Antideuterons in Galactic Cosmic Rays

A promising target for indirect dark matter detection

Donato, Fornengo & Maurin

http://arxiv.org/abs/0803.2640

PRD 78, 043506 (2008)

1. Why antideuterons ?
2. Modelling
   - *Framework (x1)*
   - *Cross sections (x2)*
   - *Coalescence model (x2)*
3. Secondary flux (standard processes)
4. Primary flux (DM contribution)
5. Discussion

David Maurin (LPNHE)
dmaurin@lpnhe.in2p3.fr

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Milestones (I)

1997 The Production of Anti-Matter in our Galaxy

Chardonnet, Orloff & Salati, Phys.Lett. B **409,** 313 (1997)

*« [...] We therefore conclude that **AMS should detect a few cosmic ray anti-deuterons.** [...] The detection of a single anti-helium [...] would be a smoking gun for the presence of large amounts of anti-matter in the universe and **for the existence of anti-stars** and of antigalaxies.*

2000 Antideuterons as a Signature of Supersymmetric Dark Matter

Donato, Fornengo & Salati, Phys. Rev. D **62**, 043003 (2000)

*« **If a few low–energy antideuterons are measured** [by the future AMS experiment on board ISSA], **this should be seriously taken as a clue for the existence of massive neutralinos** in the Milky Way »*

2002 A Novel Antimatter Detector Based on X-Ray Deexcitation of Exotic Atoms

Mori *et al. (GAPS collab.)*, ApJ **566**, 604 (2002)

*« We propose **a novel antiparticle detector** [...].Paradoxically, this space-based search for the neutralino is **capable of achieving comparable sensitivity to as yet unrealized third-generation**, underground dark matter experiments ».*

Milestones (II)

2005 Flux of light antimatter nuclei by CRs in the Galaxy and in the atmosphere

Duperray *et al.*, Phys. Rev. D **71**, 083013 (2005)

*«The hadronic production cross section for antinucleons is based **on a recent parametrization of a wide set of accelerator data**. The **non annihilating inelastic scattering** process for the antideuterons is taken into account **for the first time** via a more realistic procedure than used so far for antiprotons. »*

2005 Search for Cosmic-Ray Antideuterons

Fuke *et al. (BESS collab.)*, Phys. Rev. D **95**, 081101 (2005)

*« **We derived, for the first time**, **an upper limit of 1.9×10^{-4} (m^2s sr GeV/nuc)$^{-1}$** for the differential flux of cosmic-ray antideuterons, at the 95% conf. level, between **0.17-1.15 GeV/nuc** at the top of the atmosphere. »*

2006 Accelerator testing of the general antiparticle spectrometer; a novel approach to indirect dark matter detection

Hailey *et al. (GAPS collab.)*, Phys. Rev. D **01**, 007 (2006)

*« GAPS captures antideuterons into a target with the subsequent formation of exotic atoms. These exotic atoms decay with the emission of x-rays[...]. This **signature uniquely characterizes the antideuterons**. »*

- 2 -

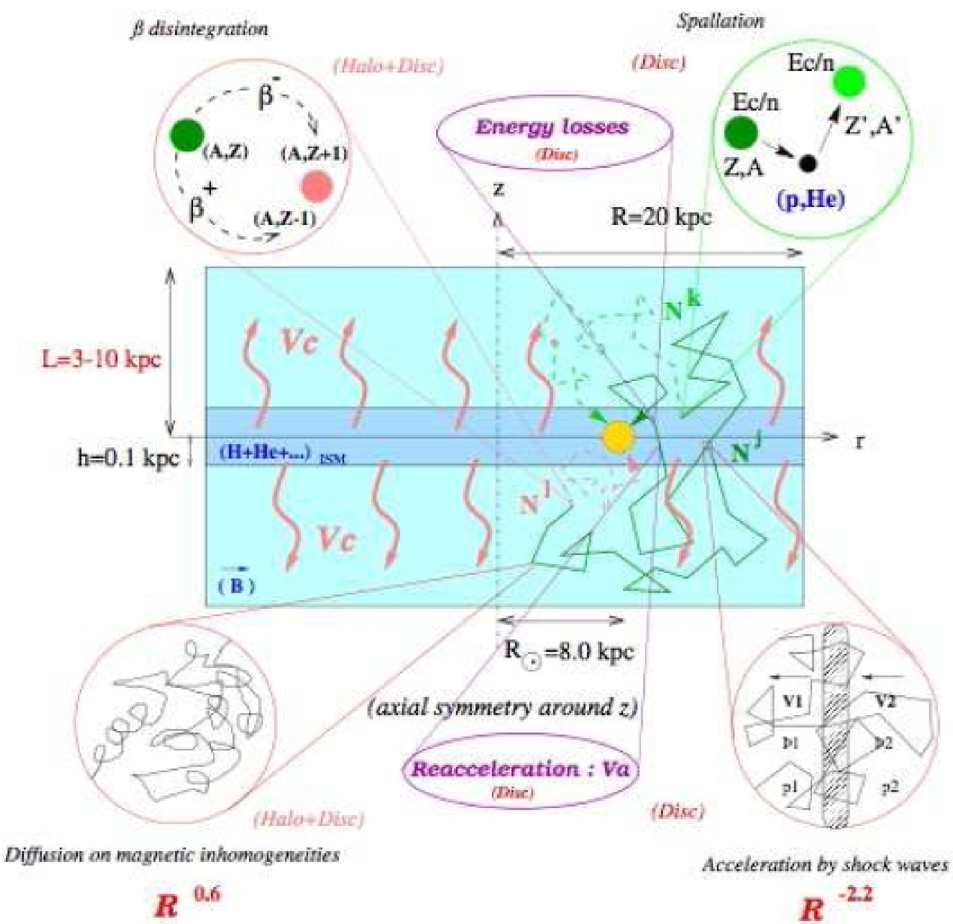
Modelling

- Framework (x1)
- Cross sections (x2)
- Coalescence (x2)

Modelling (I): framework

$$-\vec{\nabla}\left[K\vec{\nabla}N(\vec{r})-\vec{V}_c N(\vec{r})\right]-\frac{\partial}{\partial E}\left[-f_o N(\vec{r})+s_o\frac{\partial N(\vec{r})}{\partial E}\right]$$
$$=Q_{\rm source}(\vec{r})-n(\vec{r})v\sigma_{\rm ine}N(\vec{r})\,. \qquad (1)$$

Transport equation



- Geometry: L (R=20 kpc, h=100 pc)
- Diffusion: K_0, δ
- Réacceleration: V_a
- Galactic wind: V_c

