

# Can One Determine $T_R$ at the LHC with $\tilde{a}$ or $\tilde{G}$ Dark Matter?

Leszek Roszkowski

Astro–Particle Theory and Cosmology Group  
Sheffield, England

with K.-Y. Choi and R. Ruiz de Austri

arXiv:0710.3349 → JHEP'08

# Non-commercial advert

# SuperBayes

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MCMC scan + Bayesian study of SUSY models

new development, led by two groups: B. Allanach (Cambridge), and us

prepare tools for data from LHC and dark matter searches

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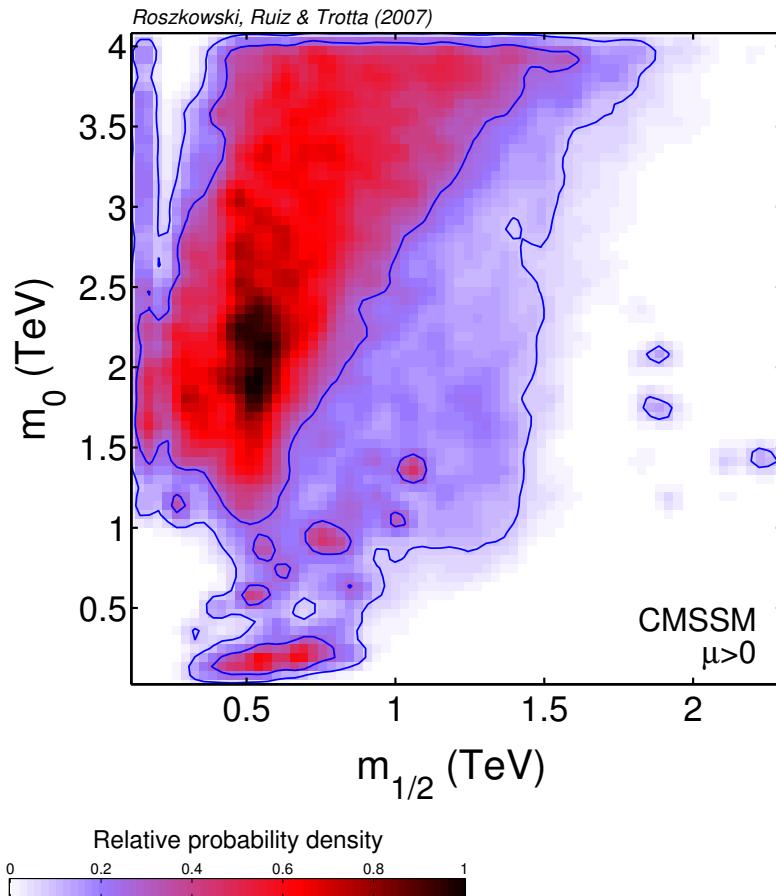
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arXiv:0705.2012 (flat priors)



