E–WIMPs

Do We Live in a False Vacuum?

Leszek Roszkowski

Astro–Particle Theory and Cosmology Group

Sheffield, England

E–WIMP?

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WIMP?

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WIMP?

a weak and cowardly person (English Oxford Dictionary)

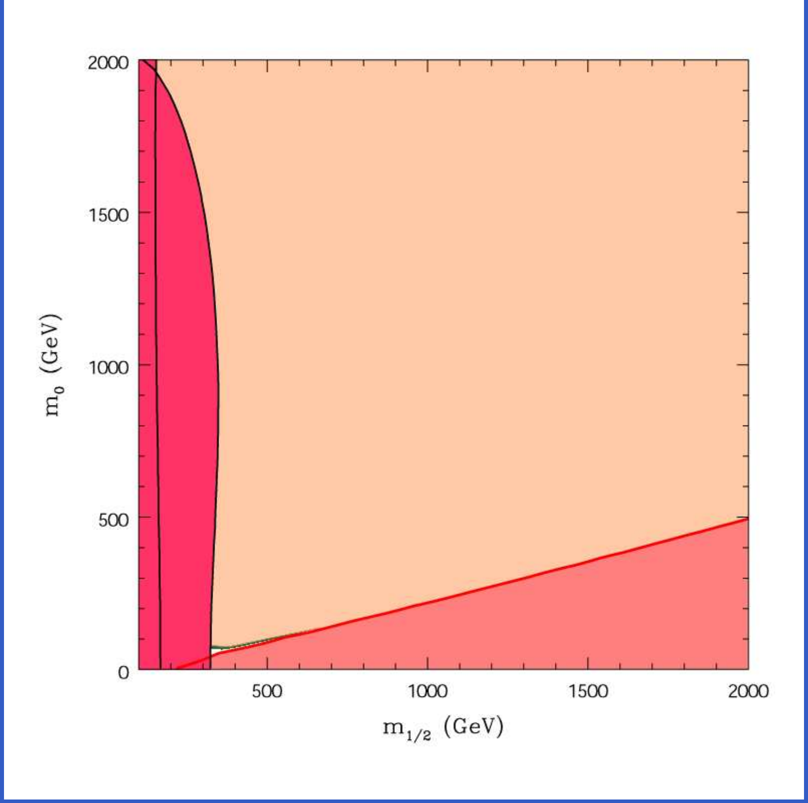
E–WIMP?

WIMP?

weakly interacting massive particle

CMSSM, neutralino LSP, small $\tan\beta$

$\tan\beta \lesssim 45$



neutralino (bino) χ LSP

green: $0.094 < \Omega_\chi h^2 < 0.129$

tightly constrained

E–WIMP?

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exotic WIMP?

exciting WIMP?

E–WIMP?

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extremely weakly interacting massive particle

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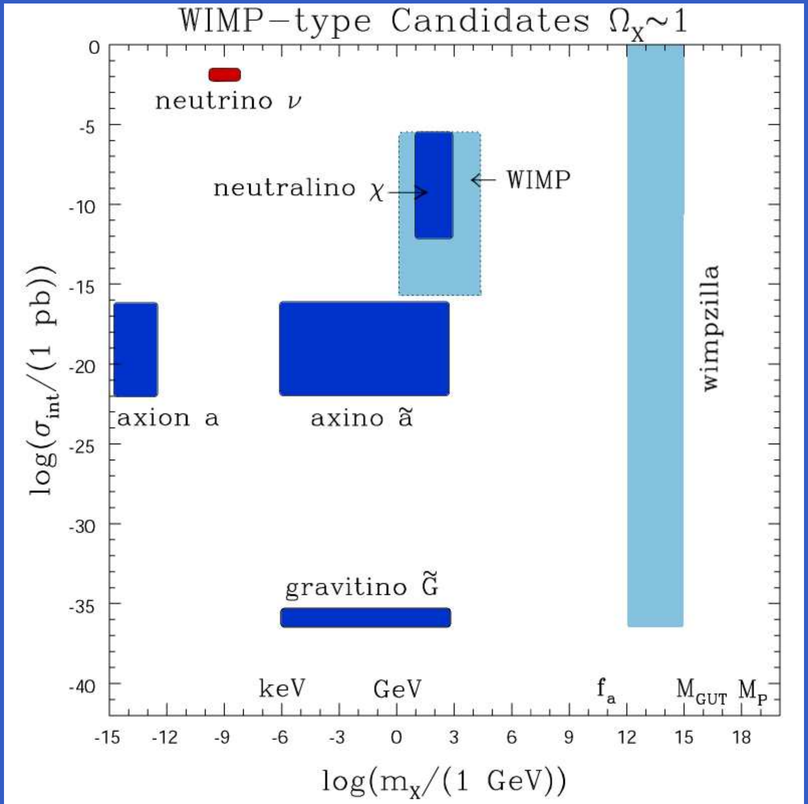
extremely weakly interacting massive particle

testable... ...at LHC

The Big Picture

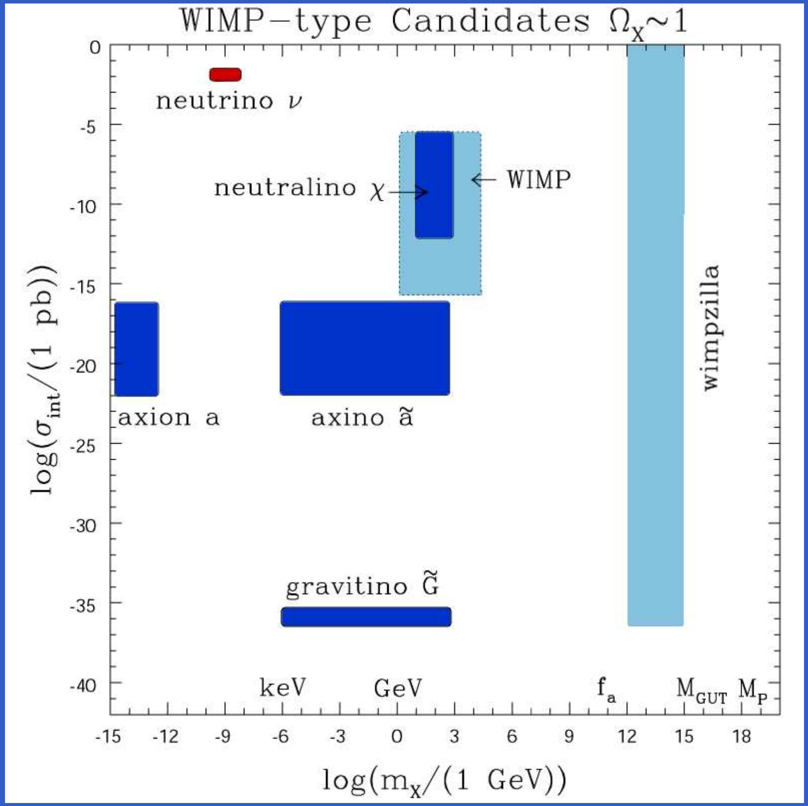
well–motivated particle candidates s.t. $\Omega \sim 0.1$

The Big Picture



- neutrino ν – hot DM
- neutralino χ
- “generic” WIMP
- axion a
- axino $\widetilde{a}$
- gravitino $\widetilde{G}$
- wimpzilla,. . .

The Big Picture



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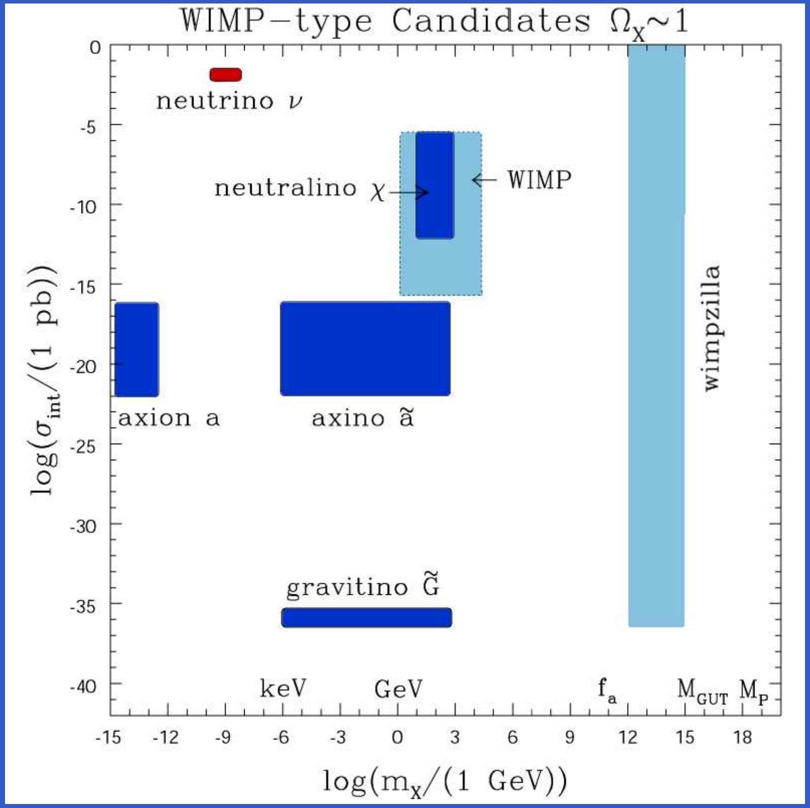
...Must go beyond SM..., SUSY (still) most promising

The Big Picture



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- wimpzilla,. . .

...Each interesting energy scale $\Leftrightarrow$ CDM candidate

Recent activity...

axino – work with:

- L. Covi, J.E. Kim, PRL'99 (hep-ph/9905212);
- L. Covi, H.-B. Kim, J.E. Kim, JHEP'01 (hep-ph/0101009);
- L. Covi, M. Small, JHEP'02 (hep-ph/0206119);
- L. Covi, R. Ruiz de Austri, M. Small, JHEP'04 (hep-ph/0402240)
- A. Brandenburg+L. Covi+K. Hamaguchi+L.R.+F. Steffen, PLB '05 (hep-ph/0501287)

related recent work:

- H.-B. Kim, J.E. Kim, hep-ph/0108101
- D. Hooper, L.-T. Wang, hep-ph/0402220
- A. Brandenburg, F.D. Steffen, hep-ph/0406021
- . . .

gravitino – work with:

- R. Ruiz de Austri, JHEP'05 (hep-ph/0408227)
- Cerdeño+K.-Y. Choi+Jedamzik+L.R.+Ruiz de Austri, in prep.

related recent work:

- al et Buchmüller (BBP, '98, BBB '00)
- Feng et al, '02-'04
- Ellis, Olive et al. (EOSS), hep-ph/0312262
- Allahverdi+Drees, hep-ph/0408289
- Jedamzik, Lemoine, Moultaka, hep-ph/0504021, hep-ph/0506129 and astro-ph/0508141
- . . .

Outline

- E–WIMPs: axinos and gravitinos (mostly in CMSSM)

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- constraints from BBN and CMB
- constraints from false vacuua
- results

‘Exotic’ SUSY WIMPs: $\widetilde{G}$ and $\widetilde{a}$

historically first:

$\widetilde{G}$: Pagels+Primack, Weinberg (’82)

$\widetilde{a}$: Tamvakis+Wyler (’82)

$\widetilde{\gamma}$: Goldberg (’83)

χ: Ellis, *et al* (EHNOS) (’84)

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(assume usual gravity mediated SUSY breaking)

	axino	gravitino
spin	1/2	3/2
interaction	$\sim 1/f_a^2$	$\sim 1/M_{\rm P}^2$
mass	$\not\propto M_{\rm SUSY}$	$\propto M_{\rm SUSY}$

- mass model dependent
  take it as free parameter

$f_a \sim 10^{9-12}$ GeV – PQ scale
$M_{\rm P} = 2.4 \times 10^{18}$ GeV – reduced Planck mass
$M_{\rm SUSY} \sim 100$ GeV — 1 TeV – soft SUSY mass scale

$\tilde{a}$ Interactions

consider Kim, Shifman, Veinstein, Zakharov model

heavy singlet (chiral) quark superfield

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- axino–gluino–gluon (dim–5)

$$\mathcal{L}(\tilde{a}g\tilde{g}) = \frac{\alpha_s}{8\pi(f_a/N)}\bar{\widetilde{a}}\gamma_5\sigma^{\mu\nu}\widetilde{g}^b G^b_{\mu\nu}$$

dominant in $\widetilde{a}$ production from scatterings (high T_R)

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dominant in $\widetilde{a}$ production from $\widetilde{q}$ decays (low T_R)

- ...plus $\widetilde{a}\gamma\chi$ interactions...

dominant in $\widetilde{a}$ production from NLSP freezeout and decay

Axino WIMP

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L. Covi+J.E. Kim+LR, PRL'99

consider: (KSVZ model)

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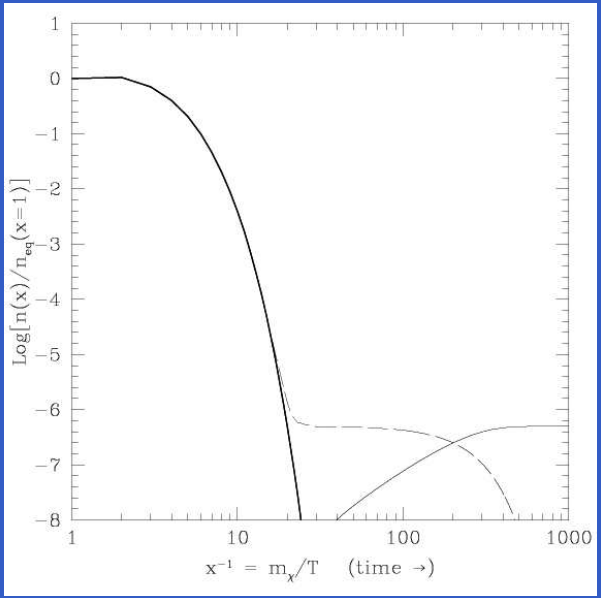

