# Prospects for SUSY at the LHC in light of Dark Matter

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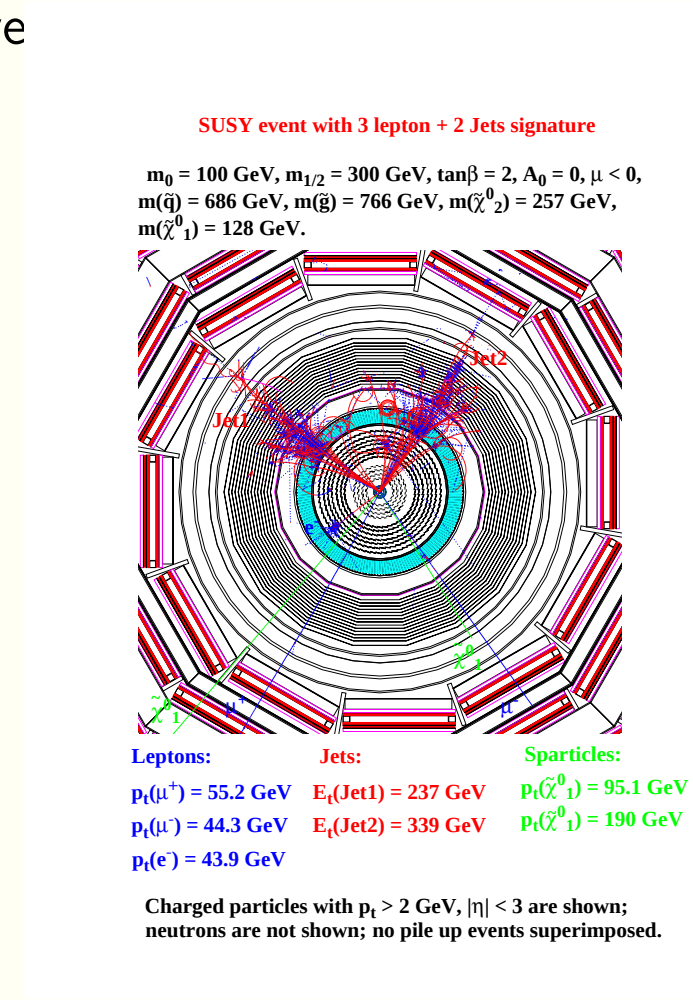
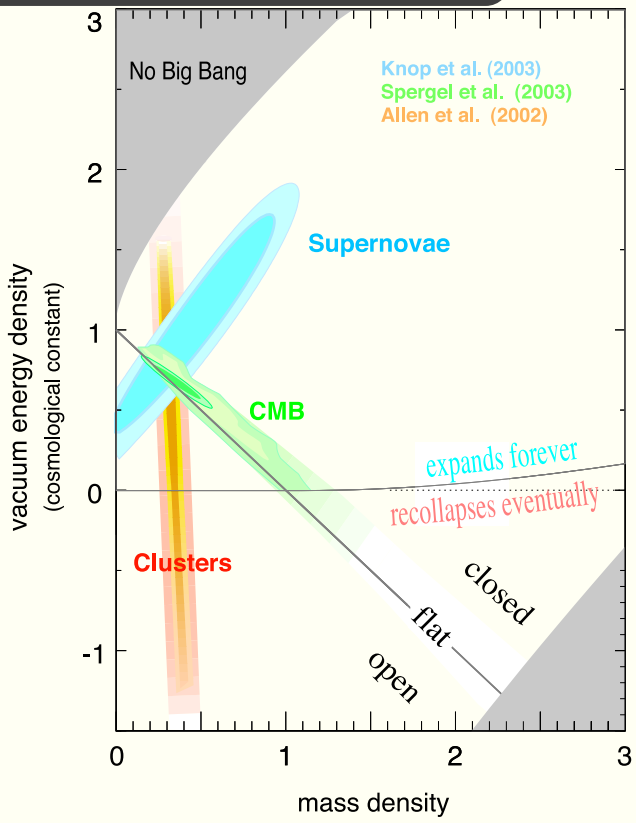
- ⋆ Supersymmetric models
  - WMAP allowed regions
- ⋆ SUSY at LHC in mSUGRA
- ⋆ Models with non-universal soft terms
  - scalar mass non-universality
  - gaugino mass non-universality



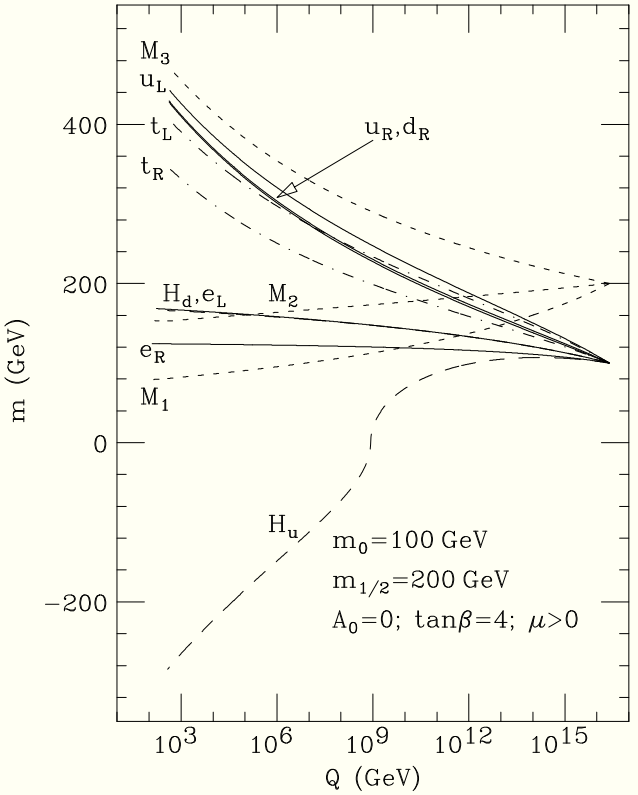
# Many SUSY models, each with large p-space

- ★ SUSY models typified by large p-space
- ★ vast number of possible signatures at colliders
- ★ WMAP result greatly reduces the possibilities!
- ★ We will adopt the WMAP1 result
  - $\Omega_{CDM}h^2 = 0.113 \pm 0.009$
  - as a guide to prospects for SUSY discovery
  - at the LHC and ILC



