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))

D. Tran (arXiv:0804.4596, to appear in JCAP)

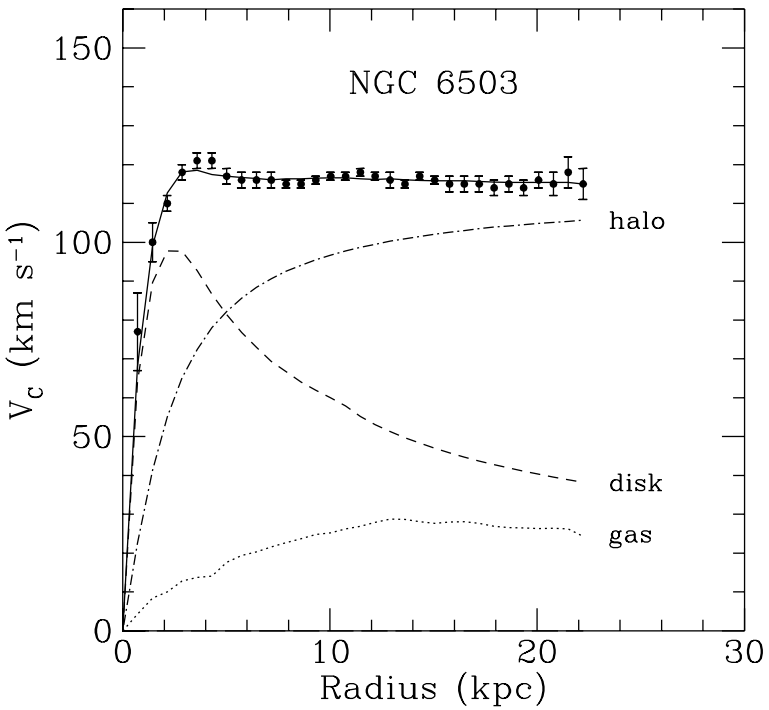
SUSY'08

Seoul

19th June 2008

Introduction

Many evidences of dark matter at different scales



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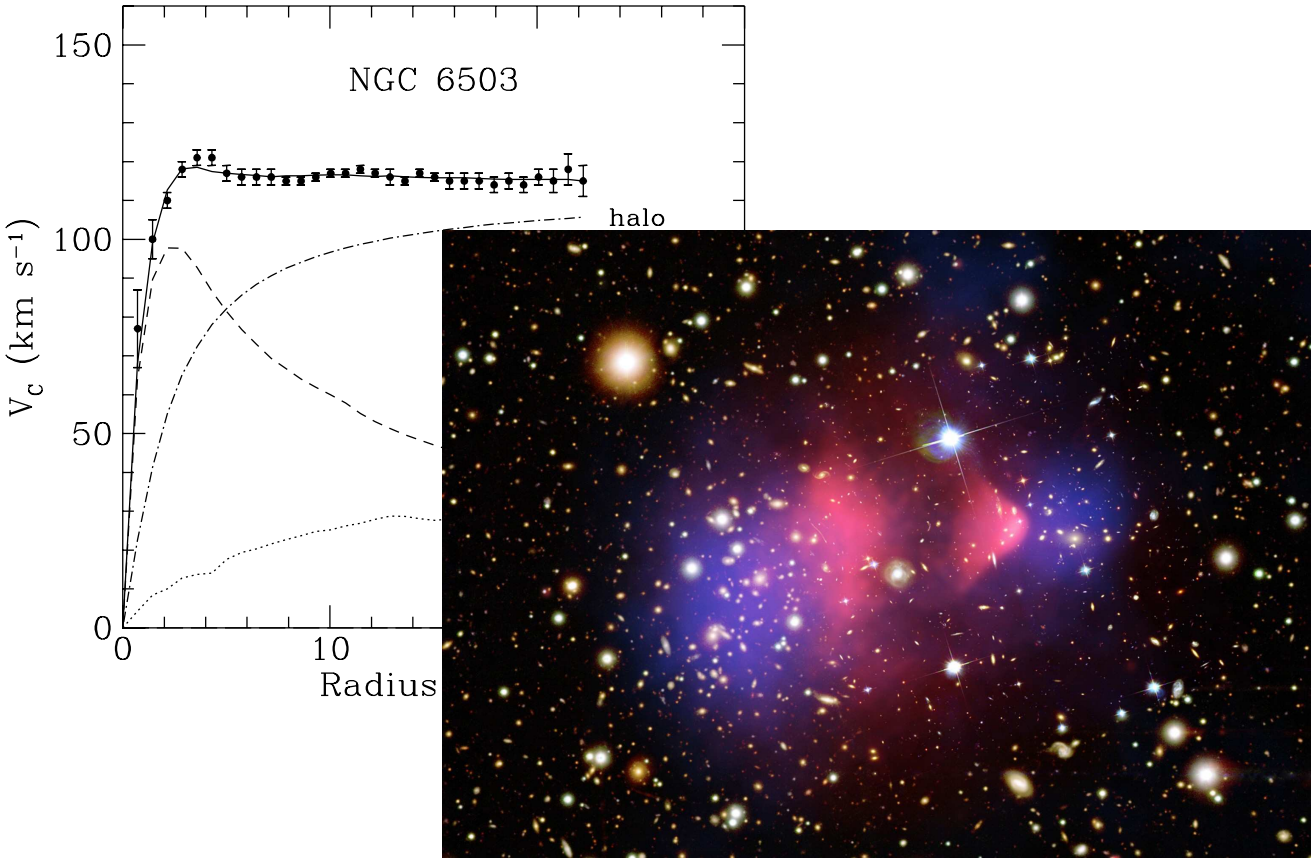

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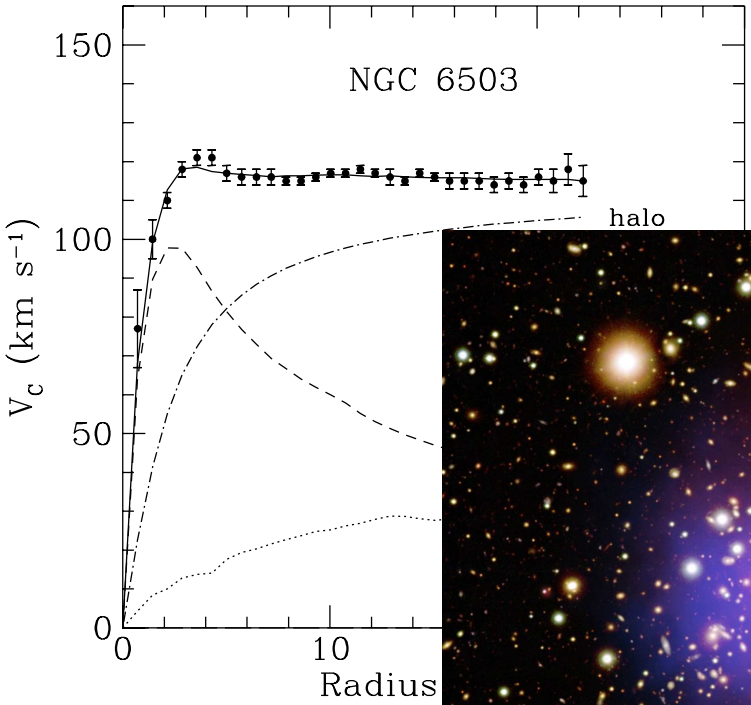

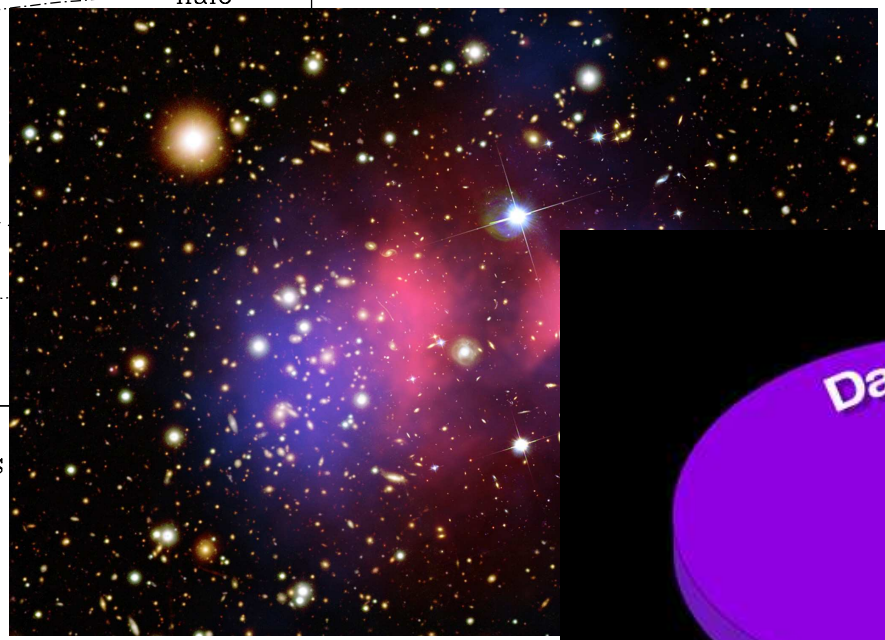

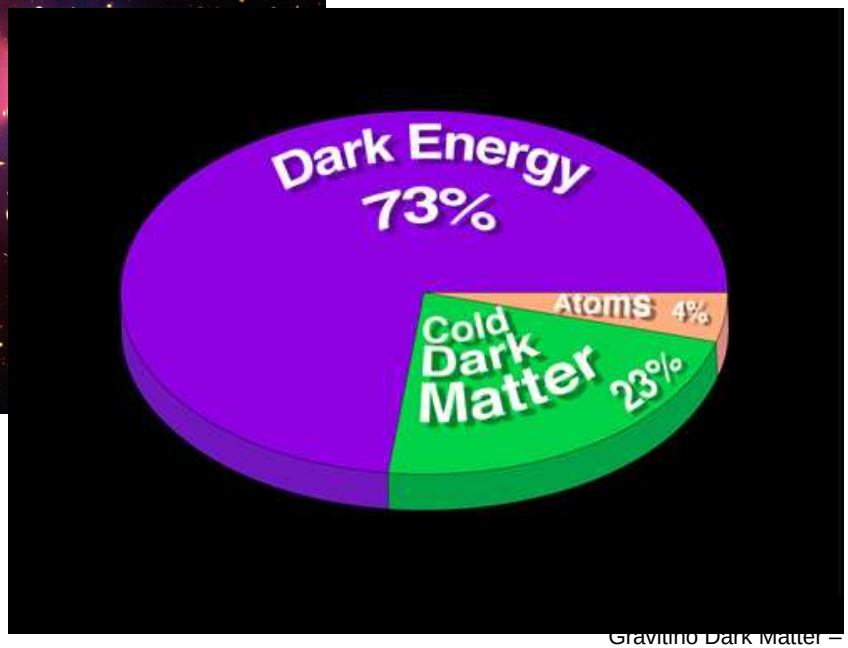

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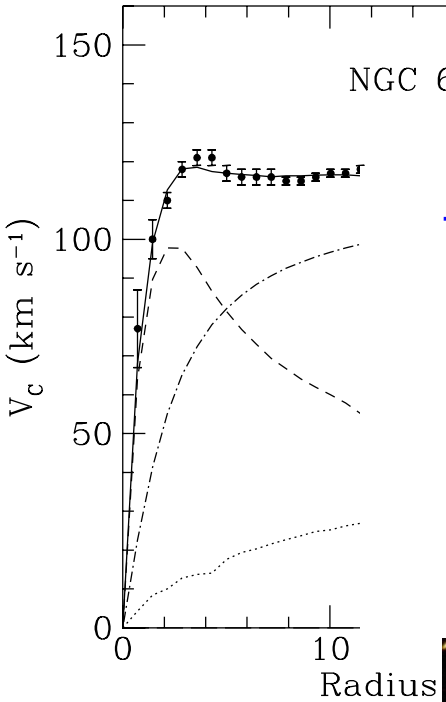
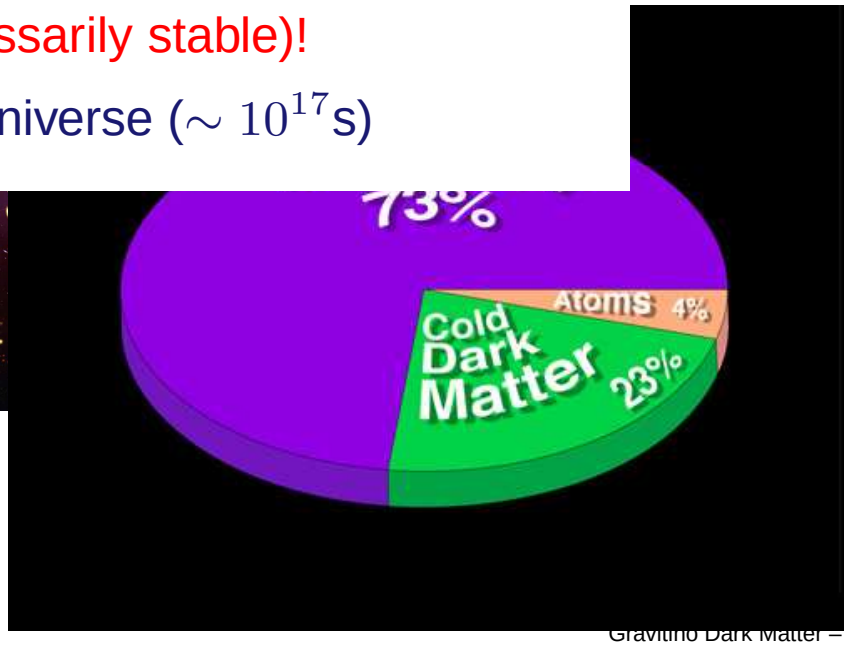