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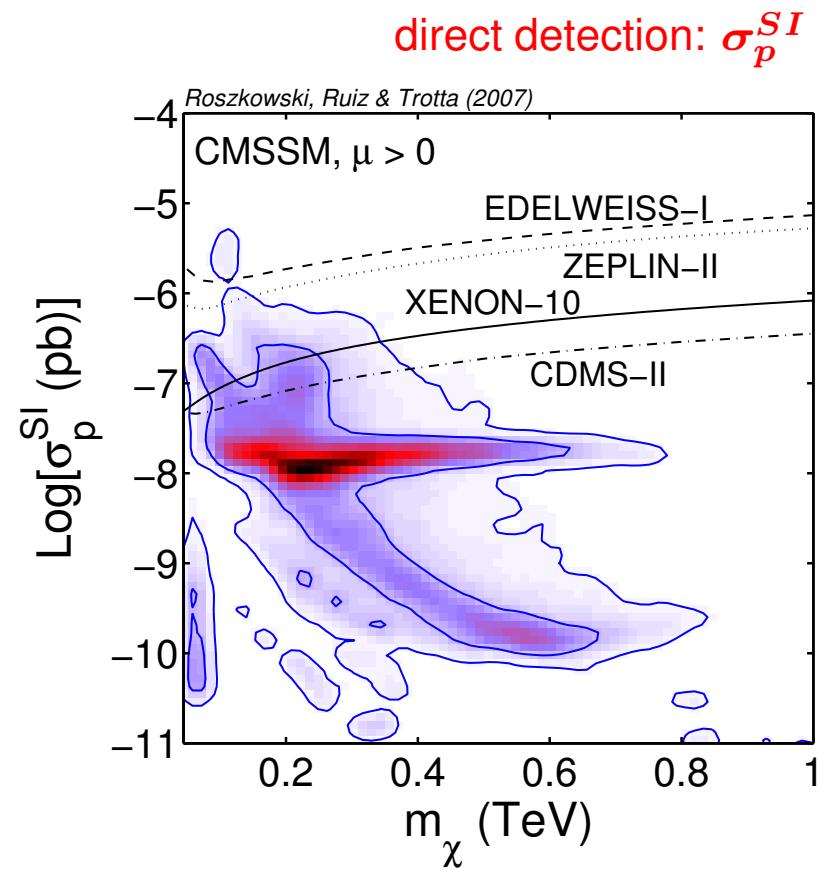
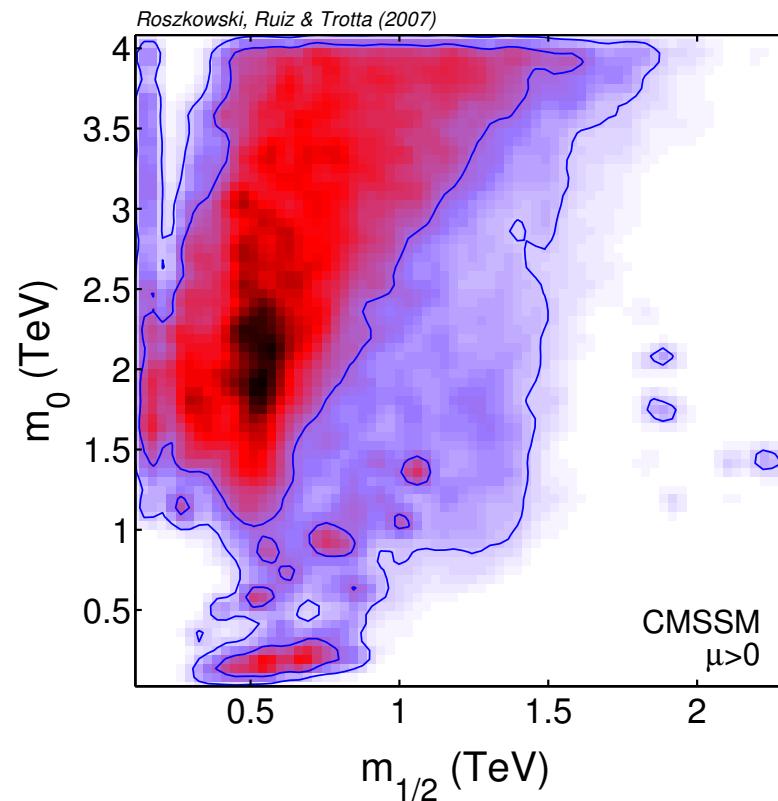
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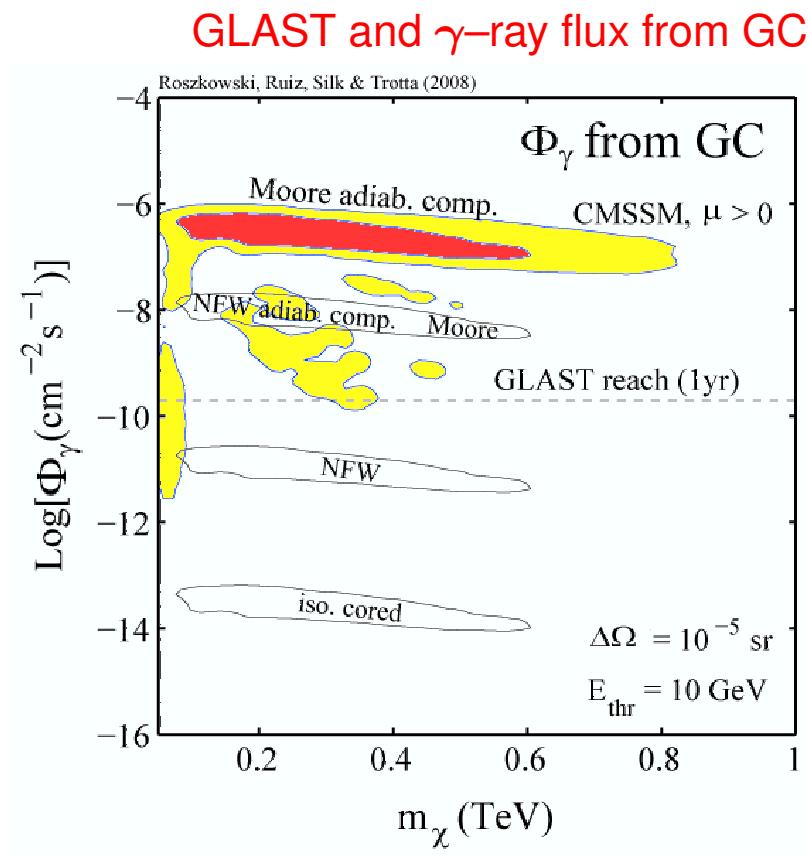
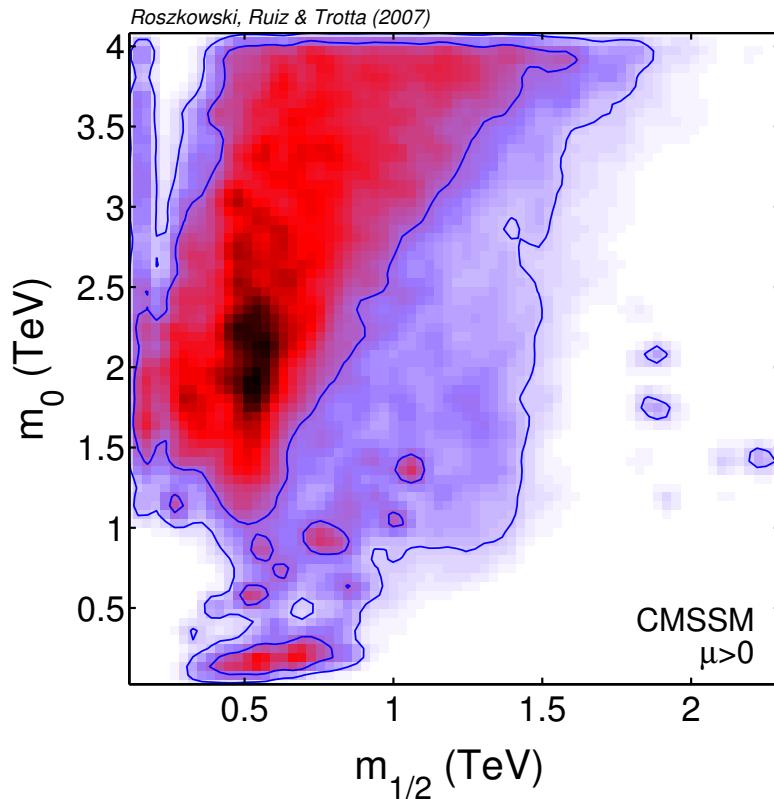
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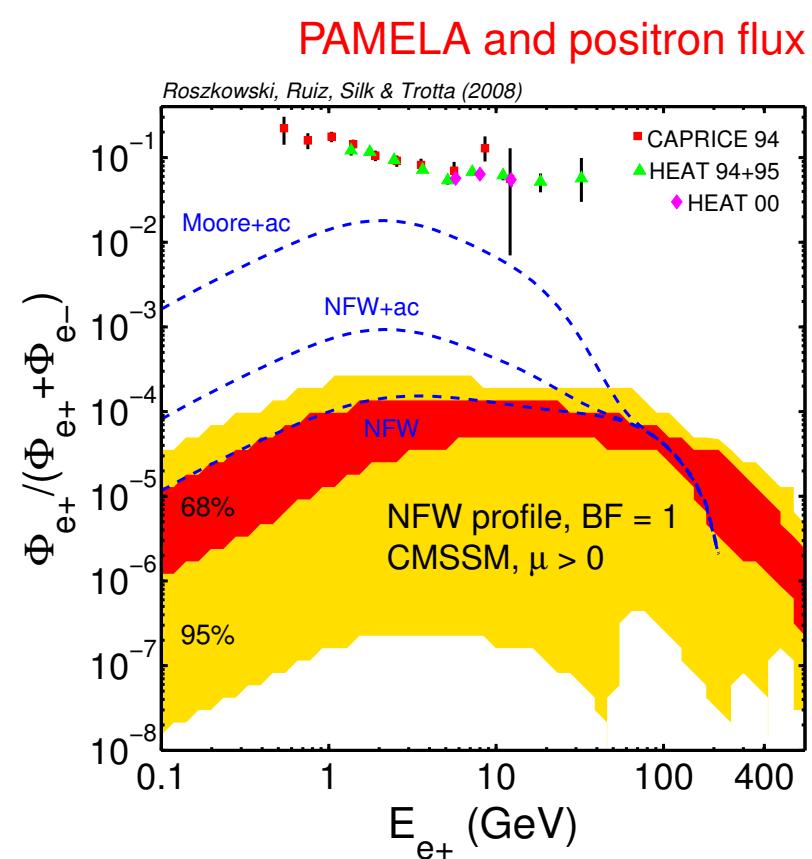
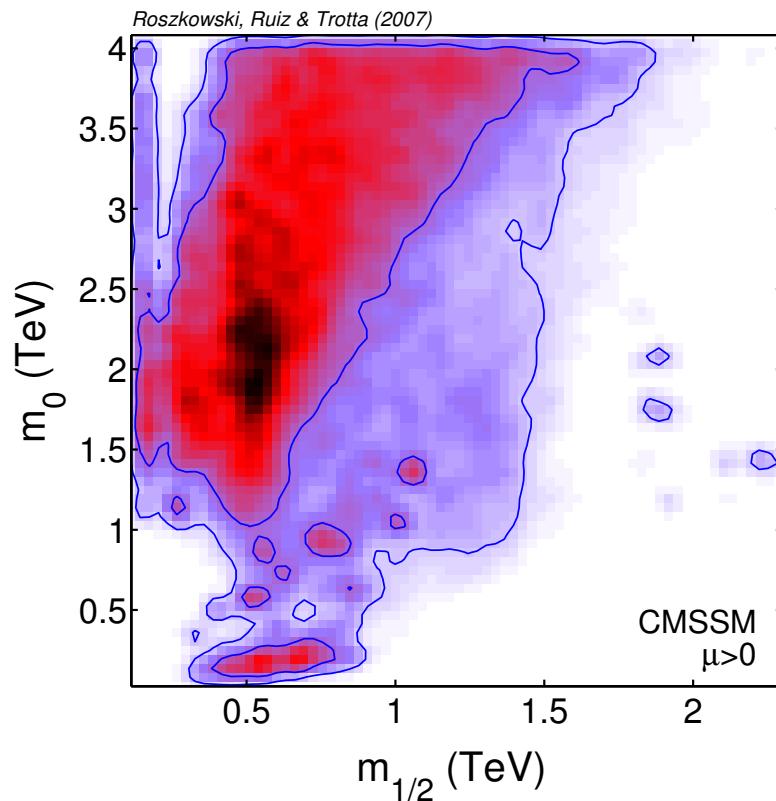
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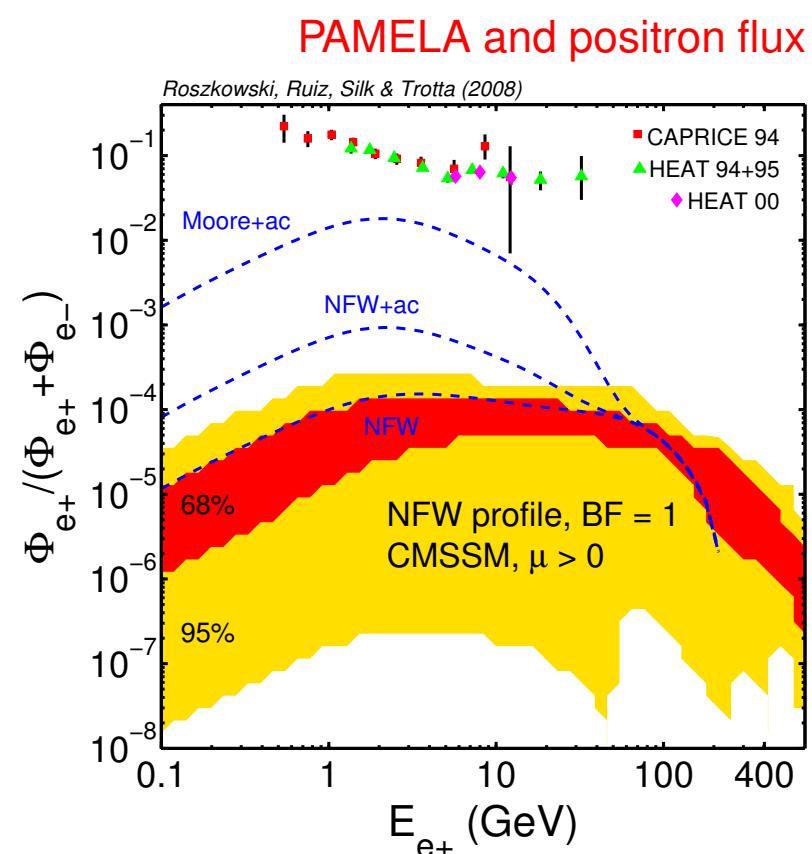
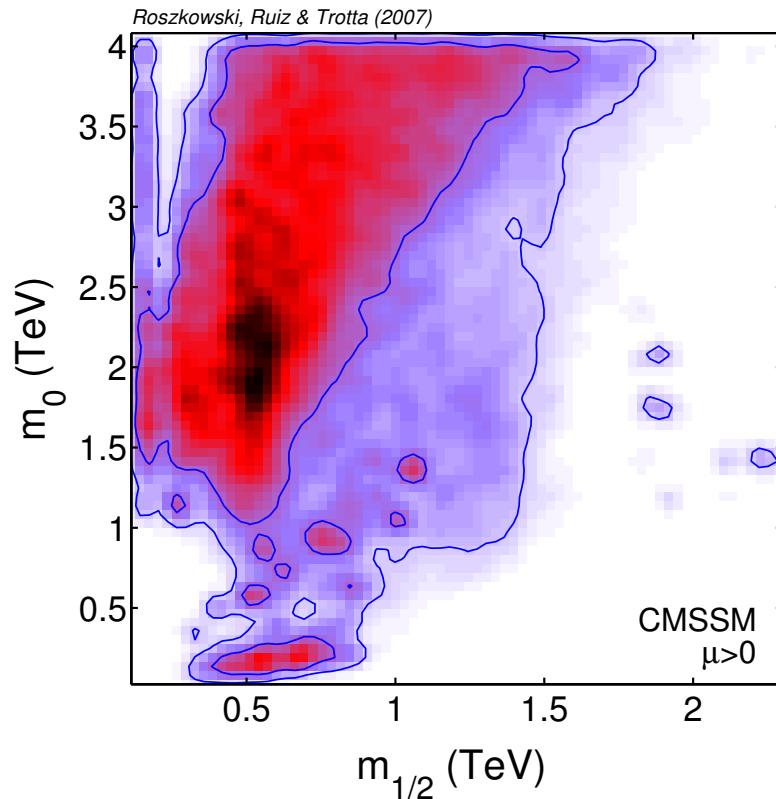
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software package available from [SuperBayes.org](http://SuperBayes.org)

