Antideuterio: prospettive teoriche per la ricerca di DM

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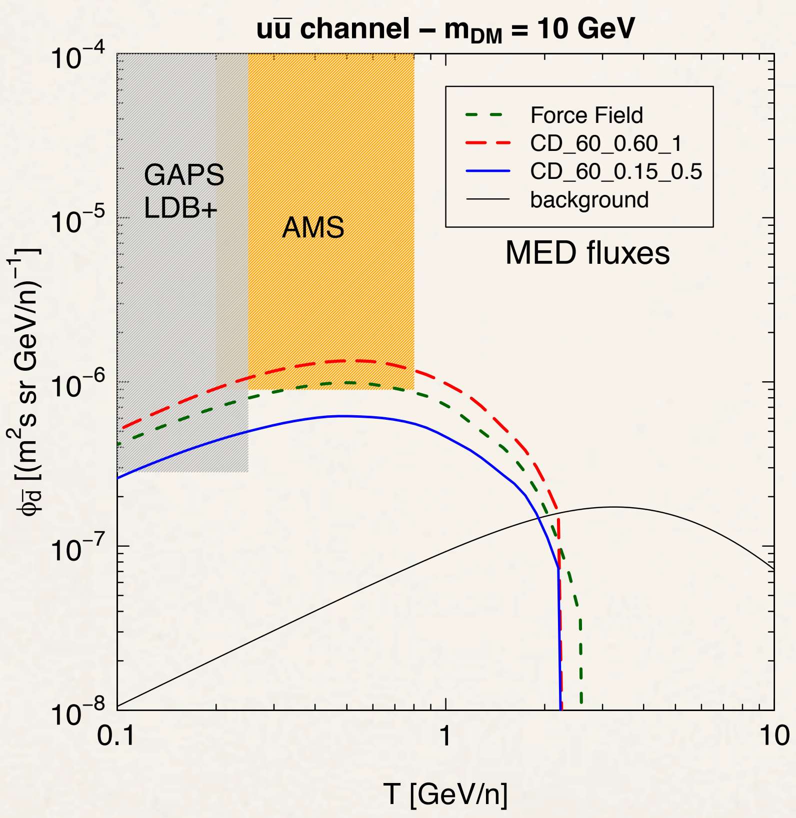
What Next DM GdL SeeVogh Meeting 4, 10/07/2014

Why anti-deuterons?

We expect the DM signal to **dominate** over the astrophysical background at **low energies** (i.e. below a few GeV/n)

The background flux is given by **spallation** of cosmic ray particles over the interstellar medium

$$\begin{cases} p + p \to \bar{d} + X & E_{thr} = 17 m_p \\ p + p \to {}^3\overline{He} + X & E_{thr} = 31 m_p \end{cases}$$

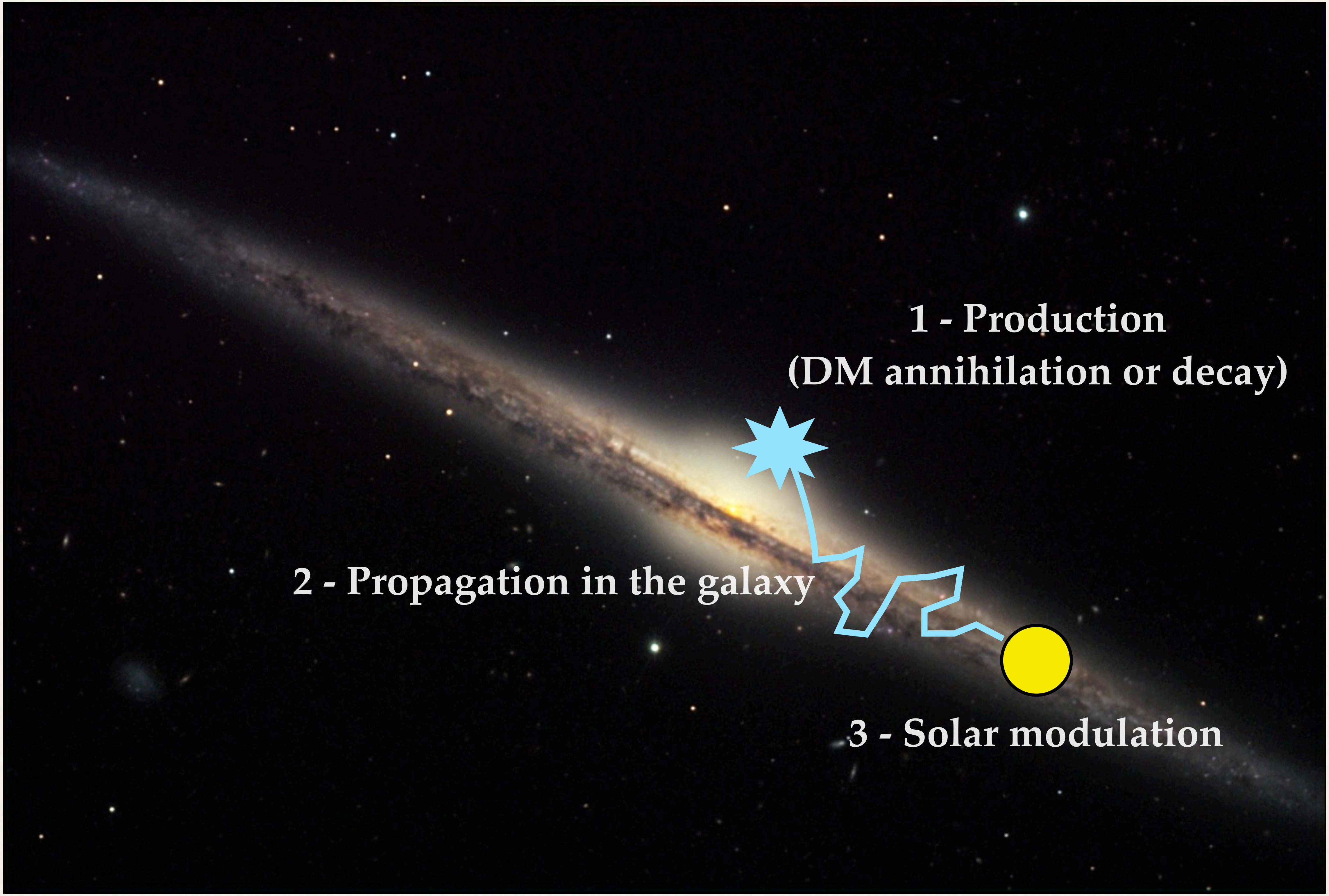


The large energy thresholds, together with the steeply falling primary CR spectra make the astrophysical background **highly suppressed** at **low energies**

Anti-nuclei are a promising tool to detect **low or intermediate mass WIMPs**

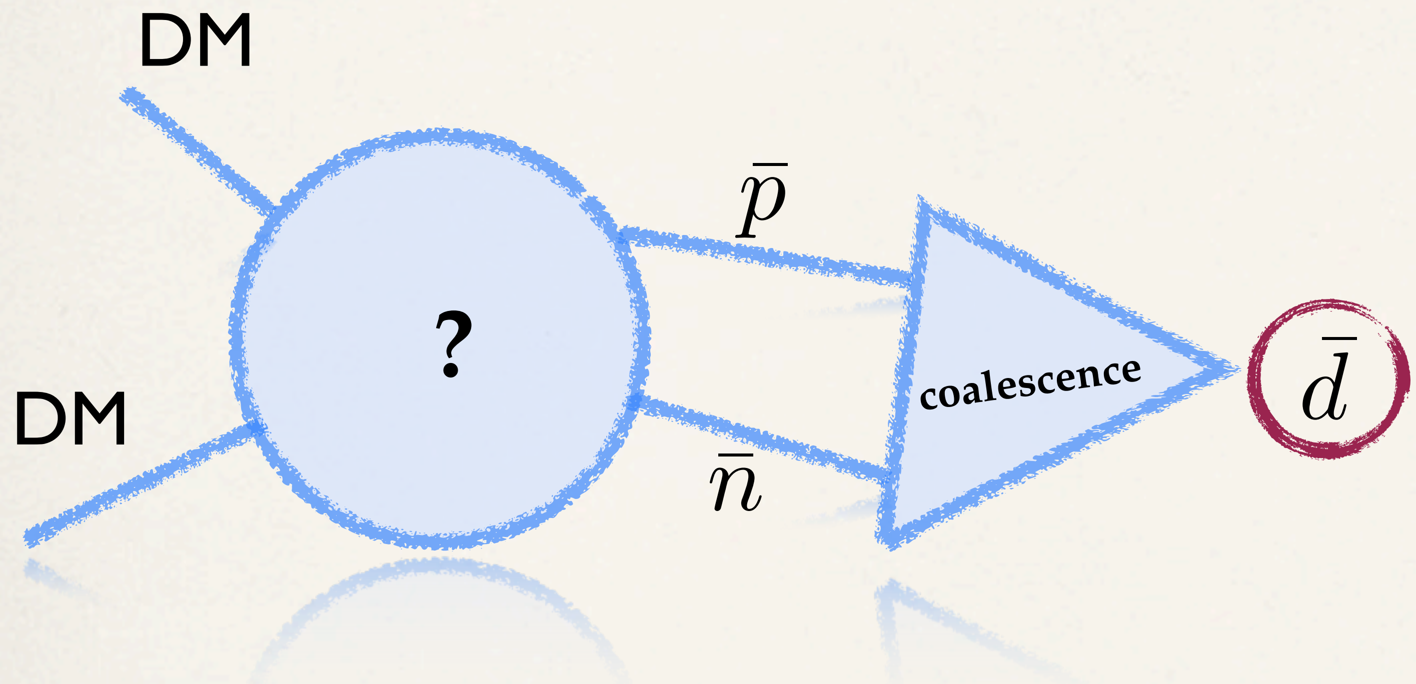
Donato, Fornengo, Salati Phys.Rev. D62 (2000) 043003

A computation in various steps



Anti-deuteron production

Butler and Pearson, PRL 7 (1961)
Schwartzschild and Zupancic, PR 129 (1963)



