Title: Collider Signatures of Extremely Weakly Interacting Dark Matter Candidates

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Abstract:

Collider Signatures of Extremely Weakly Interacting Dark Matter Candidates

Frank Daniel Steffen

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Werner Heisenberg Institut

TUM
LMU
Excellence Cluster
Universe

May 31st, 2008

BBN Workshop @ Perimeter Institute

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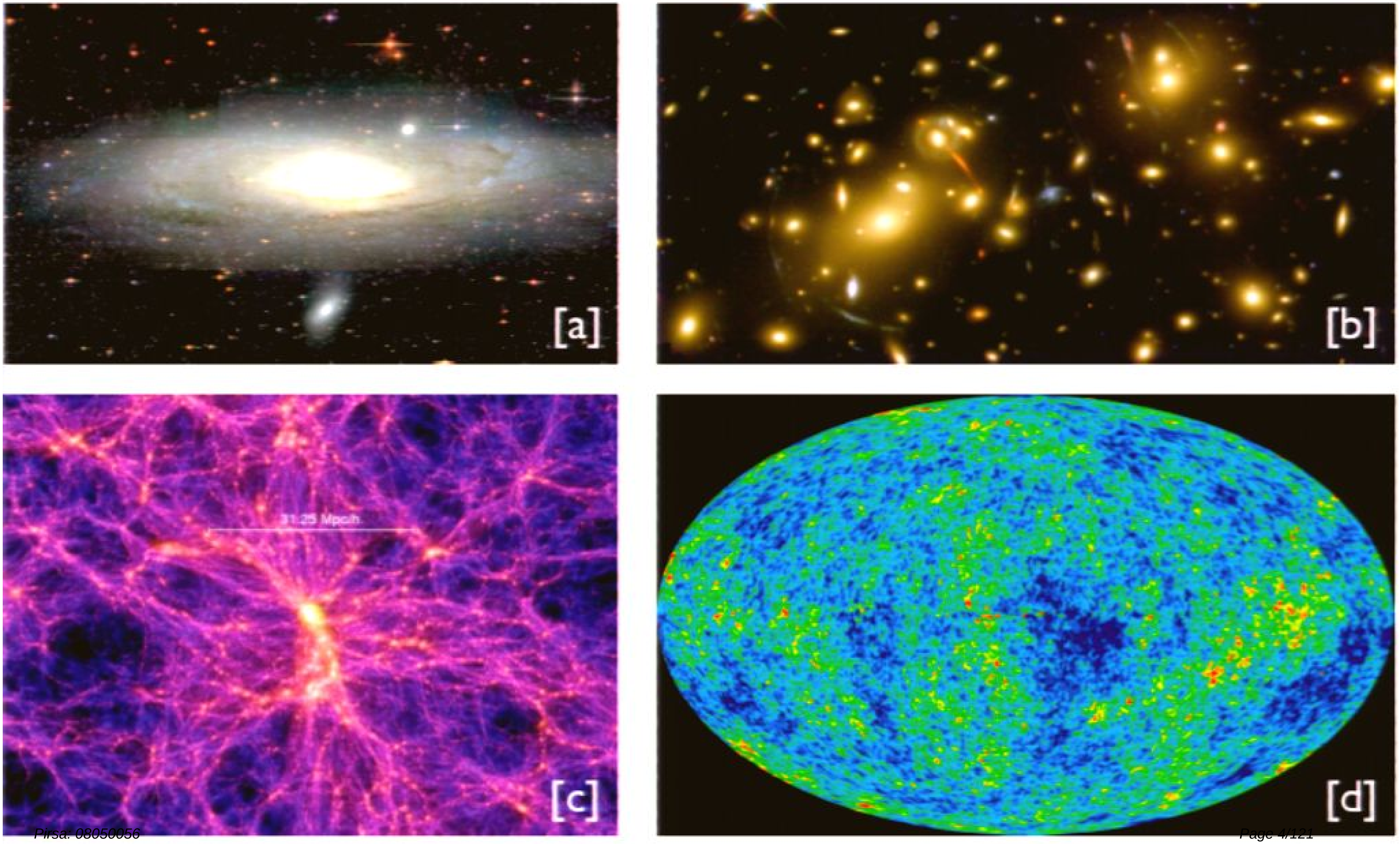
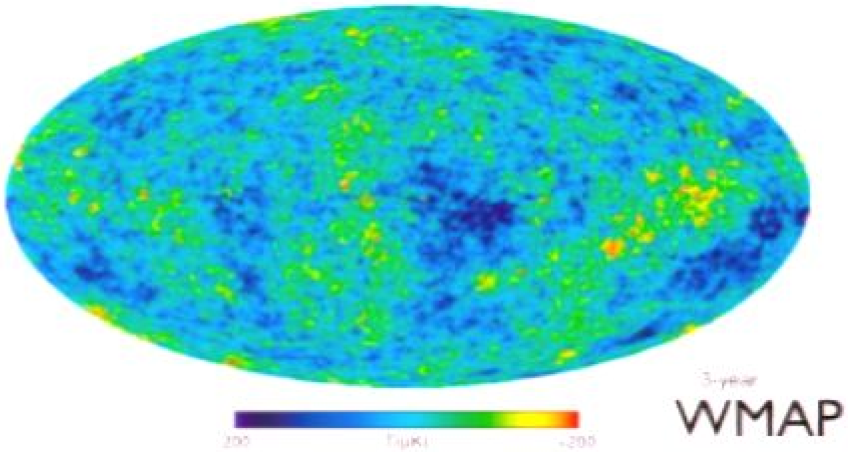
Evidence for Dark Matter in the Universe

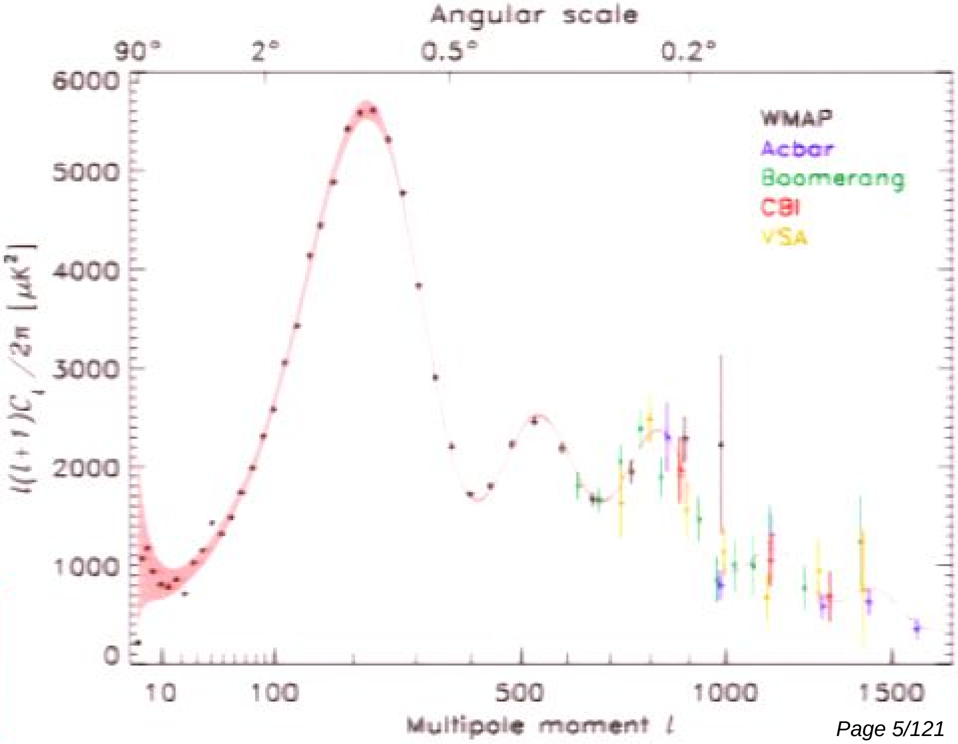


Evidence for Dark Matter in the Universe

- ☐ 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, ...
  - * $\Omega_{\rm tot} = 100\%$
  - * $\Omega_{\rm M} = 27\%$
  - * $\Omega_{\rm B} = 5\%$

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

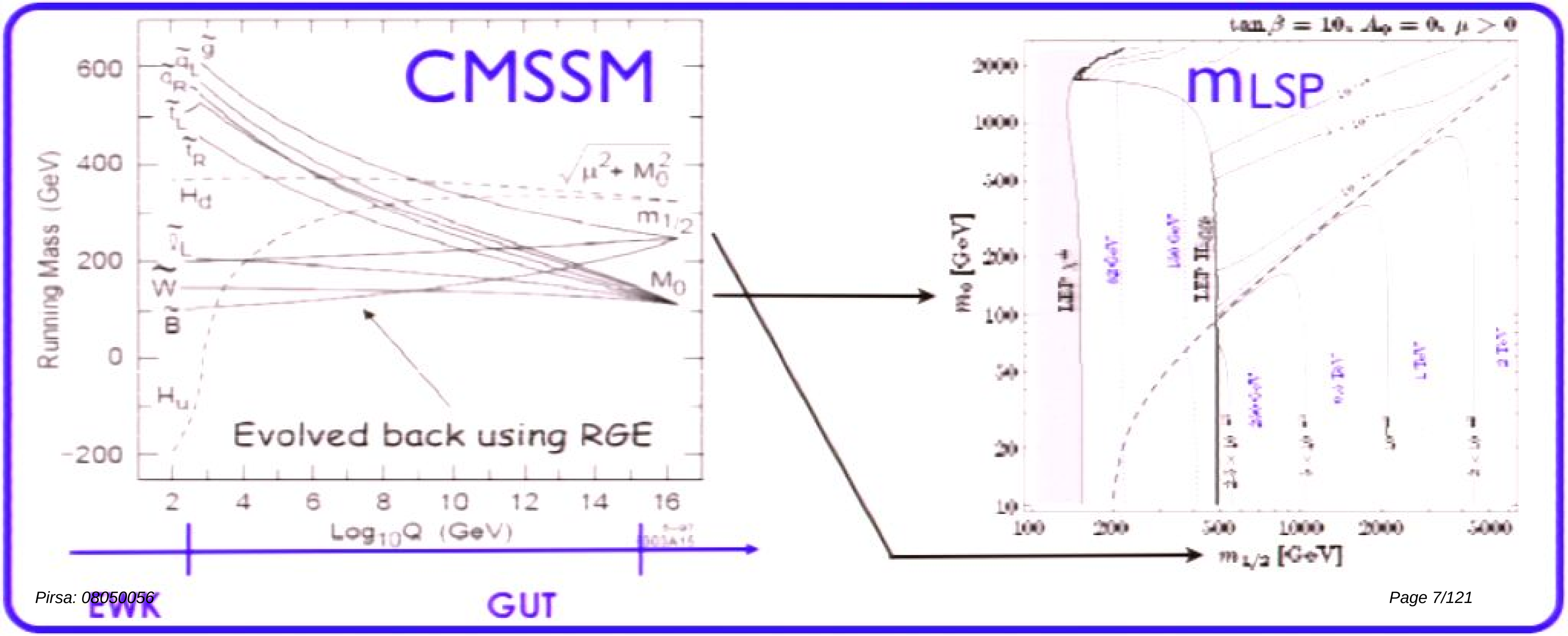




What is the identity of Dark Matter ?

Supersymmetric Dark Matter Candiates

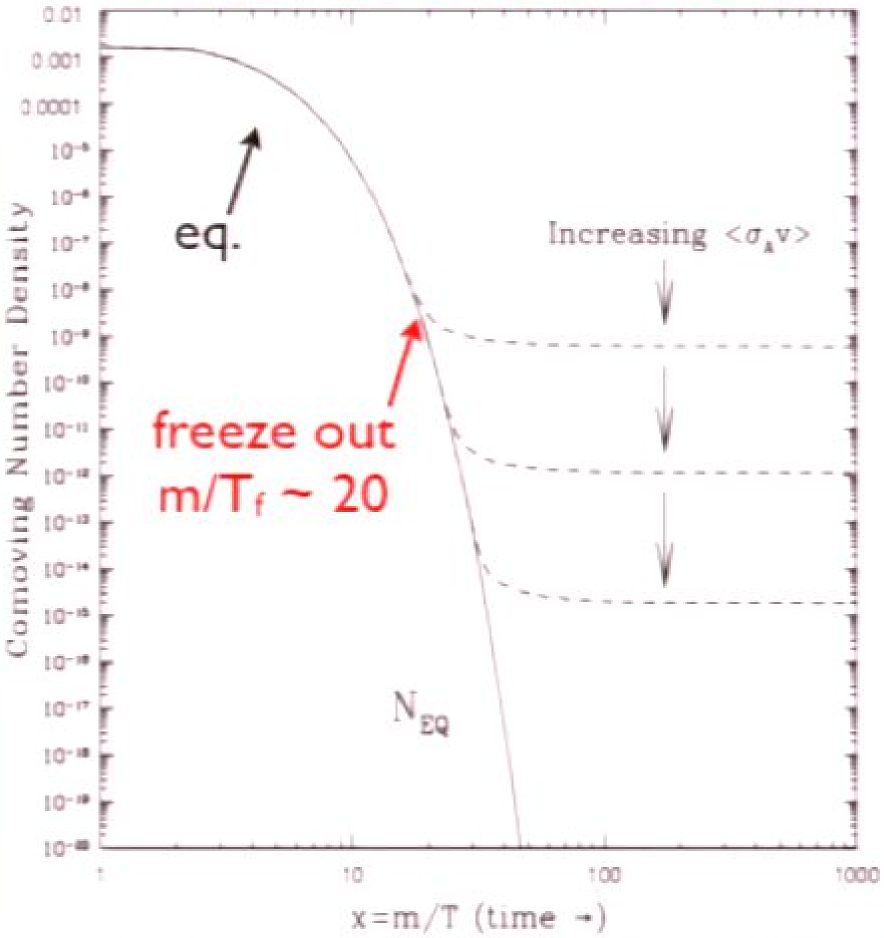
	LSP	ID	spin	mass	interaction
lightest neutralino	$\tilde{\chi}_1^0$	$\widetilde{B}, \widetilde{W}, \widetilde{H}_u^0, \widetilde{H}_d^0$	$\frac{1}{2}$	$\mathcal{O}(100\text{ GeV})$	g, g'
$\in$ MSSM		mixture		$M_1, M_2, \mu, \tan\beta$	weak



$\tilde{\chi}_1^0$ LSP Dark Matter: Production, Constraints, Experiments

LSP	interaction	production	constraints
$\tilde{\chi}_1^0$	g, g'	WIMP	← cold
	weak	freeze out	

Cold Thermal Relic



[... , Jungman, Kamionkowski, Griest, '96, ...]

$\tilde{\chi}_1^0$ LSP Dark Matter: Production, Constraints, Experiments

LSP	interaction	production	constraints
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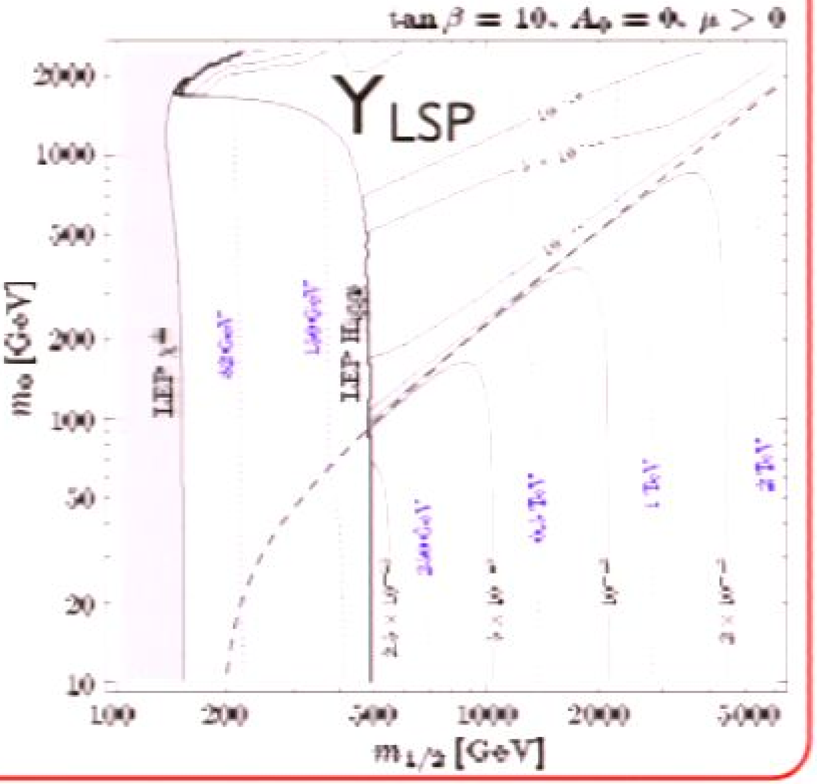
micrOMEGAs 1.37

[Belanger et al., '03 & '06]



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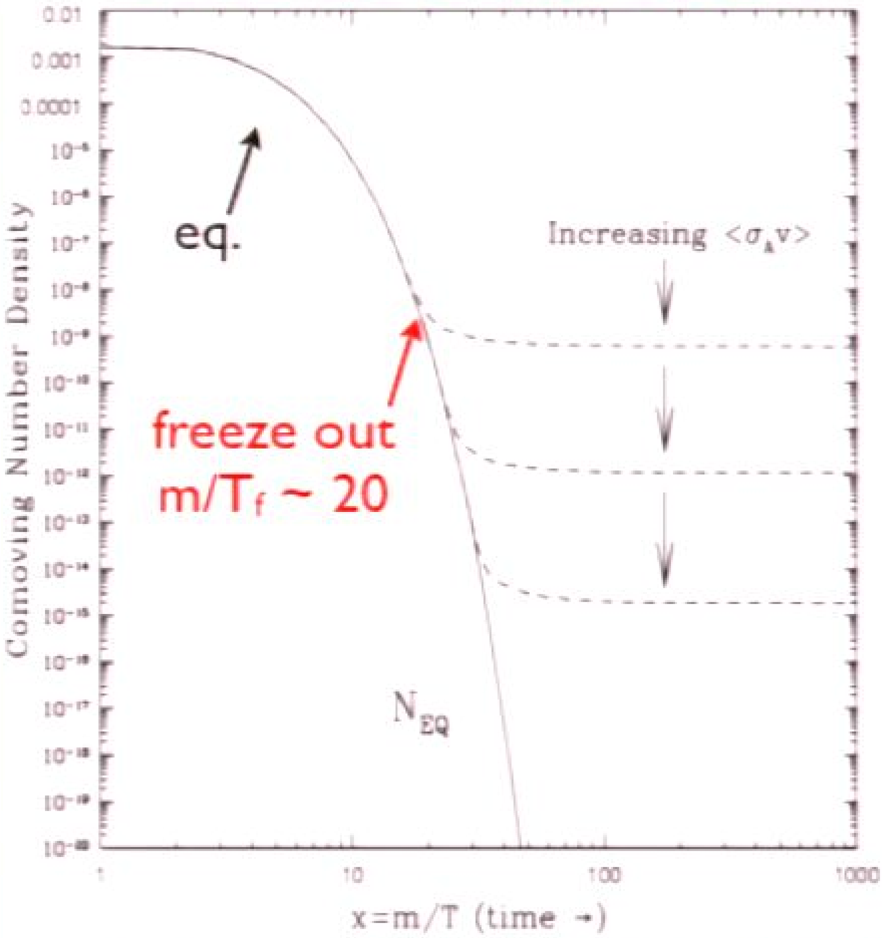


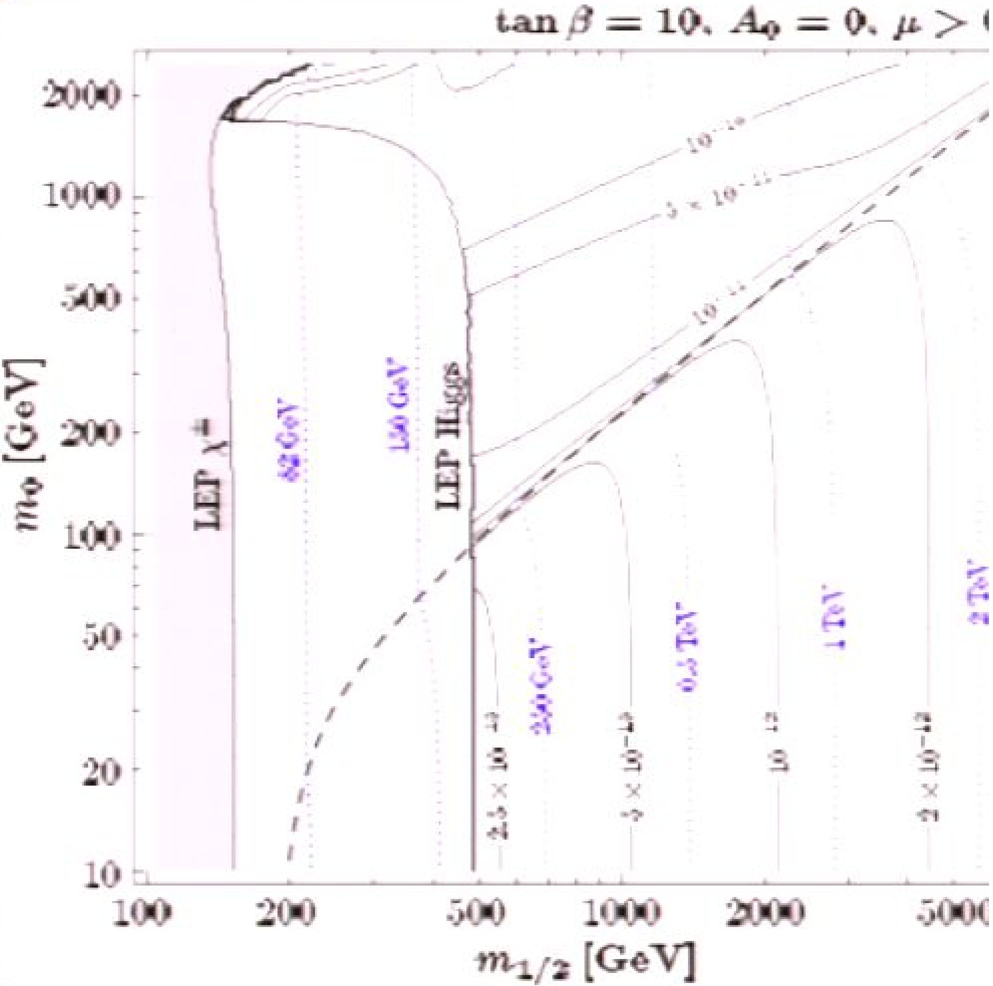
[… , Jungman, Kamionkowski, Griest, '96, …]

$\tilde{\chi}_1^0$ LSP Dark Matter: Production, Constraints, Experiments

LSP	interaction	production	constraints
$\tilde{\chi}_1^0$	g, g'	WIMP	— cold
	weak	freeze out	

$$\Omega_{\tilde{\chi}_1^0} h^2 = m_{\tilde{\chi}_1^0} Y_{\tilde{\chi}_1^0}^{\mathrm{dec}} s(T_0) h^2/\rho$$

$\Omega_{\tilde{\chi}_1^0} = \Omega_{\mathrm{DM}}$ is possible!!!



$\tilde{\chi}_1^0$ LSP Dark Matter: Production, Constraints, Experiments

LSP	interaction	production	constraints
$\tilde{\chi}_1^0$	g, g'	WIMP	— cold
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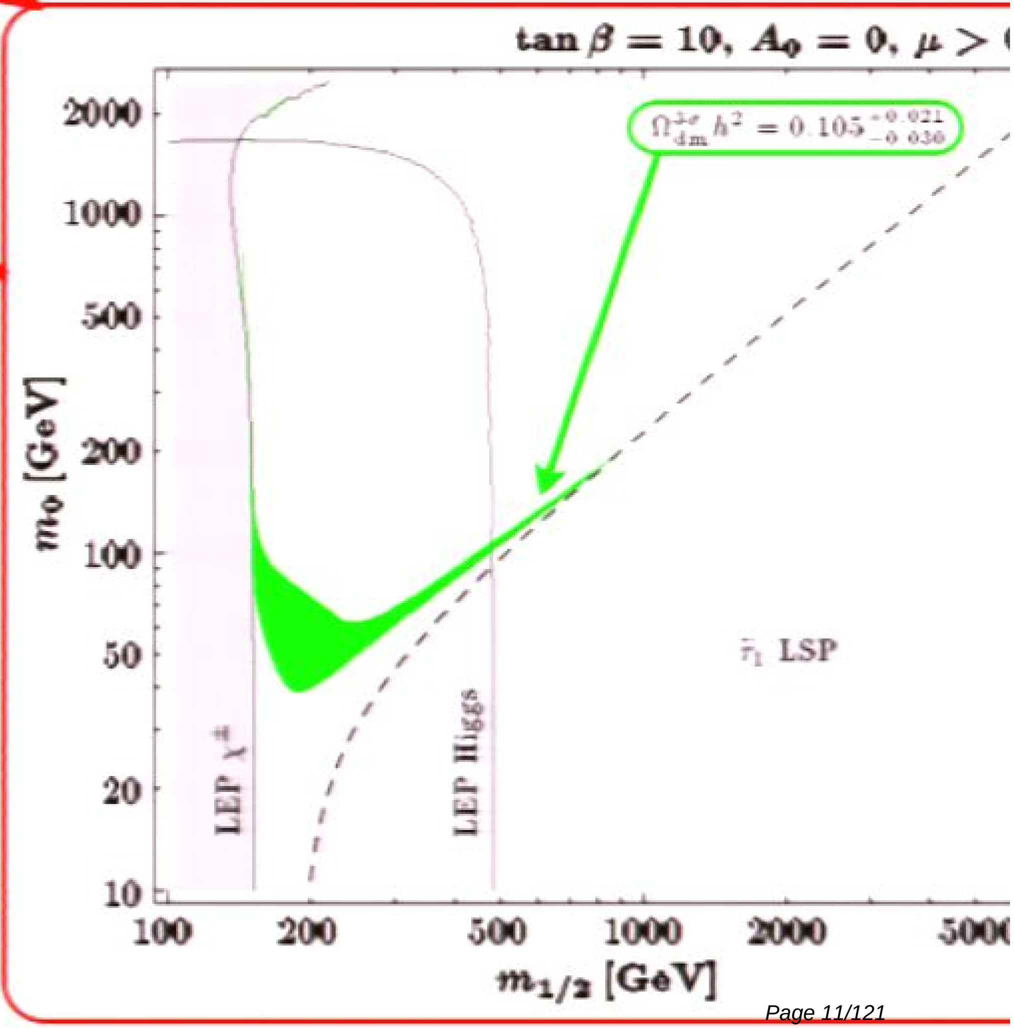


$$\boxed{\Omega_{\tilde{\chi}_1^0} = \Omega_{\rm DM} \text{ is possible!!!}}$$

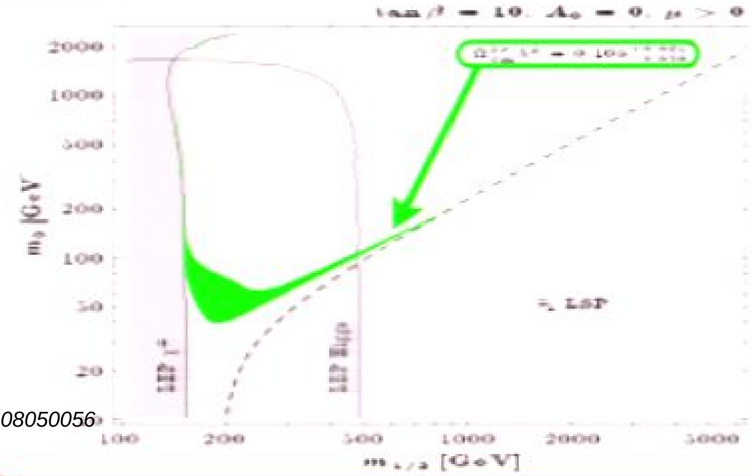
$\tilde{\chi}_1^0$ LSP Dark Matter: Production, Constraints, Experiments

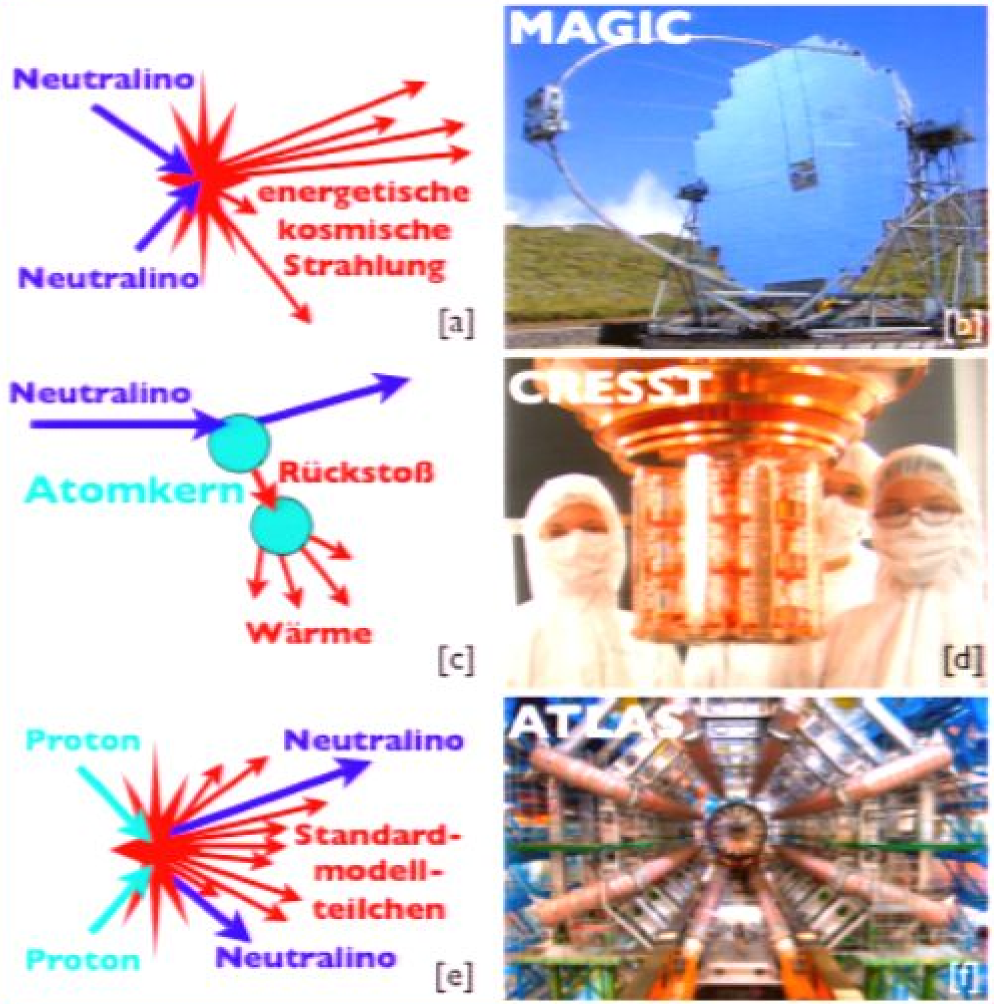
LSP interaction production constraints experiments

$\tilde{\chi}_1^0$ g, g' WIMP ← cold

weak freeze out

$\Omega_{\tilde{\chi}_1^0} = \Omega_{\mathrm{DM}}$ is possible!!!





promising experimental prospects

Supersymmetric Dark Matter Candiates

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

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

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)

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

gravitino

gauge boson

Planck scale

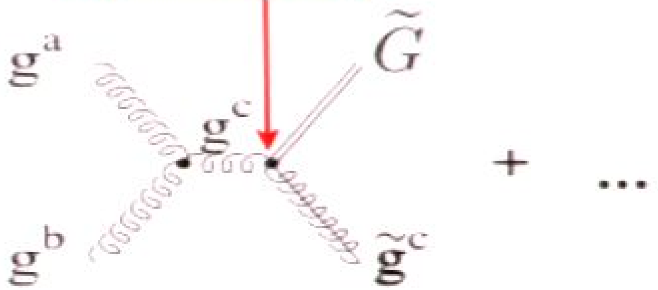
gaugino

LSP Dark Matter: Production, Constraints, Experiments

LSP	interaction	production	constraints	experiments
$\tilde{\chi}_1^0$	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, ...)
$\tilde{G}$	$\left(\frac{p}{M_{Pl}}\right)^n$	therm. prod.	← cold	
	extremely weak	NLSP decays	← warm	
	$M_{Pl} = 2.44 \times 10^{18}$ GeV	...		

Very Early Hot Universe

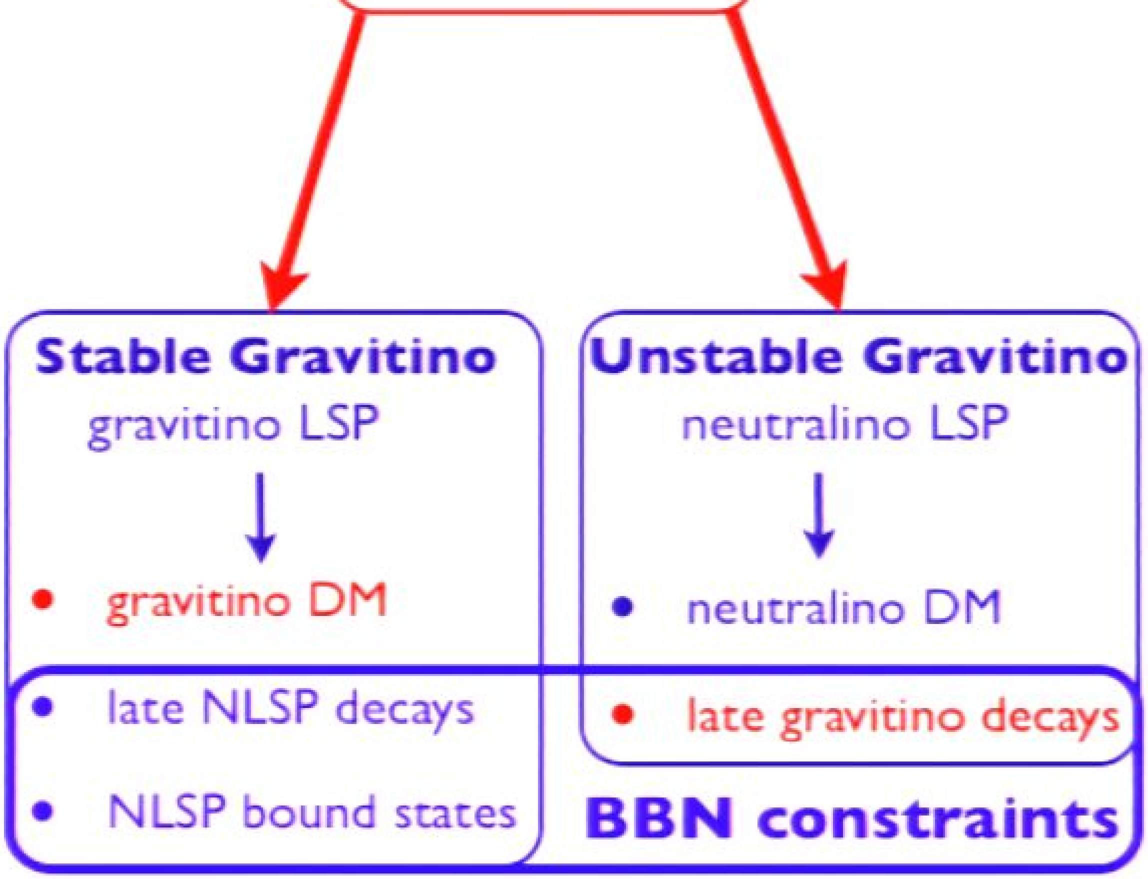
T ~ 10^7 GeV



[Ellis, Nanopoulos, Olive, Rey, '96]
[Bolz, Brandenburg, Buchmuller, '01]
[Pradler, FDS, '06]
[Rychkov, Strumia, '07] (gauge dep.)

Thermal Gravitino Production

gauge-field of
local SUSY
(supergravity)



Stable Gravitino

gravitino LSP

↓

- gravitino DM
- late NLSP decays
- NLSP bound states

Unstable Gravitino

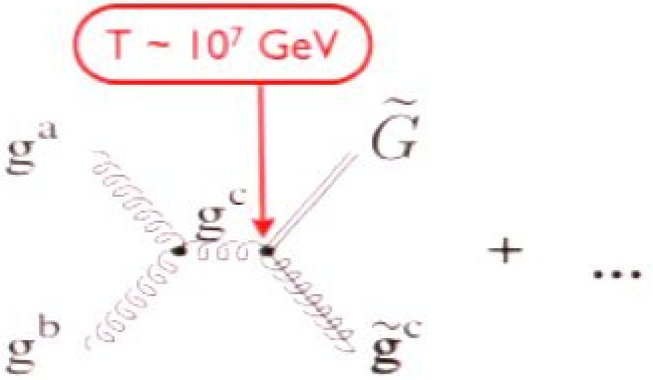
neutralino LSP

↓

- neutralino DM
- late gravitino decays

BBN constraints

Very Hot Early Universe



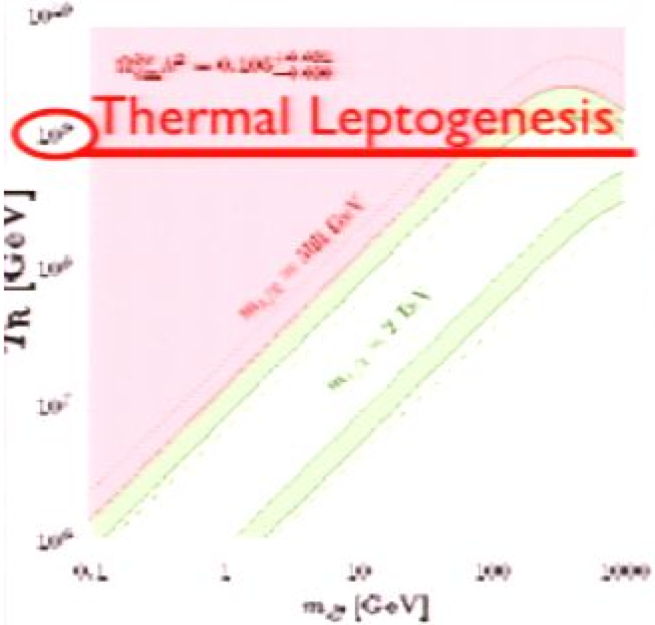
gauge-invariant treatment
(hard thermal loop resummation)

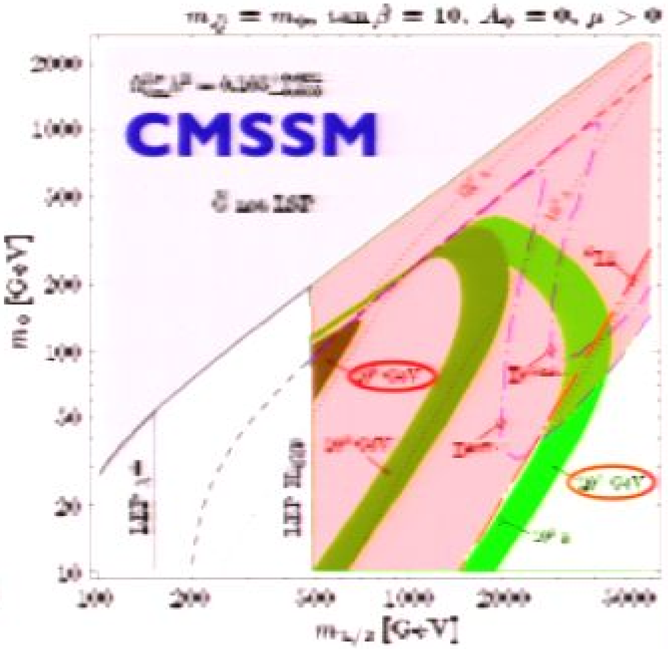
SUSY QCD
[Bolz, Brandenburg, Buchmüller, '01]

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

Upper Limits on the Reheating Temperature

Stable Gravitino





$\Omega_{\rm DM}$ **constraint for gravitino DM**

[Moroi, Murayama, Yamaguchi, '93;

...

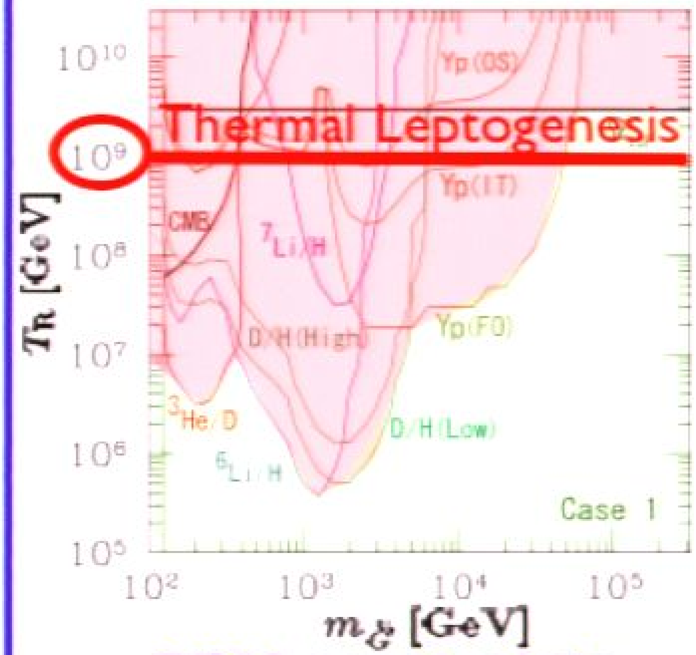
Pradler, Steffen, '07]

+ BBN constraints

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

[Pradler, Steffen, arXiv:0710.2213]

Unstable Gravitino



BBN constraints

+ $\Omega_{\rm DM}$ **constraint for neutralino DM**

[Kohri, Moroi, Yotsuyanagi, '05]

Thermal Leptogenesis requires T >10⁹ GeV

LSP Dark Matter: Production, Constraints, Experiments

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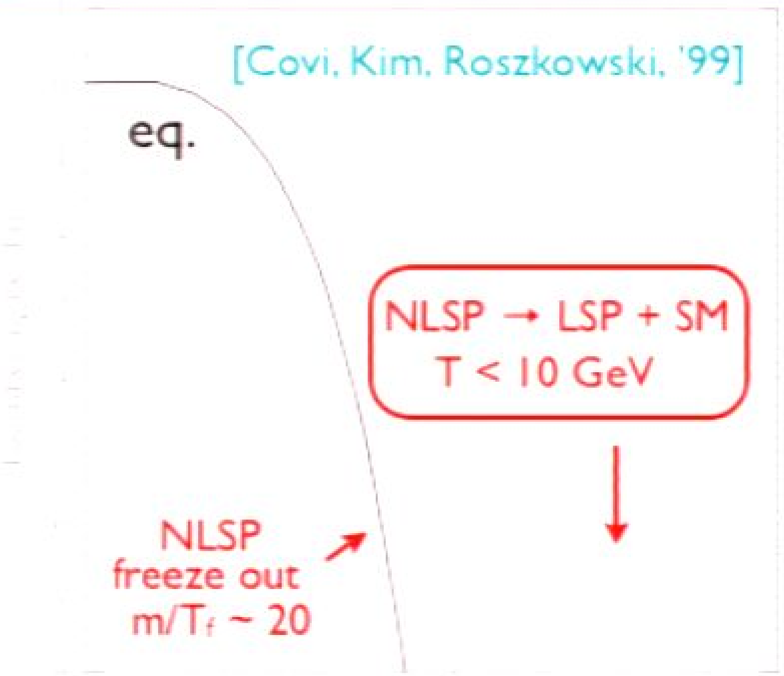
$\tilde{G}$	$\left(\frac{p}{M_{Pl}}\right)^n$	therm. prod.	← cold	
	extremely weak	NLSP decays	← warm	
	$M_{Pl} = 2.44 \times 10^{18}$ GeV	...		

