Particle Dark Matter

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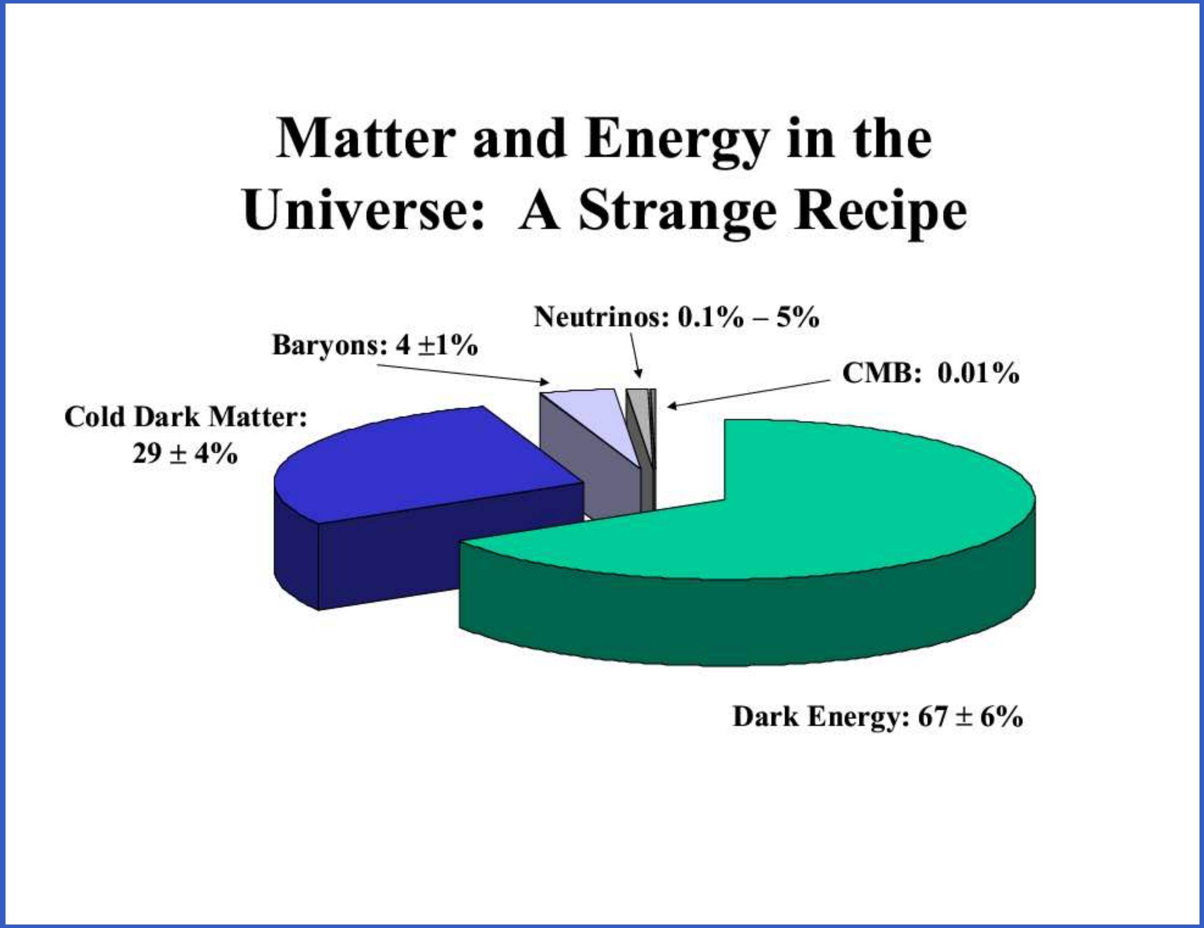
Cosmic ‘Balance of Powers’



The dominance of the ‘dark’...

Freedman+Turner

DM after WMAP...

Post WMAP (Mar 06) ...+ACBAR+CBI+... $\Omega = \rho/\rho_{crit}$

Hubble $H_0 = 100\,h\,\text{km/ s/ Mpc}$

- $\Omega_{\rm m} h^2 = 0.131 \pm 0.009$
- $\Omega_{\rm b} h^2 = 0.0223 \pm 0.0008$
- $\ldots$

$\Rightarrow$ most matter non–baryonic (DM problem)

- observations: haloes, etc.
- numerical simulations of LSS

$\Rightarrow$ cold DM (non–relativistic)

$$\Omega_{\rm CDM} h^2 = 0.109 \pm 0.009$$

(after WMAP–yr1: $\Omega_{\rm CDM} h^2 = 0.129 \pm 0.009$)

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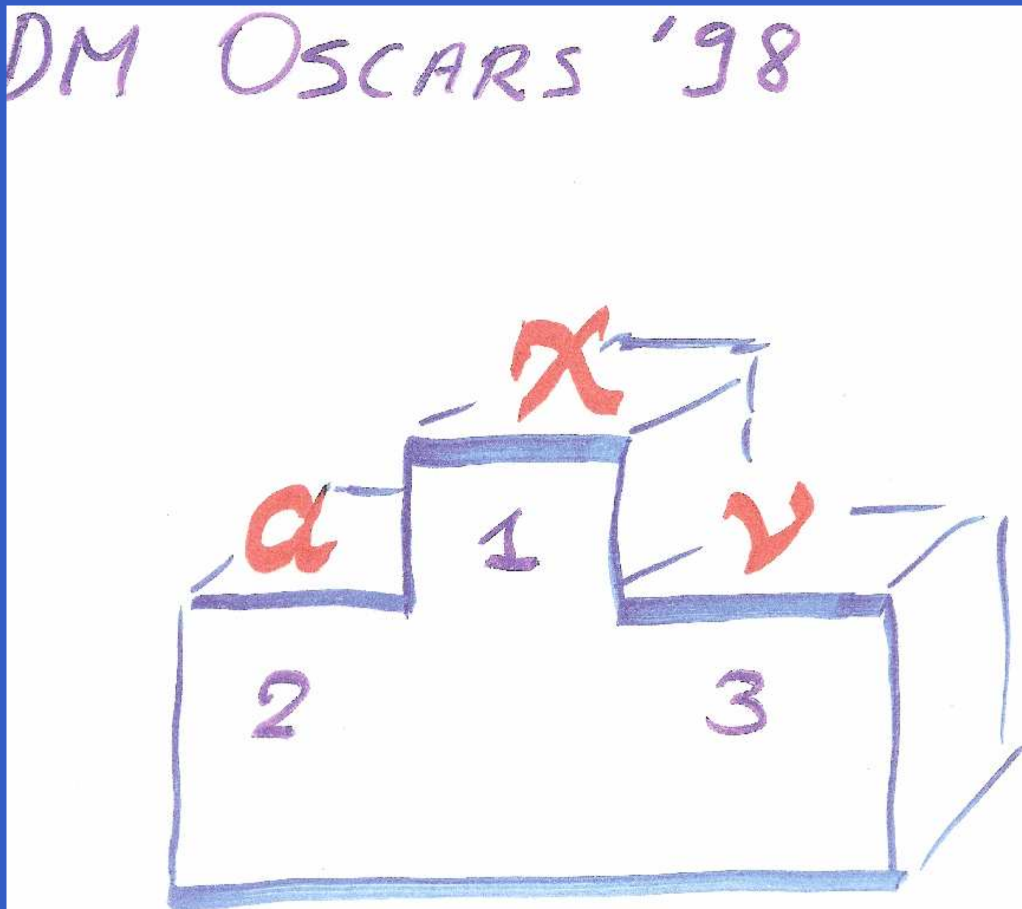
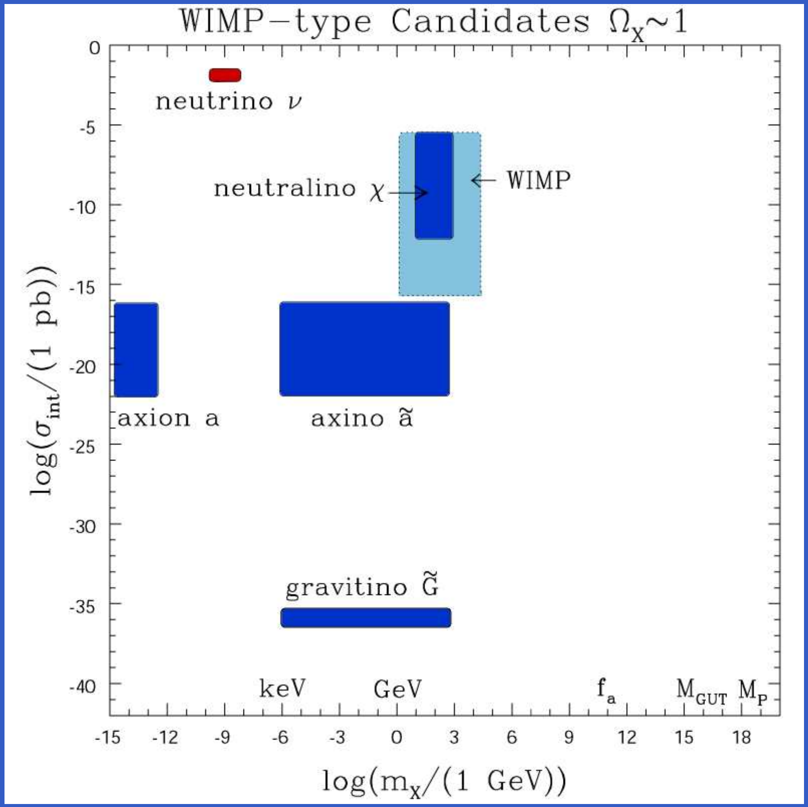
1998: $\Omega_\Lambda = 0$, $0.02 \lesssim \Omega_{\rm CDM} h^2 \lesssim 0.15$, hot+cold DM (?), ...

At PHENO–98...



DM: The Big Picture (2006)

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



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

The Neutralino – Prime Suspect

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neutralino $\chi =$ lightest mass eigenstate
of neutral gauginos $\widetilde{B}$ (bino), $\widetilde{W}_3^0$ (wino)
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Ellis, et al (EHNOS) ('84)

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typically when $\chi \simeq$bino

LR (PLB, 1990)

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- huge industry, many many authors

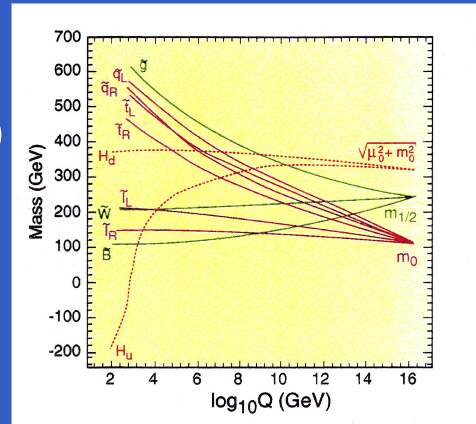
...apologies for not mentioning many interesting contributions

I will focus on direct detection and on links with detector searches

Constrained MSSM

...aka mSUGRA

At M_{GUT}:



- gauginos $M_1 = M_2 = m_{\tilde{g}} = m_{1/2}$ (c.f. MSSM)
- scalars $m^2_{\tilde{q}_i} = m^2_{\tilde{l}_i} = m^2_{H_b} = m^2_{H_t} = m_0^2$
- 3–linear soft terms $A_b = A_t = A_0$
- radiative EWSB

$$\mu^2 = \frac{\left(m^2_{H_b} + \Sigma_b^{(1)}\right) - \left(m^2_{H_t} + \Sigma_t^{(1)}\right)\tan^2\beta}{\tan^2\beta - 1} - \frac{m_Z^2}{2}$$

- five independent parameters: $\tan\beta,\ m_{1/2},\ m_0,\ A_0,\ \mathrm{sgn}(\mu)$
- mass spectra at m_Z:
  run RGEs, 2–loop for g.c. and Y.c, 1-loop for masses
- some important quantities $(\mu, m_A, \ldots)$ very sensitive to procedure of computing EWSB & minimizing V_H

we use Suspect

Constraining SUSY

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$\Rightarrow m_{\chi^+} > 104$ GeV (LEP)

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SM–like: $m_h > 114.4$ GeV (LEP)

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  $2.7\,\sigma$ effect (e^+e^-)

  where $a_\mu = (g_\mu - 2)/2$

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⇐ $b \to s\gamma$:

(full LO) + ($\tan\beta$–enhanced NLO)

in MFV framework

highly unstable

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$b \longrightarrow s\gamma$ and GFM

general flavor mixing

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general flavor mixing

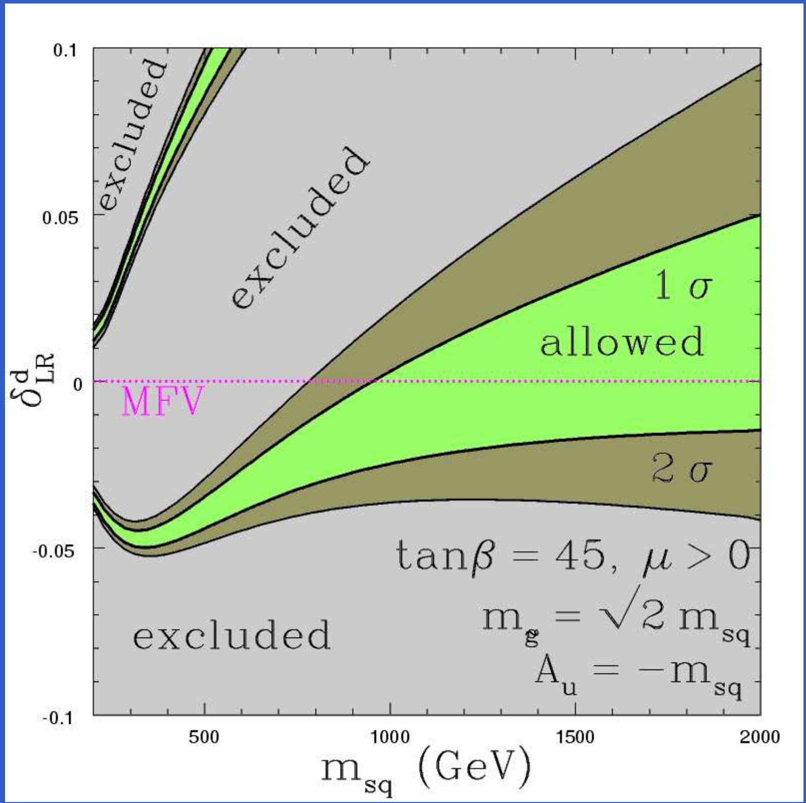
Okumura+Roszkowski, PRL'04

include dominant NLO–level contributions

enhanced at large $\tan\beta$

$$(\delta^d_{LL}) = \left(m^2_{d,LL}\right)_{23} / \sqrt{\left(m^2_{d,LL}\right)_{22}\left(m^2_{d,LL}\right)_{33}}$$

