THE QUEST OF DARK MATTER

Angel Morales, a Friend and a Scientist
Meeting in Venise, February 10, 2006

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Università di Torino/INFN

Contents

- Looking for candidates for cold dark matter
- Relic particles in the Universe: relic abundance
- Strategies for detection of cold relic particles
- Astrophysical uncertainties
- WIMP interactions with ordinary matter
- WIMP self-annihilation: indirect signals
- Perspectives
- *Recalling Angel's involvement in search for DM*

From a host of astrophysical and cosmological observations the matter density in the Universe is

$$\Omega_m \approx 0.3$$

to be compared to: $\Omega_{vis} < 0.01 \quad \Omega_b \approx 0.03 - 0.05$

Most matter is dark, only a small fraction of it is baryonic

From $\Omega_m = \Omega_b + \Omega_\nu + \Omega_{CDM}$

and using $\Omega_\nu / \Omega_{CDM} < 0.12$ (formation of cosmological structures)

$$\Omega_{CDM} \approx 0.22$$

Alternatives to dark matter ?

Modification of Newtonian gravity

etc

A particle is a good dark matter candidate if

- it is stable (protected by a conserved quantum number)
- it is weakly-interacting (uncharged and uncoloured)
- its relic abundance is $\approx \Omega_{CDM}$

Notice that also relic particles whose relic abundance is less than Ω_{CDM} are very interesting to be investigated, though representing subdominant components of DM – their detection rates can be large!

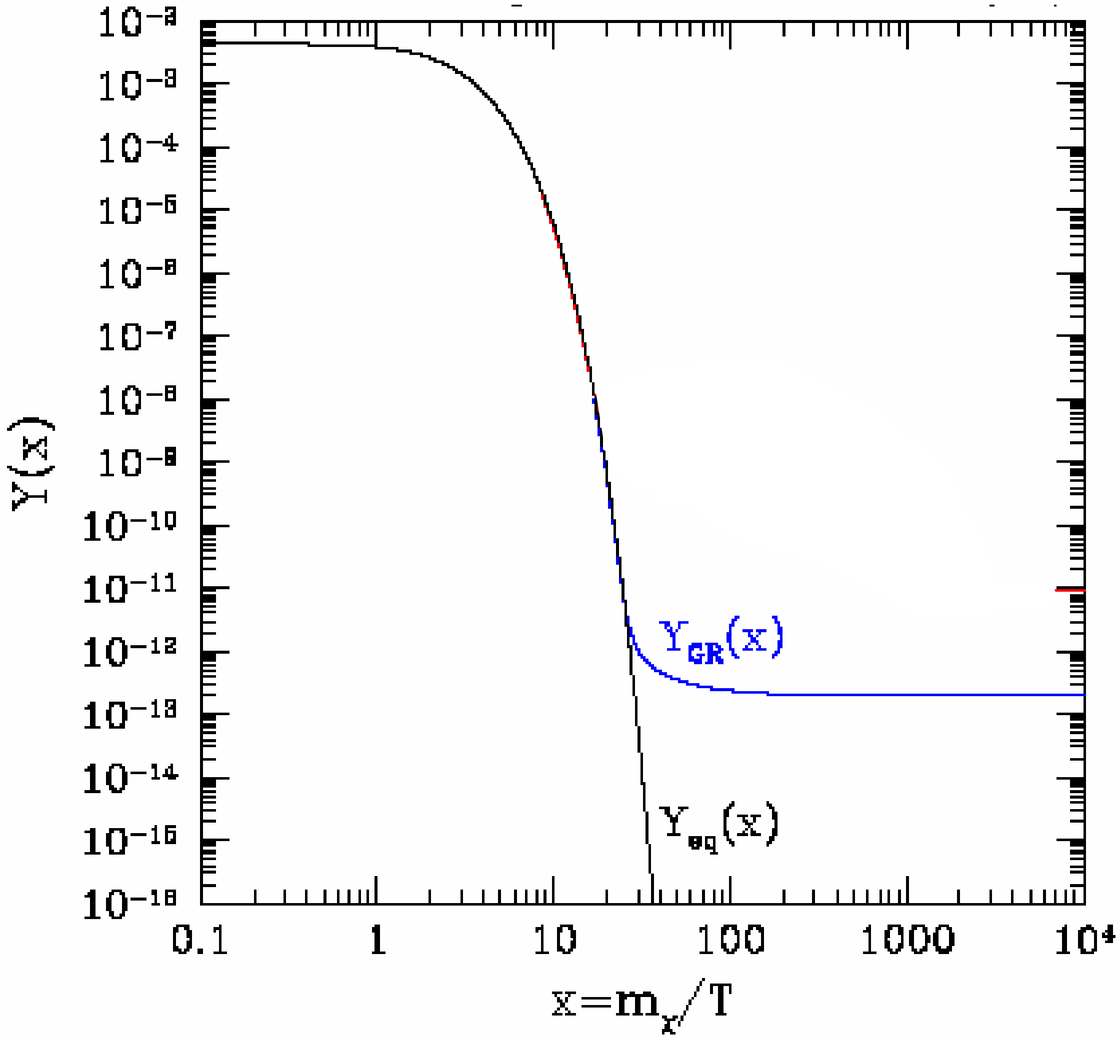
Production of relic particles

- Thermal production
  - ☆ **hot candidates** (relativistic at decoupling)
  - ☆ **cold candidates** (non-relativistic at decoupling)

- Non-thermal production

Cold relic particles are needed for the formation of cosmological structures

$$Y = nR^3$$



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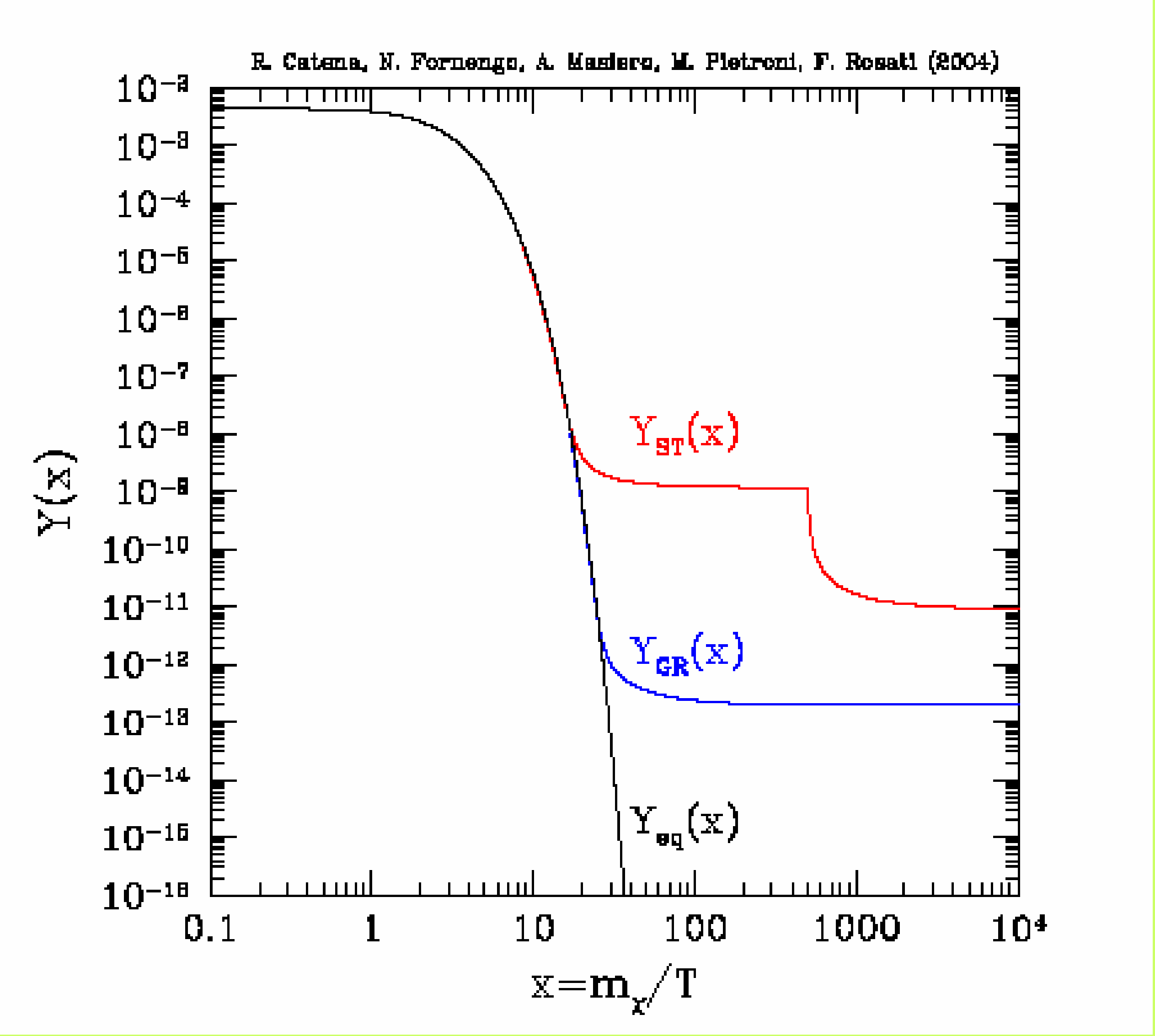


Catena, Fornengo, Masiero, Pietroni and Rosati: astro–ph/0403614

No candidate for cold dark matter (CDM) can be found in the Standard Model

Many natural candidates for CDM are found in extensions of the Standard Model not motivated by cosmological reasons

Particle Physics	Dark Matter Candidate
• massive-ν physics $\Longrightarrow$	light ($m_\nu < 1$ MeV) and heavy ν's
• supersymmetry $\Longrightarrow$	LSP (neutralino,...)
• strong CP-problem $\Longrightarrow$	axion
• Universal Extra Dimensions models $\Longrightarrow$	lightest Kaluza-Klein state

plus many ad-hoc candidates

Two important examples

☆ **Supersymmetric theories**

the Lightest Supersymmetric Particle is stable if R-parity is conserved

the nature of the LSP depends on the properties of the susy model and on the regions of the susy parameter space: many possibilities to have a LSP which is uncoloured and uncharged

the most popular case: LSP = neutralino

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

☆ **Theories with compactification of extra dimensions**

the Lightest Kaluza-Klein Particle is stable if KK-parity is conserved

several possibilities for a good candidate:
first level modes of massive neutral gauge bosons $B_1, W_1^{(3)}$
first level mode of the neutrino

Relic Abundance

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

$<\sigma_{\rm ann}\mathrm{v}>_{\rm int} \equiv$ thermal average of $\sigma_{\rm ann}\times$ relative velocity, integrated from the decoupling time to the present epoch.

