Antimatter and Gamma-rays from Dark Matter Annihilation

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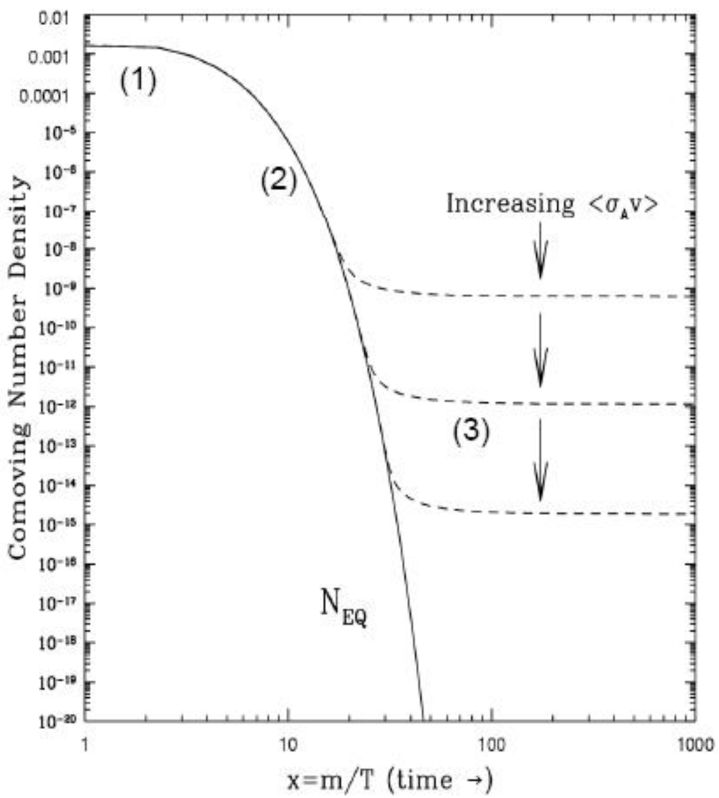
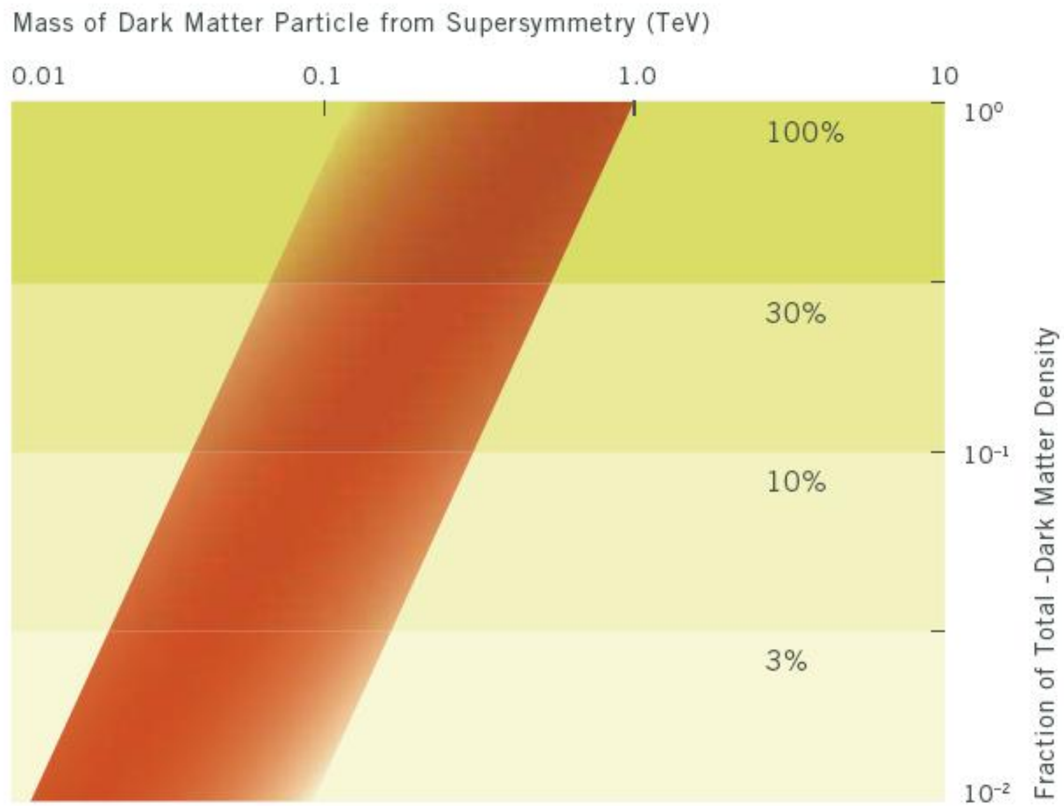
The "WIMP miracle"





J. Feng & al, ILC report 2005

I will not cover super-WIMPS, like gravitinos or right-handed neutrinos – they may also be part of this "miracle", but have quite different phenomenology.

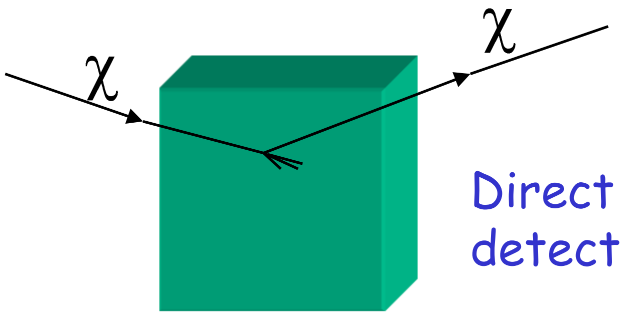
Methods of WIMP Dark Matter detection:

• Discovery at accelerators (Fermilab, LHC, ILC…).

• Direct detection of halo particles in terrestrial detectors.

• Indirect detection of neutrinos, gamma rays, X-rays, microwaves & radio waves, antiprotons, positrons in earth- or space-based experiments.

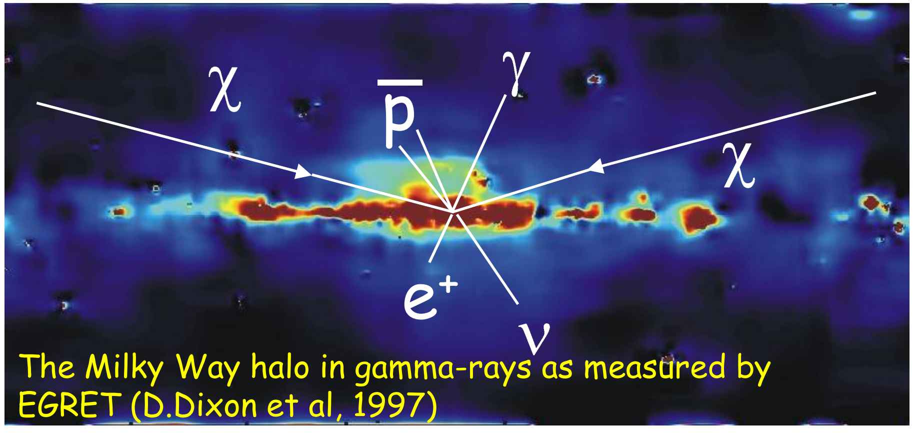
•For a convincing determination of the identity of dark matter, will plausibly need detection by at least two different methods.



Direct detection

$$\frac{d\sigma_{si}}{dq} = \frac{1}{\pi v^2}\left(Zf_p + (A-Z)f_n\right)^2 F_A(q) \propto A^2$$

Indirect detection



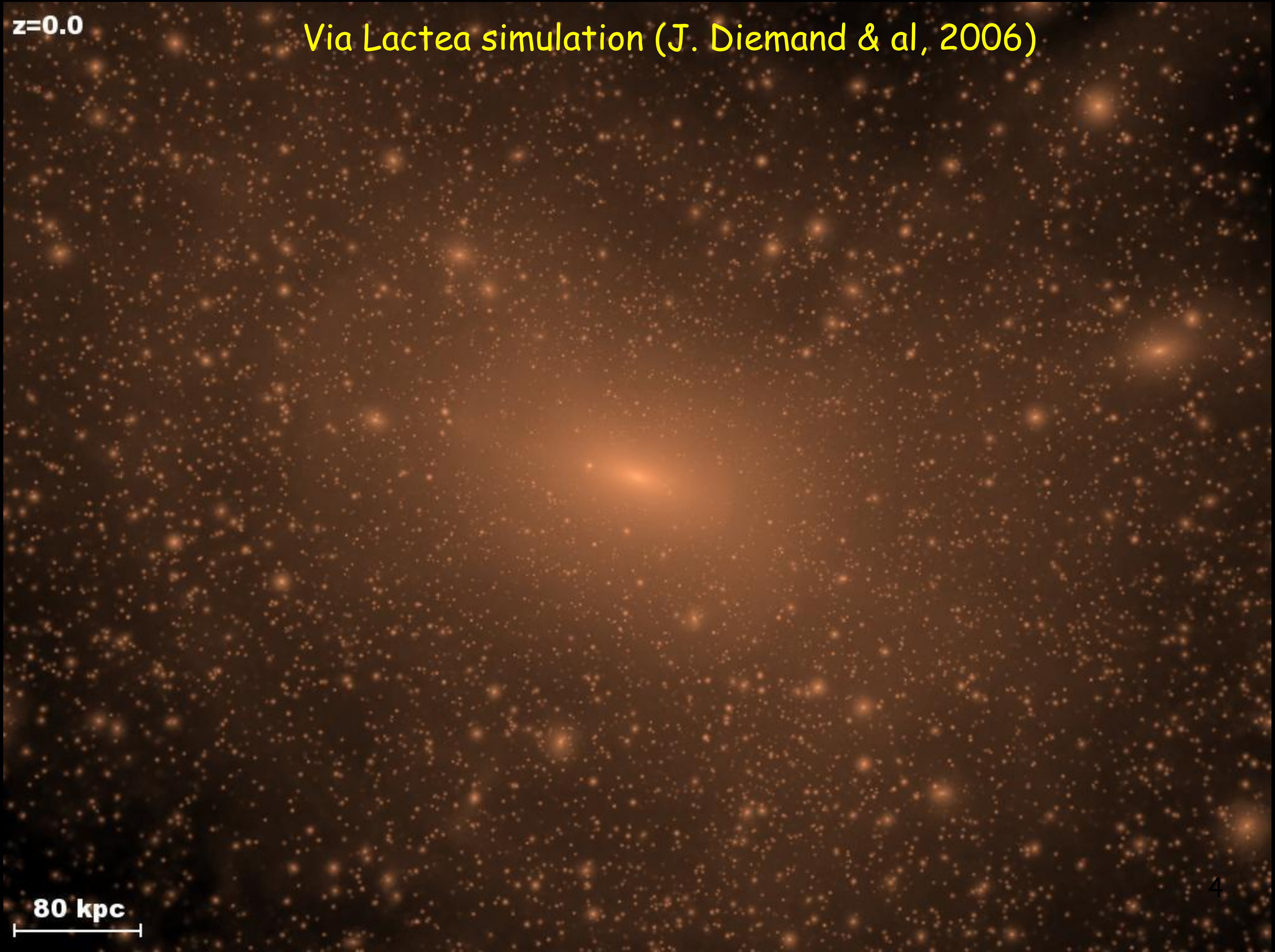
The Milky Way halo in gamma-rays as measured by EGRET (D.Dixon et al, 1997)

Neutralinos are Majorana particles

$$\Gamma_{ann} \propto n_\chi^2 \sigma v$$

Enhanced for clumpy halo; near galactic centre and in Sun & Earth

Via Lactea simulation (J. Diemand & al, 2006)



Dark SUSY

P. Gondolo, J. Edsjö, L.B., P. Ullio, Mia Schelke and E. A. Baltz, JCAP 0407:008, 2004 [astro-ph/0406204]

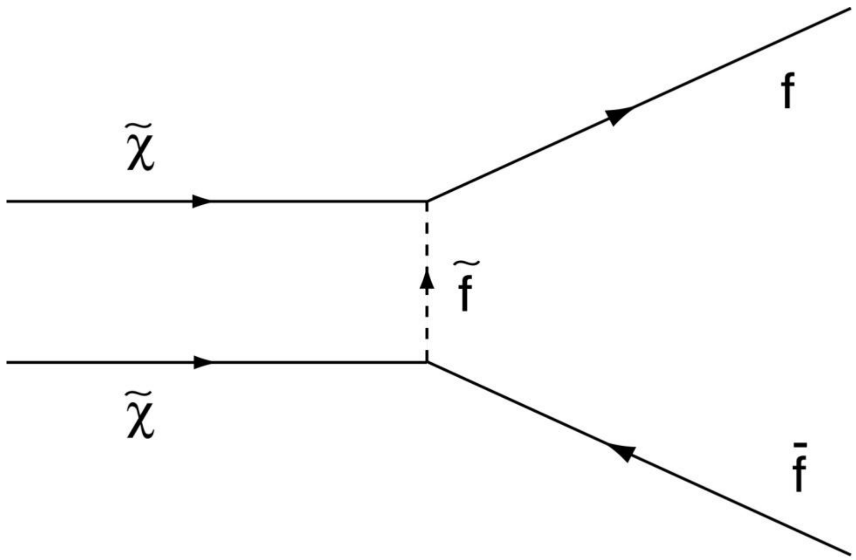
"Neutralino dark matter made easy" – public code. Can be freely dowloaded from http://www.physto.se/~edsjo/ds

Release 4.1: includes coannihilations & interface to Isasugra

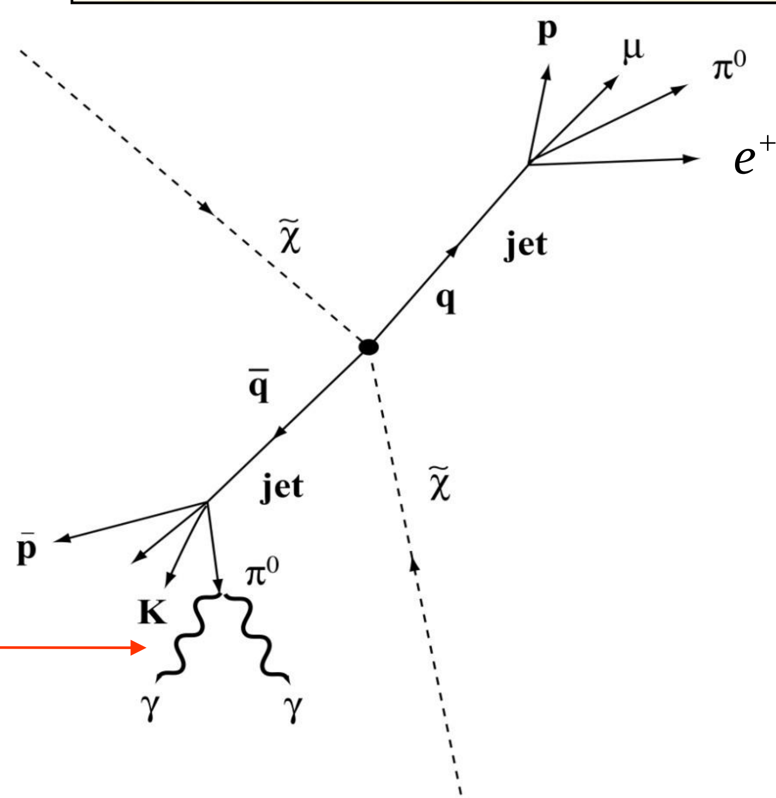
New release soon (with contributions also by T. Bringmann)

Other codes: micrOMEGAs (Bélanger & al. - public); Baer & al.; Bottino & al.; Falk & al.; Roszkowski & al…

Example of indirect detection: annihilation of neutralinos in the galactic halo

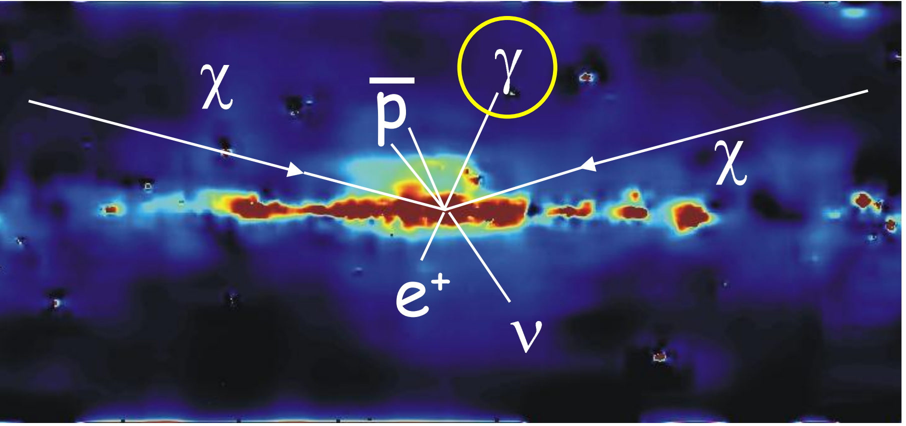


Majorana particles: helicity factor for fermions $\sigma v \sim m_f^2$: Usually, the heaviest kinematically allowed final state dominates (b or t quarks; W & Z bosons)



Note: equal amounts of matter and antimatter in annihilations - source of antimatter in cosmic rays?