NLSP Candidates

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



[Covi, Kim, Roszkowski, '99]

NLSP → LSP + SM
T < 10 GeV

NLSP
freeze out
$m/T_f \sim 20$

LSP Dark Matter: Production, Constraints, Experiments

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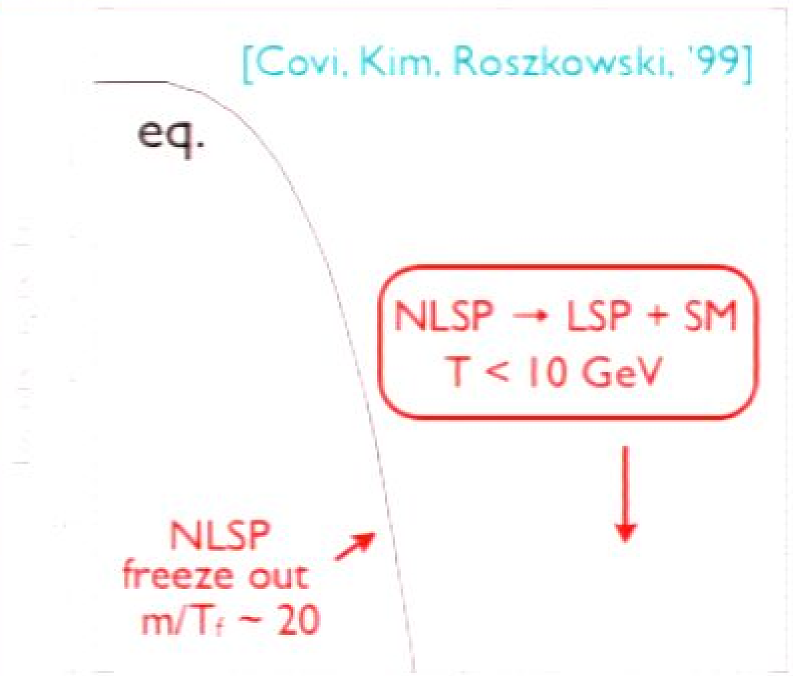

[Covi, Kim, Roszkowski, '99]

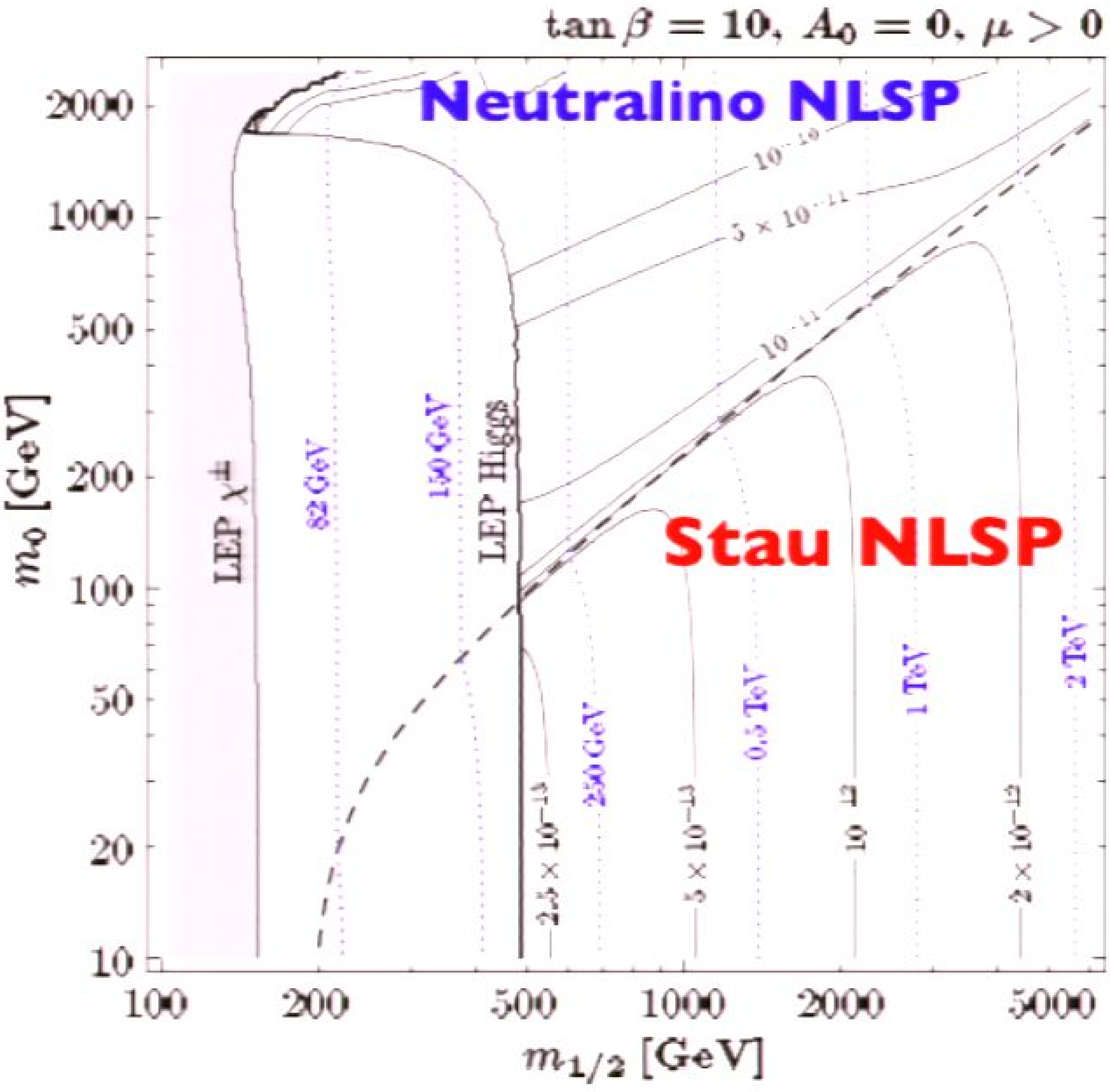
NLSP → LSP + SM
T < 10 GeV

NLSP freeze out $m/T_f \sim 20$

NLSP Candidates

electrically charged →

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


$\tan\beta = 10,\ A_0 = 0,\ \mu > 0$
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]
2000
1000
500
200
100
50
20
10
100
200
500
1000
2000
5000
$m_{1/2}$ [GeV]

LSP Dark Matter: Production, Constraints, Experiments

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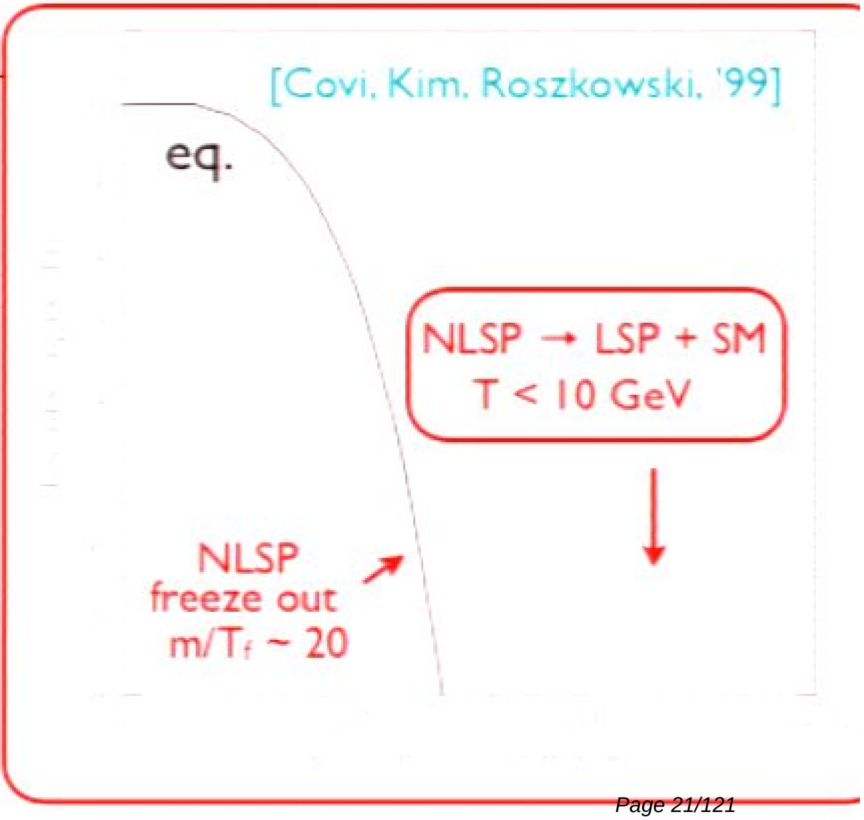

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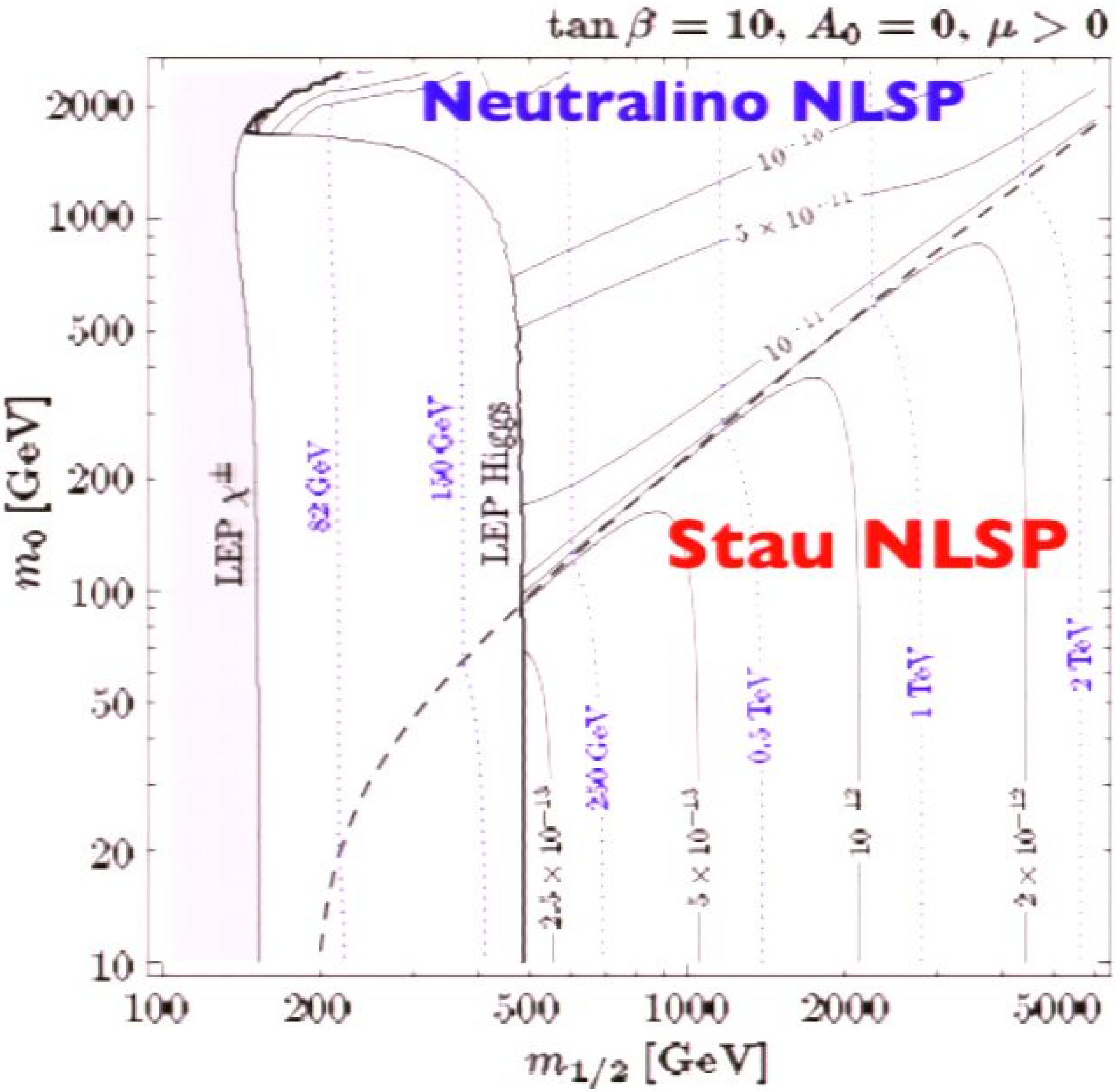
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Neutralino NLSP
Stau NLSP
m_0 [GeV]
$m_{1/2}$ [GeV]
2000
1000
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200
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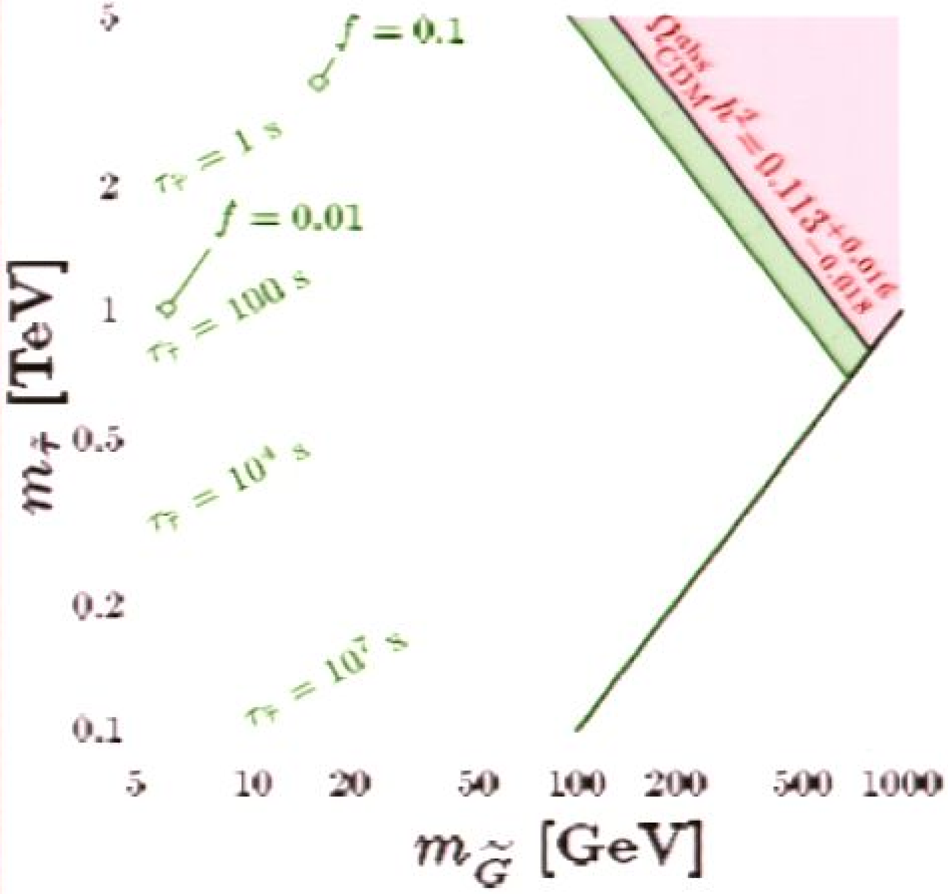
2000
5000
LEP $\chi^\pm$
82 GeV
150 GeV
LEP Higgs
250 GeV
0.5 TeV
1 TeV
2 TeV
10^{-10}
5×10^{-11}
10^{-11}
2.5×10^{-13}
5×10^{-13}
10^{-12}
2×10^{-12}

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



see also [Borgani, Masiero, Yamguchi, '96,
Asaka, Hamaguchi, Suzuki, '00, Ellis et al., '04,
Feng, Su, Takayama, '04]

[FDS, '06]

Constraints from Observ./Simul. of Cosmic Structures

Probe/Observable	$m_{\rm WDM}^{\rm min}$	$(v_{\rm FS}^{\rm rms,0})_{\rm WDM}^{\rm max}$	Ref.
Dwarf spheroidal galaxies	0.7 keV	0.06 km/s	[Dalcanton et al., '00]
Lyman-α forest at $z \simeq 3$	0.75 keV	0.05 km/s	[Narayanan et al., '00]
Lyman-α forest at $z \simeq (2-3)$	0.55 keV	0.08 km/s	[Viel et al., '05]
Supermassive black hole at $z \simeq 5.8$	0.5 keV	0.09 km/s	[Barkana et al., '01]
Cosmological reionization by $z \simeq 5.8$	0.75 keV	0.05 km/s	[Barkana et al., '01]
(Cosmological reionization at $z \simeq 17$	10 keV	0.002 km/s	[Yoshida et al., '03])

Collisionless CDM $\longrightarrow$ Too Much Power on Small Scales ($\lesssim 1$ Mpc)

- excess in the number of low mass halos
- overdensity of halo cores

[FDS, '06]

Free Streaming of Gravitinos from Stau NLSP Decays

☐ Comoving Free-Streaming Scale

$$\lambda_{\mathrm{FS}}^{\tau_{\tilde{\tau}} \ll t_{\mathrm{eq}}} \simeq \int_0^{t_{\mathrm{eq}}} dt \, \frac{v(t)}{a(t)}$$

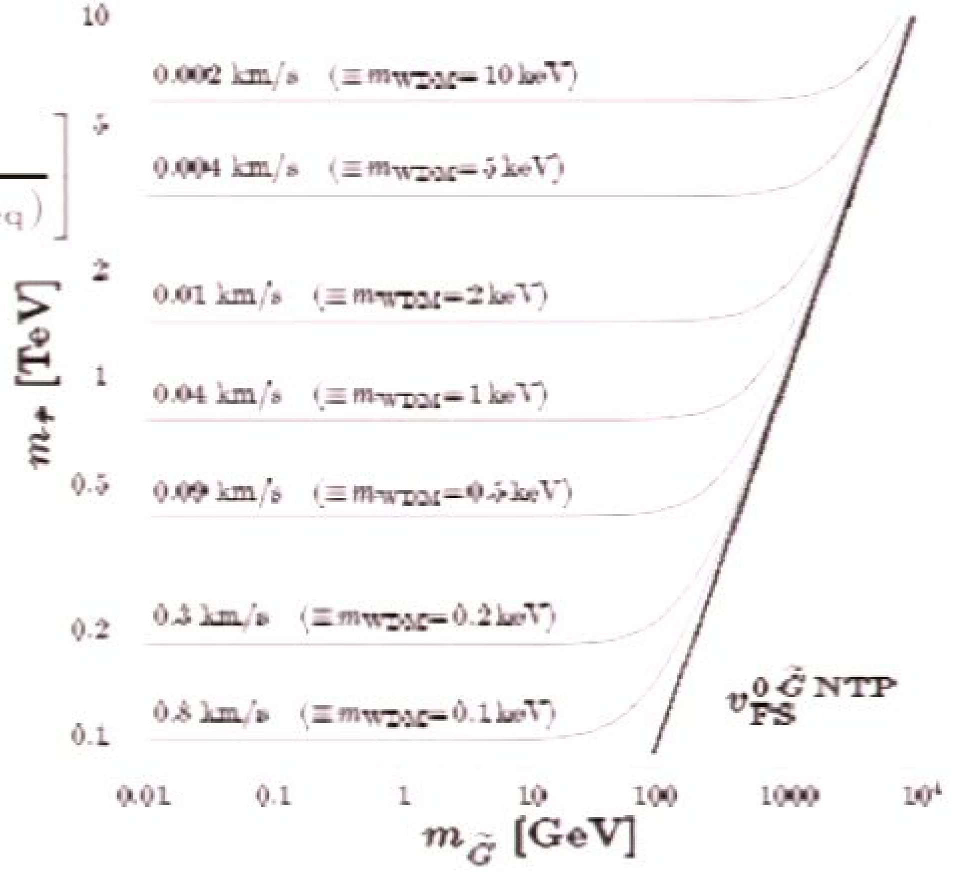
$$= v_0 t_{\mathrm{eq}} (1+z_{\mathrm{eq}})^2 \ln\left[\sqrt{1+\frac{1}{v_0^2(1+z_{\mathrm{eq}})^2}} + \frac{1}{v_0(1+z_{\mathrm{eq}})}\right]$$

☐ Present Free-Streaming Velocity

$$v_{\mathrm{FS}}^{0\,\tilde{G}\,\mathrm{NTP}} = 0.024\,\frac{\mathrm{km}}{\mathrm{s}} \left(\frac{g_*(t_i = \tau_{\tilde{\tau}})}{3.36}\right)^{1/4} \times \left(\frac{m_{\tilde{\tau}}}{1\ \mathrm{TeV}}\right)^{-3/2} \left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}}^2}\right)^{-1}$$

$$\boxed{|\vec{p}_{\tilde{G}}(t_i)| = \frac{m_{\tilde{\tau}}^2 - m_{\tilde{G}}^2 - m_{\tau}^2}{2\, m_{\tilde{\tau}}}}$$

Present Velocity of Gravitinos from $\tilde{\tau} \to \tau \tilde{G}$



Collisionless WDM ⟶ Solution of Small Scale ($\lesssim$ 1 Mpc) Structure Problems

[Borgani et al., '96; Kaplinghat, '05; Cembranos et al., '05; Jedamzik et al., '05]

Free Streaming of Gravitinos from Thermal Production

☐ Comoving Free-Streaming Scale

$$\lambda_{\rm FS}^{t_i \ll t_{\rm eq}} \simeq \int_0^{t_{\rm eq}} dt\, \frac{v(t)}{a(t)} = v_0\, t_{\rm eq}\, (1+z_{\rm eq})^2 \ln\left(\sqrt{1+\frac{1}{v_0^2\,(1+z_{\rm eq})^2}} + \frac{1}{v_0\,(1+z_{\rm eq})}\right)$$

☐ Present Free-Streaming Velocity $\quad v_0 = v_{\rm FS}^{\rm rms,0}$

- Gravitinos from Thermal Production

$$(v_{\rm FS}^{\rm rms,0})^{\widetilde{G}\,\rm TP} = 5.8 \times 10^{-6}\, \frac{\rm km}{\rm s} \left(\frac{10\ \rm MeV}{m_{\widetilde{G}}}\right) \left(\frac{230}{g_{*S}(T_R)}\right)^{1/3}$$

- Warm Dark Matter — Hot Thermal Relics

$$(v_{\rm FS}^{\rm rms,0})_{\rm WDM} = 0.77\, \frac{\rm km}{\rm s} \left(\frac{\Omega_{\rm WDM} h^2}{0.113}\right)^{1/3} \left(\frac{100\ \rm eV}{m_{\rm WDM}}\right)^{4/3}$$

$$\Omega_{\rm WDM} h^2 = 0.115 \left(\frac{100}{g_{*S}(T_{\rm f})}\right) \left(\frac{m_{\rm WDM}}{100\ \rm eV}\right)$$

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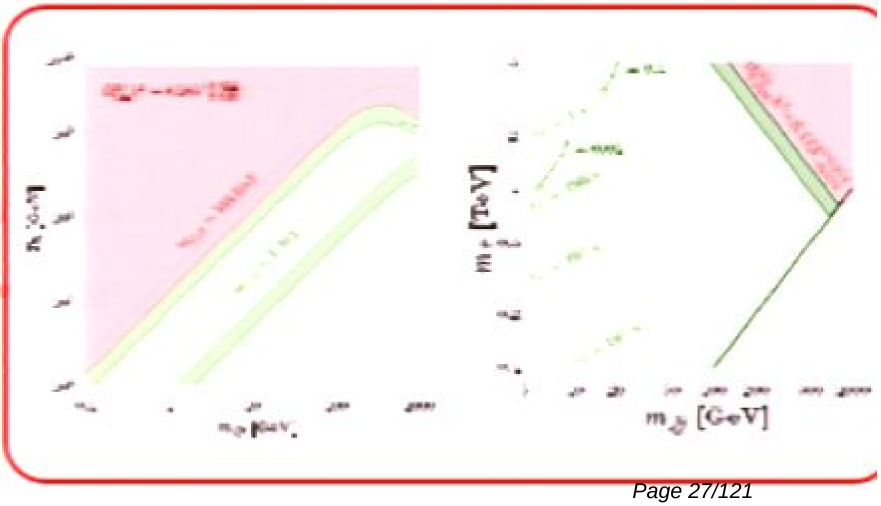
	extremely weak	NLSP decays	← warm	
	$M_{Pl} = 2.44 \times 10^{18}$ GeV	...		



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

is possible!!!

LSP Dark Matter: Production, Constraints, Experiments

LSP	interaction	production	constraints	experiments
$\tilde{\chi}_1^0$	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, ...)
$\tilde{G}$	$\left(\frac{p}{M_{Pl}}\right)^n$	therm. prod.	← cold	
	extremely weak	NLSP decays	← warm	
			BBN	
			CMB	
			γ rays	

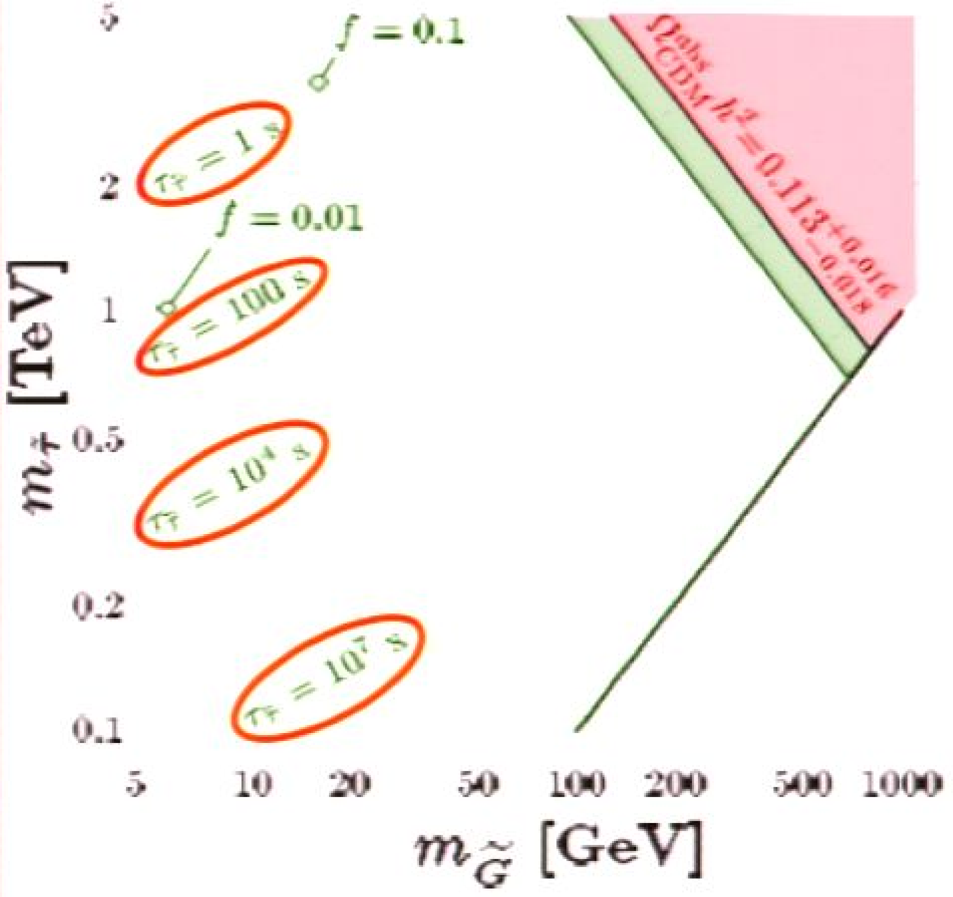
Can we probe Gravitino DM in experiments?

Signatures of Gravitinos in Experiments

- Direct Detection of $\widetilde{G}$
- Direct Production of $\widetilde{G}$

long-lived NLSP

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

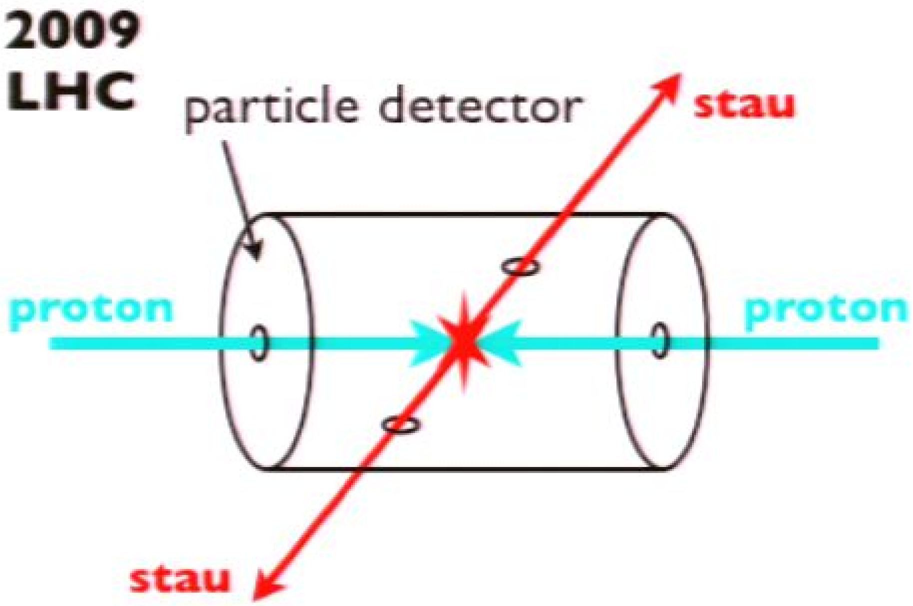


Signatures of Gravitinos in Experiments

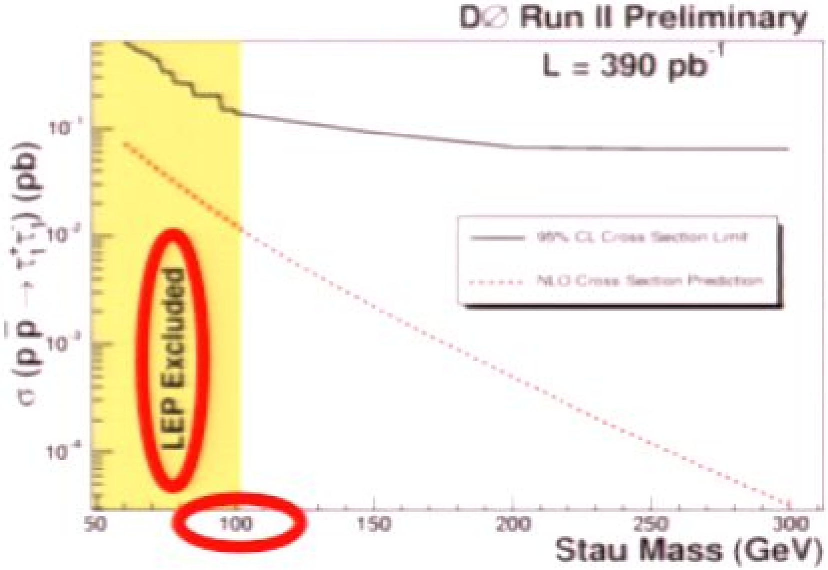
- Direct Detection of $\widetilde{G}$
- Direct Production of $\widetilde{G}$

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

* "stable" charged sparticles

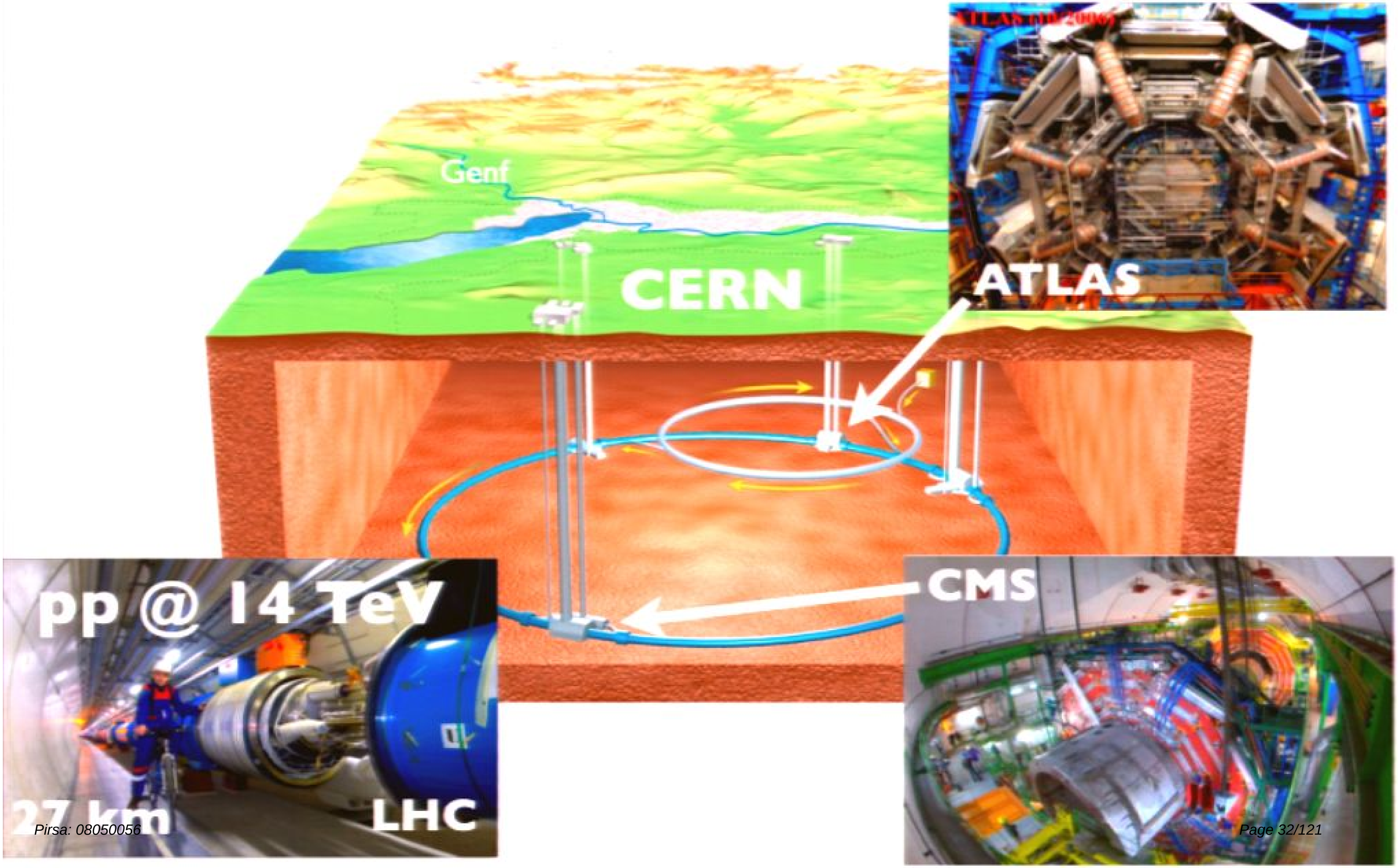


Tevatron

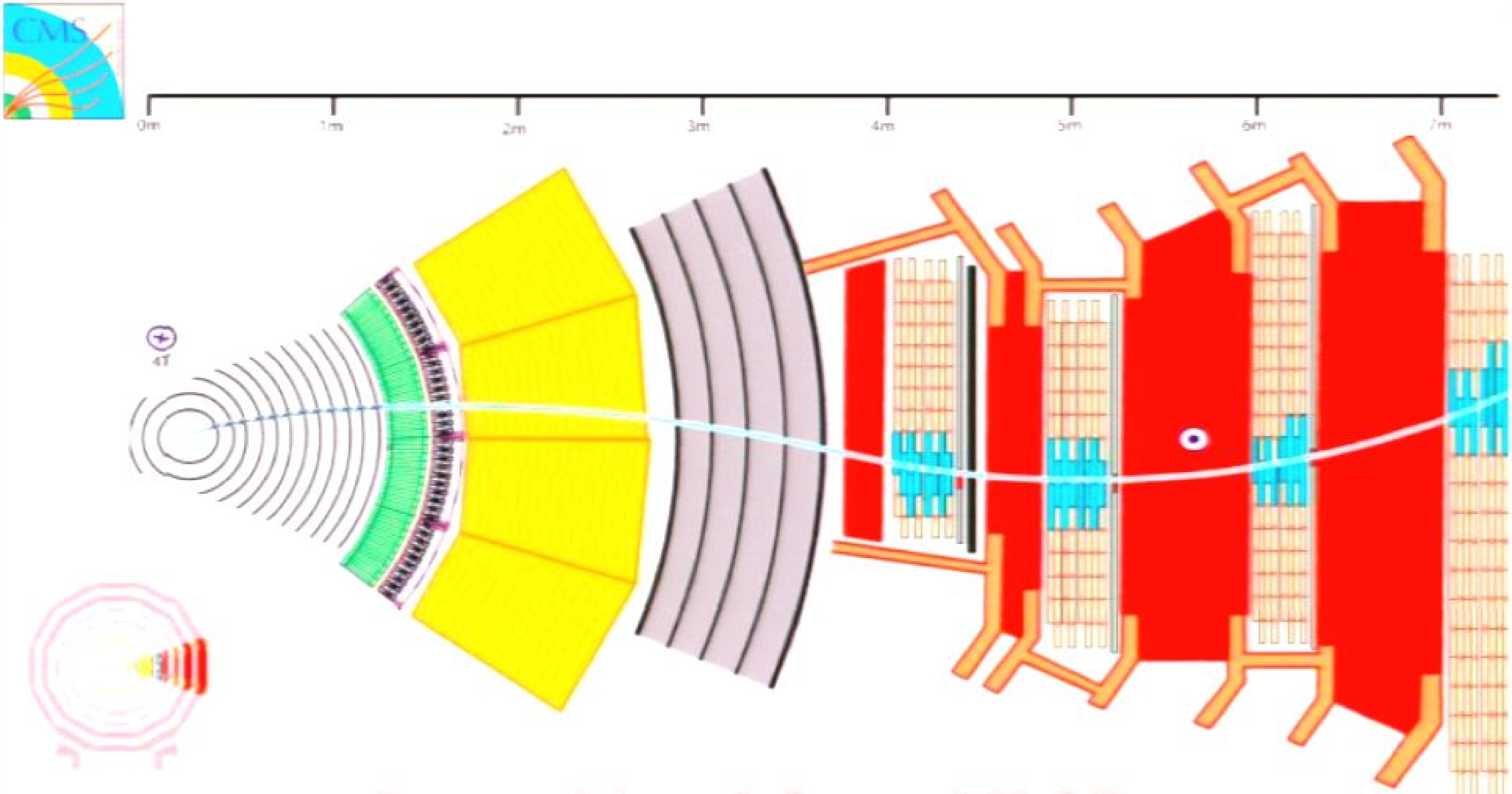


[from Gershtein's Talk, SUSY2007]

The Large Hadron Collider



“Stable” Charged Massive Particle @ LHC



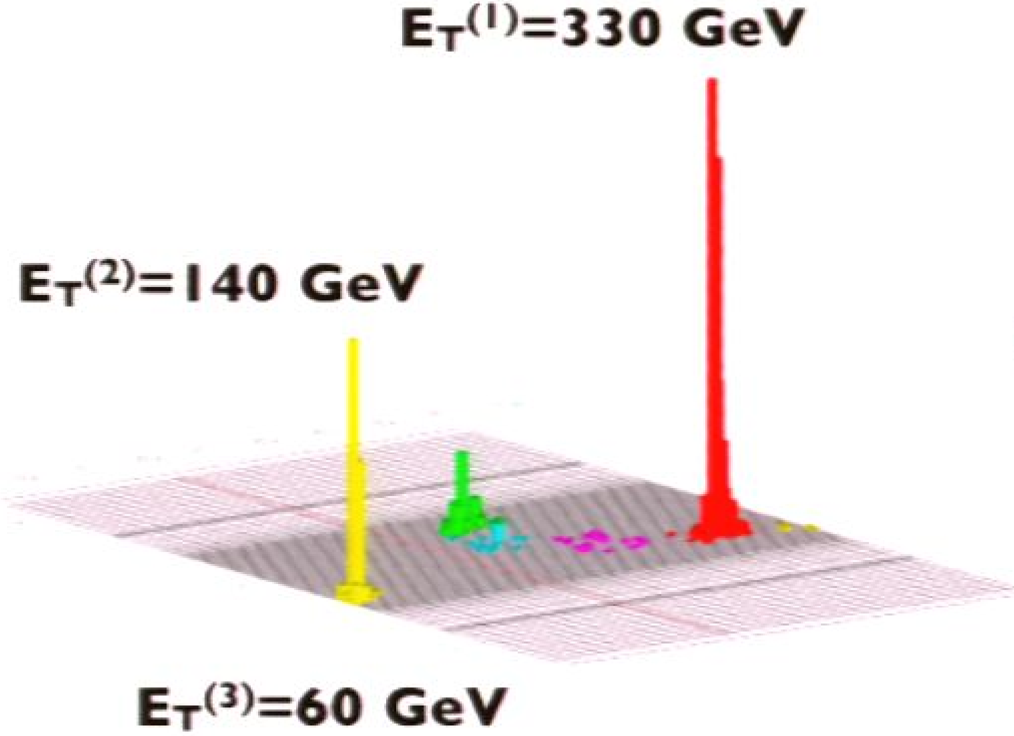
Long-Lived Stau NLSP

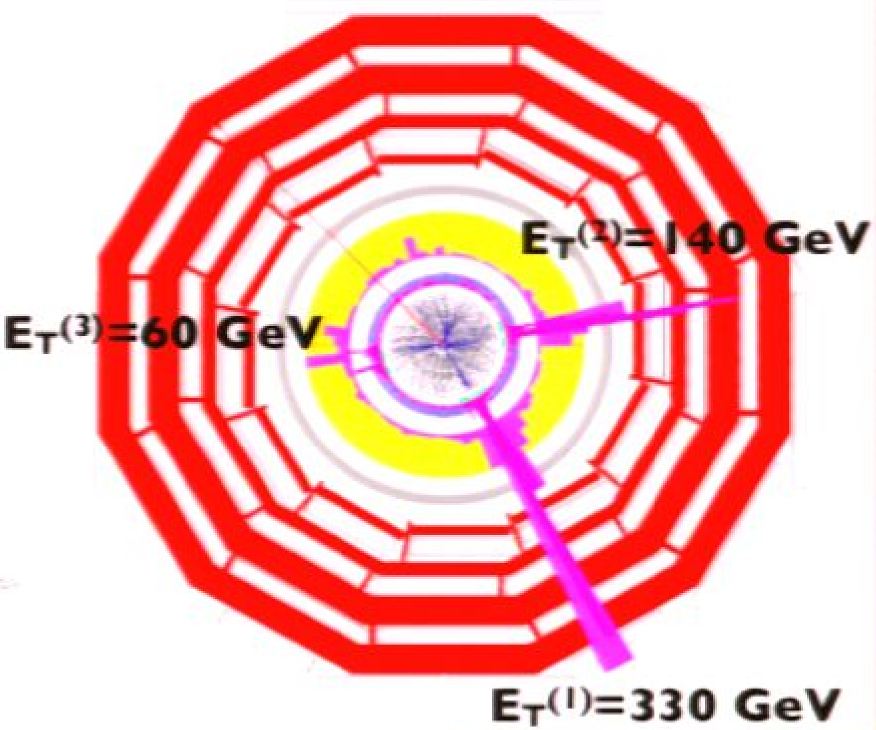
[from P. Zalewski's Talk, SUSY 2007]

For comparison ...

