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GRAVITINO DARK MATTER

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In collaboration with: W. Buchmuller, M. Grefe, K. Hamaguchi, A. Ibarra, J. Kersten, JK Kim, HB Kim, S. Kraml, F. Palorini, L. Roszkowski, R. Ruiz-de Austri, K. Schmidt-Hoberg, F. Steffen, D. Tran, T. Yanagida...

OUTLINE

- Introduction: Dark Matter properties
  Why Supersymmetry ?
- Gravitino/axino DM production:
  - thermal scatterings
  - NLSP decay
- BBN constraints and NLSP:
  - CMSSM
  - gaugino mediation
- R-parity or not R-parity...:
  - gravitino decay at GLAST
  - signatures at colliders
- Outlook

Introduction: DARK MATTER Properties

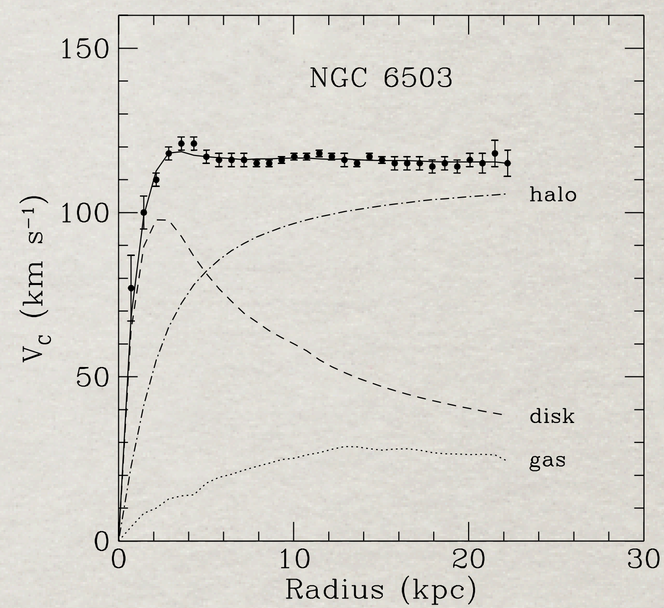
THE MATTER CONTENT

The clumpy energy density/matter divides into

Particles	$\Omega_i(t_{\text{now}})h^2$ (WMAP)	Type
Baryons	0.0224	Cold
Massive ν	$6.5 \times 10^{-4} - 0.01$	Hot
???	$\sim 0.1 - 0.13$	COLD

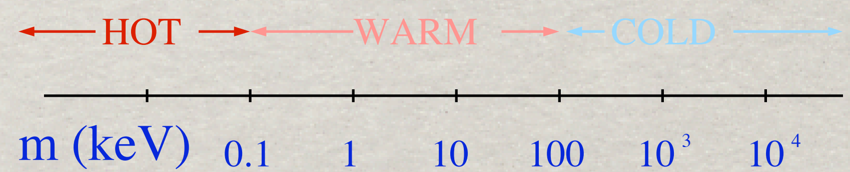
DARK matter !

[Begeman, Broeils & Sanders '91]



Note: DM first discovered in 1933 by F. Zwicki from the rotational curve of the COMA cluster...

Structure formation requires COLD Dark Matter, otherwise the structure formation on scales smaller than its free-streaming length at t_{eq} is suppressed.

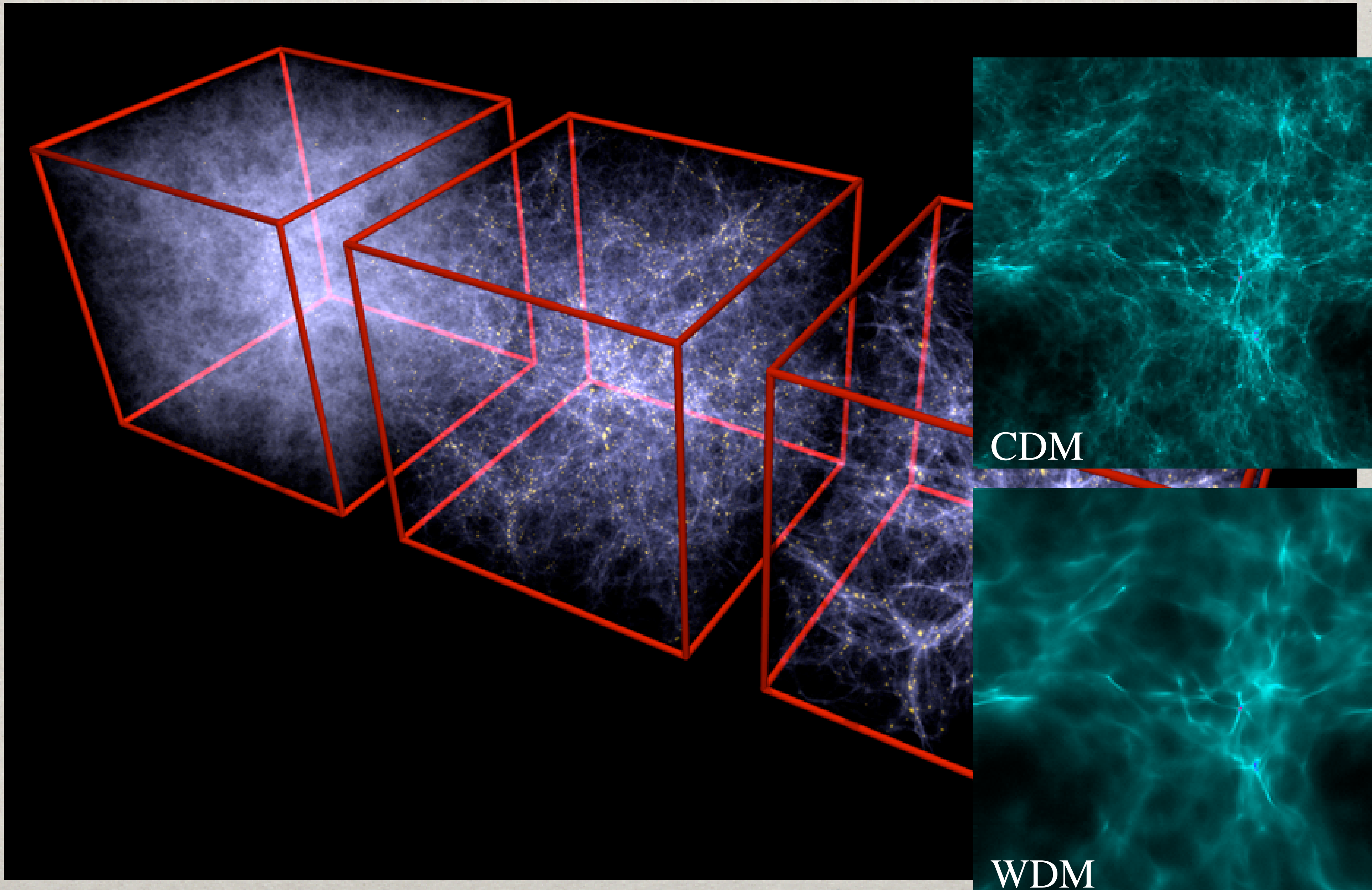


NEED to produce after inflation a large number of particles sufficiently massive, stable and neutral !

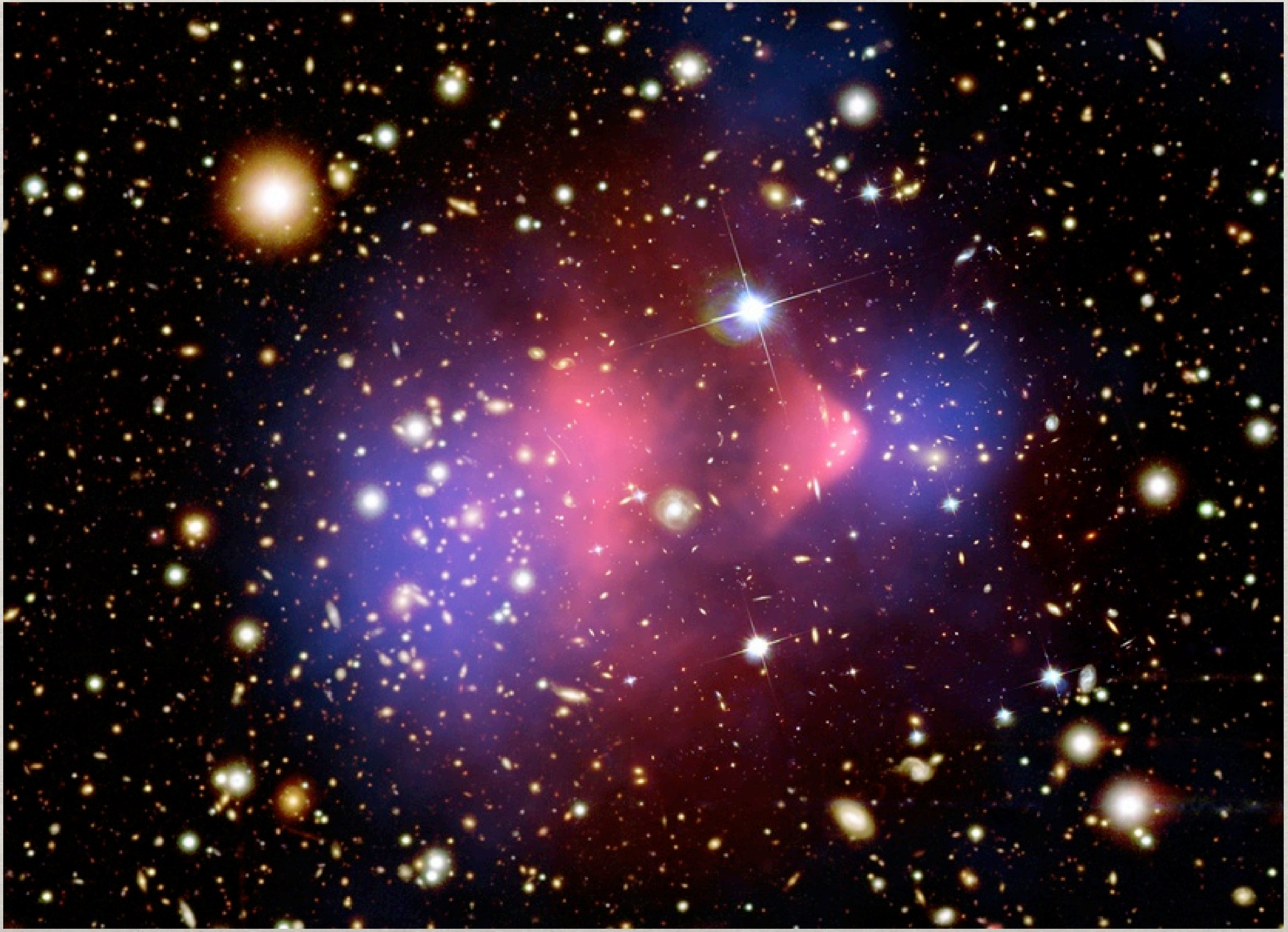
Structure Formation

V. Springel @MPA Munich

Yoshida et al 03



Nowadays even more impressive evidence...:
strong gravitational lensing SEES DM,
e.g. in the BULLET CLUSTER 1E 0657-56



WHY SUPERSYMMETRY ?

