Perspectives of dark matter searches with antideuterons

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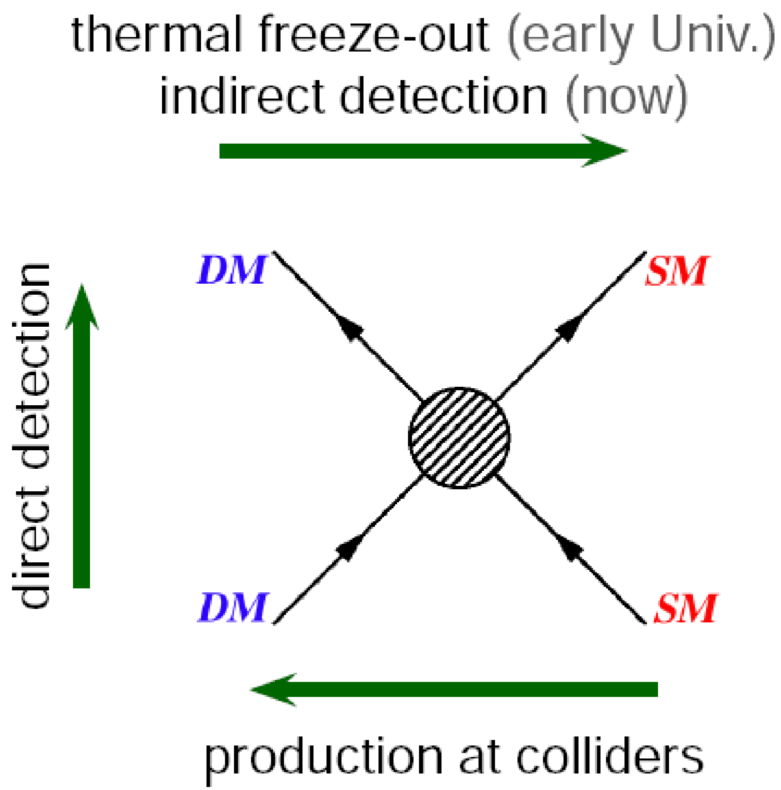
DM indirect detection



Dark matter can be indirectly detected by looking at the products of its annihilation (or decay)

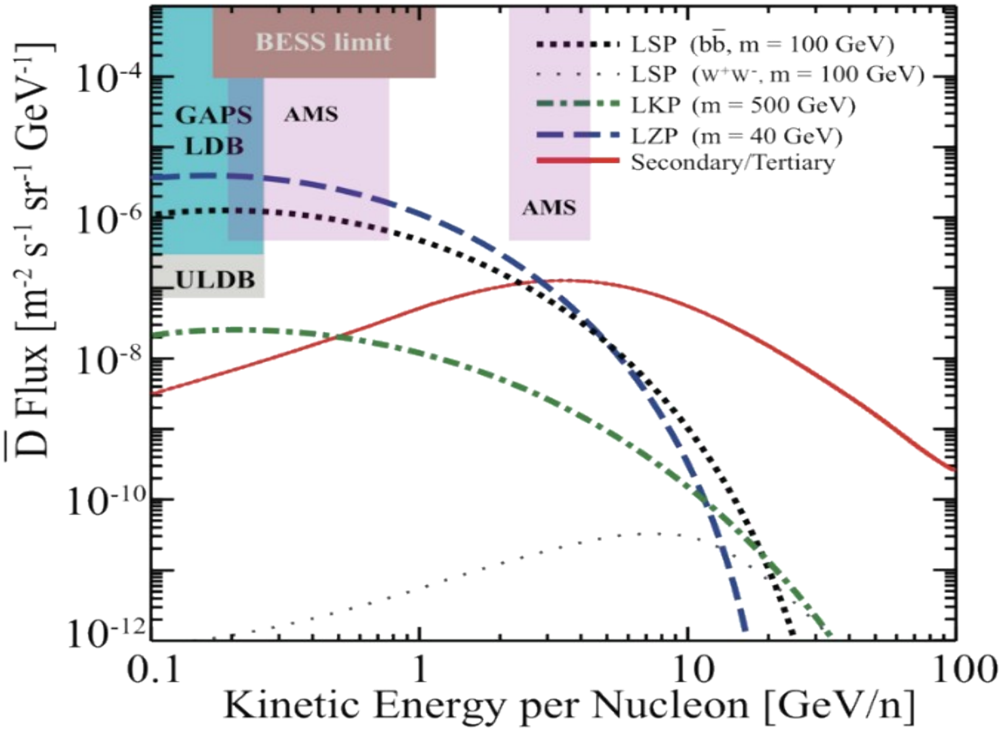
A good DM signature would be represented by an **excess of antimatter** in the cosmic rays flux

Antideuterons seems to be more promising than antiprotons or positrons

[F.Donato, N.Fornengo and P.Salati, Phys. Rev. D 62 (2000)]

Why antideuterons?

For kinematical reasons, it is very difficult to produce low energy antideuterons in a spallation reaction



When propagating, astrophysical antiprotons lose their energy through inelastic but non-annihilating reactions while antideuterons fragmentate **(B_d = 2.2 MeV)**

[H.Baer and S.Profumo, JCAP 12 (2005)]

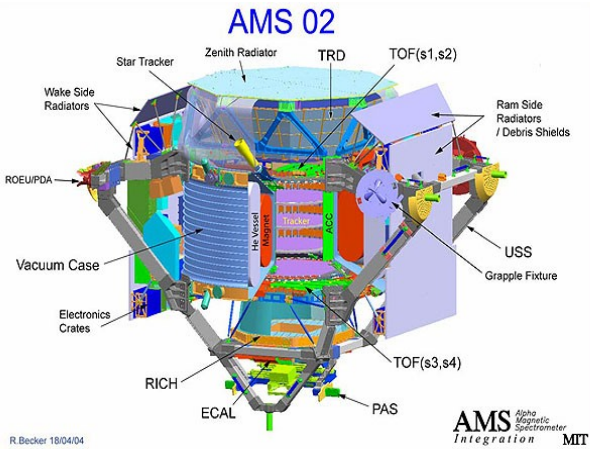
Very large signal-to-background ratio in the low-energy band

Experiments

- GAPS

- It's a balloon borne experiment, scientific flights are expected to begin in 2016
- In the LDB+ setup, GAPS will fly for 210 days

- AMS



- It's a multipurpose experiment that will look for any kind of antimatter signal
- It's operative, on board of the ISS, since 2011
- We will consider, in this analysis, a data taking period of 3 years

Antideuterons from DM annihilation

We work in a **model indipendent** framework (pure annihilations channels)

Our spectra are the **building blocks** for any DM model

Modeled with **Pythia 6.4.26** in its default configuration

Different phenomenological models can be used

What can we say about coalescence?

Event per event coalescence

$$dN_{\bar{d}} = \int d^3 \vec{\Delta} \, F_{\bar{p},\bar{n}} \times C(\vec{\Delta})$$

$C(\vec{\Delta})$: Probability that the two antinucleons coalesce

$F_{\bar{p},\bar{n}}$: Probability that the two antinucleons are formed

$$\vec{\Delta} = \vec{k}_{\bar{p}} - \vec{k}_{\bar{n}}$$

$$C(\vec{\Delta}) = \theta(\Delta^2 - p_0^2)$$

We do not assume a form for the function $F_{\bar{p},\bar{n}}$

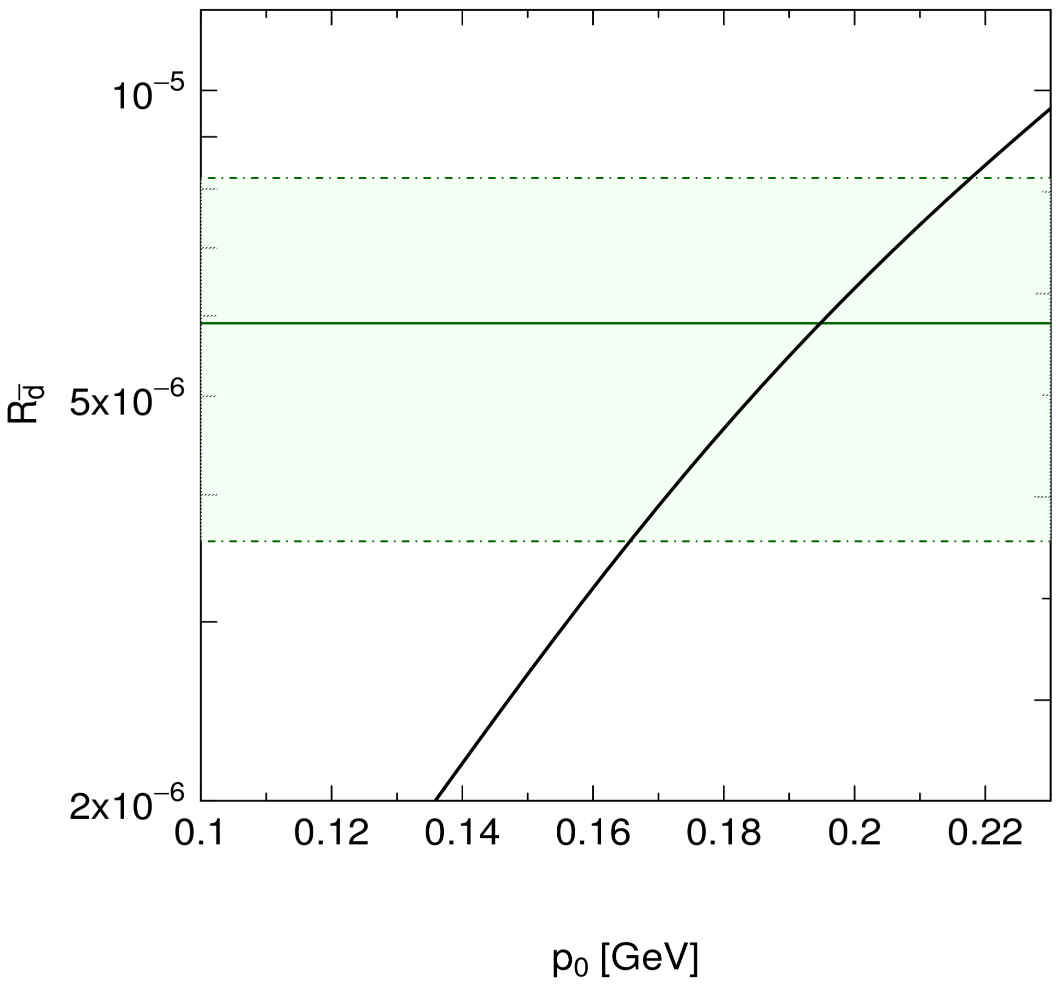
For each event we scan over the final state antinucleons and we consider them **as antideuterons if:**

