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News on axino and gravitino Dark Matter

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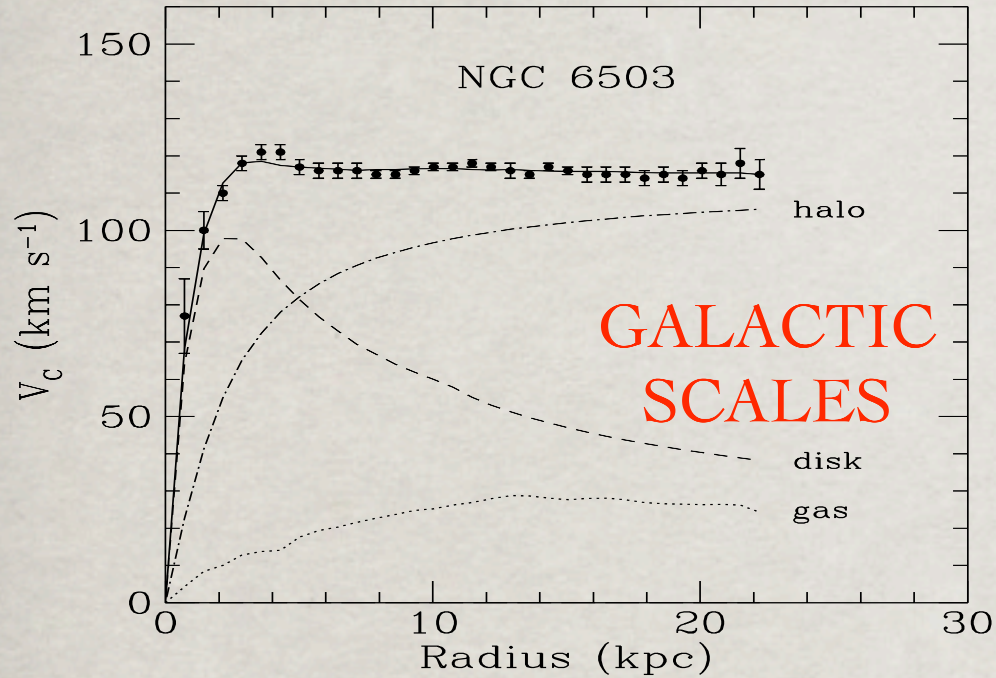
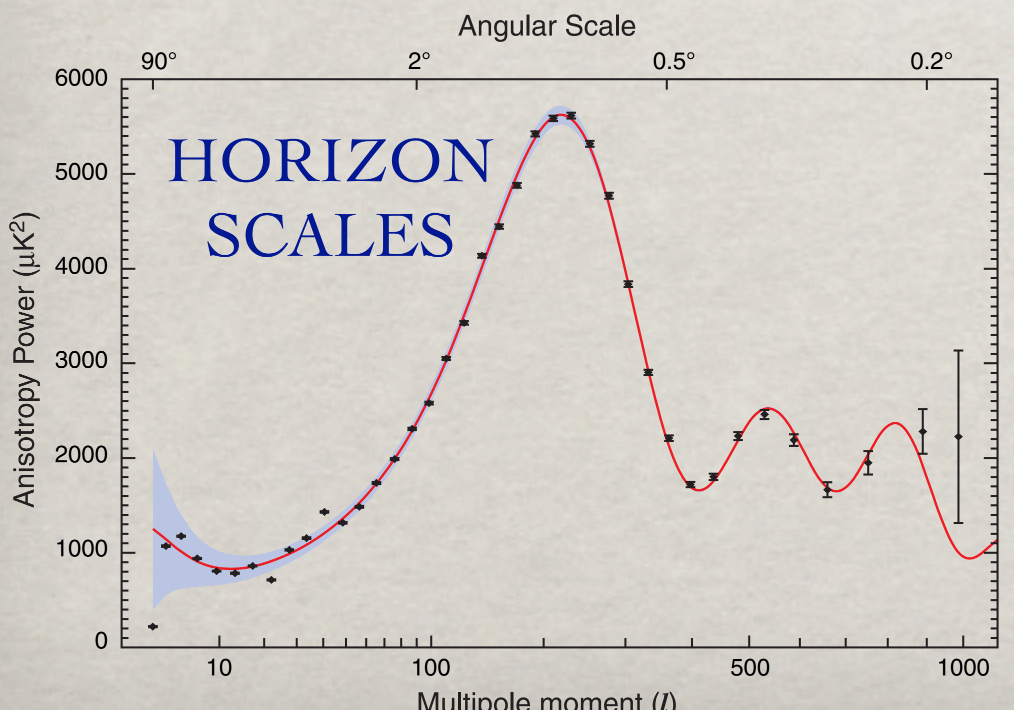
OUTLINE

- Introduction: Dark Matter properties
  Axino & gravitino properties
- Cosmological constraints on (stable) gravitino and axino Dark Matter
- Stable axino and gravitino
- Unstable DM and indirect detection
- Signals at LHC...
- Outlook

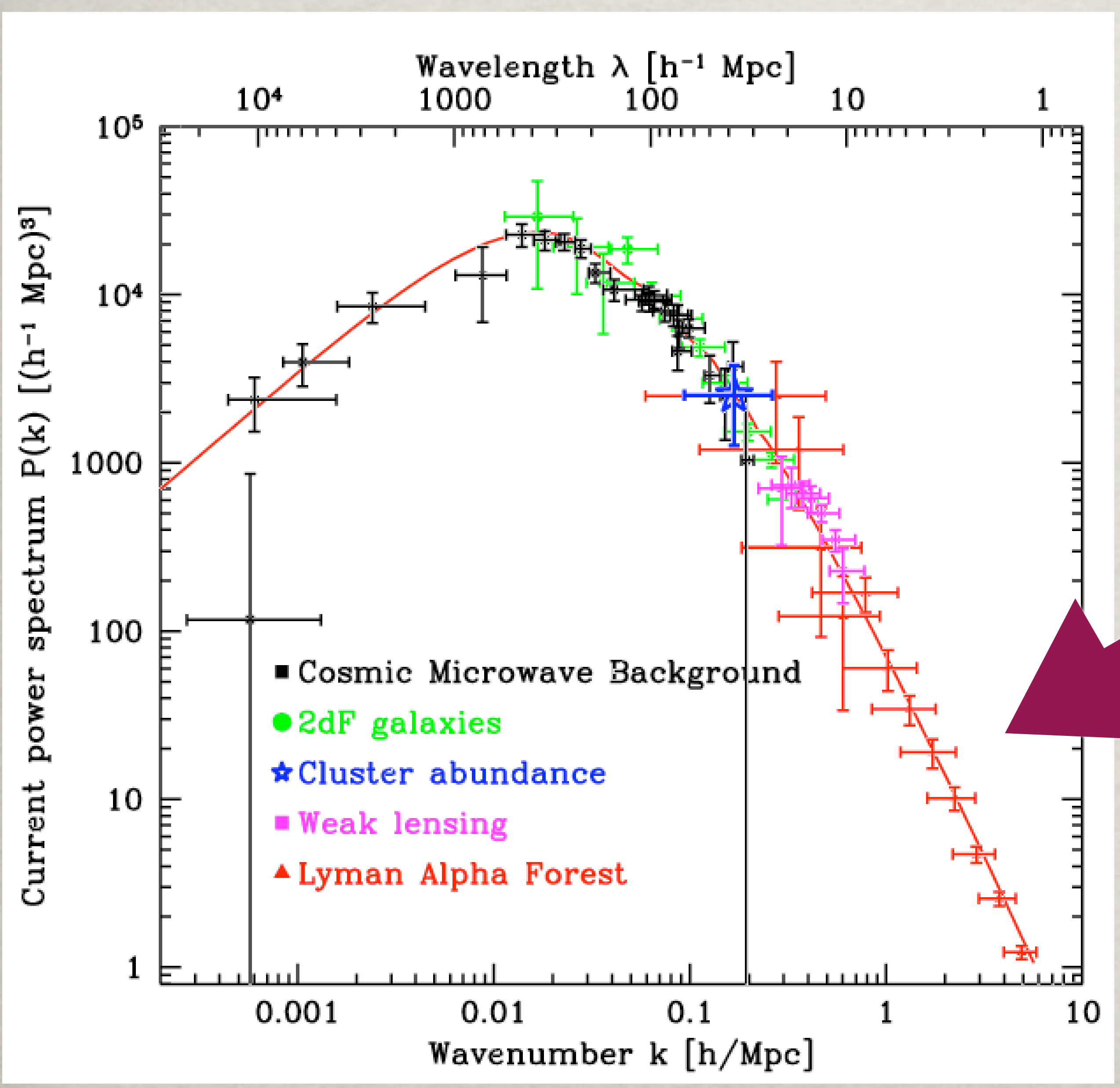
DARK MATTER EVIDENCE





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

WDM & the Power spectrum



WARM DM suppresses perturbations on scales smaller than its free-streaming length:

$$\lambda_{FS} \sim \mathrm{Mpc}\left(\frac{m_{WDM}}{1\mathrm{keV}}\right)$$

Compare with the data:

$$m_{WDM} > 4\ \mathrm{keV}$$

[Viel et al. '07]

Why Gravitino/axino DM?

- To identify DM within gravity or the PQ sector, solving the strong CP problem.
- 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 (most) of the couplings are fixed by symmetry.
- Relaxes the gravitino problem and possibly allows for thermal leptogenesis...
- R-parity conservation is not strictly necessary...

