Horiba International Conference

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Gravitino DM and the SUSY breaking spectrum

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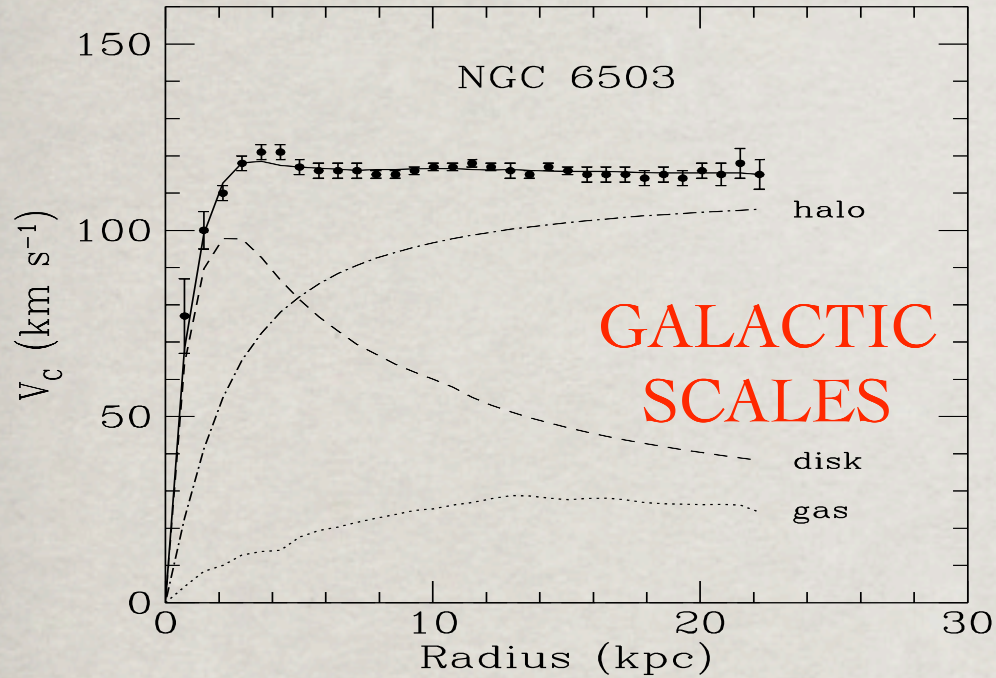
DESY

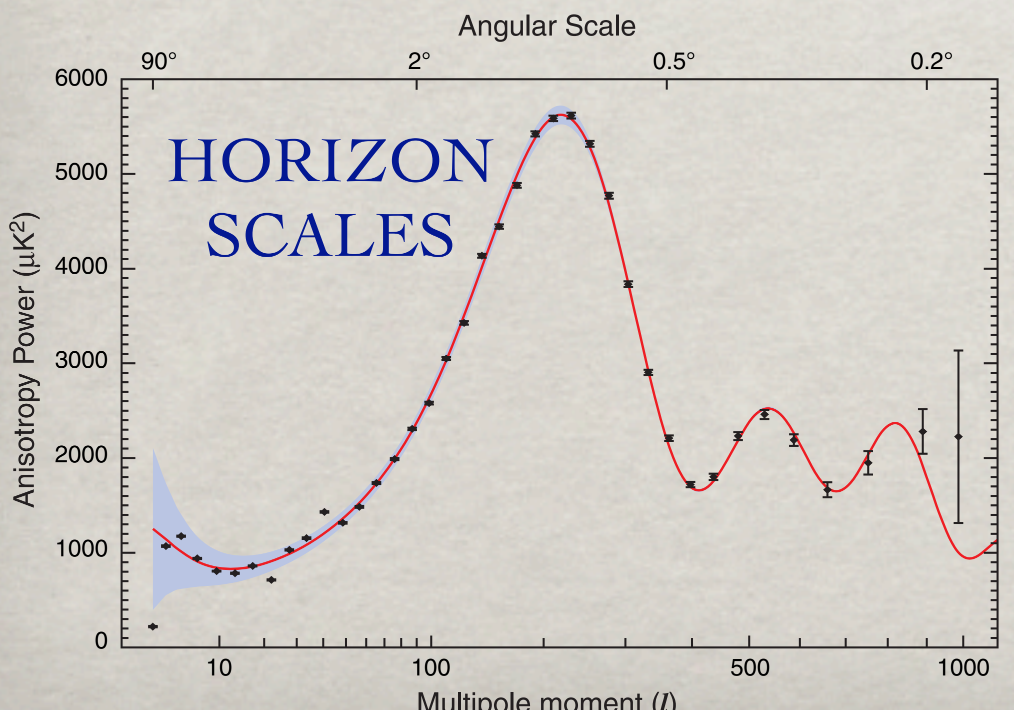
HELMHOLTZ | ASSOCIATION

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 with degenerate gauginos
- Decaying gravitino Dark Matter
- 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 K.Y. Choi

- Opens a WINDOW ON SUSY BREAKING !

GRAVITINO properties: completely fixed by SUGRA !

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

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

~~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

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

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NLSP DECAY
OUT OF EQUILIBRIUM

$\Omega \ldots {}^2 \propto \ldots h^2$

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.

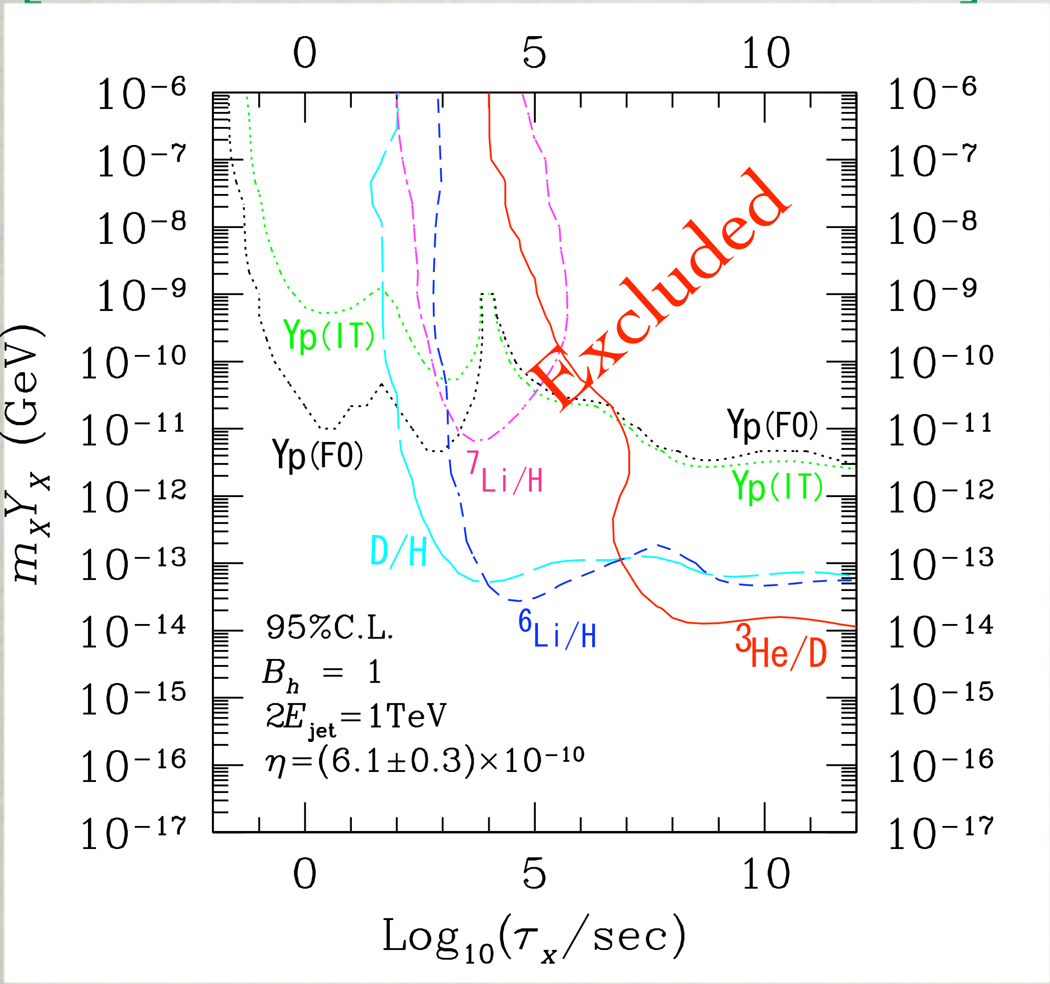
Tension with thermal leptogenesis for small gravitino masses !

