Neutralino Dark Matter: update on direct and indirect detection

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KIAS-APCTP-DMRC Workshop on
"The Dark Side of the Universe"

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Outline of the talk

- gaugino non universality & neutralino mass
- cosmological lower bound on m $_{\chi}$ from WMAP
- direct searches
- indirect searches

LIGHT NEUTRALINOS!
($m_{\chi} \leq 50$ GeV)

“**Neutralino annihilation into γ rays in the Milky Way and in external galaxies**”, N. Fornengo, L. Pieri and S. Scopel, Phys. Rev. D 70, 103529 (2004)

“**Indirect signals from light neutralinos in supersymmetric models without gaugino mass unification**”, A. Bottino, F. Donato, N. Fornengo, S. Scopel, Phys.Rev. D 70, 015005 (2004)

“**Light neutralinos and WIMP direct searches**”, A. Bottino, F. Donato, N. Fornengo, S. Scopel, Phys.Rev.D69, 037302 (2004)

“**Lower bound on the neutralino mass from new data on CMB and implications for relic neutralinos**”, A. Bottino, F. Donato, N. Fornengo, S. Scopel, Phys. Rev. D 68, 043506 (2003)

“**Light relic neutralinos**”, A. Bottino, N. Fornengo, S. Scopel, Phys. Rev. D 67, 063519 (2003)

The neutralino

- The neutralino is defined as the lowest-mass linear superposition of bino $\tilde{B}$, wino $\tilde{W}^{(3)}$ and the two higgsino states $\tilde{H}_1^0$, $\tilde{H}_2^0$:

$$\chi \equiv a_1 \tilde{B} + a_2 \tilde{W}^{(3)} + a_1 \tilde{H}_1^0 + a_1 \tilde{H}_2^0$$

- neutral, colourless, only weak-type interactions
- stable if R-parity is conserved, thermal relic
- non relativistic at decoupling → Cold Dark Matter (required by CMB data + structure formation models)
- relic density can be compatible with cosmological observations: $0.095 \leq \Omega_\chi h^2 \leq 0.131$

→IDEAL CANDIDATE FOR COLD DARK MATTER

- Most analysis on the SUSY model assume that gaugino soft masses unify at the GUT scale
- Gaugino mass unification implies a lower bound on the neutralino mass:

$$m_\chi \gtrsim 50 \text{ GeV}$$

- However the assumption of gaugino mass unification at the GUT scale might not be justified (for instance, the gaugino unification scale may be much lower than the standard GUT scale)

Effective MSSM scheme (effMSSM) – Independent parameters

- M_1 U(1) gaugino soft breaking term
- M_2 SU(2) gaugino soft breaking term
- μ Higgs mixing mass parameter
- $\tan\beta$ ratio of two Higgs v.e.v.'s
- m_A mass of CP odd neutral Higgs boson (the extended Higgs sector of MSSM includes also the neutral scalars h, H, and the charged scalars $H^{\pm}$)
- $m_{\tilde{q}}$ soft mass common to all squarks
- $m_{\tilde{l}}$ soft mass common to all sleptons
- A common dimensionless trilinear parameter for the third family ($A_{\tilde{b}} = A_{\tilde{t}} \equiv Am_{\tilde{q}}$; $A_{\tilde{\tau}} \equiv Am_{\tilde{l}}$)
- $R \equiv M_1/M_2$

SUGRA→$R=0.5$

Lower limit on the neutralino mass from PDG

Citation: S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B **592**, 1 (2004) (URL: http://pdg.lbl.gov,

Table 1: Lower limits on supersymmetric particle masses. 'GMSB' refers to models with gauge-mediated supersymmetry breaking, and 'RPV' refers to models allowing R-parity violation.

particle		Condition	Lower limit (GeV/c^2)	Source
$\widetilde{\chi}_1^0$	indirect	any $\tan\beta$, $M_{\widetilde{\nu}} > 500$ GeV/c^2	39	LEP 2
		any $\tan\beta$, any m_0	36	LEP 2
		any $\tan\beta$, any m_0, SUGRA Higgs	59	LEP 2 combined
	GMSB		93	LEP 2 combined
	RPV	$LL\overline{E}$ worst case	R̸ 23	LEP 2

$$m_\chi \geq 36\,\text{GeV}$$

✗ **Warning: this limit is model dependent**

Lower limits on the neutralino mass from accelerators

- Indirect limits from chargino production ($e^+e^- \to \chi^+\chi^-$):

0.5

$$m_{\chi^\pm} \gtrsim 100 \text{ GeV} \Rightarrow m_\chi \gtrsim 50 \text{ GeV} \quad \text{if} \quad R \equiv \frac{M_1}{M_2} = \frac{5}{3}\tan^2\theta_w$$

- Direct limits from $e^+e^- \to \chi_0^i \chi_0^j$ $\quad (\chi_0^1 \equiv \chi,\ m_{\chi_0^1} < m_{\chi_0^2} < m_{\chi_0^3} < m_{\chi_0^4})$ †:
  - Invisible width of the Z boson (upper limit on number N_ν of neutrino families)
  - Missing energy + photon(s) or $f\bar{f}$ from $\chi_0^{i>1} \to \chi_0^1$ decay

- Direct limits from $\tilde{t} \to c\,\chi$ and $\tilde{b} \to b\,\chi$ at Tevatron ‡

† small production cross sections
‡ light squark masses ($\lesssim 100$ GeV) required

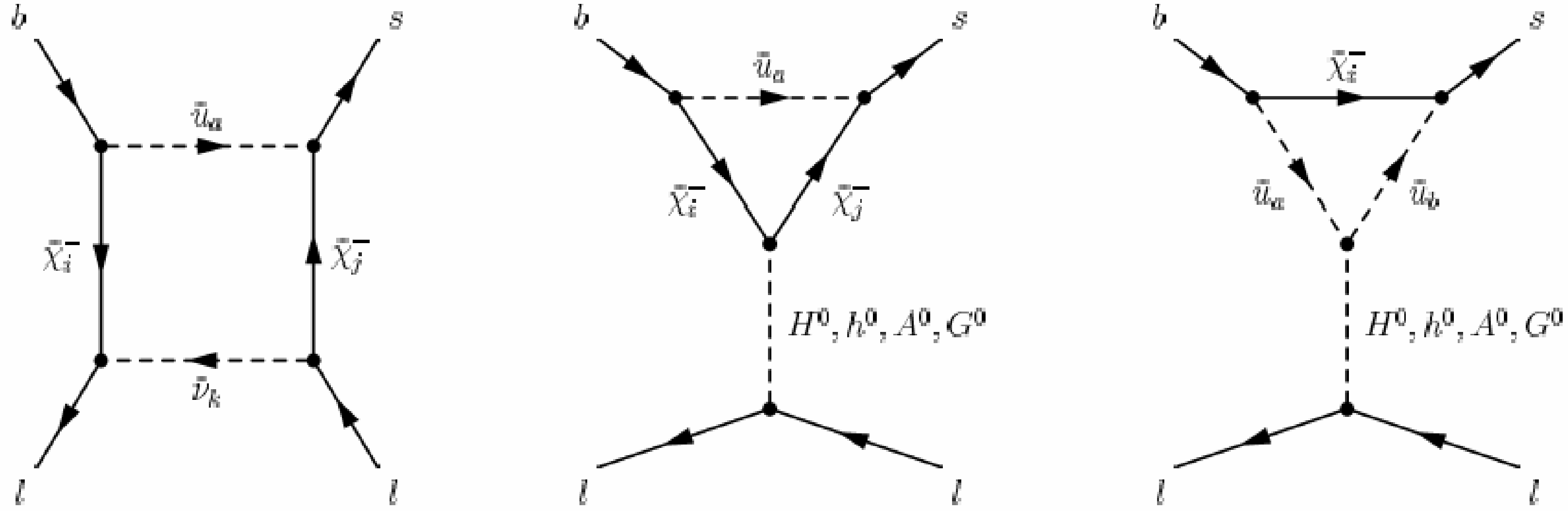
➠ No absolute direct lower bounds on m_χ

Experimental constraints

- accelerators data on supersymmetric and Higgs boson searches (CERN e^+e^- collider LEP2 and Collider Detector CDF at Fermilab)
- measurements of the $b \to s\gamma$ decay
- measurement of the muon anomalous magnetic moment $a_\mu \equiv (g_\mu - 2)/2$
  (we use $-142 \le \Delta a_\mu \cdot 10^{11} \le 474$ (τ+e data combined), M. Davier et al., Eur. Phys. J. C31 (2003) 503; K. Hagiwara et al., hep-ph/0312250)
- $B_S \to \mu^+ \mu^-$ decay, D. Acosta *et al.* (CDF Collaboration), PRL93,032001(2004), V.M. Abazov et al. (D0 Collaboration), PRL94,071802,(2005))

$B_s \rightarrow \mu^+\mu^-$ decay

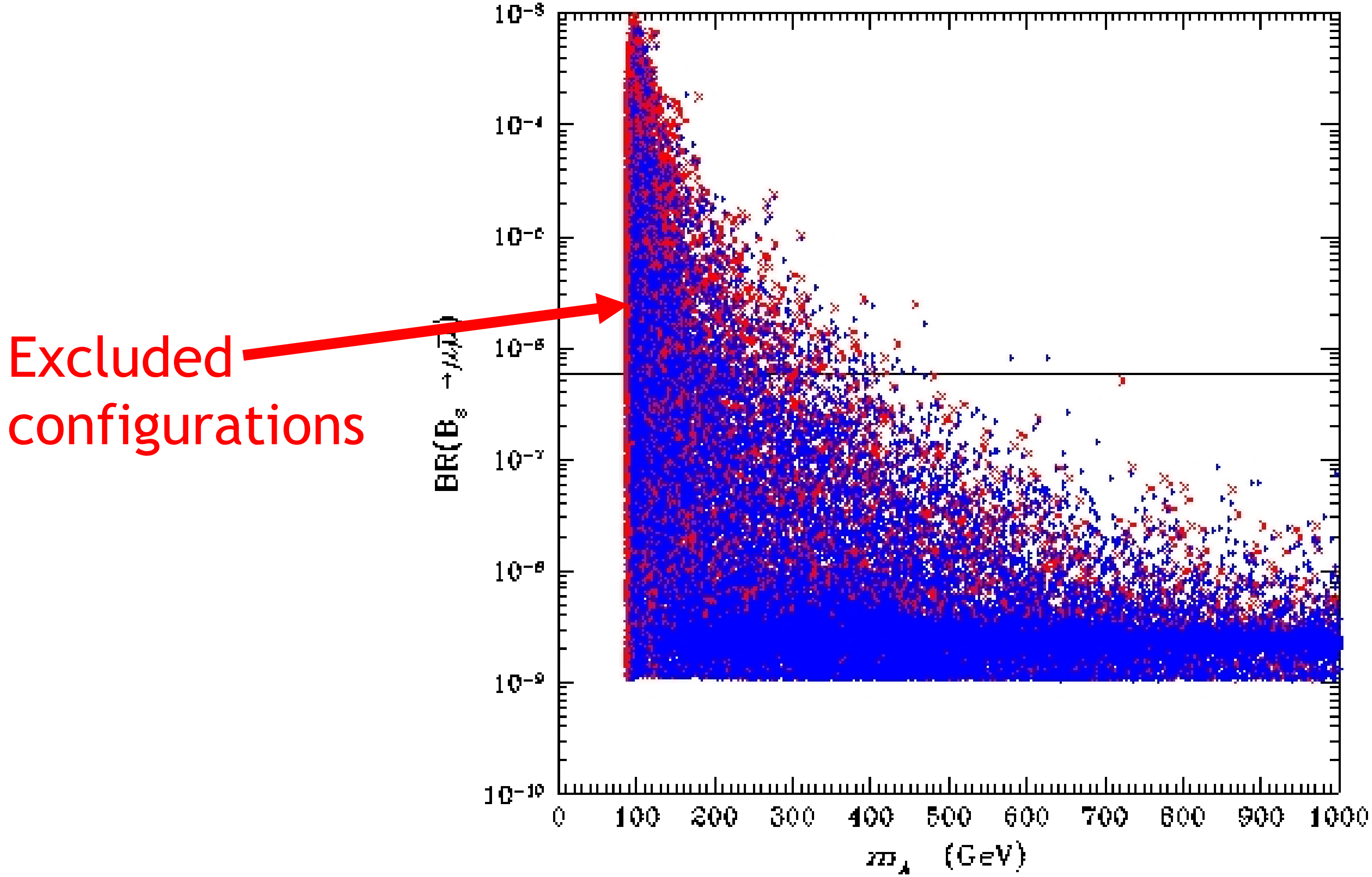
➢SUSY contribution strongly enhanced at high *tan β* and low m_A ($\propto (\tan\beta)^6/m_A^4$)



(C. Bobeth, T. Ewerth, F. Kruger and J. Urban, PRD64(2001) 074014)

➢*tan β – enhanced SUSY QCD corrections to b Yukawa coupling included*

$B_S \rightarrow \mu^+\mu^-$ decay



✓Strong correlation with direct detection signals (S. Baek, Y. G. Kim, P. Ko, JHEP 0502:067,2005; S. Baek, D. G. Cerdeño, Y.G. Kim, P. Ko and C. Muñoz, hep-ph/0505019)

Sign of b-> s γ amplitude

- the measurement of B(B-> X_s μ μ) is sensitive to the sign of the b -> s γ amplitude C_7:

$$\frac{d\Gamma[\bar{B} \to X_s l^+ l^-]}{d\hat{s}} = \frac{G_F^2 m_{b,\text{pole}}^5 |V_{ts}^* V_{tb}|^2}{48\pi^3} \left(\frac{\alpha_{em}}{4\pi}\right)^2 (1-\hat{s})^2 \times \left\{ (1+2\hat{s})(|\tilde{C}_9^{\text{eff}}|^2 + |\tilde{C}_{10}^{\text{eff}}|^2) + \left(4 + \frac{8}{\hat{s}}\right)|\tilde{C}_7^{\text{eff}}|^2 + 12\,\text{Re}(\tilde{C}_7^{\text{eff}} \tilde{C}_9^{\text{eff}*}) \right\},$$

- b -> s γ decay depends on $|C_7|^2$

•Belle and BABAR data favour a negative sign of C_7 (same of the standard model) (Gambino, Haisch, Misiak, PRL94,061803 (2005))

•sizeable SUSY correction (light stop and chargino, high *tan* β) can drive C_7 to positive values compatible to BR(b -> s γ) but potentially in conflict with B(B-> X_s μ μ) (not in SUGRA)

Dark matter density from WMAP

- CMB data, used in combination with other cosmological observations, are narrowing down the range of the matter abundance $\Omega_m h^2$ and some of its constituents, $\Omega_\nu h^2$ and $\Omega_b h^2$:

$$0.095 < \Omega_{CDM} h^2 < 0.131 \quad \text{(2 } \sigma \text{ range)}$$

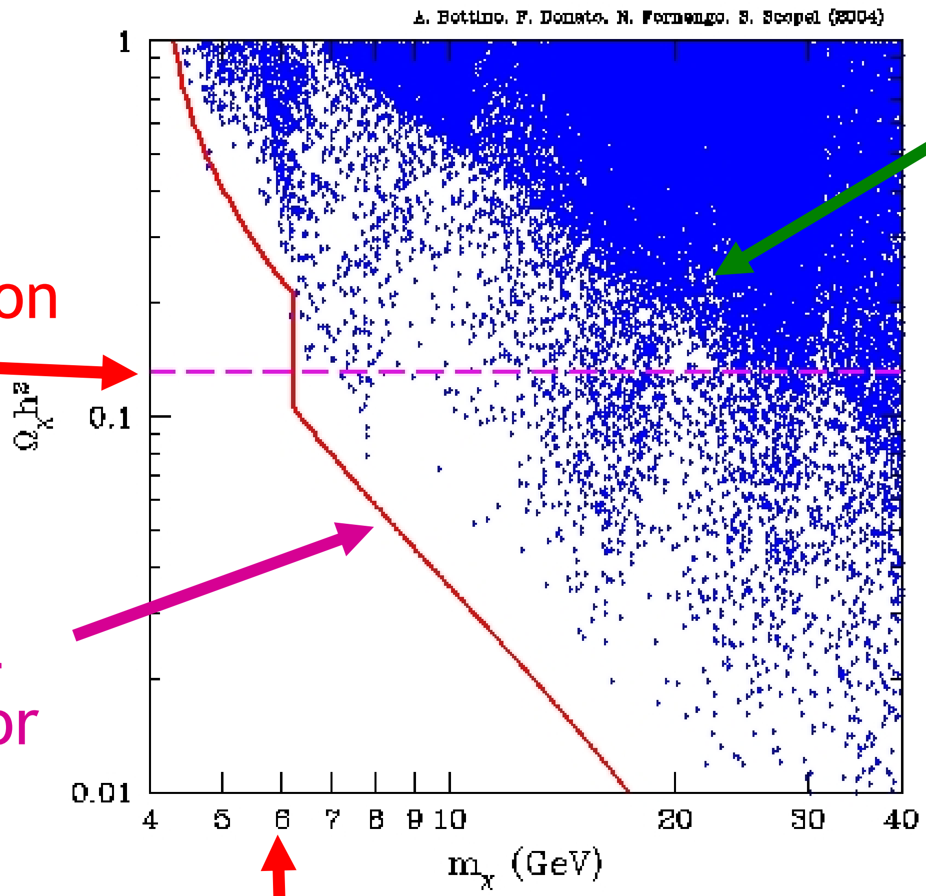
- The upper bound $(\Omega_{CDM} h^2)_{max}$ establishes a strict upper limit for any specific cold species

