Anti-nuclei from Dark Matter

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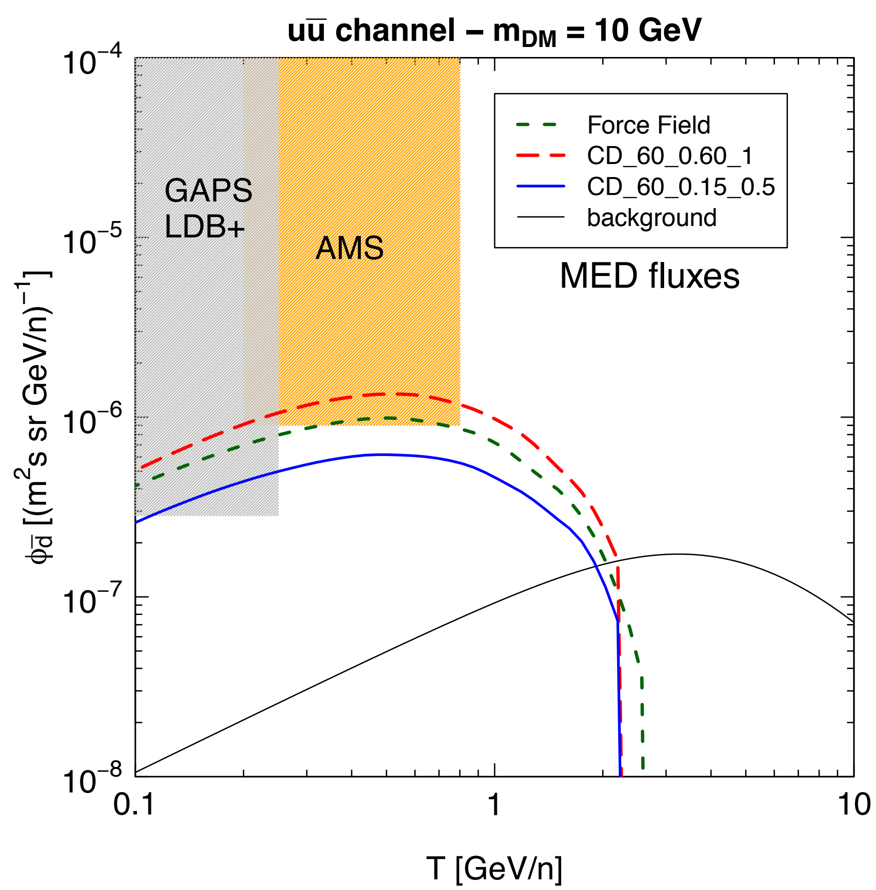
Why anti-nuclei?

Basically because we expect the DM signal to dominate over the astrophysical background at low energies

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

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

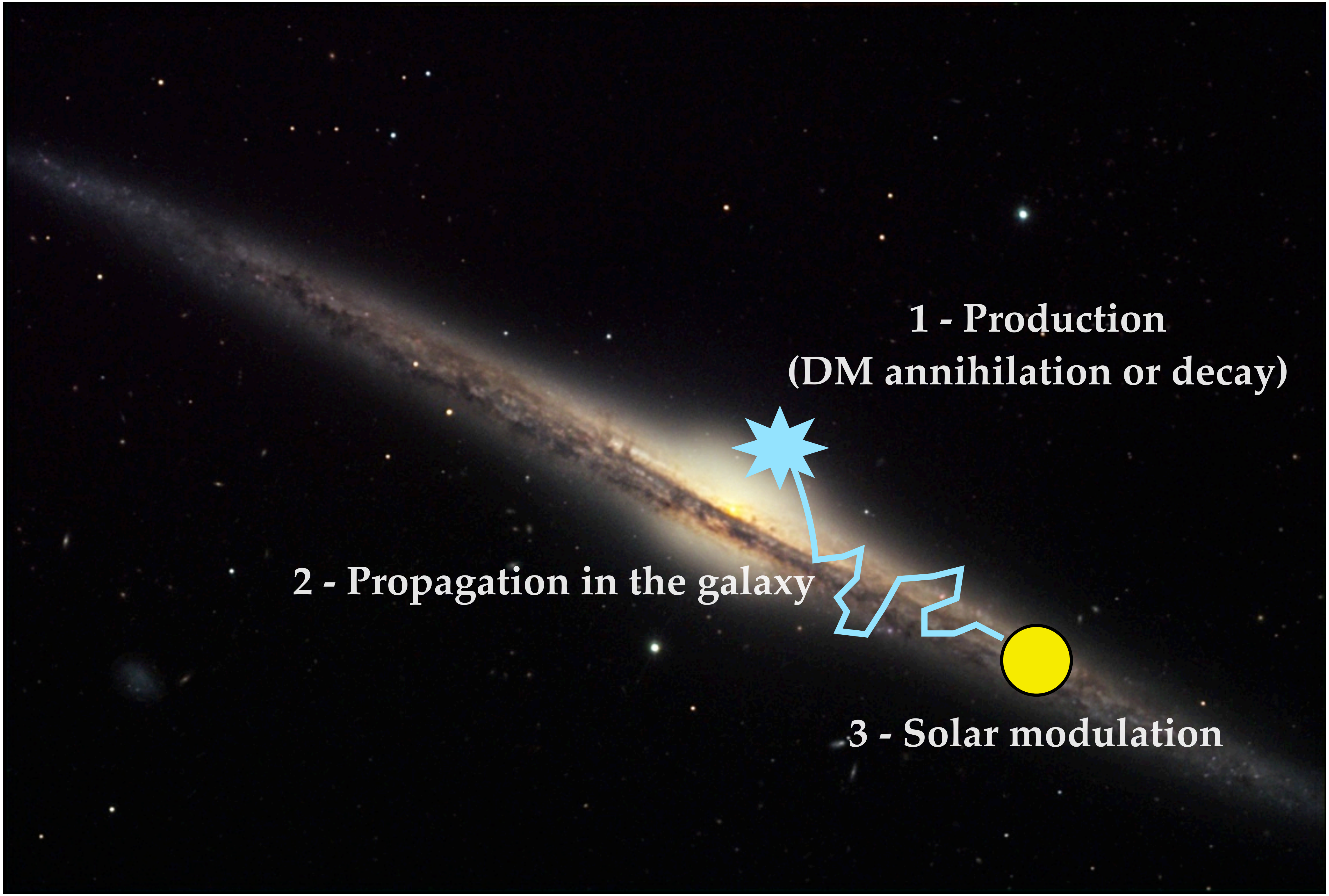


The large energy thresholds, together with the steeply falling primary spectra make the astrophysical background **highly suppressed** at low energies

