Cosmic-Ray Anomalies and Decaying Dark Matter

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ENTApP Dark Matter Workshop
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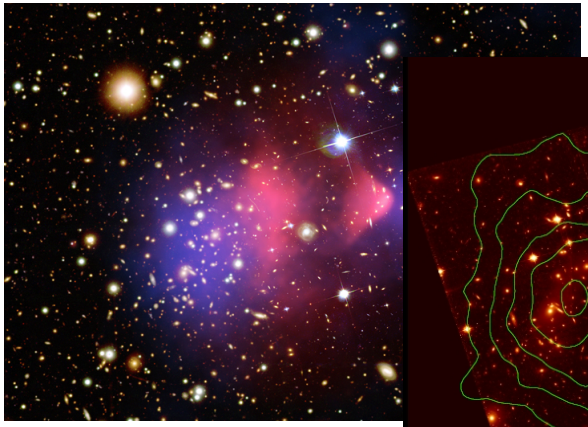
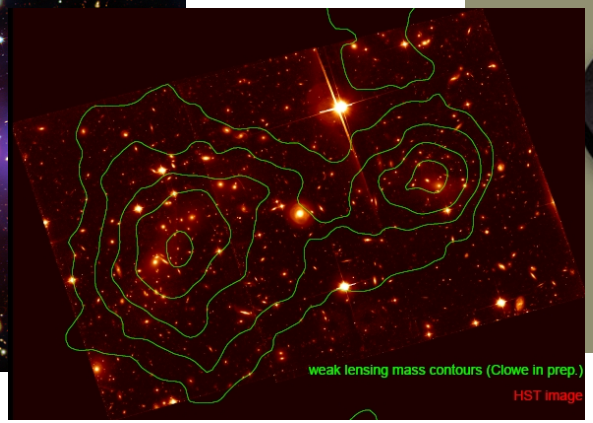
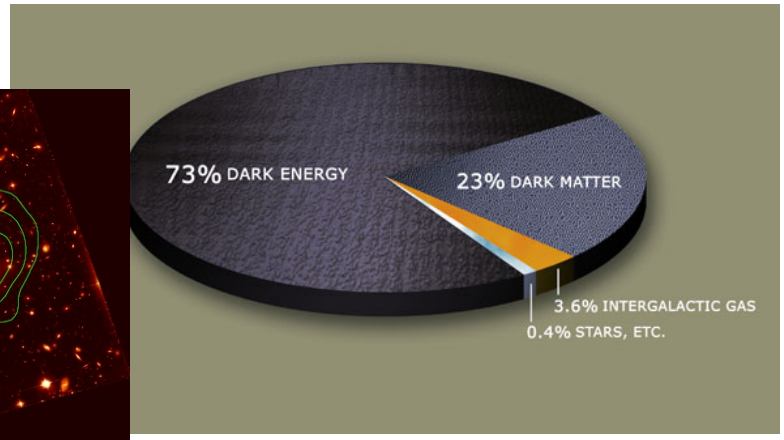
What Properties Must Dark Matter Have?







We know that the dark matter is

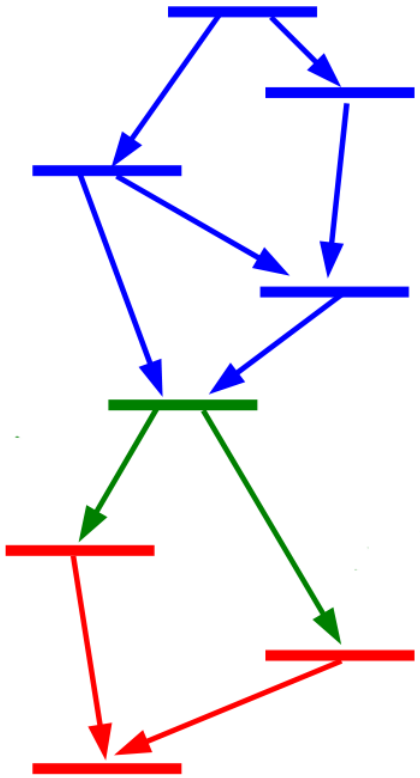
- non-baryonic
- (at most) weakly interacting
- cold
- very long-lived, but not necessarily stable:

  The dark matter lifetime must be longer than the age of the Universe

WIMPs are excellent dark matter candidates, but they require an enormous suppression of their decay rate

