# Indirect Dark Matter Searches

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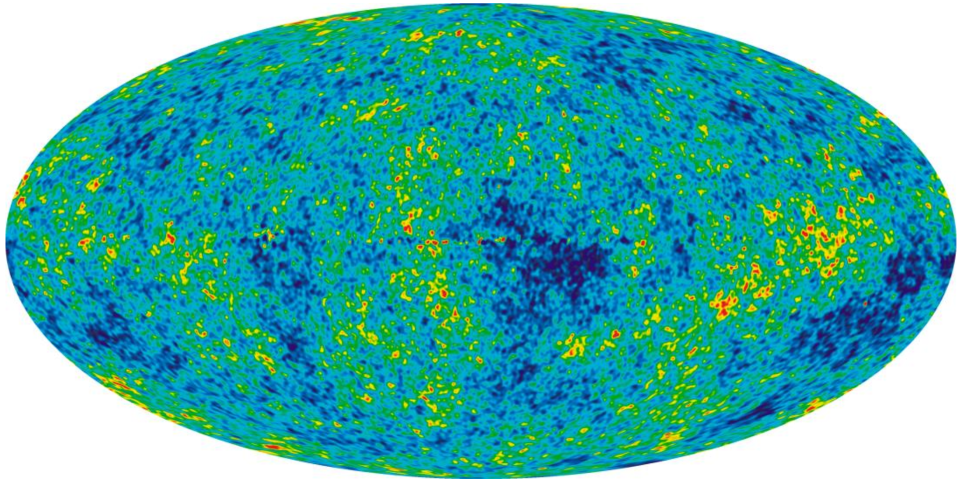
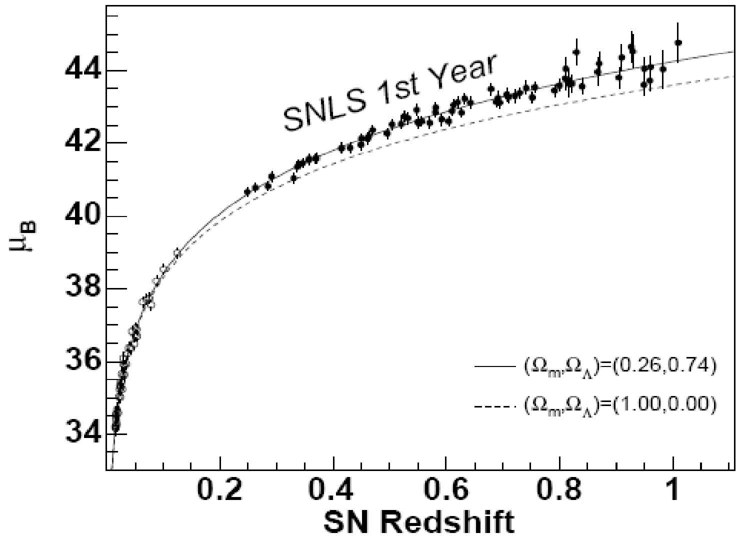
TeV Particle Astrophysics 2007
Venice, August 27

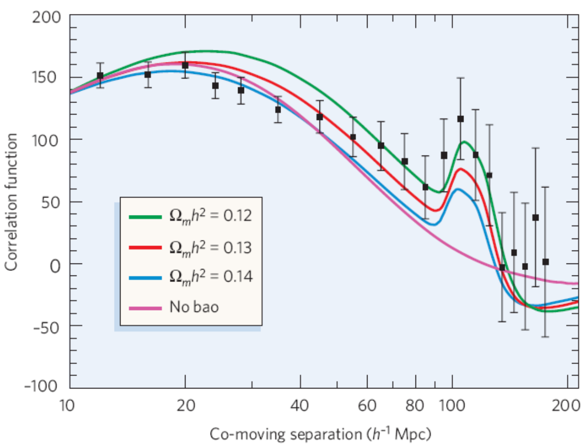
WMAP, 3-year data



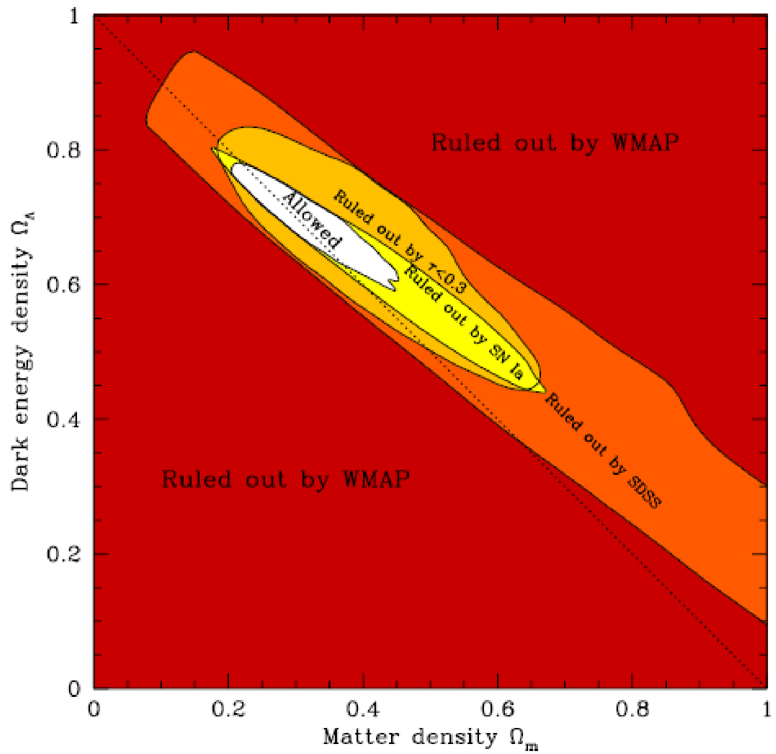
G. Hinshaw et al., 2006

P. Astier, et al., 2005

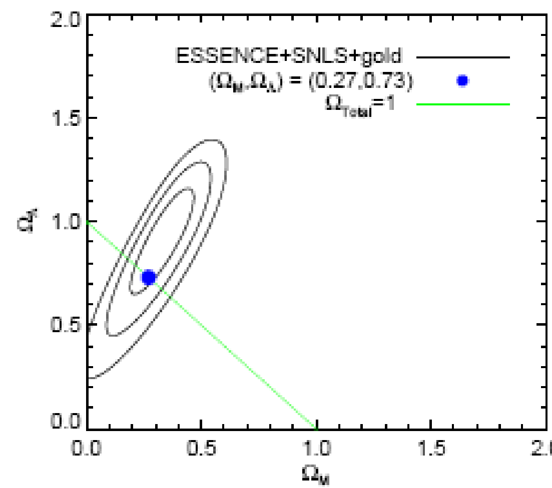



SDSS, 2005




M. Tegmark et al, 2004



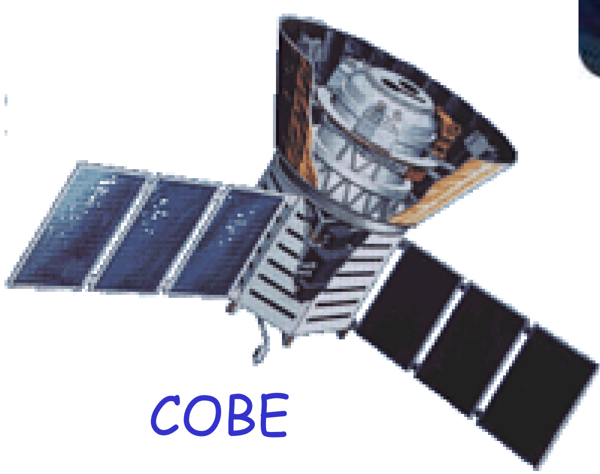

W.M. Wood-Vasey et al., 2007

1990's: Opening of a new era, which has turned the tide in favour of cold dark matter: Precision Cosmology

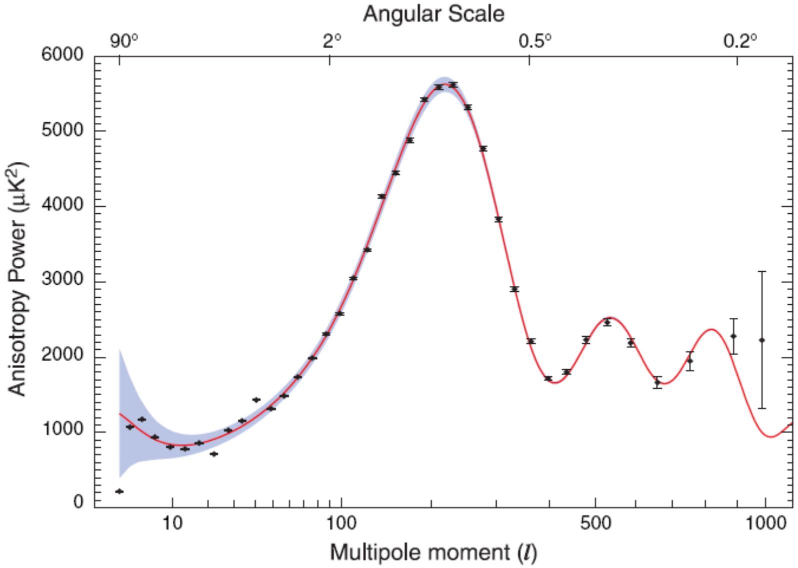
Nobel Prize in Physics 2006

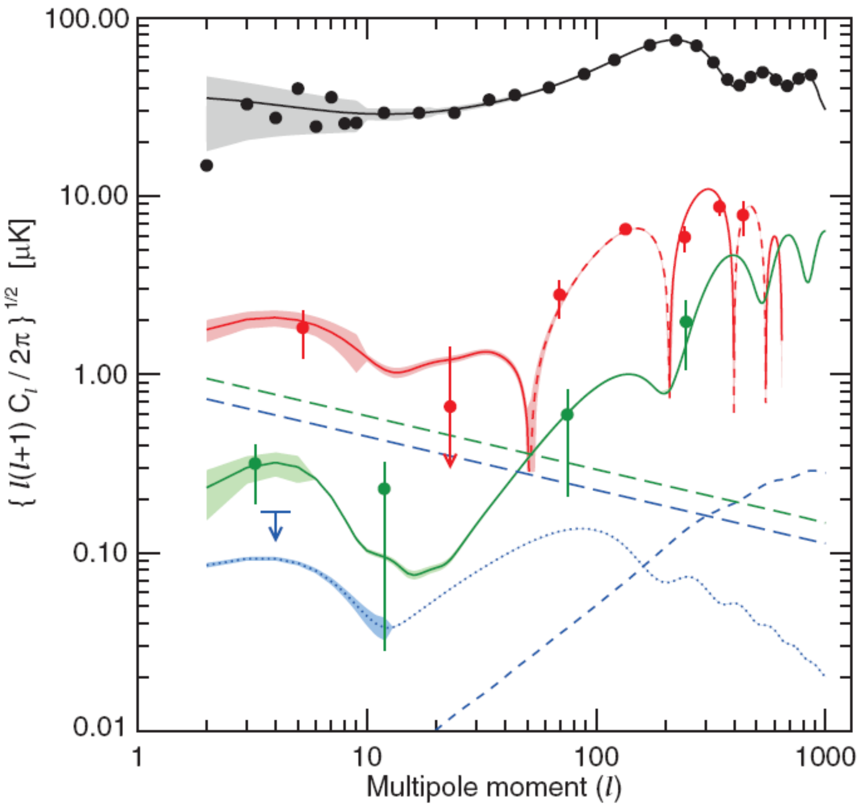
John Mather George Smoot

"... for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation."



COBE



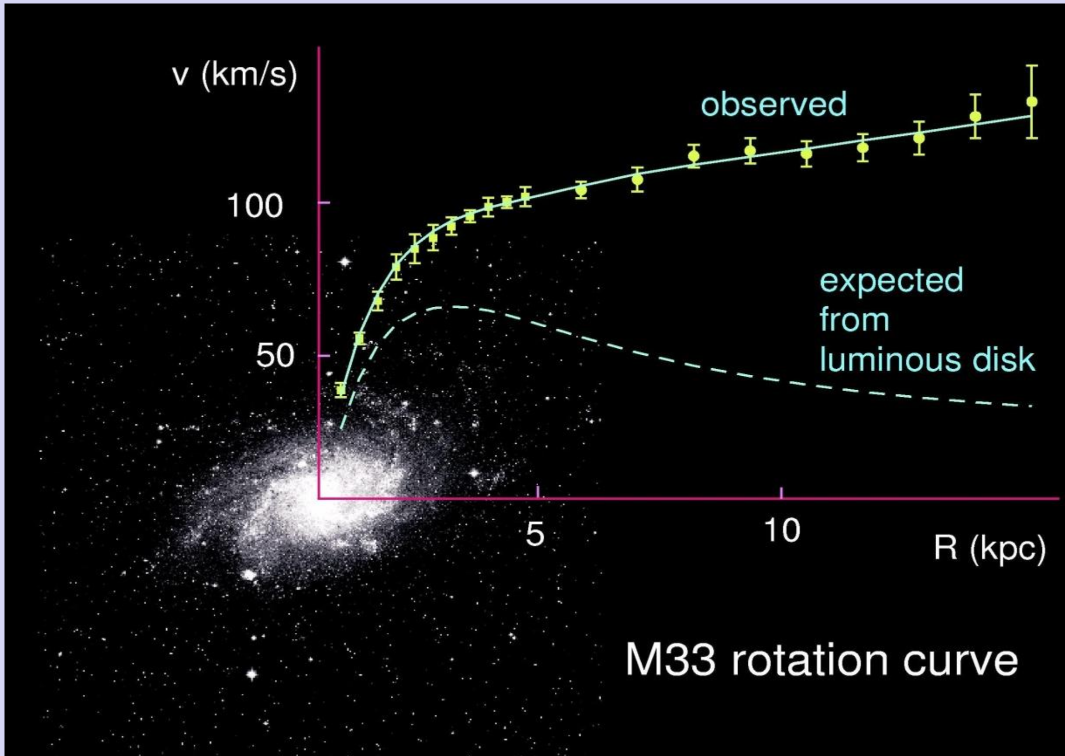




Result from best-fit model from WMAP3, Concordance $\Lambda$CDM Model (for flat Universe):

- Only 4.4 % baryonic matter, $\Omega_b h^2 = 0.0223$ 0.0009
- Around 22 % Cold Dark matter, $\Omega_{CDM} h^2 = 0.105$ 0.013
- Around 74 % "Dark energy", $\Omega_\Lambda = 0.74$ 0.04
- Age of Universe: $13.7 \pm 0.2$ Gyr

Dark matter needed on all scales!
(⇒ MOND and other *ad hoc* attemps to modify Einstein or Newton gravity very unnatural & unlikely)

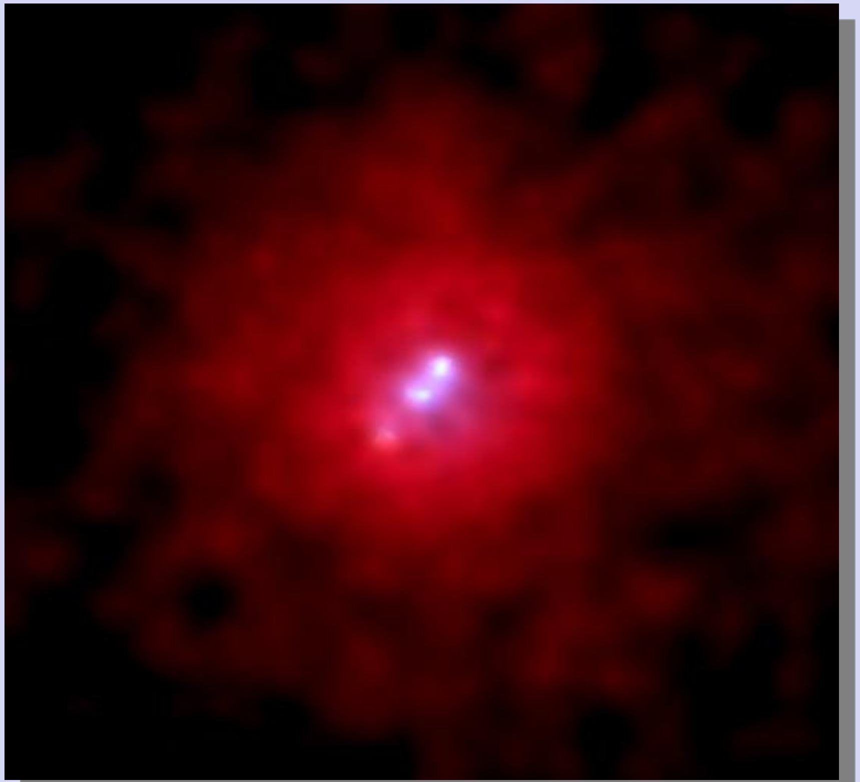
## Galaxy rotation curves




L.B., Rep. Prog. Phys. 2000

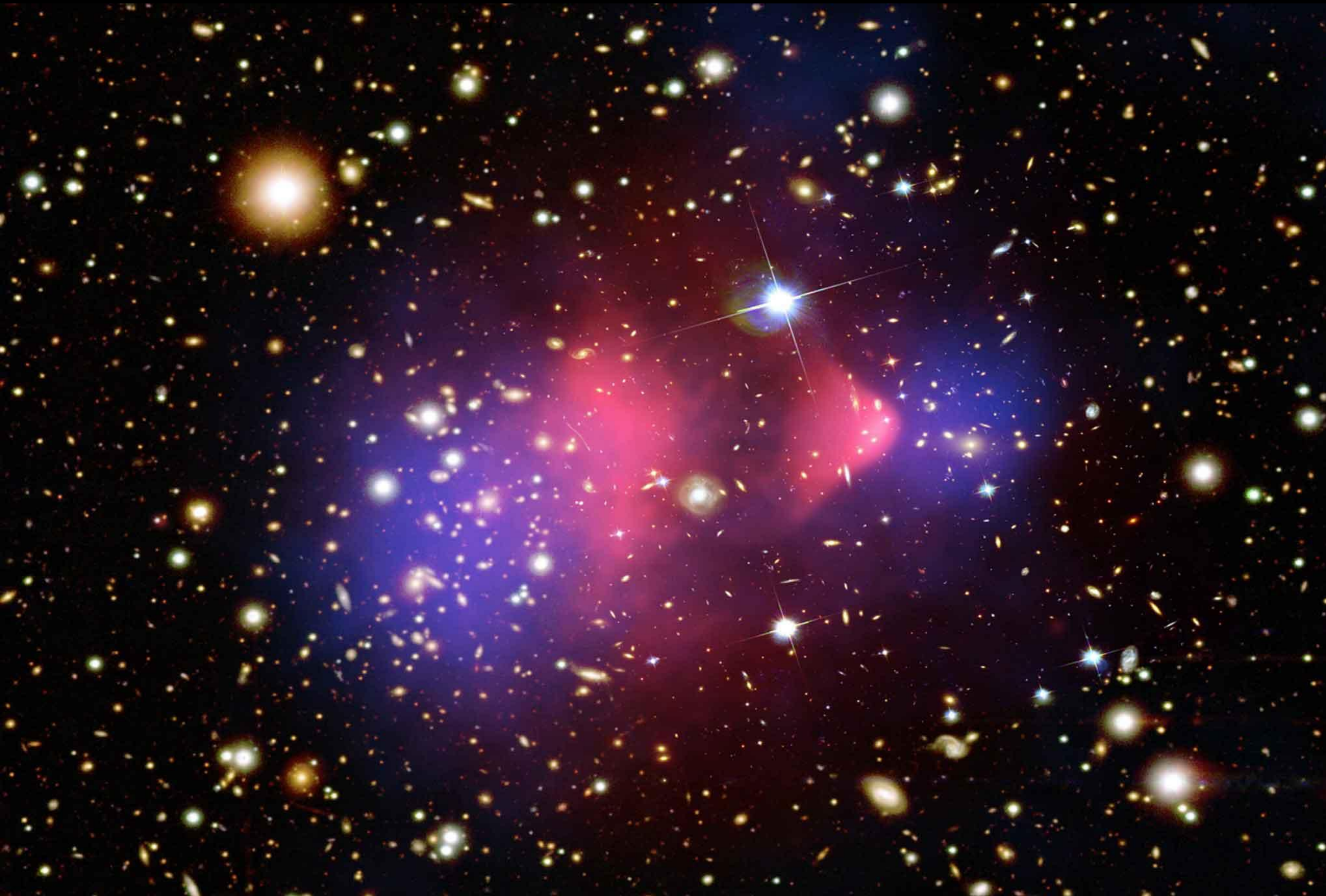
cf. Babcock, 1939

## X-ray emitting clusters



Cluster 3C295 (Chandra)