Decays from neutral pions: Dominant source of continuum gammas in halo annihilations. Fragmentation of quark jets to gammas, antiprotons, positrons well known in particle physics. (DarkSUSY uses PYTHIA.)



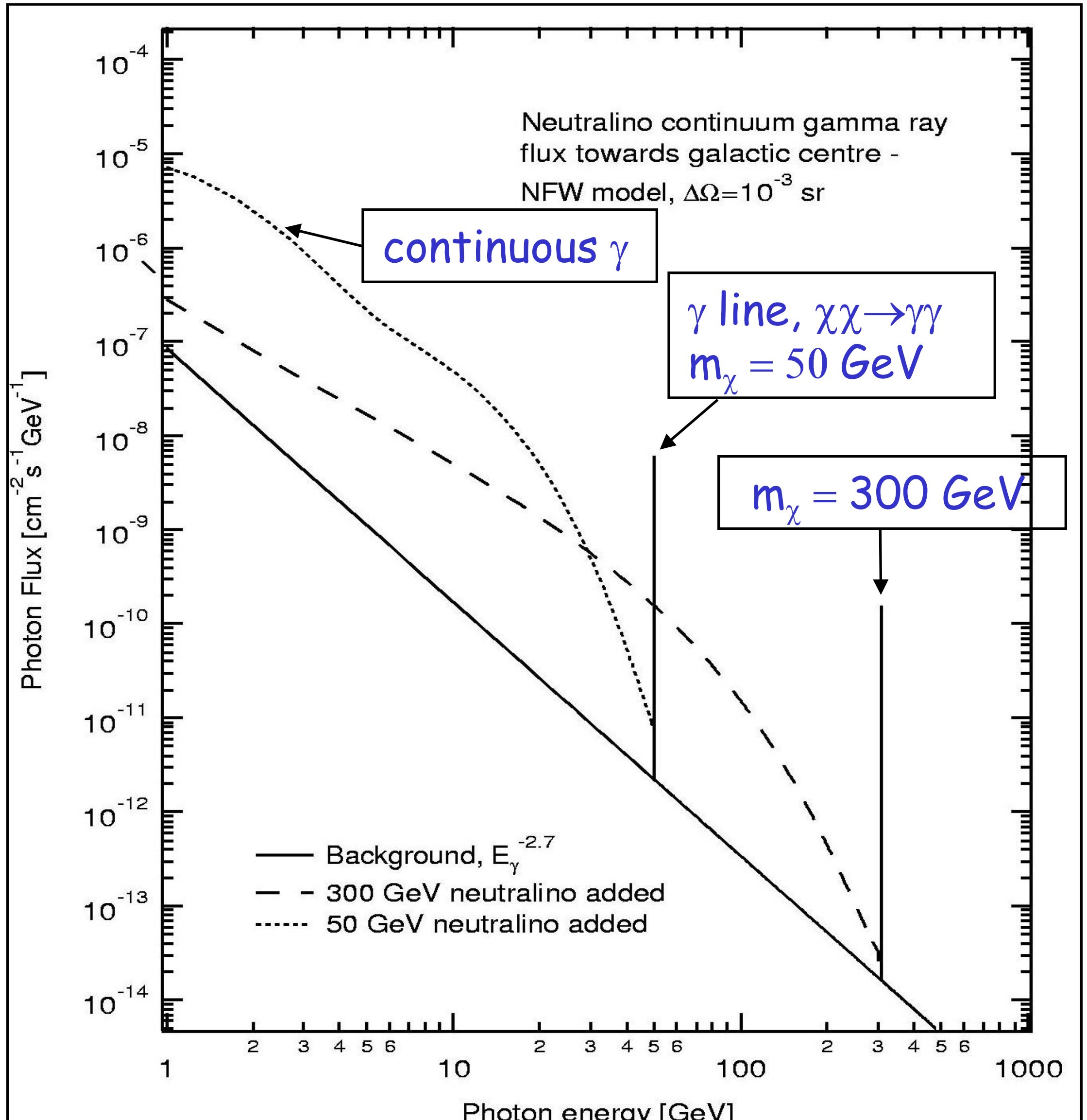
Gamma-rays

Indirect detection through γ-rays.
Two types of signal: Continuous (large rate but at lower energies, difficult signature except some cases with large internal bremsstrahlung) and Monoenergetic line (often too small rate but is at highest energy $E_\gamma = m_\chi$; "smoking gun")

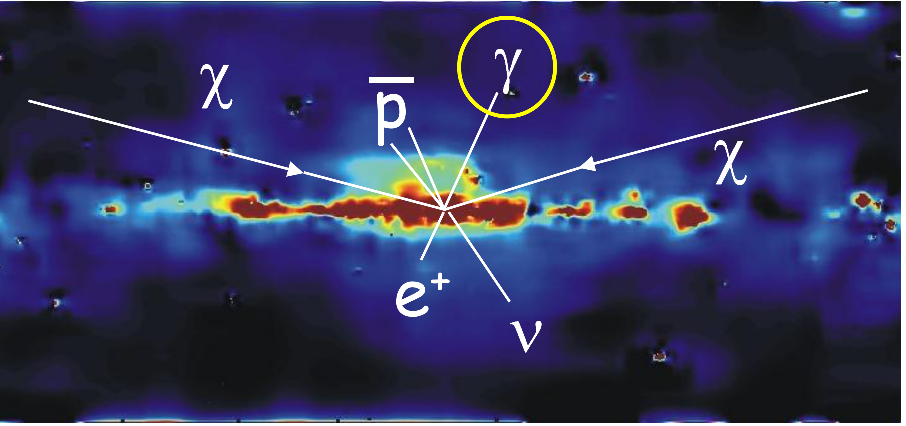
Advantage of gamma rays: Point back to the source (no absorption).

Enhanced flux possible thanks to halo density profile and substructure (as predicted by CDM)

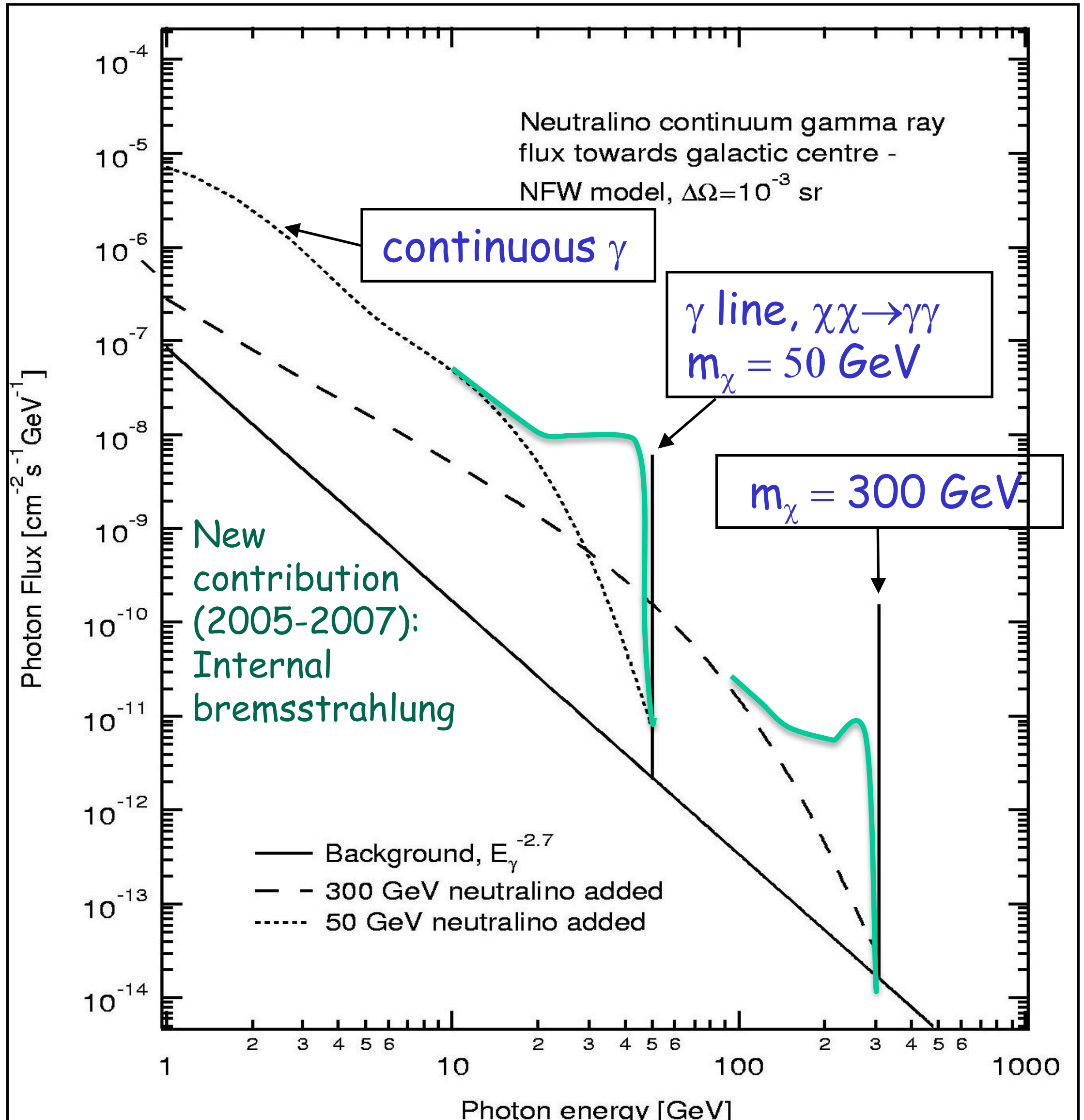
Unfortunately, large uncertainties in the predictions of absolute rates



L.B., P.Ullio & J. Buckley 1998



Gamma-rays



L.B., P.Ullio & J. Buckley 1998

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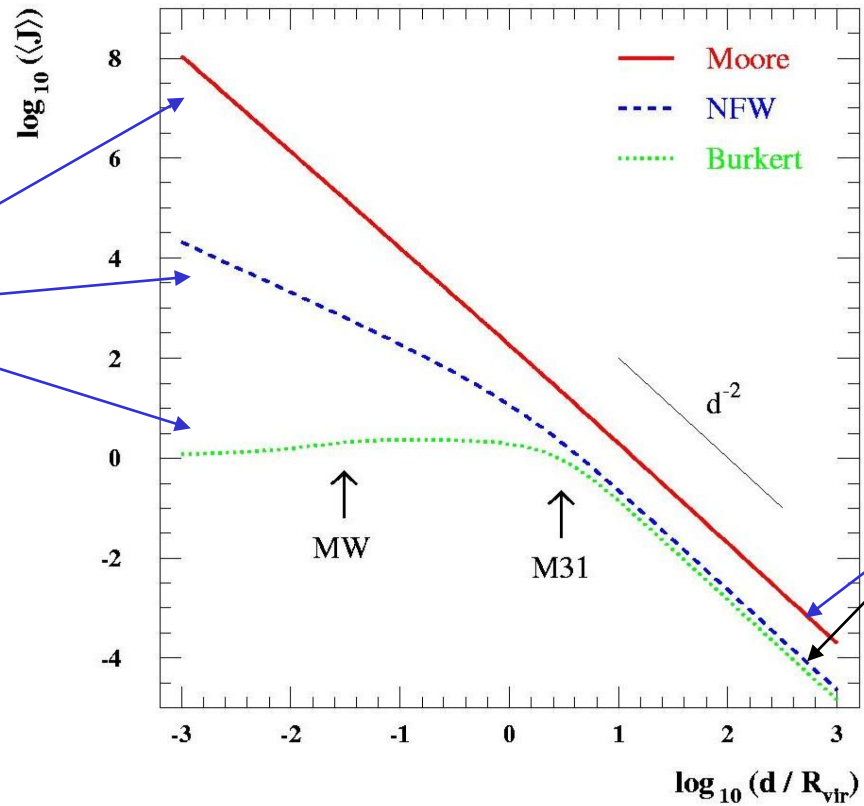
Detection rate = (PPP)×(APP)

~ <σv>   ~ J

$$\bar{J}(\hat{n};\Delta\Omega) \equiv \frac{1}{\Delta\Omega}\int d\Omega \int \frac{dl}{(8.5\,kpc)}\left(\frac{\rho(\vec{r})}{0.3\,GeV/cm^3}\right)^2$$

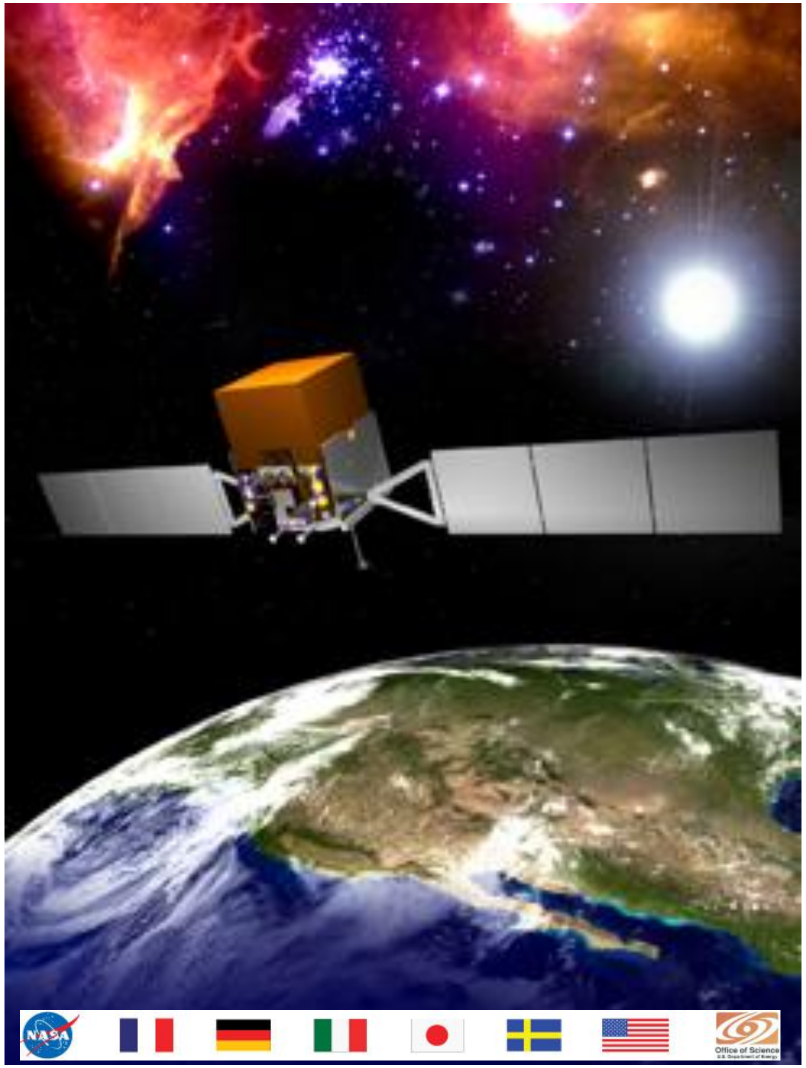
Note large uncertainty of flux for nearby objects (Milky Way center, LMC, Draco,...)