WIMP Dark Matter

- Spectrum of a Beyond-the-Standard-Model theory



Beyond the Standard Model

WIMP, $\tau \sim 10^{-25}$ s

Standard Model

WIMP Dark Matter

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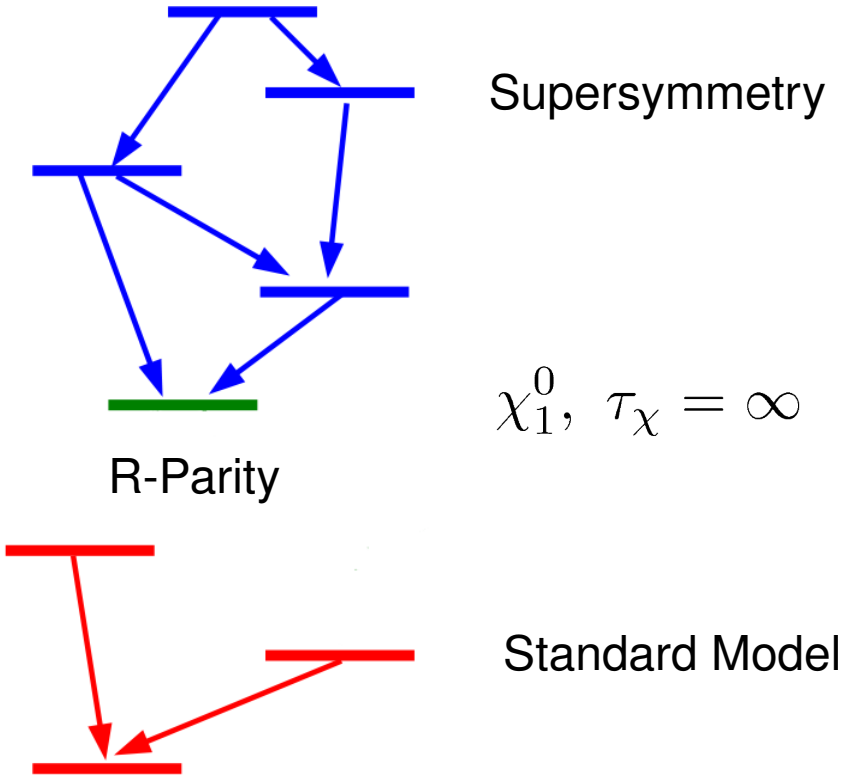
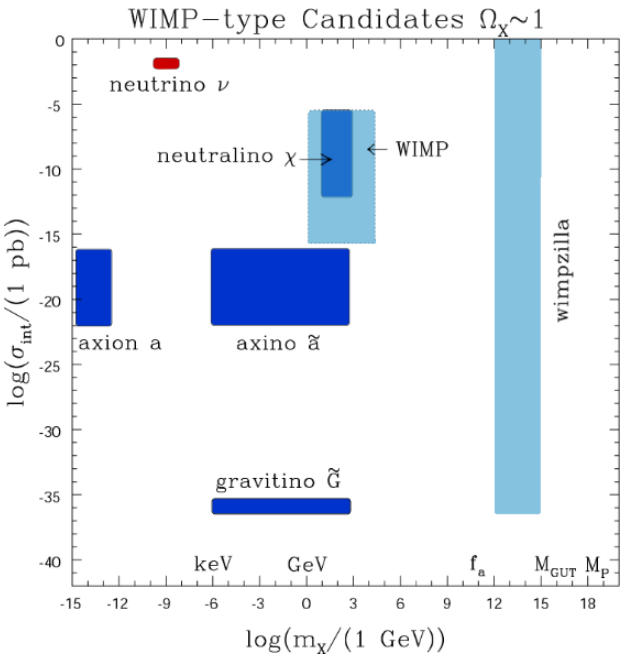


Imposing R-parity yields a perfectly stable dark matter candidate

SuperWIMP Dark Matter

- SuperWIMPS have extremely weak interactions and correspondingly long lifetimes
- The lifetimes can naturally be around or some orders of magnitude smaller than the age of the Universe

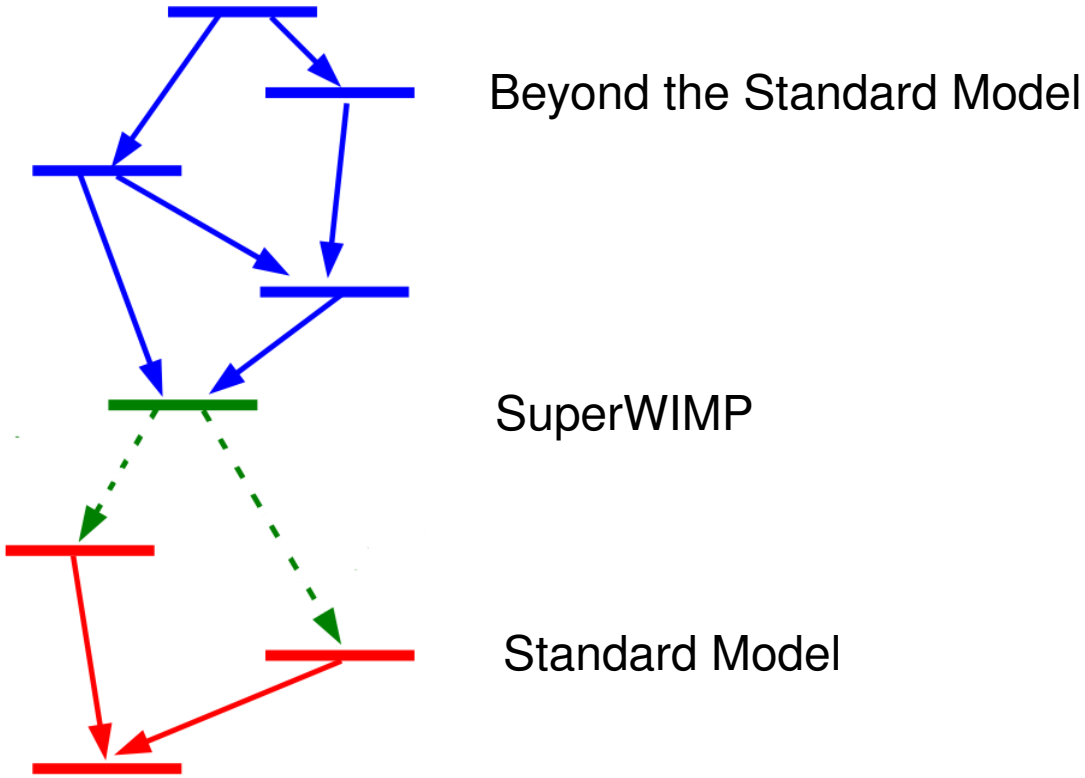
→ one needs only a moderate suppression of the couplings to get a lifetime compatible with dark matter



Choi, Roszkowski 05

SuperWIMP Dark Matter

- Spectrum of a Beyond-the-Standard-Model theory



No additional exact symmetry is necessary to get a potential dark matter candidate