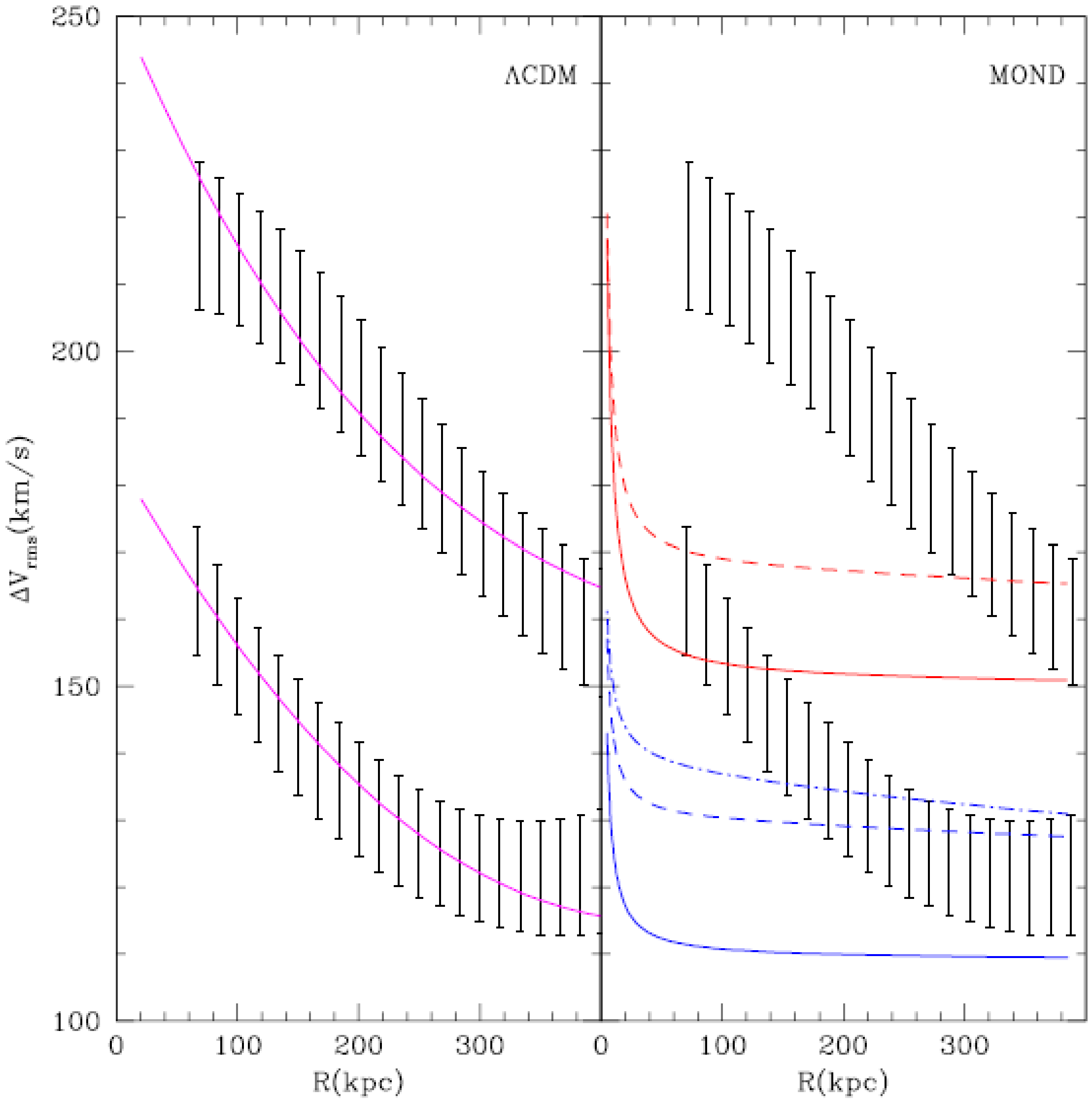
cf. Zwicky, 1933



New, November 2006: Strong new evidence for nonbaryonic dark matter

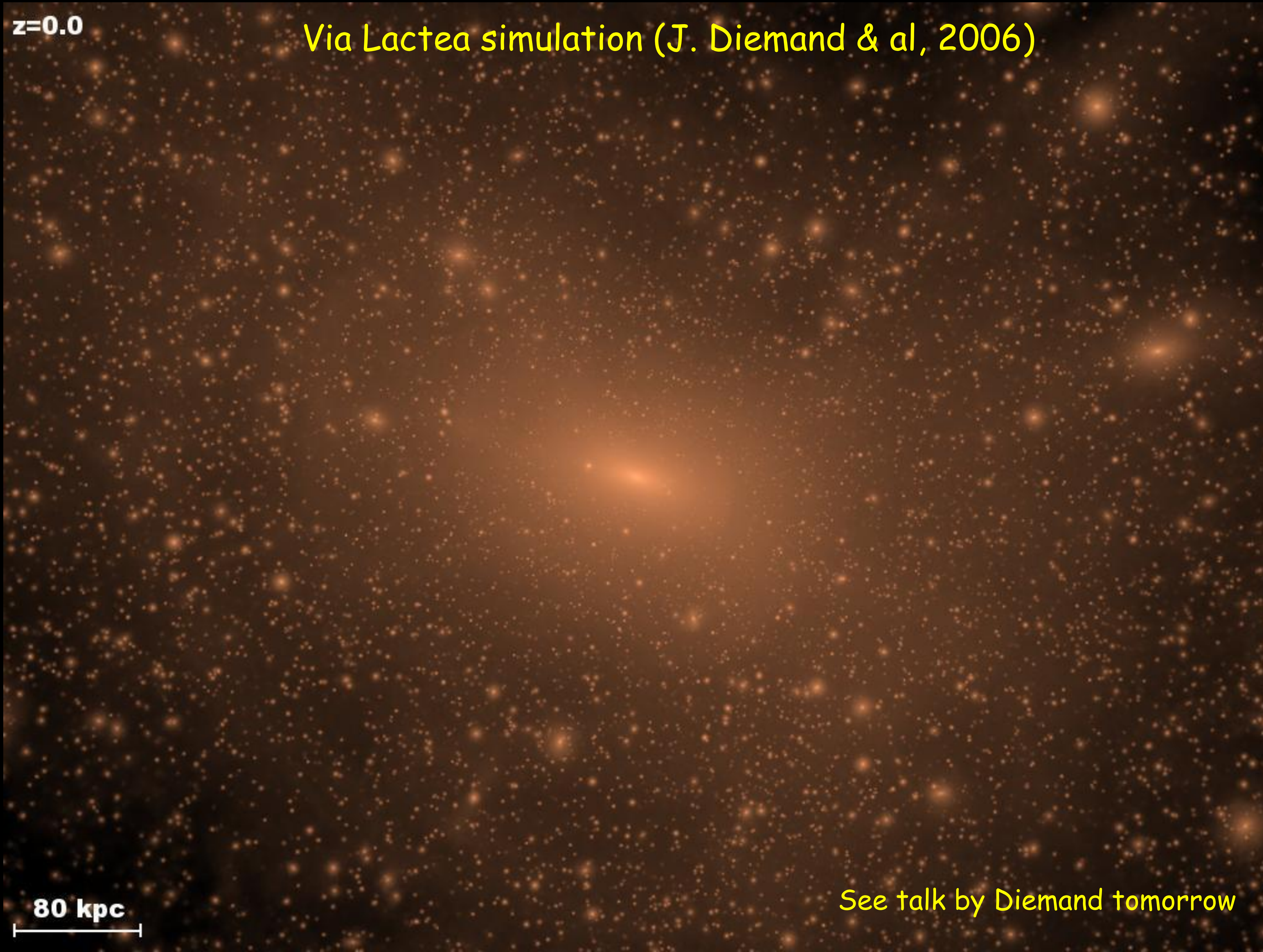
"Bullet cluster", D. Clowe & al., Ap. J., 2006

MOND ruled out (or at least has to have dark matter also… See talk by Zhao this afternoon)

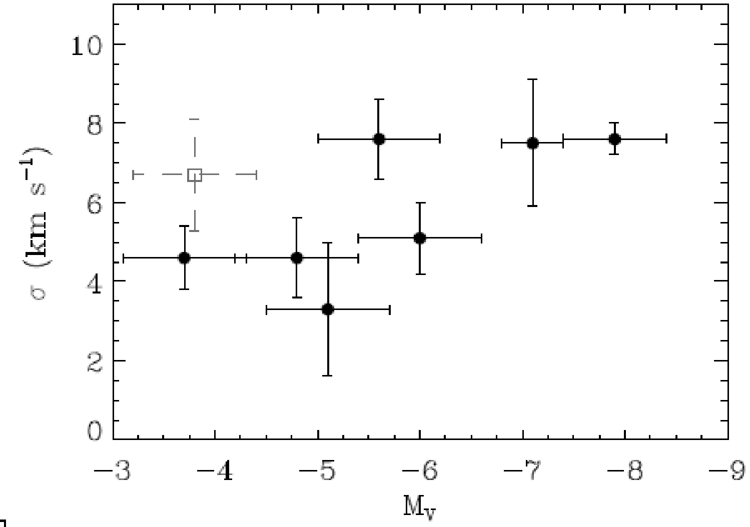



Klypin & Prada, June 2007:

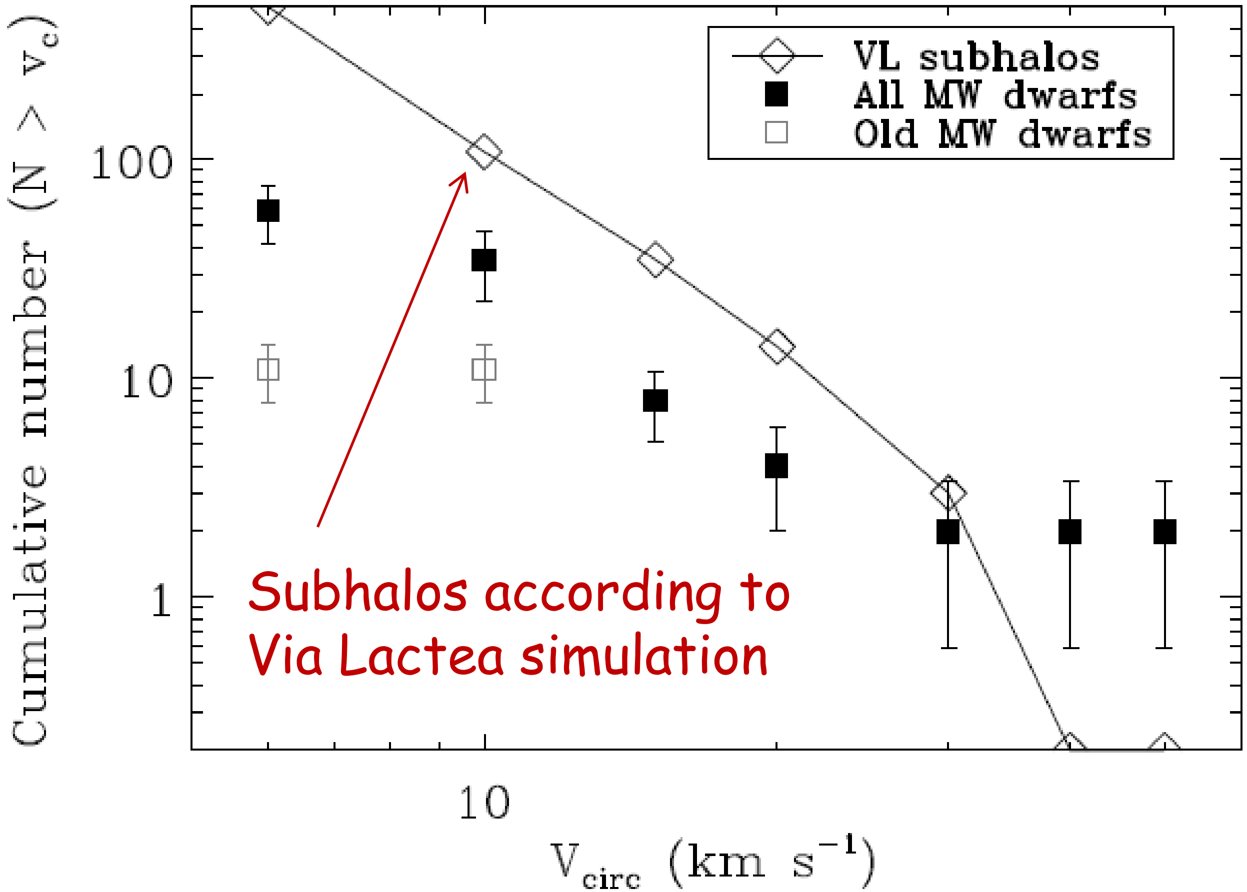
Comparison between CDM and MOND for line-of-sight velocity distribution of galactic satellites from Sloan data


z=0.0
Via Lactea simulation (J. Diemand & al, 2006)
80 kpc
See talk by Diemand tomorrow

New Keck data (2007) on ultra-faint dwarf satellites of Milky Way. Potential problem of CDM now alleviated: The lack of observed substructure (satellite galaxies) in Milky Way neighbourhood (Simon & Geha, 2007). Ishiyama, Fukushige & Makino, 2007: Simulations show that galaxies like the Milky Way, in a low density region, have much fewer subhalos.

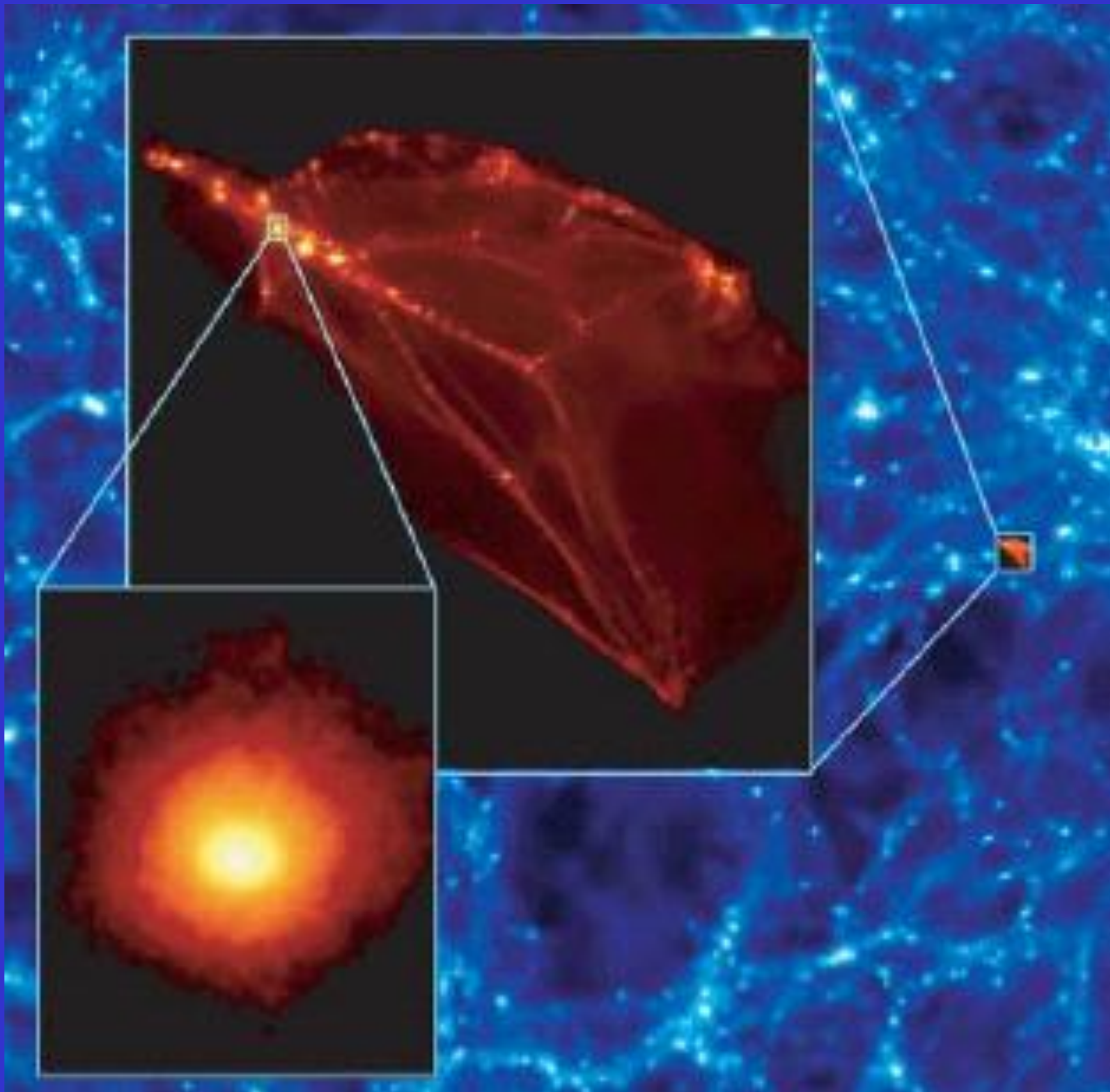



arXiv:0706.0516v1 [astro-ph] 4 Jun 2007




The "Gilmore limiting density" of 5 GeV/cm$^3$ (G. Gilmore & al, 2005) seems violated by factor ~ 5

In fact, the phase space density $Q = \rho/\sigma^3$ has an order of magnitude higher value than for previously known galaxies



Diemand, Moore & Stadel, 2005:

The first structures to form are mini-halos of $10^{-6}$ solar masses. There would be zillions of them surviving and making up a sizeable fraction of the dark matter halo.

But, will mini-halos survive tidal interactions in the host halo?

Much more work, both analytically, numerically and observationally will be needed to settle this important issue.

