Gravitino Dark Matter and Collider Implications

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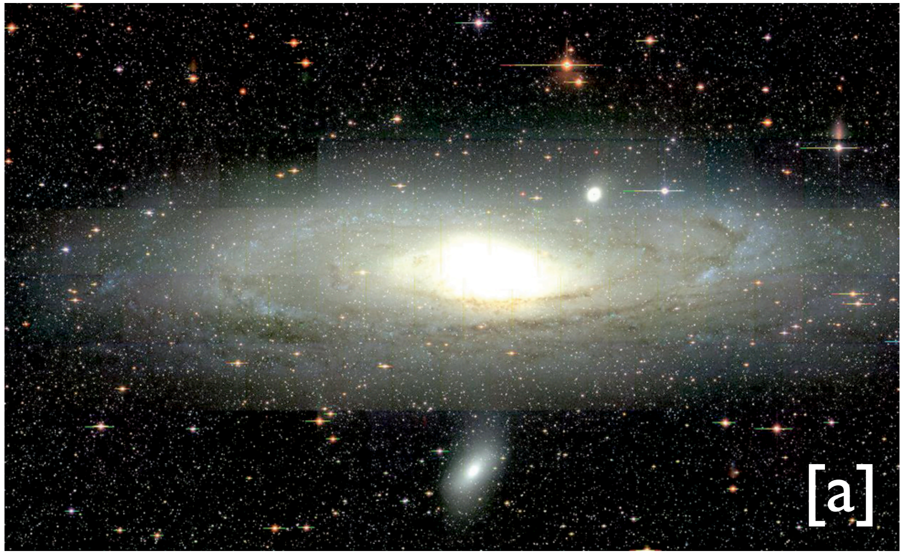
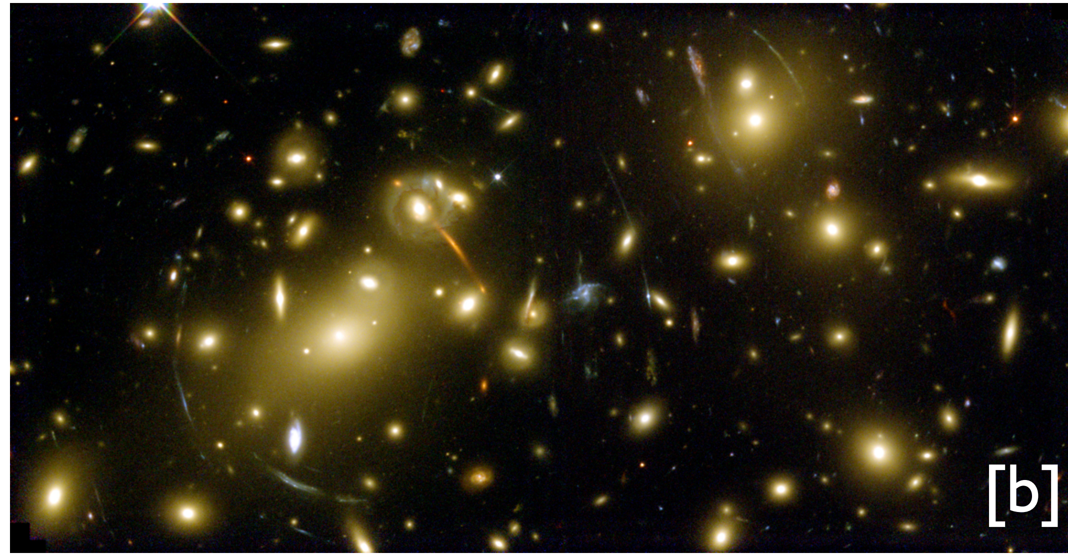
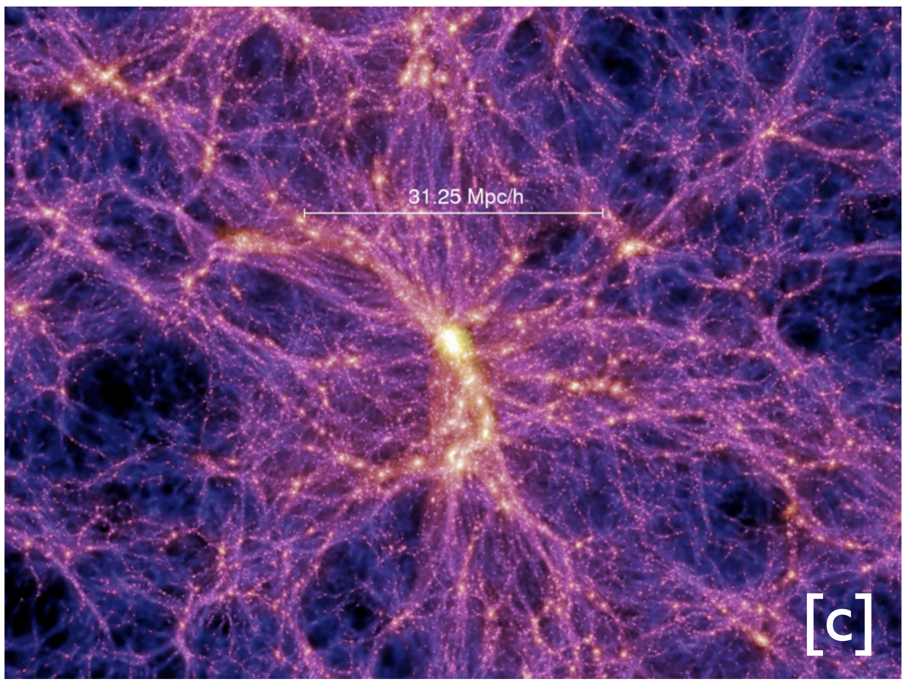
TUM
LMU
Excellence Cluster
Universe

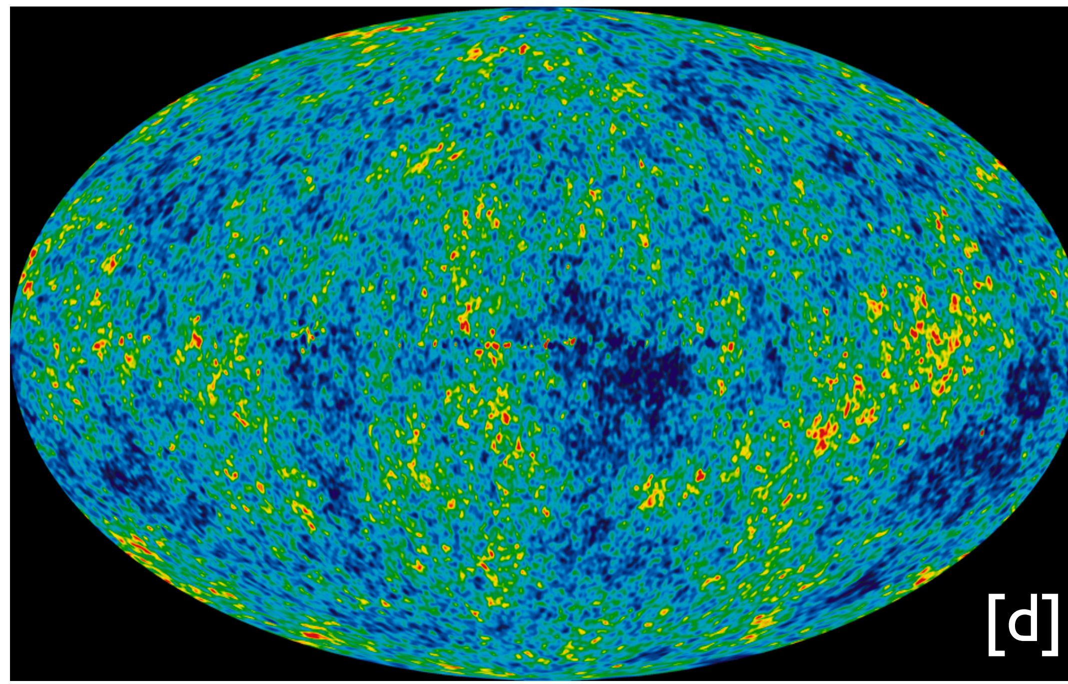
MORIOND 2008
La Thuile, Italy
March 3rd, 2008

Evidence for Dark Matter in the Universe





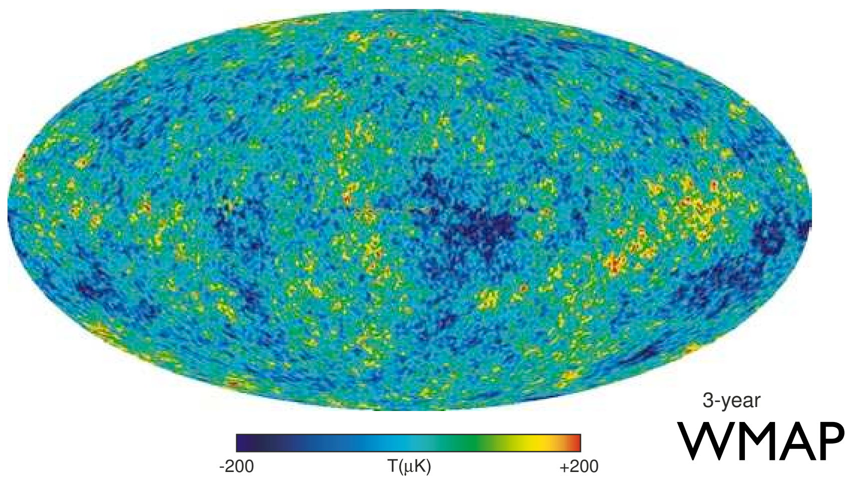


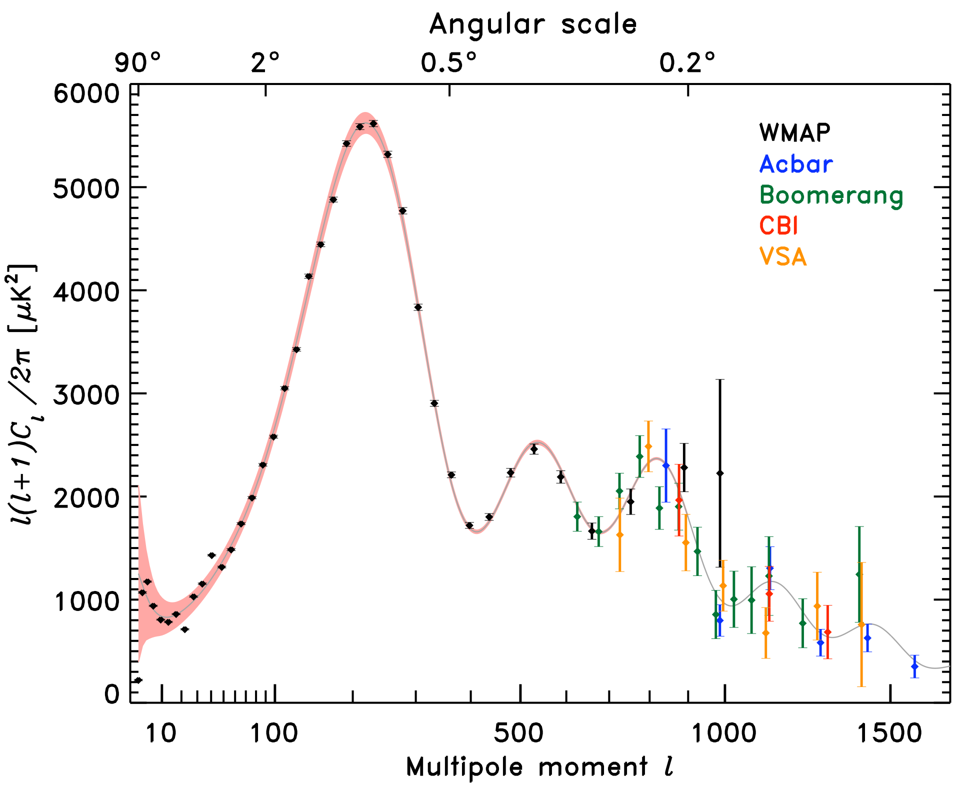


Evidence for Dark Matter in the Universe

- Spiral Galaxies
  * Rotation Curves
- (Super-) Clusters of Galaxies
  * Galaxy Velocities ↔ X-Rays
  * Weak Gravitational Lensing
  * Strong Gravitational Lensing
- Large Scale Structure
  * Structure Formation
- CMB Anisotropy: WMAP, ...
  * $\Omega_{\rm tot} = 100\%$
  * $\Omega_{\rm M} = 27\%$
  * $\Omega_{\rm B} = 5\%$

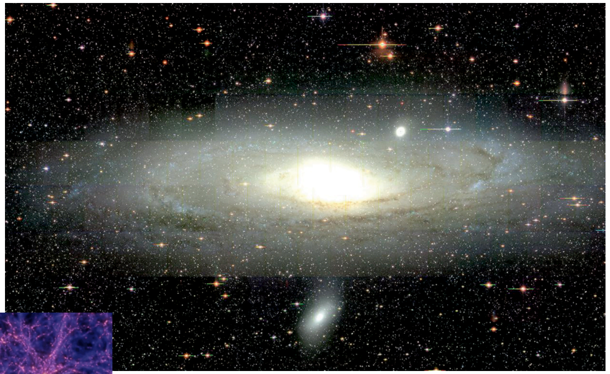
$$\Omega_{\rm DM} \simeq 22\%$$



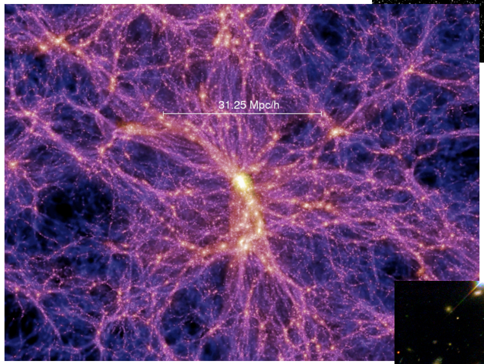


What is the identity of Dark Matter ?

Properties of Dark Matter

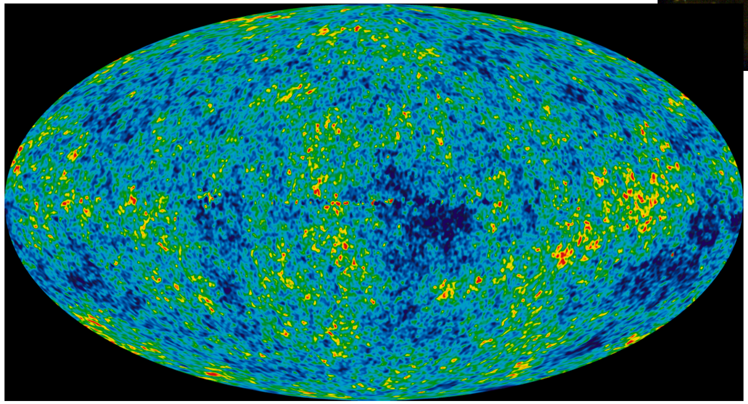


- $\tau_{\mathrm{DM}} \gtrsim$ age of our Universe
- clusters $\leftarrow$ gravitation



- slow – "cold"

- electrically neutral
- color neutral



Dark Matter

↓

Physics beyond the Standard Model

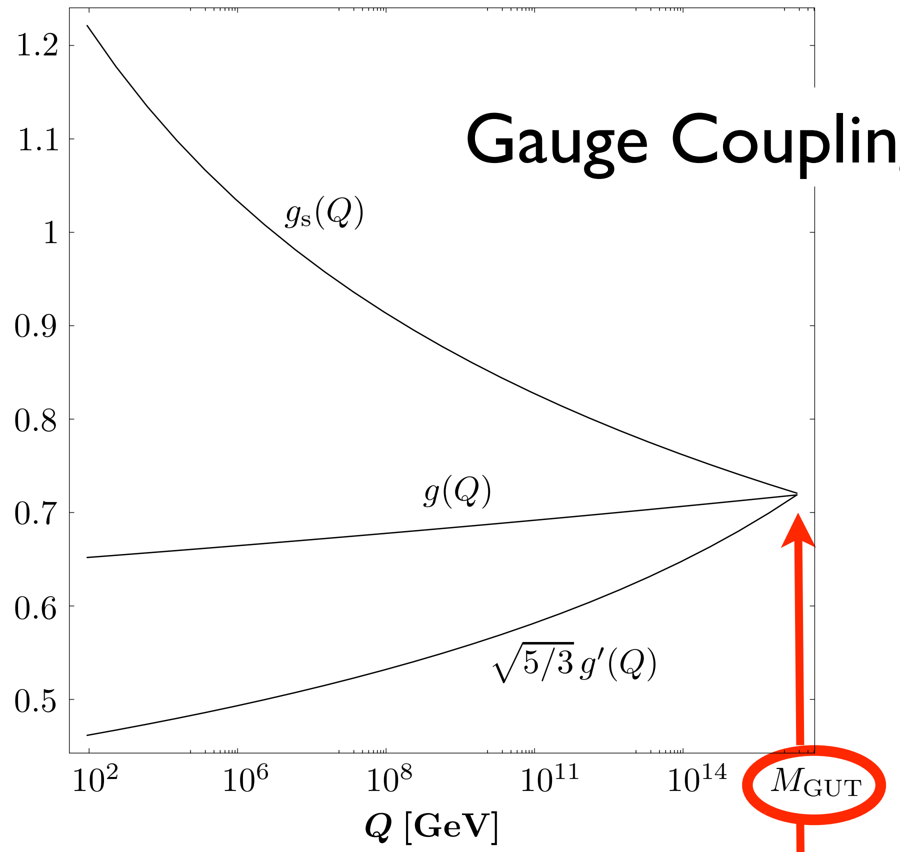
The Minimal Supersymmetric Standard Model

GAUGE	Gauge bosons	Gauginos	$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_Y$
B-boson, bino	$A_\mu^{(1)} = B_\mu$	$\lambda^{(1)} = \widetilde{B}$	$(\mathbf{1}, \mathbf{1})_0$
W-bosons, winos	$A_\mu^{(2)\,a} = W_\mu^a$	$\lambda^{(2)\,a} = \widetilde{W}^a$	$(\mathbf{1}, \mathbf{3})_0$
gluon, gluino	$A_\mu^{(3)\,a} = G_\mu^a$	$\lambda^{(3)\,a} = \widetilde{g}^a$	$(\mathbf{8}, \mathbf{1})_0$

MATTER	Sfermions	Fermions	$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_Y$
sleptons, leptons $I = 1, 2, 3$	$\widetilde{L}^I = \begin{pmatrix} \widetilde{\nu}_L^I \\ \widetilde{e}_L^{-\,I} \end{pmatrix}$	$L^I = \begin{pmatrix} \nu_L^I \\ e_L^{-\,I} \end{pmatrix}$	$(\mathbf{1}, \mathbf{2})_{-1}$
	$\widetilde{E}^{*I} = \widetilde{e}_R^{-\,*\,I}$	$E^{c\,I} = e_R^{-\,c\,I}$	$(\mathbf{1}, \mathbf{1})_{+2}$
squarks, quarks $I = 1, 2, 3$ ($\times$ 3 colors)	$\widetilde{Q}^I = \begin{pmatrix} \widetilde{u}_L^I \\ \widetilde{d}_L^I \end{pmatrix}$	$Q^I = \begin{pmatrix} u_L^I \\ d_L^I \end{pmatrix}$	$(\mathbf{3}, \mathbf{2})_{+\frac{1}{3}}$
	$\widetilde{U}^{*I} = \widetilde{u}_R^{*I}$	$U^{c\,I} = u_R^{c\,I}$	$(\overline{\mathbf{3}}, \mathbf{1})_{-\frac{4}{3}}$
	$\widetilde{D}^{*I} = \widetilde{d}_R^{*I}$	$D^{c\,I} = d_R^{c\,I}$	$(\overline{\mathbf{3}}, \mathbf{1})_{+\frac{2}{3}}$
Higgs, higgsinos	$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$	$\widetilde{H}_d = \begin{pmatrix} \widetilde{H}_d^0 \\ \widetilde{H}_d^- \end{pmatrix}$	$(\mathbf{1}, \mathbf{2})_{-1}$
	$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$	$\widetilde{H}_u = \begin{pmatrix} \widetilde{H}_u^+ \\ \widetilde{H}_u^0 \end{pmatrix}$	$(\mathbf{1}, \mathbf{2})_{+1}$

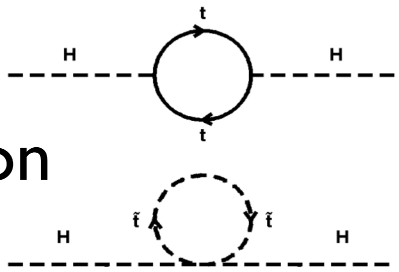
Why Supersymmetry?