Neutralino Dark Matter Production @ CMS

$E_T^{missing}=360$ GeV

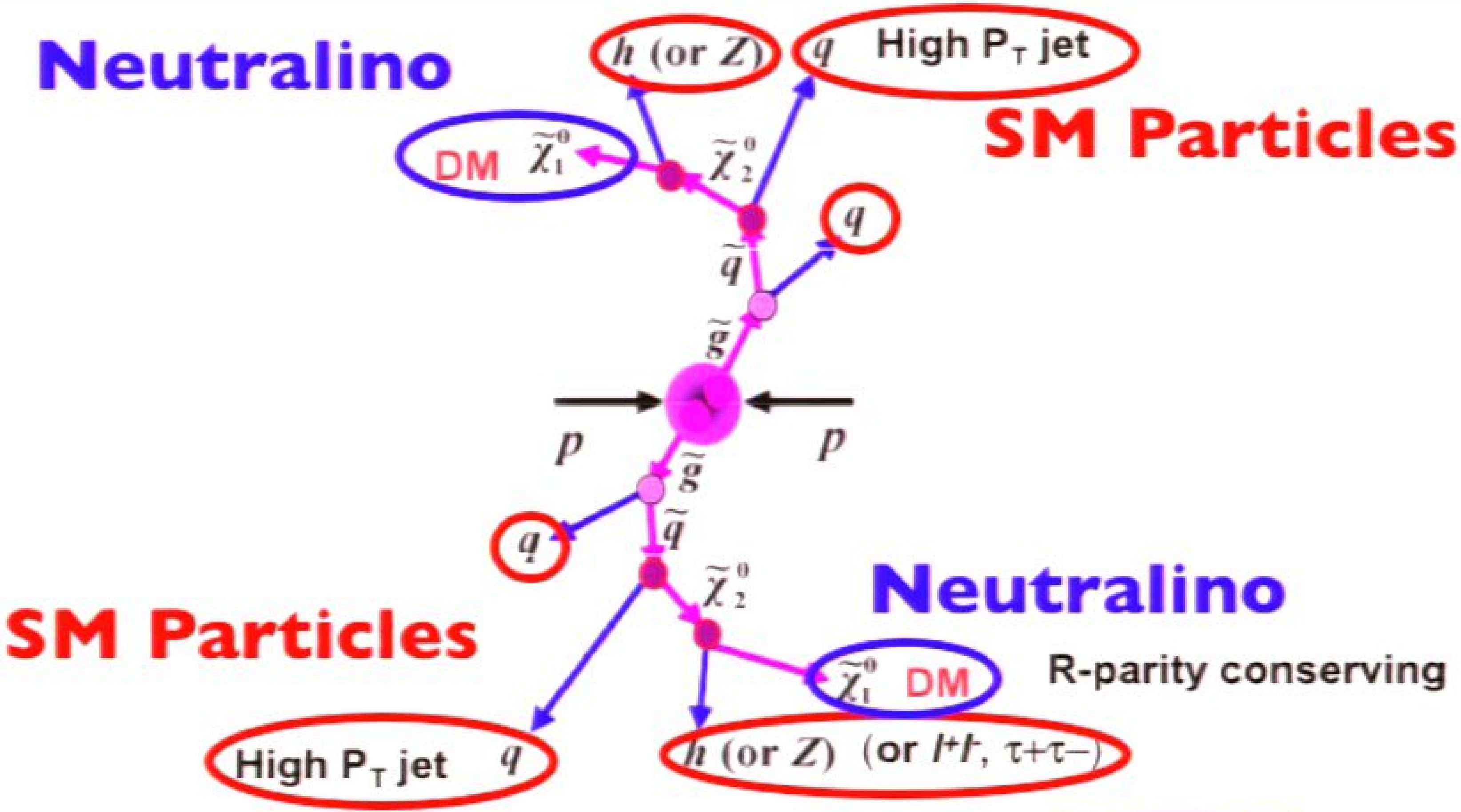




Neutralino LSP Pair

[from M. Tytgat's Talk, SUSY 2007]

Neutralino DM Production at the LHC



The signal : jets + leptons + missing E_T

[from B. Dutta's Talk, SUSY 2007]

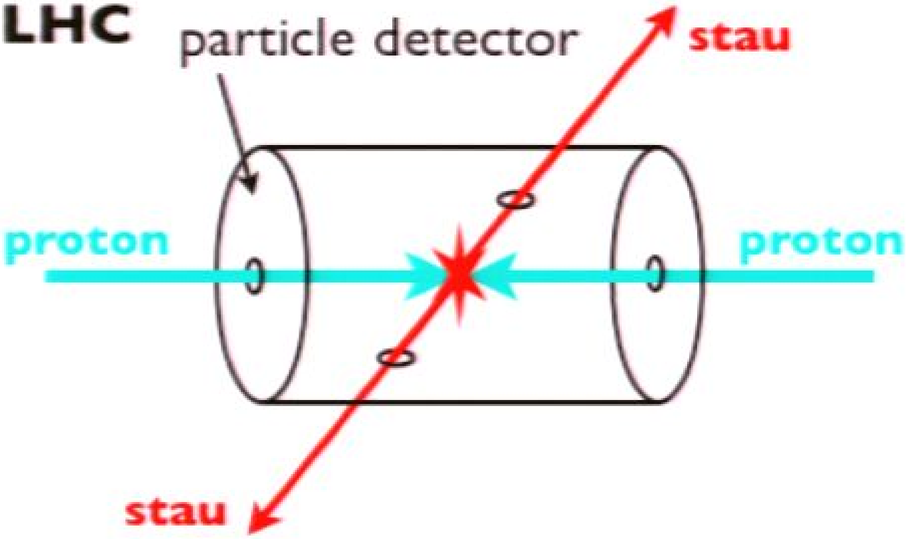
Signatures of Gravitinos in Experiments

- Direct Detection of $\widetilde{G}$

- Direct Production of $\widetilde{G}$

* "stable" charged sparticles

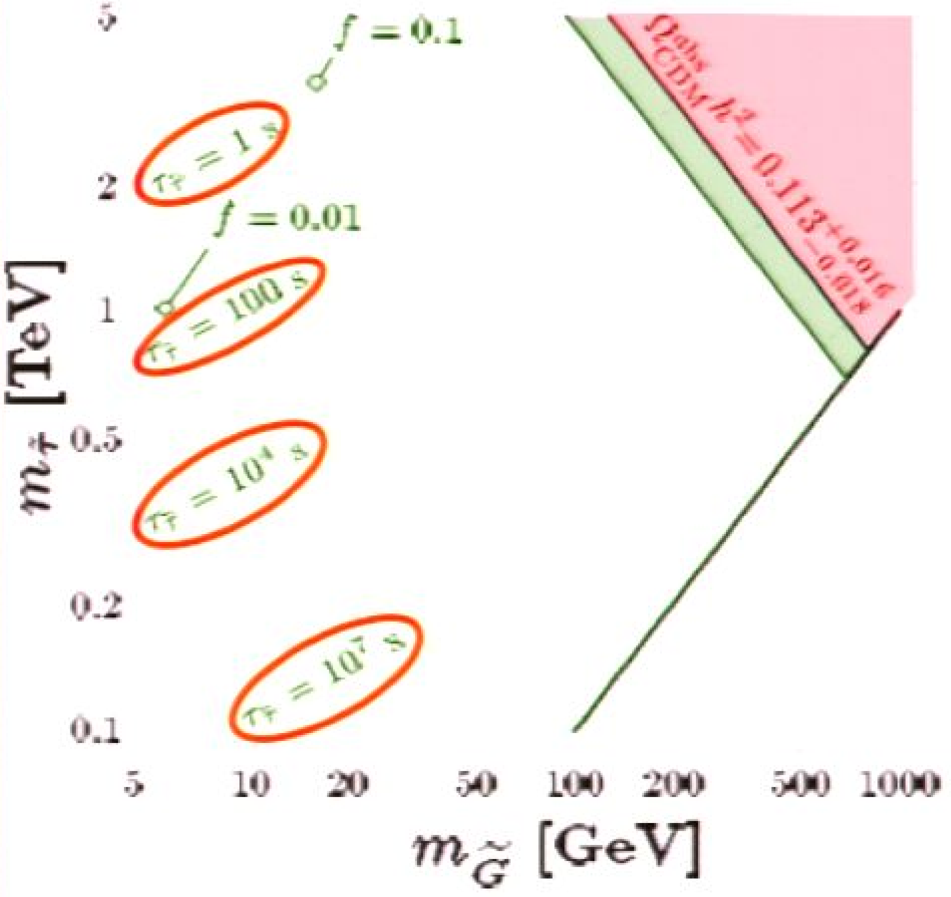
2009
LHC



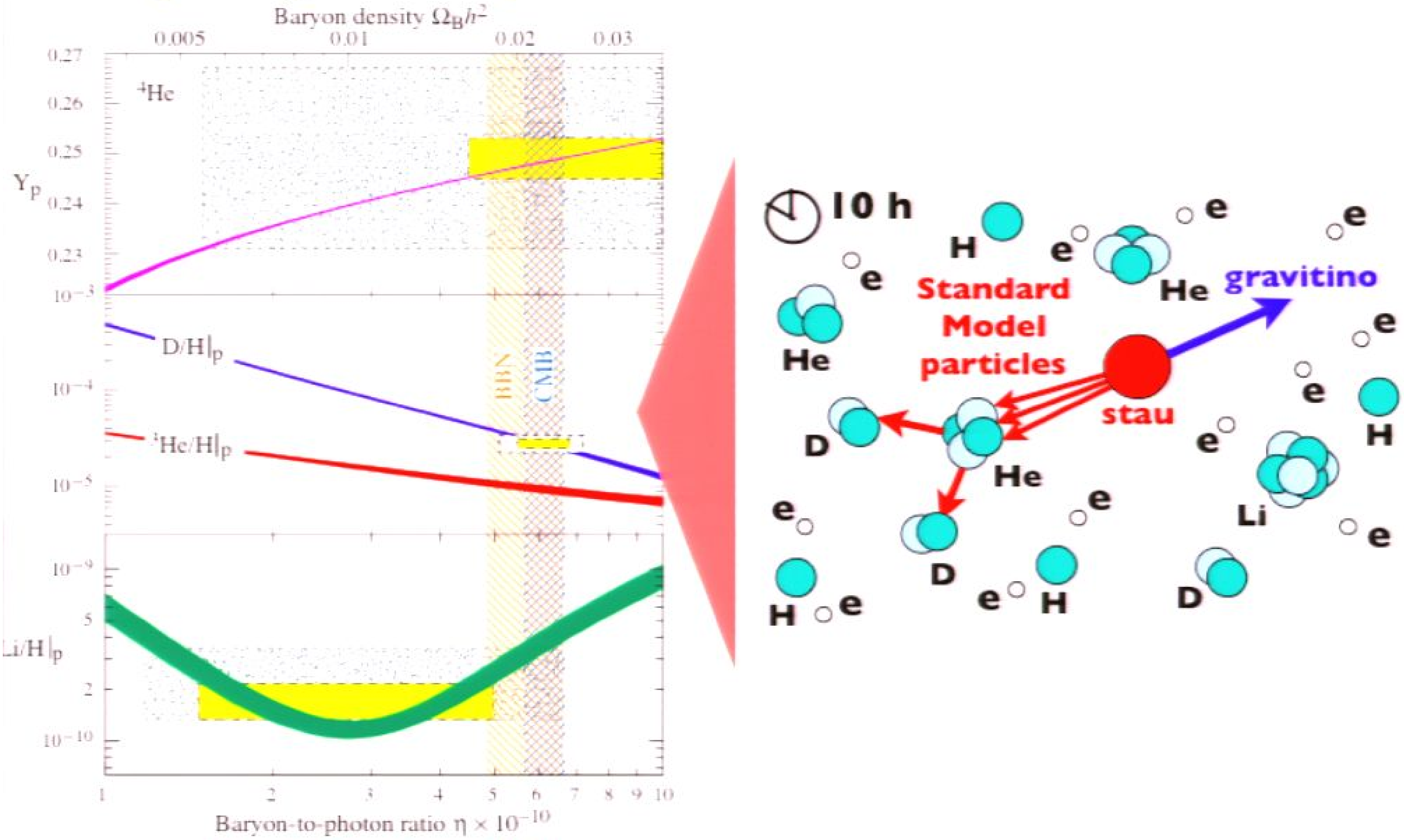
The signal:
jets + leptons
+ 2 "stable" charged particles

long-lived NLSP

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

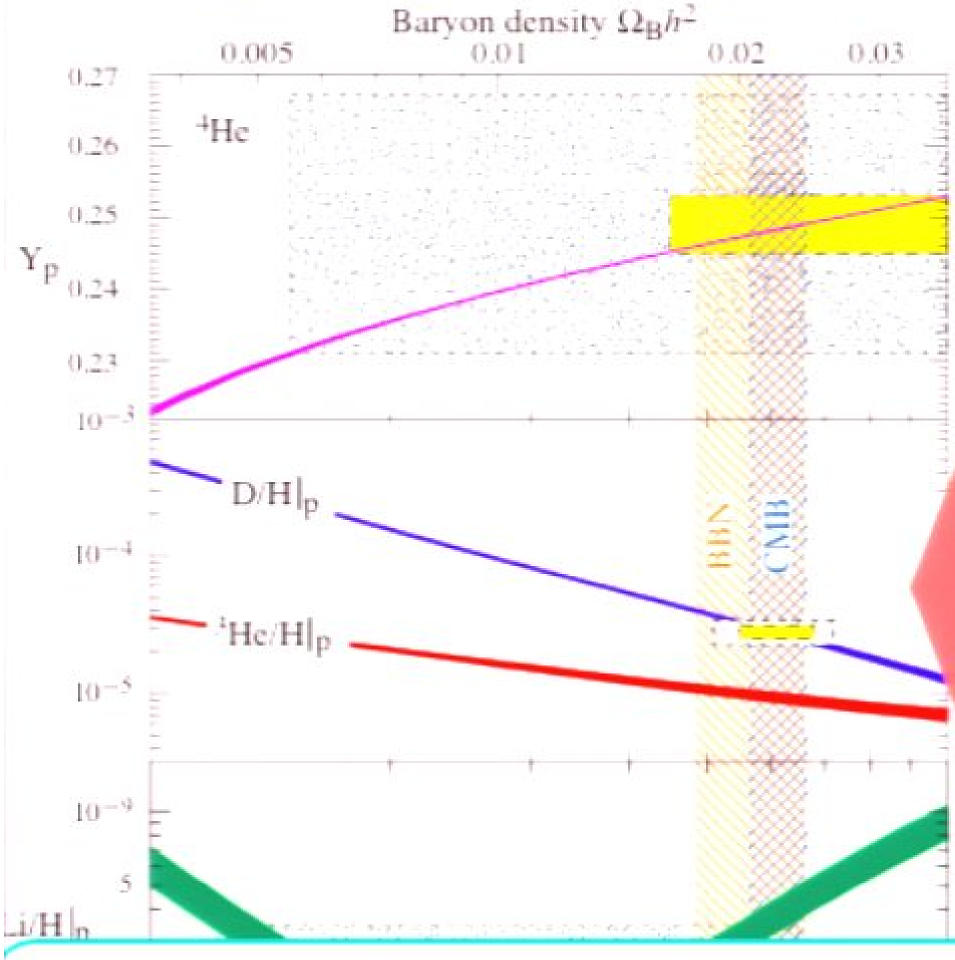


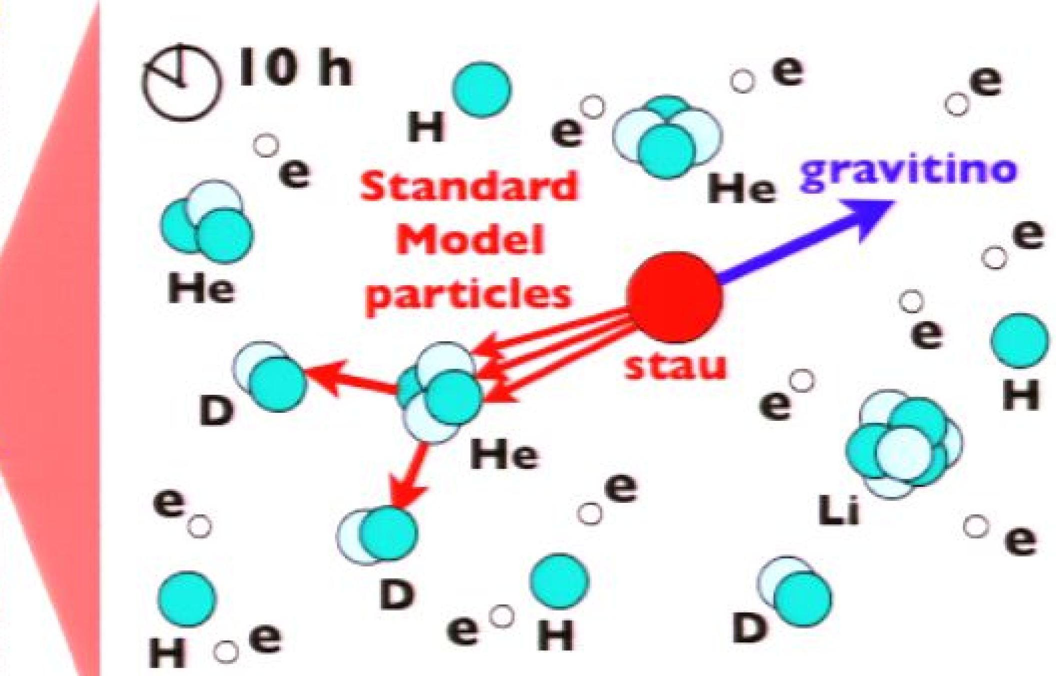
Big-Bang Nucleosynthesis



[Particle Data Book 2006]

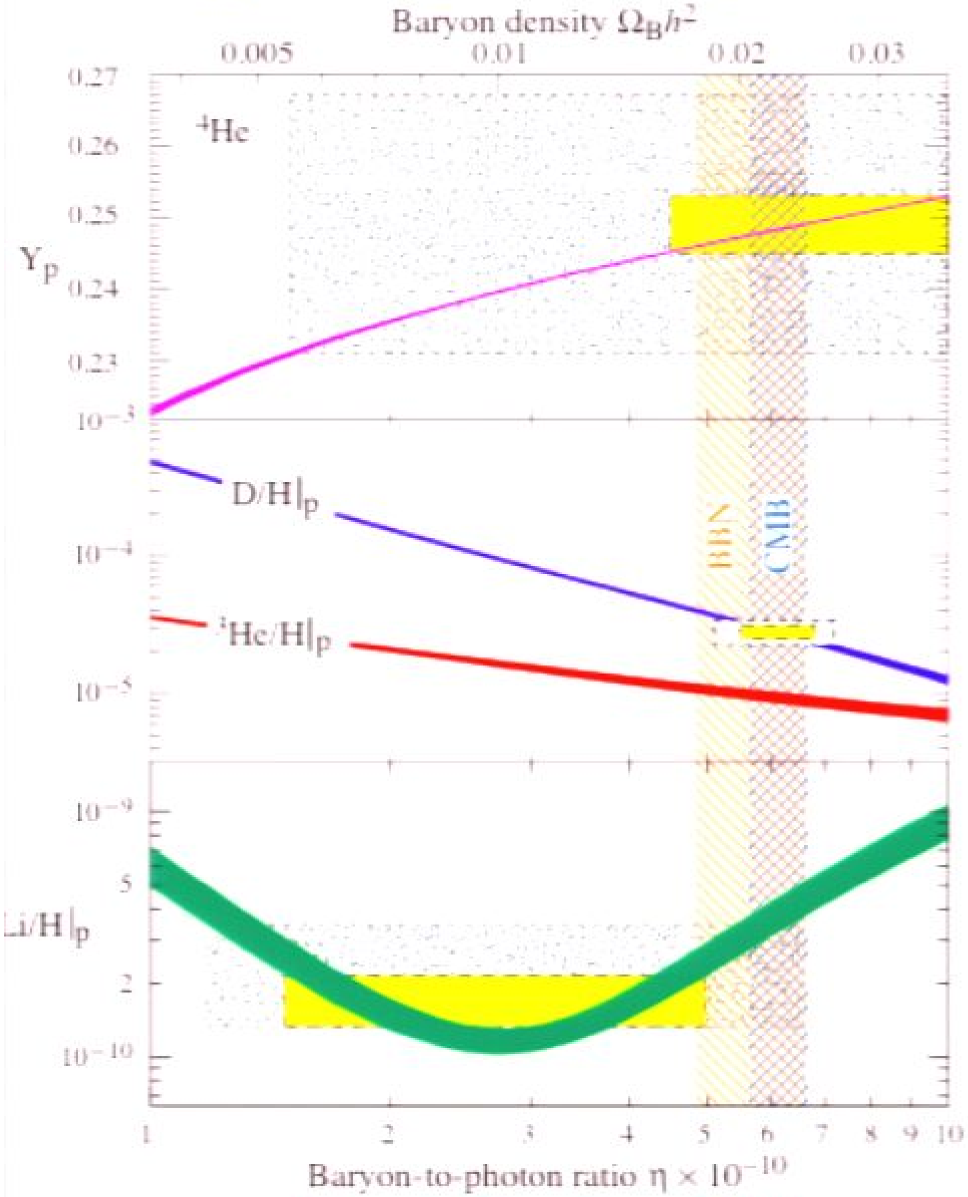
Big-Bang Nucleosynthesis



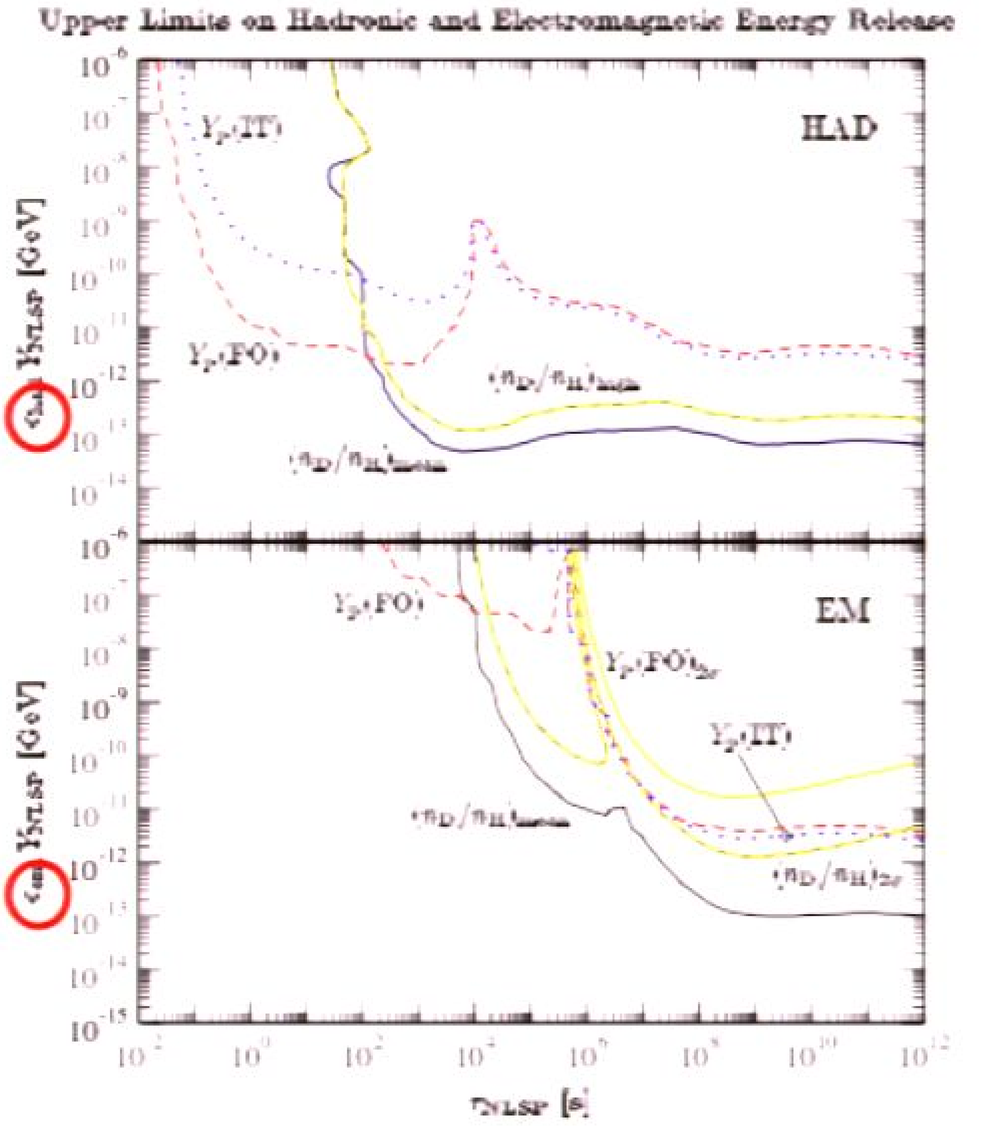


[..., Reno, Seckel, '88, Dimopoulos et al., '88 & '89, ... Ellis et al., '04, Jedamzik, '04, Kawasaki, Kohri, Moroi, '05, Feng, Su, Takayama, '04, Roszkowski et al., '05, Cerdeno et al., '06, FDS '06, Jedamzik, '06, ...]

Big-Bang Nucleosynthesis



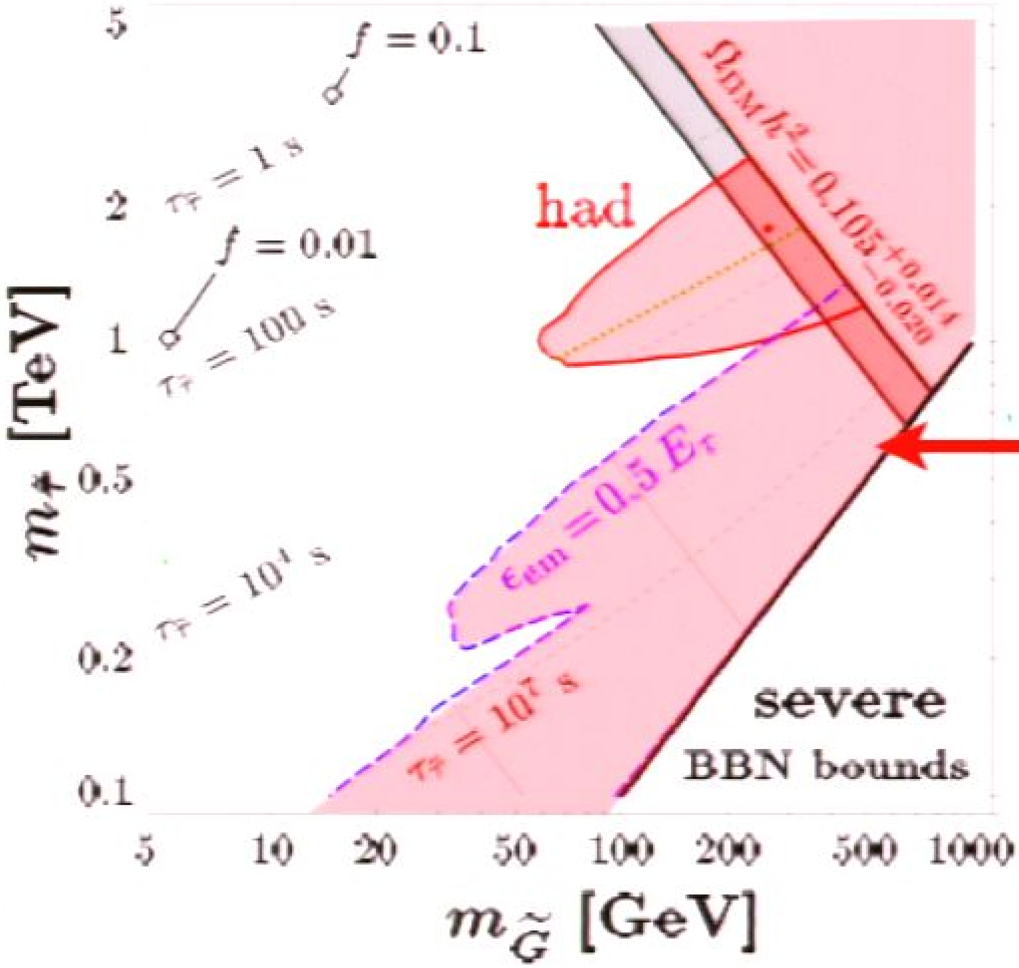
[Particle Data Book 2006]



[Kawasaki, Kohri, Moroi, '05; Cyburt et al., '03

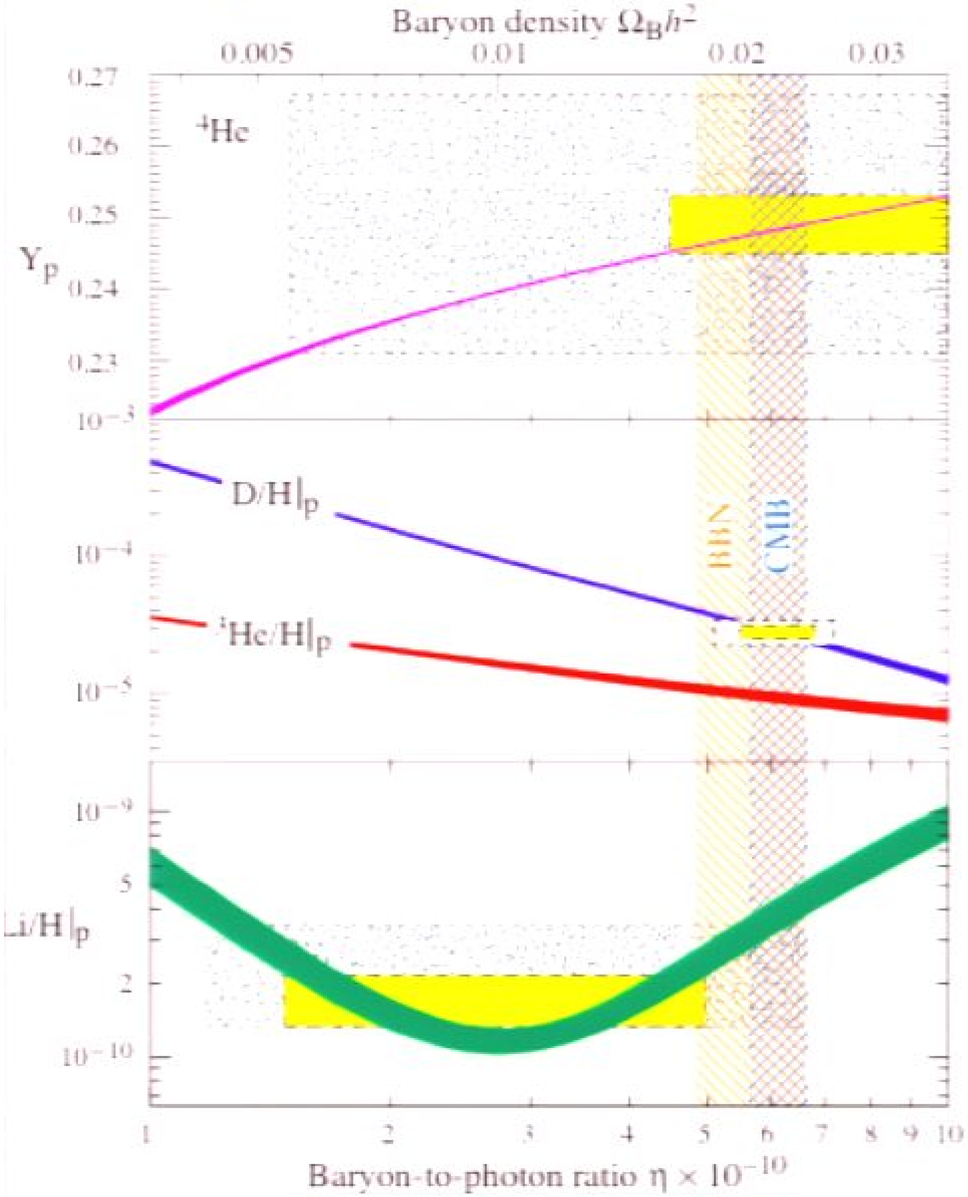
[FDS, '06]

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

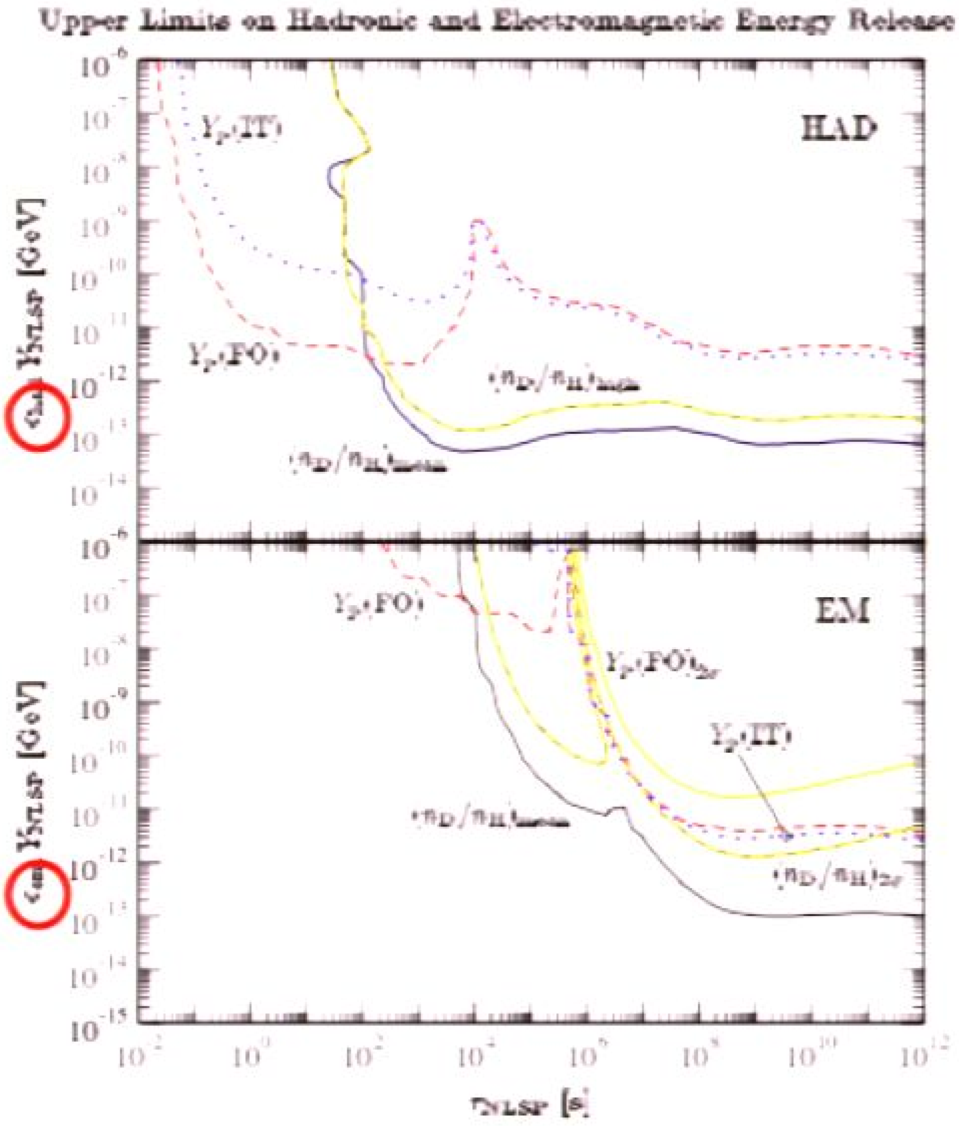


disfavored
by
cosmological
constraints

Big-Bang Nucleosynthesis



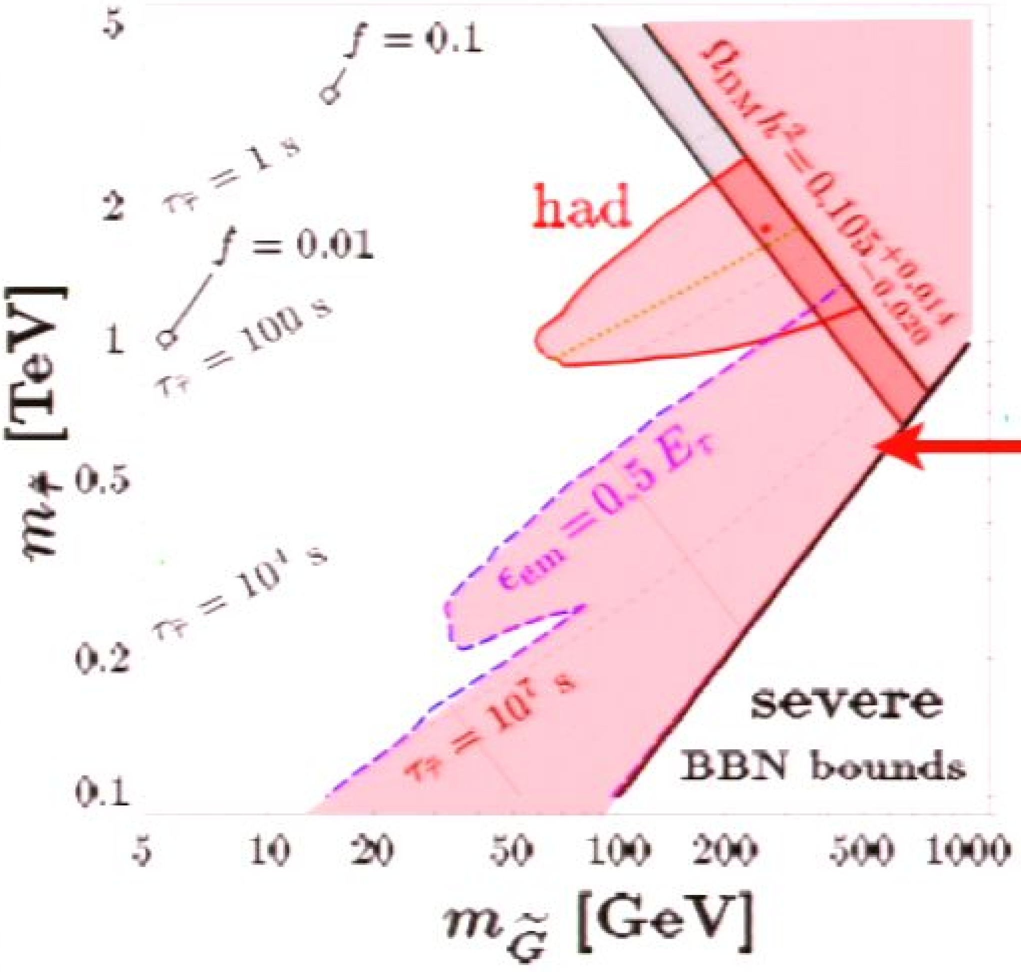
[Particle Data Book 2006]



[Kawasaki, Kohri, Moroi, '05; Cyburt et al., '03

[FDS, '06]

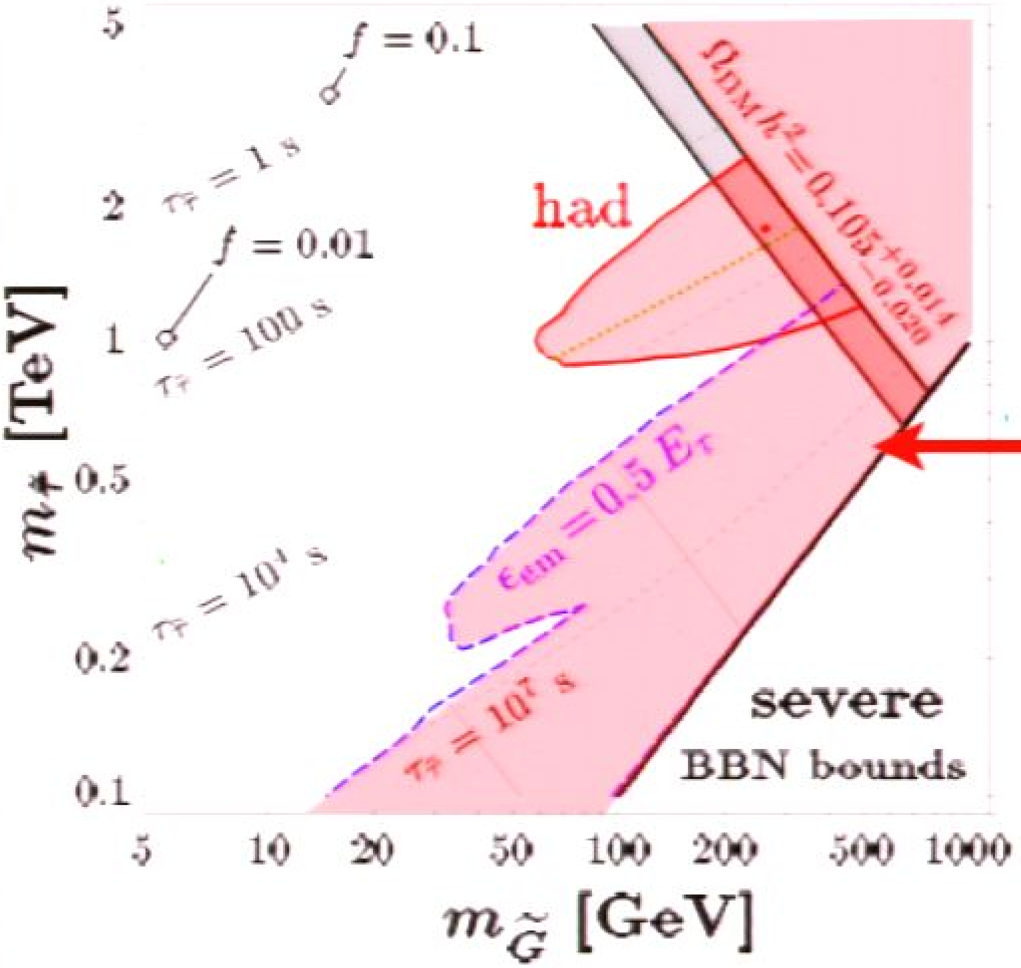
Cosmological Constraints — $\Omega_{\rm DM}$ & BBN



disfavored by cosmological constraints

[FDS, '06]

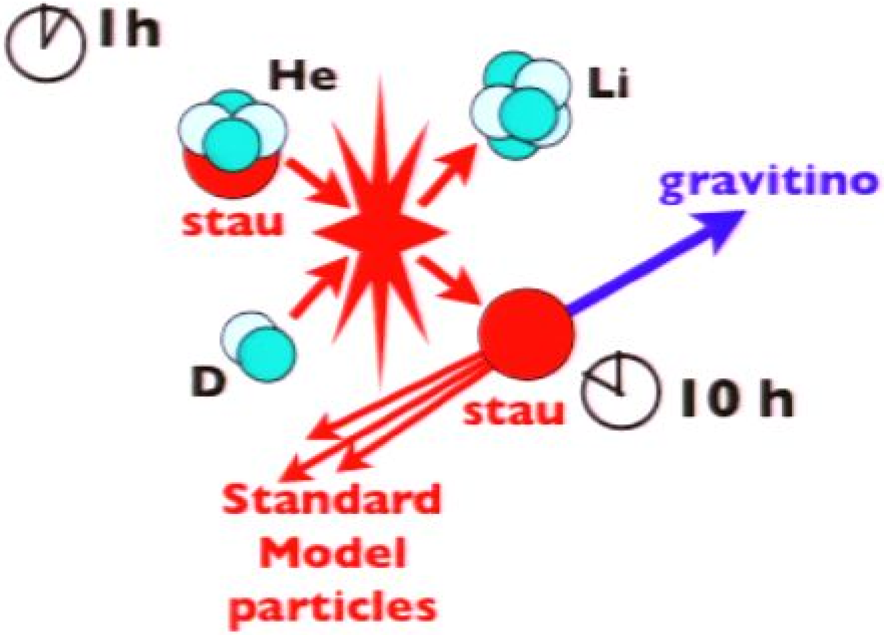
Cosmological Constraints — Ω_{DM} & BBN



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; ...]

