Gravitino Dark Matter with broken R-parity

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DESY

In collaboration with W. Buchmüller, L. Covi, K. Hamaguchi and T. Yanagida

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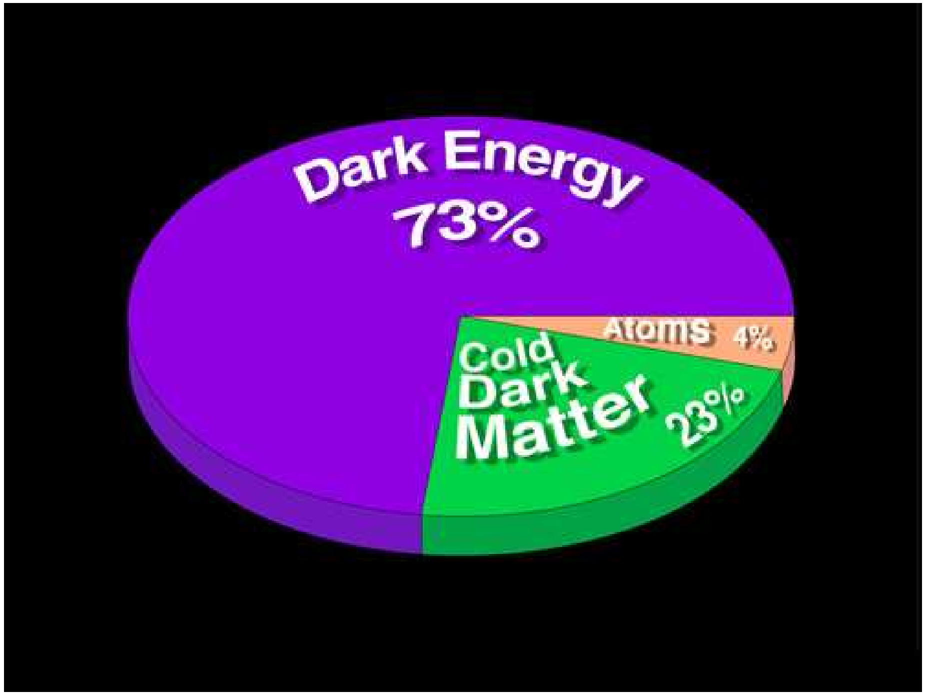
Introduction

"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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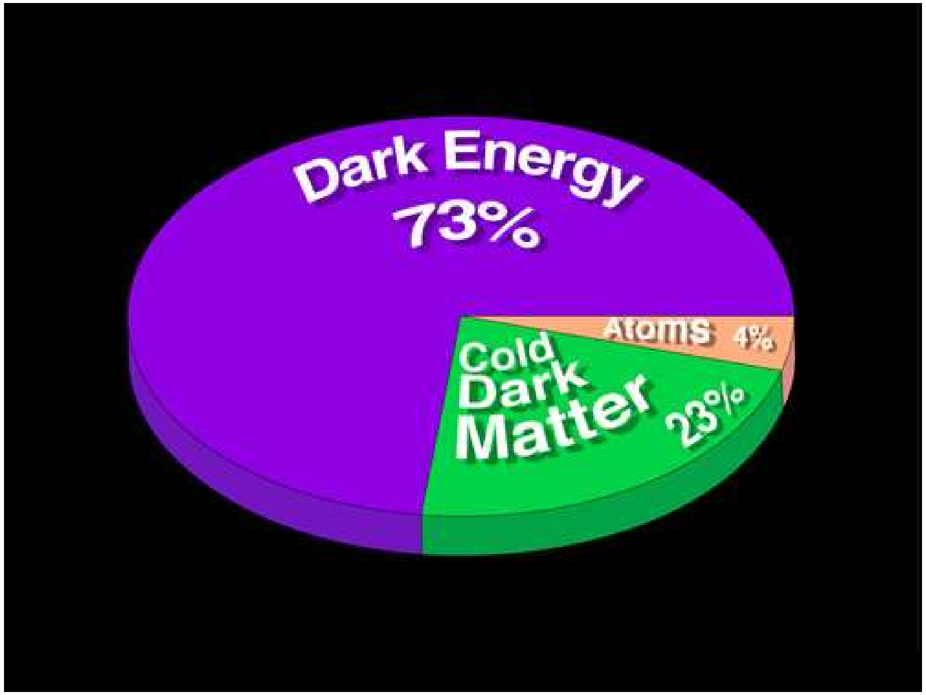