# End of advert

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- SUSY neutralino and other superpartners + Higgs discovered;  
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- or
- lightest superpartner at LHC not electrically neutral (e.g. stau)  
 $\Rightarrow$  DM is made up of exotic WIMP (axino  $\tilde{a}$  or gravitino  $\tilde{G}$ ) or another E-WIMP/superWIMP
- $\Rightarrow$  it may become possible to determine  $T_R$  from LHC data alone

( $T_R$  – highest temp. at which, after inflation, the Universe reaches thermal equilibrium)

# Outline

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- summary

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	axino	gravitino
spin	1/2	3/2
interaction	$\sim 1/f_a^2$	$\sim 1/M_P^2$
mass	$\propto M_{\text{SUSY}}$	$\propto M_{\text{SUSY}}$

- mass model dependent  
take it as free parameter

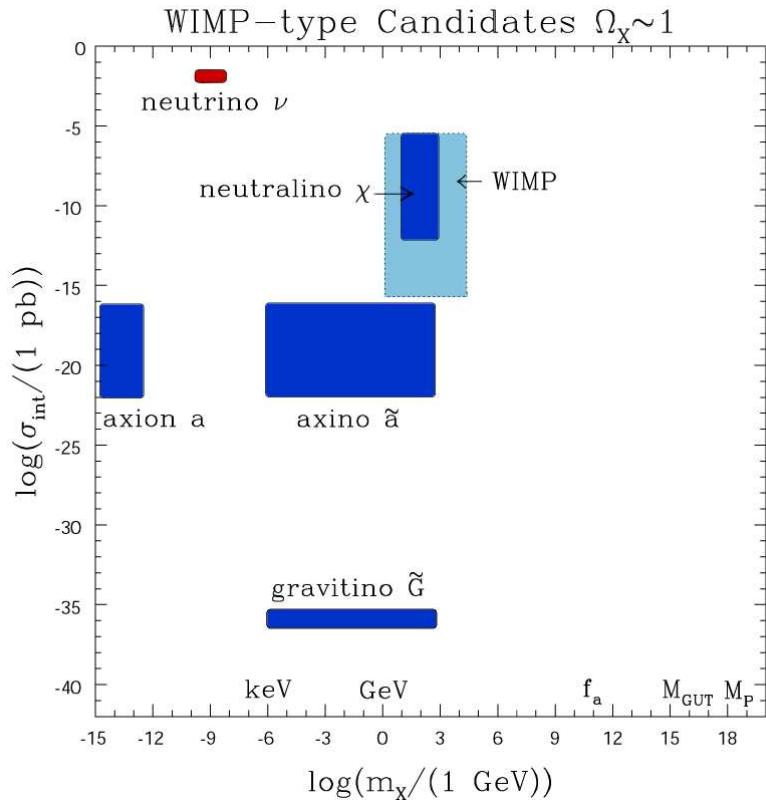
$$f_a \sim 10^{9-12} \text{ GeV} - \text{PQ scale}$$

$$M_P = 2.4 \times 10^{18} \text{ GeV} - \text{reduced Planck mass}$$

$$M_{\text{SUSY}} \sim 100 \text{ GeV} - 1 \text{ TeV} - \text{soft SUSY mass scale}$$

# The Big Picture

well-motivated particle candidates such that  $\Omega \sim 0.1$



- neutrino  $\nu$  – hot DM
- neutralino  $\chi$
- “generic” WIMP
- axion  $a$
- axino  $\tilde{a}$
- gravitino  $\tilde{G}$

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SUSY + axions

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superpotential  $W_{\text{PQ}} = \frac{g^2}{16\sqrt{2}\pi^2 f_a} \Phi W^\alpha W_\alpha$

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for cosmology: treat  $m_{\tilde{a}}$  as parameter

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

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

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Covi+J.E. Kim+Roszkowski, PRL'99

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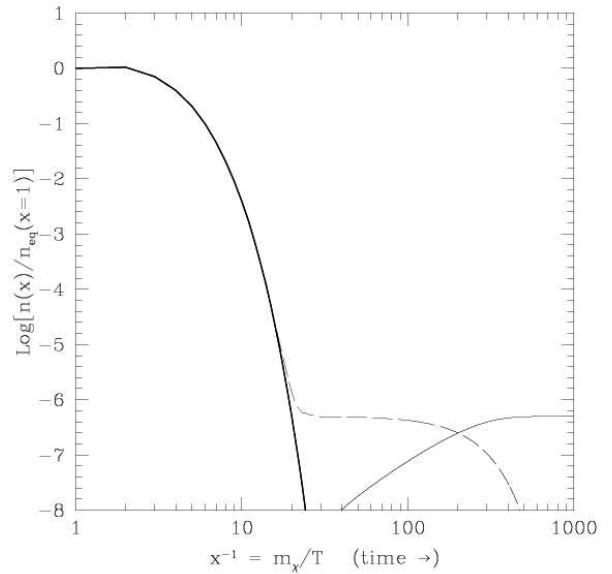
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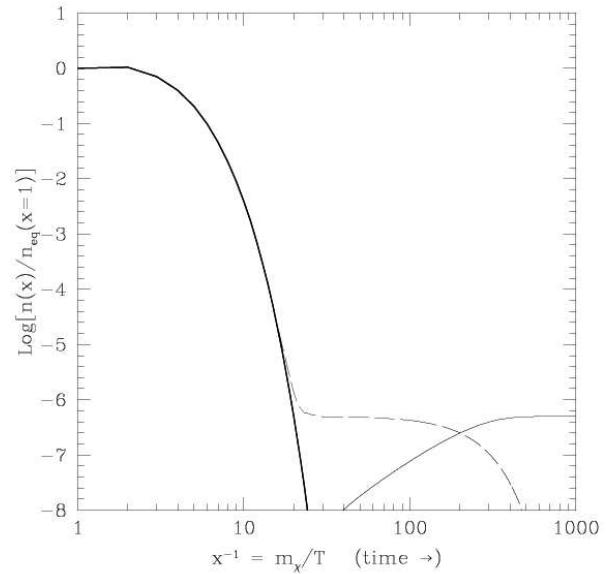
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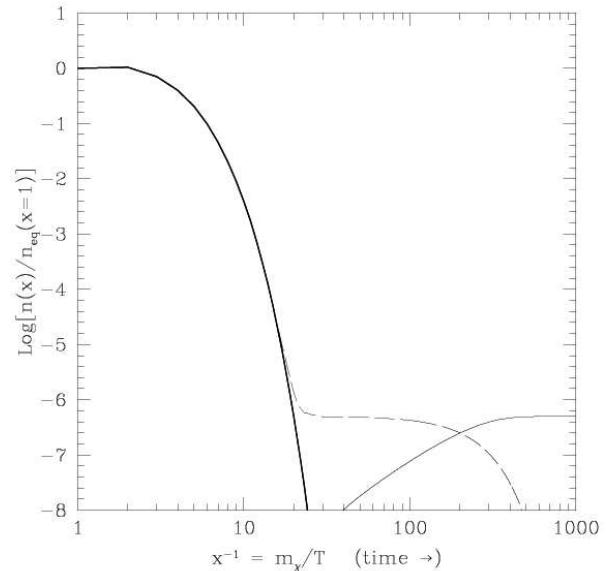
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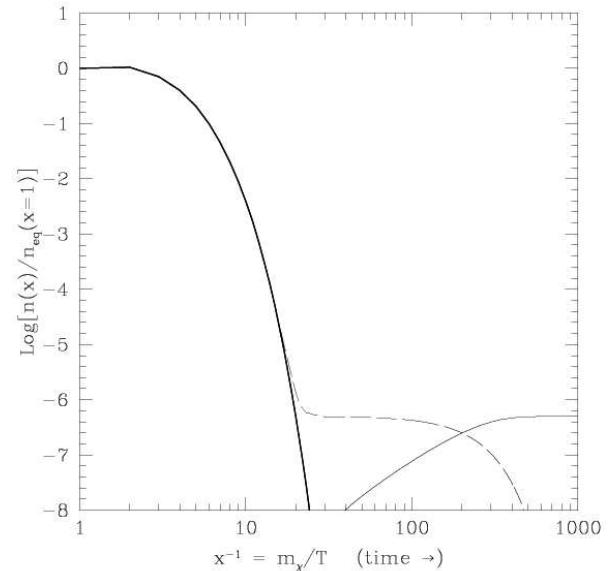
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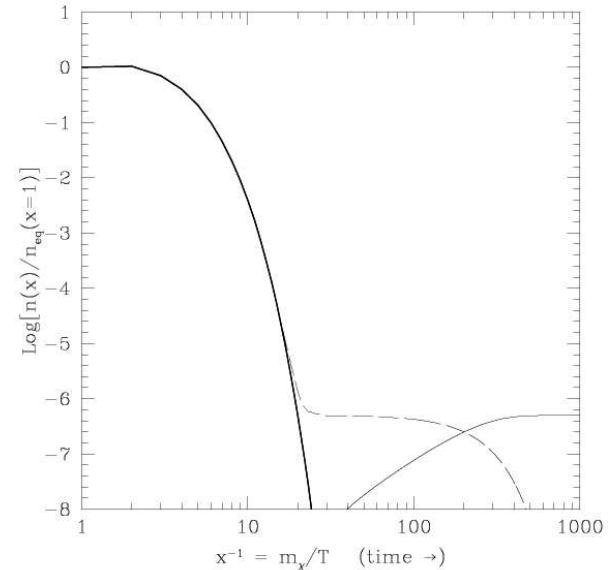
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NTP: non-thermal production

- plus TP processes:  $q \bar{q} \rightarrow \tilde{a} \tilde{g}$ ,  $\tilde{q} \rightarrow \tilde{a} q$ , ...