- Theoretically attractive: gives gauge unification, solves hierarchy problem, etc...
- Provides a coherent framework to study different signal at colliders & DM experiments
- Has a "small" number of parameters in the minimal setting apart from the SM ones...
- R-parity conservation provides a stable DM particle, but it is not strictly necessary...

DARK MATTER
SUSY Candidates

An infinite list...: any new neutral massive particle would do.
But most promising those predicted by minimal extensions...

- neutralino, superpartner of the photon/Z/Higgs √
- sneutrino, superpartner of the neutrino x
- gravitino, superpartner of the graviton √
- axino, superpartner of the axion √
- singlino, superpartner of the NMSSM singlet √
- modulino, superpartner of the moduli.... √
- ...

Too many ???

Perhaps, but as theorists we can see it as a challenge: which particle is the LSP depends strongly on the SUSY breaking and trasmission mechanisms...
If we can single out the LSP, we can already exclude many models and in general already the requirement of a neutral LSP is not trivial !

SUSY mediation	typical LSP
gauge/gaugino	gravitino
gravity	neutralino/slepton/gravitino
anomaly	slepton (tachyonic...)

We can exploit cosmology to constrain the SM extensions !

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

AXINO PROPERTIES instead:

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

Gravitino & Axino production

THE WIMP MECHANISM

Primordial abundance of stable massive species

[see e.g. Kolb & Turner '90]

The number density of a stable particle X in an expanding Universe is given by the Bolzmann equation

$$\frac{dn_X}{dt} + 3Hn_X = \langle \sigma(X + X \to \text{anything}) v \rangle \left(n_{eq}^2 - n_X^2 \right)$$

Hubble expansion   Collision integral

The particles stay in thermal equilibrium until the interactions are fast enough, then they freeze-out at $x_f = m_X/T_f$

defined by $n_{eq} \langle \sigma_A v \rangle_{x_f} = H(x_f)$ and that gives

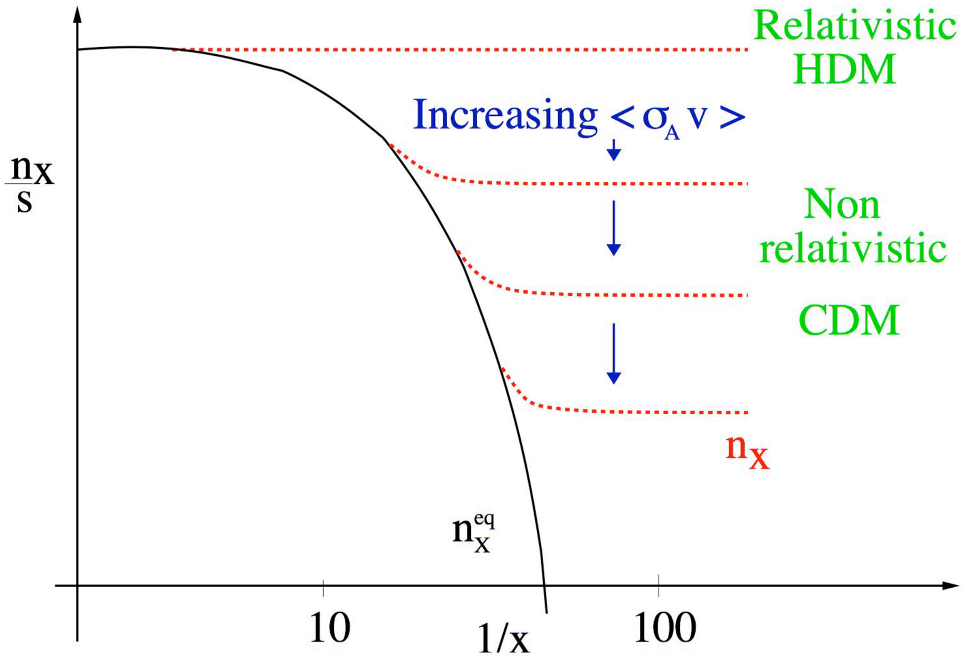
$$\Omega_X = m_X n_X(t_{now}) \quad \propto \quad \frac{1}{\langle \sigma_A v \rangle_{x_f}}$$

Abundance $\Leftrightarrow$ Particle properties

For $m_X \simeq 100$ GeV a WEAK cross-section is needed !

Weakly Interacting Massive Particle

For weaker interactions need lighter masses HOT DM !



CAN CDM BE MORE WEAKLY INTERACTING THAN A WIMP ?

Yes, if the Universe was never hot enough...,
require a reheat Temperature sufficiently low.

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

PLASMA SCATTERINGS

NLSP DECAY OUT OF EQUILIBRIUM

THERMAL PRODUCTION

THERMAL PRODUCTION: At high temperatures, the dominant contribution to the production come from 2-body scatterings with colored states, mediated by non-renormalizable operators:

- gravitino case: $$\Omega_{\tilde{G}}^{TH} h^2 \simeq 0.2 \left(\frac{100\text{GeV}}{m_{\tilde{G}}} \right) \left(\frac{m_{\tilde{g}}}{1\text{TeV}} \right)^2 \left(\frac{T_R}{10^{10}\text{GeV}} \right)$$

[Bolz, Brandenburg & Buchmüller '01]

- axino case: $$\Omega_{\tilde{a}}^{TH} h^2 \simeq 0.6 \left(\frac{m_{\tilde{a}}}{0.1\text{GeV}} \right) \left(\frac{10^{11}\text{GeV}}{f_a} \right)^2 \left(\frac{T_R}{10^4\text{GeV}} \right)$$

[LC, HB KIm, JE Kim & Roszkowski '01, Brandenburg & Steffen '04]

NOTE the completely different dependence on the "X"WIMP mass !!! It is due to the fact that the gravitino is produced via its Goldstino component, whose couplings are enhanced by the ratio $\frac{m_{\tilde{g}}}{m_{\tilde{G}}}$!

Technical point: Hard Thermal loop resummation needed to regularize the gluon IR divergences.

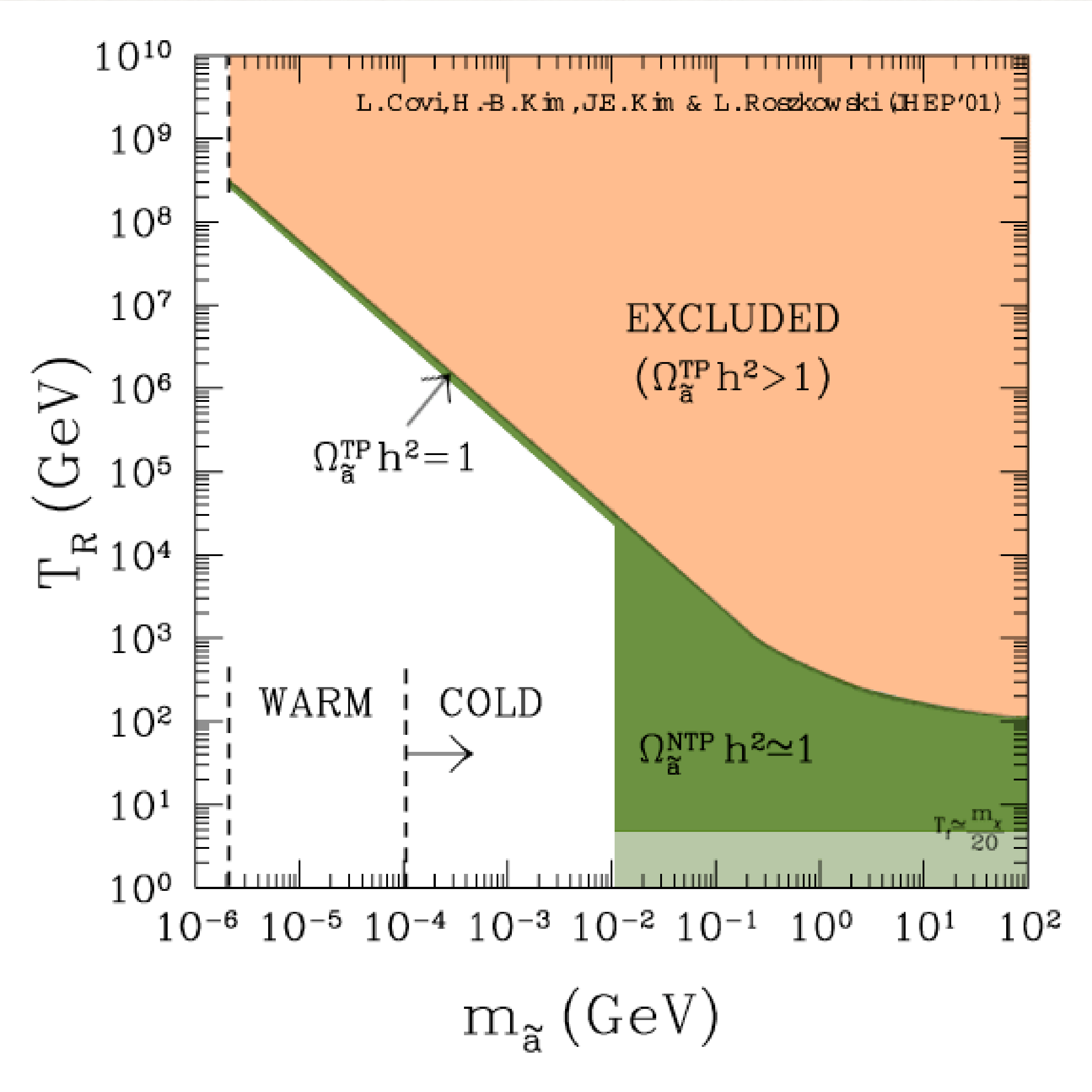
For contributions from other gauge groups, top Yukawa and thermal corrections see the recent papers [Pradler & Steffen 06, Rychov & Strumia 07].

Non thermal production via inflaton decay neglected here...

In general UPPER BOUND on the REHEAT TEMPERATURE !

Special T_{RH} needed to have the observed DM density.

