Particle Dark Matter Interpretation of Direct Searches

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Alessandro Bottino
INFN/Universita' di Torino

Outline

- Some generalities about direct detection of dark matter particles (DMP)

- A selection of possible particle candidates (neutralinos and more exotic particles)

- Constraints from indirect measurements

- Role of the Large Hadron Collider in a possible identification of particle candidates (neutralinos)

Interpretation of experiments for direct detection of Dark Matter Particles (DMP) has to deal with three main features:

1) phase-space distribution functions (DF) of the DMP in the galactic halo
2) nature of the specific DMP
3) interaction mechanisms of the DMP with the target material (and strength of the interaction).

Items 2 and 3 are obviously strictly interdependent.

Distributions of DMP in the galactic halo

Large variety of thermalized distribution functions (DF)
(standard isothermal sphere, non-isotropic distribution in space and/or in velocities) see, e.g., P. Belli, R. Cerulli, N. Fornengo and S. Scopel, Phys. Rev. D 66 (2002) 043503

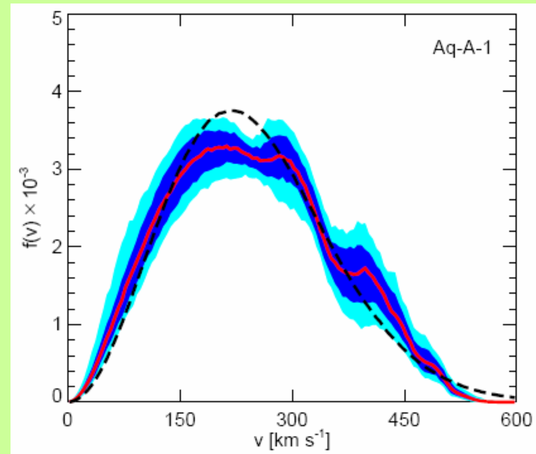
The selection of a particular distribution function plays a crucial role in the derivation

$$\text{detection rate} \Rightarrow (\text{fractional density})_{\text{DMP}} \times \sigma^{(\text{DMP})}_{\text{target particle}}$$

Some examples are discussed later

Streams (K. Freese, P. Gondolo, H.J. Newberg and M. Lewis, Phys. Rev. Lett. 92 (2004) 111301;
R. Bernabei et al., Eur. Phys. J C47 (2006) 263;
L.D. Duffy and P. Sikivie, Phys. Rev. D 78 (2008) 063508)

New high-resolution simulations (M. Vogelsberger et al., arXiv:0812.0362 [astro-ph]– Aquarious Project): the DM local velocity distribution differs from a Gaussian distribution



Dark matter disk due to late accretion of satellites (J.I.Read et al. arXiv:0901.2938 [astro-ph.GA]): potentially relevant for WIMP more massive than 50 GeV

Annual-modulation effect at 8.2 sigmas measured in DAMA/NaI and DAMA/LIBRA (total exposure of 0.82 ton yr – Eur. Phys. J. C (2008) arXiv:0804.2741) can be due to:

- **nuclear recoil (scintillation)**
- **interaction on atomic electrons**
- **inelastic transitions within the dark matter candidate**
- **conversion of the impinging particle energy into electr. magn. radiation**
- **...**

Some of these processes would not be classified as due to WIMPs in other experiments of WIMP direct search where electromagnetic signals are rejected.

A very large number of candidates and interaction mechanisms have been considered by various authors.

We concentrare here on the following few cases:

- two “exotic” ones:

  inelastic dark matter (many possible physical realizations)

  mirror dark matter

- the most popular one (for very good reasons: linked to expectations for supersymmetric theories and next investigations at LHC):

  the neutralino

Other candidates are discussed in Workshop Sessions:

Sneutrinos in extended versions of MSSM by B. Dutta and by D. Cerdeno

Axions by L. Visinelli

Candidates within the Inert Doublet Model by C. Arina

Inelastic dark matter (iDM)

(D. Tucker-Smith and N. Weiner, arXiv:hep-ph/0101138
S. Chang, G.D. Kribs, D. Tucker-Smith and N. Weiner,
arXiv:0807.2250 [hep-ph])

Features of the model:

- the dark matter particle χ has an excited state χ^* with a mass splitting

$$\delta \cong m_{\chi^*} - m_\chi \cong v^2 m_\chi \cong 100 keV$$

- the elastic scattering of χ off nuclei $\chi + N \to \chi + N$ is suppressed as compared to the inelastic scattering

$$\chi + N \to \chi^* + N$$

Consequences:

- χ interacts with target nuclei only if $v \geq v_{\min} = \sqrt{\frac{1}{2m_N E_R}}(\frac{m_N E_R}{m_{red}} + \delta)$

- heavier targets are favored over lighter ones

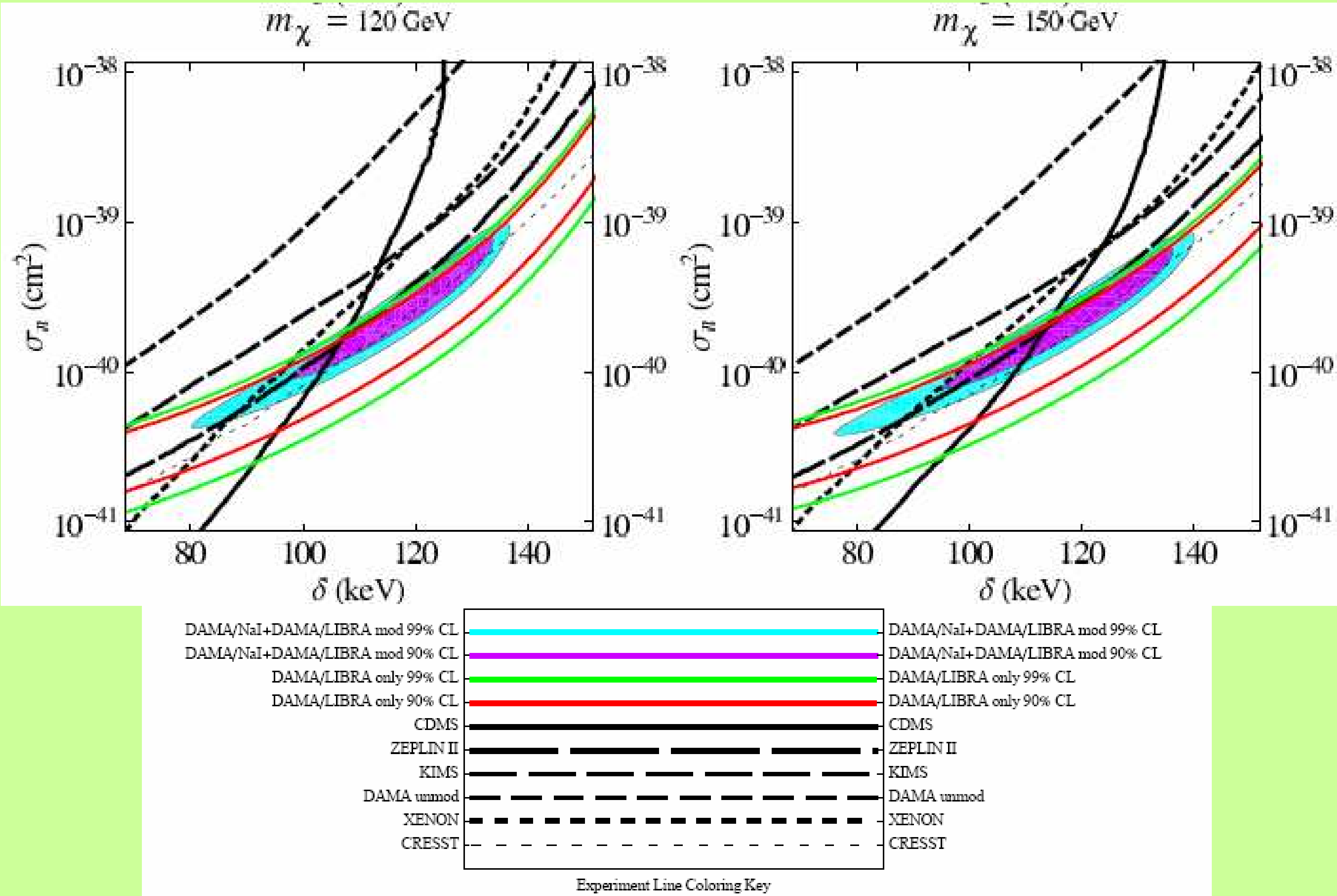
- the fractional modulation effect is enhanced as compared to the usual one