=> *Bessel expansion + numerical inversion*

Free parameters set from B/C study

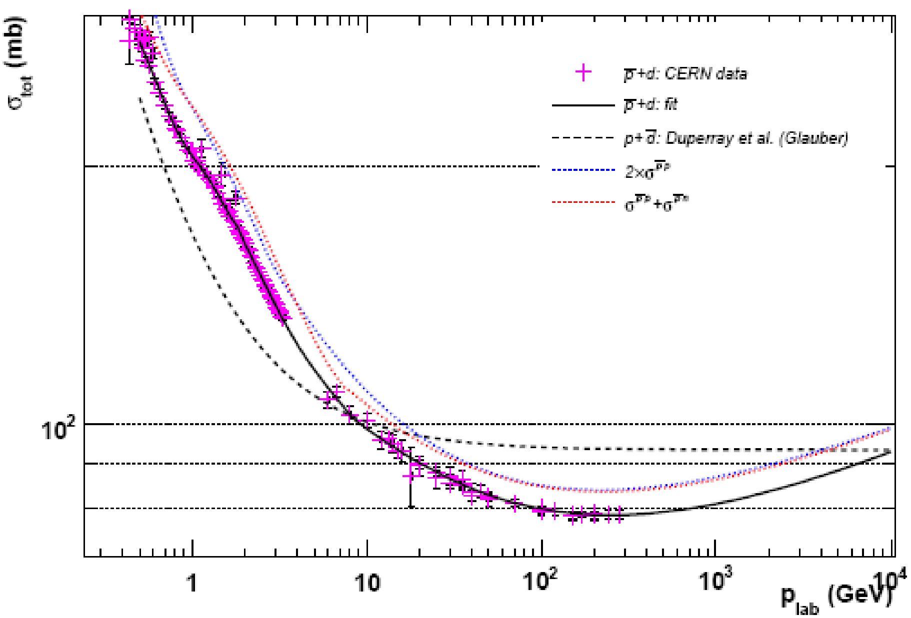
Maurin *et al.*, ApJ **555**, 585 (2001)

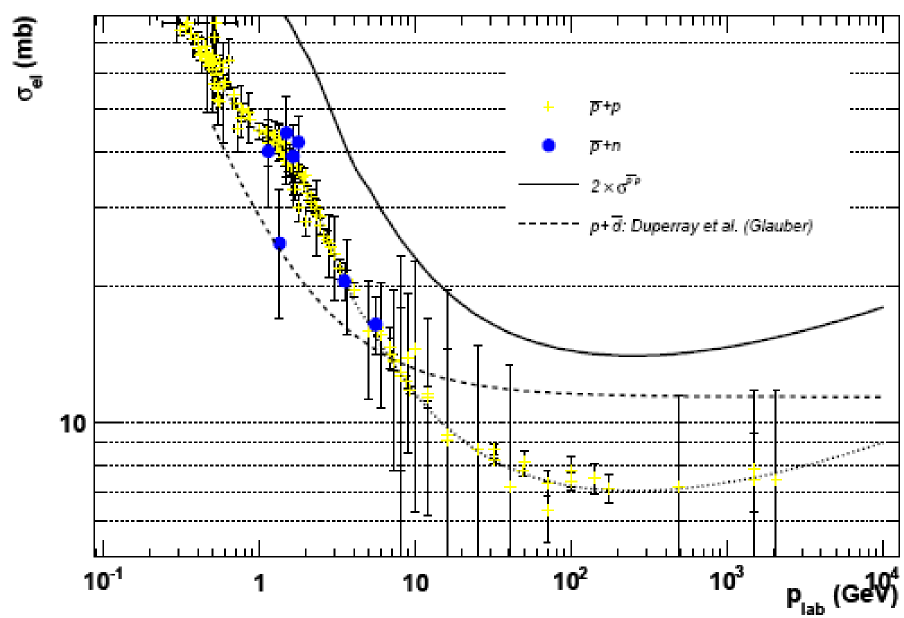
Modelling (II): cross sections

[1.Inelastic destruction (sink)]

$$
-\vec{\nabla}\left[K\vec{\nabla}N(\vec{r})-\vec{V}_c N(\vec{r})\right]-\frac{\partial}{\partial E}\left[-f_o N(\vec{r})+s_o\frac{\partial N(\vec{r})}{\partial E}\right]
$$
$$
= Q_{\rm source}(\vec{r}) - n(\vec{r})v\sigma_{\rm ine}N(\vec{r})\,. \qquad (1)
$$

$$
\boxed{\sigma_{\rm inel} = \sigma_{\rm tot} - \sigma_{\rm el}\,,}
$$



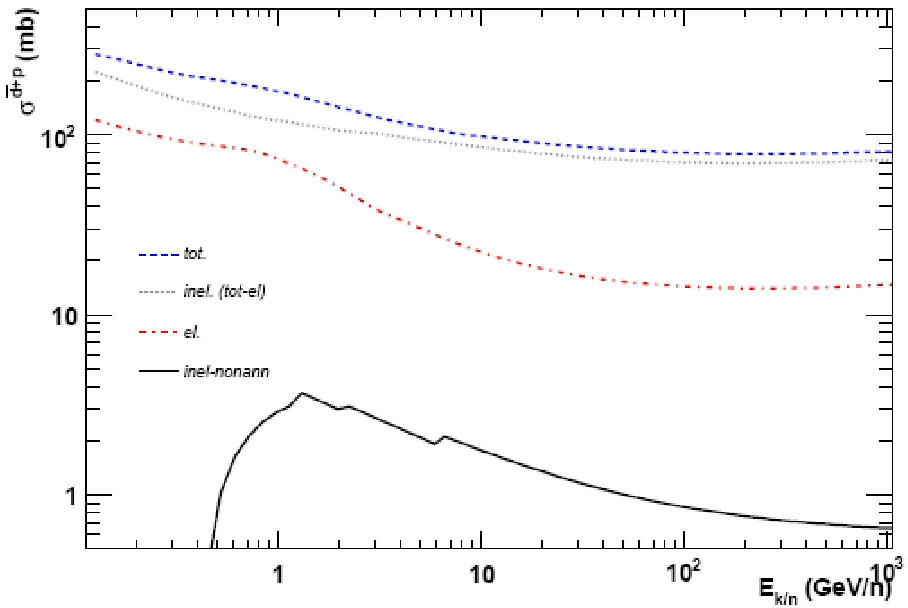


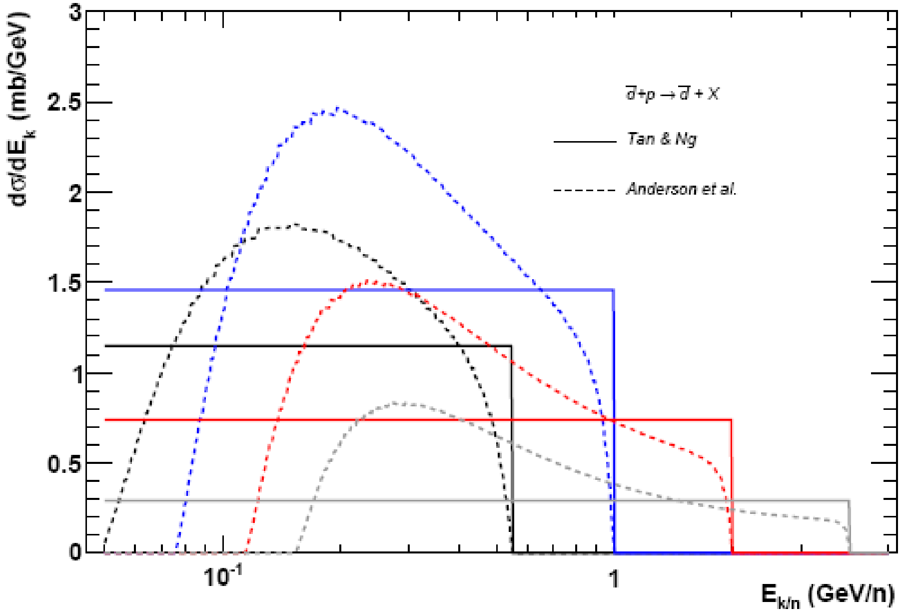
Modelling (II): cross sections

[2.Tertiaty redistribution]

$$Q_{\rm source}(\vec{r},E) = Q_{\rm prim}(\vec{r},E) + Q_{\rm sec}(\vec{r},E) + Q_{\rm ter}(\vec{r},E)$$

$$\boxed{\begin{aligned} Q_{\rm ter}(\vec{r},E) \;&=\; \int_E^{+\infty} n v' \, \frac{d\sigma^{\rm non-ann}_{\bar{d}H\to\bar{d}X}}{dE}\{E'\to E\}\; N(\vec{r},E')\; dE' \\ &-\quad n v\; \sigma^{\rm non-ann}_{\bar{d}H\to\bar{d}X}\{E\}\; N(\vec{r},E)\;. \qquad (3) \end{aligned}}$$