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

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

From the Source to the Earth



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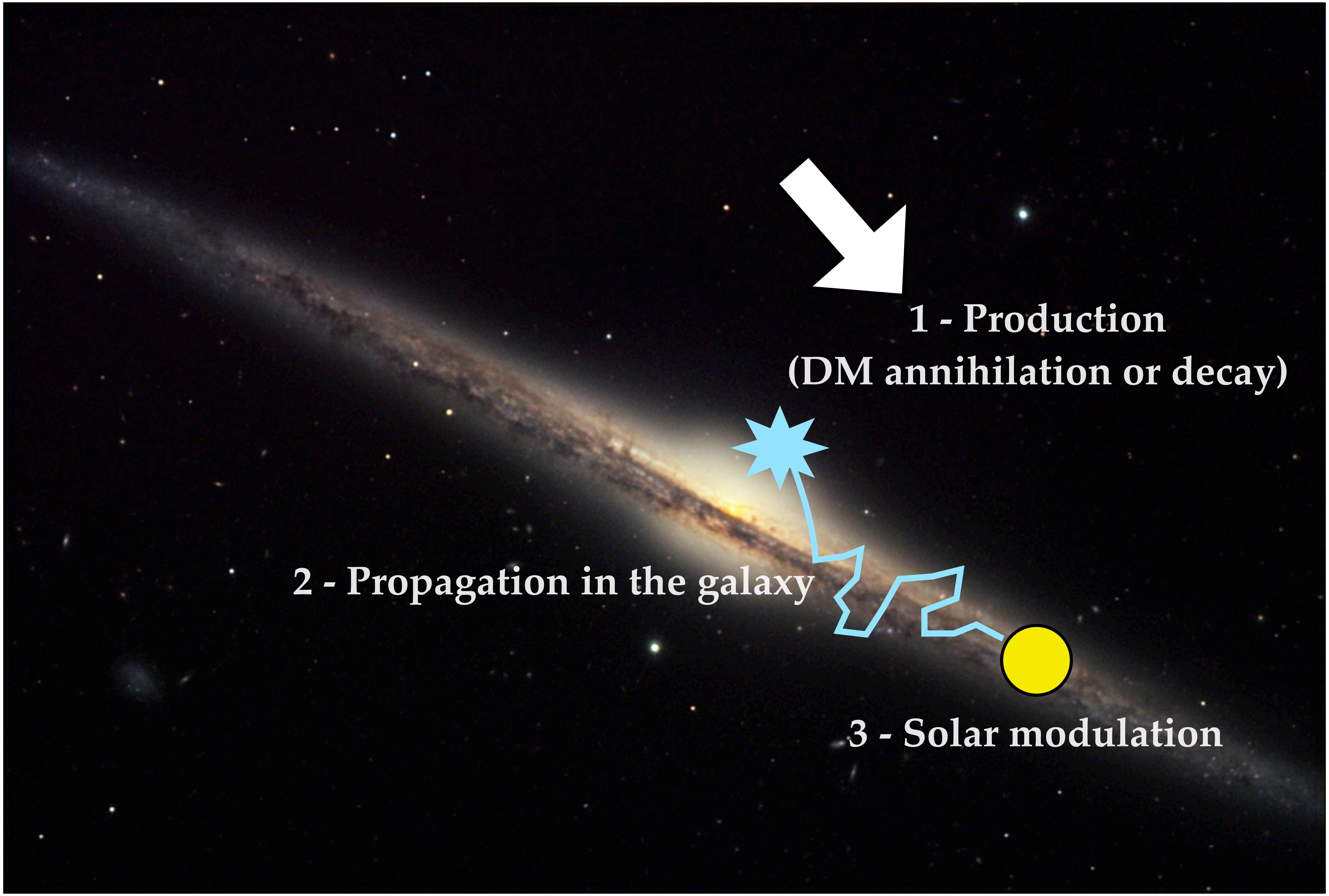
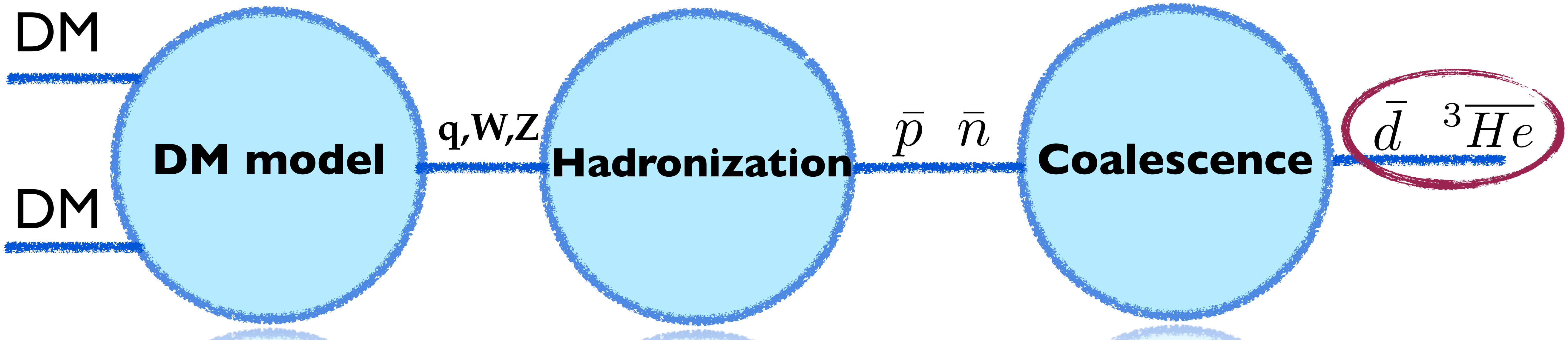


The production



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

Hadronization is modeled with a MC event generator (Pythia)

To build the anti-nuclei spectra we need to understand **how two or three anti-nucleons can merge**

What can we say about coalescence?

The coalescence puzzle

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?

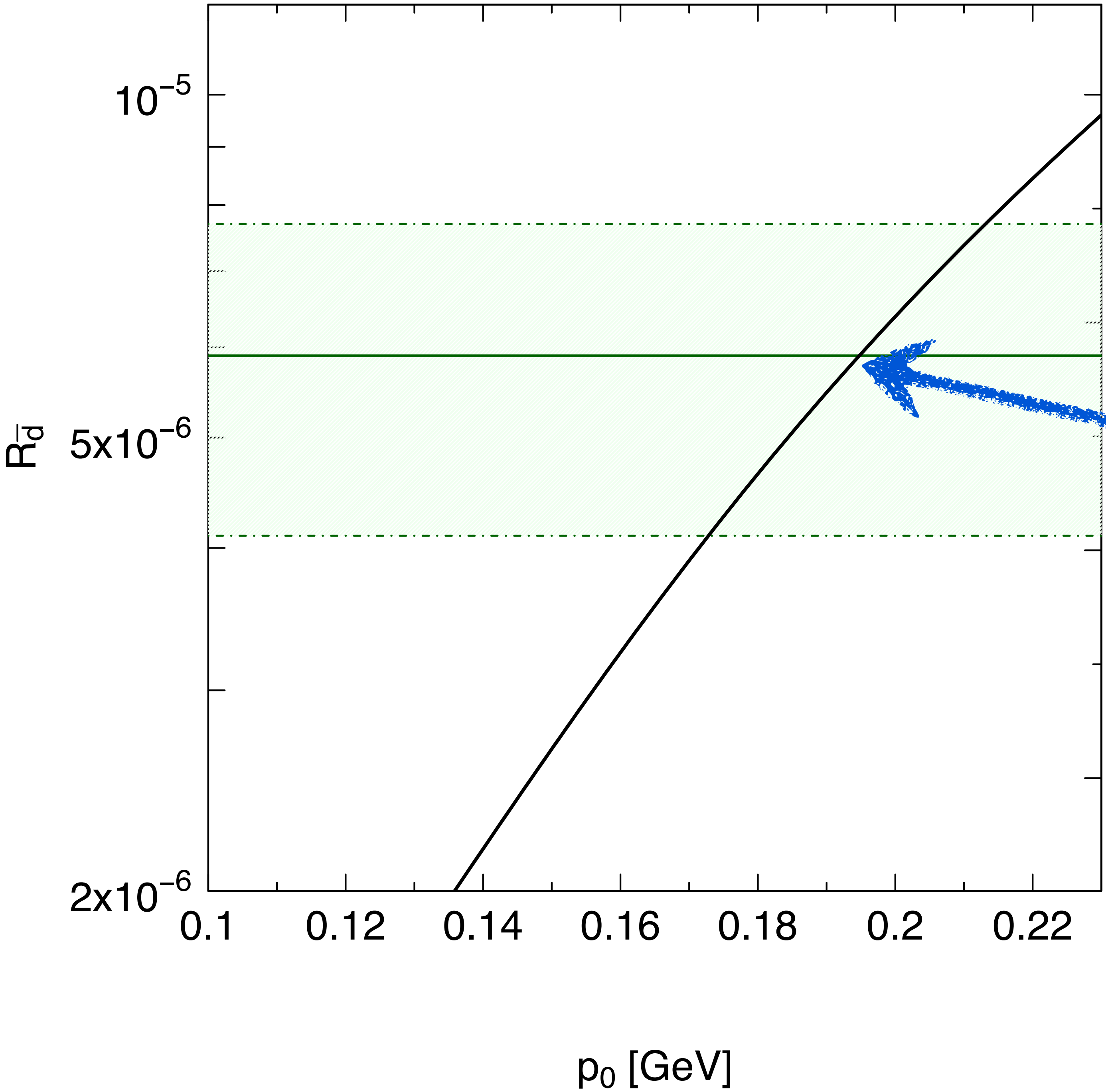
We take $r_0 \approx 2 \text{ fm}$ (radius of the anti-deuteron)

(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 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

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

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

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

The 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)

Some issues of the coalescence model

- The tuning of the coalescence momentum is based only on **one data point** (for the anti-deuteron), but the dependence of the model from p_0 is strong.