The main features of any dark matter candidate are:

- ⋆ 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:

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

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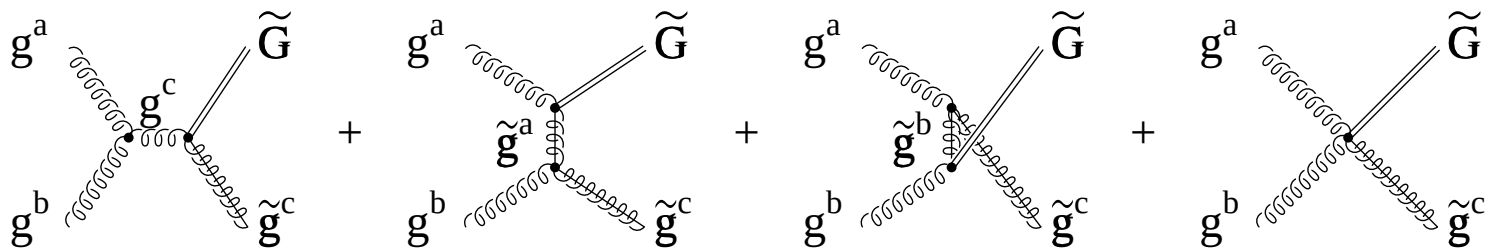
- Neutralinos (requires R-parity conservation)
- Gravitinos
- Axinos
- Lightest Kaluza-Klein particles (B^1, KK graviton), scalar singlets, Q-balls, branons, WIMPzillas, mini-black holes, cryptons, monopoles...

Why the gravitino?

Gravitino dark matter

The gravitino is present in any theory with local supersymmetry. 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:



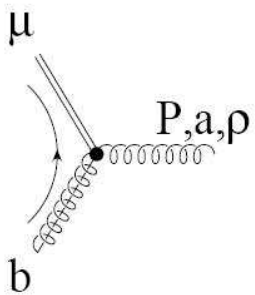
- Also produced by non-thermal processes (inflaton decay, NLSP decay)

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

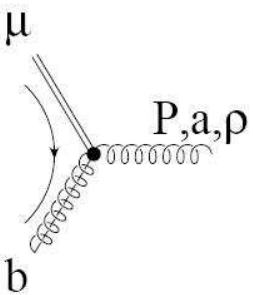
- The interactions of the gravitino with the MSSM particles are fixed by the symmetries

From M. Bolz

- Gravitino-gluon-gluino:



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



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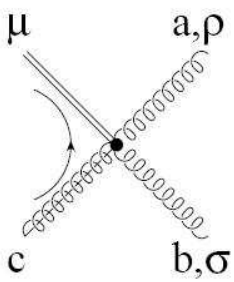
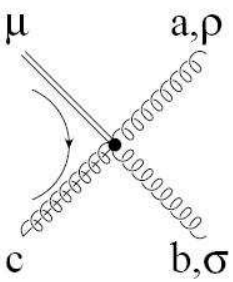


$$= -\frac{1}{4M}gf^{abc}[\gamma^\rho, \gamma^\sigma]\gamma^\mu;$$



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

- 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

$$\Omega_{3/2}h^2 \simeq 0.27 \left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right) \left(\frac{100\,\mathrm{GeV}}{m_{3/2}}\right) \left(\frac{m_{\tilde{g}}}{1\,\mathrm{TeV}}\right)^2$$

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- However, it is undetectable in dark matter searches (direct and indirect)
  This is a disadvantage rather than a problem.

- The ultimate goal would be to construct a consistent thermal history of the Universe.
- There seems to be a conflict between these three paradigms:

  ⋆ Supersymmetric dark matter

  ⋆ Big Bang Nucleosynthesis

  ⋆ Leptogenesis ($T_R \gtrsim 10^9$ GeV)

The extremely weak interactions of the gravitino can be very problematic in the early Universe

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

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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 $\longrightarrow$ R-parity violation

Gravitino DM with broken R-parity

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

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

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 no longer stable, it still constitutes a viable dark matter candidate. It decays for example $\psi_{3/2} \to \nu\gamma$, with lifetime:

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

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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.

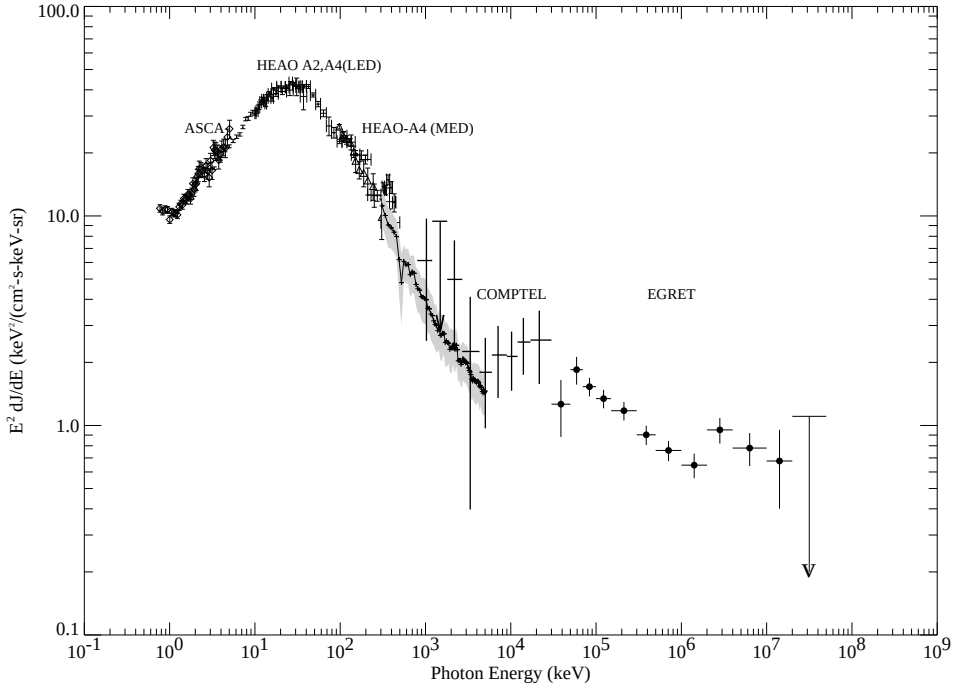
EGRET measured gamma rays with energies between 30 MeV and 100 GeV.

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

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

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 foreground
- ⋆ Is the signal isotropic/anisotropic?
- ⋆ Precise shape of the energy spectrum?

GLAST will clarify these issues soon.

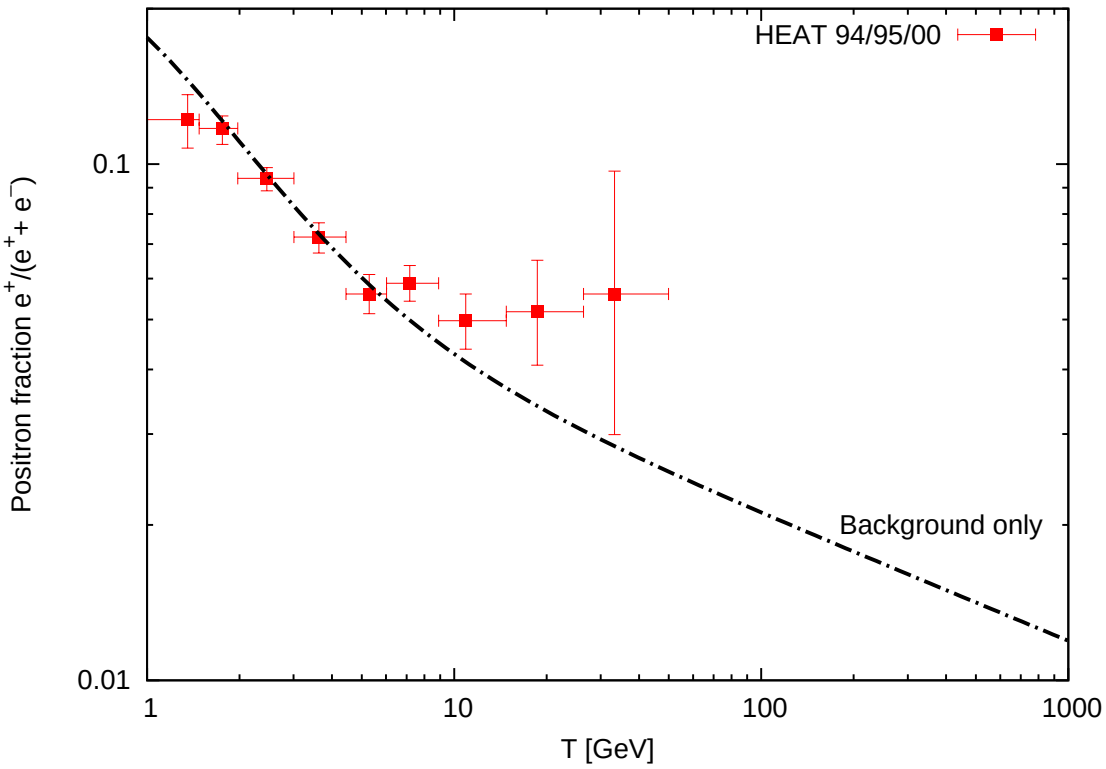
June 11th 2008

12:05 p.m. EDT

Positrons

The HEAT collaboration has reported an excess of positrons at energies $\gtrsim$ 7 GeV.

Same energies as the EGRET excess!



