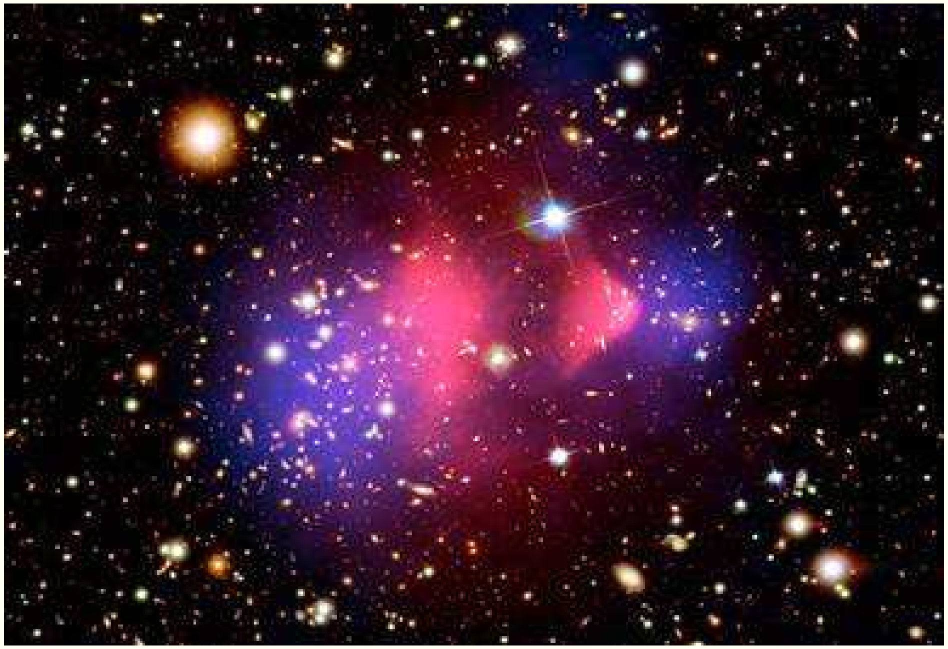
Models of SUSY Dark Matter with a well-tempered neutralino

Howard Baer
Florida State University

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



Some successes of SUSY GUT theories

- ⋆ quadratic divergence cancellation allows widely disparate scales to co-exist: $e.g.$ GUT scale $Q = 10^{16}$ GeV and weak scale $Q = 100$ GeV
- ⋆ gauge coupling unification!
- ⋆ Lightest Higgs mass $m_h \stackrel{<}{\sim} 130$ 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

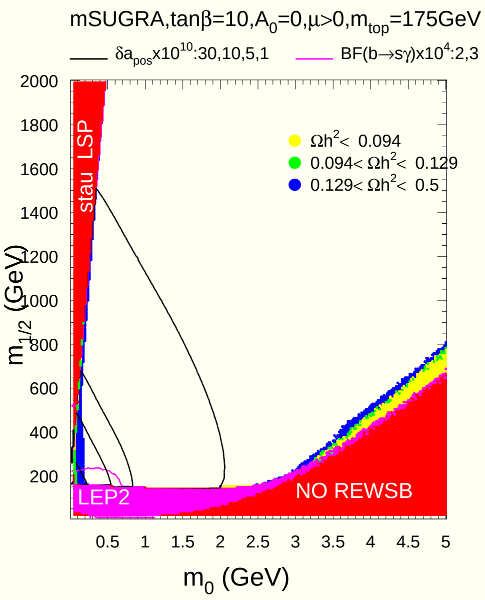
Our strategy:

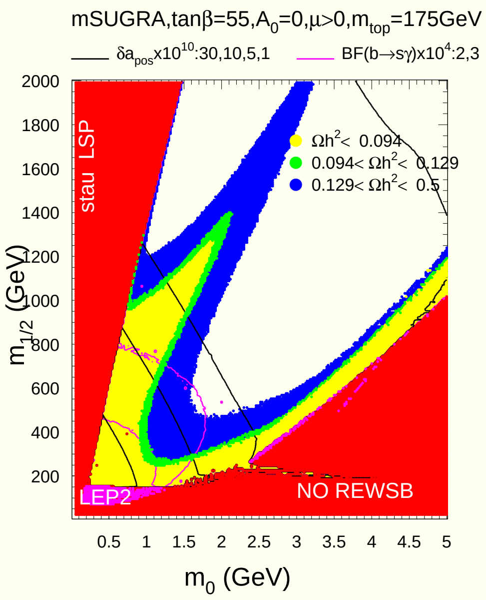
- ⋆ Assume MSSM is valid effective theory between M_{weak} and M_{GUT}
  - LSP is stable: good candidate for CDM
- ⋆ Stipulate SSB terms at $Q = M_{GUT}$ and evaluate SSB at M_{weak} via RG evolution
  - EW symmetry broken radiatively by large m_t
- ⋆ Invoke
  - minimal flavor violation
  - ignore CP-viol. phases
- ⋆ Spectra generated with Isajet/Isasugra (Paige, Protop., HB, Tata)
- ⋆ We will use the measured value $\Omega_{CDM}h^2 = 0.105 \pm 0.01$ as a guide to allowed phenomenology! (Isatools:IsaReD)

Case 1: mSUGRA (CMSSM) model

⋆ allowed parameter space: mSUGRA model

- $m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$





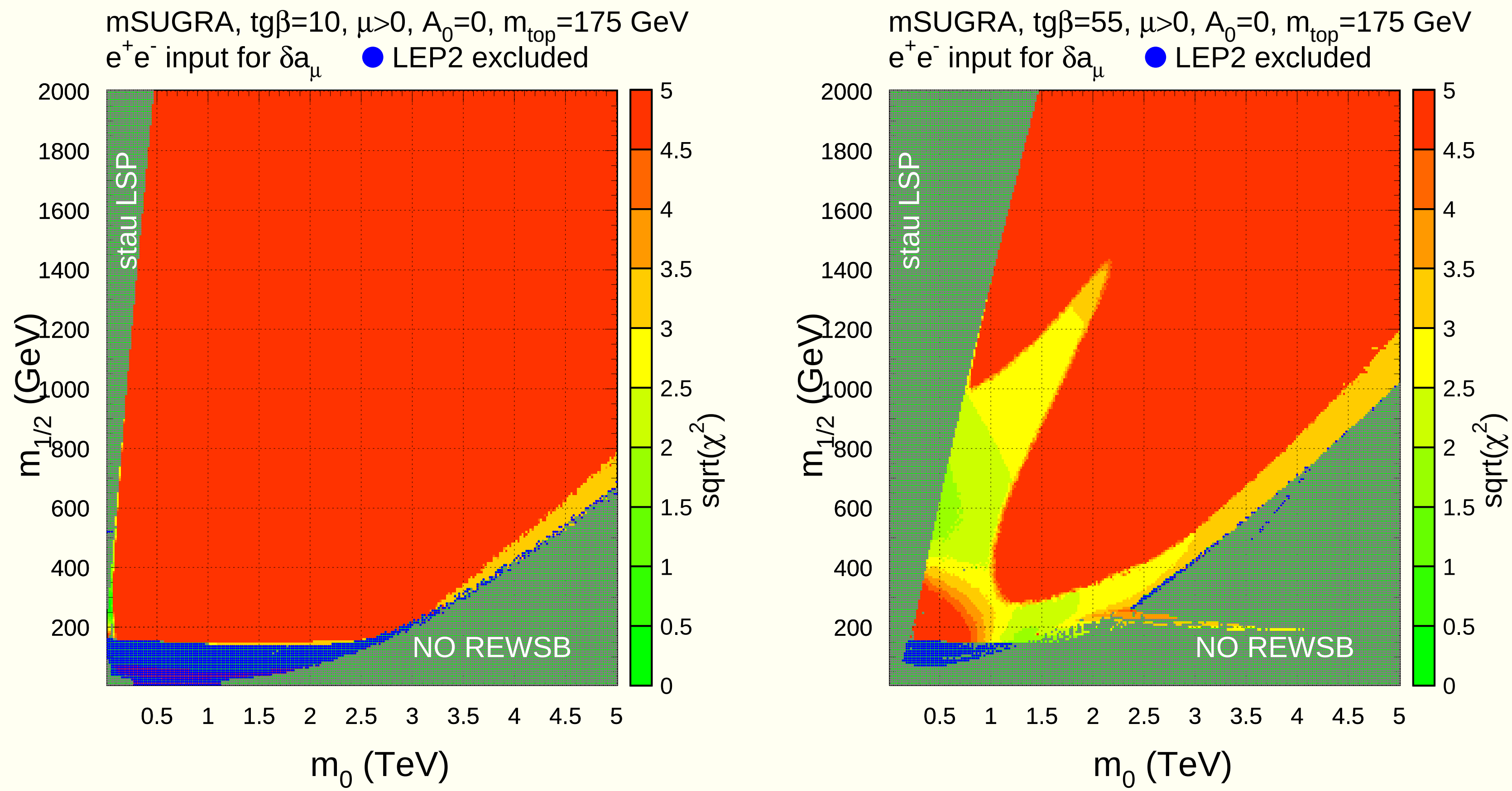
Main mSUGRA regions consistent with WMAP