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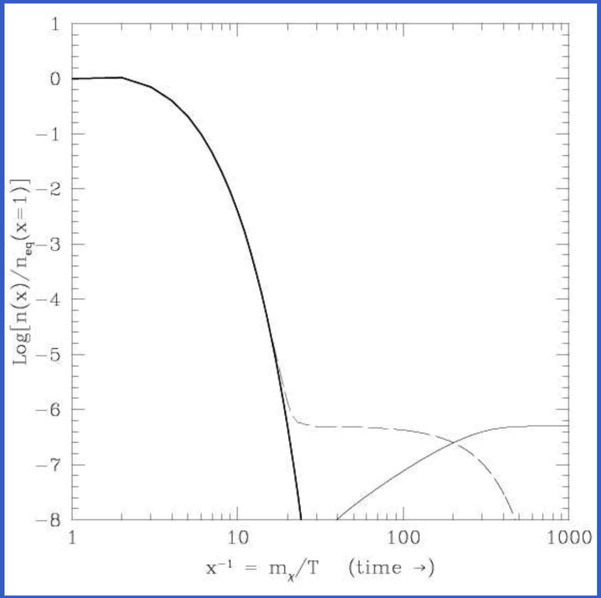
$$\boldsymbol{\tau(\chi \to \widetilde{a}\,\gamma) \simeq 0.3\,\mathrm{sec}\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)^3 \ldots}$$

...before BBN



$(\chi \simeq \widetilde{B})$

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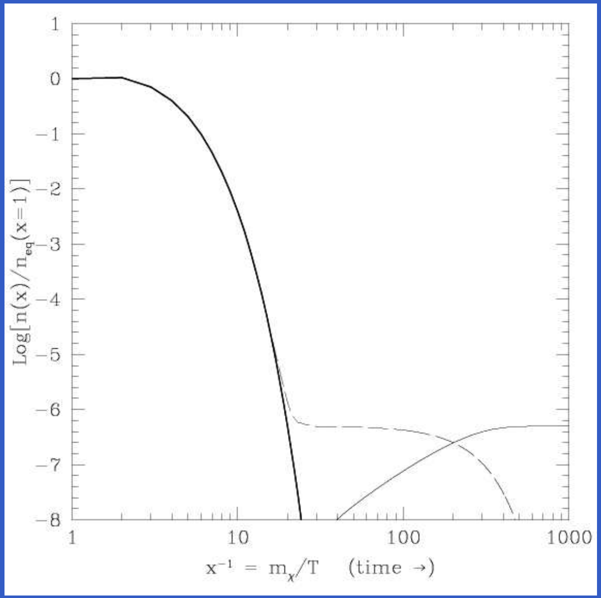

$(\chi \simeq \widetilde{B})$

- NTP: $n_{\widetilde{a}} = n_\chi$

$$\Omega_{\widetilde{a}}^{\mathrm{NTP}} = \frac{m_{\widetilde{a}}}{m_\chi}\,\Omega_\chi$$

NTP: non–thermal production

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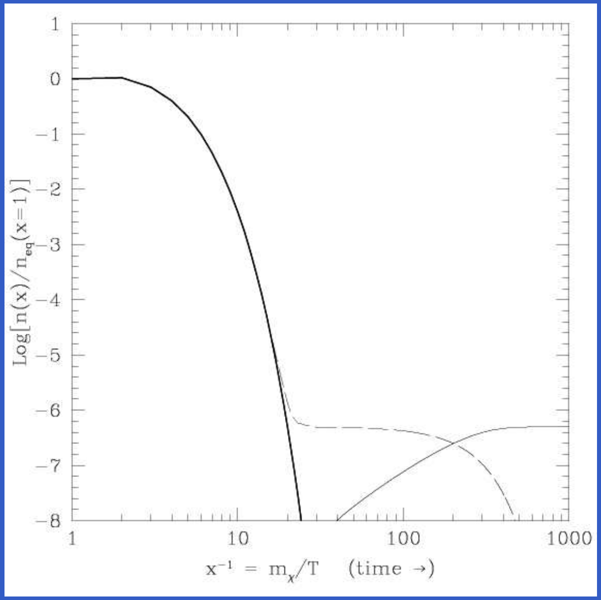

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NTP: non–thermal production

- TP: $q\,q \to \widetilde{a}\,\widetilde{g},\ \ \widetilde{q} \to \widetilde{a}\,q, \ldots$

TP: thermal production

$$\Omega_{\widetilde{a}}^{\mathrm{TP}} \propto \sigma(\widetilde{a} - \mathrm{prod.})$$

TP

L. Covi+H.-B. Kim, J.E. Kim+L.R., JHEP '01

$$\sigma(\tilde{a} - \mathrm{prod.}) : \frac{\alpha_s^3}{4\pi^2 (f_a/N)^2} \overline{\sigma}_n(s)$$

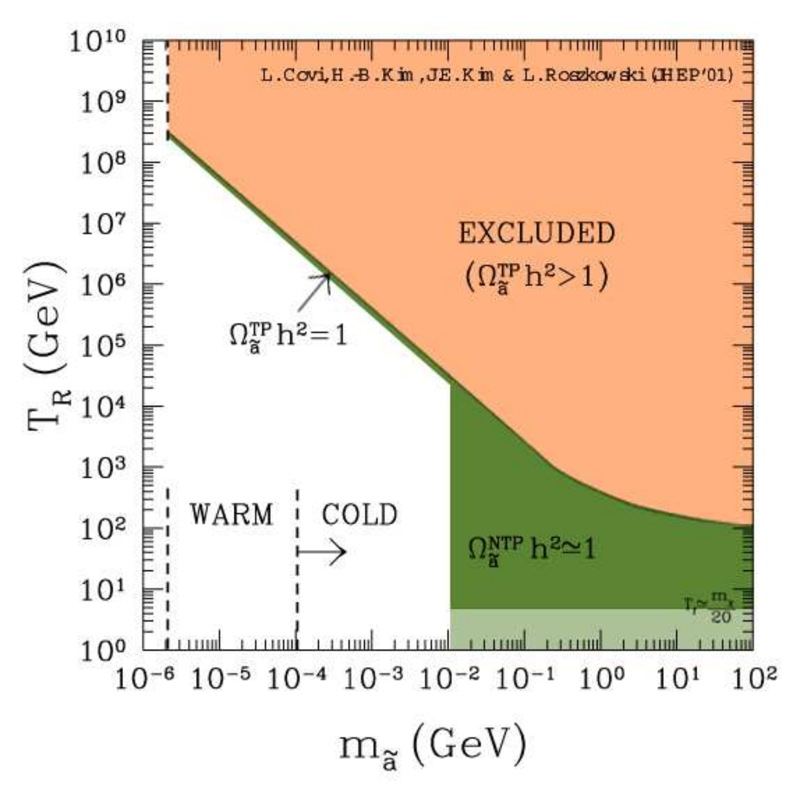
analogous to $\widetilde{G}$ (Moroi, *et al.*, '93)

n	Process	$\overline{\sigma}_n$	$n_{\rm spin}$	$n_{\rm F}$	$\eta_1\eta_2$
A	$g^a + g^b \longrightarrow \tilde{a} + \tilde{g}^c$	$\frac{1}{8}\lvert f^{abc}\rvert^2$	4	1	1
B	$g^a + \tilde{g}^b \longrightarrow \tilde{a} + g^c$	$\frac{5}{16}\lvert f^{abc}\rvert^2 \left[\log\left(s/m_{\rm eff}^2\right) - \frac{15}{8}\right]$	4	1	x $\frac{3}{4}$
C	$g^a + \tilde{q}_k \longrightarrow \tilde{a} + q_j$	$\frac{1}{8}\lvert T^a_{jk}\rvert^2$	2	$N_F \times 2$	1
D	$g^a + q_k \longrightarrow \tilde{a} + \tilde{q}_j$	$\frac{1}{32}\lvert T^a_{jk}\rvert^2$	4	$N_F \times 2$	$\frac{3}{4}$
E	$\tilde{q}_j + q_k \longrightarrow \tilde{a} + g^a$	$\frac{1}{16}\lvert T^a_{jk}\rvert^2$	2	$N_F \times 2$	$\frac{3}{4}$
F	$\tilde{g}^a + \tilde{g}^b \longrightarrow \tilde{a} + \tilde{g}^c$	$\frac{1}{2}\lvert f^{abc}\rvert^2 \left[\log\left(s/m_{\rm eff}^2\right) - \frac{29}{12}\right]$	4	1	$\frac{3}{4}\ \frac{3}{4}$
G	$\tilde{g}^a + q_k \longrightarrow \tilde{a} + q_j$	$\frac{1}{4}\lvert T^a_{jk}\rvert^2 \left[\log\left(s/m_{\rm eff}^2\right) - 2\right]$	4	N_F	$\frac{3}{4}\ \frac{3}{4}$
H	$\tilde{g}^a + \tilde{q}_k \longrightarrow \tilde{a} + \tilde{q}_j$	$\frac{1}{4}\lvert T^a_{jk}\rvert^2 \left[\log\left(s/m_{\rm eff}^2\right) - \frac{15}{8}\right]$	2	$N_F \times 2$	$\frac{3}{4}$
I	$q_k + \bar{q}_j \longrightarrow \tilde{a} + \tilde{g}^a$	$\frac{1}{24}\lvert T^a_{jk}\rvert^2$	4	N_F	$\frac{3}{4}\ \frac{3}{4}$
J	$\tilde{q}_k + \tilde{q}_j \longrightarrow \tilde{a} + \tilde{g}^a$	$\frac{1}{24}\lvert T^a_{jk}\rvert^2$	1	$N_F \times 2$	1

- solve Boltzmann eq, include scatt. and decay processes
- 12 classes of processes, B, F, G, H log–divergent: introduce plasmon mass regulator

NTP vs TP

general MSSM: Covi+H.-B. Kim+J.E. Kim+Roszkowski, JHEP '01 (hep-ph/0101009)

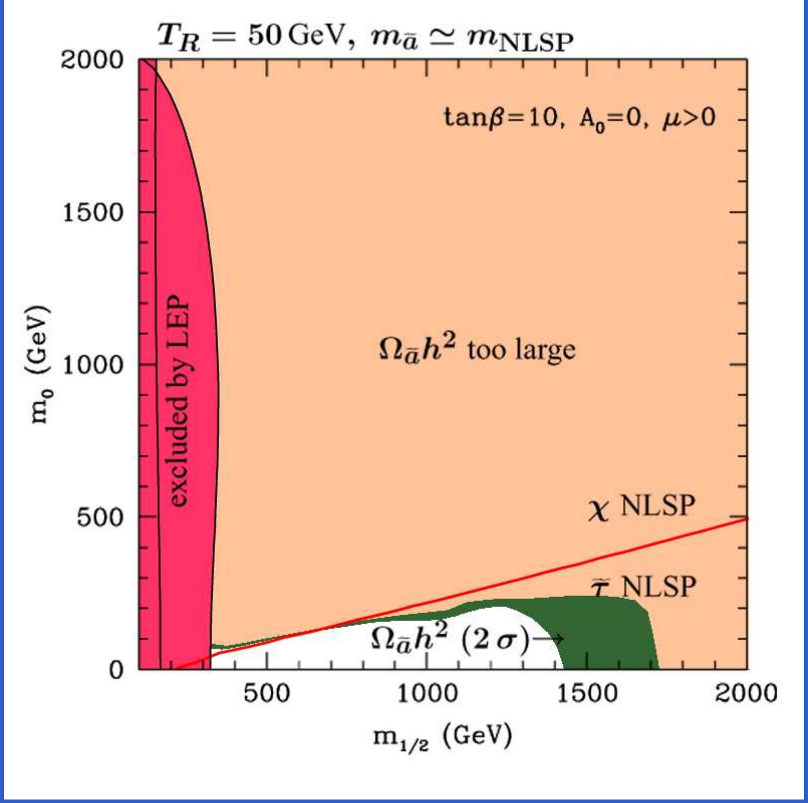


...axino cold DM: $\Rightarrow$ low $T_R \lesssim 10^6$ GeV

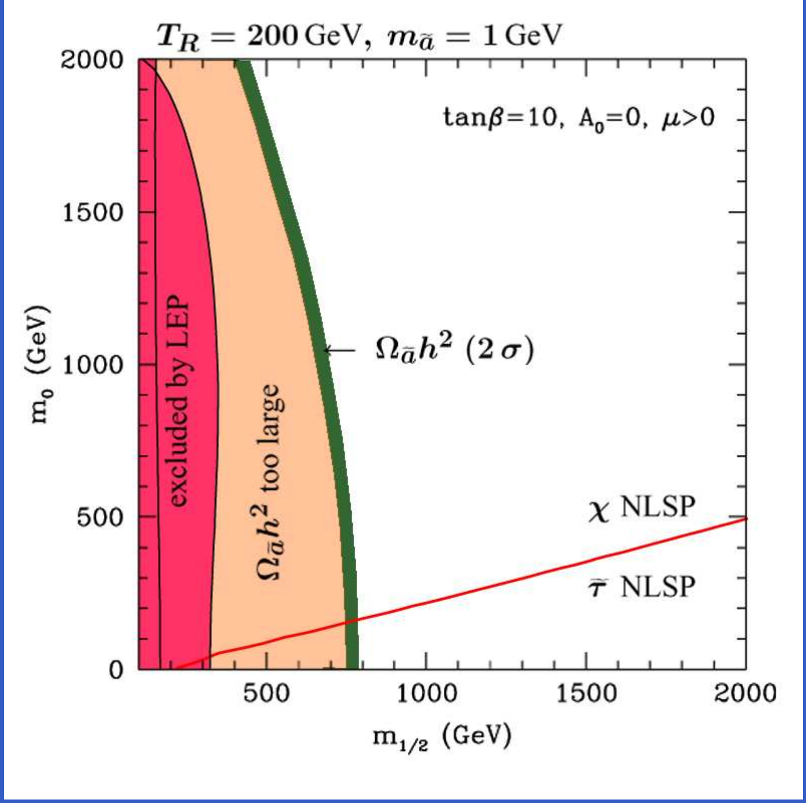
NTP vs TP

Covi+Roszkowski+Ruiz de Austri+Small, JHEP'04 (hep-ph/0402240)