# Sparticle mass spectra

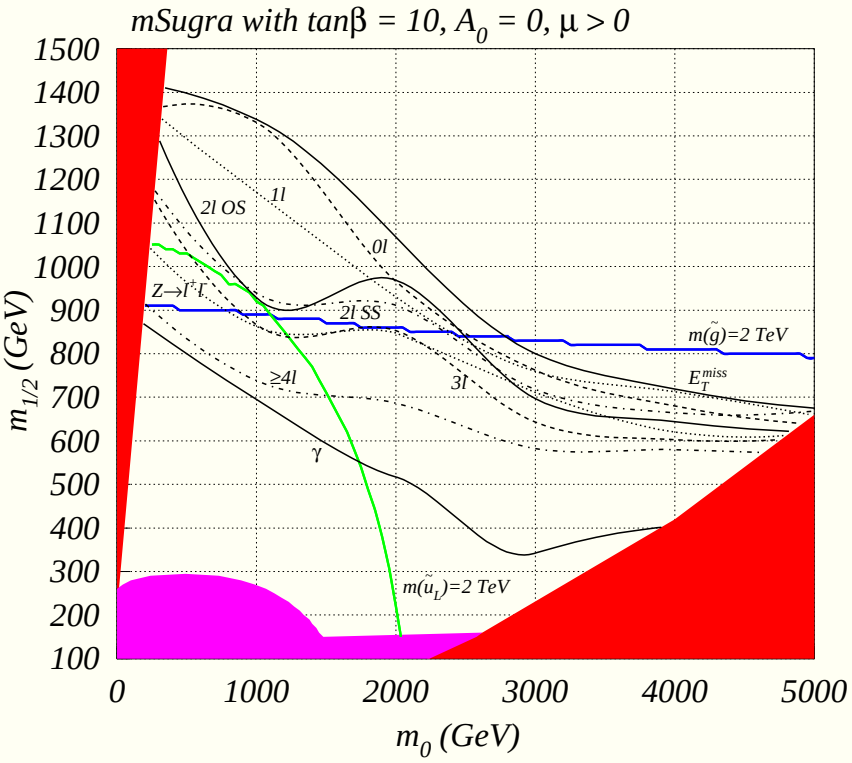
- ⋆ Mass spectra codes
- ⋆ RGE running: $M_{GUT} \rightarrow M_{weak}$
  - Isajet (HB, Paige, Protopopescu, Tata)
    - $\geq$7.72: Isatools
  - SuSpect (Djouadi, Kneur, Moultaka)
  - SoftSUSY (Allanach)
  - Spheno (Porod)
- ⋆ Comparison (Belanger, Kraml, Pukhov)
- ⋆ Website: `http://kraml.home.cern.ch/kraml/comparison/`

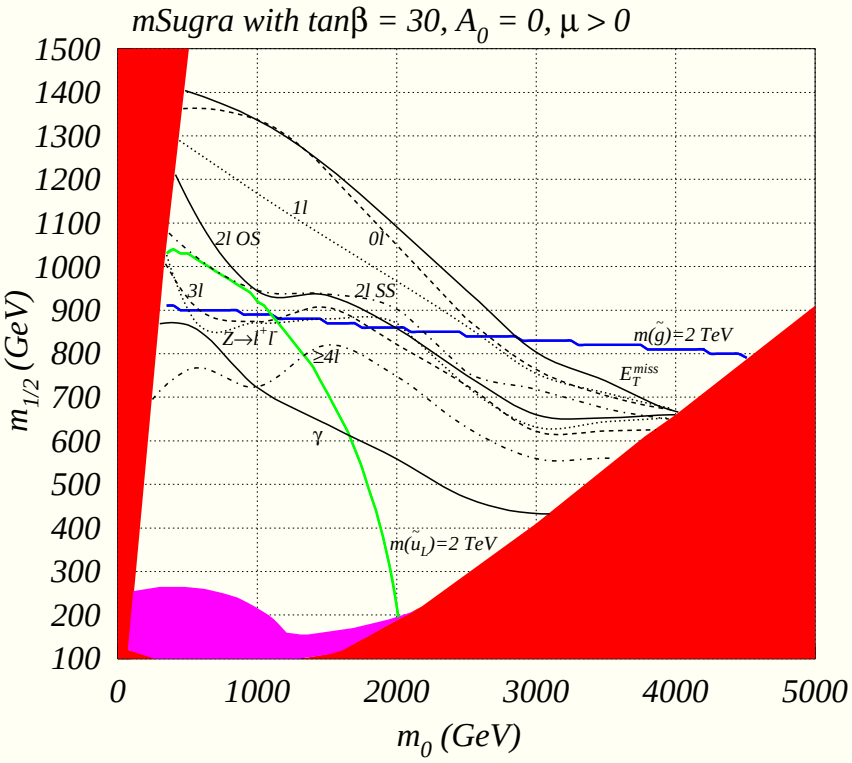


# Search for SUSY at CERN LHC in mSUGRA model

- ★ $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ production dominant for $m \lesssim 1$ TeV
- ★ lengthy cascade decays are likely
  - $\not{E}_T$+ jets
  - $1\ell$+ $\not{E}_T$+ jets
  - $OS$ $2\ell$+ $\not{E}_T$+ jets
  - $SS2\ell$+ $\not{E}_T$+ jets
  - $3\ell$+ $\not{E}_T$+ jets
  - $4\ell$+ $\not{E}_T$+ jets
- ★ BG: $W + jets$, $Z + jets$, $t\bar{t}$, $b\bar{b}$, $WW$, $4t$, $\cdots$
- ★ Grid of cuts gives optimized S/B

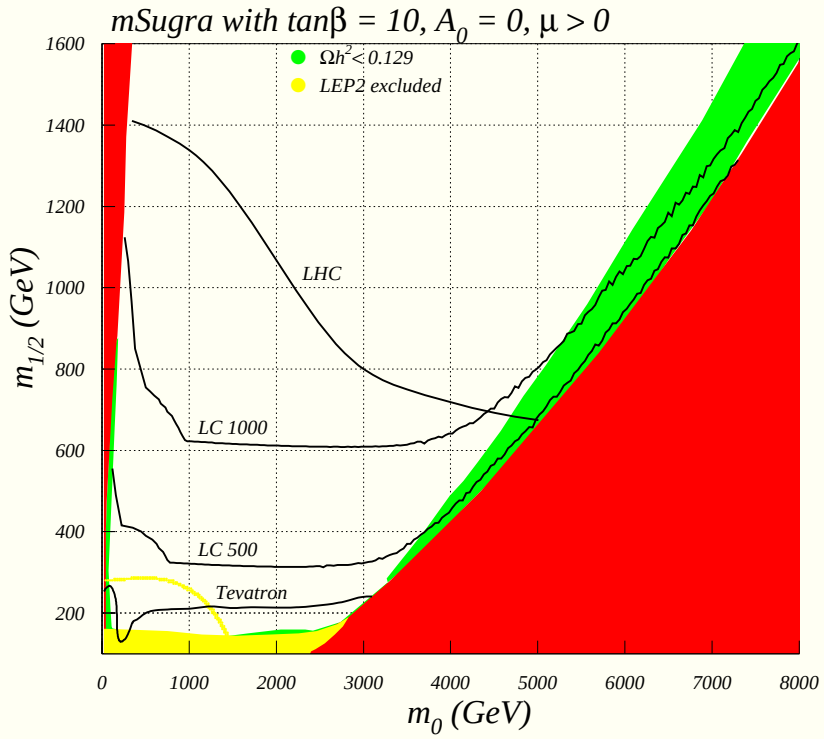
# Sparticle reach of LHC for $100^{-1}$ fb