- The lower bound $(\Omega_{CDM} h^2)_{max}$ *fixes* the value of the average abundance below which the halo density of a specific cold constituent has to be rescaled as compared to the total CDM halo density

➡ Rescaling factor: $\xi \equiv \rho_\chi / \rho_0 \equiv min(1, \Omega_\chi h^2 / (\Omega_{CDM} h^2)_{min})$

ρ_χ = local neutralino density; ρ_0 = total local dark matter density

Cosmological lower bound on m_χ (low m_A)



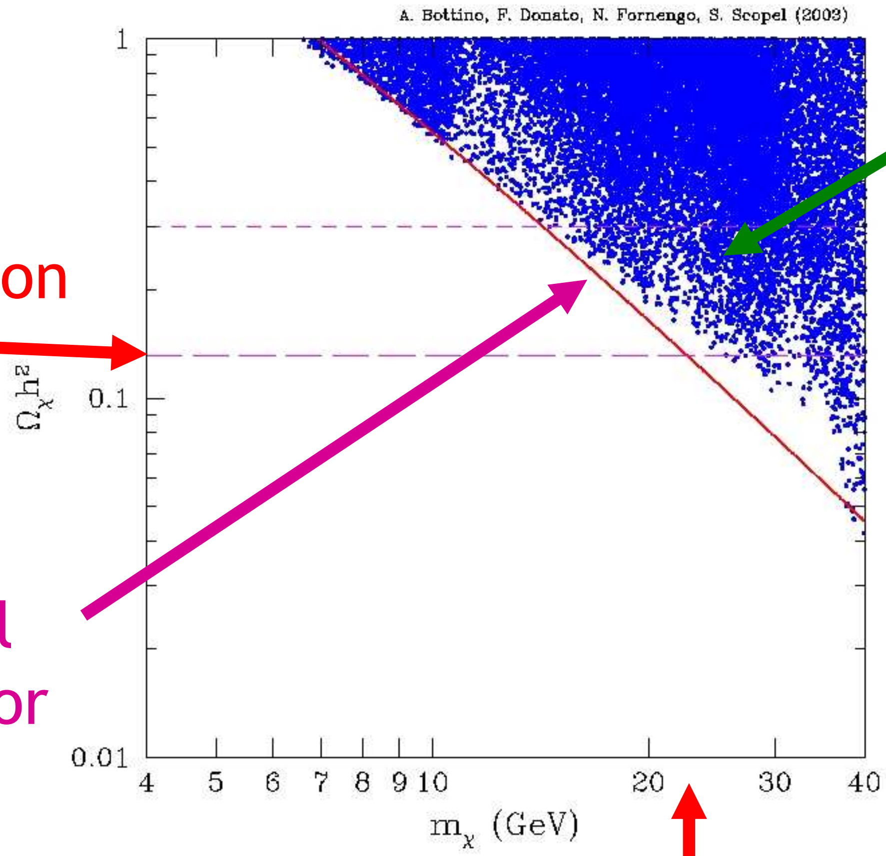
scatter plot: full calculation

upper bound on $\Omega_{CDM}h^2$

curve: analytical approximation for minimal $\Omega_{CDM}h^2$

$$m_\chi\,[1 - m_b^2/m_\chi^2]^{1/4} \gtrsim 5.3 \text{ GeV} \left(\frac{m_A}{90 \text{ GeV}}\right)^2$$

Cosmological lower bound on m_χ ($m_A > 200$ GeV)



scatter plot:
full calculation

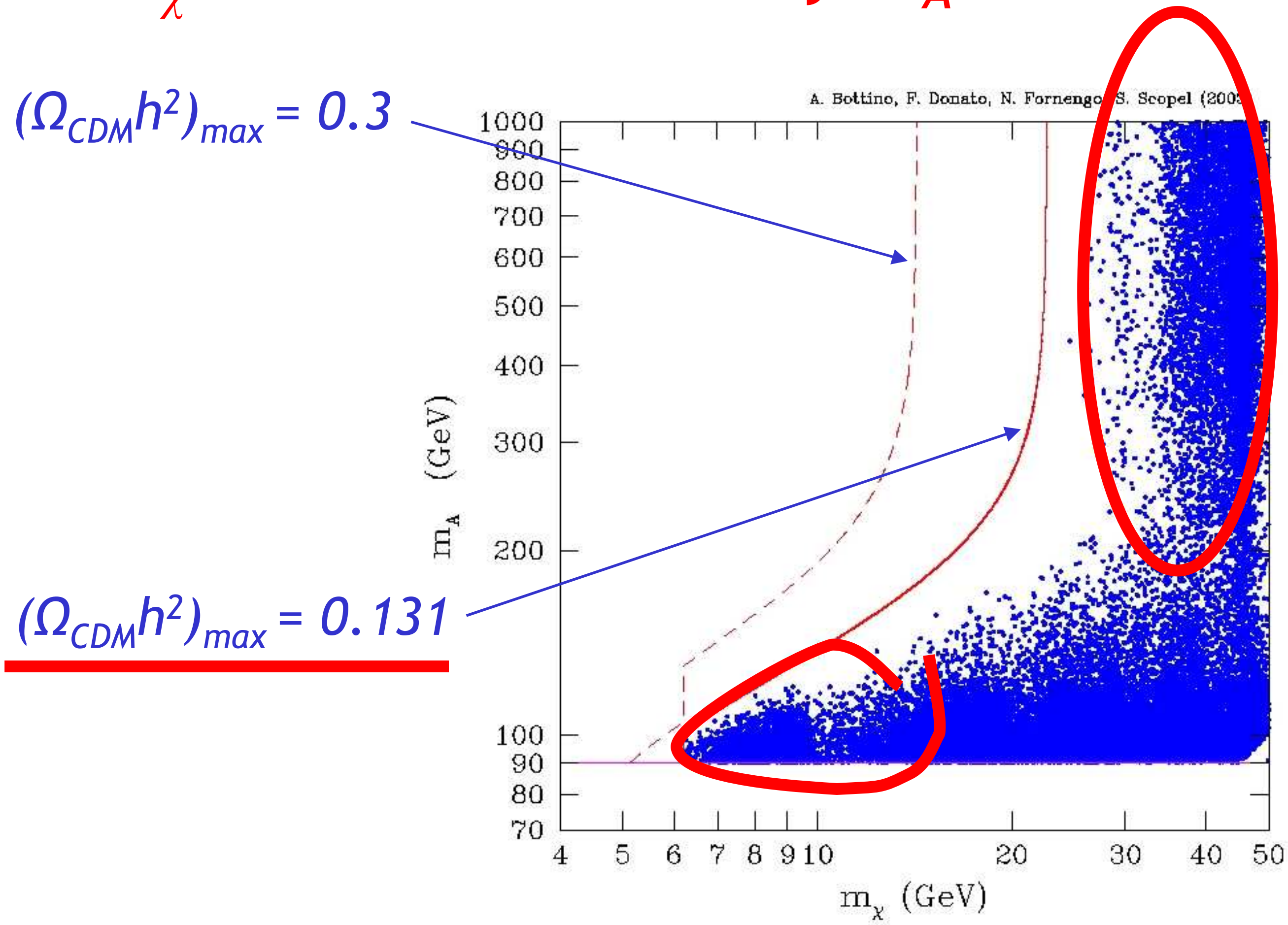
upper bound on
$\Omega_{CDM}h^2$

curve: analytical
approximation for
minimal $\Omega_{CDM}h^2$

$$m_\chi \left[1 - m_\tau^2/m_\chi^2\right]^{1/4} \gtrsim 22 \text{ GeV} \left(\frac{m_{\tilde{\tau}}}{90 \text{ GeV}}\right)^2$$

The bottom line: the cosmological lower bound on m_χ depends on the value of m_A:

- ✓ m_χ > 6 GeV for light m_A
- ✓ m_χ > 22 GeV for heavy m_A



SEARCHES

Searches for relic WIMPs

- Direct searches. Elastic scattering of χ off nuclei (∝ WIMP local density)

$$\chi + N \rightarrow \chi + N$$

- Indirect searches. Signals due to χ - χ annihilations

$$\chi + \chi \quad \rightarrow \quad \begin{matrix} g\,\underline{g} \\ f\,f \\ W^+W^- \\ ZZ \\ HH,\, hh,\, AA,\, hH,\, hA,\, HA,\, H^+H^- \\ W^+H^-,\, W^-H^+ \\ Zh,\, ZH,\, ZA \end{matrix} \quad \rightarrow \quad \nu,\, \bar{\nu},\, \gamma,\, \bar{p},\, e^+,\, \bar{d}$$

➢ Annihilations taking place in celestial bodies where χ's have been accumulated: ν's → up-going μ's from Earth and Sun

➢ Annihilations taking place in the Halo of the Milky Way or that of external galaxies: enhanced in high density regions (∝ (WIMP density)^2) ⇒ Galactic center, clumpiness

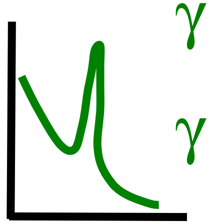
Annihilations taking place in the Halo

(∝ WIMP (local density)^2)

$\chi + \chi \rightarrow$

$\nu, \bar{\nu}$

γ (continuum)



γ line ($Z\gamma$)

} keep directionality

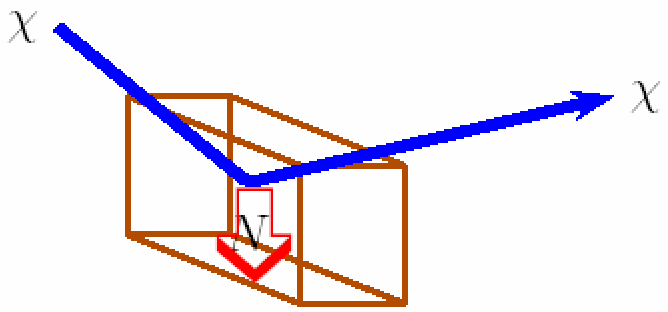
$\bar{p}$

e^+

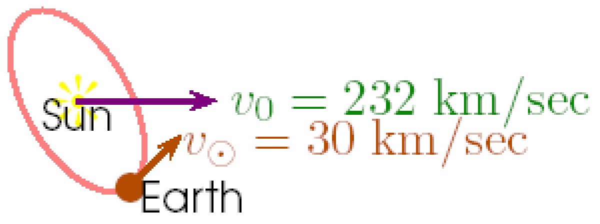
$\bar{D}$

} searches for rare components in cosmic rays (diffusion)

Neutralino direct detection



- Elastic recoil of non relativistic halo neutralinos off the nuclei of an underground detector
- Recoil energy of the nucleus in the keV range
- Yearly modulation effect due to the rotation of the Earth around the Sun (the relative velocity between the halo, usually assumed at rest in the Galactic system, and the detector changes during the year)



Differential detection rate

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{v_{\min}}^{v_{\max}} d\vec{v}\, f(\vec{v}) |\vec{v}| \frac{d\sigma(\vec{v}, E_R)}{dE_R}$$

E_R=nuclear recoil energy
N_T=number of nuclear targets
$\vec{v}$=WIMP velocity in the Earth's rest frame

Astrophysics:
* ρ_χ=neutralino local density
* $f(\vec{v})$=neutralino velocity distribution function

Particle and nuclear physics:
* $\frac{d\sigma(\vec{v}, E_R)}{dE_R}$=neutralino–nucleus elastic cross section

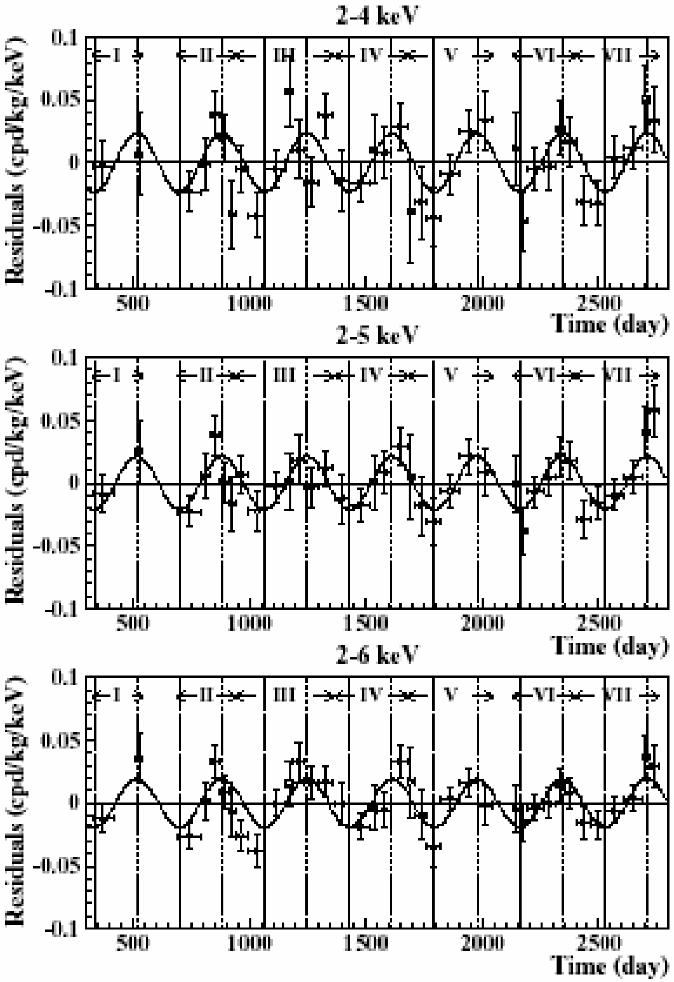
$$\frac{d\sigma(\vec{v}, E_R)}{dE_R} = \left(\frac{d\sigma(\vec{v}, E_R)}{dE_R}\right)_{\text{coherent}} + \left(\frac{d\sigma(\vec{v}, E_R)}{dE_R}\right)_{\text{spin-dependent}}$$

↑ usually dominates, $\propto$ (atomic number)^2

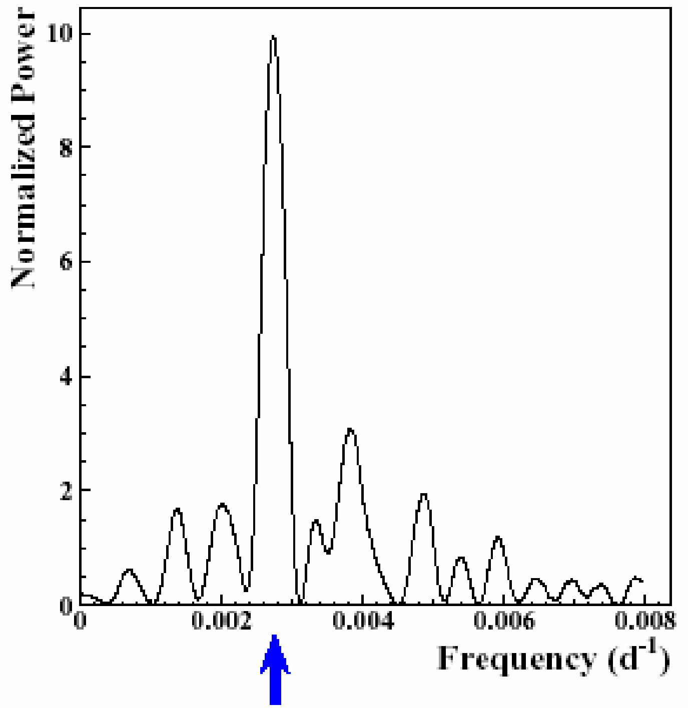
DAMA: 7 years of annual modulation (108000 kg day)

(Bernabei et al., Riv.N.Cim.26 n. 1 (2003) 1-73, astro-ph/0307403)

Residuals:



Power spectrum of residuals in the (2–6) keV energy range:



Frequency=1/365.36 d^{-1}

The DAMA annual modulation result

- The DAMA/NaI experiment shows an annual-modulation effect at the 6.3 σ C.L. after a 7-years running with a total exposure of $\simeq$ 108 000 kg $\cdot$ day.
- DAMA analysis extended to a large class of possible phase–space distribution functions (DF) for WIMPs in the galactic halo.
- The full set of experimental data analyzed in terms of a spin–independent effect over an unconstrained range for the mass of a generic WIMP.