BBN bounds on NLSP decay

talk of G. Steigman

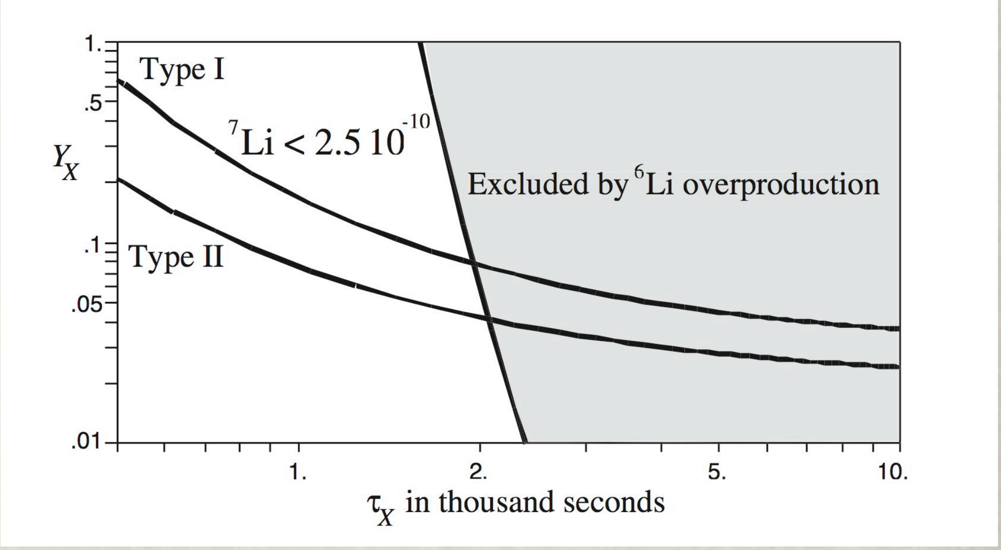
Neutral relics

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



Charged relics

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



Need short lifetime & low abundance for NLSP

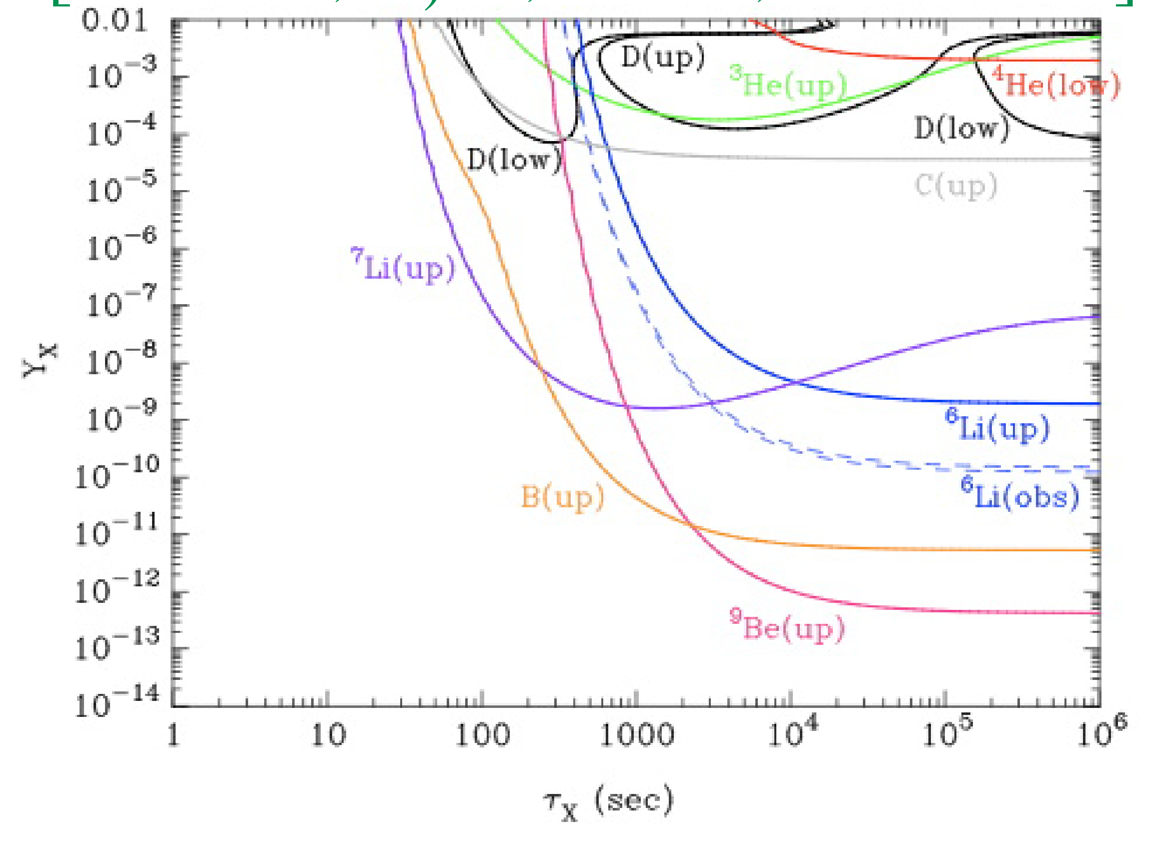
Big trouble for gravitino LSP, if the mass is above 1 GeV...

talk of L. Roszkowski

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...

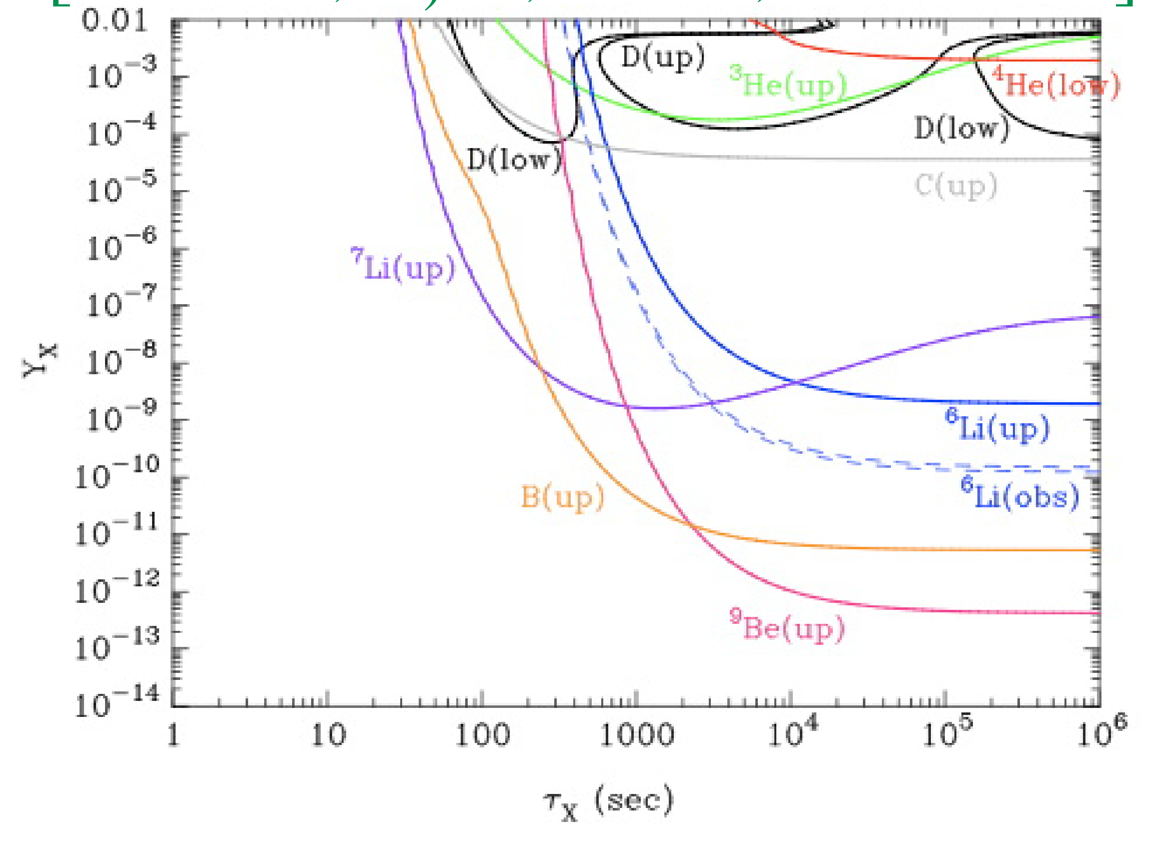
Beware:

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

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

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

[Kusakabe, Kajino, Yoshida, Mathews 09]



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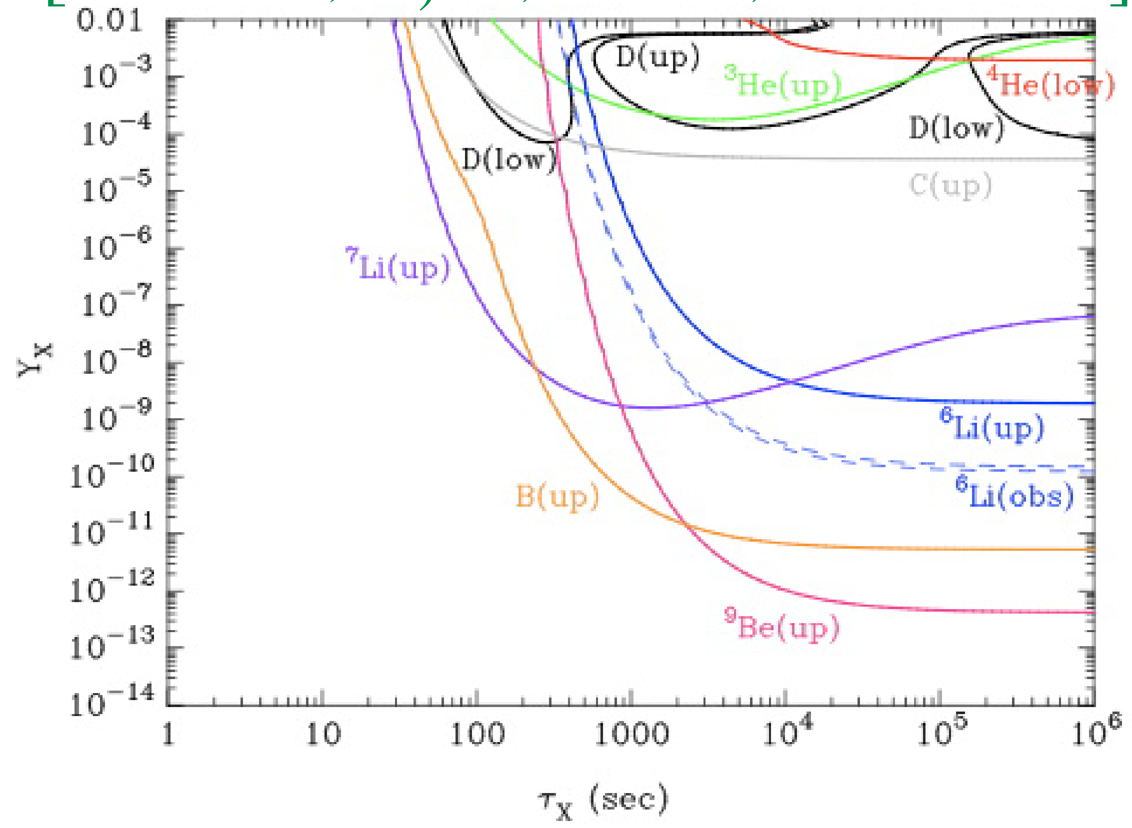
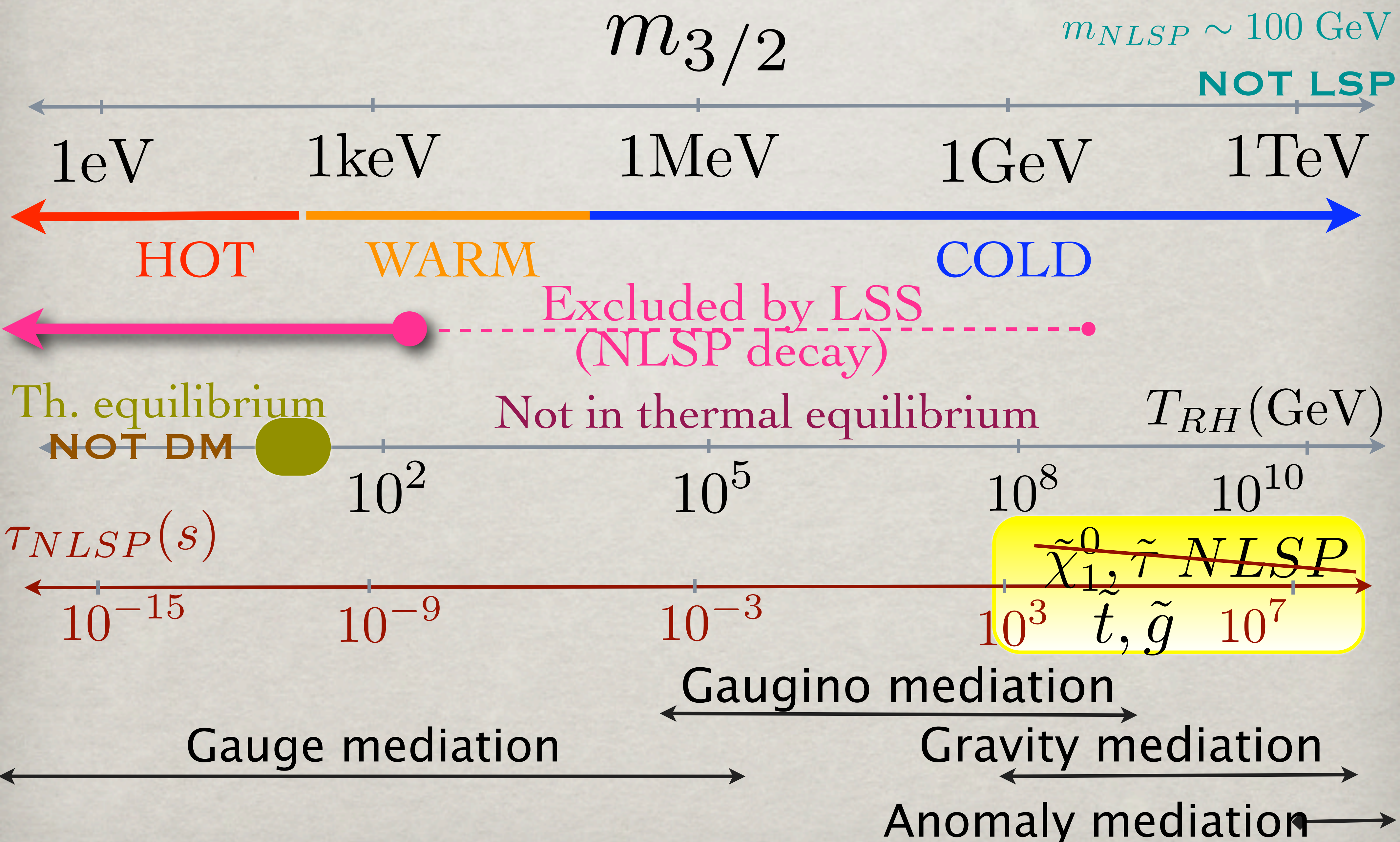