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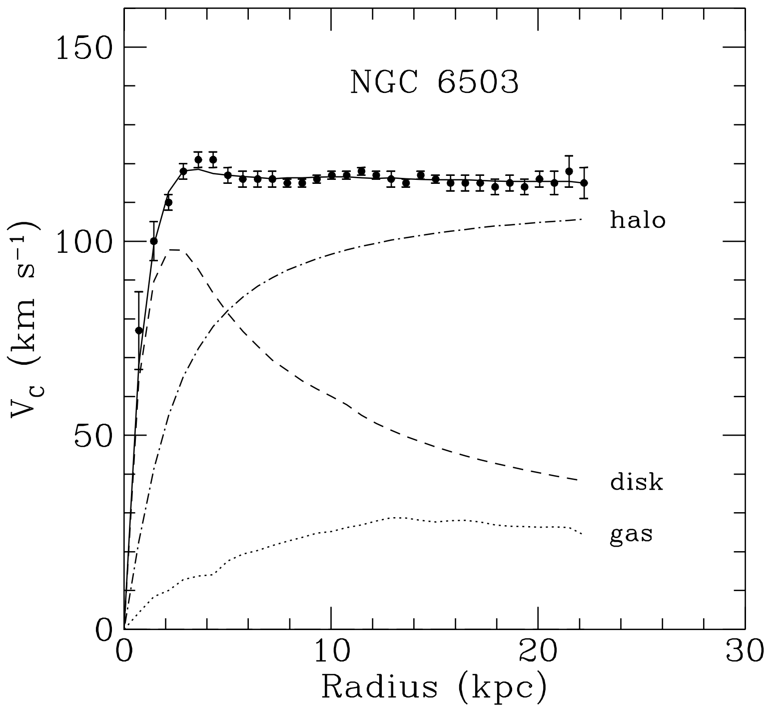

