Slightly Non-Minimal Dark Matter

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based on paper with Chris Spitzer,

e-print: arXiv: 0810.5167 [hep-ph],

and work in progress with Maurizio Piai and Chris Spitzer

Talk Outline

- Indirect detection of Dark Matter from Antimatter
- PAMELA results etc
- ATIC rumor
- Hidden Sectors and Dark Matter
- Relic Abundance Computation with hidden sector
- Stripped down hidden sector: the "XY" model of hidden sector dark matter
- Comparison with data

What is Dark Matter?

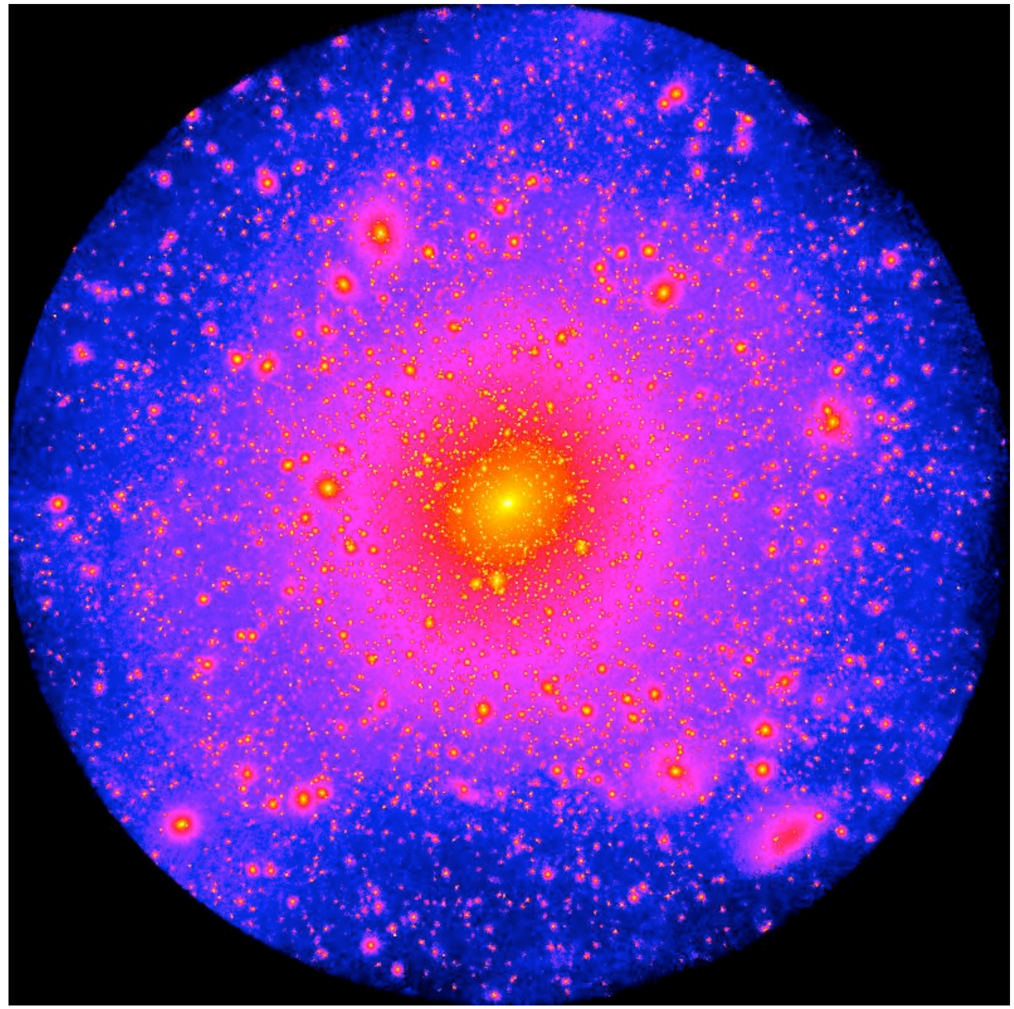
- 23% of critical density of Universe
- 84% of matter in universe
- gravitationally clumps, necessary for galaxy formation
- DARK (no electromagnetic interactions)

What is Dark Matter?

- Weakly Interacting Massive Particle?
  - well motivated (SUSY, natural relic abundance)
  - Large, multifaceted Experimental Search Program: Colliders, Direct Detection, Indirect Detection
- Axion?
  - well motivated (Strong CP, misalignment mechanism)
  - small Experimental Search Program-ADMX
- Something else? (not baryons, neutrinos, MACHOS)

Indirect Detection

- Our Dark Galaxy (simulated)
- Very Clumpy, lots of substructure
- annihilation rate/volume~ $n_x^2\ \sigma\ v$
- Can we see annihilation products?



UW N-body shop

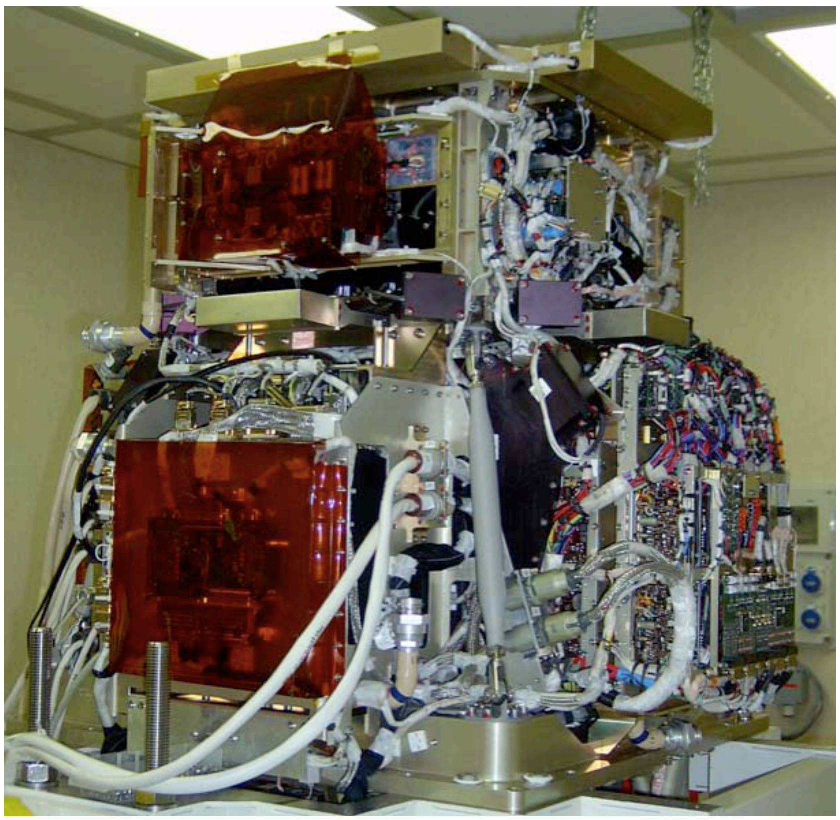
Indirect Signals of Dark Matter Annihilation