Extension of Space-Time Symmetry



Gauge Coupling Unification

Hierarchy Stabilization



(Super-) Gravity

Consistent String Theory

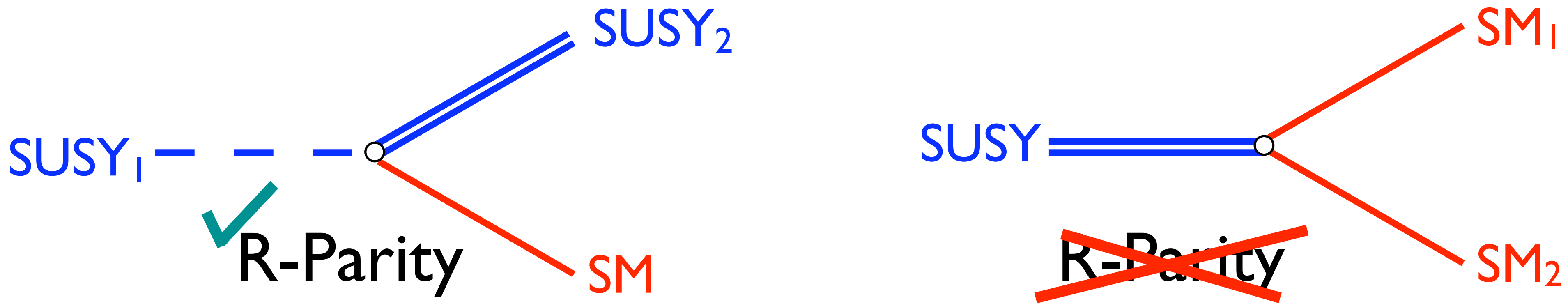
Dark Matter

Gauge Coupling Unification at $M_{GUT} \simeq 2 \times 10^{16}\,\mathrm{GeV}$

Conservation of R-Parity

- superpotential: $W_{\mathrm{MSSM}} \leftarrow W_{\Delta L} + W_{\Delta B}$
- non-observation of L & B violating processes (proton stability, ...)
- postulate conservation of R-Parity ← multiplicative quantum number

$$P_{\mathrm{R}} = (-1)^{3(B-L)+S} = \begin{cases} +1 & \text{for SM}, H_u, H_d \\ -1 & \text{for } \widetilde{X} \leftarrow \text{superpartners} \end{cases}$$



The lightest supersymmetric particle (LSP) is stable!!!

Supersymmetric Dark Matter Candiates

	LSP	ID	spin	mass	interaction
lightest neutralino	$\widetilde{\chi}_1^0$	$\widetilde{B}, \widetilde{W}, \widetilde{H}_u^0, \widetilde{H}_d^0$	$\frac{1}{2}$	$\mathcal{O}(100\ \mathrm{GeV})$	g, g'
$\in$ MSSM		mixture		$M_1, M_2, \mu, \tan\beta$	weak
gravitino	$\widetilde{G}$	superpartner of	$\frac{3}{2}$	eV – TeV	$\left(\frac{p}{\mathrm{M_{Pl}}}\right)^n$
$*$ gravity		the graviton		SUSY breaking	extremely weak

$$m_{\widetilde{G}} \sim \sum_I \frac{\langle F_I \rangle}{\mathrm{M_{Pl}}} + \sum_A \frac{\langle D_A \rangle}{\mathrm{M_{Pl}}} \sim \frac{M^2_{\mathrm{SUSY}}}{\mathrm{M_{Pl}}}$$

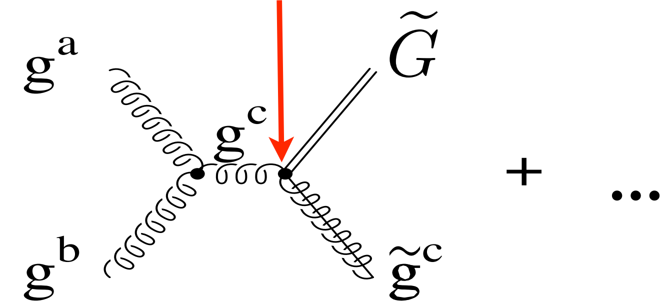
gauge-MSB	gravity-MSB gaugino-MSB	anomaly-MSB mirage-MSB
light gravitino **1 eV-1 GeV**	**weak-scale gravitino** **0.01-1 TeV**	**heavy gravitino** **1-100 TeV**

Thermal Gravitino Production

LSP	interaction	production	constraints
$\widetilde{G}$	$\left(\frac{p}{\mathrm{M_{Pl}}}\right)^n$ extremely weak	therm. prod.	$\leftarrow$ cold
		NLSP decays	$\leftarrow$ warm
	$\mathrm{M_{Pl}} = 2.44 \times 10^{18}\,\mathrm{GeV}$	...	

Very Hot Early Universe

$T \sim 10^7$ GeV



gauge-invariant treatment
(hard thermal loop resummation)

SUSY QCD
[Bolz, Brandenburg, Buchmüller, '01]

+ electroweak contributions
[Pradler, FDS, '06 & '07]

Gravitino Dark Matter from Thermal Production

- Boltzmann Equation

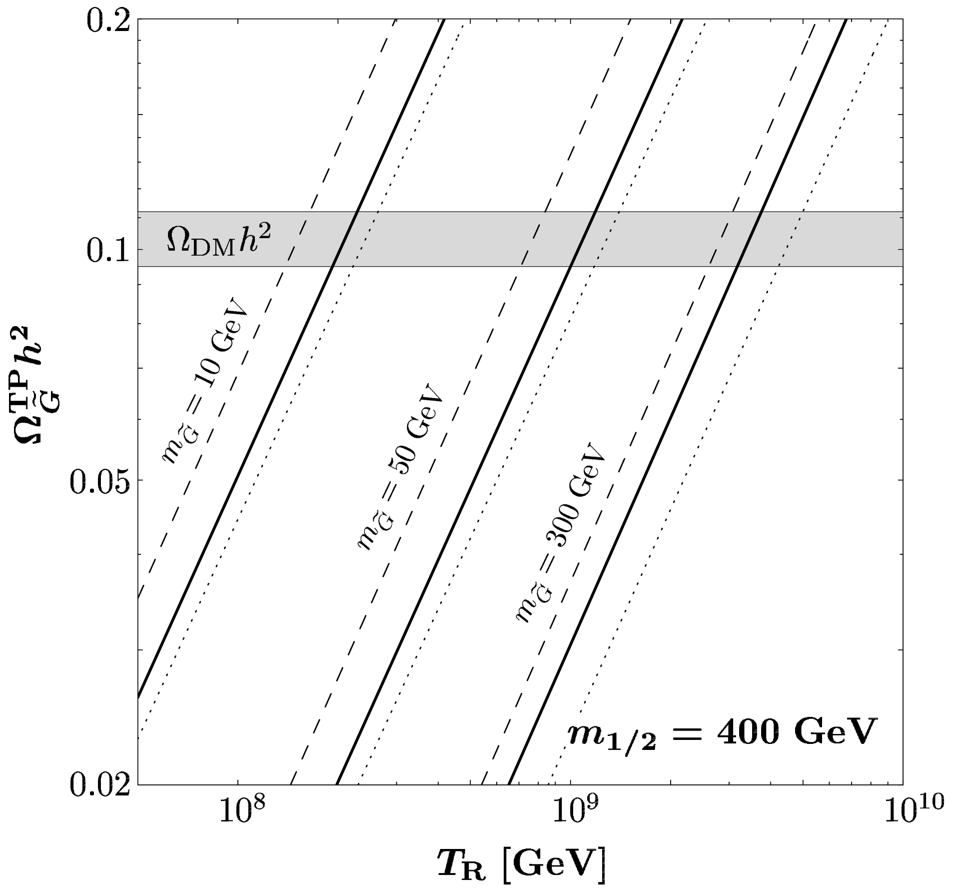
$$\frac{dn_{\widetilde{G}}}{dt} + 3Hn_{\widetilde{G}} = C_{\widetilde{G}}$$

- Collision Term

$$C_{\widetilde{G}} = \sum_{i=1}^{3} \frac{3\zeta(3)T^6}{16\pi^3 \mathrm{M}_{\mathrm{Pl}}^2} \left(1 + \frac{M_i^2}{3m_{\widetilde{G}}^2}\right) c_i\, g_i^2 \ln\left(\frac{k_i}{g_i}\right)$$

- Gravitino Density

$$\Omega_{\widetilde{G}}^{\mathrm{TP}} h^2 = \sum_{i=1}^{3} \omega_i\, g_i^2 \left(1 + \frac{M_i^2}{3m_{\widetilde{G}}^2}\right) \ln\left(\frac{k_i}{g_i}\right) \times \left(\frac{m_{\widetilde{G}}}{100\ \mathrm{GeV}}\right) \left(\frac{T_{\mathrm{R}}}{10^{10}\ \mathrm{GeV}}\right)$$



- $\mathrm{U(1)_Y \times SU(2)_L \times SU(3)_c}$

$$c_i = (11, 27, 72)$$
$$k_i = (1.266, 1.312, 1.271)$$
$$\omega_i = (0.018, 0.044, 0.117)$$

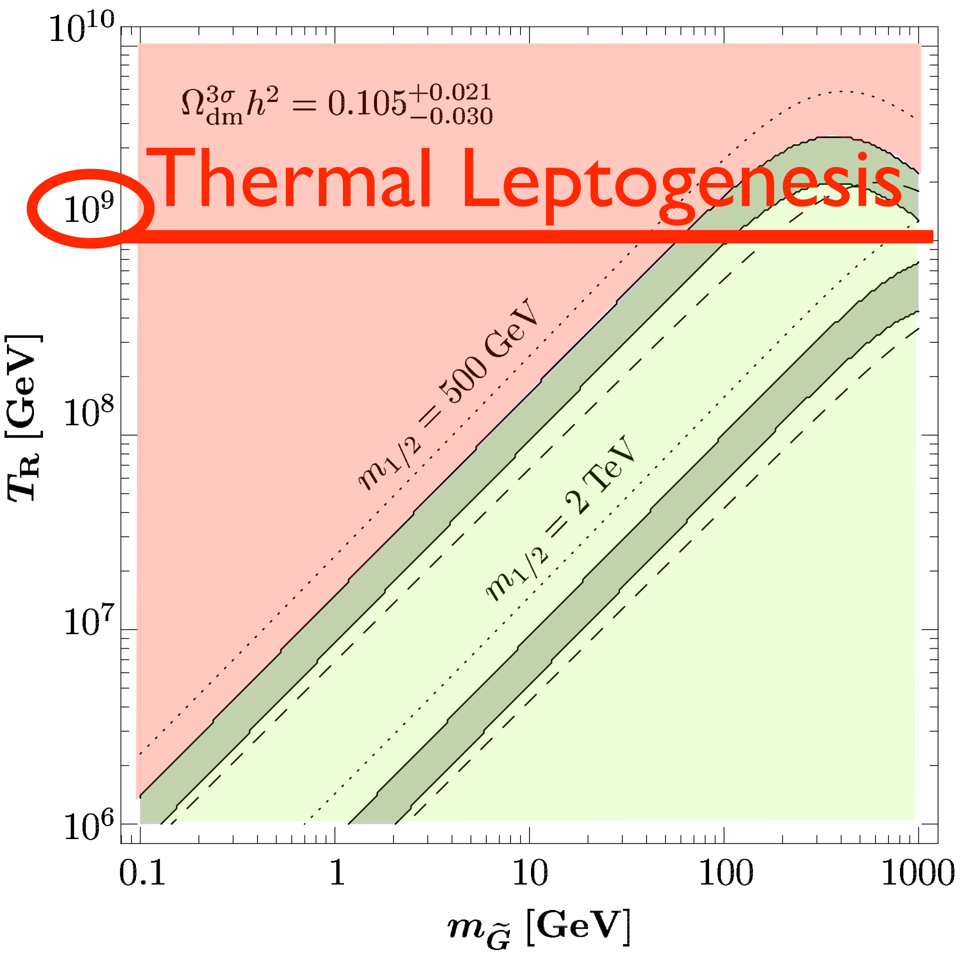
solid: $M_{1,2,3} = m_{1/2}$

dashed: $0.5\, M_{1,2} = M_3 = m_{1/2}$

dotted: $M_3 = m_{1/2}$

[... ; Bolz, Brandenburg, Buchmüller, '01; Pradler, FDS, '07]

Thermal $\widetilde{G}$ Production

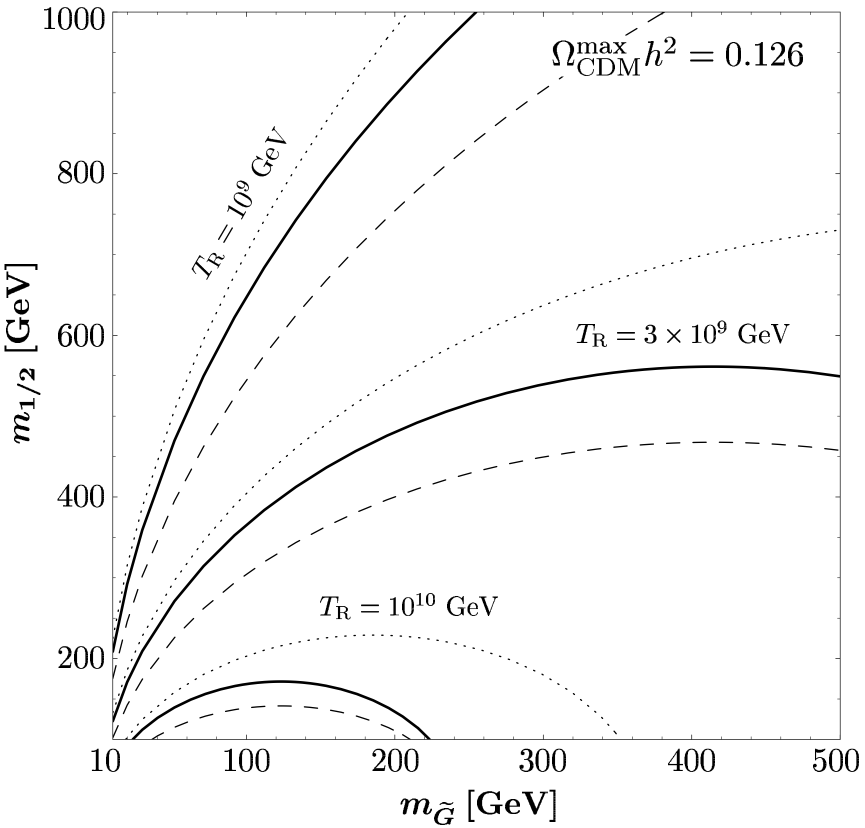


[Pradler, FDS, '07]

see also [Moroi, Murayama, Yamguchi, '93, Asaka, Hamaguchi, Suzuki, '00, Roszkowski et al., '05, Cerdeno et al., '06, FDS '06, Rychkov, Strumia, '07]

[Pradler, FDS, ’06]

Probing T_R at Colliders in Gravitino DM Scenarios



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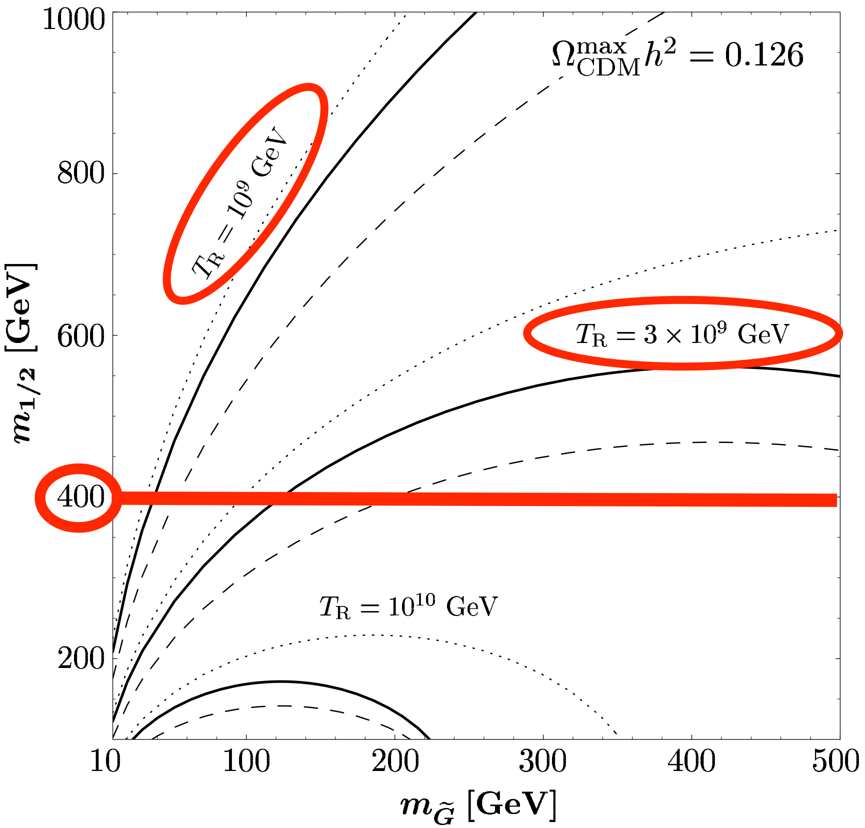