UPPER BOUND ON T_R



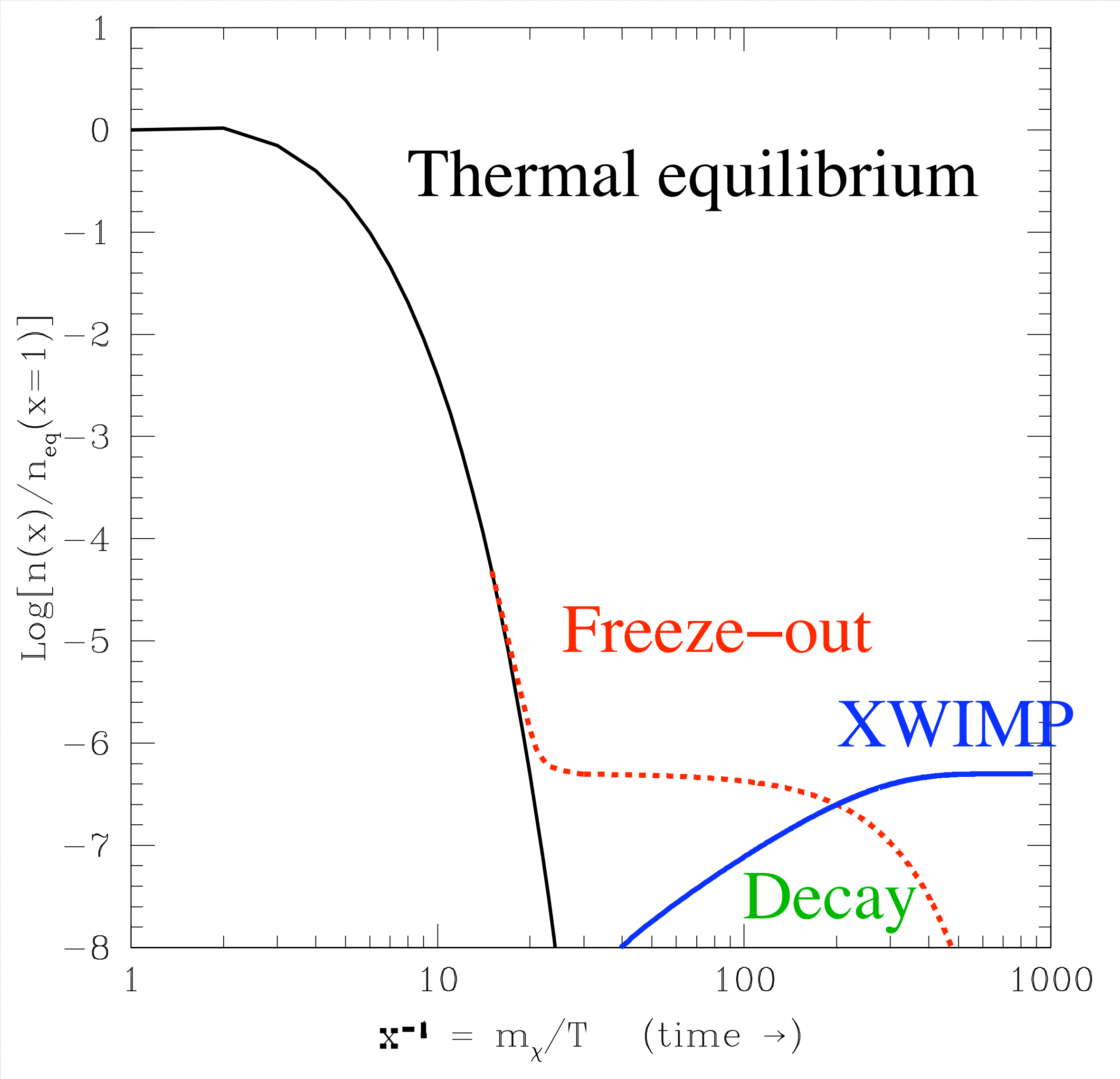
NLSP DECAY

[JE Kim, Masiero, Nanopoulos '84]
[LC, JE Kim, Roszkowski '99], [Feng et al '04]

- For long lifetime the NLSP decays after freeze-out and R-parity is conserved

$$\Omega_X^{NT} = \frac{m_X}{m_{NLSP}} \Omega_{NLSP}$$

- The LSP is not thermal
- Other energetic particles are produced in the decay: beware of BBN...



THE TROUBLE OF LATE DECAYING PARTICLES...

- Moduli problem (if they dominate before decay)

- BBN disruption if very energetic hadronic or electromagnetic particles are released after 1 s

- CMB distortion if energetic photons are released after 10000 s or so

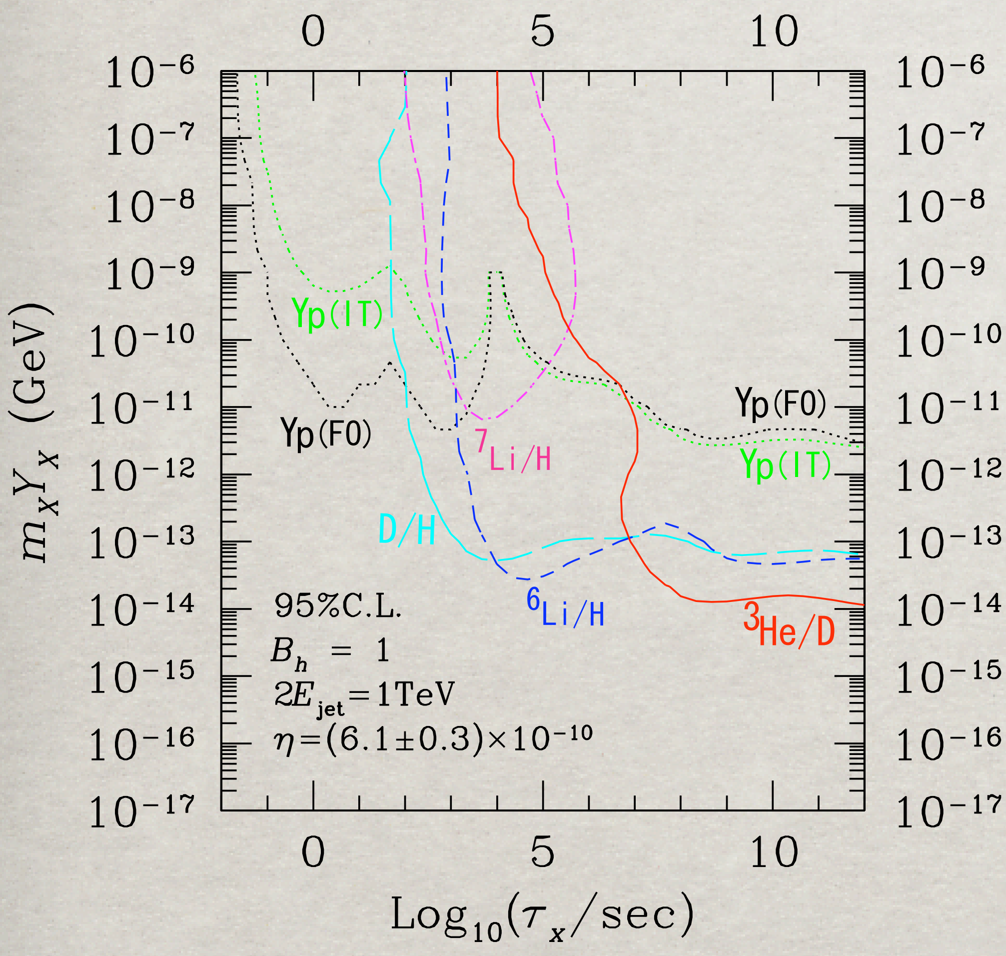
- COLD or WARM ? The decaying particles do not have thermal spectrum and have larger velocities then thermal relics...

BBN constraints and the NLSP

BBN bounds on NLSP decay

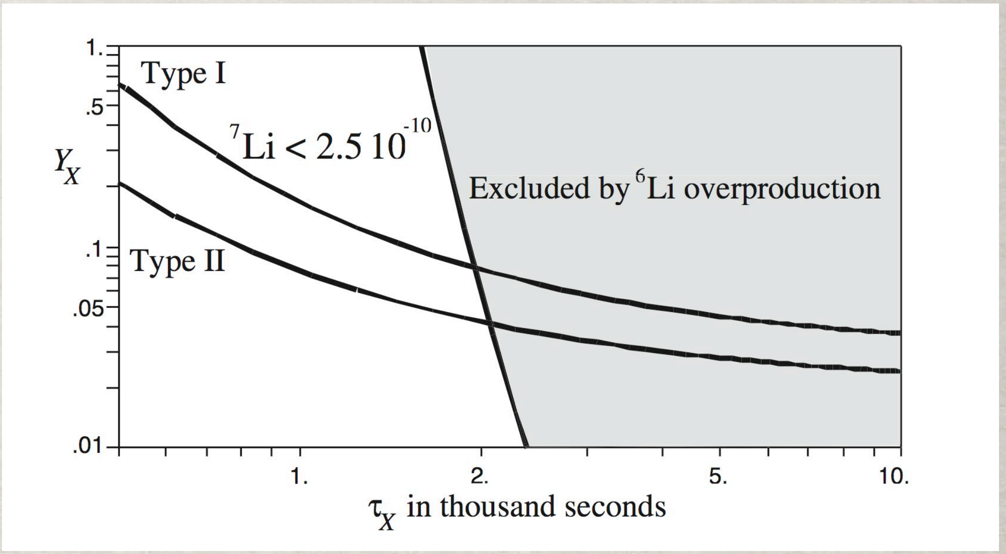
Neutral relics

[...,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 problem for gravitino LSP, not so much for the axino...

