PHYSICS AND ASTROPHYSICS OF LIGHT NEUTRALINOS

The Dark Side of the Universe 2007

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Alessandro Bottino
Università di Torino/INFN

- *In this talk I mainly focus on light neutralinos (mass less of about 50 GeV) , though a number of considerations also apply to higher masses*
- *Light neutralinos naturally arise in supersymmetric models characterized by a minimum of theoretical assumptions (MSSM without unification hypotheses)*
- *These neutralinos offer a very rich phenomenology, explorable by a host of independent experimental means*
- *A number of properties can be worked out analytically*

effective -MSSM

⋆ **Minimal Supersymmetric extension of the Standard Model at the electroweak scale (M_Z) in terms of the following parameters:**

$\tan\beta = \frac{<H_2>}{<H_1>} \equiv \frac{v_2}{v_1} \qquad [{v_1}^2 + {v_2}^2 = v^2]$

M_2 **SU(2) gaugino mass**

M_1 **U(1) gaugino mass** $\Longrightarrow R \equiv \frac{M_1}{M_2}$

μ **Higgs mixing parameter**

m_A **CP-odd neutral Higgs boson**

$m_{0\tilde{q}}, m_{0\tilde{l}}$ **squark, slepton masses**

A **trilinear coupling**

Notice that no gaugino-mass unification is assumed

Properties of light neutralinos (R<0.5)

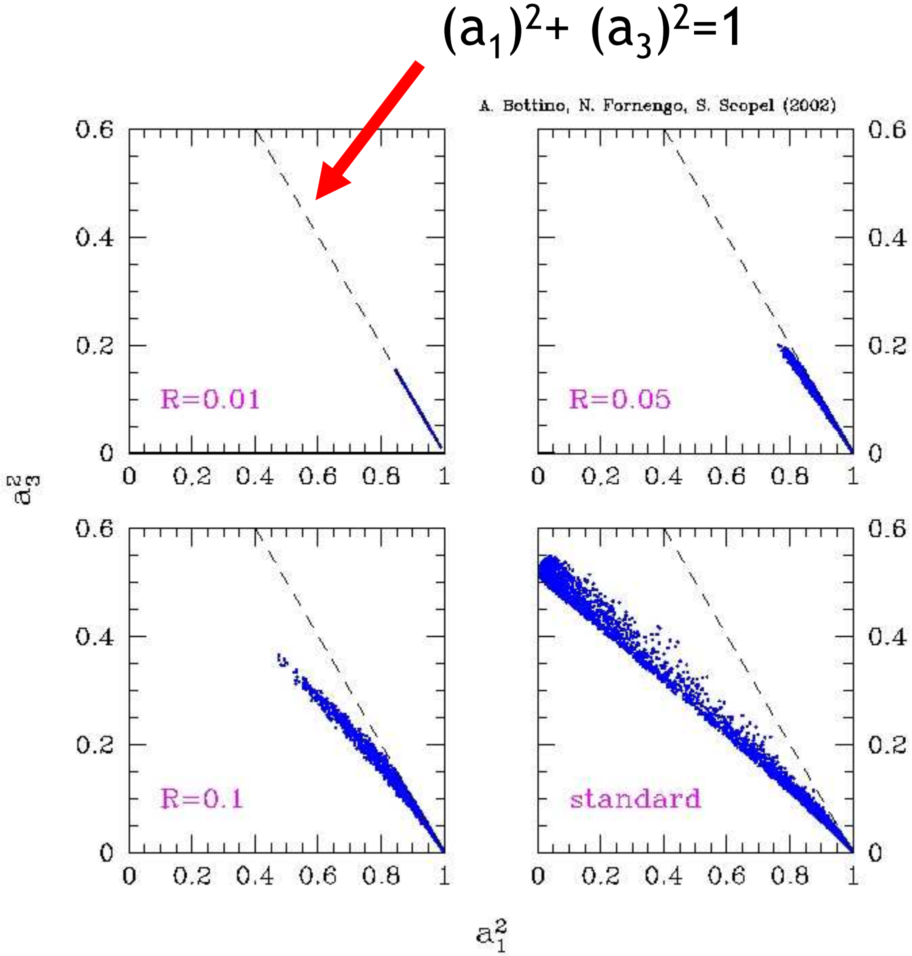
$$\chi = a_1 \tilde{B} + a_2 \tilde{W}^{(3)} + a_3 \tilde{H}_0^{(1)} + a_4 \tilde{H}_0^{(2)}$$

By diagonalizing the neutralino mass matrix for $M_1 << M_2, \mu$:

- $\chi \approx \tilde{B}$
- small $\tilde{H}^0_1$ component: $a_3/a_1 \approx \sin\theta_W \sin\beta \times \frac{M_Z}{\mu}$

$$\left|\frac{a_3}{a_1}\right| \leq 0.42 \sin\beta$$

(taking into account the experimental lower bound |μ|>100 GeV)



Lower bound on the neutralino mass

Relic Abundance for Cold Candidates (WIMPs)

$$\Omega_{\chi} h^2 \approx \frac{3 \times 10^{-39}\ \mathrm{cm}^2}{< \sigma_{\mathrm{ann}} \mathrm{v} >_{\mathrm{int}}}$$

$\Omega_{\chi} h^2$ *is limited from below by upper bounds on* $< \sigma_{\mathrm{ann}} \mathrm{v} >_{\mathrm{int}}$
due to particle physics constraints

