Detecting or Limiting Dark Matter through Gamma-Ray Telescopes

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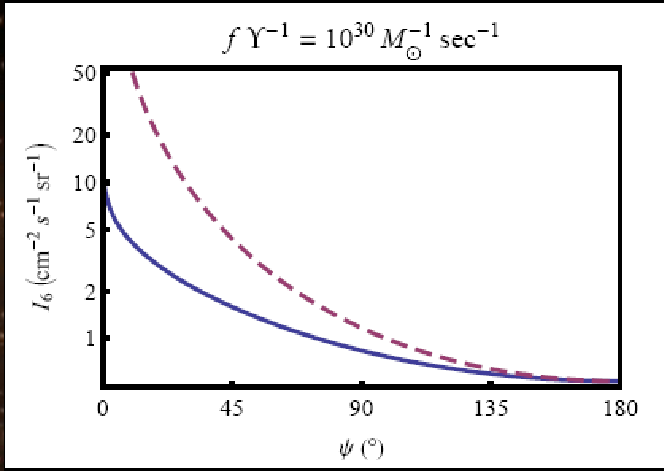
Via Lactea II simulation (J. Diemand & al, 2008)

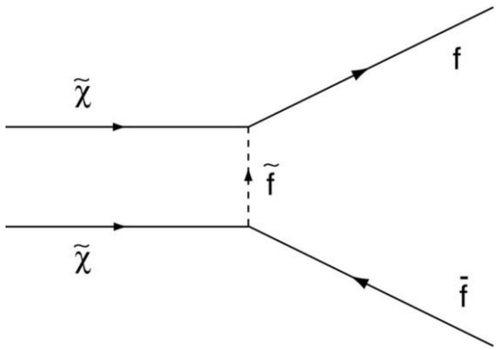


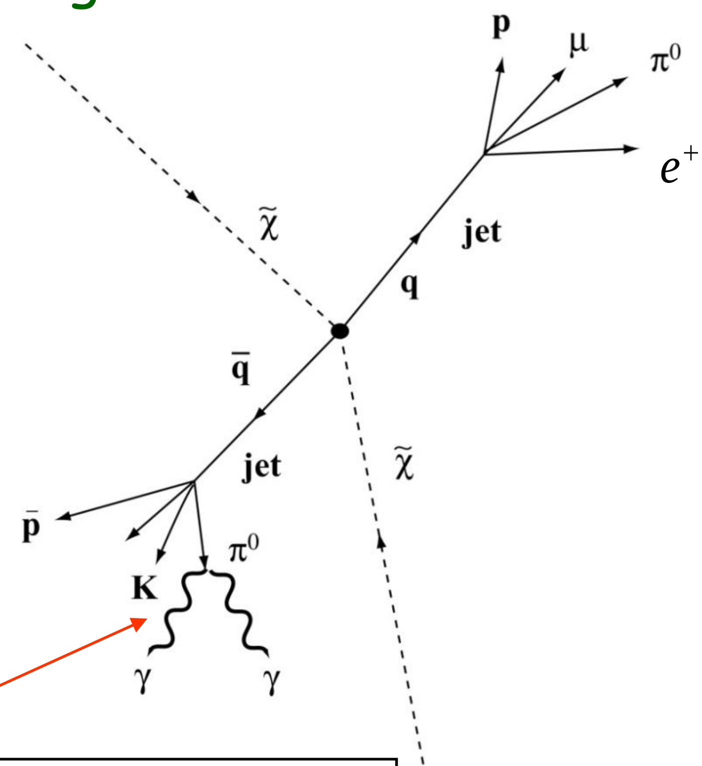
Lee, Ando & Kamionkowski, arXiv: 0810.1284

Lots of clumps of dark matter in the halo! Strategy for identifying DM using gamma-rays:

1. Gamma-rays from DM should directly reflect the spatial distribution of the halo.
2. No diffusion of gamma-rays ⇒ possible fingerprints of DM also in the energy spectrum.
3. Other probes (radio, X-rays, antiprotons, positrons, neutrinos) should be within observational bounds

Indirect detection, example: annihilation of neutralinos in the galactic halo

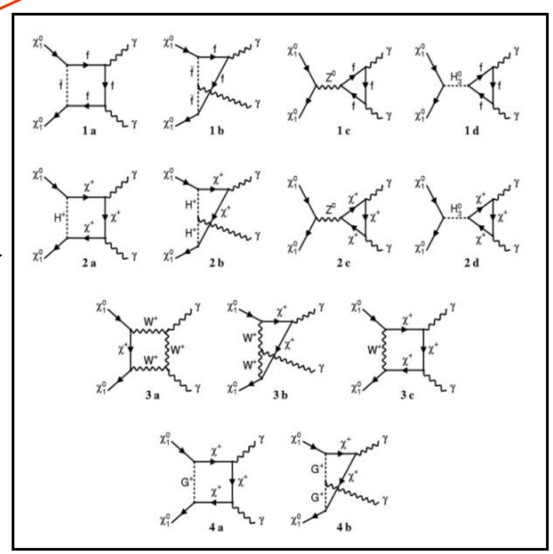




Majorana particles: helicity factor for fermions $\sigma v \sim m_f^2$

Note: equal amounts of matter and antimatter in annihilations

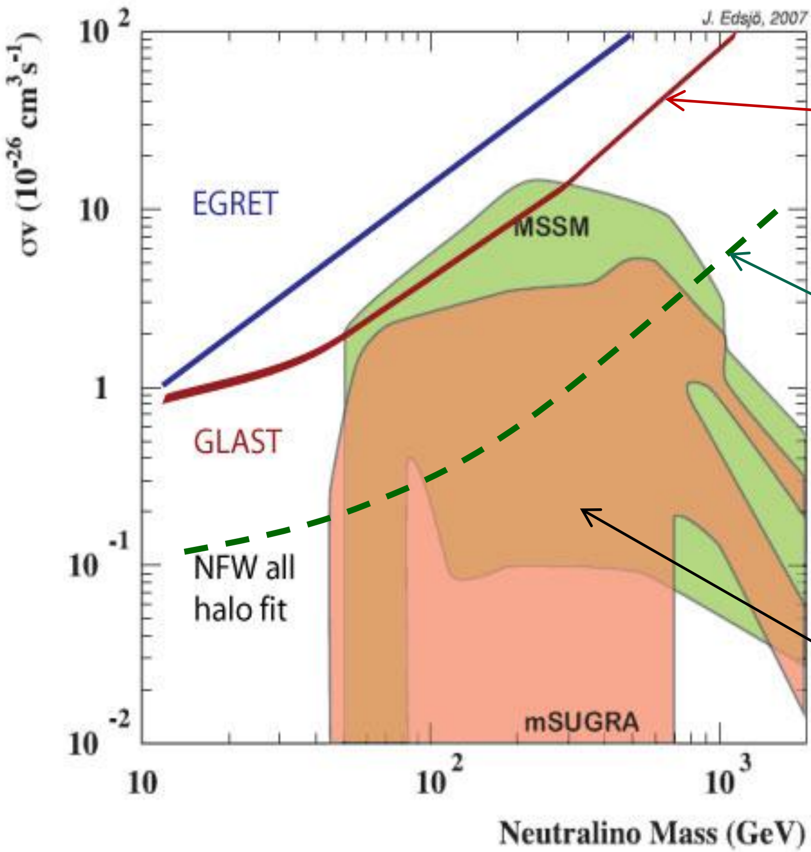
Decays from neutral pions, kaons etc:
DarkSUSY uses PYTHIA.



One-loop effect: 2γ or $Z\gamma$ final state gives narrow lines.
Internal bremsstrahlung also contributes to high-energy gammas

3σ exclusion limit, 1 year of GLAST data

Note: the regions with high gamma rates are very weakly correlated with models of high direct detection rates ⇒ complementarity



"Conservative" approach, g.c.,

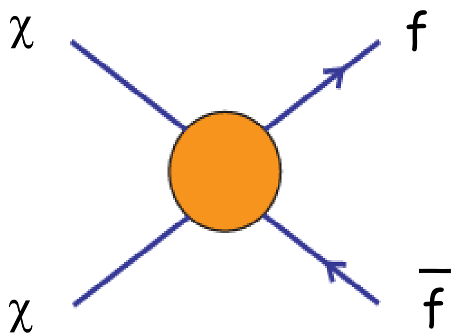
NFW halo profile assumed, no substructure.

Including all halo, with substructure

Vast region of opportunity for next generation of gamma-ray instruments!

Cf. GLAST working group on Dark Matter and New Physics, E.A. Baltz, et al.. arXiv:0806.2911

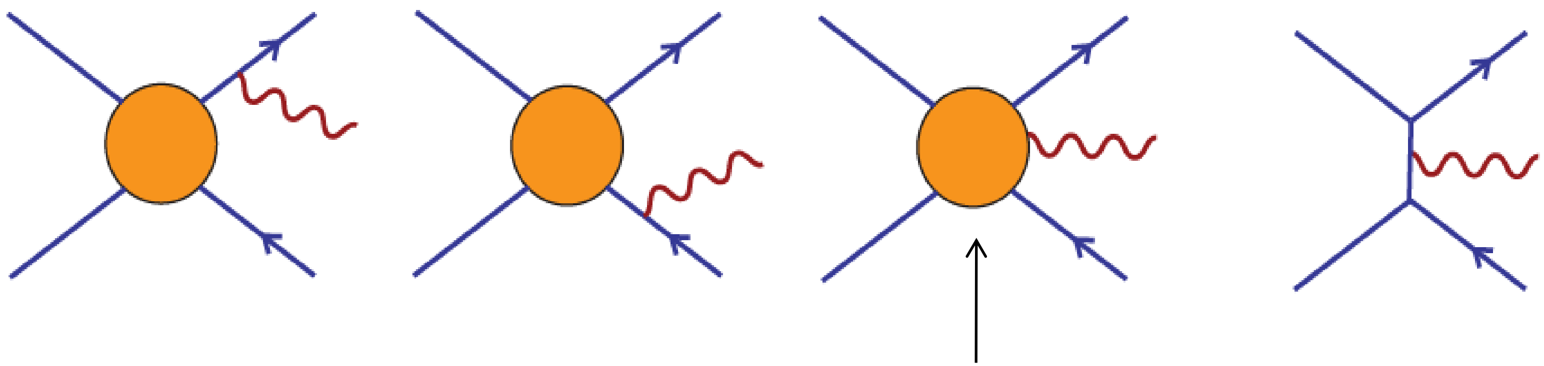
Recent development: New observational signature for Majorana particles (like neutralinos)



$\sim m_f$ for Majorana particles in limit $v/c \to 0$

"Final state radiation"

"Internal bremsstrahlung", IB

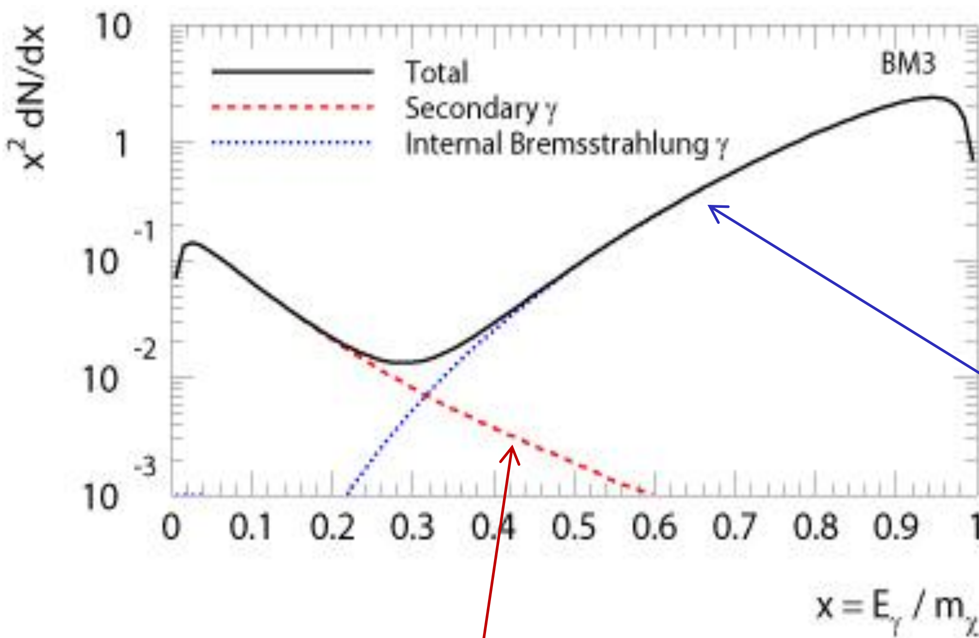


$\sim m_f$ $\sim m_f$ No m_f suppression! Simplest example

L.B., 1989; T. Bringmann & al, 2007-8

QED corrections (Internal Bremsstrahlung) in the MSSM: good news for detection probability in gamma-rays:

T. Bringmann, L.B., J. Edsjö, JHEP, 2008

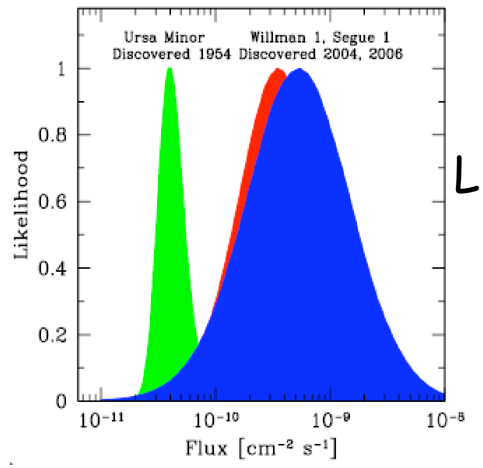


Example: benchmark point BM3, mass = 233 GeV, fulfils all accelerator constraints, has WMAP-compatible relic density (stau coannihilation region).