Only short lifetime for colored NLSP allowed:

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

Gravitino DM summary



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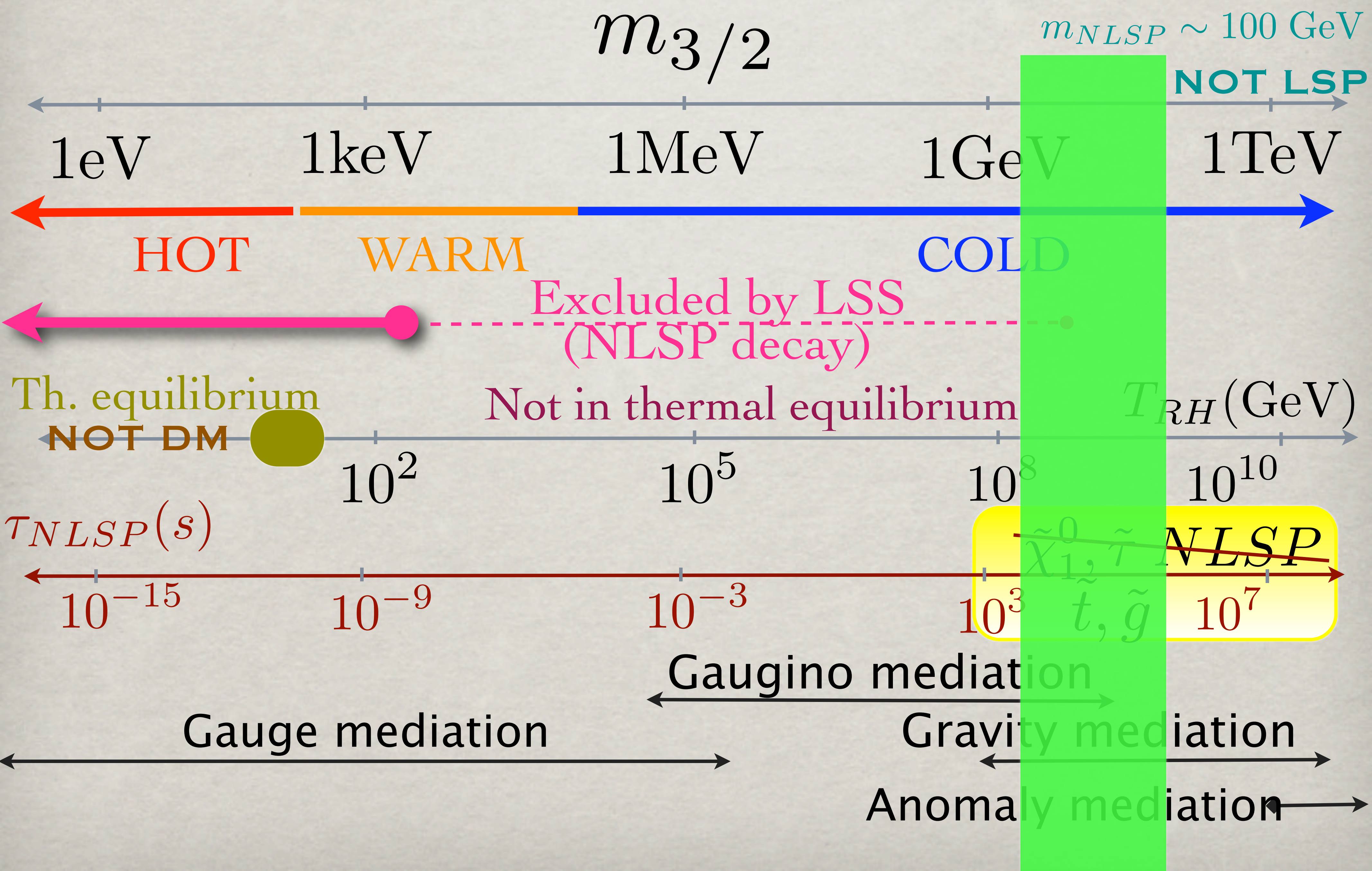


Revisiting neutralino NLSP

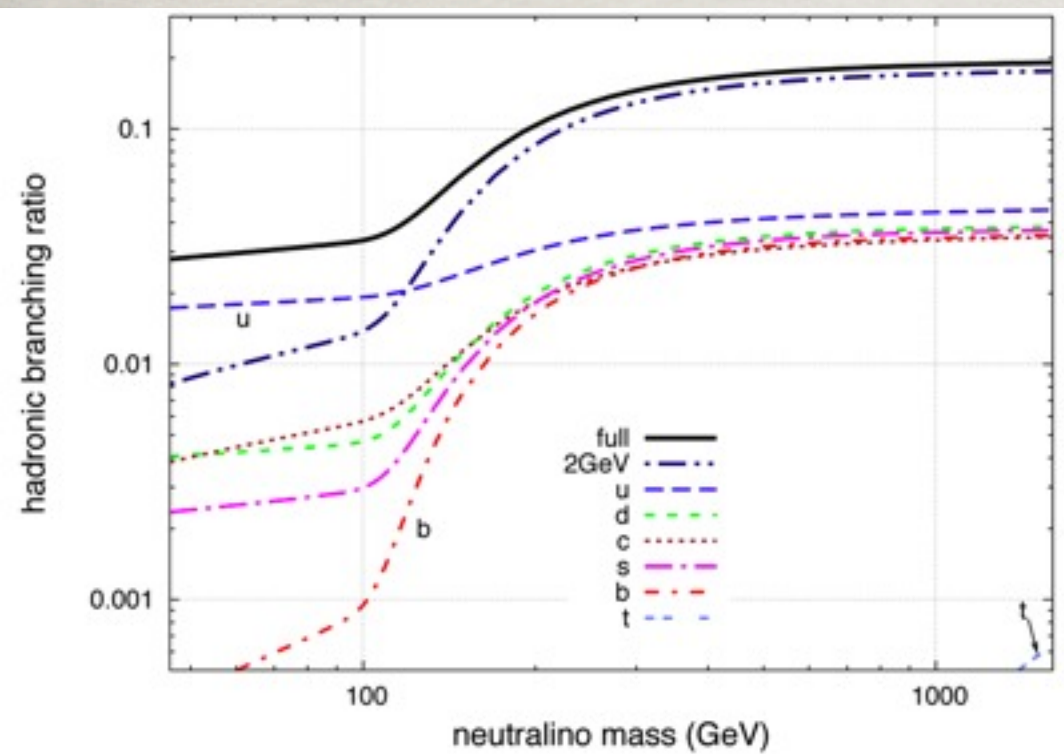
General neutralino NLSP

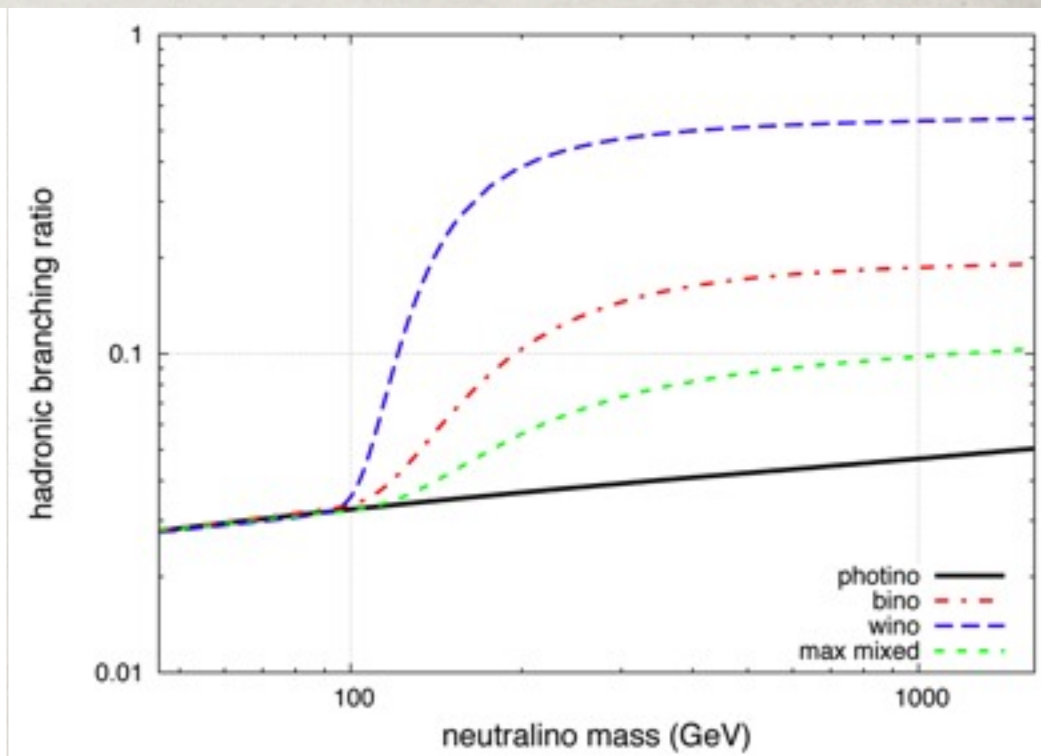
[LC, Hasenkamp, Roberts & Pokorski 09]

- 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]

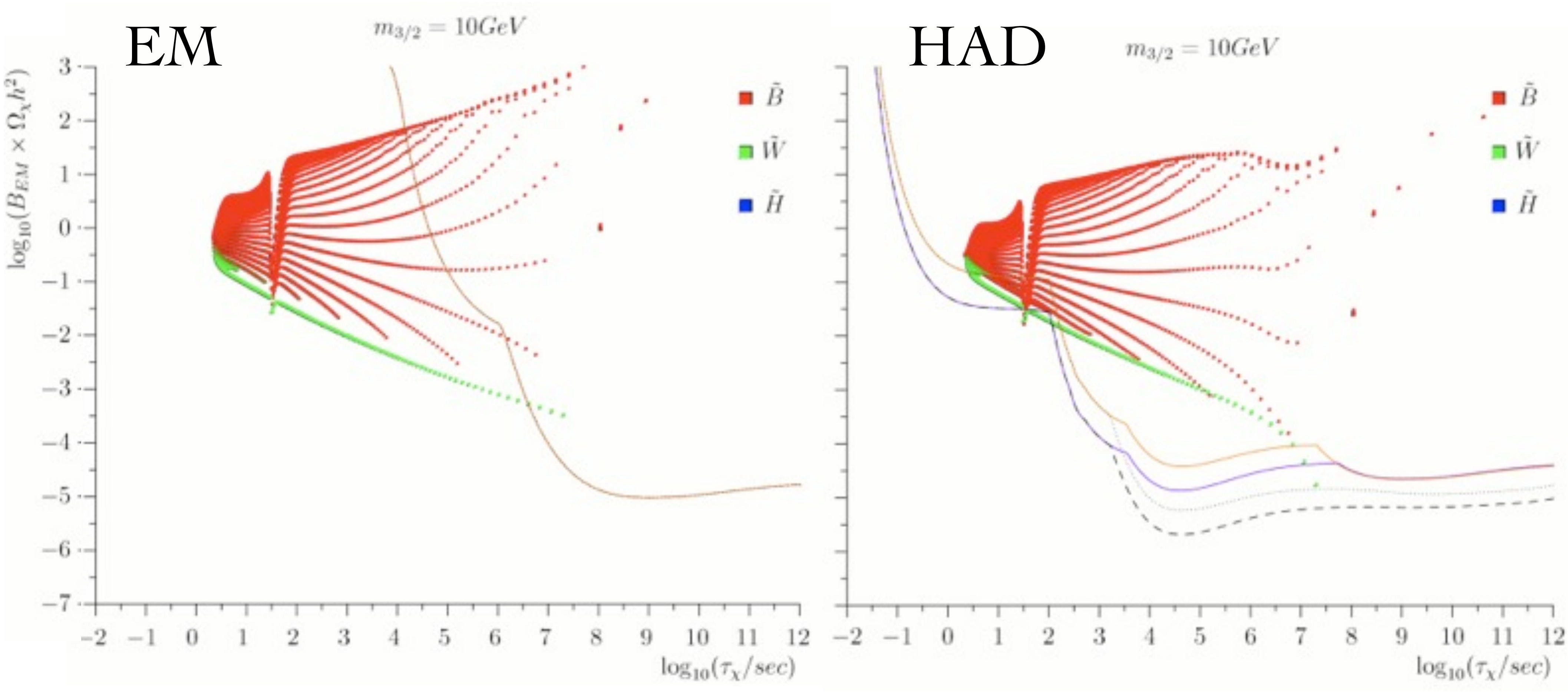




Reconsider the neutralino case in the most general terms: Compute the hadronic branching ratio exactly, including the contribution of intermediate photon, Z, Higgs and squarks.... The hadronic BR is always larger than 0.03, but for large masses it can be suppressed by interference effects...