Other consequences of the iDM model depend sensitively on the specific features of the various experiments:

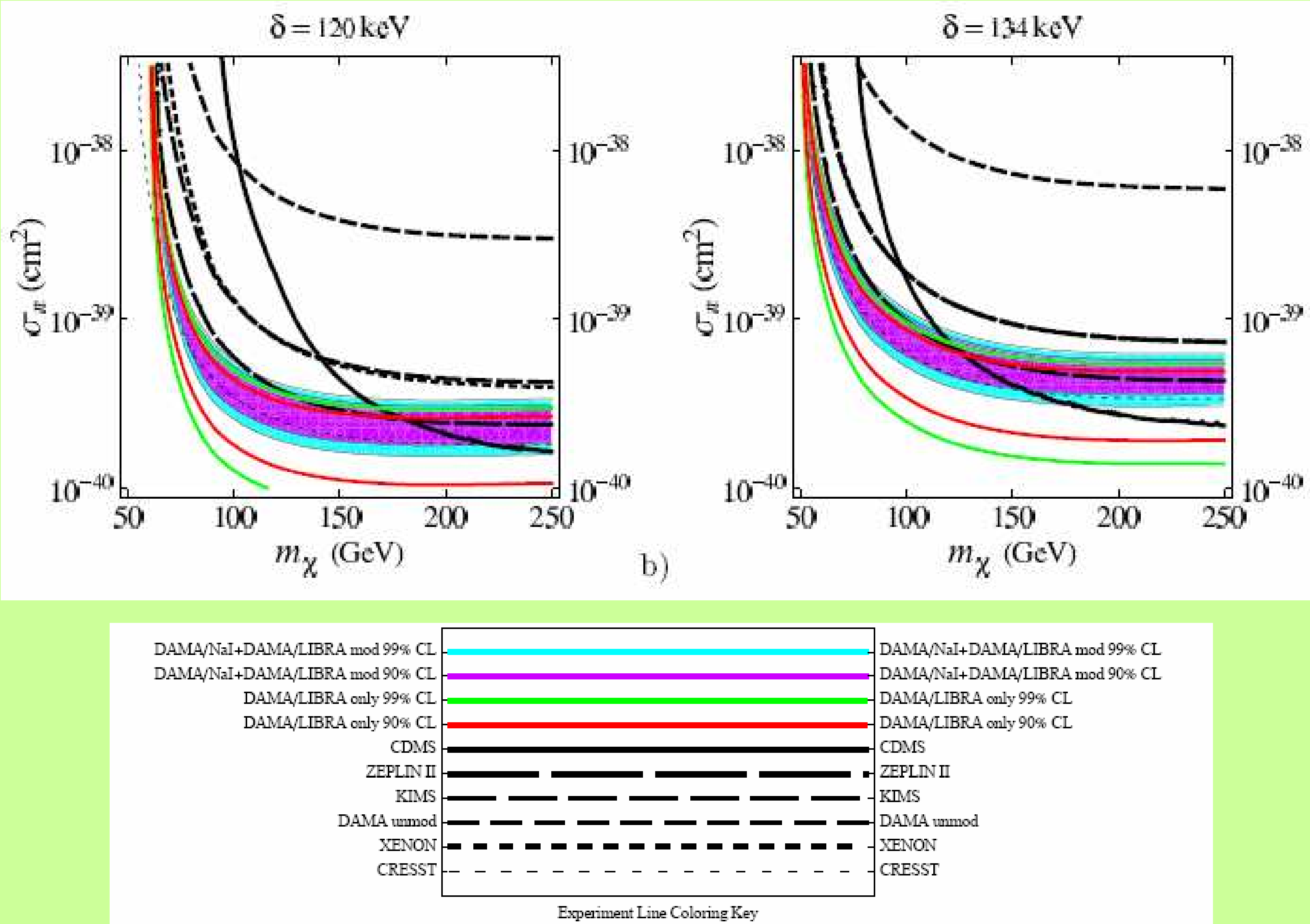
- **energy thresholds**

- **period of year** of the experimental run

S. Chang, G.D. Kribs, D.TuckerSmith and N. Weiner, arXiv:0807.2250 [hep-ph])



S. Chang, G.D. Kribs, D.TuckerSmith and N. Weiner, arXiv:0807.2250 [hep-ph])



According to arXiv:0906.4119 [astro-ph] by D.B. Cline, W. Ooi and H. Wang the upper bound set by ZEPLIN II on iDM is sensitively more severe than the one reproduced in the previous plots.

Physical realizations:

sneutrinos with lepton-number violation ⟹ sneutrinos mix with anti-sneutrinos generating a mass splitting in the mass eigenstates

Hall, Moroi and Murayama, Phys. Lett. B424 (1998) 305
Tucker-Smith and Weiner, Phys. Rev. D 64 (2001) 043502
Arina and Fornengo, JHEP 0711:029 (2007)

a fourth generation Dirac neutrino constituted by 2 Majorana states originally degenerate under an U(1) symmetry

breaking of this U(1) ⟹ splitting between the two Majorana fermions

Tucker-Smith and Weiner, Phys. Rev. D72 (2005) 063509

Mirror dark matter (R. Foot, Phys. Rev. D78 (2008) 043529)

Exact parity symmetry model as a minimal extension of the standard model allowing for an exact unbroken parity symmetry: x → -x,t → t. To each type of ordinary particle corresponds a mirror partner of the same mass:

electron ⟹ mirror electron, quark ⟹ mirror quark, etc

T.D. Lee and C.N. Yang, Phys. Rev. 104 (1956) 256

I. Kobzarev, L. Okun and I. Pomeranchuk, Sov. J. Nucl. Phys. 3 (1966) 837

Couplings of the particles in the mirror sector are the same as the corresponding couplings in the ordinary sector.

