Indirect Detection of Dark Matter

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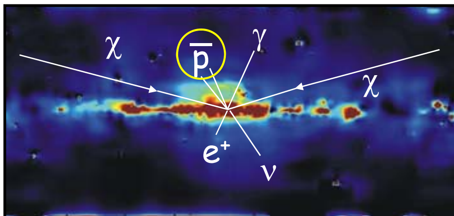
Dark Matter
FROM THE COSMOS TO THE LABORATORY

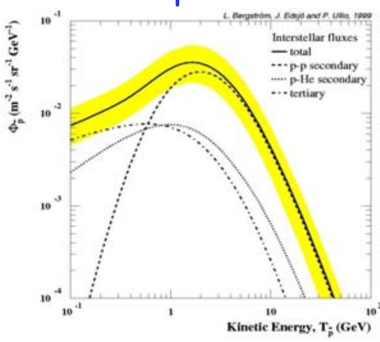
XXXV SLAC Summer Institute
July 30th - August 10, 2007
Stanford Linear Accelerator Center

Lecture II:

- Antiprotons and antideuterons from DM annihilations
- Neutrinos from DM annihilation
- More on gamma-rays:
- TeV gamma rays, resonant enhancement
- Air Cherenkov Telescopes, HESS, MAGIC, Veritas,…
- Possible enhancements from DM clumps, Black Holes
- MeV gamma rays – INTEGRAL data
- de Boer’s model for galactic gamma-rays
- Conclusions



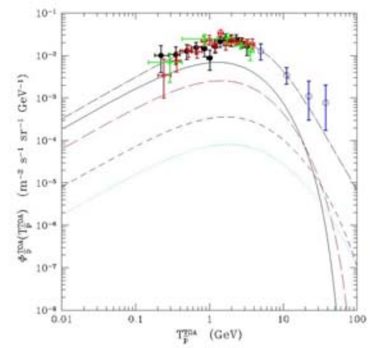
Antiprotons



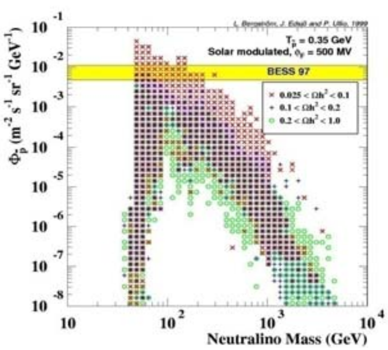
L.B., J. Edsjö and P. Ullio, 2000;
Bieber & Gaisser, 2000

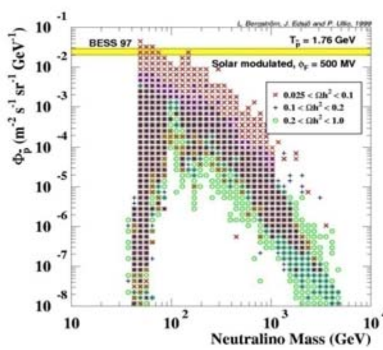
Antiprotons at low energy can not be produced in pp collisions in the galaxy, so that may be DM signal?

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)



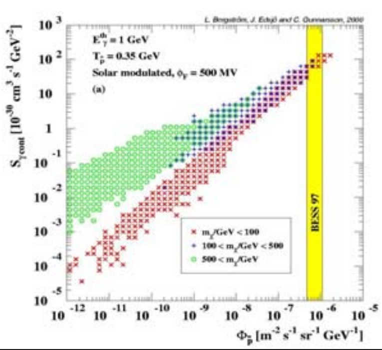
F. Donato et al., 2003

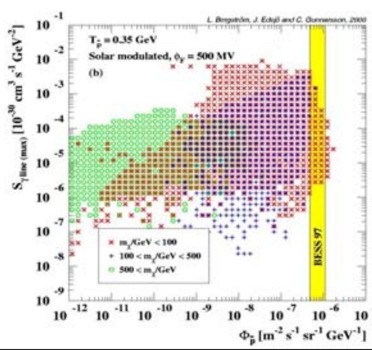




Existing data cuts into MSSM parameter space.

PAMELA will soon have more data





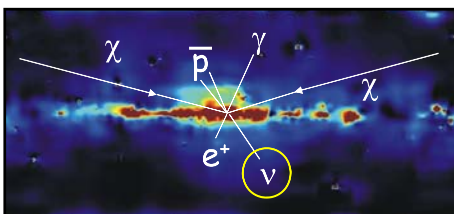
Antiprotons and continuum gamma rays are strongly correlated (through fragmentation of quark jets).

No correlation for lines

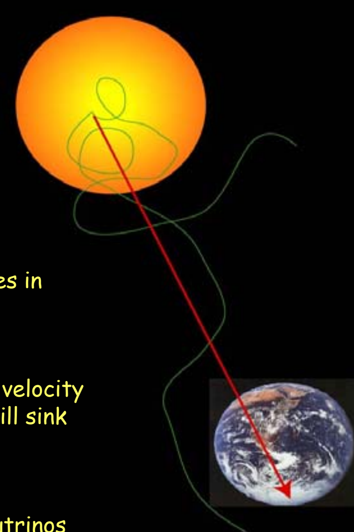
Summary for antiprotons

Measured rate agrees well with standard background estimate (secondary production from cosmic rays interacting with gas and dust in the galaxy). This can be used to set limits on the yield of antiprotons from "exotic" sources like dark matter annihilation.

The production rate for antiprotons in DM annihilation is strongly correlated to the continuum gamma rate.



Neutrinos

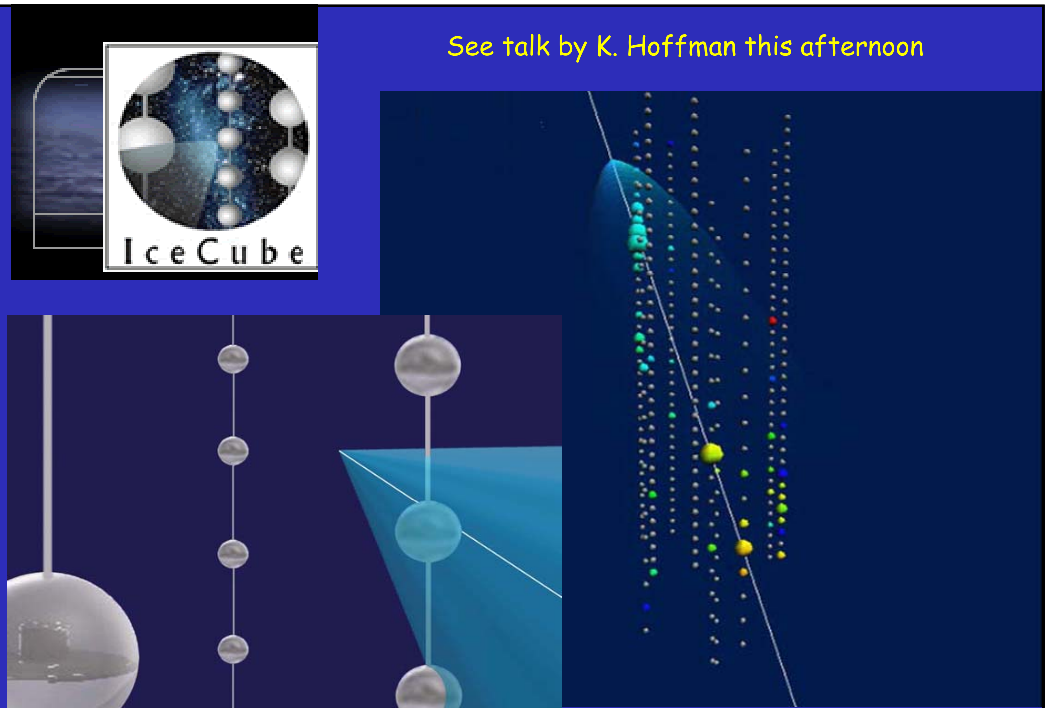


Neutrinos from the center of the Earth or Sun in large neutrino telescopes: IceCUBE at the South Pole, Antares in Mediterranean