HOW TO EVADE BOUNDS

- Make the lifetime shorter:
  heavy(er) NLSP or light(er) gravitino LSP

  $$\tau_{NLSP} \sim 10^5 s \left(\frac{m_{NLSP}}{200GeV}\right)^{-5} \left(\frac{m_{3/2}}{10GeV}\right)^2$$

  axino LSP

  $$\tau_{NLSP} \sim 1s \left(\frac{m_{NLSP}}{200GeV}\right)^{-3} \left(\frac{f_a}{10^{11}GeV}\right)^2$$

  violate R-parity

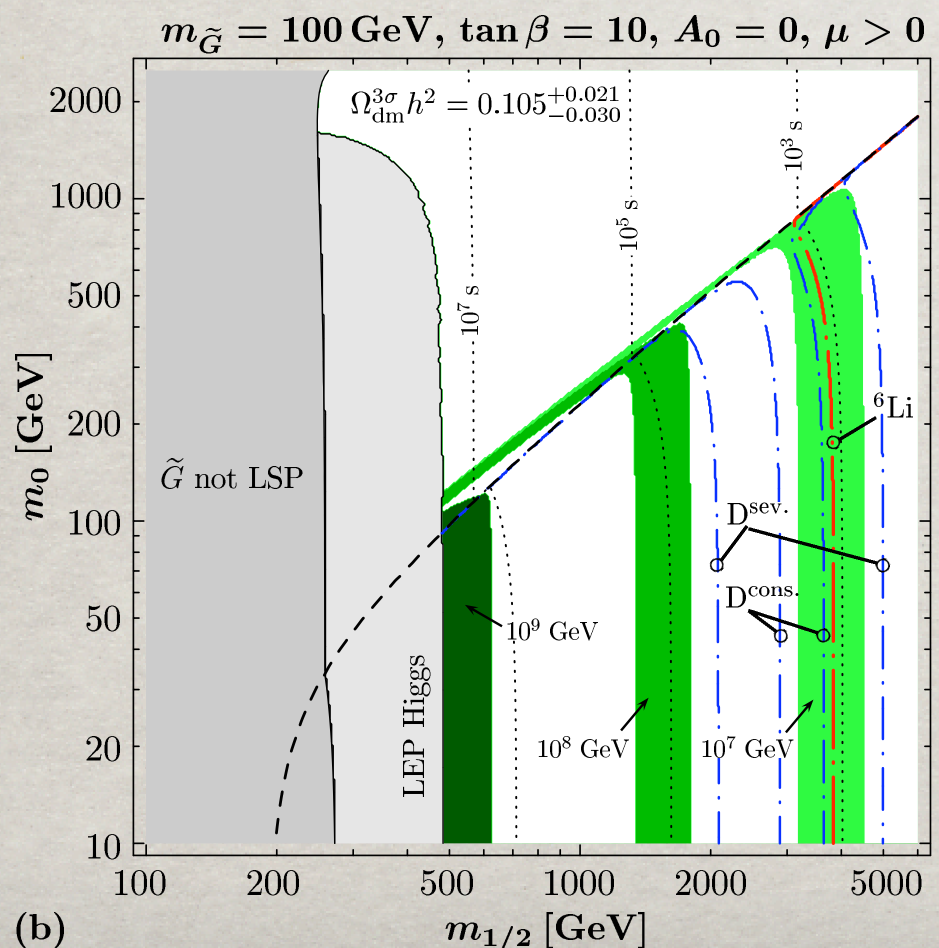
- Choose a harmless NLSP:
  sneutrino LH or RH (weaker bounds...) [LC, S. Kraml 07]
  stop (low abundance and annihilation at QCD transition)
  [Diaz-Cruz, Ellis, Olive & Santoso et al. 07]

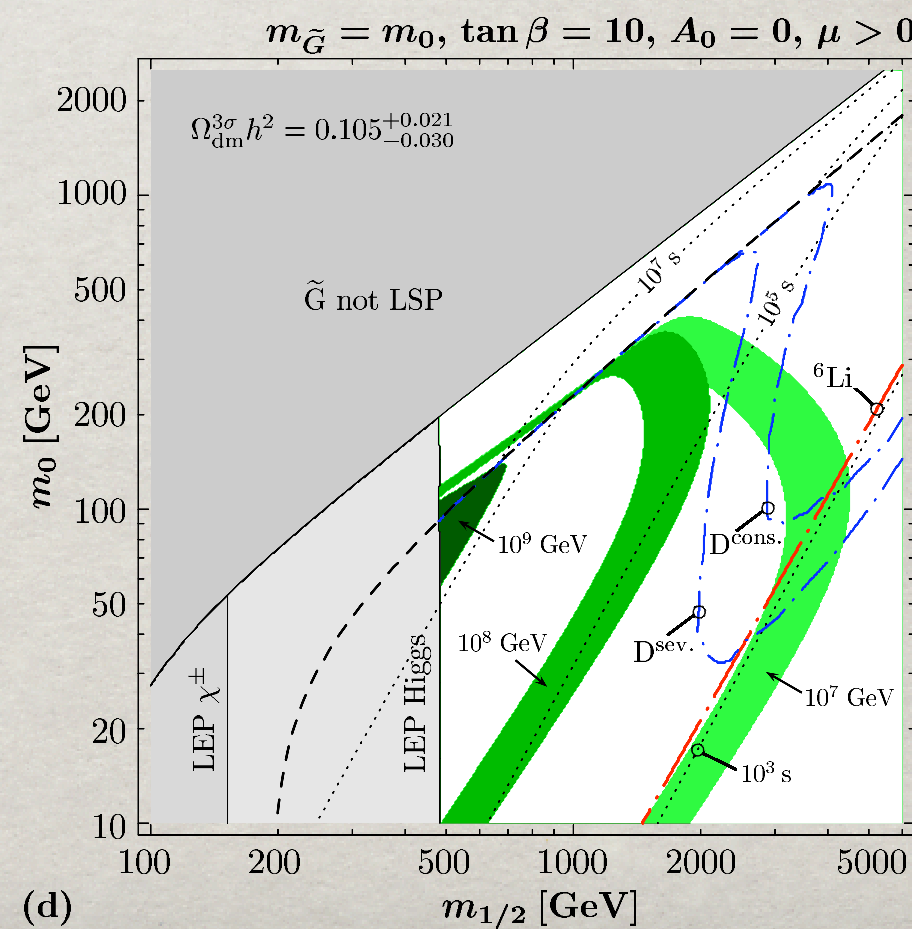
- dilute the NLSP abundance with entropy production
  [Buchmuller et al 05, Hamaguchi et al 07...]

Gravitino DM in the CMSSM Difficult to see at LHC ?

Only the large stau mass region > 1 TeV is still allowed in the CMSSM for gravitino LSP...

[Pradler & Steffen '06]