Modelling (III): coalescence model

[1.Factorization and link to data]

The $\overline{d}$ density in momentum space is thus written as the $\overline{p}$ density times the probability to find an $\bar{n}$ within a sphere of radius p_0 around $\vec{k}_{\bar{p}}$

$$\gamma \frac{d\mathcal{N}_{\bar{d}}}{d\vec{k}_{\bar{d}}} = \frac{4\pi}{3} p_0^3 \cdot \gamma \frac{d\mathcal{N}_{\bar{\mathrm{p}}}}{d\vec{k}_{\bar{p}}} \cdot \gamma \frac{d\mathcal{N}_{\bar{\mathrm{n}}}}{d\vec{k}_{\bar{n}}}$$

$$\vec{k}_{\bar{p}} \simeq \vec{k}_{\bar{n}} \simeq \frac{\vec{k}_{\bar{d}}}{2}$$

$$\boxed{E_{\bar{d}} \frac{d^3 \sigma^{\mathrm{R}}_{\bar{d}}}{d\vec{k}_{\bar{d}}} = \frac{1}{\sigma^{\mathrm{R}}_{\mathrm{inel}}} \cdot \frac{4\pi}{3} p_0^3 \cdot \frac{m_{\bar{d}}}{m_{\bar{p}}^2} \cdot \left(E_{\bar{p}} \frac{d\sigma^{\mathrm{R}}_{\bar{\mathrm{p}}}}{d\vec{k}_{\bar{p}}} \right)^2}$$

=> In practice, more complicated (phase space factor at low energy)

Link to data

$$B_2 \;\equiv\; \sigma^{\mathrm{R}}_{\mathrm{inel}} \cdot E_{\bar{d}} \frac{d^3 \sigma^{\mathrm{R}}_{\bar{d}}}{d\vec{k}_{\bar{d}}} \cdot \left(E_{\bar{p}} \frac{d\sigma^{\mathrm{R}}_{\bar{\mathrm{p}}}}{d\vec{k}_{\bar{p}}} \right)^{-2}$$

$$p_0 = \left(\frac{1}{B_2} \cdot \frac{m_{\bar{d}}}{m_{\bar{p}}^2} \cdot \frac{4\pi}{3} \right)^{-1/3}$$

The B_2 coefficient has been measured for proton-proton, proton-nucleus and heavy ion collisions (see a summary and references in Refs. [8, 35]). More recently, several other channels have also been measured at high energy: photo-production [35], DIS production [36] and e^+e^- production at the Z [37] and $\Upsilon(1S)$ [38] resonances. The e^+e^- channel is of particular interest for the DM annihilation reactions.

Modelling (III): coalescence

[2. Same p_0 for background and signal?]

Hadronic production

Duperray *et al.*,
Phys. Rev. D **71**, 083013 (2005)

$$p_0 = 79 \text{ MeV}$$

Weak production

At LEP energies, (anti)deuteron production occurs through e^+e^- annihilations into $q\bar{q}$ pairs, a mechanism similar to the $\overline{d}$ production in DM annihilation reactions. Based on theoretical arguments, it has been argued [31] that the antideuteron yields in e^+e^- reactions should be smaller than in hadronic reactions. However, the ALEPH Collaboration [37] has found that this theoretical prediction (see Fig. 5 in ALEPH paper) underestimates their measured $\overline{d}$ inclusive cross section. They derive (see their Fig. 6) a value $B_2 = 3.3 \pm 0.4 \pm 0.1 \times 10^{-3}$ GeV^2 at the Z resonance, which translates into $p_0 = 71.8 \pm 3.6$ MeV, very close to the $p_0 = 79$ MeV derived for the hadronic production. Hence, in the remaining of the Paper, the value of $p_0 = 79$ MeV will be retained for both the processes of hadronic and electroweak origin.

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Secondary flux (background)

