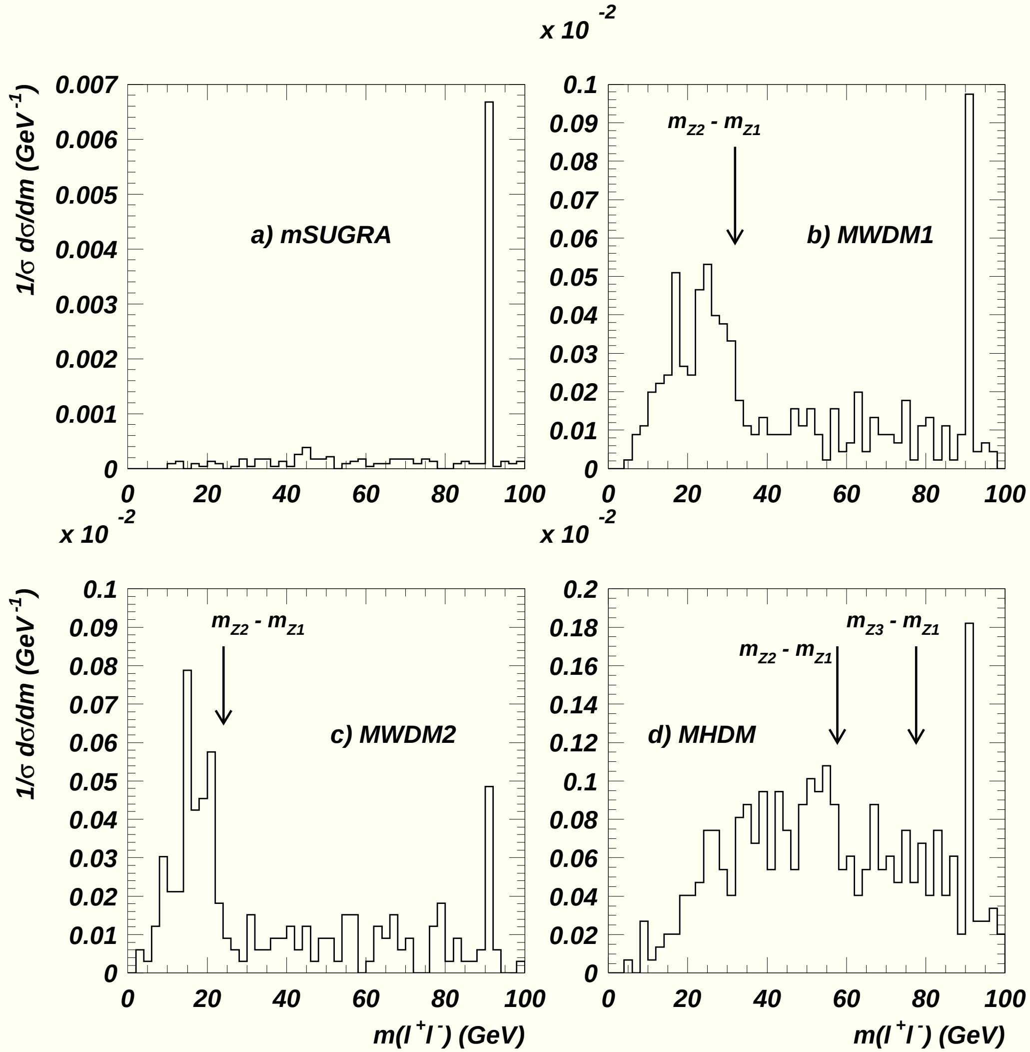


MWDM: small $\widetilde{Z}_2 - \widetilde{Z}_1$ mass gap



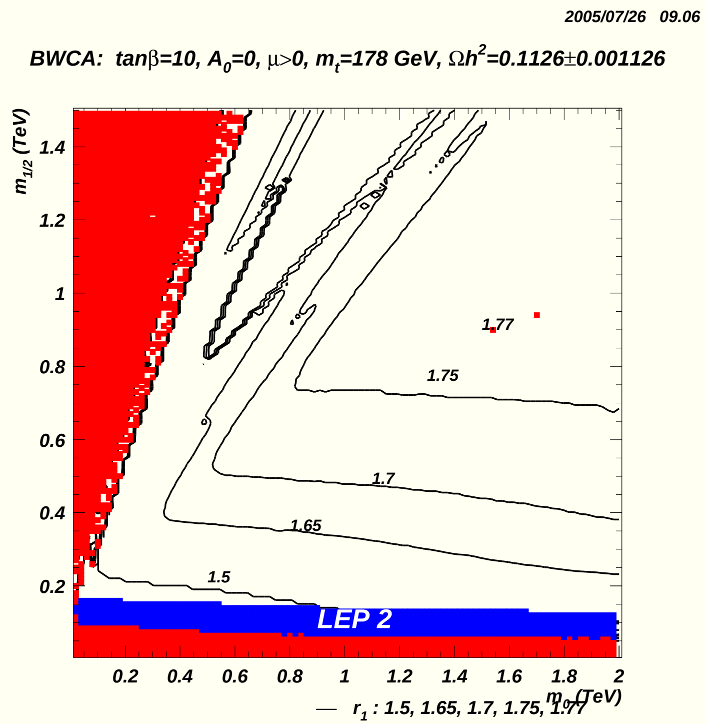


$m(\ell^+\ell^-)$: mass gap observable at LHC for MWDM



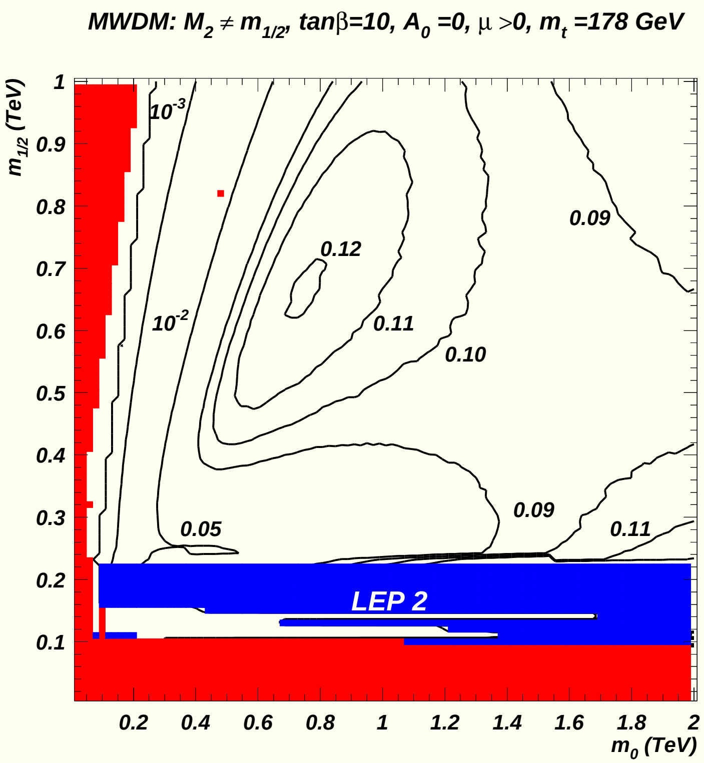
Bino-wino co-annihilation (BWCA) scenario

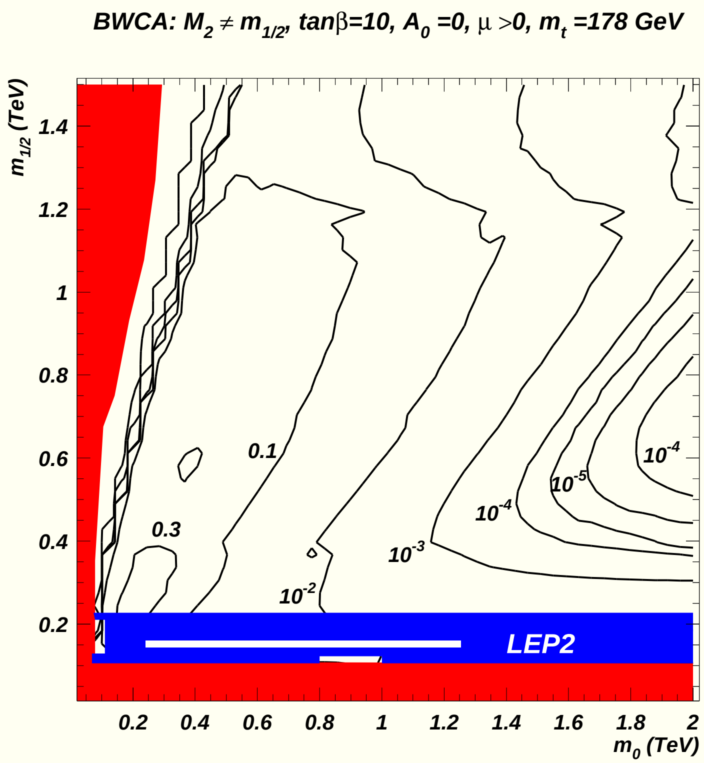
- If $M_1/M_2 < 0$, then no mixing between bino-wino
- Can only reduce relic density via bino-wino co-annihilation ($m_{\widetilde{Z}_1} \sim m_{\widetilde{W}_1} \sim m_{\widetilde{Z}_2}$) when $M_1 \simeq -M_2$ at $Q = M_{weak}$
- plot $r_1 = -M_1/M_2$ (at M_{GUT})



2005/07/26 09.06
BWCA: tanβ=10, A0=0, μ>0, mt=178 GeV, Ωh2=0.1126±0.001126
m1/2 (TeV)
1.4
1.2
1
0.8
0.6
0.4
0.2
1.77
1.75
1.7
1.65
1.5
LEP 2
0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
m0 (TeV)
r1 : 1.5, 1.65, 1.7, 1.75, 1.77