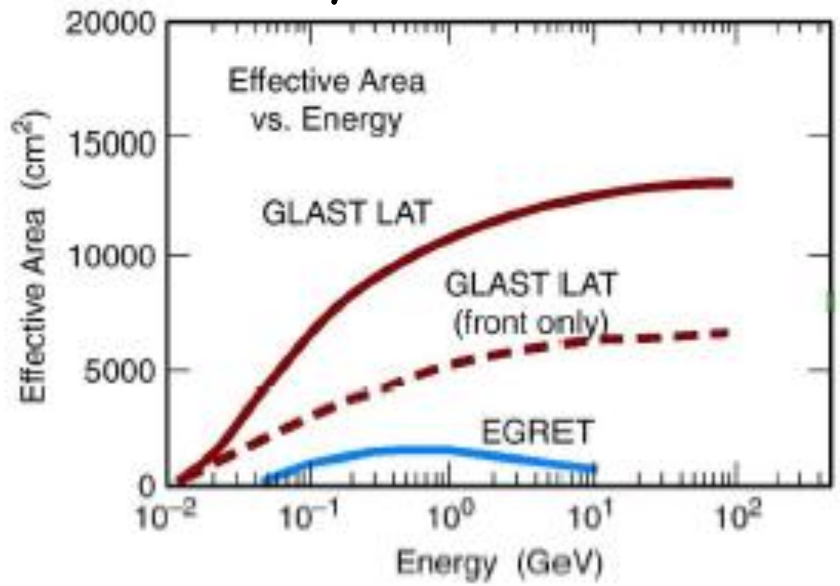
In this region (at cosmological distances), the uncertainty is much smaller

P. Ullio, L.B., J. Edsjö, 2002

FIG. 4: Scaling of the collected γ-ray flux with the distance d between the detector and the center of a halo, for three different halo profiles. The angular acceptance of the detector is assumed to be $\Delta\Omega = 10^{-3}$sr. The plot is for a $10^{12} M_\odot$ halo, the arrows indicate the position on the horizontal axis for the Milky Way and Andromeda; the case for other masses is analogous.



USA-France-Italy-Sweden-Japan – Germany collaboration, launch early 2008



GLAST can search for dark matter signals up to 300 GeV. It is also likely to detect a few thousand new AGNs (GeV blazars).

Other model I.

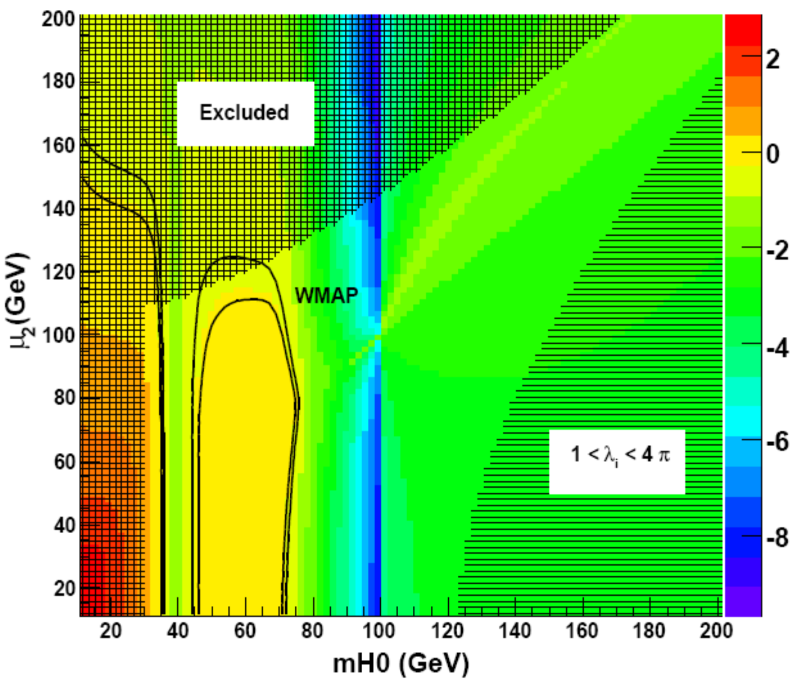
Inert Higgs model

Introduce extra Higgs doublet H_2, impose discrete symmetry $H_2 \rightarrow -H_2$ similar to R-parity in SUSY (Deshpande & Ma, 1978, Barbieri, Hall, Rychkov 2006) .

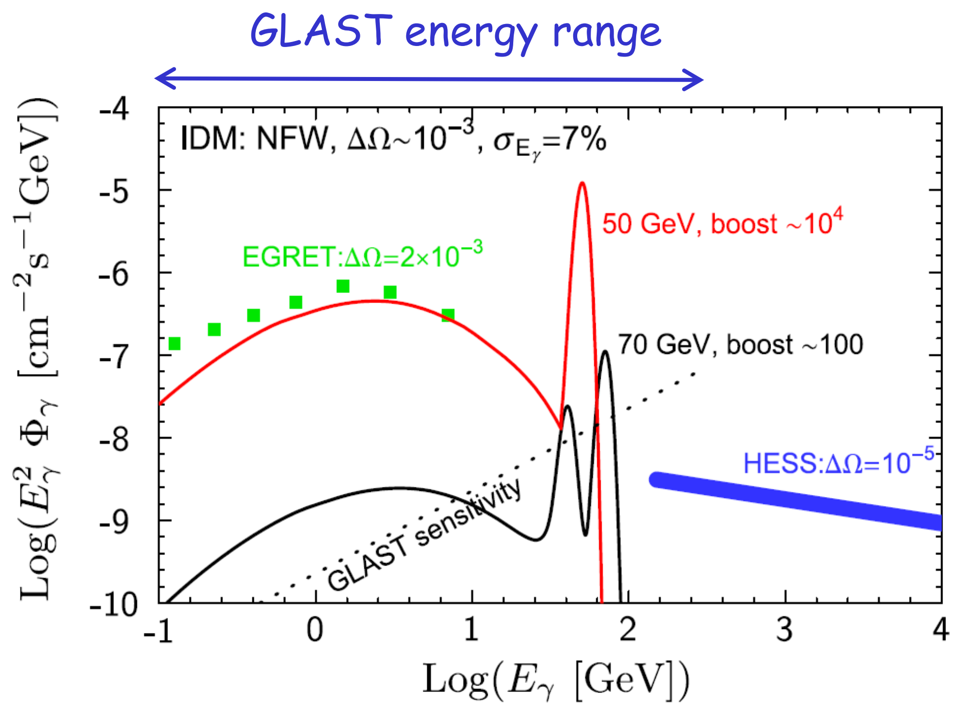
This model may also break EW symmetry radiatively, the Coleman-Weinberg Mechanism (Hambye & Tytgat, 2007).

Interesting phenomenology: Tree-level annihilations are very weak in the halo; loop-induced $\gamma\gamma$ and $Z\gamma$ processes may dominate!

The perfect candidate for detection in GLAST!



Lopez Honorez et al, 2007



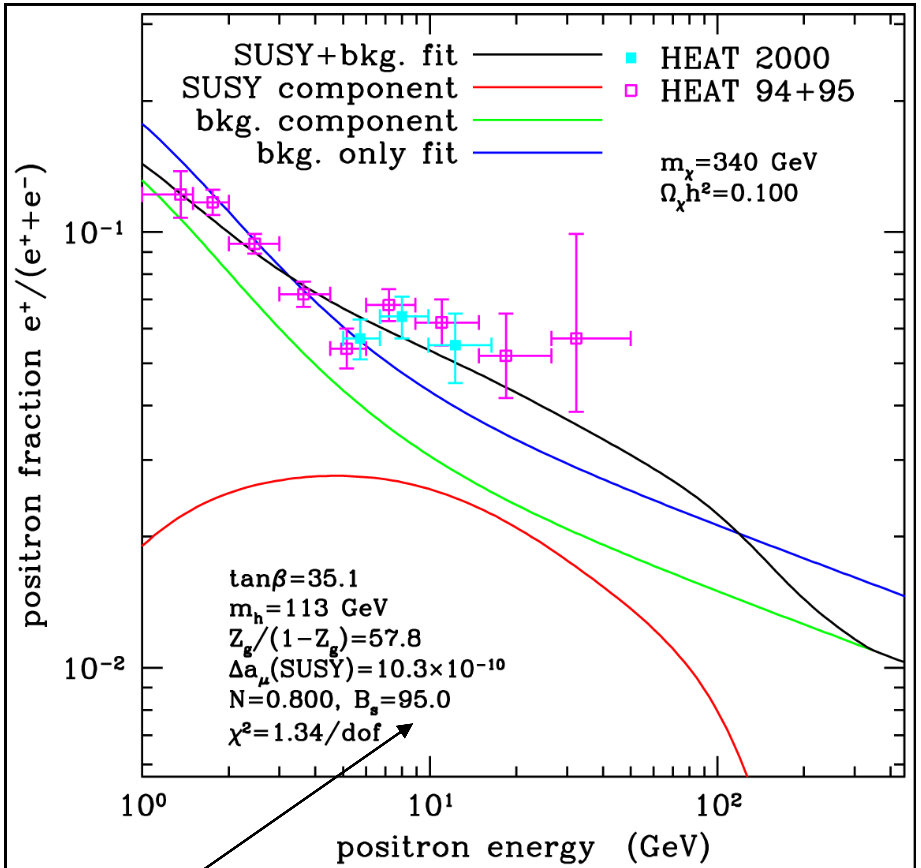
M. Gustafsson , L.B., J. Edsjö, E. Lundström, PRL, July 27, 2007

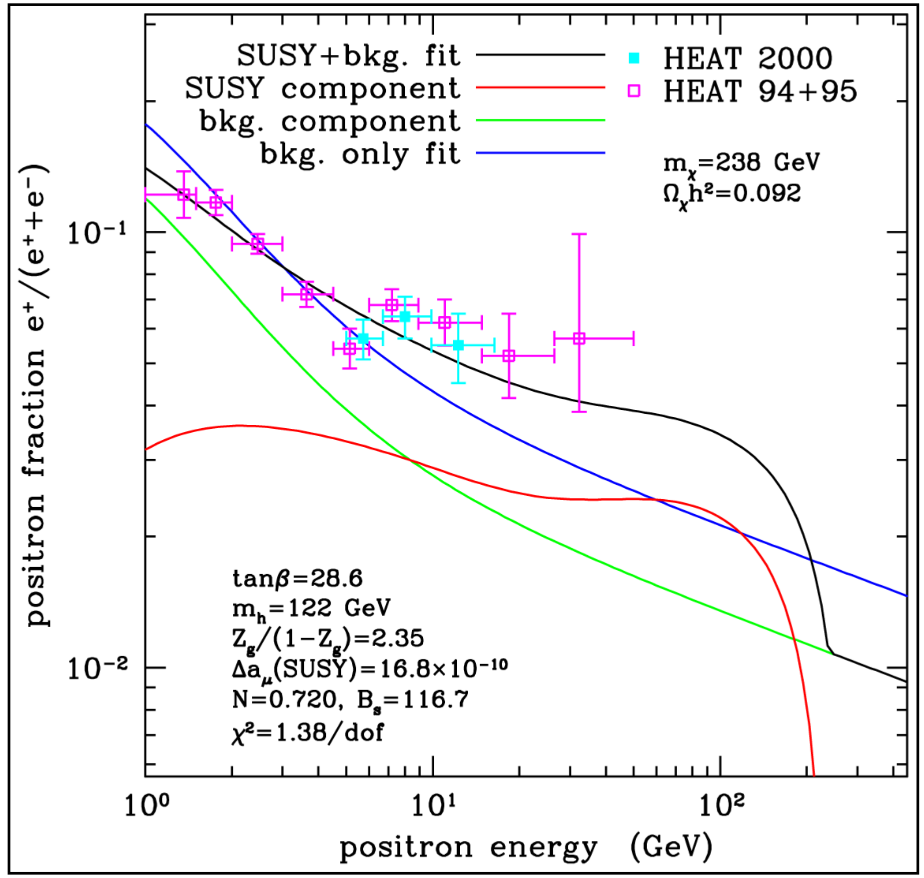
Note on boost factors:

- The overall average enhancement over a smooth halo, from DM substructure etc, is **hardly greater than 2 – 10** (cf. Berezinsky, Dokuchaev & Ereshenko, 2003).
- In one specific location, however, like the region around the **galactic center**, factors up to 10^5 are easily possible from cusps or spikes (large variation between different halos).
- Also, the existence of **intermediate mass black holes** may give very large local boost factors (Bertone, Zentner & Silk, 2005).
- Baryon contraction of the dark matter may give another few orders of magnitude near the g.c (Gnedin & Primack, 2004).
- The downside of this is a **lack of predictability** of absolute counting rates for indirect detection. If a signal is found, however, important information about **particle physics** will be obtained (mass of particle, spin, branching ratios etc).

Positrons from neutralino annihilations – explanation of feature at 10 – 30 GeV?

New experiments will come: Pamela (successful launch, June 2006; will present results soon?) and AMS (When?)





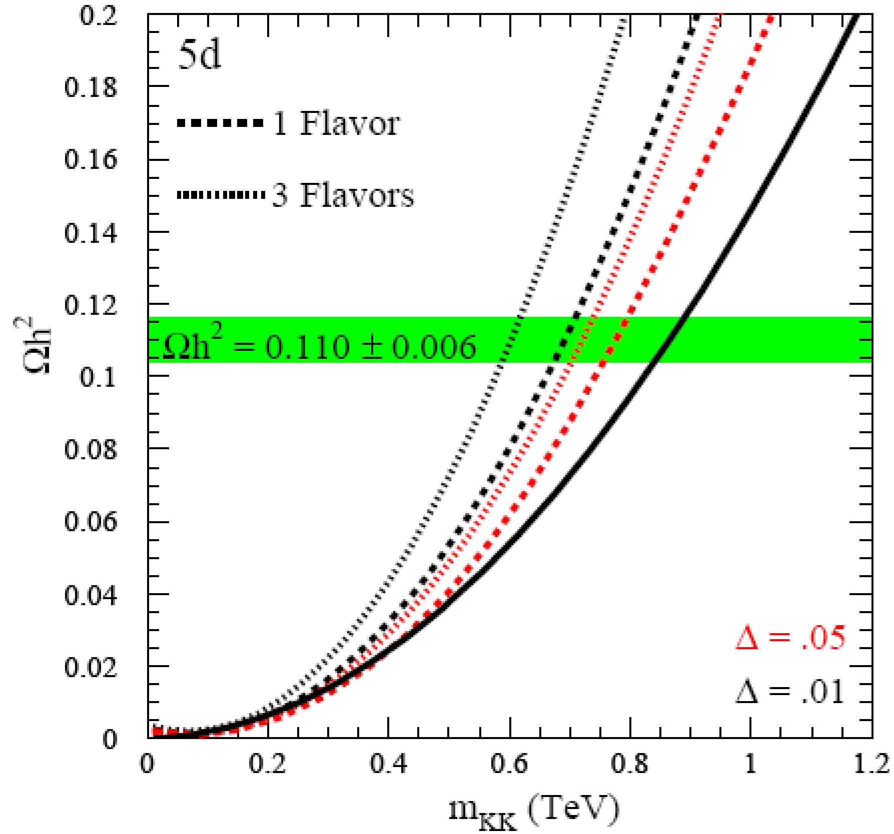
Need high "boost factor"

Baltz, Edsjö, Freese, Gondolo 2002; Kane, Wang & Wells, 2002; Hooper & Kribs, 2004; Hooper & Silk, 2004 .