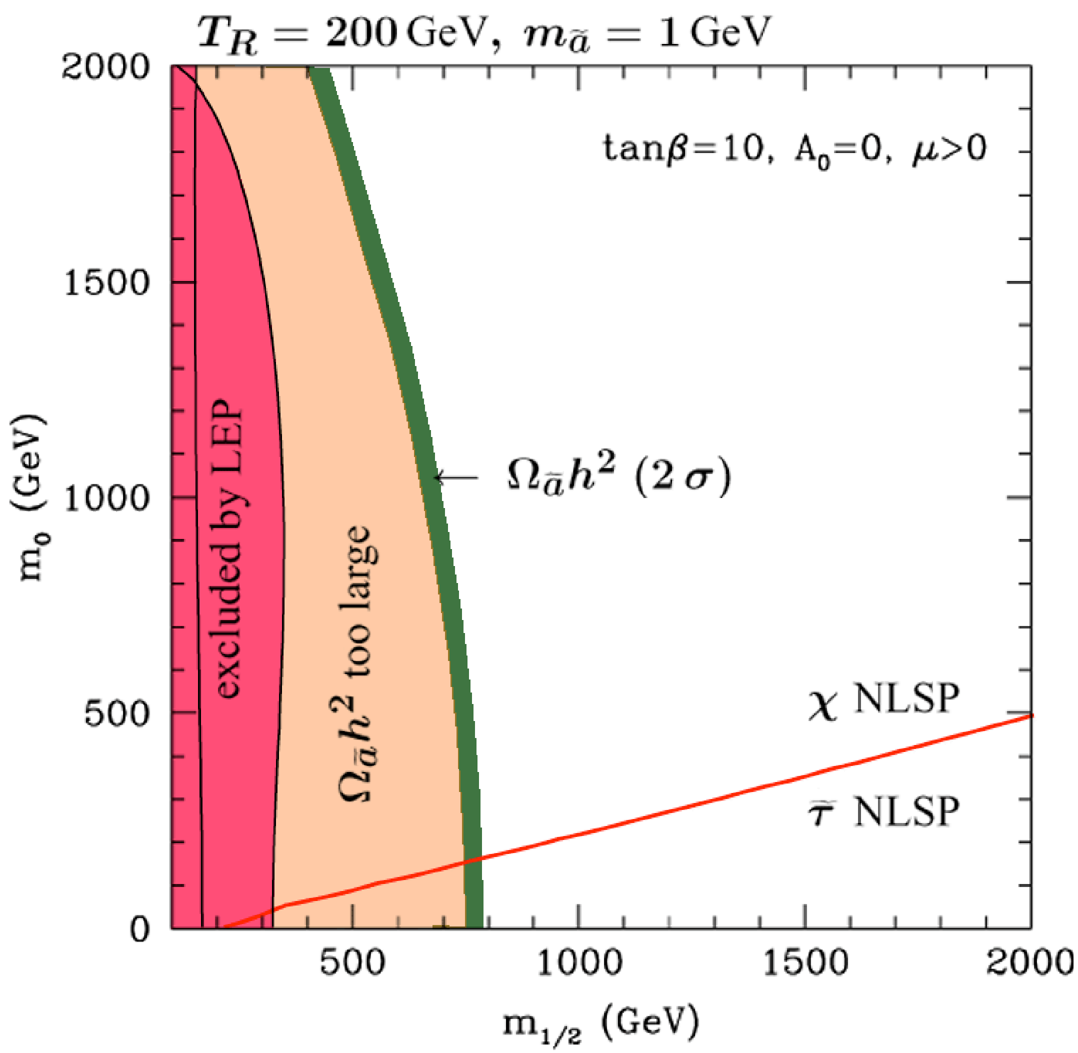


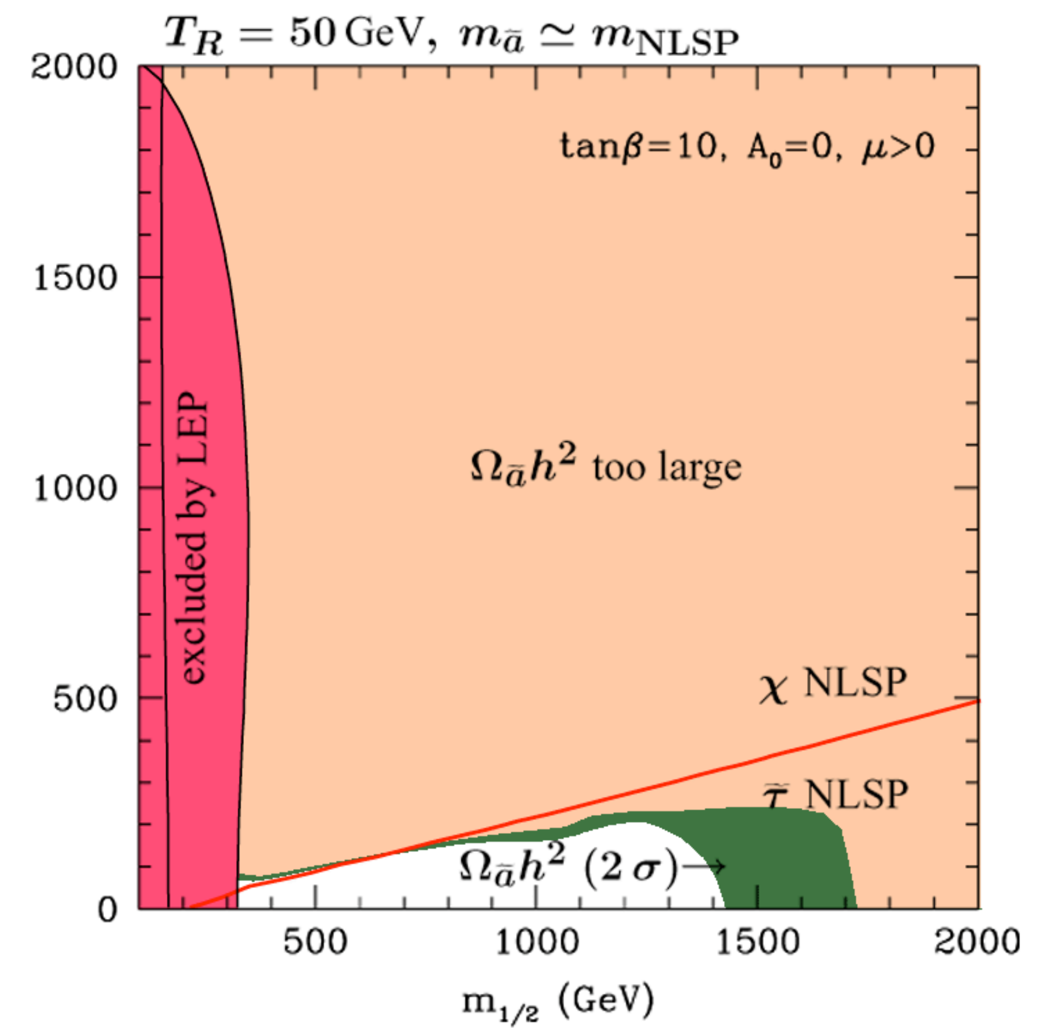
Axino and the CMSSM

[LC, Roszkowski, Ruiz de Austri & Small '04]

Thermal Production

NLSP decay





Another type of mediation:

GAUGINO MEDIATION

In extra dimensional models, SUSY breaking can take place away from the observable brane and be transmitted to the observable sector by the gauginos in the bulk or other bulk fields.

[Kaplan, Kribs & Schmaltz 99, Chacko, Luty, Nelson & Ponton 99]

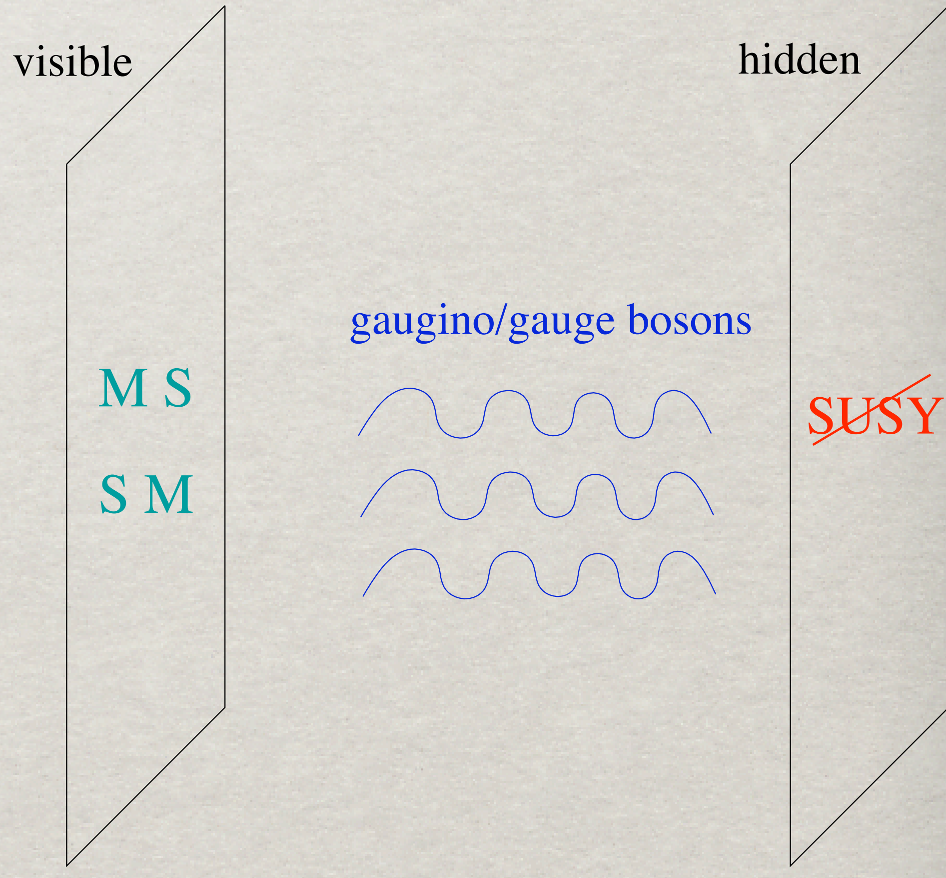
The gaugino and gravitino mass are given by the same SUSY breaking scale, but arise from different non-renormalizable operators

$$m_{1/2} = \frac{g_4^2 h F_S}{\Lambda} \qquad m_{3/2} = \frac{F_S}{\sqrt{3} M_P}$$

where $\Lambda < M_P$ is the cut-off of the extra-dimensional theory...

If the gaugino mass is not suppressed by the coupling, the gravitino can be naturally the lightest particle.

[Buchmüller, Hamaguchi & Kersten 05]

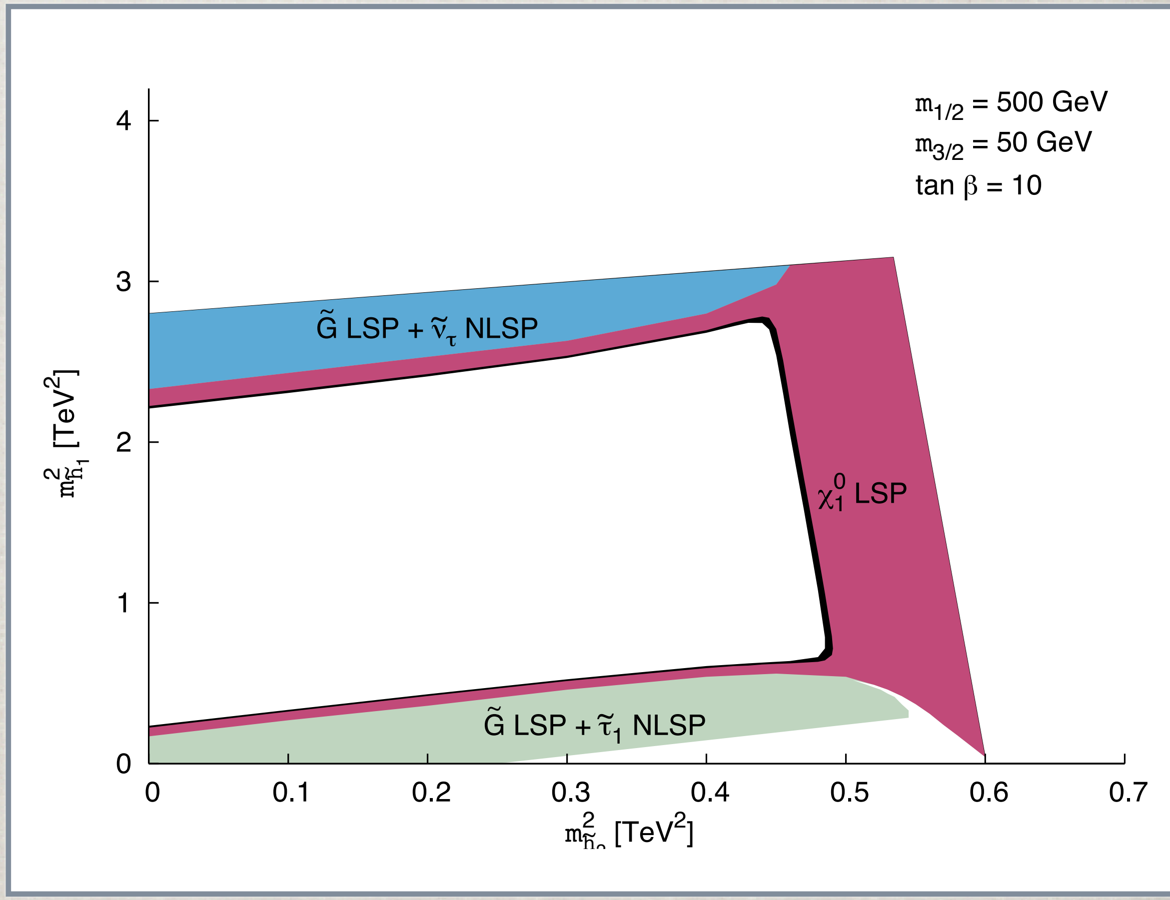


Different SUSY breaking masses for bulk/brane fields !

Gaugino mediation & DM

[Buchmuller, LC, Kersten & Schmidt-Hoberg]

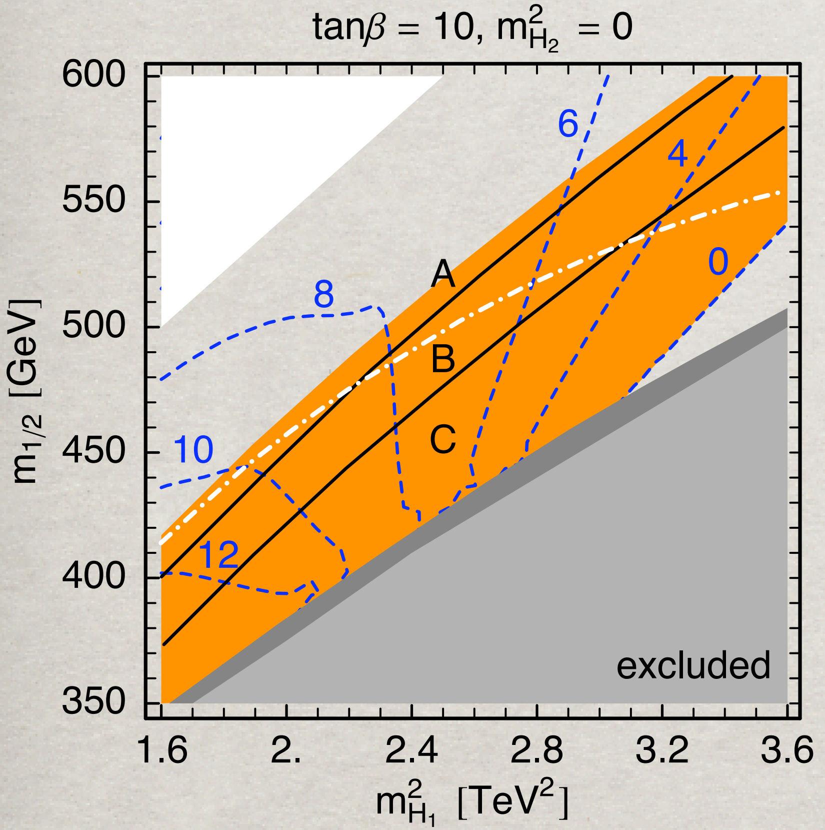
- Non Universal Higgs masses driving the RGE evolution
- Vanishing other scalar masses and trilinear couplings
- ONLY viable DM: neutralino LSP gravitino LSP with sneutrino NLSP



