Indirect Detection of Dark Matter

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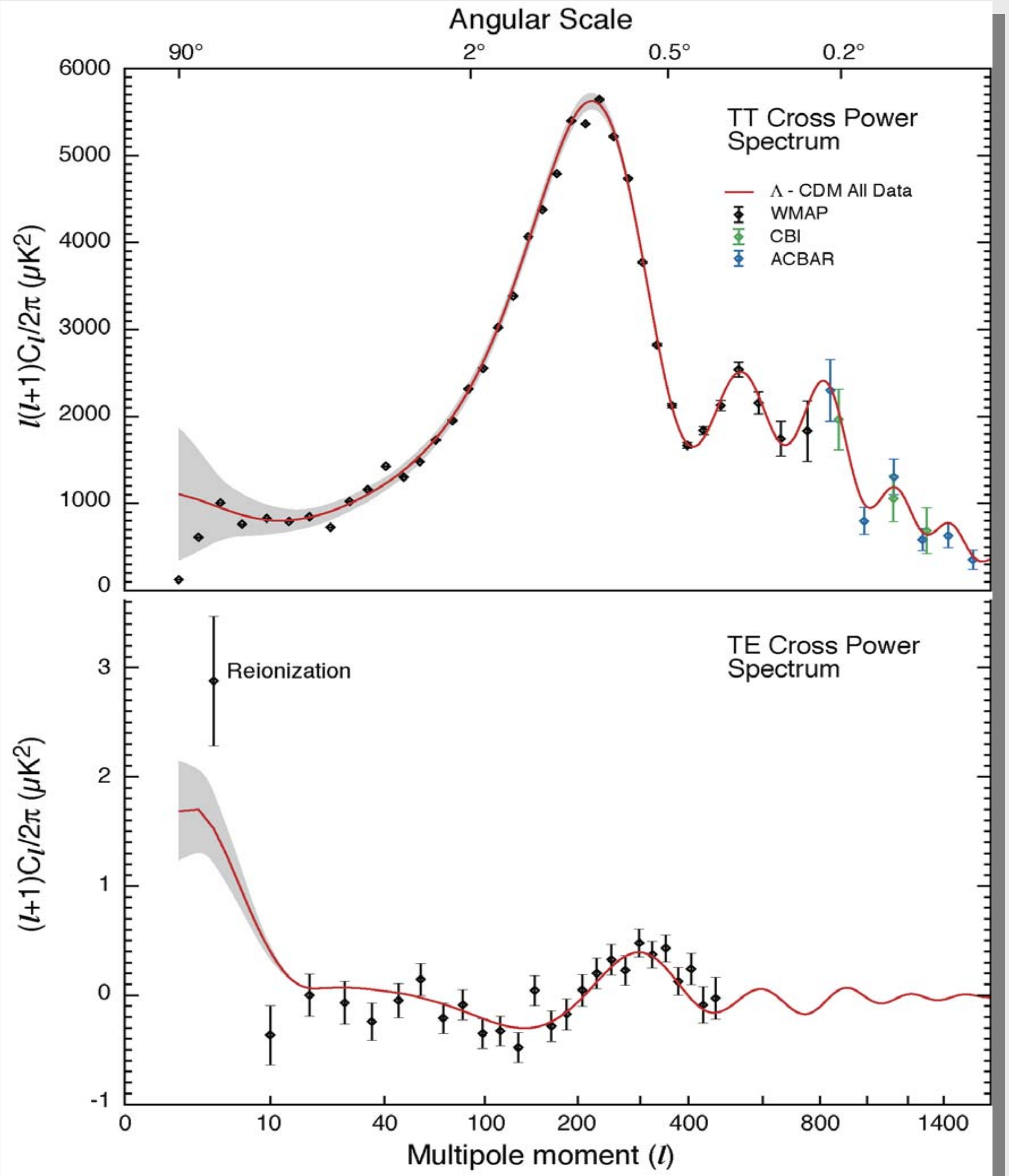
Hamburg, October 1, 2004



Result from best-fit model for WMAP (for flat Universe):

- **Only 4.4 % baryonic matter, $\Omega_b h^2 = 0.024 \pm 0.0009$**
- **Around 23 % Cold Dark matter, $\Omega_{CDM} h^2 = 0.11 \pm 0.01$**
- **Around 73 % ”Dark energy”, $\Omega_\Lambda = 0.73 \pm 0.04$**
- **Age of Universe: 13.7±0.2 Gyr**
- **$\Omega_\nu h^2 < 0.0076$**

<u>Good</u> particle physics candidates for Cold Dark Matter:

Independent motivation from particle physics; detectable by other means than through gravity only

- **Axions** (introduced to solve strong CP problem)
- Weakly Interacting Massive Particles (**WIMPs**, 3 GeV < m_X < 50 TeV), thermal relics from Big Bang: **Supersymmetric neutralino**
  Axino, gravitino
  Kaluza-Klein states
  Heavy neutrino-like particles
  Mirror particles
  "Little Higgs"
  plus hundreds more in literature…
- Non-thermal (maybe superheavy) relics: wimpzillas, cryptons, …

"The WIMP miracle": for typical gauge couplings and masses of order the electroweak scale, $\Omega_{wimp}h^2 \approx 0.1$ (within factor of 10 or so)

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”

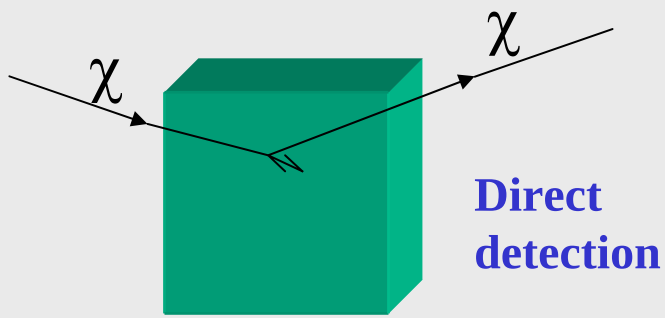
Can be freely dowloaded from

http://www.physto.se/~edsjo/ds

New release 2004:
includes coannihilations
& interface to Isasugra

Methods of WIMP Dark Matter detection:

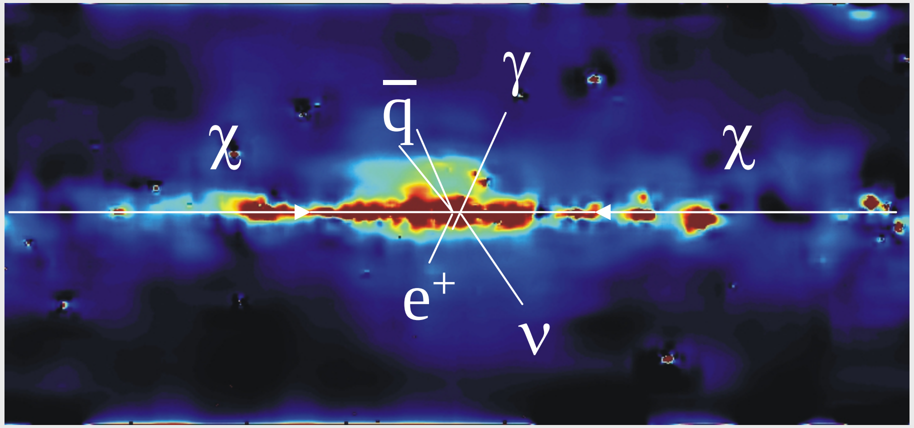
- **Discovery at accelerators (Fermilab, LHC,..)**
- **Direct detection of halo particles in terrestrial detectors**
- **Indirect detection of neutrinos, gamma rays, radio waves, antiprotons, positrons in earth- or space-based experiments**



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

The basic process for indirect detection is annihilation, e.g, neutralinos:

Neutralinos are Majorana particles

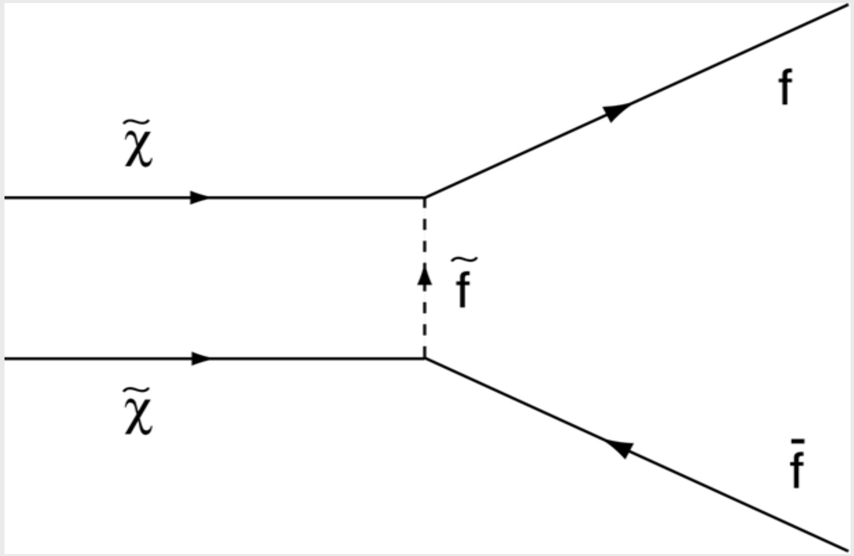


Indirect detection

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

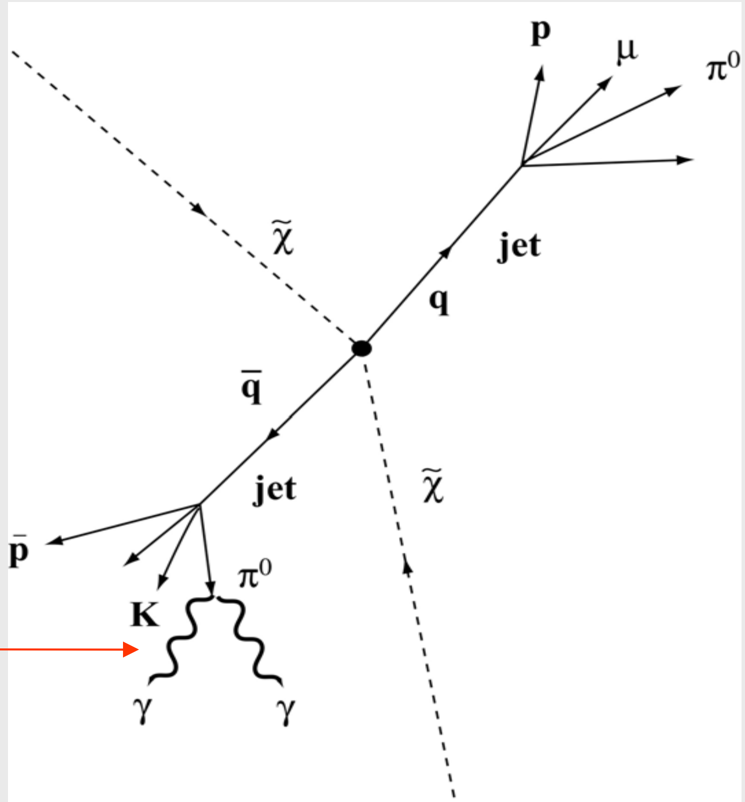
Enhanced for clumpy halo; near galactic centre and in Sun & Earth

Indirect detection: annihilation of neutralinos



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



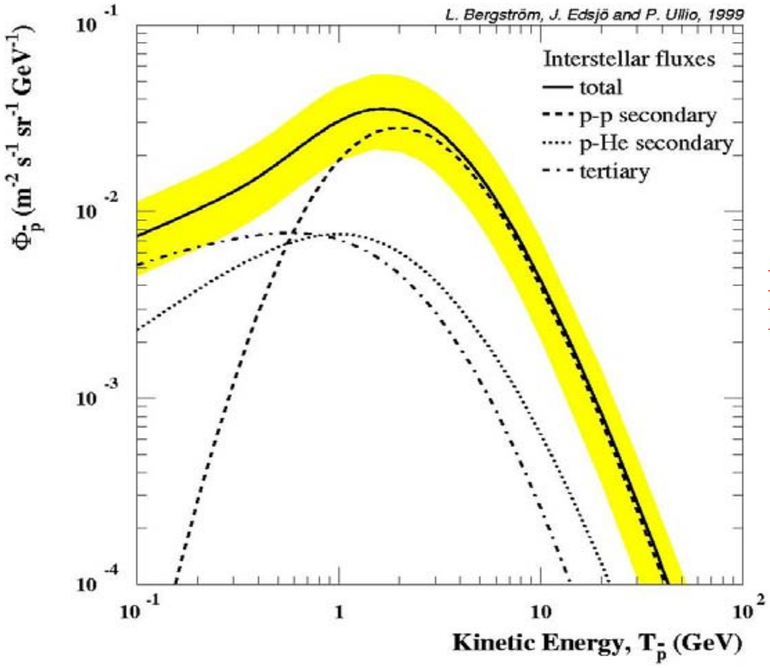
Decays from neutral pions: Dominant source of continuum gammas in halo annihilations

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

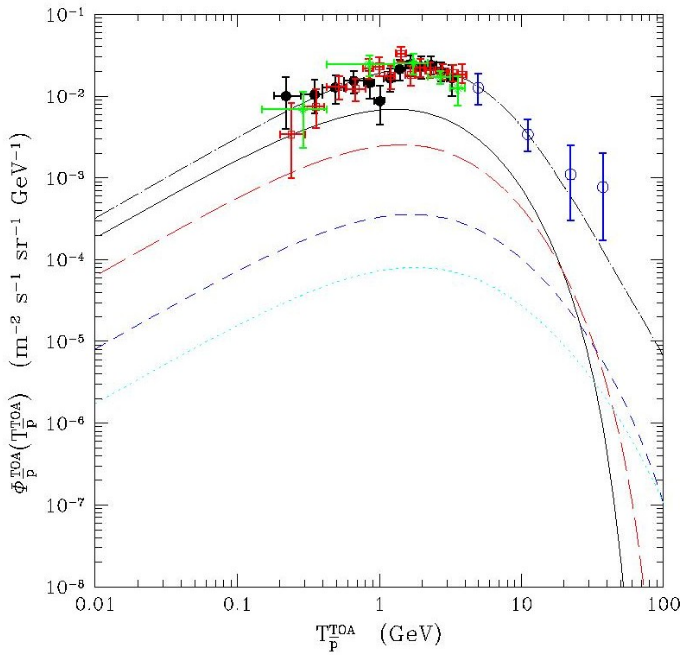
However, conventional models of secondary production by cosmic rays work well.

