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Stable Gravitino DM and the SUSY spectrum

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In collaboration with:

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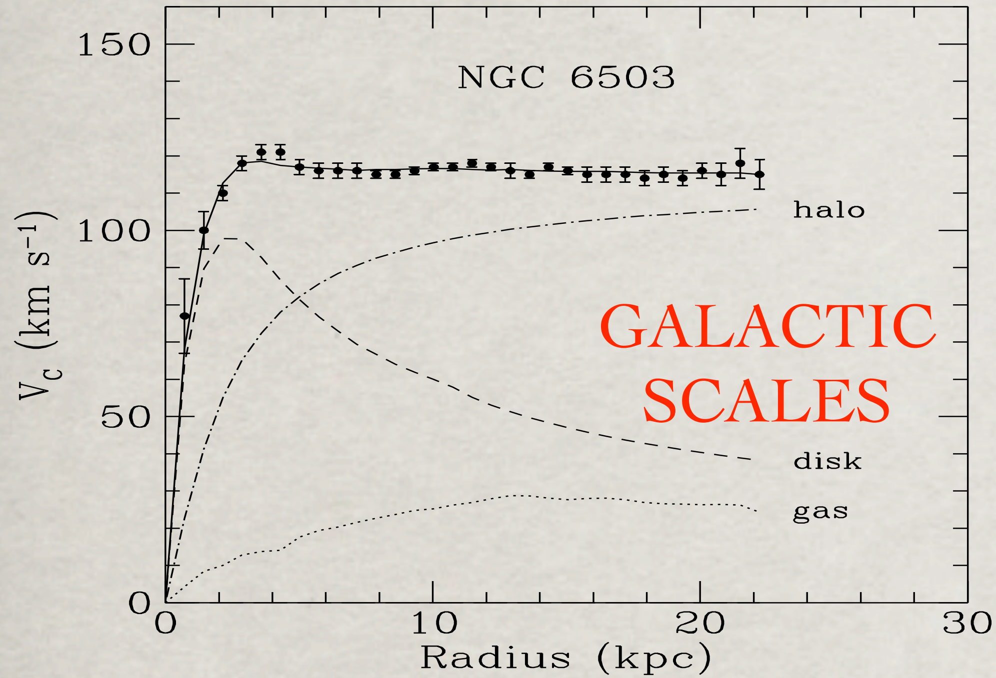
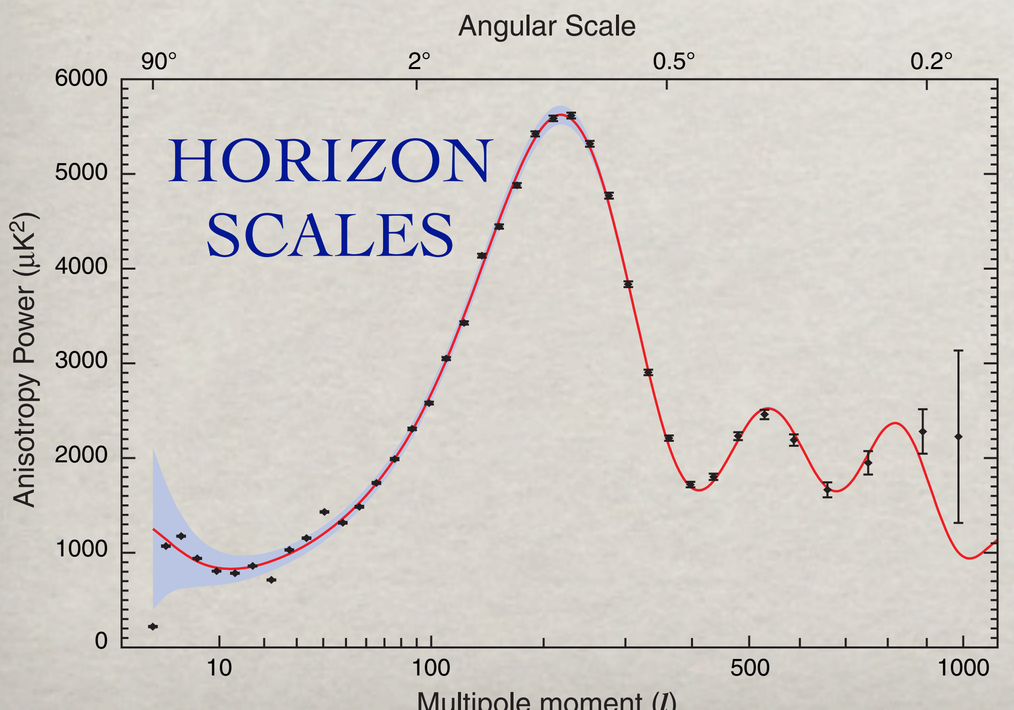
M. Olechowski, S. Pokorski, K. Turzynski, J.D. Wells

OUTLINE

- Introduction: Dark Matter properties
  Why gravitino DM ?
- Cosmological constraints on the gravitino and leptogenesis
- Revisiting neutralino NLSP:
  Wino and Higgsino NLSP ?
- Maximizing the reheat temperature and degenerate gauginos
- Outlook

DARK MATTER EVIDENCE





Particles	Ωh^2	Type
Baryons	0.0224	Cold
Neutrinos	< 0.01	Hot
Dark Matter	0.1-0.13	Cold

WHY GRAVITINO DM?

- Solves the DM problem within gravity.
- Is based on supersymmetric extension, i.e. very theoretically attractive: gives gauge unification, solves hierarchy problem, etc...
- Allows for coherent framework, with a very small number of parameters, since the couplings are fixed by the symmetry.
- Relaxes the gravitino problem and possibly allows for thermal leptogenesis...
- R-parity conservation is not strictly necessary...

  talk of W. Buchmueller, Y. Zhang
- Opens a WINDOW ON SUSY BREAKING !

GRAVITINO properties: completely fixed by SUGRA !

Gravitino mass: set by the condition of "vanishing" cosmological constant

$$m_{\tilde{G}} = \langle W e^{K/2} \rangle = \frac{\langle F_X \rangle}{M_P} \qquad \text{~~SUSY~~}$$

It is proportional to the SUSY breaking scale and varies depending on the mediation mechanism, e.g. gauge mediation can accomodate very small $\langle F_X \rangle$ giving $m_{\tilde{G}} \sim$ keV, while in anomaly mediation we can even have $m_{\tilde{G}} \sim$ TeV (but then it is not the LSP...).

Gravitino couplings: determined by masses, especially for a light gravitino since the dominant piece becomes the Goldstino spin 1/2 component: $\psi_\mu \simeq i\sqrt{\frac{2}{3}}\frac{\partial_\mu \psi}{m_{\tilde{G}}}$. Then we have:

$$-\frac{1}{4M_P}\bar{\psi}_\mu \sigma^{\nu\rho}\gamma^\mu \lambda^a F^a_{\nu\rho} - \frac{1}{\sqrt{2}M_P}\mathcal{D}_\nu \phi^* \bar{\psi}_\mu \gamma^\nu \gamma^\mu \chi_R - \frac{1}{\sqrt{2}M_P}\mathcal{D}_\nu \phi \bar{\chi}_L \gamma^\mu \gamma^\nu \psi_\mu + h.c.$$

$$\Rightarrow \quad \frac{-m_\lambda}{4\sqrt{6}M_P m_{\tilde{G}}}\bar{\psi}\sigma^{\nu\rho}\gamma^\mu \partial_\mu \lambda^a F^a_{\nu\rho} + \frac{i(m_\phi^2 - m_\chi^2)}{\sqrt{3}M_P m_{\tilde{G}}}\bar{\psi}\chi_R \phi^* + h.c.$$

Couplings proportional to SUSY breaking masses and inversely proportional to $m_{\tilde{G}}$!

The gravitino gives us direct information on SUSY breaking

Cosmological Constraints on Gravitino DM

CAN THE GRAVITINO BE COLD DARK MATTER ?

YES, if the Universe was never hot enough
for gravitinos to be in thermal equilibrium...

Very weakly interacting particles as the gravitino
are produced even in this case, at least by two mechanisms

PLASMA
SCATTERINGS

$$\Omega_{3/2}h^2 \propto \frac{m_{1/2}^2}{m_{3/2}} T_R$$

NLSP DECAY
OUT OF EQUILIBRIUM

$$\Omega_{3/2}h^2 \propto \frac{m_{3/2}}{m_{\mathrm{NLSP}}} \Omega_{\mathrm{NLSP}} h^2$$

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NLSP DECAY OUT OF EQUILIBRIUM

Ω ... $^2 \propto$ ... h^2

DANGER !!!
BBN at risk !