and limited from above by the cosmological bound

$$\Omega_{CDM} h^2 \leq 0.12$$

Dominant contributions to $<\sigma_{\rm ann} {\rm v}>_{\rm int}$

if $m_A < 200\,GeV$

$$\chi + \chi \rightarrow b + \bar{b}$$

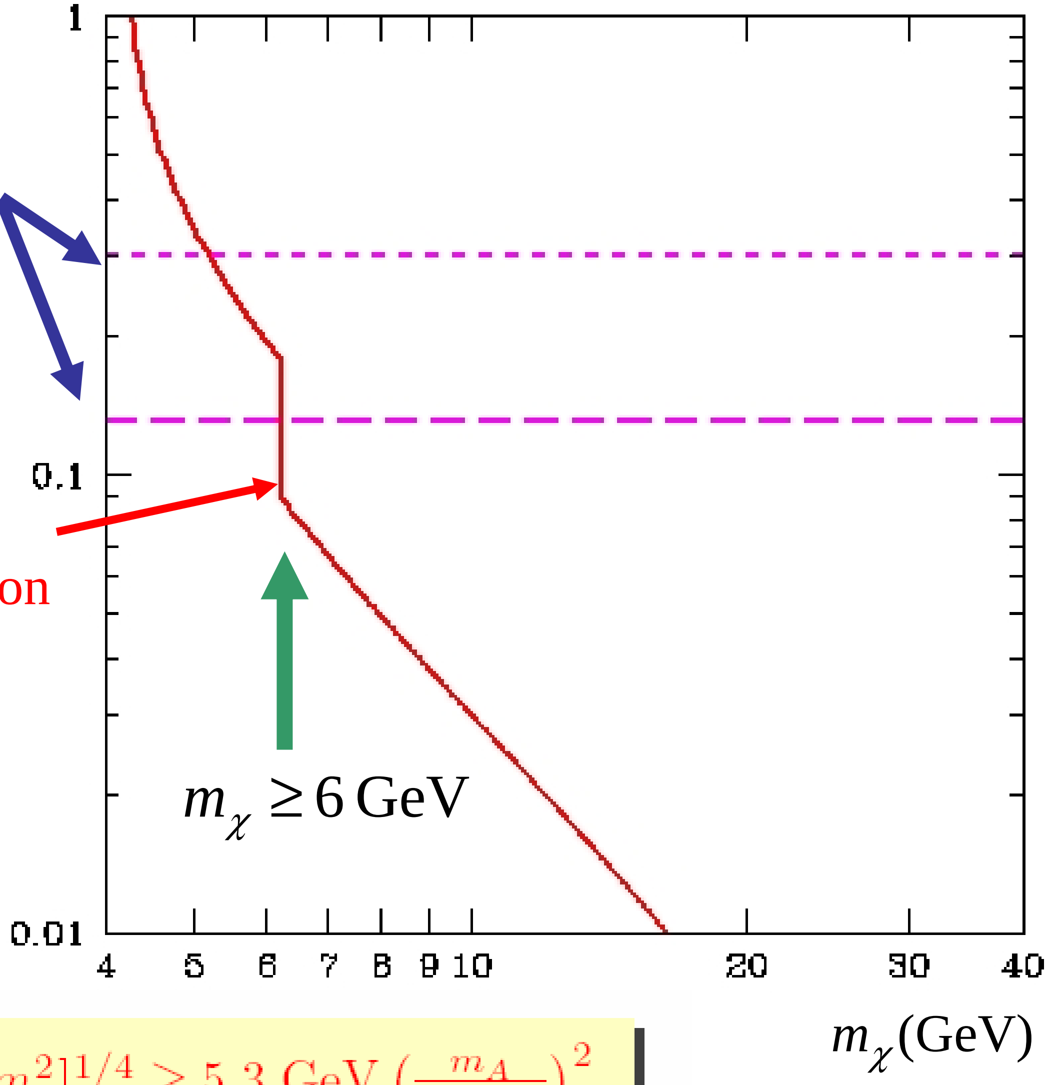
via A-exchange in the s-channel

if $m_A > 200\,GeV$

$$\chi + \chi \rightarrow \tau^+ + \tau^-$$

via stau-exchange in the t,u-channels

Cosmological bound on m_χ



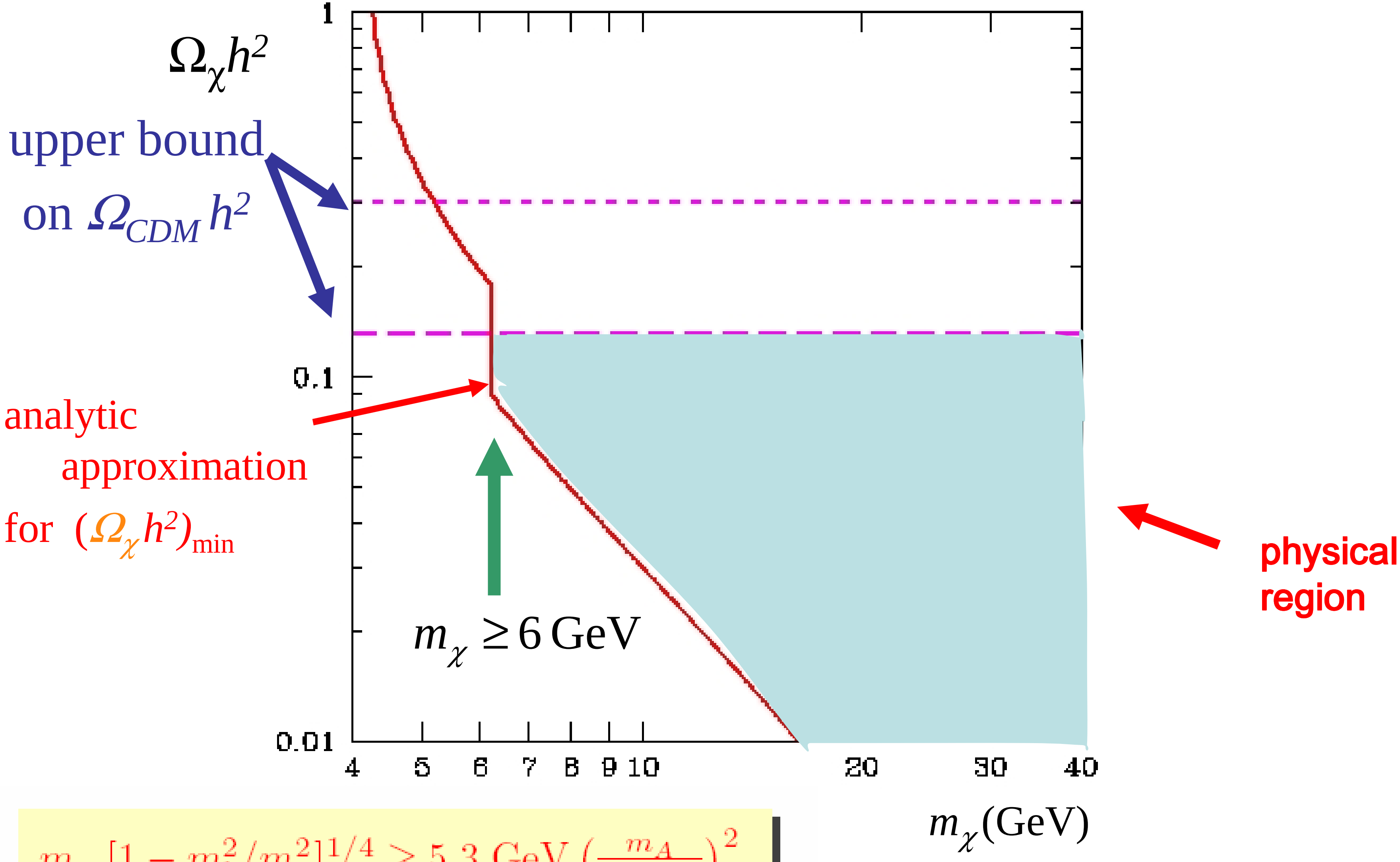
upper bound on $\Omega_{CDM} h^2$

analytic approximation for $(\Omega_\chi h^2)_{\min}$

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

A.B., Donato, Fornengo, Scopel hep-ph/0304080

Cosmological bound on m_χ



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A.B., Donato, Fornengo, Scopel
hep-ph/0304080

Much lighter neutralinos are allowed in Next-to-Minimal Supersymmetric extensions of the Standard Model :

R. Flores, K.A. Olive and D. Thomas, Phys. Lett. B263 (1991) 425

S.A. Abel, S. Sarkar and I.B. Whittingham, hep-ph/9209292

D.G. Cerdeno, C. Hugonie, D.E. Lopez-Fogliani, C. Munoz and A.M. Teixera hep-ph/0408102

J. Gunion, D. Hooper, and B. McElrath, hep-ph/0509024

MSSM is extended by adding a new gauge singlet chiral supermultiplet

- special features:

a very light CP-odd Higgs boson

a 5-components neutralino (the usual 4 components + a singlino)

$$\chi = a_1\tilde{B} + a_2\tilde{W}^{(3)} + a_3\tilde{H}_0{}^{(1)} + a_4\tilde{H}_0{}^{(2)} + a_5\tilde{S}$$

Also direct detection rates for relic neutralinos are sizeably enhanced

Lighter neutralino masses are also possible in MSSM with explicit CP-violation, see for instance

J.S. Lee and S. Scopel, hep-ph/0701221

Detection of relic particles

☆ Direct detection : scattering of a WIMP off a nucleus in an appropriate detector

☆ Annihilations taking place in the Halo

$\chi + \chi \rightarrow$ $\nu, \bar{\nu}$

γ (continuum)

γ line ($Z\gamma$)

} keep directionality

e^+

$\bar{p}$

$\bar{D}$

} searches for rare components in cosmic rays

Detection rates depend sensitively on the following properties:

☆ ***phase-space distribution function for the WIMPs in the galactic halo***

-- deviations of the smooth component from the isothermal sphere

-- possible existence of streams and clumps

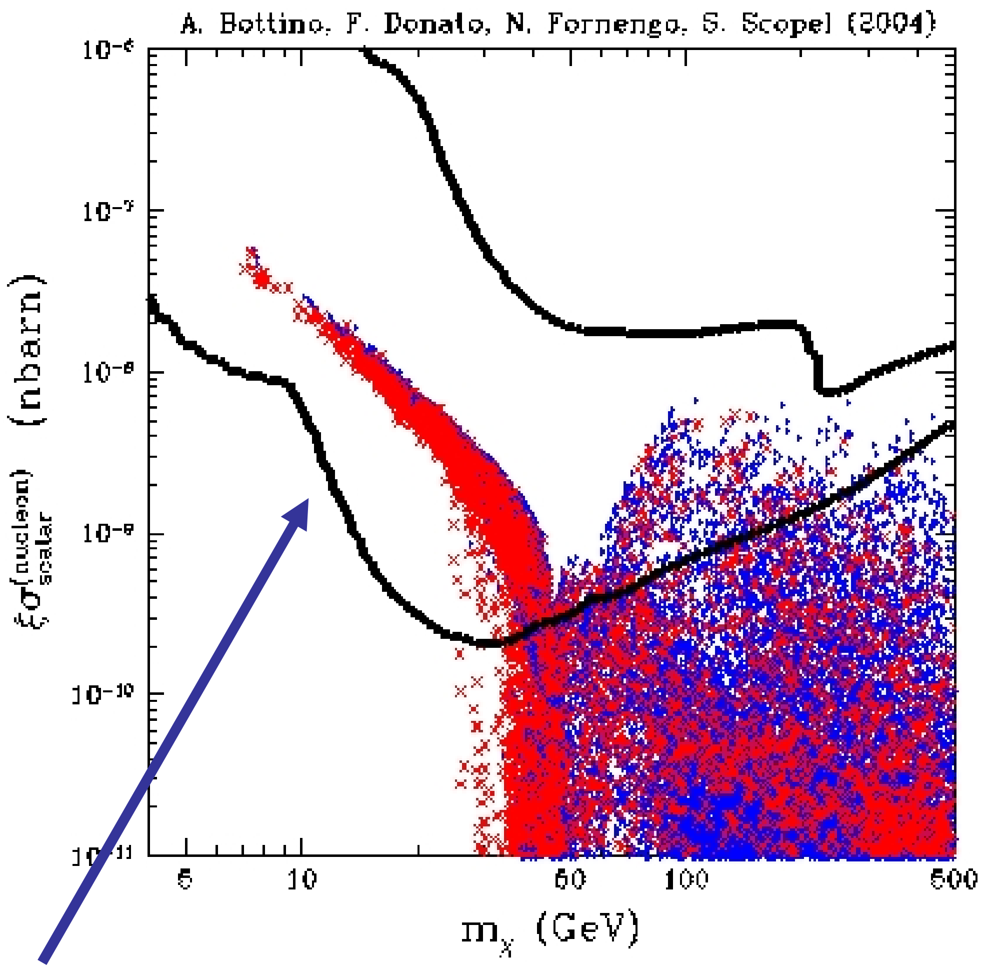
☆ ***for signals due to*** $e^{+}, \overline{p}, \overline{d}$ ***produced by WIMP self-annihilations in the galactic halo***

-- propagation and diffusion of the charged particles in the halo

-- evaluation of the secondary productions (background)

Which constraints on relic neutralinos from WIMP direct searches ?