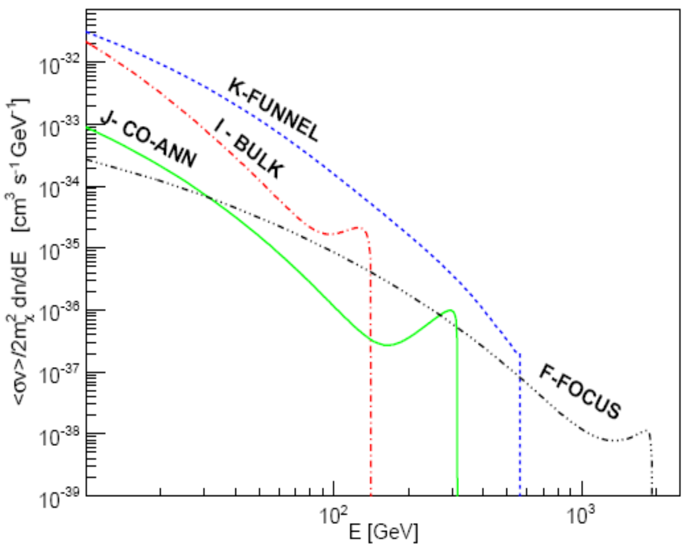
New calculation including Internal Bremsstrahlung (DarkSUSY 5.0). Spectral drop att 233 GeV is nicely inside the GLAST range…

Previous estimate of gamma-ray spectrum (DarkSUSY 4.1)

Some of the newly found dwarf galaxies may give favourable rates:



L. Strigari & al, 2008



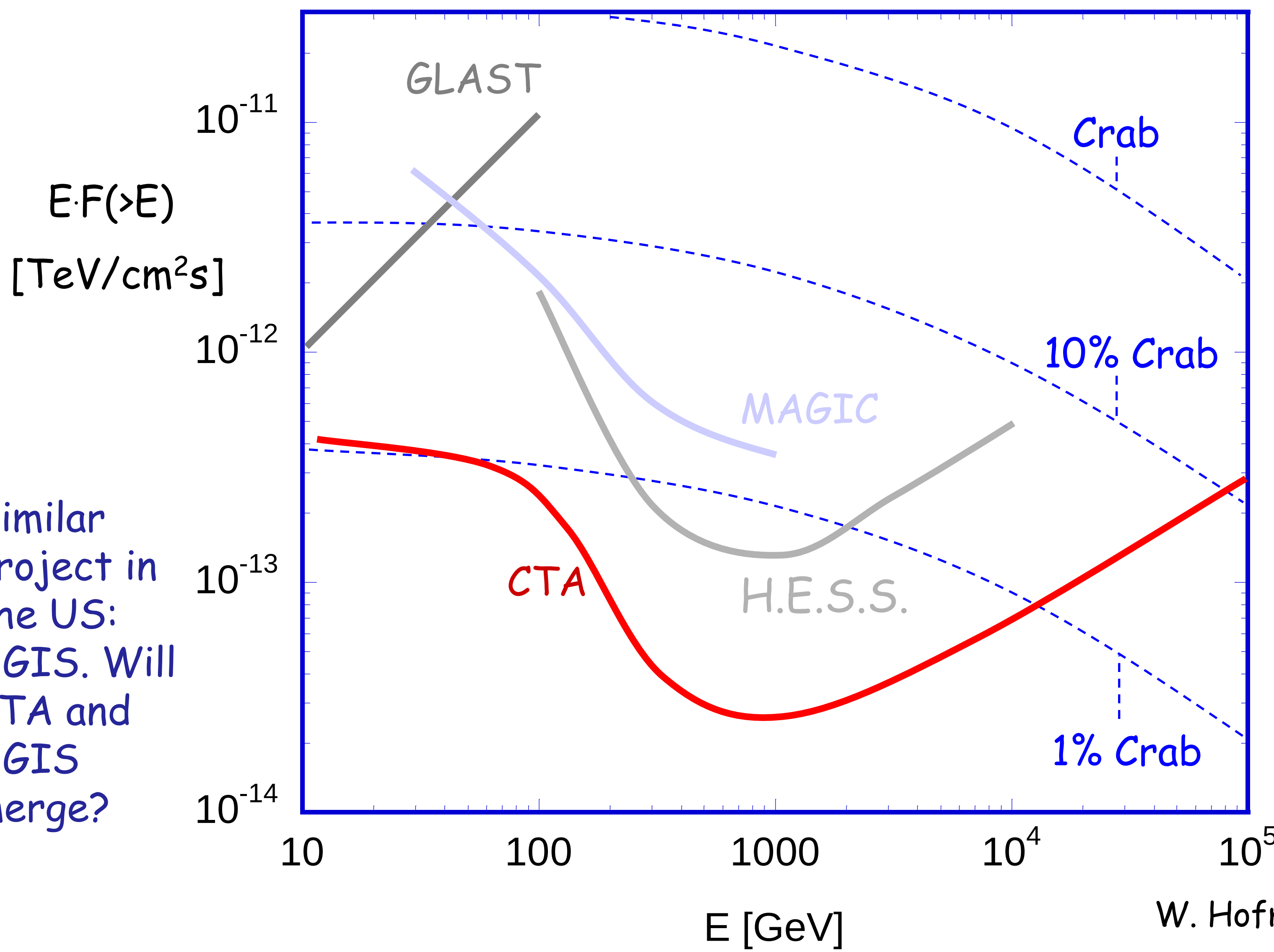
T. Bringmann & al, 2008

MAGIC Oct. 2008: Boost factors corresponding to upper limits from Willman I, needed to see a signal

BM	Φ^{model}	$\Phi^{u.l.}$	$B^{u.l.}$
I'	2.64×10^{-16}	9.87×10^{-12}	3.7×10^{4}
J'	4.29×10^{-17}	5.69×10^{-12}	1.3×10^{5}
K'	2.32×10^{-15}	6.83×10^{-12}	2.9×10^{3}
F^*	2.09×10^{-16}	7.13×10^{-12}	3.4×10^{4}

Much more observing time needed. (So far, only 15 hours.) The future CTA may be ideal instrument.

The future? Possible Cherenkov Telescope Array (CTA) sensitivity

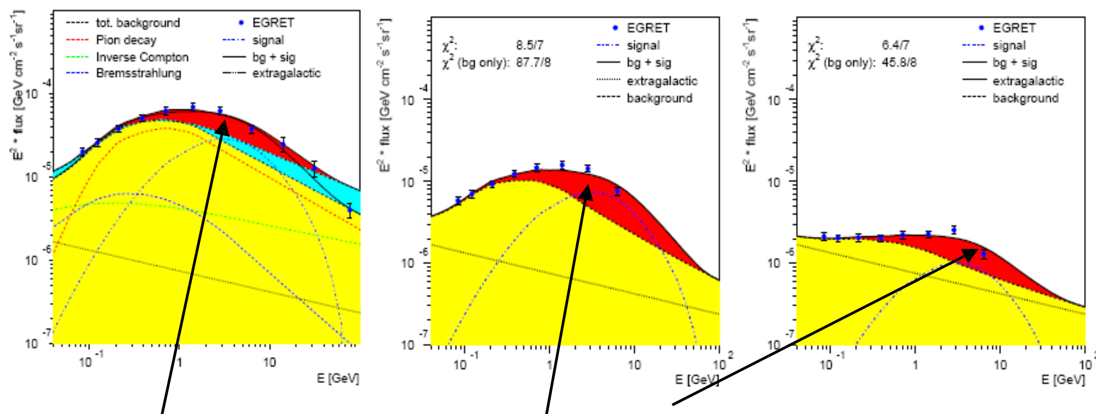


Similar project in the US: AGIS. Will CTA and AGIS merge?

W. Hofmann

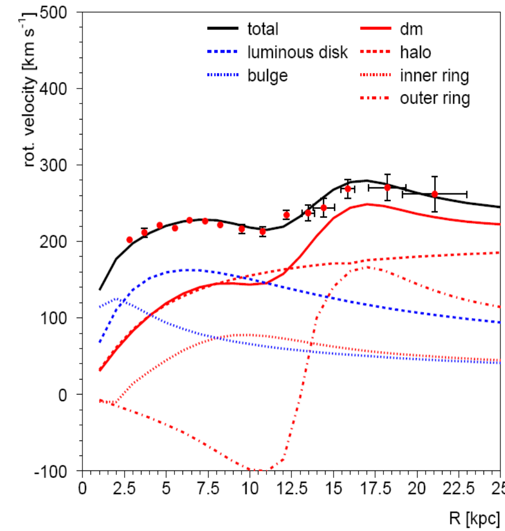
Has supersymmetric dark matter already been seen in indirect detection?

W. de Boer, 2003-2008



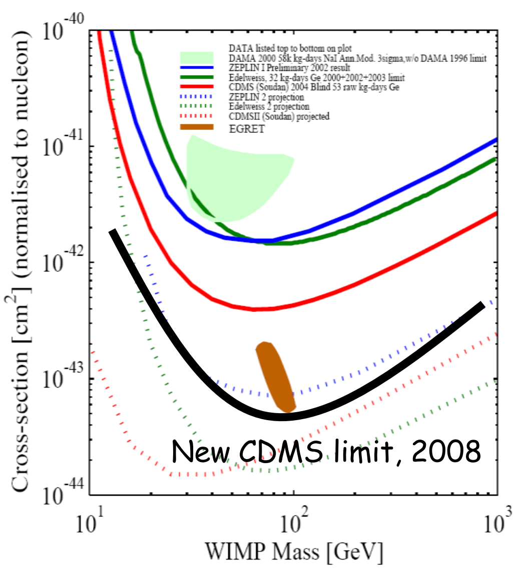
"EGRET excess of gamma-rays"

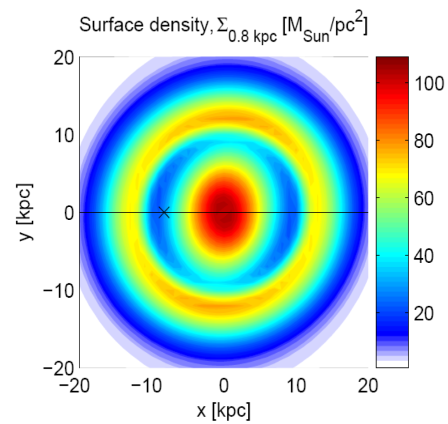
Filled by 65 GeV neutralino annihilation

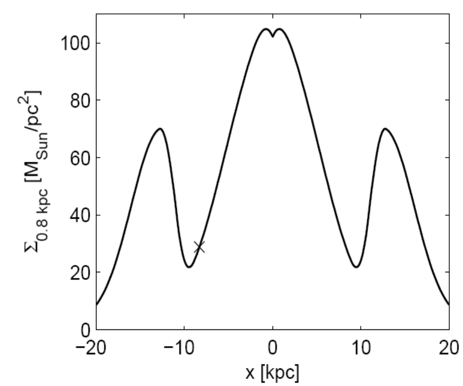


Galactic rotation curve

Data explained by 50-100 GeV neutralino?







