Title: Gravitino Dark Matter and Implications for Phenomenology at the LHC

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Abstract: Considering gravitino dark matter scenarios, cosmological constraints on the sparticle masses and on the reheating temperature of inflation will be discussed. These constraints are relevant for prospects of phenomenology at the LHC and for our understanding of inflation and the baryon asymmetry of the Universe.

Gravitino Dark Matter and Implications for Phenomenology at the LHC

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(Werner-Heisenberg-Institut)

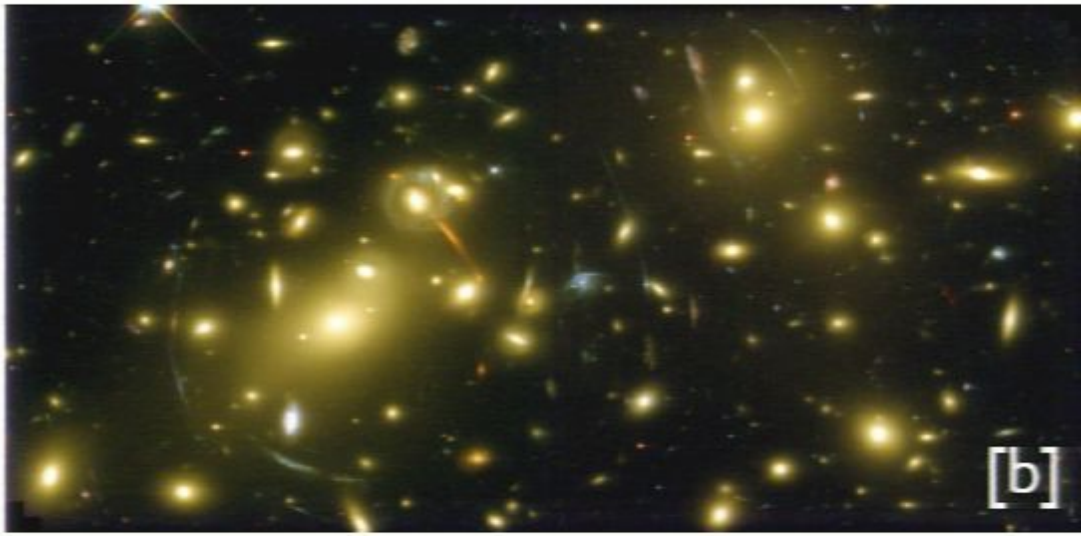
Excellence Cluster Universe

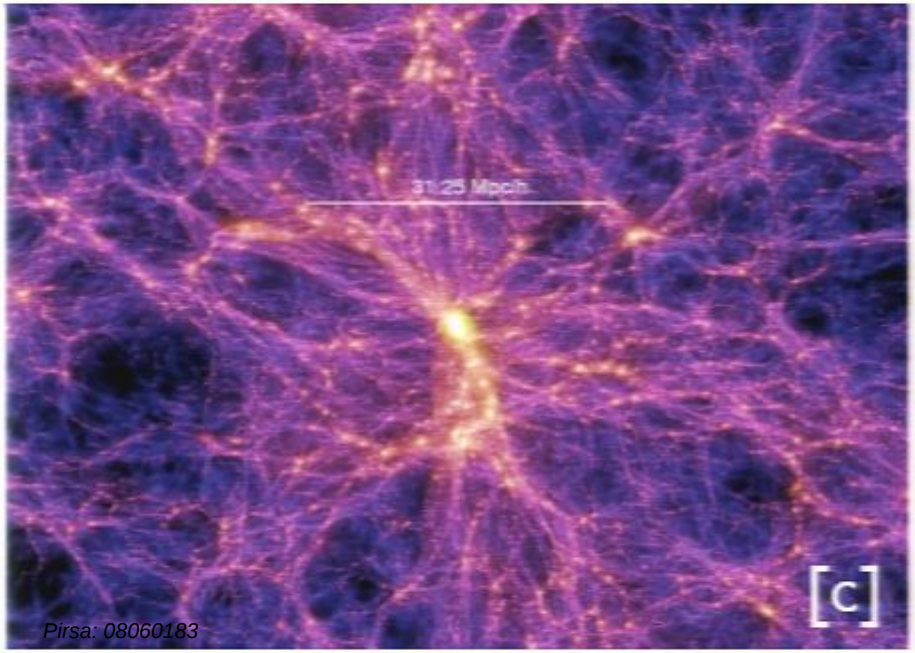
June 6th, 2008

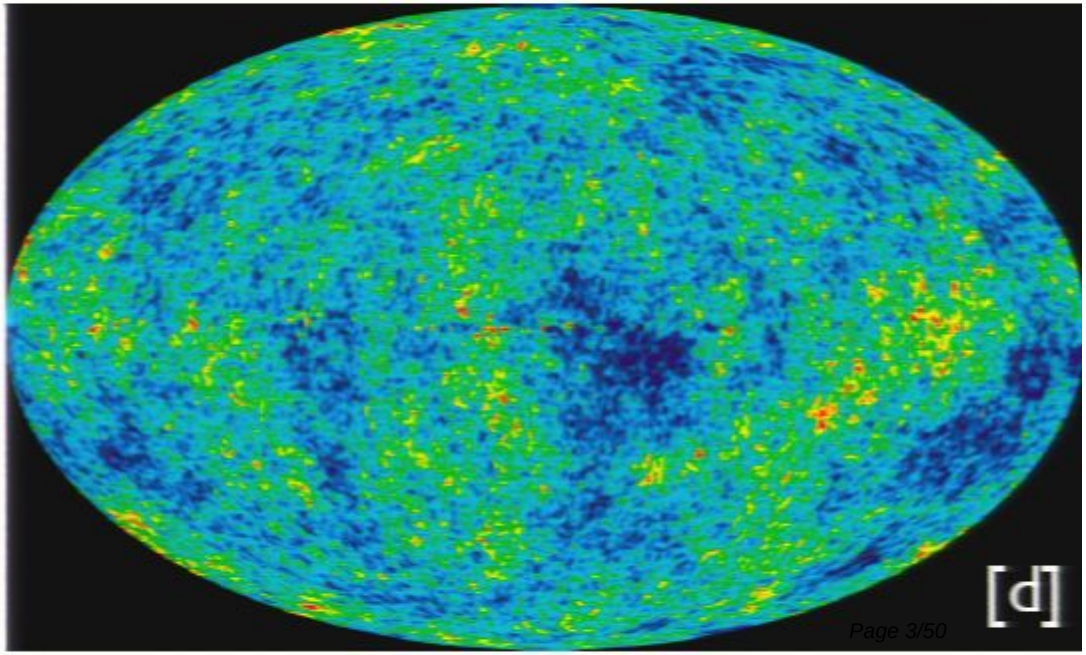
PASCOS 2008 @ Perimeter Institute



Evidence for Dark Matter in the Universe



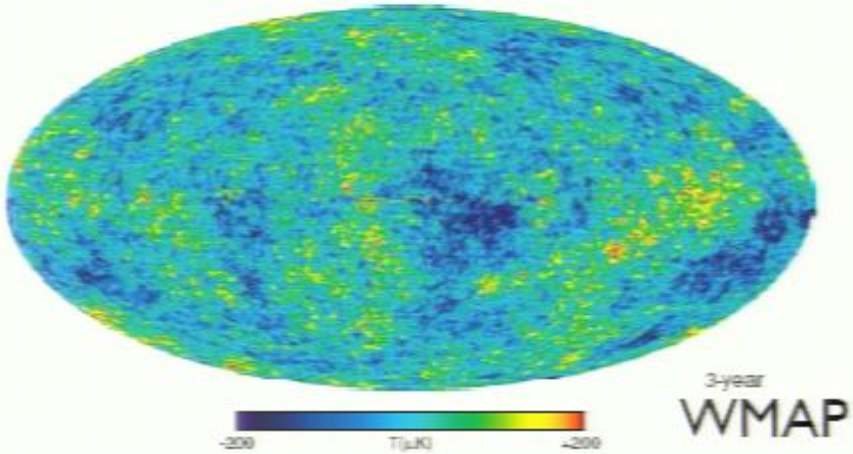


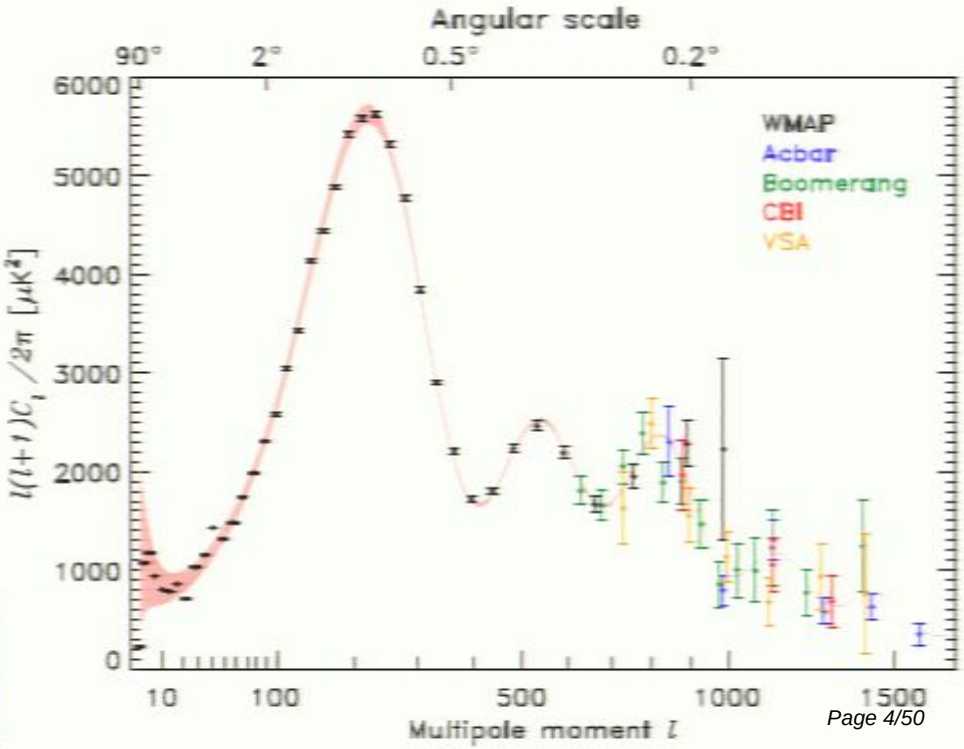


Evidence for Dark Matter in the Universe

- 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 ?

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$^{\cdot}$
$\in$ 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

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

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

[Cremmer, Ferrara, Girardello, Van Proeyen, '83]

The Supergravity Lagrangian (N=1, d=4)

$$
\begin{aligned}
\frac{1}{e}\mathcal{L} \;=\; & -\frac{M_{\rm P}^2}{2}R + g_{ij^*}\mathcal{D}_\mu\phi^i\mathcal{D}^\mu\phi^{*j} - \frac{1}{2}g^2\left[(\mathrm{Re}f)^{-1}\right]^{ab}D_aD_b \\
& + ig_{ij^*}\overline{\chi}^j_L\gamma^\mu\mathcal{D}_\mu\chi^i_L + \varepsilon^{\mu\nu\rho\sigma}\overline{\psi}_{L\mu}\gamma_\nu\mathcal{D}_\rho\psi_{L\sigma} \\
& - \frac{1}{4}\mathrm{Re}f_{ab}F^a_{\mu\nu}F^{b,\mu\nu} + \frac{1}{8}\varepsilon^{\mu\nu\rho\sigma}\mathrm{Im}f_{ab}F^a_{\mu\nu}F^b_{\rho\sigma} \\
& + \frac{i}{2}\mathrm{Re}f_{ab}\overline{\lambda}^a\gamma^\mu\mathcal{D}_\mu\lambda^b - e^{-1}\frac{1}{2}\mathrm{Im}f_{ab}\mathcal{D}_\mu\left[e\overline{\lambda}^a_R\gamma^\mu\lambda^b_R\right] \\
& + \Bigg[-\sqrt{2}g\partial_i D_a\overline{\lambda}^a\chi^i_L + \frac{1}{4}\sqrt{2}g\left[(\mathrm{Re}f)^{-1}\right]^{ab}\partial_i f_{bc}D_a\overline{\lambda}^c\chi^i_L \\
& + \frac{i}{16}\sqrt{2}\partial_i f_{ab}\overline{\lambda}^a[\gamma^\mu,\gamma^\nu]\chi^i_L F^b_{\mu\nu} - \frac{1}{2M_{\rm P}}gD_a\overline{\lambda}^a_R\gamma^\mu\psi_\mu \\
& - \frac{i}{2M_{\rm P}}\sqrt{2}g_{ij^*}\mathcal{D}_\mu\phi^{*j}\overline{\psi}_\nu\gamma^\mu\gamma^\nu\chi^i_L + \mathrm{h.c.}\Bigg] \\
& - \frac{i}{4M_{\rm P}}\mathrm{Re}f_{ab}\overline{\psi}_\mu[\gamma^m,\gamma^n]\gamma^\mu\lambda^a F^a_{mn} \\
& - e^{K/2M_{\rm P}^2}\left[\frac{1}{4M_{\rm P}^2}W^*\overline{\psi}_{R\mu}[\gamma^\mu,\gamma^\nu]\psi_{L\nu} + \frac{1}{2M_{\rm P}}\sqrt{2}D_iW\overline{\psi}_\mu\gamma^\mu\chi^i_L\right. \\
& \left. + \frac{1}{2}\mathcal{D}_iD_jW\overline{\chi^c_L}^i\chi^j_L + \frac{1}{4}g^{ij^*}D_{j^*}W^*\partial_i f_{ab}\overline{\lambda}^a_R\lambda^b_L + \mathrm{h.c.}\right] \\
& - e^{K/M_{\rm P}^2}\left[g^{ij^*}\left(D_iW\right)\left(D_{j^*}W^*\right) - 3\frac{|W|^2}{M_{\rm P}^2}\right] + \mathcal{O}(M_{\rm P}^{-2})\,.
\end{aligned}
$$

gravitino

gauge boson

Planck scale

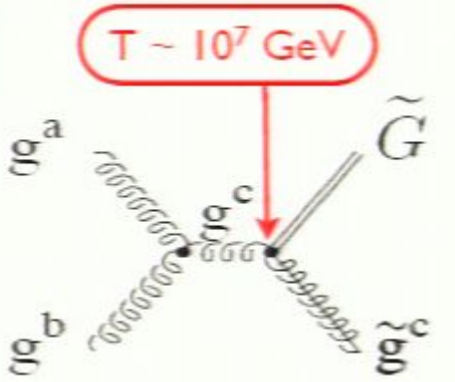
gaugino

Thermal Gravitino Production

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

$M_{Pl} = 2.44 \times 10^{18}$ GeV ...

Very Hot Early Universe



gauge-invariant treatment
(hard thermal loop resummation)
[Ellis, Nanopoulos, Olive, Rey, '96]

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

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

Reheating after Inflation - Definition of T_R

$$\Gamma_\phi = \xi\, H_{\rm rad}(T_{\rm R})$$

$$T_{\rm R}^{\xi} \equiv \left[\frac{90}{g_*(T_{\rm R})\pi^2}\right]^{1/4}\sqrt{\frac{\Gamma_\phi {\rm M_P}}{\xi}}$$

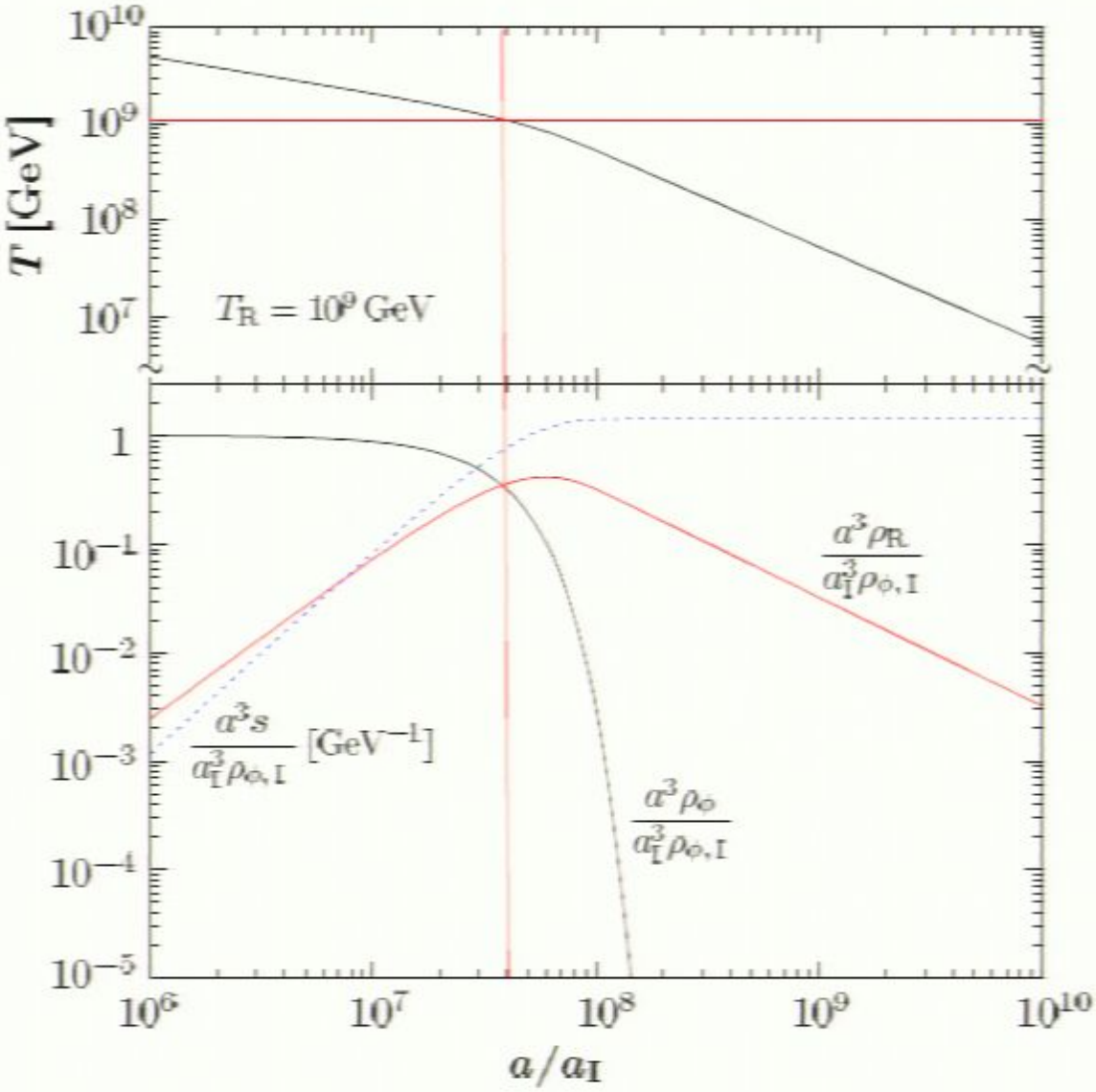
$$\frac{d\rho_{\rm rad}}{dt} + 4H\rho_{\rm rad} = \Gamma_\phi \rho_\phi.$$