Antideuterons maybe better signal – but rare? (Donato et al., 2000)

Antiprotons still a good check of models – boosting halo densities may lead to overproduction of antiprotons (ex: light neutralinos, A. Bottino & al., 2004)



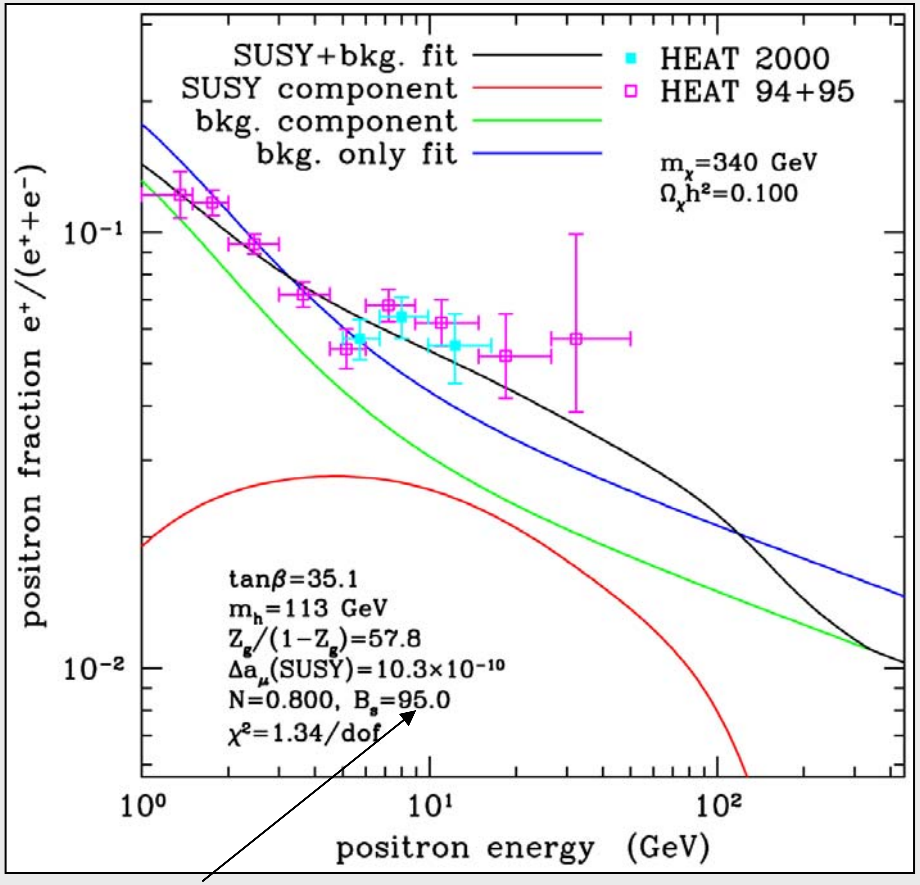
L.B., J. Edsjö and P. Ullio, 2000
Bieber & Gaisser, 2000

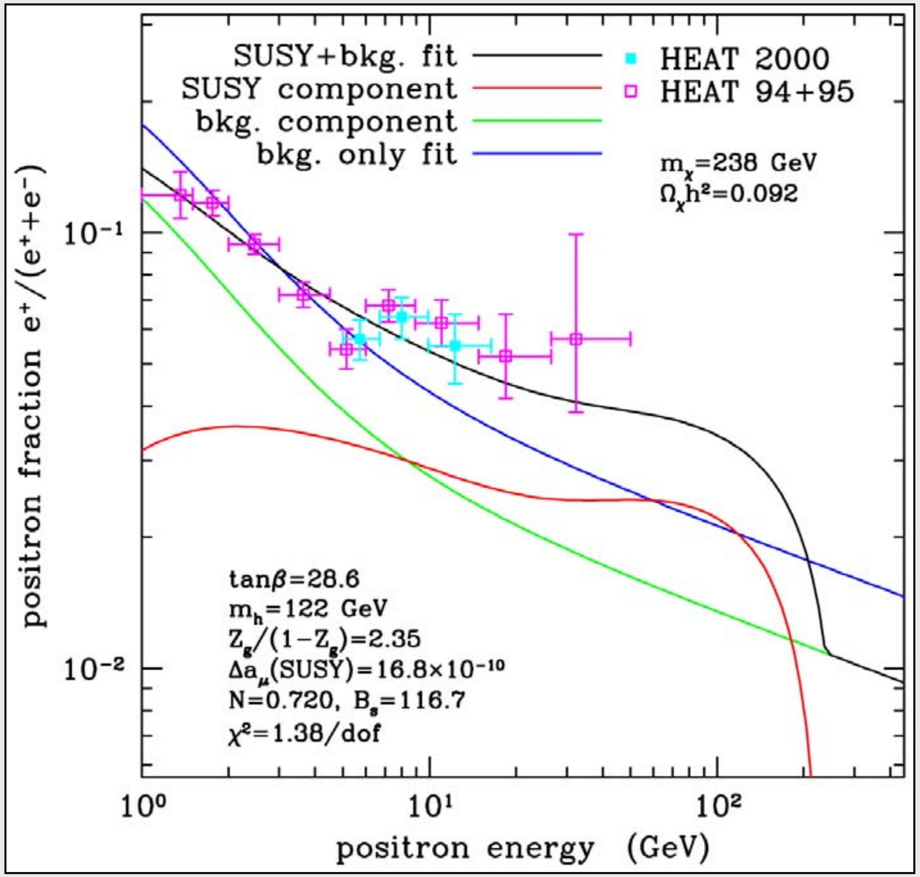


F. Donato et al., 2003

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

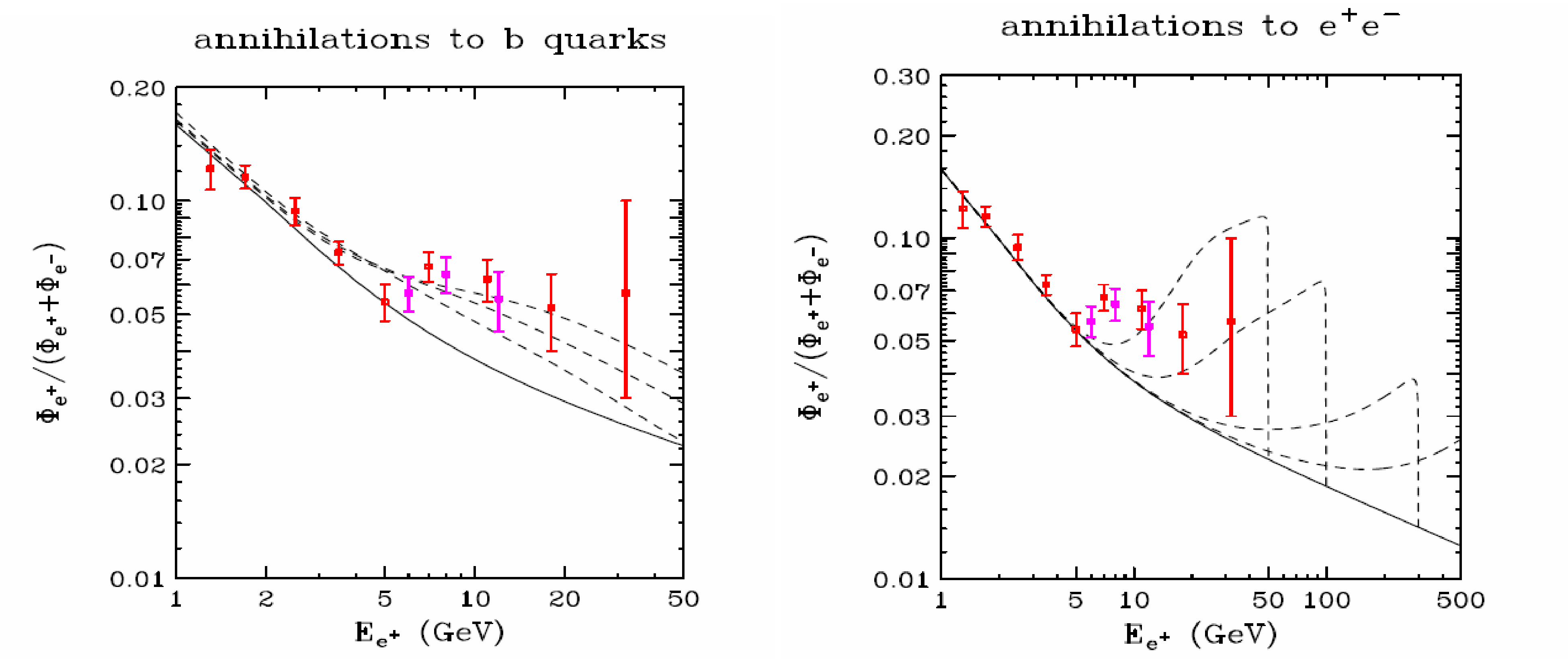
New experiments will come: Pamela (2005) and AMS (2007?)





Need high ”boost factor”

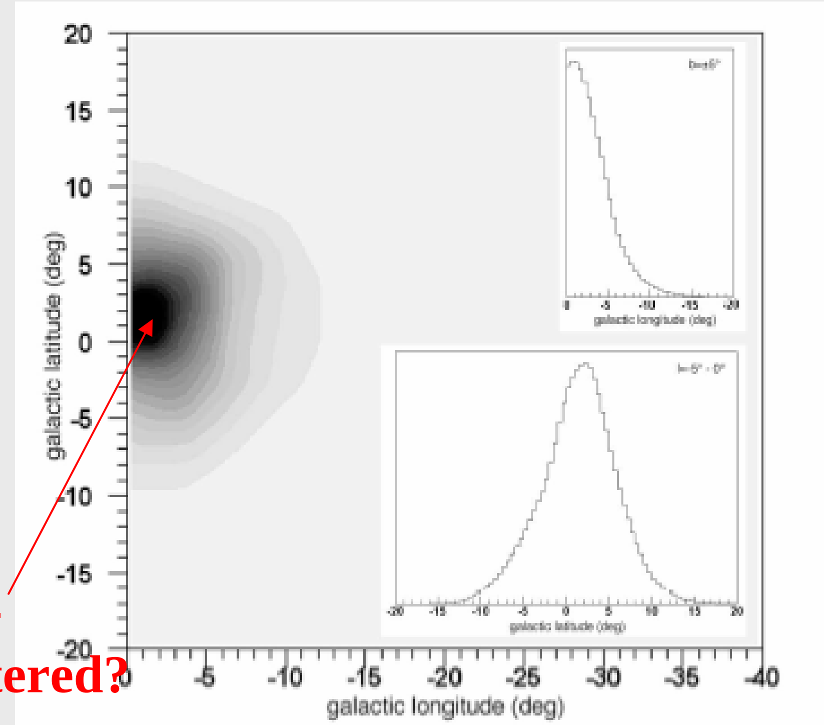
Baltz, Edsjö, Freese, Gondolo 2002; Kane, Wang & Wells, 2002; Hooper & Kribs, 2004; Hooper & Silk, 2004



D. Hooper & J. Silk, hep-ph/0409104

Boehm, Hooper, Silk, Casse, Paul (2003):

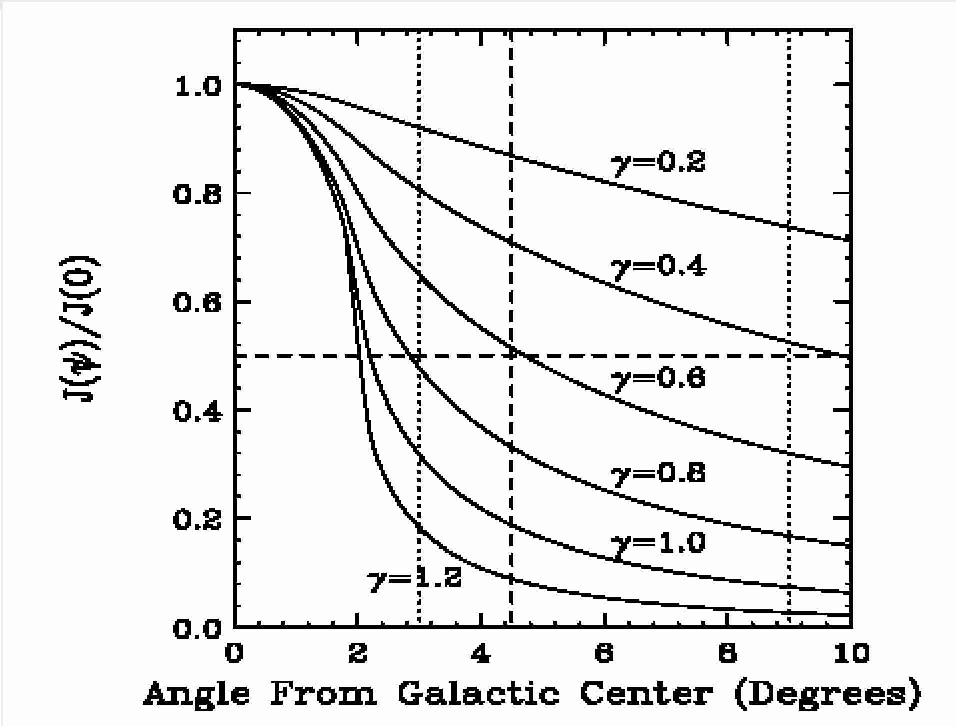
Galactic positrons (511 keV line) from low mass (10 – 100 MeV) dark matter particle annihilation?



Off-centered?

Fig. 2. 511 keV gamma-ray line intensity map of the galactic centre region (only negative longitudes). Black corresponds to regions of maximum 511 keV line intensity. Longitude and latitude profiles, integrated over $b = \pm 5^\circ$ and $l = -5^\circ - 0^\circ$, respectively, are shown as insets.

INTEGRAL satellite measurements



Problem: How does one find a reasonable particle physics candidate with low mass and strong couplings to electrons??