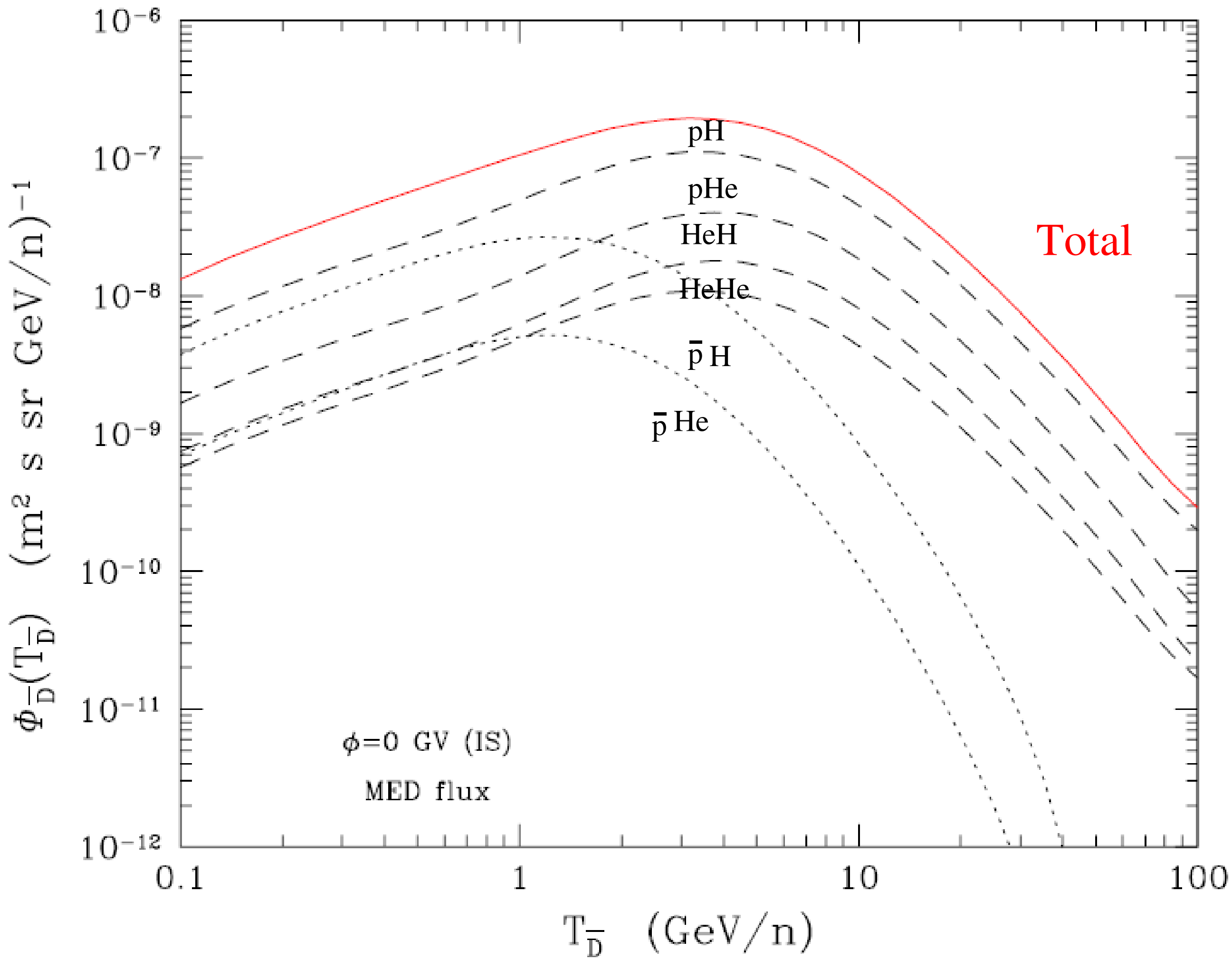
- Separate contributions

- Propagation uncertainty

- Nuclear uncertainty

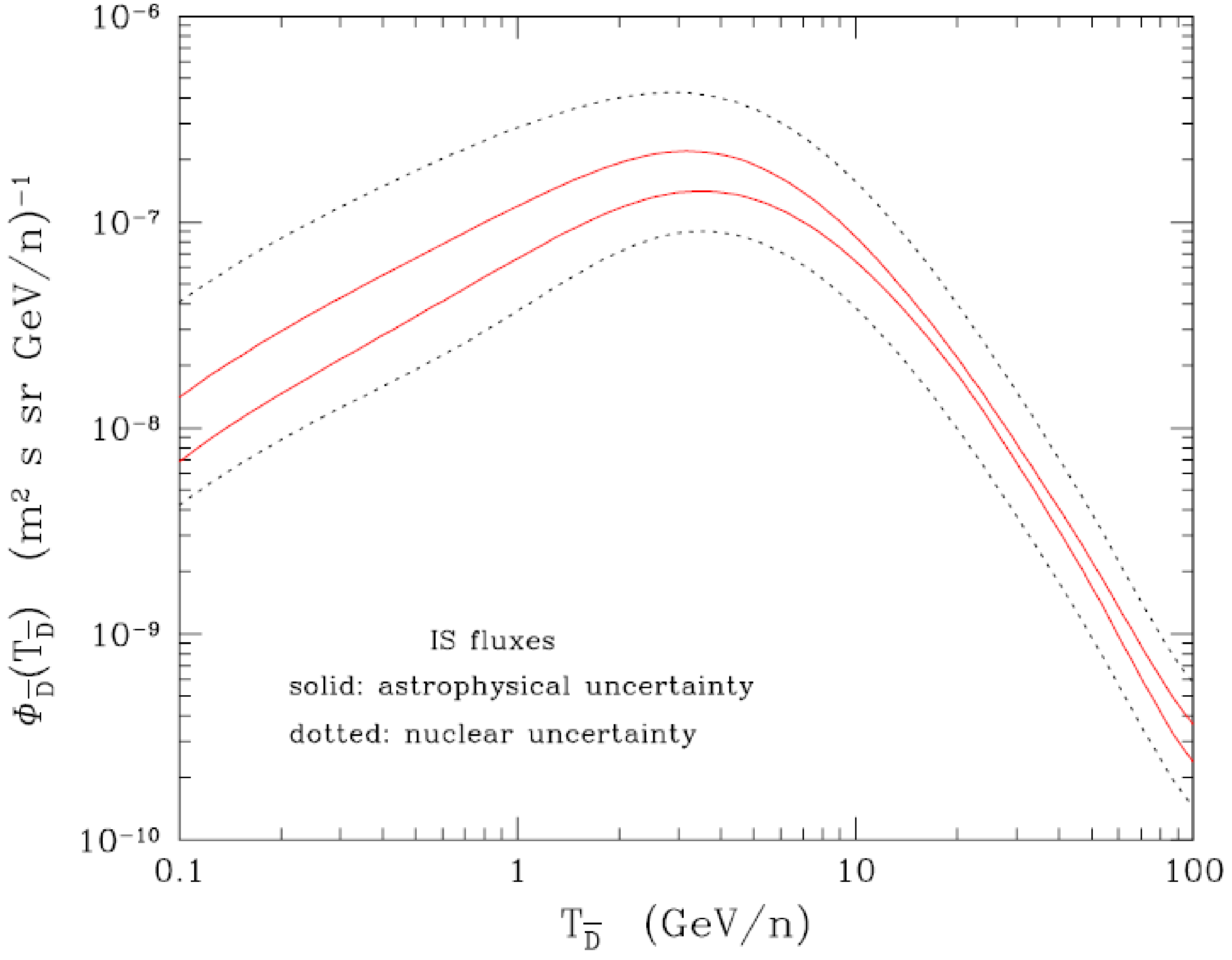
Secondary flux (I): separate contributions

$$Q^{\rm sec}_{\bar{\rm N}}(\vec{r},E) = \sum_{\rm CR}^{(\bar{\rm p})\,{\rm p,He}} \; \sum_{\rm ISM}^{\rm H,He} \int_{E^{\rm th}_{\rm CR}}^{+\infty} n_{\rm ISM}\, v_{\rm CR}\, N_{\rm CR}(\vec{r},E_{\rm CR})\, \frac{d\sigma}{dE_{\bar{\rm N}}}(E_{\rm CR} \to E_{\bar{\rm N}})\, dE_{\rm CR}.$$



Secondary flux (II): astrophys. uncertainty

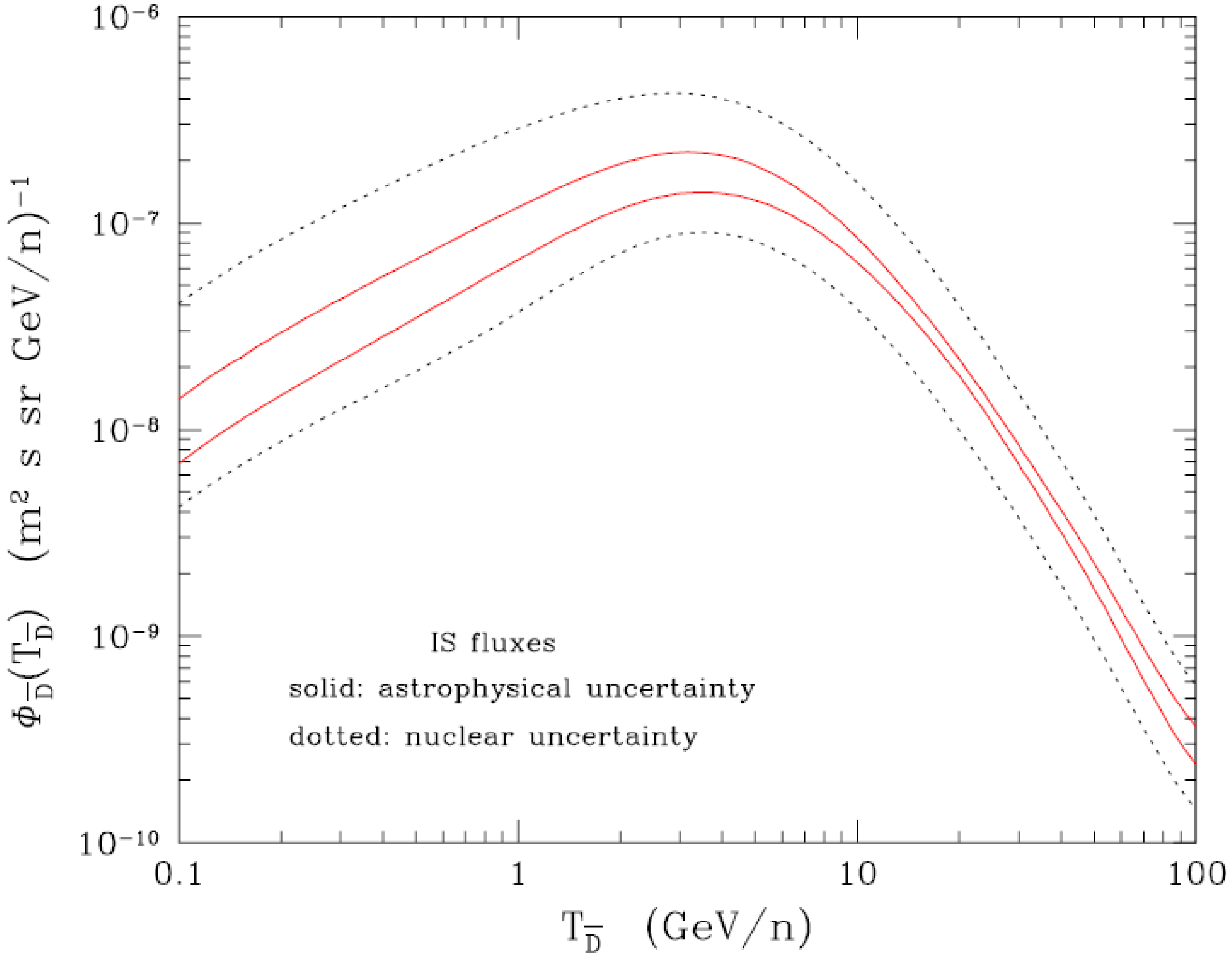
[Combine all sets of parameters leading to a «good» fit to B/C]