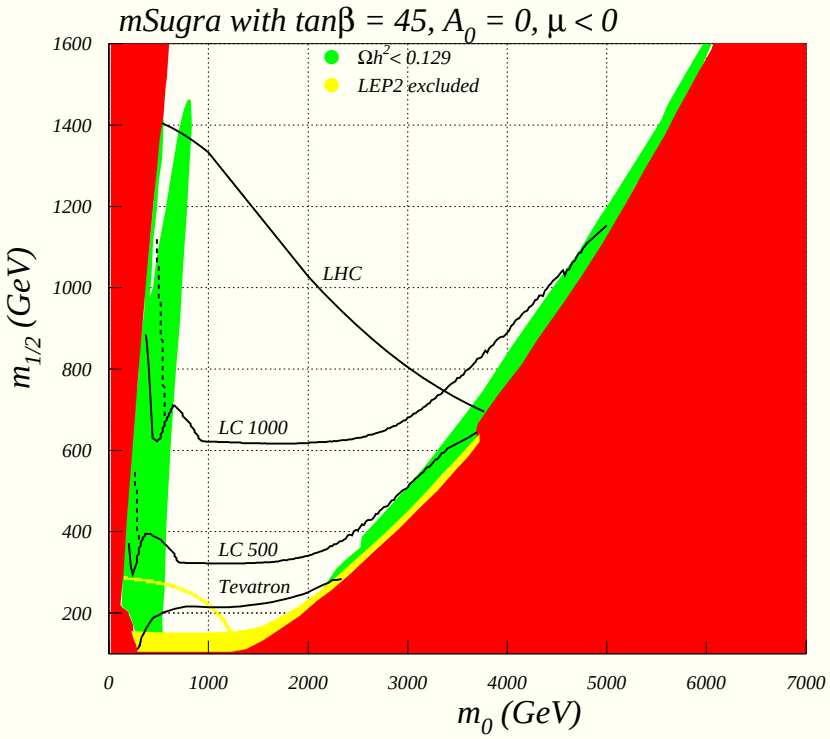



HB, Balazs, Belyaev, Krupovnickas, Tata: JHEP 0306, 054 (2003)

# Sparticle reach of all colliders and relic density




HB, Belyaev, Krupovnickas, Tata: JHEP 0402, 007 (2004)

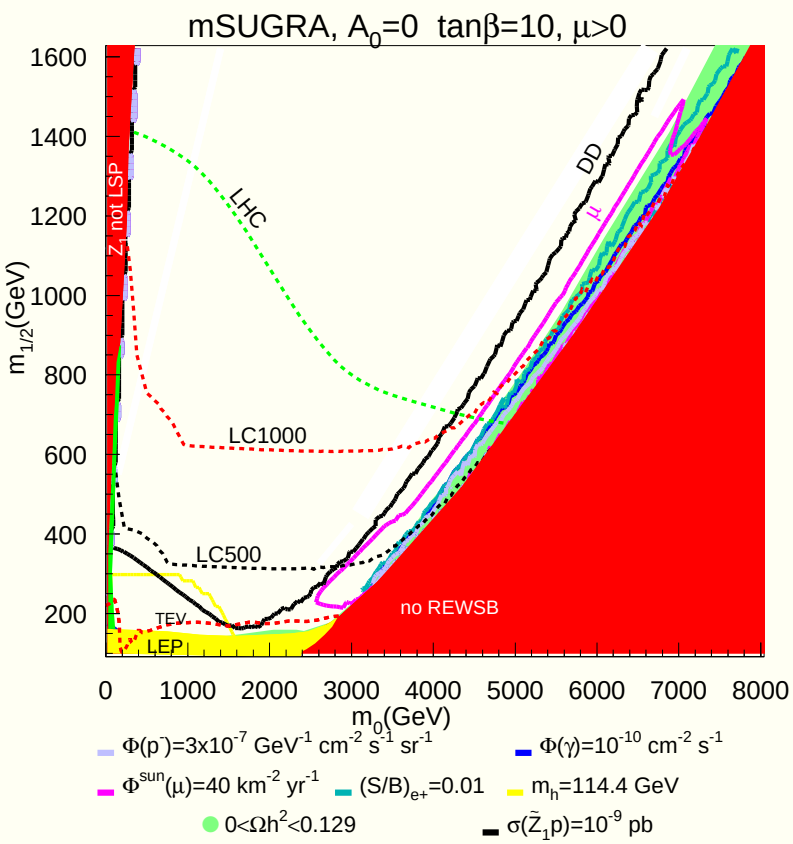
## Main mSUGRA regions consistent with WMAP

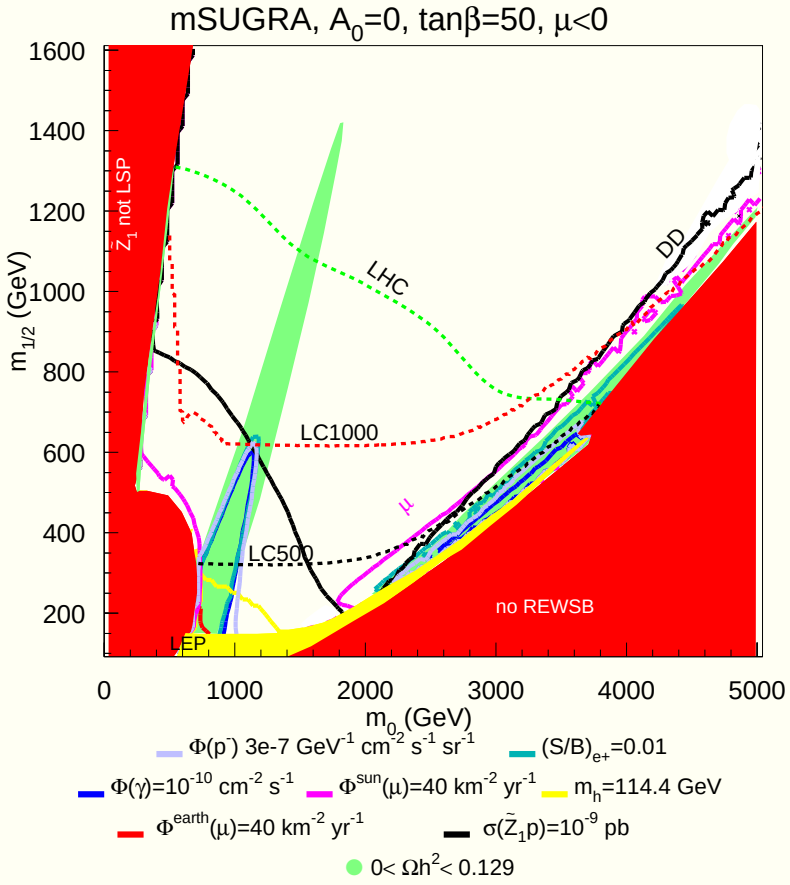
- ⋆ bulk region (low $m_0$, low $m_{1/2}$)
  - nearly excluded
- ⋆ stau co-annihilation region ($m_{\tilde{\tau}_1} \simeq m_{\widetilde{Z}_1}$)
  - $m_{\tilde{q}} \lesssim m_{\tilde{g}}$; $\widetilde{Z}_2 \to \ell\tilde{\ell},\ \tau\tilde{\tau}_1$
- ⋆ HB/FP region (large $m_0$ where $|\mu| \to small$)
  - only $\tilde{g}$, $\widetilde{Z}_i$, $\widetilde{W}_j$ accessible
- ⋆ $A$-funnel ($2m_{\widetilde{Z}_1} \simeq m_A,\ m_H$)
  - $H,\ A,\ H^{\pm}$ accessible directly or via CDs
- ⋆ $h$ corridor ($2m_{\widetilde{Z}_1} \simeq m_h$)
- ⋆ stop co-annihilation region (particular $A_0$ values $m_{\tilde{t}_1} \simeq m_{\widetilde{Z}_1}$)

# Direct and indirect detection of SUSY DM

- ⋆ Direct search via neutralino-nucleon scattering
- ⋆ Indirect search for SUSY DM: (HB, J. O'Farrill)
  - $\tilde{Z}_1\tilde{Z}_1 \to b\bar{b}, etc.$ in core of sun (or earth): $\Rightarrow \nu_\mu \to \mu$ in $\nu$ telescopes
    - ∗ Amanda, Icecube, Antares
  - $\tilde{Z}_1\tilde{Z}_1 \to q\bar{q}, etc. \to \gamma$ 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
    - ∗ $\bar{D}$ recently detected (BESS)
    - ∗ future: Gaseous Antiparticle Spectrometer (GAPS)-
      - · slow $\bar{D}$; look for x-rays after capture on atoms
      - · HB and Profumo, JCAP 0512, 008 (2005)