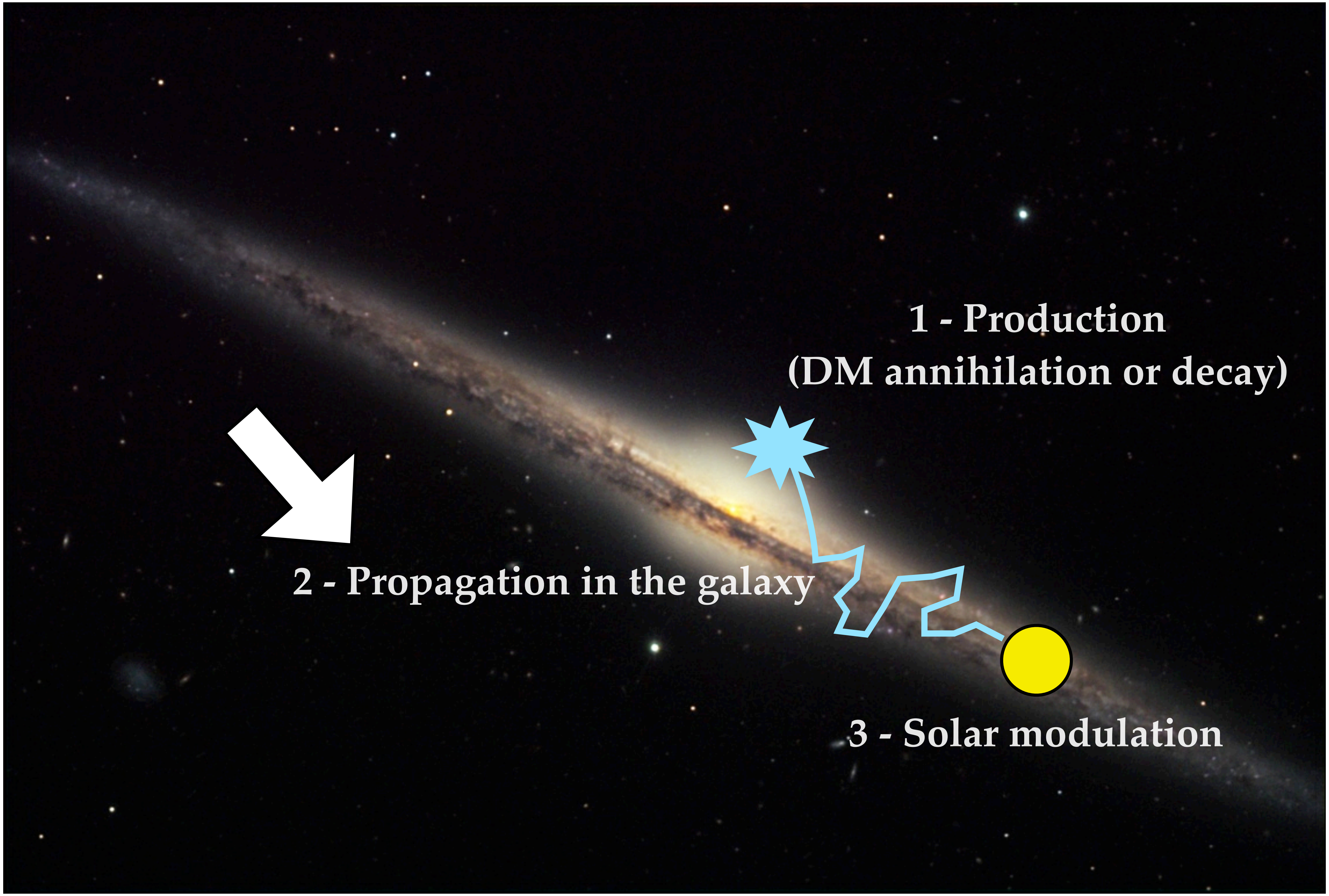
We cannot study any possible dependence on the energy of the process (i.e. a single p_0 for any DM mass is probably an oversimplification)

- MC event generators are usually not tuned to reproduce two (or three) particles correlations in phase space. If we want to build a coalescence model that works for every kind of reaction (DM annihilations and spallation reactions for the background) also **the hadronization parameters** of the event generator should be tuned together with p_0

Dal, Kachelriess Phys.Rev. D86 (2012) 103536
Dal, Raklev Phys.Rev. D89 (2014) 103504

In any case, the impact of any refinement of the coalescence model will be limited by the scarcity of available experimental data

From the Source to the Earth



Galactic propagation

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

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

diffusion

convection

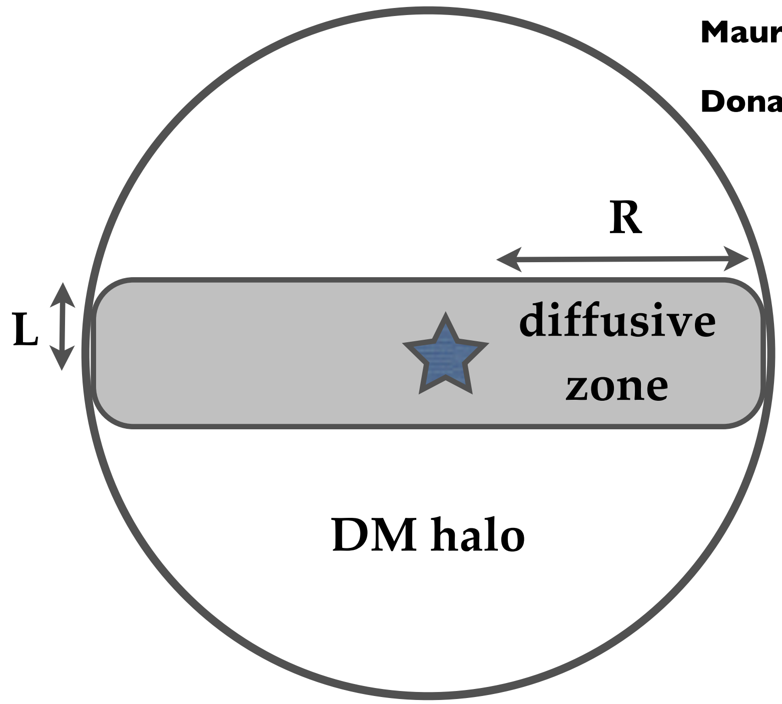
annihilation

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

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

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

CAVEAT: no energy losses and no reacceleration!