[Takayama, '07; Pradler, FDS, arXiv:0710.2213]

Catalyzed Big Bang Nucleosynthesis (CBBN)

$$({}^4\mathrm{He}X^-) + \mathrm{D} \to {}^6\mathrm{Li} + X^-$$ [Pospelov, '06]

$$\frac{dY_{\mathrm{BS}}}{dt} = \langle\sigma_{\mathrm{r}}v\rangle sY_\delta - \Gamma_{X^-}Y_{\mathrm{BS}} - \langle\sigma_C v\rangle sY_{\mathrm{BS}}Y_{\mathrm{D}}.$$

$$\frac{dY_{X^-}}{dt} = -\langle\sigma_{\mathrm{r}}v\rangle sY_\delta - \Gamma_{X^-}Y_{X^-} + \langle\sigma_C v\rangle sY_{\mathrm{BS}}Y_{\mathrm{D}}.$$

$$\frac{dY_{^4\mathrm{He}}}{dt} = -\langle\sigma_{\mathrm{r}}v\rangle sY_\delta + \Gamma_{X^-}Y_{\mathrm{BS}}.$$

$$\frac{dY_{^6\mathrm{Li}}}{dt} = \langle\sigma_C v\rangle sY_{\mathrm{BS}}Y_{\mathrm{D}}.$$

$$\frac{dY_{\mathrm{D}}}{dt} = -\langle\sigma_C v\rangle sY_{\mathrm{BS}}Y_{\mathrm{D}}.$$

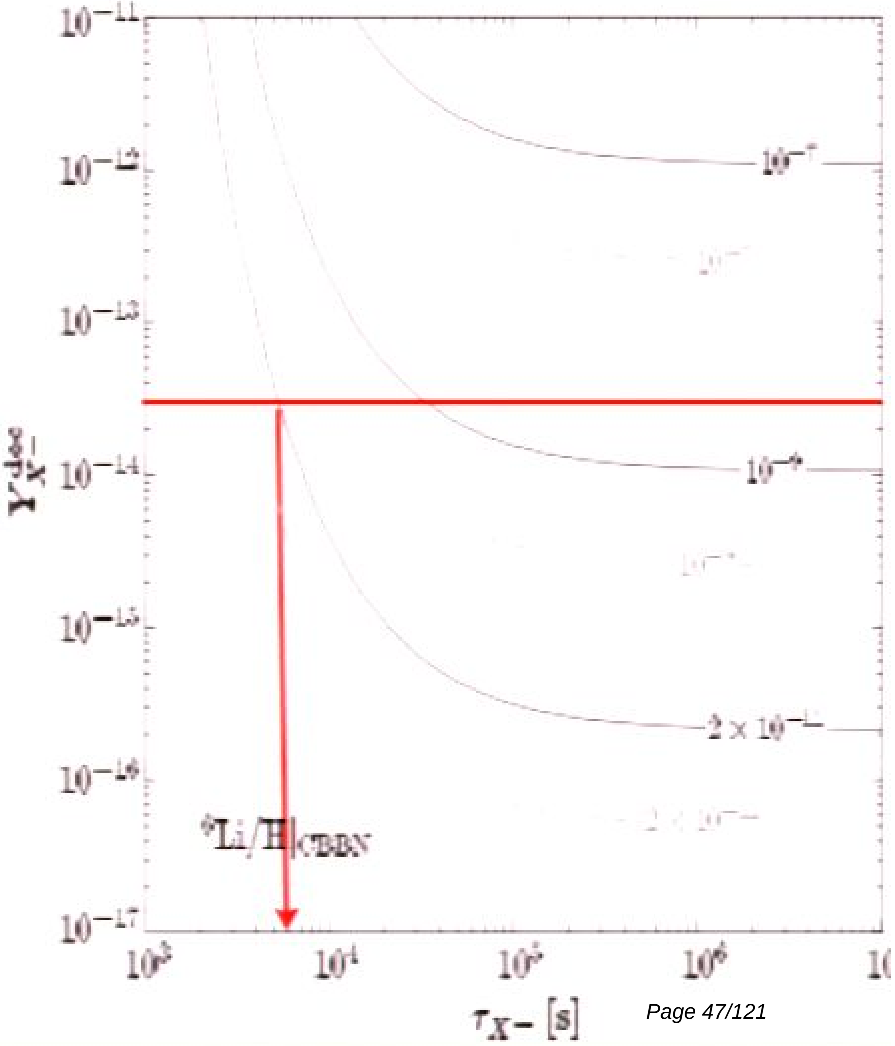
$$\langle\sigma_C v\rangle = 2.37 \times 10^8\,(1 - 0.34T_9)\,T_9^{-2/3}e^{-5.33T_9^{-1/3}}$$

[Hamaguchi et al., '07]

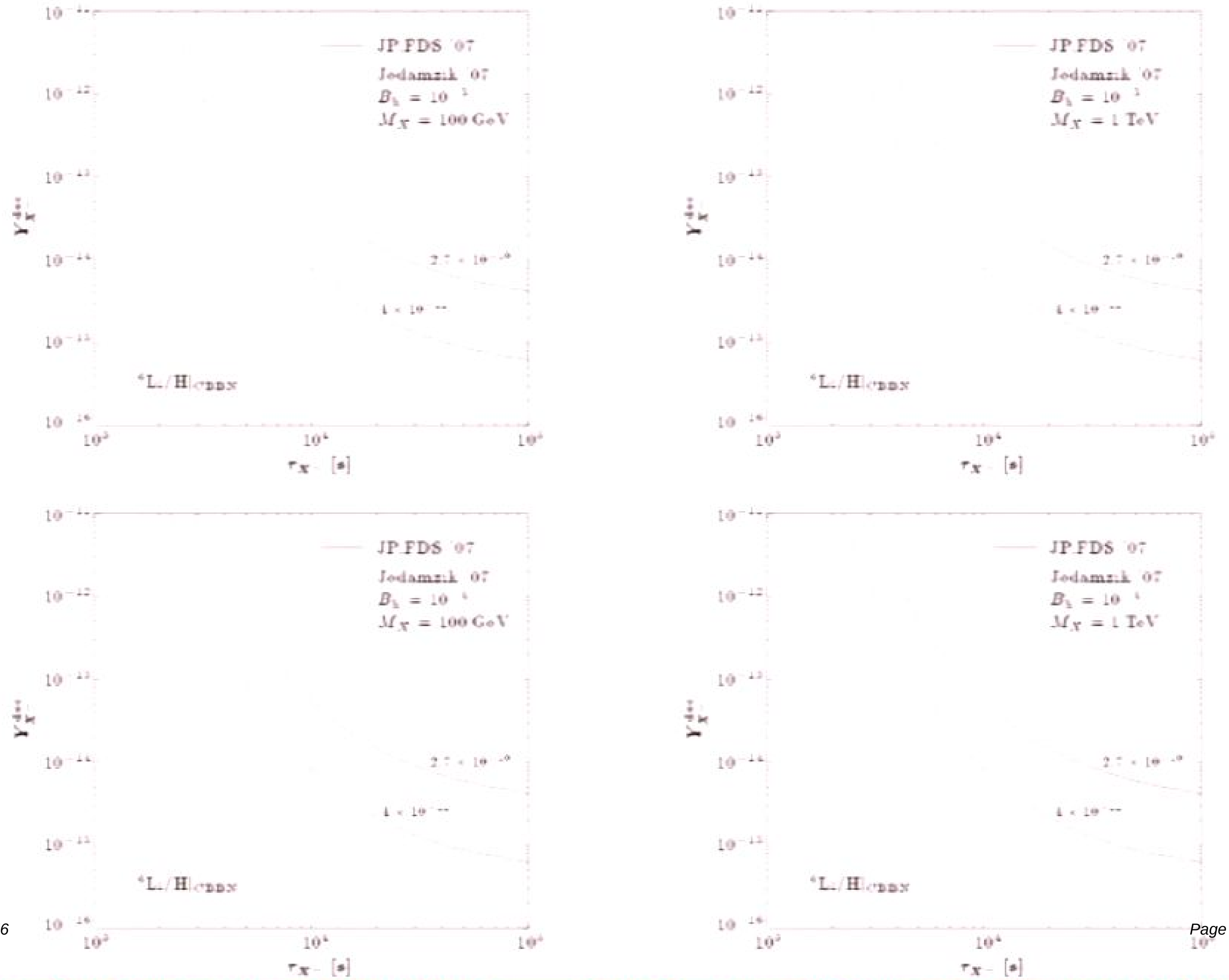
$$\langle\sigma_{\mathrm{r}}v\rangle = \frac{2^9\pi\alpha Z_\alpha^2\sqrt{2\pi}}{3e^4}\frac{E_{\mathrm{b}}}{m_\alpha^2\sqrt{m_\alpha T}}$$

$$Y_\delta \equiv (Y_{X^-}Y_{^4\mathrm{He}} - Y_{\mathrm{BS}}\widetilde{Y}_\gamma)$$

$$E_{\mathrm{b}} = 337.33\ \mathrm{keV} \qquad \widetilde{n}_\gamma \equiv n_\gamma(E > E_{\mathrm{b}})$$

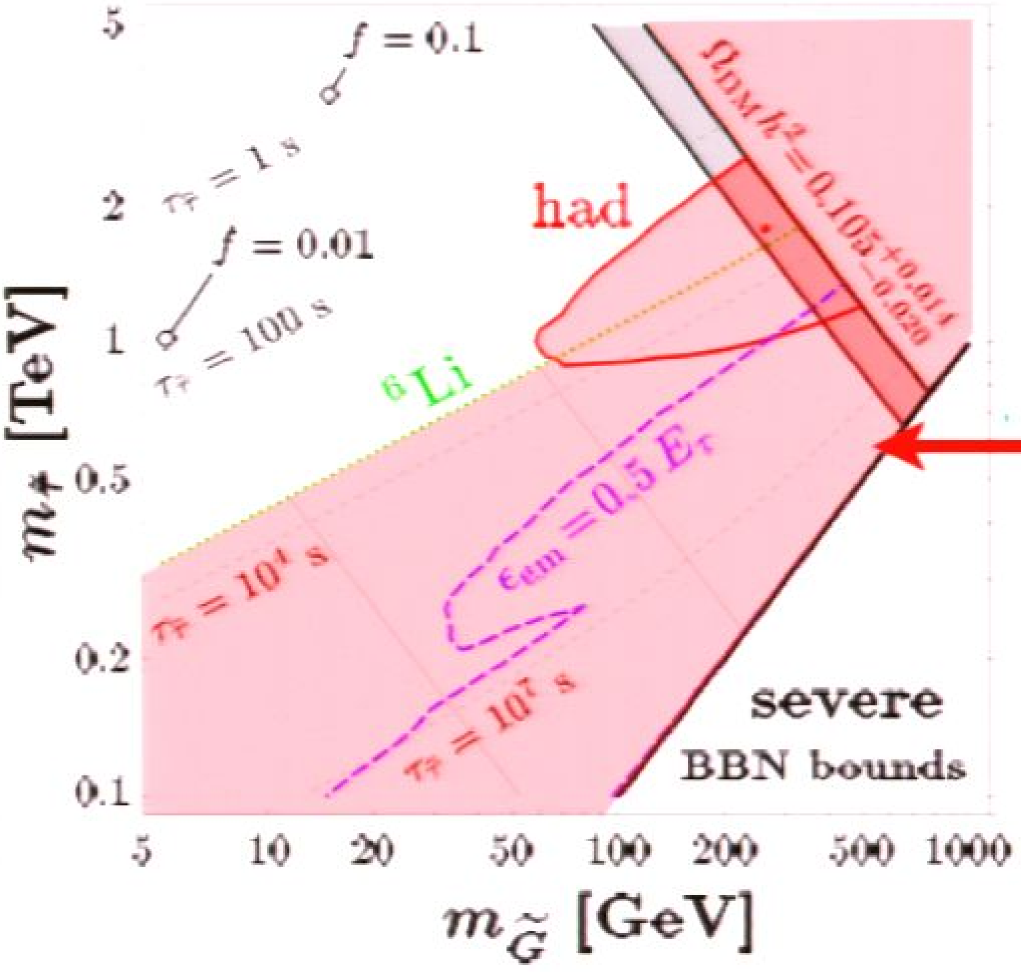


Comparison of [Pradler, FDS, arXiv:0710.2213] with [Jedamzik, arXiv:0710.5153]



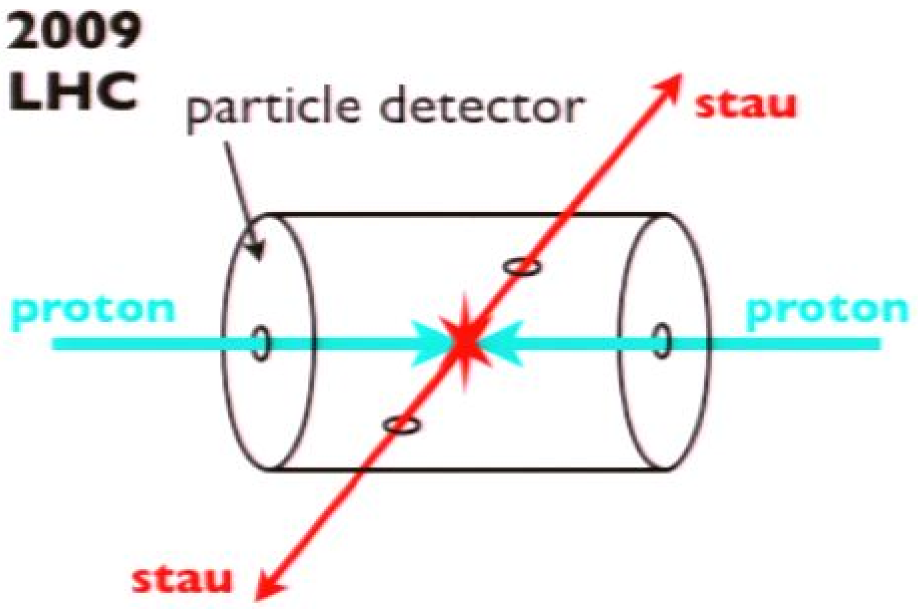
[FDS. hep-ph/0611027]

Cosmological Constraints — Ω_{DM} & BBN



disfavored by cosmological constraints

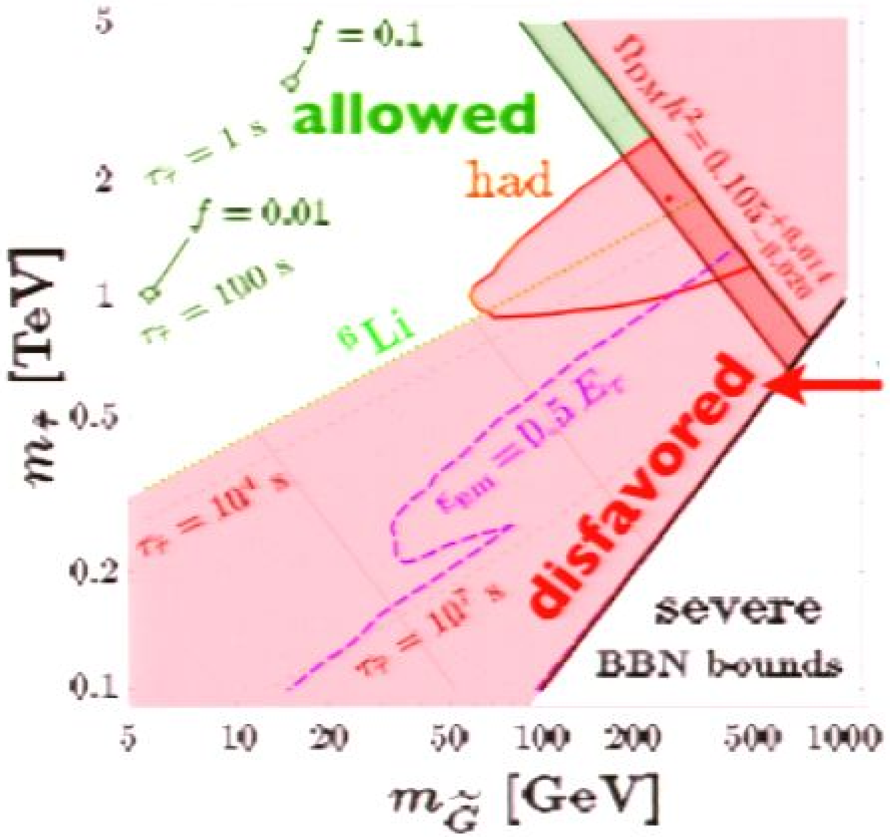
Gravitino DM @ LHC ← Stau NLSP



The signal:

jets + leptons

+ 2 "stable" charged particles



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

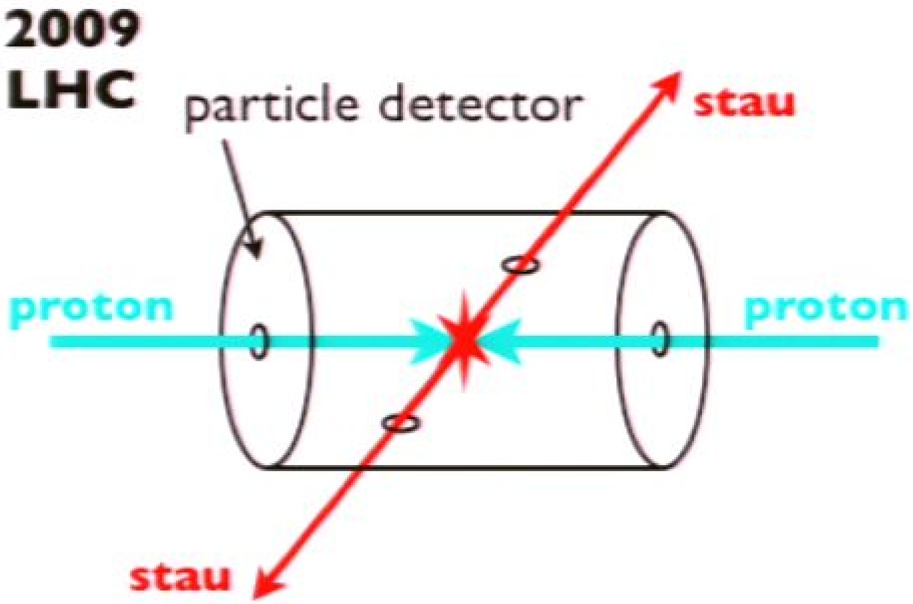
Cosmological Constraints

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

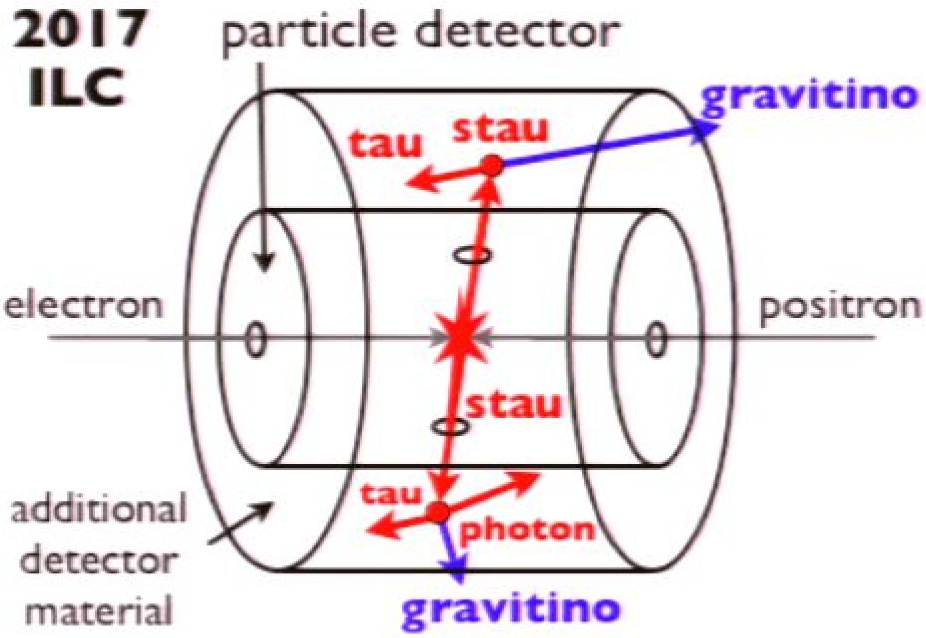
Signatures of Gravitinos in Experiments

- Direct Detection of $\widetilde{G}$
- Direct Production of $\widetilde{G}$

*** "stable" charged sparticles**

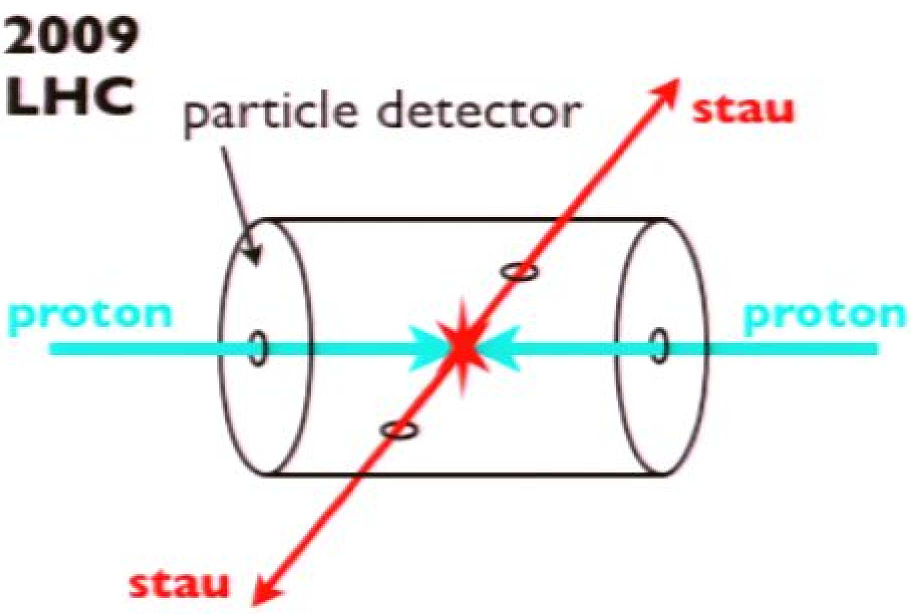


*** long-lived charged sparticles**



[...; Buchmüller et al., '04; Hamaguchi et al., '04; Feng, Smith, '05; Martyn, '06; ...]

Gravitino DM @ LHC ← Stau NLSP



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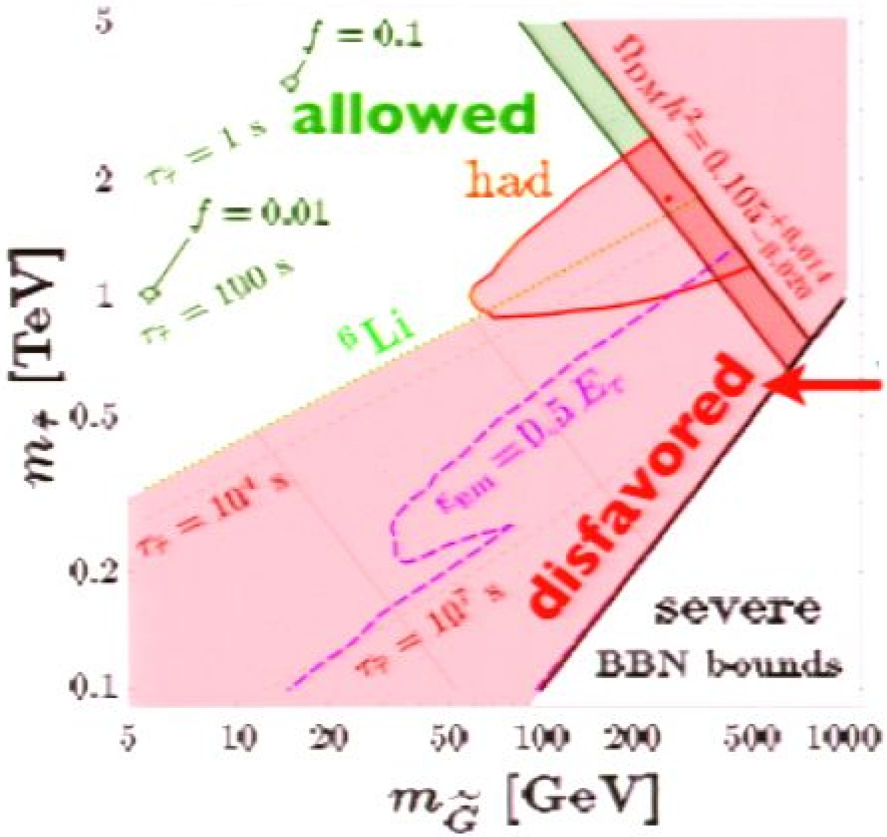

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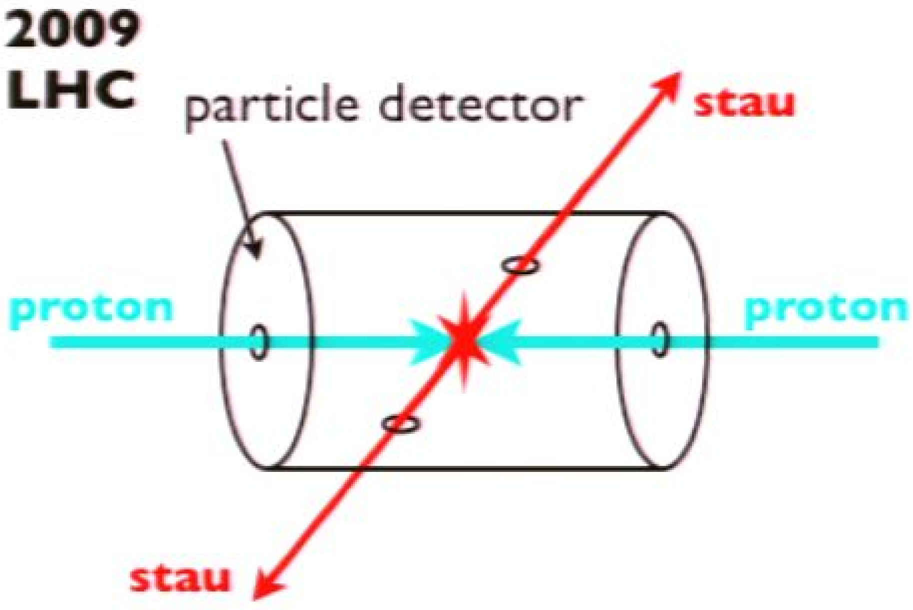

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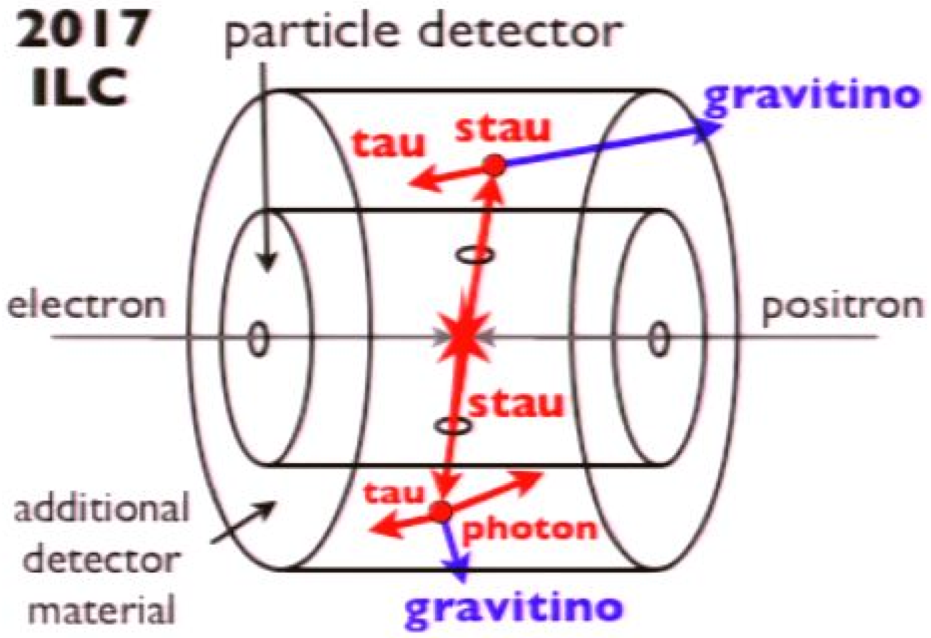
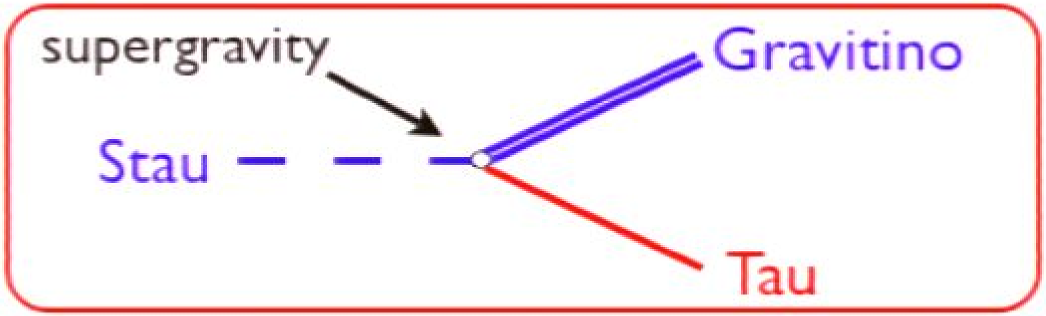


[... Buchmüller et al., '04; Hamaguchi et al., '04; Feng, Smith, '05; Martyn, '06; ...]

[Buchmüller, Hamaguchi, Ratz, Yanagida, '04]

$\widetilde{G}$ LSP → Planck Scale M_{Pl} & Gravitino Mass $m_{\widetilde{G}}$



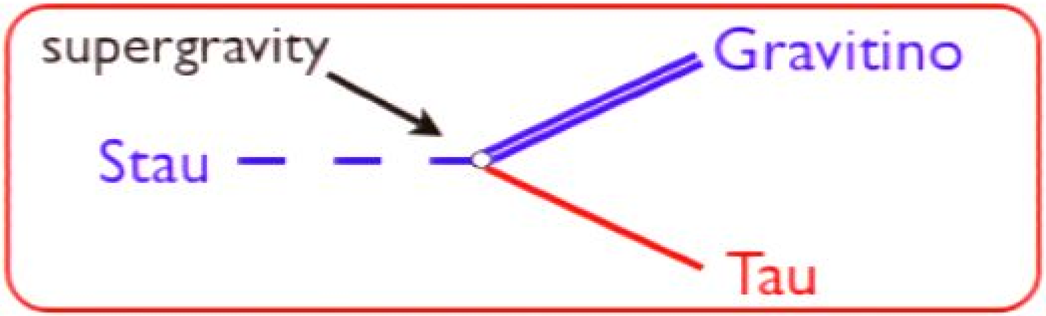
☐ Assumption: $\widetilde{\tau}_R$ NLSP

- 2-Body Decay $\widetilde{\tau}_R \rightarrow \tau + \widetilde{G}$

$$\Gamma(\widetilde{\tau}_{\mathrm{R}} \rightarrow \tau\,\widetilde{G}) = \frac{m_{\widetilde{\tau}}^5}{48\pi \enclose{circle}{m_{\widetilde{G}}^2} \mathrm{M}_{\mathrm{Pl}}^2}\left(1 - \frac{\enclose{circle}{m_{\widetilde{G}}^2}}{m_{\widetilde{\tau}}^2}\right)^4$$

[Buchmüller, Hamaguchi, Ratz, Yanagida, '04]

$\widetilde{G}$ LSP → Planck Scale M_{Pl} & Gravitino Mass $m_{\widetilde{G}}$



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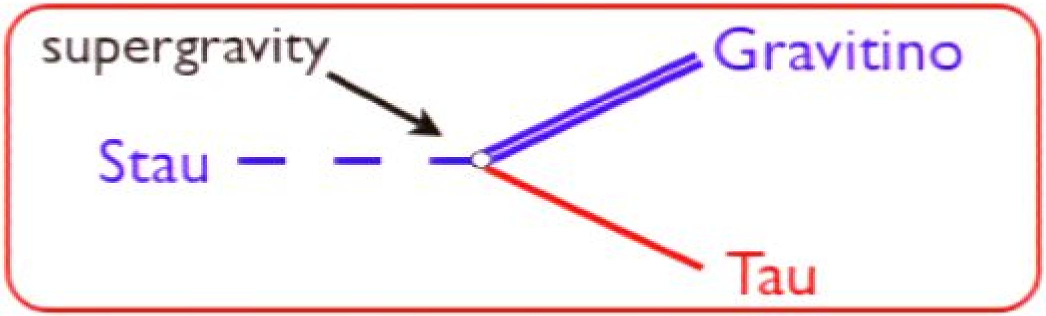
- Gravitino Mass $m_{\widetilde{G}} = \sqrt{m_{\widetilde{\tau}}^2 + m_{\tau}^2 - 2 m_{\widetilde{\tau}} E_{\tau}}$ ⟵ Kinematics

[Buchmüller, Hamaguchi, Ratz, Yanagida, '04]

$\widetilde{G}$ LSP → Planck Scale $\mathrm{M_{Pl}}$ & Gravitino Mass $m_{\widetilde{G}}$



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- Planck Scale $\mathrm{M_{Pl}}$ ⟵ NLSP Lifetime $\tau_{\widetilde{\tau}} \approx 1/\Gamma(\widetilde{\tau}_R \rightarrow \tau\,\widetilde{G})$

$$\boxed{\mathrm{M_{Pl}^2}} = \frac{\tau_{\widetilde{\tau}}}{48\pi} \frac{m_{\widetilde{\tau}}^5}{m_{\widetilde{G}}^2} \left(1 - \frac{m_{\widetilde{G}}^2}{m_{\widetilde{\tau}}^2}\right)^4 \quad \overset{???}{\longleftrightarrow} \quad \boxed{\mathrm{M_{Pl}^2}} = \frac{1}{8\pi\, G_N} = (2.44 \times 10^{18}\,\mathrm{GeV})^2$$

- Gravitino Mass $m_{\widetilde{G}} = \sqrt{m_{\widetilde{\tau}}^2 + m_{\tau}^2 - 2 m_{\widetilde{\tau}} E_{\tau}}$ ⟵ Kinematics

[Pradler, FDS, '06]

Probing the Viability of Thermal Leptogenesis at Colliders

☐ $\Omega^{\rm TP}_{\tilde G} + \Omega^{\rm NTP}_{\tilde G} \le \Omega^{\rm max}_{\rm CDM}$

☐ $m_{\tilde G} < m_{\tilde\tau_1} = 143.4\ \mathrm{GeV}$

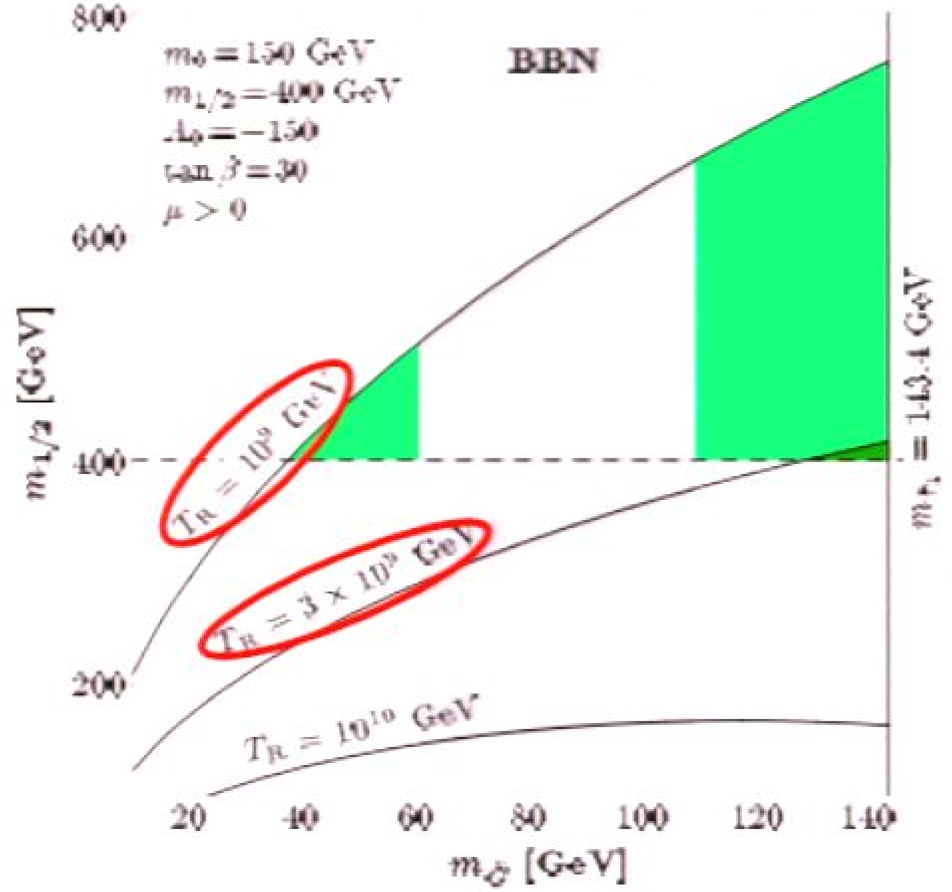
☐ BBN Constraints

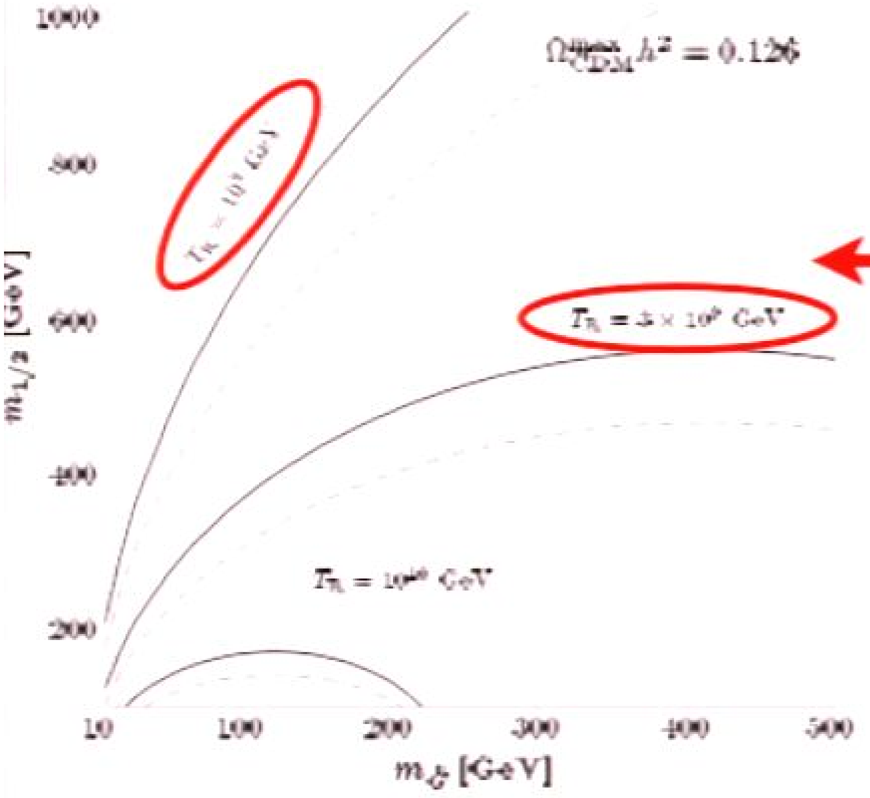
☐ Stau NLSP Lifetime

$$\tau_{\tilde\tau} \simeq \Gamma^{-1}(\tilde\tau \to \tilde G \tau)$$
$$= \frac{48\pi m^2_{\tilde G} \mathrm{M}^2_{\rm Pl}}{m^5_{\tilde\tau}} \left(1 - \frac{m^2_{\tilde G}}{m^2_{\tilde\tau}}\right)^{-4}$$

☐ $\tilde\tau \to \tilde G \tau$ Kinematics

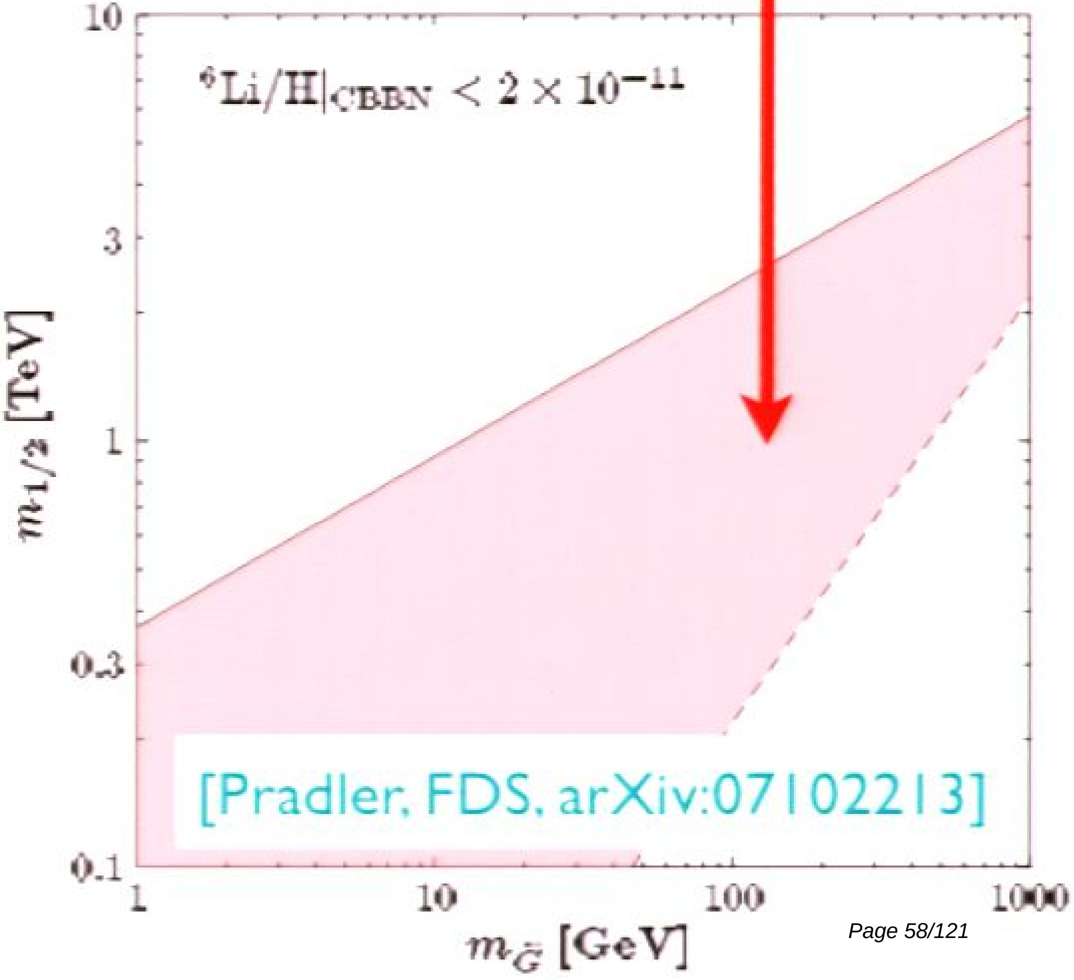
$$m_{\tilde G} = \sqrt{m^2_{\tilde\tau} - m^2_{\tau} - 2m_{\tilde\tau} E_{\tau}}$$