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

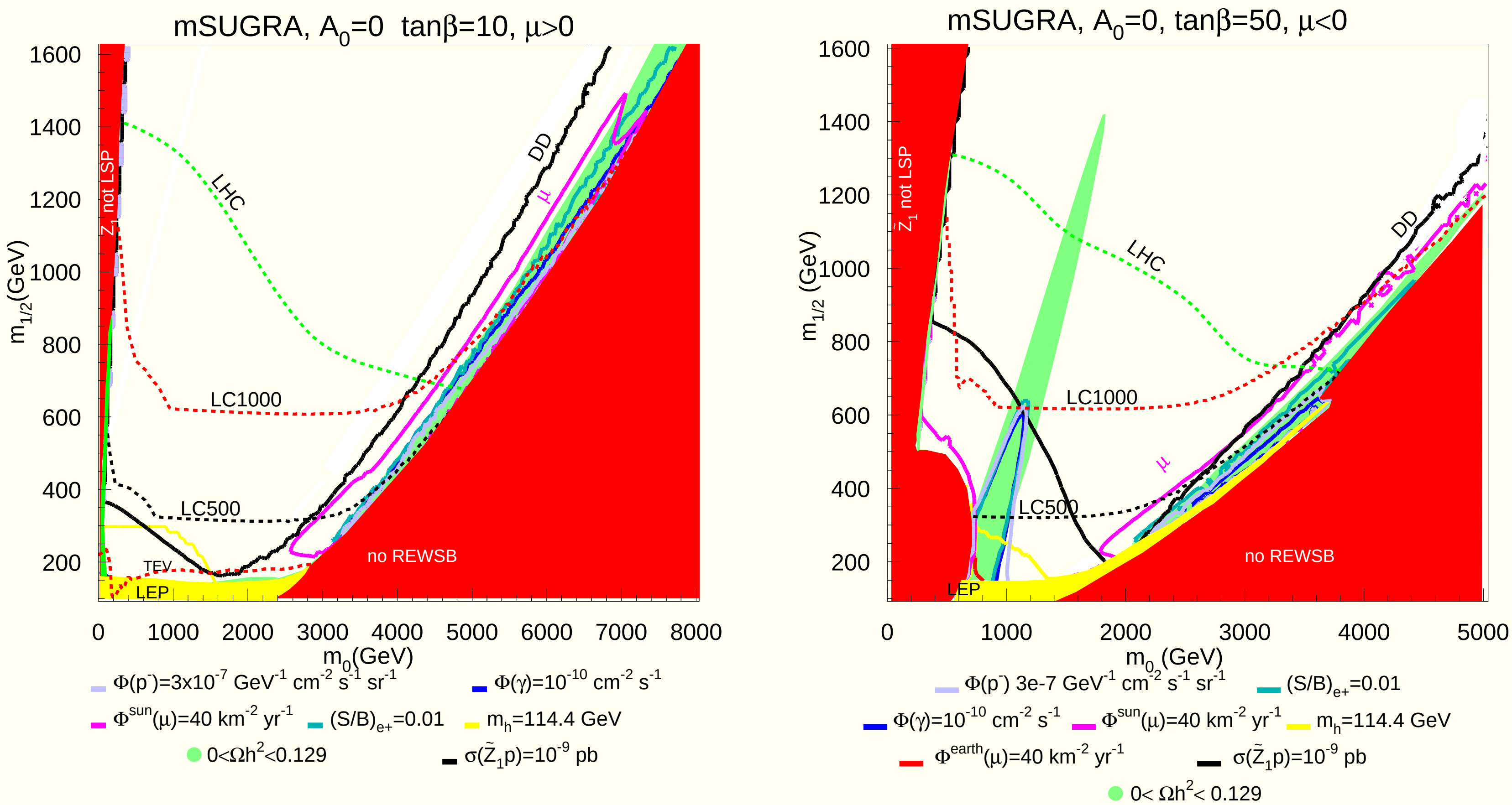
★ Exceptions:

- 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 $|\mu| \rightarrow small$)
- 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 $m_{\tilde{t}_1} \simeq m_{\widetilde{Z}_1}$)

χ^2 from $\Omega_{\widetilde{Z}_1}h^2,\ (g-2)_\mu,\ BF(b\to s\gamma)$



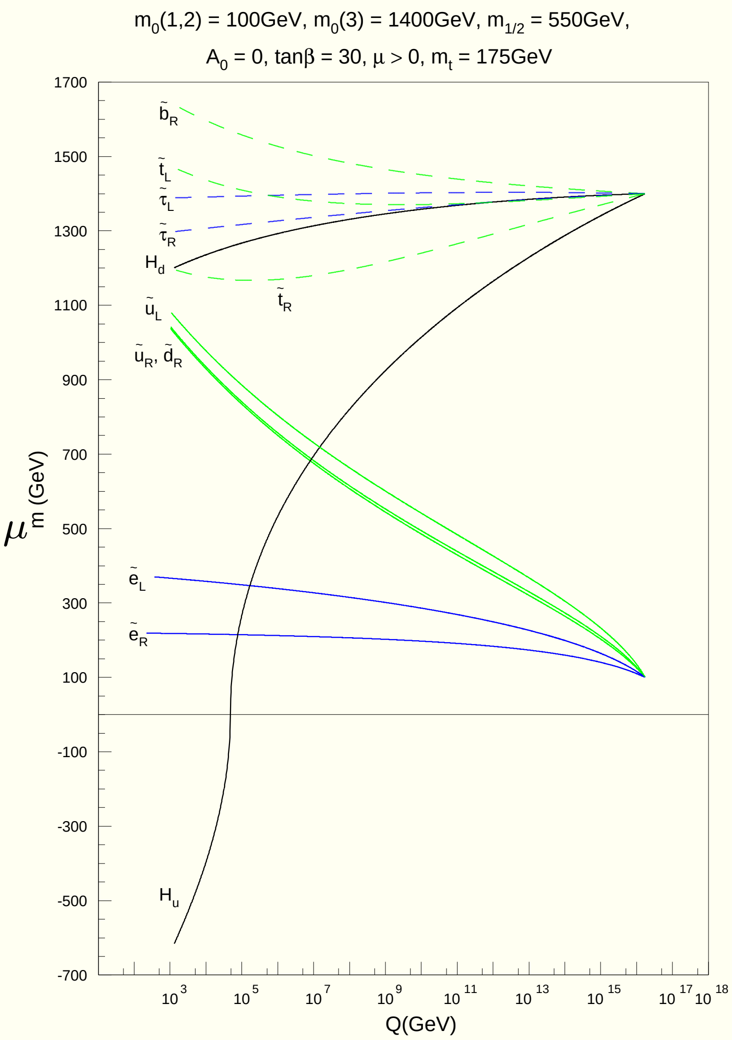
Direct, indirect, collider detection of neutralino DM



HB, Belyaev, Krupovnickas, O'Farrill

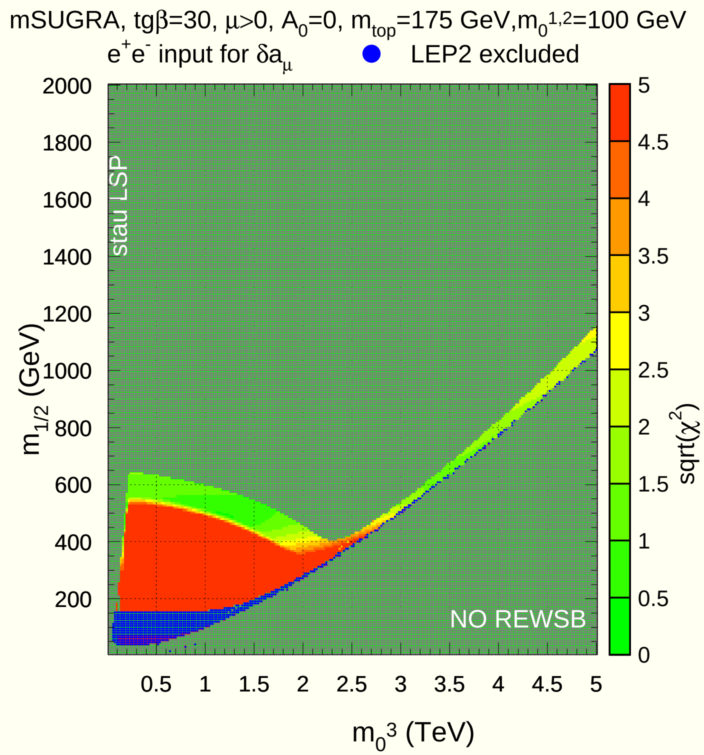
Case 2: non-universal generations

- 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)



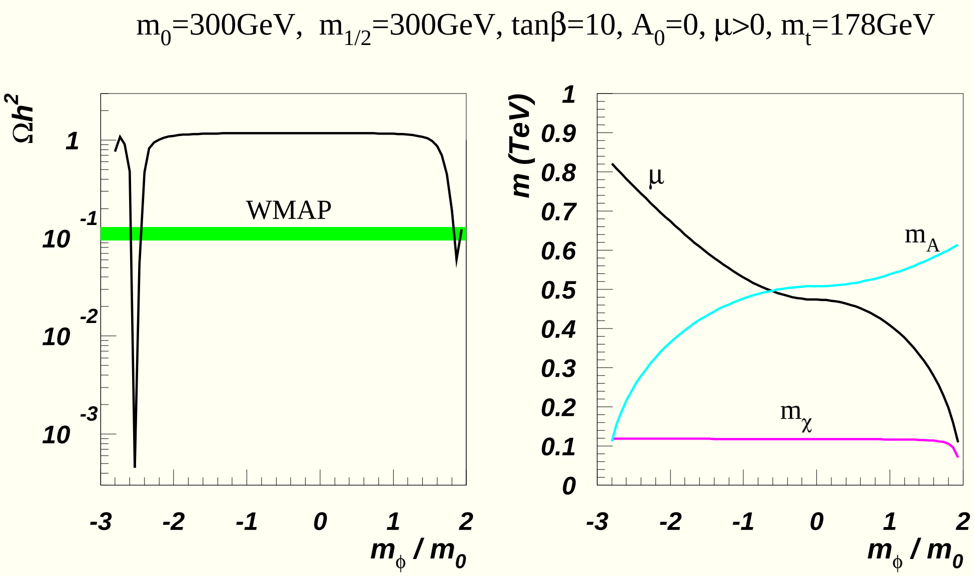
Normal scalar mass hierarchy: parameter space

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



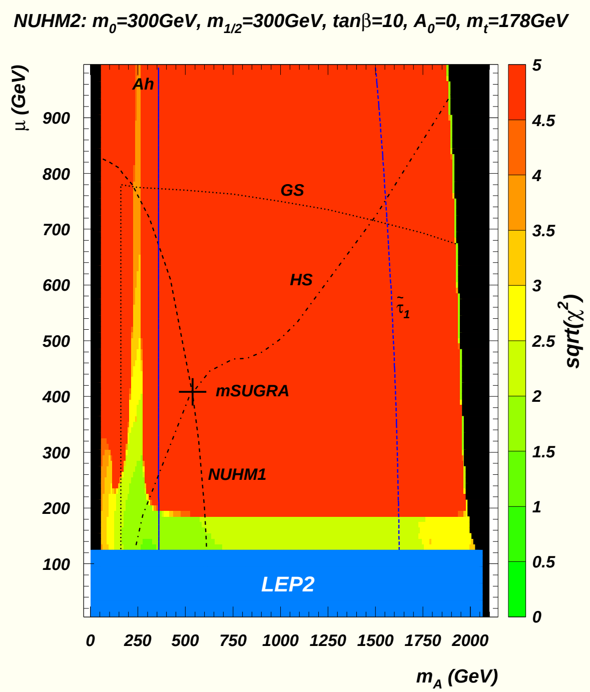
Case 3: NUHM1 (non-universal Higgs mass: 1 param.)