Comparing theoretical results with DAMA



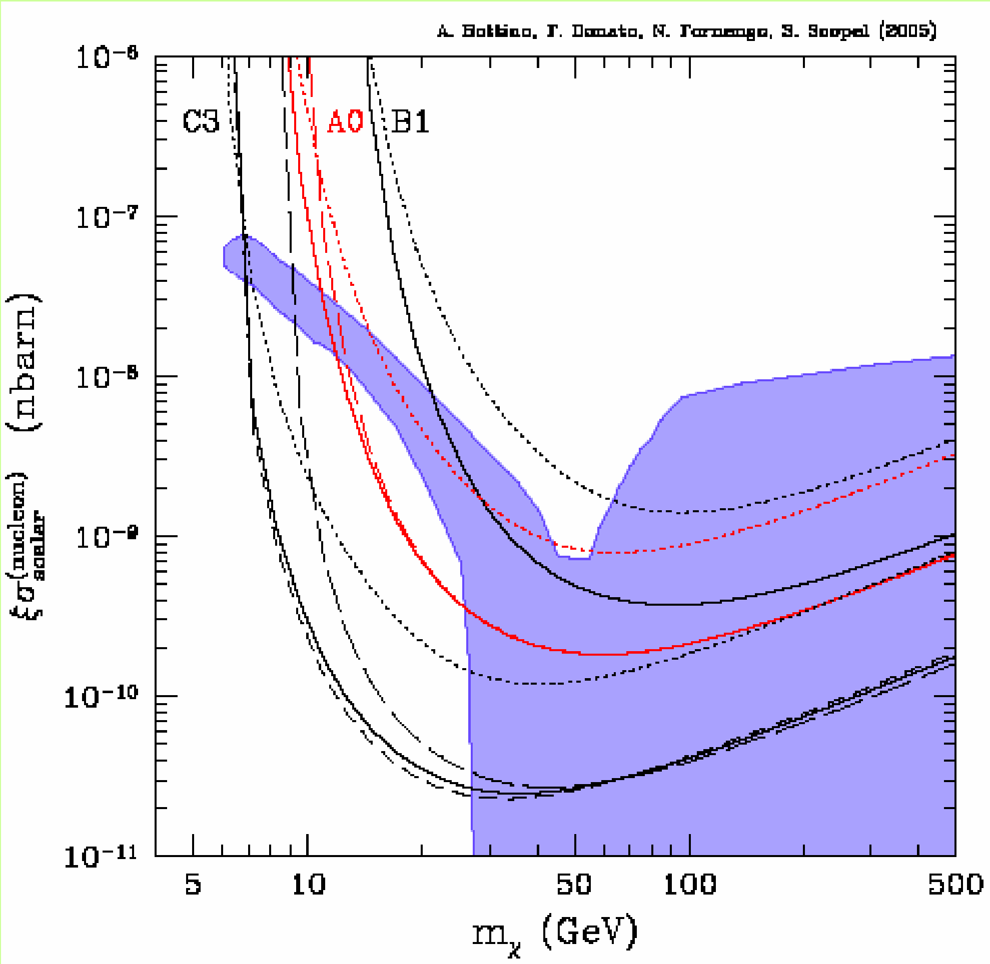
Color code:

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

$$\xi \equiv \frac{\rho_\chi}{\rho_{tot}}$$

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
Exposure: about 108.000 kg day

Dependence of the upper bounds on the WIMP galactic distribution function

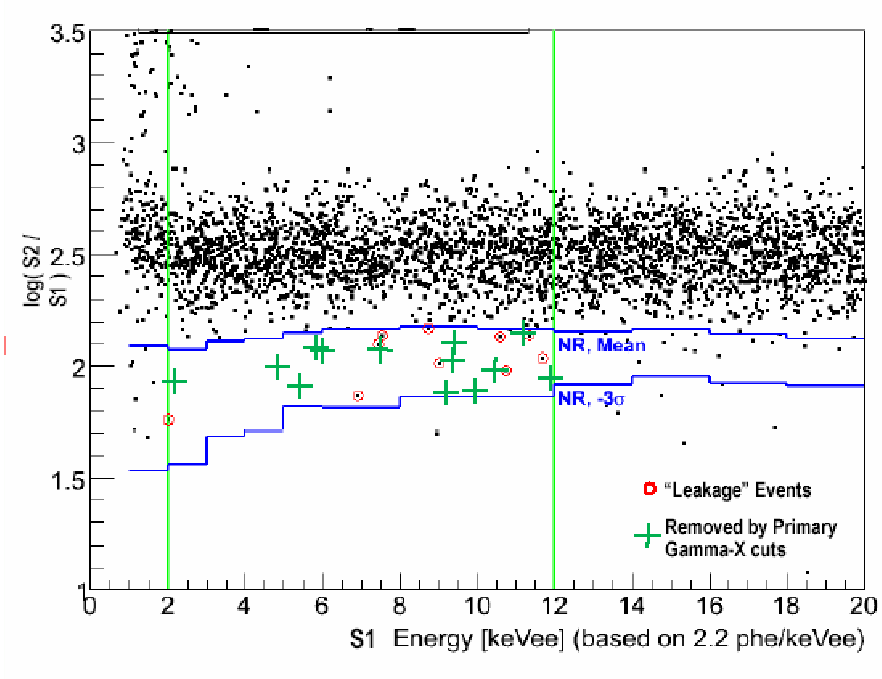


B1 = non-isotropic velocity dispersion

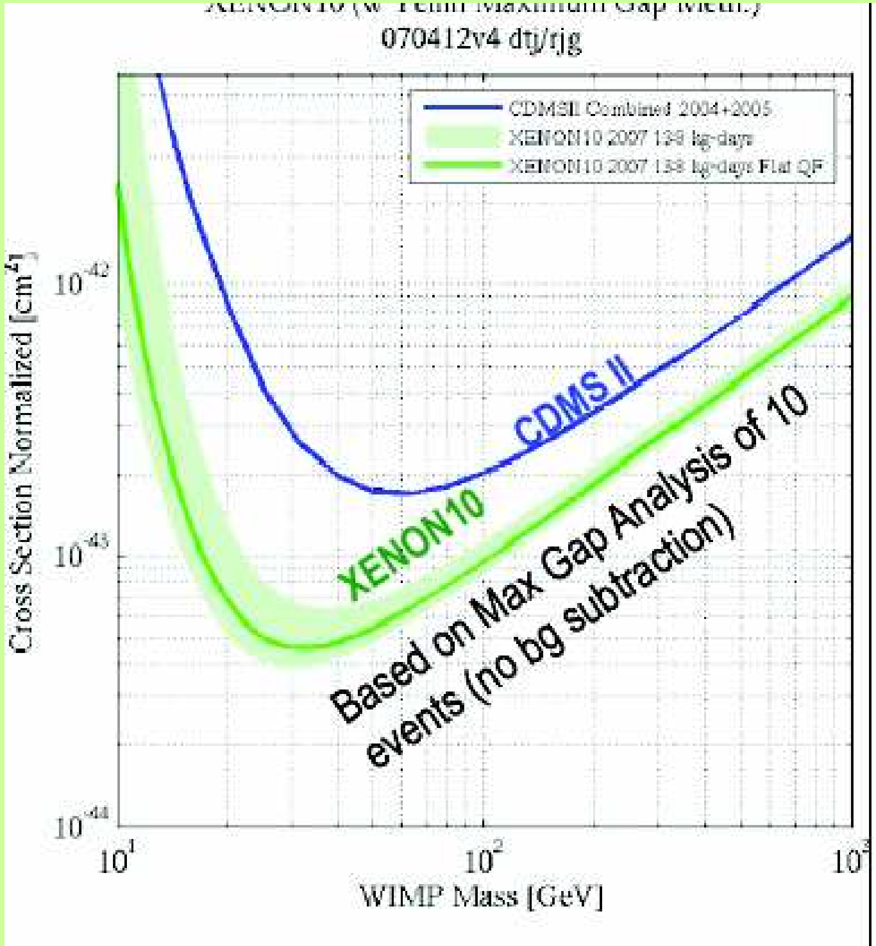
A0 = isothermal sphere

C3 = axisymmetric spatial distribution

Experimental data from CDMS
Akerib et al., astro-ph/0509259



The XENON10 Collaboration



astro-ph/0706.0039

Rare components in cosmic rays:

antiprotons, antideuterons, positrons

Propagated antiproton differential flux at a generic point of coordinates r, z in the Galaxy

$$\Phi_{\bar{p}}(r,z,E) = \frac{v_{\bar{p}}}{4\,\pi}\;\Upsilon\;\frac{dN}{dT_{\bar{p}}} S^{\bar{p}}_{\rm astro}(r,z,E)$$