$$\mathbf{\Delta p < p_0 \;\; and \;\; \Delta r_{min} < r_0}$$

We assume r_0 = 2 fm (radius of the $\bar{d}$) while p_0 **has to be tuned**

Tuning the model

DM pair annihilation is assumed to be the **analogous to an e^+e^- collision**



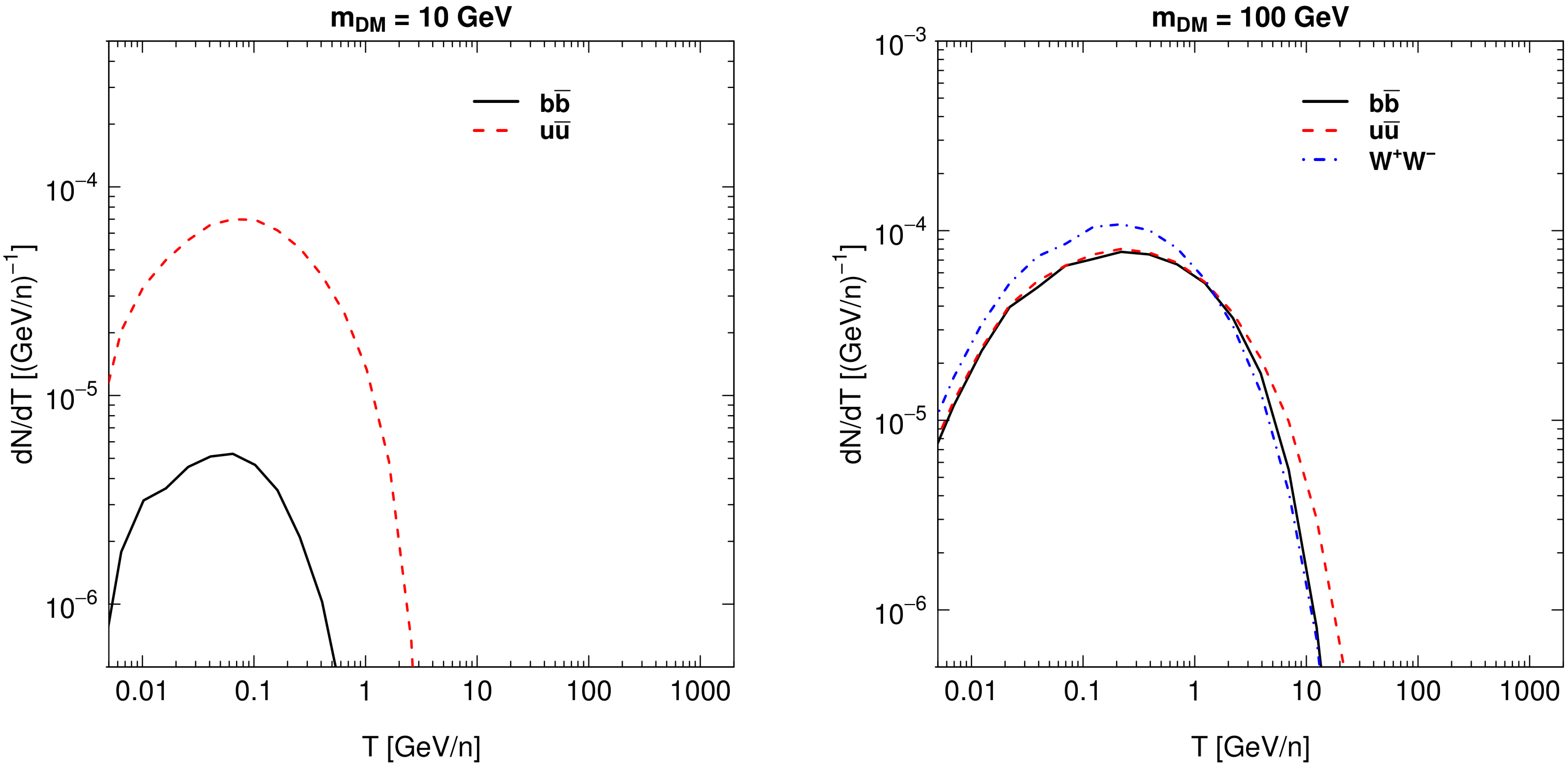
We tune our coalescence model in order to reproduce **ALEPH** data on antideuterons production rate at the Z resonance

$$\sqrt{s}=91.2\,GeV$$

[ALEPH collaboration, Phys. Lett. B 369 (2006) 192]

p_0=(195 ± 22) MeV

Injected spectra



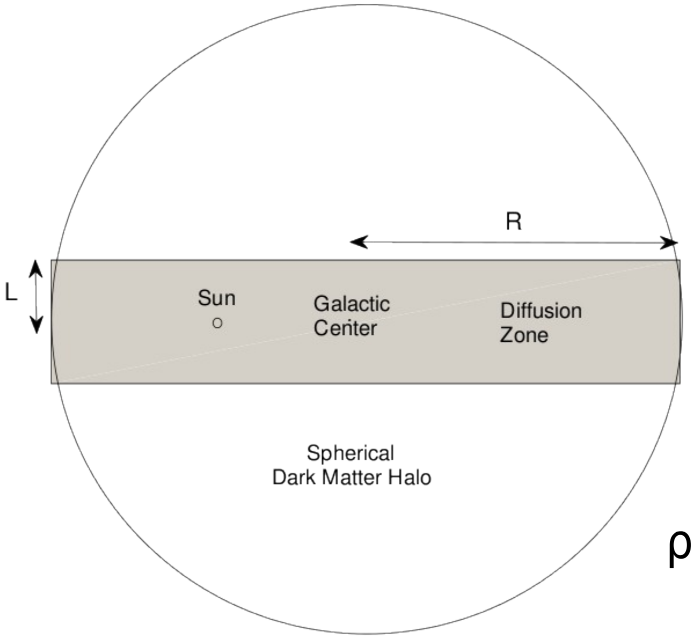
Galactic propagation

$$-\nabla[K(\vec{r},E)\nabla n_{\bar{d}}(\vec{r},E)]+\frac{\partial}{\partial z}V_c(z)n_{\bar{d}}(E,\vec{r})+2h\delta(z)\Gamma_{ann}n_{\bar{d}}(E,\vec{r})=q_{\bar{d}}(\vec{r},E)$$

Two-zone diffusion model

$$K(x,E)=K_0\beta\left(\frac{R}{1GV}\right)^{\delta}$$

$$\vec{V}_c=sign(z)V_c$$



$$q_{\bar{d}}(x,E)=\frac{1}{2}<\sigma v>\frac{dN_{\bar{d}}}{dT}\left(\frac{\rho(x)}{m_\chi}\right)^2$$

$\rho(r)$ Is the DM halo profile (e.g. Einasto, NFW, isothermal)

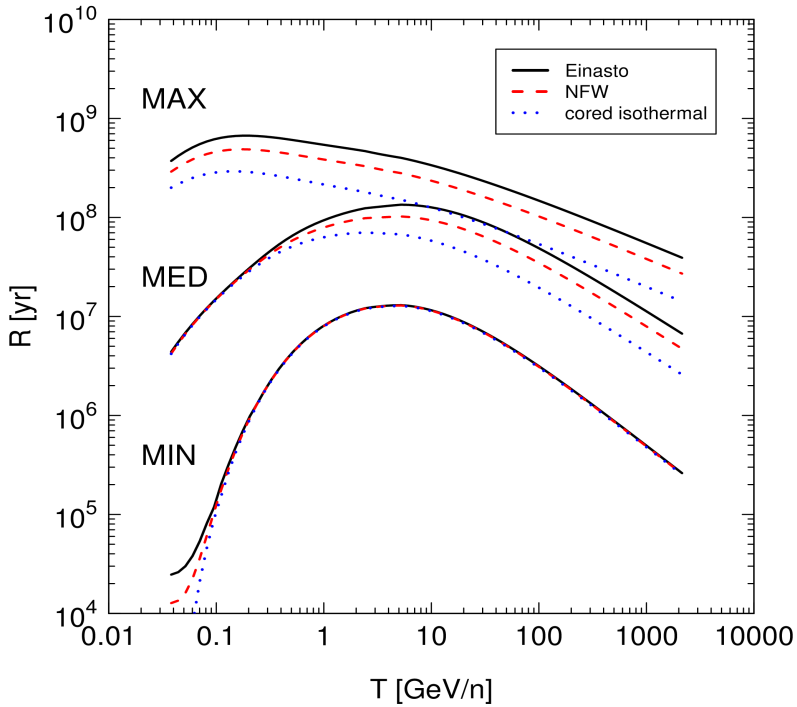
CAVEAT : No energy losses and no reacceleration!

Galactic propagation - II

No reacceleration & energy losses → **the solution can be factorized**:

$$\phi_{\bar{d}}(T)=\left(\frac{v_{\bar{d}}}{4\pi}\left(\frac{\rho_{\odot}}{m_{\chi}}\right)^2\frac{1}{2}<\sigma v>\frac{dN_{\bar{d}}}{dT}\right)\times R_{\bar{d}}(T)$$

All the astrophysics is here!

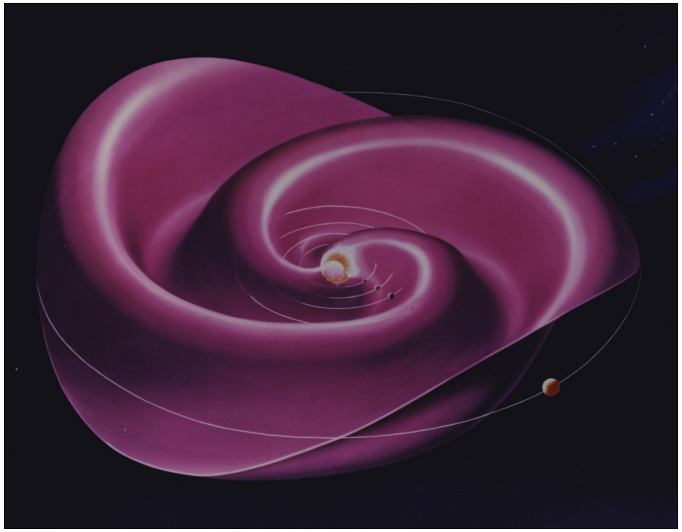


	δ	K_0 [Kpc^2/Myr]	L [Kpc]	V_c [Km/s]
MIN	0.85	0.0016	1	13.8
MED	0.70	0.0112	4	12
MAX	0.46	0.0765	15	5

K_0,V_c and δ constrained by B/C data

Interactions with the heliosphere

How can we model the motion of a charged particle inside the SMF?