- $m_{H_u}^2 = m_{H_d}^2 \equiv m_\phi^2 \neq m_0$: 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 $\tan\beta$



Case 4: 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: case 5-7

⋆ Motivation:

- 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)
- $\cdots$

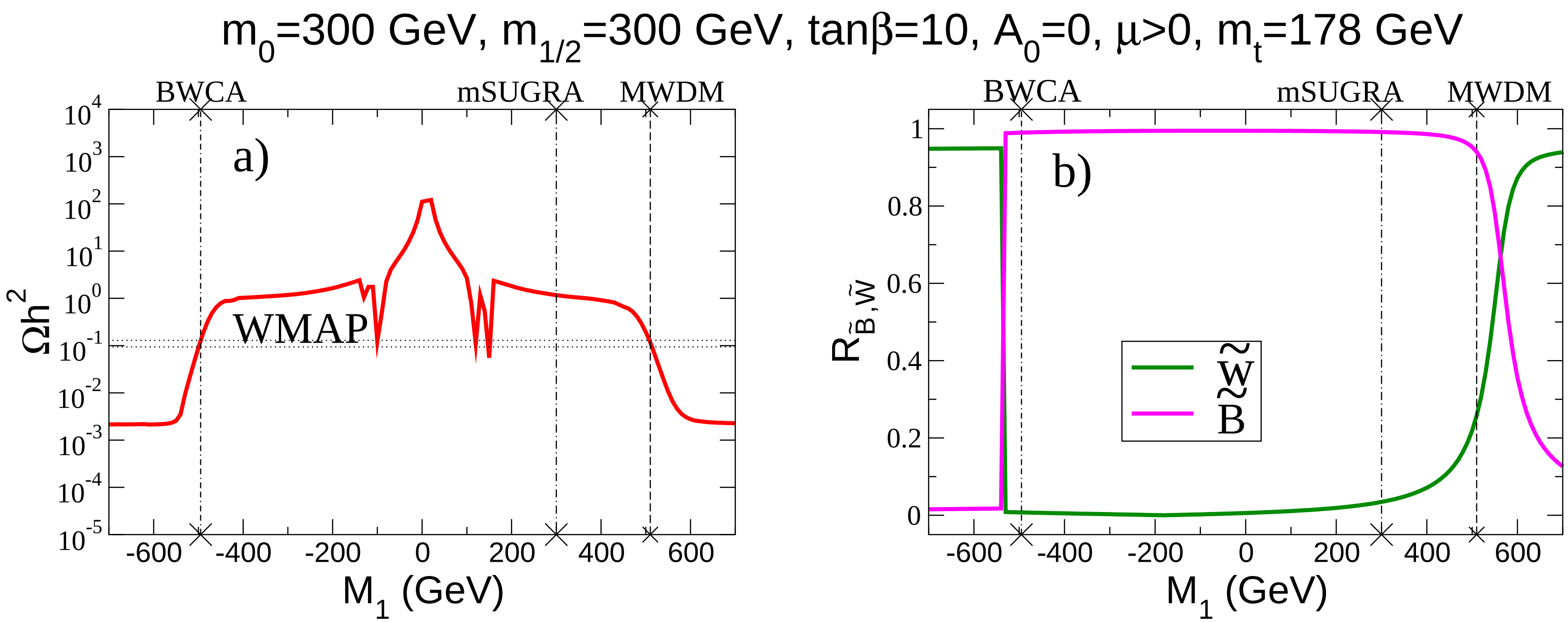
⋆ Here we adopt a phenomenological approach:

- 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.

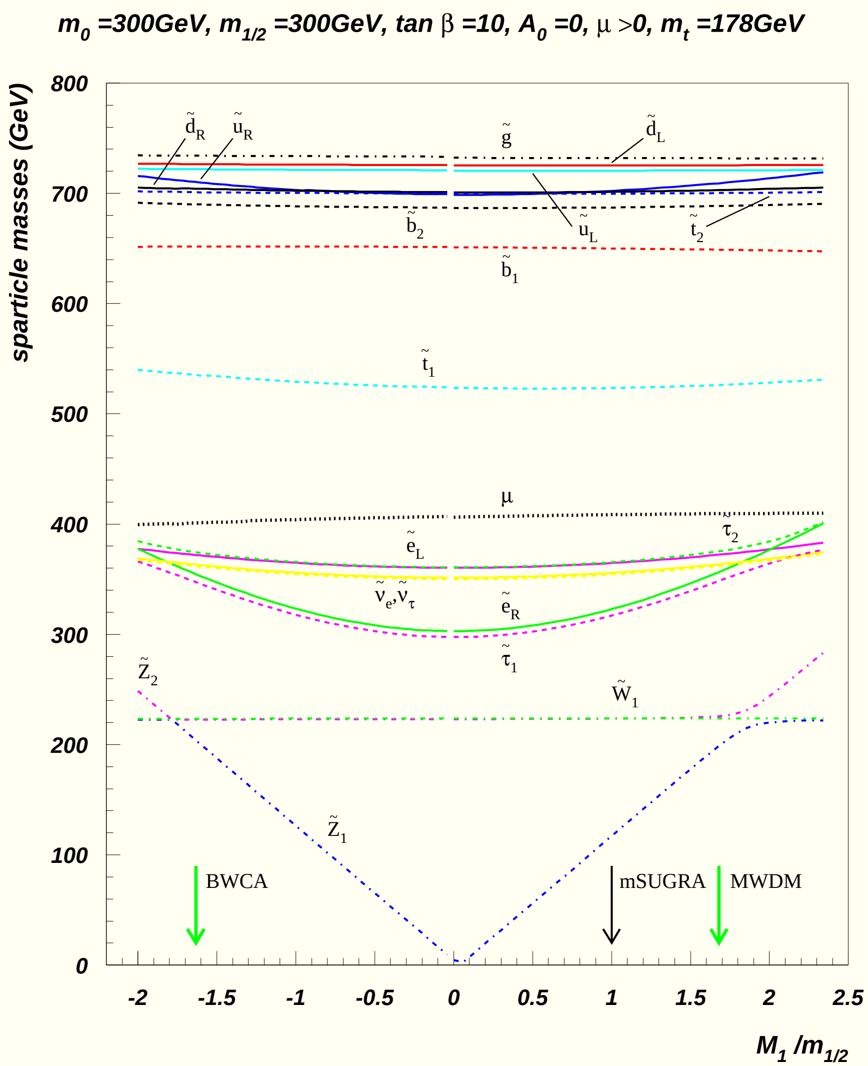
* LM3DM: HB, Mustafayev, Park, Profumo, Tata, JHEP**0604** (2006) 041.