TP: thermal production

$$\Omega_{\tilde{a}}^{\text{TP}} h^2 \simeq 5.5 g_s^6 \ln \left( \frac{1.108}{g_s} \right) \left( \frac{m_{\tilde{a}}}{0.1 \text{ GeV}} \right) \left( \frac{10^{11} \text{ GeV}}{f_a} \right)^2 \left( \frac{T_R}{10^4 \text{ GeV}} \right)$$

TP dominance  $\Rightarrow$

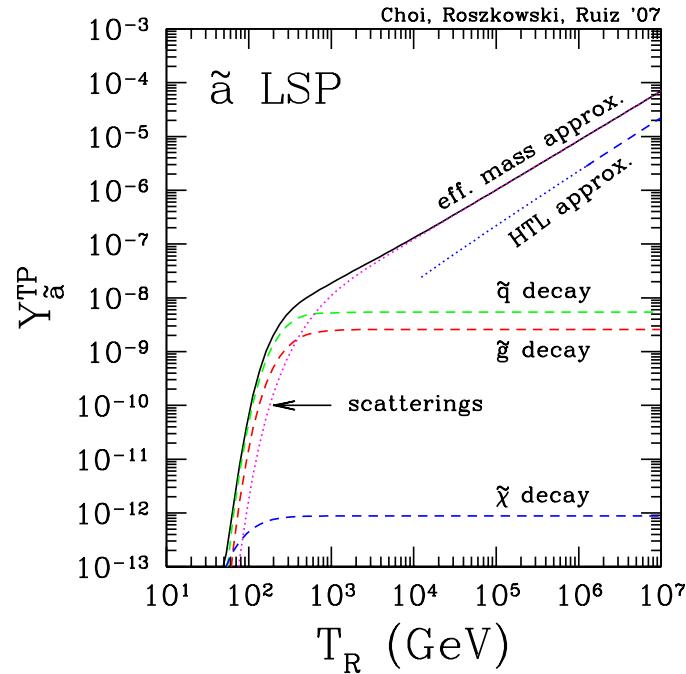
$$T_R \propto f_a^2 / m_{\tilde{a}}$$

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

Brandenburg and Steffen ('04)

# Yield vs $T_R$

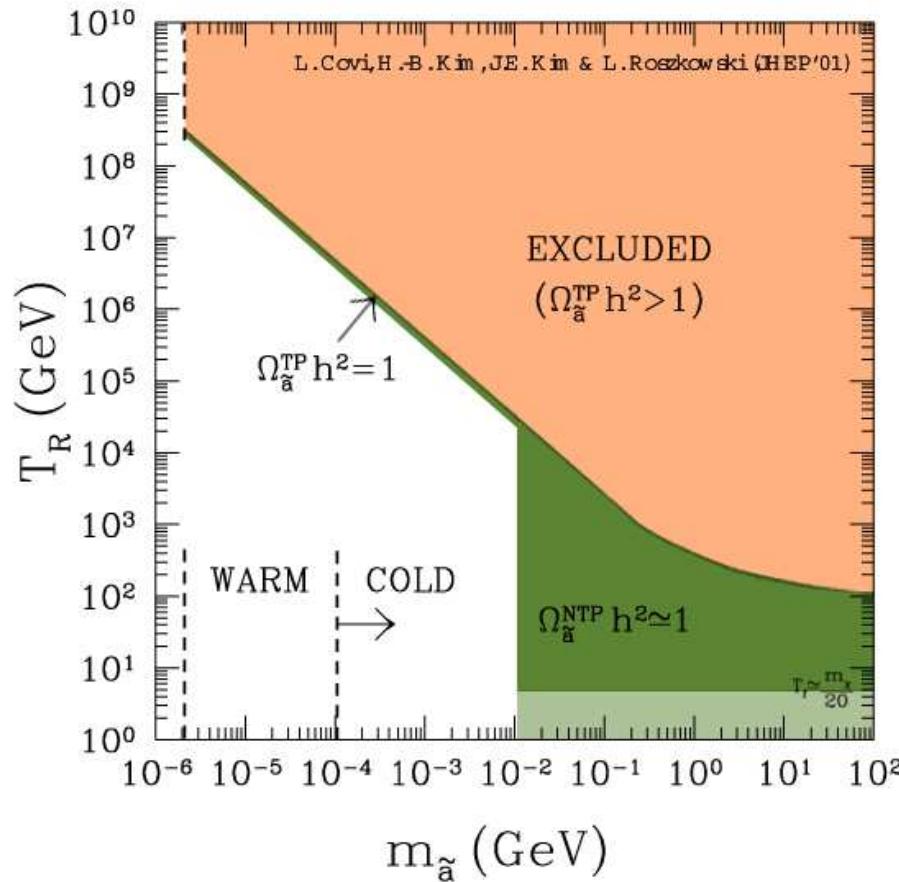
$m_\chi = 300 \text{ GeV}$ ,  $m_{\tilde{\tau}_1} = 474 \text{ GeV}$ ,  $m_{\tilde{g}} = m_{\tilde{q}} = 1 \text{ TeV}$



# Axino Relic: NTP vs TP

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

general MSSM:



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

# Gravitino $\tilde{G}$

spin-3/2 partner of the graviton

in gravity-mediated SUSY breaking models:

- mass:

$$m_{\tilde{G}} = \frac{F}{\sqrt{3}M_P}$$

$F \sim 10^{11}$  GeV – SUSY breaking scale

$M_P = 2.4 \times 10^{18}$  GeV – reduced Planck mass

soft masses  $\sim F/M_P$

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- couplings: suppressed by  $M_P$ , 5-dim goldstino  $\psi_G$  term

$$\mathcal{L}_{\tilde{G}} = \frac{m_{\tilde{g}}}{\sqrt{26}M_P m_{\tilde{G}}} \bar{\psi}_G [\gamma^\mu, \gamma^\nu] \tilde{g}^a F_{\mu\nu}^a$$

$\tilde{G}$ : cold DM

# Producing Relic Gravitinos

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

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

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

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

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⇒ NTP:

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

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

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

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

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

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

...well after BBN

⇒ NTP:

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

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

Ellis, et al (EOSS 03), CMSSM

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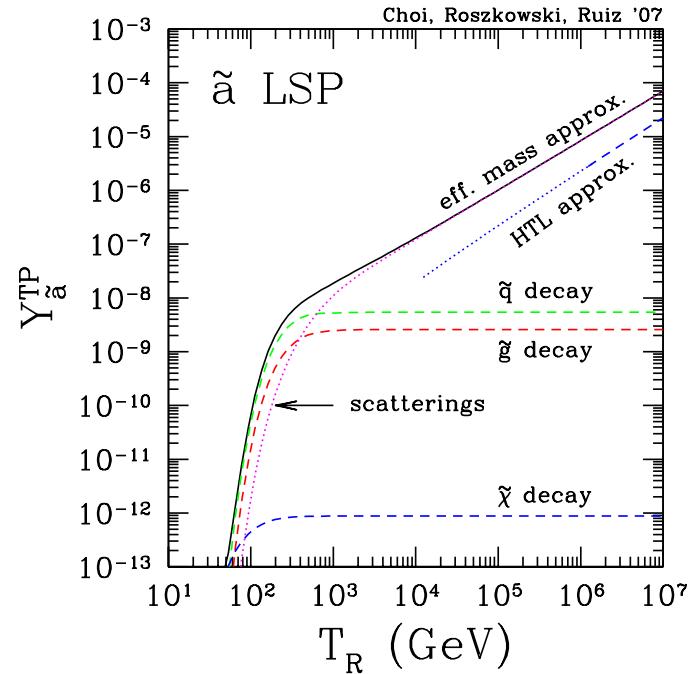
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At high  $T_R \gtrsim 10^9 \text{ GeV}$ , TP is important