Stau NLSP region excluded by bound state constraints

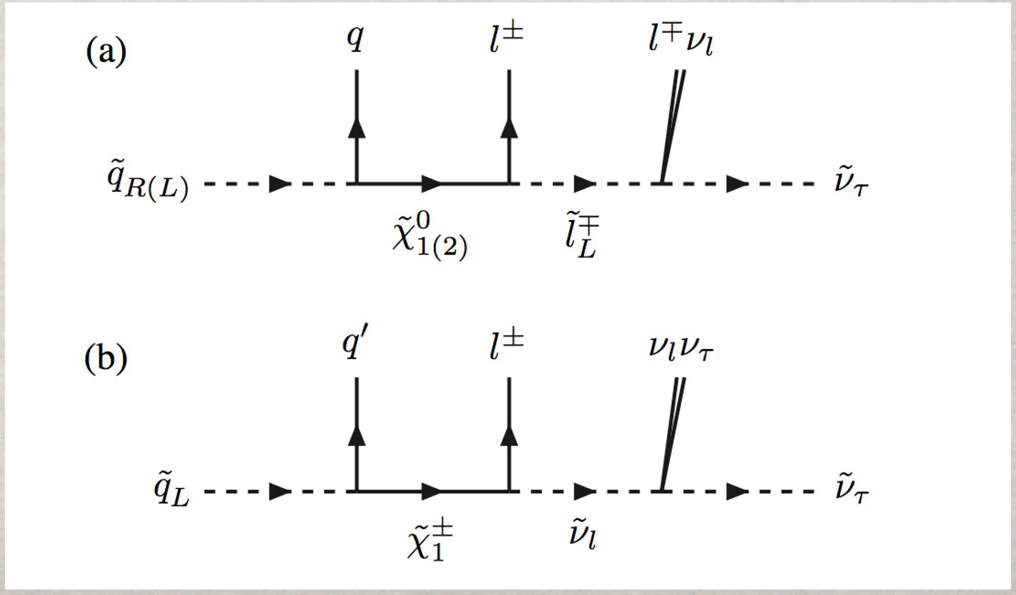
How to measure sneutrino NLSP in gaugino mediation

[LC & S. Kraml 07]



Very strong degeneracy in the spectrum between $\tilde{\nu}, \tilde{\tau}, \tilde{e}, \tilde{\chi}^0$

- NNLSP decays via 3-body
- Different decay chains
- Many soft leptons produced



ILC could allow also to study chargino decay and ISR in $e^- e^+ \rightarrow \tilde{\nu}\tilde{\nu}\gamma$

R-parity or not R-parity ?

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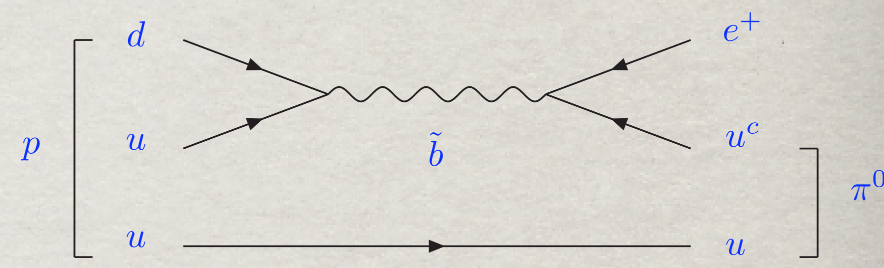
R-parity is imposed by hand in the MSSM in order to avoid fast proton decay due to renormalizable couplings explicitly violating B and L:



$$W = \lambda LLE^c + \lambda' LQD^c + \lambda'' U^c D^c D^c + \mu_i L_i H_2$$

$\Rightarrow$ Dimension 4 proton decay operators $\propto \frac{\lambda' \lambda''}{m_{\tilde{q}}^2}$

R-parity = $(-1)^{3B+L+2s}$ forbids these terms $\Rightarrow$ No dimension 4 proton decay (and LSP is stable)!

Proton decay can be avoided also if only B violating couplings λ'' are forbidden. So do we really need R-parity to have gravitino DM ? NO: the decay rate of the gravitino is doubly suppressed by M_P and the R-parity breaking couplings:

$$\tau_{3/2} \simeq 10^{26} s \left(\frac{\lambda^{(\prime)}}{10^{-7}} \right)^2 \left(\frac{m_{3/2}}{10\text{GeV}} \right)^{-3}$$

It is sufficient to have $\lambda, \lambda' < 10^{-7}$ for the gravitinos to live long enough. Such small value also gives sufficient suppression to L violating wash out processes and allows for leptogenesis. On the other hand, requiring the NLSP to decay before BBN just gives $\lambda, \lambda' > 10^{-14}$.

ANY NLSP is allowed if R-parity is broken and still we can have supersymmetric DM !

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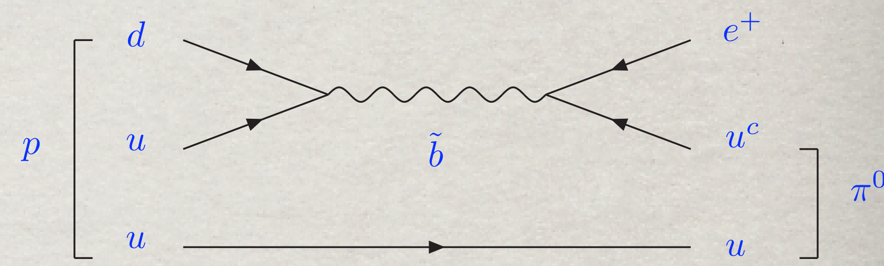

$$W = \lambda L L E^c + \lambda' L Q D^c + \lambda'' U^c D^c D^c + \mu_i L_i H_2$$

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$$\tau_{3/2} \simeq 10^{26} s \left(\frac{\lambda^{(')}}{10^{-7}}\right)^2 \left(\frac{m_{3/2}}{10\text{GeV}}\right)^{-3} \gg H_0^{-1} \sim 10^{17}\text{s}$$

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GRAVITINO CDM WITH R-parity VIOLATION

A SIMPLE MODEL with (suppressed) BROKEN R-PARITY

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

R-parity is usually not a fundamental symmetry of the MSSM completion. Our idea is to tie the R-parity breaking to the $B-L$ breaking: the v.e.v. of a single field Φ generates both the Majorana mass for RH neutrinos and bilinear R-parity breaking $\mu_i L_i H_u$:

$$W_{B-L} = X(NN^c - \Phi^2) + \frac{NNN_i^c N_j^c}{M_P} \quad \Rightarrow \quad \langle N \rangle = \langle N^c \rangle = \langle \Phi \rangle = v_{B-L}$$

$$\delta K_1 = \left[\frac{(a_i Z + a_i' Z^\dagger)\Phi^\dagger N^c}{M_P^3} + \frac{(c_i Z + c_i' Z^\dagger)\Phi N^\dagger}{M_P^3} \right] H_u L_i \quad \Rightarrow \quad \delta W_1 = \mu_i H_u L_i$$

Then we have

$$M_3 = \frac{v_{B-L}^2}{M_P} \qquad\qquad \mu_i \propto m_{3/2} \frac{v_{B-L}^2}{M_P^2}$$

The charge of Φ is such that the other R-parity breaking terms are generated only with higher powers of $\left(\frac{v_{B-L}}{M_P}\right)^{4+n}$ and are harmless.

	$\mathbf{16}_i$	H_u	H_d	N	N^c	Φ	X	Z
R	1	0	0	0	-2	-1	4	0

Effectively a model with bilinear R-parity violation, but with a coupling smaller than those usually discussed in the literature...

$$\Rightarrow \quad \epsilon_i = \frac{\mu_i}{\mu} \leq 10^{-7}$$

A SIMPLE MODEL with (suppressed) BROKEN R-PARITY II

[Takayama & Yamaguchi 00, Buchmüller *et al.* 07]

We have then a small R-parity breaking bilinear term governed by $\epsilon_i = \frac{\mu_i}{\mu} \leq 10^{-7}$.

Rotating away the bilinear, generates couplings $\lambda, \lambda' \simeq \epsilon_i Y_{\ell,d}$ at the required level to avoid BBN/leptogenesis bounds, while the contribution to the neutrino masses from the mixing with the neutralinos remains small:

$$m_\nu \simeq 10^{-4}\text{eV} \left(\frac{\epsilon_3}{10^{-7}}\right)\left(\frac{\tilde{m}}{200\text{ GeV}}\right)$$

The largest neutrino mass comes still from the seesaw mechanism.

Another consequence of neutrino-neutralino mixing: the gravitino can decay into neutrino and photon at tree-level with lifetime given by:

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

This lifetime is much longer than the age of the Universe, but nevertheless some of the gravitinos have already decayed or are decaying now $\rightarrow$ (redshifted) photon and neutrino line at $m_{3/2}/2$!

Diffuse photon/neutrino flux... Are we in the middle of a DM decay experiment ???