# Direct and indirect detection of neutralino DM

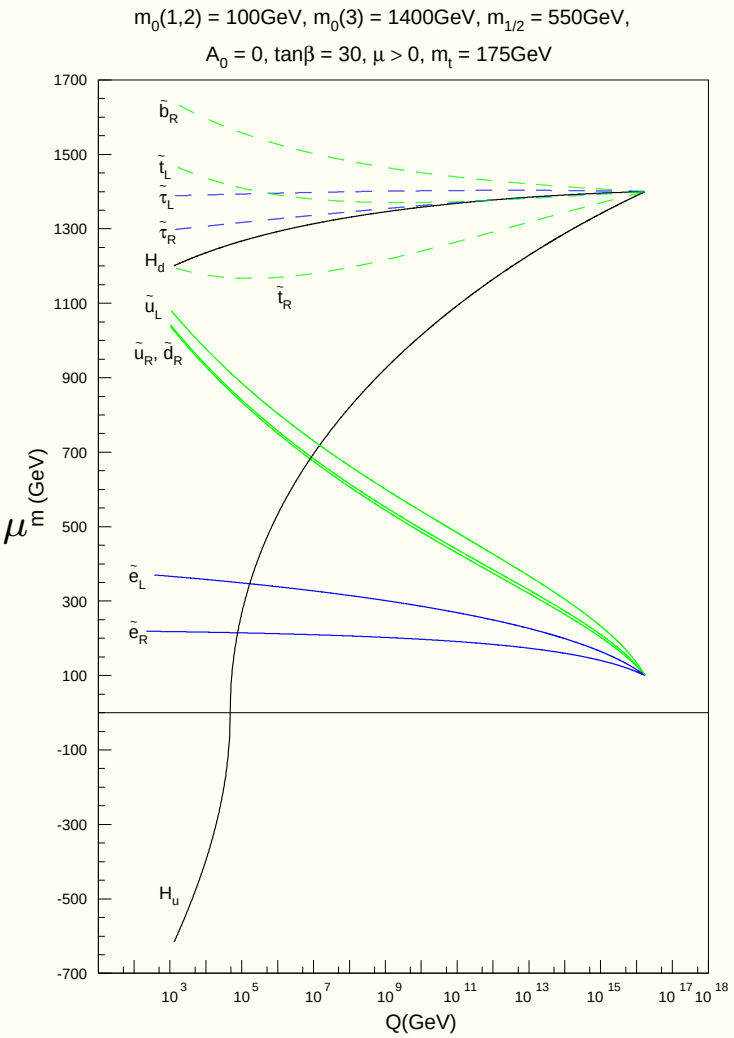



HB, Belyaev, Krupovnickas, O'Farrill: JCAP 0408, 005 (2004)

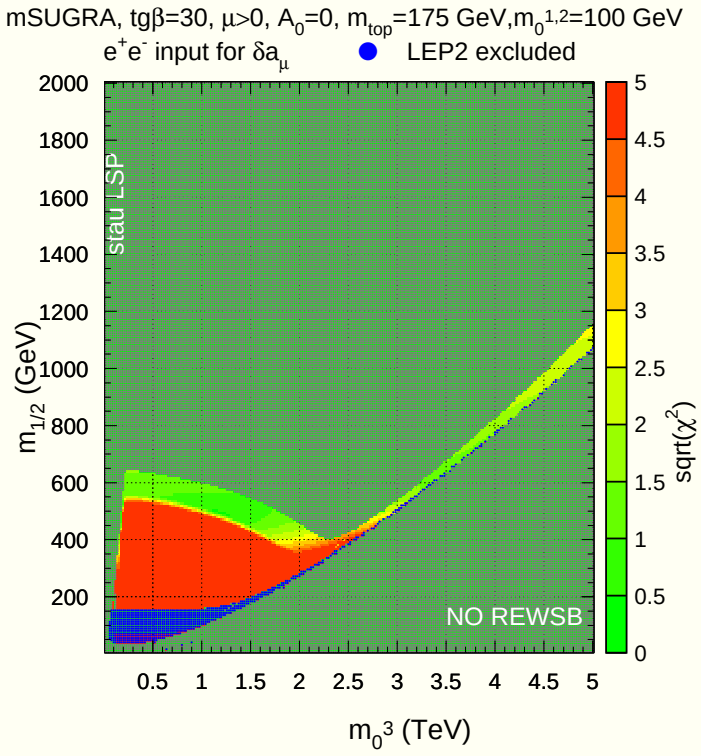
# SUGRA models with non-universal scalars

- 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)



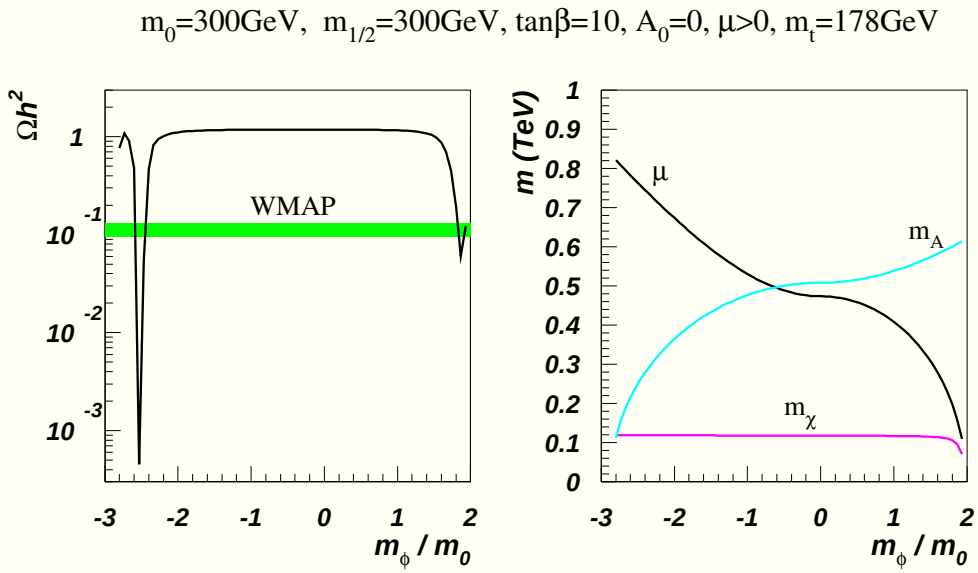
# Normal scalar mass hierarchy: parameter space

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



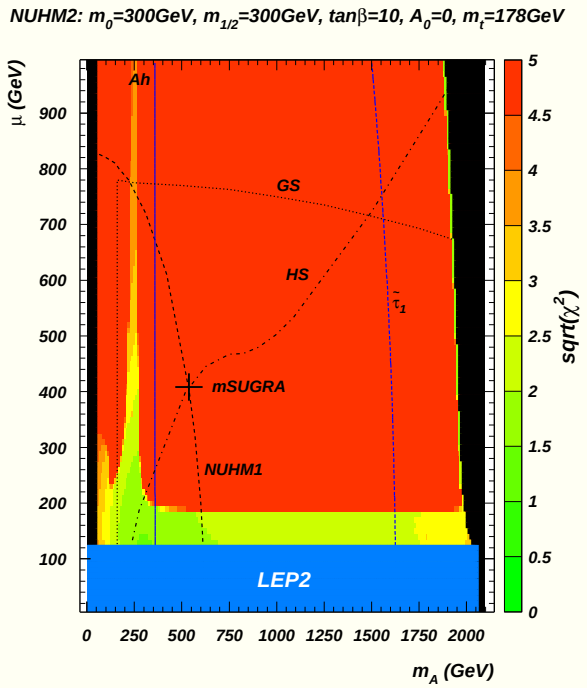
# SUGRA models with non-universal Higgs mass (NUHM1)

