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Dark Matter candidates: axino and gravitino

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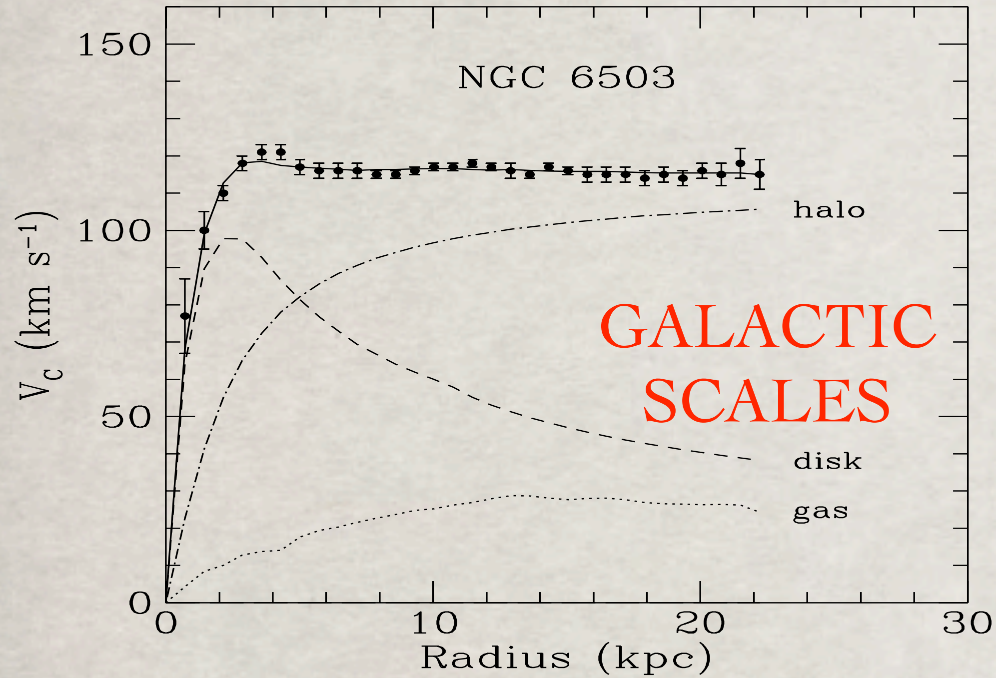
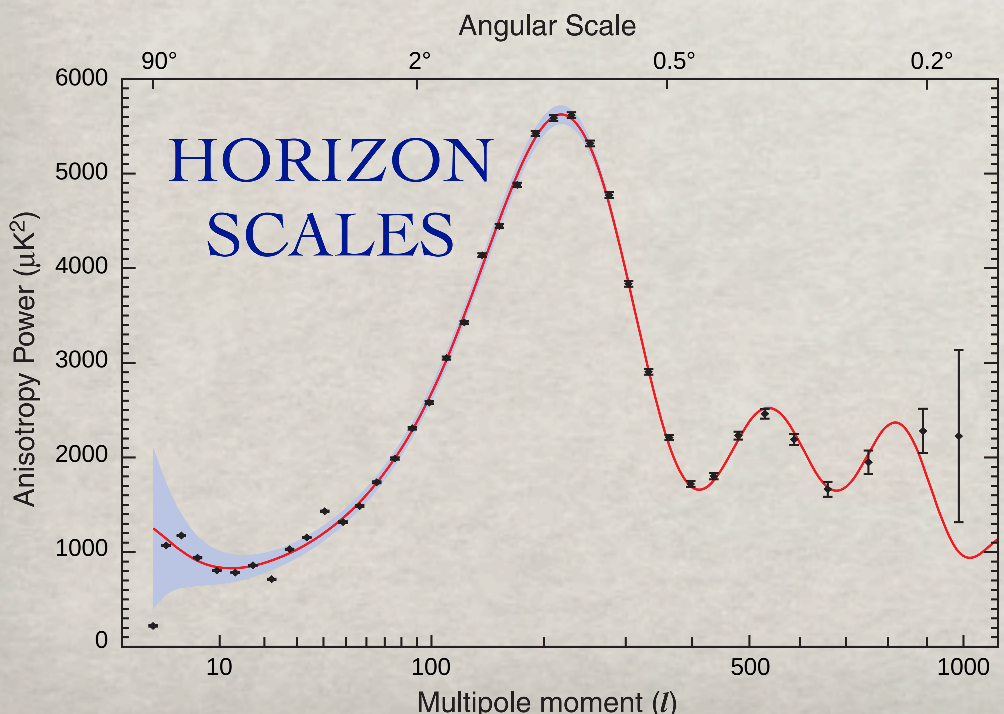
OUTLINE

- Introduction: Dark Matter properties
  Axino & gravitino properties
- Cosmological constraints on (stable) gravitino and axino Dark Matter
- Maximizing the reheat temperature for leptogenesis with degenerate gauginos
- Unstable DM, indirect detection & LHC
- Outlook

DARK MATTER EVIDENCE





Particles	Ωh^2	Type
Baryons	0.0224	Cold
Neutrinos	< 0.01	Hot
Dark Matter	0.09-0.11	Cold

All these evidences are just based on the gravitational force: either directly on the attraction of the Dark Matter on the visible matter or on the effect of the Dark Matter energy component on the Universe expansion or on the evolution of the density perturbation...

So there is no doubt:

DARK MATTER
IS GRAVITATING !

But what about other interactions ???

Only upper bounds from Bullet cluster or the shape of halos, at the order σ/m ~ 1-0.04 barn/GeV, but no lower bound down to gravity !

DM could be a WIMP, but may also be much more weakly interacting, like the candidates I will discuss...

Super/E-WIMPs DM

- Super/E-WIMPs like the gravitino and axino are particles that are much more weakly interacting than weakly, so there is no hope of direct detection...

- They are usually not thermal relics since if they are thermal their number density is compatible only with Hot/Warm DM.

- Moreover they do not need to have an exactly conserved quantum number to be sufficiently stable...

  Dark Matter may decay !!!

AXION:

STRONG CP problem $\Rightarrow$ PQ symmetry [Peccei & Quinn 1977]

$\theta_{QCD} < 10^{-9}$ axion a

Introduce a global $U(1)_{PG}$ symmetry broken at f_a, then θ becomes the dynamical field a,

a pseudogoldstone boson with interaction:

$$\mathcal{L}_{PQ} = \frac{g^2}{32\pi^2 f_a} a \, F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$$

A small axion mass is generated at the QCD phase transition by instanton's effects

$$m_a = 6.2 \times 10^{-5} \text{eV} \left(\frac{10^{11} \text{ GeV}}{f_a} \right)$$

Axion physics constrains

$$5 \times 10^9 \text{ GeV} \leq f_a \leq 10^{12} \text{ GeV}$$

SN cooling $\Omega_a h^2 \leq 1$ [Raffelt '98]

ADD SUSY: $a \Rightarrow \Phi_a \equiv (s + ia, \tilde{a})$ with $W_{PQ} = \frac{g^2}{16\sqrt{2}\pi^2 f_a} \Phi_a W^\alpha W_\alpha$ [Nilles & Raby '82] [Frére & Gerard '83]

AXINO couplings equal mostly to those of the axion
AXINO mass depends on SUSY breaking : free parameter
Possibility of mixed axino/axion DM depending on f_a !

AXION and AXINO MODELS

KSVZ

[Kim ’79], [Shifman, Vainstein & Zakharov ’80]

$W = h_H \Phi_a \bar{Q} Q$ $\quad \bar{Q}, Q$ heavy quarks

SM fields are not charged under $U(1)_{PQ}$

$$m_Q = h_H f_a$$

$$h_H \simeq \mathcal{O}(1)$$

DFSZ

[Dine, Fischler & Srednicki ’81], [Zhitnitskii ’80]

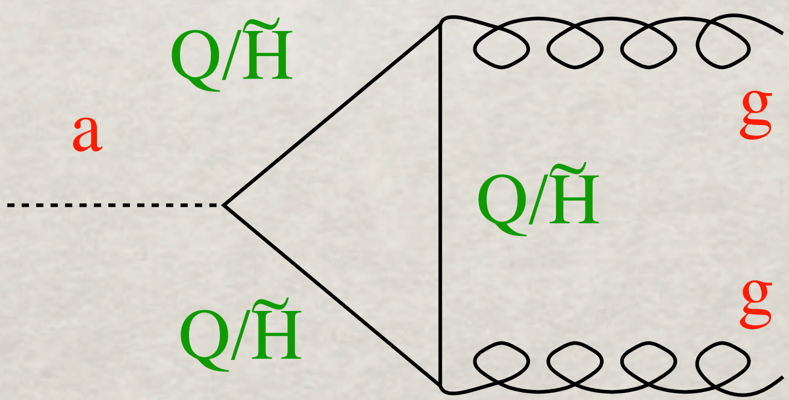
$W = h\,\Phi_a H_u H_d$ $\quad H_u, H_d$ Higgs multiplets

SM fields are charged under $U(1)_{PQ}$

$h f_a = \mu$ $\quad \mu$-term

$$\rightarrow h \ll 1$$

~ NMSSM



While the axion/axino couplings to QCD are model independent, the couplings to matter, quarks and leptons, and also Higgses, are model-dependent.

GRAVITINO properties: completely fixed by SUGRA !

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

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

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:

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

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

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

The gravitino gives us direct information on SUSY breaking

CAN THE AXINO/GRAVITINO BE **COLD DARK MATTER** ?

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

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

PLASMA SCATTERINGS

$$\Omega_{DM} h^2 \propto T_R \begin{cases} \dfrac{m_{\tilde{a}}}{f_a^2} \\[2ex] \dfrac{m_{\tilde{g}}^2}{m_{\tilde{G}} M_P^2} \end{cases}$$

NLSP DECAY OUT OF EQUILIBRIUM

$$\Omega_{DM} h^2 \propto \frac{m_{DM}}{m_{NLSP}} \Omega_{NLSP} h^2$$

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$$\Omega_{DM} h^2 \propto T_R \begin{cases} \dfrac{m_{\tilde{a}}}{f_a^2} \\ \dfrac{m_{\tilde{g}}^2}{m_{\tilde{G}} M_P^2} \end{cases}$$

NLSP DECAY
OUT OF EQUILIBRIUM

Ω_{D} ... $\propto$

DANGER !!!
BBN at risk !