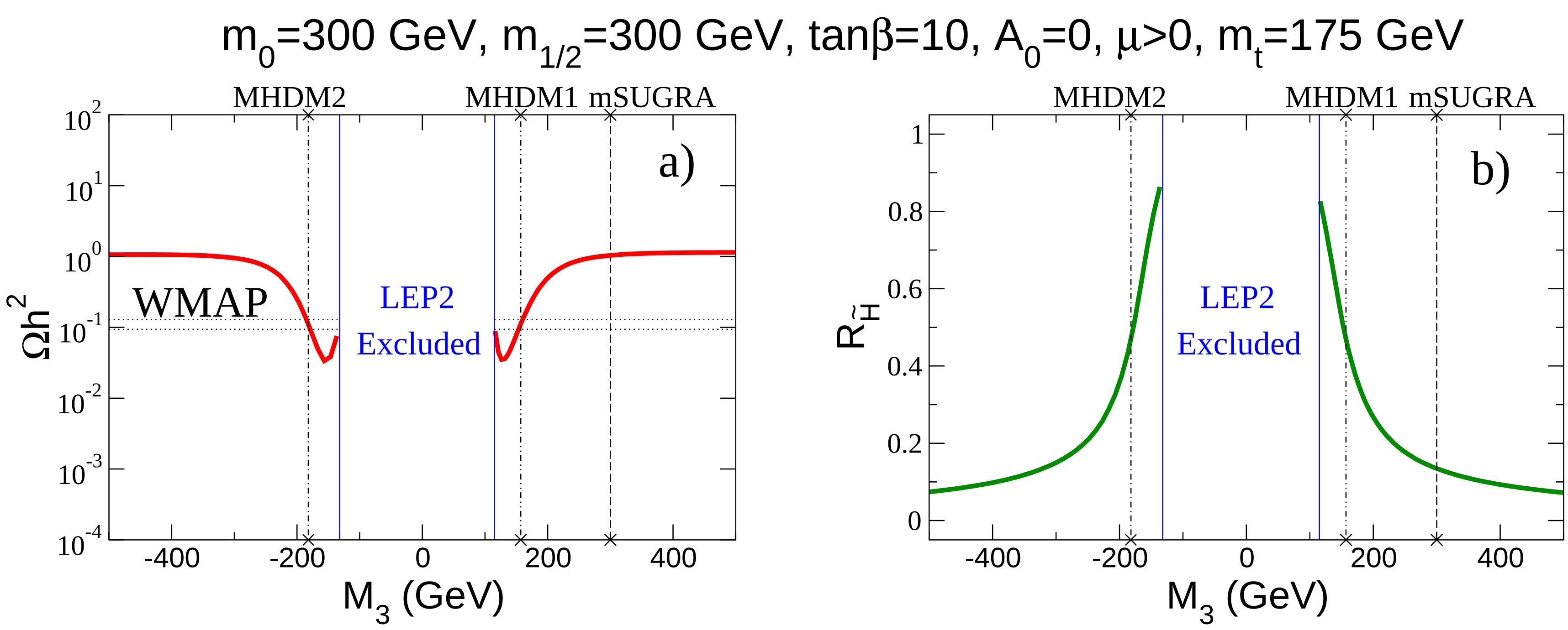
In BWCA at $m_0 \lesssim 500$ GeV, $BF(\widetilde{Z}_2 \to \widetilde{Z}_1\gamma)$ enhanced!





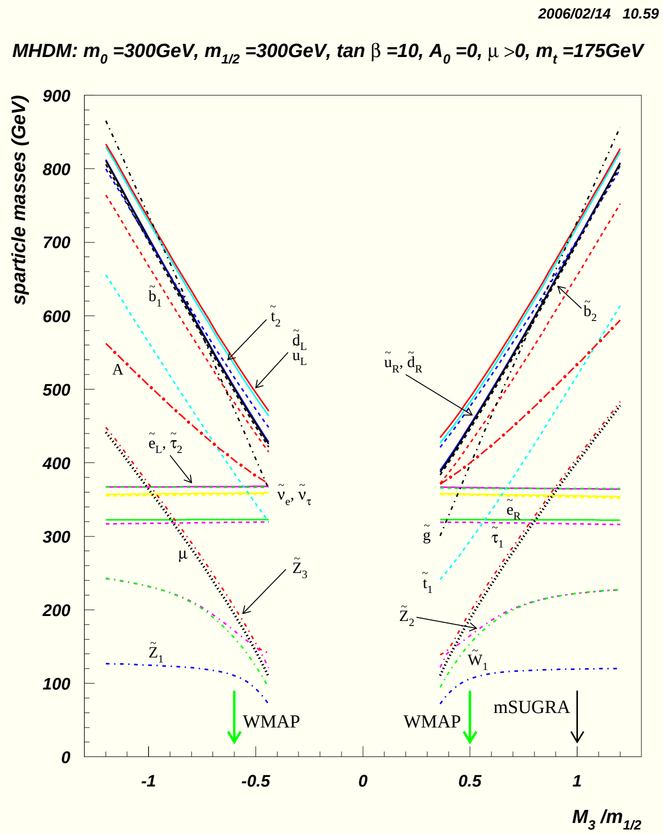
Haber+Wyler; Ambrosanio+Mele; Baer+Krupovnickas: JHEP 0209, 038 (2002)

Mixed higgsino DM from a low M_3 (LM3DM)