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

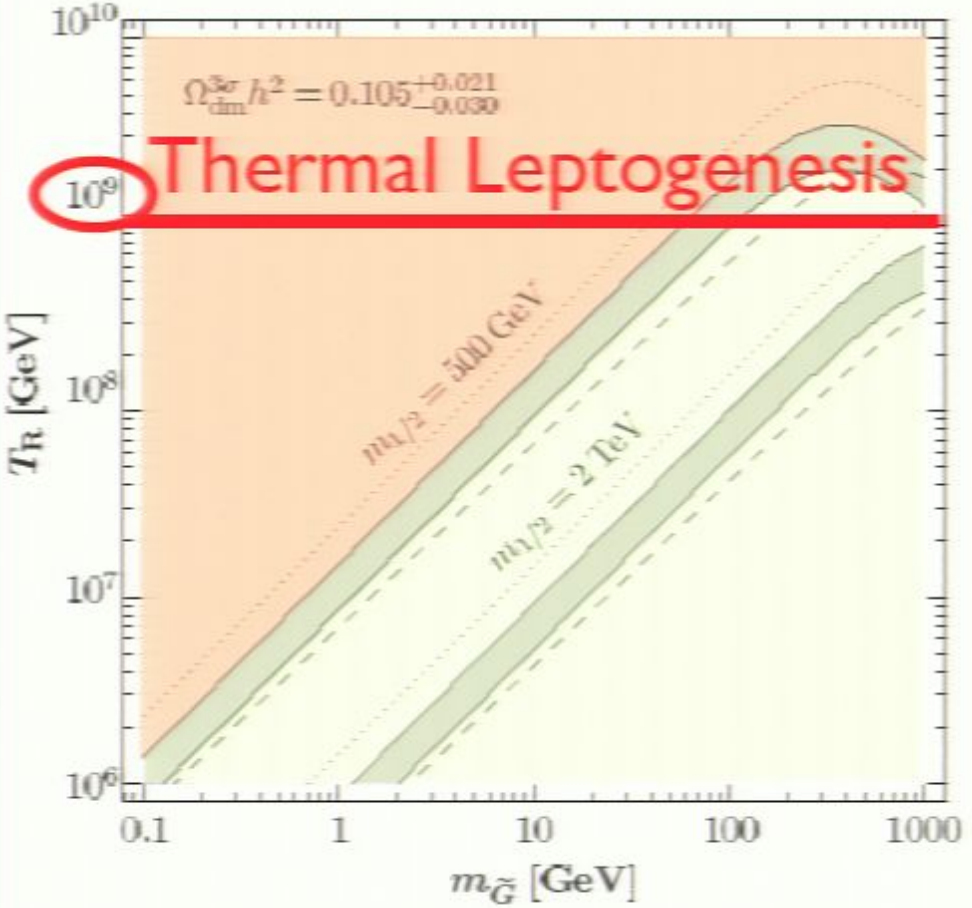
$$\frac{dn_{\widetilde{G}}}{dt} + 3Hn_{\widetilde{G}} = C_{\widetilde{G}}.$$

$$C_{\widetilde{G}} = \sum_{i=1}^{3} \frac{3\zeta(3)T^6}{16\pi^3 {\rm M_P^2}}\left(1 + \frac{M_i^2}{3m_{\widetilde{G}}^2}\right) c_i g_i^2 \ln\left(\frac{k_i}{g_i}\right).$$

[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]

Gravitino Dark Matter from Thermal Production

- Boltzmann Equation

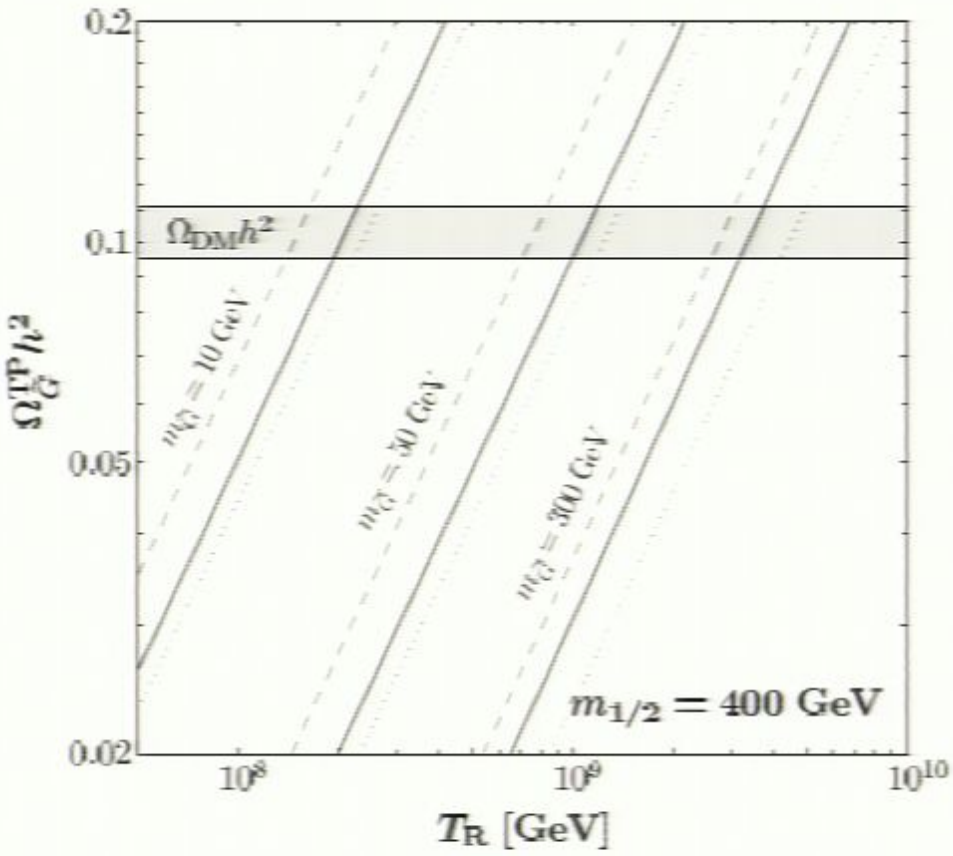
$$\frac{dn_{\widetilde{G}}}{dt} + 3Hn_{\widetilde{G}} = C_{\widetilde{G}}$$

- Collision Term

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

- Gravitino Density

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



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

$$\begin{aligned} c_i &= (11.\,27.\,72) \\ k_i &= (1.266.\,1.312.\,1.271) \\ \omega_i &= (0.018.\,0.044.\,0.117) \end{aligned}$$

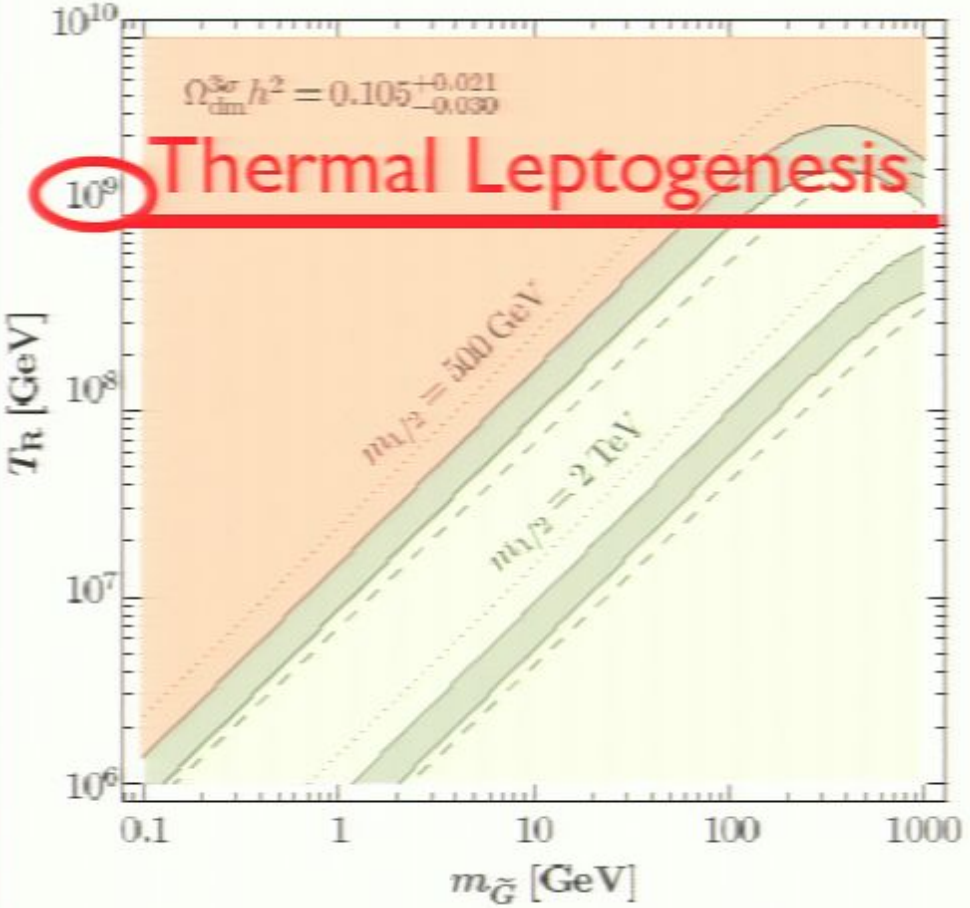
solid: $M_{1.2.3} = m_{1/2}$

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



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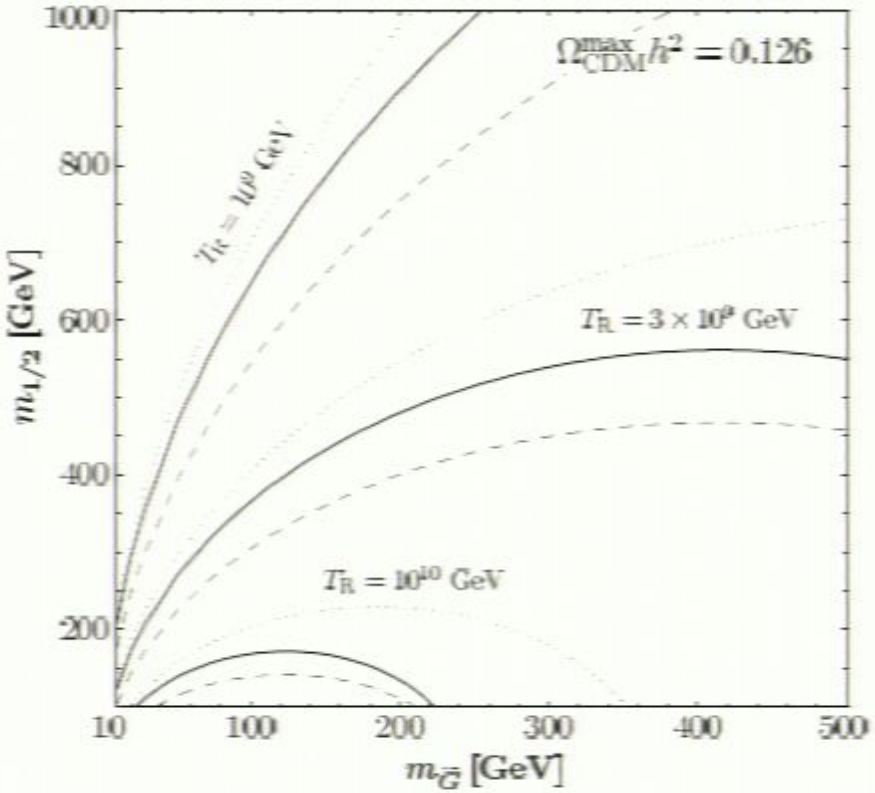
[Pradler, FDS, '06]

Probing T_R at Colliders in Gravitino DM Scenarios



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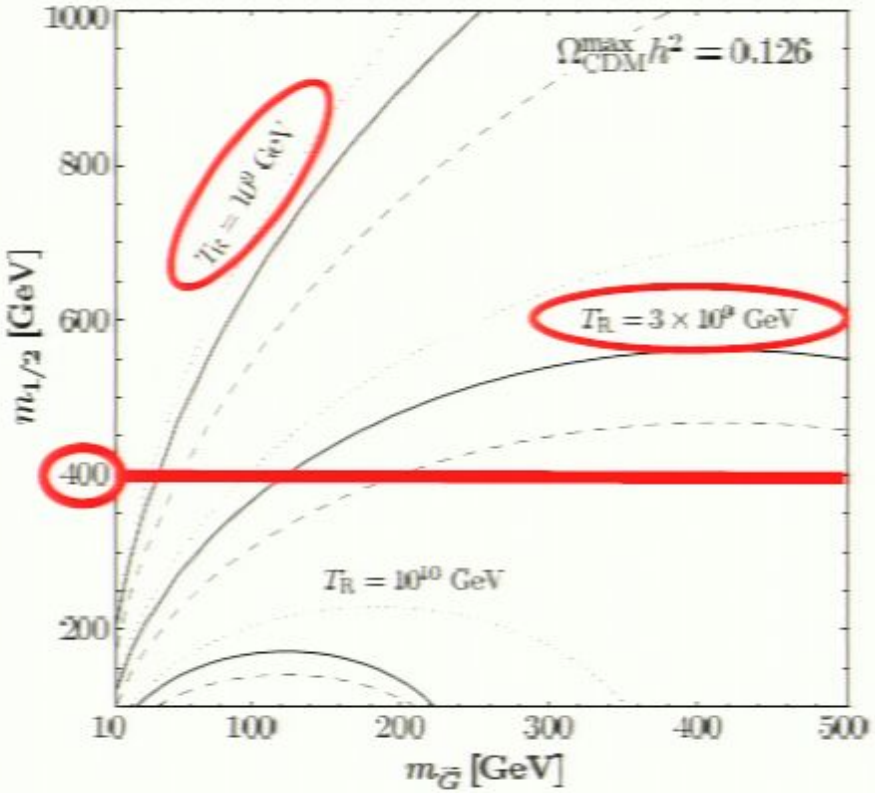

Thermal Leptogenesis

Non-Thermal Gravitino Production

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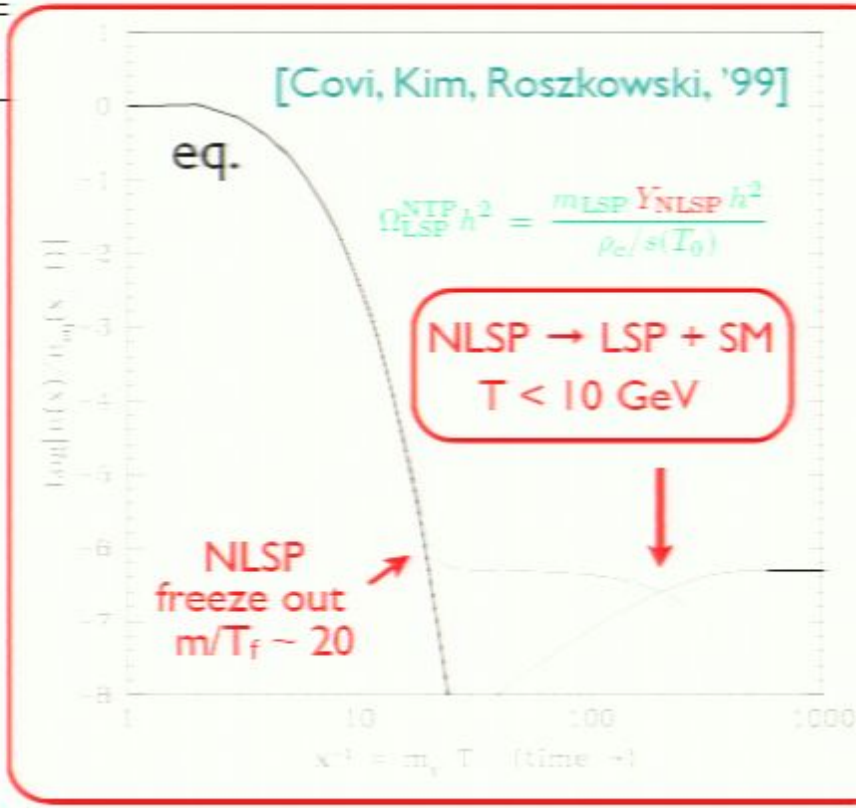

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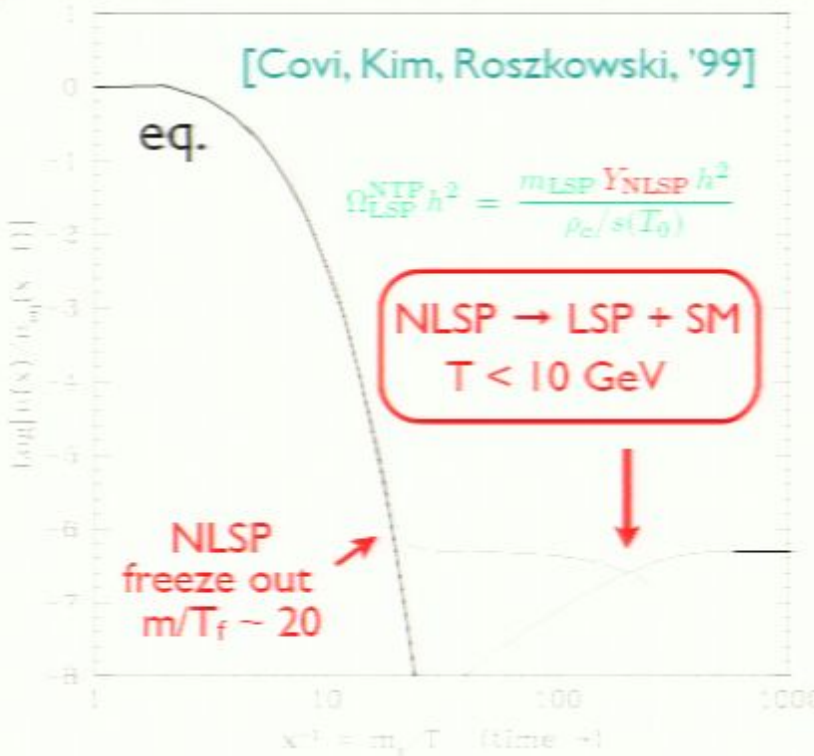

NLSP Candidates

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

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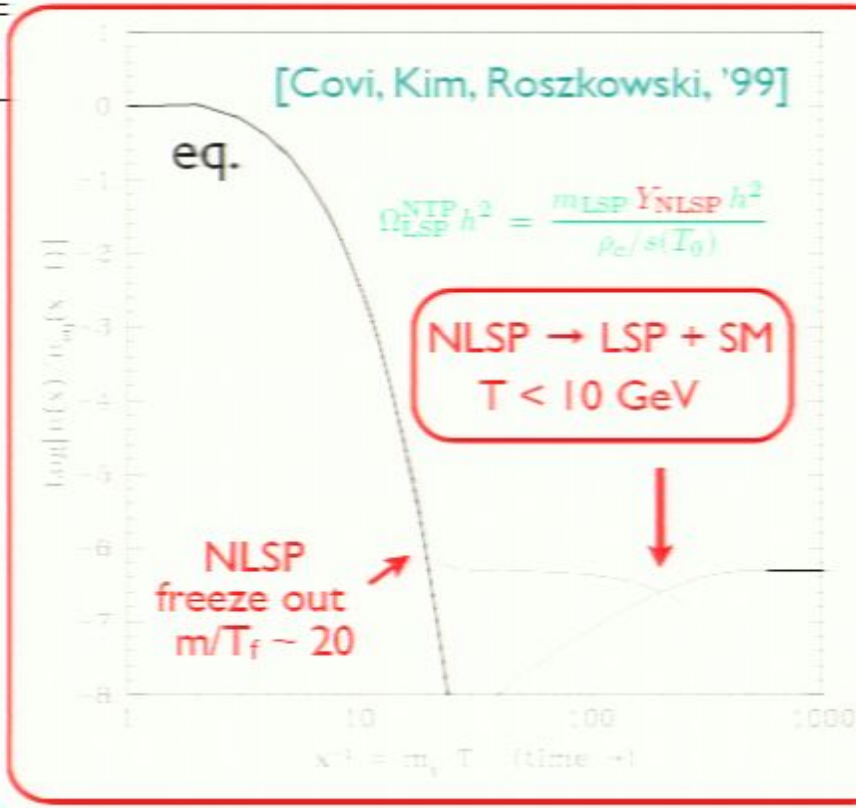