Ordinary particles and mirror particles interact with each other via gravity. Other interactions are possible, e.g. via a photon-mirror photon interaction Lagrangian

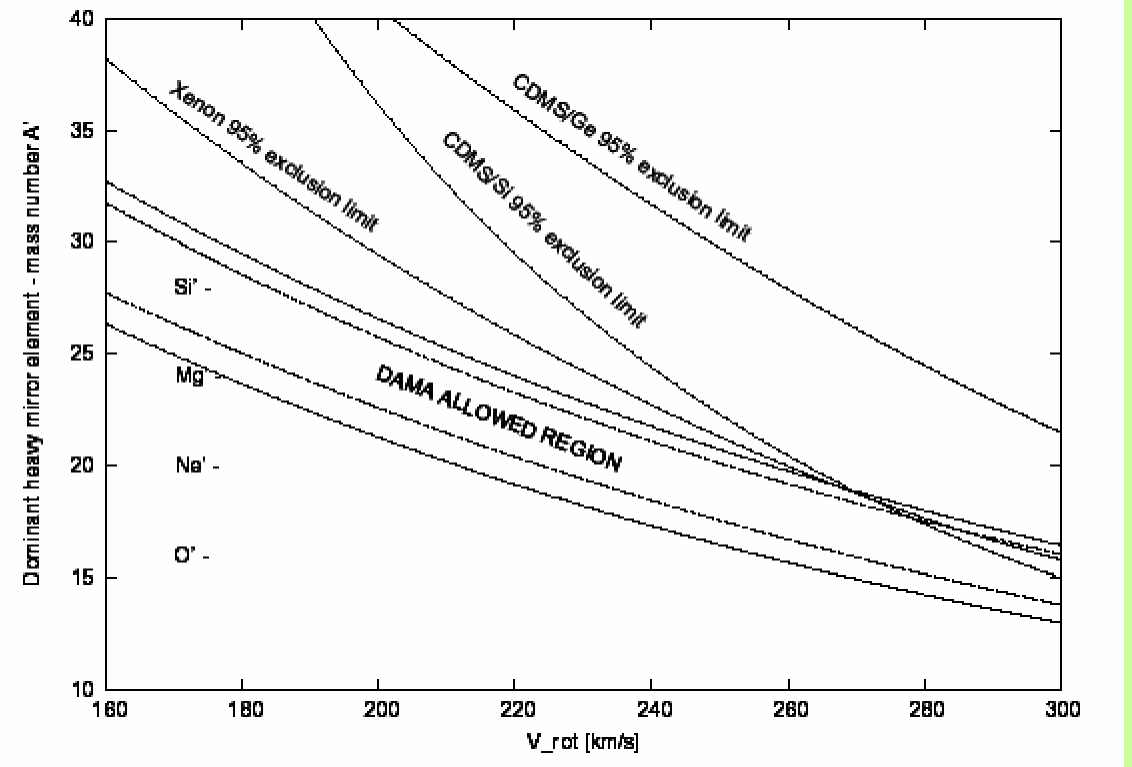
$$L = \frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

This term implies that a charged mirror particle couples to ordinary photon with an effective charge $\varepsilon \times e$

Mirror particles might play the role of non-baryonic DM
S.I. Blinnikov and M. Yu. Khoplov, Sov. J. Nucl. Phys. 36 (1982) 472

The relevant cosmology is rather involved (see R. Foot and references therein).

Signals in experiments of DMP direct detection would be caused by halo mirror nuclei which scatter off an ordinary nucleus in the detector by a standard Rutherford scattering (induced by photon-mirror photon Lagrangian).



Relic neutralinos

effective -MSSM

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

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

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

Relic abundance for cold relics: (thermal decoupling) $\Omega_\chi h^2 \approx \frac{3 \times 10^{-39}\ \mathrm{cm}^2}{<\sigma_{\mathrm{ann}} v>_{\mathrm{int}}}$

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

and limited from above by the cosmological bound $\Omega_{CDM} h^2 \leq 0.12$

This implies a lower limit à la Lee-Weinberg on the neutralino mass

$$m_\chi \geq 6\,\mathrm{GeV}$$

much smaller than the CMSSM limit: $m_\chi \geq 50\,\mathrm{GeV}$.

A.B., Donato, Fornengo and Scopel, Phys. Rev. D67 (2003) 063519

For large values of the Higgs mass $m_A \geq 200\mathrm{GeV}$: $m_\chi \geq 18\,\mathrm{GeV}$

D. Hooper and T. Plehn, Phys. Lett. B562 (2003) 18
G. Belanger, F. Boudjema, A. Puhkov and S. Rosier-Lees, hep-ph/0212227

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, Nucl. Phys. B392 (1993) 83
D.G. Cerdeno, C. Hugonie, D.E. Lopez-Fogliani, C. Munoz and A.M. Teixera , JHEP0412:048 (2004)
J. Gunion, D. Hooper, and B. McElrath, Phys. Rev. D76 (2006) 015011

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)

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

Also direct detection rates for relic neutralinos are sizably enhanced once a specific WIMP distribution function (DF) is assumed, the expected detection rate is

$$R \propto \rho_\chi \times \sigma_{\chi-\mathrm{nucleus}} = \rho_{tot} \times \xi \times \sigma_{\chi-\mathrm{nucleus}}$$

where

$$\xi \equiv \frac{\rho_\chi}{\rho_{tot}} = \min\left(1, \frac{\Omega_\chi h^2}{(\Omega_{\mathrm{CDM}} h^2)_{\min}}\right)$$

computed

from observational data

in case of coherent interaction:

$$\sigma_{\chi-\mathrm{nucleus}} \propto A^2 \sigma_{\mathrm{scalar}}^{(\mathrm{nucleon})} \Rightarrow R \propto \xi \sigma_{scalar}^{(nucleon)}$$

The neutralino-nucleon scattering cross section takes its largest values when it is mediated by Higgs exchange.
This cross section is dominated by the term

$$g_d \simeq \frac{2}{27}(m_N + \frac{23}{4}\sigma_{\pi N} + \frac{25}{4} r(\sigma_{\pi N} - \sigma_0))$$

Due to the large uncertainties in the hadronic quantities:

pion-nucleon sigma term

$$41 \text{ MeV} \lesssim \sigma_{\pi N} \lesssim 57 \text{ MeV}$$ Koch 1982

$$55 \text{ MeV} \lesssim \sigma_{\pi N} \lesssim 73 \text{ MeV}$$ Pavan et al. hep-ph/0111066

SU(3) symmetry breaking term

$$\sigma_0 = 30 \div 40 \text{ MeV}$$ Gasser and Leutwyler (1982)

is affected by an uncertainty factor of order 30.