- 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

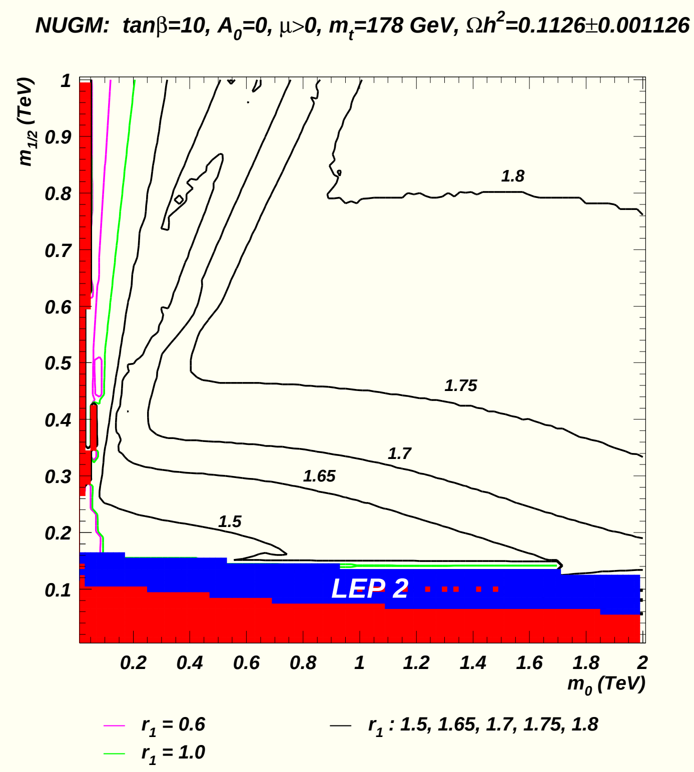


Sparticle mass spectra vs M_1



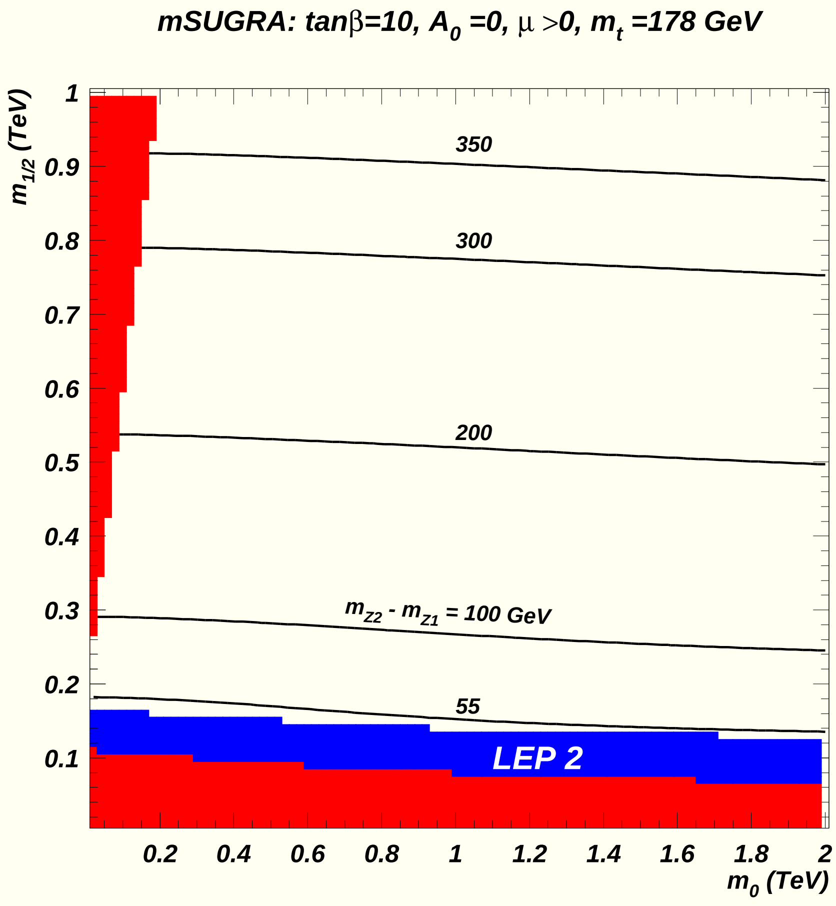
Case 5: MWDM (mixed wino DM)

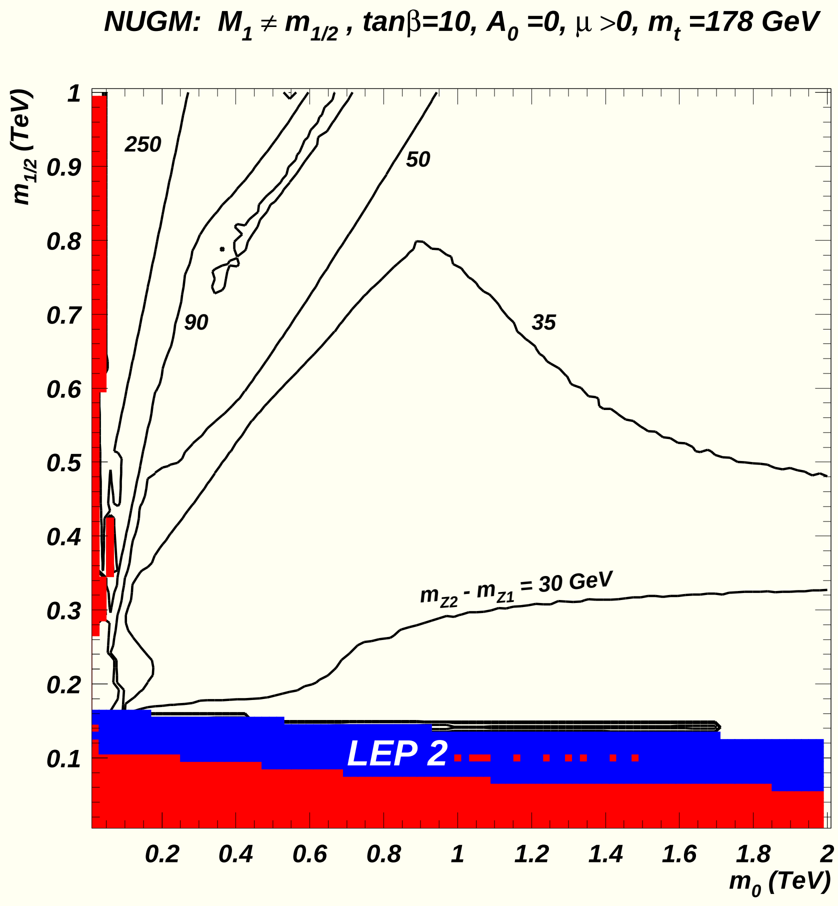
- plot $r_1 \equiv M_1/M_2(M_{GUT})$ s.t. $\Omega_{CDM}h^2 \simeq 0.11$



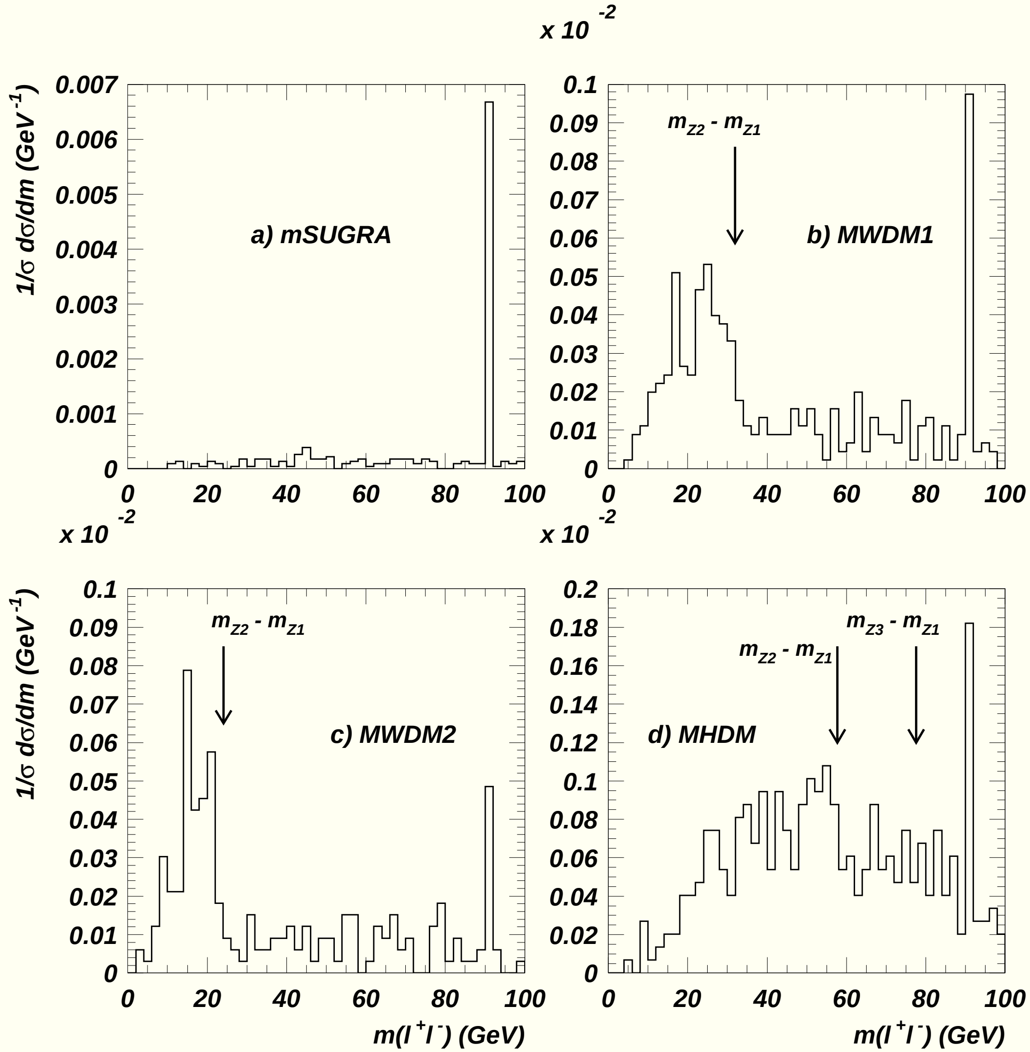
MWDM: small $\widetilde{Z}_2 - \widetilde{Z}_1$ mass gap

- mSUGRA: $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1} \sim m_{\tilde{g}}/7$
- MWDM: $m_{\widetilde{Z}_2} - m_{\widetilde{Z}_1} \sim 20 - 60$ GeV: two body $\widetilde{Z}_2$ decays closed!