=> Small band (<40%), as for antiprotons **[would « vanish » with good B/C data]**

Secondary flux (III): nuclear uncertainty

Max = +100% for all cross sections (including tertiary)
Min = ~50% and pbar+(pHe) switched off)



=> Large band (~ x10!) [not expected to « vanish » soon]

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Primary flux (signal)

- Source term and channels
- Propagation uncertainty
- DM profile uncertainty

Primary flux (I): source term

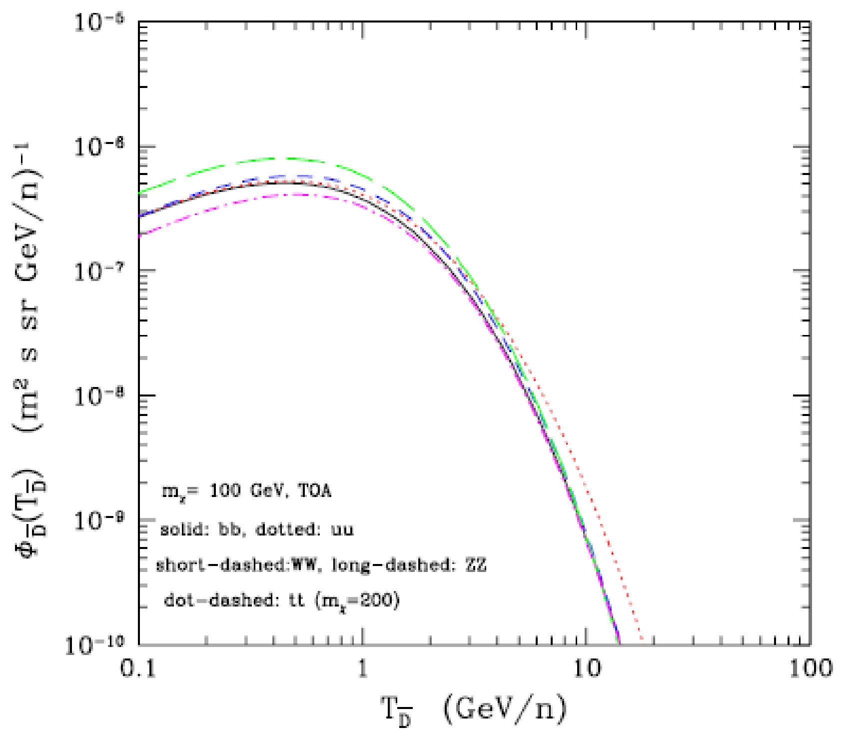
$$q_{\bar{d}}^{\rm prim}(r,z,E) = \eta\,\xi^2 \langle\sigma_{\rm ann}v\rangle_0 \, \frac{dN_{\bar{d}}}{dE_{\bar{d}}} \left(\frac{\rho_{\rm DM}(r,z)}{m_\chi}\right)^2$$

Channel

$$\frac{dN_{\bar{p}}}{dE_{\bar{p}}} = \sum_{\rm F,h} B^{\rm (F)}_{\chi{\rm h}} \frac{dN^{\rm h}_{\bar{p}}}{dE_{\bar{p}}}$$

The annihilation into a quark or a gluon h is realized through the various final states F with branching ratios $B^{\rm (F)}_{\chi{\rm h}}$. Quarks or gluons may in fact be directly produced when a WIMP pair annihilates or they may alternatively result from the intermediate production of Higgs bosons or gauge bosons. Each quark or gluon h then generates jets whose subsequent fragmentation and hadronization yield an antiproton energy spectrum $dN^{\rm h}_{\bar{p}}/dE_{\bar{p}}$.

$$\frac{dN_{\bar{d}}}{dE_{\bar{d}}} = \left(\frac{4\,p_0^3}{3\,k_{\bar{d}}}\right)\cdot\left(\frac{m_{\bar{d}}}{m_{\bar{p}}^2}\right)\cdot\sum_{\rm F,h} B^{\rm (F)}_{\chi{\rm h}} \left\{\frac{dN^{\rm h}_{\bar{p}}}{dE_{\bar{p}}}\left(E_{\bar{p}} = \frac{E_{\bar{d}}}{2}\right)\right\}^2$$



=> in the rest, $b\bar{b}$...

Primary flux (II): astrophys. uncertainty

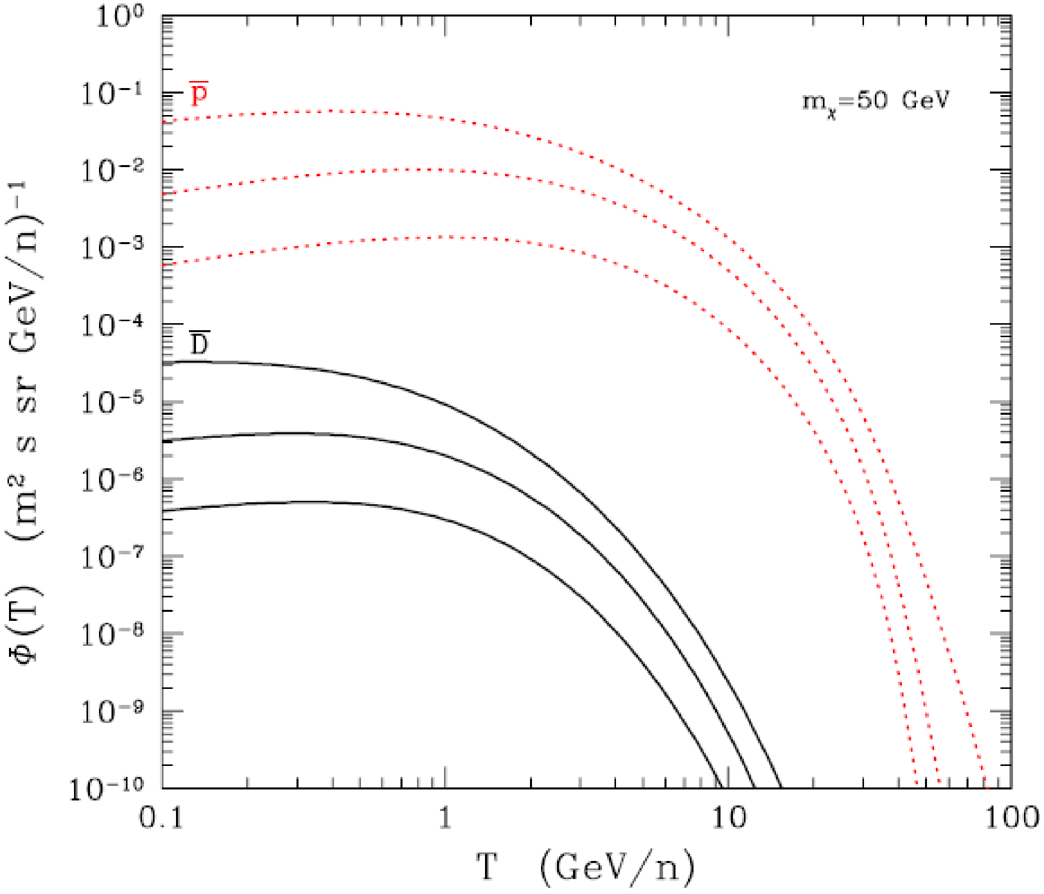
[Combine all sets of parameters leading to a «good» fit to B/C]

