Candidates and Prospects of Detection for Particle Dark Matter

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Basic facts:

$$\Omega_i \equiv \frac{\rho_i}{\rho_{crit}}$$

$$\rho_{crit} = \frac{3H_0^2 m_{Pl}^2}{8\pi} = 1.88h^2 \cdot 10^{-29}\ g/cm^3$$

$$h \equiv \frac{H_0}{100\ kms^{-1}Mpc^{-1}}$$

Observations give 0.6 < h < 0.8

Big Bang nucleosynthesis (deuterium abundance) and cosmic microwave background (WMAP) determine baryon contribution $\Omega_B h^2 \approx 0.024$, so $\Omega_B \approx 0.04$

$\Omega_{lum} \approx (4 \pm 2) \cdot 10^{-3}$ (stars, gas, dust) => baryonic dark matter has to exist (maybe as warm intergalactic gas?)

But, now we know that $\Omega_M >$ 0.2, so there has to exist non-baryonic dark matter!

Helium maybe underabundant?

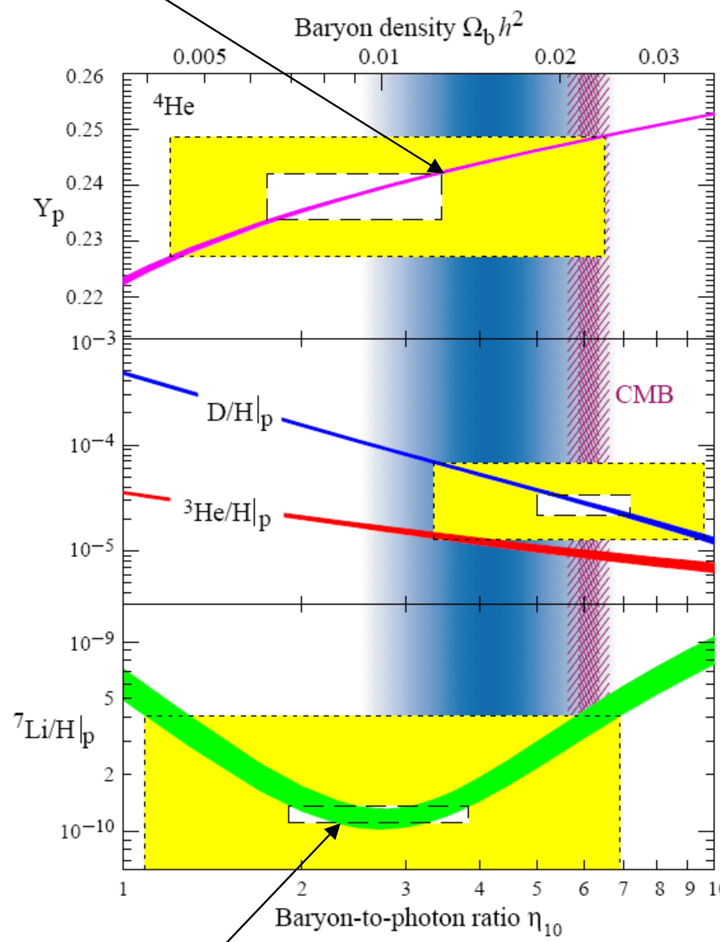
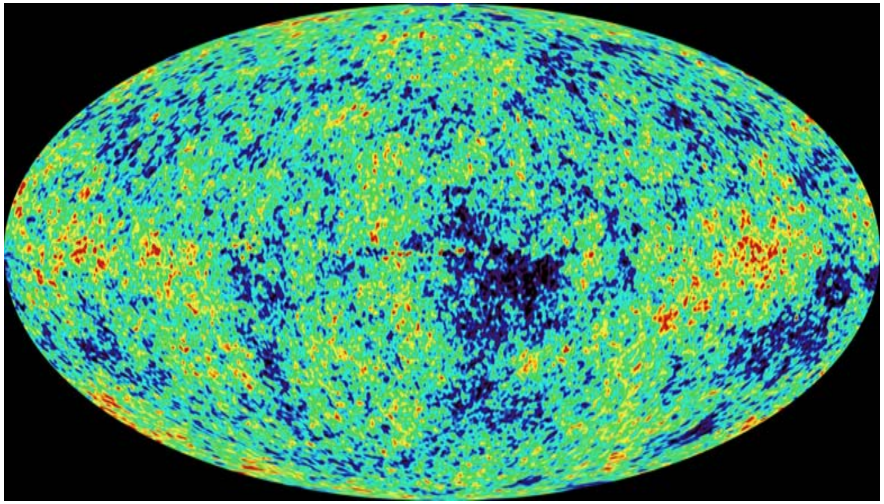


Figure 20.1: The abundances of ^{4}He, D, ^{3}He and ^{7}Li as predicted by the standard model of big-bang nucleosynthesis. Boxes indicate the observed light element abundances (smaller boxes: 2σ statistical errors; larger boxes: $\pm 2\sigma$ statistical and systematic errors added in quadrature). The narrow vertical band indicates the CMB measure of the cosmic baryon density. See full-color version on color pages at end of book.

Fields & Sarkar, 2004

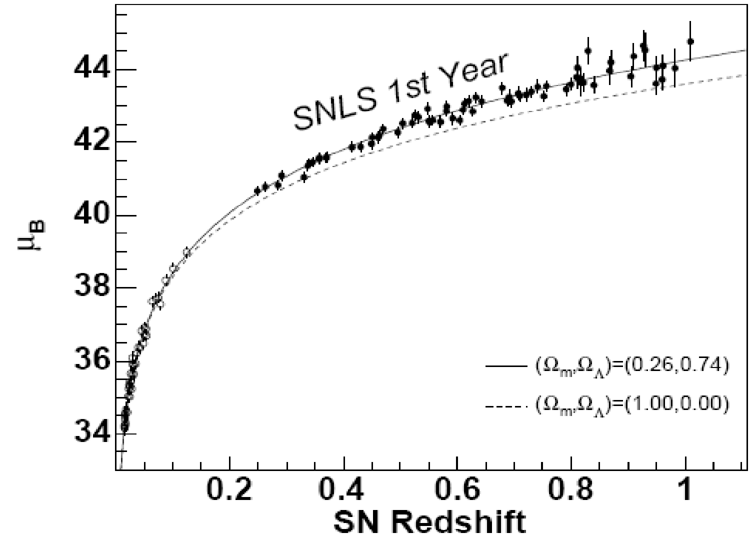
Lithium underabundant?

WMAP

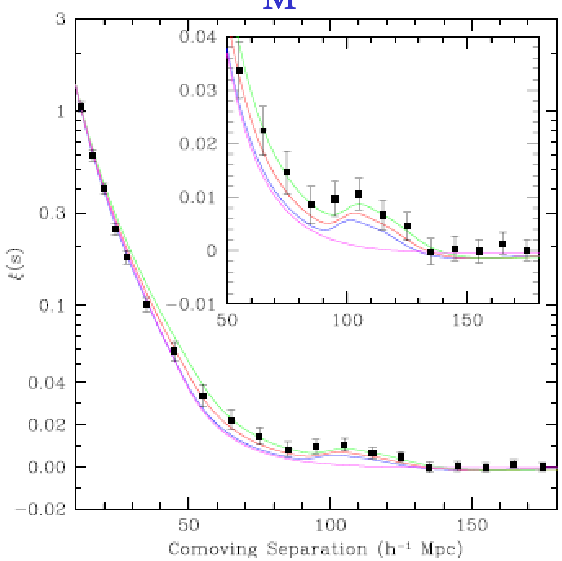


D.N. Spergel et al., 2003

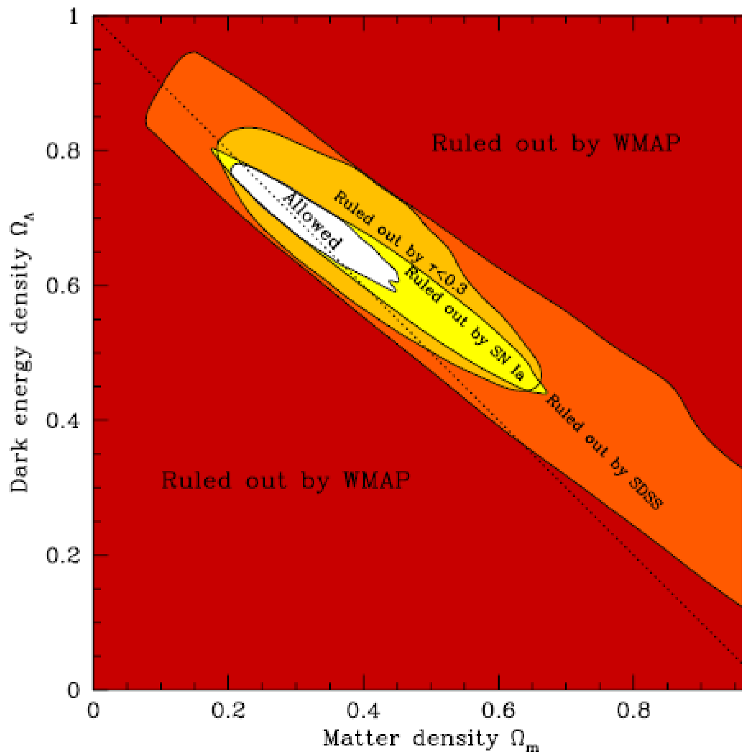
P. Astier, et al., 2005



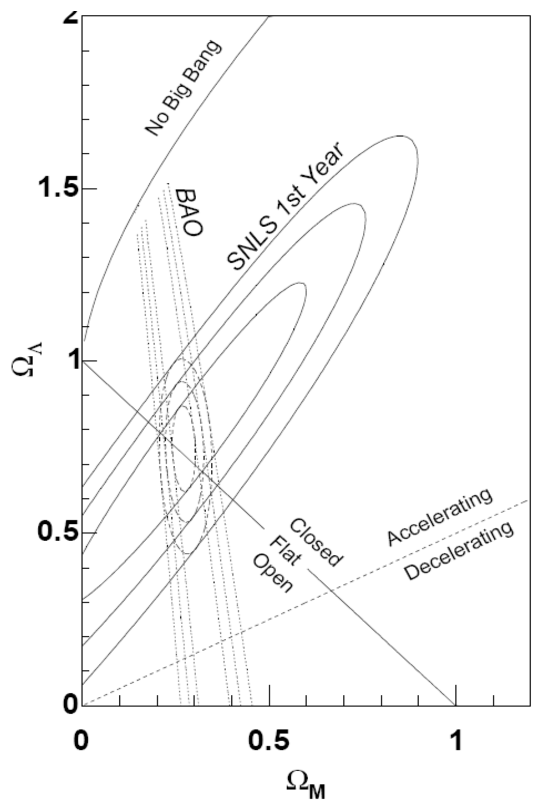
— $\Omega_M h^2$=0.12

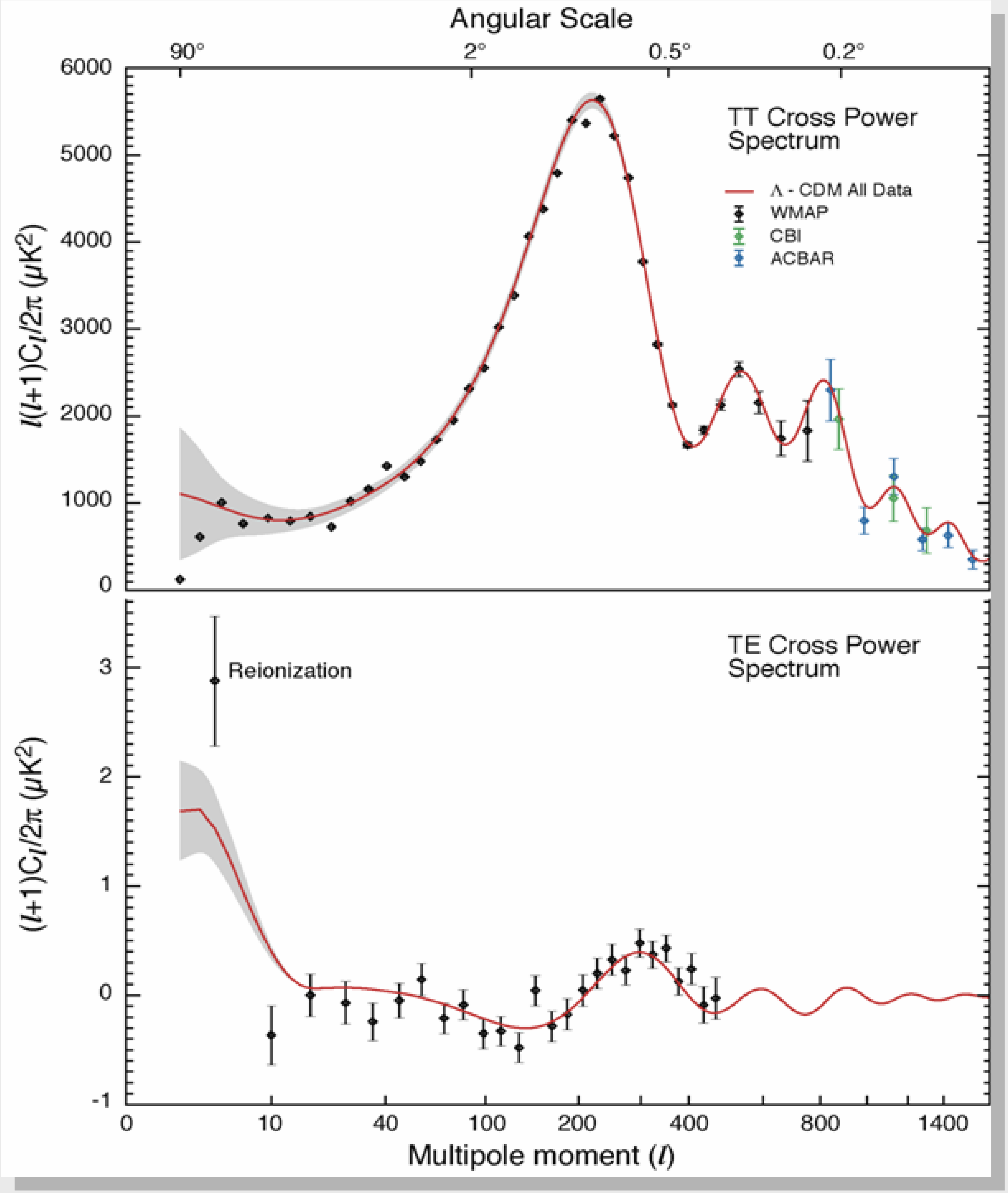


SDSS, 2005



M. Tegmark et al, 2004



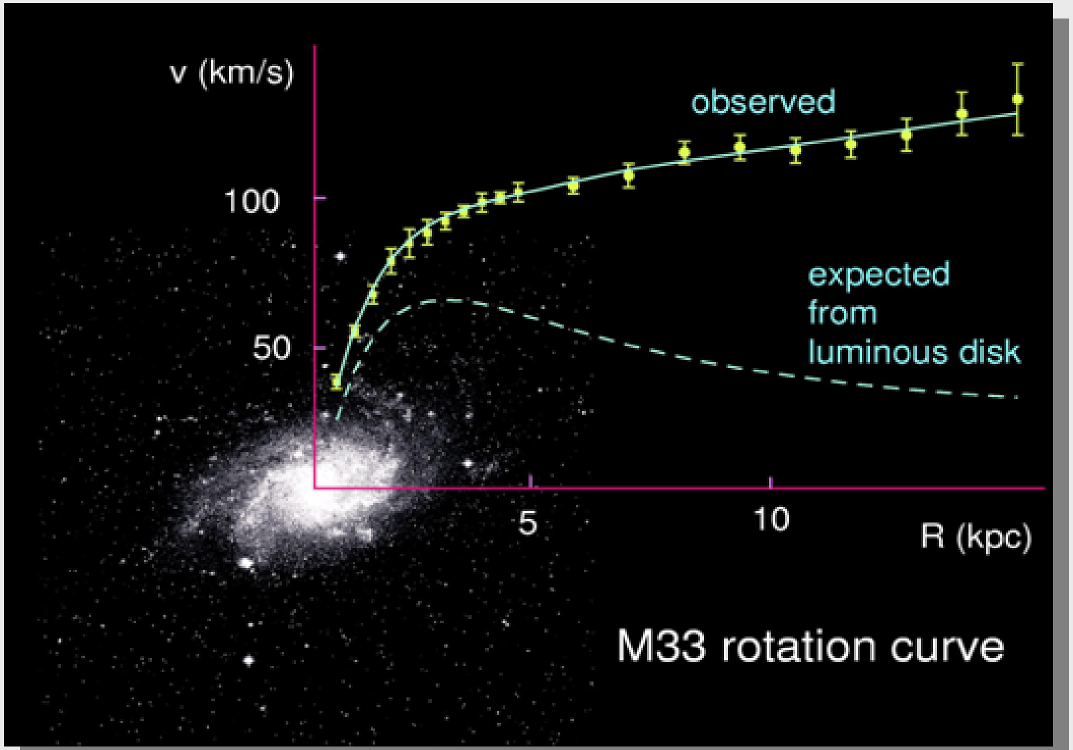


Result from best-fit model for WMAP (for flat Universe):

- **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**
- **$\Omega_\nu h^2 < 0.0076$**

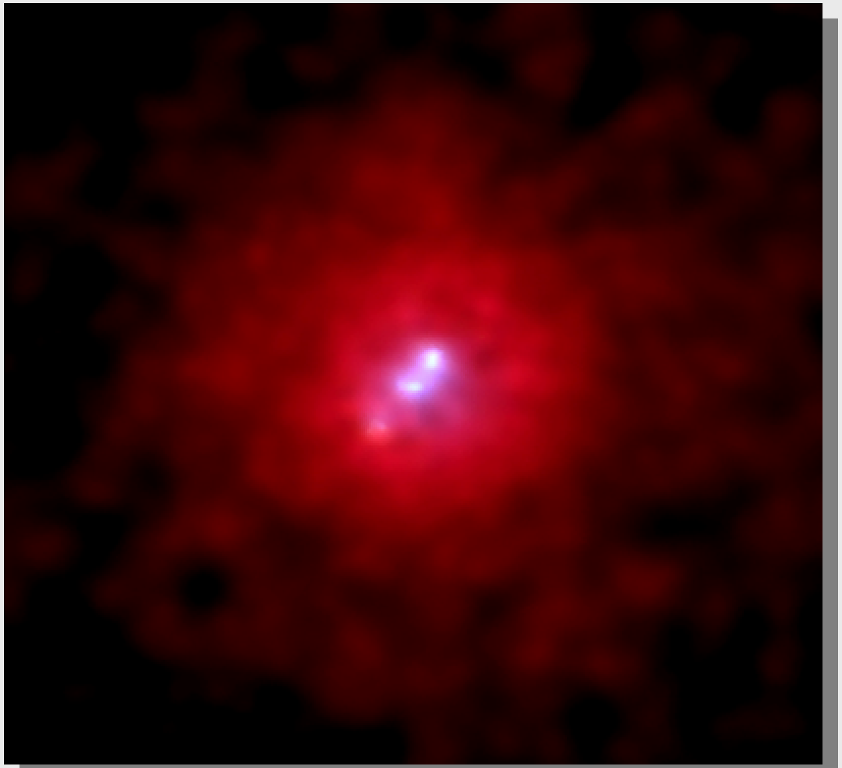
Dark matter needed on all scales!
(⇒ MOND and other *ad hoc* attemps to modify Einstein or Newton gravity very unnatural & unlikely)

Galaxy rotation curves



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

X-ray emitting clusters



Cluster 3C295 (Chandra)

Since 1998 (Super-K), we know that non-baryonic dark matter exists!