Remember: Strategy for identifying DM using gamma-rays

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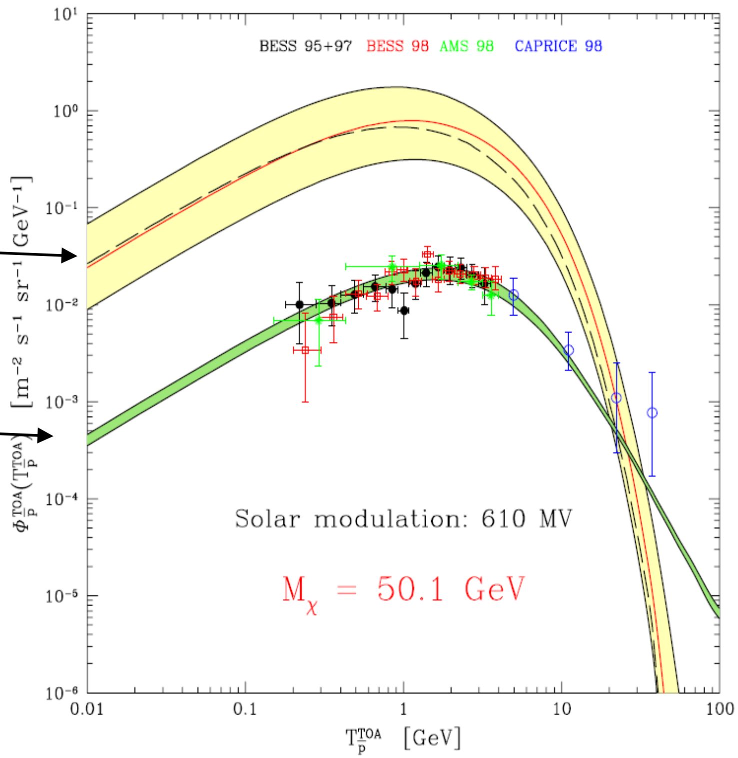
We would argue that the weird halo model violates (1). It also violates (3):

Expected antiproton flux from de Boer's supersymmetric models (with standard diffusion)

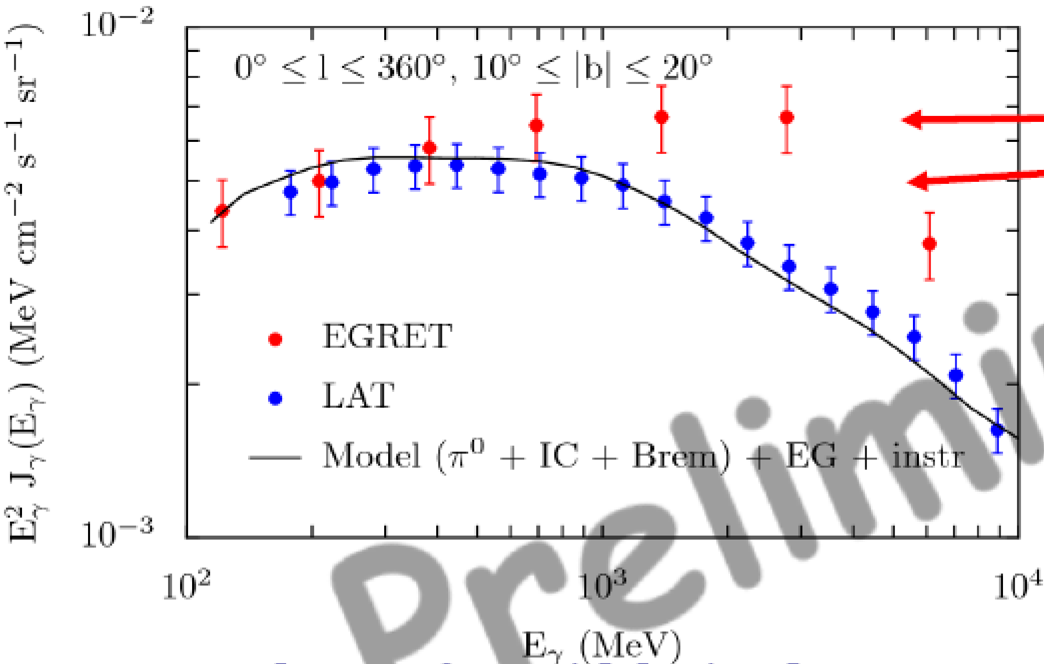
Standard (secondary) production from cosmic rays

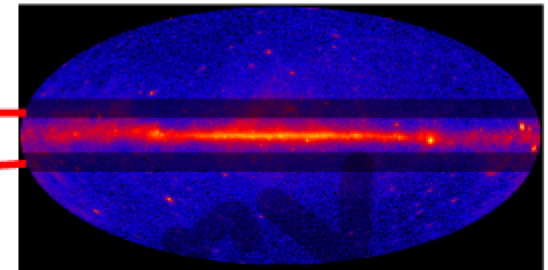


L.B., J. Edsjö, M. Gustafsson & P. Salati, 2006

Stecker & al 2007: EGRET GeV anomaly may be instrument calibration error (?)

The Fermi LAT View

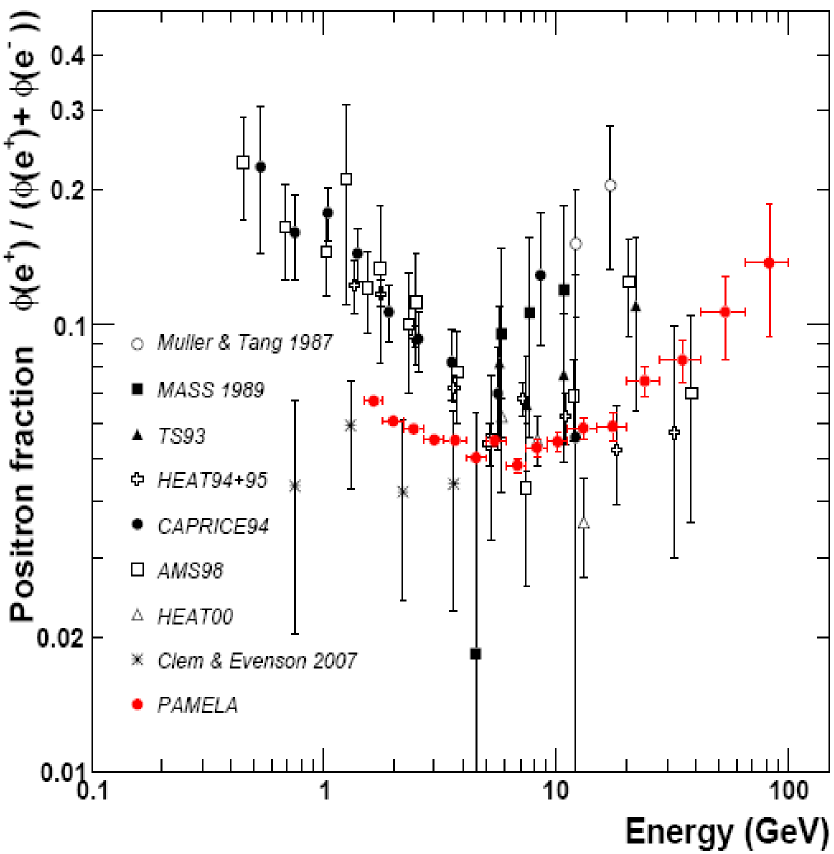


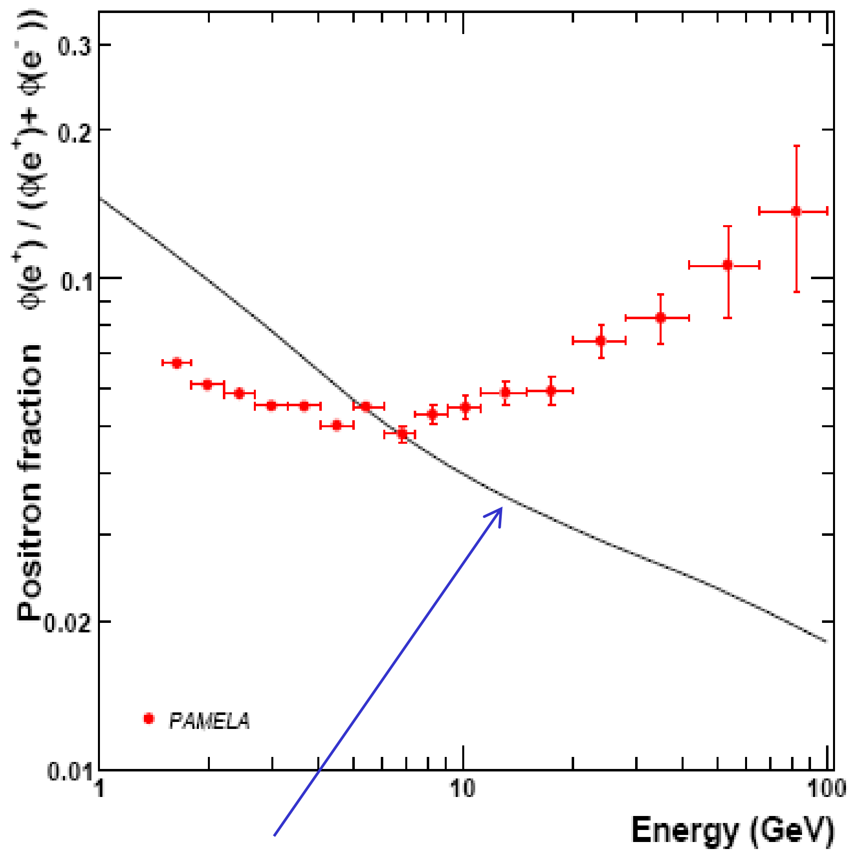


- Spectra shown for mid-latitude range -> GeV excess in this region is not confirmed.
- LAT errors are dominated by systematic uncertainties and are currently estimated to be ~10% - this is preliminary.
- EGRET data is prepared as in Strong, et al. 2004 with a 15% systematic error assumed to dominate (Esposito, et al. 1996).

What are the results for the inner Galaxy? – This is where DM could be important…

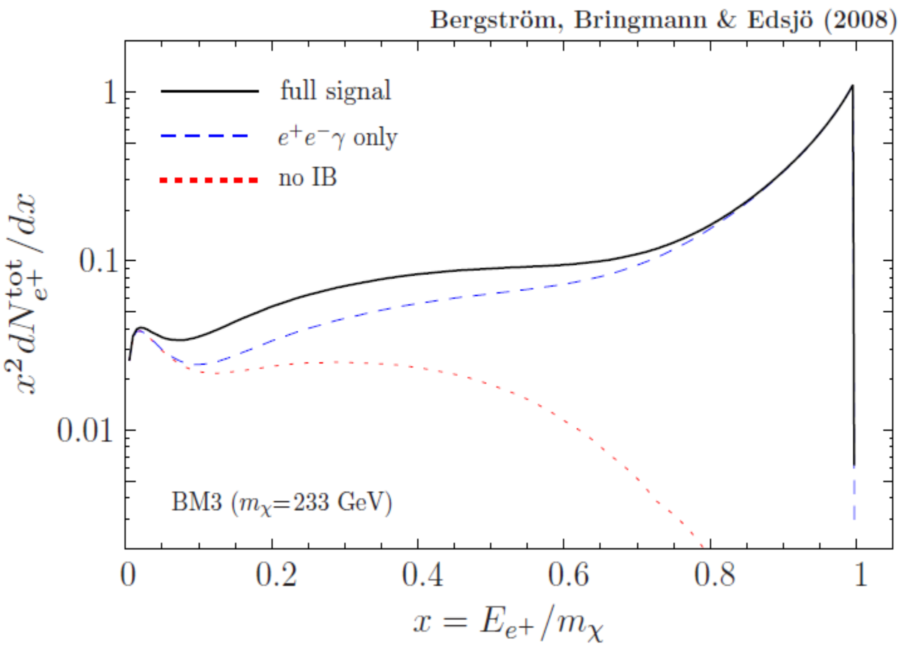
Oct 2008: The awaited PAMELA data on the positron ratio up to 100 GeV (first presented in a "paparazzi session" at the Identification of Dark Matter Conference in Stockholm in August) .
O. Adriani et al., Nature, submitted, arXiv:0810.4995

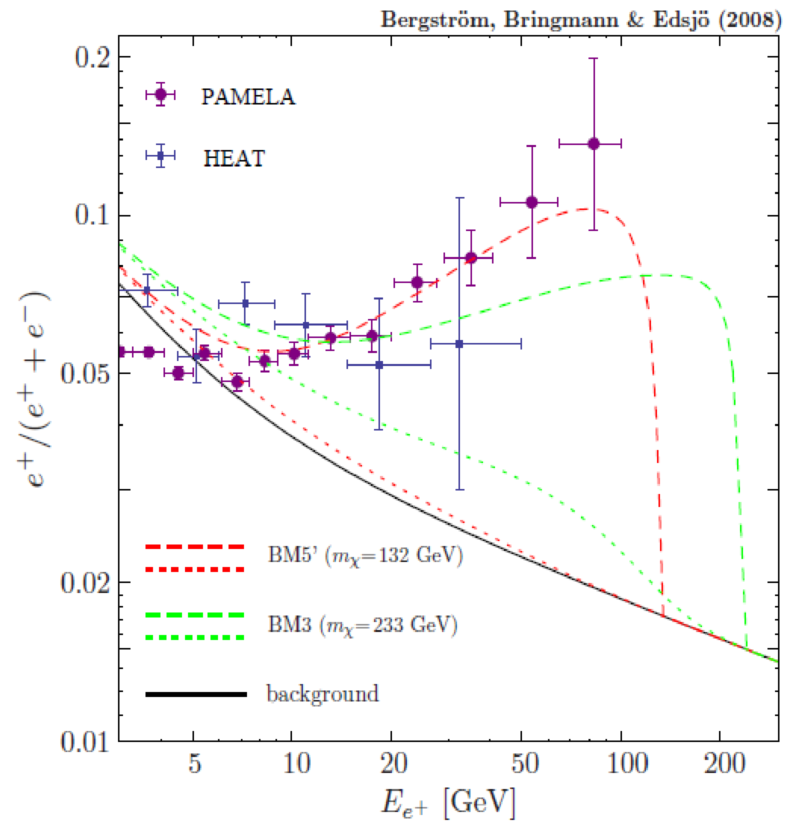




Prediction from secondary production by cosmic rays: Moskalenko & Strong, 1998

Good news: SUSY with internal bremsstrahlung can give the right spectrum:





Bad news: one needs to artificially enhance the annihilation cross section by a "boost factor" of more than 10000. For KK-like models which go directly to electron-positron pairs, only a factor of a few – 10 is needed. Sharp drop at DM mass would be a clear signature.