(See next talk, by Anne Green, also Diemand, Pieri tomorrow)

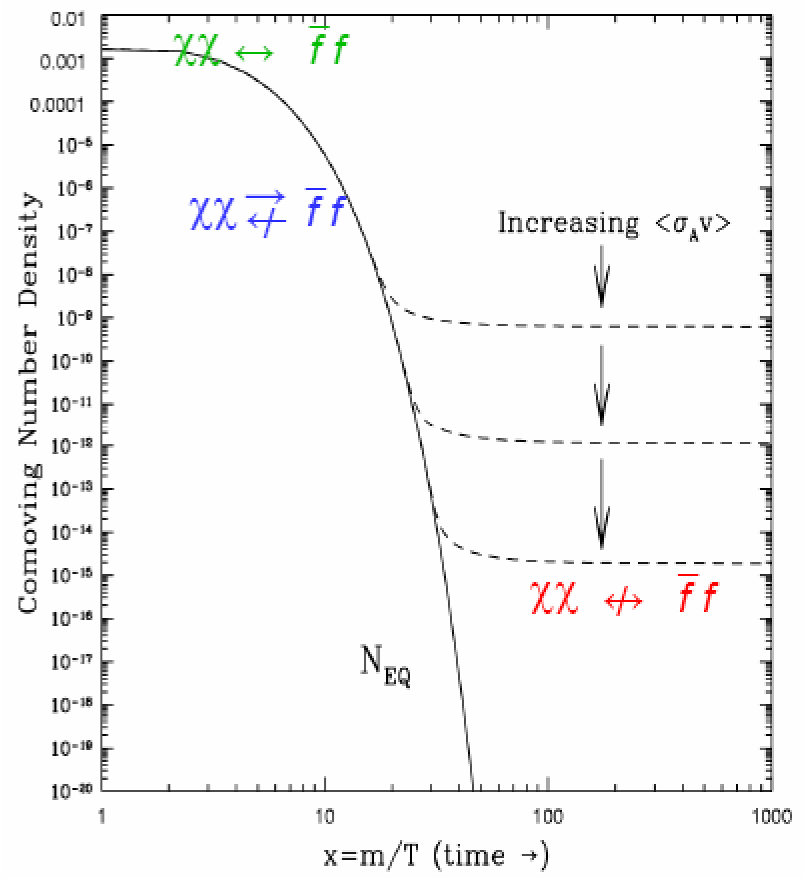
# The situation today:

The existence of Dark Matter, especially Cold DM, has been established by a host of different methods…

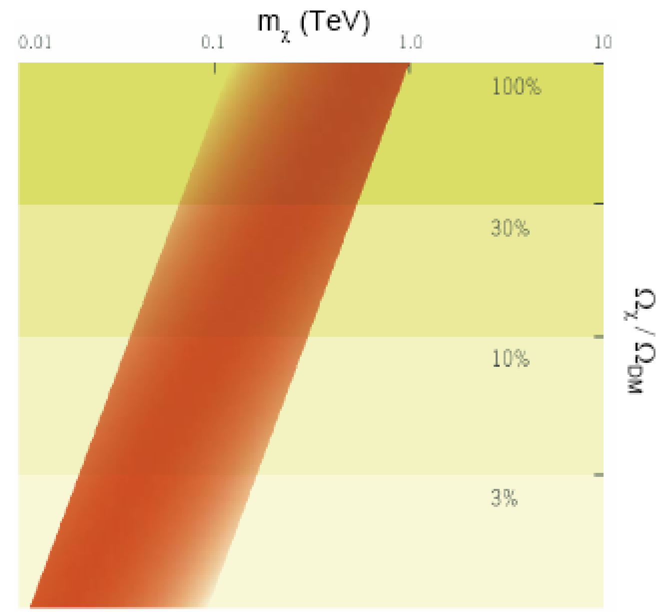
…but, the question remains: what is it?

From J. Feng:

# The WIMP "Miracle"




$$\Omega_\chi \sim <\sigma_A v>^{-1} \sim m_\chi^2/(k\alpha^2)$$




HEPAP LHC/ILC Subpanel (2005)

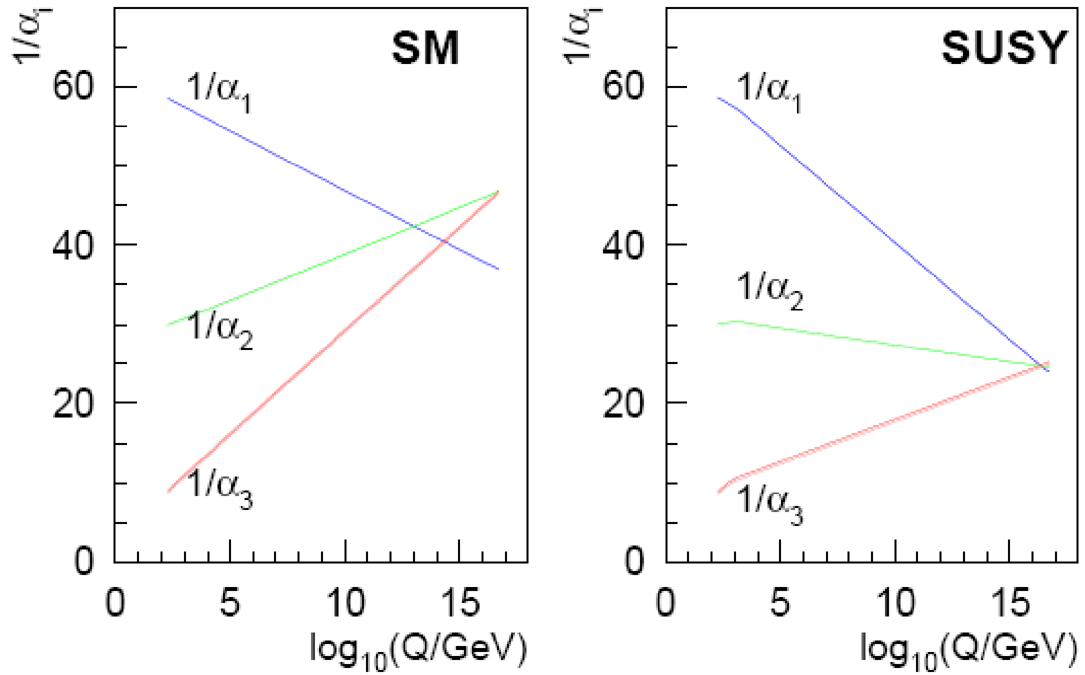
[k = 0.5 – 2, S- and P-wave]

R parity conservation ⇒ Lightest SUSY particle stable ⇒ relic density can be computed from thermal freeze-out in early Universe

Note that a larger annihilation cross section means a smaller relic density.

# Supersymmetry

- Invented in the 1970's
- Necessary in most string theories
- Restores unification of couplings
- Can solve the hierarchy problem
- Gives right scale for neutrino masses
- Predicts light Higgs ( < 130 GeV)
- May be detected at Fermilab/LHC
- Gives an excellent dark matter candidate (If R-parity is conserved ⇒ stable on cosmological timescales)
- May generate EW symmetry breaking radiatively
- Useful as a template for generic WIMP - Weakly Interacting Massive Particle




The lightest neutralino: the most natural SUSY dark matter candidate (H. Goldberg 1983; J. Ellis & al., 1984). Gravitinos are quite different, see talk by L. Covi.

$$\tilde{\chi}^0 = a_1\tilde{\gamma} + a_2\tilde{Z}^0 + a_3\tilde{H}_1^0 + a_4\tilde{H}_2^0$$

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

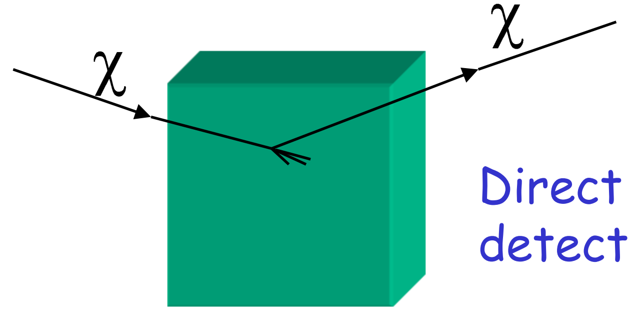
"Neutralino dark matter made easy" - Can be freely dowloaded from http://www.physto.se/~edsjo/ds

Release 4.1: includes coannihilations & interface to Isasugra

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

Methods of WIMP Dark Matter detection:

- Discovery at accelerators (Fermilab, LHC, ILC…). See talk by Battaglia.
- Direct detection of halo particles in terrestrial detectors. See talks by Chardin and Rubbia.
- 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.

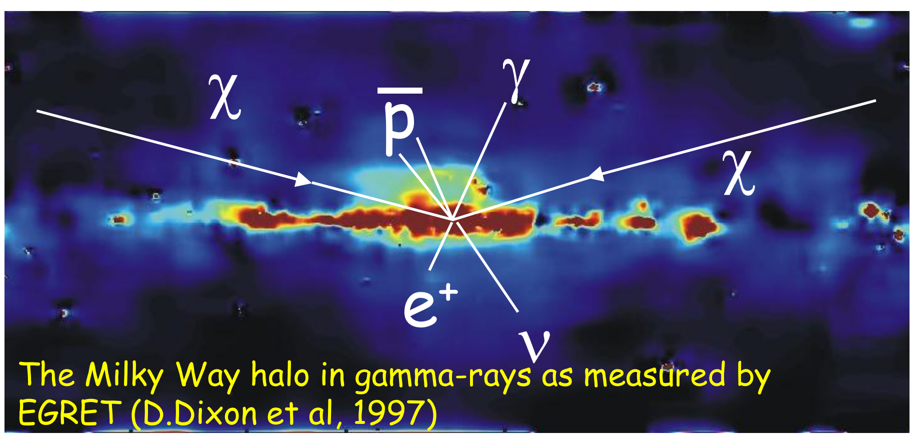



Direct detection

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

Neutralinos are Majorana particles

Indirect detection

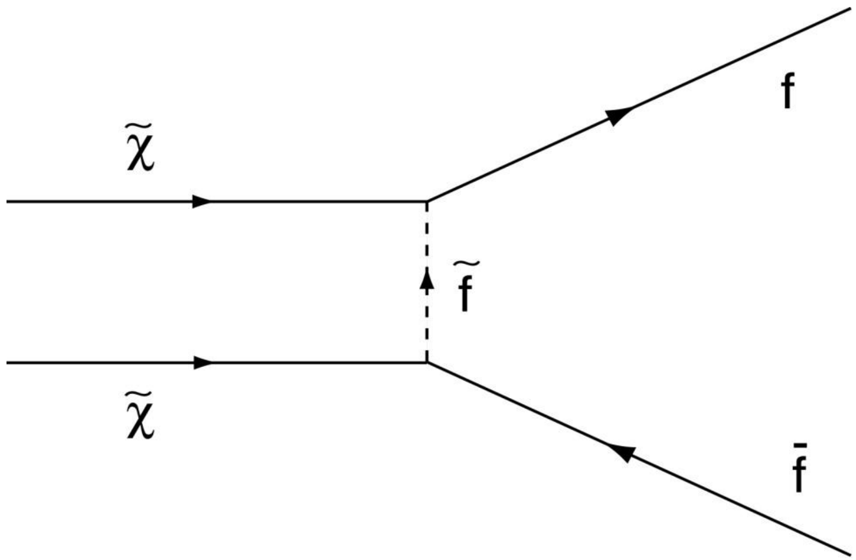



The Milky Way halo in gamma-rays as measured by EGRET (D.Dixon et al, 1997)

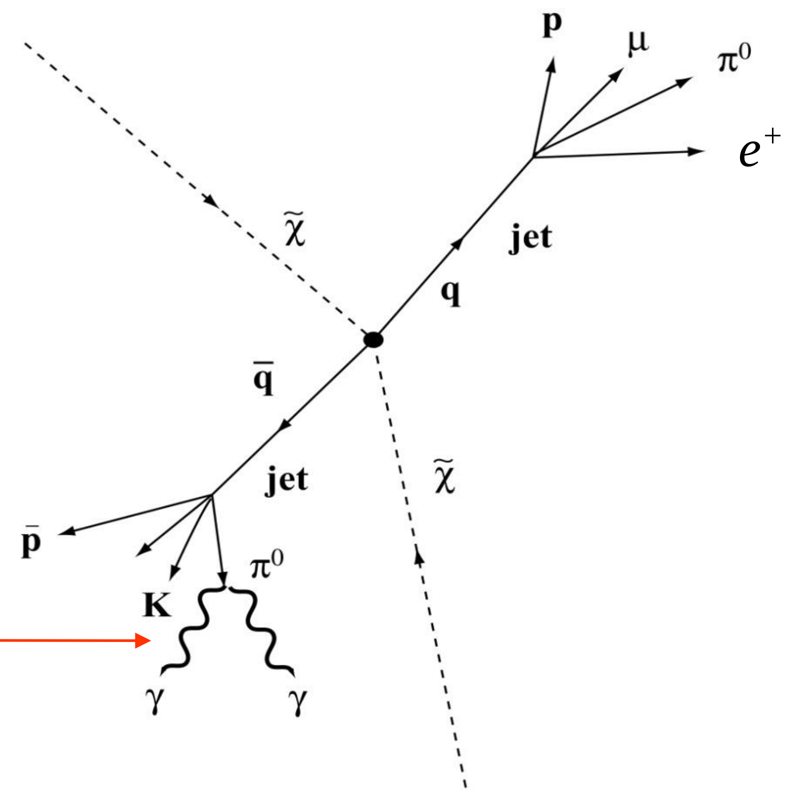
$$\Gamma_{ann} \propto n_\chi^2 \sigma v$$

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

# 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.)

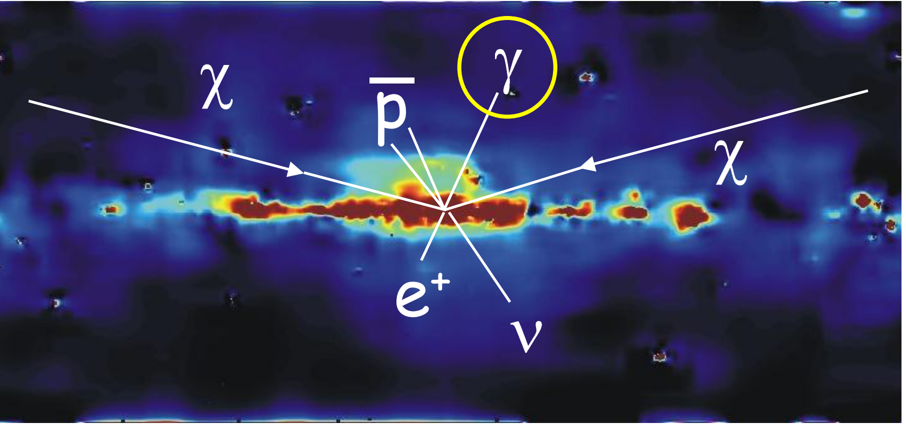
Indirect detection rate = (Particle Physics Part) ∗ (Astrophysical Part)

Particle Physics Part: Model for DM particle (spin, mass); $\langle\sigma v\rangle$ at $v/c \sim 10^{-3}$; branching ratio and energy distribution for a given final state particle. Even for relic abundance fixed by cosmology (e.g., $\Omega h^2 = 0.11$), the yield of a specific final state particle at a specific energy can vary by orders of magnitude.

Astrophysical Part: Density of DM particle at production site (halo model and model for subhalos); eventual effects of diffusion and absorption, etc. May give rise to model-dependent predictions which also differ by orders of magnitude.

Disclaimer: Unfortunately, no really solid predictions for detection rates can be made; in particular, the absence of a signal cannot directly be converted to a useful limit of particle physics parameters.

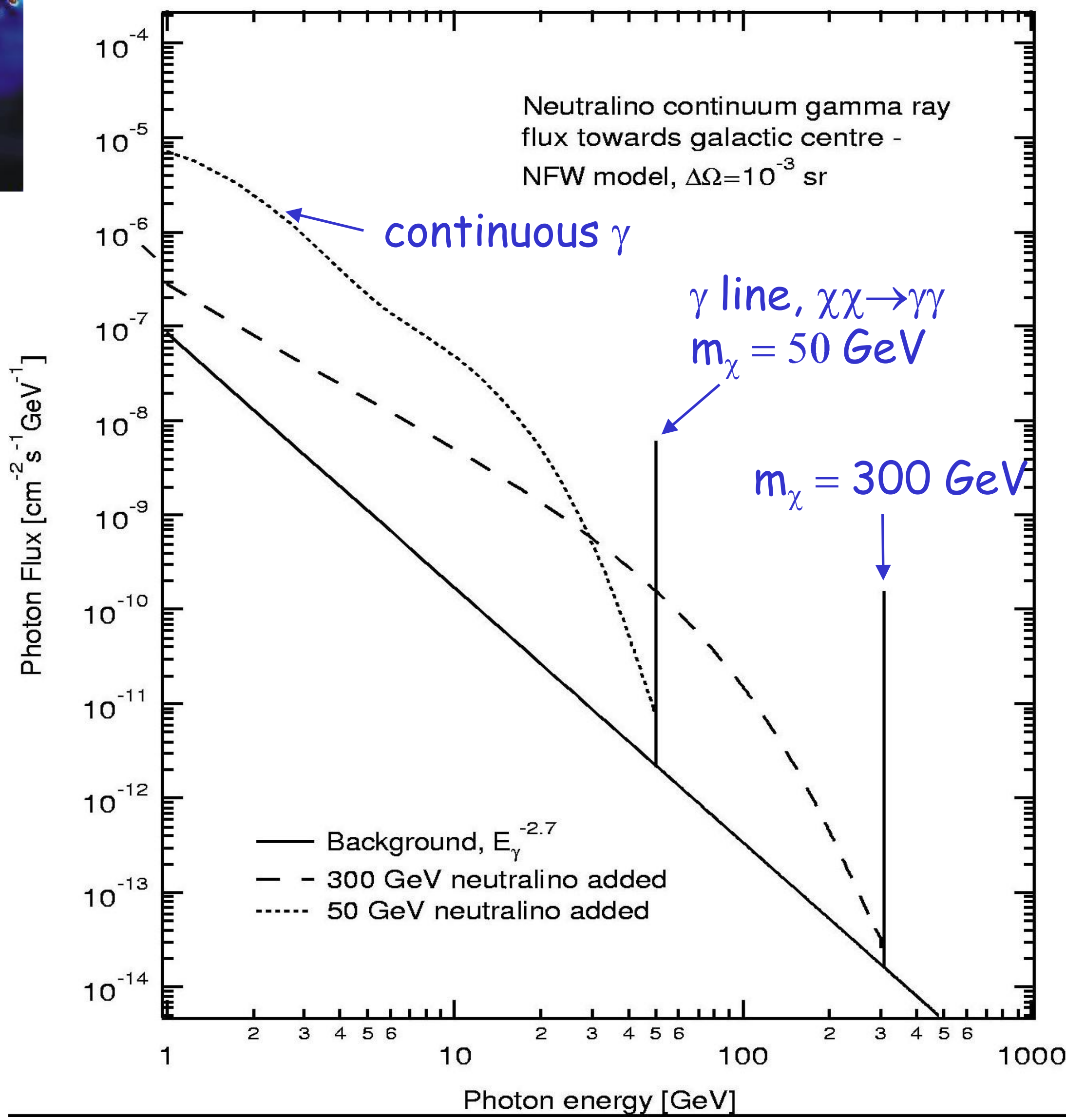
If a signal is claimed to be found, one will probably need some distinctive feature, e.g. energy or angular distribution, to be convinced. Also, cross-correlations between different detection methods (direct, indirect, accelerator) will be crucial. A positive detection will give important information both about particle physics (e.g. the mass of the DM particle) and astrophysical properties (e.g, halo DM density distribution).




