Gravitino Dark Matter with broken R-parity

Alejandro Ibarra

DESY

In collaboration with

W. Buchmüller, L. Covi, K. Hamaguchi and T. Yanagida (JHEP 0703:037, 2007)

G . Bertone, W. Buchmüller, L. Covi (JCAP11(2007)003)

D. Tran (arXiv:0709.4593. To appear in PRL)

Bonn

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Outline

- Introduction: thermal history of the Universe.
- Supersymmetric dark matter. Constraints.
- Gravitino cosmology/Next-to-LSP cosmology.
- Gravitino dark matter with broken R-parity.
- A model for small R-parity breaking.
- Experimental signatures from gamma ray observatories and colliders
- Conclusions.

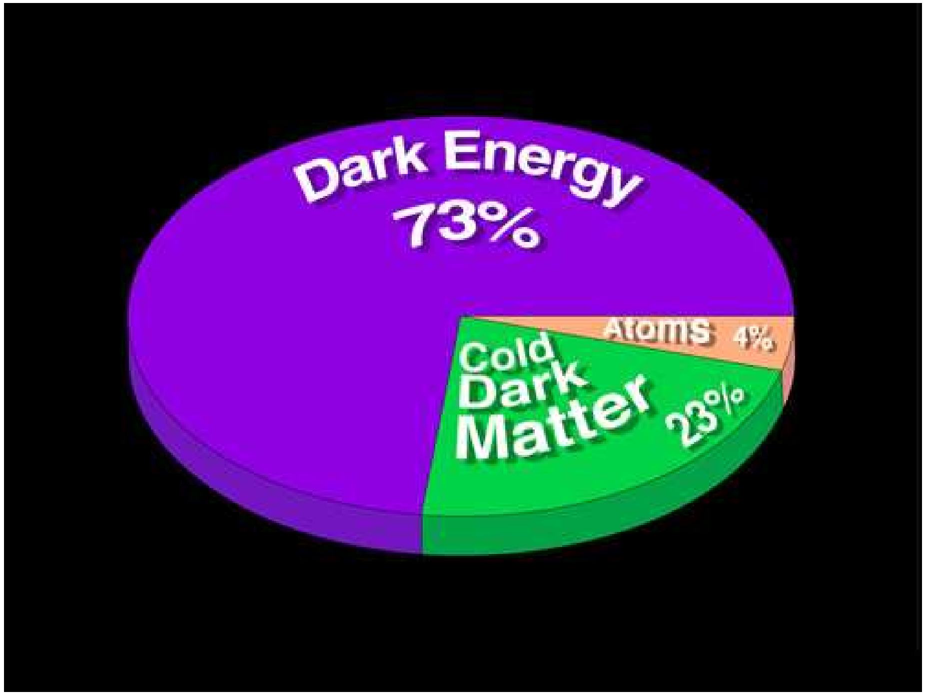
Introduction

"Standard" thermal history of the Universe

Temperature	time	
1eV	10^{13}s	decoupling of photons/CMB
1MeV	1s	decoupling of neutrinos
0.1MeV-10MeV	$10^{2}-10^{-2}$s	BBN
100MeV	10^{-4}s	QCD phase transition
100GeV	10^{-10}s	EW phase transition
$10^{9}-10^{10}$ GeV	$10^{-24}-10^{-26}$s	leptogenesis?
?	?	reheating
?	?	inflation
?	0	Big Bang

New elements have to be incorporated into the thermal history of the Universe:

- Dark matter
- Dark energy



Cosmic pie determined by WMAP

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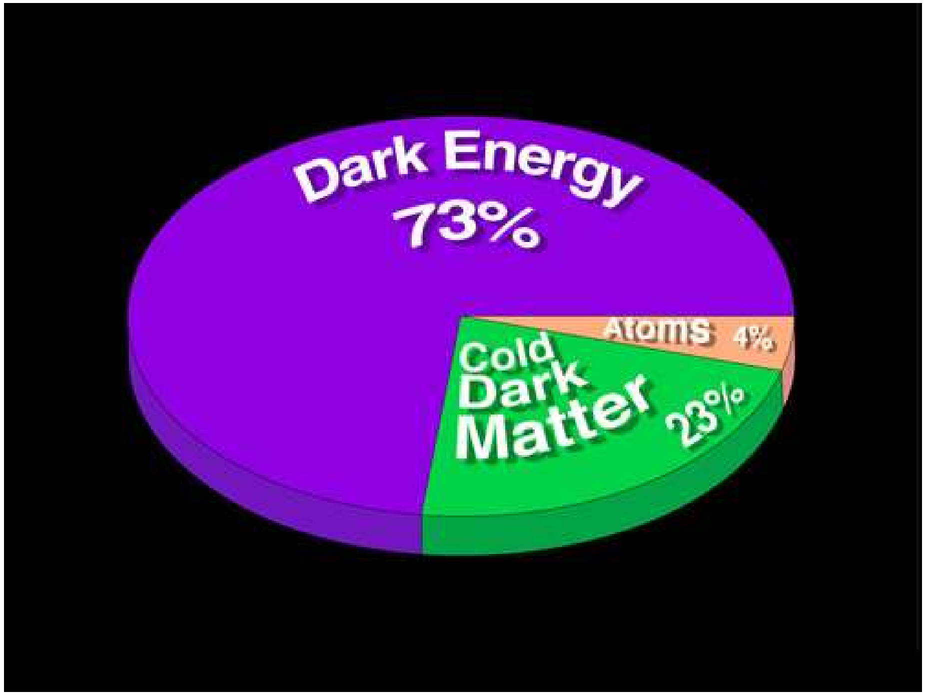

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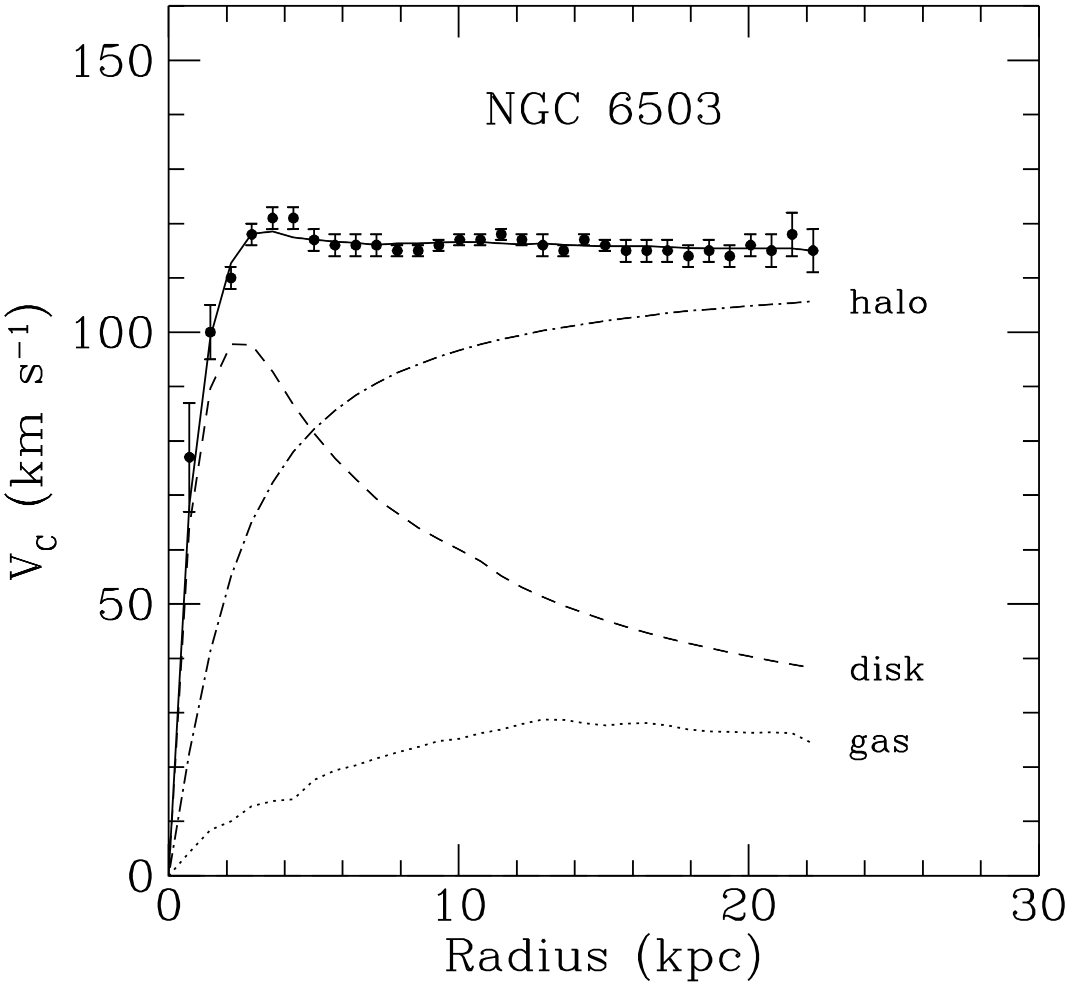
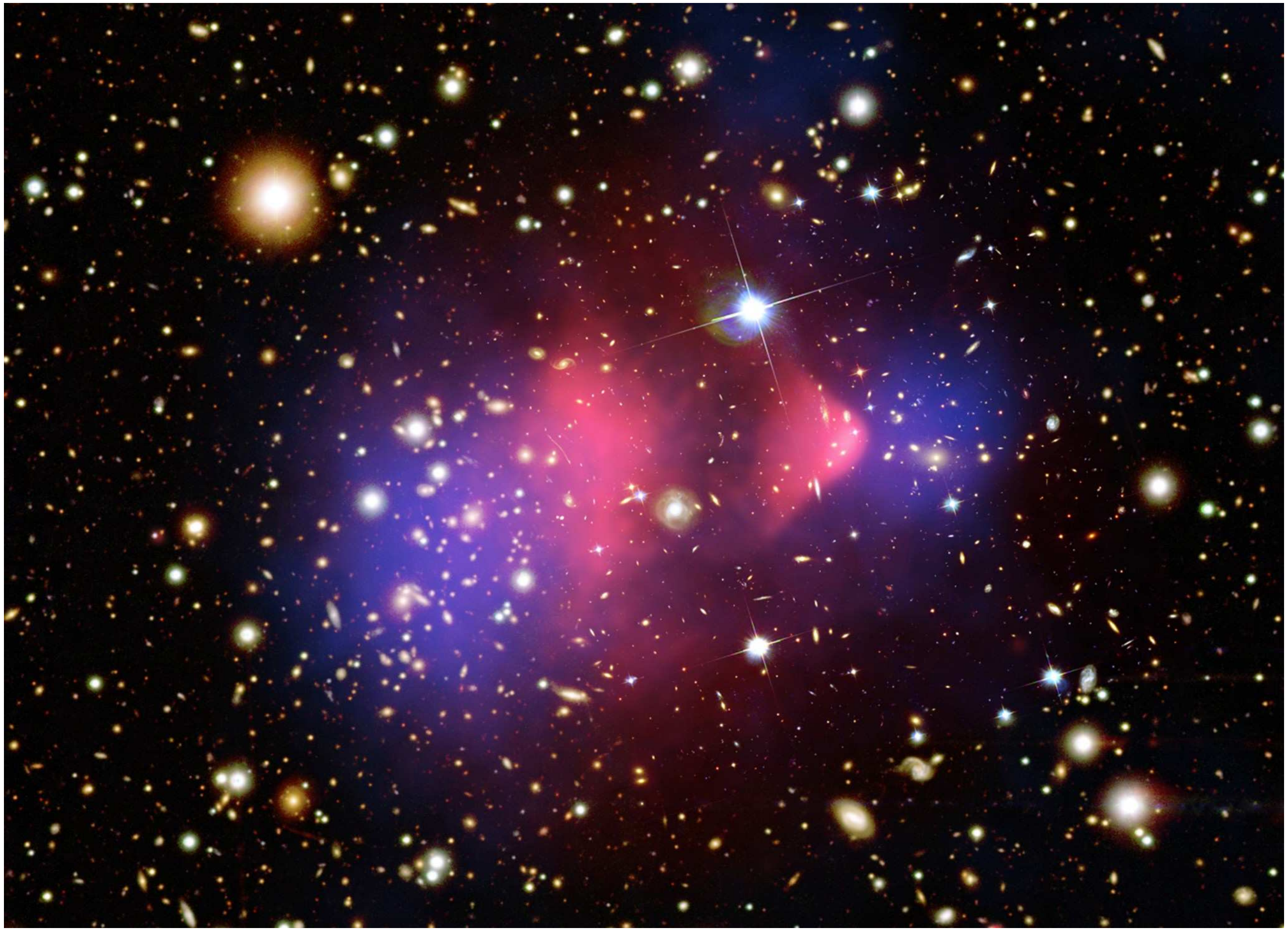
More evidences for dark matter





Clowe et al.
astro-ph/0608407

Composite image from NASA of the Bullet Cluster (1E 0657-56). Superposition of an optical image by the Hubble Space Telescope, an X-ray image from Chandra (red), and a weak lensing map (blue). The X-ray image shows the distribution of hot gas (baryonic matter) and the weak lensing map, the distribution of matter. There is more matter apart from the baryonic matter $\Longrightarrow$ direct evidence for dark matter?

Candidates for dark matter

Many! Some interesting candidates are:

- Massive SM neutrinos (now excluded)
- Axions
- Heavy sterile neutrinos

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Goal: construct a consistent thermal history of a Universe with supersymmetric dark matter (neutralino/gravitino)

Constraints:

- leptogenesis ($T \gtrsim 10^9$GeV, $t \lesssim 10^{-24}$s)
- BBN ($T \sim 0.1 - 10$MeV, $t \sim 10^2 - 10^{-2}$s)
- CMB ($T \sim 1$eV, $t \sim 10^{13} s$)

And of course, the relic dark matter abundance should be the observed one $\Omega_{DM} \simeq 0.23$.

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Leptogenesis

Fukugita, Yanagida

After the discovery of neutrino oscillations, leptogenesis stands as one of the most appealing explanations for the observed baryon asymmetry of the Universe.

Simplest realization: the lightest right-handed neutrino decays out of equilibrium, producing a lepton asymmetry. Sphaleron processes partially convert the lepton asymmetry into a baryon asymmetry.

$$\eta_B = \frac{n_B}{n_\gamma} \simeq 0.01 \epsilon_1 \kappa_f$$

- $\epsilon_1 \equiv$ CP asymmetry

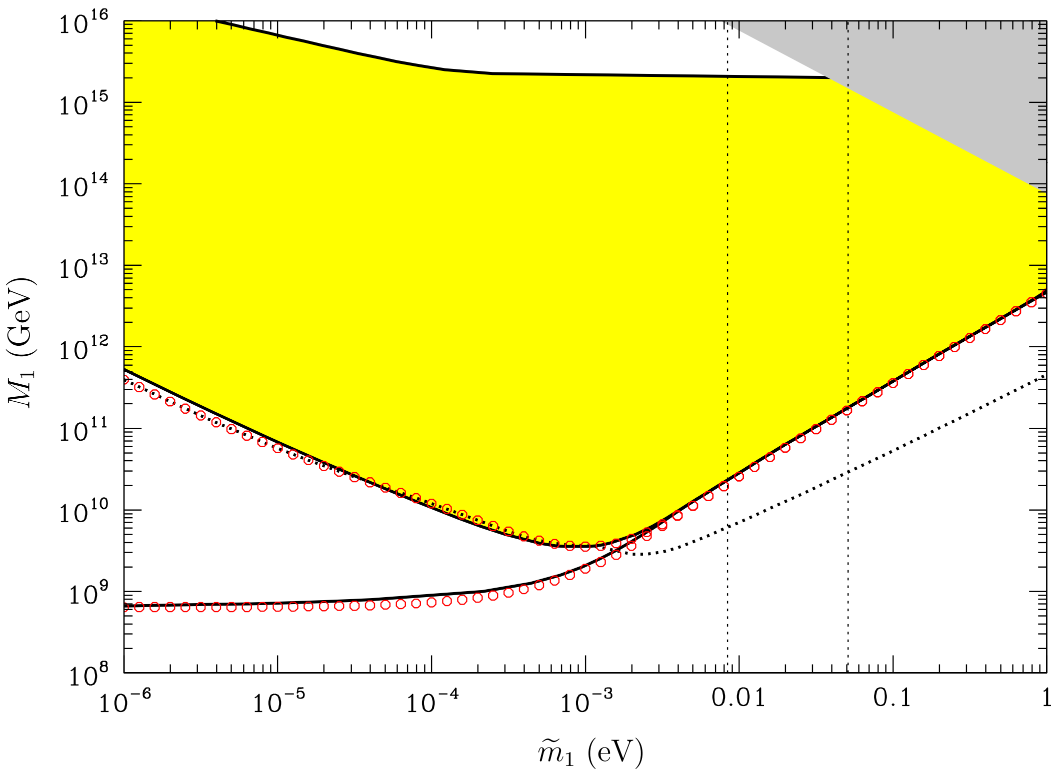
  $\epsilon_1 \leq \frac{3}{8\pi} \frac{M_1 m_3}{\langle H^0 \rangle^2}$ Davidson, A.I.