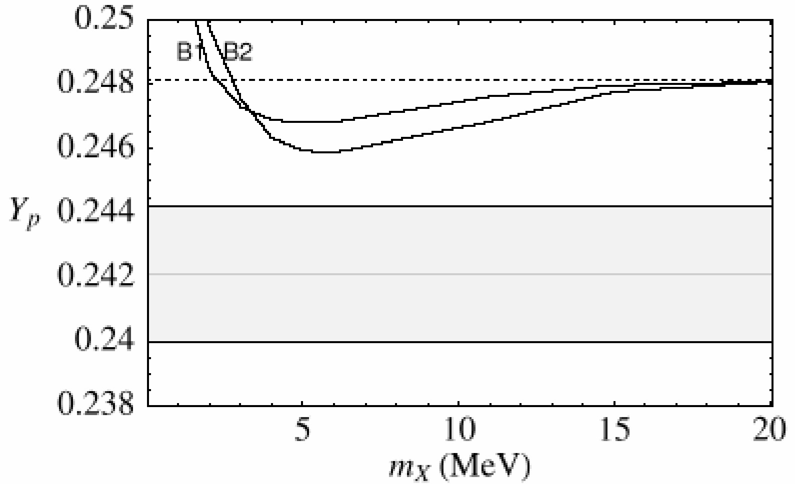
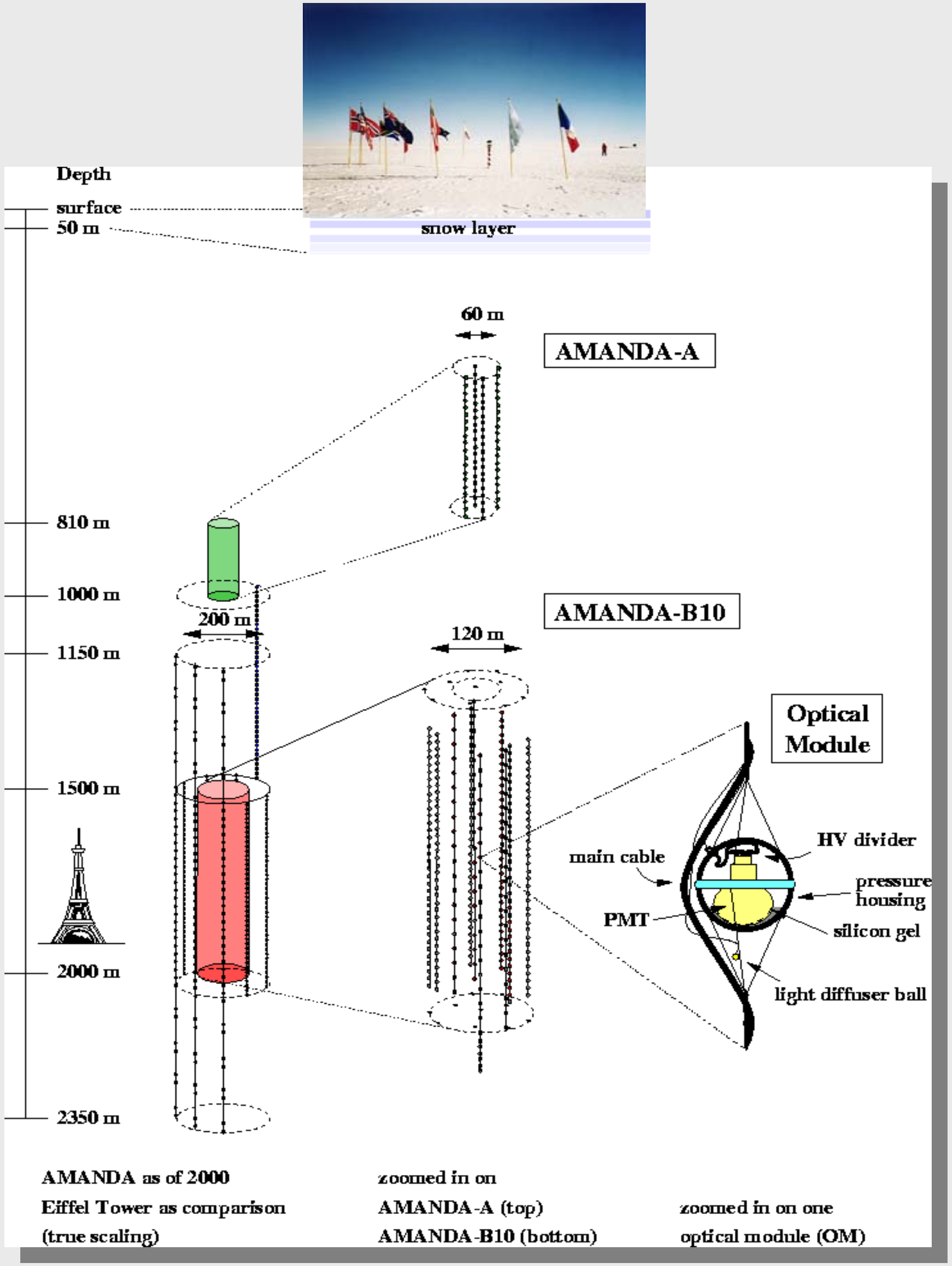


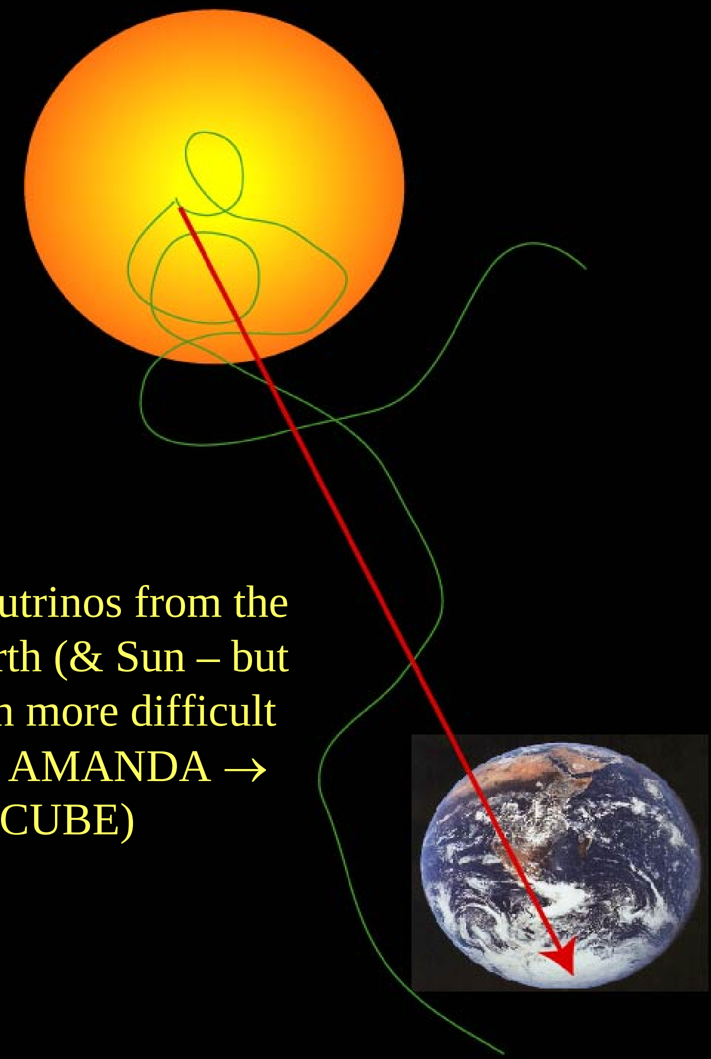
FIG. 3: ^{4}He abundance as in Fig. 2, here on a linear scale for m_X. The horizontal dotted line indicates the standard prediction for $N_{\rm eff} = 3$. The gray band is the 1σ observational range for Y_p according to Ref. [19].

P. Serpico and G. Raffelt, astro-ph/0403417

Light (5 – 15 MeV) dark matter actually improves agreement with BBN!

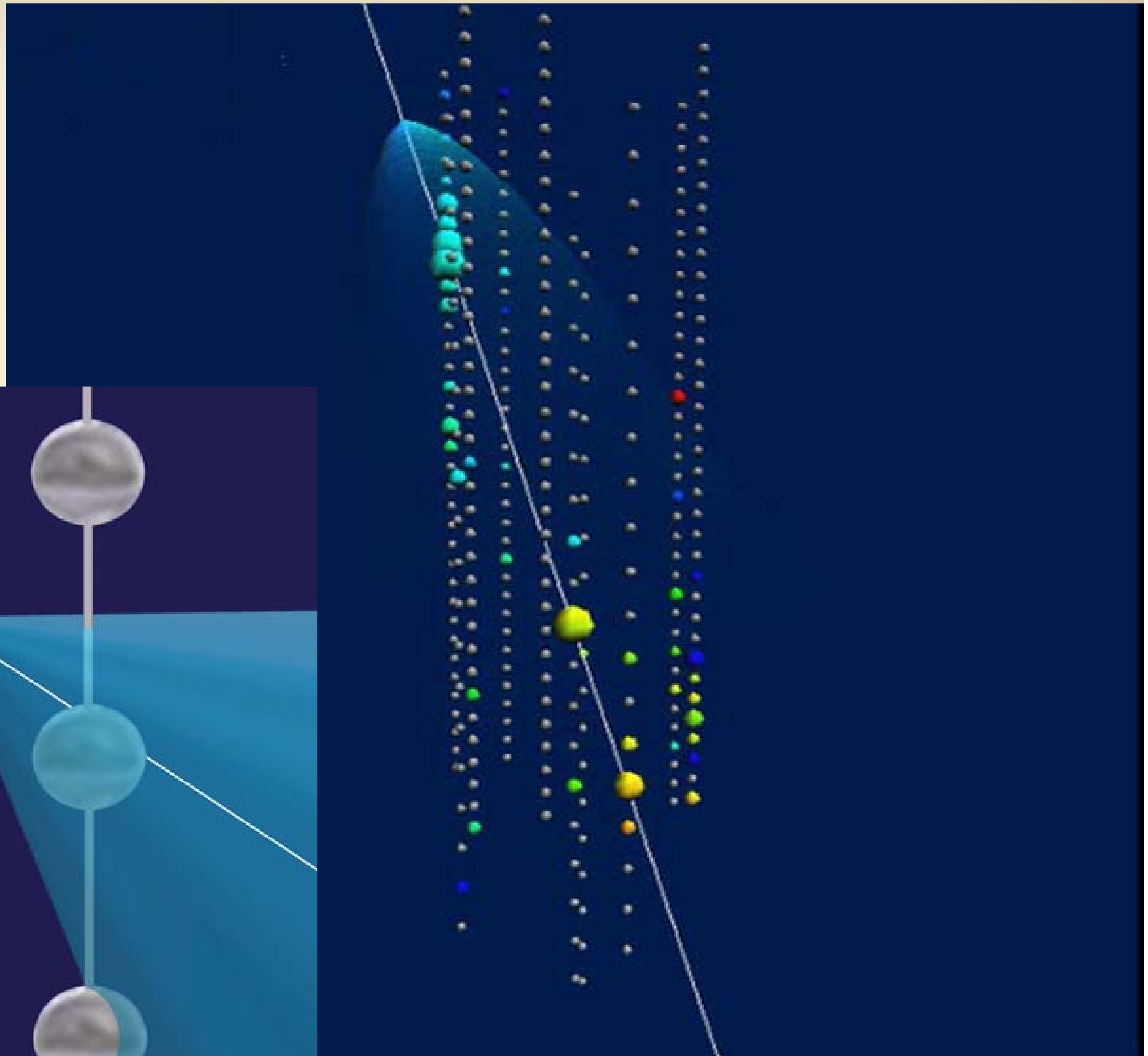
D. Hooper et al (astro-ph/0311150): If INTEGRAL signal is due to light dark matter annihilation flux should also be detectable from Sagittarius dwarf spheroidal galaxy

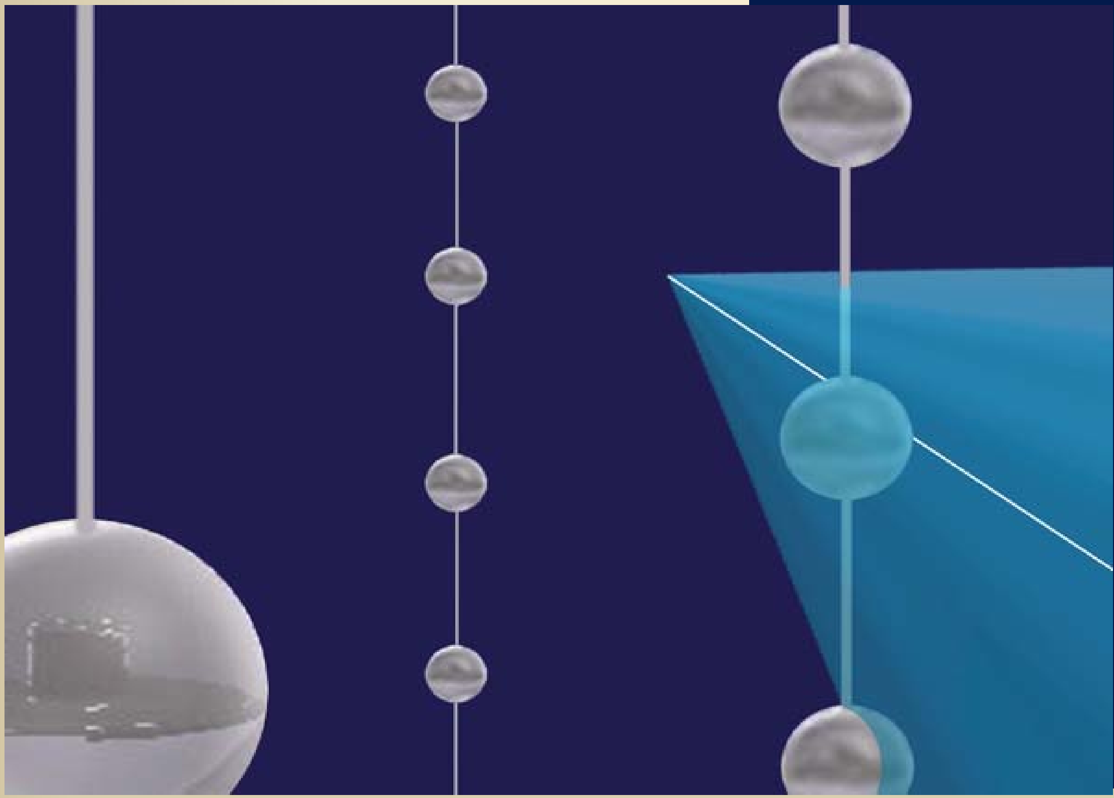




Neutrinos from the Earth (& Sun – but Sun more difficult for AMANDA → IceCUBE)