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

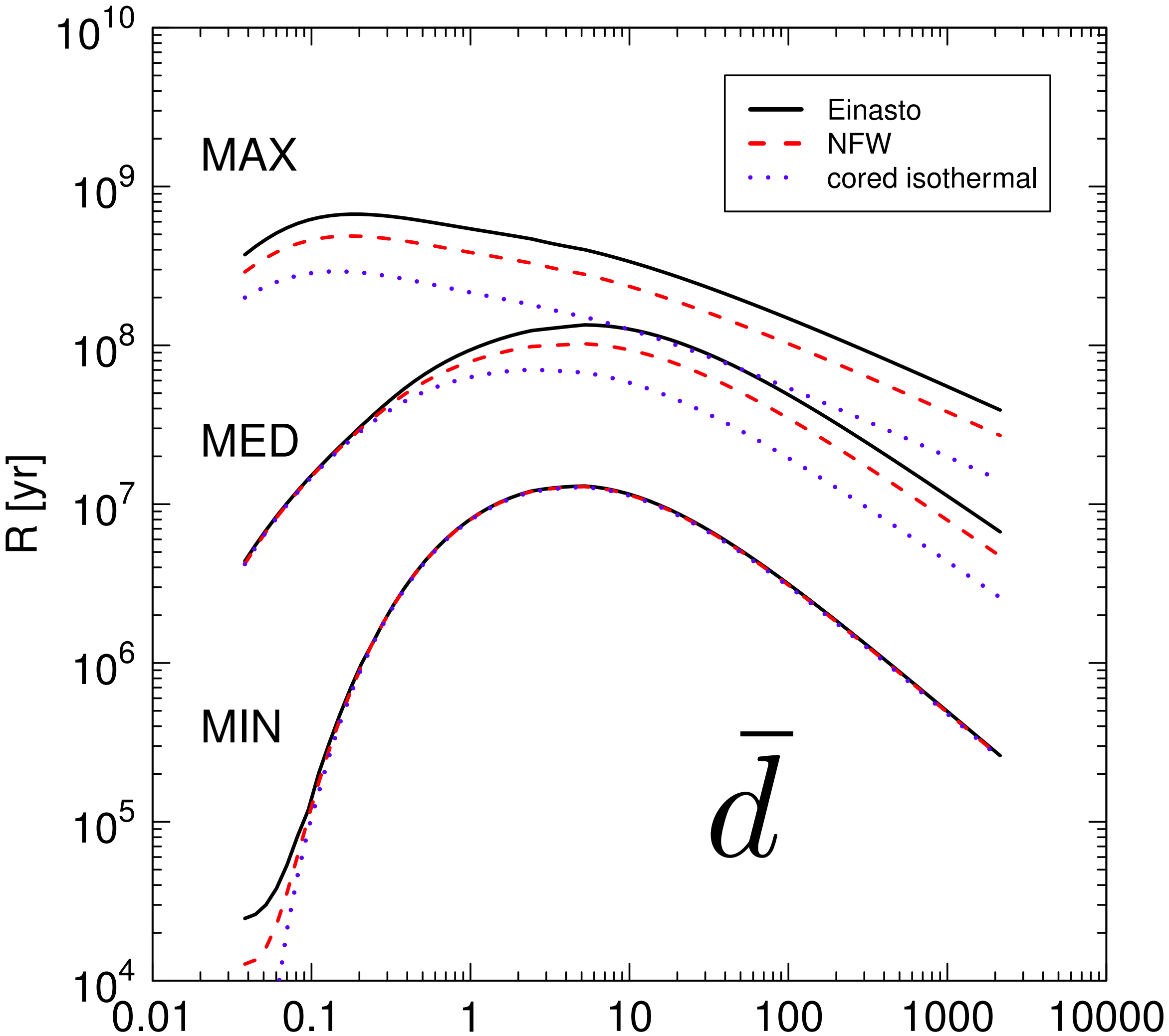
$$\phi(E) = \frac{\beta}{4\pi} R(E) \times \frac{1}{2}\left(\frac{\rho_\odot}{m_{DM}}\right)^2 \frac{dN}{dE} < \sigma v >$$

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

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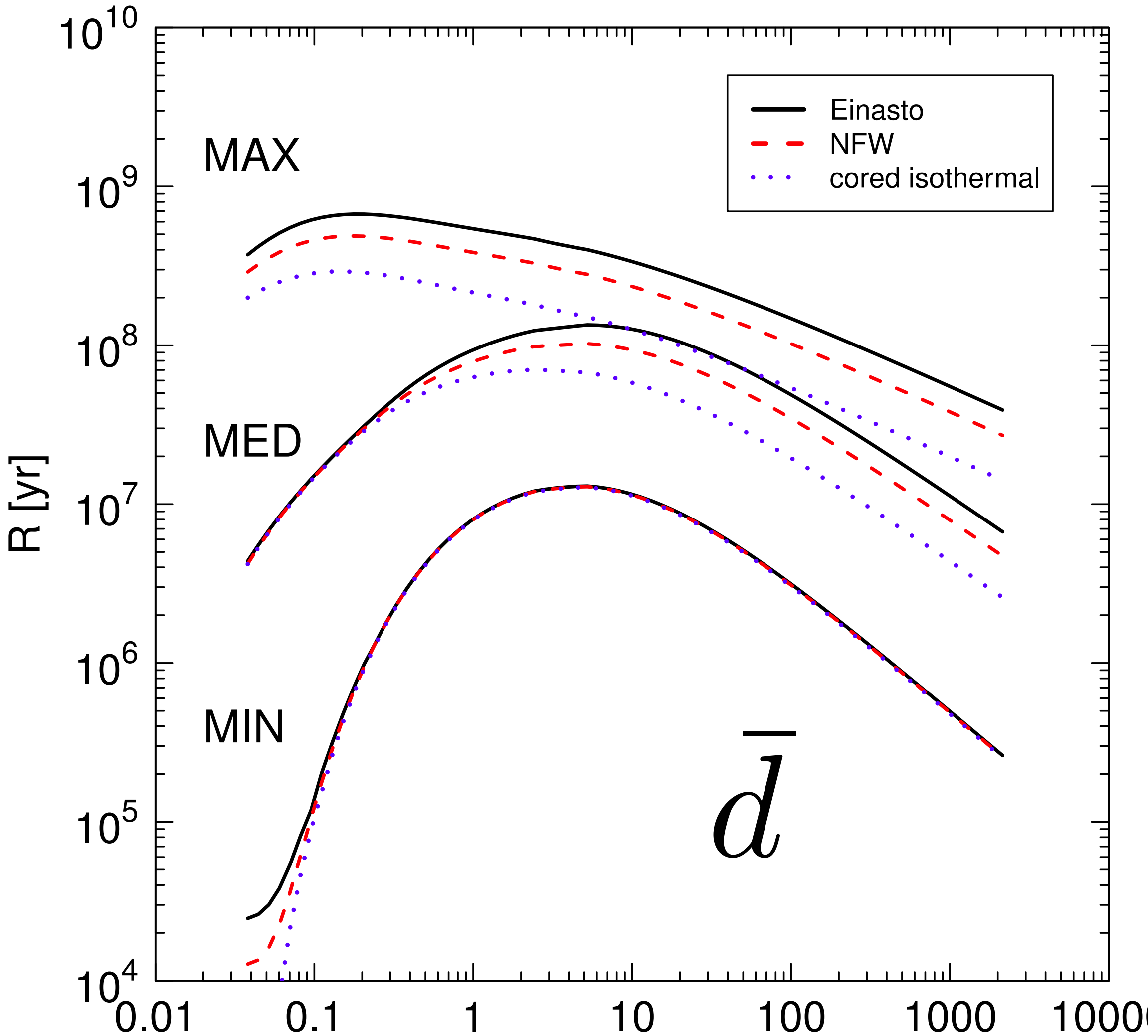
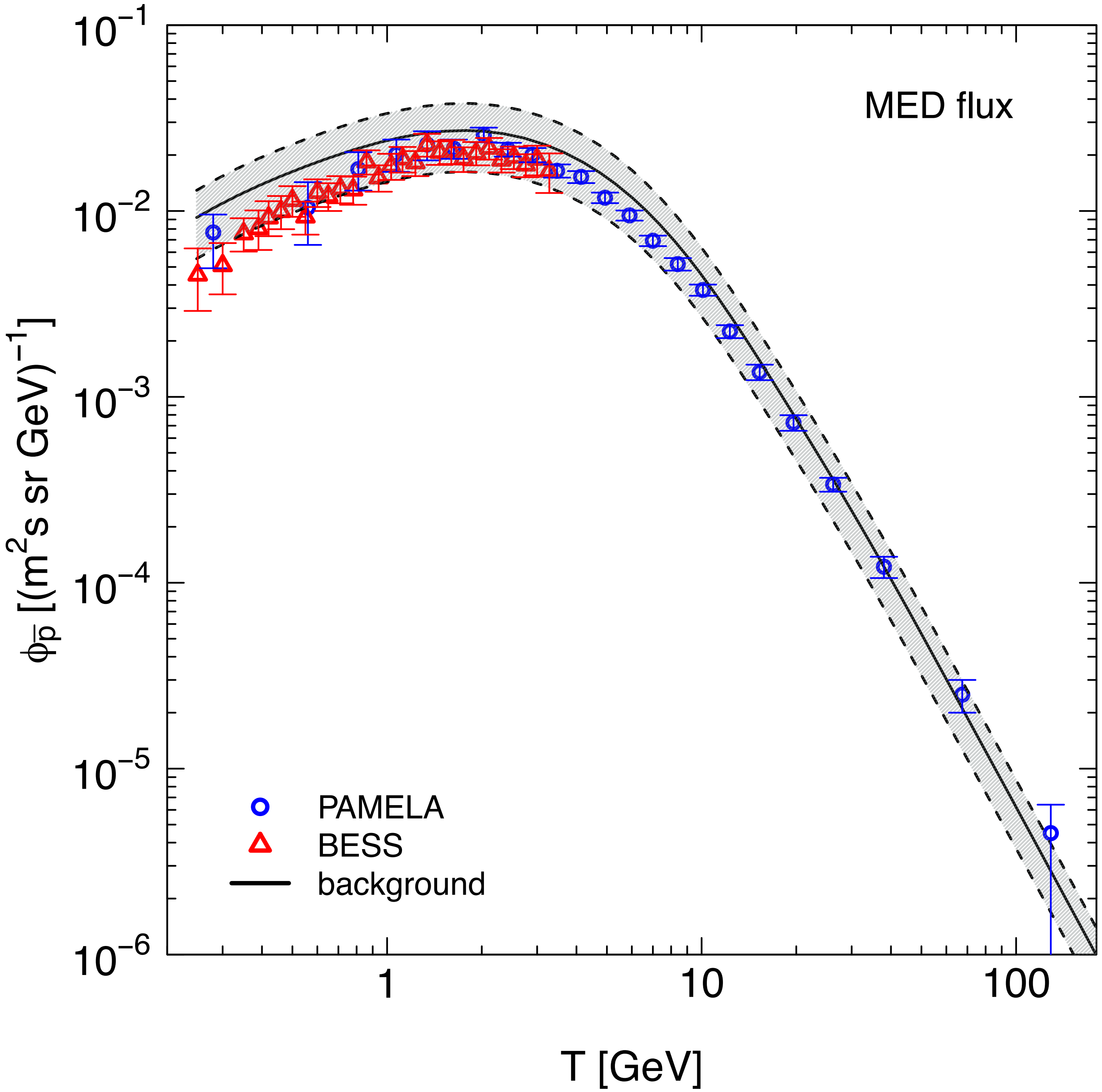