Neutralino – nucleon cross section

Color code from now on:

- $\Omega_\chi h^2 < 0.095$
- $\times\ \Omega_\chi h^2 > 0.095$

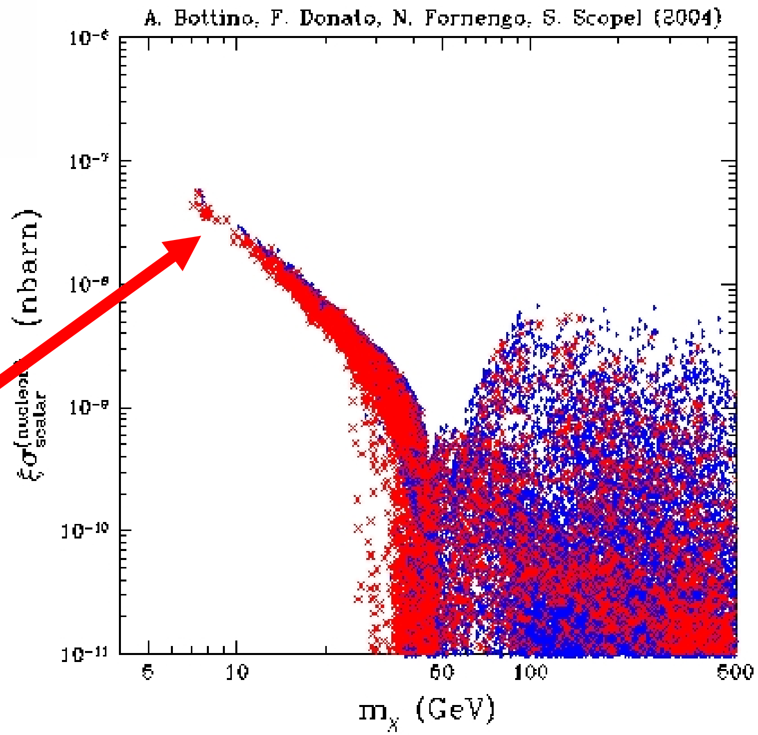
$$\Omega_\chi h^2 \le (\Omega_{CDM} h^2)_{max}$$

$$\Downarrow$$

$$\sigma^{(\mathrm{nucleon})}_{\mathrm{scalar}} \gtrsim \frac{10^{-40} cm^2}{(\Omega_{CDM} h^2)_{max}} \frac{\mathrm{GeV}^2}{m_\chi^2\,[1 - m_b^2/m_\chi^2]^{1/2}} \quad \text{for } m_\chi \lesssim 20\ \text{GeV}$$

The elastic cross section is bounded from below:

→ "funnel" at low mass



Neutralino – nucleon cross section

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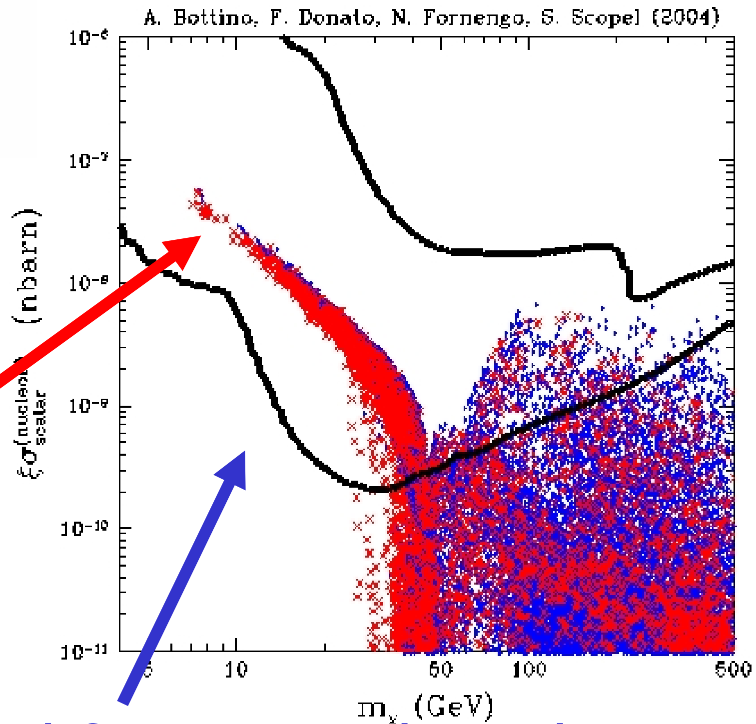
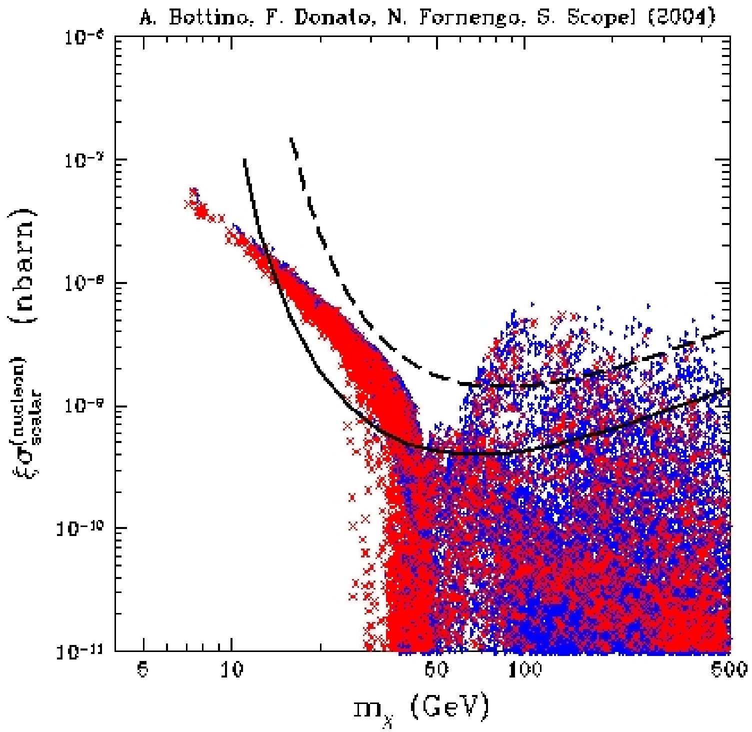


DAMA modulation region, likelyhood function values distant more than 4 σ from the null result (absence on modulation) hypothesis, Riv. N. Cim. 26 n. 1 (2003) 1-73, astro-ph/0307403

Neutralino – nucleon cross section

Upper limits from direct searches

assumptions:
isothermal sphere,
v_0=220 km/sec,
ρ_0=0.3 GeV/cm^3



CDMS, D. S. Akerib *et al.*, PRL93,211301 (2004)

Edelweiss, A. Benoit *et al.*, Phys. Lett. B 545, 43 (2002); V. Sanglard et al., astro-ph/0503265

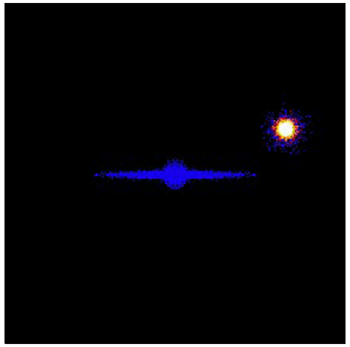
CRESST limit (similar to Edelweiss), Angloher et al., astro-ph/0408006

Uncertainty due to velocity distribution

- Many possible departures from the isothermal sphere model, which is the parameterization usually adopted to describe the halo.
- Different density profiles, effects due to anisotropies of the velocity dispersion tensor, rotation of the galactic halo.
- Non thermal components:
  - numerical simulations, see for instance A. Helmi, S. D. M. White and V. Springel, Phys. Rev. D 66 063503 (2002); D. D. Stiff, L. M. Widrow and J. Frieman, Phys. Rev. D 64 , 083516 (2001) ☛ Size of the effect?
  - Sgr tidal stream, K. Freese, P. Gondolo and H. Newberg,

PRD71,043516,2005

wrong direction
to explain DAMA



Compatibility DAMA-CDMS-Edelweiss?

No combined analysis of all experiments available

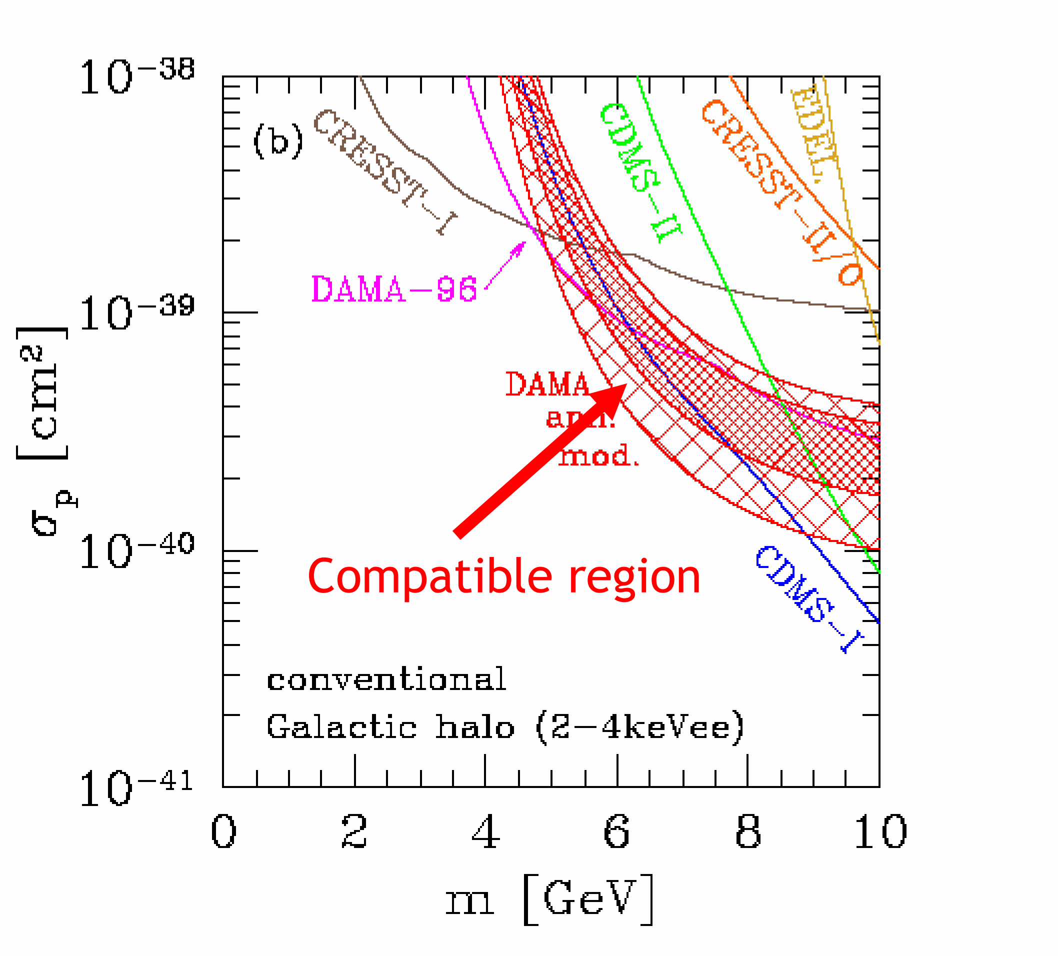
However, some trivial considerations:

for $m_\chi \geq 25$ GeV capture on DAMA is dominated by the I target $\rightarrow$ WIMPS above threshold in DAMA are also above threshold in CDMS - Edelweiss Ge

for $m_\chi \leq 25$ Ge capture on DAMA is dominated by the Na target $\rightarrow$ WIMPS above threshold in DAMA can be below threshold in the CDMS - Edelweiss Ge

$\rightarrow$ Gelmini and Gondolo, hep-ph/0504010, compatibility both for a thermalized maxwellian (light WIMP) and for high velocity (extragalactic?) streams (not Sgr stream, wrong direction)

Gelmini and Gondolo, hep-ph/0504010



important parameter: v_{escape}=650 km/sec compatible region:

6 GeV < m_x < 8 GeV , $\sigma^{(nucleon)}_{scalar}$= few x 10^{-7} nbarn

can we make it?

previous slides:
6 GeV < m_x < 8 GeV , $\sigma^{(nucleon)}_{scalar} \approx 6 \times 10^{-8}$ nbarn
but:

- π-nucleon sigma term Σ≈64 MeV (Ellis,Olive,Santoso,Spanos, hep-ph/0502001) we used Σ≈45 MeV -> factor of 2 enhancement
- in flattened halo models $\rho_{loc} \approx$ 1 GeV/cm^3 (even higher for high values of the rotational velocity) ->factor of 3 enhancement compared to ρ_{loc} =0.3 GeV/cm^3

hard but still possible

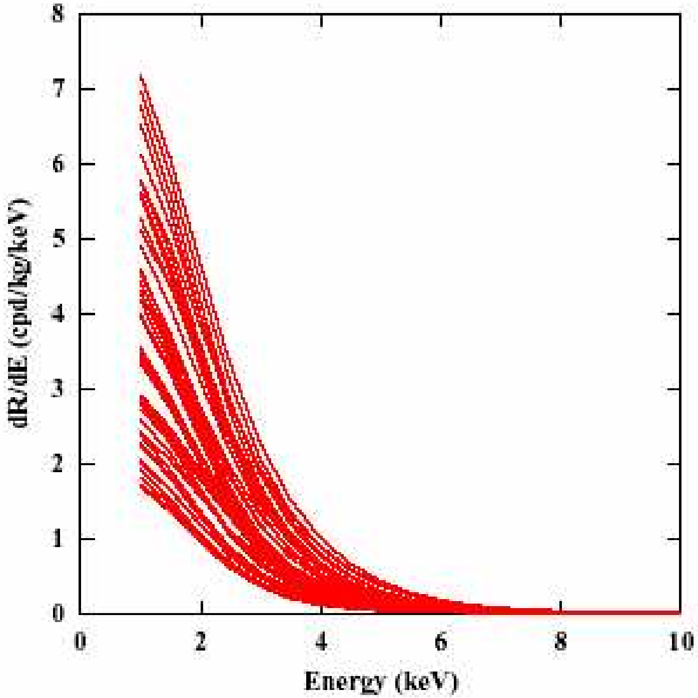
Compatibility between CDMS and low mass neutralinos

Uncertainty due to velocity distribution

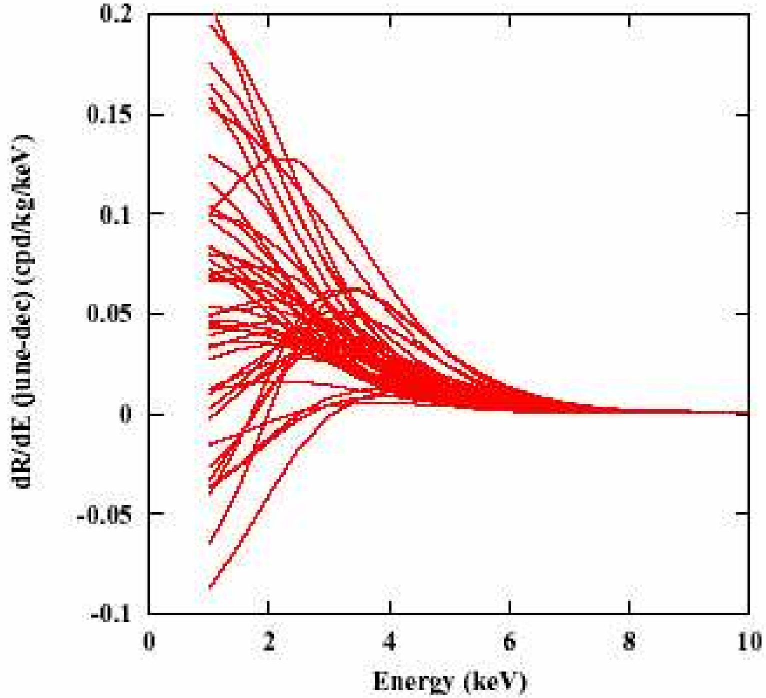
Sodium Iodide

m_{WIMP}=50 GeV
$\sigma_{\rm scalar}^{\rm nucleon}$=$10^{-8}$ nbarn
v_0= 220 km/sec

Each curve corresponds to a different halo model:



Time–independent component



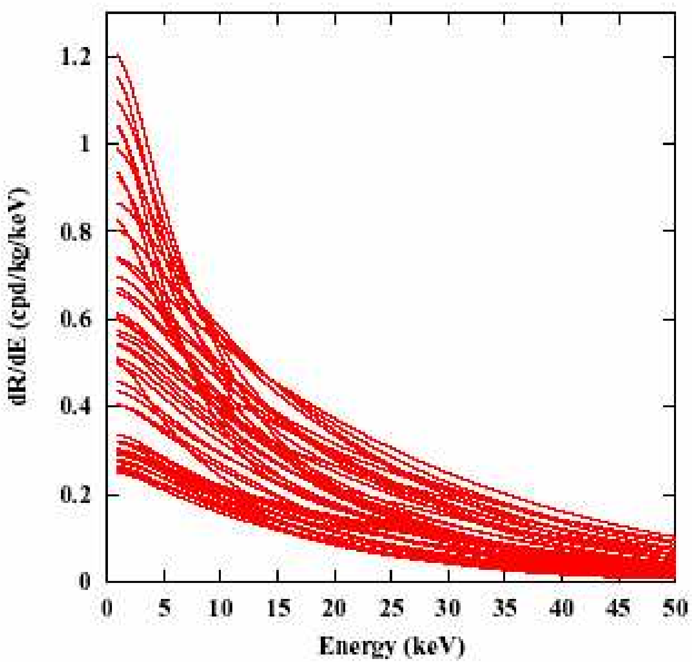
Modulation amplitude

Uncertainty due to velocity distribution

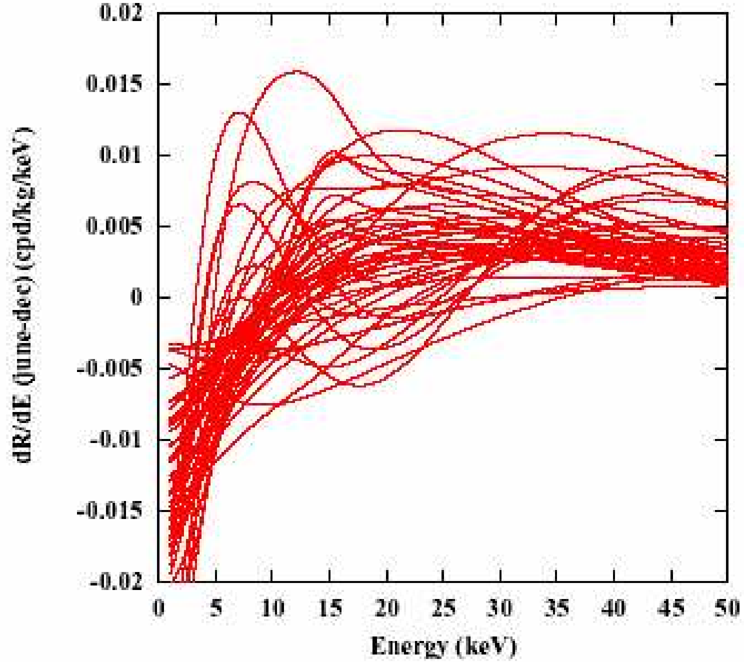
Germanium

m_{WIMP}=50 GeV
$\sigma^{\rm nucleon}_{\rm scalar}$=$10^{-8}$ nbarn
v_0= 220 km/sec