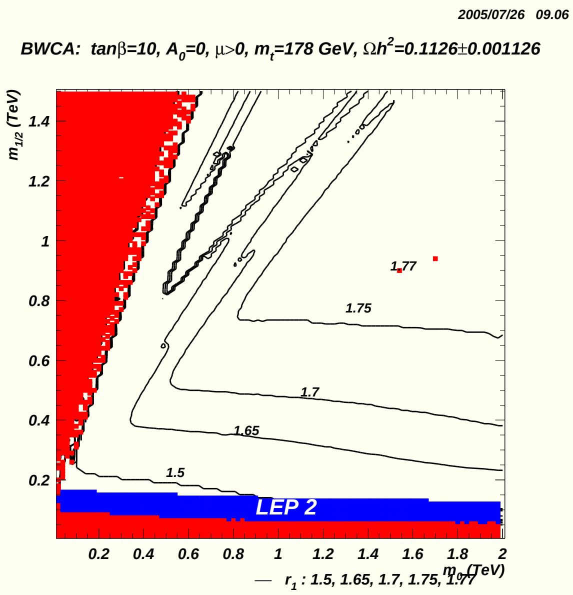


$m(\ell^+\ell^-)$: mass gap observable at LHC for MWDM

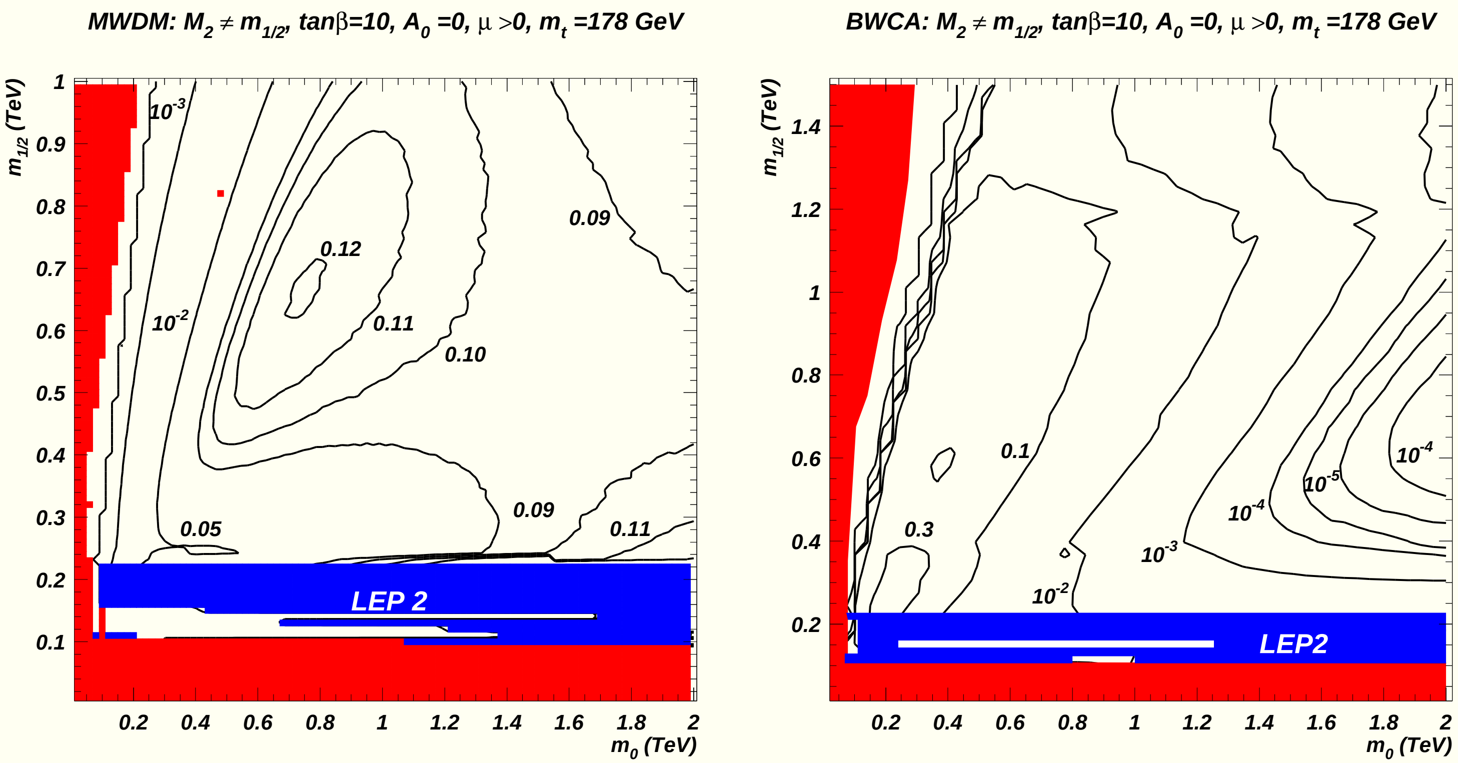


Case 6: Bino-wino co-annihilation (BWCA)

- 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 $r_1 = -M_1/M_2(M_{GUT})$

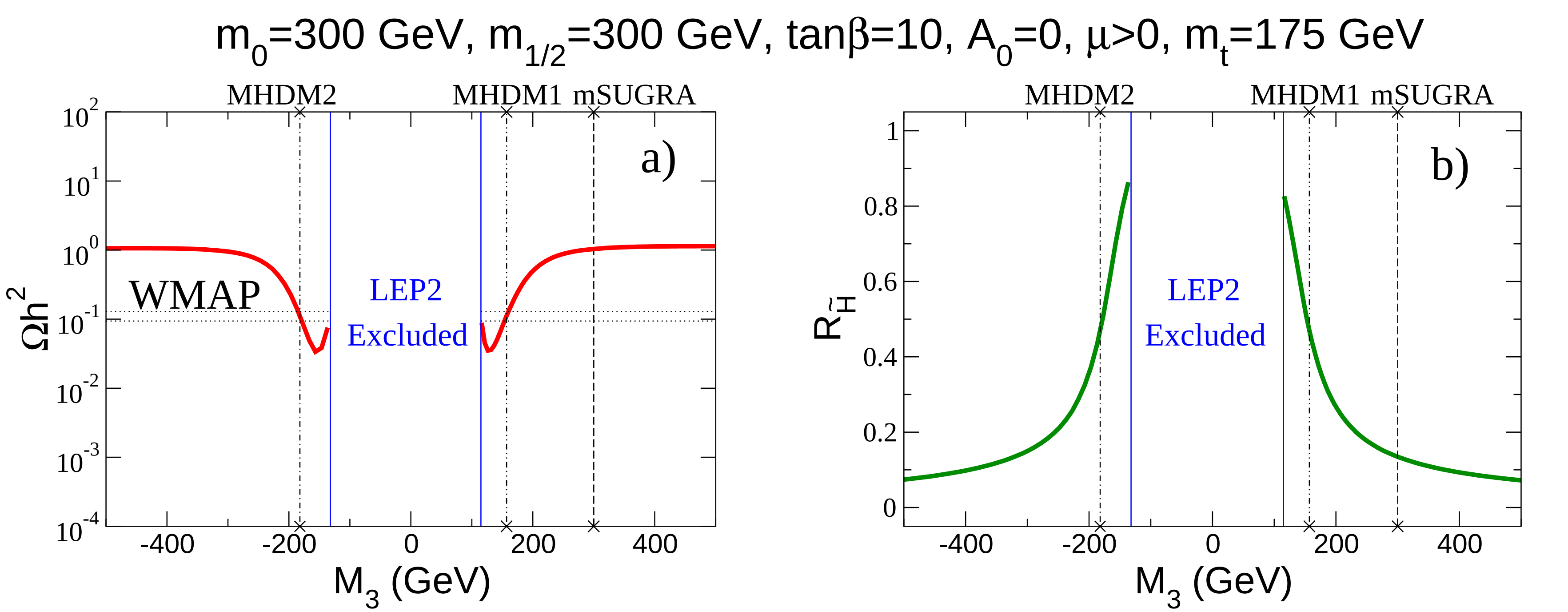


In BWCA at $m_0 \lesssim 500$ GeV, $BF(\widetilde{Z}_2 \to \widetilde{Z}_1\gamma)$ enhanced!



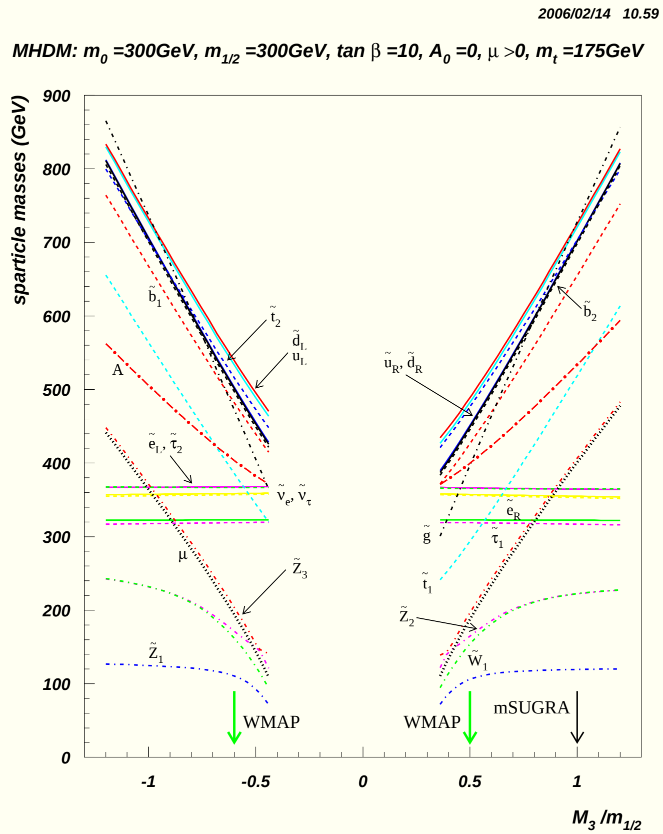
Haber+Wyler; Ambrosanio+Mele; Baer+Krupovnickas: JHEP 0209, 038 (2002)

Case 7: LM3DM (mixed higgsino DM from a low M_3)