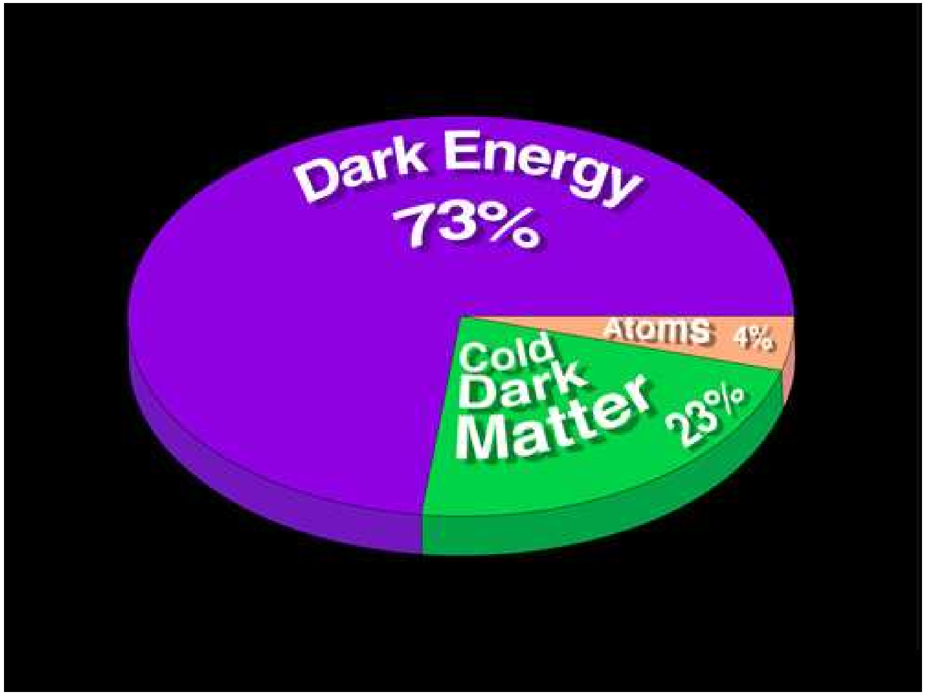

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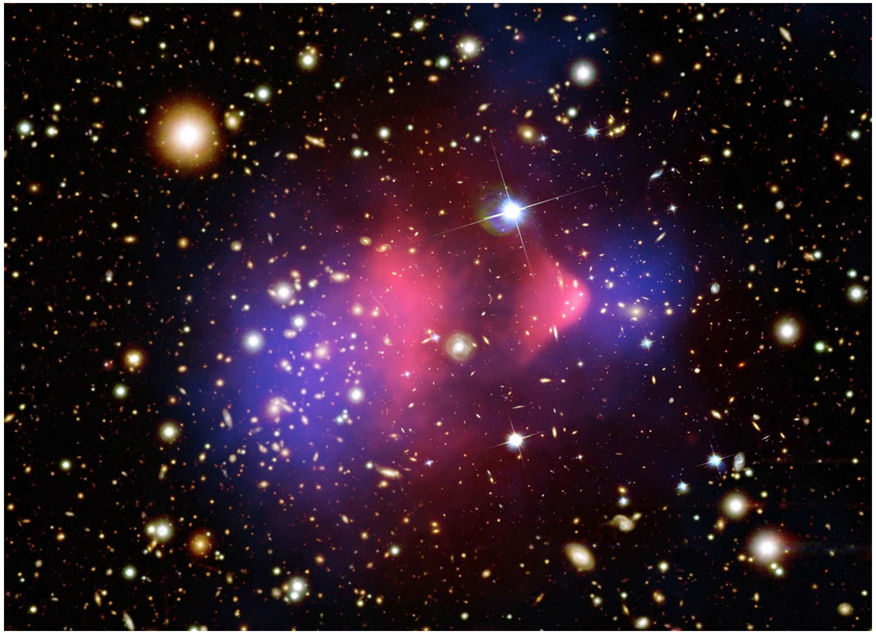