Super/E-WIMPs

- 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 a thermal relic 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

J.E. Kim

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

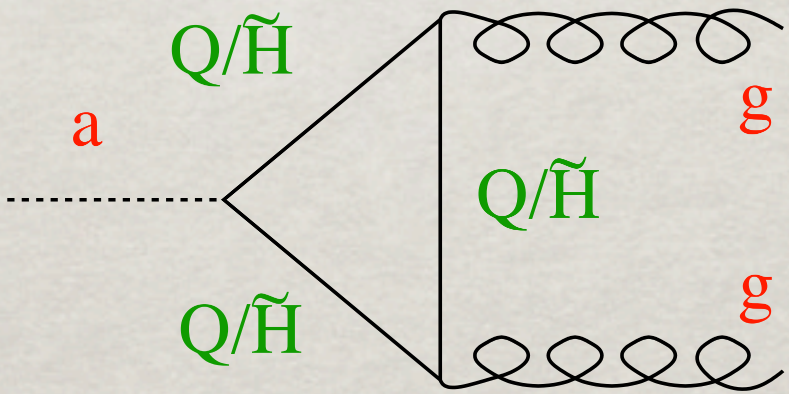
[Dine, Fischler & Srednicki '81], [Zhitnitskii '80]

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

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

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

$$\rightarrow h \ll 1$$



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:

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

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

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

The gravitino gives us direct information on SUSY breaking

Cosmological Constraints on Axino/Gravitino Dark Matter

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

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

NLSP DECAY OUT OF EQUILIBRIUM

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

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PLASMA
SCATTERINGS

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

NLSP DECAY
OUT OF EQUILIBRIUM

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:

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

[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 !

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:

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

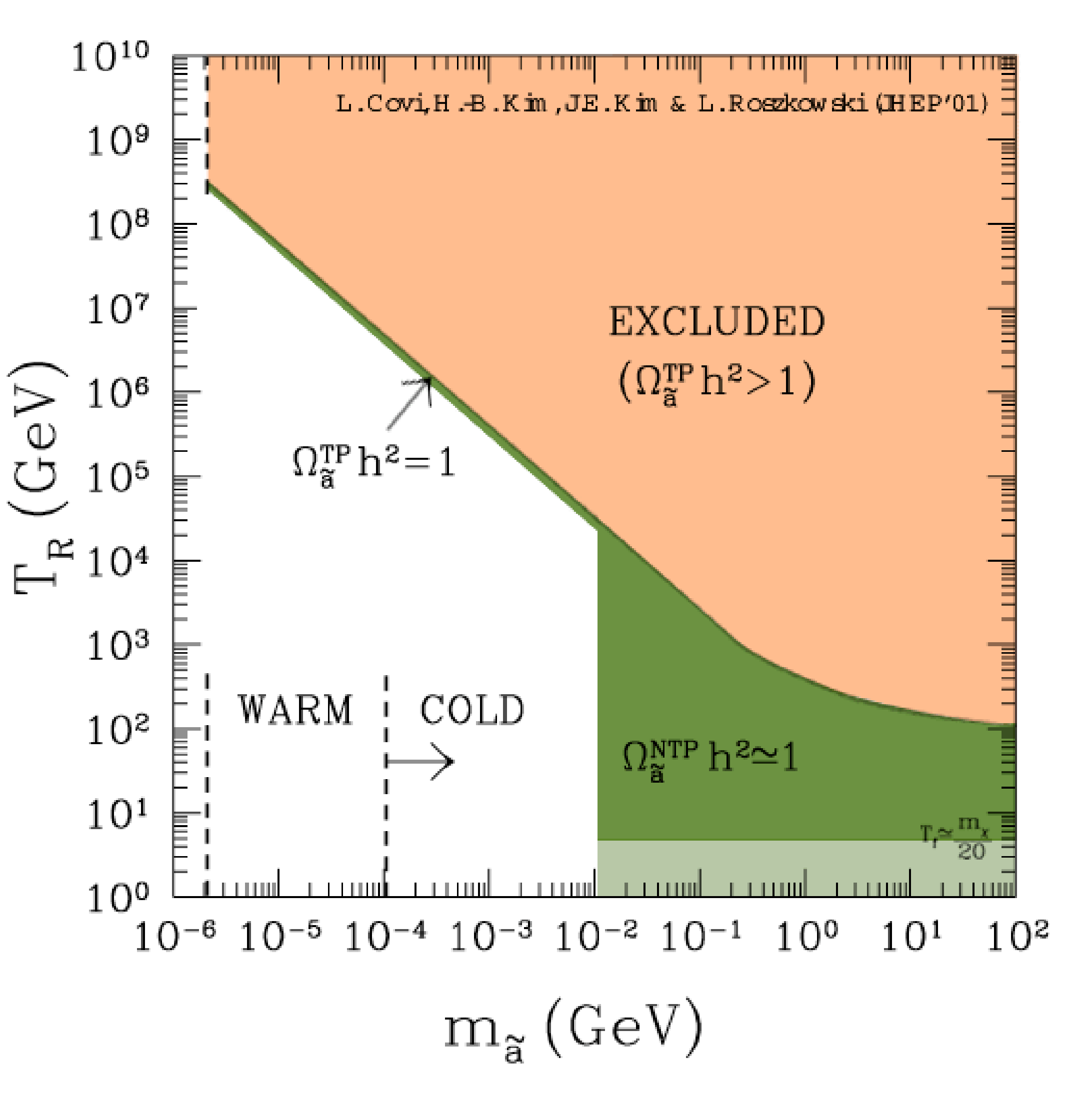
[Strumia 10]

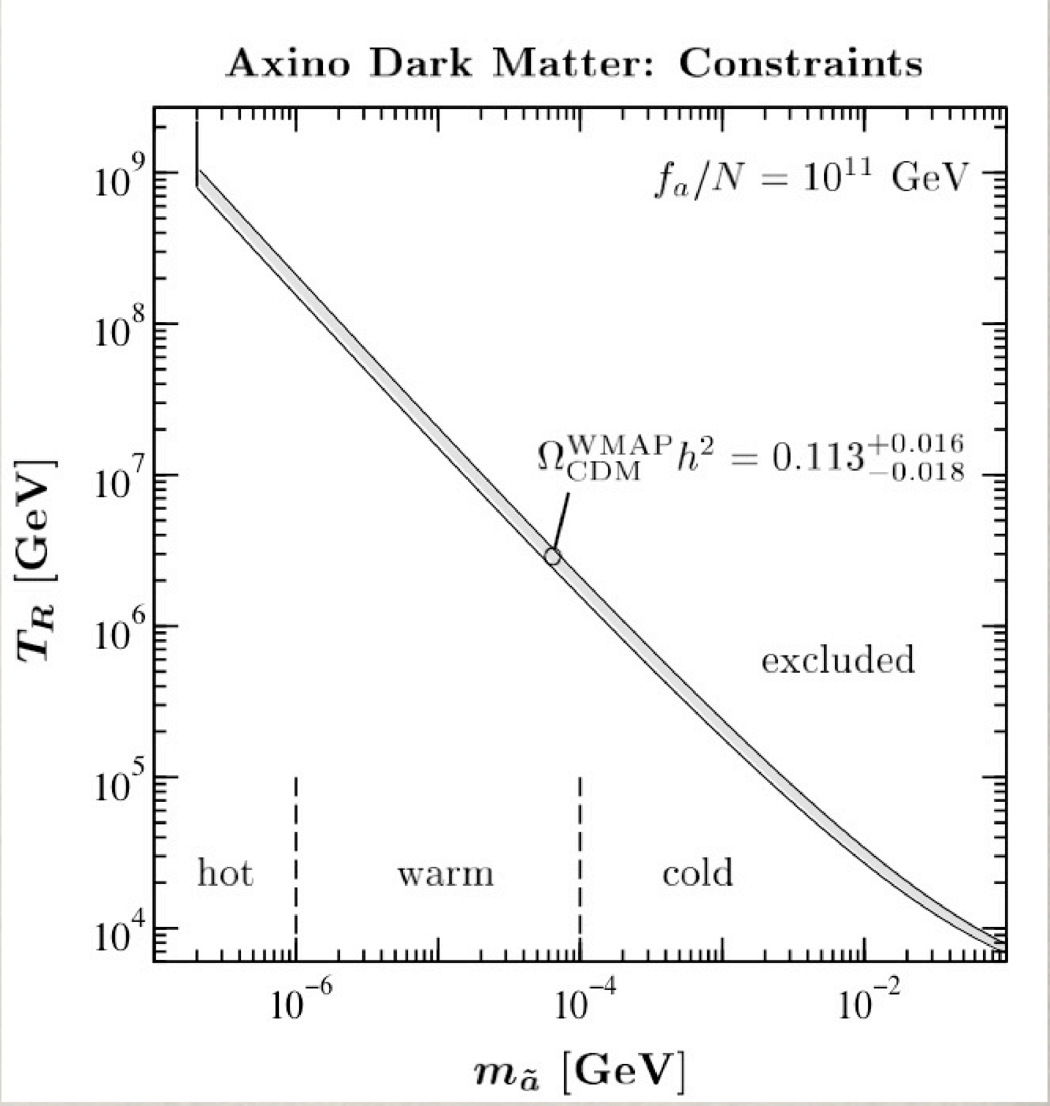
This includes a D-term contribution previously neglected and the effect of (thermally massive) gluon decay.
This is a factor ~ 2-3 smaller than [Brandenberger & Steffen 04] and nearly equal to our earlier one with a gluino thermal mass introduced per hand [LC, HB Kim, JE Kim & Roszkowski 01].