WIMPs are trapped gravitationally by scattering; when velocity after scattering is below escape velocity, the WIMPs will sink down to the center

Annihilation rate $\sim\rho^2 \Rightarrow$ Good signature: high energy neutrinos pointing back to the center of the Earth or Sun

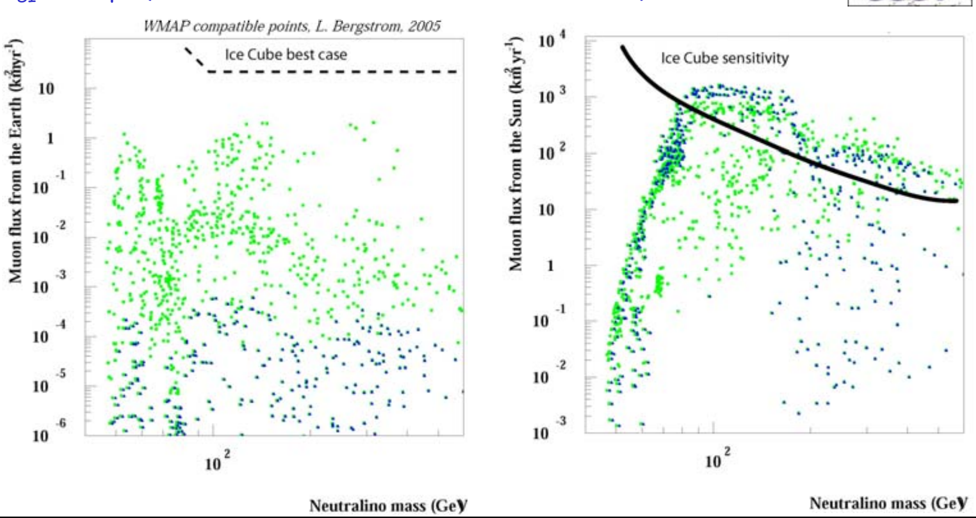
See talk by K. Hoffman this afternoon



Neutralino signal: Neutrinos from the Earth & Sun, MSSM

Rates computed with DarkSUSY

- Present case (green points): 25 GeV threshold, WMAP relic density, CDMS-II limit on cross section
- Future (blue points): 25 GeV threshold, WMAP relic density, $\sigma_{SI} < 10^{-8}$ pb (factor of 3 below the 2007 XENON10 data)



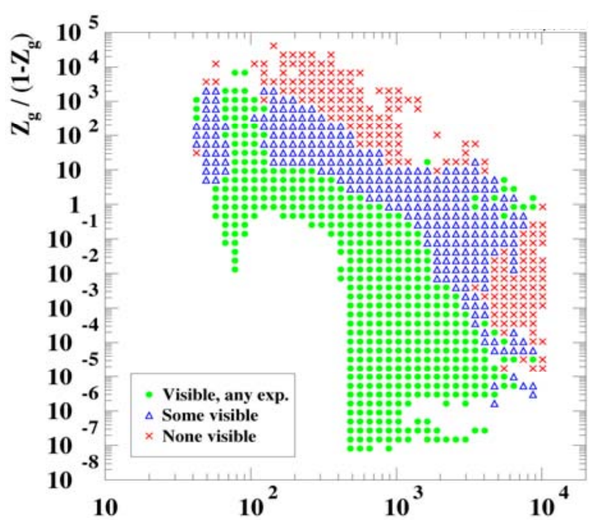
Summary for neutrinos

Can not be detected from annihilation in the halo (the interaction rate of neutrinos are too small), except perhaps in the case of an extreme concentration of DM (a "spike") near the black hole at the galactic center.

However, gravitational trapping of DM in the Sun may give a signal with a striking signature. The Earth seems less promising due to the strong limits now coming from direct detection.

Summary of detection methods: MSSM parameter space
All next generation dark matter searches combined

(courtesy J. Edsjö)



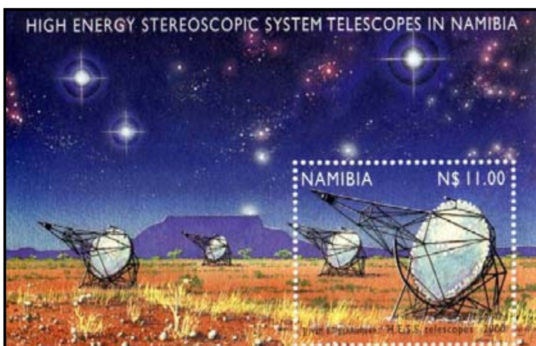
Rates computed with DarkSUSY

Large parts of SUSY parameter space can be probed by future searches – combining direct and indirect (gamma, antiproton, positron, neutrino) detection methods

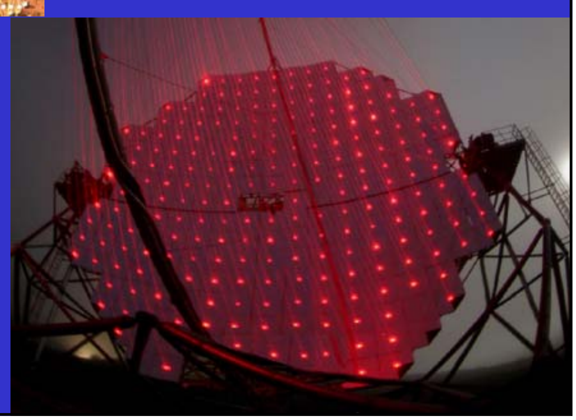
In most (but not all) of parameter space, LHC will have an impact

Special topics in gamma-ray detection of DM

I. TeV Dark Matter



H.E.S.S. in Namibia



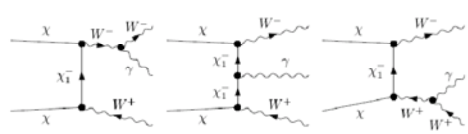
MAGIC in Canary Islands

+ VERITAS, CANGAROO,...