  $\Longrightarrow$ Lower bound on M_1

- $\kappa_f \equiv$ efficiency factor, that can be parametrized by

  $\widetilde{m}_1 = \frac{Y^\dagger Y}{M_1} \langle H^0 \rangle^2$

Buchmüller, di Bari, Plümacher



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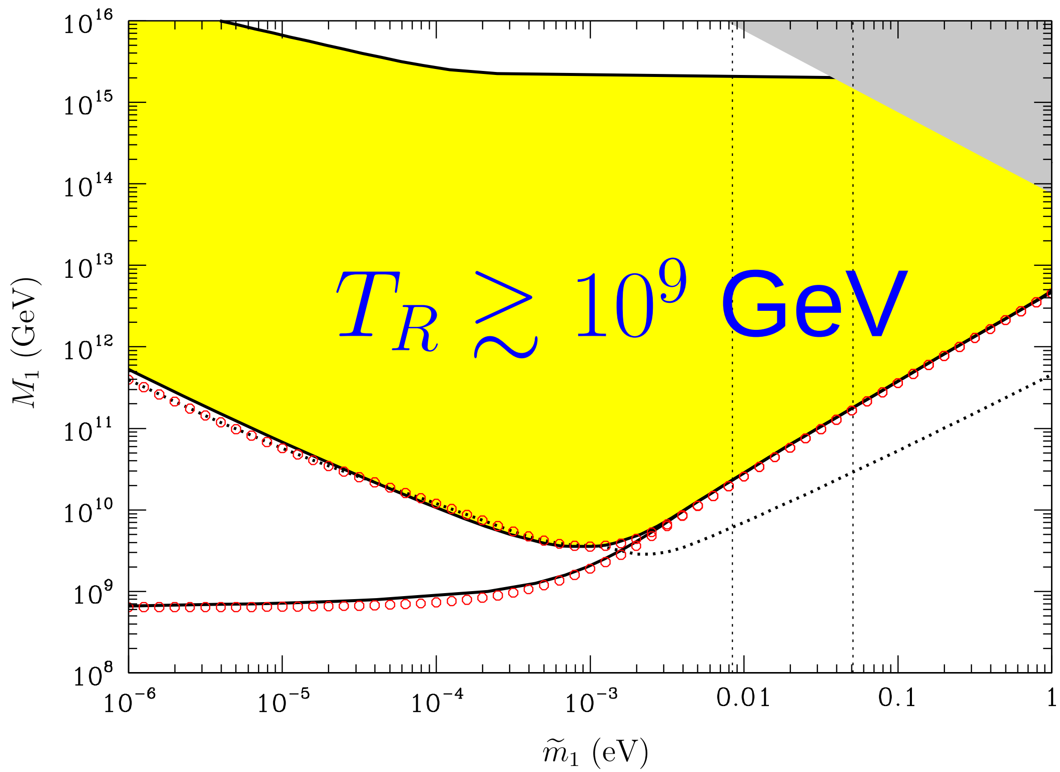
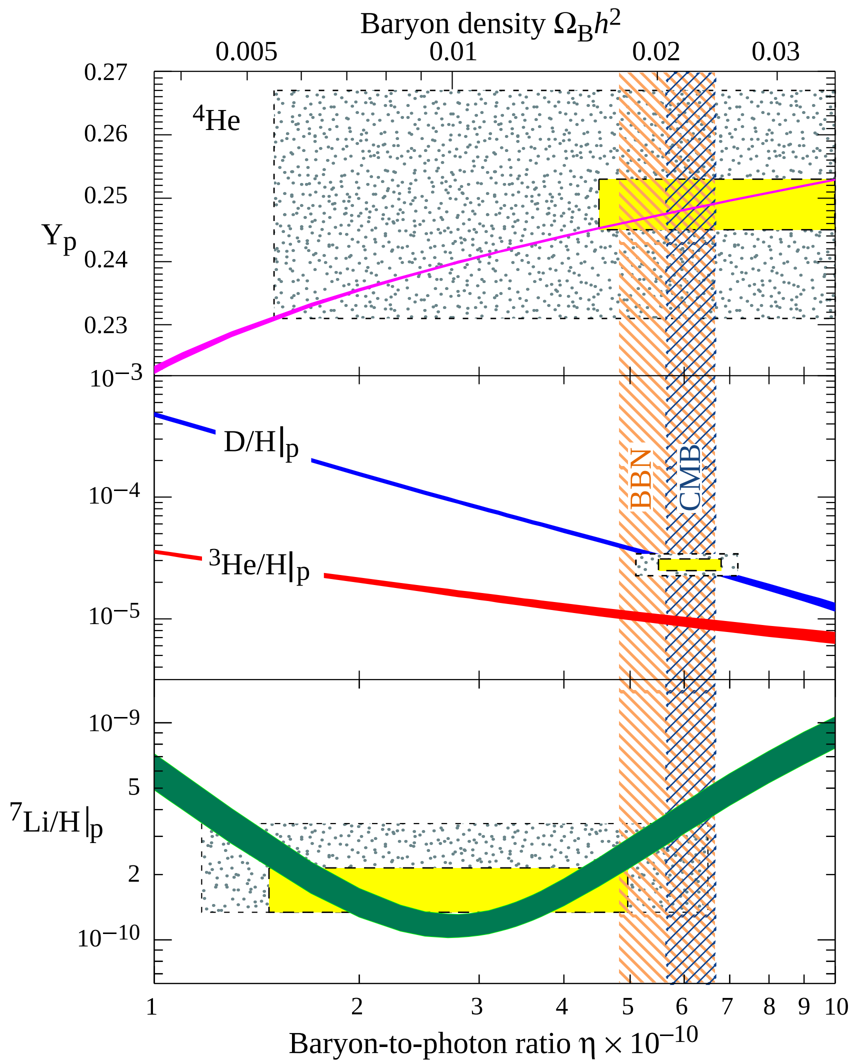


Big Bang Nucleosynthesis

The Standard Model prediction for the abundances of primordial elements are in good overall agreement with the observations.



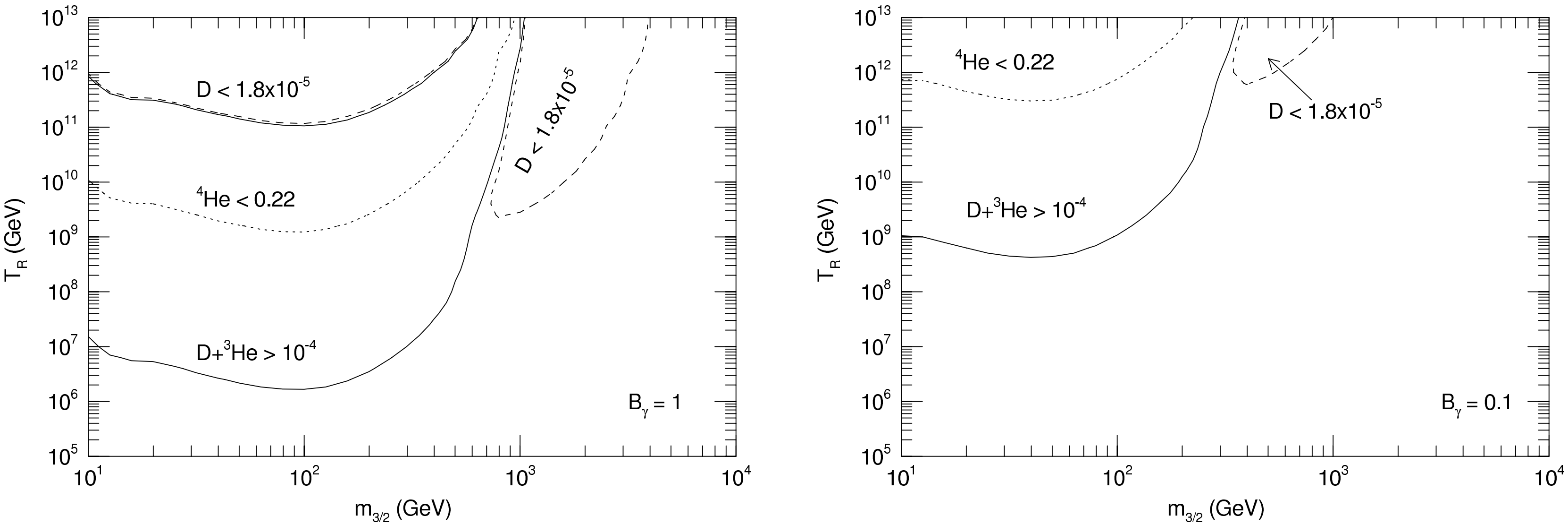
Fields, Sarkar, for PDG

If the gravitino is NOT the lightest supersymmetric particle (*i.e.* the neutralino is the LSP), it decays into the lightest neutralino and a photon: $\psi_{3/2} \rightarrow \chi_1^0 \gamma$.

Potentially problematic for BBN!

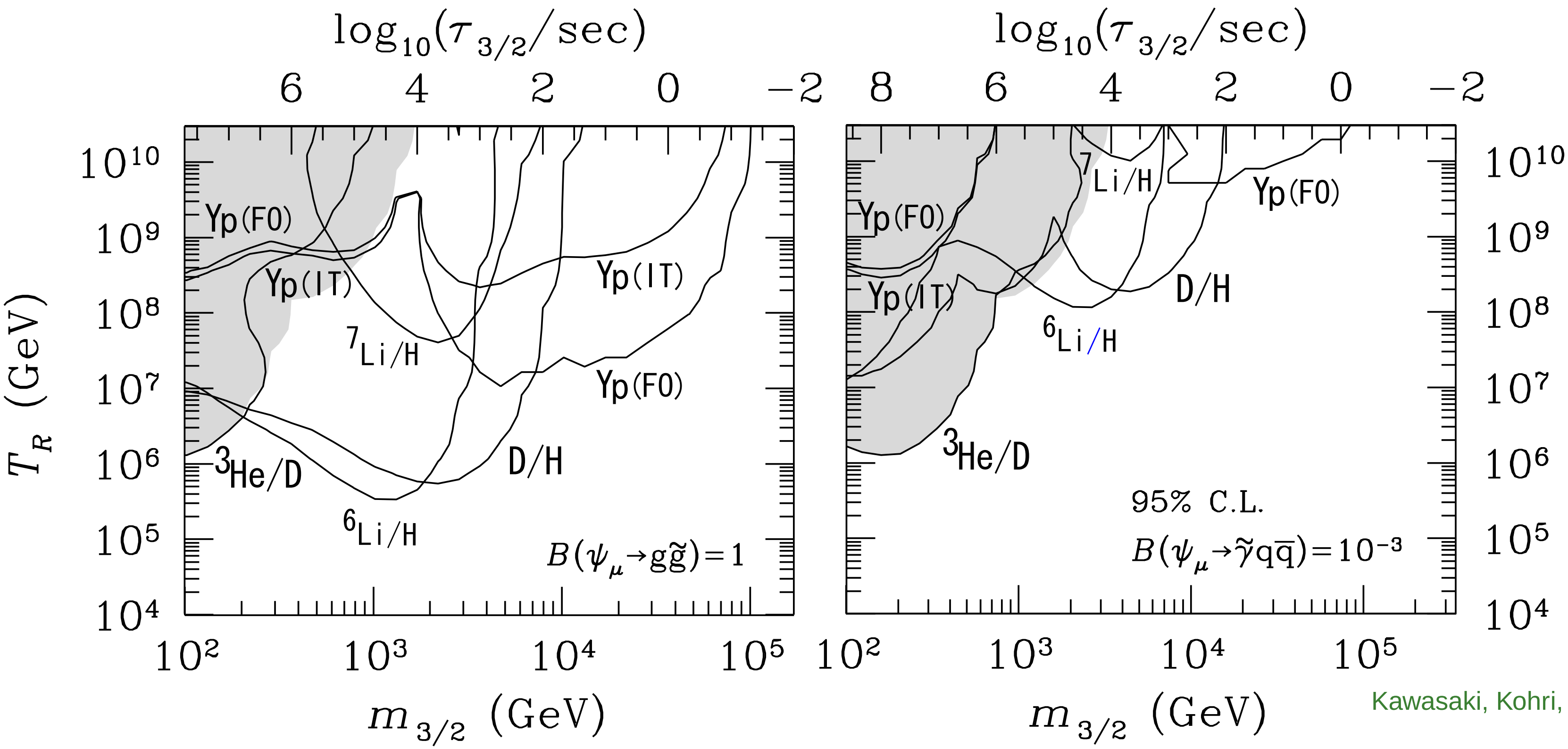
The photons can dissociate the light-elements if the photon energy is above a certain threshold. For example

$$\mathrm{D} + \gamma \rightarrow n + p,\ E_{th} = 2.225\mathrm{MeV}$$



Kawasaki, Moroi

Even worst, if $m_{3/2} > m_{\tilde{g}}$ the gravitino could decay into gluon and gluino, that hadronize producing energetic hadrons $\longrightarrow$ hadro-dissociation of the primordial elements. Other hadronic channels are also dangerous.