IceCube



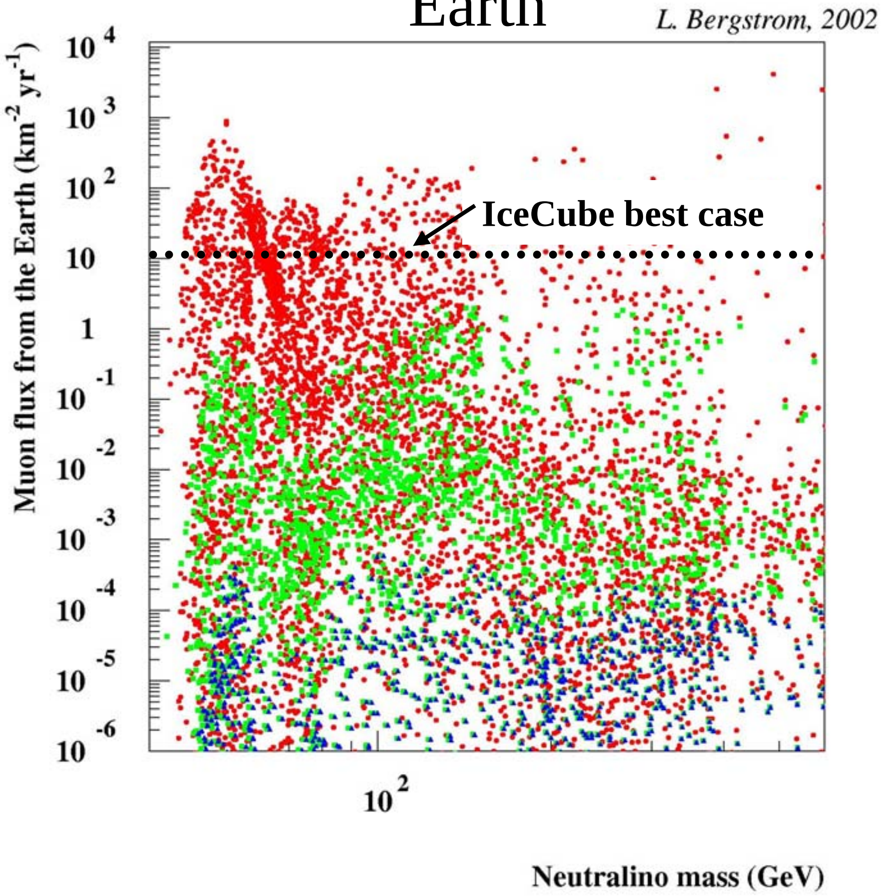


Neutralino signal: Neutrinos from the Earth & Sun

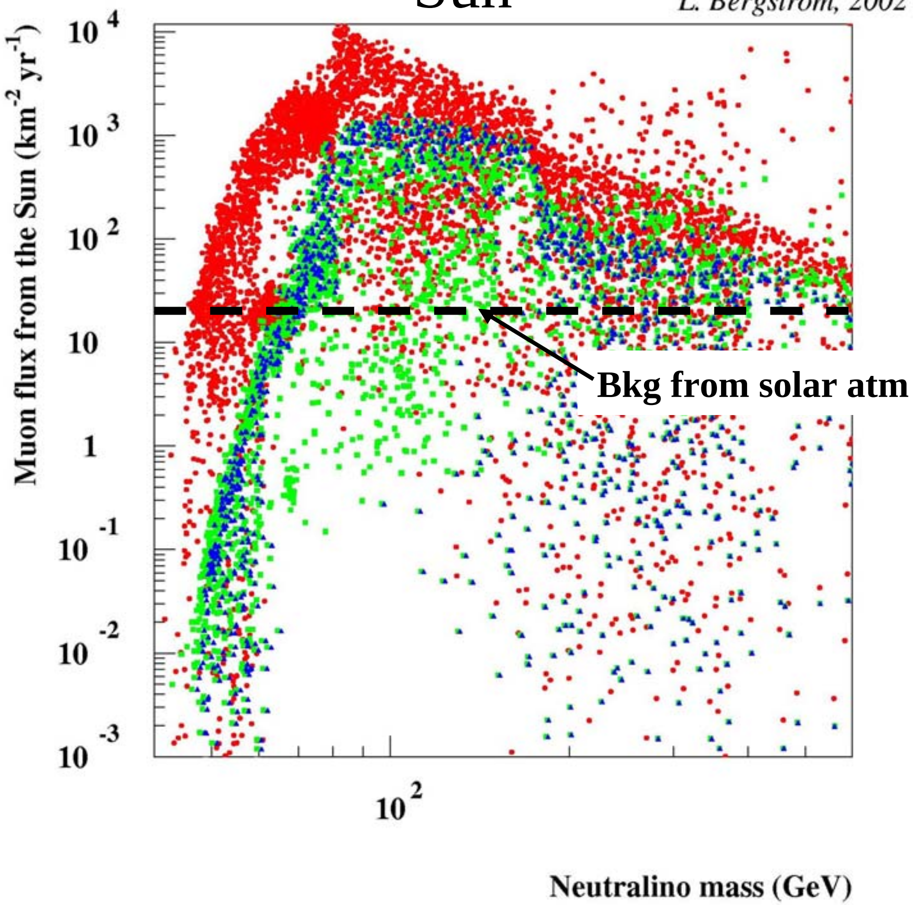
- Idealized case: 1 GeV threshold, $\Omega h^2 > 0.03$, $\sigma_{SI} < 10^{-5}$ pb
- Realistic case: 25 GeV threshold, $\Omega h^2 > 0.09$, $\sigma_{SI} < 10^{-6}$ pb
- Future: 25 GeV threshold, $\Omega h^2 > 0.09$, $\sigma_{SI} < 10^{-8}$ pb

Rates computed with DarkSUSY

Earth



Sun



Neutrino detection of Kaluza-Klein particles (Hooper & Kribs, 2002)

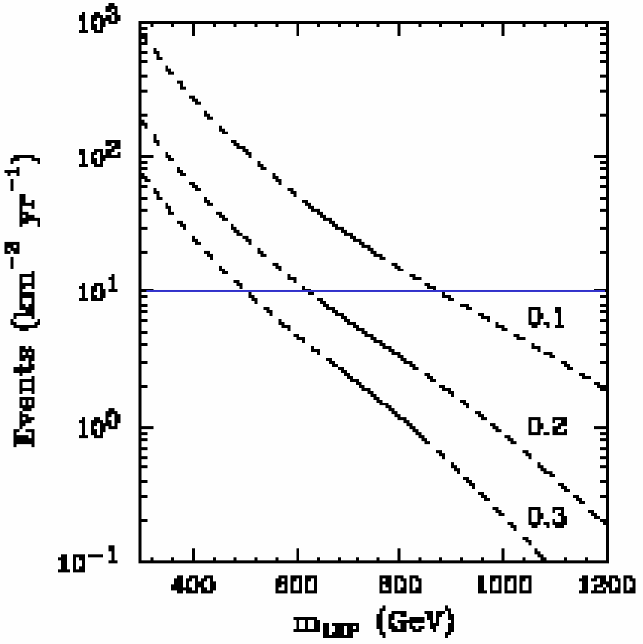


Figure 1. The rate of muon-induced neutrinos above 50 GeV predicted in a kilometer-scale neutrino telescope, such as IceCube. Curves are shown for Kaluza-Klein quarks 10%, 20% and 30% heavier than the LKP .

Positrons (Cheng, Feng & Matchev, 2003)

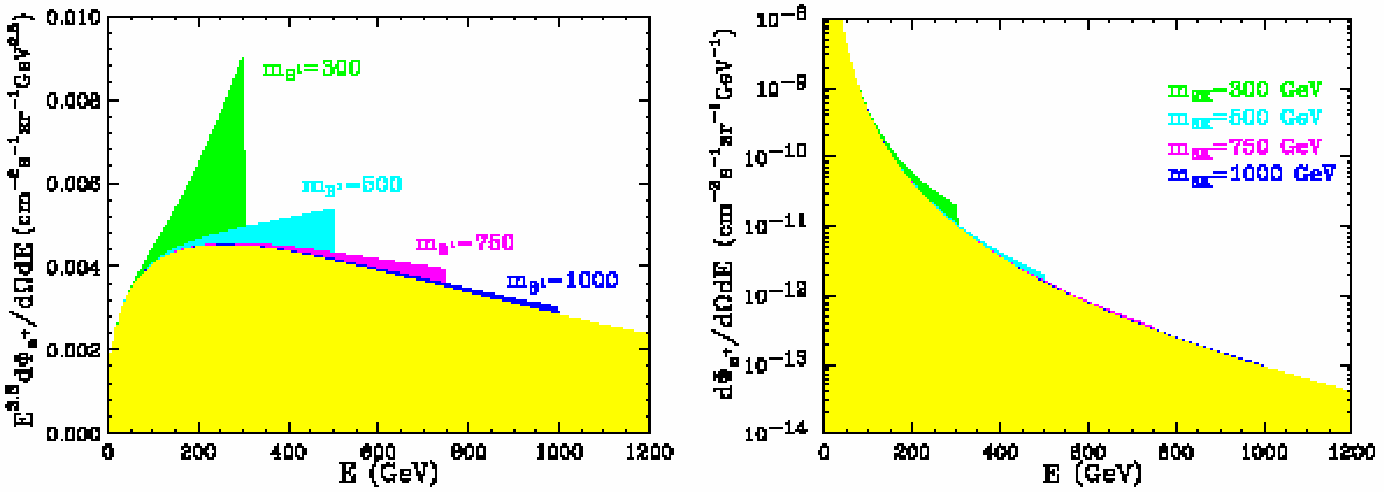
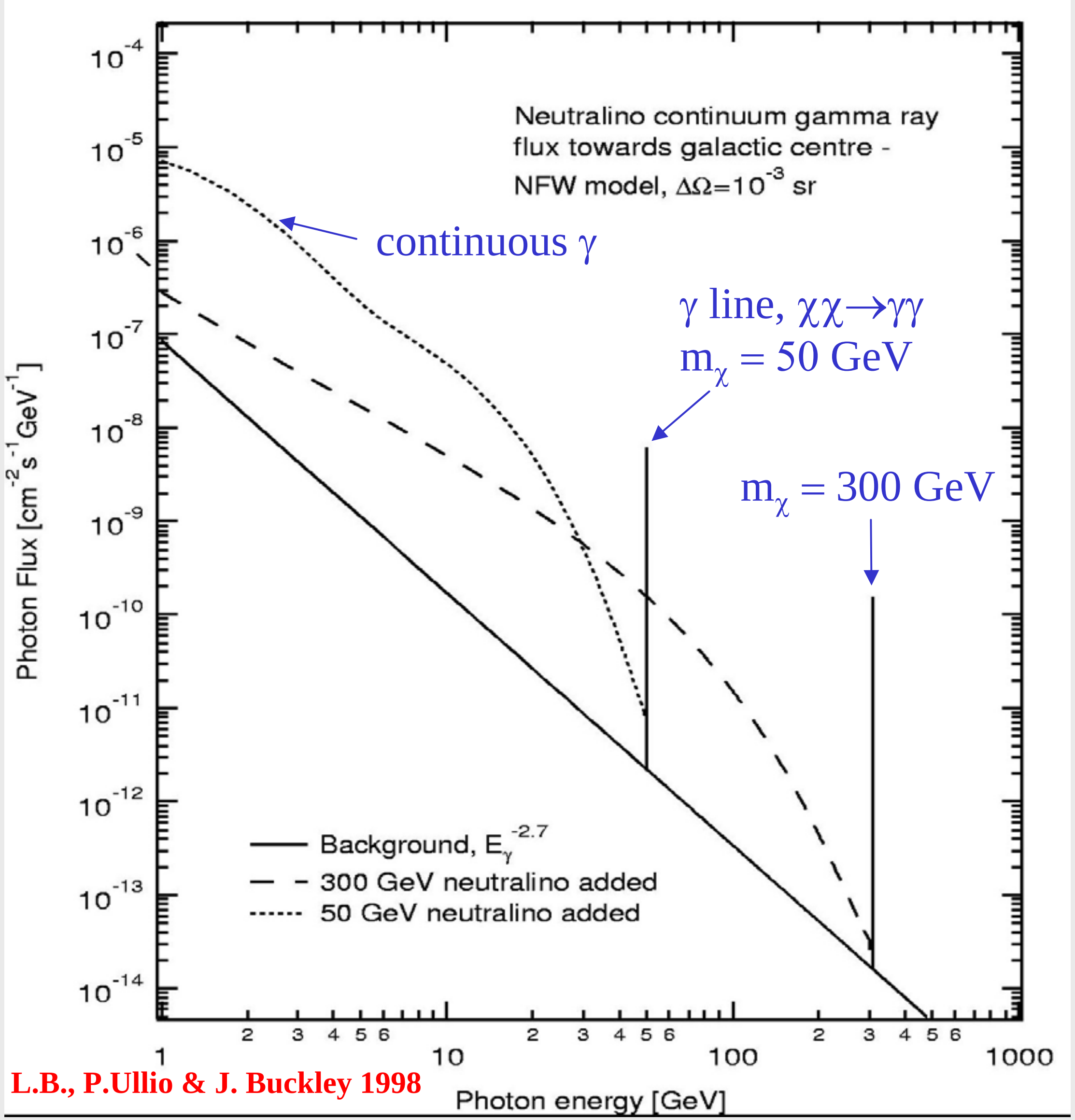


Figure 3. Positron spectra from B^1 dark matter annihilation for various B^1 masses as indicated [22]. The yellow (light shaded) region is the expected background. The differential flux is given in the right panel, and is modified by the factor E^3 in the left panel.