THERMAL PRODUCTION

At high temperatures, the dominant gravitino production is due to 2-to-2 scatterings with the gauge sector, mostly QCD:

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

[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 !

THERMAL PRODUCTION

Similarly for the axino, but the couplings are not enhanced by a small axino mass. Recently a new computation by Strumia exploiting the similarity between axino & gravitino gives:

$$\Omega h^2 \simeq 2.72 \left(\frac{m_{\tilde{a}}}{0.1\mathrm{GeV}}\right)\left(\frac{T_R}{10^4\mathrm{GeV}}\right)\left(\frac{10^{11}\mathrm{GeV}}{f_a}\right)^2$$

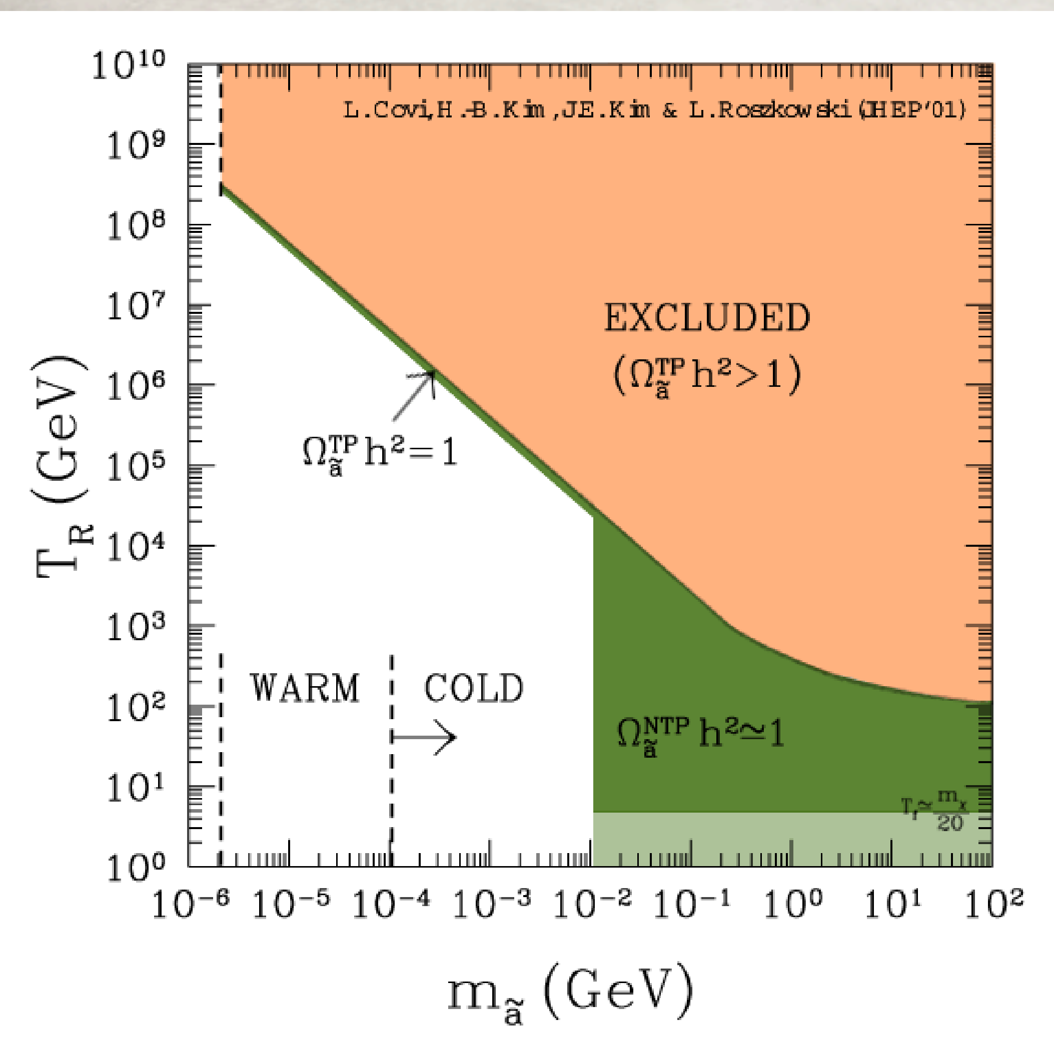
[Strumia 10]

This includes a D-term contribution previously neglected and the effect of (thermally massive) gluon decay.

This is a factor ~ 2-3 larger than [Brandenberger & Steffen 04] and nearly equal to our earlier one with a gluino thermal mass introduced per hand [LC, HB Kim, JE Kim & Roszkowski 01].

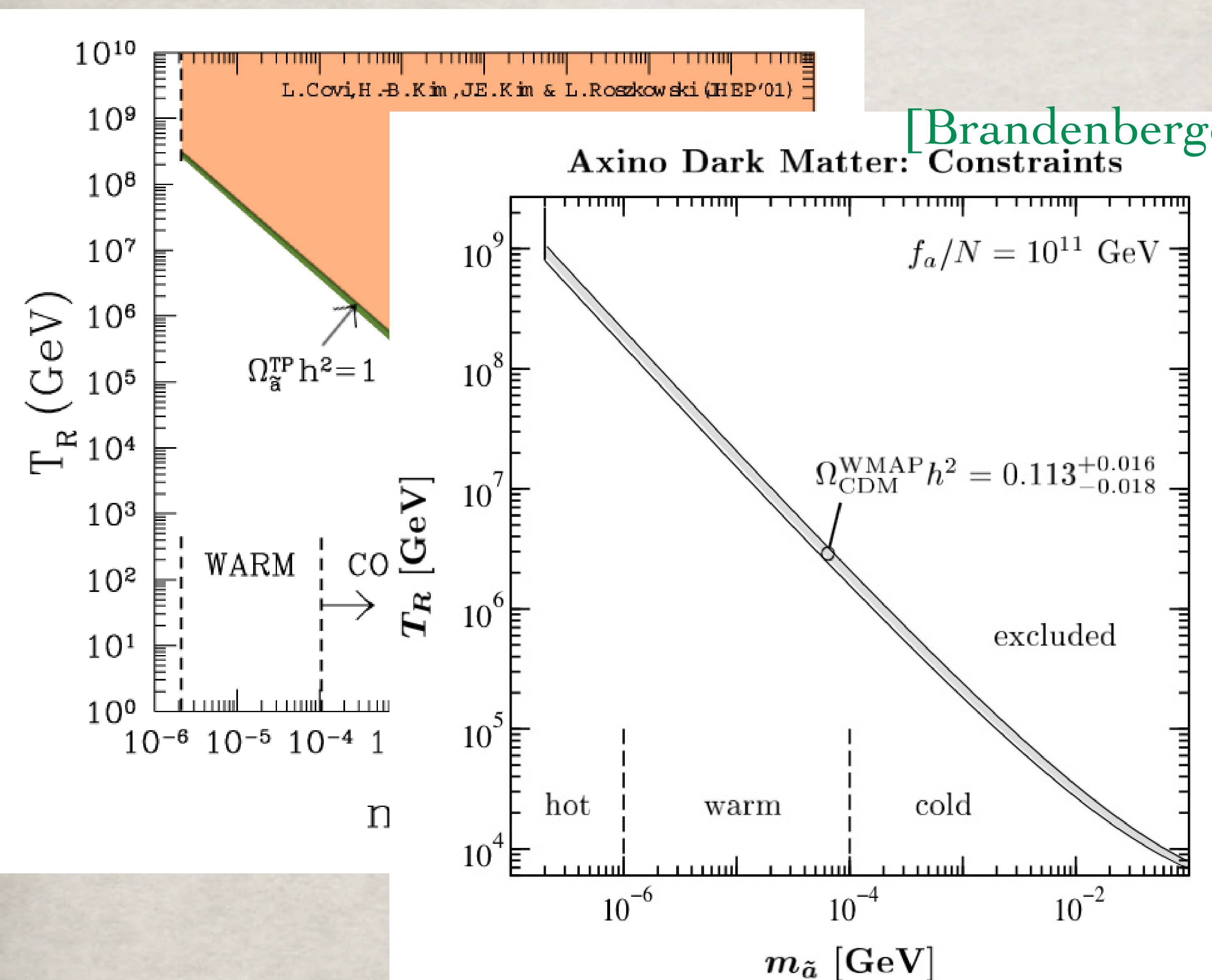
Tension with thermal leptogenesis is stronger, even for small axino masses ! Non-thermal leptogenesis ? [Baer et al...]

UPPER BOUND ON T_R



UPPER BOUND ON T_R

[Brandenberger & Steffen 04]