Major effect: L and V_c

[same as for antiprotons]

case	δ	K_0 (kpc^2/Myr)	L (kpc)	V_c (km/s)	V_A (km/s)	$\chi^2_{B/C}$
max	0.46	0.0765	15	5	117.6	39.98
med	0.70	0.0112	4	12	52.9	25.68
min	0.85	0.0016	1	13.5	22.4	39.02

~ 10^2 at low energy



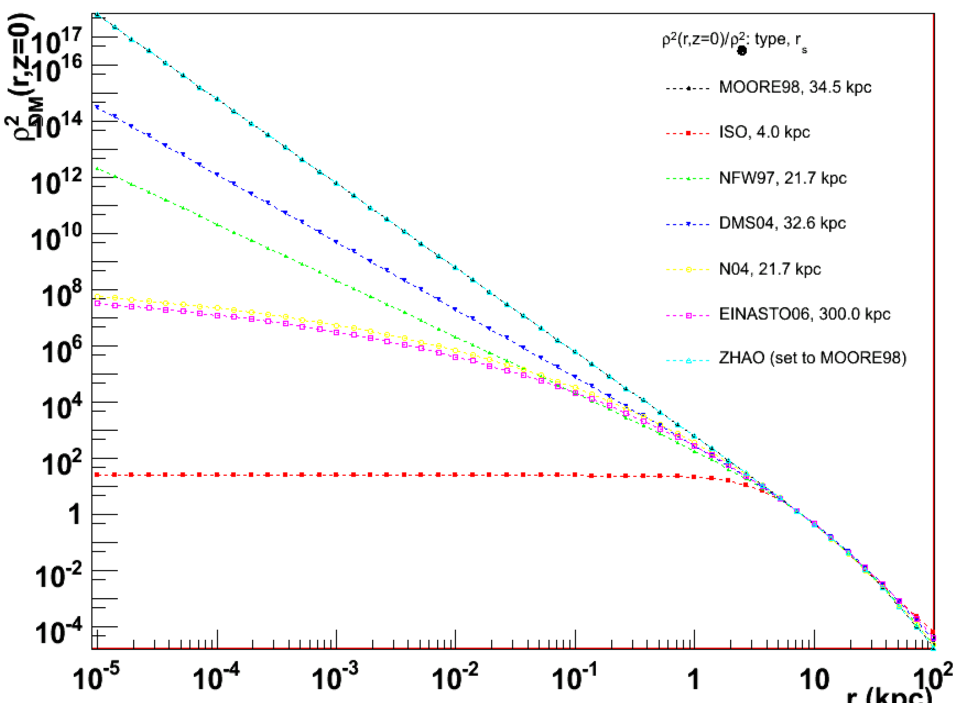
=> Will be reduced with new data on nuclei (and radioactive nuclei)

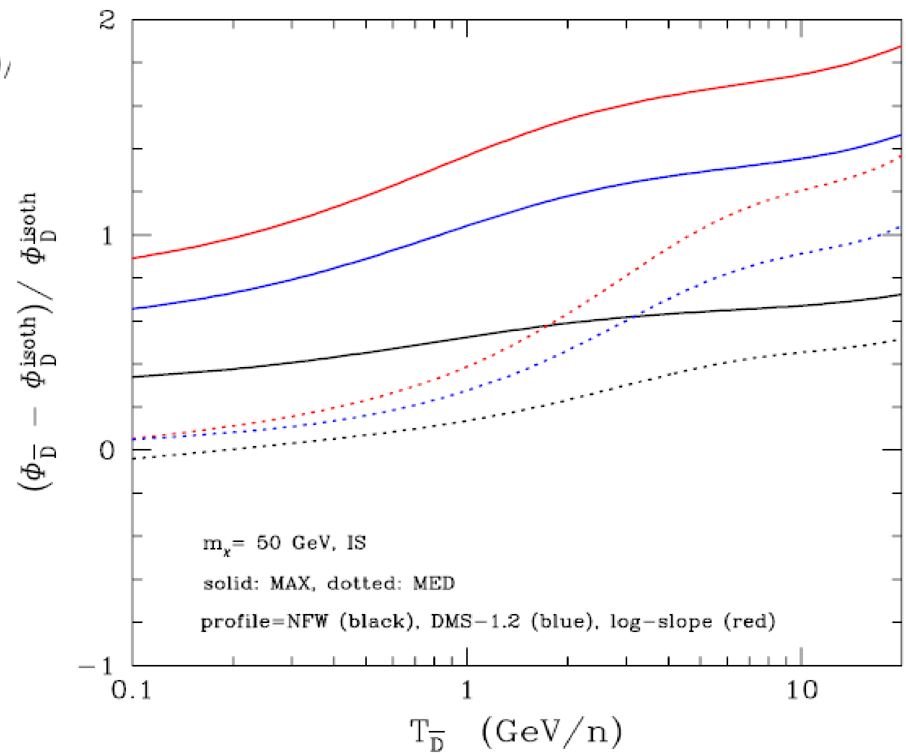
Primary flux (III): DM profile uncertainty

[N.B.: result depends on which parameter is varied...]

$$\rho_\chi \equiv \rho_{\rm CDM}(r) = \rho_\odot \left\{\frac{r_\odot}{r}\right\}^\gamma \left\{\frac{1+(r_\odot/a)^\alpha}{1+(r/a)^\alpha}\right\}^{(\beta-\gamma)/}$$

N.B.: Local density set to 0.42 GeV cm^{-3}





=> Sensitive to the DM density
in the solar neighbourhood
(see previous studies on pbar)

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Discussion

- Total flux

- GAPS and AMS sensitivity

- Scatter plots

Discussion(I): total flux

[for IS and TOA (solar minimum), 3 neutralino masses]