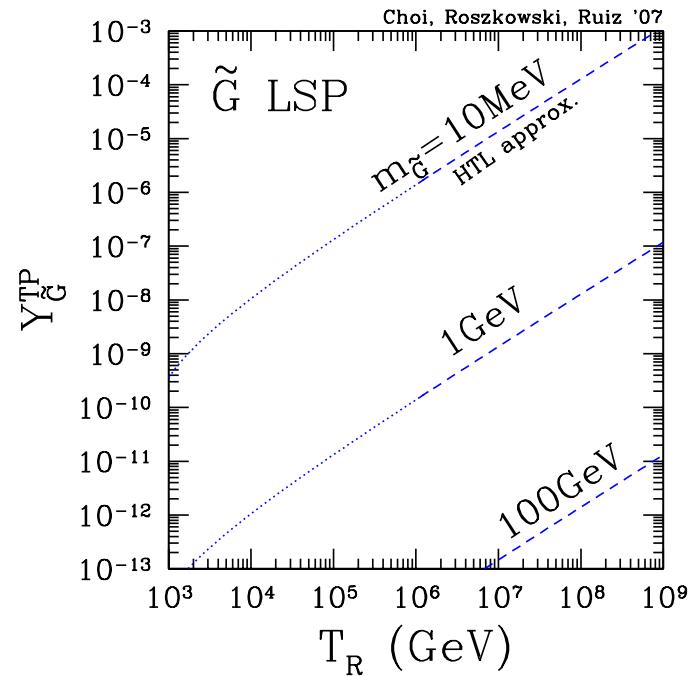
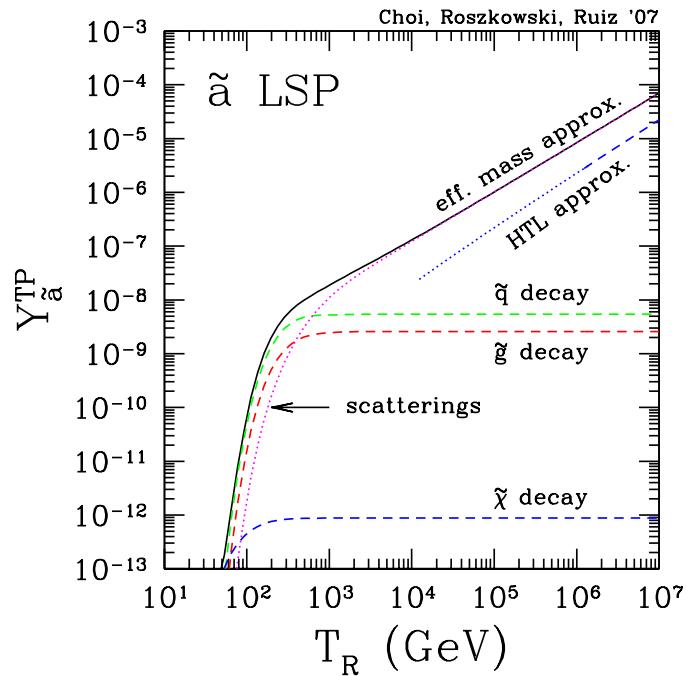
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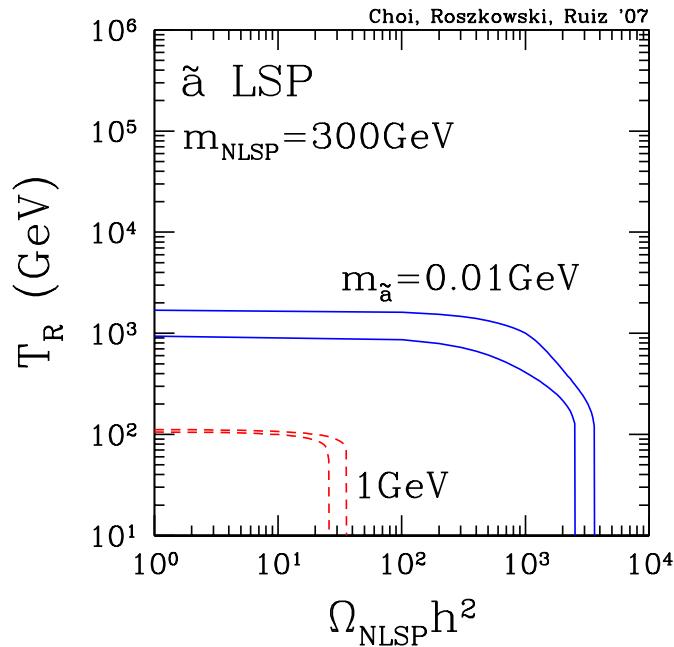
TP can dominate even if  $\Omega_\chi h^2 \gg 0.1$ , or (accidentally)  $\Omega_\chi h^2 \simeq 0.1$

# Example for $\tilde{a}$ LSP

- assume neutralino  $\chi$  to be NLSP and its “density”  $\Omega_{\text{NLSP}} h^2$  determined at LHC

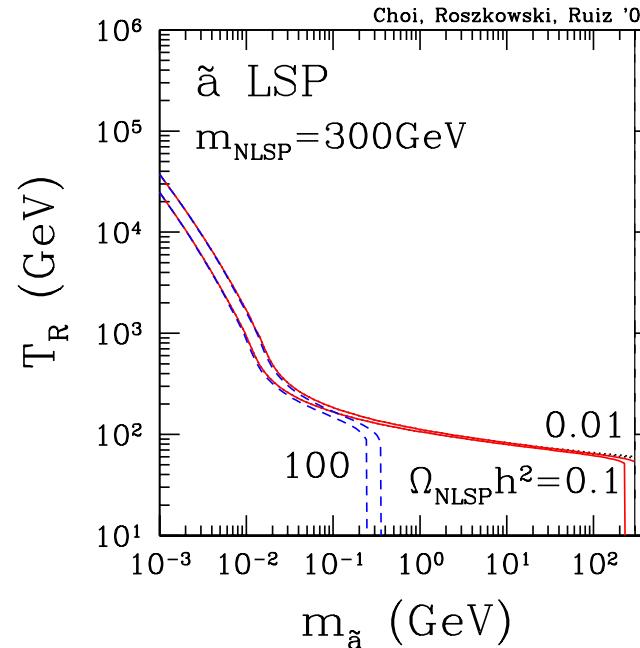
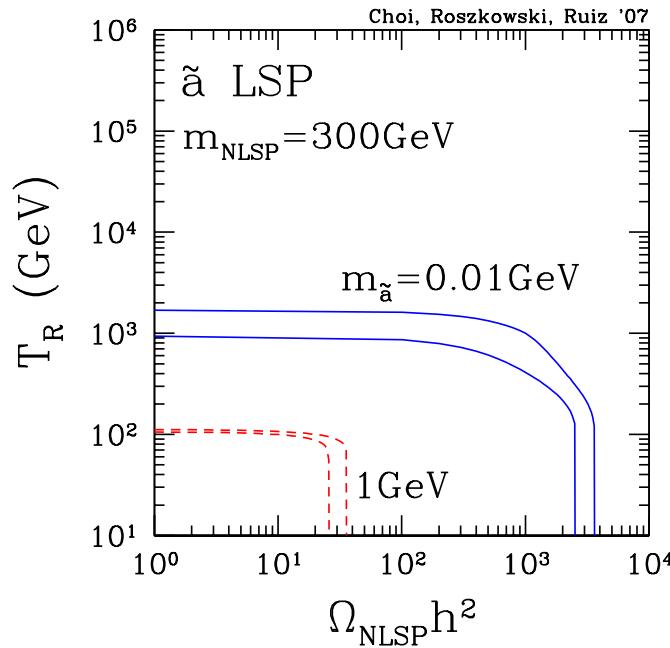
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- both panels: TP (NTP) dominant on left (right) side
- $\tilde{a}$  cold DM:  $m_{\tilde{a}} \gtrsim 100 \text{ keV}$  (Covi, et al, (CKKR))  
 $\Rightarrow T_R^{\max} < 4.9(f_a/10^{11} \text{ GeV})^2 \times 10^5 \text{ GeV}$  (+ weak dependence on  $m_{\text{NLSP}}$ )

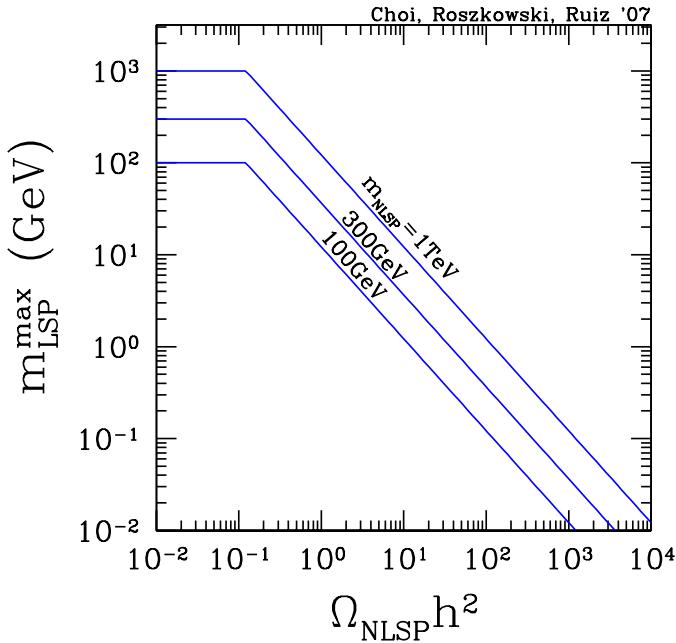
$\Rightarrow$  if axino = CDM, upper bound  $T_R \lesssim 10^5 \text{ GeV}$  can be set

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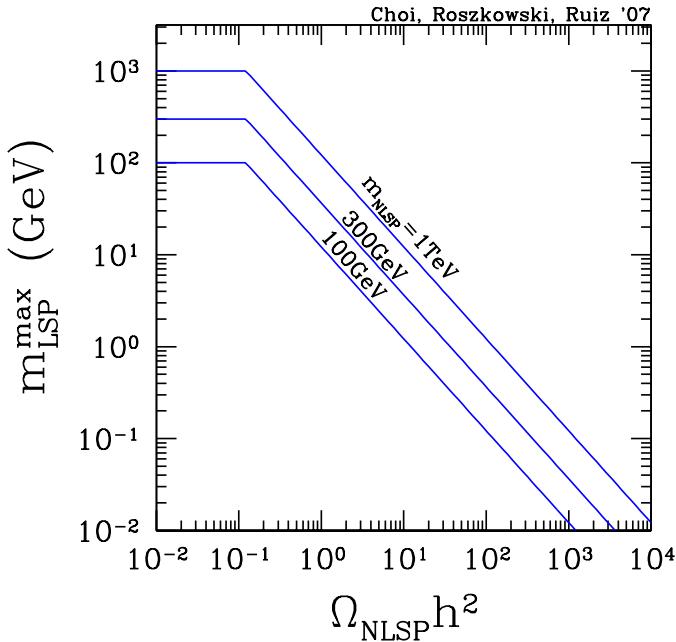