The Sun's magnetic field is a **large rotating spiral**

An **heliospheric current sheet (HCS)**, whose shape varies with time following solar activity, separates field lines directed toward or away from the sun

Generally, this is done by using the **force field approximation**:

$$\Phi_{TOA}(T_{TOA}) = \frac{2mT_{TOA}+T_{TOA}}{2mT_{IS}+T_{IS}} \Phi_{IS}(T_{IS})$$

$$T_{TOA} = T_{IS} - \phi$$

[J. S. Perko, Astron. Astrophys. 184 (1987) 119]

Charge dependent solar modulation

Given the distribution f of a CR particle in the phase space:

[E. N. Parker, P&SS 13, 9 (1965)]

$$\frac{\partial f}{\partial t} = -(\vec{V}_{sw} + \vec{v}_d)\cdot\nabla f + \nabla\cdot(K\cdot\nabla f) + \frac{P}{3}(\nabla\cdot\vec{V}_{sw})\frac{\partial f}{\partial p}$$

convection — drifts — diffusion (random walk) — adiabatic losses

We varies three parameters:

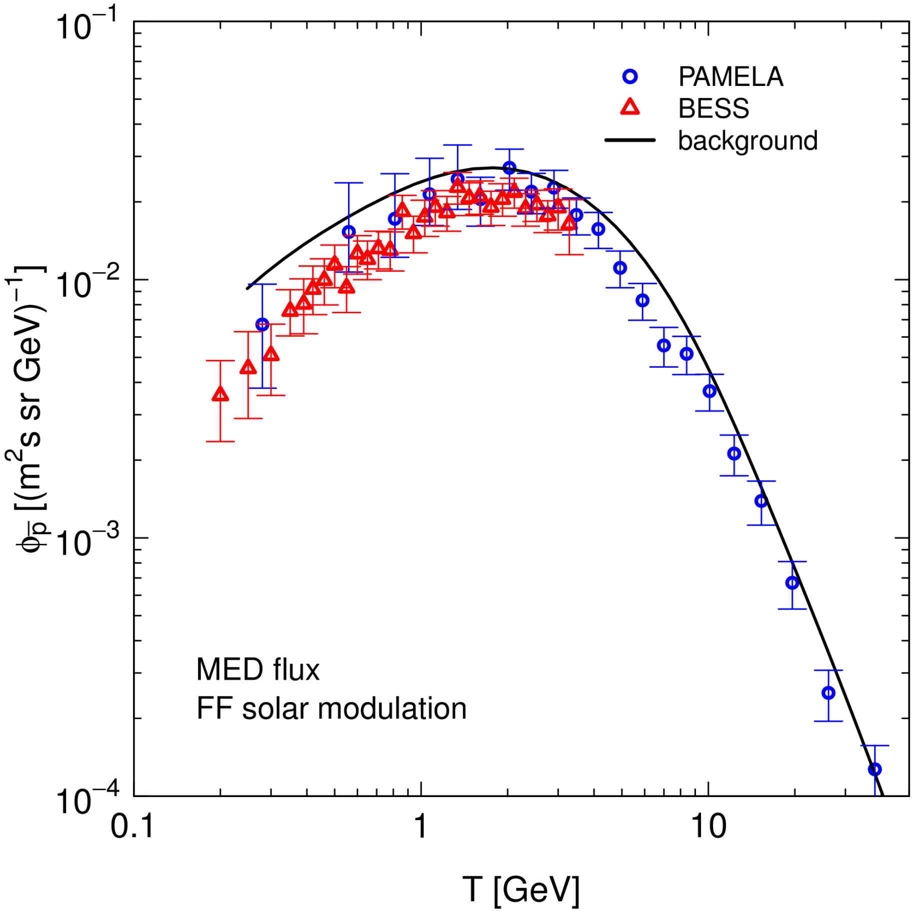
- The **tilt angle α**: it describes the spatial extent of the HCS
- The **mean free path λ** of the CR particle along the magnetic field direction
- The **spectral index δ** that relates the solar diffusion to the particle's energy

We exploit the recently developed code **HELIOPROP**

[L. Maccione, Phys.Rev.Lett. 110, 081101(2013),arXiv:1211.6905[astro-ph.HE]]

Antipotons bounds - I

The antiproton flux was recently measured by **PAMELA** and **BESS POLAR II**



The measured flux is well fitted by the pure background

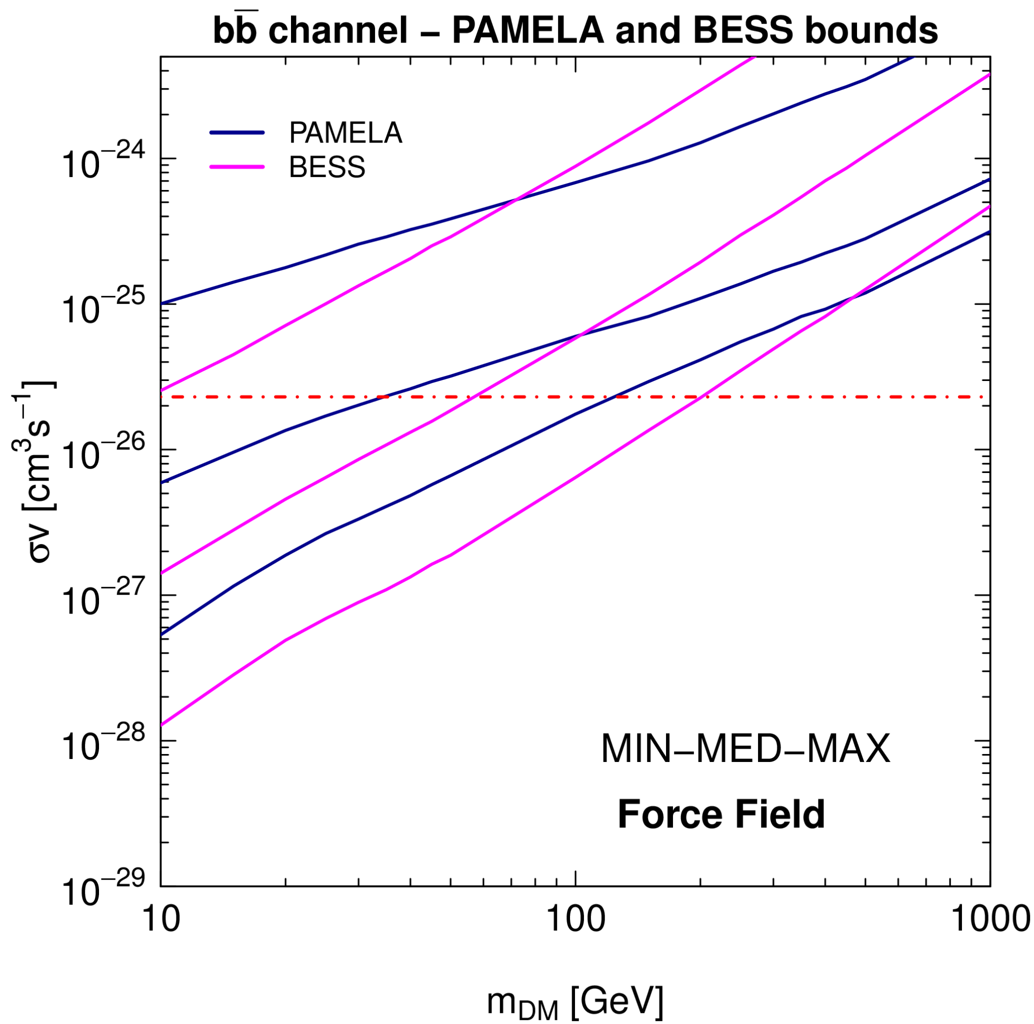
↓

Very little space for dark matter!

We calculate the bounds on DM annihilation cross section by imposing an **uncertainty of the 40%** on the calculated astrophysical background

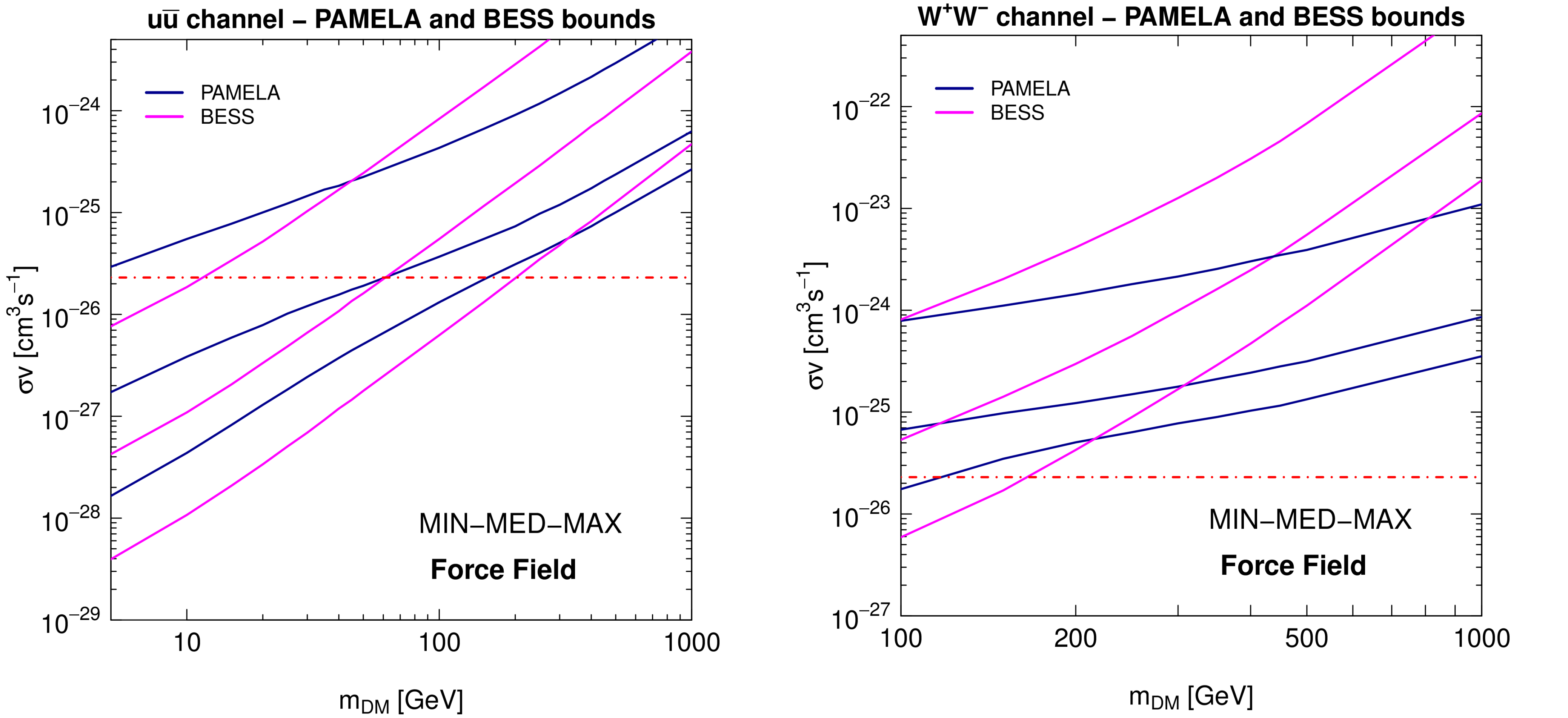
F.Donato, N.Fornengo and D.Maurin, Phys. Rev. D 78 (2008)