Each curve corresponds to a different halo model:



Time–independent component

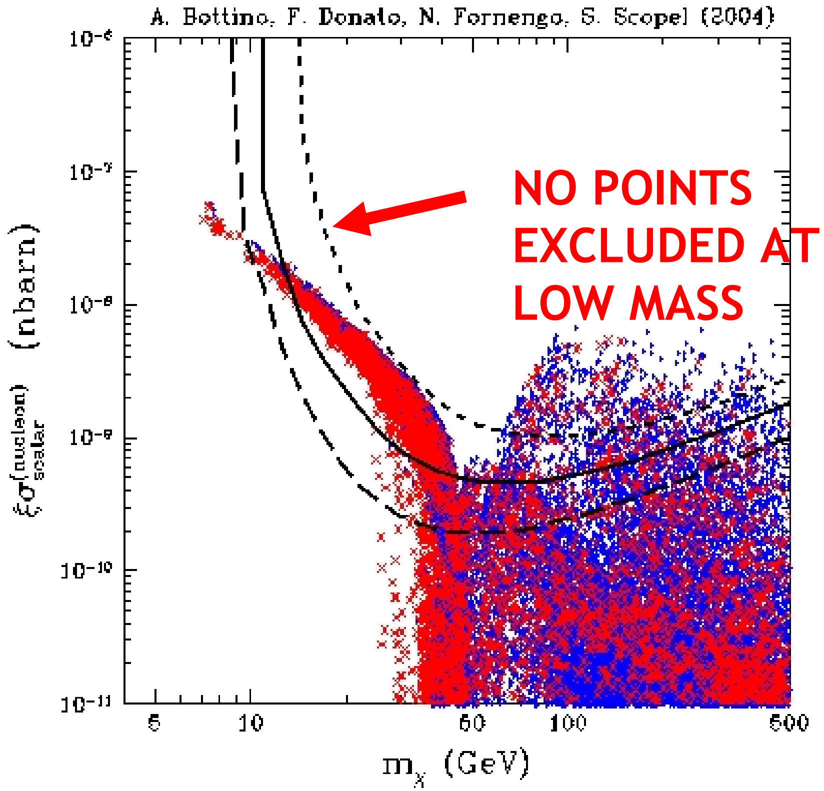


Modulation amplitude

Neutralino – nucleon cross section

Upper limit from CDMS using a different velocity distribution

assumptions:
NFW, anisotropic velocity dispersion
ρ_0=0.2 GeV/cm^3



——— v_0=220 km/sec

— — — v_0=270 km/sec

········· v_0=170 km/sec

Uncertainty due to velocity distribution

(P. Belli, R. Cerulli, N. Fornengo and S. Scopel, PRD66(2002)043503)

Class A: Spherical ρ_{DM}, isotropic velocity dispersion			
A0	Isothermal sphere		Eq.(20)
A1	Evans' logarithmic [15]	$R_c = 5$ kpc	Eq.(18)
A2	Evans' power–law [16]	$R_c = 16$ kpc, $\beta = 0.7$	Eq.(23)
A3	Evans' power–law [16]	$R_c = 2$ kpc, $\beta = -0.1$	Eq.(23)
A4	Jaffe [14]	Table I	Eq.(26)
A5	NFW [18]	Table I	Eq.(26)
A6	Moore at al. [19]	Table I	Eq.(26)
A7	Kravtsov et al. [20]	Table I	Eq.(26)
Class B: Spherical ρ_{DM}, non–isotropic velocity dispersion (Osipkov–Merrit, $\beta_0 = 0.4$)			
B1	Evans' logarithmic	$R_c = 5$ kpc	Eqs.(18,28)
B2	Evans' power–law	$R_c = 16$ kpc, $\beta = 0.7$	Eqs.(23,28)
B3	Evans' power–law	$R_c = 2$ kpc, $\beta = -0.1$	Eqs.(23,28)
B4	Jaffe	Table I	Eqs.(26,28)
B5	NFW	Table I	Eqs.(26,28)
B6	Moore at al.	Table I	Eqs.(26,28)
B7	Kravtsov et al.	Table I	Eqs.(26,28)
Class C: Axisymmetric ρ_{DM}			
C1	Evans' logarithmic	$R_c = 0$, $q = 1/\sqrt{2}$	Eqs.(33,34)
C2	Evans' logarithmic	$R_c = 5$ kpc, $q = 1/\sqrt{2}$	Eqs.(33,34)
C3	Evans' power–law	$R_c = 16$ kpc, $q = 0.95$, $\beta = 0.9$	Eqs.(37,38)
C4	Evans' power–law	$R_c = 2$ kpc, $q = 1/\sqrt{2}$, $\beta = -0.1$	Eqs.(37,38)
Class D: Triaxial ρ_{DM} [17] (q = 0.8, p = 0.9)			
D1	Earth on major axis, radial anisotropy	$\delta = -1.78$	Eqs.(43,44)
D2	Earth on major axis, tangential anis.	$\delta = 16$	Eqs.(43,44)
D3	Earth on intermediate axis, radial anis.	$\delta = -1.78$	Eqs.(43,44)
D4	Earth on intermediate axis, tangential anis.	$\delta = 16$	Eqs.(43,44)

model used in previous example

Uncertainty on ρ_0 due to velocity distribution

(P. Belli, R. Cerulli, N. Fornengo and S. Scopel, PRD66(2002)043503)

	$v_0 = 170$ km sec^{-1}		$v_0 = 220$ km sec^{-1}		$v_0 = 270$ km sec^{-1}	
Model	ρ_0^{min}	ρ_0^{max}	ρ_0^{min}	ρ_0^{max}	ρ_0^{min}	ρ_0^{max}
A0	0.18	0.28	0.30	0.47	0.45	0.71
A1 , B1	0.20	0.42	0.34	0.71	0.62	1.07
A2 , B2	0.24	0.53	0.41	0.89	0.97	1.33
A3 , B3	0.17	0.35	0.29	0.59	0.52	0.88
A4 , B4	0.26	0.27	0.44	0.45	0.66	0.67
A5 , B5	0.20	0.44	0.33	0.74	0.66	1.11
A6 , B6	0.22	0.39	0.37	0.65	0.57	0.98
A7 , B7	0.32	0.54	0.54	0.91	0.82	1.37
C1	0.36	0.56	0.60	0.94	0.91	1.42
C2	0.34	0.67	0.56	1.11	0.98	1.68
C3	0.30	0.66	0.50	1.10	0.97	1.66
C4	0.32	0.65	0.54	1.09	0.96	1.64
D1 , D2	0.32	0.50	0.54	0.84	0.81	1.27
D3 , D4	0.19	0.30	0.32	0.51	0.49	0.76

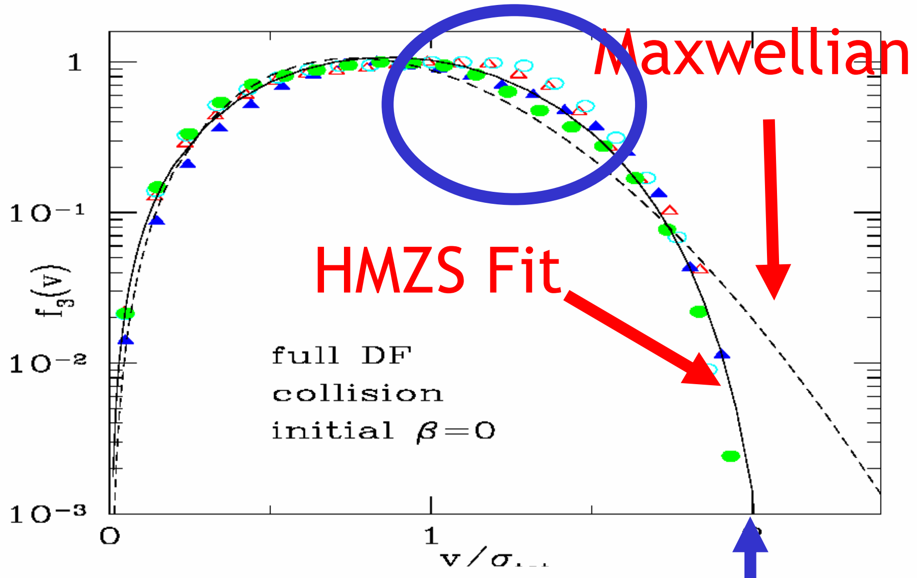
model used in previous example

$(0.17 \lesssim \rho_0 \lesssim 1.68)$

(v_0 $\equiv$ galactic rotational velocity at the Earth's position)

A universal distribution function for relaxed collisionless structures? (S. H. Hansen, B. Moore, M. Zemp and J. Stadel, astro-ph/0505420)

- A recent analysis (HMZS) has extracted the velocity distribution function (DF) from a large range of numerical simulations, where the initial configurations include isotropic and highly non-isotropic structures, as well as cosmological CDM structures.
- All structures have in common that they have been perturbed violently (head-on mergers) and subsequently allowed to relax, and range from almost spherical to highly triaxial.
- The authors find that the DF has a universal shape, which depends only on one free parameter, the total velocity dispersion σ_{tot}.



$$f(v) = v^{2q} \cdot \left(1 - (1-q) \cdot \left(\frac{v}{\kappa_3\, \sigma_{\mathrm{tot}}}\right)^2\right)^{\frac{q}{1-q}}$$

$q=0.8$, $k_3=0.95$

- cut-off at high velocity

$$\frac{v}{\sigma_{tot}} \leq \frac{k_3}{\sqrt{1-q}} \approx 2.12$$

- "flat topped" shape

Distortion of the signal time dependence

N. Fornengo, S. Scopel, PLB 576 (2003) 189

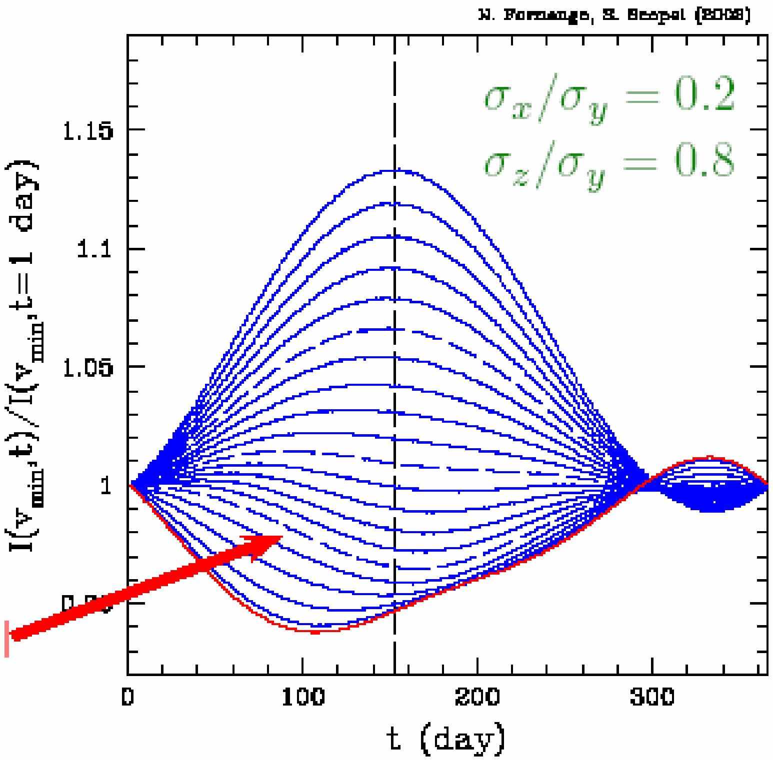
Triaxial system described by a multivariate gaussian:
(Galaxy rest frame)

$$f(\vec{v}) = N \exp\left(-\frac{v_x^2}{2\sigma_x^2} - \frac{v_y^2}{2\sigma_y^2} - \frac{v_z^2}{2\sigma_z^2}\right)$$

Rate=F($v_{\rm min}$)

$v_{\rm min} \equiv$ minimal WIMP incoming velocity at fixed recoil energy
(Earth rest frame)

Each curve corresponds to a different value of $v_{\rm min}$:



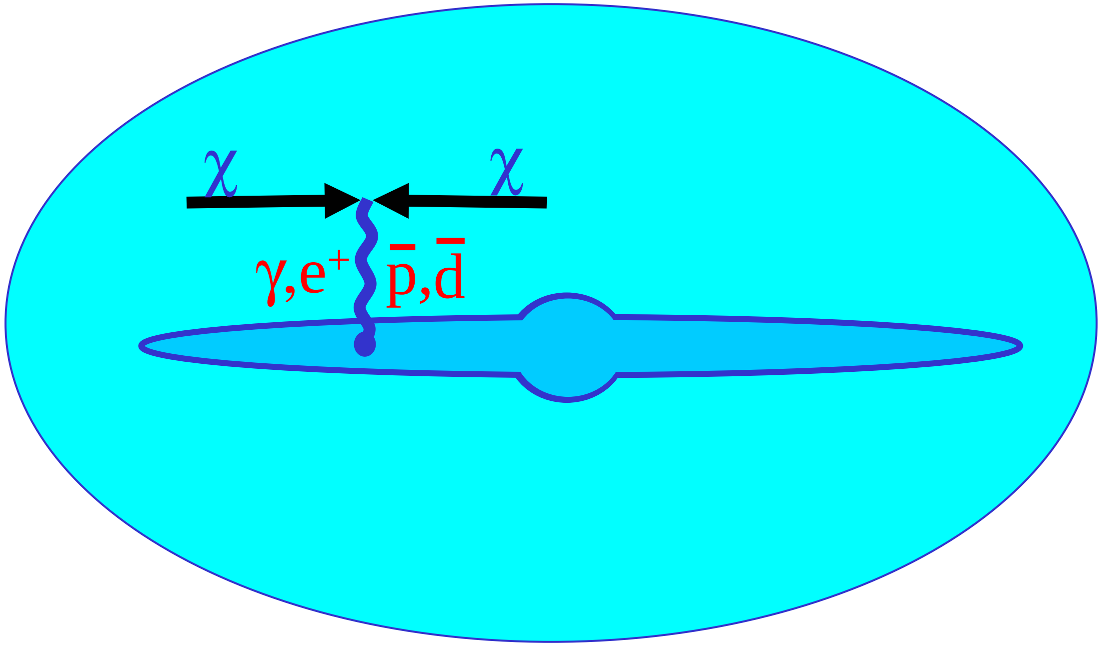
Departure from sinusoidal behavior at low $v_{\rm min}$
($\rightarrow$ low recoil energies)

- To set a solid constraint on theoretical predictions it is necessary to derive from the experimental data the upper bounds on $\xi\sigma_{scalar}^{(nucleon)}$ for a large variety of DFs and of the corresponding astrophysical parameters (with their own uncertainties)

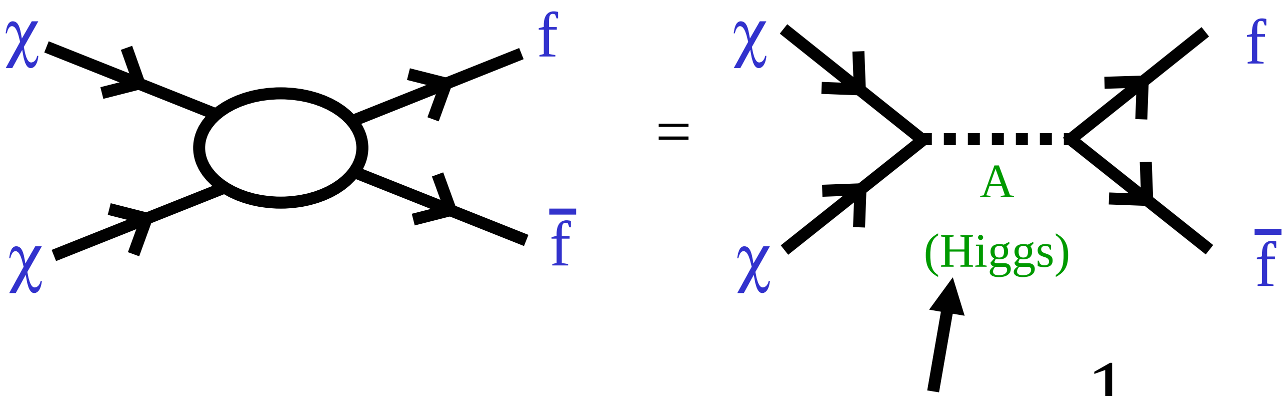
- Only the intersection of these bounds would provide an absolute limit to be used to possibly exclude a subset of supersymmetric population.

