Indirect signatures of Gravitino Dark Matter

Alejandro Ibarra

DESY

In collaboration with

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

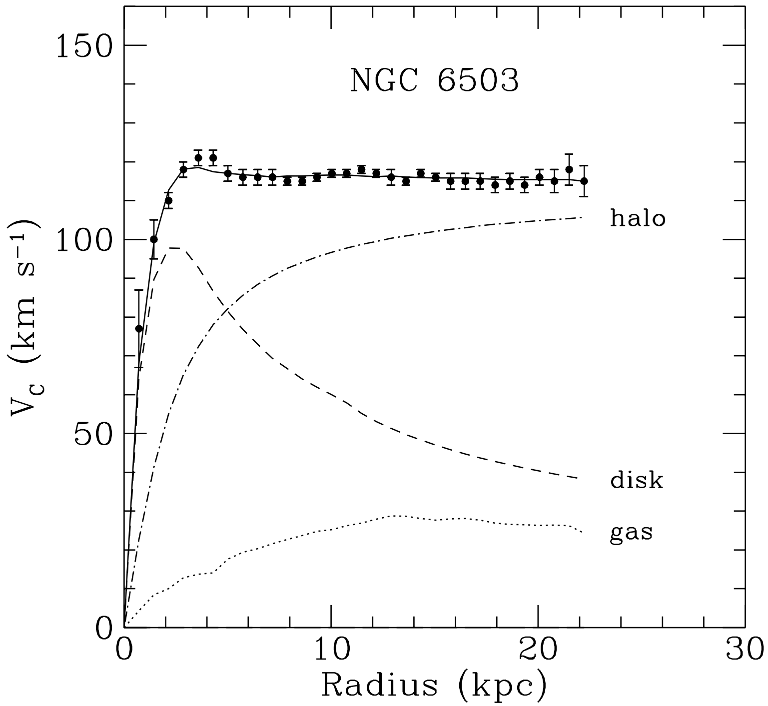
G . Bertone, W. Buchmüller, L. Covi (JCAP11(2007)003)

D. Tran (Phys.Rev.Lett.100,061301 (2008) and work in progress)

SFB tagung
Zeuthen
14th February 2008

Introduction

Many evidences of dark matter at different scales



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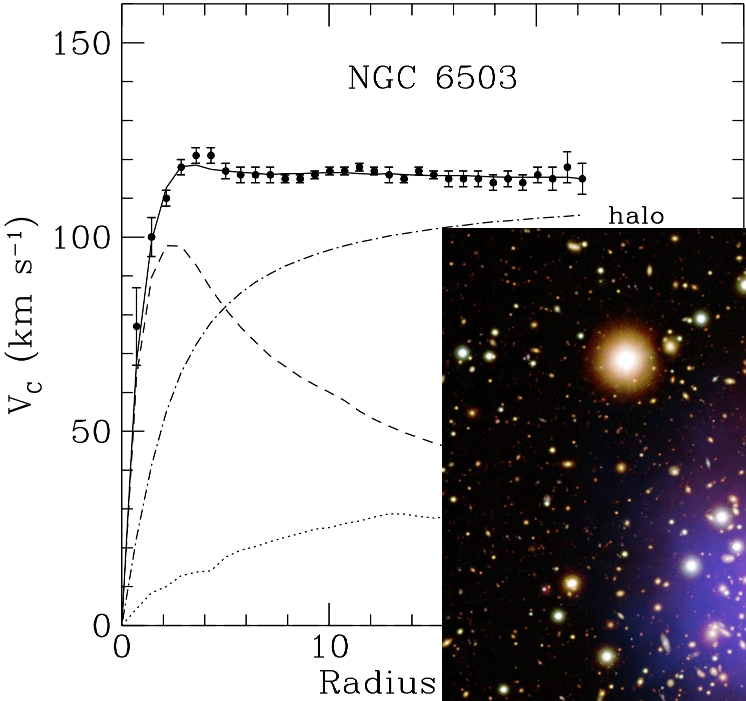

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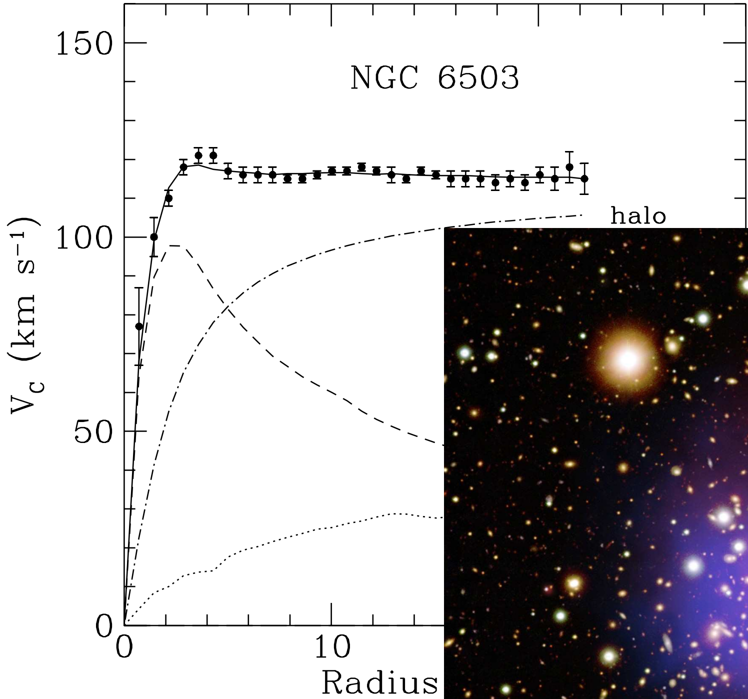

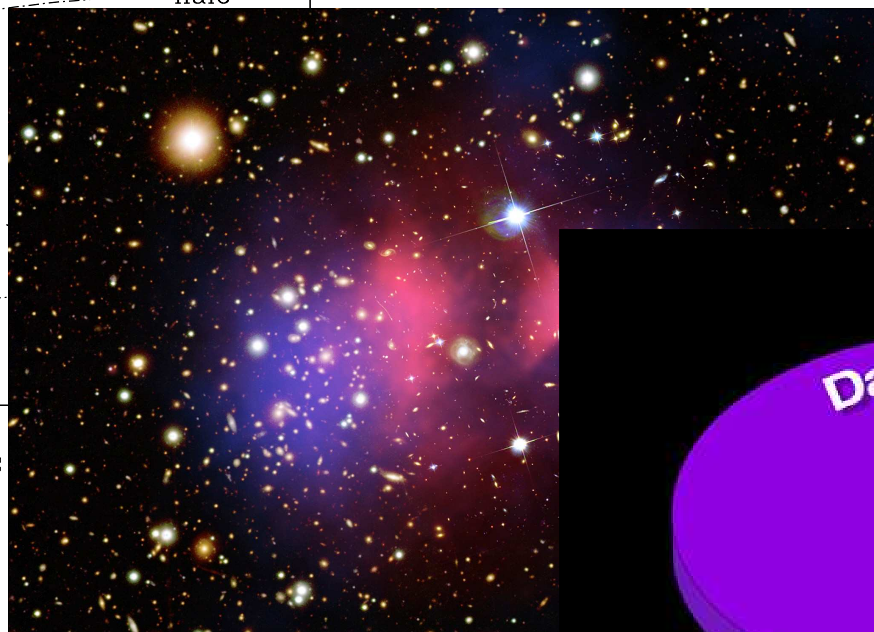

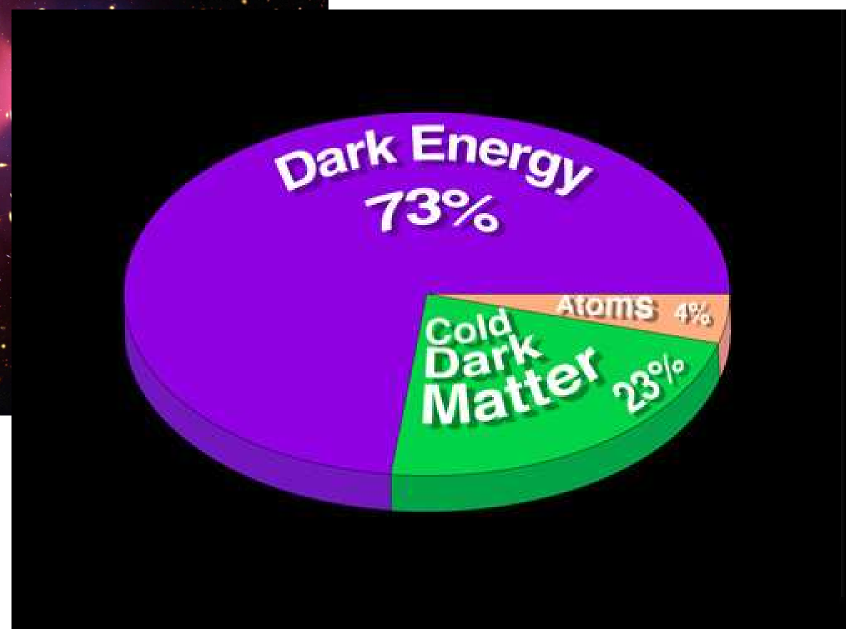

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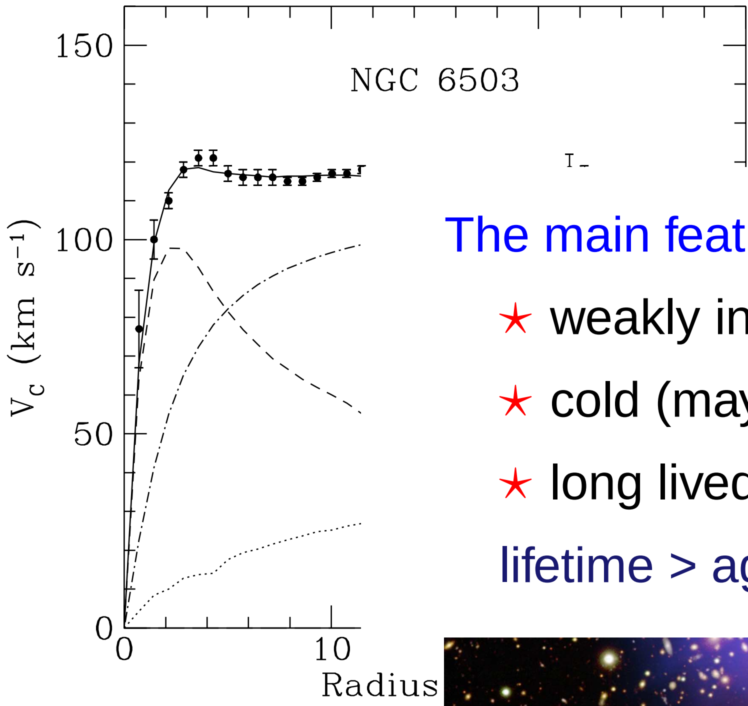
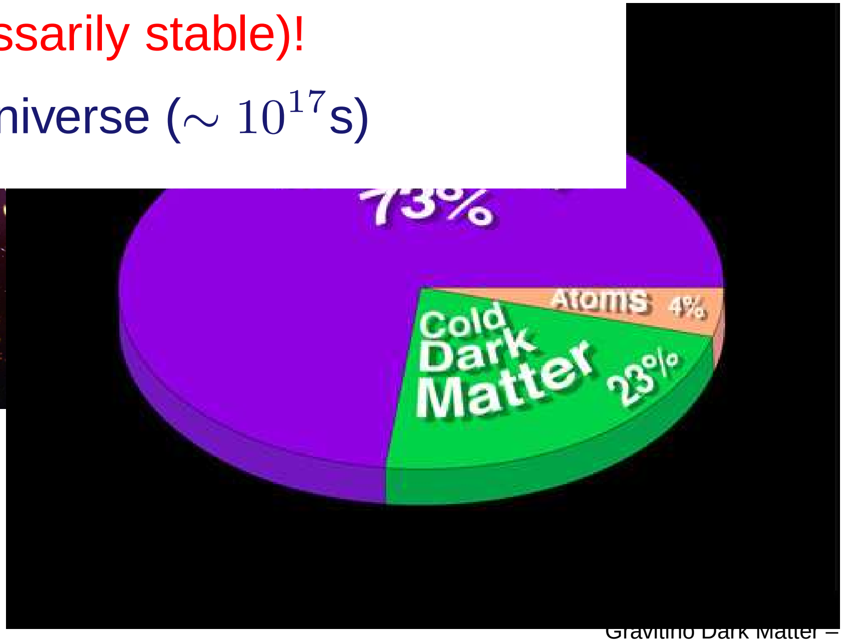