Some Candidates for Decaying Dark Matter

- Gravitino dark matter with R-parity violation → See talk by M. Lola
  - Takayama, Yamaguchi 00
  - Buchmüller, Covi, Hamaguchi, Ibarra, Yanagida 07
  - Ibarra, DT 08
  - Ishiwata, Matsumoto, Moroi 08
- Hidden sector gauge bosons/gauginos
  - Chen, Takahashi, Yanagida 08
  - Ibarra, Ringwald, Weniger 08
  - Chun, Park 08
- Right-handed sneutrinos with Dirac masses
  - Pospelov, Trott 08
- Hidden sector fermions
  - Hamaguchi, Shirai, Yanagida 08
  - Arvanitaki, Dimopoulos, Dubosky, Graham, Harnik, Rajendran 08
- Bound states of strongly interacting particles
  - Hamaguchi, Nakamura, Shirai, Yanagida 08
  - Nardi, Sannino, Strumia 08

Indirect Dark Matter Detection

- All previous evidence for dark matter is gravitational and will not allow us to determine its nature → we need complementary approaches:

  Direct detection:
  DM nucleus → DM nucleus

  Collider searches:
  SM SM → DM

  Indirect detection:
  DM DM → SM SM dark matter annihilation

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  Indirect detection:
  DM DM → SM SM dark matter annihilation
  DM → SM SM dark matter decay

- Unstable dark matter will eventually decay into Standard Model particles and produce

  - Gamma rays
  - Positrons/electrons
  - Antiprotons
  - Neutrinos
  - ...

Indirect Signatures of Decaying Dark Matter

Decaying dark matter

Flux $\propto \dfrac{\rho_{\rm DM}}{m_{\rm DM}\tau_{\rm DM}}$

Annihilating dark matter

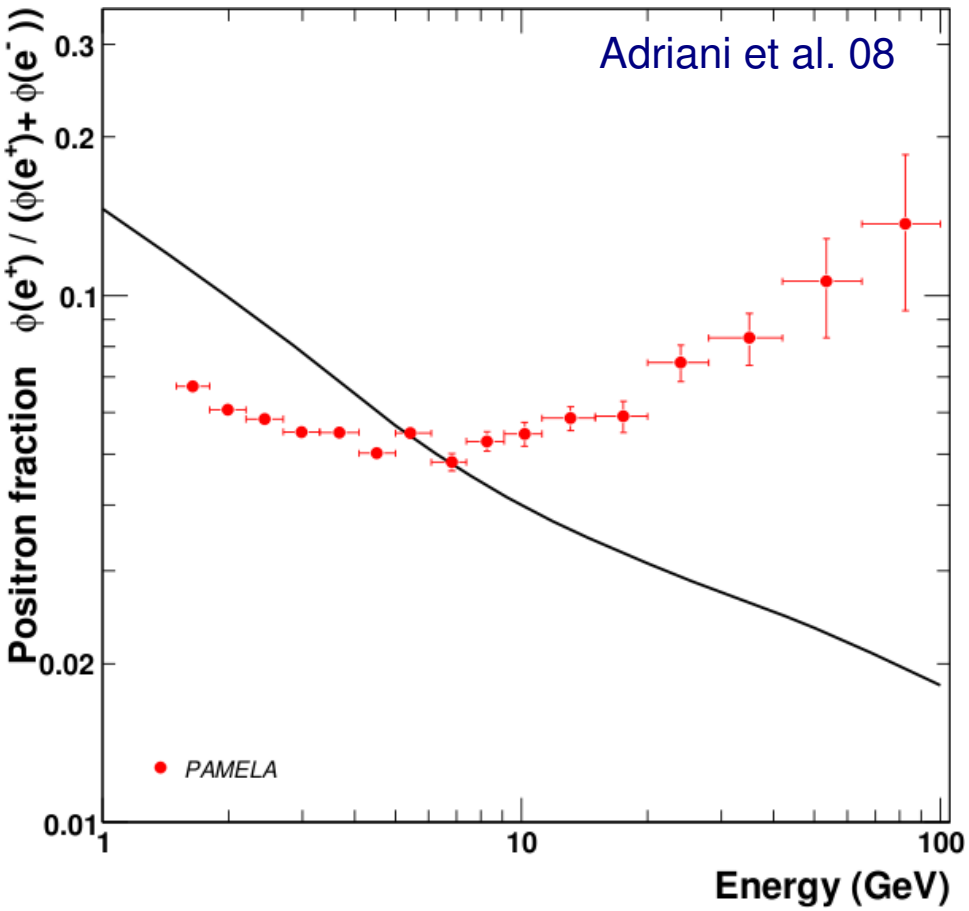
Flux $\propto \langle \sigma v \rangle \dfrac{\rho_{\rm DM}^2}{m_{\rm DM}^2}$

→ Qualitative differences in cosmic-ray fluxes from dark matter decay:

- Less dependence on the dark matter halo profile
- No enhancements from dark matter substructure
- Strategies such as observing annihilation signals from the center of the Galaxy or neutrinos from the Sun or the Earth do not work

Recent Experimental Breakthroughs

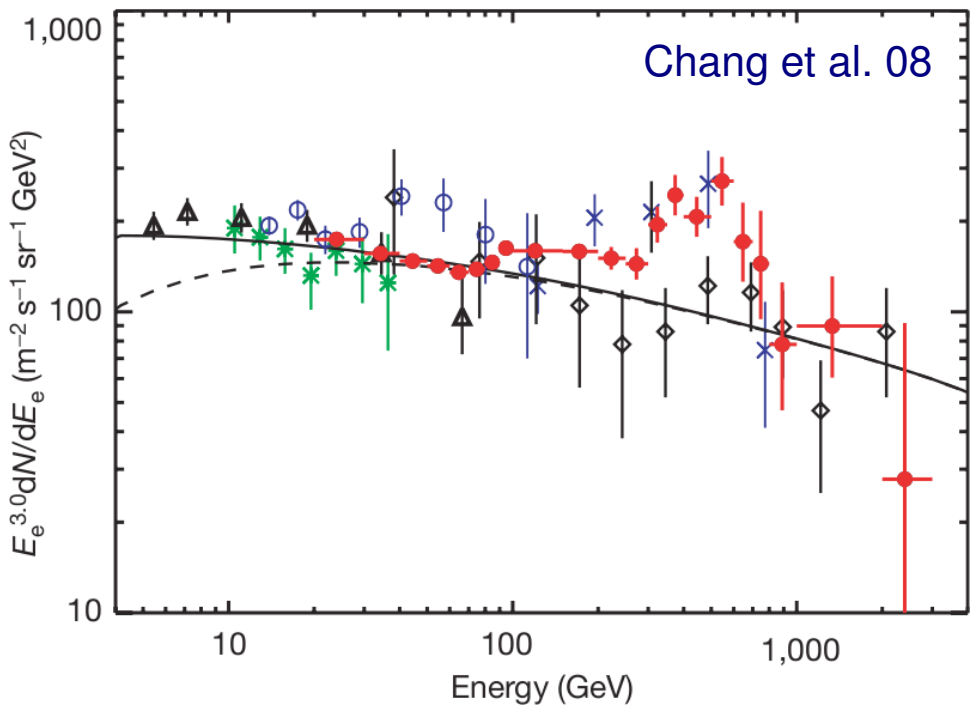
- Recent results from PAMELA
  - A steep rise in the positron fraction from 10 – 70 GeV
  - Evidence for charge-sign dependent solar modulation