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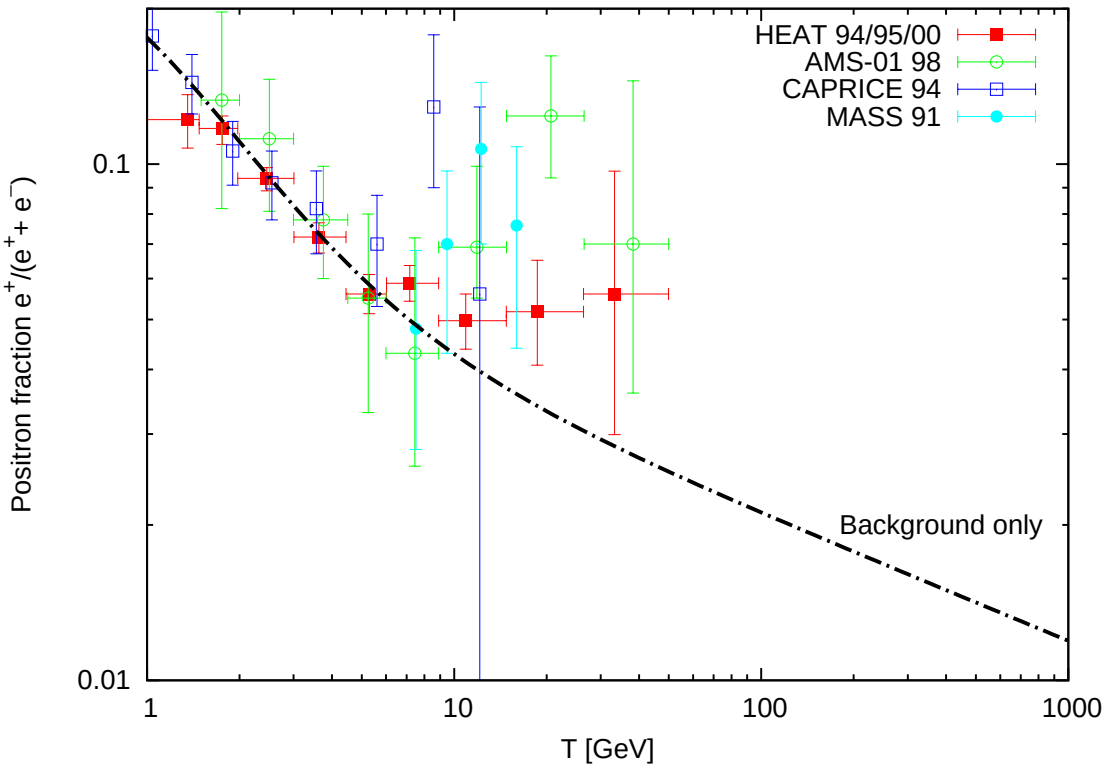
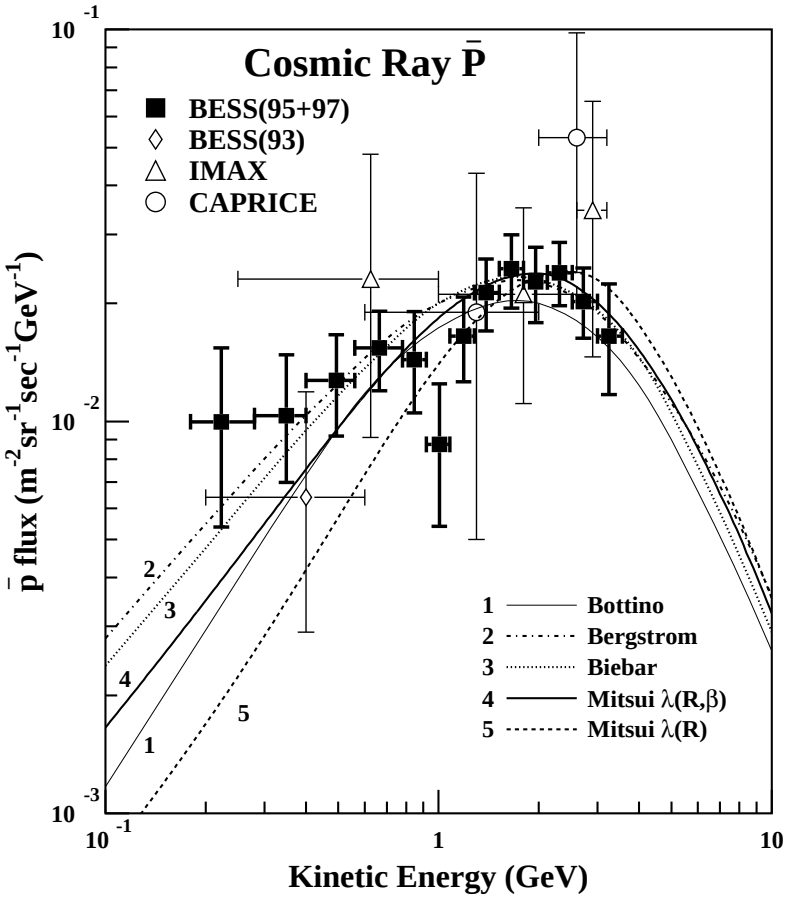


PAMELA will provide an accurate measurement of the positron fraction.

Antiprotons

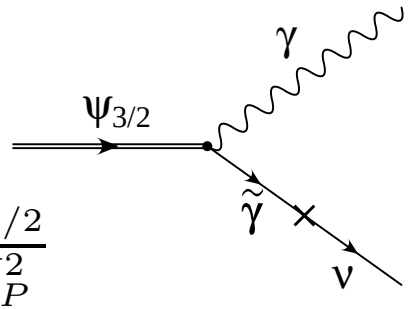


The antiproton flux is consistent with the astrophysical models

Gravitino decay channels

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

$$\Gamma(\psi_{3/2} \to \gamma\nu) = \frac{1}{32\pi} |U_{\tilde{\gamma}\nu}|^2 \frac{m_{3/2}^3}{M_P^2}$$



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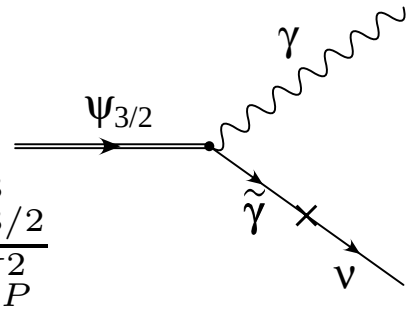

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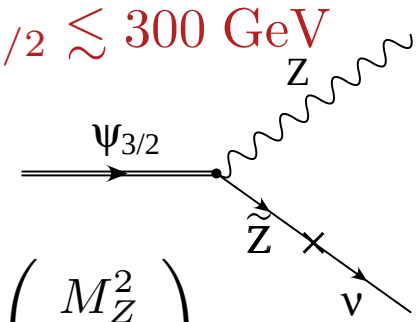
- "not-so-light" gravitino $100\ \mathrm{GeV} \lesssim m_{3/2} \lesssim 300\ \mathrm{GeV}$
  - $\psi_{3/2} \to Z^0\nu$



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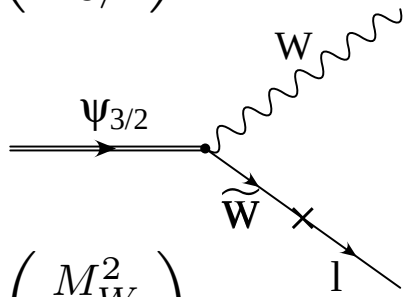

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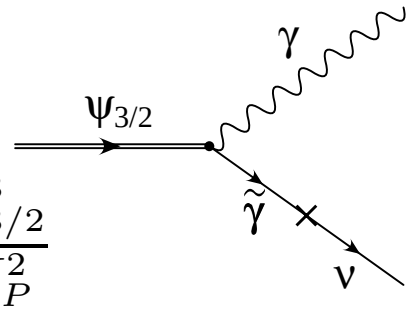

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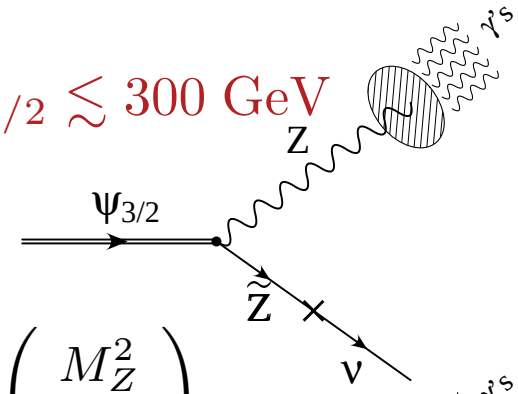

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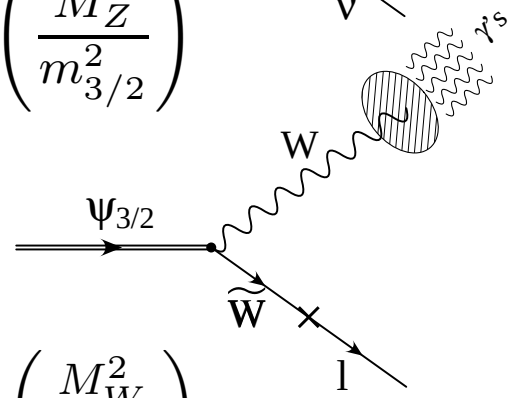

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Gamma-ray flux from gravitino decay

The energy spectrum of photons from gravitino decay is

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

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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,

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

$m_{3/2}$	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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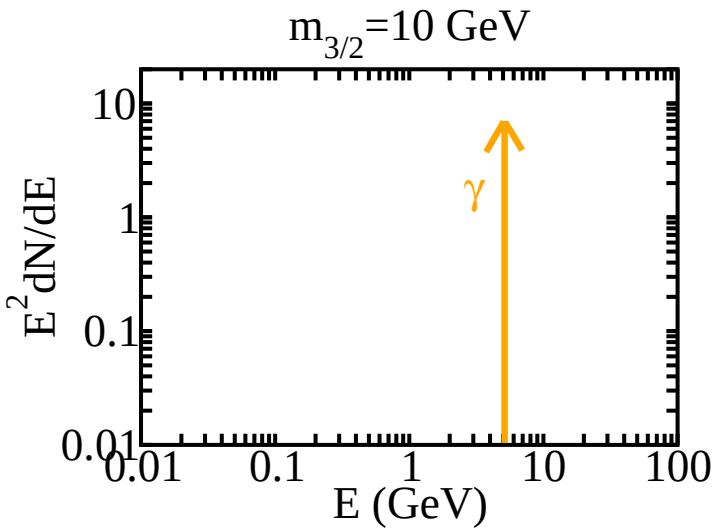
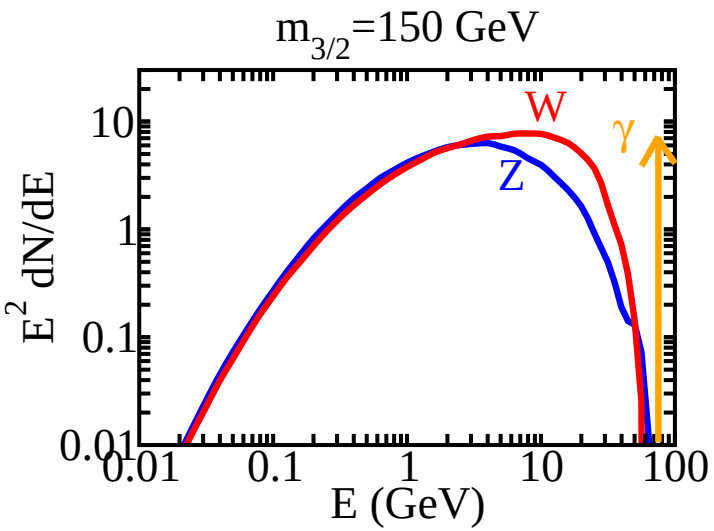


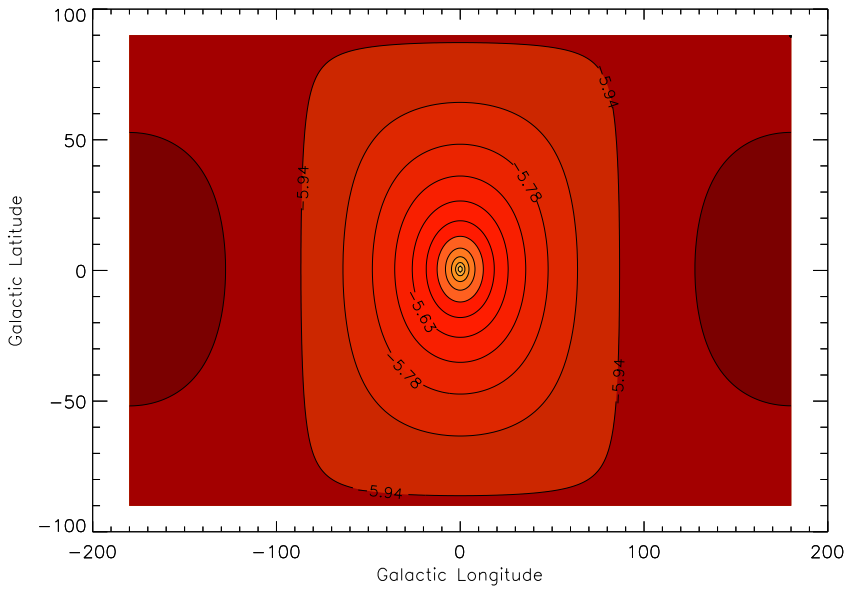


Gamma ray spectrum

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 gamma ray flux. The angular distribution depends on the halo profile.

We find that the halo contribution dominates over the cosmological contribution.