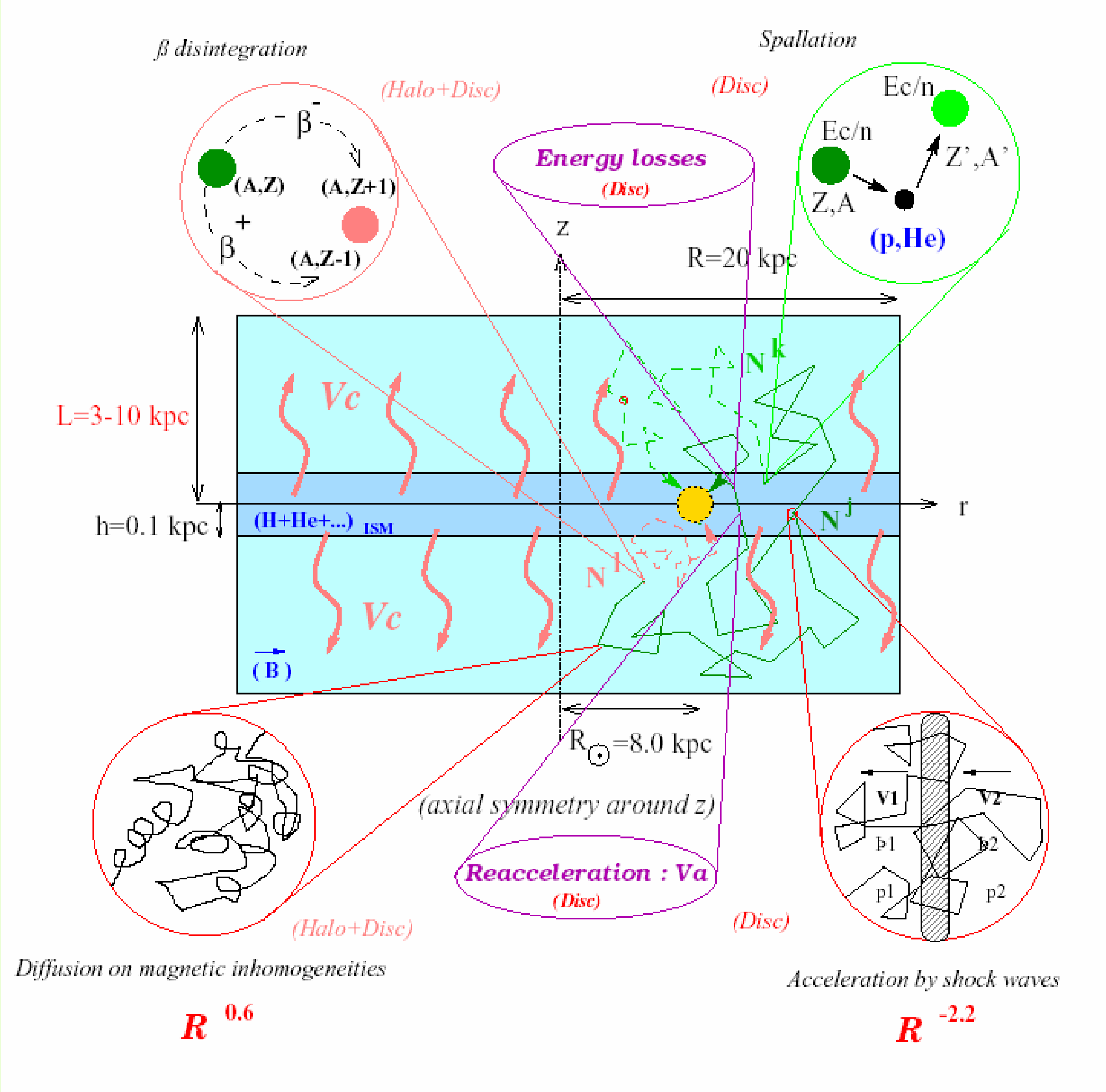
$$\Upsilon = \frac{1}{2}\xi^2\,\frac{\langle\sigma_{\rm ann} v\rangle_0}{m_\chi^2}$$

$$\frac{dN_{\bar{p}}}{dT_{\bar{p}}} = \sum_F BR(\chi\chi \to \bar{p} + X)\frac{dN^F_{\bar{p}}}{dT_{\bar{p}}}$$

$S^{\bar{p}}_{\rm astro}$ *takes into account all propagation effects and includes the square of the density profile*

$$\rho(r,z) = \rho_l\,\frac{a^2 + R_\odot^2}{a^2 + r^2 + z^2}$$

Propagation and diffusion of cosmic rays in the halo



Maurin, Taillet, Donato, Salati, Barrau, Boudoul, astro-ph/0212111

Propagation and diffusion can be conveniently described in terms of 5 parameters:

K_0, δ *entering in the energy-dependent diffusion coefficient*

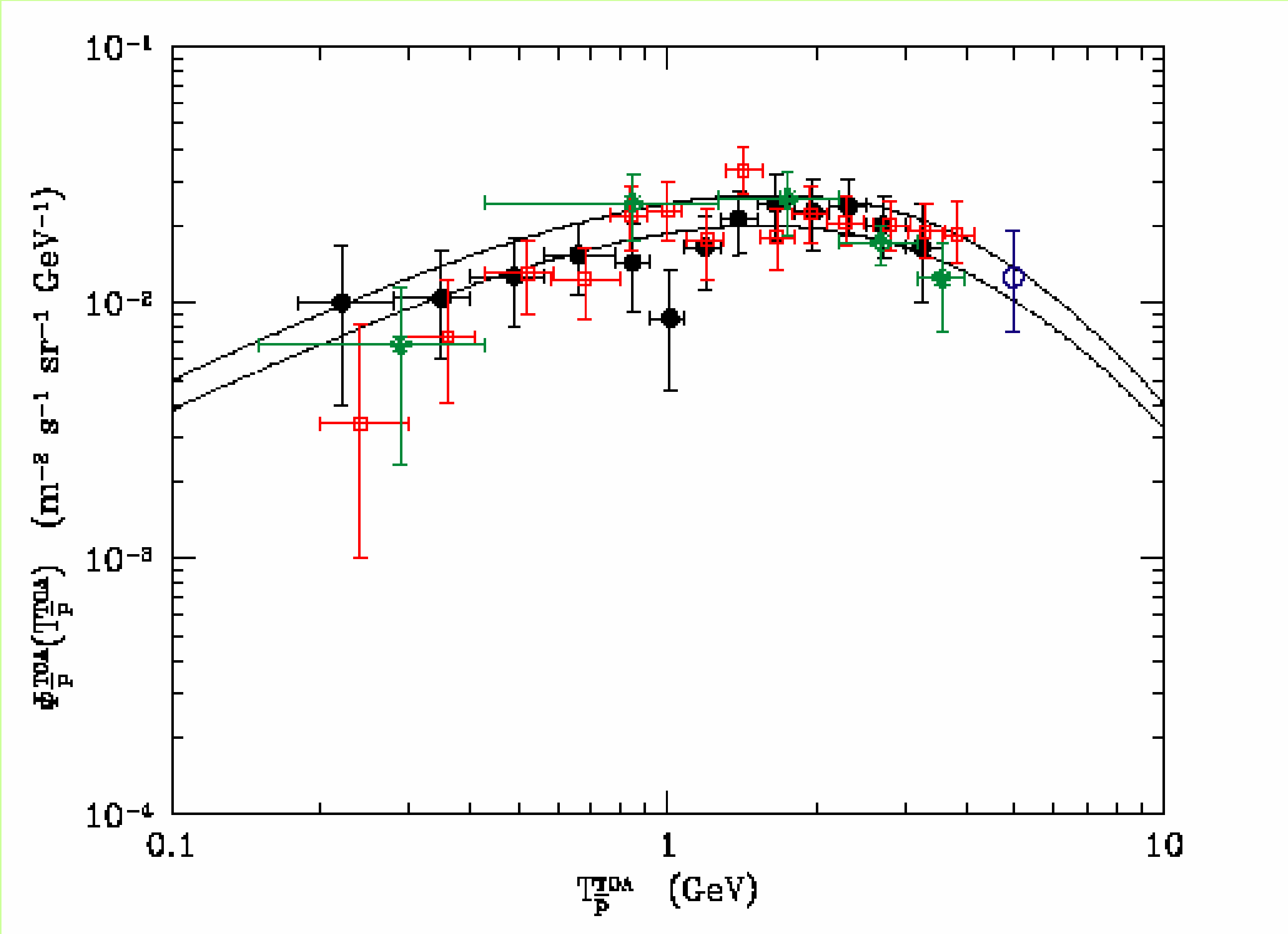
$$K = K_0 \beta R^{\delta}$$

L *thickness of the diffusion layer*

V_A *Alfven speed*

V_c *velocity of the convective wind*

Secondary antiproton flux calculated using a full analysis on stable nuclei (B/C etc) in cosmic rays: F. Donato et al., Astrophys. J. 563 (2001) 172



- *excellent agreement with experimental data*
- *20% uncertainty band*

TABLE I. Astrophysical parameters compatible with B/C analysis and yielding the maximal, median and minimal primary antiproton flux.