Cosmological bound:

$$\Omega_\chi h^2 \le (\Omega_{\rm CDM} h^2)_{\rm max} \approx 0.13$$

$$\Rightarrow\ <\sigma_{\rm ann}\mathrm{v}>_{\rm int} \ge 2.3\times 10^{-38}\mathrm{cm}^2$$

Theories with compactification of extra dimensions
Universal Extra Dimensions models

▷ mass-shell relation in a (4 + D)-dimensional space

$$P^2 = p_0^2 - p_1^2 - p_2^2 - p_3^2 - \sum_i p_i^2 = m_0^2$$

in the four-dimensional space

$$\Rightarrow \quad M_{KK}^2 = p_0^2 - p_1^2 - p_2^2 - p_3^2 = m_0^2 + \sum_i p_i^2$$

▷ periodicity of the wave functions along any compact dimension

$$p_i = \frac{n_i}{R_i}$$

(n_i = mode number, R_i = size of the compact dimension)

$$\Rightarrow \quad M_{KK}^2 = m_0^2 + \sum_i \frac{n_i^2}{R_i^2}$$

i.e. a tower of states above each SM particle

From G. Servant and T.M.P. Tait, hep-ph/0206071

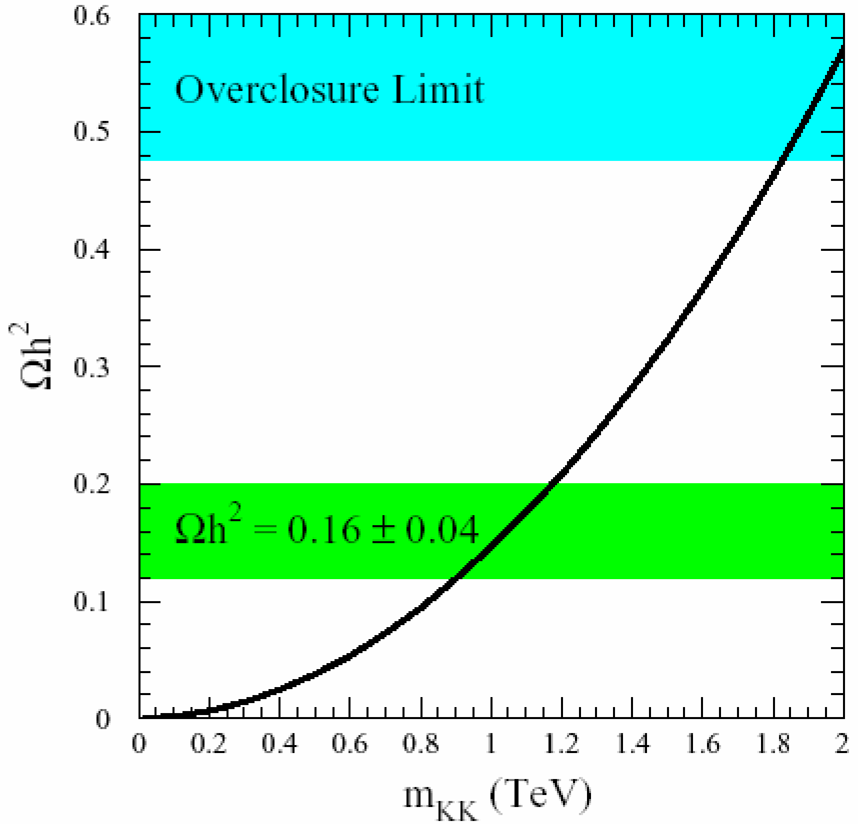
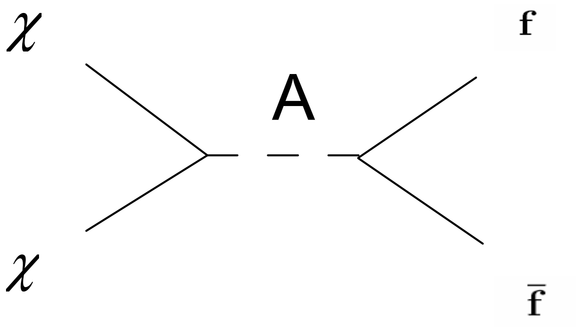
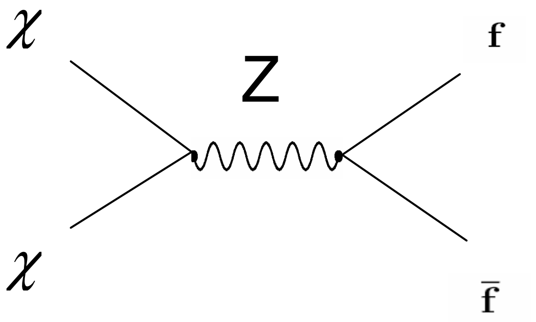


Figure 1: Prediction for $\Omega_{B^{(1)}} h^2$ as a function of the KK mass (when neglecting coannihilation). The upper horizontal region delimits the values of Ωh^2 above which the contribution from $B^{(1)}$ to the energy density would overclose the universe. The lower horizontal band denotes the region $\Omega = 0.33 \pm 0.035$ (using $h = 0.69 \pm 0.06$) and defines the KK mass window if all the dark matter is to be accounted for by the $B^{(1)}$ LKP.

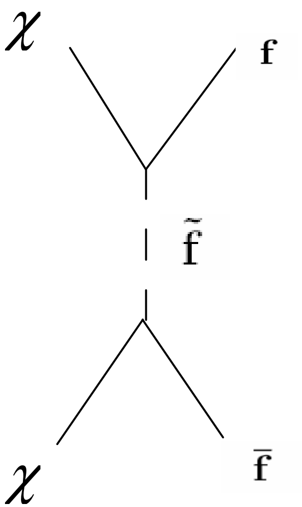
Neutralino – neutralino annihilation diagrams