THERMAL PRODUCTION

At high temperatures, the dominant contribution comes from 2-to-2 scatterings with the gauge sector, mostly QCD:

$$\Omega_{3/2} h^2 \simeq 0.3 \left(\frac{1\mathrm{GeV}}{m_{3/2}} \right) \left(\frac{T_R}{10^{10}\ \mathrm{GeV}} \right) \sum_i c_i \left(\frac{M_i}{100\ \mathrm{GeV}} \right)^2$$

[Bolz,Brandenburg & Buchmuller 01], [Pradler & Steffen 06, Rychkov & Strumia 07]

where M_i are the gaugino masses and $c_i \sim 0(1)$

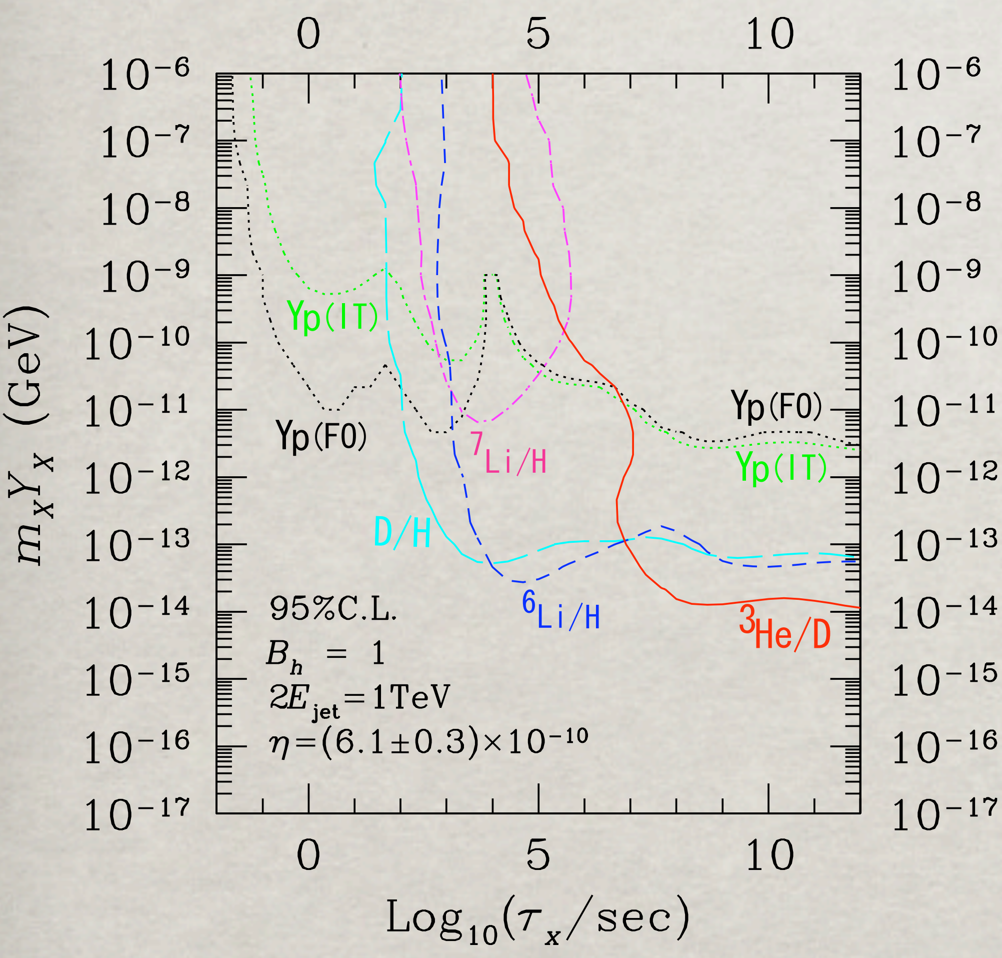
So in general there is always a bound on the reheat temperature and such temperature has to take a specific value in order to match the DM density. Note that the smaller $m_{3/2}$, the smaller the temperature has to be.

Tension with thermal leptogenesis for small gravitino masses !

BBN bounds on NLSP decay

Neutral relics

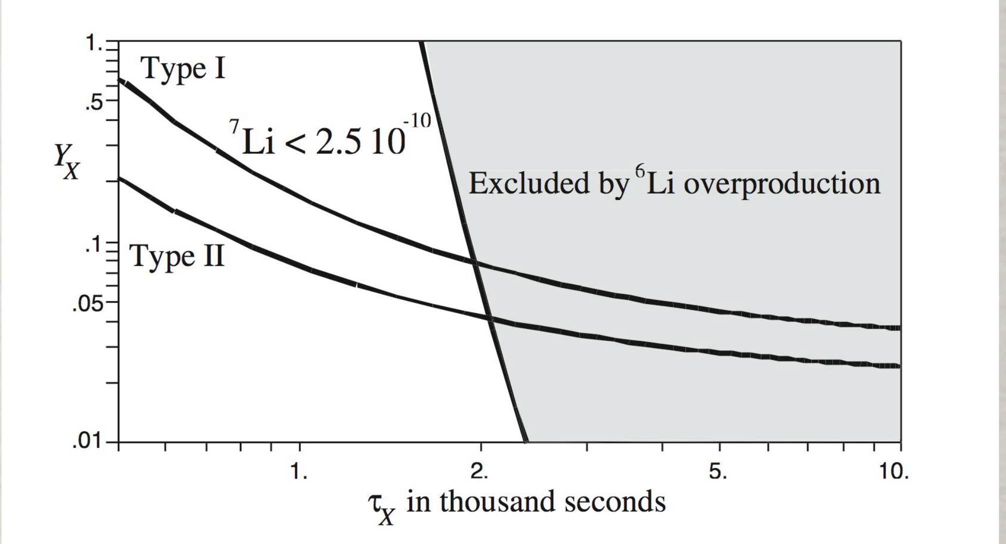
[...,Kohri, Kawasaki & Moroi 04]



EM charged relics

[Pospelov 05, Kohri & Takayama 06, Cyburt at al 06, Jedamzik 07,...]

talk of J. Pradler



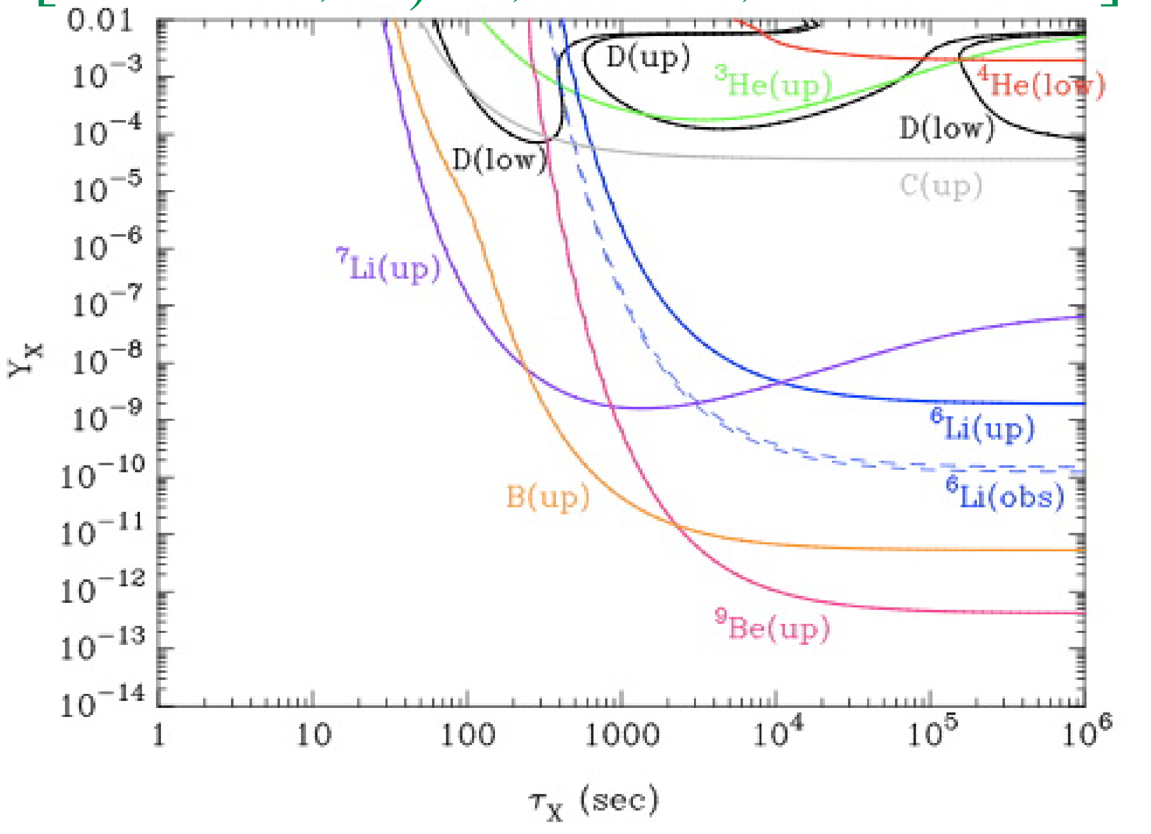
Need short lifetime & low abundance for NLSP

Big problem for gravitino LSP, if the mass is above 1 GeV...

Even worse for colored LSP

Colored relics: even stronger BBN bound state effects...

[Kusakabe, Kajino, Yoshida, Mathews 09]



Even worse for colored LSP

Colored relics: even stronger BBN bound state effects...