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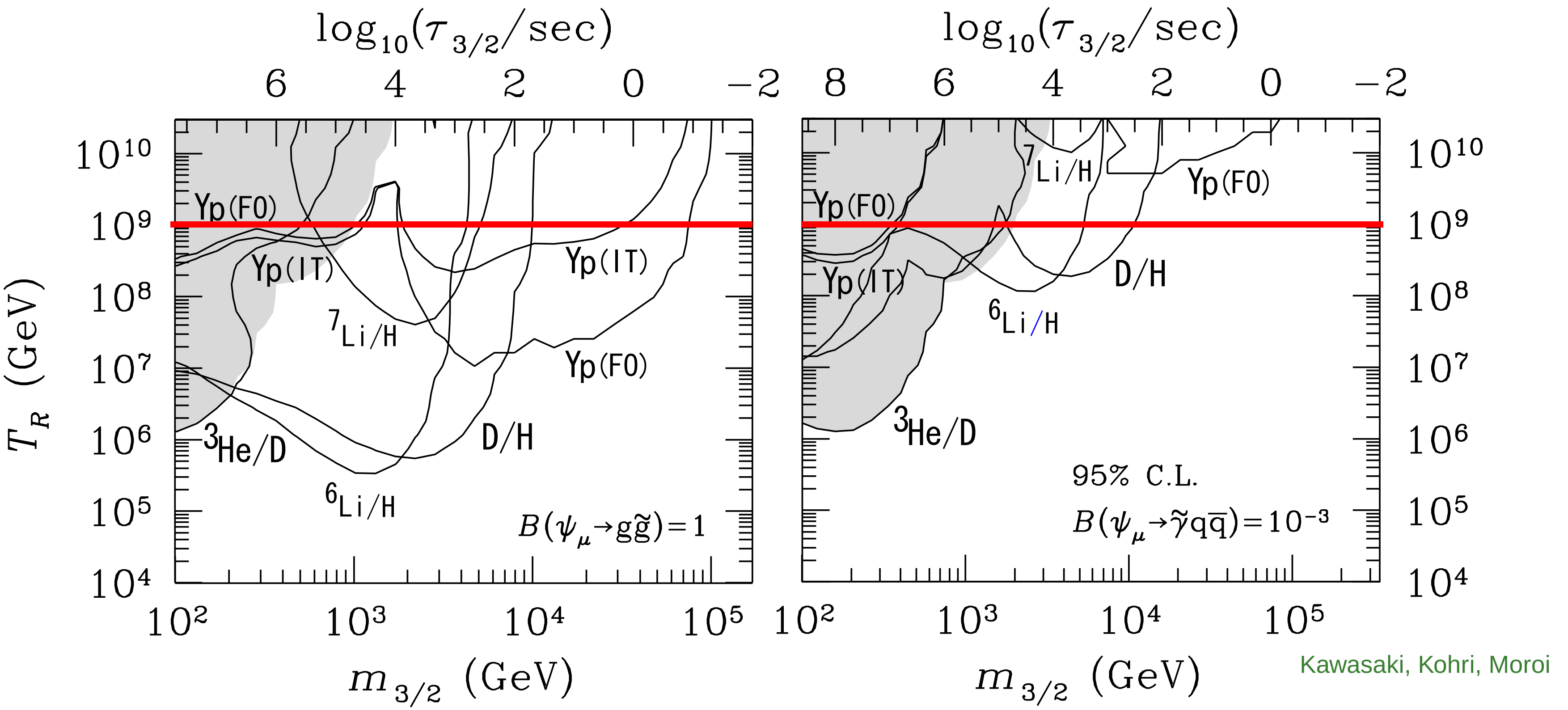

Kawasaki, Kohri, Moroi

Difficult to reconcile with the leptogenesis requirement $T_R \gtrsim 10^9$GeV.

Hadronic decays of the gravitino are an important constraint for the scenario with thermal leptogenesis and neutralino dark matter.

Solutions:

- Very heavy gravitino (anomaly mediation) Ibe, Kitano, Murayama, Yanagida
- late-time entropy production Kohri, Yamaguchi, Yokoyama
- The “standard” (thermal) leptogenesis scenario is not valid.
  Alternative mechanisms have to be advocated working at lower T: resonant leptogenesis, Affleck-Dine baryo/leptogenesis, electroweak baryogenesis...
- The gravitino IS the LSP $\longrightarrow$ gravitino dark matter Pagels, Primack ’81

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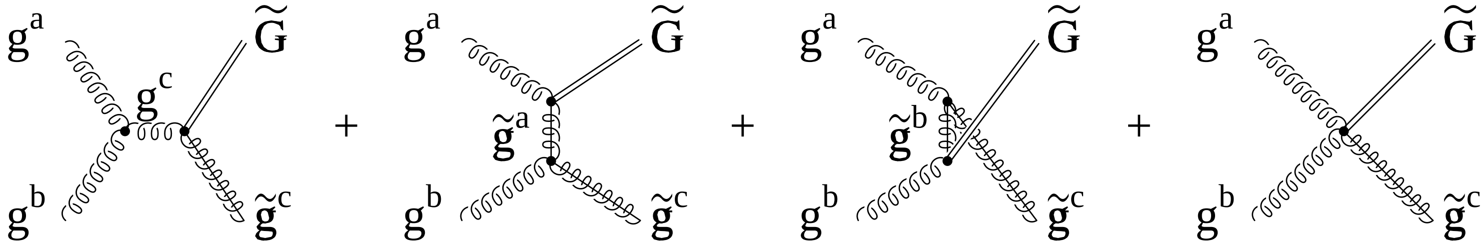
Gravitino dark matter

- Gravitinos are thermally produced in the early Universe by QCD processes. For example:



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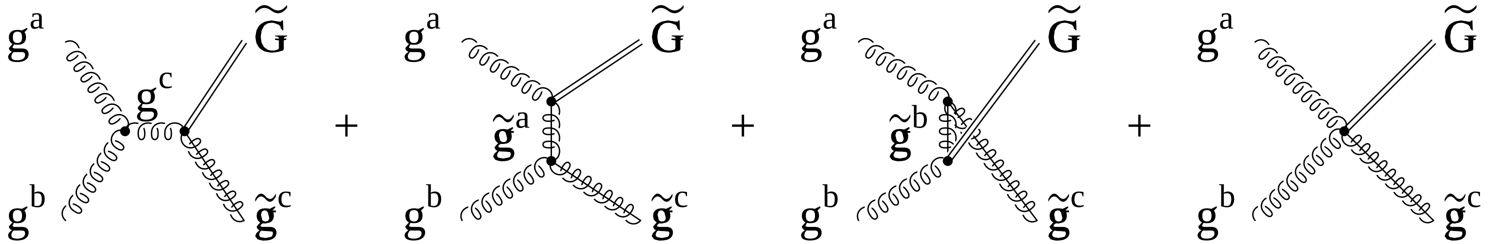

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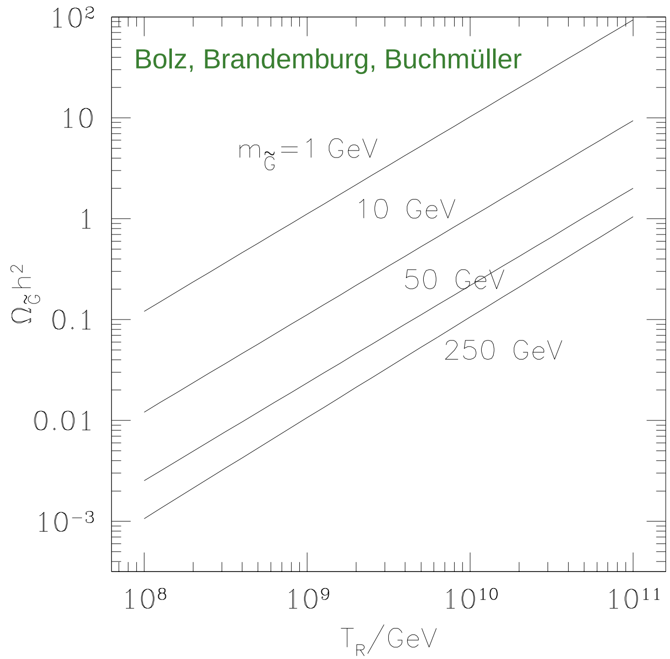

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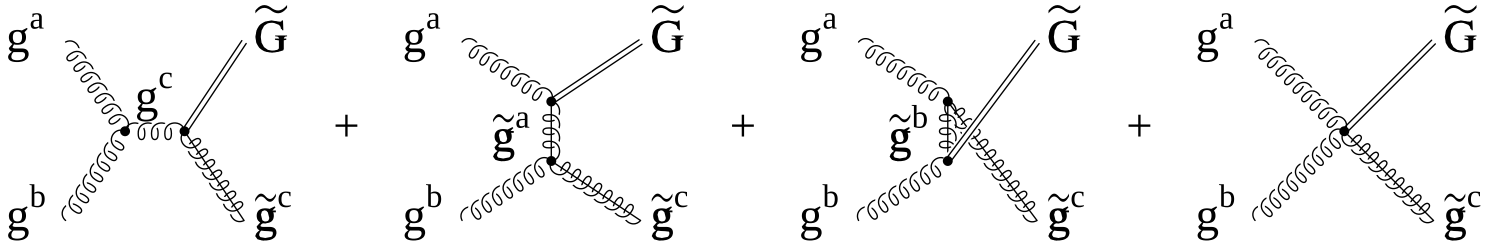

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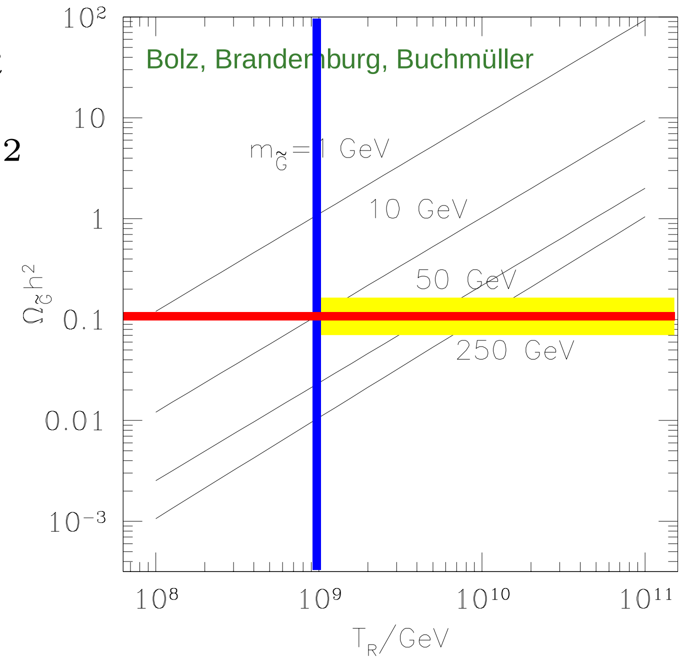
$$\Omega_{3/2}h^2 \simeq 0.1 \left(\frac{T_R}{10^9\ \mathrm{GeV}}\right)\left(\frac{5\ \mathrm{GeV}}{m_{3/2}}\right)\left(\frac{m_{\tilde{g}}}{500\ \mathrm{GeV}}\right)^2$$



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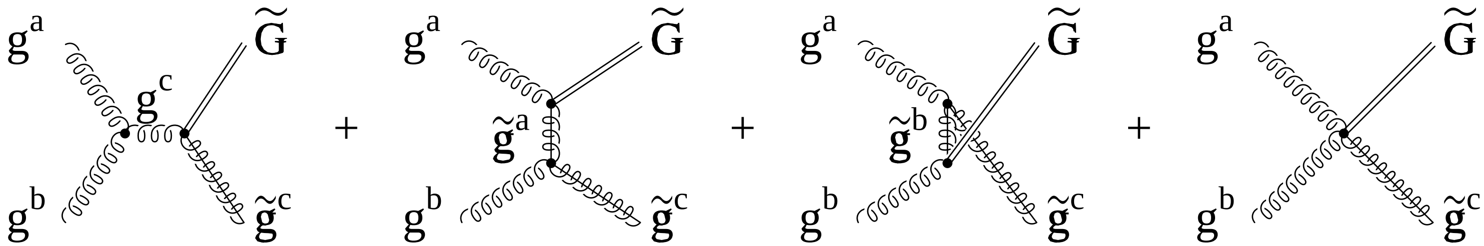

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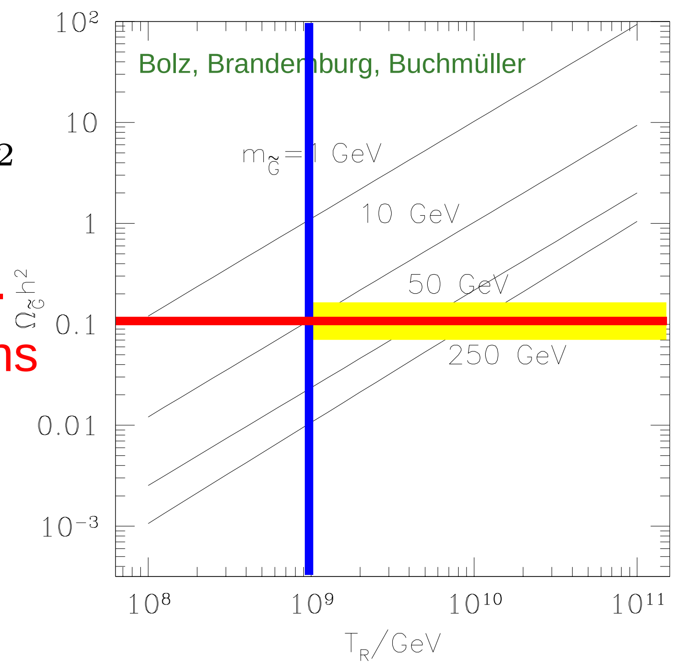


- Very interesting candidate for dark matter. Theoretically very attractive: all interactions are fixed by symmetries. And also, it is nicely compatible with leptogenesis!

  (But it is undetectable with direct searches)

The next-to-lightest SUSY particle

Most likely candidates: lightest neutralino, lightest charged slepton (right-handed stau). (In some speciphic models, the NLSP could also be a sneutrino or a stop.)

If the gravitino is the LSP and R-parity is conserved, the NLSP can only decay gravitationally into gravitinos and SM particles, with a decay rate suppressed by M_P:

$$\Gamma_{\widetilde{\tau}} \simeq \frac{m_{\widetilde{\tau}}^5}{48\pi m_{3/2}^2 M_P^2} \Longrightarrow \text{very long lifetimes.}$$

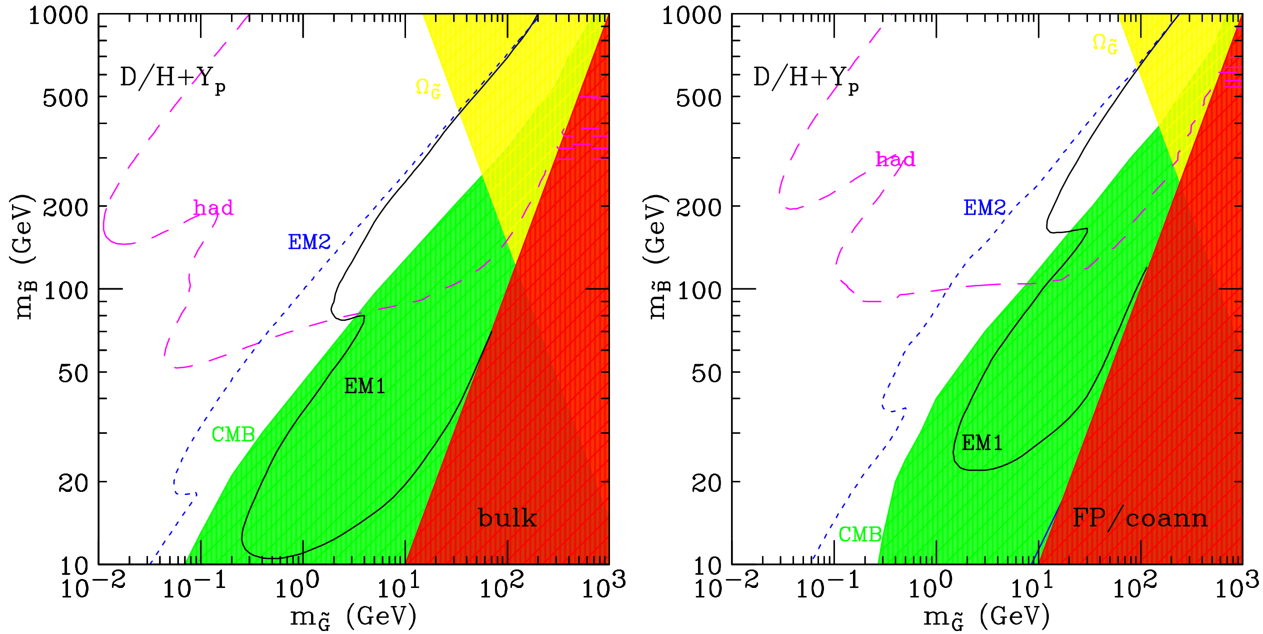
- Stau: $\widetilde{\tau}_R \to \tau \psi_{3/2}, \quad \tau_{\widetilde{\tau}} \simeq 9 \text{ days} \left(\frac{m_{3/2}}{10\text{GeV}}\right)^2 \left(\frac{150\text{GeV}}{m_{\widetilde{\tau}}}\right)^5$
- Neutralino: $\chi_1^0 \to \gamma \psi_{3/2}, \quad \tau_{\widetilde{\chi}_1^0} \simeq 9 \text{ days} \left(\frac{m_{3/2}}{10\text{GeV}}\right)^2 \left(\frac{150\text{GeV}}{m_{\widetilde{\chi}_1^0}}\right)^5$ (for $\chi_1^0 = \widetilde{\gamma}$).