Antiprotons bounds - II



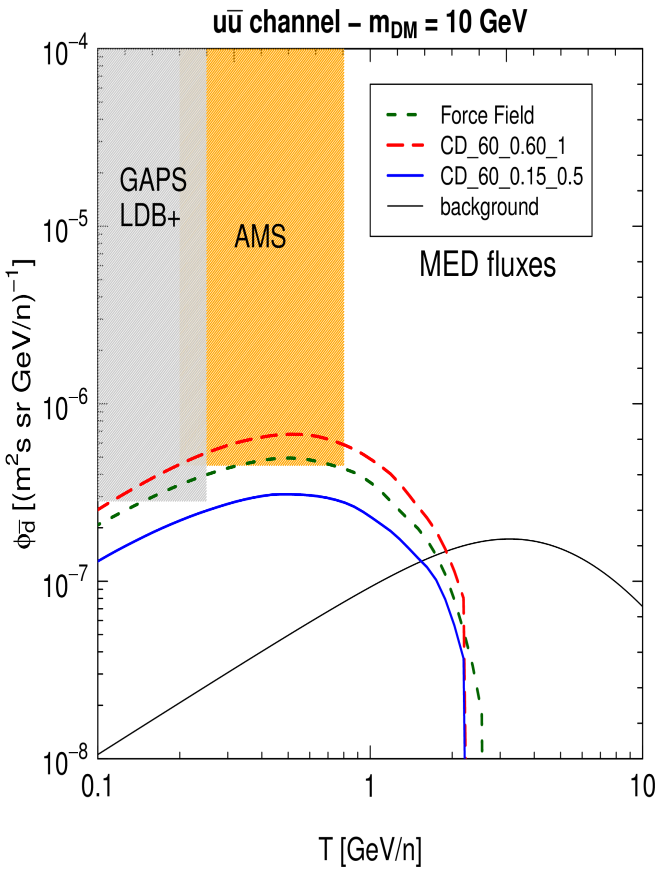
- Bounds calculated with a 99% c.l.
- 3 set of curves for 3 propagation models (MIN, MED and MAX)
- We want to be as conservative as possible -> in the following analysis we will only consider PAMELA bounds