An anti-deuteron is the result of the merging (**coalescence**) of a $\bar{p}\bar{n}$ pair

For this merging to occur, anti-nucleons have to be **close enough** in phase space (i.e. $\Delta k < p_0$ and $\Delta r < r_0$). The final anti-deuteron flux will **strongly depend on p_0** (p_0^3)

Open issue : This coalescence momentum p_0 is usually tuned to reproduce **experimental measurements**, which unfortunately are **extremely scarce**

Anti-deuteron propagation

- **Galactic transport**

q(r,z,E) —Transport in the interstellar medium→ $\phi_{IS}(E)$

DM source term — diffusion, convection, annihilation in the ISM,etc... — interstellar flux

As for antiprotons, the galactic propagation is still the main source of uncertainty (~ 1 order of magnitude from MIN to MAX)

- **Solar modulation**

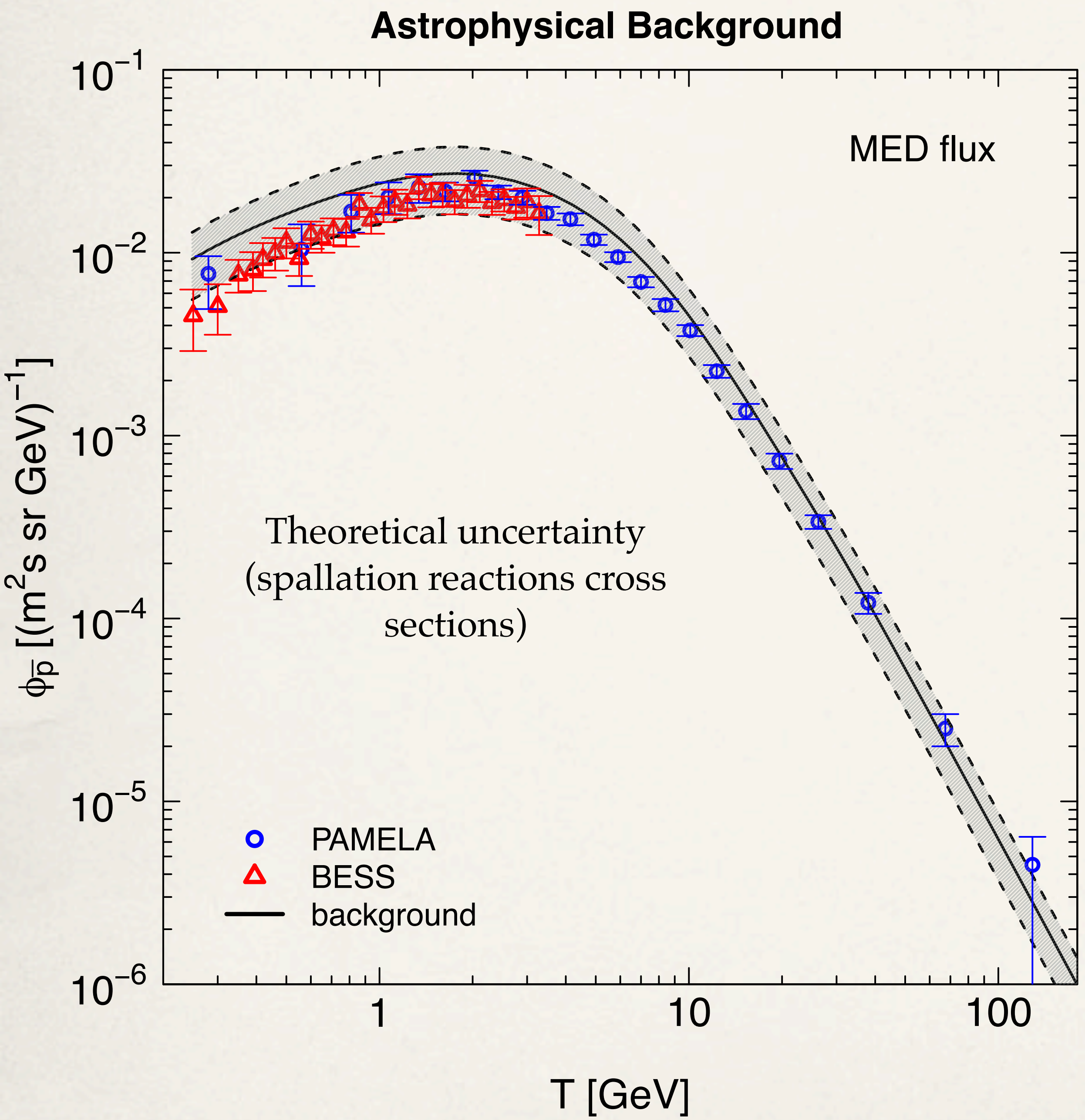
$\phi_{IS}(E)$ —Propagation in the solar magnetic field→ $\phi_{TOA}(E)$

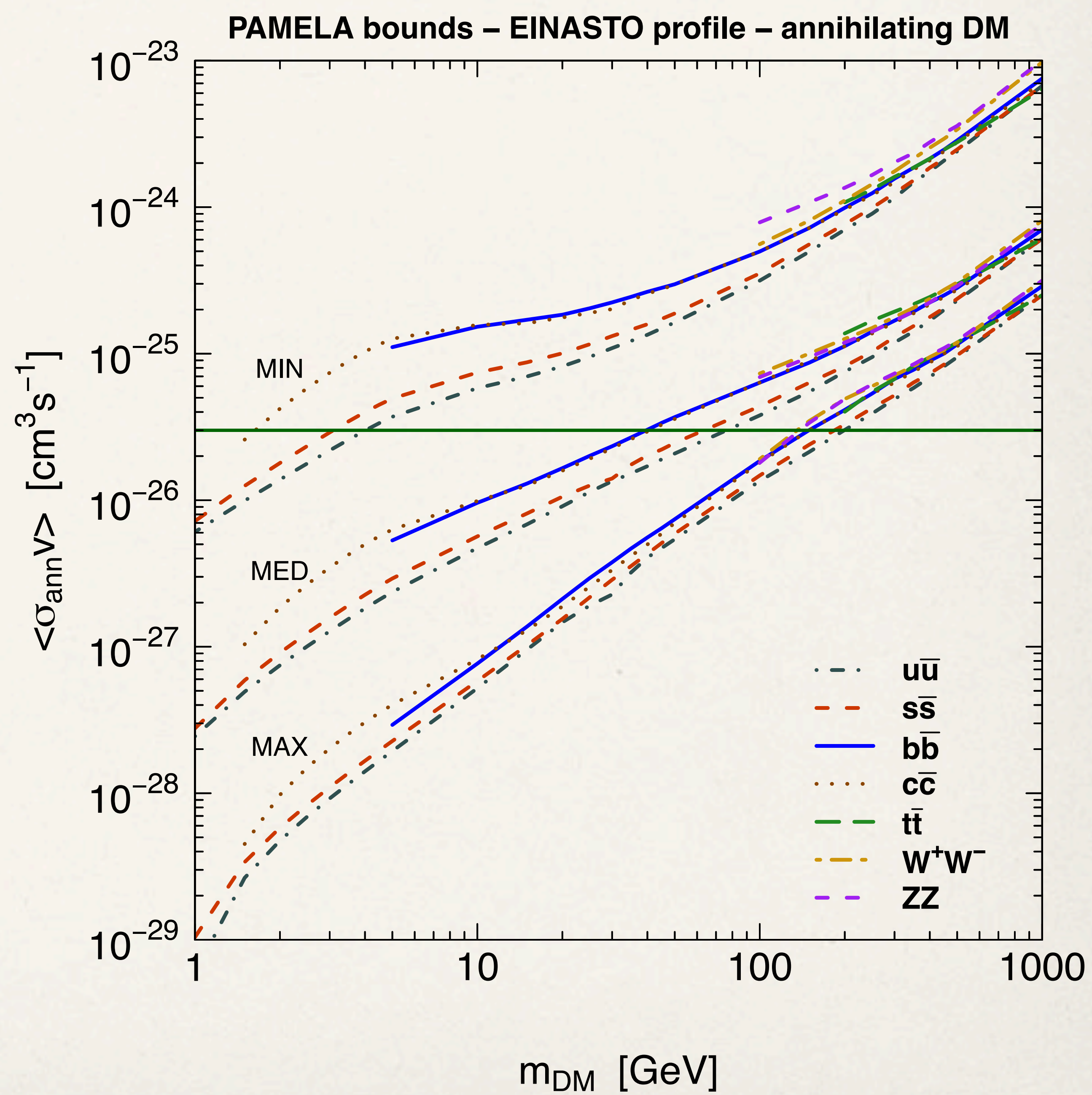
interstellar flux — analytical approximation (force-field approx) or numerical methods — top-of-atmosphere flux

Since the most promising window for a DM discovery is in the low-energy range, solar modulation represent a key ingredient

Antiproton bounds

Every process that generates anti-deuterons will also produce a much larger amount of antiprotons