☛ A combined investigation of all experiments along these lines is not available at the moment.

WIMP indirect detection: annihilations in the halo



example:



$$\sigma_{ann} \propto \frac{1}{m_{\mathrm{A}}^{4}}$$

Neutralino self annihilations and dark matter density distribution

Signals depend quadratically on the dark matter density *ρ*.

Common parametrization:

$$\rho(r) = \rho_l \left(\frac{R_\odot}{r}\right)^\gamma \left[\frac{1+(R_\odot/a)^\alpha}{1+(r/a)^\alpha}\right]^{(\beta-\gamma)/\alpha}$$

ρ_l =dark matter local density

$r = |\vec{r}|$, $R_\odot = 8$ kpc

a=scale length

$(\alpha,\beta,\gamma)=(2,2,0)$ Isothermal

$(\alpha,\beta,\gamma)=(1,3,1)$ NFW, $\propto r^{-1}$ in GC ← our reference model

$(\alpha,\beta,\gamma)=(1.5,3,1.5)$ Moore *et al.*, $\propto r^{-1.5}$ in GC

Numerical simulation suggest the non-singular form:(J. F. Navarro et al., Mon.Not.Roy.Astron.Soc.349,1039(2004))

$$\rho(r) = \rho_{-2} \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_{-2}}\right)^\alpha - 1\right]\right\}$$

$d(\ln(\rho))/d(\ln(r))\big|_{r=r_{-2}} = -2$

$\rho_{-2} \equiv \rho(r_{-2})$

$\alpha \approx 0.17$

Large differences in the behaviour towards GC

N.B. Anyway, current simulations not reliable for radii smaller than 0.1 – 1 kpc

Gamma rays from neutralino pair annihilations

$$\Phi_\gamma(E_\gamma,\psi) = \frac{1}{4\pi}\frac{\langle\sigma_{\rm ann}v\rangle}{m_\chi^2}\frac{dN_\gamma}{dE_\gamma}\frac{1}{2}I(\psi)$$

particle physics and astrophysics are factorized

$\langle\sigma_{ann}v\rangle\equiv$annihilation cross section time relative velocity mediated over the galactic velocity distribution

Integration along the line of sight:

$$I(\psi) = \int_{\rm l.o.s} \rho^2(r(\lambda,\psi))\, d\lambda(\psi)$$

, ψ=angle between l.o.s and G.C

$$I_{\Delta\psi} \equiv \frac{1}{\Delta\psi}\int_{\Delta\psi} I(\psi)\, d\psi$$

$\Delta\psi$ ≡ telescope aperture

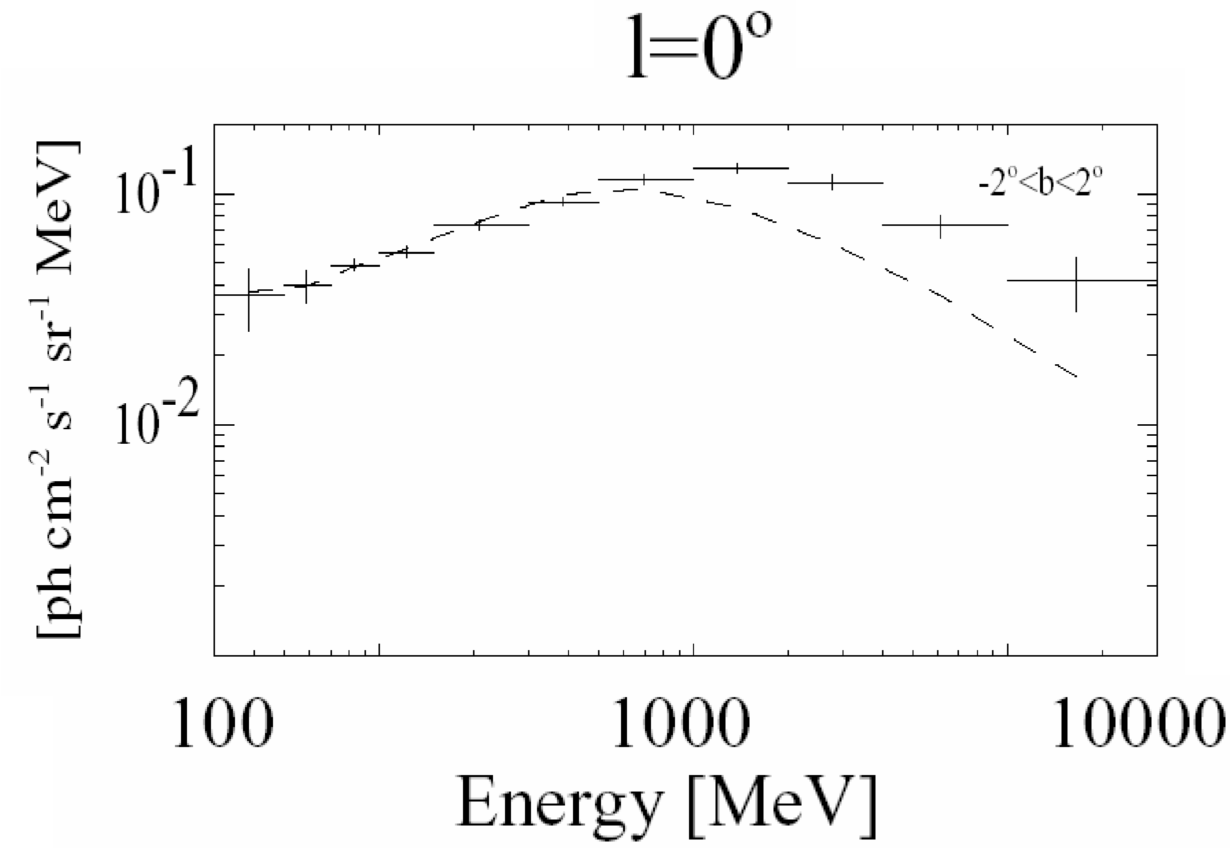
$|\Delta l| \leq 5^\circ,\ |\Delta b| \leq 2^\circ$

Isothermal	Isothermal	NFW	Moore et al.	r–dependent log–slope Eq.(2)
$a = 3.5$ kpc	$a = 2.5$ kpc	$a = 25$ kpc $r_c = 0.01$ pc	$a = 30$ kpc $r_c = 0.01$ pc	$\alpha = 0.142$ $r_{-2} = 26.4$ kpc $\rho_{-2} = 0.035$ GeV cm^{-3}
18.5	42.5	184.2	10866	600

Toward GC
strong dependence on profile, less relevant in other directions

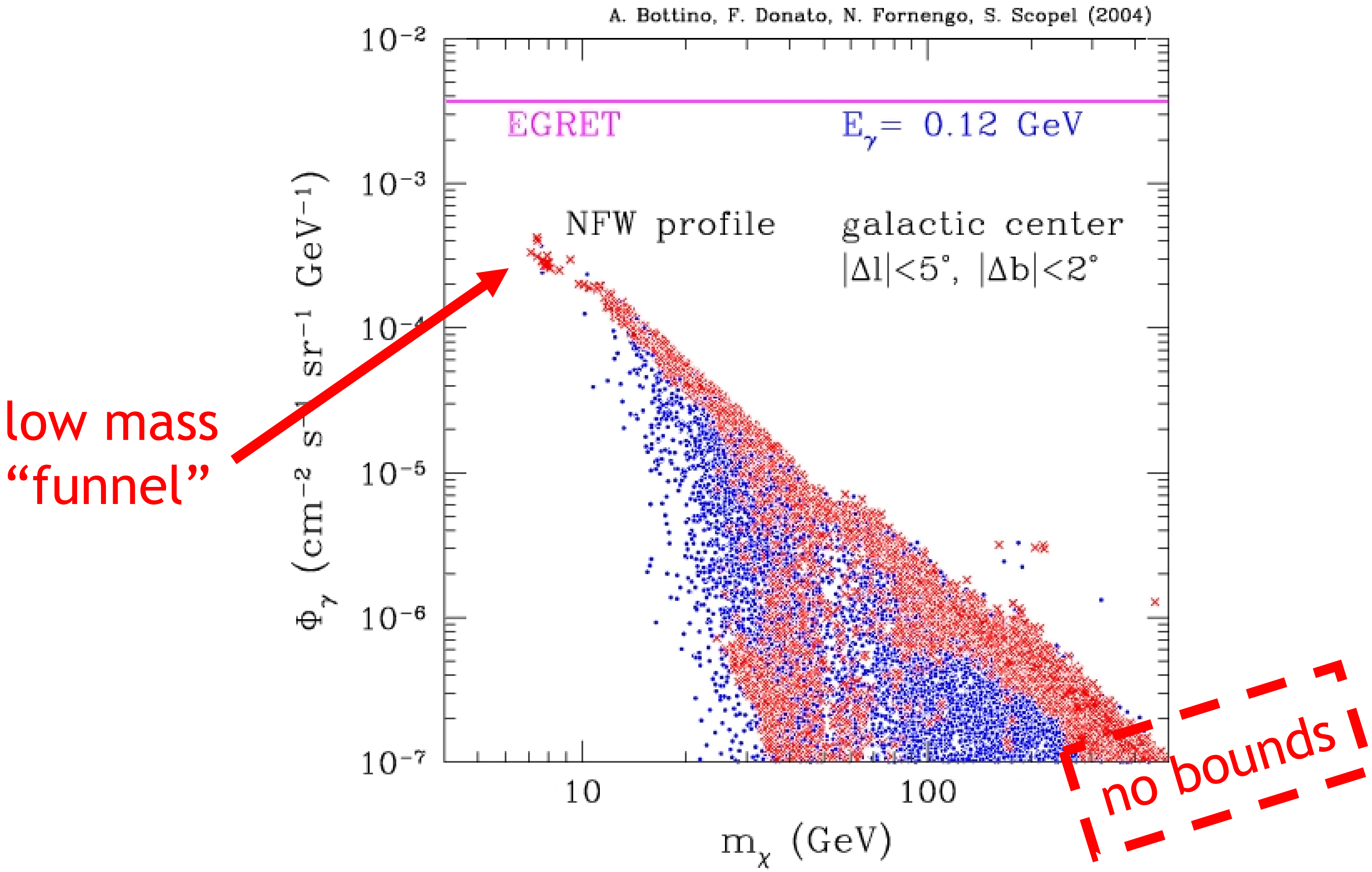
EGRET excess toward GC?

S. D. Hunter *et al.*, Astrophys. J. **481,** 205 (1997)

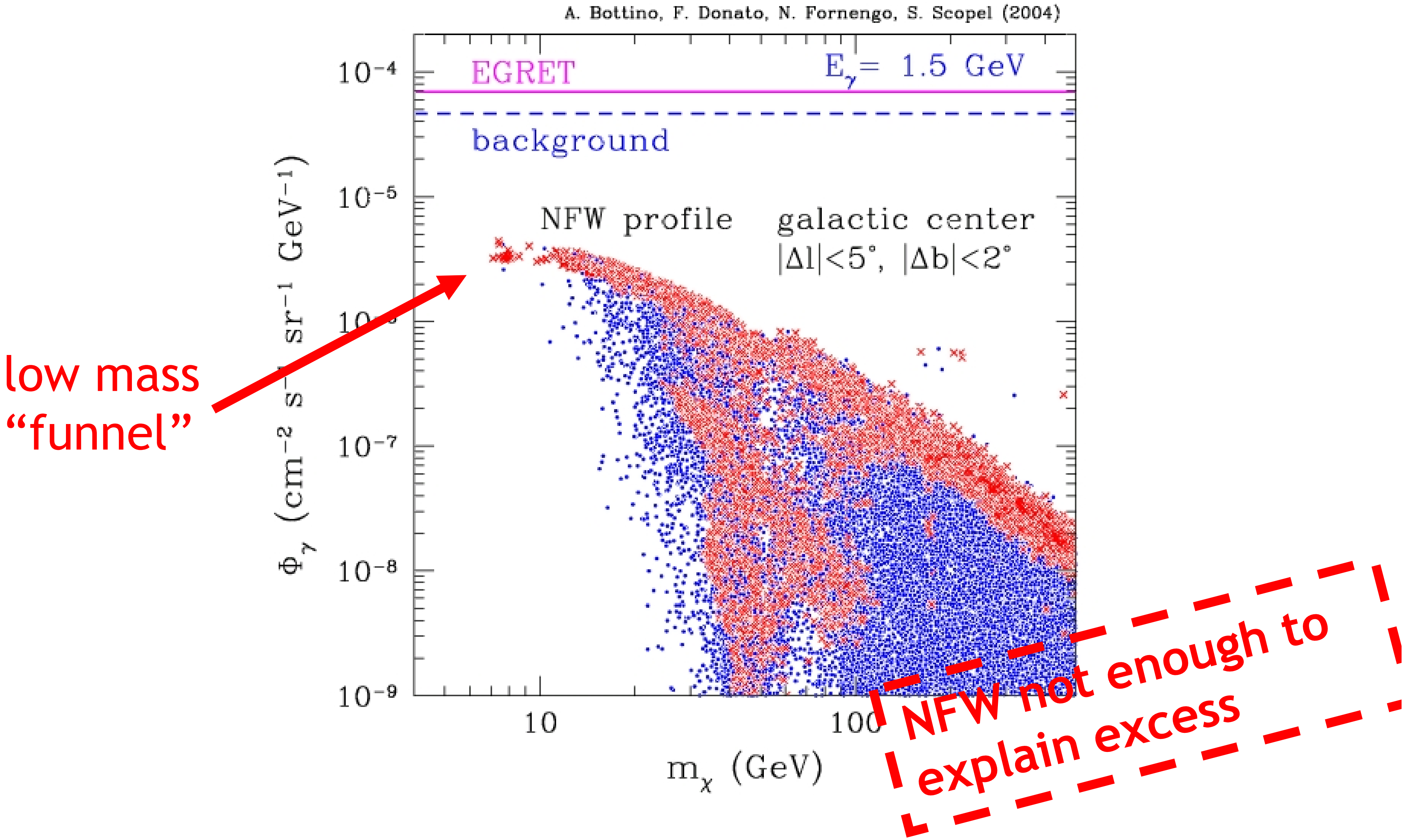


– – – estimated background, D.L.Bertsch et al., Astrophys. J. **416,** 587 (1993)

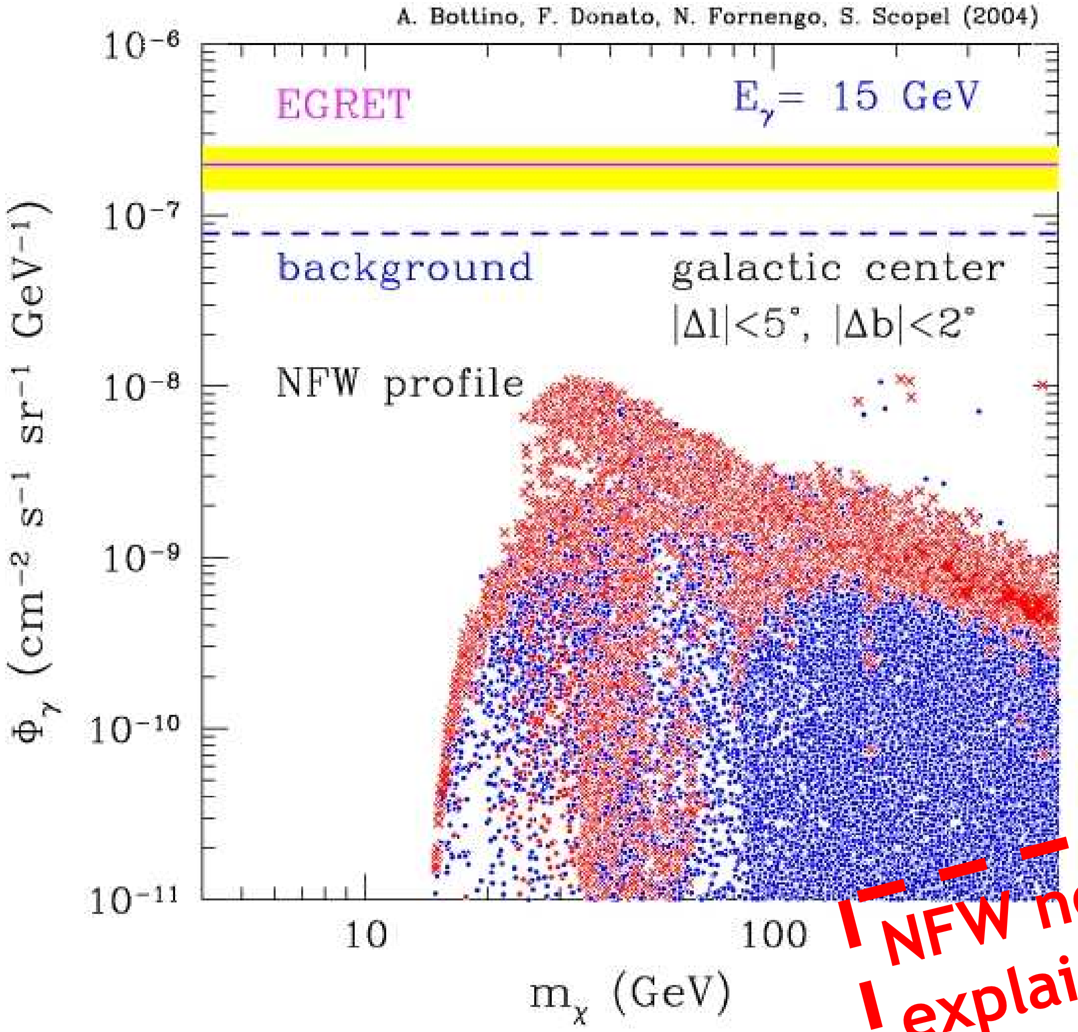
Gamma flux due to neutralino annihilation from Galactic Center