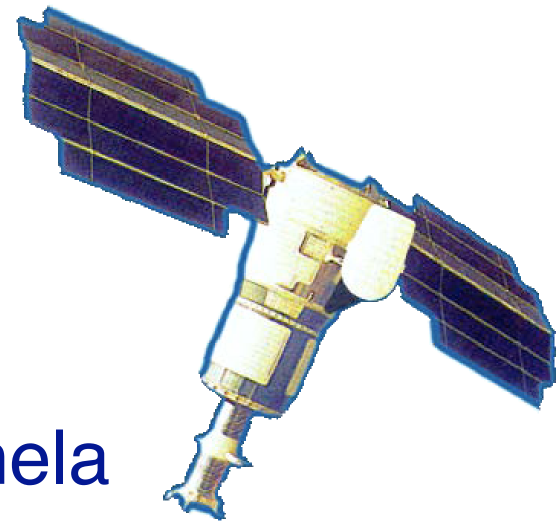
- Photons
- Neutrinos (particularly from DM captured by Sun)
- charged Cosmic Rays
  - antiprotons
  - ***positrons***
  - electrons

PAMELA!

- arXiv:0810.4995v1 “Observation of an anomalous positron abundance in the cosmic radiation”
- “Our high energy data deviate significantly from predictions of secondary production models, and may constitute the first indirect evidence of dark matter particle annihilations, or the first observation of positron production from near-by pulsars.”

a Payload for Antimatter Matter Exploration and Light-Nuclei Astrophysics





Pamela
in Samara,
Russia
4/09/05

from 2006 talk
by A. Morselli

“Slightly nonminimal Dark Matter”

- abstracted and simplified weakly coupled version of ‘hidden valley’ dark matter, inspired to account for PAMELA, ATIC cosmic ray positron and electron excesses
- also possible gamma ray excess from dark matter annihilation

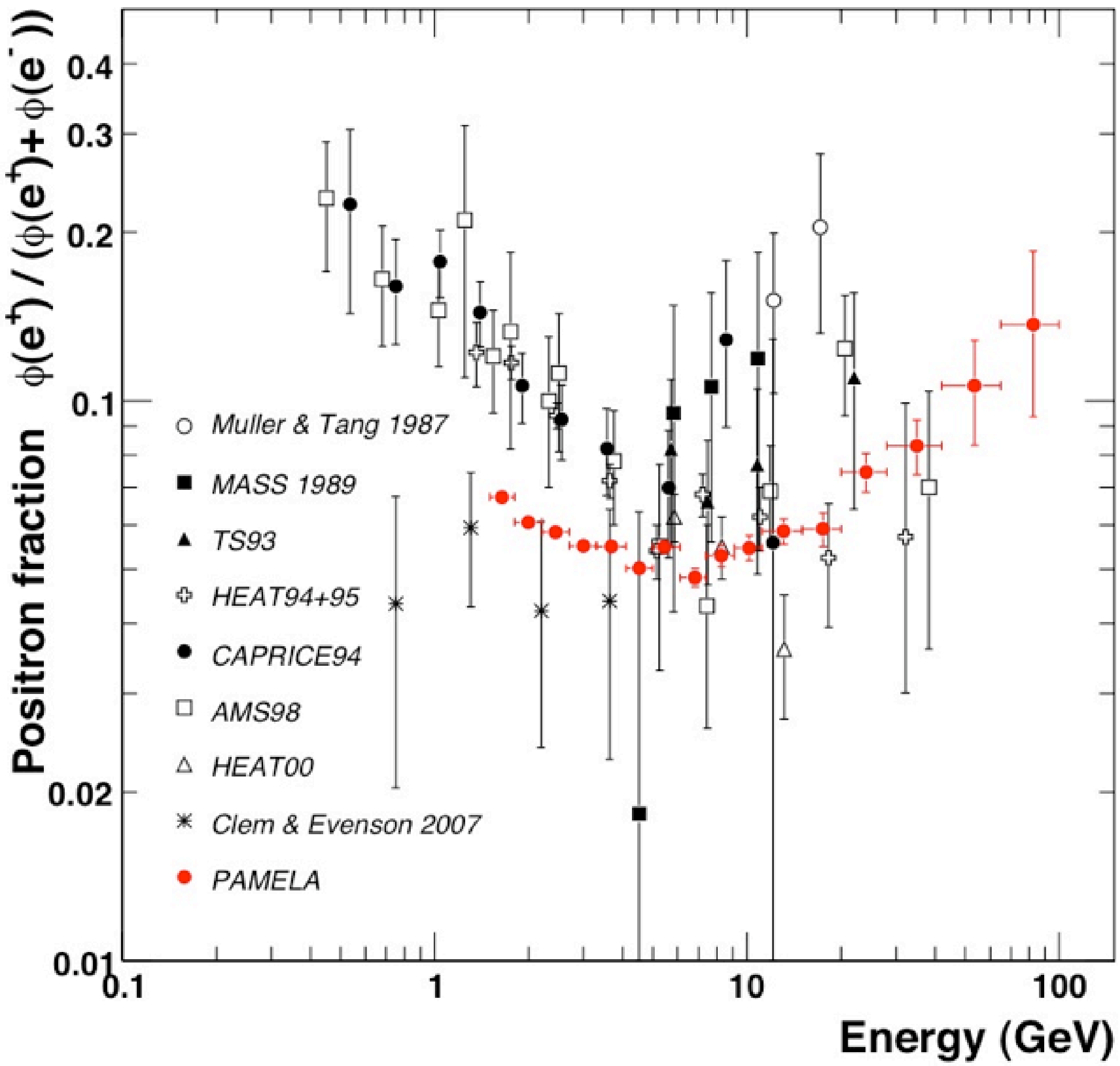


FIG. 3: **PAMELA positron fraction with other experimental data.** The positron fraction measured by the PAMELA experiment compared with other recent experimental data[24, 29, 30, 31, 32, 33, 34, 35]. One standard deviation error bars are shown. If not visible, they lie inside the