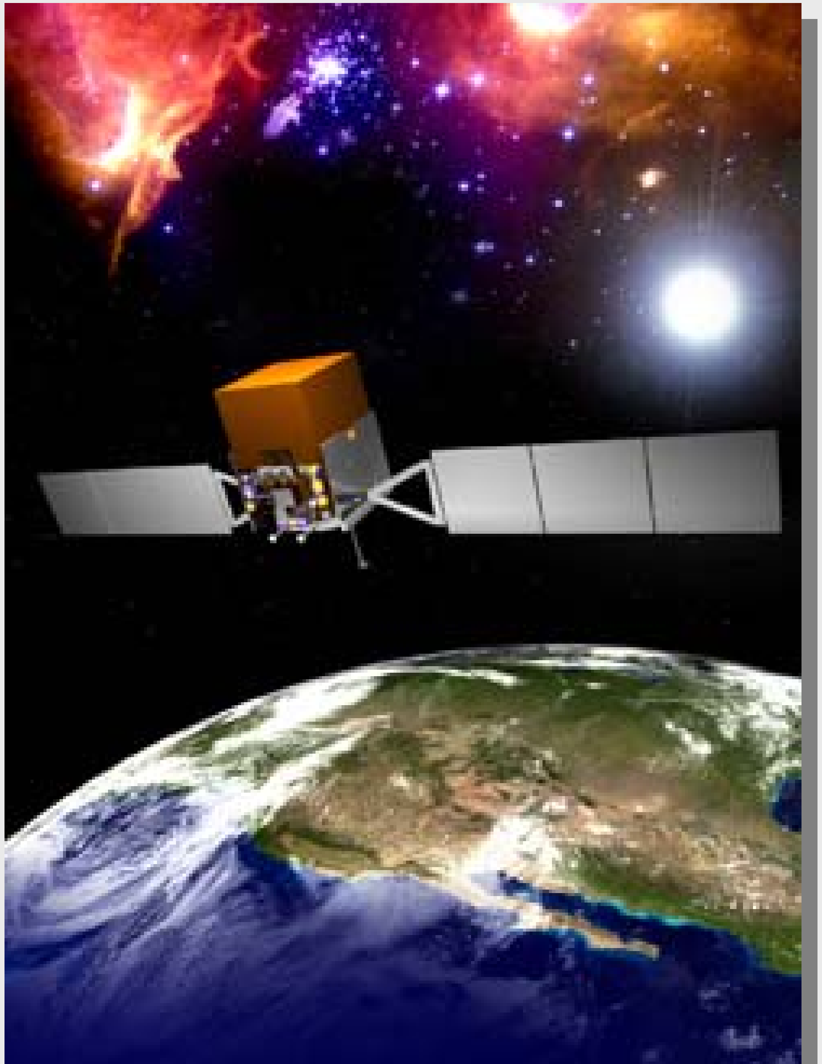
Gamma-rays

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

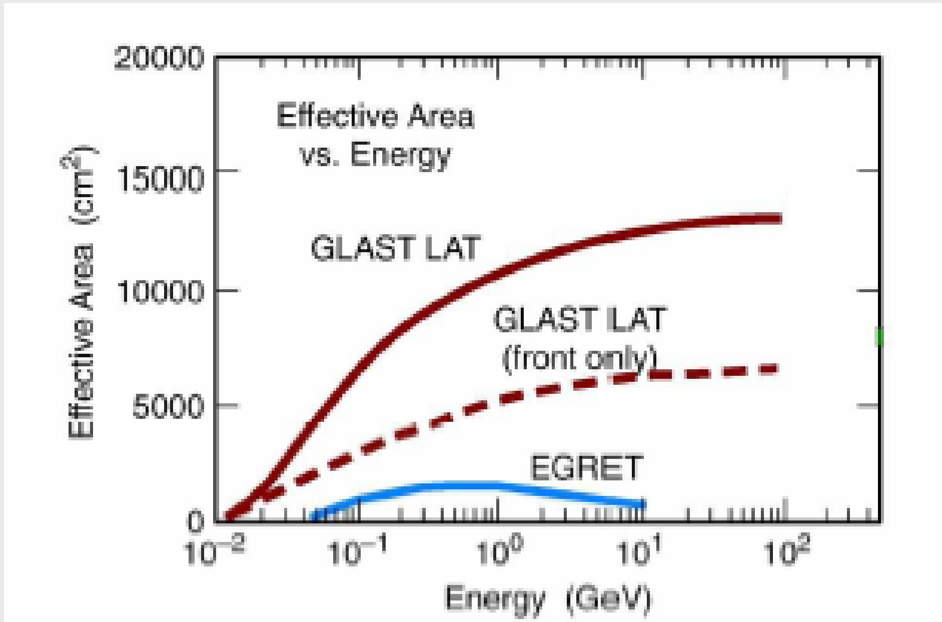
Advantage of gamma rays: point back to the source. Enhanced flux possible thanks to halo density profile and substructure (as predicted by CDM)



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



USA-France-Italy-Sweden-Japan (-Germany) collaboration, launch 2007



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

W. de Boer et al, astro-ph/0408272

Excess of gamma-rays **Filled by neutralino annihilation**

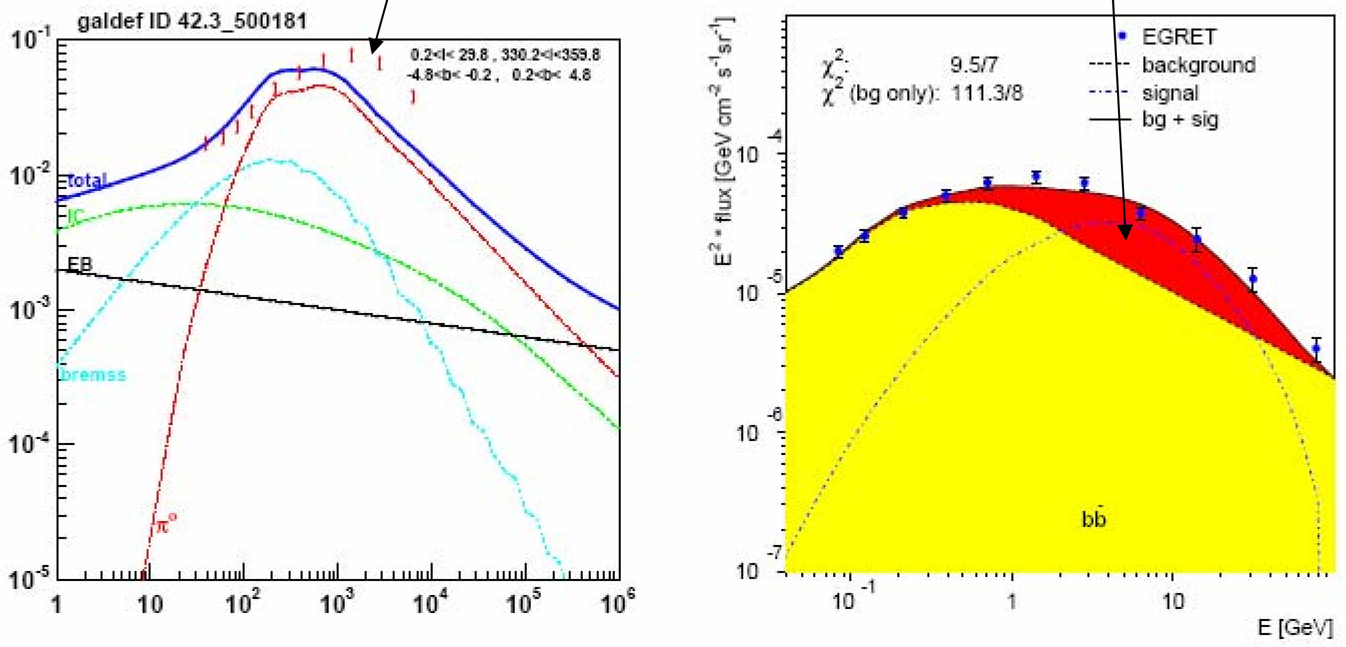
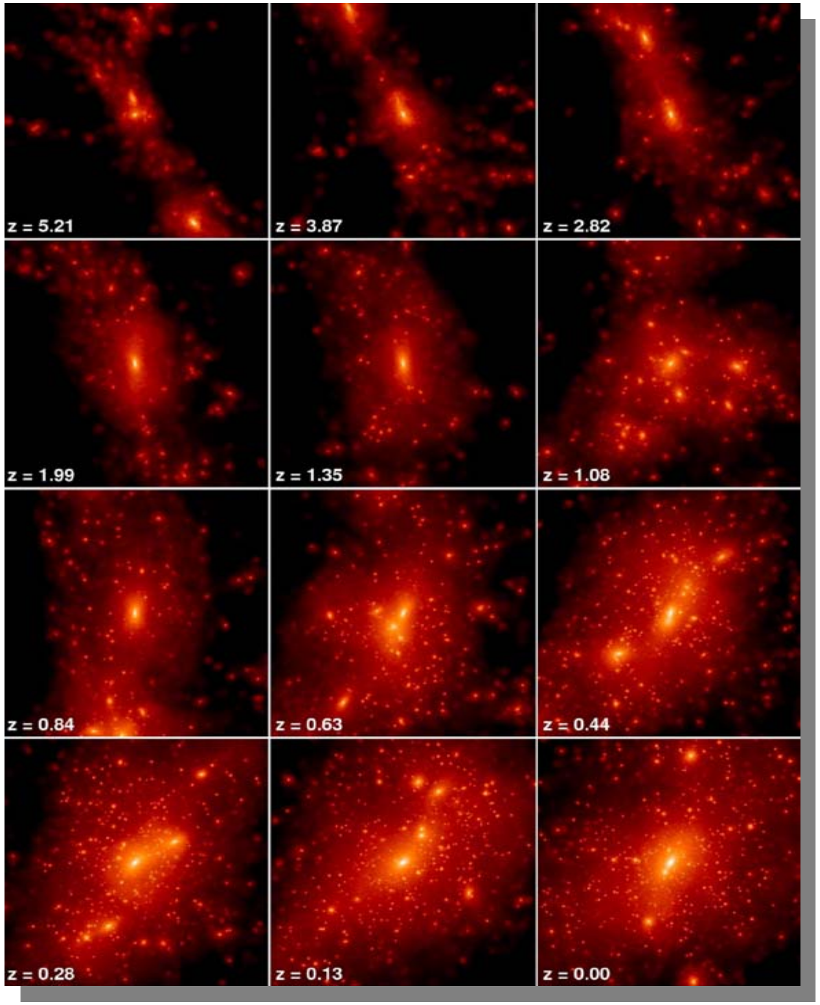


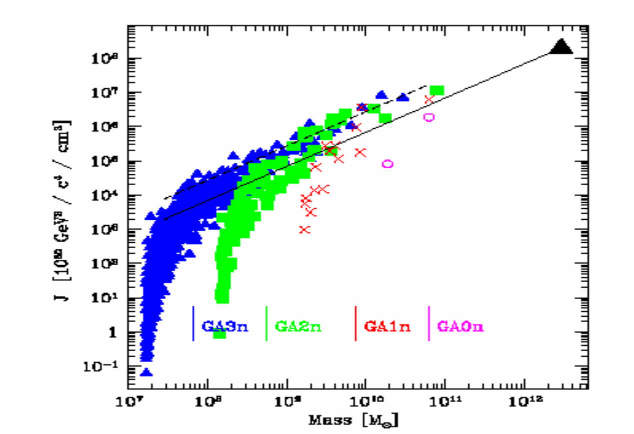
Fig. 1. Left: The diffuse gamma-ray energy spectrum of the inner Galaxy as calculated with the conventional GALPROP model in comparison with EGRET data. Right: as on the left, but with an additional component from Dark Matter Annihilation. The EGRET data above 10 GeV are from Ref. [10]

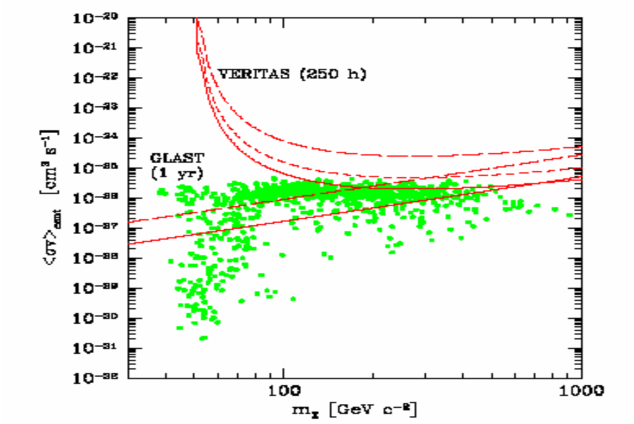
cf. also A. Cecarini et al., 2003: large ”boost factor” needed

However, how reliable is the program GALPROP for the background?
T. Kamae (unpublished, 2004): diffractive events may explain difference

Dark matter clumps in the halo?







Rates computed with DarkSUSY

Stoehr, White, Springel,Tormen, Yoshida, MNRAS 345, (2003) 1313 [astro-ph/0307026].

'Milky Way' simulation, Helmi, White & Springel, PRD, 2002

Important problem: What is the fate of the smallest substructures? V. Berezinsky, V. Dokuchaev & Y. Eroshenko, astro-ph/0301551; A.M. Green, S. Hofmann & D. Schwarz, astro-ph/0309621

Major uncertainty for gamma-ray detection from galactic center: Halo dark matter density distribution.