Moskalenko and Strong

Recent Experimental Breakthroughs

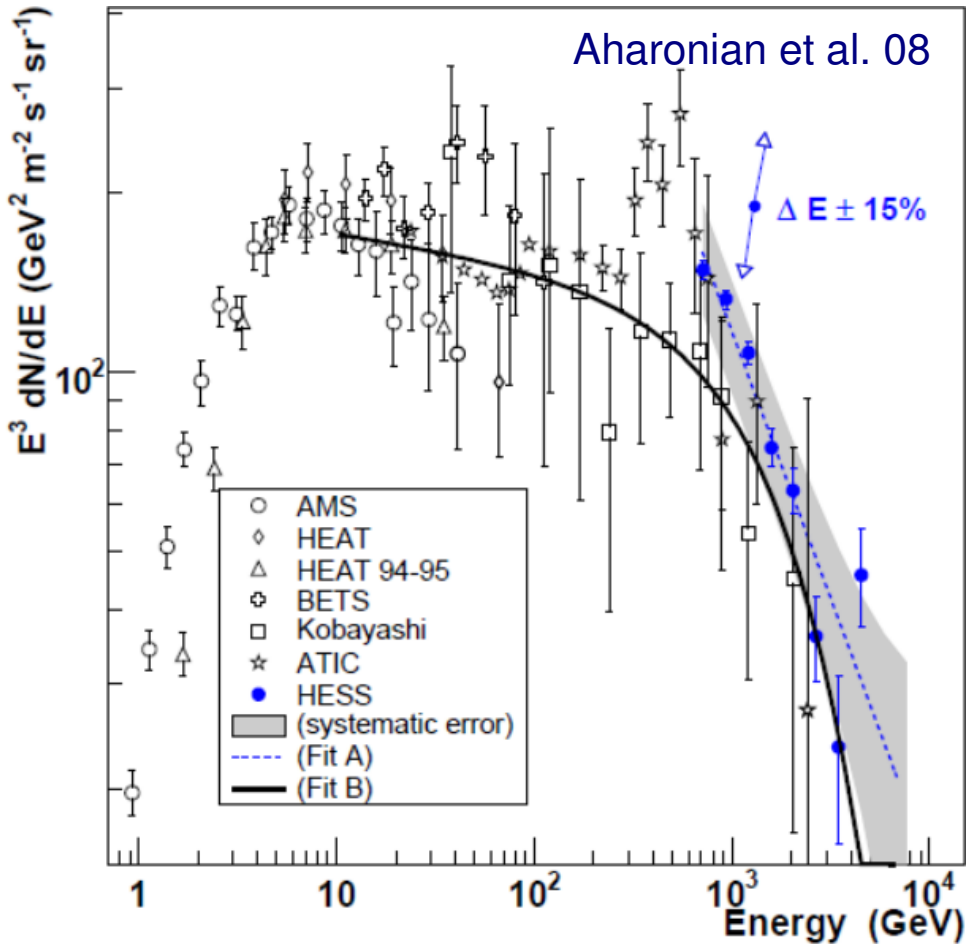
- Recent results from ATIC
  - Spectral features in the electron flux at 100 – 700 GeV?



Moskalenko and Strong

Recent Experimental Breakthroughs

- Recent results from HESS
  - Significant steepening of the electron spectrum above ~ 1 TeV

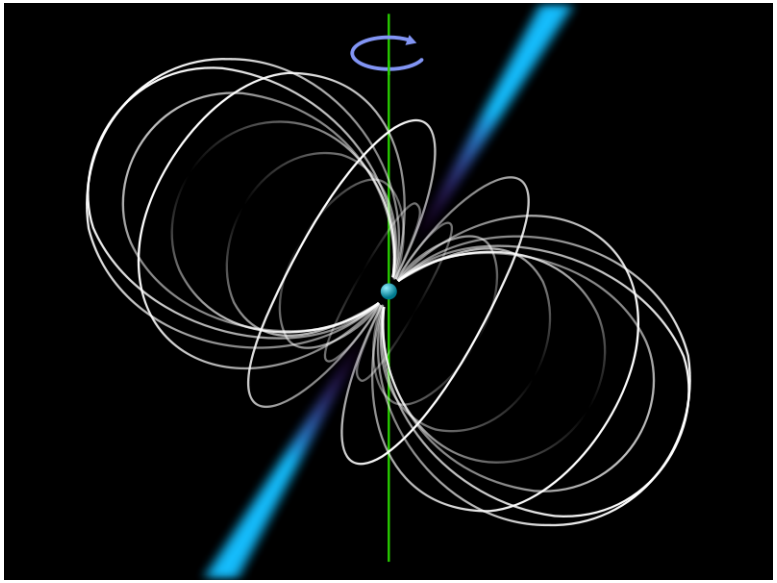


Propagation of Positrons/Electrons in the Galaxy

- Fairly complicated propagation:
  - diffusion
  - energy loss (inverse Compton, synchrotron radiation)

