The role of antiprotons and antideuterons in dark matter indirect detection

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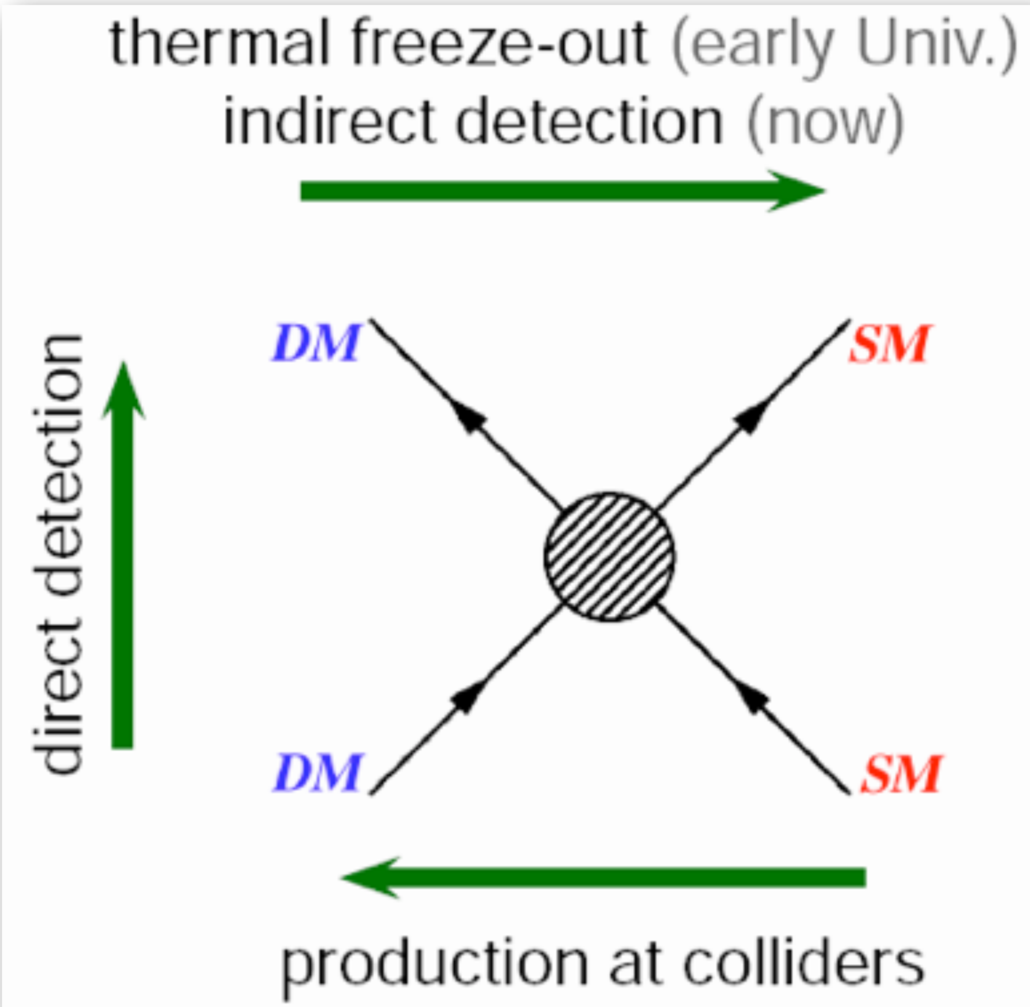
New perspectives in DM
Lyon, October 24 2013

DM indirect detection



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

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

In this talk we will investigate the role of **antiprotons** and **antideuterons** in DM indirect detection

Antiprotons and antideuterons

- Some years ago, antideuterons have been proposed as an almost **background free** channel for DM indirect detection **[F. Donato, N. Fornengo, P.Salati, Phys.Rev. D62 (2000) 043003]**

Antideuterons are a good **discovery** channel for DM!

- A reaction that generates many antideuterons also generates a lot of antiprotons. We can derive very strong bounds on DM annihilation cross section from PAMELA measurements on the antiprotons flux

[See talk by Gaelle Giesen]

Antiprotons are an excellent tool to **constrain** DM properties

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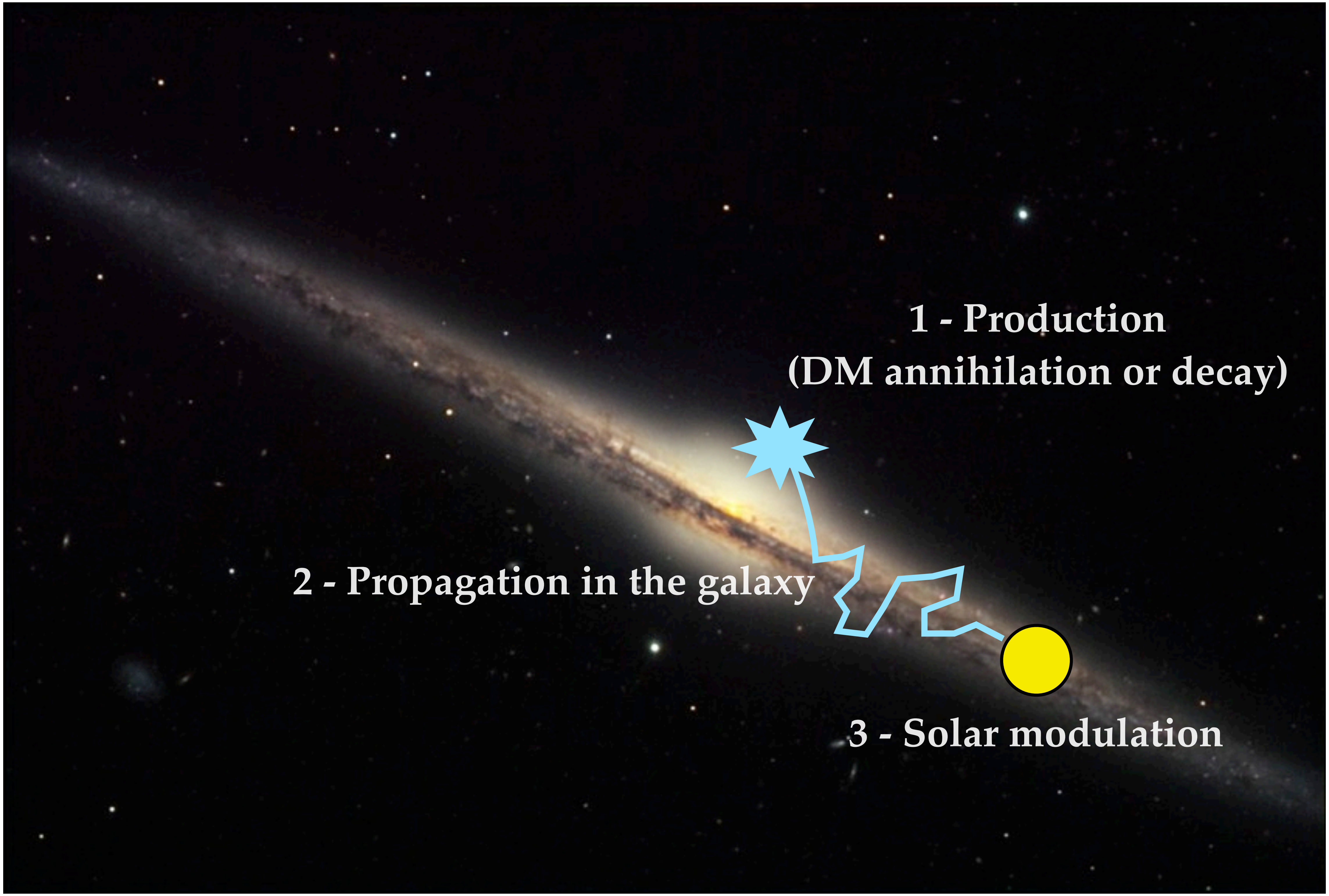
[See talk by Gaelle Giesen]

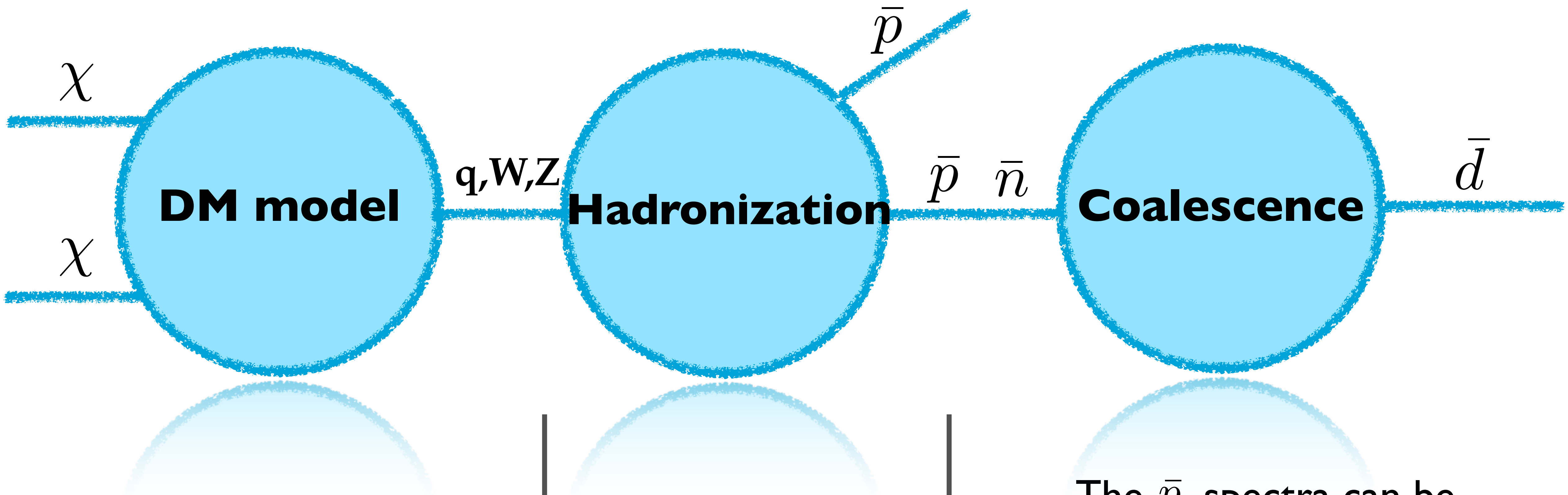
Antiprotons are an excellent tool to **constrain** DM properties

How do we calculate antiprotons and antideuterons fluxes?

From the source to the Earth



Production



We work in a **model indipendent** way (i.e. pure annihilation channels)

Hadronization is modeled with a MC event generator (Pythia)

The $\bar{p}$ spectra can be taken directly from Pythia, while for the spectra we $\bar{d}$ have to merge two antinucleons

We will deal with the coalescence later

Galactic propagation

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

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

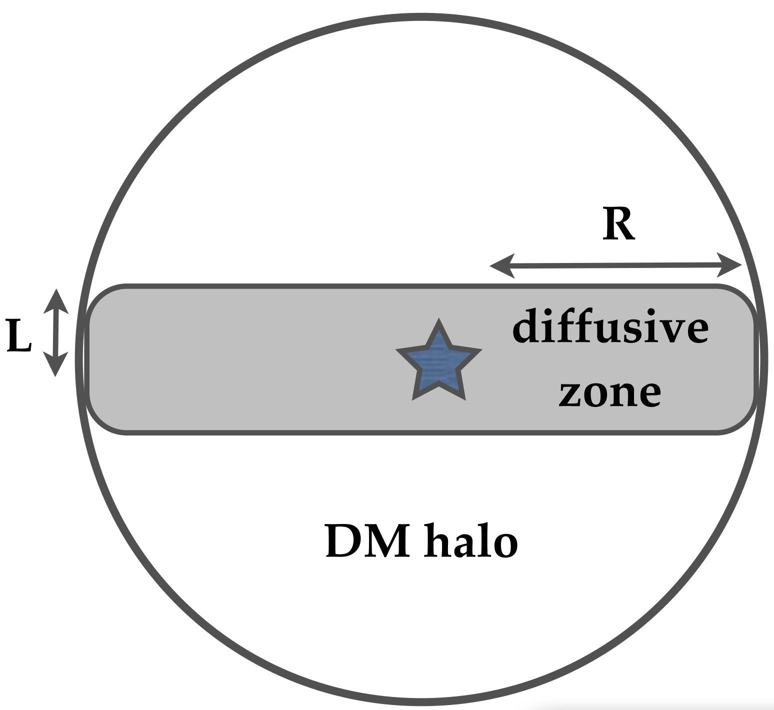
diffusion

convection

annihilation

source term

Two-zone diffusion model



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

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

$$\frac{1}{2} < \sigma v > \frac{dN_{\bar{p},\bar{d}}}{dT} \left(\frac{\rho(r,z)}{m_{DM}}\right)^2$$

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

CAVEAT: no energy losses and no reacceleration!

If we have **no reacceleration** and **no energy losses** we can factorize the flux:

$$\phi_{\bar{d}.\bar{p}}(E) = \frac{\beta_{\bar{d},\bar{p}}}{4\pi} n_{\bar{d},\bar{p}}(r = r_\odot, z = 0, E) = \frac{\beta_{\bar{d},\bar{p}}}{4\pi} \left(\frac{\rho_\odot}{m_{DM}}\right)^2 \boxed{R_{\bar{d},\bar{p}}(E)} \frac{1}{2} < \sigma v > \frac{dN_{\bar{d},\bar{p}}}{dE}$$

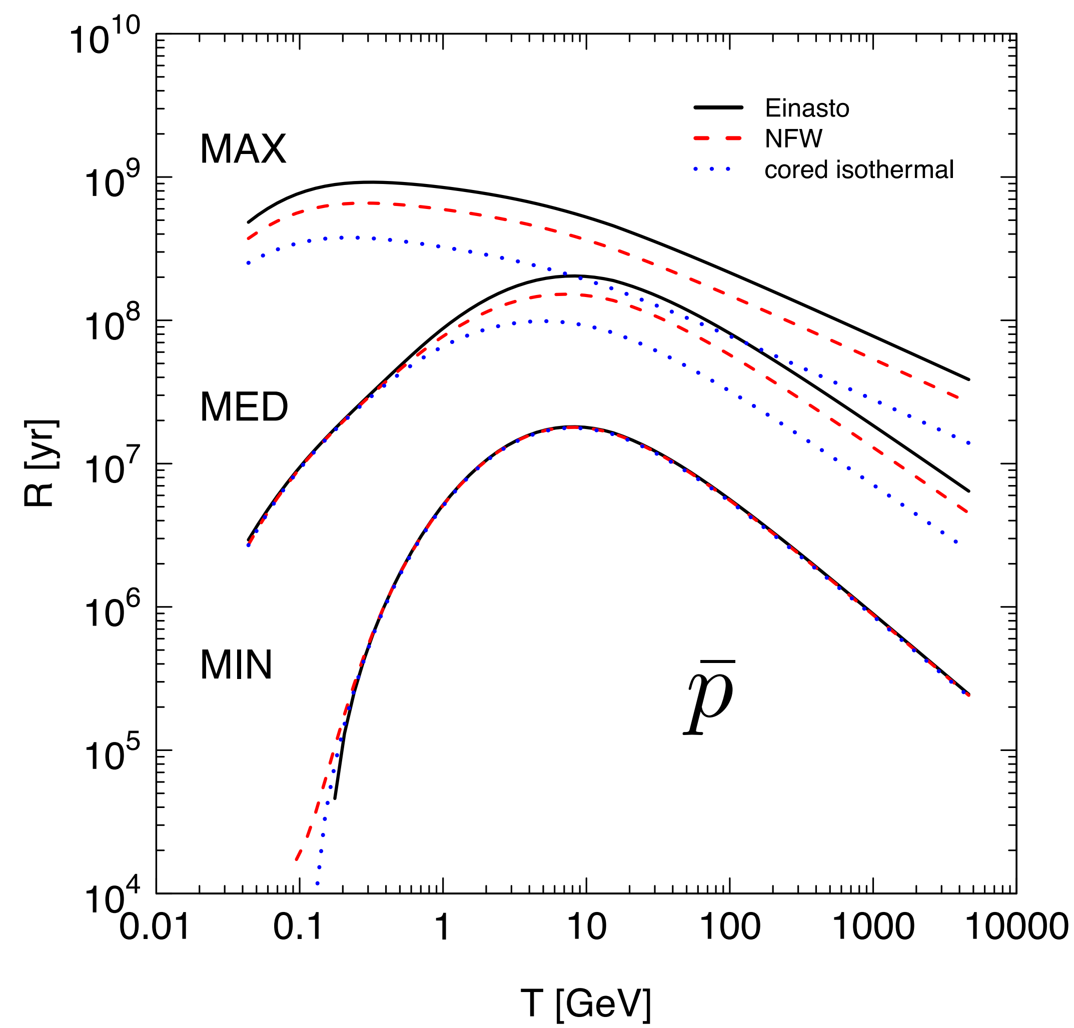
All the astrophysics is confined here!