$\Delta m_\nu \neq 0 \Rightarrow m_\nu \neq 0$

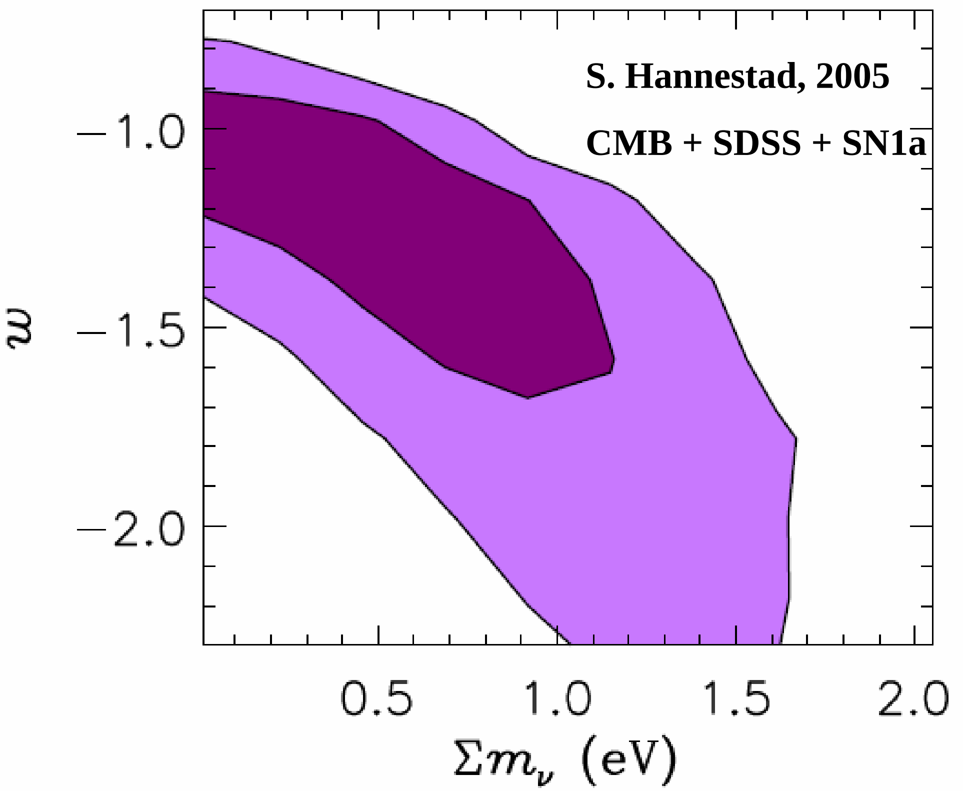
However, neutrinos are not the main component of dark matter (10% at most) :

- Pauli principle $\Rightarrow$ cannot clump in dwarf halos
- Galaxy distribution $\Rightarrow$ limit on sum of ν masses

WMAP: $\Sigma\, m_\nu < 0.7$ eV, depends on addition of 2dF data and Ly-α forest data

Ø. Elgarøy & O. Lahav (2DF Collaboration), 2003; S. Hannestad 2003, 2005: $\Sigma\, m_\nu < 1$ eV (depending on priors and ν chemical potential)

Future galaxy surveys + Planck satellite (CMBR) + weak lensing $\Rightarrow$ perhaps $m_\nu \approx \Delta m_\nu^{atm} \approx 0.06$ eV may be detectable! (Hu, Eisenstein & Tegmark, 1998)



Cold Dark Matter

- Part of the "Concordance Model"
- Gives excellent description of CMB, large scale structure, Ly-α forest, gravitational lensing, supernova distances …
- If consisting of particles, may be related to electroweak mass scale: weak cross section, non-dissipative Weakly Interacting Massive Particles (WIMPs). Potentially detectable, directly or indirectly.
- May or may not describe small-scale structure in galaxies: Controversial issue, but alternatives (self-interacting DM, warm DM, self-annihilating DM) seem less successful. Probably non-linear astrophysical feedback processes are acting (bar formation, tidal effects, mergers, supernova winds, …). This is a crucial unsolved problem of great importance for dark matter detection rates.

Good particle physics candidates for Cold Dark Matter:

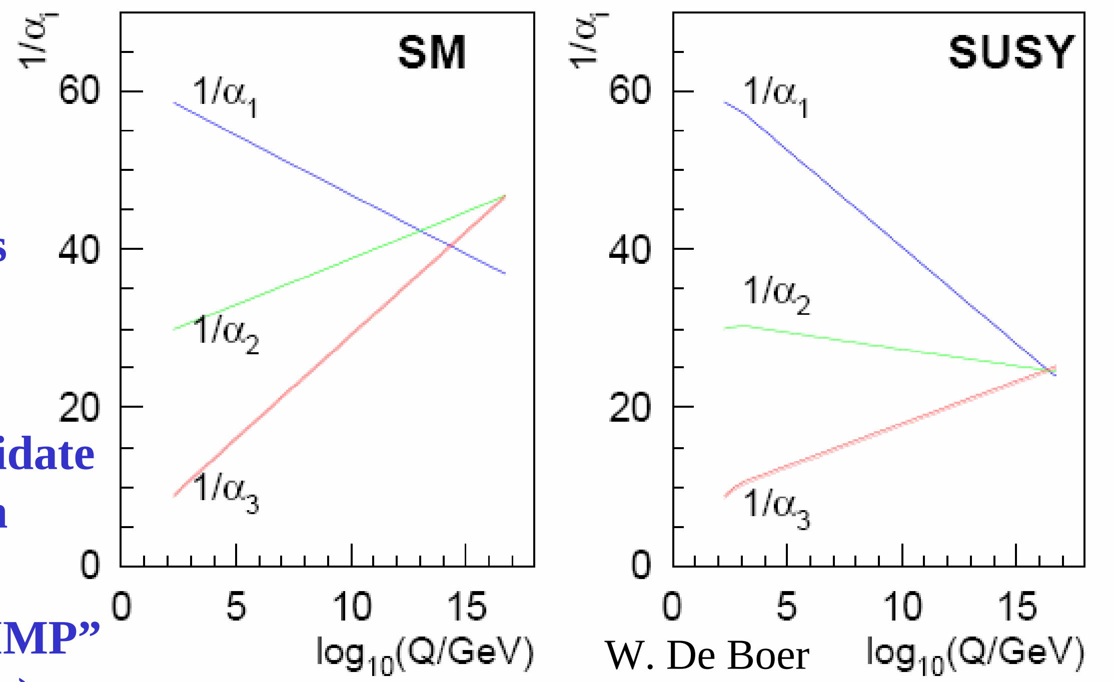
Independent motivation from particle physics

- **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**
  - **Kaluza-Klein states**
  - **Axino, gravitino (SuperWIMPS) – no time**
  - **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)

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)
- Useful as a template for generic "WIMP" (Weakly Interacting Massive Particle)



The lightest neutralino: the most natural SUSY dark matter candidate

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

Gaugino part Higgsino part

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

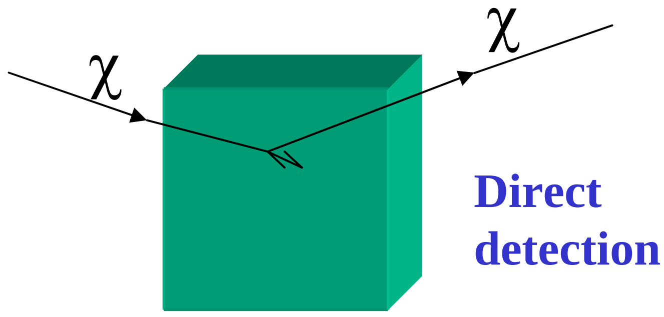
”Neutralino dark matter made easy” - Can be freely dowloaded from http://www.physto.se/~edsjo/ds

Release 4.1: includes coannihilations & interface to Isasugra

Other package: MicrOMEGAs, G. Bélanger, F. Boudjema, A. Pukhov and A. Semenov, http://lappweb.in2p3.fr/lapth/micromegas/

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

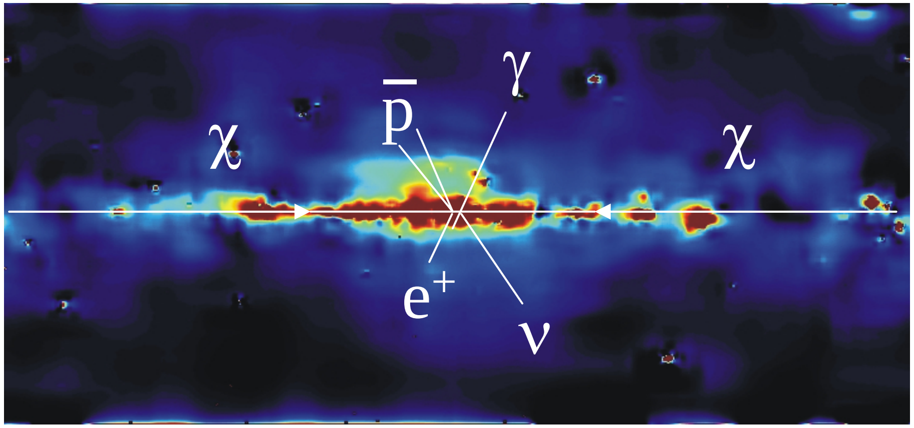


Direct detection

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

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

Neutralinos are Majorana particles

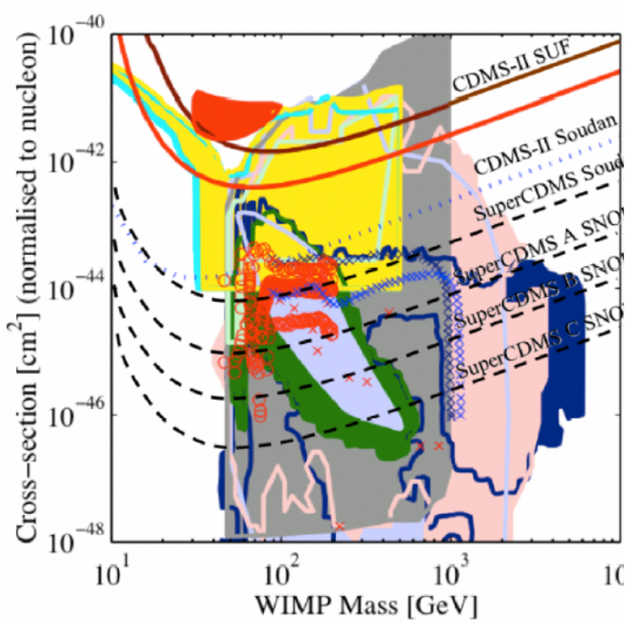


Indirect detection

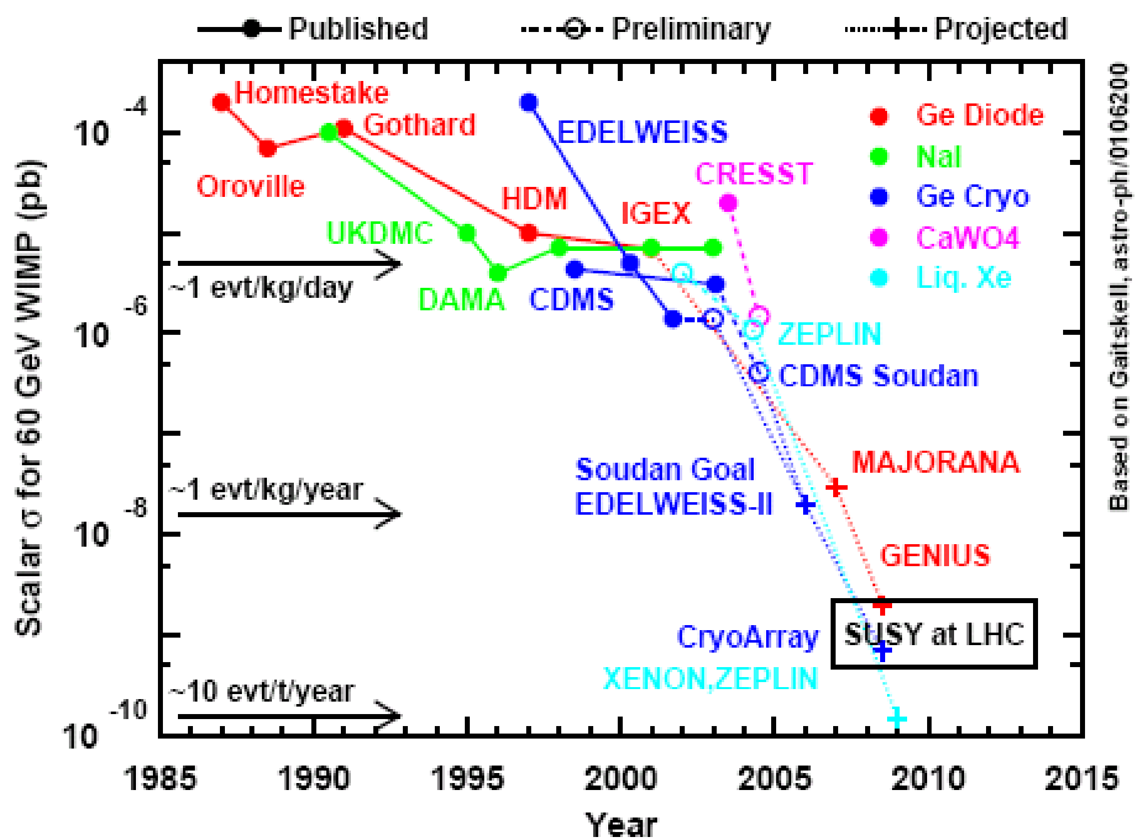
$$\Gamma_{ann} \propto n_\chi^2 \sigma v$$

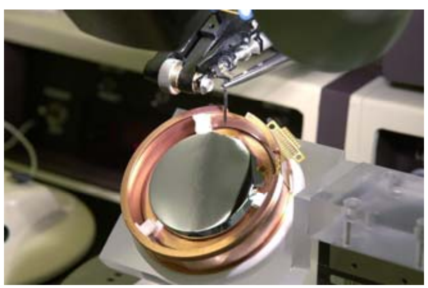
Enhanced for clumpy halo; near galactic centre and in Sun & Earth

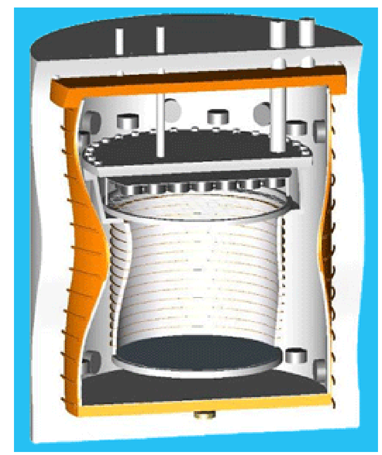
Direct detection – many experiments doing rapid progress



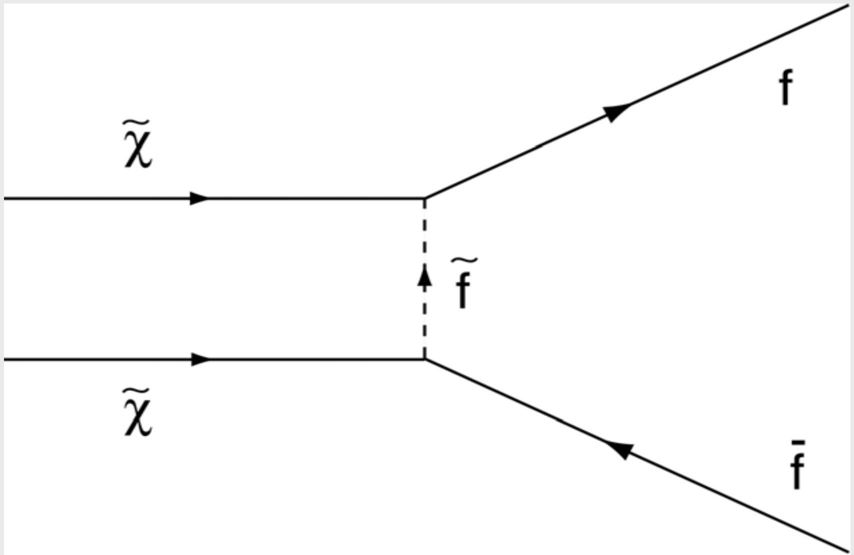
J. Gascon, astro-ph/0504241



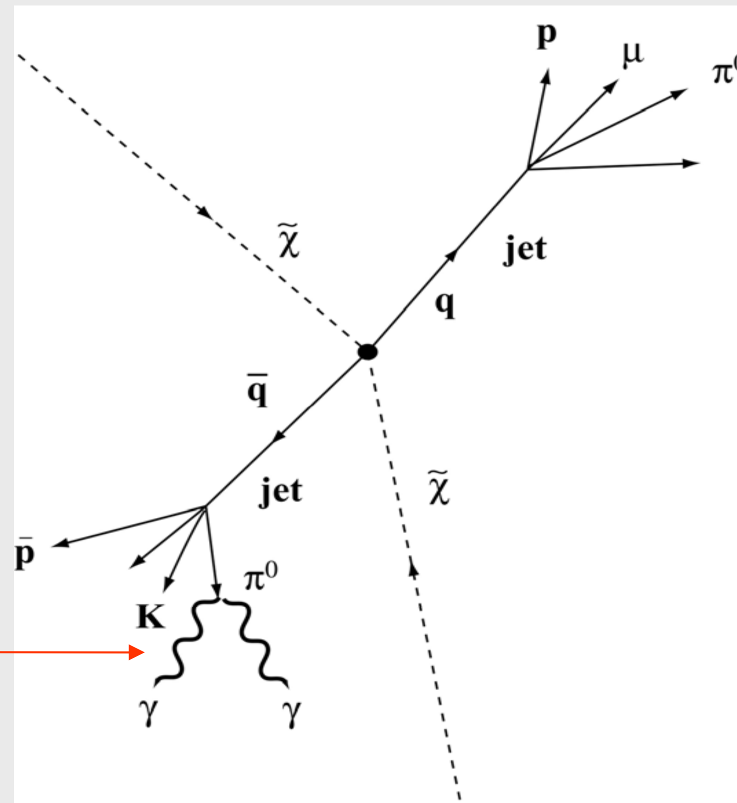




Indirect detection: annihilation of neutralinos



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)

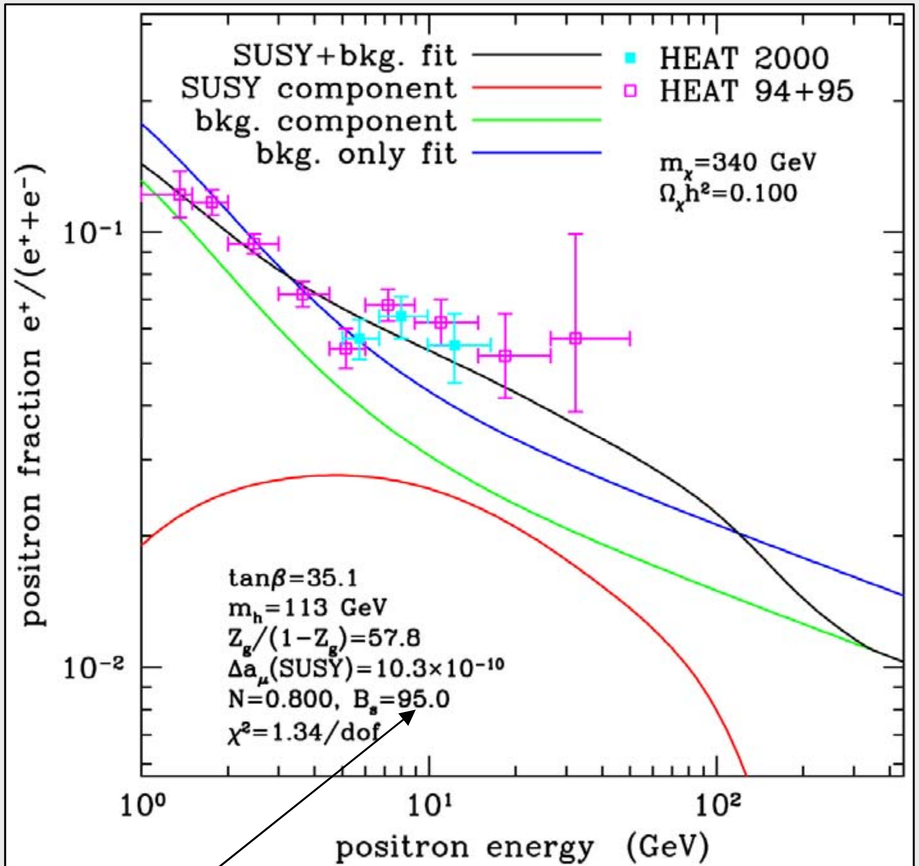


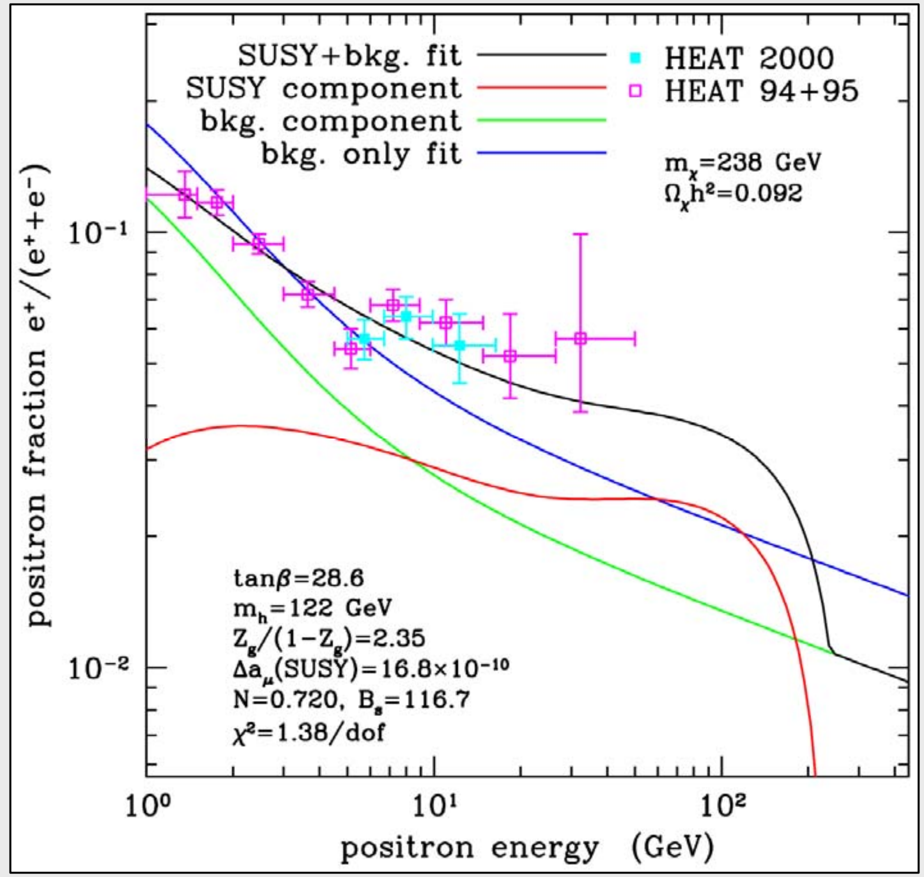
Note: equal amounts of matter and antimatter in annihilations - source of antimatter in cosmic rays?