- Use stationary two-zone diffusion model to calculate fluxes at our position in the Galaxy

Pulsar Contributions to the Positron Flux



- Pulsars are known to be a source of high-energy positrons
- Possible nearby candidates: Geminga, B0656+14
- The sum of all pulsars in the Galaxy could also produce a sizable positron flux
- Difficult to quantitatively assess the pulsar contribution to the total positron flux

Model-Independent Analysis of the PAMELA results

- Possible decay channels for fermionic dark matter:

$$\psi \to Z^0\nu,\ W^\pm\ell^\mp,\ \ell^\pm\ell^\mp\nu$$

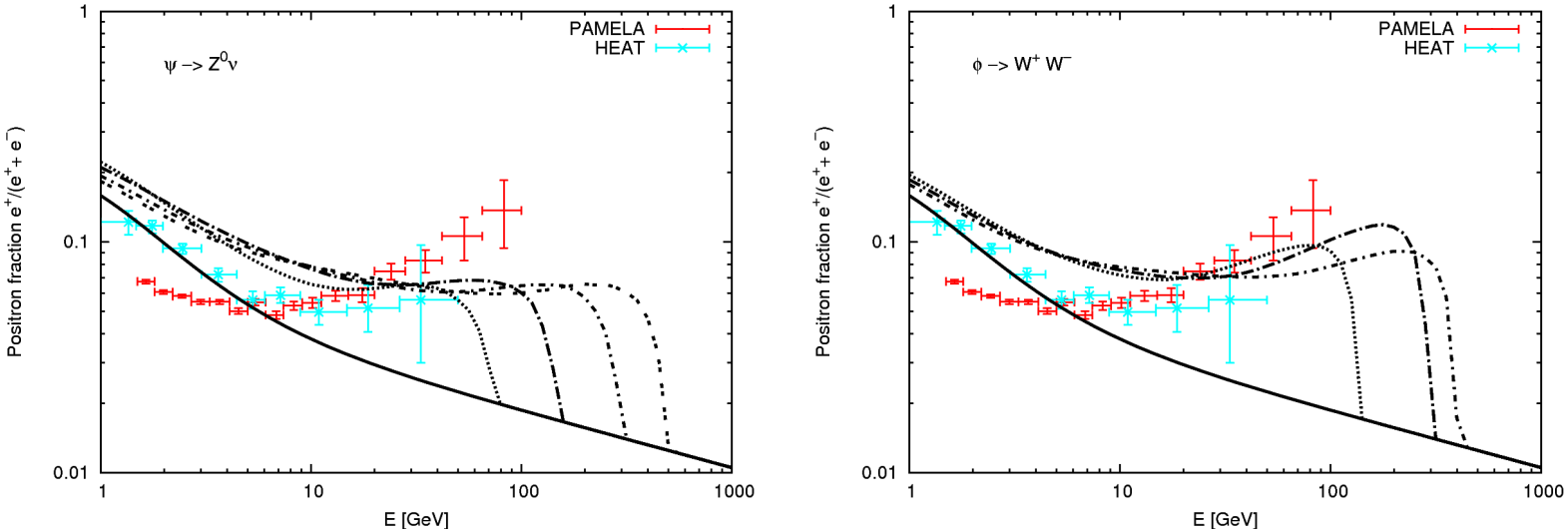
- Possible decay channels for scalar dark matter:

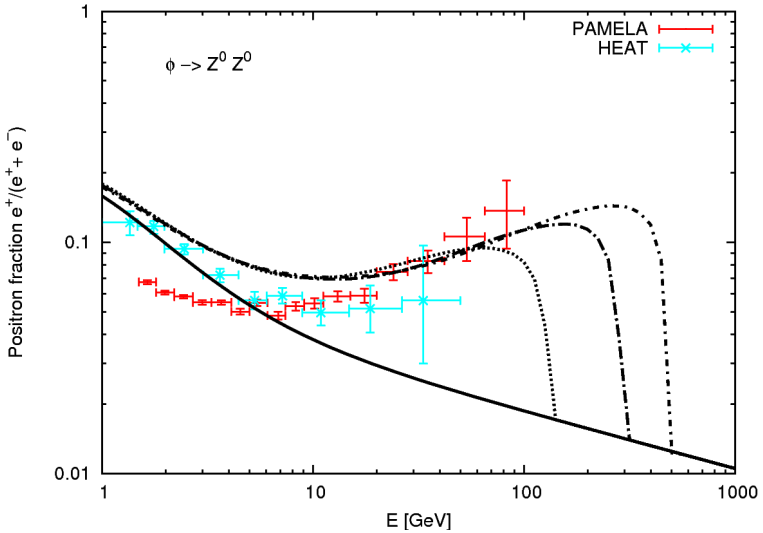
$$\phi \to Z^0 Z^0,\ W^\pm W^\mp,\ \ell^\pm\ell^\mp$$

- We get hard leptons from direct decay as well as softer leptons from the hadronization of the gauge bosons
- Propagate the positrons to our position in the Galaxy and compare with the PAMELA measurements