once  $m_{\text{NLSP}}$  and (at least lower bound on)  
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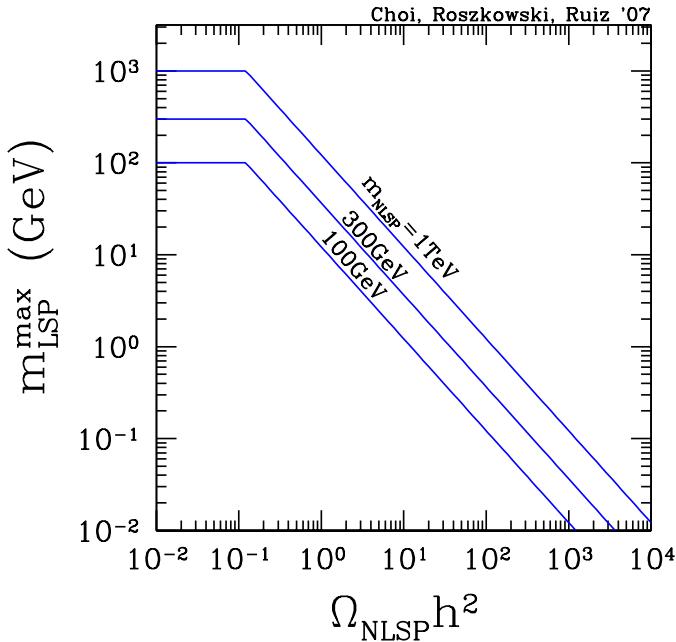
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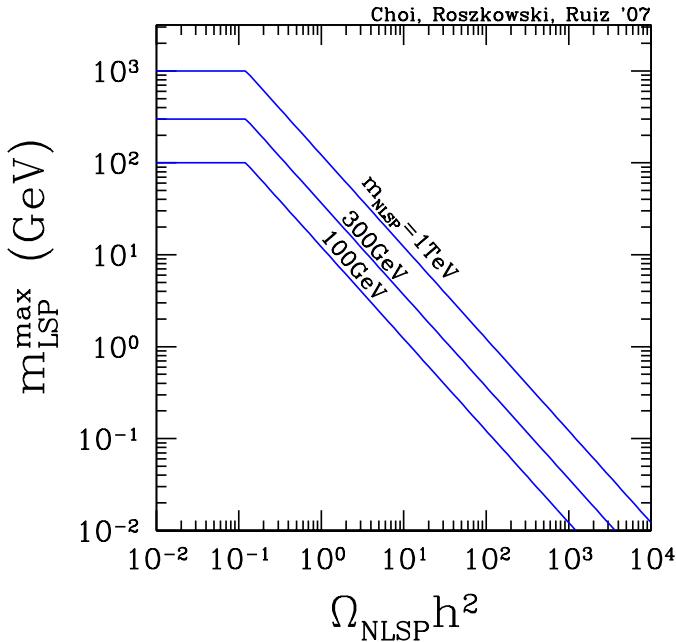
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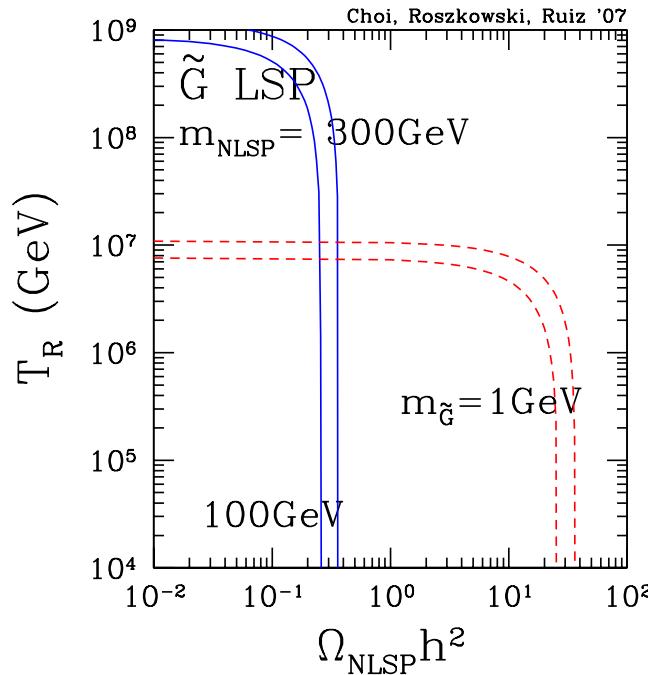
⇒ upper bound applies to both axino and gravitino LSP

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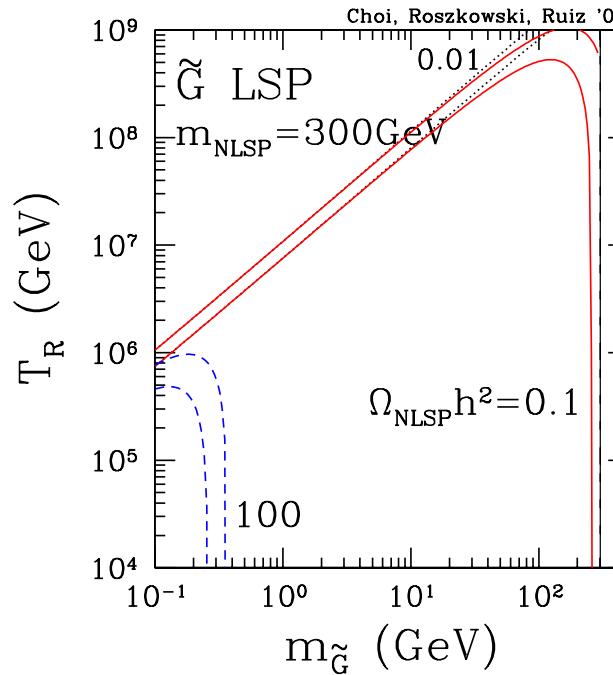
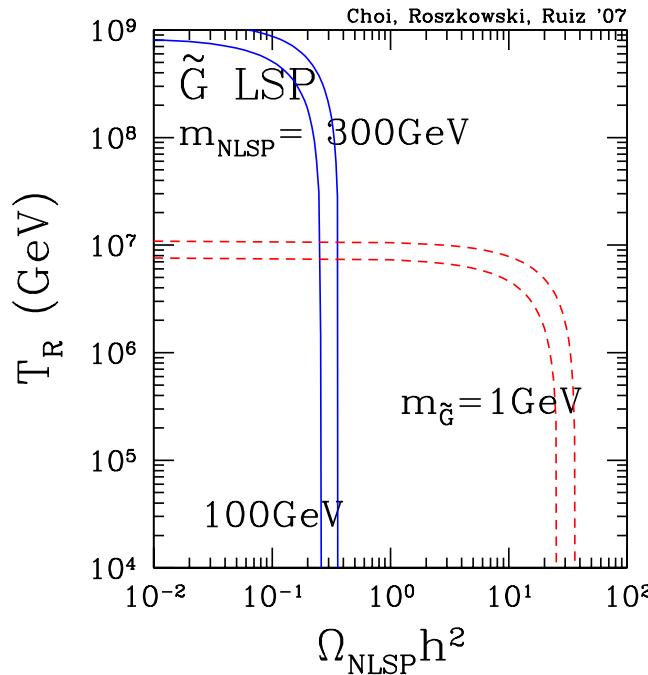
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- $T_R \propto m_{\tilde{G}}$

⇒ upper bound on  $T_R$  can be set (indep. of  $\tilde{G}$  being CDM)