# Gamma-rays

Indirect detection through $\gamma$-rays. Two types of signal: Continuous (large rate but at lower energies, difficult signature) 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)



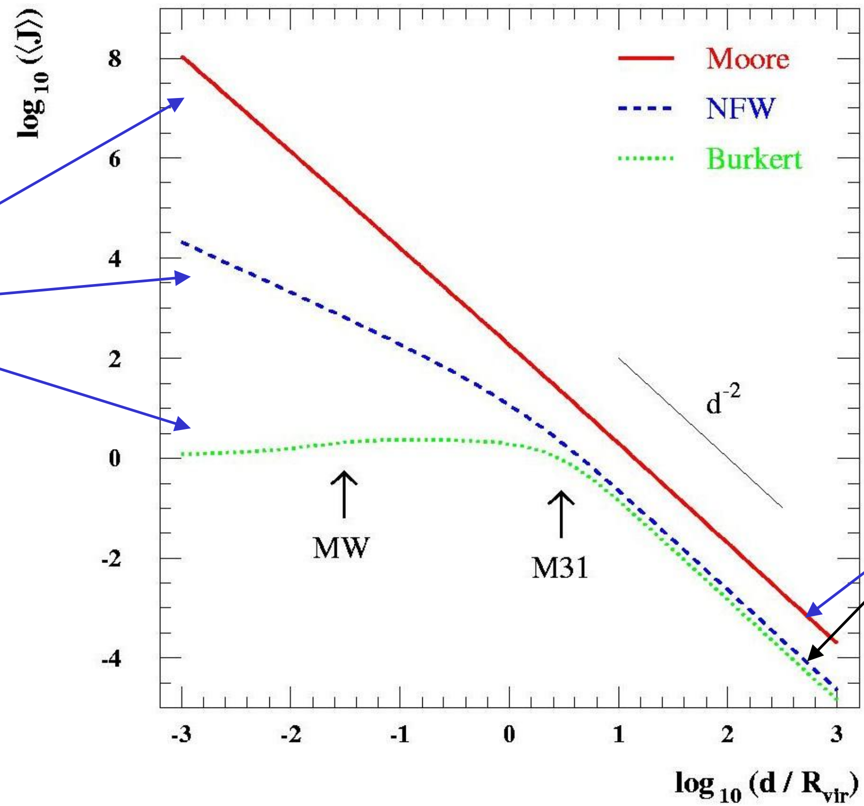

L.B., P.Ullio & J. Buckley 1998

Detection rate = (PPP)×(APP)

~ <σv>   ~ J

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

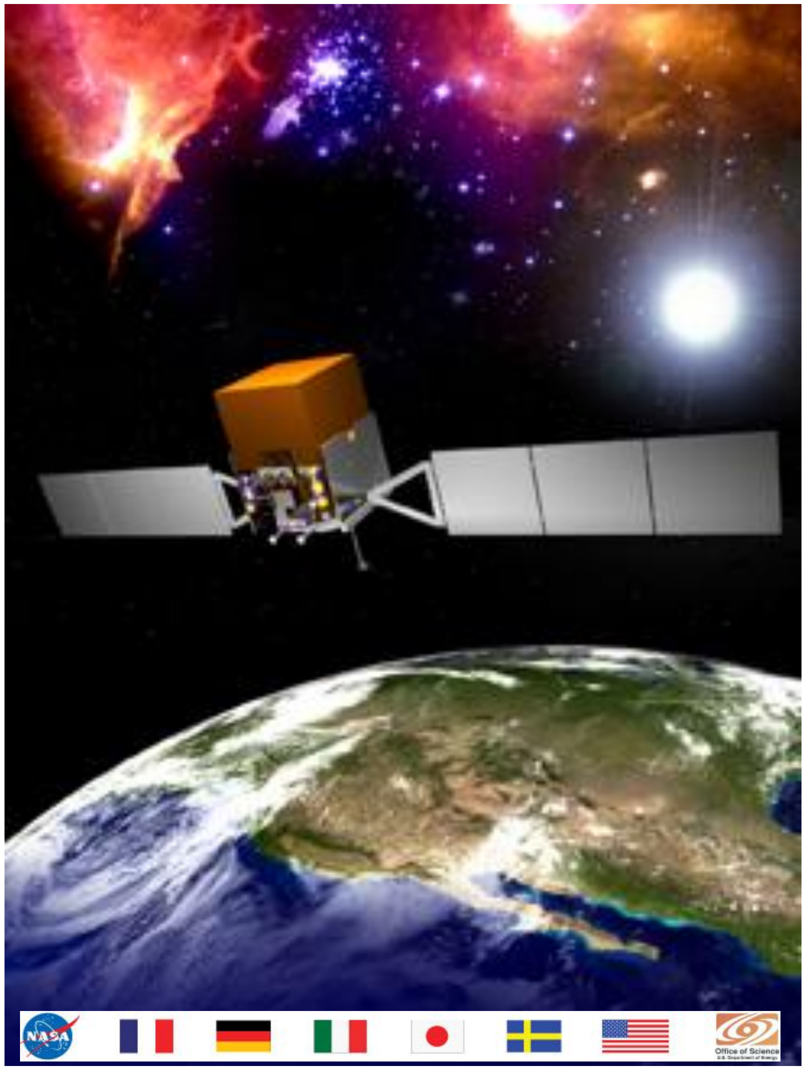
Note large uncertainty of flux for nearby objects (Milky Way center, LMC, Draco,...)



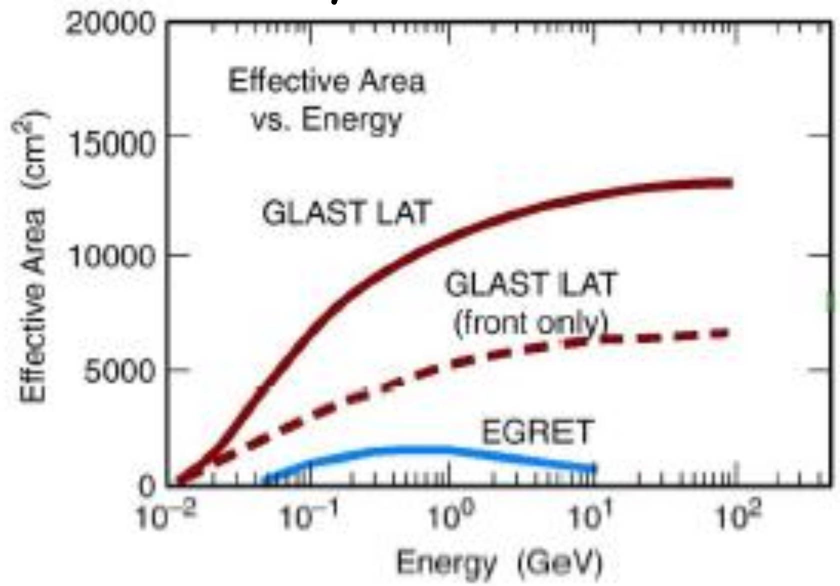

In this region (at cosmological distances), the uncertainty is much smaller

P. Ullio, L.B., J. Edsjö, 2002

FIG. 4: Scaling of the collected $\gamma$-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 AGN (GeV blazars). See talk by P. Michelson.

Must Nature be supersymmetric?

## Other model I: A more "conventional" dark matter model with a spin-0 dark matter candidate: Inert Higgs Doublet 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)

$$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \lambda_5 Re\left[(H_1^\dagger H_2)^2\right]$$

$\Rightarrow$ Ordinary Higgs h can be as heavy as 500 GeV without violation of electroweak precision tests

$\Rightarrow$ 40 – 70 GeV inert Higgs $H^0$ gives correct dark matter density

$\Rightarrow$ Coannihilations with pseudoscalar A are important

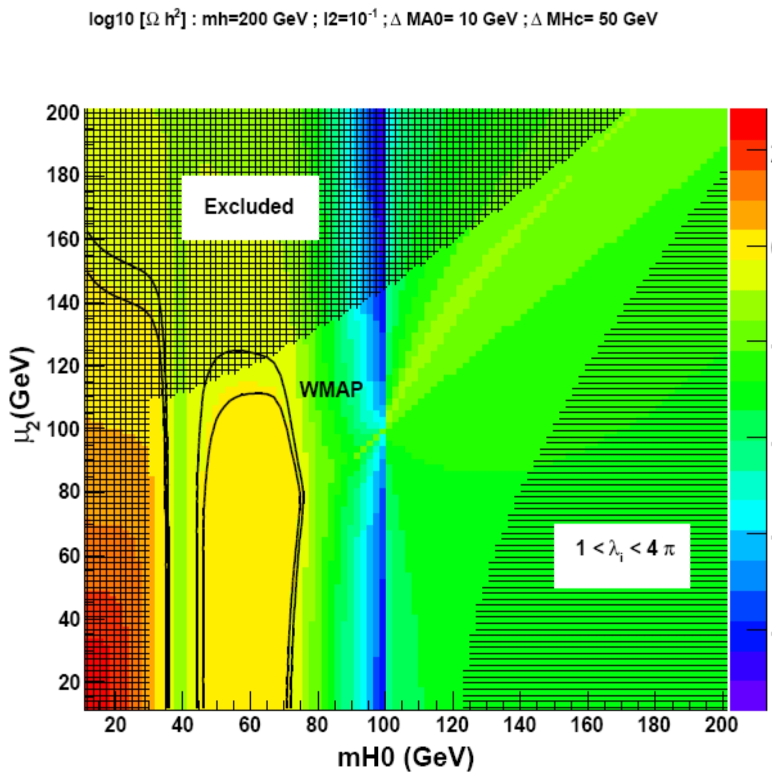
$\Rightarrow$ Can be searched for at LHC

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

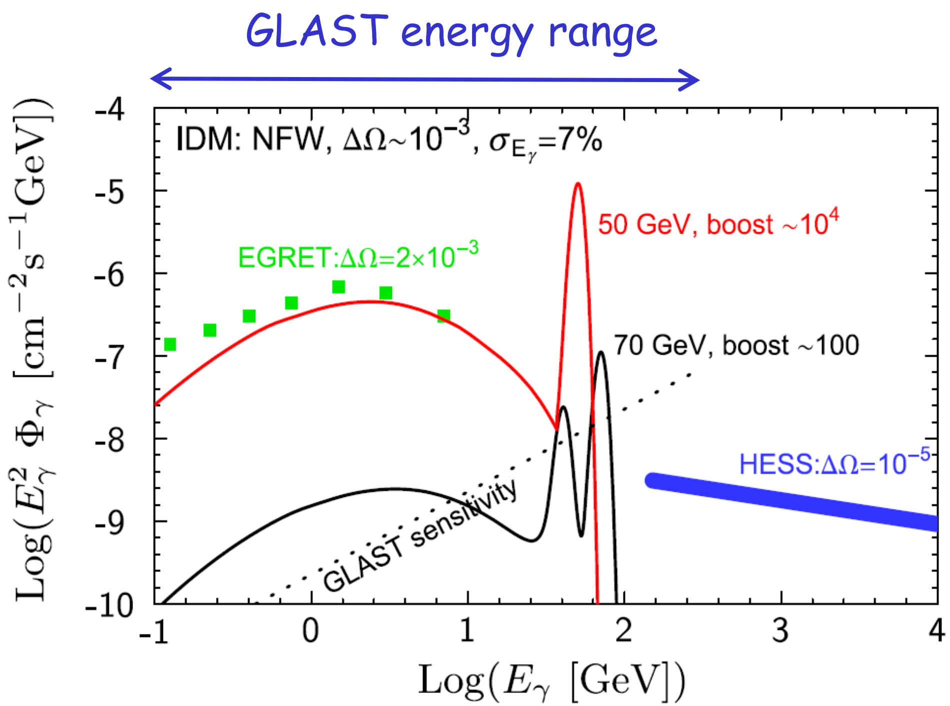
$\Rightarrow$ The perfect candidate for detection in GLAST!

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

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

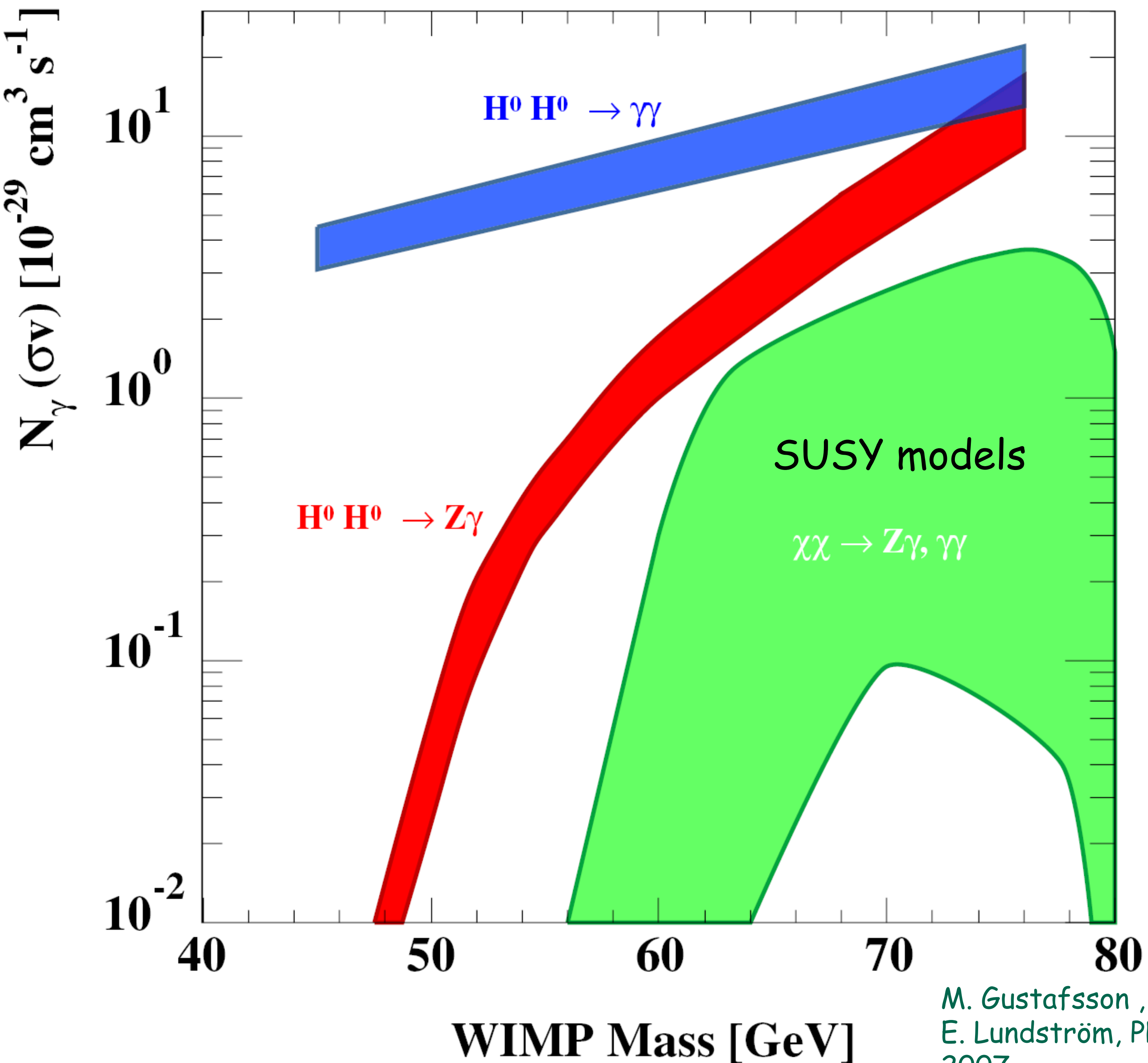



Lopez Honorez et al, 2007




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

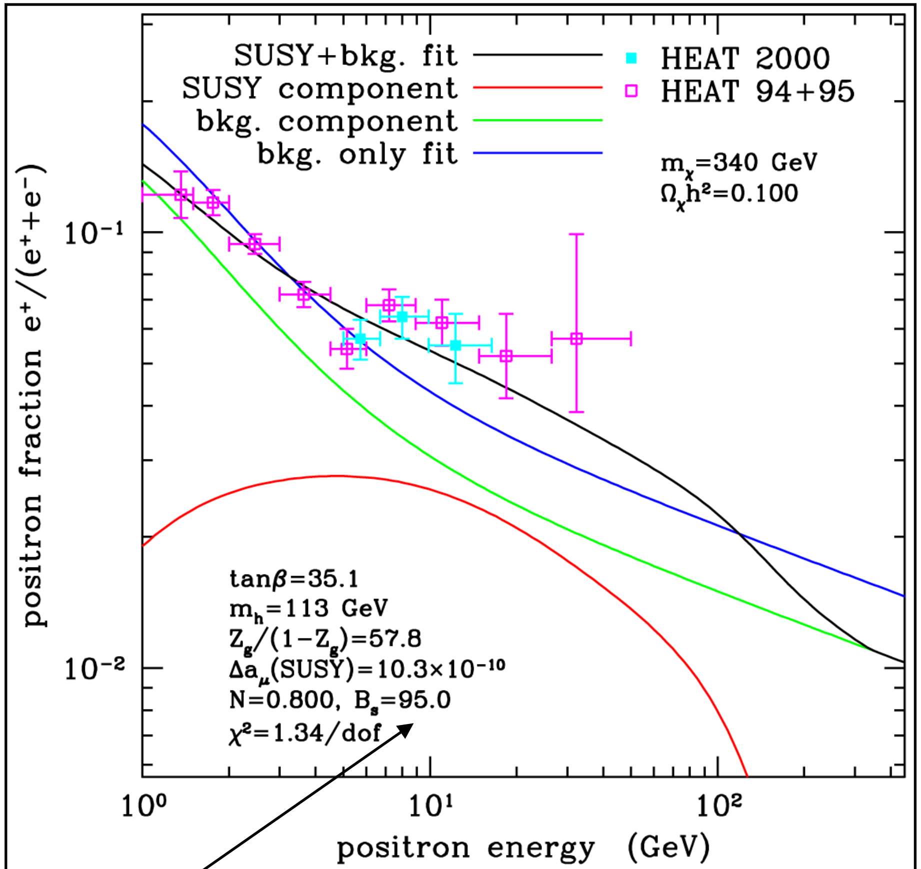
**Note on boost factors:** The overall average enhancement over a smooth halo, from DM substructure etc, is hardly greater than 2 – 10. In one specific location, however, like the region around the **galactic center**, factors up to **$10^5$** are easily possible. Also, the existence of **intermediate mass black holes** may give very large local boost factors (Bertone, Zentner & Silk, 2005).