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

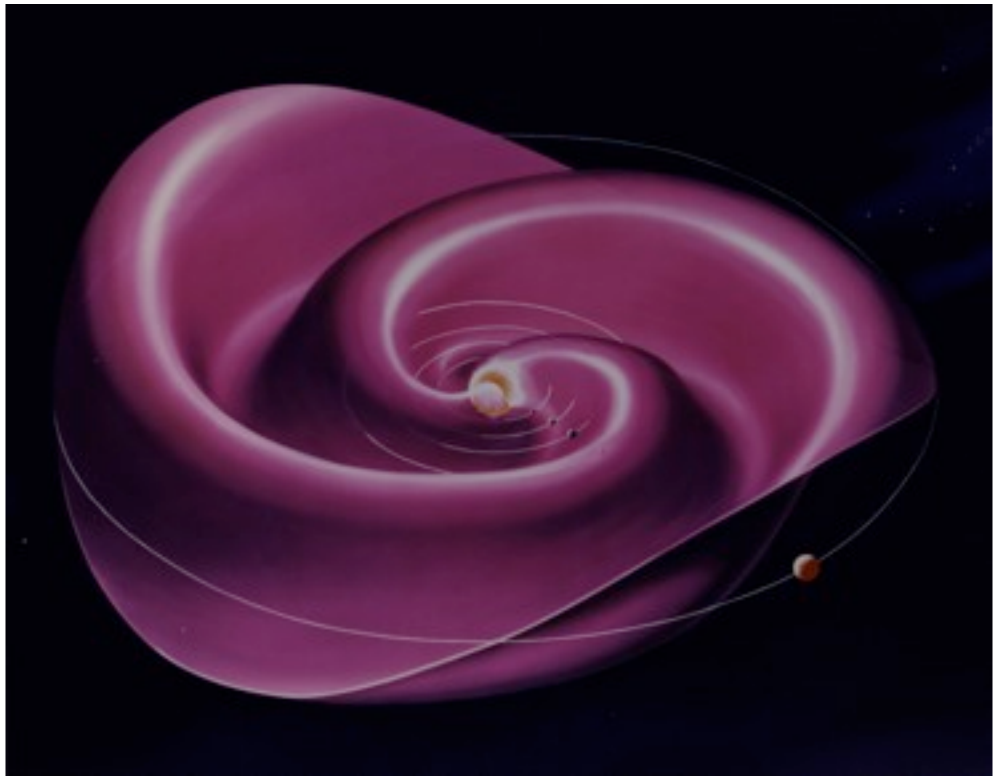
	δ	K_0 (kpc^2/Myr)	L (kpc)	V_c (km/s)
MIN	0.85	0.0016	1	13.5
MED	0.70	0.0112	4	12
MAX	0.46	0.0765	15	5

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**:

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

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

Charge dependent solar modulation

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

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

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

Convection

Drifts

Diffusion
(random walk)

Adiabatic losses

We vary 2 parameters:

- The tilt angle α : it describes the spatial extent of the HCS. Its value depends on the intensity of the solar activity
- 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)

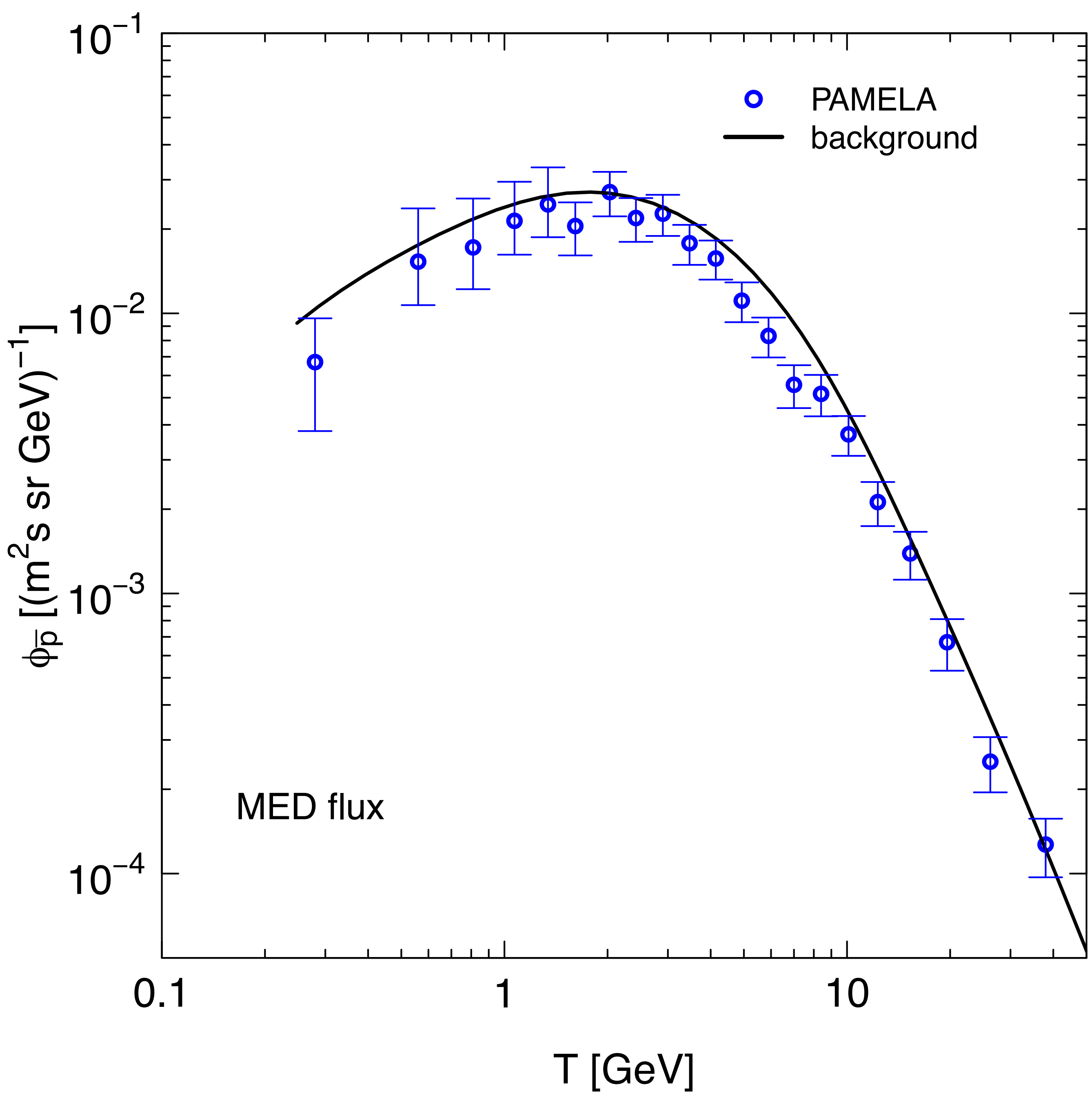
Antiprotons

based on **N.Fornengo, L.Maccione, A.Vittino, in preparation**

Pamela bounds

The flux of cosmic antiprotons has been measured by the PAMELA experiment:

O. Adriani et al. [PAMELA Collaboration] Phys. Rev. Lett. 105 (2010) 121101



The measured flux appears to be very well fitted by a pure astrophysical background

Very little room left for dark matter!

However, the background has a theoretical uncertainty related to **nuclear factors** (pp and pHe cross sections)

F.Donato et al, Phys.Rev.D 69 (2004) 063501

Calculation of the bounds

We calculate the bounds on the annihilation cross section by performing a chi-squared analysis (over all PAMELA bins):

We take into account also a theoretical uncertainty on the background flux

$$\chi^2_{DM+bg} = \sum_i \frac{(\phi_{DM+bg} - \phi_{exp})^2}{\sigma^2_{i,tot}}$$

$$\Delta\chi^2 = \chi^2 - \chi^2_{bestfit} < 10.27$$

3 sigma confidence level (one sided distribution)

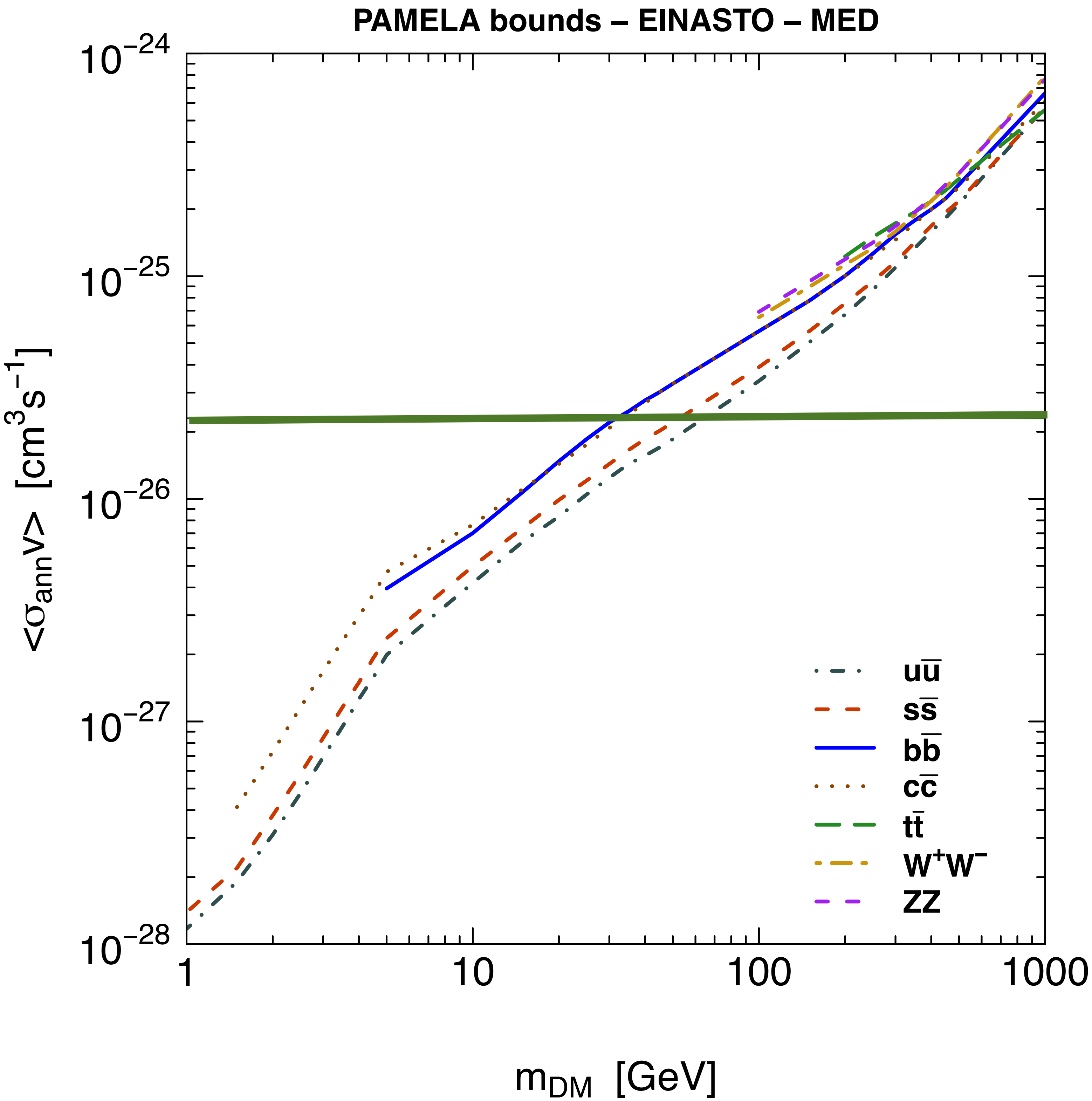
$$\sigma_{i,tot} = \sqrt{\sigma^2_{i,exp} + \sigma^2_{i,theo}}$$

$\sigma^2_{i,exp}$: systematic + statistical error

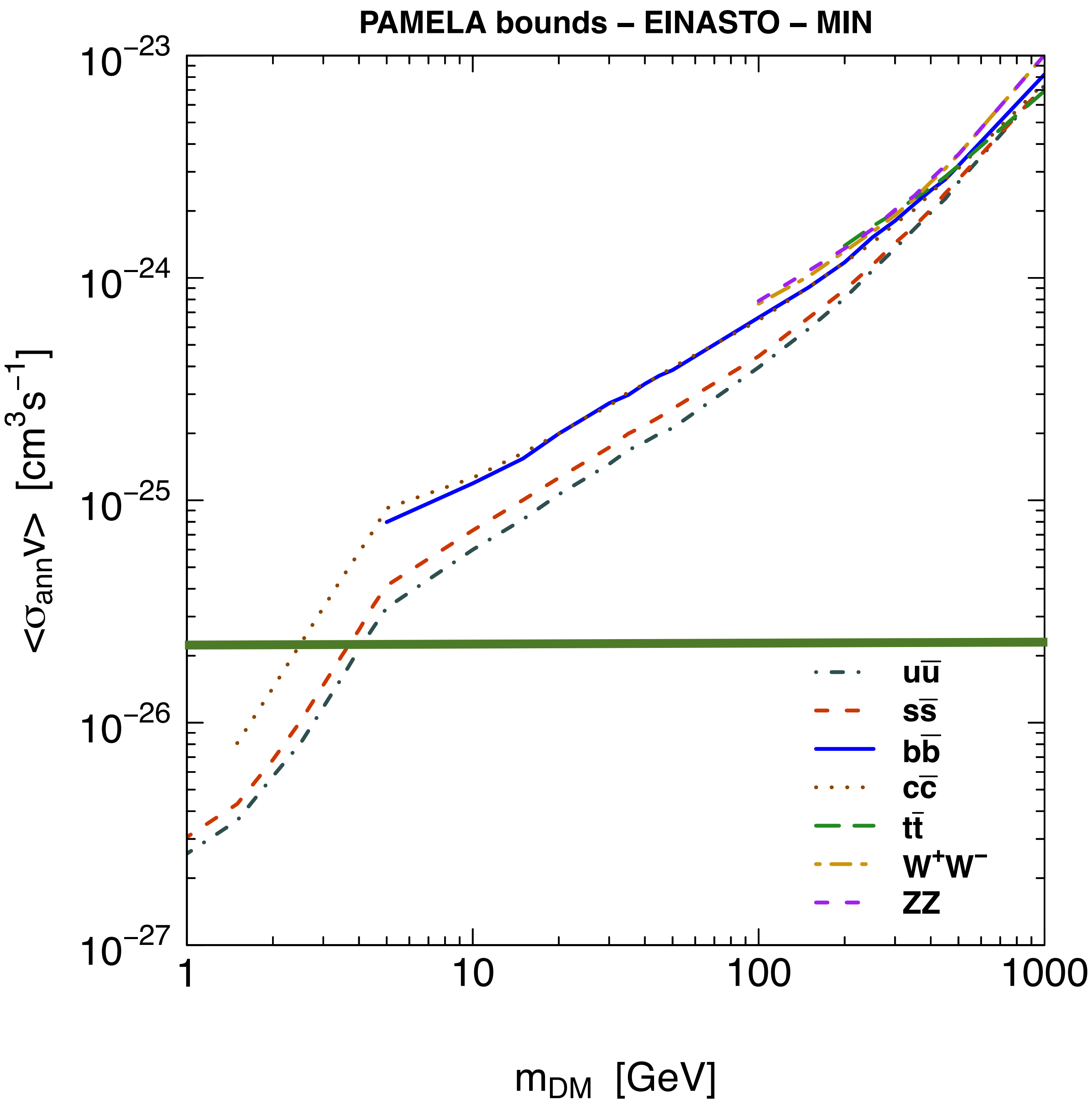
$\sigma^2_{i,theo}$: 40% of the background flux