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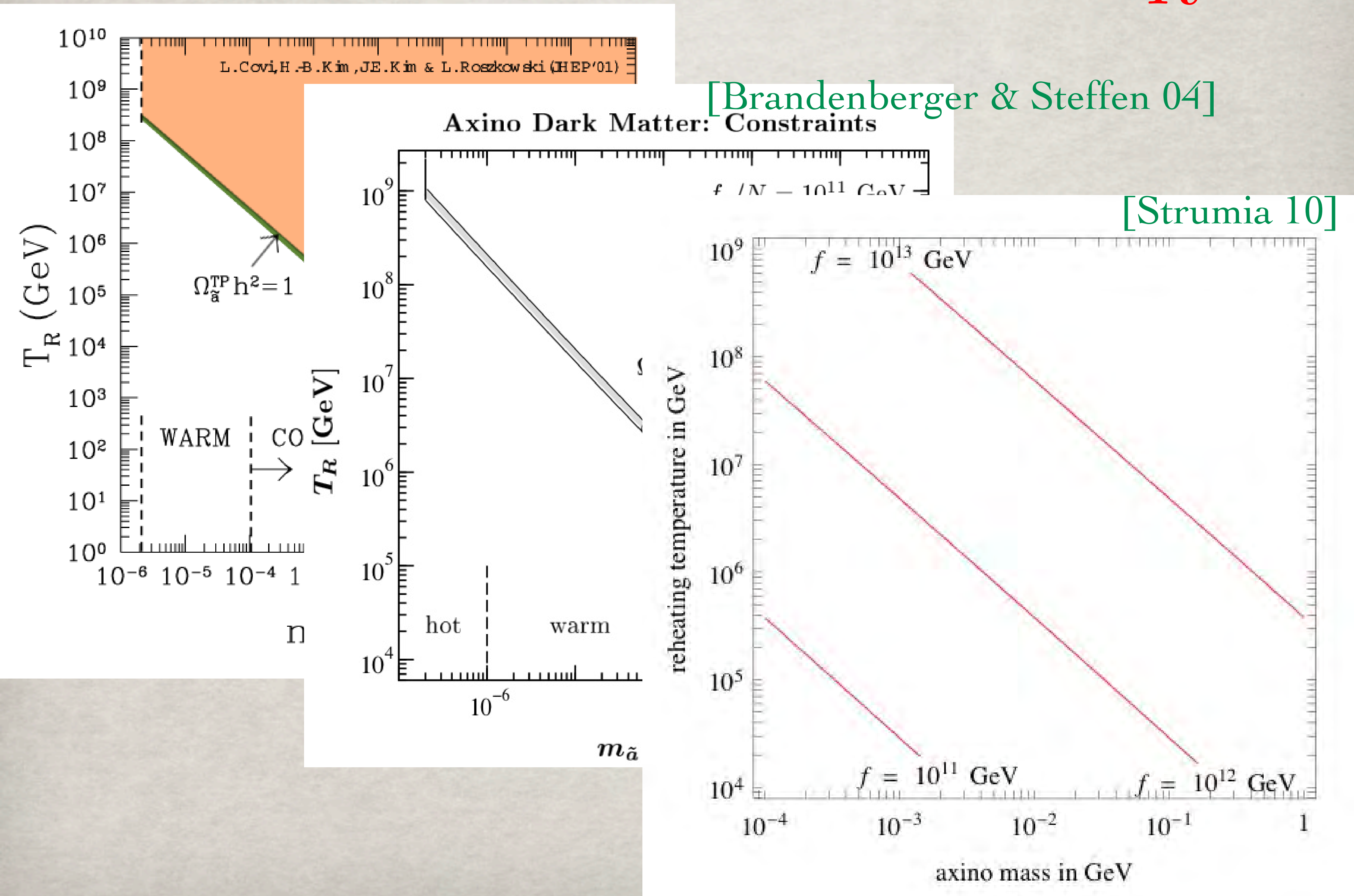
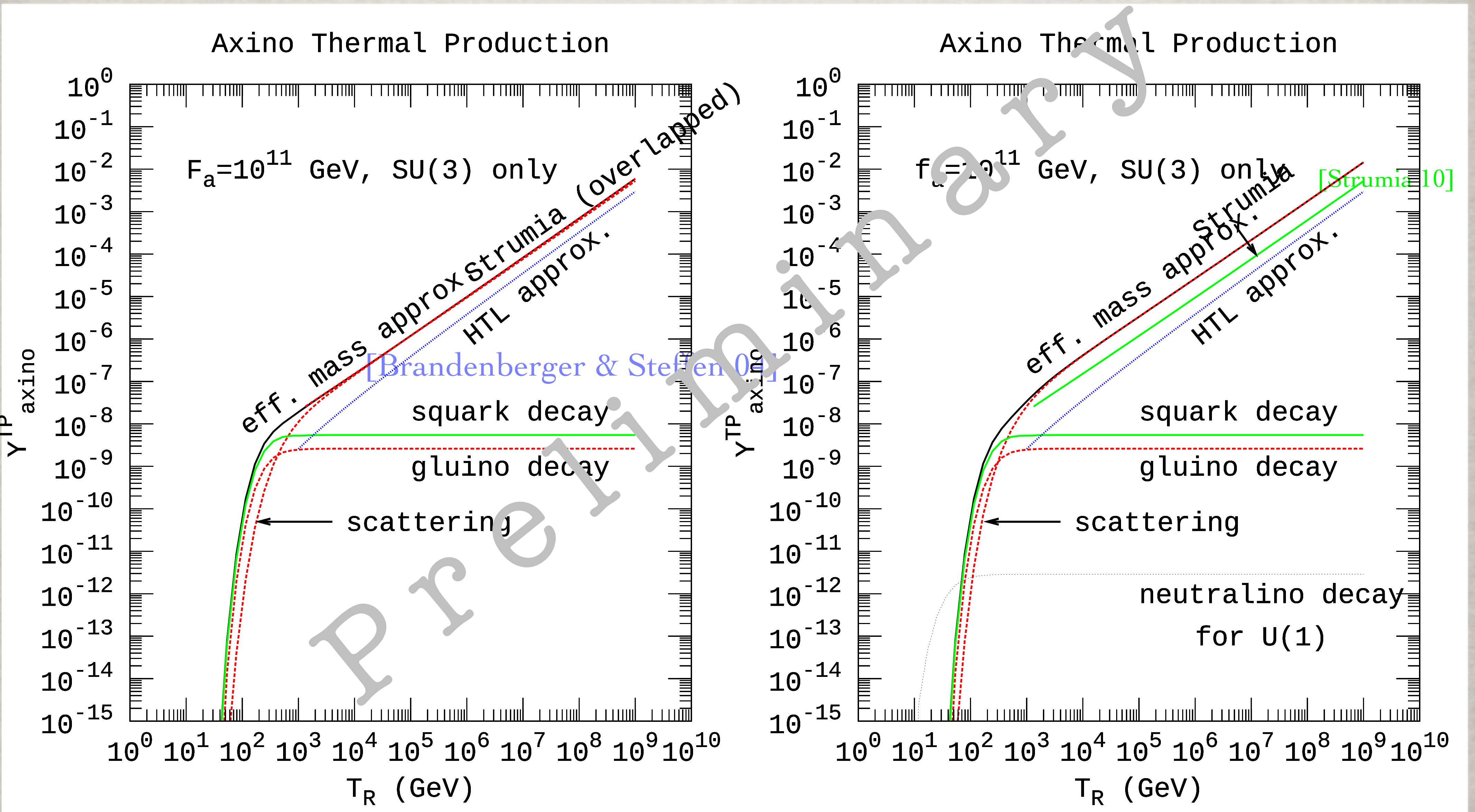


Revisiting axino production

[K.Y. Choi, LC, J.E. Kim, L. Roszkowski xx]

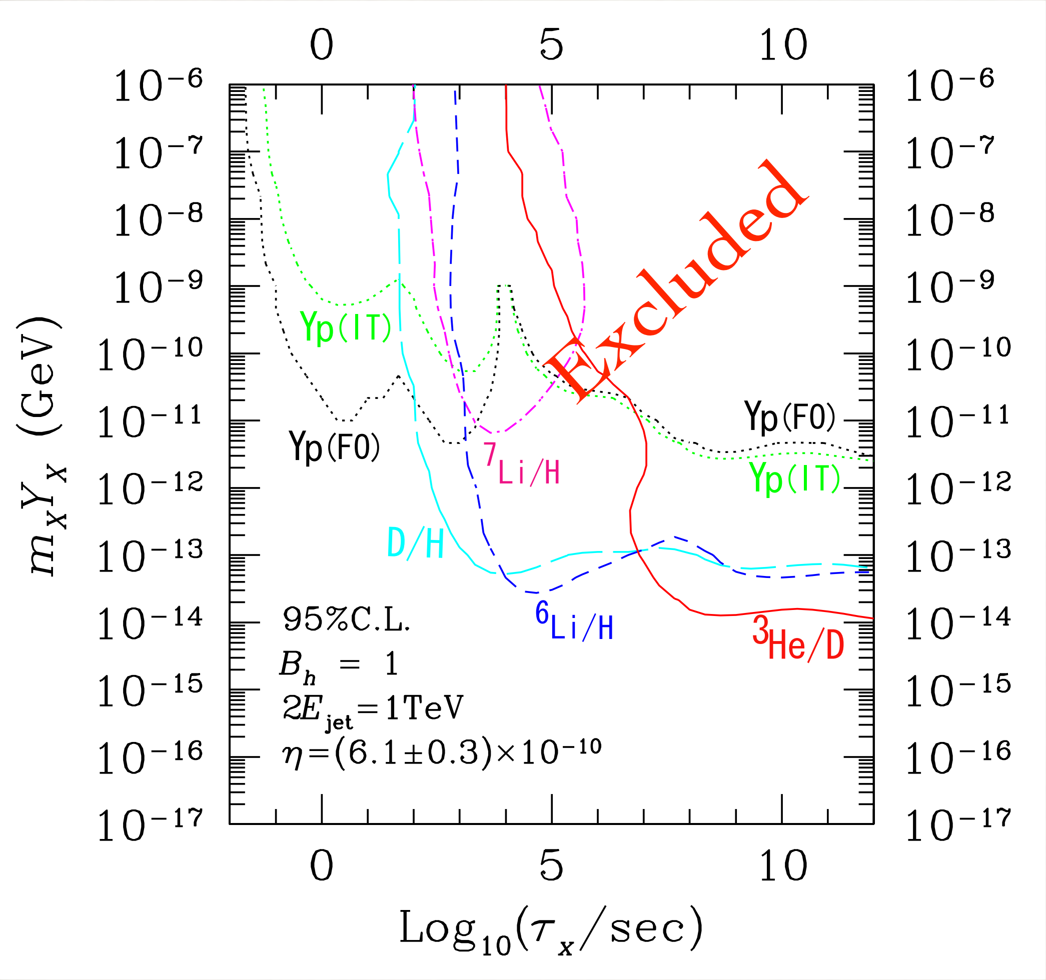


Do not worry: Perturbation series seems converging...

BBN bounds on NLSP decay

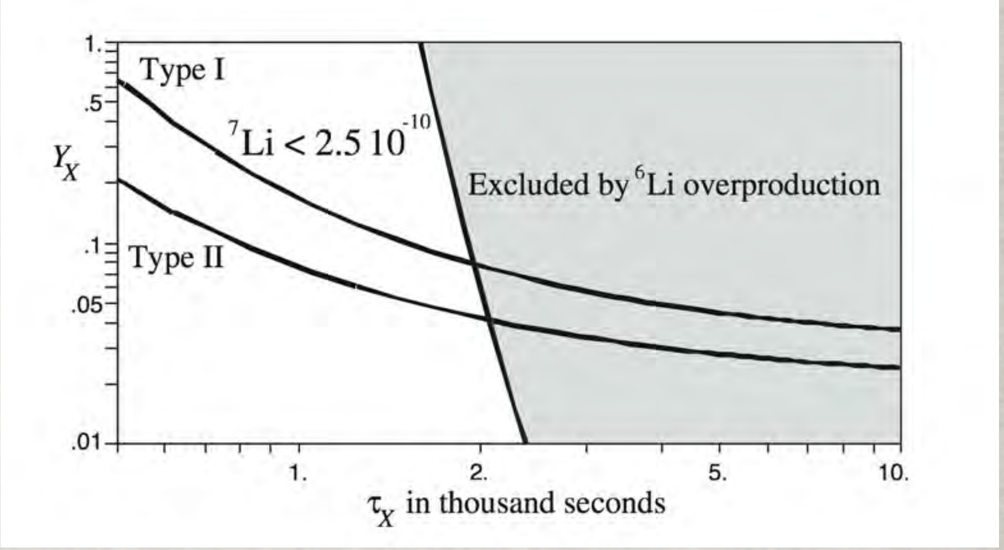
Neutral relics

[...,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 lifetimes larger than 1 s or ~3000 s...