Gamma flux due to neutralino annihilation from Galactic Center



Gamma flux due to neutralino annihilation from Galactic Center

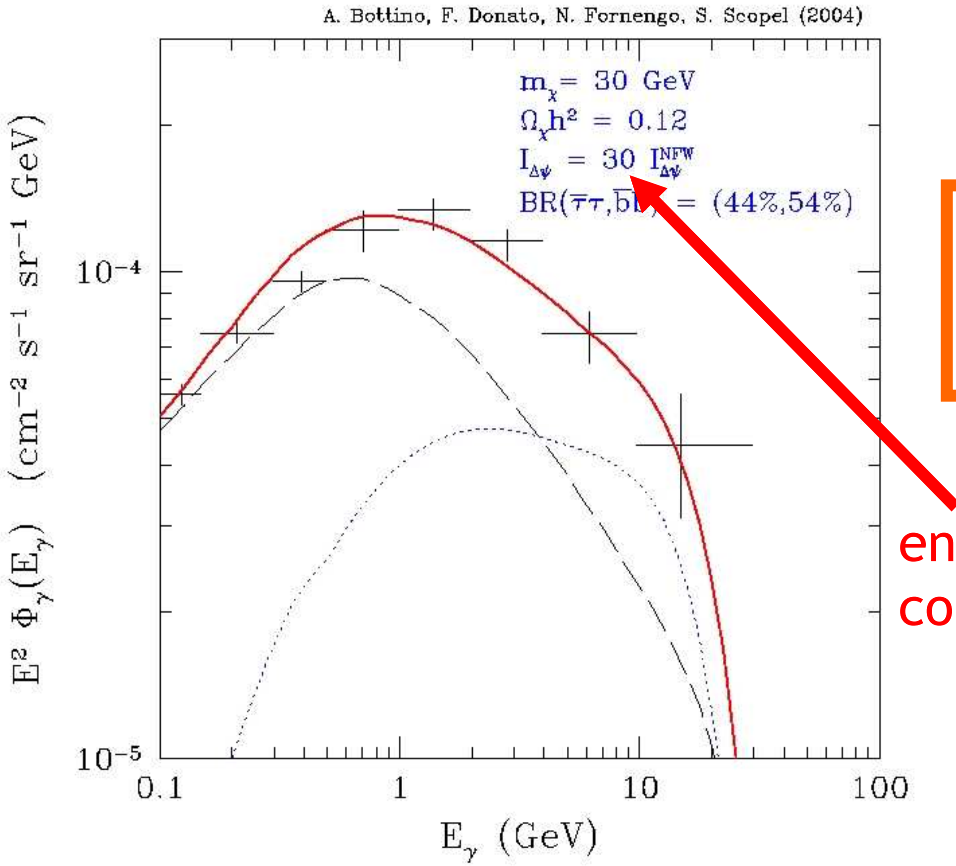


NFW not enough to explain excess

It has already been shown that neutralinos with $m_\chi > 50$ GeV could explain the EGRET excess (A. Cesarini, F. Fucito, A. Lionetto, A. Morselli and P. Ullio, astro-ph/0305075)

Could the EGRET excess be explained also by light neutralinos?

YES



m_χ=30 GeV

.... Neutralino contribution

- - - - Background rescaled by 10%

——— Signal+background

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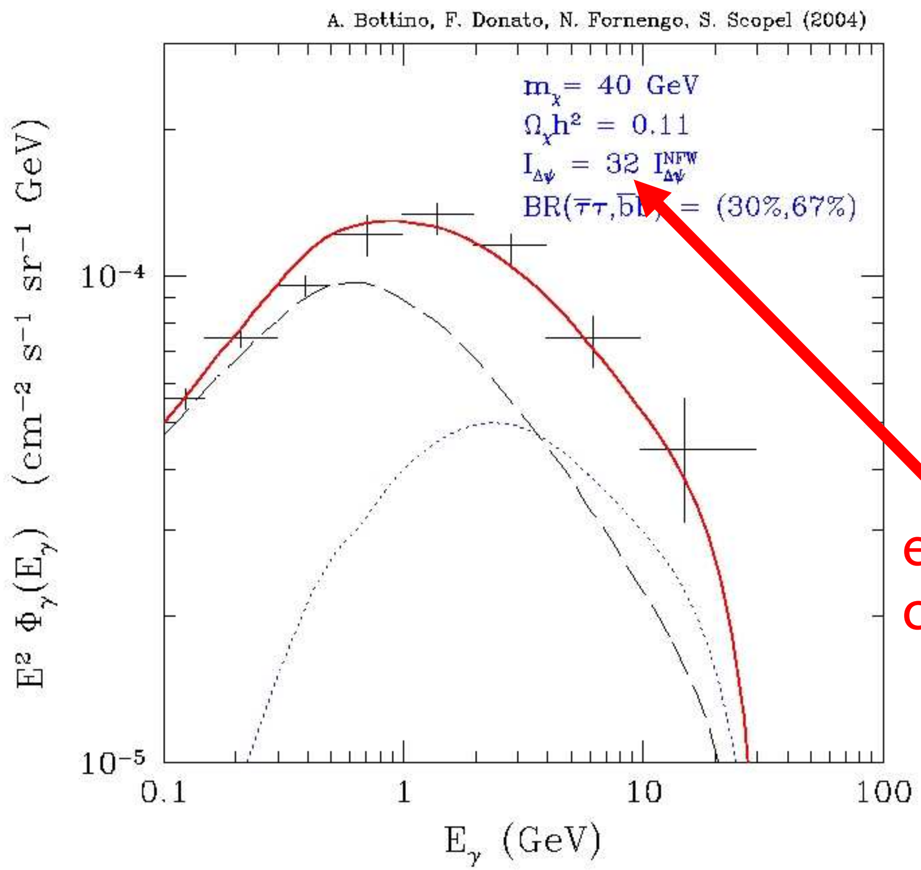


$m_\chi = 40$ GeV

enhancement required compared to NFW

.... Neutralino contribution

- - - - Background rescaled by 10%

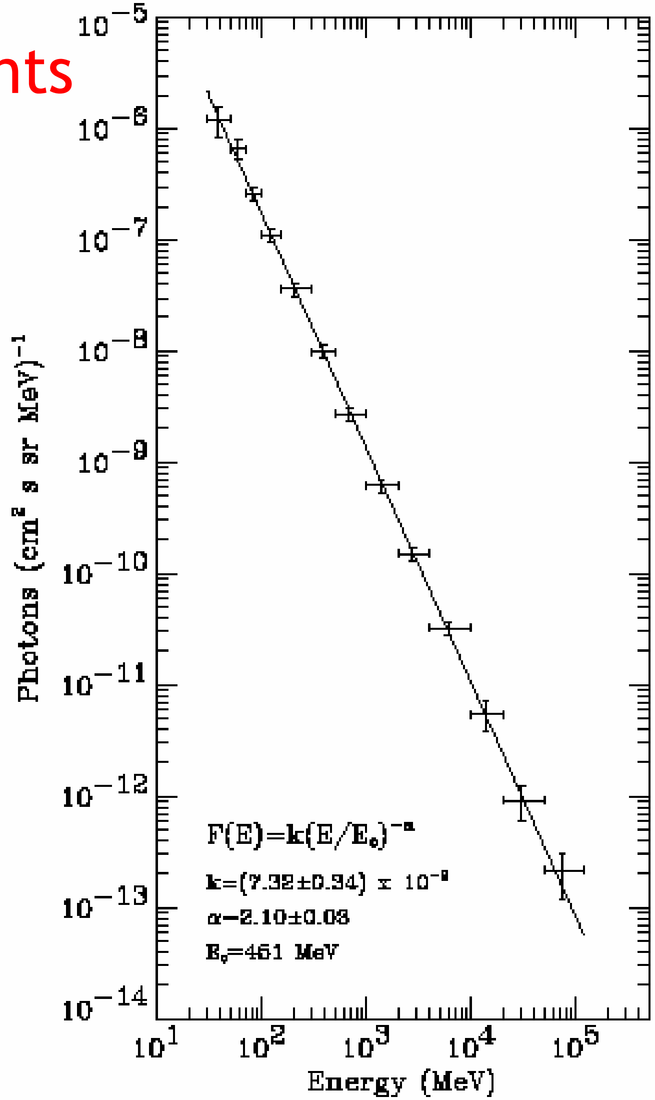
——— Signal+background

EGRET residual flux at high latitudes

after subtraction of known components

(identified sources, spectrum due to cosmic rays interaction with the galactic disk)

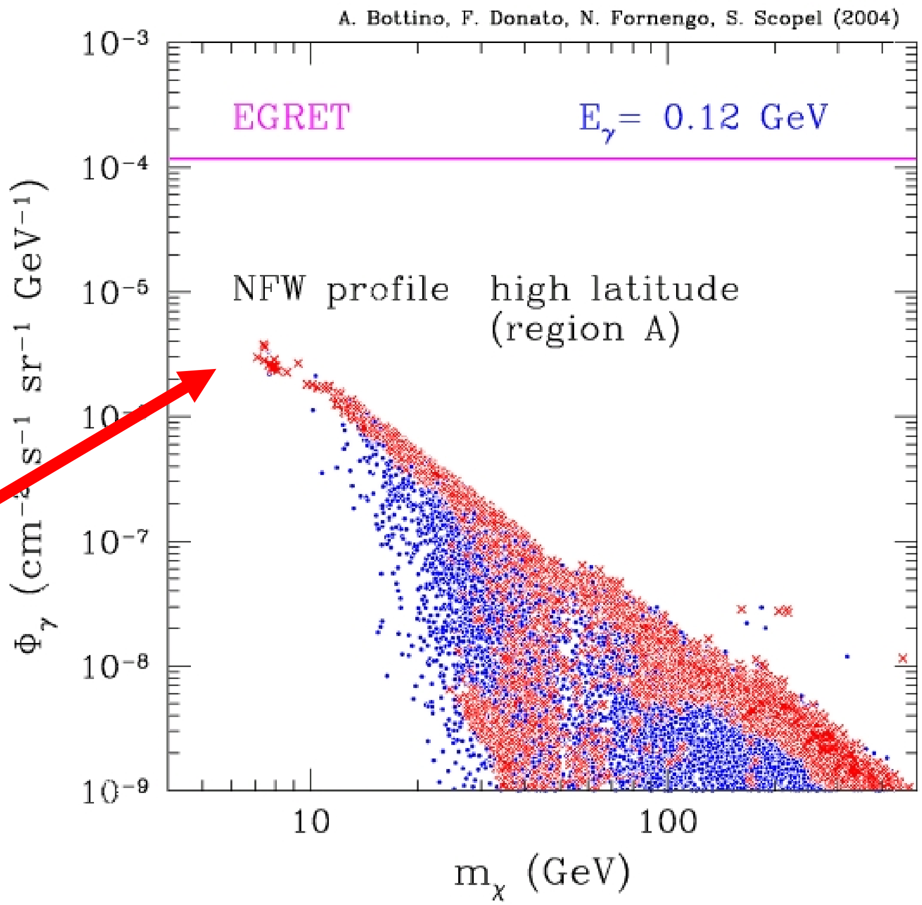
P. Sreekumar *et al.*, Astrophys. J. **494**, 523 (1998)



extragalactic origin?

…or exotic production?

Gamma flux due to neutralino annihilation from high latitudes

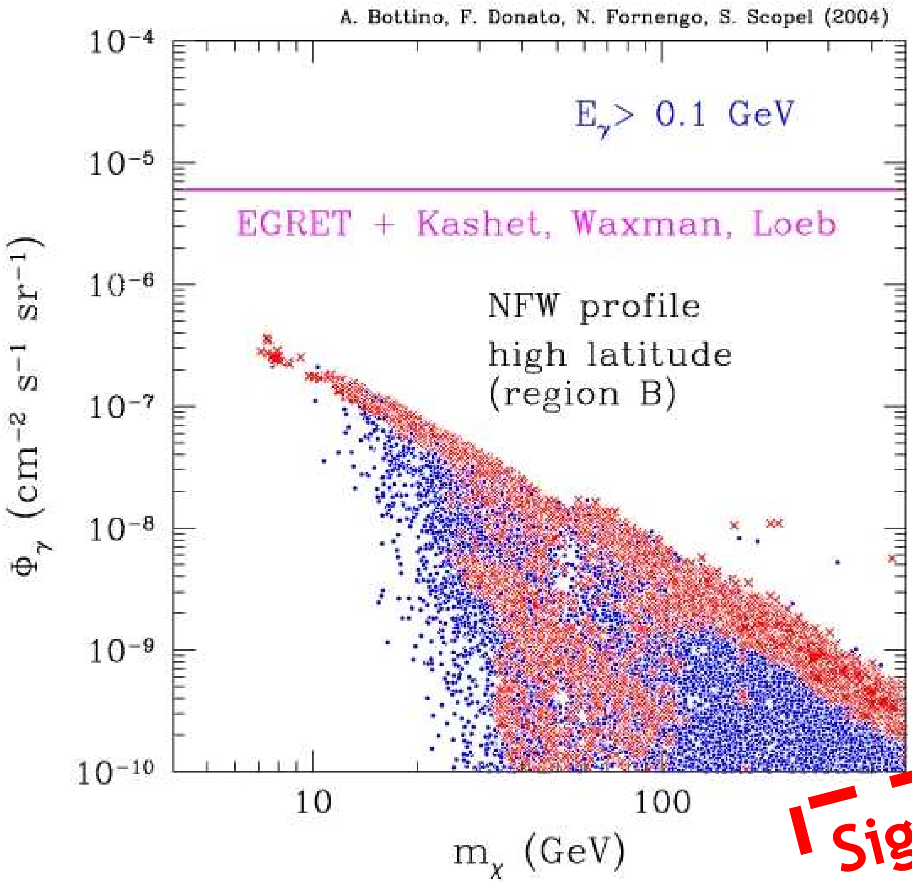


Region A:
$|b|>10^0$, $|l|>40^0$
$10^0<|b|<30^0$

low mass "funnel"

EGRET residual flux,
P. Sreekumar *et al.*, Astrophys. J. **494**, 523 (1998)

Gamma flux due to neutralino annihilation from high latitudes



Region B:
$|b|>86^0$

Signal well below data

Re-analysis of EGRET data,
U. Keshet, E. Waxman, A. Loeb, astro-ph/0306442

Gamma flux due to neutralino annihilation from high latitudes

- γ signals from high altitudes turn out to be one order of magnitude below present sensitivities.
- Contrary to GC, in this case $I_{\Delta\psi}$ is practically independent on the halo profile.

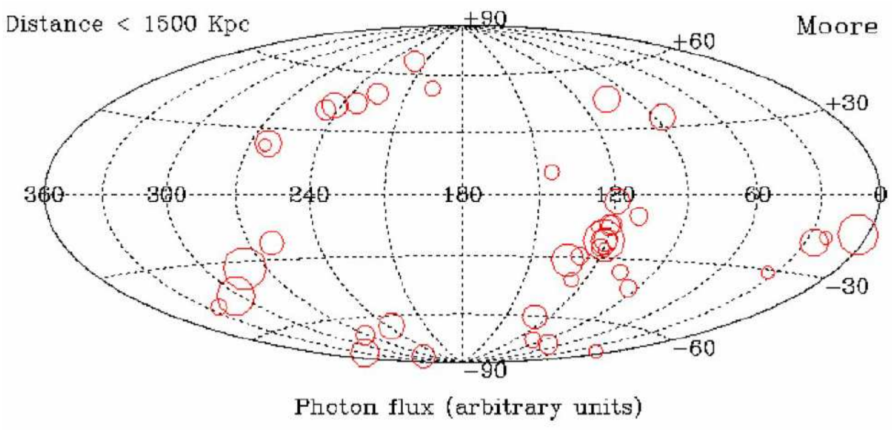
Clumpiness?

Effect discussed by several authors, sometimes with signal improvements at the level of a few orders of magnitude.

However, recent analytical investigation on the production of small-scale dark matter clumps suggest that the clumpiness effect would not be large. Enhancement effect on the annihilation signals limited to a factor of a few. Similar conclusions also reached with high-resolution numerical simulations. (V. Berezinsky, et al., Phys. Rev. D68, 103003 (2003); F. Stoher et al., Mon. Not. Roy. Astron. Soc. **345**, 1313 (2003)).