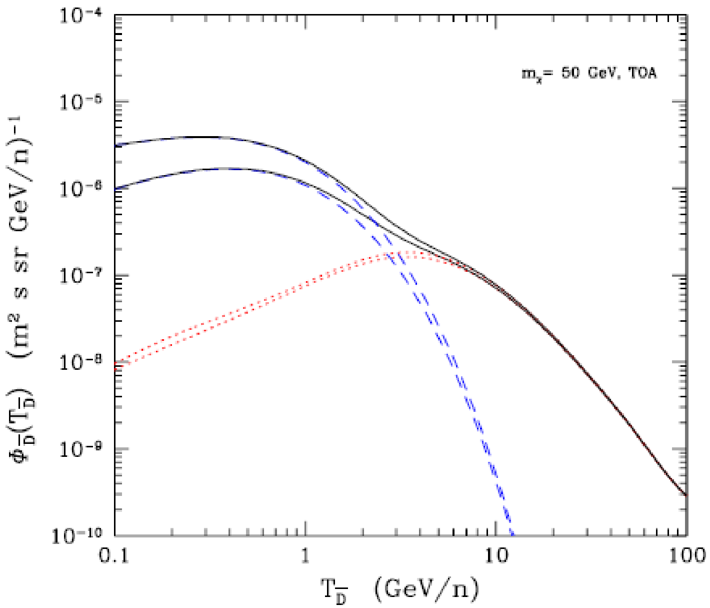


FIG. 7: Interstellar and Top–Of–Atmosphere (TOA) antideuteron fluxes. The dashed (blue) line shows the primary flux for m_χ=50 GeV and $\langle\sigma_{\rm ann} v\rangle_0 = 2.3 \cdot 10^{-26}$ cm^3 s^{-1}, the (red) dotted line denotes the secondary component and the (black) solid line stands for the total (signal+background) flux. Propagation model is the median one in Table I.

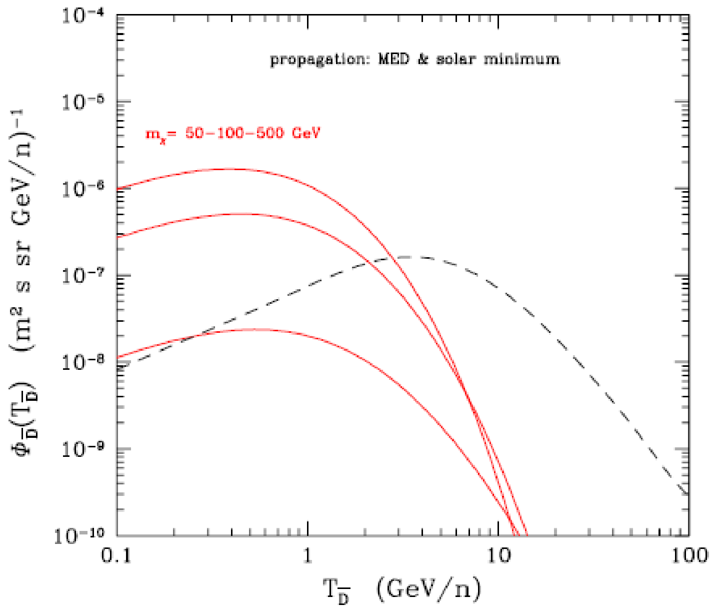
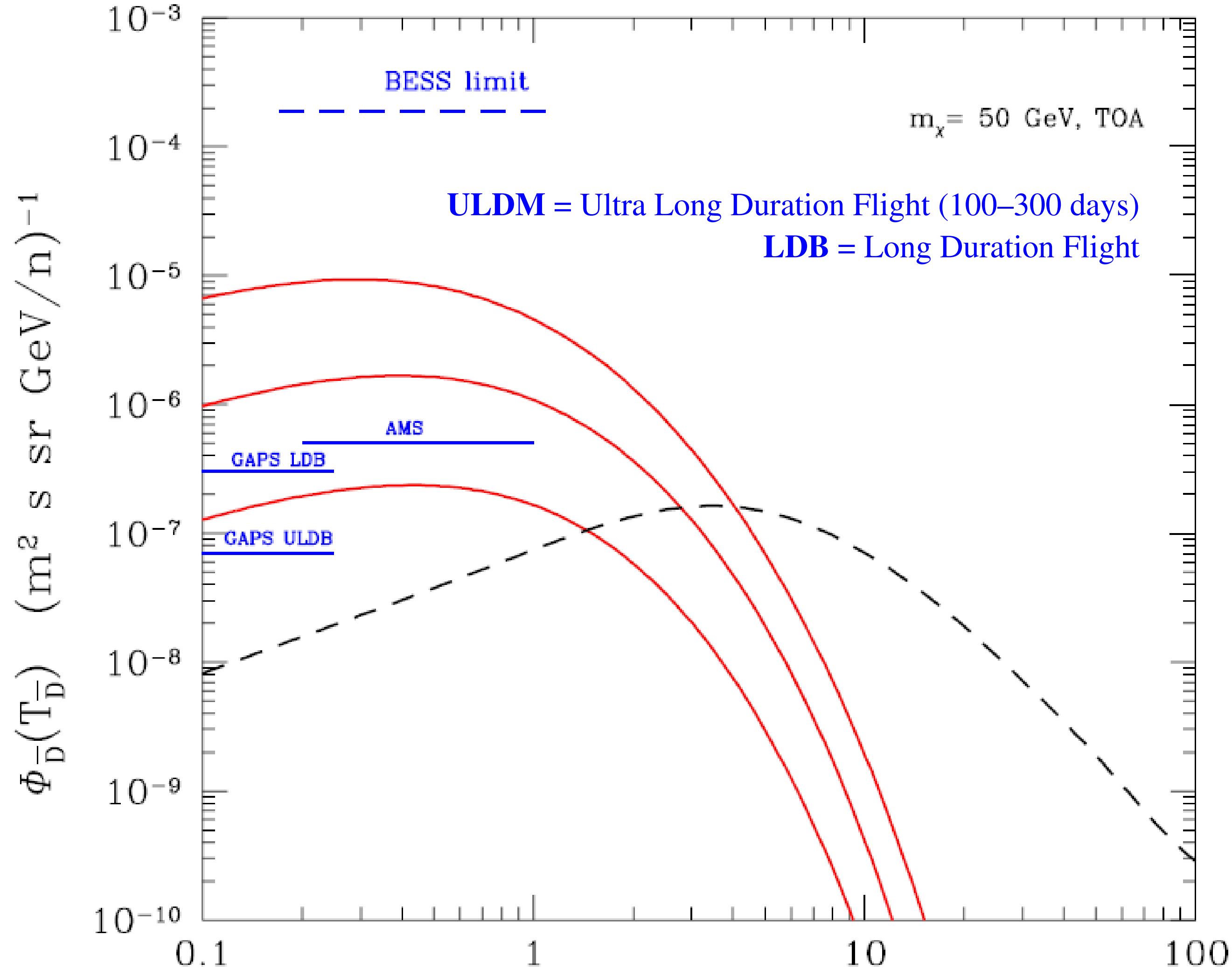


FIG. 8: TOA fluxes for primary (solid lines) and secondary (dashed line) antideuterons for the median propagation parameters. From top to bottom, the solid lines refer to WIMPs with mass m_χ=50, 100, 500 GeV.

=> Not too sensitive to modulation – OK for $m_\chi \leq 200$ GeV

Discussion (II): GAPS & AMS sensitivity



=> Very good perspectives for the near future!!!!