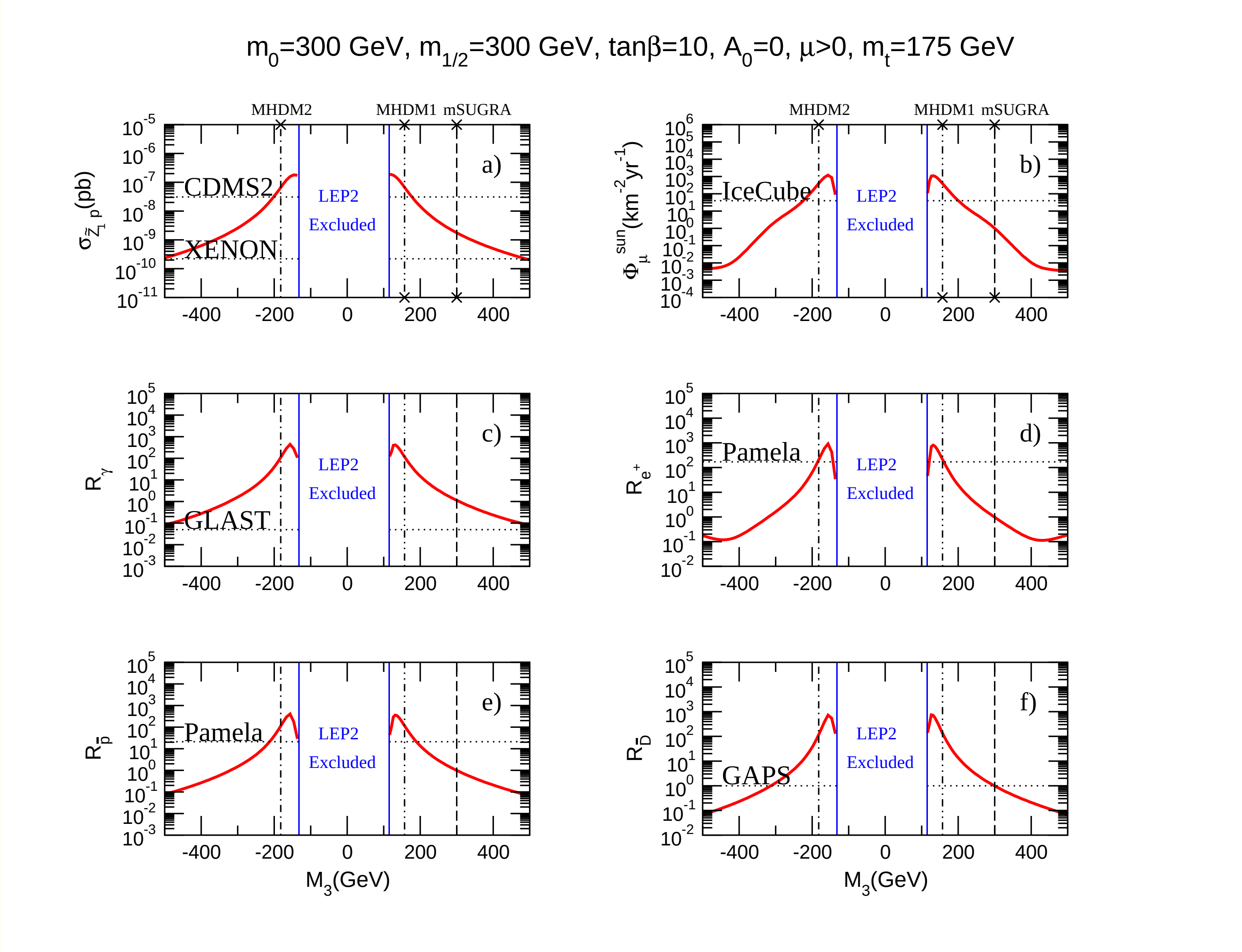
- low $M_3 \Rightarrow$ low $m_{\tilde{g}},\ m_{\tilde{q}},\ \mu$
- called "compressd SUSY" in related scenario by S. P. Martin