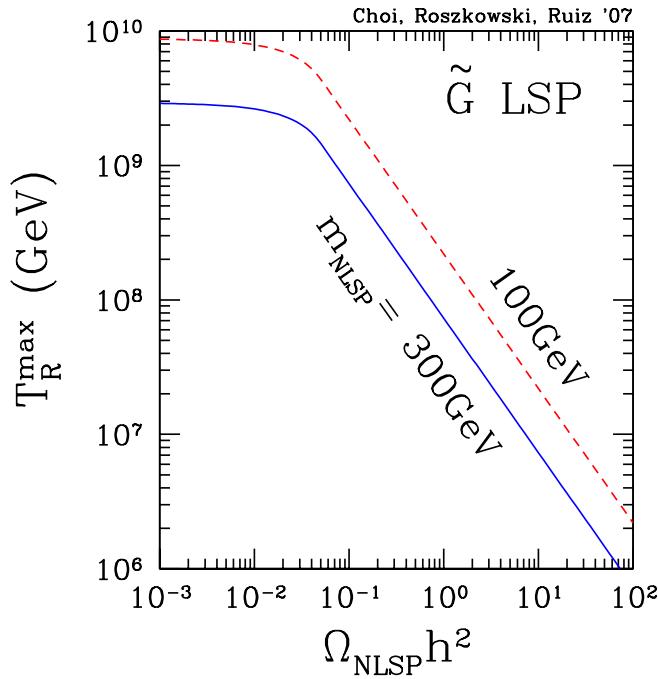
BBN constraints not imposed

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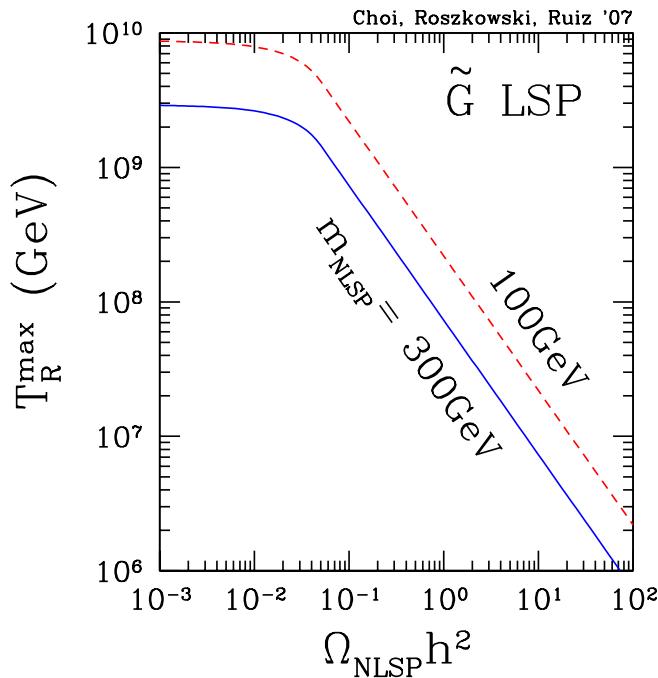
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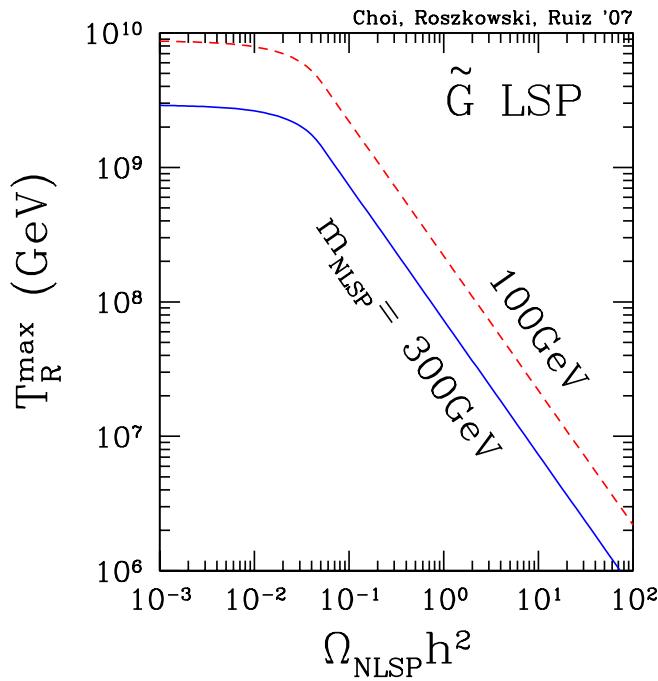
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$$T_R^{\text{max}} =$$

$$\begin{cases} \frac{10^8 \text{ GeV}}{0.27} \left( \frac{1 \text{ TeV}}{m_{\tilde{g}}} \right)^2 \left( \frac{m_{\text{NLSP}}}{100 \text{ GeV}} \right) \frac{1}{4\Omega_{\text{NLSP}} h^2}, & \text{for } \Omega_{\text{NLSP}} h^2 > 0.05 \\ \frac{10^{10} \text{ GeV}}{0.27} \left( \frac{1 \text{ TeV}}{m_{\tilde{g}}} \right)^2 \left( \frac{m_{\text{NLSP}}}{100 \text{ GeV}} \right) (0.1 - \Omega_{\text{NLSP}} h^2), & \text{for } \Omega_{\text{NLSP}} h^2 < 0.05 \end{cases}$$

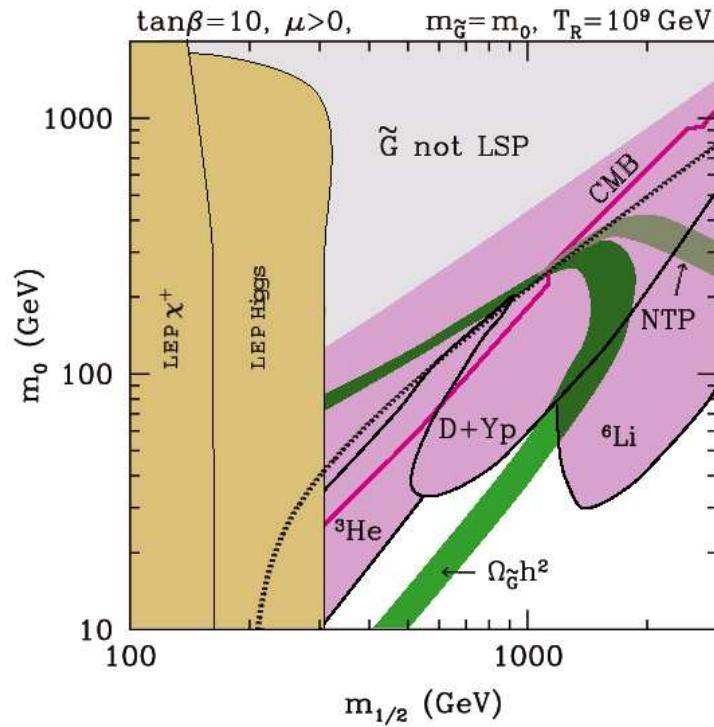
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# Impact of BBN

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

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

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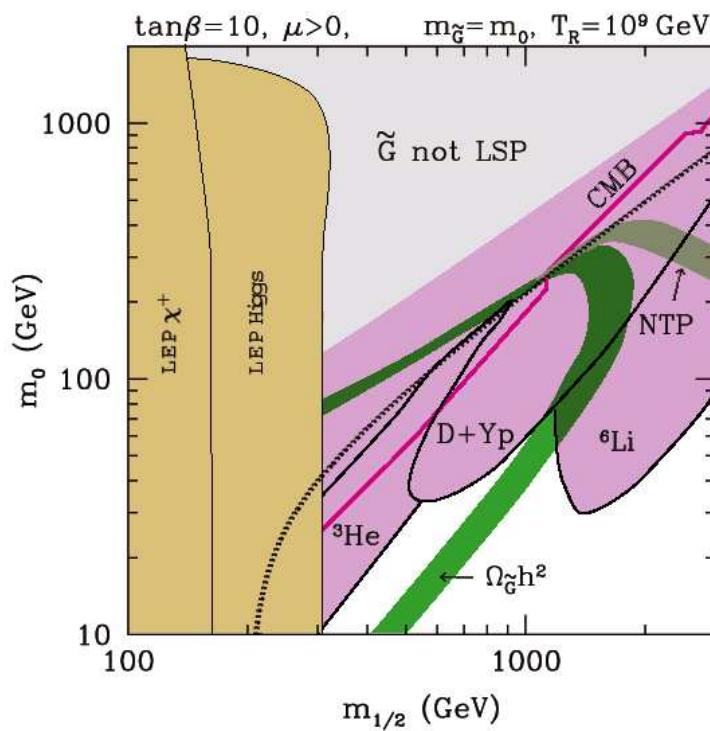


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- neutralino  $\chi$  NLSP region excluded
- only  $\tilde{\tau}_1$  NLSP region remains allowed  
 $\Rightarrow$  at LHC see charged “stable” LOSP  $\tilde{\tau}_1$   
 confirmed Feng, et al (Apr 04)
- low  $T_R$  basically excluded (NTP part only), *must* include TP contribution to  $\Omega_{\tilde{G}} h^2$   
 $\Rightarrow m_{\tilde{G}} = \mathcal{O}(100 \text{ GeV})$ : (typically) need high  $T_R \sim 10^9 \text{ GeV}$

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Nojiri, Polesello, Tovey '04: SPA point: 5-10% error achievable

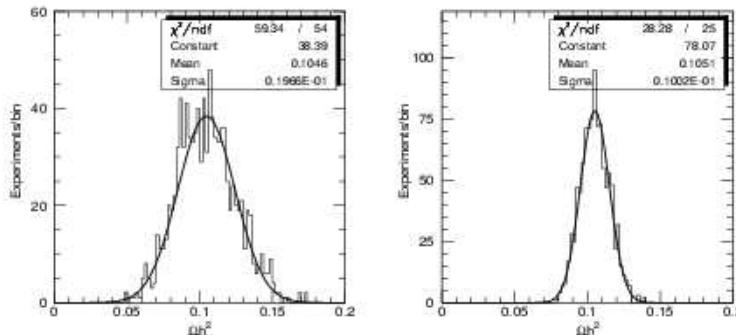


Figure 7: Distributions of the predicted relic density  $\Omega_\chi h^2$  incorporating the experimental errors. The distributions are shown for an assumed error on the  $\tau\tau$  edge respectively of 5 GeV (left) and 0.5 GeV (right).

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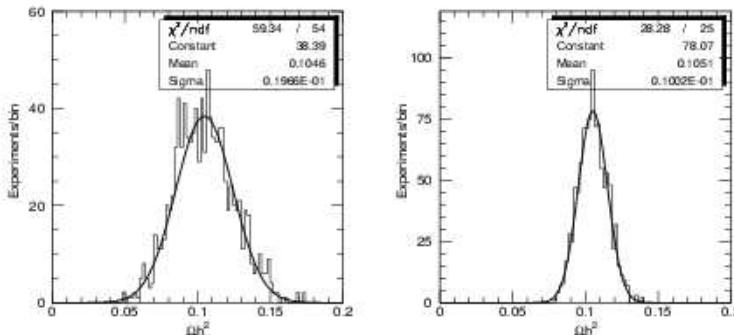


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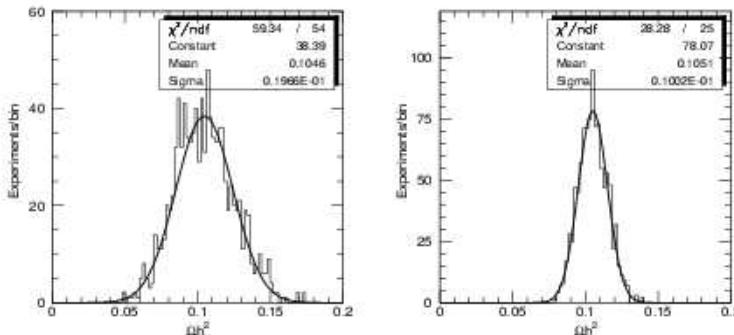


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- even with fewer measurements a lower bound on  $\Omega_\chi h^2$  should be achievable by not finding states that can reduce  $\Omega_\chi h^2$  to  $\sim 0.1$

e.g., no Higgs at  $\sim 2m_\chi$ , nor other channels

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  - except that BBN bounds become weaker
- if more production mechanisms: make upper bounds on  $T_R$  stronger
- for axino or gravitino LSP different LHC observables can be selected, e.g.  $m_{\text{NLSP}}$  and NLSP lifetime
  - e.g., Steffen (arXiv:0806.3266) reproduced our results for  $\tilde{G}$  LSP and stau NLSP
- no strong assumptions made about specific SUSY model
- method applies in principle to any DM candidate whose density depends on  $T_R$