Boost factor:

$$B = B_n^{\Delta V} \times B_{\sigma v} = \frac{\left\langle n^2(\vec{r}) \right\rangle_{\Delta V}}{\left\langle n_{NFW}^2(\vec{r}) \right\rangle_{\Delta V}} \times \frac{\left\langle \sigma v \right\rangle_{v/c \approx 10^{-3}}}{\left\langle \sigma v \right\rangle_{v/c \approx 0.3}}$$

Cosmology Particle physics

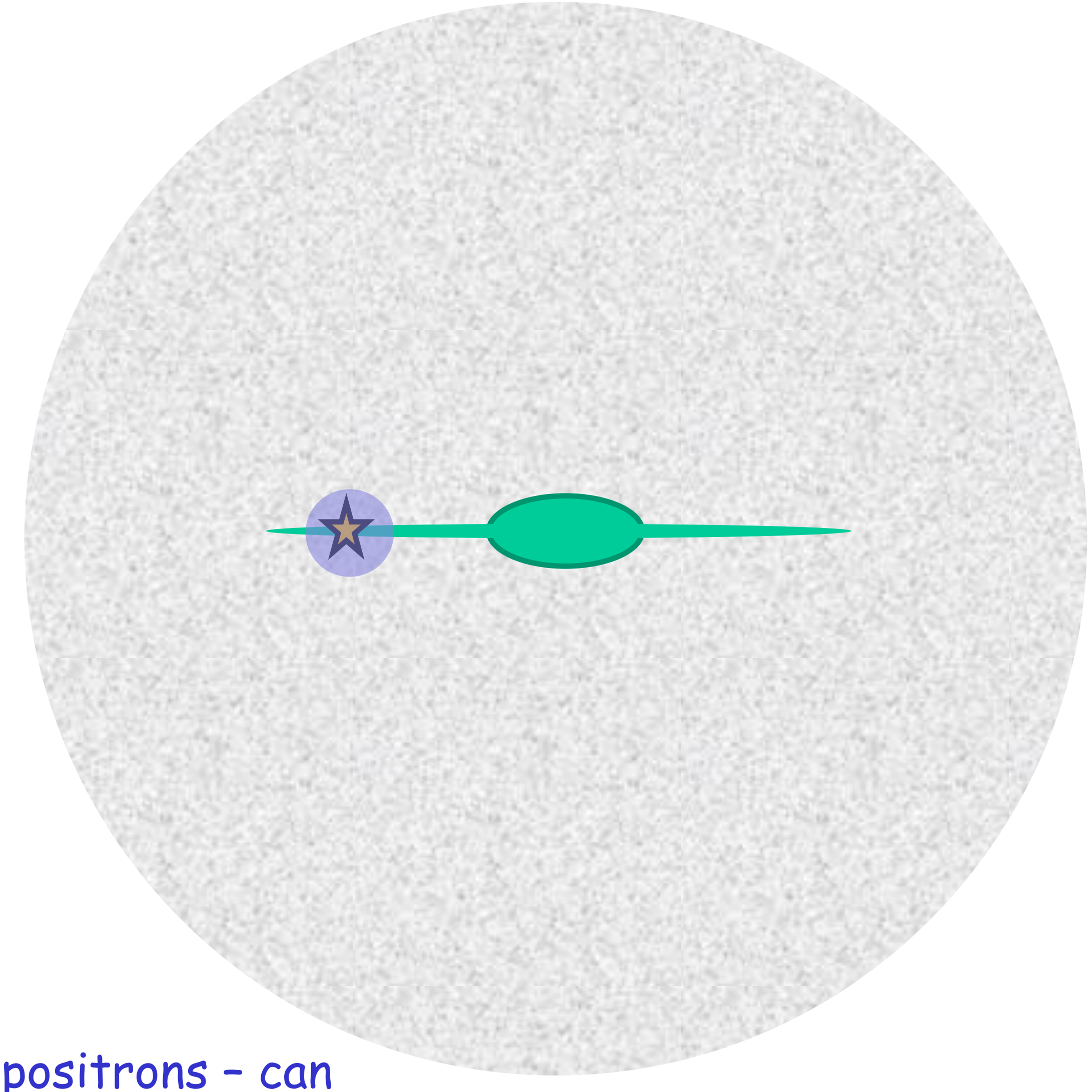
For explaining PAMELA positrons in terms of conventional Dark Matter models, need B ~ 100 – 10000

The cosmology B-factor for $\Delta V \sim (10\ \text{kpc})^3$, such as for antiprotons, is between a few (Springel & al, 2008) and 20 (Diemand & al, 2008)

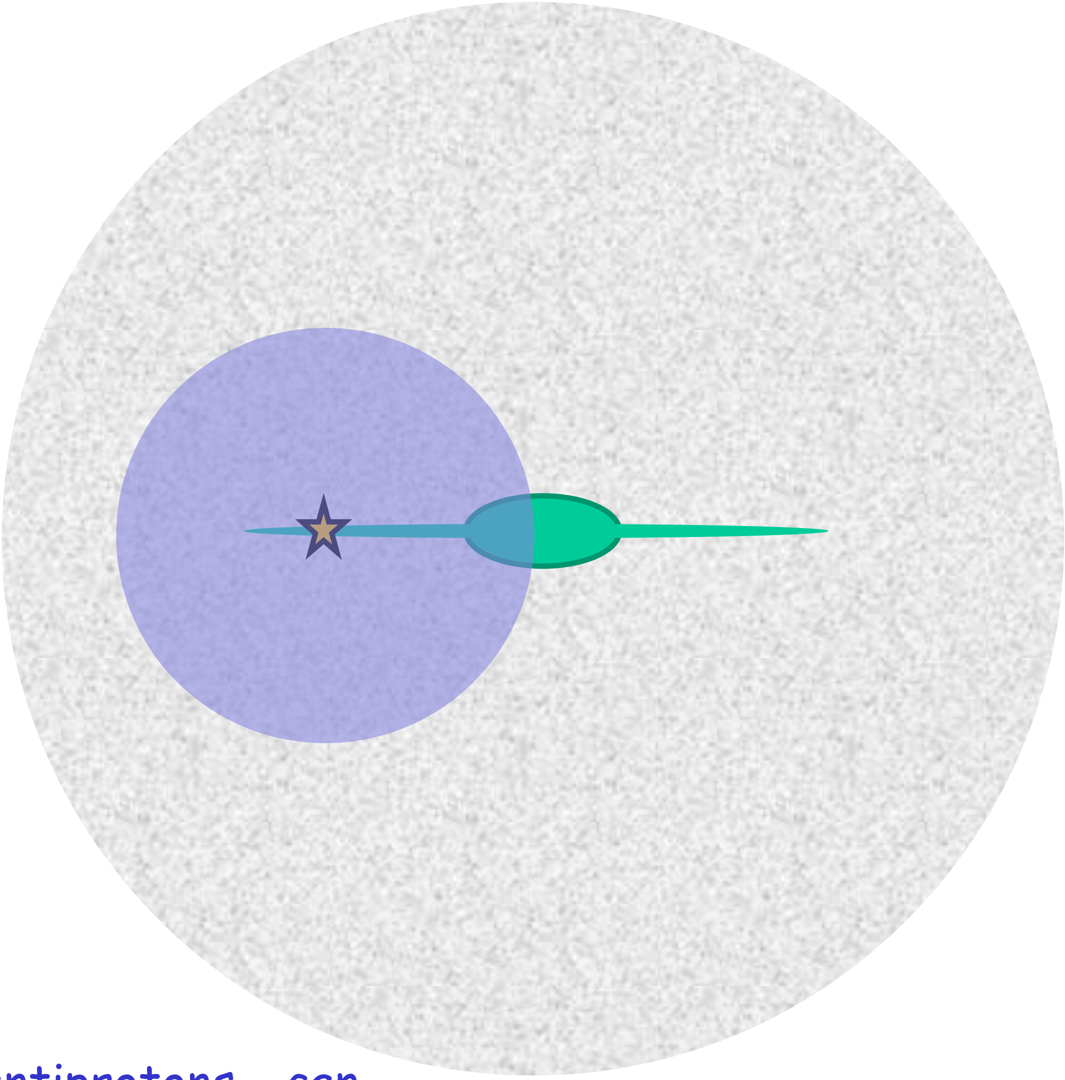
However, $\Delta V \sim (0.1 - 1\ \text{kpc})^3$ for high energy positrons

$\Rightarrow$The solution is either to assume a strong local source (DM clump, intermediate mass black hole, etc) or to increase σv

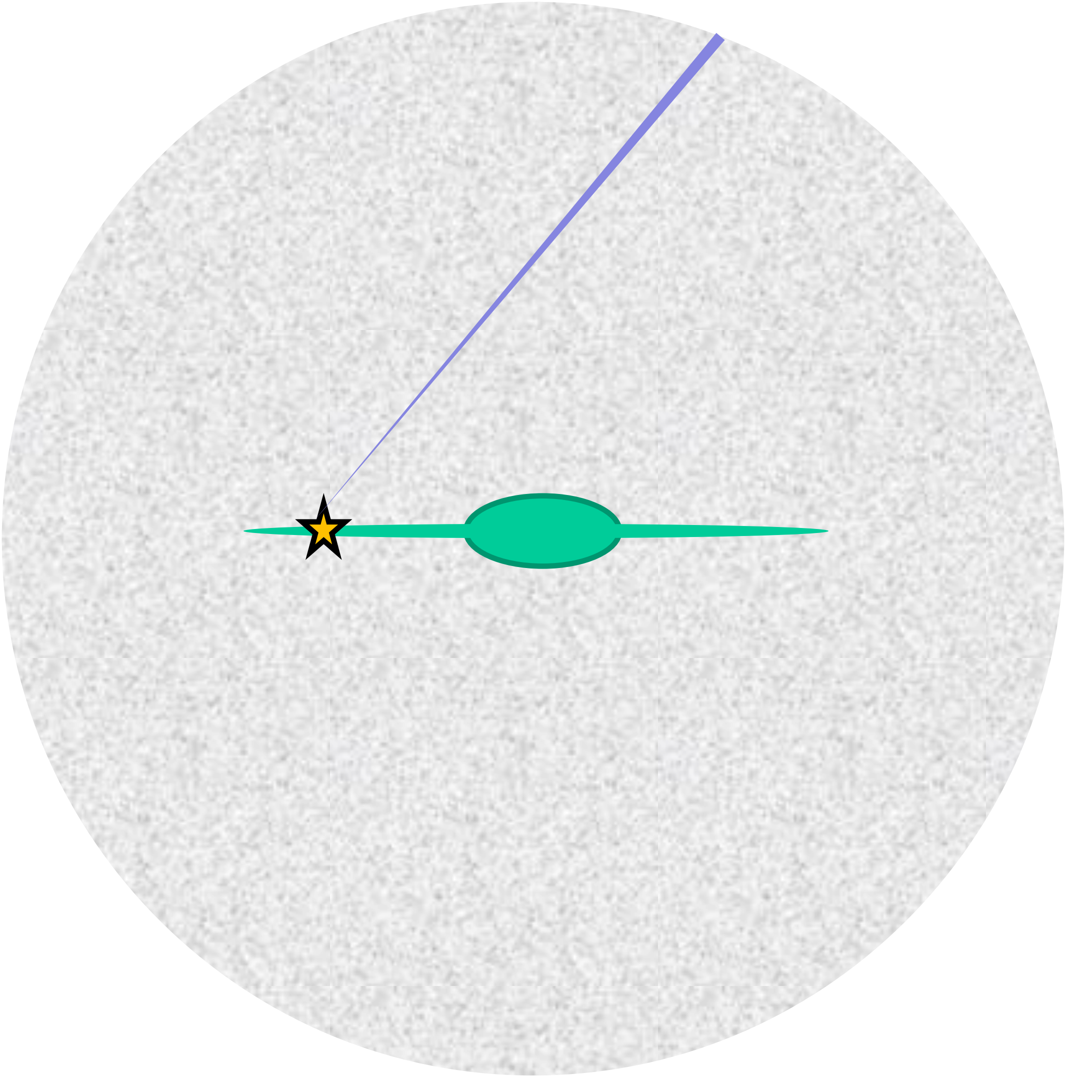
(Note that for gamma-ray detection in a given direction, e.g., the galactic centre, ΔV is very small, and therefore the boost can be very large.)