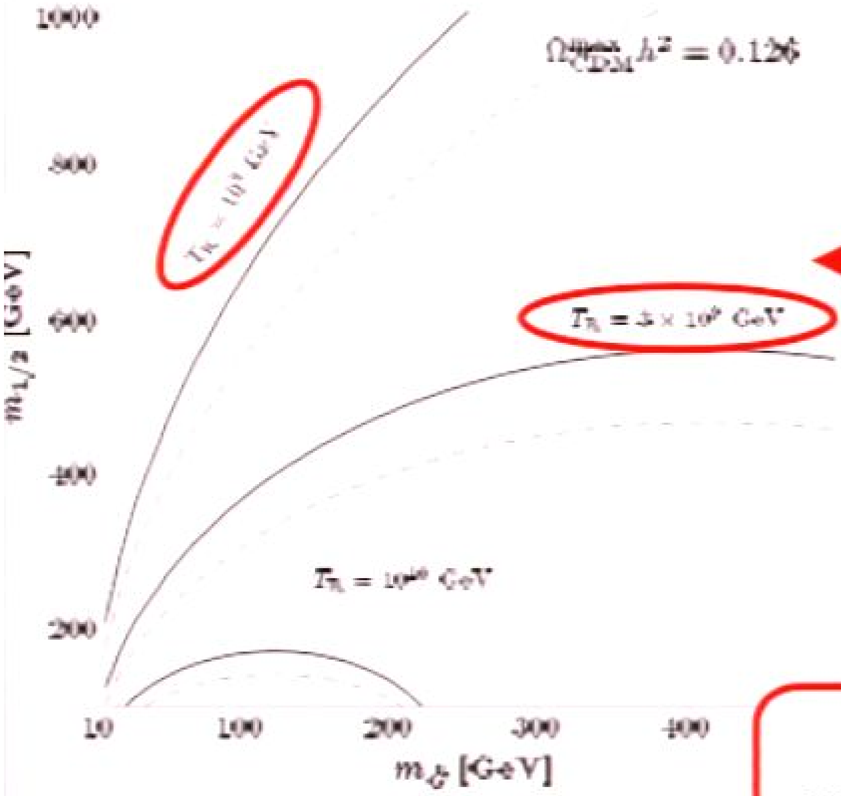


[Pradler, FDS, '06]

disfavored by cosmological constraints

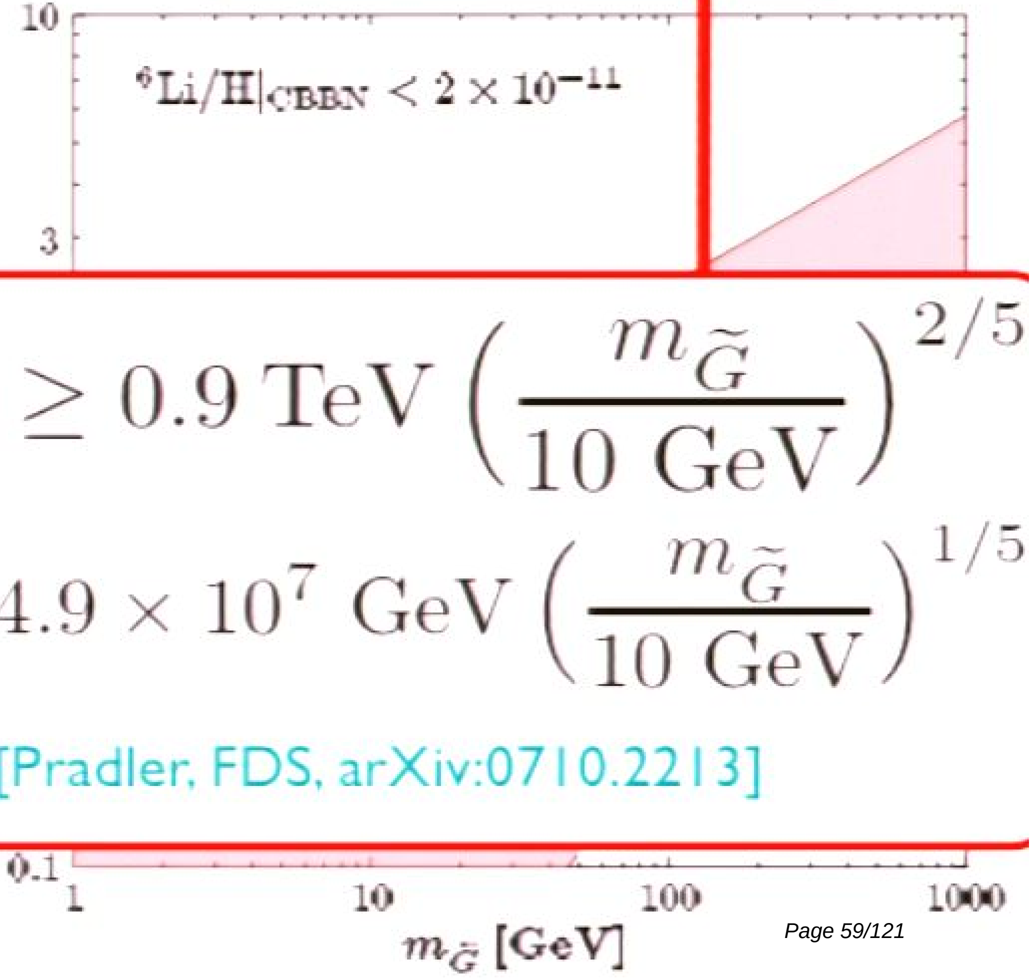


[Pradler, FDS, arXiv:0710221 3]



[Pradler, FDS, '06]

disfavored by cosmological constraints



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

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

[Pradler, FDS, arXiv:0710.2213]

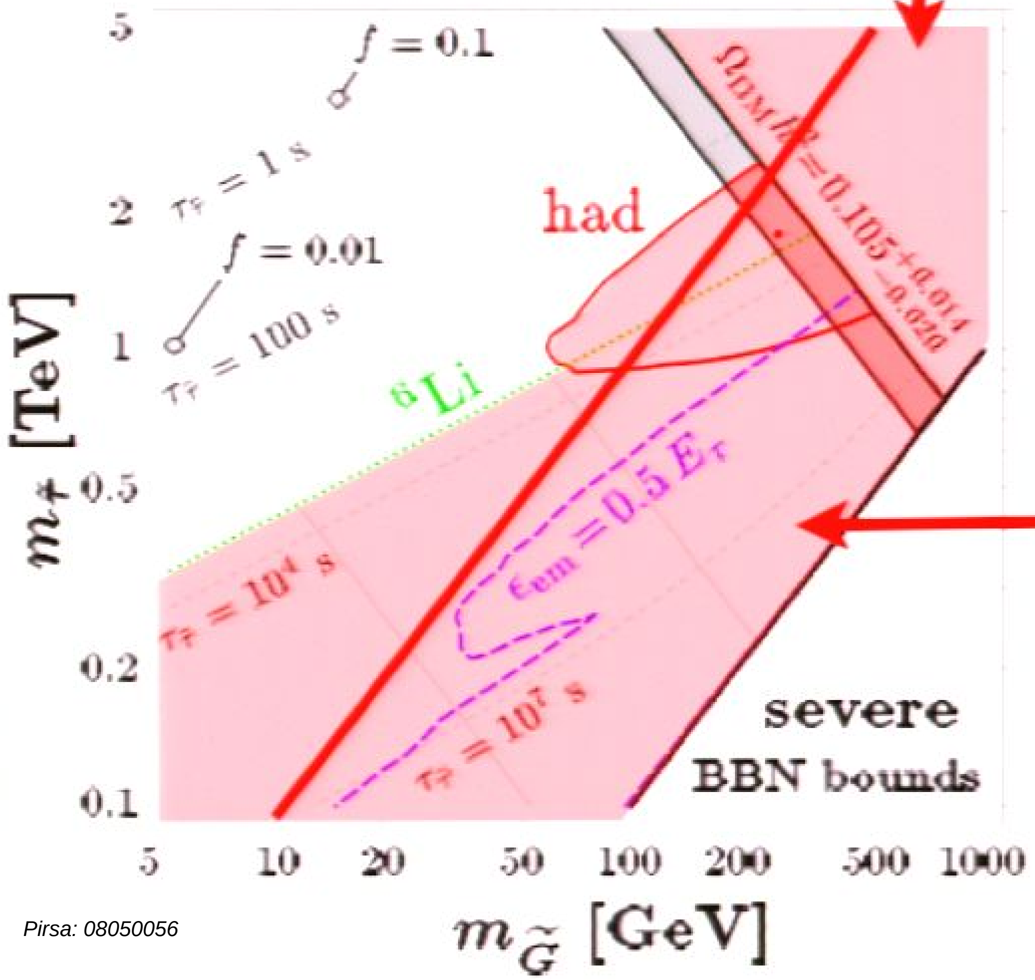
Can one identify the gravitino LSP experimentally?

Can one identify the gravitino LSP experimentally?

MPI Measurement

… requires $\boxed{m_{\tilde{G}} > 0.1 m_{\tilde{\tau}}}$ [..., Martyn, '06, ...]

... requires $\boxed{m_{\tilde{G}} > 0.1 m_{\tilde{\tau}}}$

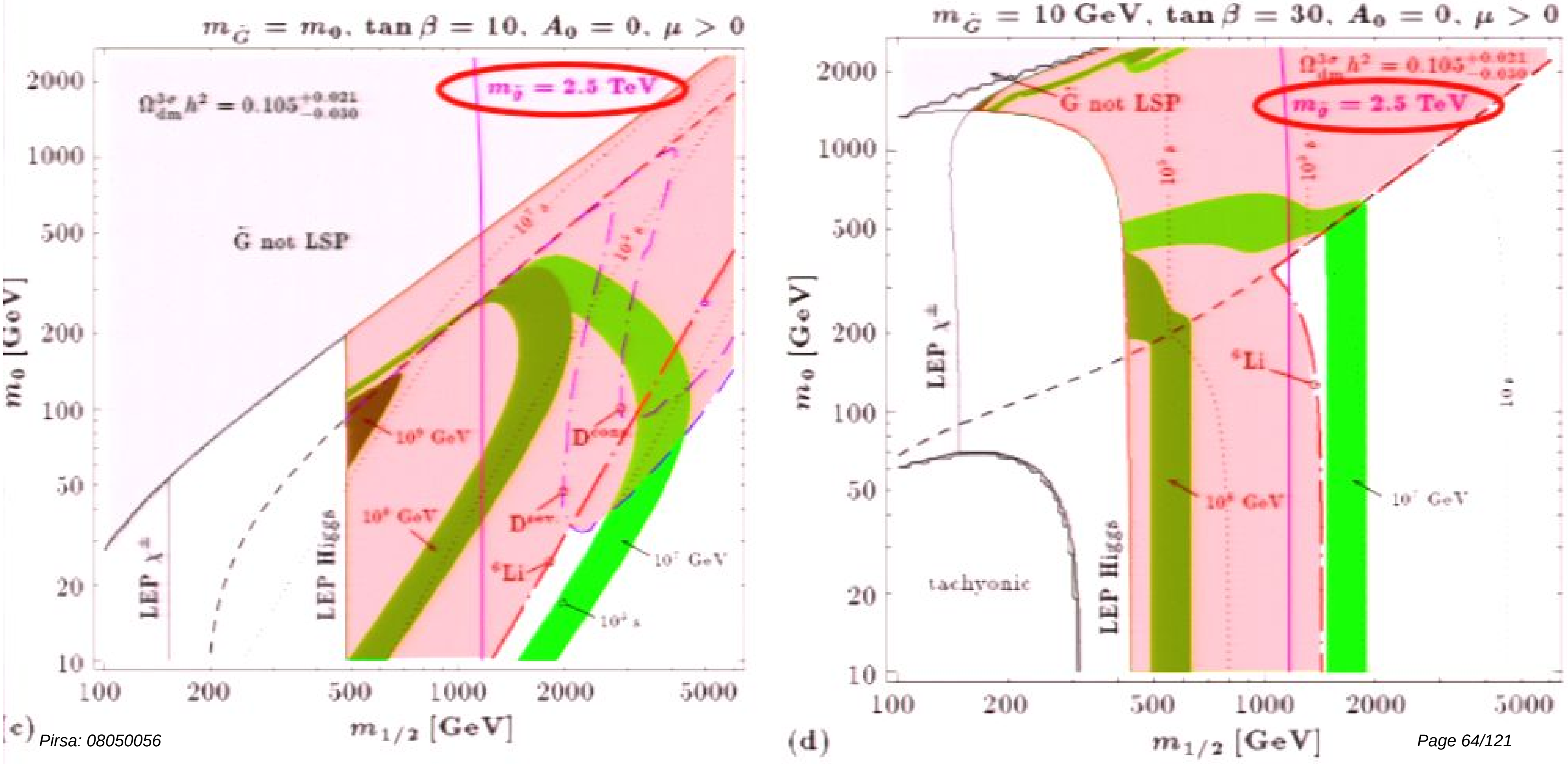


disfavored by cosmological constraints

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

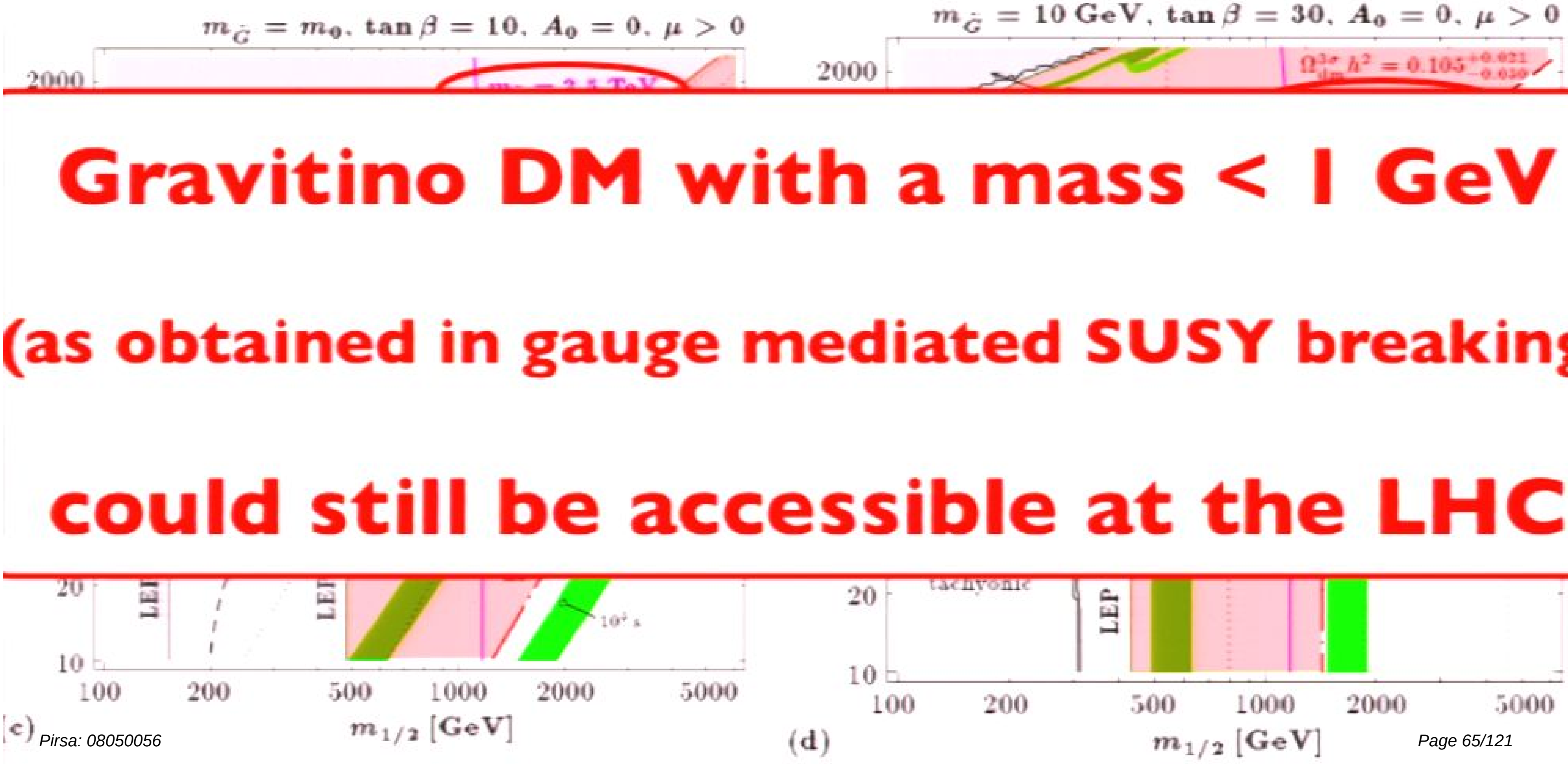
Gravitino DM with a GeV scale mass (as obtained in gravity med. SUSY breaking) could be very difficult to probe at the LHC

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



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]



Gravitino DM with a mass < 1 GeV

(as obtained in gauge mediated SUSY breaking)

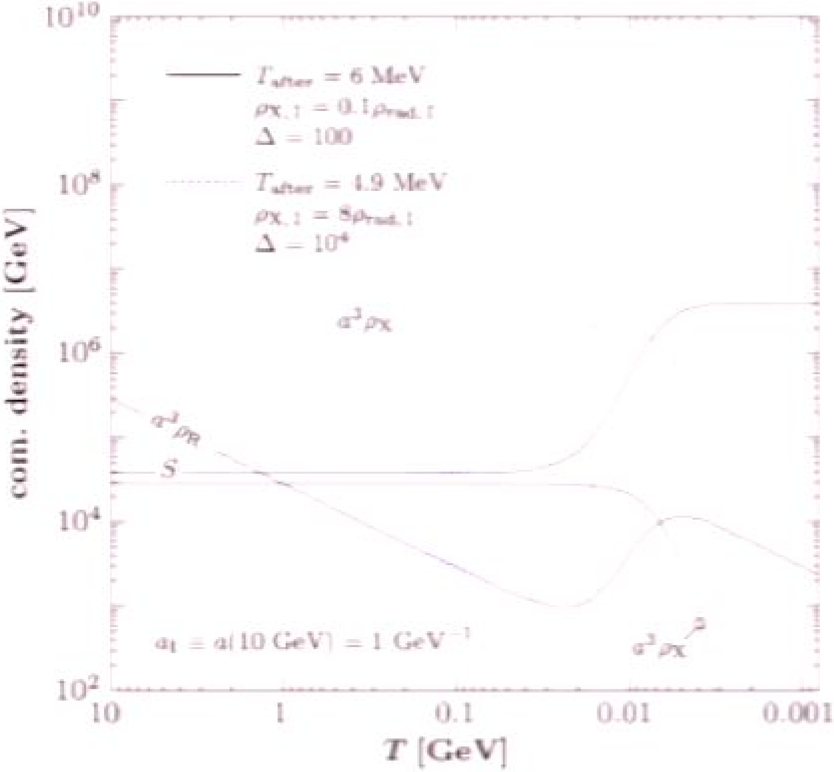
could still be accessible at the LHC

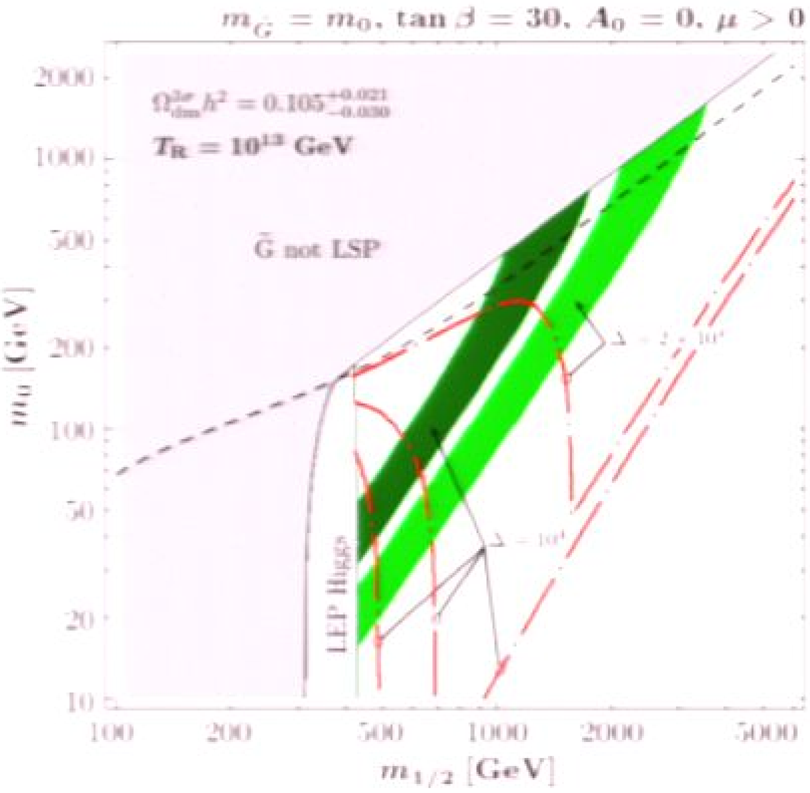
Warning:

Standard Cosmological History

Late-Time Entropy Production

[Pradler, FDS, hep-ph/0612291, Hamaguchi et al., hep-ph/0702274]





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

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

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

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

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

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

LSP Dark Matter: Production, Constraints, Experiments

LSP	interaction	production	constraints	experiments
$\tilde{\chi}^0_1$	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, ...)
$\tilde{G}$	$\left(\frac{p}{M_{Pl}}\right)^n$	therm. prod.	← cold	$\tilde{\tau}$ prod. at colliders (LHC, ILC, ...)
	extremely weak	NLSP decays	← warm	+ $\tilde{\tau}$ collection
	$M_{Pl} = 2.44 \times 10^{18}$ GeV	...		+ $\tilde{\tau}$ decay analysis: $m_{\tilde{G}}$, M_{Pl} (?), ...
			BBN	
			CMB	
			γ rays	

Supersymmetric Dark Matter Candiates

	LSP	ID	mass	interaction
lightest neutralino	$\tilde{\chi}_1^0$	$\tilde{B}, \widetilde{W}, \tilde{H}_u^0, \tilde{H}_d^0$	$\mathcal{O}(100\ \mathrm{GeV})$	g, g'
$\in$ MSSM		mixture	$M_1, M_2, \mu, \tan\beta$	weak
				$M_W \sim 100\ \mathrm{GeV}$
gravitino	$\tilde{G}$	superpartner of	eV – TeV	$\left(\frac{p}{M_{Pl}}\right)^n$
* gravity		the graviton	SUSY breaking	extremely weak
* local SUSY				$M_{Pl} = 2.44 \times 10^{18}\ \mathrm{GeV}$
axino	$\tilde{a}$	superpartner of	???	$\left(\frac{p}{f_a}\right)^n$
* strong CP		the axion	model	extremely weak
				$f_a \gtrsim 10^9\ \mathrm{GeV}$

LSP Dark Matter: Production, Constraints, Experiments

LSP	interaction	production	constraints	experiments
$\tilde{\chi}_1^0$	g, g'	WIMP	— cold	indirect detection (EGRET, GLAST, ...)
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	$\mathrm{M}_{\mathrm{Pl}} = 2.44 \times 10^{18}$ GeV	...	BBN	+ $\tilde{\tau}$ decay analysis: $m_{\tilde{G}}$, M_{Pl} (?)
$\tilde{a}$	$\left(\frac{p}{f_a}\right)^n$	therm. prod.	— cold	$\tilde{\tau}$ prod. at colliders (LHC, ILC, ...)
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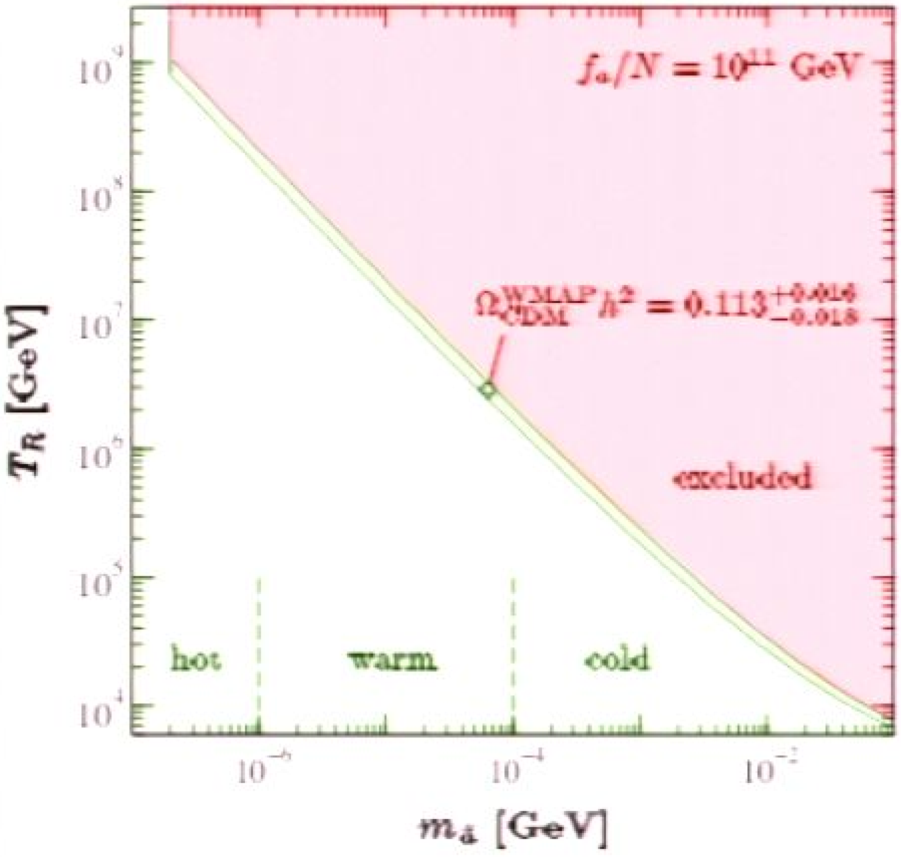
	$f_a \gtrsim 10^9$ GeV	...	BBN	+ $\tilde{\tau}$ decay analysis: $m_{\tilde{a}}$, f_a

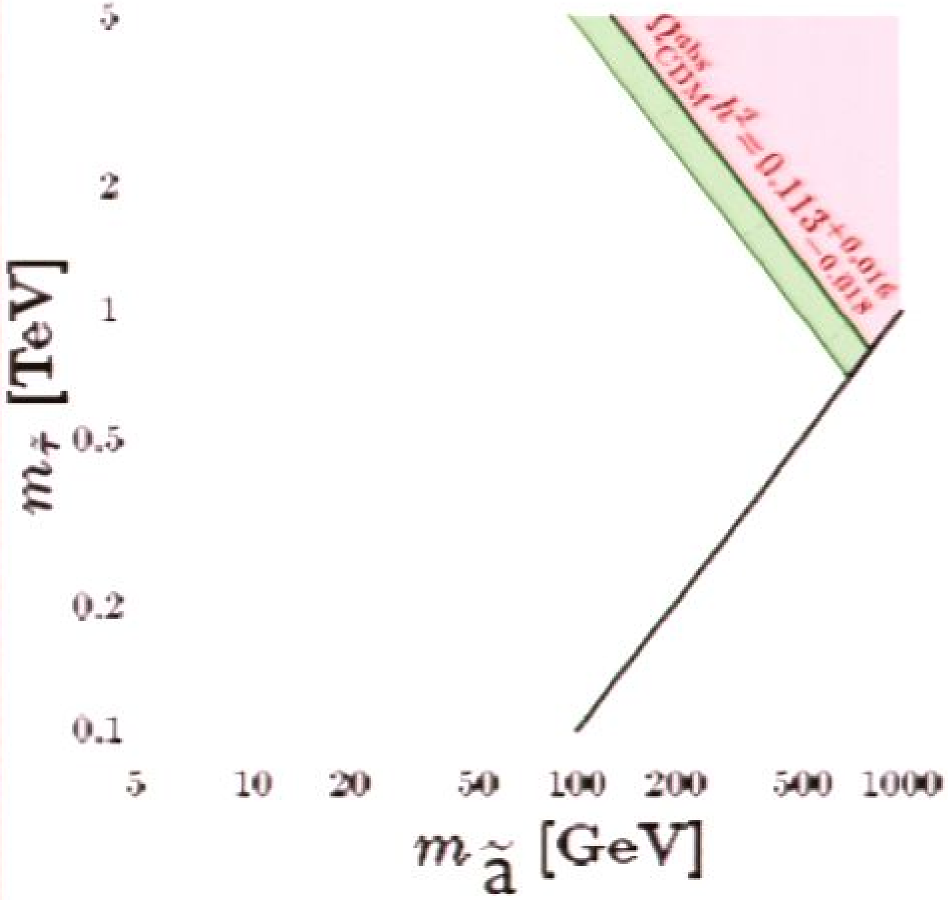
Thermal $\tilde{a}$ Production



[Brandenburg, FDS, '04]

see also [Covi et al., '01]

$\tilde{\tau}$ NLSP $\longrightarrow$ $\tilde{a} + \tau$



identical to the gravitino case

LSP Dark Matter: Production, Constraints, Experiments

LSP	interaction	production	constraints	experiments
$\widetilde{\chi}_1^0$	g, g'	WIMP	— cold	indirect detection (EGRET, GLAST, ...)
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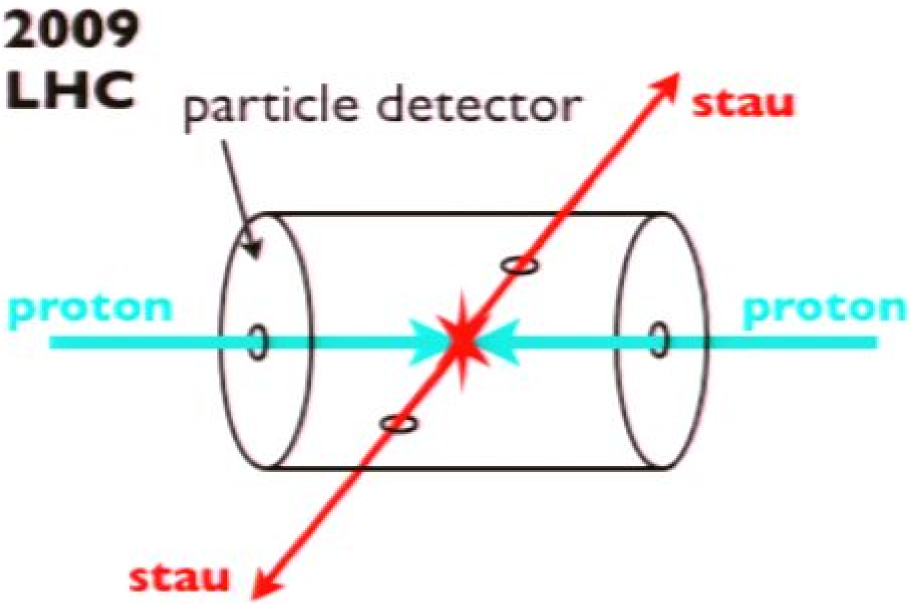
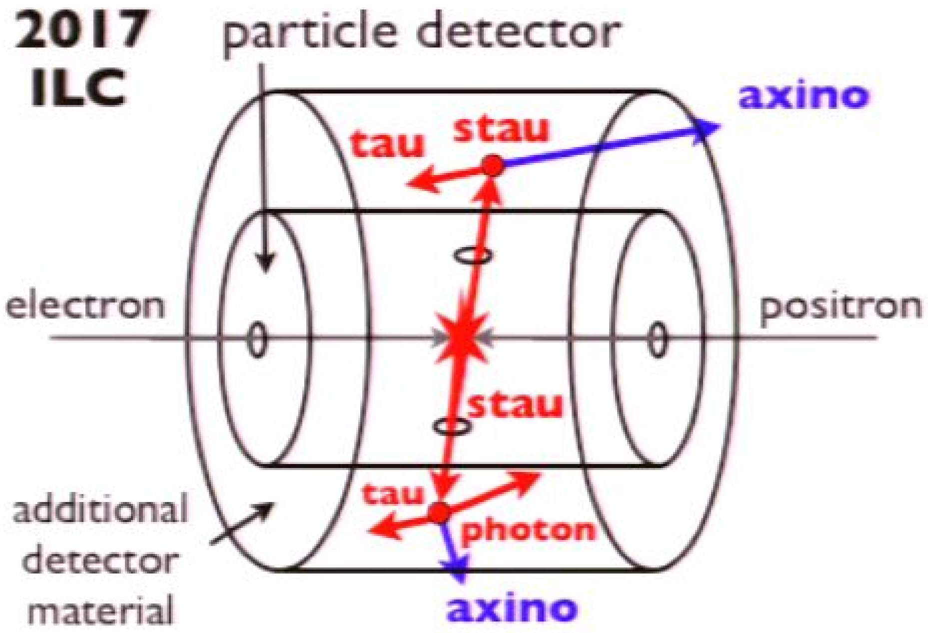

2009
LHC
particle detector
stau
proton
proton
stau


2017
ILC
particle detector
axino
tau
stau
electron
positron
stau
additional detector material
tau
photon
axino

Can one distinguish between

$\tilde{a}$ LSP and $\widetilde{G}$ LSP

experimentally?

[Brandenburg, Covi, Hamaguchi, Roszkowski, FDS, '05]

Can one distinguish between the $\tilde{a}/\widetilde{G}$ LSP Scenarios?

- Lifetime of the NLSP ⟵ Assumption: $\tilde{\tau}_R = \mathrm{NLSP}$ & $\tilde{\chi}^0 \approx \widetilde{B}$

$\tilde{a}$ = LSP

$$\tau_{\tilde{\tau}}^{\tilde{a}\,\mathrm{LSP}} \longleftarrow m_{\tilde{\tau}}, m_{\widetilde{B}}, m_{\tilde{a}}, f_a$$

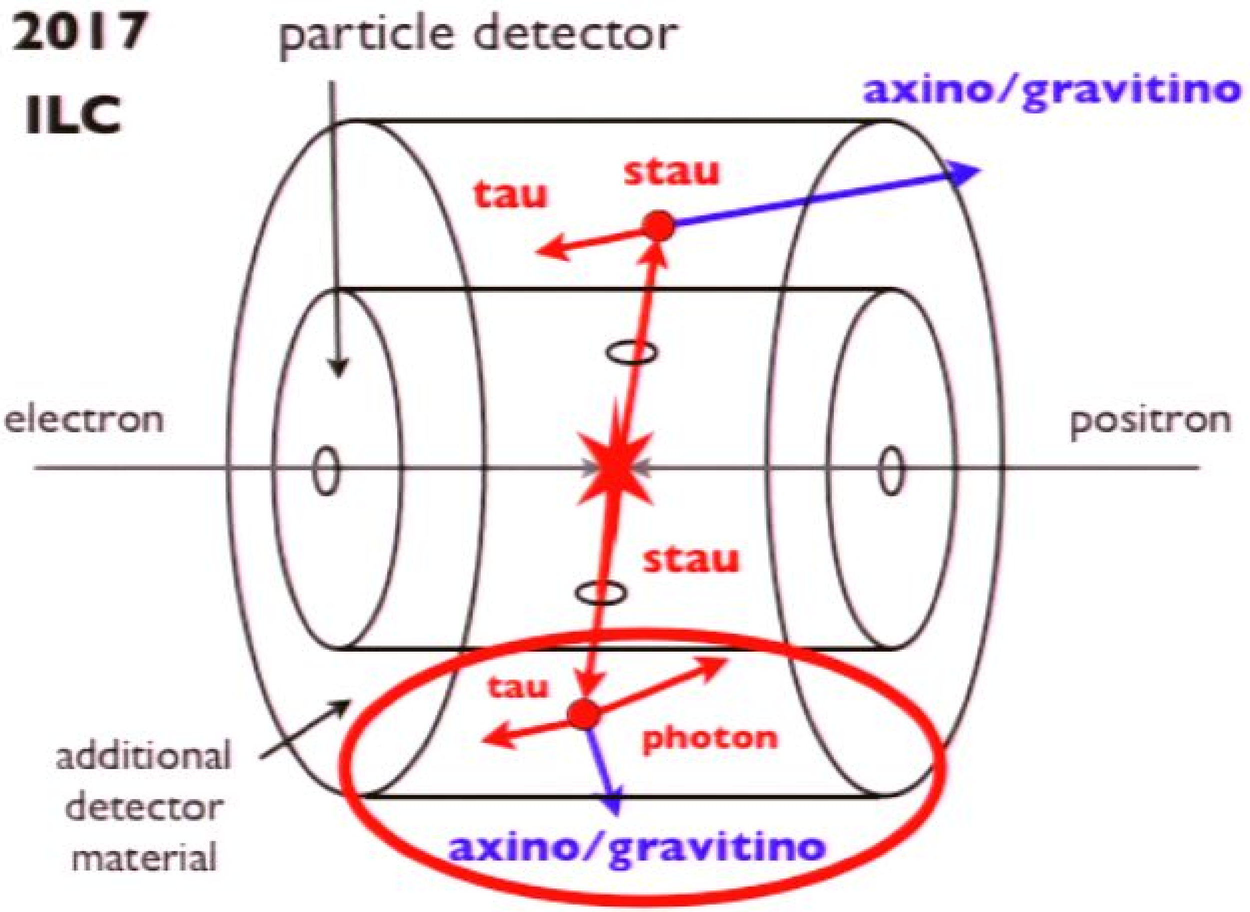
$$\begin{array}{ccc} \mathcal{O}(0.01\ \mathrm{sec}) & \lesssim \tau_{\tilde{\tau}}^{\tilde{a}\,\mathrm{LSP}} \lesssim & \mathcal{O}(10\ \mathrm{h}) \\ \uparrow & & \uparrow \\ f_a \sim 10^9\ \mathrm{GeV} & & f_a \sim 10^{12}\ \mathrm{GeV} \end{array}$$

$\widetilde{G}$ = LSP

$$\tau_{\tilde{\tau}}^{\widetilde{G}\,\mathrm{LSP}} \longleftarrow m_{\tilde{\tau}}, m_{\widetilde{B}}, m_{\widetilde{G}}$$

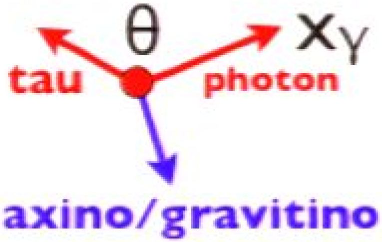
$$\begin{array}{ccc} \mathcal{O}(10^{-8}\ \mathrm{sec}) & \lesssim \tau_{\tilde{\tau}}^{\widetilde{G}\,\mathrm{LSP}} \lesssim & \mathcal{O}(15\ \mathrm{y}) \\ \uparrow & & \uparrow \\ m_{\widetilde{G}} \sim 1\ \mathrm{keV} & & m_{\widetilde{G}} \sim 50\ \mathrm{GeV} \end{array}$$