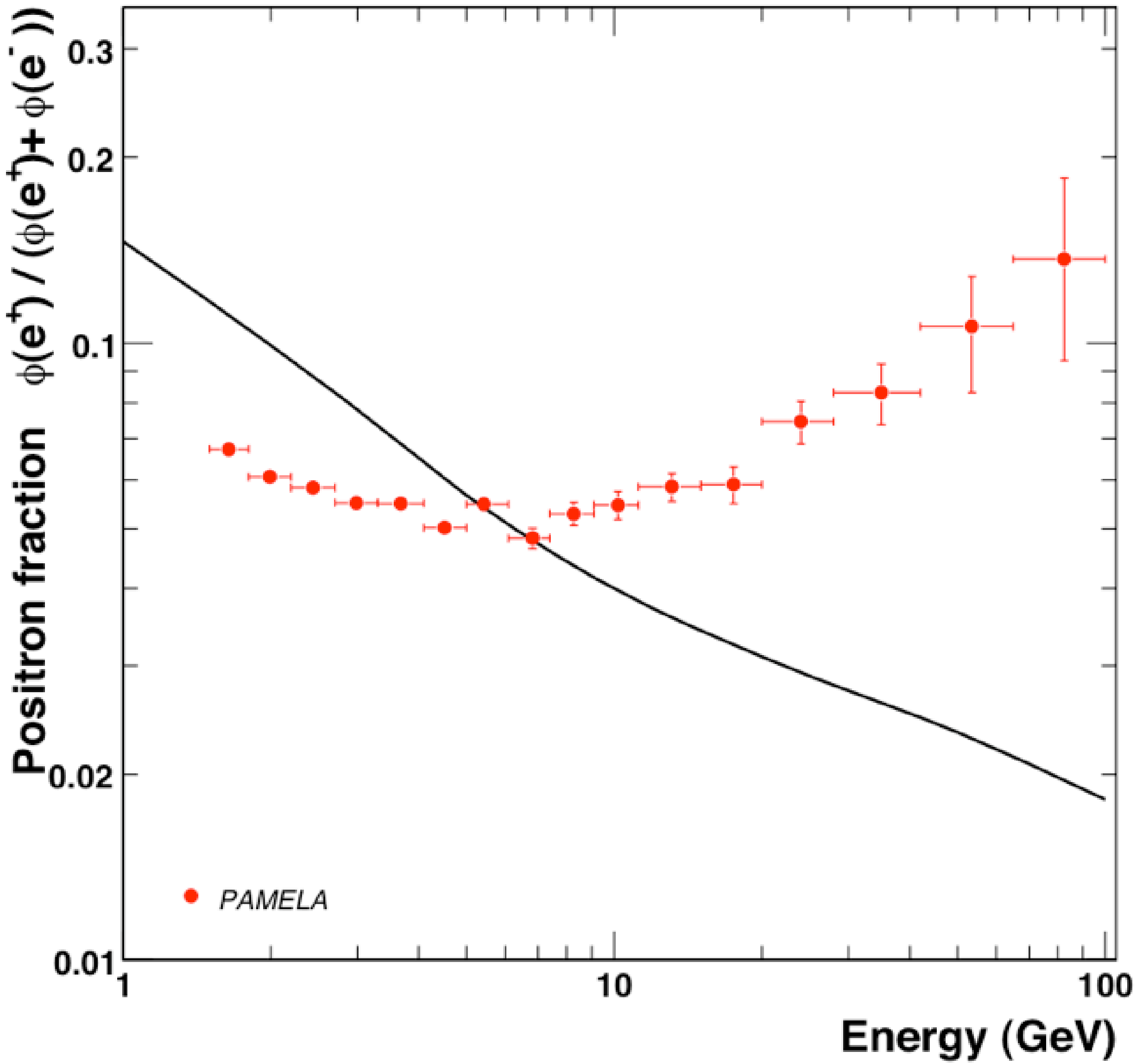


FIG. 4: **PAMELA positron fraction with theoretical models.** The PAMELA positron fraction compared with theoretical model. The solid line shows a calculation by Moskalenko & Strong[39] for pure secondary production of positrons during the propagation of cosmic-rays in the

