Indirect detection of Dark Matter candidates in gamma-rays

Soon the GLAST satellite will be launched, and a window will open in energy between 30 and 300 GeV, a range where most of the Weakly Interacting Massive Particles (WIMPs) are predicted to give a signal, if the dark matter halo follows the predictions of N-body simulations. A review of the various candidates and their potential of being detected in gamma-rays is given.

Rome, June 21, 2007

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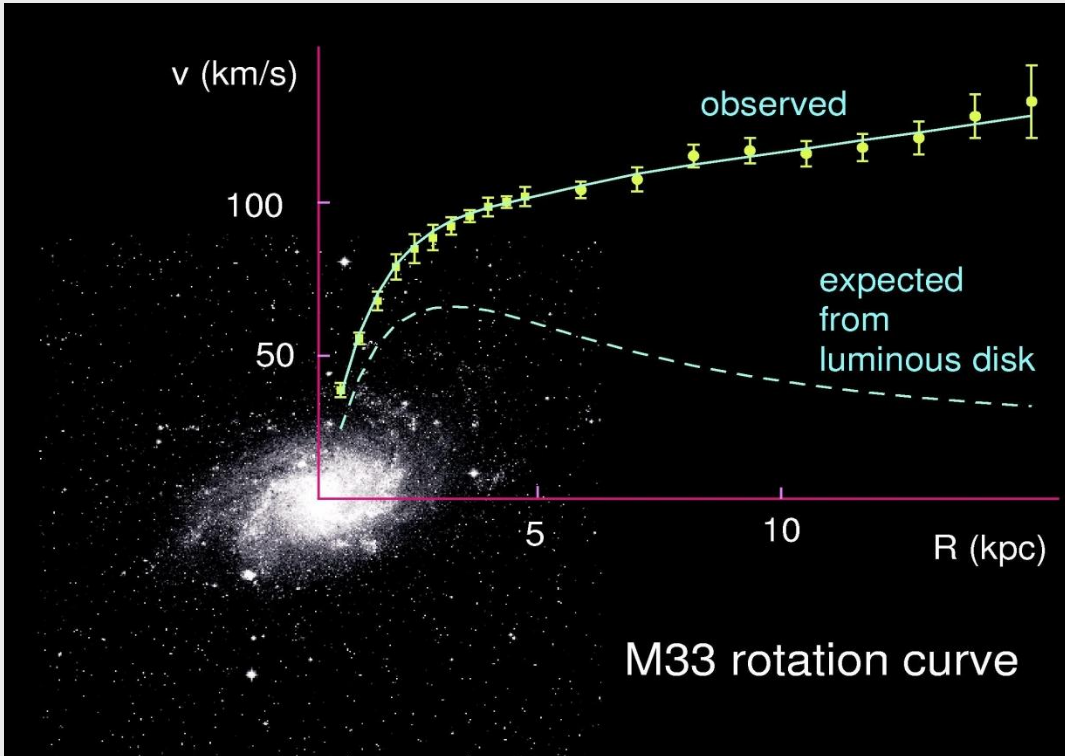
Fritz Zwicky, 1933: Velocity dispersion of Coma cluster indicates Dark Matter , $\sigma \sim 1000$ km/s $\Rightarrow$ M/L ~ 50

"If this overdensity is confirmed we would arrive at the astonishing conclusion that dark matter is present [in Coma] with a much greater density than luminous matter."

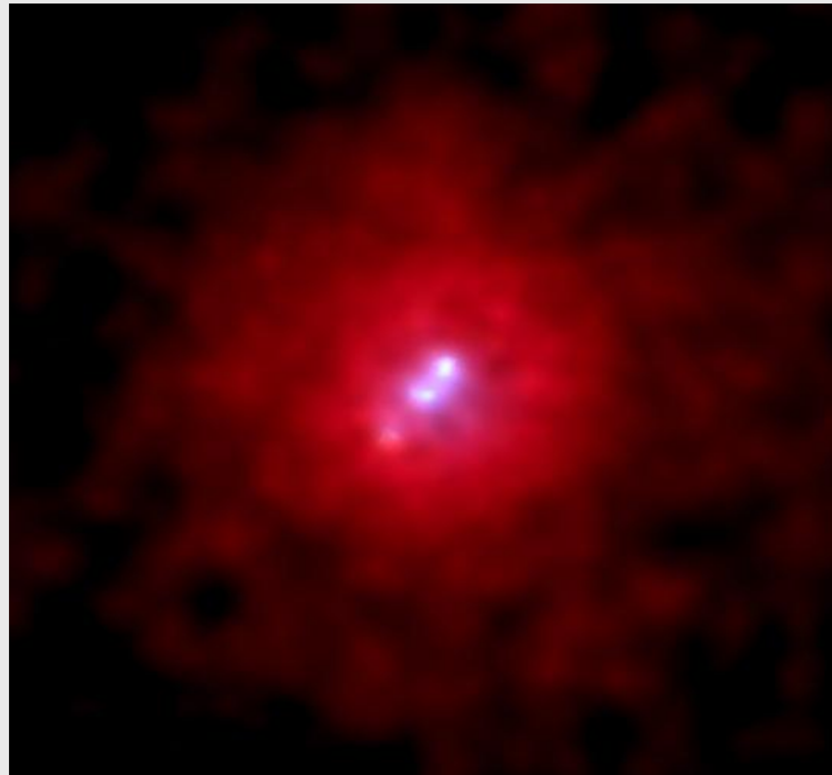
Dark matter needed on all scales!
(⇒ MOND and other *ad hoc* attemps to modify Einstein or Newton gravity very unnatural & unlikely)

Galaxy rotation curves



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

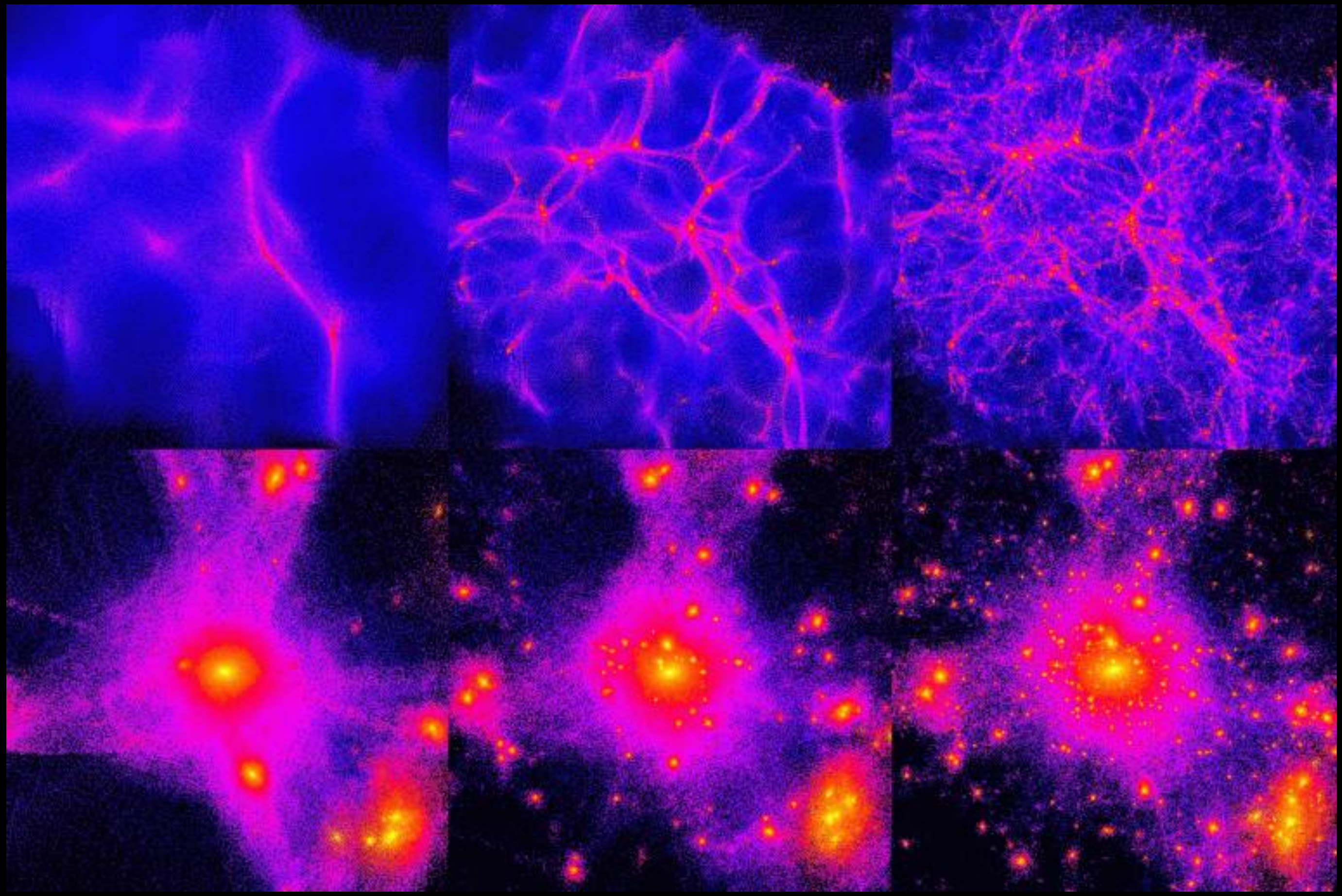
X-ray emitting clusters



Cluster 3C295 (Chandra)

Around 1982 (Peebles; Bond, Szalay, Turner; Sciama) came the Cold Dark Matter paradigm: Structure formation scenarios (investigated through N-body simulations) favours hierarchical formation. Hot Dark Matter (like neutrinos) first forms structure at large scales (Zel'dovich pancakes) which then fragments to smaller scales .

Melott et al 1983; Blumenthal, Faber, Primack & Rees 1984



B. Moore

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

Potential problem alleviated: The lack of observed substructure (satellite galaxies) in Milky Way neighbourhood

THE KINEMATICS OF THE ULTRA-FAINT MILKY WAY SATELLITES: SOLVING THE MISSING SATELLITE PROBLEM

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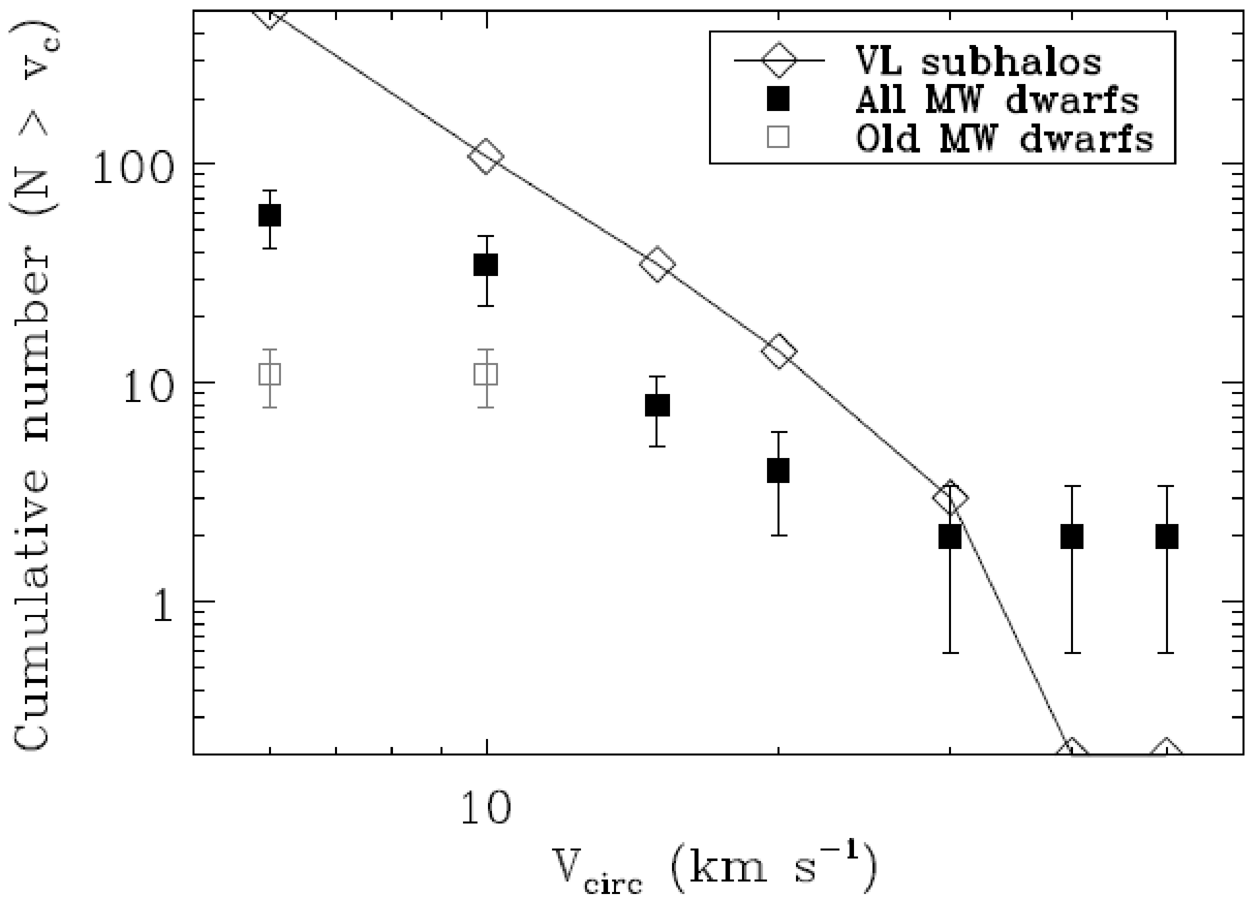
Submitted to ApJ