Other model II: Kaluza-Klein (KK) dark matter in Universal Extra Dimensions

Universal Extra Dimensions, UED (Appelquist & al, 2002):

- All Standard Model fields propagate in the bulk → in effective 4D theory, each field has a KK tower of massive states
- Unwanted d.o.f. at zero level disappear due to orbifold compactification, e.g., S^1/Z_2 , $y \leftrightarrow -y$
- KK parity $(-1)^n$ conservation → lightest KK particle (LKP) is stable → possible dark matter candidate
- One loop calculation (Cheng & al, 2002): LKP is $B^{(1)}$
- Difference from SUSY: spin 1 WIMP → no helicity suppression of fermions
- Variant (Agashe & Servant, 2004): Randall-Sundrum warped GUT with Z_3 symmetry, LZP stable



Servant & Tait, 2003

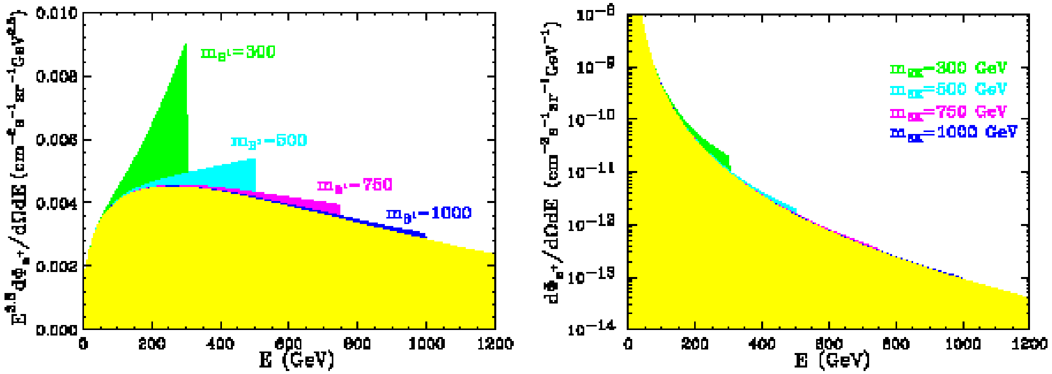
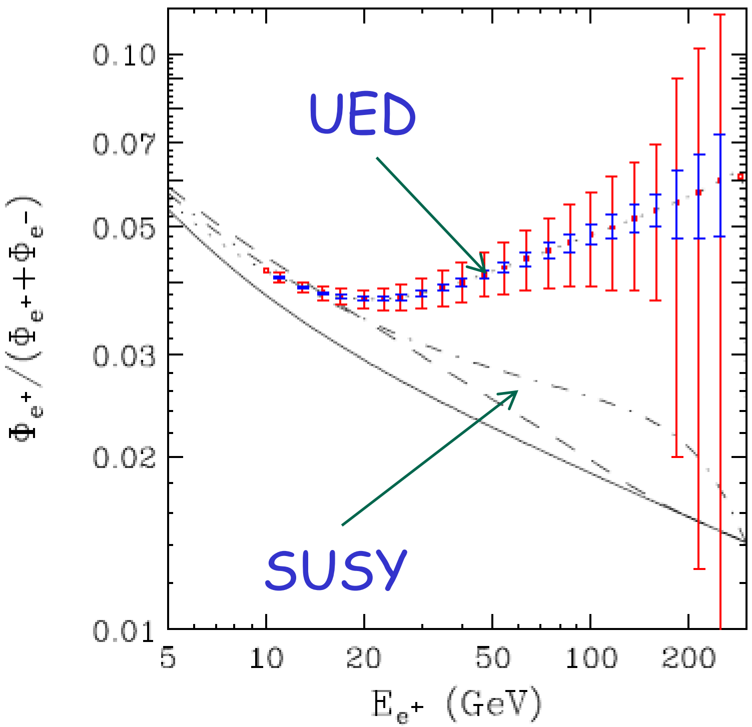
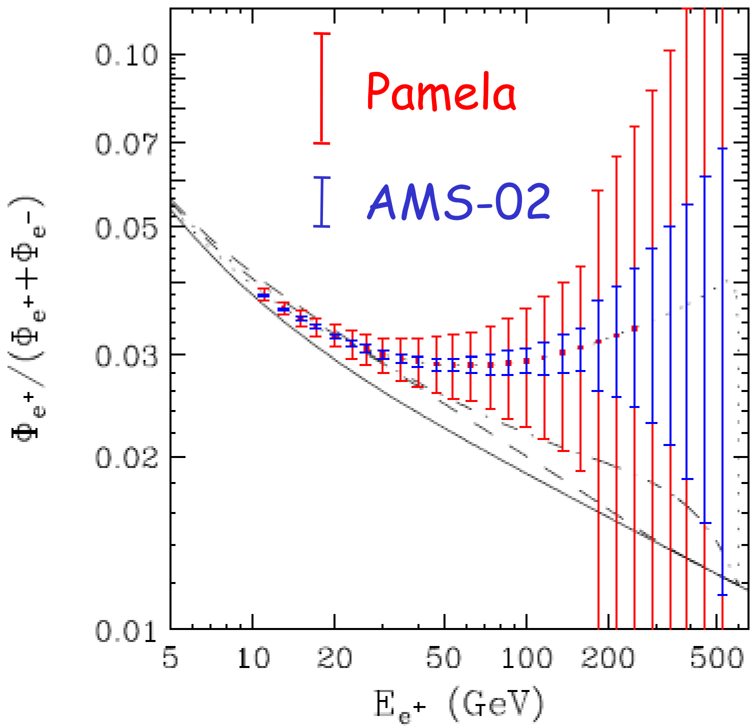


Figure 3. Positron spectra from B^1 dark matter annihilation for various B^1 masses as indicated [22]. The yellow (light shaded) region is the expected background. The differential flux is given in the right panel, and is modified by the factor E^3 in the left panel.

Prediction of positron flux from UED model (Cheng, Feng & Matchev, 2003)



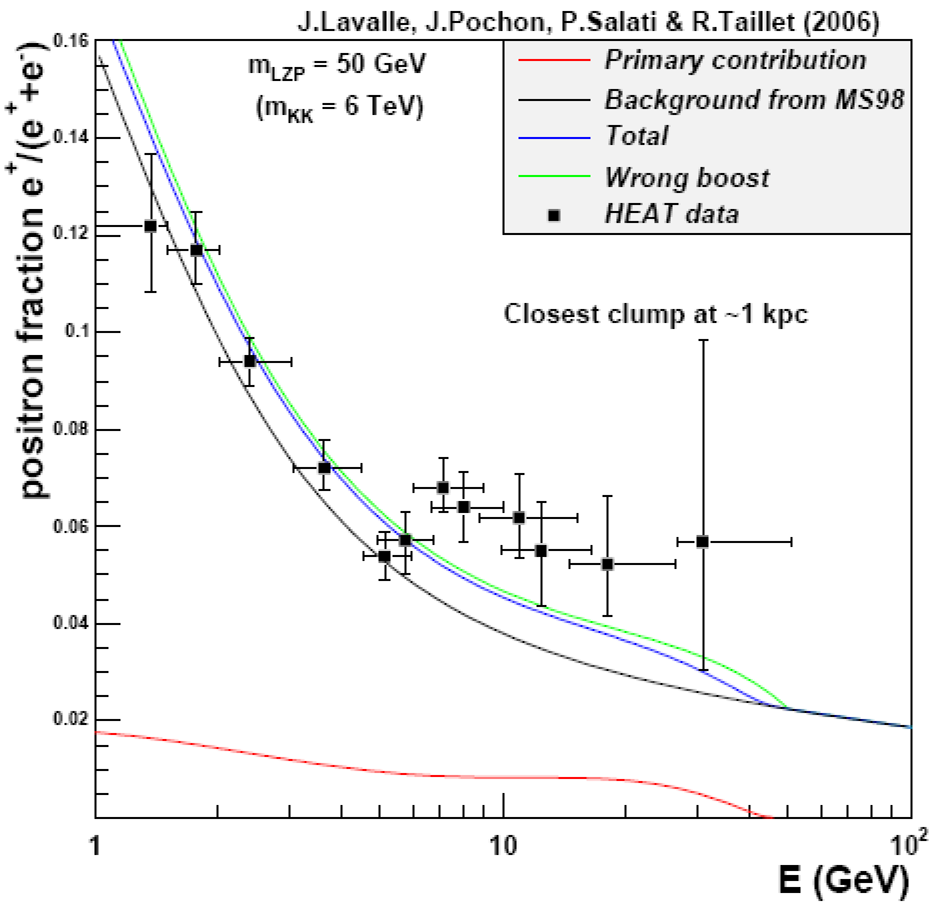
M = 300 GeV

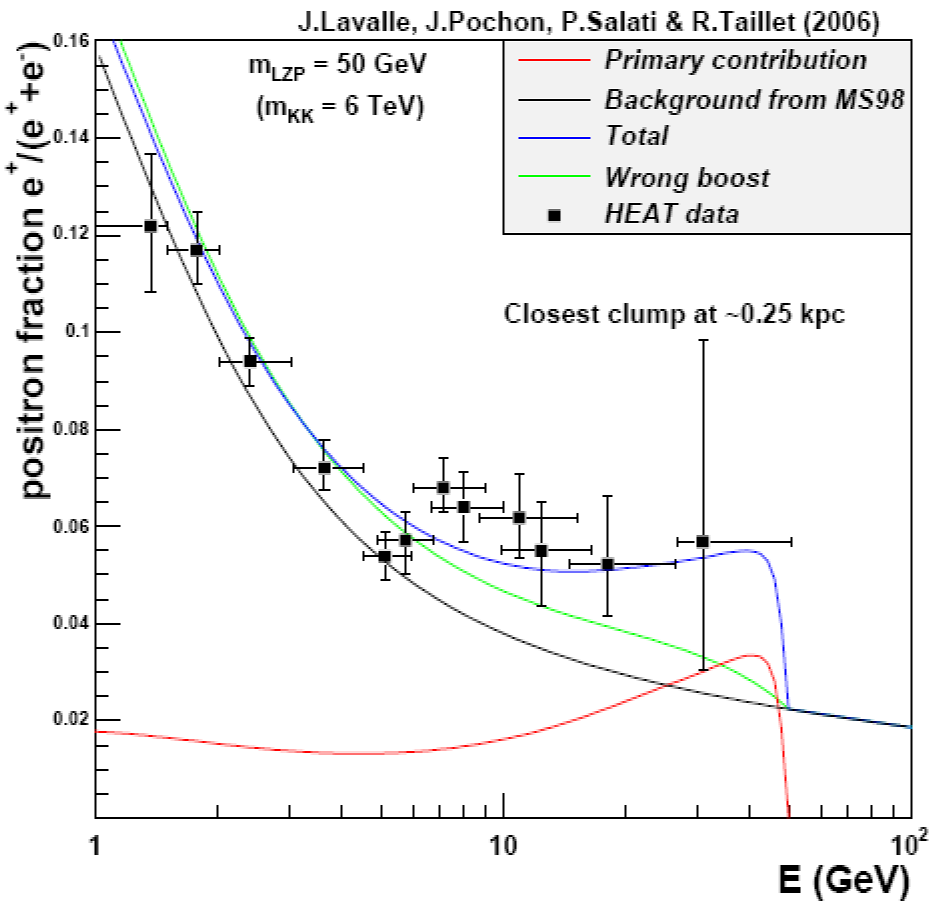


M = 600 GeV

Hooper & Zaharijas, 2007

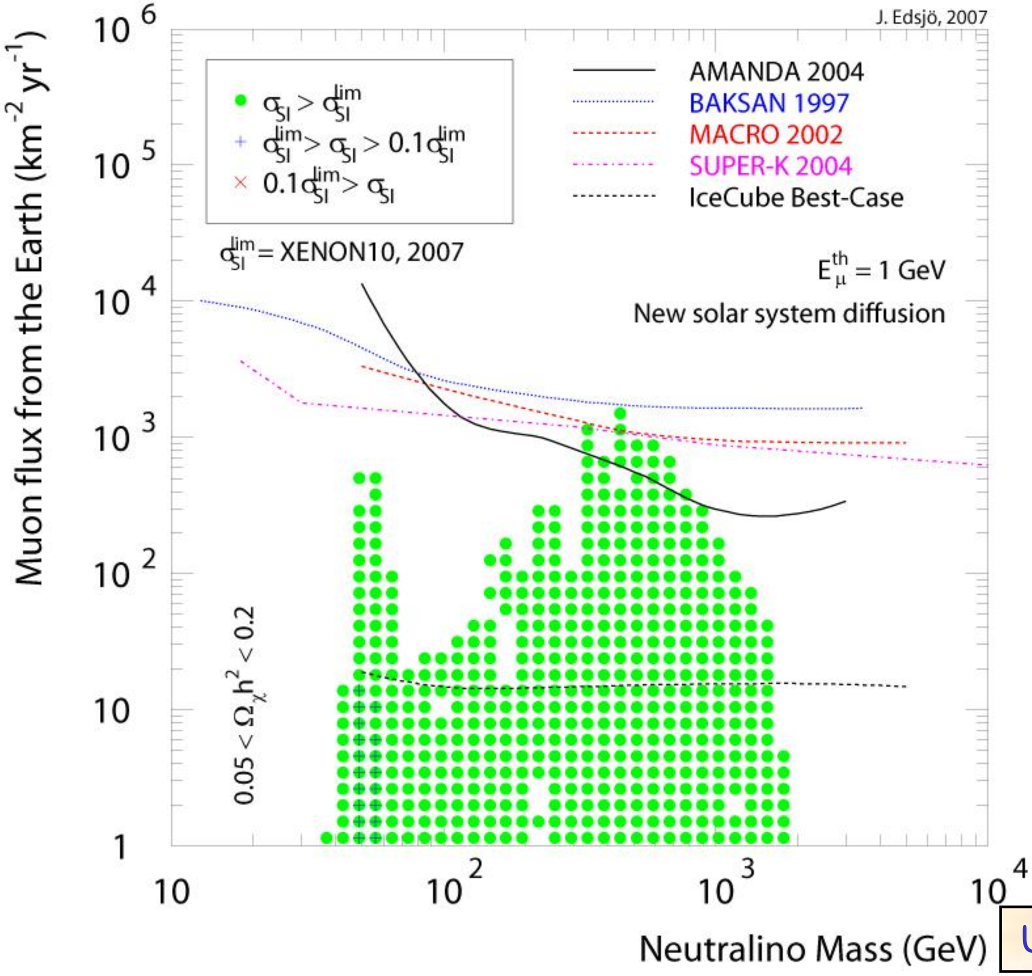
J. Lavalle, J. Pochon, P. Salati & R. Taillet (2006): Energy-dependent boost factor for positrons may in principle explain the "bump" around 10 – 50 GeV for a 50 GeV WIMP with large B.R. into lepton pairs (Cumberbatch Silk, 2006). However, the probability for a very nearby clump dominating the yield is exceedingly small…

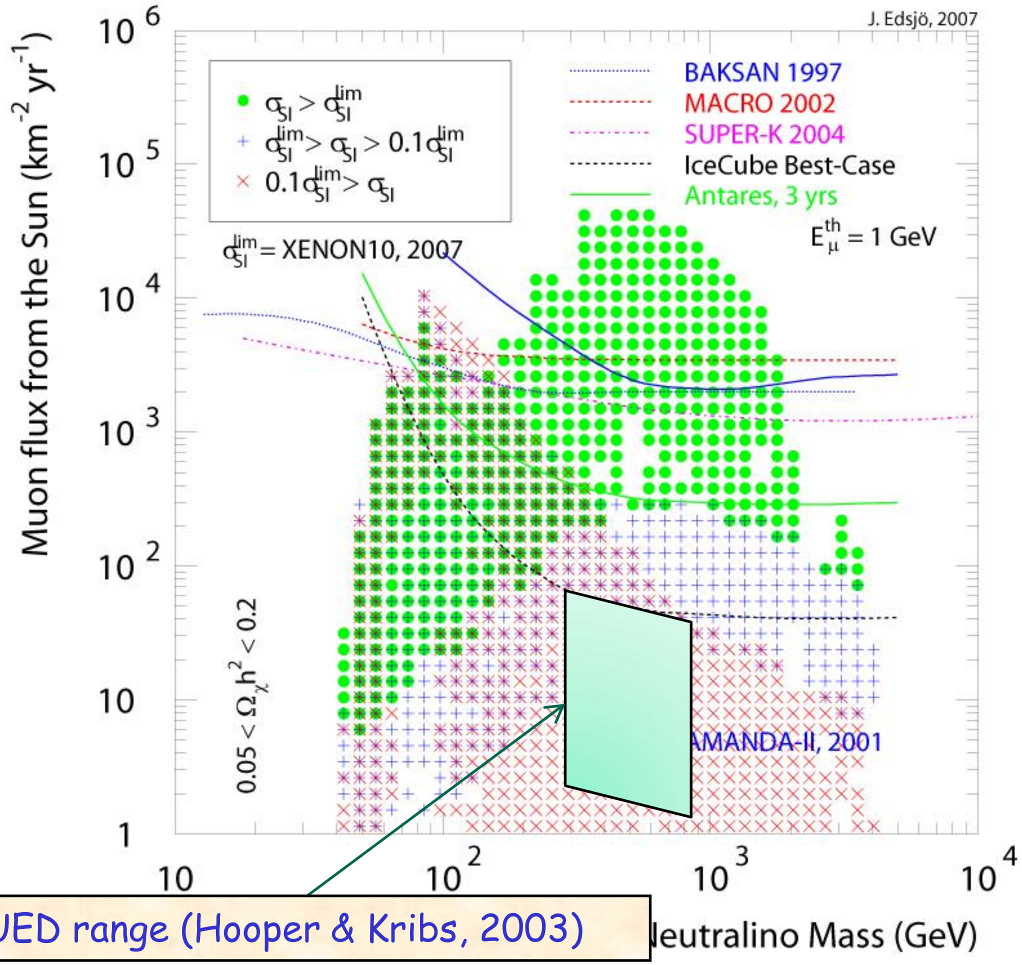




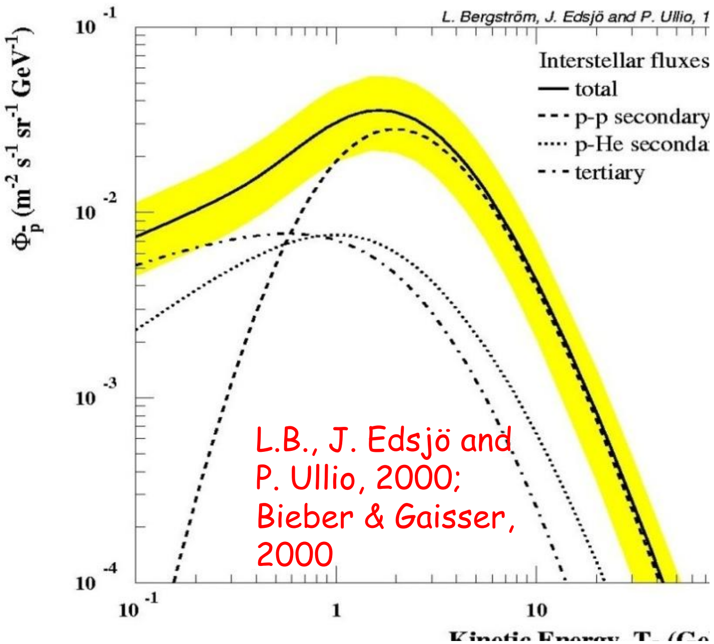
Other indirect detection method: Neutrinos from the Earth & Sun, MSSM