NTP dominant



TP dominant



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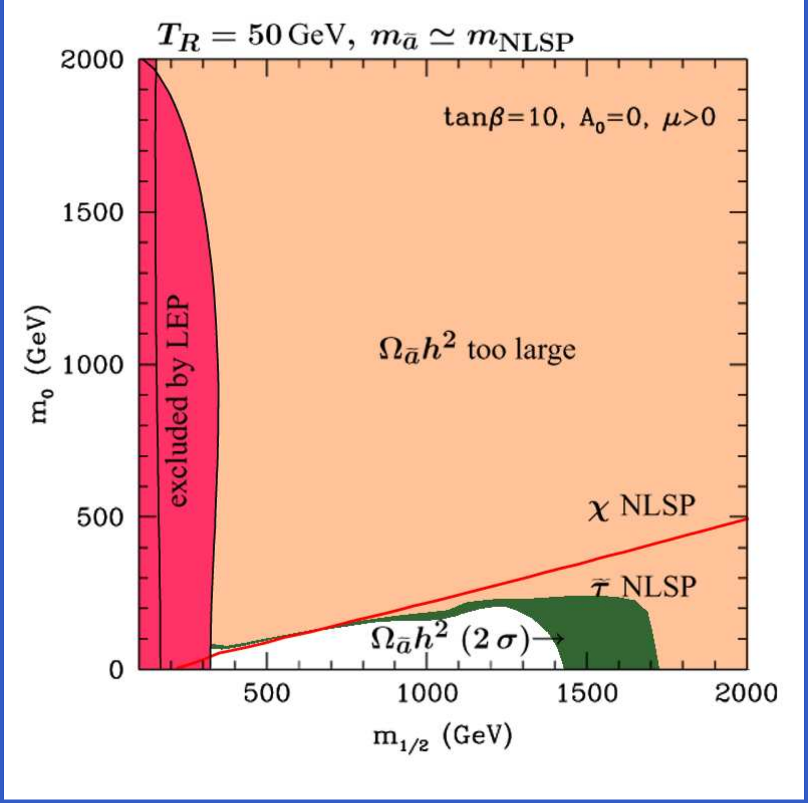

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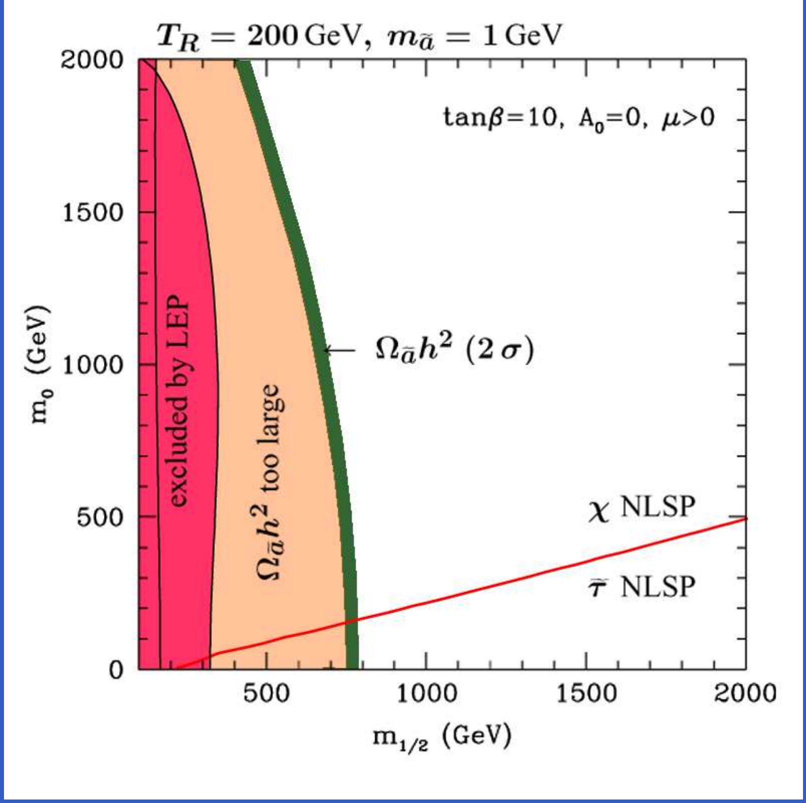
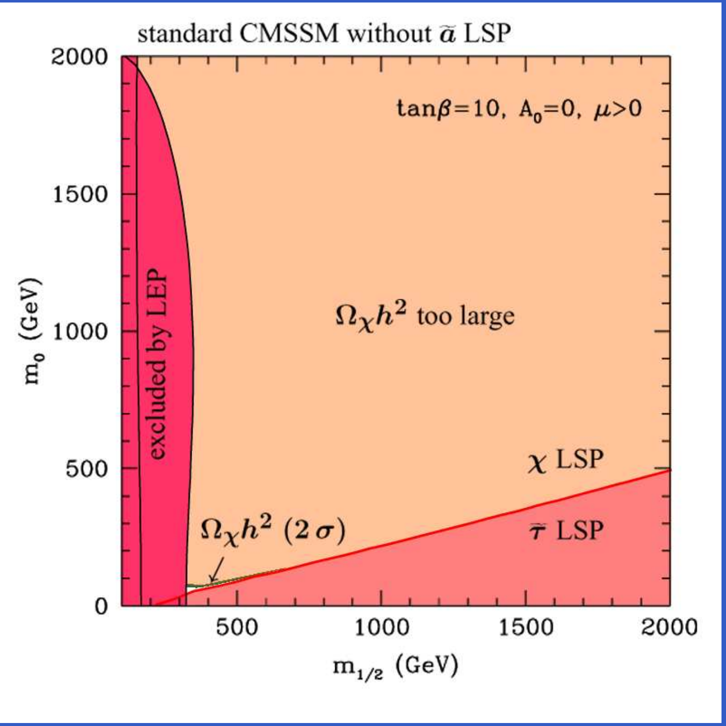


low T_R!

At LHC: A very different picture?

Covi+LR+Ruiz de Austri+Small, JHEP'04 (hep-ph/0402240)

CMSSM, (standard) χ LSP



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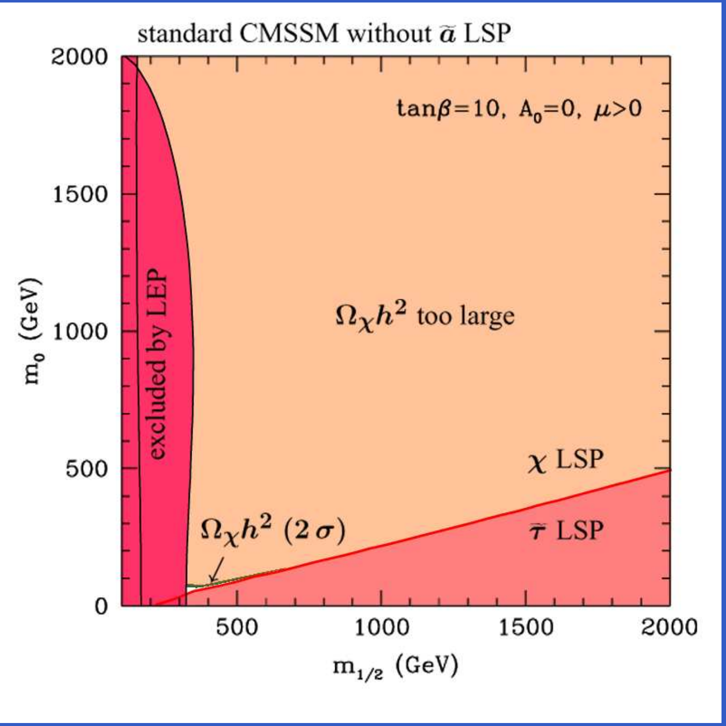
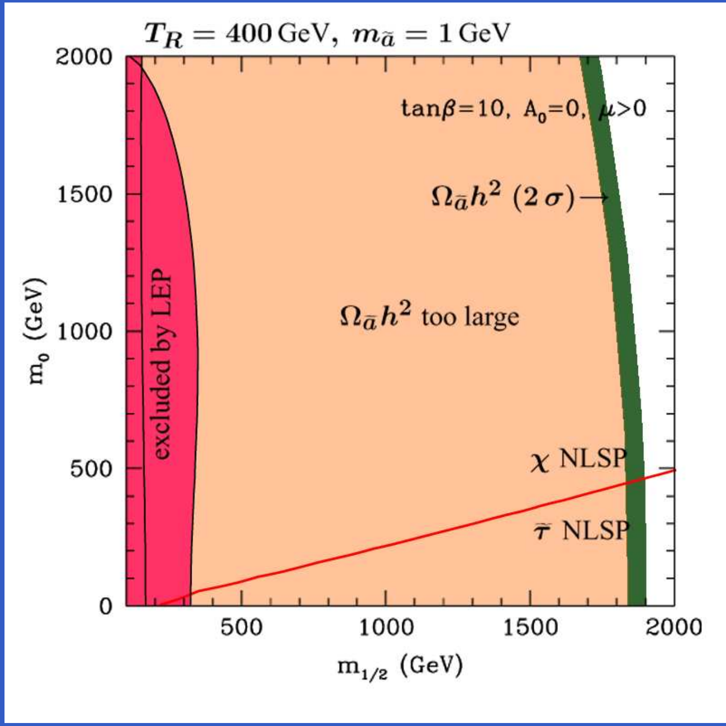


CMSSM, $\tilde{a}$ LSP, $m_{\tilde{a}} \simeq m_\chi$



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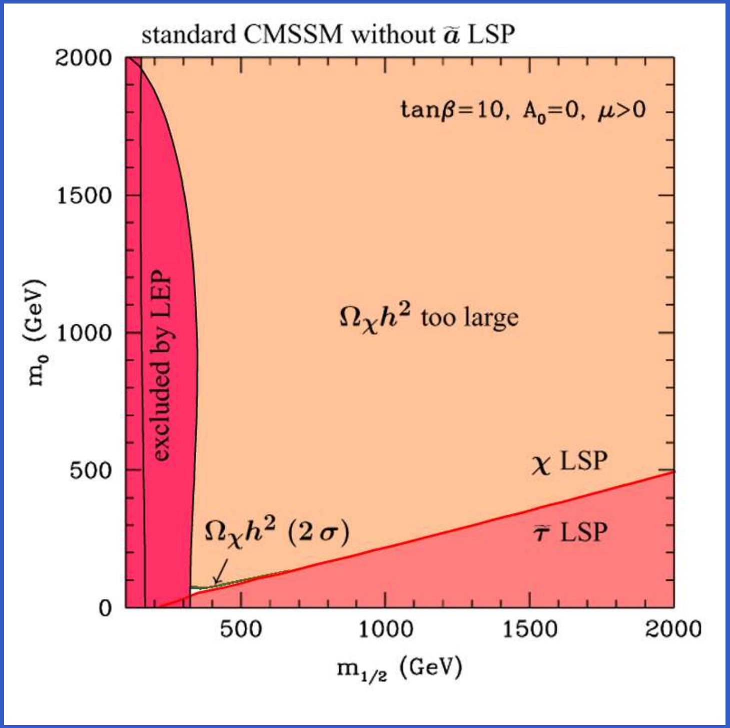

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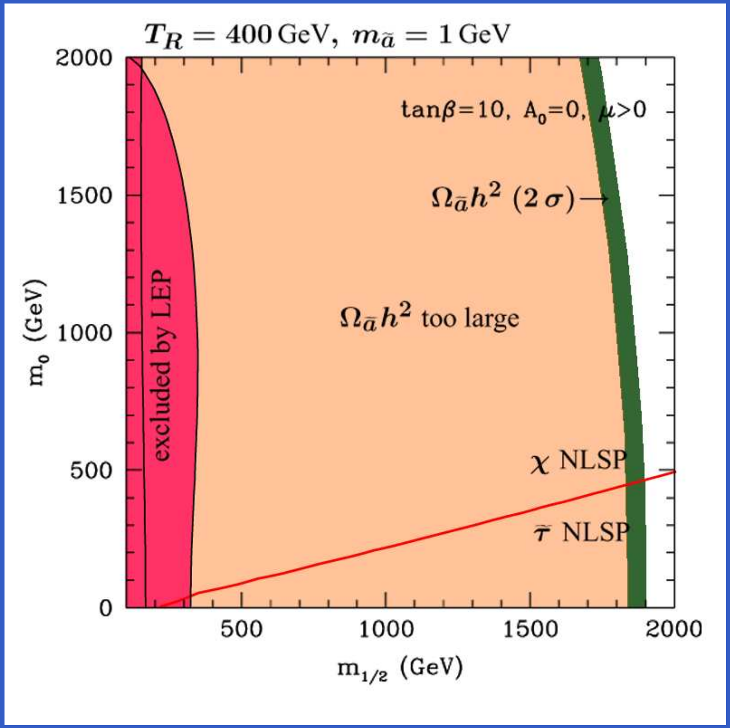

NLSP: either standard "missing energy" signature (χ) or charged ($\widetilde{\tau}_1$)

NLSP lifetime $\gg 10^{-7}\,\mathrm{sec} \Rightarrow$ at LHC it will appear stable