- $m_{H_u}^2 = m_{H_d}^2 \equiv m_\phi^2 \neq m_0$: 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, $m_{\tilde{e}_L} < m_{\tilde{e}_R}$

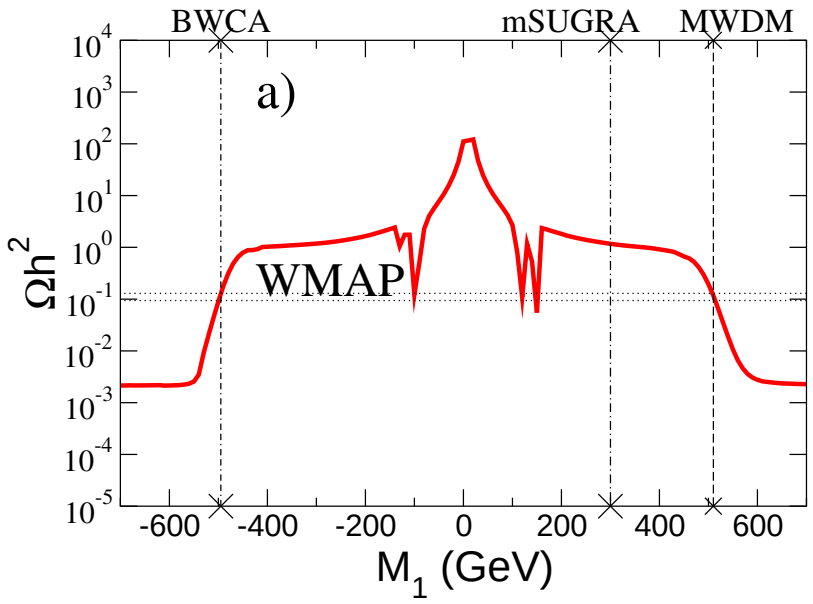


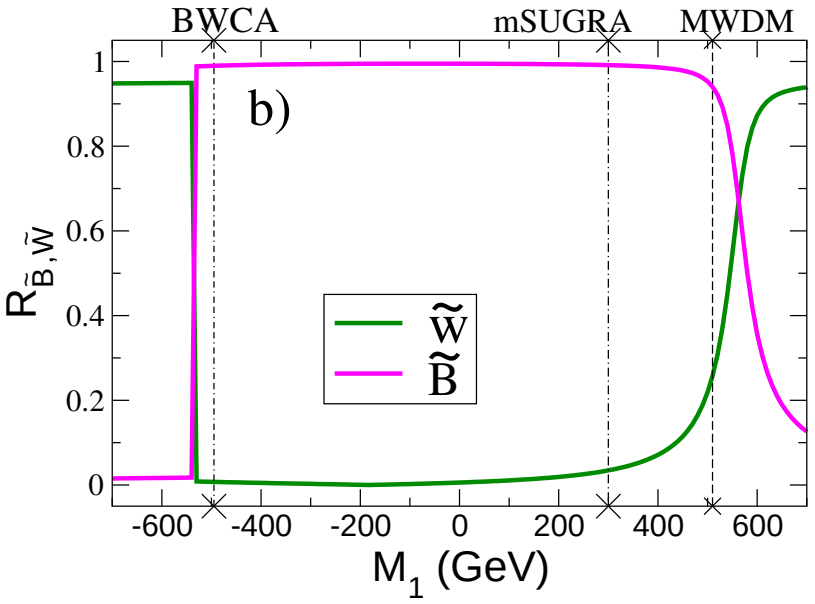
## Non-universal gaugino masses

- ⋆ SUGRA models where GKF transforms non-trivially (Snowmass '96)
- ⋆ Heterotic superstring models with orbifold compactification: SUSY breaking dominated by the moduli field
- ⋆ Mixed modulus-AMSB (KKLT construction)
- ⋆ 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
  - Low $M_3$ DM: HB, Mustafayev, Park, Profumo, Tata

# $\Omega_{\tilde{Z}_1} h^2$ vs. $M_1$: MWDM or BWCA

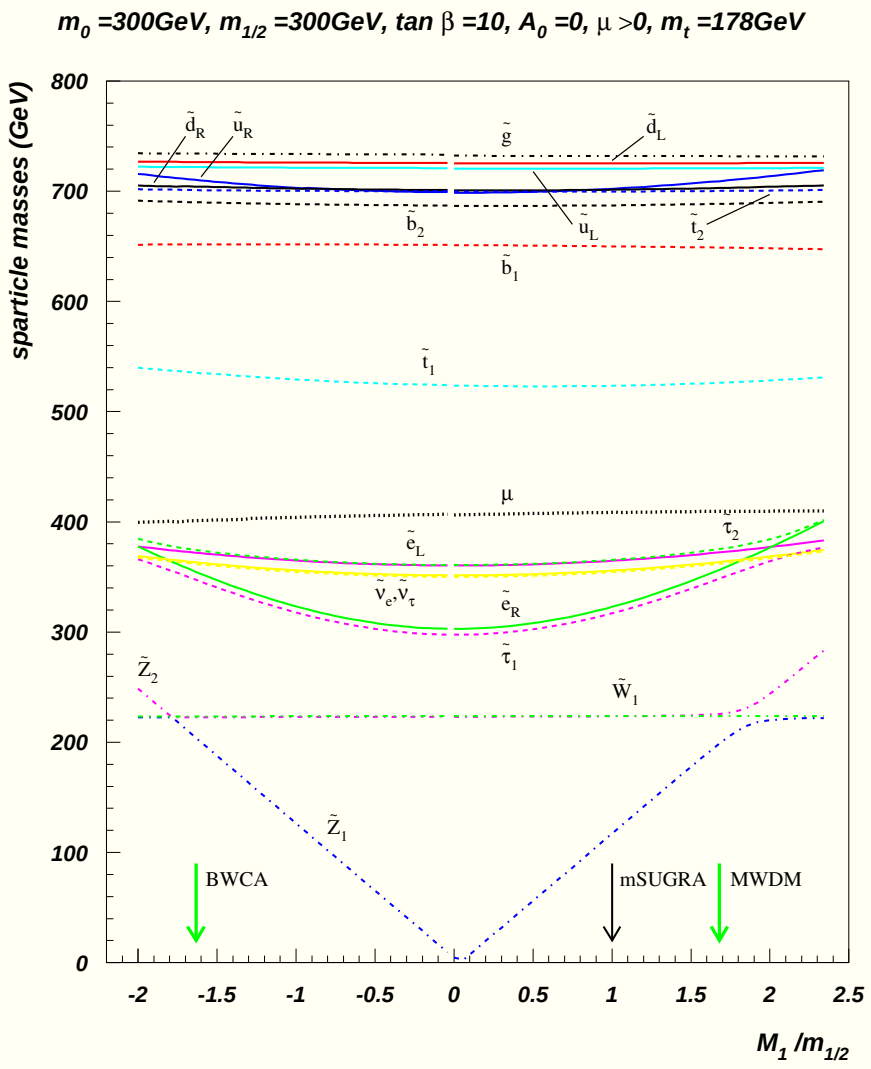
$m_0$=300 GeV, $m_{1/2}$=300 GeV, tanβ=10, $A_0$=0, μ>0, $m_t$=178 GeV