Tension with thermal leptogenesis is stronger, especially for large axino masses ! Non-thermal leptogenesis ? H. Baer

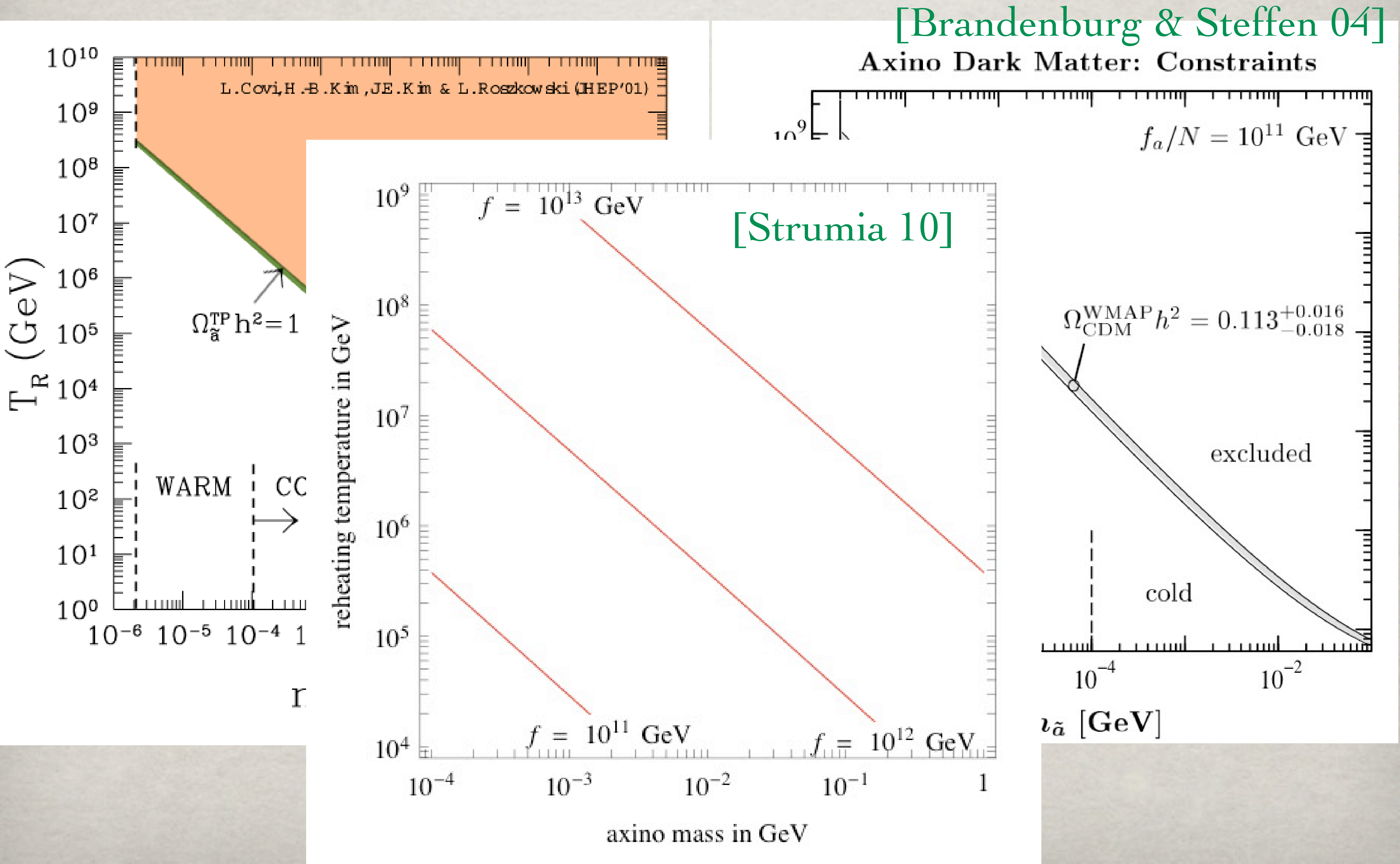
UPPER BOUND ON T_R

[Brandenburg & Steffen 04]





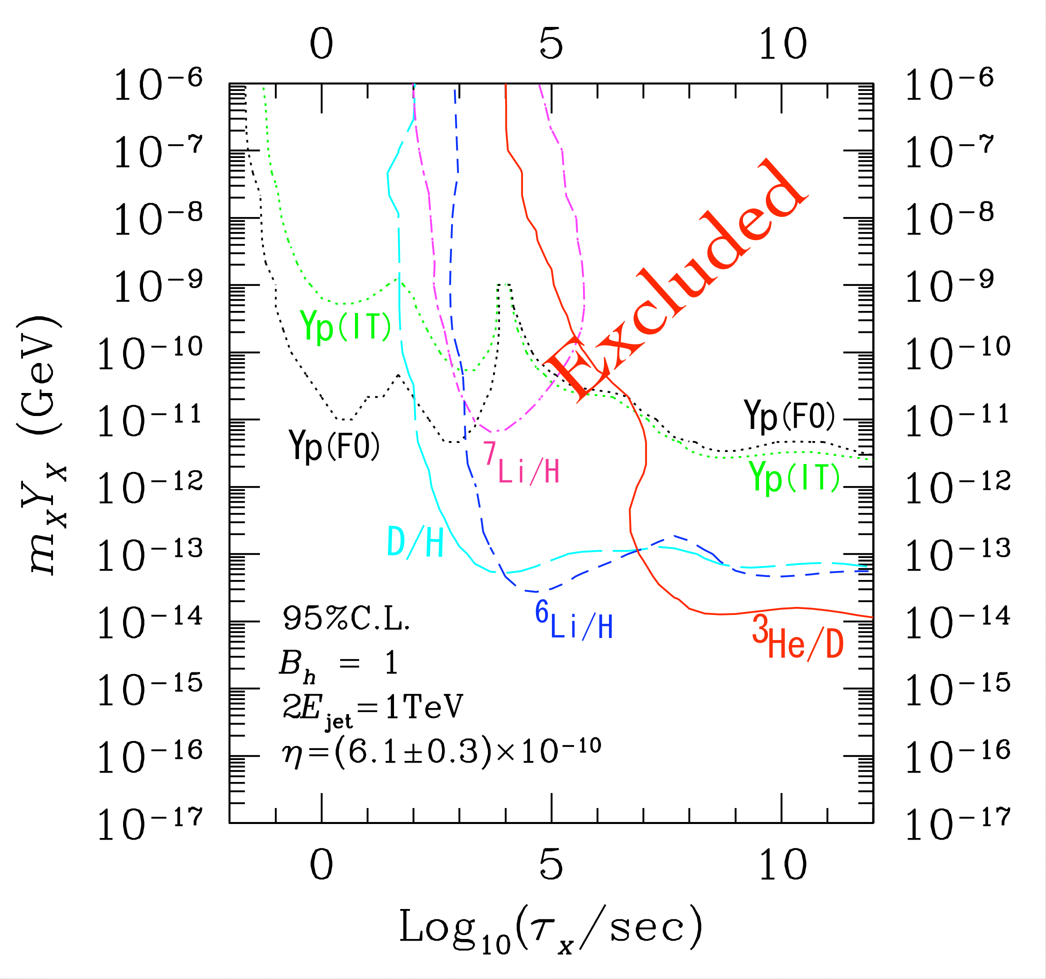
UPPER BOUND ON T_R



BBN bounds on NLSP decay

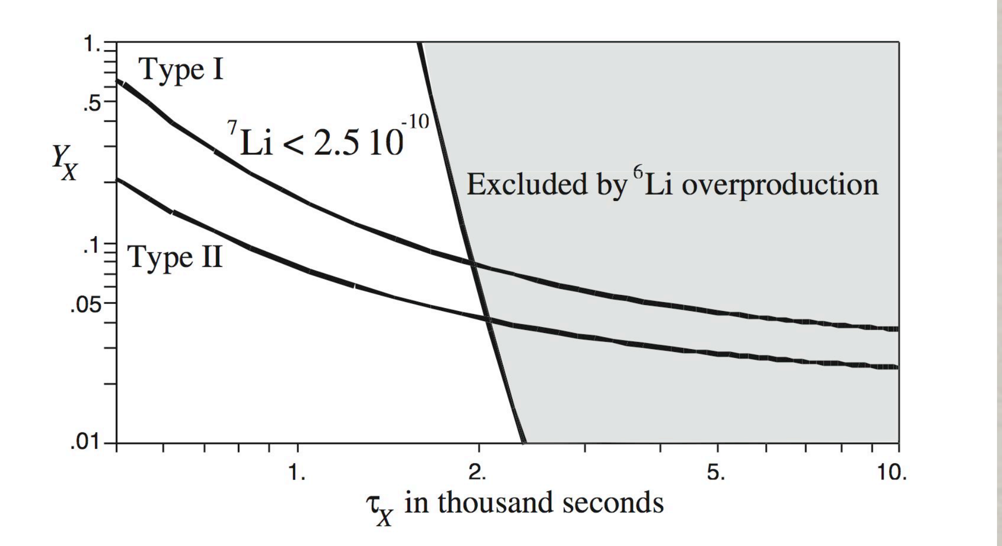
Neutral relics

[...,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...

Even worse for colored LSP

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

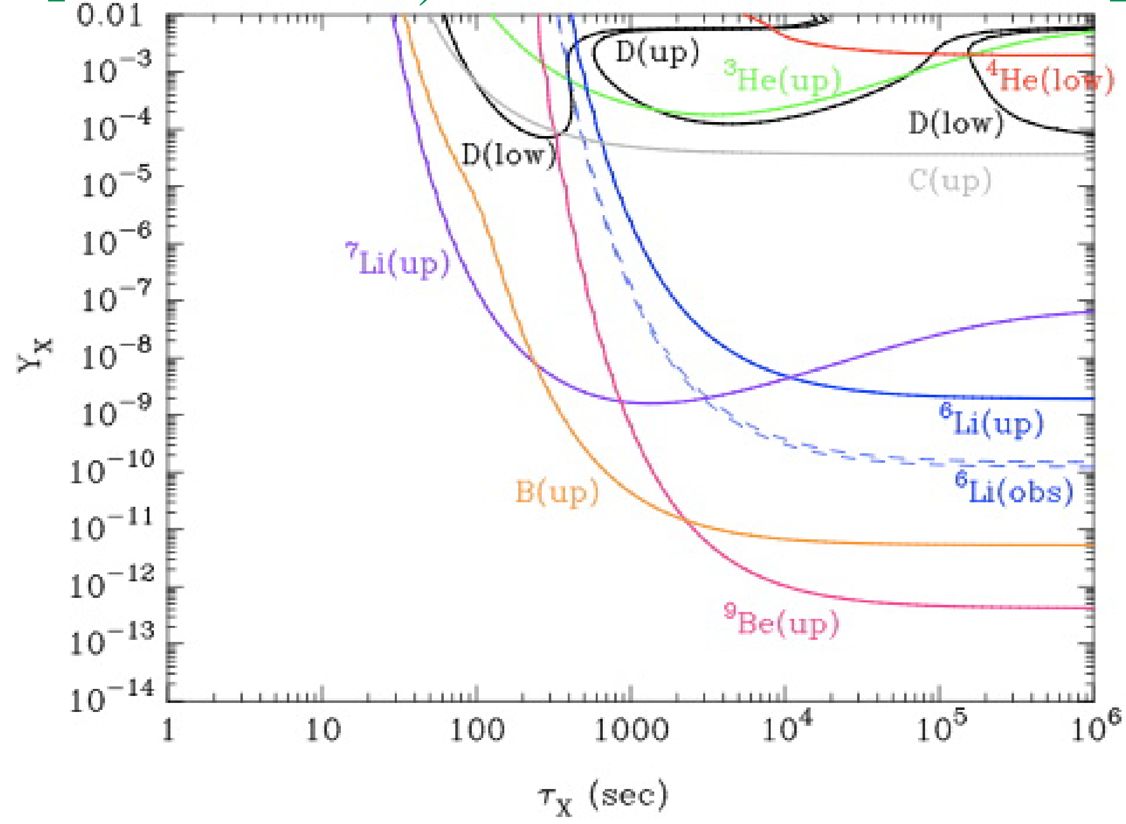
Beware:

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

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

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

[Kusakabe, Kajino, Yoshida, Mathews 09]



Only short lifetime for colored NLSP allowed:

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

Stable gravitino/axino

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 ???