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electrically charged

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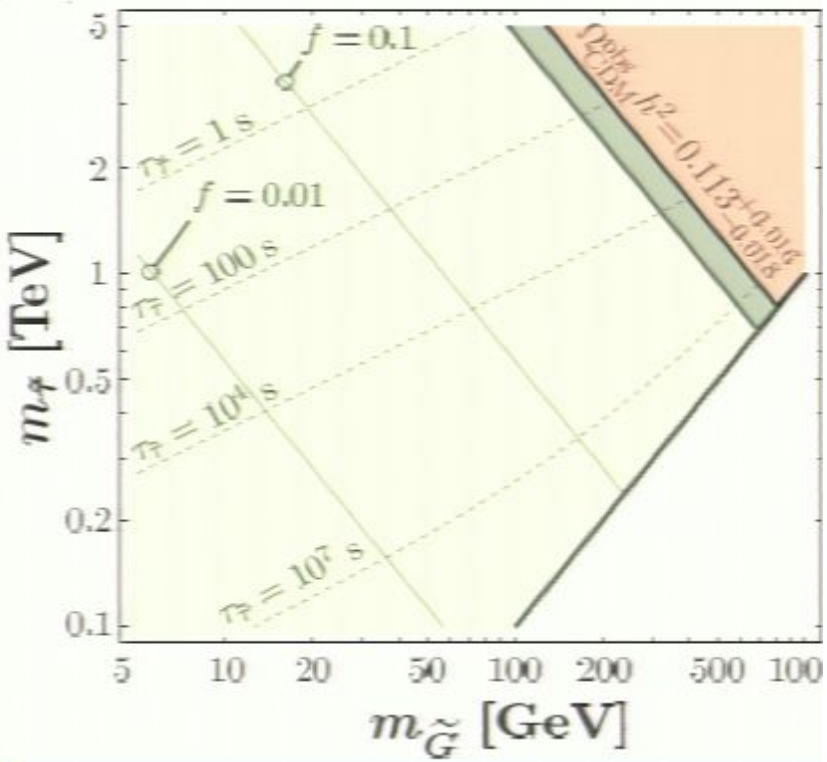

NLSP Candidates

electrically charged →

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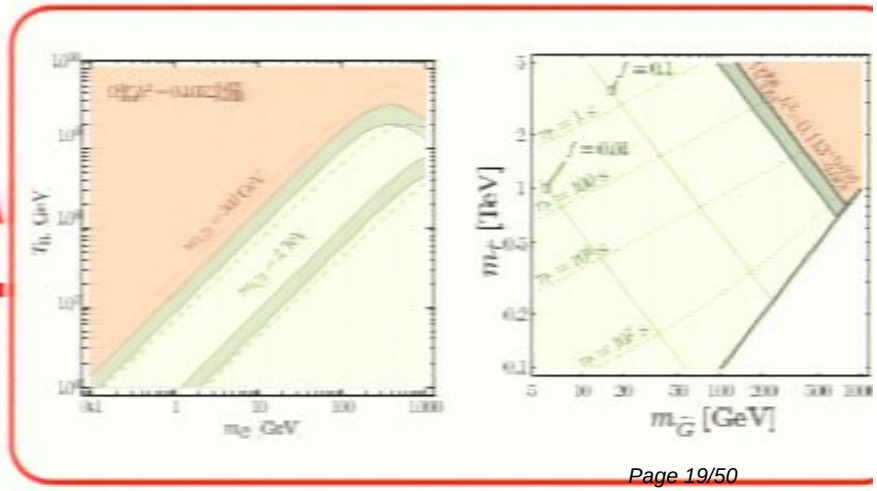
LSP Dark Matter: Production, Constraints, Experiments

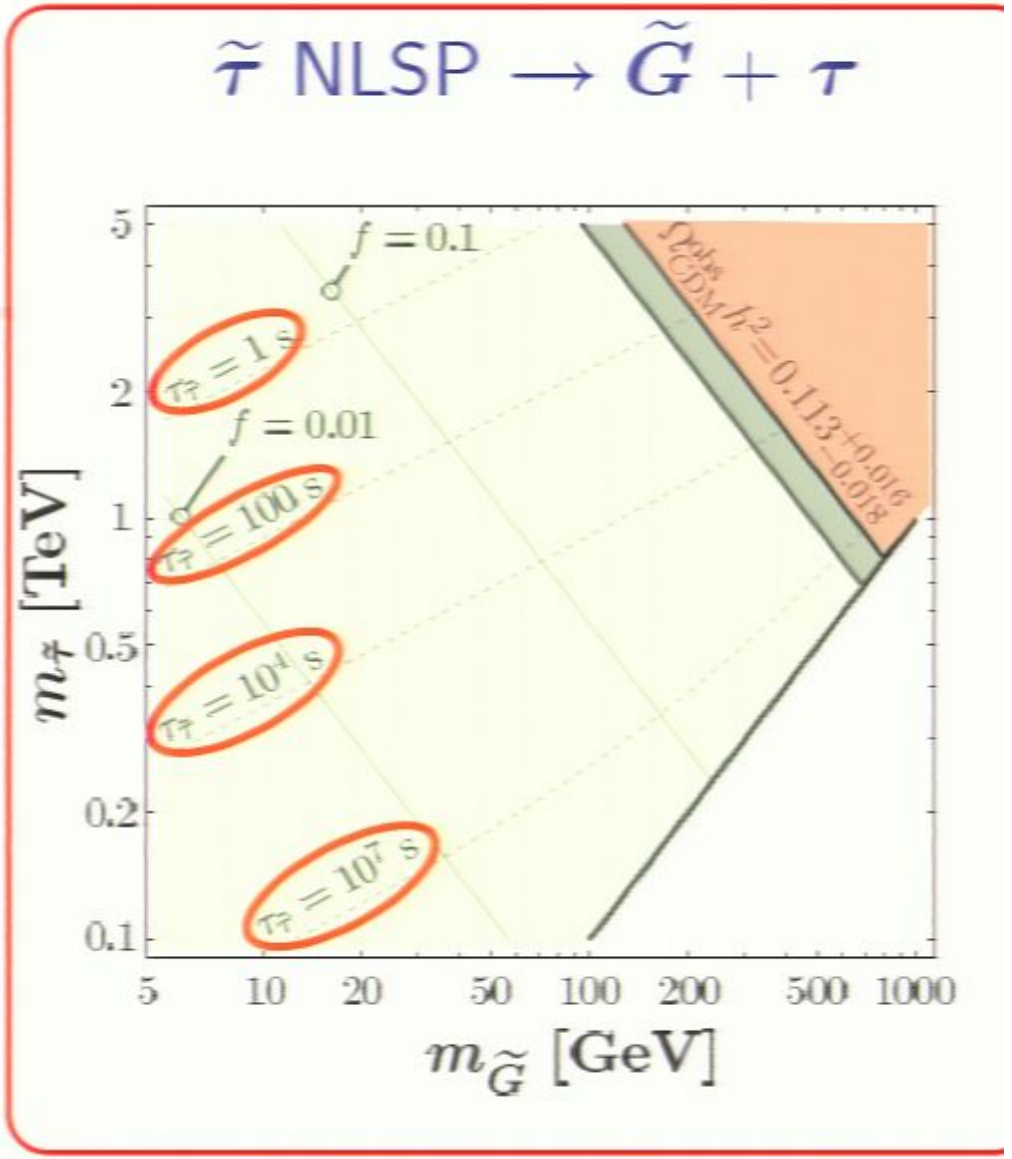
LSP	interaction	production	constraints	experiments
$\widetilde{\chi}_1^0$	g, g'	WIMP	← cold	indirect detection (EGRET, GLAST, ...)
	weak	freeze out		direct detection (CRESST, EDELWEISS, ..
	$M_W \sim 100$ GeV			prod.@colliders (Tevatron, LHC, ILC, ...)
$\widetilde{G}$	$\left(\frac{p}{M_{Pl}}\right)^n$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

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

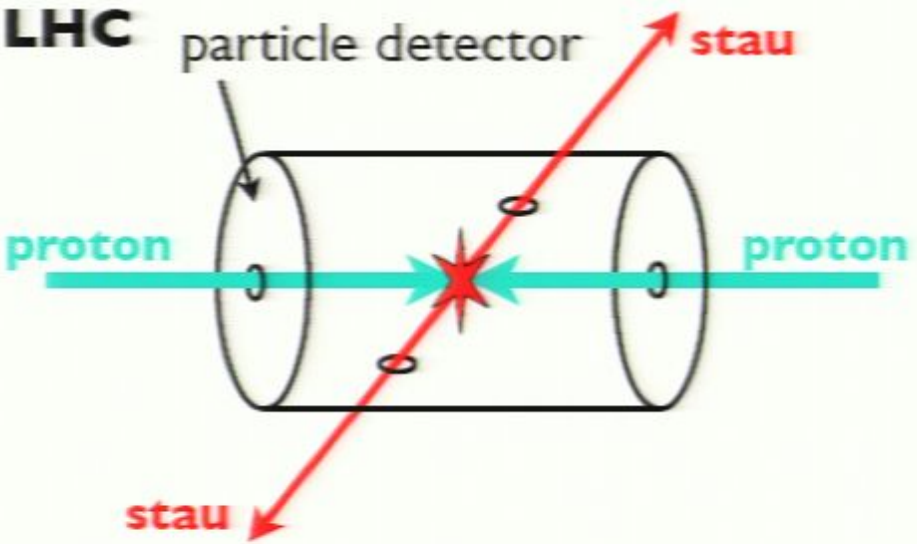
is possible!!!



long-lived NLSP



Gravitino DM @ LHC ← Stau NLSP



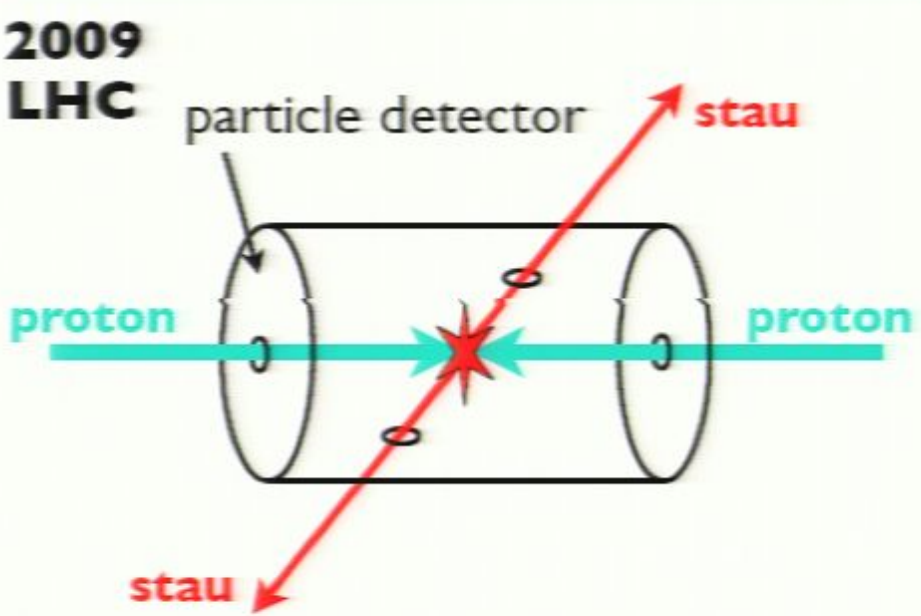
The signal:

jets + leptons

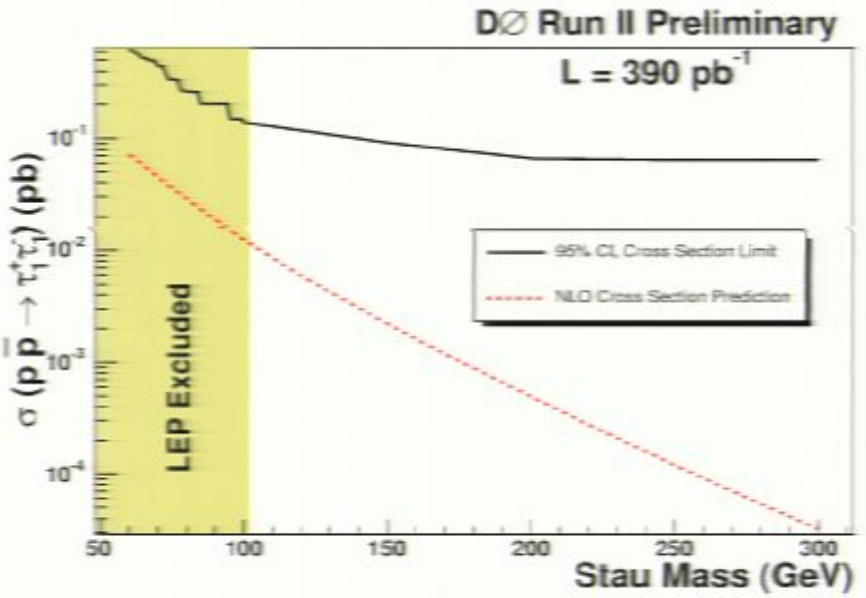
+ 2 "stable" charged particles

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

Gravitino DM @ LHC ← Stau NLSP



Tevatron



[from Gershtein's Talk, SUSY2007]

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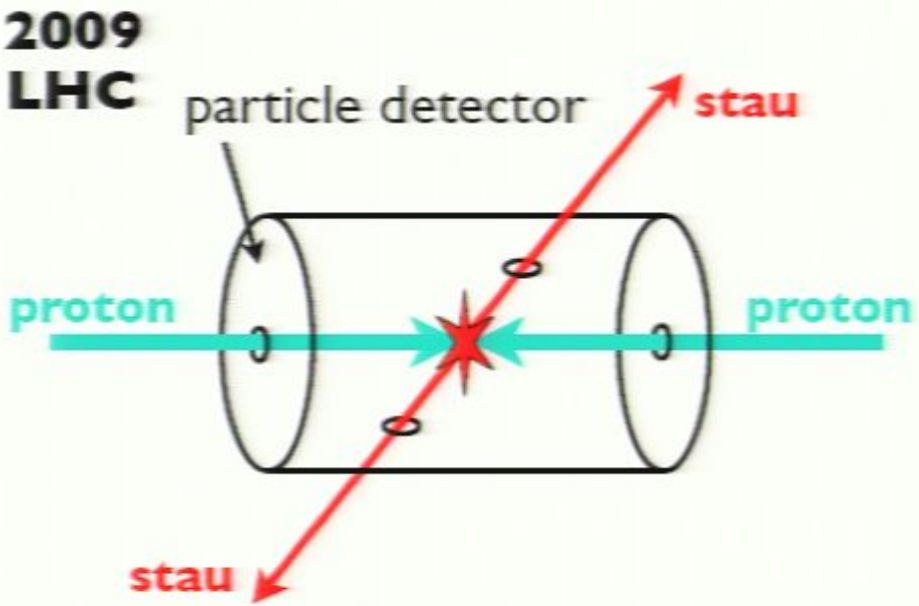

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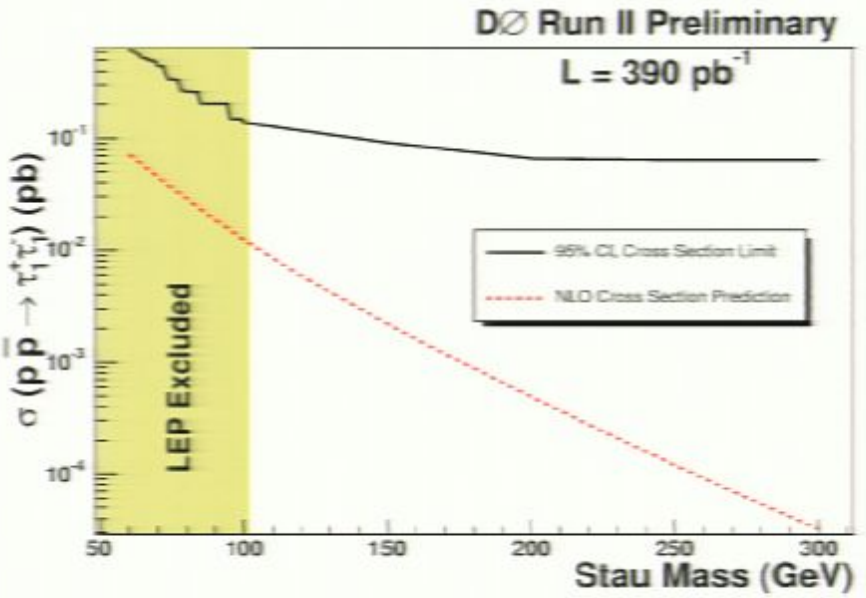

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The signal:

jets + leptons

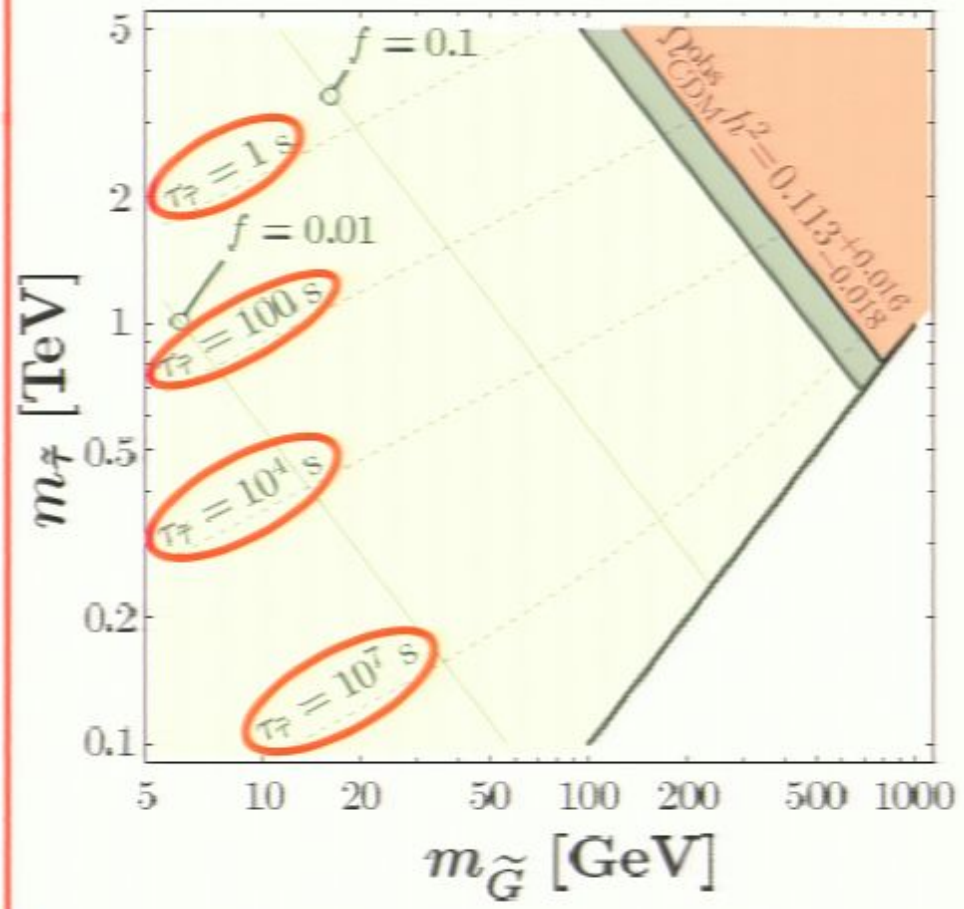
+ 2 "stable" charged particles

[Drees, Tata, '88, Nisati, Petrarca, Salvini, '97, Ambrosanio, Kribs, Martin, '97, Feng, Moroi, '98, Martin, Wells, '99, Ambrosanio et al., '01, ...]