exchange of a Higgs boson

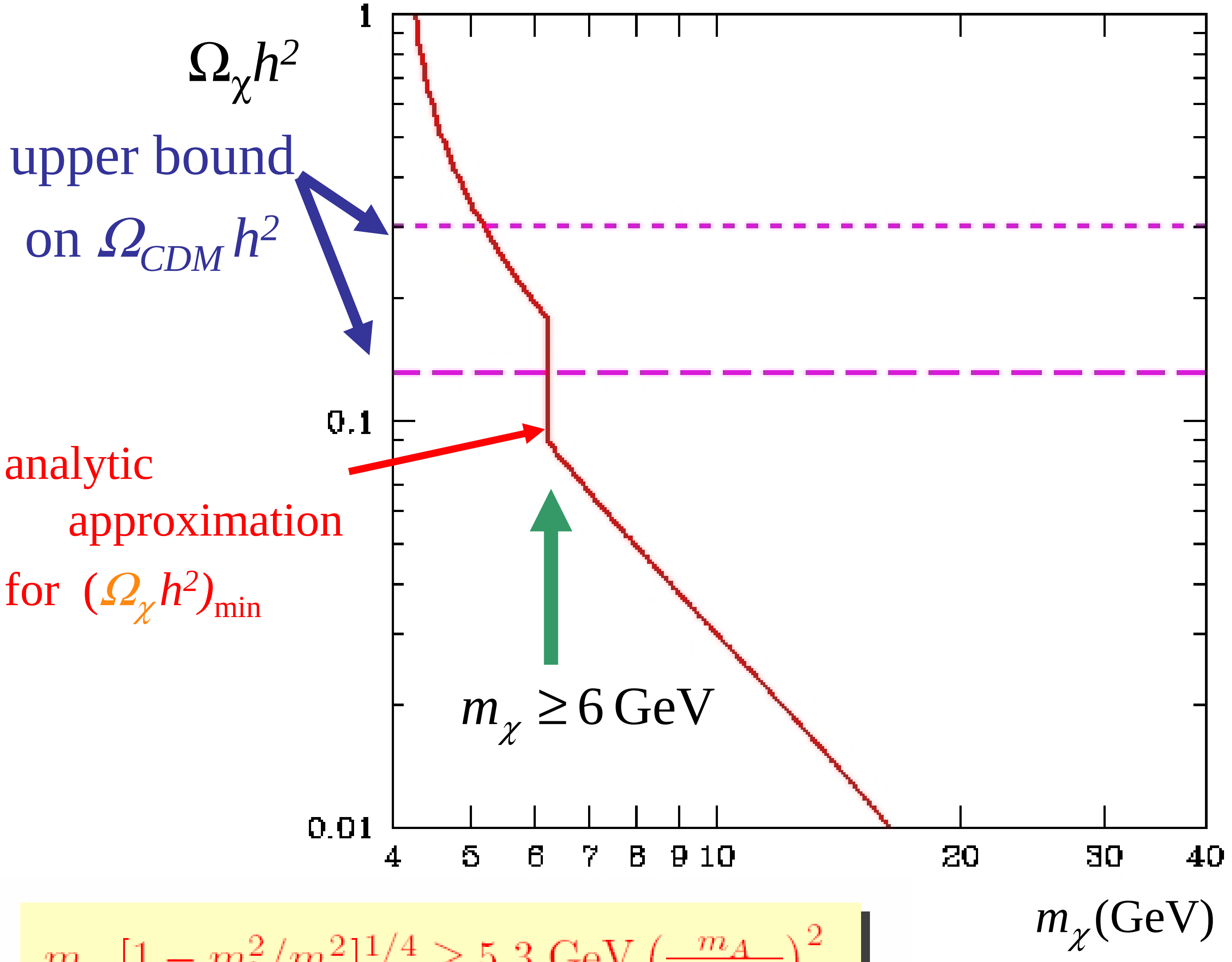


exchange of the Z boson



exchange of a sfermion

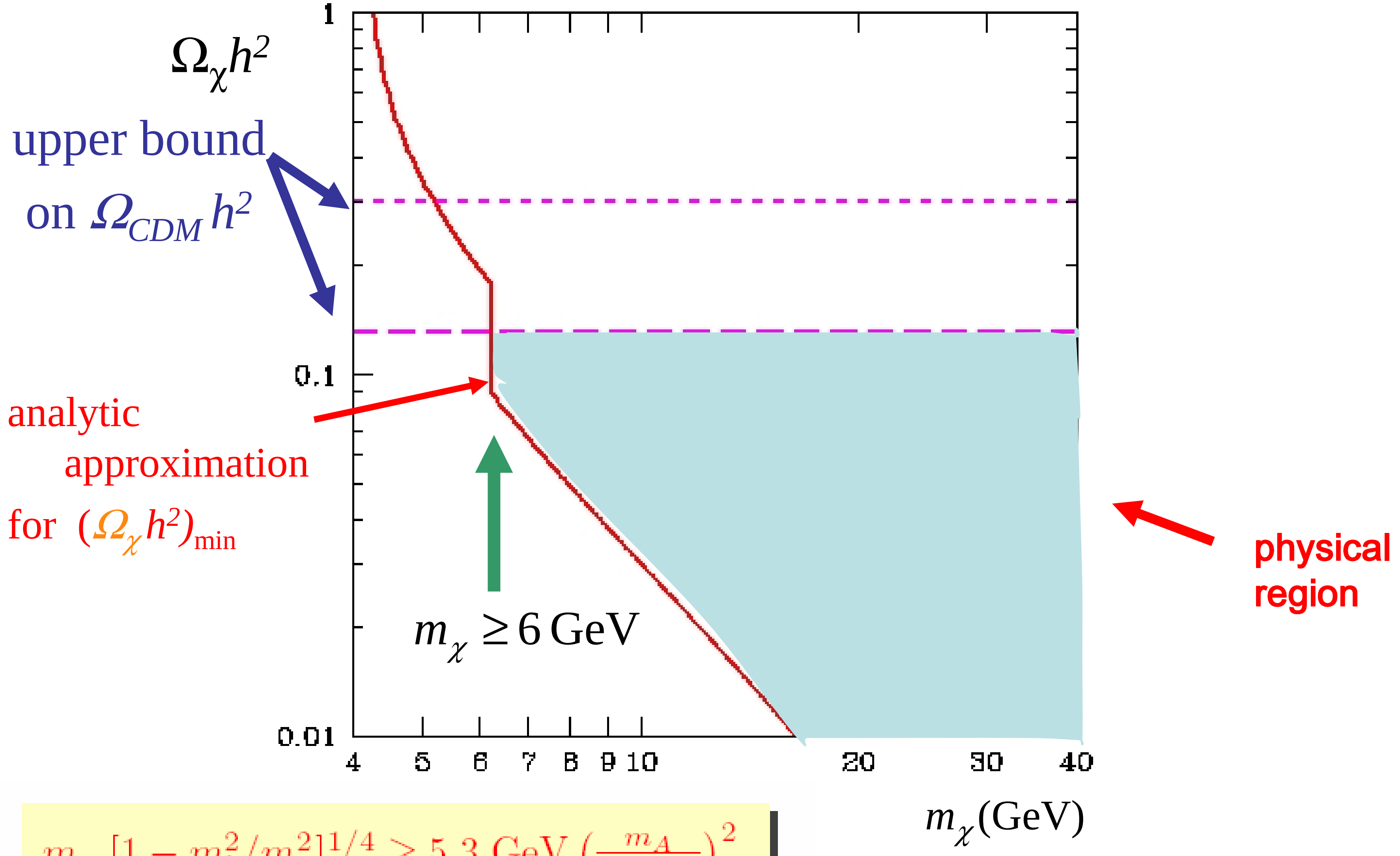
Cosmological bound on m_χ



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

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

Cosmological bound on m_χ



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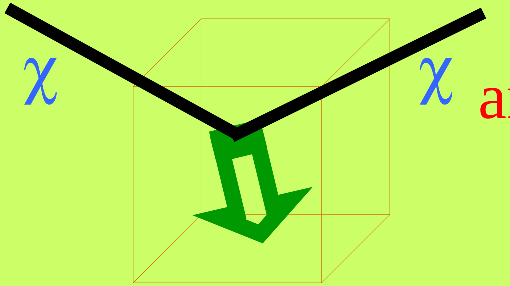
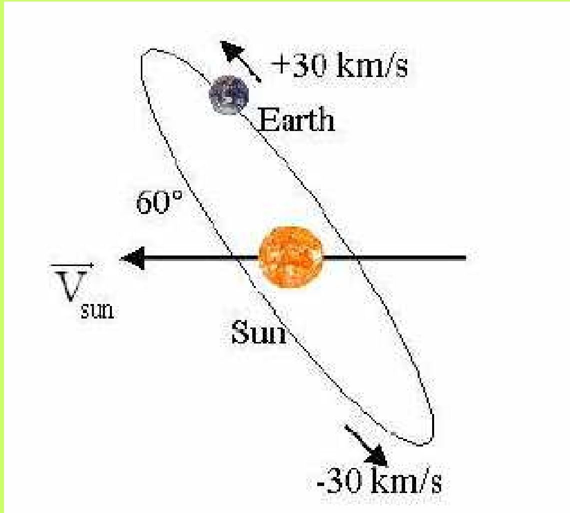
Detection of relic particles