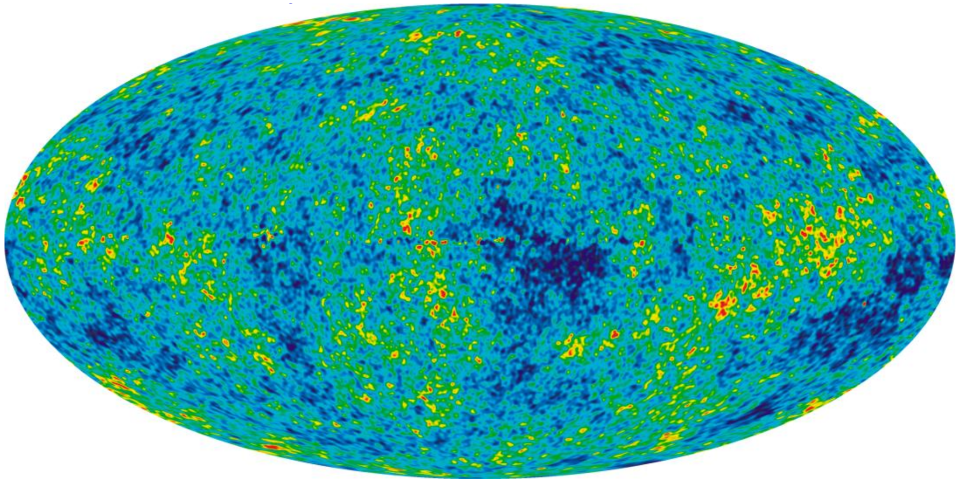
arXiv:0706.0516v1 [astro-ph] 4 Jun 2007



Also, the "Gilmore limiting density" of 5 GeV/cm^3 seems violated by factor ~ 5

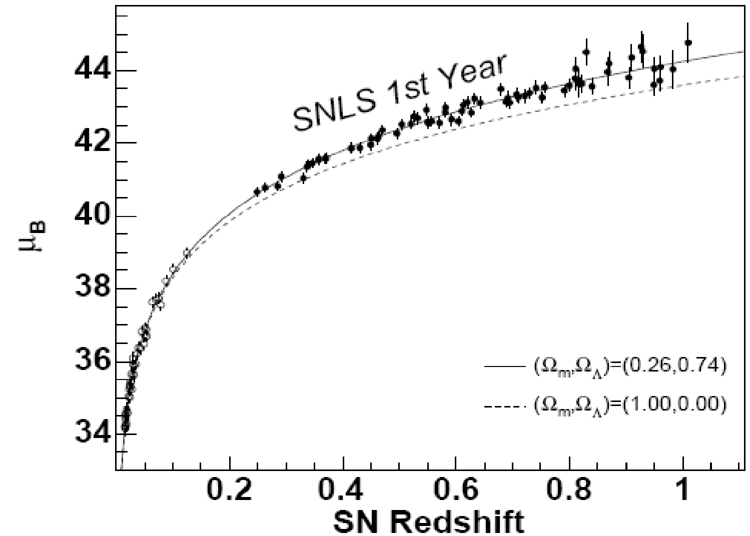
In fact, the phase space density $Q = \rho/\sigma^3$ has an order of magnitude higher value than for previously known galaxies

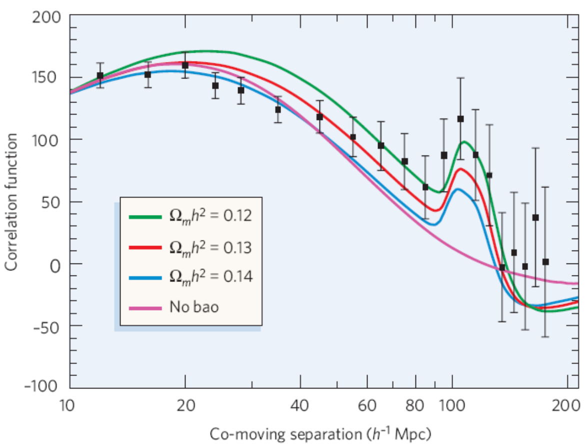
WMAP, 3-year



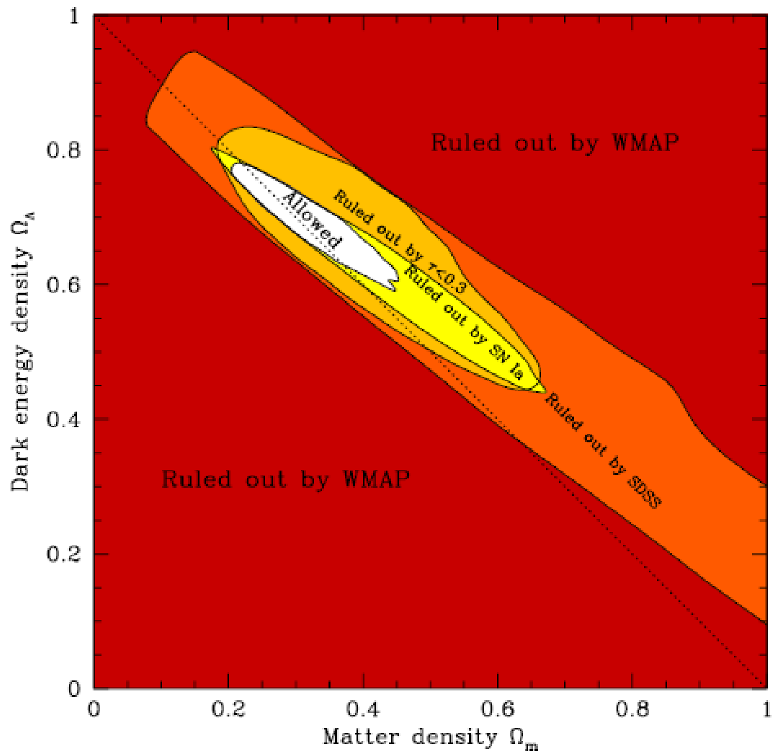
G. Hinshaw et al., 2006

P. Astier, et al., 2005

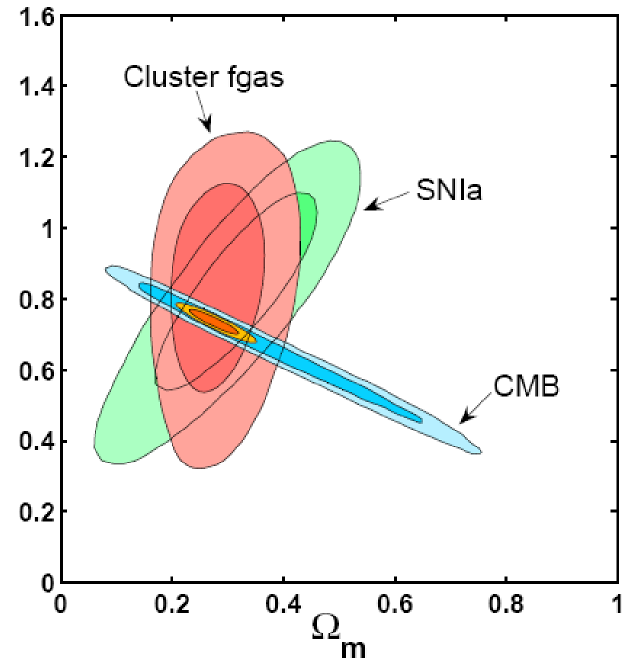




SDSS, 2005



M. Tegmark et al, 2004

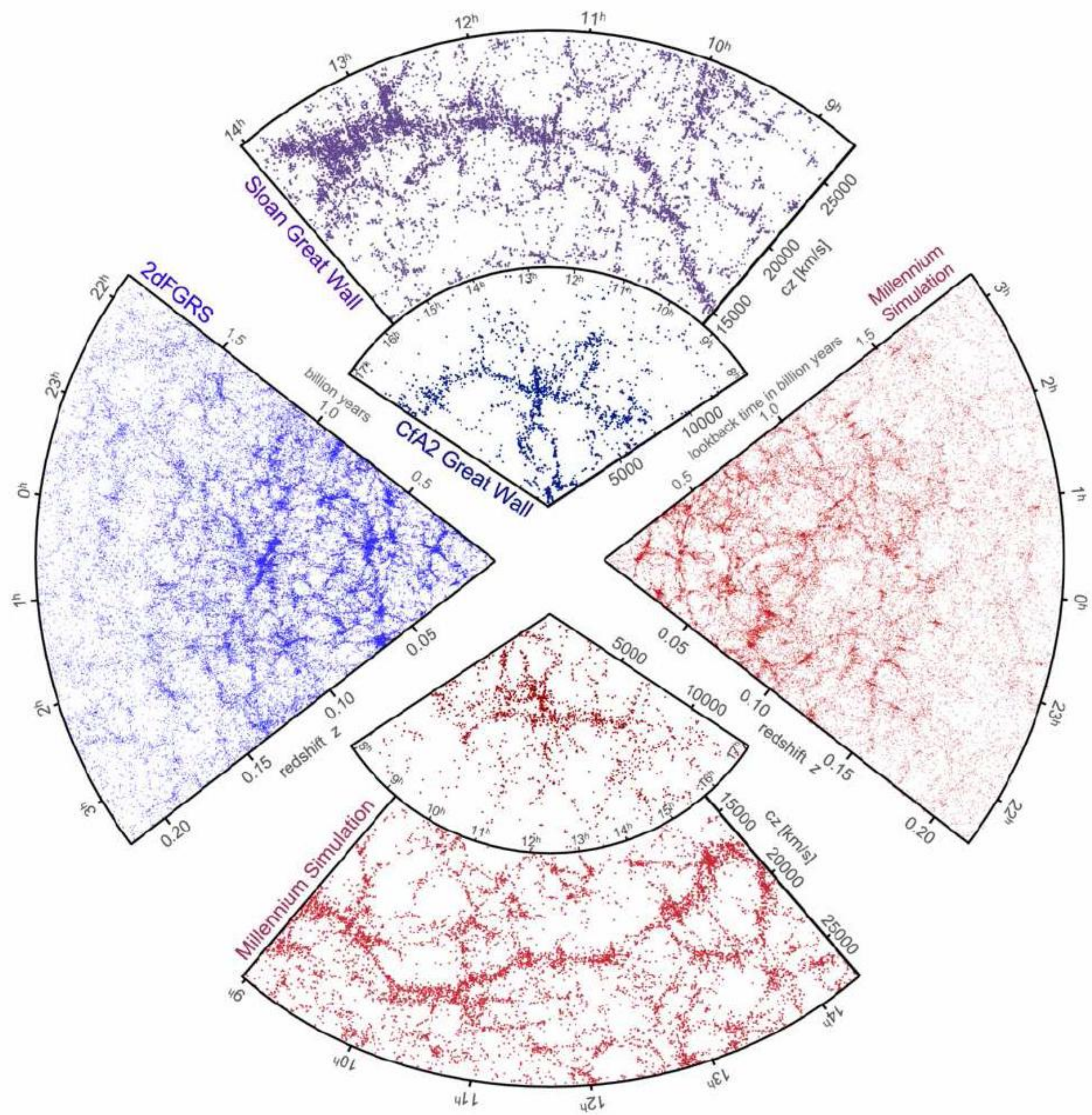


S. Allen & al., 2007

WMAP Collaboration (Spergel & al), 2006:

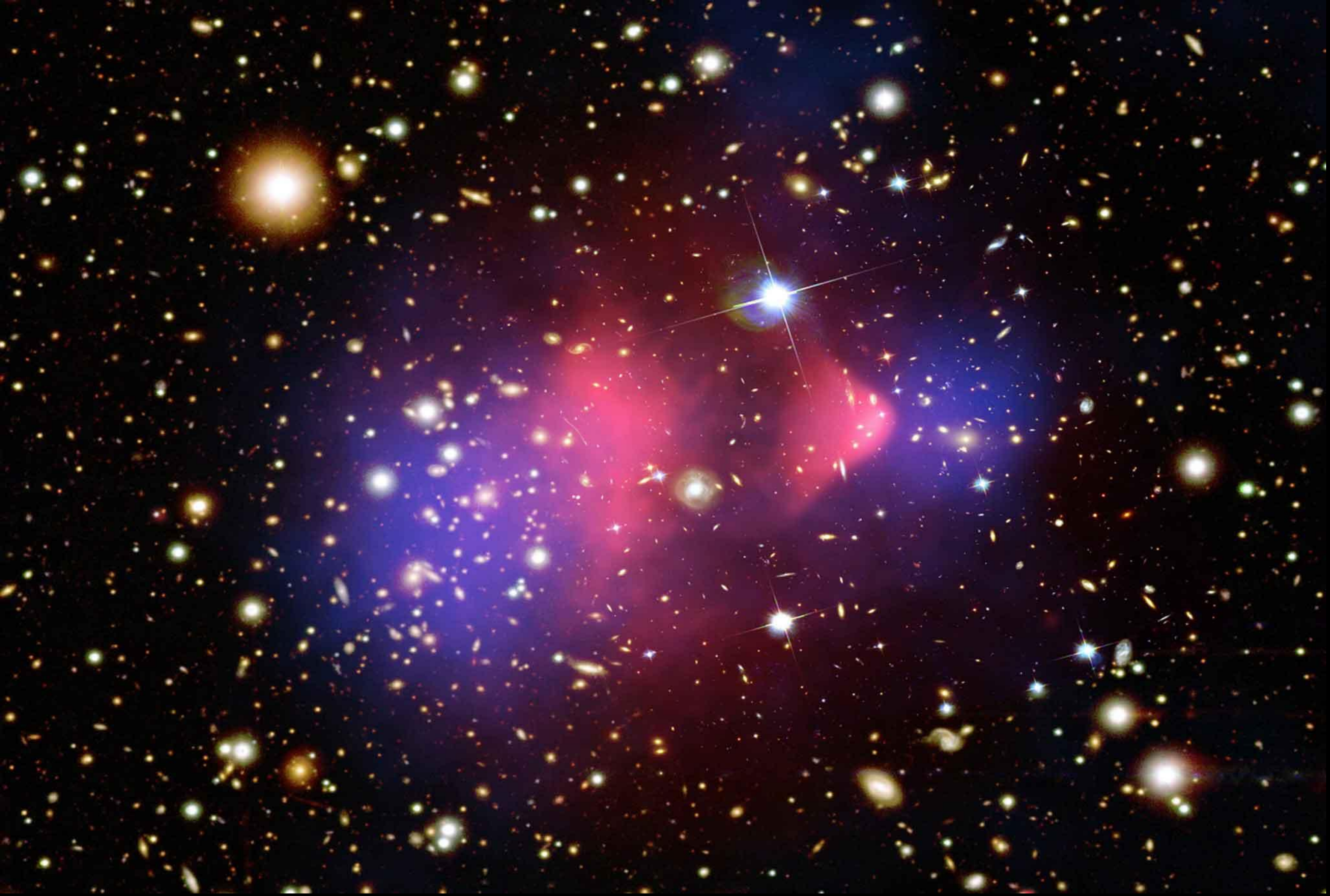
Nonbaryonic Dark Matter exists!

	Model	$-\Delta(2\ln\mathcal{L})$	N_{par}
M1	Scale Invariant Fluctuations ($n_s = 1$)	8	5
M2	No Reionization ($\tau = 0$)	8	5
M3	No Dark Matter ($\Omega_c = 0, \Omega_\Lambda \neq 0$)	248	6
M4	No Cosmological Constant ($\Omega_c \neq 0, \Omega_\Lambda = 0$)	0	6
M5	**Power Law ΛCDM**	0	6
M6	Quintessence ($w \neq -1$)	0	7
M7	Massive Neutrino ($m_\nu > 0$)	0	7
M8	Tensor Modes ($r > 0$)	0	7
M9	Running Spectral Index ($dn_s/d\ln k \neq 0$)	−3	7
M10	Non-flat Universe ($\Omega_k \neq 0$)	−6	7
M11	Running Spectral Index & Tensor Modes	−3	8
M12	Sharp cutoff	−1	7
M13	Binned $\Delta^2_{\mathcal{R}}(k)$	−22	20



Springel, Frenk & White, 2006

Comparing the distribution of mass on the largest scales (CfA, Sloan and 2dF data), with simulations in a ΛCDM model (millennium simulation)



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

”Bullet cluster”, Clowe, Randall, Markevitch, astro-ph/0611496

Two colliding clusters (”the bullet cluster”). The red is the X-ray signal, the blue is the reconstructed mass from weak gravitational lensing. The baryonic mass is separated from the weakly interacting dark matter!

Structure of the Universe

Standard Model physics

Not understood at all

Physics or anthropic principle?

New physics beyond the Standard Model

Good particle physics candidates for Cold Dark Matter:

Independent motivation from particle physics

- Weakly Interacting Massive Particles (WIMPs, $3 \text{ GeV} < m_X < 50 \text{ TeV}$), thermal relics from Big Bang: Supersymmetric neutralino

  Kaluza-Klein states

  Extended Higgs sector

  Axino, gravitino (SuperWIMPS)

  Heavy neutrino-like particles

  Mirror particles

  ...

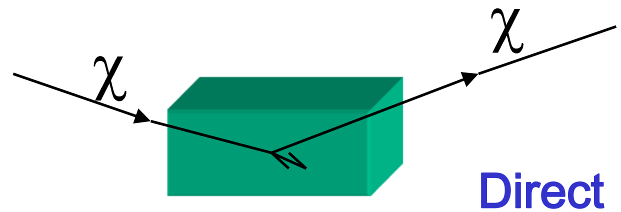
  plus hundreds more in literature

- **Axions** (introduced to solve strong CP problem)
- 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)

Methods of Weakly Interacting Massive Particle (WIMP) Dark Matter detection:

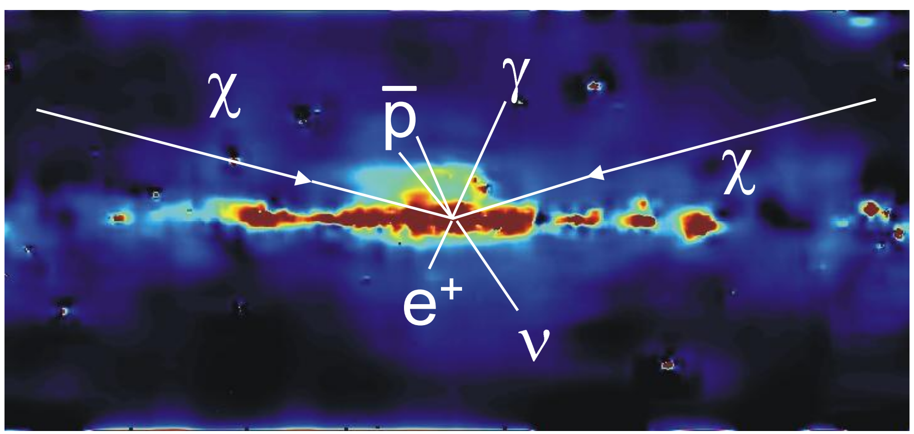
- Discovery at accelerators (Fermilab, LHC,...)
- Direct detection of halo particles in terrestrial detectors
- Indirect detection of neutrinos, gamma rays, radio waves, antiprotons, positrons in earth- or space-based experiments



Direct detection

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

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



Indirect detection

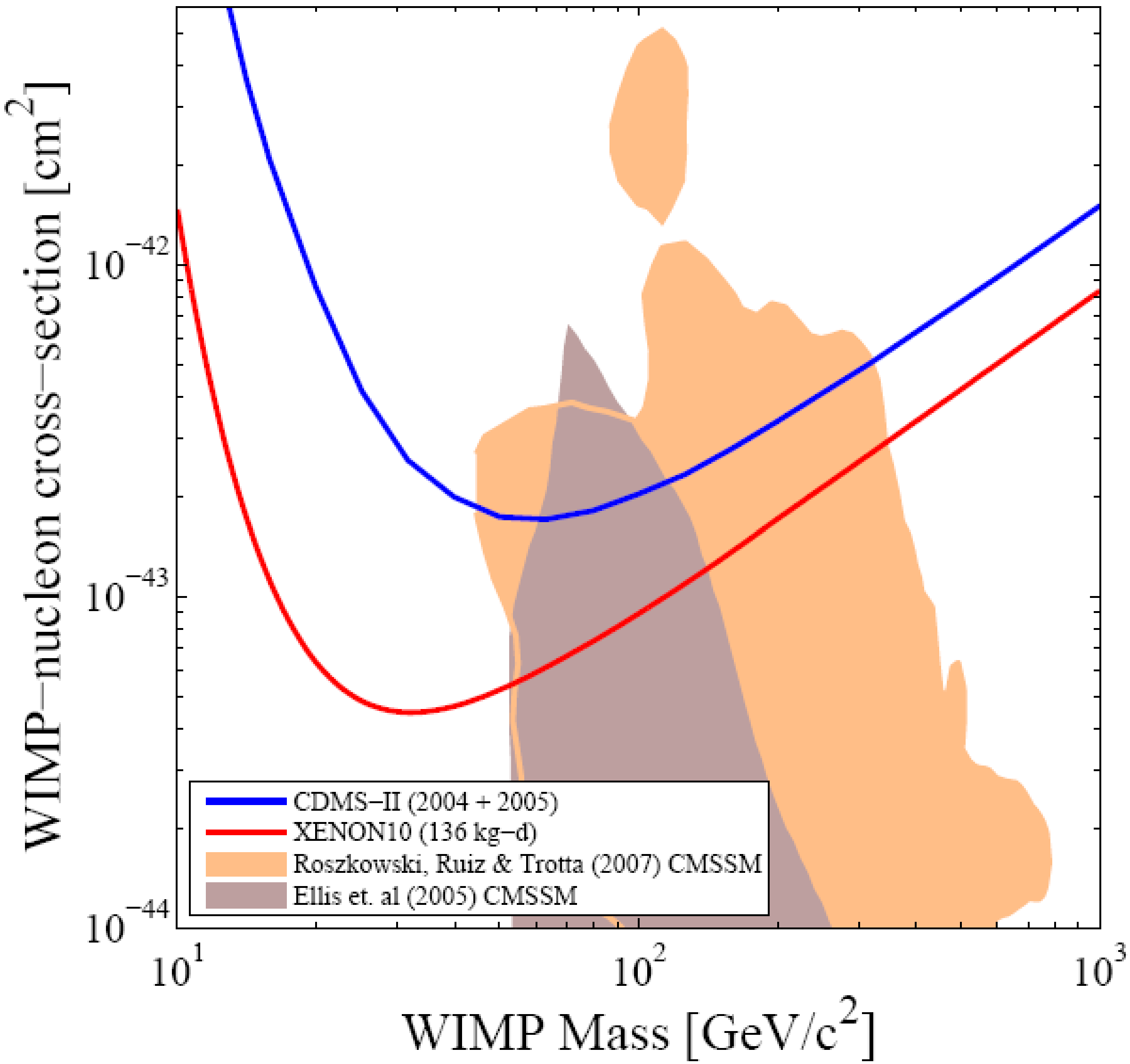
Neutralinos are Majorana particles

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

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

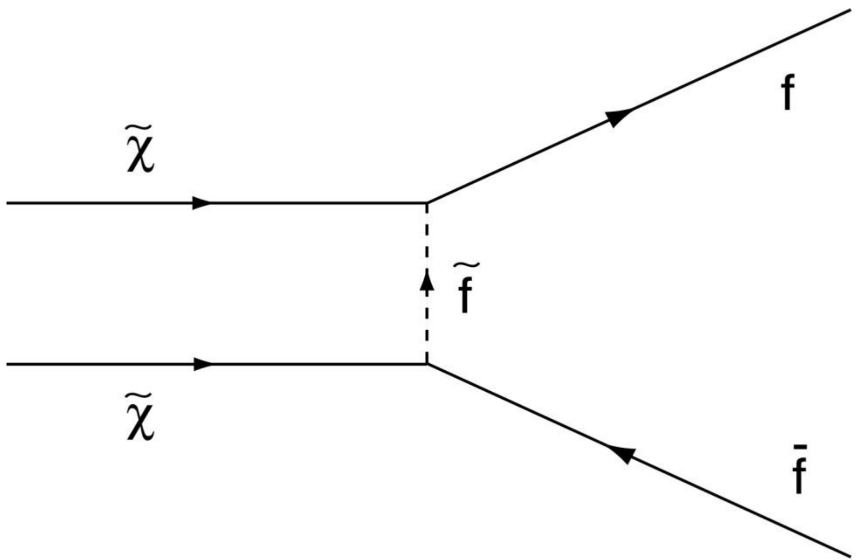
First Results from the XENON10 Dark Matter Experiment at the Gran Sasso National Laboratory