The effect of the theoretical error is to make the upper limits that we find sensibly weaker

Bounds for the MED propagation:

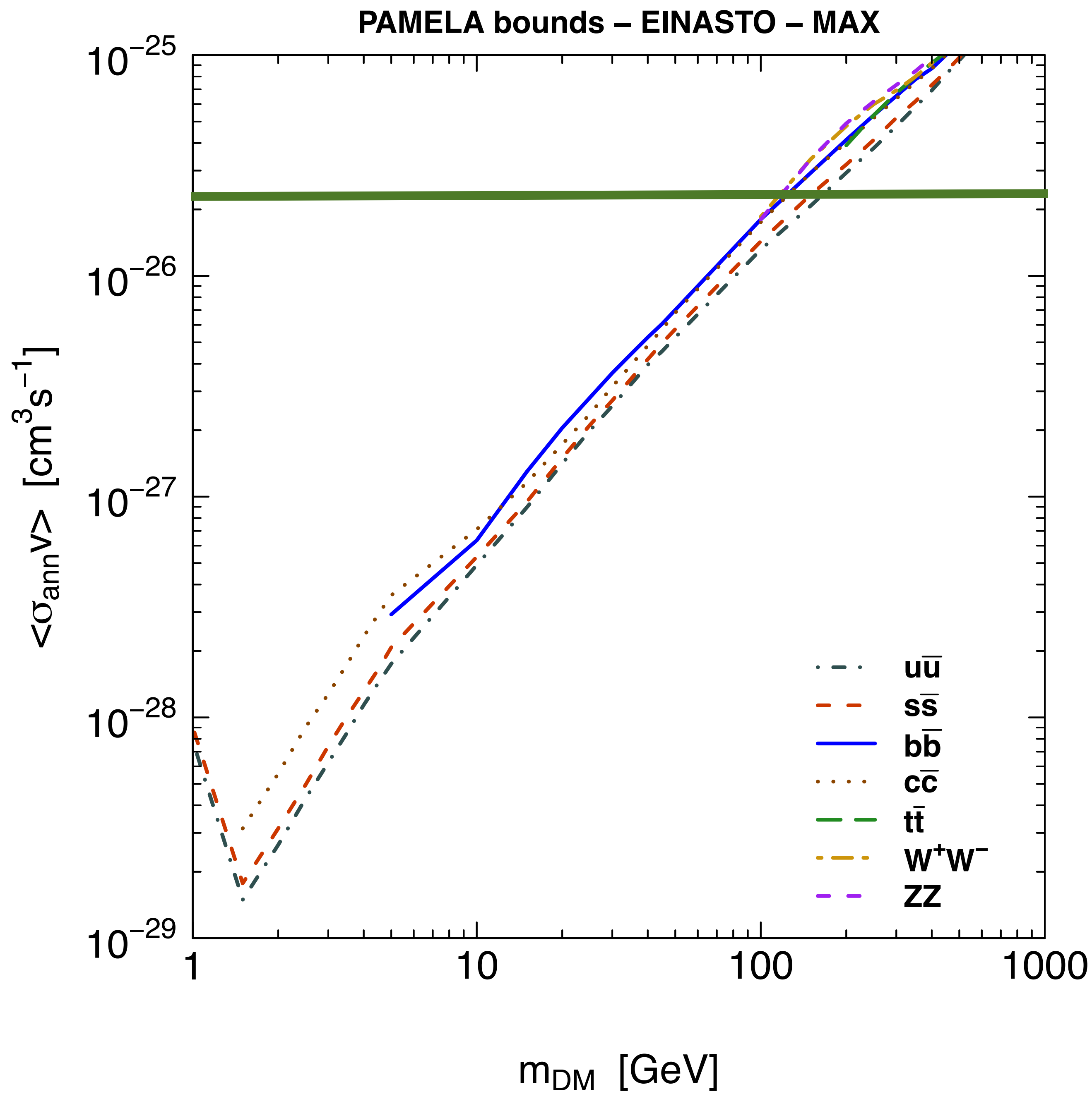


MIN



PAMELA bounds – EINASTO – MIN
$<\sigma_{ann}v>$ [cm^{3}s^{-1}]
m_{DM} [GeV]
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
1
10
100
1000
$u\bar{u}$
$s\bar{s}$
$b\bar{b}$
$c\bar{c}$
$t\bar{t}$
W^+W^-
ZZ

MAX



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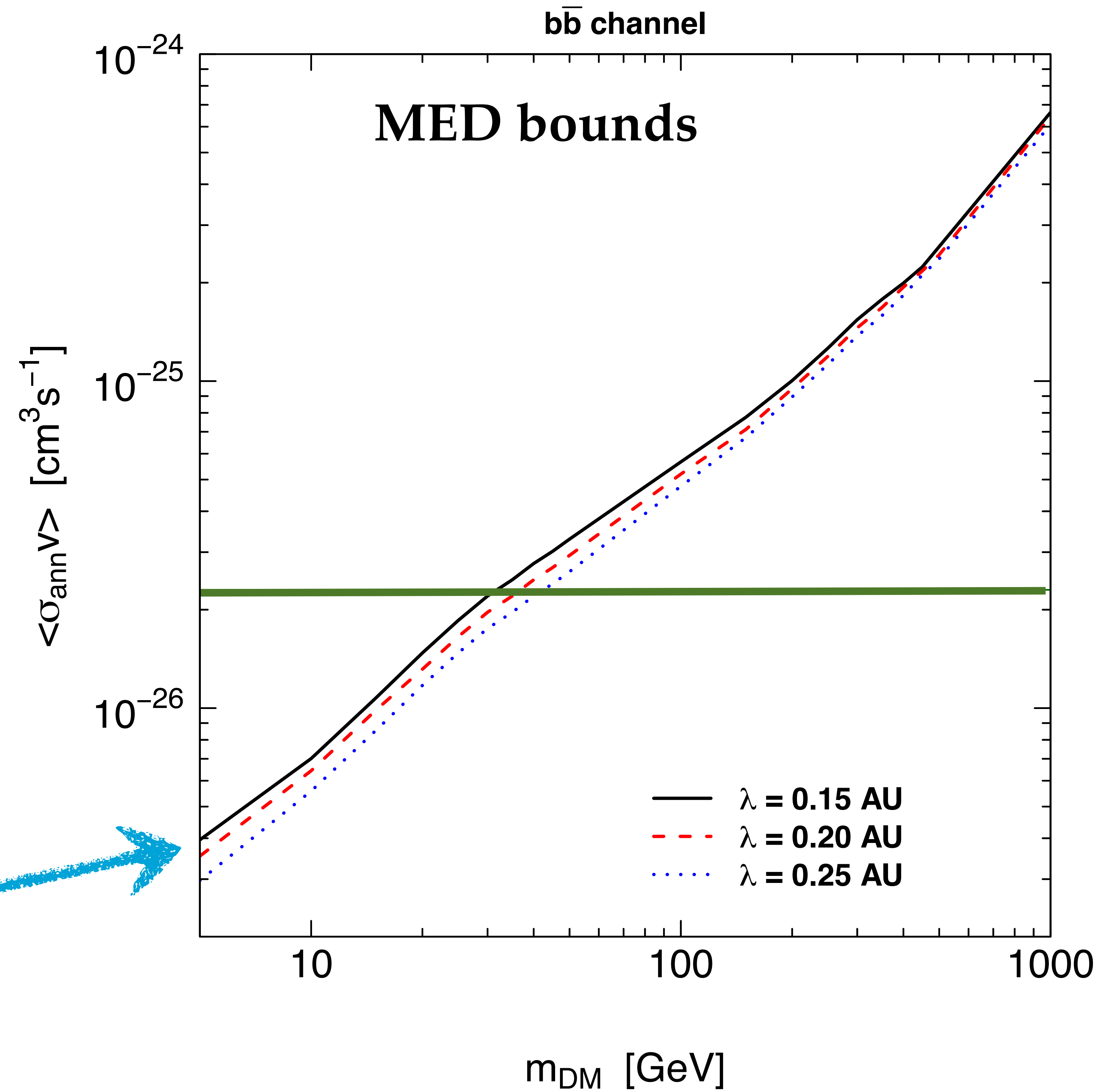
$s\bar{s}$
$b\bar{b}$
$c\bar{c}$
$t\bar{t}$
W^+W^-
ZZ

The role of solar modulation

For the solar modulation we have used parameters compatible with the PAMELA data-taking period (**negative polarity, α = 20° λ=0.15 A.U.**)

We vary the value of the mean free path in the SMF direction

Very small effect!

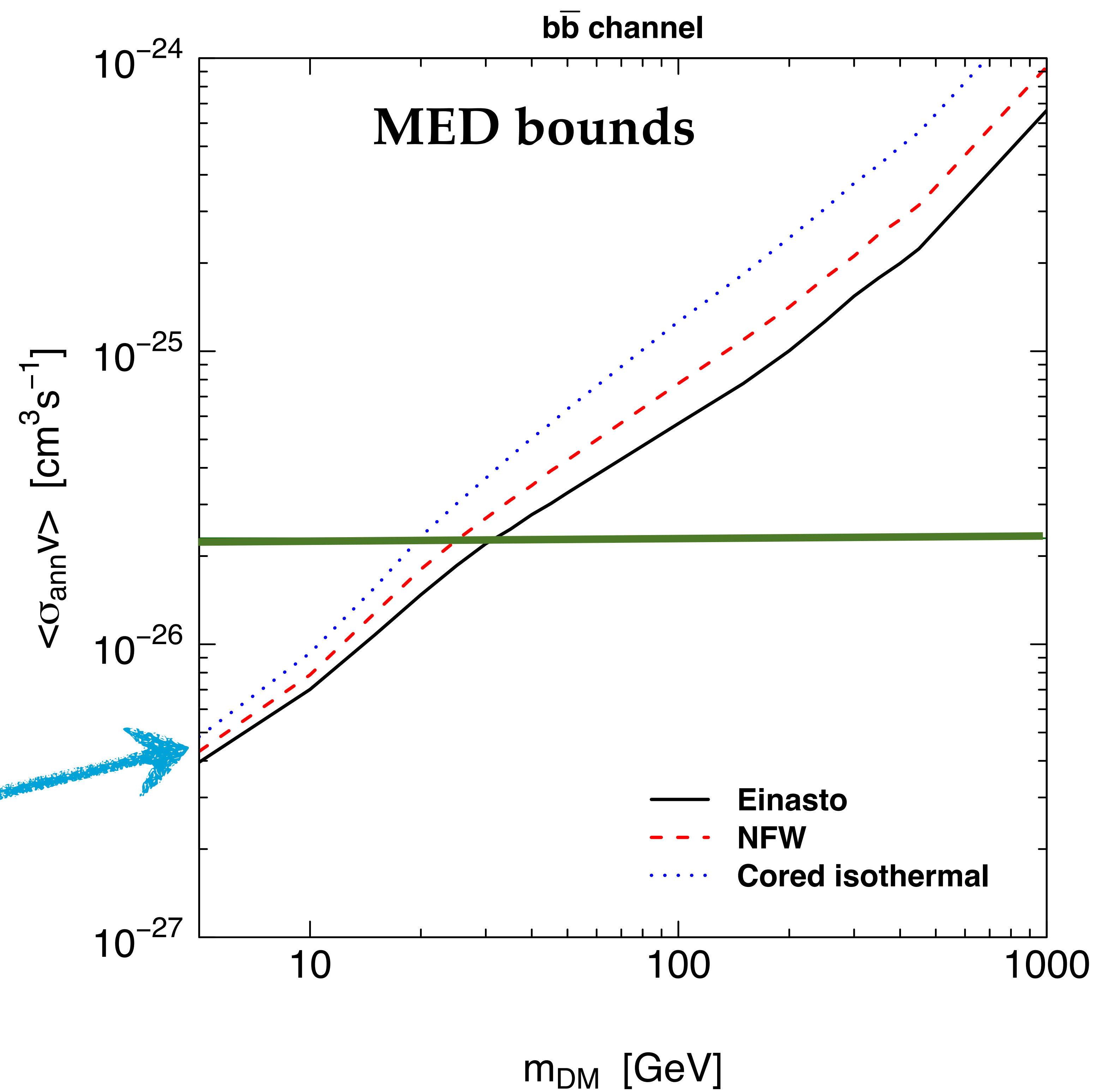


The role of the DM profile

In our calculations we have used an Einasto profile

Here we consider also an NFW and a cored isothermal profile

The effect seems to be quite large, in particular for high DM masses



Antideuterons

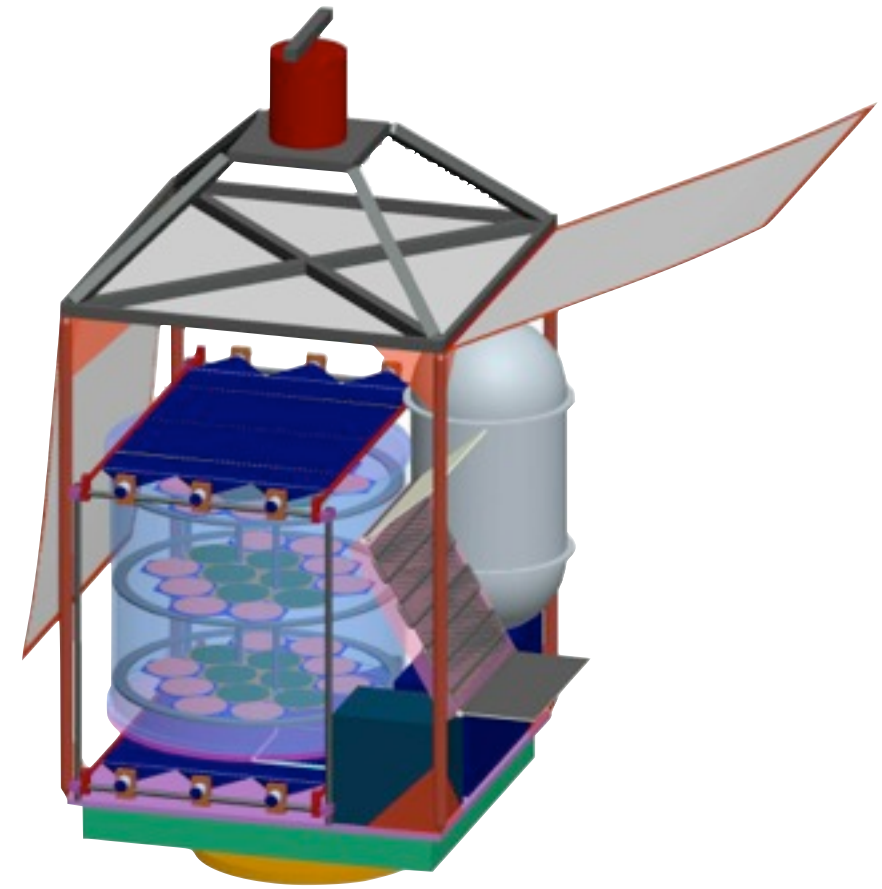
based on **N.Fornengo, L.Maccione, A.Vittino, JCAP09(2013)031**