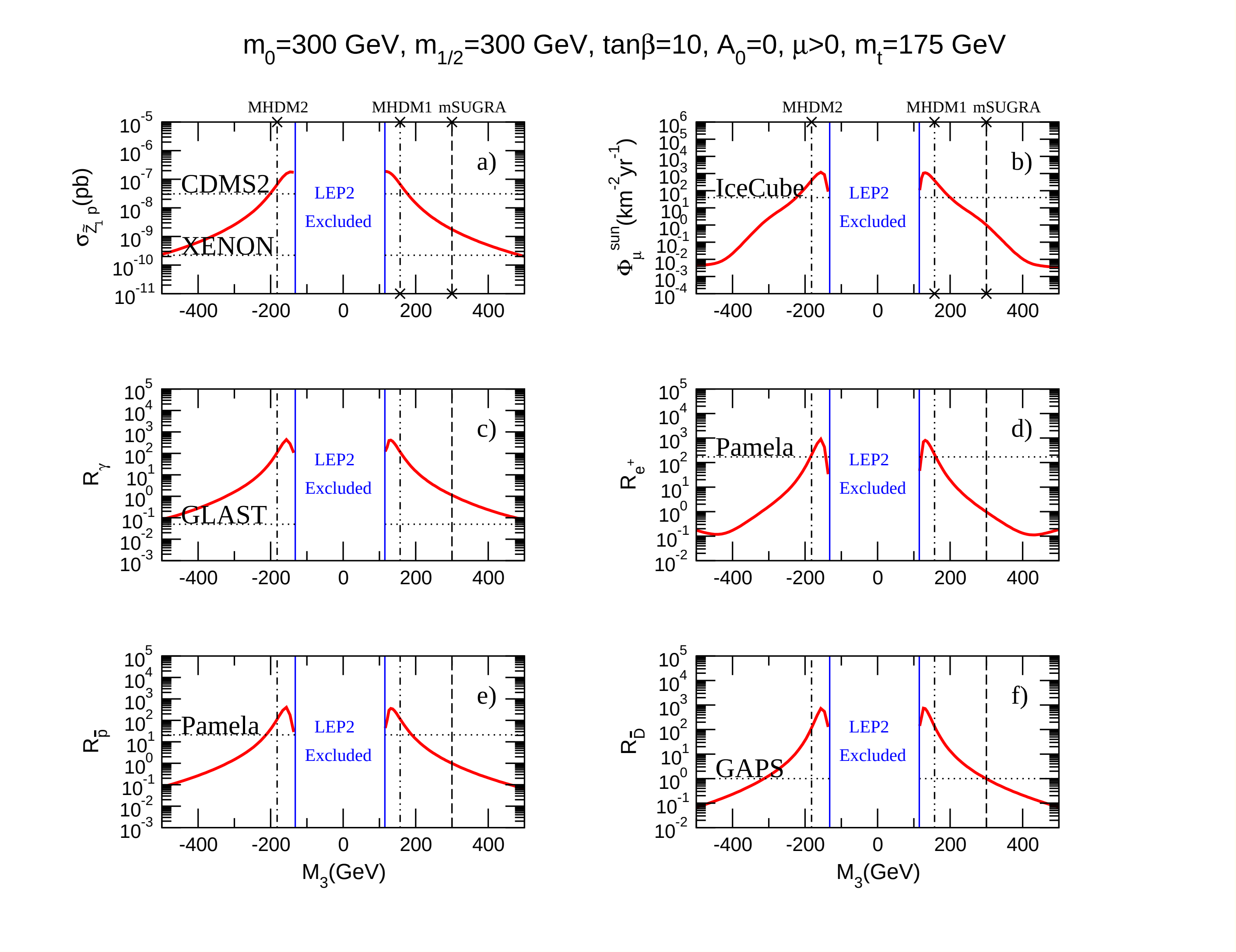
- low $M_3 \Rightarrow$ low $m_{\tilde{g}},\ m_{\tilde{q}},\ \mu$
- called "compressd SUSY" in related scenario by S. P. Martin

Sparticle mass spectra for LM3DM

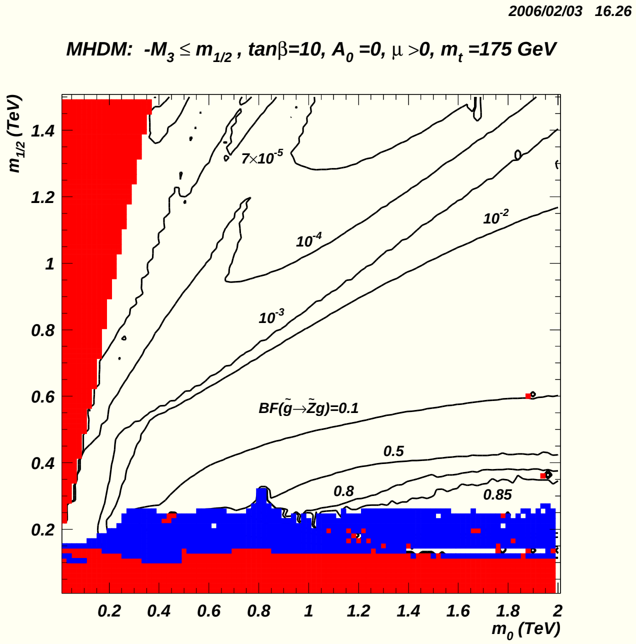


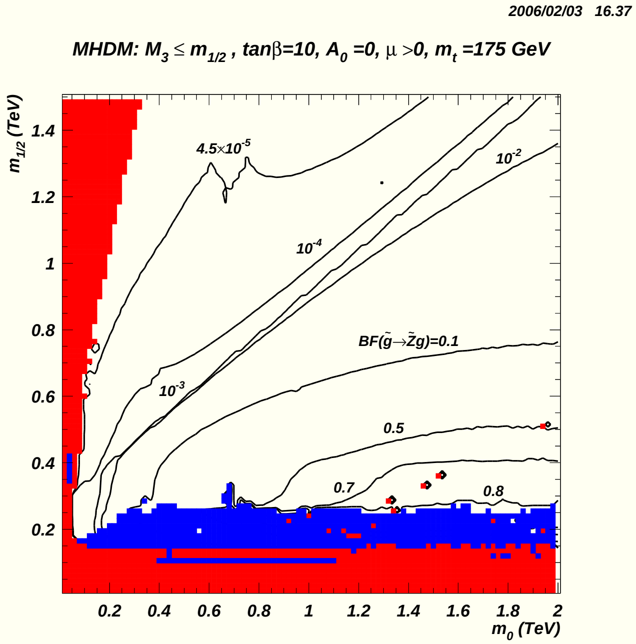
- low $m_{\tilde{g}},\ m_{\tilde{q}},\ \mu \Rightarrow$ huge DM detection rates!

Direct/indrct DM rates greatly enhanced for LM3DM



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

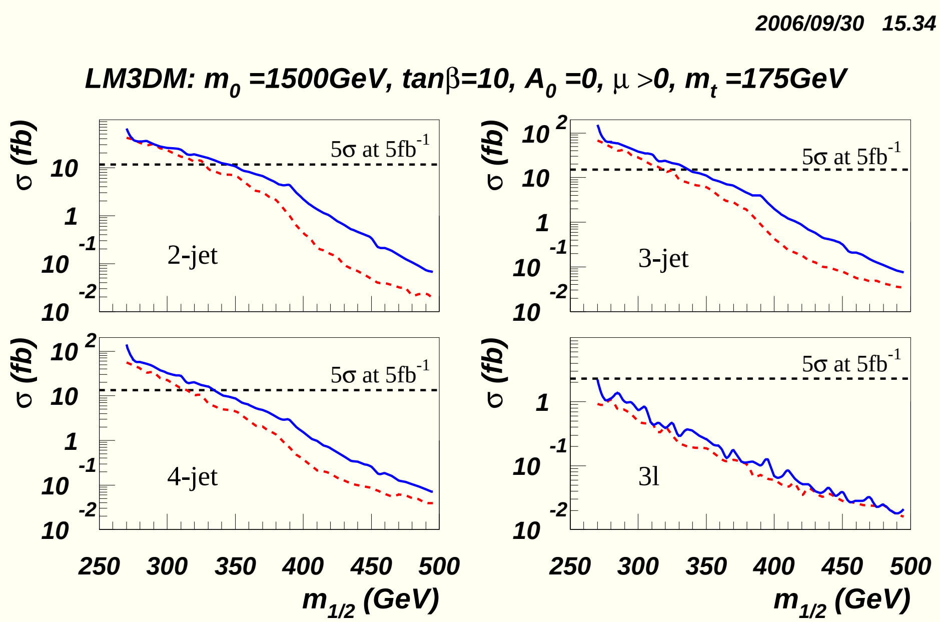




Baer, Tata, Woodside: PRD**42** (1990) 1568.

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

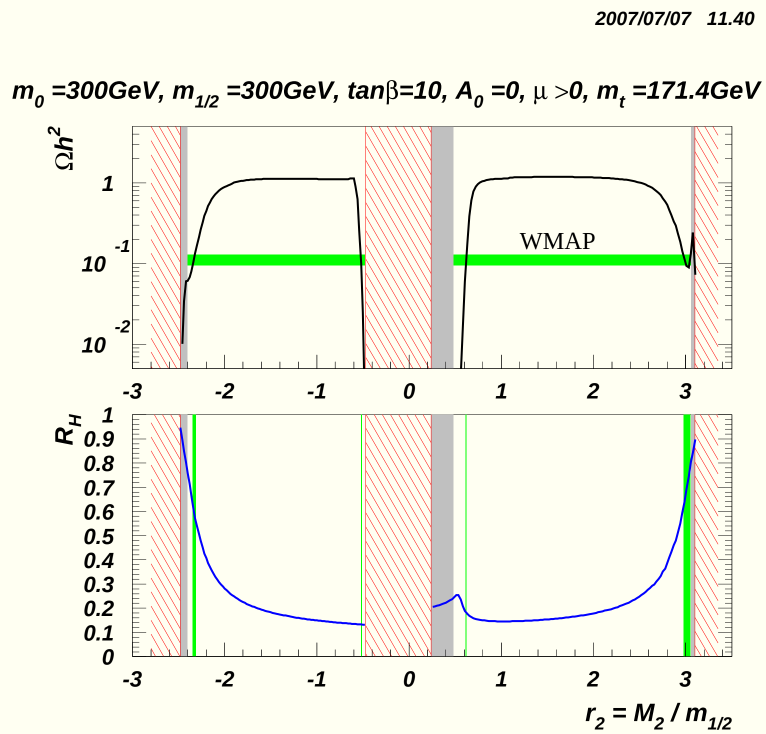
- Can search for $p\bar{p} \to \tilde{g}\tilde{g} \to jets + \not{E}_T$ at Tevatron;
- Search is not pre-empted by LEP2 bouds on $m_{\widetilde{W}_1}$
- Can see $m_{\tilde{g}}$ from $200 - 340$ GeV: HB, Mustafayev, Tata PRD**75**,035004 (2007)