The NLSP is present during and after BBN. The decays could jeopardize the abundances of primordial elements.

Neutralino NLSP

The photons from $\chi_1^0 \to \gamma\psi_{3/2}$ can dissociate primordial elements. Also, $\chi_1^0 \to Z\psi_{3/2}$ could be kinematically allowed, and the hadronic decays of the Z could be disastreous.

For $\chi_1^0 = \widetilde{B}$,



Feng, Su, Takayama

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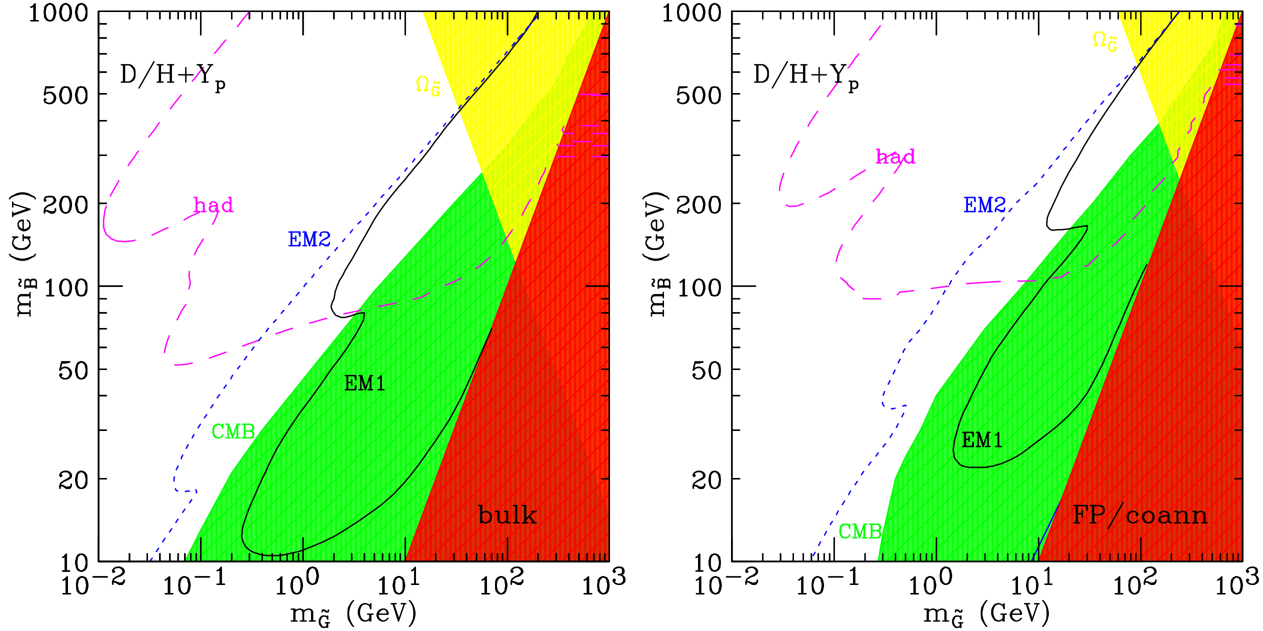
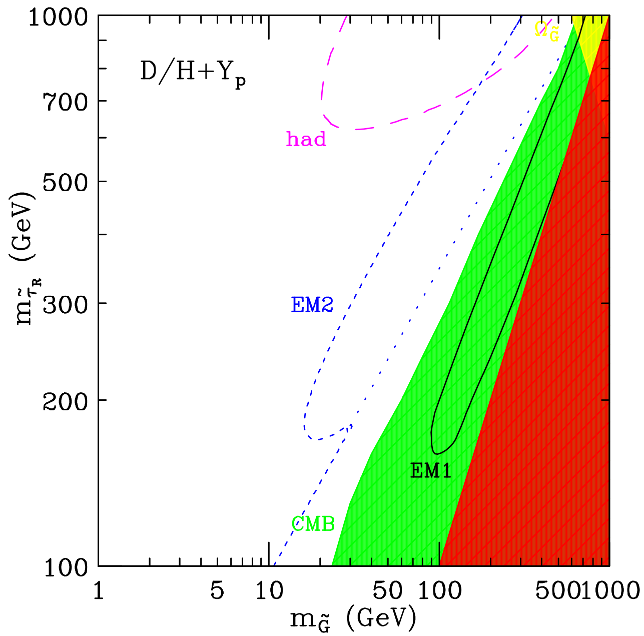


Feng, Su, Takayama

Incompatible with leptogenesis ($m_{3/2} \sim 10 - 300$ GeV).

Right-handed stau NLSP

The two body decay $\widetilde{\tau}_R \to \tau \psi_{3/2}$ only releases electromagnetic energy. Hadronic decays only arise in three body decay processes: $\widetilde{\tau}_R \to \tau Z \psi_{3/2}$ or $\widetilde{\tau}_R \to \nu_\tau W \psi_{3/2}$, with suppressed branching ratio.



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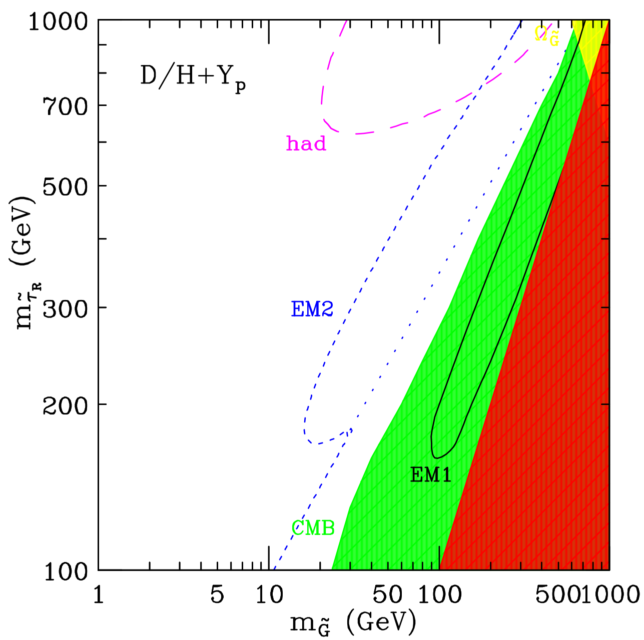


Feng, Su, Takayama

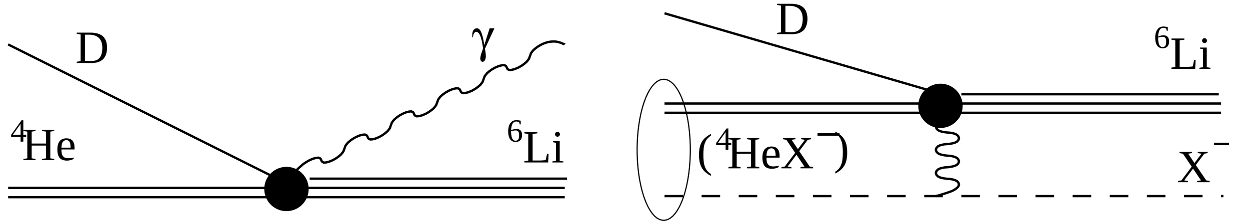
Compatible with leptogenesis ($m_{3/2} \sim 10 - 300$GeV)!

The "revised" thermal history of the Universe seems to point to gravitino LSP, with $m_{3/2} \sim 10 - 300$ GeV, and stau NLSP.

A new turn of the screw

Recently another effect of stau NLSP during BBN has been realized:

stau catalysis of lithium 6. Pospelov



$$^4\mathrm{He} + \mathrm{D} \to \ ^6\mathrm{Li} + \gamma \qquad (^4\mathrm{He}X^-) + \mathrm{D} \to \ ^6\mathrm{Li} + X^-$$

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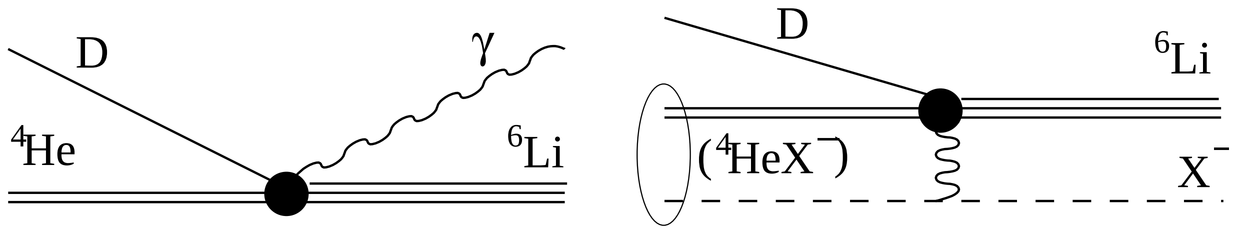

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The cross section for the catalyzed channel is around eight orders of magnitude larger than the standard channel! This leads to an overproduction of $^6\mathrm{Li}$ of a factor 300-600.

Summary of the implications of a high reheat temperature ($T_R \gtrsim 10^9$ GeV) for SUSY dark matter:

neutralino LSP

$\psi_{3/2} \to \chi_1^0$ hadrons
Hadrodissociation of primordial elements

Conflict with BBN

gravitino LSP

- neutralino NLSP
  - $\chi_1^0 \to \psi_{3/2}$ hadrons
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  - **Conflict with BBN**
- RH stau NLSP
  - Catalytic production of $^6\mathrm{Li}$
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- other candidates
  - stop
  - LH sneutrino
  - RH sneutrino

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BBN is the Achilles' heel of SUSY dark matter

<u>Root of all the problems</u>: the NLSP is very long lived.

<u>Simple solution</u>: get rid of the NLSP before BBN $\longrightarrow$ $\boxed{\text{R-parity violation}}$

Gravitino DM with broken R-parity

★ When R-parity is broken, the superpotential reads:

$$W = W_{MSSM} + \mu_i (H_u L_i) + \frac{1}{2}\lambda_{ijk}(L_i L_j)e^c_k + \lambda'_{ijk}(Q_i L_j)d^c_k + \lambda''_{ijk}(u^c_i d^c_j d^c_k)$$

The coupling λ_{ijk} induces the decay of the right-handed stau. For example, $\widetilde{\tau}_R \to \mu\, \nu_\tau$ with lifetime:

$$\tau_{\widetilde{\tau}} \simeq 10^3 \mathrm{s} \left(\frac{\lambda}{10^{-14}}\right)^{-2} \left(\frac{m_{\widetilde{\tau}}}{100\ \mathrm{GeV}}\right)^{-1}$$

Even with a tiny amount of R-parity violation ($\lambda \gtrsim 10^{-14}$) the stau will decay before the time of BBN.

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★ The lepton/baryon number violating couplings λ, λ', λ'' can erase the lepton/baryon asymmetry. The requirement that an existing baryon asymmetry is not erased before the electroweak transition implies:

$$\boxed{\lambda,\, \lambda' \lesssim 10^{-7}}$$

Campbell, Davidson, Ellis, Olive
Fischler, Giudice, Leigh, Paban
Dreiner, Ross

Plenty of room! $10^{-14} \lesssim \lambda,\, \lambda' \lesssim 10^{-7}$. In this range leptogenesis is unaffected.

★ Interestingly, even though the gravitino is not stable anymore, it still constitutes a viable dark matter candidate. It decays for example $\psi_{3/2} \to \nu\gamma$, with lifetime:

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

(Remember: age of the Universe $\sim 10^{17}$s)

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In summary: The existence of a gravitino LSP with a mass in the range 5-300 GeV, and a small amount of R-parity violation $10^{-14} \lesssim \lambda, \lambda' \lesssim 10^{-7}$, is consistent with the "standard" thermal history of the Universe + SUSY dark matter (allows leptogenesis, and does not spoil BBN or CMB observations).

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Question 1: is $10^{-14} \lesssim \lambda, \lambda' \lesssim 10^{-7}$ reasonable?

Question 2: which are the experimental signatures for this scenario?

A model for small (and peculiar) R-parity breaking

Buchmüller, Covi, Hamaguchi, AI, Yanagida

We want to construct a model with small lepton number violation $(10^{-14} \lesssim \lambda, \lambda' \lesssim 10^{-7})$ and tiny baryon number violation ($\lambda' \lambda'' \lesssim 10^{-27}$)

Some insights to construct such a model:

- For convenience, we use $SO(10)$ notation (but no GUT in our model!). Quarks and leptons in $\mathbf{16}_i$, Higgses in $\mathbf{10}_H$.
- To give Majorana masses to neutrinos, $B-L$ has to be broken, either by a $\overline{\mathbf{16}}$, $\mathbf{16}$ (with $B-L=\pm 1$) , or by $\mathbf{126}$ (with $B-L=2$). To have just small representations, we use $\mathbf{16}$ and $\overline{\mathbf{16}}$ $\rightarrow$ R-parity is necessarily broken when $\langle \mathbf{16} \rangle \simeq \langle \overline{\mathbf{16}} \rangle = v_{B-L}$.

- There are two type of terms in the superpotential:

  $\mathbf{16}_i\mathbf{16}_j\mathbf{10}_H$. "Good term". Produces Dirac masses.

  $\mathbf{16}_i\mathbf{16}_j\overline{\mathbf{16}}\,\overline{\mathbf{16}}$. "Good term". Produces right-handed neutrino masses.

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- We will forbid the bad terms by means of a $U(1)_R$ symmetry:

	$\mathbf{16}_i$	$\mathbf{10}_H$	$\overline{\mathbf{16}}$	$\mathbf{16}$	$\mathbf{1}$
R	1	0	0	-2	-1

(the $SO(10)$ singlet has been introduced to break the R-symmetry).

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- Key point 2: the Kähler potential is not protected by holomorphicity. Terms line $\mathbf{1}\,\overline{\mathbf{16}}^\dagger\mathbf{16}_i\mathbf{10}_H$, $\mathbf{1}^\dagger\overline{\mathbf{16}}\,\mathbf{16}_i\mathbf{10}_H$ can appear in the Kähler potential, producing eventually bilinear R-parity violation.

The model

Particle content:

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The model

Particle content:

	Q, u^c, e^c, d^c, L, ν^c	H_u, H_d	N	N^c	Φ	X	Z
$B-L$	$\pm 1/3, \pm 1$	0	1	-1	0	0	0
R	1	0	0	-2	-1	4	0

Φ and Z are spectator fields, $\langle \Phi \rangle = v_{B-L}$ and $\langle Z \rangle = F_Z \theta\theta$.