DM searches with antideuterons

AMS-02

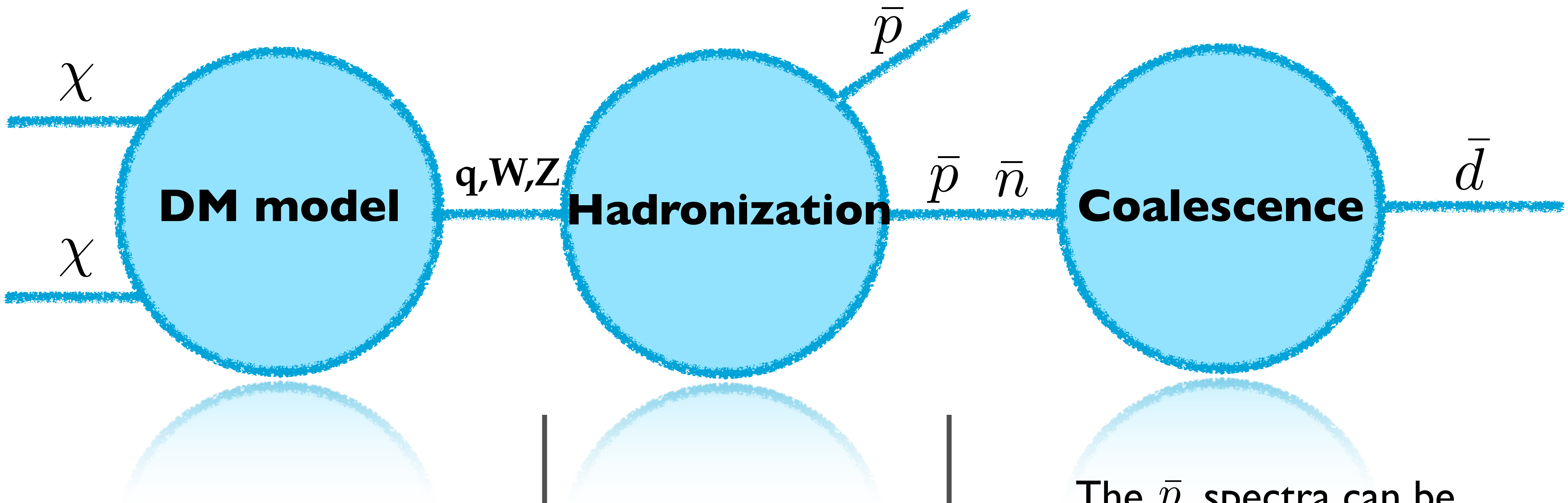
It’s operative since 2011
(here we will refer to a 3 year
data-taking period)

GAPS



It’s a proposed experiment which
will begin its science flights in 2017/2018
(in the LDB+ setup a data-taking period
of 210 days)

Injected spectra



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Hadronization is modeled with a MC event generator (Pythia)

The $\bar{p}$ spectra can be taken directly from Pythia, while for the $\bar{d}$ spectra we have to merge two antinucleons

What can we say about coalescence?

The coalescence puzzle

A simple idea: antinucleons coalesce if they are close enough (in the phase space)

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

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

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

If we assume them to be produced isotropically (classical model)

$$\boxed{\frac{dN_{(\bar{p}\bar{n})}}{d^3\vec{k}_{\bar{p}} d^3\vec{k}_{\bar{n}}} = \frac{dN_{\bar{p}}}{d^3\vec{k}_{\bar{p}}} \frac{dN_{\bar{n}}}{d^3\vec{k}_{\bar{n}}}}$$

Not correct! we neglect the jet-like structure of the event

To be more accurate, we build $F_{(\bar{p}\bar{n})}$ directly from the MC event generator

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The function C is the probability that the antinucleons merge; usually we have:

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

We take into account also the physical distance:

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

We take $r_0 \; = \; 2 \text{ fm}$ (radius of the antideuteron)

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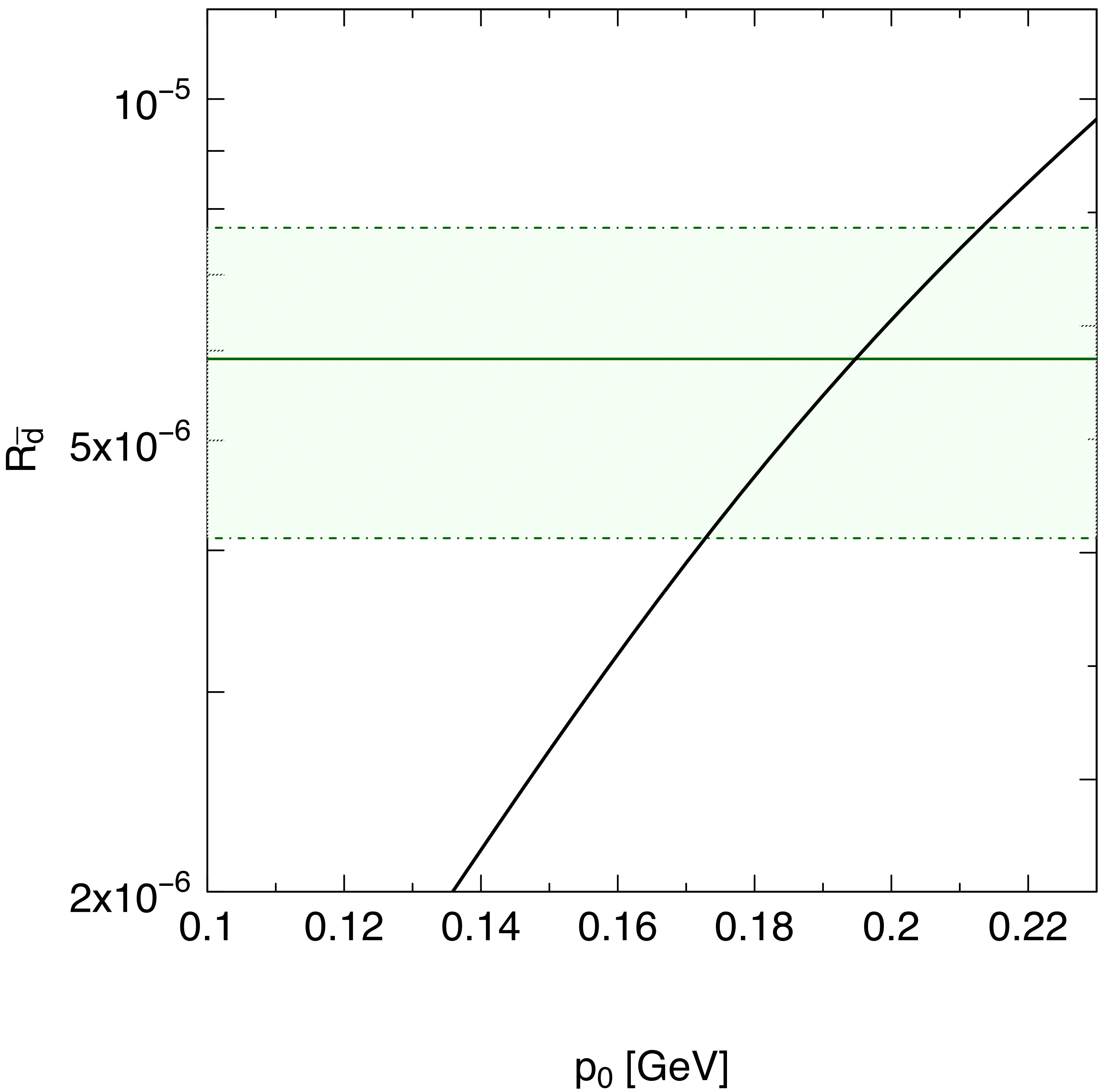
p_0 is a free parameter. Which is its value?

We take $r_0 = 2\ \mathrm{fm}$ (radius of the antideuteron)

The coalescence puzzle

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

$$p_0 = (195 \pm 22)\ \mathrm{MeV}$$

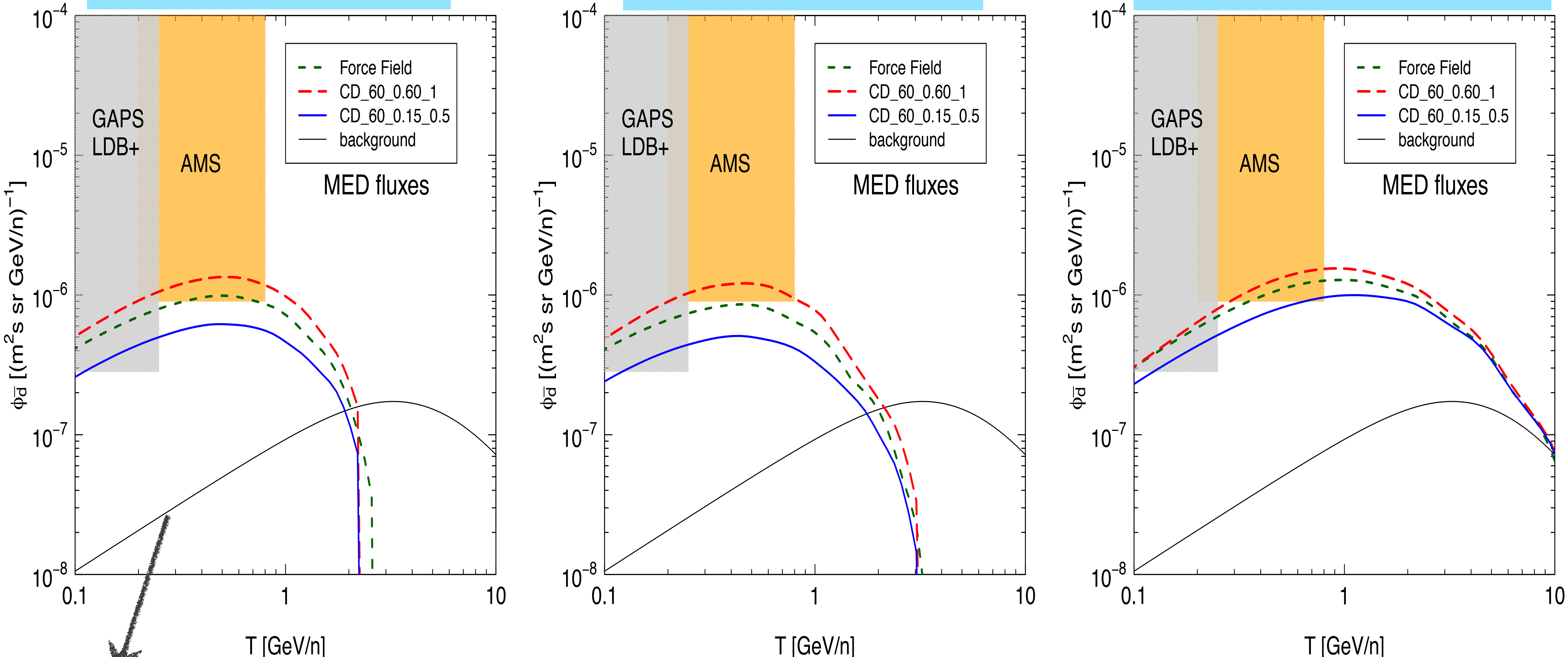
Basically, a $\bar{d}$ is formed if

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

Fluxes at Earth

With the maximal cross section allowed by PAMELA constraints:

uu - m_{DM} = 10 GeV | bb - m_{DM} = 20 GeV | WW - m_{DM} = 100 GeV



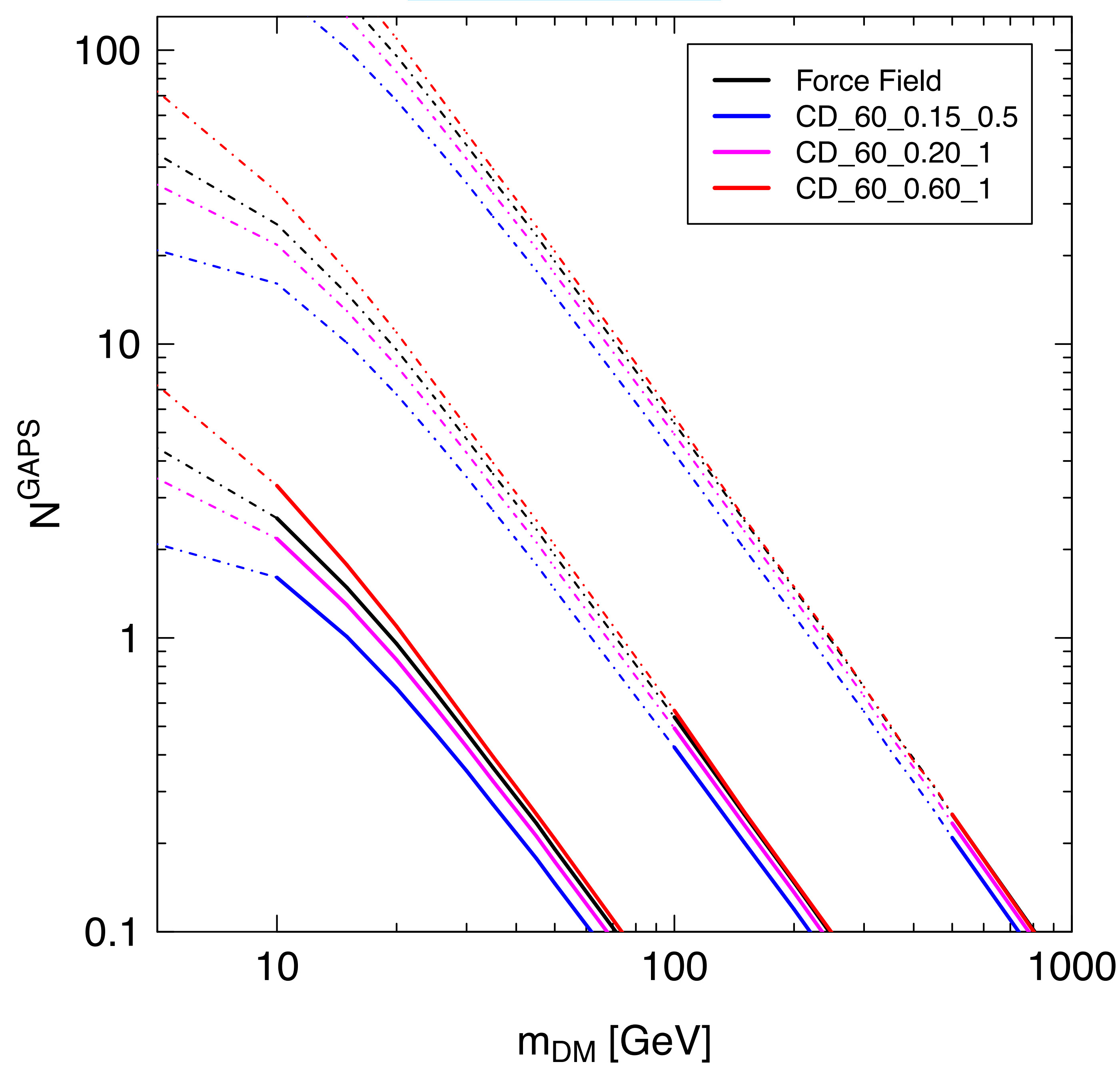
Background [**F.Donato, N.Fornengo and D.Maurin, Phys. Rev. D 78 (2008)**]