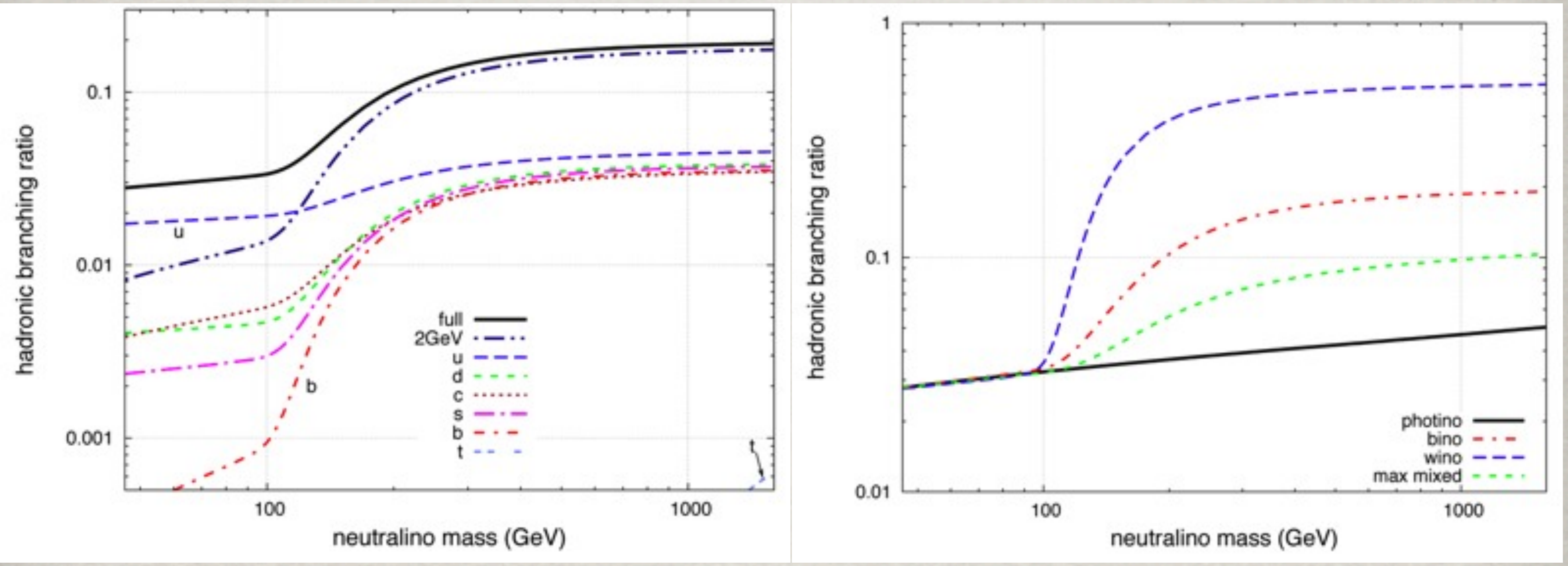
General neutralino NLSP

[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...
- One 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

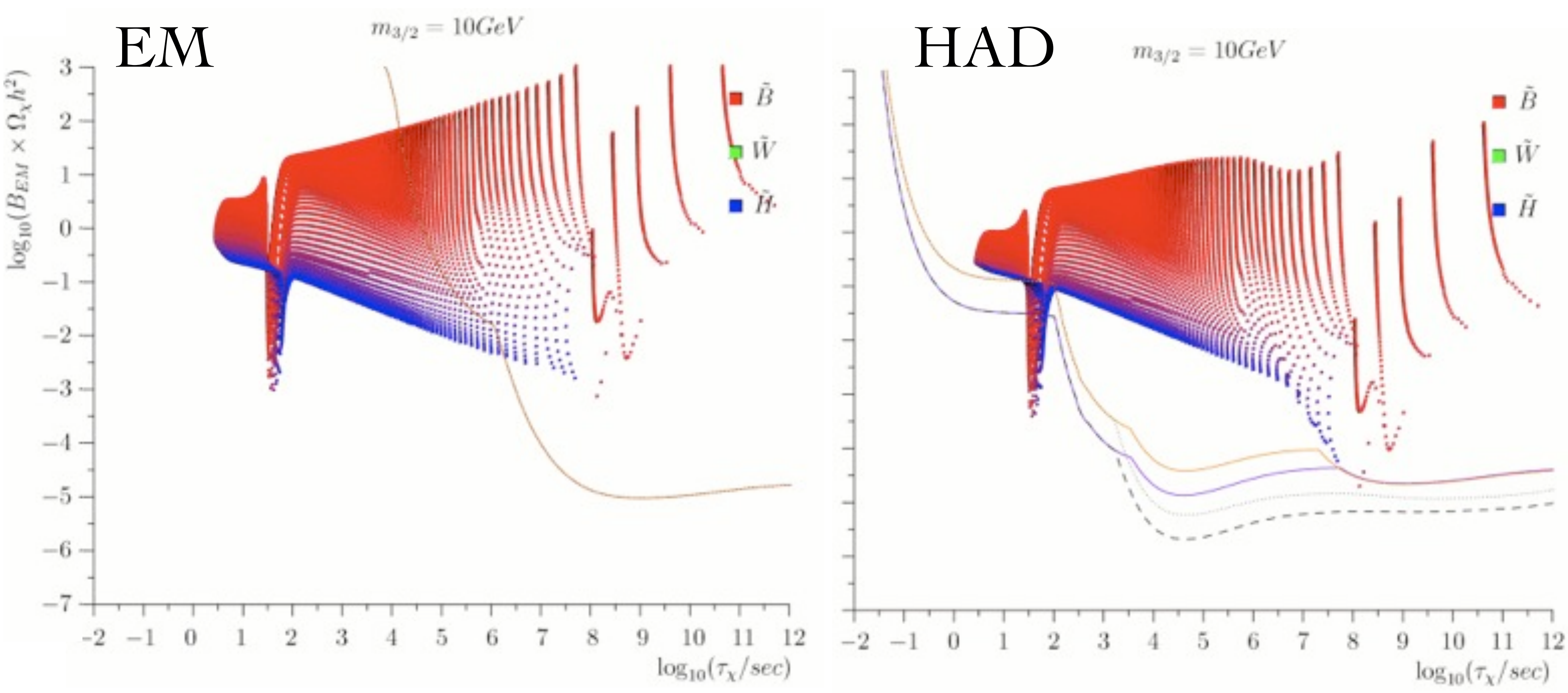
[LC, Hasenkamp, Roberts & Pokorski 09]



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: photino !

Bino-Higgsino

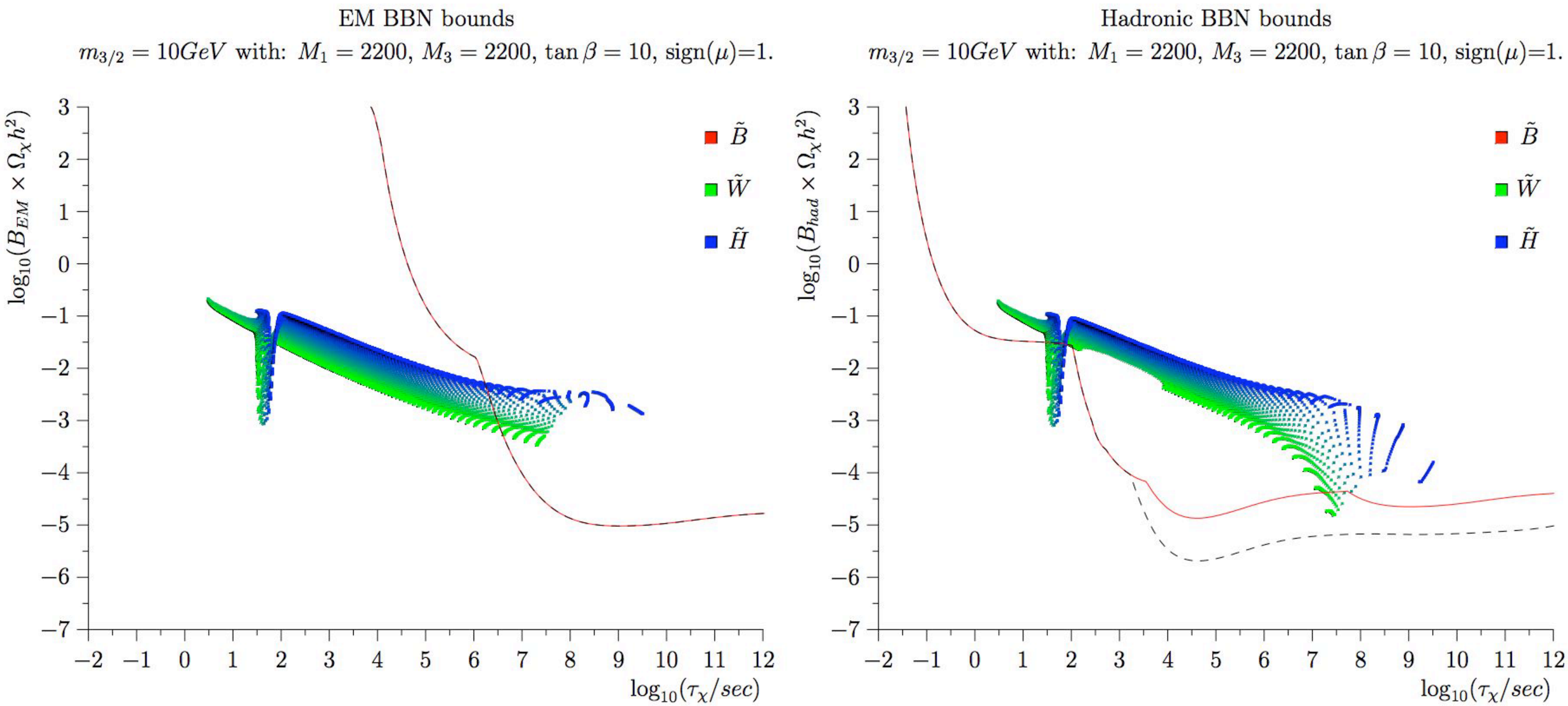
[LC, Hasenkamp, Roberts & Pokorski 09]



The resonant annihilation into heavy Higgses becomes much more effective & reduces the density by 4 orders of magnitude ! Gravitino masses of order ~ 70 GeV possible if $2\, m_\chi \sim M_{A/H}$

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...