The effective theory is described by $W \simeq W_{MSSM} + W_{\nu^c} + W_{\not{R}_p}$:

- $W_{MSSM} = h^e L H_d e^c + h^d Q H_d d^c + h^u Q H_u u^c + \mu H_u H_d$
- $W_{\nu^c} = h^\nu L H_u \nu^c + M \nu^c \nu^c$, with $M_3 \sim \frac{v_{B-L}^2}{M_P}$
- $W_{\not{R}_p} = \frac{1}{2} \lambda \; L L e^c + \lambda' Q L d^c + \lambda'' u^c d^c d^c$

$$\lambda \sim C \frac{v_{B-L}^2}{M_P^2} h^e \sim C \frac{M_3}{M_P} h^e$$

$$\lambda' \sim C \frac{v_{B-L}^2}{M_P^2} h^d \sim C \frac{M_3}{M_P} h^d$$

$$\lambda'' \sim m_{3/2} \frac{v_{B-L}^4}{M_P^5} \sim \frac{m_{3/2}}{M_P} \left(\frac{M_3}{M_P} \right)^2$$

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In a particular flavour model

Buchmüller, Yanagida

$$\lambda \sim C\frac{v_{B-L}^2}{M_P^2} h^e \sim C\frac{M_3}{M_P} h^e \qquad \lambda \sim 10^{-7} h^e$$

$$\lambda' \sim C\frac{v_{B-L}^2}{M_P^2} h^d \sim C\frac{M_3}{M_P} h^d \qquad \lambda' \sim 10^{-7} h^d$$

$$\lambda'' \sim m_{3/2}\frac{v_{B-L}^4}{M_P^5} \sim \frac{m_{3/2}}{M_P}\left(\frac{M_3}{M_P}\right)^2 \qquad \lambda'' \sim 10^{-28}$$

$\boxed{\text{Then, } \lambda_{3ij}, \lambda'_{3ij} \sim 10^{-8}, \text{ within } 10^{-14} \lesssim \lambda, \lambda' \lesssim 10^{-7}}$

I- Signatures at gamma ray observatories

The gravitino lifetime is much longer than the age of the Universe, but a few decays are happening **NOW**, and the decay products could be observed.
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Shining dark matter

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Shining dark matter

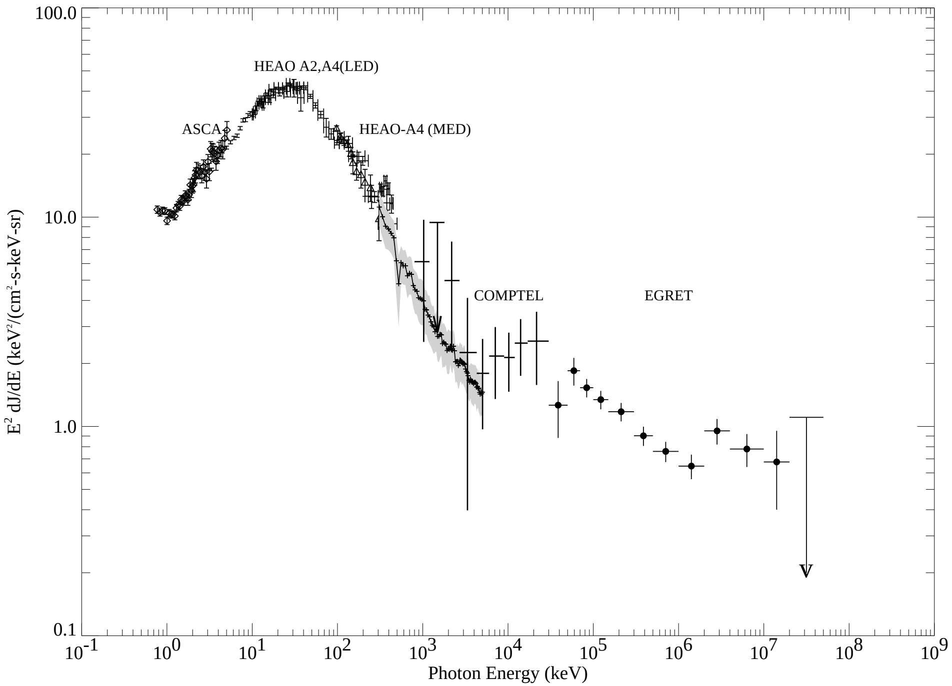
DATA! First analysis of Sreekumar *et al.* from the EGRET data gave an extragalactic flux described by the power law.

$E^2 \frac{dJ}{dE} = 1.37 \times 10^{-6} \left(\frac{E}{1 \text{ GeV}}\right)^{-0.1} (\text{cm}^2 \text{str s})^{-1} \text{GeV}$, for 50 MeV$\lesssim E \lesssim$ 10 GeV

This flux is close to the predictions of models.

This scenario might be tested soon!!

The more recent analysis by Strong, Moskalenko and Reimer ('04) shows a power law behaviour between 50 MeV and 2 GeV, but a clear excess between 2 GeV and 50GeV!!



The extragalactic gamma ray flux from the decay of gravitinos may be hidden in this excess.

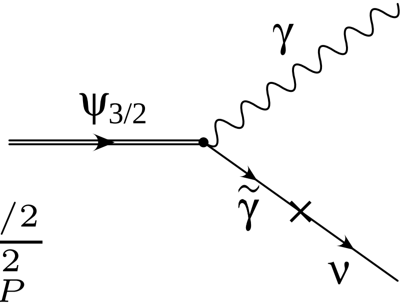
Still, many open questions:

- ⋆ Extraction of the signal from the galactic background
- ⋆ Is the signal isotropic/anisotropic?
- ⋆ Precise shape of the energy spectrum?
- ⋆ Is the excess really there? Stecker, Hunter & Kniffen

GLAST will clarify these issues.

Gravitino decay channels

- Light gravitino $m_{3/2} \lesssim M_W$
  - $\psi_{3/2} \to \gamma\nu$



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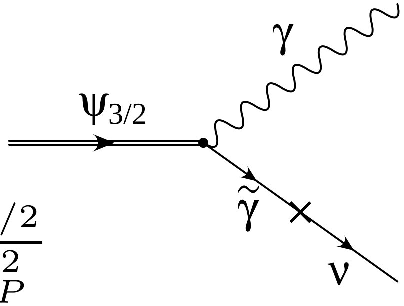

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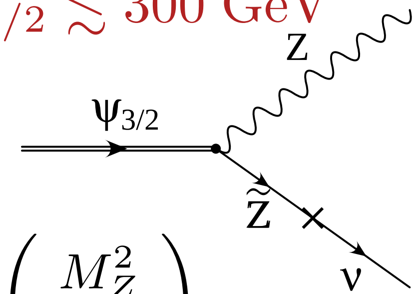

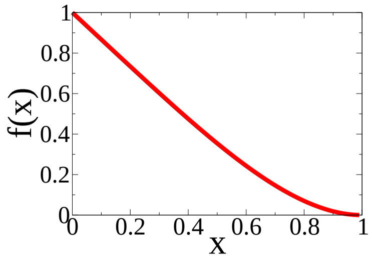

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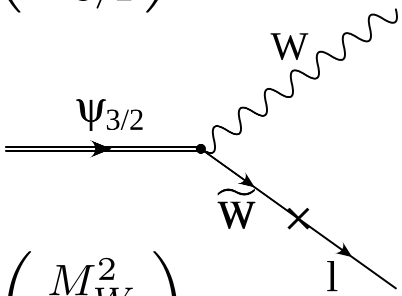

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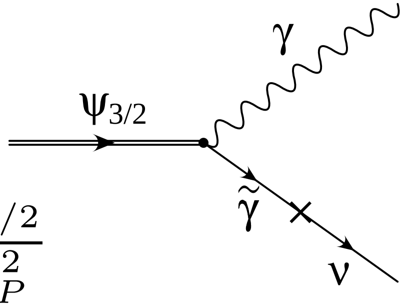

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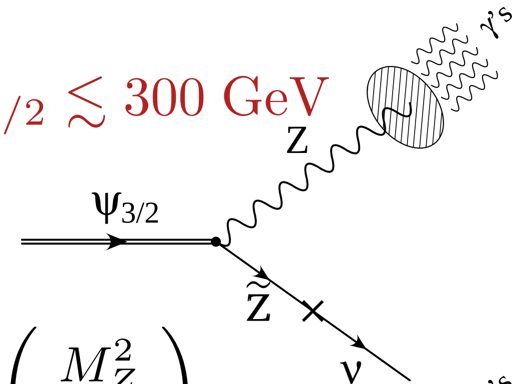

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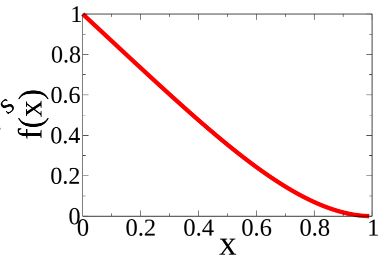

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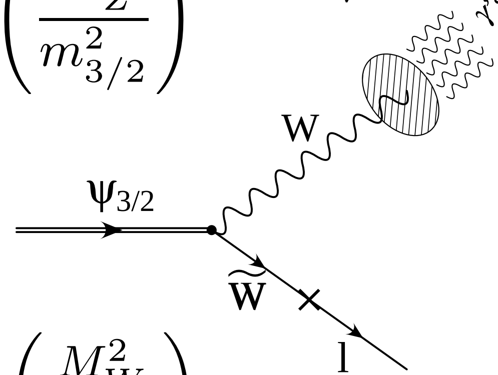

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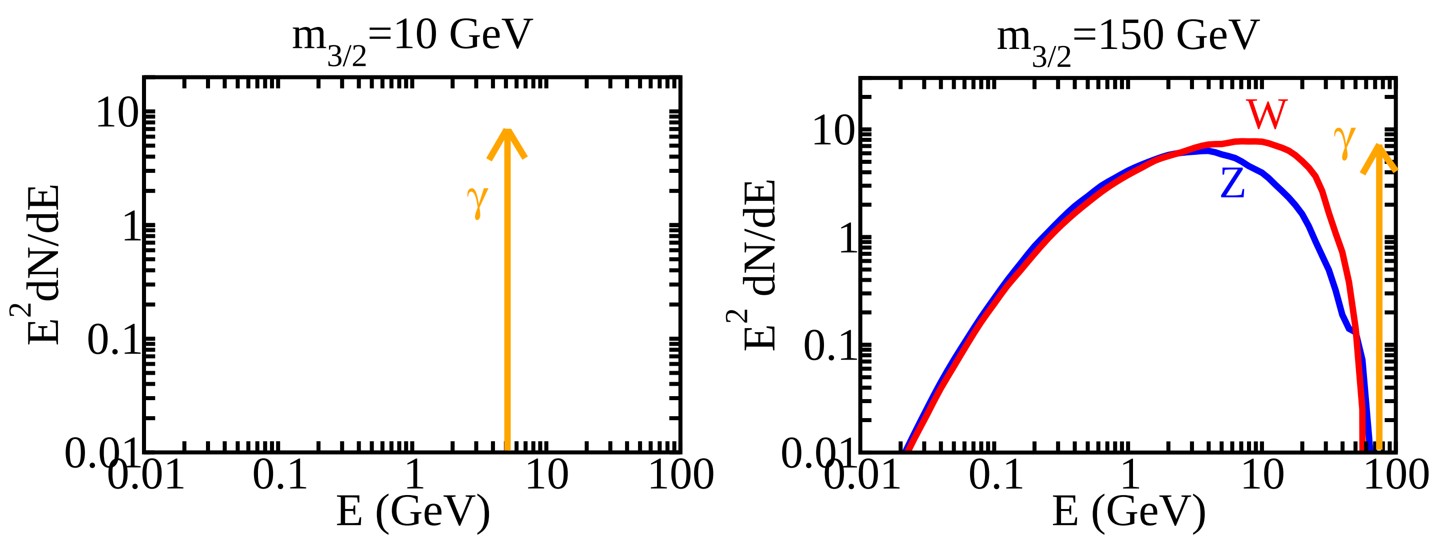
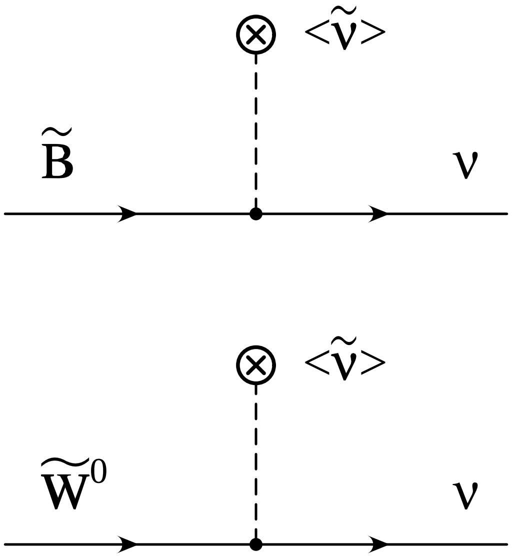


What are typical values for $|U_{\tilde{\gamma}\nu}|$, $|U_{\tilde{Z}\nu}|$, $|U_{\tilde{W}\ell}|$?

When R-parity is broken neutralinos mix with neutrinos, through the sneutrino vev



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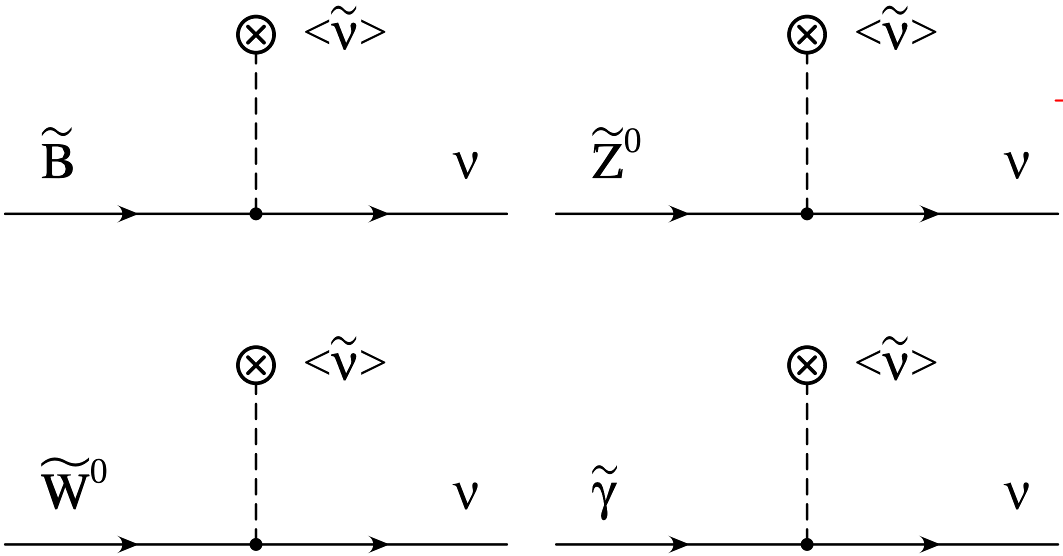

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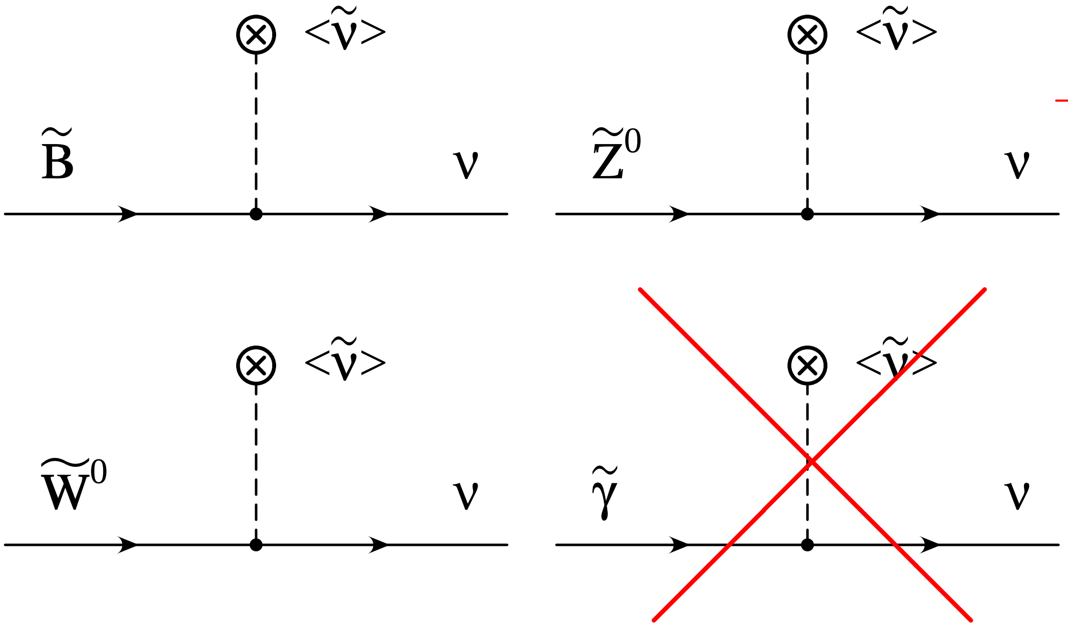