Thermal Leptogenesis

Non-Thermal Gravitino/Axino Production

LSP	interaction	production	constraints
$\widetilde{G}$	$\left(\frac{p}{\mathrm{M_{Pl}}}\right)^n$	therm. prod.	$\leftarrow$ cold
	extremely weak	NLSP decays	$\leftarrow$ warm
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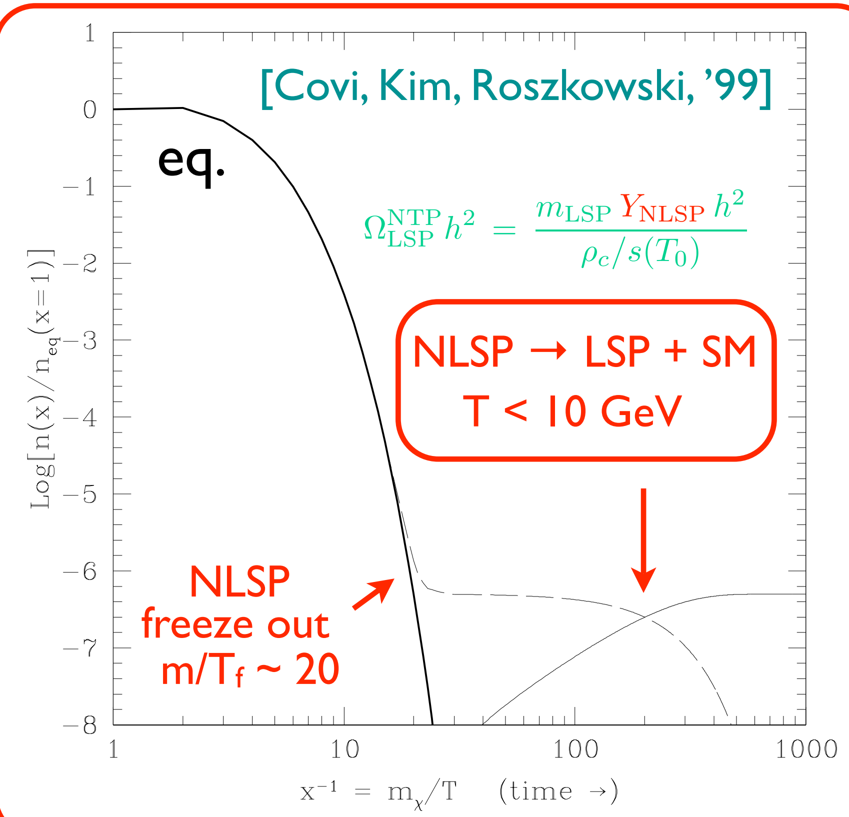

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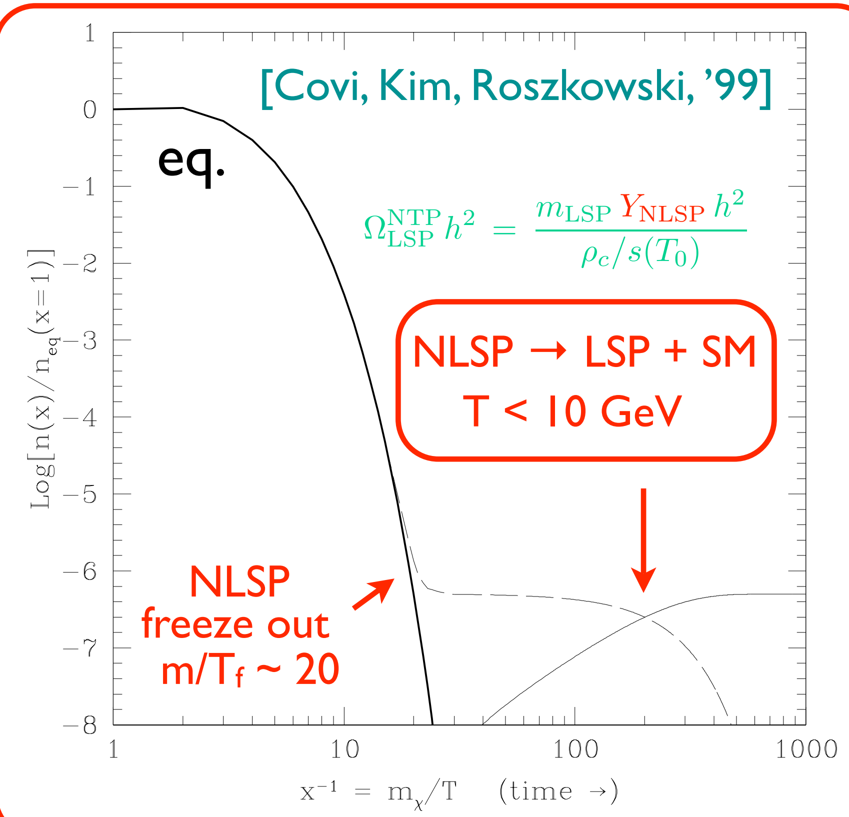

NLSP Candidates

- **lightest neutralino**
- **lighter stau**
- **lighter stop**
- **lightest sneutrino**

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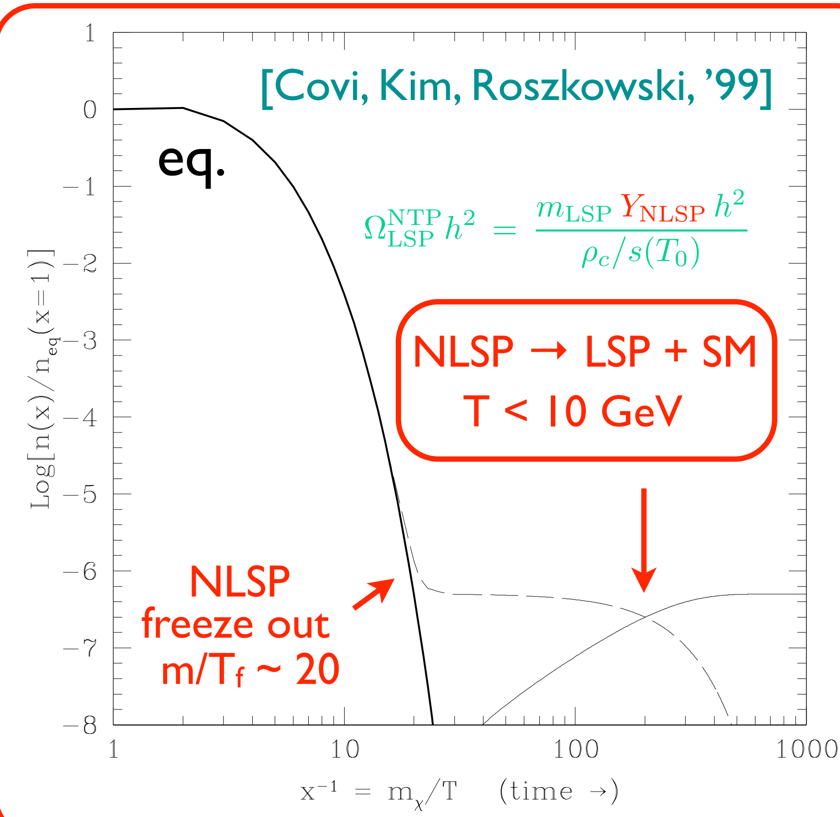

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electrically charged →

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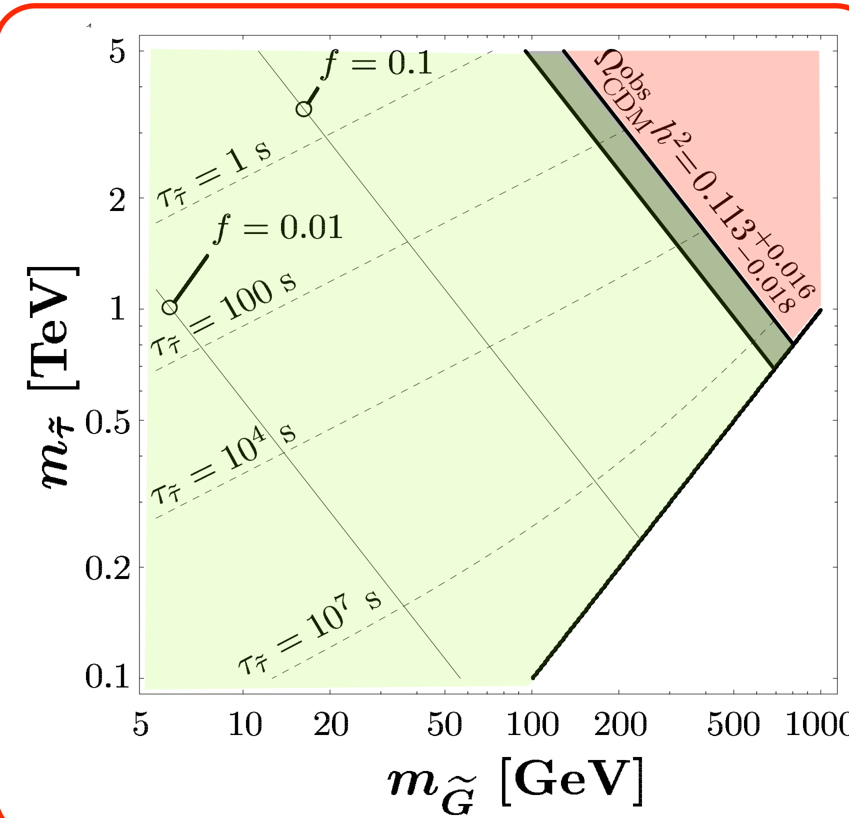

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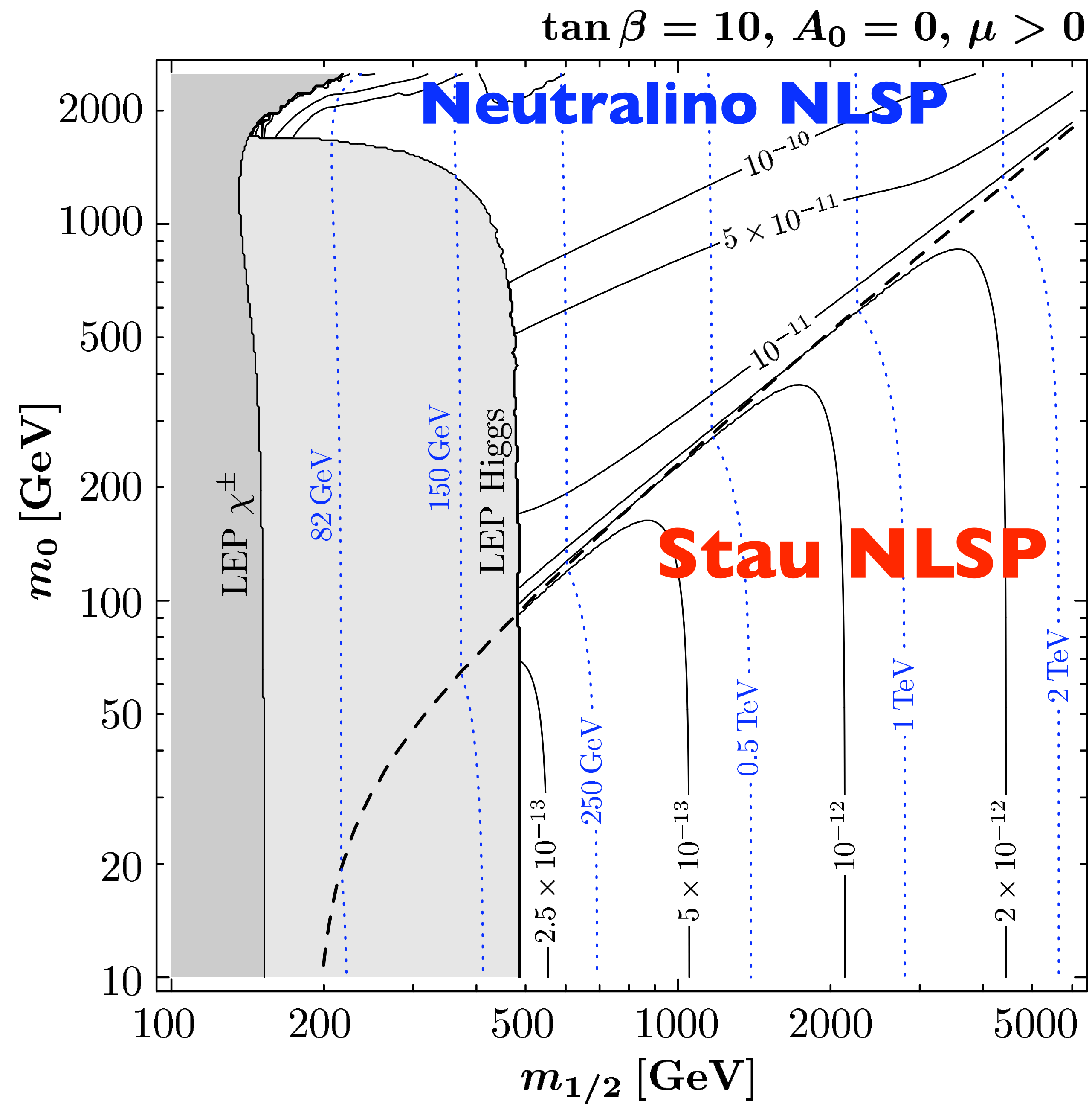
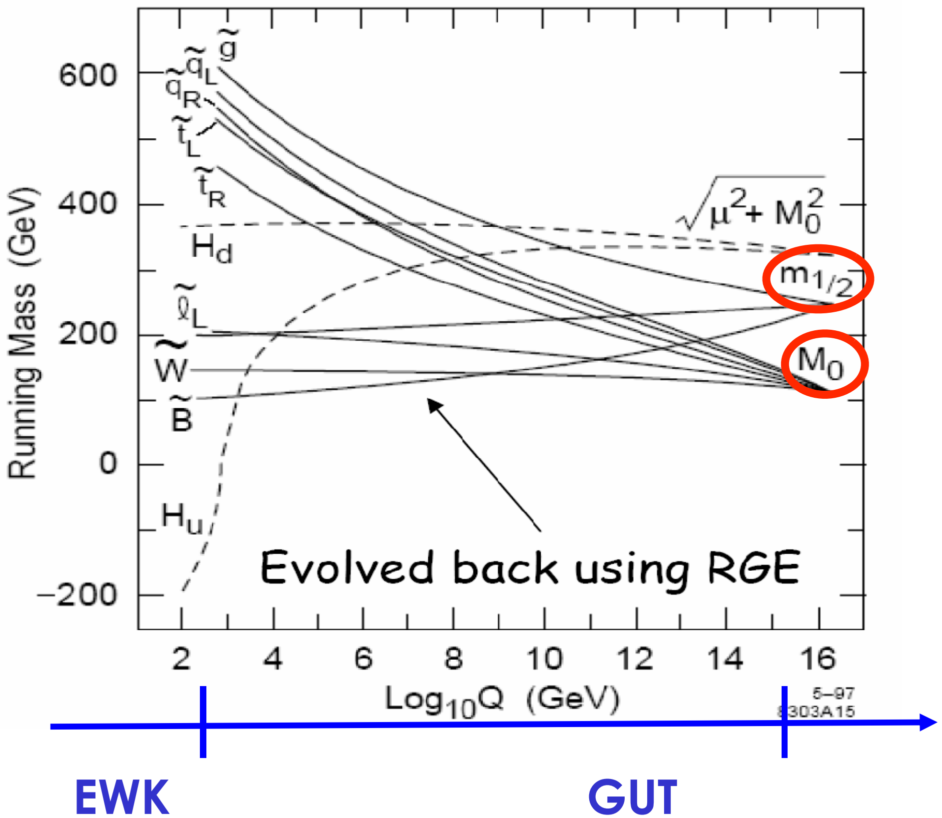