J. Angle et al, 31 May, 2007



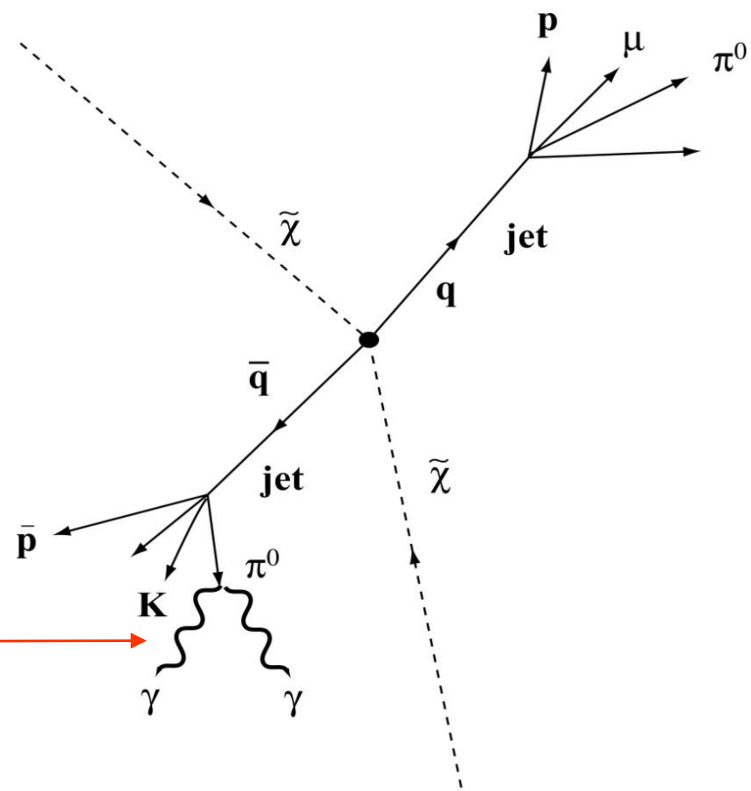
Based on 50 days in Gran Sasso with a 5 kg liquid Xe detector. Technology is scalable to 1 ton!

Indirect detection: neutralino example



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

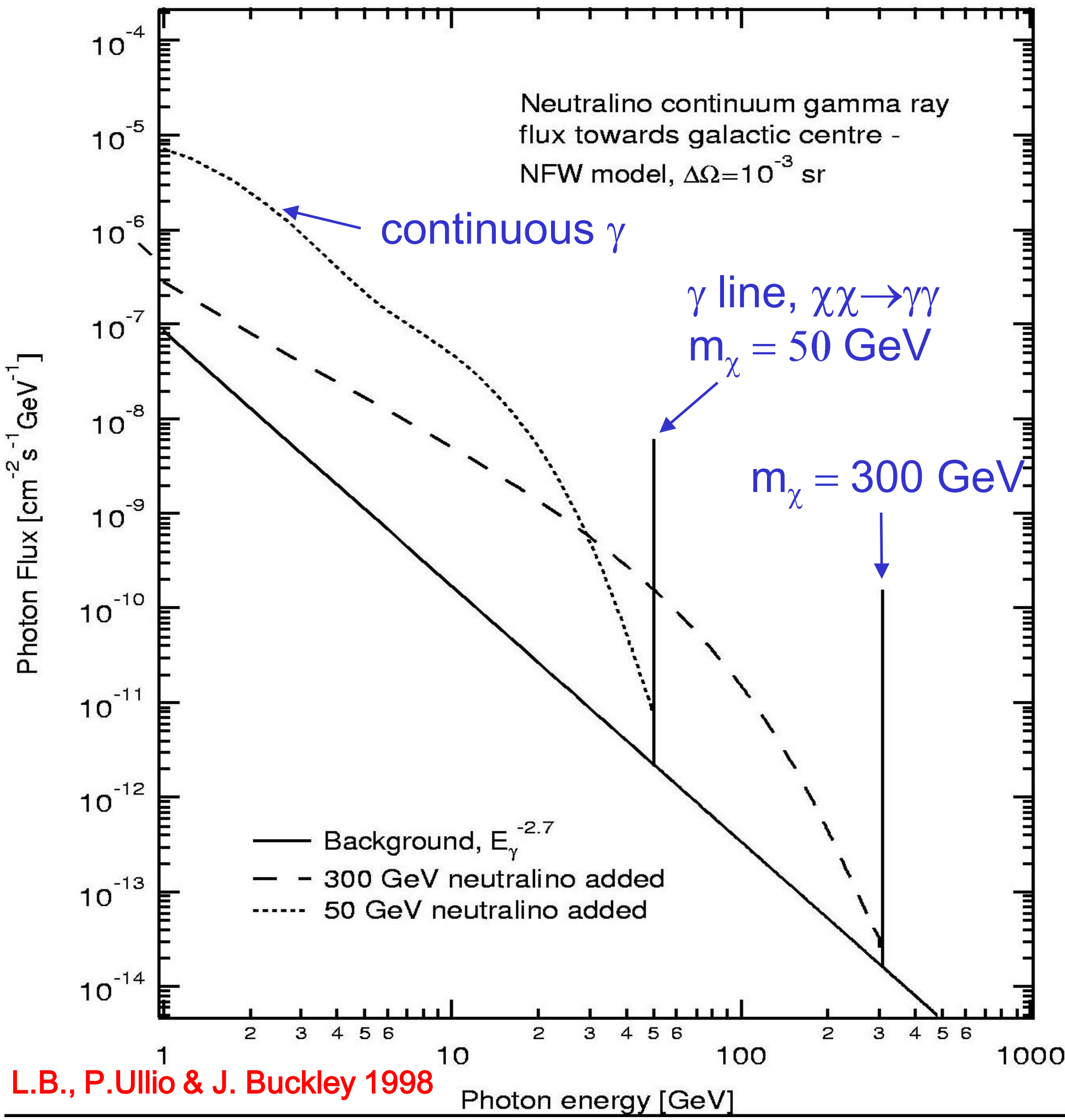


Decays of neutral pions: Dominant source of continuum gammas in halo annihilations

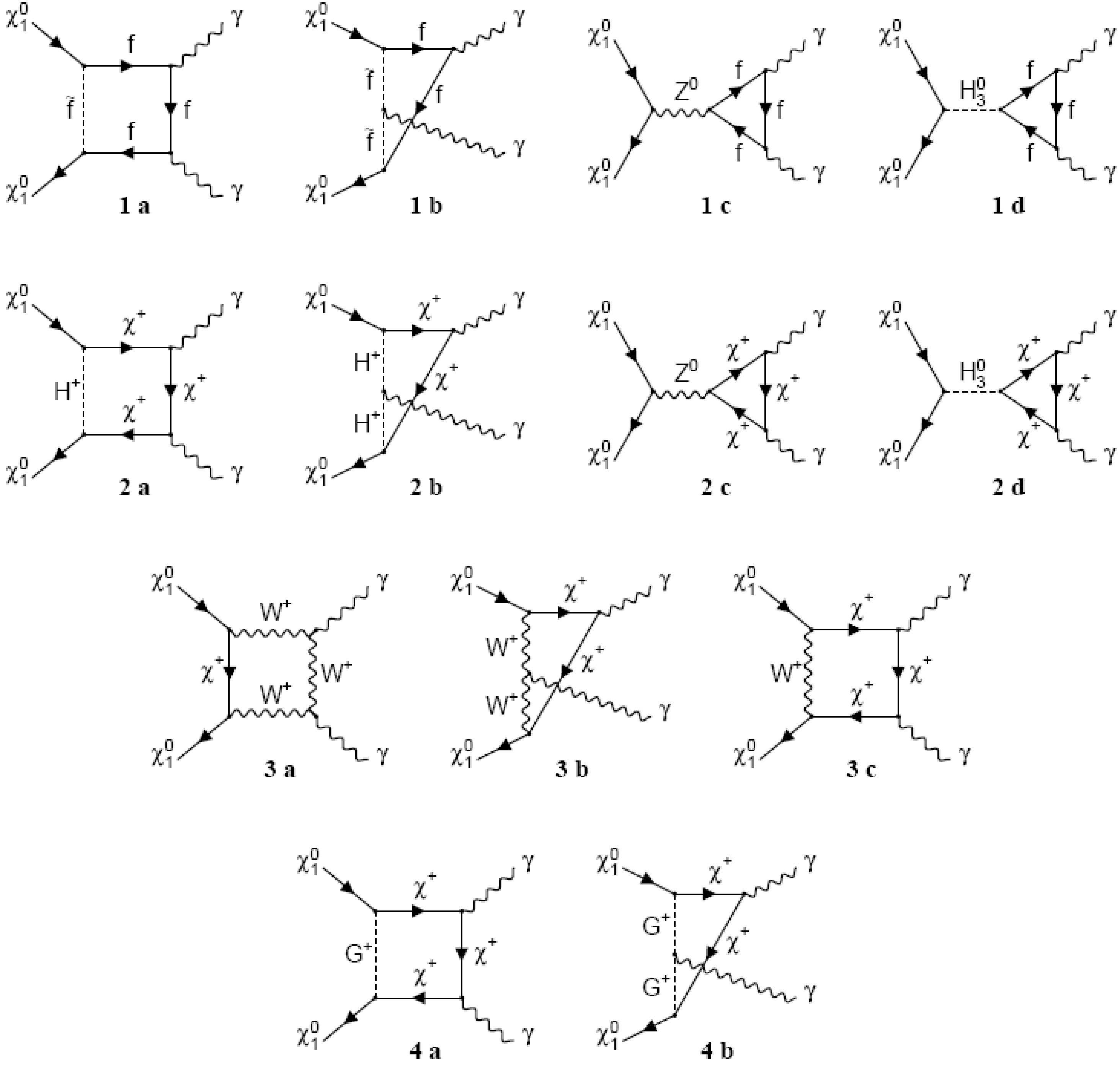
Gamma-rays

Indirect detection through γ-rays. Two types of signal: Continuous (large rate but at lower energies - difficult signature) and Monoenergetic line (often small rate but is 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)