Antiprotons bounds - III

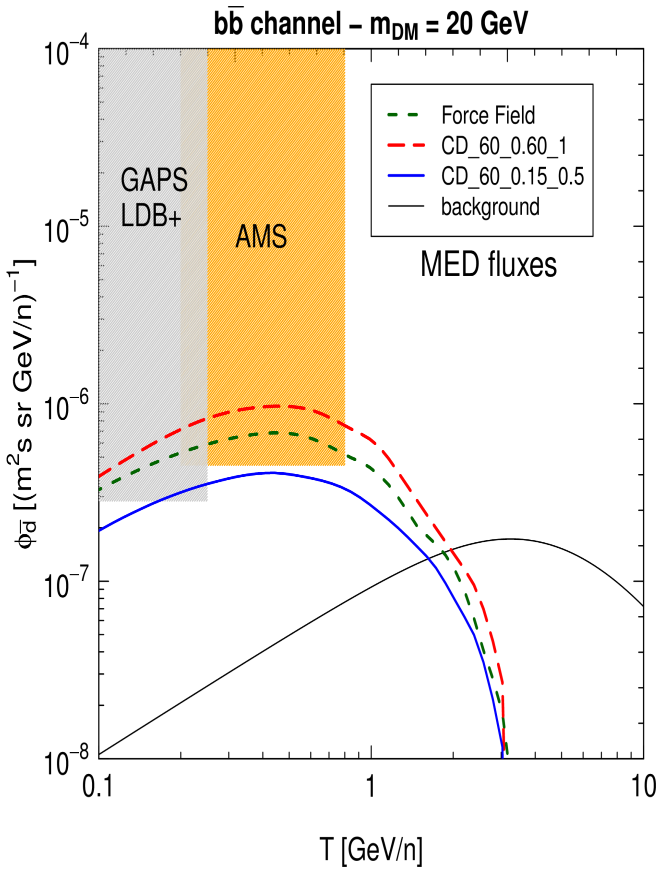


Fluxes at Earth

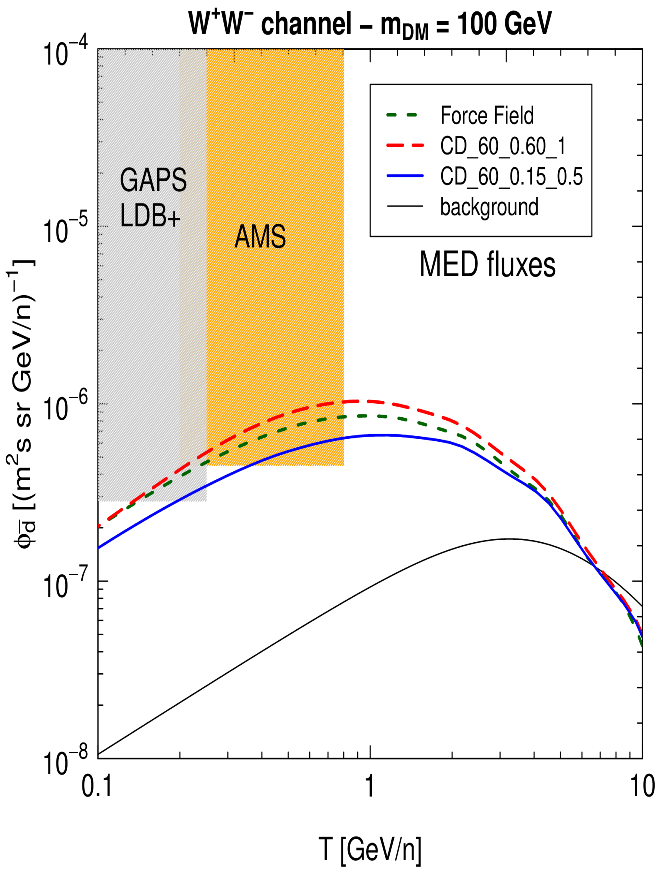
uu channel



bb channel

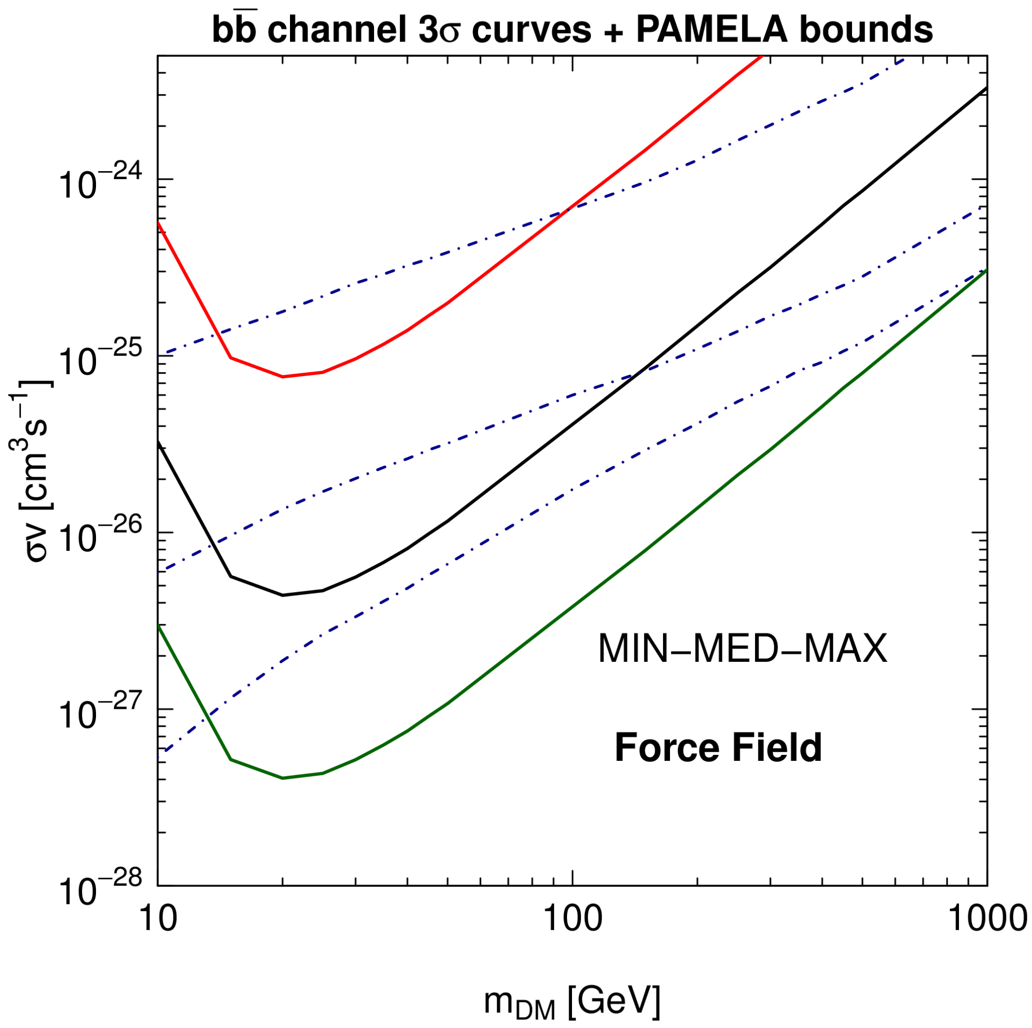


W^+W^- channel



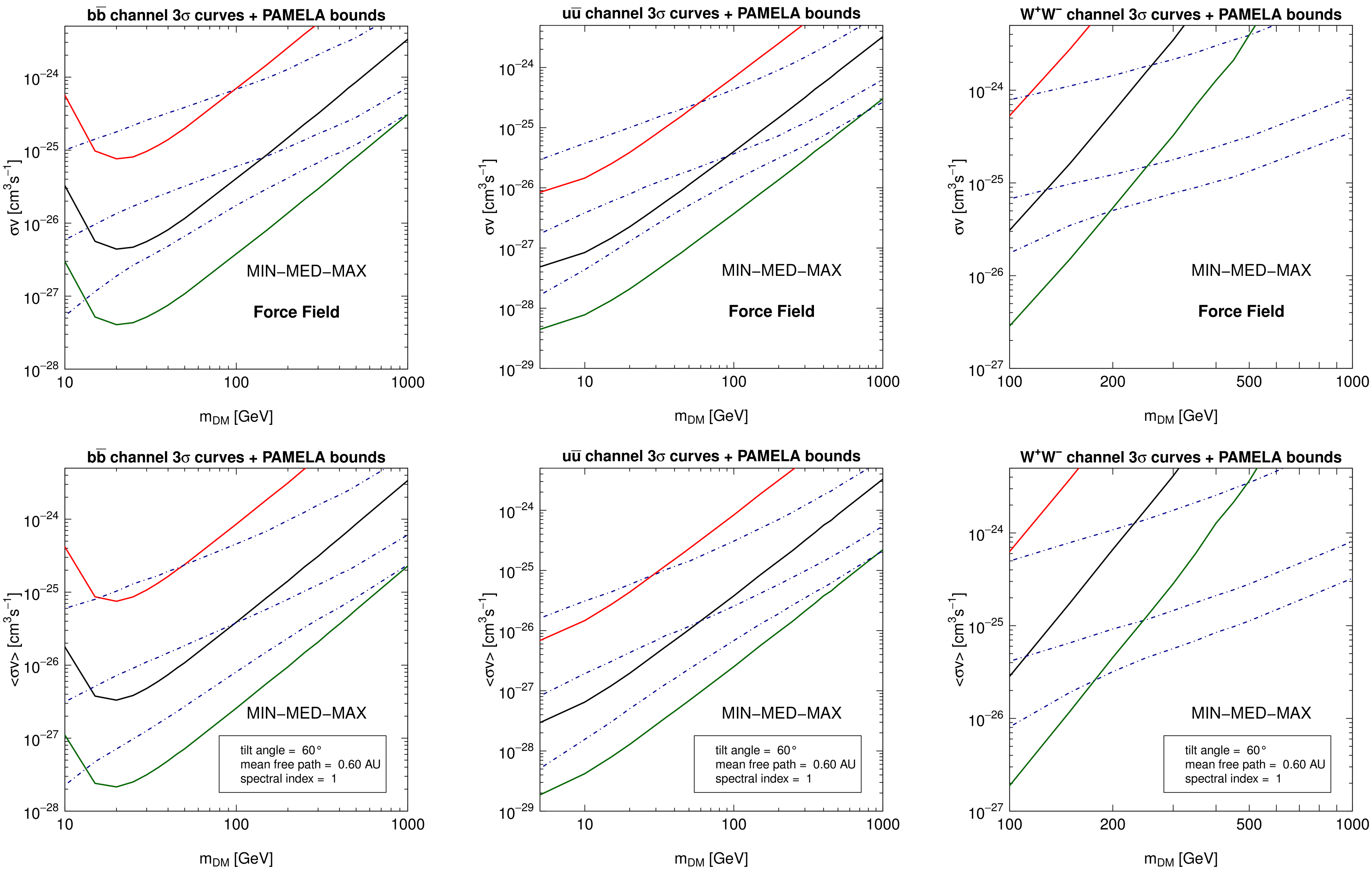
Cross section are ~the maximal permitted by antiprotons bounds

Experimental reachabilities (GAPS) - I

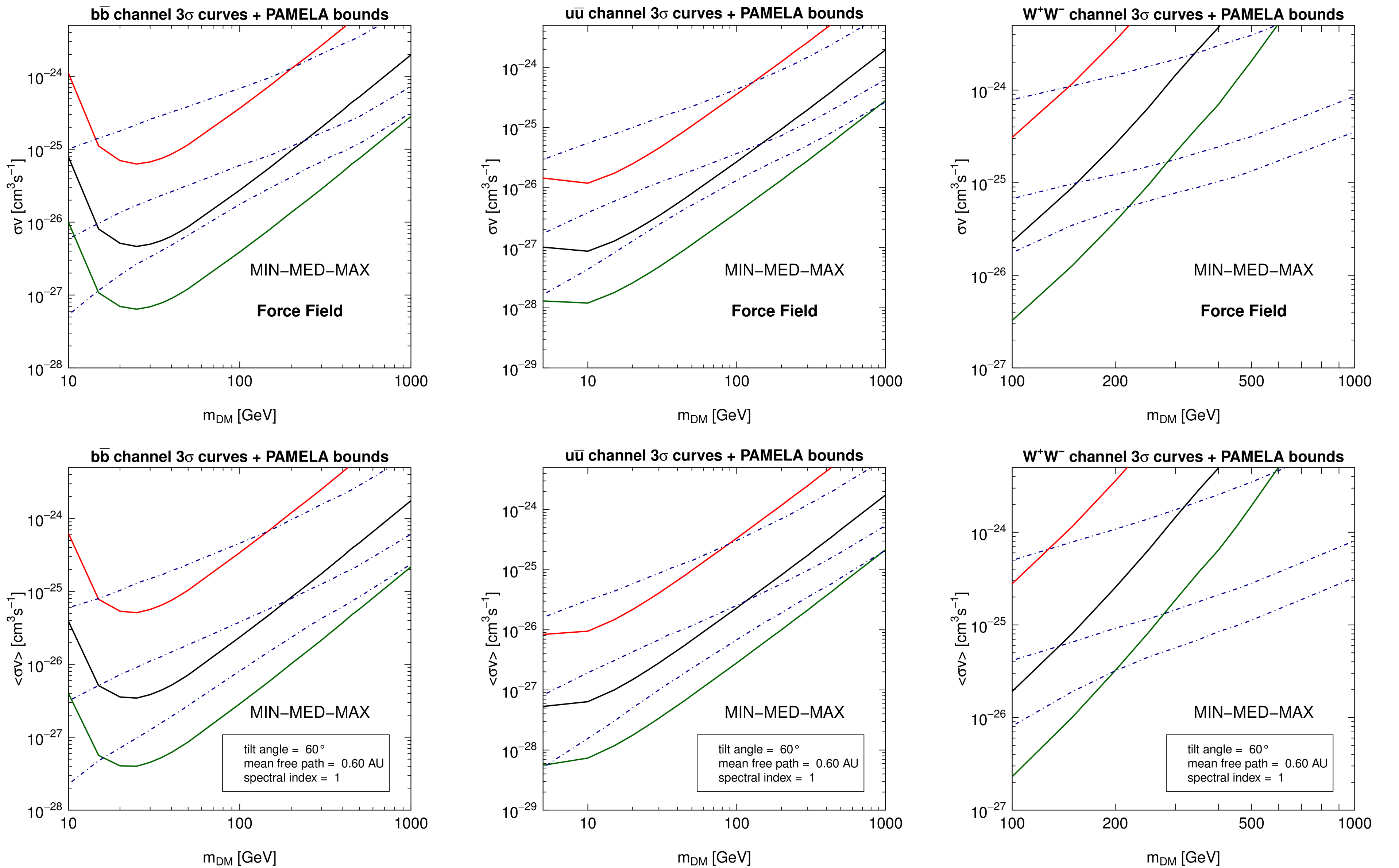


- Reachability curves for a 3σ c.l. (i.e. 1 signal + bkg event)
- 3 set of curves for 3 propagation models (MIN, MED and MAX)
- Only PAMELA bounds are considered