For larger gravitino masses also decay in Z/W and ν/e possible

[A. Ibarra & D. Tran 07]

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.

$$\tilde{G} \rightarrow \gamma\nu \qquad \tilde{G} \rightarrow \ell_L \bar{\ell}_L e_R \qquad \tilde{G} \rightarrow \ell_L \bar{q}_L d_R$$

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

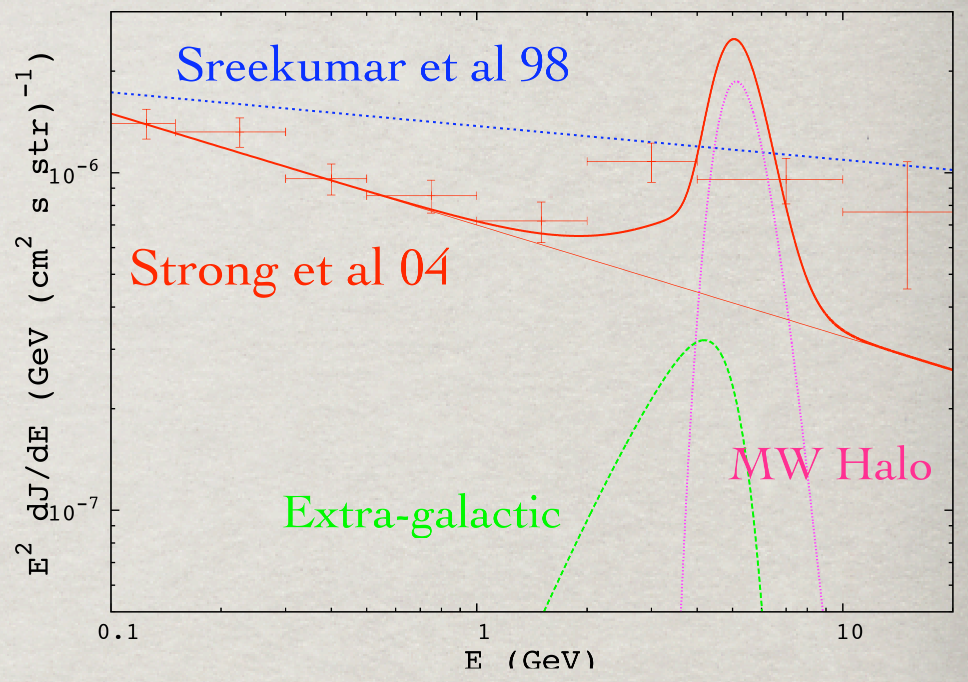
$$\tau_{\tilde{G}} = 4 \times 10^{27} s \left(\frac{U_{\tilde{\gamma}\nu}}{10^{-8}} \right)^2 \left(\frac{m_{\tilde{G}}}{10\mathrm{GeV}} \right)^{-3}$$

Recently [Lola, Osland & Raklev 07] computed also the 2-body one-loop decay and found it also important with respect to the 3-body one for most parameter space.

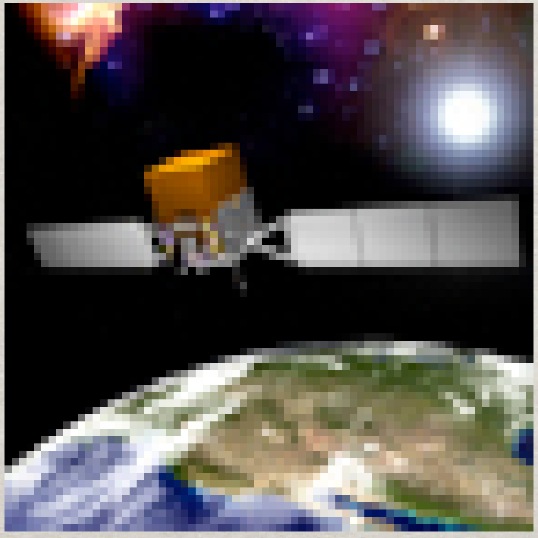
How to see the gravitino

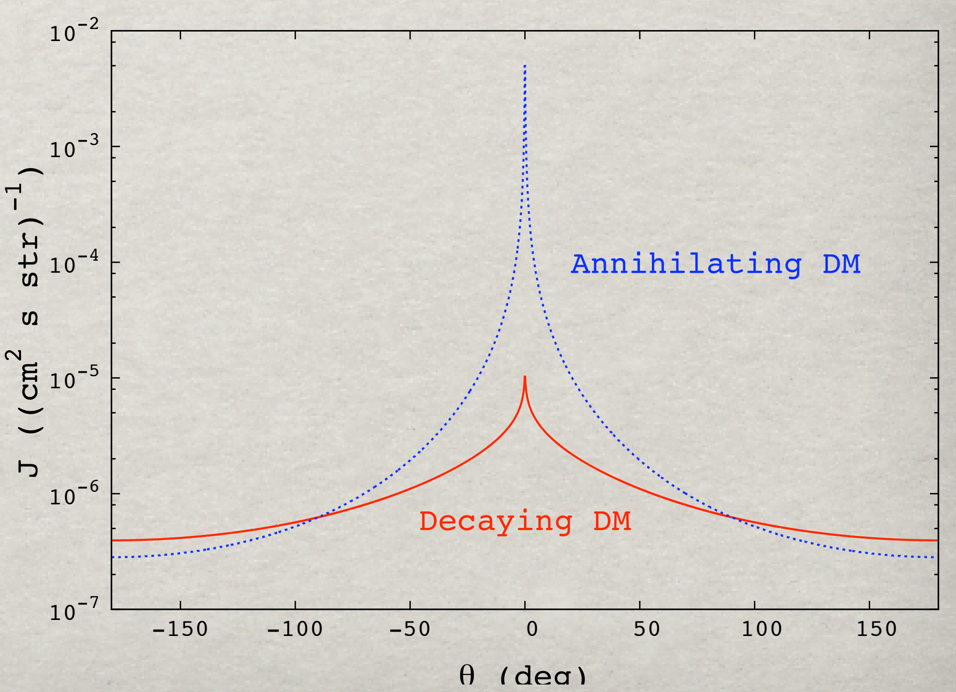
For bilinear R-parity breaking, the gravitino decays into photon and neutrino with flux:

$$J \sim 10^{-7}(\mathrm{cm}^2\mathrm{s\ str})^{-1}\left(\frac{\tau_{DM}}{10^{27}s}\right)^{-1}\left(\frac{m_{DM}}{10\mathrm{GeV}}\right)^{-1}$$



Look at the photons with GLAST





Bertone, Buchmuller, LC, Ibarra '07

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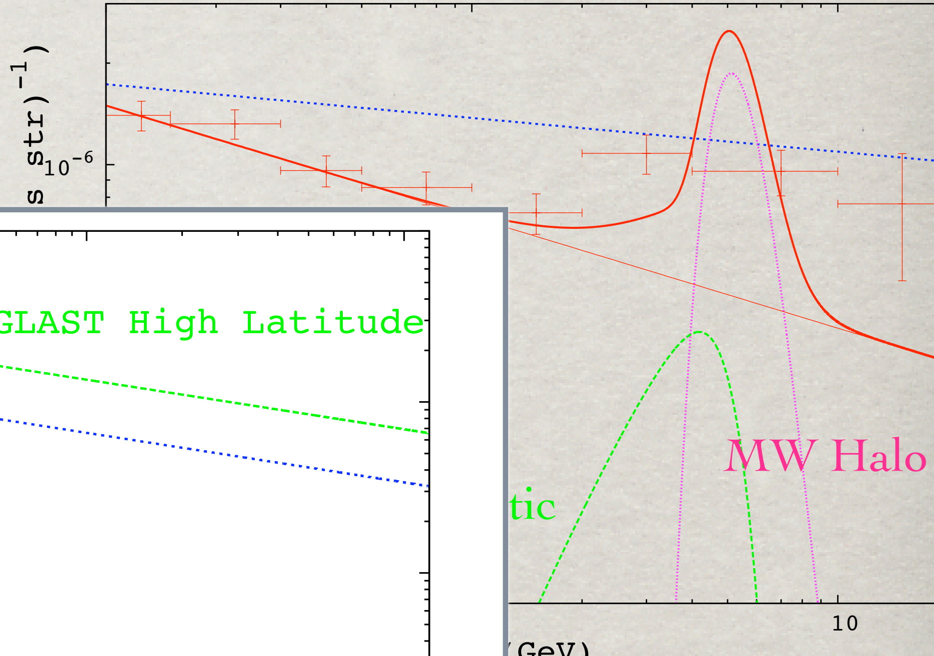
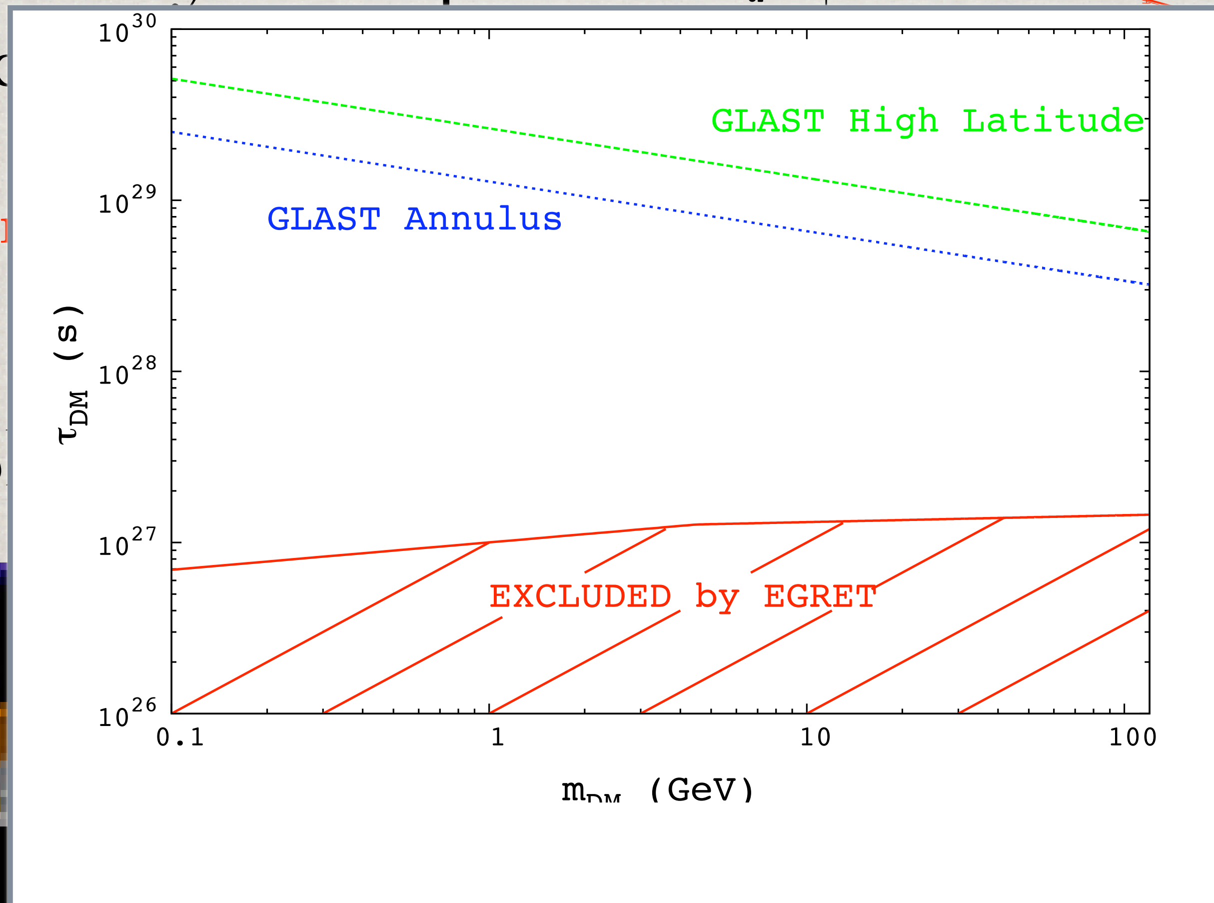
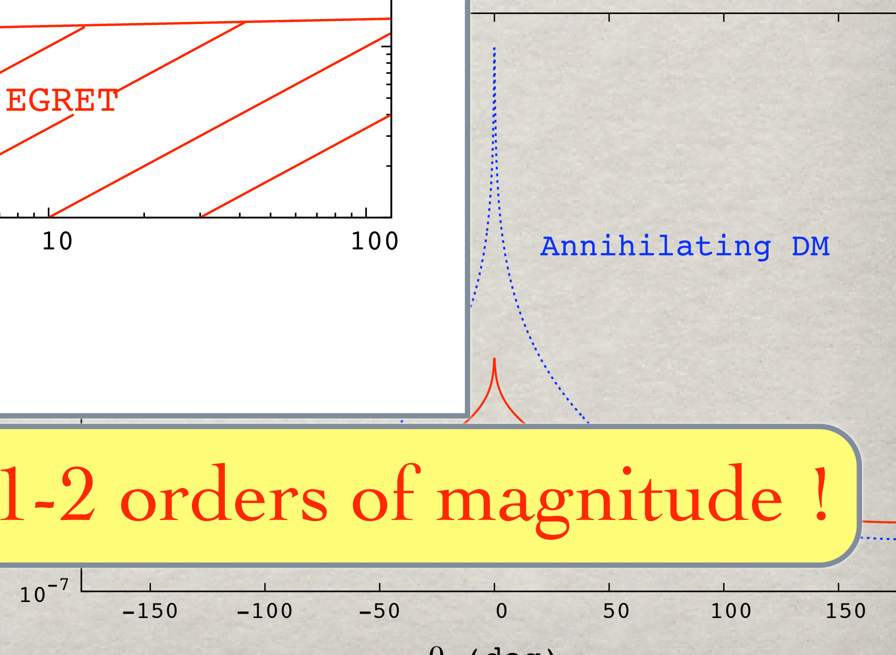
$J \sim 10^{-7}(\mathrm{cm}^2 \mathrm{s}\ \mathrm{st}$