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:

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

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.

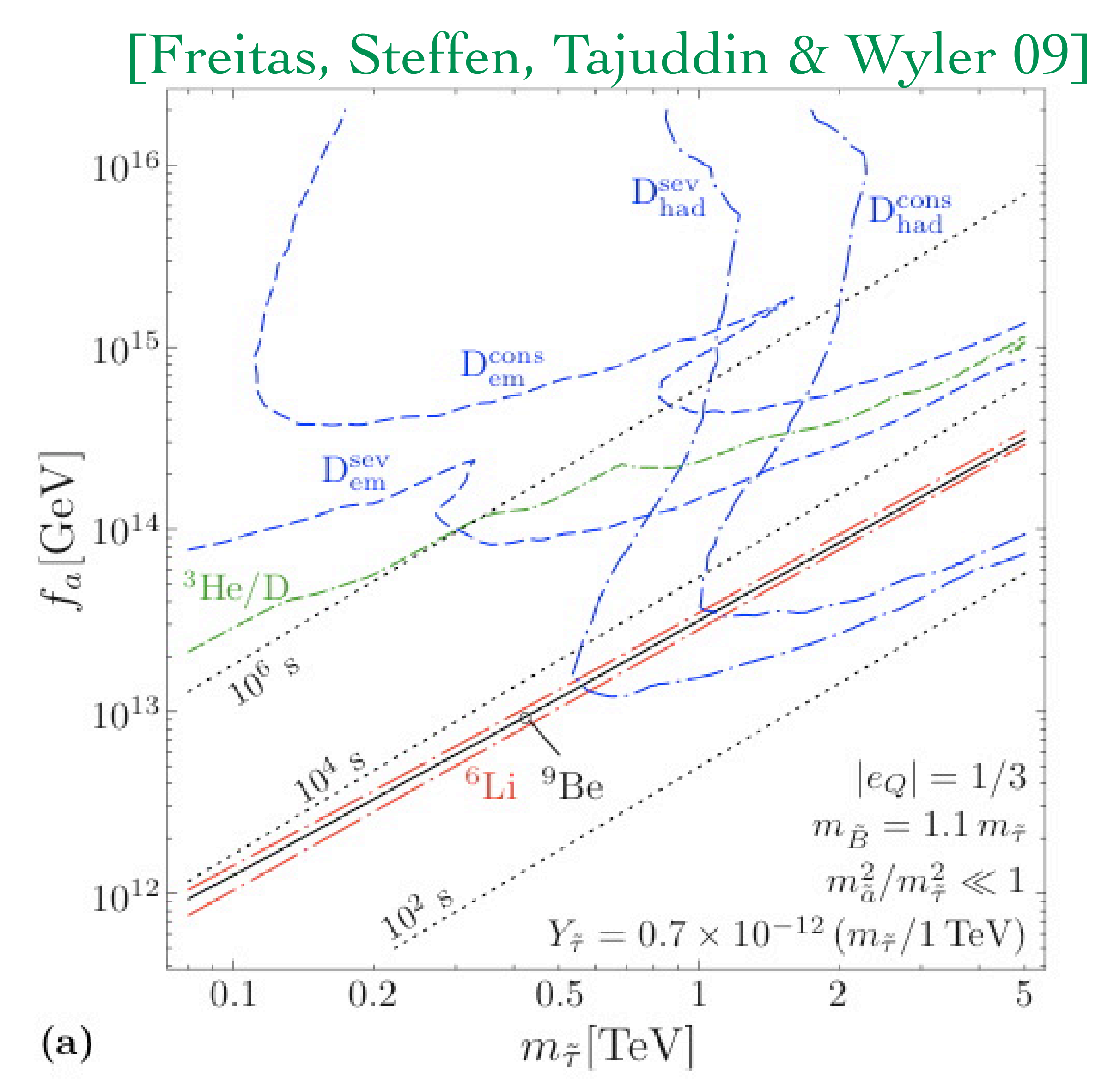
It gives ~ 20% correction to the previous computation using an effective one loop approximation [LC, L. Roszkowski, M. Small, 02]

This is important for computing the stau NLSP lifetime !

UPPER BOUND ON f_a

For

τ_R NLSP



More stringent than for neutralino NLSP

H. Baer

Other ways out:

- Dilute the NLSP abundance with entropy production
  [Buchmuller et al 05, Hamaguchi et al 07...] J. Hasenkamp, F. Staub
- Reduce the NLSP number density via coannihilation with the gluinos K. Turzynski
- Reduce the energy released during BBN by making the gravitino mass degenerate with the NLSP O. Vives
- Choose a relatively harmless NLSP, e.g. sneutrino
  [LC & Kraml 07, Santoso et al. 08, ...]
- Make the NLSP lifetime shorter:
  heavy(er) NLSP or light(er) gravitino LSP or breaking R-parity and allowing the NLSP decay to SM.
  But then the (axino)/gravitino DM is unstable !!!

Unstable axino/gravitino

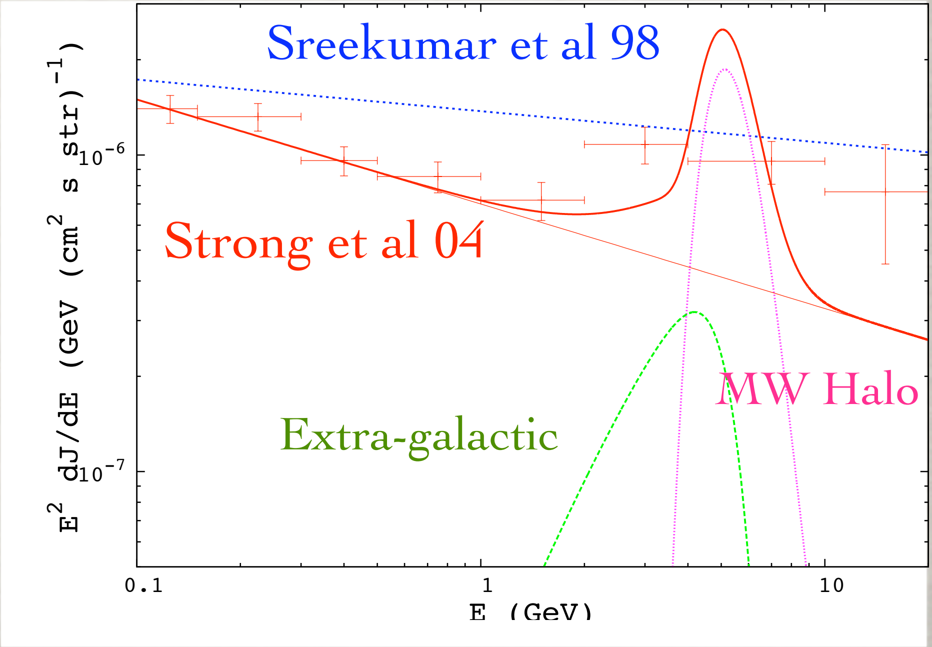
DECAYING DM

- 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...



Decaying axino/gravitino?

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

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

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

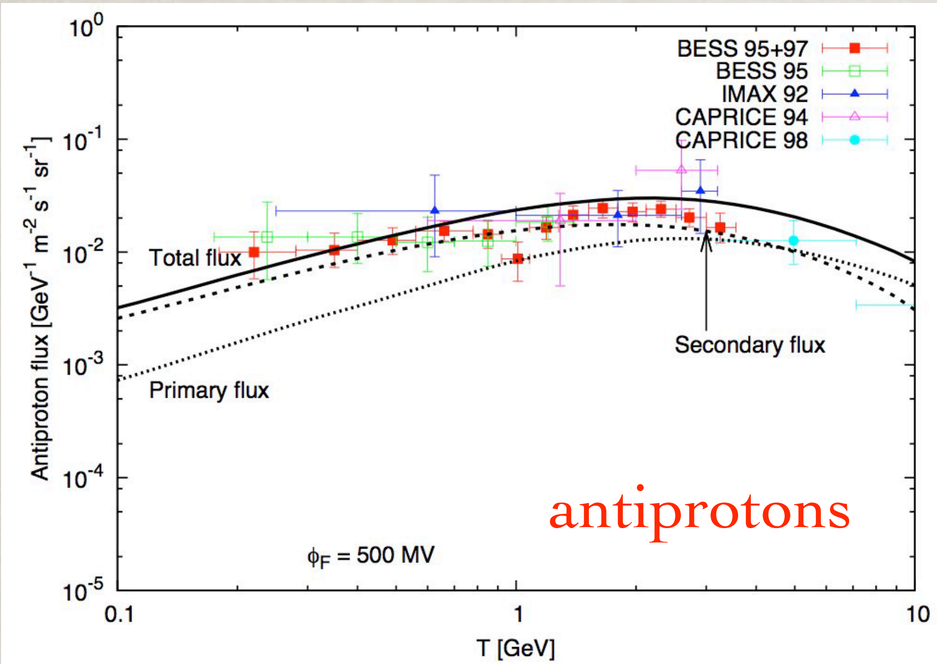
- For bilinear R-parity breaking, they decay similarly to gauge boson/Higgs and neutrino