The main features of any dark matter candidate are:

- ⋆ weakly interacting
- ⋆ cold (may be warm)
- ⋆ long lived (not necessarily stable)!

lifetime > age of the Universe ($\sim 10^{17}$s)



Candidates for dark matter

Many! Some interesting candidates are:

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- Axions
- Heavy sterile neutrinos

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- Neutralinos (requires R-parity)
- Gravitinos
- Axinos
- Lightest Kaluza-Klein particle
- ...

from Alessandro Strumia

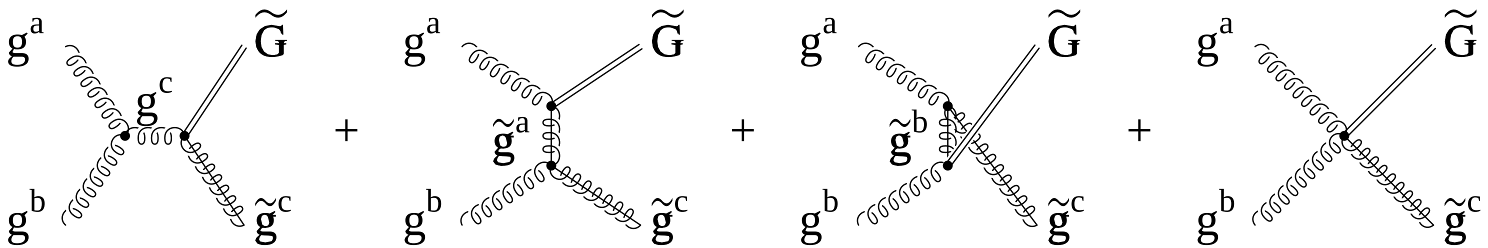
Neutrino (excluded), sterile neutrino, right-handed neutrino, neutralino, higgsino, bino, photino, wino, gravitino, sneutrino, possibly split or anthropic, right-handed sneutrino, scalar singlet, singlino, Kaluza Klein LKP: graviton$_1$, photon$_1$, neutrino$_1$, Z_1, Z', axion, axino, B-balls, Q-balls, odd-balls, inflatino, quintissencino, scalar condensate, Pseudo-Goldstone, ultra light PG, radion, radino, modulus, modulinos, Planck relicts, quark nugget, encapsulated atoms, top bound state, shadow matter, mirror matter, branon, branino, normal matter on folded brane or on another brane or membrane or D-brane or p-brane, cosmic string, cosmic necklace, mini black hole, soliton, monopole, techni-baryon, techni-meson, Chaplygin gas, fuzzy DM, WIMPzilla, familion, famili
CP pseudoscalar, preon, dilaton, doubly-charged lepton, degenerate fermion, kination, H dibaryon, crypton, hiddenon, heterotic, d-quark from Wilson lines, 4th generation, ...

Why the gravitino?

Gravitino dark matter

When the gravitino is the lightest supersymmetric particle, it constitutes a very interesting (and promising!) candidate for the dark matter of the Universe.

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



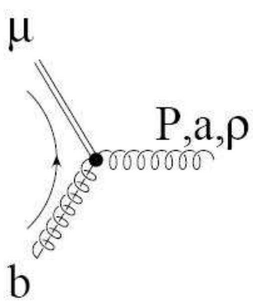
- Also produced by non-thermal processes (inflaton decay, NLSP decay)

The existence of relic gravitinos is *unavoidable*. Whether they constitute the dark matter or not is just a quantitative question.

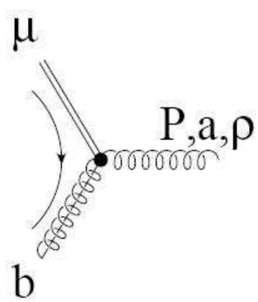
- The interactions of the gravitino with the MSSM particles are fixed by the symmetries

- Gravitino-gluon-gluino:

From M. Bolz



$$= -\frac{i}{4M}\delta_{ab}[\not{P}, \gamma^{\rho}]\gamma^{\mu};$$



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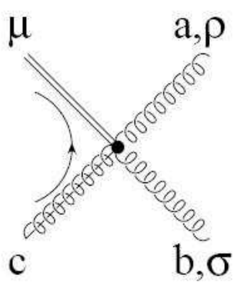
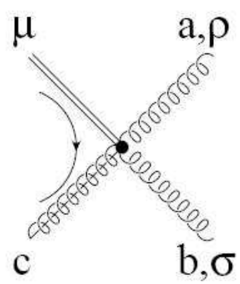


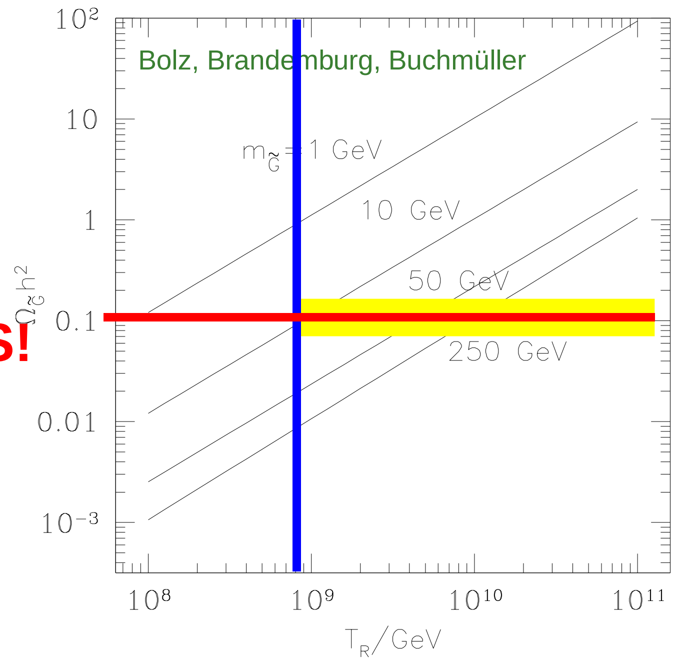
$$= -\frac{1}{4M} g f^{abc}[\gamma^{\rho}, \gamma^{\sigma}]\gamma^{\mu};$$



$$= -\frac{1}{4M} g f^{abc}\gamma^{\mu}[\gamma^{\rho}, \gamma^{\sigma}]$$

- The interactions of the gravitino with the MSSM particles are fixed by the symmetries
- The relic abundance is calculable in terms of very few parameters

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



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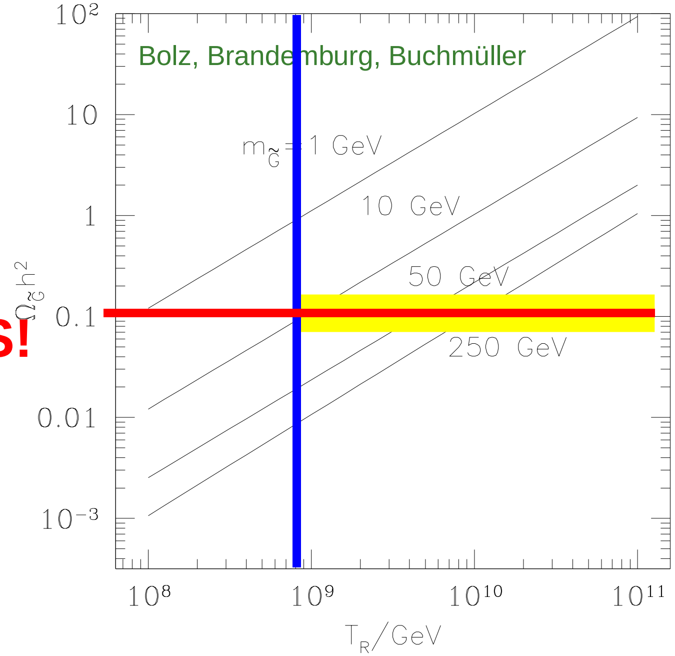

NICELY COMPATIBLE WITH LEPTOGENESIS!

($T_R \gtrsim 10^9$GeV)

- However, it is undetectable in direct searches.
  This is a disadvantage rather than a problem.

- There is a potential conflict between leptogenesis and Big Bang Nucleosynthesis.

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

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

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  The leptogenesis constraint $T_R \gtrsim 10^9$ GeV requires for gravitino dark matter $m_{3/2} \gtrsim 5$ GeV. Then,

$$\tau_{\rm NLSP} \simeq 2 \text{ days} \left(\frac{m_{3/2}}{5 \text{ GeV}}\right)^2 \left(\frac{150\text{GeV}}{m_{\rm NLSP}}\right)^5$$

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

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

gravitino LSP

neutralino NLSP

$\chi_1^0 \rightarrow \psi_{3/2}$ hadrons

Hadrodissociation of primordial elements

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 gravitino dark matter

Root of all the problems: the NLSP is very long lived.

Simple solution: 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:

$$W = W_{MSSM} + \mu_i(H_u L_i) + \frac{1}{2}\lambda_{ijk}(L_i L_j)e_k^c + \lambda'_{ijk}(Q_i L_j)d_k^c + \lambda''_{ijk}(u_i^c d_j^c d_k^c)$$

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

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

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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 no longer stable, 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: A scenario with the gravitino as LSP with a mass in the range 5-300 GeV, and a small amount of R-parity violation, $10^{-14} \lesssim \lambda, \lambda' \lesssim 10^{-7}$, provides a good candidate for dark matter and provides a consistent thermal history of the Universe (allows leptogenesis and successful BBN).

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The gravitino is still undetectable in direct dark matter searches. But the R-parity violating decay of the gravitino into photons, positrons, antiprotons and neutrinos opens the possibility of the indirect detection.

DATA!

Gamma rays

Gravitinos with a mass of several GeV decay producing photons in the GeV range $\longrightarrow$ gamma rays.

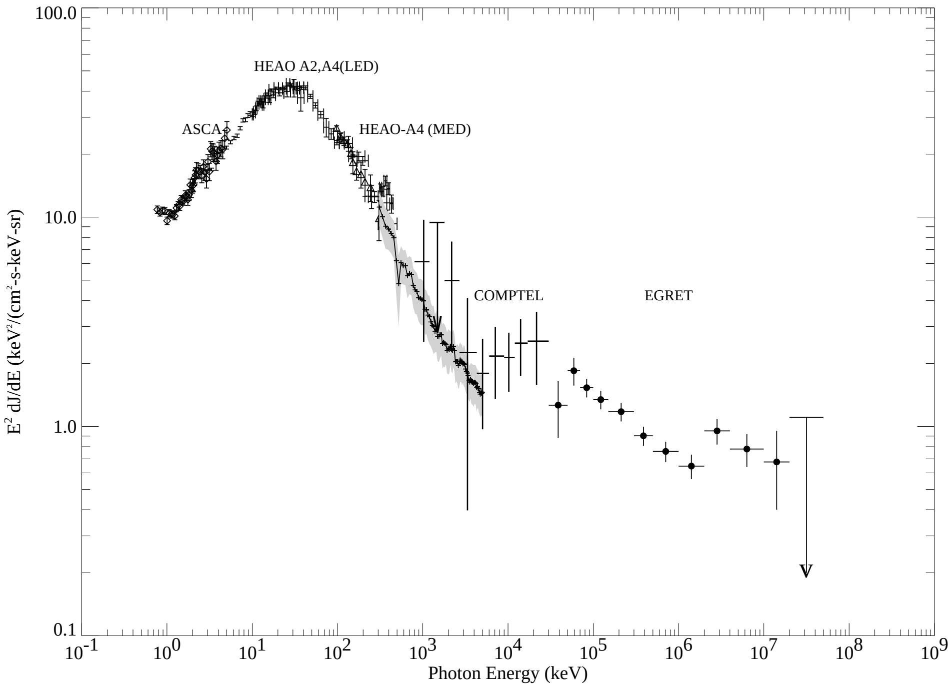
EGRET measured gamma rays with energies between 30 MeV and 100 GeV.