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

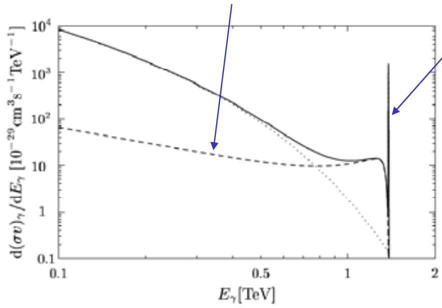
- Heavy MSSM neutralinos are almost pure higgsinos (in standard scenario) or pure winos (in AMSB & split SUSY models)
- Just for these cases, the gamma line signal is particularly large (L.B. & Ullio, 1998)
- In contrast to all other detection scenarios (accelerator, direct detection, positrons, antiprotons, neutrinos,..) the expected signal/background increases with mass $\Rightarrow$ unique possibility, even if LHC finds nothing.
- Rates may be further enhanced by non-perturbative binding effects in 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 TeV $\leq E_\gamma \leq$ 20 TeV
- A new generation of ACT arrays is presently being planned: AGIS, HAWC, CTA

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)

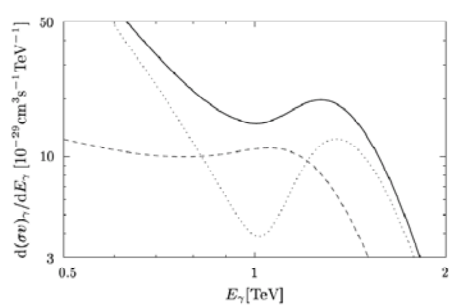


New contribution (internal bremsstrahlung)

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



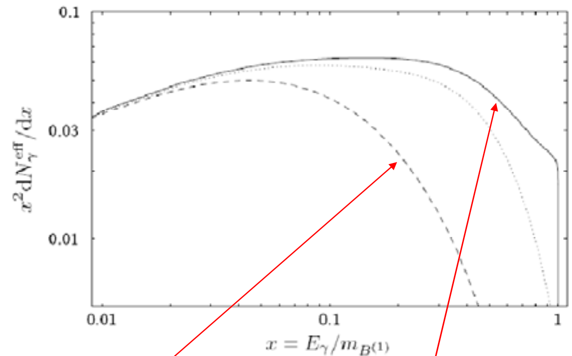
Gamma-ray spectrum seen by an ideal detector



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

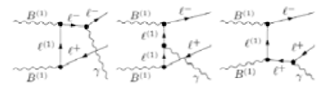
Cf. Kaluza-Klein models

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



With internal bremsstrahlung

Quark fragmentation (e.g., SUSY)

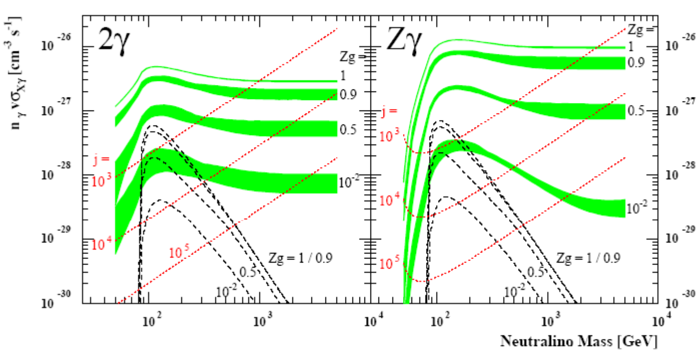


For supersymmetry, these processes will be included in the next release of DarkSUSY

(T. Bringmann, L. Bergström, J. Edjö, in prep., 2007)

Wino case

P. Ullio, 2001, AMSB scenario (cf Arvanitaki & Graham 2004; Masiero, Profumo, Ullio, 2005; Cheung and Chiang 2005 – split SUSY)

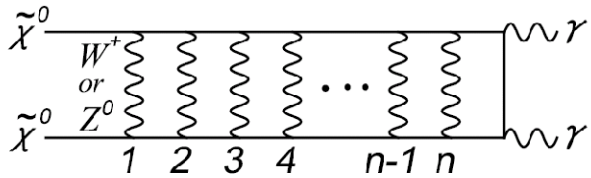


Zγ line is exceptionally strong for wino DM

Rates computed with DarkSUSY

Interesting possibility for these high-mass WIMPs:

Hisano, Matsumoto and Nojiri, 2003; Hisano, Matsumoto, Nojiri and Saito, 2004



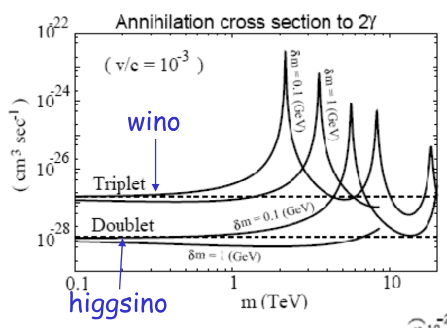
$$S^{(II)} = \int d^4x d^3r\, \Phi^\dagger(x,\vec{r}) \left\{ \left(i\partial_{x^0} + \frac{\nabla_x^2}{4m} + \frac{\nabla_r^2}{m} \right) - \mathbf{V}(\vec{r}) + 2i\mathbf{\Gamma}\delta(\vec{r}) \right\} \Phi(x,\vec{r})$$

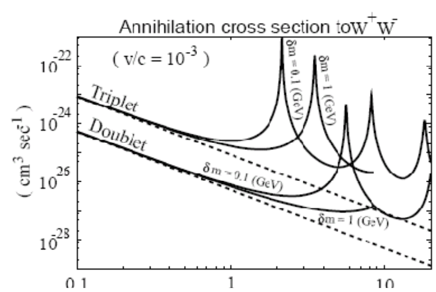
$$\mathbf{V}(r) = \begin{pmatrix} 2\delta m - \frac{\alpha}{r} - \alpha_2 c_W^2 \frac{e^{-m_Z r}}{r} & -\sqrt{2}\alpha_2 \frac{e^{-m_W r}}{r} \\ -\sqrt{2}\alpha_2 \frac{e^{-m_W r}}{r} & 0 \end{pmatrix}$$

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

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

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"!

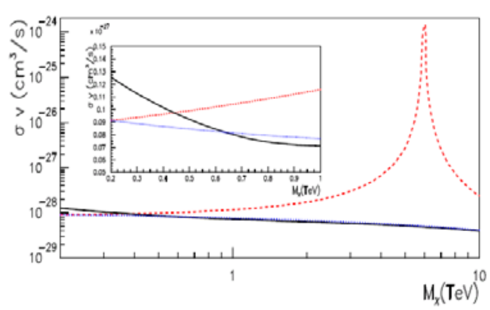




In MSSM without standard GUT condition (AMSB; split SUSY) m_{wino} ~ 2 – 3 TeV; δm ~ 0.2 GeV

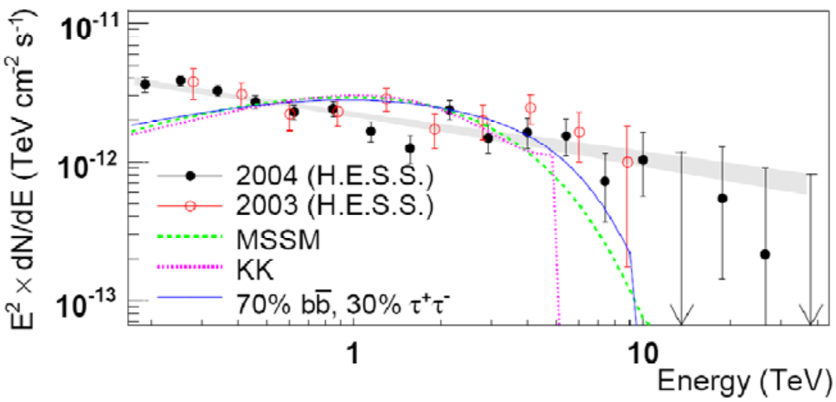
Factor of 100 – 1000 enhancement of annihilation rate possible. B.R. to γγ and Zγ is of order 0.2 – 0.8!