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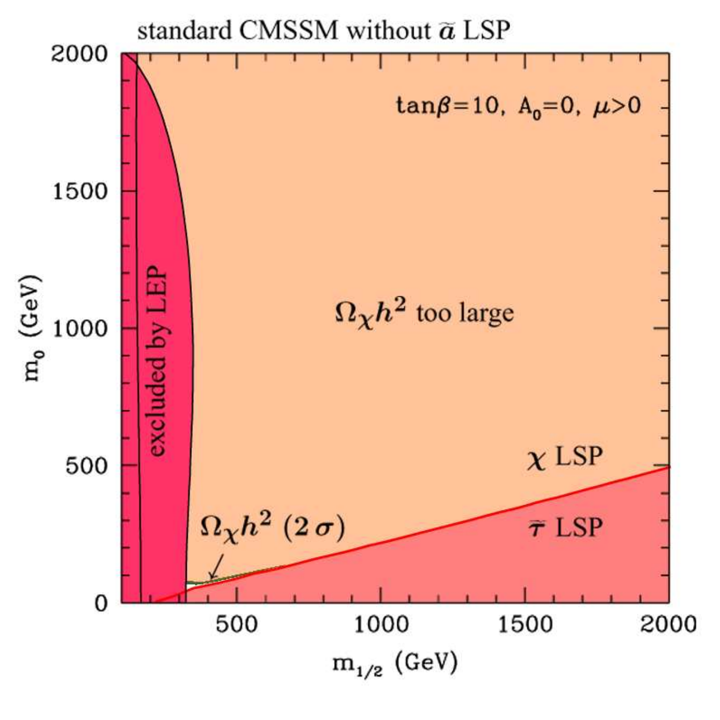

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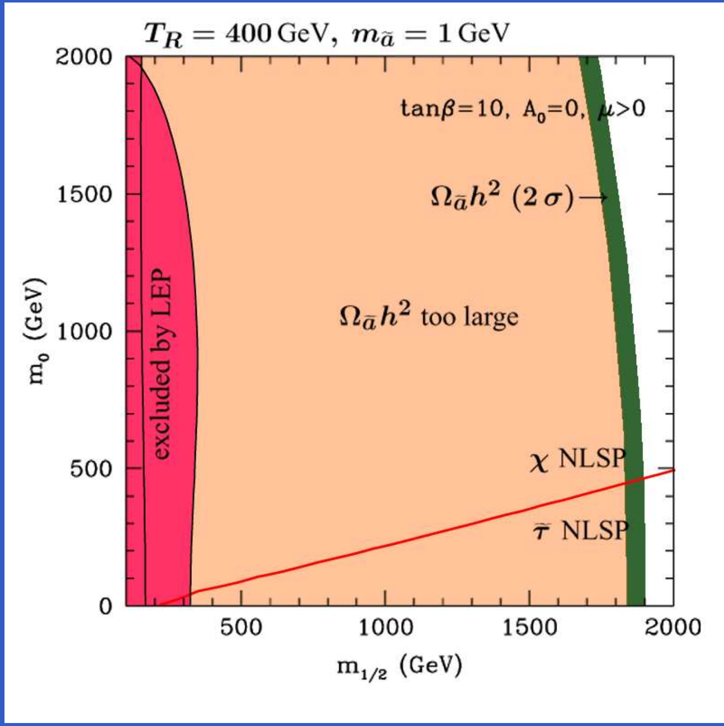

if $\widetilde{\tau}_1$–NLSP $\Rightarrow$ a striking signature at the LHC:

a stable, charged, massive ($\sim \mathcal{O}(100\,\mathrm{GeV})$) particle

The Gravitino $\widetilde{G}$

spin–$3/2$ partner of the graviton

- in gravity–mediated SUSY breaking models

$$m_{\widetilde{G}} = \frac{F}{\sqrt{3}M_{\rm P}}$$

$F \sim 10^{11}$ GeV – SUSY breaking scale
$M_{\rm P} = 2.4 \times 10^{18}$ GeV – reduced Planck mass
soft masses $\sim F/M_{\rm P}$

natural to expect: $m_{\widetilde{G}} \sim$ GeV $-$ TeV

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- if it is the LSP. . .

can $\widetilde{G}$ give $\Omega_{\rm CDM} h^2 \sim 0.1$?

$\widetilde{G}$: cold (not warm) DM

Gravitino WIMP in the CMSSM

Gravitino WIMP in the CMSSM

(analogous to $\tilde{a}$ LSP)

Roszkowski+Ruiz de Austri+K.-Y. Choi,
hep-ph/0408227

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Roszkowski+Ruiz de Austri+K.-Y. Choi, hep-ph/0408227

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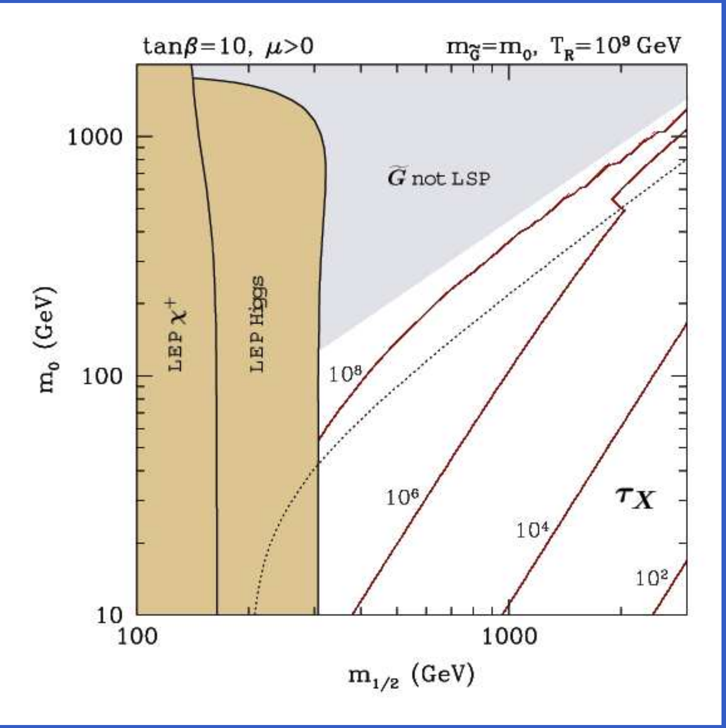
$$\tau(\text{NLSP}\to\widetilde{G}+\gamma/\tau)\sim 10^8\,\mathbf{sec}\left(\frac{\mathbf{100\,GeV}}{m_{\mathbf{NLSP}}}\right)^5\left(\frac{m_{\widetilde{G}}}{\mathbf{100\,GeV}}\right)^2\ldots$$

$(\mathbf{NLSP}=\chi(\simeq\widetilde{B}),\widetilde{\tau}_1)$

...well after BBN

NLSP Lifetime

Roszkowski+Ruiz de Austri+K.-Y. Choi, hep-ph/0408227



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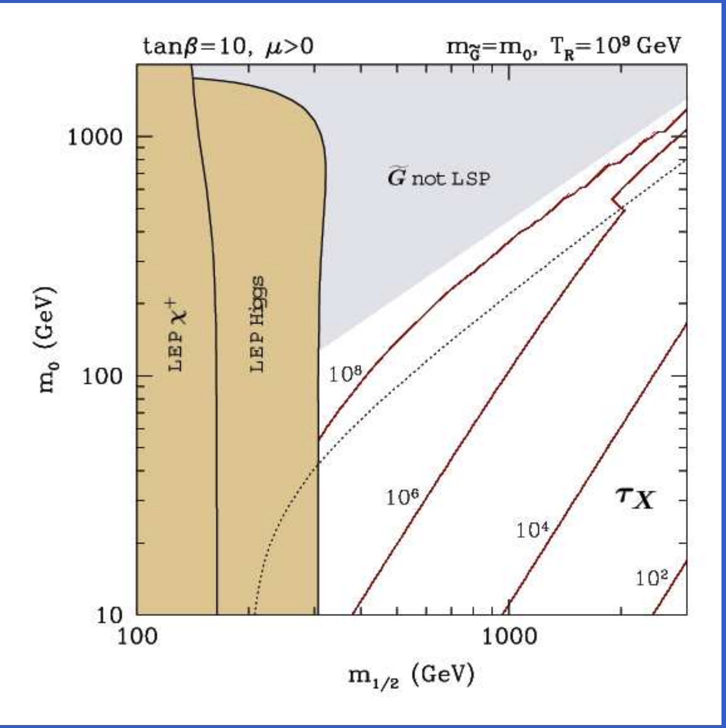
Roszkowski+Ruiz de Austri+K.-Y. Choi, hep-ph/0408227



- χ–NLSP: $\chi \longrightarrow \widetilde{G}\gamma$ dominant

$$\Gamma \simeq \frac{(\cos\theta_W)^2}{48\pi M_P^2}\frac{m_\chi^5}{m_{\widetilde{G}}^2}\left(1-\frac{m_{\widetilde{G}}^2}{m_\chi^2}\right)^3\left(1+3\frac{m_{\widetilde{G}}^2}{m_\chi^2}\right)$$

when $\chi \simeq \mathrm{bino}$

- $\widetilde{\tau}_1$–NLSP: $\widetilde{\tau}_1 \longrightarrow \widetilde{G}\tau$ dominant

$$\Gamma = \frac{1}{48\pi M_P^2}\frac{m_{\widetilde{\tau}_1}^5}{m_{\widetilde{G}}^2}\left(1-\frac{m_{\widetilde{G}}^2}{m_{\widetilde{\tau}_1}^2}\right)^4$$

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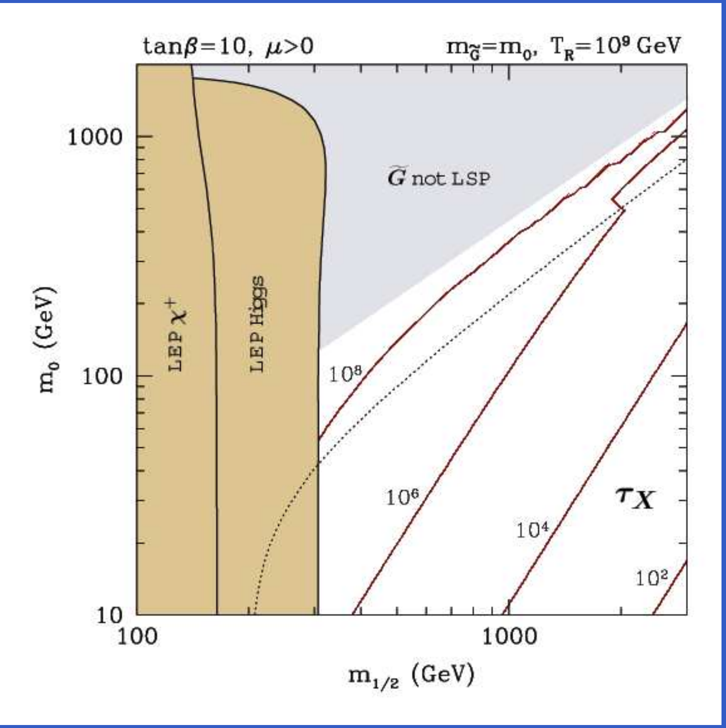

- χ–NLSP: $\chi \longrightarrow \widetilde{G}\gamma$ dominant

$$\Gamma \simeq \frac{(\cos\theta_W)^2}{48\pi M_P^2}\frac{m_\chi^5}{m_{\widetilde{G}}^2}\left(1-\frac{m_{\widetilde{G}}^2}{m_\chi^2}\right)^3\left(1+3\frac{m_{\widetilde{G}}^2}{m_\chi^2}\right)$$

when $\chi \simeq \mathbf{bino}$

- $\widetilde{\tau}_1$–NLSP: $\widetilde{\tau}_1 \longrightarrow \widetilde{G}\tau$ dominant

$$\Gamma = \frac{1}{48\pi M_P^2}\frac{m_{\widetilde{\tau}_1}^5}{m_{\widetilde{G}}^2}\left(1-\frac{m_{\widetilde{G}}^2}{m_{\widetilde{\tau}_1}^2}\right)^4$$

longer lifetimes $\Rightarrow$ stronger constraints

Gravitino WIMP in the CMSSM

(analogous to $\widetilde{a}$ LSP)

Roszkowski+Ruiz de Austri+K.-Y. Choi,
hep-ph/0408227

- $\widetilde{G} =$ LSP
- NLSP (χ or $\widetilde{\tau}_1$) first freezes out, then decays

$$\tau(\text{NLSP} \rightarrow \widetilde{G} + \gamma/\tau) \sim \mathbf{10^8\,sec} \left(\frac{\mathbf{100\,GeV}}{m_{\mathbf{NLSP}}}\right)^{\mathbf{5}} \left(\frac{m_{\widetilde{G}}}{\mathbf{100\,GeV}}\right)^{\mathbf{2}} \ldots$$

$(\mathbf{NLSP} = \chi(\simeq \widetilde{B}), \widetilde{\tau}_1)$

...well after BBN

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$\Rightarrow$ NTP:

NTP: non–thermal production (neglect other possible contr's)

$$\Omega_{\widetilde{G}}^{\mathrm{NTP}} = \frac{m_{\widetilde{G}}}{m_{\mathrm{NLSP}}}\,\Omega_{\mathrm{NLSP}}$$

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Feng, et al (FST 02-04), MSSM

Ellis, et al (EOSS 03), CMSSM

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$\Rightarrow$ TP: $q\,q \to \widetilde{G}\,\widetilde{g},\quad \widetilde{q} \to \widetilde{G}\,q, \ldots$