The first analysis from Sreekumar *et al.* gave an extragalactic flux described by the power law

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

Close to the prediction for the γ- ray flux from gravitino decay when $\lambda \simeq 10^{-7}$!!

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!!



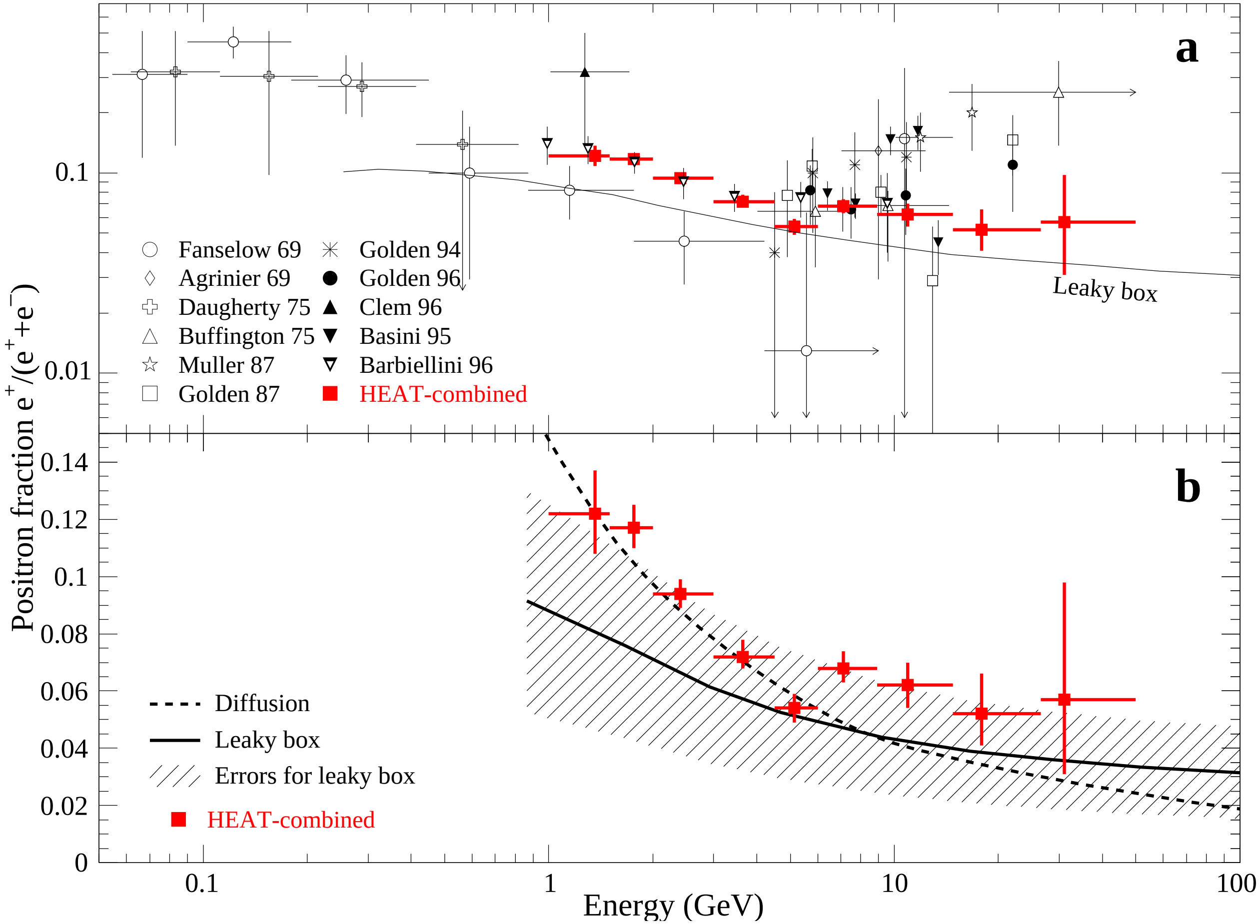
The photon flux from the decay of gravitinos may be hidden in this excess.

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.

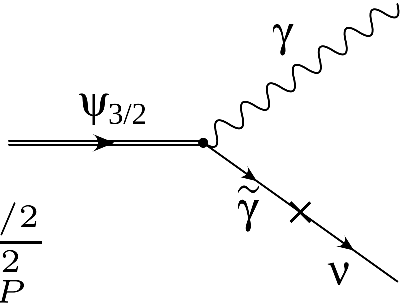
Positrons



PAMELA will provide an accurate measurement of the positron fraction.

Gravitino decay channels

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



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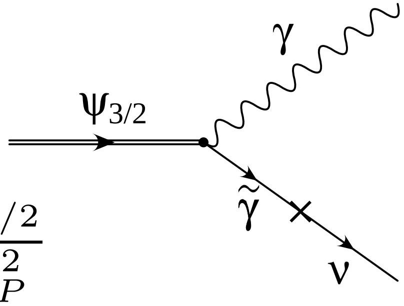

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- “not-so-light” gravitino $100 \text{ GeV} \lesssim m_{3/2} \lesssim 300 \text{ GeV}$
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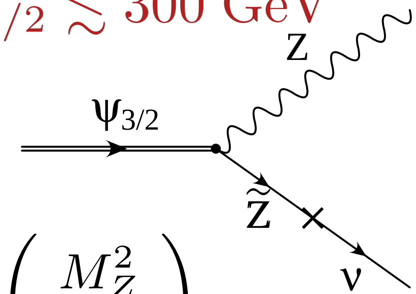

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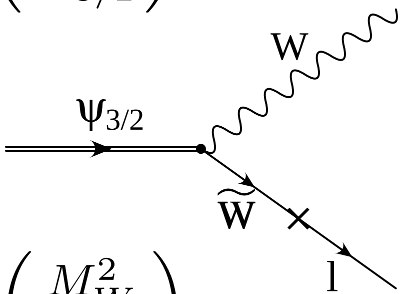

$$\Gamma(\psi_{3/2} \to W^\pm \ell^\mp) = \frac{2}{32\pi} |U_{\tilde{W}\ell}|^2 \frac{m_{3/2}^3}{M_P^2} f\left(\frac{M_W^2}{m_{3/2}^2}\right)$$

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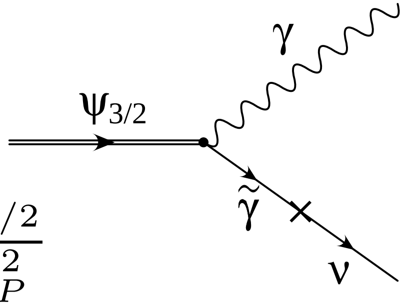

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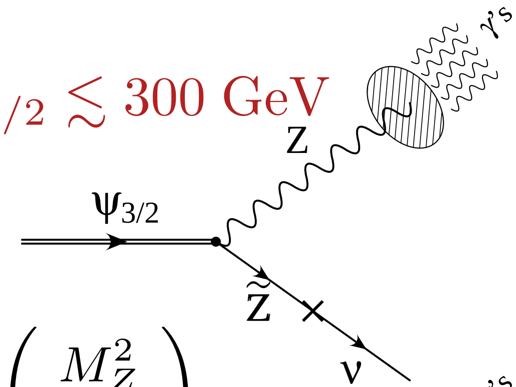

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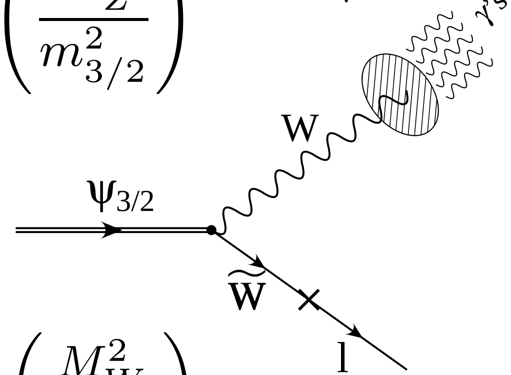

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Gamma-ray flux from gravitino decay

The energy spectrum of photons from gravitino decay is

$$\frac{dN_\gamma}{dE} \simeq \; \mathsf{BR}(\psi_{3/2} \to \gamma\nu)\; \delta\left(E - \frac{m_{3/2}}{2}\right) \; + \; \mathsf{BR}(\psi_{3/2} \to W\ell)\; \frac{dN_\gamma^W}{dE} \; + \; \mathsf{BR}(\psi_{3/2} \to Z^0\nu)\; \frac{dN_\gamma^Z}{dE}$$

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The branching ratios are determined by the relative size of the mixing parameters

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

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

Assuming gaugino mass universality at the Grand Unified Scale,

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

$m_{3/2}$	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

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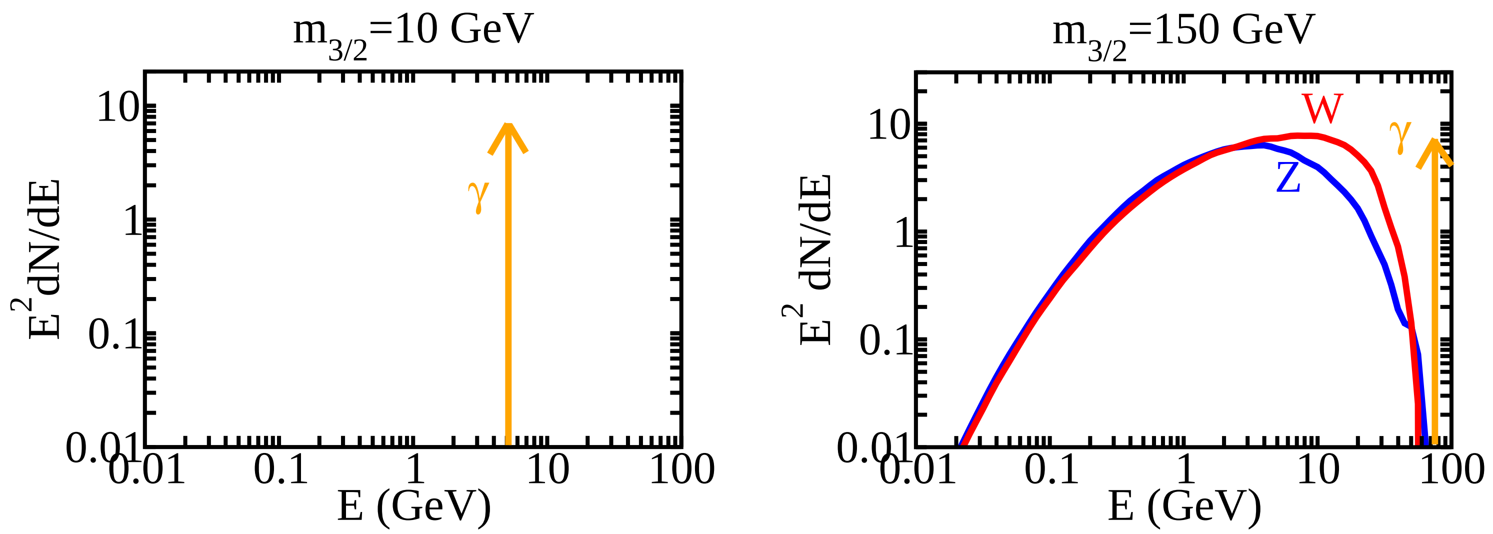
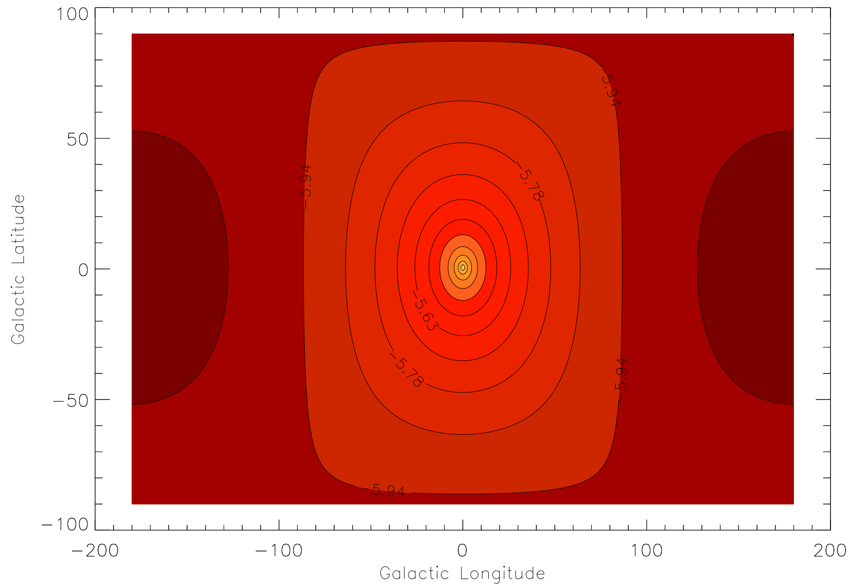