WIMP direct measurements

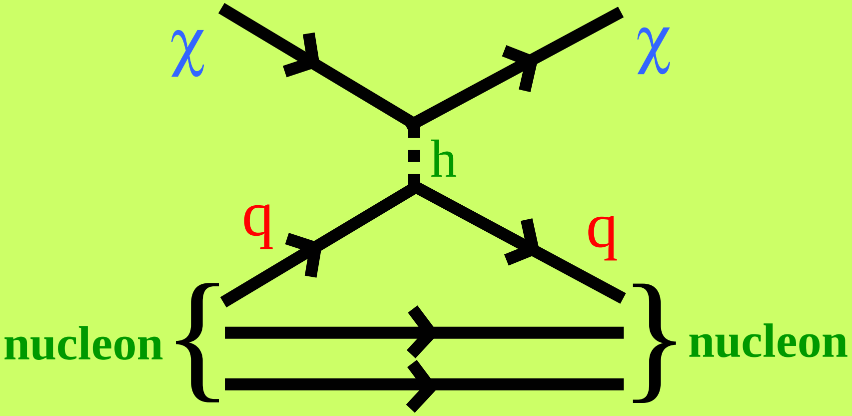


annual-modulation effect

nuclear-recoil measurement



"elementary" process

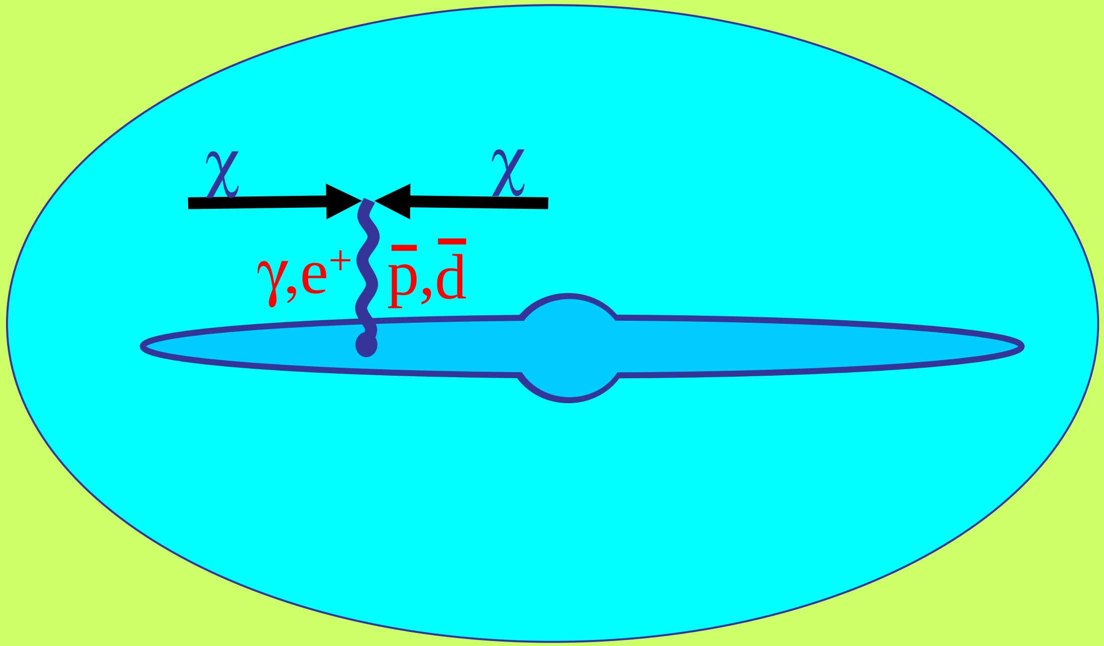


$$\sigma^{\text{(nuclear)}}_{\text{scalar}} \propto \frac{1}{m_{\text{h}}^4}$$

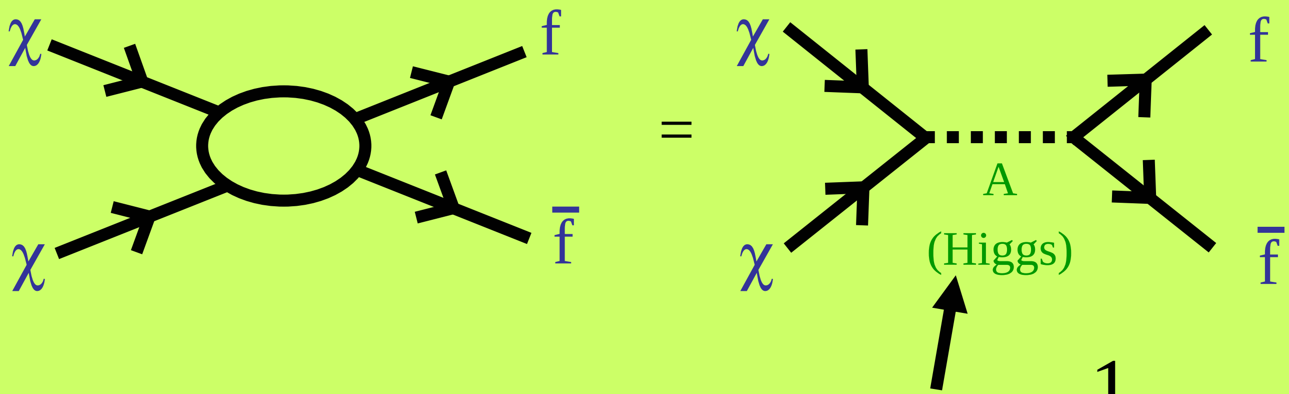
in susy, 3 neutral Higgs bosons

h, H	even under CP
A	odd under CP

Pair annihilation in the halo



an example:



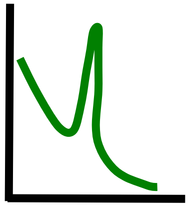
$$\sigma_{ann} \propto \frac{1}{m_{\mathrm{A}}^{4}}$$

Annihilations taking place in the Halo

$\chi + \chi \rightarrow$

$\nu, \bar{\nu}$

γ (continuum)



γ line (Zγ)

} keep directionality

e^+

$\bar{p}$

$\bar{D}$

} searches for rare components in cosmic rays

$$\text{detection rates} \propto (\text{Wimp density})^2$$

➡ **if halo is clumpy, strong enhancement in signal**

Bengtsson, Salati, Silk,
Silk, Stebbins
Berezinsky, A.B., Mignola

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)

Signals versus WIMP mass

(only orientative)

direct detection

exotic components of CRs

adequate for search of WIMPs with $m_\chi \approx$ *10 - a few hundreds GeV*

gamma-rays

neutrinos from Earth and Sun at km-cube neutrino telescopes

adequate for search of WIMPs with $m_\chi \approx$ *1-10 TeV*

Neutralino – nucleon cross section

Color code from now on:

● $\Omega_\chi h^2 < 0.095$

× $\Omega_\chi h^2 > 0.095$

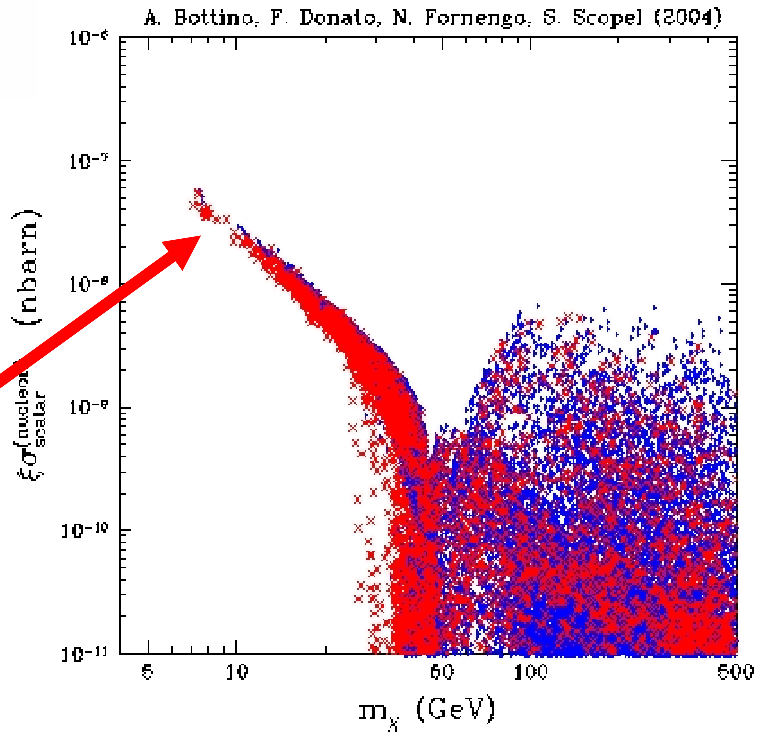
$$\Omega_\chi h^2 \le (\Omega_{CDM} h^2)_{max}$$

$$\Downarrow$$

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

The elastic cross section is bounded from below:

→ "funnel" at low mass



Neutralino – nucleon cross section

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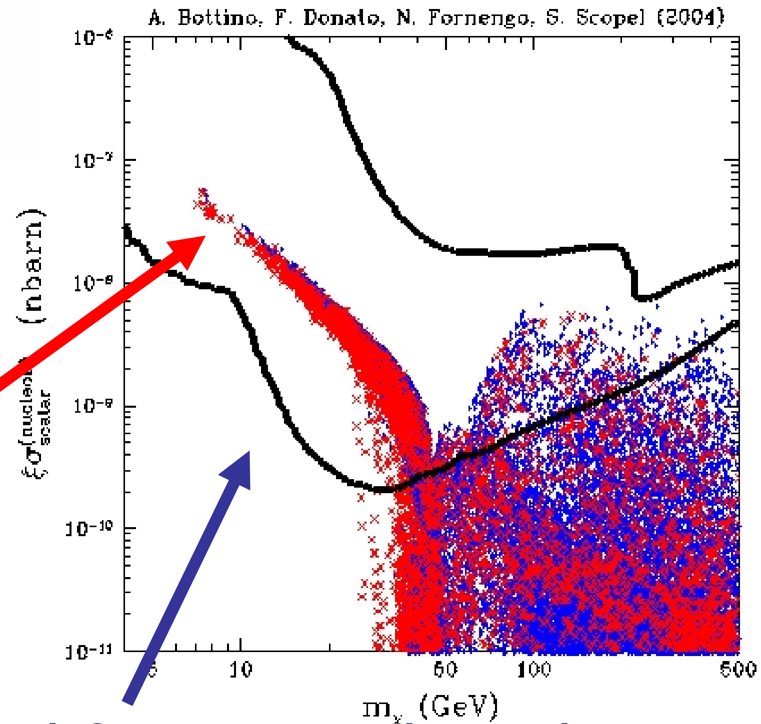
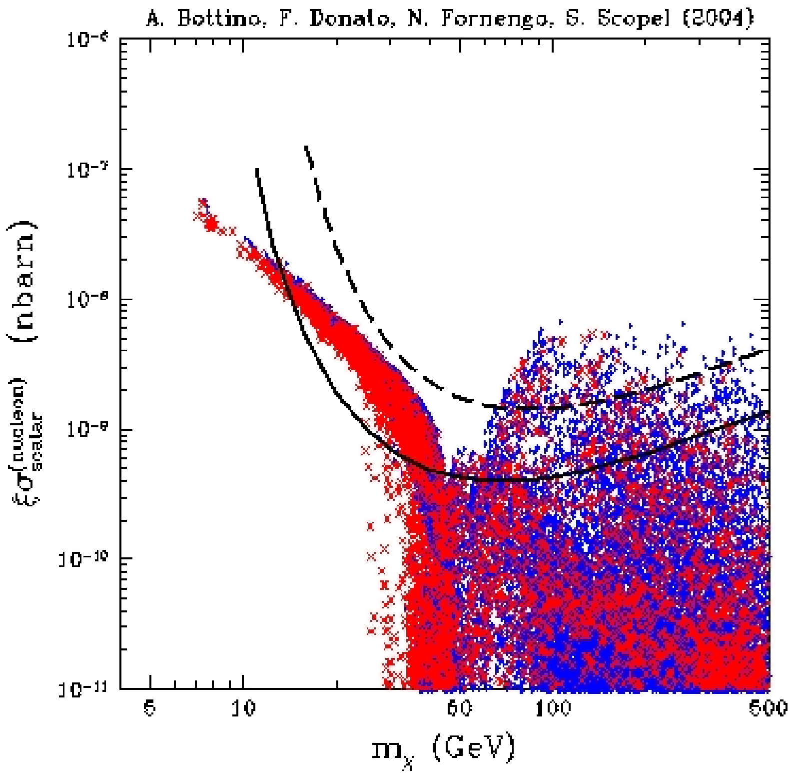