A MATTER OF LIFETIME...

Due to the suppressed couplings, the NLSP decays slowly into an axino/gravitino and a SM particle.
Consider a Bino neutralino NLSP and R-parity conservation.
What is its lifetime for axino or gravitino LSP?

For an axino LSP:

$$\Gamma_{\tilde{B}}^{-1} = 0.25\,\mathrm{s} \left(\frac{m_{\tilde{B}}}{100\ \mathrm{GeV}} \right)^{-3} \left(\frac{f_a}{10^{11}\ \mathrm{GeV}} \right)^{2}$$

For a gravitino LSP:

$$\Gamma_{\tilde{B}}^{-1} = 5.7 \times 10^{4}\mathrm{s} \left(\frac{m_{\tilde{B}}}{100\ \mathrm{GeV}} \right)^{-5} \left(\frac{m_{\tilde{G}}}{1\ \mathrm{GeV}} \right)^{2}$$

Quite different timescale, apart for large f_a or small gravitino mass... Trouble for a gravitino heavier than 1 GeV !
Is there a way out apart light gravitino/heavy NLSP ???

Axino-stau coupling

Recently the full two-loop computation of the axino couplings to sleptons-lepton and quark-squarks in the hadronic axion models has been done by [Freitas, Steffen, Tajuddin & Wyler 09], which is important for the stau NLSP decay:

$$\Gamma(\tilde{\tau}_R \to \tau \tilde{a}) = \frac{81\, \alpha^4 e_Q^4}{128\pi^5 \cos^8\theta_W} \frac{m_{\tilde{\tau}} m_{\tilde{B}}^2}{f_a^2} \ln^2\left(\frac{y f_a}{m_{\tilde{\tau}}}\right)$$

at leading log, where the e.m. charge and mass of the heavy quarks are $e_Q, y f_a$ respectively. It is suppressed by loop factors and large powers of the coupling.

It gives ~ 20% correction to the previous computation using an effective one loop approximation [LC, L. Roszkowski, M. Small, 02]

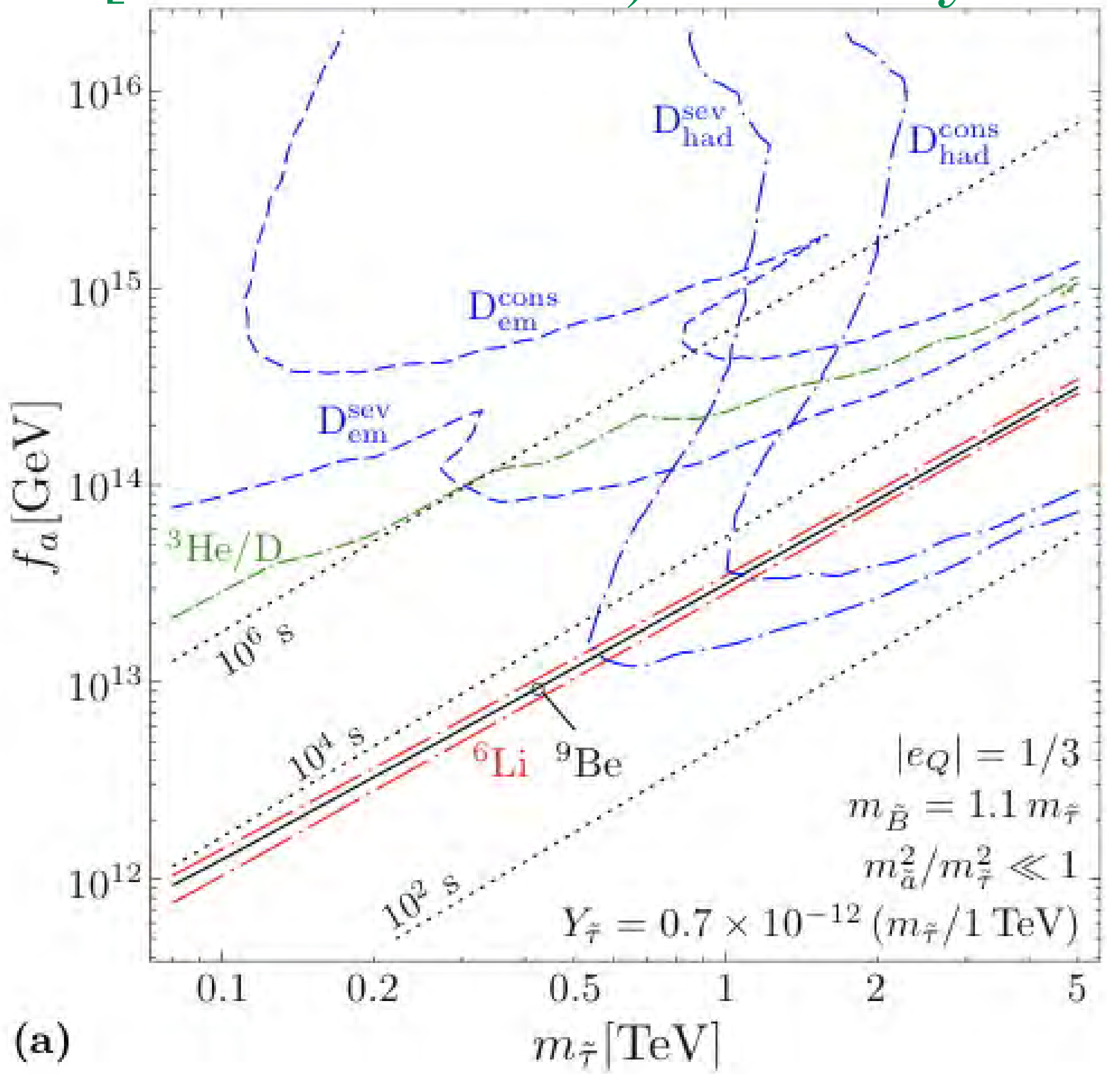
This is important for computing the stau NLSP lifetime !

UPPER BOUND ON f_a

For

τ_R NLSP

[Freitas, Steffen, Tajuddin & Wyler 09]



More stringent bounds than for neutralino NLSP [H. Baer et al]

Other ways out:

- Dilute the NLSP abundance with entropy production
  [Buchmuller et al 05, Hamaguchi et al 07...] J. Kersten
- Choose a relatively harmless NLSP, e.g. sneutrino
  [LC & Kraml 07, Santoso et al. 08, ...]
- Reduce the energy released during BBN by making the gravitino mass degenerate with the NLSP
  [Boubekeur, Choi, Ruiz de Austri, Vives 10]
- Reduce the NLSP number density via coannihilation with the gluinos [LC, Olechowski, Pokorski, Turzynski,Wells 10]
- Make the NLSP lifetime shorter by breaking R-parity
  But then the (axino)/gravitino DM is unstable !!!
  [Buchmuller, LC, Hamaguchi, Ibarra & Yanagida 07, ...]

MAXIMAL T_R

Look again at the thermal production yield:

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

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

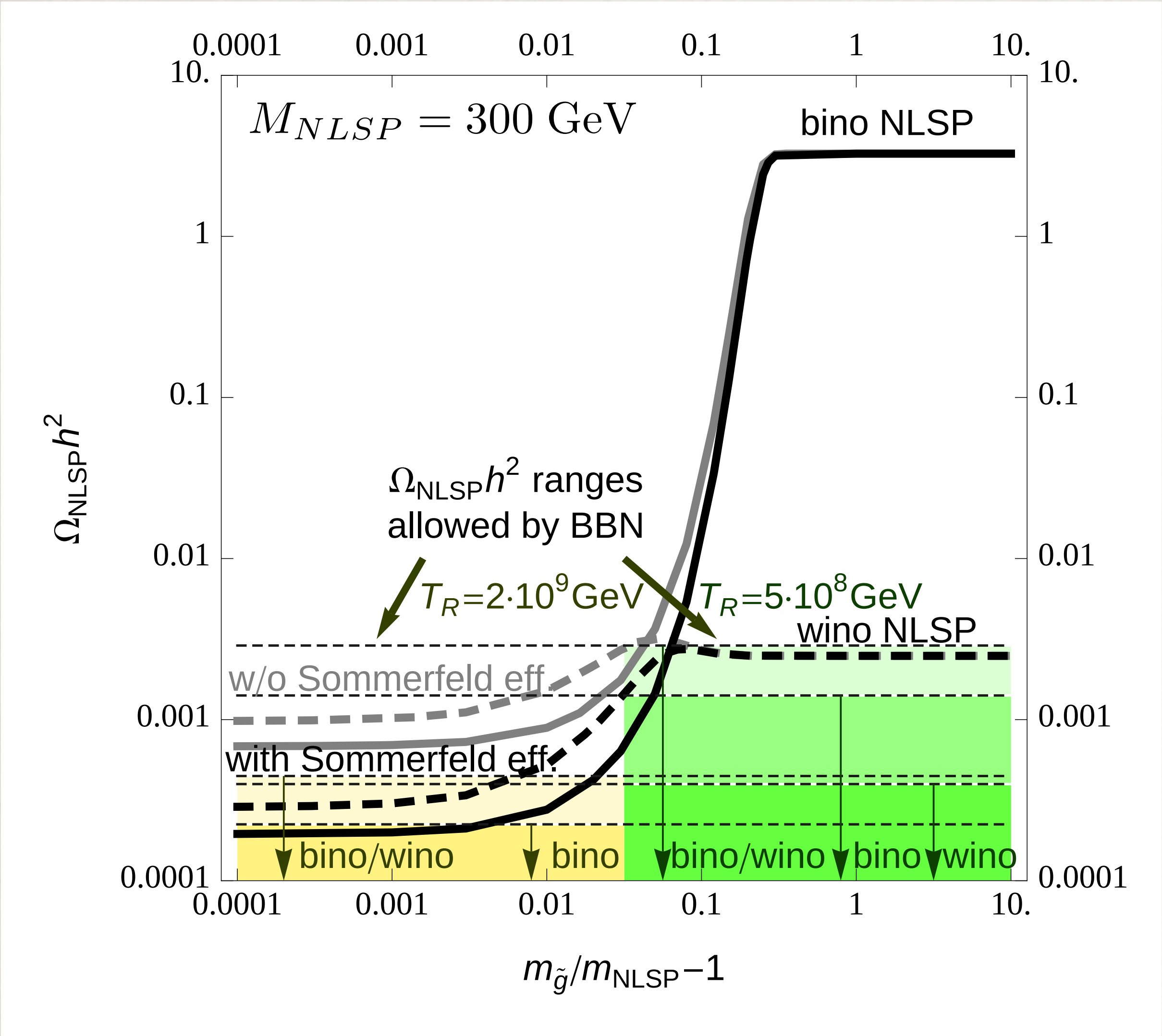
[Olechowski, Pokorski, Turzynski,Wells 09]