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

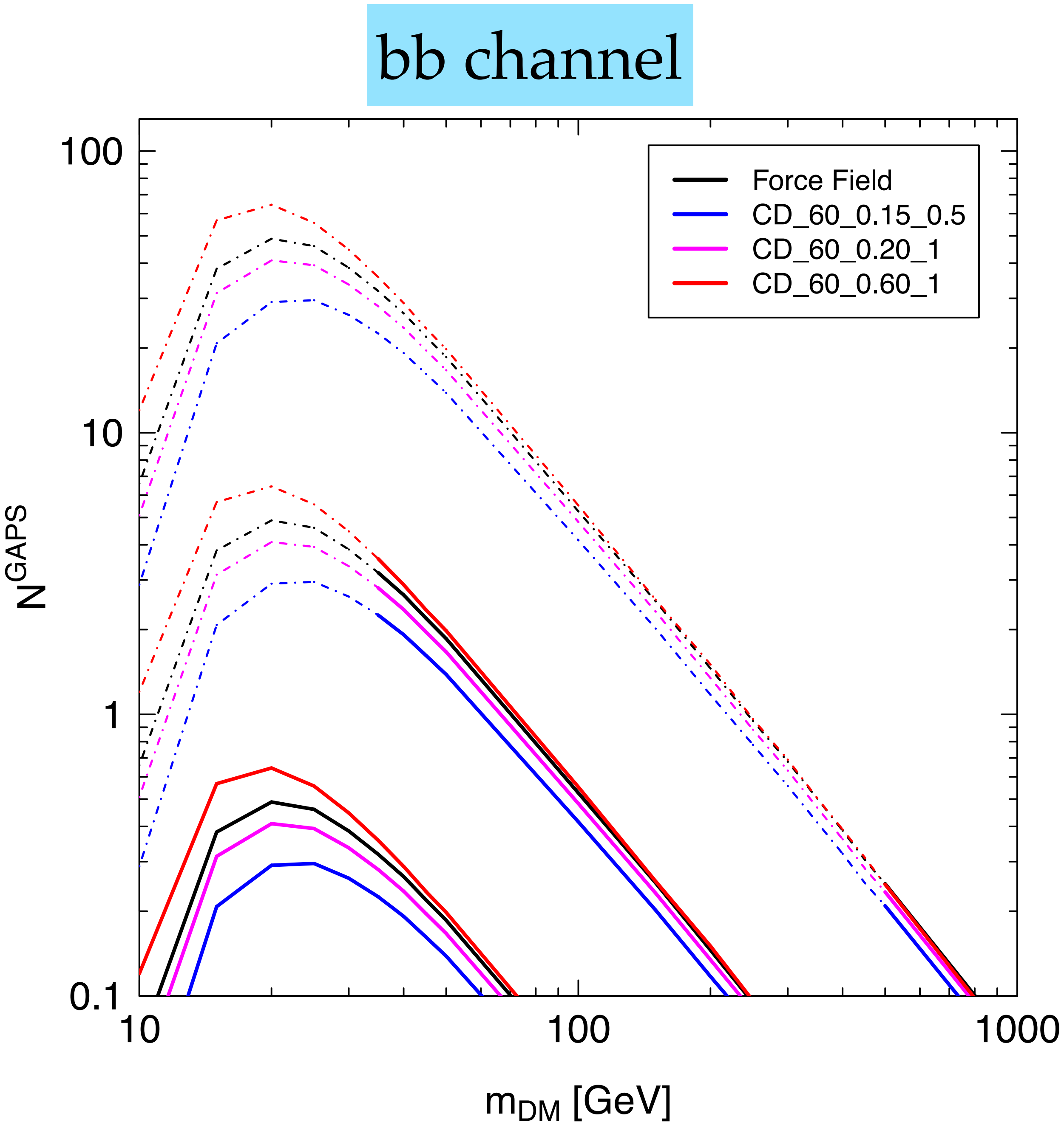
How many events do we have?

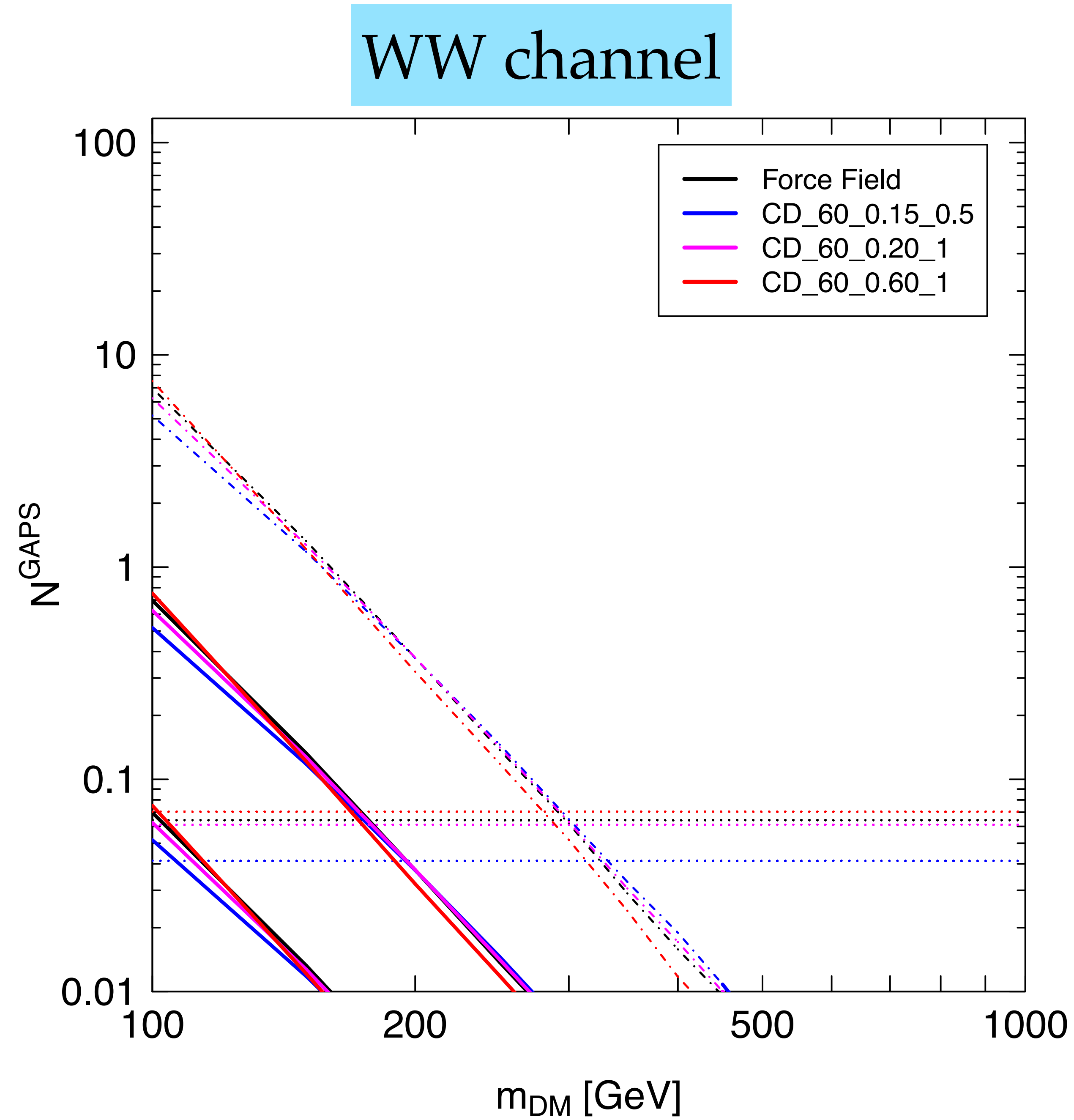
- Number of signal events for 4 models of solar modulation
- 3 set of curves for 3 values of <σv> (thermal, 0.1xthermal, 10xthermal)
- solid lines = allowed by PAMELA bounds, dot-dashed lines= forbidden by PAMELA bounds

uu channel

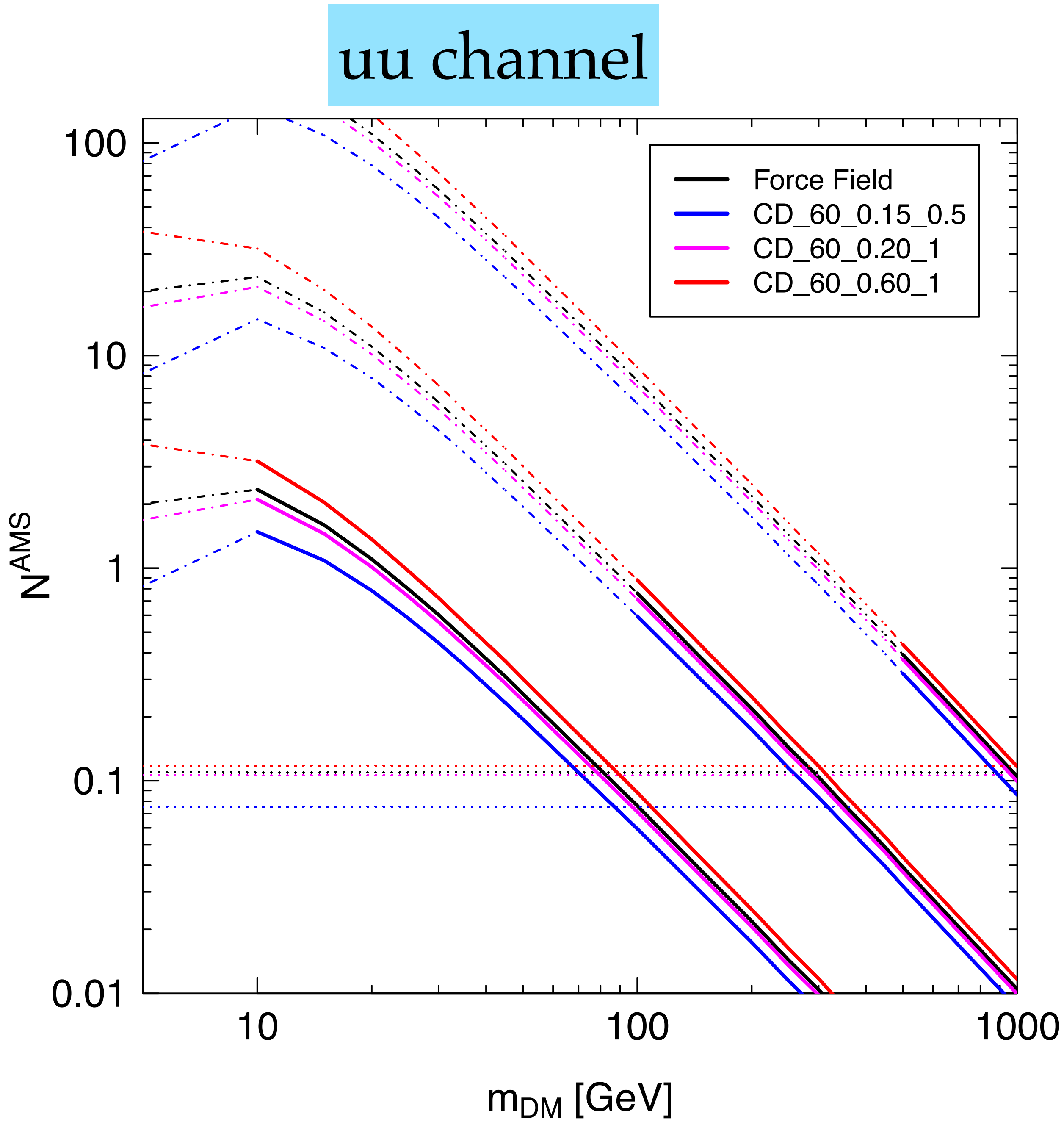


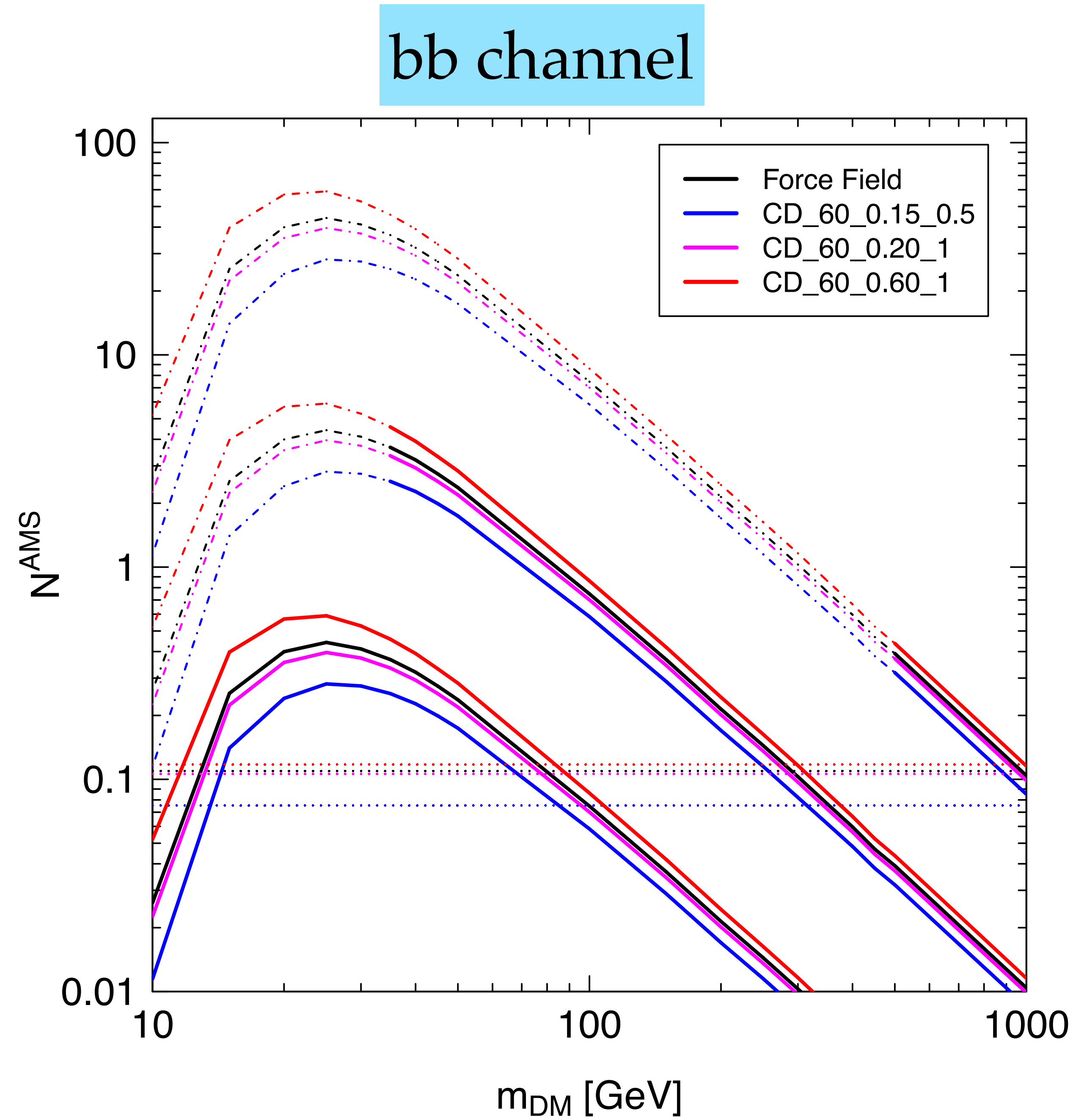
GAPS experiment:





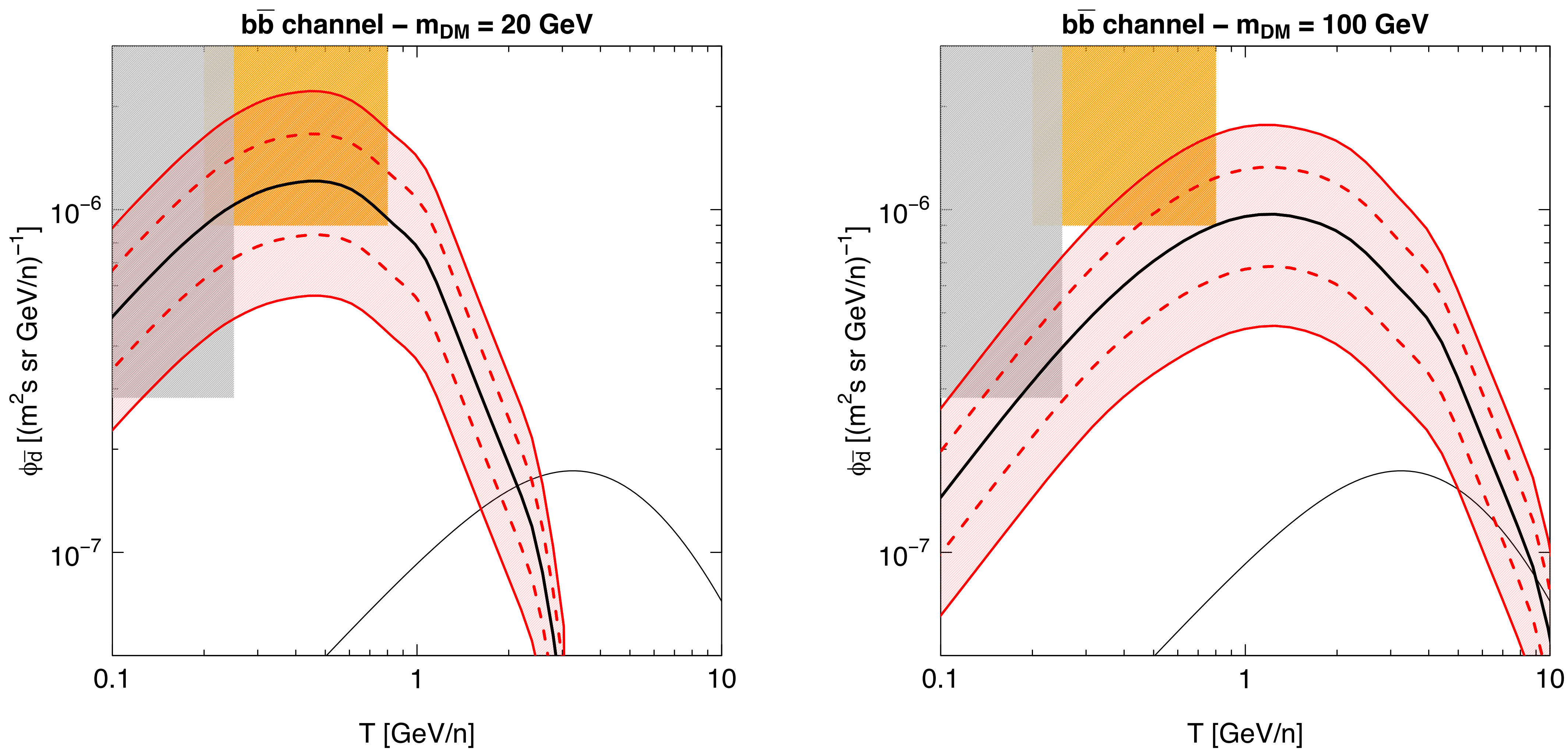
AMS experiment:





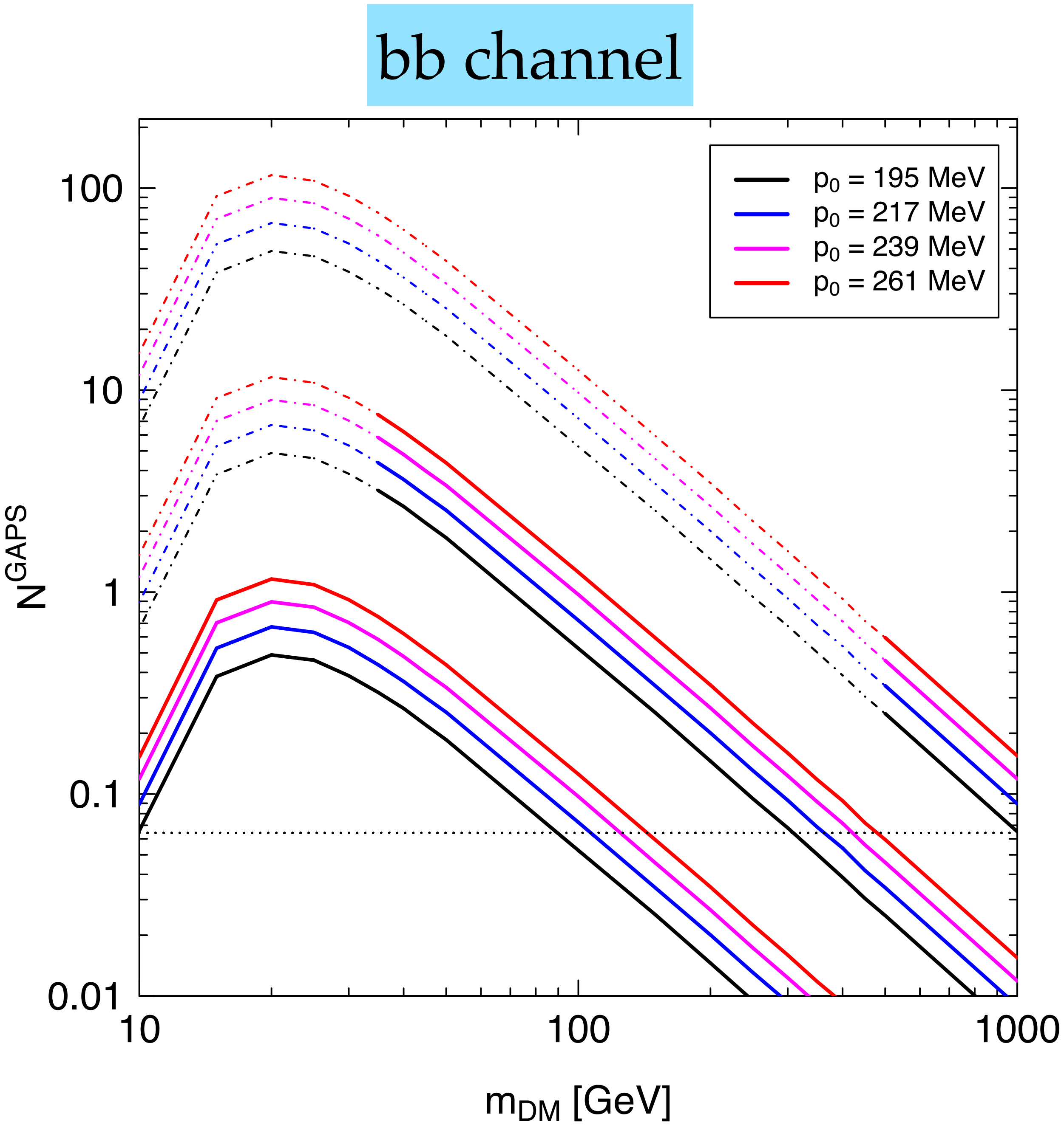
Role of the coalescence momentum

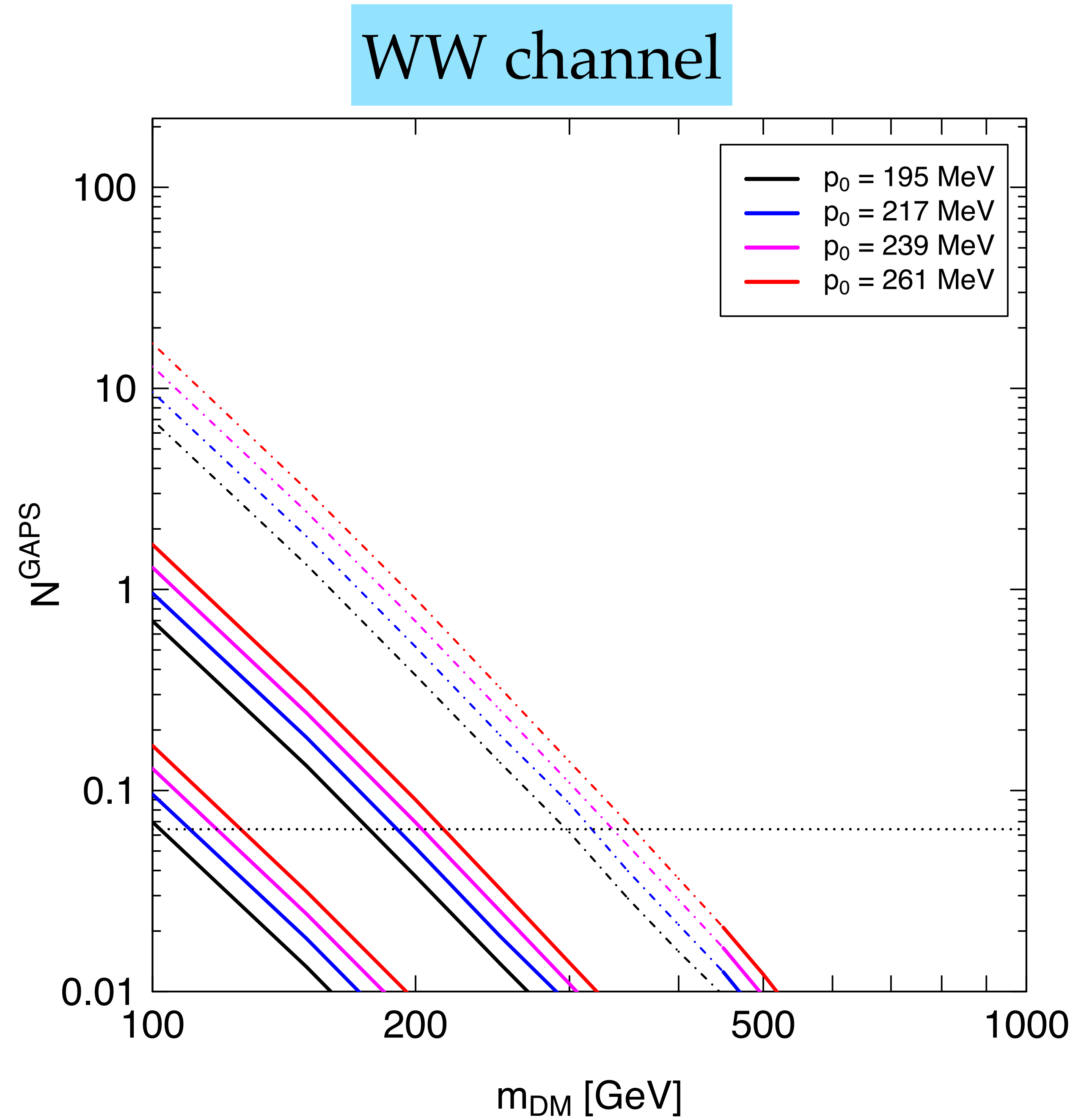
The coalescence momentum that we derive from ALEPH has an uncertainty.
We can vary it in his 2σ interval:



In the most optimistic case we can have a detection also for higher mass WIMPs (e.g. 100 GeV)!

Number of expected events:





Conclusions

- ★ We have discussed the role of antiprotons and antideuterons in dark matter indirect detection. We have seen that antiprotons can be used to constrain the DM parameter space, while antideuterons are a promising channel for a discovery.

- ★ In order to properly calculate bounds arising from antiprotons measurements, we need to take into account both the theoretical and the astrophysical uncertainties

- ★ Despite the strong bounds that we have, a possibility to detect DM through its antideuterons emission is still there

Conclusions

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- ★ In order to properly calculate bounds arising from antiprotons measurements, we need to take into account both the theoretical and the astrophysical uncertainties

- ★ Despite the strong bounds that we have, a possibility to detect DM through its antideuterons emission is still there

Thank you!

Backup slides

How many events do we need?

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

The answer is given by poissonian statistics: we need N_{crit} events being N_{crit} the smallest N satisfying:

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

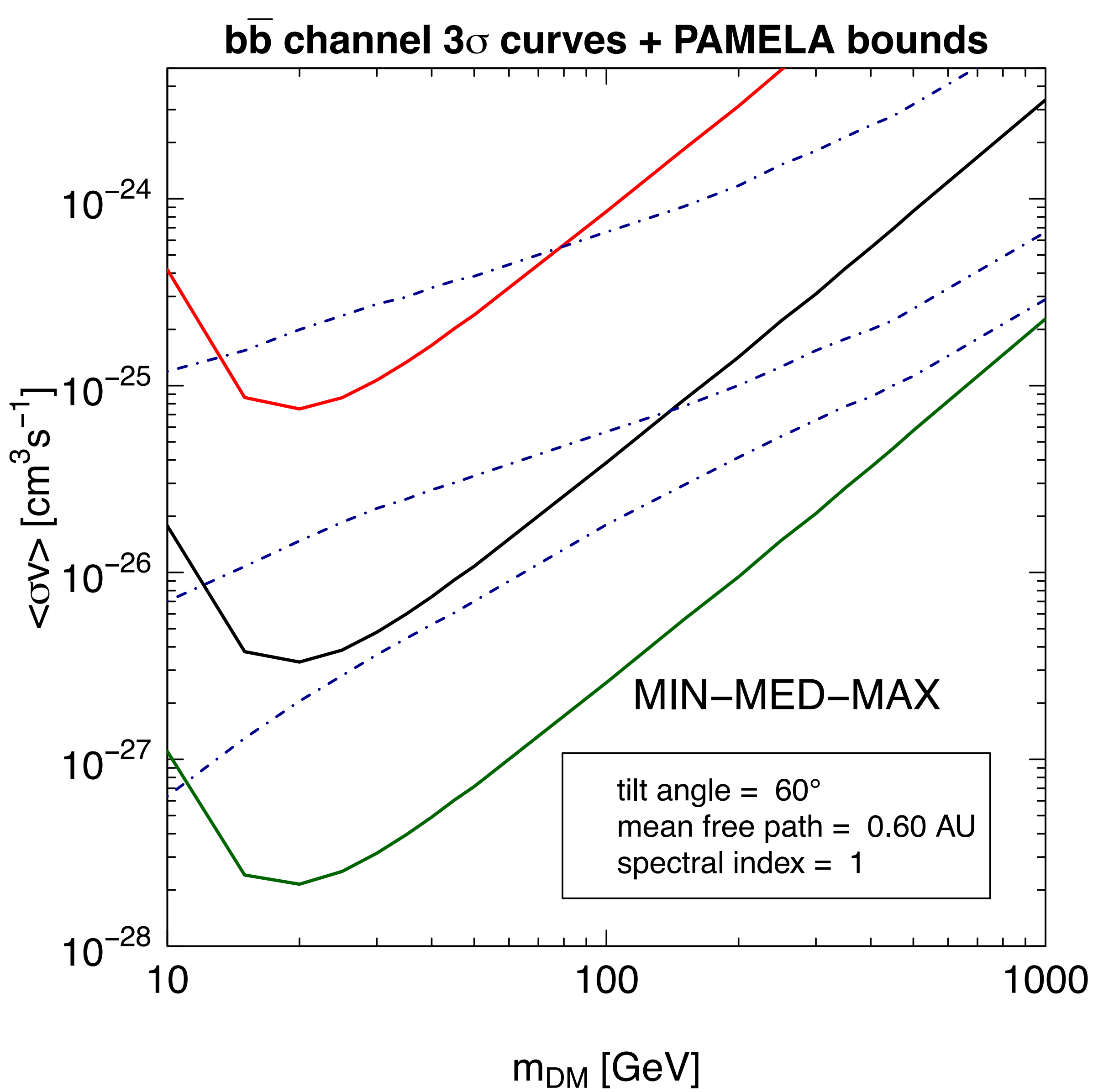
$$\boxed{P(n,b) = \frac{b^n e^{-b}}{n!}}$$