$\tan\beta = 10,\ A_0 = 0,\ \mu > 0$
Neutralino NLSP
Stau NLSP
10^{-10}
5×10^{-11}
10^{-11}
LEP $\chi^{\pm}$
82 GeV
150 GeV
LEP Higgs
250 GeV
0.5 TeV
1 TeV
2 TeV
2.5×10^{-13}
5×10^{-13}
10^{-12}
2×10^{-12}
m_0 [GeV]
$m_{1/2}$ [GeV]
2000
1000
500
200
100
50
20
10
100
200
500
1000
2000
5000

mSUGRA / CMSSM

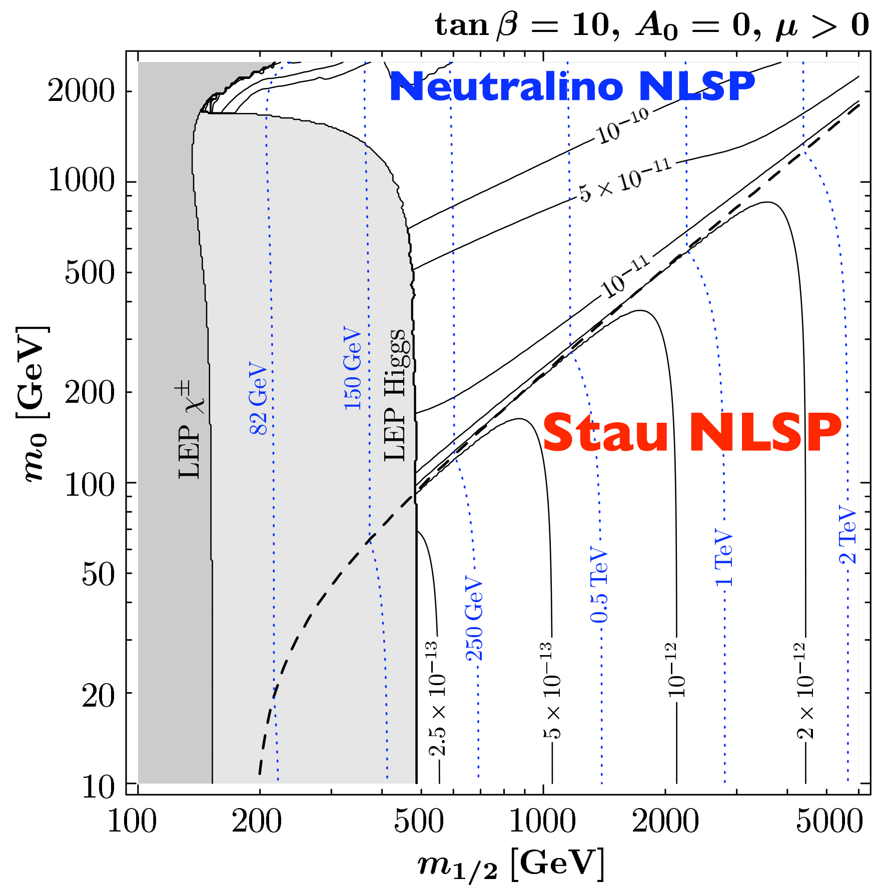


1. Unified gaugino mass $m_{1/2}$
2. Unified scalar mass m_0
3. Ratio of H_1, H_2 vevs tanβ
4. Trilinear coupling A_0
5. Higgs mass term sgn(μ)

[Pradler, FDS, arXiv:0710.4548]

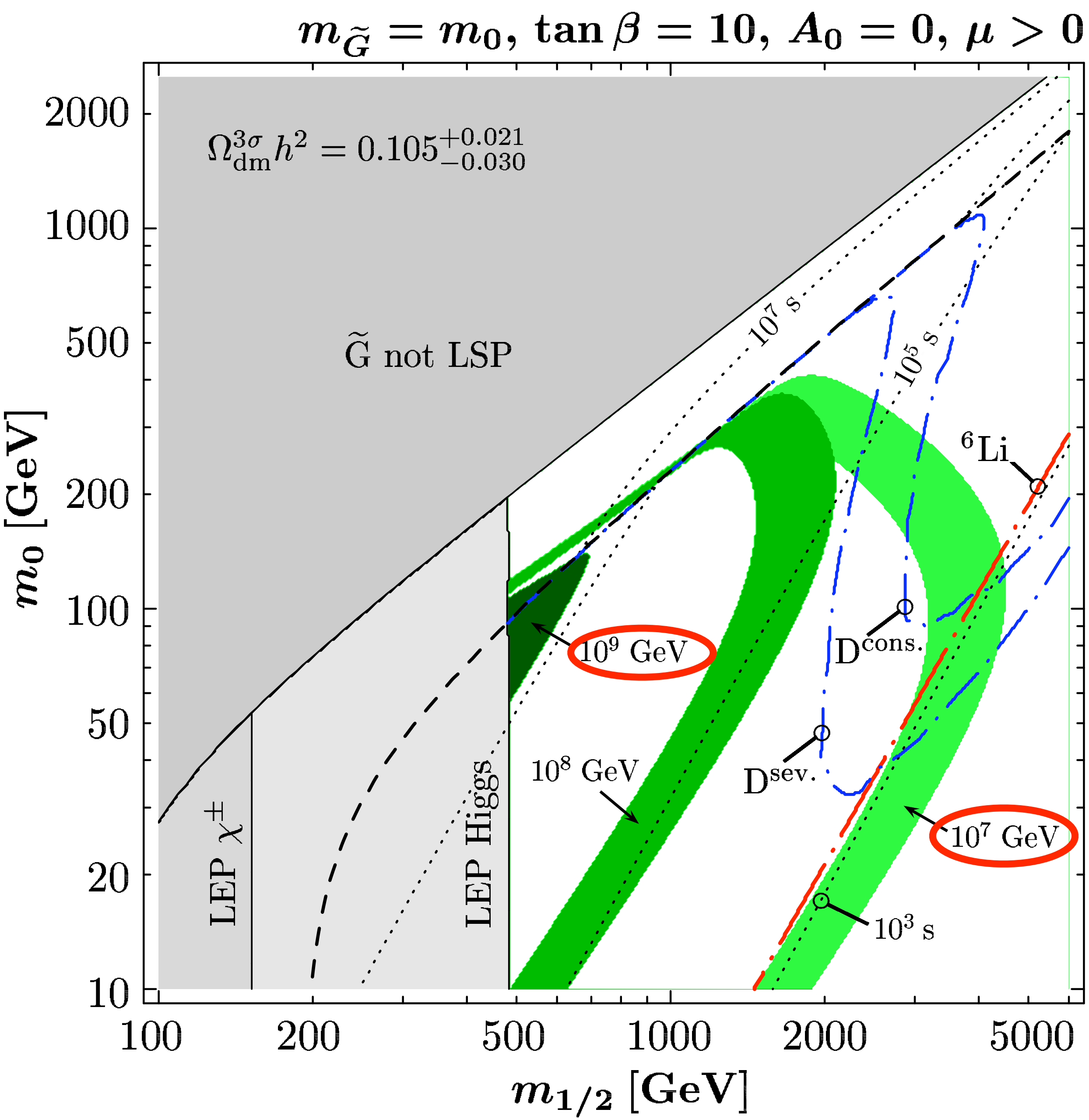
CMSSM Scan

m_{LOSP} & Y_{LOSP}

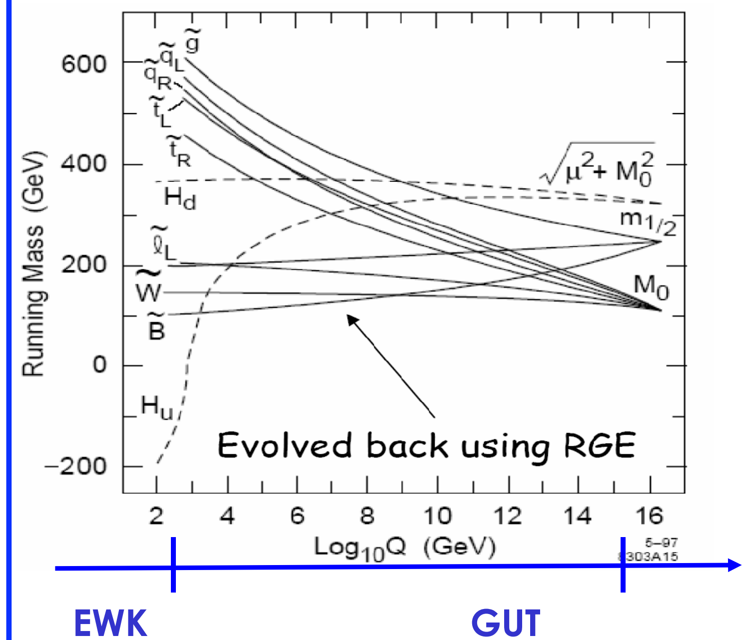


[Josef Pradler, FDS, hep-ph/0612291]

TP + NTP of Gravitino DM within the CMSSM



mSUGRA / CMSSM



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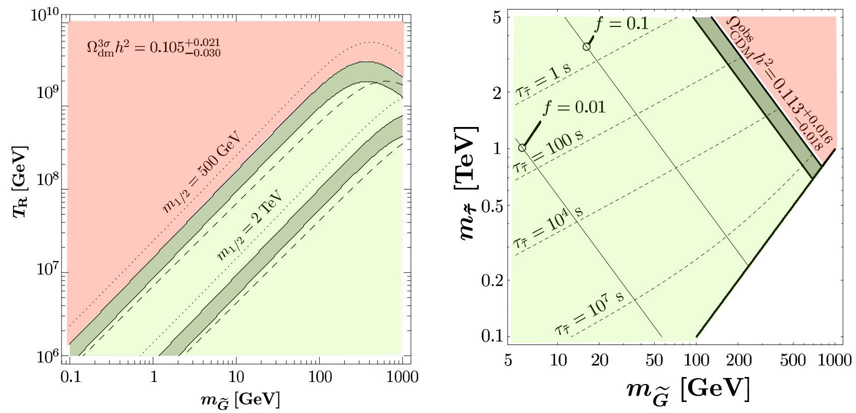
LSP Dark Matter: Production, Constraints, Experiments

LSP	interaction	production	constraints	experiments
$\widetilde{\chi}_1^0$	g, g'	WIMP	$\leftarrow$ cold	indirect detection (EGRET, GLAST, ...)
	weak	freeze out		direct detection (CRESST, EDELWEISS, ...)
	$M_W \sim 100$ GeV			prod.@colliders (Tevatron, LHC, ILC, ...)
$\widetilde{G}$	$\left(\frac{p}{\mathrm{M_{Pl}}}\right)^n$	therm. prod.	$\leftarrow$ cold	
	extremely weak	NLSP decays	$\leftarrow$ warm	
	$\mathrm{M_{Pl}} = 2.44 \times 10^{18}$ GeV	...		

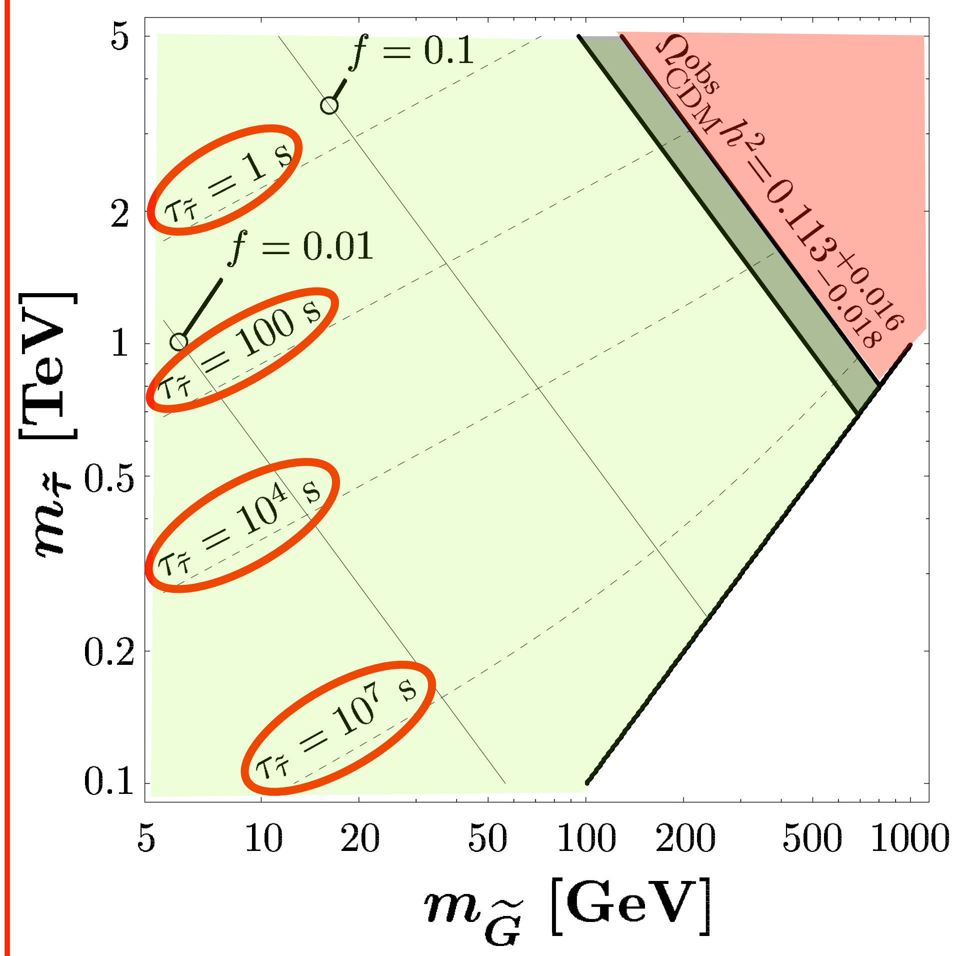


$\Omega_{\widetilde{G}} = \Omega_{\rm DM}$

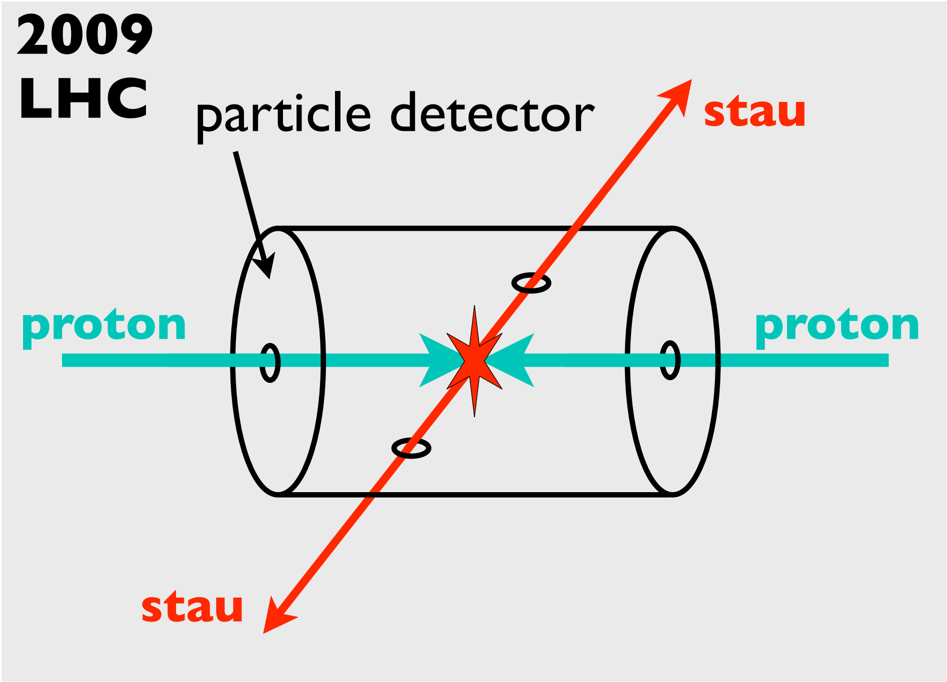
is possible!!!

long-lived NLSP

$\widetilde{\tau}$ NLSP $\longrightarrow \widetilde{G} + \tau$



Gravitino DM @ LHC ← Stau NLSP



The signal:
jets + leptons

+ 2 “stable” charged particles

Very different from the large E_T^{miss} signal of Neutralino DM

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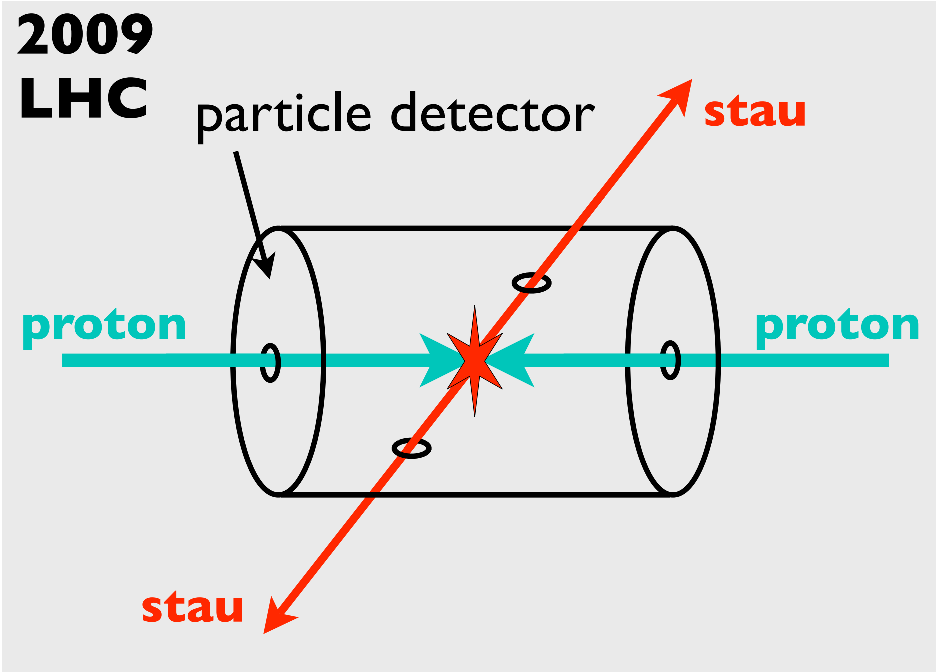

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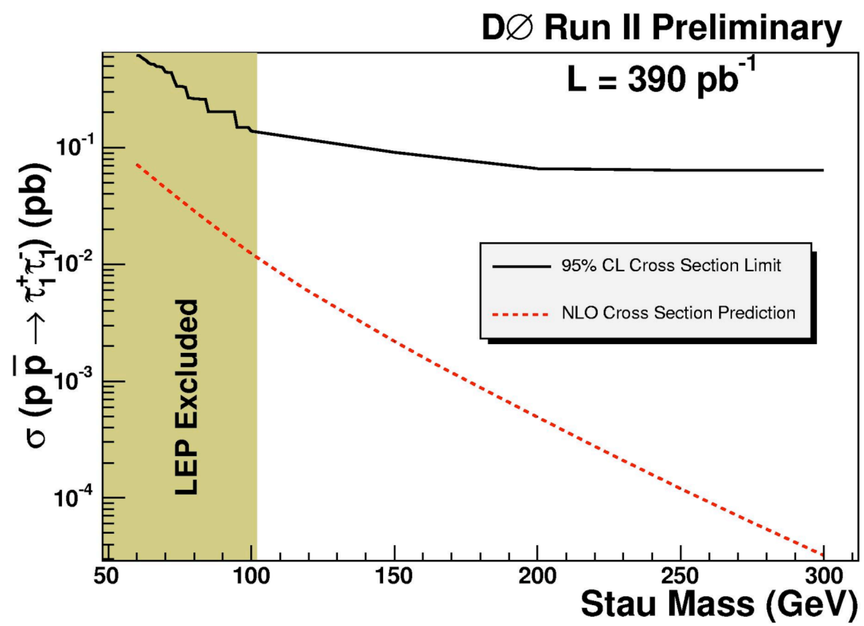
Tevatron