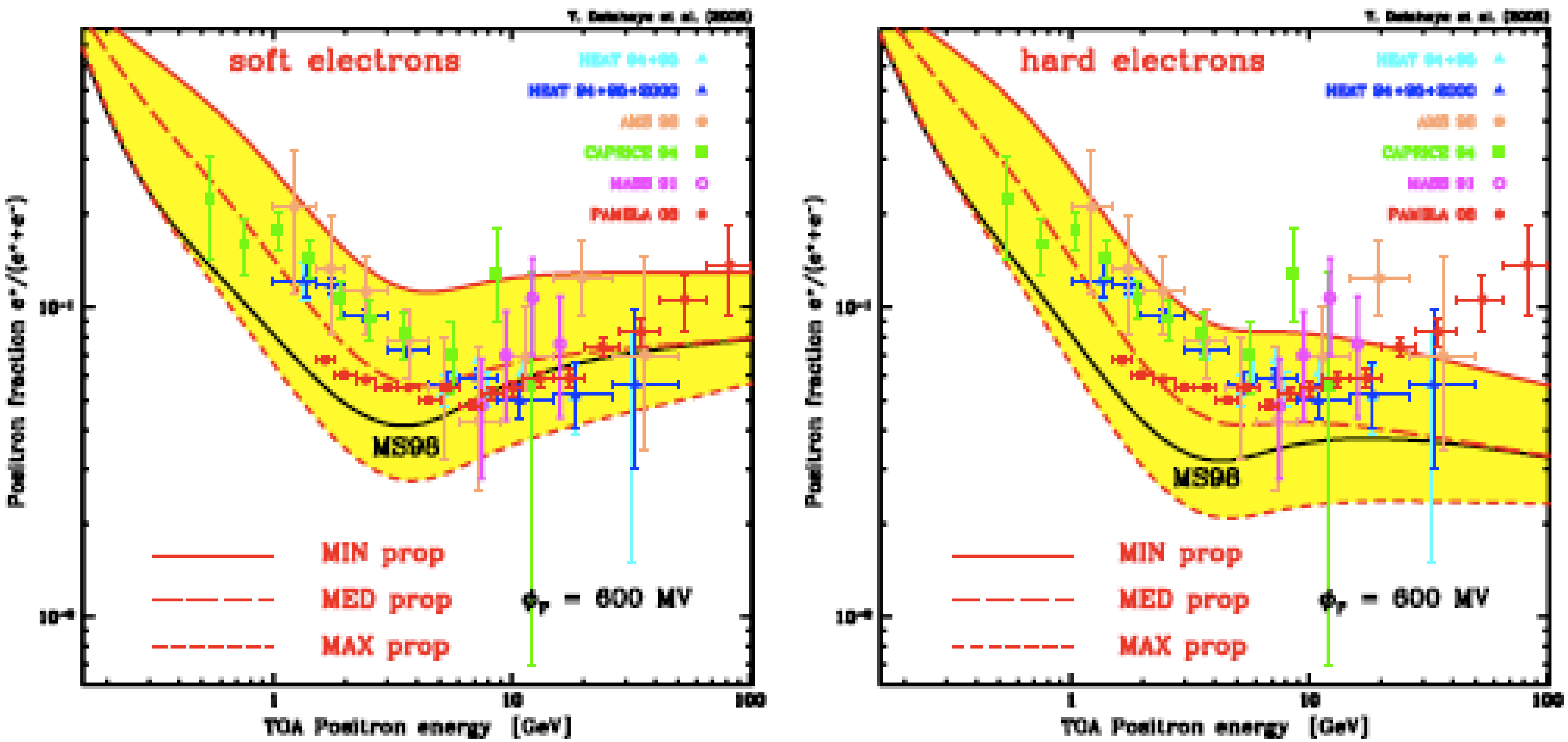


Fig. 10. Positron fraction as a function of the positron energy, for a soft (left panel) and hard (right panel) electron spectrum. Data are taken from CAPRICE (Boezio et al. 2000), HEAT (Barwick et al. 1997), AMS (Aguilar et al. 2007; Alcaraz et al. 2000), MASS (Grimani et al. 2002) and PAMELA (Adriani et al. 2008).

from Delahaye et al.

Note: no excess anti-protons for PAMELA

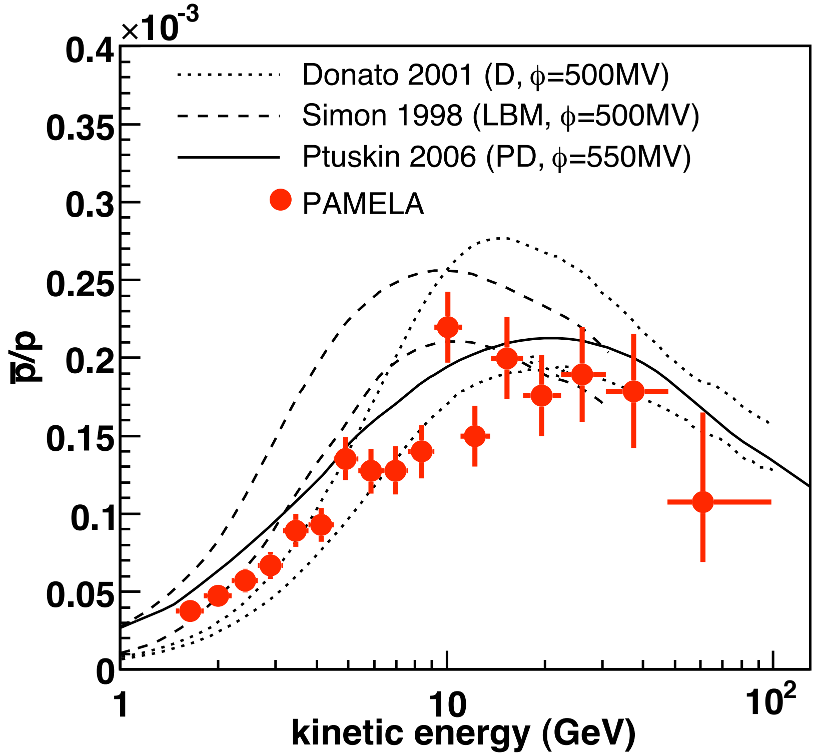


FIG. 3: The antiproton-to-proton flux ratio obtained in this work compared with theoretical calculations for a pure secondary production of antiprotons during the propagation of cosmic rays in the galaxy. The dashed lines show the upper and lower limits calculated by Simon et al. [17] for the standard Leaky Box Model, while the dotted lines show the limits from Donato et al. [18] for a Diffusion model. The solid line shows the calculation by Ptuskin et al. [19] for the case of a Plain Diffusion model. The curves were obtained using appropriate solar modulation parameters (indicated as ϕ) for the PAMELA data taking period.