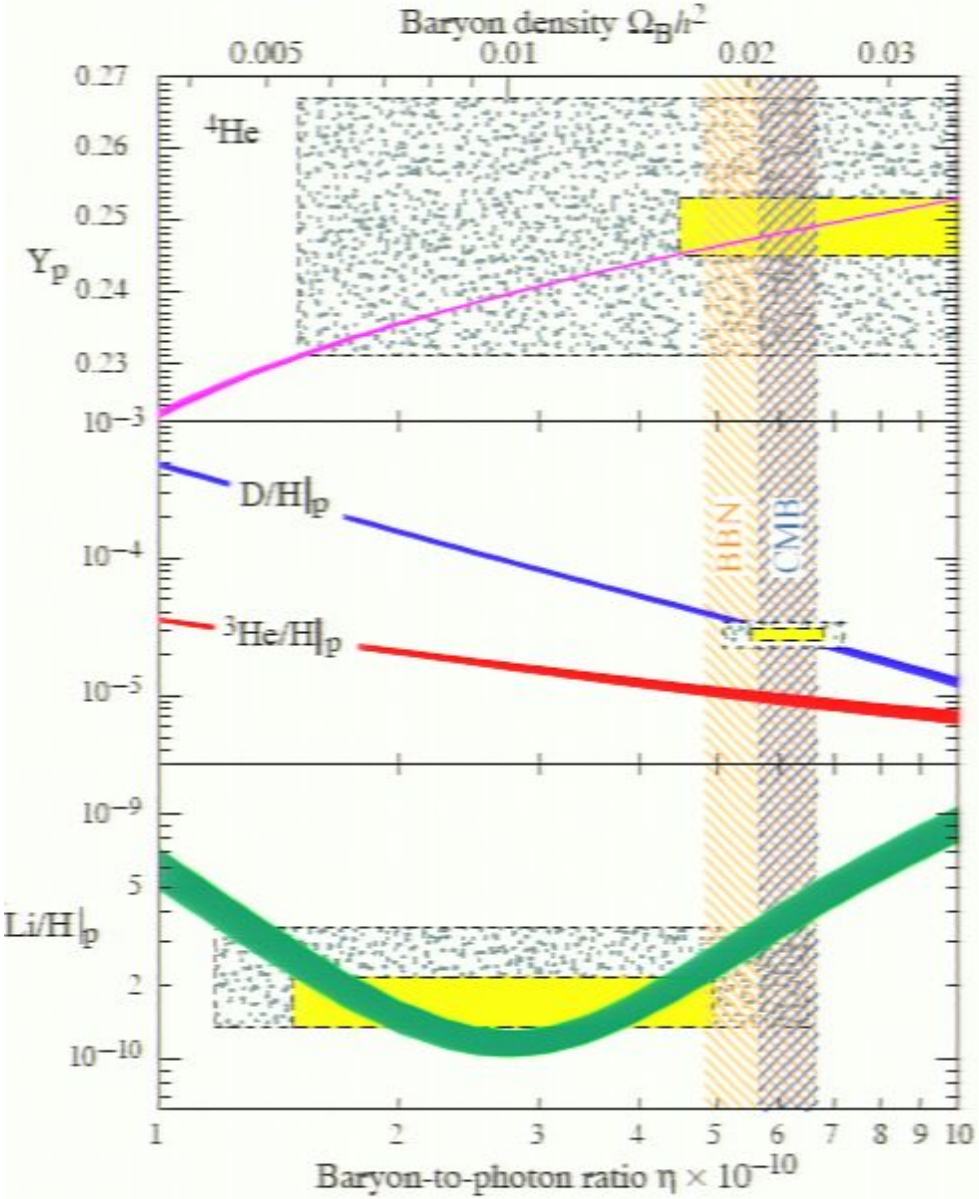
Very different from the large E_T^{miss} signal of Neutralino DM

long-lived NLSP

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

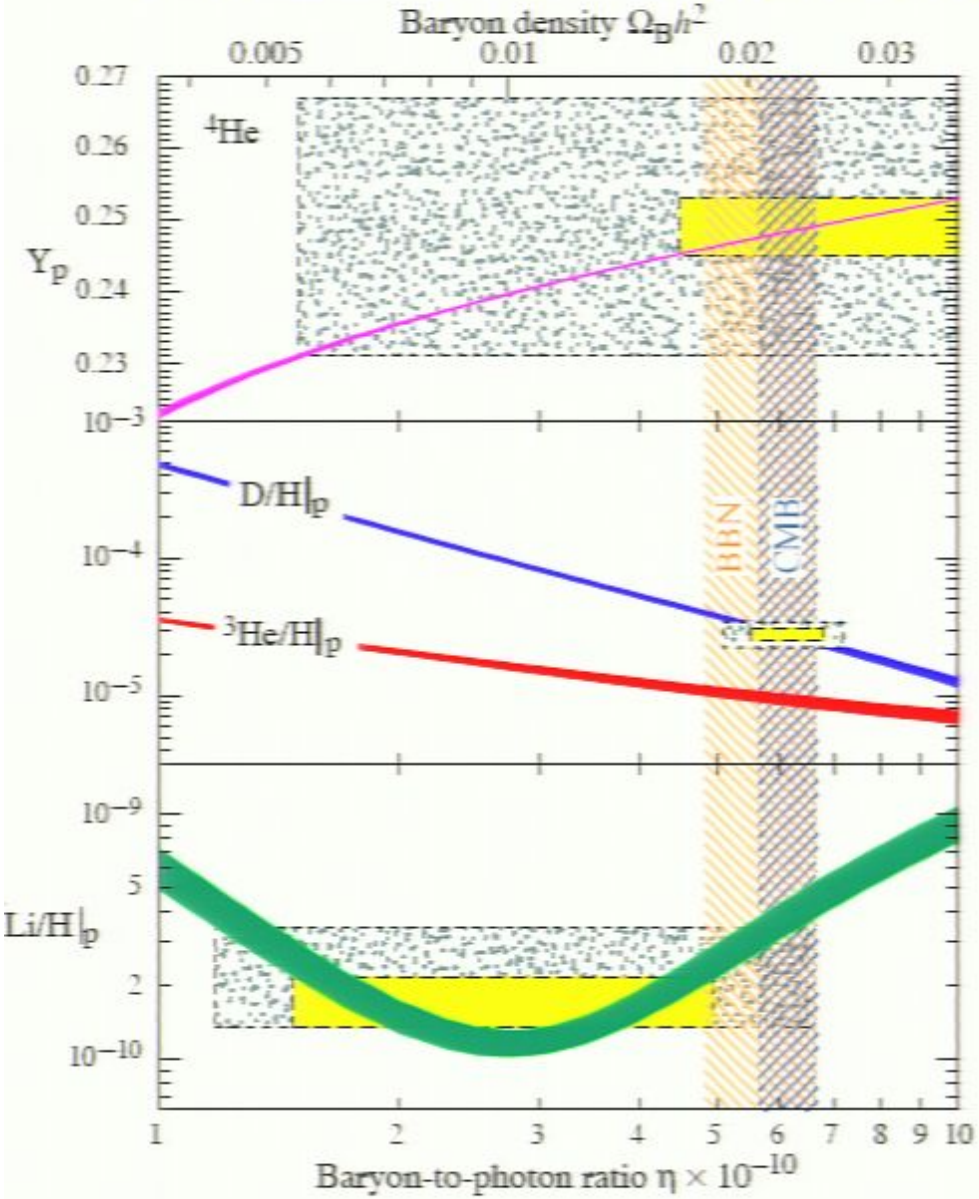


Big-Bang Nucleosynthesis



[Particle Data Book 2006]

Big-Bang Nucleosynthesis

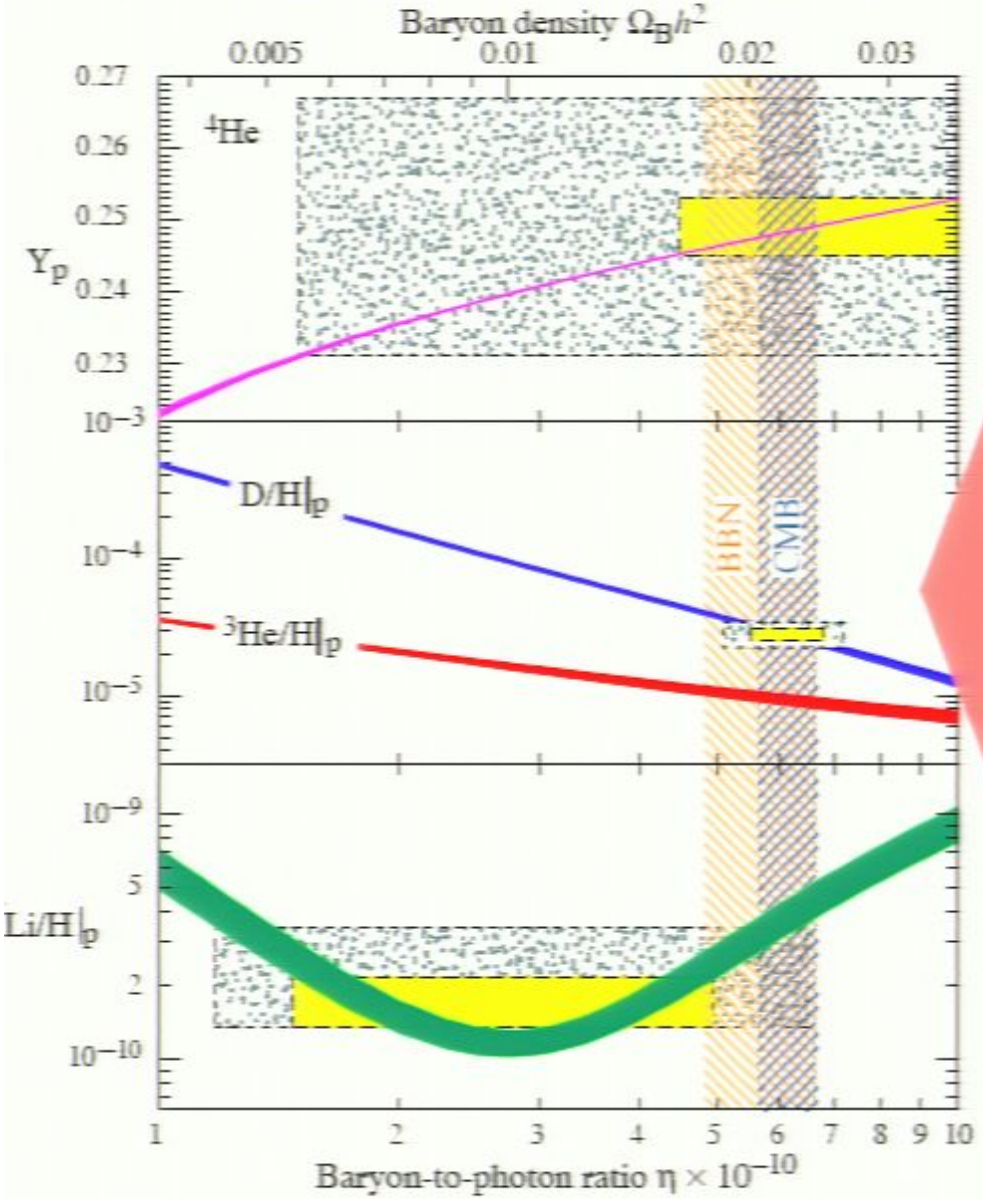


[Particle Data Book 2006]

Big Bang Nucleosynthesis and Particle Physics

Workshop @ Perimeter Institute

Big-Bang Nucleosynthesis



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Big Bang Nucleosynthesis and Particle Physics

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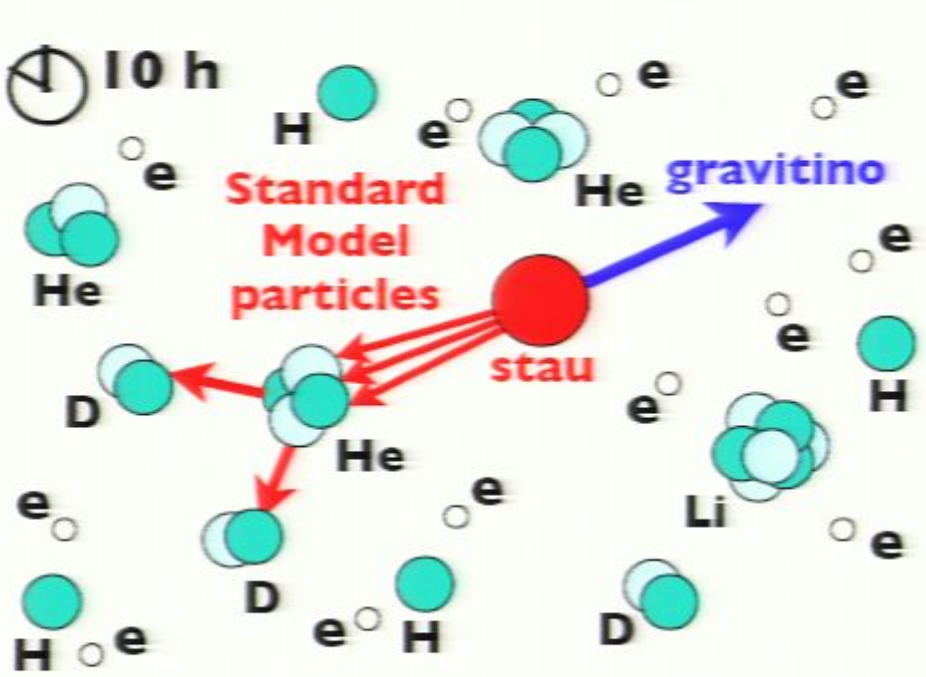

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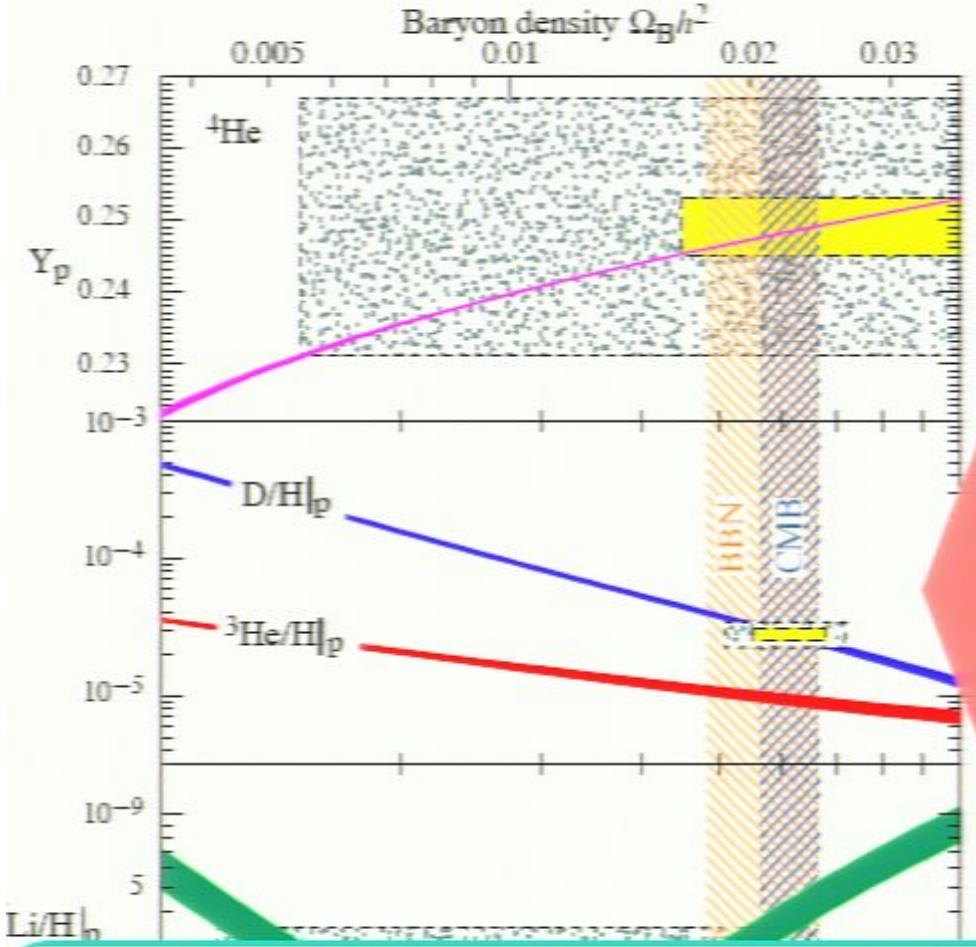

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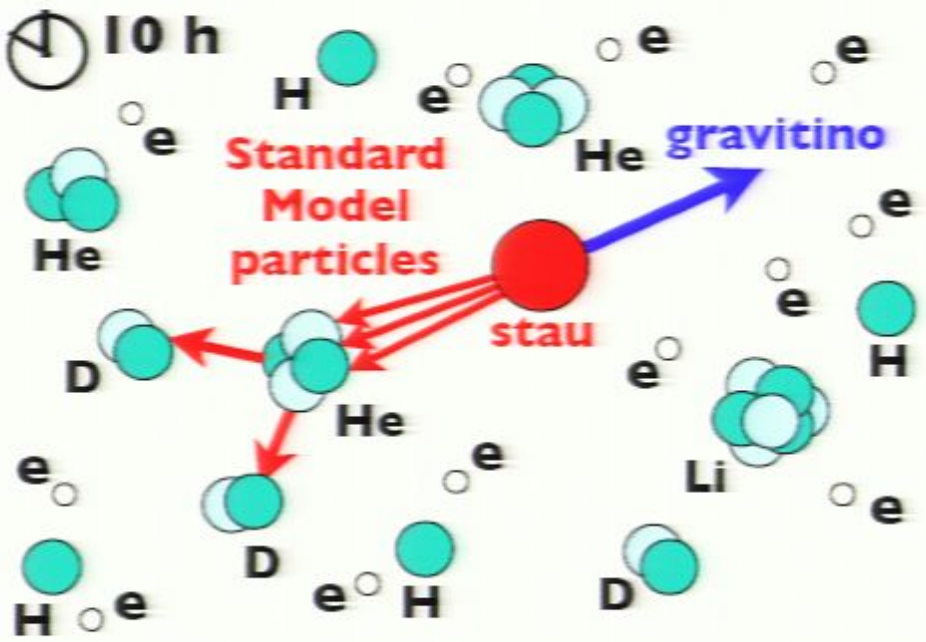
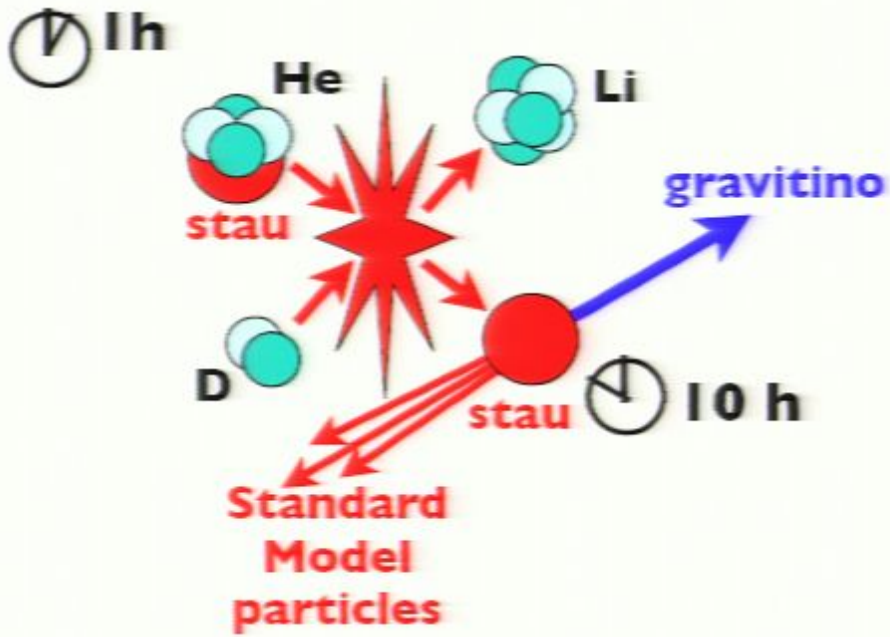


[..., Reno, Seckel, '88, Dimopoulos et al., '88 & '89, ... Ellis et al., '04, Jedamzik, '04, Kawasaki, Kohri, Moroi, '05, Feng, Su, Takayama, '04, Roszkowski et al., '05, Cerdeno et al., '06, FDS '06, Jedamzik, '06,...]