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

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

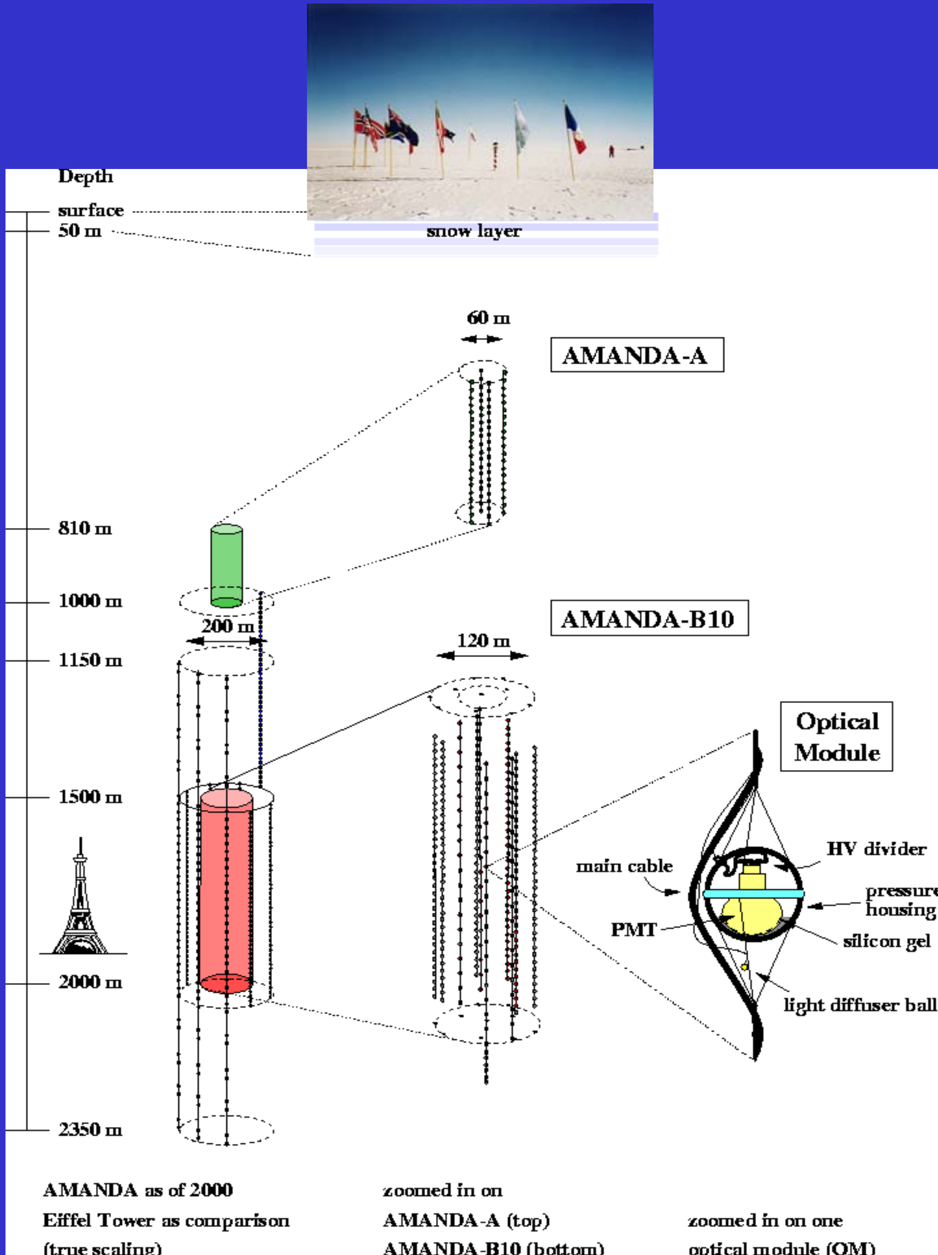
New experiments will come: Pamela (2006?) and AMS (2008?)



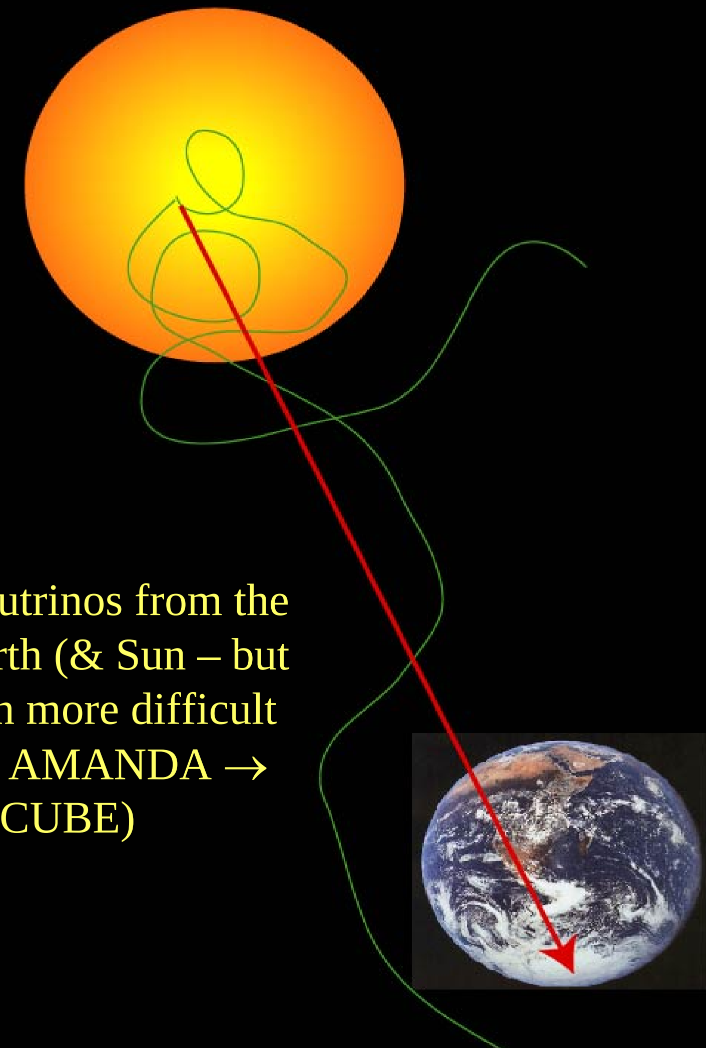


Need high ”boost factor”

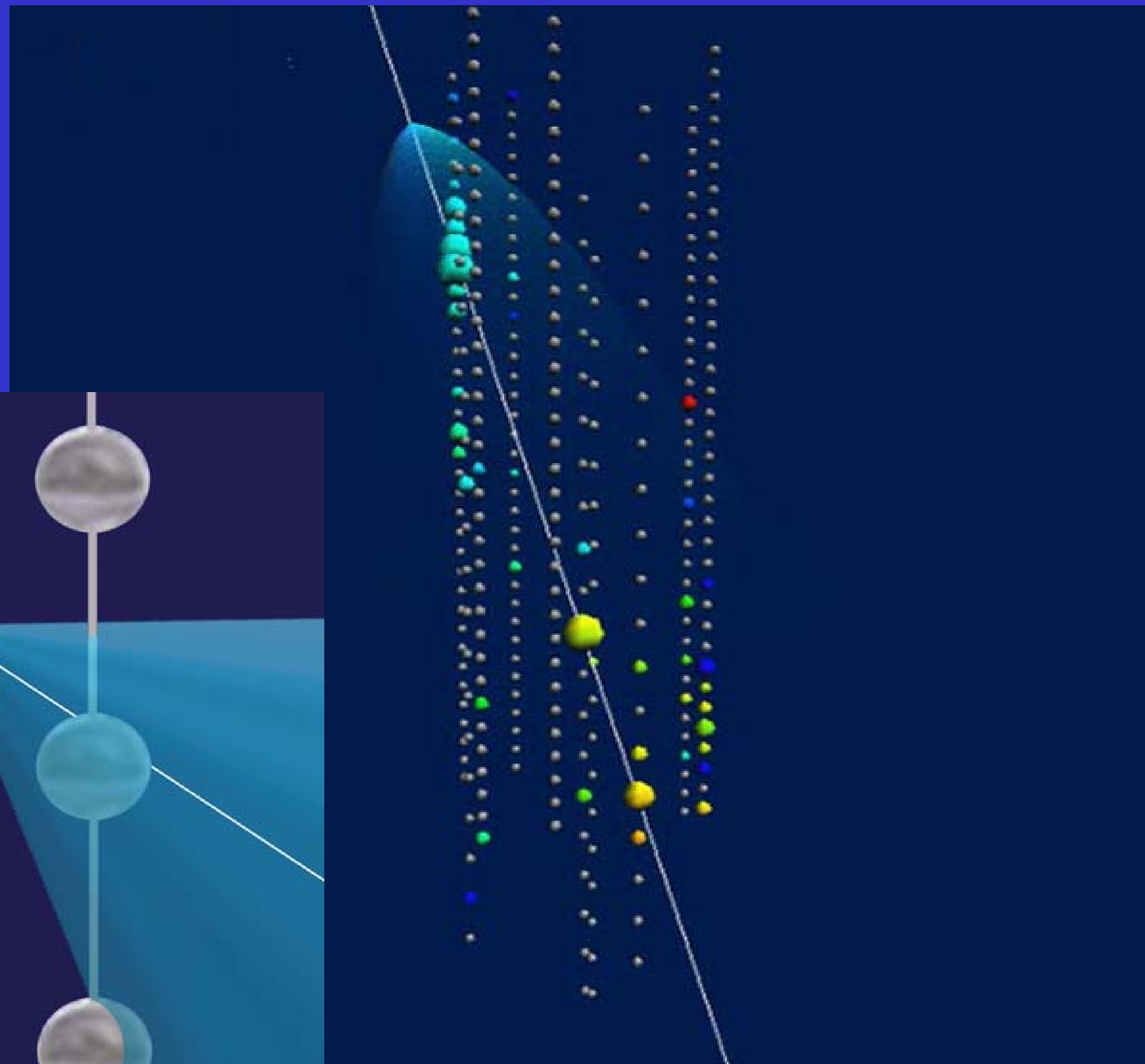
Baltz, Edsjö, Freese, Gondolo 2002; Kane, Wang & Wells, 2002; Hooper & Kribs, 2004; Hooper & Silk, 2004

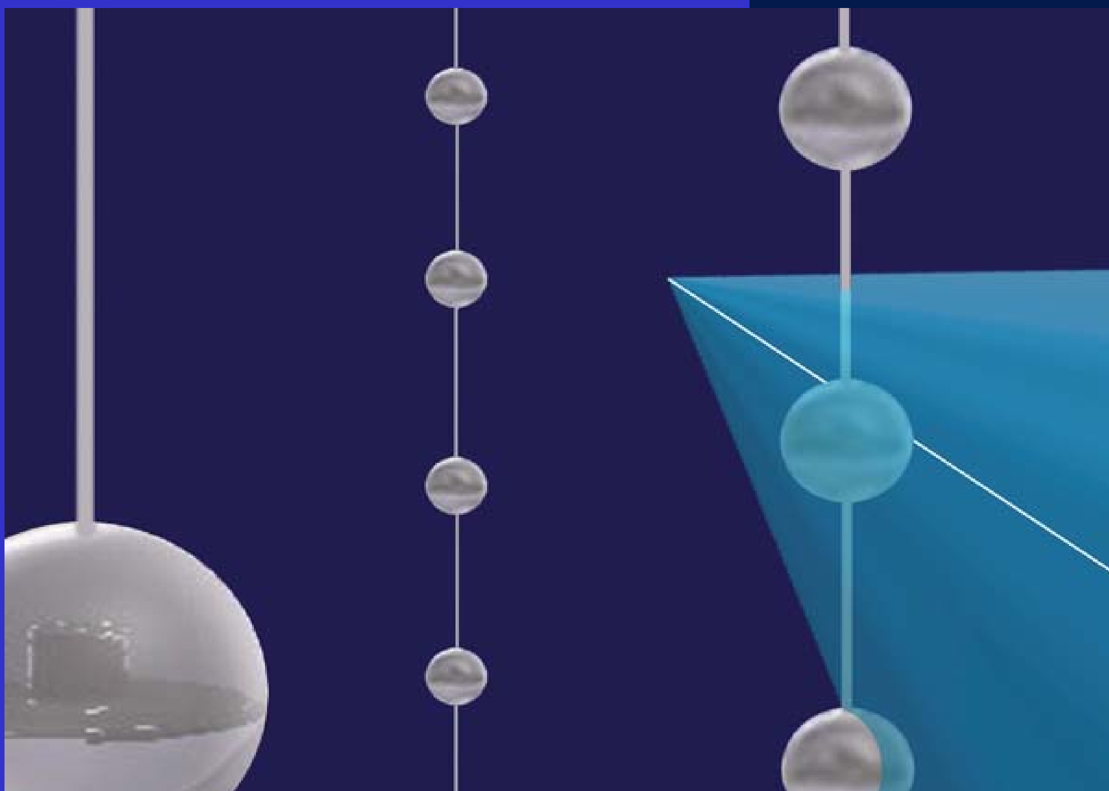


Neutrinos from the Earth (& Sun – but Sun more difficult for AMANDA → IceCUBE)



IceCube

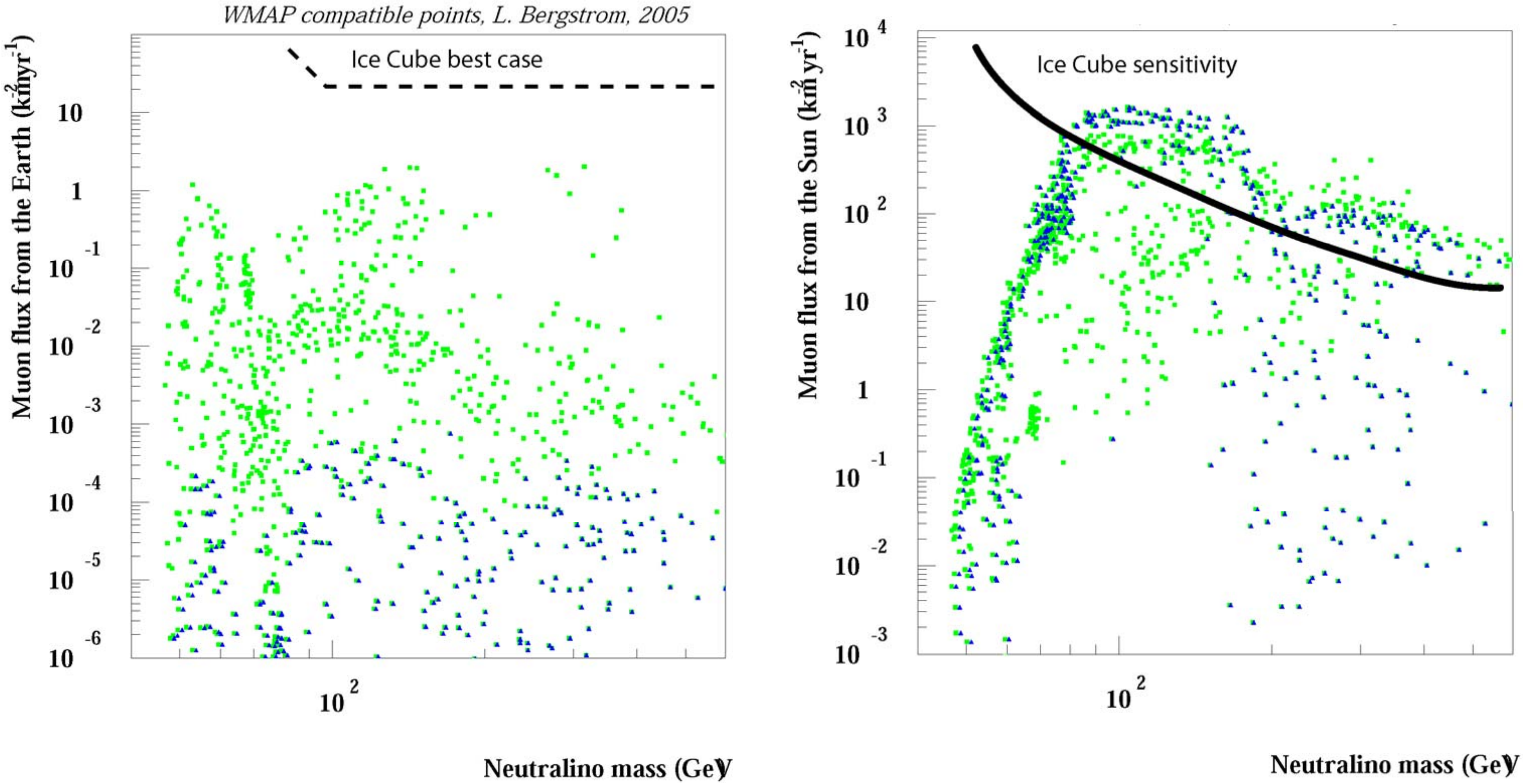




Neutralino signal: Neutrinos from the Earth & Sun, MSSM

Rates computed with DarkSUSY

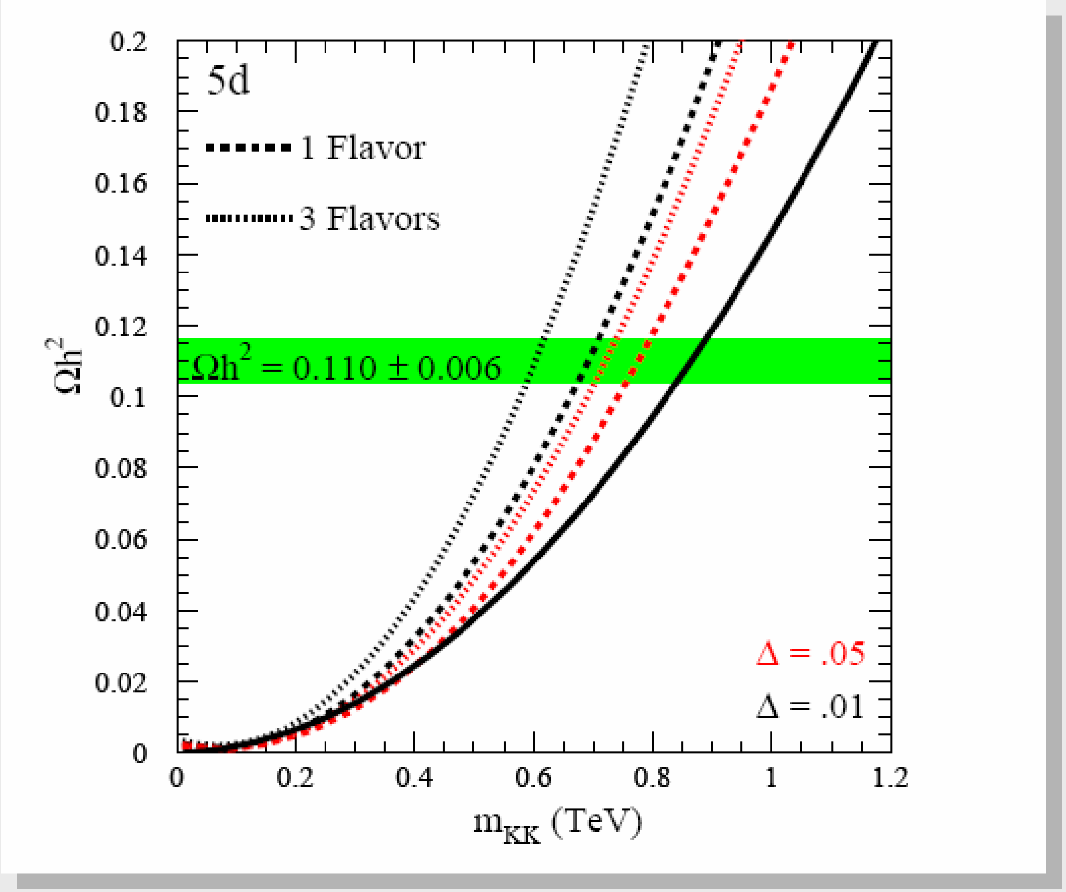
- Present case: 25 GeV threshold, WMAP relic density, CDMS-II limit on cross section
- Future: 25 GeV threshold, WMAP relic density, $\sigma_{SI} < 10^{-8}$ pb