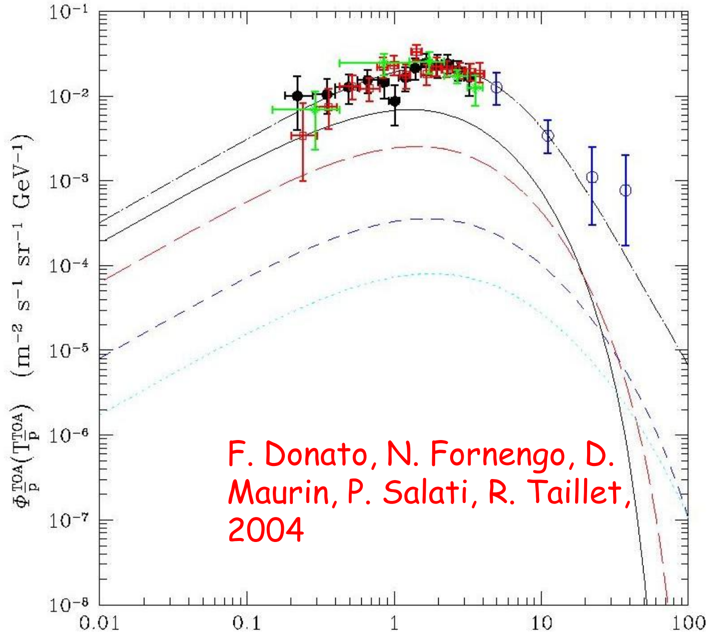
Rates computed by J. Edsjö with DarkSUSY

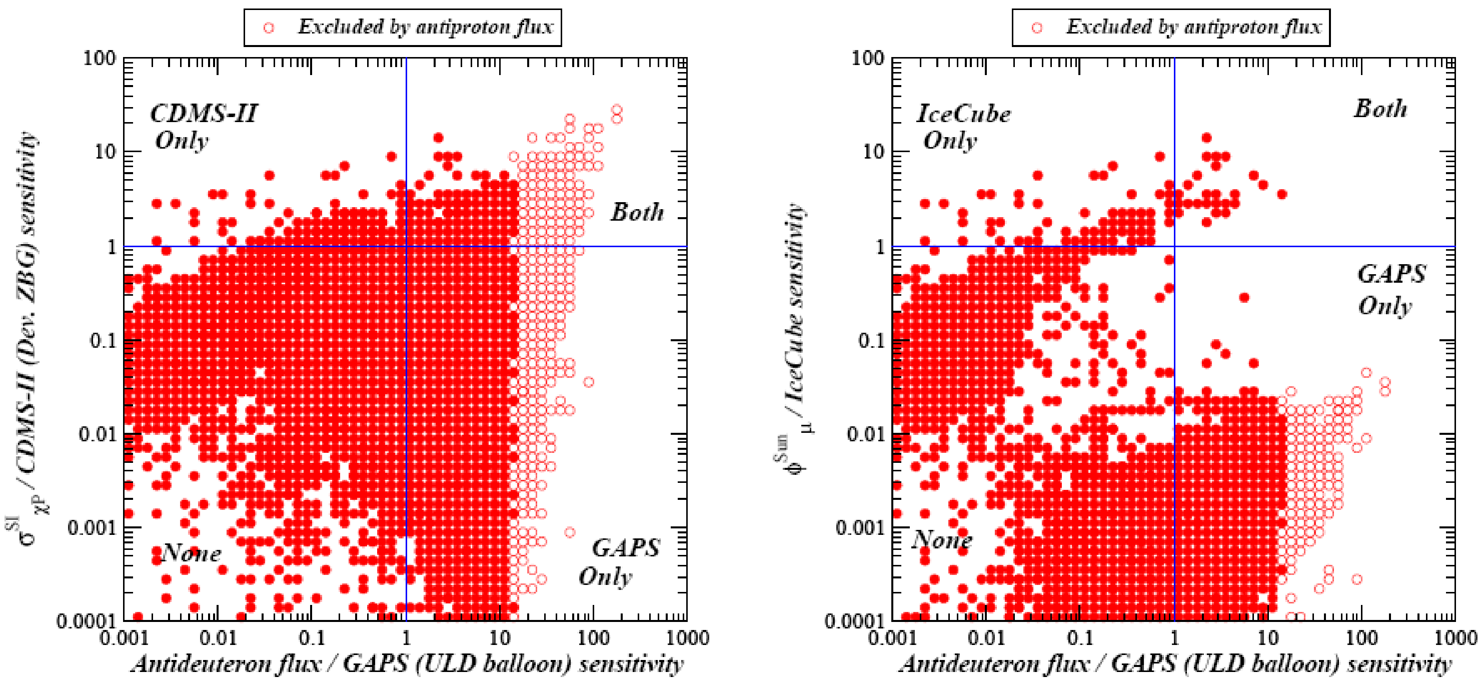




UED range (Hooper & Kribs, 2003)







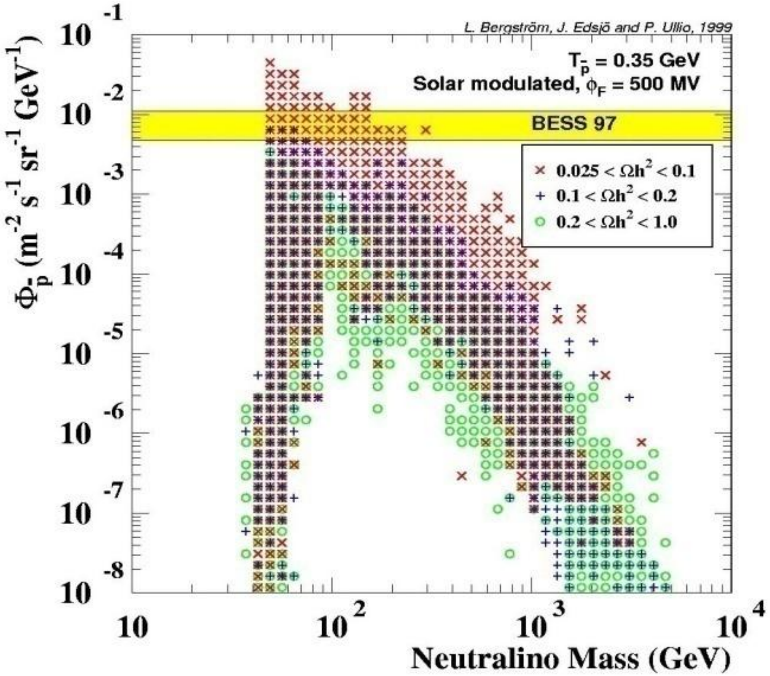
H. Baer & S. Profumo, 2005

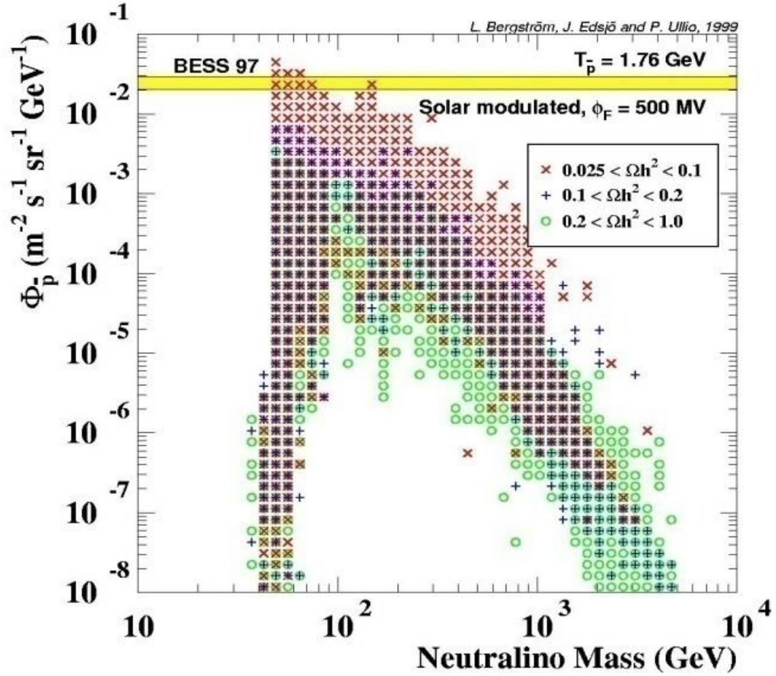
Antiprotons at low energy can not be produced in pp collisions in the galaxy, so that may be DM signal?

However, p-He reactions and energy losses due to scattering of antiprotons ⇒ low-energy gap is filled in. BESS data are compatible with conventional production by cosmic rays.

Antideuterons may be a better signal – but rare? (Donato et al., 2000; 2004.)

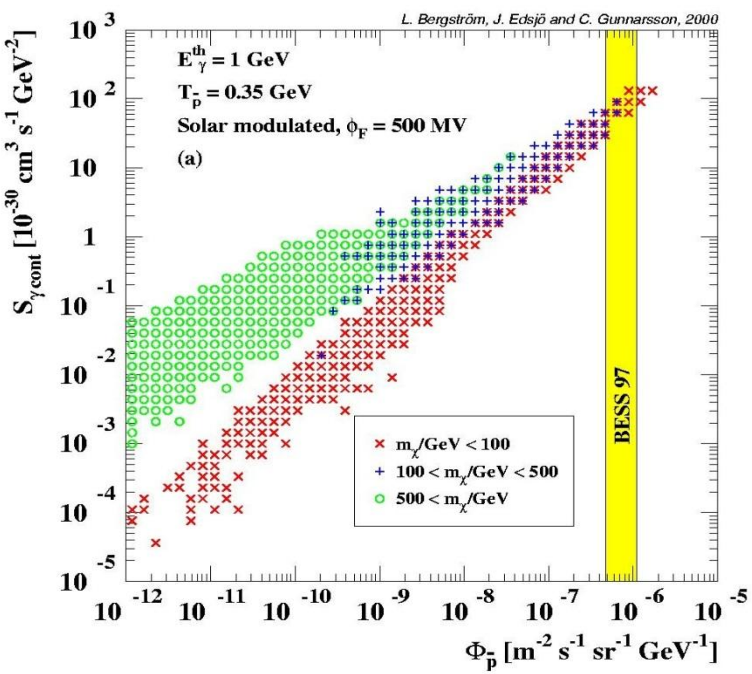
GAPS Ultra-long duration balloon experiment may test this (around 2013?).

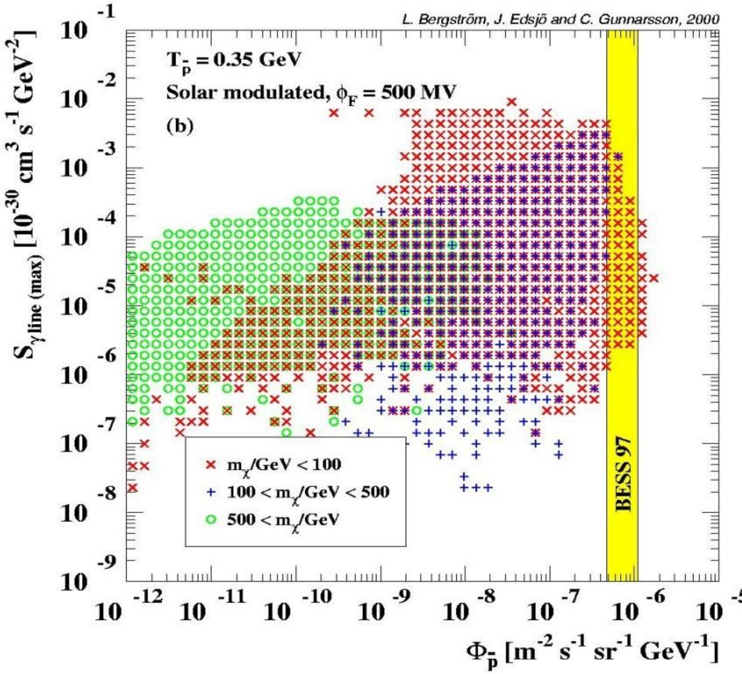




Existing data cuts into MSSM parameter space. PAMELA will soon have more data.

High mass KK & SUSY models may give high energy signal (Bringmann & Salati, 2007).





Antiprotons and continuum gamma rates are **strongly correlated** (through fragmentation of quark jets).

No strong correlation for gamma lines

"Miracles" in gamma-rays for heavy (> 1 TeV) neutralinos:

• Heavy MSSM neutralinos are almost pure higgsinos (in standard scenario) or pure winos (in AMSB & split SUSY models)

• Just for these cases, the gamma line signal is particularly large (L.B. & P.Ullio, 1998)

• In contrast to all other detection scenarios (accelerator, direct detection, positrons, antiprotons, neutrinos,..) the expected signal/background increases with mass ⇒ unique possibility, even if LHC finds nothing.

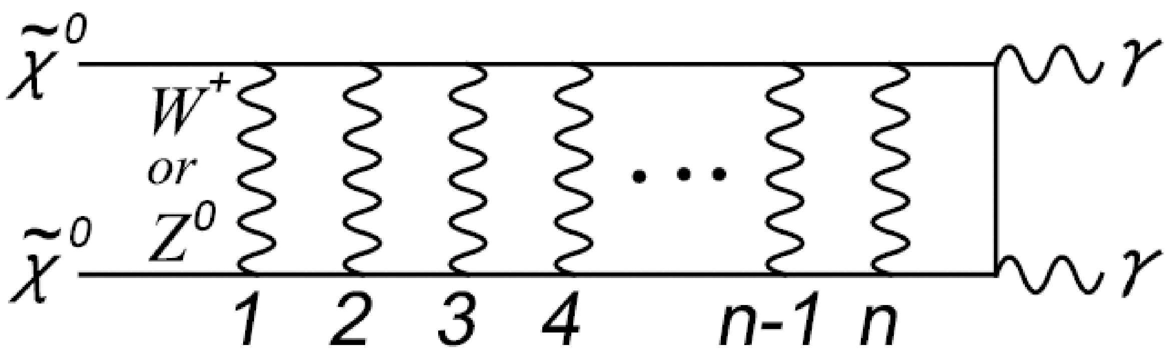
• Rates may be further enhanced by non-perturbative binding effects in the initial state (Hisano, Matsumoto & Nojiri, 2003)

• There are many large Air Cherenkov Telescopes (ACT) either being built or already operational (CANGAROO, HESS, MAGIC, VERITAS) that cover the interesting energy range, $1\ \text{TeV} \leq E_\gamma \leq 20\ \text{TeV}$.