Case	δ	K_0 [kpc^2/Myr]	L [kpc]	V_c [km s^{-1}]	V_A [km s^{-1}]
Max	0.46	0.0765	15	5	117.6
Med	0.70	0.0112	4	12	52.9
Min	0.85	0.0016	1	13.5	22.4

The median case provides a chi-squared of 33.6 for the antiproton spectrum with 32 data points

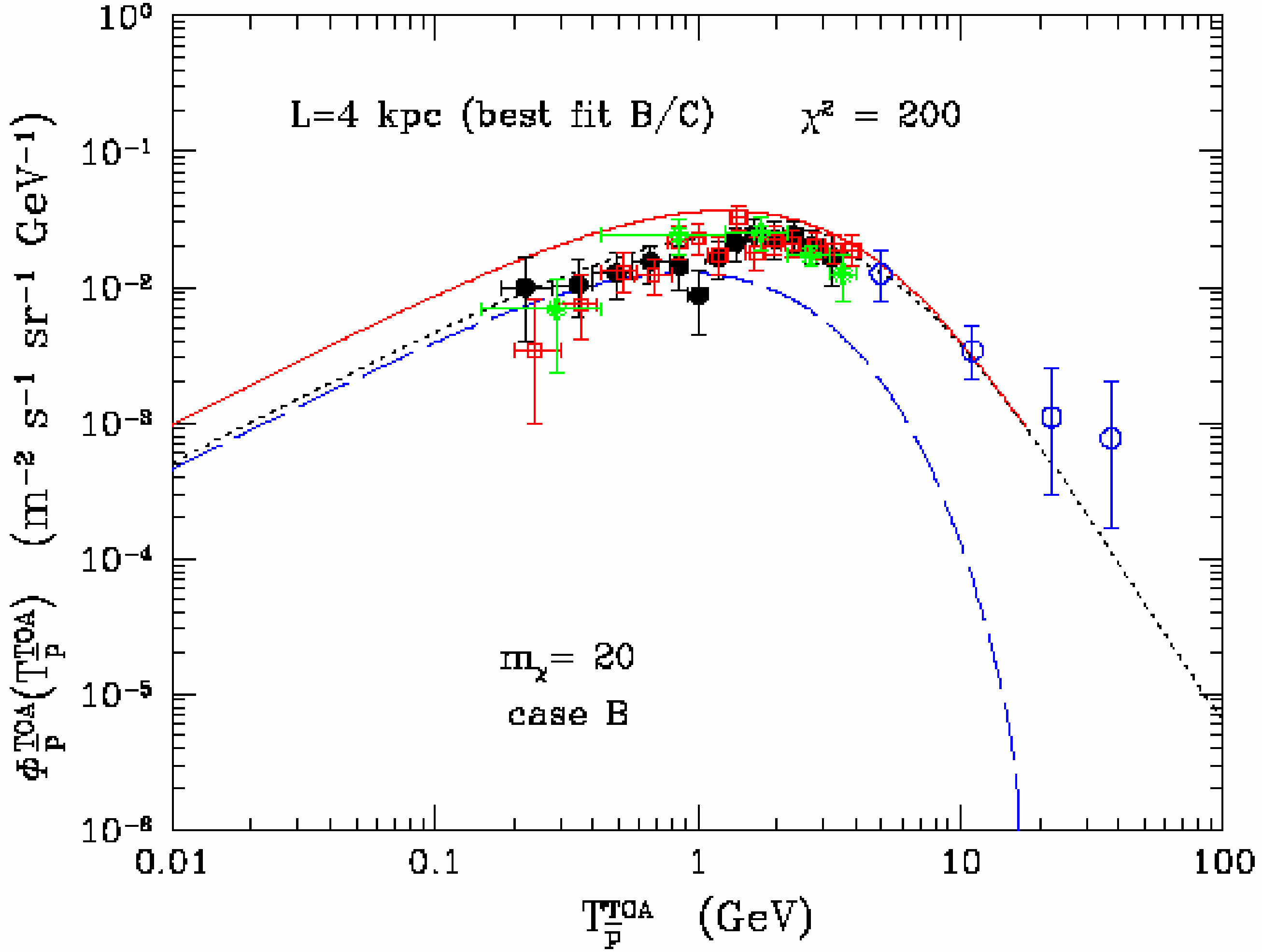
- effects due to light neutralinos can be sizeable, but hardly distinguishable from the background

- antiproton data can be used to put constraints on supersymmetric configurations

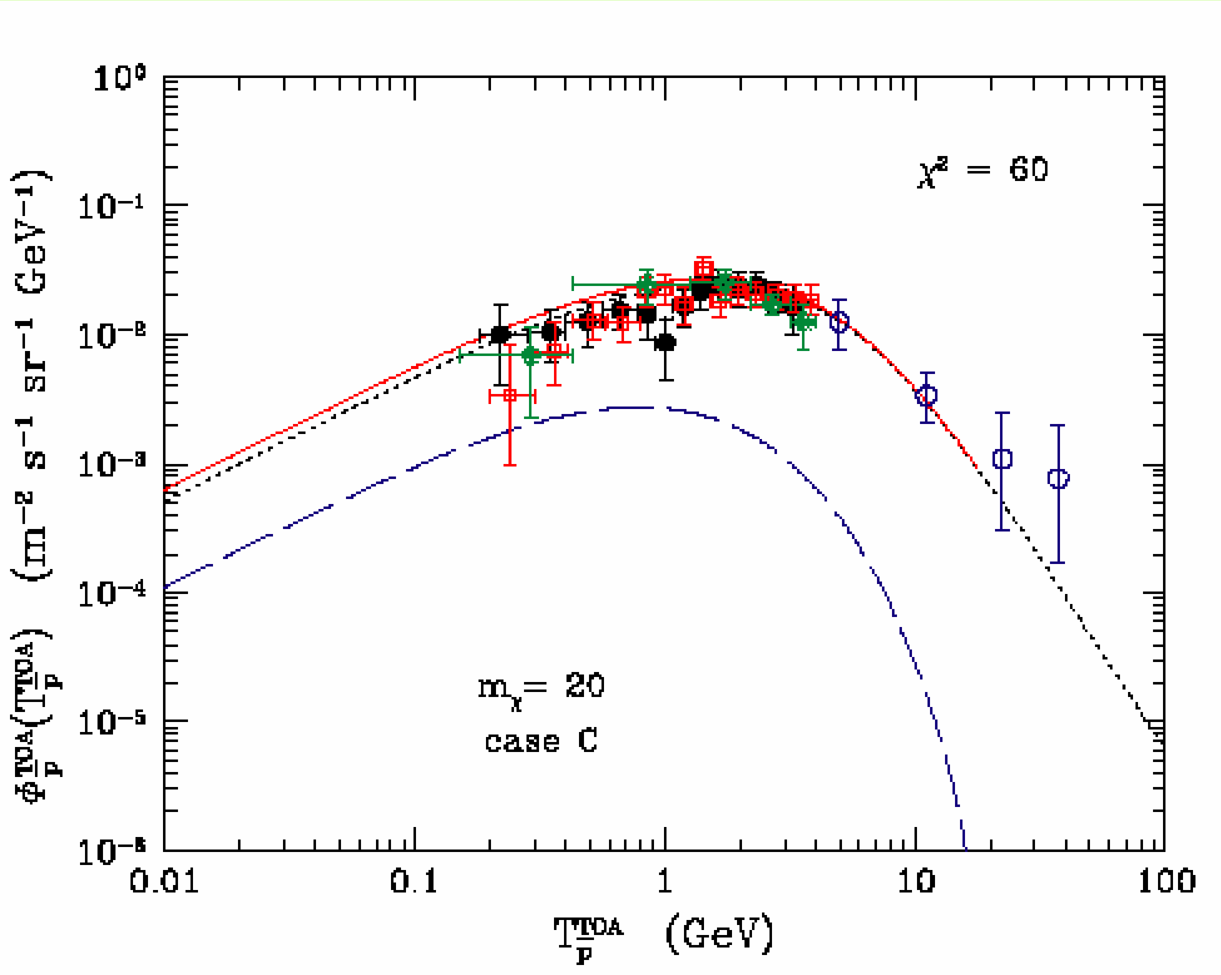
- constraints are relaxed by the astrophysical uncertainties of primary fluxes (effect of uncertainties on primary fluxes is much larger than the effect on secondary flux)

- supersymmetric configurations are excluded at a confidence level of 99.5%, if they produce a total flux with a chi-squared > 60