Bino-Wino neutralino

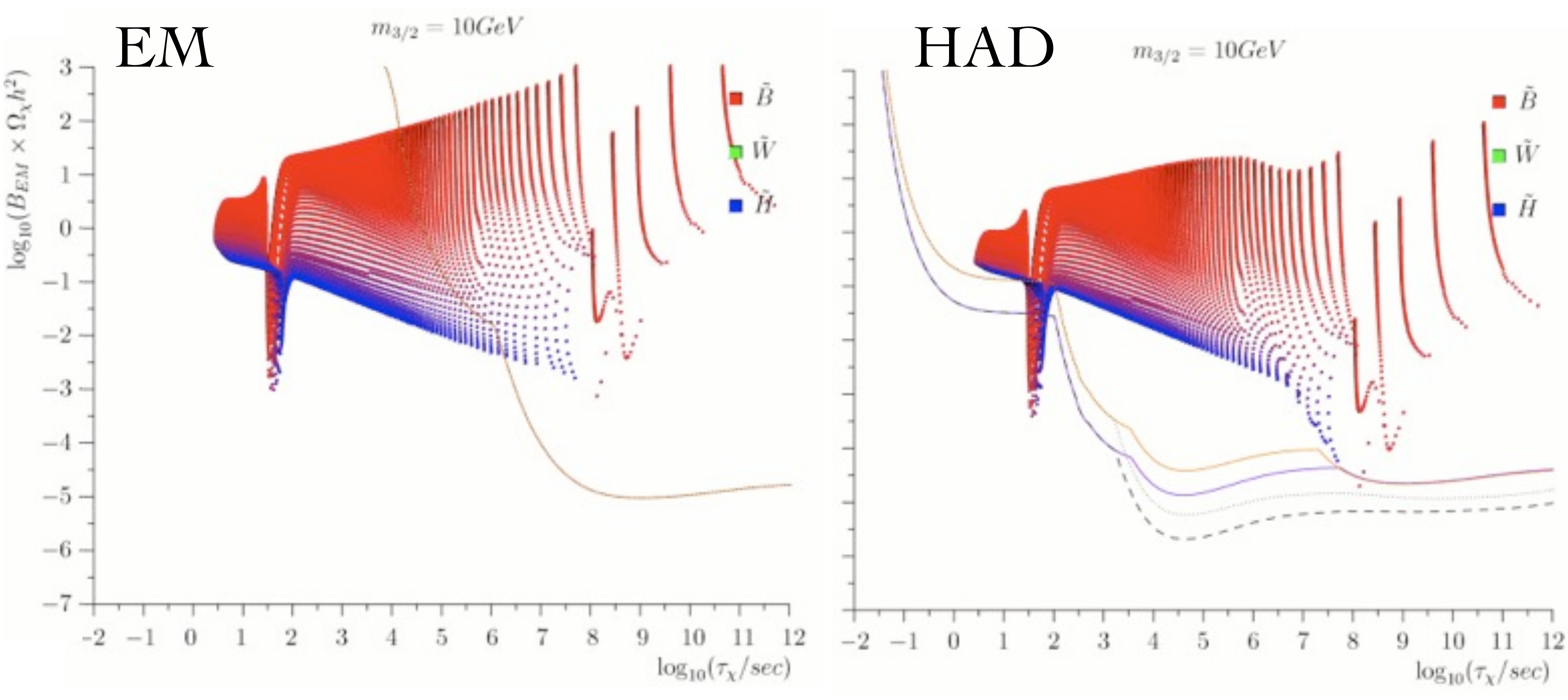
[LC, Hasenkamp, Roberts & Pokorski 09]



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

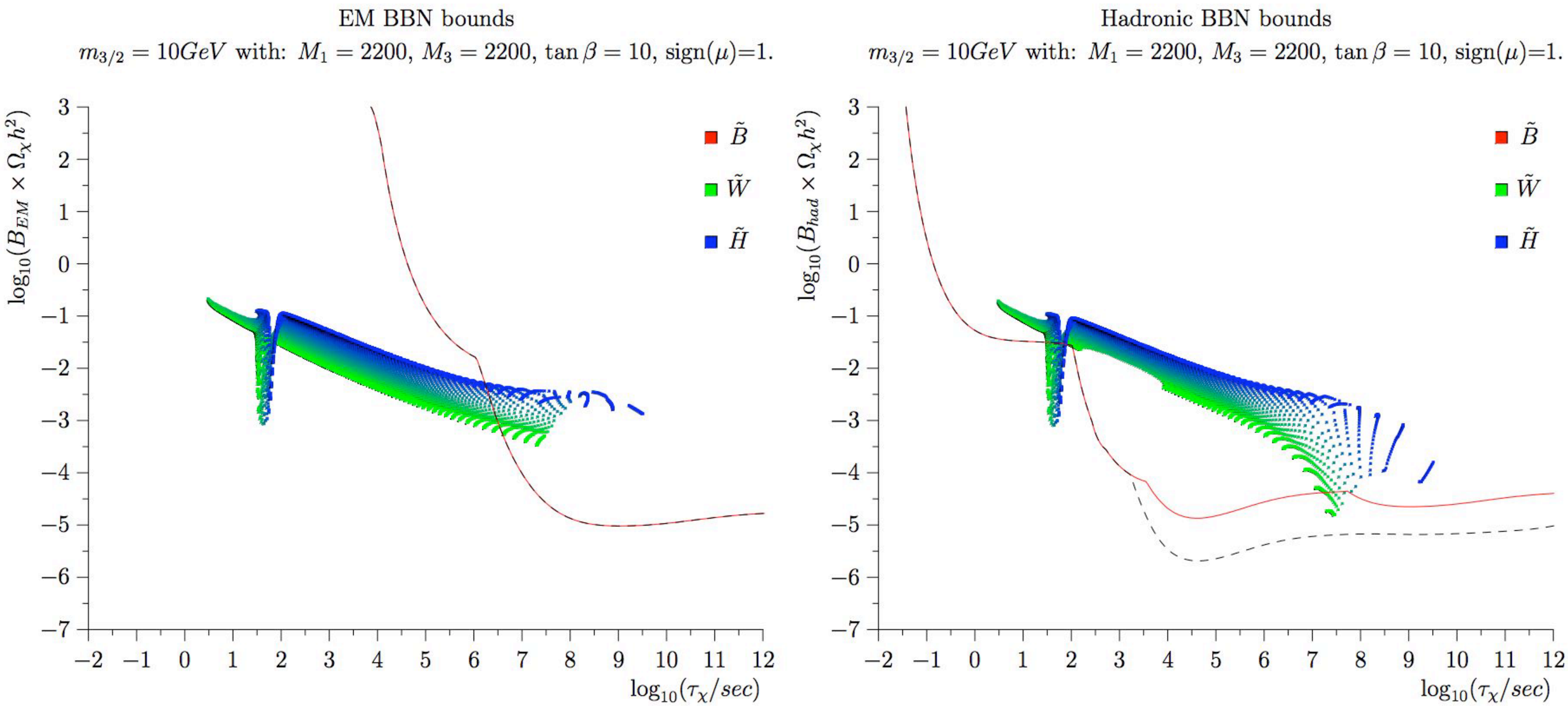
[LC, Hasenkamp, Roberts & Pokorski 09]



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

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...

Open windows

[LC, Hasenkamp, Roberts & Pokorski 09]

- Higgs resonance: it is effective only in a small region of parameter space, but allows for a gravitino mass up to 10-70 GeV ! But needs a quite mixed gaugino/higgsino neutralino and very strong degeneracy:

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

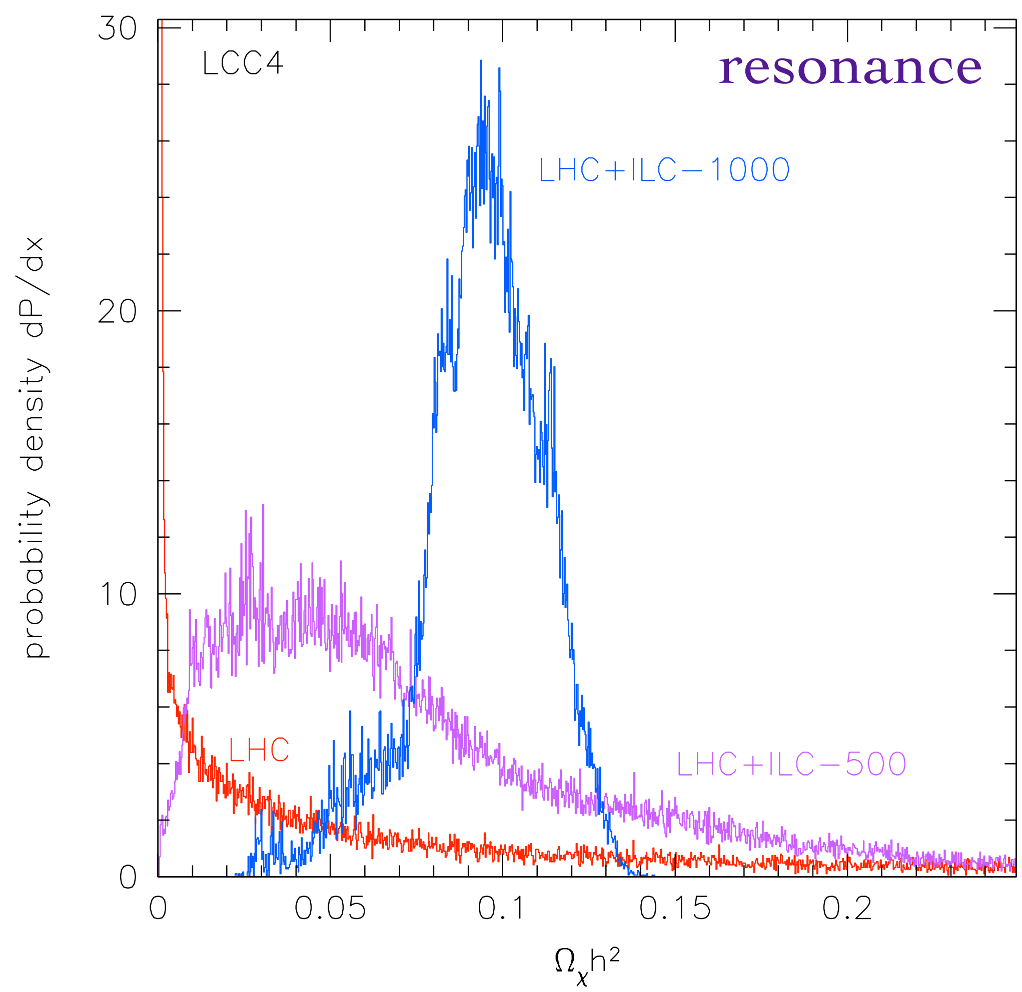
Fine-tuning ???