MFV: $\delta^d_{\cdot\cdot} = 0$



bounds highly unstable against small perturbations of MFV

Constrained MSSM

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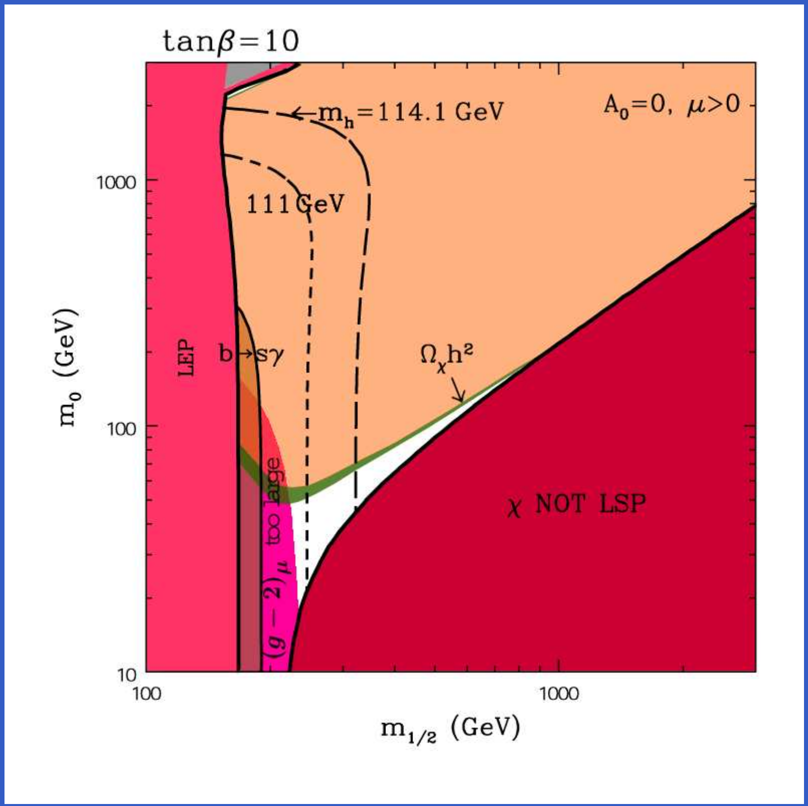
$\tan\beta \lesssim 45$



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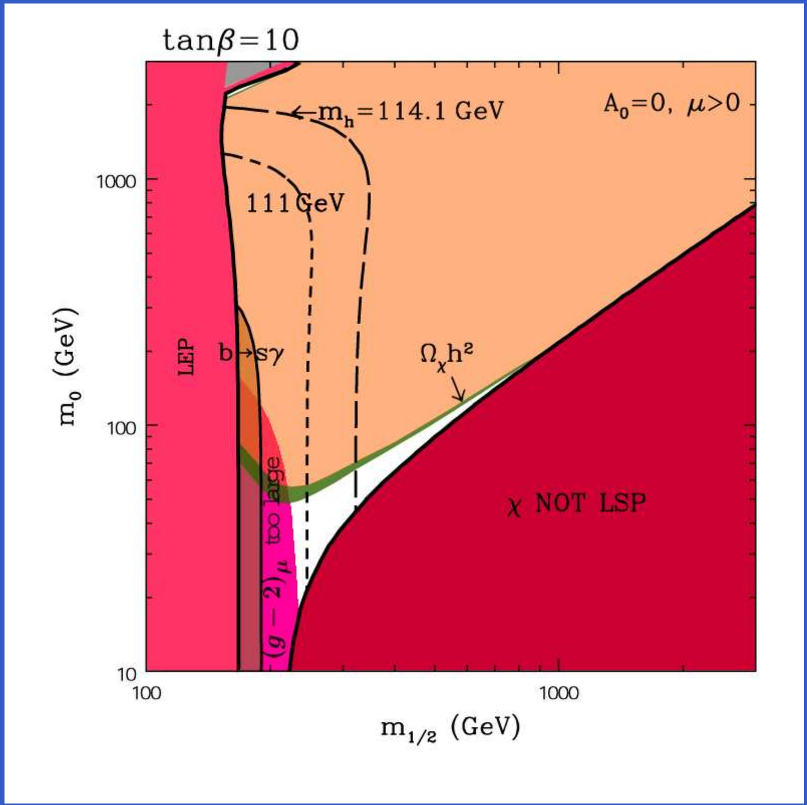
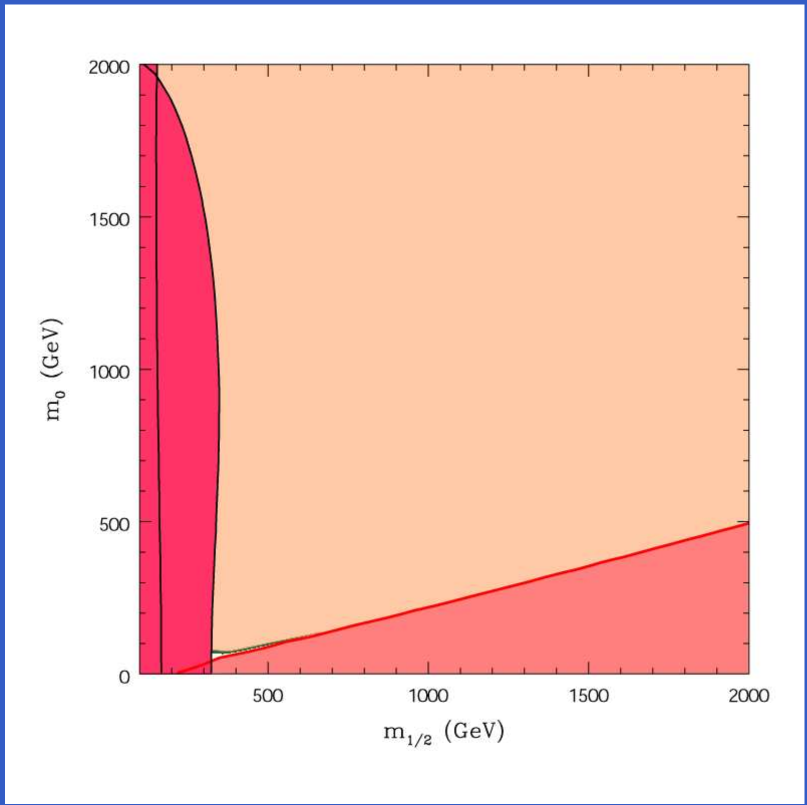


$\tan\beta \lesssim 45$, linear



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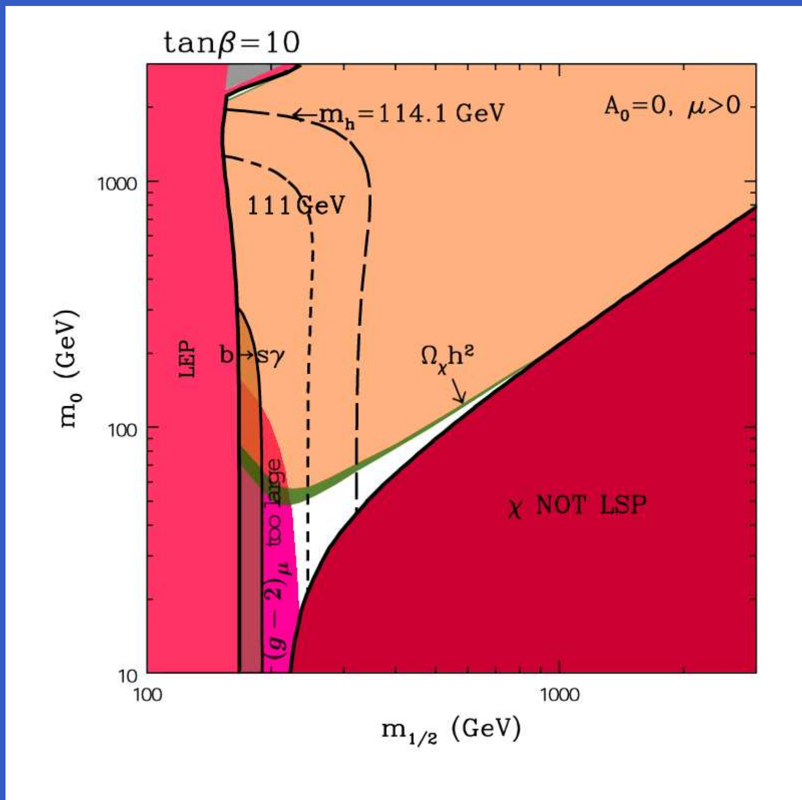

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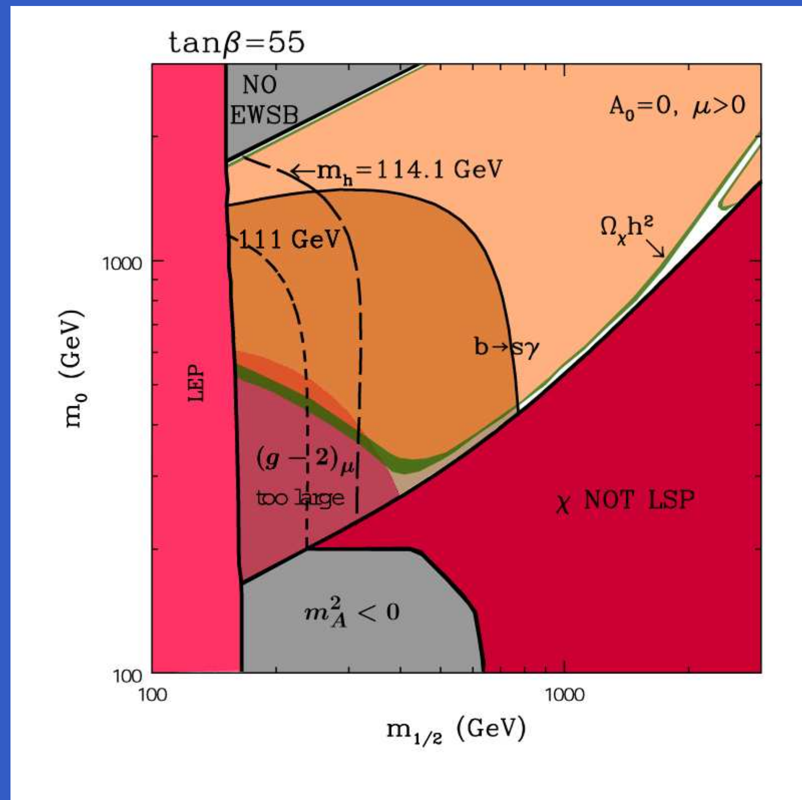

. . .left allowed

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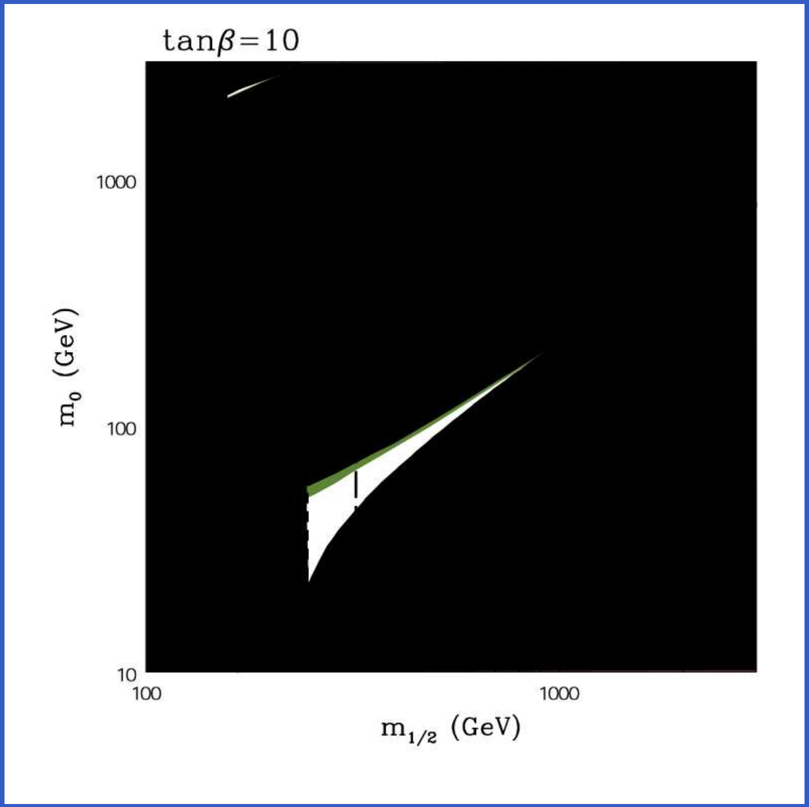