A.B., Donato, Fornengo and Salati: hep-ph/0507086

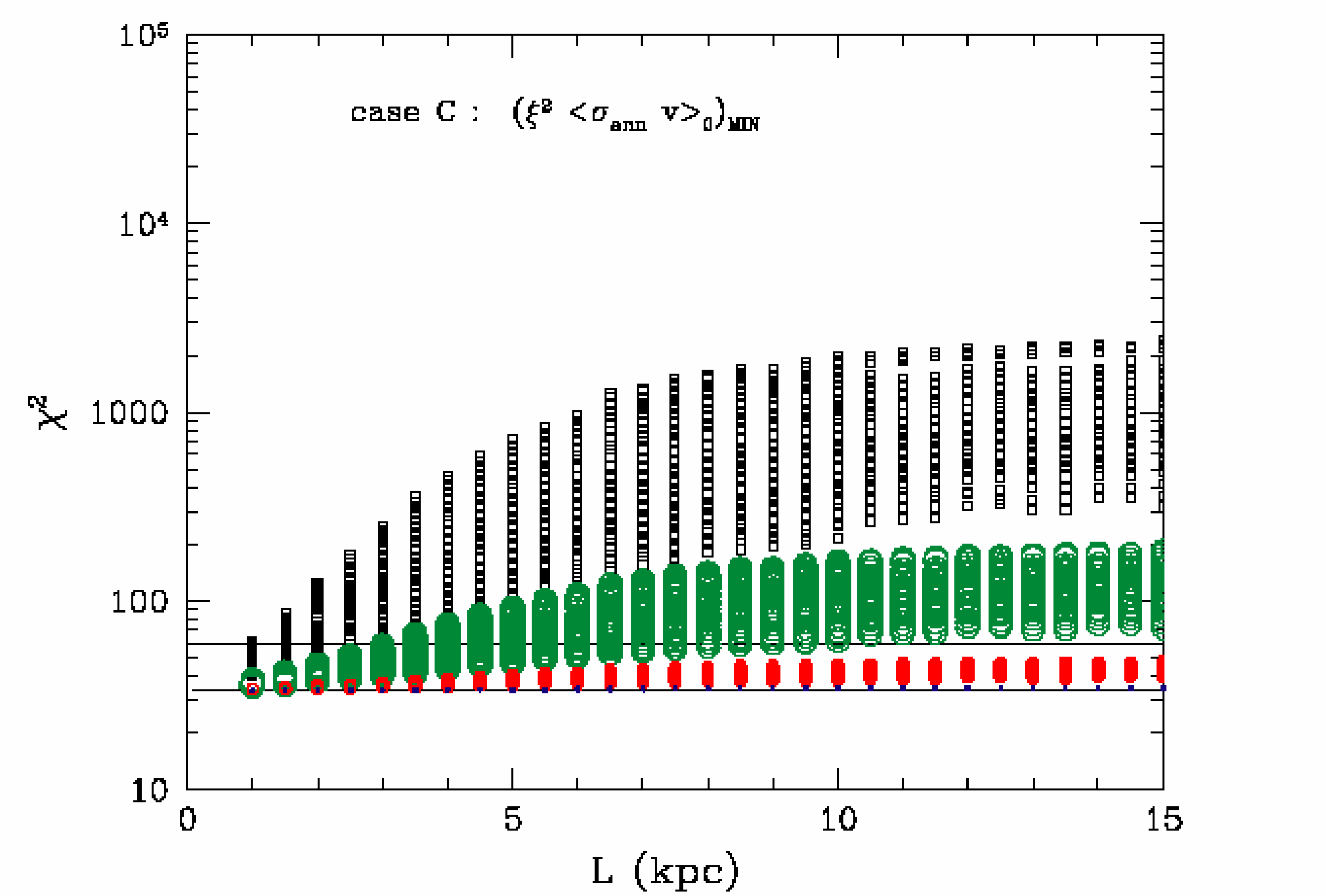


example of an excluded configuration



$\chi^2 = 60$
$m_\chi = 20$
case C
$T_{\bar{p}}^{TOA}$ (GeV)
$\Phi_{\bar{p}}^{TOA}(T_{\bar{p}}^{TOA})$ $(m^{-2}\ s^{-1}\ sr^{-1}\ GeV^{-1})$

a



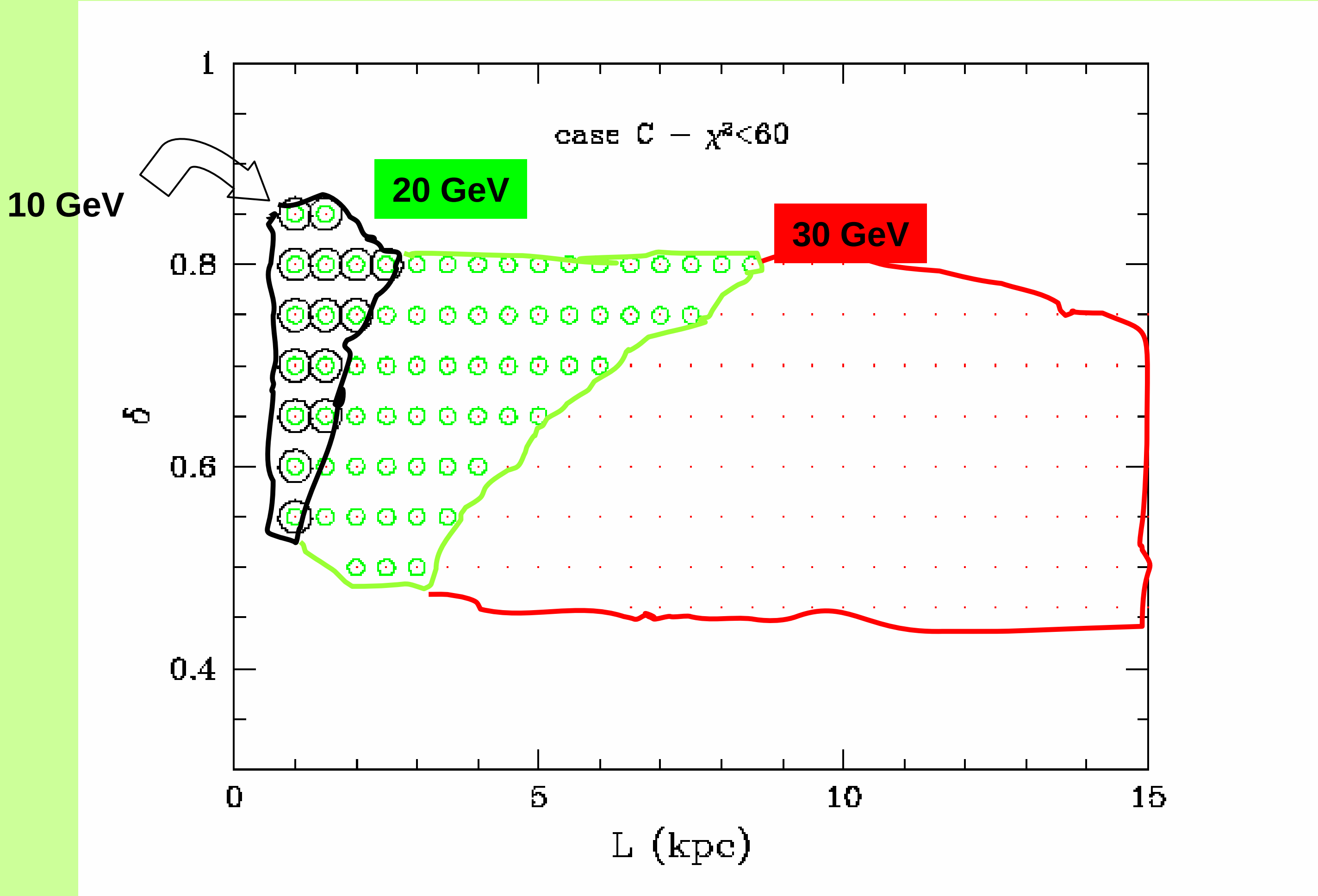
black dots: neutralino mass = 10 GeV

green dots: neutralino mass = 20 GeV

red dots: neutralino mass = 30 GeV

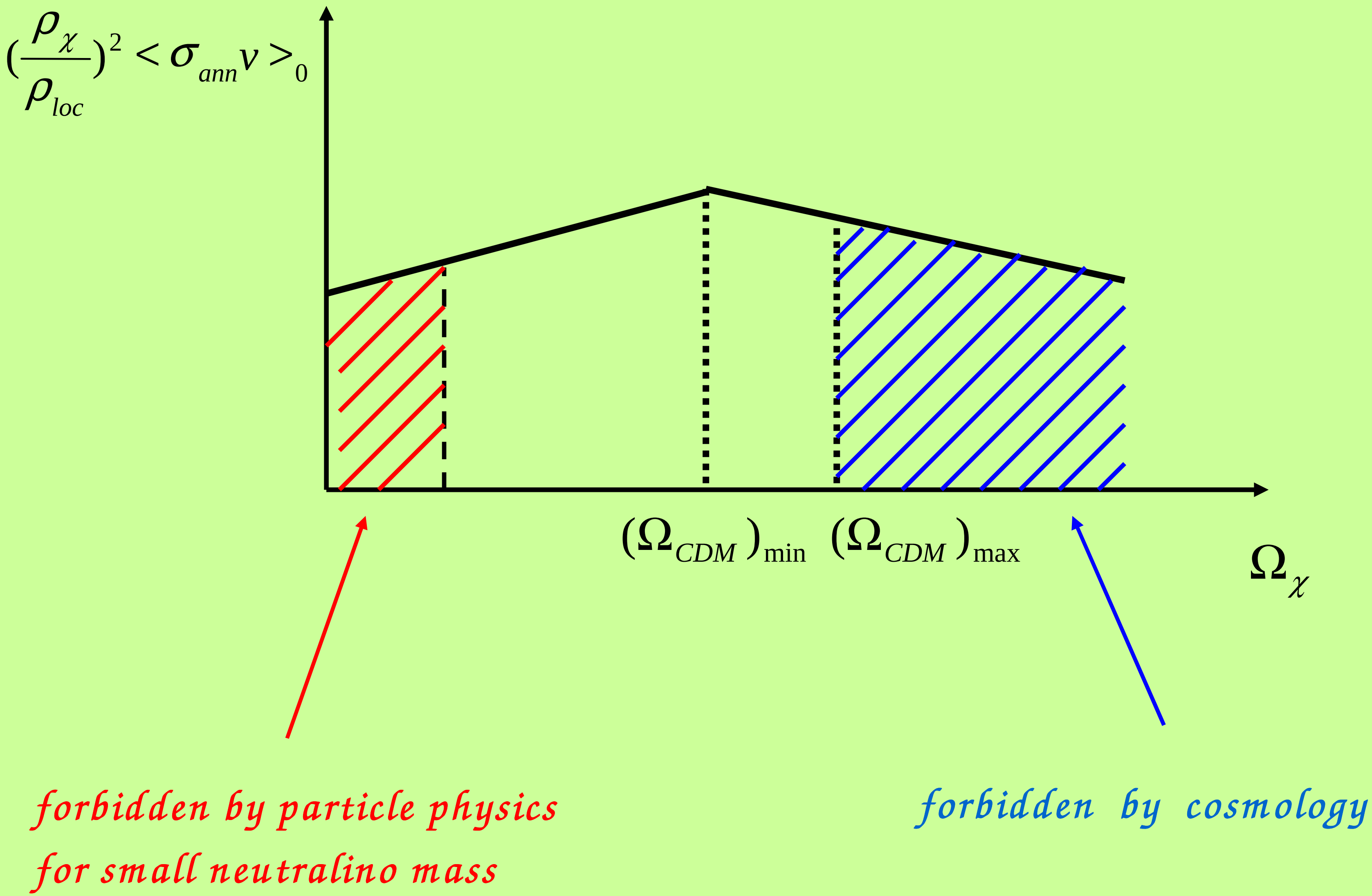
Compatibility among the WIMP and the astrophysical parameters