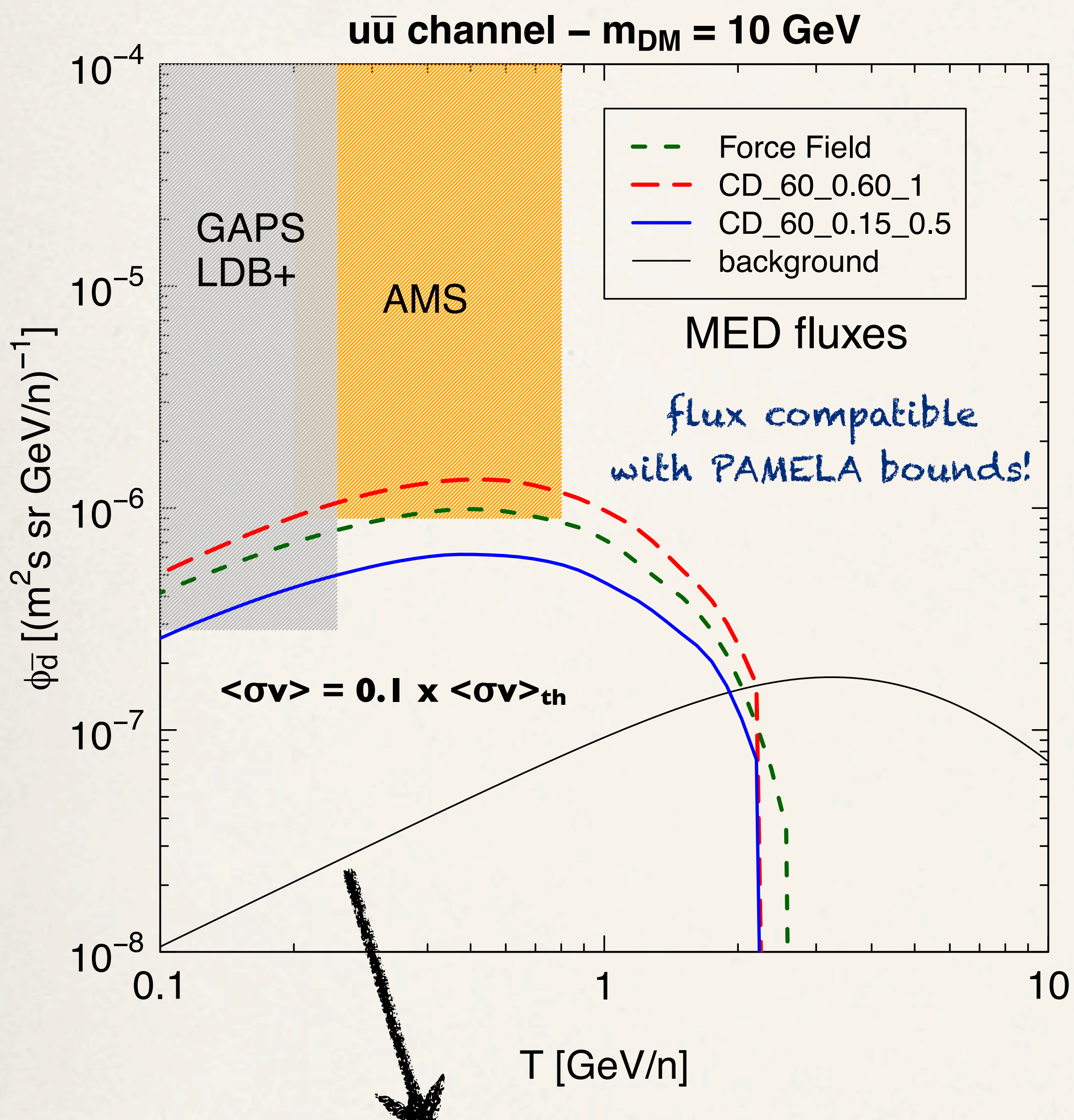


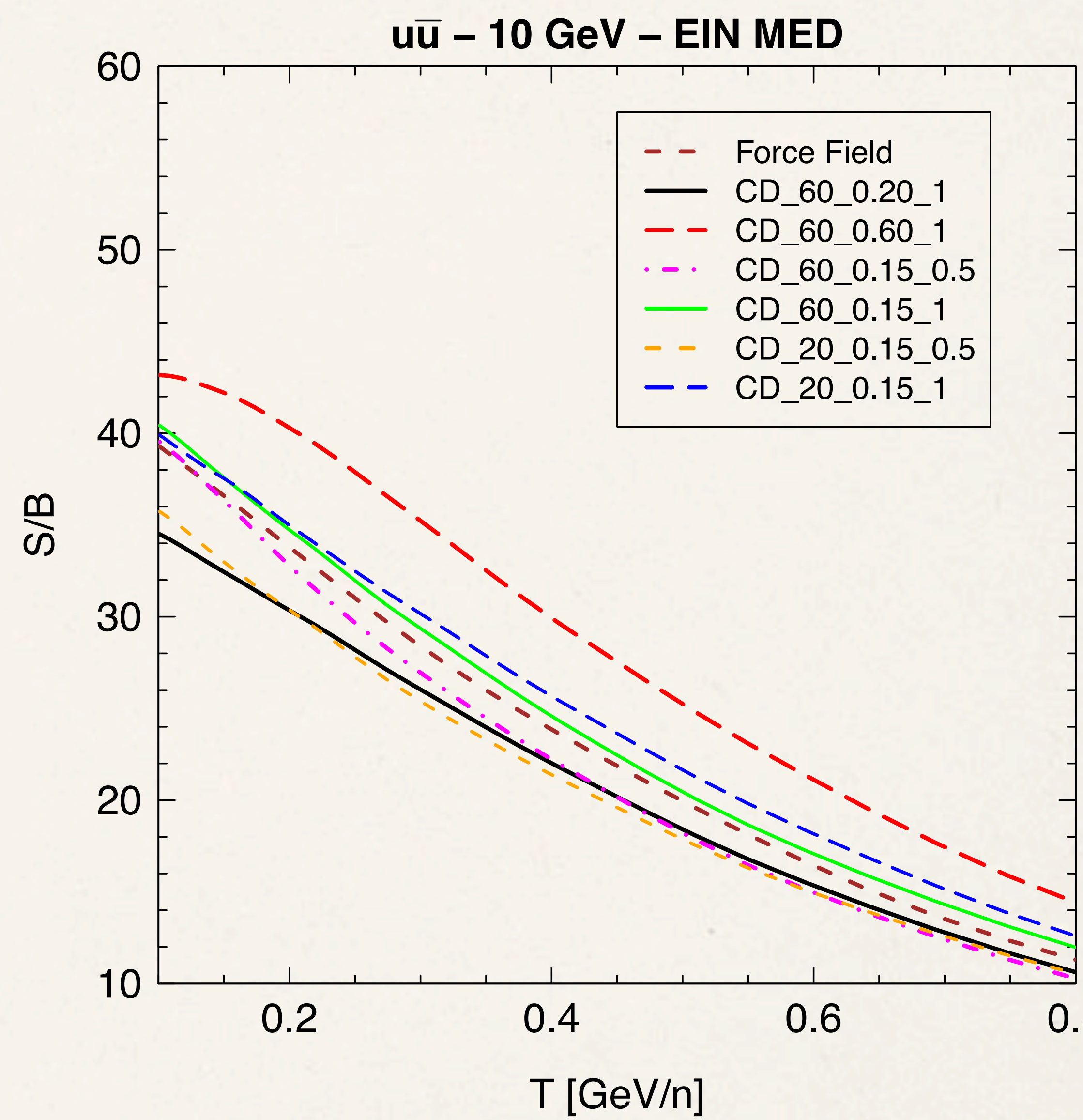


N.Fornengo, L.Maccione, A. Vittino, JCAP 04 (2014) 003

Anti-deuteron fluxes at Earth

N.Fornengo, L.Maccione, A. Vittino, JCAP 09 (2013) 031





Background from **Donato et al, Phys.Rev. D78 (2008) 043506** *

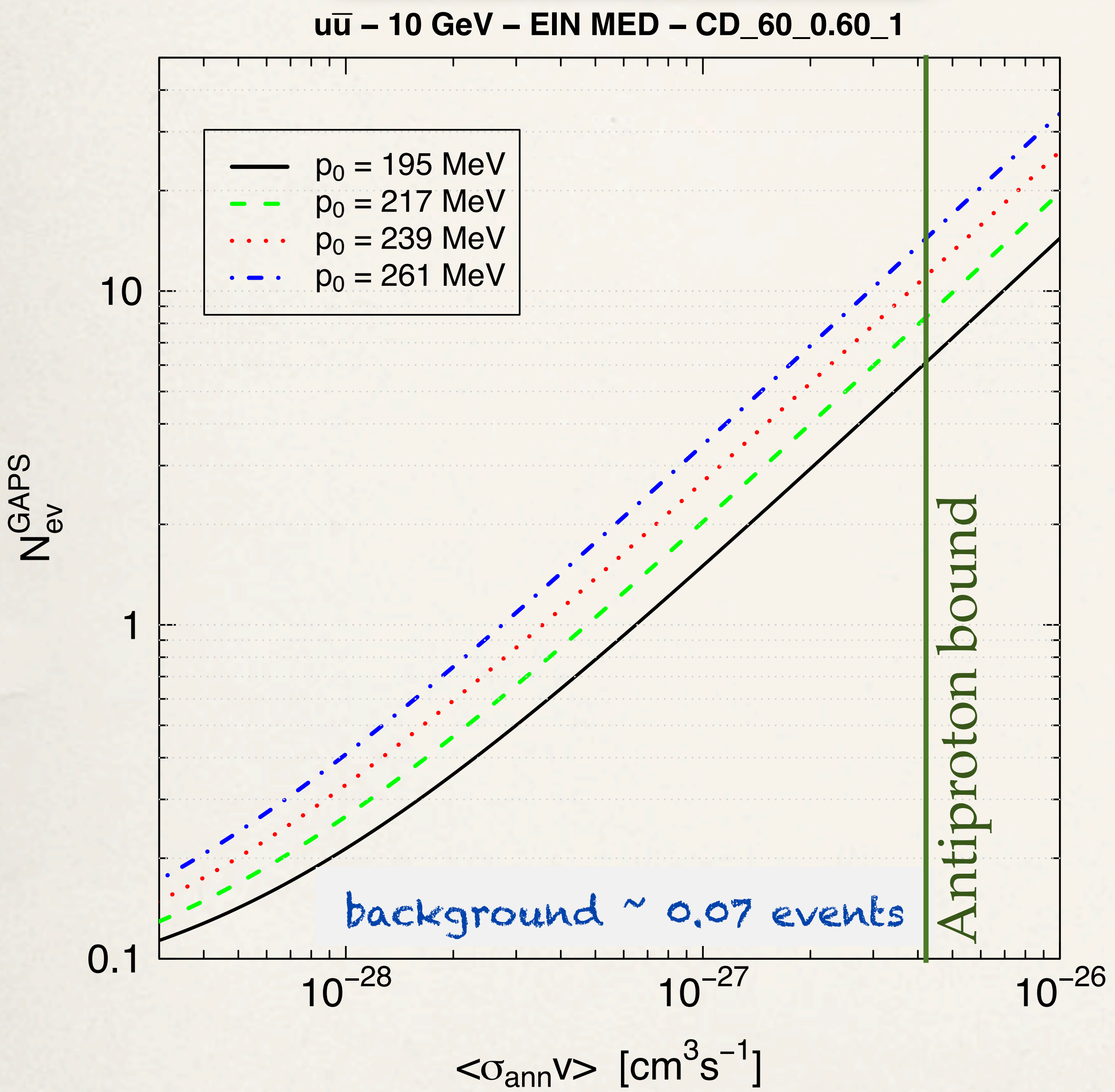
We can have a flux on the reach of both experiments!