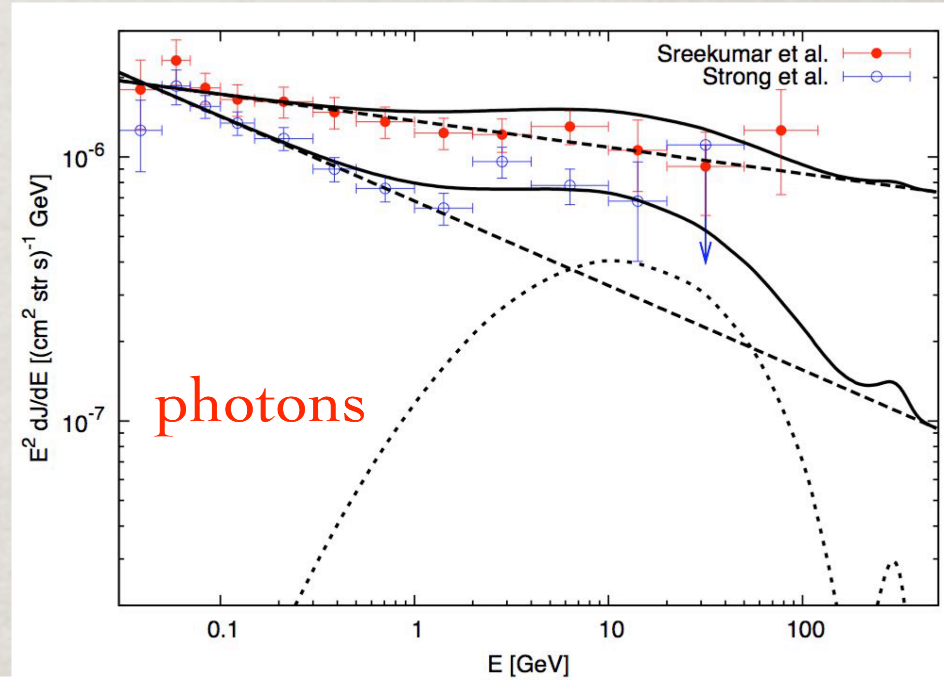
  [Takayama &Yamaguchi 00, Buchmuller et al '07, LC & JE Kim 09]

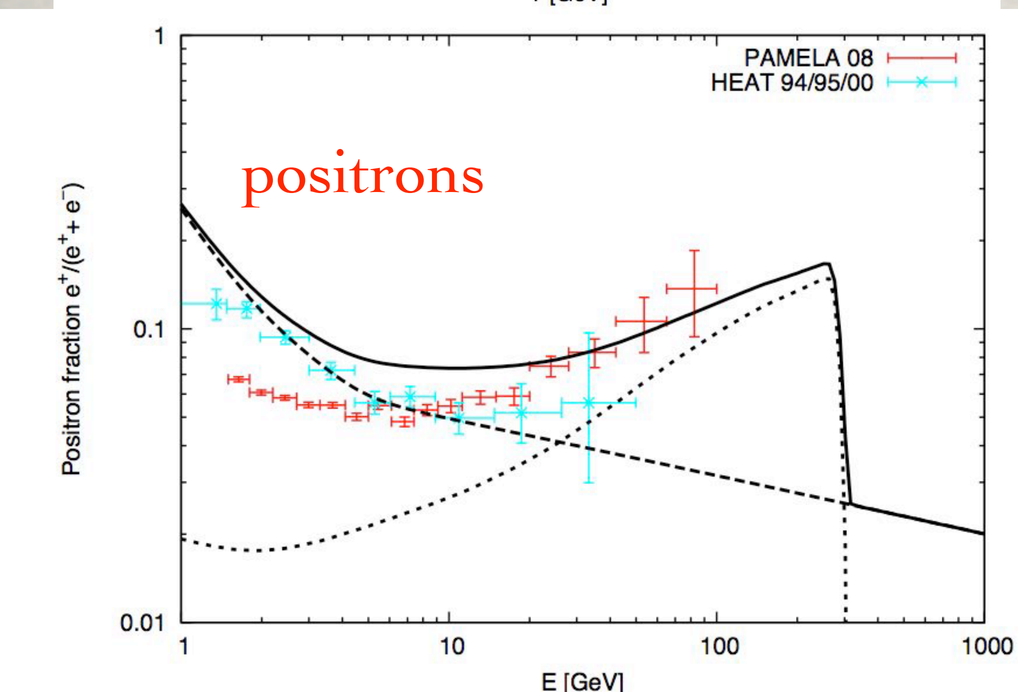
  For trilinear R-parity breaking, the 3-body decays into leptons can dominate and give a leptophilic DM
  [Bomark et al 09, LC & JE Kim 09]

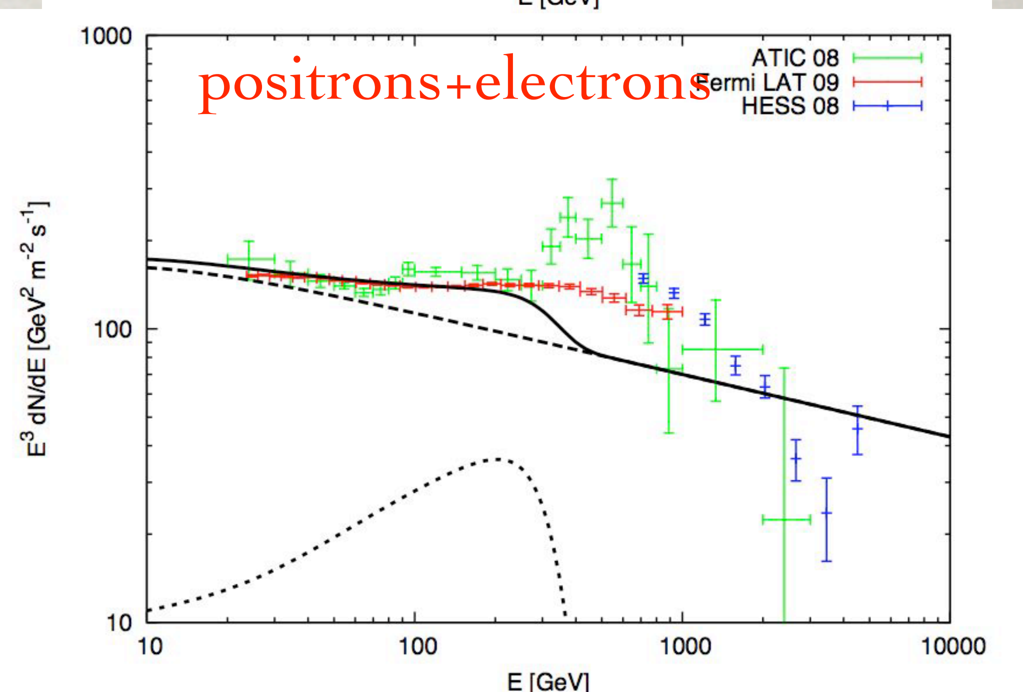
Gravitino DM without R_p

[Buchmuller, Ibarra, Shindou, Takayama, Tran 09]