Non-perturbative resummation explains large lowest-order rates to γγ and Zγ. It also restores unitarity at largest masses



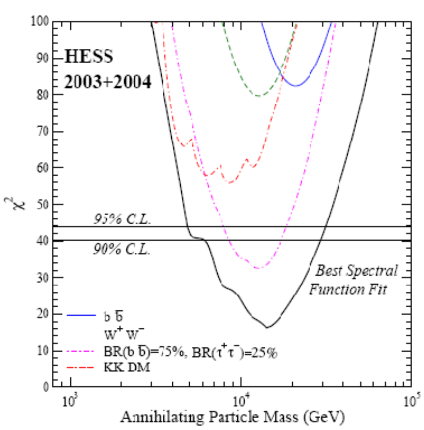
F. Boudjema, A. Semenov, D. Temes, 2005

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

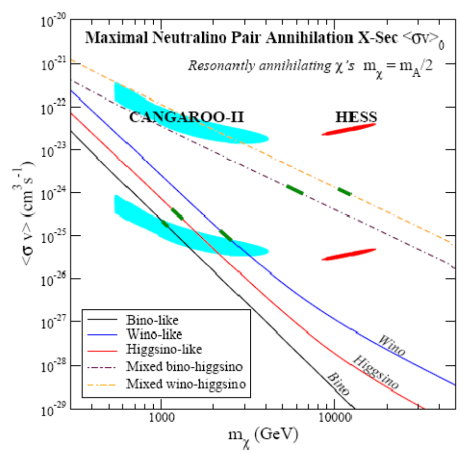


MAGIC (2006) agrees completely with HESS spectrum

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



S. Profumo, 2005

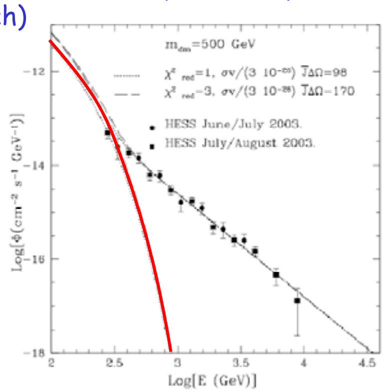


"Fine-tuning" solutions giving very massive neutralinos

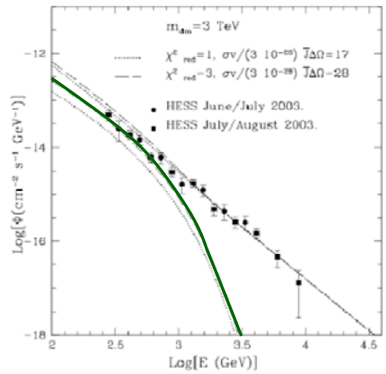
The Galactic Center very high energy signal detected by HESS is probably not related to dark matter (at least not SUSY). Maybe shock acceleration in stellar winds in the central parsec?

Zaharijas & Hooper, 2006:

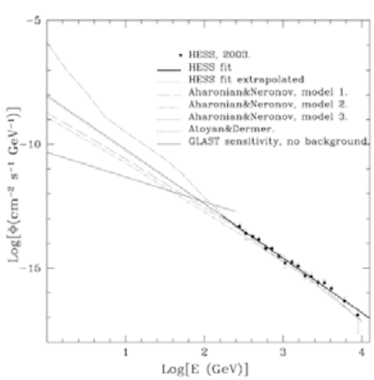
The HESS result means that a dark matter signal has to be found below a large background (→ the galactic center may not be optimal for DM search)



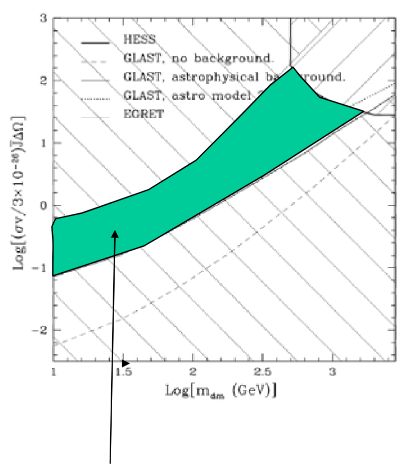
m_χ = 500 GeV



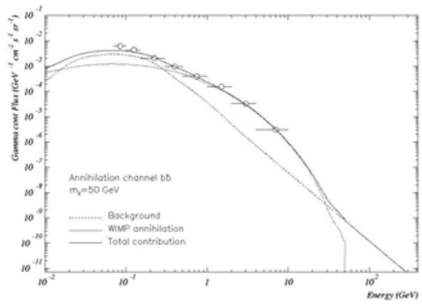
m_χ = 3 TeV

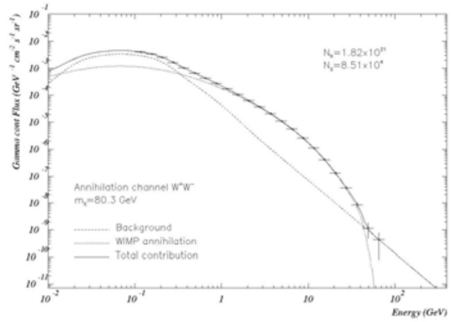


Zaharijas & Hooper, 2006

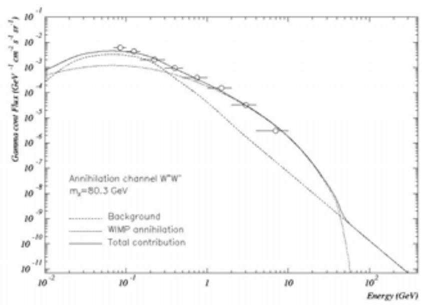


"Window of opportunity" for GLAST





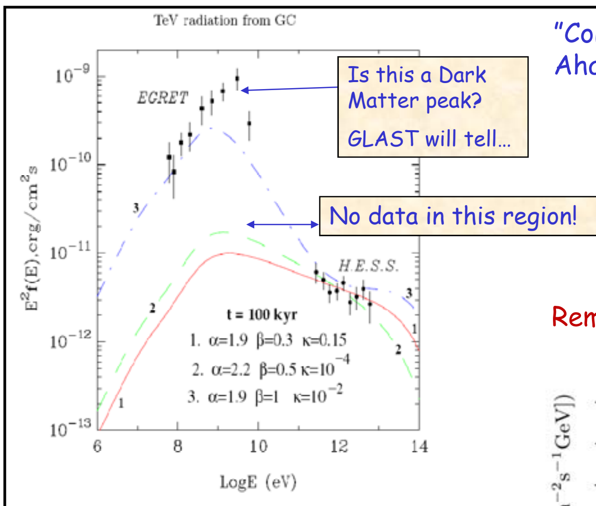
GLAST simulation



At lower energies, the gamma-ray excess towards Galactic center measured by EGRET may be explained by WIMP annihilation