ΔV for positrons – can give large boost if nearby dark matter clump (unlikely)



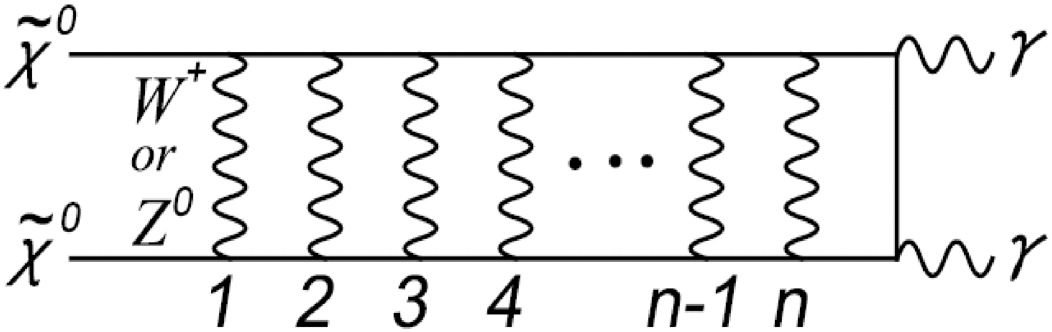
ΔV for antiprotons – can not give large boost factor for realistic halo models



ΔV for gamma-rays – can give very large boost factors in directions where dark matter is concentrated (the galactic center; subhalos)

Interesting possibility for high-mass WIMPs

Hisano, Matsumoto and Nojiri, 2003; Hisano, Matsumoto, Nojiri and Saito, 2004, expanding on the 2γ calculation of L.B. and P. Ullio (1998):



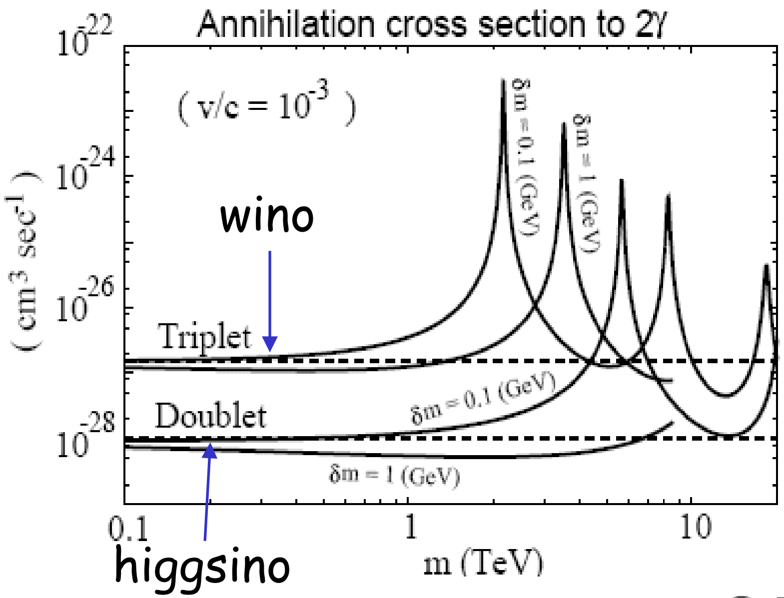
$$\mathcal{S}^{(II)} = \int d^4x d^3r \; \Phi^\dagger(x,\vec{r}) \left\{ \left(i\partial_{x^0} + \frac{\nabla_x^2}{4m} + \frac{\nabla_r^2}{m} \right) - \mathbf{V}(\vec{r}) + 2i\mathbf{\Gamma}\delta(\vec{r}) \right\} \Phi(x,\vec{r})$$

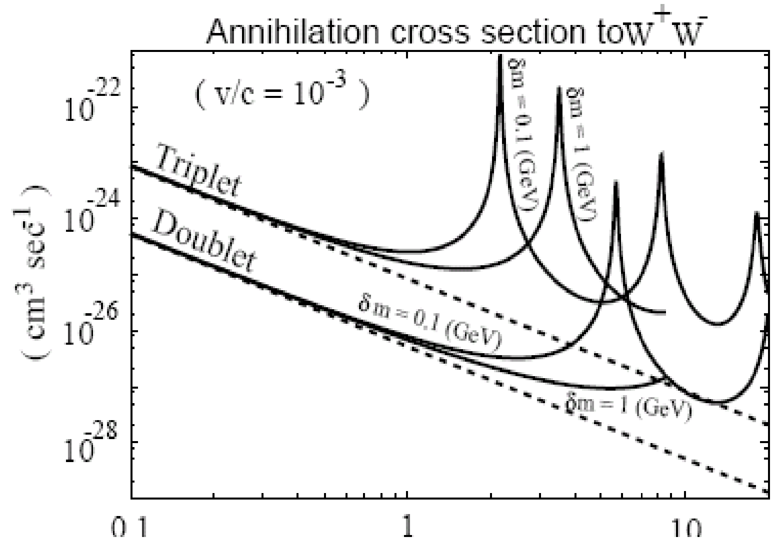
$$\mathbf{V}(r) = \begin{pmatrix} 2\delta m - \frac{\alpha}{r} - \alpha_2 c_W^2 \frac{e^{-m_Z r}}{r} & -\sqrt{2}\alpha_2 \frac{e^{-m_W r}}{r} \\ -\sqrt{2}\alpha_2 \frac{e^{-m_W r}}{r} & 0 \end{pmatrix}$$

$$\mathbf{\Gamma}_{W^+W^-} = \frac{\pi\alpha_2^2}{4m^2} \begin{pmatrix} 2 & \sqrt{2} \\ \sqrt{2} & 4 \end{pmatrix}, \qquad \mathbf{\Gamma}_{Z^0Z^0} = \frac{\pi\alpha_2^2}{m^2} \begin{pmatrix} c_W^4 & 0 \\ 0 & 0 \end{pmatrix},$$

$$\mathbf{\Gamma}_{\gamma Z^0} = \frac{\pi\alpha\alpha_2}{m^2} \begin{pmatrix} 2c_W^2 & 0 \\ 0 & 0 \end{pmatrix}, \qquad \mathbf{\Gamma}_{\gamma\gamma} = \frac{\pi\alpha^2}{m^2} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}.$$

Neutralino and chargino nearly degenerate; attractive Yukawa force from W and Z exchange $\Rightarrow$ bound states near zero velocity, "Sommerfeld resonance" $\Rightarrow$ enhancement of annihilation rate for small (Galactic) velocities. Little effect on relic density (higher v). "Explosive annihilation"!

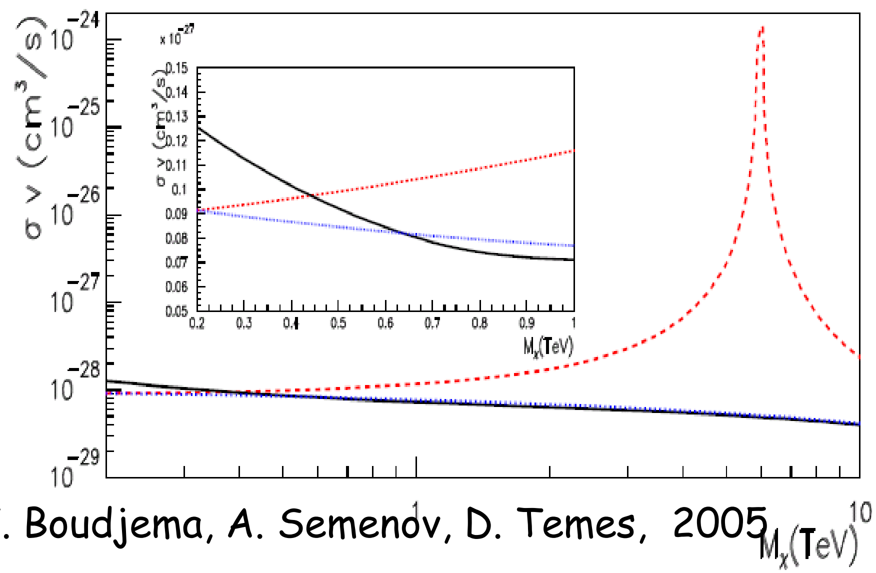




In MSSM without standard GUT condition (AMSB; split SUSY) $m_{wino} \sim 2 - 3$ TeV; $\delta m \sim 0.2$ GeV

Factor of 100 – 1000 enhancement of annihilation rate possible. B.R. to $\gamma\gamma$ and $Z\gamma$ is of order 0.2 – 0.8!

Non-perturbative resummation explains large lowest-order rates to $\gamma\gamma$ and $Z\gamma$. It also restores unitarity at largest masses



F. Boudjema, A. Semenov, D. Temes, 2005

See also M. Cirelli & A. Strumia, 2008, N. Arkani-Hamed, D. Finkbeiner, T. Slatyer and N. Weiner, 2008, M. Lattanzi & J. Silk, 2008,...

Nature, November 19, 2008
ATIC: Balloon experiment which measures sum of electron and positron flux

HESS, Nov. 24, 2008

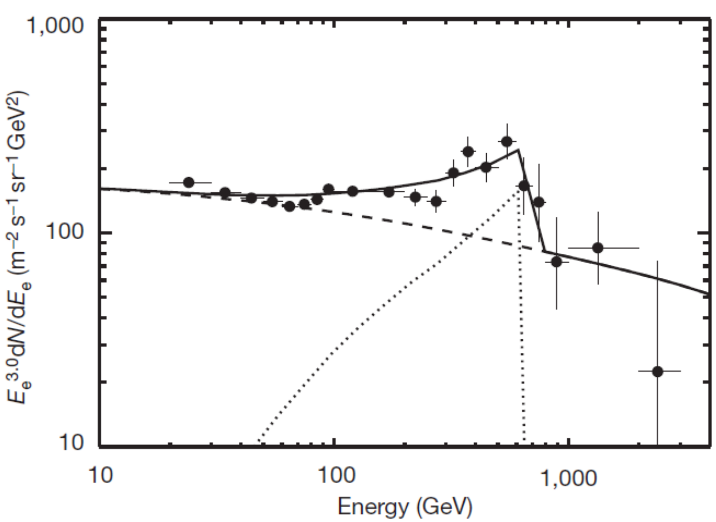


Figure 4 | Assuming an annihilation signature of Kaluza–Klein dark matter, all the data can be reproduced. The GALPROP general electron

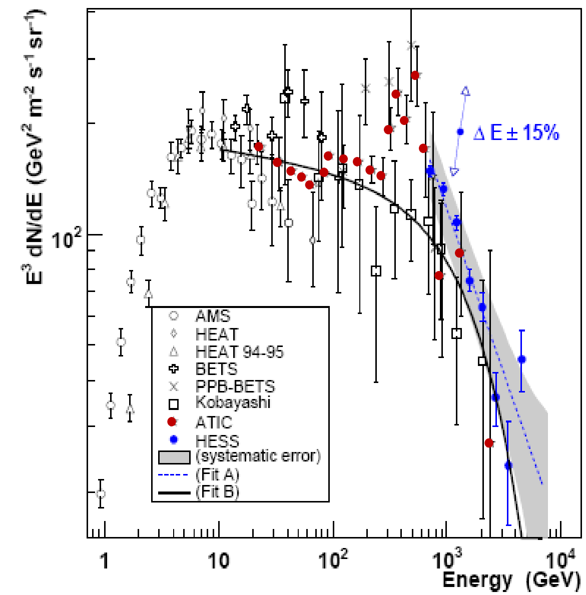


FIG. 3: The energy spectrum E^3 dN/dE of CR electrons as measured by H.E.S.S. in comparison with previous measurements. The H.E.S.S. data are shown as solid points. The two fit functions (A and B) are described in the main text. The shaded band indicates the approximate systematic error arising from uncertainties in the modeling of hadronic interactions and in the atmospheric model. The double arrow indicates the effect of an energy scale shift of 15%, the approximate systematic uncertainty on the H.E.S.S. points. Previous data are reproduced from: AMS [18], HEAT [19], HEAT 94-95 [20], BETS [21], PPB-BETS [22], Kobayashi [2] and ATIC [23].

Is the dark matter feature really there? Or is the true distribution a smooth curve (indications of a pulsar origin). Fermi can measure this spectrum to 1 TeV with superior accuracy. The results should appear shortly (within a few months)…

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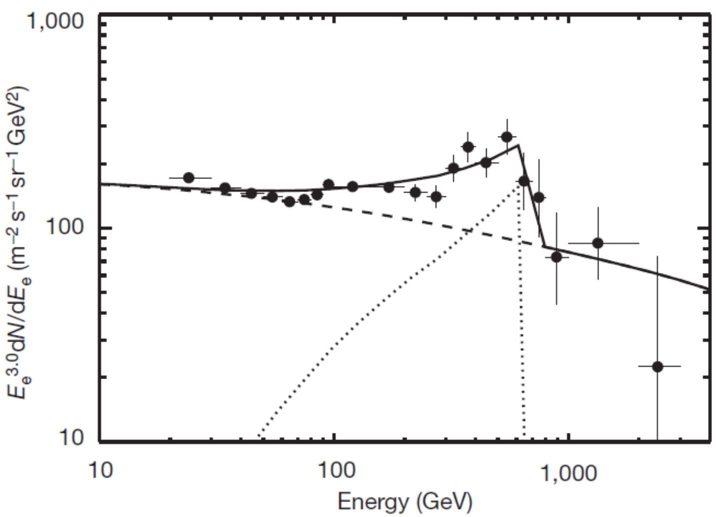
Upcoming Fermi data?