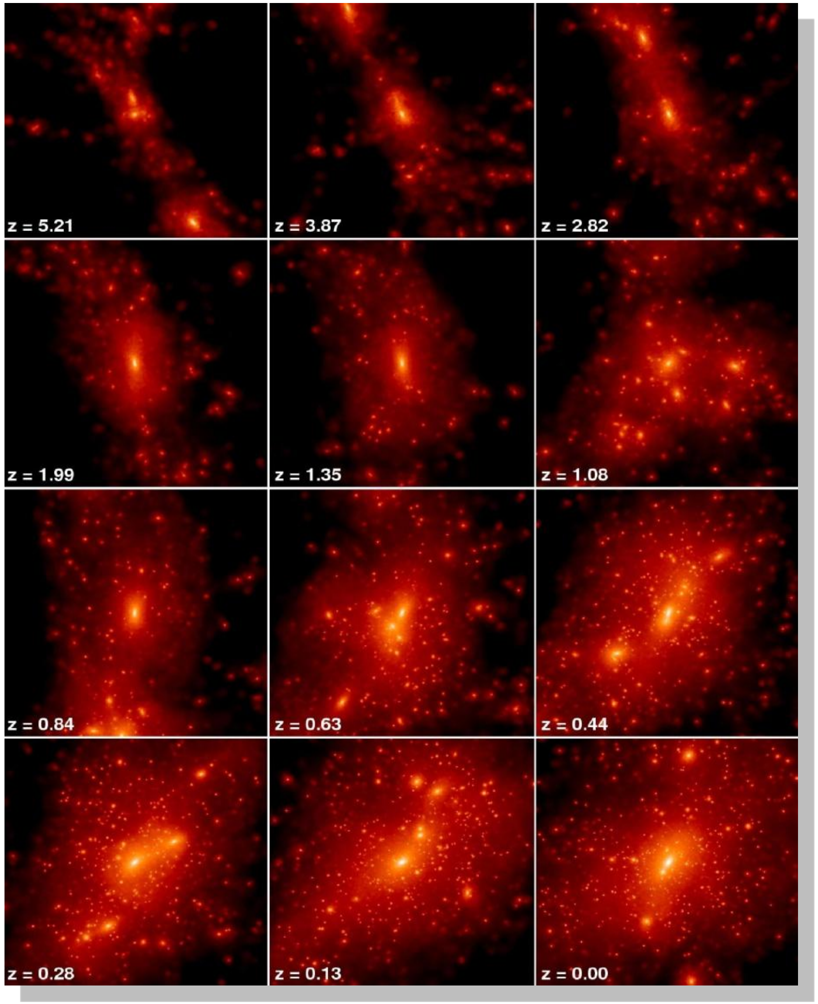


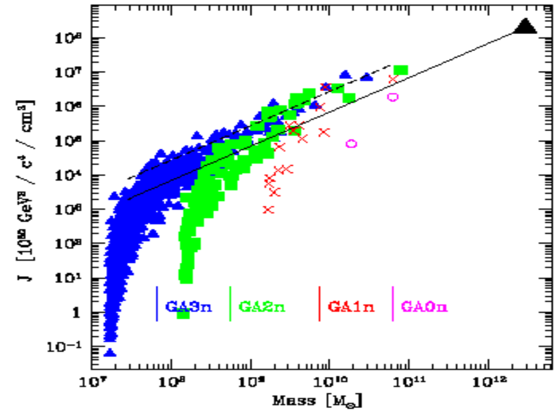
L.B., P.Ullio & J. Buckley 1998

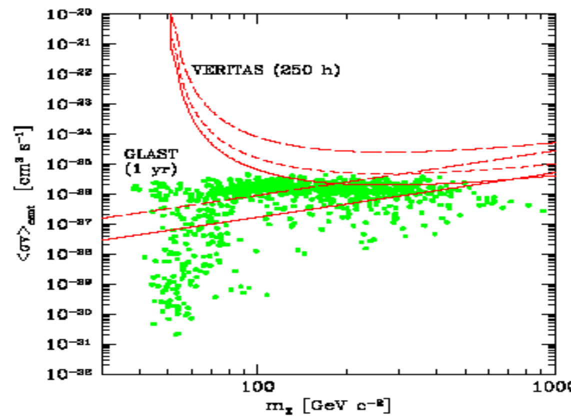


χ_1^0
γ
f
$\tilde{f}$
Z^0
H_3^0
χ^+
H^+
W^+
G^+
1 a
1 b
1 c
1 d
2 a
2 b
2 c
2 d
3 a
3 b
3 c
4 a
4 b

Dark matter clumps in the halo?







Rates computed with

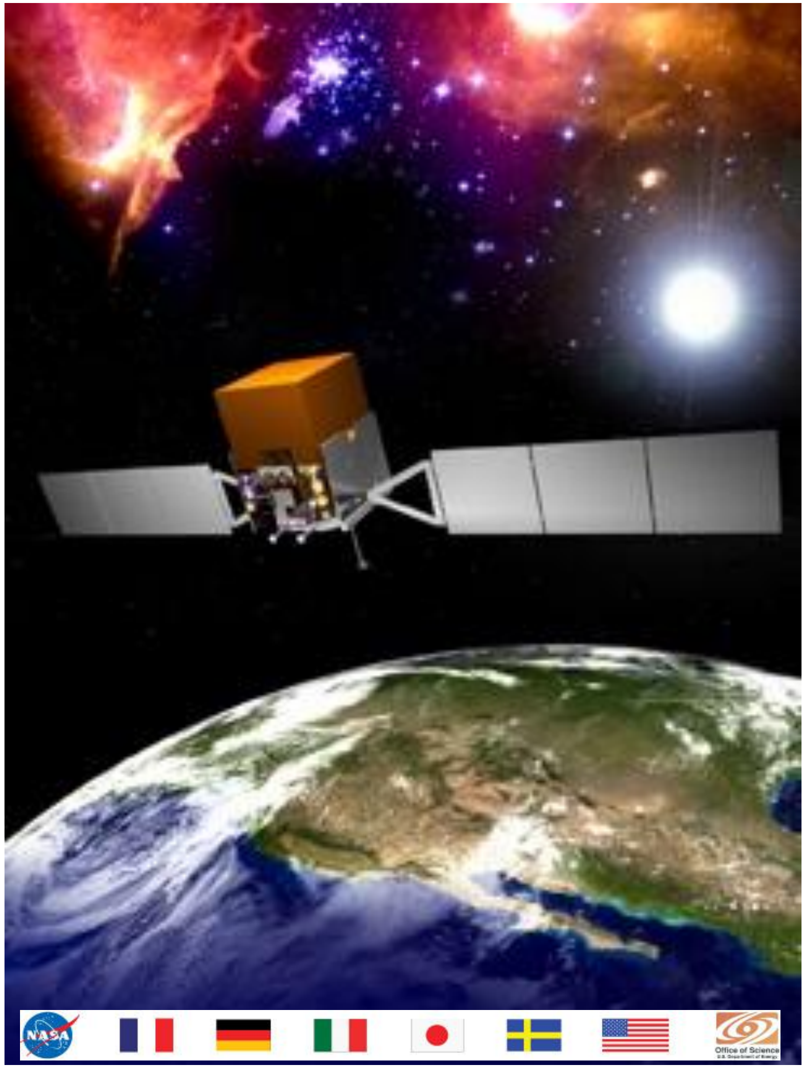
Dark SUSY

Stoehr, White, Springel,Tormen, Yoshida, MNRAS 2003. (Cf Calcaneo-Roldan & Moore, PRD, 2000.)

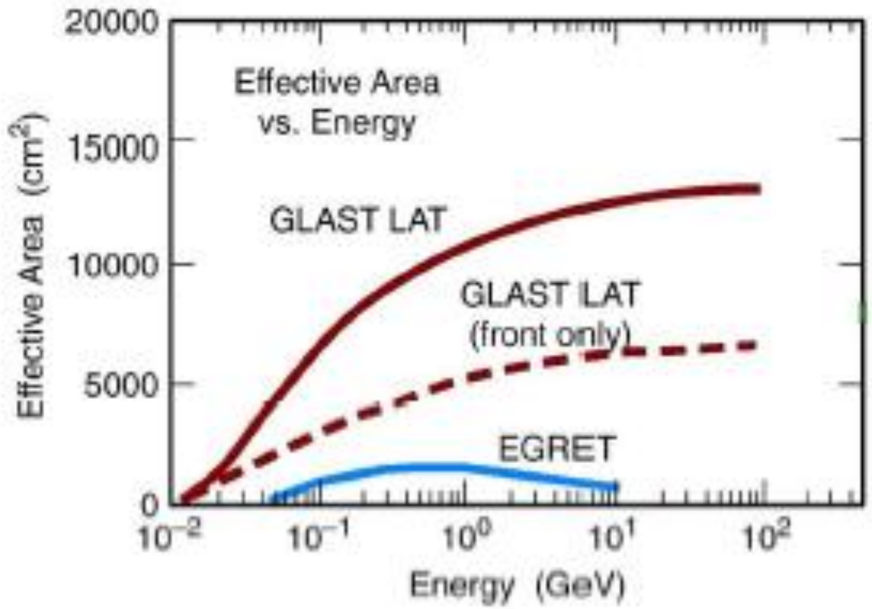
'Milky Way' simulation, Helmi, White & Springel, PRD, 2002

Important problem: What is the fate of the smallest substructures? Berezinsky, Dokuchaev & Eroshenko, 2003 & 2005; Green, Hofmann & Schwarz, 2003

GLAST GAMMA-RAY LARGE AREA SPACE TELESCOPE



USA (NASA & DoE) – France – Italy – Japan – Germany - Sweden collaboration, launch December 2007



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

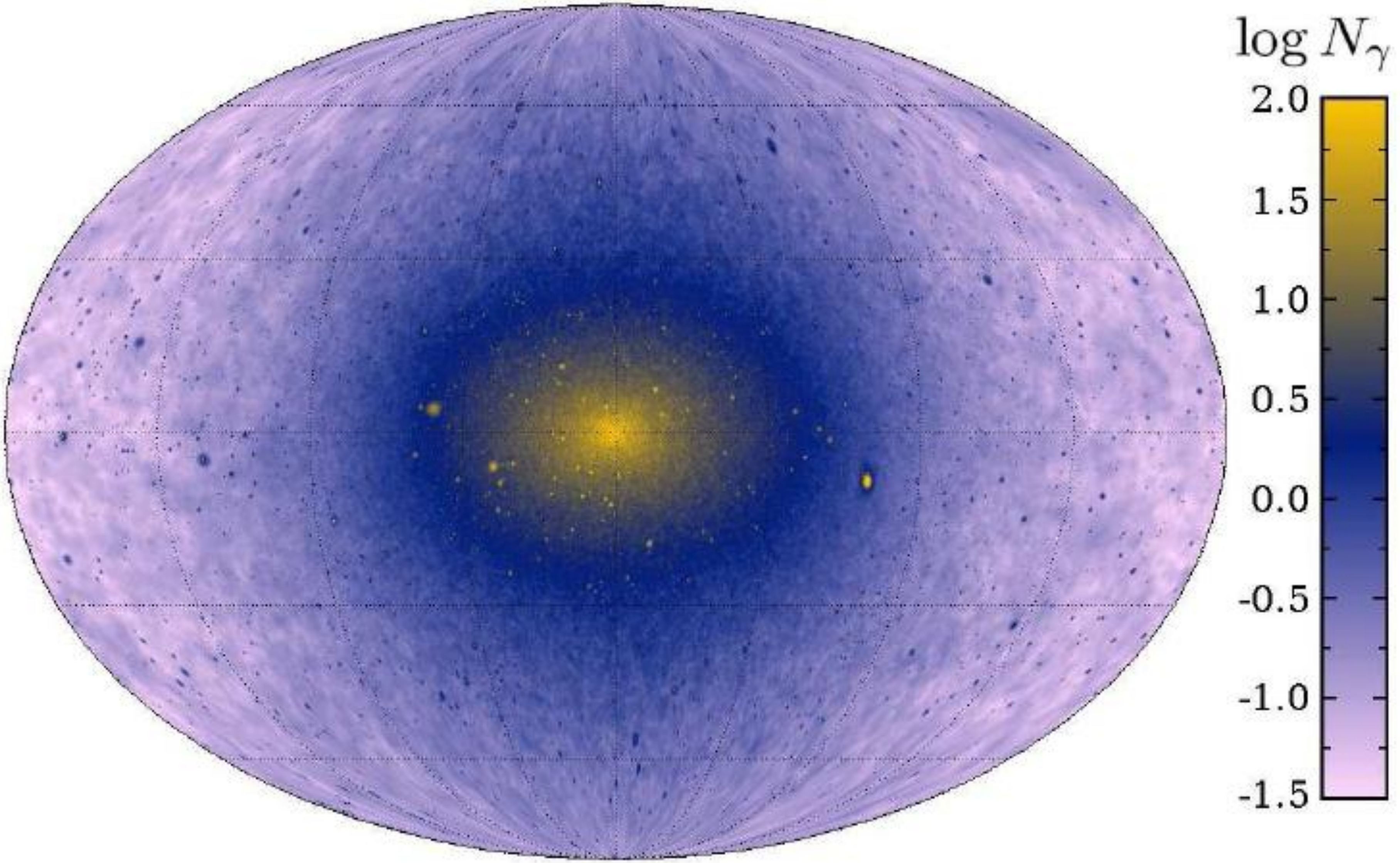


FIGURE 2. Simulated GLAST allsky map of neutralino DM annihilation in the Galactic halo, for a fiducial observer located 8 kpc from the halo center along the intermediate principle axis. We assumed $M_\chi = 46$ GeV, $\langle \sigma v \rangle = 5 \times 10^{-26}$ cm^3 s^{-1}, a pixel size of 9 arcmin, and a 2 year exposure time. The flux from the subhalos has been boosted by a factor of 10 (see text for explanation). Backgrounds and known astrophysical gamma-ray sources have not been included.