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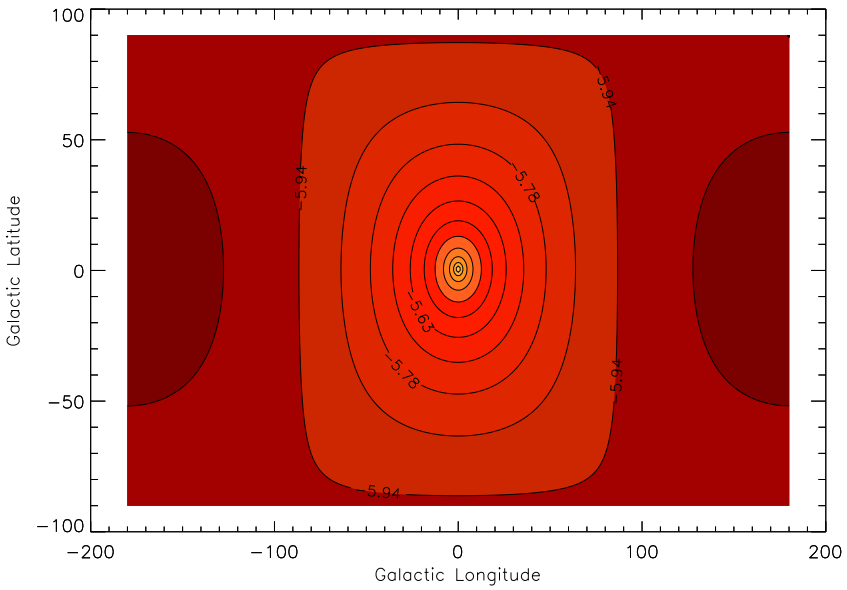
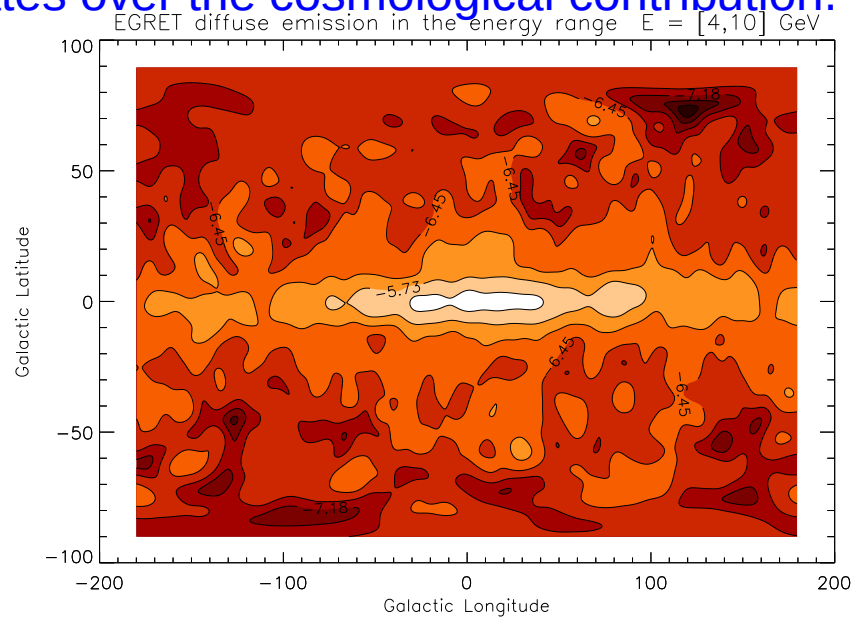
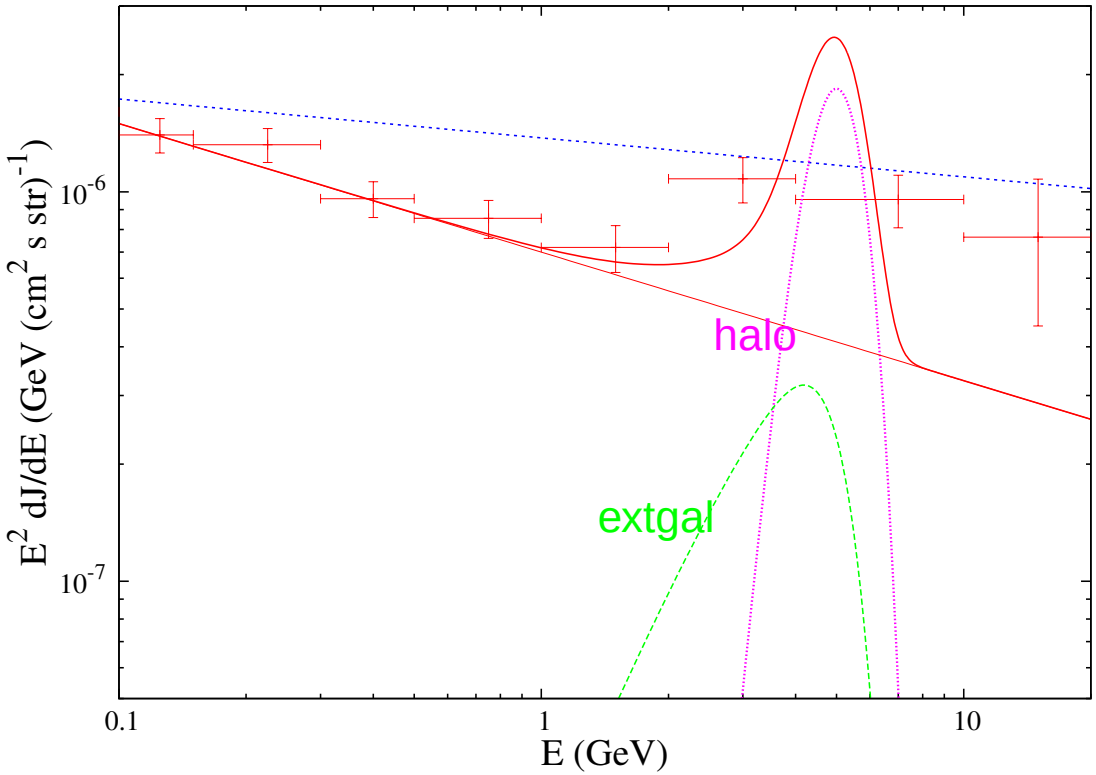




γ ray spectrum for light gravitinos $m_{3/2} \lesssim M_W$

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



Bertone, Buchmüller, Covi, AI

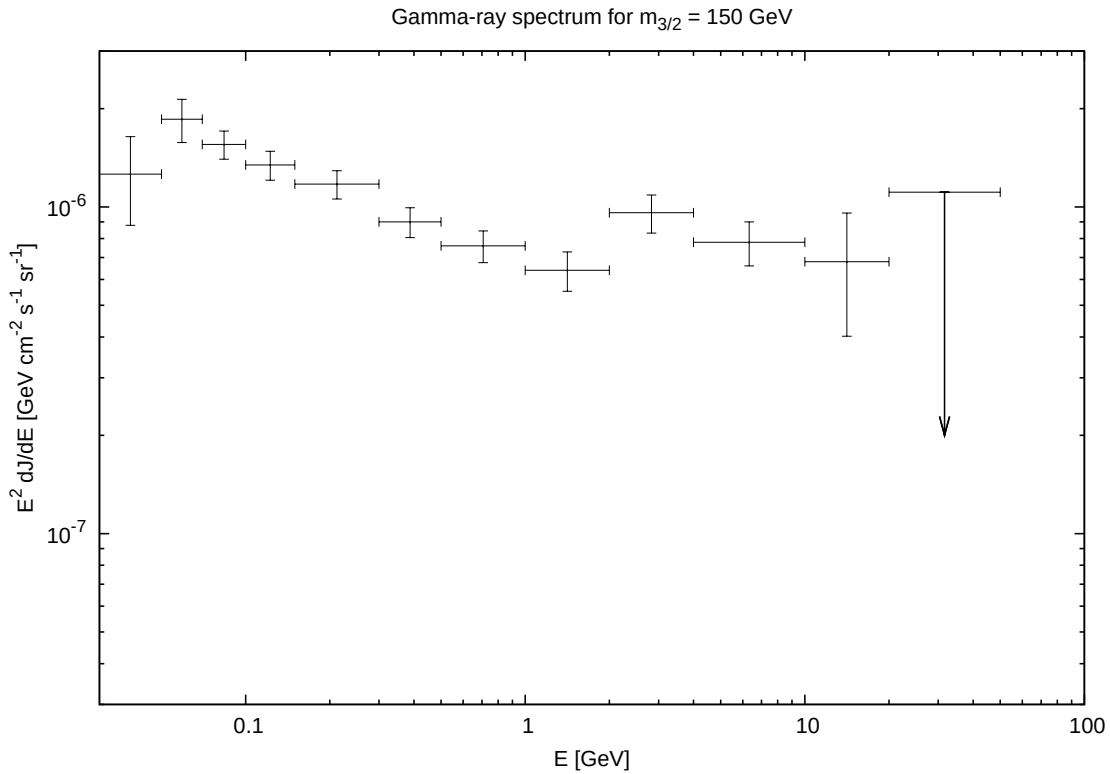
energy resolution of EGRET: 15%

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

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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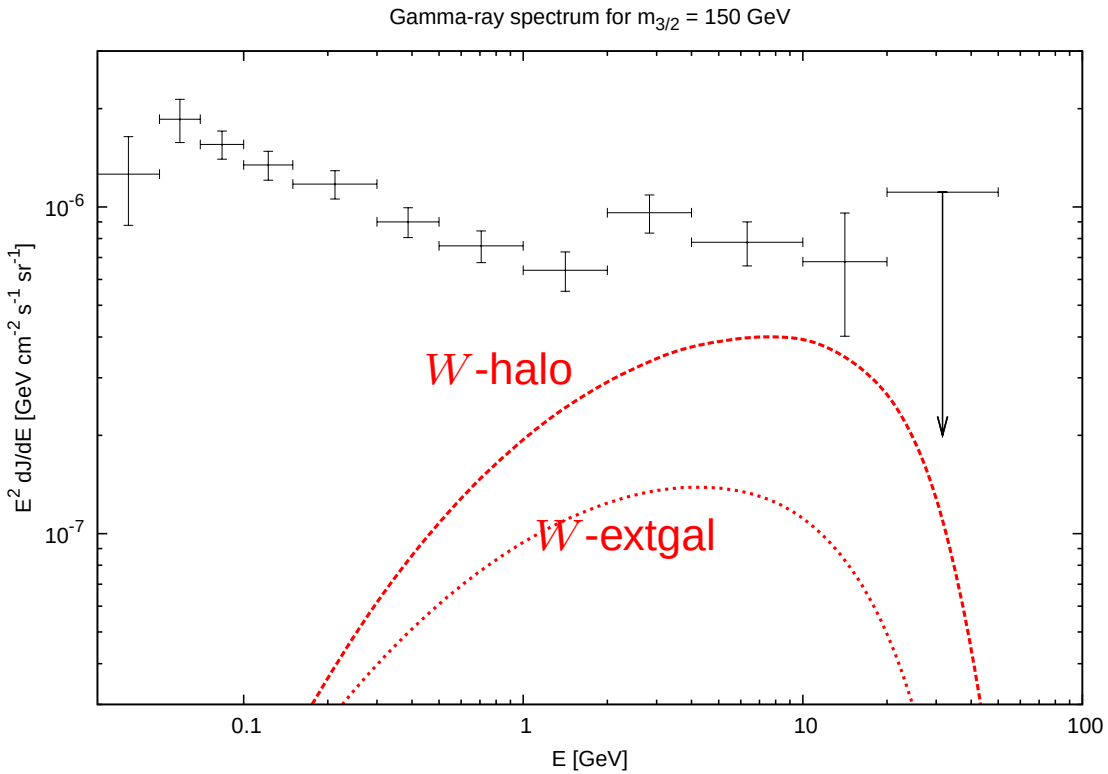

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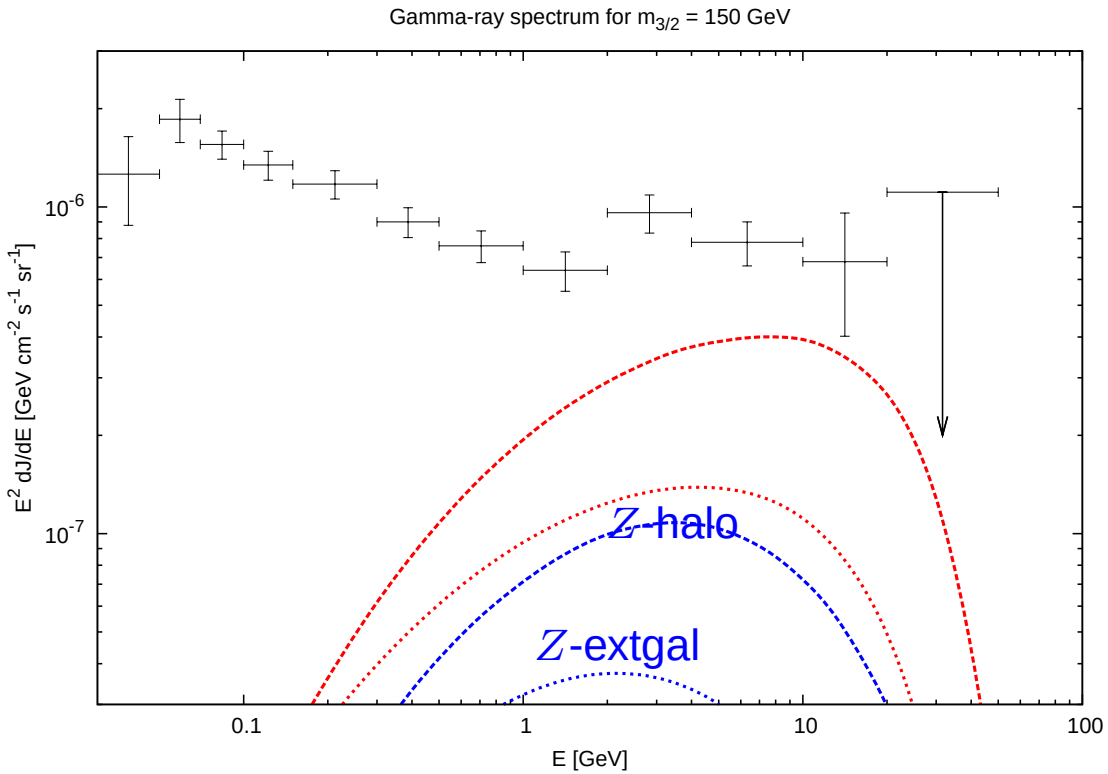