F.Donato, N.Fornengo, D.Maurin, P.Salati and R.Taillet
Phys.Rev.D 69 (2004) 063501

Antiproton bounds

Every reaction that produces anti-nuclei **also produces antiprotons**

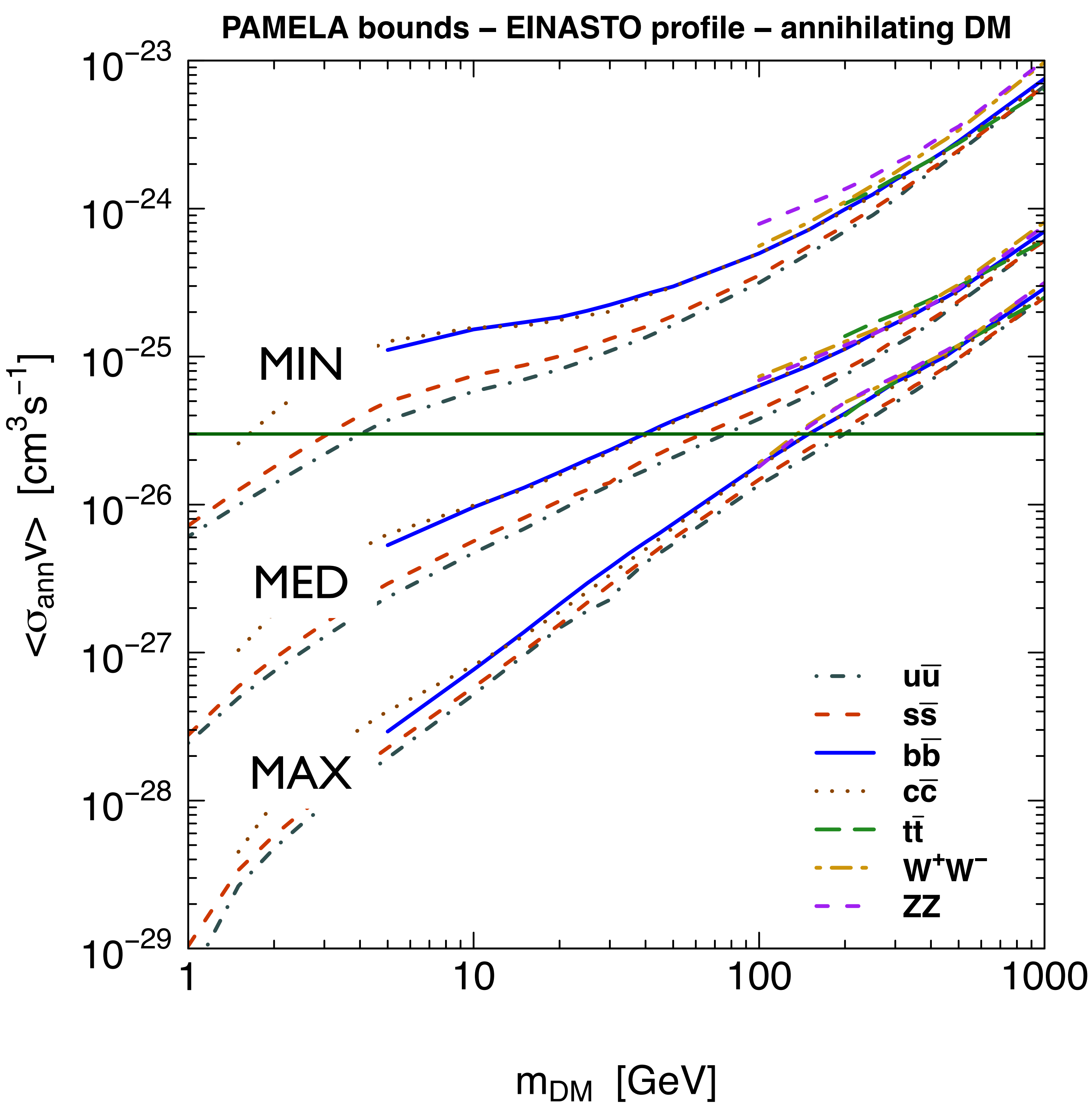


The antiproton flux measured by the PAMELA and BESS experiments appears to be very well fitted by a pure astrophysical background

Very little room left for dark matter!