Fits to N-body simulations

$$\rho_{\text{Moore}}(r) = \frac{c}{r^{3/2}(a^{3/2}+r^{3/2})};$$

$$\rho_{\text{NFW}}(r) = \frac{c}{r(a+r)^2};$$

Fits to rotation curves

$$\rho_{\text{Burkert}}(r) = \frac{c}{(r+a)(a^2+r^2)};$$

$$\rho_{\text{CIS}}(r) = \frac{c}{a^2+r^2};$$

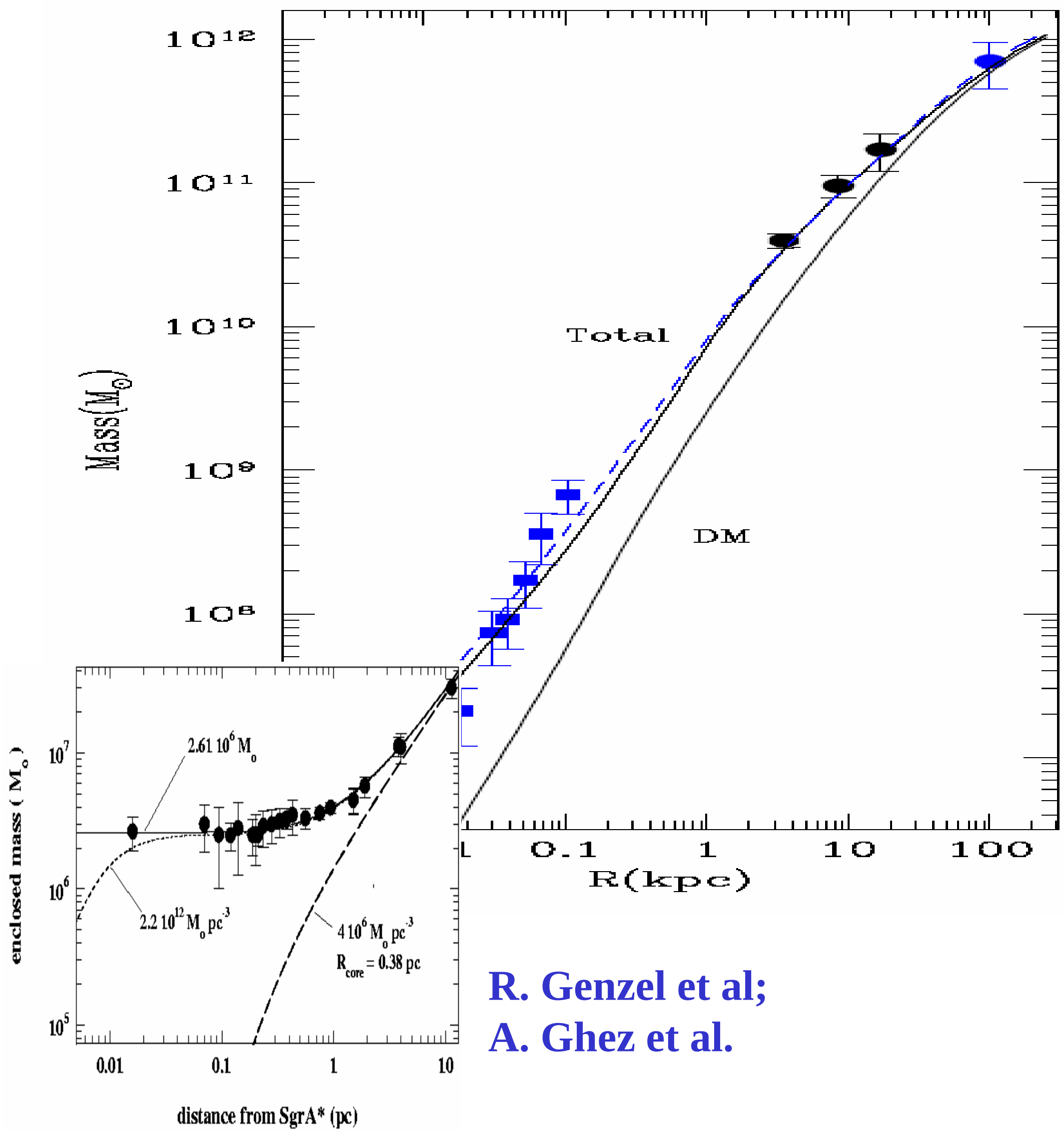
Fit to lensing (elliptical galaxies)

$$\rho_{\text{SIS}}(r) = \frac{c}{r^2};$$

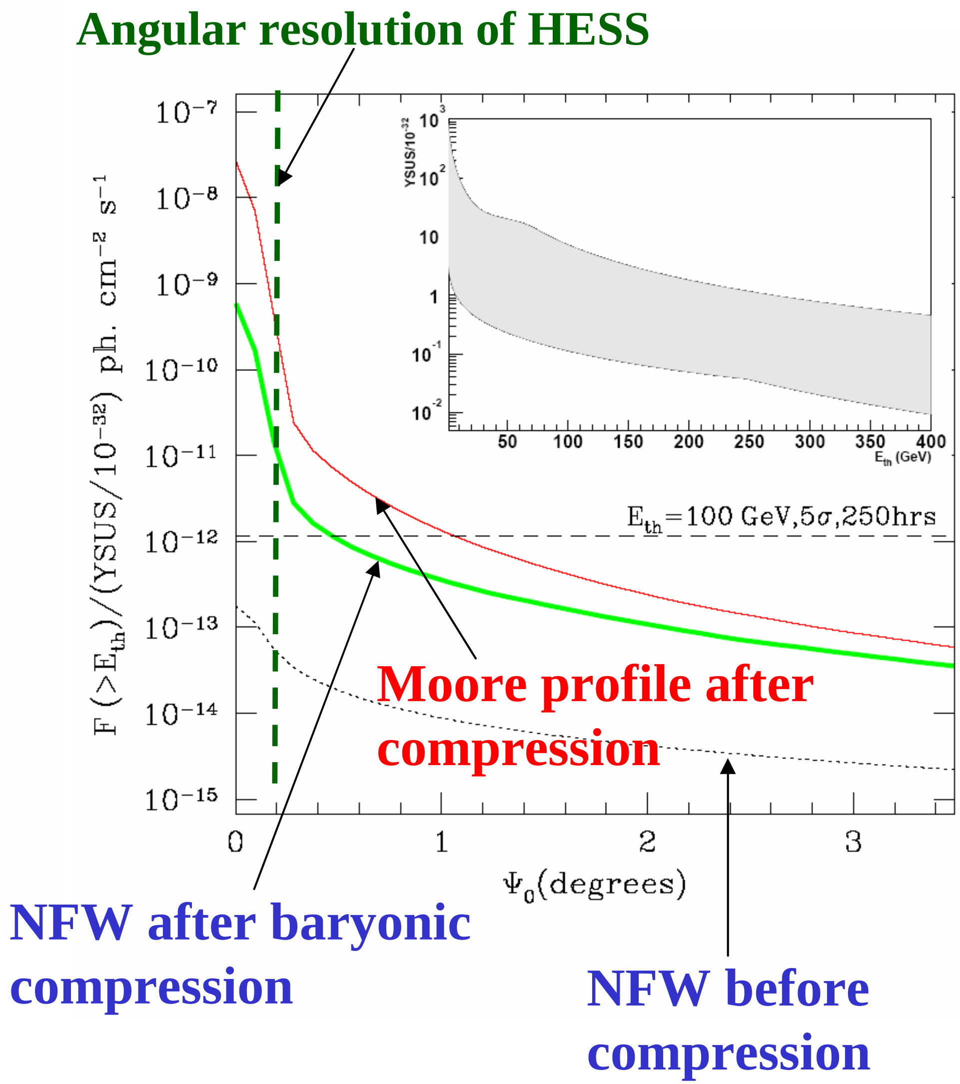
Berezinsky, Gurevich, Zybin model

$$\rho_{BGZ}(r) = \frac{c}{r^{1.8}};$$

Dense star cluster near the Galactic Centre → adiabatic compression of dark matter



R. Genzel et al;
A. Ghez et al.



F. Prada, A. Klypin, J. Flix, M. Martinez and E. Simmoneau, astro-ph/0401512; see also Gnedin & Primack 2003; D. Merritt, 2003. (Historical roots: Eggen, Lynden-Bell & Sandage, 1962; Yu.B. Zeldovich & al, 1980)

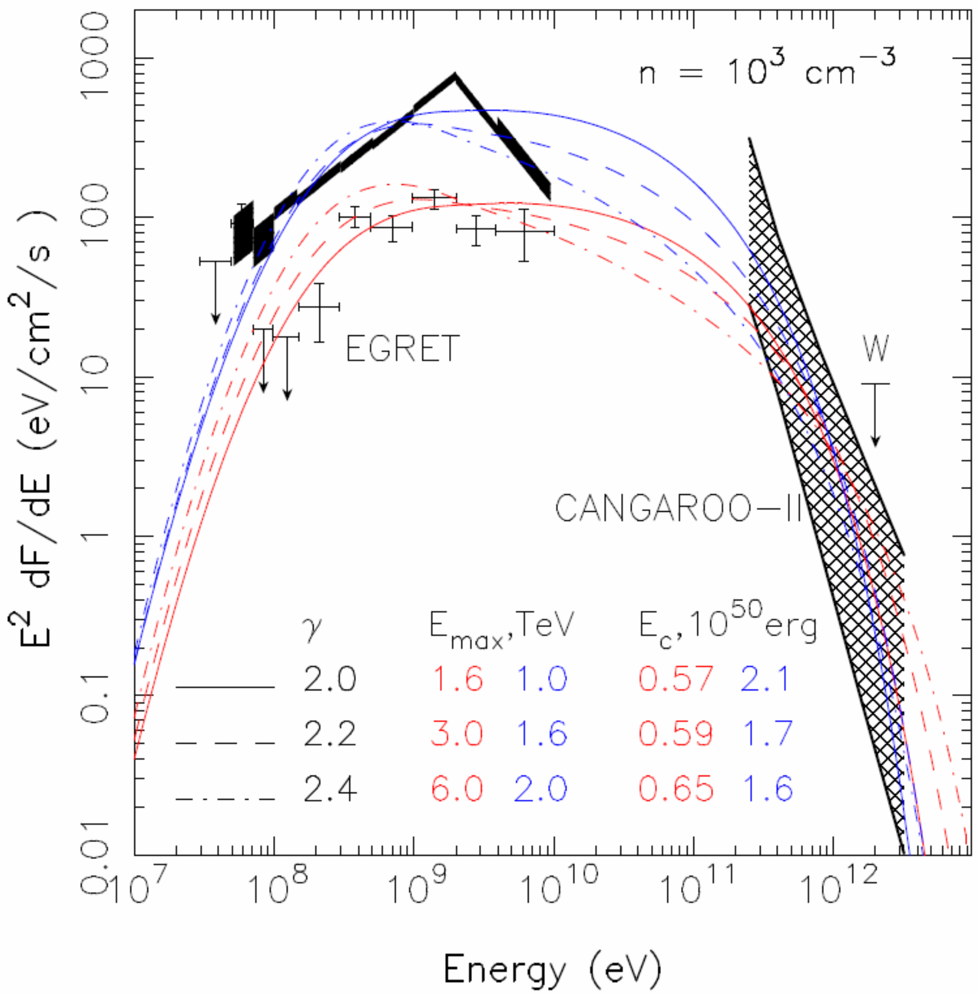
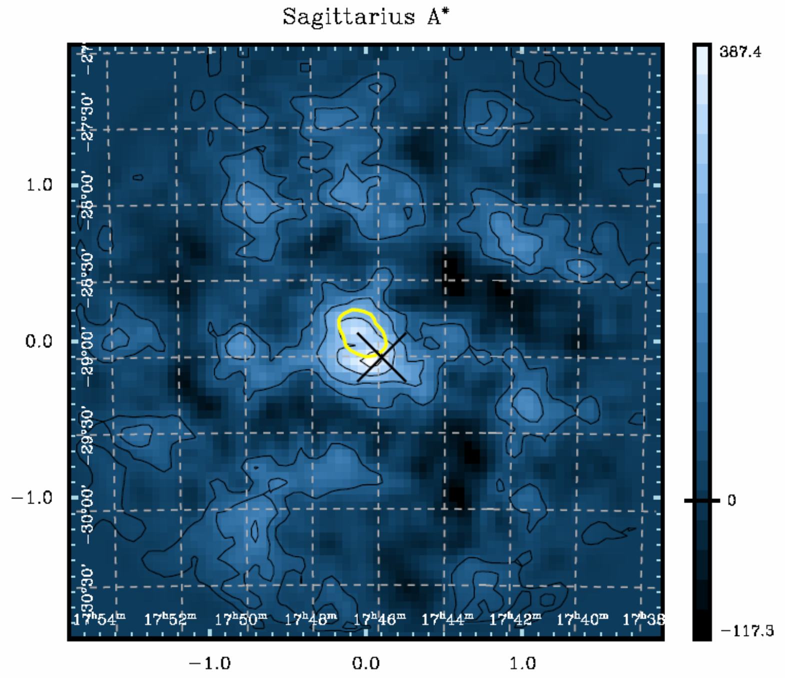


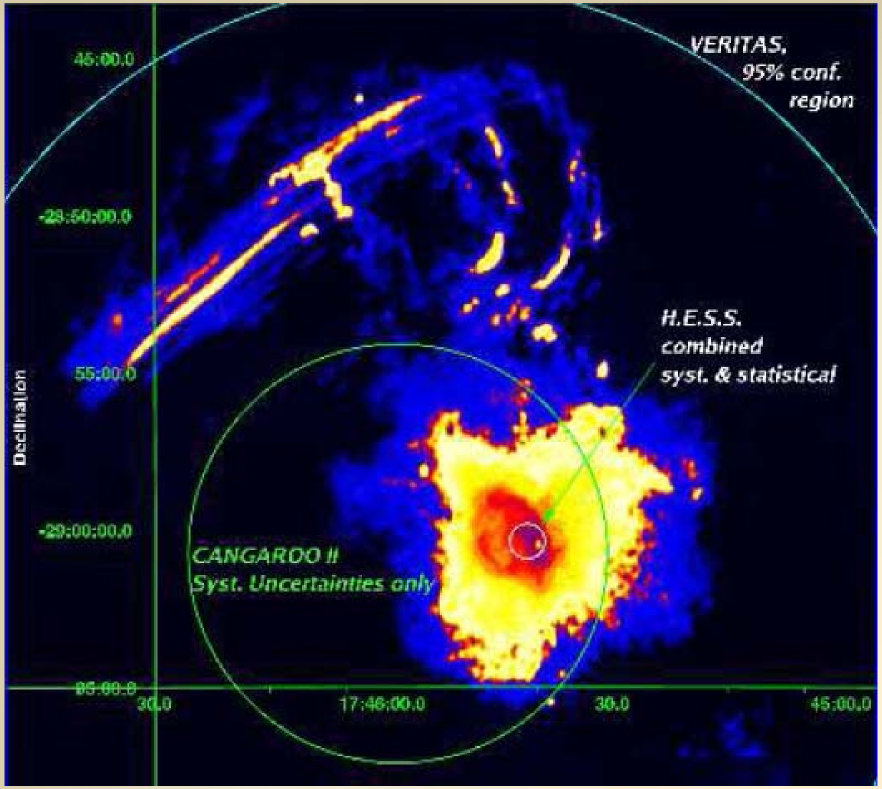
Fig. 3.— Spectral energy distribution of the GC region. The cross-hatched area is the 1σ allowed region for the TeV observations in the energy range of Table 1. Here the energy uncertainties in Table 1 were assumed to be correlated bin by bin. The arrow (W) is the Whipple 2σ upper limit at 2 TeV (Buckley et al. 1997). The two analyses of the EGRET data are shown by the black hatched region (Mayer-Hasselwander et al. 1998) and the crosses (Hartman et al. 1999). The lines are estimations for π^0 gamma-rays, the details of which are given in the body of the figure and in the text.