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]



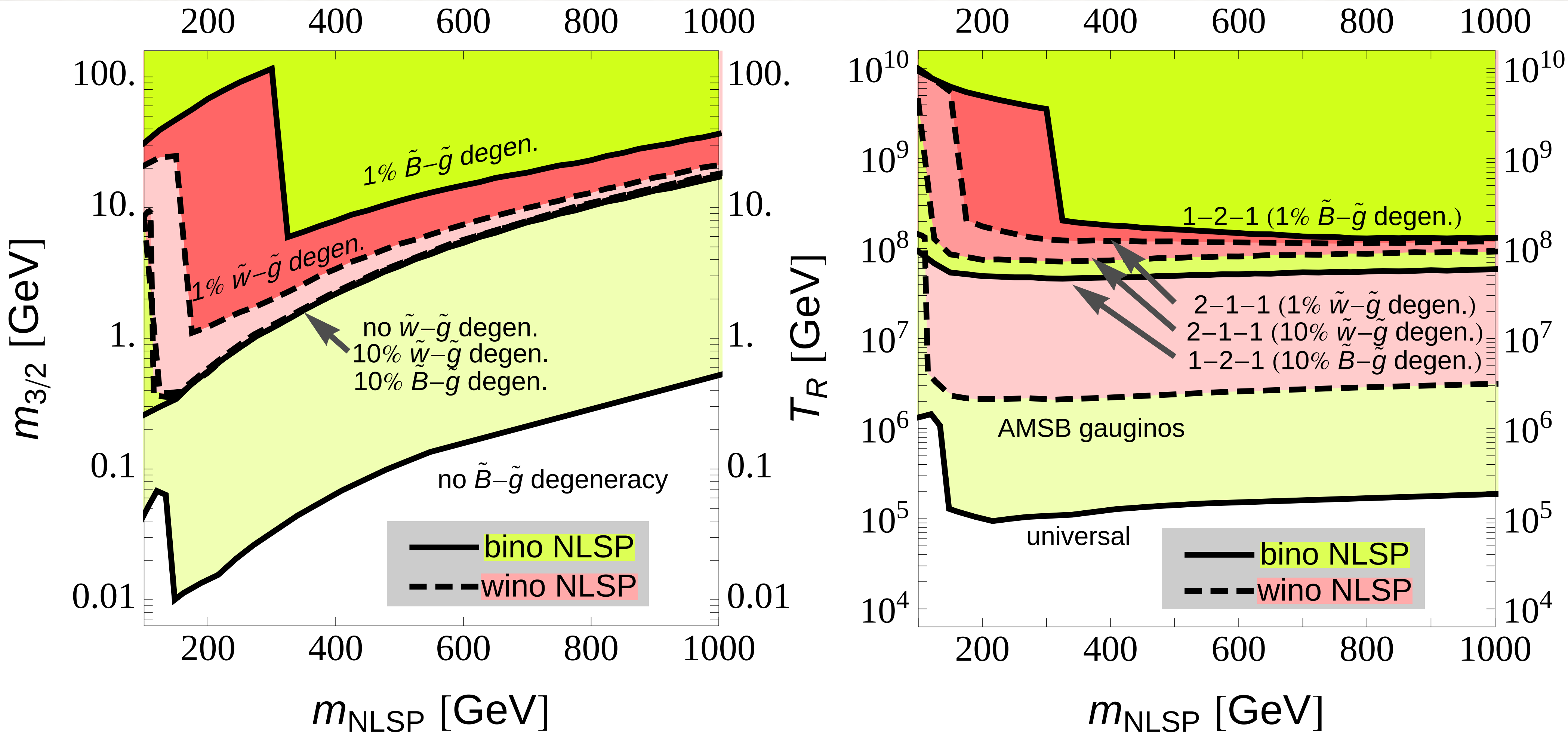
Gluinos annihilate most efficiently, but are a bad NLSP due to BBN constraints from bound state effects...

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

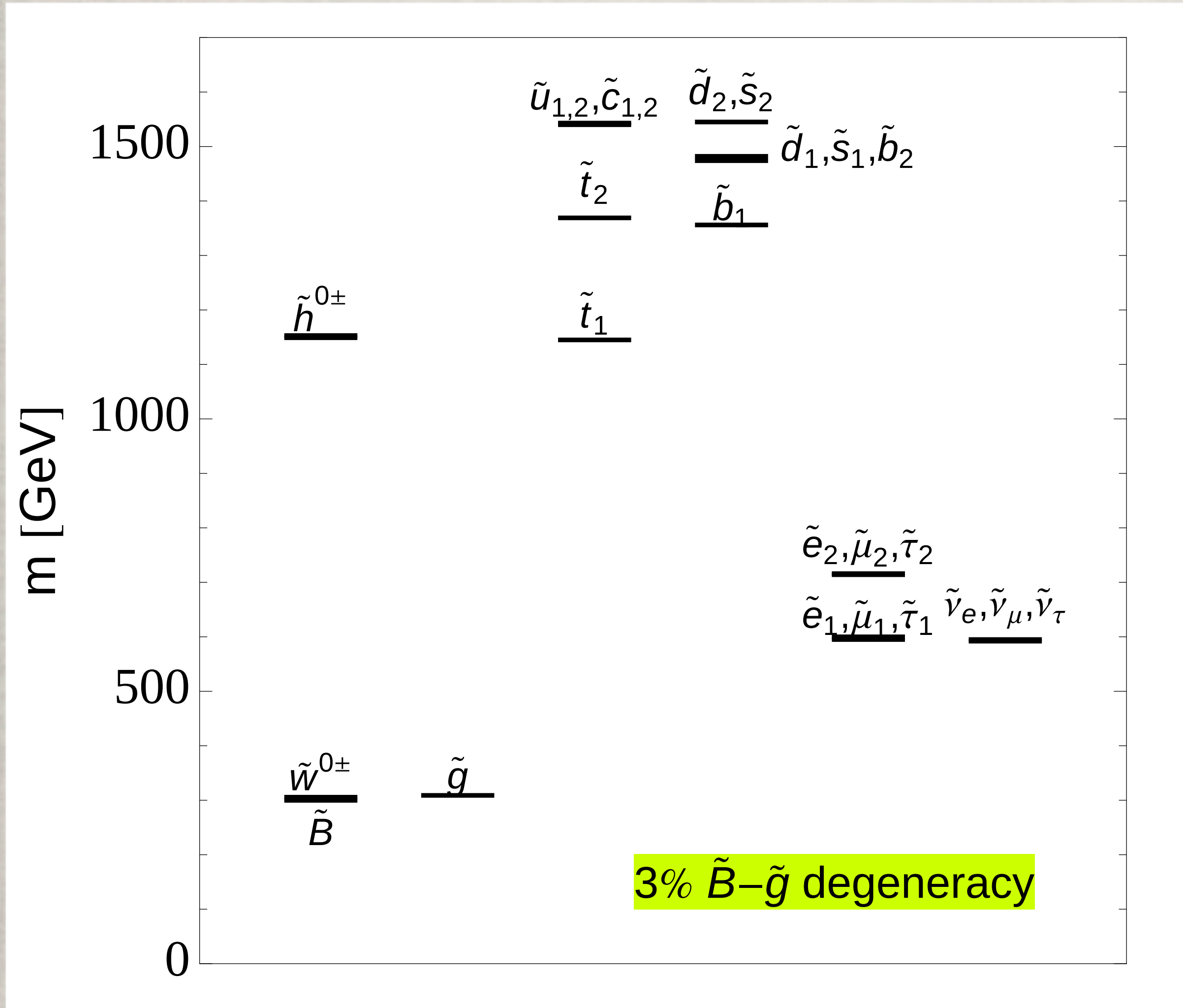
[LC, Olechowski, Pokorski, Turzynski,Wells 10]



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.

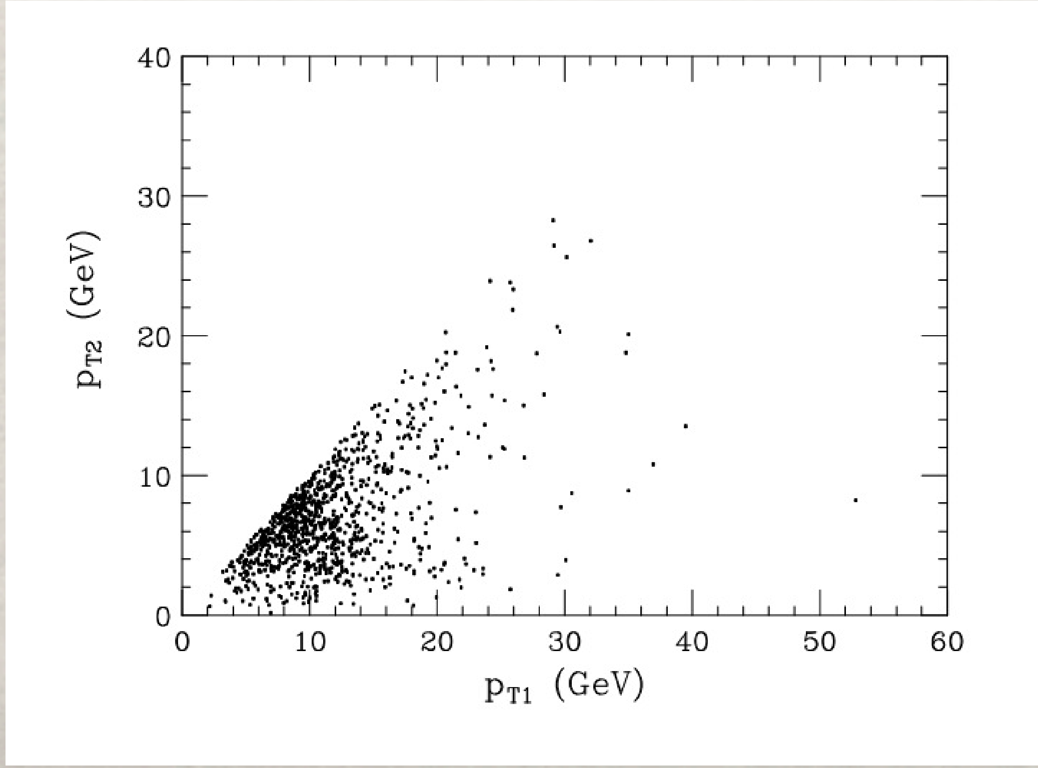
LHC: DEGENERATE GAUGINOS?