Case 8: Compressed SUSY (Steve Martin)

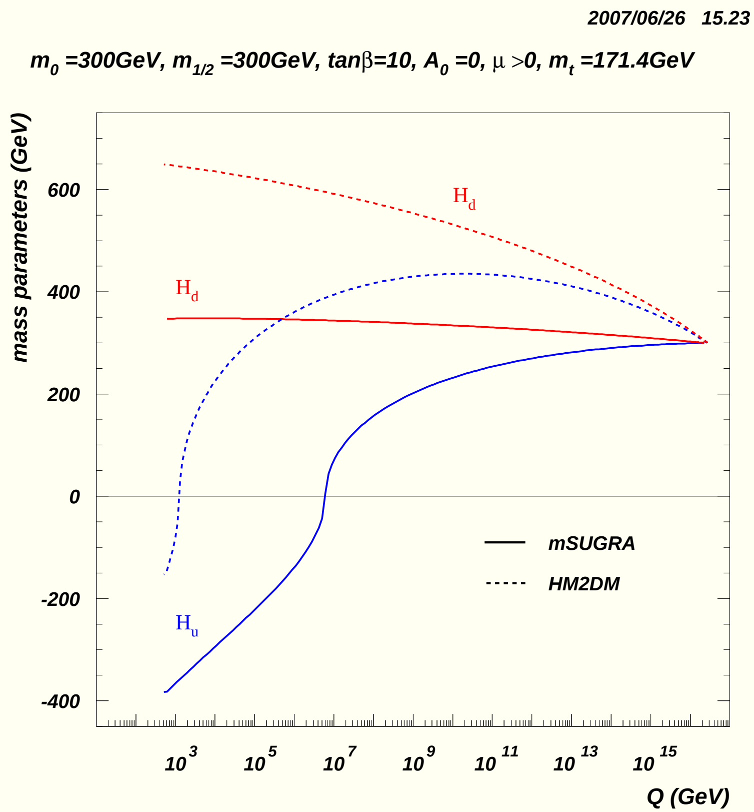
- in models with low M_3 and $A_0 \sim -M_1$, the $\tilde{t}_1$ becomes quite light
- Martin finds that if
  - $m_t < m_{\widetilde{Z}_1} \lesssim m_t + 100$ GeV and
  - $m_{\widetilde{Z}_1} + 25\ \mathrm{GeV} \lesssim m_{\tilde{t}_1} \lesssim m_{\widetilde{Z}_1} + 100$ GeV, then
- $\widetilde{Z}_1\widetilde{Z}_1 \to t\bar{t}$ is dominant dark matter annihilation mechanism in early Universe!
- implications for LHC, DD, IDD: (HB, Box, Park, Tata: arXiv:0707.0618)
  - light $m_{\tilde{g}}$ with $\tilde{t}_1 = NLSP$
  - collider signatures depend on whether $\tilde{t}_1 \to c\widetilde{Z}_1$ or $bW\widetilde{Z}_1$
  - if $\tilde{t}_1 \to c\widetilde{Z}_1$, then large $\not{E}_T + jets$, but very low isolated lepton rates
  - IDD halo annihilation signals enhanced since $\widetilde{Z}_1\widetilde{Z}_1 \to t\bar{t} \to \gamma$s, anti-matter

Case 9: Mixed higgsino DM from high M_2 (HM2DM)



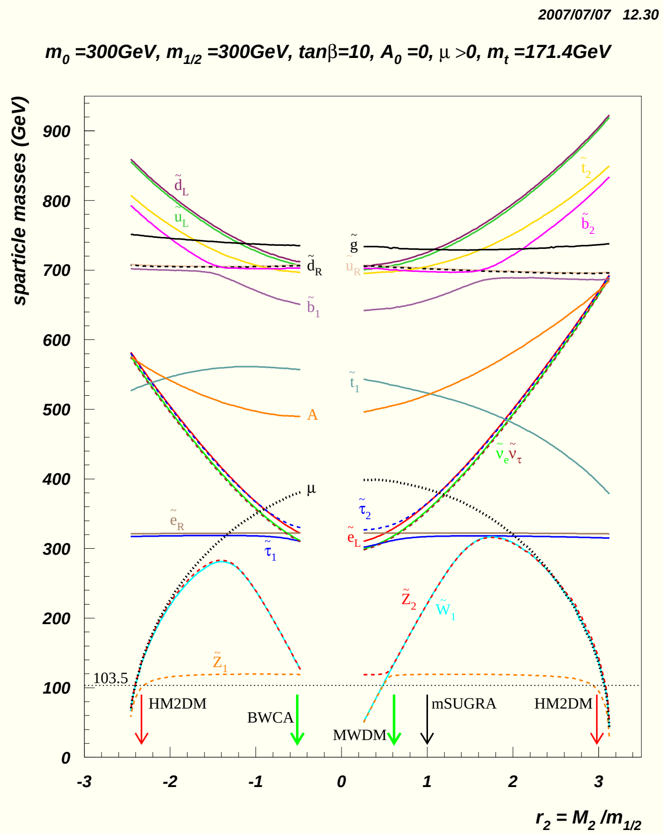
- high $M_2 \Rightarrow$ low $|mu|$ so MHDM but high $m_{\tilde{q}_L}$
- HB, Mustafayev, Summy, Tata

Higgs soft mass evolution with large M_2 (HM2DM)



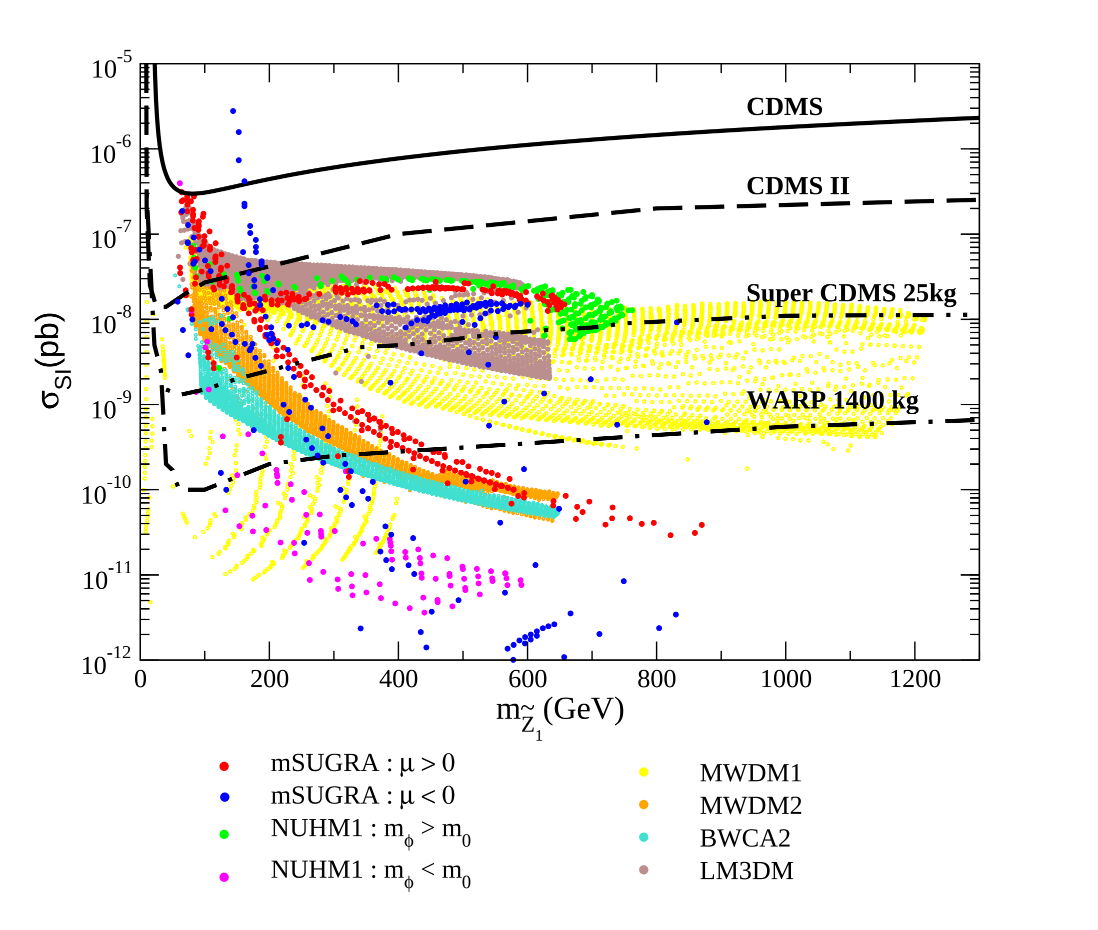
- high M_2 pushes $SU(2)$ scalar masses up: then enhance top-Yukawa push down! $\mu^2 \sim -m_{H_u}^2$ lowered

Sparticle mass spectra for HM2DM



- low $|\mu| \Rightarrow$ MHDM: large DM detection rates!

Direct DM detection: well-tempered $\widetilde{Z}_1$ models



- well-tempered $\widetilde{Z}_1$ models asymptote at $\sigma(\widetilde{Z}_1 p) \sim 10^{-8}$ pb!