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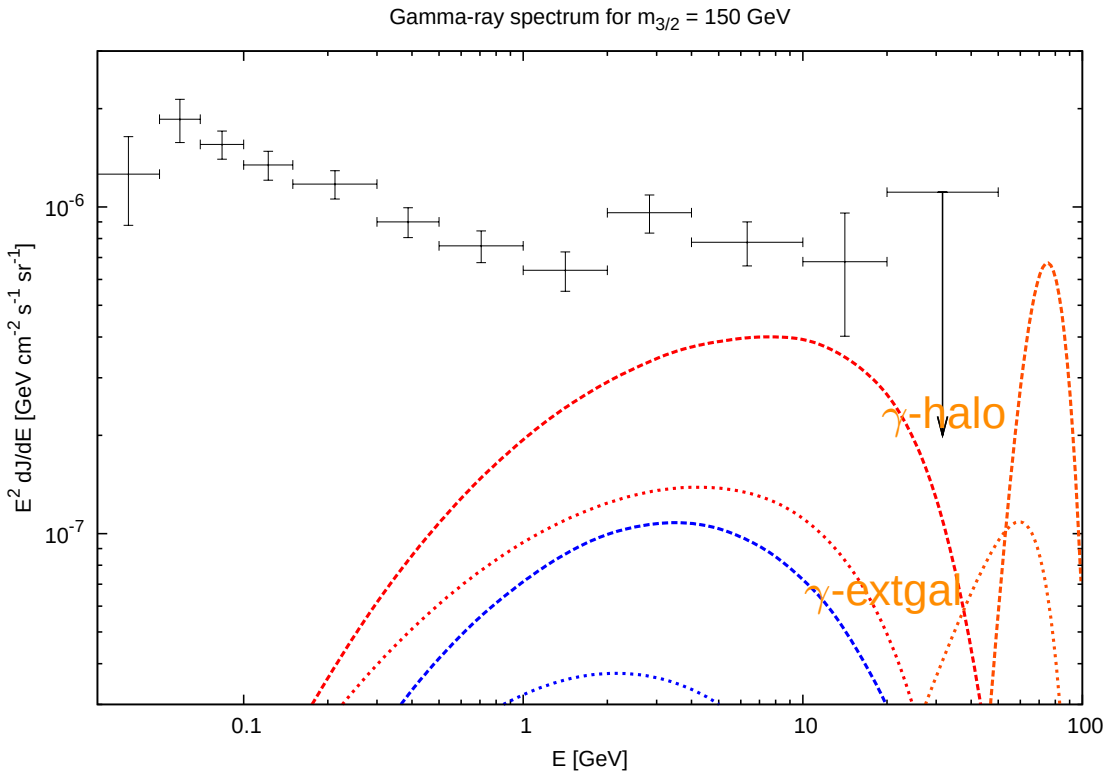

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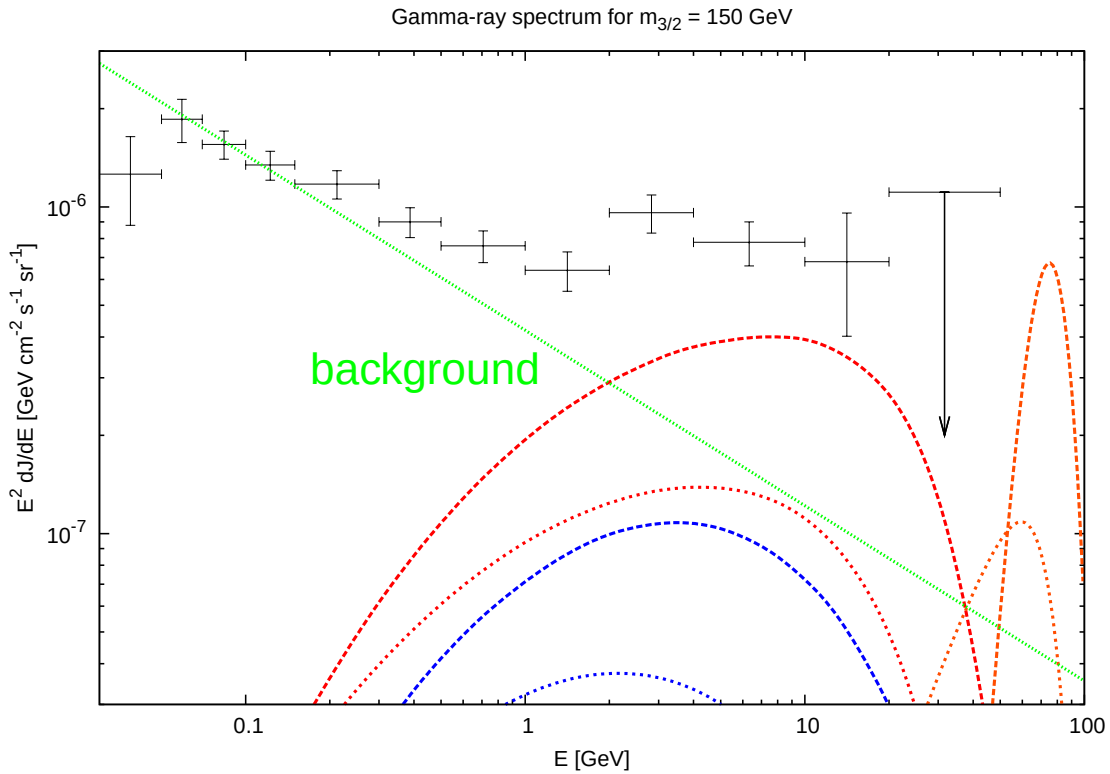

AI, Tran

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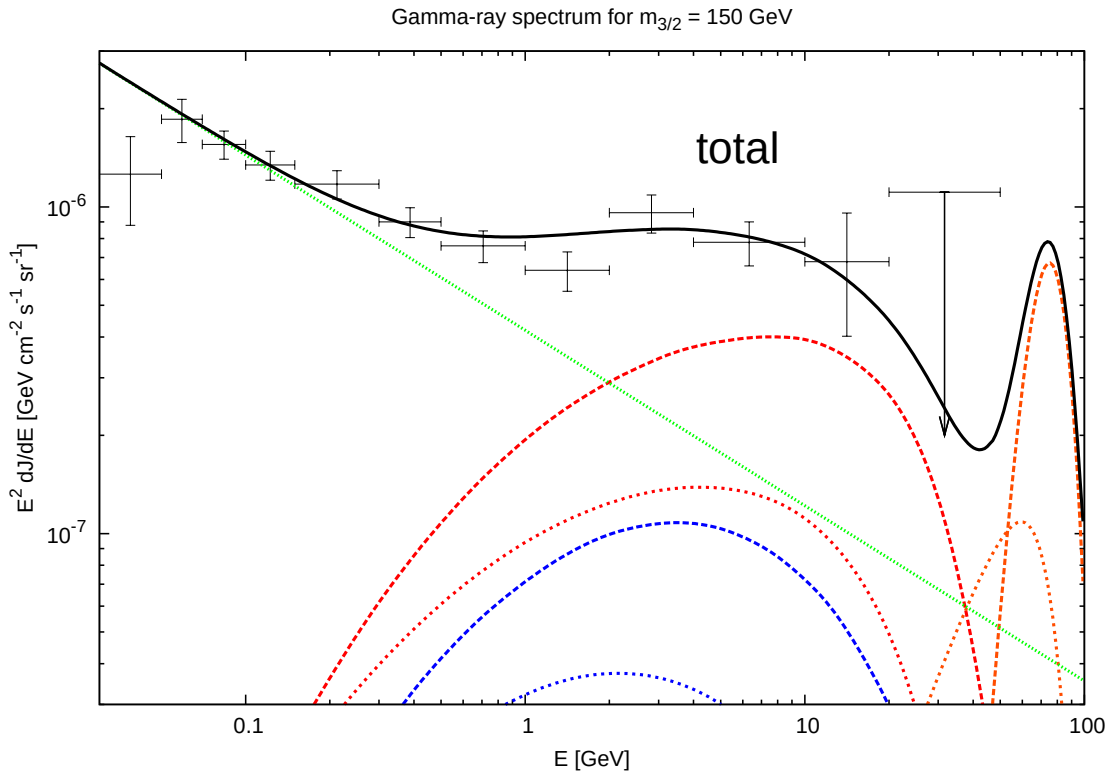


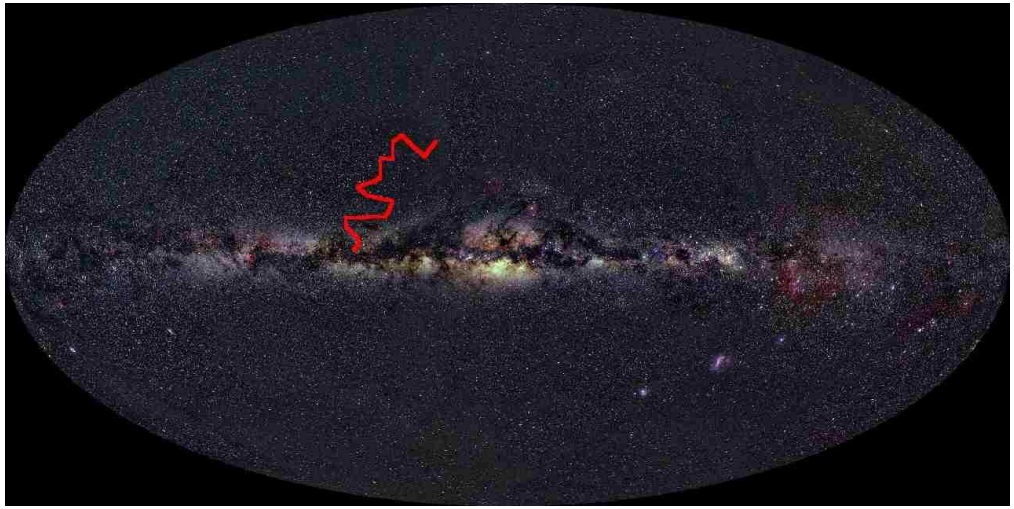
AI, Tran

$$\tau_{3/2} = 1.3 \times 10^{26}\mathrm{s} \Longrightarrow |U_{\widetilde{\gamma}\nu}| \simeq 2 \times 10^{-10}$$

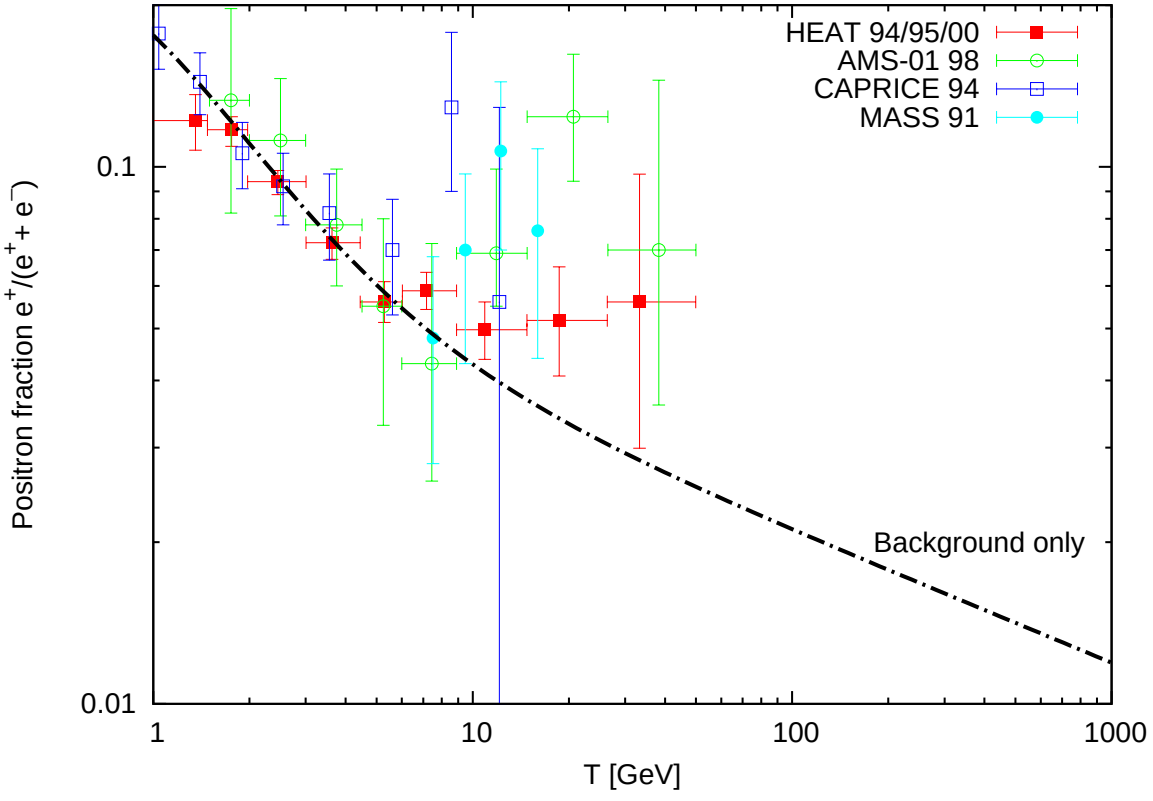
See also Ishiwata, Matsumoto, Moroi, arXiv:0805:1133