A.B., Donato, Fornengo, Salati, hep-ph/0507086



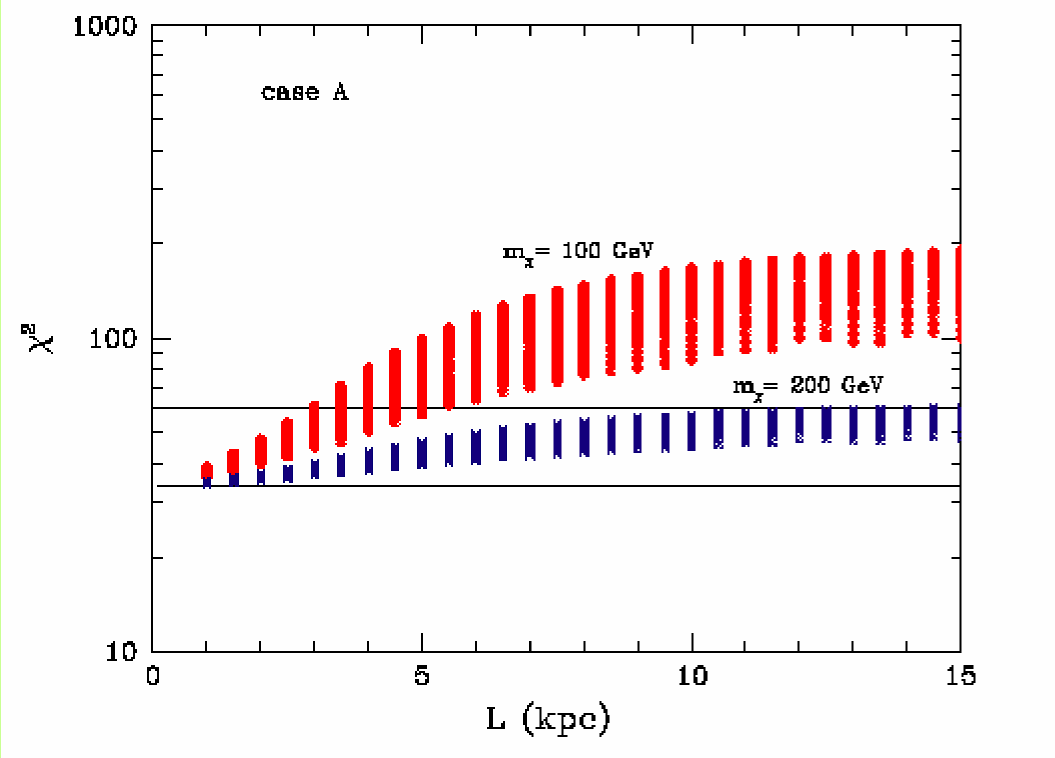
Diffusion in a two-zones halo:

- **energy-dependent coefficient** $K = K_0 \beta R^{\delta} (R = rigidity)$
- **L = halo thickness parameter**



$(\frac{\rho_\chi}{\rho_{loc}})^2 < \sigma_{ann} v >_0$
$(\Omega_{CDM})_{min}$
$(\Omega_{CDM})_{max}$
Ω_χ
forbidden by particle physics
for small neutralino mass
forbidden by cosmology

The occurrence of a maximum in $(\frac{\rho_\chi}{\rho_{loc}})^2 < \sigma_{ann} v >_0$ *entails that neutralinos heavier than about 200 GeV are irrelevant for the antiproton spectrum , unless a clumpiness effect enhances the signal*



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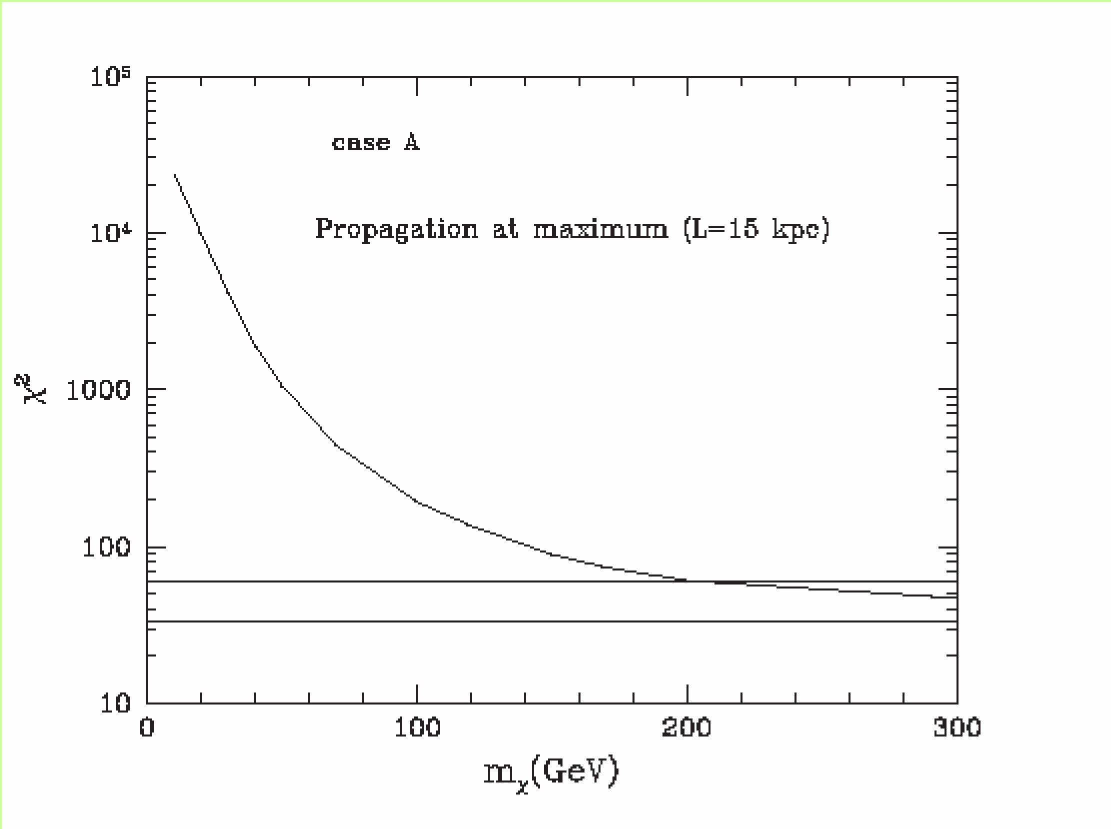

case A
Propagation at maximum (L=15 kpc)
χ^2
10^5
10^4
1000
100
10
0
100
200
300
m_χ(GeV)

a

Antideuterons in cosmic rays

- Formation of antideuterons in CRs proceeds through:
  production of an antiproton-antineutron pair
  by spallation (secondary production) or
  by WIMP-annihilation (primary production)

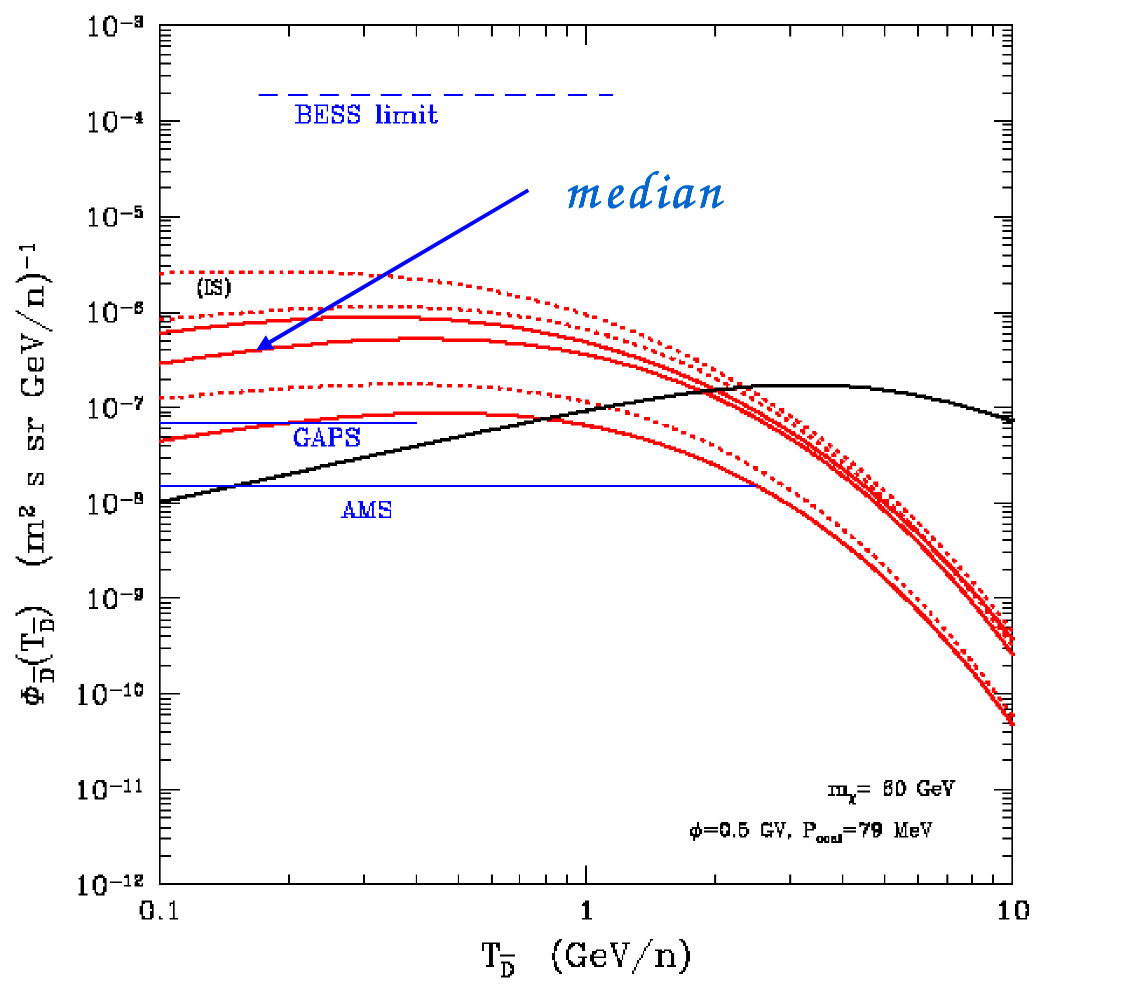
  fusion (coalescence) of antiproton and antineutron
  into an antideuteron - made easier in WIMP annihilation
  which occurs with particles at rest in the galactic frame