Catalyzed BBN [Pospelov, '06]

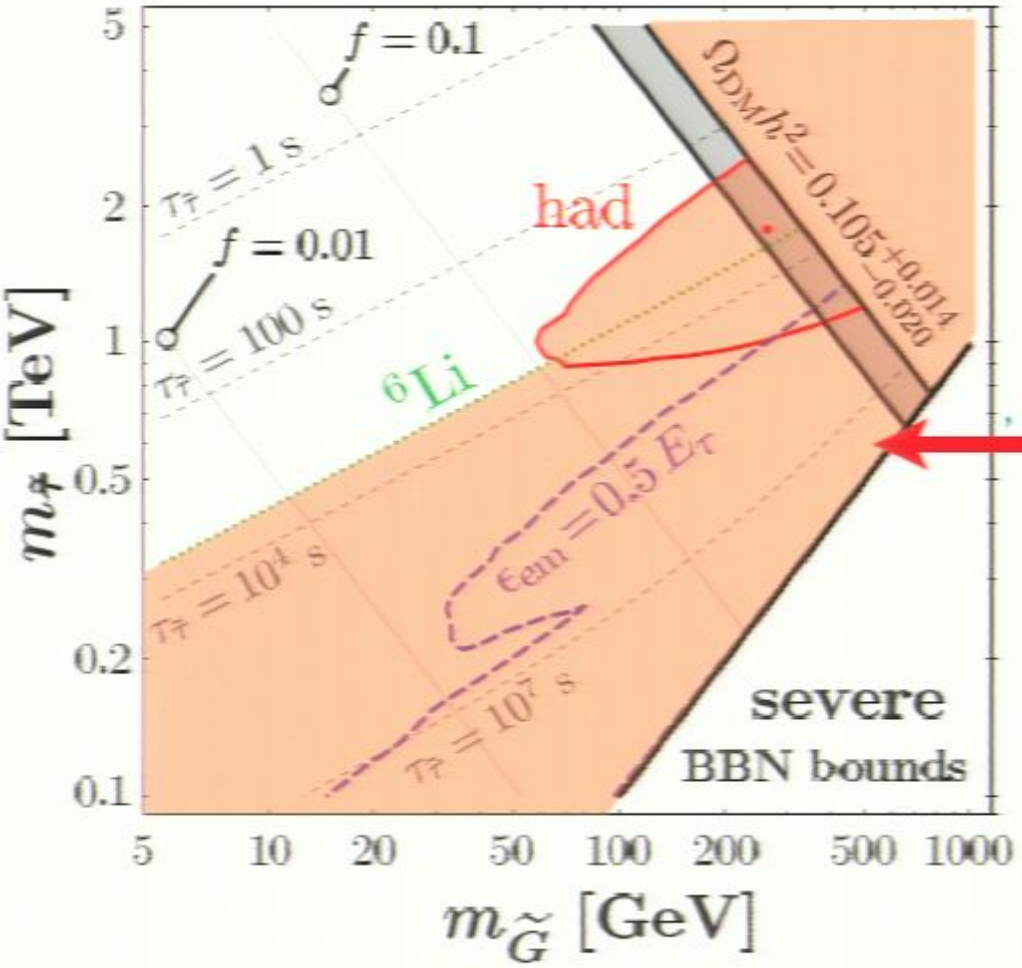


Recent Result: [Hamaguchi et al., '07]

[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; ...]

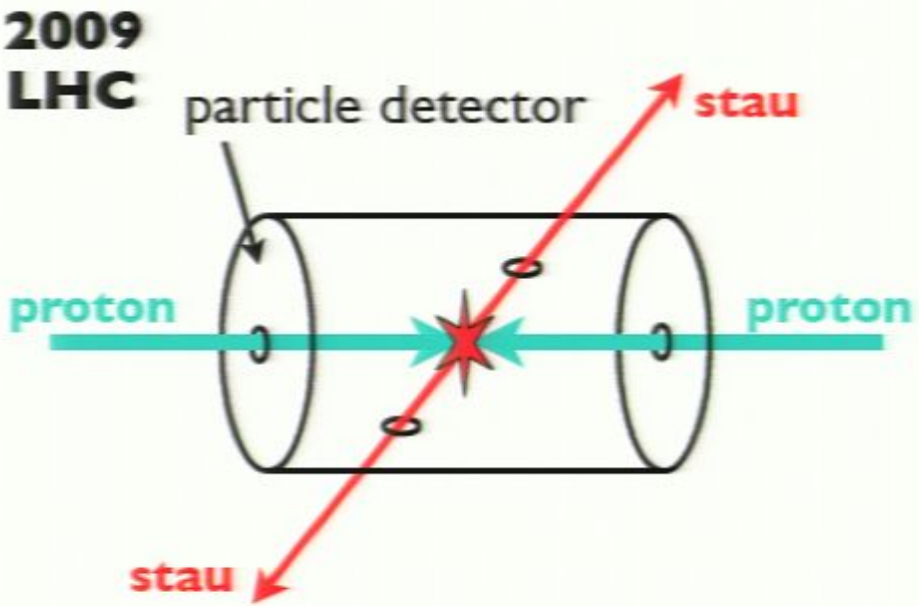
[FDS, hep-ph/0611027]

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



disfavored by cosmological constraints

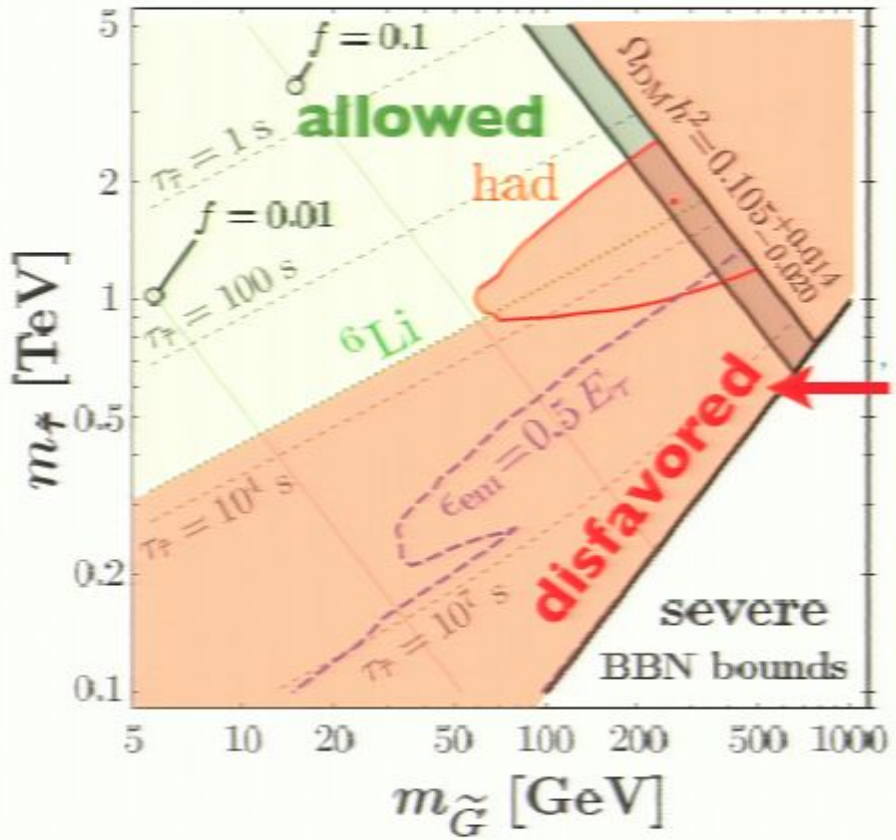
Gravitino DM @ LHC ← Stau NLSP



The signal:

jets + leptons

+ 2 "stable" charged particles



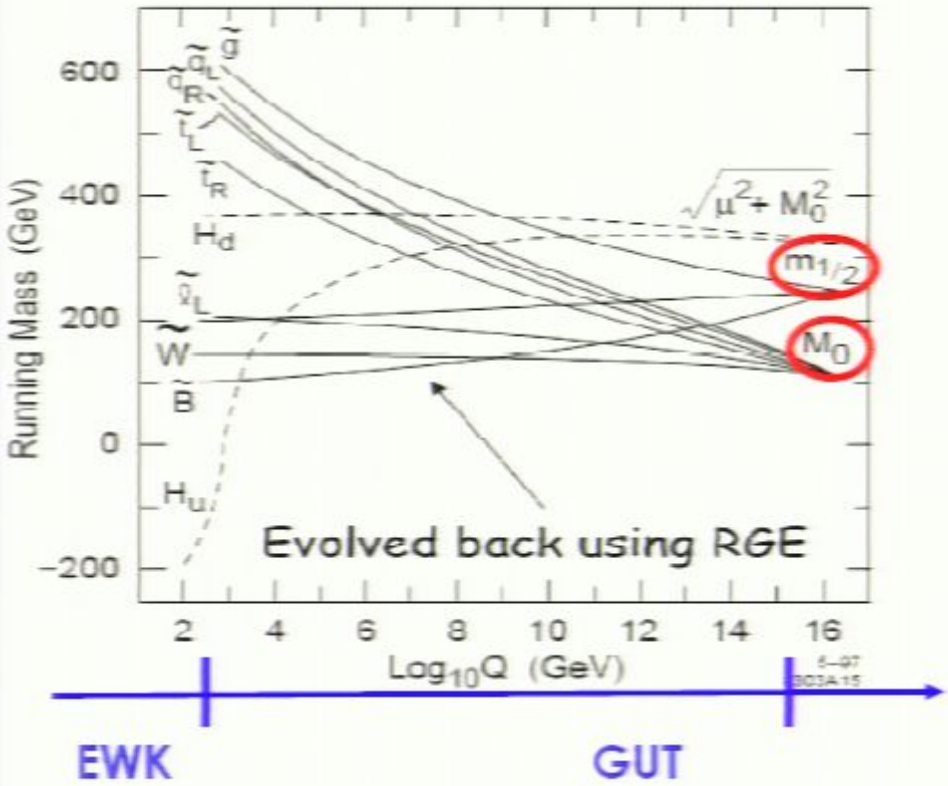
Cosmological Constraints

[FDS, hep-ph/0611027 & arXiv:0711.1240, Kawasaki, Kohri, Moroi, hep-ph/0703122, ...]

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

CMSSM with Gravitino DM

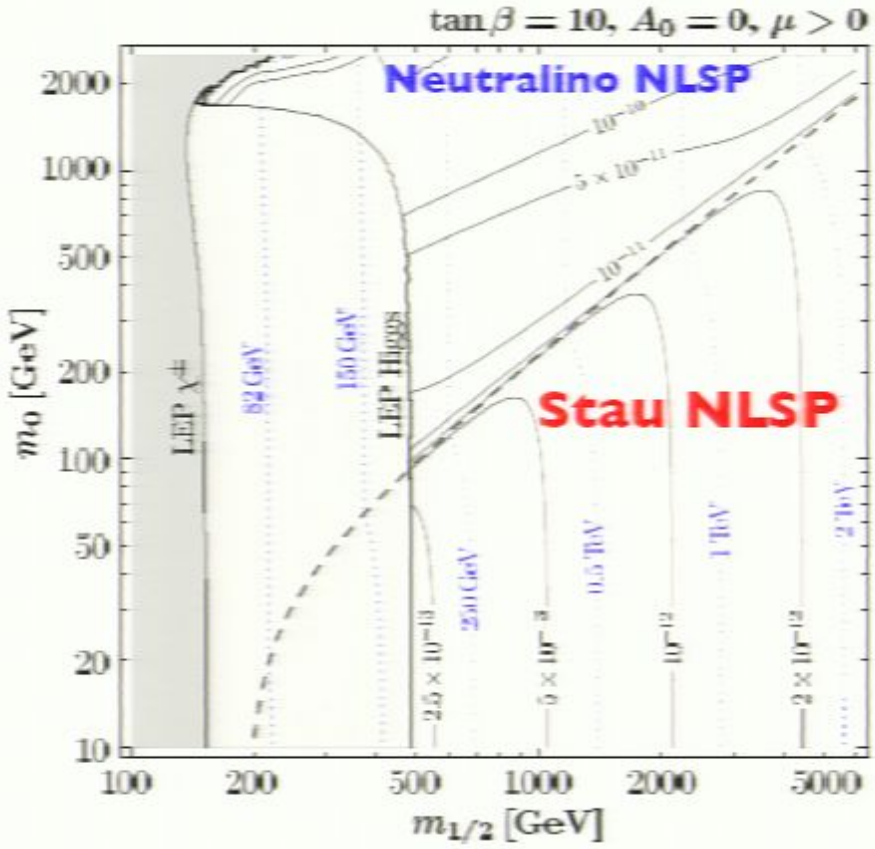
mSUGRA / CMSSM



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)

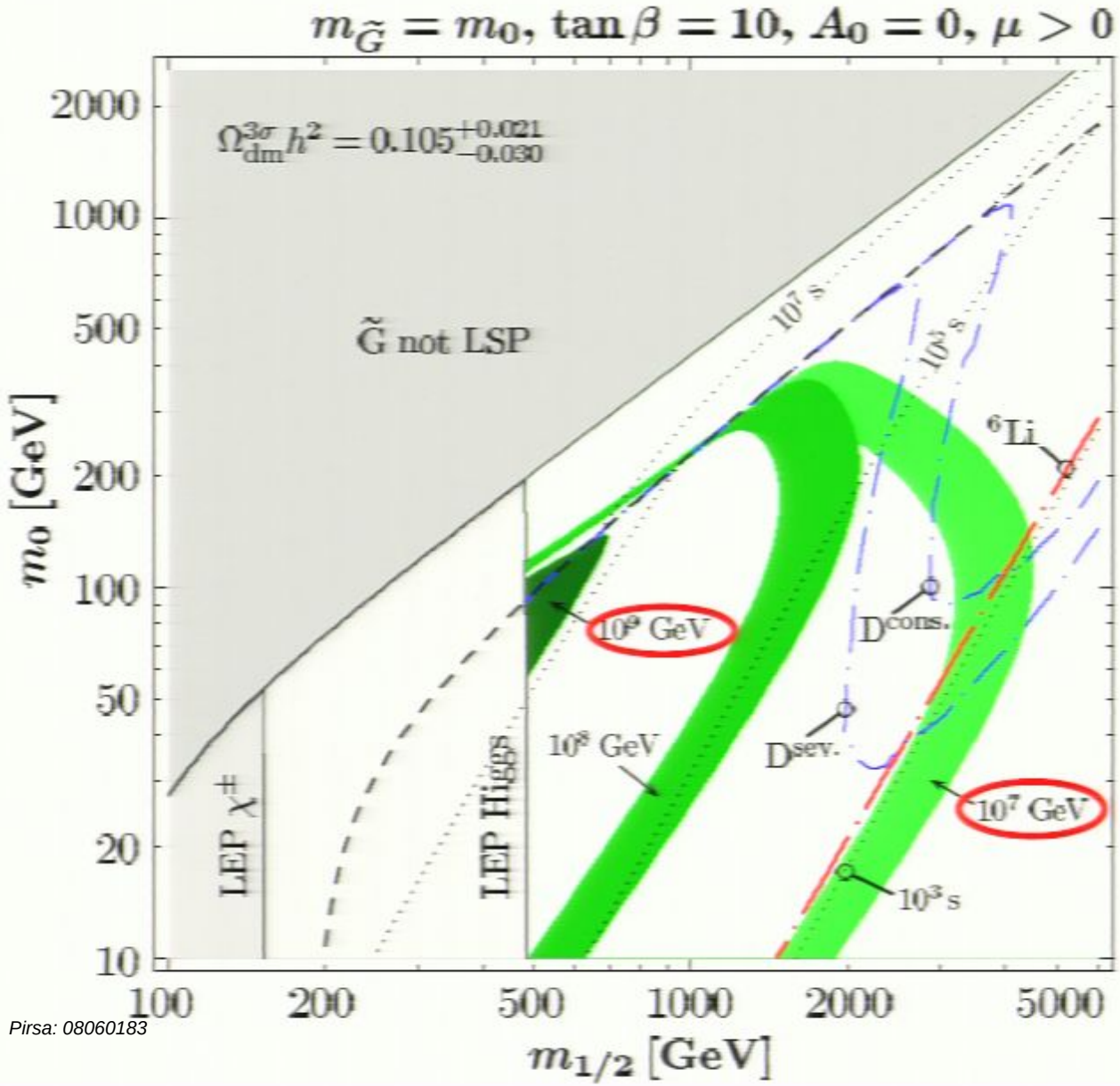
CMSSM Scan
m_{LOSP} & Y_{LOSP}

[Pradler, FDS, arXiv:0710.4548]

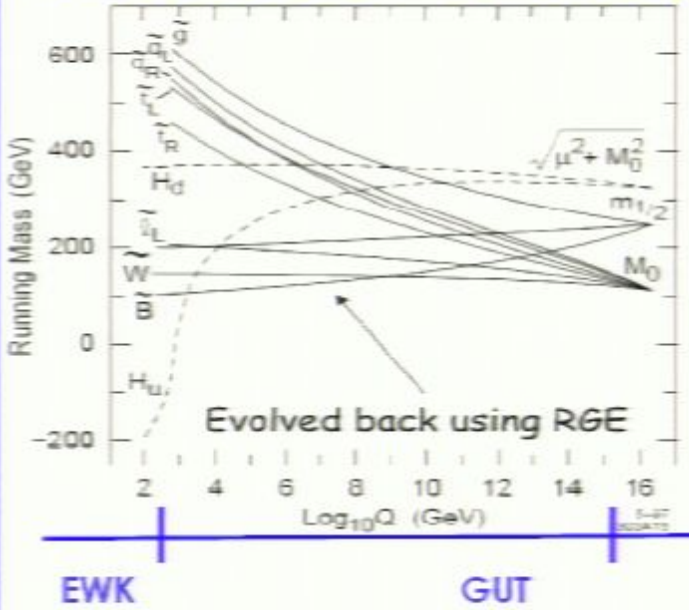


[Josef Pradler. FDS. hep-ph/0612291]

