The LSP Relic Density

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I) Introduction

*) Still need non-baryonic Dark Matter (DM)!

Current best fit: $0.30 \lesssim \underset{\hookrightarrow \equiv \rho/\rho_{crit}}{\Omega_{matter}} \lesssim 0.45$; $\Omega_{baryon} = 0.05$

$H = h \cdot \frac{100 \, km}{Mpc \, sec}$

$\Rightarrow \Omega_{DM} \simeq 0.35$, $\Omega_{DM} h^2 \simeq 0.15$

Conservative bound: $\Omega_{DM} h^2 < 0.5$

*) Best SUSY candidate: Lightest neutralino $\tilde{\chi}_1^0$

If stable: lightest superparticle (LSP) must be neutral

$\tilde{\nu}$ excluded by DM searches $\Rightarrow \tilde{\chi}_1^0$! In the MSSM:

$$\tilde{\chi}_1^0 = N_{11} \underset{U(1)_Y}{\tilde{B}} + N_{12} \underset{SU(2)}{\tilde{W}_3} + N_{13} \underset{Y=-\frac{1}{2}}{\tilde{h}_1^0} + N_{14} \underset{Y=+\frac{1}{2}}{\tilde{h}_2^0}$$

If gaugino masses unify (like gauge couplings):

$\tilde{B}$-mass $M_1 \simeq \frac{1}{2} \cdot \tilde{W}_3$-mass M_2

$\Rightarrow \tilde{\chi}_1^0$ cannot be $\tilde{W}_3$-like

Extreme cases: $M_1^2 \ll \mu^2 \Rightarrow \tilde{\chi}_1^0 \simeq \tilde{B}$

$M_1^2 \gg \mu^2 \Rightarrow \tilde{\chi}_1^0 \simeq \frac{1}{\sqrt{2}} (\tilde{h}_1^0 - \mathrm{sign}(\mu) \tilde{h}_2^0)$

*) Recall: main motivation for SUSY independent of DM! (Hierarchy problem.)

II) The density of thermal relic LSPs

If:

1) LSP's were in thermal equilibrium after inflation: reheat Temperature $T_R \gtrsim m_{\tilde\chi_1^0}/10$; and

2) Universe evolved adiabatically for $T < T_F \simeq m_{\tilde\chi_1^0}/20$

then: $\Omega_{DM}^{therm.} h^2 \simeq \frac{10^{-10}\,\mathrm{GeV}^{-2}}{\langle v\sigma(\tilde\chi_1^0\tilde\chi_1^0 \to \mathrm{any})\rangle}$ ↙ thermal average

~0.1 for "weak" cross section: WIMP!

Results in the MSSM: (Goldberg 83; Ellis et al. 84; ...)

*) If $\tilde\chi_1^0 \simeq \tilde B \Rightarrow \Omega_{\tilde\chi} h^2 \simeq \frac{1.1\cdot 10^{-6}\,\mathrm{GeV}^{-2}}{\sigma_{\tilde B}}$, with

$$\sigma_{\tilde B} \equiv \frac{m^2_{\tilde\chi_1^0}}{(m^2_{\tilde e_R}+m^2_{\tilde\chi_1^0})^2}\cdot\left[\left(1-\frac{m^2_{\tilde\chi_1^0}}{m^2_{\tilde e_R}+m^2_{\tilde\chi_1^0}}\right)^2+\frac{m^4_{\tilde\chi_1^0}}{(m^2_{\tilde e_R}+m^2_{\tilde\chi_1^0})^2}\right],$$

if $m_{\tilde e_R} \simeq m_{\tilde\mu_R} \simeq m_{\tilde\tau_R}$. $Y(\tilde e_R) = 2Y(\tilde e_L)$!

Gives $\Omega_{\tilde\chi_1^0} h^2 \sim 0.1$ for $m_{\tilde e_R}, m_{\tilde\chi_1^0} \sim 100$ GeV: natural!

*) As $\tilde h$-components increase: $\Omega_{\tilde\chi_1^0} h^2$ decreases!