- Light Wino NLSP, with a nearly degenerate chargino... Coannihilation helps in decreasing the density and the hadronic BR is low. In this case less fine-tuned since both masses are driven by a single parameter, M_2 , but only gravitino masses of a few GeV are reached.

LHC: MISMATCH IN $\Omega_{DM} h^2$?

For a neutralino NLSP, light Wino or Higgsino annihilating at the resonance allow to relax the BBN constraints.
Unluckily it will be difficult to reconstruct precisely the relic density in the resonance case by LHC measurements alone in this case;
still possible perhaps to improve when data are coming...

[Baltz, Battaglia, Peskin & Wizanski '06]



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

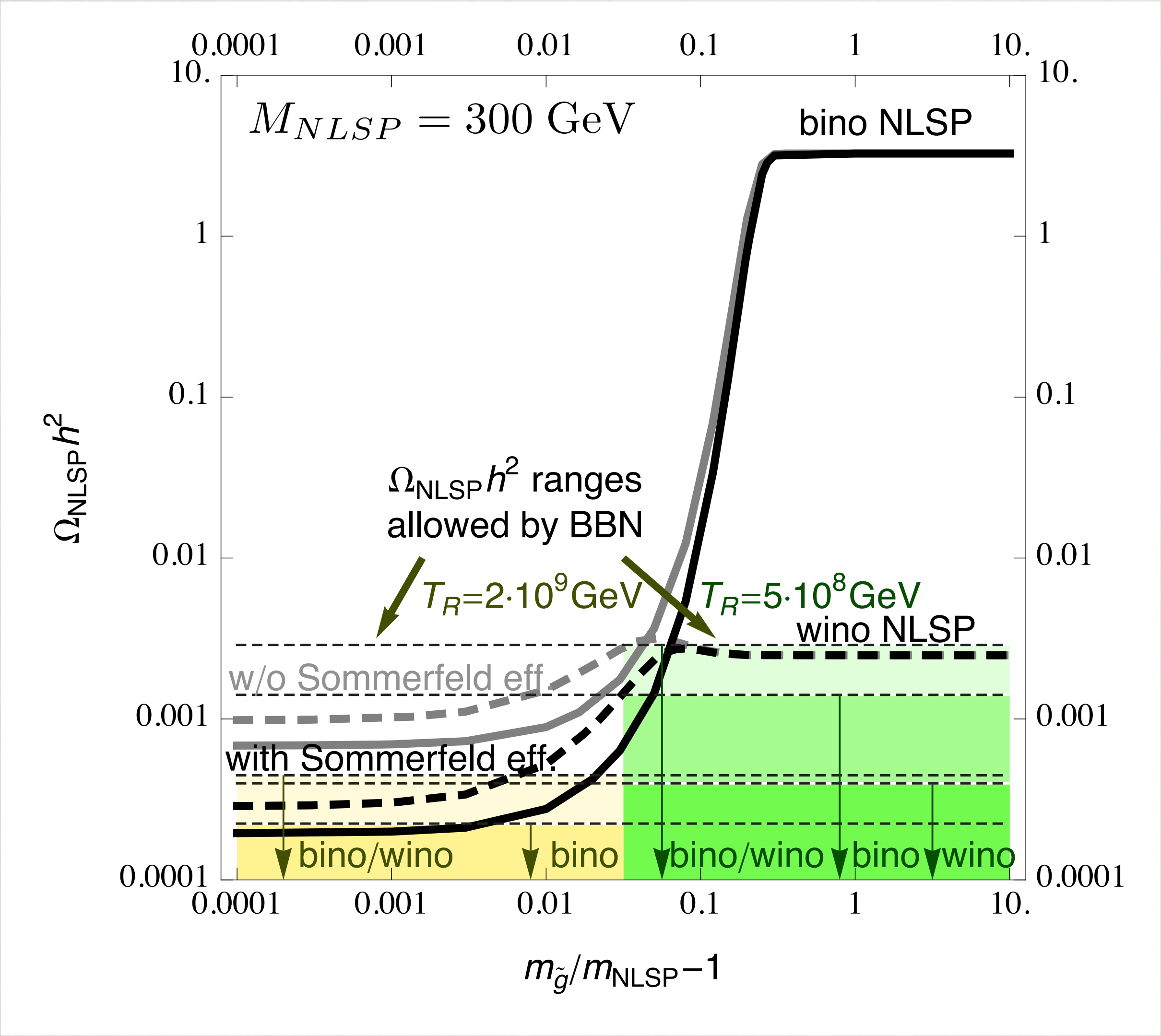
[Olechowski, Pokorski, Turzynski, Wells 09]

Light and degenerate gaugino or "compressed susy" also ameliorates the fine-tuning problem, while heavy scalar superpartners help with the flavour problem...

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

Degenerate gauginos NLSP

[LC, Olechowski, Pokorski, Turzynski, Wells 10]



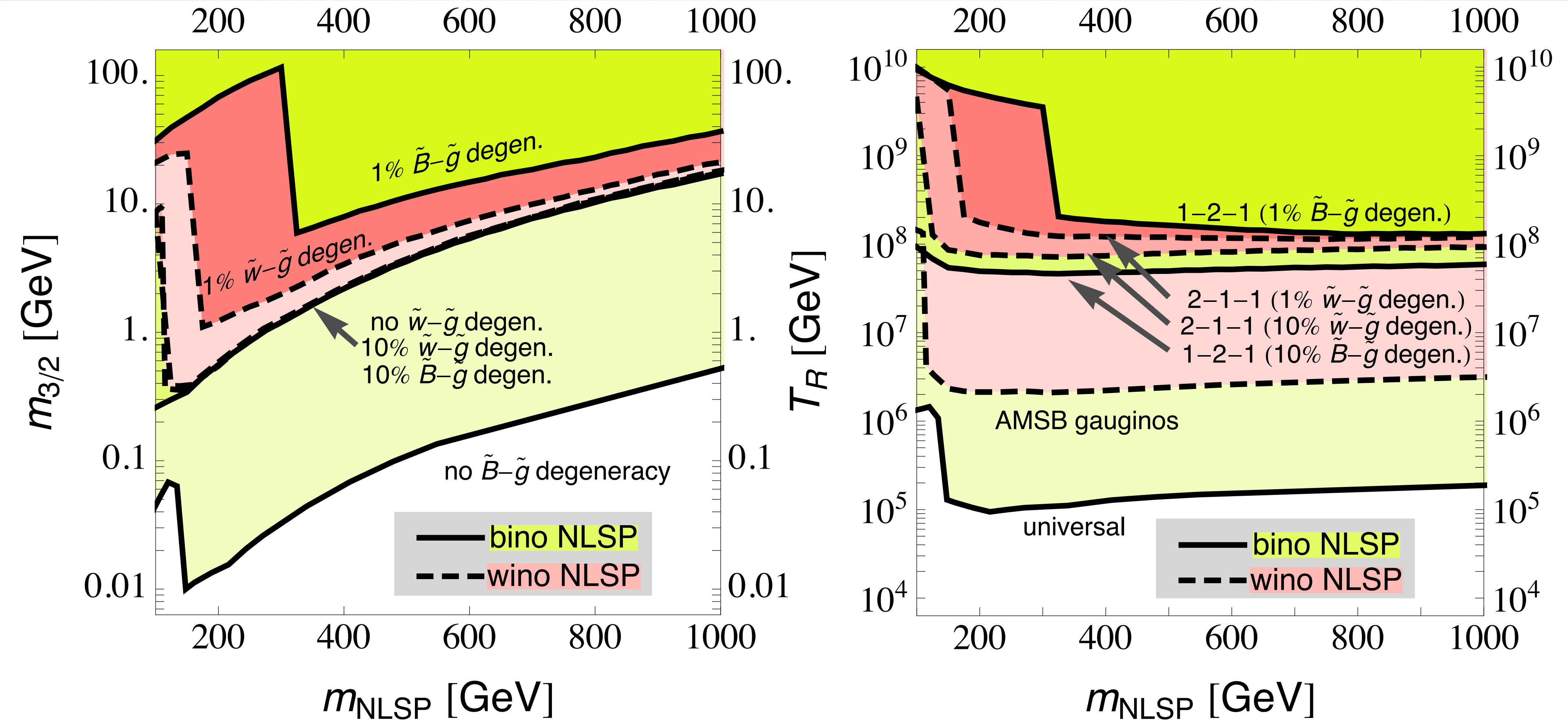
Gluinos annihilate most efficiently, but are a bad NLSP due to BBN bound state effects...

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. Weaker effect for the Wino.

Degenerate gauginos NLSP

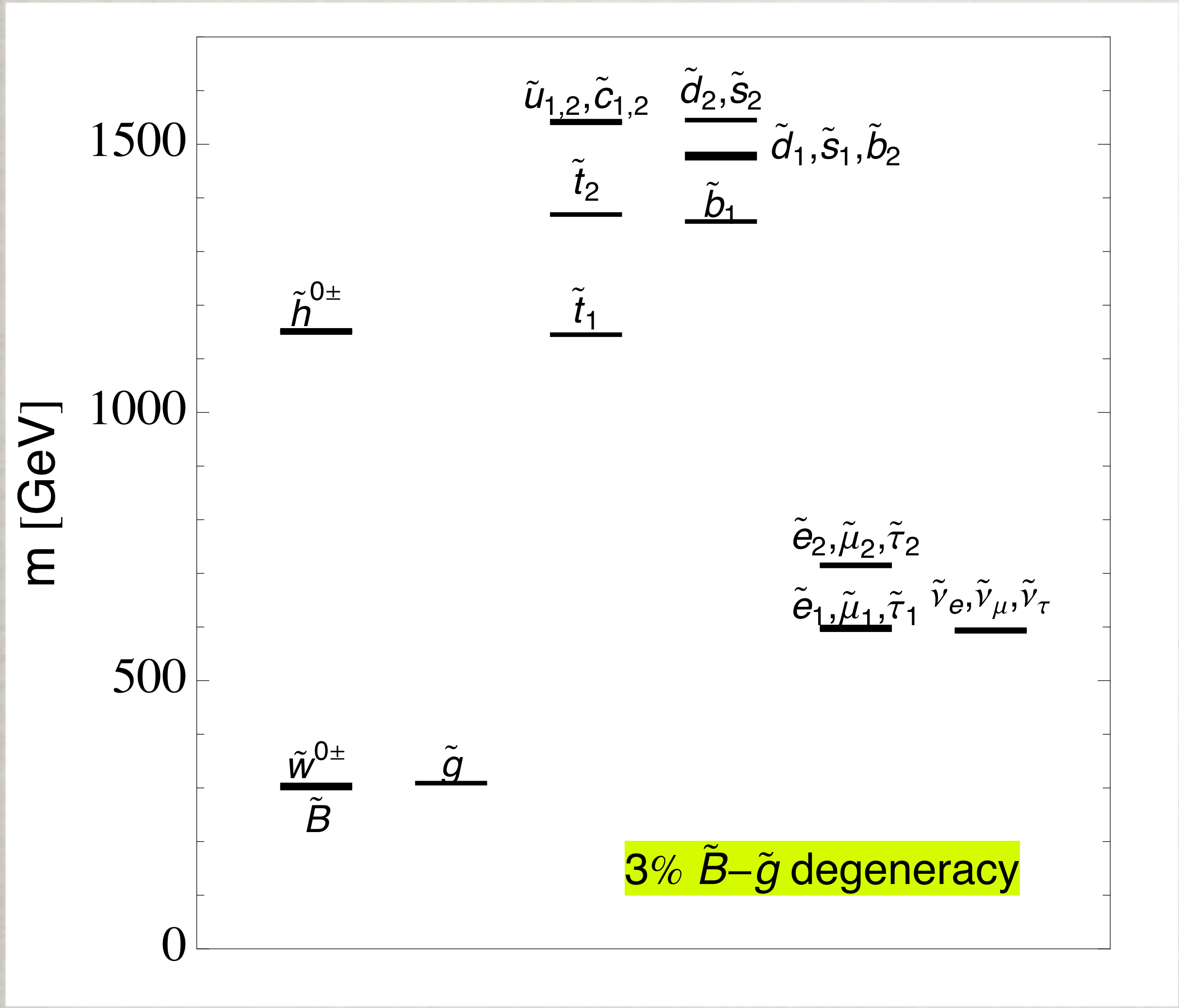
[LC, Olechowski, Pokorski, Turzynski, Wells 10]



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

Possible SUSY Spectrum ?