Kaluza-Klein (KK) dark matter in Universal Extra Dimensions

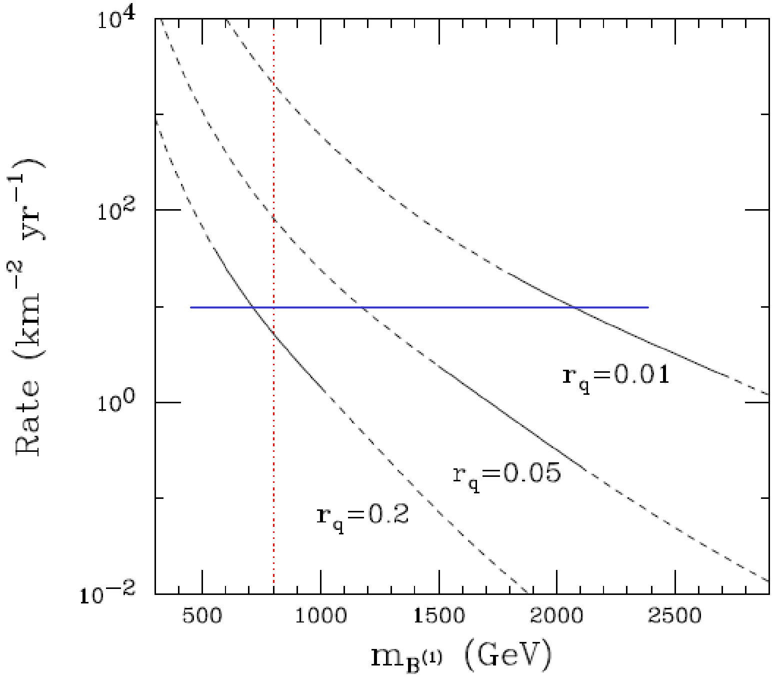
Universal Extra Dimensions (Appelquist & al, 2002):

- **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

Neutrino detection of Kaluza-Klein particles (Halzen & Hooper, 2005)



Positrons (Cheng, Feng & Matchev, 2003)

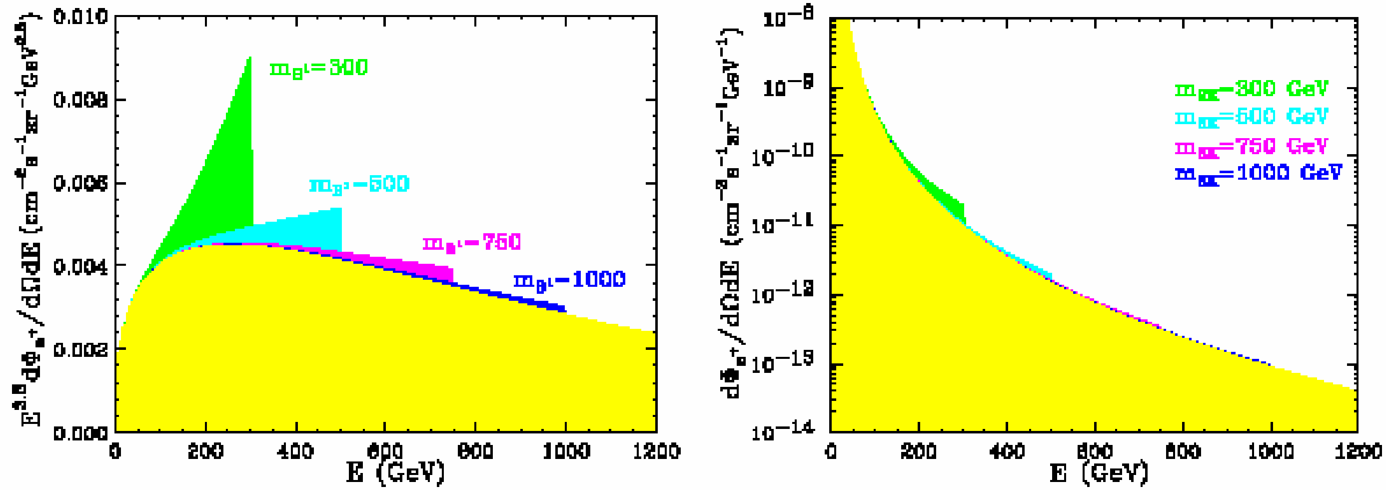
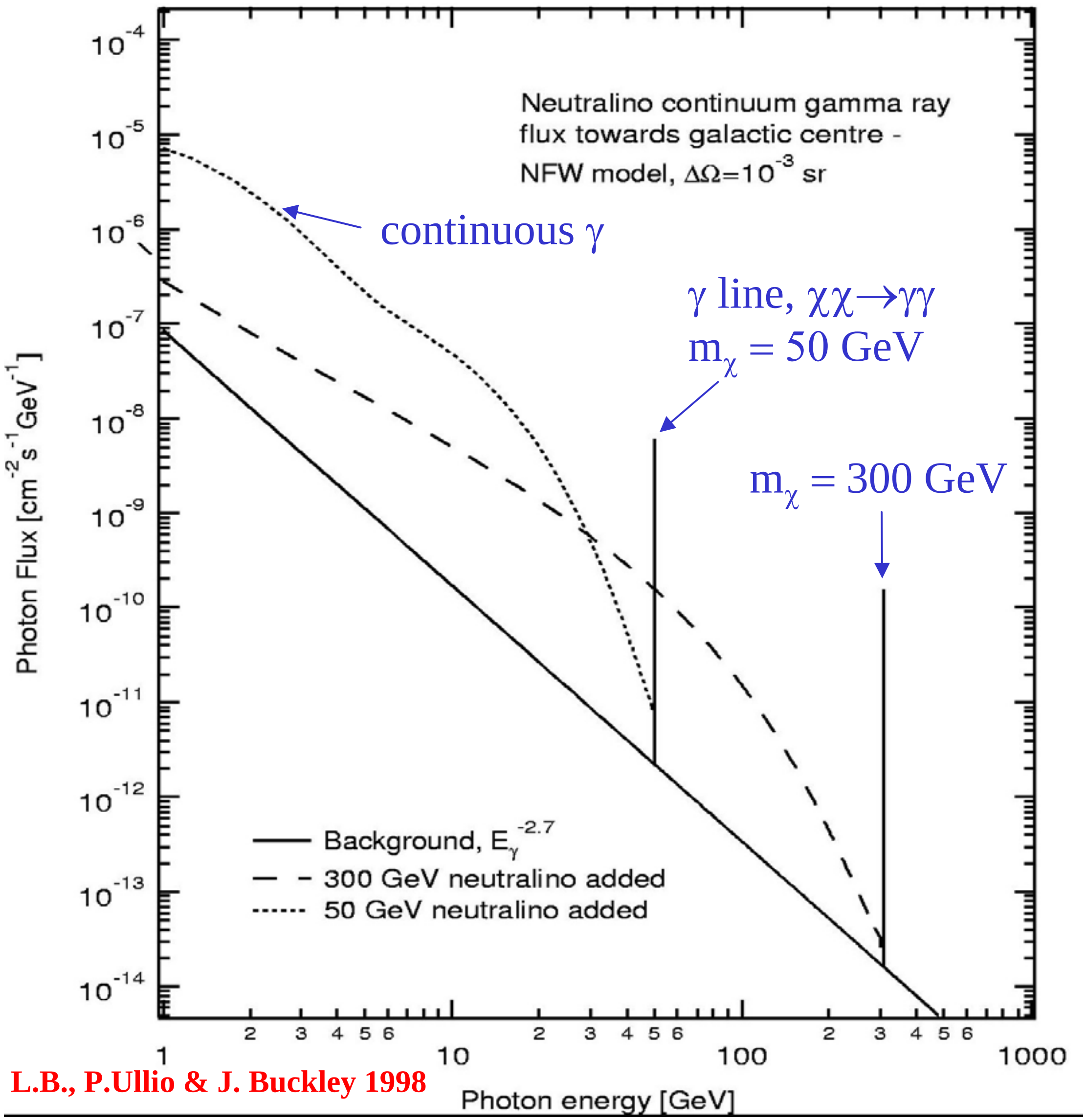


Figure 3. Positron spectra from B^1 dark matter annihilation for various B^1 masses as indicated [22]. The yellow (light shaded) region is the expected background. The differential flux is given in the right panel, and is modified by the factor E^3 in the left panel.

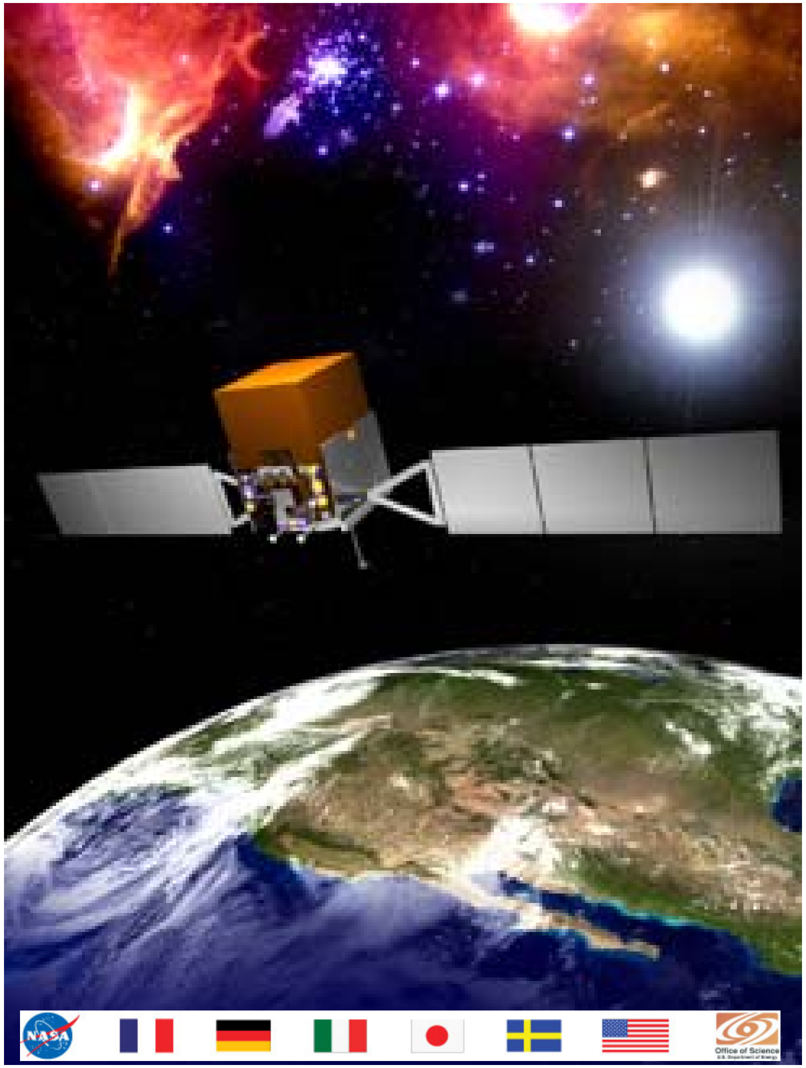
Gamma-rays

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 is at highest energy $E_\gamma = m_\chi$; "smoking gun")

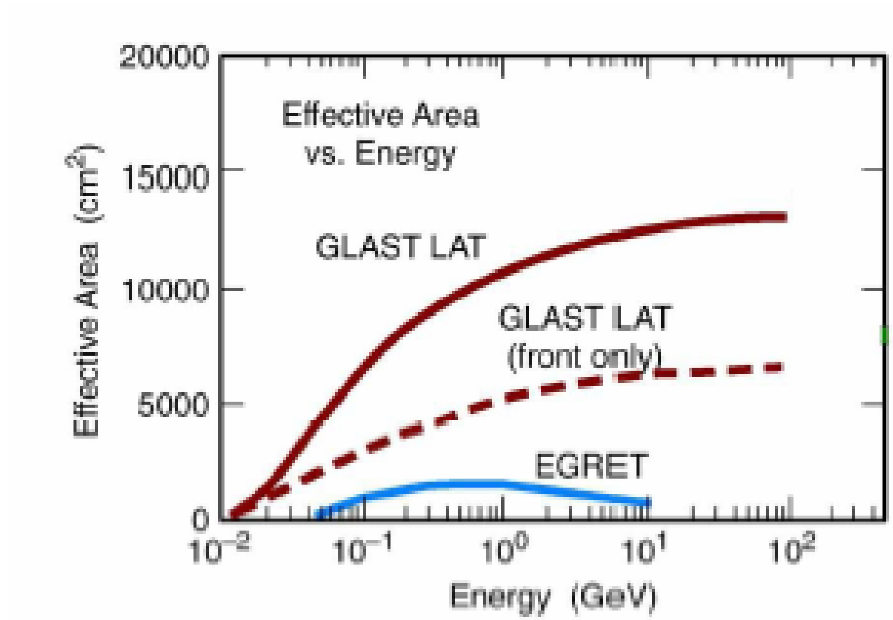
Advantage of gamma rays: point back to the source. Enhanced flux possible thanks to halo density profile and substructure (as predicted by CDM)



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

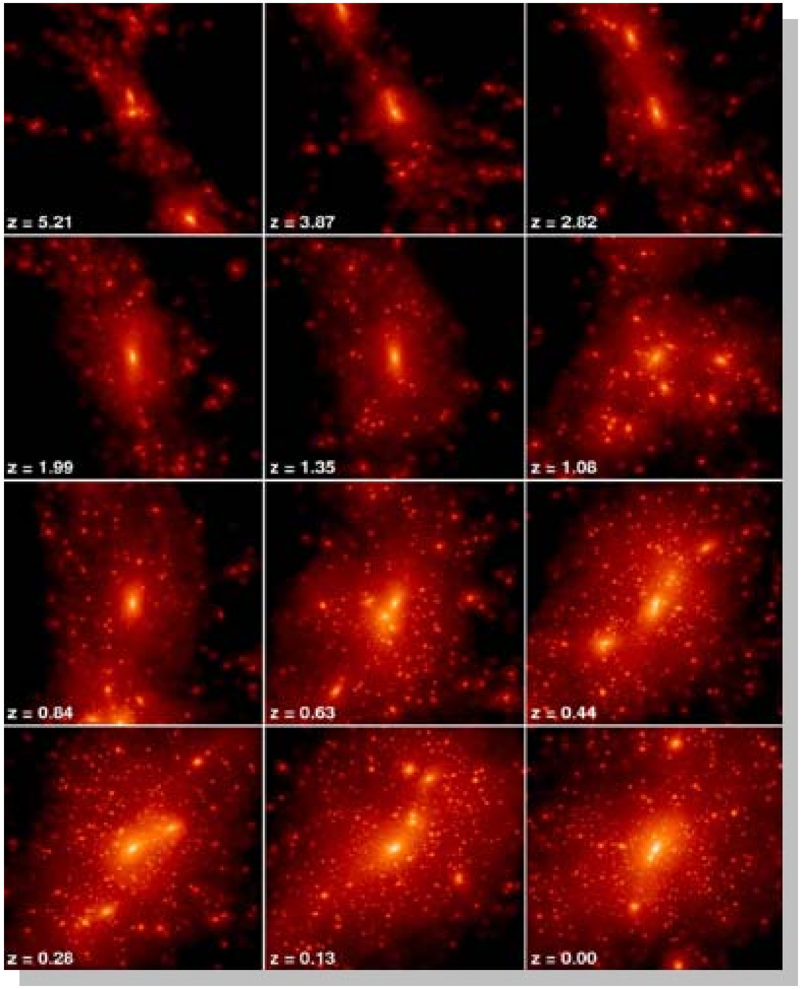


USA-France-Italy-Sweden-Japan Germany collaboration, launch 2007

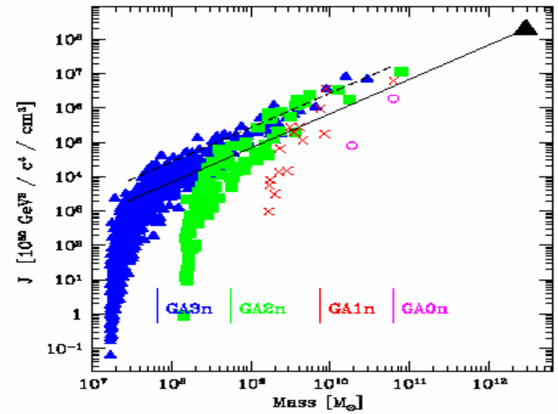


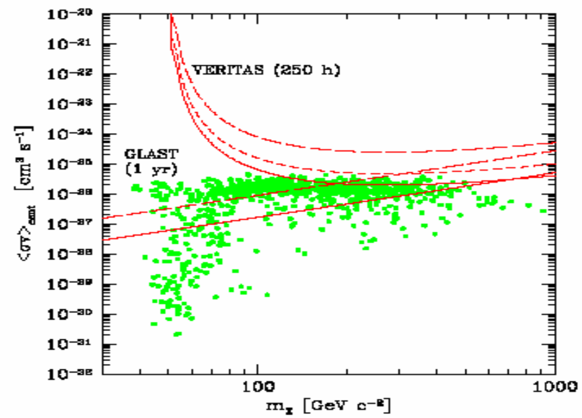
GLAST can search for dark matter signals up to 300 GeV. (It is also likely to detect a few thousand new GeV blazars …)

Dark matter clumps in the halo?