TP: thermal production

$$\Omega_{\widetilde{G}}^{\mathrm{TP}} \simeq 0.2\left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)\left(\frac{100\,\mathrm{GeV}}{m_{\widetilde{G}}}\right)\left(\frac{m_{\widetilde{g}}(\mu)}{1\,\mathrm{TeV}}\right)^2$$

Bolz+Brandenburg+Buchmüller ('00)

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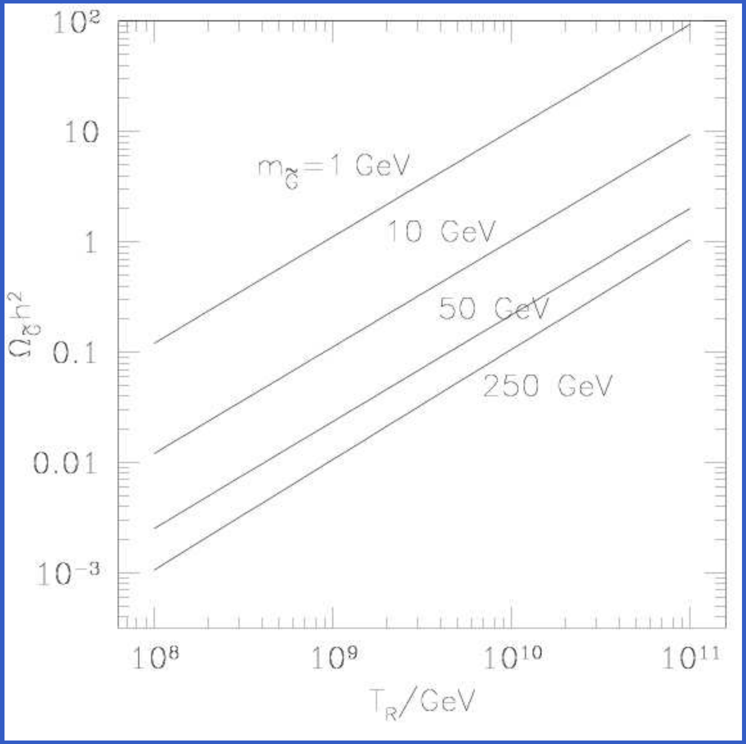
Bolz+Brandenburg+Buchmüller ('00)

At high $T_R \gtrsim 10^9$ GeV, TP is important

$\Omega^{\rm TP}_{\widetilde{G}} h^2$ – Thermal Production

with thermal QCD effects, Bolz+Brandenburg+Buchmüller ('00)

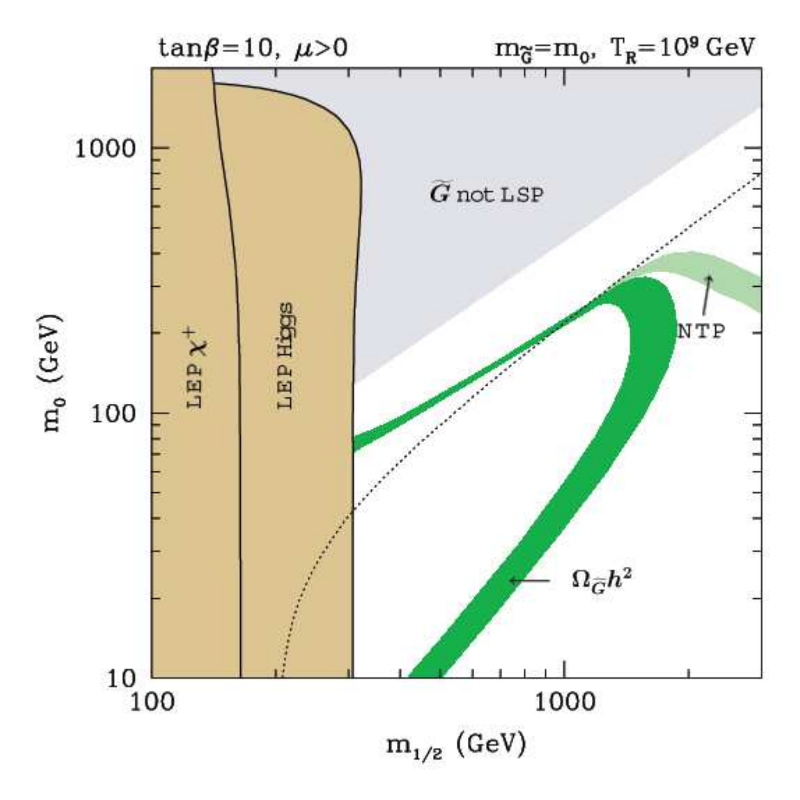
$$\Omega^{\rm TP}_{\widetilde{G}} \simeq 0.2 \left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)\left(\frac{100\,\mathrm{GeV}}{m_{\widetilde{G}}}\right)\left(\frac{m_{\widetilde{g}}(\mu)}{1\,\mathrm{TeV}}\right)^2$$



old calculation, cf. Ellis, *et al.* (EKN, '84), Moroi, *et al.* (MMY '93)

Relic Abundance

Roszkowski+Ruiz de Austri+K.-Y. Choi, hep-ph/0408227 ⟶ JHEP



- NTP: contribution to $\Omega_{\widetilde{G}}h^2$ from NLSP freezeout and decay
- $\Omega_{\widetilde{G}}h^2 = \Omega_{\widetilde{G}}^{\rm NTP}h^2 + \Omega_{\widetilde{G}}^{\rm TP}h^2$ (sum of NTP and TP contributions)

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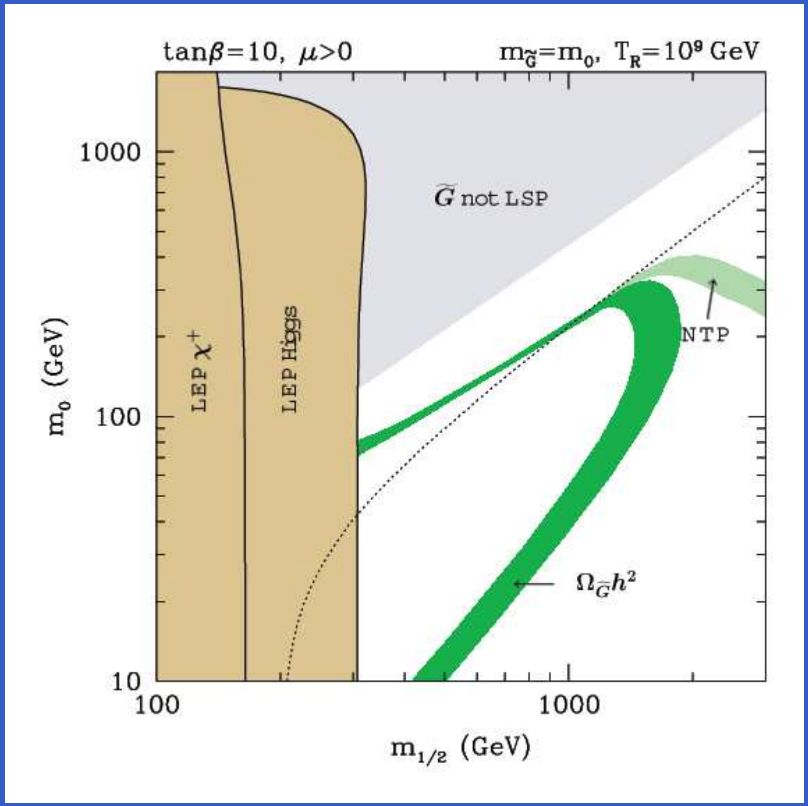

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at large $T_R \sim 10^9$ GeV TP dominates

. . . Constraints

"gravitino problem"

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  $\Longrightarrow$ EM showers

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- CMB: late injection of EM energy $\Rightarrow$ possible distortion of blackbody spectrum

  BE dist'n f'n $f_\gamma(E) = 1/\left(e^{E/(kT)+\mu} - 1\right)$ $(\mu - \mathrm{chemical\ potential})$

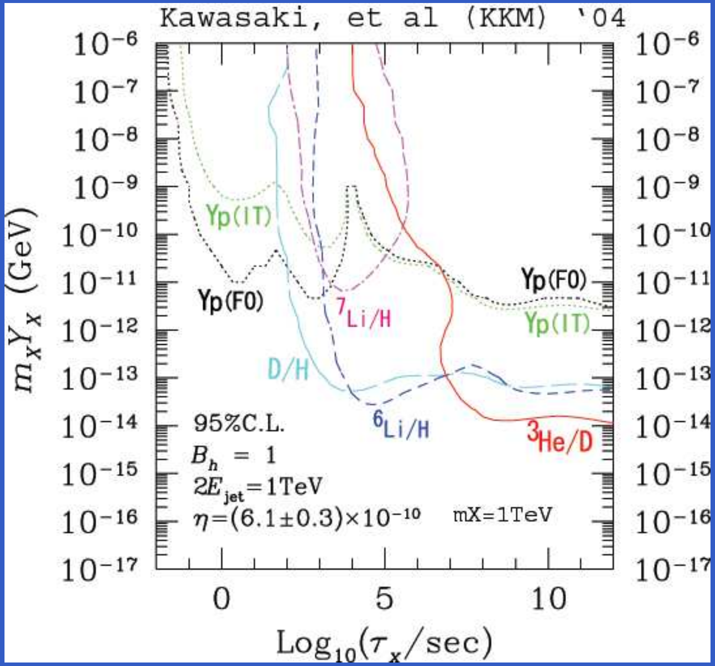
  current bound: $\mu < 9 \times 10^{-5}$

...BBN Constraints

Some main processes:

- 10^1 sec $\lesssim \tau \lesssim 10^2$ sec:
  ^4He overprod'n: $n + p \to D \to {}^4He$
- $\tau \gtrsim 10^2$ sec:
  D overprod'n: $n + p \to D$, $n + {}^4He \to D$
- 10^4 sec $\lesssim \tau \lesssim 10^6$ sec:
  D overdestruction: $\gamma + D \to n + p$
- 10^6 sec $\lesssim \tau \lesssim 10^8$ sec:
  D overproduction: $\gamma + {}^4He \to D + D$

Kawasaki+Kohri+Moroi (Jun '04)



note $B_h = 1$
(CMSSM $\sim 10^{-2} - 10^{-4}$)

BBN Constraint

- apply $D/H + Y_p + {}^7Li/H + {}^3He/D + {}^6Li/{}^7Li$

Cerdeño+K.-Y. Choi+Jedamzik+L.R.+Ruiz de Austri, in prep.
new, improved analysis
follow the initial hep-ph/0408227 (L.R.+Ruiz de Austri+K.-Y. Choi)

- self–consistent, both EM & HAD, vary B_h as f'n of SUSY parameters
- adopt abundances of light elements from observations (Jedamzik):

$$2.2 \times 10^{-5} < D/H < 5.3 \times 10^{-5}$$

$$0.232 < Y_p < 0.258$$

$$1.11 \times 10^{-10} < {}^7Li/H < 4.5 \times 10^{-10}$$

$${}^3He/D < 1.72$$

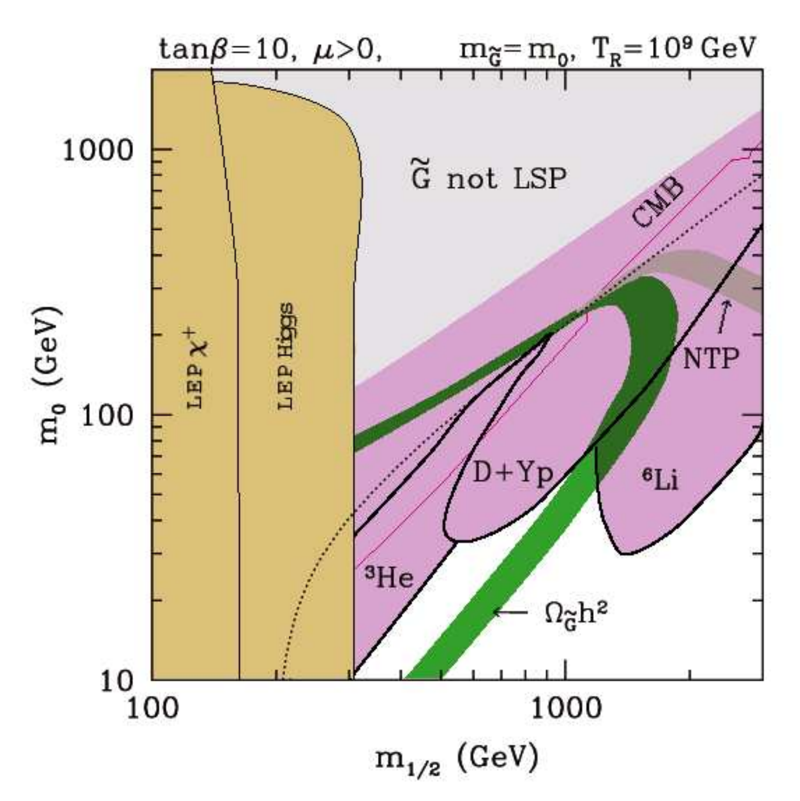
$${}^6Li/{}^7Li < 0.1875$$

- Jedamzik's inputs somewhat more conservative than KKM
- Jedamzik's analysis more complete (EM+HAD) than Cyburt, *et al.*, (CEFO) (EM only)

Example: $m_{\tilde{G}} = m_0$

Cerdeño+K.-Y. Choi+Jedamzik+L.R.+Ruiz de Austri, in prep.