Gamma ray spectrum

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

  The precise value of the flux 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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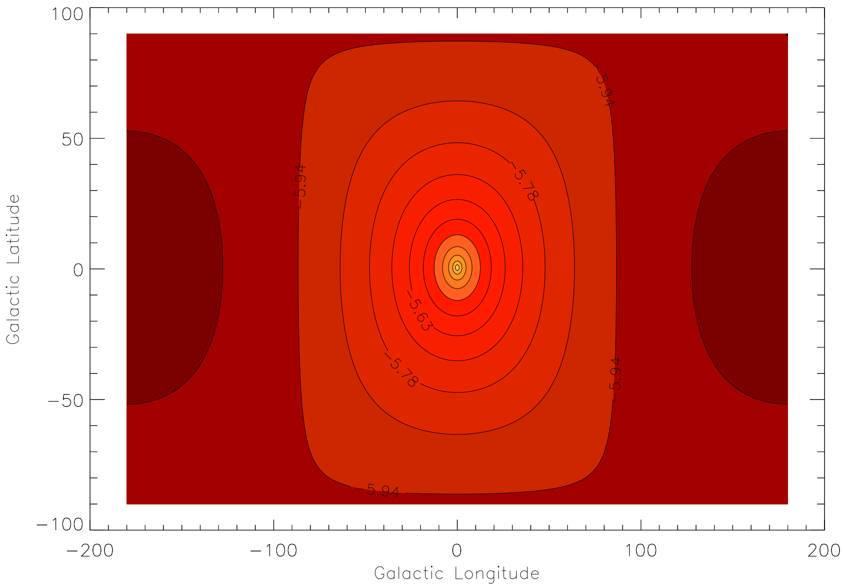
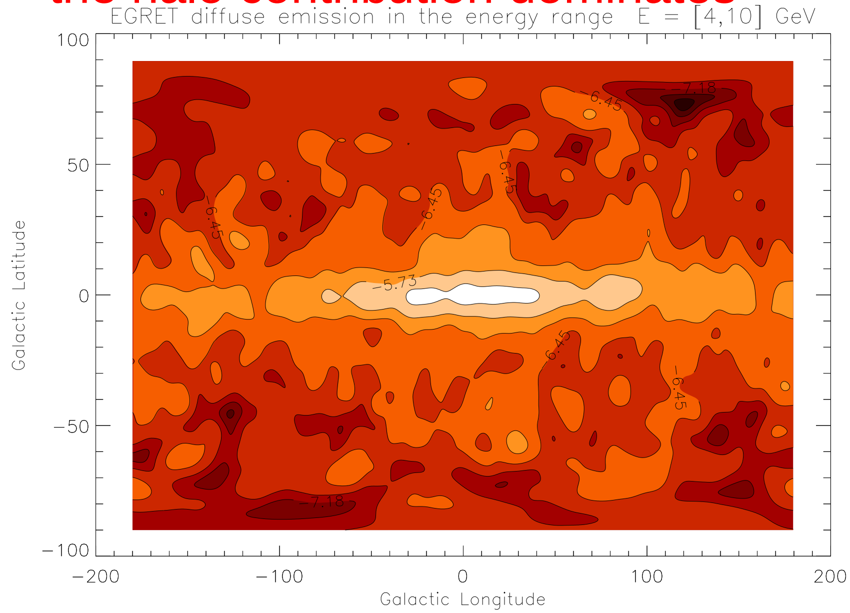
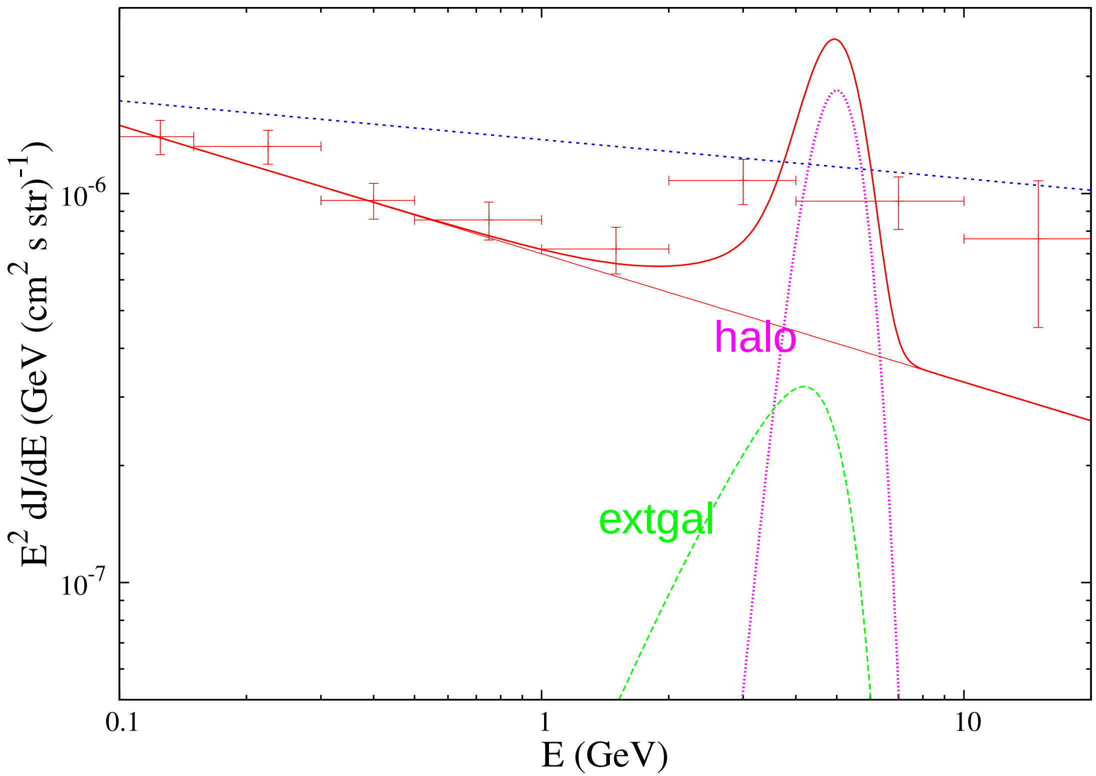




γ ray spectrum for light gravitinos $m_{3/2} \lesssim M_W$

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



$m_{3/2} = 10$ GeV, $\tau_{3/2} = 10^{27}$ s

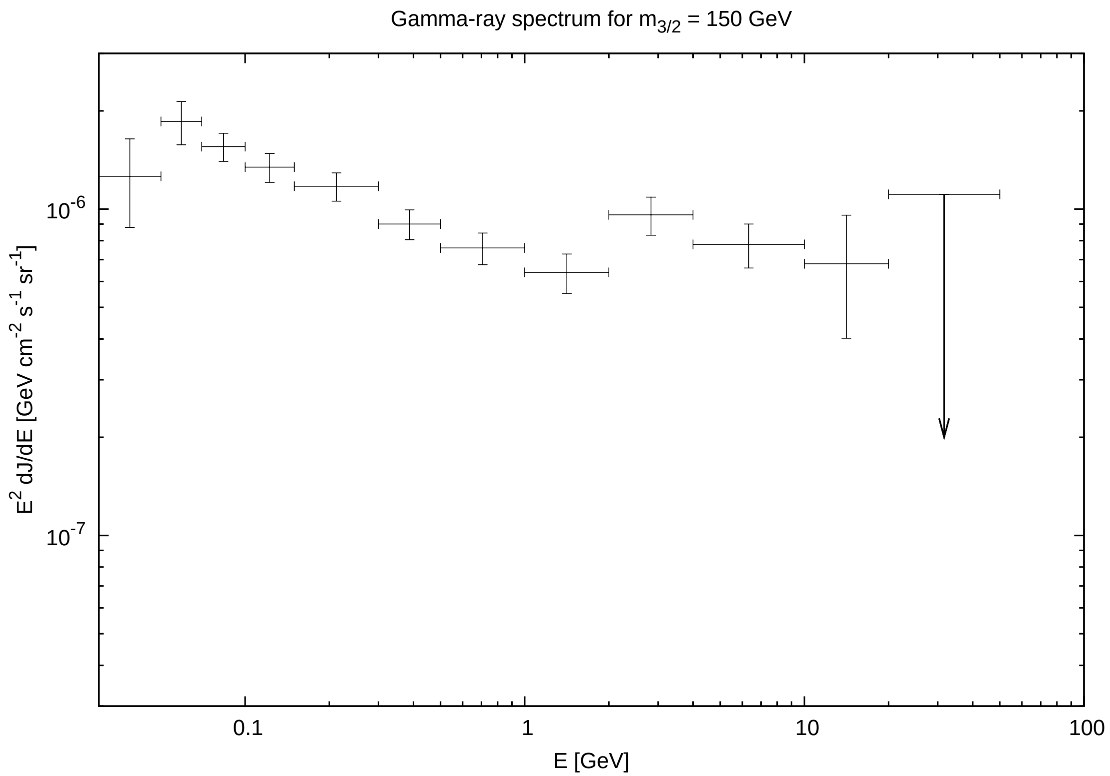
Bertone, Buchmüller, Covi, AI

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.