External galaxies

(N. Fornengo, L. Pieri and S.Scopel, PRD70, 103529 (2004))

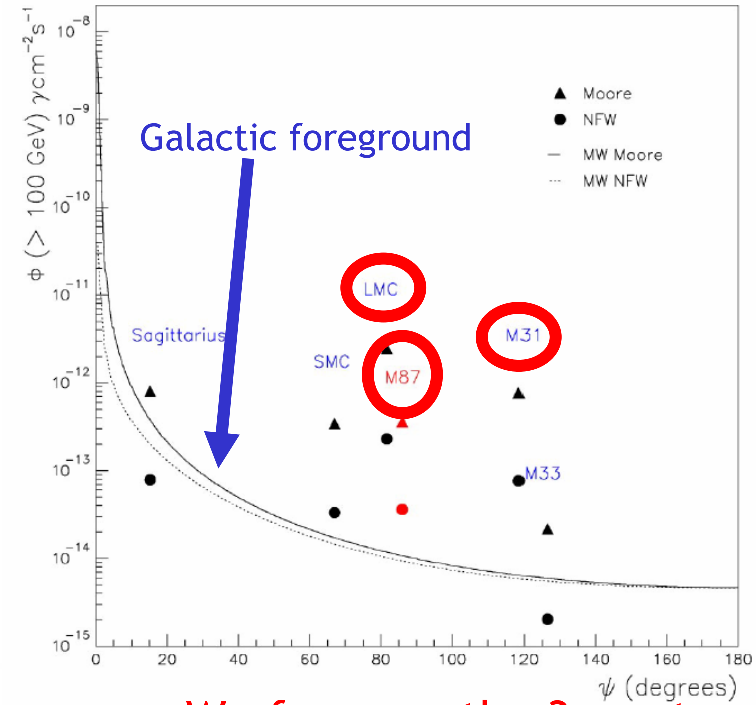


44 LG nearest galaxies in Galactic coordinates. The size of each symbol is scaled to the γ-ray flux emitted by a host DM halo with a Moore profile within a viewing angle of 1° from the halo center.

Masses, distances and virial radii for the Milky Way, the LMC and M31.

Galaxy	mass ($M_\odot$)	distance (kpc)	$r_{\rm vir}$ (kpc)
MW	1.0×10^{12}	8.5	205
LMC	1.4×10^{10}	49	49
M31	2.0×10^{12}	770	258

Flux vs. angle from GC



We focus on the 3 most prominent galaxies at large angles form the GC, LMC (Large Magellanic Cloud) M31(Andromeda) and M87 (Virgo A)

Modeling Dark Matter Halos

- NFW97, Navarro, Frenk, White, Astrophys.J.490,493 (1997)
- M99, Moore, Ghigna, Governato, Lake, Quinn, Stadel, Tozzi, Astrophys.J.524,L19,(1999)
- M04, Diemand, Moore, Stadel, Mon.Not.Roy.Astron.Soc. 353 (2004) 624

Modeling Dark Matter Halos

Scale radii and scale densities for the NFW97, M99, M04, and isocore density profiles calculated for M31.

Profile	scale radius r_s (kpc)	scale density ρ_s ($M_\odot \mathrm{kpc}^{-3}$)
NFW97	30.271	4.20×10^6
M99	47.298	0.86×10^6
M04	44.697	1.55×10^6
isocore	4	7.898×10^6

$$\rho_\chi^{\mathrm{NFW97}} = \frac{\rho_s^{\mathrm{NFW97}}}{(r/r_s^{\mathrm{NFW97}})(1 + r/r_s^{\mathrm{NFW97}})^2}$$

$$\rho_\chi^{\mathrm{M99}} = \frac{\rho_s^{\mathrm{M99}}}{(r/r_s^{\mathrm{M99}})^{1.5}[1 + (r/r_s^{\mathrm{M99}})^{1.5}]}$$

$$\rho_\chi^{\mathrm{iso-core}} = \frac{\rho_s^{\mathrm{iso-core}}}{[1 + (r/r_s^{\mathrm{iso-core}})^2]}$$

$$\rho_\chi^{\mathrm{M04}} = \frac{\rho_s^{\mathrm{M04}}}{(r/r_s^{\mathrm{M04}})^{1.16}(1 + r/r_s^{\mathrm{M04}})^{1.84}}$$

Effect of baryons on the inner parts of galaxies

The effect of baryon is still not well known: it may either enhance or disrupt the central cusp:

- adiab-NFW profile includes adiabatic growth of a central black hole which pulls in DM and enhances an initial NFW profile (Ullio, Zhao, Kamionkowski, PRD64, 043504 (2001))
- but formation of a SBH binary (by merging of halos) leads to a depletion of the central spike (Merrit at al., PRL88, 191301 (2002))

Effect of the inner core

- minimal radius r_{cut} within which the self annihilation rate is equal to the dynamical time (Berezinski et al., PLB294(1992)221):

$$r_{cut} \approx \begin{cases} 10^{-9} \div 10^{-8} \text{ kpc (M99 profile)} \\ 10^{-14} \div 10^{-13} \text{ kpc (NFW97 profile)} \end{cases}$$

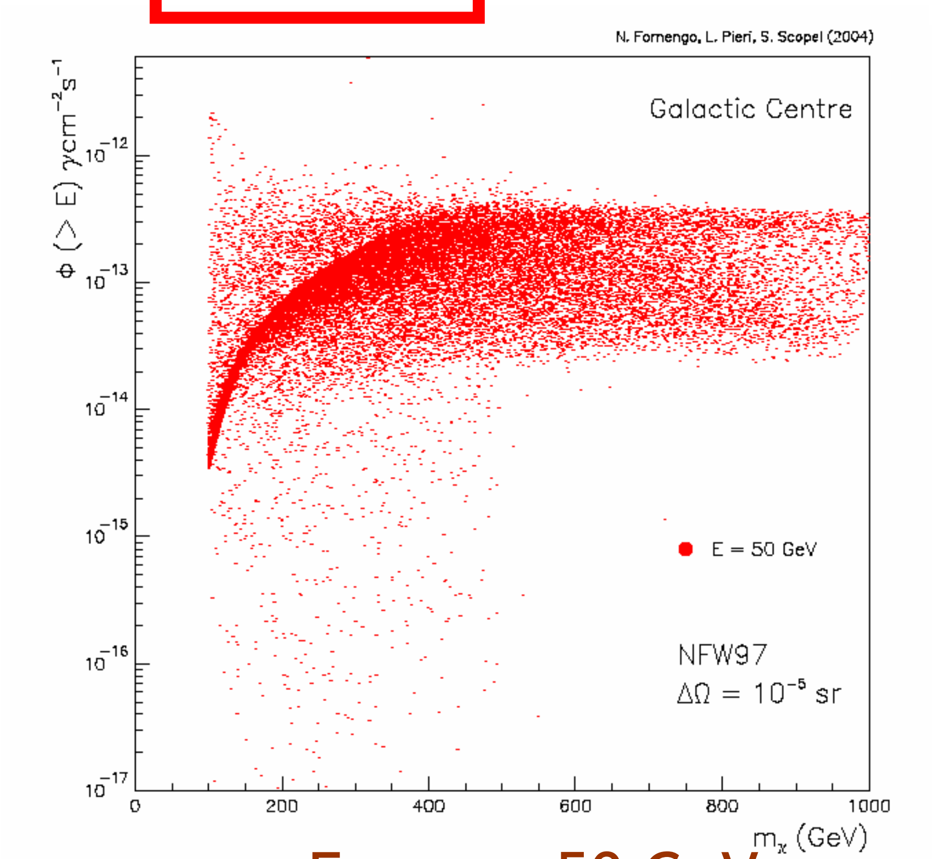
- effect of baryons: presence of BH erases DM within 3×10^{-9} kpc (MW) and 3×10^{-7} kpc (M87)

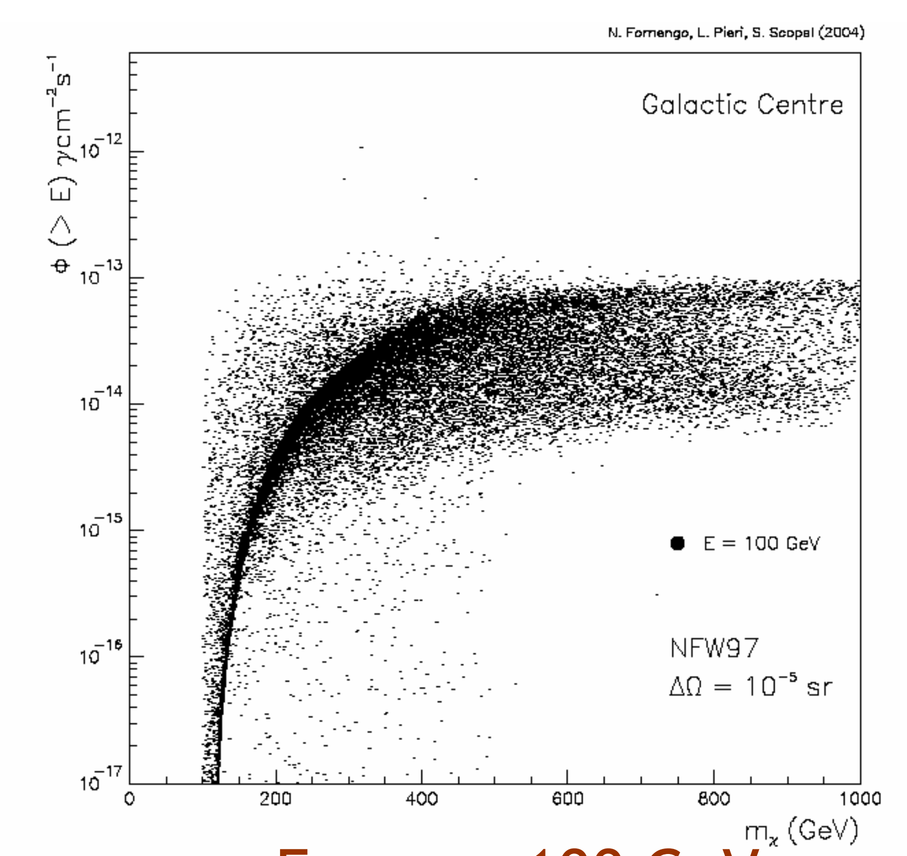
- including other effects, like tidal interactions, the central core of galaxies can reach 0.1 – 1 kpc

numerical simulations reliable down to ≈ 0.1 kpc

Integrated gamma-ray flux (galactic center, NFW97 profile)

$\Delta\Omega = 10^{-5}$ sr



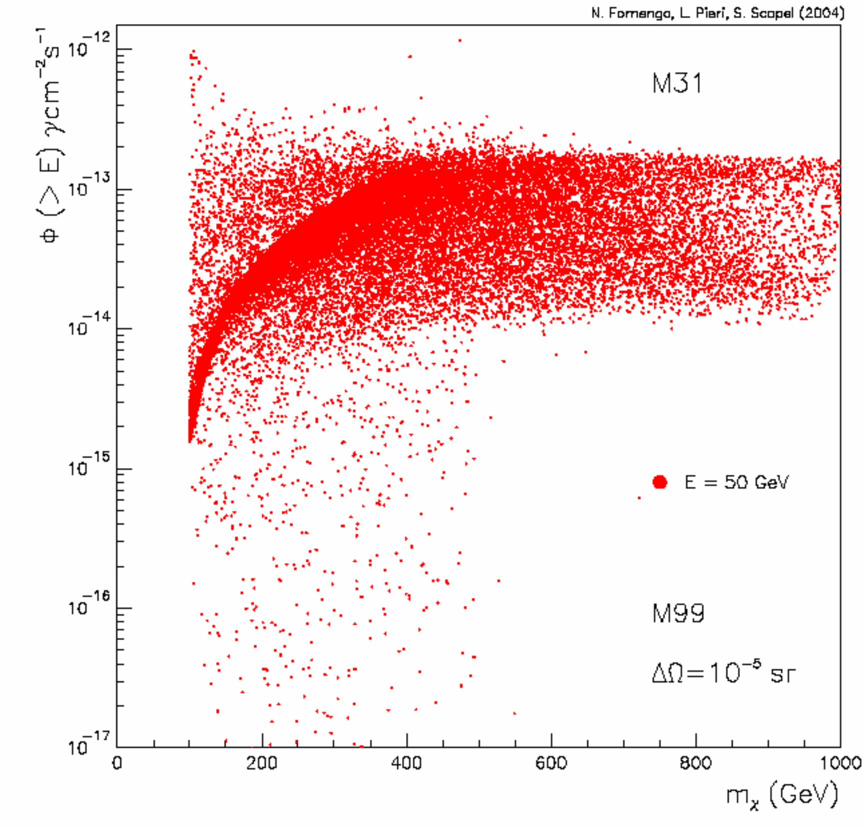


$E_{threshold}$=50 GeV $E_{threshold}$=100 GeV

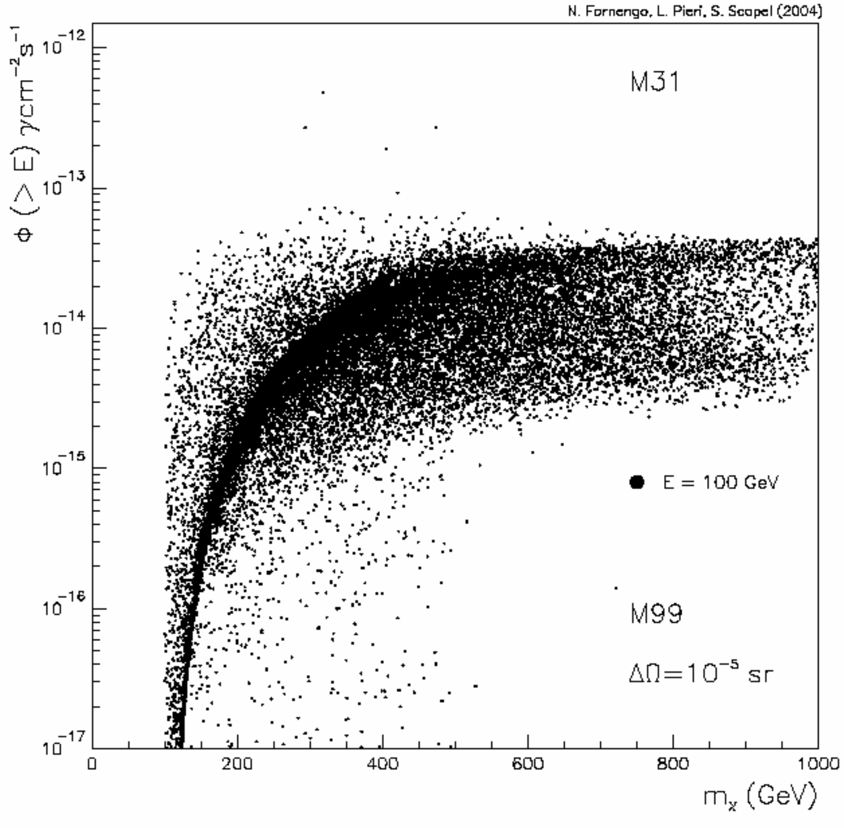
- NFW97 → M99 : fluxes encreased by a factor ≈ 160
- $E_{threshold}$ 50 → 100 GeV: fluxes decrease 1 order of magnitude

Integrated gamma-ray flux (M31, M99 profile)

$\Delta\Omega = 10^{-5}$ sr



$E_{threshold}$=50 GeV

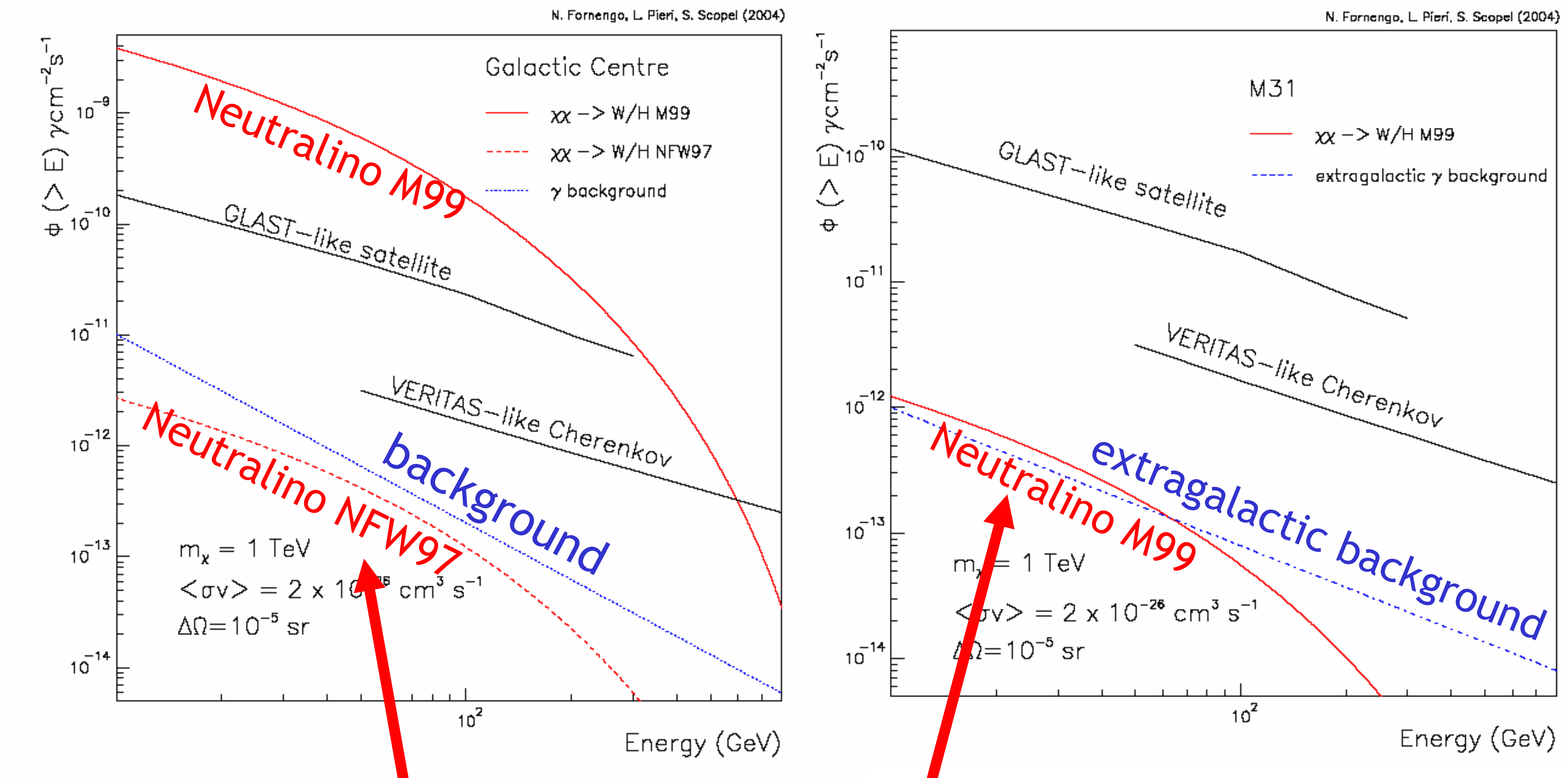


$E_{threshold}$=100 GeV

same flux level as GC with NFW97, but using M99 profile

5 σ sensitivity curves for satellite and Čerenkov detectors

Galactic center | Andromeda(M31)