Kuhlen, Diemand, Madau, 2007; cf. also Pieri, Bertone, Branchini, 2007

Example of more "conventional" dark matter model

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 and Ma, 1978; Barbieri, Hall, Rychkov 2006)

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

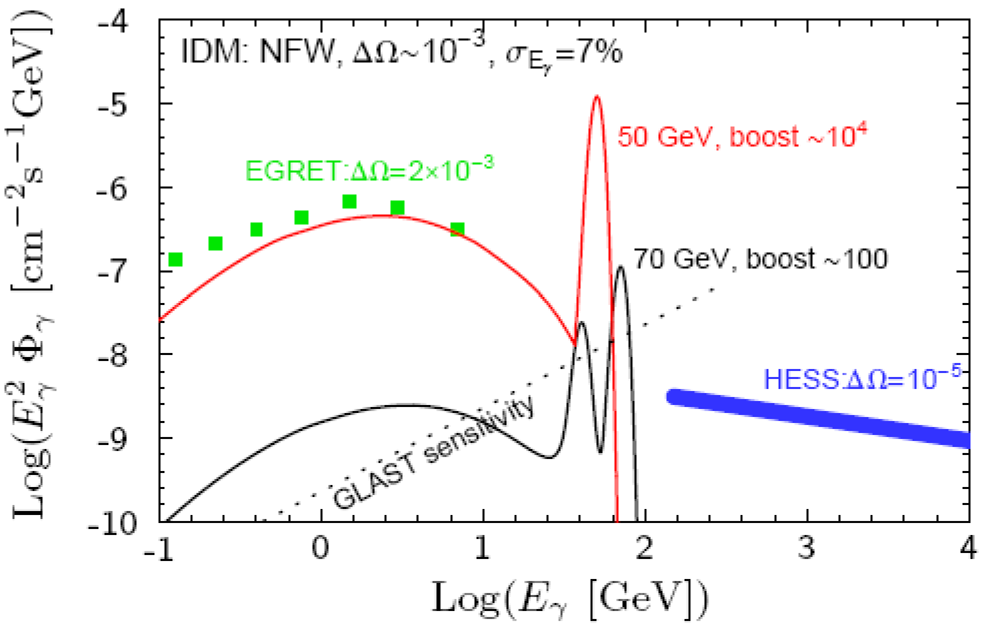
⇒ Ordinary Higgs can be as heavy as 500 GeV without violation of electroweak precision tests

⇒ 40 – 70 GeV inert Higgs gives correct dark matter density

⇒ Coannihilations with pseudoscalar A are important

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

⇒ The perfect candidate for detection in GLAST!



M. Gustafsson, L.B., J. Edsjö, E. Lundström, PRL to appear, 2007

Can be searched for at LHC through

$$pp \rightarrow W^* \rightarrow HA \text{ or } HS$$

$$pp \rightarrow Z^*(\gamma^*) \rightarrow SA \text{ or } H^+H^-$$

Branching ratios of more than 50 % to gamma lines are possible!

TABLE II: *IDM benchmark model results.*

Model	$v\sigma_{tot}^{v\to 0}$ [cm^{3}s^{-1}]	Branching ratios [%]: $\gamma\gamma$	$Z\gamma$	$b\bar{b}$	$c\bar{c}$	$\tau^+\tau^-$	$\Omega_{DM}h^2$
I	1.6×10^{-28}	36	33	26	2	3	0.10
II	8.2×10^{-29}	29	0.6	60	4	7	0.10
III	8.7×10^{-27}	2	2	81	5	9	0.12
IV	1.9×10^{-26}	0.04	0.1	85	5	10	0.11

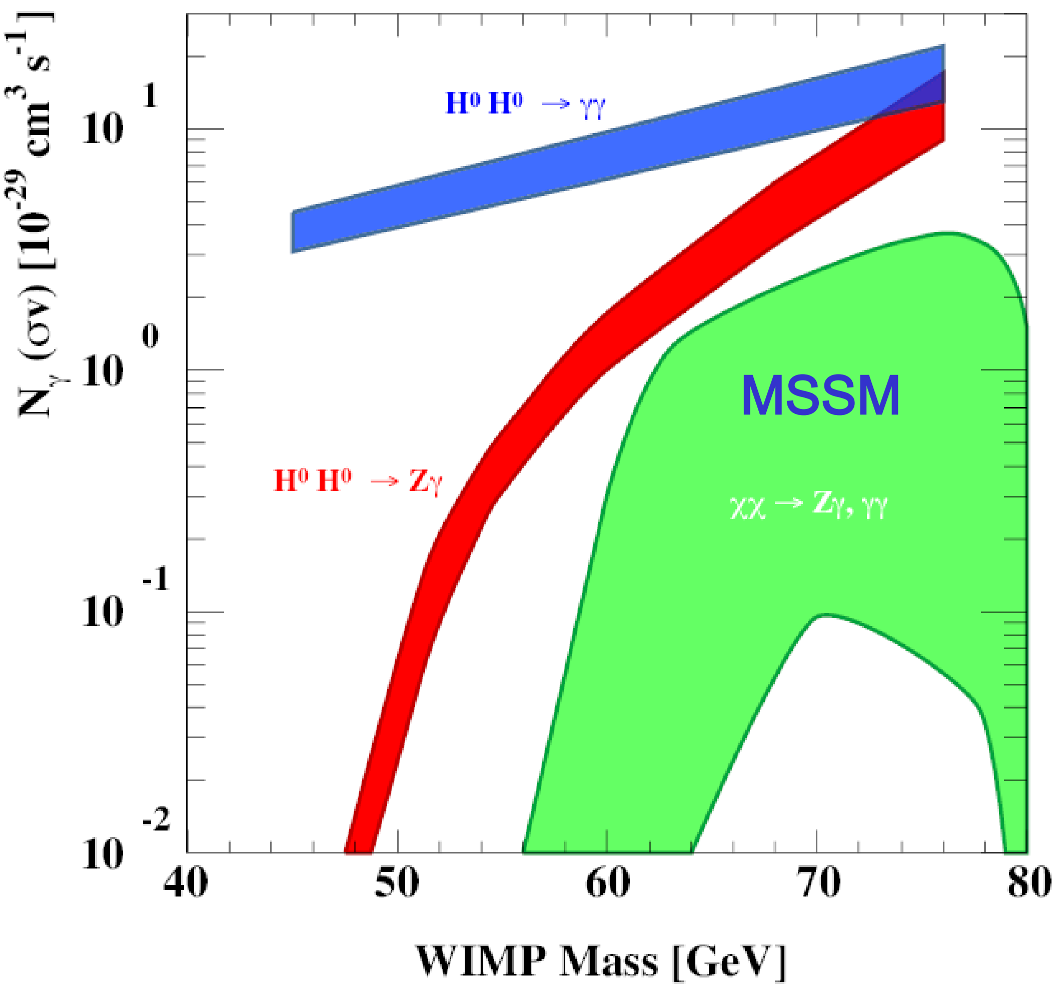
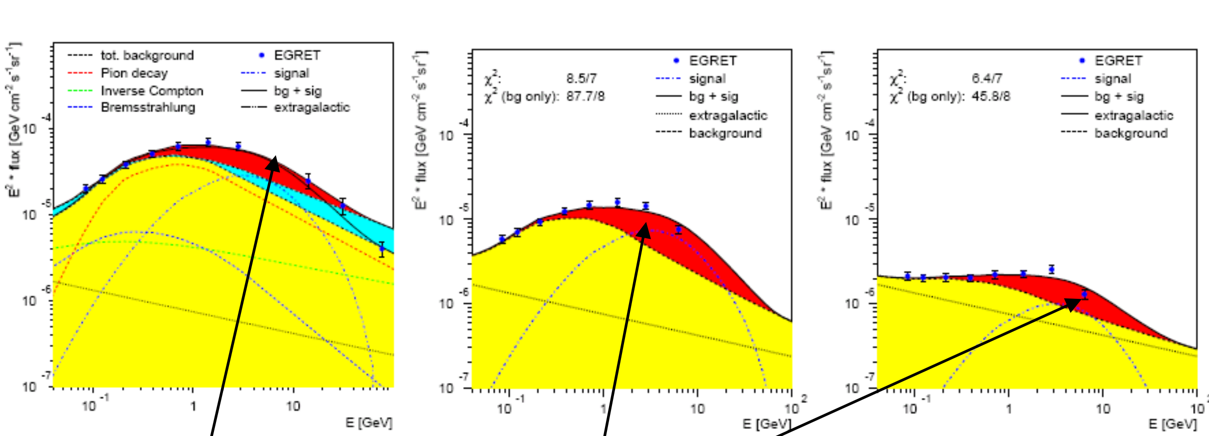


FIG. 3: *Annihilation rates into gamma-ray lines $2v\sigma_{\gamma\gamma}$ (upper band) and $v\sigma_{Z\gamma}$ (middle band) from the scan over the IDM parameter space. For comparison the lower-right region indicate the corresponding results within MSSM as obtained with the DarkSUSY package [16].*

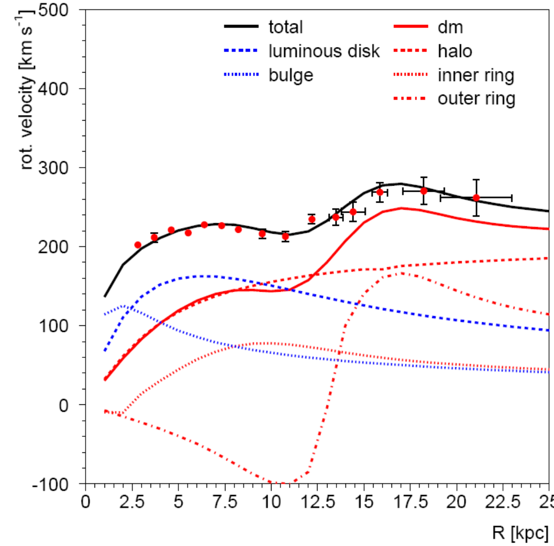
W. de Boer, 2003-2007



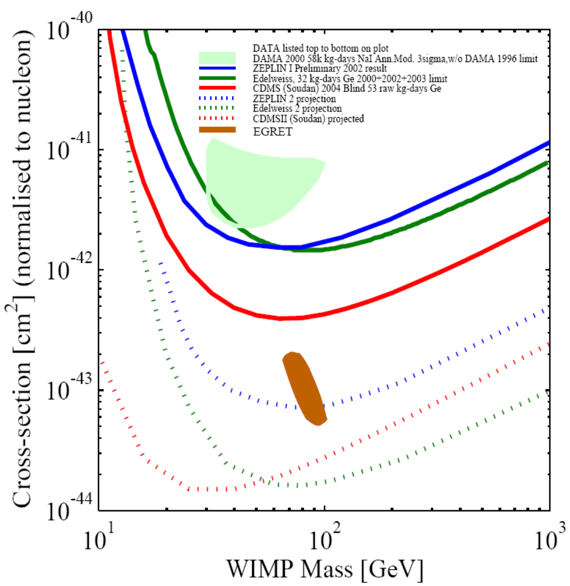
Excess of gamma-rays

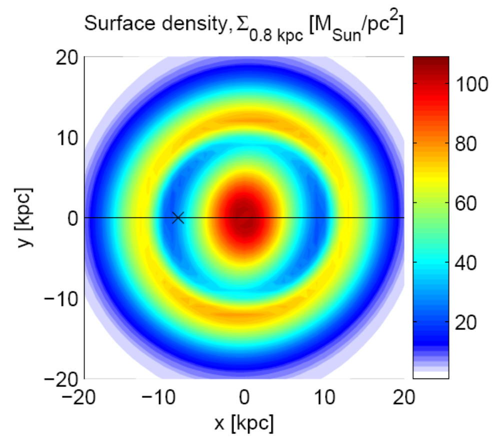
Filled by 65 GeV neutralino annihilation

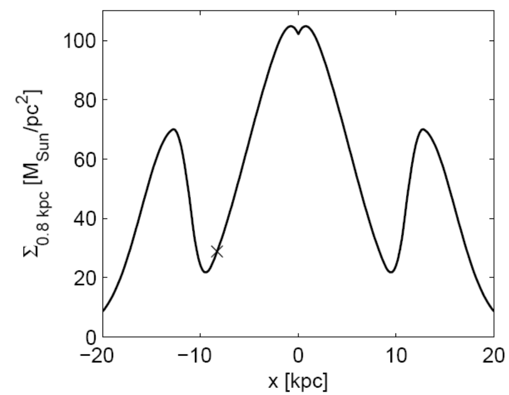
Data explained by 50-100 GeV neutralino?