[LC, Olechowski, Pokorski, Turzynski, Wells 10]



Extended gauge mediation can provide the necessary spectrum, with moderate tuning...

Here the LSP is a Bino with 3% degeneracy to the gluinos and the Wino inbetween...

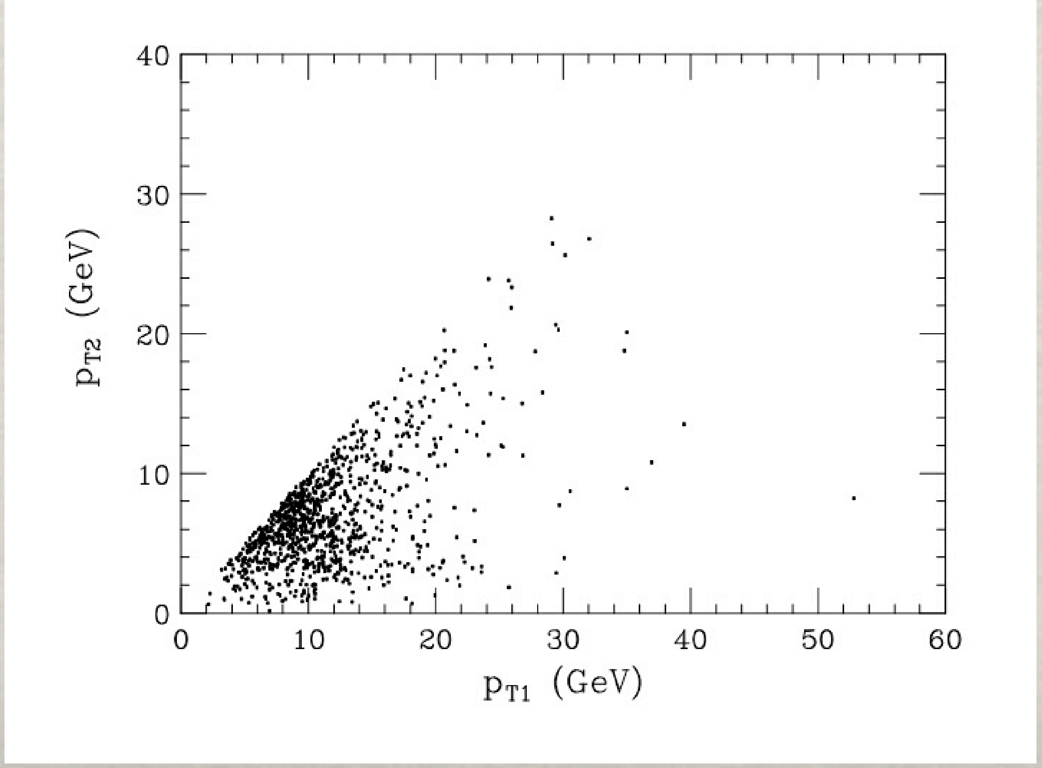
The reheat temperature can reach 0.3 10^9 GeV, m_3/2 ~ 5 GeV.

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...

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

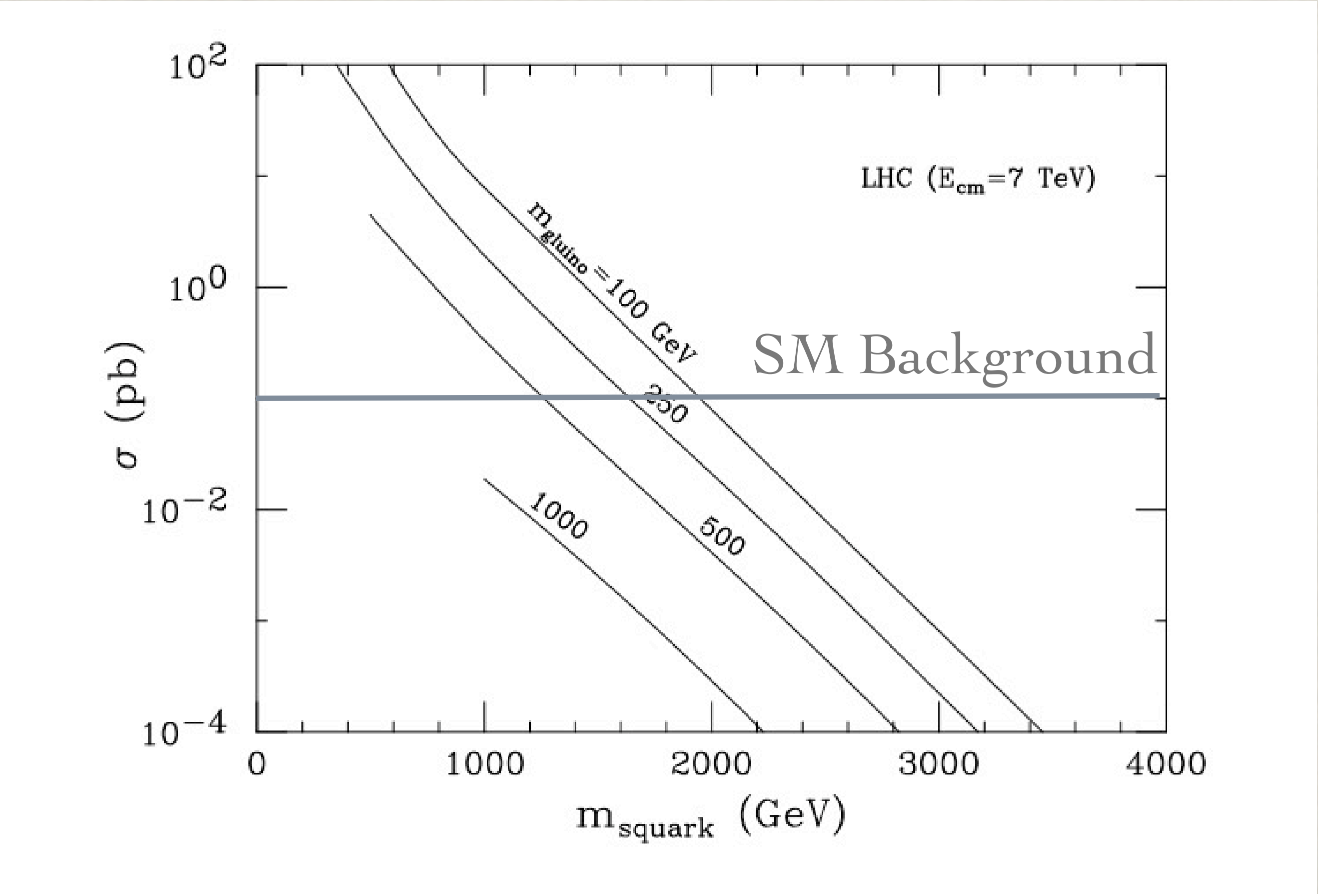


to low p_T !

talk of S. Asai

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.



Detectable in the 1st LHC phase up to 1.8 TeV squark mass !

Unstable Gravitino Dark Matter

R-parity or not R-parity

[Buchmuller, LC, Hamaguchi, Ibarra & Yanagida 07]

Actually there is a simple way to avoid BBN constraints: break R-parity a little... ! Then the NLSP decays quickly to SM particles before BBN and the cosmology returns standard.

$$W_{R\!\!\!/p} = \mu_i L_i H_u + \lambda L L E^c + \lambda' L Q D^c + \lambda'' U^c D^c D^c$$

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Open window:

$$10^{-12-14} < |\frac{\mu_i}{\mu}|, |\lambda|, |\lambda'| < 10^{-6-7}$$

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For the NLSP to decay before BBN

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For the NLSP to decay before BBN

To avoid wash-out of lepton number

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For the NLSP to decay before BBN

To avoid wash-out of lepton number

Explicit bilinear R-parity breaking model which ties R-parity breaking to B-L breaking and explains the small coupling.

Gravitino LSP decay

[Takayama & Yamaguchi 00, Buchmuller et al 07]

If R-parity is broken, the gravitino can decay into photon and neutrino via neutralino-neutrino mixing or via a one-loop diagram or into 3 SM fermions via the trilinear couplings.

$$\tilde{G} \to \nu\, \gamma/Z/h, \ell W \quad \tilde{G} \to \ell_L \bar{\ell}_L e_R \quad \tilde{G} \to \ell_L \bar{q}_L d_R$$

For bilinear R-parity breaking the 2-body channel dominates:

$$\tau_{\tilde{G}} = 4 \times 10^{27} s \left(\frac{U_{\tilde{\gamma}\nu}}{10^{-8}} \right)^2 \left(\frac{m_{\tilde{G}}}{10\mathrm{GeV}} \right)^{-3}$$

Note that the 2-body one-loop decay can also be larger than the 3-body one [Lola, Osland & Raklev 07], while below the W/Z thresholds, the 3-body decays via virtual W/Z are important when the photon channel is suppressed [K-Y. Choi & Yaguna 10]

DECAYING DM

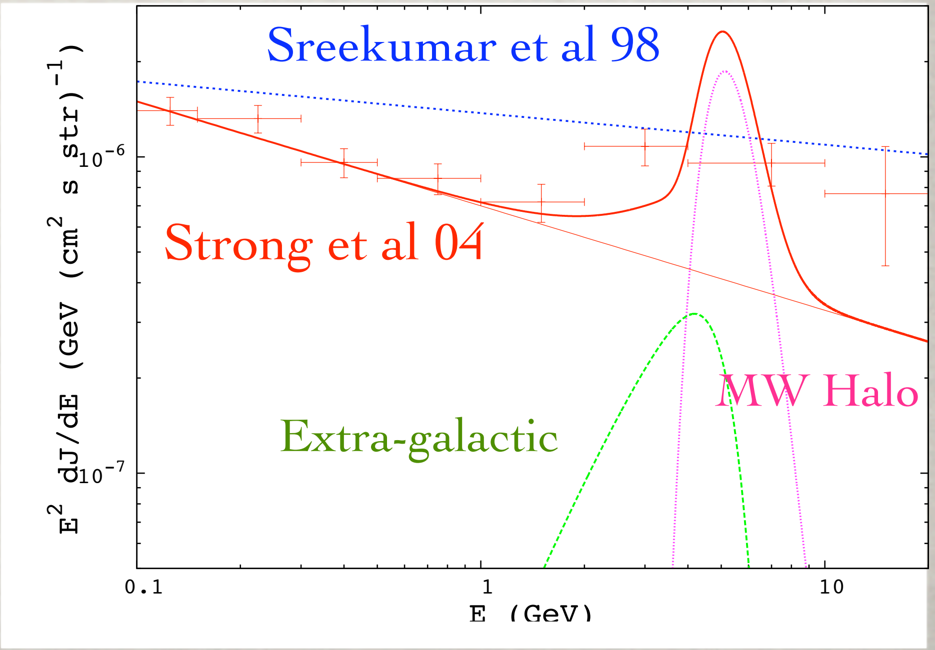
talk of D. Marfatia

- The flux from DM decay in a species i is given by

$$\Phi(\theta, E) = \frac{1}{\tau_{DM}} \frac{dN_i}{dE} \frac{1}{4\pi m_{DM}} \int_{l.o.s.} ds\ \rho(r(s,\theta))$$