- At low energies, the primary spectrum is much enhanced as compared to the secondary one

  F. Donato, N. Fornengo and P. Salati, hep-ph/9904481
  H. Baer and S. Profumo, astro-ph/0510722

F. Donato, N. Fornengo and D. Maurin, preprint DFTT 6/2007

(preliminary)



secondary flux

interstellar primary flux

top-of-atmosphere primary flux

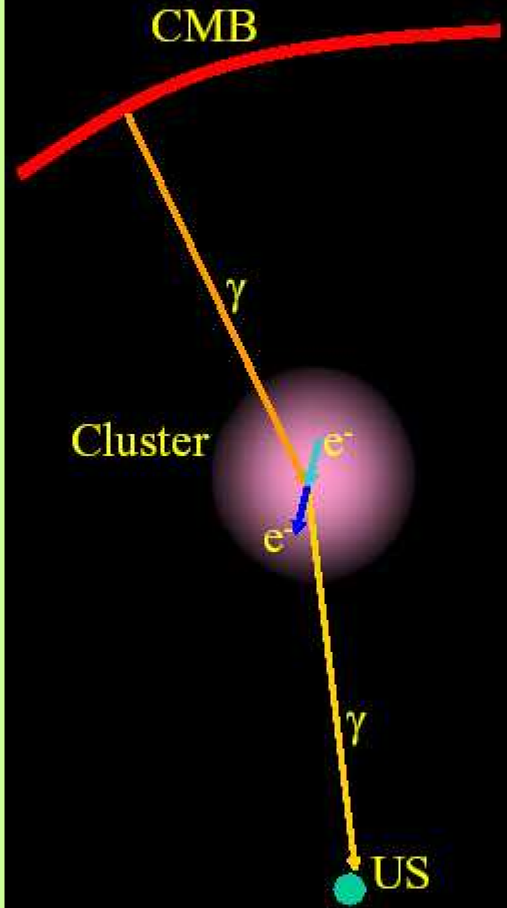
Sunyaev-Zeldovich effect due to WIMP annihilation in galaxy clusters

S. Colafrancesco, astro/ph-0405456

S. Colafrancesco, P. de Bernardis, S. Masi, G. Polenta and P. Ullio, astro-ph/0702568

P. Ullio, this conference

Sunyaev-Zeldovich effect



Inverse Compton scattering of CMB photons against hot electrons in the intergalactic medium of rich clusters of galaxies

About 1% of the photons acquire about 1% boost in energy, thus slightly shifting the spectrum of CMB to higher frequencies.

$\Delta T/T \sim 10^{-4}$

The result is a decrease of CMB brightness in the line of sight crossing the cluster at ν<217 GHz, and an increase at ν>217 GHz

Independent of redshift !

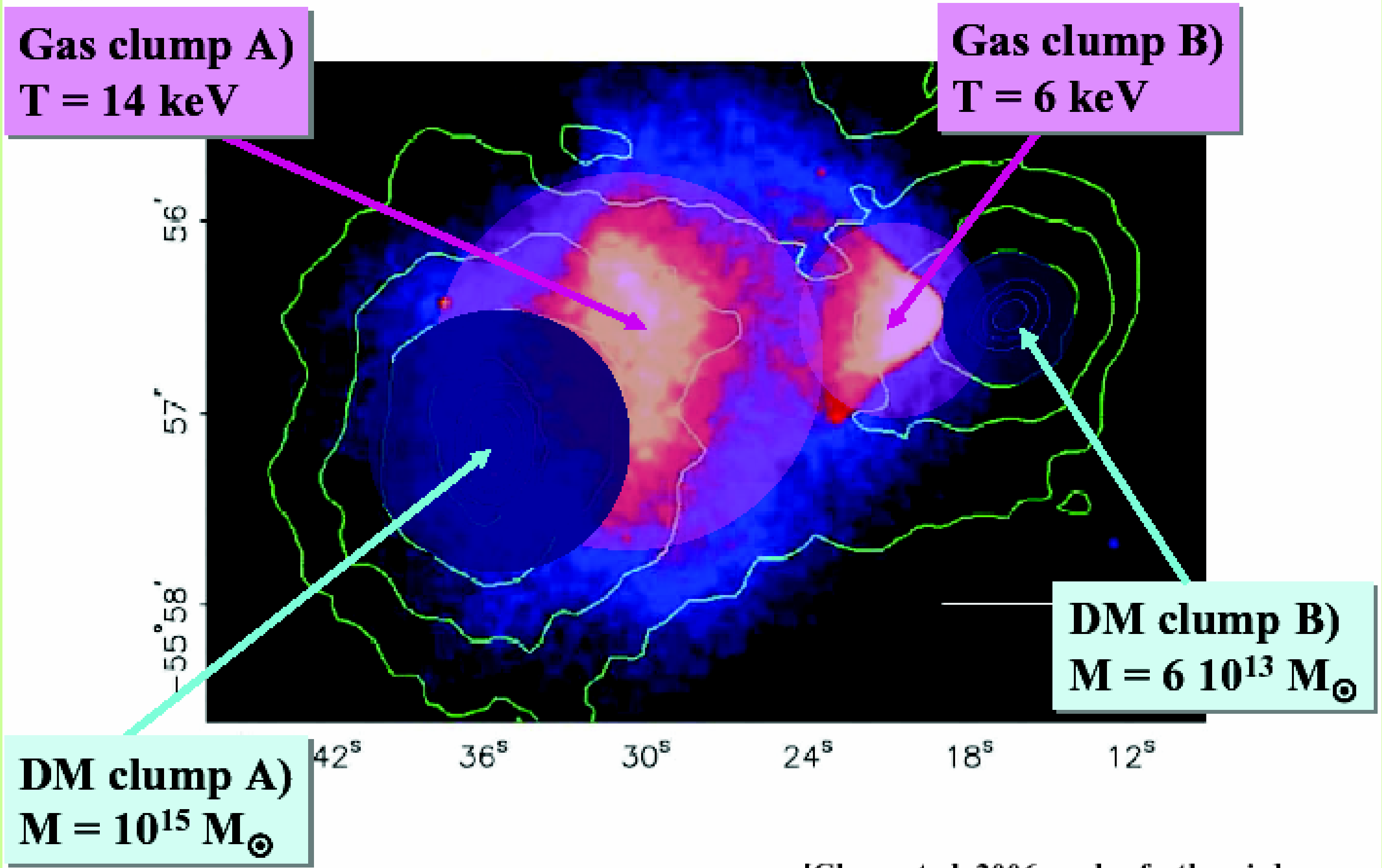
From P. de Bernardis, talk at Neutrino Telescopes XXII, Venezia (2007)

Secondary electrons produced in WIMP annihilations in clusters of galaxies can create a peculiar SZ effect
(S. Colafrancesco, astro/ph-0405456)

In standard situations it is difficult to disentangle the DM-induced SZ effect from the one produced by the hot X-ray emitting gas

Ideal case where the DM-induced SZ effect can be singled out occurs when the DM distribution is spatially separated from the intercluster gas, as in the "bullet cluster" 1ES0657-556 – it would be possible to detect this SZ/DM effect by using a special observational strategy
(S. Colafrancesco, P. de Bernardis, S. Masi, G. Polenta and P. Ullio, astro-ph/0702568)

1ES0657-556: DM + thermal gas



[Clowe et al. 2006, and refs. therein]

Conclusions

- Light neutralinos offer a very rich phenomenology , both for particle-physics aspects and astrophysical aspects

- Relic light neutralinos can be investigated by a variety of independent experimental means:
direct searches, rare components in CRs, gamma-rays, Sunyaev-Zeldovich effect, etc

- BUT, signals are affected by large uncertainties :
WIMP distribution function, propagation and diffusion properties of CRs, ...

- THUS, the interpretation of experimental data requires a conservative approach