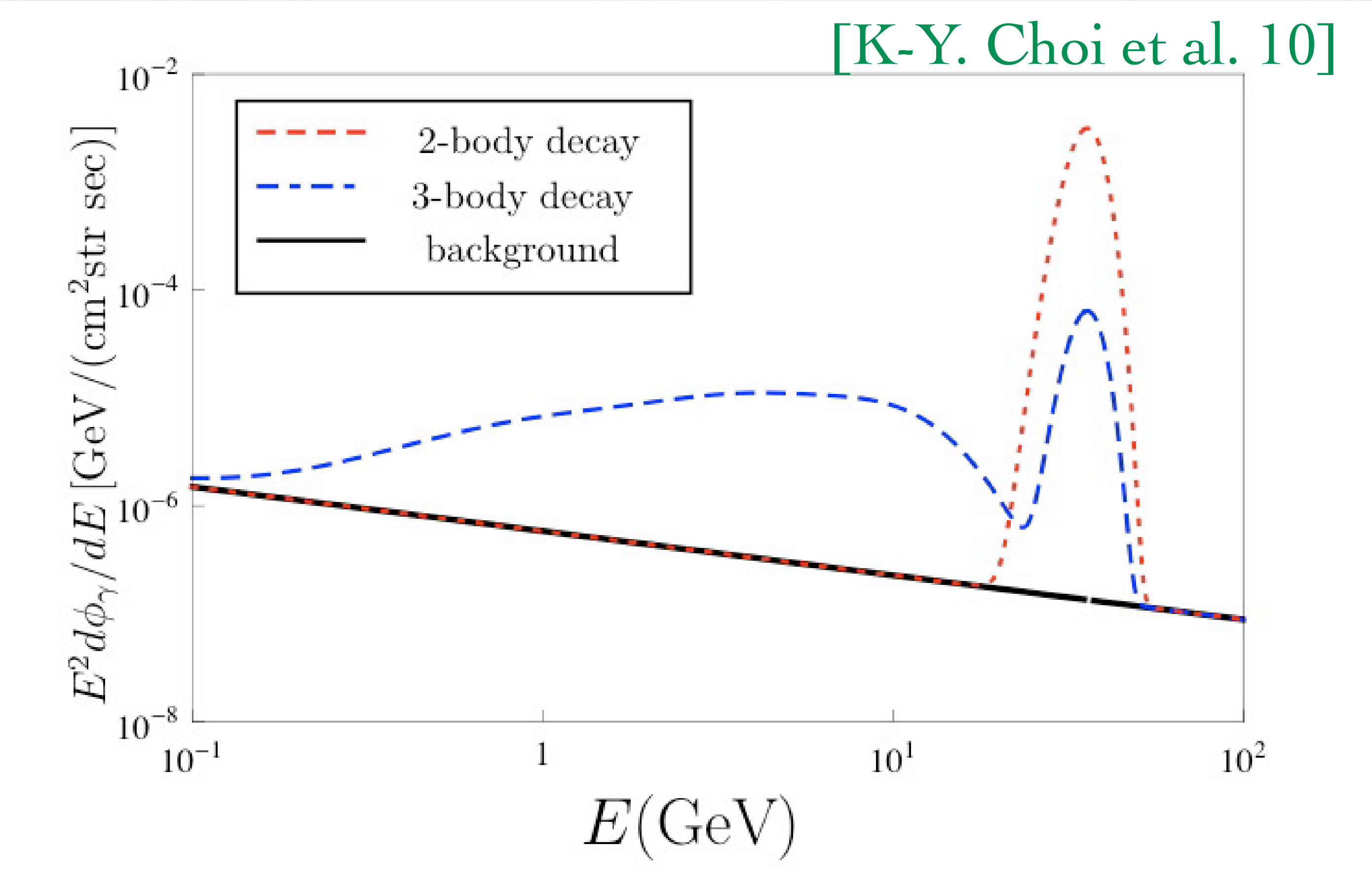








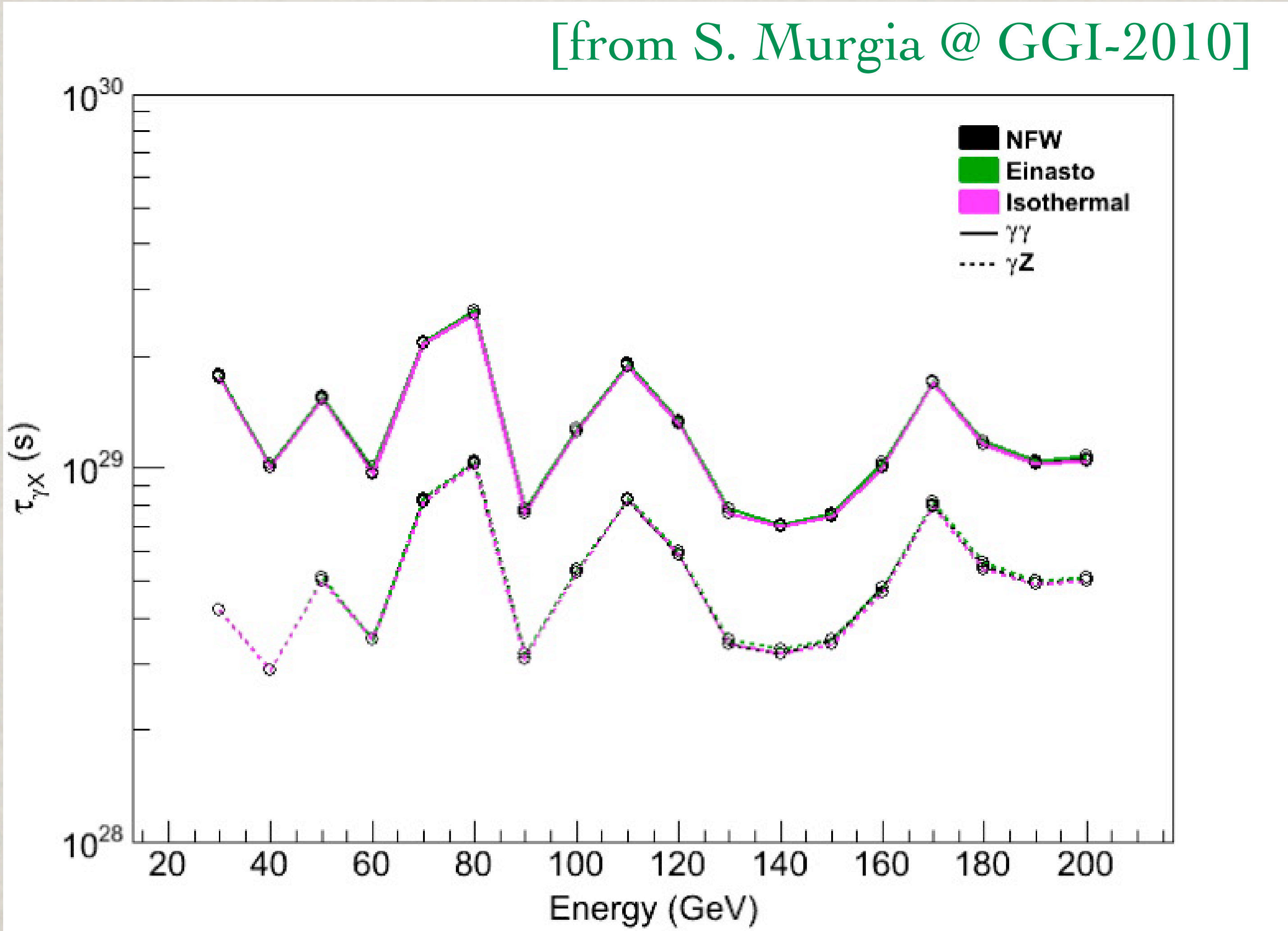
Below M_W also 3-body



For bilinear R-parity breaking, the gravitino decays mostly into lepton and gauge boson... Below the W/Z threshold though, also the 3-body decay via virtual W/Z are important because the photon channel can be suppressed... [K-Y. Choi & Yaguna 10]

Different decays for the trilinear Rp-breaking case

FERMI LINE CONSTRAINTS



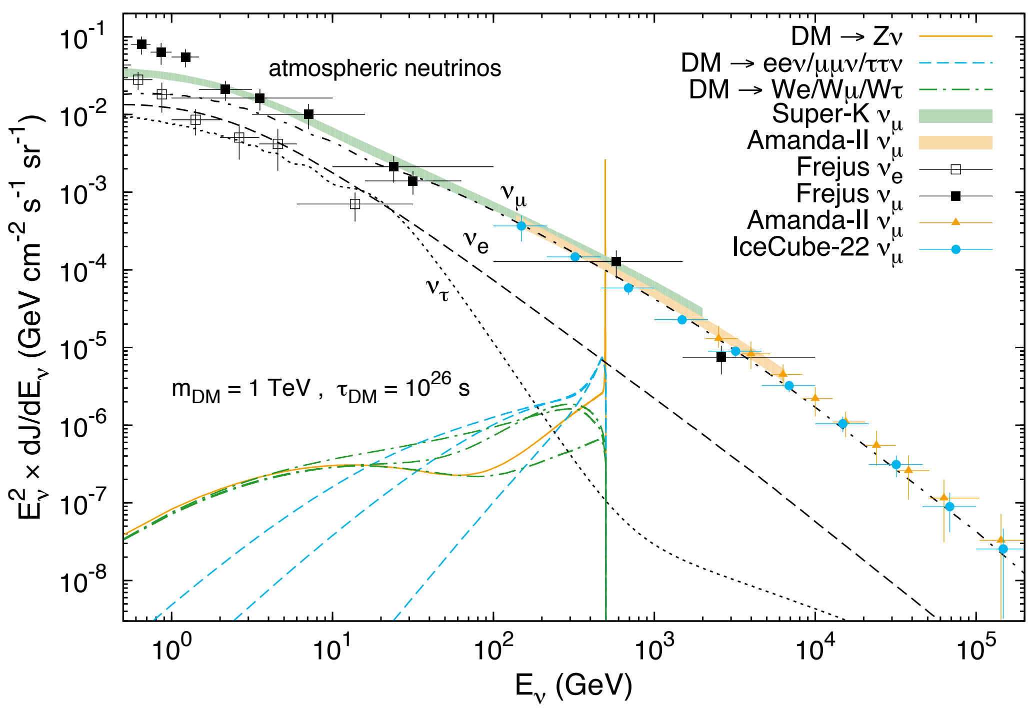
The FERMI space telescope looks for lines in the galactic emissions in the energy range 30-200 GeV and gives the stronger constraint for gravitinos below 400 GeV:

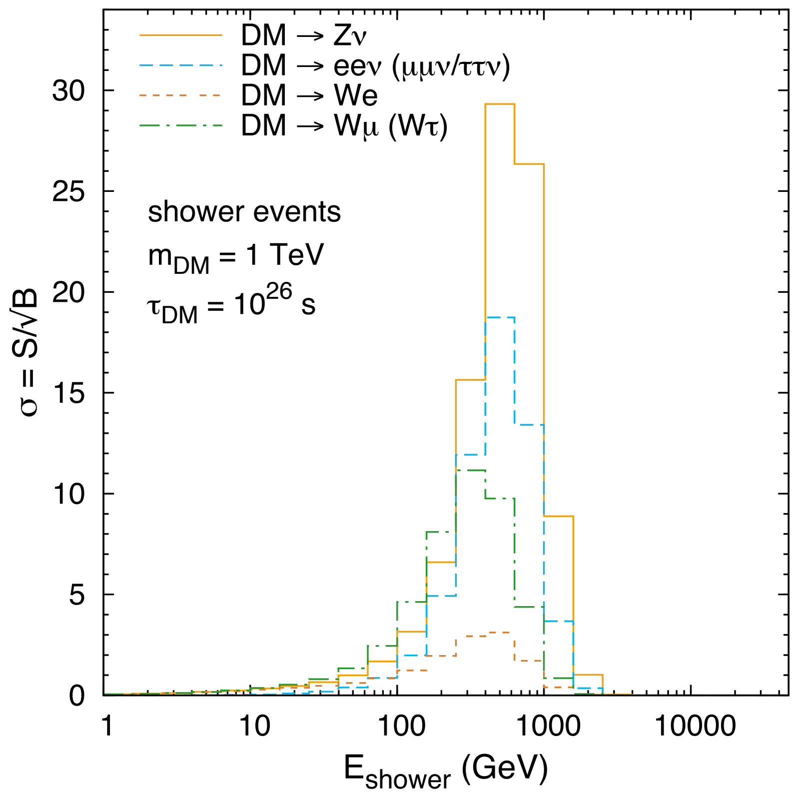
From the FERMI gamma-line search: $\tau \leq 5\ 10^{28}$s @ 95% CL

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 ?

Signals @ LHC

LHC: Displaced vertices ?

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.