•A new generation of ACT arrays is presently being planned: AGIS, HAWC, CTA

Interesting possibility for these high-mass WIMPs:
Hisano, Matsumoto and Nojiri, 2003; Hisano, Matsumoto, Nojiri and Saito, 2004

Wino



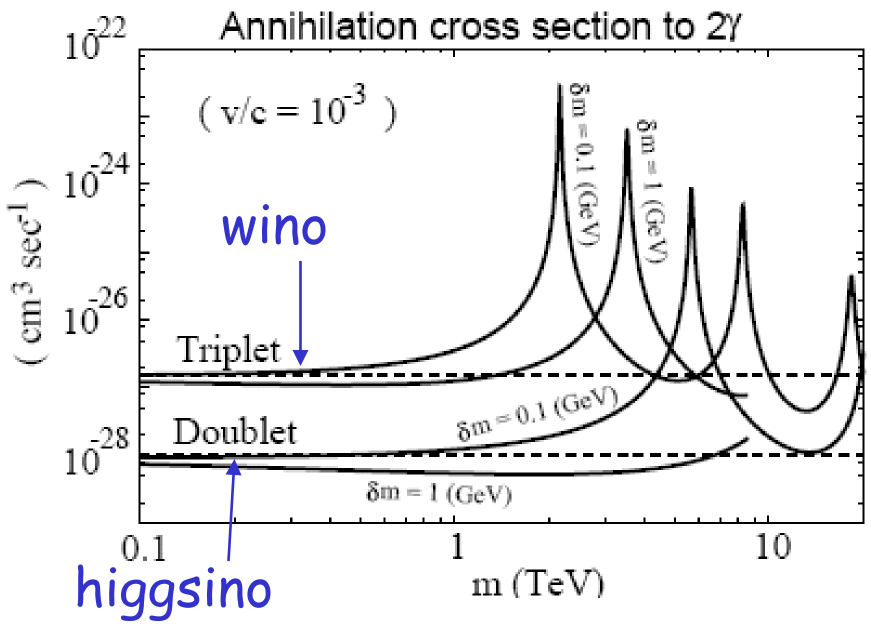
$$\mathcal{S}^{(II)} = \int d^4x d^3r \; \Phi^\dagger(x,\vec{r}) \left\{ \left(i\partial_{x^0} + \frac{\nabla_x^2}{4m} + \frac{\nabla_r^2}{m} \right) - \mathbf{V}(\vec{r}) + 2i\mathbf{\Gamma}\delta(\vec{r}) \right\} \Phi(x,\vec{r})$$

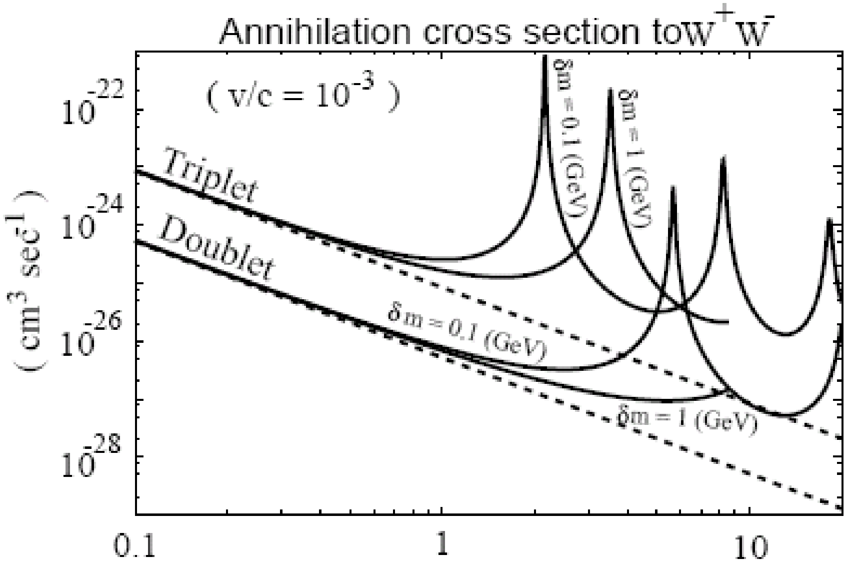
$$\mathbf{V}(r) = \begin{pmatrix} 2\delta m - \frac{\alpha}{r} - \alpha_2 c_W^2 \frac{e^{-m_Z r}}{r} & -\sqrt{2}\alpha_2 \frac{e^{-m_W r}}{r} \\ -\sqrt{2}\alpha_2 \frac{e^{-m_W r}}{r} & 0 \end{pmatrix}$$

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

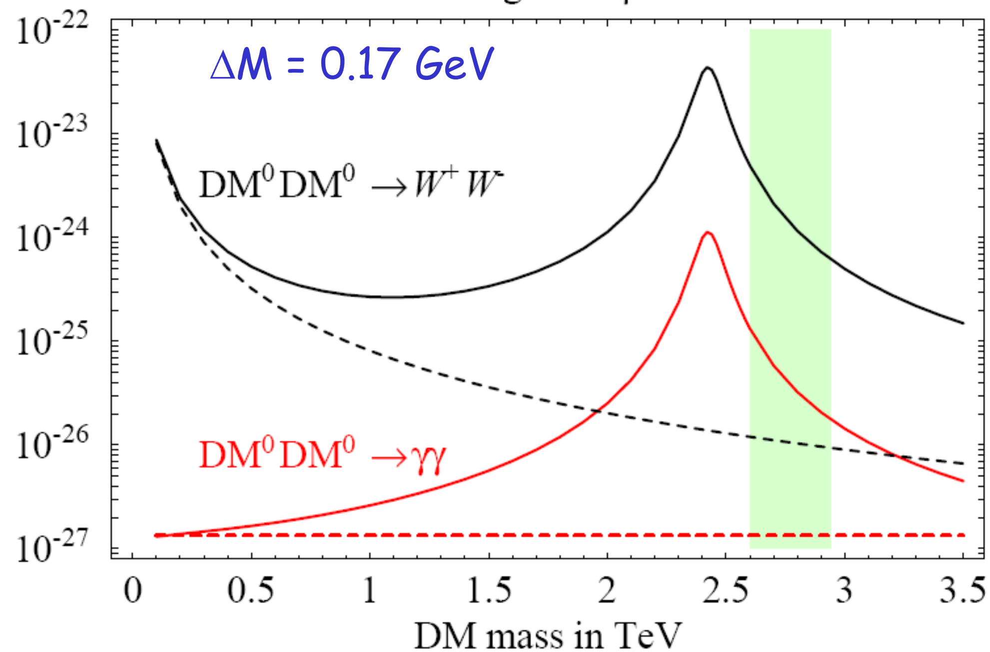
$$\mathbf{\Gamma}_{\gamma Z^0} = \frac{\pi\alpha\alpha_2}{m^2} \begin{pmatrix} 2c_W^2 & 0 \\ 0 & 0 \end{pmatrix}, \qquad \mathbf{\Gamma}_{\gamma\gamma} = \frac{\pi\alpha^2}{m^2} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}.$$

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





Indirect signal at $\beta = 10^{-3}$

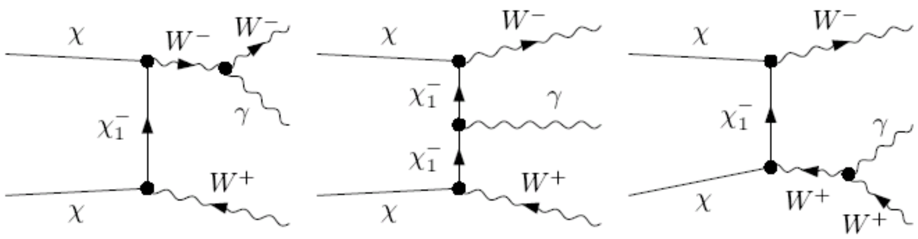


In MSSM without standard GUT condition (AMSB; split SUSY) m_{wino} ~ 2 – 3 TeV; δm ~ 0.2 GeV. Factor of 100 – 1000 enhancement of annihilation rate possible. B.R. to $\gamma\gamma$ and $Z\gamma$ is of order 0.2 – 0.8!

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

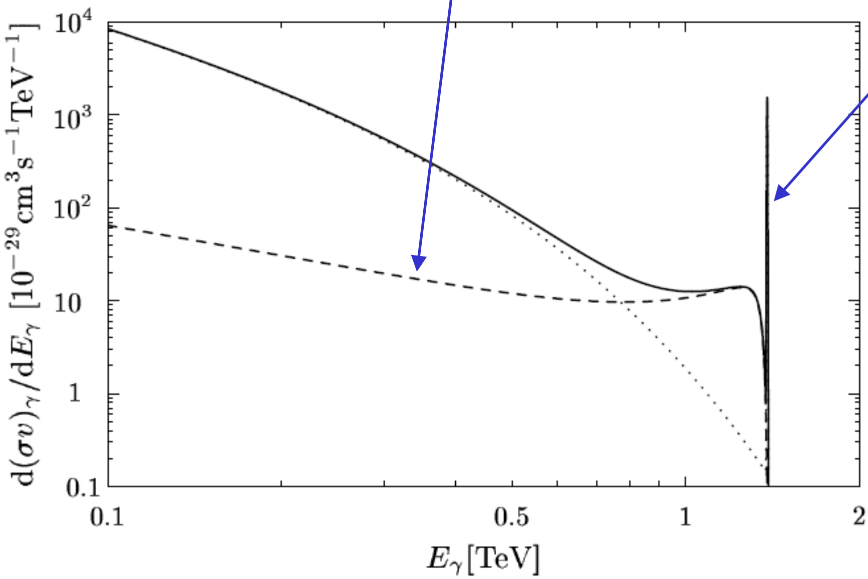
M. Cirelli, A. Strumia & M. Tamburini, 2007

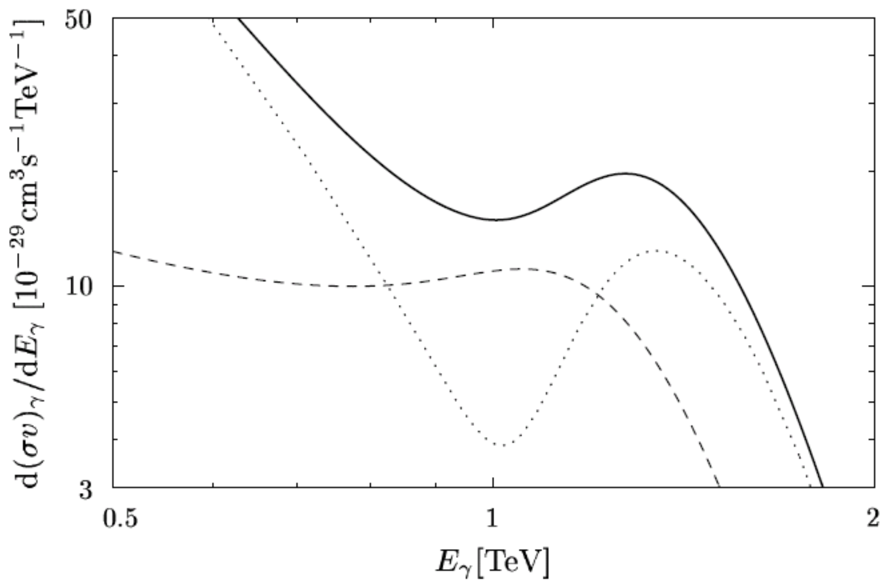
For higher energies than the GLAST limit, 300 GeV, Air Cherenkov Telescopes become advantageous. Example: 1.4 TeV higgsino with WMAP relic density, like in split SUSY (L.B., T.Bringmann, M.Eriksson and M.Gustafsson, PRL 2005)



New contribution (internal bremsstrahlung)

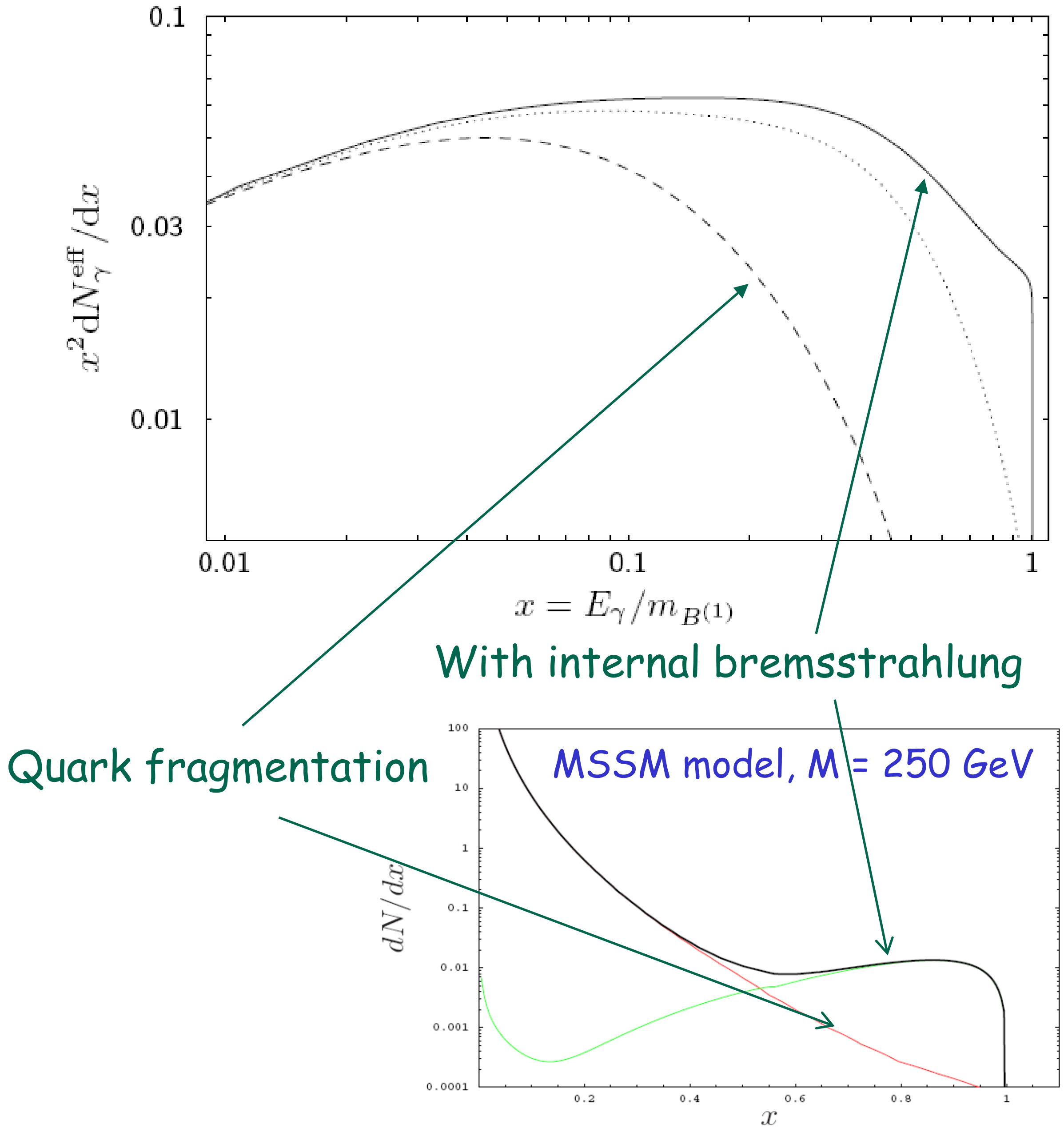
Intrinsic line width $\Delta E/E \sim 10^{-3}$





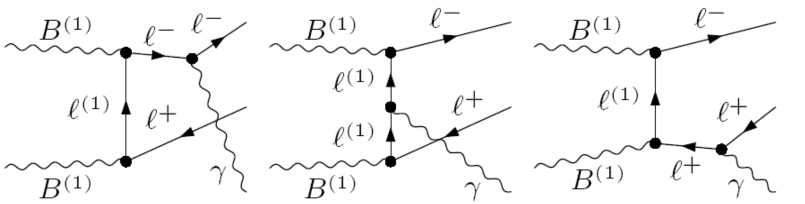
Gamma-ray spectrum seen by an ideal detector

Same spectrum seen with 15% energy resolution (typical of ACT)