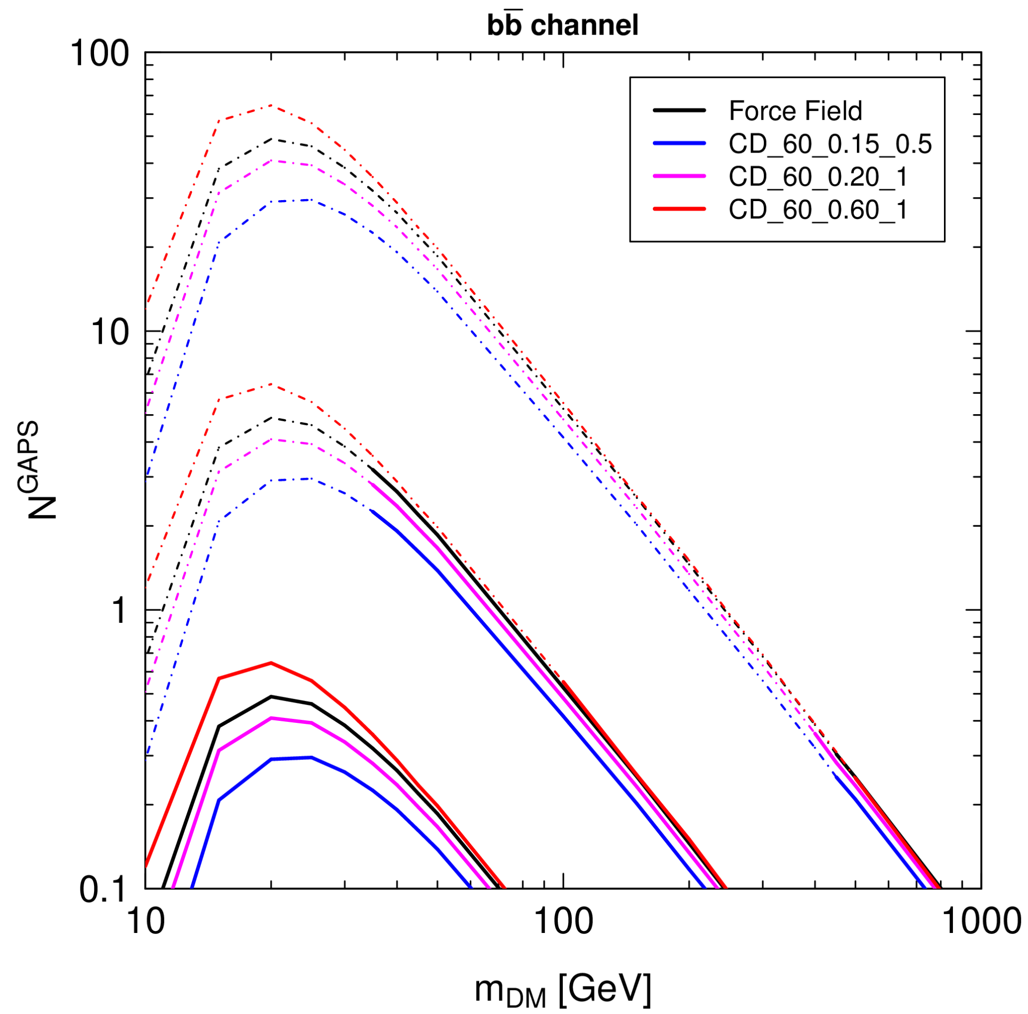
Experimental reachabilities (GAPS) - II



Experimental reachabilities (AMS)



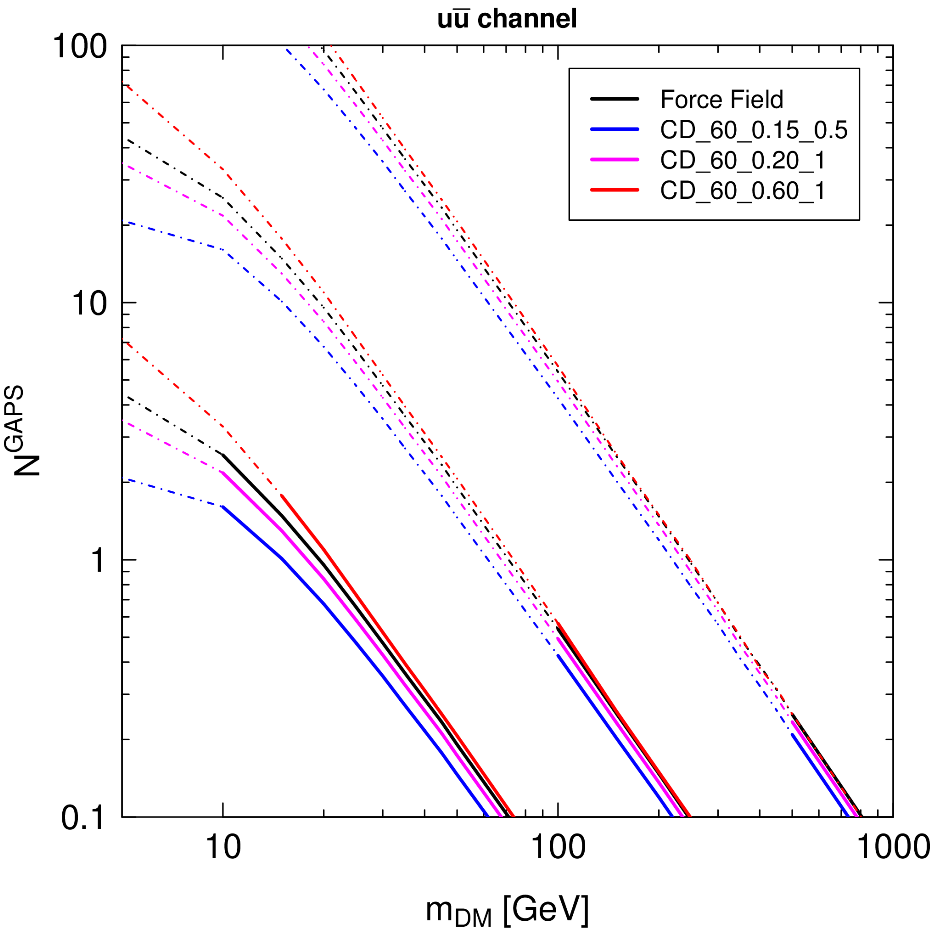
How many events?



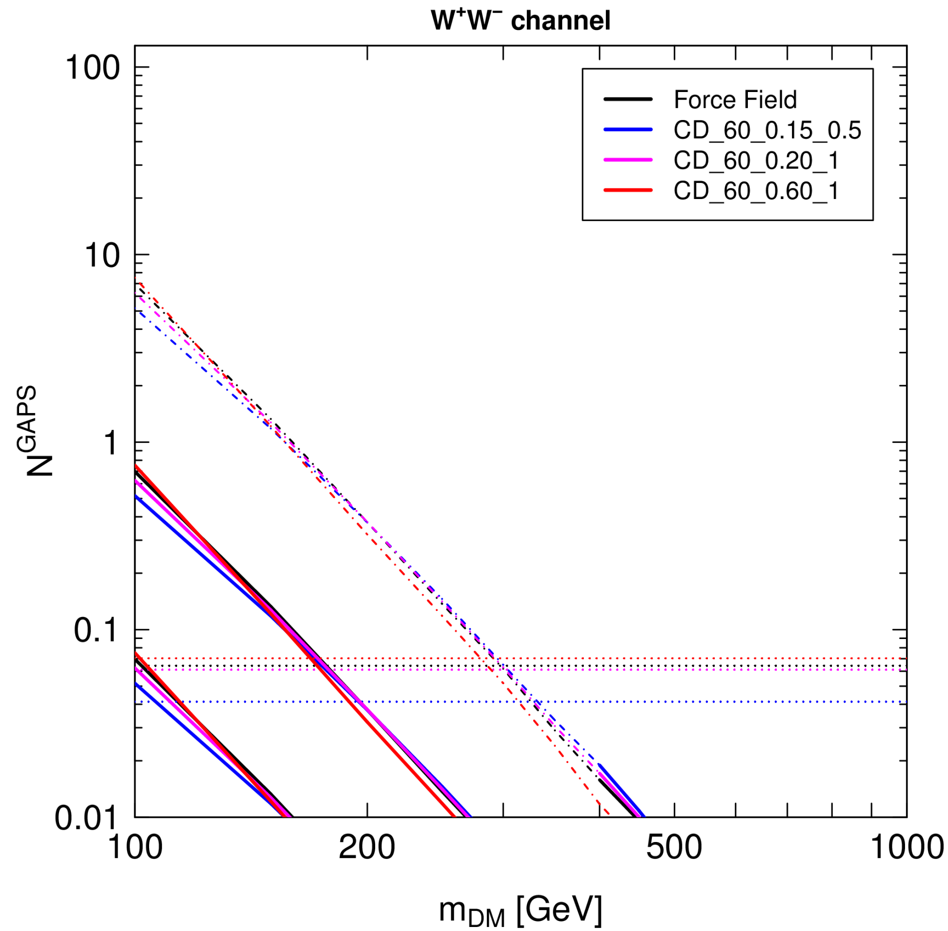
- Number of signal events for 4 models of solar modulation (Einasto MED configuration)
- 3 set of curves for 3 values of <σv> (thermal, 0.1 x thermal, 10 x thermal)
- Solid lines = **allowed** by PAMELA bounds
  Dot-dashed lines = **forbidden** by PAMELA bounds