apply all BBN: $D/H + Y_p + {}^7Li/H + {}^3He/D + {}^6Li/{}^7Li$



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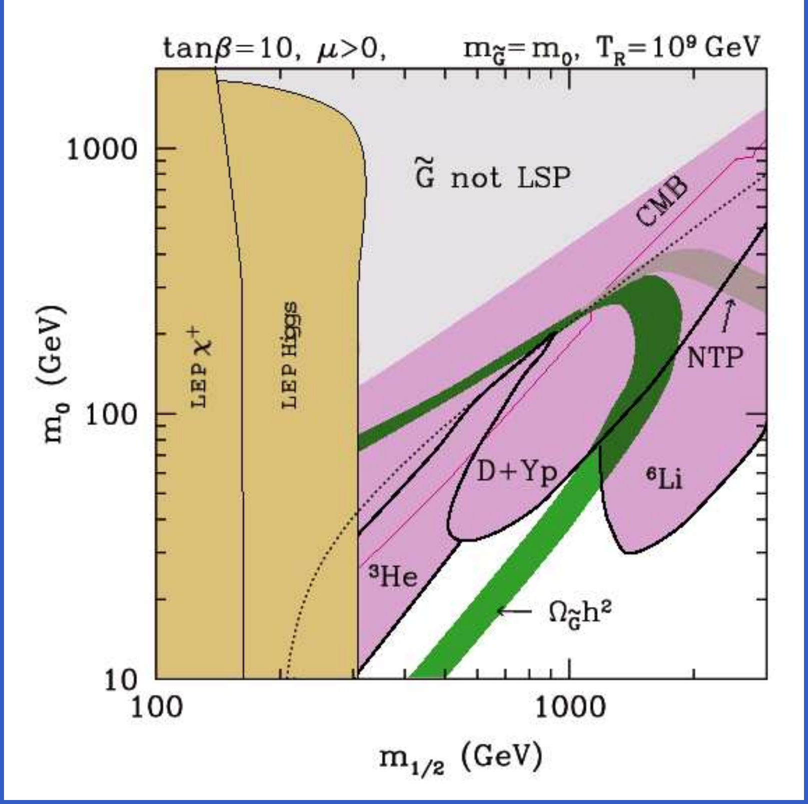


- only $\widetilde{\tau}_1$–NLSP region remains allowed

$\Rightarrow$ at LHC see charged "stable" LOSP $\widetilde{\tau}_1$ (instead of "expected" neutral χ)

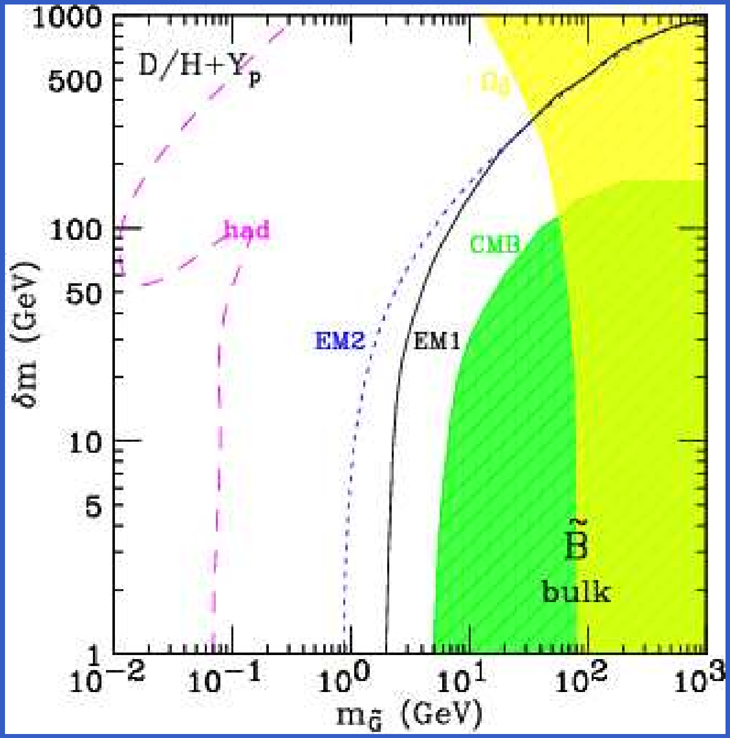
confirmed Feng, et al (Apr 04)

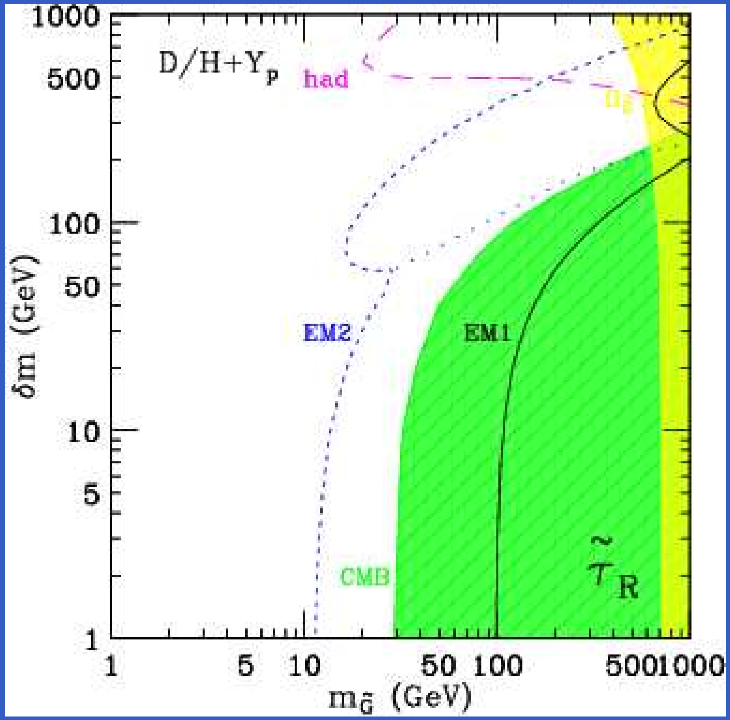
- low T_R basically excluded (NTP part only), must include TP contribution to $\Omega_{\widetilde{G}}h^2$

$\Rightarrow$ $m_{\widetilde{G}} = \mathcal{O}(100\,\text{GeV})$: (typically) need high $T_R \sim 10^9$ GeV

Feng+Su+Takayama, hep-ph/0404231

...used stronger BBN constraints (from KKM)





χ region excluded, stau region OK

Wrong Vacuua, Roll down to –Infinity...

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dangerous UFB-3$= (H_u, \nu_{L_i}, e_{L_j}, e_{R_j})$, $i \neq j$ (Casas, Lleyda, Muñoz)

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dangerous UFB-3$= (H_u, \nu_{L_i}, e_{L_j}, e_{R_j}), \; i \neq j$ (Casas, Lleyda, Muñoz)

- use 1–loop improved RGE to obtain masses and couplings, plug them into a tree–level potential, minimize at $\hat{Q} \sim \max(\lambda_{top}|H_u|, M_{SUSY})$
- condition

$$V_{\rm UFB-3}(Q = \hat{Q}) > V_{\rm SM\ min} = -\frac{1}{8}\left(g'^2 + g_2^2\right)\left(v_u^2 - v_d^2\right)^2$$

...UFB

Casas, Lleyda, Muñoz (98)

for any value of $|H_u| < M_{GUT}$ s.t.

$$|H_u| > \sqrt{\frac{\mu^2}{4\lambda_{e_j}^2} + \frac{4m_{L_i}^2}{g'^2+g_2^2}} - \frac{|\mu|}{2\lambda_{e_j}}$$

one finds

$$V_{\mathrm{UFB-3}} = (m_{H_u}^2 + m_{L_i}^2)|H_u|^2 + \frac{|\mu|}{\lambda_{e_j}}(m_{L_j}^2 + m_{e_j}^2 + m_{L_i}^2)|H_u| - \frac{2m_{L_i}^4}{g'^2+g_2^2}$$

otherwise

$$V_{\mathrm{UFB-3}} = m_{H_u}^2|H_u|^2 + \frac{|\mu|}{\lambda_{e_j}}(m_{L_j}^2 + m_{e_j}^2)|H_u| + \frac{1}{8}(g'^2 + g_2^2)\left[|H_u|^2 + \frac{|\mu|}{\lambda_{e_j}}|H_u|\right]^2$$

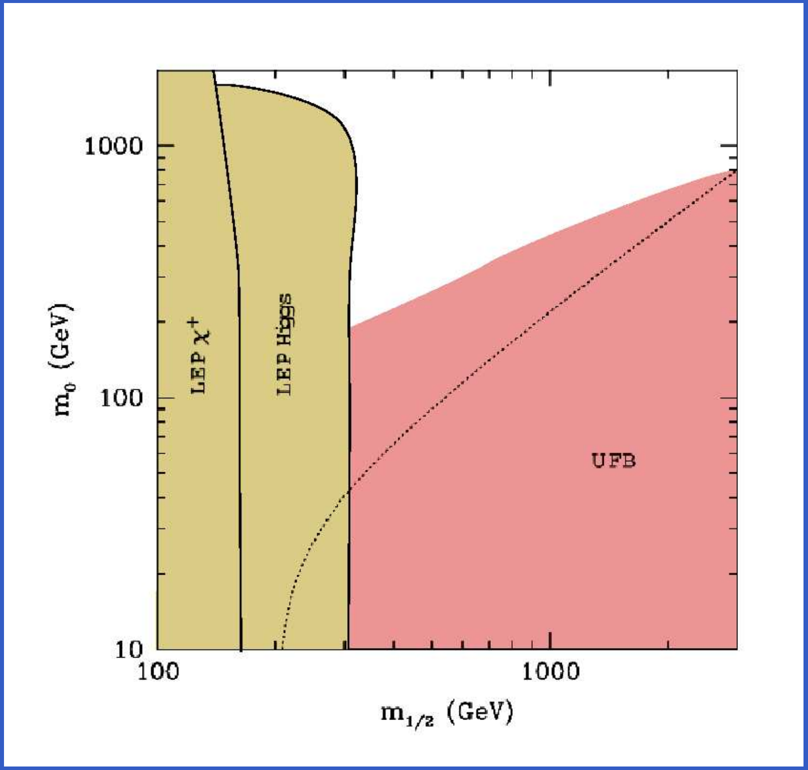
- -ve contribution: $m_{H_u}^2|H_u|^2$
- +ve contribution mostly from terms $\propto 1/\lambda_{e_j}$

  $\Rightarrow$ constraint strongest for λ_τ
- large $\tan\beta$: UFB condition becomes stronger

Impact of UFB Constraint

Cerdeño+K.-Y. Choi+Jedamzik+L.R.+Ruiz de Austri, in prep.

$\tan\beta = 10$, $A_0 = 0$



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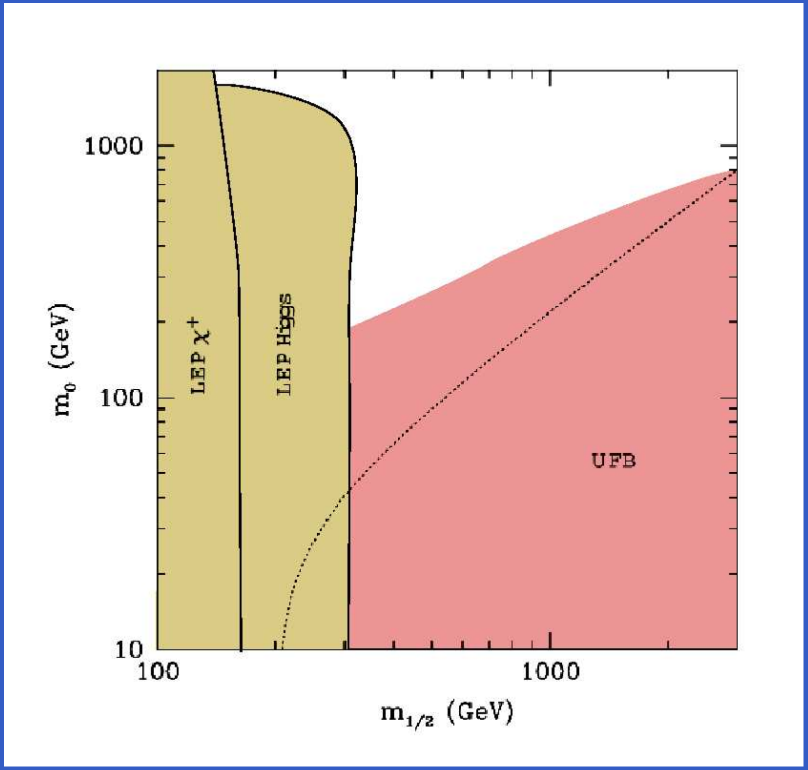
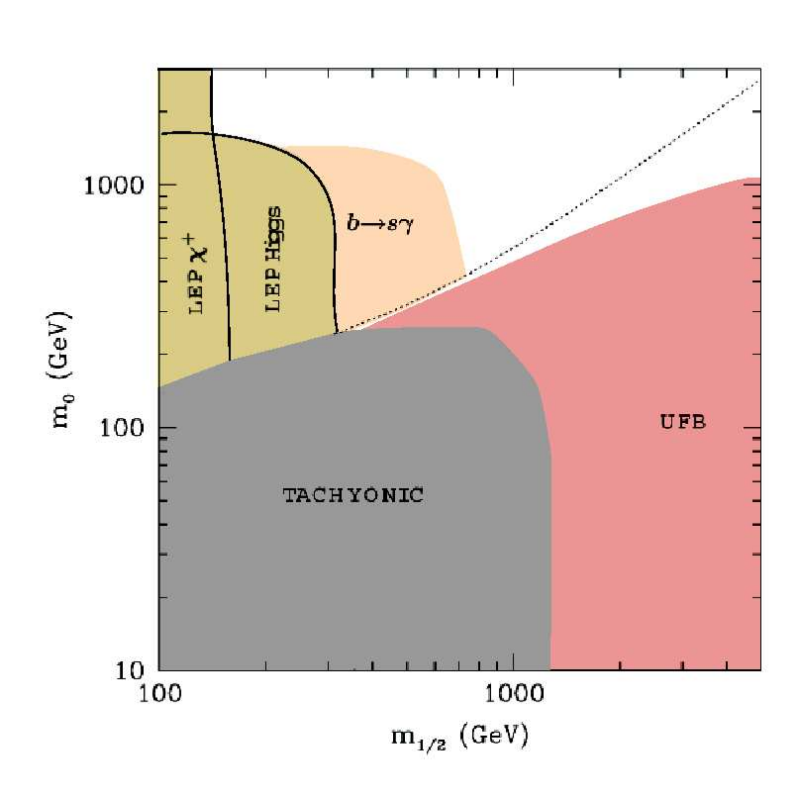