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



AI, Tran

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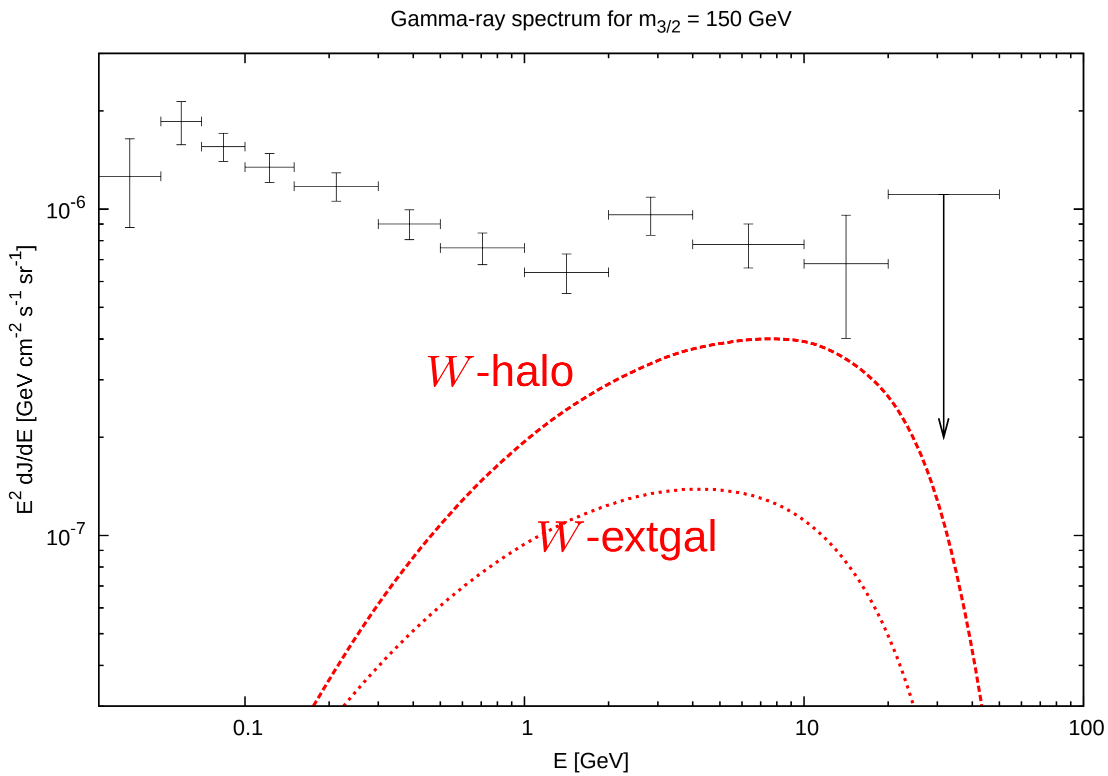

AI, Tran

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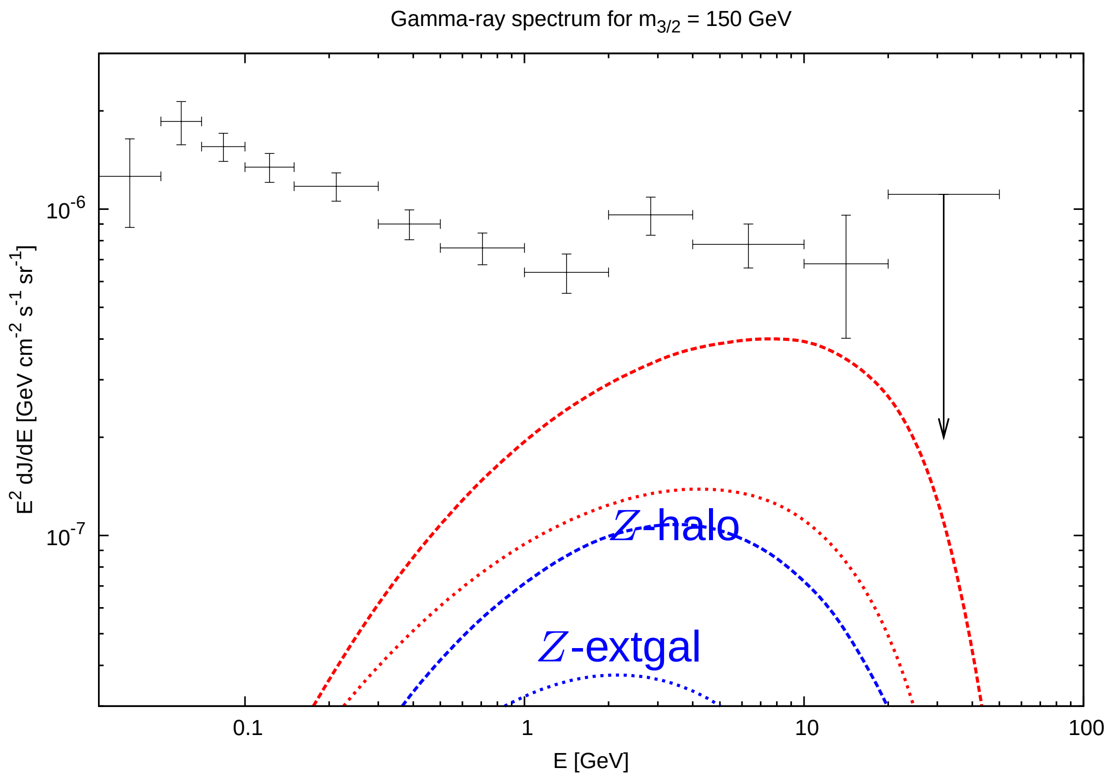

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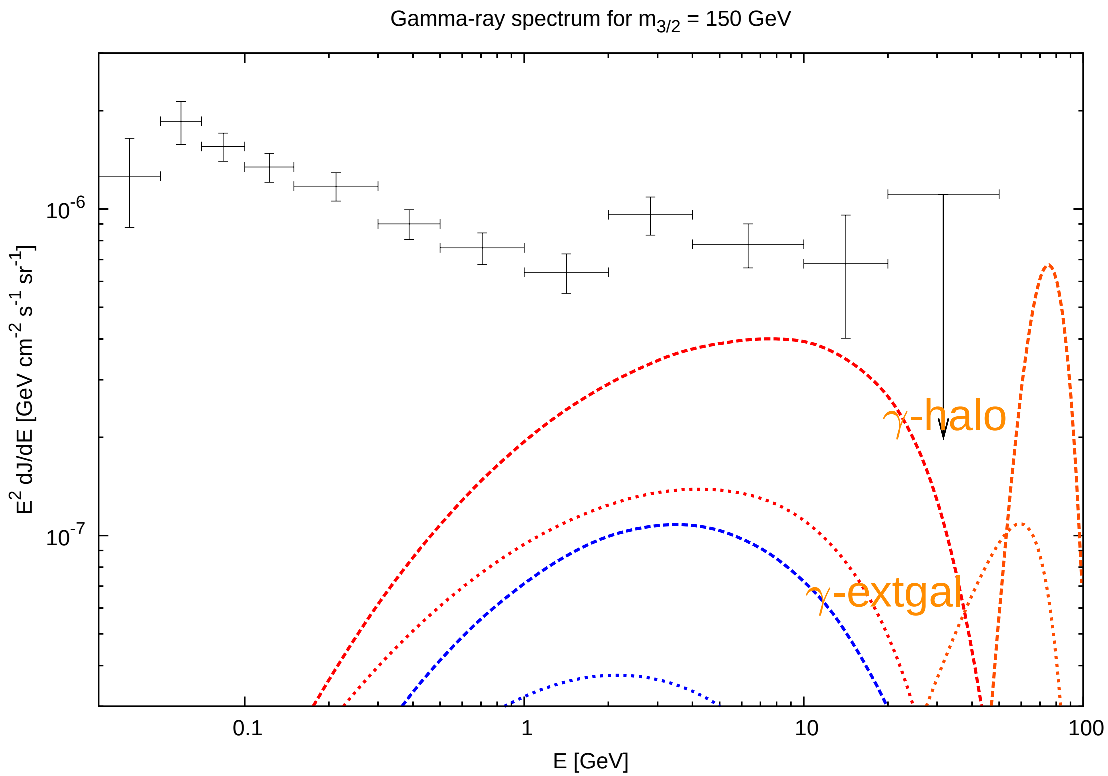

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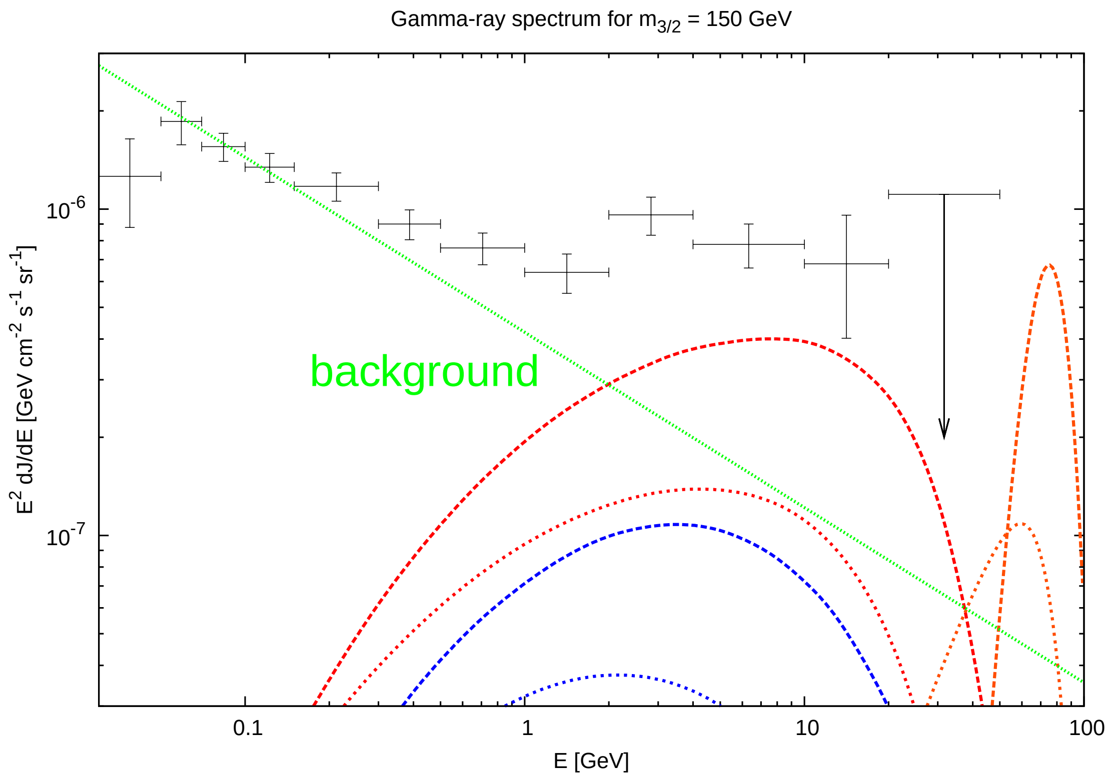

AI, Tran

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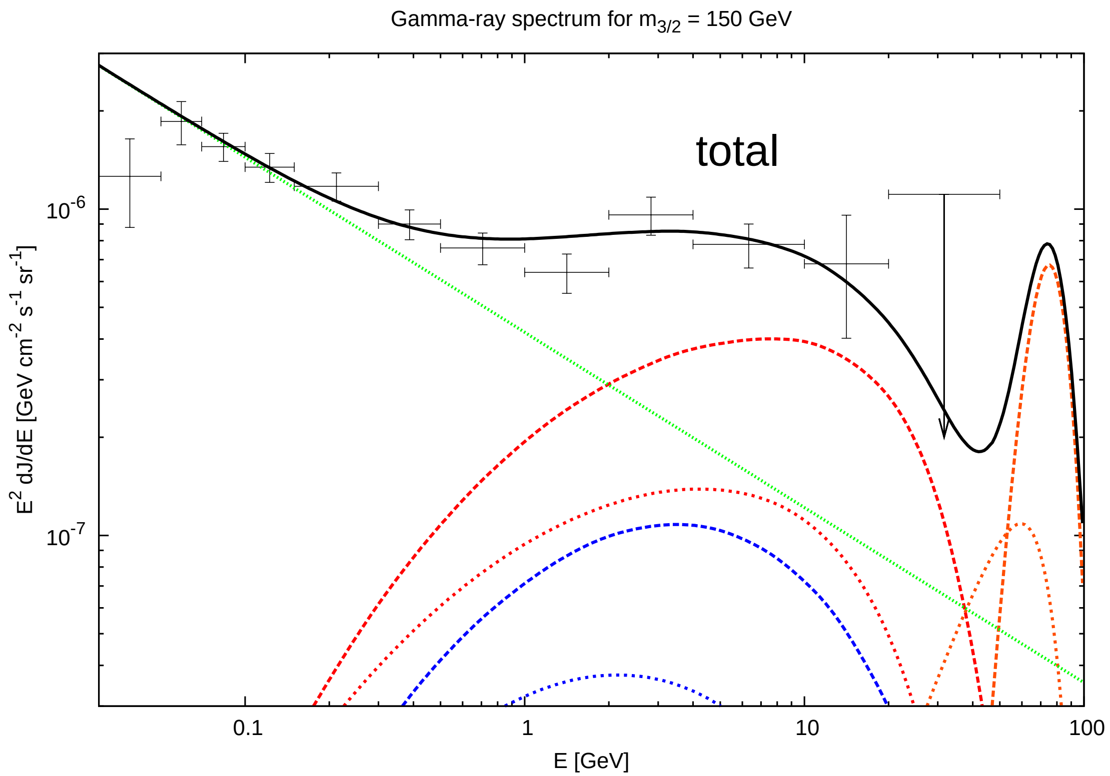
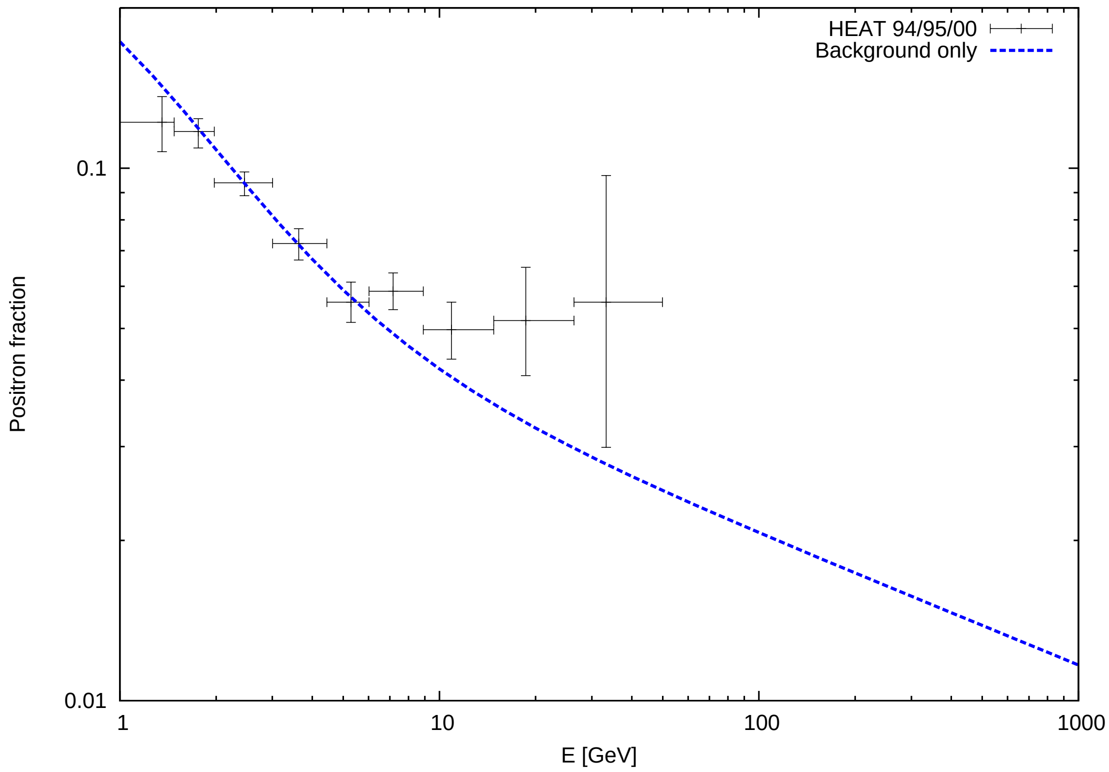