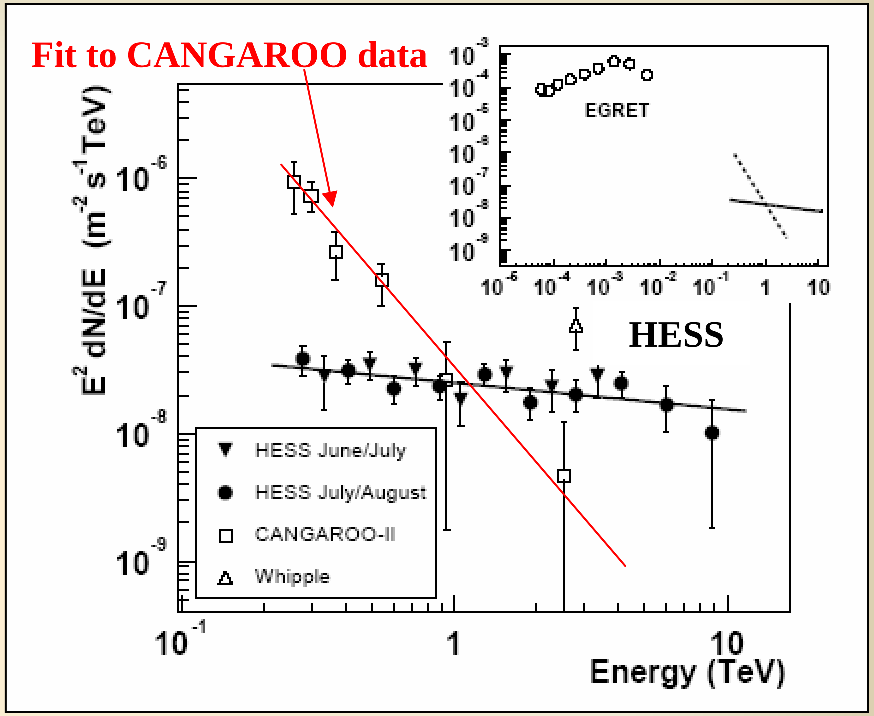


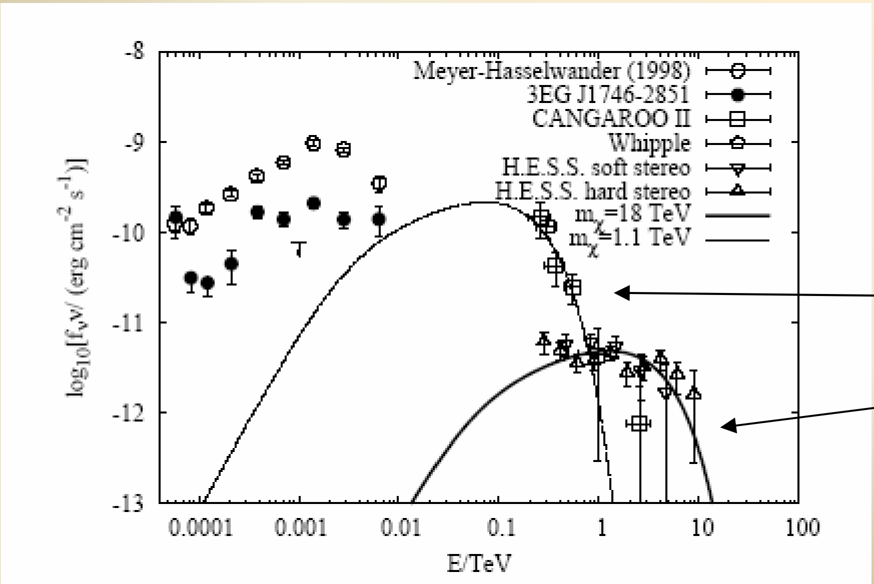
> 2 TeV gamma-rays also (marginally) detected by Whipple (Veritas collaboration, 2004)

CANGAROO results towards g.c. (2004)

July 2004: H.E.S.S. data





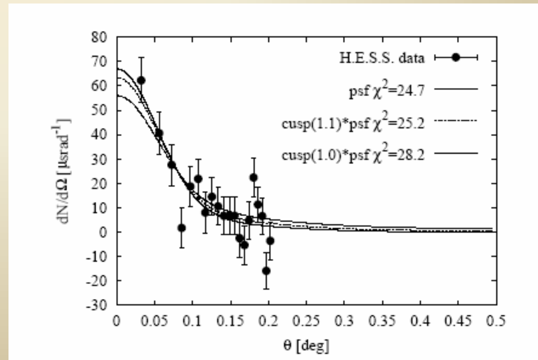


D. Horns, astro-ph/0408192

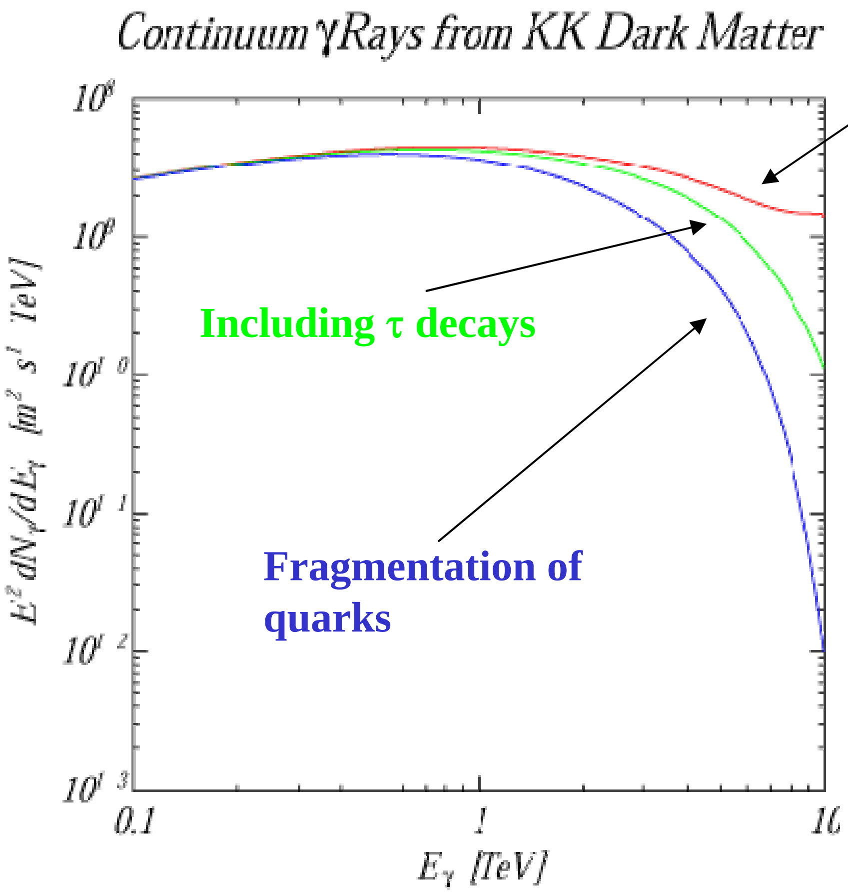
m_χ = 1.1 TeV

m_χ = 18 TeV, too high for neutralino?

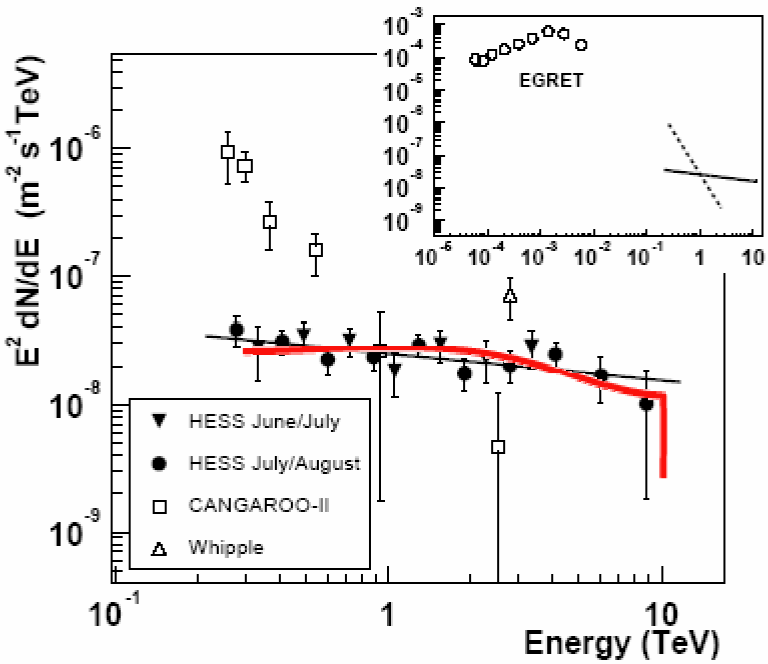
Angular distribution consistent with cusp



Preliminary! (L.B., T. Bringmann, M. Eriksson, M. Gustafsson, in preparation)

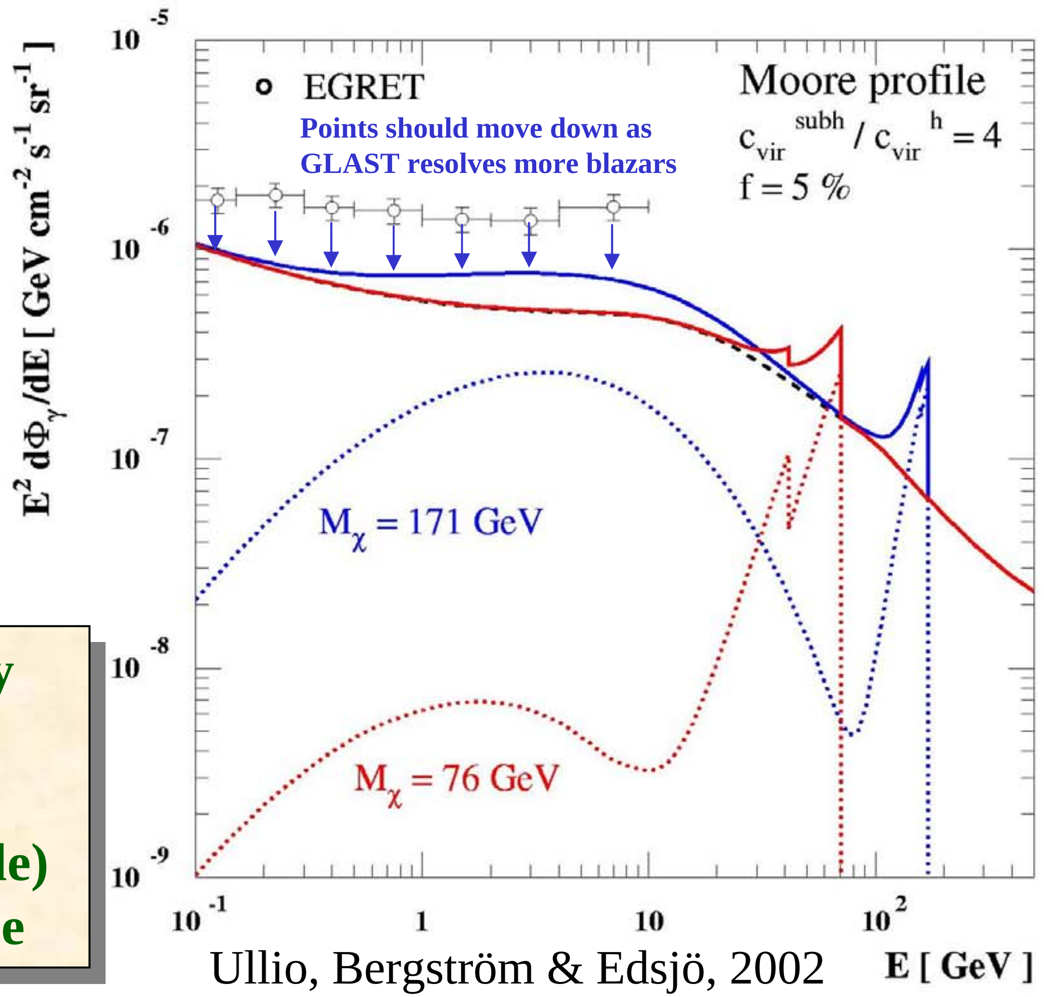


Total including hard radiation from charged lepton



NFW profile with adiabatic compression, factor 500. Expected mass range 0.5 – 1.2 TeV. Maybe nonstandard thermal history → 10 TeV??