Discussion (III): Scatter plots

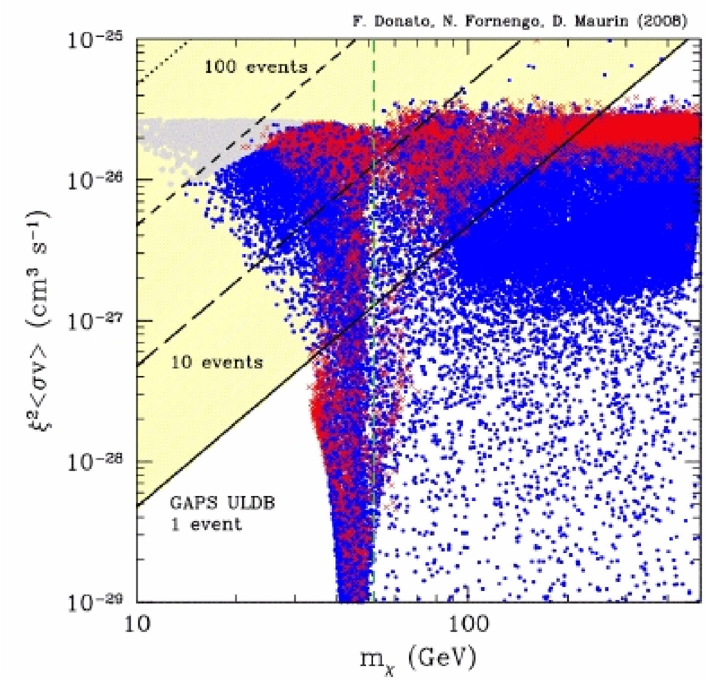


FIG. 11: GAPS ULDB reach compared to predictions for neutralino dark matter in low–energy supersymmetric models, shown in the plane effective annihilation cross section $\xi^2\langle\sigma_{\rm ann}v\rangle_0$ vs. neutralino mass m_χ. The solid, long–dashed and short–dashed lines show our estimate for the capability of GAPS ULDB of measuring 1, 10 and 100 events, respectively, for the median propagation model of Table I. The scatter plot reports the quantity $\xi^2\langle\sigma_{\rm ann}v\rangle_0$ calculated in a low–energy MSSM (for masses above the vertical [green] dashed line) and in non–universal gaugino models which predict low–mass neutralinos [56, 71, 76–80]. [Red] Crosses refer to cosmologically dominant neutralinos, while [blue] dots stand for subdominant neutralinos. Grey point are excluded by antiproton searches.

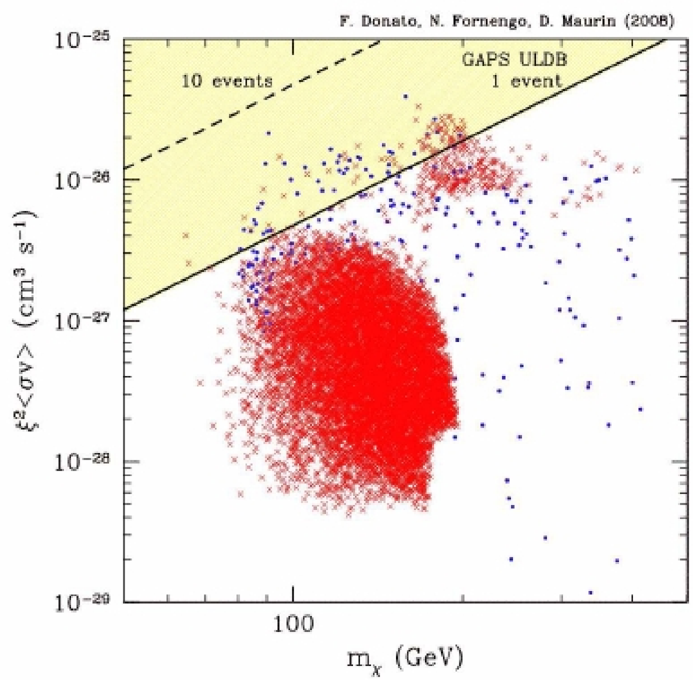


FIG. 12: The same as in Fig. 11, except that the supersymmetric predictions refer to a minimal SUGRA scheme.

Discussion (III): Scatter plots

[interesting perspectives, even with minimal asto. set]

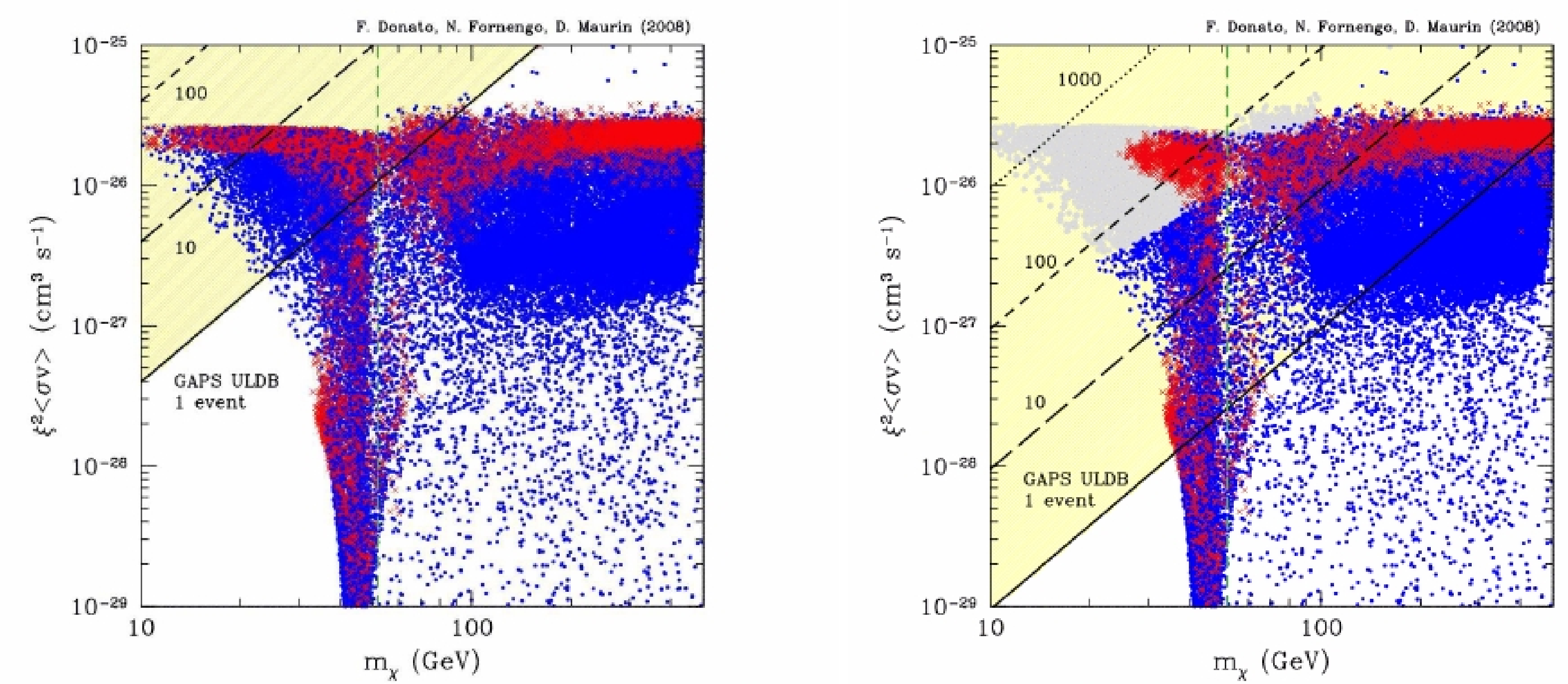


FIG. 13: The same as in Fig. 11, except that the astrophysical propagation parameters are those which predict minimal (left panel) and maximal (right panel) antideuteron fluxes. In the right panel, grey point are excluded by antiproton searches.

Conclusion

Antideuteron is one of the most promising GCR-related target for indirect detection of DM!

Hailey *et al. (GAPS collab.)*, Phys. Rev. D **01**, 007 (2006)