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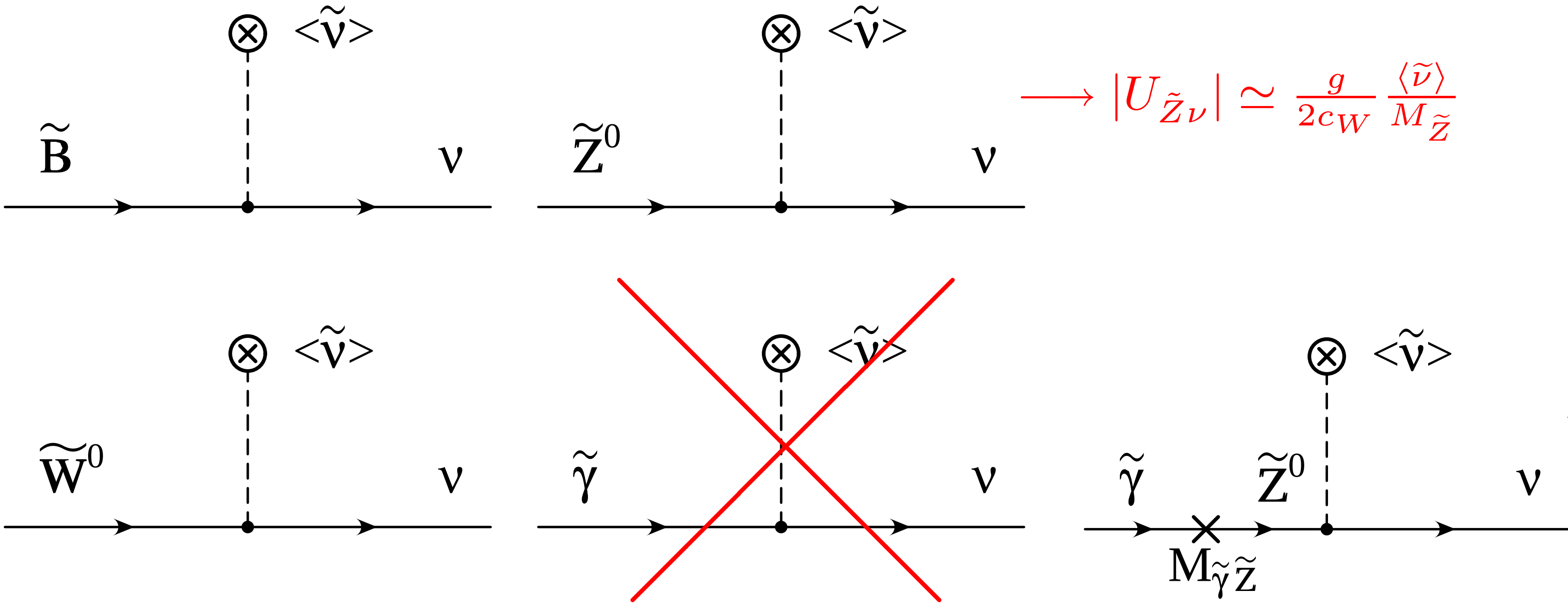


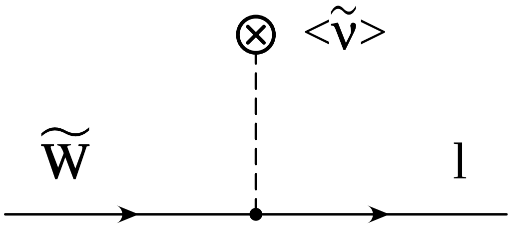
$\longrightarrow |U_{\tilde{Z}\nu}| \simeq \frac{g}{2c_W}\frac{\langle\tilde{\nu}\rangle}{M_{\tilde{Z}}}$

$\longrightarrow |U_{\tilde{\gamma}\nu}|$

$$|U_{\tilde{\gamma}\nu}| \simeq \left(\frac{(M_2 - M_1)s_W c_W}{M_1 c_W^2 + M_2 s_W^2}\right)|U_{\tilde{Z}\nu}|$$

Assuming universality at the GUT scale, $|U_{\tilde{\gamma}\nu}| \simeq 0.32|U_{\tilde{Z}\nu}|$

Also, the charginos mix with the charged leptons



$$\longrightarrow |U_{\tilde{W} l}| \simeq \frac{g}{\sqrt{2}} \frac{\langle \tilde{\nu} \rangle}{M_{\widetilde{W}}}$$

$$|U_{\widetilde{W}\ell}| \simeq \sqrt{2} c_W \frac{M_1 s_W^2 + M_2 c_W^2}{M_2} |U_{\widetilde{Z}\nu}|$$

Assuming universality at the GUT scale, $|U_{\widetilde{W}\ell}| \simeq 1.09 |U_{\widetilde{Z}\nu}|$

The branching ratios are determined by the size of the mixing parameters $U_{\tilde{\gamma}\nu}$, $U_{\tilde{Z}\nu}$, $U_{\tilde{W}\ell}$. This is very model dependent, however, their relative size is fairly model independent:

$$
\begin{aligned}
|U_{\widetilde{\gamma}\nu}| &\simeq \left[\frac{(M_2 - M_1) s_W c_W}{M_1 c_W^2 + M_2 s_W^2}\right] |U_{\widetilde{Z}\nu}| \\
|U_{\widetilde{W}\ell}| &\simeq \sqrt{2} c_W \frac{M_1 s_W^2 + M_2 c_W^2}{M_2} |U_{\widetilde{Z}\nu}|
\end{aligned}
$$

Assuming gaugino mass universality at the Grand Unified Scale,

$$|U_{\widetilde{\gamma}\nu}| : |U_{\widetilde{Z}\nu}| : |U_{\widetilde{W}\ell}| \simeq 1 : 3.2 : 3.5$$

$m_{3/2}$	BR($\psi_{3/2} \to \gamma\nu$)	BR($\psi_{3/2} \to W\ell$)	BR($\psi_{3/2} \to Z^0\nu$)
10 GeV	1	0	0
85 GeV	0.66	0.34	0
100 GeV	0.16	0.76	0.08
150 GeV	0.05	0.71	0.24
250 GeV	0.03	0.69	0.28

The energy spectrum of photons from gravitino decay is

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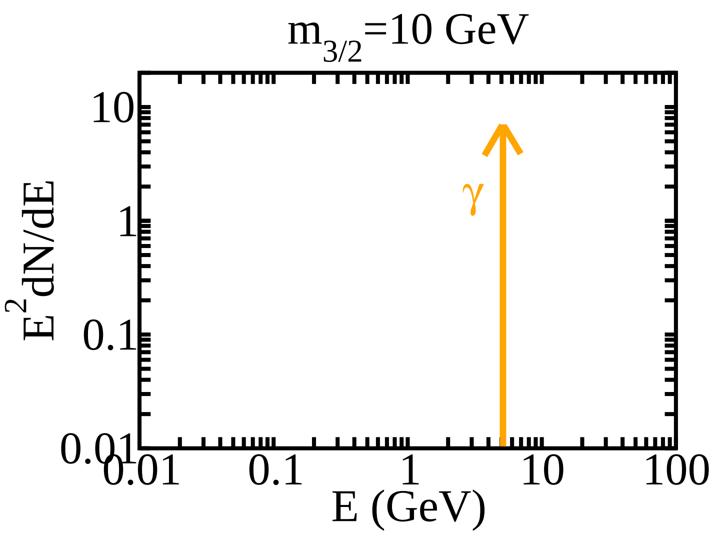
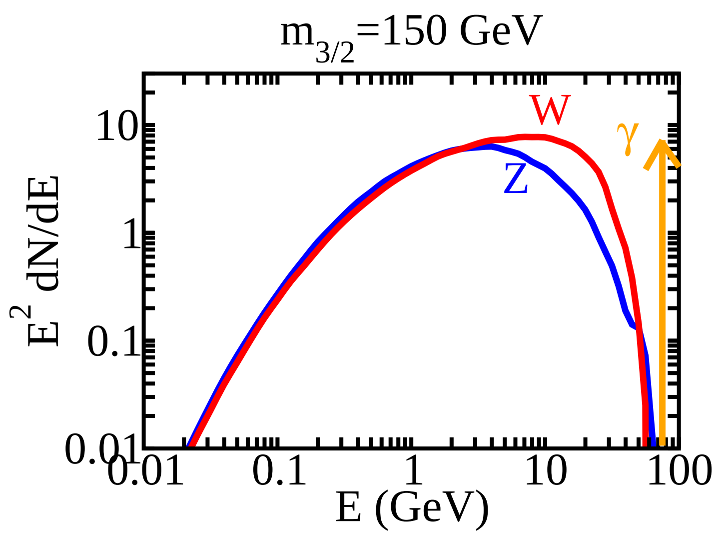




Gamma ray spectrum

If gravitinos decay, we expect a diffuse background of gamma rays with two different sources.

- The decay at cosmological distances gives rise to a perfectly isotropic extragalactic diffuse gamma-ray flux.

$$\left[E^2 \frac{dJ}{dE}\right]_{\text{extgal}} = \frac{2E^2}{m_{3/2}} C_\gamma \int_1^\infty dy \; \frac{dN_\gamma}{d(Ey)} y^{-3/2} \left(1 + \frac{\Omega_\Lambda}{\Omega_M} y^{-3}\right)^{-1/2}$$

where $y = 1 + z$,

$$C_\gamma = \frac{\Omega_{3/2}\rho_c}{8\pi\tau_{3/2} H_0 \Omega_M^{1/2}} = 10^{-7} (\mathrm{cm}^2 \ \mathrm{str \ s})^{-1} \mathrm{GeV} \left(\frac{\tau_{3/2}}{10^{28} \ \mathrm{s}}\right)^{-1}$$

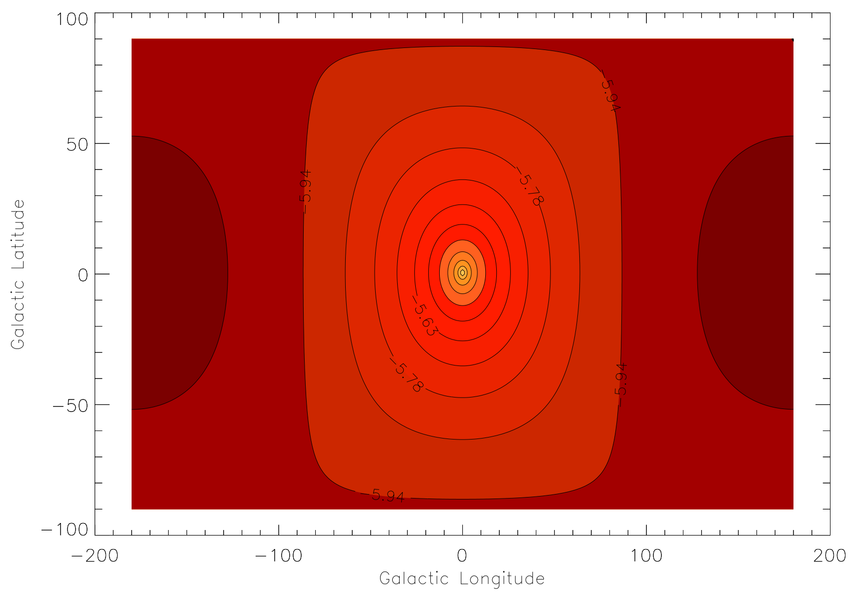
and $\frac{dN_\gamma}{dE}$ is the spectrum of photons from gravitino decay

- The decay of the gravitinos in the Milky Way halo gives rise to an anisotropic γ ray flux

$$\left[E^2 \frac{dJ}{dE}\right]_{\text{halo}} = \frac{2E^2}{m_{3/2}} D_\gamma \frac{dN_\gamma}{dE}$$

where $$D_\gamma = \frac{1}{8\pi\tau_{3/2}} \int_{\text{los}} \rho_{\text{halo}}(\vec{l}) d\vec{l}$$

The precise value of $D_\gamma(b,l)$ depends on the halo profile. Averaging over all sky, one finds typically $\bar{D}_\gamma / C_\gamma \sim \mathcal{O}(1) \longrightarrow$ the halo contribution dominates



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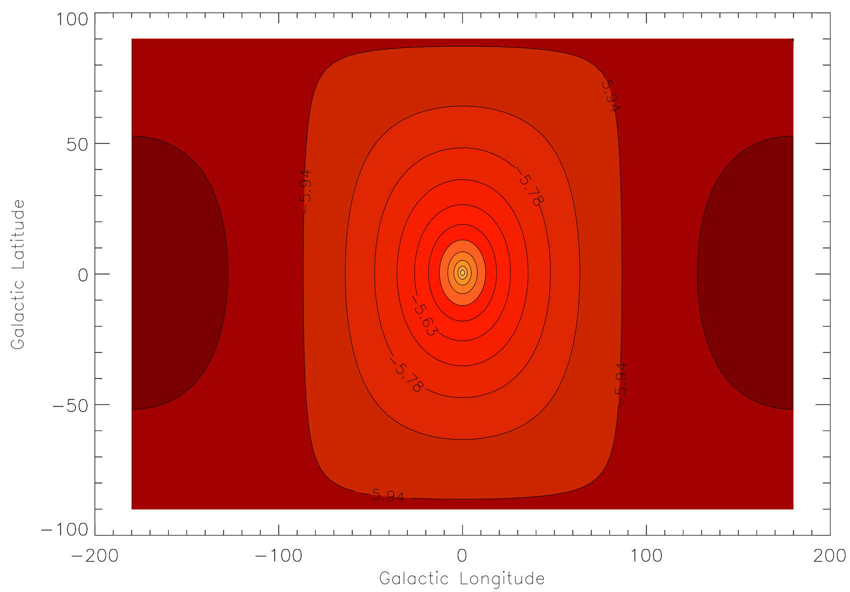

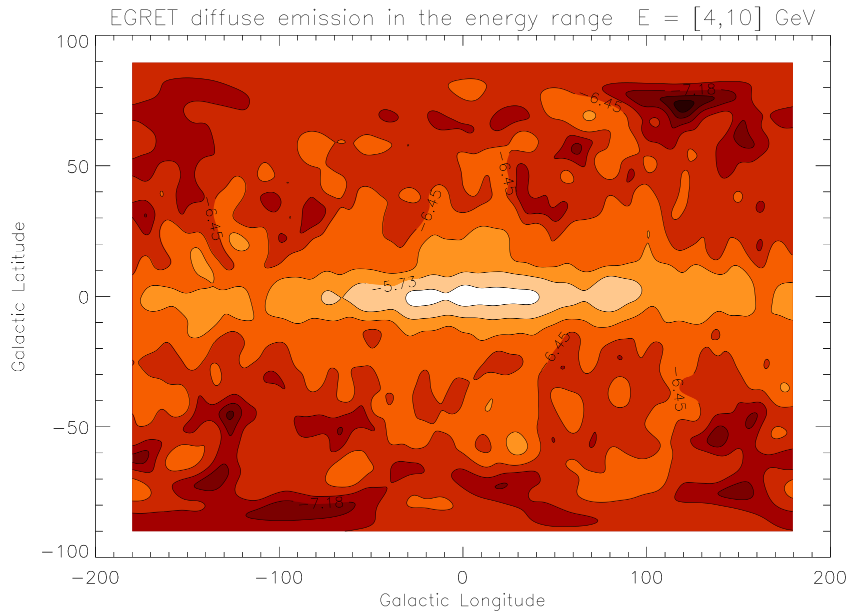

γ ray spectrum for light gravitinos $m_{3/2} \lesssim M_W$

The energy spectrum from gravitino decay is just a delta function: $\frac{dN_\gamma}{dE} = \delta\left(E - \frac{m_{3/2}}{2}\right)$

$$\left[E^2 \frac{dJ}{dE}\right]_{\text{extgal}} = C_\gamma \left[1 + \frac{\Omega_\Lambda}{\Omega_M}\left(\frac{2E}{m_{3/2}}\right)^3\right]^{-1/2} \left(\frac{2E}{m_{3/2}}\right)^{5/2} \theta\left(1 - \frac{2E}{m_{3/2}}\right)$$