Need high boost factor – this may be OK towards galactic center

A. Cesarini, F. Fucito, A. Lionetto, A. Morselli and P. Ullio,2003



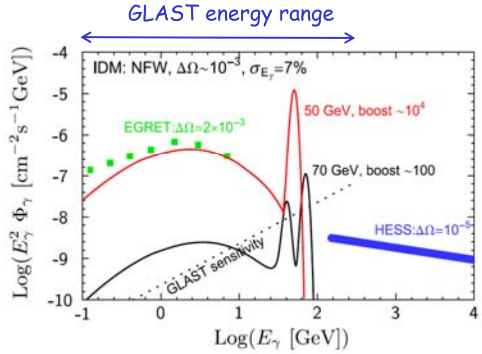
"Conventional explanation", Aharonov & Neronov, 2005

Prediction: variability on 1-hour timescale

GLAST will fill in data between EGRET and HESS

Remember:

GLAST energy range



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

Summary for TeV dark matter

Unique opportunity for ground-based Air Cherenkov telescopes. Many interesting possibilities for enhanced rates, for masses even beyond the LHC limit.

Unfortunately, the striking TeV signal from the galactic center detected by HESS does not seem to be compatible with DM annihilation.

The g.c. source, what ever it is, produces a difficult background for DM searches. Hoever, still an important window at 10 – 200 GeV to probe for GLAST.

Special topics in gamma-ray detection of DM

II. MeV Dark Matter

INTEGRAL all-sky picture of positronium gamma line (511 keV) emission – unknown origin (J. Knödlseder et al., 2005)

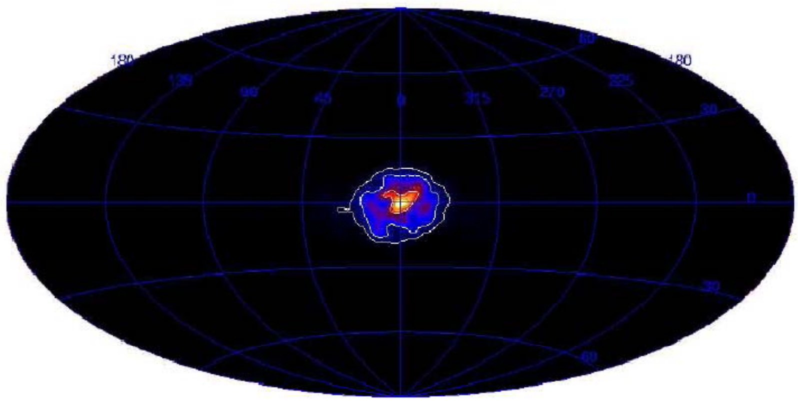


Fig. 4. Richardson-Lucy image of 511 keV gamma-ray line emission (iteration 17). Contour levels indicate intensity levels of 10^{-2}, 10^{-3}, and 10^{-4} ph $cm^{-2}s^{-1}sr^{-1}$ (from the centre outwards).

Is it dark matter annihilation (very low mass needed: 10 - 20 MeV)? Could also be explained by type Ia supernovae, or low mass X-ray binaries?

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

Galactic positrons (511 keV line) from low mass (10 – 100 MeV) dark matter particle decay or annihilation? Beacom, Bell, Bertone (2004): mass has to be less than 20 MeV due to radiative processes

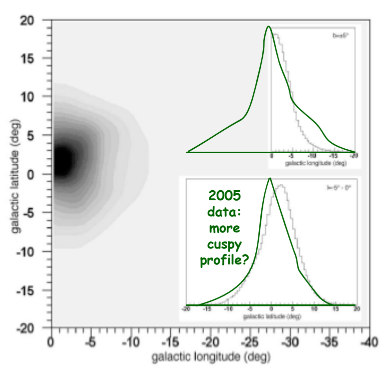
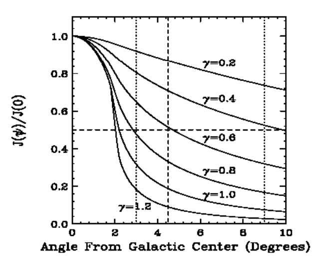


Fig. 2. 511 keV gamma-ray line intensity map of the galactic centre region (only negative longitudes). Black corresponds to regions of maximum 511 keV line intensity. Longitude and latitude profiles, integrated over $b = \pm 5°$ and $l = -5° - 0°$, respectively, are shown as insets.

INTEGRAL satellite measurements



$$\rho \propto r^{-\gamma}$$

Y. Ascasibar & al., 2005: $\gamma = 1.03 \pm 0.04$, NFW-like

Problem: How does one find a reasonable particle physics candidate with low mass and strong couplings to electrons?? (Boehm & Fayet, 2003 have some models, also Kawasaki & Yanagida, 2005; Pospelov & Ritz, 2007; Finkbeiner & Weiner, 2007, see talk tomorrow by N. Weiner).

Beacom and Yüksel, 2005

Inflight annihilation → mass has to be less than around 3 MeV!

Very difficult to find viable particle physics models…

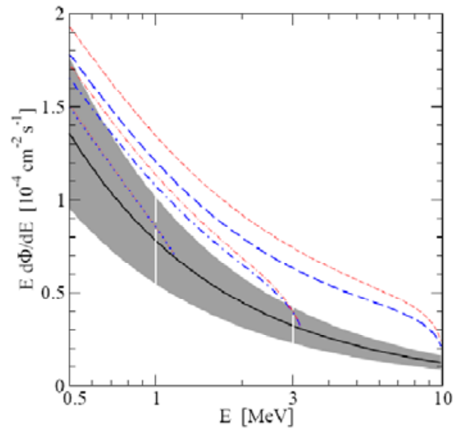


FIG. 2: The INTEGRAL and COMPTEL diffuse gamma ray flux measurements are shown with a black solid line, and their ±30% uncertainties by the gray shaded band. For positron injection energies of 1, 3, and 10 MeV (dotted, dot-dashed and dashed lines), the thick lines show how this would be increased by the inflight annihilation gamma ray flux (thin lines also include the internal bremsstrahlung flux). All results are for a 5°-diameter region at the Galactic Center. The 0.511 MeV line flux is not shown.

Summary for MeV dark matter

Intriguing signal from the central galactic region still unexplained.

DM models not ruled out – but will probably involve some amount of fine-tuning to work.