* for a new computation see **Ibarra and Wild Phys.Rev. D88 (2013) 023014**

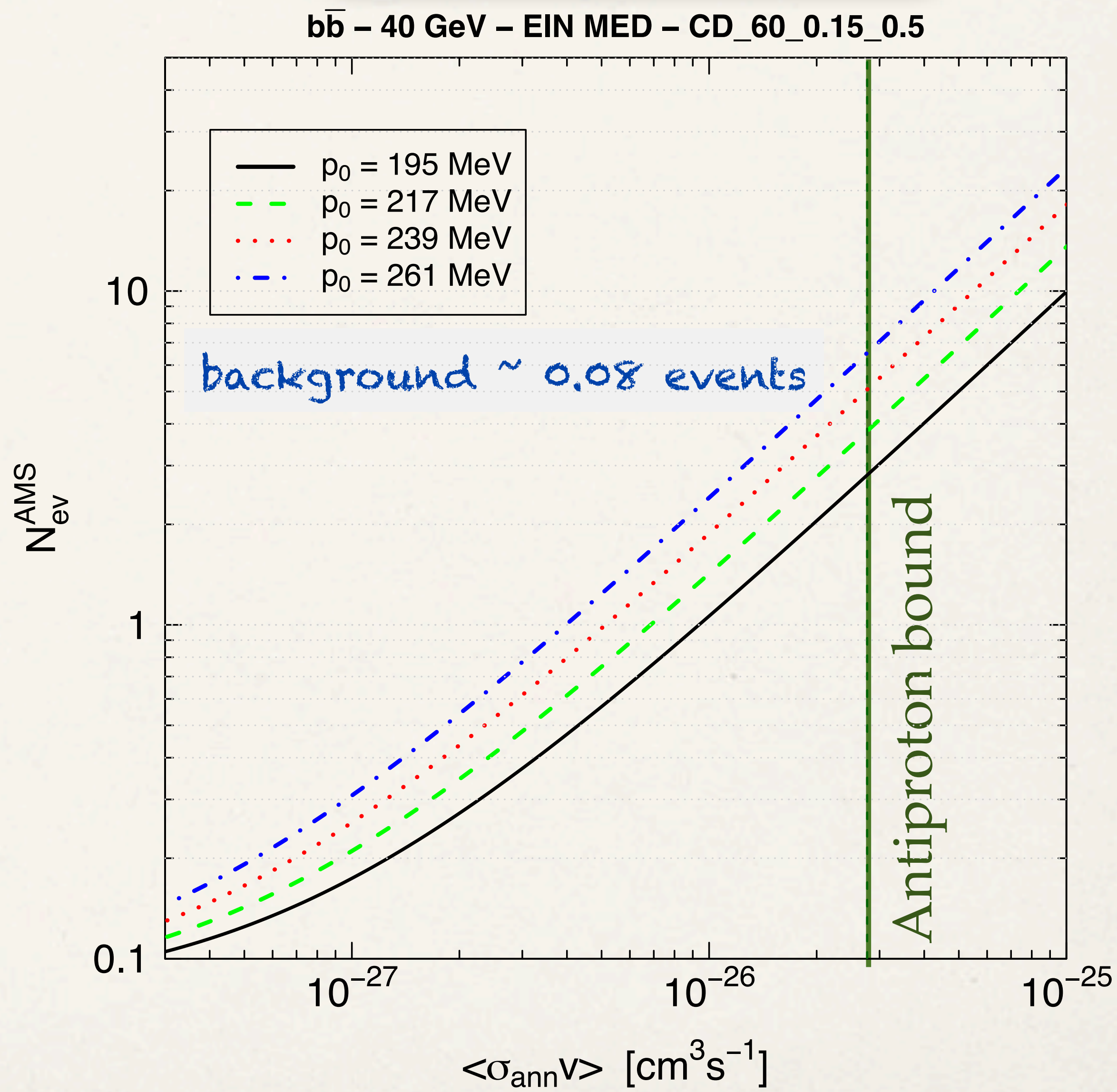
Number of expected events

For GAPS (in the LDB+ setup) and AMS-02 (3 years) :

uu - m_{DM} = 10 GeV



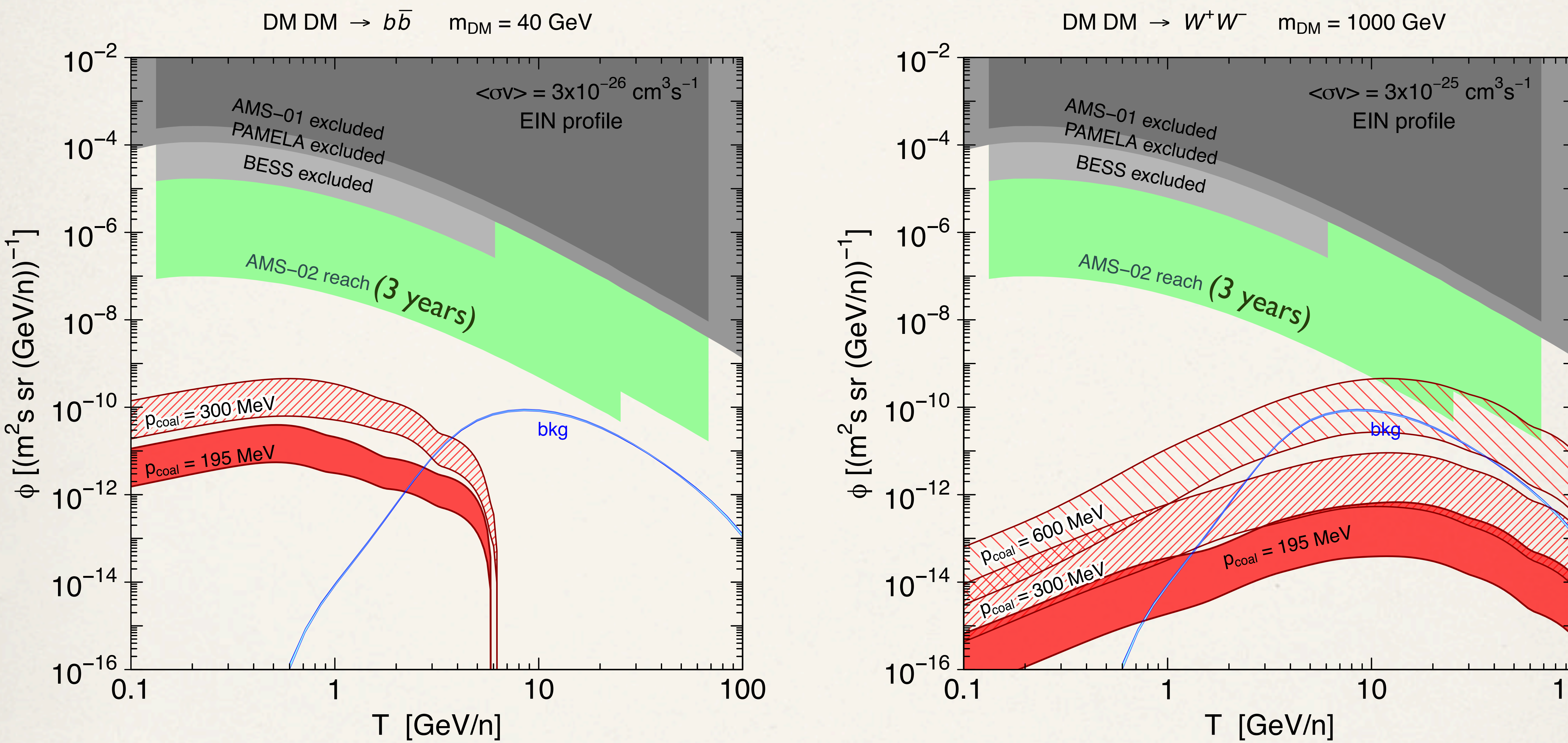
bb - m_{DM} = 40 GeV



N.Fornengo, L.Maccione, A. Vittino, JCAP 09 (2013) 031

DM searches with anti-helium

M. Cirelli, N.Fornengo, M.Taoso, A.Vittino, to appear in JHEP



Prospects for detection are **rather weak**, unless the coalescence momentum is really large (~600 MeV)

on this topic see also **Carlson, Coogan, Ibarra, Linden, Wild Physical Review D, 89, 076005 (2014)**

Conclusions

Take home message:

Anti-deuterons can be considered a **DM discovery channel** especially for **light or intermediate mass WIMPs**

Where could DM be found?

The largest signal-to-background ratio occurs in the **low energy tail of the anti-deuteron flux** (i.e. below a few GeV/n)

Can we be close to a discovery?