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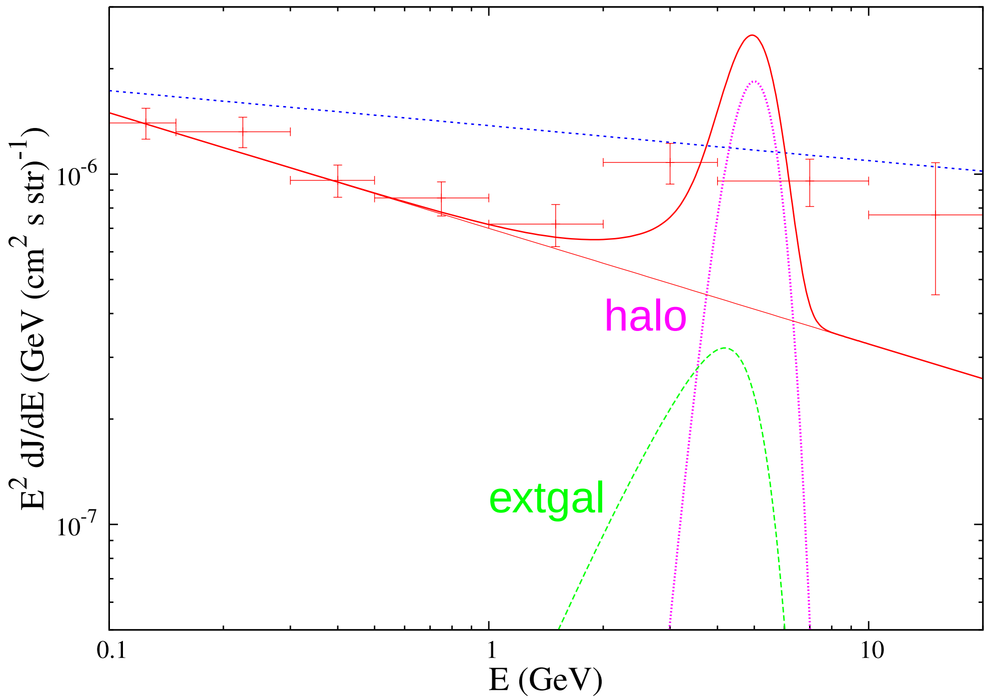

Bertone, Buchmüller, Covi, AI

energy resolution of EGRET: 15%

γ **ray spectrum for "not-so-light" gravitinos** $100\ \mathrm{GeV} \lesssim m_{3/2} \lesssim 300\ \mathrm{GeV}$

The total flux receives contribution from different sources.

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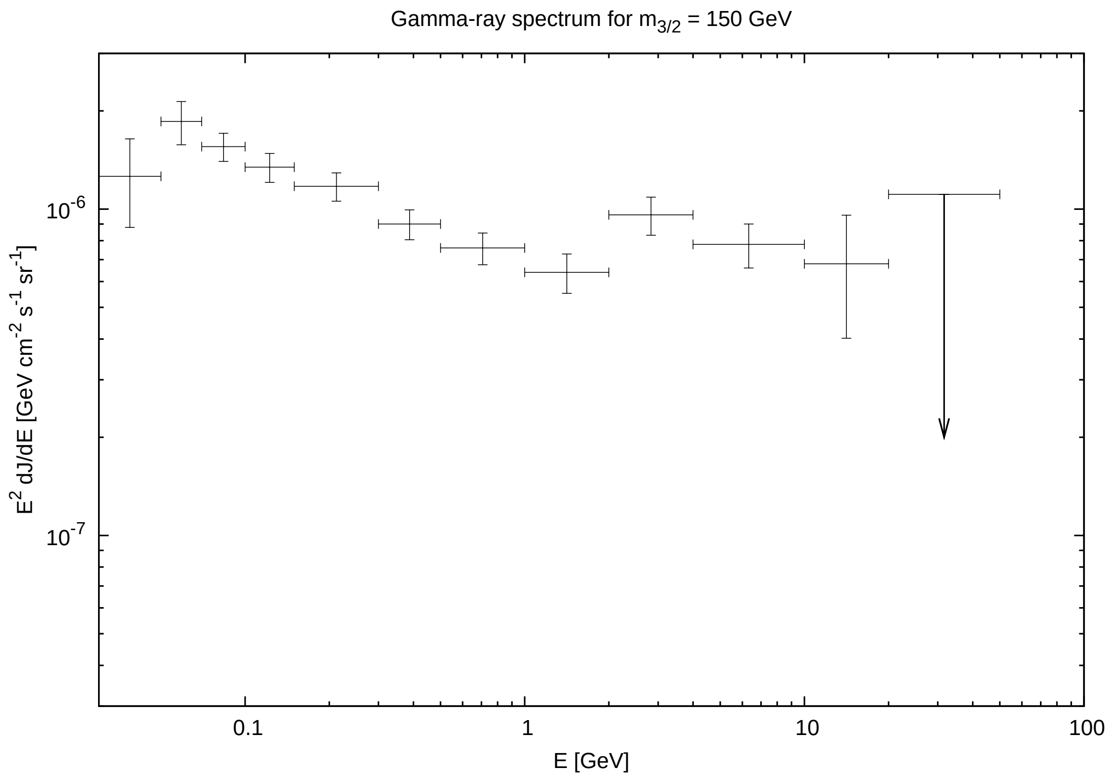

AI, Tran

γ ray spectrum for “not-so-light” gravitinos $100\ \mathrm{GeV} \lesssim m_{3/2} \lesssim 300\ \mathrm{GeV}$

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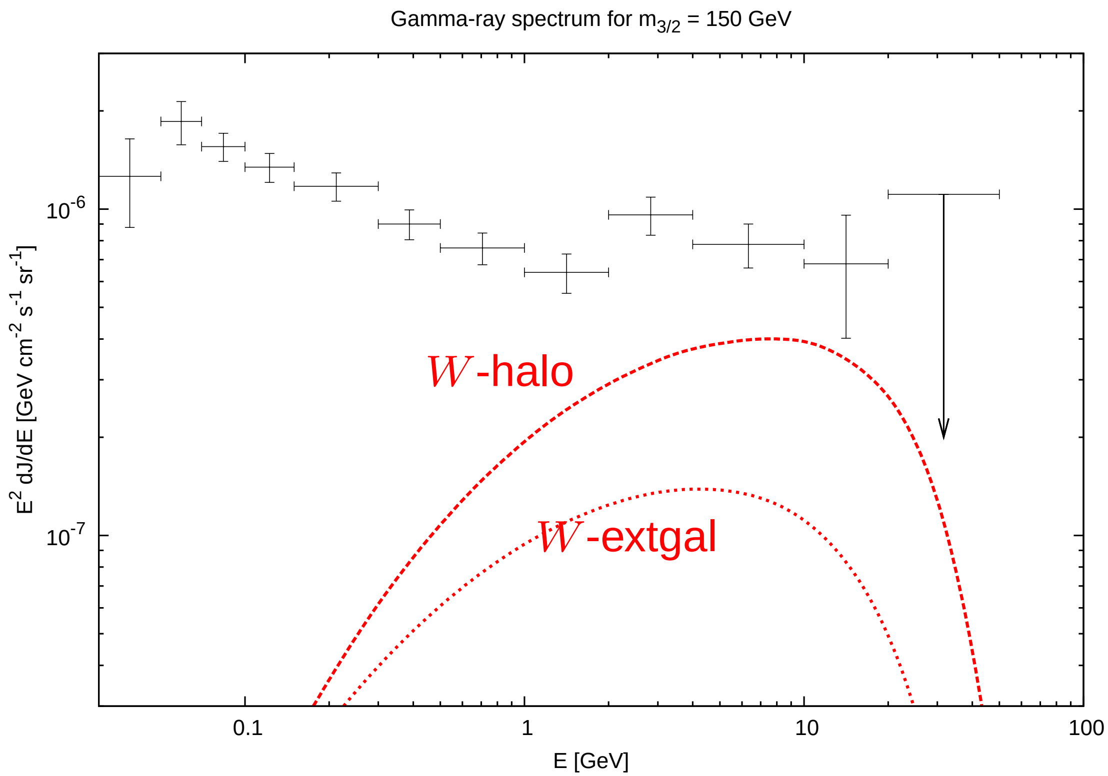

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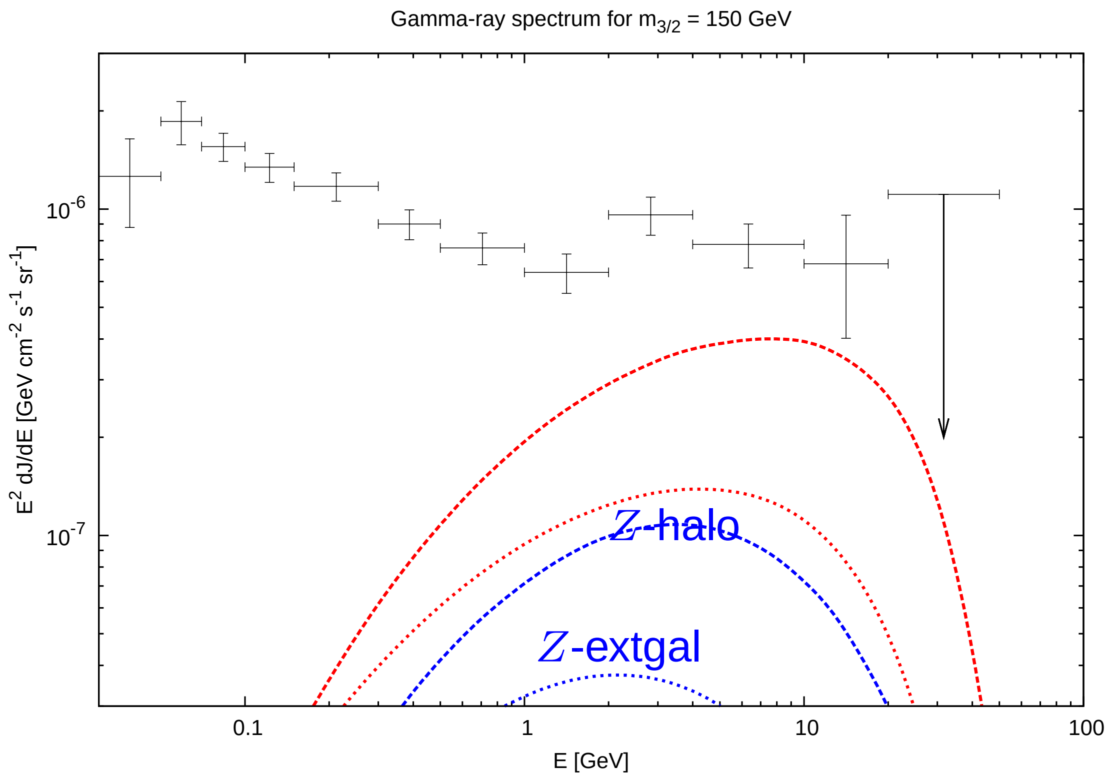

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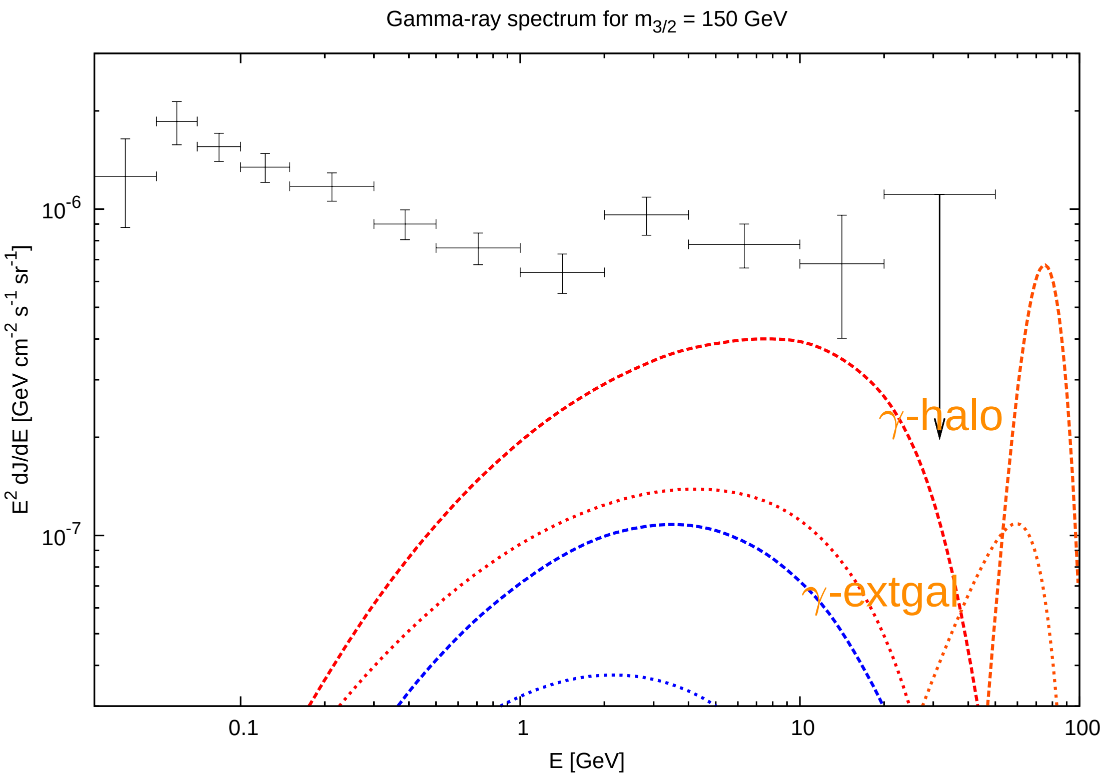

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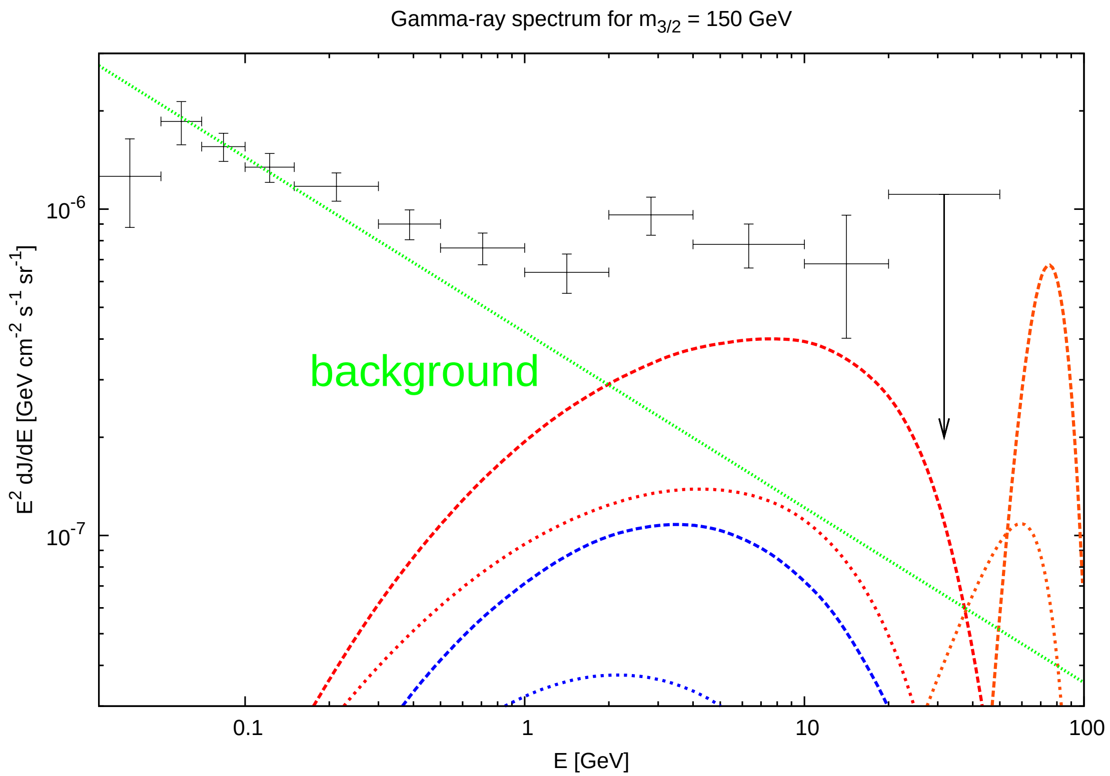