Special topics in gamma-ray detection of DM

III. Extragalactic Dark Matter

Idea: Redshifted gamma-ray line gives peculiar energy feature – may be observable for CDM-type cuspy halos and substructure (L.B., J. Edsjö, P. Ullio, 2001; L.B., J. Edsjö, P. Ullio & C. Lacey, 2002)

Master formula:

$$\phi_\gamma = \frac{c}{4\pi}\frac{dn_\gamma}{dE_0} = 8.3\cdot 10^{-14}\ \mathrm{cm^{-2}s^{-1}sr^{-1}GeV^{-1}} \times \frac{\Gamma_{26}\Omega_M^2 h^3}{m_{100}^2}\int_0^{z_{up}} dz\, \frac{\Delta^2(z)\, e^{-z/z_{\max}}}{h(z)}\, \frac{dN_\gamma(E_0(1+z))}{dE}$$

Redshift factor

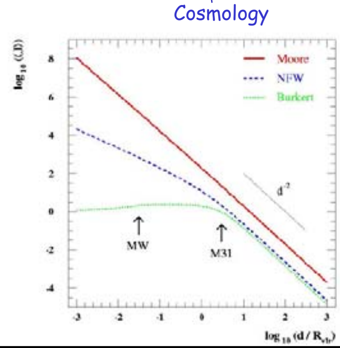
Enhancement factor due to substructure

Cosmology

Absorption on IR and optical background radiation

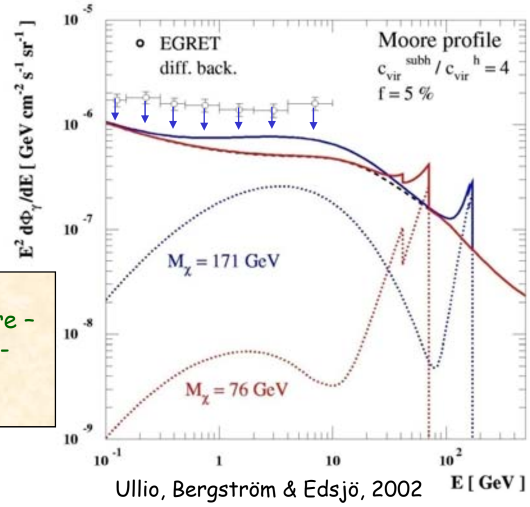
Note that the z-dependence of various factors makes the analysis more convolved than the usual situation with Rate = PPP×APP. However, the averaging over z also means less dependence on details such as the halo density radial distribution

See poster by A. Sellerholm



Diffuse cosmic gamma-rays

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



EGRET points have been moved down by reconsidering galactic foreground, GLAST will also resolve more AGNs

Ullio, Bergström & Edsjö, 2002

This is being upgraded: A. Sellerholm et al., 2007

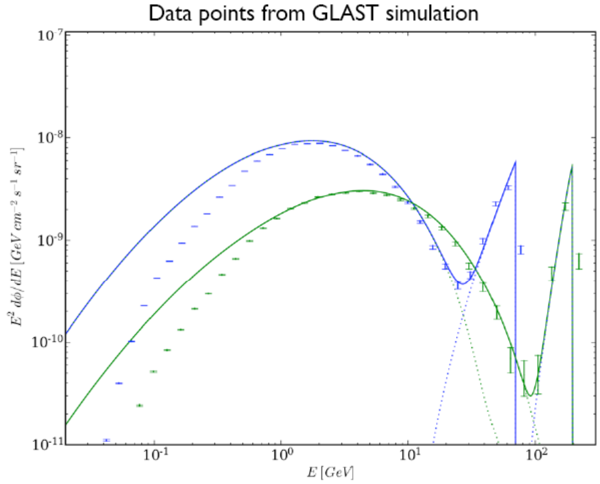
FIG. 13: Extragalactic gamma-ray flux (multiplied by E^2) for two sample thermal relic neutralinos in the MSSM (dotted curves), summed to the blazar background expected for GLAST (dashed curve). Normalizations for the signals are computed assuming halos are modelled by the Moore profile, with 5% of their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

Spectra

M_χ = 70 , 200 GeV
$\sigma v = 3 \times 10^{-26}$ cm^{3}s^{-1}

$b_{\gamma\gamma} = 10^{-3}$

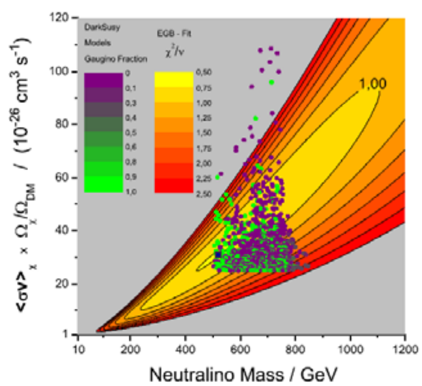
Data points from GLAST simulation

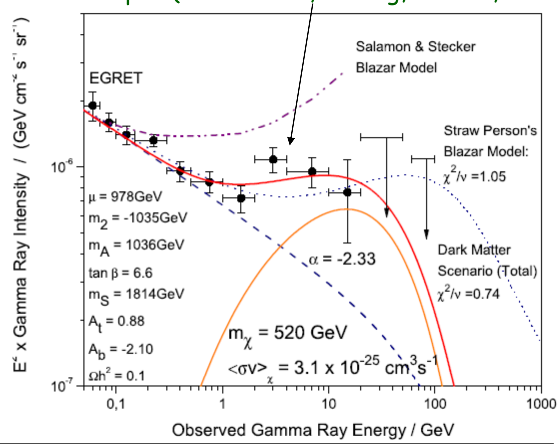


GLAST simulation by A. Sellerholm

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

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

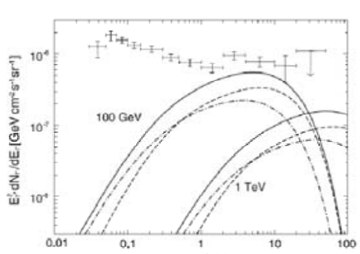
Elsässer & Mannheim, Phys. Rev. Lett. 94:171302, 2005

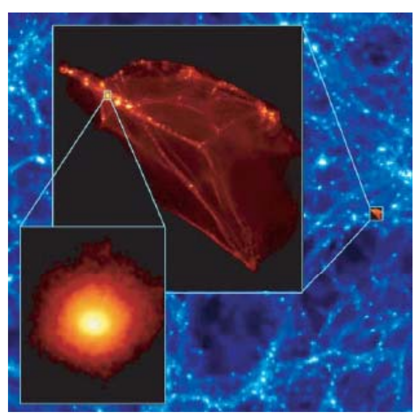
Energy range is optimal for GLAST!

Problem (Ando, PRL 2005): It is difficult to reproduce extragalactic result of Elsässer & Mannheim, without overproducing gammas from g.c.

Resolution (Oda, Totani & Nagashima, 2005): clumpy halos; tidal effects remove substructure near halo canters

Effects of a clumpy halo on diffuse galactic plus extragalactic gamma-ray signal. Satisfies bound from gal. centre:





Oda, Totani and Nagashima, 2005; cf. also Pieri, Branchini and Hofmann, 2005

Summary for Extragalactic DM

Only possible for gamma-rays (or perhaps neutrinos) – positrons and antiprotons do not propagate over large distances.

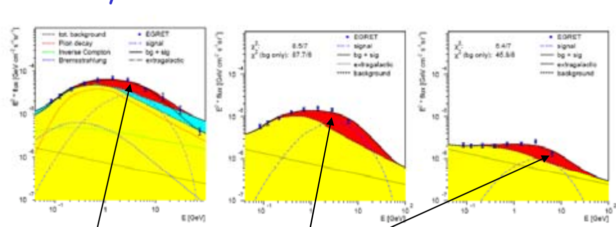
Predictions for signals are becoming more robust. However, the experimental extraction is challenging – have first to correctly model the galactic foregrounds. This will probably take several years with GLAST.