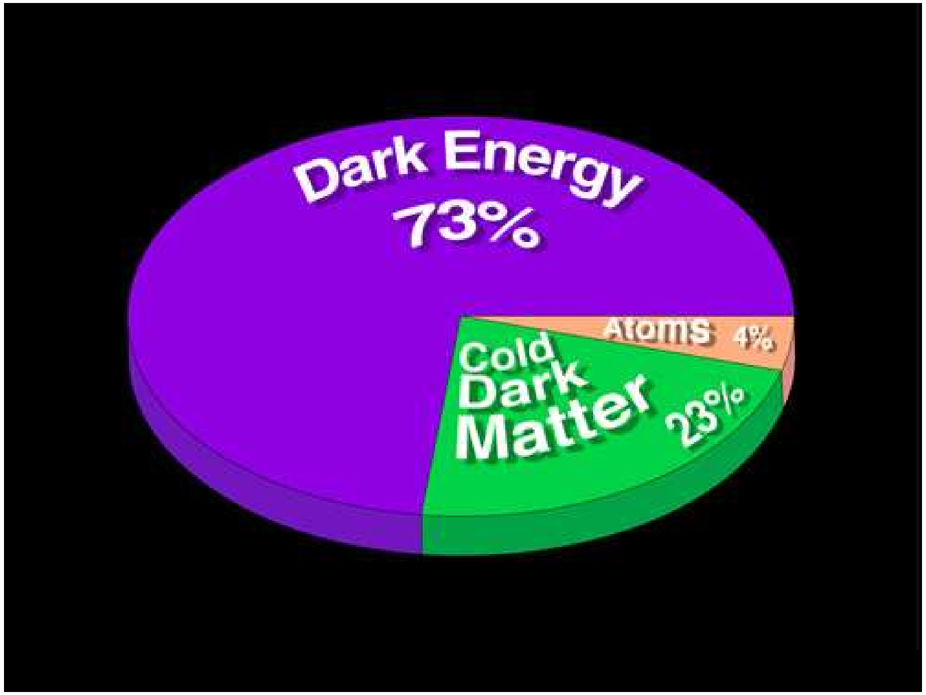

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Goal for this talk: construct a consistent thermal history of a Universe with supersymmetric dark matter (neutralino/gravitino

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, $t \sim 10^{13} s$)

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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

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- **RH stau NLSP**
  Catalytic production of $^6\mathrm{Li}$
  Conflict with BBN
- **other candidates**
  stop $\rightarrow$ Santoso
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  Jedamzik, hep-ph/0707.2070

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BBN is the Achilles' heel of SUSY 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

★ The gravitino is a very interesting candidate for dark matter. The relic abundance is:

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

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★ 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, $\widetilde{\tau}_R \rightarrow \mu\,\nu_\tau$, with lifetime:

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

Even with a tiny amount of R-parity violation, the stau will decay well 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
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$$\tau_{3/2} \sim 10^{26}\mathrm{s} \left(\frac{\lambda}{10^{-7}}\right)^{-2} \left(\frac{m_{3/2}}{10 \ \mathrm{GeV}}\right)^{-3}$$

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In summary: The existence of a gravitino LSP with a mass in the range 5-100 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

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.

  $\mathbf{16}_i\mathbf{16}\mathbf{10}_H$. "Bad term". Produces $v_{B-L}LH_u$. Too large 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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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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- $W_{R\!\!\!/_p} = \frac{1}{2}\lambda\, L L e^c + \lambda' Q L d^c + \lambda'' u^c d^c d^c$

In a particular flavour model

Buchmüller, Yanagida

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

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

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

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

Signatures for gravitino DM with broken R-parity

I- Signatures at gamma ray observatories

The gravitino decays into photon and neutrino with a decay rate:

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

with $|U_{\tilde{\gamma}\nu}|$ the photino-neutrino mixing. One gets approximately:

$$\tau_{3/2} \simeq 4 \times 10^{27}\text{s} \left(\frac{\epsilon_3}{10^{-7}}\right)^{-2} \left(\frac{\widetilde{m}}{200\text{ GeV}}\right)^2 \left(\frac{m_{3/2}}{10\text{GeV}}\right)^{-3}$$

where $\epsilon_3 \equiv C\frac{v_{B-L}^2}{M_P^2} \sim C\frac{M_3}{M_P}$ parametrizes the size of the R-parity breaking.

The lifetime is much longer than the age of the Universe, but a few decays are happening **NOW**.

The measurement of the extraterrestrial neutrino flux with an energy between 5-50 GeV is very difficult (same energy range as atmospheric neutrinos).

On the other hand, the photon flux could be observable as an extragalactic diffuse gamma-ray flux with a characteristic spectrum.