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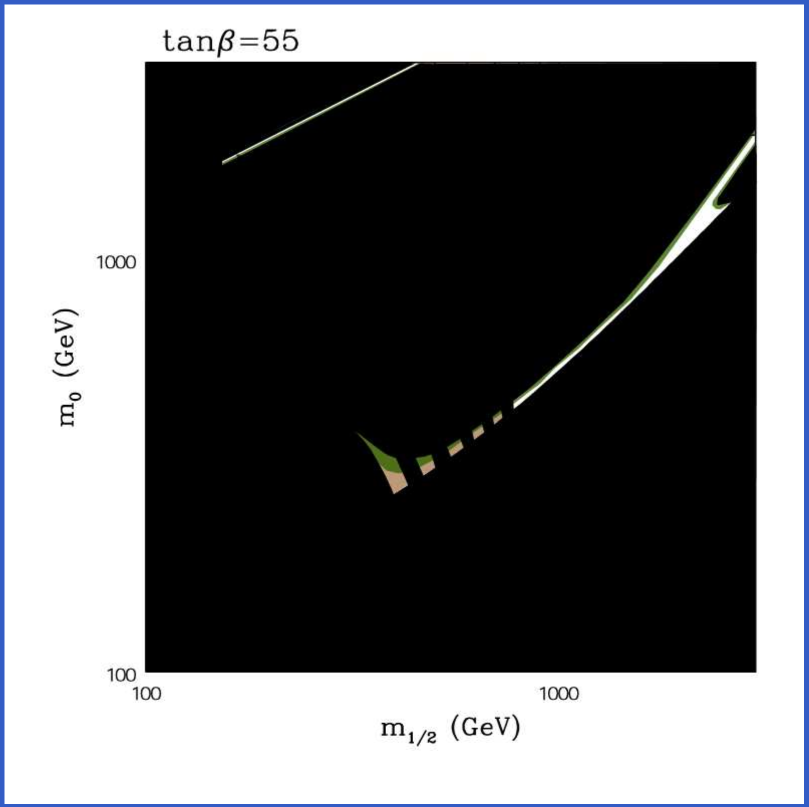
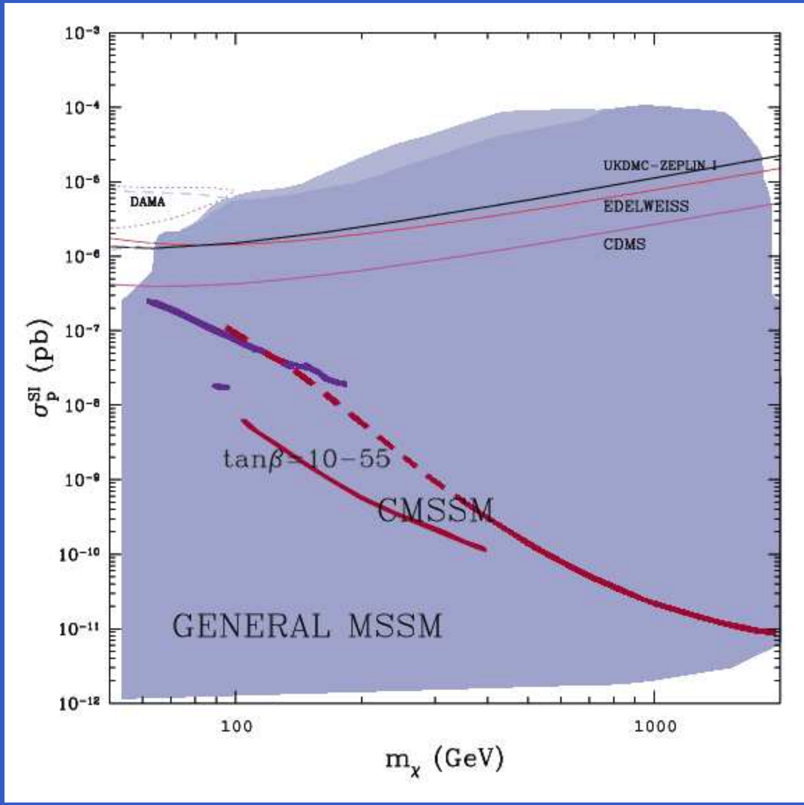


Expectations for σ_p^{SI} with unification



σ_p^{SI} – WIMP–proton SI elastic scatt. c.s.

blue: general MSSM

red: Constrained MSSM

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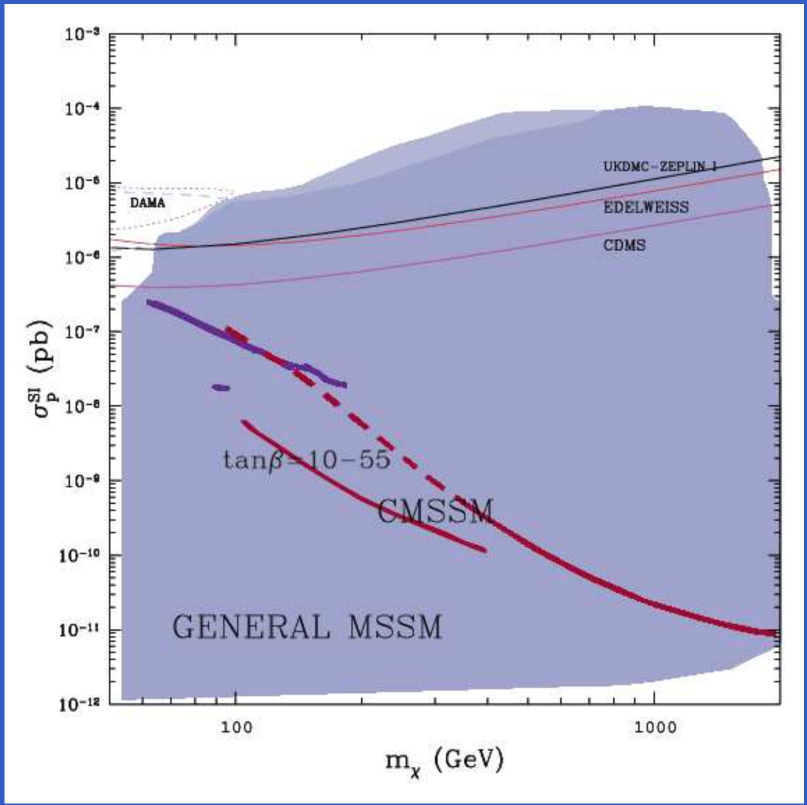

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blue: general MSSM

red: Constrained MSSM

- CMSSM: much (!) more predictive
- CMSSM: rates still below current sensitivity

Full MCMC Scan of the CMSSM

(MCMC=Markov Chain Monte Carlo) Ruiz de Austri, Trotta, LR, hep-ph/0602028

Bayesian analysis, relative probability density fn (pdf), flat priors

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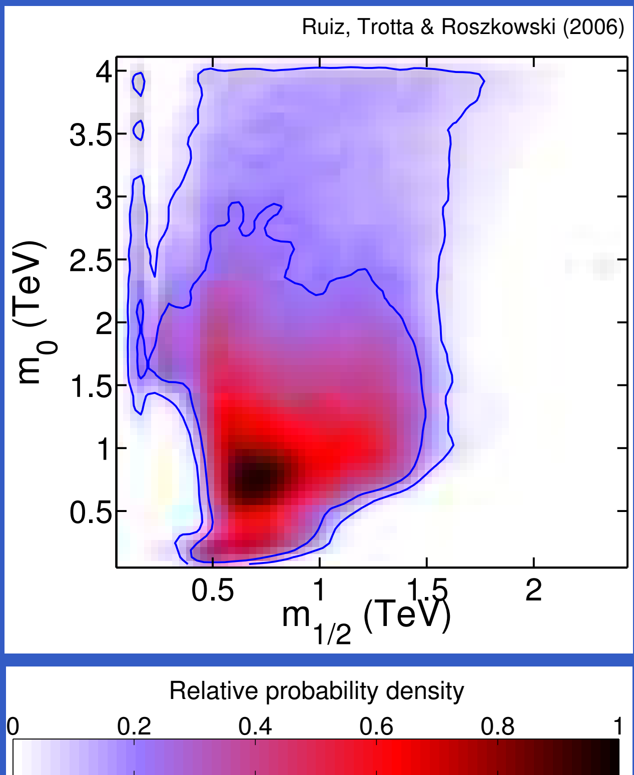

- map out relative probability regions of the CMSSM param's: $\theta = (m_0, m_{1/2}, A_0, \tan\beta)$
- marginalize (integrate) over SM (nuissance parameters: $\psi = (m_t^{\rm pole}, m_b(m_b)^{\overline{MS}}, \alpha_{\rm em}(M_Z), \alpha_s)$
- compute posterior pdf $p(\theta|d) = \int p(\theta, \psi|d)\, d^4\psi$
- project on, eg., $(m_0, m_{1/2})$ $p(m_0, m_{1/2}|d) = \int p(\theta|d)\, d\tan\beta\, dA_0$

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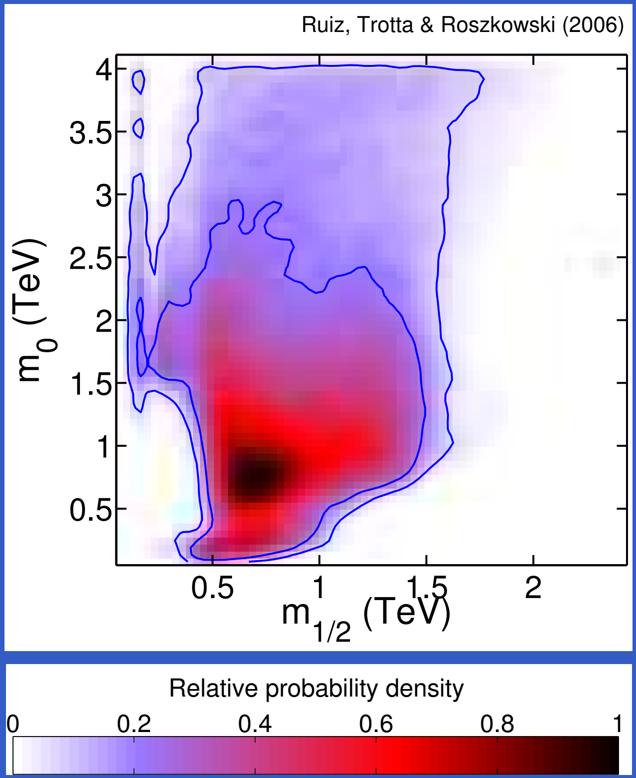

explore wide ranges of CMSSM parameters:

- 50 GeV $< m_{1/2} < 4$ TeV
- 50 GeV $< m_0 < 4$ TeV
- $|A_0| < 7$ TeV

also vary SM parameters:

- $m_t^{\rm pole} = 172.7 \pm 2.9$ GeV
- $m_b(m_b)^{\overline{MS}} = 4.24 \pm 0.11$ GeV
- $1/\alpha_{\rm em}(M_Z) = 127.958 \pm 0.048$ ($\overline{MS}$)
- $\alpha_s = 0.1186 \pm 0.002$ ($\overline{MS}$)

go beyond 1σ error bars

a powerful method of exploring multi–parameter models

related studies by Balz+Gondolo (MCMC scan, no pdfs), Allanach+Lester (no DM), Ellis, et al (EHOW, χ^2 approach)