$\tilde\chi_1^0\tilde\chi_1^0 Z$, $\tilde\chi_1^0\tilde\chi_1^0$ Higgs couplings go up

Can probably predict $\Omega^{therm}_{\tilde\chi_1^0} h^2$ to ~20% using LHC data, if $|\mu| \gtrsim M_1$! (hep-ph/0007202)

*) $\tilde\chi_1^0 \simeq \tilde h$: Need $m_{\tilde\chi_1^0} \gtrsim 0.5$ TeV ⇒ unnatural! (→ Olive's talk)

IIb) Co-annihilation

So far: Assumed, only $\tilde\chi_1^0$ and SM-particles are around at $T \simeq T_F$. Let NLSP $\equiv \tilde\chi'$. If $m_{\tilde\chi'} \lesssim 1.1\, m_{\tilde\chi_1^0}$:

$\tilde\chi_1^0 + f \leftrightarrow \tilde\chi' + f'$ much faster than $\tilde\chi_1^0 \tilde\chi_1^0 \leftrightarrow f\bar f$,

SM-particle @ $T \sim T_F \sim m_{\tilde\chi_1^0}/20$

$\Rightarrow$ $\tilde\chi_1^0$ and $\tilde\chi'$ are in relative equilibrium even after $\tilde\chi_1^0$ decouples

$\Rightarrow$ need to include $\tilde\chi_1^0 \tilde\chi' \leftrightarrow f f'$, $\tilde\chi' \tilde\chi'^{(*)} \leftrightarrow f\bar f$:

can have much higher cross section than $\tilde\chi_1^0 \tilde\chi_1^0 \leftrightarrow f\bar f$

$\Rightarrow \Omega_{\tilde\chi_1^0} h^2$ decreases! (NLSP need not be neutral!)

Formalism: (Griest + Seckel, 91)

Replace $\sigma(\tilde\chi_1^0 \tilde\chi_1^0 \to \text{any})$ by

$$\sigma_{\text{eff}} \equiv \sum_{i,j=1}^{N} \sigma_{ij \to \text{any}} \cdot \frac{g_i g_j}{g_{\text{eff}}^2} R_i R_j\, e^{-\frac{m_i + m_j - 2 m_{\tilde\chi_1^0}}{T}}$$

$$R_i \equiv \left(1 + \frac{m_i - m_{\tilde\chi_1^0}}{m_{\tilde\chi_1^0}}\right)^{3/2}; \quad g_{\text{eff}} = \sum_{i=1}^{N} \underset{\uparrow}{g_i} R_i\, e^{-(m_i - m_{\tilde\chi_1^0})/T}$$

d.o.f. per particle

Examples:

*) $\underline{\tilde\chi_1^0 \simeq \tilde h^0} \Rightarrow \tilde\chi' = \tilde h^\pm , \tilde\chi'' = \tilde h'^0 : g_{W\tilde\chi_1^0\tilde\chi'} \gg g_{Z\tilde\chi_1^0\tilde\chi_1^0}$

Co-annihilation suppresses density of light higgsinos

(Mizuta + Yamaguchi 92; M.D. + Nojiri 92; M.D., Nojiri, Roy + Yamada 96;
heavy $\tilde h^0$: Bergström + Gondolo '97)

*) $\underline{\tilde\chi' \equiv \tilde\tau_1}$: Quite common in mSUGRA!
Can reduce $\Omega^{\text{therm}}_{\tilde\chi_1^0} h^2$ by ~ factor 10!

(Ellis, Falk, Olive, Srednicki, hep-ph/9905481; ⇉
Gómez, Lazarides, Pallis, hep-ph/9907261)

*) $\underline{\tilde\chi' = \tilde t_1}$: Not so well motivated, but
can reduce $\Omega^{\text{therm}}_{\tilde\chi_1^0} h^2$ by factor 10^3!