TP + NTP of Gravitino DM within the CMSSM



mSUGRA / CMSSM



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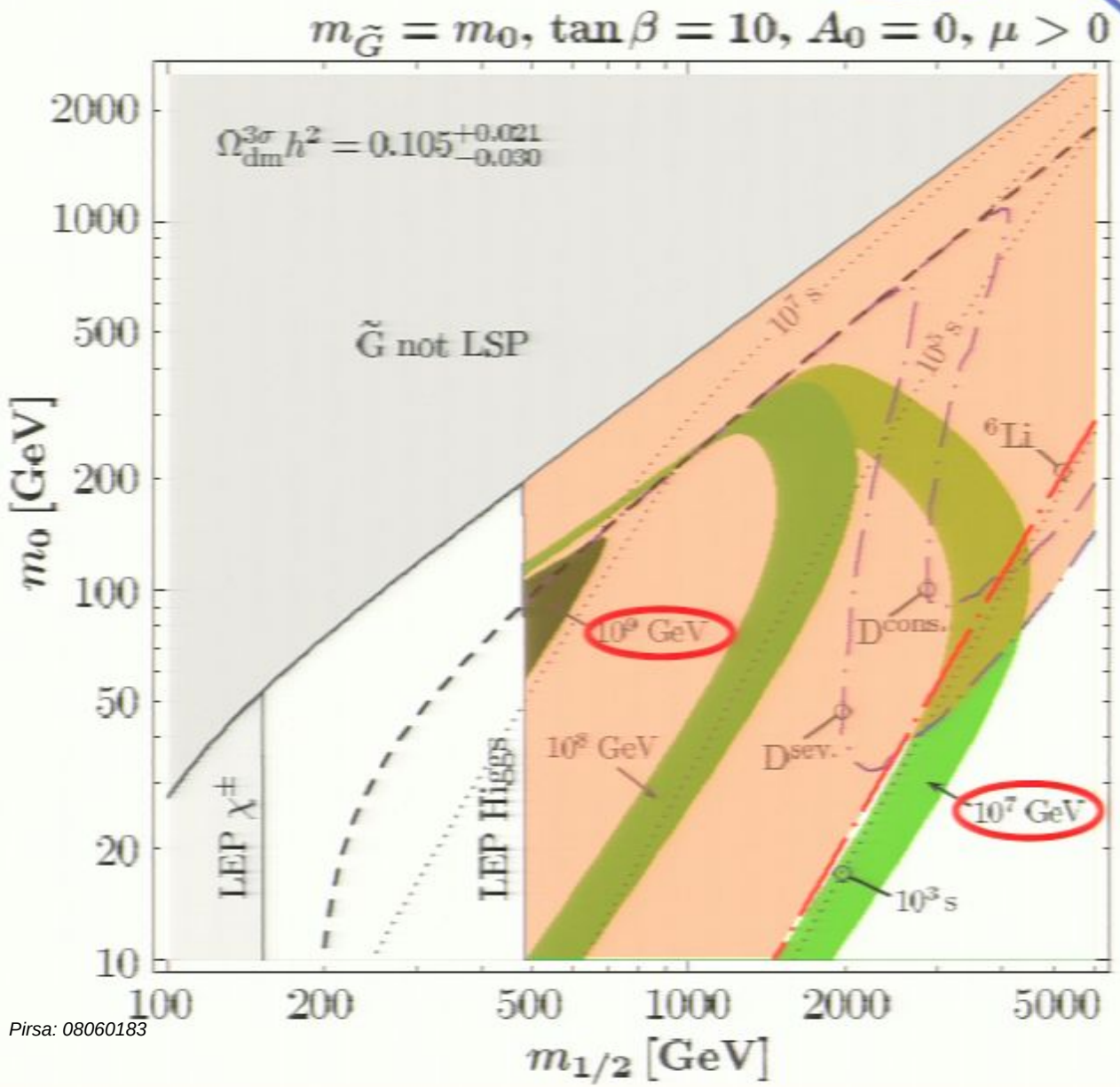
[Josef Pradler. FDS. hep-ph/0612291]

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



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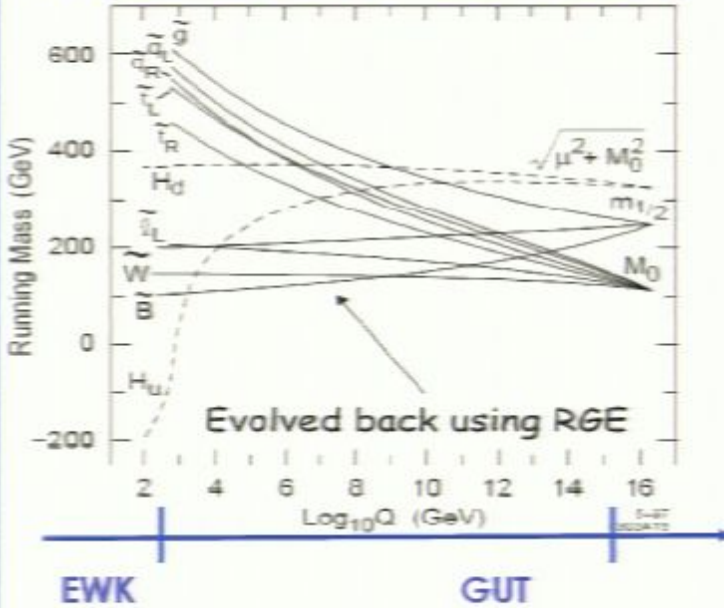

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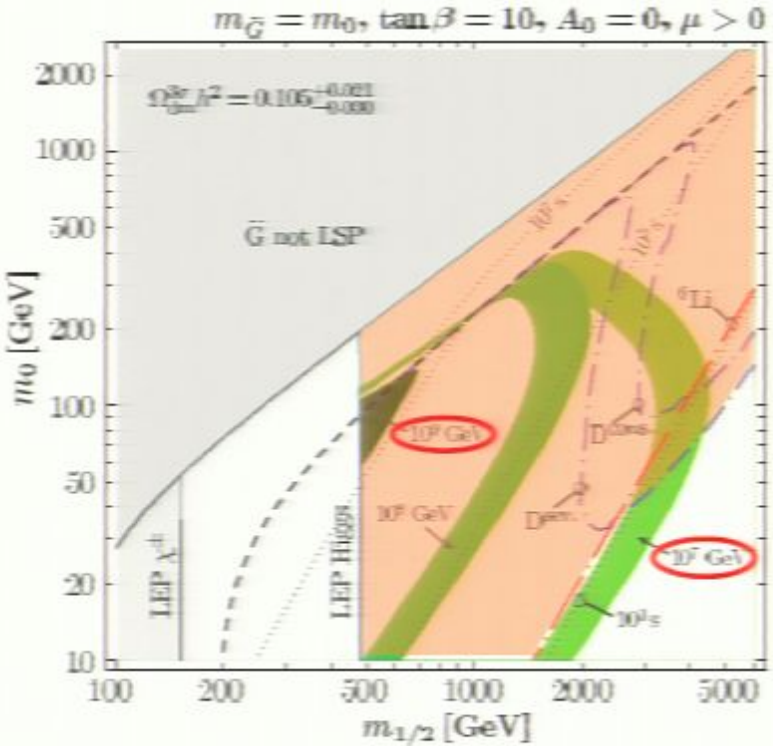
[Josef Pradler, FDS, hep-ph/0612291]

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 >10⁹ GeV

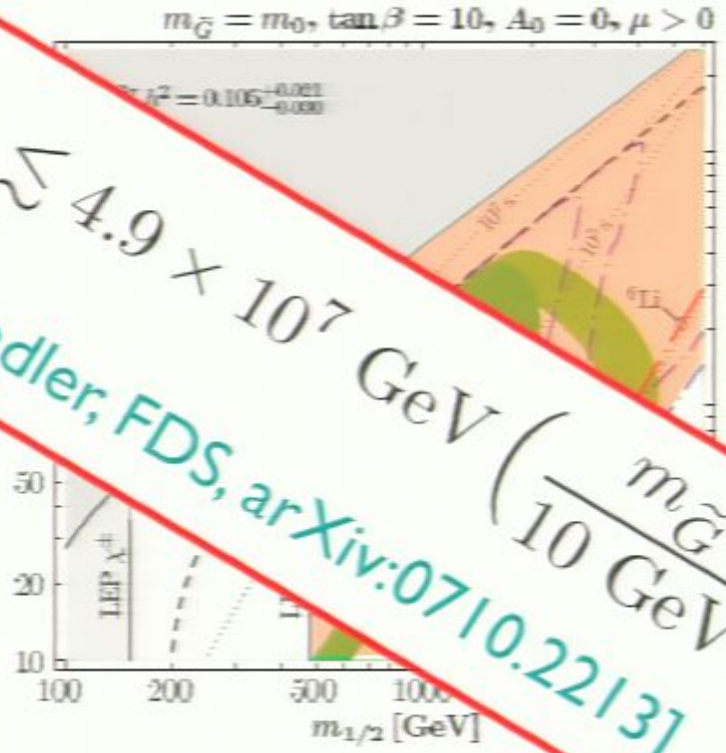
[Josef Pradler, FDS, hep-ph/0612291]

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

Implications for inflation and the origin of the baryon asymmetry

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

[Pradler, FDS, arXiv:0710.2213]



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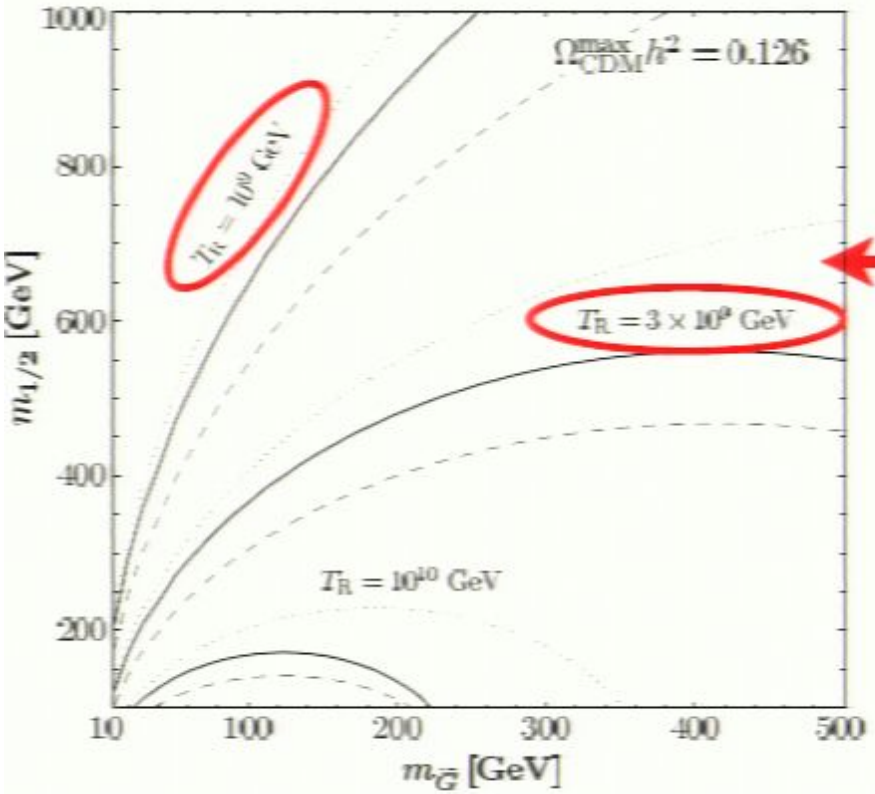
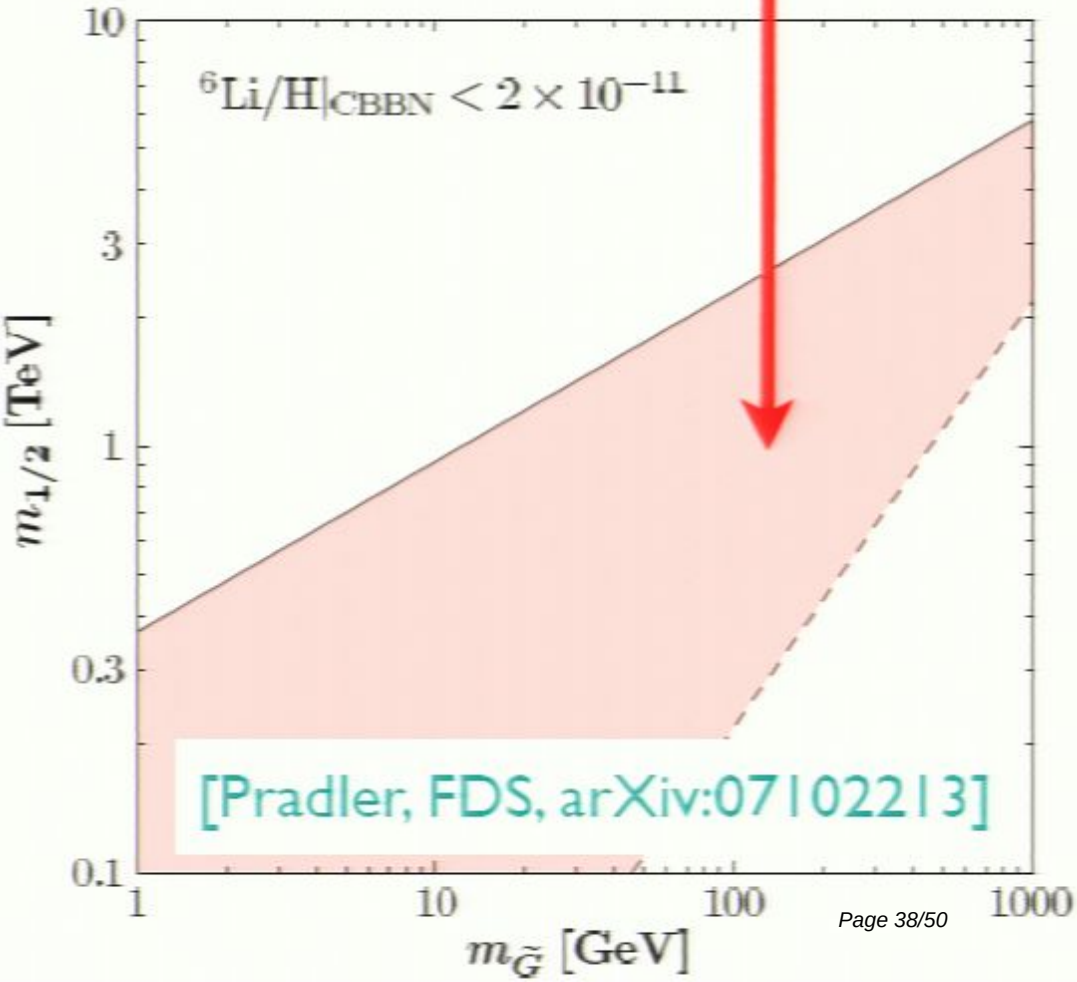


[Pradler, FDS, '06]

disfavored by cosmological constraints



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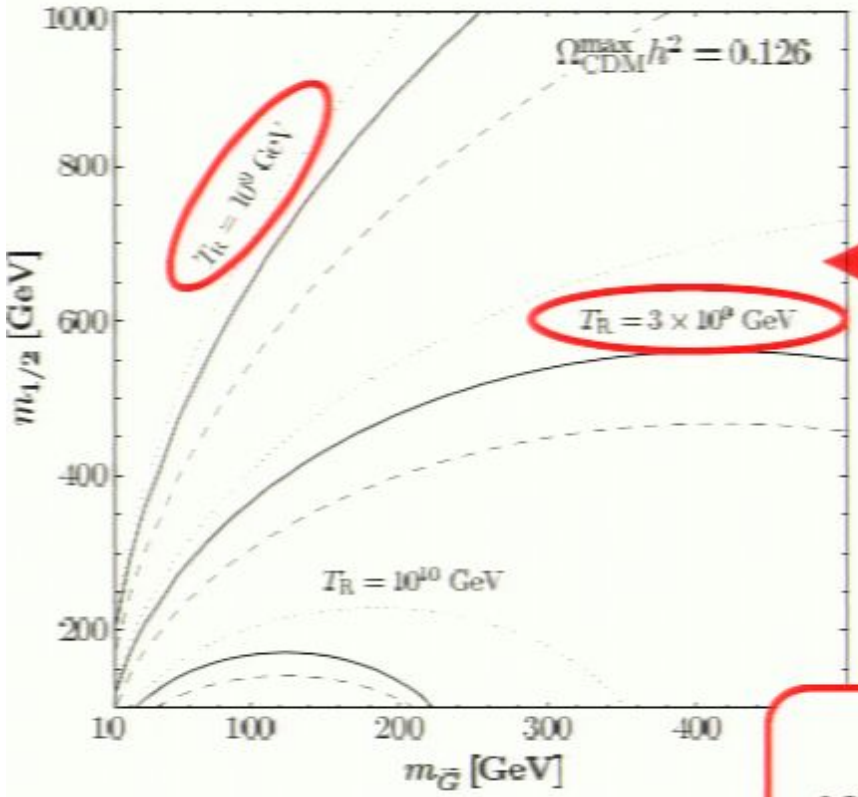

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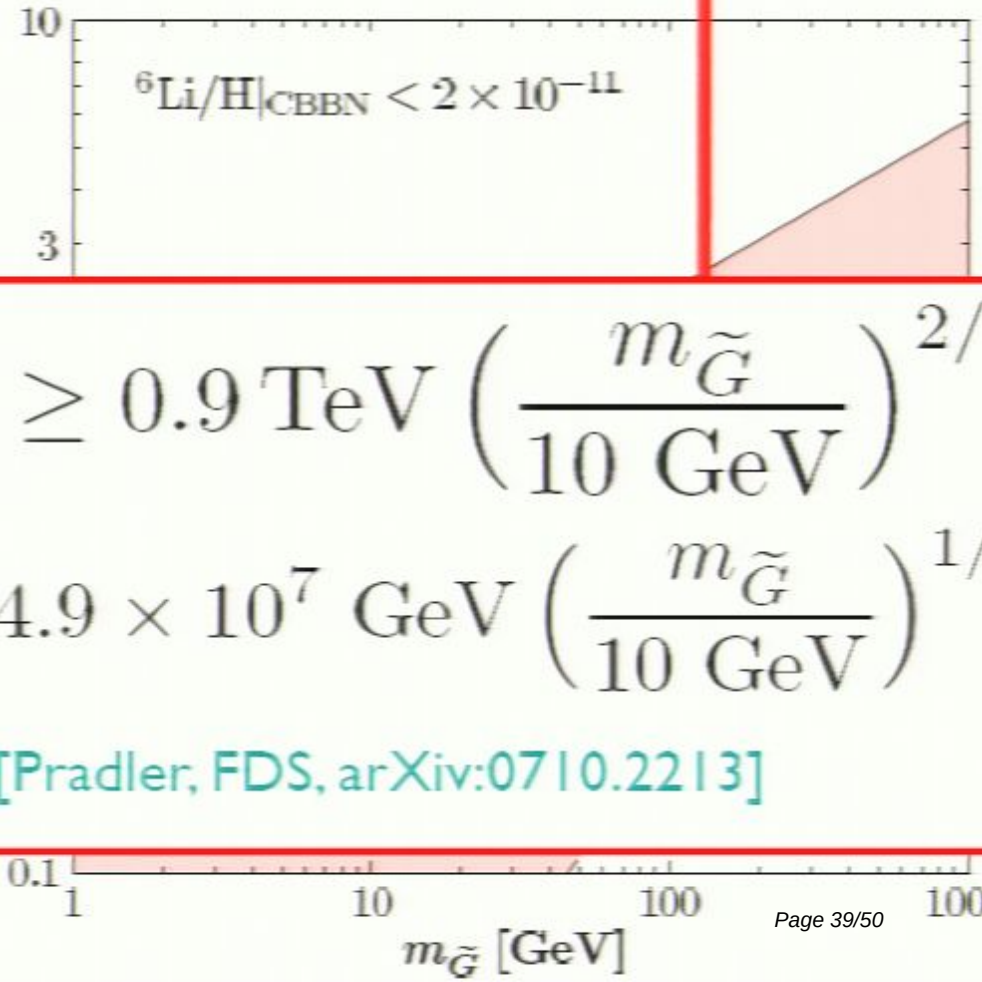

$$m_{1/2} \geq 0.9\,\mathrm{TeV}\left(\frac{m_{\tilde{G}}}{10\ \mathrm{GeV}}\right)^{2/5}$$