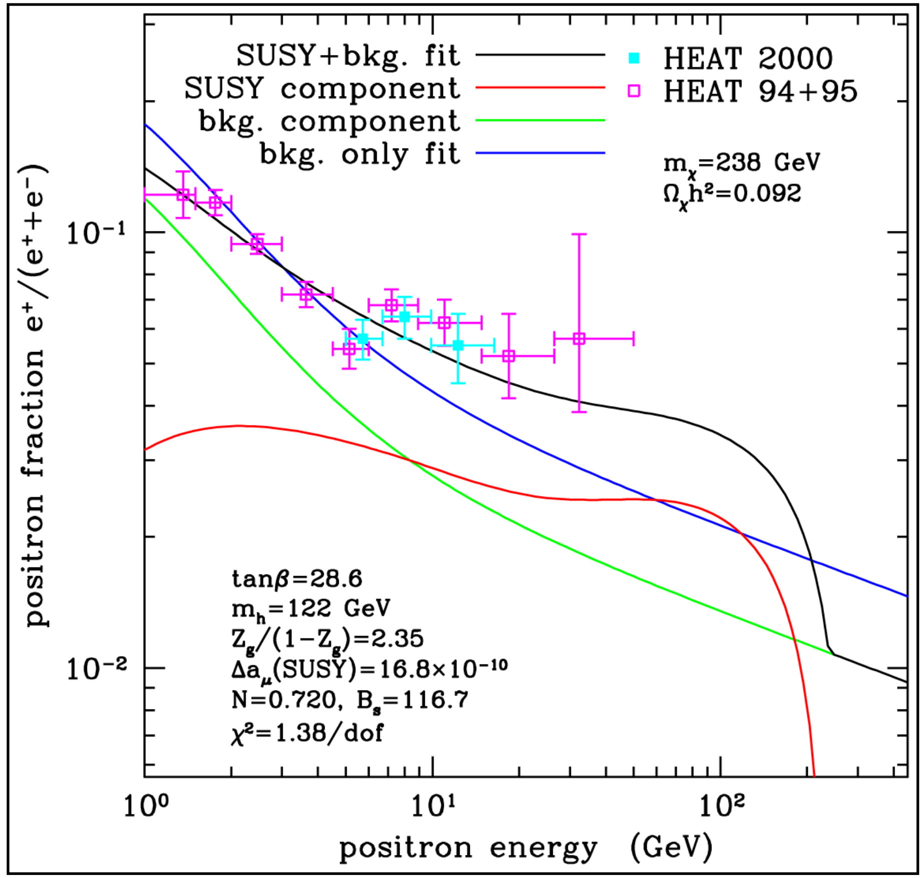



M. Gustafsson , L.B., J. Edsjö, E. Lundström, PRL, July 27, 2007

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"

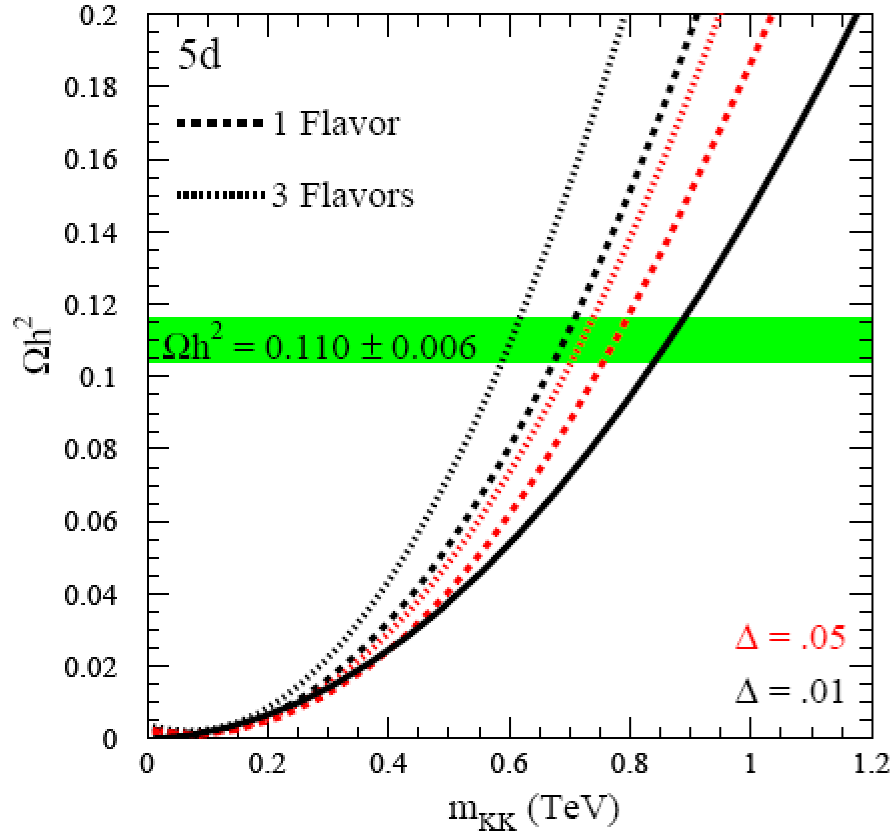
Baltz, Edsjö, Freese, Gondolo 2002; Kane, Wang & Wells, 2002; Hooper & Kribs, 2004; Hooper & Silk, 2004 .

Also a low energy, **annihilation signal of positronium towards g.c.** – see **Finkbeiner** this afternoon. Positrons & electrons emit synchrotron radiation: the "haze" in WMAP data caused by WIMP annihilation? See talk by **Dobler**.

# 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




Servant & Tait, 2003

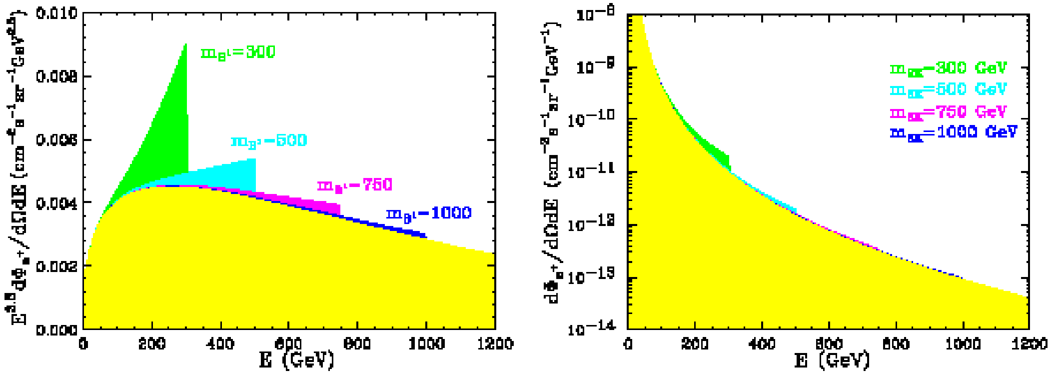
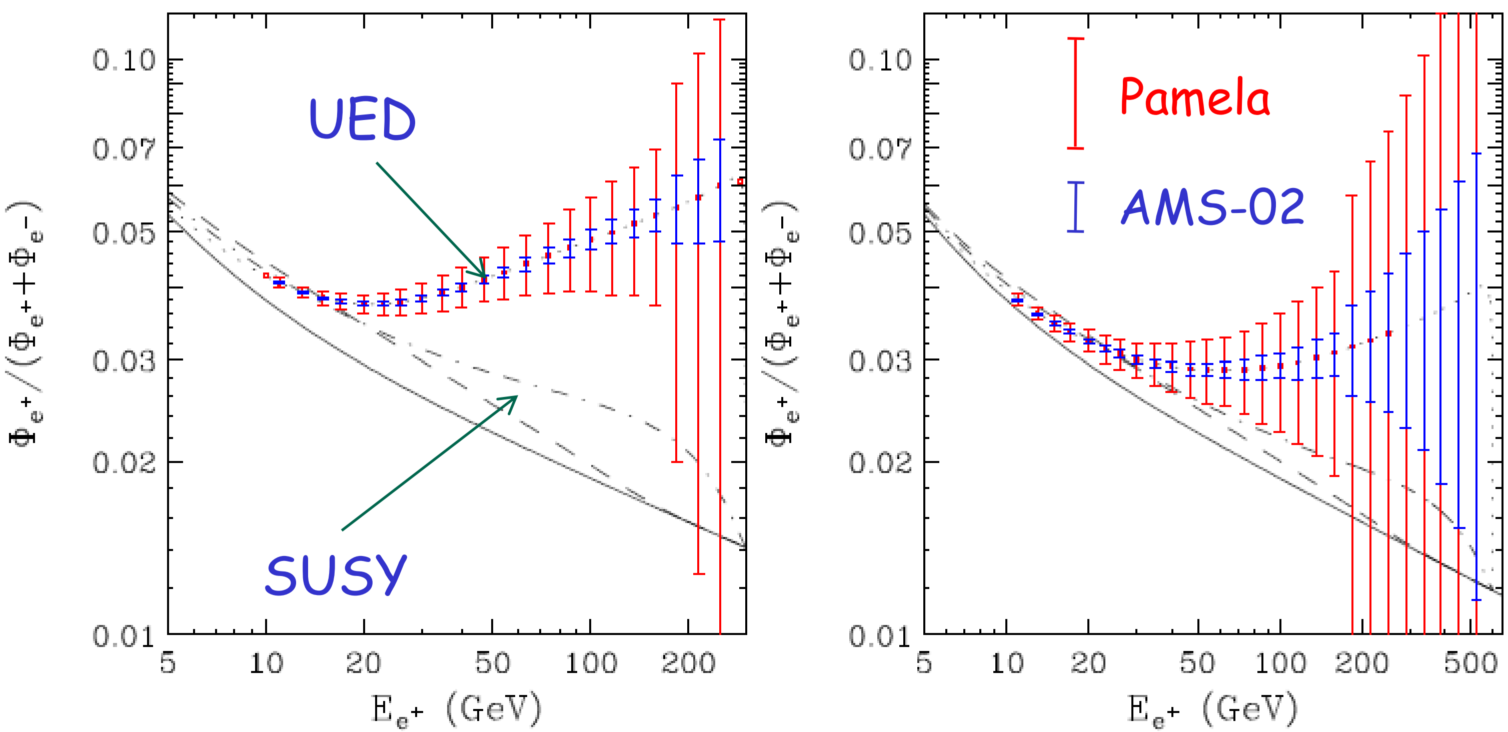



Figure 3. Positron spectra from $B^1$ dark matter annihilation for various $B^1$ masses as indicated [22]. The yellow (light shaded) region is the expected background. The differential flux is given in the right panel, and is modified by the factor $E^3$ in the left panel.

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




Hooper & Zaharijas, 2007

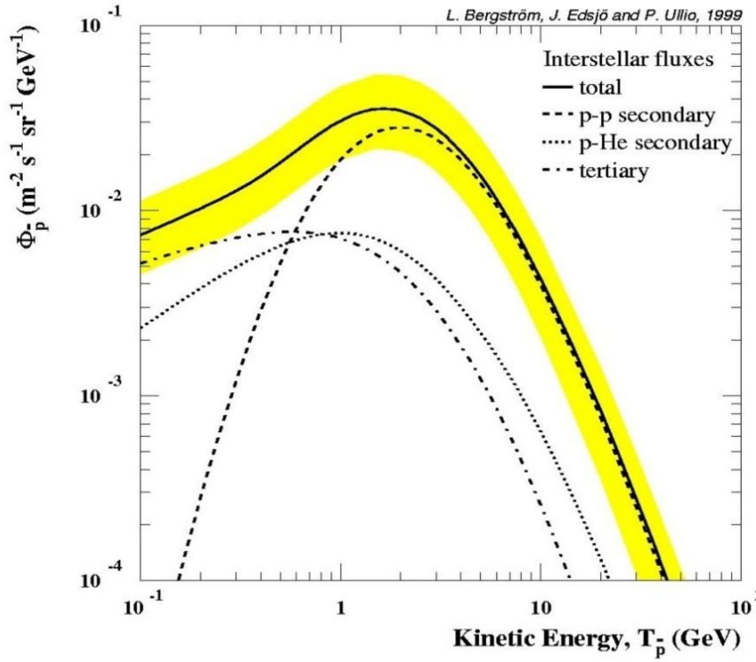
M = 300 GeV

M = 600 GeV

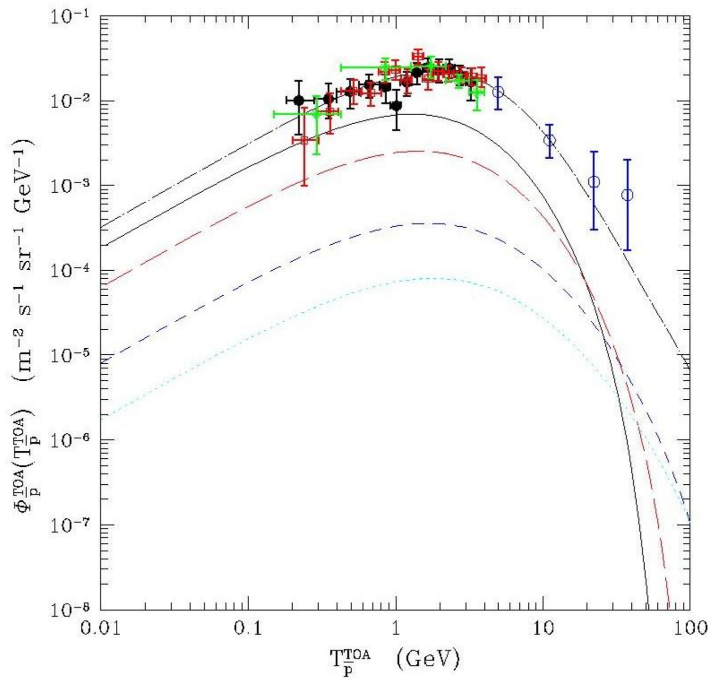
Antiprotons at low energy can not be produced in pp collisions in the galaxy, so that may be DM signal?

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)

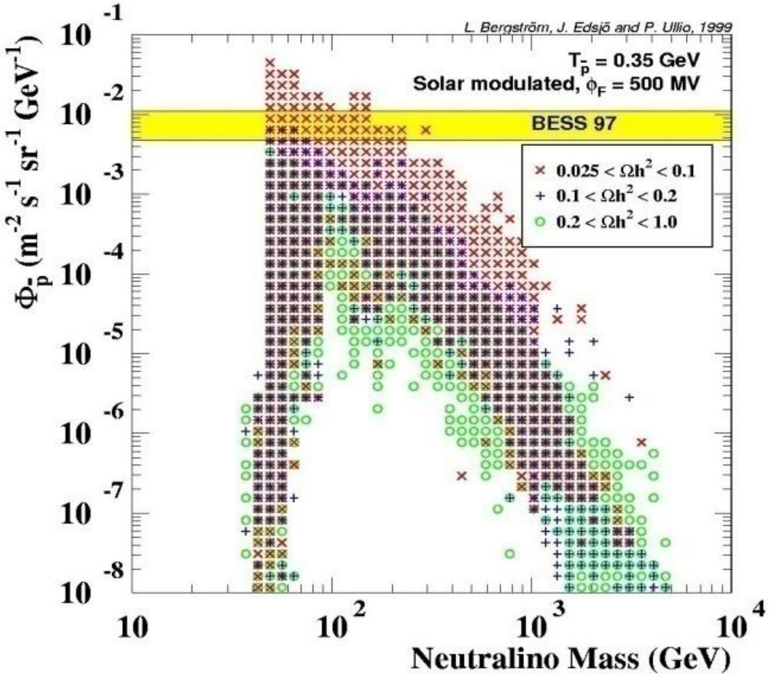
See talk by Donato this afternoon.

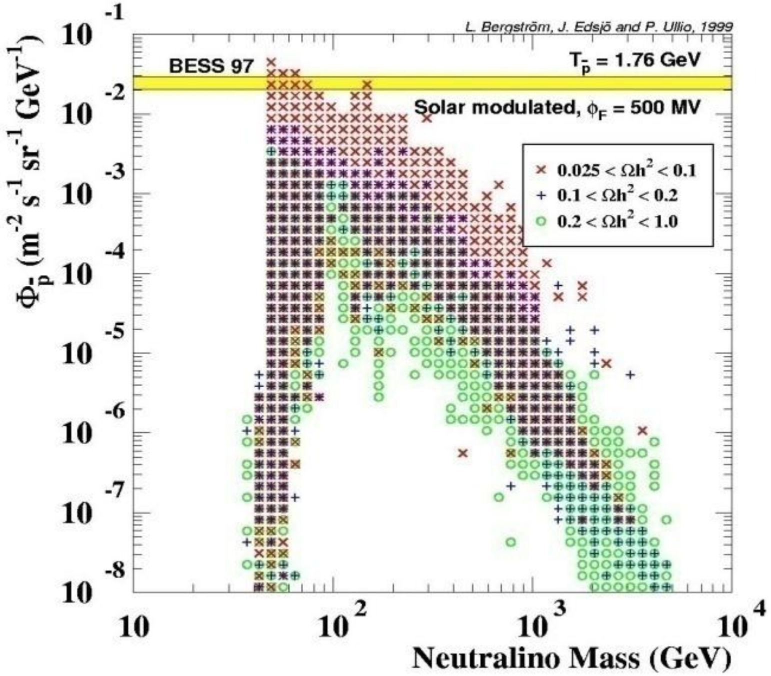



L.B., J. Edsjö and P. Ullio, 2000;
Bieber & Gaisser, 2000



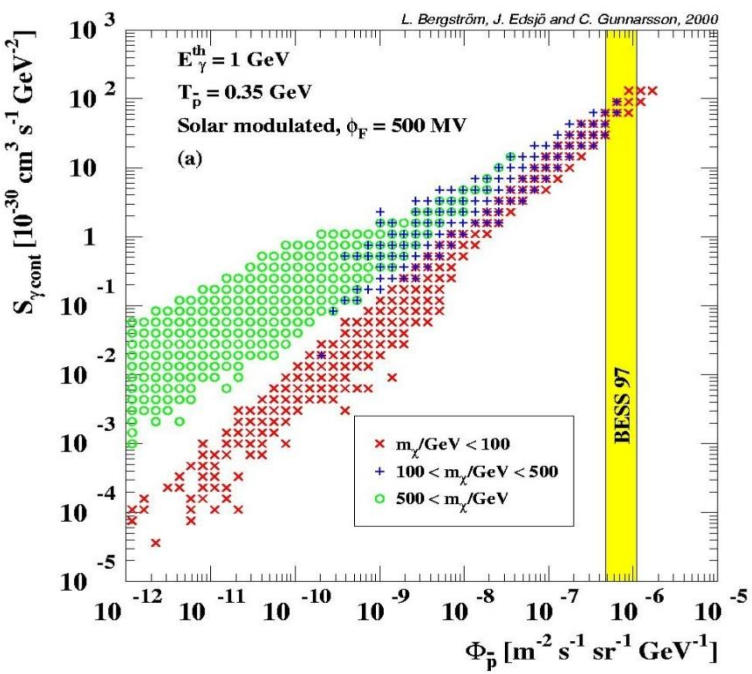

F. Donato, N. Fornengo, D. Maurin, P. Salati, R. Taillet, 2004

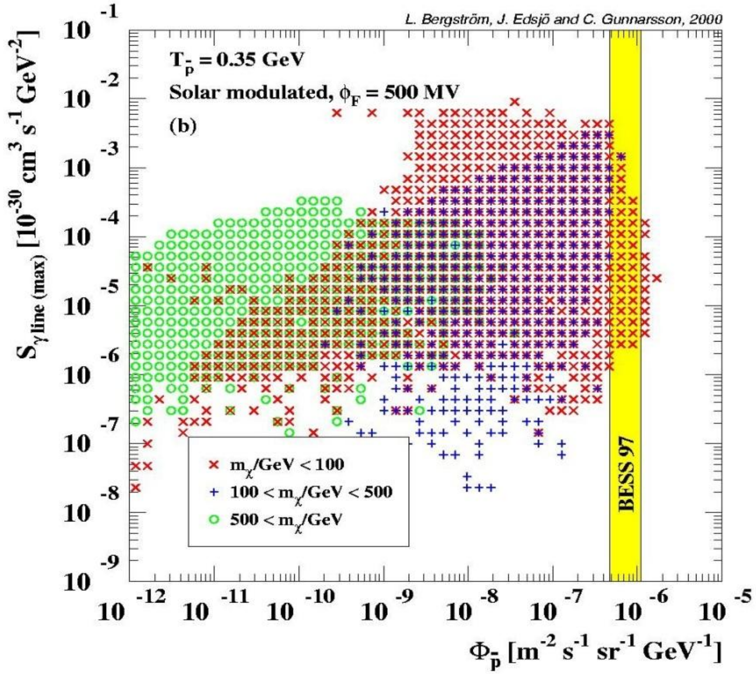



Existing data cuts into MSSM parameter space. PAMELA will soon have more data.