A.B., F. Donato, N. Fornengo and S. Scopel:
Astrop. Phys. 13 (2000) 215 (hep-ph/9909228)
Astrop. Phys. 18 (2002) 205 (hep-ph/0111229)

In the following:

★ in the supersymmetric scatter plot the reference values

$$g_{u,ref} = 123 MeV, g_{d,ref} = 290 MeV$$

are used

★ to take into account hadronic uncertainties, an extension of the physical region is introduced: the WIMP-nucleon cross section is scaled upwards roughly by a factor

$$(\frac{g_{d,\max}}{g_{d,ref}})^2 \cong 3.3$$

and downwards by a factor

$$(\frac{g_{d,\min}}{g_{d,ref}})^2 \cong \frac{1}{8.6}$$

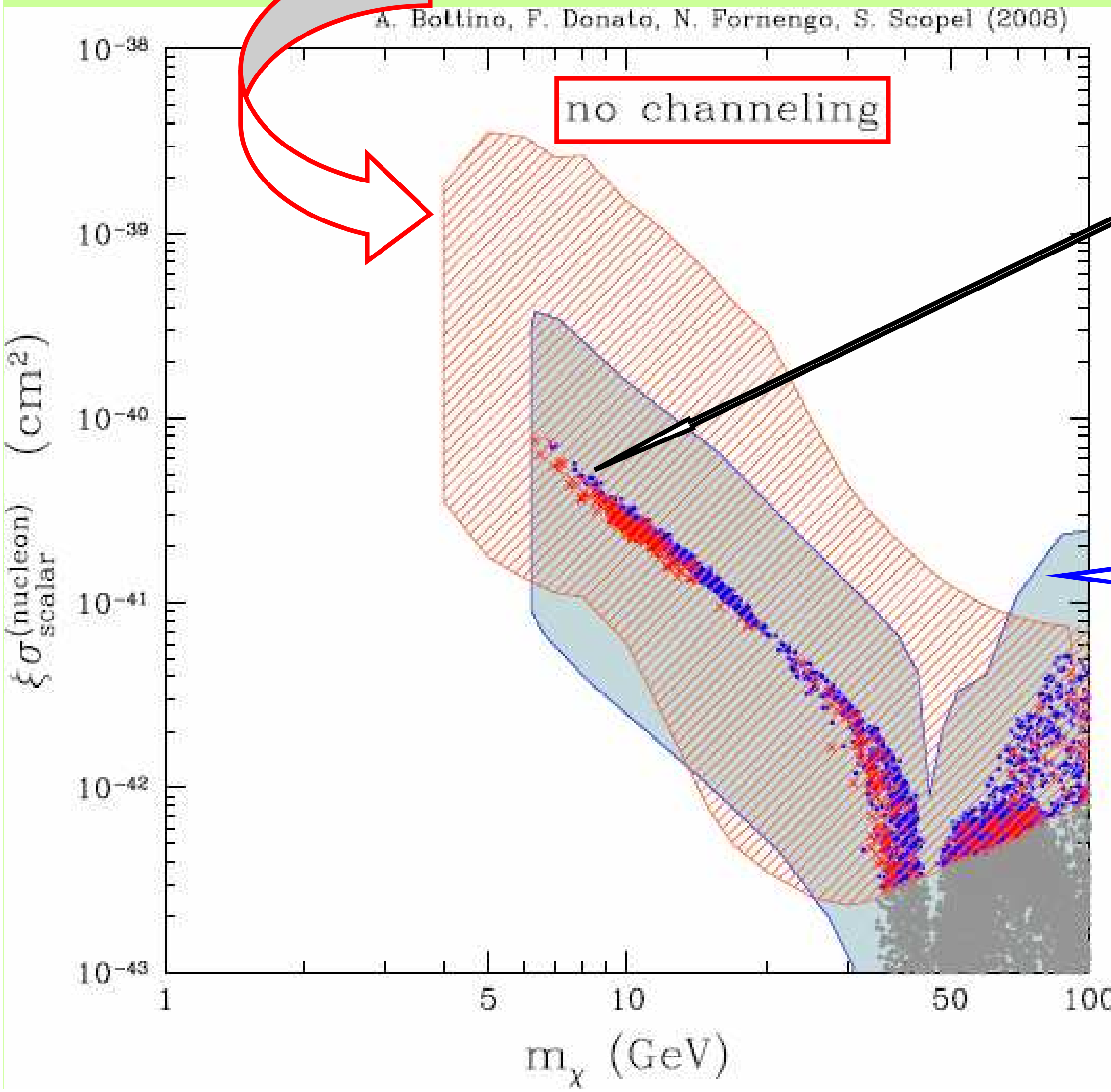
Other references on uncertainties in the hadronic quantities :

J. Ellis, A. Ferstl and K.A. Olive, Phys. Lett. B481 (2000) 304
E. Accomando, R. Arnowitt, B. Dutta and Y. Santoso, Nucl.Phys. B585 (2000) 124
A. Corsetti and P. Nath, [arXiv:hep-ph/0003186]
J.L. Feng, K.T. Matchev and F. Wilczek, Phys.Lett. B482} (2000) 388
J. Ellis, K.A. Olive and C. Savage, arXiv:0801.3656 [hep-ph]

DAMA region DAMA/(NaI + LIBRA) for a WIMP with coherent interaction , domain where likelihood values differ more than 6.5 sigmas from null hypothesis

convolution over DFs .

For aspects of model-dependence in the derivation see arXiv:0710.0288.



Relic neutralinos as DM: scatter plot at the reference point: $g_{u,ref} = 123 MeV, g_{d,ref} = 290 MeV$