Cf. Kaluza-Klein models

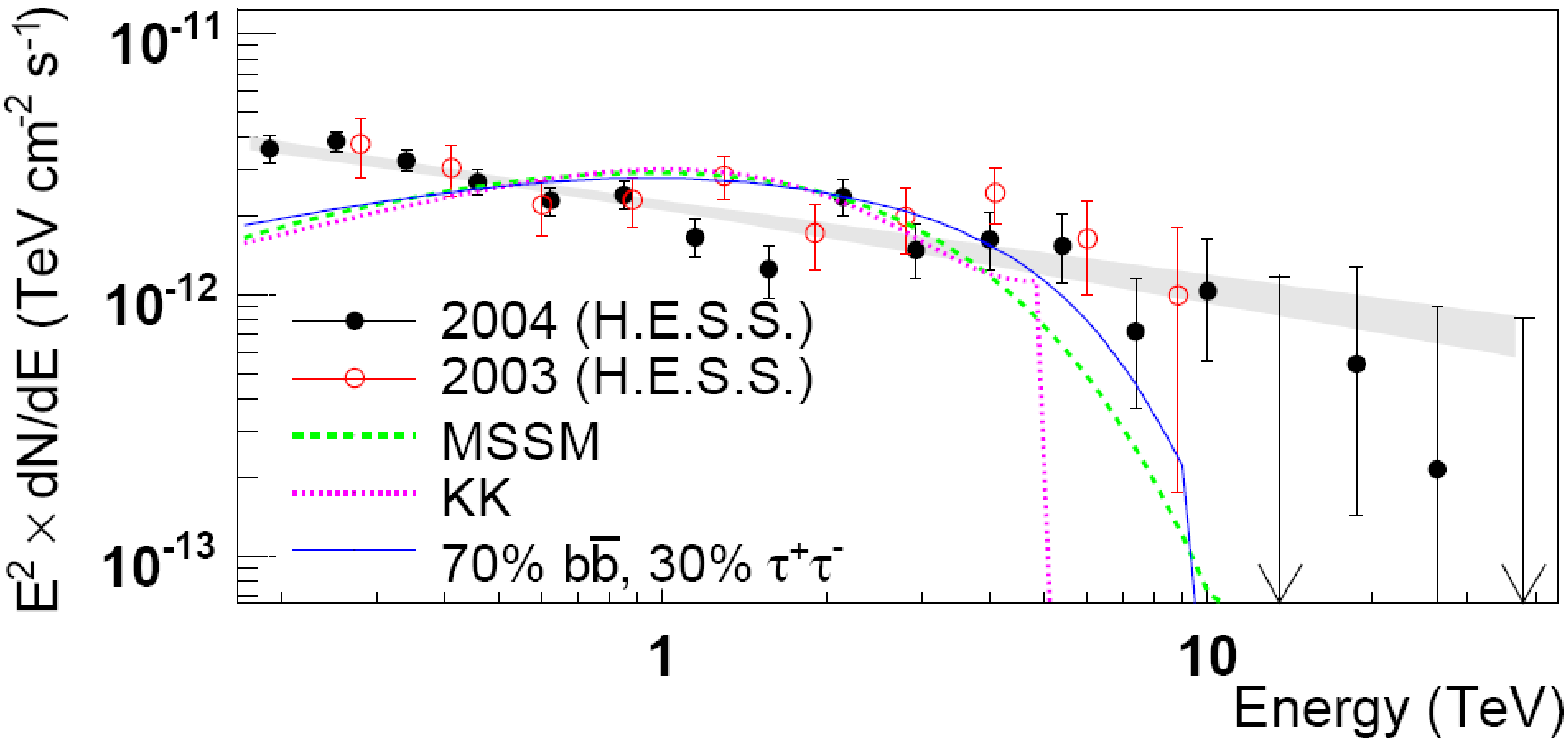
L.B., T. Bringmann, M.Eriksson & M. Gustafsson, PRL 2005



For supersymmetry, these processes will be included in the next release of DarkSUSY

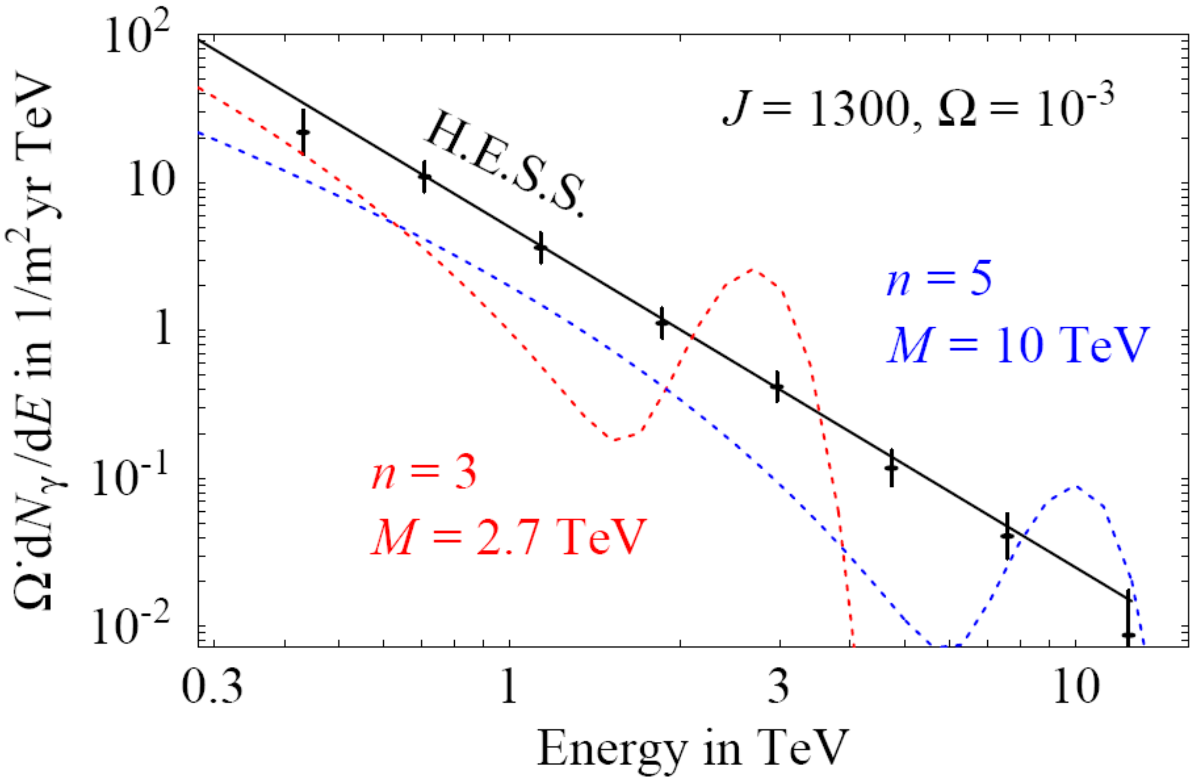
(T. Bringmann, L.B., J. Edsjö, in prep., 2007)

2006: H.E.S.S. data towards galactic centre



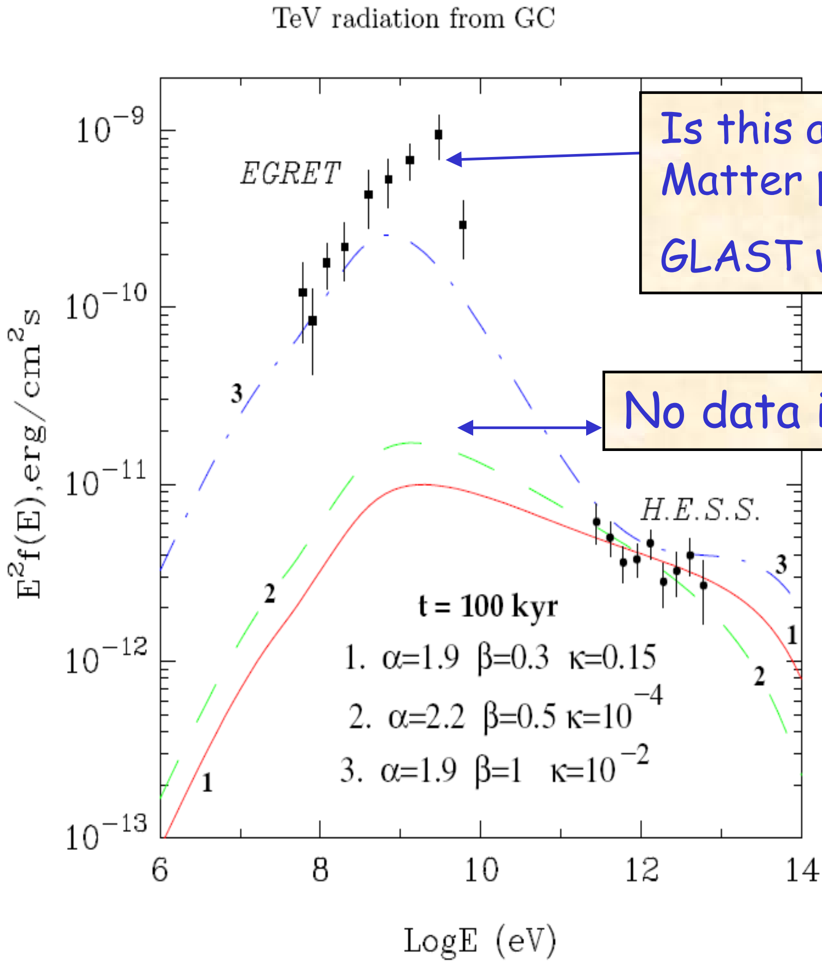
MAGIC (2006) data agree completely with HESS

Steady (time-independent) spectrum, consistent with extended source like NFW cusp! But: Too high energy (and wrong shape of spectrum) for WIMP explanation



M. Cirelli, A. Strumia & M. Tamburini, 2007

Striking gamma-line signature possible for ACT arrays. G.C. probably not optimal because of power law background process. Dwarf galaxies may be more suitable?



Is this a Dark Matter peak?

GLAST will tell...

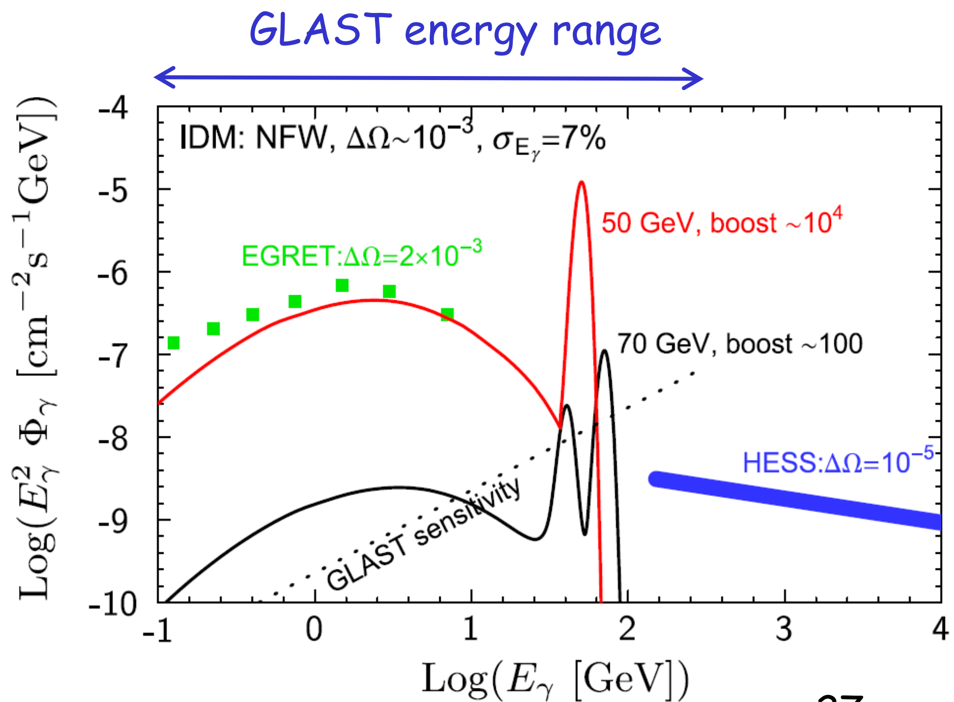
No data in this region!

"Conventional explanation", Aharonov & Neronov, 2005

Prediction: variability on 1-hour timescale

GLAST will fill in data between EGRET and HESS

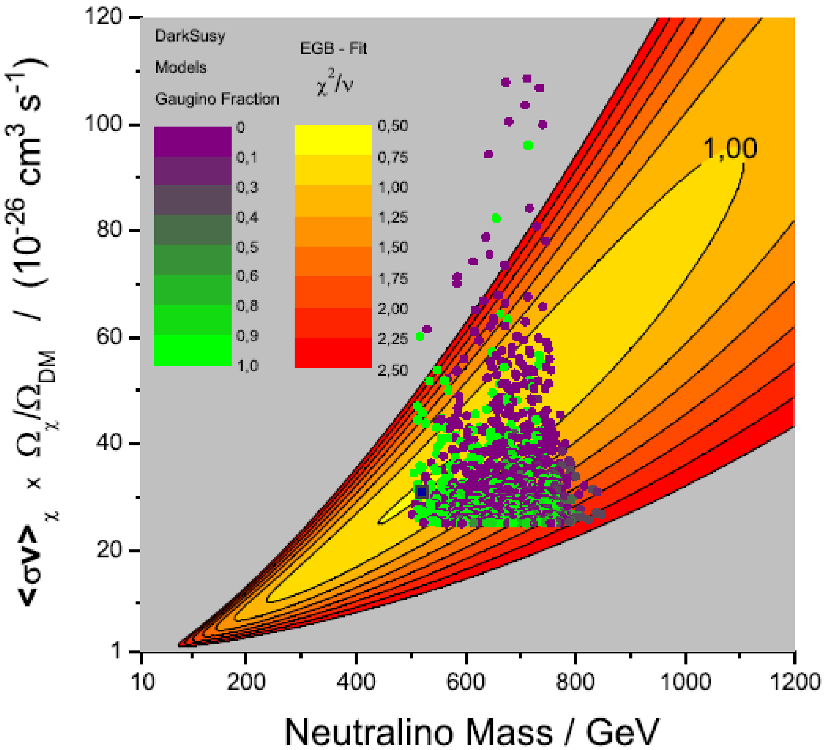
Remember:

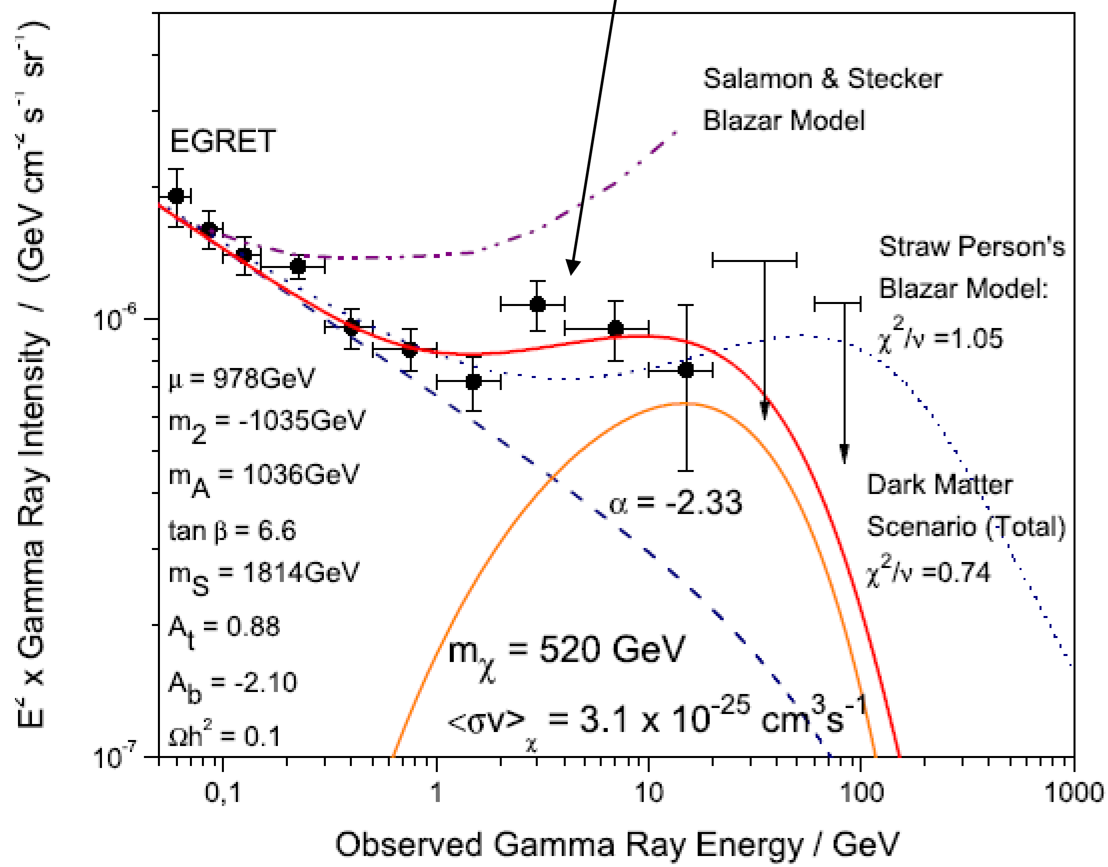


M. Gustafsson , L.B., J. Edsjö, E. Lundström, PRL, July 27, 2007

Could the diffuse extragalactic gamma-ray background have a contribution from neutralino annihilations (L.B., J. Edsjö & P. Ullio, 2001; J. Taylor & J. Silk, 2002)?