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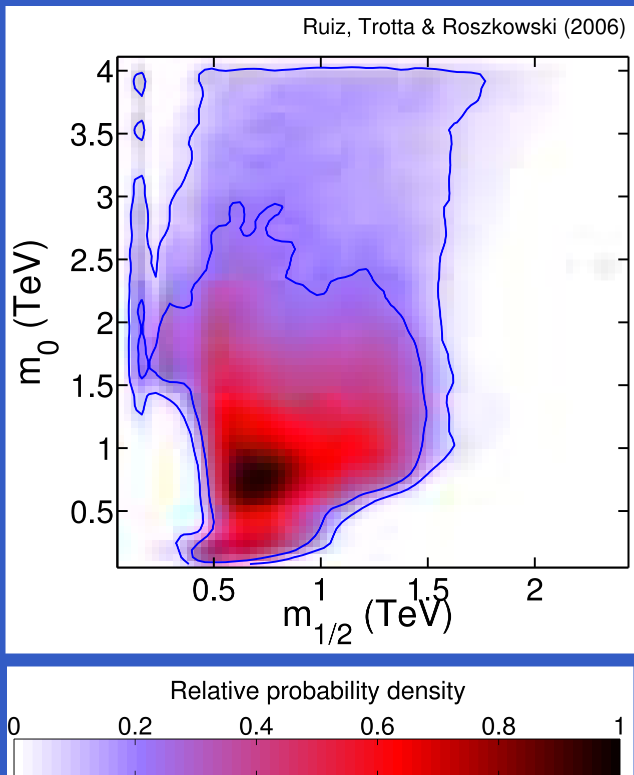
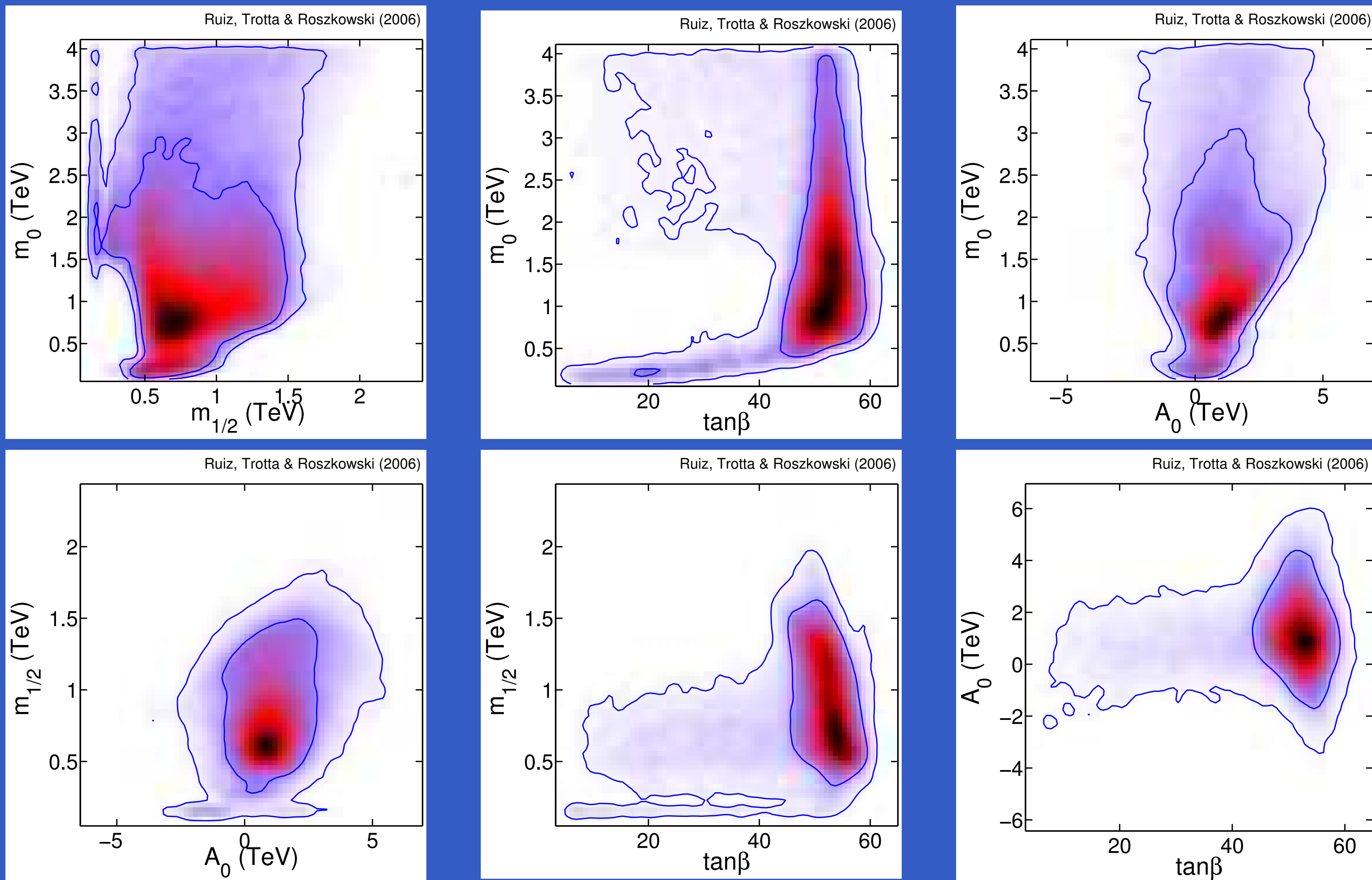


unlike others (except for A+L), we vary also SM parameters

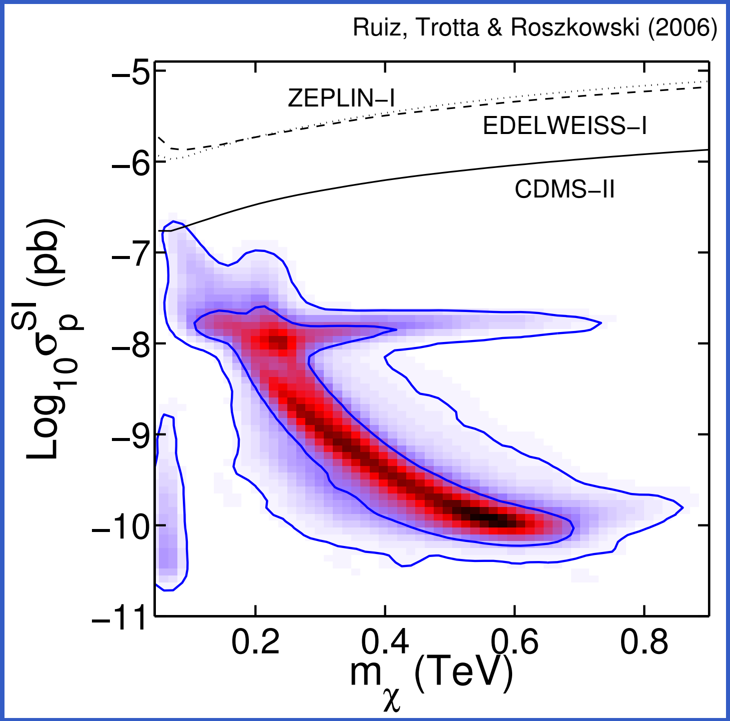
Full MCMC Scan of the CMSSM

Ruiz de Austri, Trotta, Roszkowski, hep-ph/0602028



Full MCMC Scan of the CMSSM

implications for σ_p^{SI}



internal (external): 68% (95%) region

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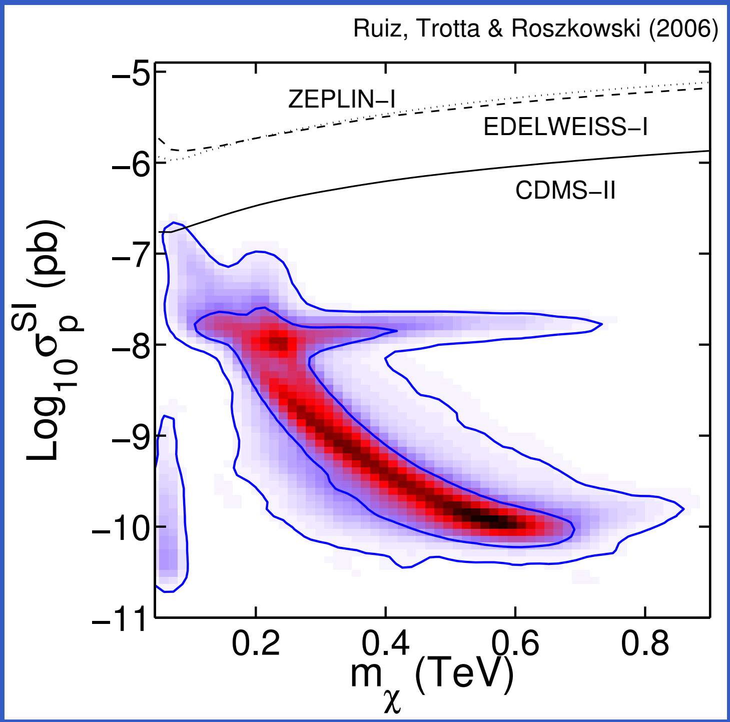

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CDMS (this year?):

will reach down to $\sigma_p^{SI} \sim 10^{-8}$ pb:

also Edelweiss–II and/or ZEPLIN–II (?)

$\Rightarrow$ explore the FP region

(large $m_0 \gg m_{1/2}$), outside of the LHC reach

ultimately: "1 tonne" detectors:

$\sigma_p^{SI} \lesssim 10^{-10}$ pb

will cover all 68% region

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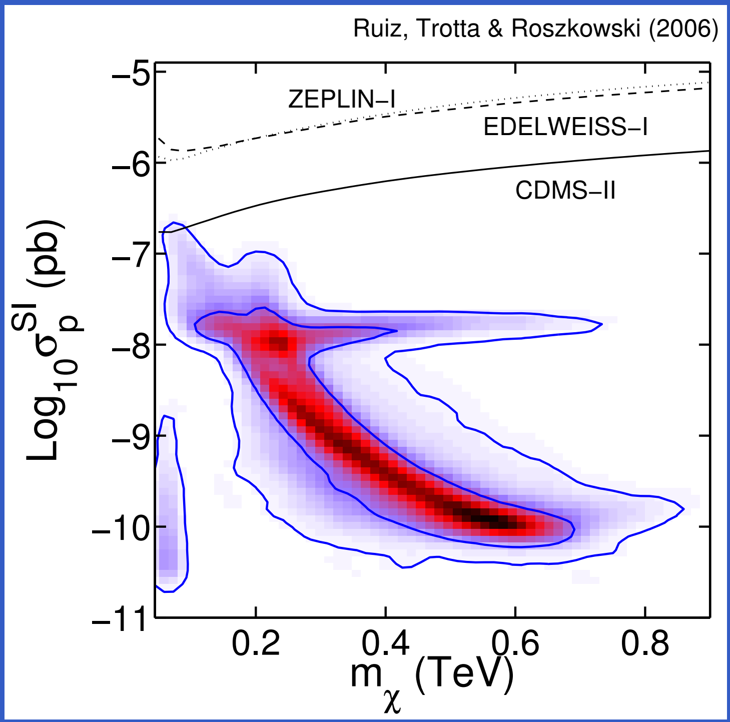

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most probable range: 10^{-8} pb $\lesssim \sigma_p^{SI} \lesssim 10^{-10}$ pb

partly outside of the LHC reach ($m_\chi \lesssim 400$ GeV)

Minimal SUSY $SO(10)$ GUT Model

a fully realistic GUT

Raby, et al.

- matter $\mathbf{16} \supset \mathbf{10} + \mathbf{5} + \overline{\nu}_s$
- Higgs

  $\mathbf{10}_H \supset \mathbf{5}_H + \mathbf{5} + \overline{\mathbf{5}}_H \supset H_t, H_b$
- spotential $W = \lambda \mathbf{16}\, \mathbf{10}_H\, \mathbf{16}$
- g. c. unification $\surd$

  $\epsilon_s = \frac{(\alpha_s(M_G) - \alpha_G)}{\alpha_G} \approx -4\%$
- Y. c. unification $\surd$

  large $\tilde{g} - \chi^-$ corr's to

  $\lambda_b \Rightarrow \tan\beta \sim 50$
- realistic fermion masses $\surd$
- proton decay $\surd$

- 11 input parameters

M_G, α_G, ϵ_s, λ, μ, $m_{1/2}$, A_0, $\tan\beta$,

m_{16}, m_{10},

$m^2_{H_{t,b}} = m_{10}\,(1 \mp \Delta m^2_H)$

- 2–loop RGE's for gauge and Yukawa
- full 1–loop threshold corrections at both m_Z and M_G
- 1–loop RGE's for scalars
- EWSB with 1–loop corrections
- fit 9 observables

α_{em}, G_μ, $\alpha_s(m_Z)$, m_Z, m_W,

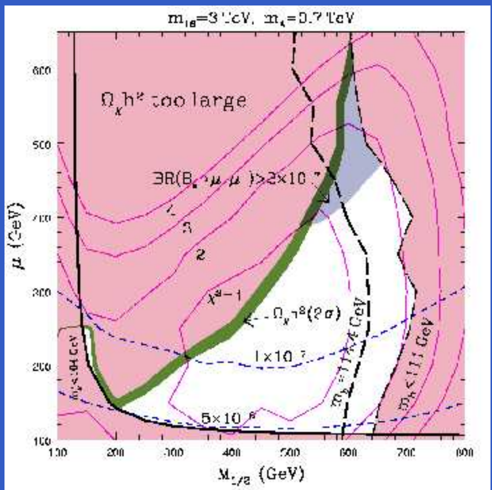
ρ, M_τ, M_t, $m_b(m_b) = 4.20 \pm .20$ GeV

$\Rightarrow m_{16} > 1.2$ TeV; $A_0 \approx -2\, m_{16}$; $m_{10} \approx \sqrt{2}\, m_{16}$;

$\mu,\ m_{1/2} \ll m_{16}$

$SO(10)$: Implications for σ_p^{SI}

Dermíšek, Raby, Roszkowski, Ruiz de Austri (JHEP ’05)