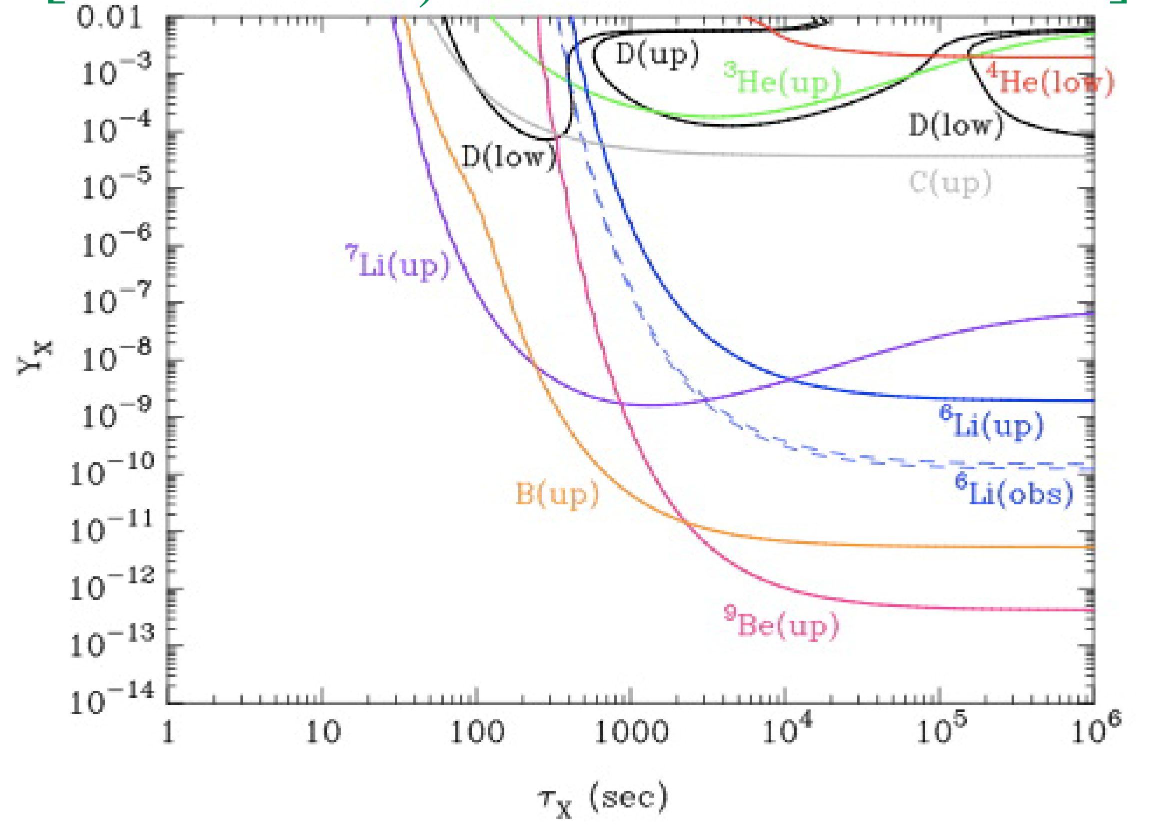
Beware:

$$Y_X^{BBN} = \frac{n_X}{n_b} \sim 10^{-9}\, Y_X$$

$$\rightarrow 0.02\, \frac{m_X}{GeV} \text{ in } \Omega h^2$$

Bounds so strong that even strong interaction is not strong enough...

[Kusakabe,Kajino,Yoshida, Mathews 09]



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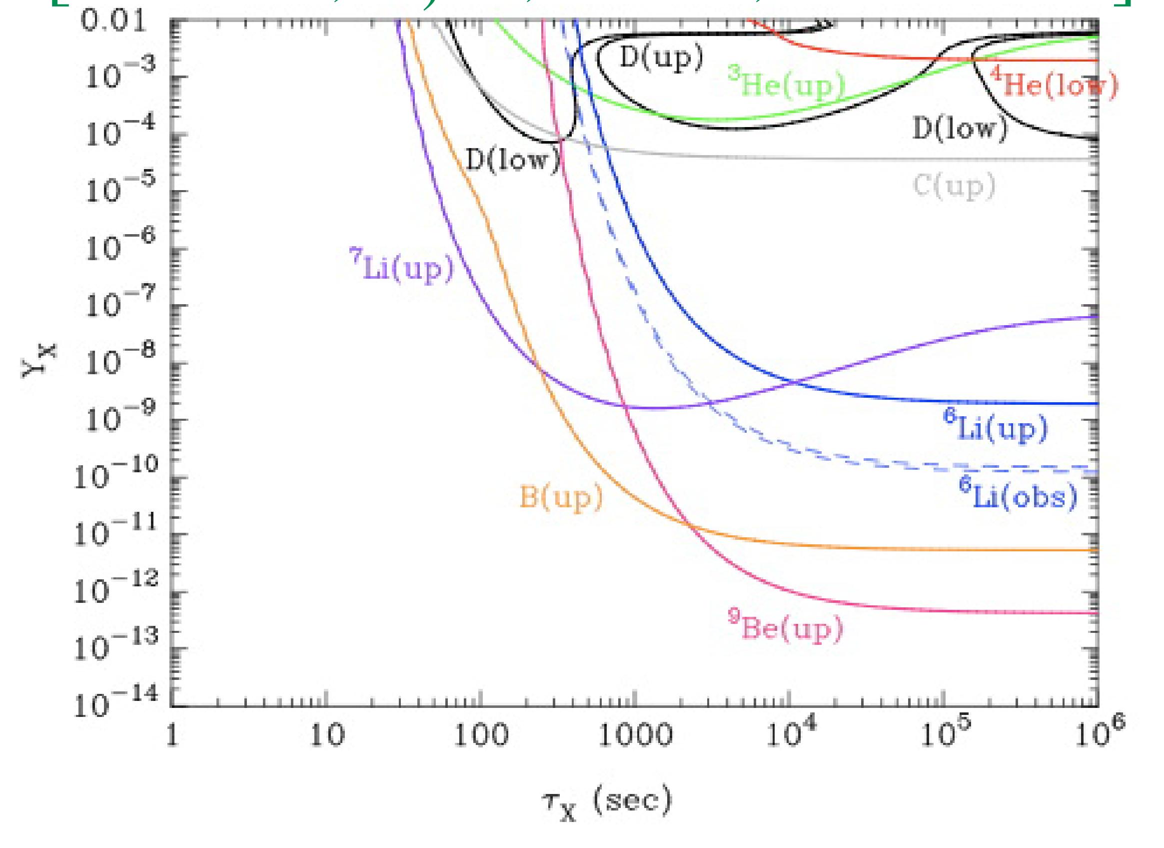
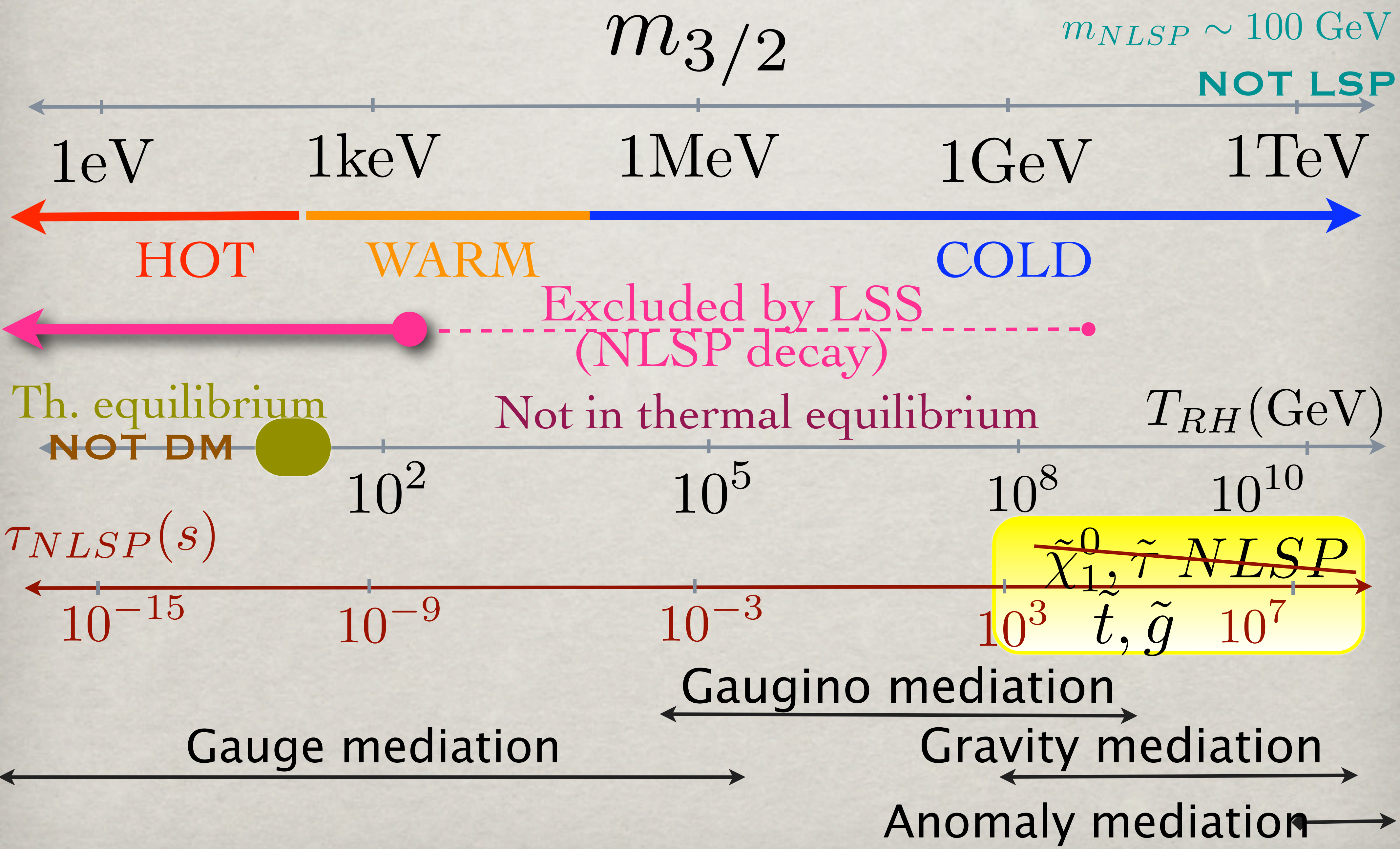