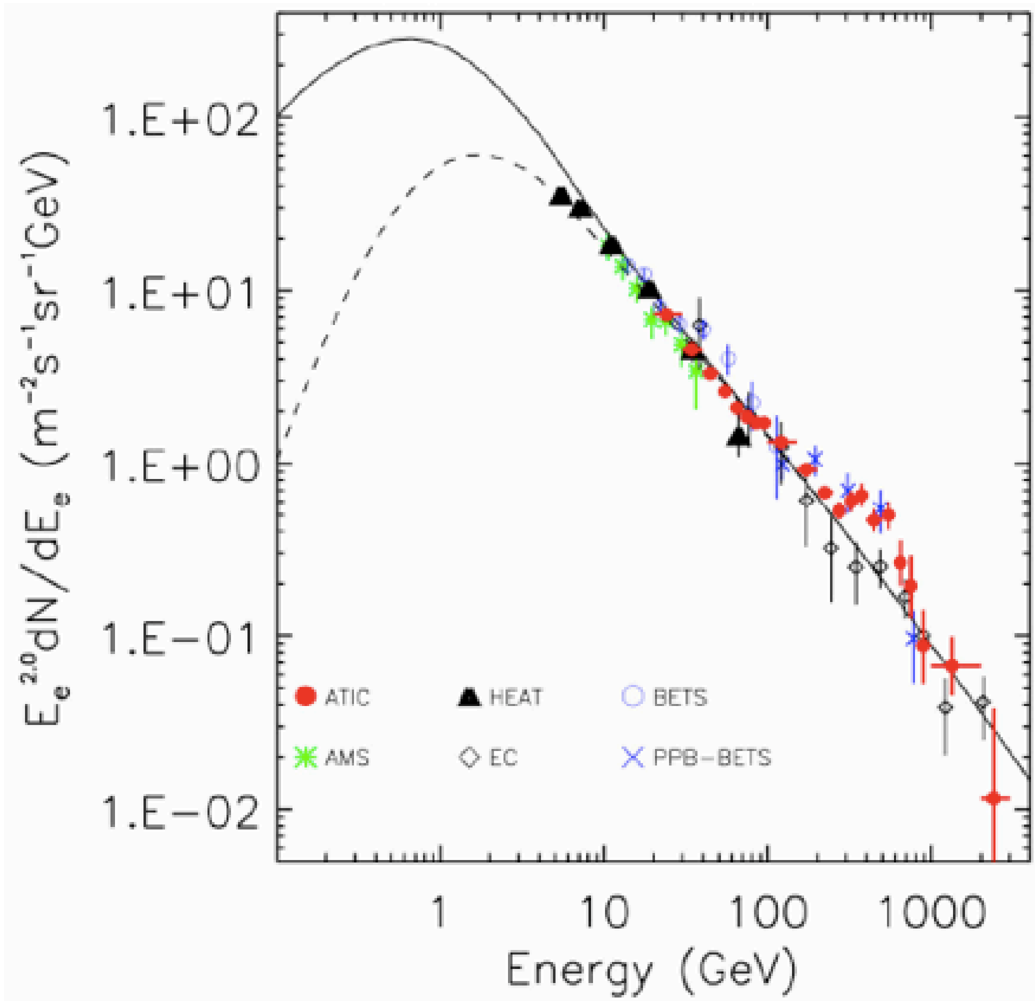
The ATIC electron results exhibits a feature

Curves are from GALPROP diffusion propagation simulation code

- Solid curve is local interstellar space
- Dashed curve is with solar modulation (500 MV)

“Excess” at about 300 – 600 GeV

Also seen by recent PPB-BETS



Astrophysics explanation from nearby pulsar?

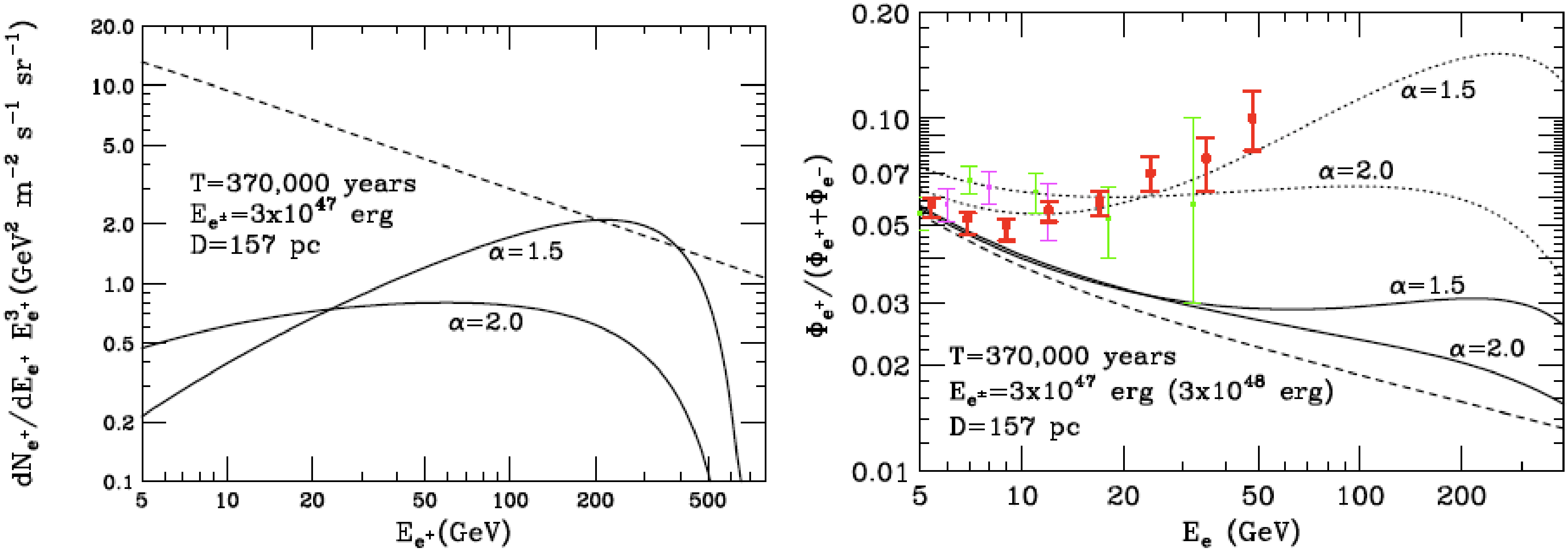


FIG. 2: The spectrum of positrons (left) and ratio of positrons to electrons plus positrons (right) from the pulsar Geminga, with the dashed lines as in Fig. 1. In the right frames, the measurements of HEAT [3] (light green and magenta) and preliminary measurements of PAMELA [2] (dark red) are also shown. Here we have used an injected spectrum such that $dN_e/dE_e \propto E^{-\alpha}\ \exp(-E_e/600\,\mathrm{GeV})$, with $\alpha = 1.5$ and 2.2. The solid lines correspond to an energy in pairs given by 3×10^{47} erg, while the dotted lines require an output of 3×10^{48} erg.

from 0810.1527, Hooper, Blasi, Serpico

Pulsar explanation for PAMELA looks ok but

- check with more data, higher energies (PAMELA to go to 270 GeV)
- check directionality (GEMINGA in opposite direction from galactic center)
- ATIC?