Very Short/Very Long Lived NLSP → $\widetilde{G}$ LSP Scenario

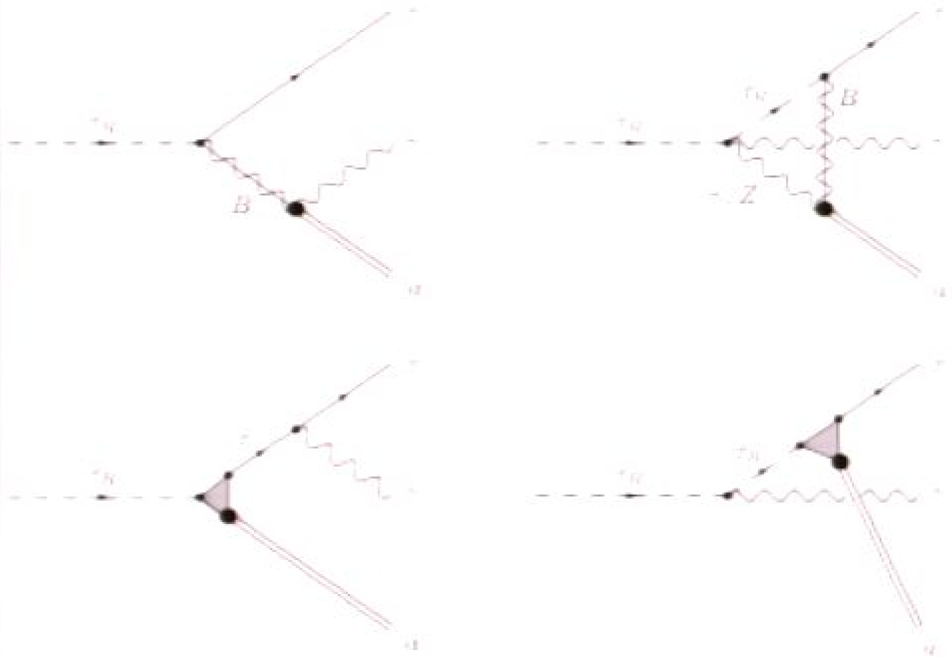


3-Body Decays

The 3-Body Decays

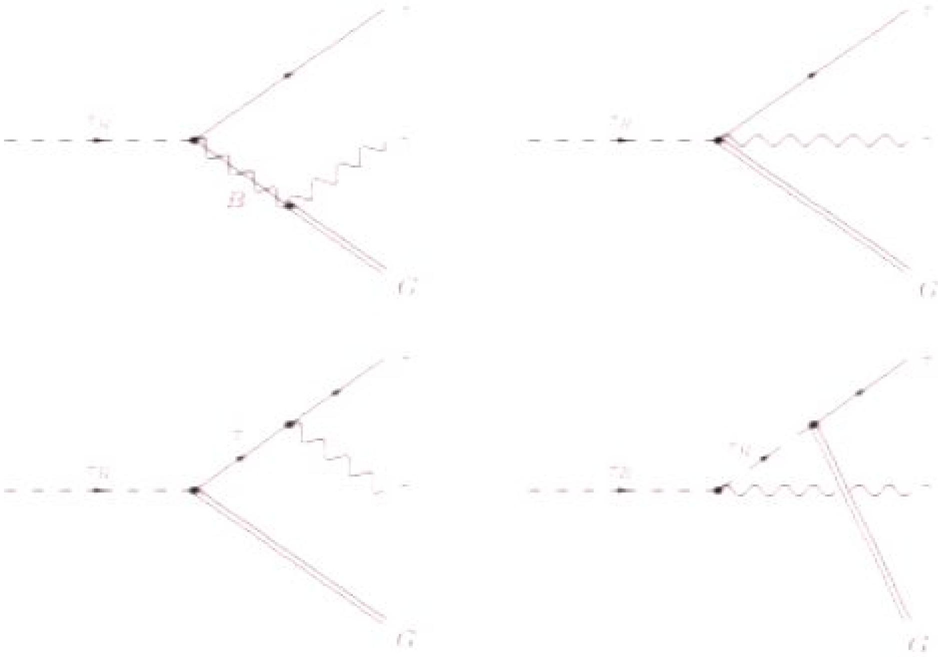


$\tilde{a}$ = LSP: $\widetilde{\tau}_R \to \tau + \gamma + \tilde{a}$



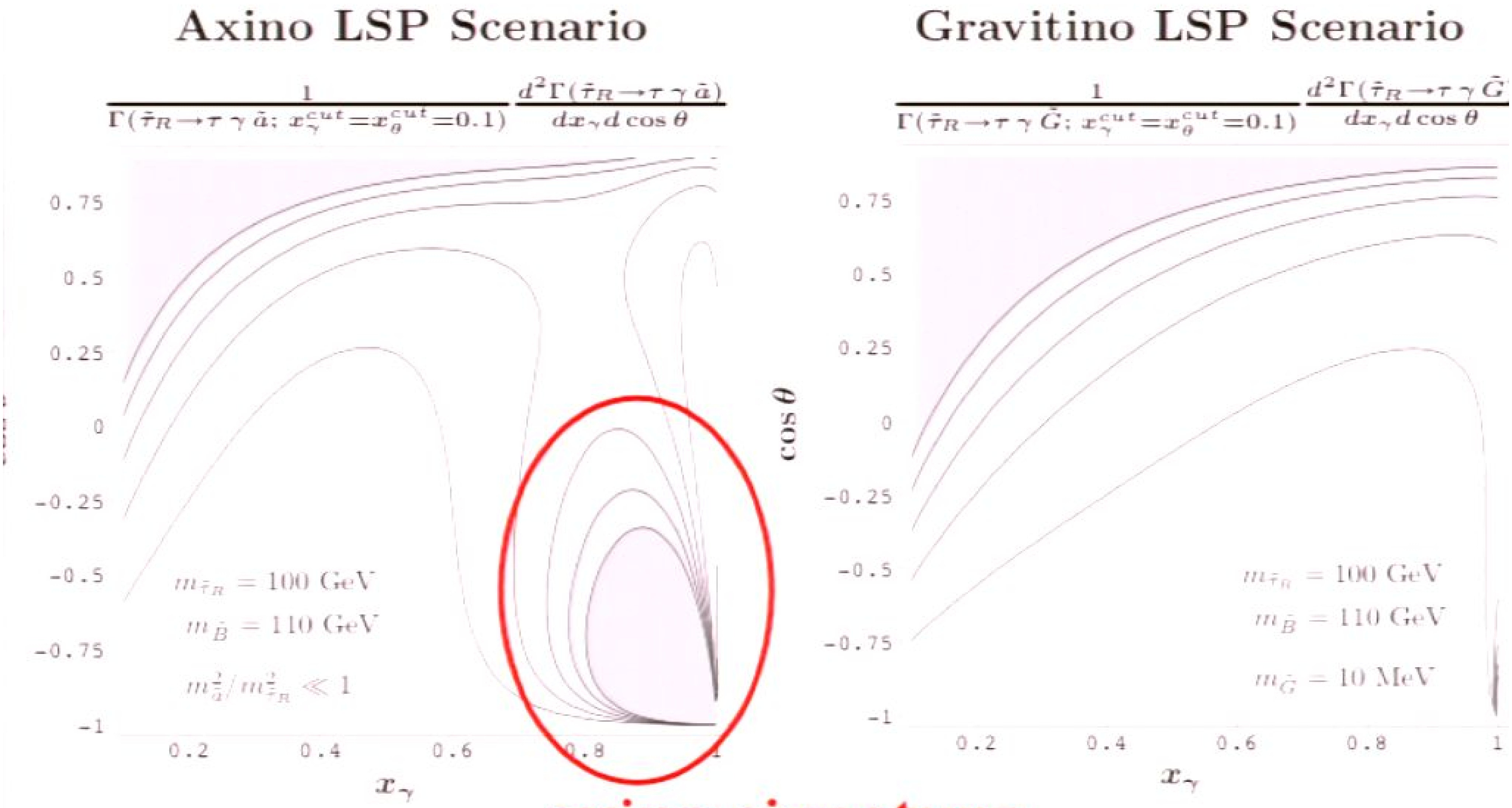
$$\frac{d^2\Gamma(\widetilde{\tau}_\mathrm{R} \to \tau\,\gamma\,\widetilde{a})}{dx_\gamma\,d\cos\theta} = \ldots$$

$\widetilde{G}$ = LSP: $\widetilde{\tau}_R \to \tau + \gamma + \widetilde{G}$



$$\frac{d^2\Gamma(\widetilde{\tau}_\mathrm{R} \to \tau\,\gamma\,\widetilde{G})}{dx_\gamma\,d\cos\theta} = \ldots$$

[Brandenburg, Covi, Hamaguchi, Roszkowski, FDS, '05]

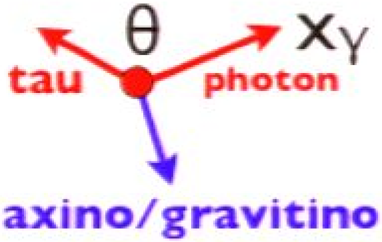

Axino LSP Scenario

Gravitino LSP Scenario

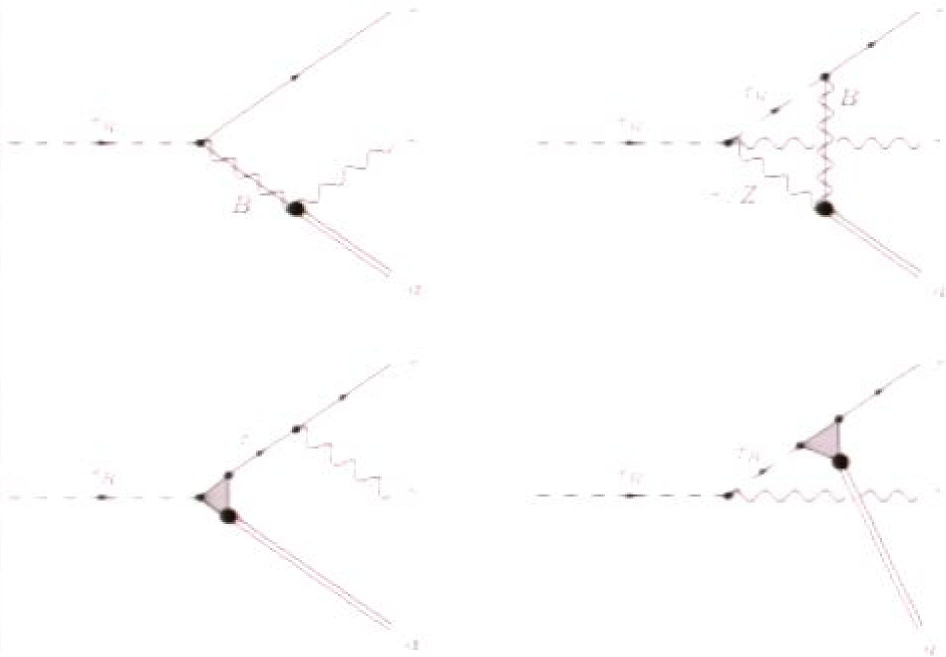
axino signature

Differential Distribution of the Visible Decay Products

The 3-Body Decays

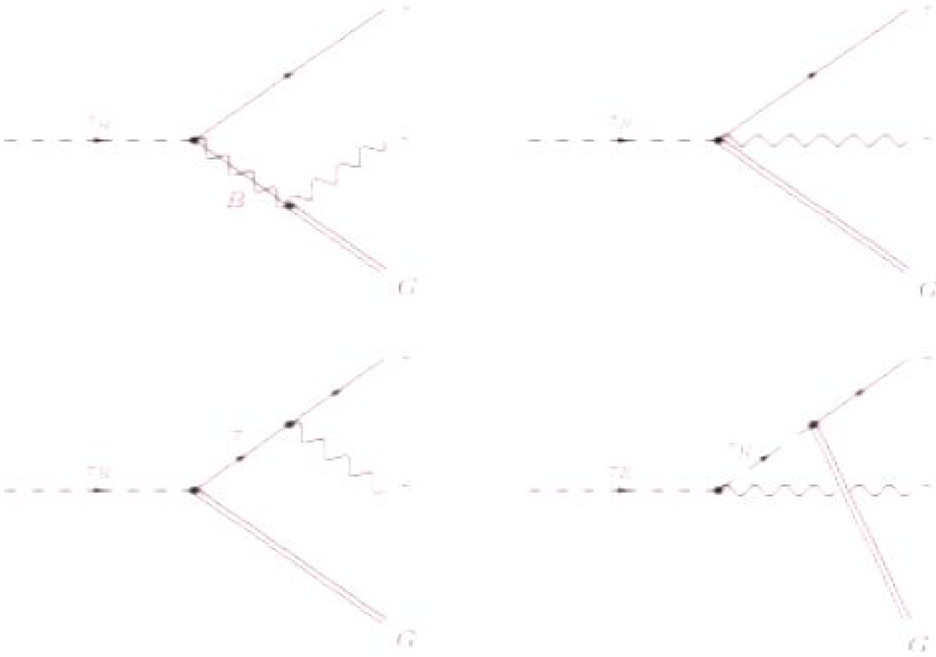


$\tilde{a}$ = LSP: $\quad \widetilde{\tau}_R \to \tau + \gamma + \tilde{a}$



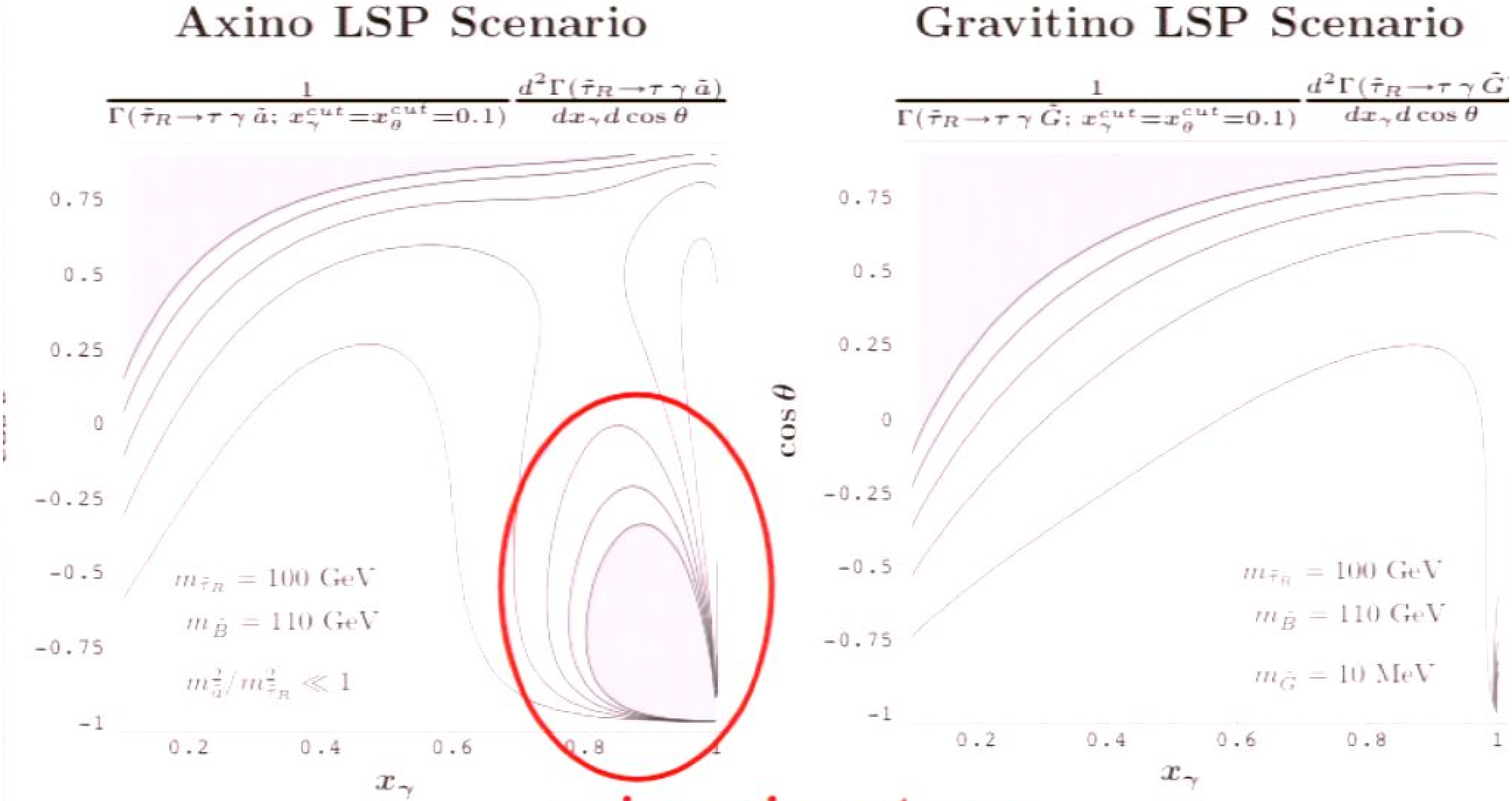
$$\frac{d^2\Gamma(\widetilde{\tau}_{\rm R} \to \tau\,\gamma\,\widetilde{a})}{dx_\gamma\, d\cos\theta} = \dots$$

$\widetilde{G}$ = LSP: $\quad \widetilde{\tau}_R \to \tau + \gamma + \widetilde{G}$



$$\frac{d^2\Gamma(\widetilde{\tau}_{\rm R} \to \tau\,\gamma\,\widetilde{G})}{dx_\gamma\, d\cos\theta} = \dots$$

[Brandenburg, Covi, Hamaguchi, Roszkowski, FDS, '05]



Axino LSP Scenario

Gravitino LSP Scenario

axino signature

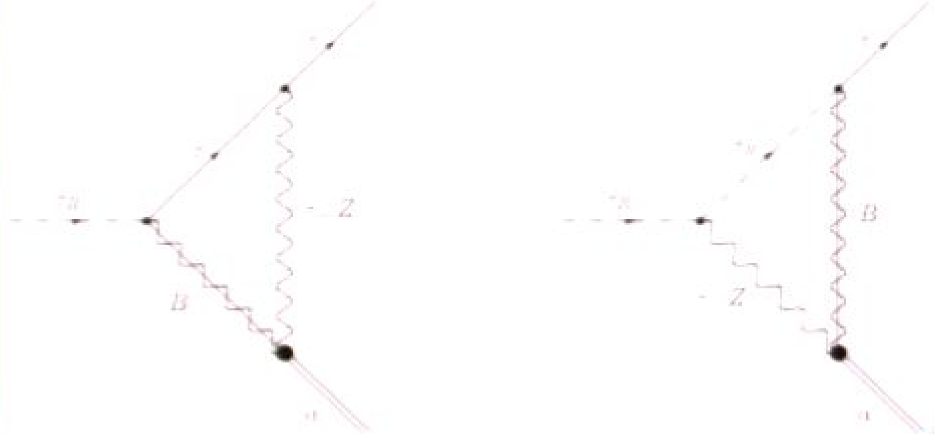
Differential Distribution of the Visible Decay Products

[Brandenburg, Covi, Hamaguchi, Roszkowski, FDS, '05]

$\tilde{a}$ LSP → Peccei–Quinn Scale f_a & Axino Mass $m_{\tilde{a}}$

☐ Assumption: $\widetilde{\tau}_R$ NLSP & $\widetilde{\chi}^0 \simeq \widetilde{B}$

hadronic (KSVZ) axion model



- 2-Body Decay $\widetilde{\tau}_R \to \tau + \tilde{a}$

$$\Gamma(\widetilde{\tau}_{\mathrm{R}} \to \tau\widetilde{a}) \simeq \xi^2\,(25\,\mathrm{sec})^{-1} C_{\mathrm{aYY}}^2 \left(1 - \frac{m_{\widetilde{a}}^2}{m_{\widetilde{\tau}}^2}\right)\left(\frac{m_{\widetilde{\tau}}}{100\,\mathrm{GeV}}\right)\left(\frac{10^{11}\,\mathrm{GeV}}{f_a}\right)^2\left(\frac{m_{\widetilde{B}}}{100\,\mathrm{GeV}}\right)^2$$

[Brandenburg, Covi, Hamaguchi, Roszkowski, FDS, '05]

$\tilde{a}$ LSP → Peccei–Quinn Scale f_a & Axino Mass $m_{\tilde{a}}$

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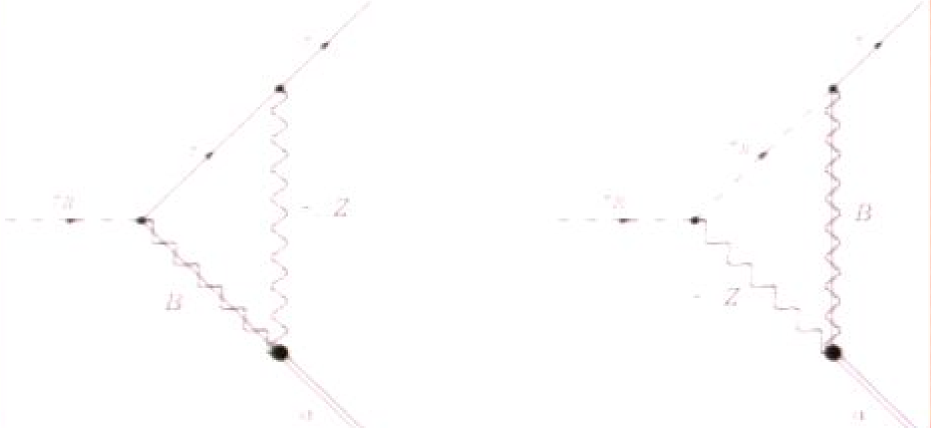

$$\Gamma(\tilde{\tau}_{\mathrm{R}} \to \tau \tilde{a}) \simeq \xi^2 \, (25\,\mathrm{sec})^{-1} C_{\mathrm{aYY}}^2 \left(1 - \frac{m_{\tilde{a}}^2}{m_{\tilde{\tau}}^2}\right)\left(\frac{m_{\tilde{\tau}}}{100\,\mathrm{GeV}}\right)\left(\frac{10^{11}\,\mathrm{GeV}}{\boxed{f_a}}\right)^2\left(\frac{m_{\tilde{B}}}{100\,\mathrm{GeV}}\right)^2$$

- Axino Mass $m_{\tilde{a}} = \sqrt{m_{\tilde{\tau}}^2 + m_{\tau}^2 - 2 m_{\tilde{\tau}} E_{\tau}}$ ⟵ Kinematics

[Brandenburg, Covi, Hamaguchi, Roszkowski, FDS, '05]

$\tilde{a}$ LSP → Peccei–Quinn Scale f_a & Axino Mass $m_{\tilde{a}}$

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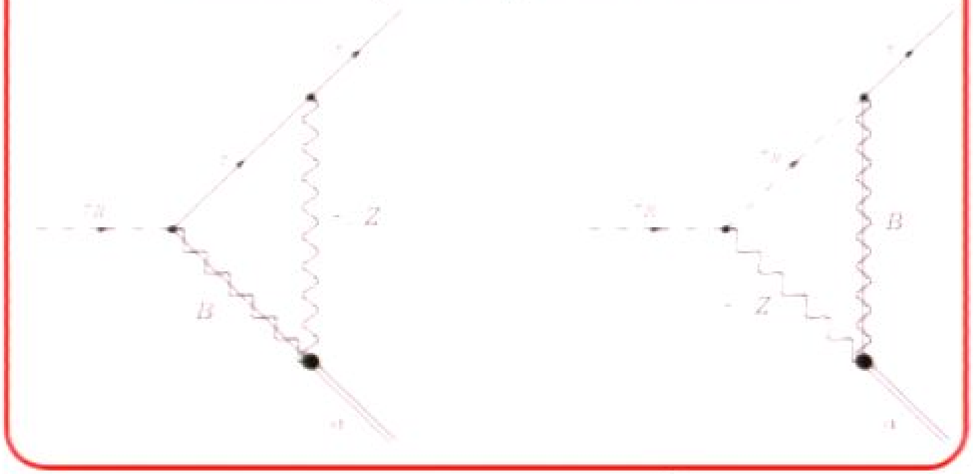

☐ Assumption: $\tilde{\tau}_R$ NLSP & $\tilde{\chi}^0 \simeq \tilde{B}$

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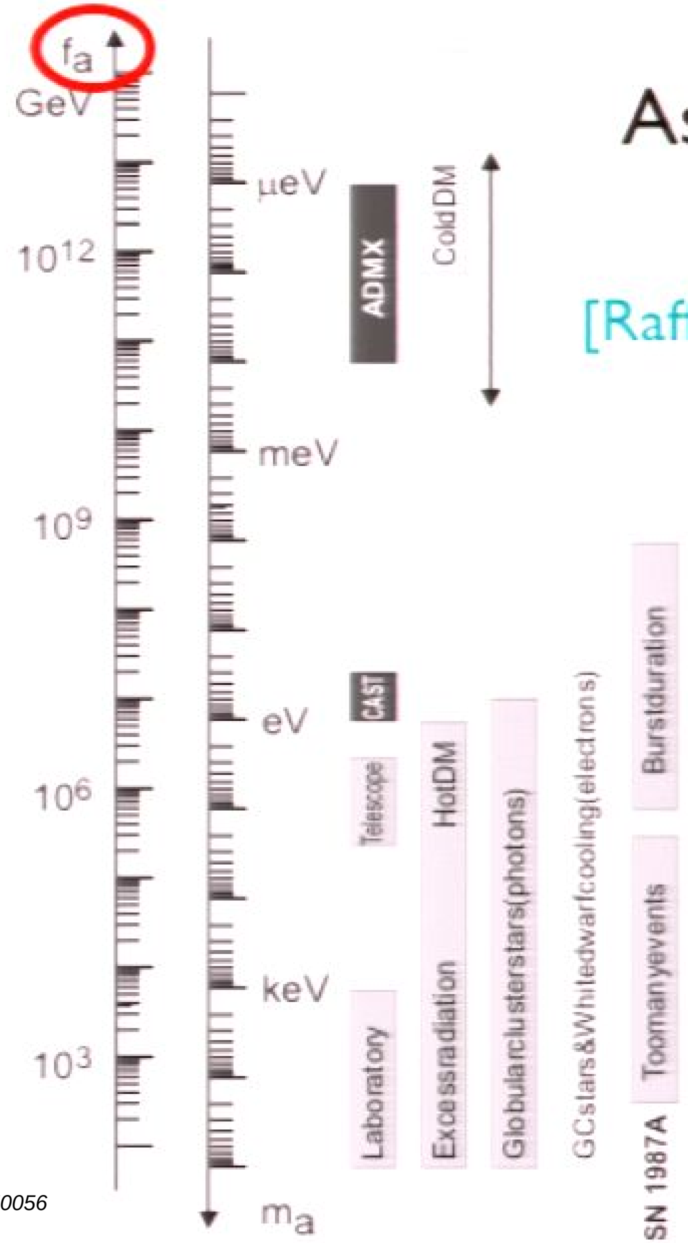
$$\Gamma(\widetilde{\tau}_{\mathrm{R}} \to \tau \widetilde{a}) \simeq \xi^2 \, (25\,\mathrm{sec})^{-1} C_{\mathrm{aYY}}^2 \left(1 - \frac{m_{\widetilde{a}}^2}{m_{\widetilde{\tau}}^2}\right)\left(\frac{m_{\widetilde{\tau}}}{100\,\mathrm{GeV}}\right)\left(\frac{10^{11}\,\mathrm{GeV}}{f_a}\right)^2\left(\frac{m_{\widetilde{B}}}{100\,\mathrm{GeV}}\right)^2$$

- Peccei–Quinn Scale f_a ⟵ NLSP Lifetime $\tau_{\tilde{\tau}} \approx 1/\Gamma(\tilde{\tau}_R \to \tau\,\tilde{a})$

$$f_a^2 \simeq \left(\frac{\tau_{\tilde{\tau}}}{25\ \mathrm{sec}}\right) \xi^2\, C_{\mathrm{aYY}}^2 \left(1 - \frac{m_{\tilde{a}}^2}{m_{\tilde{\tau}}^2}\right) \left(\frac{m_{\tilde{\tau}}}{100\,\mathrm{GeV}}\right) \left(\frac{m_{\tilde{B}}}{100\,\mathrm{GeV}}\right)^2 (10^{11}\ \mathrm{GeV})^2$$

- Axino Mass $m_{\tilde{a}} = \sqrt{m_{\tilde{\tau}}^2 + m_{\tau}^2 - 2 m_{\tilde{\tau}} E_{\tau}}$ ⟵ Kinematics

Bounds on the Peccei-Quinn Scale



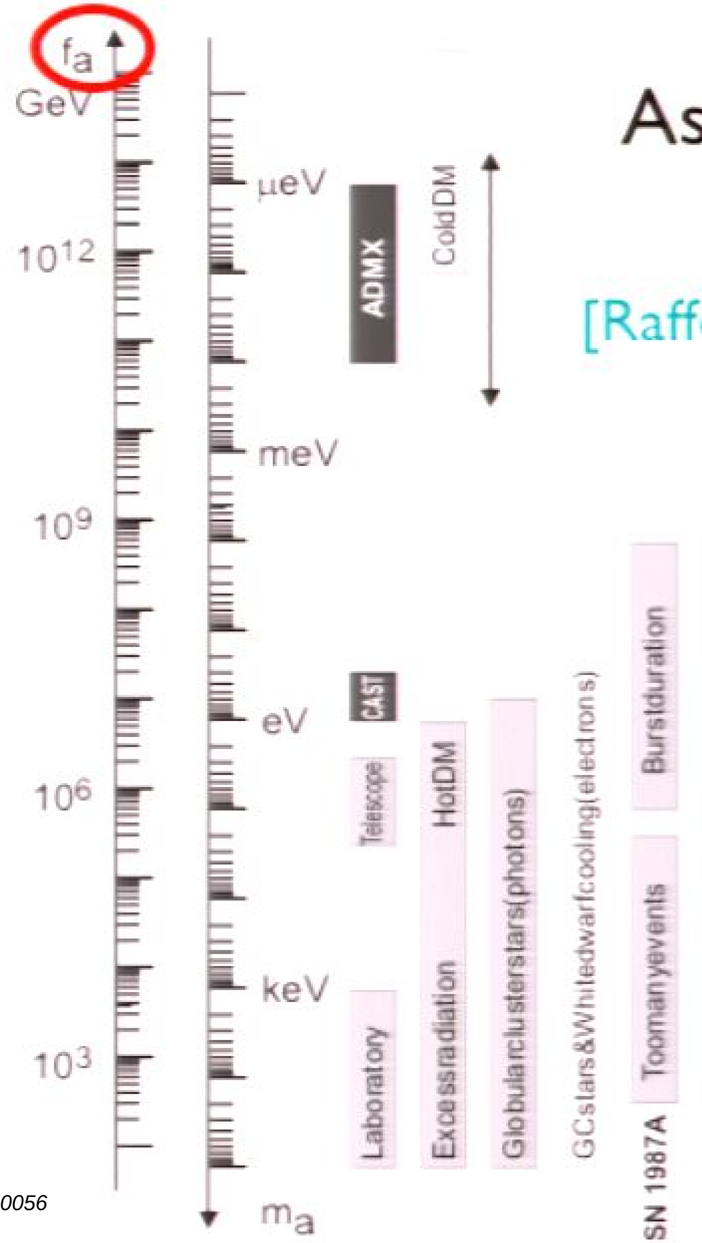
Astrophysical Axion Bounds

Bounds from Axion Searches

[Raffelt, '06]

Is the value of the Peccei-Quinn scale inferred from axino searches consistent with astrophysical axion bounds and results from axion searches?

Bounds on the Peccei-Quinn Scale



Astrophysical Axion Bounds

Bounds from Axion Searches

[Raffelt, '06]

Agreement between Axion & Axino Searches

↓

Strong Hint for the Axino LSP

Supersymmetric Dark Matter Candidates

LSP	interaction	production	constraints	experiments
$\tilde{\chi}_1^0$	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, ...)
$\widetilde{G}$	$\left(\frac{p}{\mathrm{M}_{\mathrm{Pl}}}\right)^n$	therm. prod.	— cold	$\tilde{\tau}$ prod. at colliders (LHC, ILC, ...)
	extremely weak	NLSP decays	— warm	+ $\tilde{\tau}$ collection
	$\mathrm{M}_{\mathrm{Pl}} = 2.44 \times 10^{18}$ GeV	...	BBN	+ $\tilde{\tau}$ decay analysis: $m_{\widetilde{G}}$, M_{Pl} (?)
$\widetilde{a}$	$\left(\frac{p}{f_a}\right)^n$	therm. prod.	— cold	$\tilde{\tau}$ prod. at colliders (LHC, ILC, ...)
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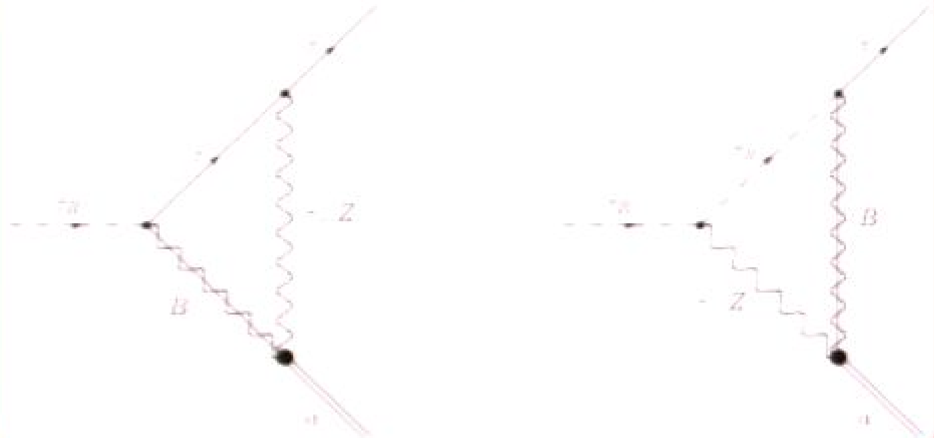
[Brandenburg, Covi, Hamaguchi, Roszkowski, FDS, '05]

$\tilde{a}$ LSP → Peccei–Quinn Scale f_a & Axino Mass $m_{\tilde{a}}$

☐ Assumption: $\tilde{\tau}_R$ NLSP & $\tilde{\chi}^0 \simeq \tilde{B}$

- 2-Body Decay $\tilde{\tau}_R \to \tau + \tilde{a}$

hadronic (KSVZ) axion model



$$\Gamma(\widetilde{\tau}_{\rm R} \to \tau \widetilde{a}) \simeq \xi^2\,(25\,{\rm sec})^{-1} C^2_{\rm aYY} \left(1 - \frac{m^2_{\widetilde{a}}}{m^2_{\widetilde{\tau}}}\right)\left(\frac{m_{\widetilde{\tau}}}{100\,{\rm GeV}}\right)\left(\frac{10^{11}\,{\rm GeV}}{\boxed{f_a}}\right)^2\left(\frac{m_{\widetilde{B}}}{100\,{\rm GeV}}\right)^2$$

- Peccei–Quinn Scale f_a ⟵ NLSP Lifetime $\tau_{\tilde{\tau}} \approx 1/\Gamma(\tilde{\tau}_R \to \tau\,\tilde{a})$

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- Axino Mass $m_{\tilde{a}} = \sqrt{m^2_{\tilde{\tau}} + m^2_{\tau} - 2 m_{\tilde{\tau}} E_{\tau}}$ ⟵ Kinematics

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$\tilde{a}$ LSP $\rightarrow$ Peccei–Quinn Scale f_a & Axino Mass $m_{\tilde{a}}$

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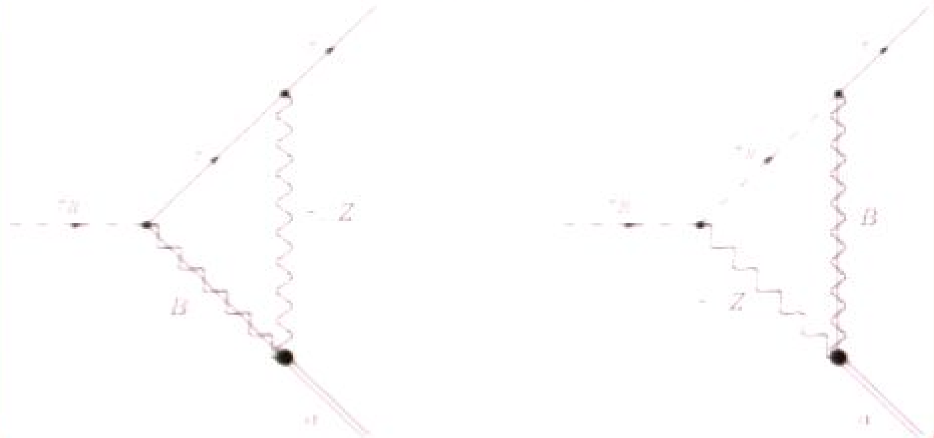

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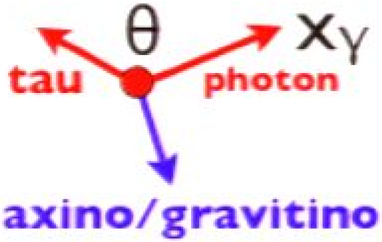
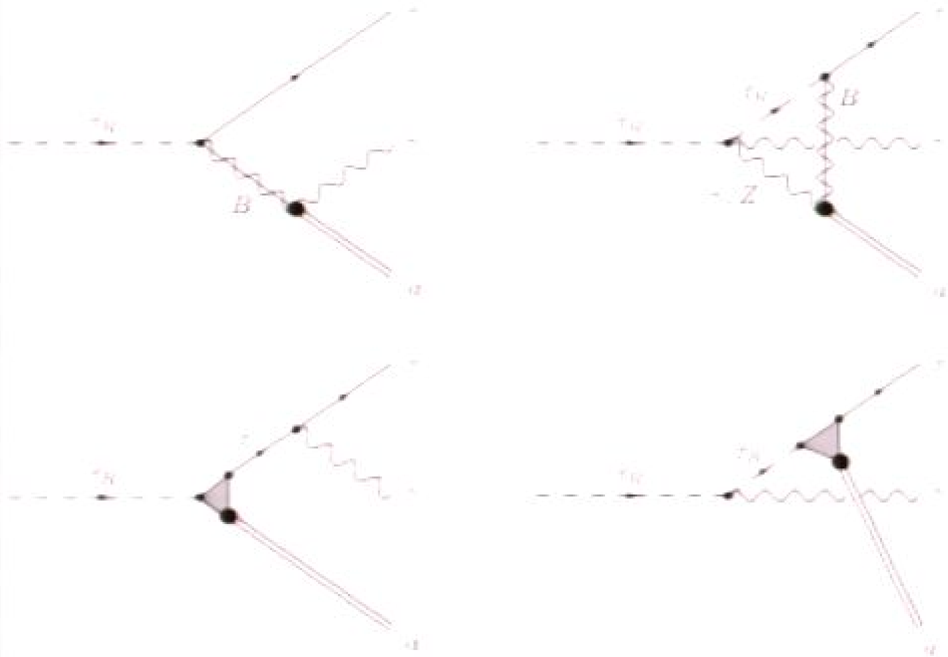
The 3-Body Decays

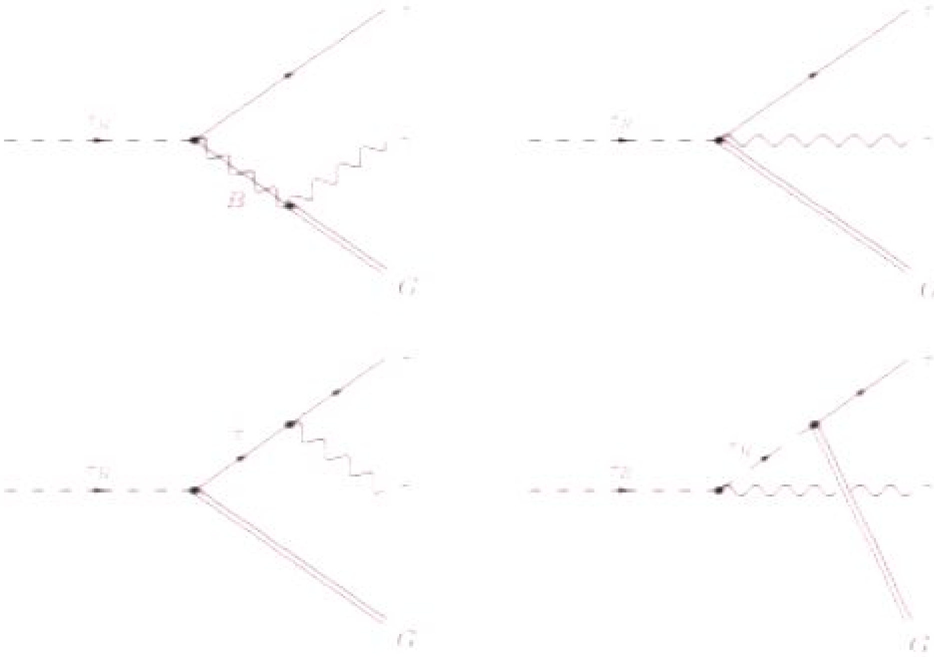


$\tilde{a} = \mathrm{LSP}: \quad \widetilde{\tau}_R \to \tau + \gamma + \tilde{a}$

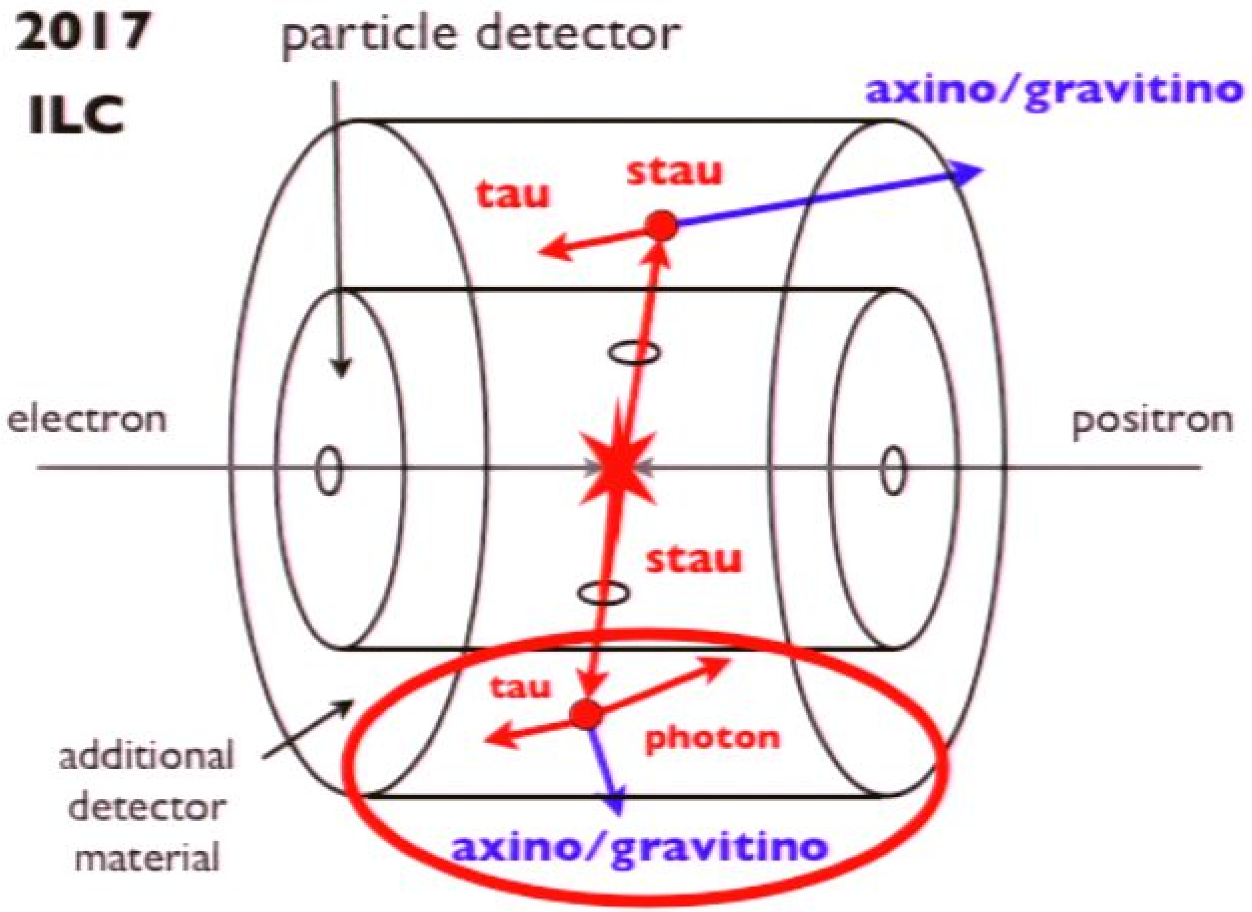


$$\frac{d^2\Gamma(\widetilde{\tau}_{\mathrm{R}} \to \tau\,\gamma\,\widetilde{a})}{dx_\gamma\, d\cos\theta} = \ldots$$

$\widetilde{G} = \mathrm{LSP}: \quad \widetilde{\tau}_R \to \tau + \gamma + \widetilde{G}$



$$\frac{d^2\Gamma(\widetilde{\tau}_{\mathrm{R}} \to \tau\,\gamma\,\widetilde{G})}{dx_\gamma\, d\cos\theta} = \ldots$$



3-Body Decays

Very Short/Very Long Lived NLSP $\rightarrow \widetilde{G}$ LSP Scenario

Can one distinguish between

$\tilde{a}$ LSP and $\widetilde{G}$ LSP

experimentally?