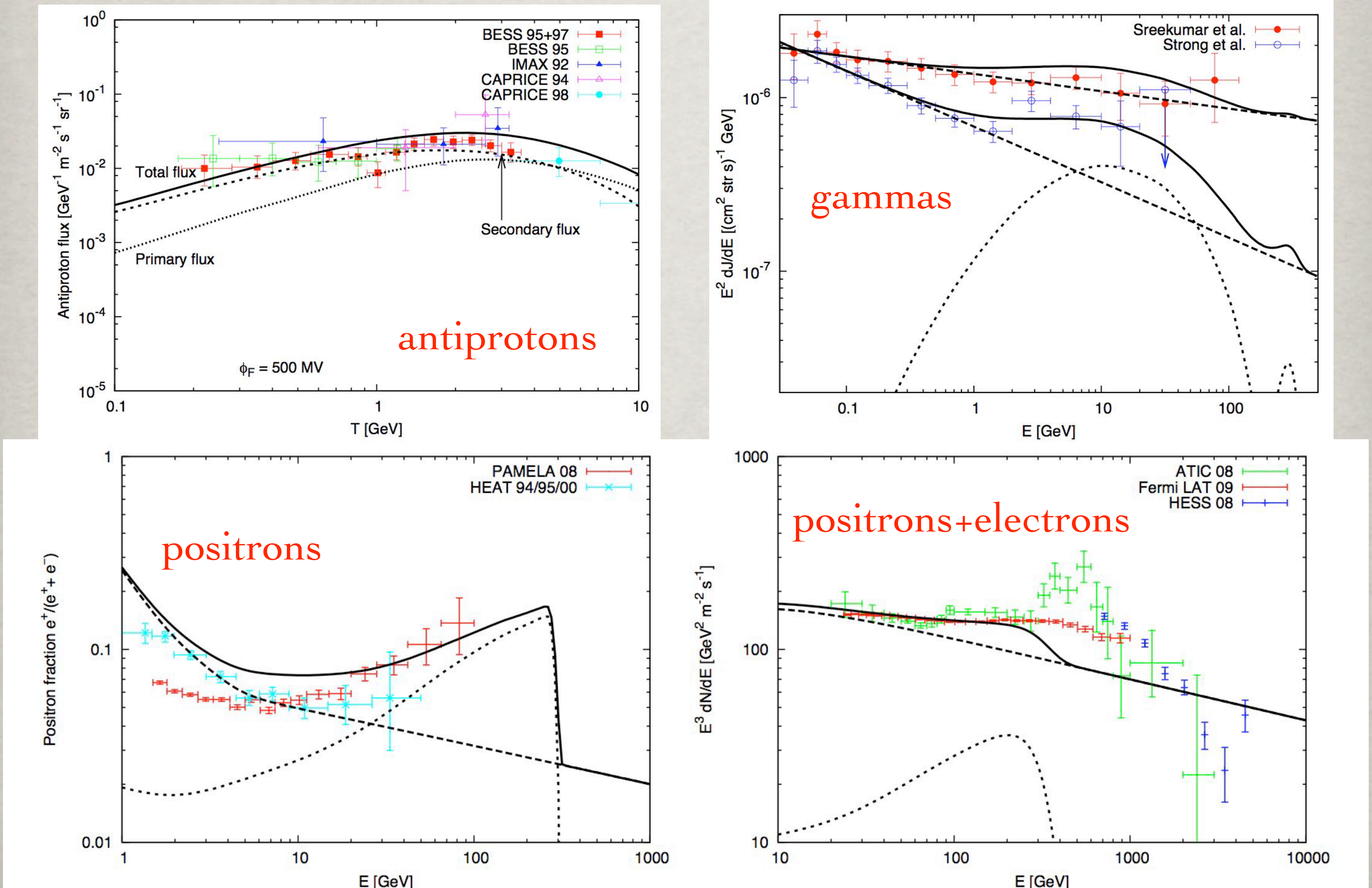
Particle Physics — Halo property

- Very weak dependence on the Halo profile; key parameter is the DM lifetime...
- Spectrum in gamma-rays given by the decay channel! Smoking gun: gamma line...
- Galactic/extragalactic signal are comparable...



Gravitino DM without R_p

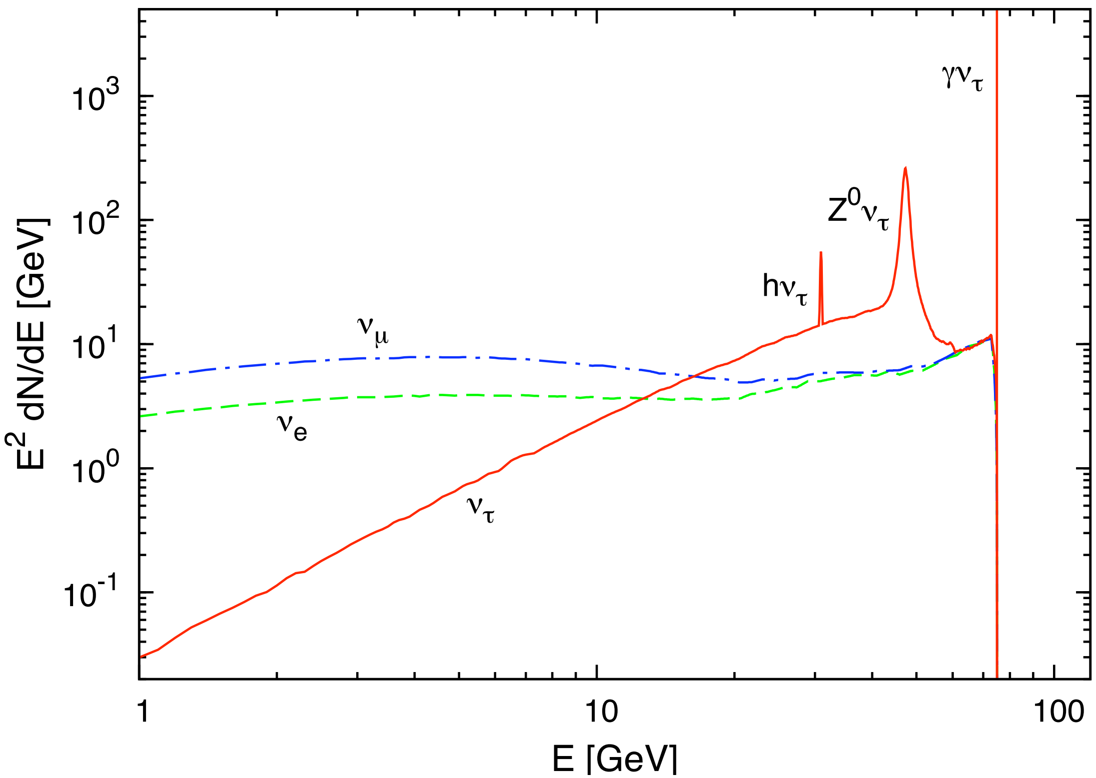
[Buchmuller, Ibarra, Shindou, Takayama, Tran 09], [Ishiwata, Matsumoto & Moroi 08]

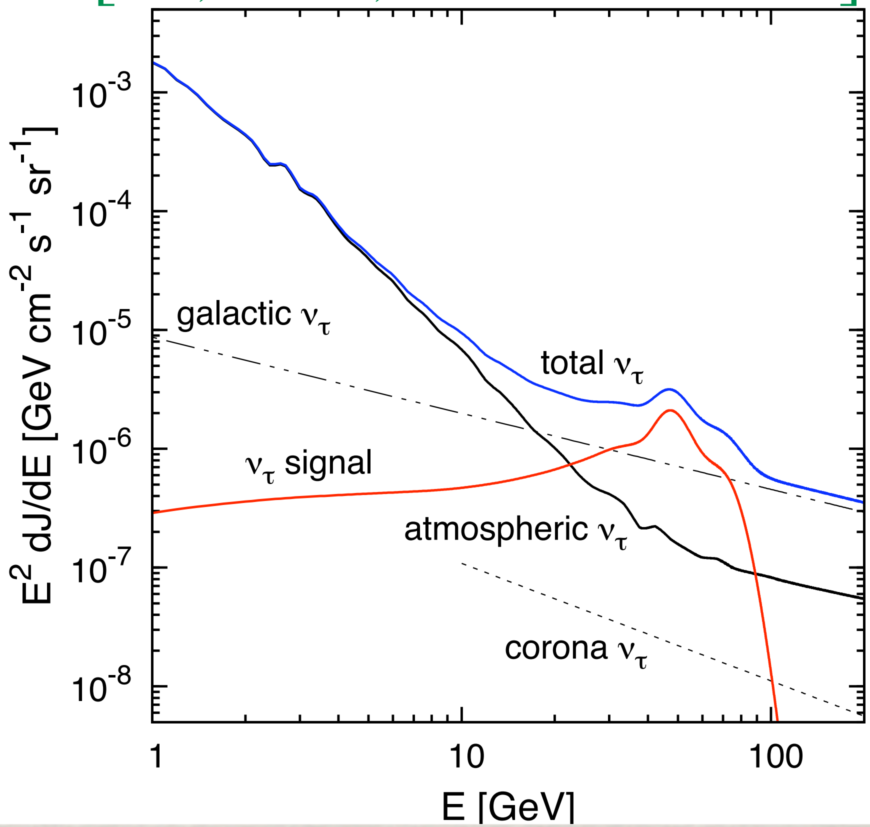


What about neutrinos ?

For light gravitino, wonderful signal with 3 peaks..., but neutrino detector's resolution not sufficient to see them

[LC, Grefe, Ibarra & Tran 08]





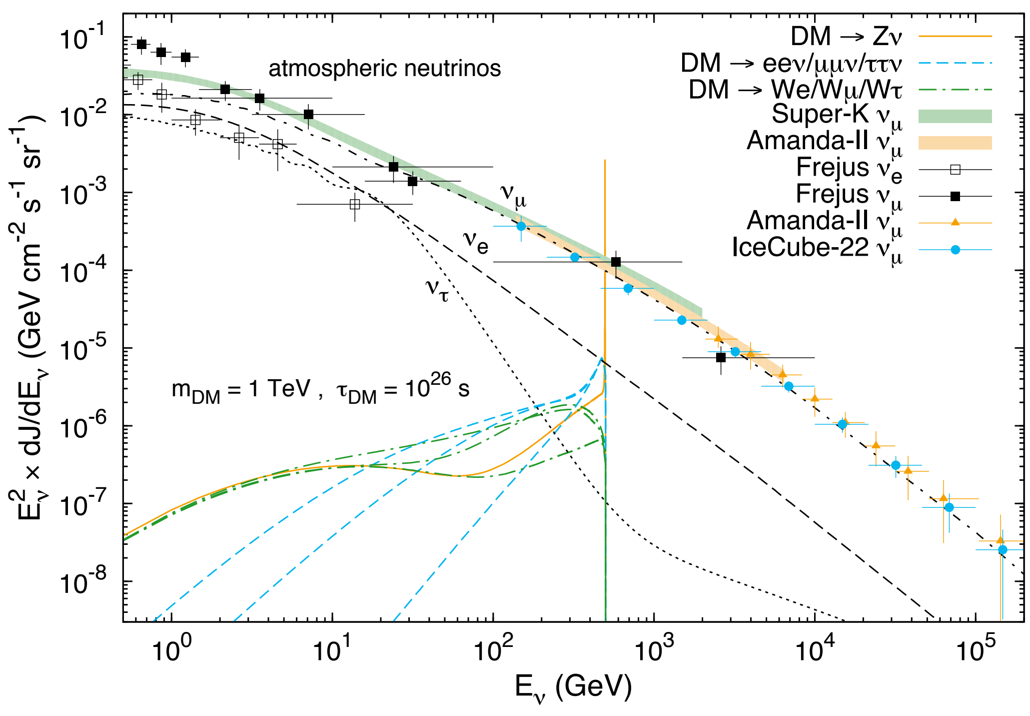
Best signal to background ratio for a tau neutrino looking up...