Dark Matter annihilation?

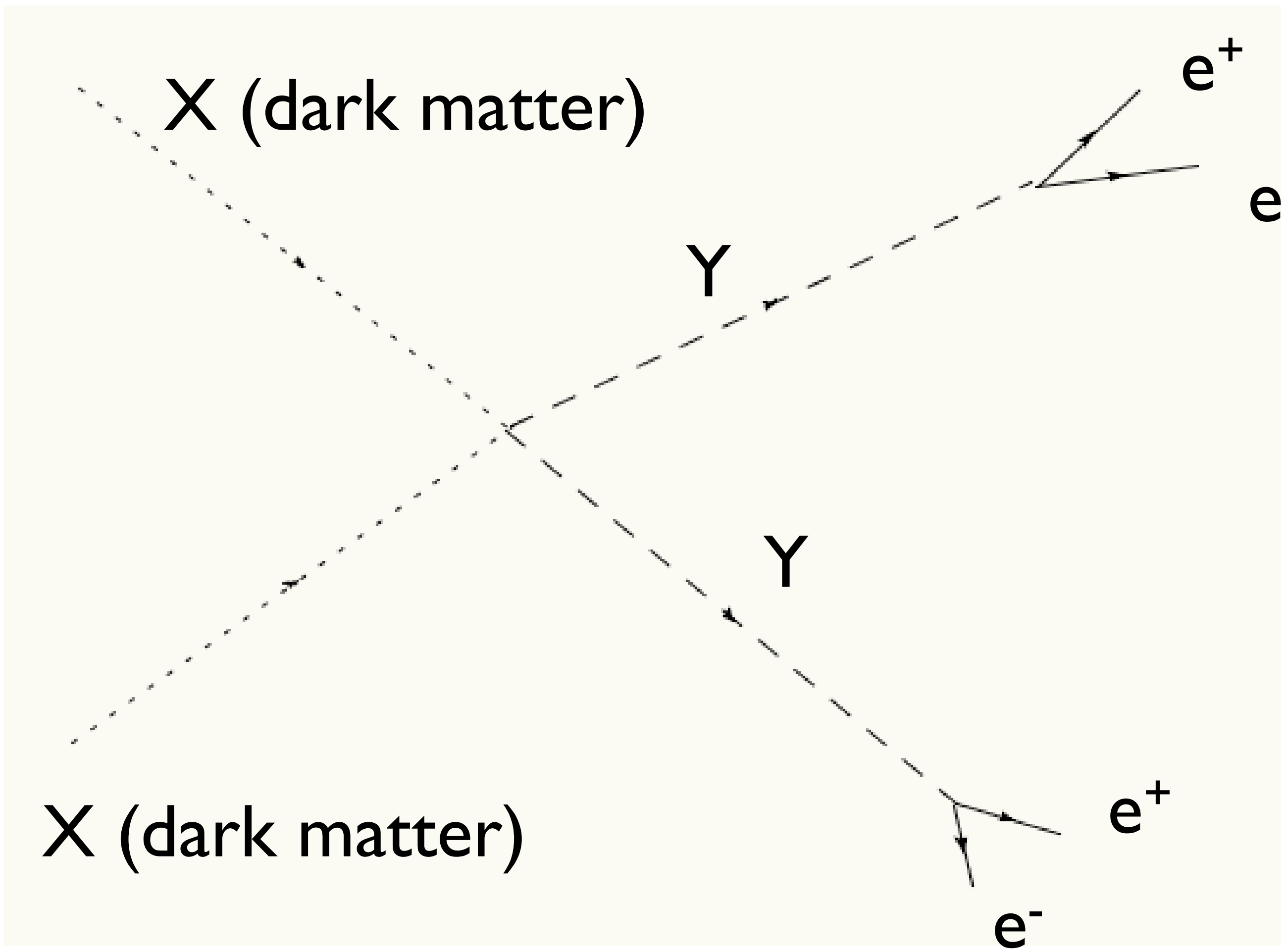
- Rate of order 100 x bigger than expected for SUSY WIMP (could enhance via clumpiness "boost factor", Sommerfield mechanism, or have nonthermal production)
- lack of antiprotons a problem for most WIMPs
- arXiv:0809.2409: Cirelli, Kadastik, Raidal,Strumia, "either the DM particles that annihilate into W,Z,h must be heavier than about 10 TeV or (ii) the DM must annihilate only into leptons."
- A non SUSY WIMP?
- Lots of new models with lots of new particles!

“X-Y model”

$$\mathcal{L} \supset M^2X^2 + m^2Y^2 + \lambda X^2Y^2 + hY\bar{e}e$$

- dark sector contains at least 2 new particles
  - X, a stable WIMP, no direct SM coupling, mass 80-1000 GeV
  - Y, a light (100 MeV) metastable particle, O(1) coupling to X, tiny coupling to SM
- motivation: new strongly coupled exotic dark sector with stable heavy ‘baryons’ and ‘mesons’ (X) and metastable light pseudo Goldstone mesons (Y). (work in progress with Maurizio Piai, Chris Spitzer)

WIMP Annihilation via intermediate light boson



Relic Abundance in X-Y model

- Early universe timeline:
- X,Y part of hidden sector which goes out of thermal equilibrium with standard model while still in thermal equilibrium with each other
- different temperatures for hidden and visible sectors
- assume hidden sector temperature much higher

WIMP annihilation and relic WIMP abundance

- Rate for annihilations: $\Gamma \approx n_x v \sigma$, where
  - n_x is WIMP density, v is velocity
  - σ is annihilation cross section$\sim 1/v$.
  - in equilibrium $n_x \sim (M_X T_{hid})^{3/2} e^{(-M_X/T_{hid})}$
- WIMP abundance/comoving volume frozen when $\Gamma \sim 1/t \sim H \sim \rho^{1/2}/m_P$