High mass KK & SUSY models may give high energy signal (Bringmann & Salati, 2007). See talk by Salati this afternoon.

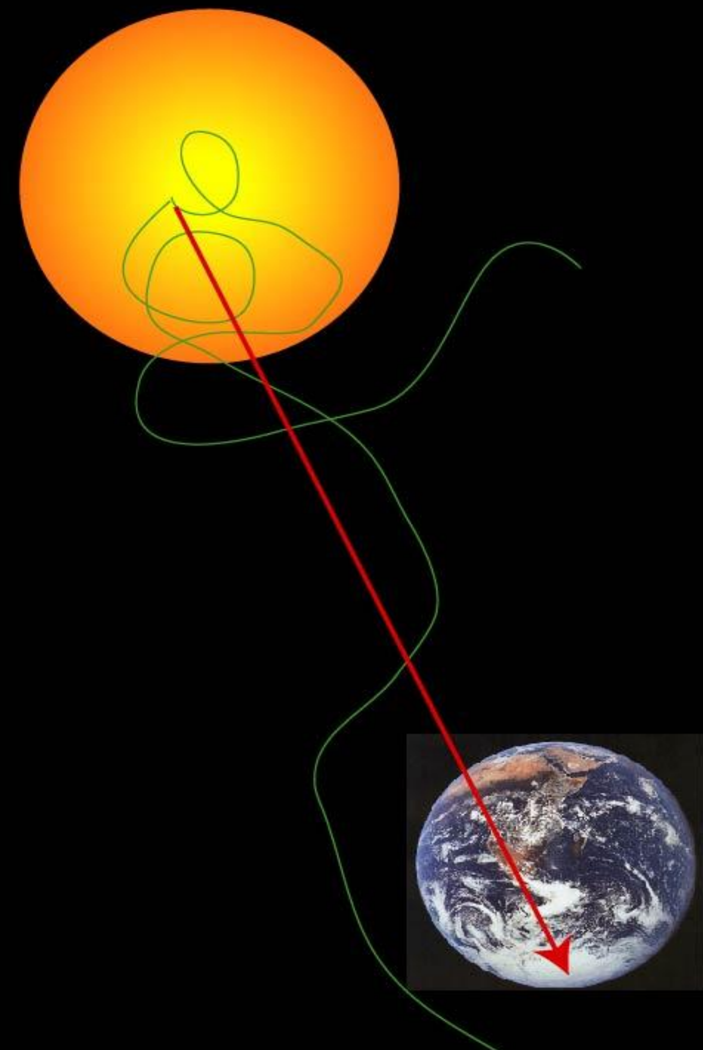



Antiprotons and continuum gamma rays are strongly correlated (through fragmentation of quark jets).

No strong correlation for gamma lines

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



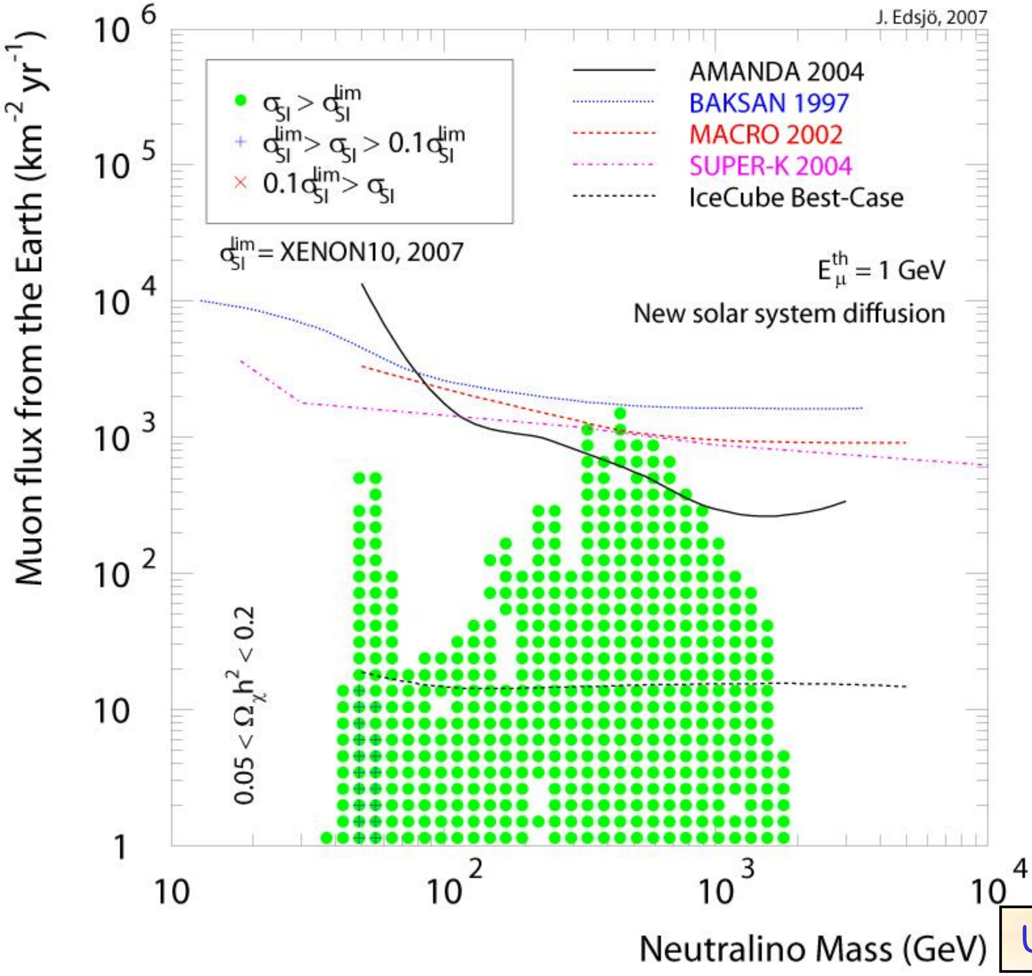
WIMPs are trapped gravitationally by scattering; when velocity after scattering is below escape velocity, the WIMPs will sink down to the center

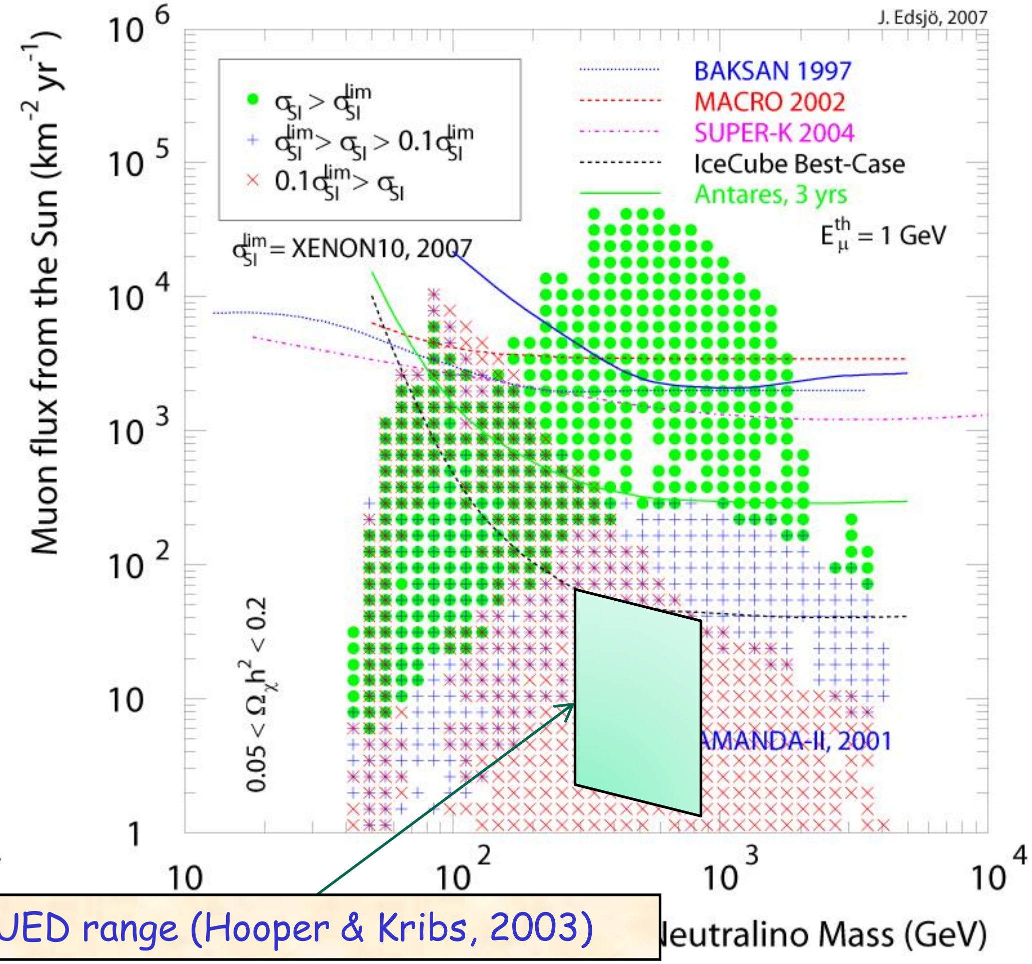
Annihilation rate $\sim\rho^2 \Rightarrow$ Good signature: high energy neutrinos pointing back to the center of the Earth or Sun

# Neutralino signal: Neutrinos from the Earth & Sun, MSSM

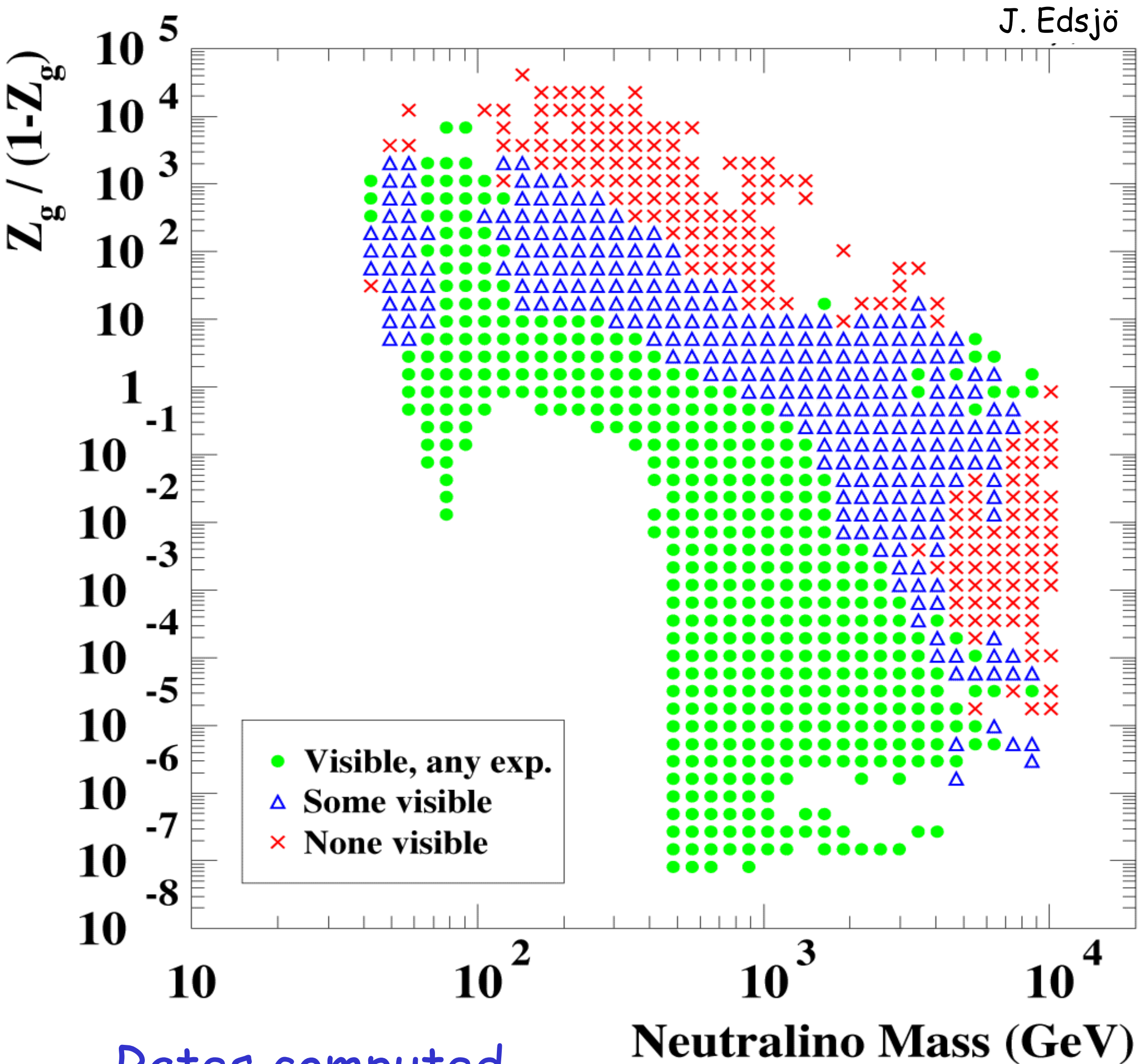
Rates computed by J. Edsjö with

Dark SUSY



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




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

Rates computed with DarkSUSY

## "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)

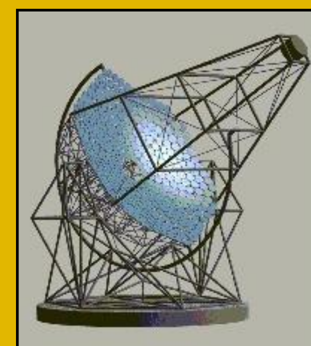
• Just for these cases, the gamma line signal is particularly large (L.B. & P.Ullio, 1998)

• 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.

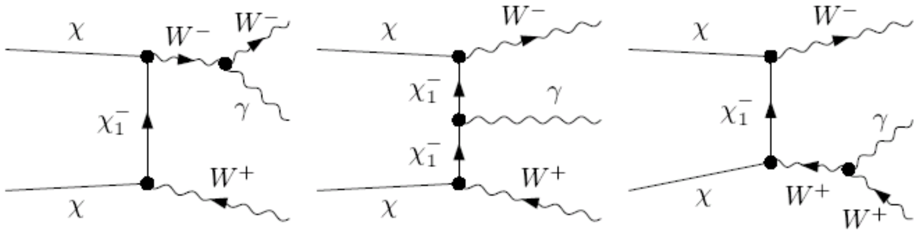
• Rates may be further enhanced by non-perturbative binding effects in the initial state (Hisano, Matsumoto & Nojiri, 2003)

• 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 TeV $\leq E_\gamma \leq$ 20 TeV. See talk by Hofmann.

•A new generation of ACT arrays is presently being planned: AGIS, HAWC, CTA (see talk by Drury later today)

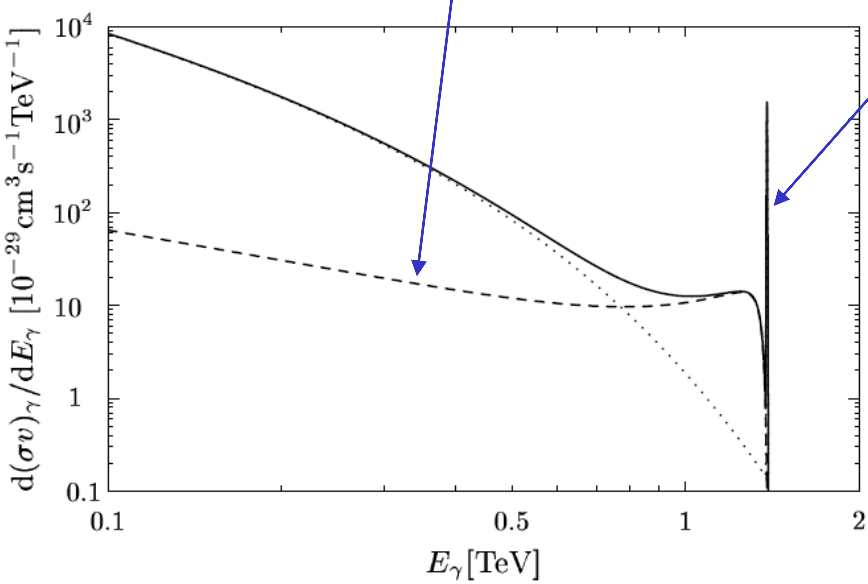


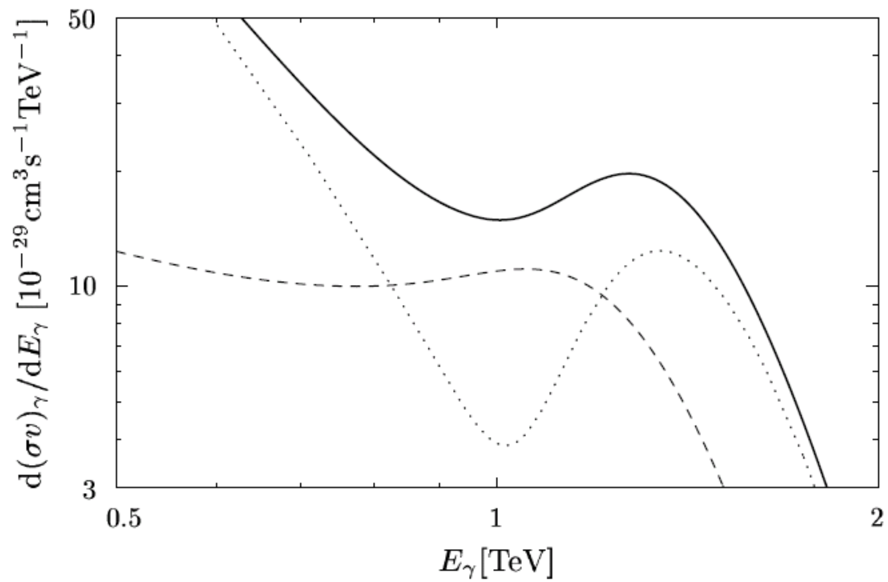
For higher energies than the GLAST limit, 300 GeV, Air Cherenkov Telescopes become advantageous. Example: 1.4 TeV higgsino with WMAP relic density, like in split SUSY (L.B., T.Bringmann, M.Eriksson and M.Gustafsson, PRL 2005)




New contribution (internal bremsstrahlung)