Special topics in gamma-ray detection of DM

IV: de Boer's model

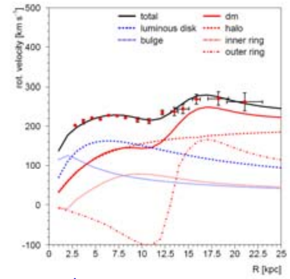
Has supersymmetric dark matter already been detected?

W. de Boer, 2003-2007



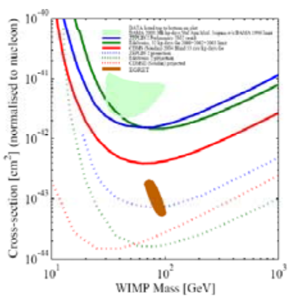
Excess of gamma-rays

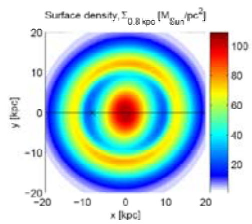
Filled by 65 GeV neutralino annihilation

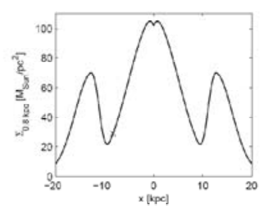


Galactic rotation curve

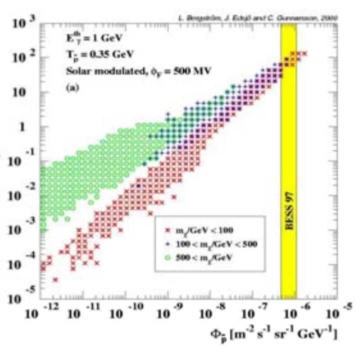
Data explained by 50-100 GeV neutralino?

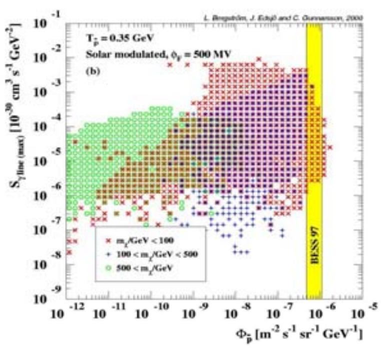






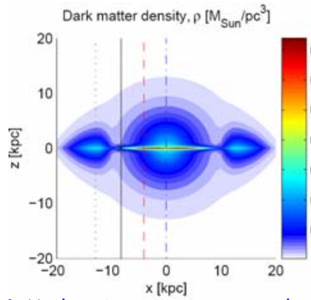
Remember?

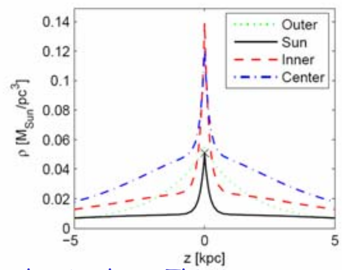




Antiprotons and continuum gamma rays are strongly correlated (through fragmentation of quark jets).

No correlation for lines





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

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

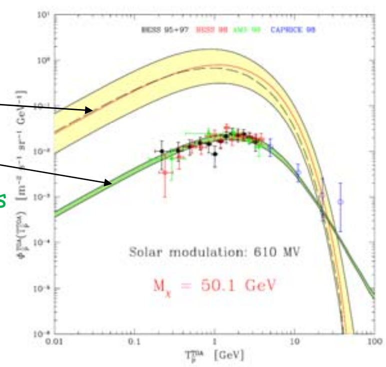
Antiprotons pose a major problem for this type of model:

Expected antiproton flux from de Boer's supersymmetric models

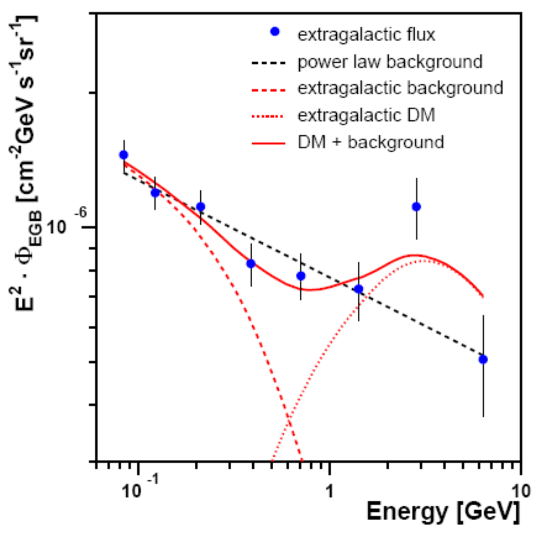
Standard (secondary) production from cosmic rays

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.)



W. De Boer et al., May 2007:
Extragalactic signal?



W. de Boer, A. Nordt, C. Sander, V. Zhukov

There are several problems with this:

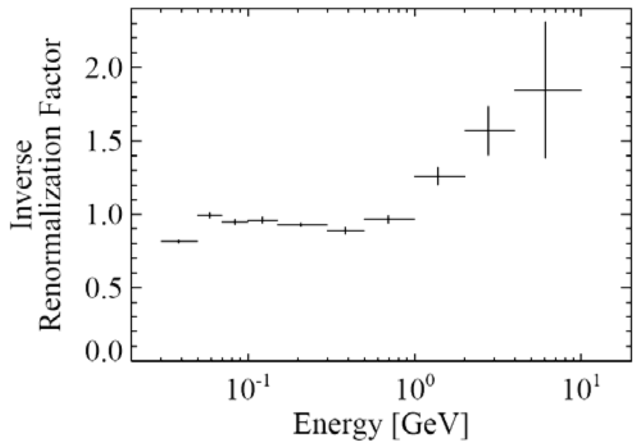
- Only a 2 sigma effect!
- Unknown systematics in the diffuse background extraction. The "bump" seen does not exist in the orignal EGRET data, but was found in a more recent reanalysis by Moskalenko, Strong & Reimer. A very recent paper (Stecker, Hunter & Kniffen, 2007) points out an instrument problem in EGRET as a likely cause of the effect.
- To produce the extragalactic diffuse dark matter signal, the redshift has to be included – this has not been done! (A.Sellerholm)

The Likely Cause of the EGRET GeV Anomaly and its Implications

F. W. Stecker* and S. D. Hunter†
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…

Summary for de Boer's model

There is definitely a "GeV" excess seen in the EGRET data. Can be due to

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!

Special topics in gamma-ray detection of DM

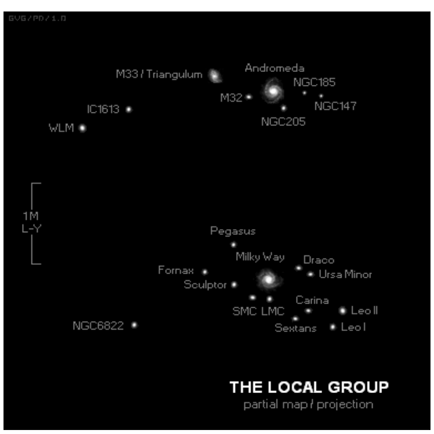
V: Gamma-rays from dwarf galaxies

Dwarf galaxies and dark matter

Example: Draco, dwarf spheroidal galaxy in the Local Group. Estimated total mass: 10^7 – 10^9 solar masses; luminosity ~2 x 10^5 L_{sun} ⇒ mass-to-light ratio 100-1000. One of the most dark matter-dominated galaxies known! Starpoor ⇒ much cleaner observation conditions than galactic center

Draco: Size 0.5 degrees across. Optically very faint.