Positrons from Dark Matter Decay

- Spectrum from W, Z boson fragmentation too flat to account for the steep rise

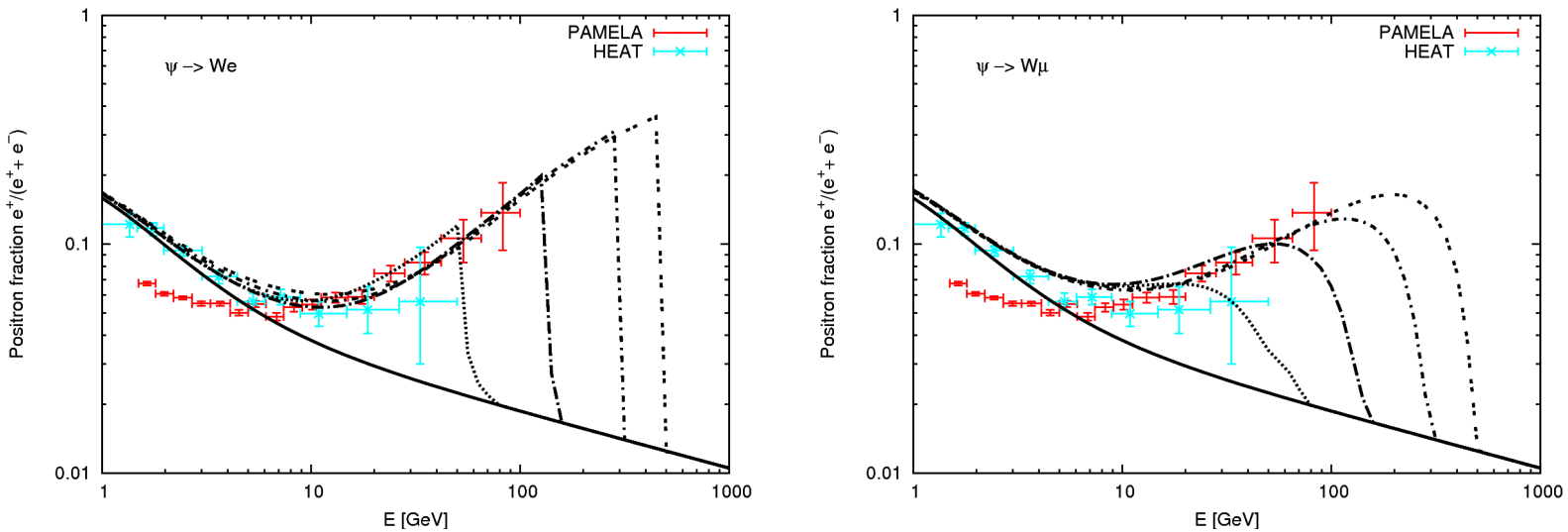


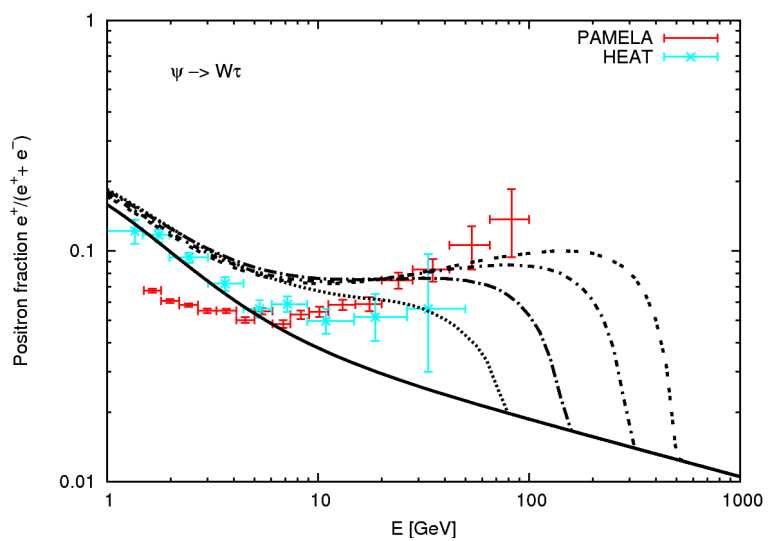


Ibarra, DT 08

Positrons from Dark Matter Decay

- Hard positrons/muons can reproduce the steep rise in the positron fraction, the spectrum from tau leptons is too soft

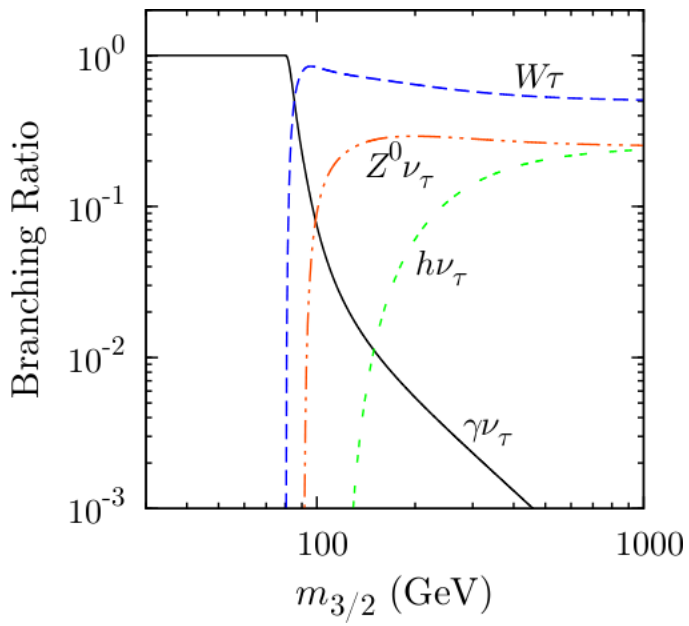




Ibarra, DT 08

Gravitino Dark Matter with Broken R-Parity

- Very attractive scenario: leads to a consistent thermal history of the Universe if the gravitino lifetime is between 10^{23} s and 10^{37} s
- Branching ratios into SM particles depend mostly on the gravitino mass