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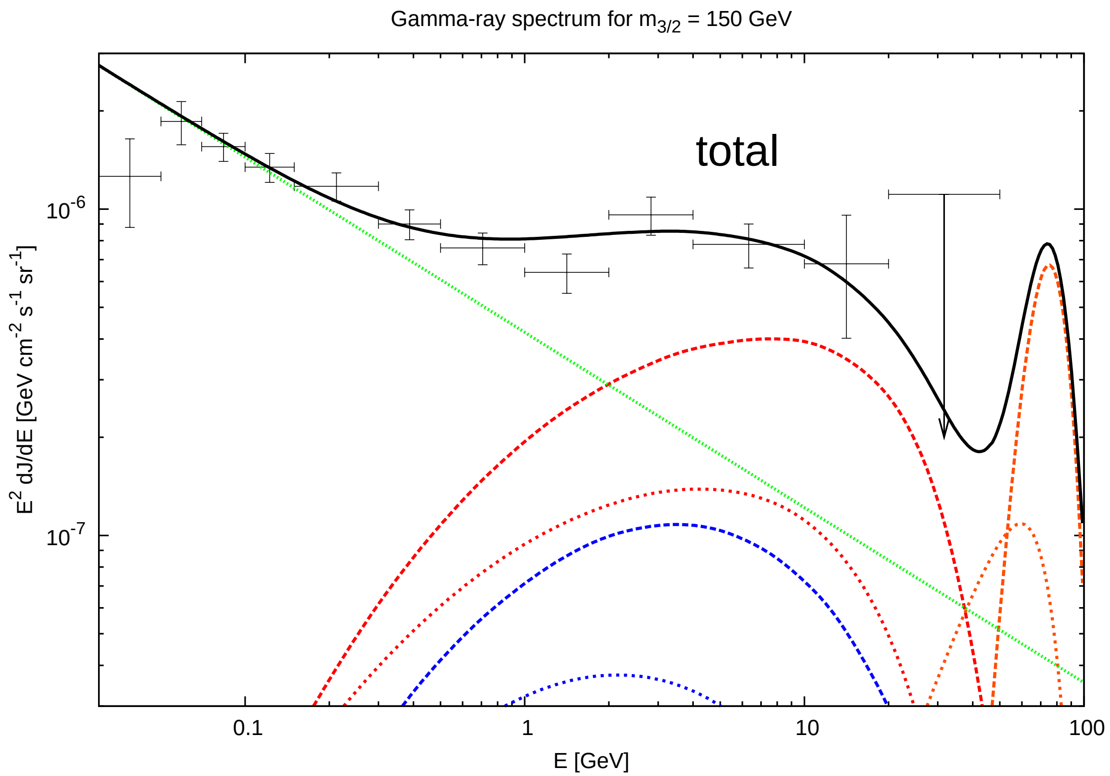
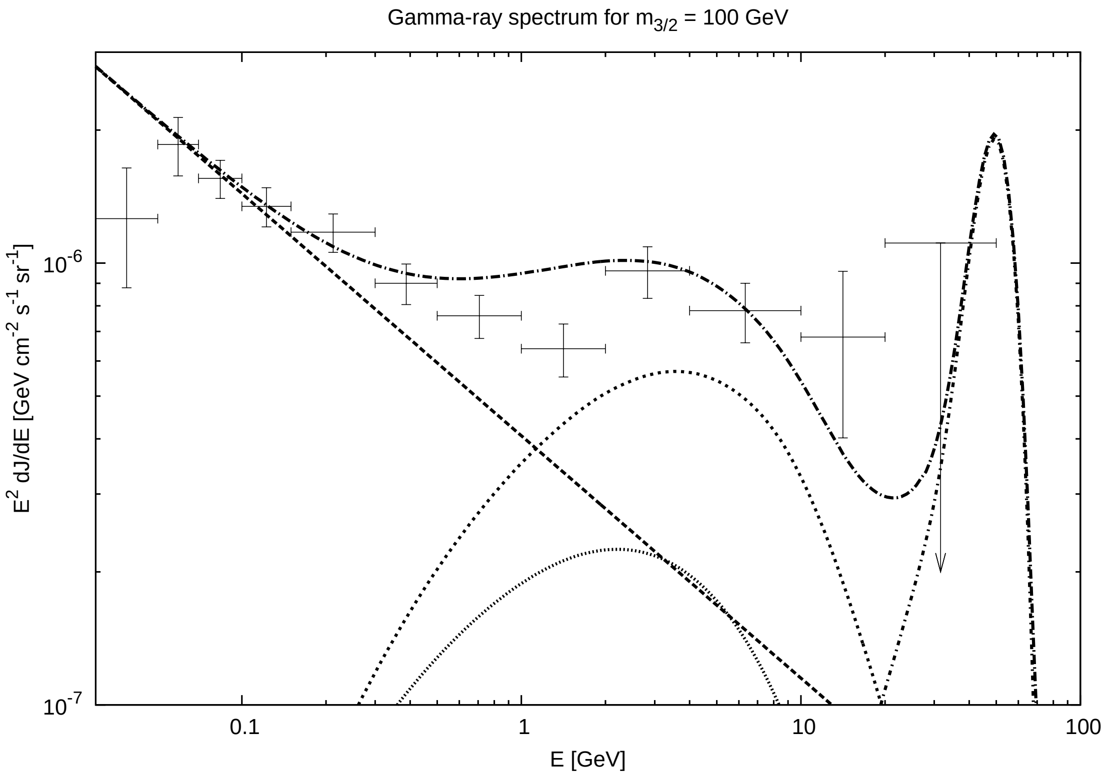
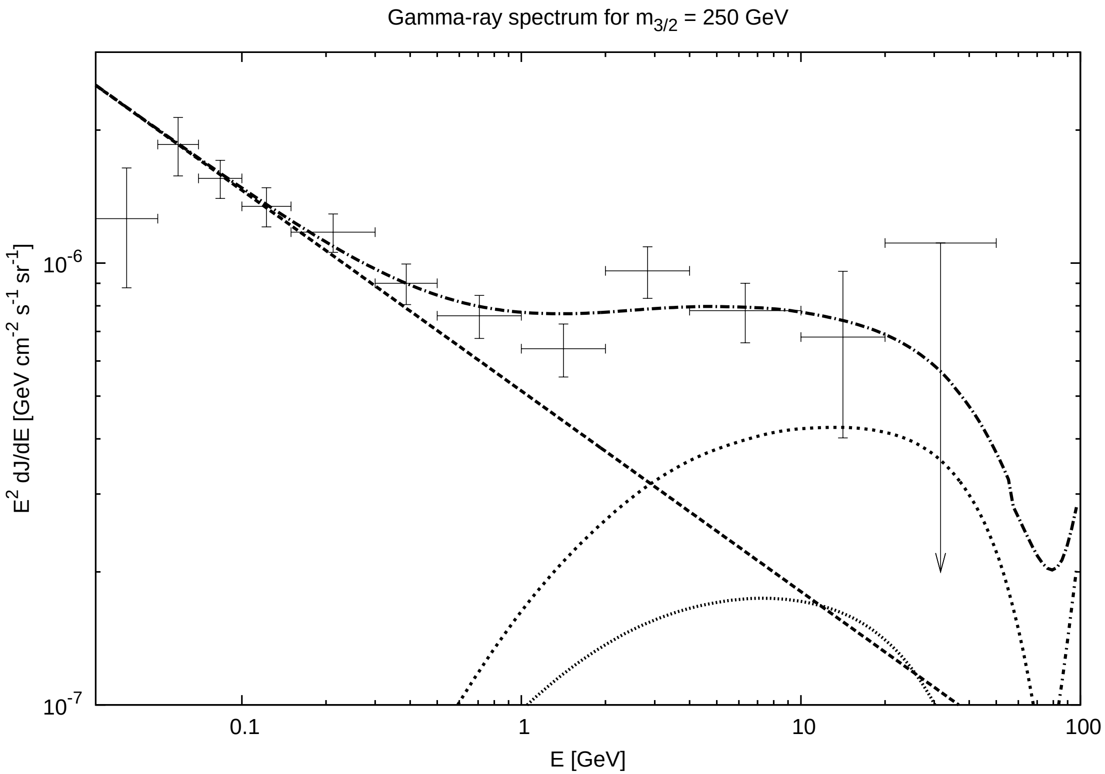


AI, Tran

$$\tau_{3/2} = 2 \times 10^{26}\mathrm{s} \Longrightarrow |U_{\widetilde{\gamma}\nu}| \simeq 2 \times 10^{-10}$$


Gamma-ray spectrum for $m_{3/2}$ = 100 GeV
E^2 dJ/dE [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
0.1
1
10
100
E [GeV]



Gamma-ray spectrum for $m_{3/2}$ = 250 GeV
E^2 dJ/dE [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
0.1
1
10
100
E [GeV]

II- Signatures for colliders

The signatures depend on the nature of the NLSP (stau/neutralino)

- If the NLSP is a (mainly right-handed) stau
  - Main decay: $\widetilde{\tau}_R \longrightarrow \tau\ \nu_\mu, \mu\ \nu_\tau$ (through $\lambda L L e^c$)

$$c\tau_{\tilde{\tau}}^{lep} \sim 30\ \mathrm{cm} \left(\frac{m_{\tilde{\tau}}}{200\mathrm{GeV}}\right)^{-1} \left(\frac{\epsilon_2}{10^{-7}}\right)^{-2} \left(\frac{\tan\beta}{10}\right)^{-2}$$

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- If the NLSP is a neutralino
  - Main decays: $\chi^0_1 \to \tau^\pm W^\mp$, or $\chi^0_1 \to b\, b^c\, \nu$

    $$c\tau^{2-\text{body}}_{\chi^0_1} \sim 20 \text{ cm} \left(\frac{m_{\chi^0_1}}{200 \text{ GeV}}\right)^{-3} \left(\frac{\epsilon_3}{10^{-7}}\right)^{-2} \left(\frac{\tan\beta}{10}\right)^{2}$$

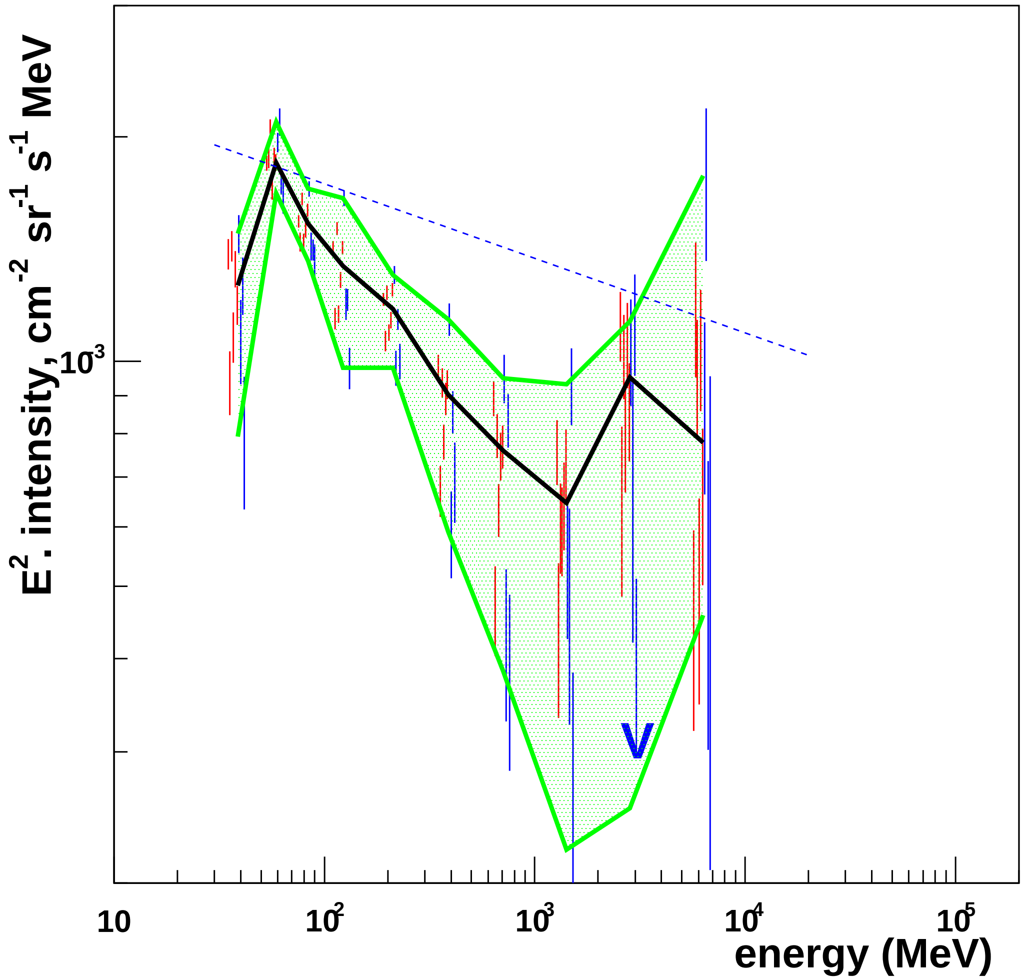
    $$c\tau^{3-\text{body}}_{\chi^0_1} \sim 600 \text{ m} \left(\frac{m_{\tilde{\nu}_L}}{300 \text{ GeV}}\right)^{4} \left(\frac{m_{\chi^0_1}}{200 \text{ GeV}}\right)^{-5} \left(\frac{\epsilon_3}{10^{-7}}\right)^{-2} \left(\frac{\tan\beta}{10}\right)^{-2}$$

    If the neutralino decays inside the detector, jets will be observed.

Conclusions

- During the 20th century, a consistent thermal history of the Universe was outlined. The recent discoveries of dark matter and dark energy require a revision of the thermal history.
- We have concentrated on incorporating the supersymmetric dark matter into the thermal history of the Universe.
- The requirements of succesful thermal leptogenesis and Big Bang Nucleosynthesis essentially lead to a scenario with gravitino dark matter and tiny R-parity violation.
- The photons from the gravitino decay contribute to the diffuse gamma background. They may have already been observed by EGRET. Future experiments, such as GLAST, AMS-02 or Cherenkov telescopes, will provide unique oportunities to test this scenario. A flux of positrons, antiprotons and neutrinos is also expected $\longrightarrow$ in preparation
- This scenario predicts striking signatures at the LHC, in particular a vertex of the NLSP significantly displaced from the beam axis.

Isotropy of the signal



Strong, Moskalenko, Reimer

l	b	Intensity 0.1-10 GeV	Description
0–360	$< -10, > +10$	11.10 ± 0.12	N+S hemispheres
0–360	< -10	11.70 ± 0.15	N hemisphere
0–360	$> +10$	9.28 ± 0.21	S hemisphere
270–90	$< -10, > +10$	11.90 ± 0.17	Inner Galaxy N+S
90–270	$< -10, > +10$	9.75 ± 0.17	Outer Galaxy N+S
0–180	$< -10, > +10$	10.80 ± 0.17	Positive longitudes N+S
180–360	$< -10, > +10$	11.60 ± 0.16	Negative longitude N+S
270–90	$> +10$	13.00 ± 0.22	Inner Galaxy N
270–90	< -10	9.14 ± 0.32	Inner Galaxy S
90–270	$> +10$	10.60 ± 0.22	Outer Galaxy N
90–270	< -10	8.18 ± 0.34	Outer Galaxy S