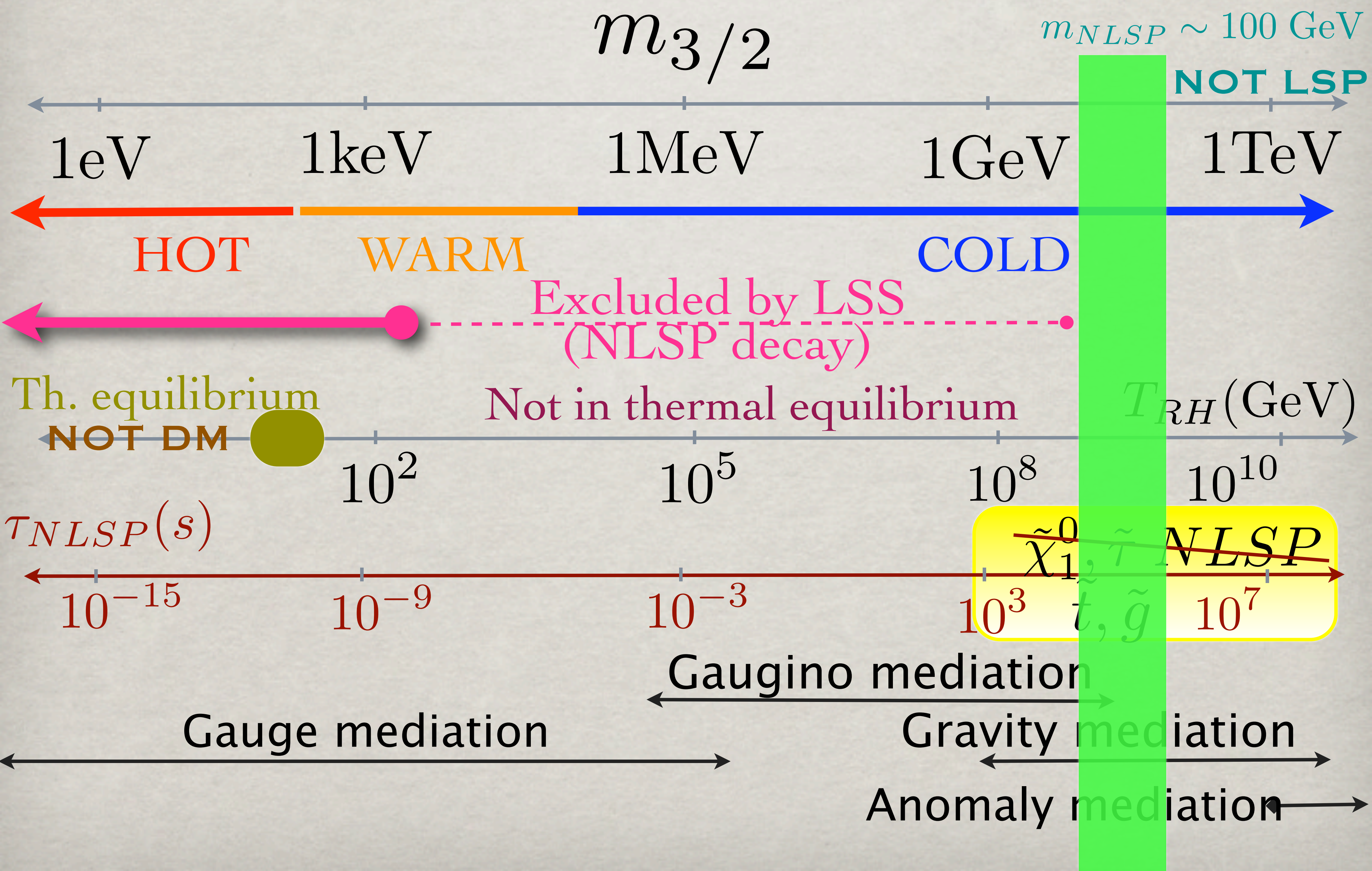
Only short lifetime for colored NLSP allowed:

$$\tau_{\tilde g, \tilde t} < 200 \text{ s} \quad \rightarrow \quad m_{\tilde g, \tilde t} > 800 \text{ GeV} \left(\frac{m_{3/2}}{10 \text{ GeV}}\right)^{2/5}$$

Gravitino DM summary



Gravitino DM summary



Revisiting neutralino NLSP

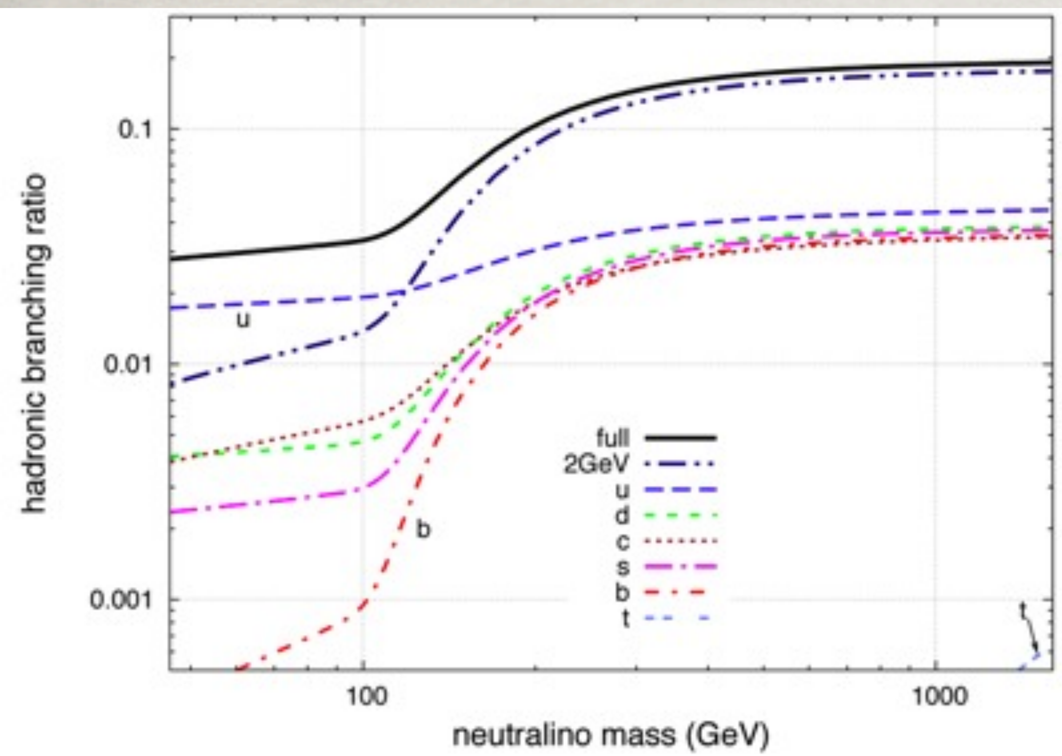
General neutralino NLSP

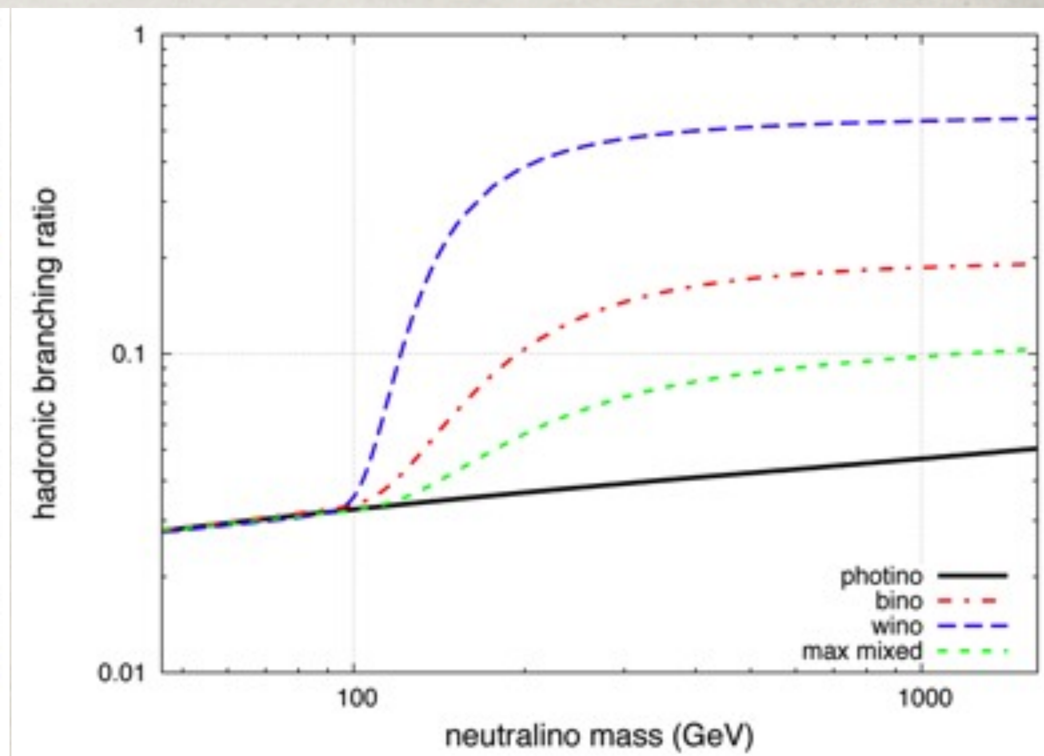
[LC, Hasenkamp, Roberts & Pokorski 09]