DAMA modulation region, likelyhood function values distant more than 4 σ from the null result (absence on modulation) hypothesis, Riv. N. Cim. 26 n. 1 (2003) 1-73, astro-ph/0307403
Exposure: about 108.000 kg day

Neutralino – nucleon cross section

Upper limits from direct searches

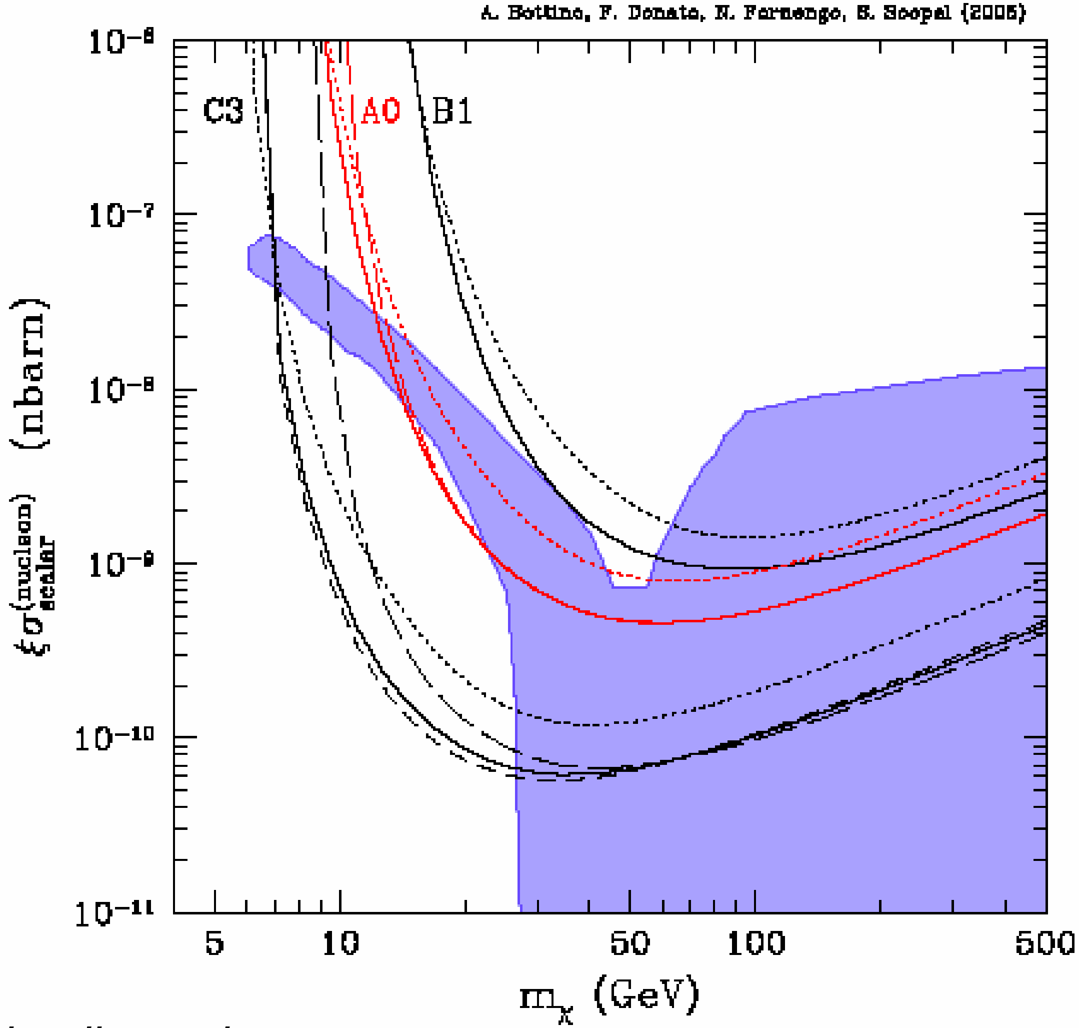
assumptions:
isothermal sphere,
v_0=220 km/sec,
ρ_0=0.3 GeV/cm^3



— — — EDELWEISS
A. Benoit *et al.*,
Phys. Lett. B 545, 43 (2002)

——— CDMS
D. S. Akerib *et al.*, astro-ph/0405033
(in astro-ph/0509259 the upper limit is improved by a factor of 2.5)

Dependence of the upper bounds on the WIMP galactic distribution function

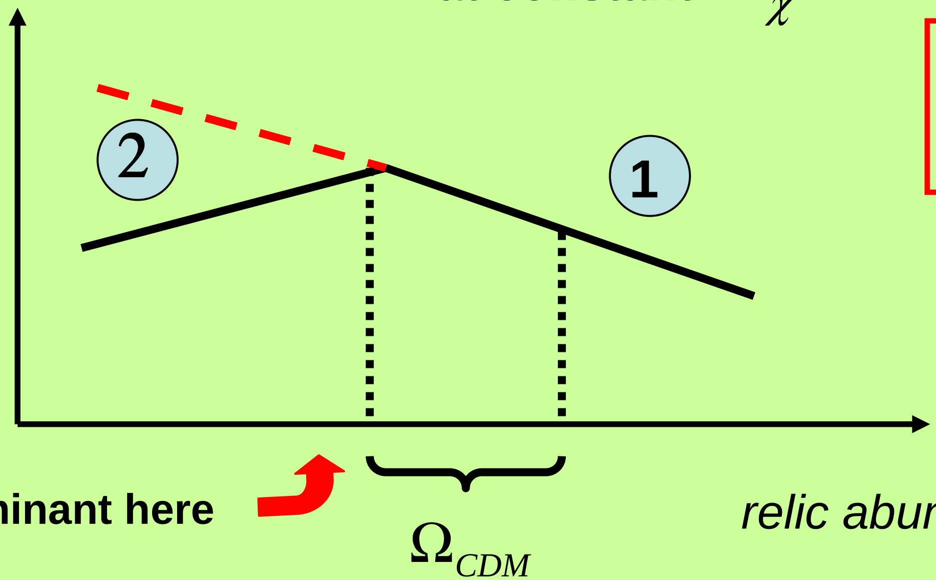


B1 = non-isotropic velocity dispersion

A0 = isothermal sphere

C3 = axisymmetric spatial distribution

Signals due to WIMP self-annihilation in the halo



$$R \propto \left(\frac{\rho_\chi}{\rho_{loc}}\right)^2 < \sigma_{ann} v >_0 \frac{1}{m_\chi^2}$$

$$\Omega_\chi \propto \frac{1}{< \sigma_{ann} v >_{\text{int}}}$$

1 $R \propto < \sigma_{ann} v >_0 \frac{1}{m_\chi^2}$

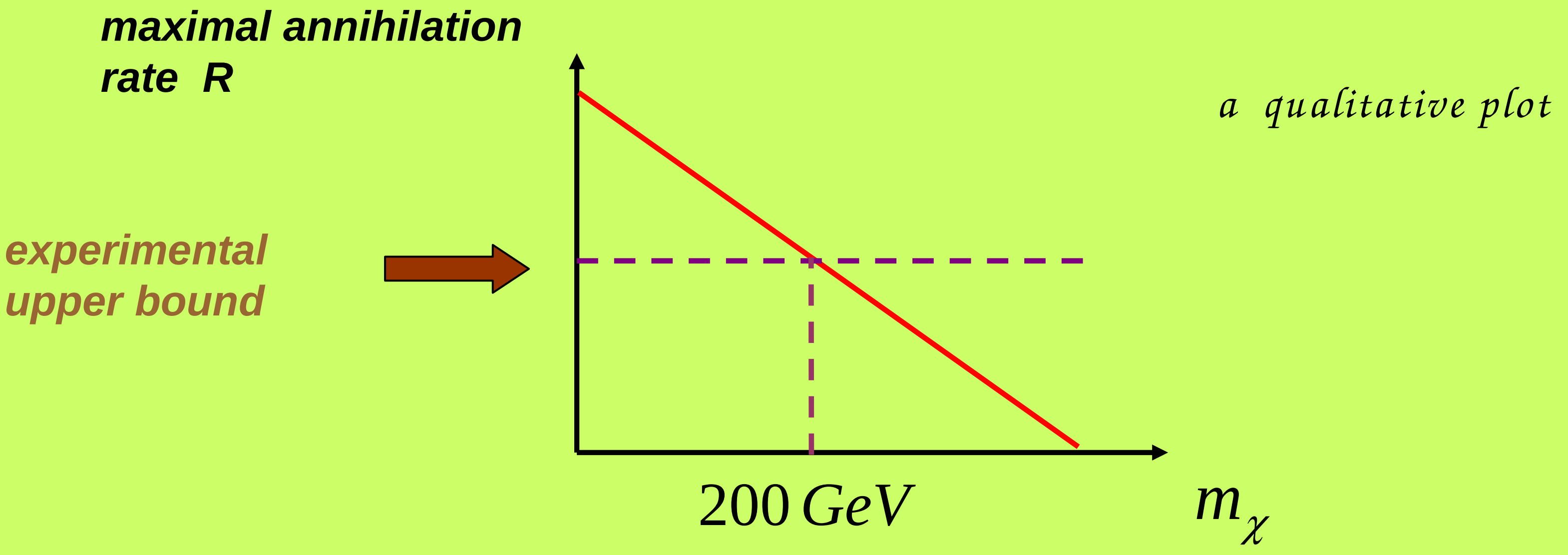
2 $R \propto \left(\frac{\rho_\chi}{\rho_{loc}}\right)^2 < \sigma_{ann} v >_0 \frac{1}{m_\chi^2} \propto \frac{< \sigma_{ann} v >_0}{< \sigma_{ann} v >_{\text{int}}^2} \frac{1}{m_\chi^2}$