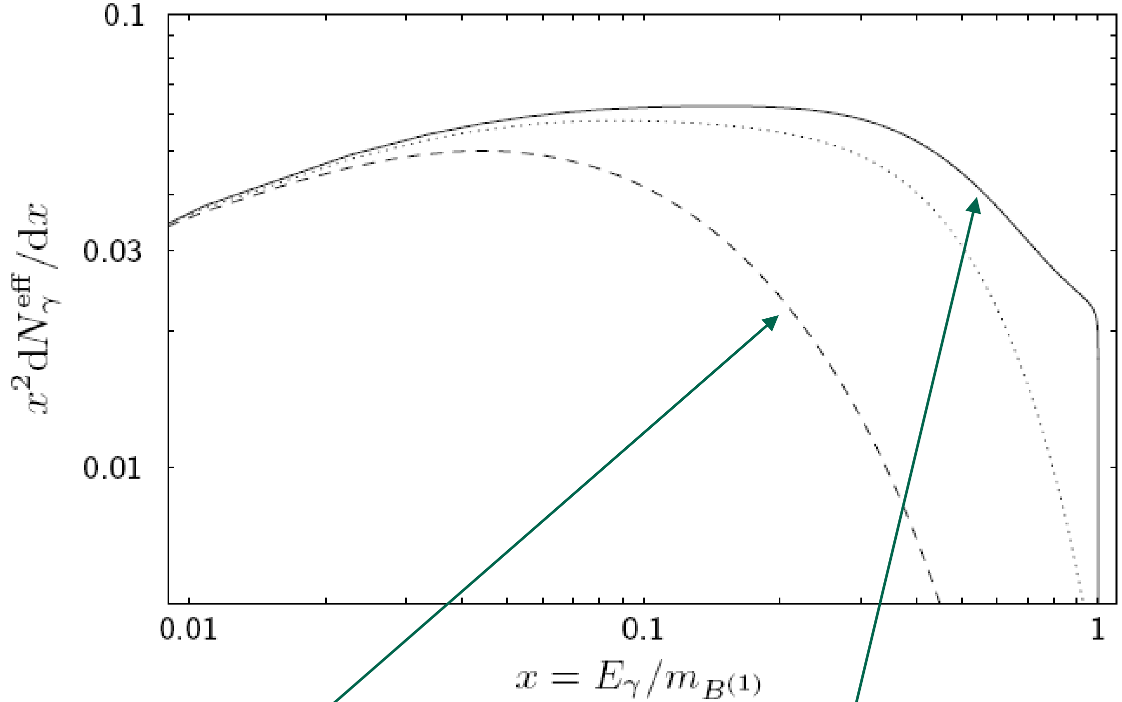
Intrinsic line width $\Delta E/E \sim 10^{-3}$



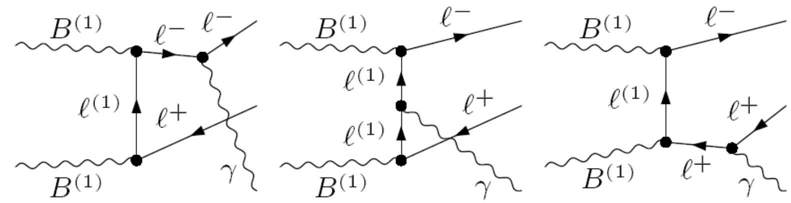

Gamma-ray spectrum seen by an ideal detector

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



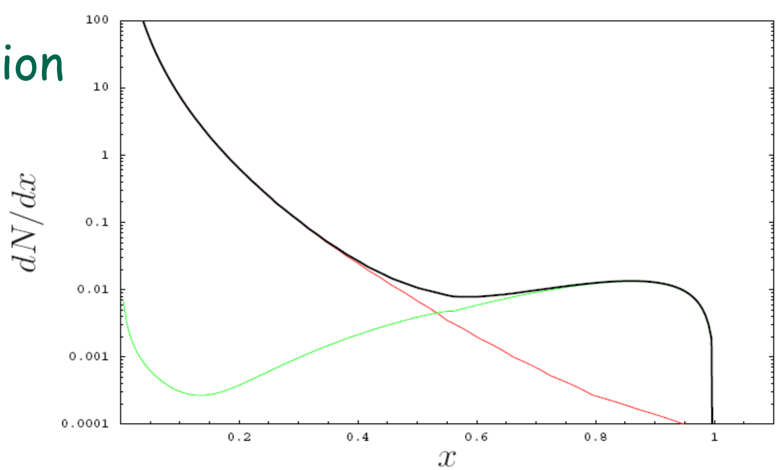

Cf. Kaluza-Klein models

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




With internal bremsstrahlung

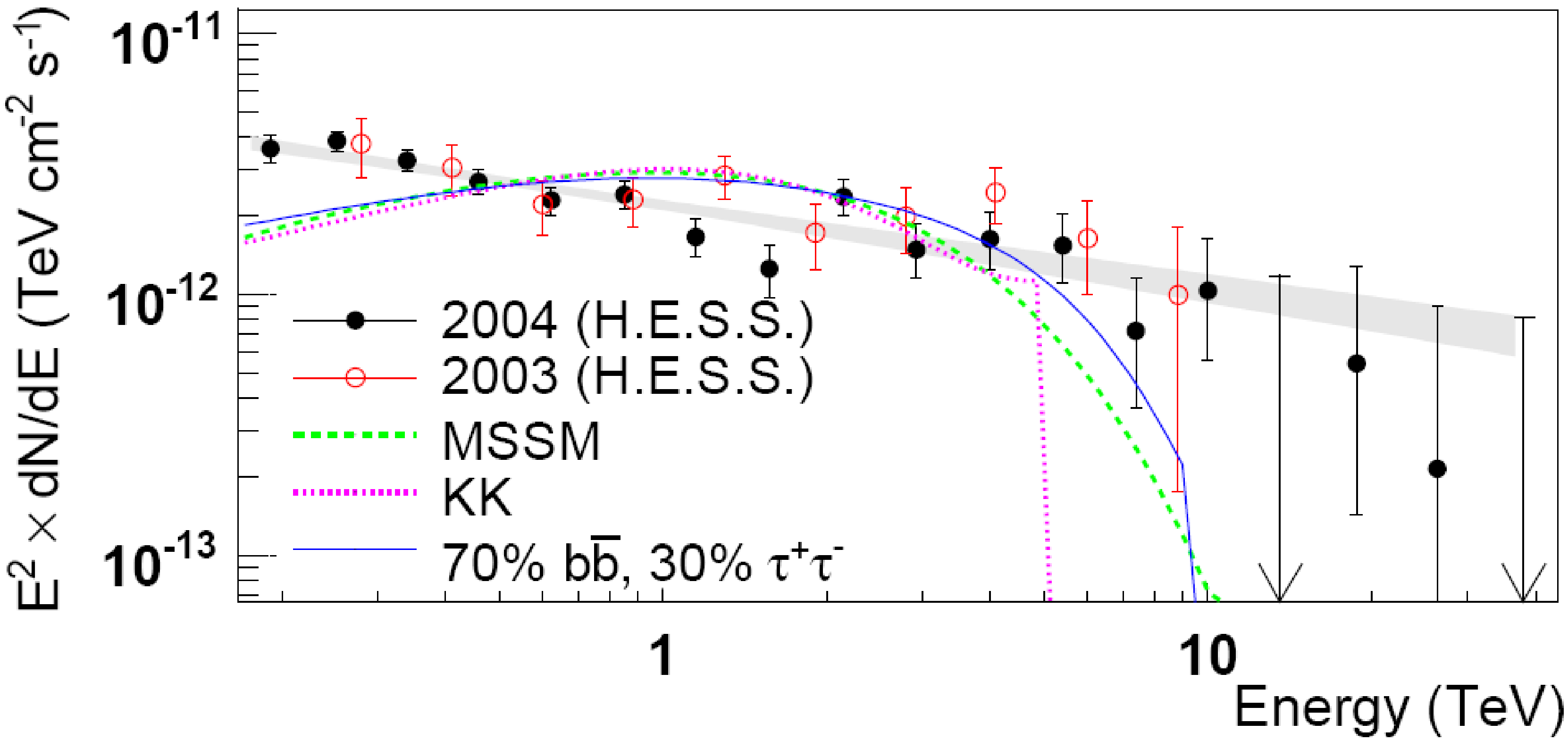
Quark fragmentation (e.g., SUSY)




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

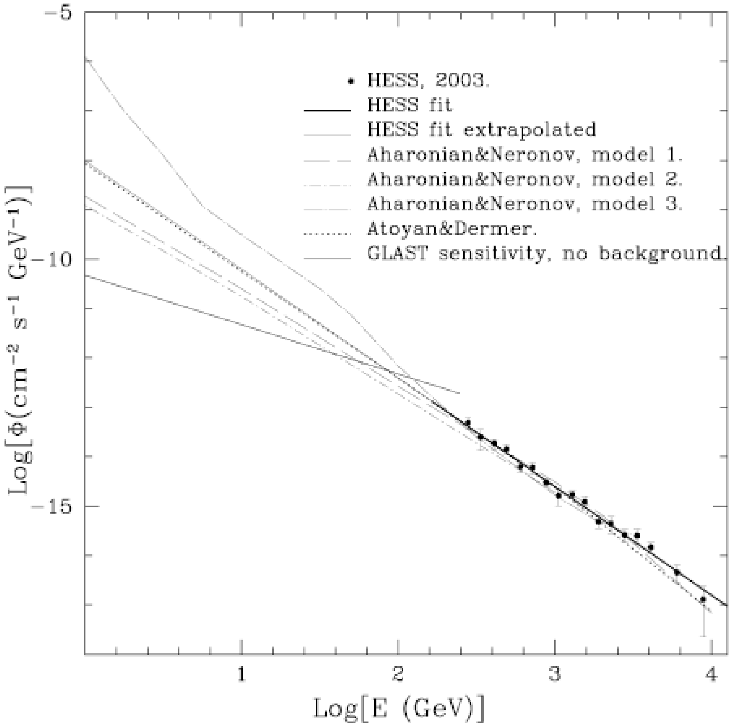
(T. Bringmann, L. Bergström, J. Edjö, in prep., 2007.) See talk by T. Bringmann this afternoon.

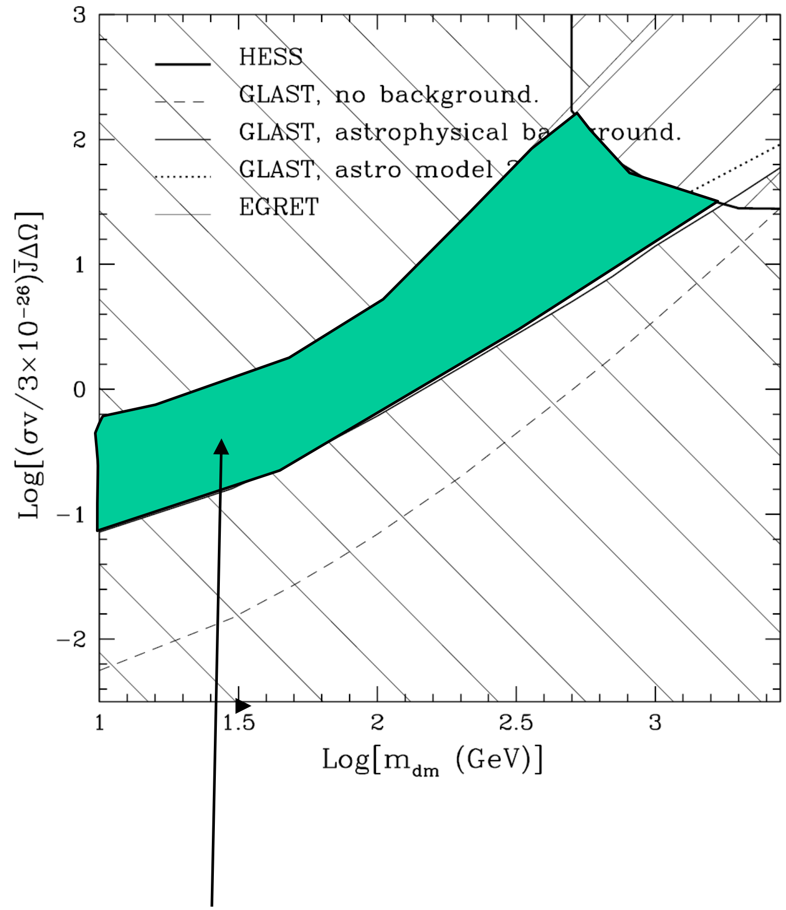
# 2006: H.E.S.S. data towards galactic centre




MAGIC (2006) data agree completely with HESS

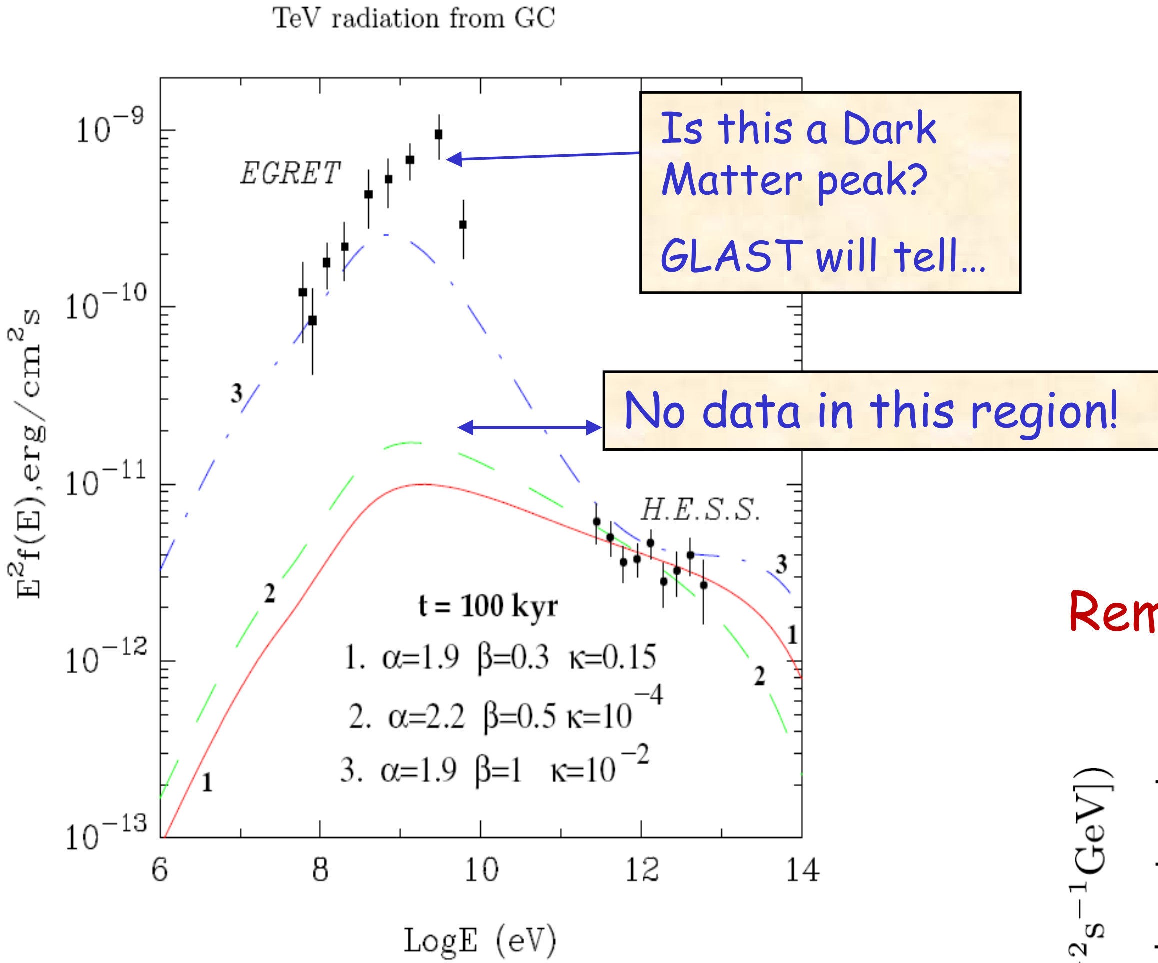
Steady (time-independent) spectrum, consistent with extended source like NFW cusp! But: Too high energy (and wrong shape of spectrum) for WIMP explanation




Zaharijas & Hooper, 2006

"Window of opportunity" for GLAST

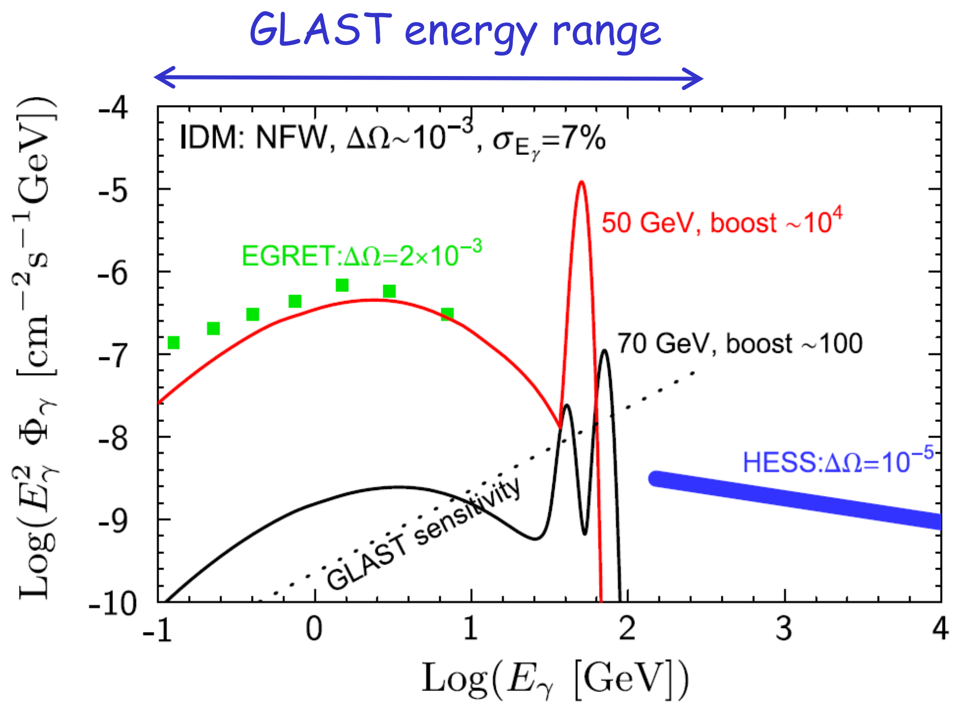



"Conventional explanation", Aharonov & Neronov, 2005

Prediction: variability on 1-hour timescale

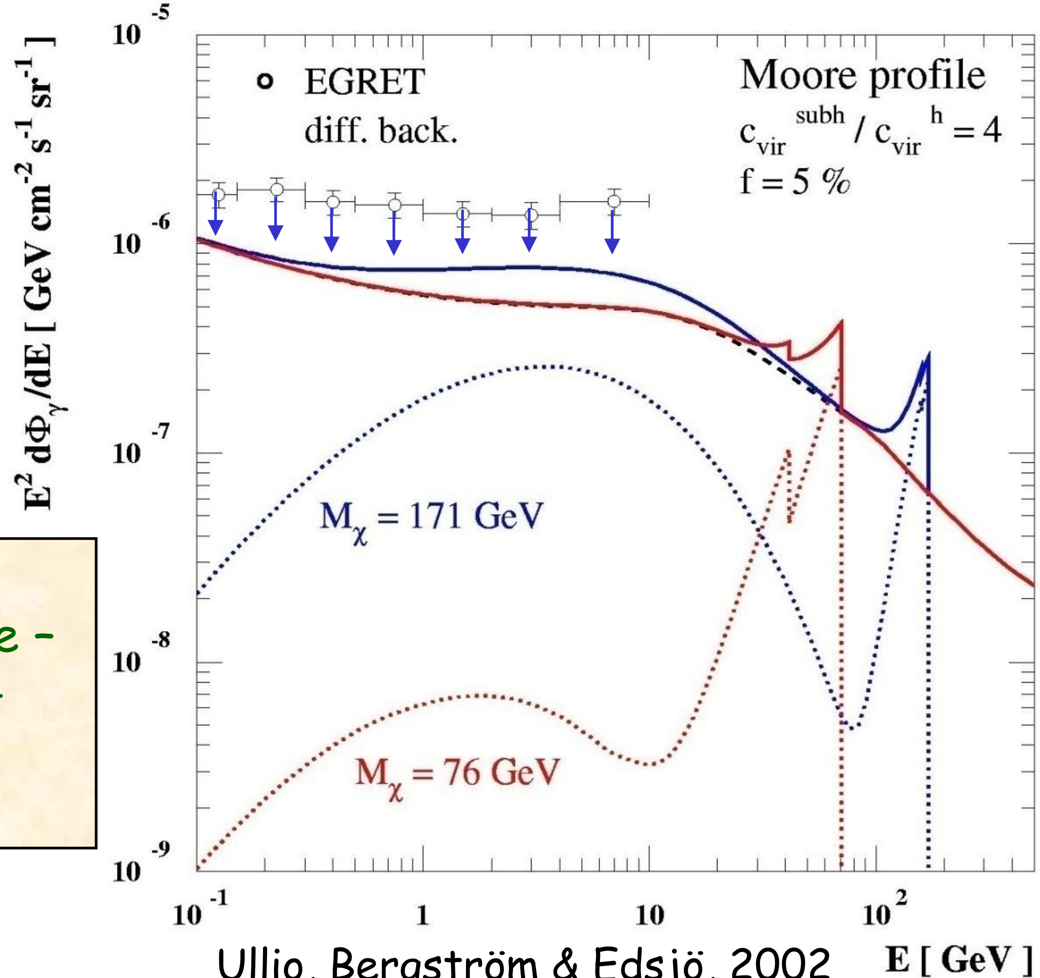
GLAST will fill in data between EGRET and HESS