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

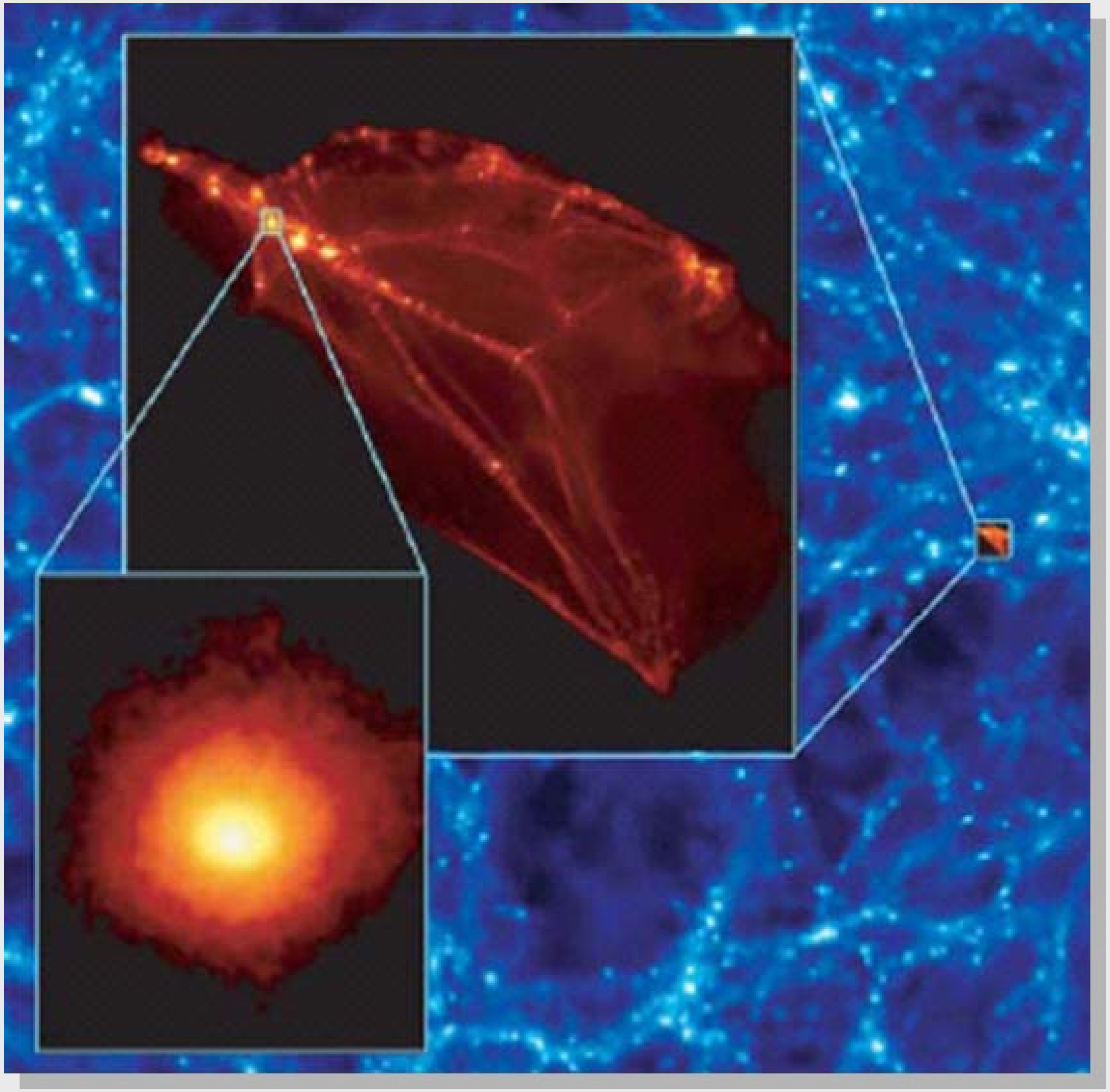




Rates computed with

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

Important problem: What is the fate of the smallest substructures? Berezinsky, Dokuchaev & Eroshenko, astro-ph/0301551 & 0511494; Green, Hofmann & Schwarz, astro-ph/0309621



Diemand, Moore & Stadel, Nature 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.

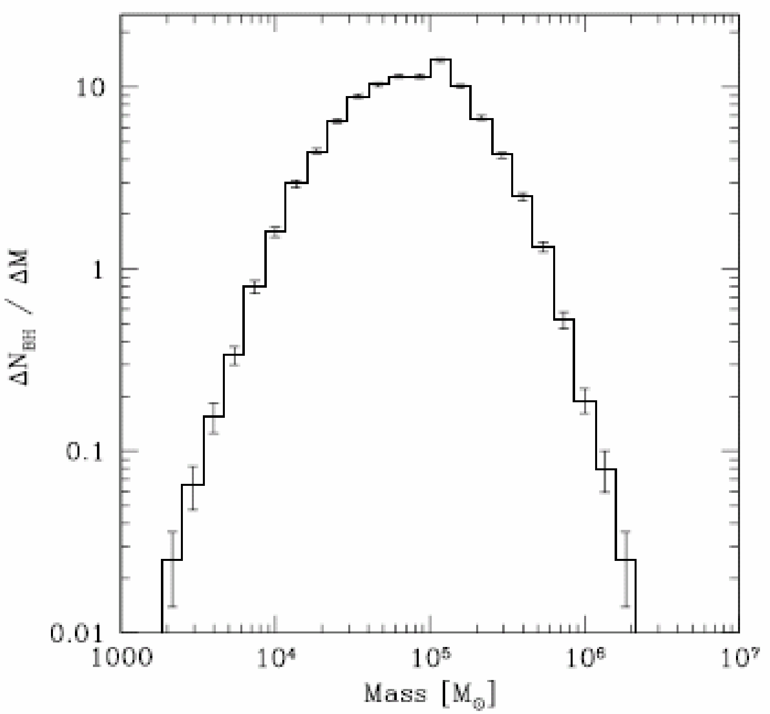
Maybe the dark matter detection schemes will have to be quite different! Oda, Totani, Nagashima, 2005; Pieri, Branchini, Hofmann, 2005.

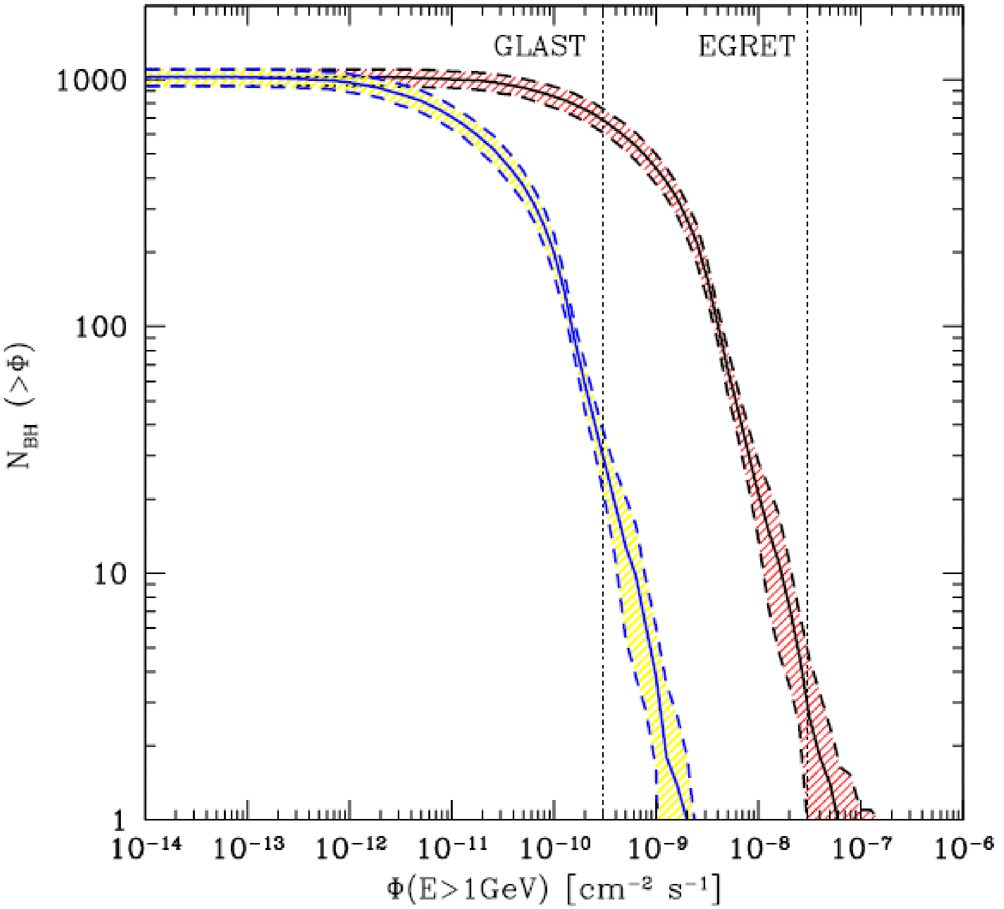
(For instance, when the Earth enters such a solar system-sized object, counting rates would be very high, and then drop drastically…)

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

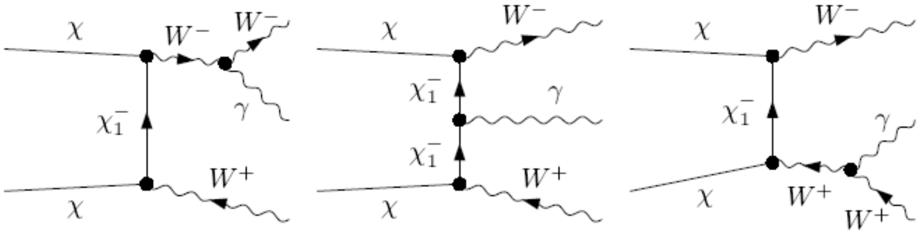
Also: ”spike” possible in density profile near Black Hole (Gondolo & Silk, 1999)

Intermediate mass black holes: Bertone, Zentner & Silk, 2005. Maybe a few EGRET ”unidentified sources” - > 20 – 30 sources detectable by GLAST



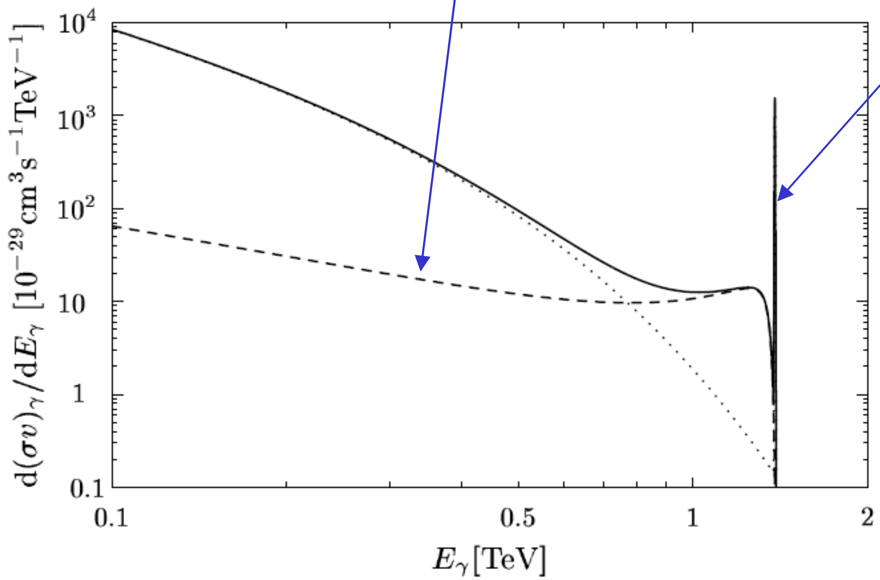


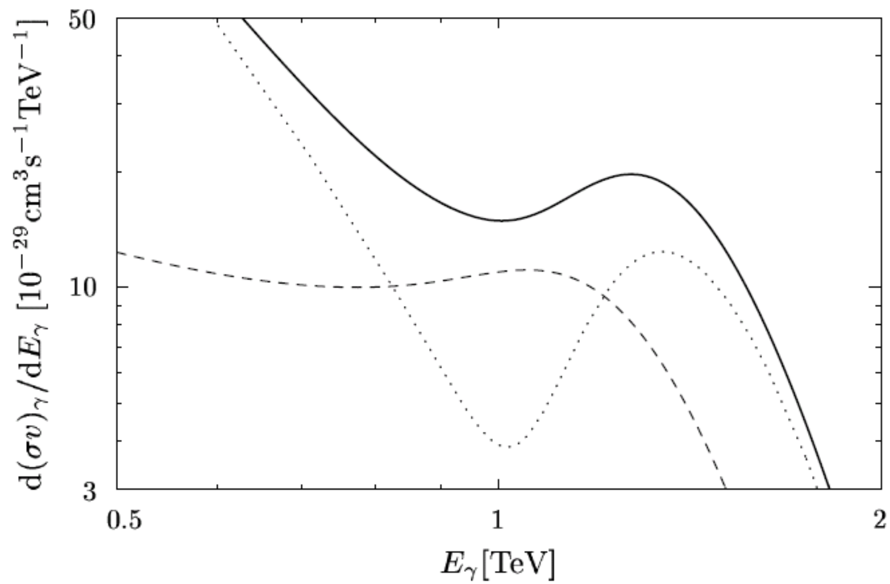
GLAST can cover energies up to 300 GeV. For higher energies, Air Cherenkov Telescopes become competitive. Example: 1.4 TeV higgsino with WMAP-compatible relic density (L.B., T. Bringmann, M. Eriksson and M. Gustafsson, PRL 2005)



New contribution (internal bremsstrahlung)

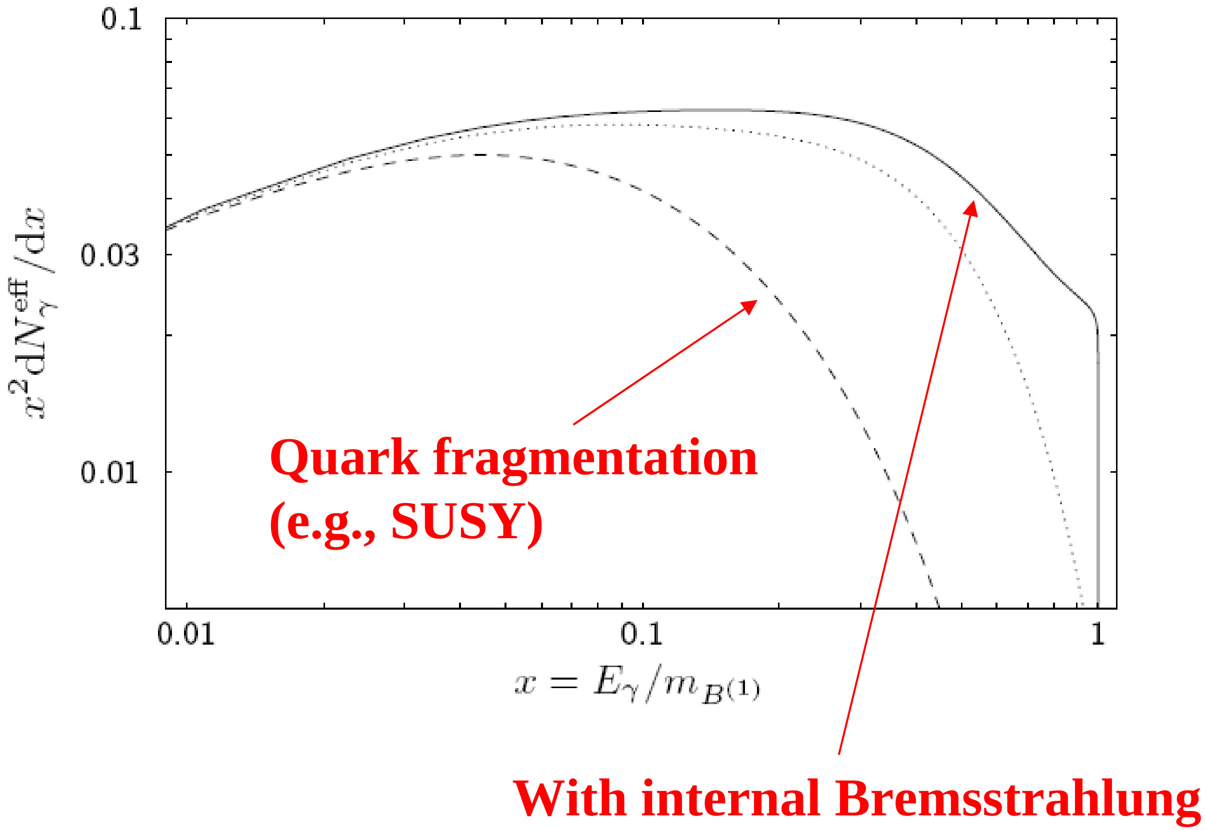
Intrinsic line width $\Delta E/E \sim 10^{-3}$

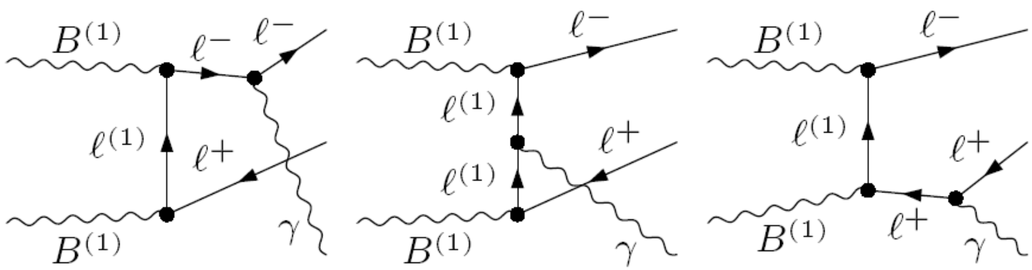




Gamma-ray spectrum seen by an ideal detector

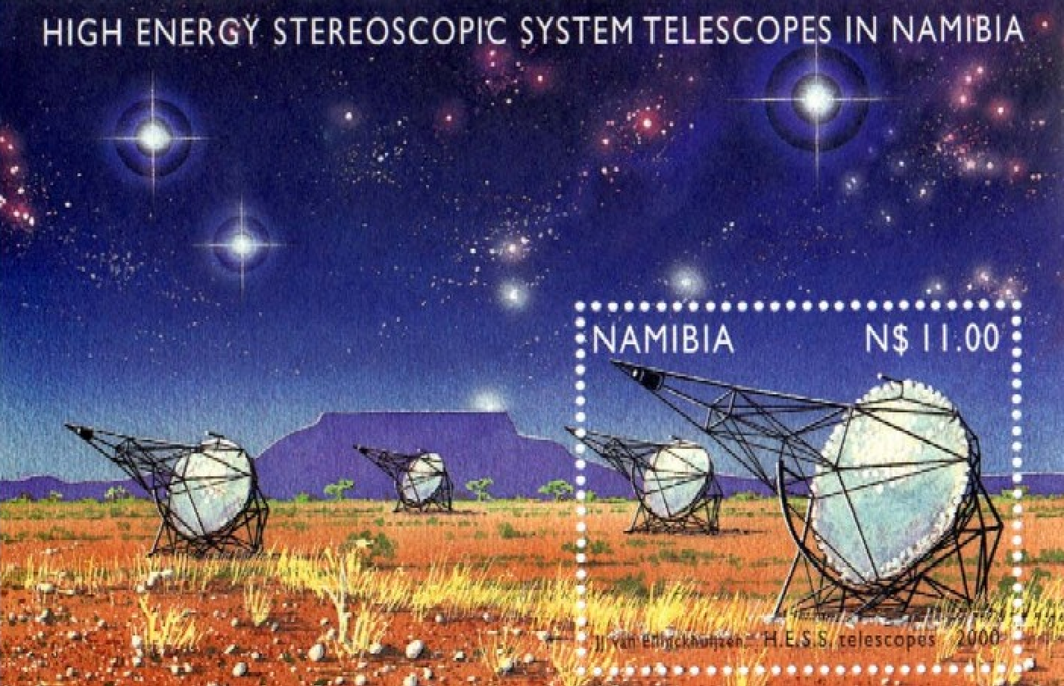
Same spectrum seen with 15% energy resolution (typical of ACT)