- In the CMSSM the neutralino NLSP is strongly constrained and requires a gravitino mass < 1 GeV. Check which regions are still open in the general case and how light the gravitino has to be...
- Important parameter is the neutralino branching ratio into hadrons e.g. via 3 body decay.
- The other important parameter for BBN constraints is the number density: We compute it with Micromegas 2.0 by [Belanger et al. 06] in the general mixed case.
- We compare our results with the BBN bounds for neutral relics given for the pure electromagnetic decays and also for different values of the hadronic branching ratios by [K. Jedamzik 06]

Gaugino hadronic BR

[LC, Hasenkamp, Roberts & Pokorski 09]

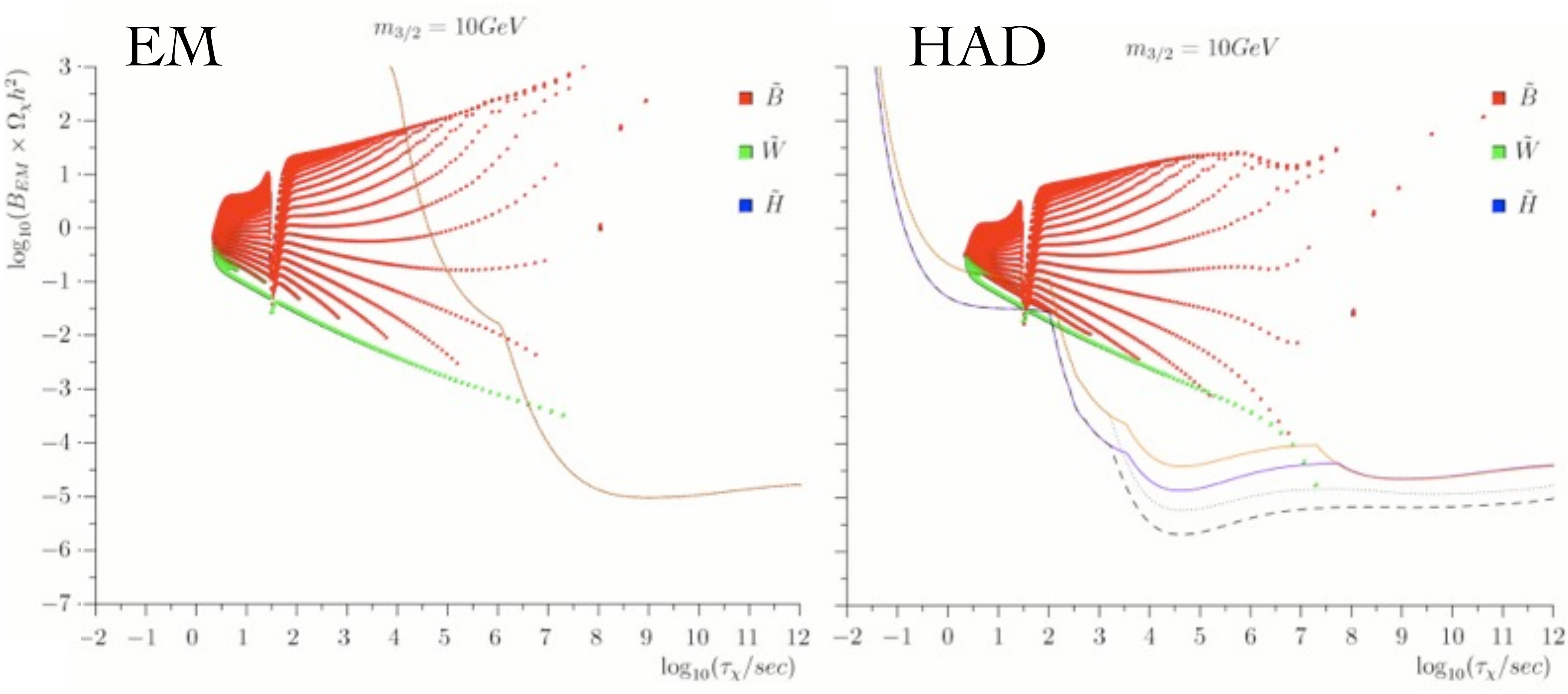




Reconsider the neutralino case in the most general terms: Compute the hadronic branching ratio exactly, including the contribution of intermediate photon, Z, Higgs and squarks.... The hadronic BR is always larger than 0.03, but for large masses it can be suppressed by interference effects...

Bino-Wino neutralino

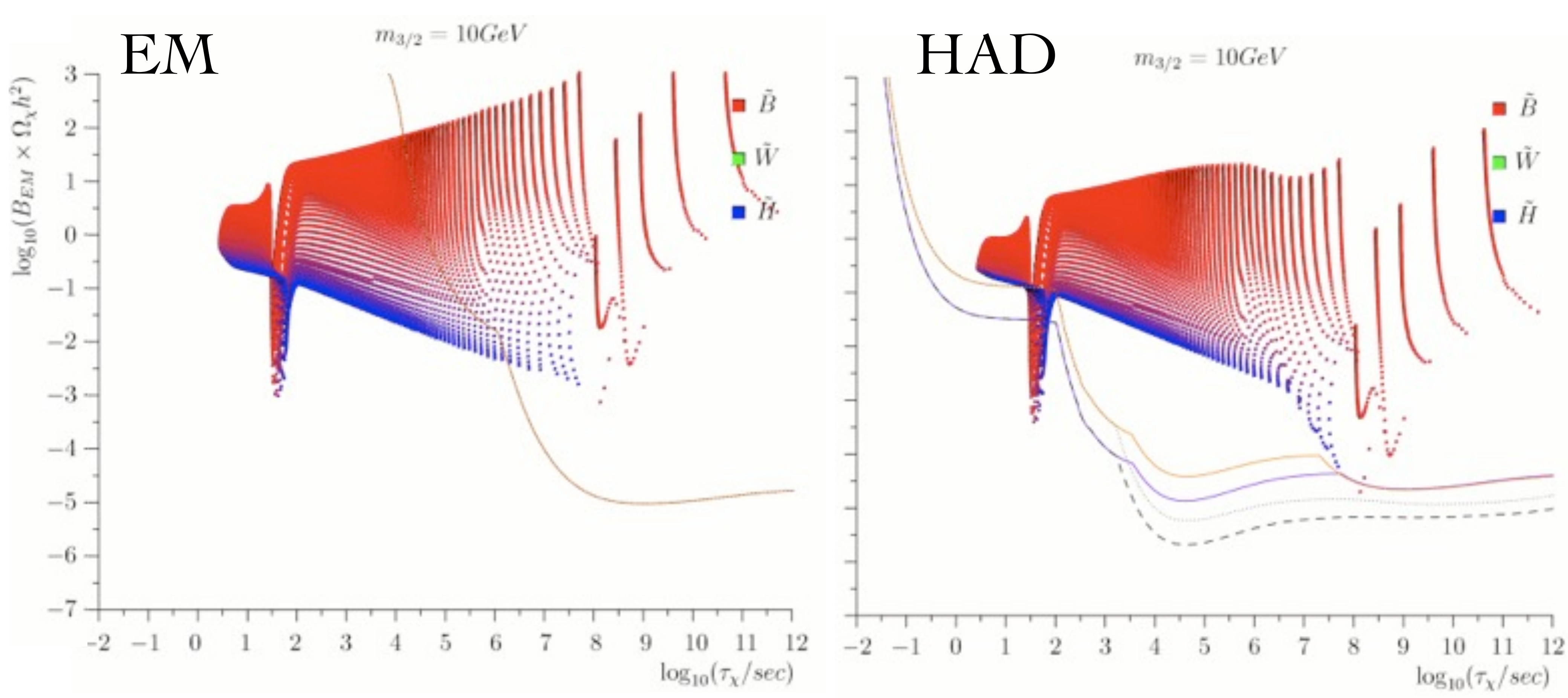
[LC, Hasenkamp, Roberts & Pokorski 09]



Not much room for Bino-Wino neutralino, even when the branching ratio is reduced by interference...
Still for low Wino masses the EM constraints are stronger !

Bino-Higgsino

[LC, Hasenkamp, Roberts & Pokorski 09]



The resonant annihilation into heavy Higgses becomes much more effective & reduces the density by 4 orders of magnitude !

The Higgs resonance

[LC, Hasenkamp, Roberts & Pokorski 09]