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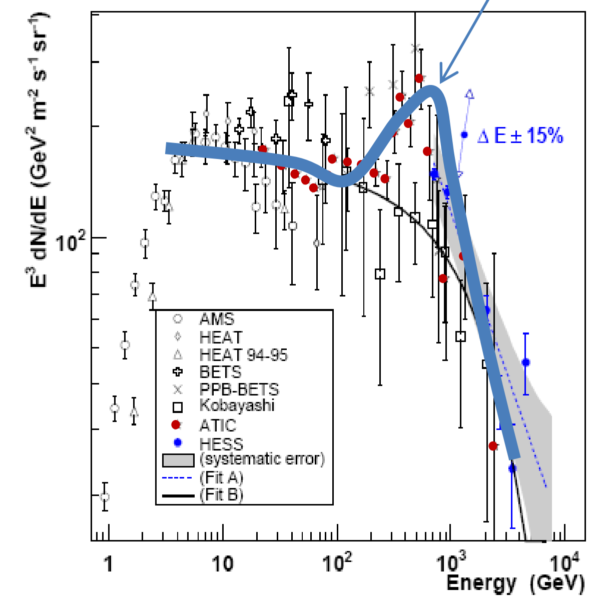

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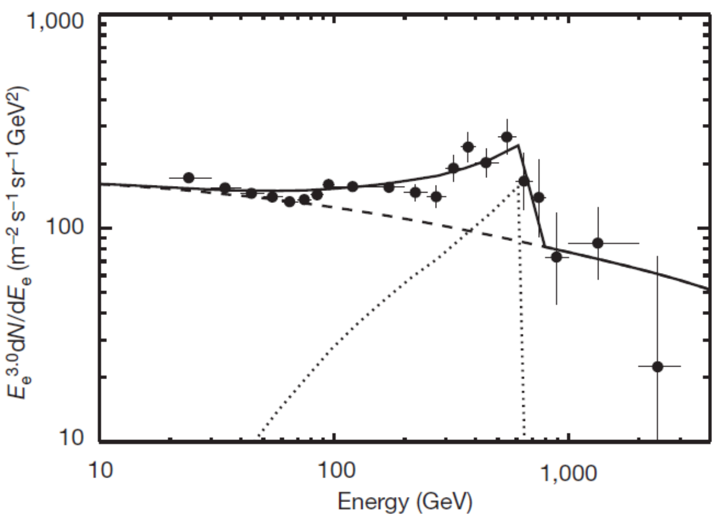

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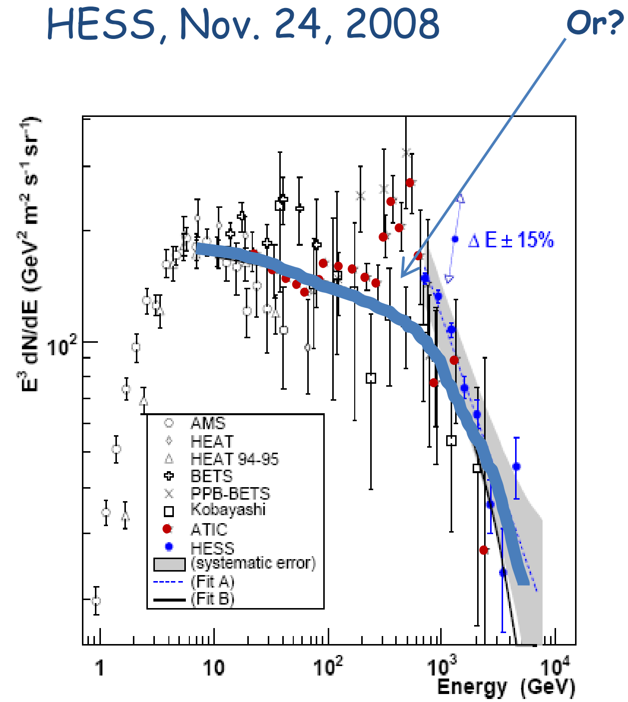

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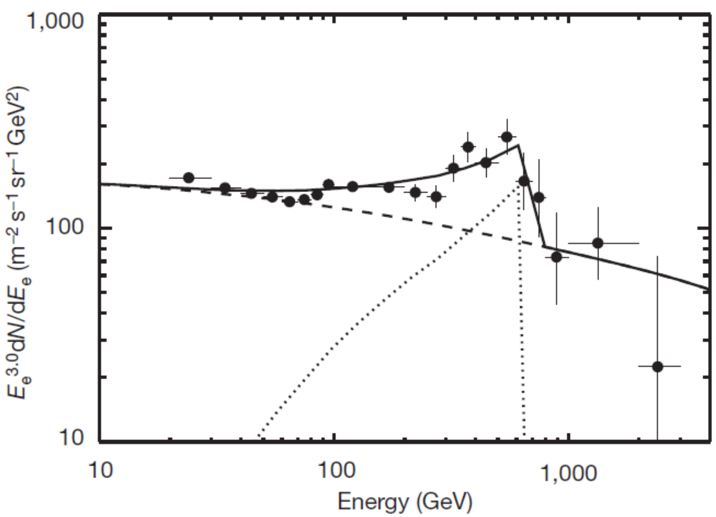

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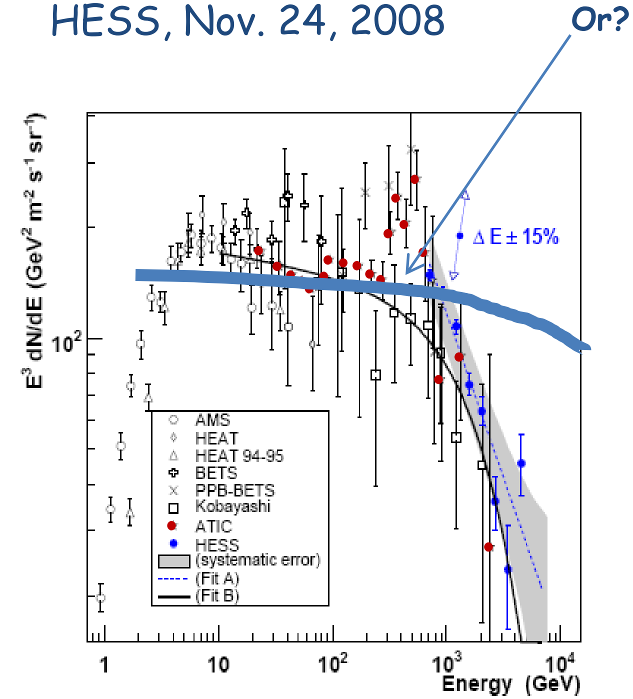

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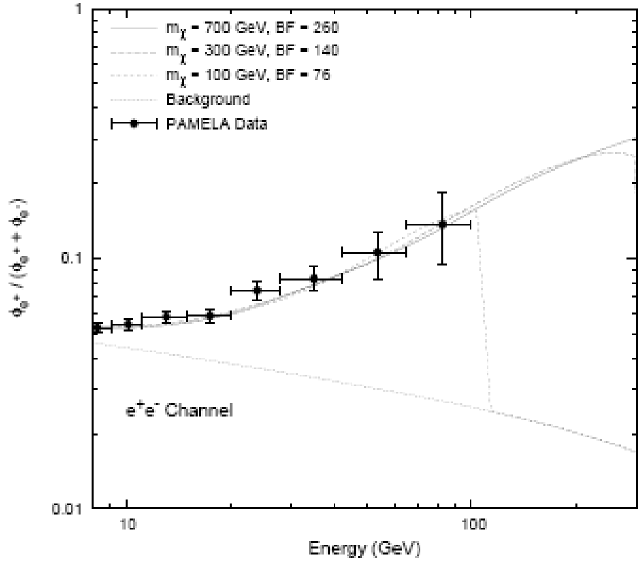
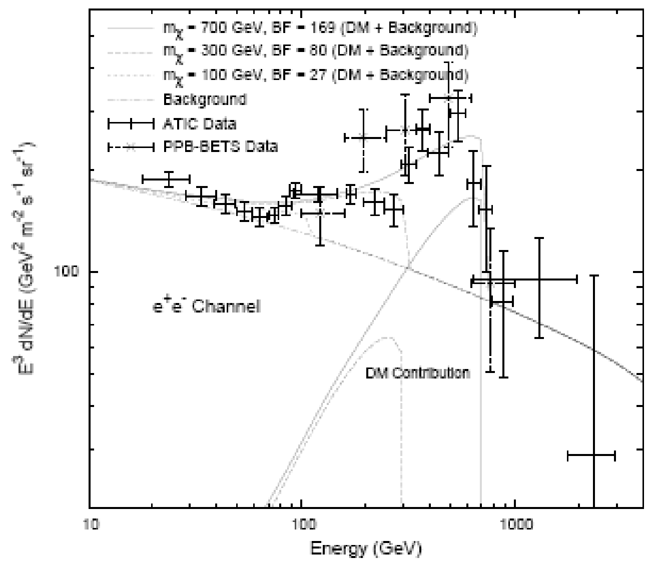
I. Cholis, G. Dobler, D. Finkbeiner., L. Goodenough, N. Weiner, arXiv: 0811.3641

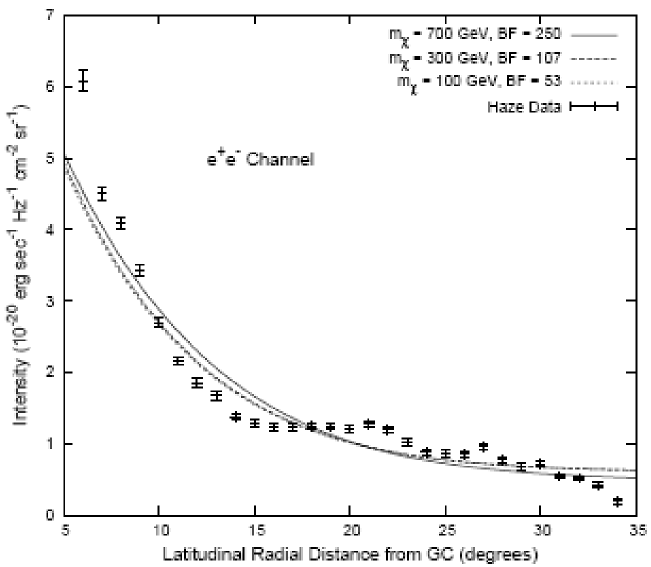
PAMELA

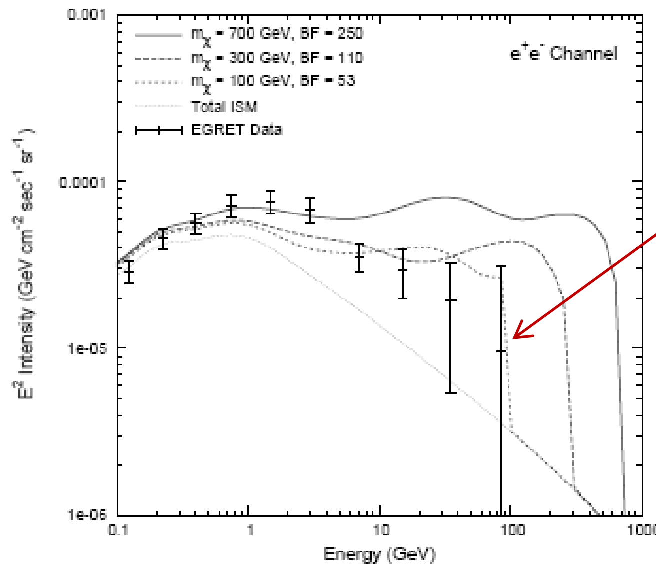


ATIC

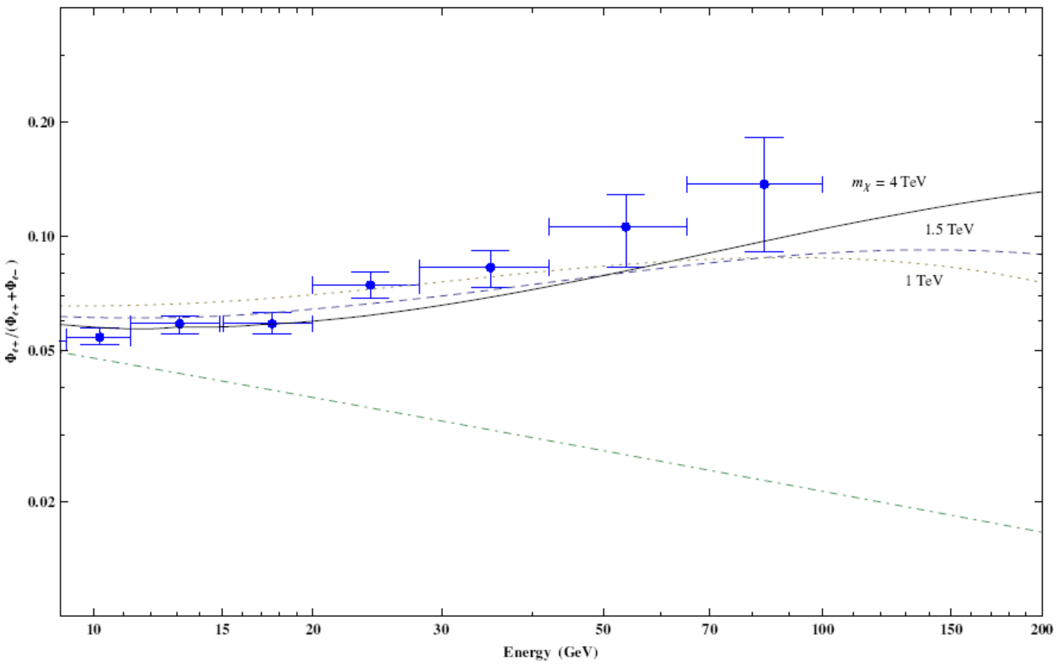


WMAP haze (but see reanalysis by Cumberbatch, Zuntz, Silk and Eriksen, arXiv:0902.0039)