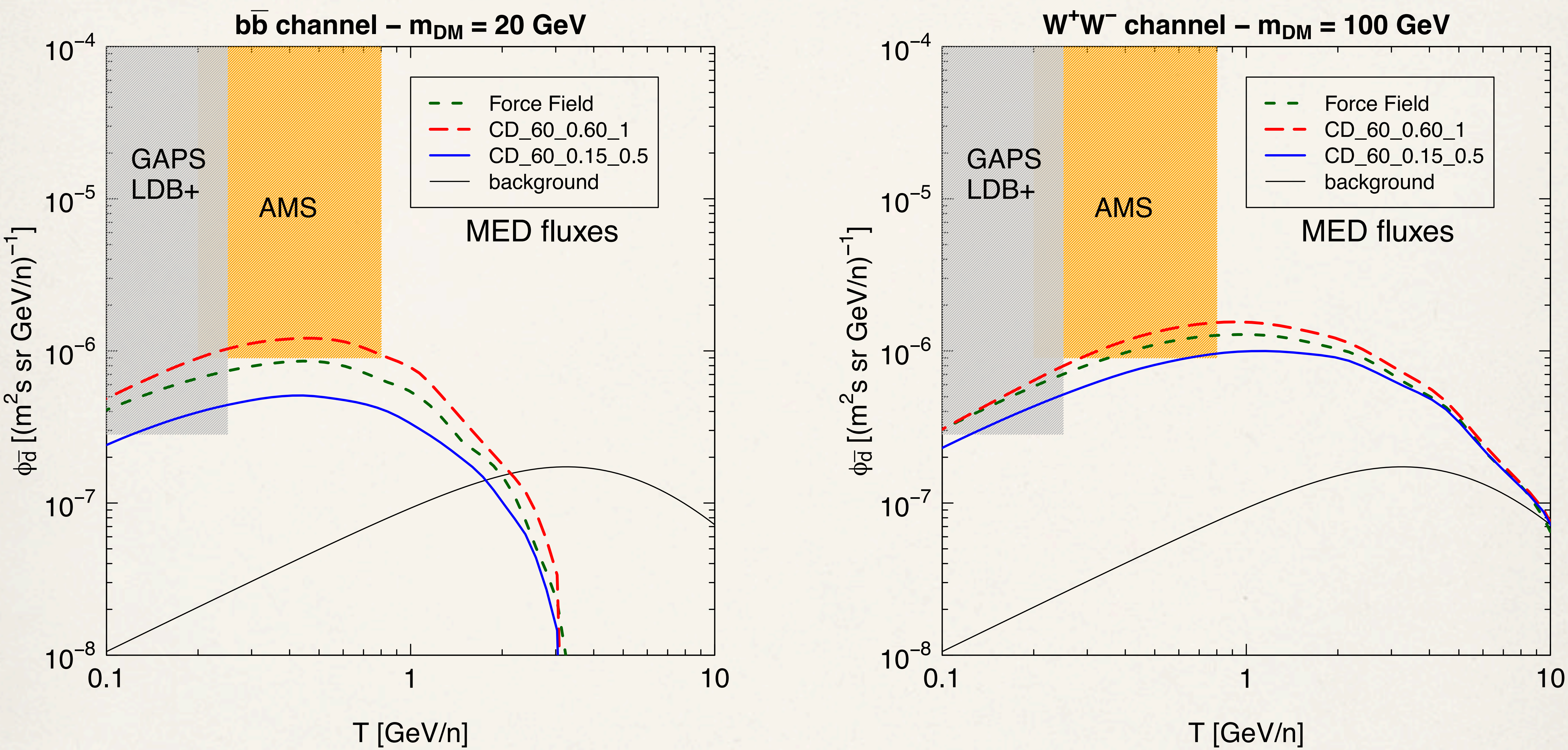
Despite the strong antiproton bounds, an anti-deuteron signal from a large region of the DM parameter space is **at the reach of current (AMS-02) and proposed (GAPS) experiments**

Future outlook:

To detect an imprint of DM in the **anti-helium** channel a **much larger sensitivity** (a dedicated innovative experiment?) **is needed.** This would also access antiD and antiP making a **multichannel investigation possible**

Anti-deuteron fluxes at Earth

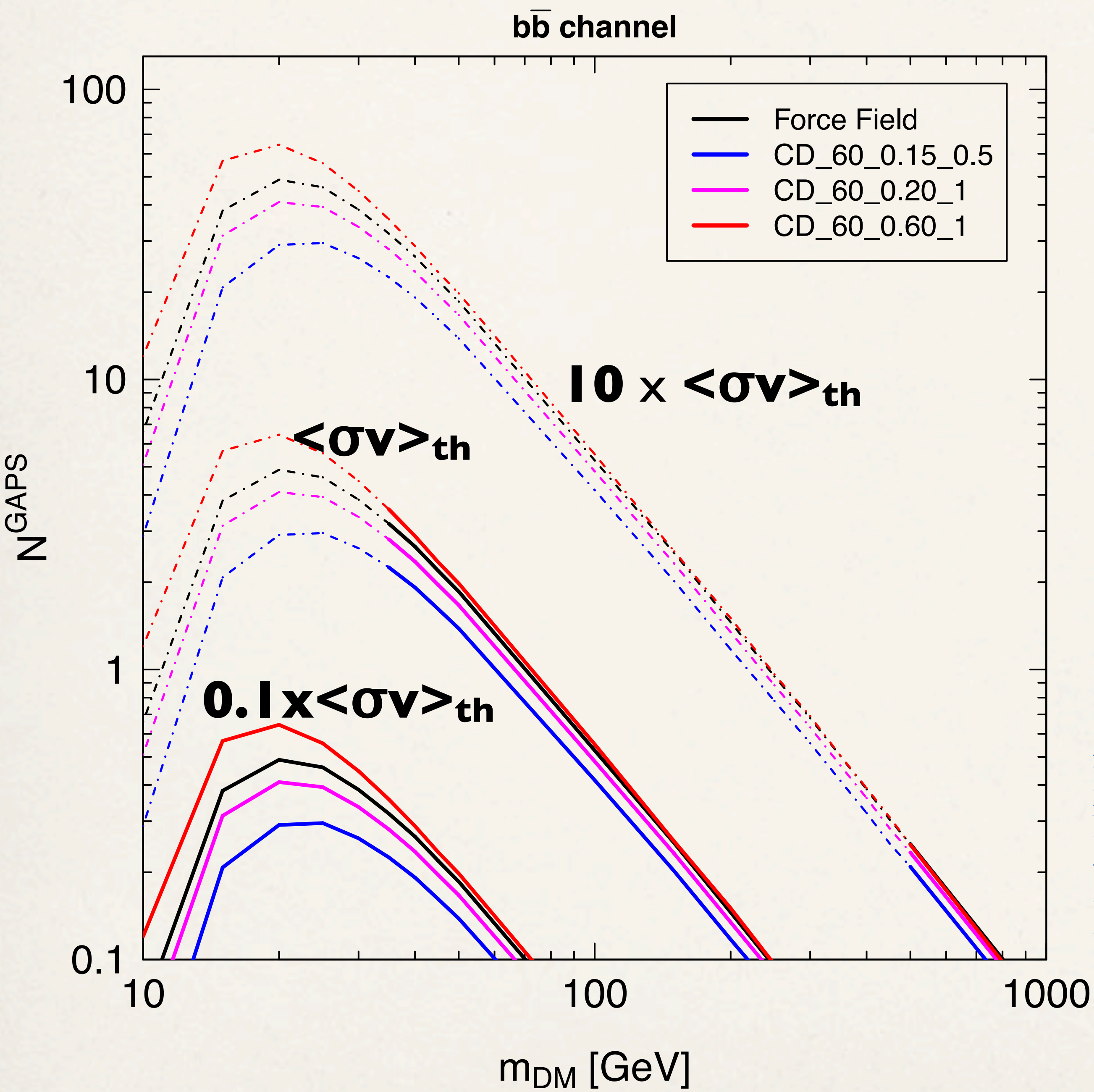
N.Fornengo, L.Maccione, A. Vittino, JCAP 09 (2013) 031



fluxes compatible with PAMELA bounds!

Number of expected events

Number of events expected for the GAPS experiment (in the LDB+ setup), for a WIMP annihilating in the **bb channel**



Solid lines: configurations compatible with PAMELA bounds

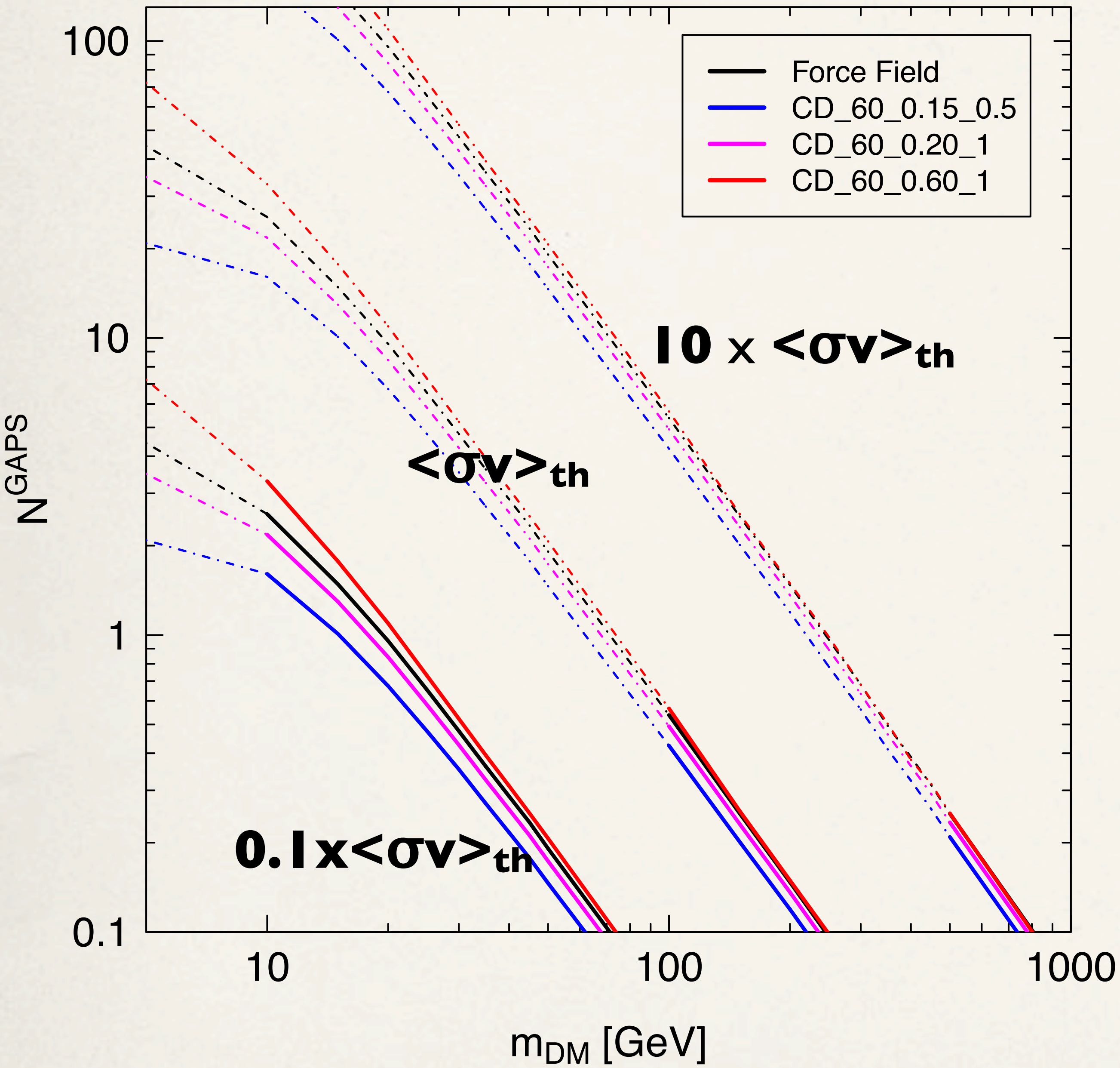
Dot-dashed lines: configurations not compatible with PAMELA bounds