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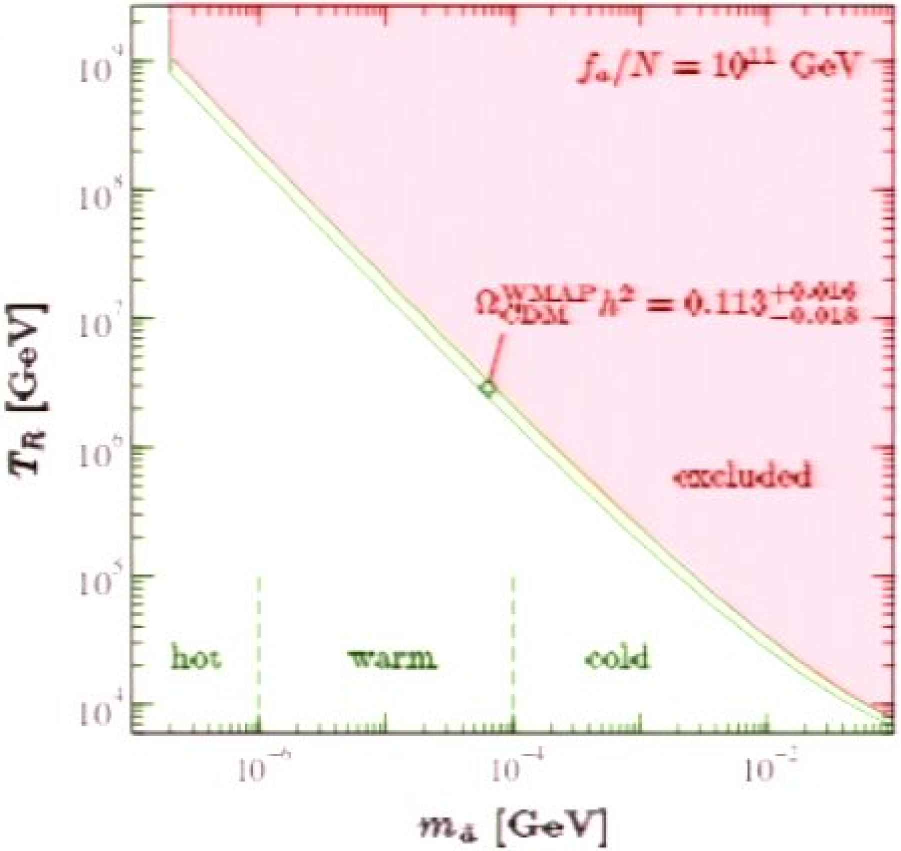
$\widetilde{G}$	$\left(\frac{p}{M_{Pl}}\right)^n$	therm. prod.	— cold	$\tilde{\tau}$ prod. at colliders (LHC, ILC, ...)
	extremely weak	NLSP decays	— warm	+ $\tilde{\tau}$ collection
	$M_{Pl} = 2.44 \times 10^{18}$ GeV	...	BBN	+ $\tilde{\tau}$ decay analysis: $m_{\widetilde{G}}$, M_{Pl} (?)
$\tilde{a}$	$\left(\frac{p}{f_a}\right)^n$	therm. prod.	— cold	$\tilde{\tau}$ prod. at colliders (LHC, ILC, ...)
	extremely weak	NLSP decays	— warm	+ $\tilde{\tau}$ collection
	$f_a \gtrsim 10^9$ GeV	...	BBN	+ $\tilde{\tau}$ decay analysis: $m_{\tilde{a}}$, f_a

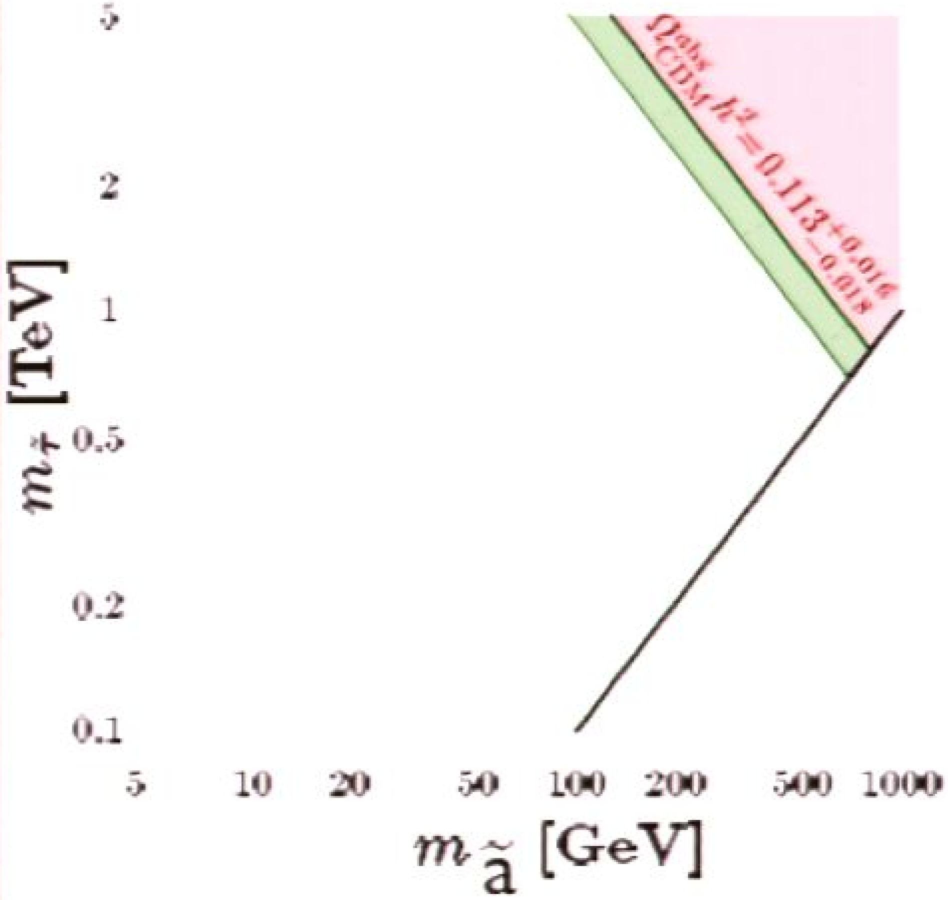
Thermal $\tilde{a}$ Production



[Brandenburg, FDS, '04]

see also [Covi et al., '01]

$\tilde{\tau}$ NLSP $\longrightarrow$ $\tilde{a} + \tau$



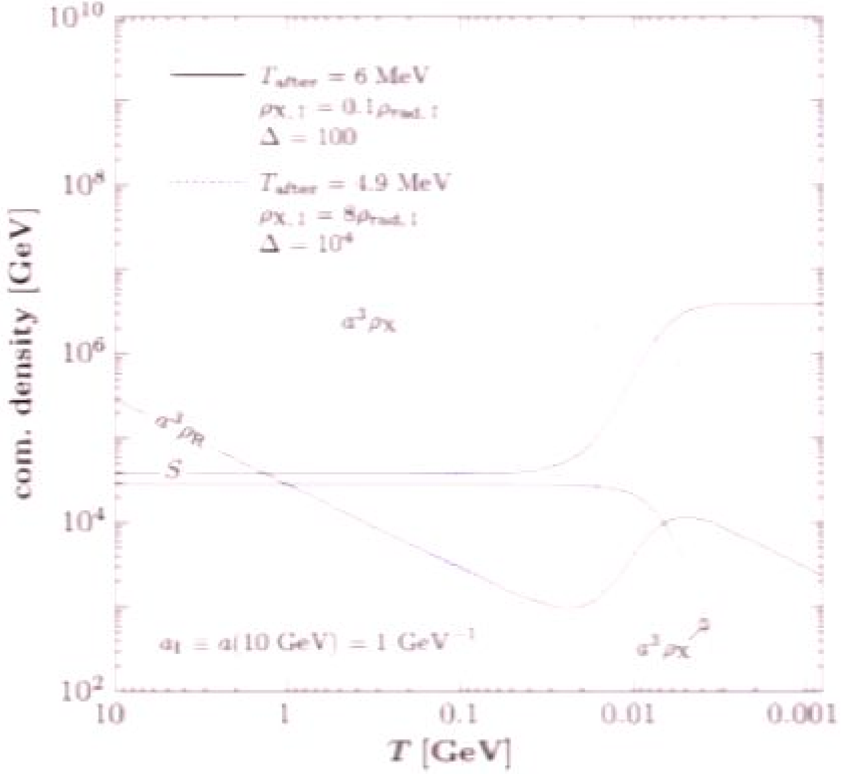
identical to the gravitino case

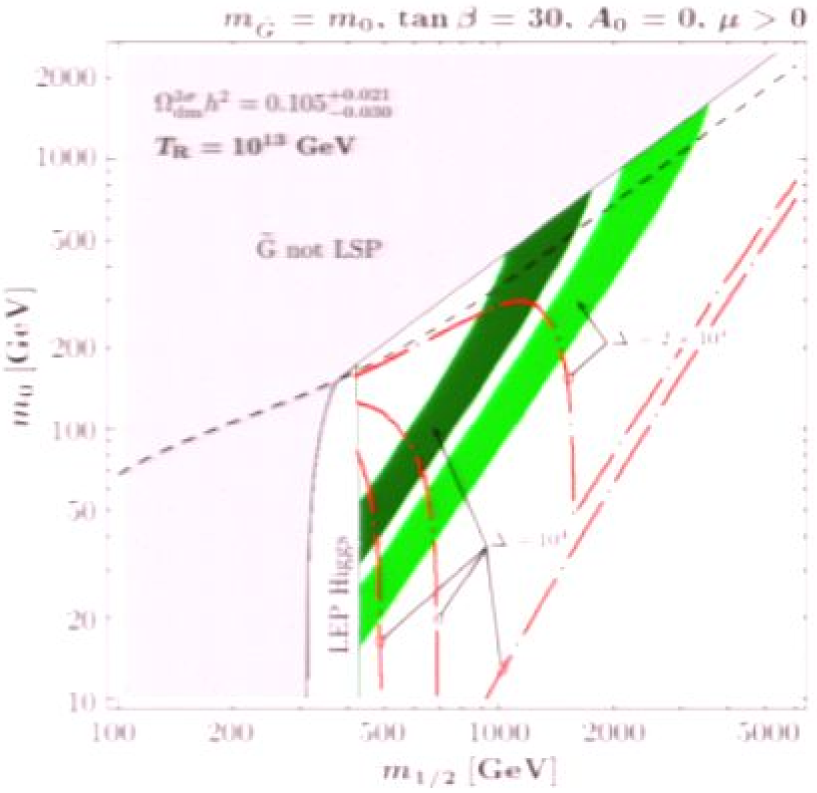
Supersymmetric Dark Matter Candiates

	LSP	ID	mass	interaction
lightest neutralino	$\tilde{\chi}_1^0$	$\tilde{B}, \widetilde{W}, \tilde{H}_u^0, \tilde{H}_d^0$	$\mathcal{O}(100\ \mathrm{GeV})$	g, g'
∈ MSSM		mixture	$M_1, M_2, \mu, \tan\beta$	weak
				$M_W \sim 100$ GeV
gravitino	$\tilde{G}$	superpartner of	eV – TeV	$\left(\frac{p}{M_{Pl}}\right)^n$
* gravity		the graviton	SUSY breaking	extremely weak
* local SUSY				$M_{Pl} = 2.44 \times 10^{18}$ GeV
axino	$\tilde{a}$	superpartner of	???	$\left(\frac{p}{f_a}\right)^n$
* strong CP		the axion	model	extremely weak
				$f_a \gtrsim 10^9$ GeV

Late-Time Entropy Production

[Pradler, FDS, hep-ph/0612291, Hamaguchi et al., hep-ph/0702274]





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

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

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

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

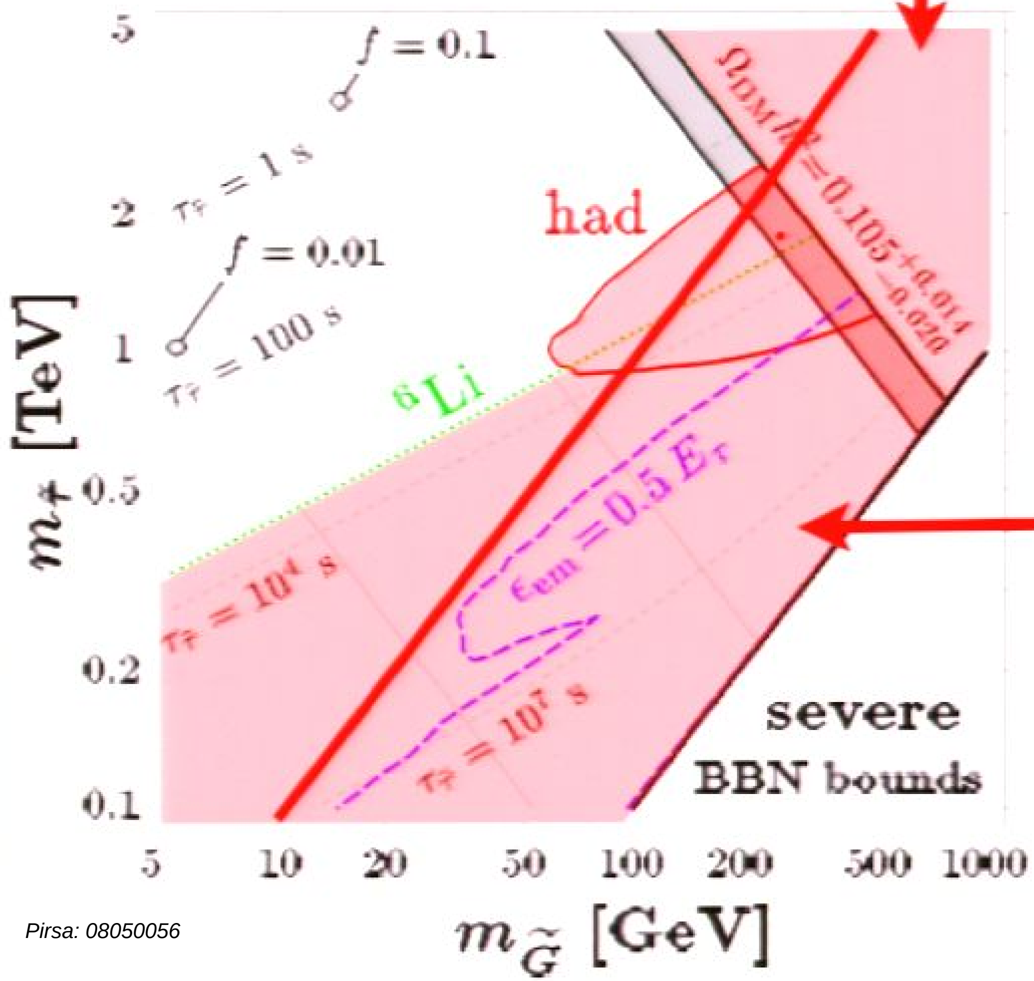
$$Y_{\rm NLSP}(T_0) = \frac{1}{\Delta}Y_{\rm NLSP}(T_{\rm low})$$

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

Warning:

Standard Cosmological History

… requires $\boxed{m_{\tilde{G}} > 0.1 m_{\tilde{\tau}}}$



disfavored by cosmological constraints

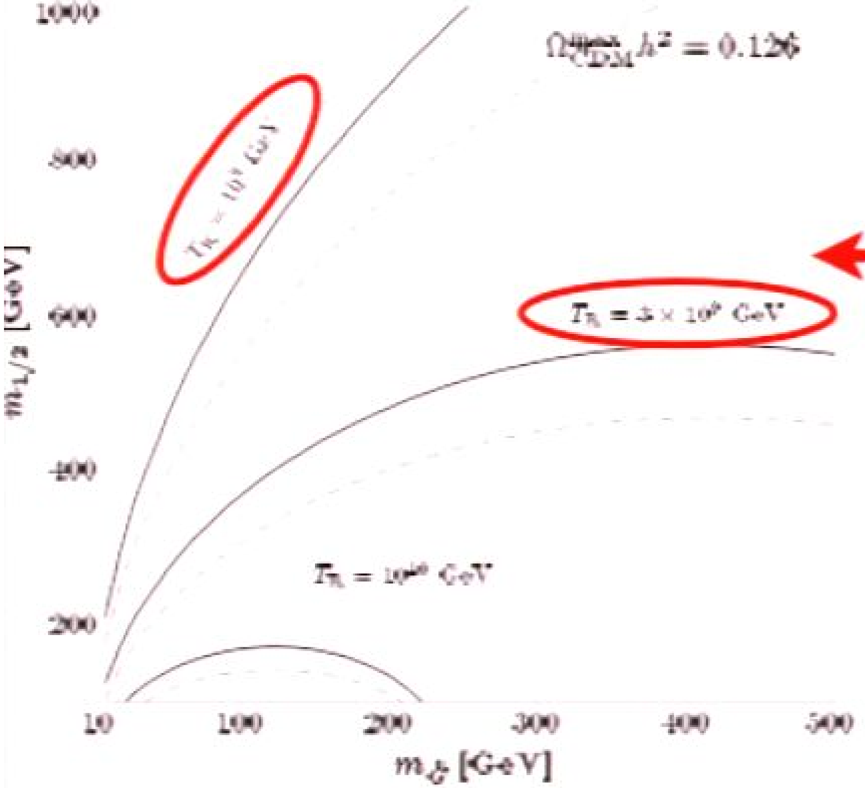
[FDS, hep-ph/0611027 & arXiv:0711.1240, Kawasaki, Kohri, Moroi, hep-ph/0703122, ...]

... requires $\boxed{m_{\tilde{G}} > 0.1 m_{\tilde{\tau}}}$ [..., Martyn, '06, ...]

Can one identify

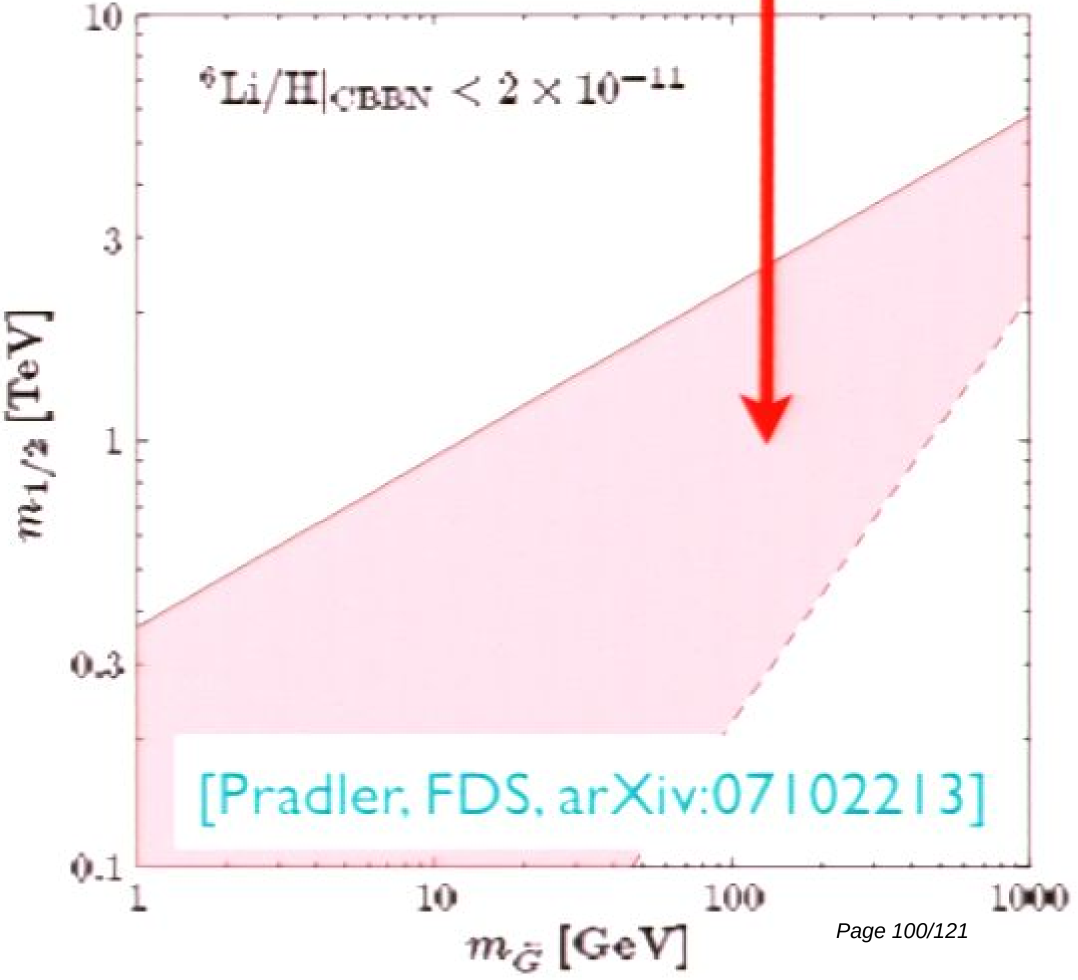
the gravitino LSP

experimentally?



[Pradler, FDS, '06]

disfavored by cosmological constraints



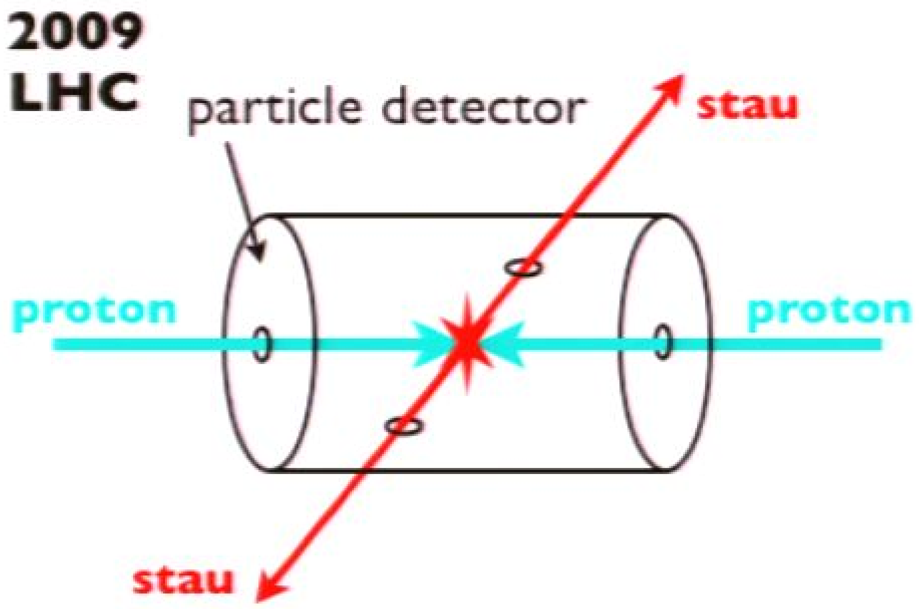
[Pradler, FDS, arXiv:0710221 3]

Signatures of Gravitinos in Experiments

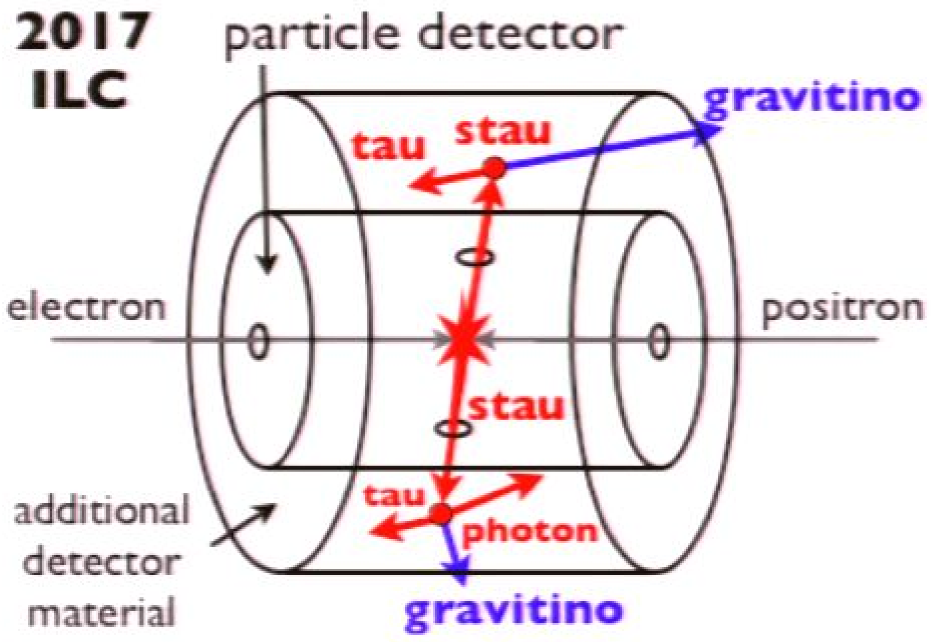
- Direct Detection of $\widetilde{G}$

- Direct Production of $\widetilde{G}$

⁎ “stable” charged sparticles



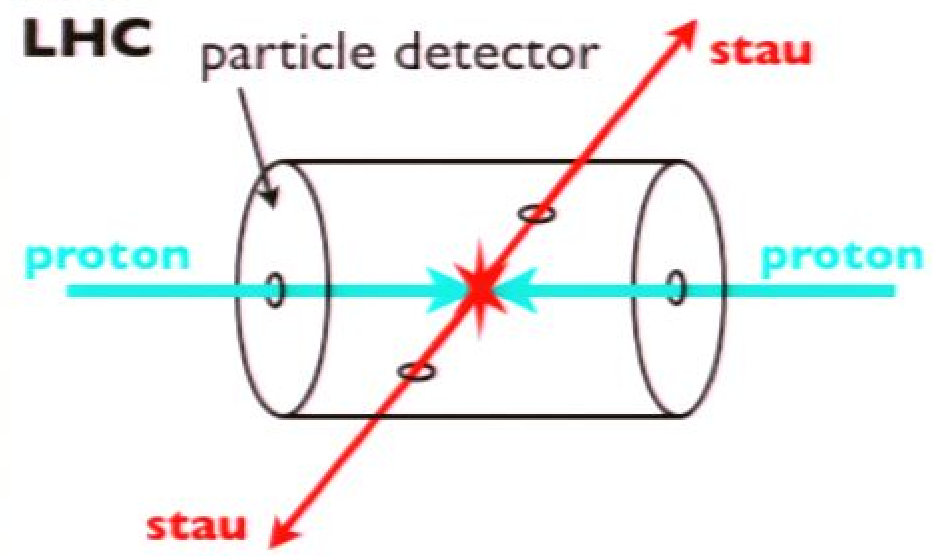
⁎ long-lived charged sparticles



[...; Buchmüller et al., '04; Hamaguchi et al., '04; Feng, Smith, '05; Martyn, '06; ...]

Gravitino DM @ LHC ← Stau NLSP

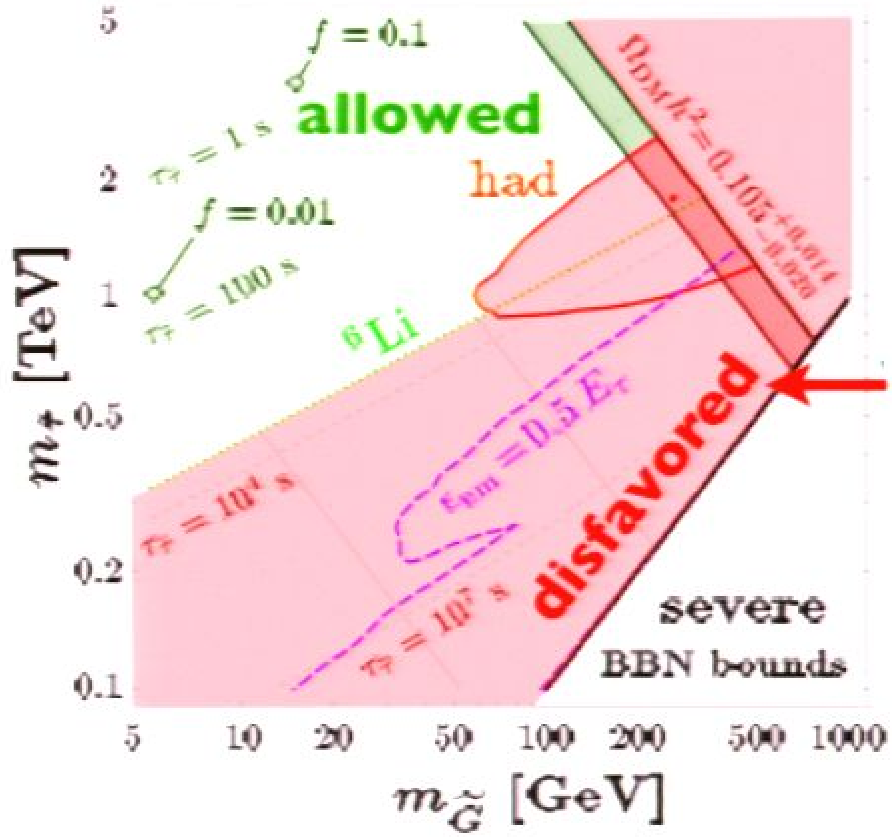
2009
LHC



The signal:

jets + leptons

+ 2 "stable" charged particles



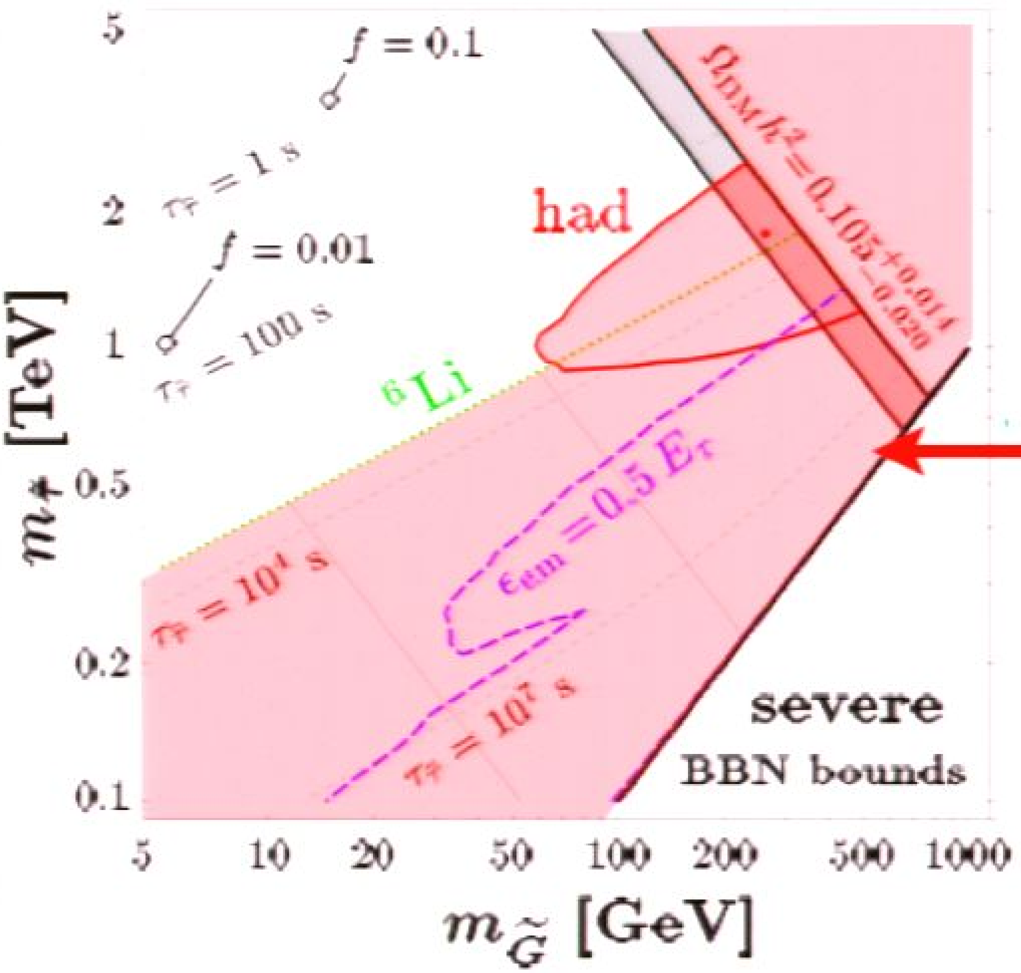
[FDS, hep-ph/0611027 & arXiv:0711.1240, Kawasaki, Kohri, Moroi, hep-ph/0703122, ...]

Cosmological Constraints

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

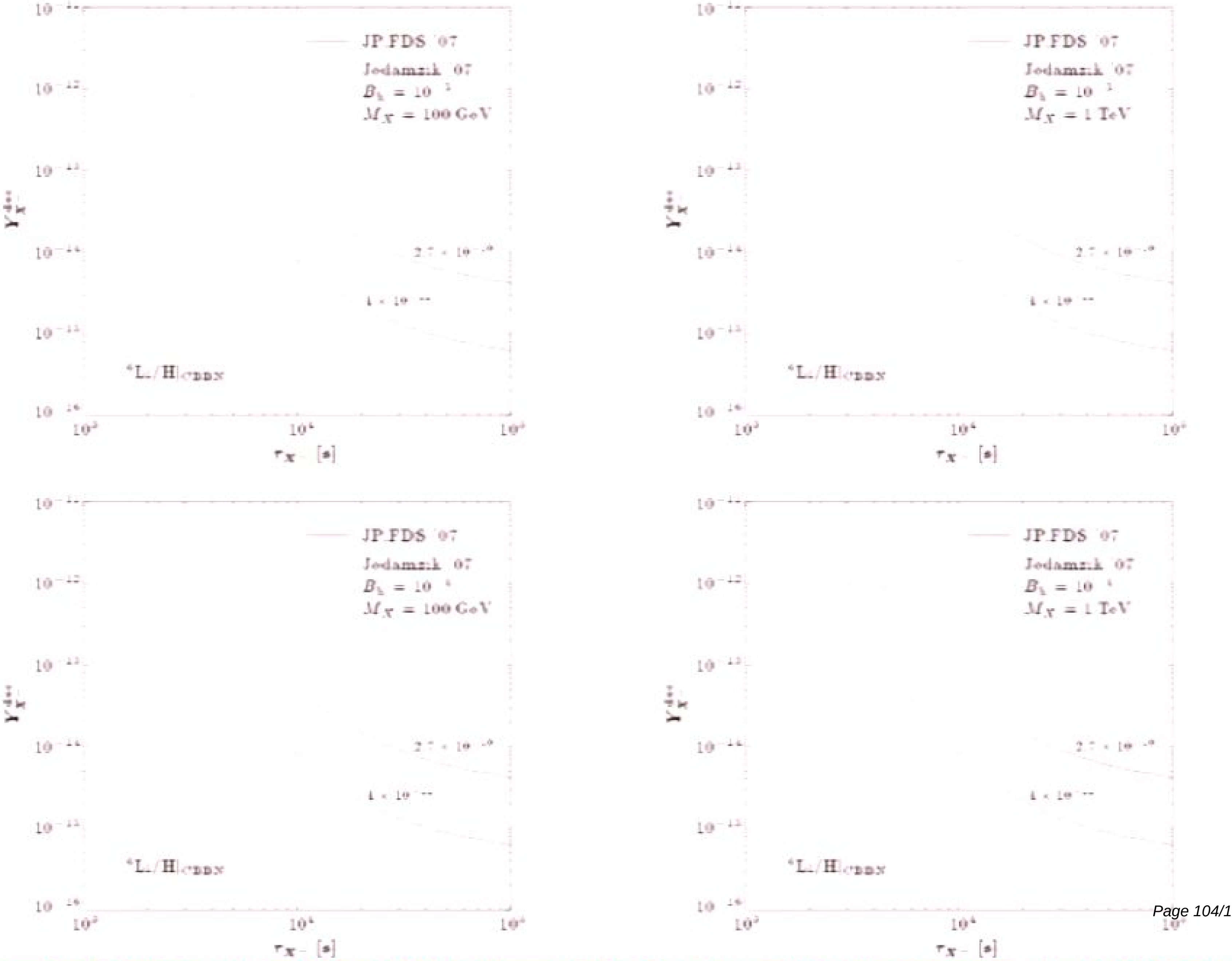
[FDS. hep-ph/0611027]

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



disfavored by cosmological constraints

Comparison of [Pradler, FDS, arXiv:0710.2213] with [Jedamzik, arXiv:0710.5153]



[Takayama, '07; Pradler, FDS, arXiv:0710.2213]

Catalyzed Big Bang Nucleosynthesis (CBBN)

$$({}^4\mathrm{He}X^-) + \mathrm{D} \longrightarrow {}^6\mathrm{Li} + X^-$$ [Pospelov, '06]

$$\frac{dY_{\rm BS}}{dt} = \langle\sigma_{\rm r} v\rangle s Y_\delta - \Gamma_{X^-} Y_{\rm BS} - \langle\sigma_{\rm C} v\rangle s Y_{\rm BS} Y_{\rm D}.$$

$$\frac{dY_{X^-}}{dt} = -\langle\sigma_{\rm r} v\rangle s Y_\delta - \Gamma_{X^-} Y_{X^-} + \langle\sigma_{\rm C} v\rangle s Y_{\rm BS} Y_{\rm D}.$$

$$\frac{dY_{^4\rm He}}{dt} = -\langle\sigma_{\rm r} v\rangle s Y_\delta + \Gamma_{X^-} Y_{\rm BS}.$$

$$\frac{dY_{^6\rm Li}}{dt} = \langle\sigma_{\rm C} v\rangle s Y_{\rm BS} Y_{\rm D}.$$

$$\frac{dY_{\rm D}}{dt} = -\langle\sigma_{\rm C} v\rangle s Y_{\rm BS} Y_{\rm D}.$$

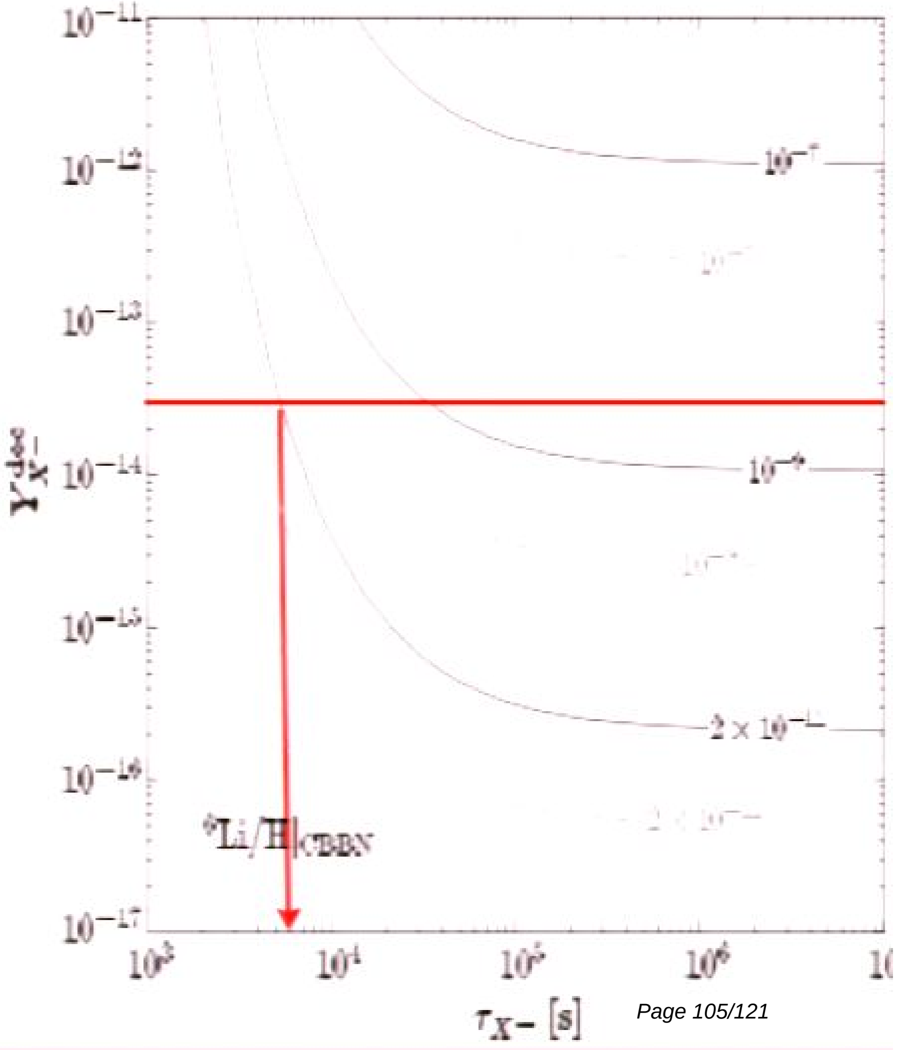
$$\langle\sigma_{\rm C} v\rangle = 2.37 \times 10^8\,(1 - 0.34 T_9)\, T_9^{-2/3} e^{-5.33 T_9^{-1/3}}$$

[Hamaguchi et al., '07]

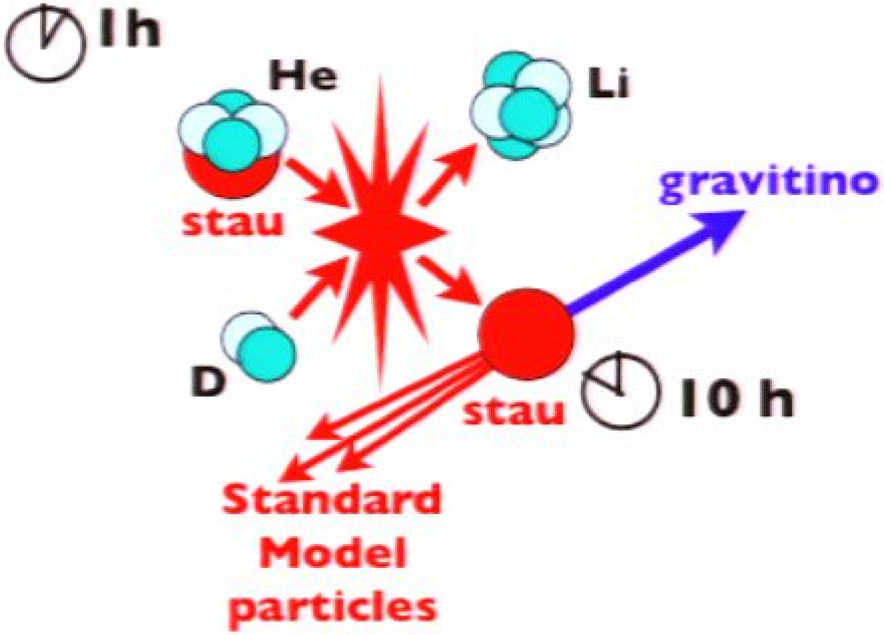
$$\langle\sigma_{\rm r} v\rangle = \frac{2^9 \pi \alpha Z_\alpha^2 \sqrt{2\pi}}{3e^4} \frac{E_{\rm b}}{m_\alpha^2 \sqrt{m_\alpha T}}$$

$$Y_\delta \equiv (Y_{X^-} Y_{^4\rm He} - Y_{\rm BS} \widetilde{Y}_\gamma)$$

$E_{\rm b} = 337.33\ \mathrm{keV}$ $\qquad \widetilde{n}_\gamma \equiv n_\gamma(E > E_{\rm b})$



Catalyzed BBN [Pospelov, '06]

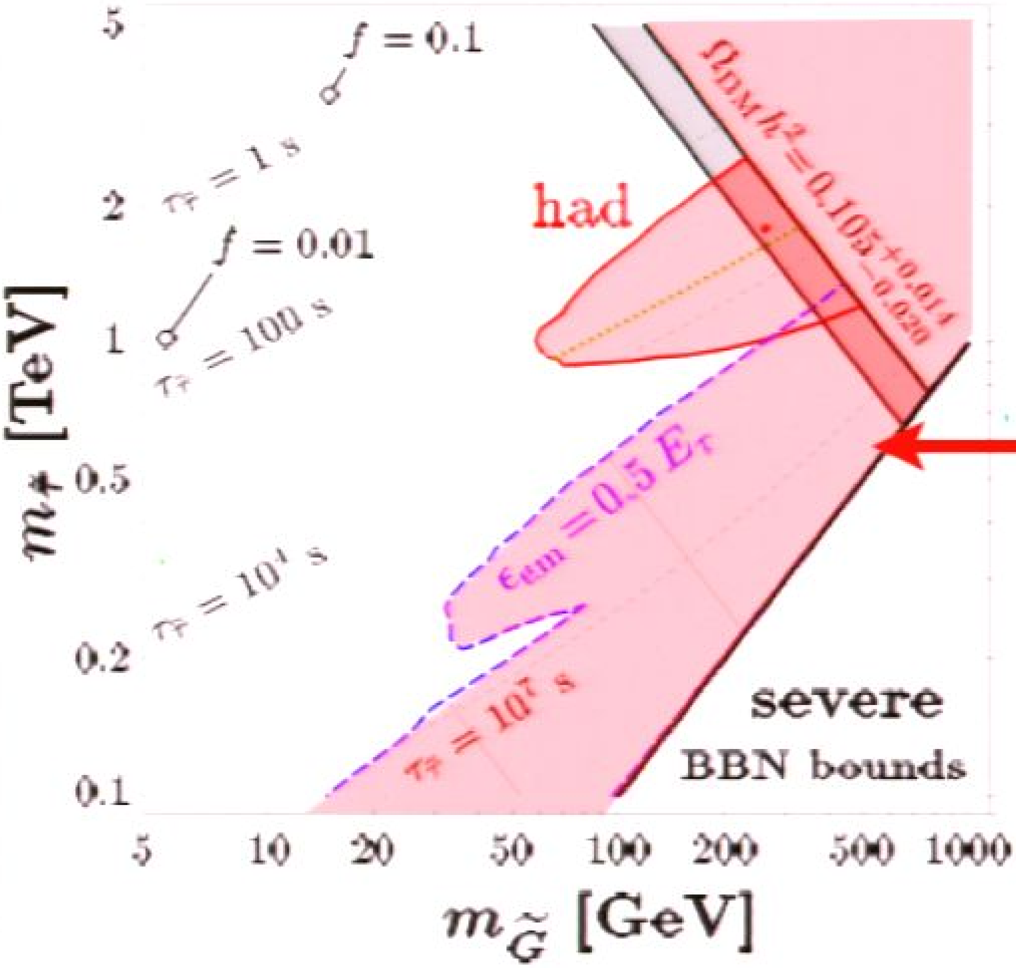


Recent Result: [Hamaguchi et al., '07]

[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; ...]