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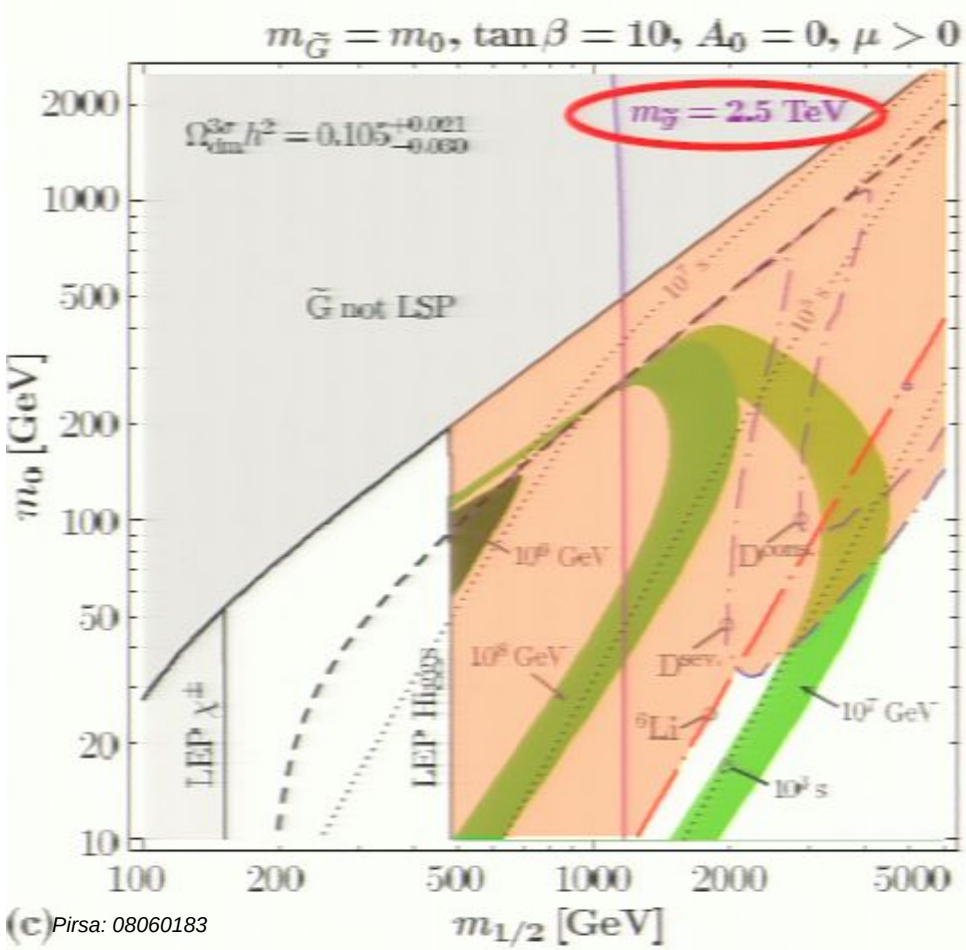
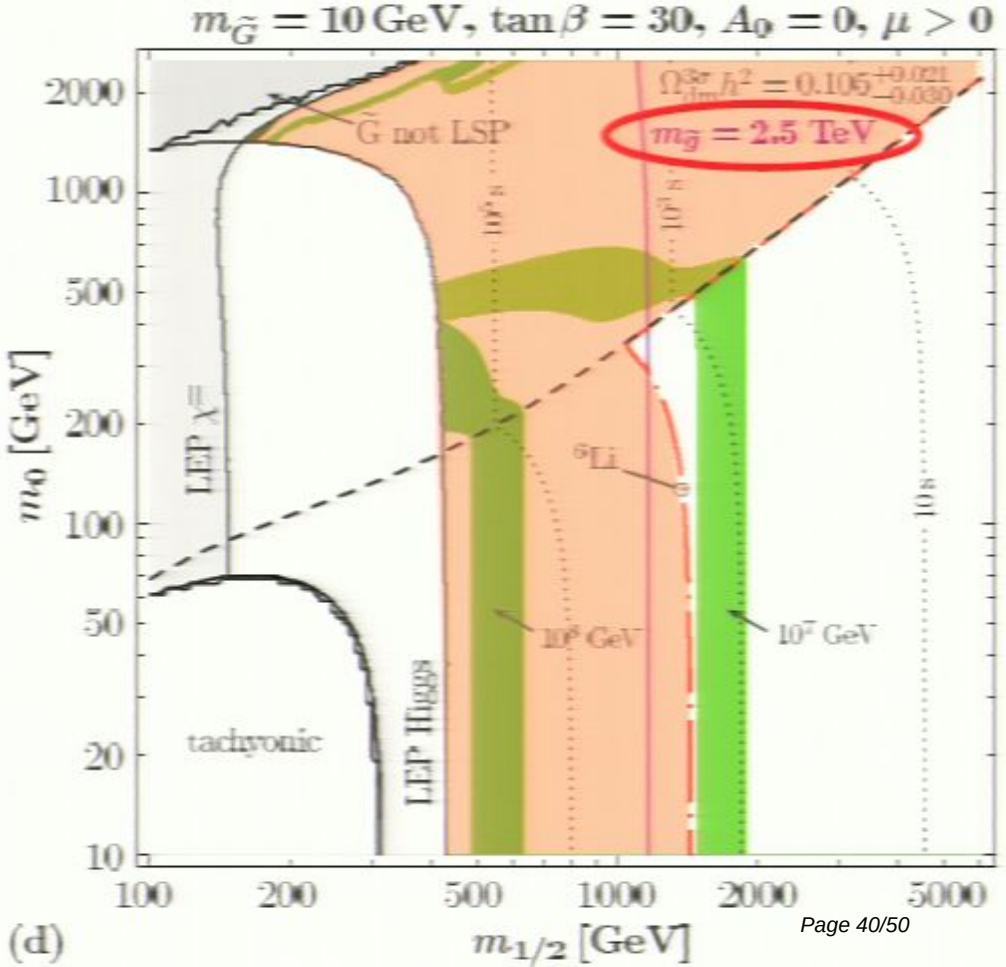
[Pradler, FDS, arXiv:0710.2213]

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

[Cyburt et al., astro-ph/0608562, Pradler, FDS, hep-ph/0612291 & arXiv:0710.4548]





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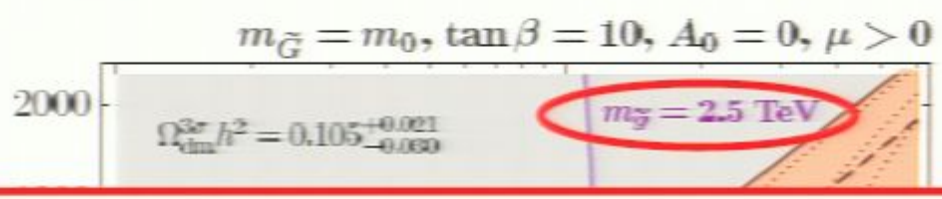
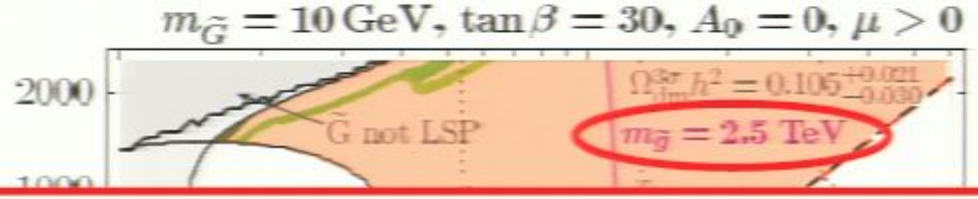
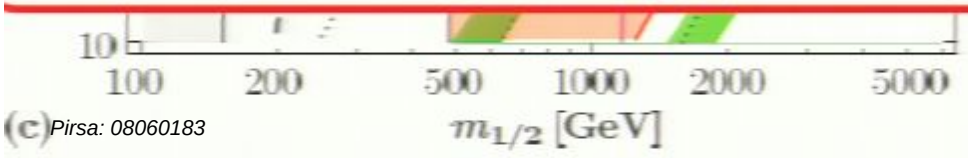




Gravitino DM with a mass < 1 GeV

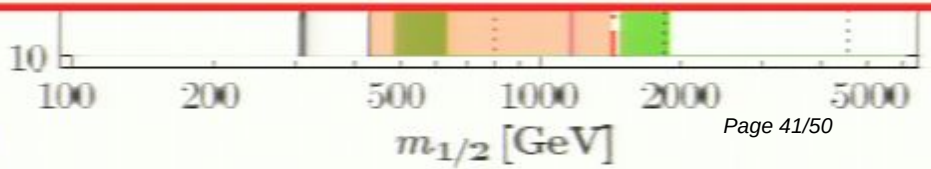
(as obtained in gauge mediated SUSY breaking)

could still be accessible at the LHC



(c)

(d)



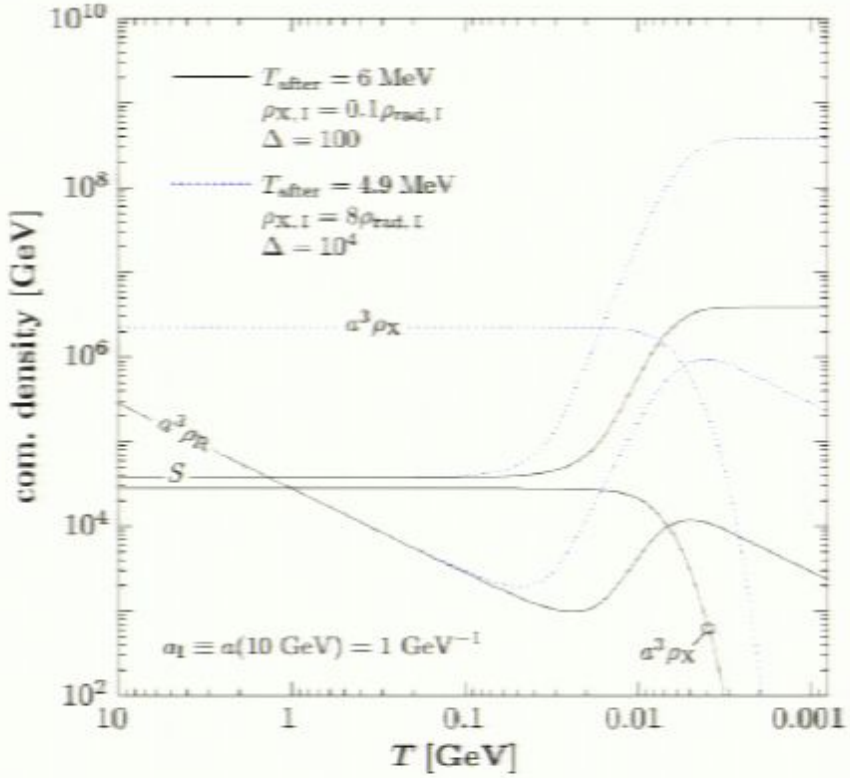
Warning:

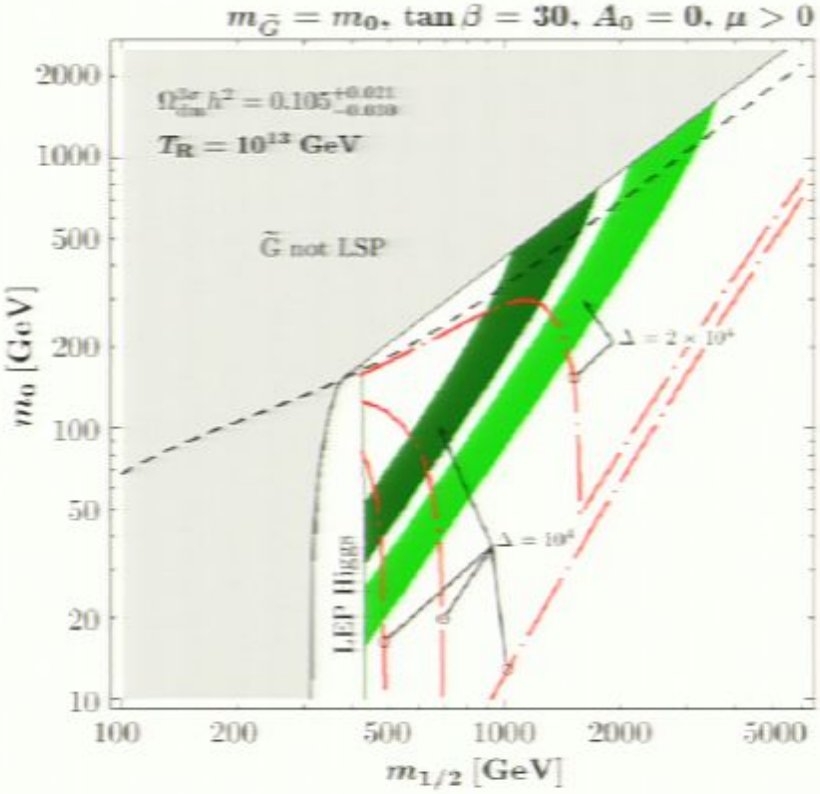
Standard Cosmological History

Late-Time Entropy Production

[Pradler, FDS, '07]

Rescuing Thermal Leptogenesis





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

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

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

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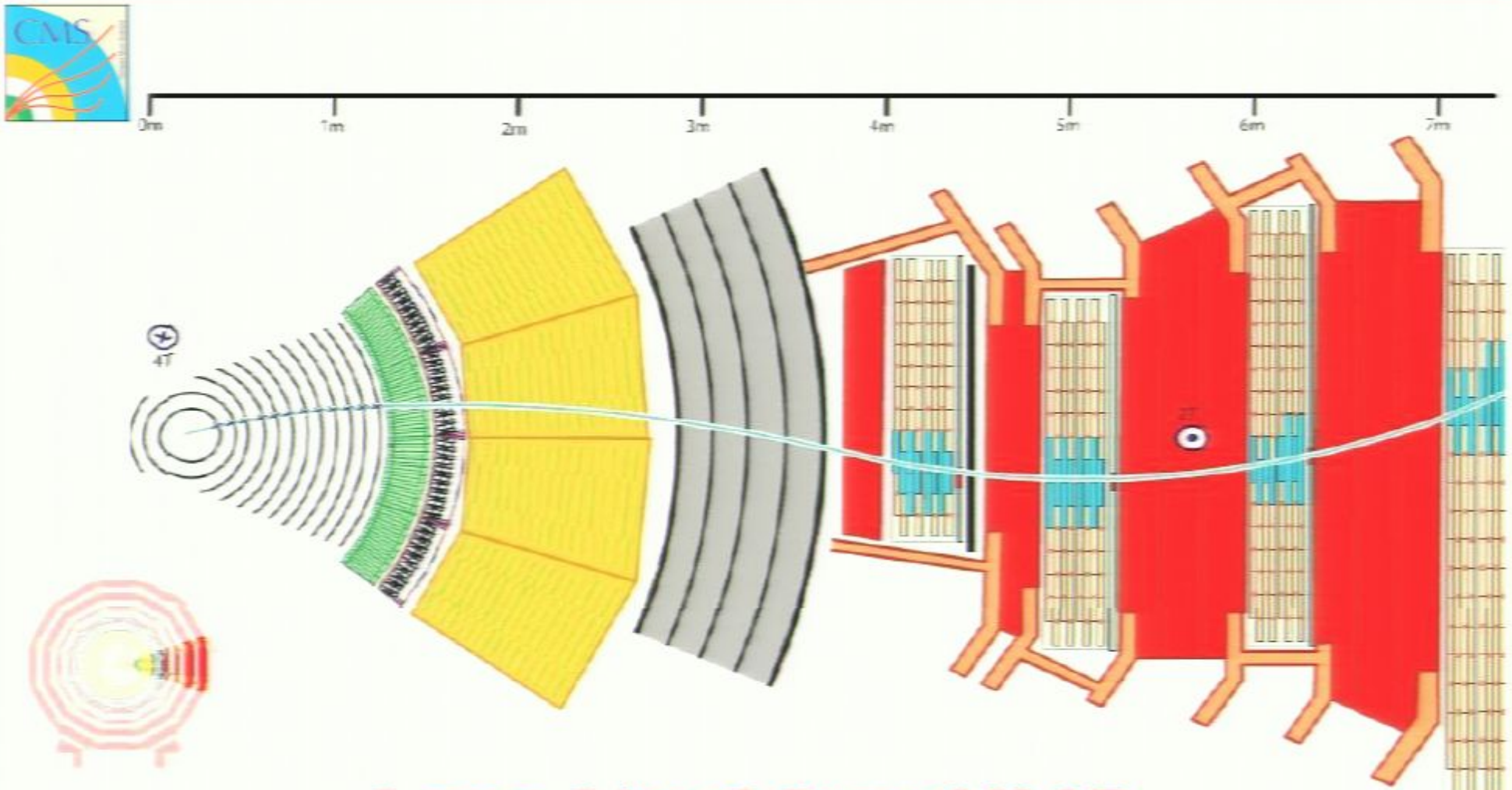
$$\eta(T_{\rm after}) = \frac{1}{\Delta} \eta(T_{\rm before})!$$

"Stable" Charged Massive Particle @ LHC



Long-Lived Stau NLSP

[from P. Zalewski's Talk, SUSY 2007]

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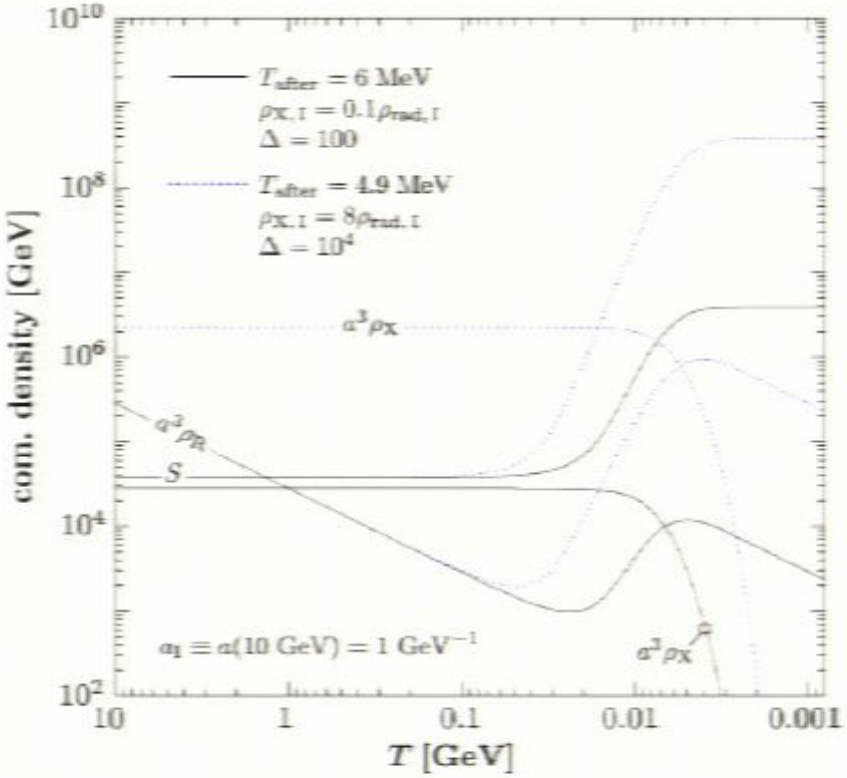