Theoretical curves: BR(W bosons)=BR(Higgs)=50%

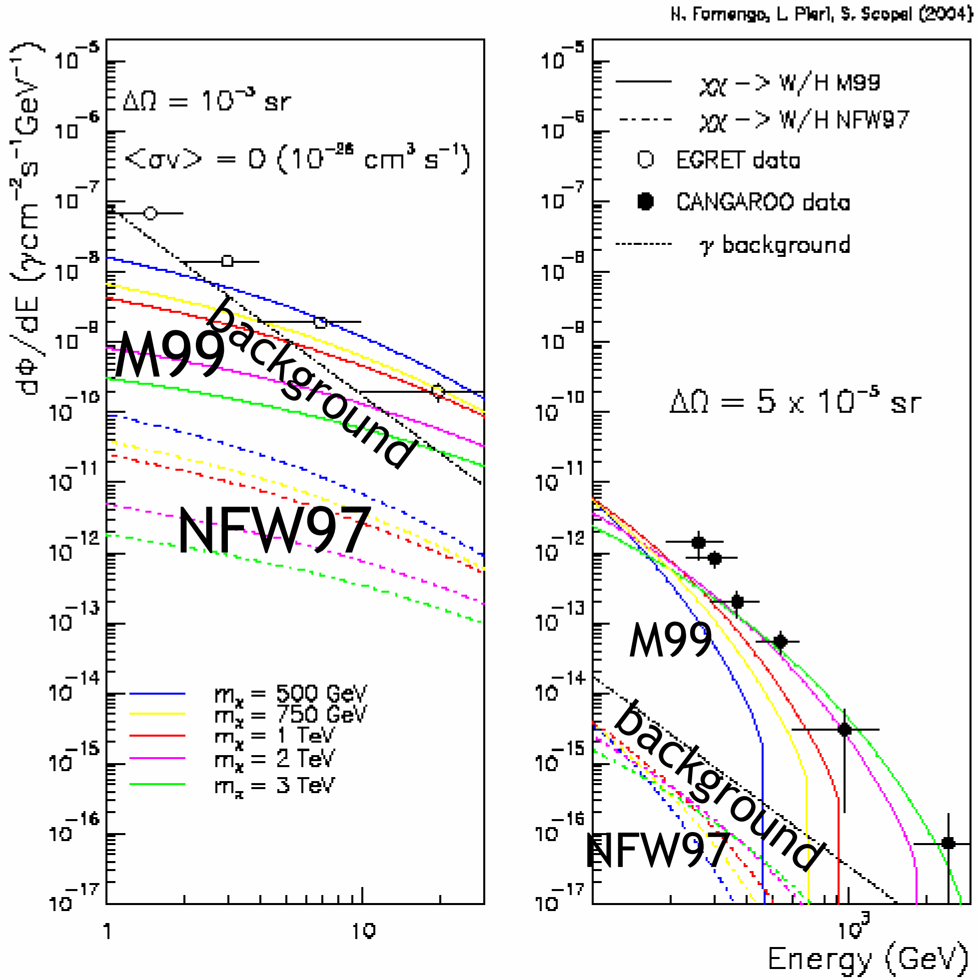
- signals from GC accessible to GLAST and VERITAS only if profile harder than NFW97
- highest possible signal from M31 well below experimental sensitivity and merely at the level of background

Comparison with data (galactic center)

- excess both from EGRET (1 GeV <E<20 GeV) and for CANGAROO (E>200 GeV)

coud both excesses be explained at the same time by neutralino?

M99+NFW97



EGRET CANGAROO

Comparison with data (galactic center)

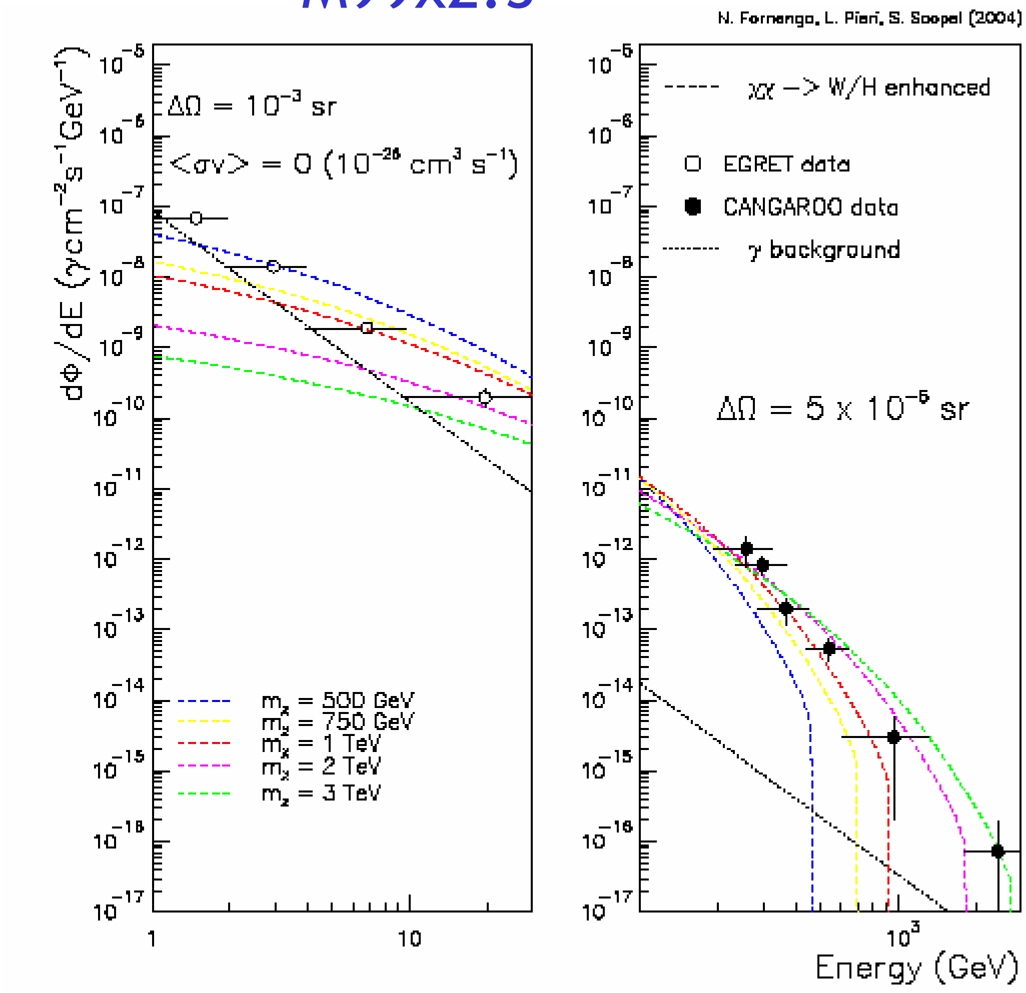
- excess both from EGRET (1 GeV <E<20 GeV) and for CANGAROO (E>200 GeV)

M99x2.5

coud both excesses be explained at the same time by neutralino?

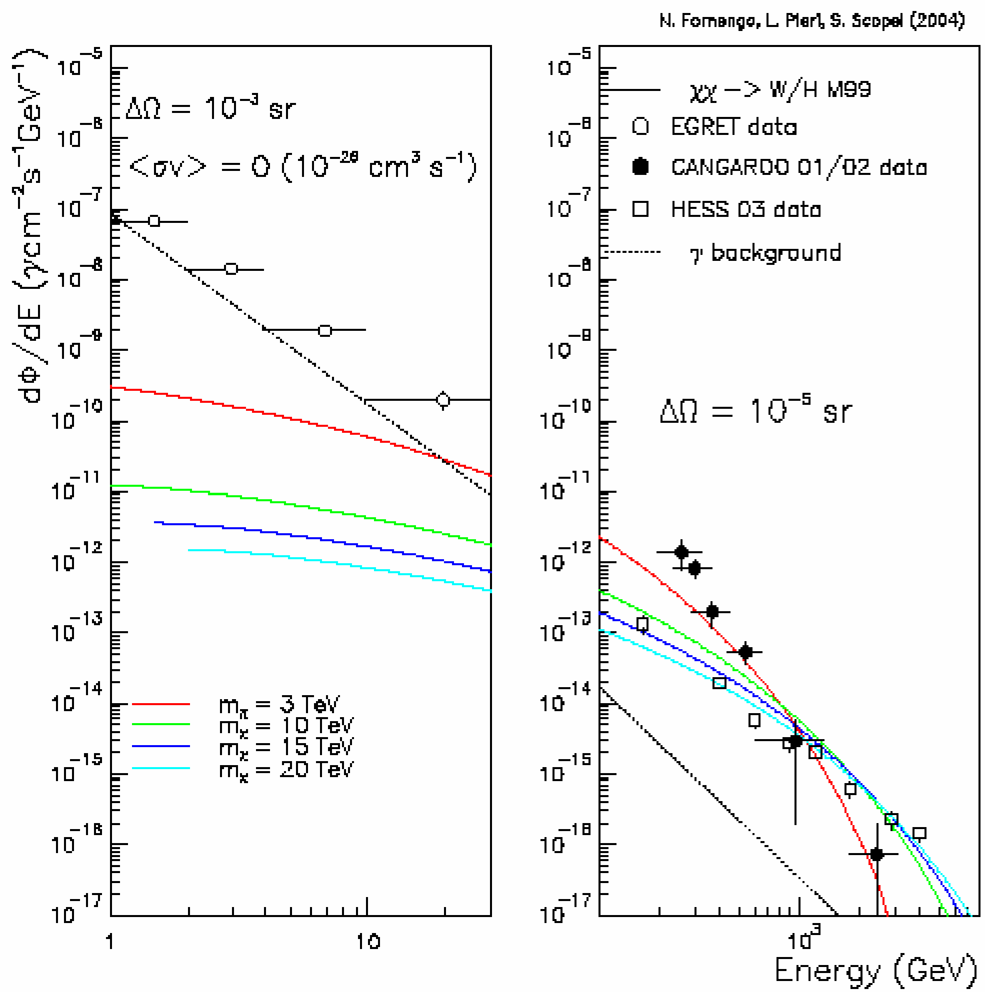
no. EGRET possibly explained by $30<m_\chi<60$ *GeV*, CANGAROO by $1<m_\chi$ <2 *TeV*, *M99x2.5* needed(spectrum too hard for EGRET).

However CANGAROO excess could possibly be explained without conflict with EGRET



EGRET CANGAROO

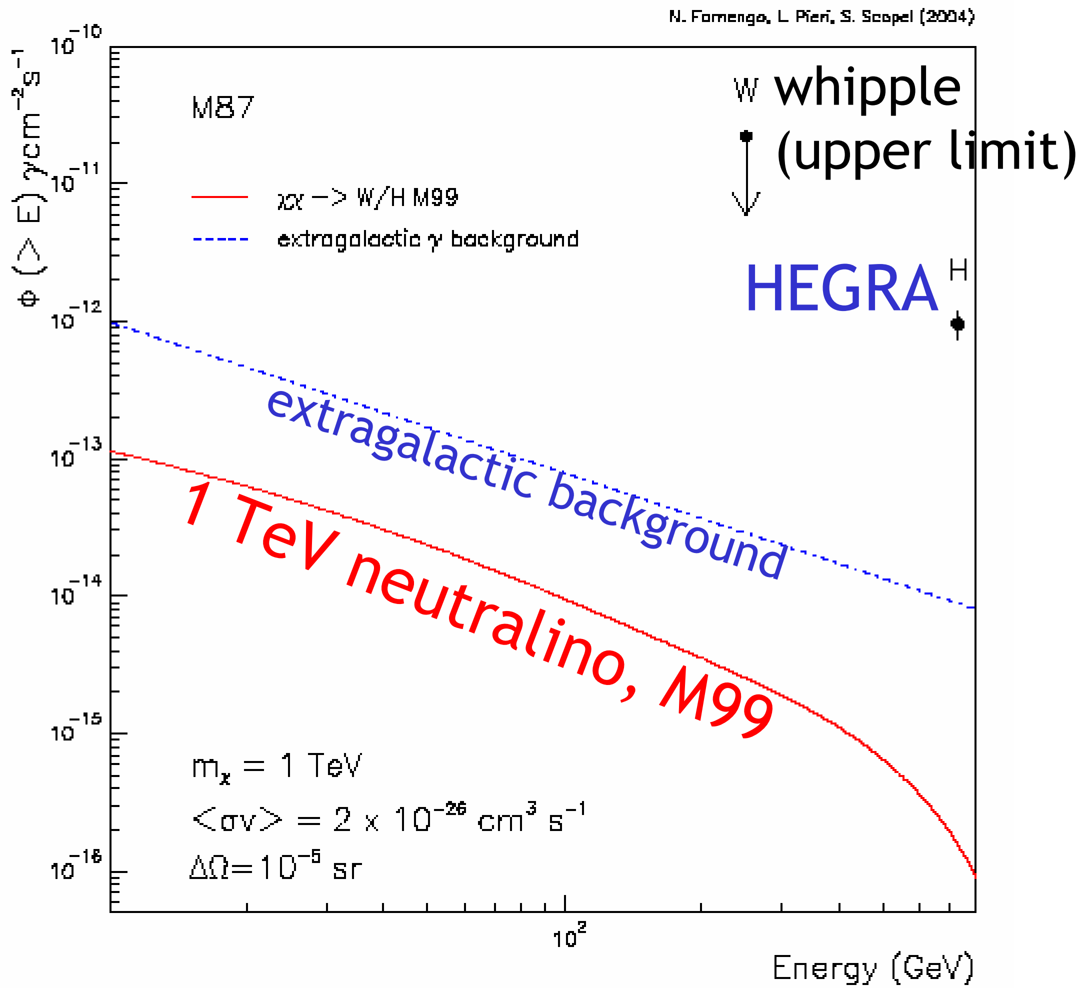
HESS data from galactic center



much harder spectrum, would require 10 TeV $< m_x <$ 20 TeV

Flux from M87 galaxy

possible excess detected, could be explained by neutralino?



no. enhancement of clumpy distribution at most factor of 5, neutralino signal always expected below background

Conclusions - 1

- Relic neutralinos with masses $m_\chi < 45$ GeV are allowed in MSSM models without gaugino-mass unification at the GUT scale.
- The cosmological lower bound on the neutralino mass from WMAP CMB data combined with other measurements is $m_\chi \geq 6$ GeV .
- For $m_\chi < 20$ GeV various direct and indirect neutralino signals are bounded from below (low -mass ``funnel”).
- These neutralinos, mainly a $\tilde{B}$ – $\tilde{H}_1$ mixture, are compatible with the final modulation result presented by the DAMA Collaboration (108000 kg day exposure).

Conclusions - 2

- WIMP direct experiments with cryogenic detectors provide severe constraints - low-mass neutralinos window still allowed
- Astrophysical uncertainties must be taken into account when comparing different experimental results.
- Current data from experiments of WIMP indirect searches ($\bar{p}$'s, γ's, up-going μ's), if interpreted conservatively, do not yet set constraints on light neutralinos.
- In case of steep distributions of dark matter in the galactic center, neutralinos of masses around 30-40 GeV could explain the EGRET excess.

Conclusions - 3

- signal from external galaxies (LMC, M31, M87) possibly above extragalactic background, but well below present sensitivities
- CANGAROO excess toward GC can be explained by 1 TeV neutralino, 2.5xM99 required, no conflict with data at lower energies (EGRET)
- EGRET and GANGAROO excess cannot be explained at the same time