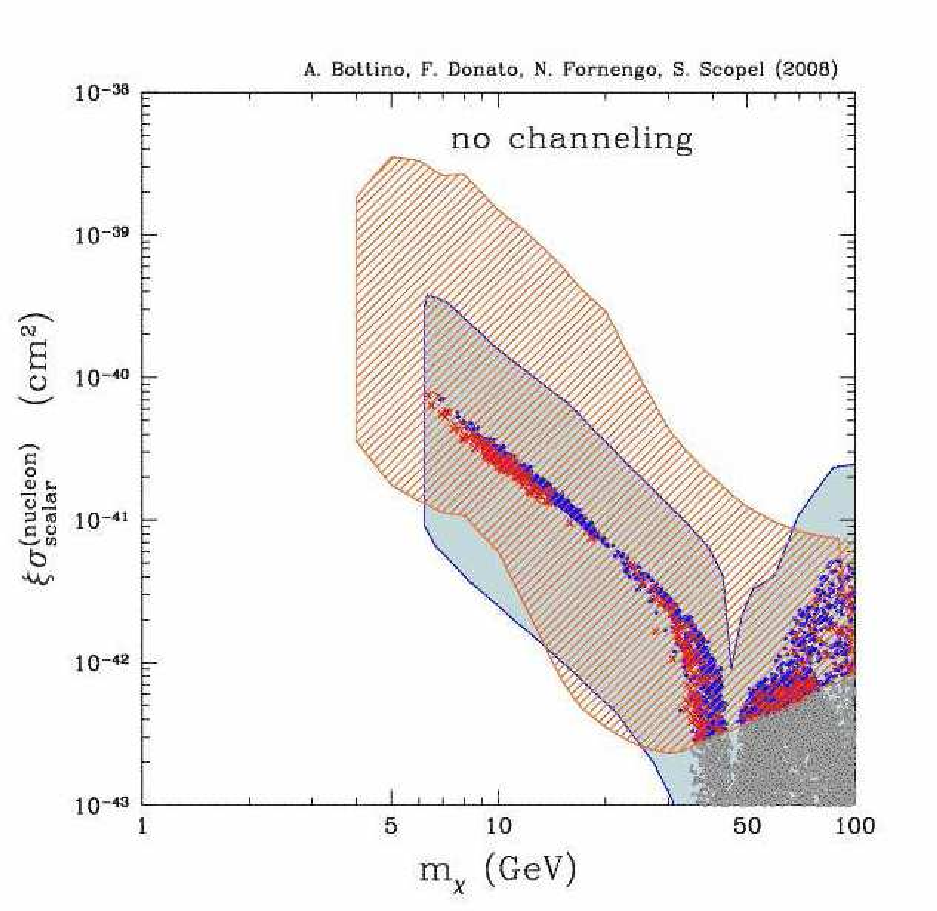
dominant: red crosses

subdominant : blue dots

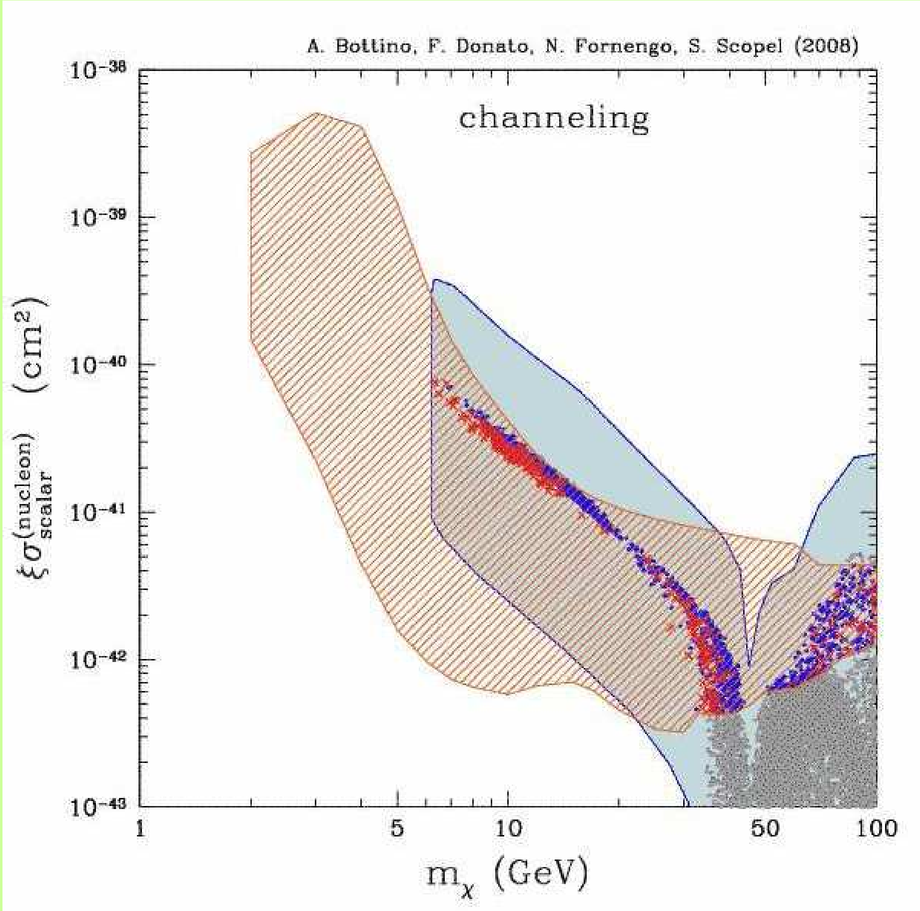
Blue region: extension of the scatter plot due to hadronic uncertainties

A.B., Donato, Fornengo, Scopel, Phys. Rev.D 78 (2008) arXiv:0806.4099 (hep-ph)

no channeling



with channeling

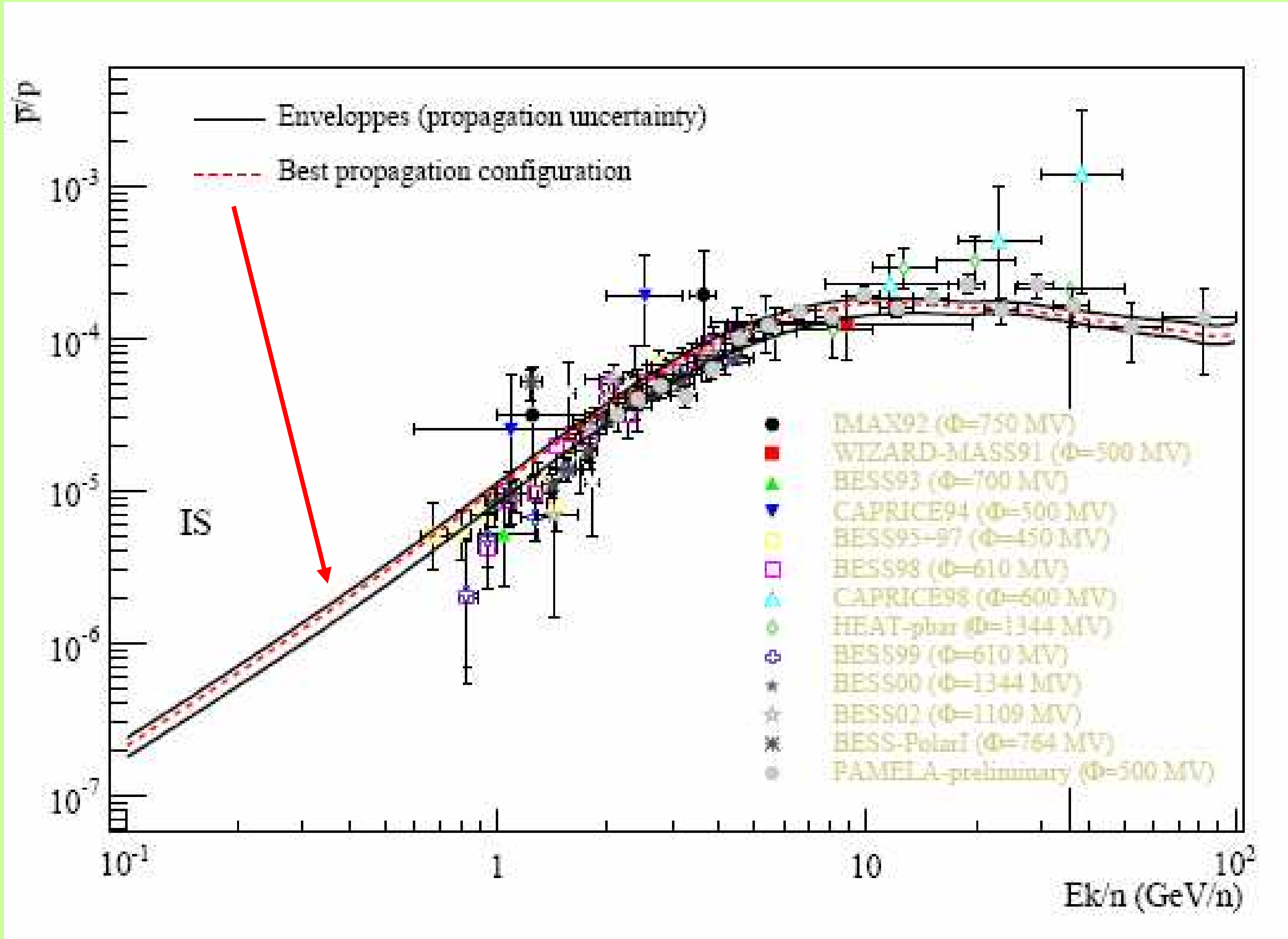


In general, light WIMPs might be severely constrained by cosmic antiprotons.

A large set of the light neutralino population discussed above is compatible with the cosmic antiproton bounds especially for values of local dark matter density and local rotational velocity in the low side of their physical ranges and for values of the diffusion parameters not too close to the values of their maximal set.