WIMP annihilation and relic WIMP abundance continued

- in early universe energy density $\rho \sim g_* T^4 + T_{hid}^4$
- Freezeout: $(M\, T_{hid})^{3/2} e^{(-M/T_{hid})}\, \sigma\, v \sim (g_* T^4 + T_{hid}^4)^{1/2} / m_P$
- WIMP density /entropy ratio n_x/s conserved until requilibrium between Y and standard model
- entropy $s \sim g_* T^3 + T_{hid}^3$
- entropy created during requilibrium between Y and standard model

- standard WIMP; for M~100 GeV, correct abundance for M/T_{freeze}~ 20 (varies as log(M))
- σ v~3 × 10^{-26} cm^3/s gives observed relic abundance for standard WIMP
- for hidden sector temperature much higher than standard model temp "as if" lower g_*, and so lower entropy during XY freezeout
  - g_* =86.25 in SM at 30 GeV, effectively g_*=1 in hidden sector
  - less entropy, less dilution of dark matter, allow larger M/T, larger σ v for observed relic abundance

Entropy created

- for late decaying Y (temp ~100 MeV) g_* in visible sector =10.75
- In "sudden decay" approximation, visible sector gets suddenly reheated.
- If Y particle is relativistic, entropy increases by factor of $11.75^{1/4}$
- annihilation cross section larger than in standard WIMP scenario by factor of $86.25^{1/2}/11.75^{1/4}$~5

WIMP Relic Abundance Summary

- WIMP abundance determined by X-Y nonequilibrium
- hidden sector (X,Y) temp different from visible sector
- visible sector reheated by Y decays before nucleosynthesis
- allows for annihilation cross section to be enhanced relative to traditional relic abundance calculation, increases indirect detection prospects
- Kinematic constraint explains why Y primarily decays to e^+e^- (some $\gamma\gamma$ possible)

Energy Spectrum in lab frame of e^+, e^-

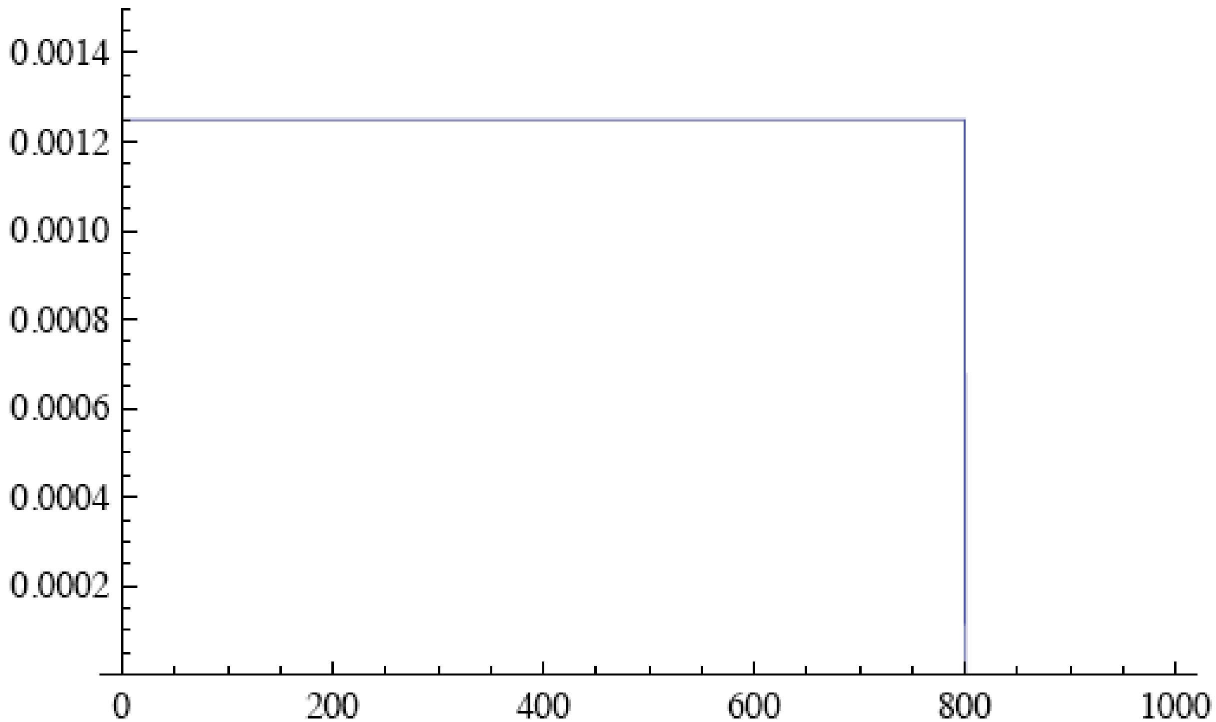


FIG. 2: The energy spectrum dN/dE of the electrons as a function of the lab frame energy for M=800GeV, m=200MeV

Galactic propagation

- Source of positrons proportional to density^2
- Various models for density profile make small difference compared with other unknowns
- inject into diffusion model for galaxy which has various adjustable parameters and "boost factor" B to account for substructure
- fit parameters within range B<20

Excess of Cosmic positrons?