Thus the quantity $\left(\frac{\rho_\chi}{\rho_{loc}}\right)^2 < \sigma_{ann} v >_0$ **is maximal at** $\Omega_\chi = (\Omega_{CDM})_{\min} \cong 0.1$

$$\left[\left(\frac{\rho_\chi}{\rho_{loc}}\right)^2 < \sigma_{ann} v >_0\right]_{\max} \cong 10^{-36} cm^2$$

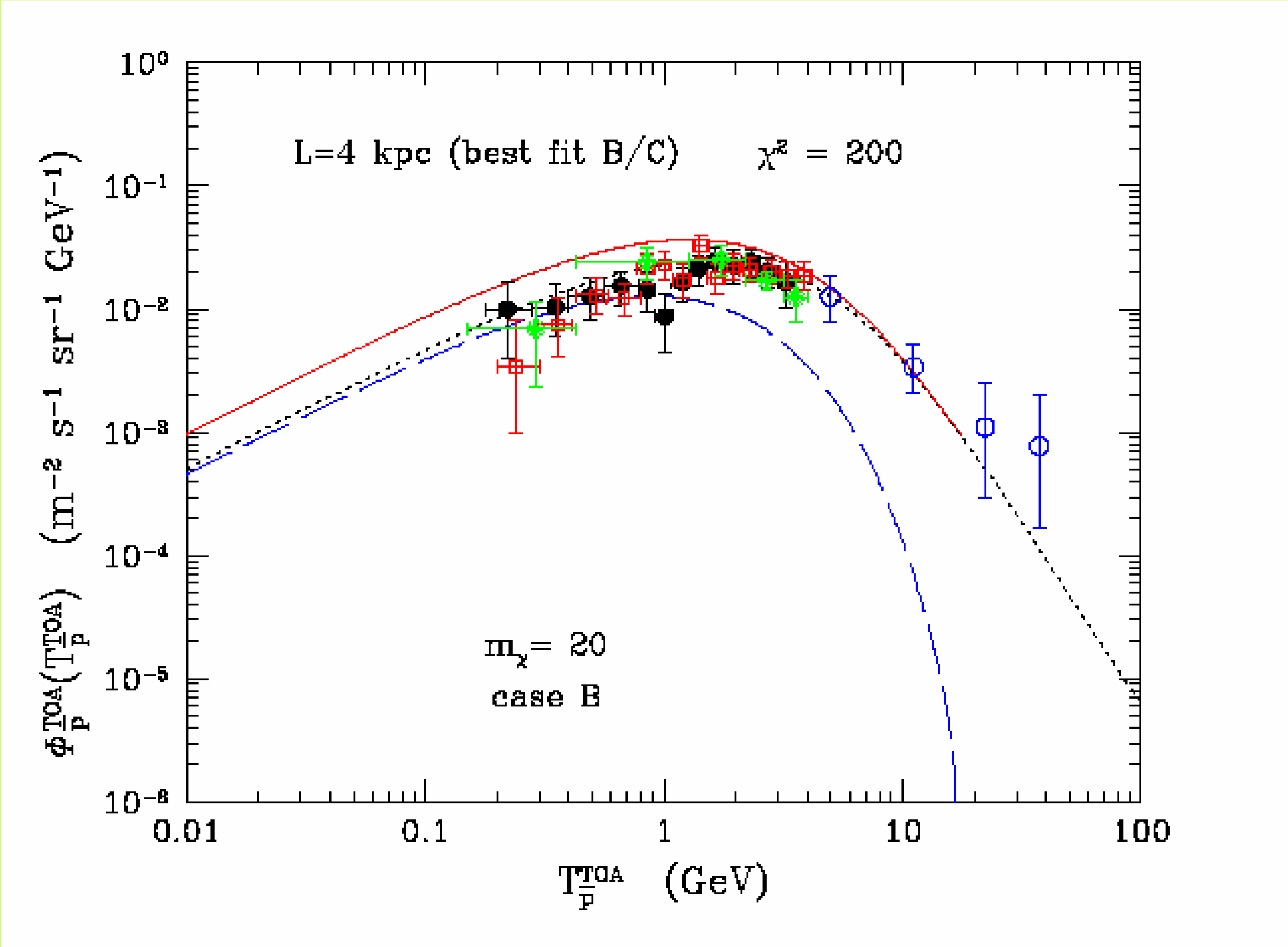
Antiprotons

Among the signals due to WIMP self-annihilation in the halo, those of antiprotons are the most constraining for relic neutralinos with masses in the range $10\,GeV \le m_\chi \le 200\,GeV$

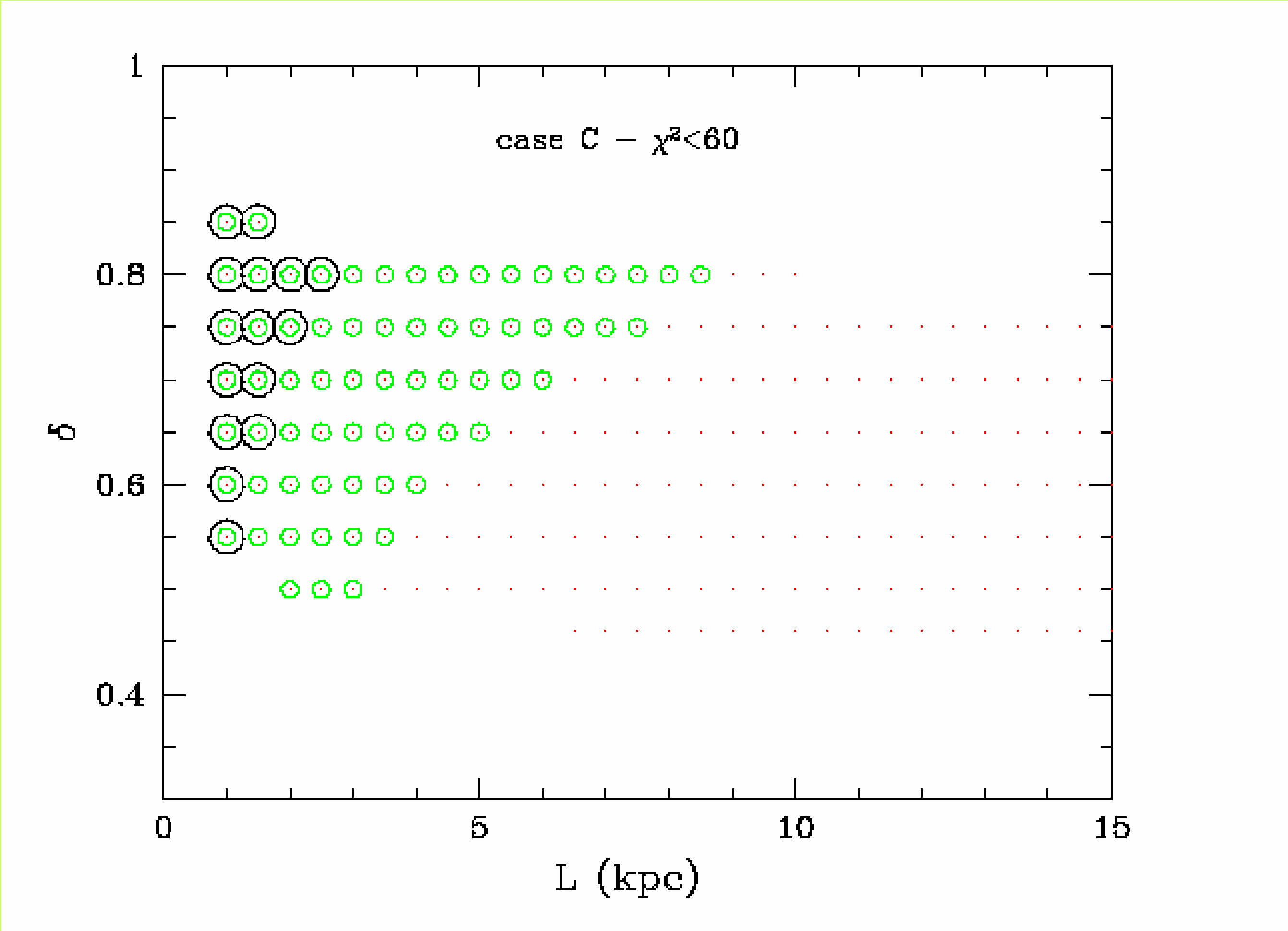


above $m_\chi \approx 200\,GeV$ ***antiprotons from neutralino self annihilation are irrelevant (e.g. are dominated by secondary production) unless the halo is substantially clumpy***