Shining dark matter

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

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

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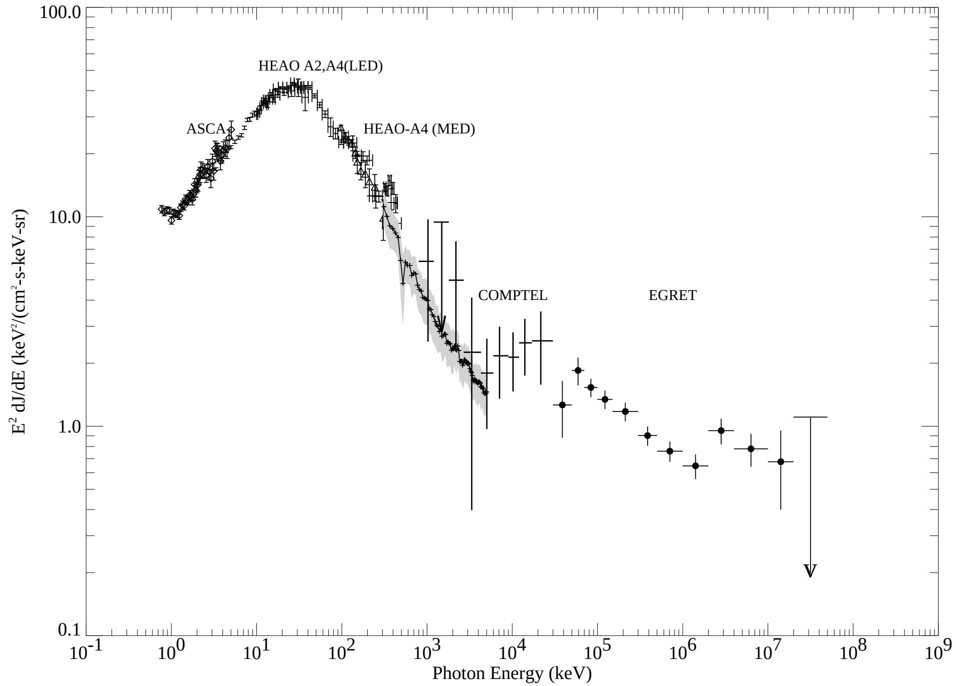
The more recent analysis by Strong, Moskalenko and Reimer ('04) shows a power law behaviour between 50 MeV and 2 GeV, but a clear excess between 2 GeV and 50GeV!!



The extragalactic gamma ray flux from the decay of a 10GeV gravitino could be hidden in this excess. GLAST will clarify this issue.

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 $\lambda L L e^c$)

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

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

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    Long heavily ionizing charged track followed by a muon track or a jet.
  - Also, the small left-handed component induces $\widetilde{\tau}_L \longrightarrow b^c t$ (through $\lambda' Q L d^c$)

    $$c\tau_{\tilde{\tau}}^{had} \sim 1.4 \text{ m} \left(\frac{m_{\tilde{\tau}}}{200\text{GeV}}\right)^{-1} \left(\frac{\epsilon_3}{10^{-7}}\right)^{-2}$$

    Long heavily ionizing charged track, followed by three jets.

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

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

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

    Long heavily ionizing charged track followed by a muon track or a jet.
  - Also, the small left-handed component induces $\widetilde{\tau}_L \to b^c t$ (through $\lambda' Q L d^c$)

    $$c\tau^{had}_{\tilde{\tau}} \sim 1.4\text{ m} \left(\frac{m_{\tilde{\tau}}}{200\text{GeV}}\right)^{-1} \left(\frac{\epsilon_3}{10^{-7}}\right)^{-2}$$

    Long heavily ionizing charged track, followed by three jets.
- If the NLSP is a neutralino
  - Main decays: $\chi_1^0 \to \tau^\pm W^\mp$, or $\chi_1^0 \to b\, b^c\, \nu$

    $$c\tau^{2-\text{body}}_{\chi_1^0} \sim 20\text{ cm} \left(\frac{m_{\chi_1^0}}{200\text{ GeV}}\right)^{-3} \left(\frac{\epsilon_3}{10^{-7}}\right)^{-2} \left(\frac{\tan\beta}{10}\right)^{2}$$

    $$c\tau^{3-\text{body}}_{\chi_1^0} \sim 600\text{ m} \left(\frac{m_{\widetilde{\nu}_L}}{300\text{ GeV}}\right)^{4} \left(\frac{m_{\chi_1^0}}{200\text{ GeV}}\right)^{-5} \left(\frac{\epsilon_3}{10^{-7}}\right)^{-2} \left(\frac{\tan\beta}{10}\right)^{-2}$$

    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 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. Unequivocal evidence for decaying dark matter would come from GLAST.
- This scenario predicts striking signatures at the LHC, in particular a vertex of the NLSP significantly displaced from the beam axis.