Positron fraction

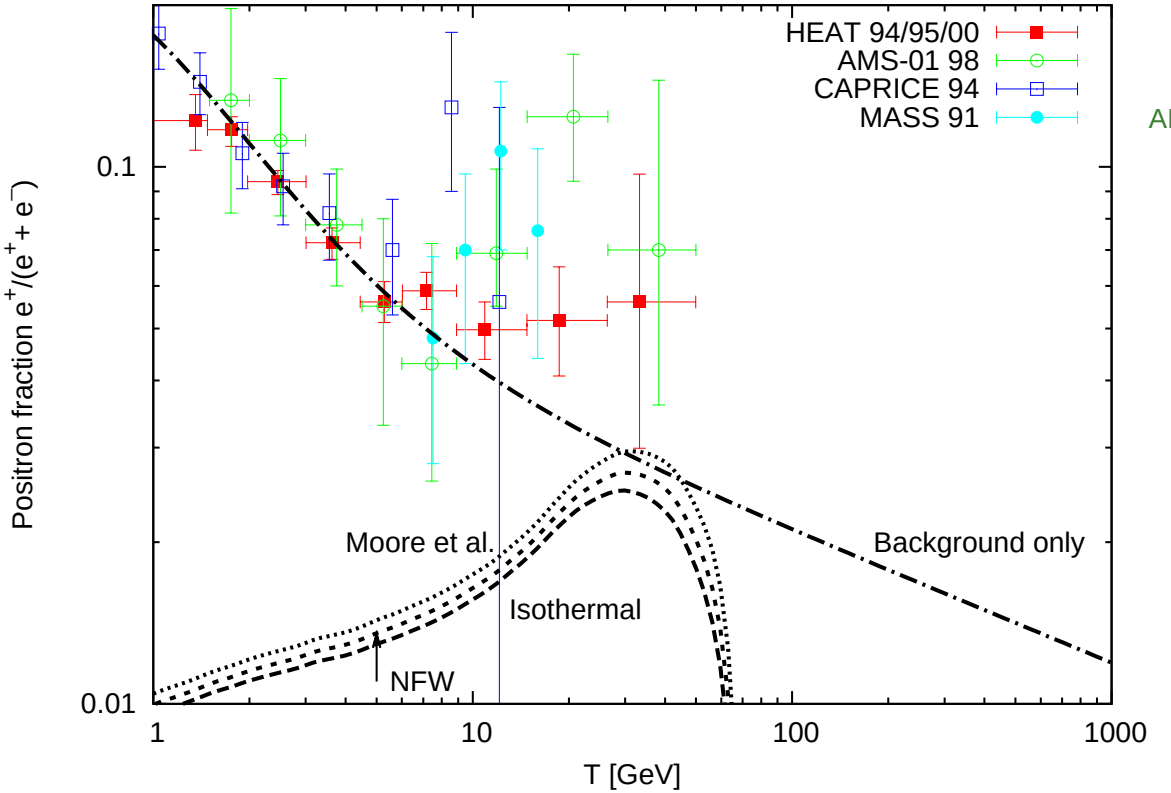
- The fragmentation of the W and Z bosons produces positrons.
- The positrons travel under the influence of the tangled magnetic field of the galaxy and lose energy $\longrightarrow$ Complicated propagation equation



- The computation of the positron fraction requires inputs from particle physics and from astrophysics. The EGRET anomaly fixes $m_{3/2} \simeq 150$ GeV and $\tau_{3/2} \simeq 1.3 \times 10^{26}\mathrm{s}$ $\longrightarrow$ few uncertainties from particle physics. However, there are many uncertainties from astrophysics: halo model? propagation model?


HEAT 94/95/00
AMS-01 98
CAPRICE 94
MASS 91
Background only
Positron fraction e+/(e++ e−)
0.1
0.01
1
10
100
1000
T [GeV]

Fix M2 propagation model. Different halo models



AI, Tran

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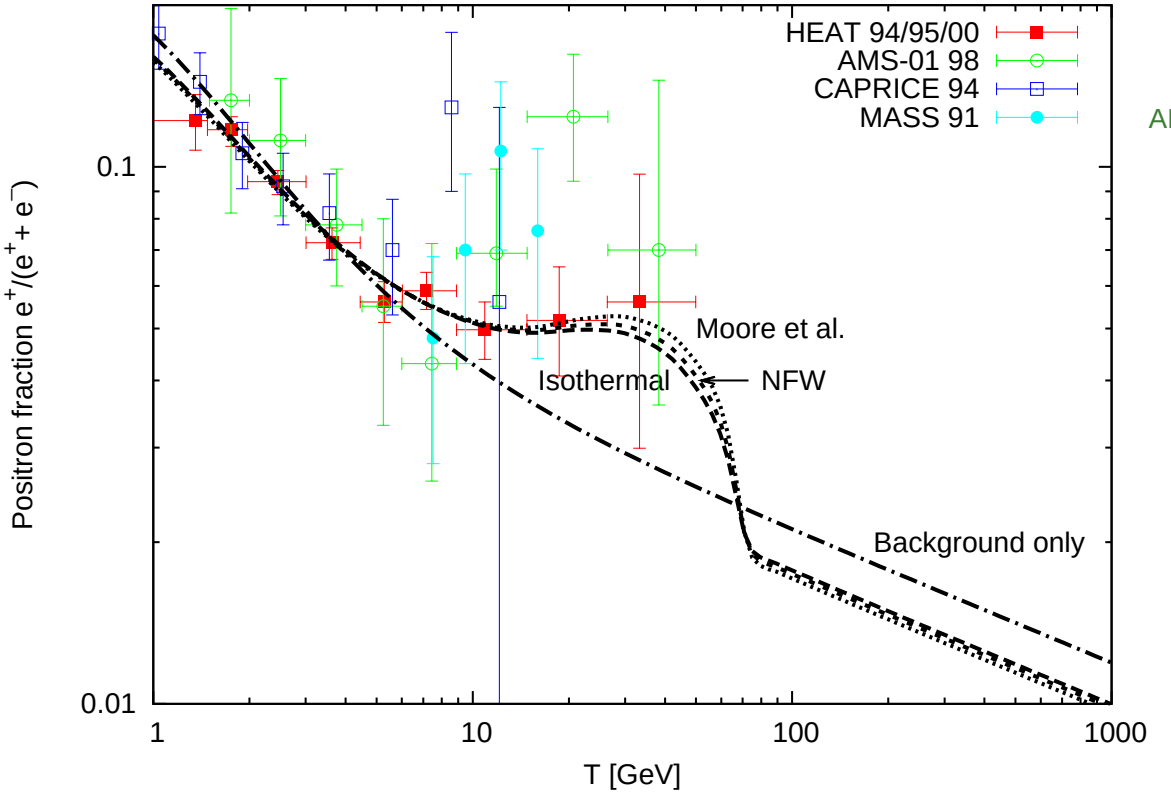
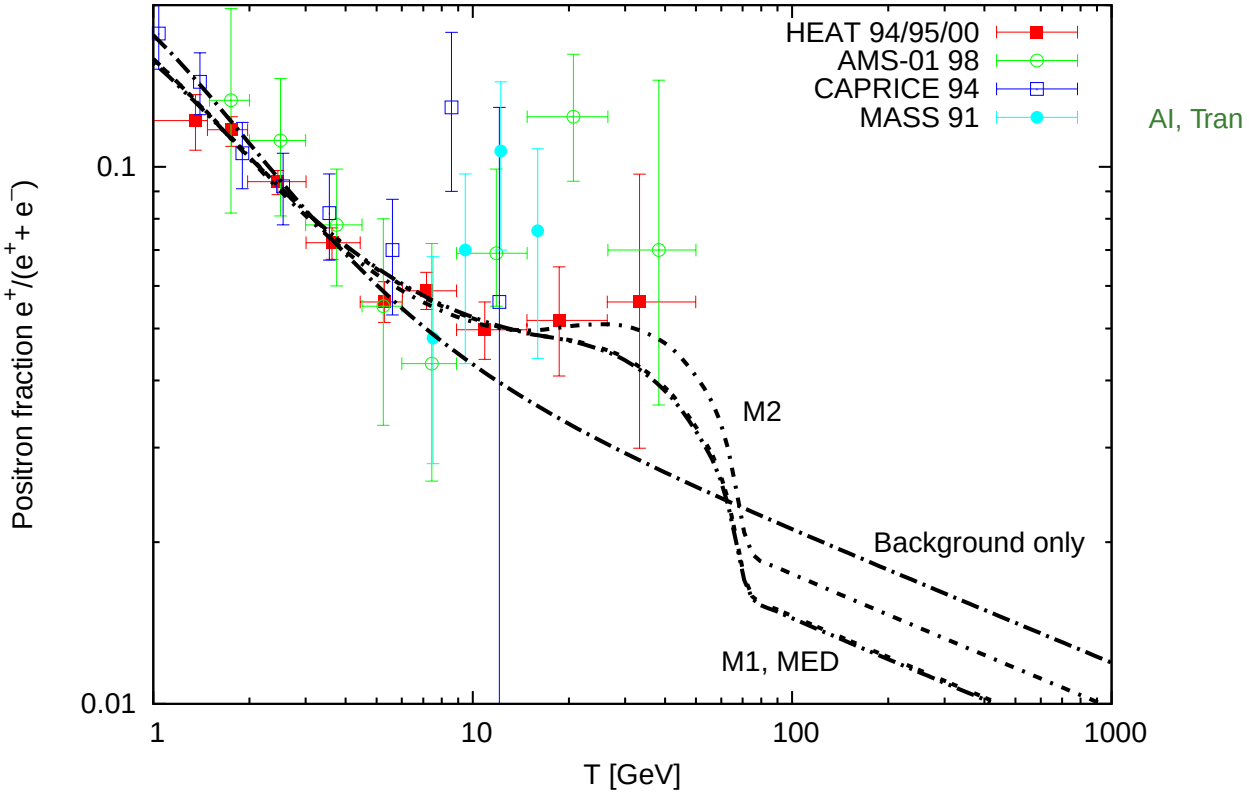


AI, Tran

The scenario of decaying gravitino dark matter predicts a bump in the right energy range, independently of the halo model