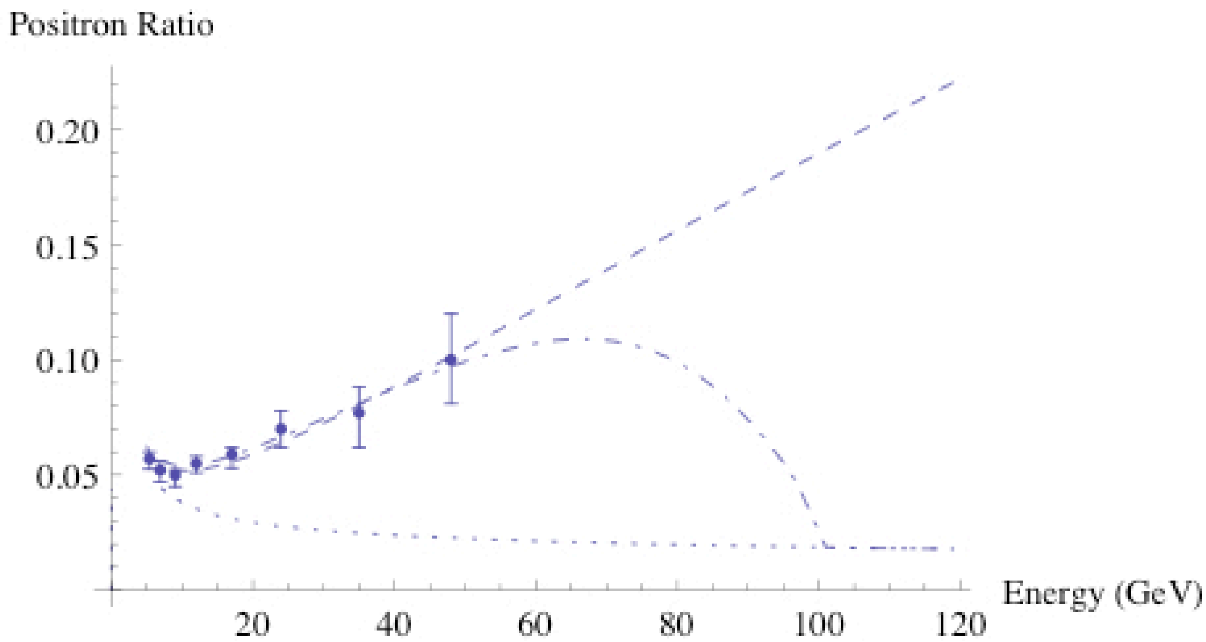
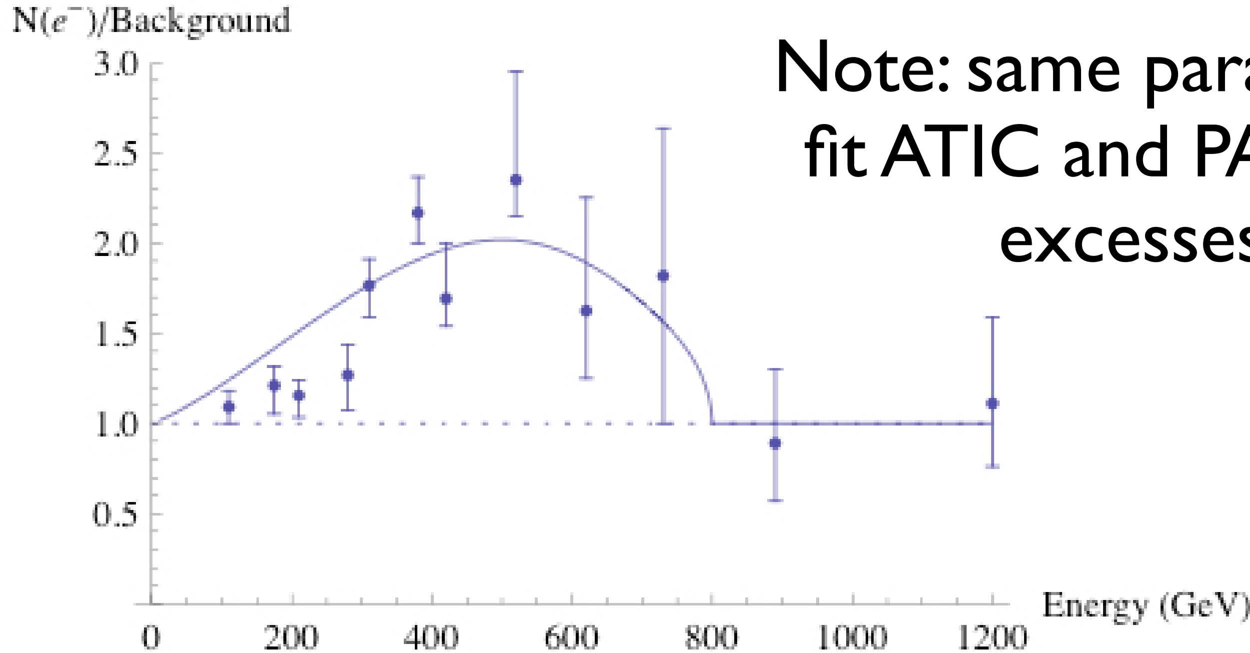


FIG. 2: Positron excess below 100GeV shown against the preliminary PAMELA data. The dash-dot curve is $M = 100$ GeV. The dashed curve is $M = 800$ GeV. The bottom dotted line is the background level.

ATIC Feature in Cosmic Electron Spectrum?



Note: same parameters fit ATIC and PAMELA excesses

FIG. 3: Ratio of number of electrons to number of background electrons show against the ATIC data for $M = 800$ GeV. The dotted line is the background level, fixed to be 1 in this ratio.

CURRENT WORK IN PROGRESS

Higgs decays into supersymmetric unparticles

(in progress with Maurizio Piai, Chris Spitzer)

- unparticles (Georgi): is there a hidden scale invariant strongly coupled dark sector?
- Seiberg: strongly coupled susy models at infrared conformal fixed point under good theoretical control
- We add such a hidden sector to a (Gauge Mediated SUSY breaking) MSSM model
- figure out how Higgs can act as "portal" (mix with unparticles) without inducing large susy breaking into the hidden sector
- provides dark matter similar to "XY model"

Higgs decays into supersymmetric unparticles continued

- small susy breaking in hidden sector triggers confinement, chiral symmetry breaking
- stable and meta stable “pions”
- “Hidden Valley” type signatures (high multiplicity, displaced vertices, missing energy) for Higgs decay
- direct detection of dark matter difficult

One more anomaly?

hep-ex arXiv:0810.5357

Title: Study of multi-muon events produced in p-pbar collisions at sqrt(s)=1.96 TeV
Authors: CDF Collaboration

...“we isolate a significant sample of events in which at least one of the muon candidates is produced outside of the beam pipe of radius 1.5cm. ...we are presently unable to fully account for the number and properties of the remaining events”

No good BSM explanation for CDF ‘ghosts’

- production cross section 100 pb? (Strassler says after eliminating junk may be 10 pb)
- no invariant mass peak
- no D0 confirmation?

Conclusions

- PAMELA, ATIC and other cosmic ray expts may have provided first clues to identity of dark matter
- or found high energy charged particles created by a pulsar or pulsars
- if dark matter, must explain large annihilation cross section or huge "boost" factor, lack of antiprotons
- a light "mediator" particle can explain both
- the X,Y model is the minimal such model, explains all data reasonably well, could be stripped down version of hidden valley or unparticle sector