GeV "bump"? (Moskalenko, Strong, Reimer, 2004)





Rates computed with DarkSUSY

Steep (Moore) profile needed for DM substructure; some fine-tuning to get high annihilation rate

Elsässer & Mannheim, Phys. Rev. Lett. 94:171302, 2005

Energy range is optimal for GLAST!

The Likely Cause of the EGRET GeV Anomaly and its Implications

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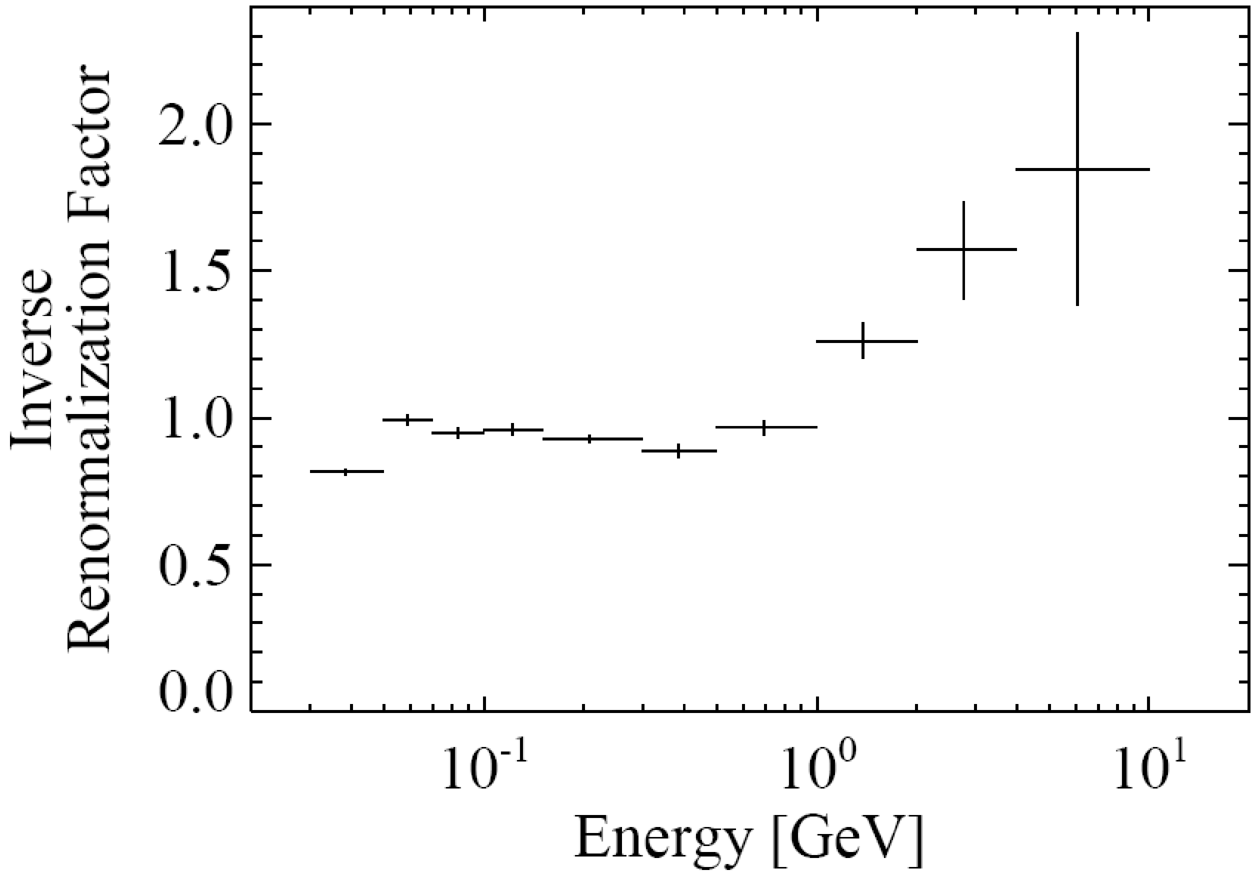
NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

D. A. Kniffen‡
NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA and University Space Research Association, Columbia, MD 21044, USA
(Dated: May 29, 2007)

arXiv:0705.4311

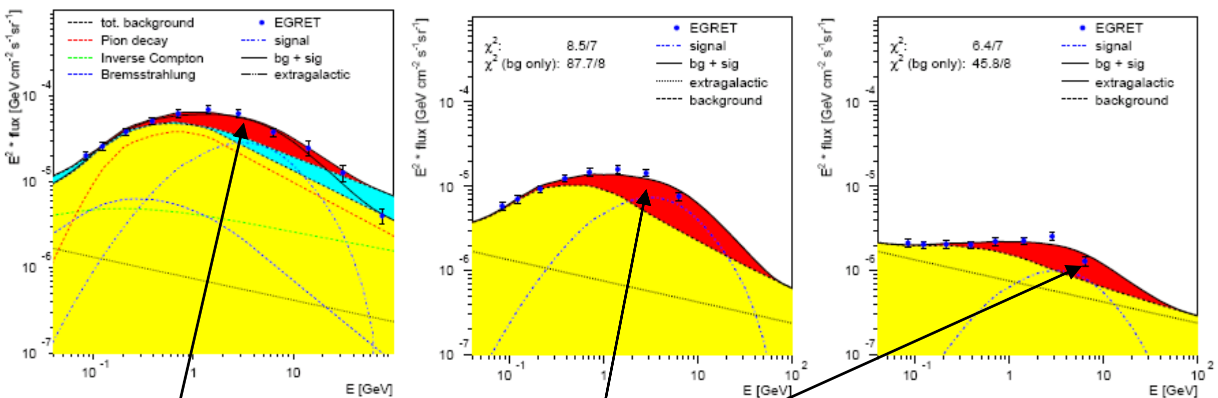


Problem with EGRET normalization: Isotropic excess above 1 GeV

Instrumental effect? Still with unknown cause…

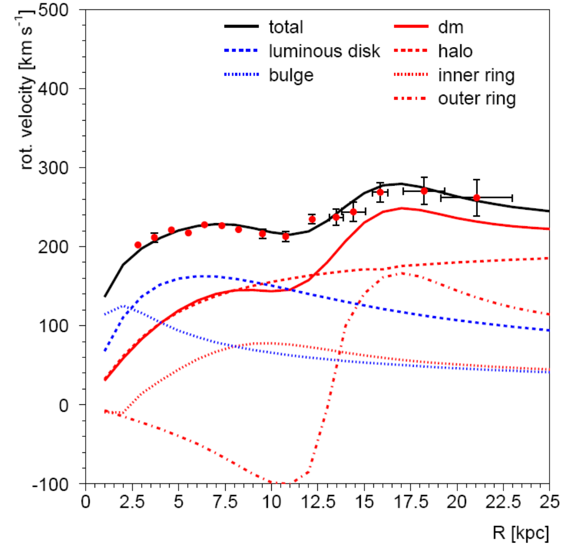
Has supersymmetric dark matter already been detected?

W. de Boer, 2003-2007



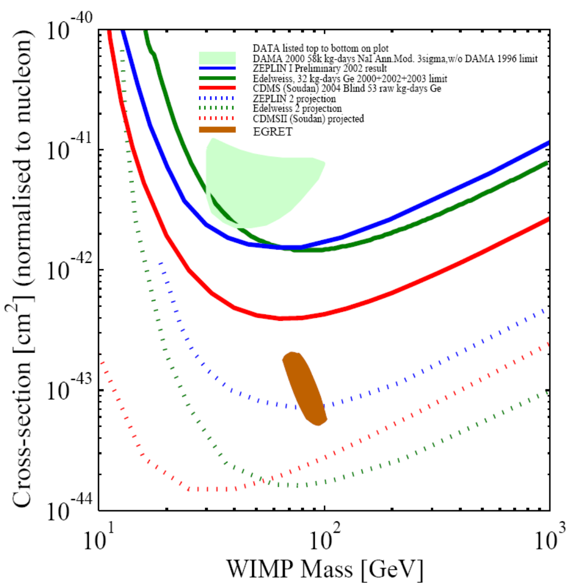
Excess of gamma-rays

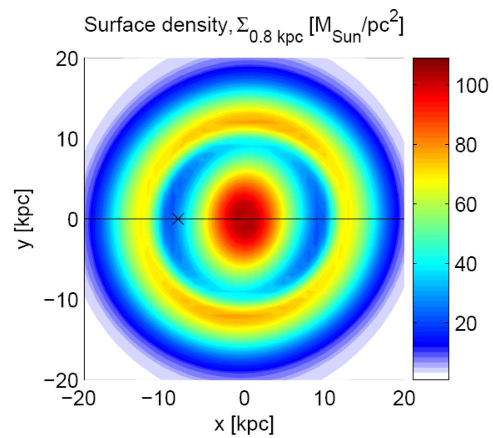
Filled by 65 GeV neutralino annihilation

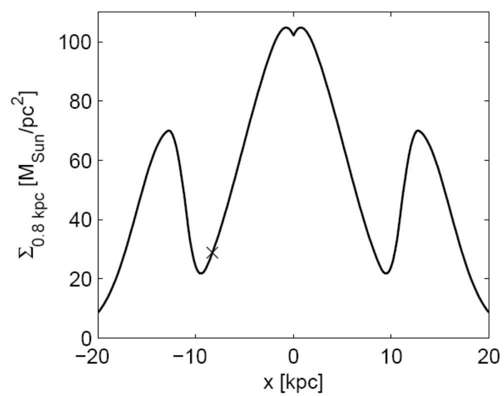


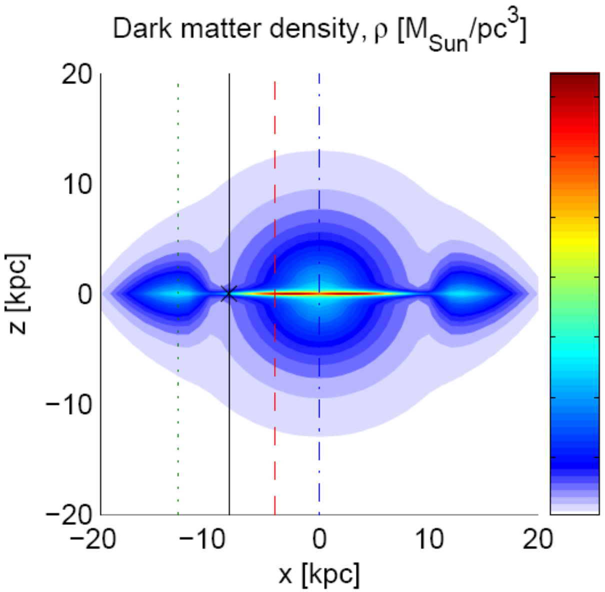
Galactic rotation curve

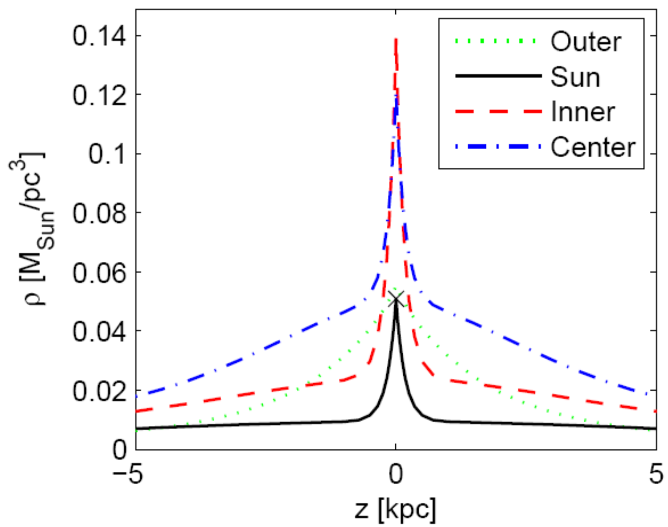
Data explained by 50-100 GeV neutralino?



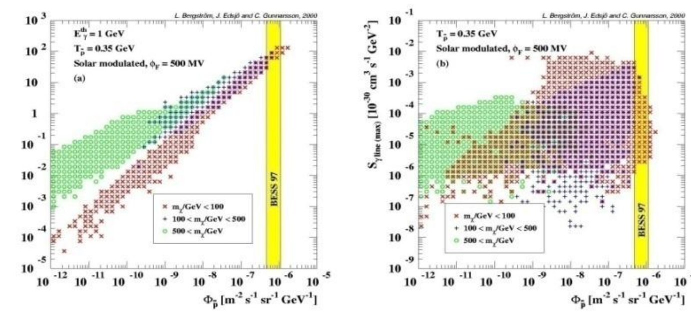








L.B., J. Edsjö, M. Gustafsson & P. Salati, 2006

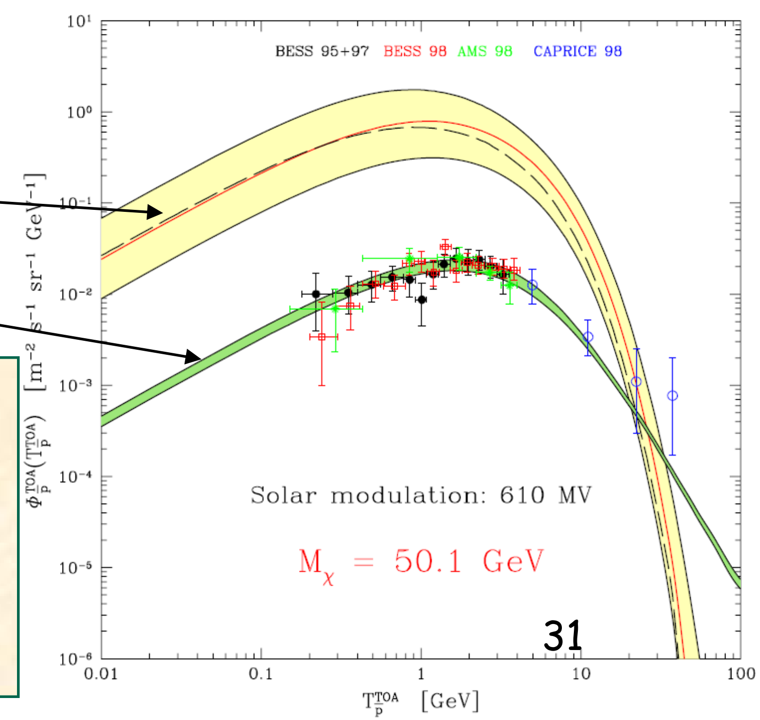


DM density concentrated to the galactic plane. This is not what one expects from CDM!

Antiprotons pose a major problem for this type of model:

Expected antiproton flux from de Boer's supersymmetric models

Standard (secondary) production from cosmic rays



De Boer: Maybe diffusion is anisotropic, so that antiprotons are ejected from the galaxy?

This seems to conflict with distribution of ordinary cosmic rays (protons) and gammas (I. Moskalenko, private commun.)

Comments on de Boer's model

There is definitely a "GeV excess" seen in the EGRET data. Can be due to one or more of the following (in order of probability, in my view):

1. Instrumental problem with EGRET

2. Too simple conventional model for galactic gamma-ray emission

3. Existence of a contribution from dark matter

Wait for GLAST!

Conclusions

- The various indirect and direct detection methods are complementary to each other and to LHC. Antiprotons and continuous gammas are strongly correlated. Positrons are more dependent on local enhancements and propagation effects.
- New indirect detection experiments will reach deep into theory parameter space, some not reachable at LHC.
- Indications of gamma-ray excess from Galactic Center and the extragalactic diffuse gamma-rays. However, need more definitive spectral signature – the gamma line or the step at $E_\gamma = M_\chi$ caused by internal bremsstrahlung would be a "smoking gun".
- GLAST opens a new window: Will search for "hot spots" in the sky with high sensitivity up to 300 GeV. For higher energies, new Air Cherenkov Telescope Arrays may have unique possibilites for detection of dark matter annihilation.
- PAMELA, AMS ans GAPS will give new precision measurements of e^+, antiprotons and antideuterons.
- The dark matter problem may be near its solution…