AI, Tran

$$\tau_{3/2} = 1.6 \times 10^{26}\mathrm{s} \Longrightarrow |U_{\widetilde{\gamma}\nu}| \simeq 2 \times 10^{-10}$$

Positron fraction

- The fragmentation of the W and Z bosons produces positrons.
- The positrons travel under the influence of the tangled magnetic field of the galaxy and lose energy $\longrightarrow$ Complicated propagation equation.



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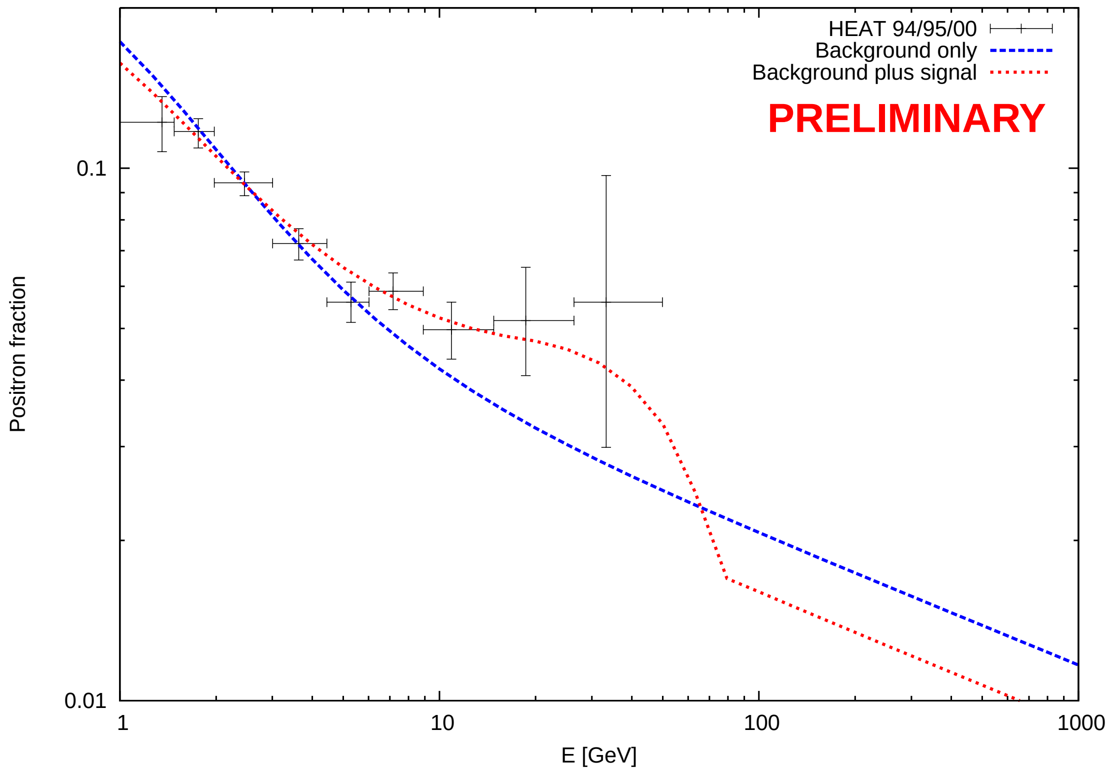

EGRET parameters: $m_{3/2} = 150$ GeV, $\tau_{3/2} = 1.6 \times 10^{26}\mathrm{s}$

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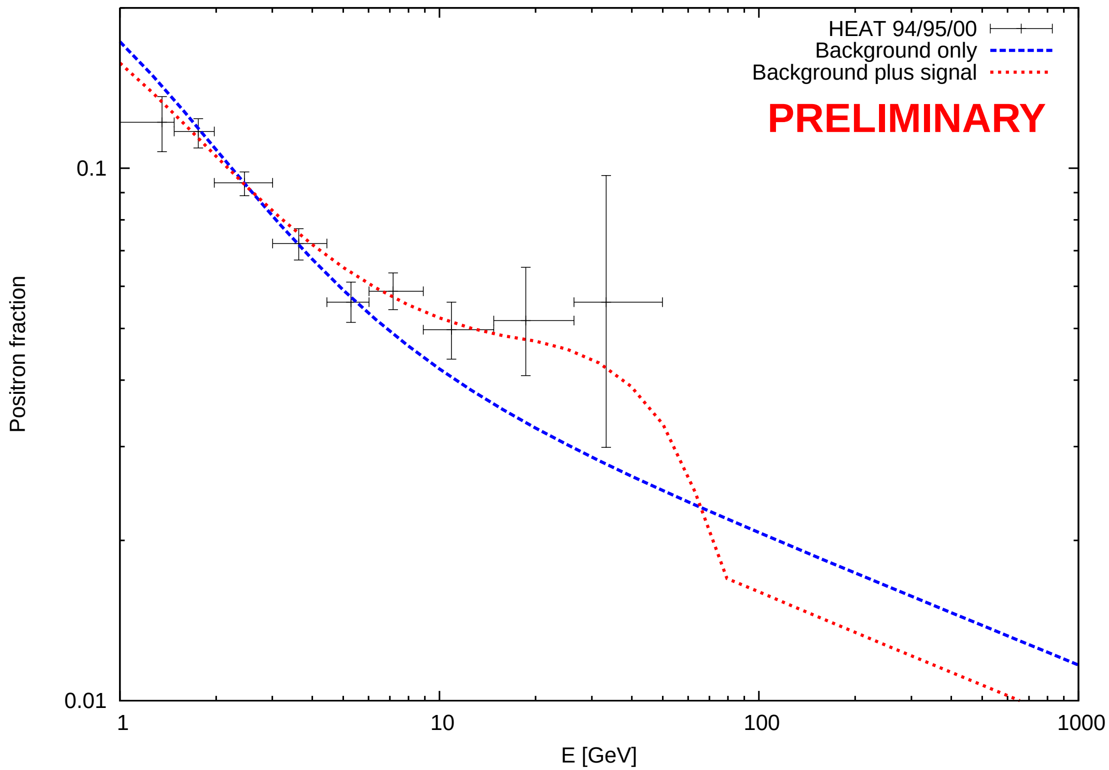

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Improved data from PAMELA soon!

Wish list

What will make me believe in decaying gravitino dark matter

1– No positive signal from direct dark matter search experiments.

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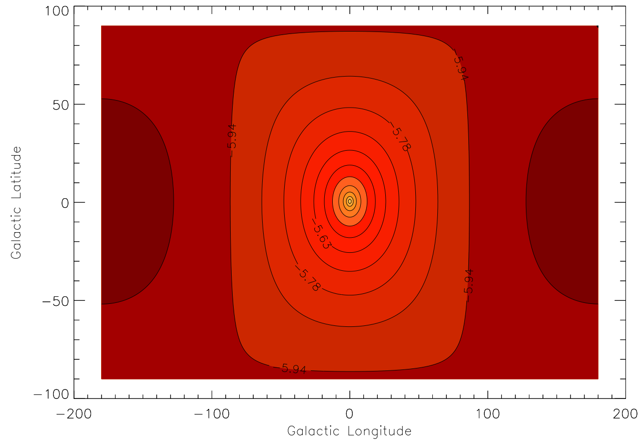

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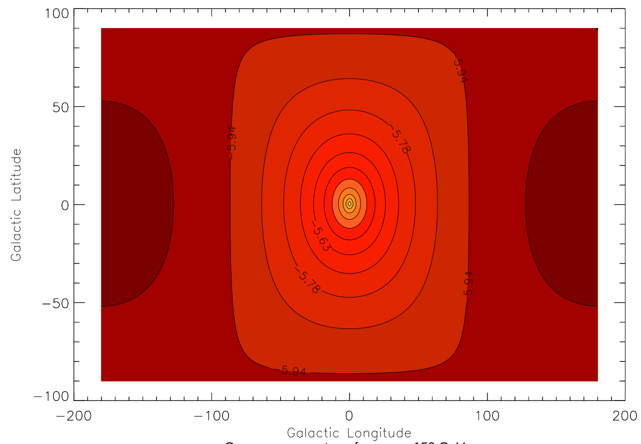
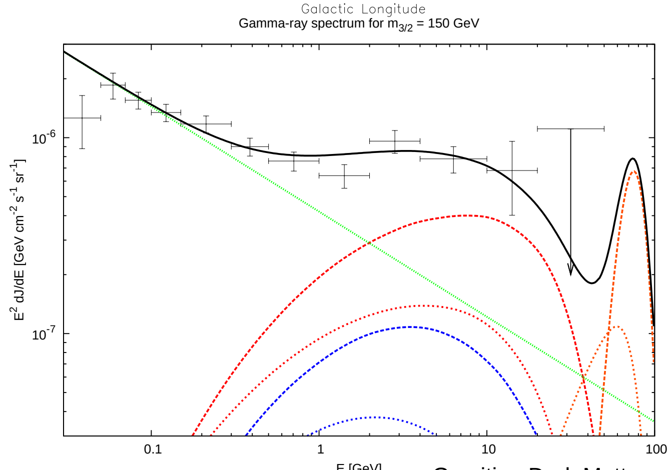


4– The energy spectrum of gamma rays is consistent with decaying gravitino dark matter $\longrightarrow m_{3/2}^{(\gamma)}, \tau_{3/2}^{(\gamma)}$.