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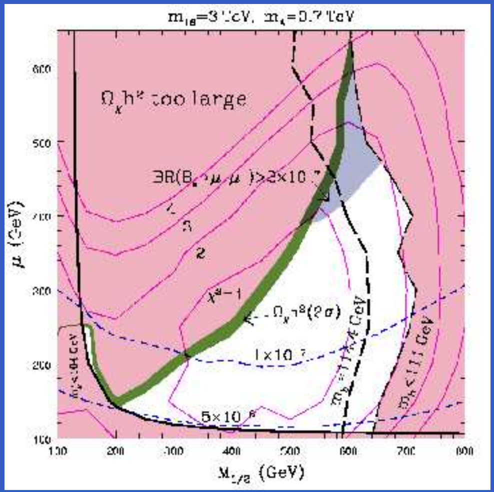
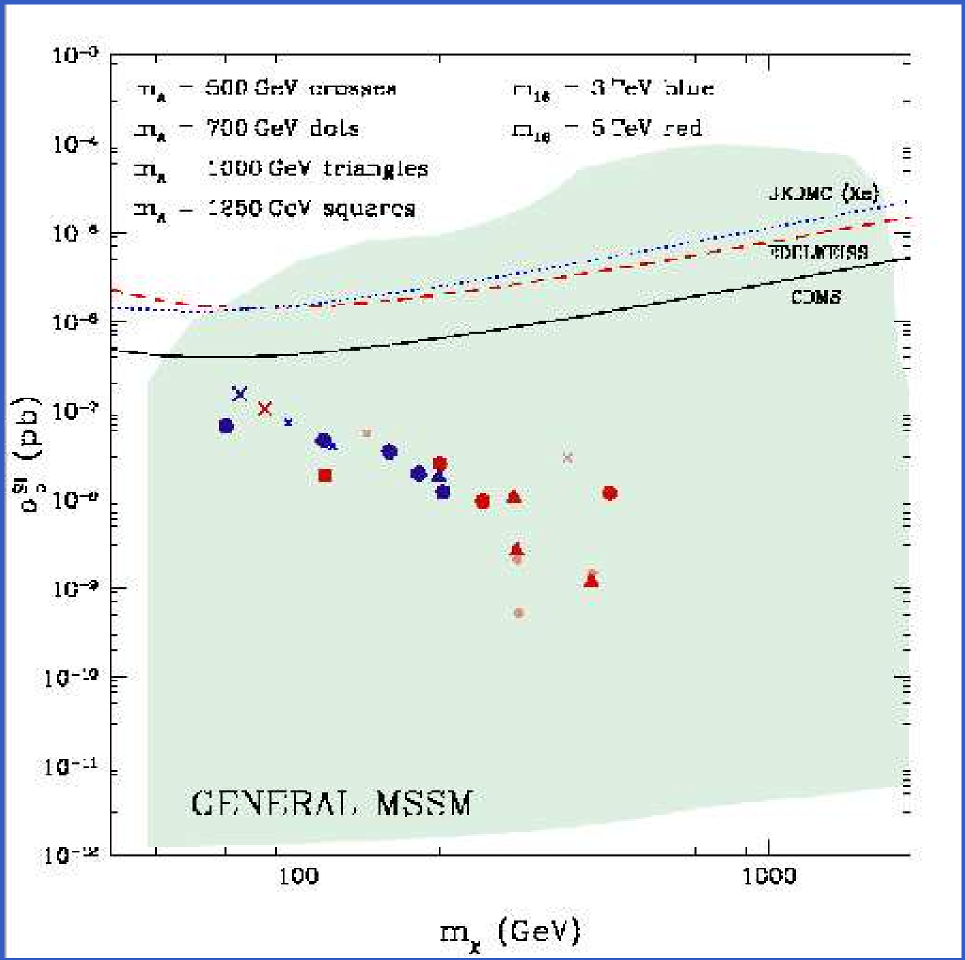




$m_{16} = 2.5$ TeV (green)

3 TeV (red)

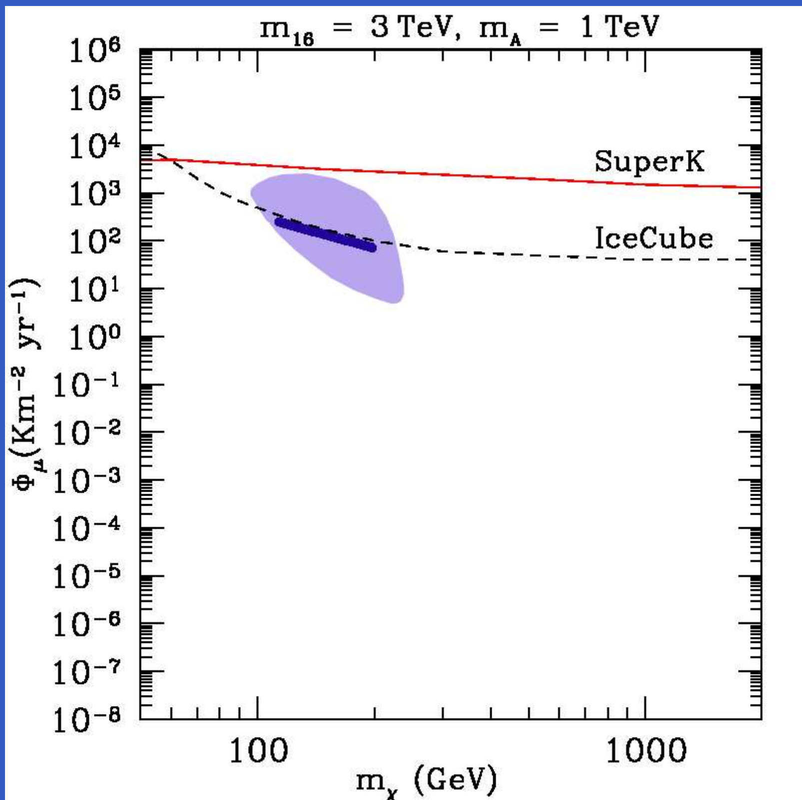
5 TeV (blue)

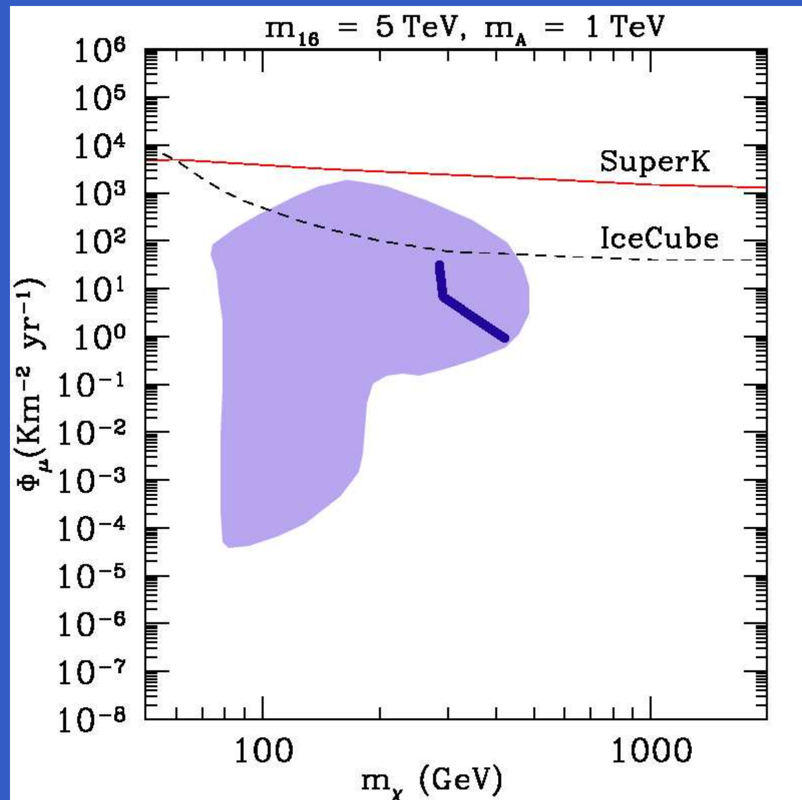
$m_A = 300$ GeV (lighter)

500 GeV (darker)

$SO(10)$ GUT: ν Telescopes

Dermíšek, Raby, Roszkowski, Ruiz de Austri (JHEP ’05)

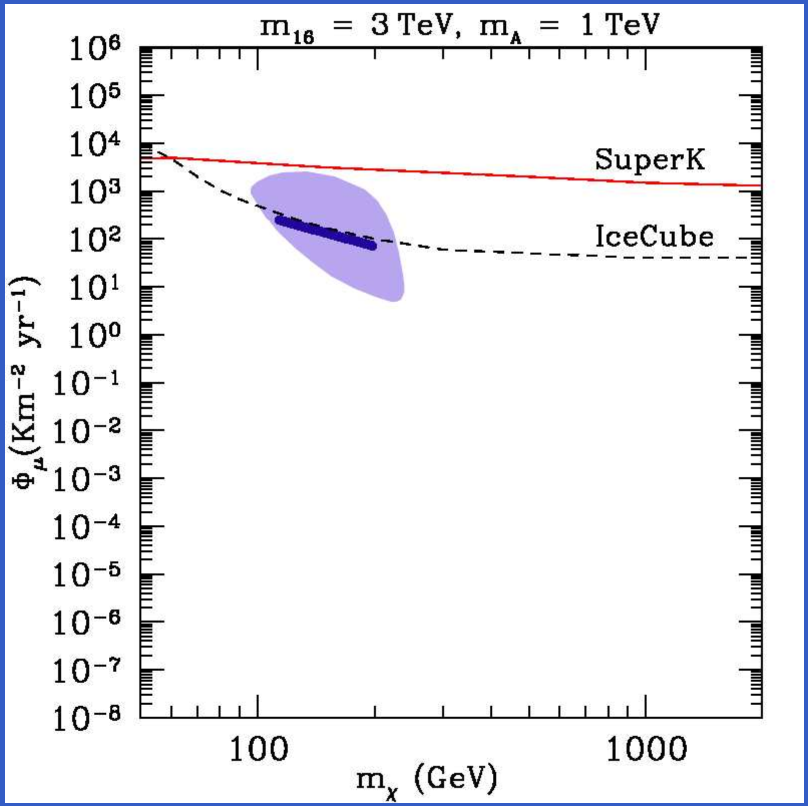


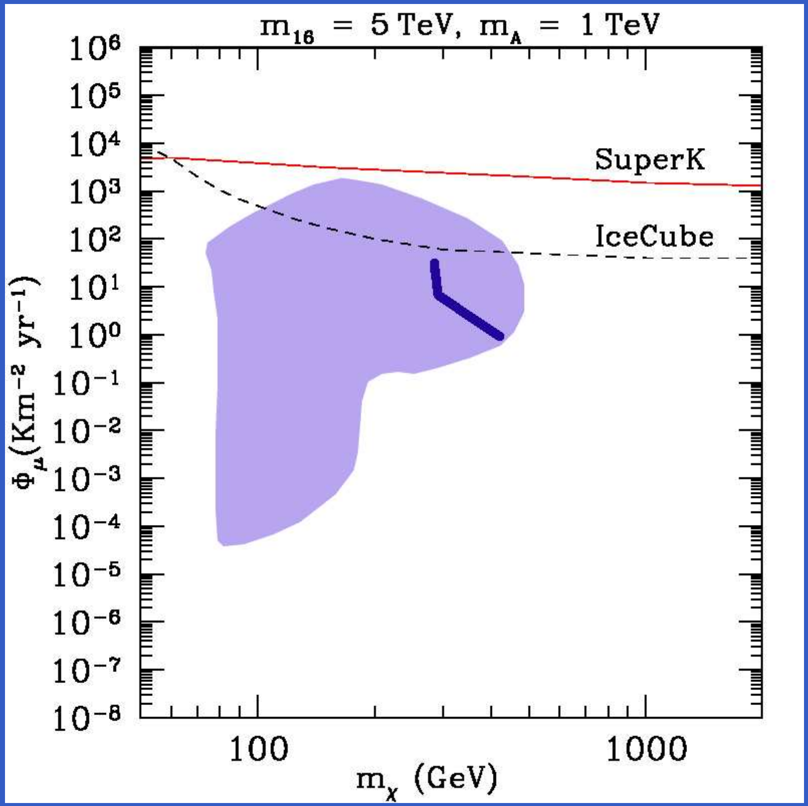


dark blue: consistent with DM abundance

$SO(10)$ GUT: ν Telescopes

Dermíšek, Raby, Roszkowski, Ruiz de Austri (JHEP '05)





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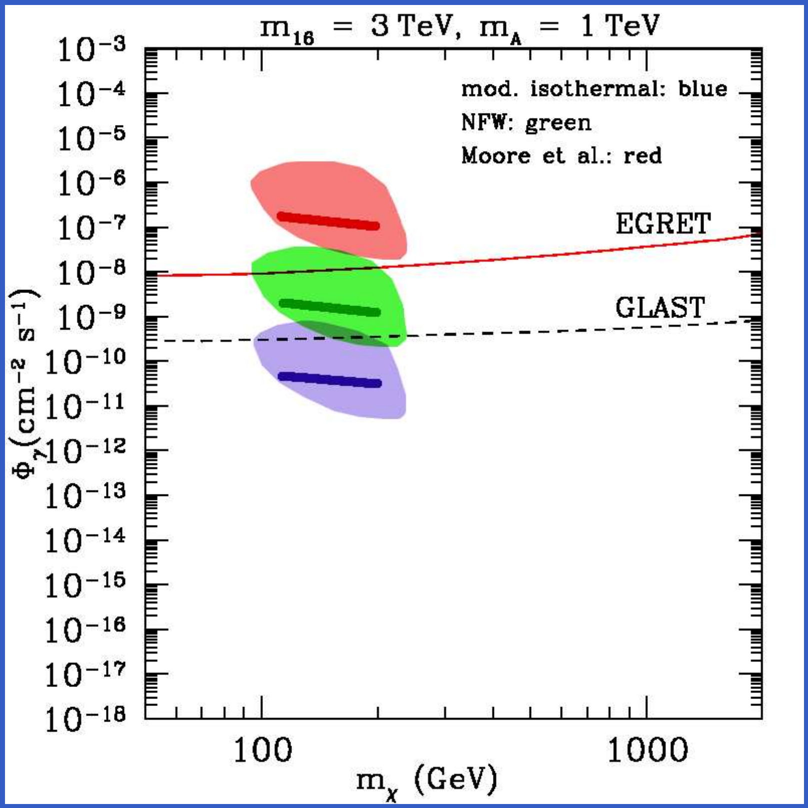
- marginal discovery prospects

$SO(10)$ GUT: γ Rays

Dermíšek, Raby, Roszkowski, Ruiz de Austri (JHEP ’05)

γ–ray flux from the Galactic Center $\rho(r) = \rho_0 \frac{(r/r_0)^{-\gamma}}{[1+(r/a)^\alpha]^{\frac{\beta-\gamma}{\alpha}}} [1 + (r_0/a)^\alpha]^{\frac{\beta-\gamma}{\alpha}}$



- $(\alpha, \beta, \gamma) = (2, 2, 0)$, $r_0 = 8.5$ kpc and $a = 3.5$ kpc (SSM Isothermal)
- $(\alpha, \beta, \gamma) = (1, 3, 1)$, $r_0 = 8.0$ kpc and $a = 20$ kpc (NFW)
- $(\alpha, \beta, \gamma) = (1.5, 3, 1.5)$, $r_0 = 8.0$ kpc and $a = 28$ kpc (Moore et al.)