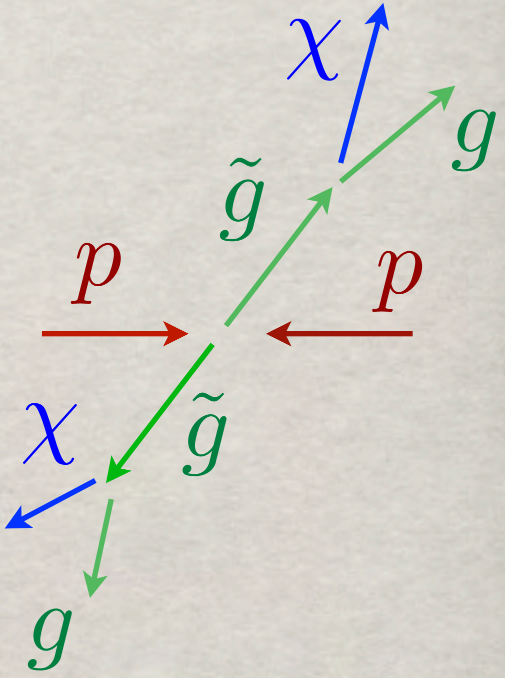
In this scenario of maximal T_R and stable gravitino DM we expect light gauginos with 1-10% degeneracy between NLSP and gluino NNLSP.

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

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

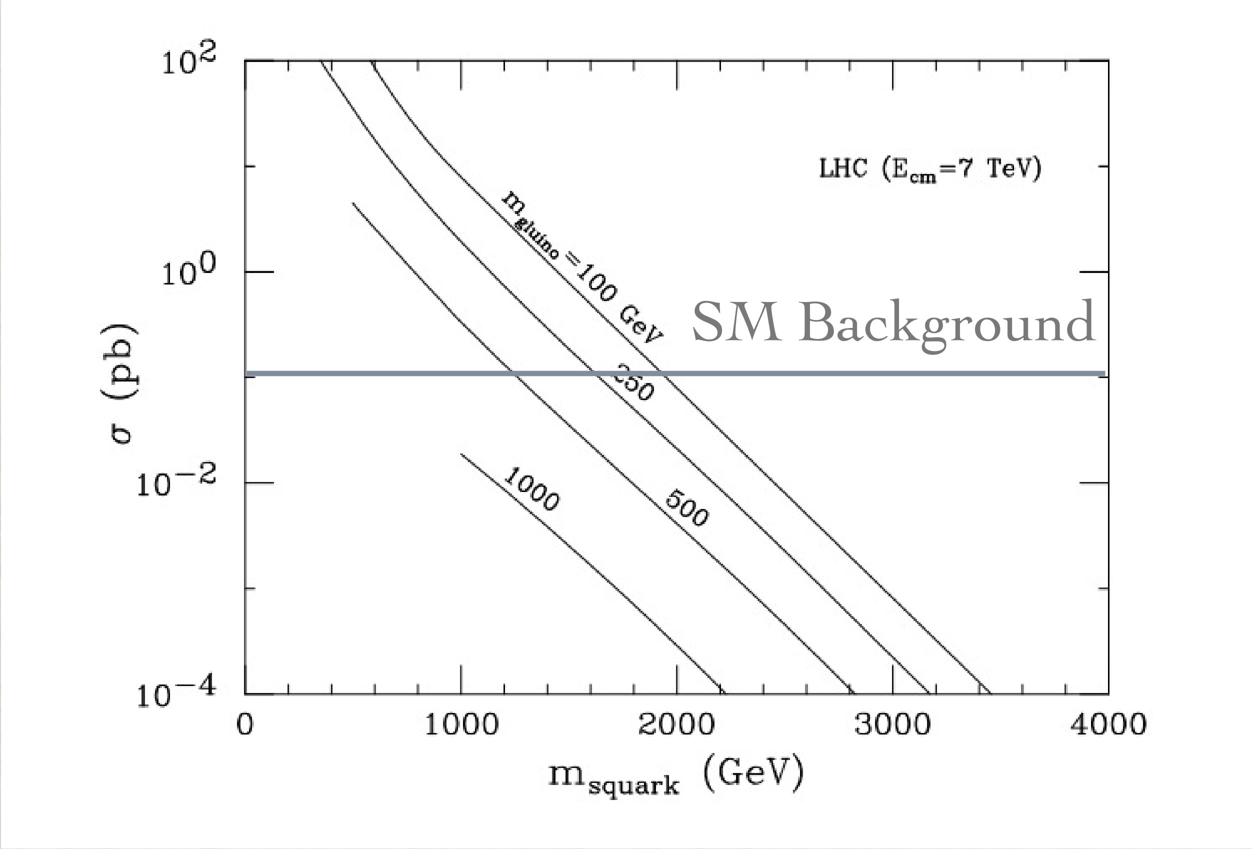
to low p_T !

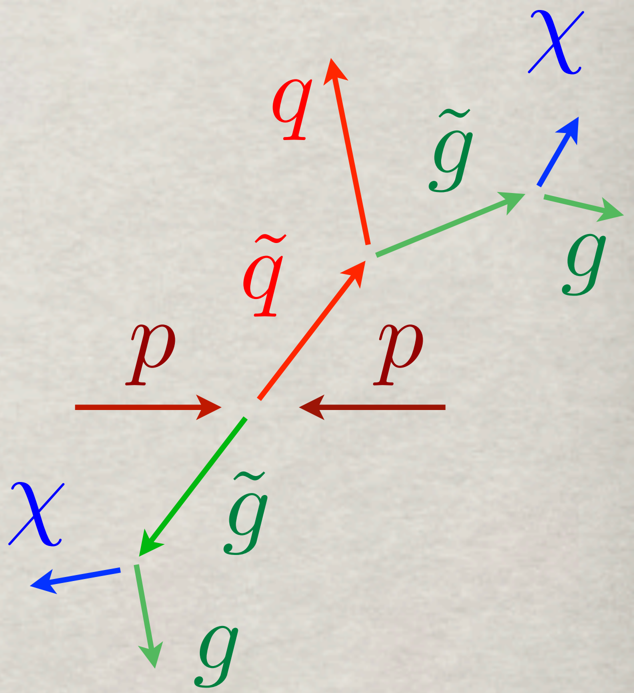




LHC: Mono-jet signature

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 mono-jet and large missing transverse momentum.





Exotica search by CMS for ED ???

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

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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no p decay

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.

Decaying axino/gravitino?

- If R-parity is broken the NLSP decays fast to SM particles, but axino & gravitino are much longer-lived

$$\tau_{\tilde{G}} \sim 10^{27}\mathrm{s} \left(\frac{\epsilon}{10^{-7}}\right)^{-2} \left(\frac{M_1}{100\mathrm{GeV}}\right)^{2} \left(\frac{m_{\tilde{G}}}{10\mathrm{GeV}}\right)^{-3}$$

$$\tau_{\tilde{a}} \sim 10^{27}\mathrm{s} \left(\frac{\epsilon}{10^{-10}}\right)^{-2} \left(\frac{M_1}{100\mathrm{GeV}}\right)^{2} \left(\frac{m_{\tilde{a}}}{10\mathrm{GeV}}\right)^{-3} \left(\frac{f_a}{10^{11}\mathrm{GeV}}\right)^{2}$$

- For bilinear R-parity breaking, they decay similarly to gauge boson/Higgs and neutrino

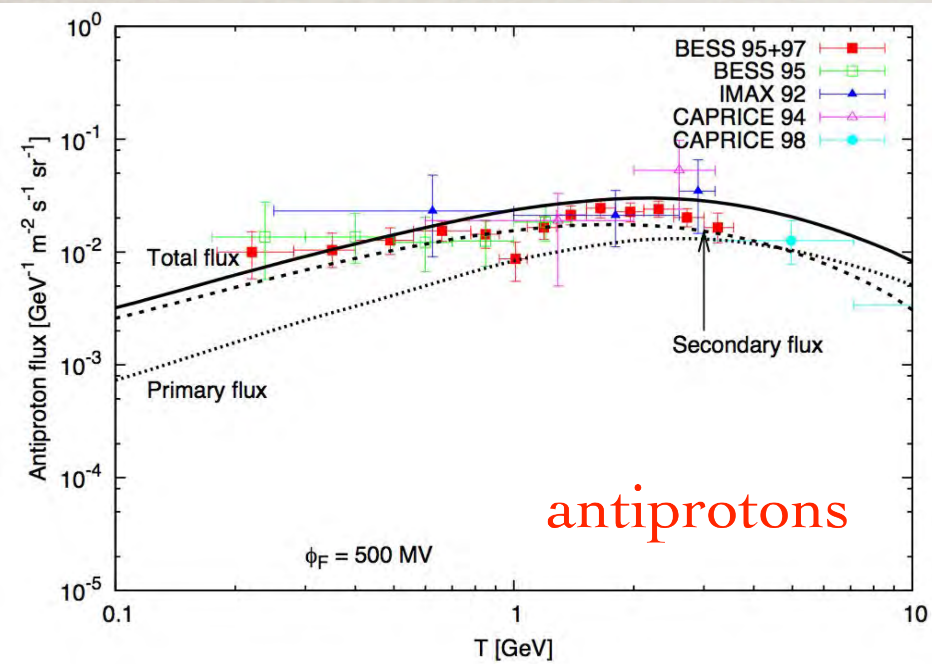
[Takayama &Yamaguchi 00, Buchmuller et al '07, LC & JE Kim 09]