From 3 to 5 events depending on the solar modulation

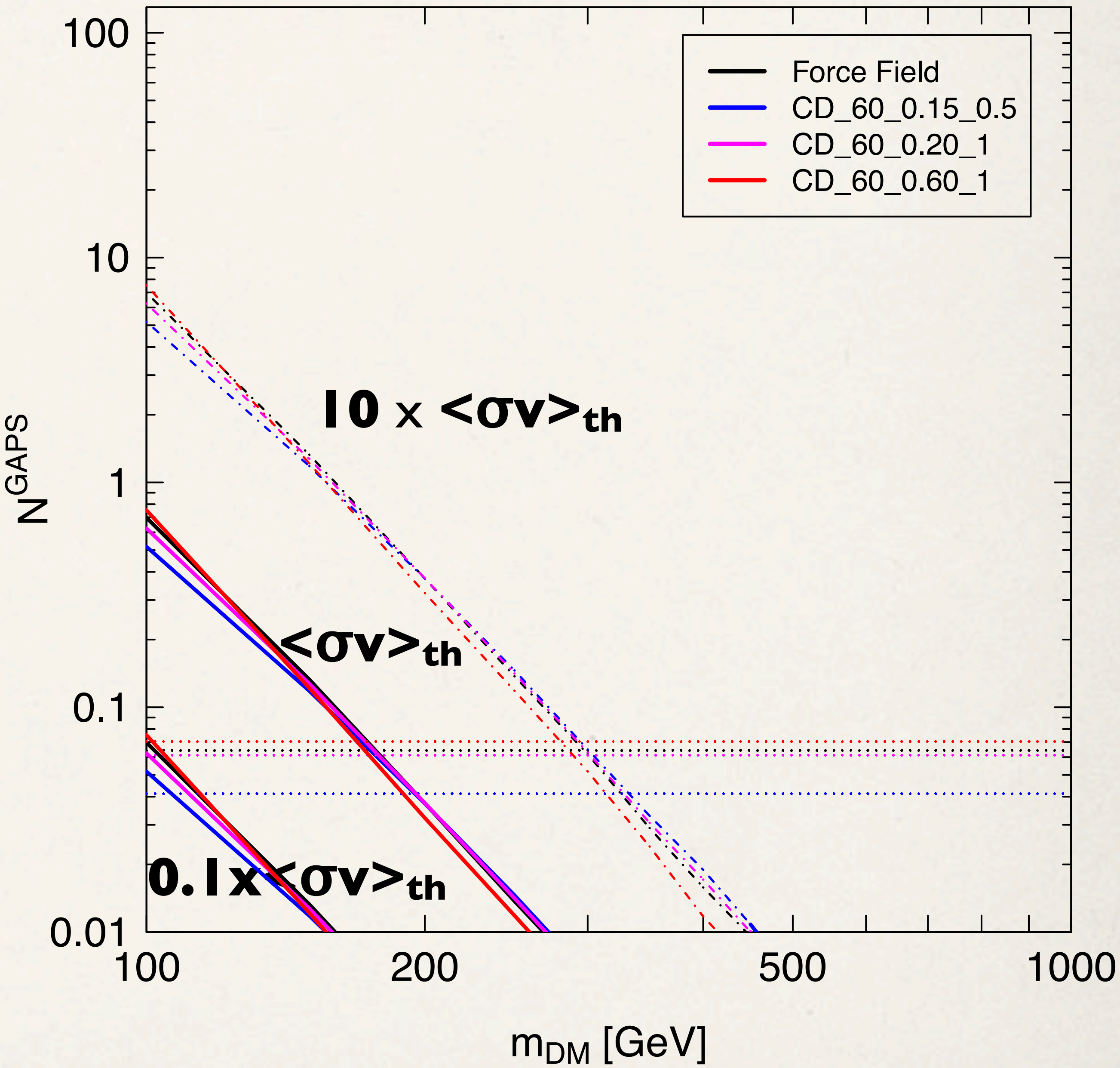
N.Fornengo, L.Maccione, A. Vittino, JCAP 09 (2013) 031

Number of expected events

uu channel



WW channel



N.Fornengo, L.Maccione, A. Vittino, JCAP 09 (2013) 031

Number of expected events

For AMS-02 (3 years) and GAPS (in the LDB+ setup):

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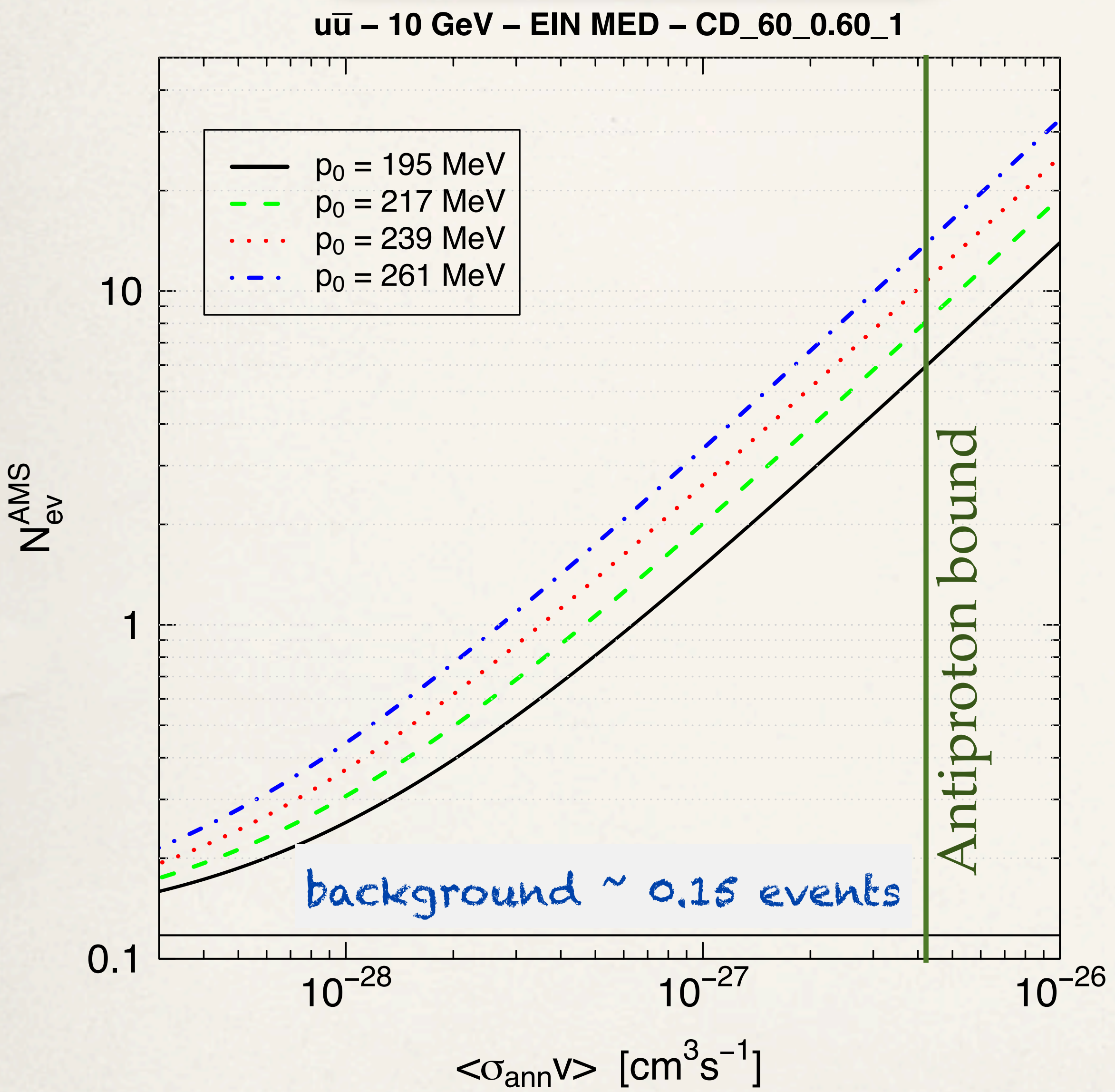