[from Gershtein’s Talk, SUSY2007]

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long-lived NLSP

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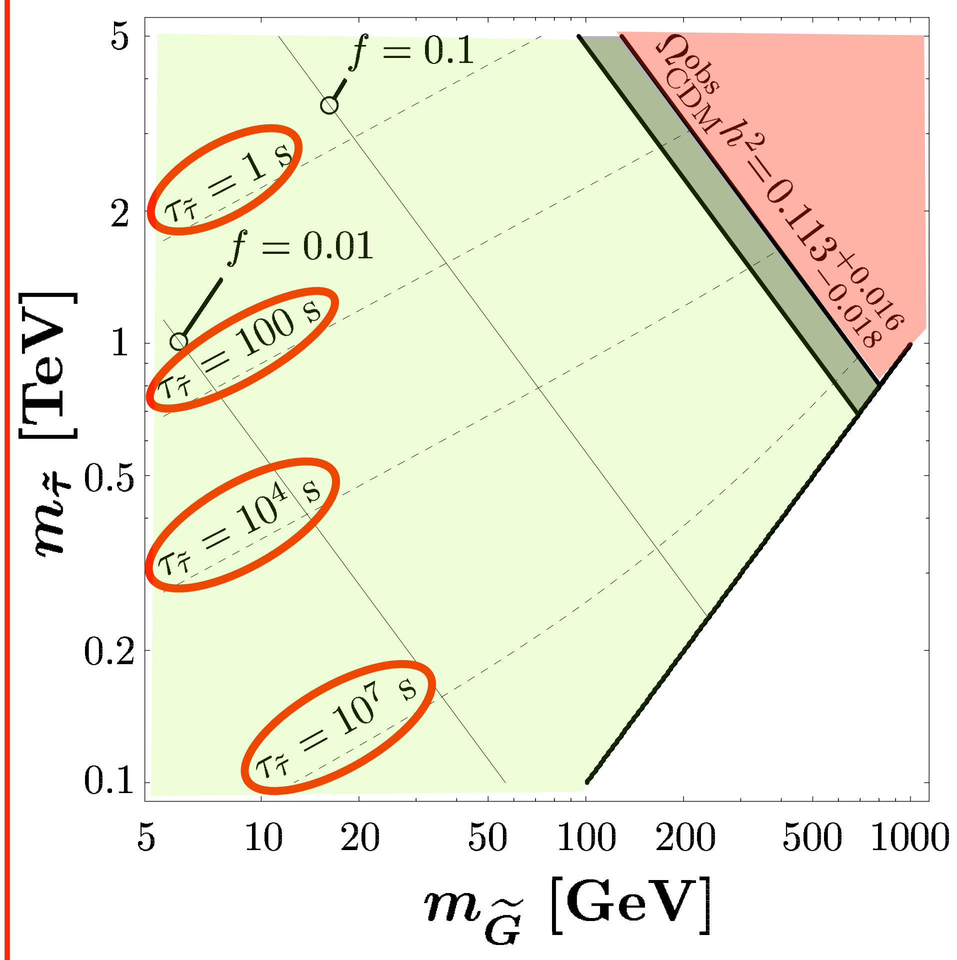
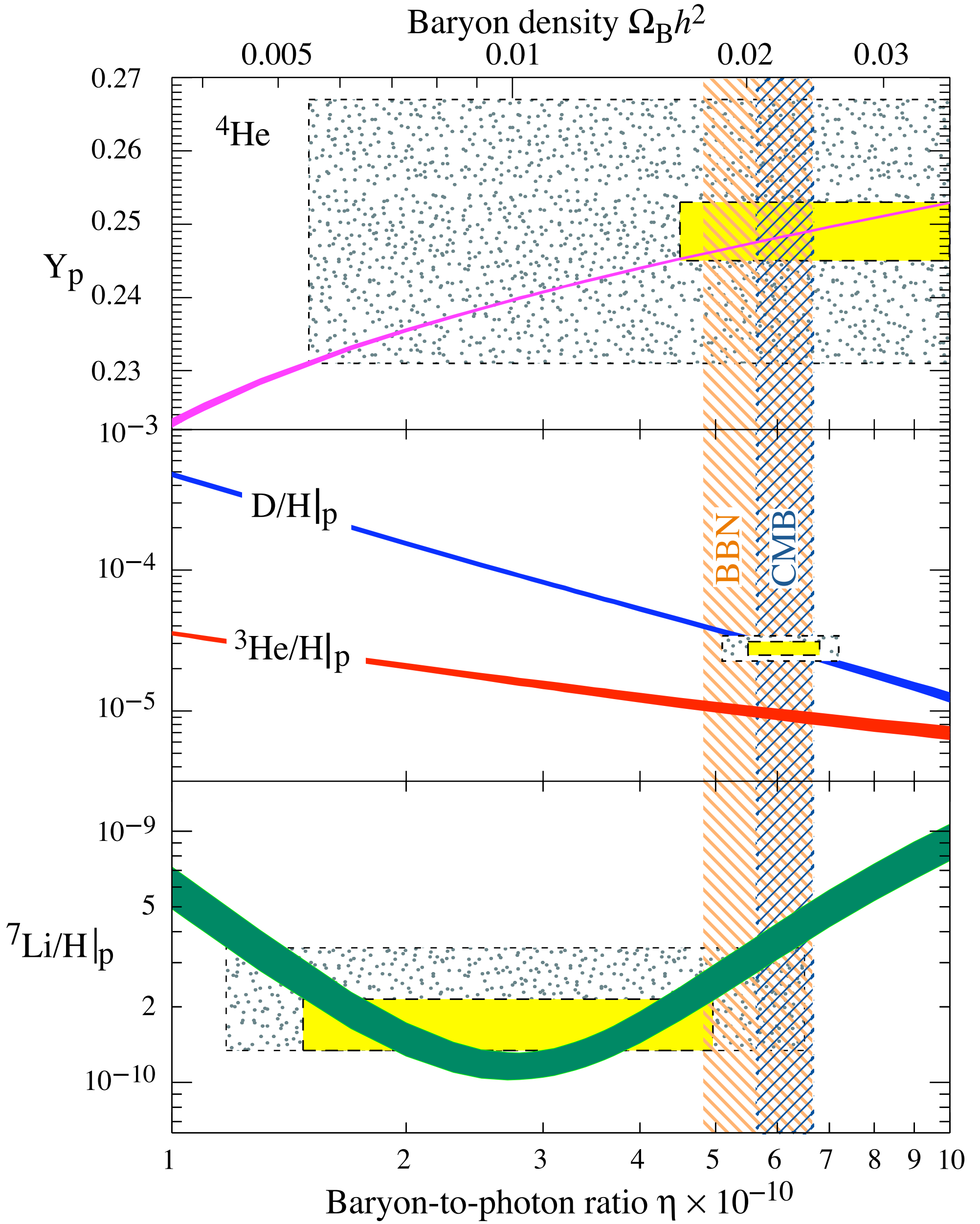
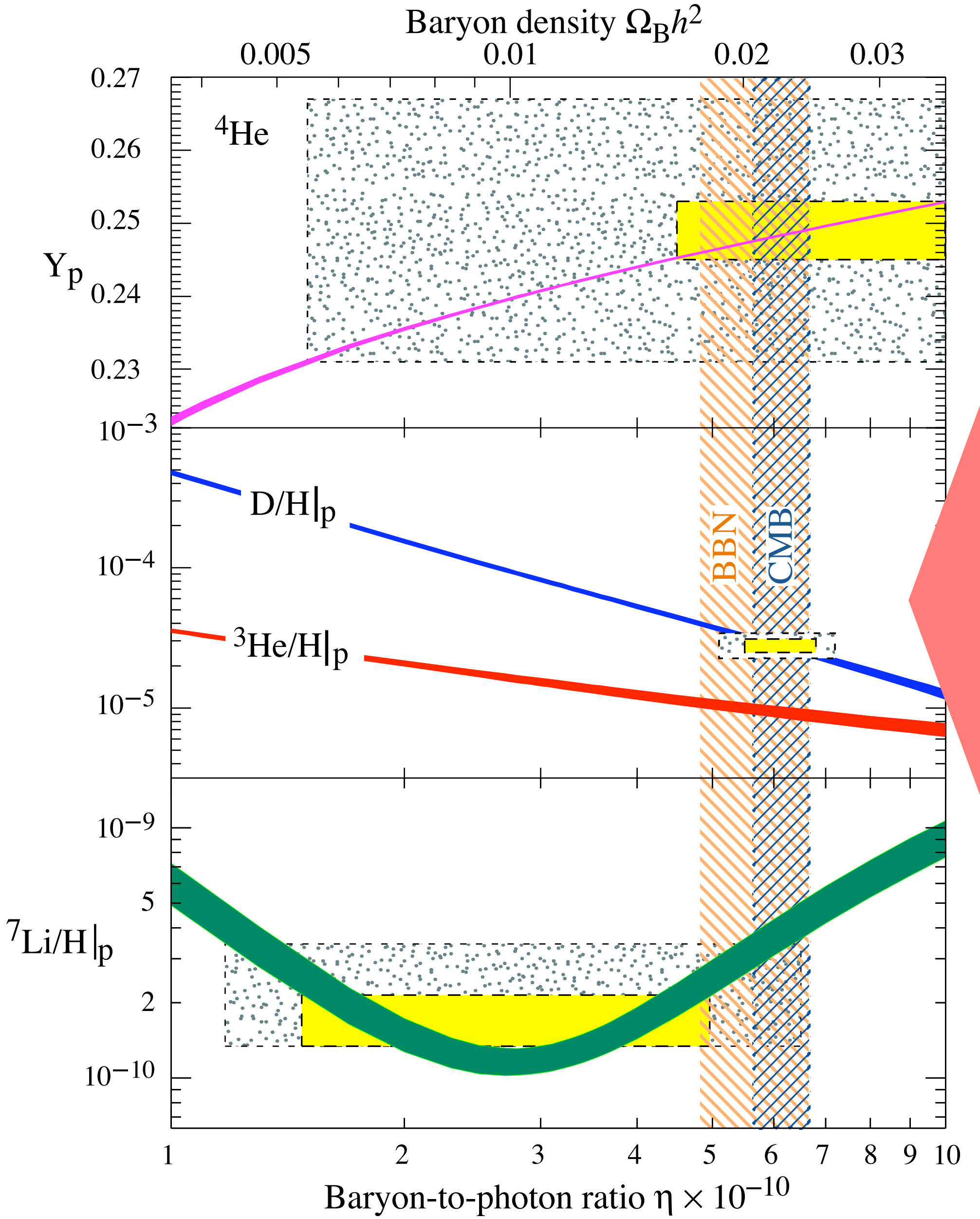


Big-Bang Nucleosynthesis

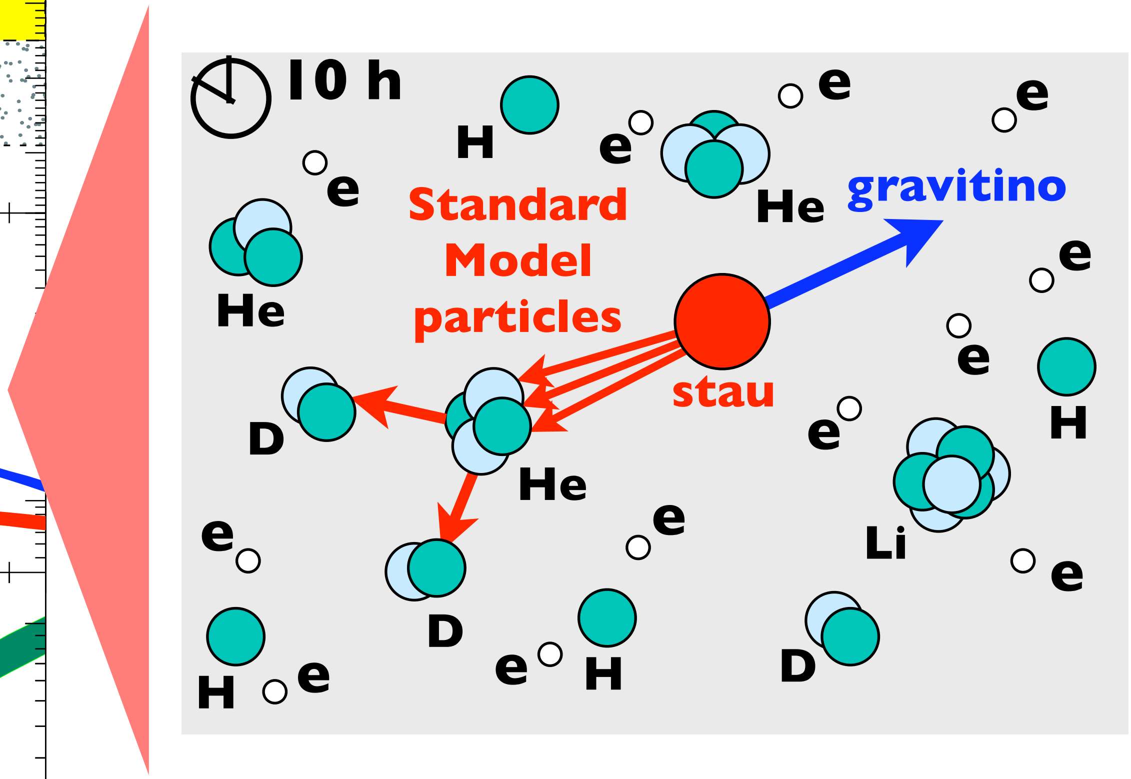


[Particle Data Book 2006]

Big-Bang Nucleosynthesis

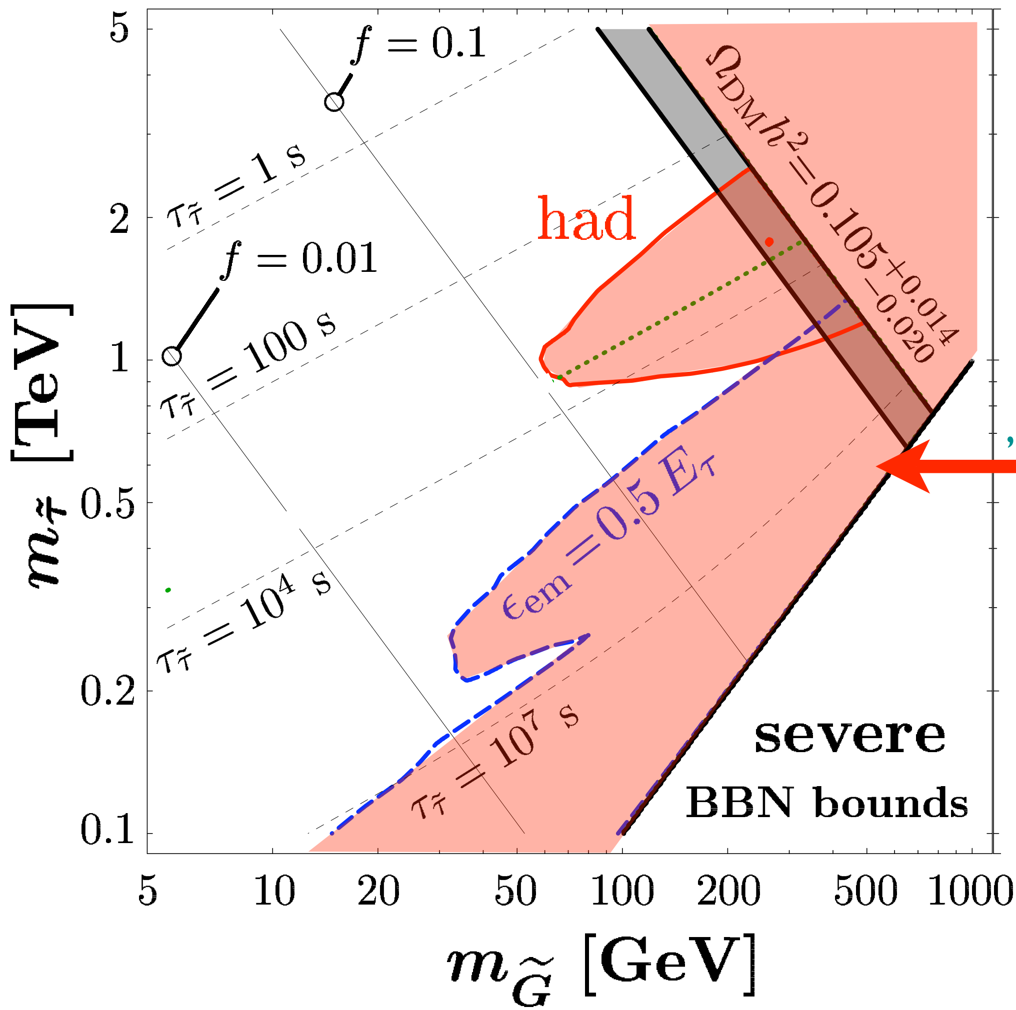


[Particle Data Book 2006]



[FDS, ’06]

Cosmological Constraints — $\Omega_{\rm DM}$ & BBN



disfavored by cosmological constraints

[FDS, ’06]