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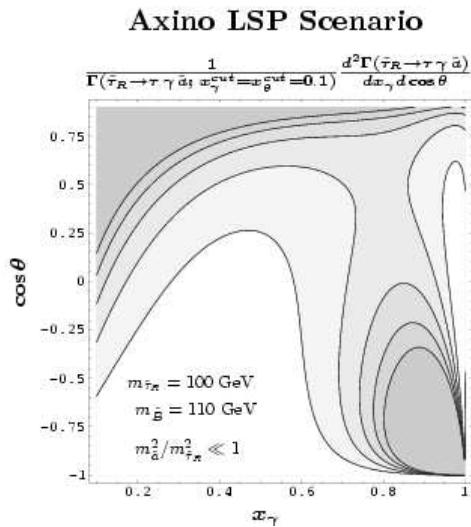
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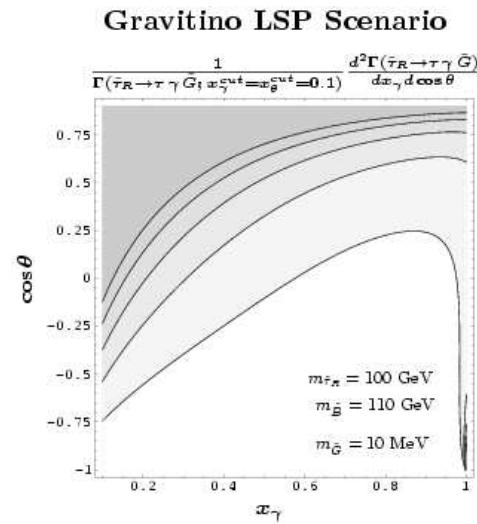
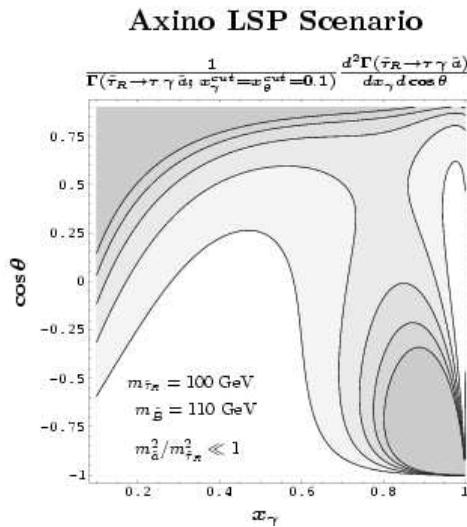
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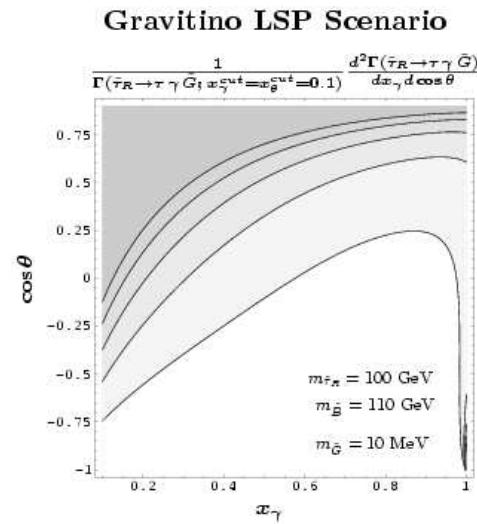
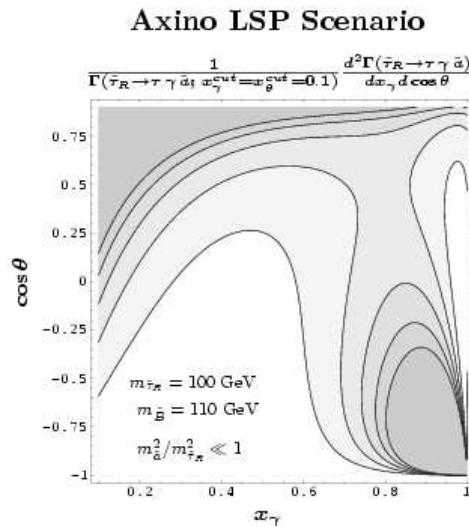
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- typically different lifetimes: shorter ( $\lesssim 1$  sec) for axino LSP, longer ( $\sim 10^{2-10}$  sec) for gravitino LSP
- different event distributions may allow one to distinguish  $\tilde{a}$  from  $\tilde{G}$  and, by comparing 2-body and 3-body decays, determine LSP mass at LHC

⇒ may be possible to distinguish  $\tilde{a}$  from  $\tilde{G}$  at LHC

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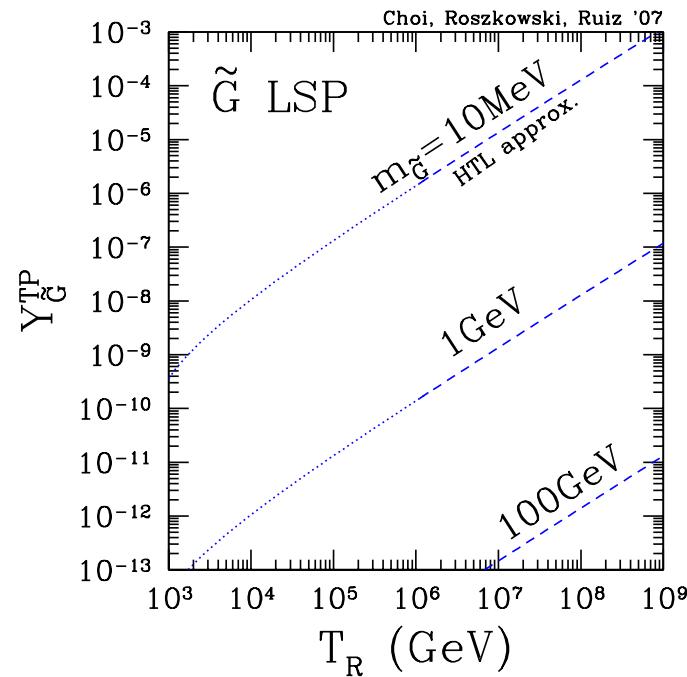
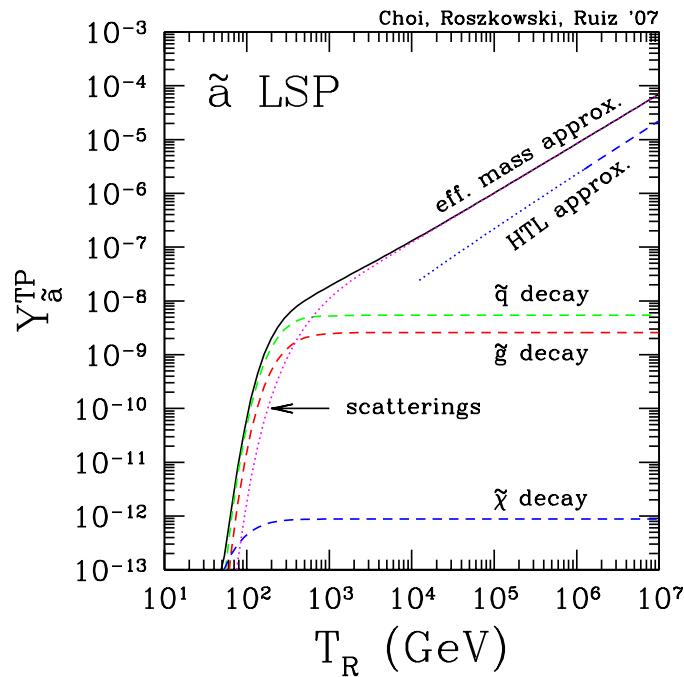
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STAY TUNED TO LHC!

# Backup...

# Yield vs $T_R$

$$m_\chi = 300 \text{ GeV}, \quad m_{\tilde{\tau}_1} = 474 \text{ GeV}, \quad m_{\tilde{g}} = m_{\tilde{q}} = 1 \text{ TeV}$$

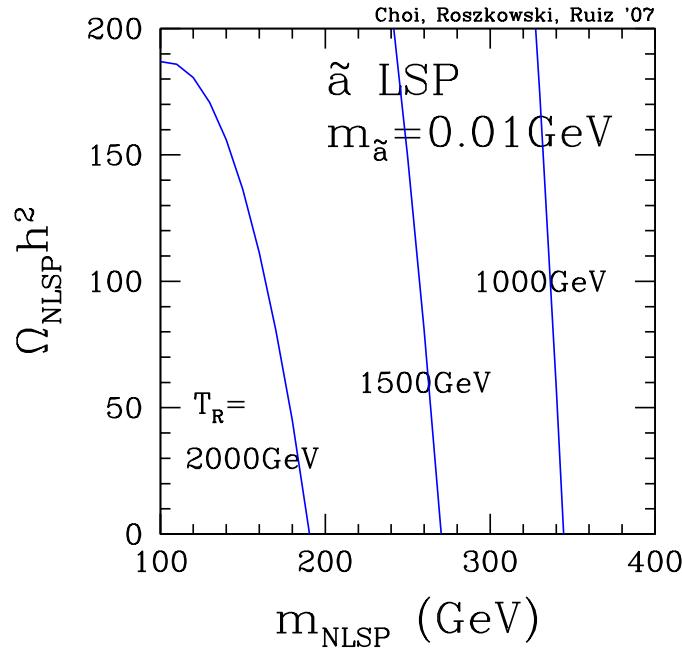


# Dependence on $\tilde{a}$ mass

contours of  $T_R$  in  $(m_{\text{NLSP}}, \Omega_{\text{NLSP}} h^2)$  plane such that  $\Omega_{\tilde{a}} h^2 = \Omega_{\text{CDM}} h^2 = 0.104$

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