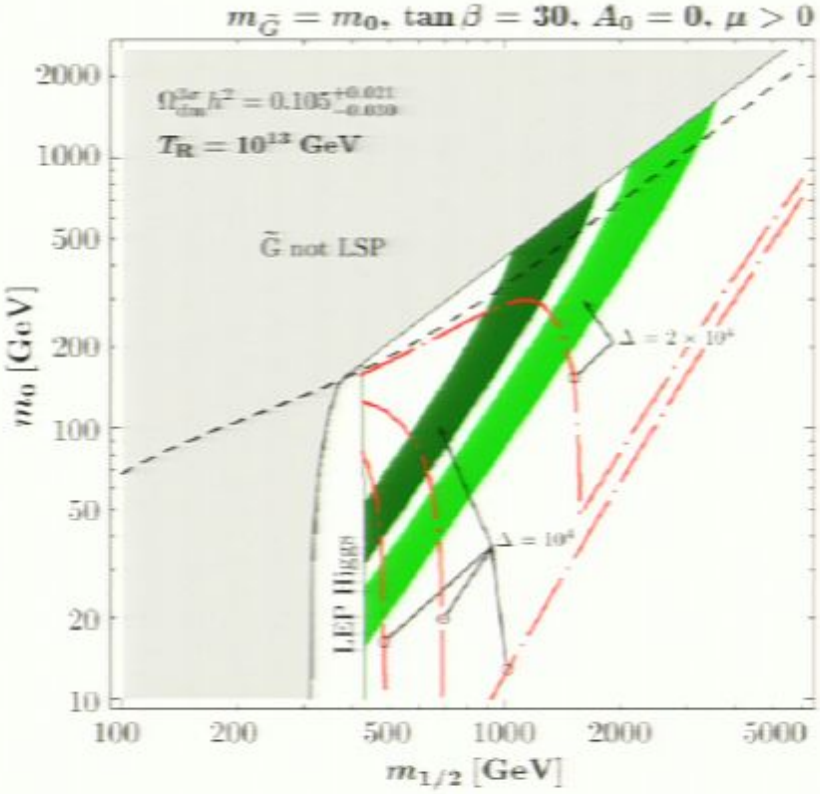

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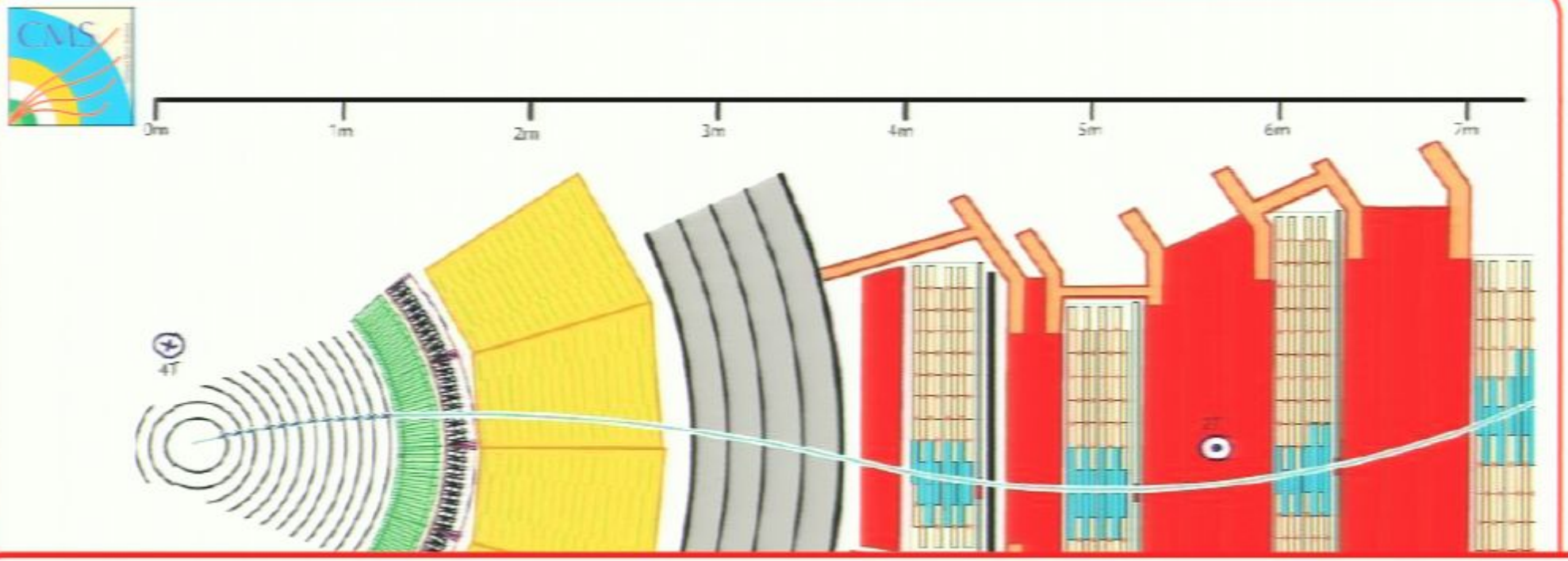
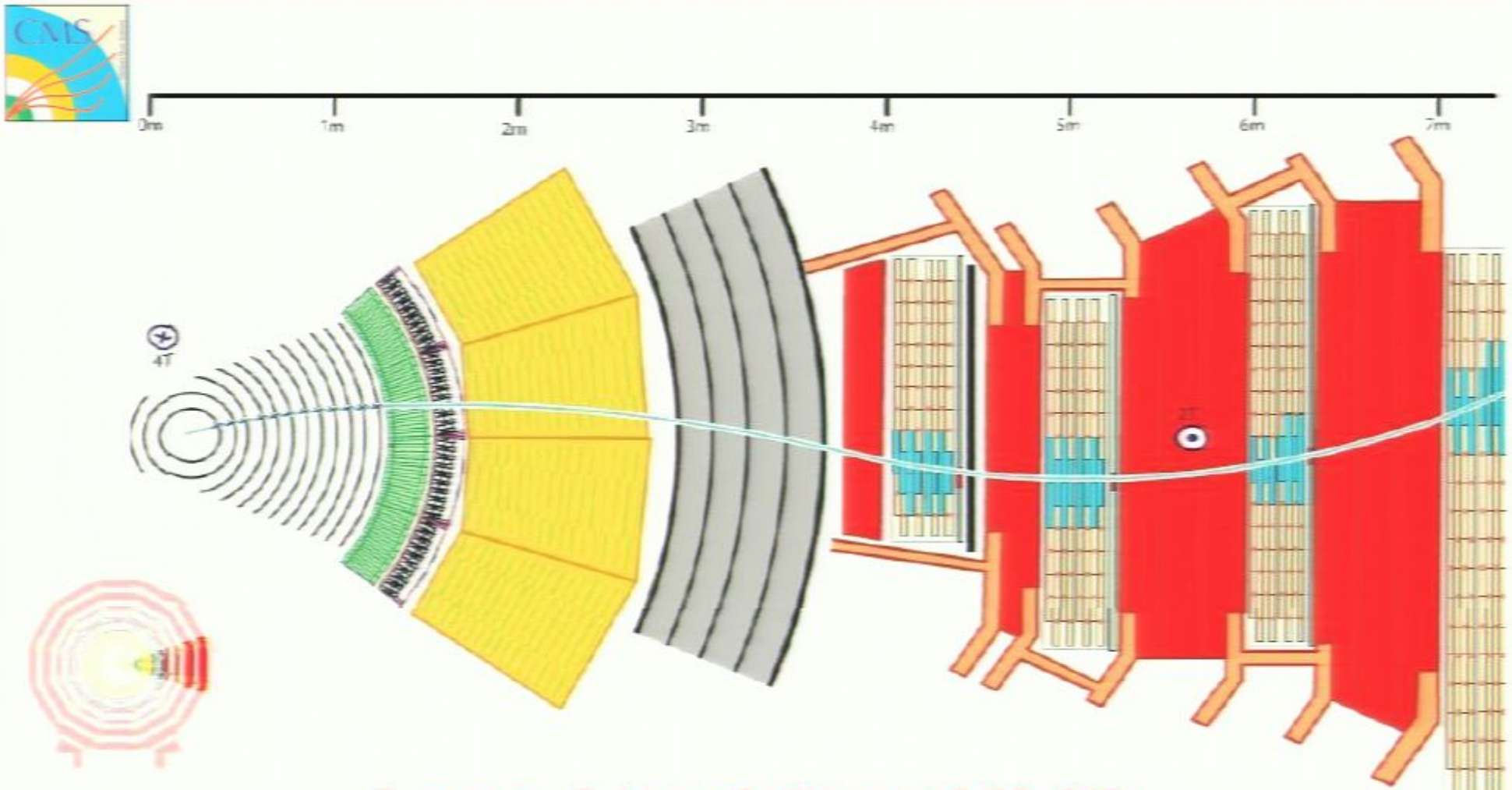


The smoking gun for

Gravitino (or Axino) Dark Matter

at the LHC

"Stable" Charged Massive Particle @ LHC



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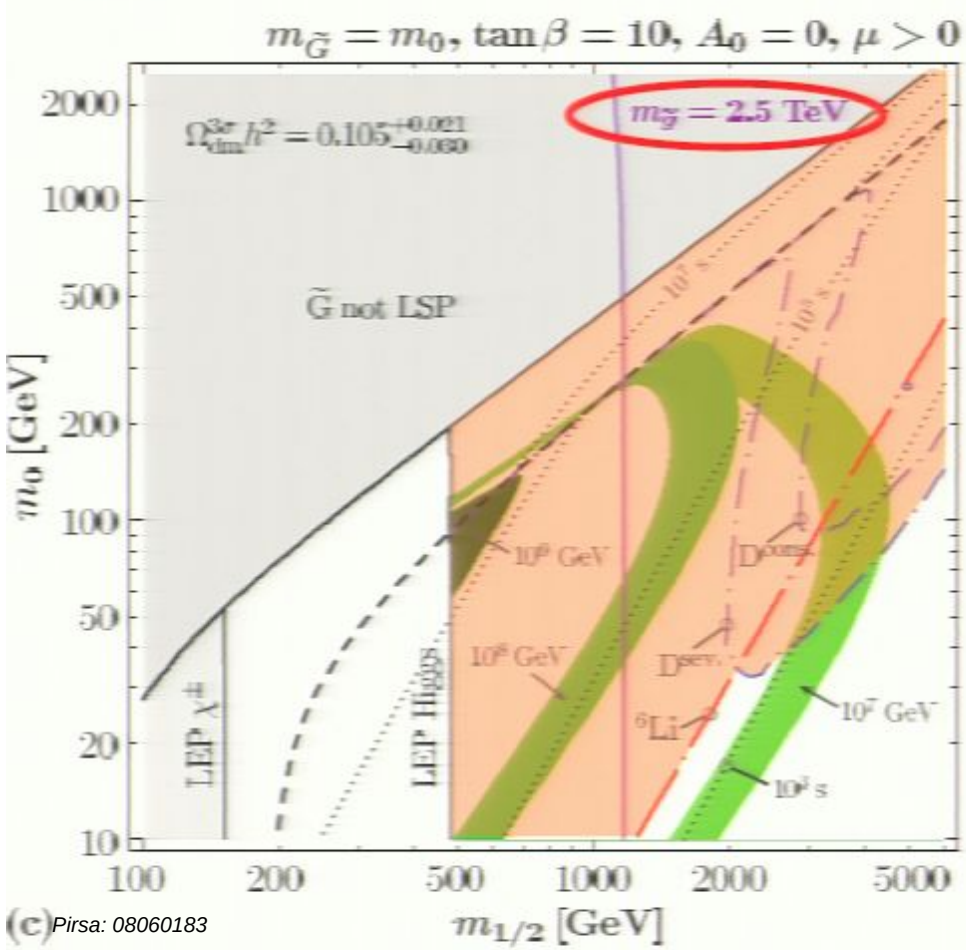

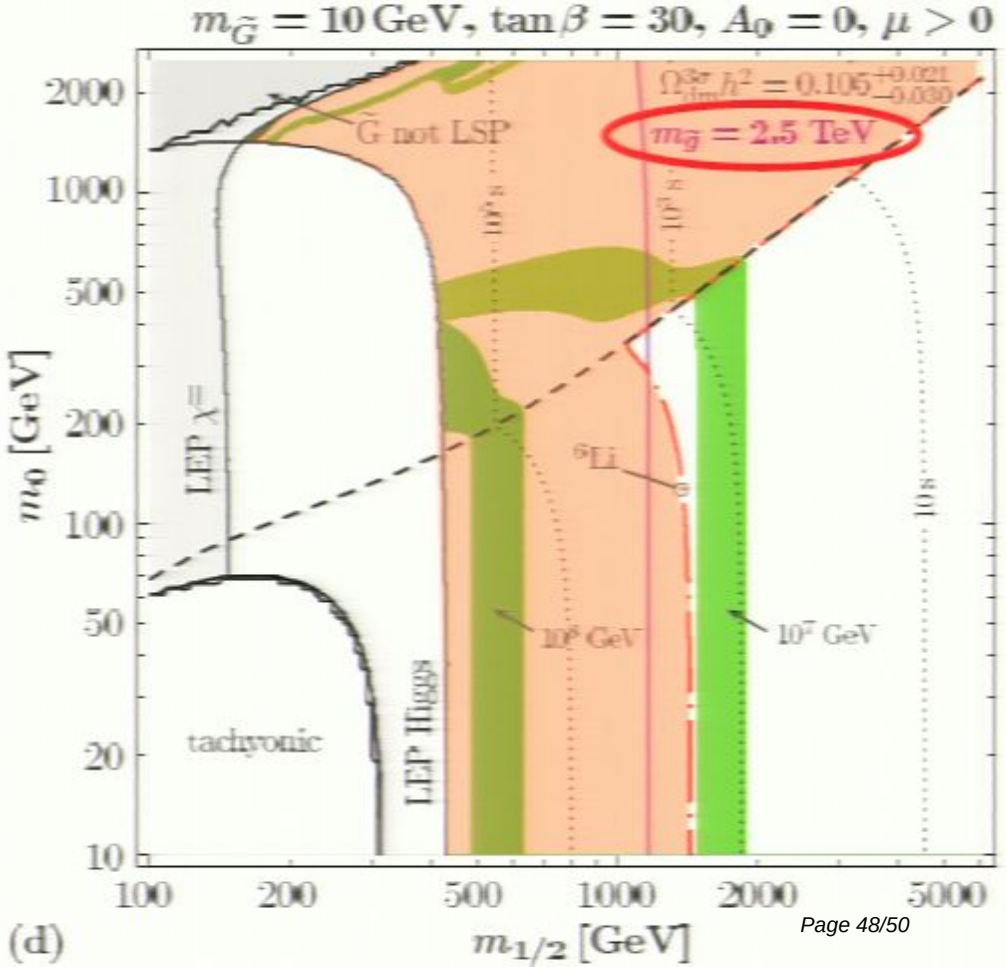

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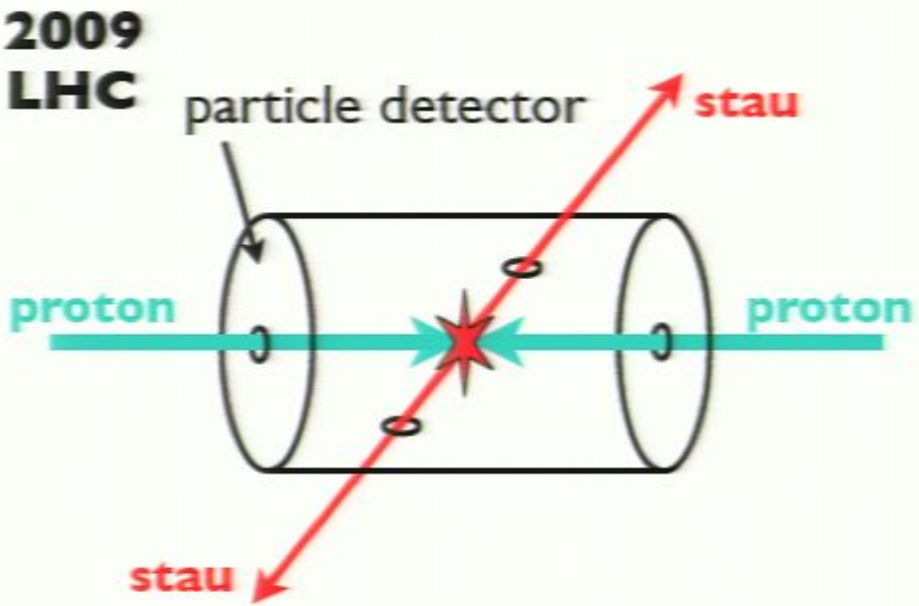

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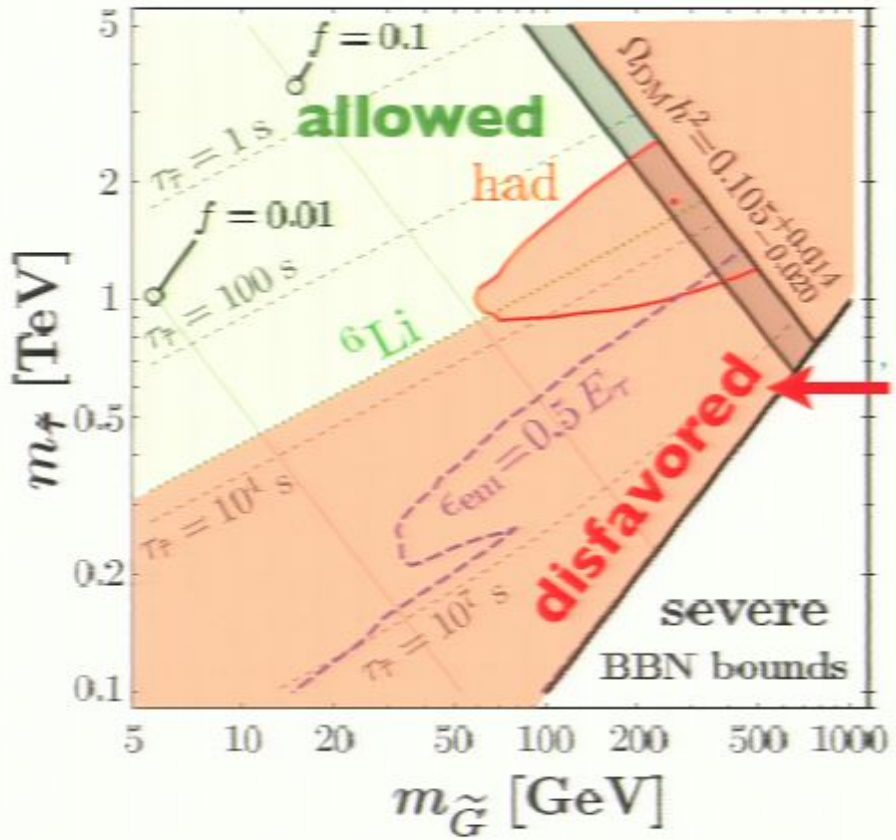

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$(k_1 + k_2 + k_3)^3 \rightarrow -k_1 + k_2 + k_3$