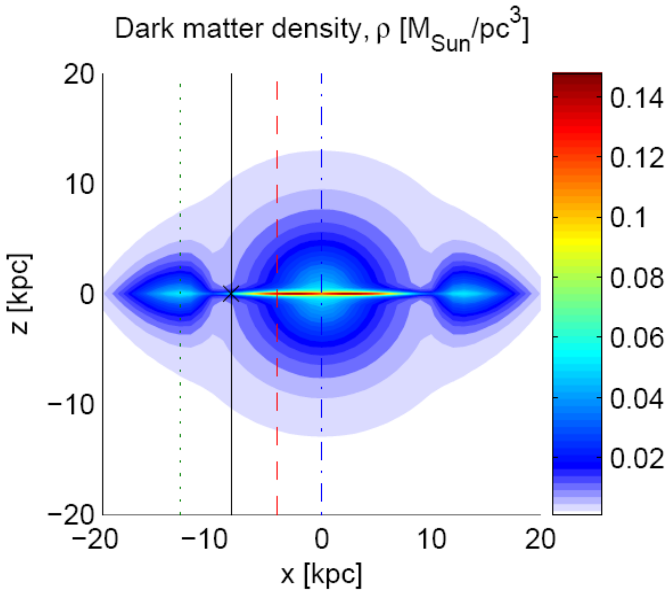
Galactic rotation curve

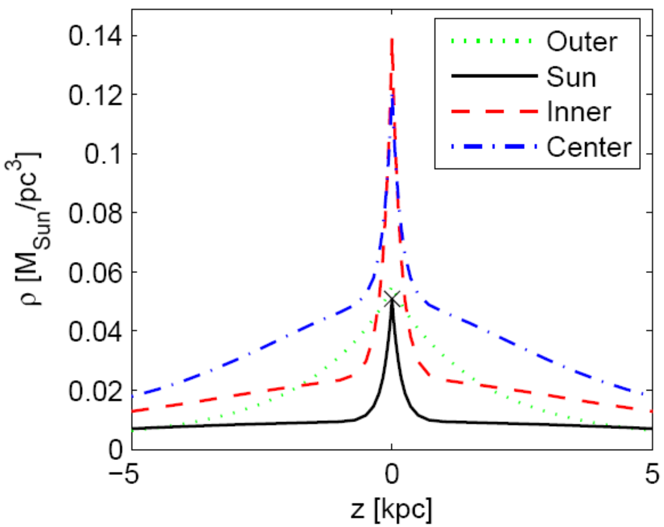






Rather weird DM distribution…





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

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

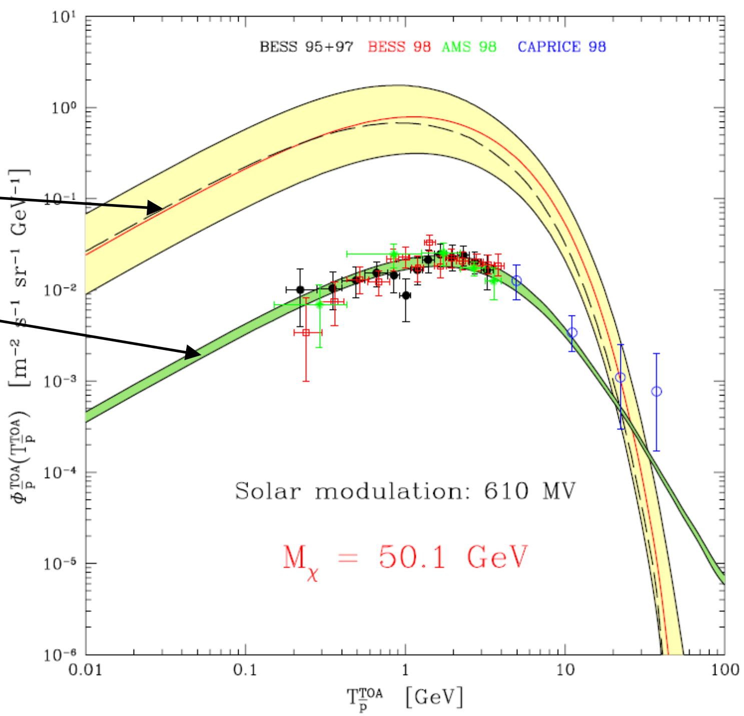
Antiprotons pose a major problem for this type of model:

Expected antiproton flux from de Boer's supersymmetric models

Standard (secondary) production from cosmic rays

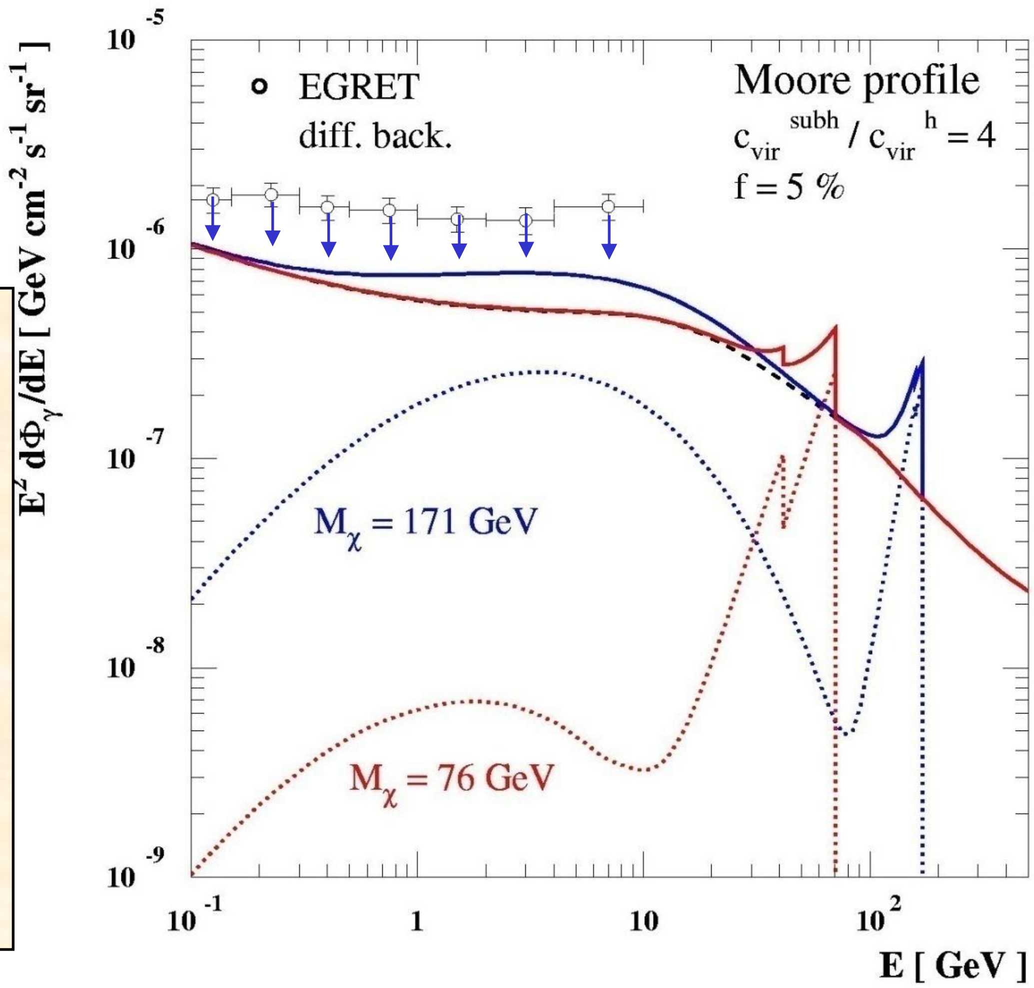
de Boer: Maybe diffusion is anisotropic, so that antiprotons are ejected from the galaxy?

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



Diffuse cosmic gamma-rays

Idea (L.B., Edsjö & Ullio, 2001): Integrated gamma-signal over all large- and small-scale structure may give observable diffuse gamma-ray flux for CDM-type cuspy halos and substructure. Redshifted gamma line in favourable cases.



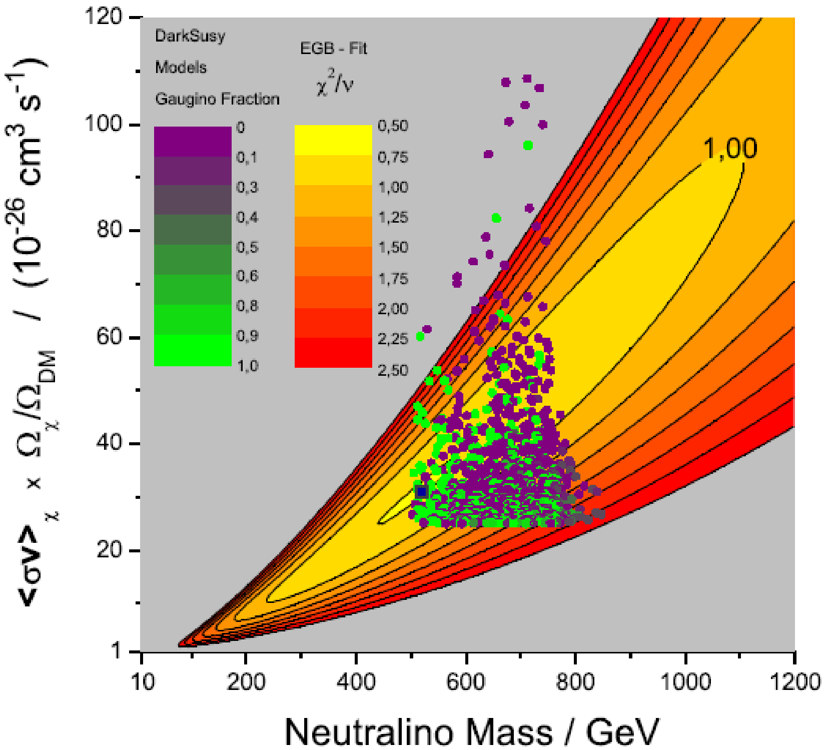
EGRET points will change as GLAST resolves more AGNs.

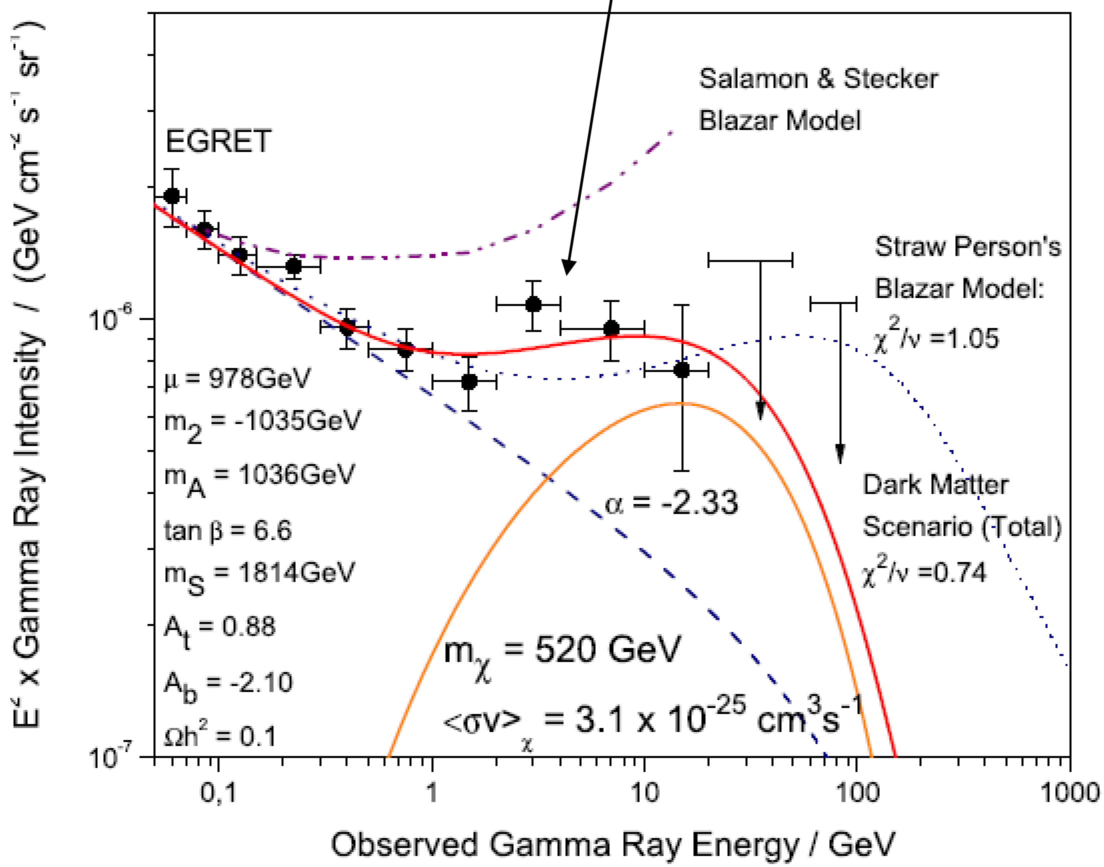
However, the EGRET points above 1 GeV are uncertain (see lalter).