For details see A.B., F. Donato, N. Fornengo, S. Scopel, Phys. Rev.D 78 (2008), arXiv:0806.4099 (hep-ph)

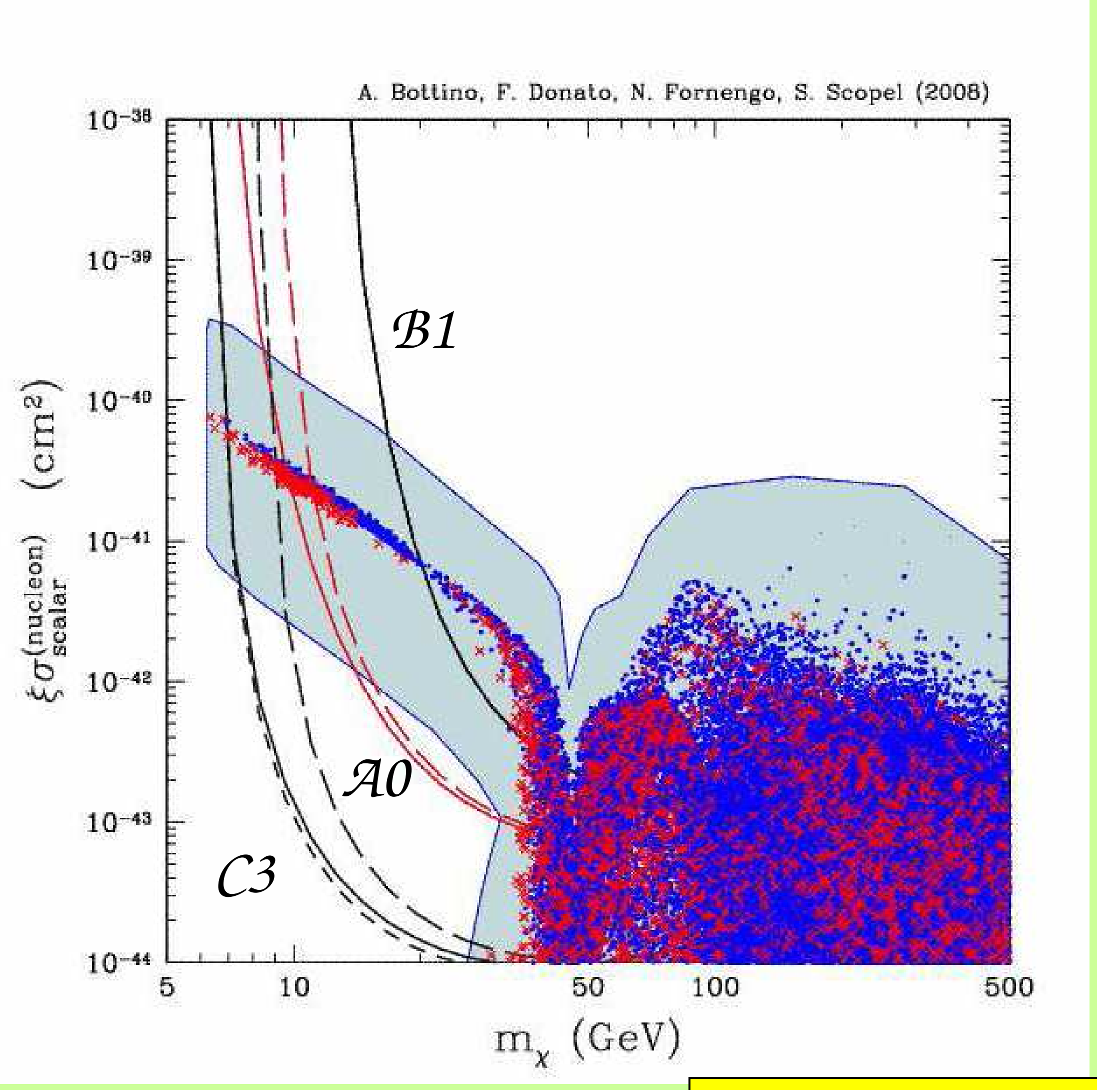
Donato, Maurin, Brun, Delahaye , Salati, arXiv:0810.5292 [astro-ph]



PAMELA data on antiprotons perfectly compatible with secondary production - these results very useful to put strict constraints on DM candidates and on boost factors

O. Adriani at al. (PAMELA Coll.), Phys. Rev. Lett. 102 (2009) 051101

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 Ahmed et al., Phys. Rev. Lett. 120: 011301, 2009

Experiments of direct dark matter search other than DAMA/LIBRA are not sensitive to the annual modulation effect which is the peculiar signature of the DM signal. In the derivation of upper bounds, event discrimination procedures, not based on the peculiar signature of the effect, are applied.

This makes the comparison of these upper limits with DAMA results somewhat uncertain.

However, these upper bounds, even when taken at their face values, are not in conflict with the annual-modulation data and with the neutralino interpretation for masses in the range 7 – 10 GeV (A.B., F. Donato, N. Fornengo and S. Scopel, arXiv: 0806.4099)

Comparisons of DAMA/LIBRA data with results of other direct experiments largely discussed in recent literature:
F.J. Petriello and K.M. Zurek, arXiv:0806.3989
J.L. Feng, J. Kumar and L.E. Strigari, arXiv:0806.3746
M. Fairbairn and T. Schwetz, arXiv:0808.0704
C. Savage, G. Gelmini, P. Gondolo and K. Freese, arXiv:0808.3607
…

The whole population of light neutralinos $6\,\mathrm{GeV} \leq m_\chi \leq 50\,\mathrm{GeV}$

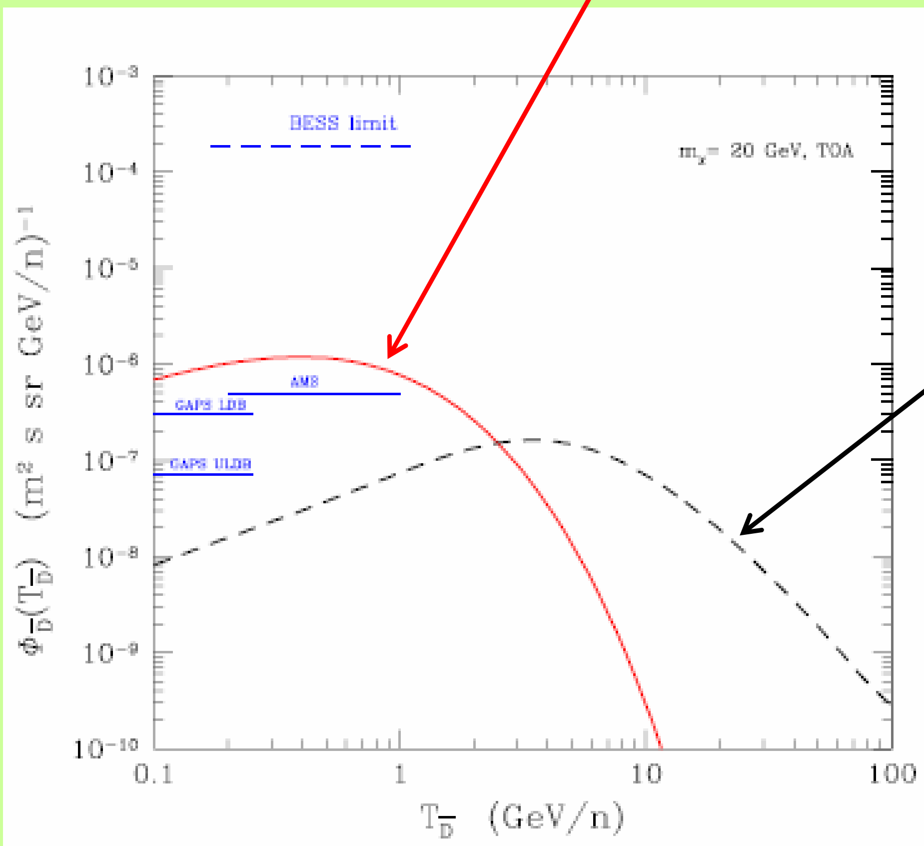
a) might produce sizable signals at neutrino telescopes
(V. Niro, contribution in Workshop sessions)
and in searches in space for antideuterons
(see also J. Koglin, contribution in Workshop sessions)