$\tan\beta = 50,\ A_0 = 0$



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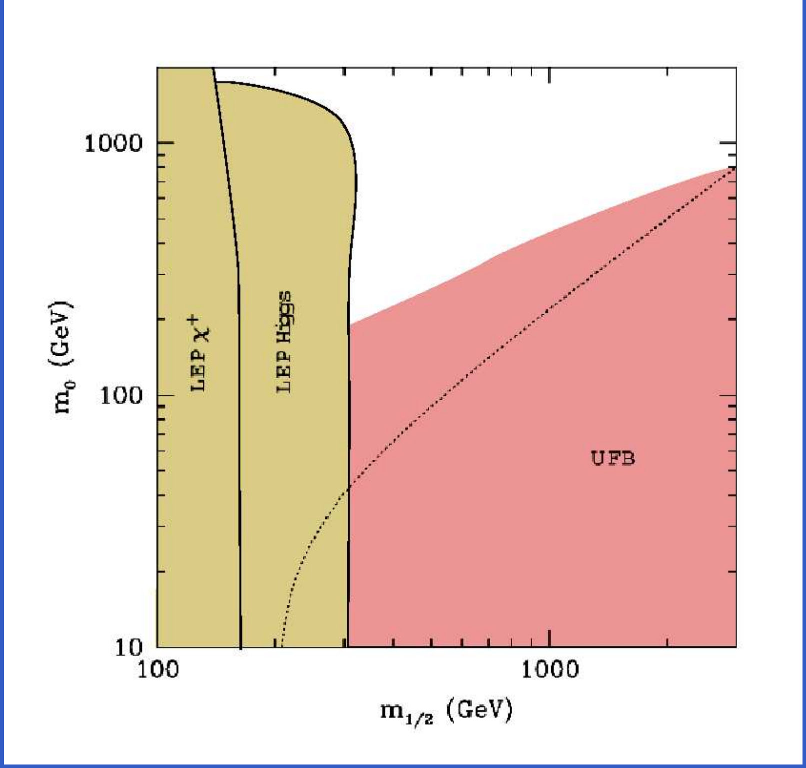

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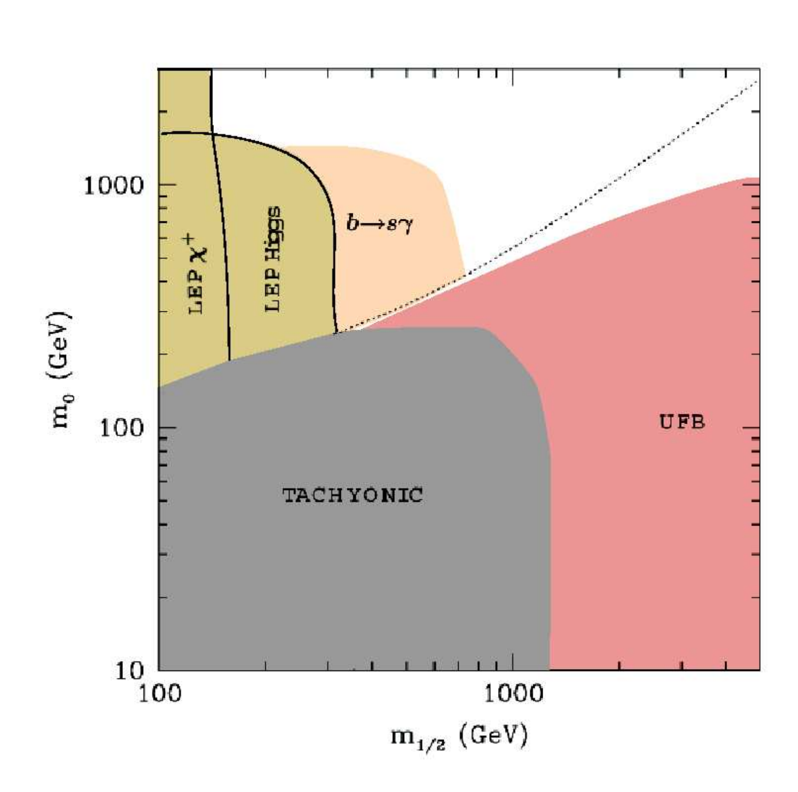

$\Rightarrow$ most of the $\widetilde{\tau}_1$–NLSP region excluded

Combine UFB and BBN

Cerdeño+K.-Y. Choi+Jedamzik+L.R.+Ruiz de Austri, in prep.

E.g., $T_R = 10^9$ GeV

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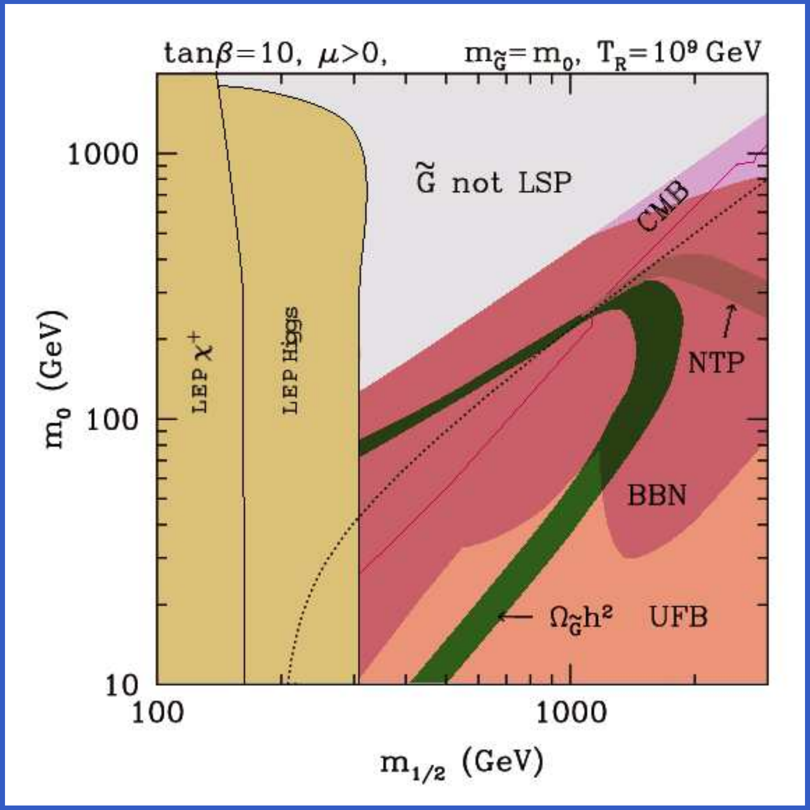

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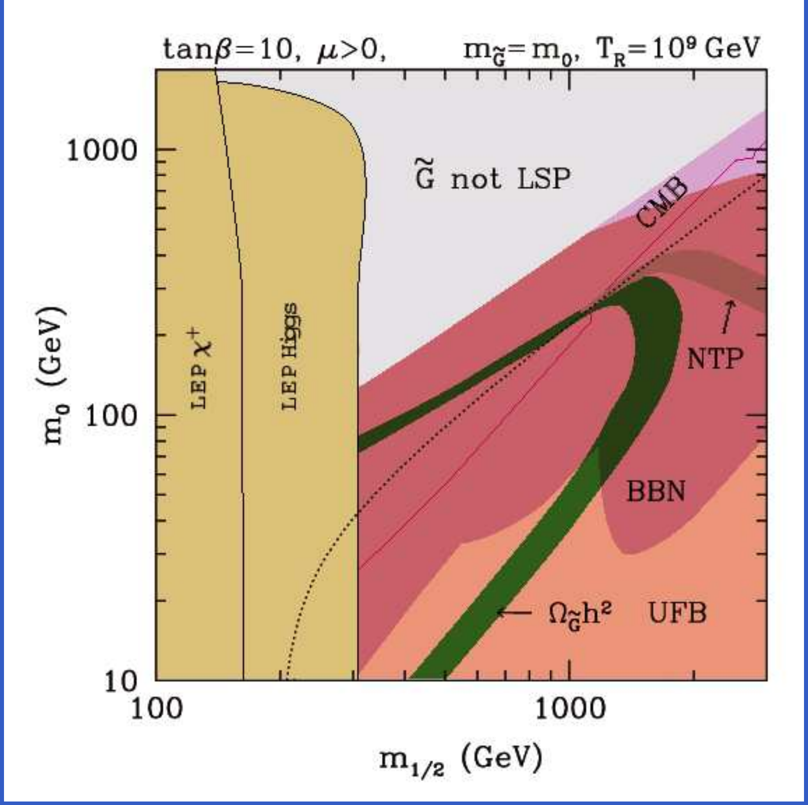

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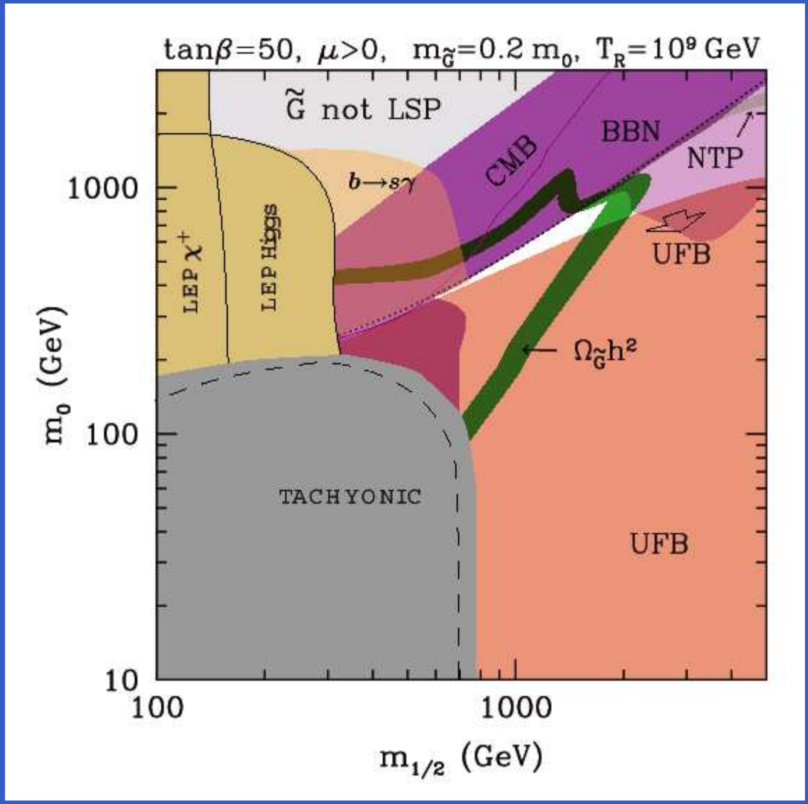

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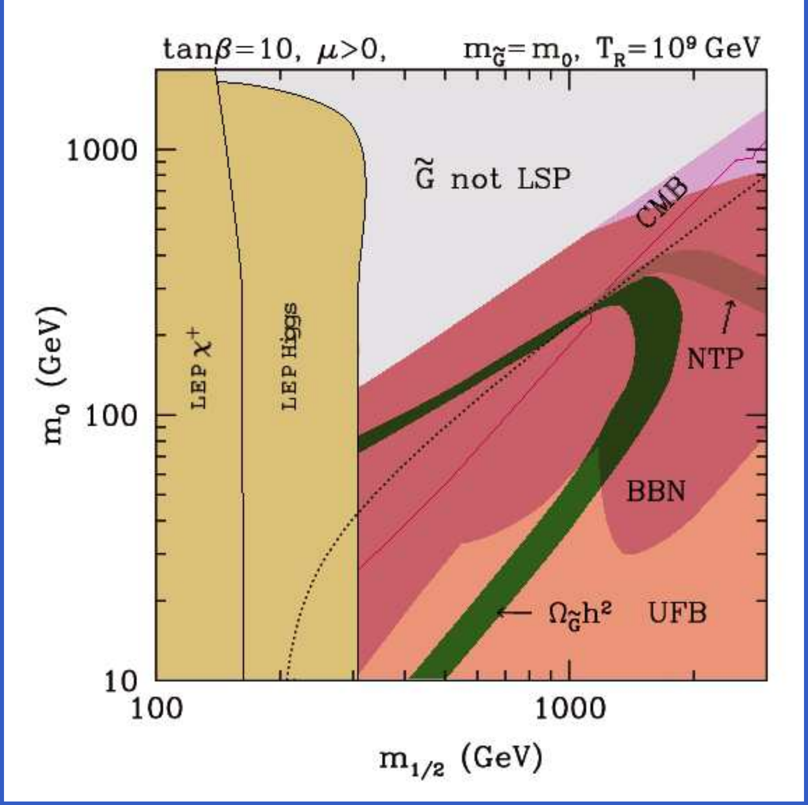