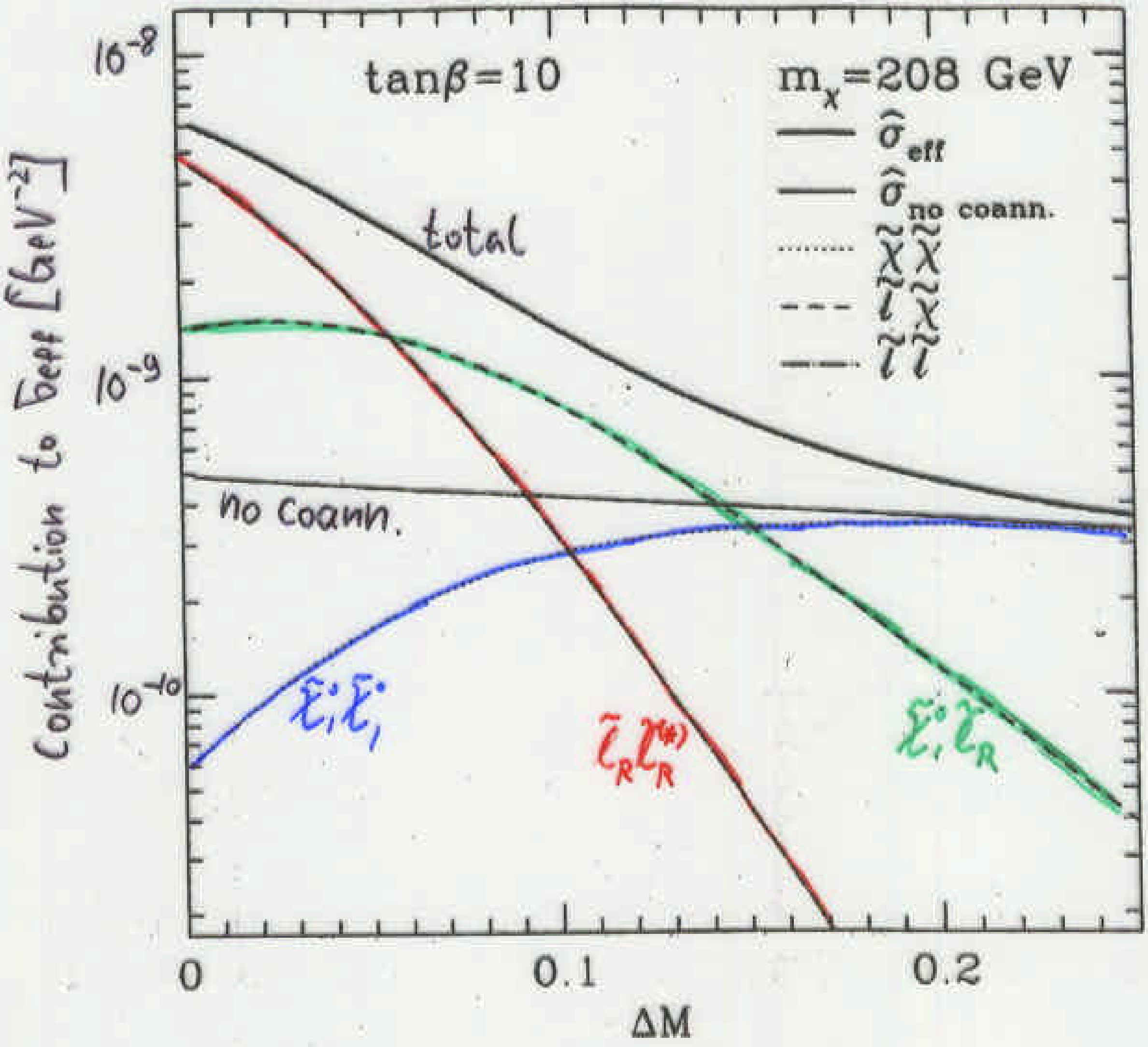
(Boehm, Djouadi, M.D., hep-ph/9911496) →

All 3 cases allow sparticle masses beyond the reach of the LHC! (Not natural!)

Exptl detection of $\tilde\chi'$ difficult, if close in mass to $\tilde\chi_1^0$.