Sparticle mass spectra for LM3DM

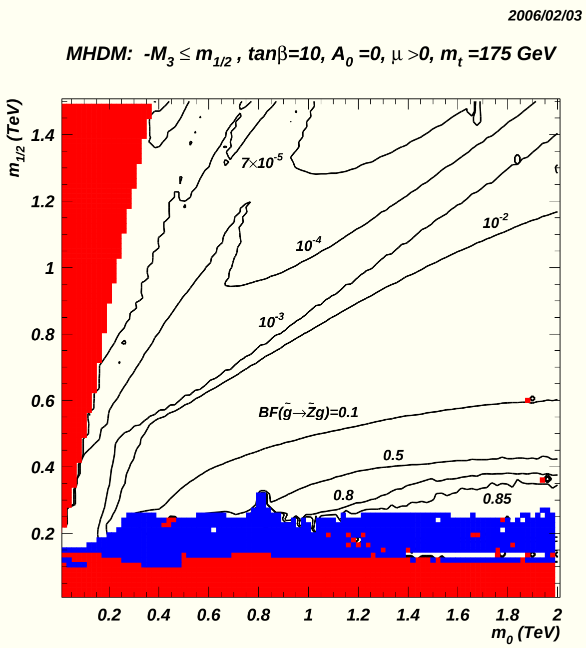


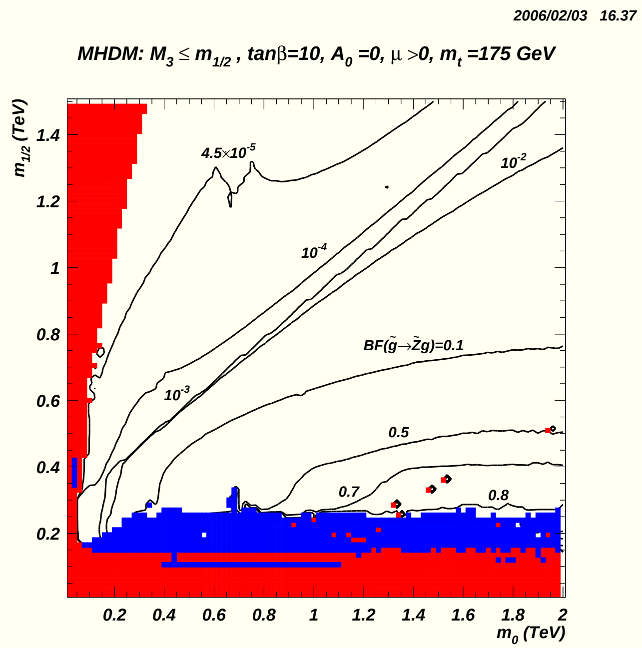
- low $m_{\tilde{g}},\ m_{\tilde{q}},\ \mu \Rightarrow$ huge DM detection rates!

Direct/indrct DM rates greatly enhanced for LM3DM



In LM3DM, $BF(\tilde{g} \to \widetilde{Z}_i)$ loop decay enhanced!

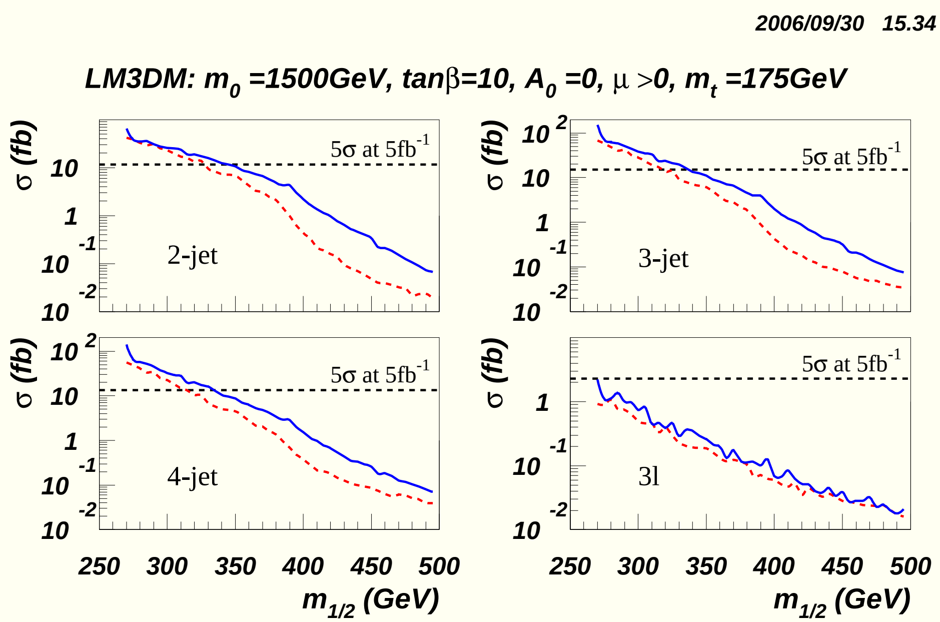




Baer, Tata, Woodside: PRD**42** (1990) 1568.

In LM3DM, ratio $m_{\tilde{g}} : m_{\widetilde{W}_1} : m_{\widetilde{Z}_1} \sim 2.5 : 1.5 : 1$

- Can search for $p\bar{p} \to \tilde{g}\tilde{g} \to jets + \not{E}_T$ at Tevatron;
- Search is *not* pre-empted by LEP2 bouds on $m_{\widetilde{W}_1}$
- Can see $m_{\tilde{g}}$ from $200 - 340$ GeV: HB, Mustafayev, Tata PRD**75**,035004 (2007)



Mixed modulus-AMSB models

- ⋆ KKLT model: type IIB superstring compactification with fluxes
  - stabilize moduli/dilaton via fluxes and e.g. gaugino condensation on $D7$ brane
  - introduce anti-$D3$ brane (uplifting potential; de Sitter universe with $\Lambda > 0$
  - small SUSY breaking due to $\overline{D3}$ brane
  - mass hierarchy: $m_{moduli} \gg m_{3/2} \gg m_{SUSY}$
- ⋆ MSSM soft terms calculated by Choi, Falkowski, Nilles, Olechowski, Pokorski
- ⋆ phenomenology: Choi, Jeong, Okumura, Falkowski, Lebedev, Mambrini,Kitano, Nomura
- ⋆ see also: HB, E. Park, X. Tata, T. Wang, JHEP**0608**, 041 (2006); PL**B641**, 447 (2006); hep-ph/0703024.