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

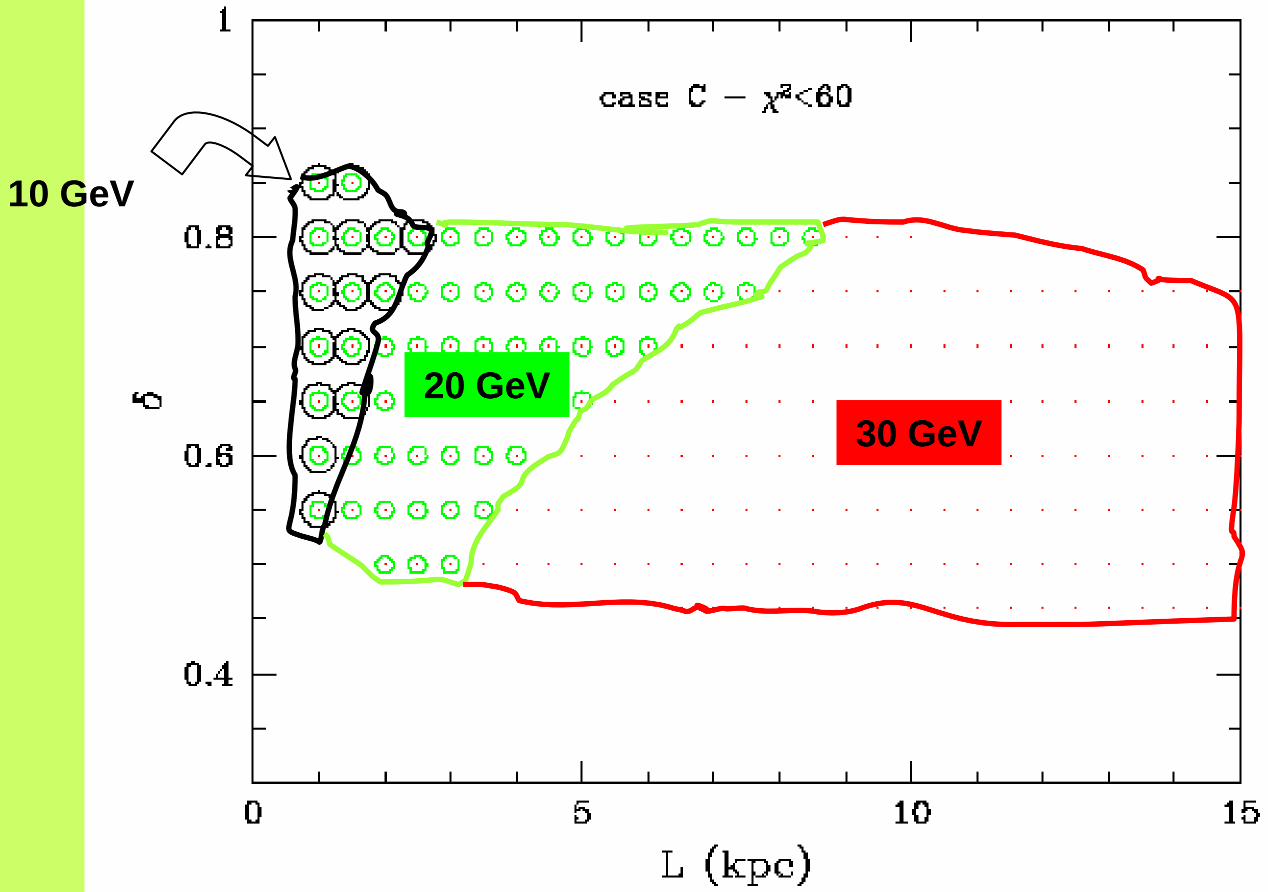


- *effects due to light neutralinos can be sizeable, but hardly distinguishable from background*
- *constraints relaxed by astrophysical uncertainties of primary fluxes*



Diffusion in a two-zones halo:

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



Diffusion in a two-zones halo:

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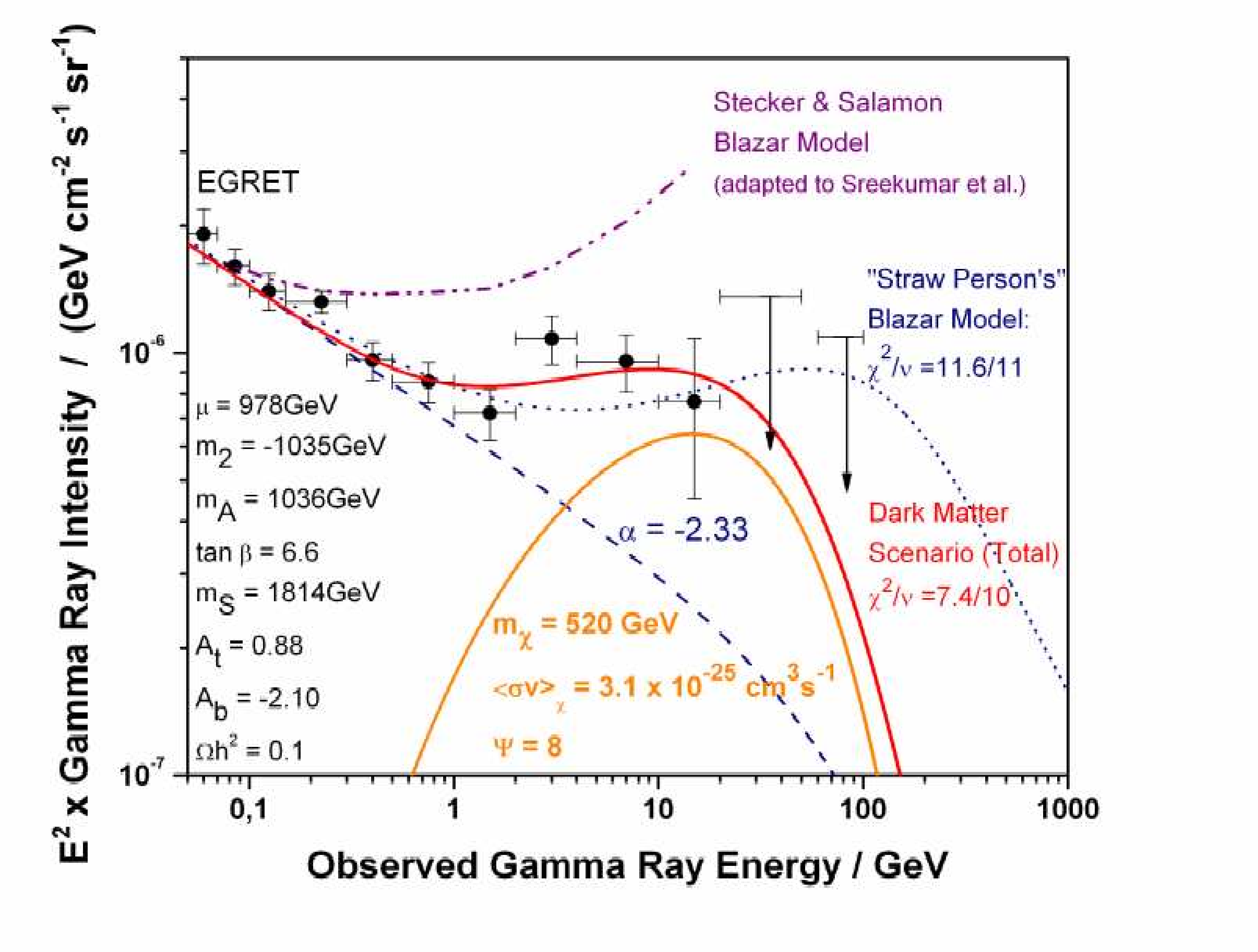
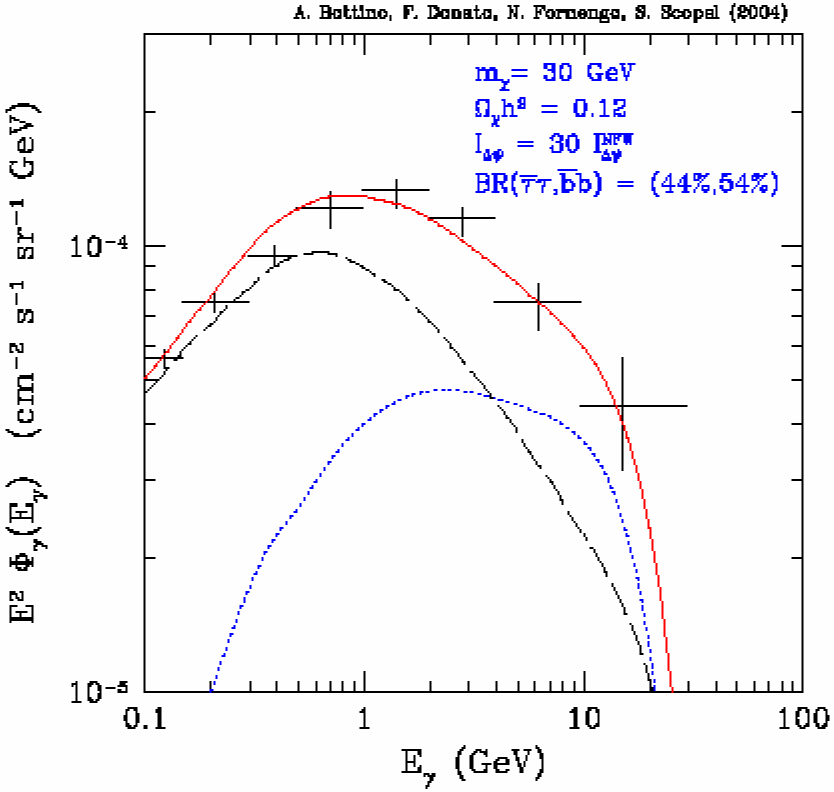
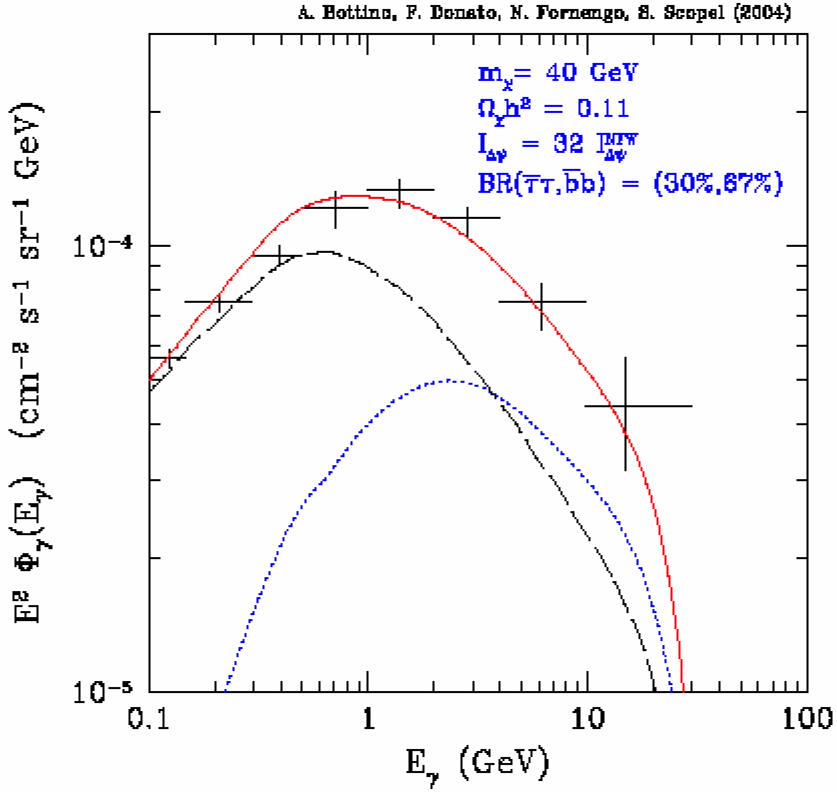
Gamma-rays