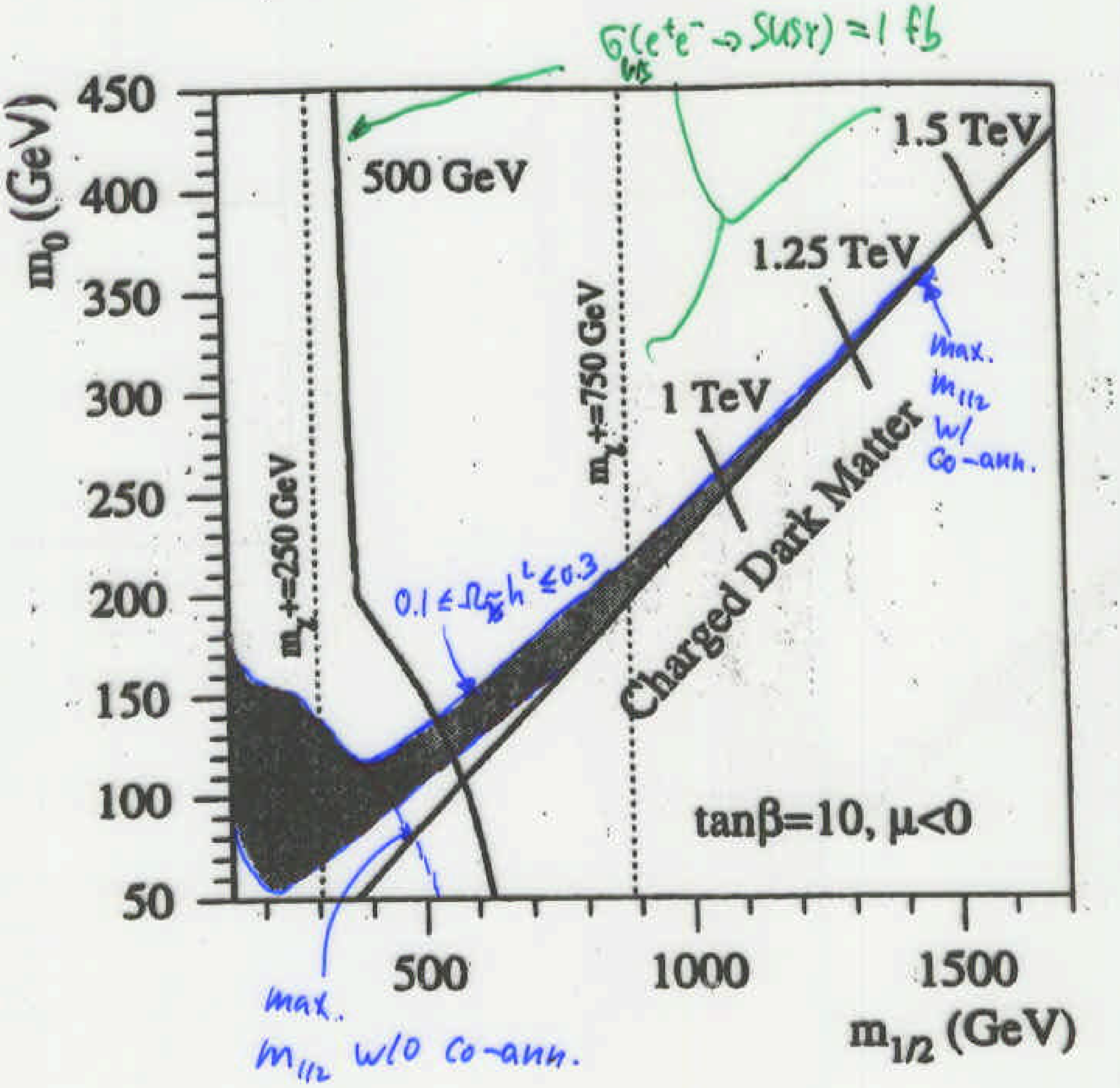
4a

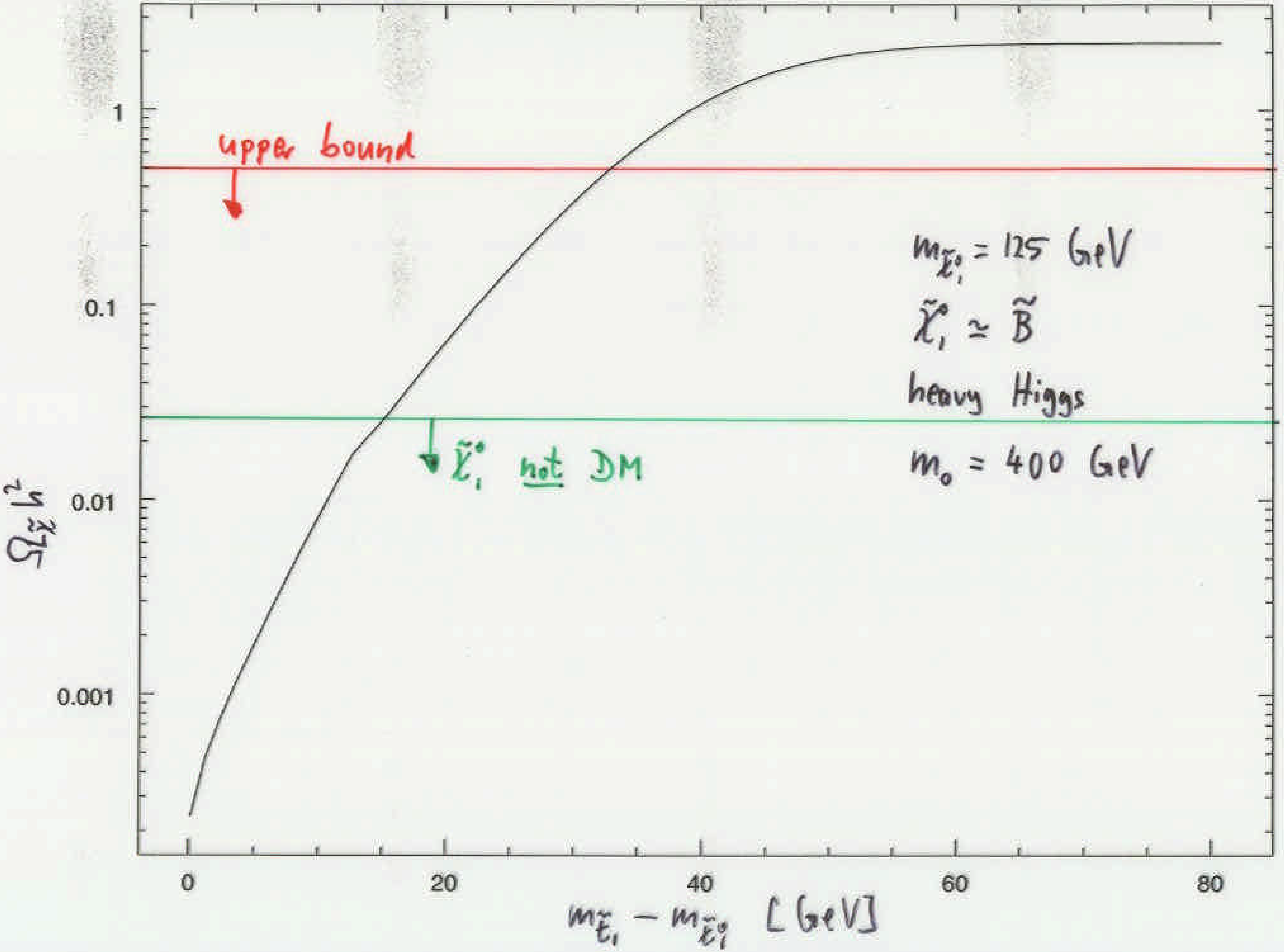
Ellis, Falk, Olive, Srednicki

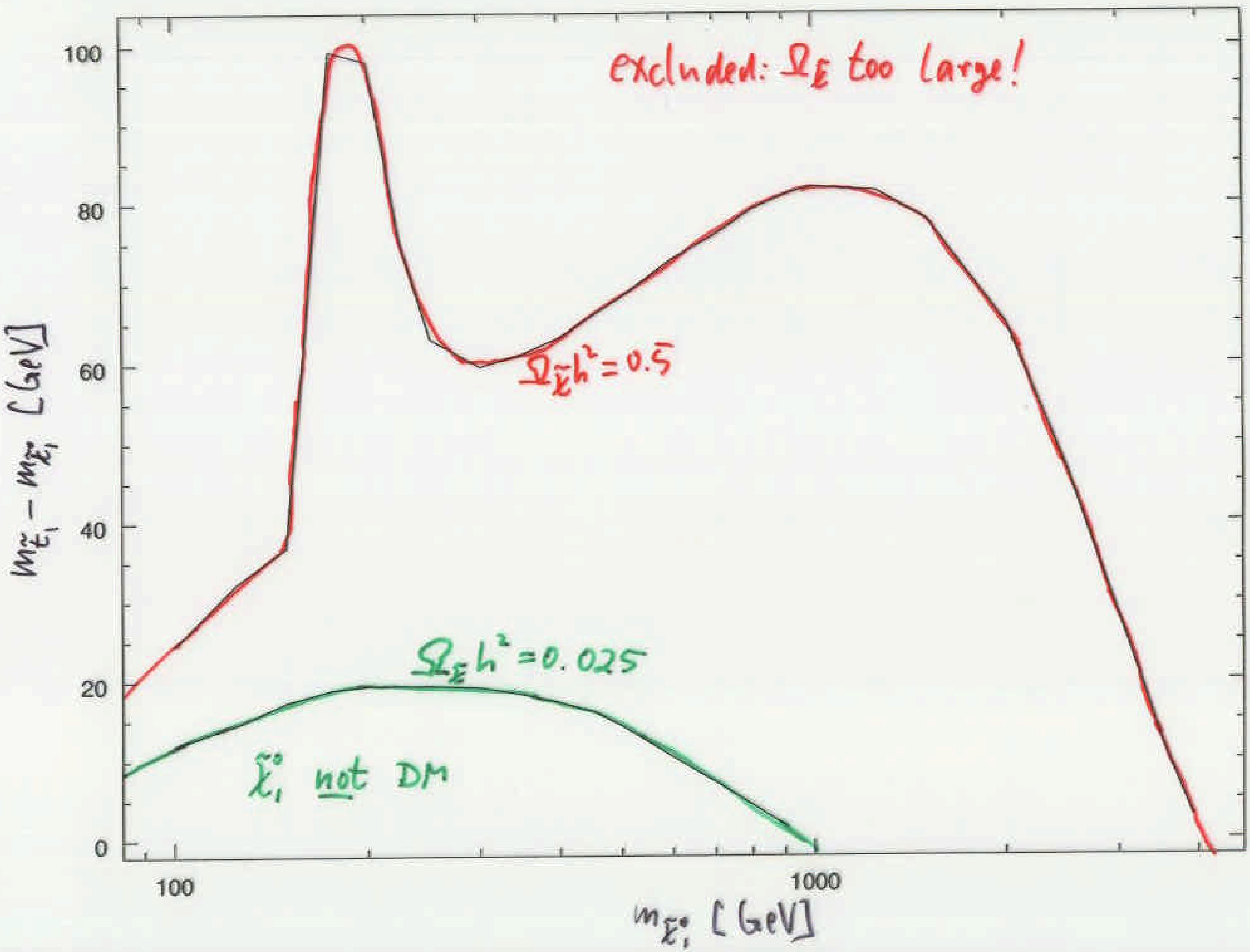


$T = m_{\tilde\chi^0_1}/23$

Ellis, Ganis, Olive, hep-ph/9912324




upper bound
$m_{\tilde{\chi}_1^0} = 125$ GeV
$\tilde{\chi}_1^0 \simeq \tilde{B}$
heavy Higgs
$m_0 = 400$ GeV
$\tilde{\chi}_1^0$ not DM
$\Omega_{\tilde{\chi}} h^2$
1
0.1
0.01
0.001
0
20
40
60
80
$m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ [GeV]


excluded: $\Omega_{\tilde{\chi}}$ too large!
$\Omega_{\tilde{\chi}} h^2 = 0.5$
$\Omega_{\tilde{\chi}} h^2 = 0.025$
$\tilde{\chi}_1^0$ not DM