How many events? - GAPS

uu channel

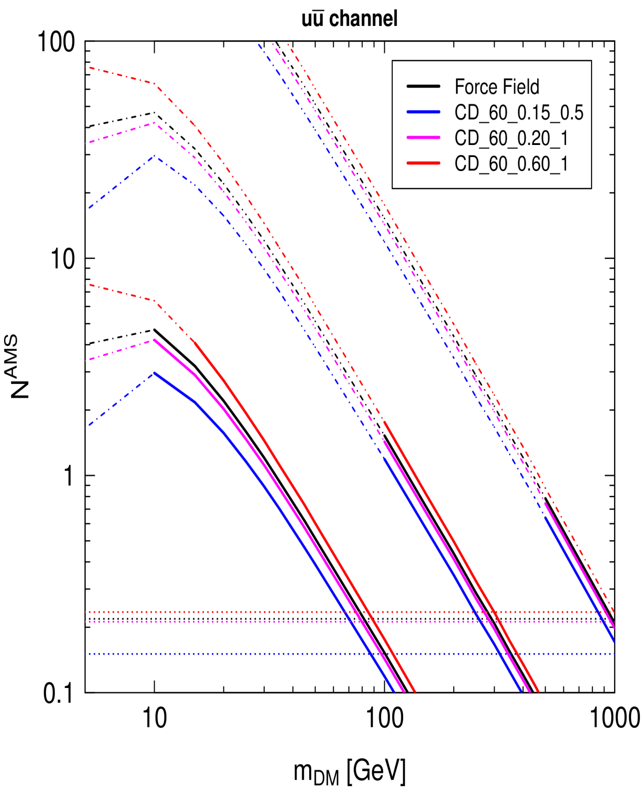


W⁺W⁻ channel

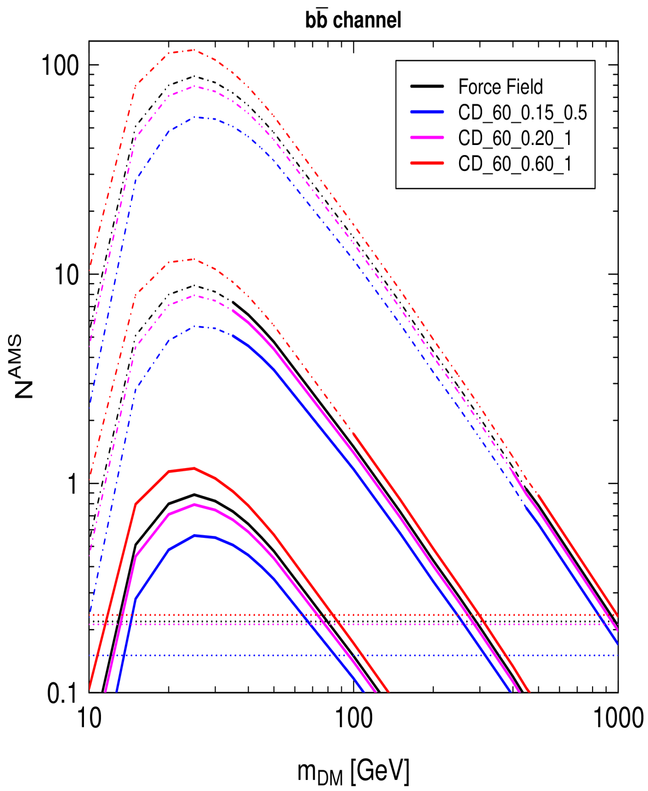


How many events? - AMS

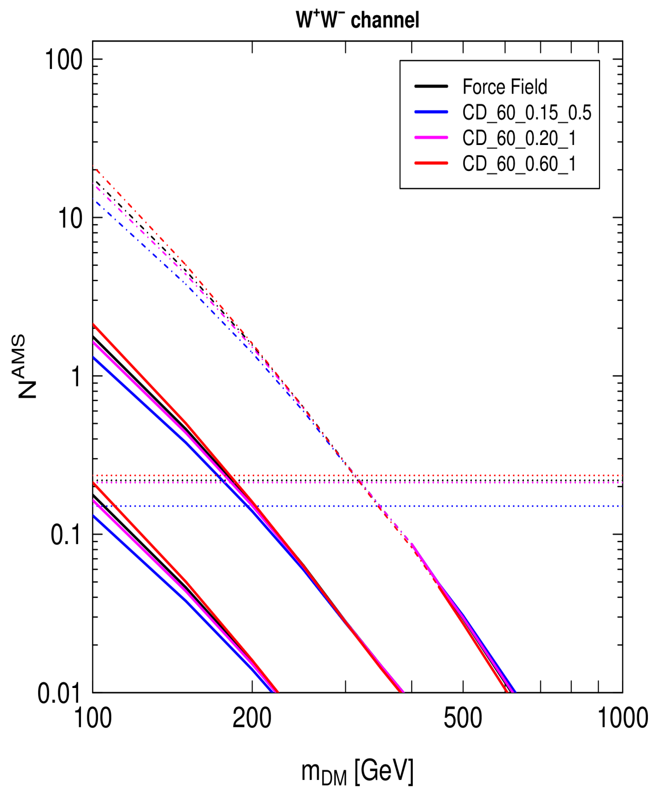
uu channel



bb channel



W^+W^- channel



Conclusions

- Antideuterons are a very promising, almost background free channel for DM indirect detection

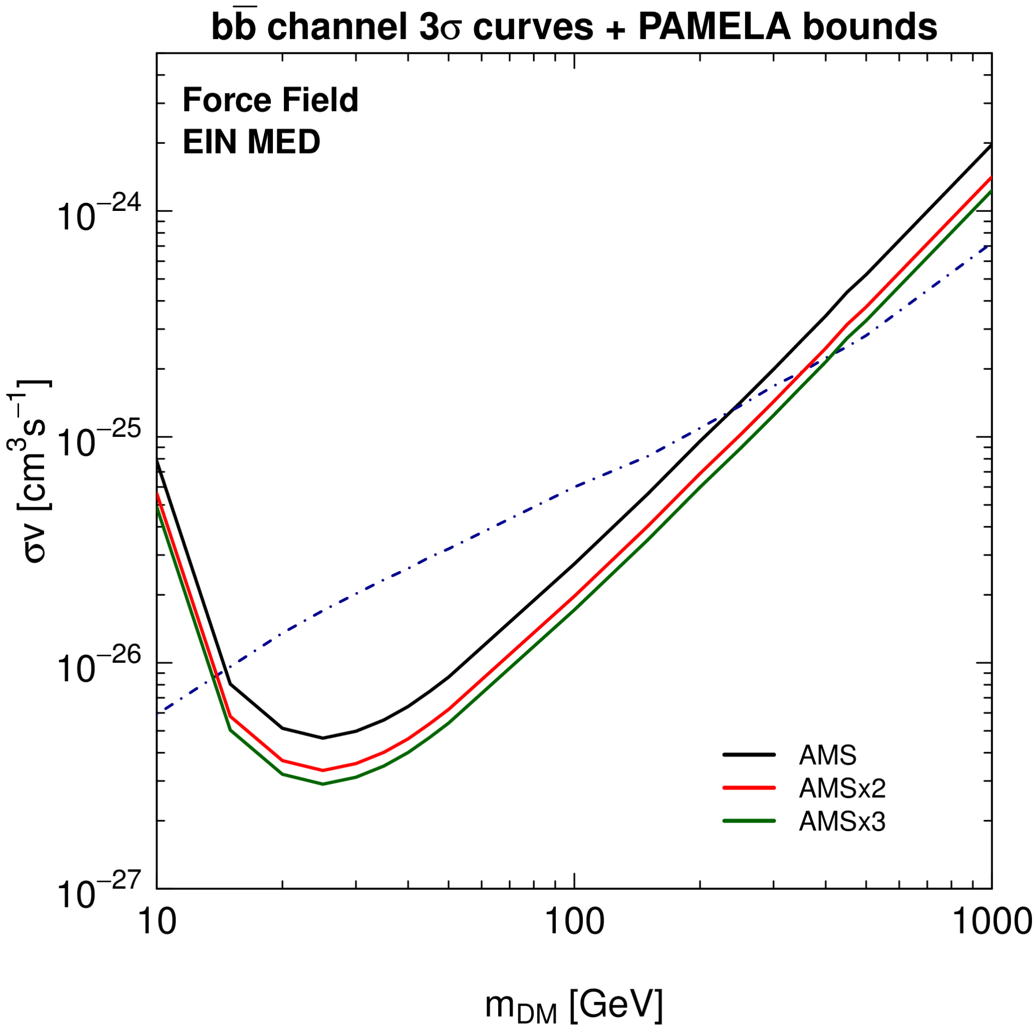
- In order to have a precise estimate of experimental reachabilities an accurate treatment of solar modulation is needed

- The bounds imposed by antiprotons experiments such as PAMELA and BESS POLAR II (and, in future, also AMS) are extremely strong. However, some space for DM is still there

To sum up, antiprotons bounds make the observation of antideuterons at current and future experiments challenging but not impossible

Back-up slides

Keeping track of data taking time



- AMS will fly and take data for a period much longer than the one that we are considering (3 years)
- Remember however that in a longer time, more background events will be detected -> we'll need more DM events to have a detection!

CD solar modulation - I

In **spherical coordinates**, the SMF is given by:

$$\vec{B} = AB_0\left(\frac{r}{r_0}\right)^{-2}\left(\hat{r} - \frac{\Omega r \sin\theta}{V_{SW}}\hat{\varphi}\right)$$

$$\begin{cases} V_{SW} = 400\ Km/s \\ |B|\ (1\ AU) = B_{\oplus} = 5\ nT \\ A = H(\theta - \theta') \\ \theta' = \frac{\pi}{2} + \sin^{-1}\left(\sin\alpha\ \sin\left(\varphi + \frac{\Omega r}{V_{SW}}\right)\right) \end{cases}$$

α: tilt angle → [20°,60°]

Ω → solar differential rotation rate

The function A takes into account the presence of the HCS which is related to the tilt angle

The SMF influences also the drifts: $\vec{v}_d = \nabla \times (K_A \vec{B} / |B|)$

K_A: Antisymmetric part of K

CD solar modulation - II

The solar diffusion depends on the symmetric part of the K tensor: $K = diag(K_{\|}, K_{\perp r}, K_{\perp\theta})$. The component parallel to the SMF direction goes like:

[0.5 or 1]

$$\begin{cases} k_{\|} = K_{\|}(\vec{B}) \times \left(\frac{\rho}{1\,GV}\right)^{\delta} & if\ \rho < 4\,GV \\ k_{\|} = K_{\|}(\vec{B}) \times \left(\frac{\rho}{1\,GV}\right)^{1.95} & if\ \rho > 4\,GV \end{cases}$$

As a function of the mean free path, we have $K_{\|,\perp} = \lambda_{\|,\perp} \frac{v}{3}$

$$\lambda_{\|} = \lambda_0 \times \lambda_{\|}(\vec{B}, \rho)$$

[0.15, 0.20 or 0.60 AU]

How many events do we need?

We want to determine how many events we need in order to claim for a DM discovery with a certain **confidence level**

The result is given by poissonian statistics:

We need N_{crit} events, being N_{crit} the smallest N satisfying (for a 3σ c.l.):

$$\sum_{n=0}^{N-1} P(n,b) > 0.997$$

$$P(n,b) = \frac{b^n e^{-n}}{n!}$$

It's a cumulative distribution (the poissonian is discrete!)