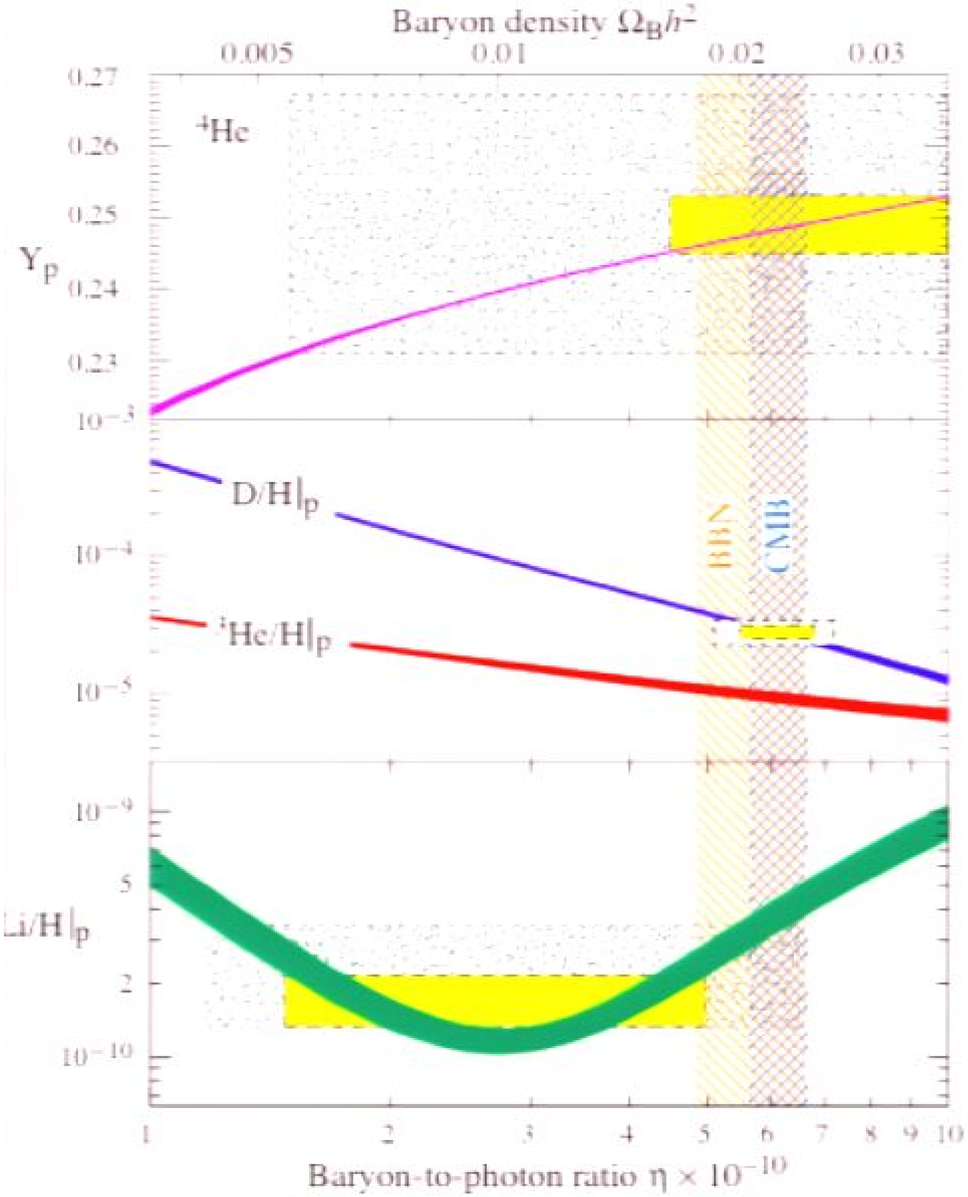
[FDS, '06]

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

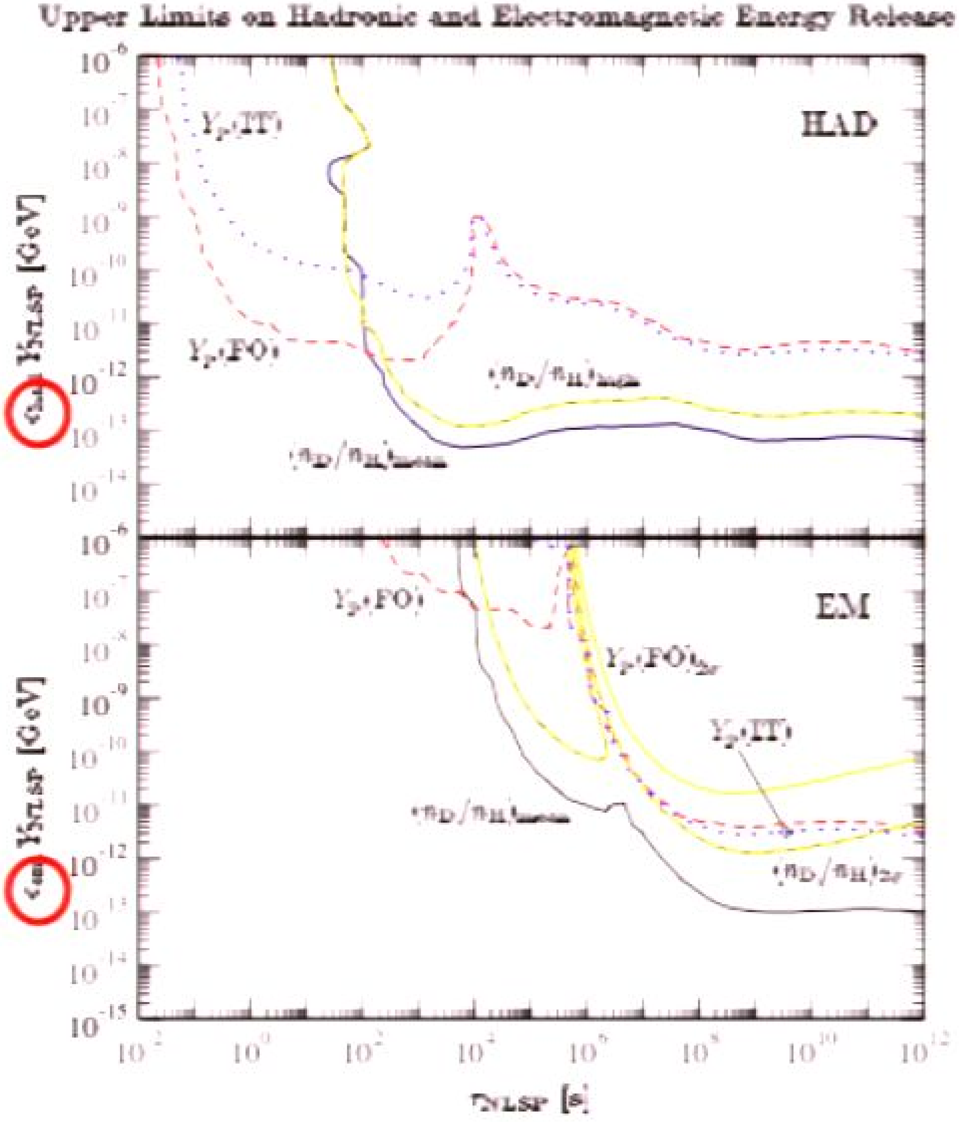


disfavored by cosmological constraints

Big-Bang Nucleosynthesis



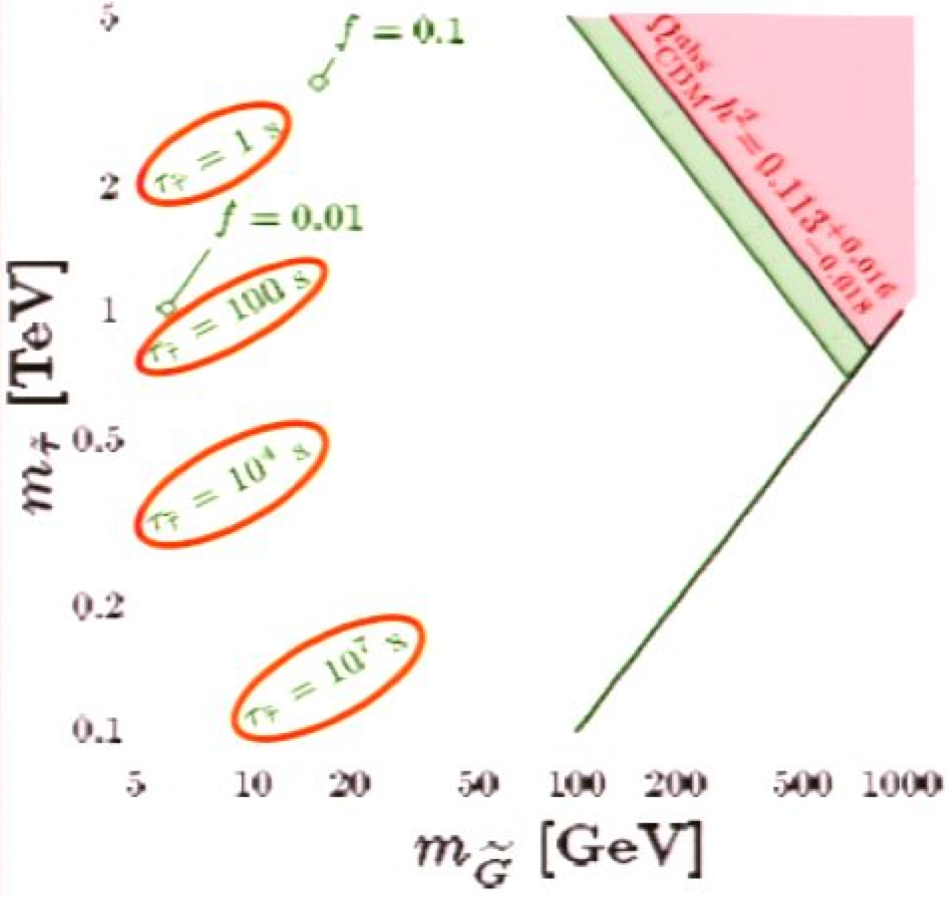
[Particle Data Book 2006]



[Kawasaki, Kohri, Moroi, '05; Cyburt et al., '03

long-lived NLSP

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

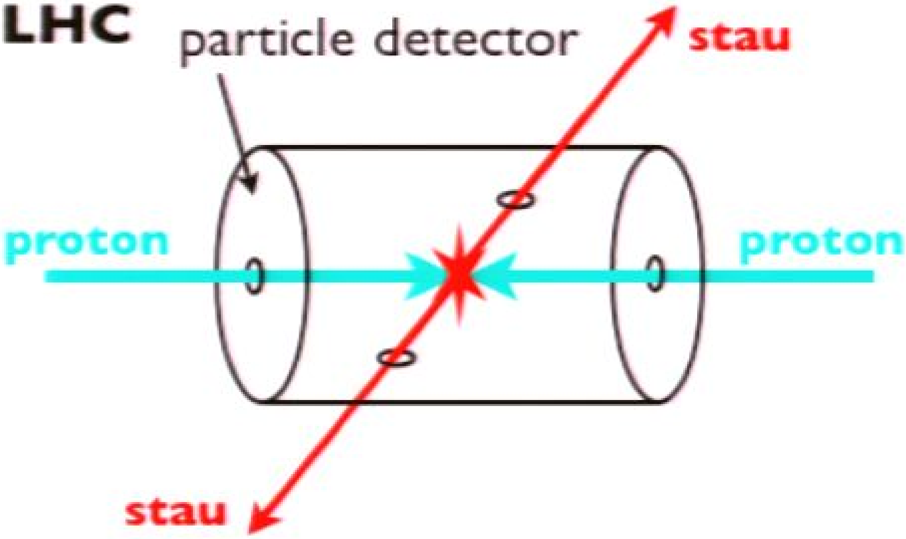


Signatures of Gravitinos in Experiments

- Direct Detection of $\widetilde{G}$
- Direct Production of $\widetilde{G}$

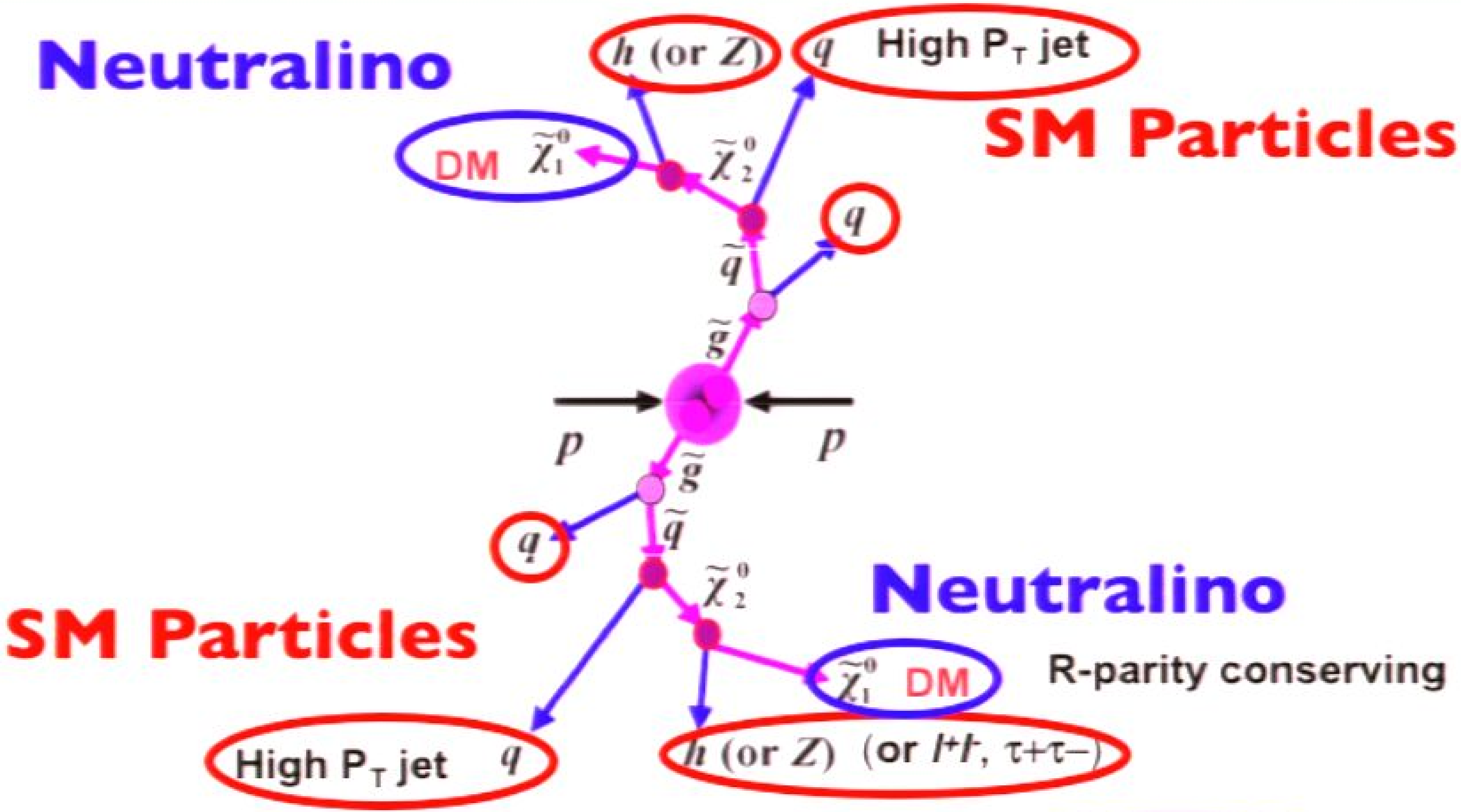
*** “stable” charged sparticles**

2009
LHC



The signal:
jets + leptons
+ 2 “stable”
charged particles

Neutralino DM Production at the LHC

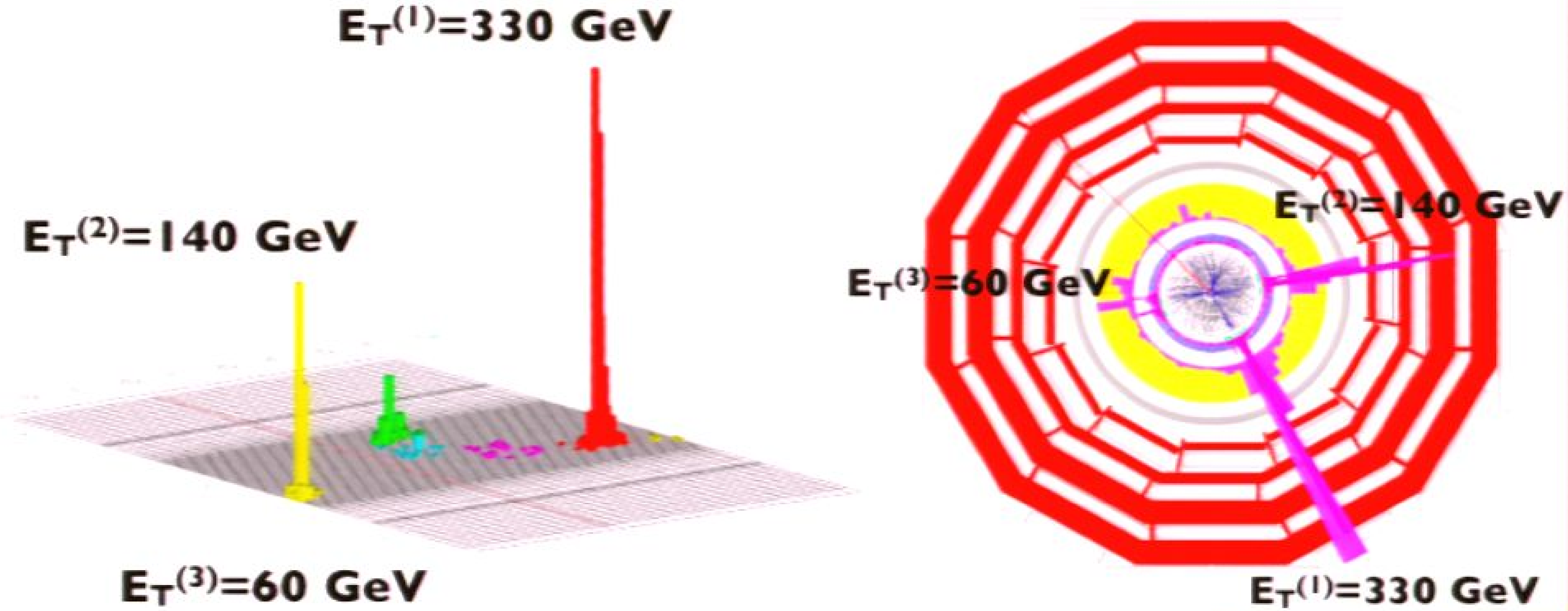


The signal : jets + leptons + missing E_T

[from B. Dutta's Talk, SUSY 2007]

Neutralino Dark Matter Production @ CMS

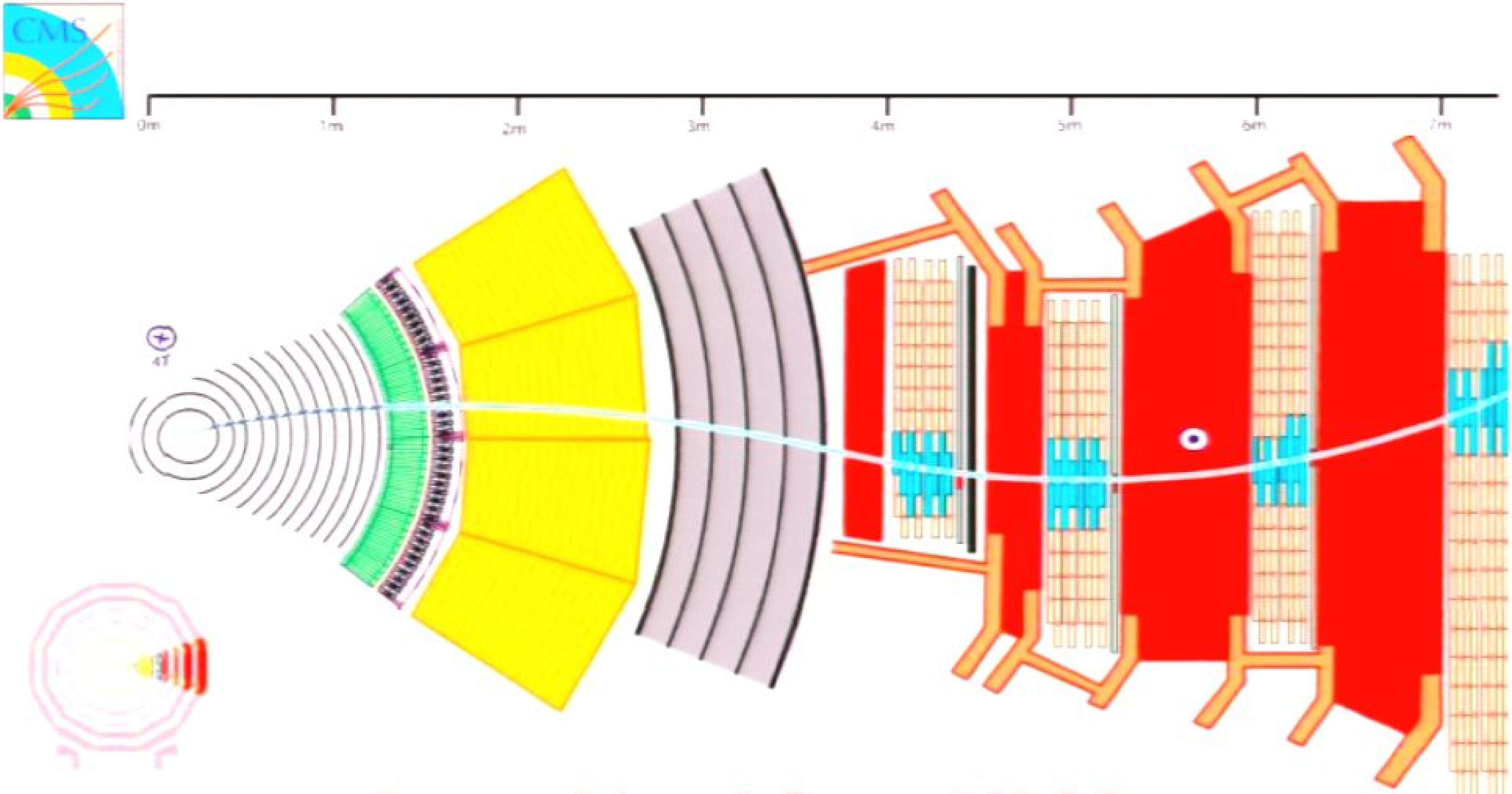
$E_T^{missing}$=360 GeV



Neutralino LSP Pair

[from M. Tytgat's Talk, SUSY 2007]

“Stable” Charged Massive Particle @ LHC

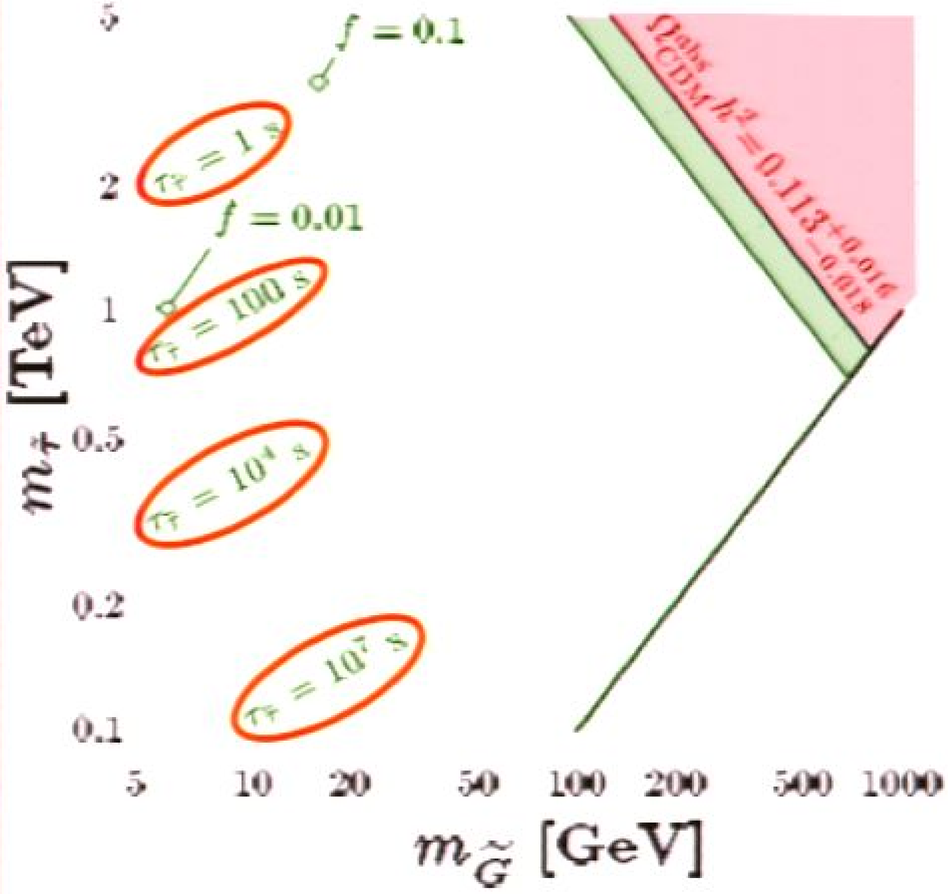


Long-Lived Stau NLSP

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

long-lived NLSP

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

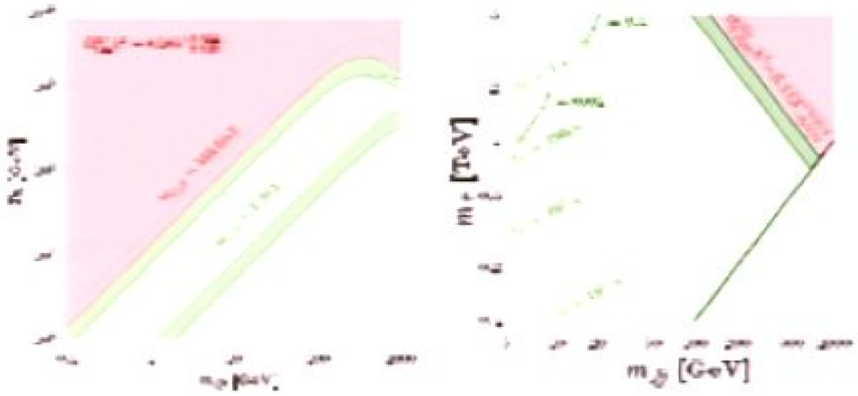


Signatures of Gravitinos in Experiments

- Direct Detection of $\widetilde{G}$
- Direct Production of $\widetilde{G}$

LSP Dark Matter: Production, Constraints, Experiments

LSP	interaction	production	constraints	experiments
$\tilde{\chi}_1^0$	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, ...)
$\tilde{G}$	$\left(\frac{p}{M_{Pl}}\right)^n$	therm. prod.	← cold	
	extremely weak	NLSP decays	← warm	
	$M_{Pl} = 2.44 \times 10^{18}$ GeV	...		



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

is possible!!!

Free Streaming of Gravitinos from Thermal Production

☐ Comoving Free-Streaming Scale

$$\lambda_{\rm FS}^{t_{\rm i}\ll t_{\rm eq}} \simeq \int_0^{t_{\rm eq}} dt\, \frac{v(t)}{a(t)} = v_0\, t_{\rm eq}\, (1{+}z_{\rm eq})^2\, \ln\left(\sqrt{1+\frac{1}{v_0^2\,(1+z_{\rm eq})^2}}+\frac{1}{v_0\,(1+z_{\rm eq})}\right)$$

☐ Present Free-Streaming Velocity $\quad v_0 = v_{\rm FS}^{\rm rms,0}$

- Gravitinos from Thermal Production

$$(v_{\rm FS}^{\rm rms,0})^{\widetilde{G}\,\rm TP} = 5.8\times10^{-6}\,\frac{\rm km}{\rm s}\left(\frac{10\ {\rm MeV}}{m_{\widetilde{G}}}\right)\left(\frac{230}{g_{*S}(T_R)}\right)^{1/3}$$

- Warm Dark Matter — Hot Thermal Relics

$$(v_{\rm FS}^{\rm rms,0})_{\rm WDM} = 0.77\,\frac{\rm km}{\rm s}\left(\frac{\Omega_{\rm WDM}h^2}{0.113}\right)^{1/3}\left(\frac{100\ {\rm eV}}{m_{\rm WDM}}\right)^{4/3}$$

$$\Omega_{\rm WDM}h^2 = 0.115\left(\frac{100}{g_{*S}(T_{\rm f})}\right)\left(\frac{m_{\rm WDM}}{100\ {\rm eV}}\right)$$

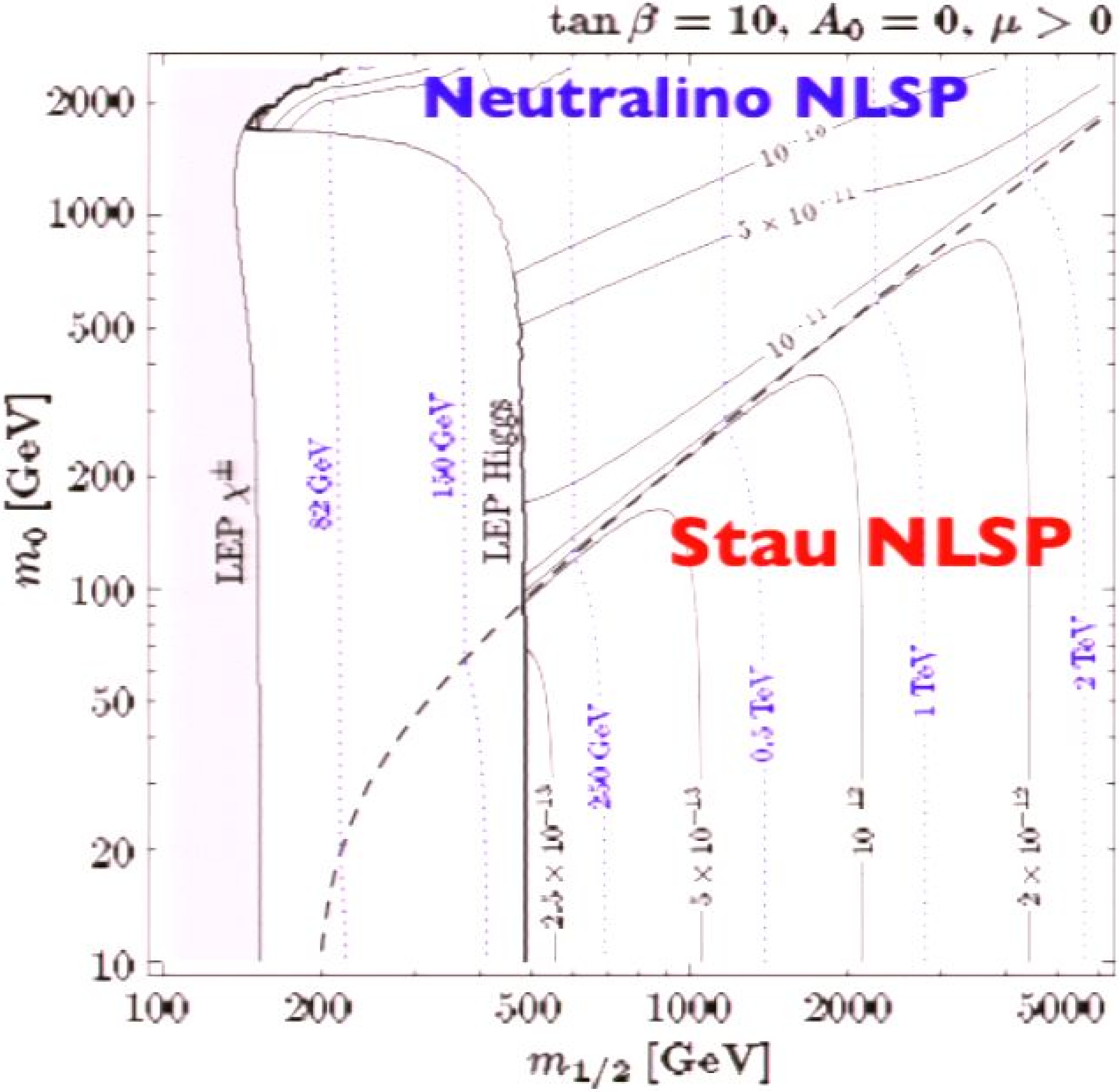
[FDS, '06]

Constraints from Observ./Simul. of Cosmic Structures

Probe/Observable	$m_{\rm WDM}^{\rm min}$	$(v_{\rm FS}^{\rm rms,0})_{\rm WDM}^{\rm max}$	Ref.
Dwarf spheroidal galaxies	0.7 keV	0.06 km/s	[Dalcanton et al., '00]
Lyman-α forest at $z \simeq 3$	0.75 keV	0.05 km/s	[Narayanan et al., '00]
Lyman-α forest at $z \simeq (2-3)$	0.55 keV	0.08 km/s	[Viel et al., '05]
Supermassive black hole at $z \simeq 5.8$	0.5 keV	0.09 km/s	[Barkana et al., '01]
Cosmological reionization by $z \simeq 5.8$	0.75 keV	0.05 km/s	[Barkana et al., '01]
(Cosmological reionization at $z \simeq 17$	10 keV	0.002 km/s	[Yoshida et al., '03])

Collisionless CDM $\longrightarrow$ Too Much Power on Small Scales ($\lesssim 1$ Mpc)

- excess in the number of low mass halos
- overdensity of halo cores

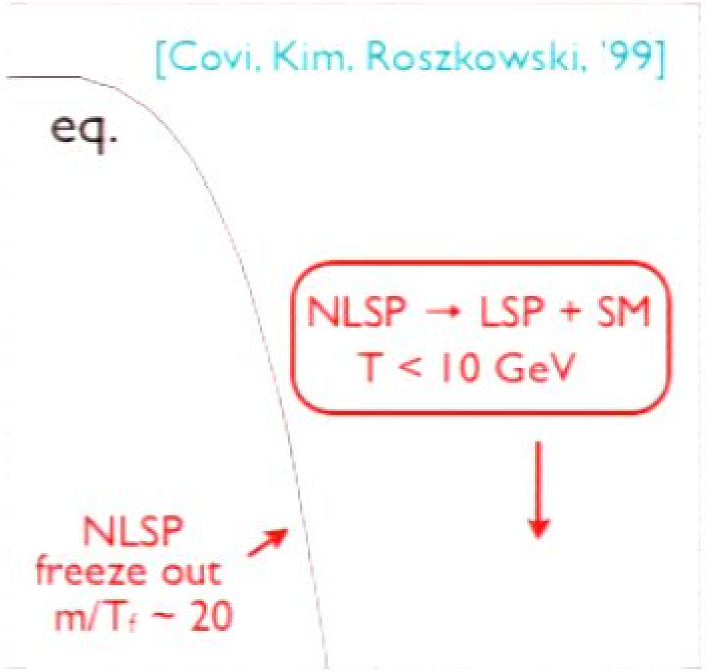

$\tan\beta = 10,\ A_0 = 0,\ \mu > 0$
Neutralino NLSP
Stau NLSP
10^{-10}
5×10^{-11}
10^{-11}
LEP $\chi^{\pm}$
82 GeV
150 GeV
LEP Higgs
250 GeV
0.5 TeV
1 TeV
2 TeV
2.5×10^{-13}
5×10^{-13}
10^{-12}
2×10^{-12}
m_0 [GeV]
$m_{1/2}$ [GeV]
10
20
50
100
200
500
1000
2000
100
200
500
1000
2000
5000

LSP Dark Matter: Production, Constraints, Experiments

LSP	interaction	production	constraints	experiments
$\tilde{\chi}_1^0$	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, ...)
$\tilde{G}$	$\left(\frac{p}{M_{Pl}}\right)^n$	therm. prod.	— cold	
	extremely weak	NLSP decays	— warm	
	$M_{Pl} = 2.44 \times 10^{18}$ GeV	...		

NLSP Candidates

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



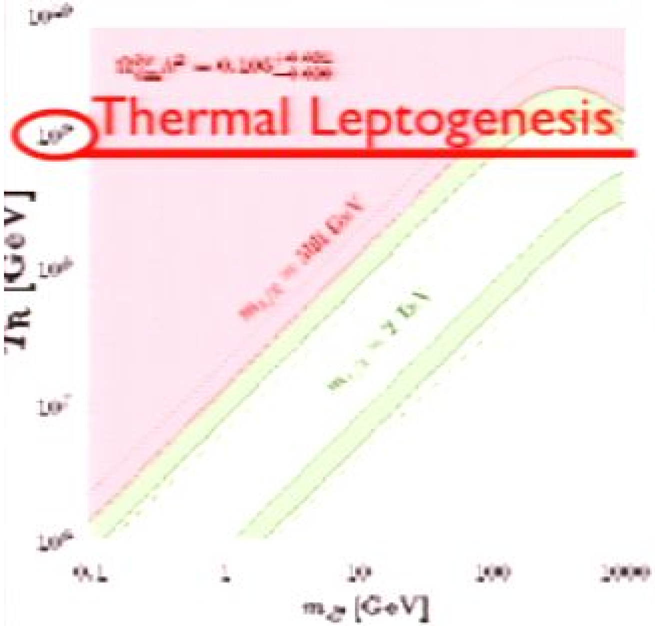
[Covi, Kim, Roszkowski, '99]

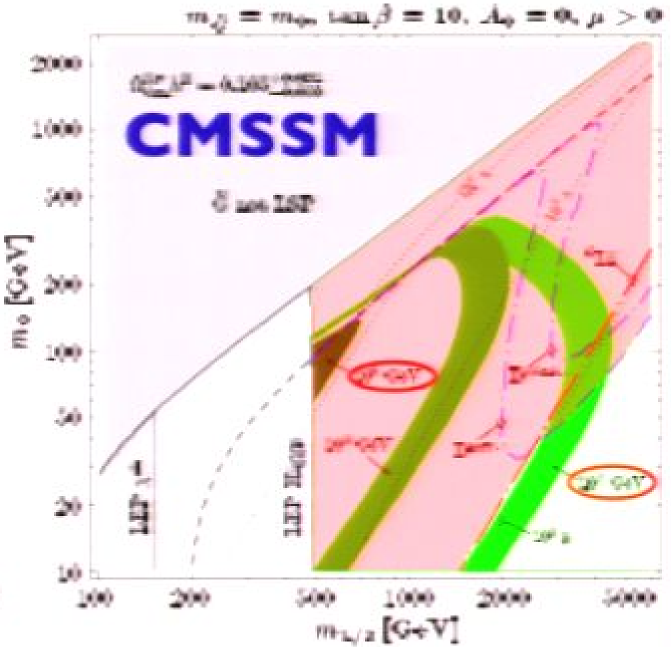
NLSP → LSP + SM
T < 10 GeV

NLSP
freeze out
$m/T_f \sim 20$

Upper Limits on the Reheating Temperature

Stable Gravitino





$\Omega_{\rm DM}$ constraint for gravitino DM

[Moroi, Murayama, Yamaguchi, '93;

...

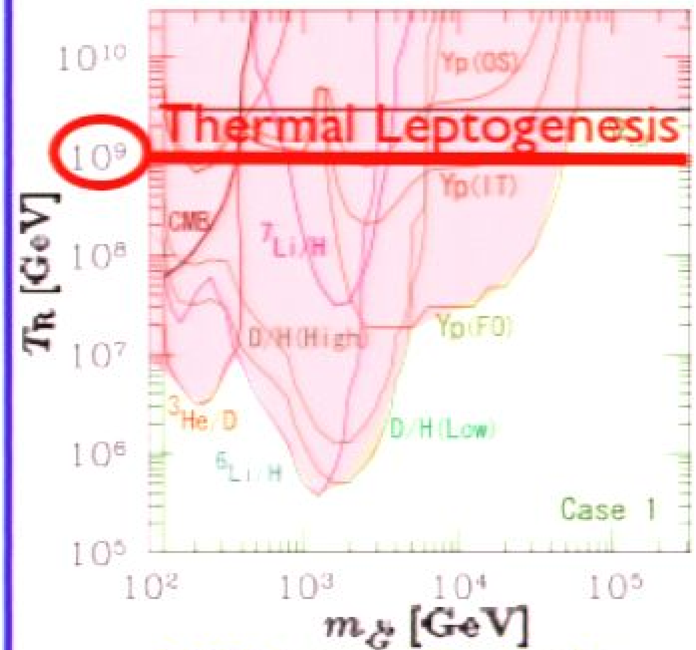
Pradler, Steffen, '07]

+ BBN constraints

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

[Pradler, Steffen, arXiv:0710.2213]

Unstable Gravitino



BBN constraints

+ $\Omega_{\rm DM}$ constraint for neutralino DM

[Kohri, Moroi, Yotsuyanagi, '05]

Thermal Leptogenesis requires T >10^9 GeV