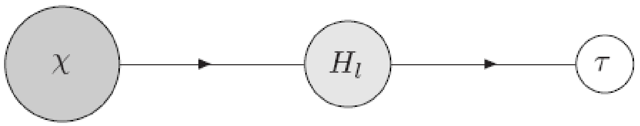




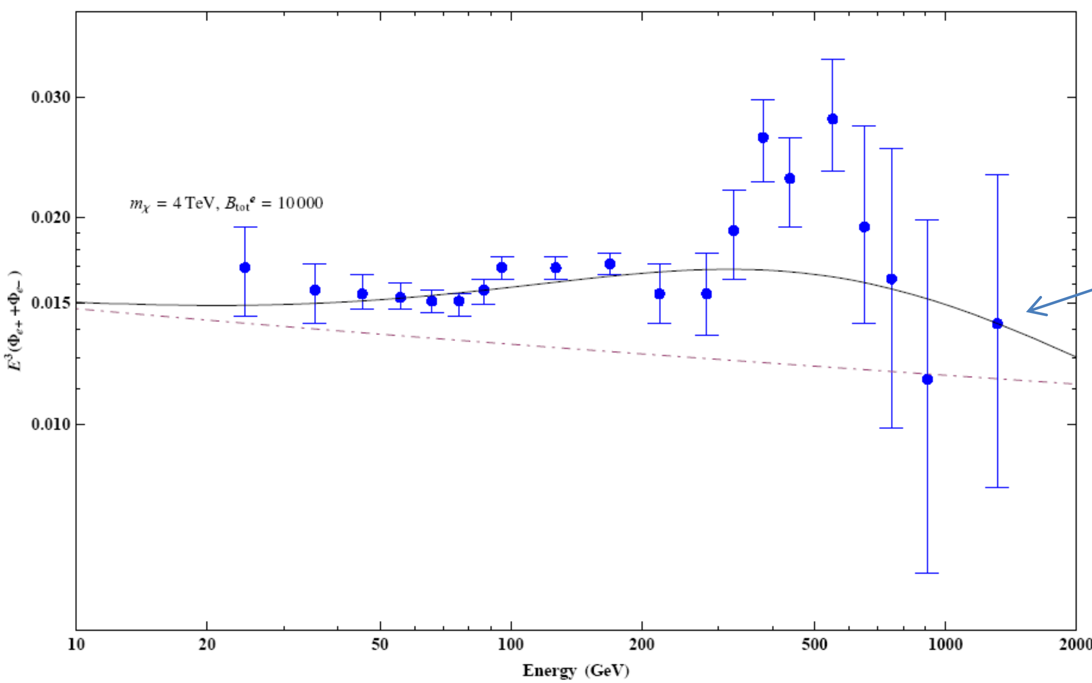
EGRET excess (now gone?)



"Leptonic Higgs"
H.-S. Goh, L.J. Hall
and P. Kumar,
arXiv:0902:0814



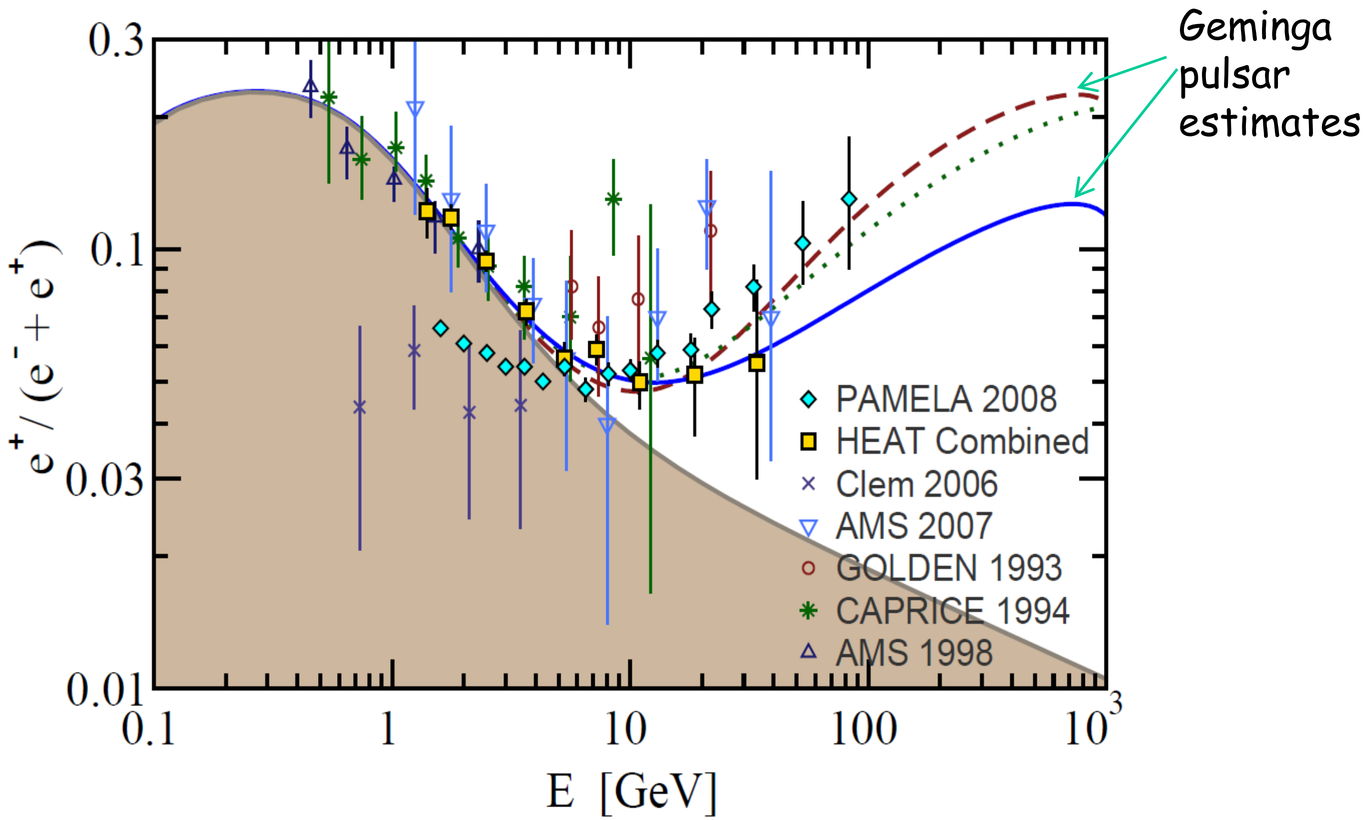
Annihilation or decay
to τ leptons



Annihilation, 4 TeV mass,
boost factor 10000…

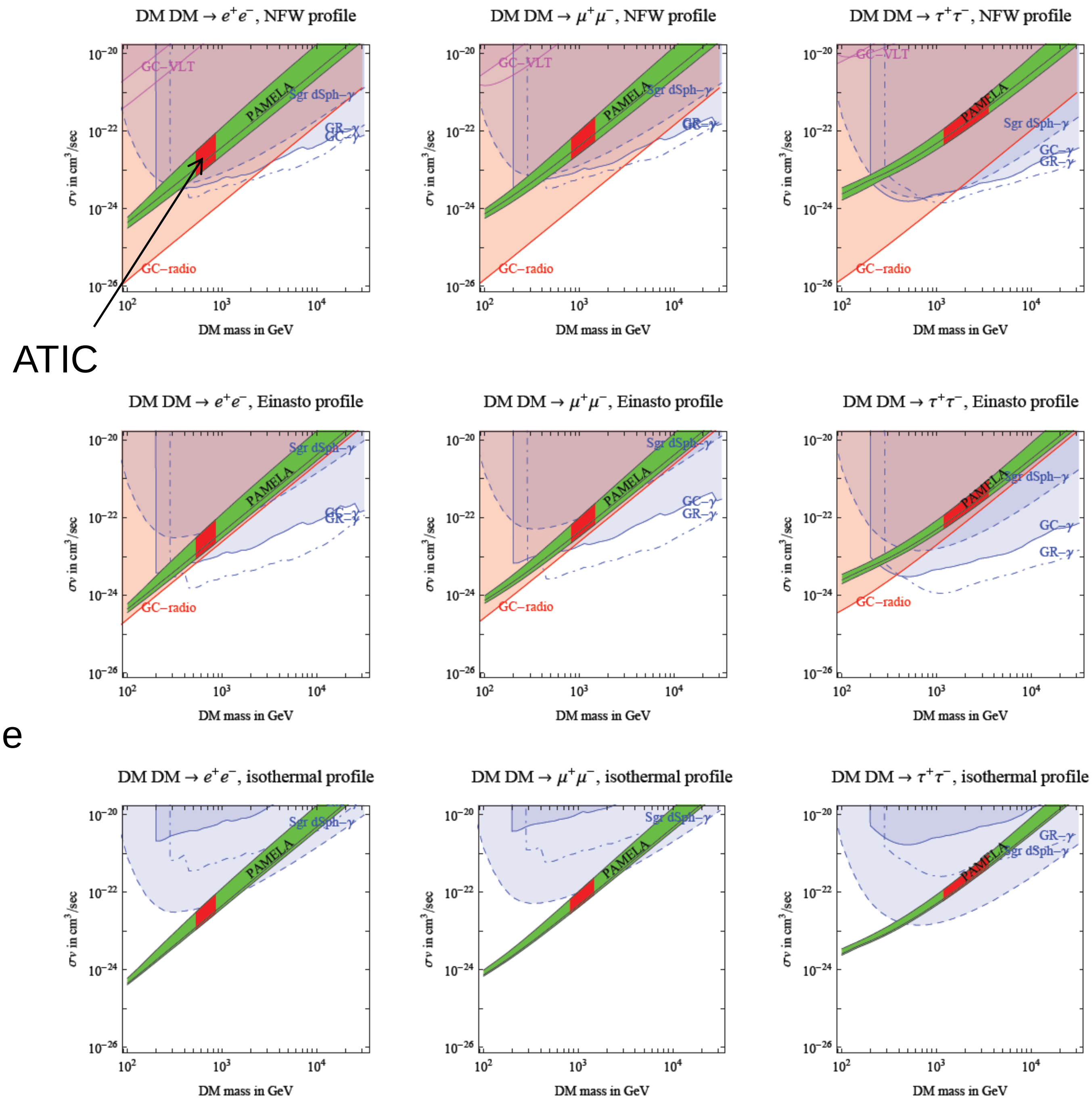
Alternative explanation for high positron flux: positrons generated by a class of extreme objects: supernova remnants (pulsars)

Vela pulsar (supernova remnant)



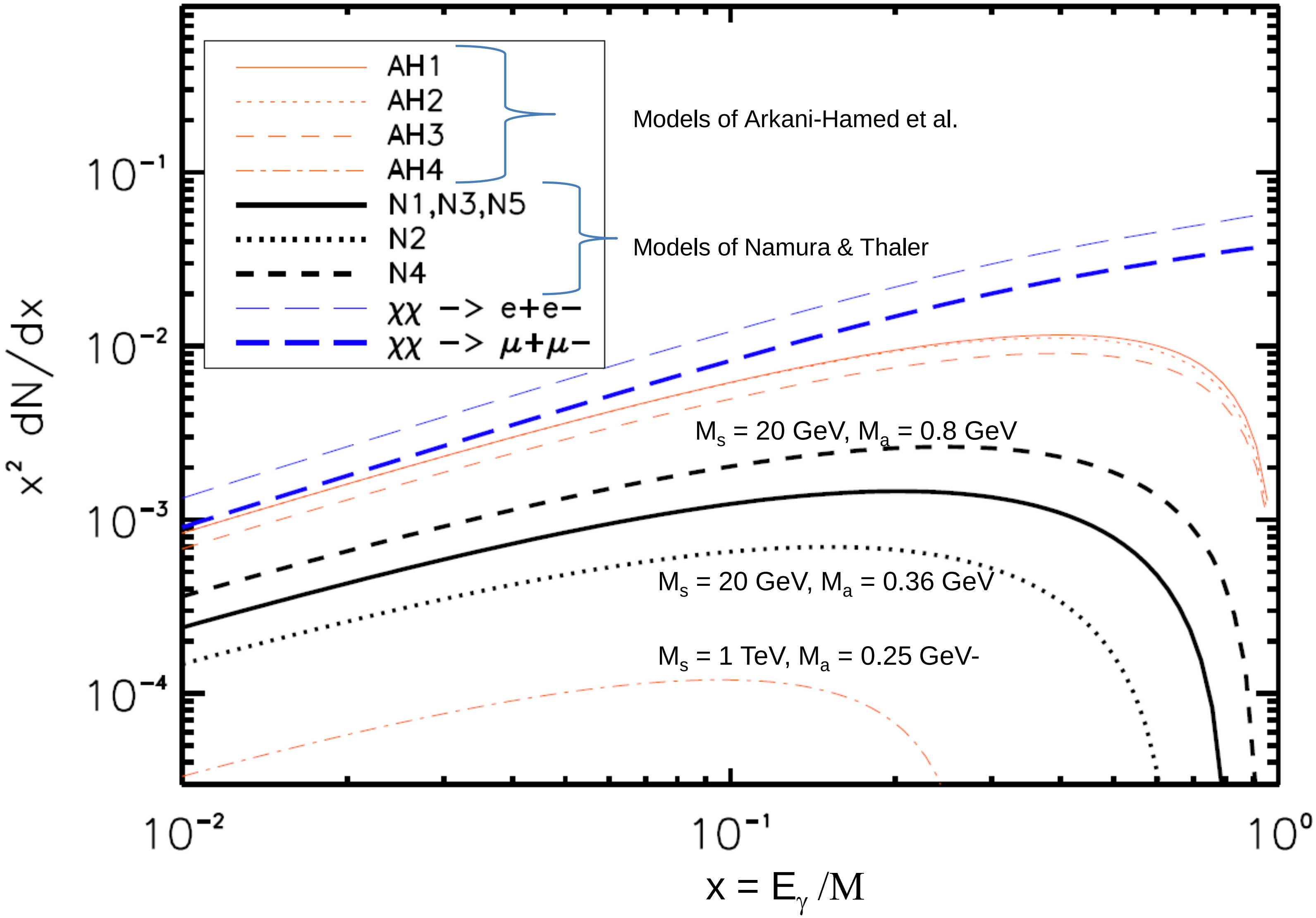
Yuksel, Kistler, Stanev, 2008 (cf. Aharonian, Atoyan and Völk, 1995; Kobayashi et al., 2004; Hooper, Blasi, Serpico, 2008; Profumo 2008;…)