Integrated magnitude ~ 11 → good candidate for ACT observations.



Dark Matter in Draco?

CACTUS solar array first claimed a preliminary signal 2005; then retracted 2006

N.W. Evans, F. Ferrer & S.Sarkar, 2004:

Typical Expected Flux Values ($cm^{-2}\ s^{-1}$) for $E > 1$ GeV

Model	Galactic Center	Sagittarius dSph	Draco dSph	Canis Major dSph
NFW	3.2×10^{-9}	1.1×10^{-10}	9.9×10^{-12}	7.8×10^{-10}
Power-law	6.0×10^{-11}	5.3×10^{-11}	5.1×10^{-12}	2.9×10^{-10}

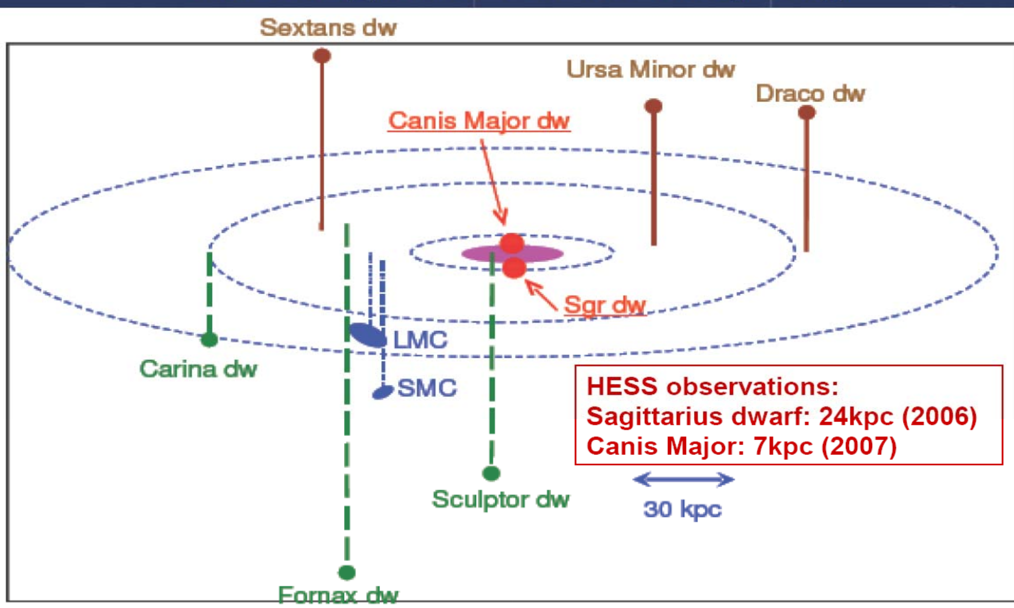
Very small rates

L.B. & D. Hooper, 2005; S. Profumo & M. Kamionkowski, 2006, Colafrancesco, Profumo and Ullio, 2006:

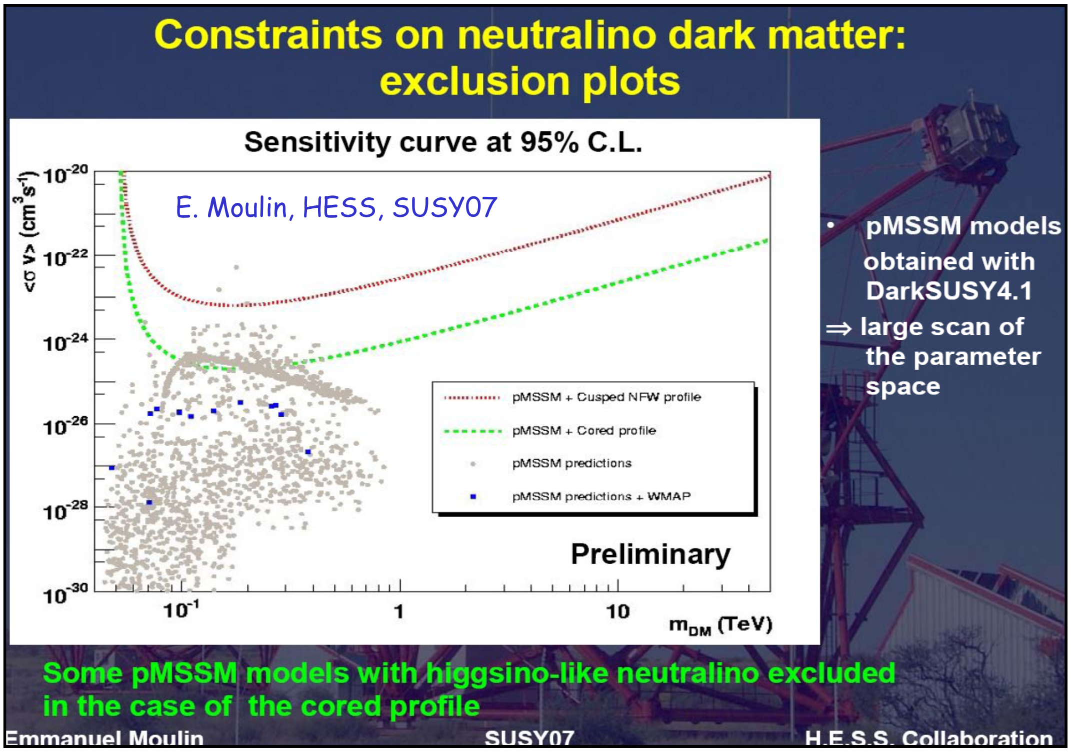
Rate may be increased by factor ~10, beyond that one needs nonthermally produced WIMPs. Tension with EGRET data → non-standard spectrum needed.

Since Sagittarius and Canis Major are much closer, rates should be higher from there. HESS has done a search (2007)

Satellite galaxies of the Milky Way



Emmanuel Moulin SUSY07 H.E.S.S. Collaboration



Summary for gamma-rays from dwarf galaxies

Promising location for DM signals – no convincing detection yet.

Conclusions

- The existence of Nonbaryonic Dark Matter has been definitely established
- CDM is favoured
- Supersymmetric particles (in particular, neutralinos) are still among the best-motivated candidates although other WIMPs (KK, extended Higgs,..) are certainly possible – LHC will be decisive
- New (direct and) 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 would be a "smoking gun"
- The various indirect and direct detection methods are complementary to each other and to LHC
- The hunt is going on – many new experiments coming!
- GLAST opens a new window: will search for "hot spots" in the sky with high sensitivity up to 300 GeV
- PAMELA may revolutionize measurements of e^+ and antiprotons
- The dark matter problem may be near its solution…