**Remember:**




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

# Diffuse cosmic (extragalactic) gamma-rays




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

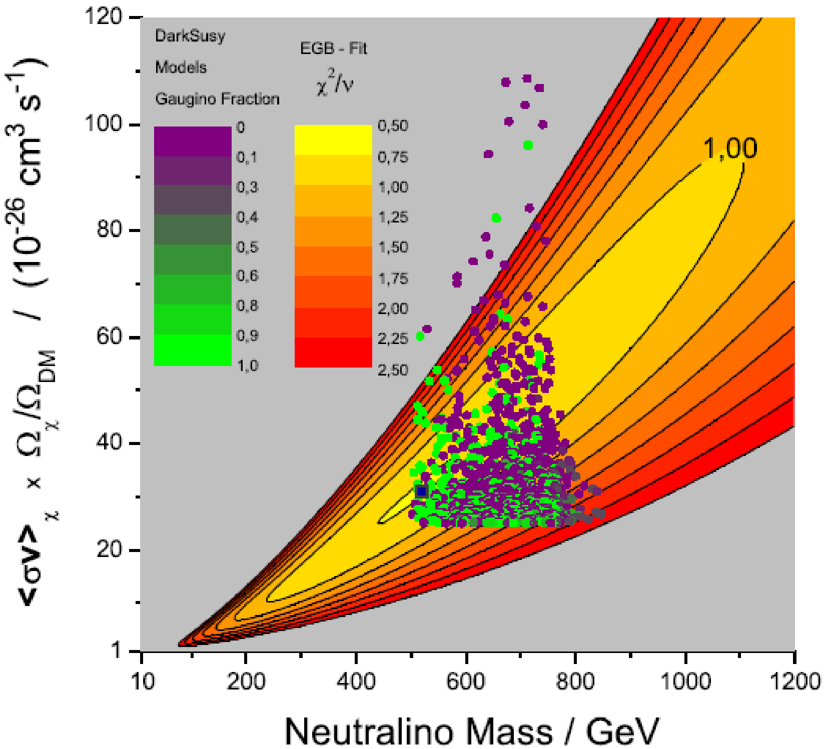
Redshifted gamma-ray line gives peculiar energy feature – may be observable for CDM-type (Moore profile) cuspy halos and substructure

Ullio, Bergström & Edsjö, 2002

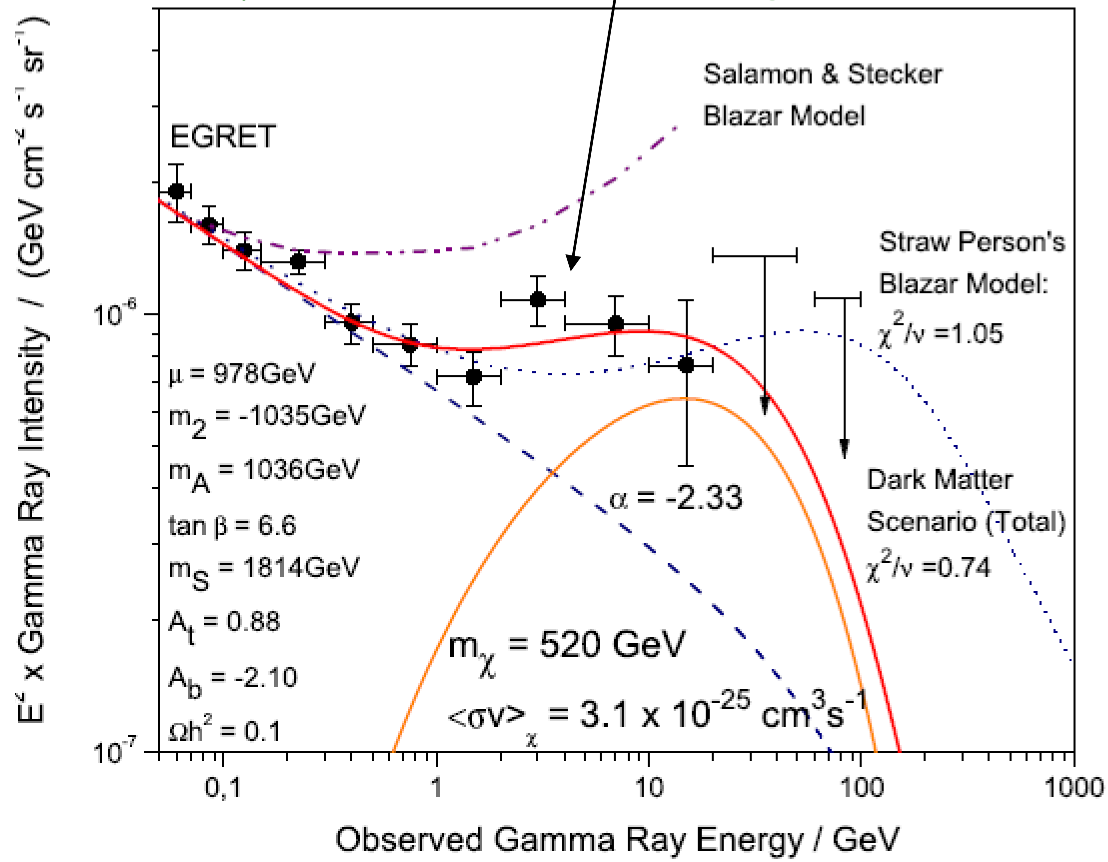
This is being updated: A. Sellerholm et al., 2007

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.

# Could the EGRET observed 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

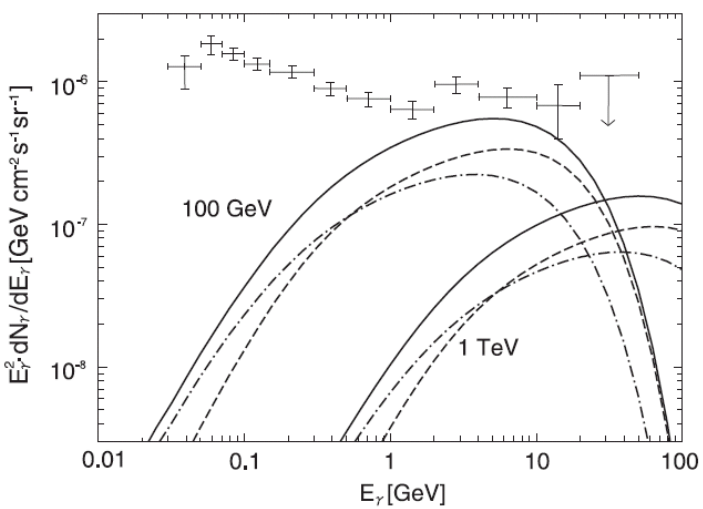
Energy range is optimal for GLAST!

Elsässer & Mannheim, PRL, 2005 fit extragalactic spectral "bump" (EGRET, modified) with neutralino annihilation. (But remember caveat with EGRET data.)

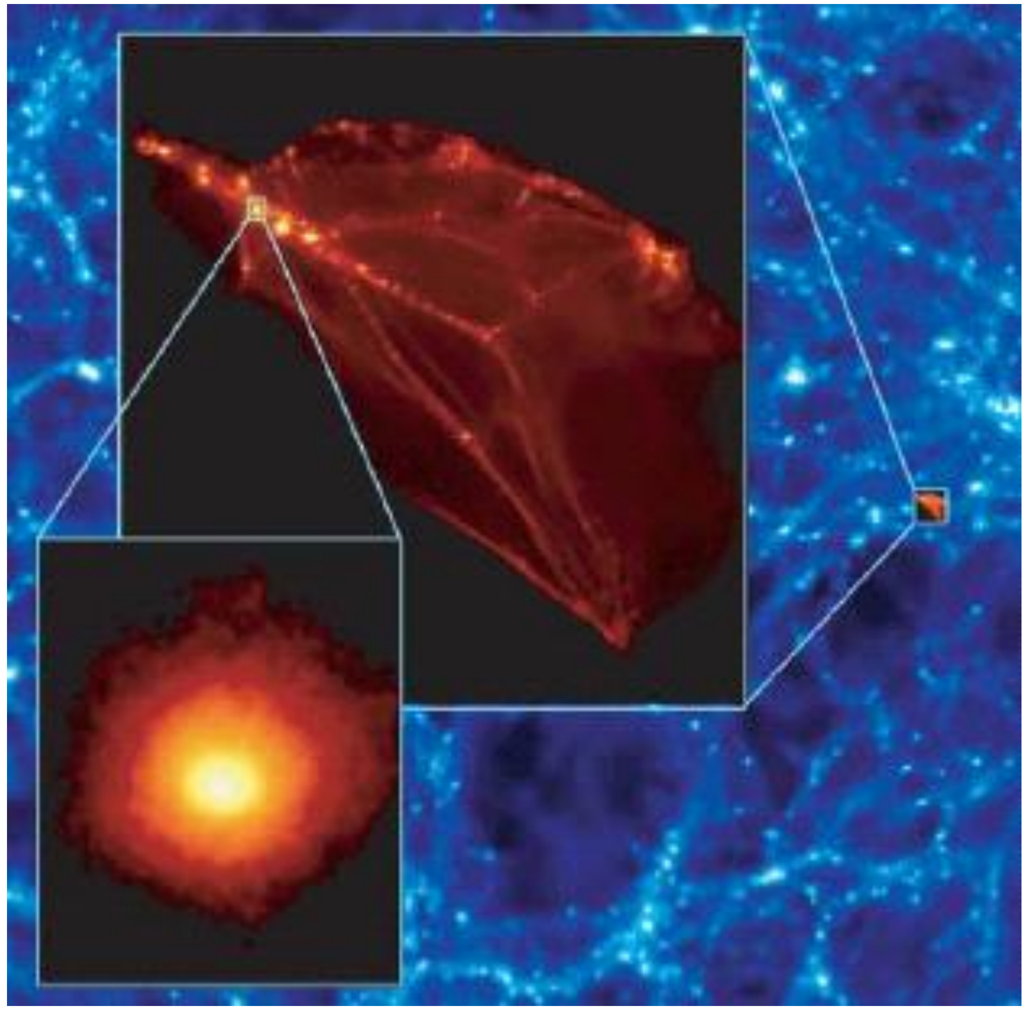
Problem (Ando, PRL 2005): It is difficult to reproduce extragalactic result of Elsässer & Mannheim, without overproducing gammas from g.c.

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

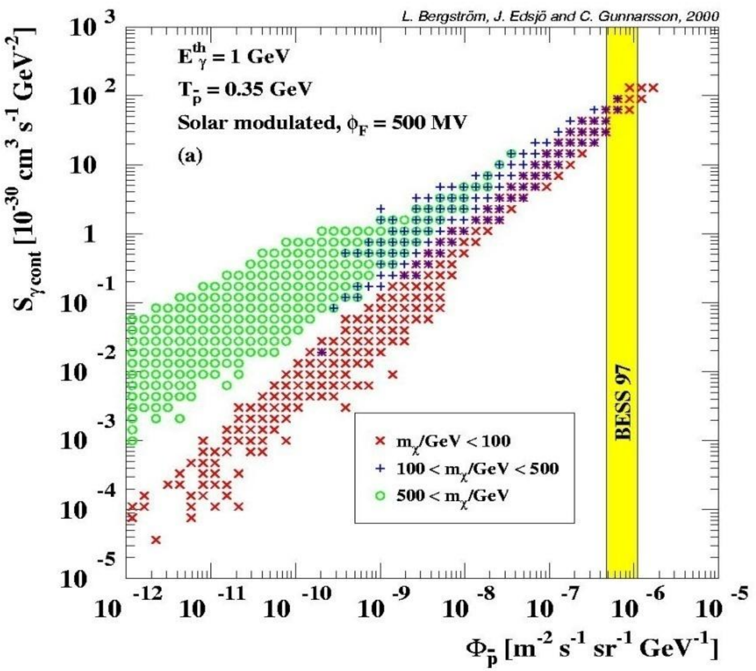


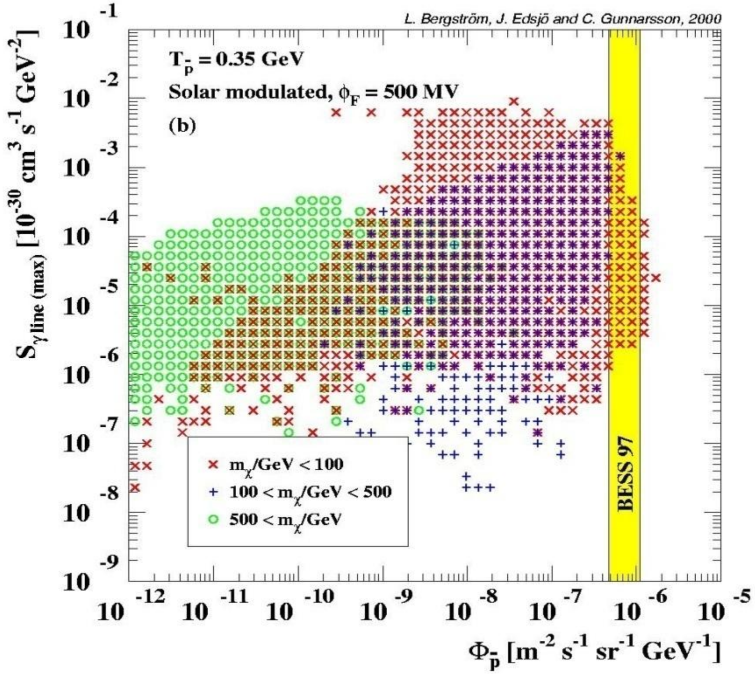
# Conclusions

- 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 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 will give precision measurements of $e^+$ and antiprotons
- The dark matter problem may be near its solution…

# Comment to de Boer's model

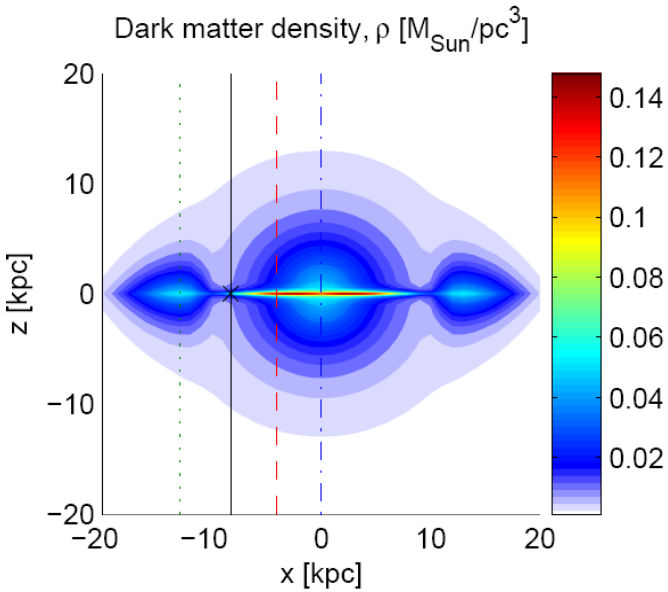
Remember?

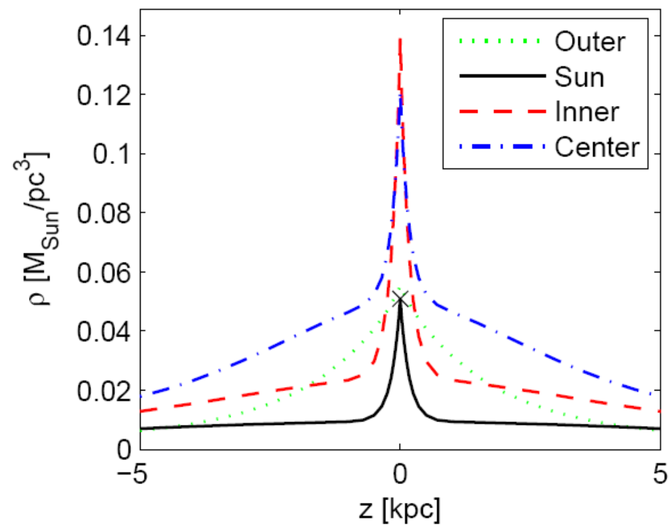



Antiprotons and continuum gamma rays are strongly correlated (through fragmentation of quark jets).

No correlation for lines



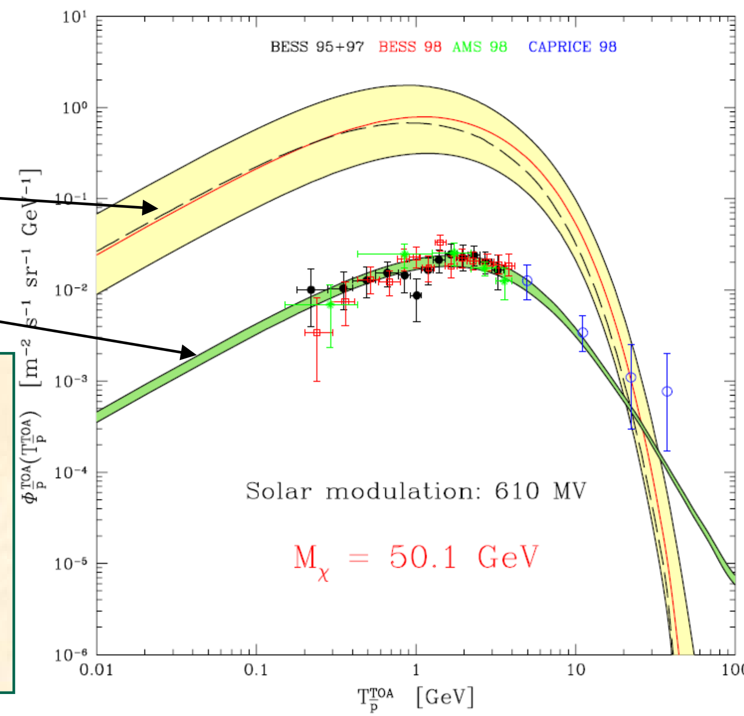

L.B., J. Edsjö, M. Gustafsson & P. Salati, 2006

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.)

## Summary for de Boer's model

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