Covi, Grefe, Ibarra, DT 08

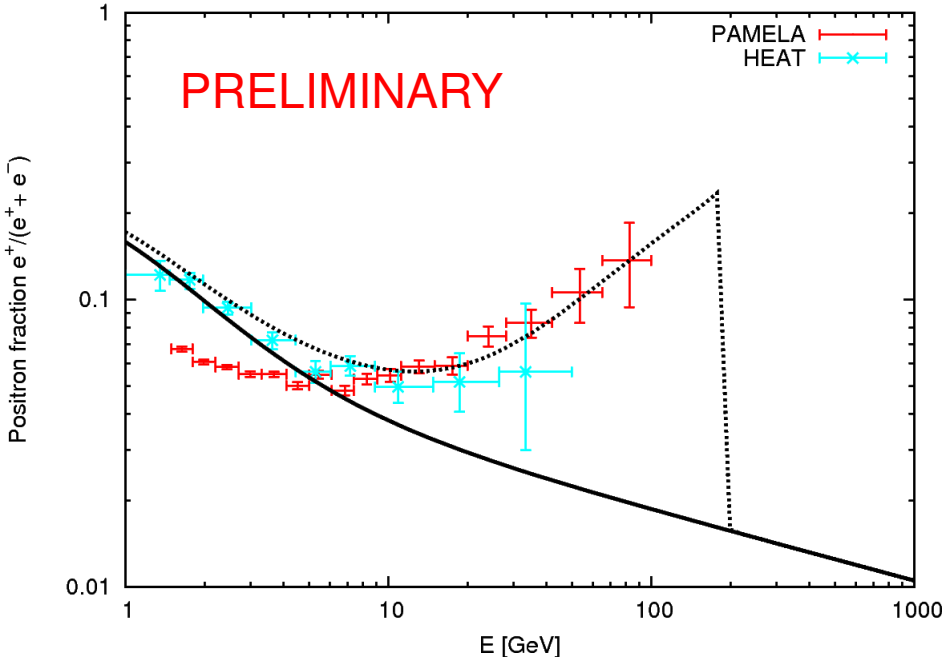
- Assumption: R-parity violation predominantly in the first generation to get hard positrons from gravitino decay

Positrons from Gravitino Decay

- MED propagation model

$$m_{3/2} = 400 \text{ GeV}, \ \tau_{3/2} = 1.7 \times 10^{26} \text{ s}$$

Ibarra, DT 09



Antiprotons from Gravitino Decay

- Important constraint from antiproton production: no excess observed in PAMELA measurements
- The results are very sensitive to the choice of propagation parameters

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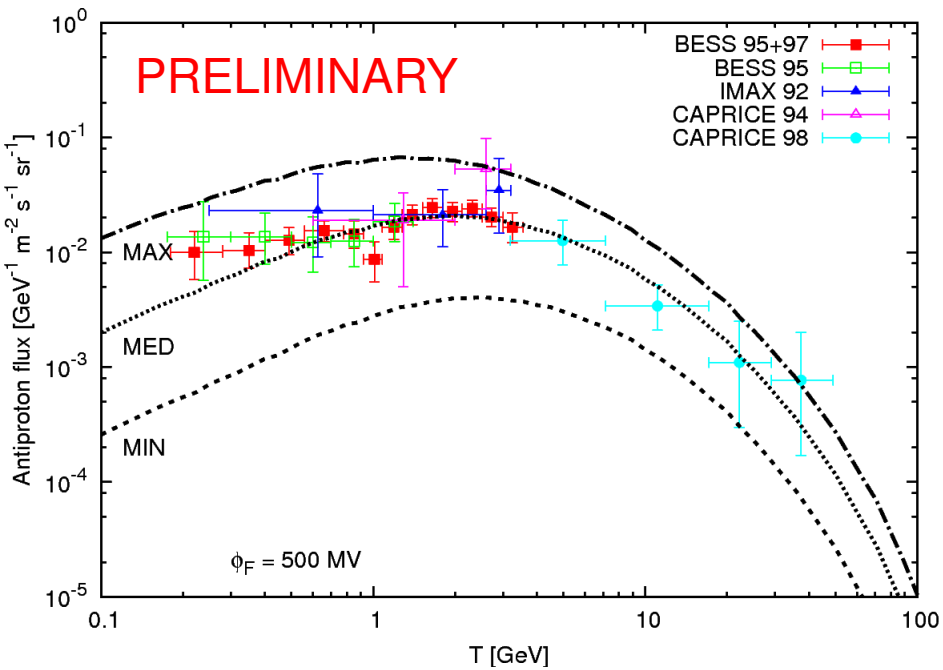
Ibarra, DT 09



Gamma Rays from Gravitino Decay

- Compatible with the break in the diffuse extragalactic gamma-ray spectrum observed by EGRET Moskalenko, Strong, Reimer

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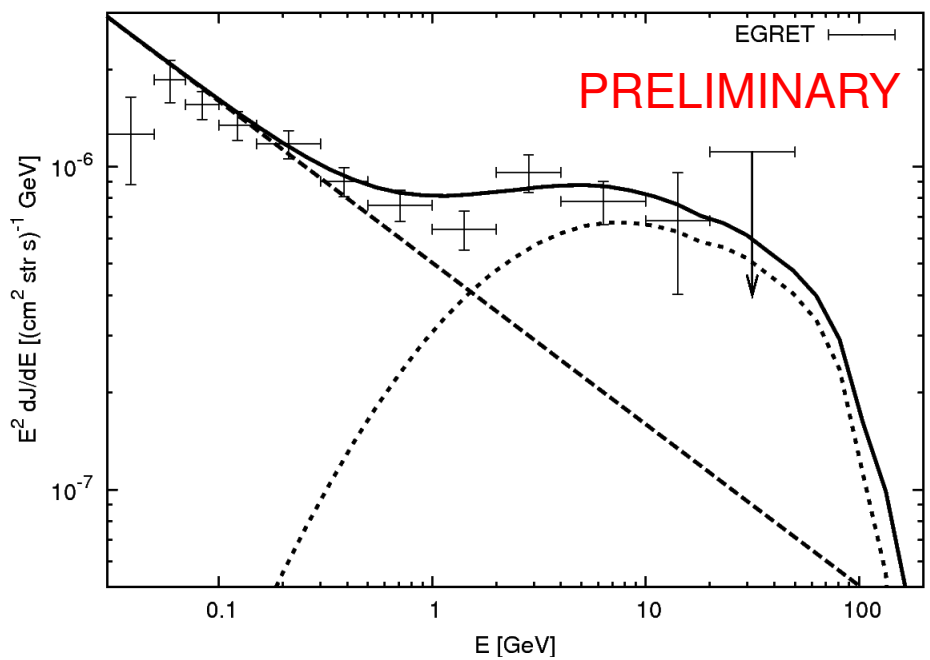
Ibarra, DT 09