$m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^0}$ [GeV]
0
20
40
60
80
100
100
1000

III) Non-thermal relic LSPs

*) If $M_2 < M_1$ (ASB) : $\tilde{\chi}_1^0 \simeq \tilde{W}_3$ possible ; has
$\Omega^{\text{therm}}_{\tilde{W}_3} h^2 \ll 1$ (Chen, M.D., Gunion 95)

But: Can produce sufficient $\Omega_{\tilde{\chi}_1^0} h^2$ from moduli decay! (Moroi + Randall, 99)

*) Q-ball baryogenesis requires $T_R \sim 1$ GeV $< T_F$
LSPs set free when Q-balls decay ⇒ $n_{\tilde{\chi}_1^0} \sim n_b$:
can be in right range! (Enqvist + McDonald, 98/9)

Lesson: Might be dangerous to exclude parameters with "wrong" $\Omega^{\text{therm.}}_{\tilde{\chi}_1^0} h^2$ from analysis!

IV) Summary & Conclusions

*) $\tilde{\chi}_1^0$ remains good DM candidate. Theoretical favorite: $\tilde{\chi}_1^0 \simeq \tilde{B}$, gives $\Omega_{\tilde{\chi}_1^0}^{therm} h^2 \sim 0.1$ naturally

*) $\Omega_{\tilde{\chi}_1^0}^{therm} h^2 \overset{!}{<} 0.5$ excludes large regions of parameter space. Assumptions: $T_R > T_F$, no entropy release for $T < T_F$; $\tau(\tilde{\chi}_1^0) > 10^{10}$ yrs. Even then, does not guarantee SUSY signal @ LHC or NLC: co-annihilation; s-channel poles; $\tilde{\chi} \simeq \tilde{h}$: all possible even in mSUGRA! ($m_0^2 \gg m_{1/2}^2$ gives $|\mu| \sim M_1$: Feng et al. 2000)