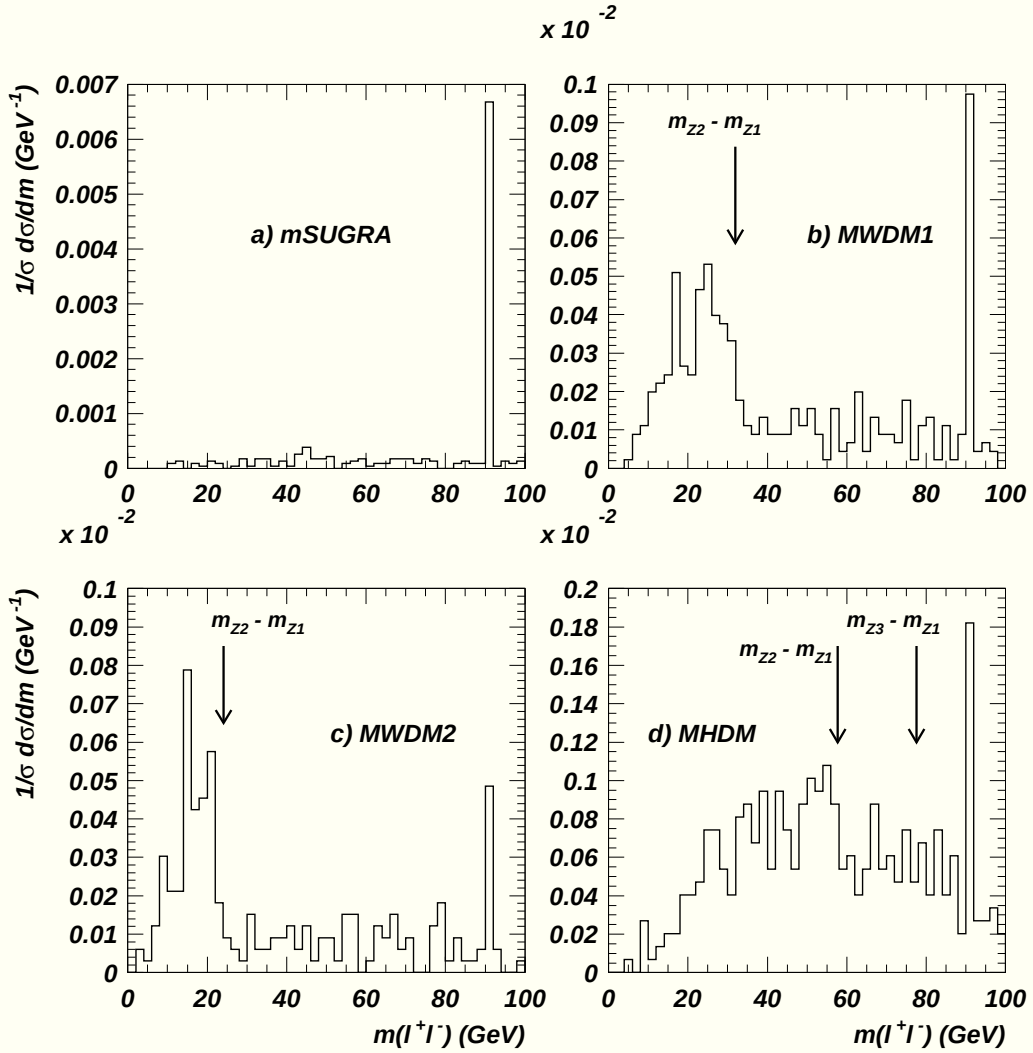




see also: talk by Eun-Kyung Park

# Sparticle mass spectra vs $M_1$

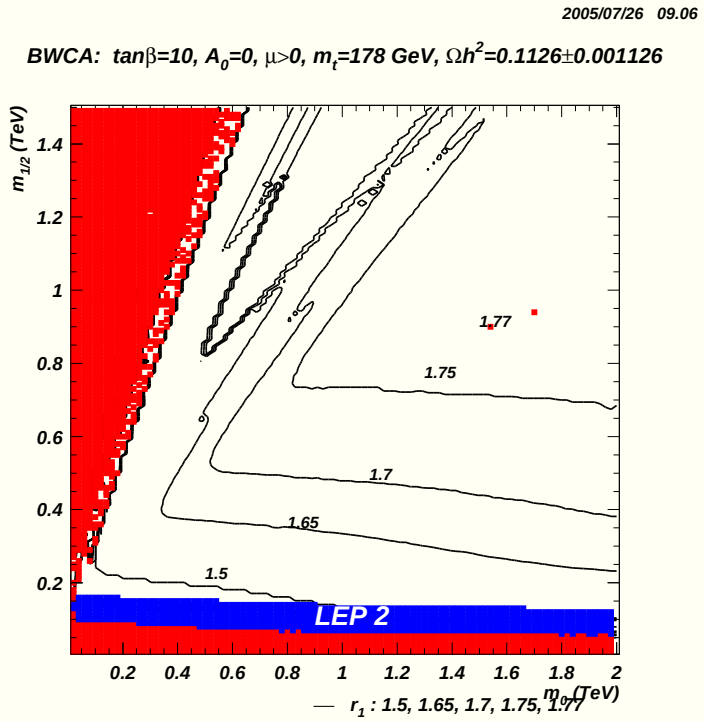


# $m(\ell^+\ell^-)$: mass gap observable at LHC for MWDM

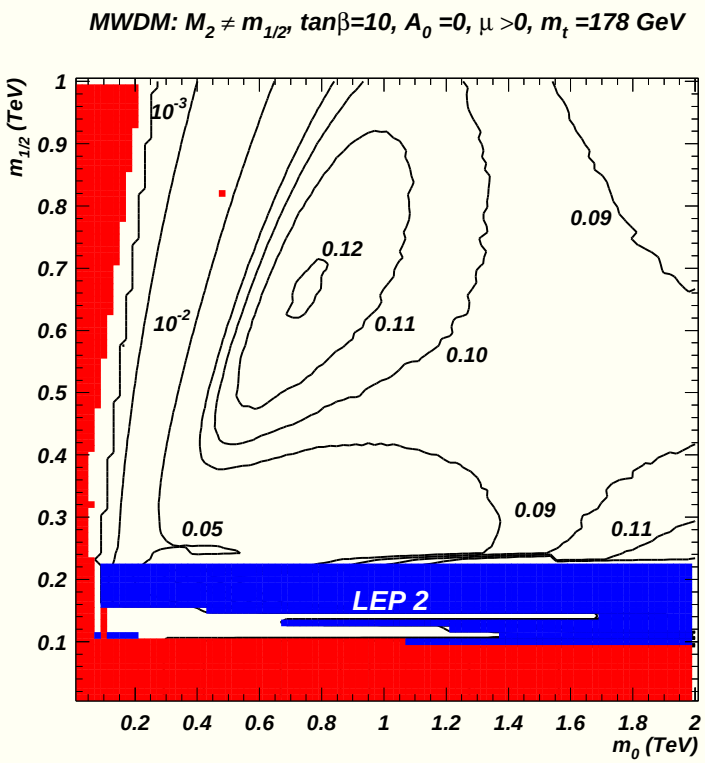


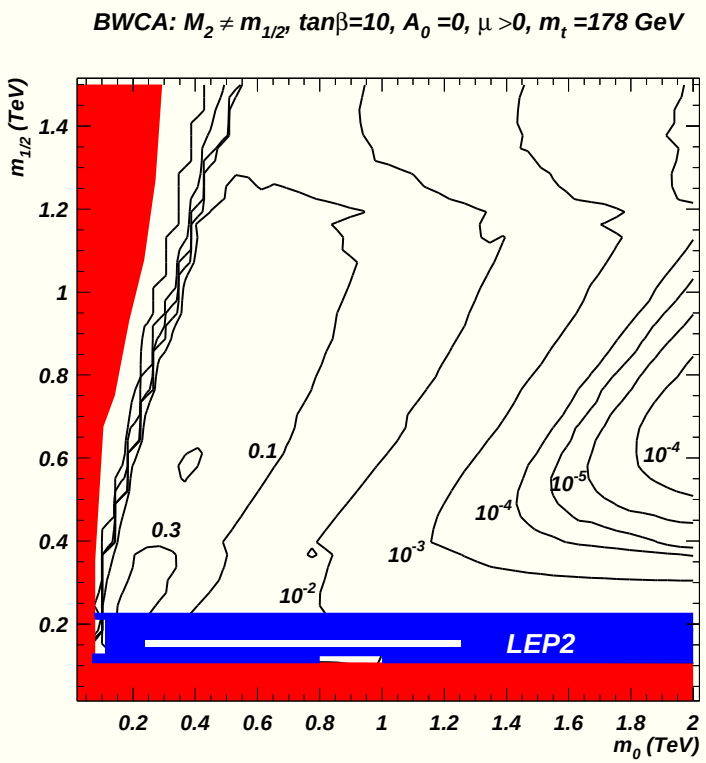
# Bino-wino co-annihilation (BWCA) scenario

- If $M_1/M_2 < 0$, then no mixing between bino-wino
- Can only reduce relic density via bino-wino co-annihilation when $M_1 \simeq -M_2$ at $Q = M_{weak}$