b) and most notably can be searched for at Large Hadron Collider

antideuterons

TOA primary flux

secondary flux

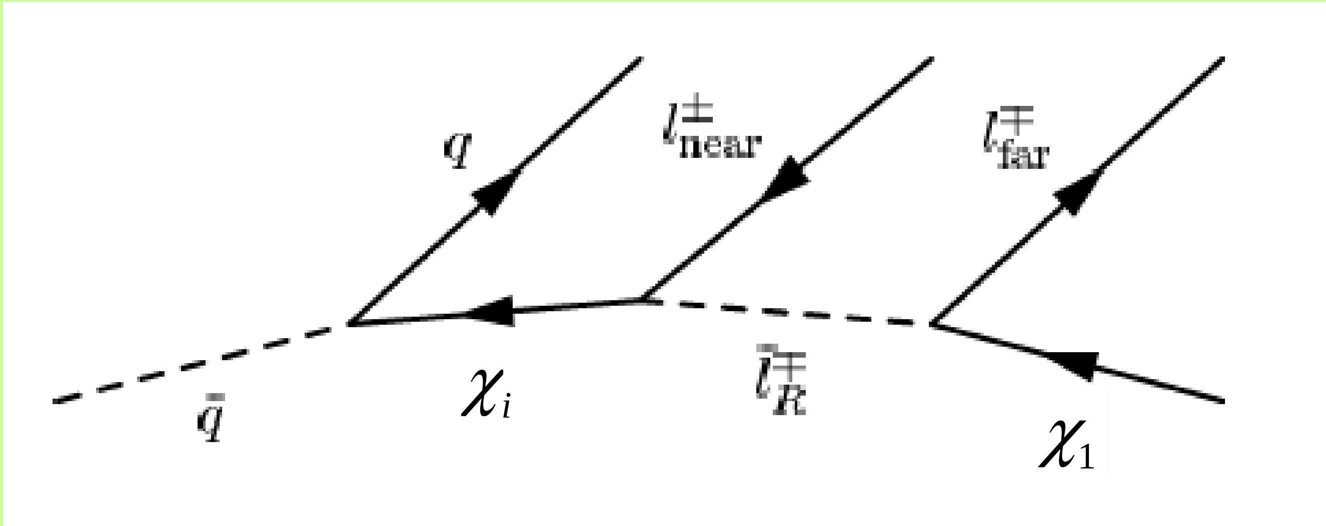


See F. Donato, N. Fornengo and D. Maurin, Phys. Rev. D78 (2008) 043506

Light neutralinos at the Large Hadron Collider

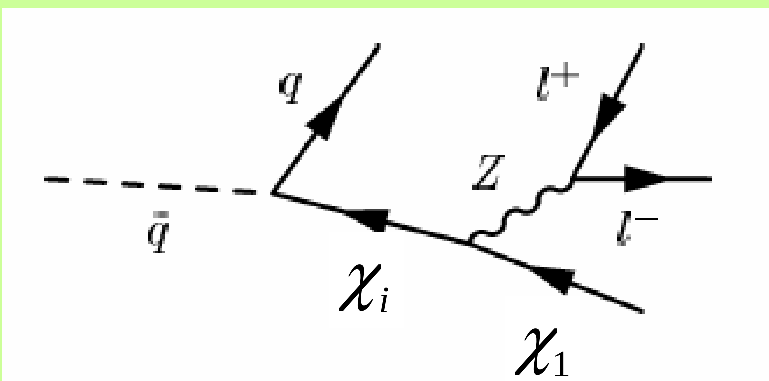
A number of scenarios at LHC inspired by light neutralino cosmology are discussed in A. B., N. Fornengo, G. Polesello and S. Scopel, Phys. Rev. D 77, arXiv:0801.3334 (hep-ph)

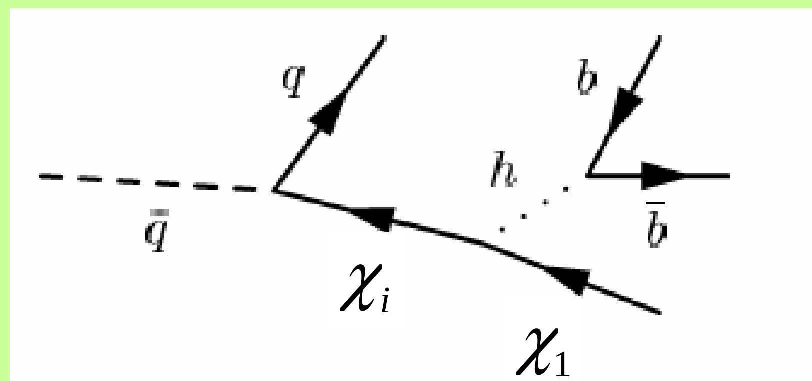
scenario	M_1 [GeV]	$\|\mu\|$ [GeV]	$\tan\beta$	m_A [GeV]	$m_{\tilde{l}}$ [GeV]
$\mathcal{A}$	~ 10	100–200	30–45	~ 90	–
$\mathcal{B}$	~ 25	$\gtrsim 500$	$\lesssim 20$	$\gtrsim 200$	100–200