Diffuse cosmic gamma-rays



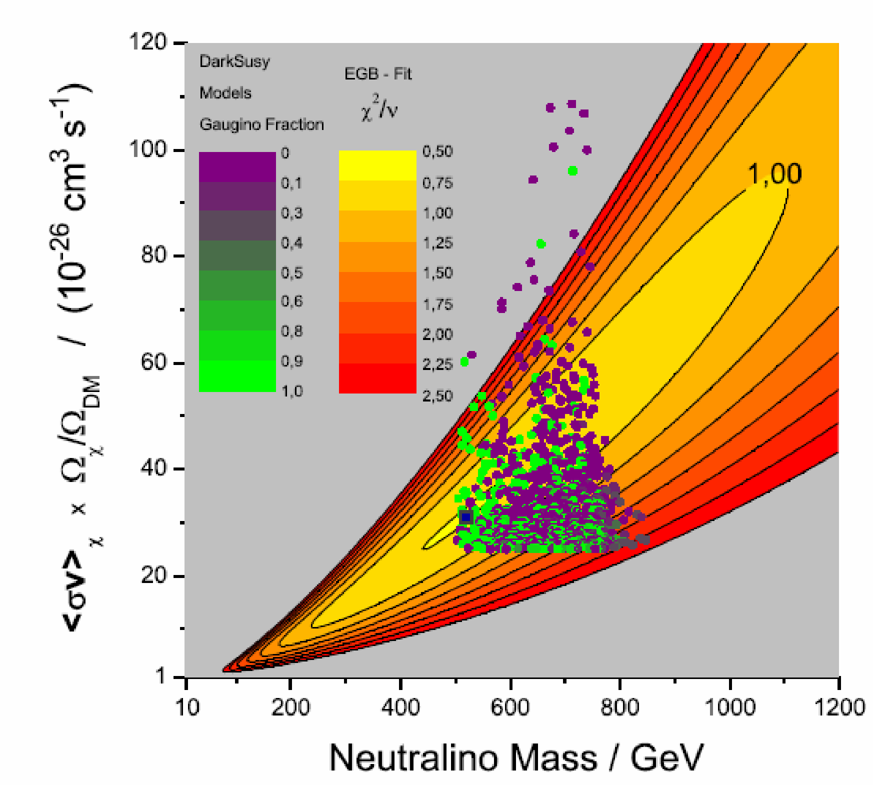
Ullio, Bergström & Edsjö, 2002

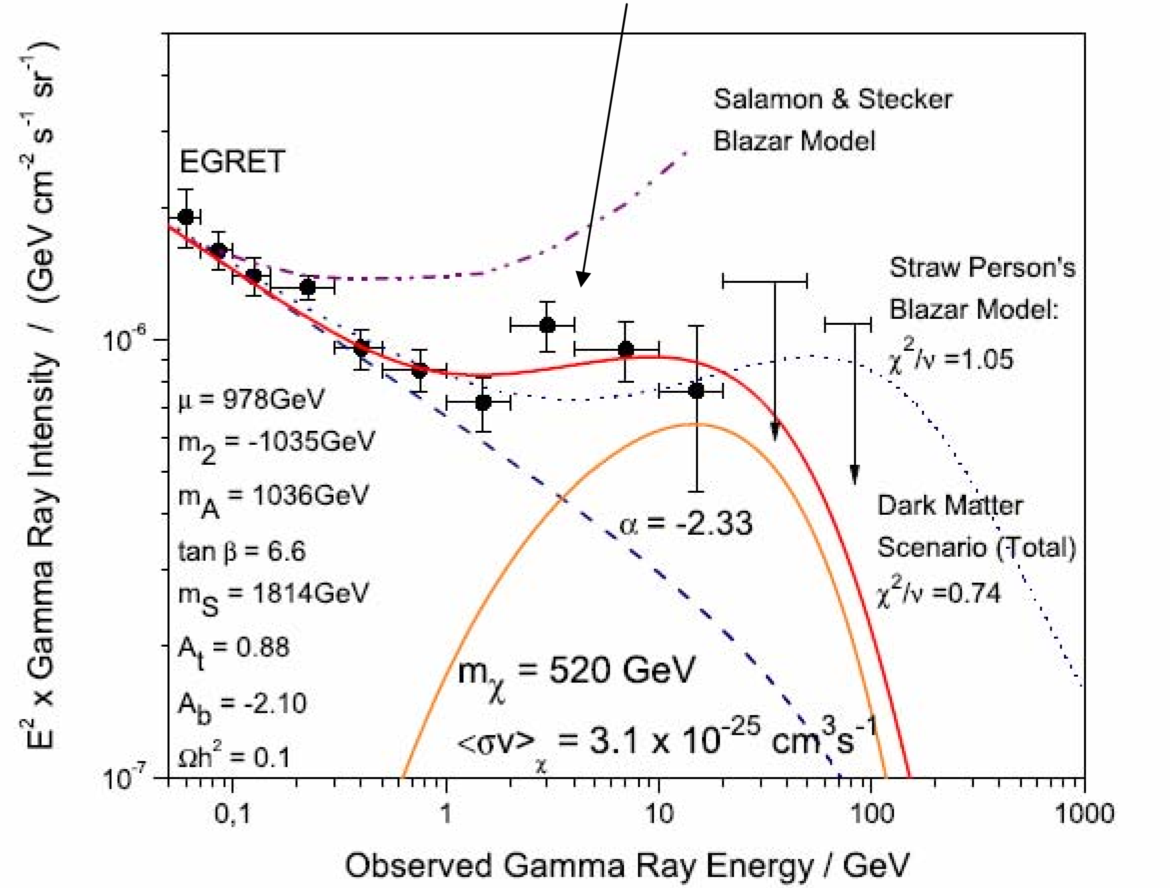
Idea: Redshifted gamma-ray line gives peculiar energy feature – may be observable for CDM-type (Moore profile) cuspy halos and substructure

FIG. 13: Extragalactic gamma-ray flux (multiplied by E^2) for two sample thermal relic neutralinos in the MSSM (dotted curves), summed to the blazar background expected for GLAST (dashed curve). Normalizations for the signals are computed assuming halos are modelled by the Moore profile, with 5% of their mass in substructures with concentration parameters 4 times larger than c_{vir} as estimated with the Bullock et al. toy model.

Could the diffuse extragalactic gamma-ray background be generated by neutralino annihilations?

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





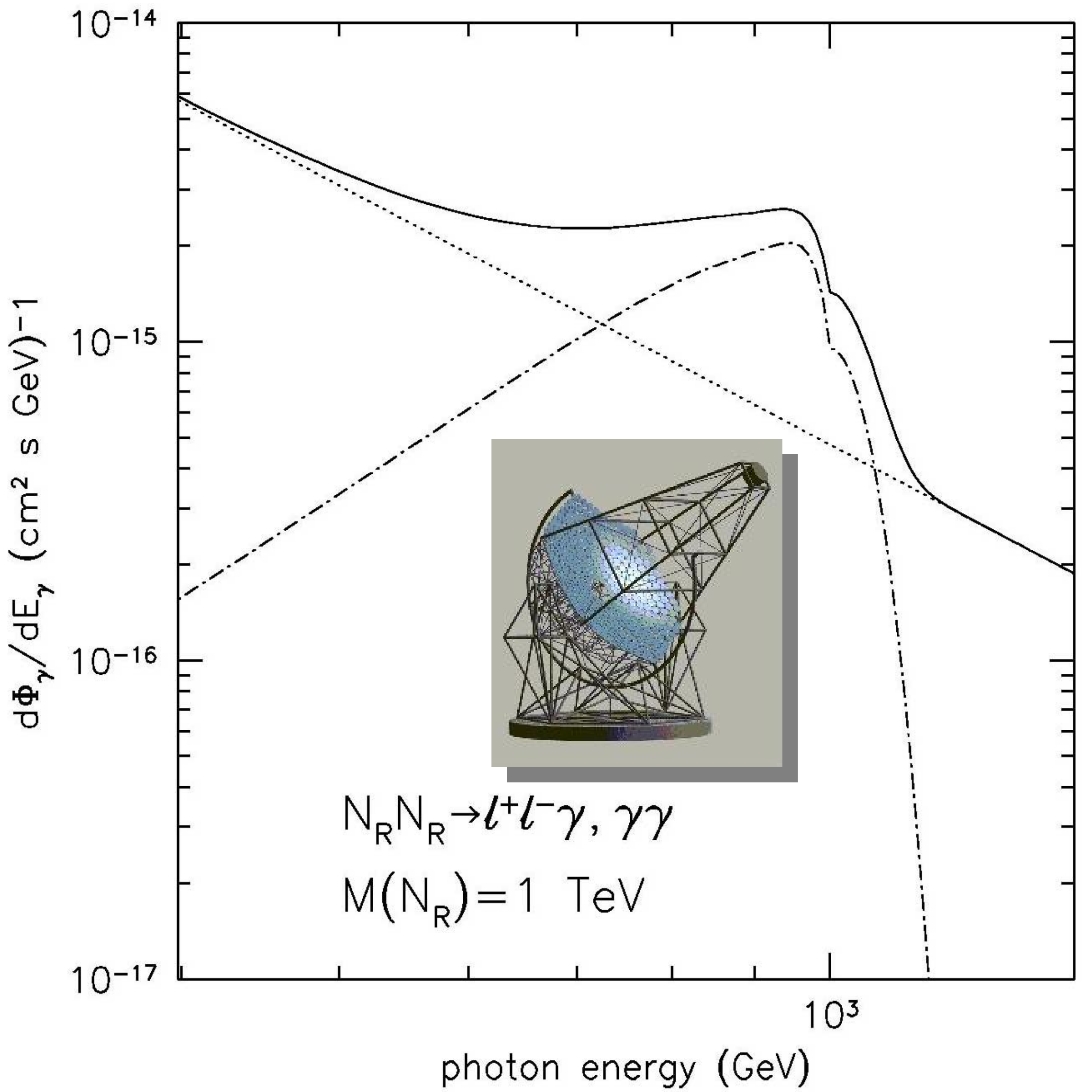
Rates computed with

Steep (Moore) profile needed for DM substructure

Elsässer & Mannheim, astro-ph/0405235

GLAST will tell!

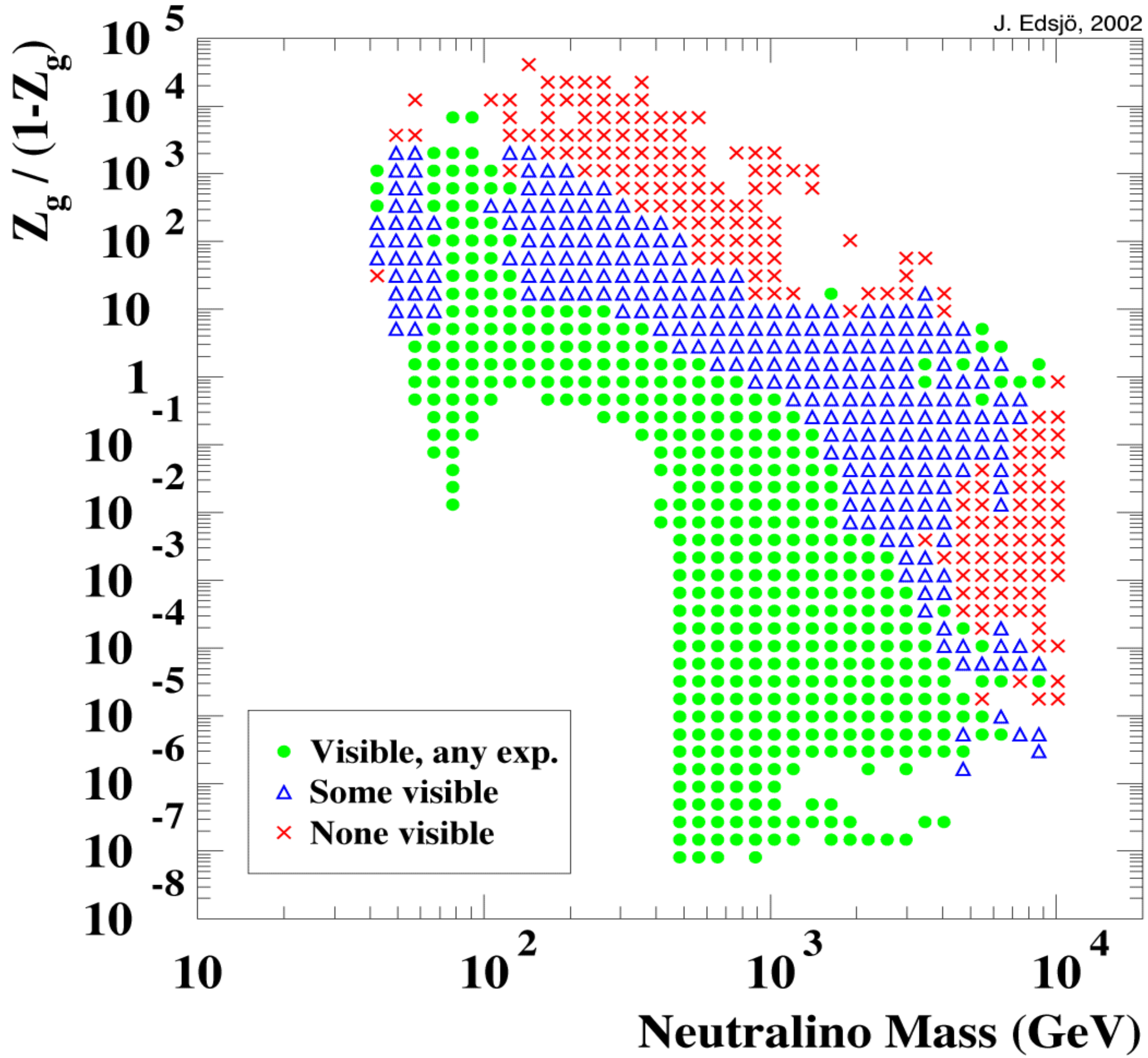
E.A. Baltz & L.B., 2003



Predicted gamma-ray signal towards galactic center for LIMP: leptonic WIMP (NFW profile assumed)

Only coupling to leptons ⇒ no direct detection, no neutrino signal from Earth & Sun, no antiproton signal. Gamma-rays (and perhaps positrons) are the only hope for LIMP detection. Air Cherenkov Telescopes (HESS) & GLAST provide ”window of opportunity”.

MSSM parameter space
All next generation dark matter searches combined



(courtesy J. Edsjö)

Large parts of SUSY parameter space can be probed by future searches – combining direct and indirect detection methods

Rates computed with DarkSUSY

Conclusions

- **Existence of Nonbaryonic Dark Datter more certain than ever**
- **CDM favoured**
- **Supersymmetric particles (neutralinos) are among the best-motivated candidates, but KK states interesting alternative**
- **New direct and indirect detection experiments will reach deep into theory parameter space**
- **Indications of gamma-ray excess from Galactic center (at MeV, GeV, and TeV energies! – maybe due to dark matter, or maybe not…)**
- **Adiabatic compression of DM at Galactic center by stellar cluster seems a robust process; gives large (detectable) gamma rates! Has HESS seen KK dark matter?**
- **The various indirect detection methods are complementary to each other and to direct detection**
- **SUSY WIMPs are generic, but there exist alternatives**
- **The hunt is going on – many new experiments coming!**