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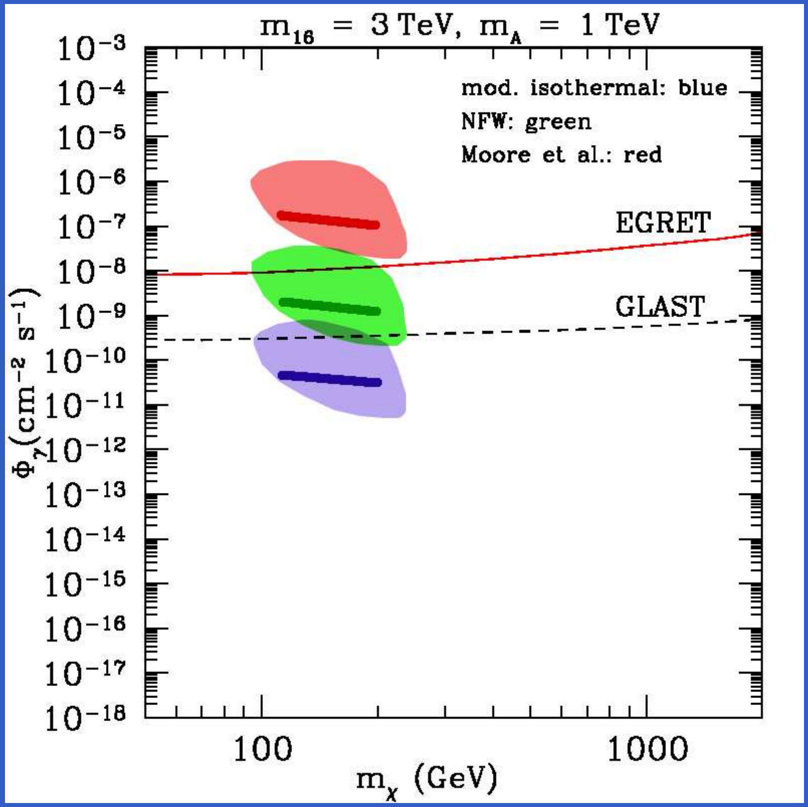

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- prospects depend on a halo model

WIMPs: Attractive and Testable

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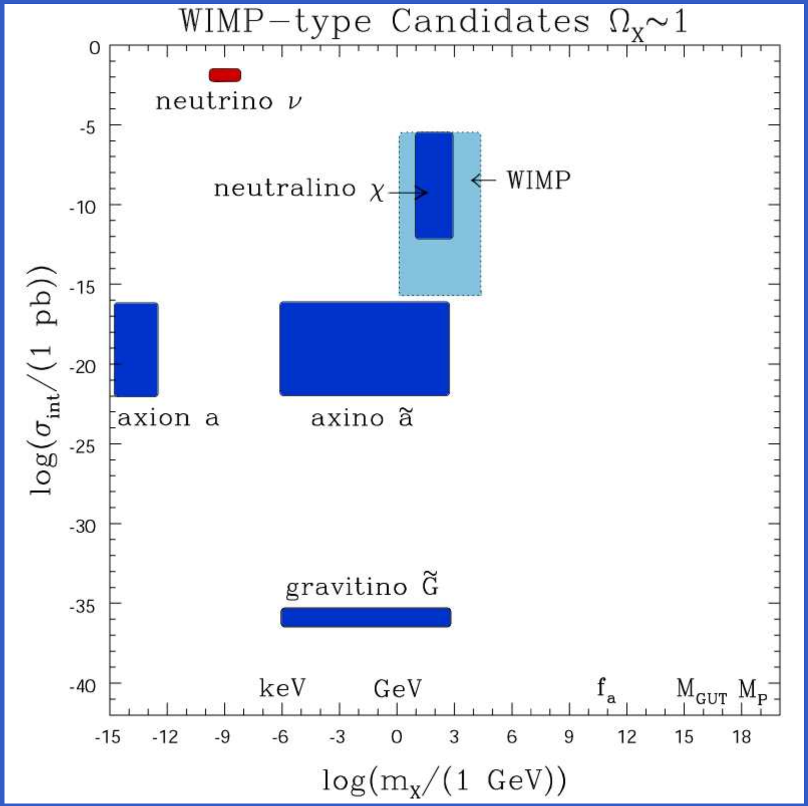
...What if Nature has made a different choice?

The Big Picture

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



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

E–WIMPs: $\widetilde{G}$ and $\widetilde{a}$

(extremely weakly interacting massive particles)

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(assume usual gravity mediated SUSY breaking)

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

- mass model dependent
  take it as free parameter

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

E–WIMPs as Cosmological Relics

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

a simple picture:

e.g. E–WIMP: axino $\widetilde{a}$ (SUSY partner of the axion)

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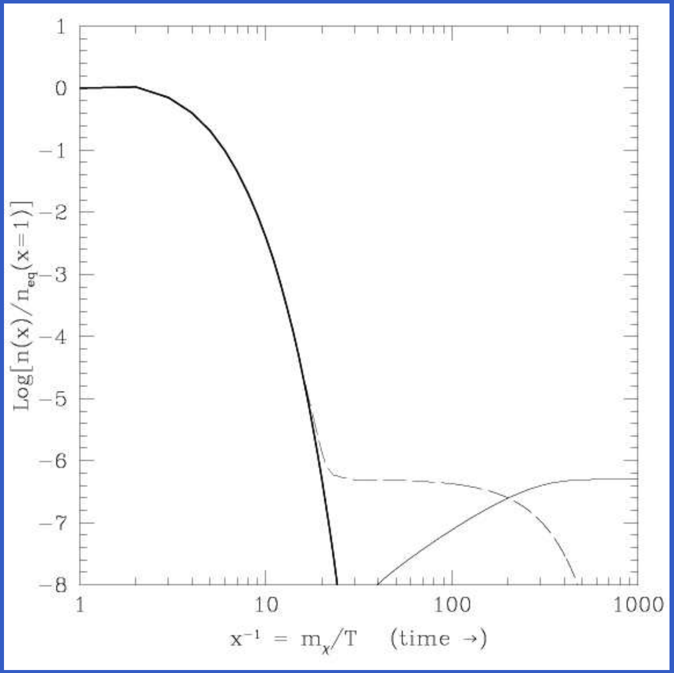
$$\chi \longrightarrow \widetilde{a}\,\gamma$$

typically before BBN (in contrast to the $\widetilde{G}$)



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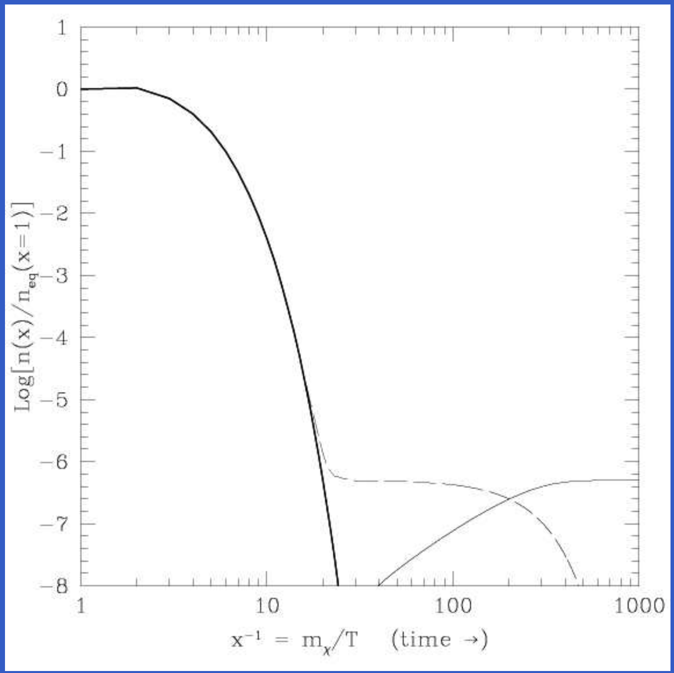

- $n_{\widetilde{a}} = n_\chi \;\Rightarrow$ $\quad \Omega_{\widetilde{a}} = \frac{m_{\widetilde{a}}}{m_\chi}\,\Omega_\chi$

NTP: non–thermal production

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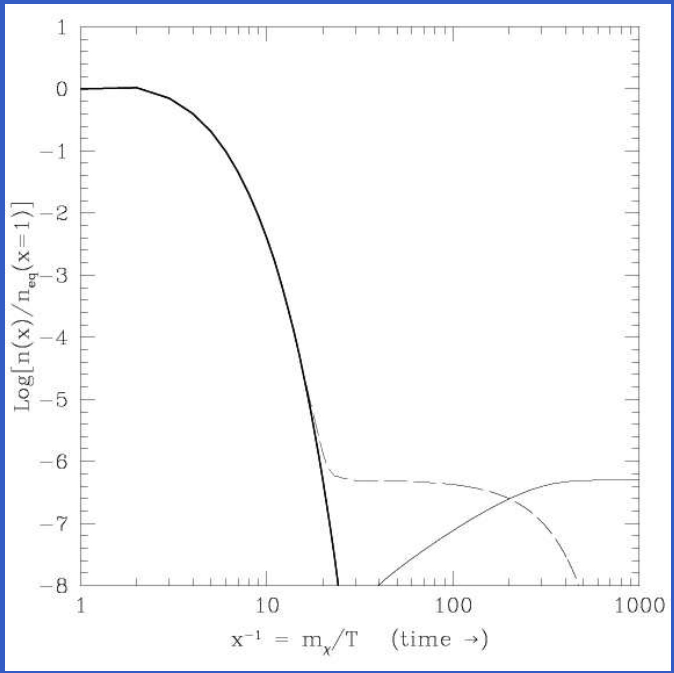

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NTP: non–thermal production

- ...plus scatterings in the plasma (dep. on T_R)

TP: thermal production

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 $\sim F/M_{\rm P}$

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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

(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

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

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

Ellis, et al (EOSS 03), CMSSM

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

Bolz+Brandenburg+Buchmüller ('00)

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

BBN Constraint

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

Cerdeño+K.-Y. Choi+Jedamzik+L.R.+Ruiz de Austri, hep-ph/0509275
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):

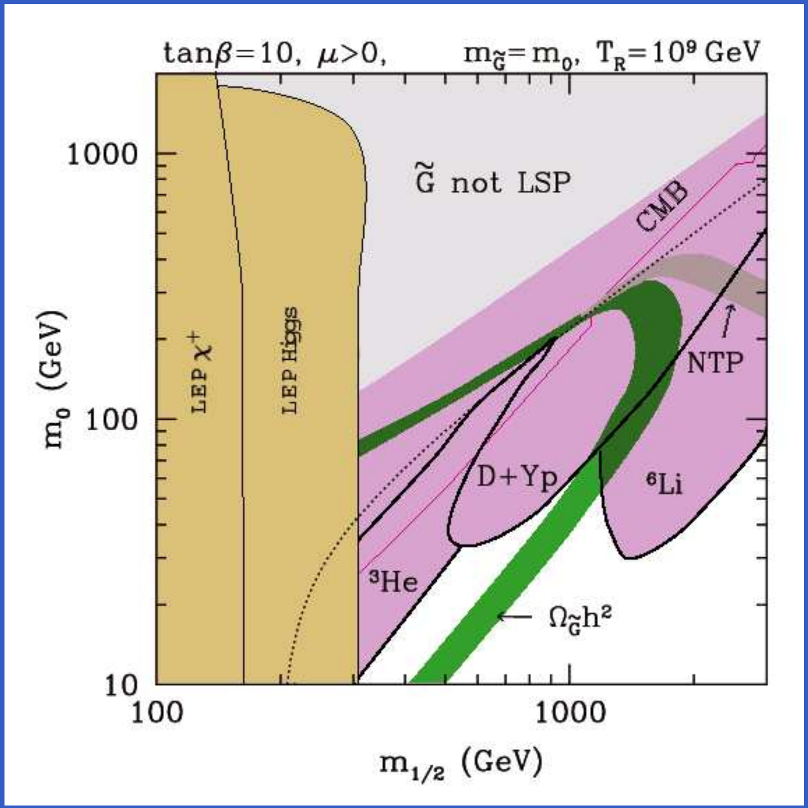
$$2.2 \times 10^{-5} < D/H < 5.3 \times 10^{-5}$$
$$0.232 < Y_p < 0.258$$
$$1.11 \times 10^{-10} < {}^7Li/H < 4.5 \times 10^{-10}$$
$${}^3He/D < 1.72$$
$${}^6Li/{}^7Li < 0.1875$$