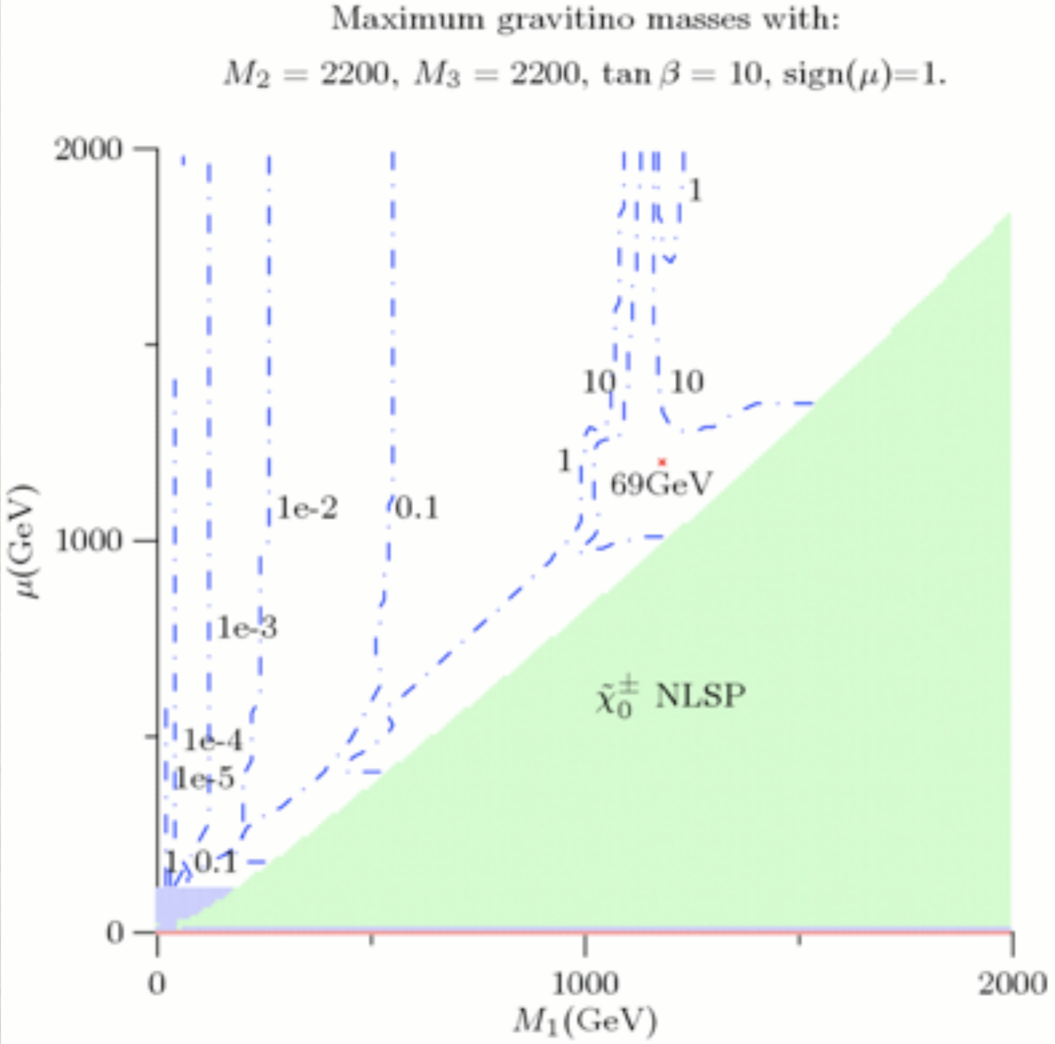
The Higgs resonance is effective only in a small region of parameter space.

It allows for a gravitino mass up to 10-70 GeV !

But needs strong degeneracy:

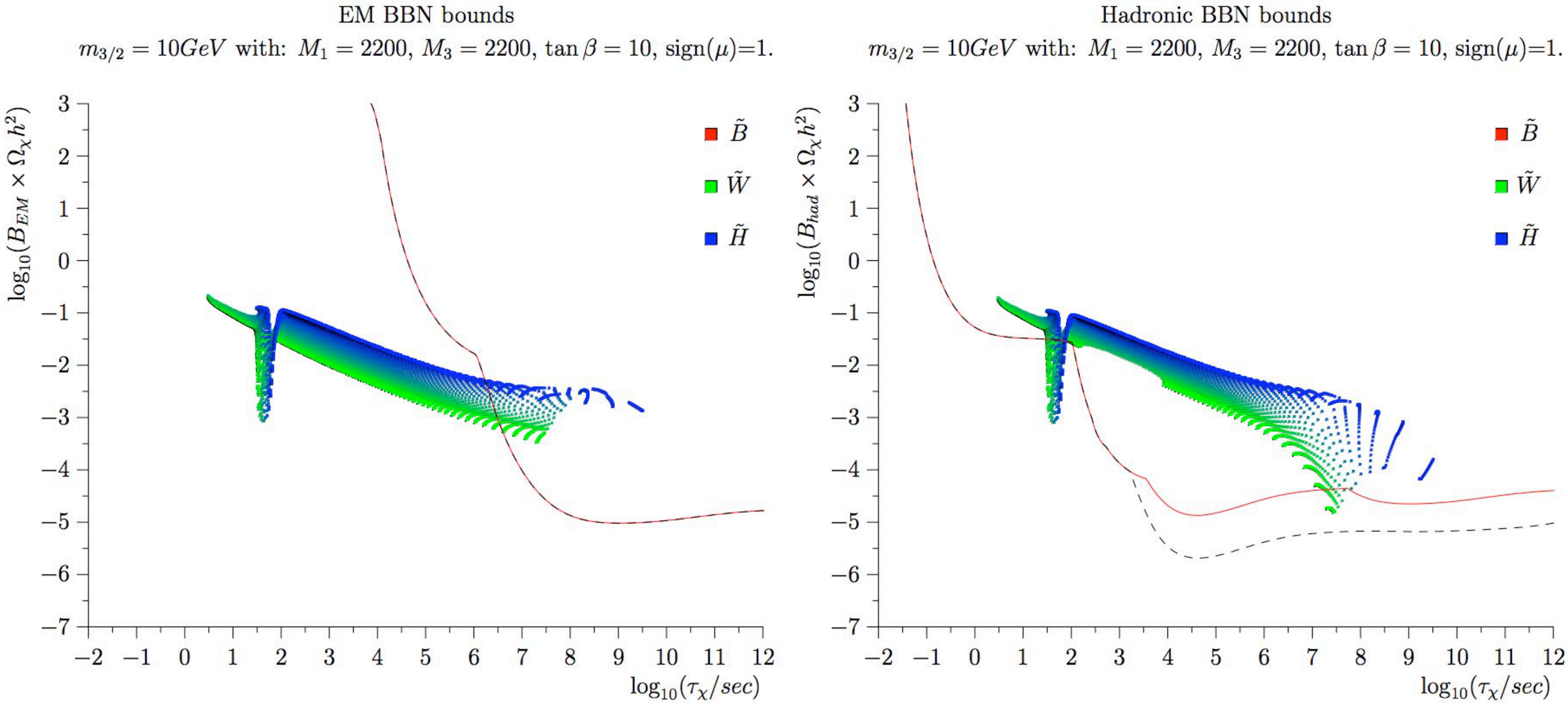
$$2\, m_\chi \sim M_{A/H}$$

Fine-tuning ???



Wino-Higgsino

[LC, Hasenkamp, Roberts & Pokorski 09]



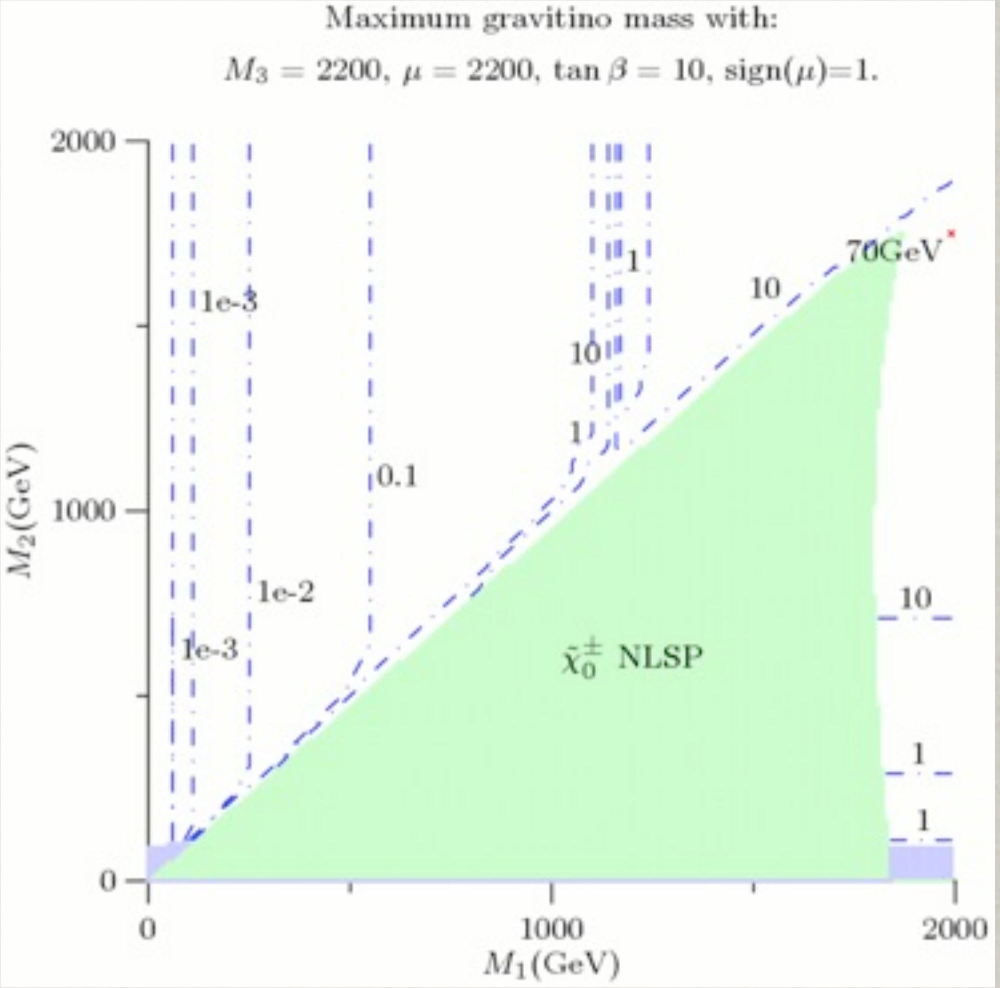
The Wino case has even stronger annihilation and lower energy density; apart for the resonance region, also a light Wino can allow for 1-5 GeV gravitino masses thanks to low BR in hadrons...

LIGHT WINO WINDOW...

This points to a relatively light Wino NLSP, with a nearly degenerate chargino...
Coannihilation helps in decreasing the density.