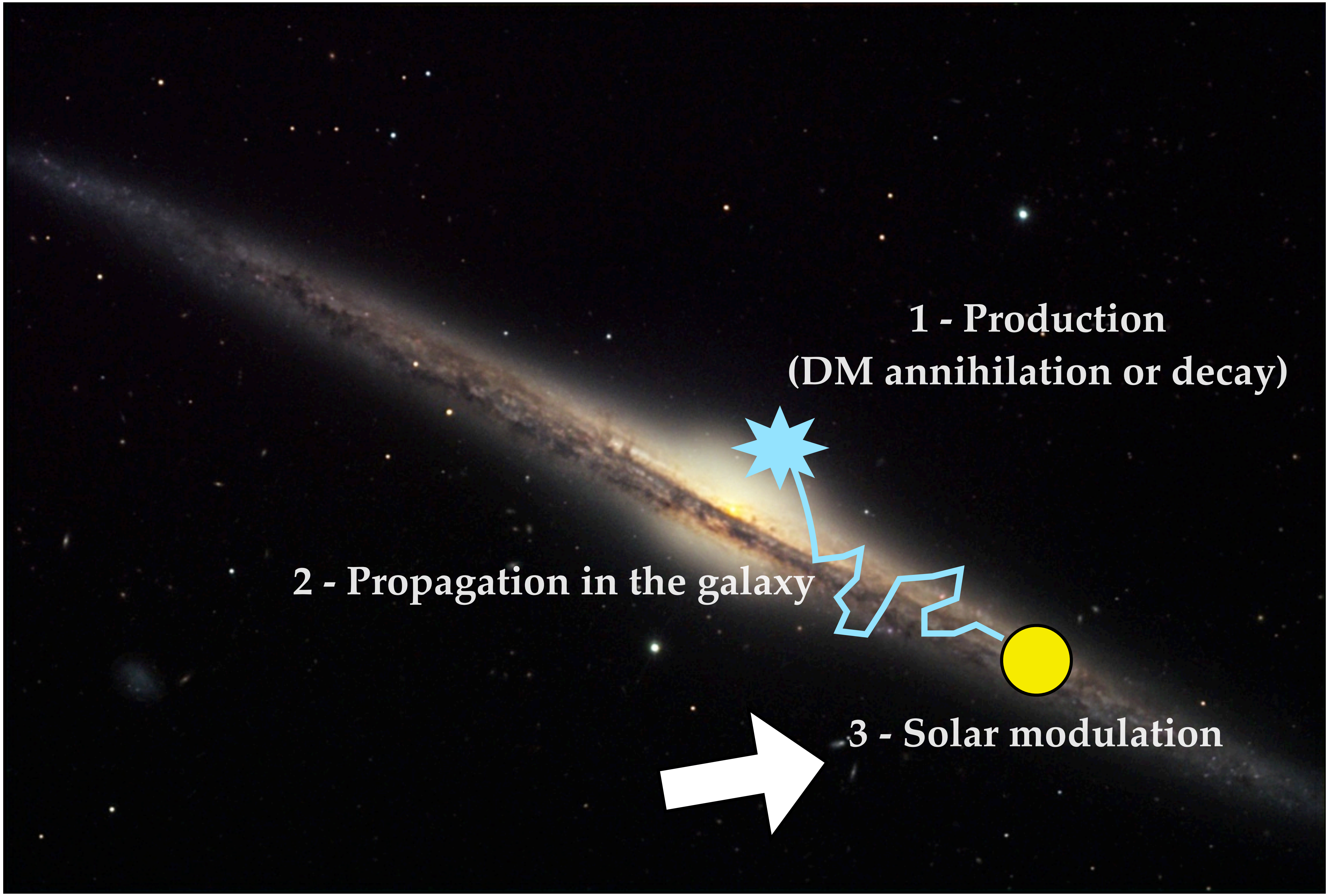
To compute the 3σ bounds on <σv> we associate to the background flux a **theoretical uncertainty of the 40%**

Antiproton bounds

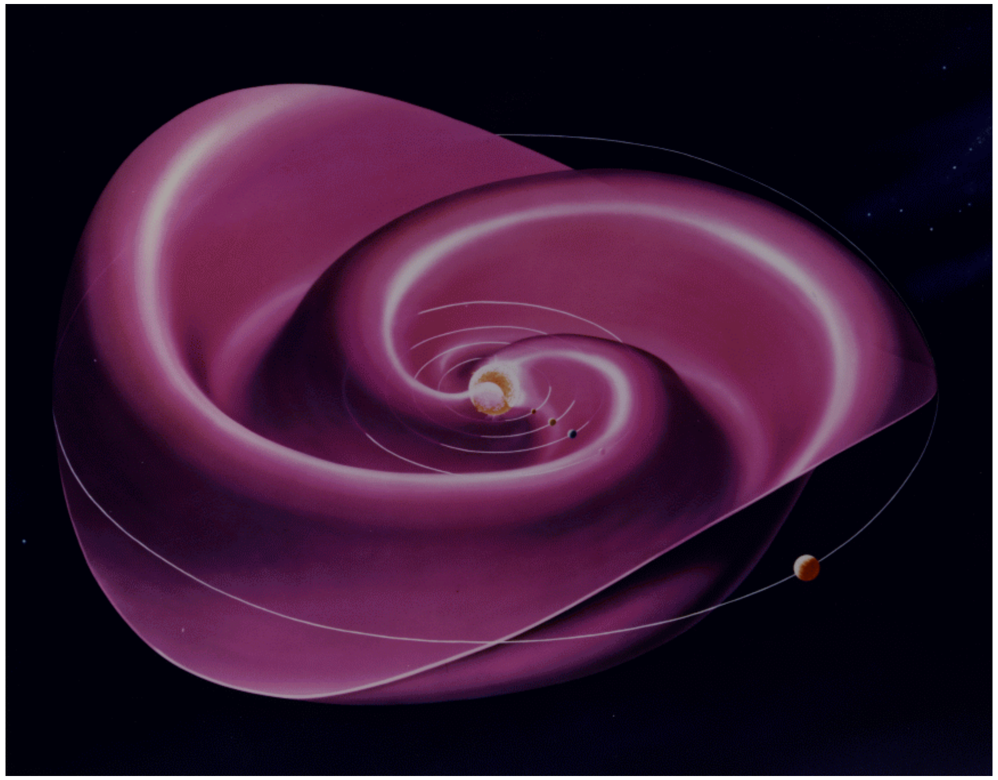


N.Fornengo, L.Maccione, A. Vittino, JCAP 04 (2014) 003

From the Source to the Earth



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)

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

Convection

Drifts

Diffusion
(random walk)

Adiabatic losses

We vary 2 parameters:

- The tilt angle α : it describes the spatial extent of the HCS. 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

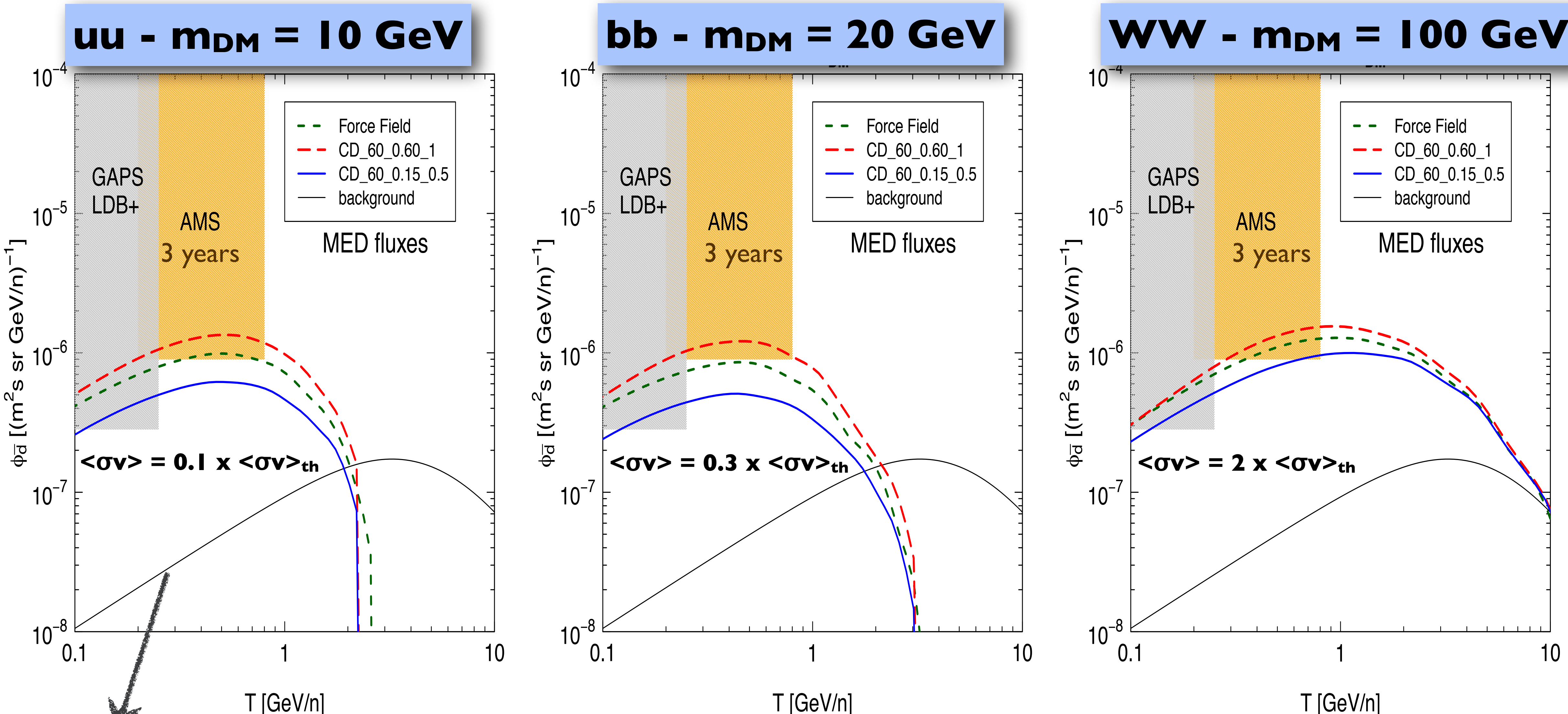
We exploit the code HELIOPROP to solve **numerically** the transport equation and explore the solar parameters space