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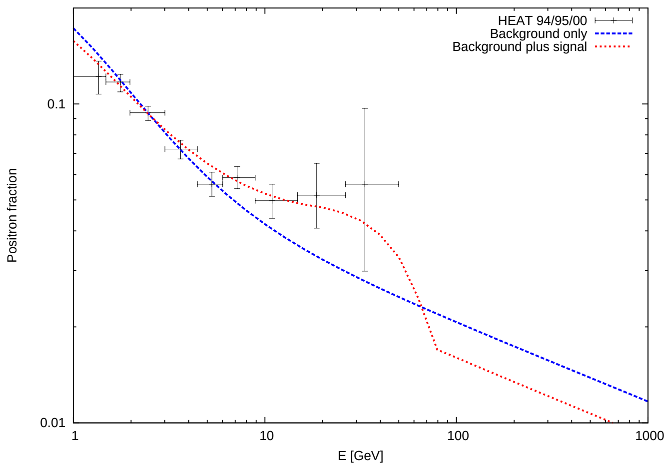

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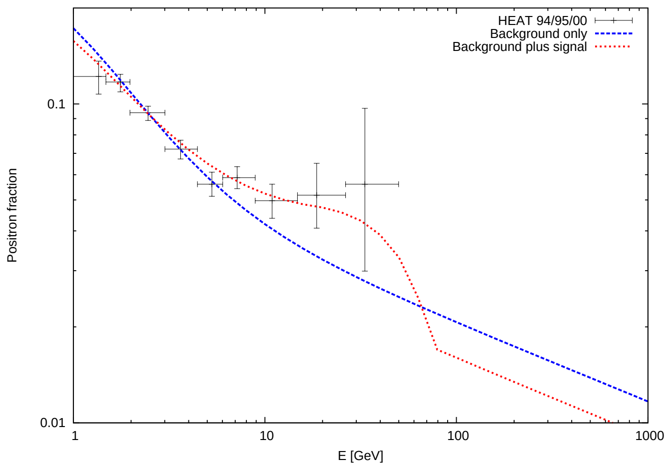
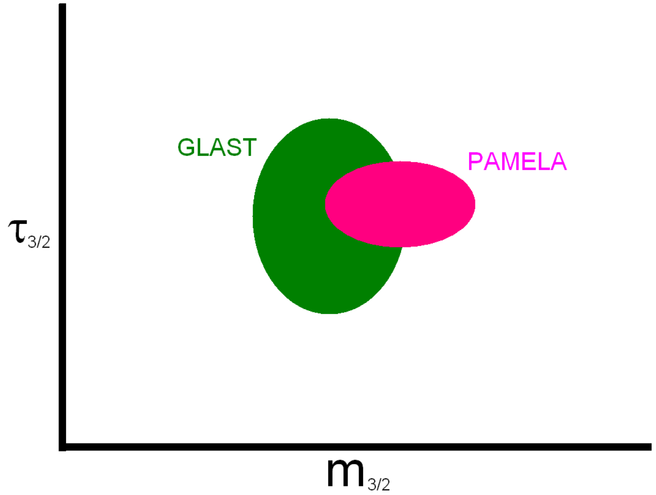


7– $m_{3/2}^{(\gamma)} \simeq m_{3/2}^{(e^+)}$
$\tau_{3/2}^{(\gamma)} \simeq \tau_{3/2}^{(e^+)}$.



8– Low energy supersymmetry is discovered at the LHC.

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9– If the stau is the NLSP, the main decay is $\widetilde{\tau}_R \longrightarrow \tau\ \nu_\mu, \mu\ \nu_\tau$ (through $\lambda L L e^c$)

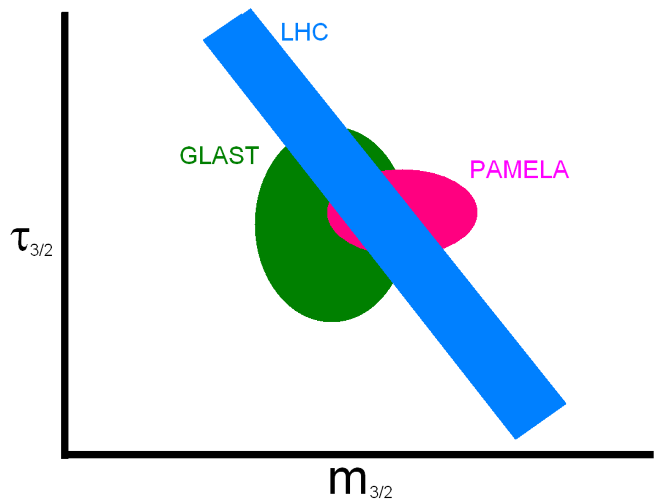
$$c\tau_{\tilde{\tau}}^{\rm lep} \sim 15\ {\rm cm} \left(\frac{m_{\tilde{\tau}}}{400{\rm GeV}}\right)^{-1} \left(\frac{\lambda_{323}}{10^{-8}}\right)^{-2}$$

Long heavily ionizing charged track followed by a muon track or a jet.

A very spectacular signal at colliders!

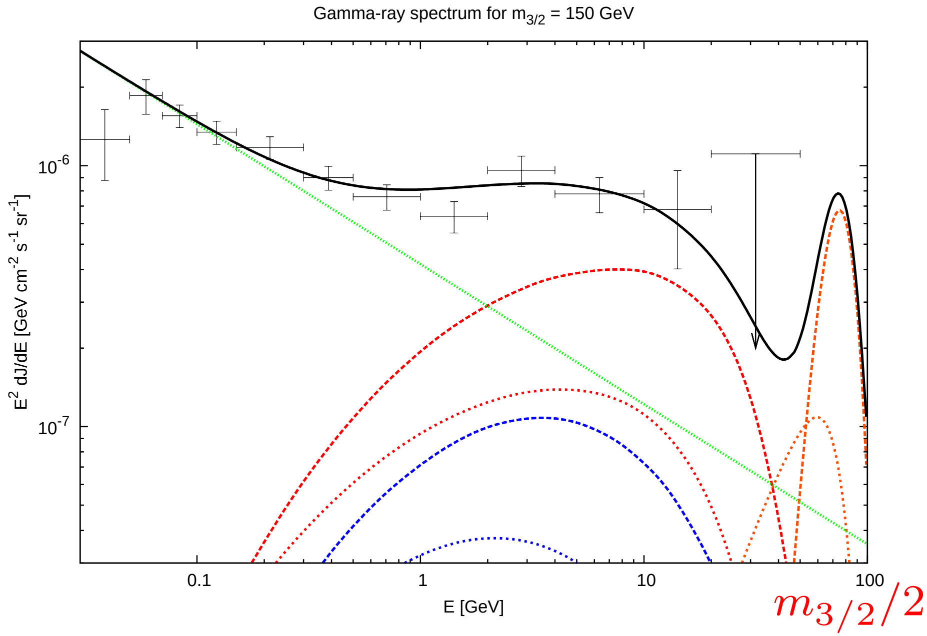
The determination of the R-parity violating coupling would lead to a relation of the gravitino lifetime and the gravitino mass:

$$\tau_{3/2} \sim 10^{26}{\rm s} \left(\frac{m_{3/2}}{150{\rm GeV}}\right)^{-3} \left(\frac{m_{\tilde{\tau}}}{400{\rm GeV}}\right) \left(\frac{\tau_{\tilde{\tau}}}{10^{-8}{\rm s}}\right)$$



Gamma rays as a thermometer of the Universe?

If the scenario of decaying dark matter turns out to be correct, there might be a chance of measuring the temperature of the early Universe.



The thermal relic abundance of gravitinos is given by

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

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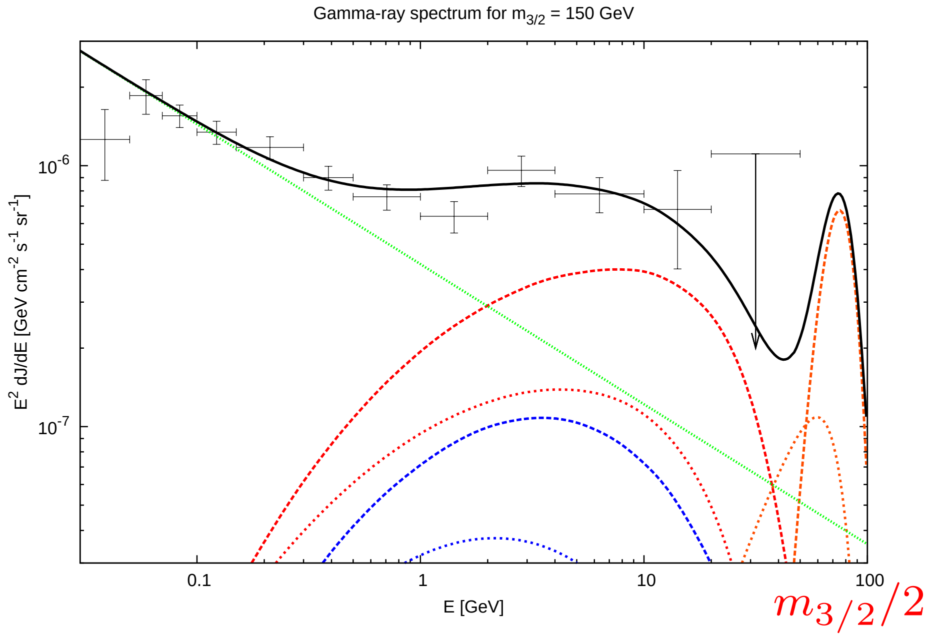

If there is only thermal production

$$T_R \simeq 3\times 10^{10}\mathrm{GeV}\left(\frac{\Omega_{3/2}h^2}{0.1}\right)\left(\frac{m_{3/2}}{150\mathrm{GeV}}\right)\left(\frac{m_{\tilde{g}}}{500\,\mathrm{GeV}}\right)^{-2}$$

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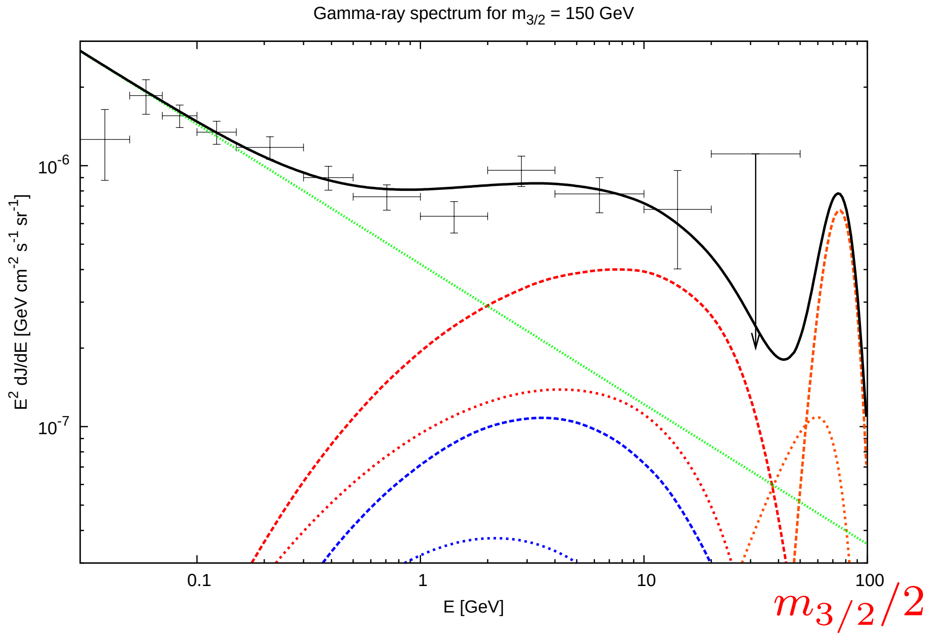