Case 10: Mixed modulus-AMSB (mirage unification)

⋆ 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

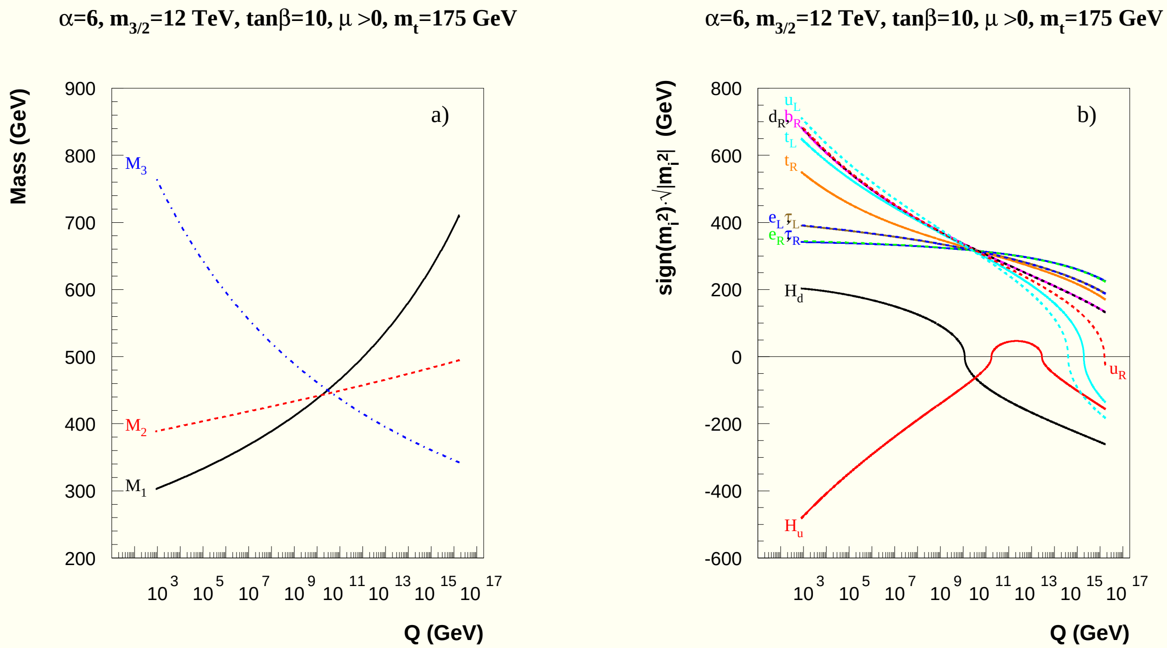
The soft terms renormalized at $Q \sim M_{\rm GUT}$ are given by,

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

with

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

Can measure modular weights in MM-AMSB model

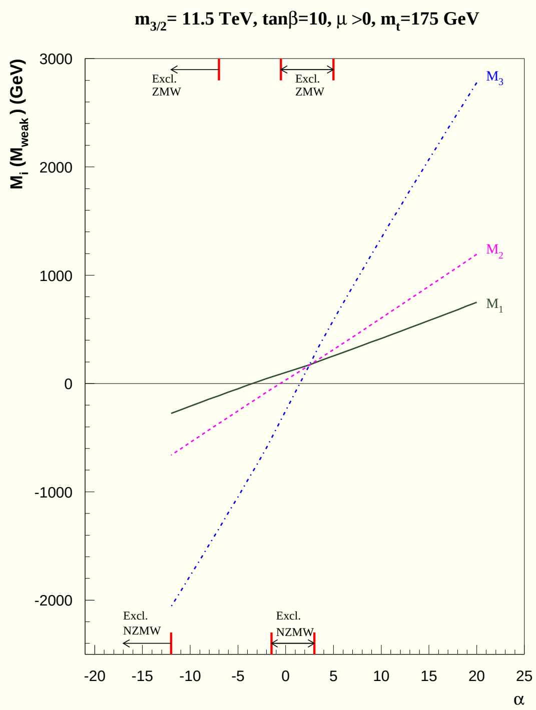


At $Q = \mu_{mir.}$, ratio of scalar to gaugino masses is given by

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

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

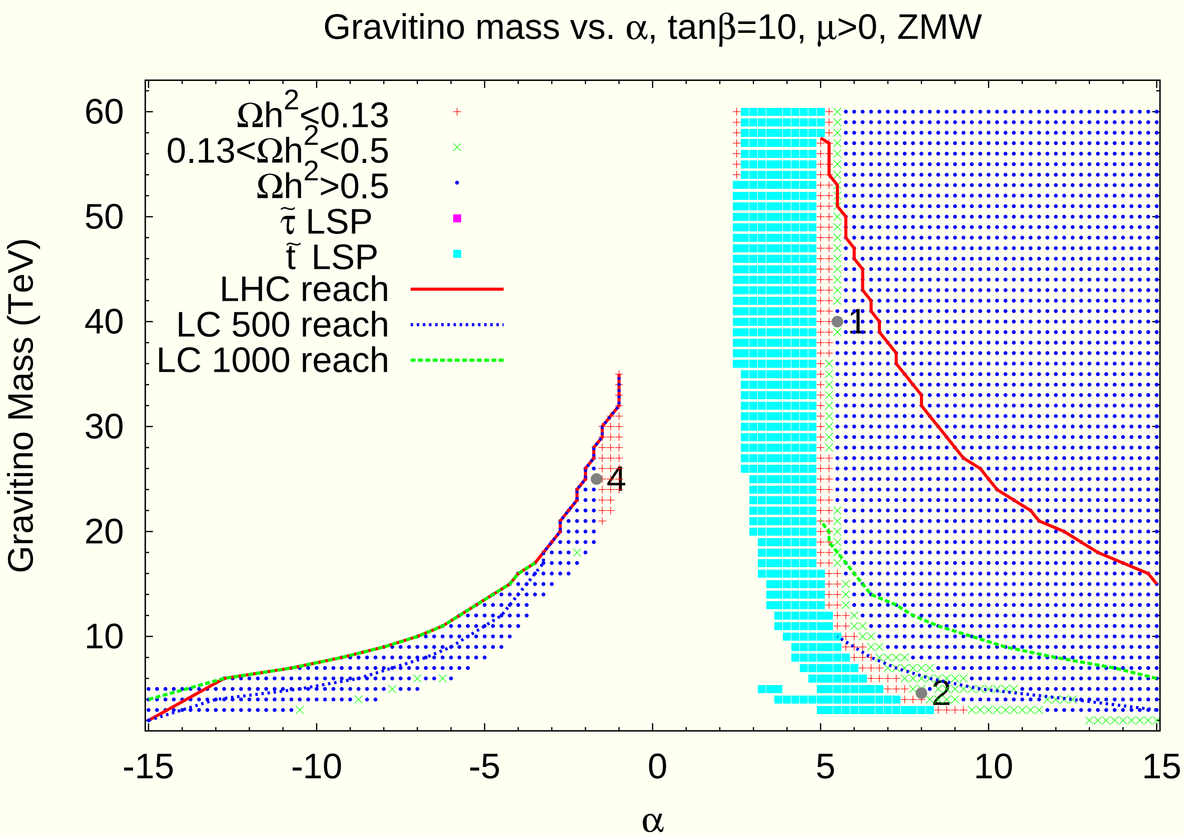
Gaugino masses at weak scale in MM-AMSB:



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 $n_m = n_H = 0$:

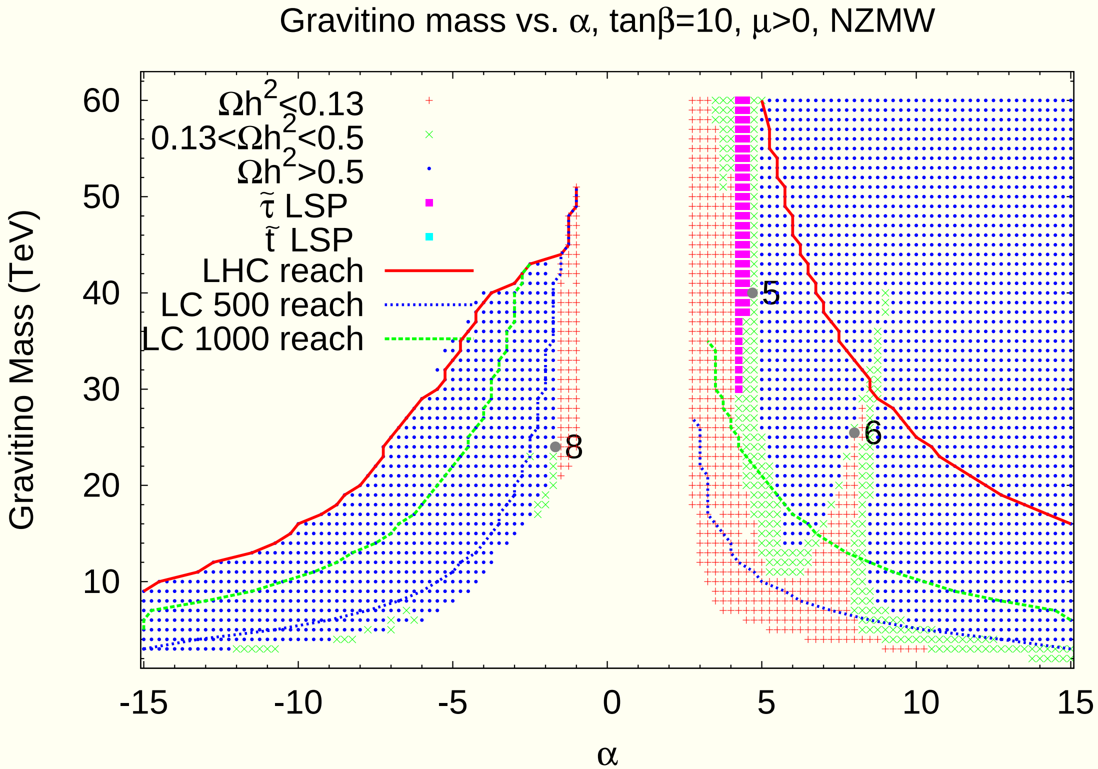


Stop coannihilation region.

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
- NMH
- NUHM1, NUHM2
- MWDM
- BWCA DM
- LM3DM, compressed SUSY
- HM2DM
- well-tempered neutralino models: $\sigma(\widetilde{Z}_1 p) \sim 10^{-8}$ pb!
- mixed moduli-AMSB (KKLT, mirage unification)

⋆ data coming soon from LHC will be final arbiter!