In this case less fine-tuned since both masses are driven by a single parameter, M_2.

[LC, Hasenkamp, Roberts & Pokorski 09]



Maximizing T_R

MAXIMAL T_R

Look again at the thermal production yield:

$$\Omega_{3/2}h^2 \simeq 0.3 \left(\frac{1\text{GeV}}{m_{3/2}}\right) \left(\frac{T_R}{10^{10}\ \text{GeV}}\right) \sum_i c_i \left(\frac{M_i}{100\ \text{GeV}}\right)^2$$

Best case scenario, all gaugino masses M_i equal and as light as possible..., while $m_{3/2}$ as large as possible.

→ light degenerate gaugino spectrum
as it is possible in general gauge mediation

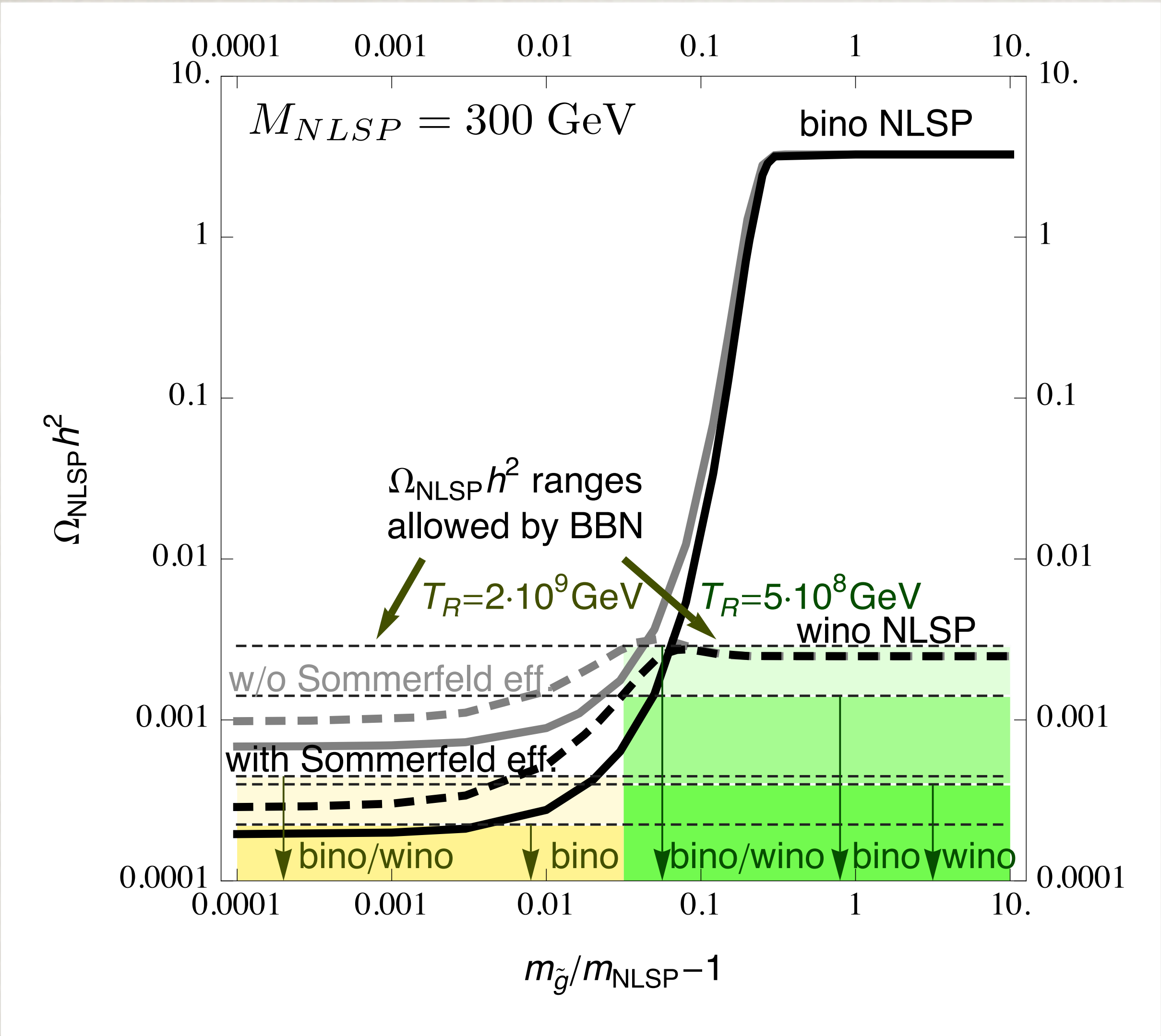
[Olechowski, Pokorski, Turzynski, Wells 09]

Light and degenerate gaugino or "compressed susy" also ameliorates the fine-tuning problem talk of G.Ross

Other advantage of degenerate masses at the low scale: coannihilation helps reducing the NLSP density !

Degenerate gauginos NLSP

[LC, Olechowski, Pokorski, Turzynski, Wells ....]



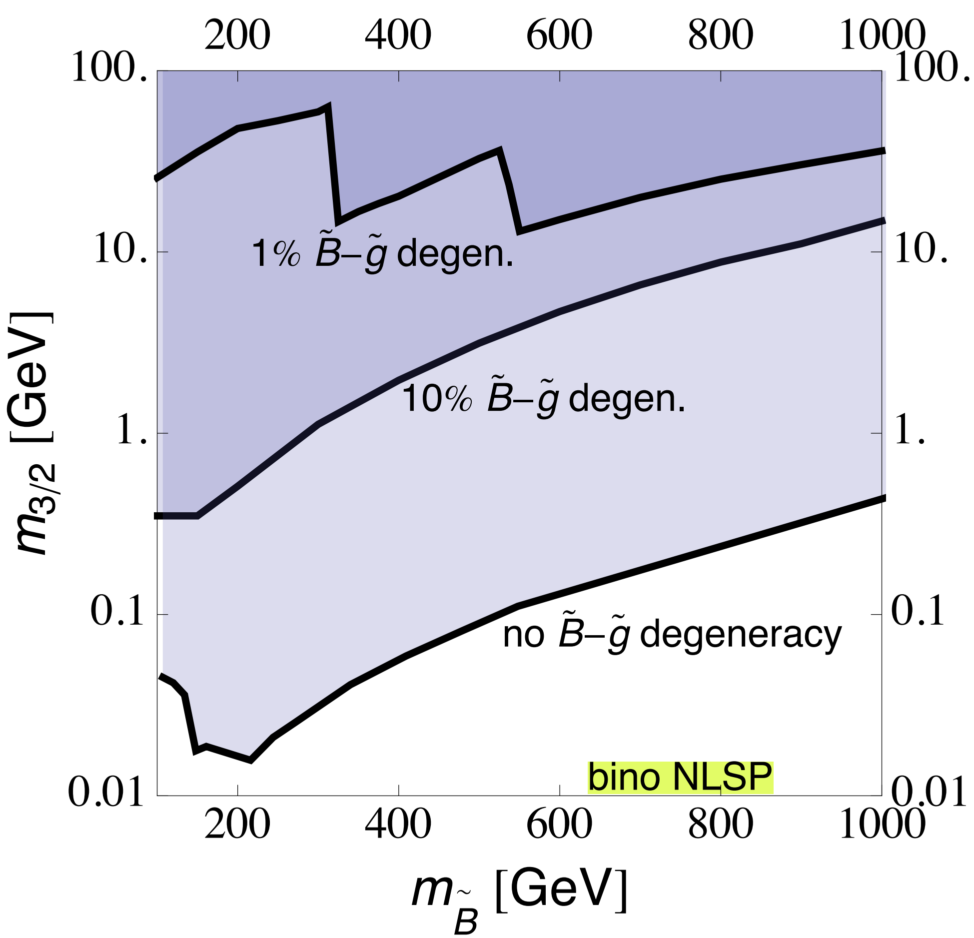
Gluinos annihilate most efficiently, but are a bad NLSP due to BBN bound state effects...