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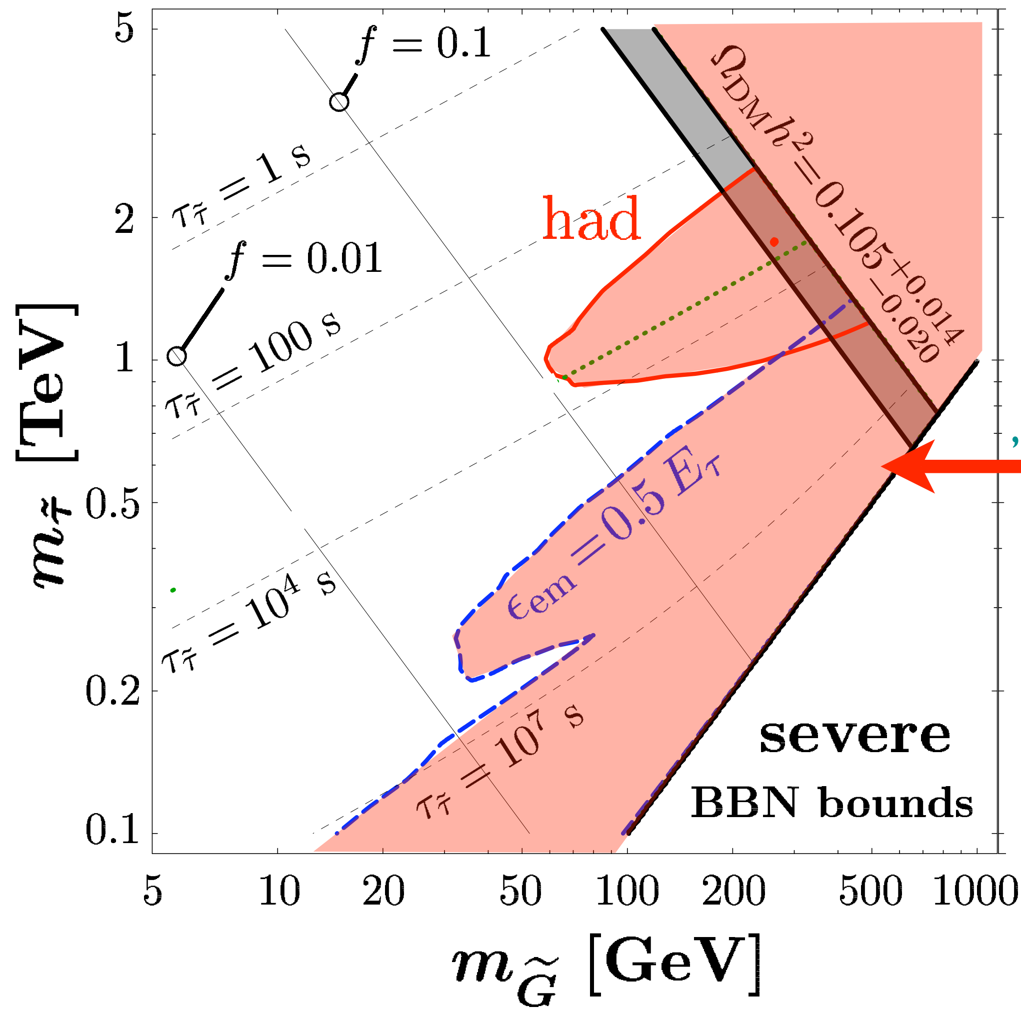
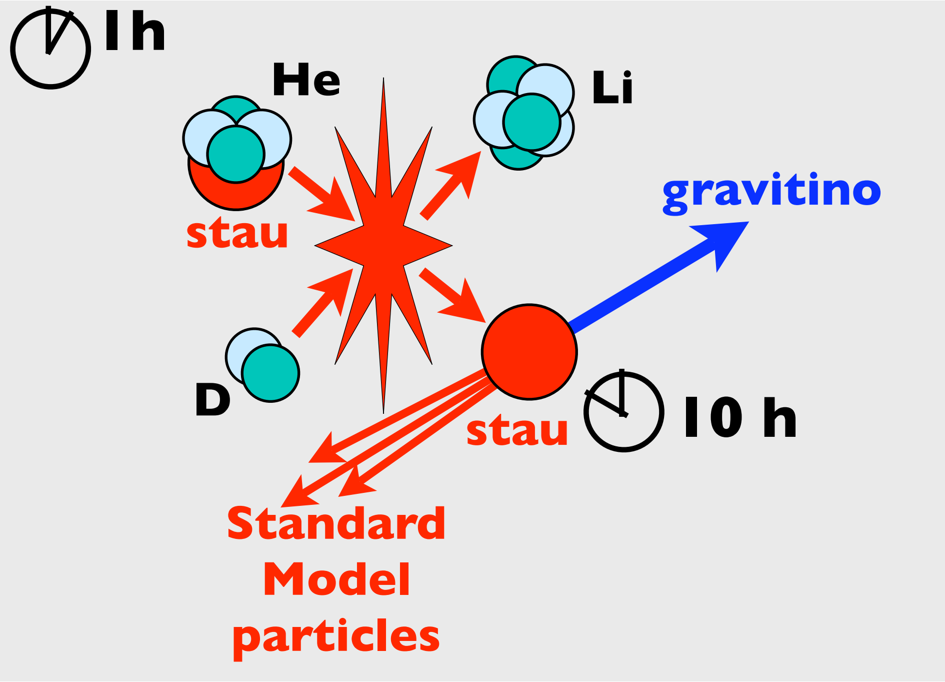


disfavored by cosmological constraints

Picture until May 2006 ...

Catalyzed BBN [Pospelov, '06]



Recent Result: [Hamaguchi et al., '07]

[Cyburt et al., '06; FDS, '06; Pradler, FDS, '07; Kawasaki, Kohri, Moroi, '07; Takayama, '07; Jedamzik, '07; Pradler, FDS, arXiv:0710.2213 & arXiv:0710.4548]

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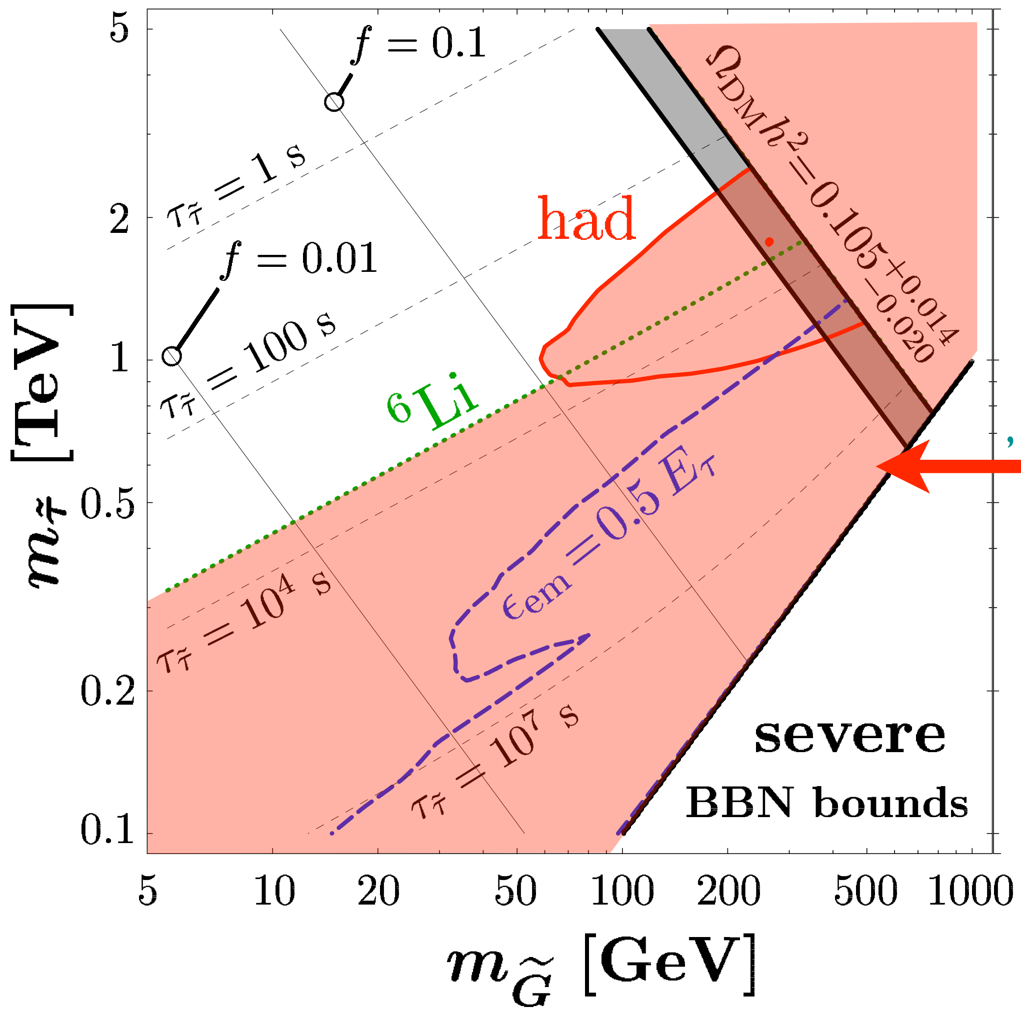
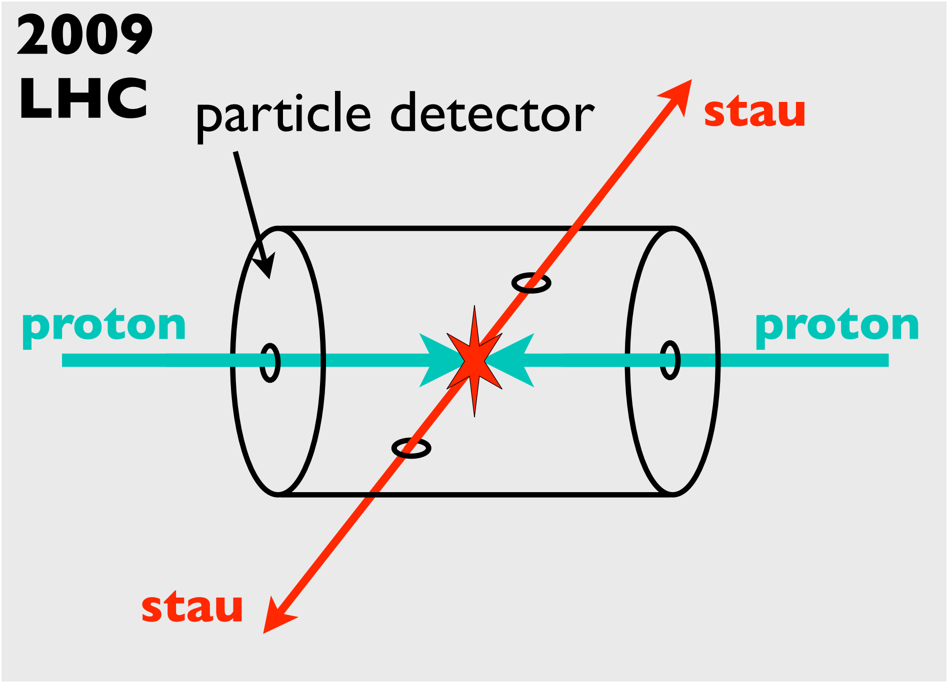
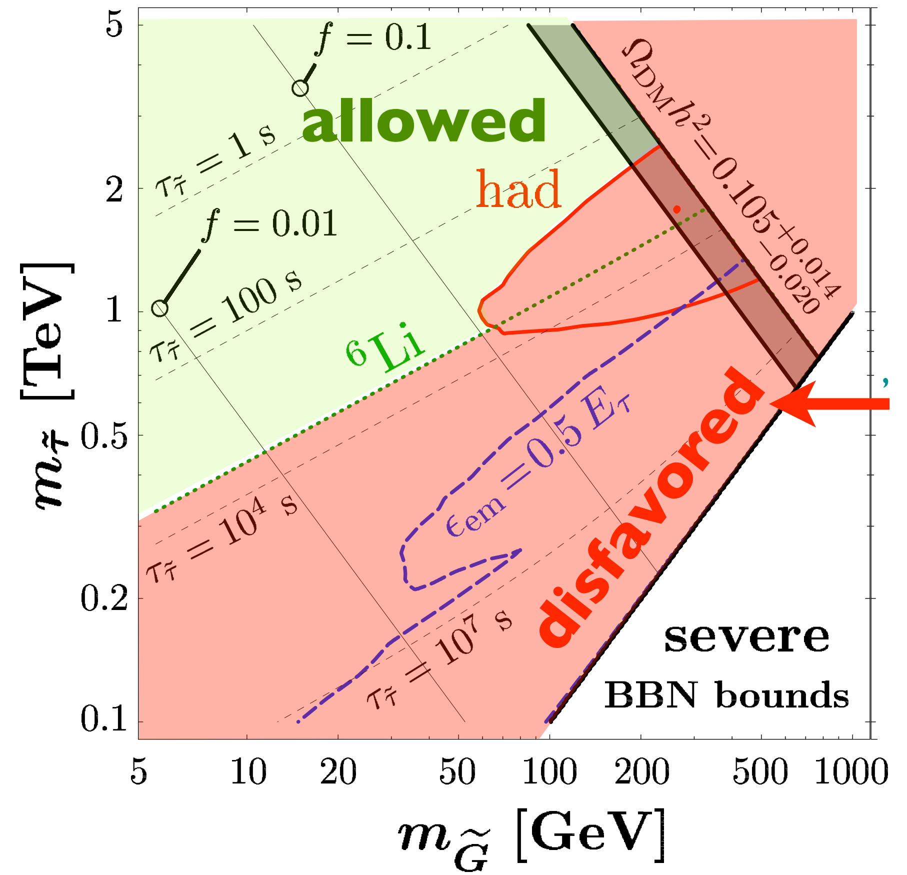


disfavored by cosmological constraints

Gravitino DM @ LHC ← Stau NLSP



The signal:
jets + leptons
+ 2 "stable" charged particles



Cosmological Constraints

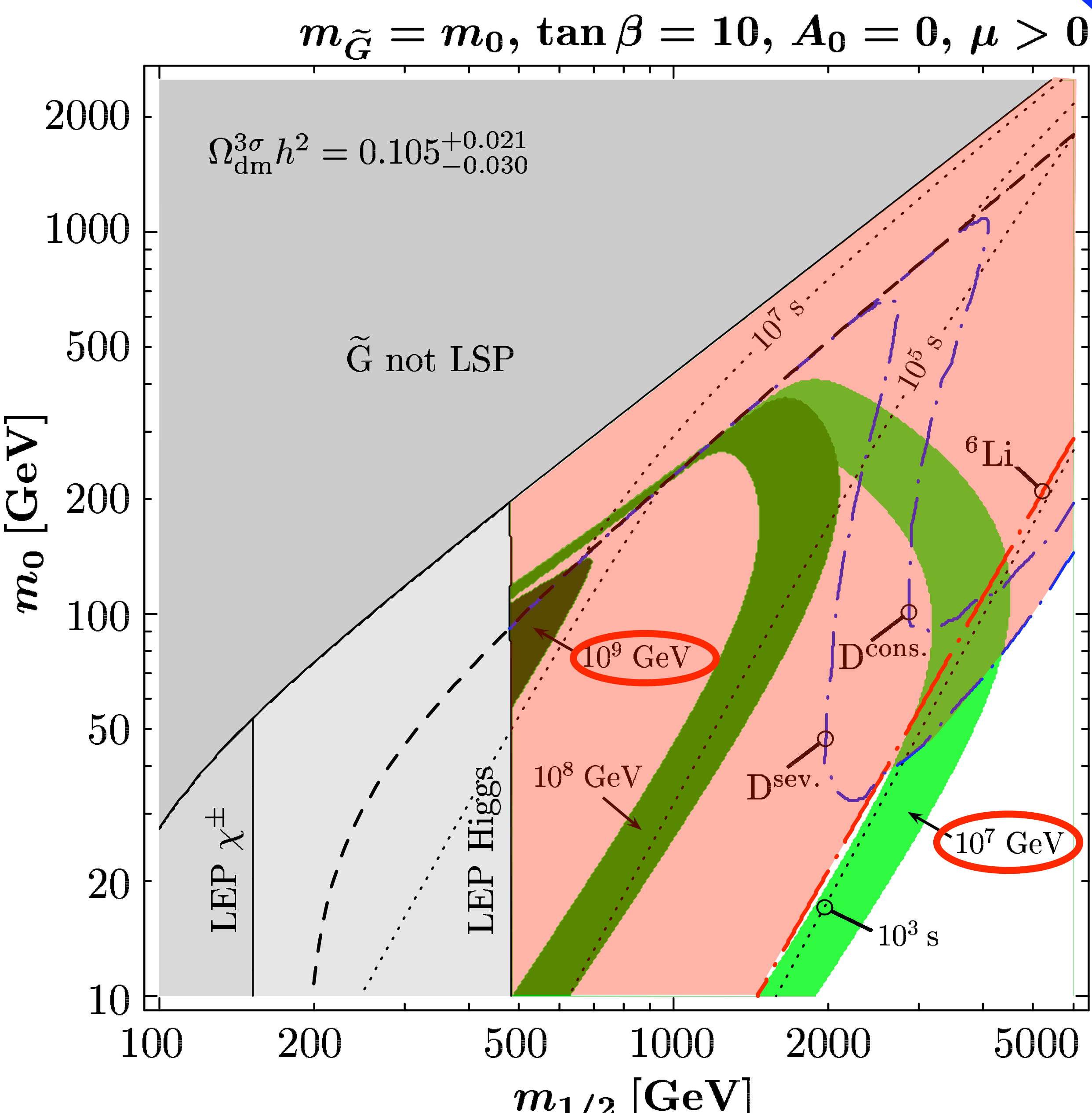
[Steffen, '06, Steffen, hep-ph/0611027]

[Pradler, Steffen, arXiv:0710.4548]

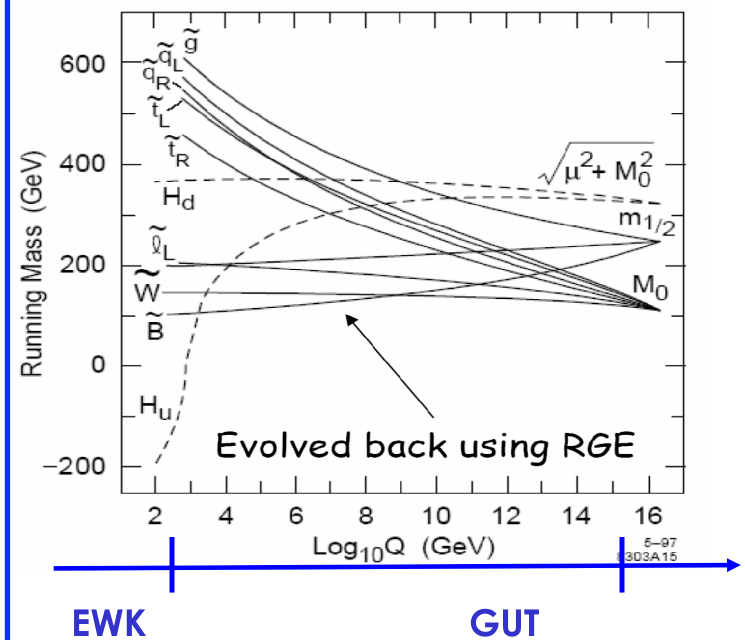
Very different from the large E_T^{miss} signal of Neutralino DM

[Josef Pradler, FDS, hep-ph/0612291]