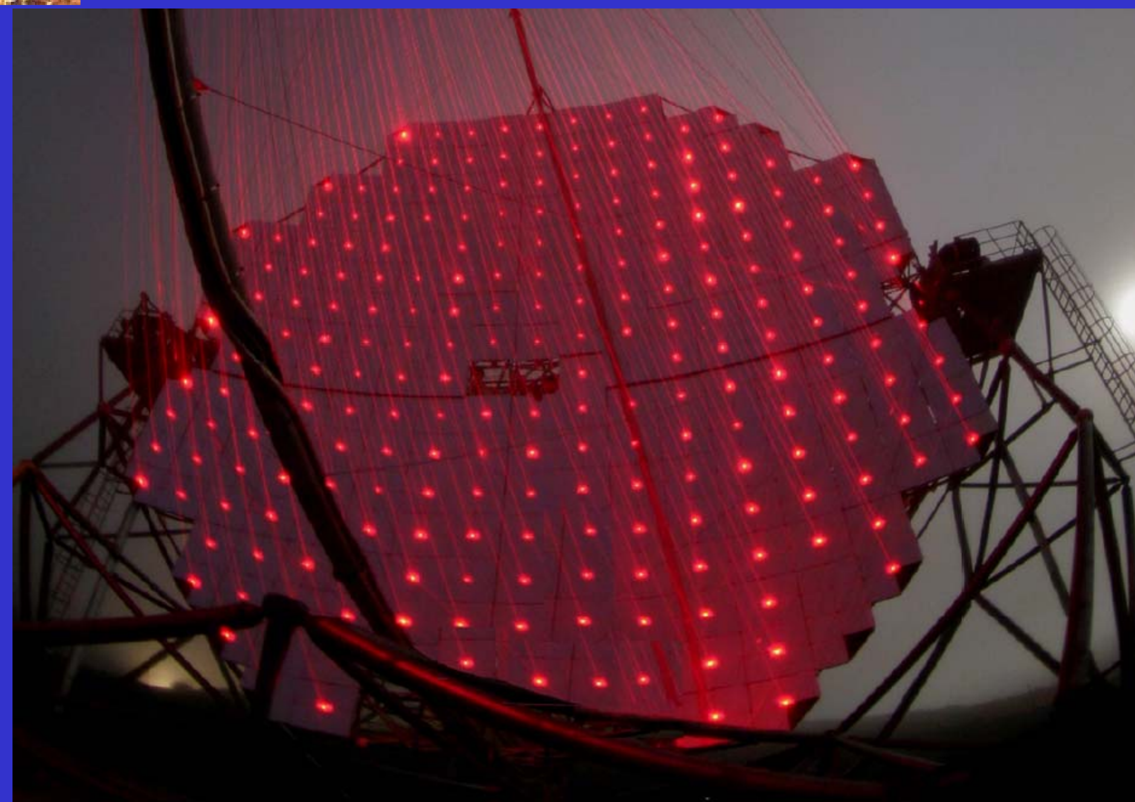
Cf. Kaluza-Klein models

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

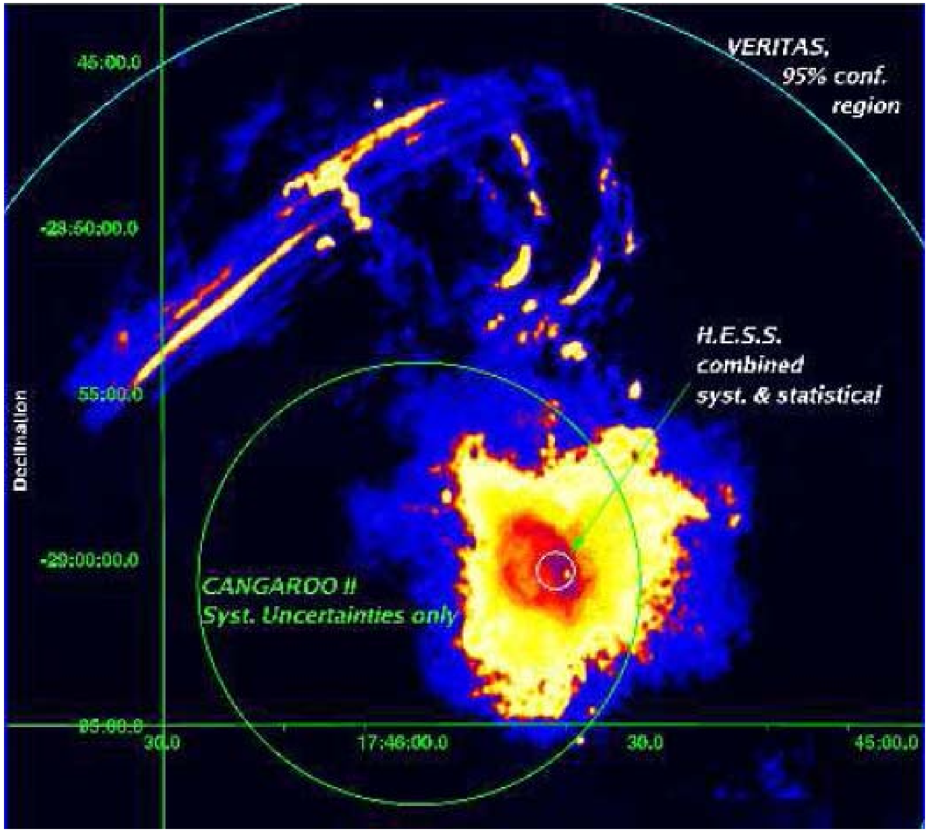


H.E.S.S. in Namibia

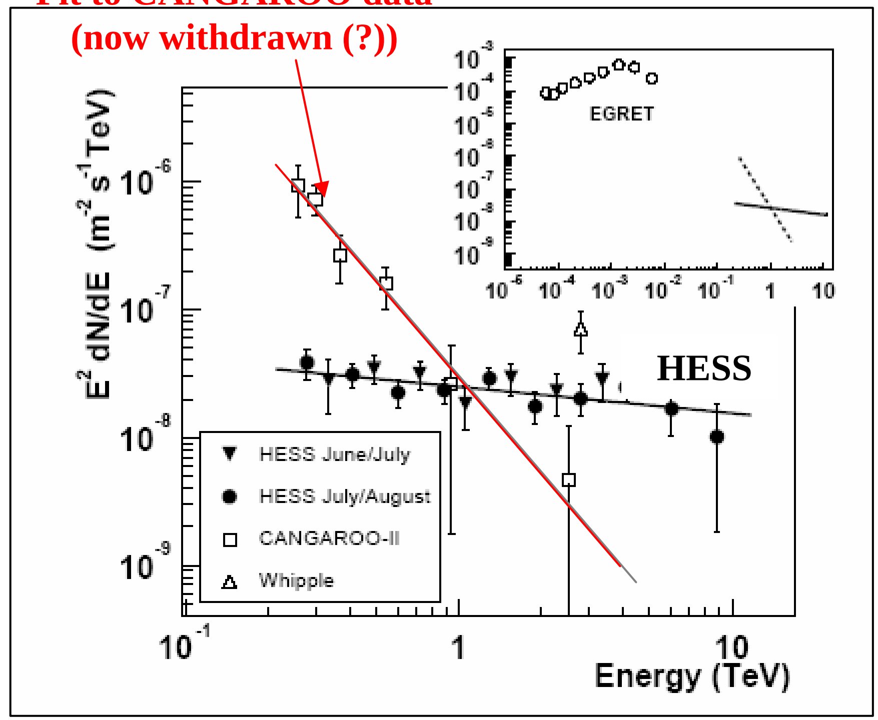
Magic in Canary Islands

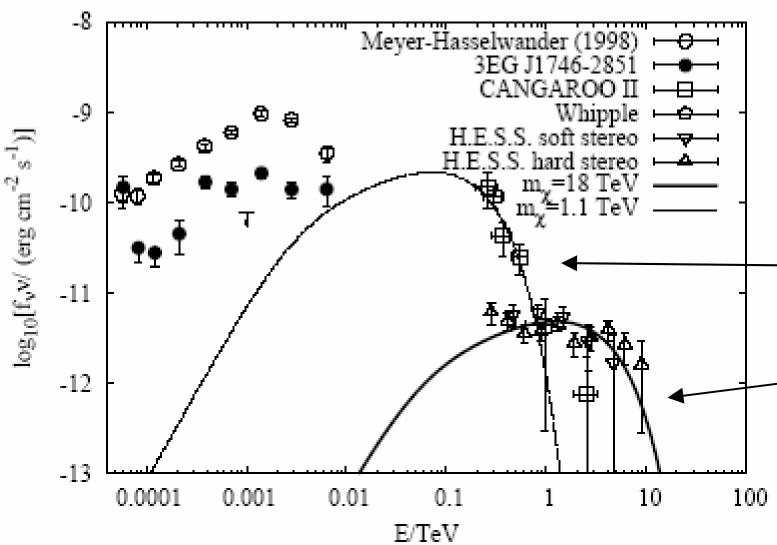


July 2004: H.E.S.S. 2003 data towards galactic centre (June 2005: preliminary 2004 data released)



Fit to CANGAROO data (now withdrawn (?))



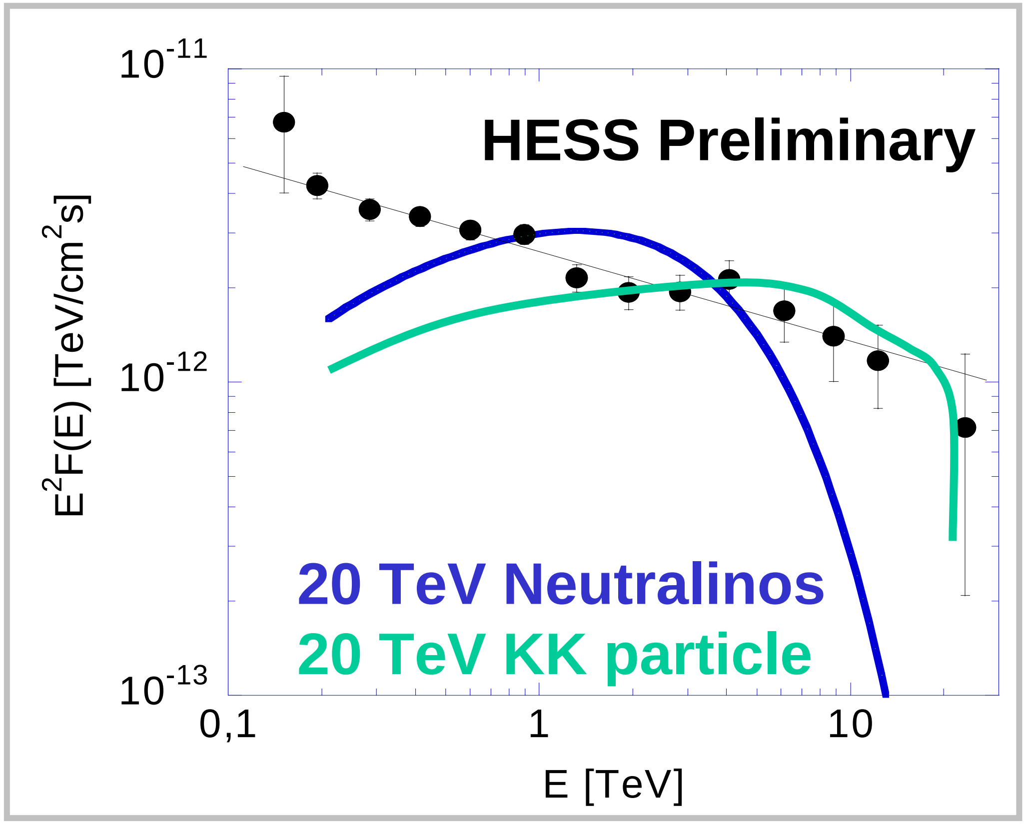


D. Horns, PLB 2004:

m_χ = 1.1 TeV (obsolete CANGAROO data)

m_χ = 18 TeV, too high for neutralino? Spectrum probably looks quite different (L.B., T.Bringmann, M.Eriksson, M. Gustafsson, 2005)

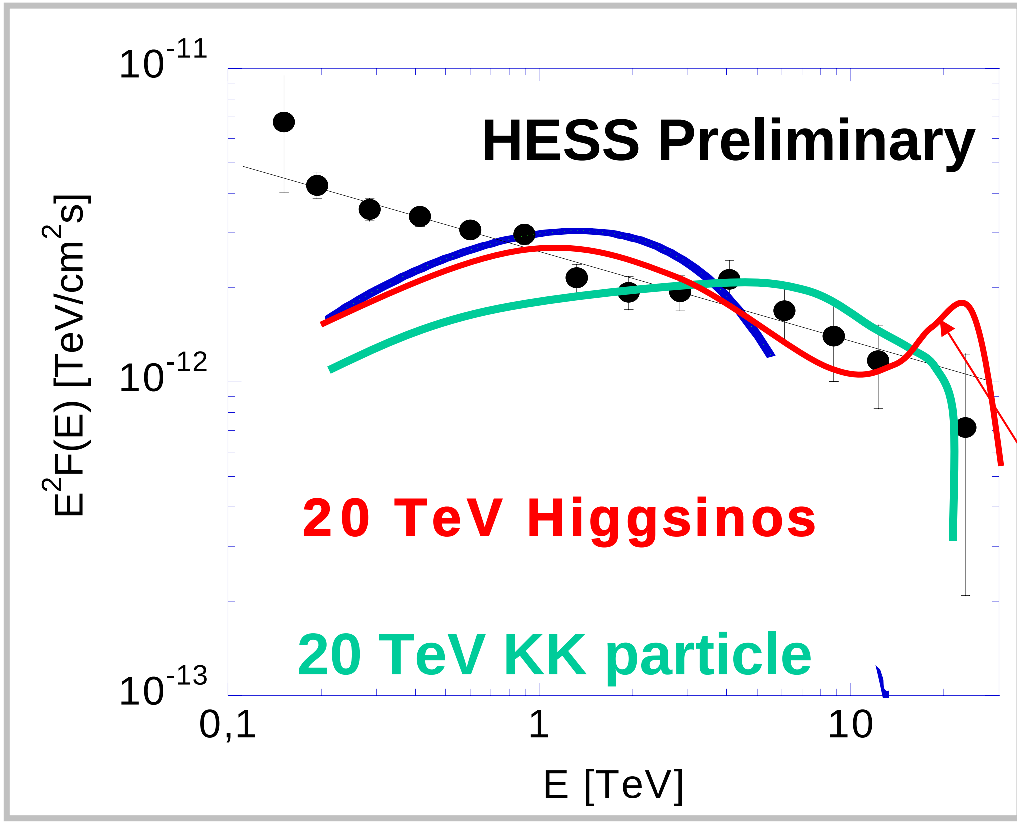
Dark matter annihilation?



Spectra will actually be very similar – the SUSY spectrum gets contribution from gamma-line and radiation from W pairs for winos or higgsinos. However, no one has found a natural MSSM model yet…

P. Vincent, Cividale del Friuli Workshop, June, 2005

Dark matter annihilation?



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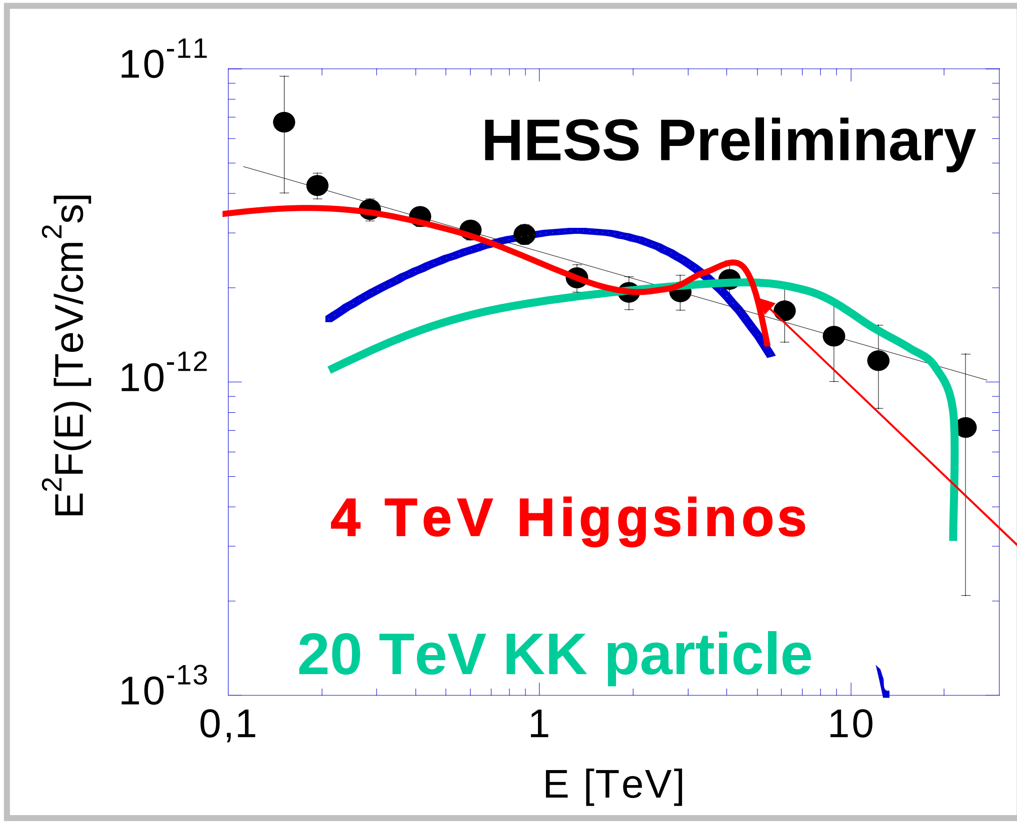

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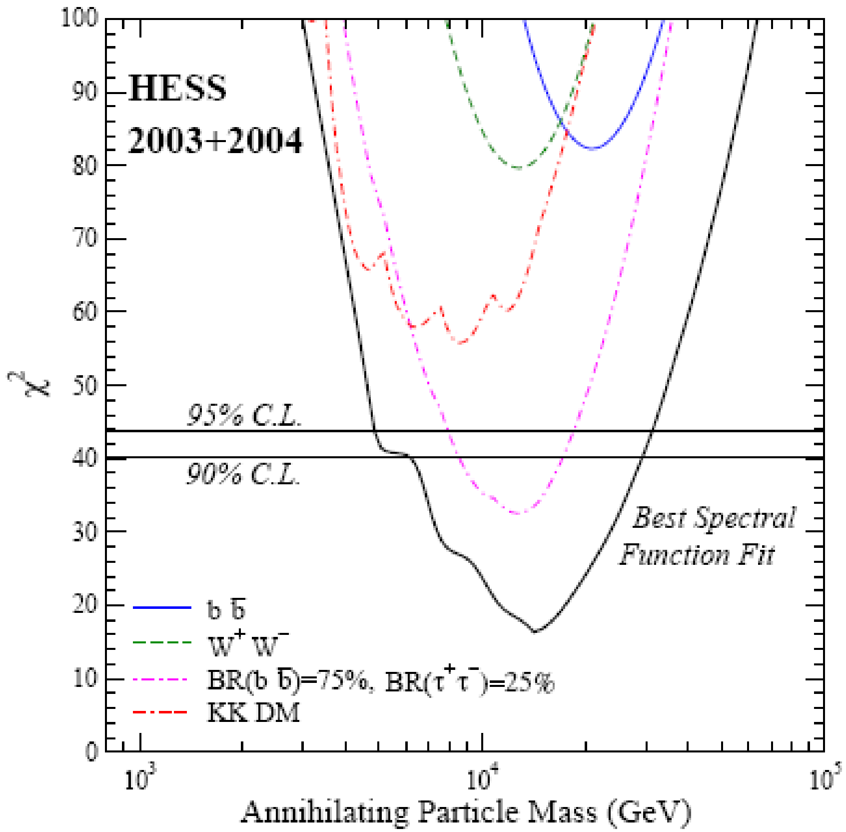
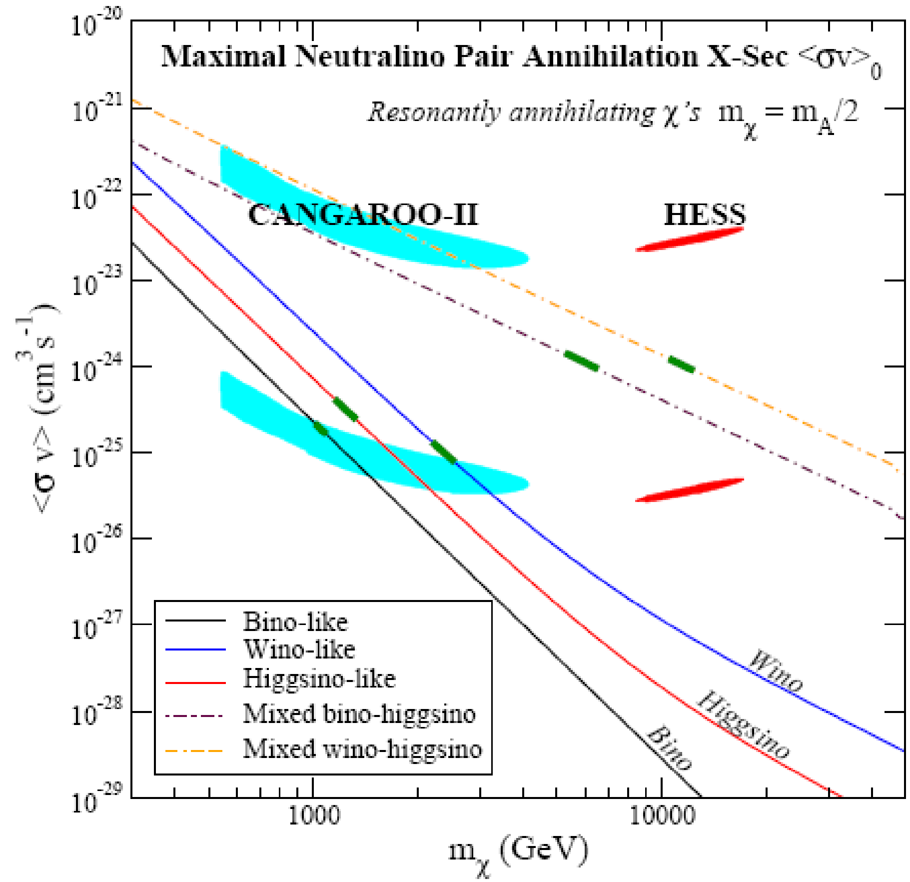