Fix NFW halo model. Different propagation model



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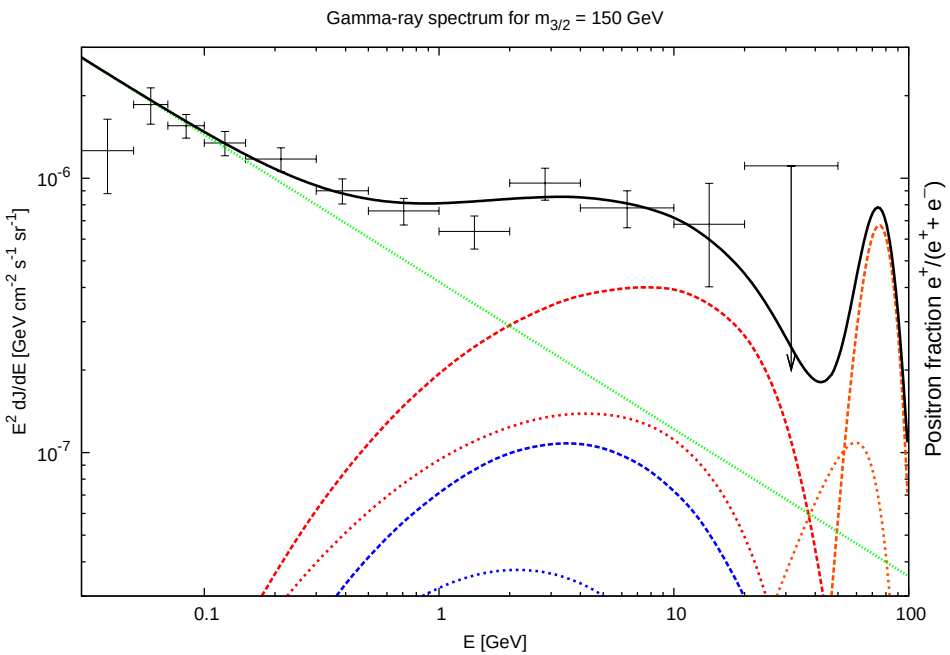
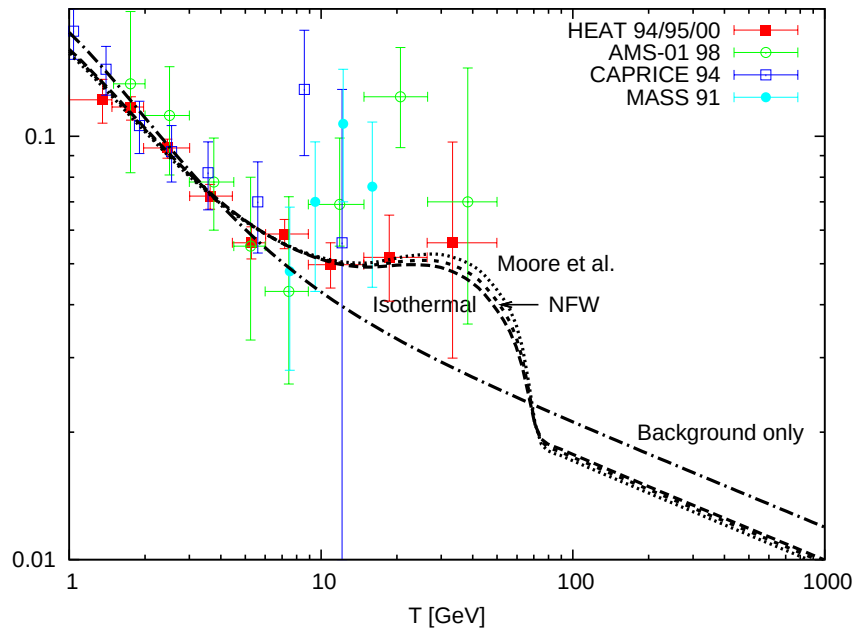
An intriguing coincidence...

The anomalies in the extragalactic gamma-ray flux and in the positron fraction can be simultaneously explained in this framework.





⋆ Recall that the scenario of decaying gravitino dark matter was initially proposed not to explain these anomalies, but to reconcile the paradigms of SUSY dark matter, leptogenesis and BBN!

⋆ This result also applies to any scenario of decaying dark matter with lifetime $\sim 10^{26}$ s which decays predominantly into Z^0 or $W^\pm$ with momentum ~ 50 GeV.

Antiproton flux

- Propagation mechanism more complicated than for the positrons. We neglect in our analysis reacceleration and tertiary contributions.
- The predicted flux suffers from huge uncertainties due to degeneracies in the determination of the propagation parameters.

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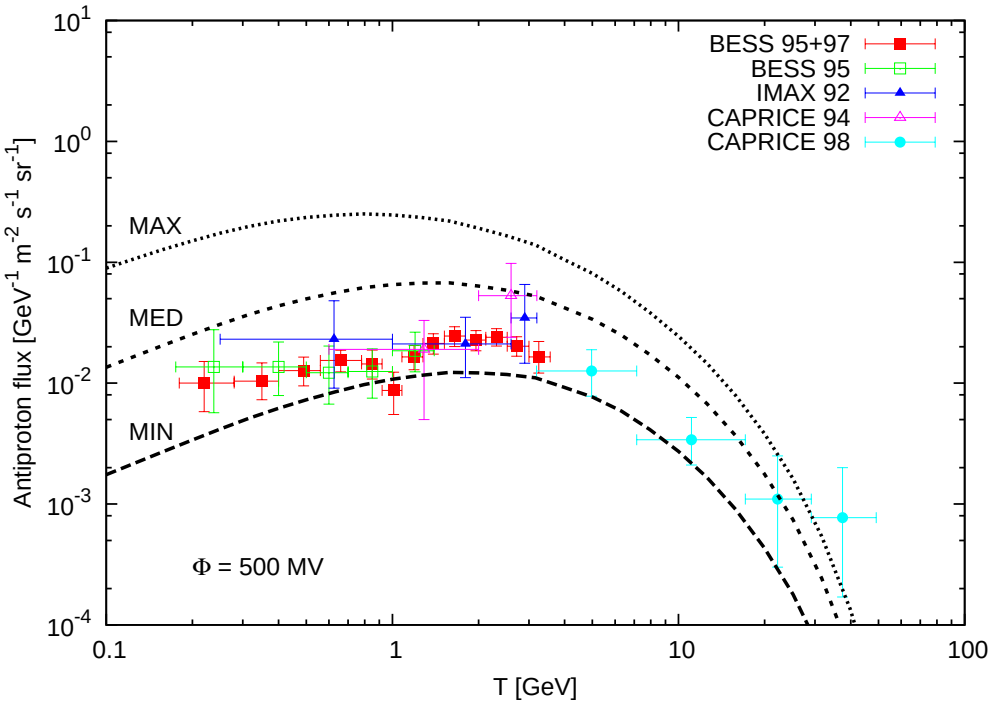

AI, Tran

The MAX and MED model are probably excluded (despite the uncertainties)

- The MIN case:

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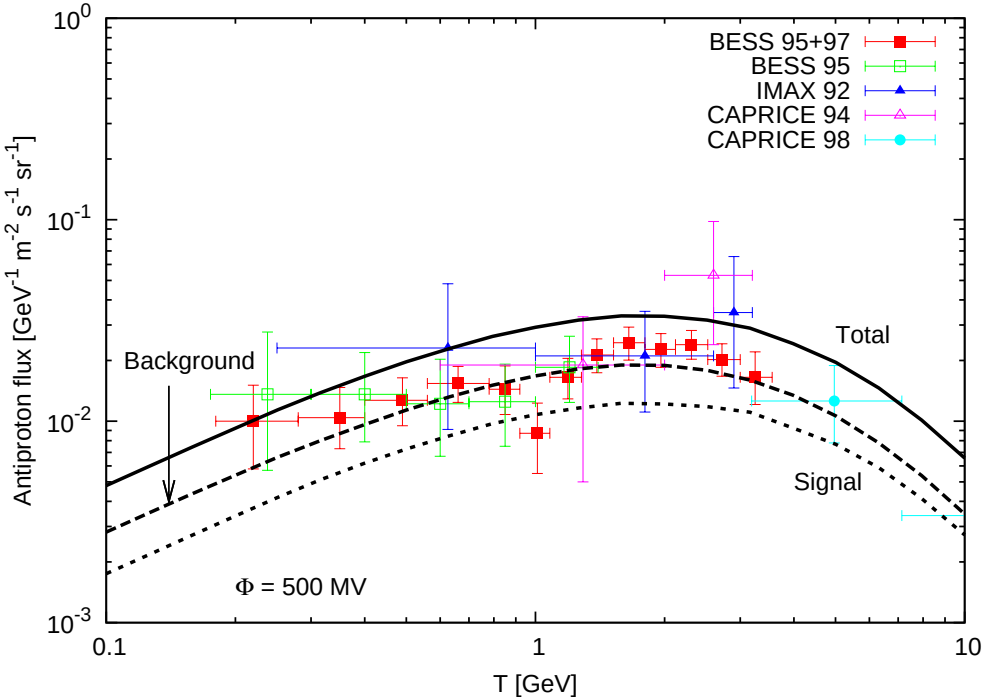


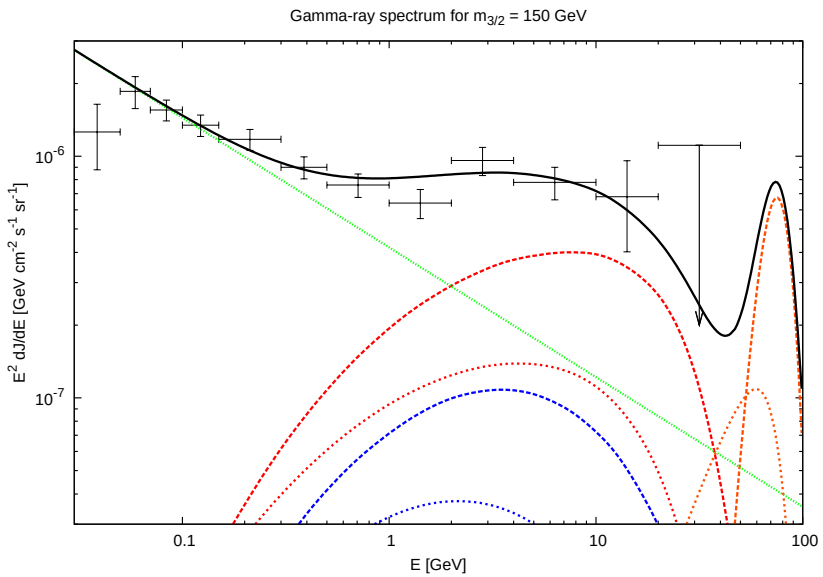
AI, Tran

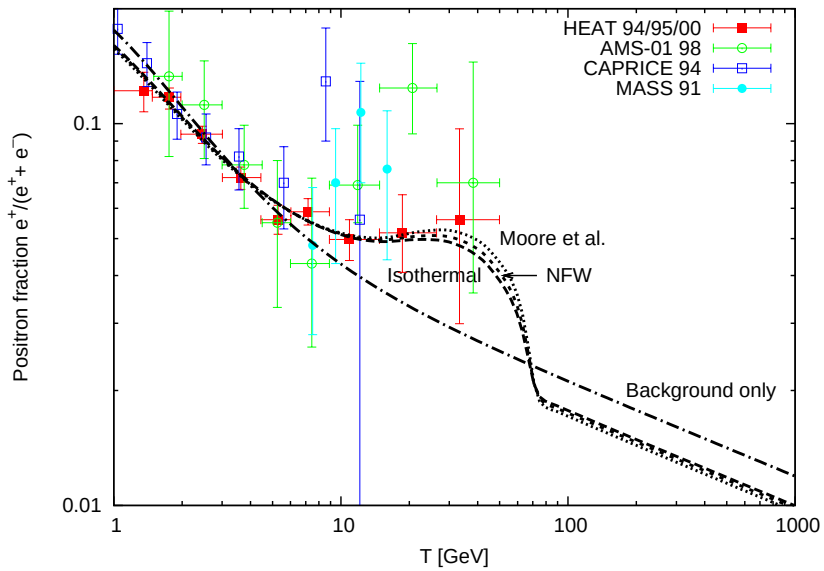
Together with the background, the total flux is a factor ~ 2 too large

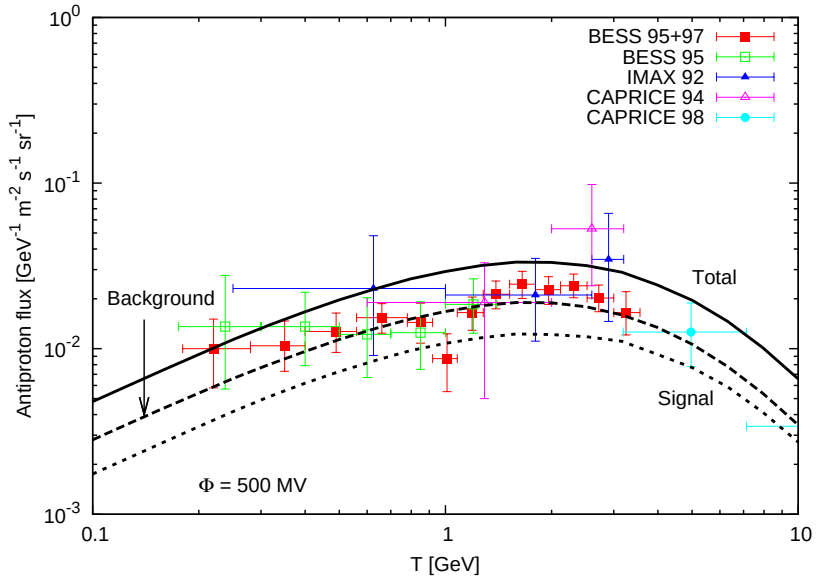
- In the view of all the uncertainties in the propagation, it might be premature to rule out the scenario of decaying gravitino dark matter on the basis of this small excess.