Parameter space of MM-AMSB (mirage unification) model

- MSSM sparticle mass scale $\sim \frac{m_{3/2}}{16\pi^2} \equiv M_s$
- Ratio of modulus-mediated and anomaly-mediated contributions set by a phenomenological parameter α
- Modulus-mediated contributions depend on location of fields in extra dimensions. These contributions depend on "modular weights" of the fields, determined by where these fields are located.
  - modular weights $n_i = 0$ (1) (($\frac{1}{2}$)) for D7 (D3) ((intersection))
  - Gauge kinetic function indices $l_a = 1$ (0) on $D7$ ($D3$) branes.

Model completely specified by

$$m_{3/2},\ \alpha,\ \tan\beta,\ sign(\mu),\ n_i,\ l_a$$

- Radiative EWSB determines μ^2 as usual; model into Isajet 7.75

Soft SUSY Breaking Terms

The soft terms renormalized at $Q \sim M_{\rm GUT}$ are given by,

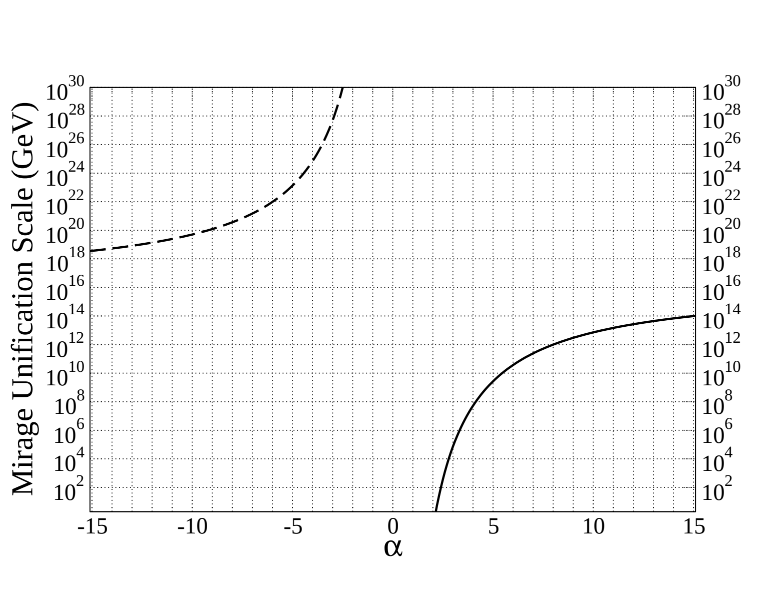
$$
\begin{aligned}
M_a &= M_s \left(\ell_a \alpha + b_a g_a^2\right), \\
A_{ijk} &= M_s \left(-(3 - n_i - n_j - n_k)\alpha + \gamma_i + \gamma_j + \gamma_k\right), \\
m_i^2 &= M_s^2 \left((1 - n_i)\alpha^2 + 4\alpha\xi_i - \dot{\gamma}_i\right),
\end{aligned}
$$

with

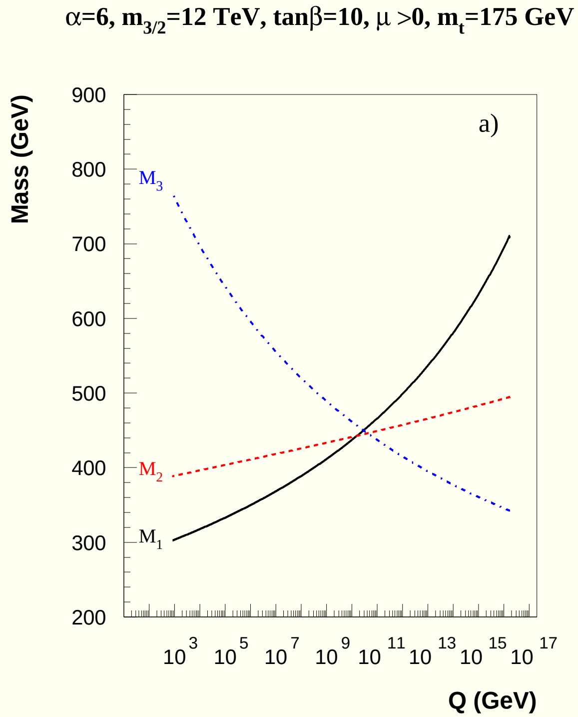
$$\xi_i = \sum_{j,k}(3 - n_i - n_j - n_k)\frac{y_{ijk}^2}{4} - \sum_a l_a g_a^2 C_2^a(f_i), \text{and } \dot{\gamma}_i = 8\pi^2 \frac{\partial \gamma_i}{\partial \log \mu}$$