Upper Bounds on T_R in the CMSSM with $\widetilde{G}$ Dark Matter



mSUGRA / CMSSM

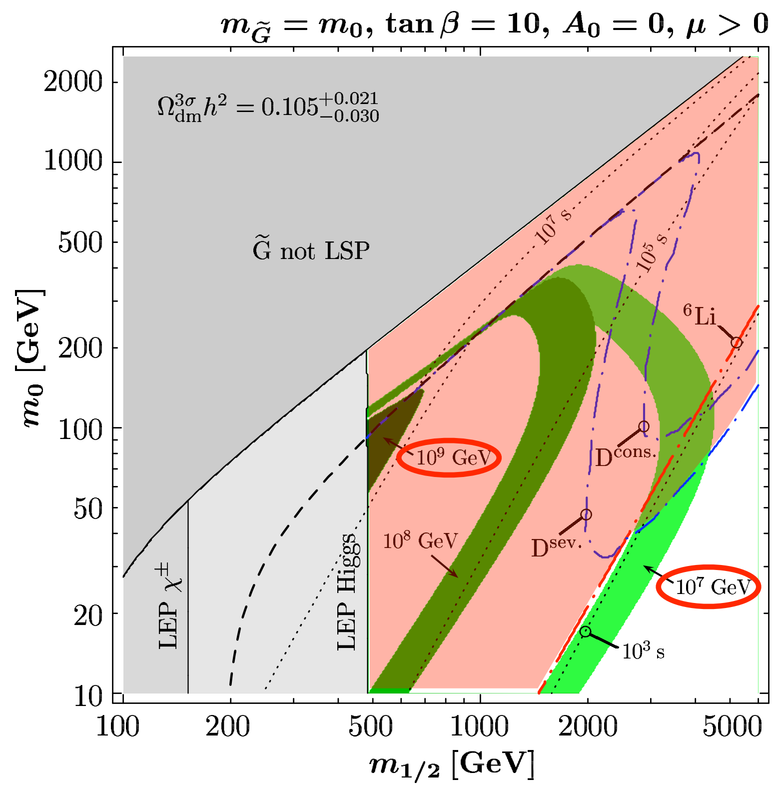


1. Unified gaugino mass $m_{1/2}$
2. Unified scalar mass m_0
3. Ratio of H_1, H_2 vevs $\tan\beta$
4. Trilinear coupling A_0
5. Higgs mass term sgn(μ)

[Josef Pradler, FDS, hep-ph/0612291]

Upper Bounds on T_R in the CMSSM with $\widetilde{G}$ Dark Matter

Implications for inflation and the origin of the baryon asymmetry

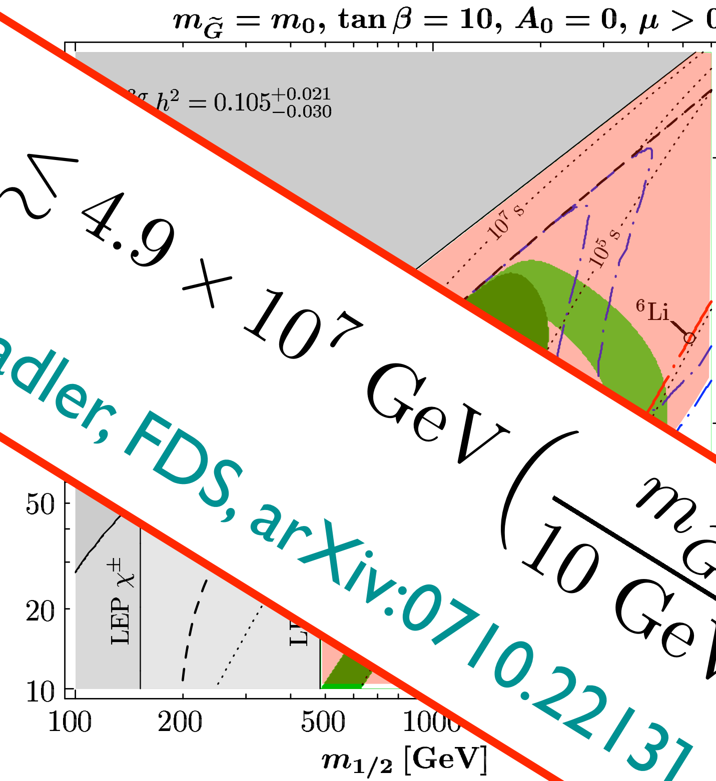


$T_R \lesssim 10^7\,\mathrm{GeV}$

Thermal Leptogenesis requires T >10^9 GeV

Upper Bounds on T_R in the CMSSM with $\widetilde{G}$ Dark Matter

Implications for inflation and the origin of the baryon asymmetry

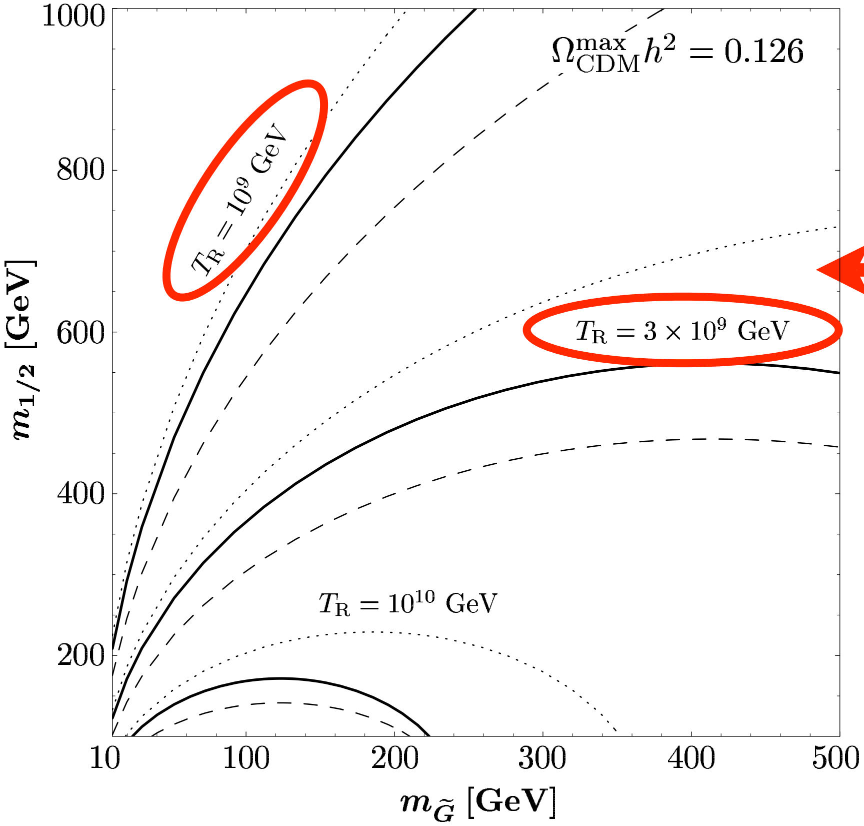


$$T_R \lesssim 4.9 \times 10^7\,\mathrm{GeV} \left(\frac{m_{\widetilde{G}}}{10\,\mathrm{GeV}}\right)^{1/5}$$

[Pradler, FDS, arXiv:0710.2213]

$$\mathrm{T_R} \lesssim 10^7\,\mathrm{GeV}$$

Thermal Leptogenesis requires $T > 10^9$ GeV



[Pradler, FDS, '06]

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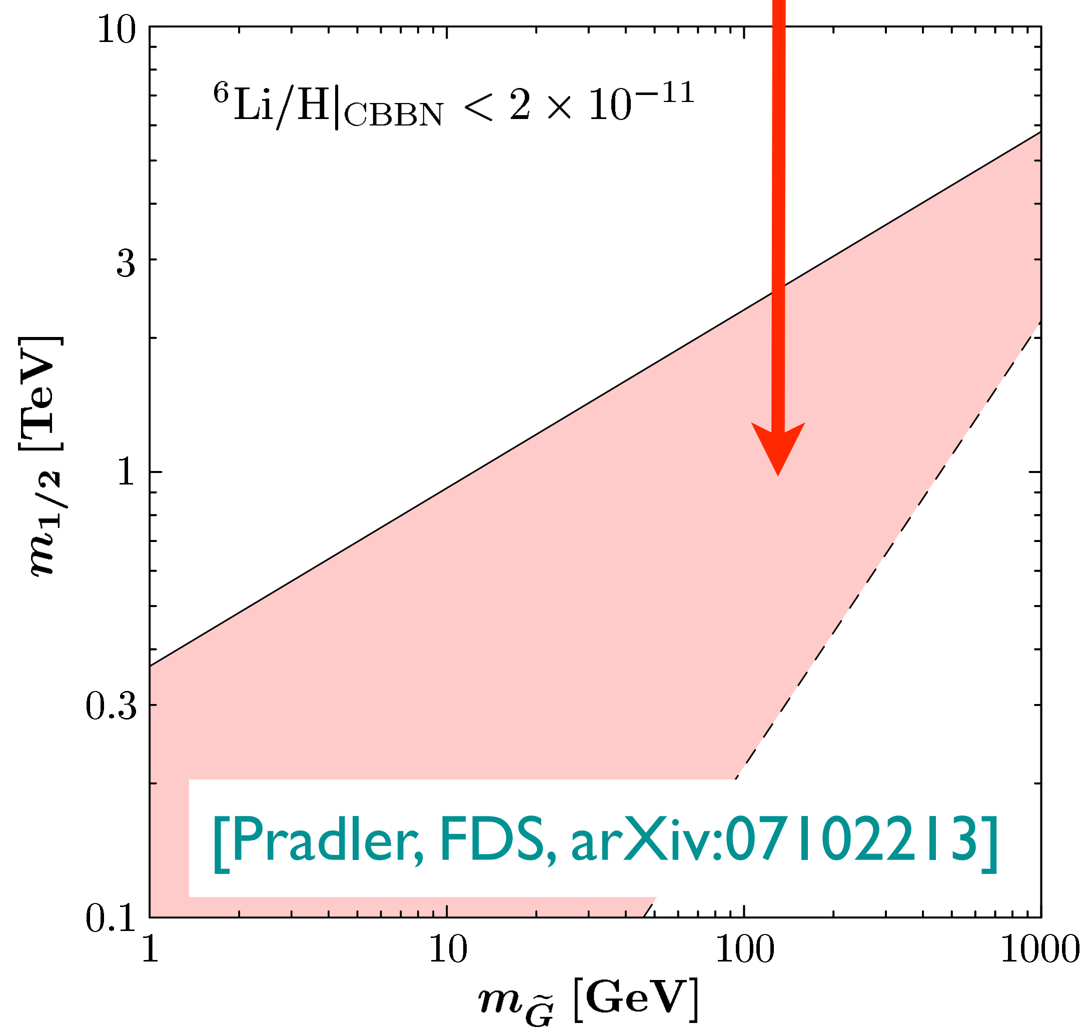
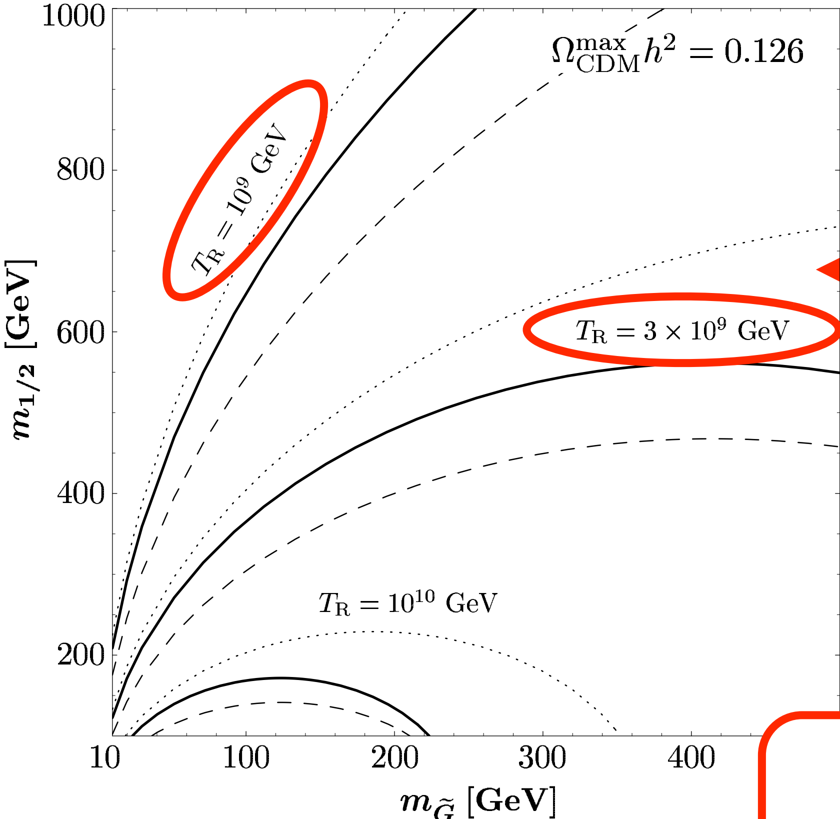
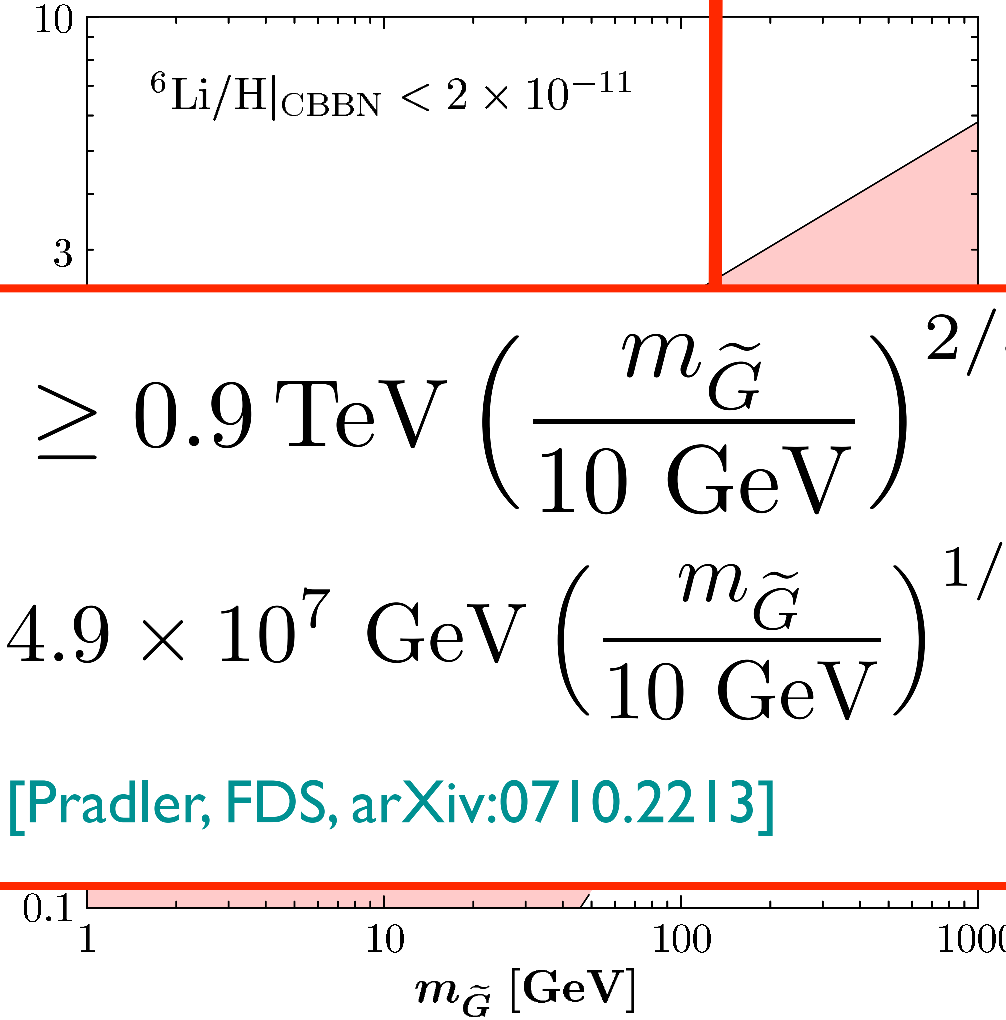




[Pradler, FDS, '06]

disfavored by cosmological constraints



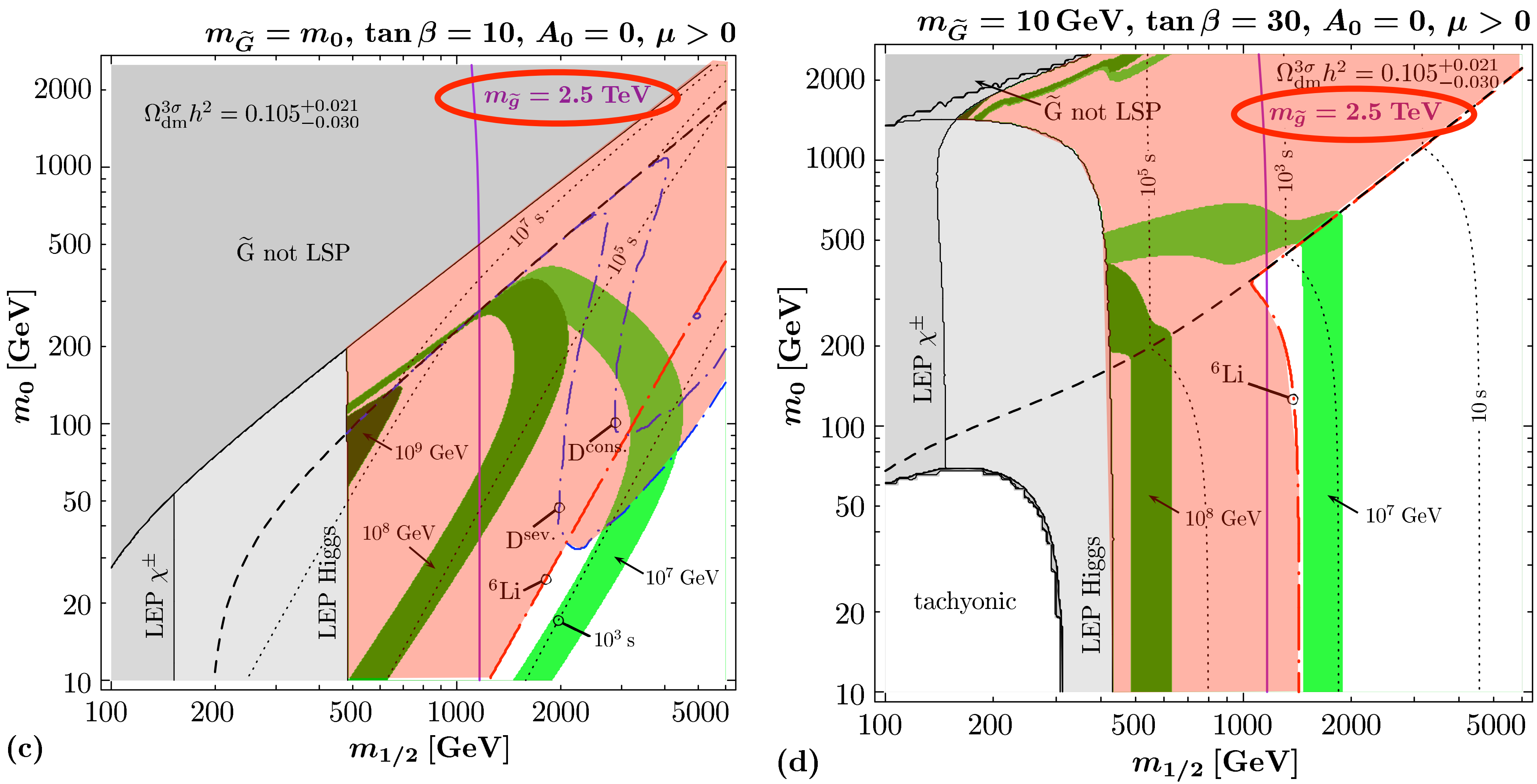
$$m_{1/2} \geq 0.9\ {\rm TeV} \left(\frac{m_{\widetilde{G}}}{10\ {\rm GeV}} \right)^{2/5}$$

$$T_{\rm R} \lesssim 4.9 \times 10^7\ {\rm GeV} \left(\frac{m_{\widetilde{G}}}{10\ {\rm GeV}} \right)^{1/5}$$