Gravitino: The decays happen 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]

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]

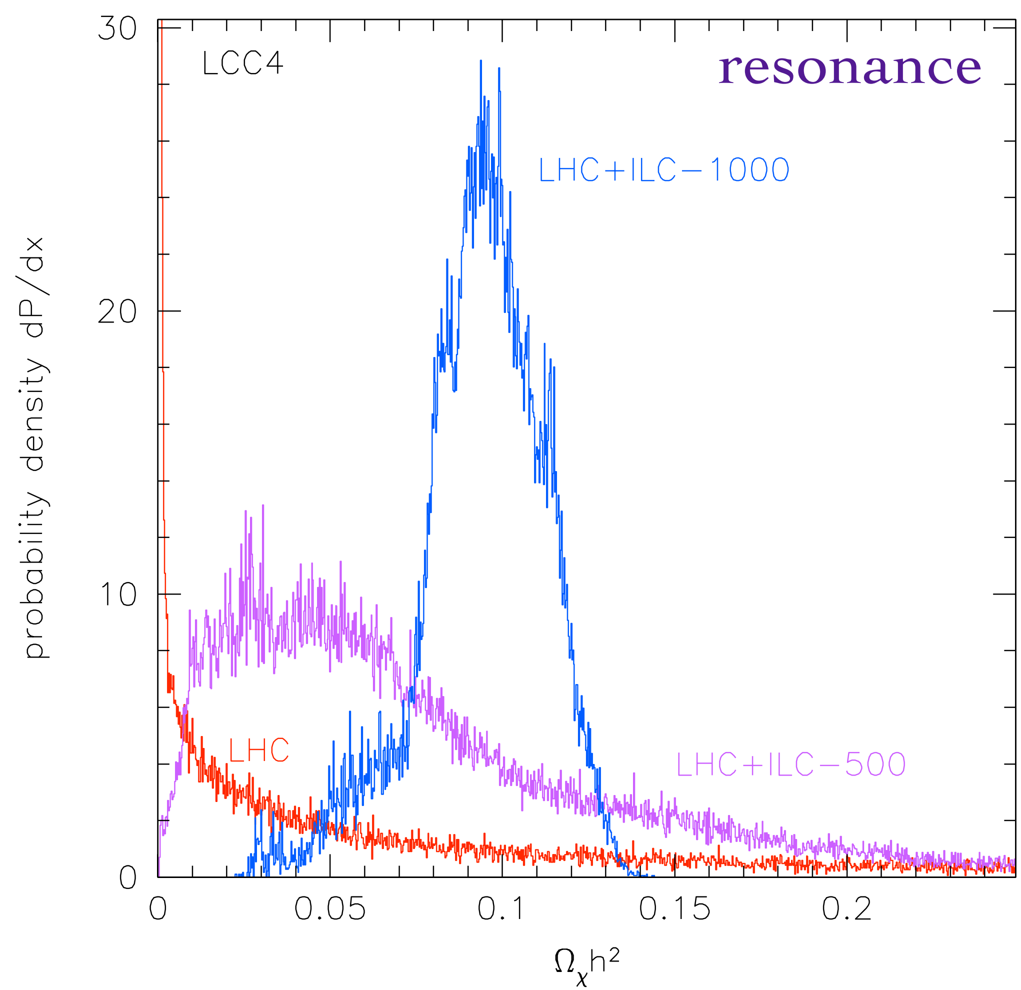
Possible perhaps to observe such (prompt) decays at the LHC even with early data N-E. Bomark, S. Fleischmann

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...

E. Ziebarth

[Baltz, Battaglia, Peskin & Wizanski '06]



LHC: Metastable charged particles

Possible for both axino and gravitino with a variety of NLSPs:
in that case it will be obvious that the particle must decay !

The observation depends on the nature of the NLSP:
it may be stopped in some part of the detector (gluino),
or flight through as a heavy muon (stau).
The experiments are developing strategies for detection

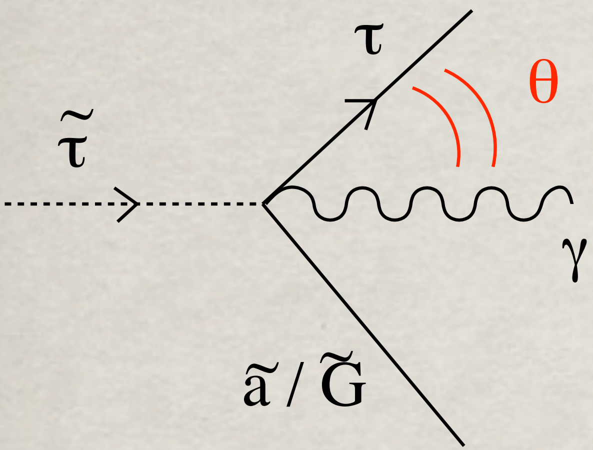
P. Jackson, F. Ratnikov, P. Traczyk

Next step: collect sufficient metastable NLSP and measure
and check their decay channel !

[Hamaguchi et al 04-06, Feng & Smith 04, Arvanitaki et al 05....]

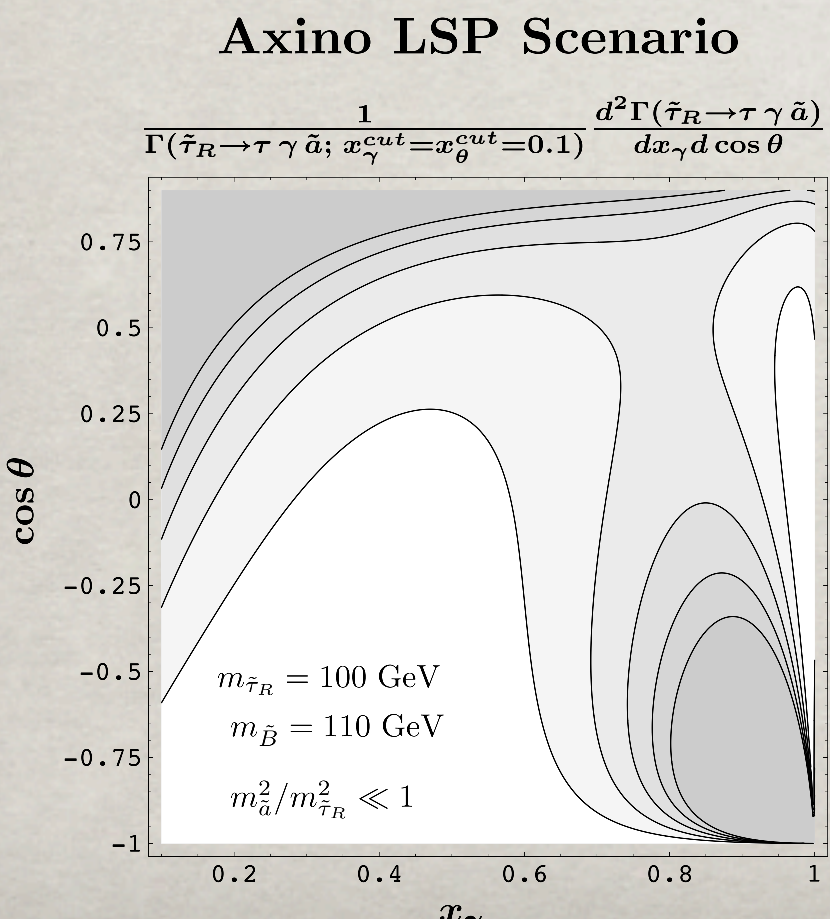
GRAVITINO VS AXINO LSP?

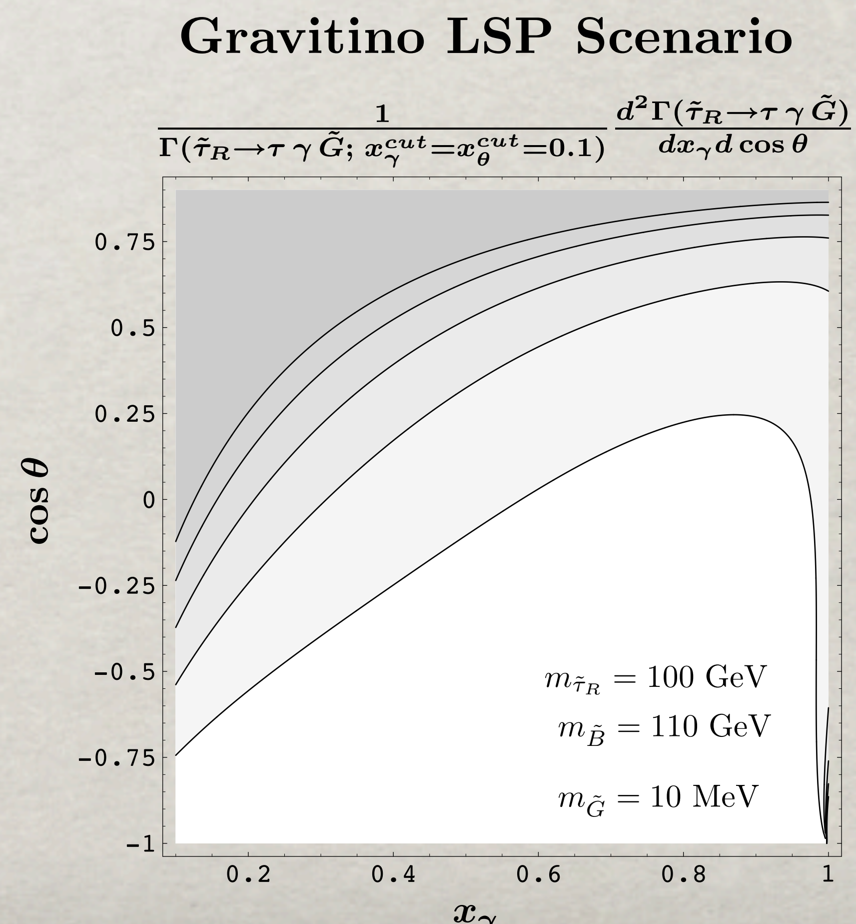
[Buchmuller et al 04, Brandenburg et al 05]



$$x_\gamma = \frac{E_\gamma}{2m_{\tilde{\tau}}}$$

Look at the angular distribution in the radiative decay and/or its branching ratio





Outlook

- The axino and the gravitino are good DM candidates, with similar properties. For both cases the reheat temperature is bounded and BBN constrains the lifetime and density of the NLSP.
- The bounds on neutralino NLSP in the gravitino case can be relaxed a bit in the general case, and allow to reach gravitino masses ~ 10 GeV
- 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 the parameters.
- Different signals are possible at the LHC: displaced vertices, missing energy or metastable charged particles

We could be very near to identify DM...