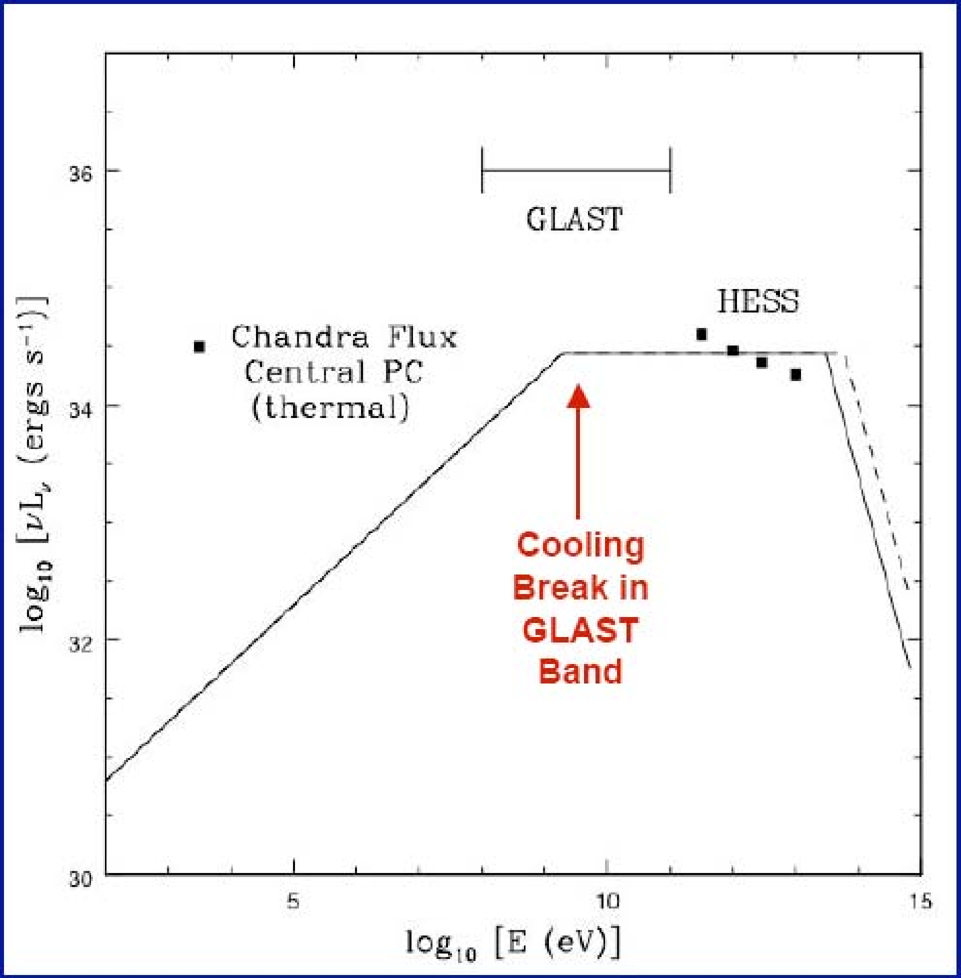


S. Profumo, astro-ph/0508628

"Fine-tuning" solutions giving very massive neutralinos

The Galactic Center 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?

TEV HESS Source & GLAST Counterpart: IC on the Stellar Radiation Field



EQ & Avi Loeb

0.3% of shock energy into rel. electrons w/ $n(\gamma) \propto \gamma^{-2}$

Central PC

$U_{ph} \sim 10^{-7}$ ergs cm^{-3} in UV
$U_{ph} \sim 10^{-8}$ ergs cm^{-3} in FIR

$t_{cool} < t_{esc} \sim R/V_{wind}$ for $\gamma > 10^4$

Cooling Break

$$E_b \approx 2\left(\frac{R_{0.5}V_8}{L_{41}}\right)^2\left(\frac{E_{ph}}{5\ \mathrm{eV}}\right)\ \mathrm{GeV}$$

E. Quataert & A. Loeb, astro-ph/0509265

Dark Matter in Draco? CACTUS solar array recent results

Located 15 miles outside Barstow, CA

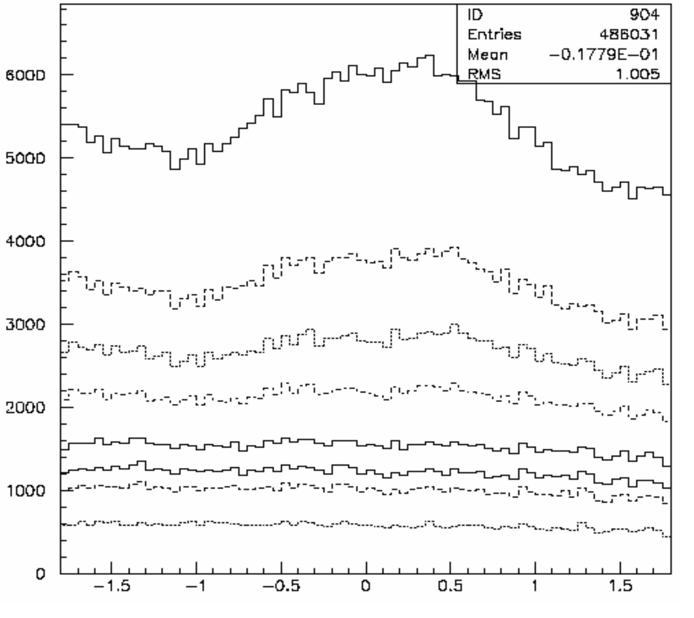
Over 1,900 42m^2 heliostats. The largest array in the world.

~160 heliostats in the FOV of the camera.

Collection area = ~64,000 m^2.

Peter Marleau, TAUP, September, 2005

Preliminary data!



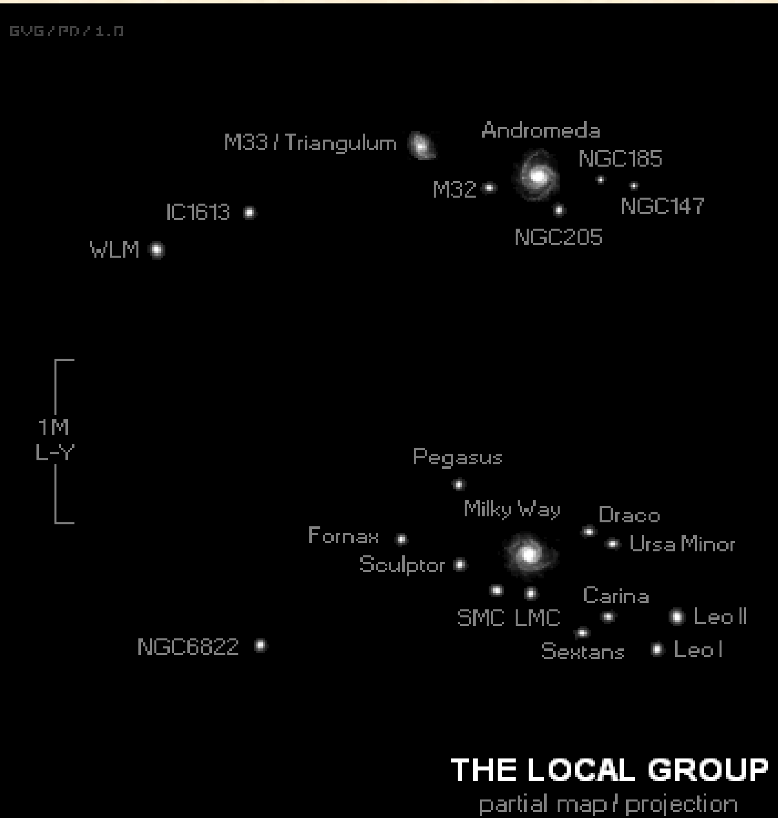
Should be easily detected by GLAST

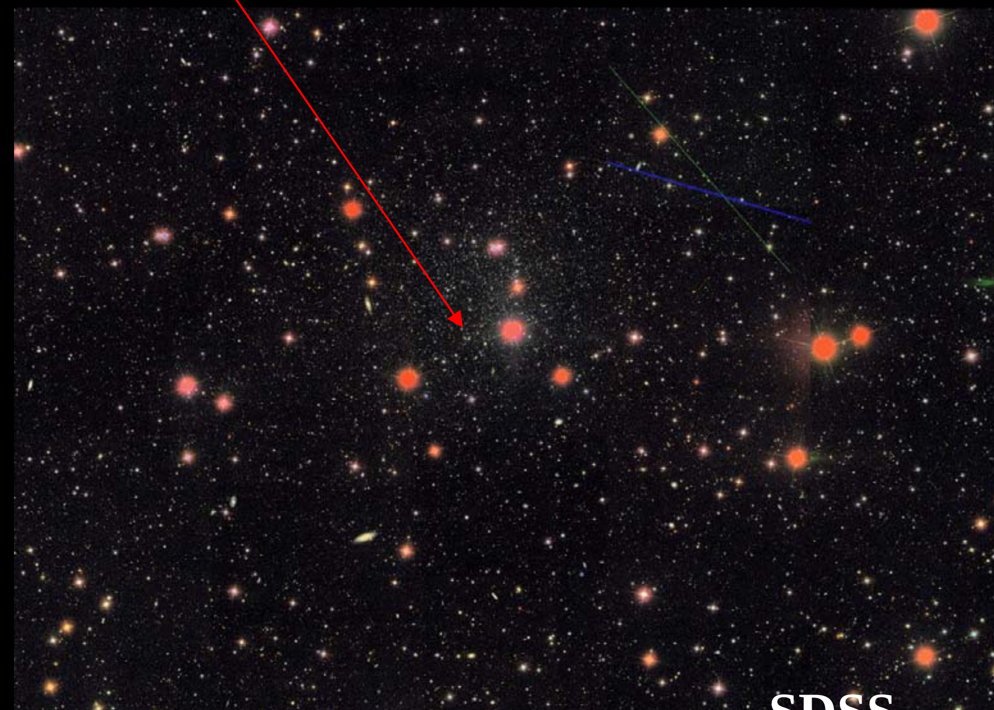
DRACO and dark matter

Draco: Dwarf spheroidal galaxy in the Local Group. Estimated total mass: 10^7 – 10^{10} solar masses; luminosity ~2×10^5 L_{sun} ⇒ mass-to-light ratio 100-10000. One of the most dark matter-dominated galaxies known! Star-poor ⇒ much cleaner observation conditions than Gal. Center

Draco is about 0.5 degrees across. It is very faint in the optical.

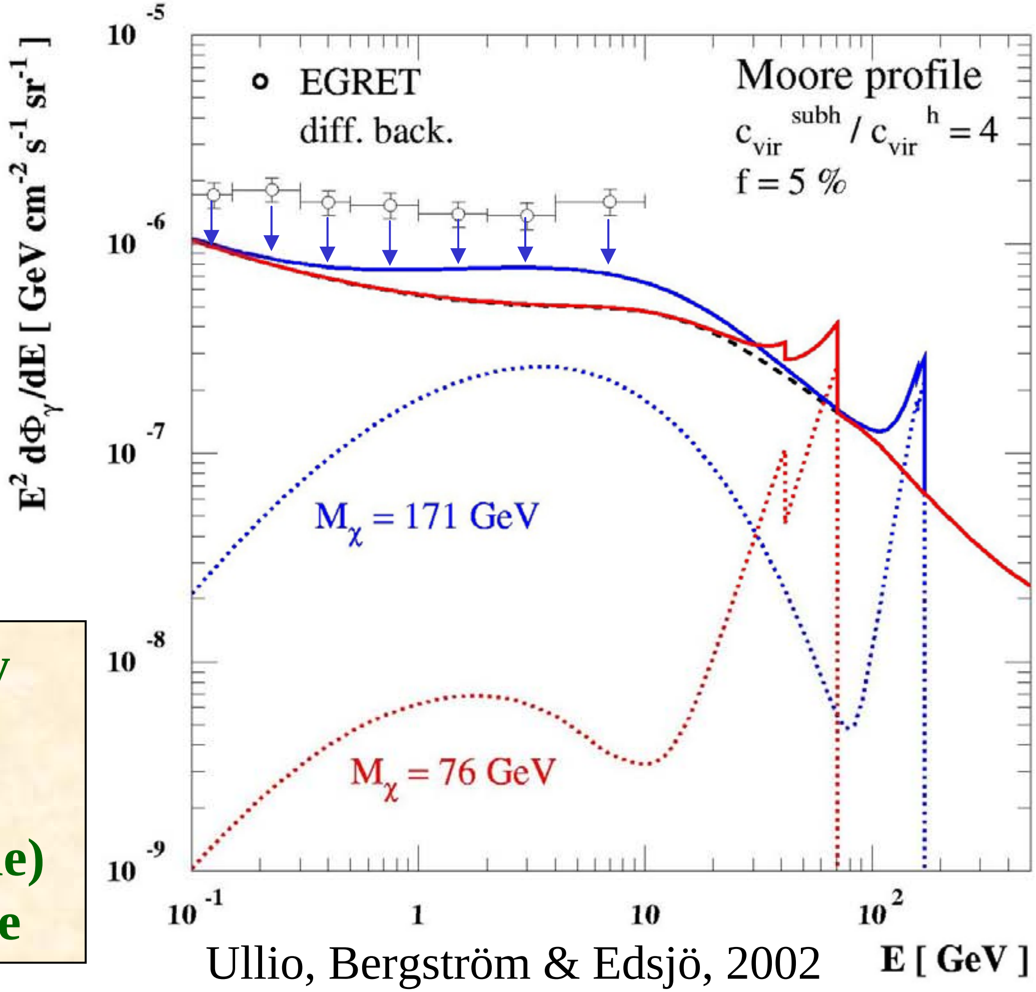
Integrated magnitude ~11 making it an ideal candidate for ACT observations.





Diffuse cosmic gamma-rays

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



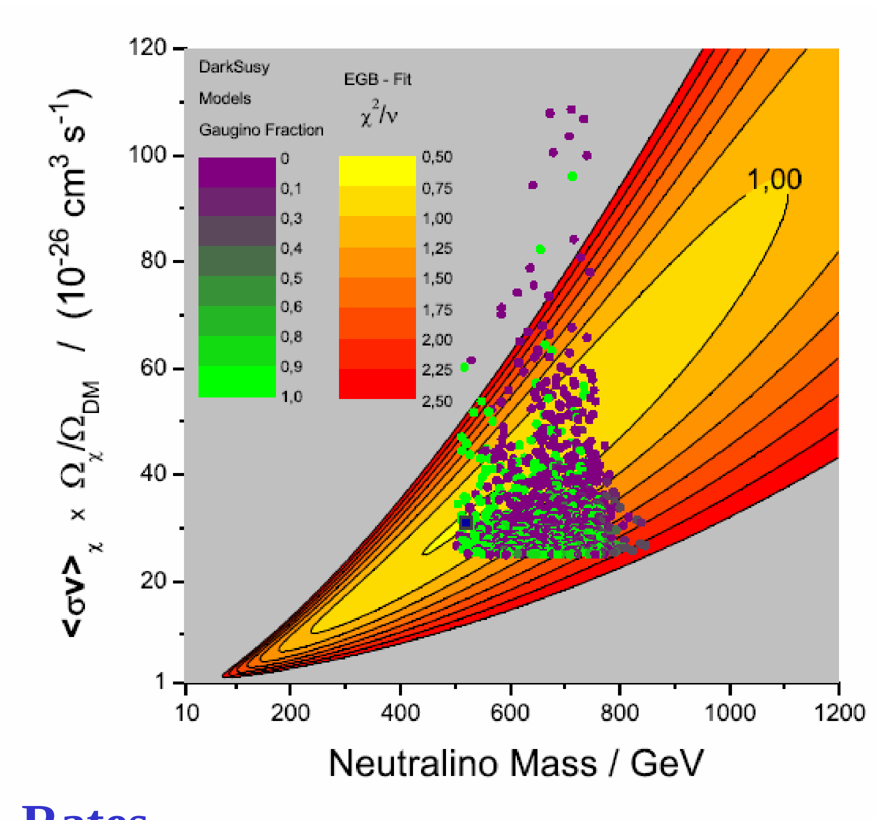
Ullio, Bergström & Edsjö, 2002

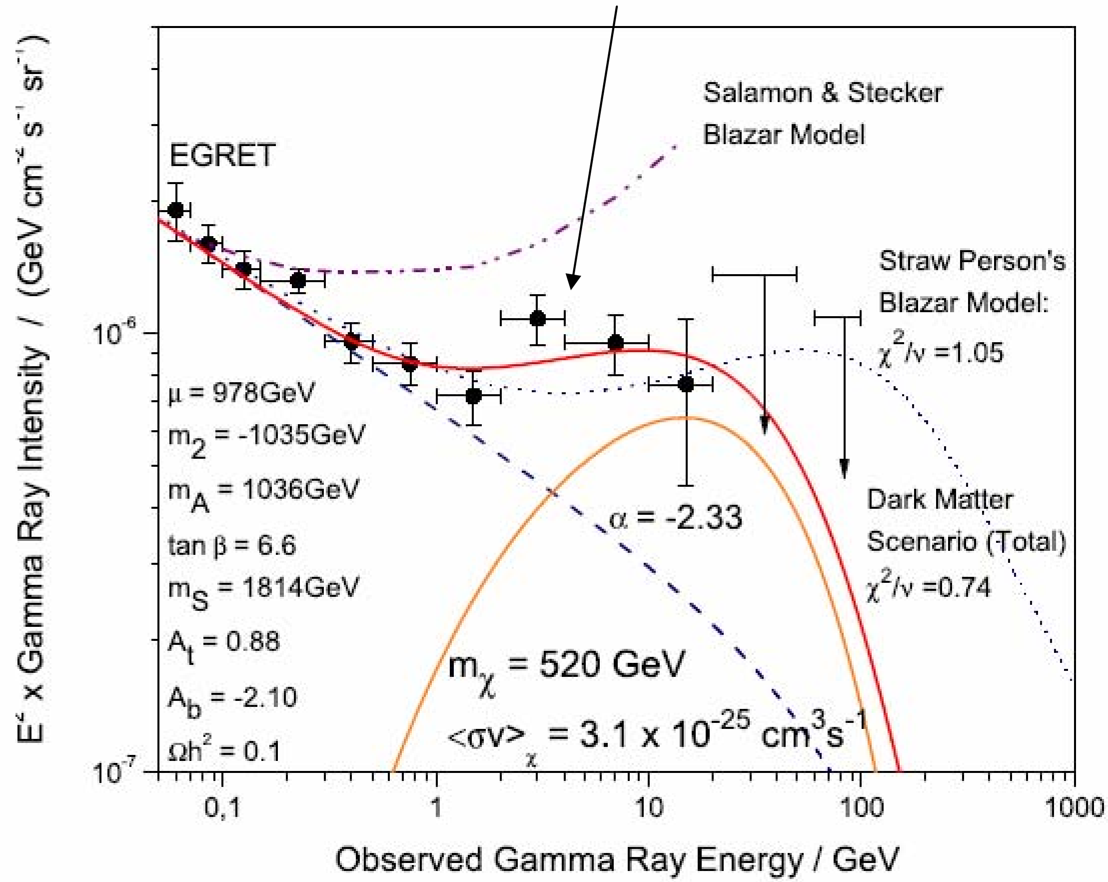
Idea: Redshifted gamma-ray line gives peculiar energy feature – may be observable for CDM-type (Moore profile) cuspy halos and substructure