Look at the p







GLAST can improve the limit by 1-2 orders of magnitude !

[Bertone,Buchmüller,LC &Ibarra]

Another chance: ν_τ

[LC, Grefe, Ibarra & Tran ...]

- The athmospheric neutrino flux at GeV energies is much larger than the photon flux, so it gives only much weaker bounds...
- BUT it does practically contain no ν_τ
- If the gravitino decay produces mainly or a substantial flux of ν_τ
- SK has measured some..., possibly some constraints also in that channel !

But this is not all...:

Clearer signal at colliders: metastable charged NLSP !

The typical signal is a (meta)stable charged particle that escapes the detector leaving a highly ionized track (a heavier μ...).

Very difficult to miss and it would immediately tell us that the neutralino is not the LSP and not DM.

Note that if R-parity breaking is "maximal", $\epsilon_i \sim 10^{-7}$, the NLSP will decay inside the detectors at LHC with $c\tau_{\tilde{\tau}} \sim 30$ cm and give a striking signal !

Unfortunately if the stau does not decay in the detector, it is not possible to identify which is the LSP and if it is stable. We need to measure the decay in order to check if R parity is conserved or not and which is the LSP. There are infact also more "X"WIMP candidates...

$$\tilde{\tau} \rightarrow \qquad \tau\psi_{3/2}, \tilde{a}, ... \qquad \text{R-parity conserved}$$

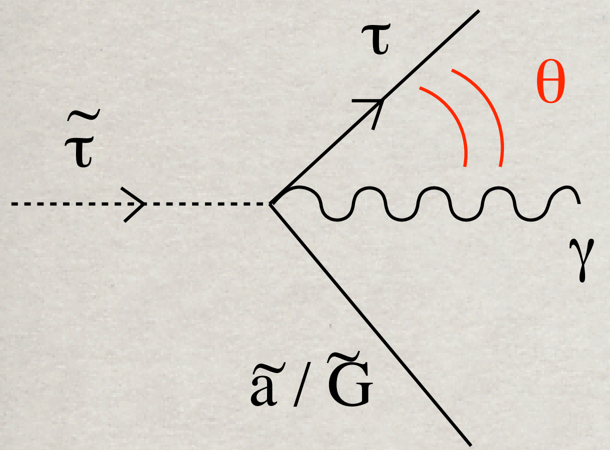
$$\tilde{\tau} \rightarrow \qquad \tau\nu_\mu, \mu\nu_\tau, 2\text{jets} \qquad \text{R-parity broken}$$

See e.g. [Hamaguchi, Kuno, Nakaya & Nojiri 04] , [Feng & Smith 04] ,[Hamaguchi, Nojiri & de Roeck 06] for proposals about stopping long-lived $\tilde{\tau}$ around the LHC/ILC.

Studying the NLSP decay can allow us to distinguish !

GRAVITINO VS AXINO LSP?

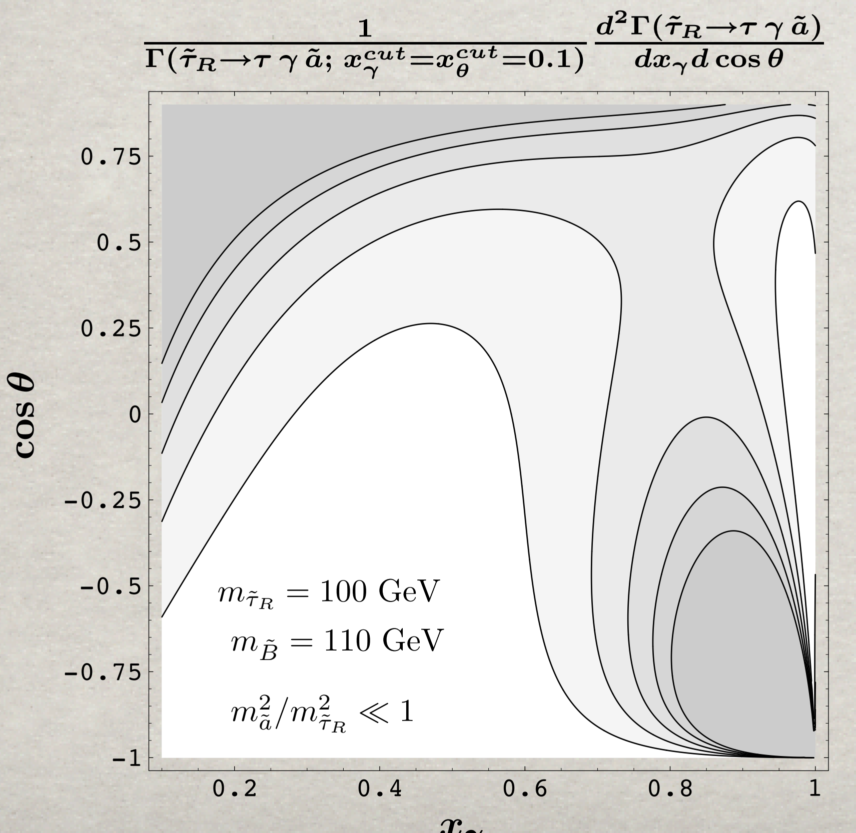
[Buchmuller et al 04, Brandenburg et al 05]



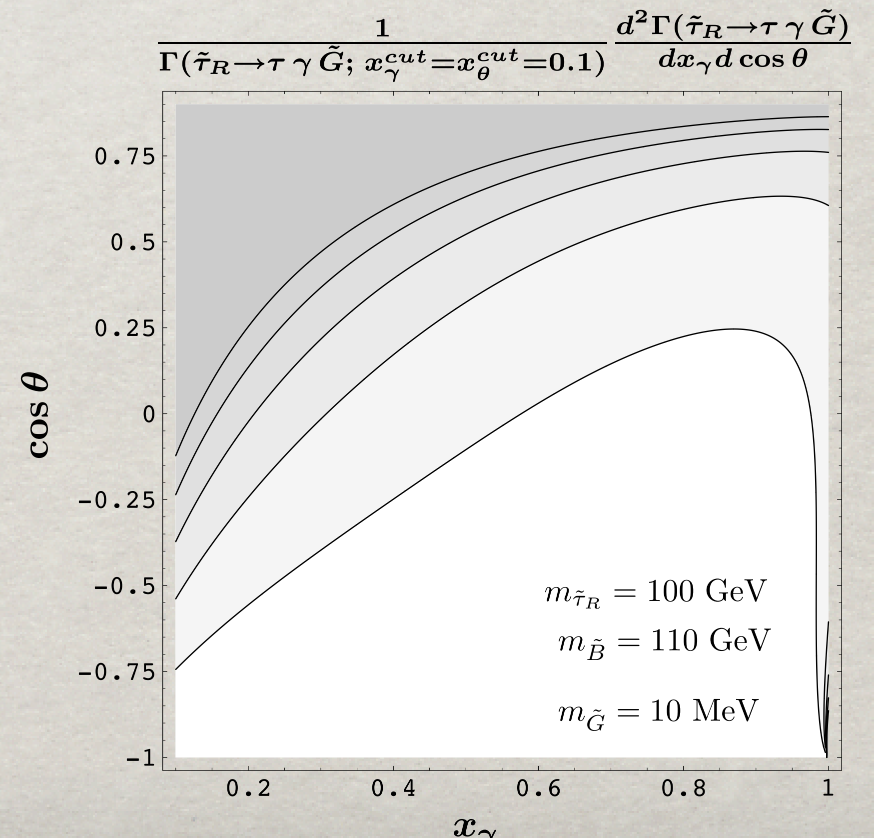
$$x_\gamma = \frac{E_\gamma}{2m_{\tilde{\tau}}}$$

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

Axino LSP Scenario



Gravitino LSP Scenario



Outlook

- Gravitino or axino DM is pretty natural if such particle is the LSP; probably substantial thermal production is needed to obtain the right abundance & avoid BBN bounds for the gravitino, i.e.

$$T_R \sim 10^{10}\mathrm{GeV}$$

- If the gravitino/axino is Dark Matter and R-parity is conserved, some signal is expected at colliders, both if the NLSP is charged or neutral...

- R-parity is not necessary to have gravitino DM. If R-parity is not too weakly broken, we could also see soon photons from DM decay.

- There is a good chance that we will know soon ! A very exciting time ahead !