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 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!

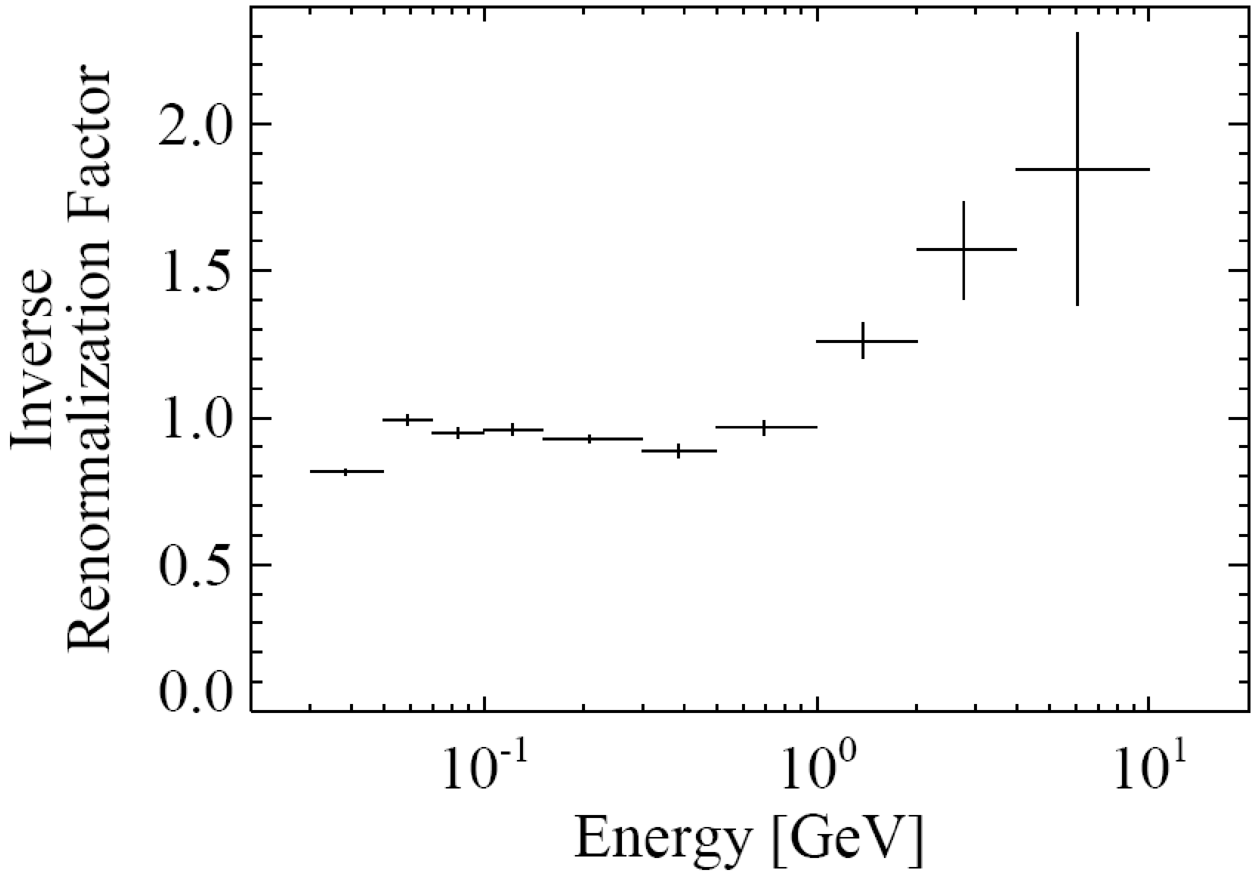
The Likely Cause of the EGRET GeV Anomaly and its Implications

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



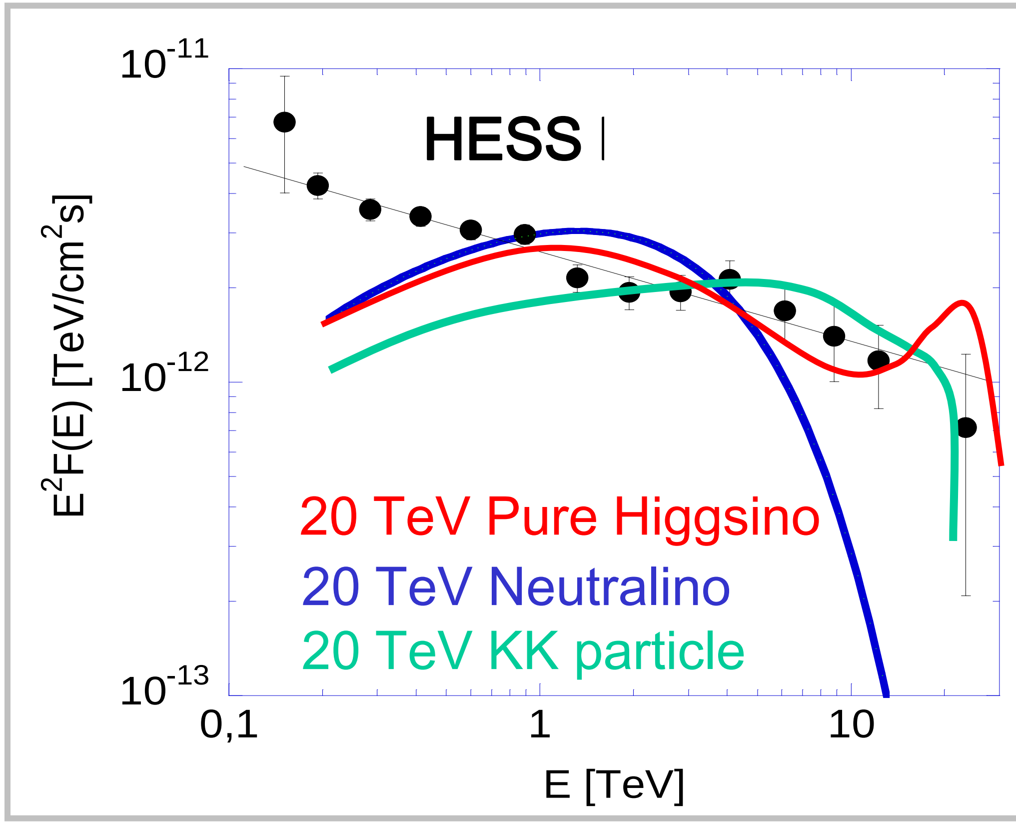
Problem with EGRET normalization:

Isotropic excess above 1 GeV

Instrumental effect? Still with unknown cause…

HESS results at high energy

Dark matter annihilation?



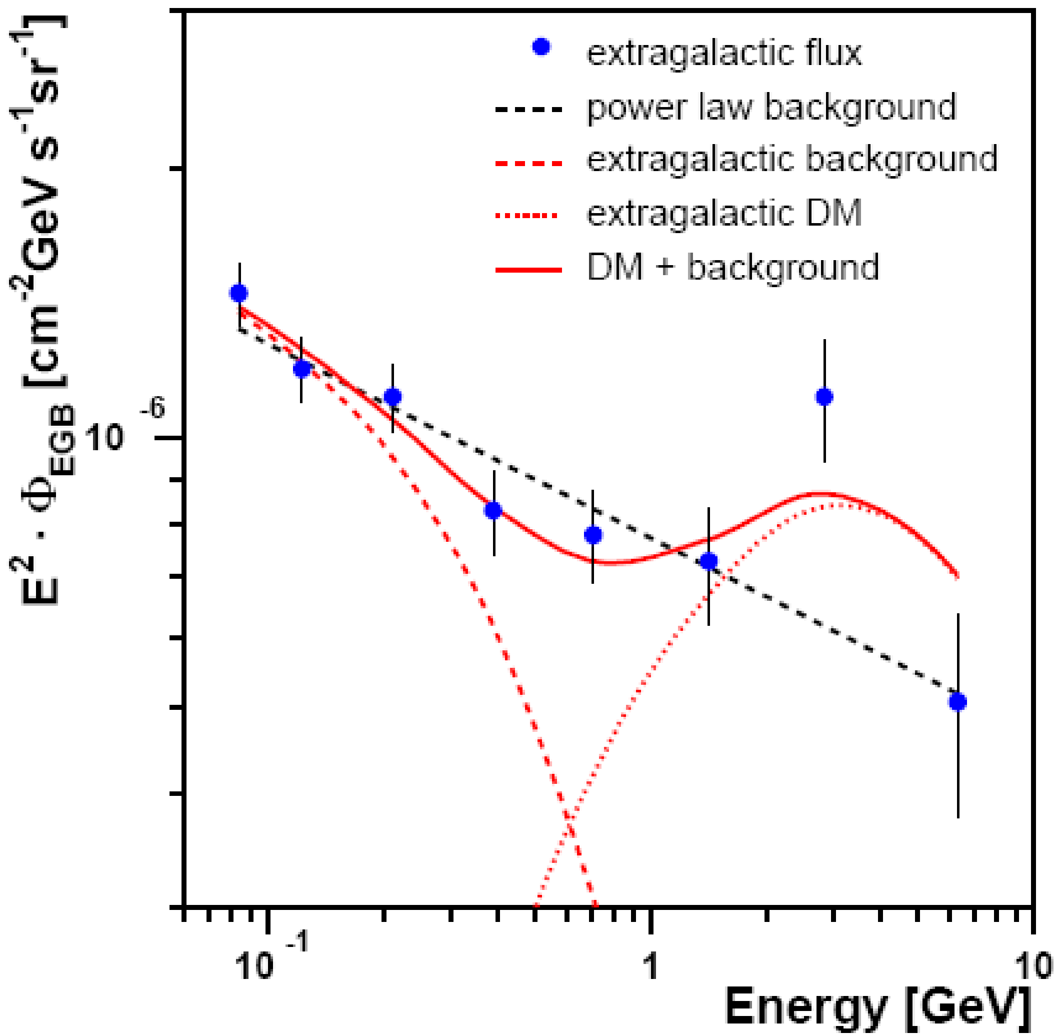
Wrong mass and shape for "natural" models

c.f. L.B., T. Bringmann, M. Eriksson, M. Gustafsson, 2005

Conclusions

- The existence of Nonbaryonic Dark Matter has been definitely established
- CDM is favoured (e.g., the lightest supersymmetric particle).
- LHC may well discover WIMP dark matter. Non-trivial to prove that it has the right properties, though.
- Indications of astrophysical excess gamma-rays. However, not compelling. Need more definitive spectral signature – the gamma line or a sharp drop at $E = m_{DM}$ would be a "smoking gun".
- The hunt is going on – many new experiments (GLAST, PAMELA, VERITAS, AMS) are coming on soon!
- Complementarity between accelarator (LHC) and astroparticle experiments
- The dark matter problem may be near its solution…

W. De Boer et al., May 2007



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 likely cause of the effect.
- To produce the extragalactic diffuse dark matter signal, the redshift has to be included – this has not been done!