[Pradler, FDS, arXiv:0710.2213]

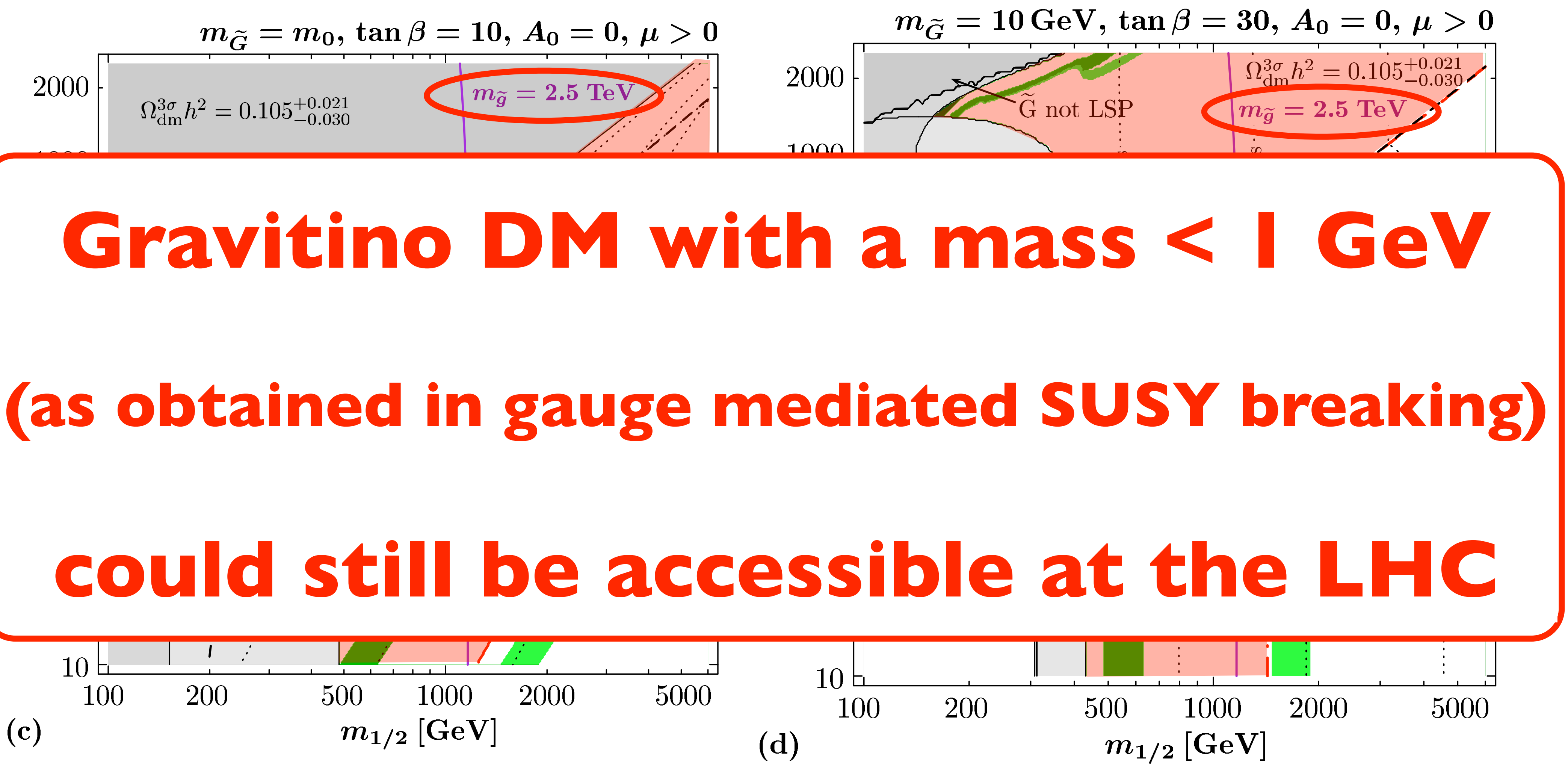
[Pradler, FDS, arXiv:0710.4548]

Gravitino DM with a GeV scale mass (as obtained in gravity med. SUSY breaking) could be very difficult to probe at the LHC



[Pradler, FDS, arXiv:0710.4548]

Gravitino DM with a GeV scale mass (as obtained in gravity med. SUSY breaking) could be very difficult to probe at the LHC

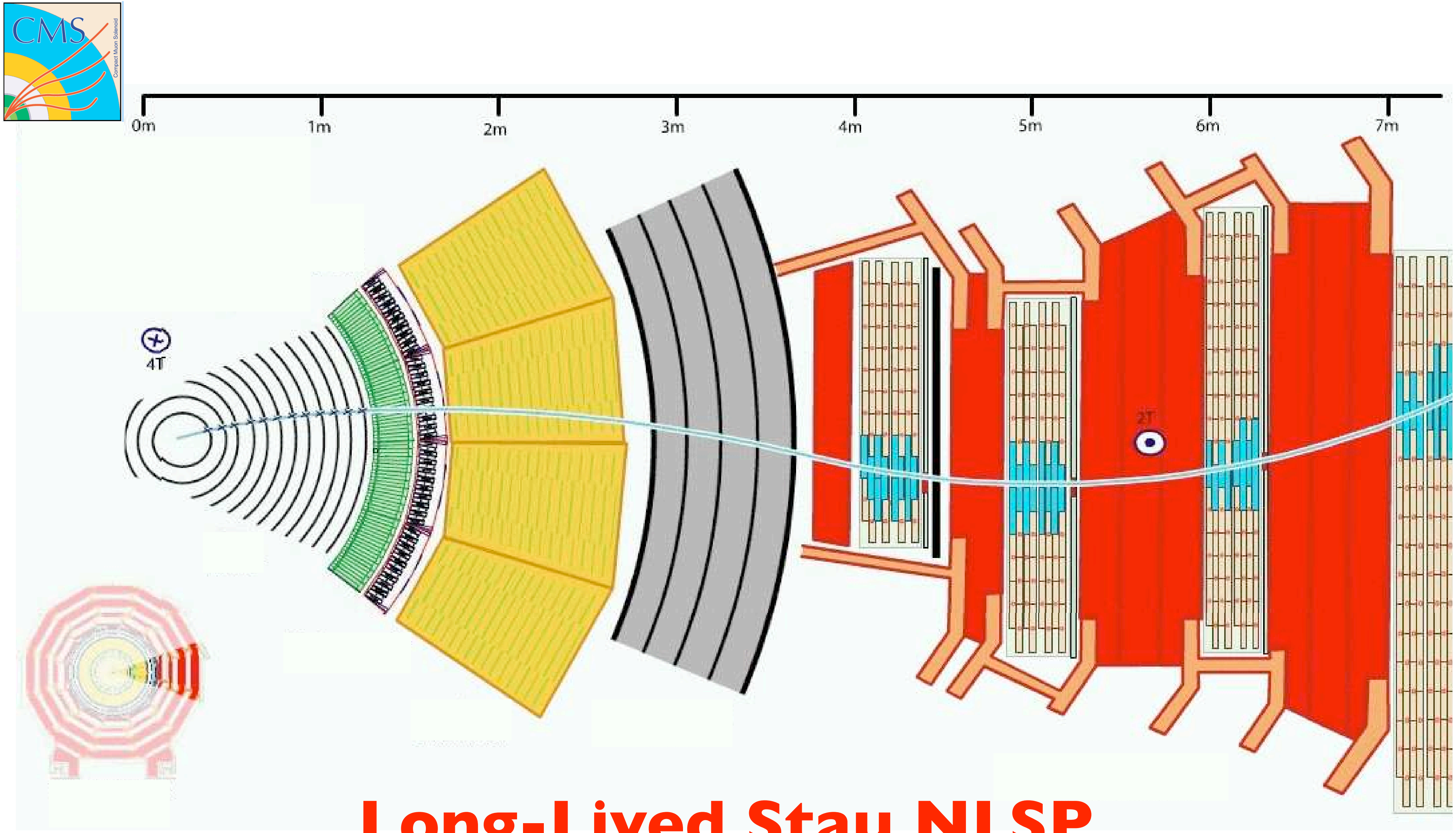


Gravitino DM with a mass < 1 GeV

(as obtained in gauge mediated SUSY breaking)

could still be accessible at the LHC

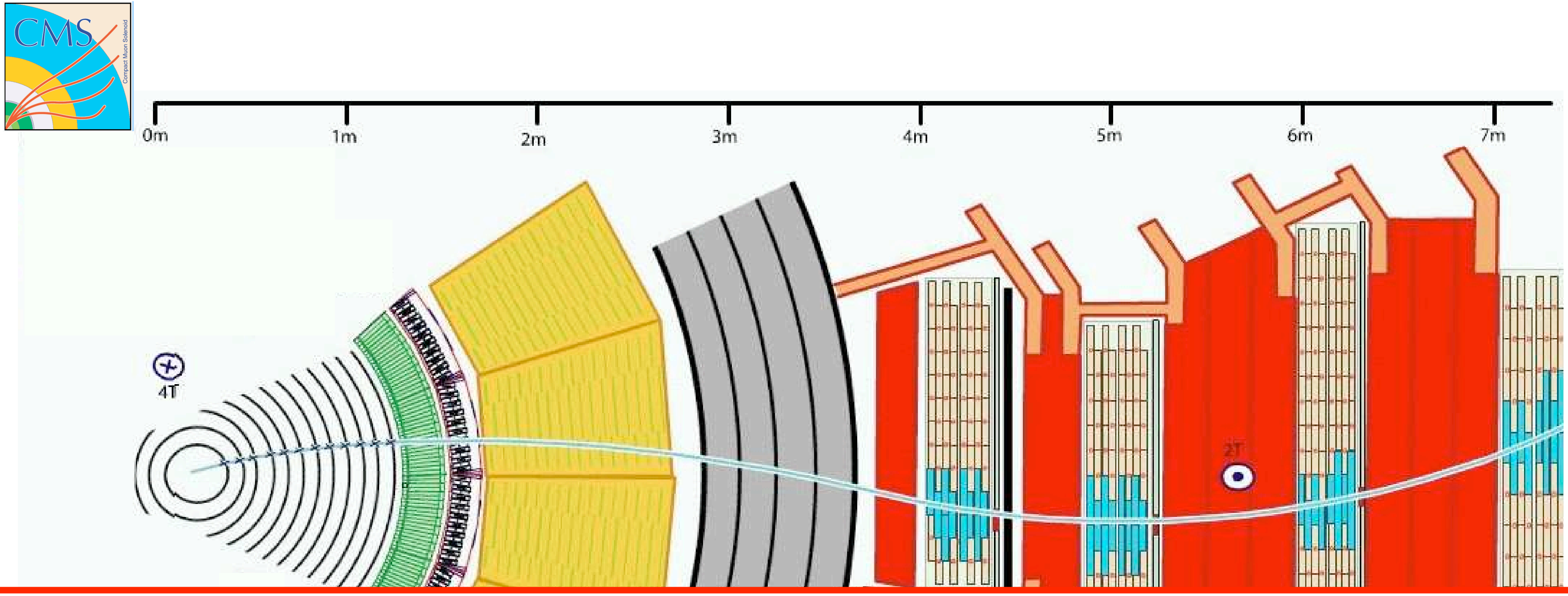
“Stable” Charged Massive Particle @ LHC



Long-Lived Stau NLSP

[from P. Zalewski’s Talk, SUSY 2007]

"Stable" Charged Massive Particle @ LHC



The smoking gun for

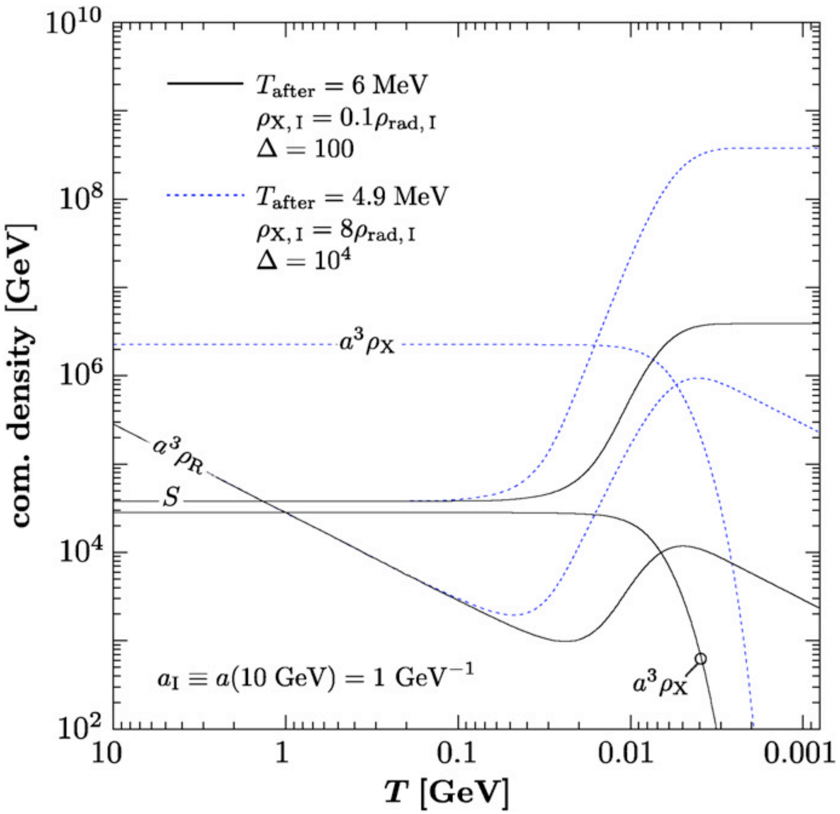
Gravitino (or Axino) Dark Matter

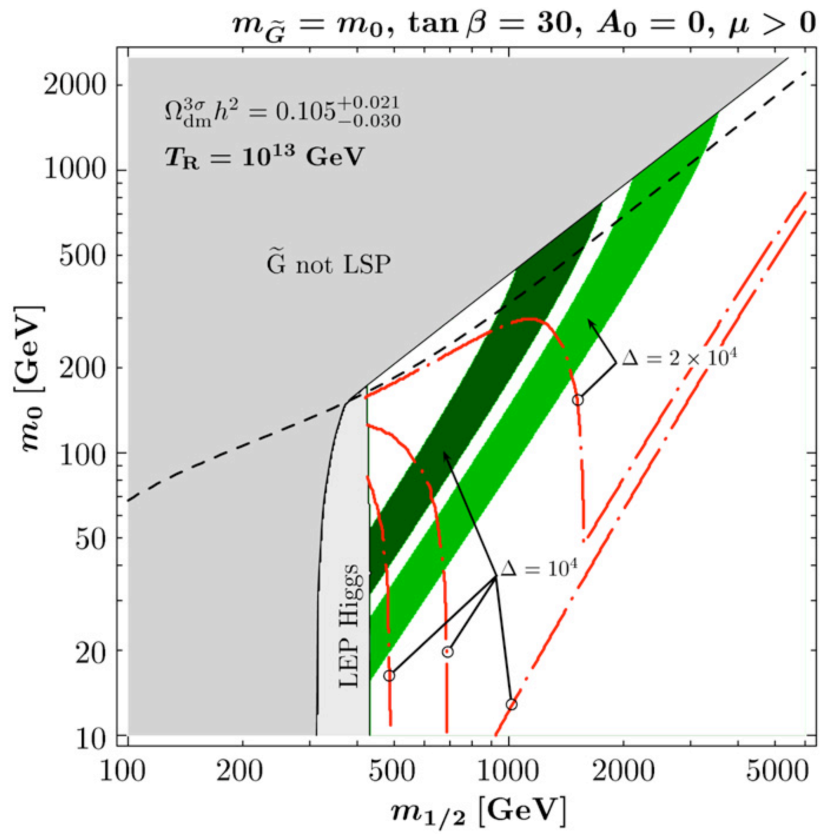
at the LHC

Late-Time Entropy Production

[Pradler, FDS, '07]

Rescuing Thermal Leptogenesis





$$\frac{d\rho_{\rm rad}}{dt} + 4H\rho_{\rm rad} = \Gamma_\phi\rho_\phi,$$

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma_\phi\rho_\phi,$$

$$\frac{dS}{dt} = \frac{\Gamma_X\rho_X a^3}{T} = \left(\frac{2\pi^2}{45}g_*\right)^{1/3}\Gamma_X\rho_X a^4 S^{-1/3}$$

$$Y^{\rm TP}_{\widetilde{G}}(T_0) = \frac{1}{\Delta}Y^{\rm TP}_{\widetilde{G}}(T_{\rm low}),$$

$$Y_{\rm NLSP}(T_0) = \frac{1}{\Delta}Y_{\rm NLSP}(T_{\rm low})$$

$$\eta(T_{\rm after}) = \frac{1}{\Delta}\eta(T_{\rm before}).$$