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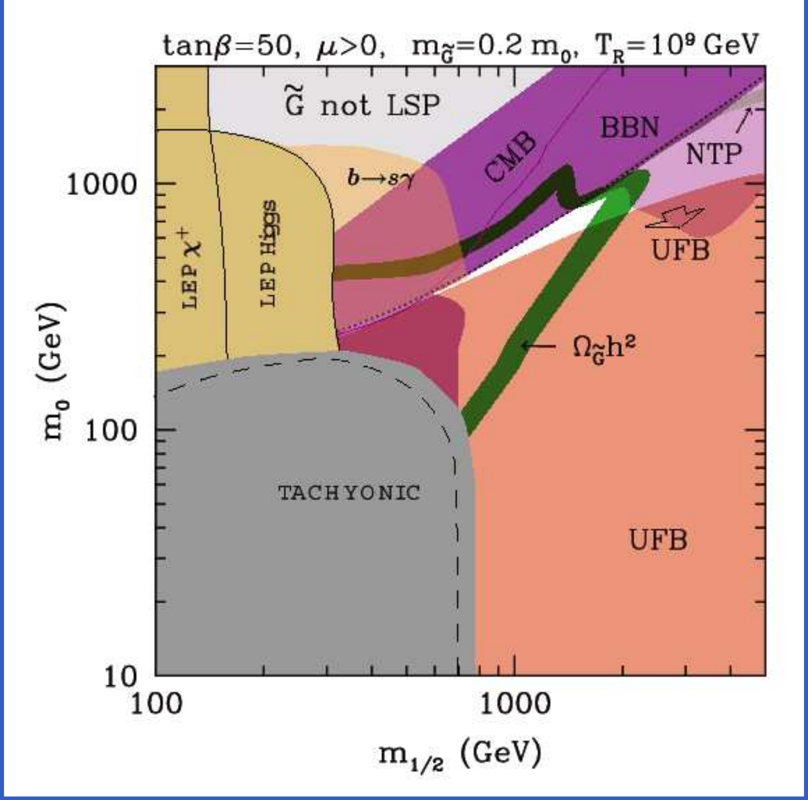


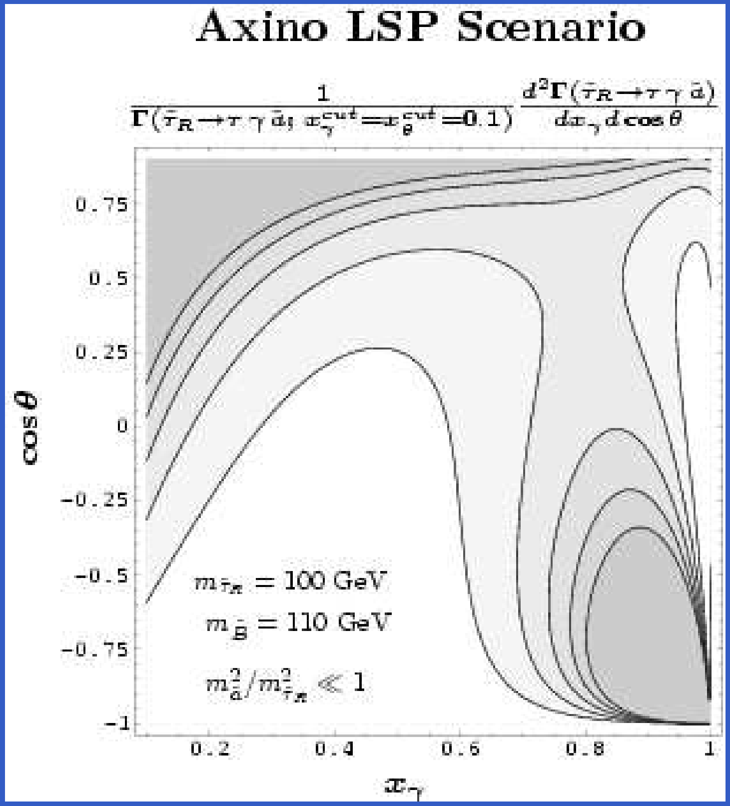
all excluded

small regions left allowed

$\widetilde{a}$ or $\widetilde{G}$ LSP?, Will we ever know?

stau decays at the LHC?

Brandenburg+Covi+Hamaguchi+L.R.+Steffen, hep-ph/0501287 ⟶ PLB



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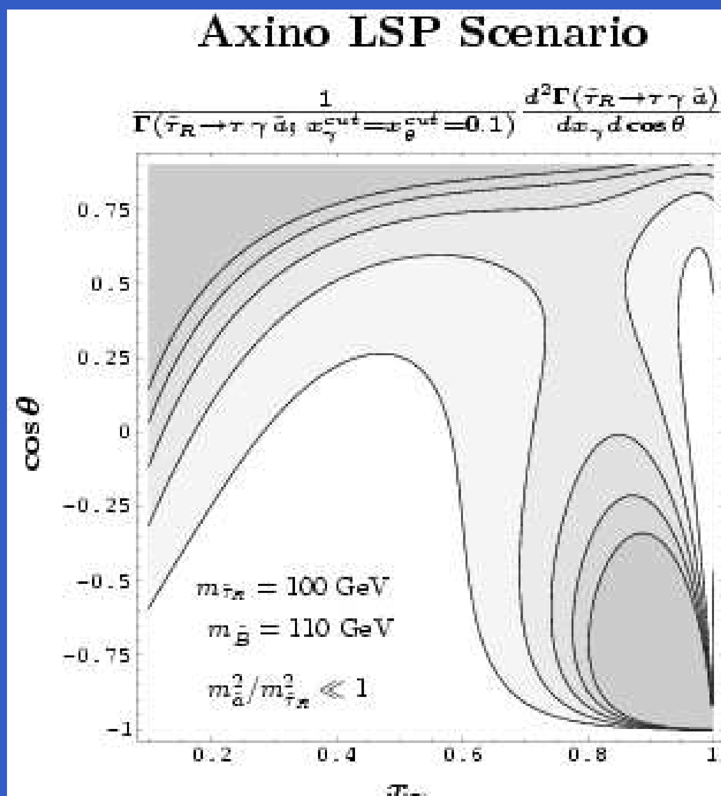

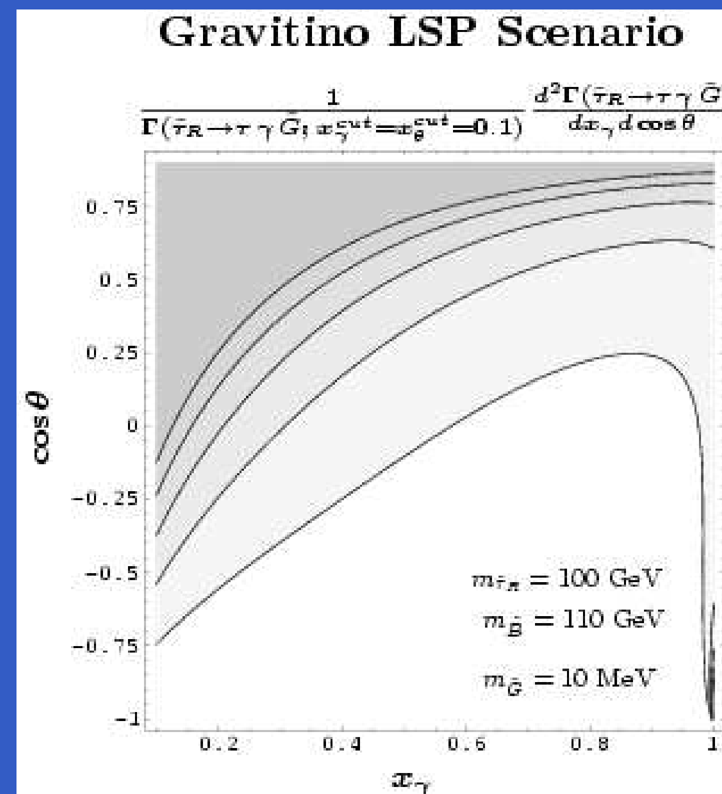

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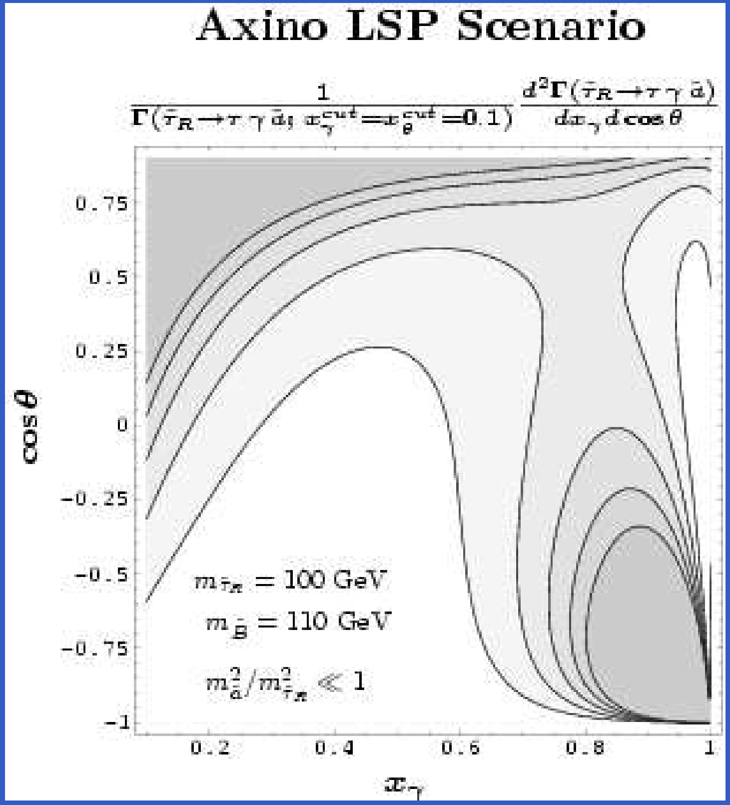

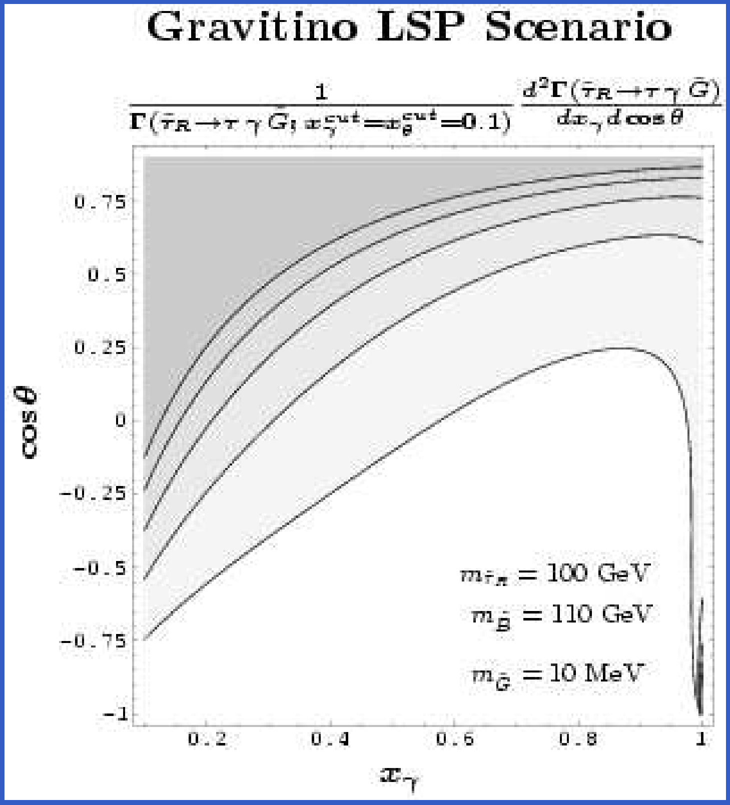

different event distributions

Summary

while the neutralino remains the prime suspect...

- $\widetilde{a}$ and $\widetilde{G}$ E–WIMPs are viable cold DM candidates

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...distinct cosmology and collider phenomenology

- if $\widetilde{a}$ LSP and CDM:
  - $\Rightarrow$ low $T_R \lesssim 10^6$ GeV
  - $\Rightarrow$ basically no bounds from BBN
  - $\Rightarrow$ NLSP either χ or $\widetilde{\tau}_1$ – to be partially probed at LHC

LHC: it will appear mostly stable but...

Summary

while the neutralino remains the prime suspect...

- $\widetilde{a}$ and $\widetilde{G}$ E–WIMPs are viable cold DM candidates

both well motivated by particle physics

...distinct cosmology and collider phenomenology

- if $\widetilde{a}$ LSP and CDM:
  - $\Rightarrow$ low $T_R \lesssim 10^6$ GeV
  - $\Rightarrow$ basically no bounds from BBN
  - $\Rightarrow$ NLSP either χ or $\widetilde{\tau}_1$ – to be partially probed at LHC

LHC: it will appear mostly stable but...

- if $\widetilde{G}$ LSP and CDM ($m_{\widetilde{G}} = \mathcal{O}(100\,\mathrm{GeV})$):
  - $\Rightarrow$ strong bounds from BBN and CMB
  - $\Rightarrow$ χ NLSP seems ruled out, $\widetilde{\tau}_1$ NLSP region partially allowed
  - $\Rightarrow$ $T_R \lesssim 10^9$ GeV

but... TP contribution to $\Omega_{\widetilde{G}} h^2$ important

Summary - cont.

- both $\widetilde{a}$ and $\widetilde{G}$:
  if $\widetilde{\tau}_1$ is NLSP $\Rightarrow$ we live in a false vacuum

we may find this out at LHC!

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Summary - cont.

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  if $\widetilde{\tau}_1$ is NLSP $\Rightarrow$ we live in a false vacuum

we may find this out at LHC!

...if insist on the Universe to occupy global minimum, then

- $\widetilde{\tau}_1$ NLSP region almost ruled out

$\Rightarrow$ $\widetilde{a}$ WIMP as CDM remains allowed

$\Rightarrow$ $\widetilde{G}$ WIMP as CDM seems basically excluded

in the CMSSM, for reasonable ranges of mass parameters:

small regions remain allowed

...still exploring...

E–WIMPs?

E–WIMPs?

exciting WIMPs?