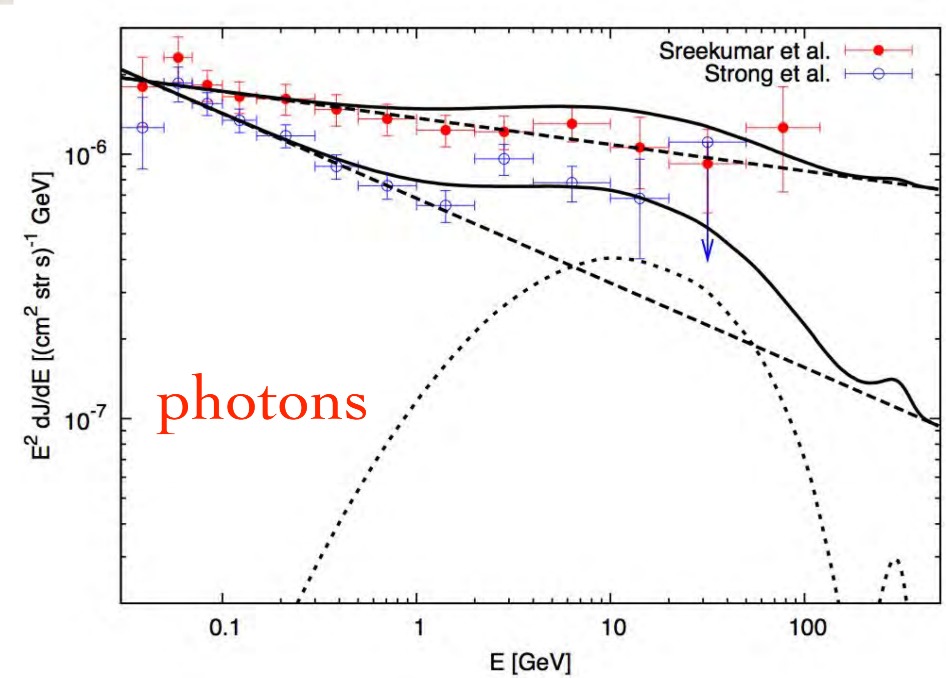
For trilinear R-parity breaking, the 3-body decays into leptons can dominate and give a leptophilic DM

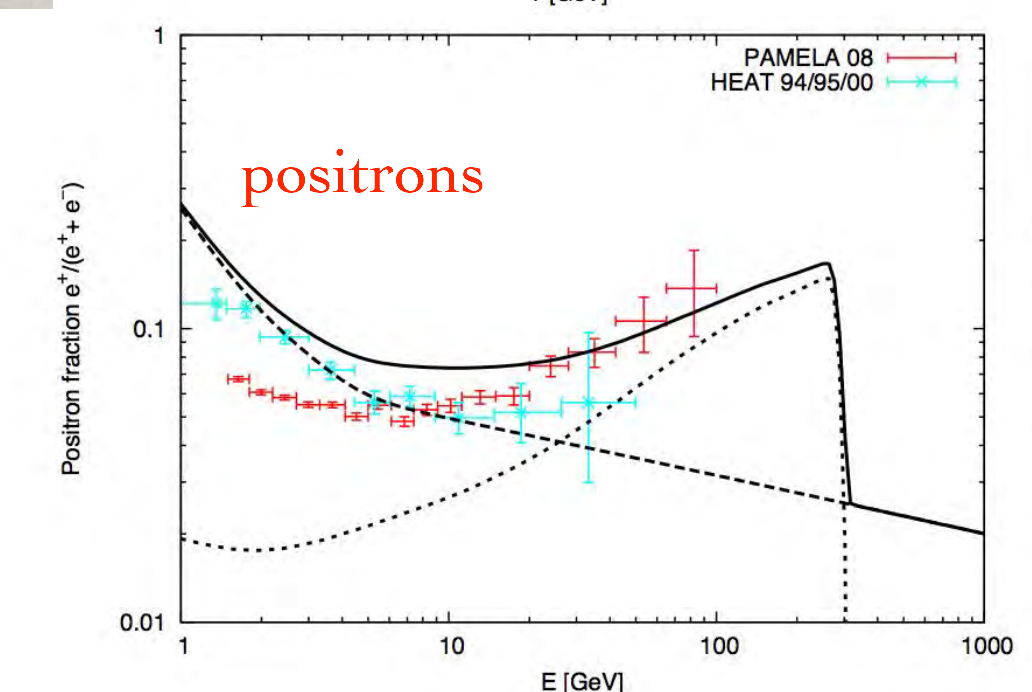
[Bomark et al 09, LC & JE Kim 09, Bajc et al 10]

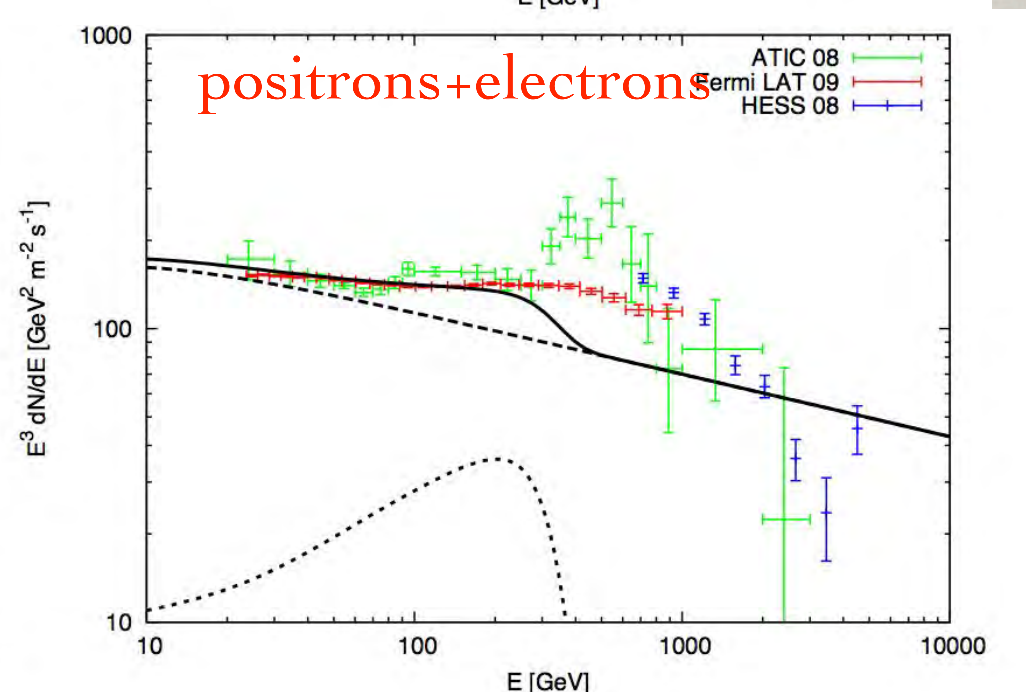
Gravitino DM without R_p

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





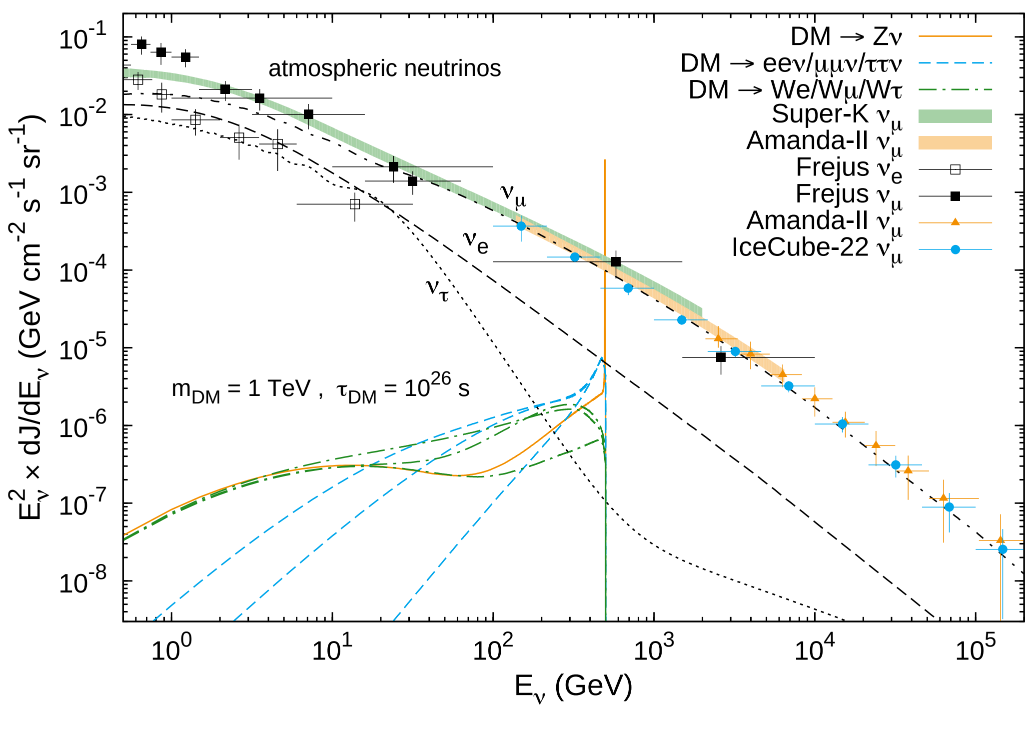


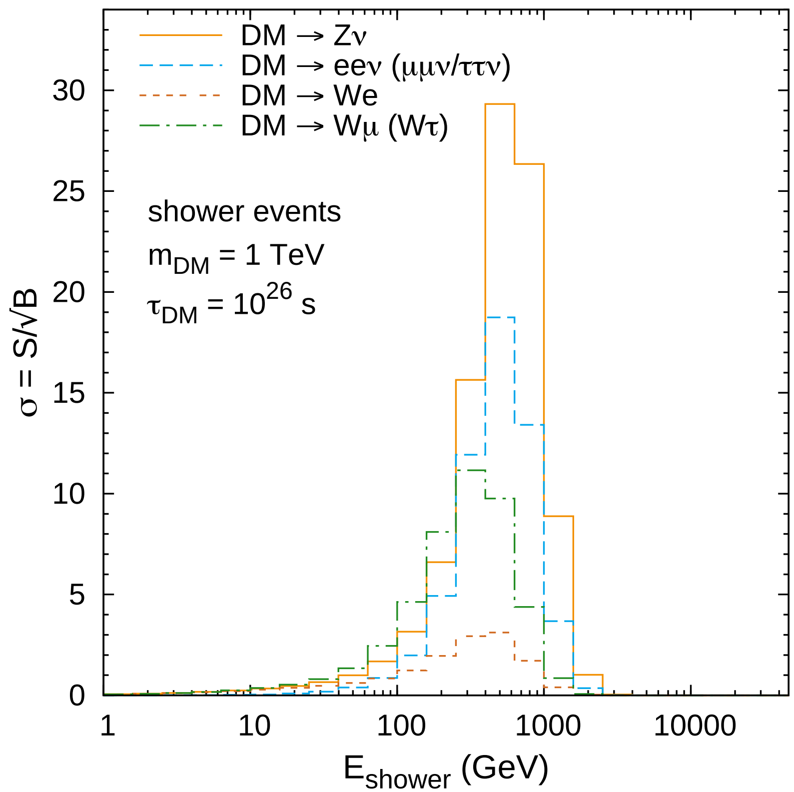


Heavy decaying DM

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

[LC, Grefe, Ibarra & Tran 09]