# In MWDM and BWCA: $BF(\widetilde{Z}_2 \to \widetilde{Z}_1\gamma)$ enhanced!

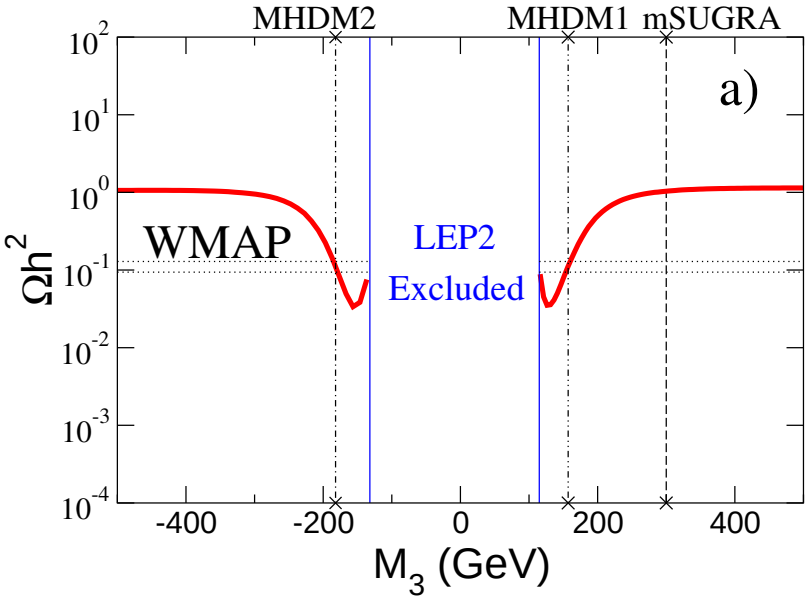


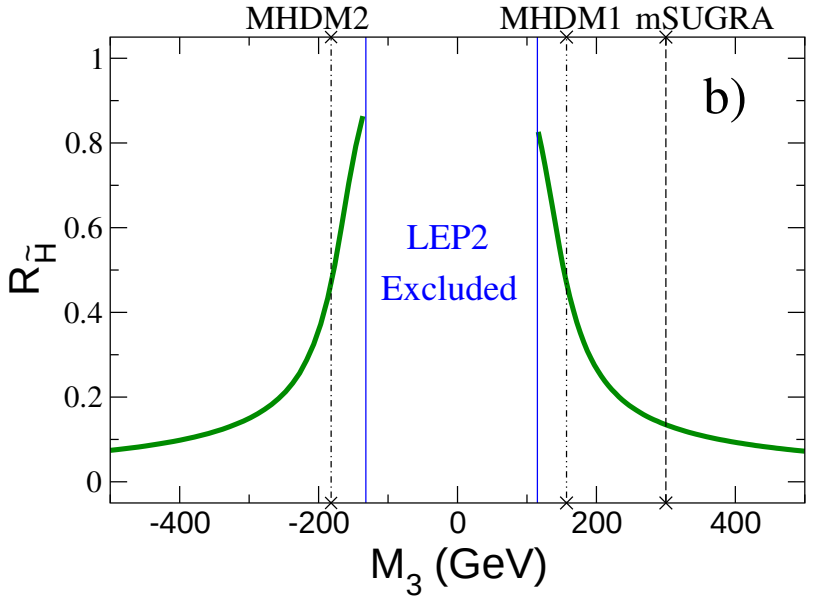




Haber+Wyler; Ambrosanio+Mele; Baer+Krupovnickas: JHEP 0209, 038 (2002)

# Mixed higgsino DM from a low $M_3$ (LM3DM)

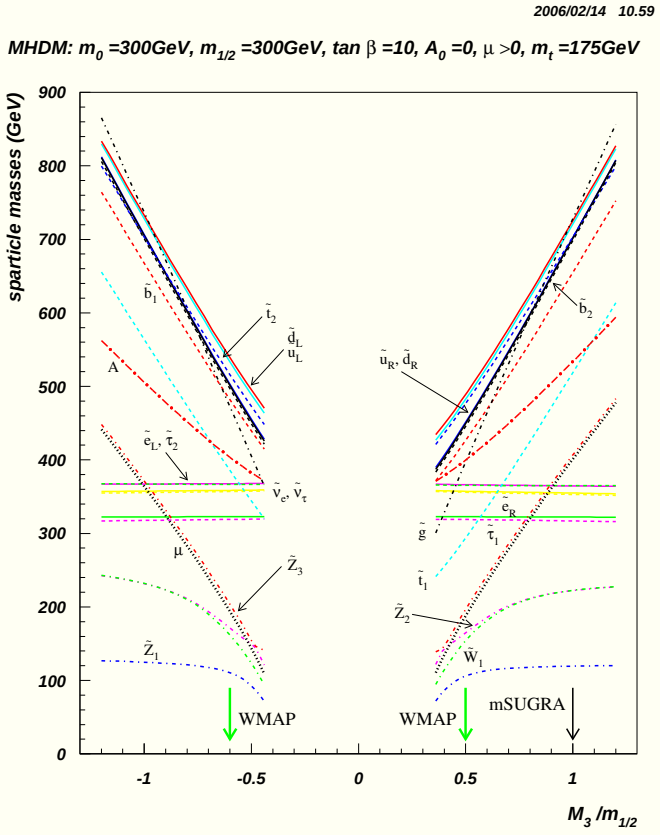
$m_0$=300 GeV, $m_{1/2}$=300 GeV, tanβ=10, $A_0$=0, μ>0, $m_t$=175 GeV