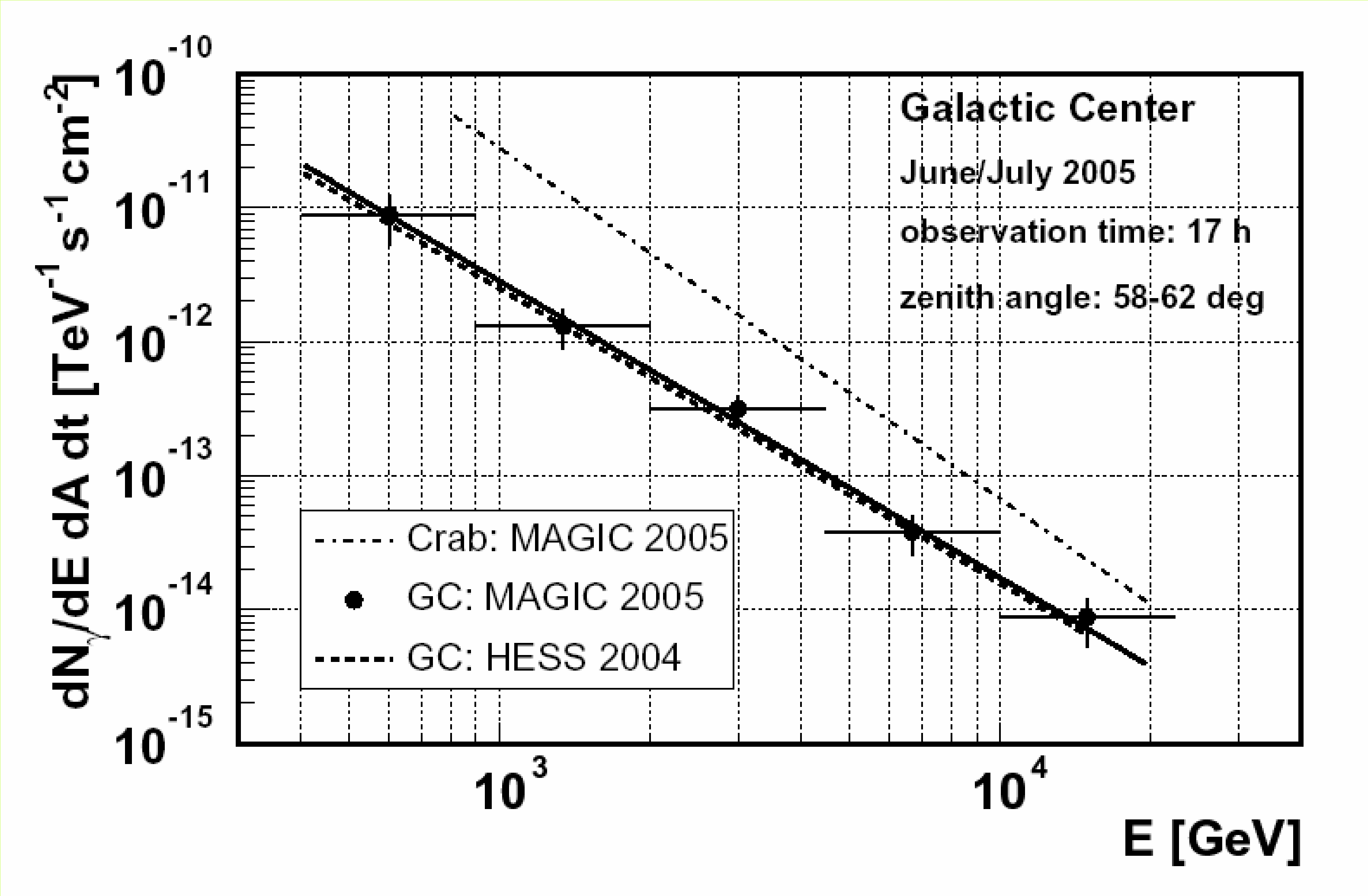
Elsasser and Mannheim: astro-ph/0405235



A. Bottino, F. Donato, N. Fornengo, S. Scopel (2004)
m_χ= 30 GeV
$\Omega_\chi h^2$ = 0.12
$I_{\Delta\psi}$ = 30 $I_{\Delta\psi}^{NFW}$
BR($\bar{\tau}\tau$,$\bar{b}b$) = (44%,54%)
$E^2\ \Phi_\gamma(E_\gamma)$ ($cm^{-2}\ s^{-1}\ sr^{-1}$ GeV)
10^{-4}
10^{-5}
0.1
1
10
100
E_γ (GeV)



A. Bottino, F. Donato, N. Fornengo, S. Scopel (2004)
m_χ= 40 GeV
$\Omega_\chi h^2$ = 0.11
$I_{\Delta\psi}$ = 32 $I_{\Delta\psi}^{NFW}$
BR($\bar{\tau}\tau$,$\bar{b}b$) = (30%,67%)
$E^2\ \Phi_\gamma(E_\gamma)$ ($cm^{-2}\ s^{-1}\ sr^{-1}$ GeV)
10^{-4}
10^{-5}
0.1
1
10
100
E_γ (GeV)



J. Albert et al, astro-ph/0512469

Conclusions (for this part)

- ***Particle dark matter is being actively searched for by different independent means***
- ***Present experimental sensitivities already allow investigation of some interesting particle physics models (e.g. neutralino in some classes of super-symmetric schemes)***
- ***Clear-cut interpretations of experimental data require a conservative approach – hopefully other independent investigations will provide significant reduction of astrophysical uncertainties***
- ***Independent information from accelerators is necessary***

Search for dark matter was one of the major scientific interests of Angel Morales

His theoretical interest extented to the experimental aspects of WIMP direct detection:

- pioneering activity in the field

- activity of the Zaragoza group on searches for dark matter at the Canfranc Laboratory:
COSME, ANAIS, ROSEBUD, IGEX-DM

- driving force also in experiments in other laboratories and in the shaping of an European coordination in this field

PHYSICAL REVIEW D VOLUME 56, NUMBER 4 15 AUGUST 1997

Results of a search for annual modulation of WIMP signals

M. L. Sarsa, A. Morales, J. Morales, E. García, A. Ortiz de Solórzano, J. Puimedón, C. Sáenz, A. Salinas, and J. A. Villar
Laboratory of Nuclear and High Energy Physics, University of Zaragoza, 50009 Zaragoza, Spain
(Received 20 January 1997)

A search for particle cold dark matter (CDM) has been carried out at the Canfranc Underground Laboratory (Spain) with a set of three sodium iodide scintillators of 10.7 kg each, during about 2 yr of data taking. The results, corresponding to an exposure of 4613.6 kg day are presented in the form of exclusion plots of the WIMP-target nuclei cross section versus WIMP mass (both for spin-independent and spin-dependent WIMP-matter interactions), obtained with the standard method of comparing the observed rate with the expected signal. A distinctive feature of the CDM signal, like its expected annual modulation, has also been looked for in 1342.8 kg day of data. The nonobservance of such a modulation has been used to draw more stringent exclusion plots than those derived from the standard method. [S0556-2821(97)02316-3]

PACS number(s): 95.35.+d, 14.60.St, 29.40.Mc

Review talks on WIMP direct detection

TAUP 2003

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Nuclear Physics B (Proc. Suppl.) 138 (2005) 135–144

NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS

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Non-cryogenics dark matter experiments

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The current status of WIMP direct searches with conventional detectors is overviewed, emphasizing strategies, achievements and prospects.