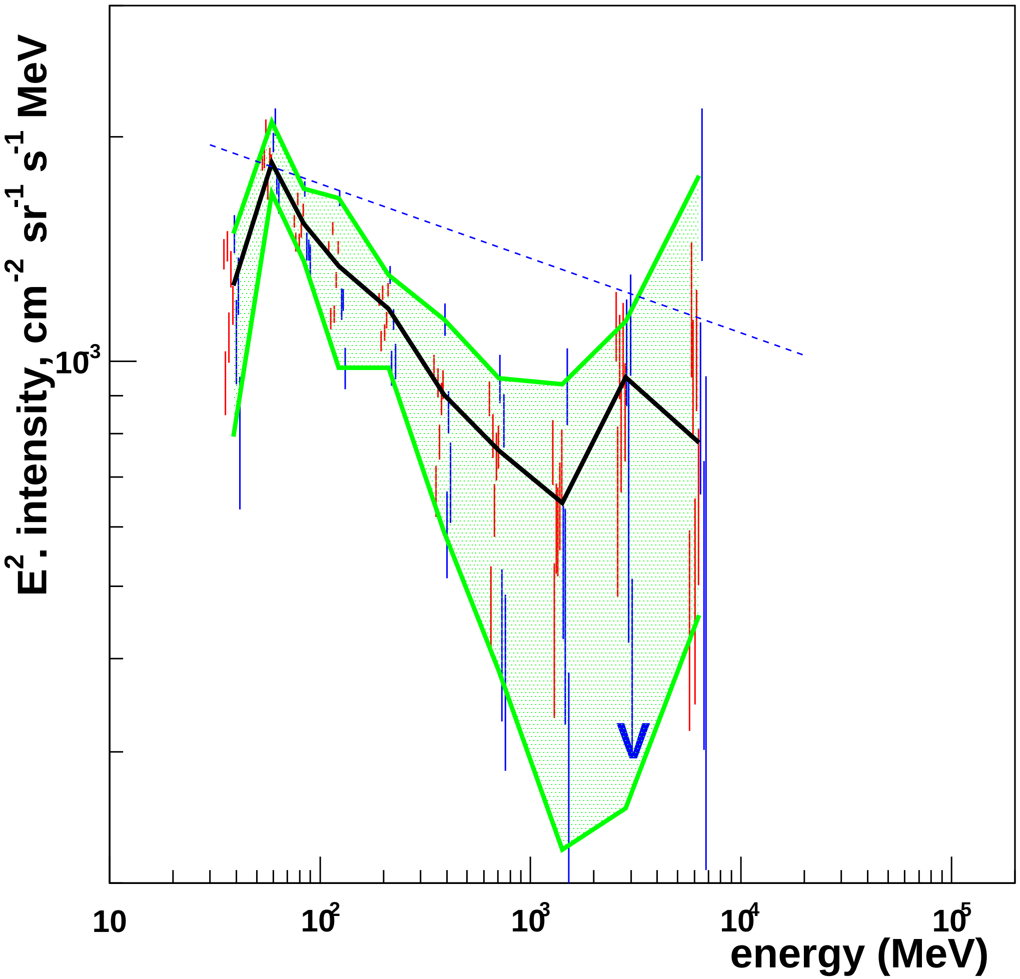
In general

$$T_R \lesssim 3 \times 10^{10} \text{GeV} \left(\frac{\Omega_{3/2} h^2}{0.1} \right) \left(\frac{m_{3/2}}{150 \text{GeV}} \right) \left(\frac{m_{\tilde{g}}}{500\,\text{GeV}} \right)^{-2}$$

Conclusions

- Gravitino dark matter is a very interesting scenario.
- Gravitino dark matter with R-parity violation is even more interesting. The potential conflict of BBN and leptogenesis is automatically solved, while preserving the nice features of the gravitino as dark matter. Also, indirect detection might be possible!
- The anomalies observed in the extragalactic gamma-ray flux (EGRET) and the positron fraction (HEAT) can be simultaneously explained by the decay of the gravitino.
- Future experiments (GLAST, PAMELA, LHC, XENON, CDMS...) will provide indications for this scenario or evidences against it.
- If this scenario is confirmed, there might be a chance of measuring the temperature of the early Universe.

Isotropy of the signal

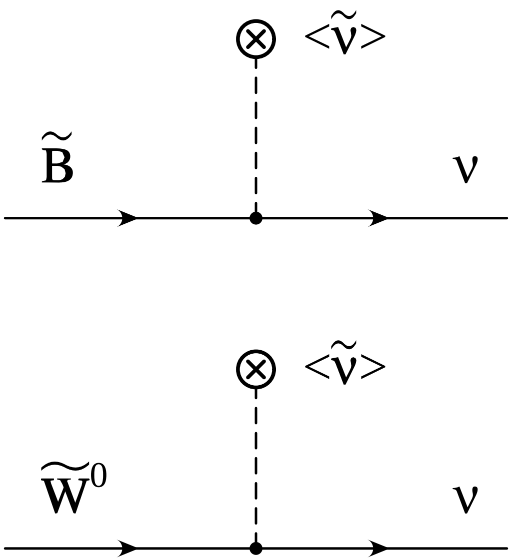


Strong, Moskalenko, Reimer

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

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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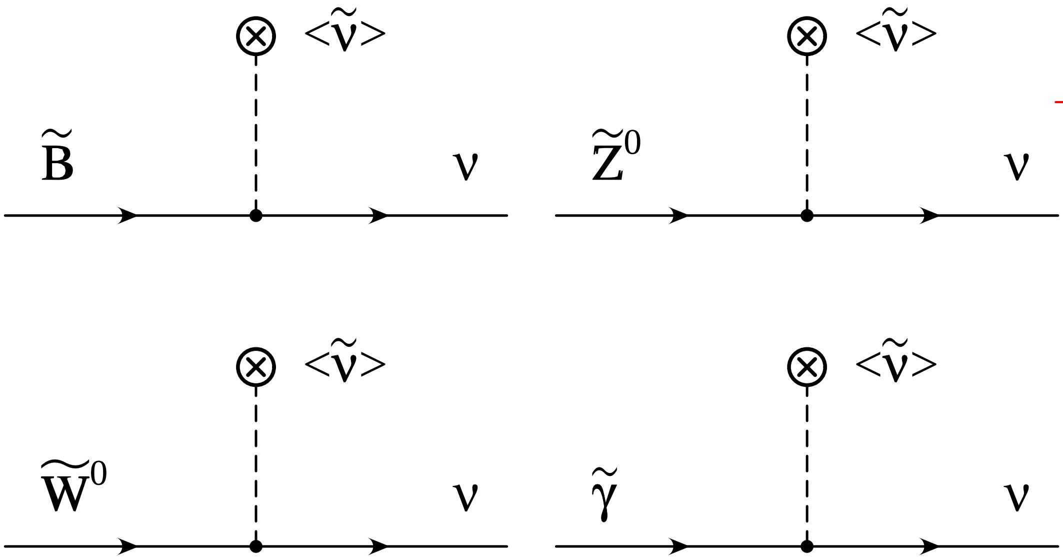

$$\longrightarrow |U_{\tilde{Z}\nu}| \simeq \frac{g}{2c_W}\frac{\langle\tilde{\nu}\rangle}{M_{\tilde{Z}}}$$

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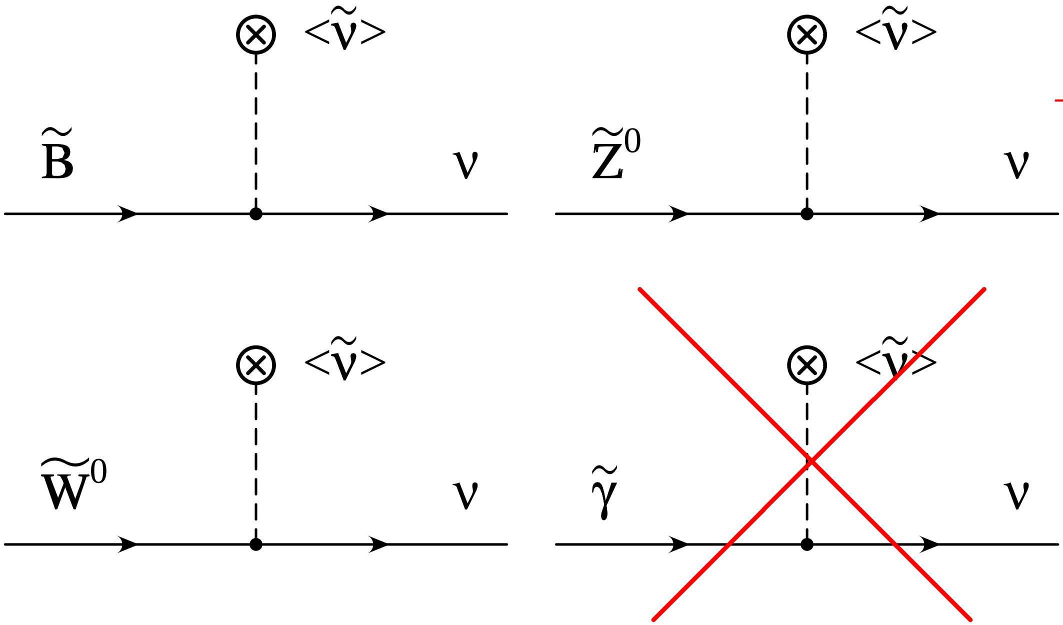

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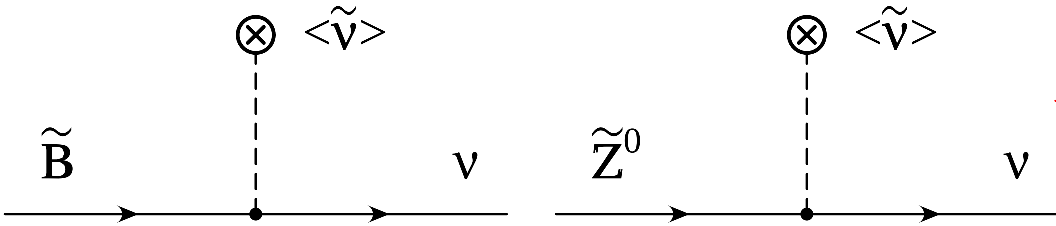

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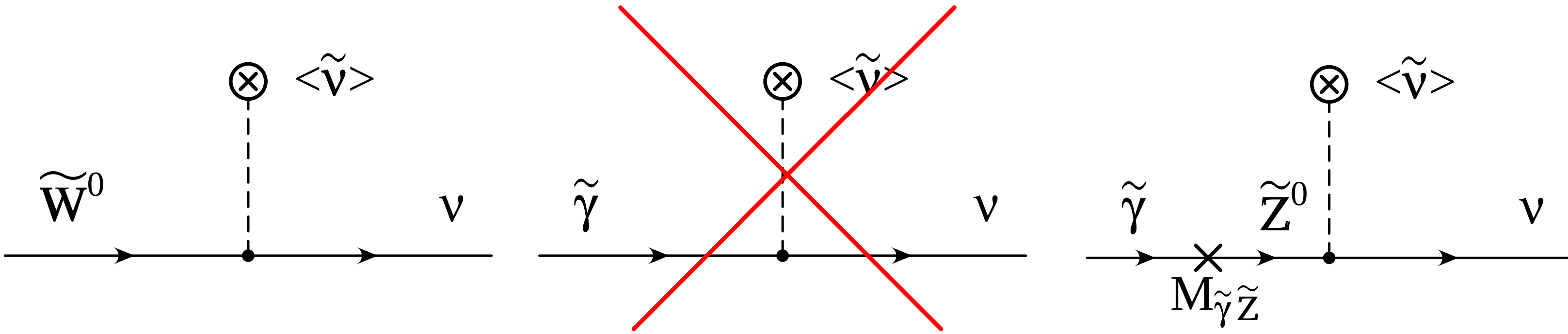
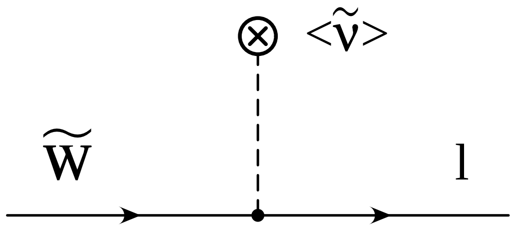


$\longrightarrow |U_{\tilde{\gamma}\nu}|$

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

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



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

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

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