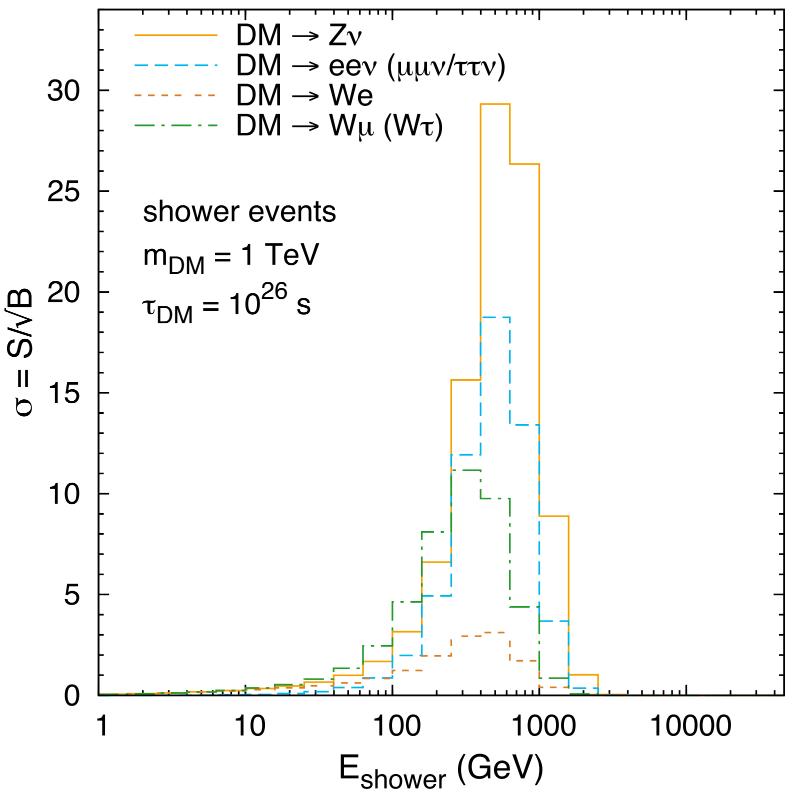
General decaying DM

For heavy decaying DM, the atmospheric neutrino background is very large, but still the signal is detectable at km3 detectors like IceCube, esp. if showers may be measured:

talk of M. Grefe

[LC, Grefe, Ibarra & Tran 09]

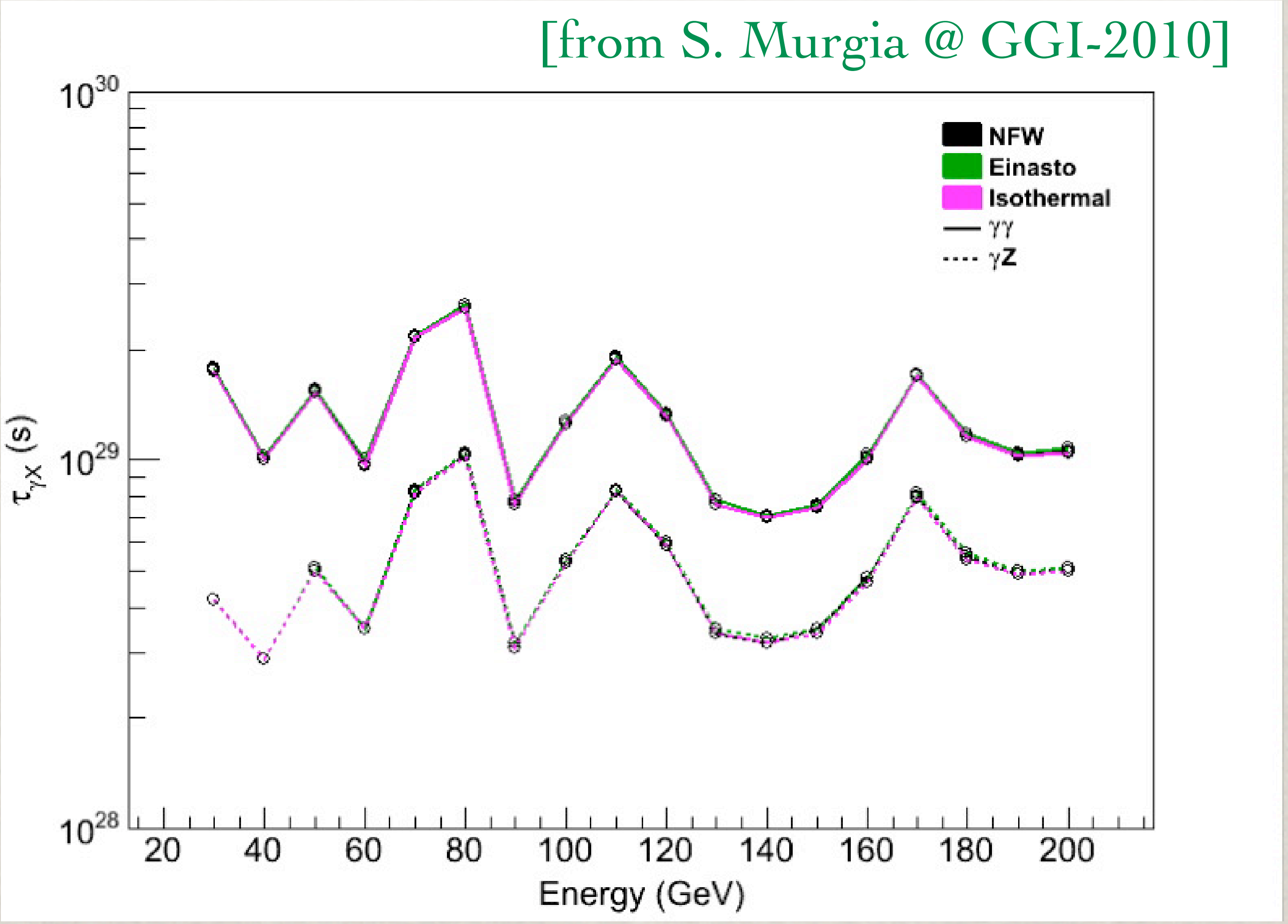




Best significance for cascade/shower events

Possible to detect in IceCube ?

FERMI LINE CONSTRAINTS



The FERMI space telescope looks for lines in the galactic emissions in the energy range 30-200 GeV and gives the stronger constraint for gravitinos below 400 GeV:

From the FERMI gamma-line search: $\tau \geq 5\ 10^{28}$s @ 95% CL

LHC: mass spectrum?

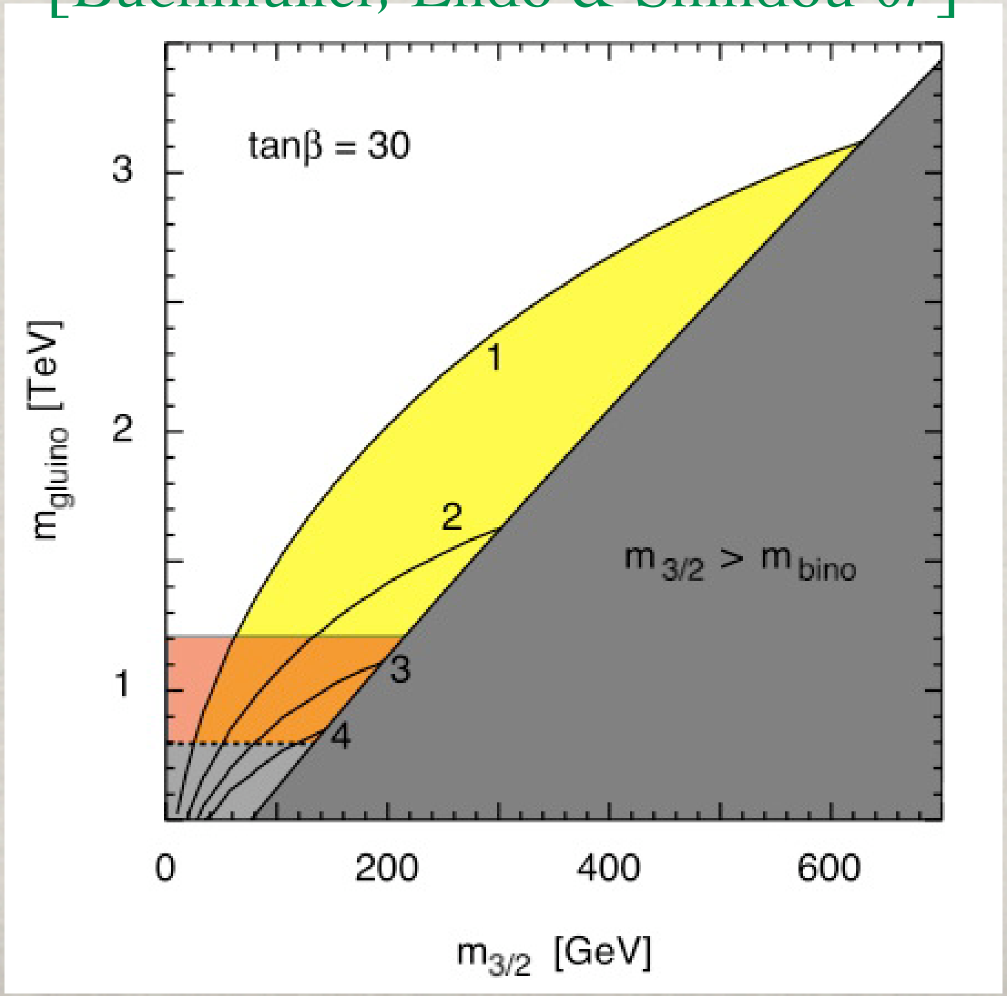
Requiring large T_R still points to relatively light gluinos

[Fujii, Ibe & Yanagida 04, Buchmuller, Endo & Shindou 07]

It should be produced at LHC, as in the case of stau NLSP

talk of K. Hamaguchi

[Buchmuller, Endo & Shindou 07]



Yellow:
Allowed region for neutralino NLSP, with gaugino mass unification.

LHC: Displaced vertices ?

Broken Rp: For bilinear R-parity breaking the Fermi limit gives a lower bound on the track length as 30 cm for a neutralino NLSP, but no definite prediction for stau NLSP...

[Bobrovskyi, Buchmuller, Hajer & Schmidt 10]

Conserved Rp: The decays happen surely within the detector for gravitino masses of 10 keV. Nevertheless thank to the sizable fraction of boosted NLSP it may be possible to reach even 0.1-1 MeV. [Ishiwata, Ito & Moroi 08]

[Chang & Luty 09, Meade, Reed & Shih 10]

Axino: The NLSP can have a large range of lifetimes, but it always decays outside the detector since $f_a > 5 \times 10^9$ GeV. Possible perhaps to observe such (prompt) decays at the LHC even with early data

Conclusion & Outlook

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. Such degenerate gauginos could be seen at LHC soon.
- There are still many other possibilities though, e.g. decaying gravitino DM which could still be seen in ID and at the LHC through displaced vertices.

A rich spectrum of signals for the LHC to discover !