- 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, hep-ph/0509275

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



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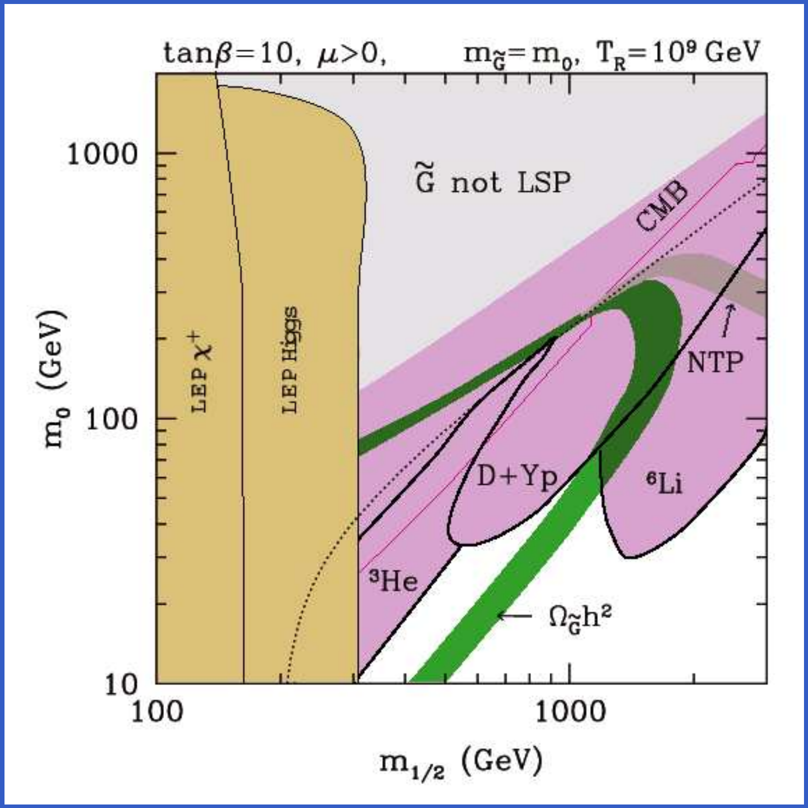

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$\Rightarrow$ at LHC see charged "stable" LOSP $\widetilde{\tau}_1$ (instead of "expected" neutral χ)

confirmed Feng, et al (Apr 04)

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Cerdeño+K.-Y. Choi+Jedamzik+L.R.+Ruiz de Austri, hep-ph/0509275

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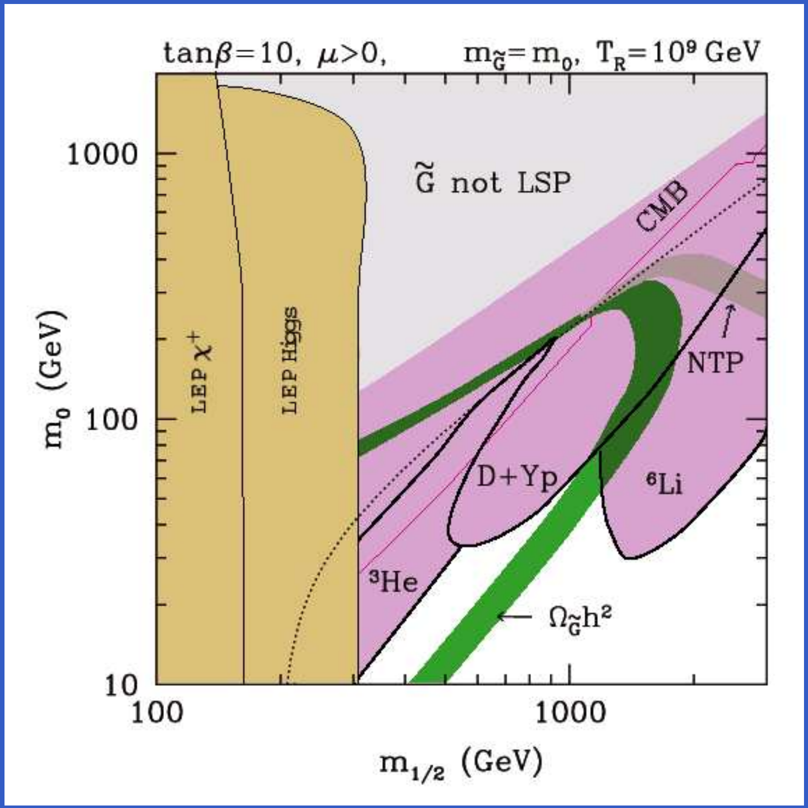

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confirmed Feng, et al (Apr 04)

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

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

$\widetilde{G}$ DM $\Rightarrow$ Universe in False Vacuum?

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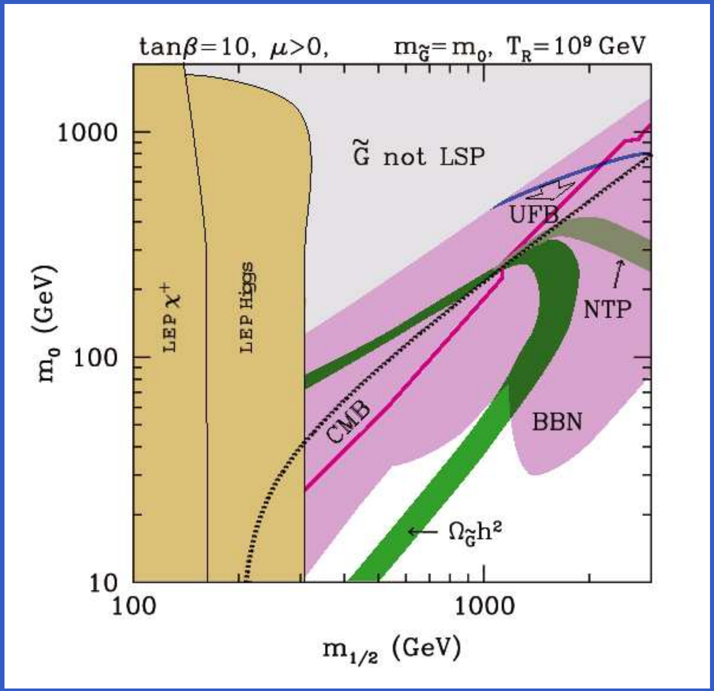
Cerdeño+K.-Y. Choi+Jedamzik+L.R.+Ruiz de Austri, hep-ph/0509275–> JCAP

“UFB”: region of local minimum



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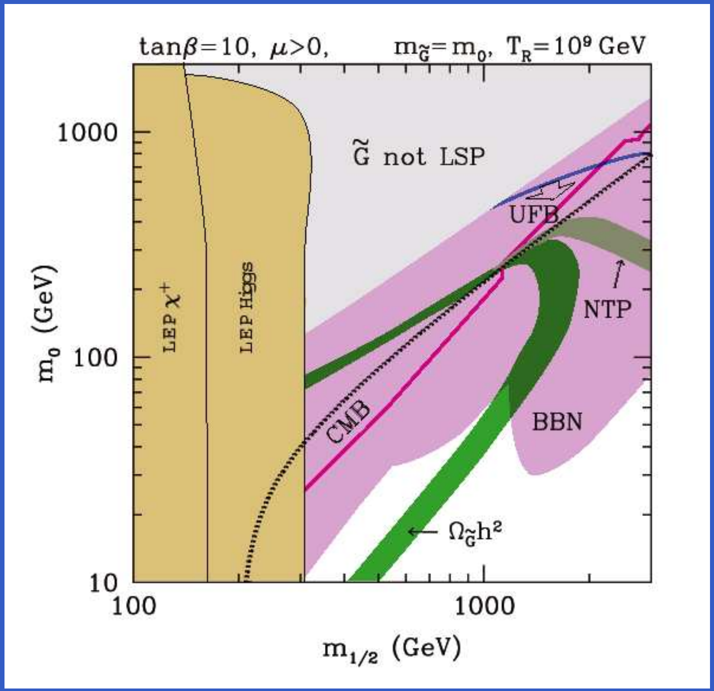

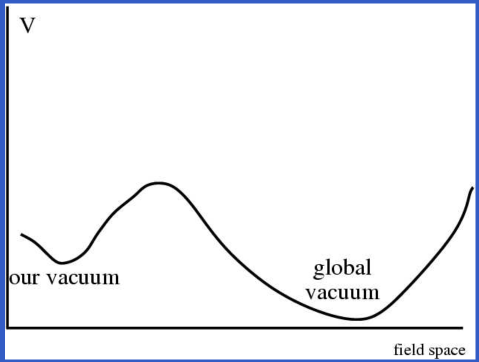

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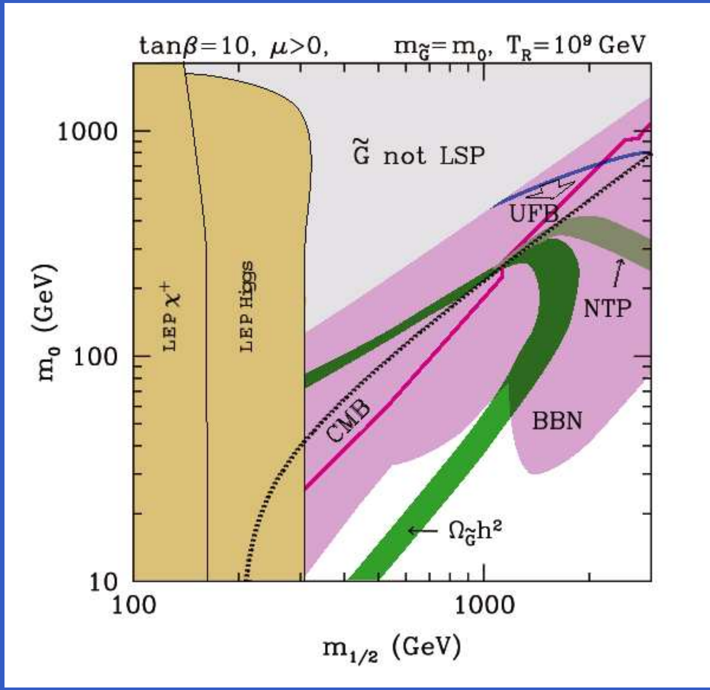

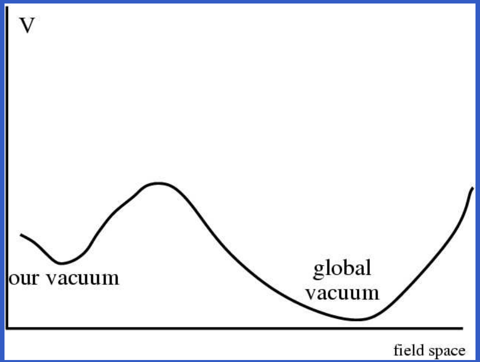

CMSSM: enough $\widetilde{G}$ DM

$\Rightarrow$ Universe in false vacuum

$\Rightarrow$ the LHC: one can learn about the ground state of the Universe

...and its ultimate fate

$\widetilde{G}$ DM $\Rightarrow$ No High T Leptogenesis?

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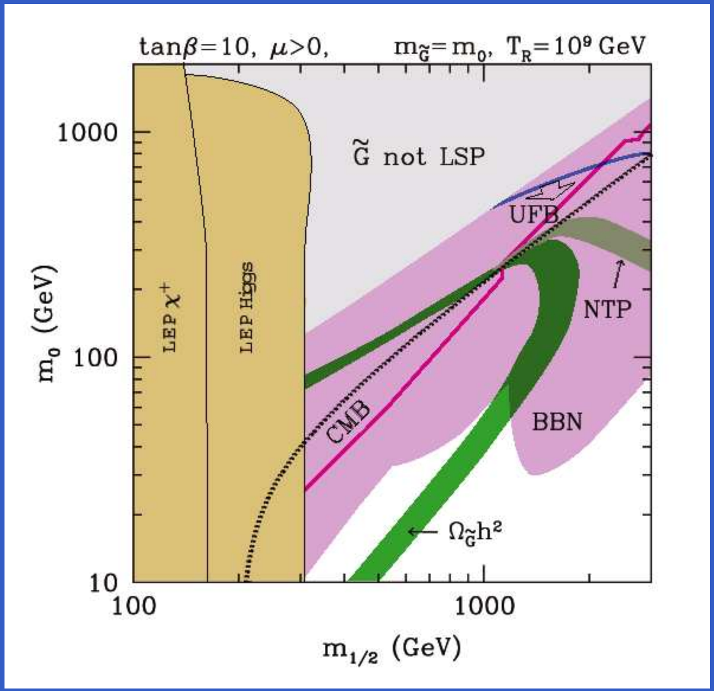
Cerdeño+K.-Y. Choi+Jedamzik+L.R.+Ruiz de Austri, hep-ph/0509275–> JCAP

thermal leptogenesis: $T_R \gtrsim 2 \times 10^9$ GeV (Fukugida+Yanagida)



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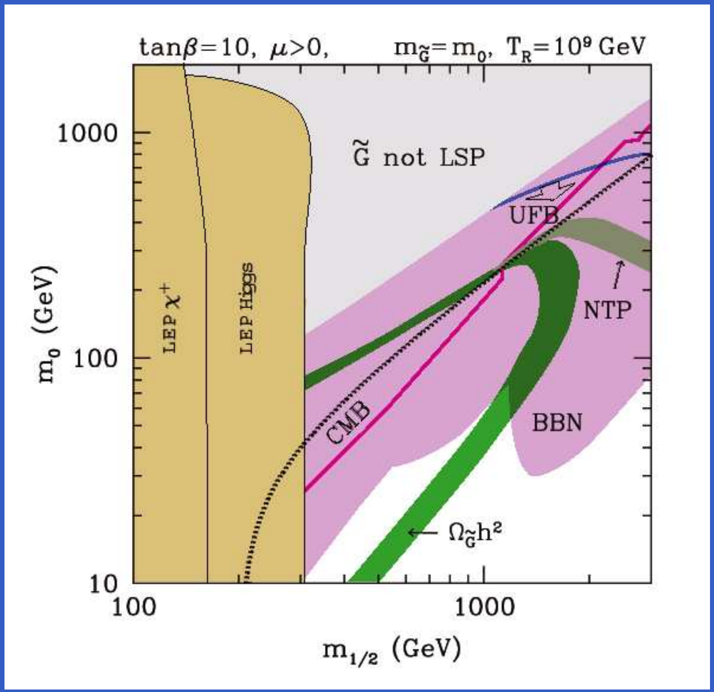