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 DarkSUSY

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

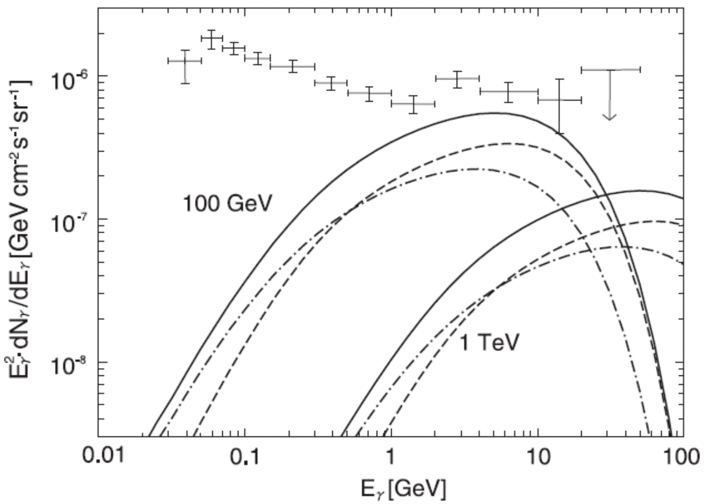
Elsässer & Mannheim, Phys. Rev. Lett. 94:171302, 2005

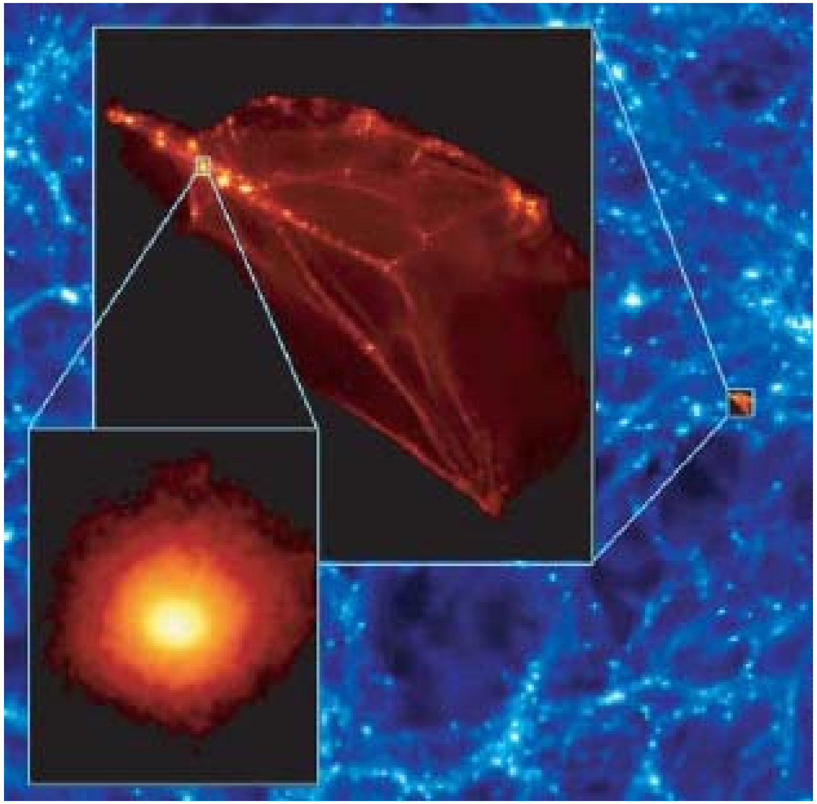
GLAST will tell!

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

Resolution (Oda, Totani & Nagashima, astro-ph/0504096): clumpy halos; tidal effects remove substructure near centres of haloes

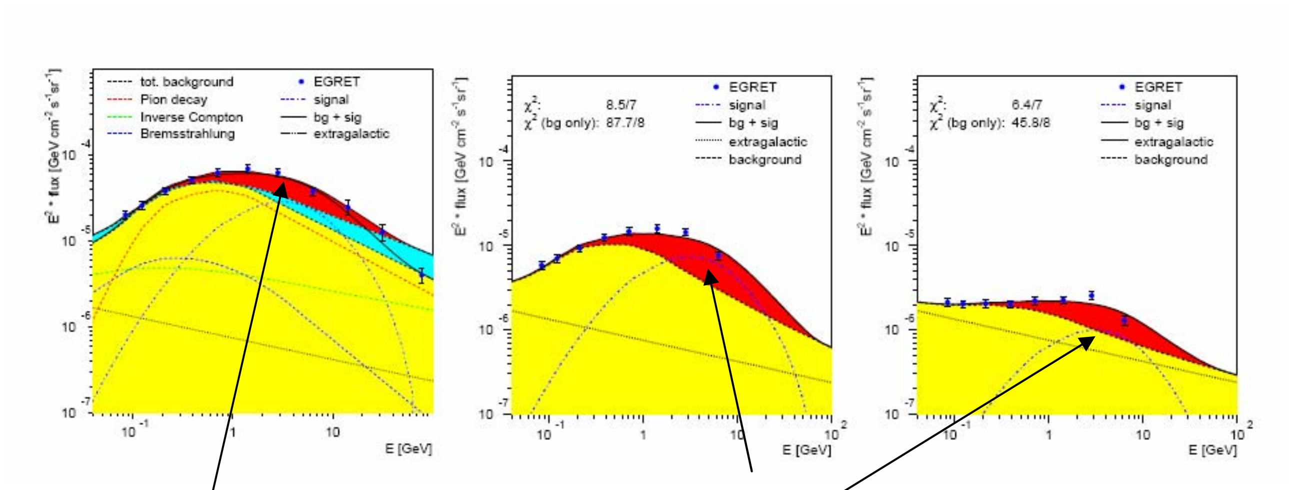
Effects of a clumpy halo on diffuse galactic plus extragalactic gamma-ray signal. Satisfies bound from gal. centre:

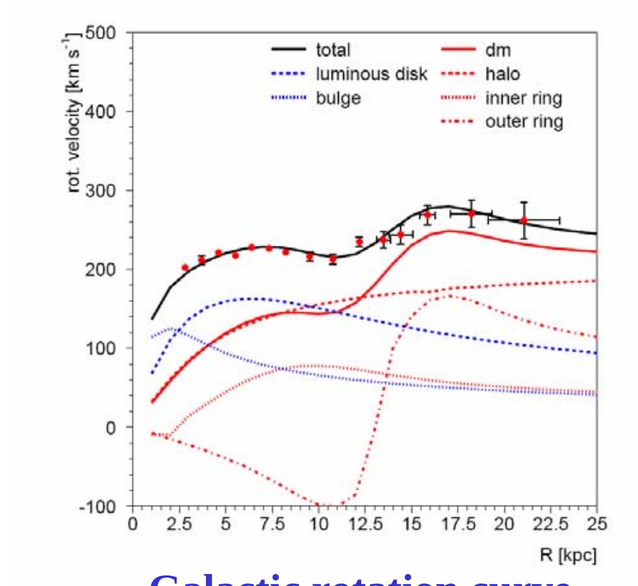




Oda, Totani and Nagashima, astro-ph/0504096; cf. also Pieri, Branchini and Hofmann, astro-ph/0505356

W. de Boer, astro-ph/0508617





Excess of gamma-rays

Filled by 65 GeV neutralino annihilation

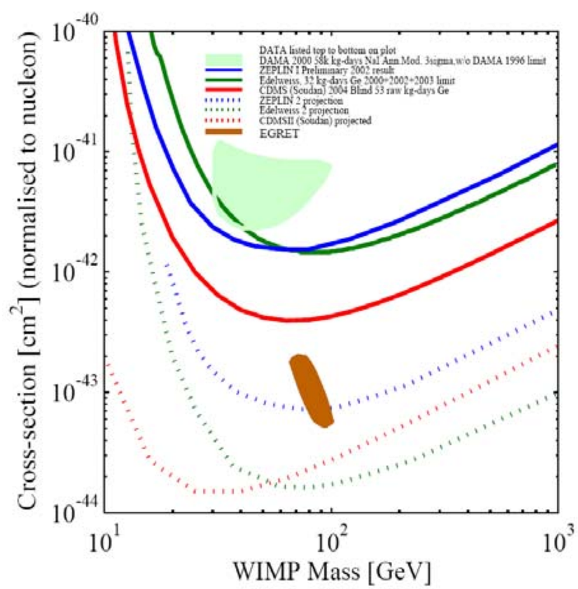
Galactic rotation curve

Data explained by 50-100 GeV neutralino?

cf. also A. Cesarini et al., 2003: large "boost factor" needed. Is that compatible with the measured antiproton flux?

Also, how reliable is GALPROP for the background? Wait for GLAST data: does the endpoint signal spectrum end in a line?

Finkbeiner, astro-ph/0409027: WMAP synchrotron foreground, "haze", can be explained by neutralino DM annihilation?



INTEGRAL all-sky picture of positronium gamma line (511 keV) emission – unknown origin (J. Knödlseder et al., astro-ph/0506026)

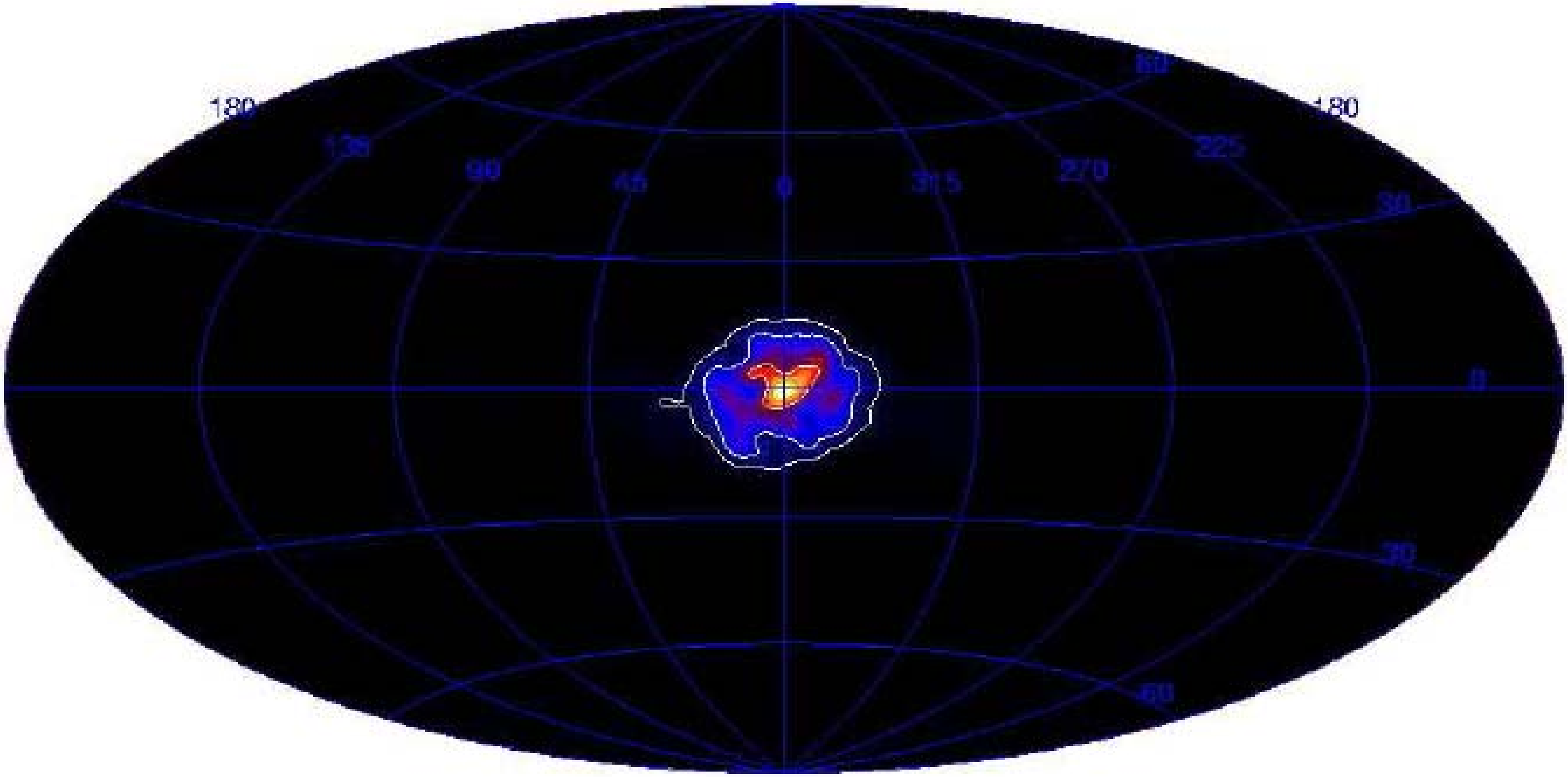


Fig. 4. Richardson-Lucy image of 511 keV gamma-ray line emission (iteration 17). Contour levels indicate intensity levels of 10^{-2}, 10^{-3}, and 10^{-4} ph cm^{-2}s^{-1}sr^{-1} (from the centre outwards).

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.

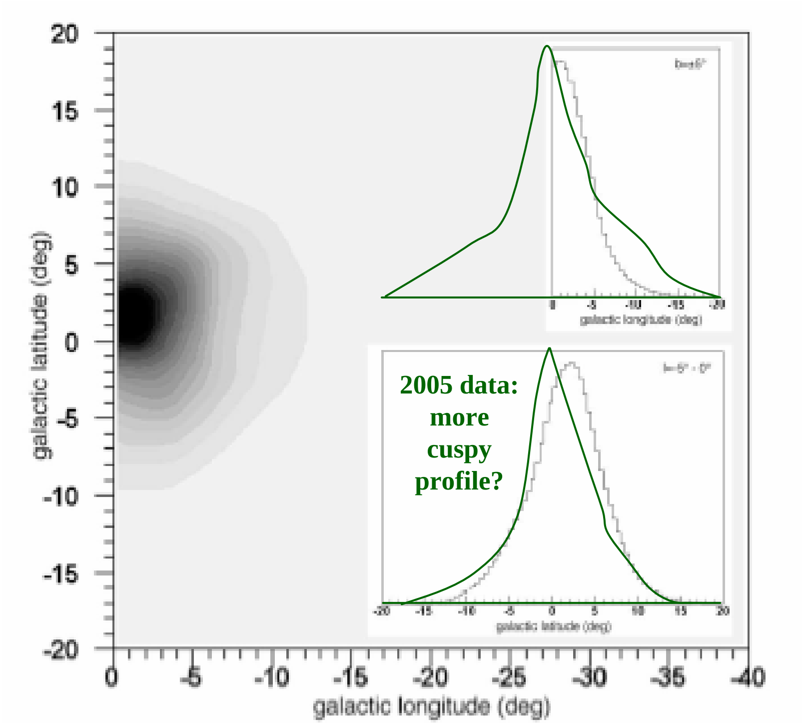
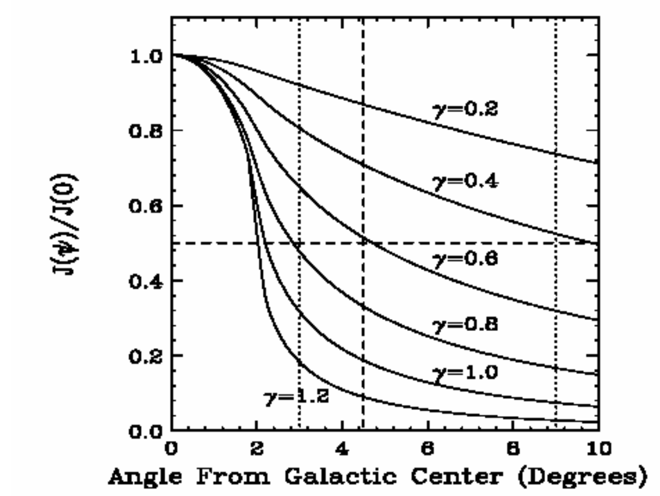


Fig. 2. 511 keV gamma-ray line intensity map of the galactic centre region (only negative longitudes). Black corresponds to regions of maximum 511 keV line intensity. Longitude and latitude profiles, integrated over $b = \pm 5°$ and $l = -5° - 0°$, respectively, are shown as insets.

INTEGRAL satellite measurements

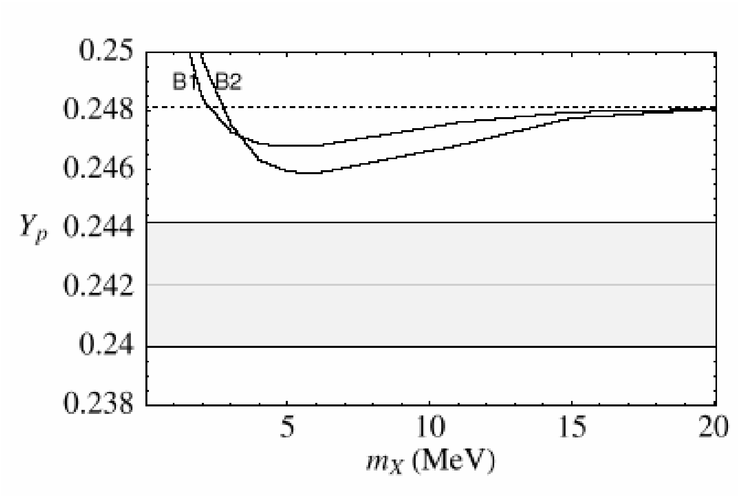


$$\rho \propto r^{-\gamma}$$

Y. Ascasibar & al., astro-ph/0507142: γ = 1.03 ± 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, hep-ph/0505157)

P. Serpico and G. Raffelt, PRD 2004



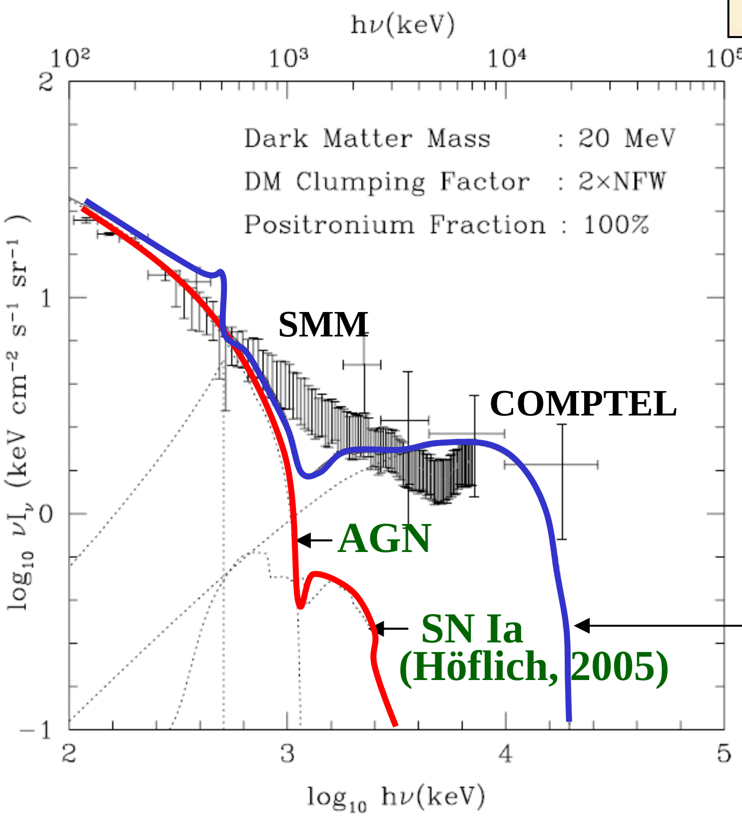
Light (5 – 15 MeV) dark matter actually improves agreement with BBN!

D. Hooper et al (PRL 2004): If signal is due to light dark matter annihilation, a flux should also be detectable,

$\phi \sim (1\text{-}7) \cdot 10^{-4}\ cm^{-2}s^{-1}$, from Sagittarius dwarf spheroidal galaxy.

New INTEGRAL upper limit (2005):

$\phi < 1.7 \cdot 10^{-4}\ cm^{-2}s^{-1} \Rightarrow$ almost entire range excluded. However, depends on density shape of subhalo vs halo.



Ahn and Komatsu, PRD 2005: What gives the diffuse extragalactic gamma-ray background above 3 - 4 MeV?

Borodatchenkova, Choudhury, Drees, hep-ph/0510147: Low-mass scalar particles can be tested at B-factories, and perhaps ϕ factories (Daphne)

20 MeV Dark Matter

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**
- **New direct and indirect detection experiments will reach deep into theory parameter space, some even deeper than LHC**
- **Indications of gamma-ray excess from Galactic Center and possibly from the Draco dwarf galaxy. 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 will search for ”hot spots” in the sky with high sensitivity**
- **The dark matter problem may be near its solution…**