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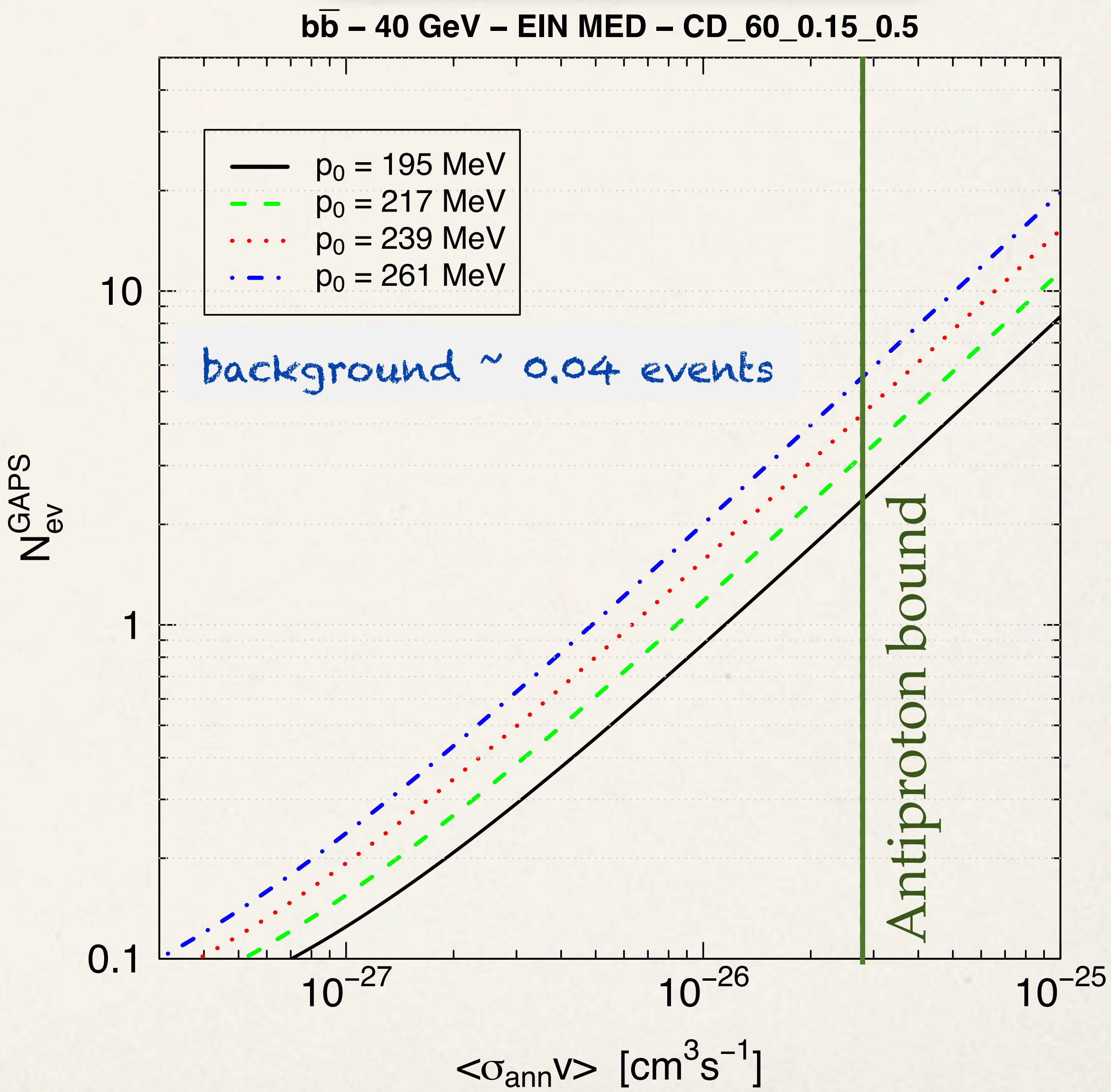


N.Fornengo, L.Maccione, A. Vittino, JCAP 09 (2013) 031

The coalescence mechanism

A simple idea: anti-nucleons coalesce if they are **close enough** (in the phase space)

$$\frac{dN_{\bar{d}}}{dT} \propto \int d^3\vec{k}_{\bar{p}} d^3\vec{k}_{\bar{n}}\ F_{\bar{p}\bar{n}}(\sqrt{s}, \vec{k}_{\bar{p}}, \vec{k}_{\bar{n}}) C(\vec{\Delta} = \vec{k}_{\bar{p}} - \vec{k}_{\bar{n}})$$

$F_{(\bar{p}\bar{n})}$ is the probability that the anti-nucleons are formed:

$$F_{(\bar{p}\bar{n})}(\sqrt{s}, \vec{k}_{\bar{p}}, \vec{k}_{\bar{n}}) = \frac{dN_{(\bar{p}\bar{n})}}{d^3\vec{k}_{\bar{p}} d^3\vec{k}_{\bar{n}}}$$

We sample it directly from the MonteCarlo (**event-by-event** coalescence)

The function C is the probability that the anti-nucleons merge:

$$C(\vec{\Delta}) = \theta(\Delta^2 - p_0^2)\ \theta(\Delta r^2 - r_0^2)$$

p_0 is a free parameter. Which is its value?

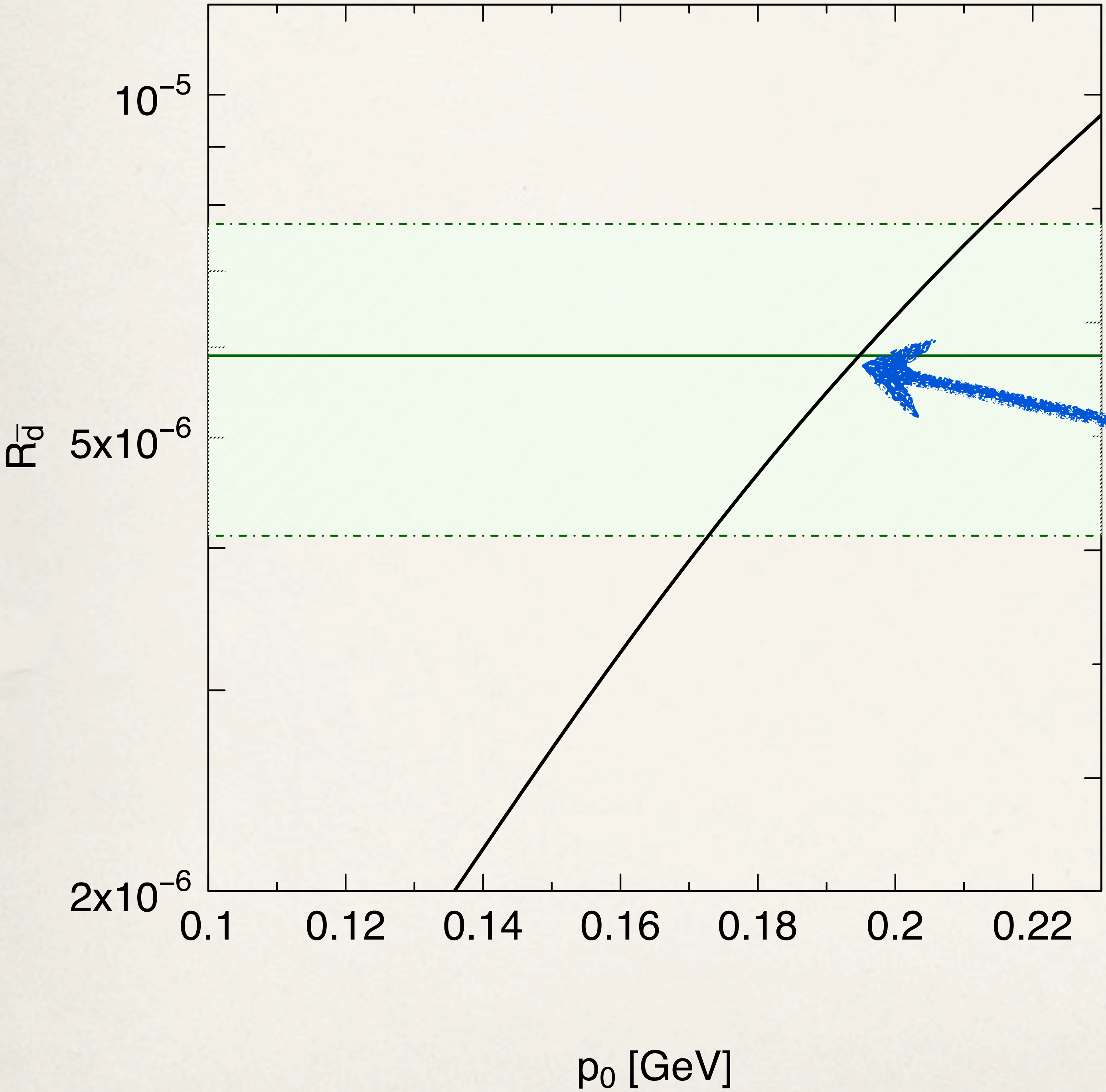
We take $r_0 \approx 2\ \mathrm{fm}$ (radius of the anti-deuteron)

(given the large spatial resolution of Pythia our results are insensitive to the exact value of r_0)

Kadastik, Raidal, Strumia Phys.Lett. B683 (2010) 248-254 Ibarra and Wild JCAP 1302 (2013) 021

The coalescence mechanism

We tune p_0 to reproduce ALEPH data: **ALEPH collaboration, Phys. Lett. B 369 (2006) 192**



$\bar{d}$ production rate in e^+e^- collisions at the Z resonance

$p_0 = (195 \pm 22)$ MeV

Basically, a $\bar{d}$ is formed if

$$\begin{cases} |\Delta(\vec{k})| < 195 \text{ MeV} \\ |\Delta(\vec{r})| < 2 \text{ fm} \end{cases}$$

Coalescence for the anti-helium

✦ For the anti-Helium, we have the coalescence of **three anti-nucleons**

✦ We consider only the pnn case, since for the ppn case we expect to have a suppression due to **Coulombian repulsion**

✦ Our algorithm is very simple: we compute the relative momentum of every anti-nucleon pair in the rest frame of the anti-He (i.e. the c.m. frame of the pnn system) and we consider the three particles as a bound state if :

$$|\Delta\vec{k}|_{max} \ \leq \ p_0$$

✦ Experimental data on anti-He production **are very scarce** and relative to pp or pA collisions whose dynamics is different from the one of a DM pair annihilation. Thus, the coalescence momentum can be considered as a **free parameter** (we set it equal to the one of the anti-deuteron)