G. Bertone, M. Cirelli, A. Strumia & M. Taoso, arXiv:0811.3744



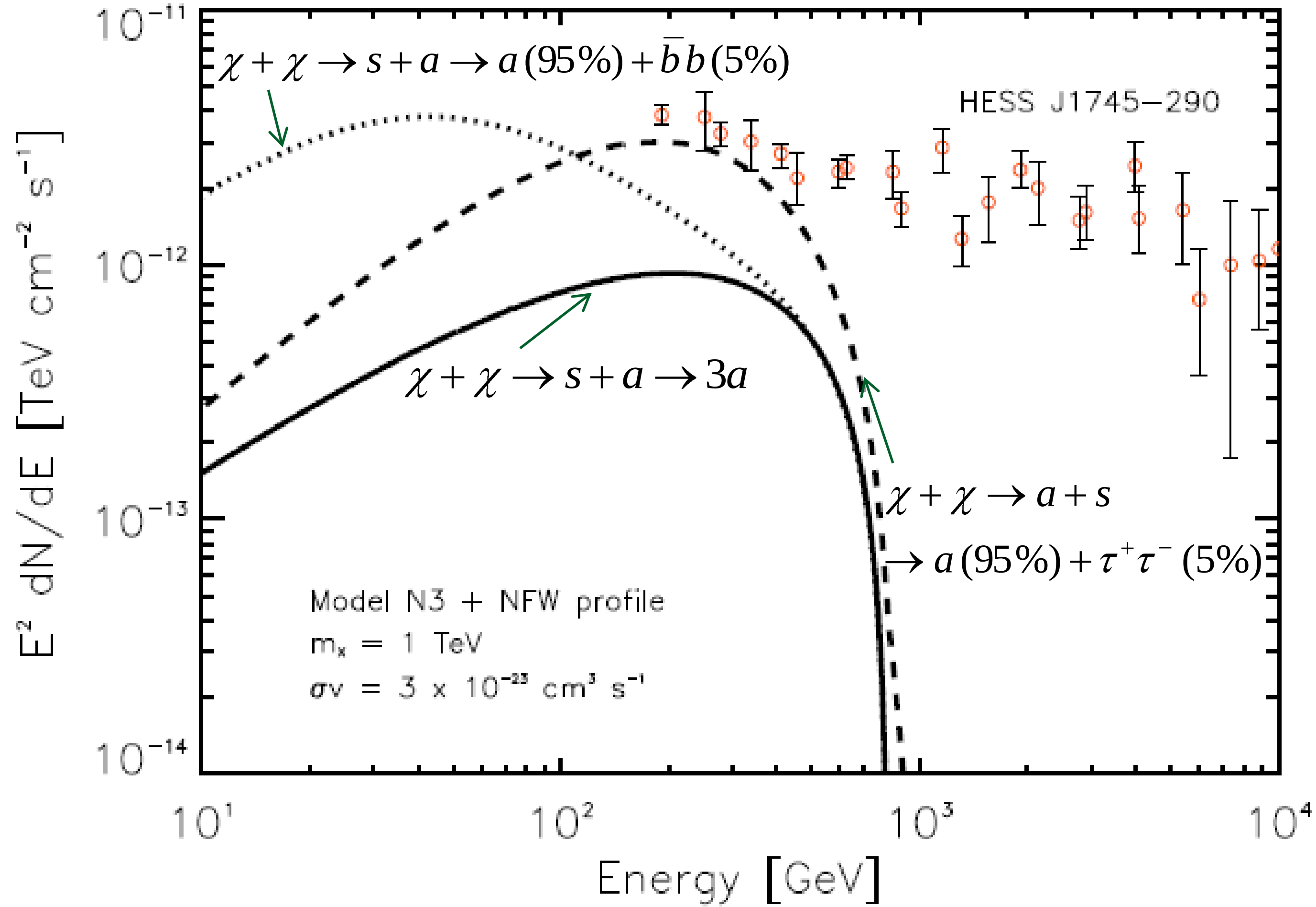
See talk by Bertone

External bremsstrahlung photon distribution



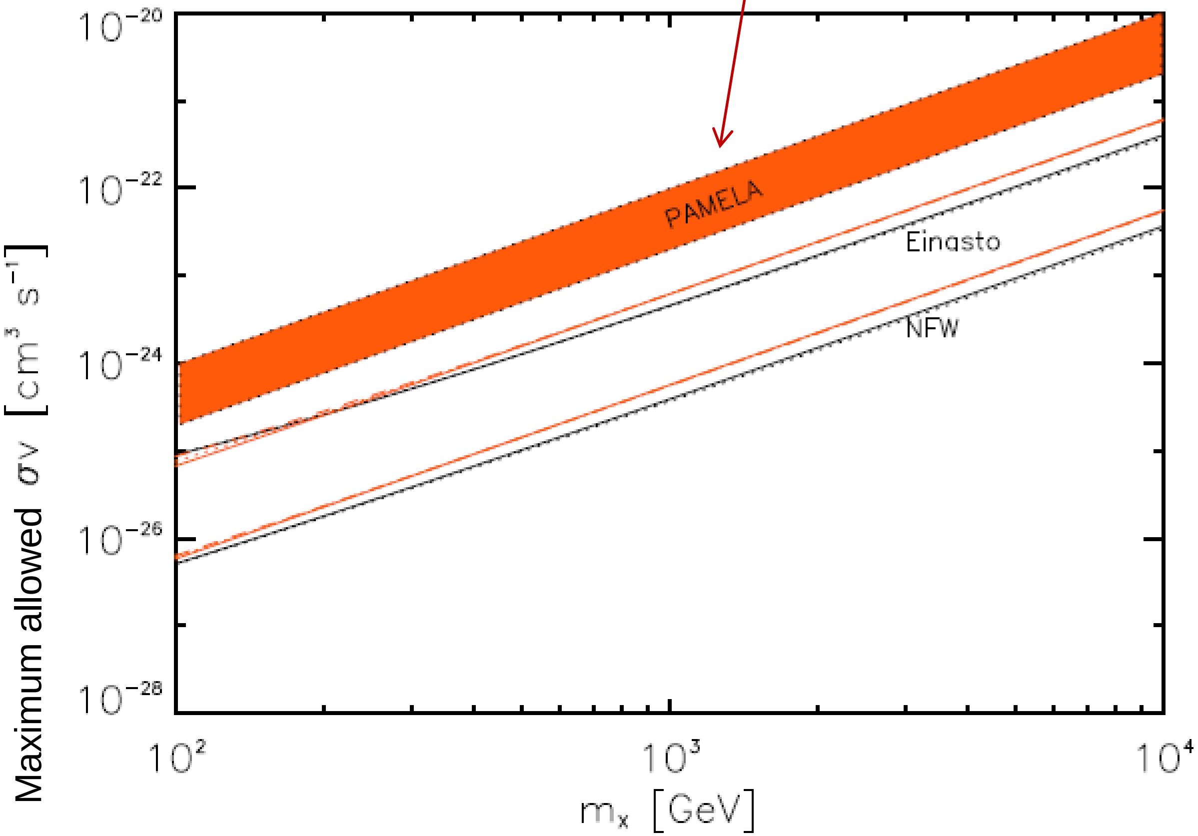
L.B., T. Bringmann, G. Bertone, J. Edsjö & M. Taoso , arXiv:0812.3895

Gammas from *a* and *s* decays (models of Nomura-Thaler type; arXiv:0810.5397). Cf. Also I. Cholis, G. Dobler, D. Finkbeiner., L. Goodenough, N. Weiner, arXiv: 0811.3641.



L.B., T. Bringmann, G. Bertone, J. Edsjö & M. Taoso , arXiv:0812.3895

Limit from radio observations of g.c. (somewhat sensitive to magnetic fields and halo density very near center)



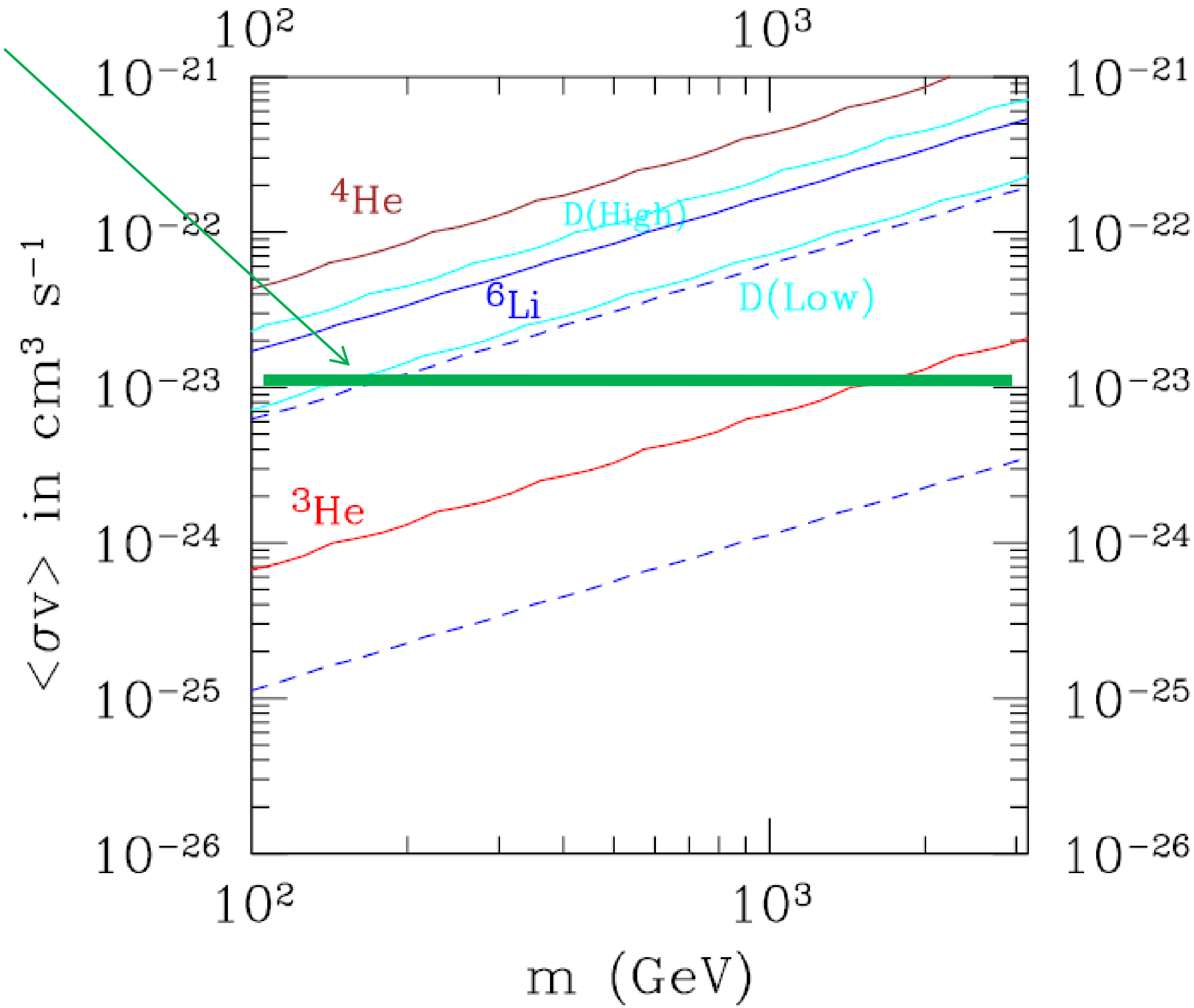
L.B., T. Bringmann, G. Bertone, J. Edsjö & M. Taoso

arXiv:0812.3895

See talk by Bertone

Constraints from BBN

Rate needed in most DM models with Sommerfeld enhancement



J. Hisano et al., arXiv:0901.3582

The PAMELA + ATIC results may be difficult to reproduce with dark matter annihilation without touching several bounds…

Both new data (Fermi, ATIC, PAMELA,…) and new theoretical analyses are needed!

In particular, I look forward to seeing (all are expected within 6 months):

- Fermi's results on (the absence of?) "GeV excess" for the inner galaxy.
- PAMELA's ratio for E > 100 GeV
- PAMELA's result on separate absolute fluxes of electrons and positrons, at least up to 100 GeV
- PAMELA's result on the sum of electrons and positrons (should reach 2 TeV)
- Fermi's sum of electrons and positrons (should reach 1 TeV)
- ATIC's unpublished data from later flights

After that, we may see if the DM option, at present possible, but in my view somewhat contrived, is still alive (or if there is a convincing pulsar interpretation).
When the suspect is to be posititively identified, the gamma-ray fingerprint may be decisive!