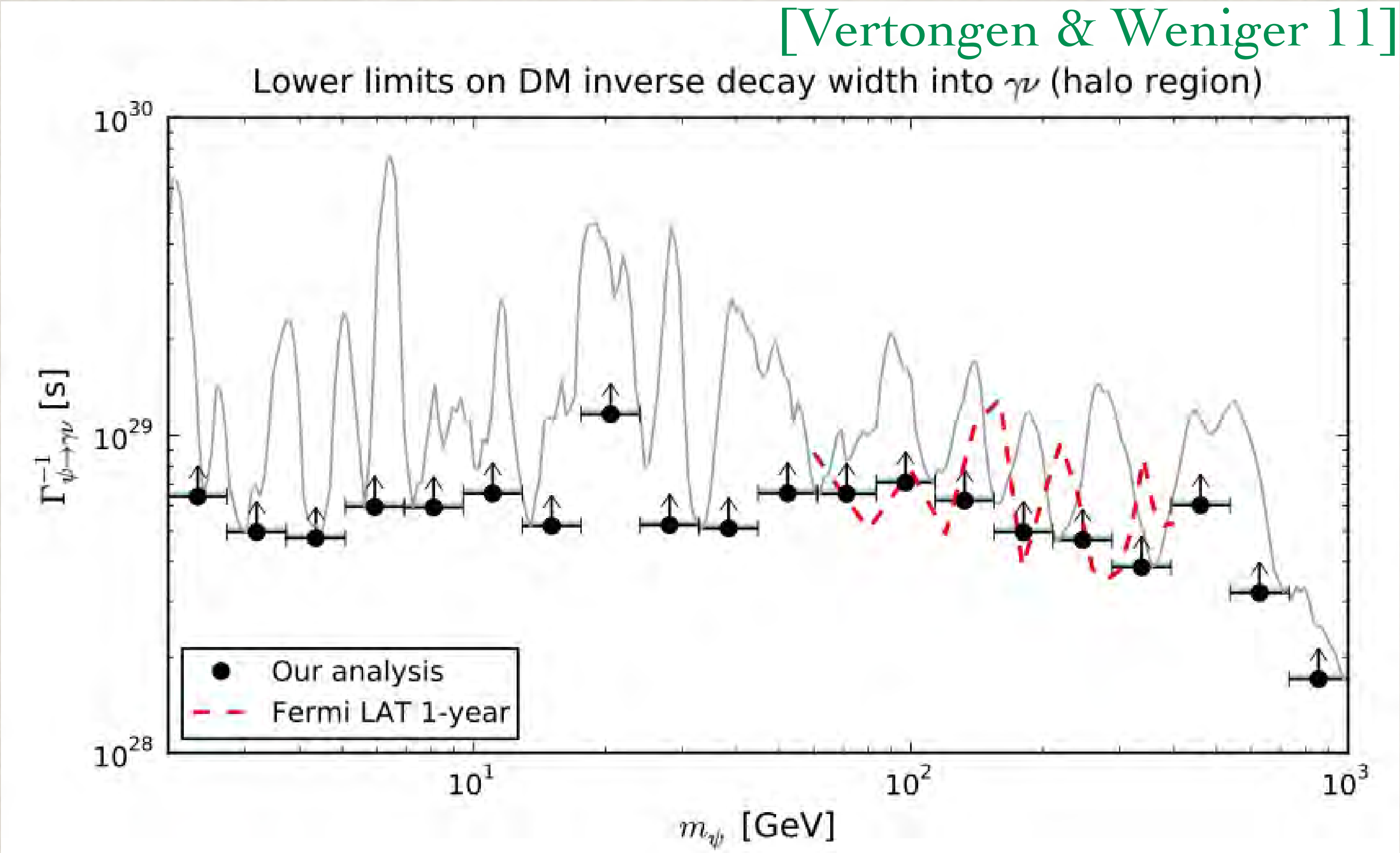




Best significance for cascade/shower events

Possible to detect in IceCube ?

FERMI LINE CONSTRAINTS



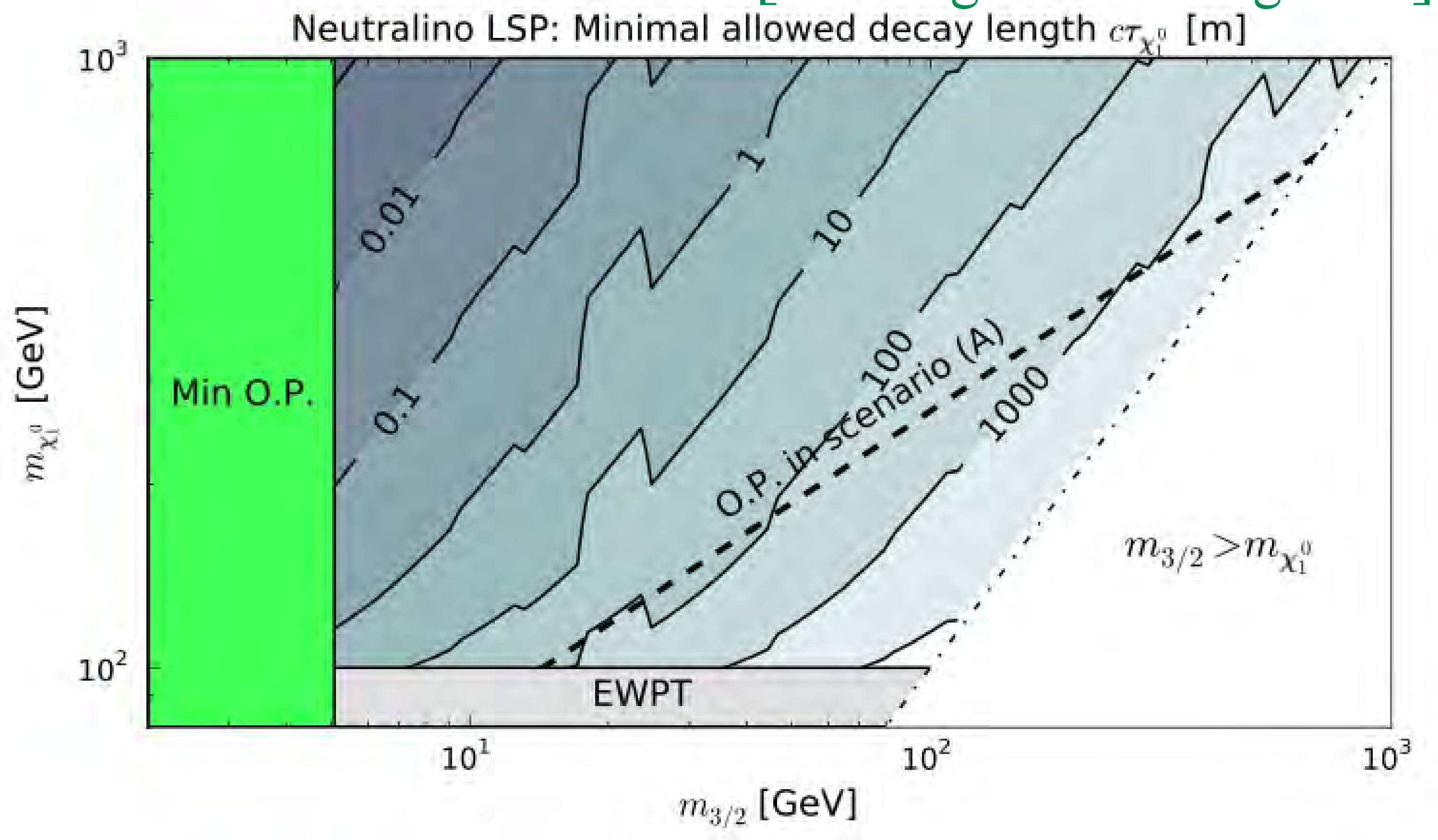
A recent analysis extends the FERMI line search in a wider mass region, for energies to 500 GeV, i.e. masses between 1-1000 GeV

From the FERMI gamma-line search: $\tau \geq 6\ 10^{28}$ s @ 95% CL

LHC:NLSP DECAY LENGTH

Broken Rp: The limits from the search for gamma-lines require a relatively large decay length for the neutralino NLSP:

[Vertongen & Weniger 11]



But no definite prediction on decay length for stau NLSP...

[Bobrovskyi, Buchmuller, Hajer & Schmidt 10]

LHC: Displaced vertices or charged tracks ?

Conserved Rp Gravitino: 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 and the R-parity breaking has to be even more suppressed. But the BBN constraints on stau NLSP case are weaker than for the gravitino: it is possible to have a metastable light stau NLSP leaving a ionizing track at LHC...

Outlook

- The axino and the gravitino are good DM candidates, with similar properties. For both cases the universe temperature is bounded from above and BBN can constrain the lifetime and density of the NLSP.
- The bounds on neutralino NLSP in the gravitino case can be relaxed for a degenerate gaugino spectrum with special signatures at the LHC !
- Axino/Gravitinos can survive as DM also for broken R-parity, but the breaking has to be suppressed. Indirect DM searches already set limits on these parameters.
- Different signals are possible at the LHC: displaced vertices, missing energy or metastable charged particles

Let us hope for a signal soon !