Galactic propagation

To propagate both the $^3\overline{He}$ and the $\bar{d}$ we have to solve a **transport equation**:

$$-\nabla[K(r,z,E)\nabla n(r,z,E)] + V_c \frac{\partial}{\partial z} n(r,z,E) + 2h\delta(z)\Gamma_{\mathrm{ann}} n(r,z,E) = q(r,z,E)$$

diffusion

convection

annihilation

source term

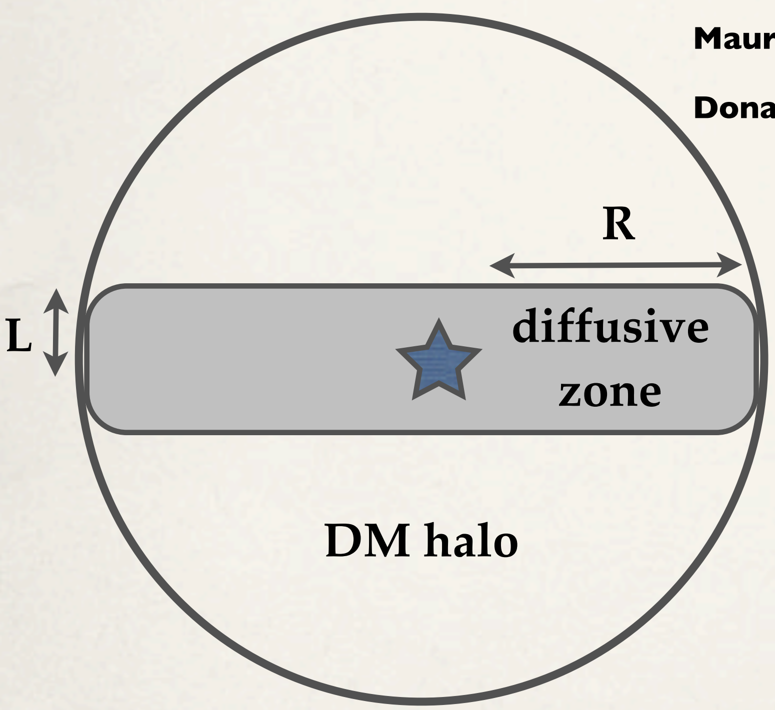
$$\frac{1}{2} < \sigma v > \frac{dN}{dE} \left(\frac{\rho(r,z)}{m_{DM}} \right)^2$$

$\rho(r,z)$ is the DM halo **density profile**

Two-zone diffusion model

Maurin,Donato,Taillet, Salati, Astrophys. J., 555 (2001) 585-596

Donato, Maurin, Taillet Astron. Astrophys. 381 (2002) 539-559



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

$$\vec{V_c} = \mathrm{sign}(z) V_c$$

CAVEAT: no energy losses and no reacceleration!

Galactic propagation

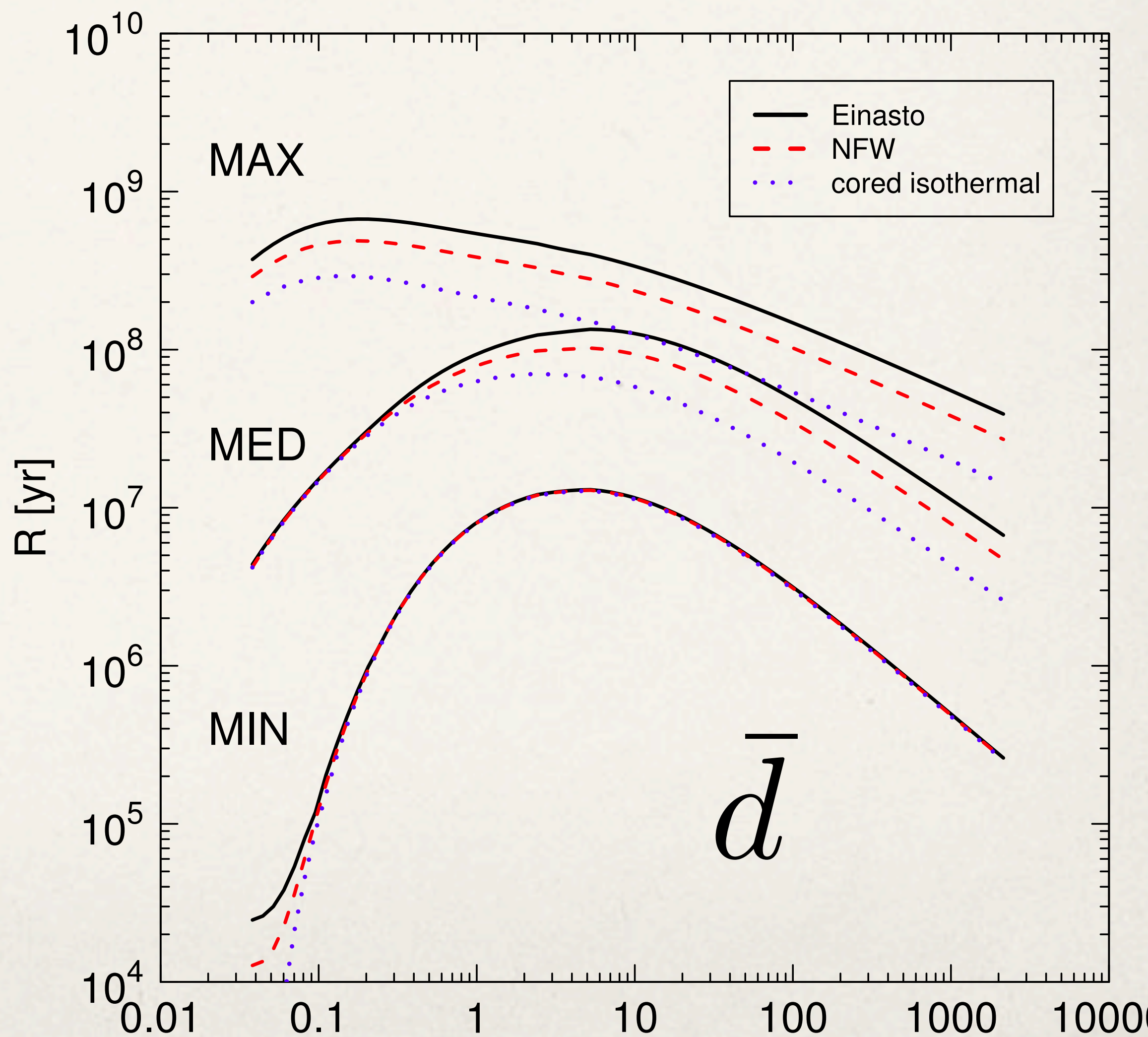
$$\phi(E) = \frac{\beta}{4\pi} R(E) \times \frac{1}{2}\left(\frac{\rho_\odot}{m_{DM}}\right)^2 \frac{dN}{dE} < \sigma v >$$

All the astrophysics is confined here!

The two-zone diffusion model is defined by these parameters:

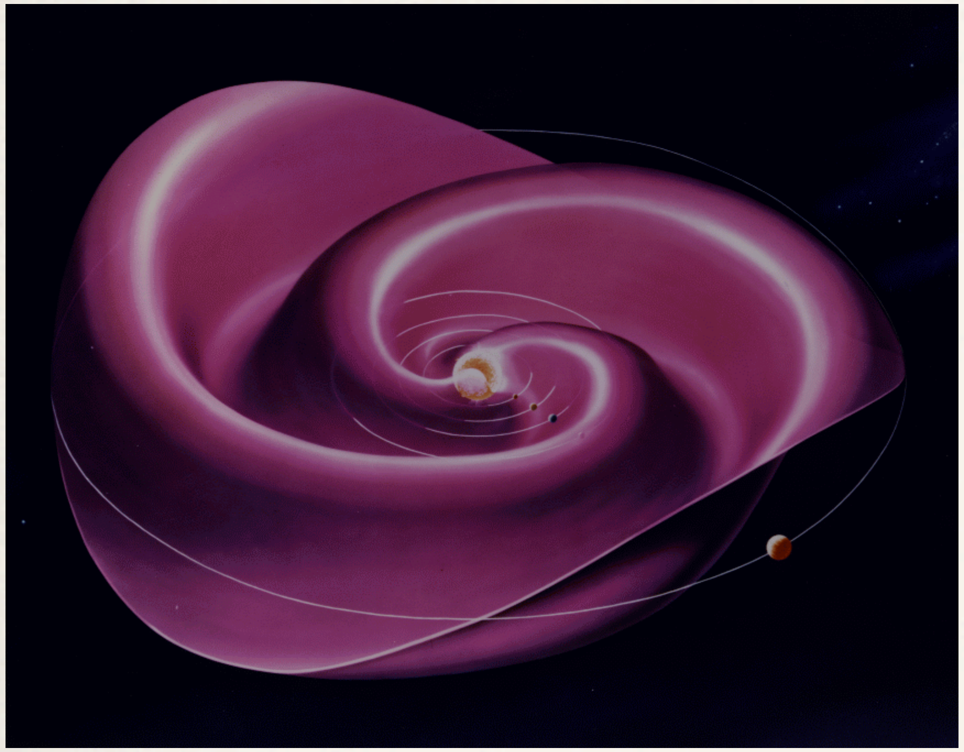
	δ	K_0 (kpc^2/Myr)	L (kpc)	V_c (km/s)
MIN	0.85	0.0016	1	13.5
MED	0.70	0.0112	4	12
MAX	0.46	0.0765	15	5

K_0, V_c and δ constrained by B/C data



F.Donato, N.Fornengo, D.Maurin, P.Salati and R.Taillet
Phys.Rev.D 69 (2004) 063501

Solar modulation



The Sun's magnetic field (SMF) has the form of a **large rotating spiral**

An heliospheric current sheet (HCS), whose shape varies with time according to solar activity, separates field lines directed towards or away from the Sun

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

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

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

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

Charge dependent solar modulation

The propagation in the heliosphere is described by the following equation:

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

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

Convection — Drifts — Diffusion (random walk) — Adiabatic losses

We vary 2 parameters:

- The tilt angle α : it describes the spatial extent of the HCS. It is proportional to the intensity of the solar activity ($\alpha \in [20^\circ, 60^\circ]$)

- The mean free path λ of the CR particle along the magnetic field direction

We exploit the code HELIOPROP to solve **numerically** the transport equation and explore the solar parameters space

L. Maccione, Phys.Rev.Lett. 110, 081101(2013)