Basically, for a 3σ c.l. we need 1 event for GAPS and 2 for AMS

Number of expected events

The number of expected events for a given experiment is calculated as:

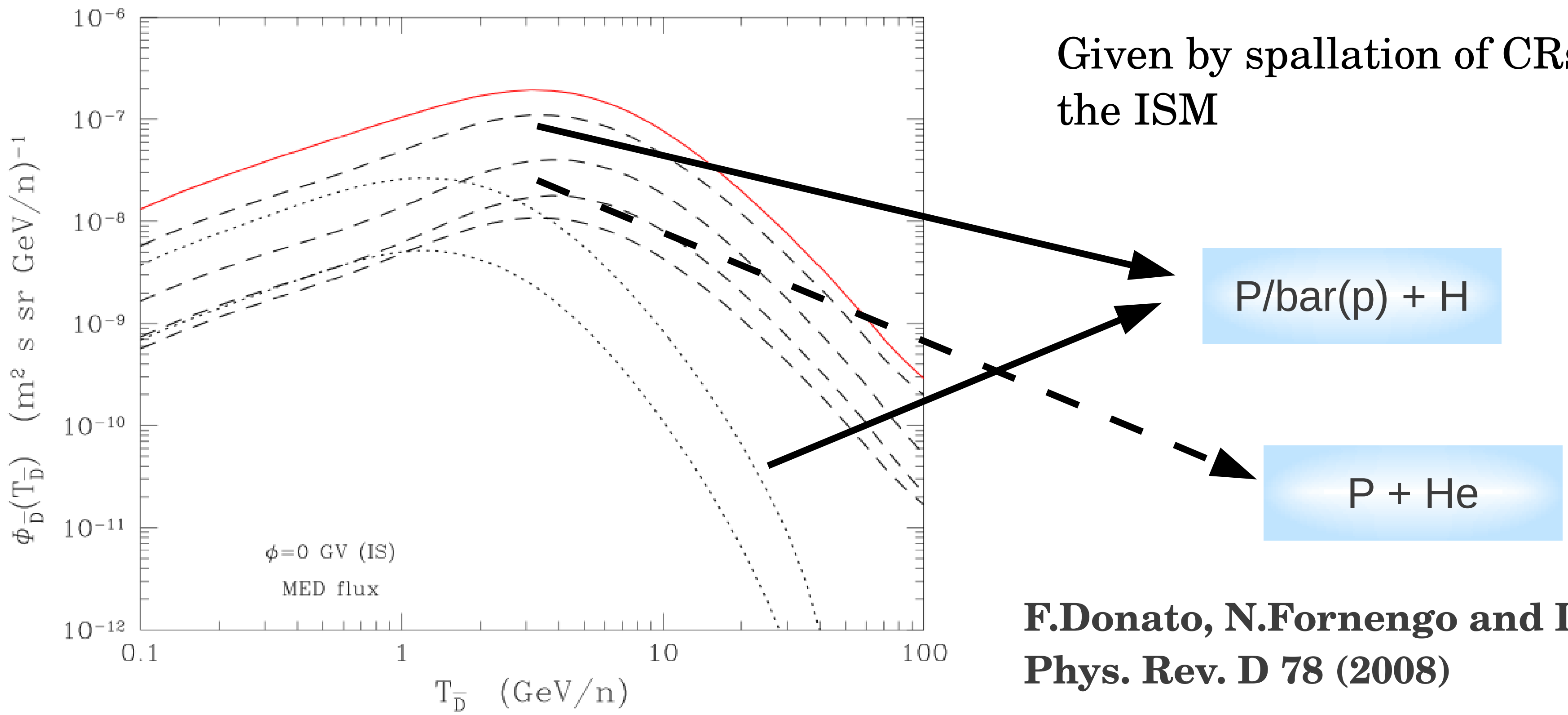
$$N_{\bar{d}} = \int_{E_{k,min}}^{E_{k,max}} dE_k \, A(E_k) \times \Phi_{TOA}(E_k)$$

Where $A(E_k)$ is the acceptance of the experiment under scrutiny. In our case we define an effective exposure:

$$N_{\bar{d}} = \left(\int_{E_{k,min}}^{E_{k,max}} dE_k \, \Phi_{TOA}(E_k) \right) \times \mathcal{E}$$

This exposure $\mathcal{E}$ can be determined from the experimental sensitivity (i.e. A flux that corresponds to 1 event for GAPS and 2 for AMS)

Background flux - IS

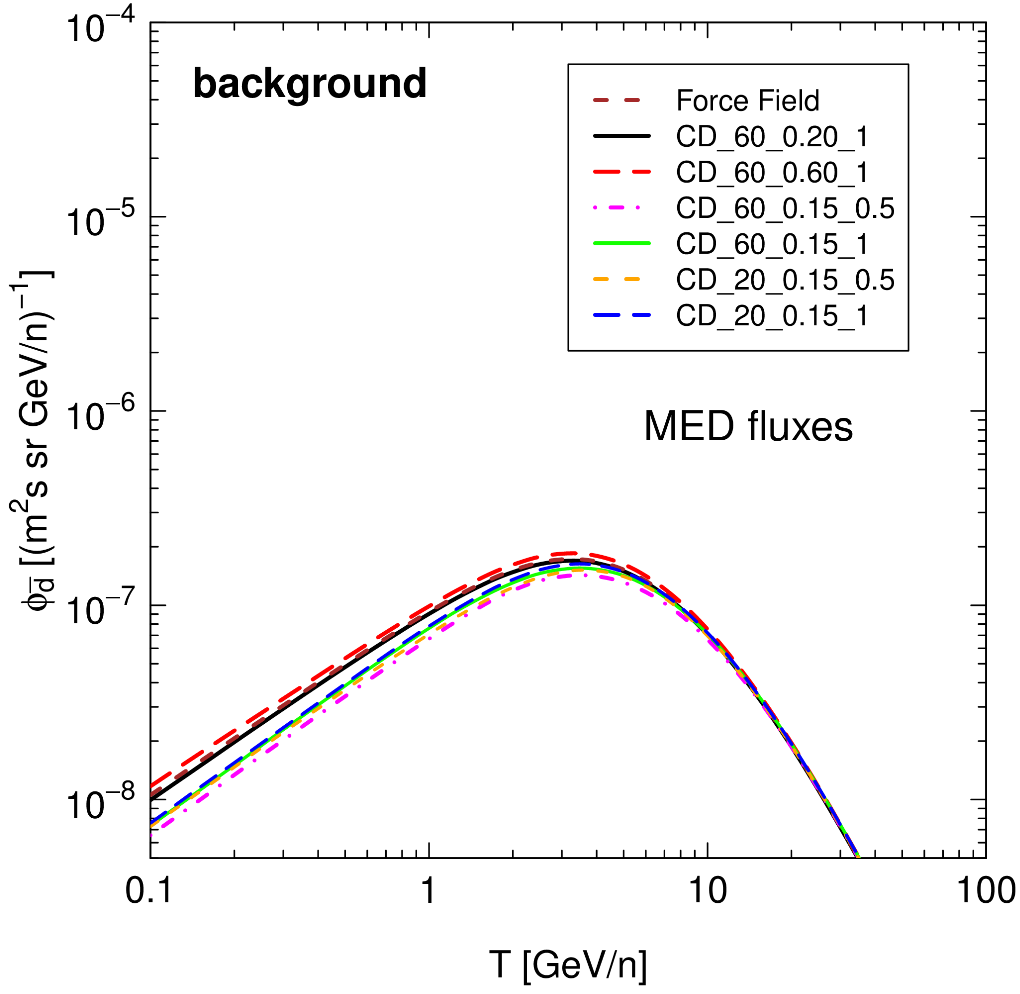


Given by spallation of CRs on the ISM

F.Donato, N.Fornengo and D.Maurin, Phys. Rev. D 78 (2008)

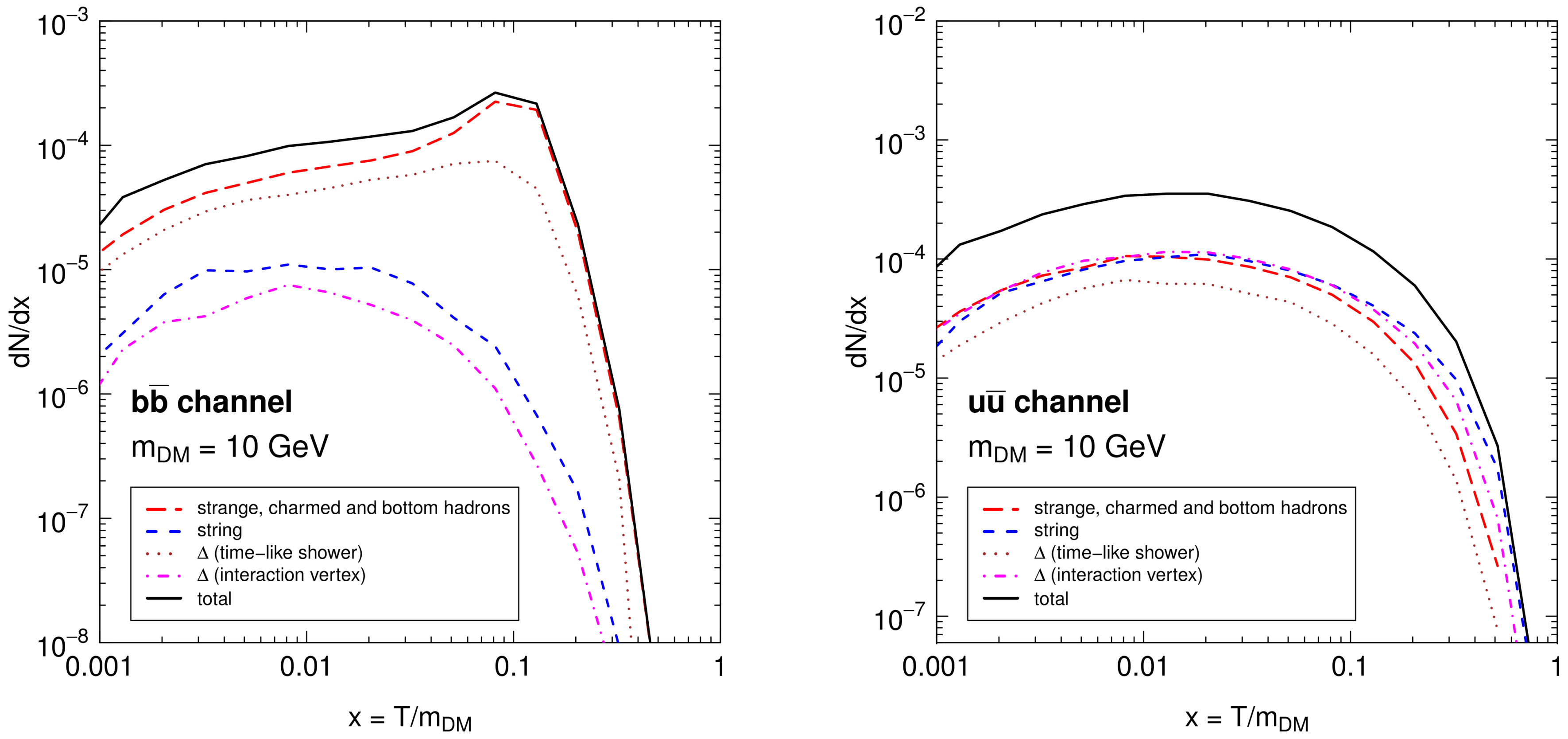
CAVEAT : it is still calculated with the OLD coalescence model

Background flux - TOA



Coalescence at low masses

Spectra obtained **without** imposing the condition $\Delta r < r_0$



For the bb channel, at low masses, the majority of pn pairs come from **long living hadrons**