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

Anti-deuteron fluxes at Earth

With the maximal cross sections allowed by antiprotons constraints:

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



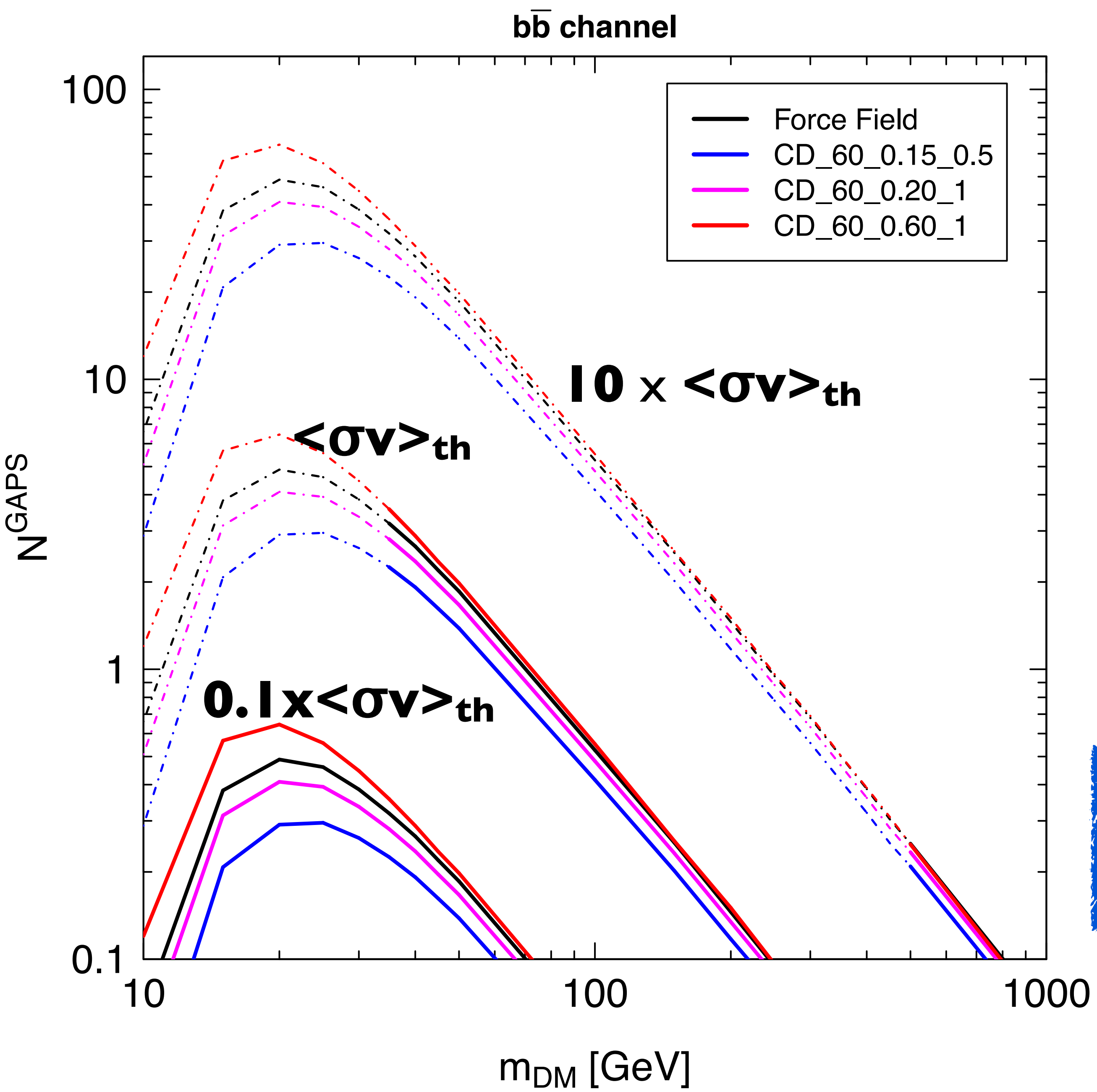
Background from **Fornengo, Maurin, Phys.Rev. D78 (2008) 043506** *

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

Number of events expected for the GAPS experiment (in the ultra-long duration setup), for a WIMP annihilating in the bb channel