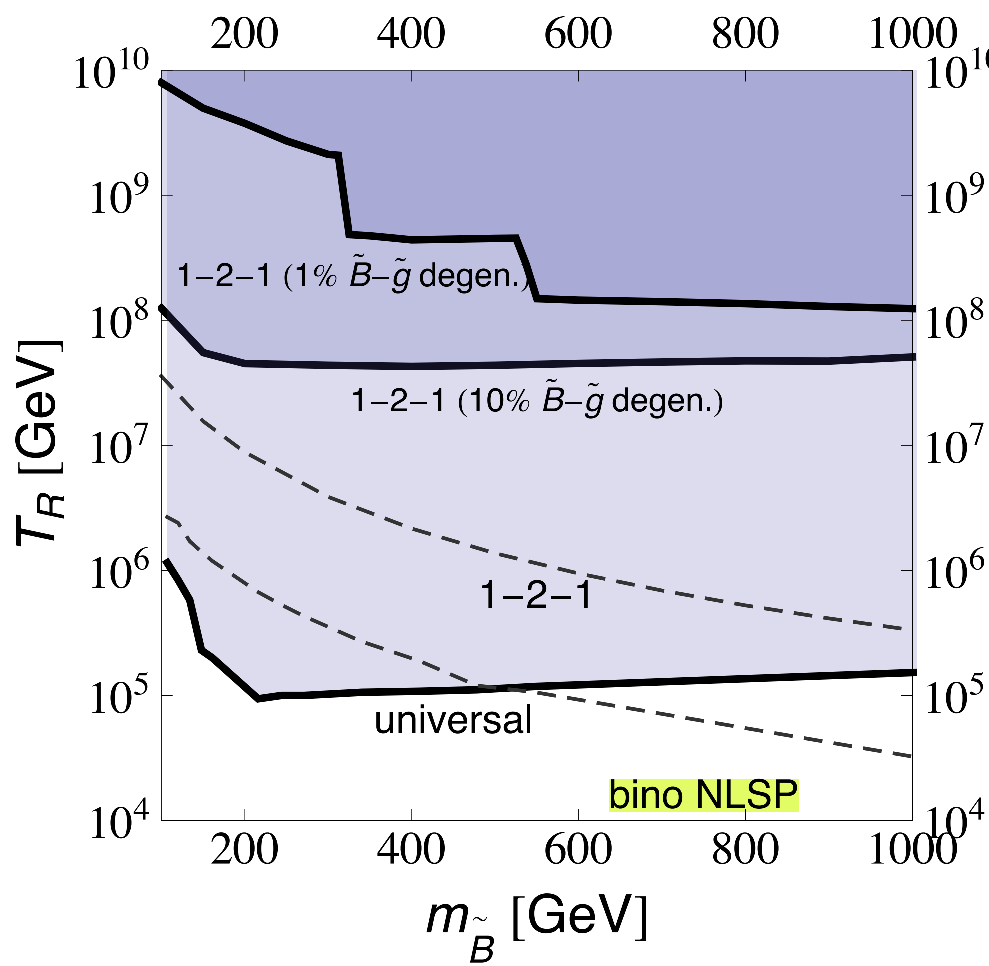
On the other hand they can help the other neutralinos NLSP.

The coannihilation with gluinos has a very strong effect on the Bino, even for just 10% degeneracy. Less effect for Wino.

Degenerate gauginos NLSP

[LC, Olechowski, Pokorski, Turzynski, Wells ....]





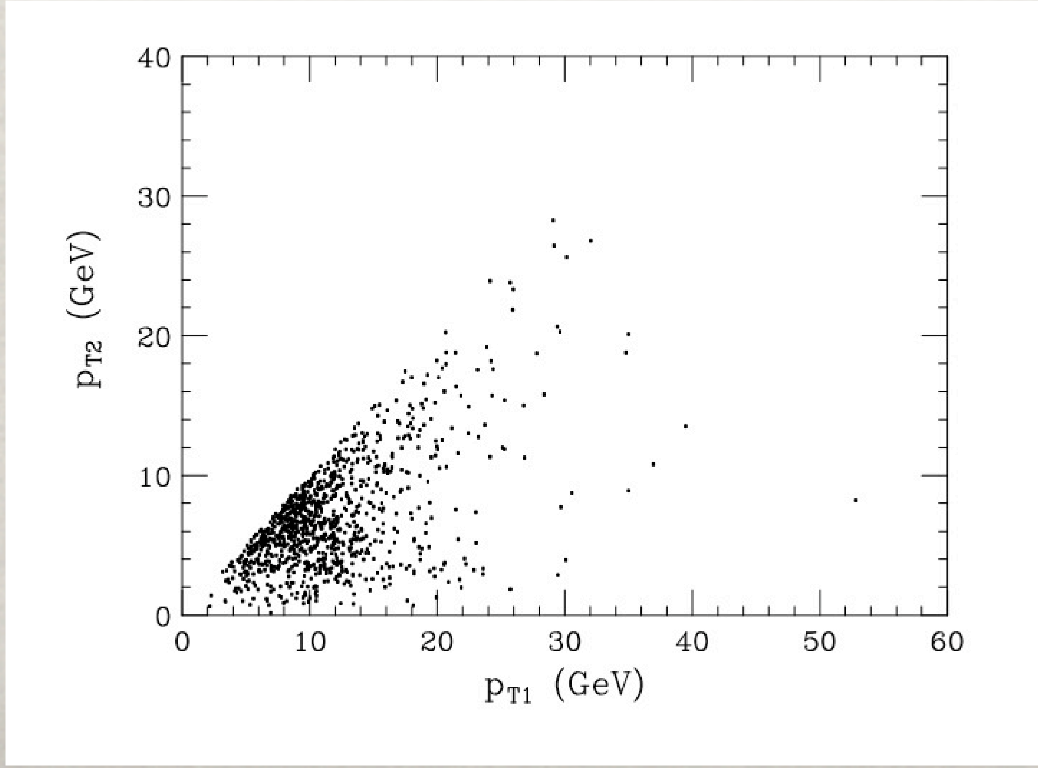
The coannihilation with gluinos allows to reach large T_R, but with very strong degeneracy...

LHC: DEGENERATE GAUGINOS?

In this scenario of maximal T_R and stable gravitino DM we expect light gauginos with 1-10% degeneracy between NLSP and gluino NNLSP.

The largest cross-section at LHC is gluino pair production, but if they decay dominantly into quark and neutralino, the arising jets are possibly too soft to trigger on...

$$m_{\tilde{g}} = 309$$
$$m_{\tilde{B}} = 300$$



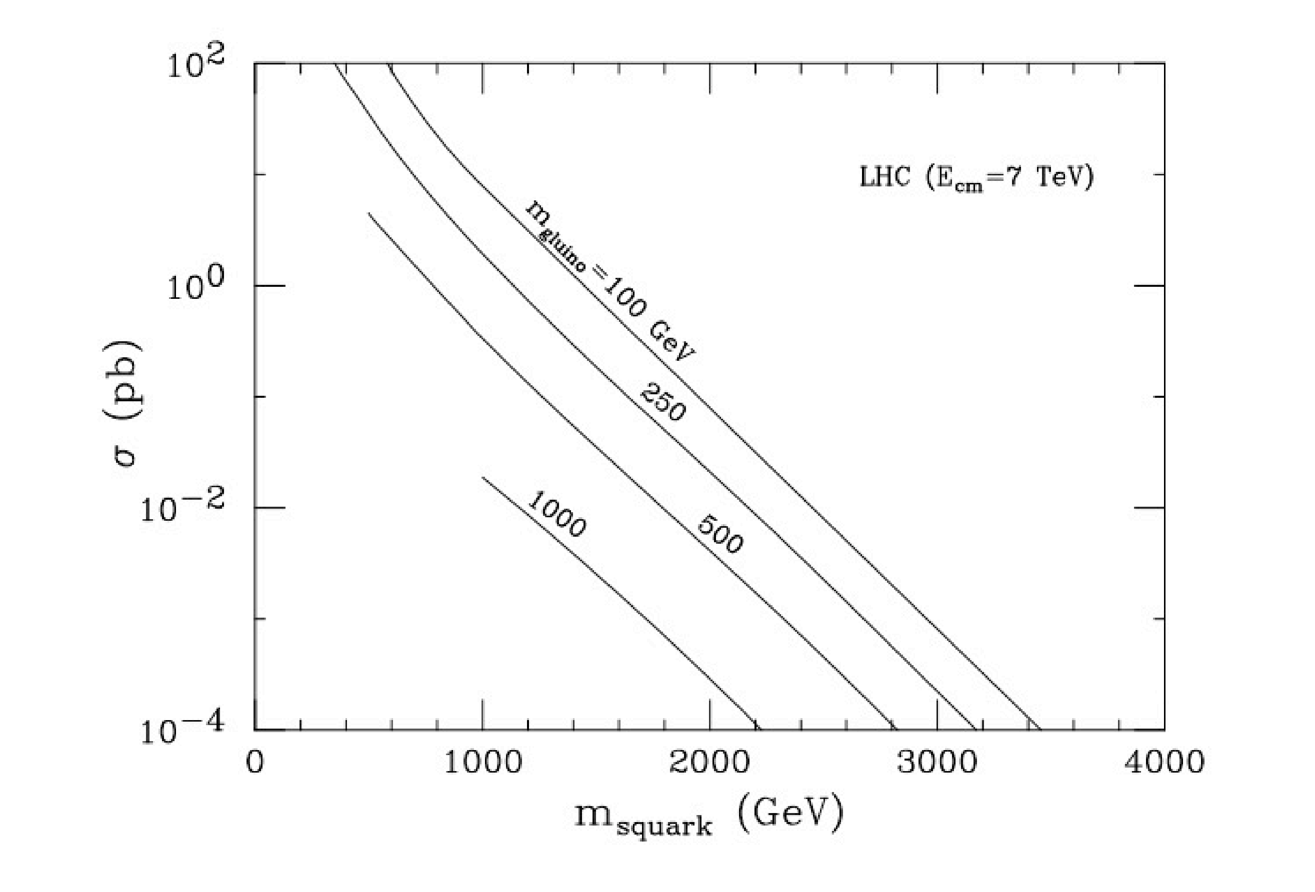
low p_T !

ISR may help ?

talk M. Nojiri

LHC: single jet signature

More promising perhaps the squark-gluino channel, where the squark decays into quark and gluino (= missing Energy !). Since the other gluino also decays invisibly, the signal is a single jet and large missing transverse momentum.



Outlook

- The gravitino is a pretty natural DM candidate, but BBN strongly constrains the nature of the NLSP, the gravitino mass and also the gaugino mass scale, in order to accomodate leptogenesis.

- A light degenerate gaugino spectrum offers many advantages: it reduces the gravitino thermal yield and increases the coannihilation of the gaugino NLSP. Then even Bino NLSP with $T_R \sim 10^9$ GeV is fine. Or: degenerate gravitinos talk of L. Boubekeur

- Such degenerate gauginos may present a challenge for LHC, but since the gluinos are light, a copious signal may be expected, e.g. in single jet + missing E_T.