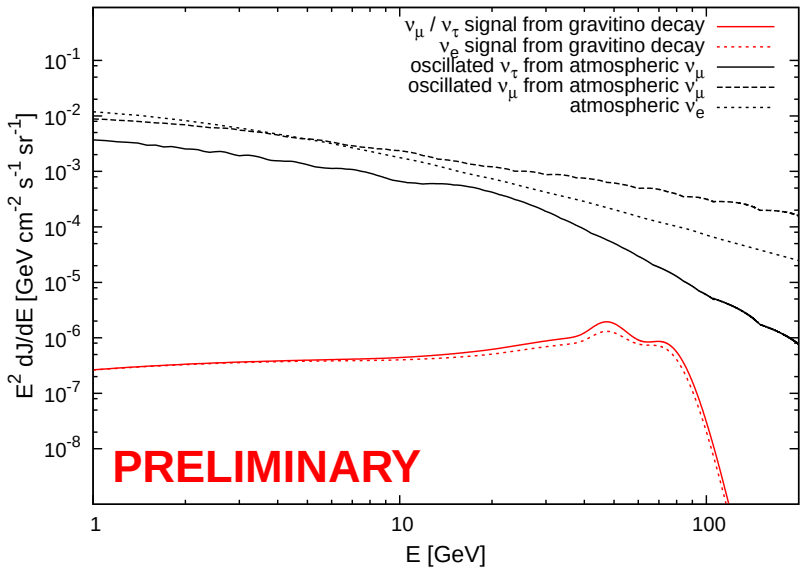
Summary of indirect detection experiments

For $m_{3/2} \simeq 150$ GeV and $\tau_{3/2} \simeq 10^{26}$ s









Wish list

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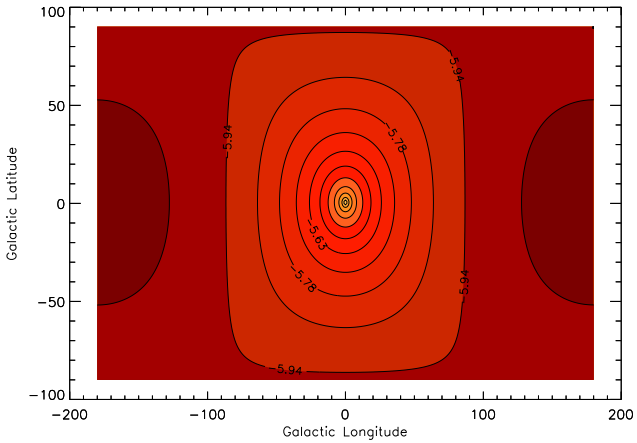

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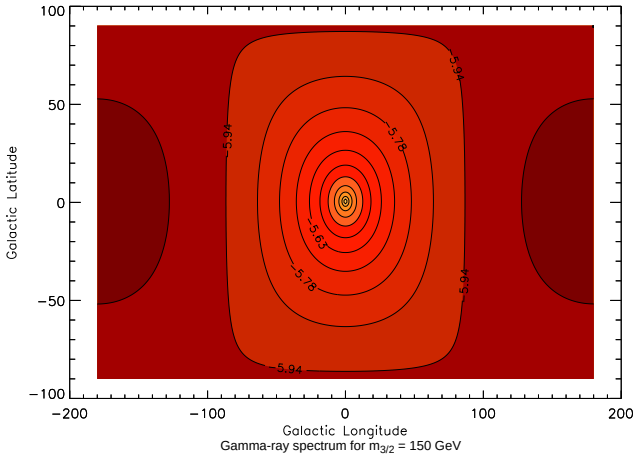
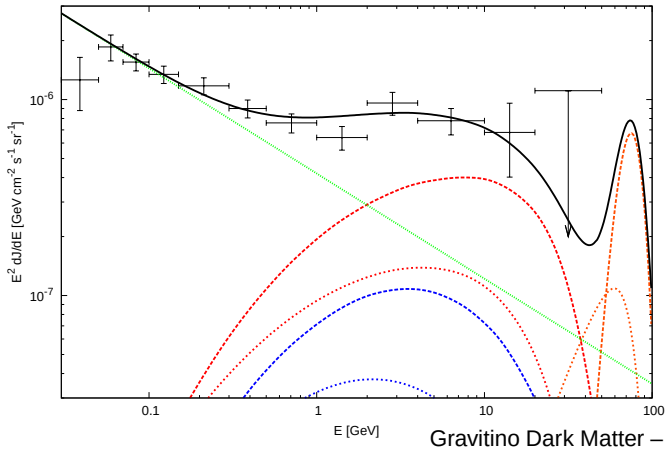


4– The energy spectrum of gamma rays is consistent with decaying gravitino dark matter $\longrightarrow m_{3/2}^{(\gamma)}, \tau_{3/2}^{(\gamma)}$.



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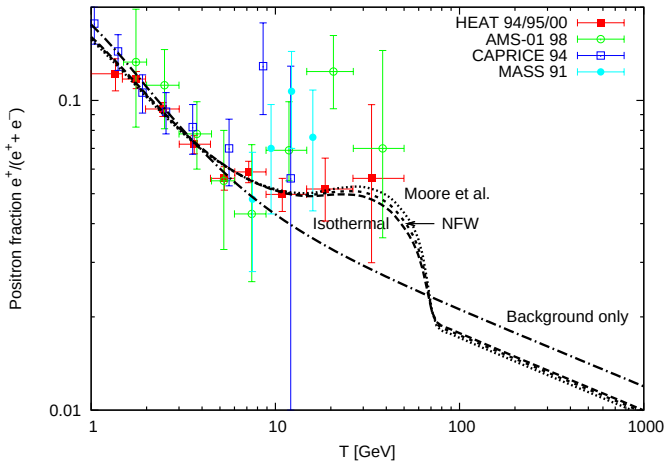

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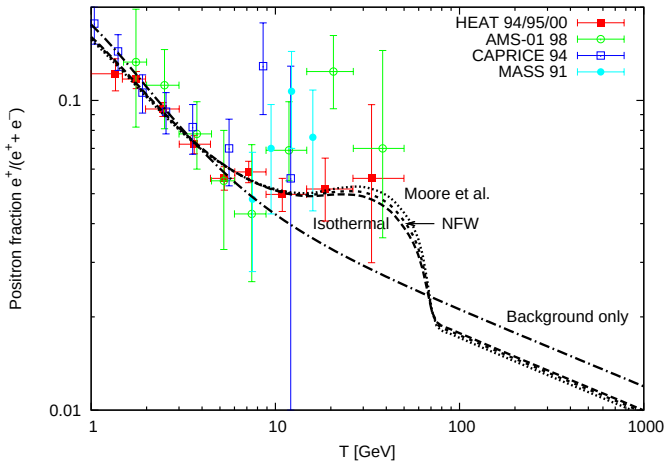
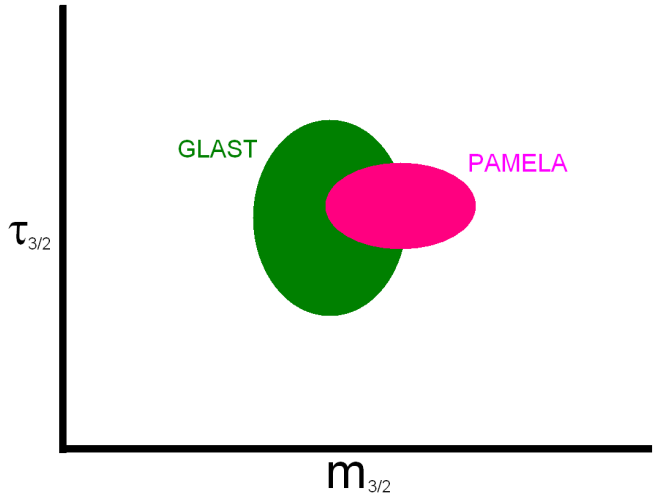


7– $m_{3/2}^{(\gamma)} \simeq m_{3/2}^{(e^+)}$
$\tau_{3/2}^{(\gamma)} \simeq \tau_{3/2}^{(e^+)}$.



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

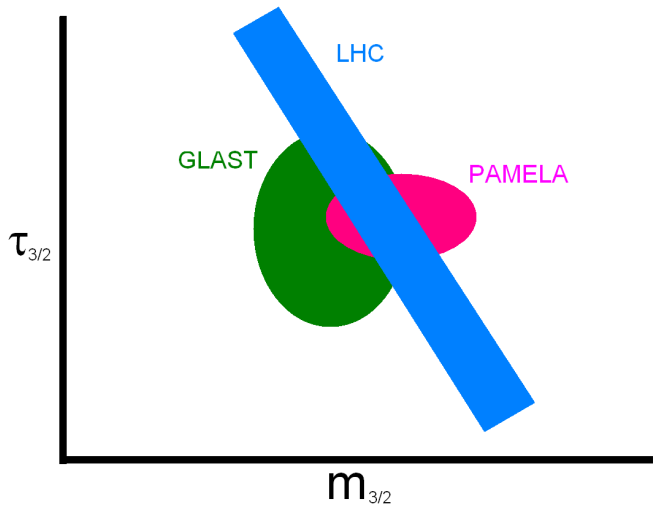
$$c\tau_{\tilde{\tau}}^{\rm lep} \sim 15\ {\rm cm} \left(\frac{m_{\tilde{\tau}}}{400{\rm GeV}}\right)^{-1} \left(\frac{\lambda_{323}}{10^{-8}}\right)^{-2}$$

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:

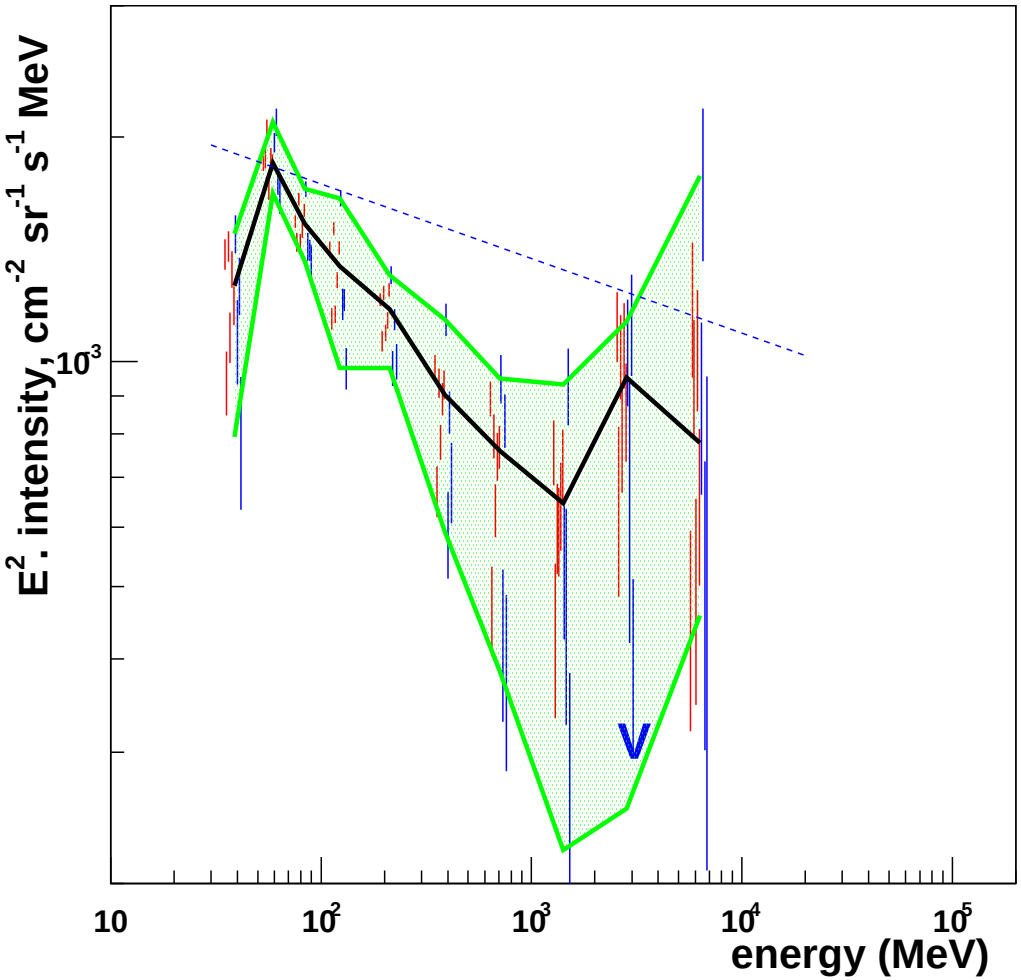
$$\tau_{3/2} \sim 10^{26}{\rm s} \left(\frac{m_{3/2}}{150{\rm GeV}}\right)^{-3} \left(\frac{m_{\tilde{\tau}}}{400{\rm GeV}}\right) \left(\frac{\tau_{\tilde{\tau}}}{10^{-8}{\rm s}}\right)$$



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 in the near future indications for this scenario or evidences against it.

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