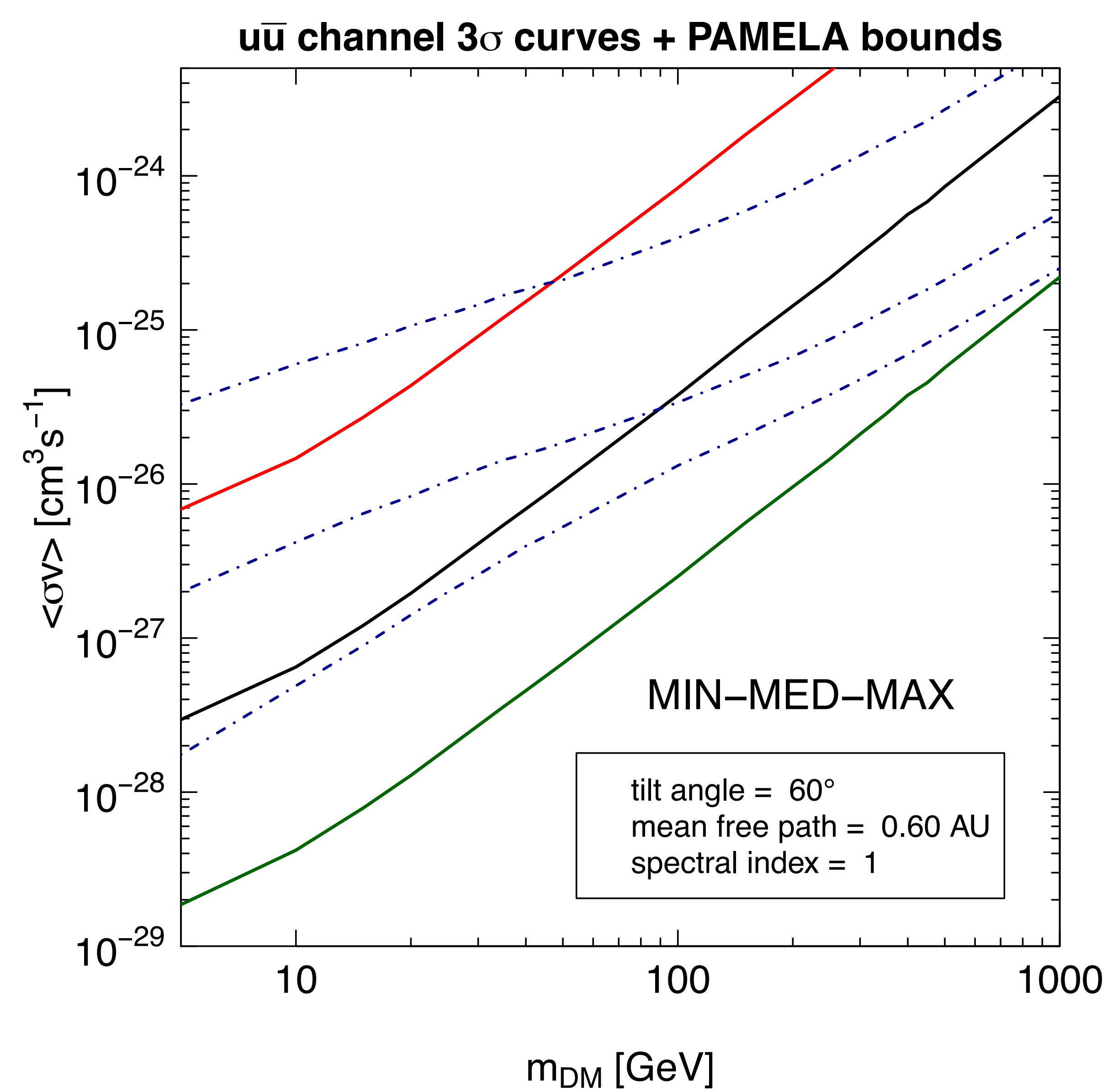
It's a cumulative distribution (the poissonian is discrete)

Basically, for a 3sigma detection, we need 1 event for GAPS and 2 for AMS

GAPS experimental reachability

Reachability = curve in the (m_{DM},$\langle\sigma v\rangle$) plane that corresponds to a detection (with a 3σ C.L.)

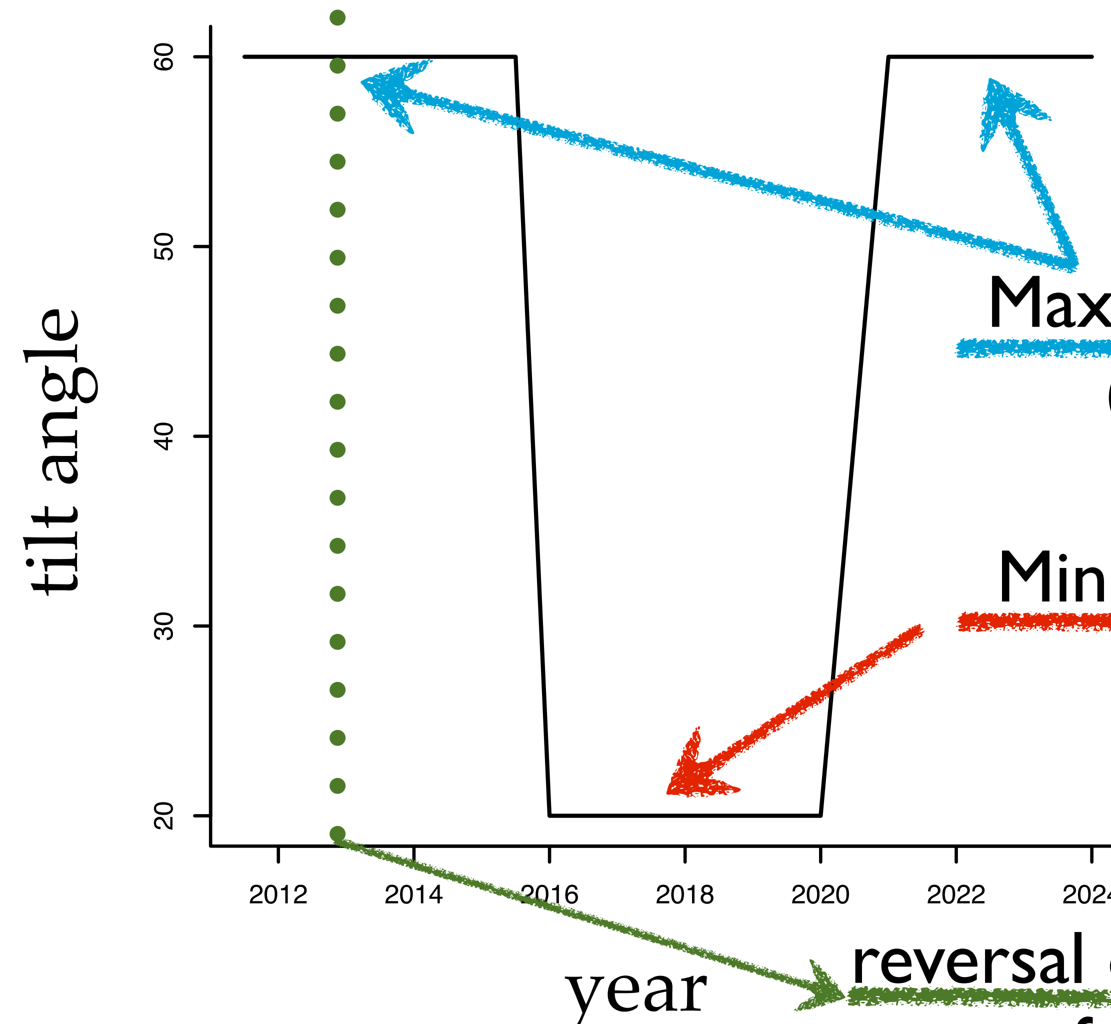




Projected AMS-02 sensitivity

In order to estimate the AMS-02 sensitivity we consider a 13 year data-taking period (2011-2024)

We take a background flux solar modulated by following the various phases of the solar activity in that period:



Maximal activity (α=60°)

Minimal activity (α=20°)

reversal of the polarity of the SMF

For all the data-taking period, the mean free path is: λ=0.2 AU

How do we generate AMS-02 mock data?

To generate AMS-02 mock data we follow the approach described by Cirelli and Giesen in **JCAP 1304 (2013) 015**

The number of events in a period in an energy bin large centered in is given by:

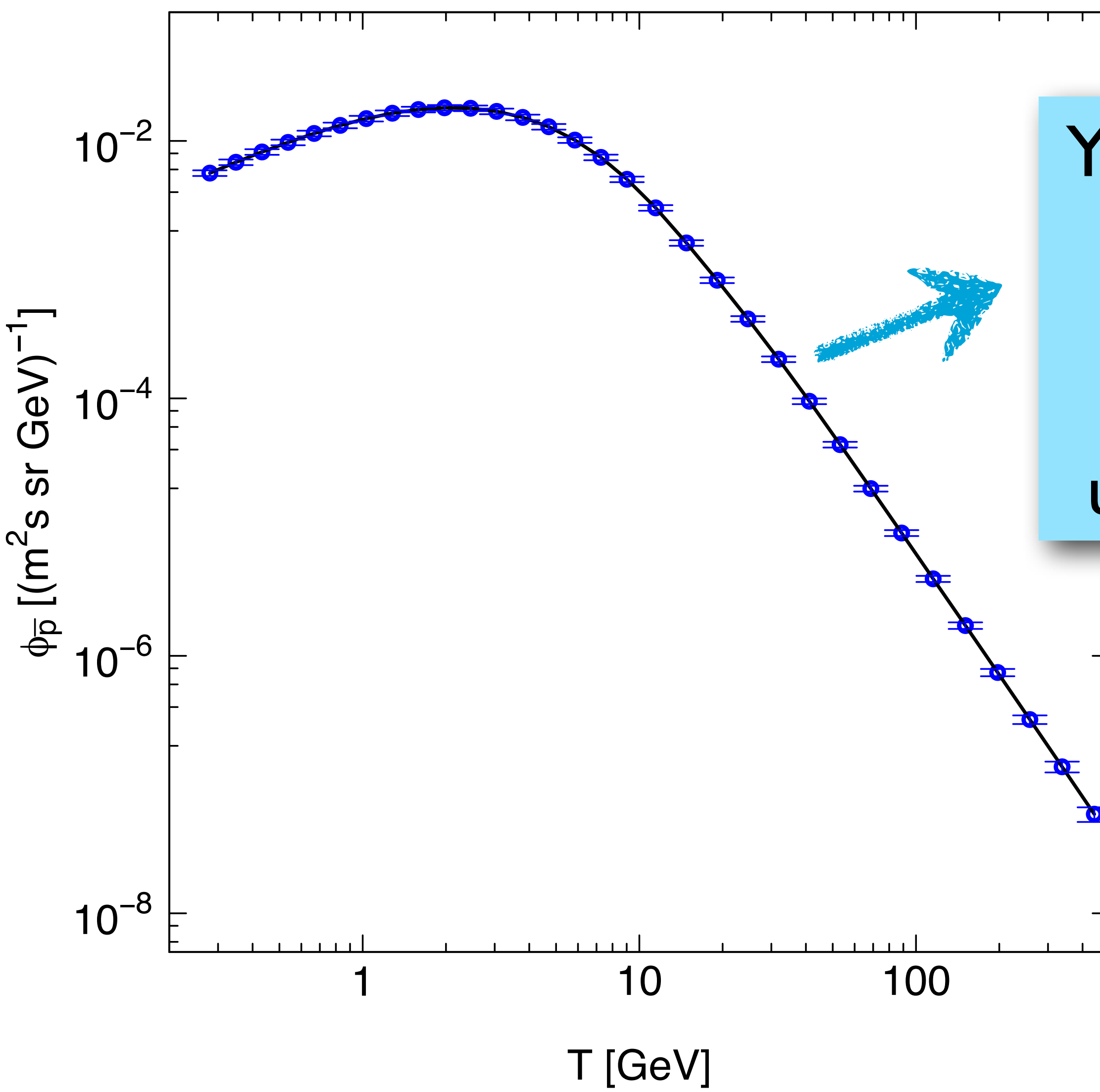
$$\boxed{N_i \;=\; \epsilon a(T_i)\phi(T_i)\Delta T_i \Delta t}$$

- ϵ is the efficiency: $\epsilon(T_i) \;=\; \theta(T_i - T_{min})$ (geomagnetic effects)

For the acceptance:

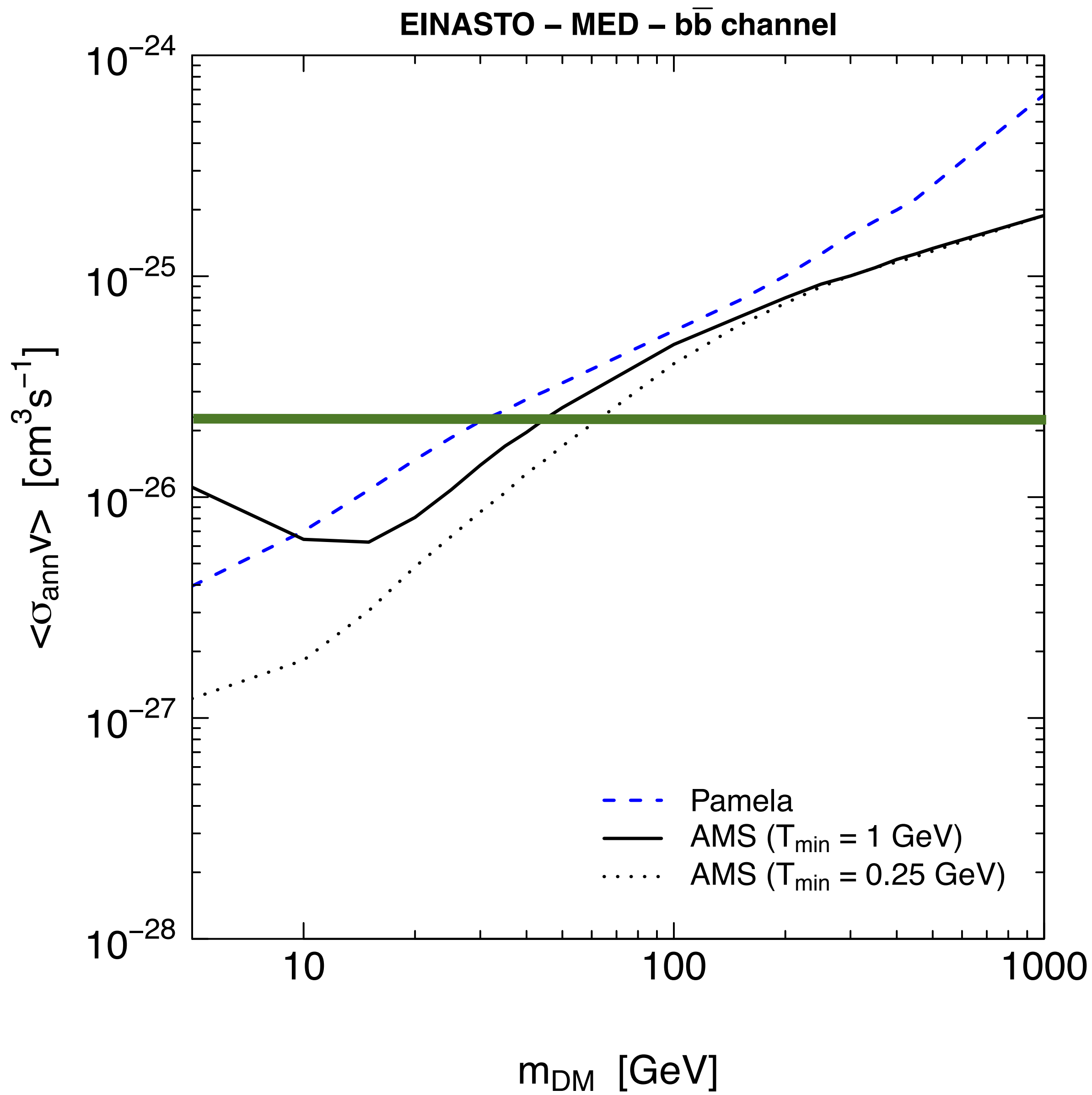
A. G. Malinin [AMS Collaboration],

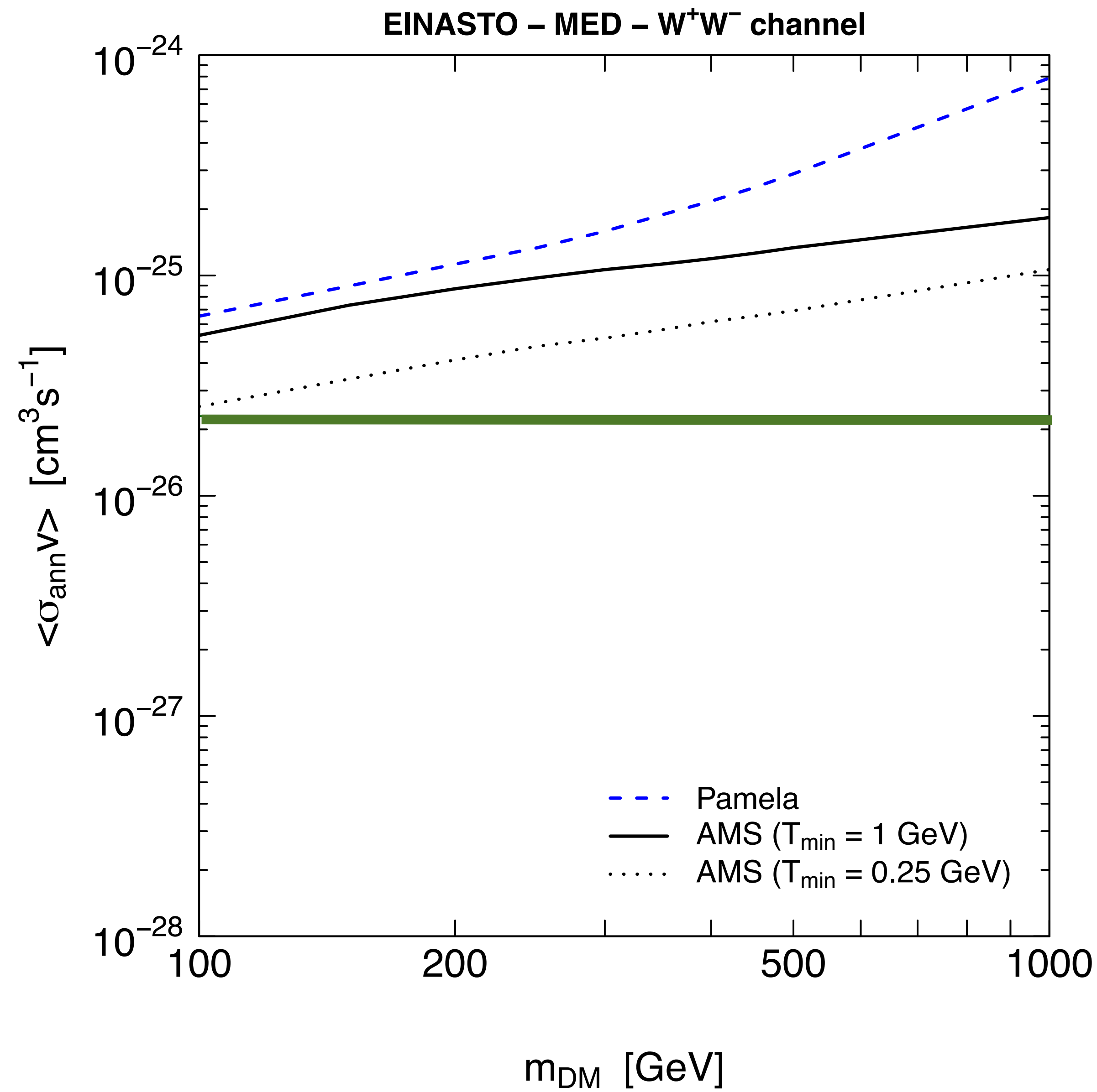
Phys. Atom. Nucl. 67, 2044 (2004)



You still need to add theoretical uncertainty!

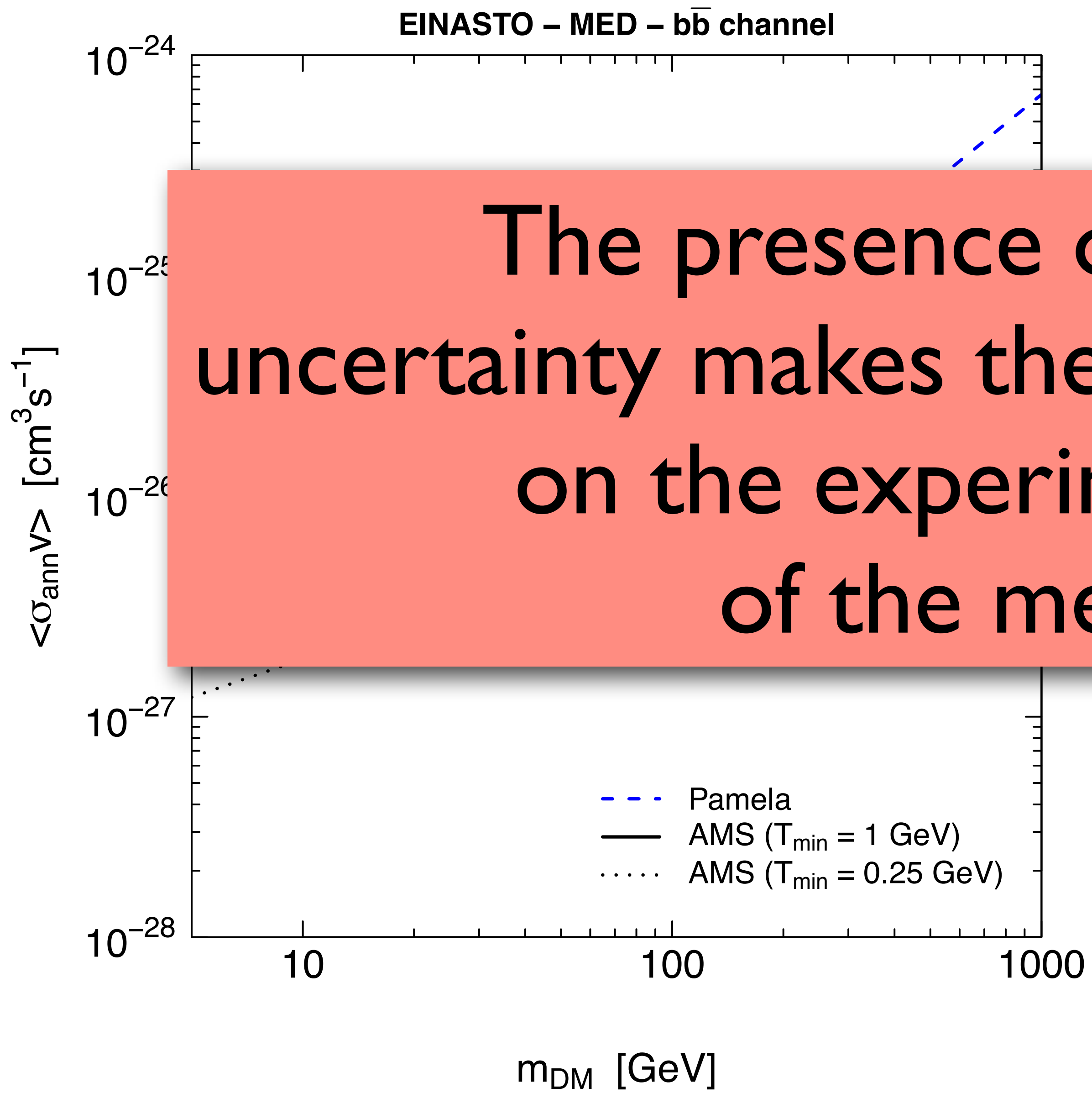
AMS projected sensitivity

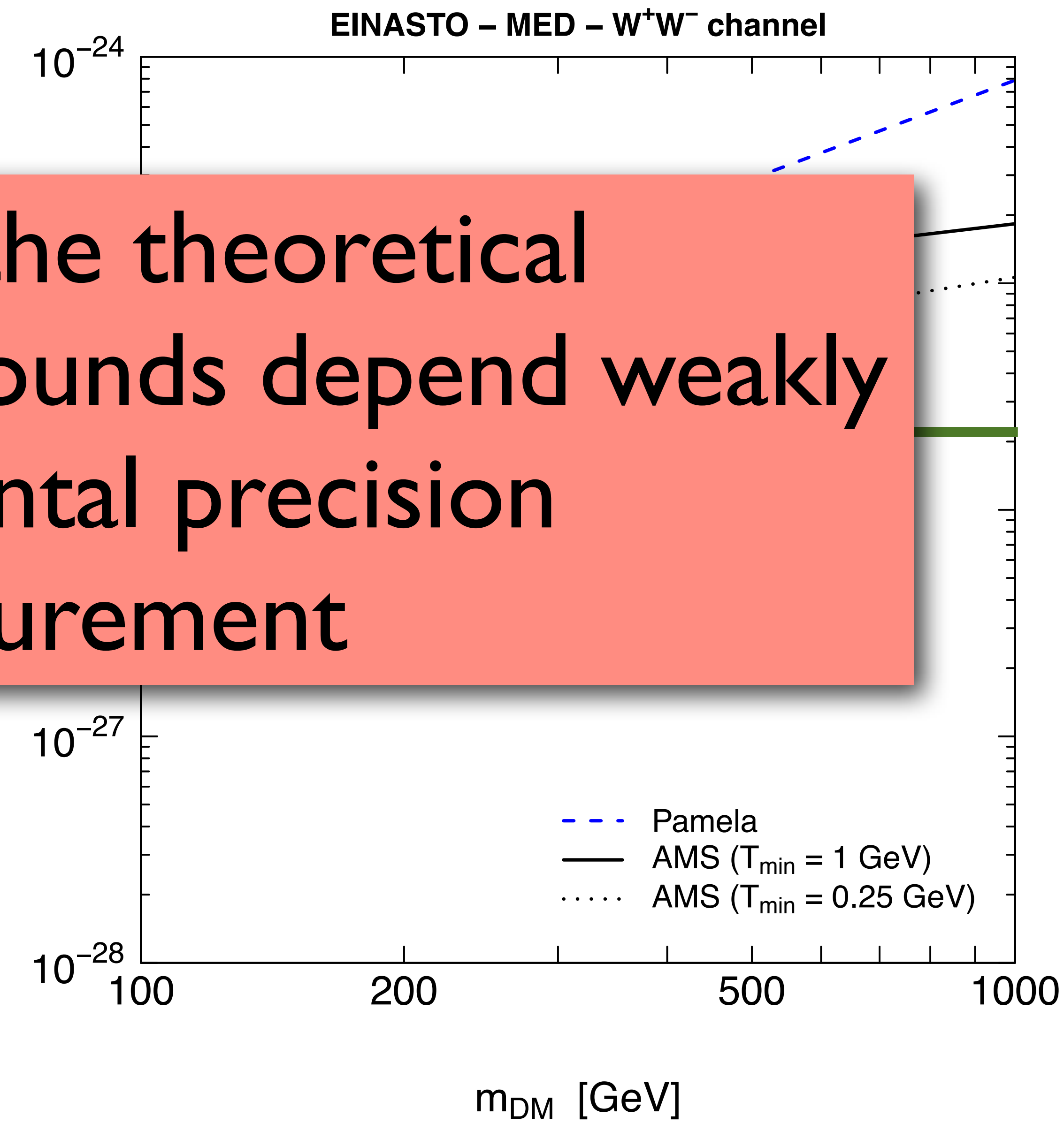




AMS will give stronger bounds only if it will be able to detect low-energy antiprotons

AMS projected sensitivity





The presence of the theoretical uncertainty makes the bounds depend weakly on the experimental precision of the measurement

AMS will give stronger bounds only if it will be able to detect low-energy antiprotons

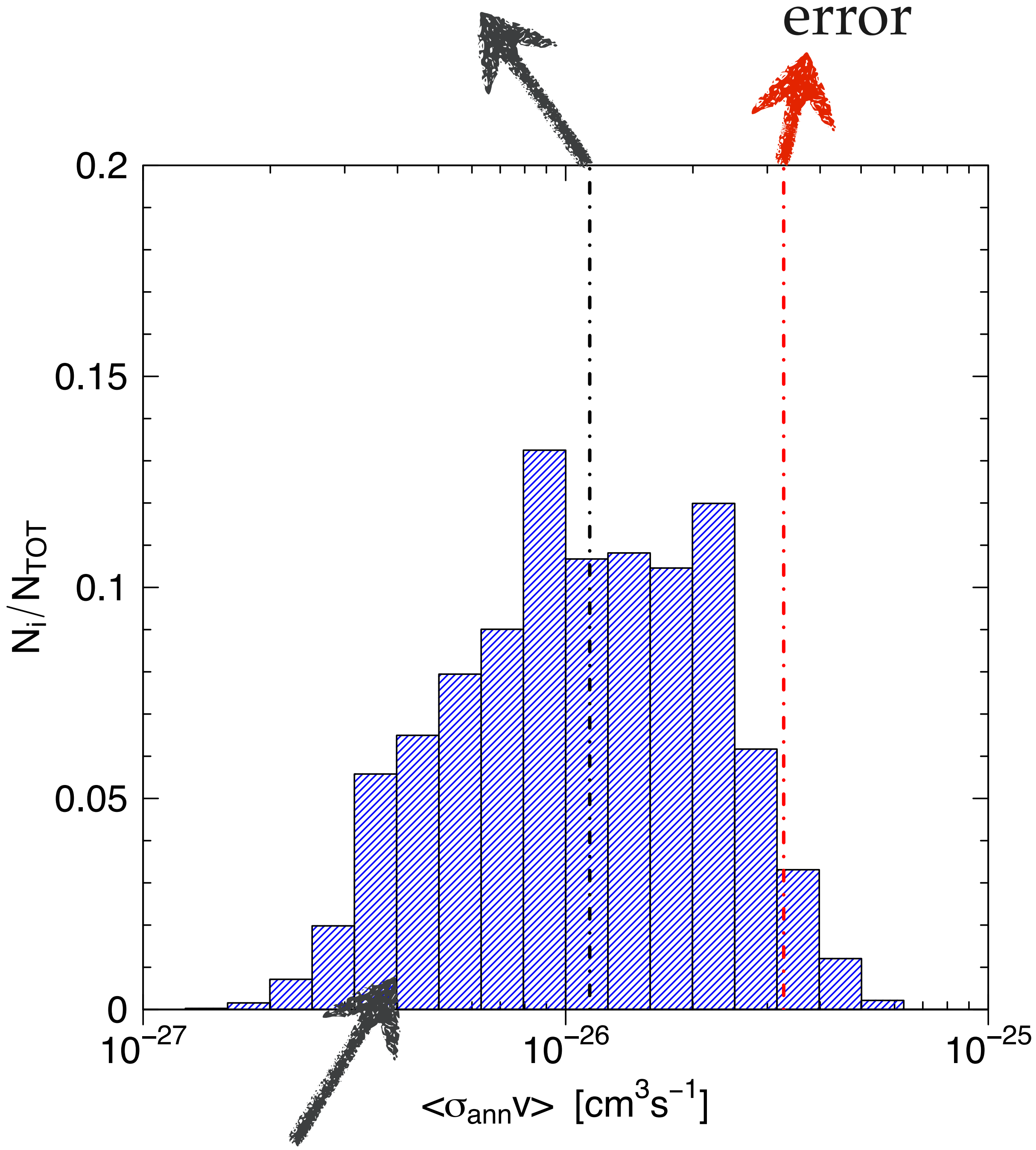
Experimental and theoretical errors

We can consider 10^5 realizations of the astrophysical background, normally distributed around the central flux with a standard deviation of the 40%

Calculating the bounds by summing theoretical and experimental errors in quadrature corresponds to take the 98~99% of the cumulative function of the bounds distribution

without theoretical error

with theoretical error



(50 GeV WIMP annihilating into bb)

CD solar modulation - I

$$\boxed{\vec{B} = A B_0 \left(\frac{r}{r_0}\right)^{-2} \left(\hat{r} - \frac{\Omega r \sin\theta}{V_{\rm SW}} \hat{\varphi}\right)}$$

$$\boxed{\begin{cases} |B|(1\ \text{AU}) = 5\ \text{nT} \\ A = \pm H(\theta - \theta') \\ \theta' = \pi/2 + \sin^{-1}\left(\sin\alpha \sin(\varphi + \Omega r/V_{\rm SW})\right) \end{cases}}$$

Ω is the 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: $\underline{\vec{v}_{\rm drift} = \nabla \times (K_A \vec{B}/|B|)}$

CD solar modulation - II

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

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

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

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