CMSSM: enough $\widetilde{G}$ DM

$\Rightarrow$ $T_R \lesssim 4 \times 10^9$ GeV

...but need large TP component

NTP not enough

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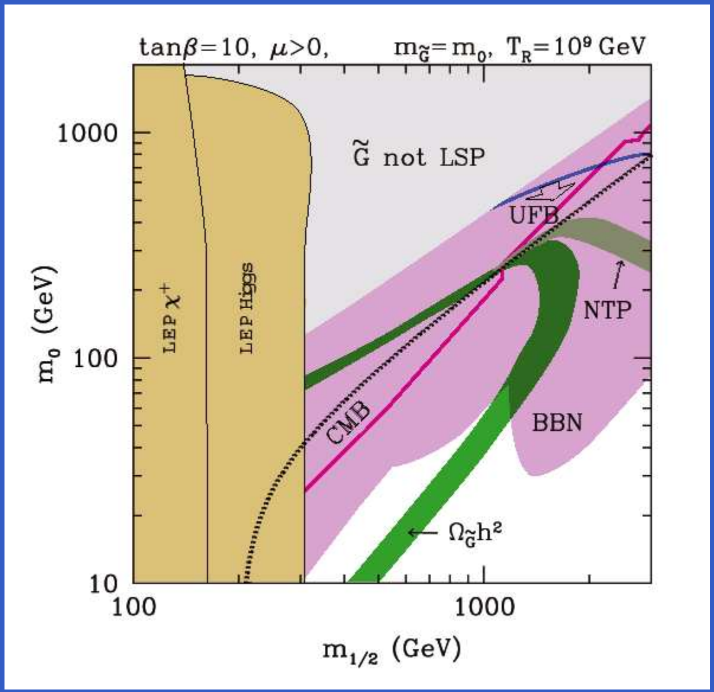

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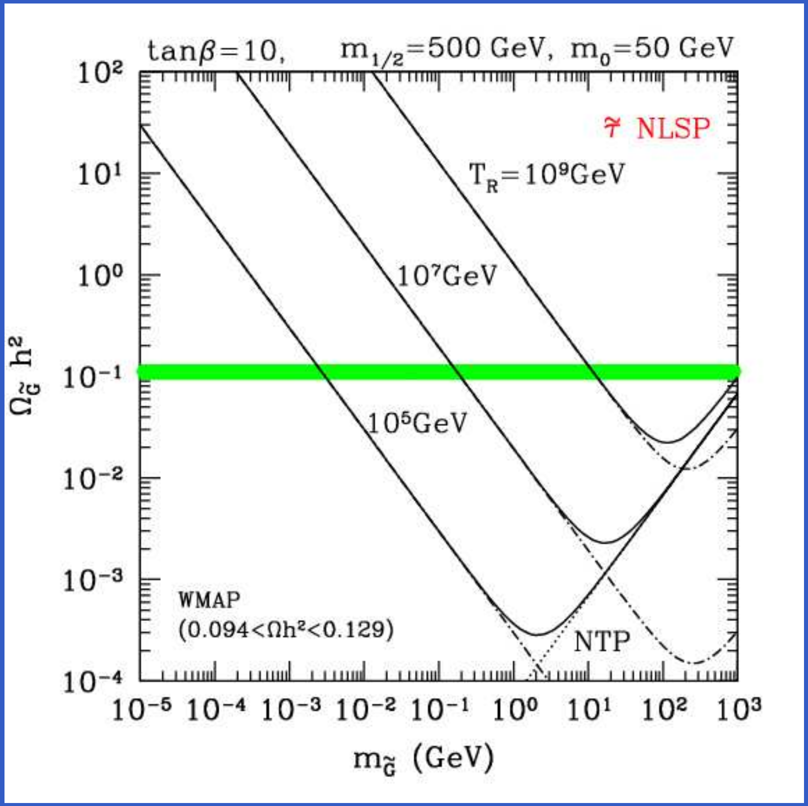
$\Rightarrow$ popular baryogenesis scenario disfavored

...in the CMSSM

Wider Range of $m_{\widetilde{G}}$

Cerdeño+K.-Y. Choi+Jedamzik+L.R.+Ruiz de Austri, hep-ph/0509275



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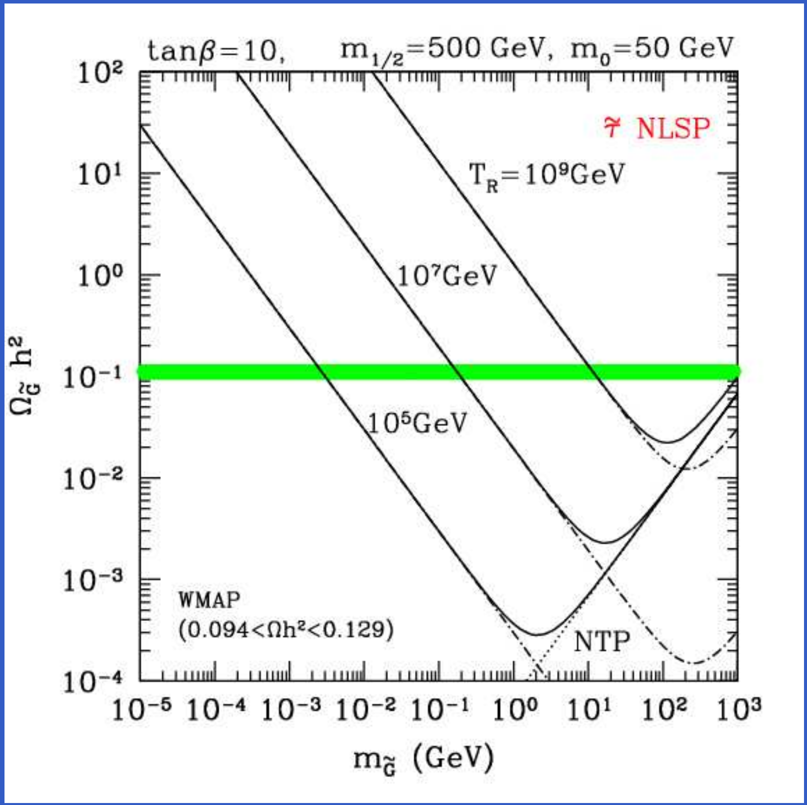
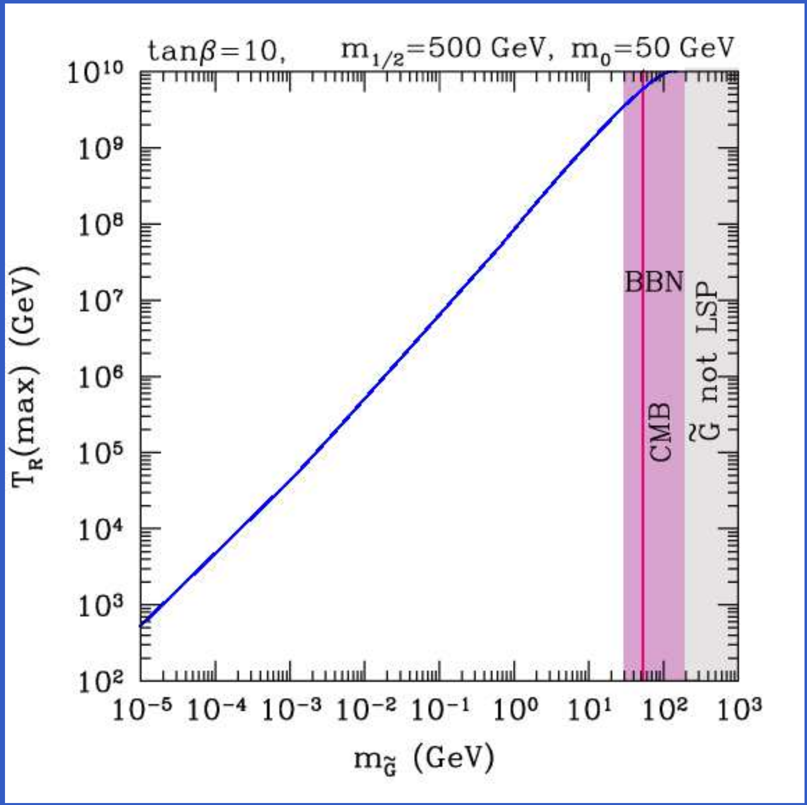
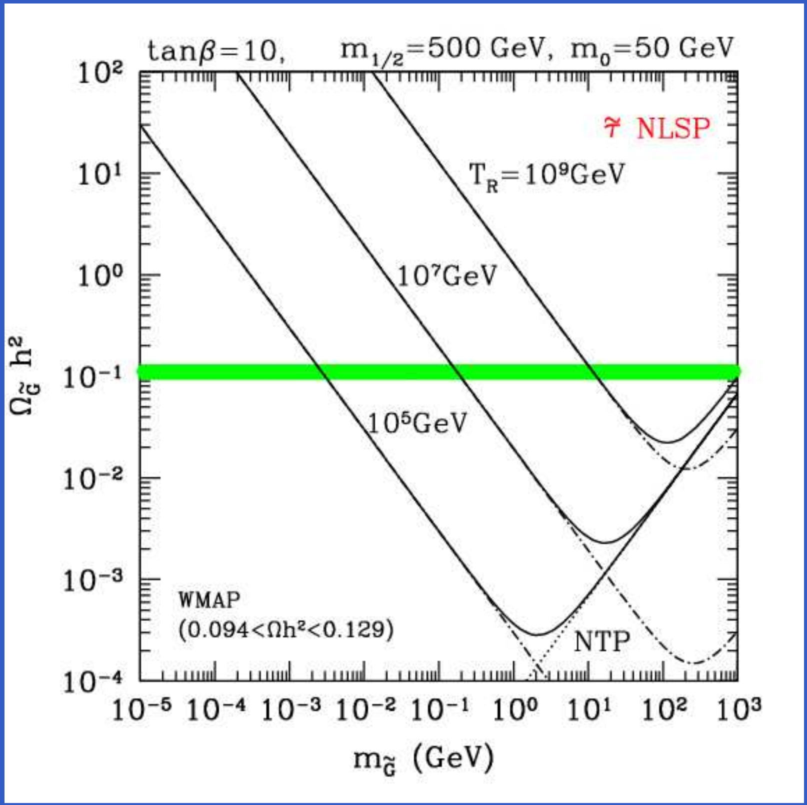
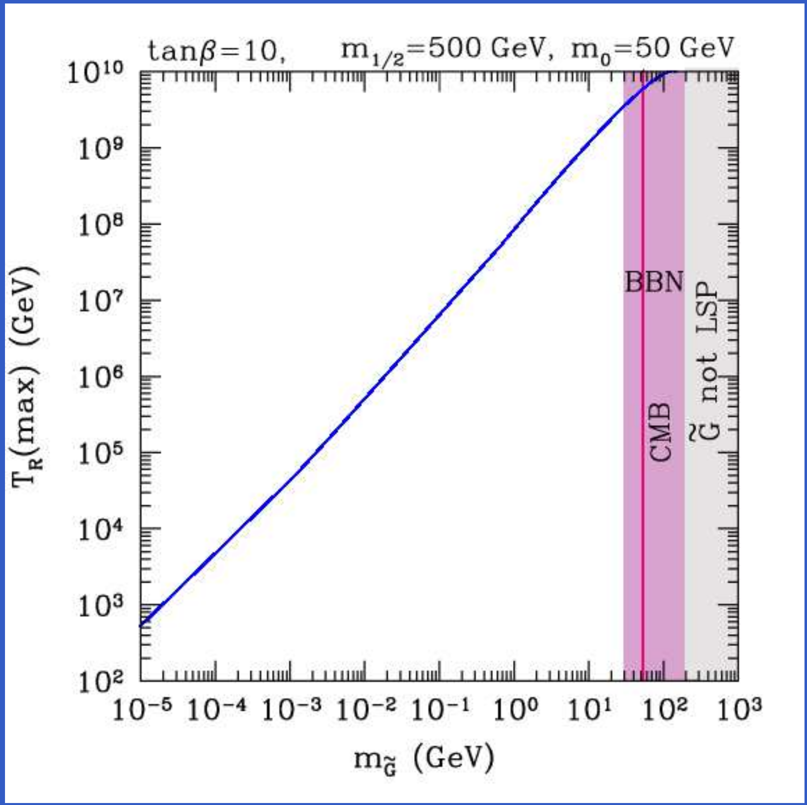




Wider Range of $m_{\tilde{G}}$

Cerdeño+K.-Y. Choi+Jedamzik+L.R.+Ruiz de Austri, hep-ph/0509275





$\Rightarrow$ light $m_{\tilde{G}}$ mostly allowed (even for χ NLSP)

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- interesting correlations between DM and collider searches

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- if $\widetilde{G}$ LSP and CDM ($m_{\widetilde{G}} = \mathcal{O}(100\,\mathrm{GeV})$):
  - $\Rightarrow$ strong bounds from BBN and CMB
  - $\Rightarrow$ in CMSSM: χ NLSP seems ruled out, $\widetilde{\tau}_1$ NLSP allowed
  - $\Rightarrow$ $T_R < 4 \times 10^9$ GeV

but... TP contribution to $\Omega_{\widetilde{G}} h^2$ must be included

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- $\widetilde{G}$ (or $\widetilde{a}$) LSP:

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

we may find this out at LHC!