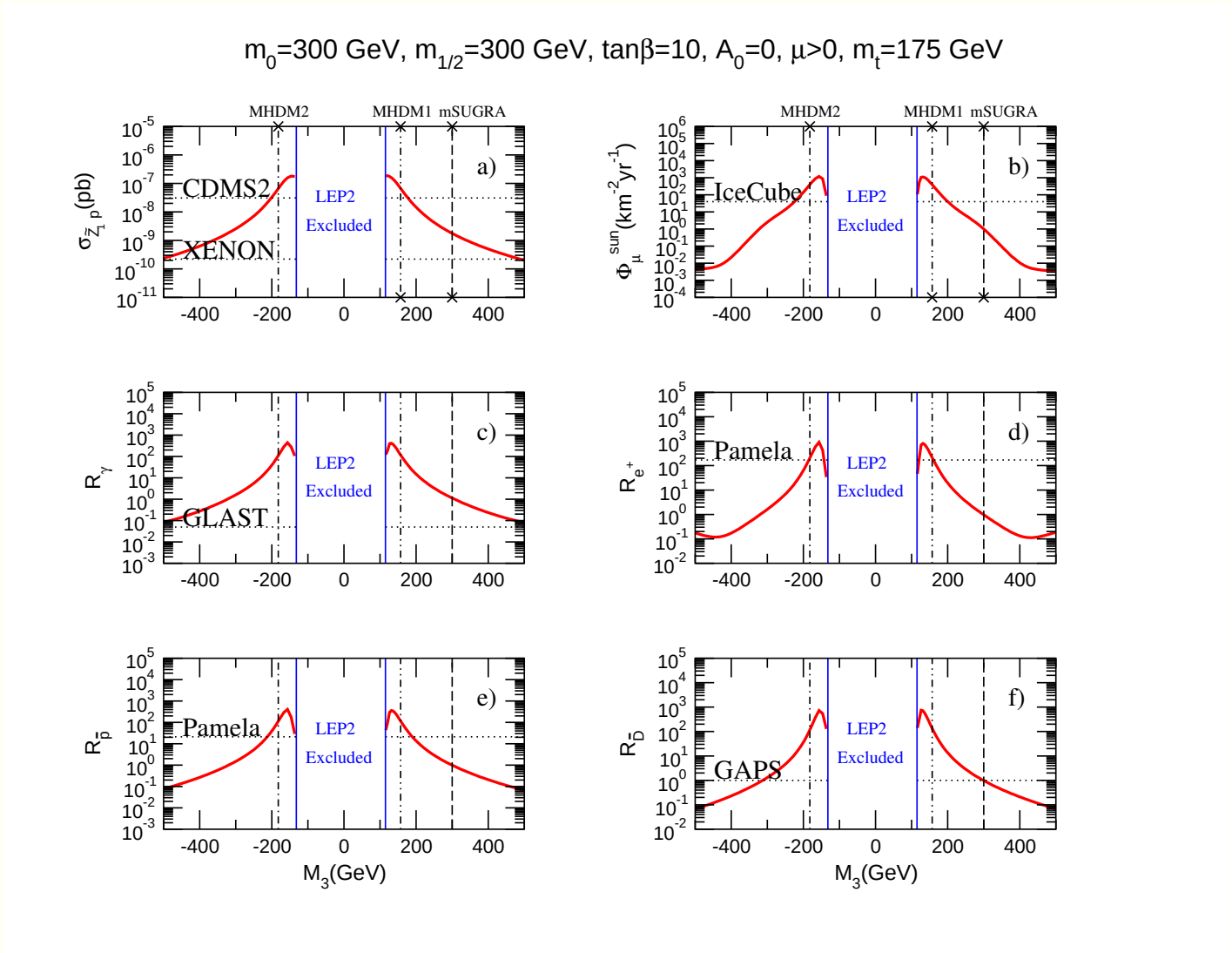

- low $M_3 \Rightarrow$ low $m_{\tilde{g}},\ m_{\tilde{q}},\ \mu$

# Sparticle mass spectra for LM3DM

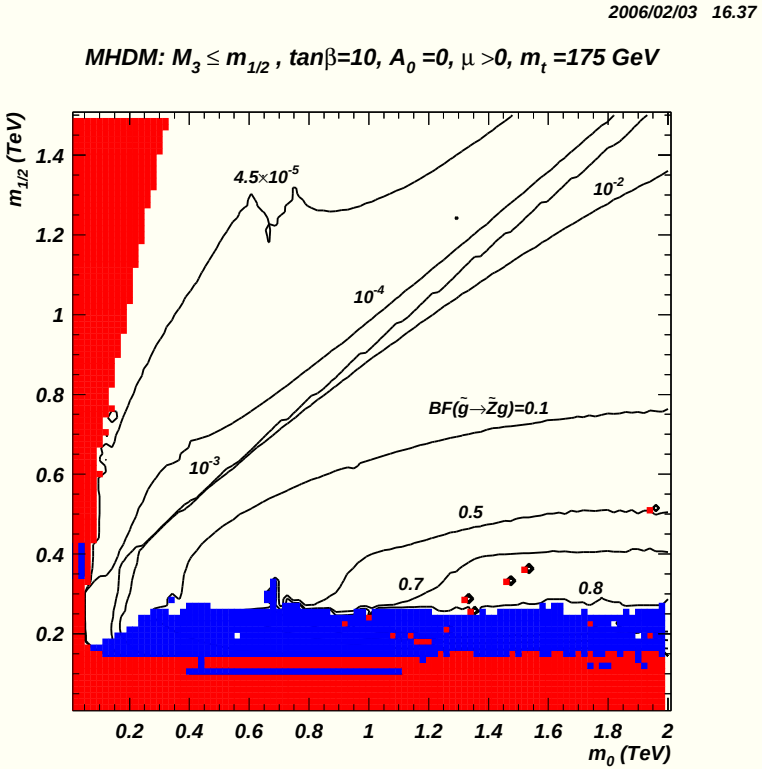



- low $m_{\tilde{g}},\ m_{\tilde{q}},\ \mu \Rightarrow$ huge DM detection rates!

# Direct/indrct DM rates greatly enhanced for LM3DM



# $\tilde{g} \to g\widetilde{Z}_i$ radiative decay in LM3DM: $\tilde{g}\tilde{g} \to$ dijet$+ \not{E}_T$




See talk by A. Mustafayev

# Conclusions

- ⋆ SUSY is standard way beyond the SM
- ⋆ SUGRA models most naturally encompass DM: thermal WIMPS
- ⋆ WMAP bound $\Omega_{\widetilde{Z}_1} h^2 = 0.113 \pm 0.009$ especially constraining
  - bulk, $\tilde{\tau}$ coann., HB/FP, $A$-funnel, $h$-funnel, $\tilde{t}_1$ coann.
- ⋆ Various regions $\Rightarrow$ distinct collider/DM signatures
- ⋆ Non-universality
  - normal scalar mass hierarchy (NMH)
  - NUHM1, NUHM2 models
  - mixed wino DM
  - bino-wino co-annihilation DM
  - mixed higgsino DM if $M_3$ reduced

# Weak Scale Supersymmetry

HB and X. Tata

Spring, 2006; Cambridge University Press

- ⋆ Part 1: superfields/Lagrangians
  - 4-component spinor notation for exp'ts
  - master Lagrangian for SUSY gauge theories
- ⋆ Part 2: models/implications
  - MSSM, SUGRA, GMSB, AMSB, $\cdots$
- ⋆ Part 3: SUSY at colliders
  - production/decay/event generation
  - collider signatures
  - $R$-parity violation