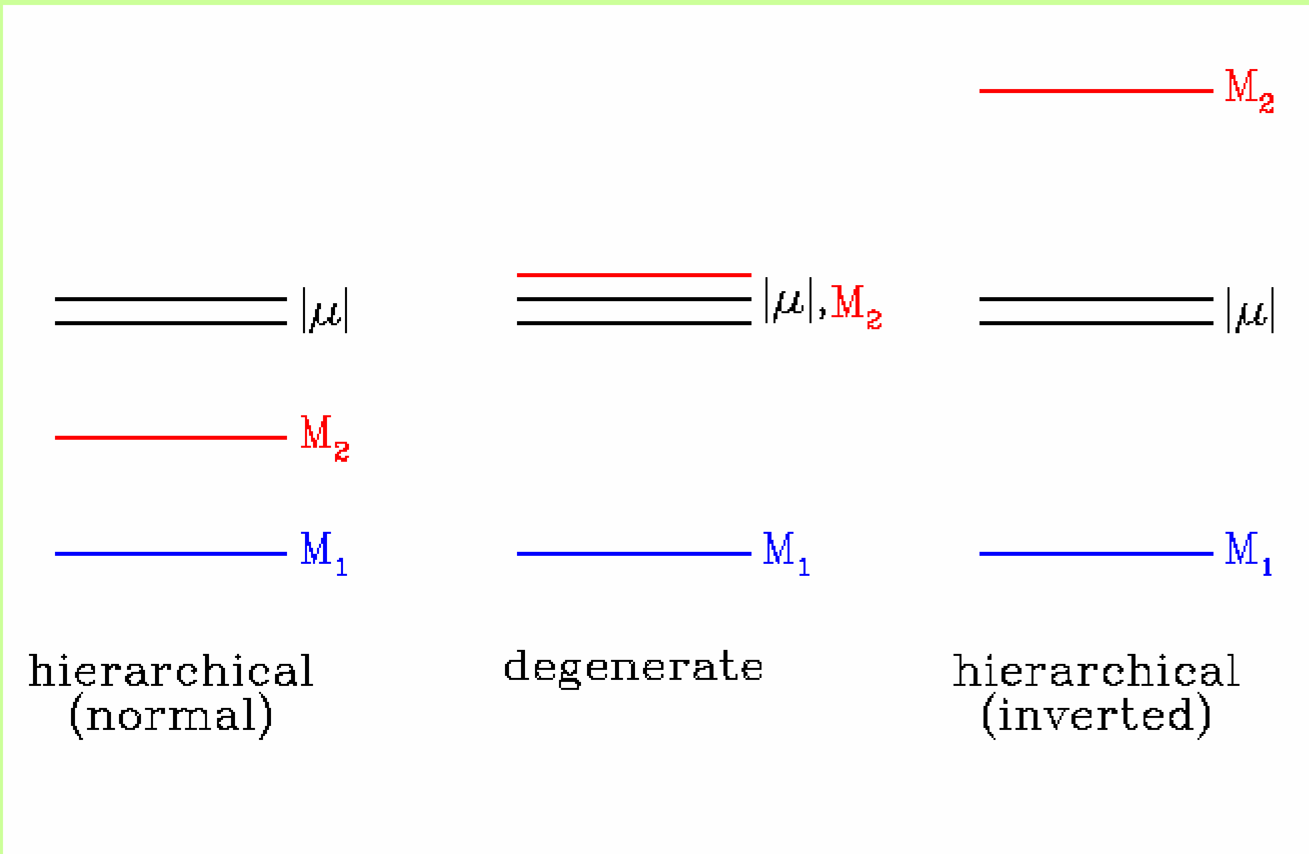
sequential chains

$i = 2,3,4$





branched chains

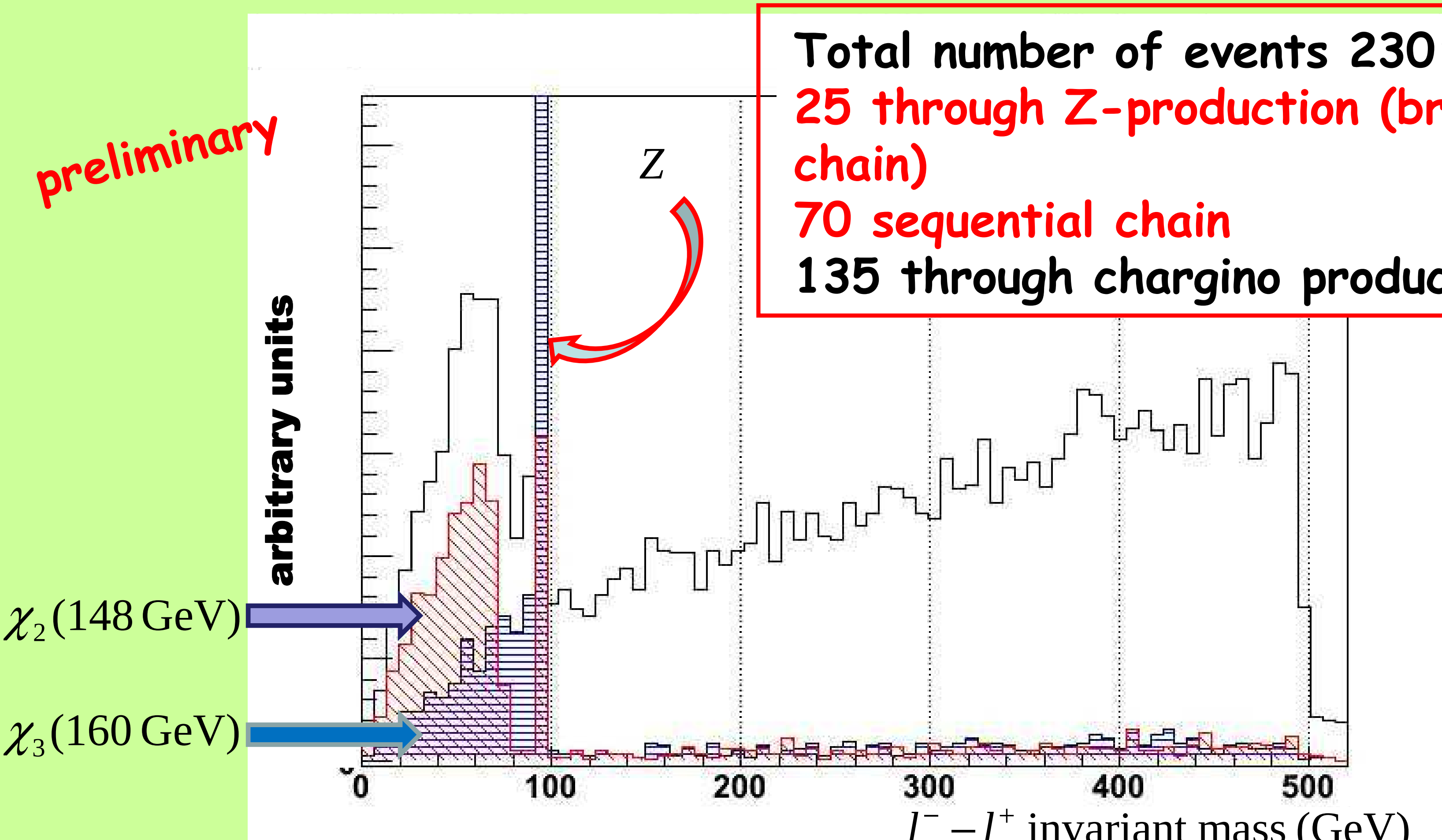


neutralino spectroscopy

Distribution of events in terms of the $l^- - l^+ \ (l = e, \mu)$ invariant mass in a Montecarlo simulation with cuts meant to reduce drastically the t-tbar background. Benchmark defined as:

$$M_1 = 10\,\text{GeV}, \mu = 110\,\text{GeV}, m_A = 90\,\text{GeV}, \tan\beta = 35, m_{\tilde{l}} = 150\,\text{GeV}, M_2 = 500\,\text{GeV}$$

Total number of events 230:
25 through Z-production (branched chain)
70 sequential chain
135 through chargino production



A.B., S. Choi, N. Fornengo, S. Scopel (work in progress)

Conclusions

☆ A wide selection of interaction mechanisms and of categories of DM candidates fits the DAMA/LIBRA annual-modulation results without conflict with other experiments of WIMP direct detection

- interpretation in terms of relic neutralinos very favorable for light masses

☆ The population of light neutralinos is compatible with the cosmic antiprotons data and offers nice perspectives of investigation at the Large Hadron Collider and with cosmic antideuterons

☆ Further developments in experimental searches for DM particles should focus on specific signatures of DM: modulations/directionality.