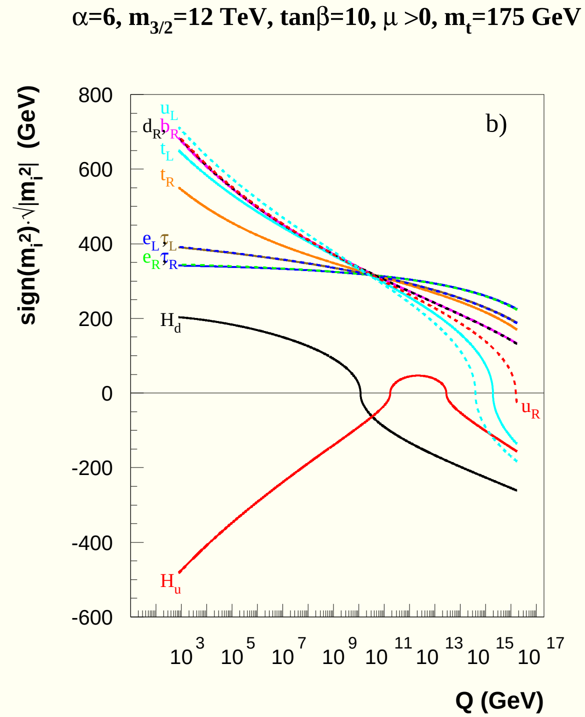
Meauring modular weights at LHC and ILC

A plot of the mirage unification scale versus modulus-AMSB mixing parameter α, assuming $l = 1$.



At $Q = \mu_{mir.} = M_{\rm GUT} e^{-8\pi^2/(l\alpha)}$, can determine soft terms via RG running up, if weak scale parameters are known.



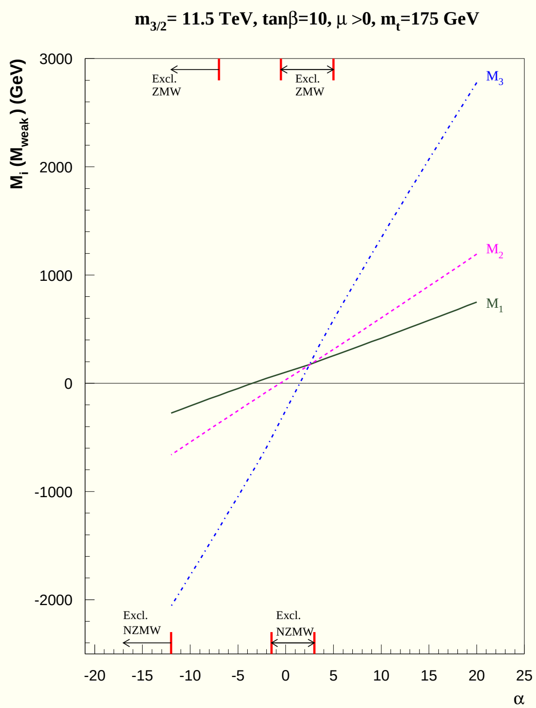


At $Q = \mu_{mir.}$, ratio of scalar to gaugino masses is given by

$$\left.\frac{m_i}{M_a}\right|_{\mu_{\rm mir}} = \frac{\sqrt{1-n_i}}{l_a}.$$

For $l_a = 1$, this measures the matter modular weight!

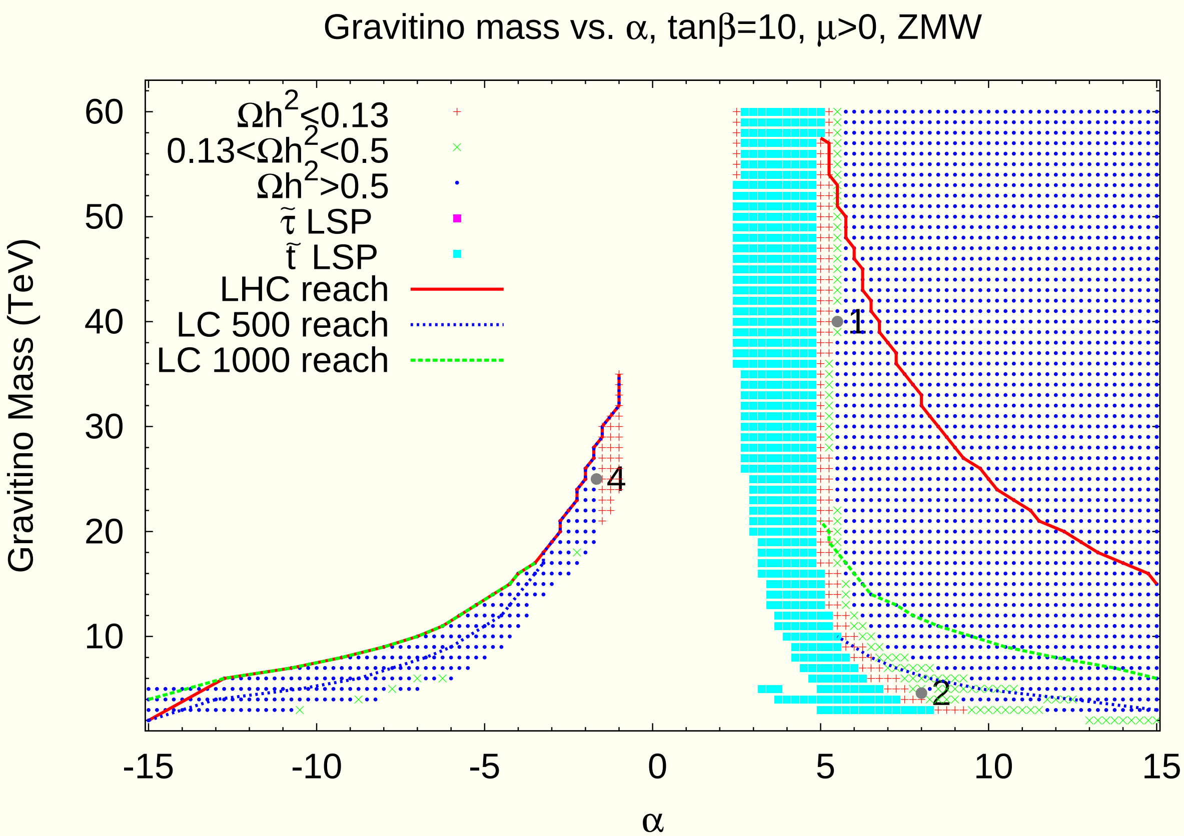
Gaugino masses at weak scale in MM-AMSB:



Low mirage unification scale

If $M_1(\text{weak}) = \pm M_2(\text{weak})$, potential for agreement with relic density via MWDM or BWCA!

α *vs.* $m_{3/2}$ **space for** $n_m = n_H = 0$:

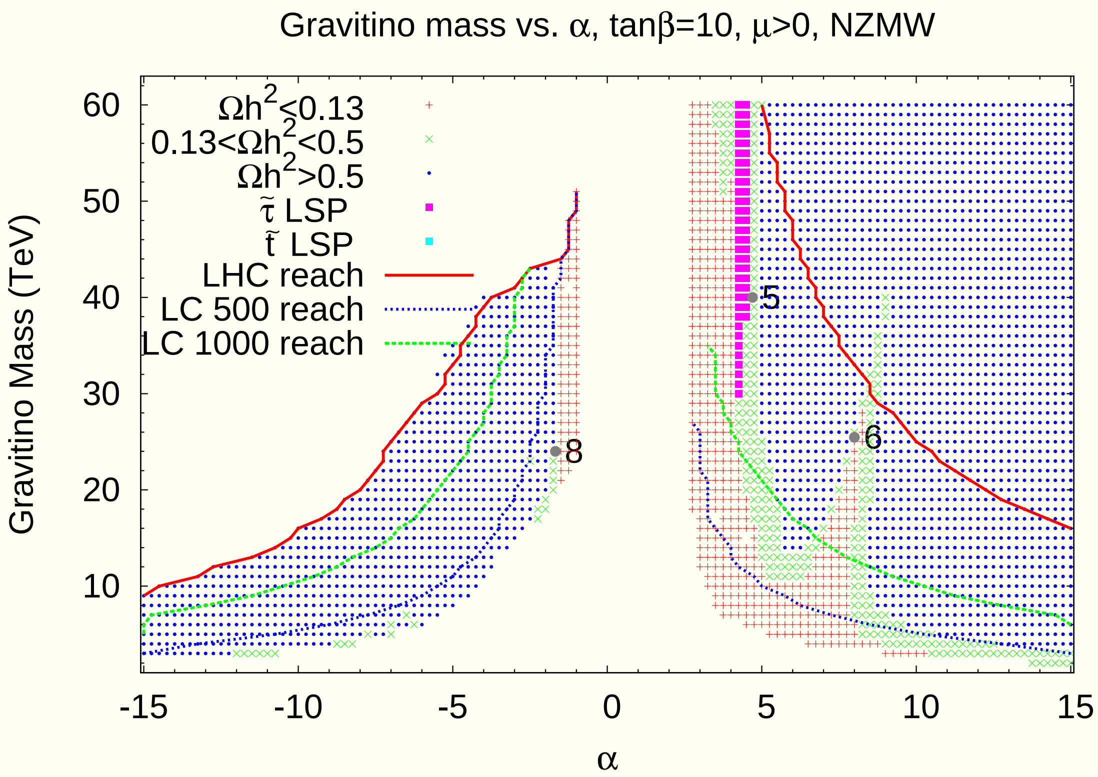


Stop coannihilation region.

Mixed higgsino region at low positive alpha.

BWCA for $\alpha < 0$. No MWDM region.

α *vs.* $m_{3/2}$ **space for** $n_m = \frac{1}{2}$, $n_H = 1$:



Stau coannihilation, Higgs funnel, MWDM and BWCA regions clearly seen.

Also, mixed bino-wino-higgsino region (via low $|M_3|$).

Bulk region at low $m_{3/2}$.

Conclusions: SUSY dark matter models

⋆ We use the measured relic density of CDM as a guide to SUSY phenomenology in the MSSM

- mSUGRA models: allowed regions
  - ∗ HB/FP region: measure $m_{\tilde{g}}$ to $\sim 8\%$
- NMH
- NUHM1
- NUHM2
- MWDM
- BWCA DM
- LM3DM
- mixed moduli-AMSB (KKLT, mirage unification)

⋆ data coming soon from LHC will be final arbiter!