Positrons from Gravitino Decay

- Can a heavier gravitino also account for the ATIC feature?
- MED propagation model

$$m_{3/2} = 1400 \text{ GeV}, \ \tau_{3/2} = 8 \times 10^{25} \text{ s}$$

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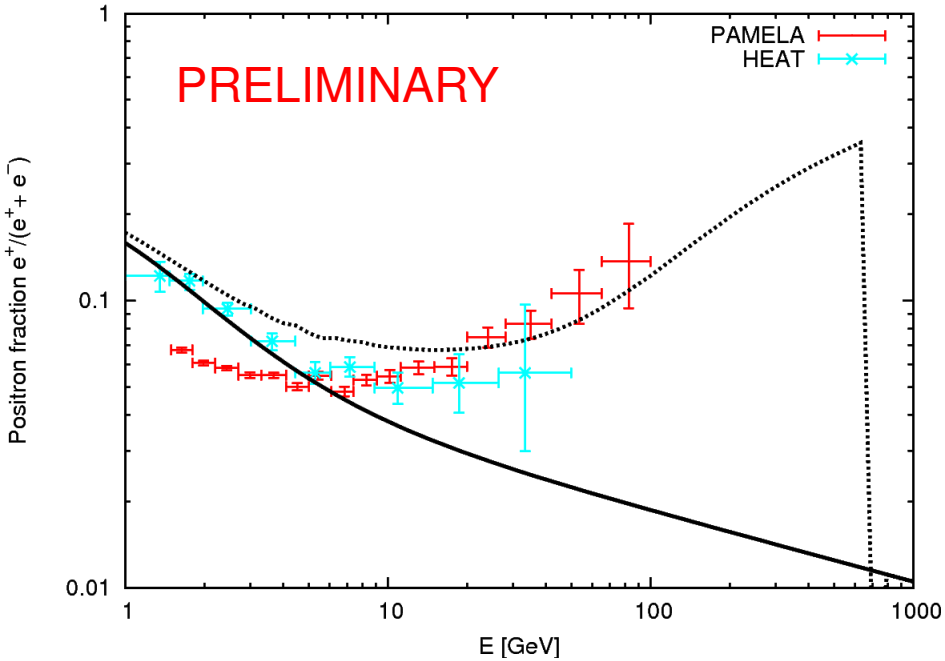

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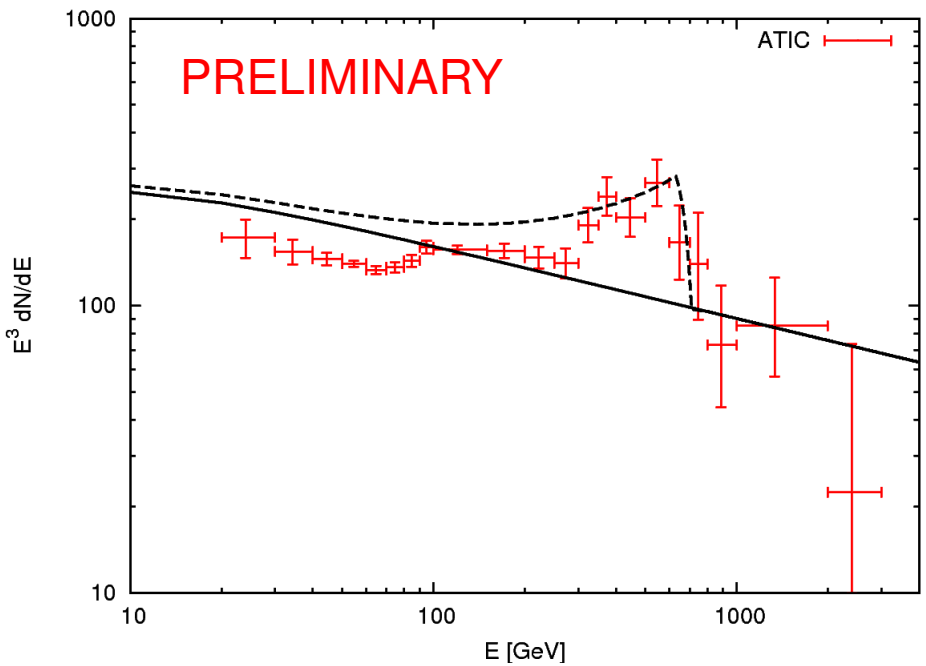

A Final Remark

- It is conceivable that the anomalous cosmic-ray signatures are caused by the decay of a subdominant dark matter component into the dominant dark matter component

  The cosmic-ray flux is invariant under a rescaling of abundance/lifetime:

  Flux $\propto \dfrac{\rho_{\rm DM}}{m_{\rm DM}\tau_{\rm DM}}$

- The dominant dark matter component might then be stable and possibly detectable in direct dark matter searches

Conclusions

- Decaying dark matter is an interesting possibility that has not been explored very thoroughly so far
- There are some well-motivated candidates for very long-lived dark matter
- Decaying dark matter can provide an explanation for the observed anomalies if $m_{\rm DM} \gtrsim 300\ {\rm GeV},\ \tau_{\rm DM} \sim 10^{26}\ {\rm s}$
  and the dark matter decays directly into electrons/muons
- However, other possible sources of positrons have to be kept in mind
- Whatever the reason for the anomalies, something very interesting might be going on:
  - First non-gravitational evidence for dark matter?
  - New astrophysics?
  - Direct observation of cosmic rays from pulsars?