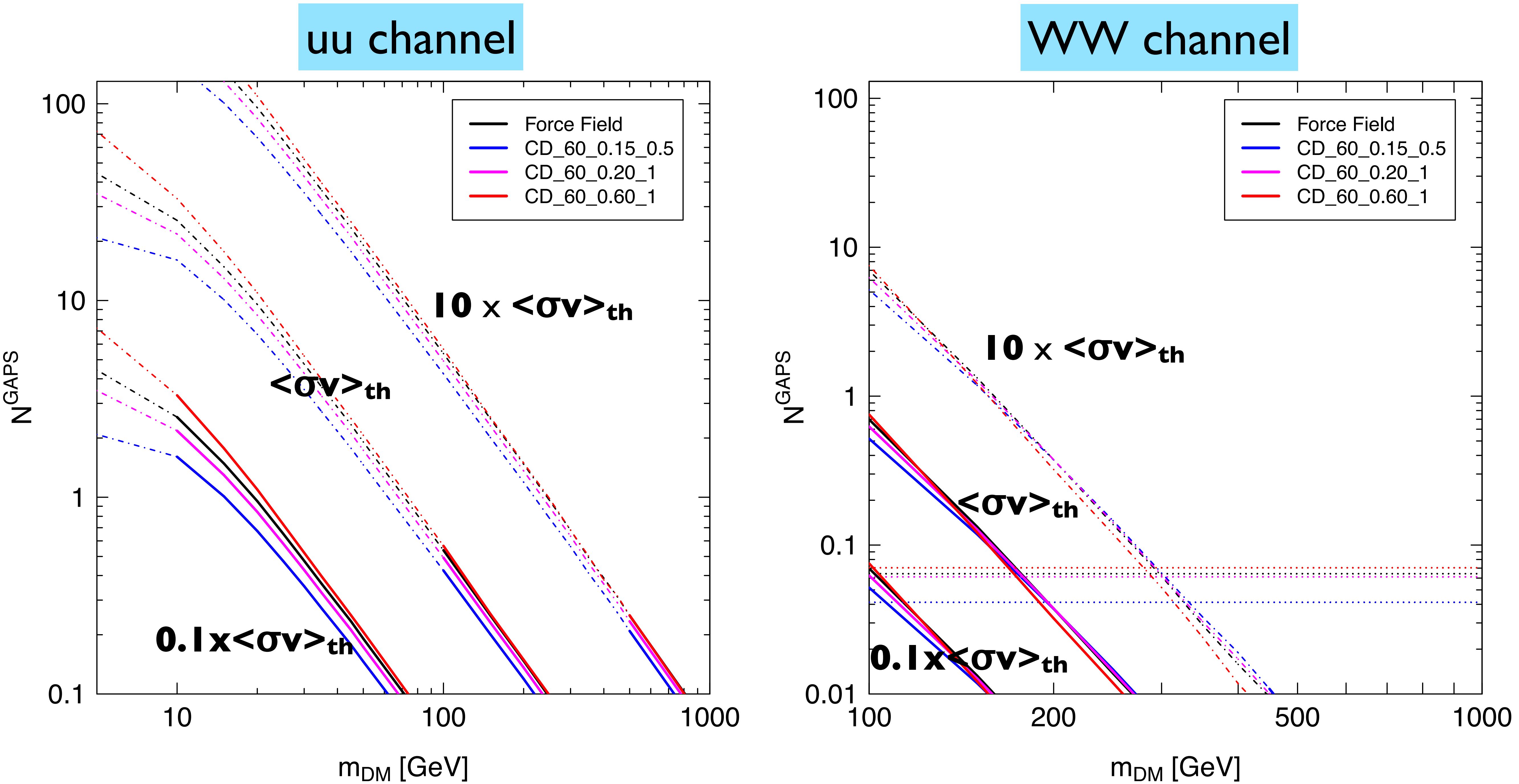


Solid lines: configurations compatible with PAMELA bounds

Dot-dashed lines: configurations not compatible with PAMELA bounds

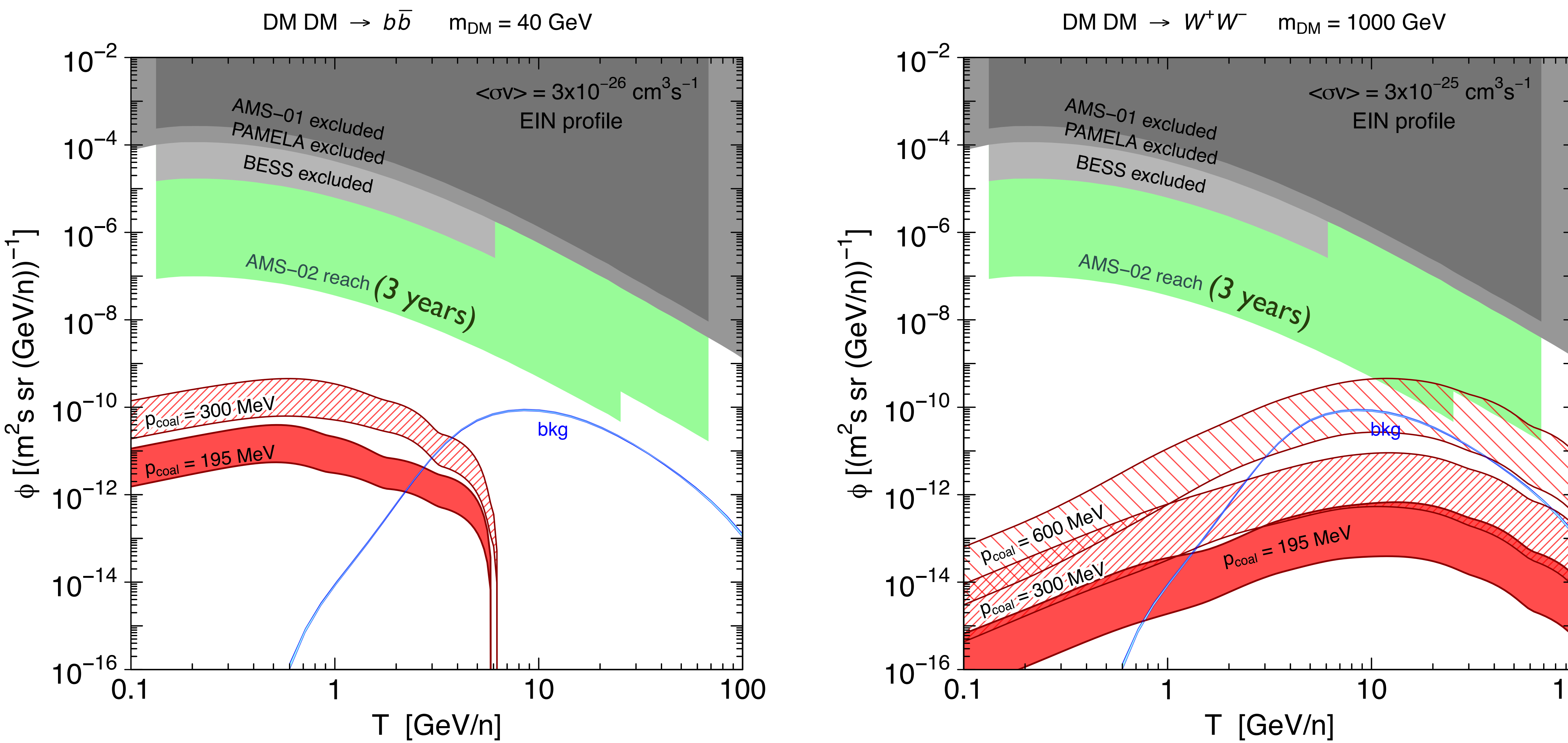
From 3 to 5 events depending on the solar modulation

Number of expected events



Anti-helium fluxes

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



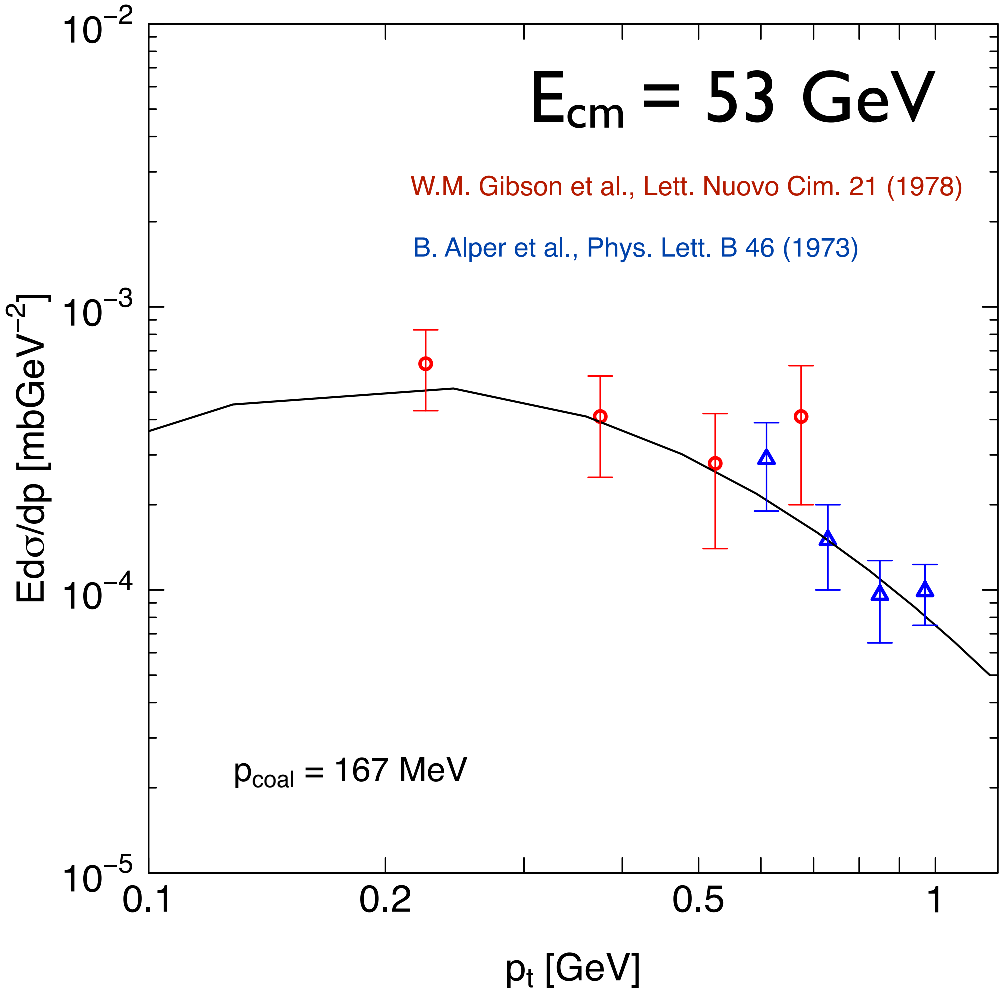
Prospects for detection are **rather weak**, unless the coalescence momentum is really large (~600 MeV)

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

The anti-helium background

The background anti-helium flux is the one produced by **spallation** of primary (and secondary) cosmic rays impinging on the interstellar medium. The source term associated to the **dominant** contribution (due to pp collisions) is:

$$Q_{\rm sec} = \int_{E_{\rm thr}}^{\infty} dE' \left(4\pi\, \phi_p(E')\right) \frac{d\sigma_{pp\to\overline{\rm He}+X}}{dE}(E,E')\; n_{\rm H}$$



we evaluate this source term with our event-by-event coalescence algorithm:

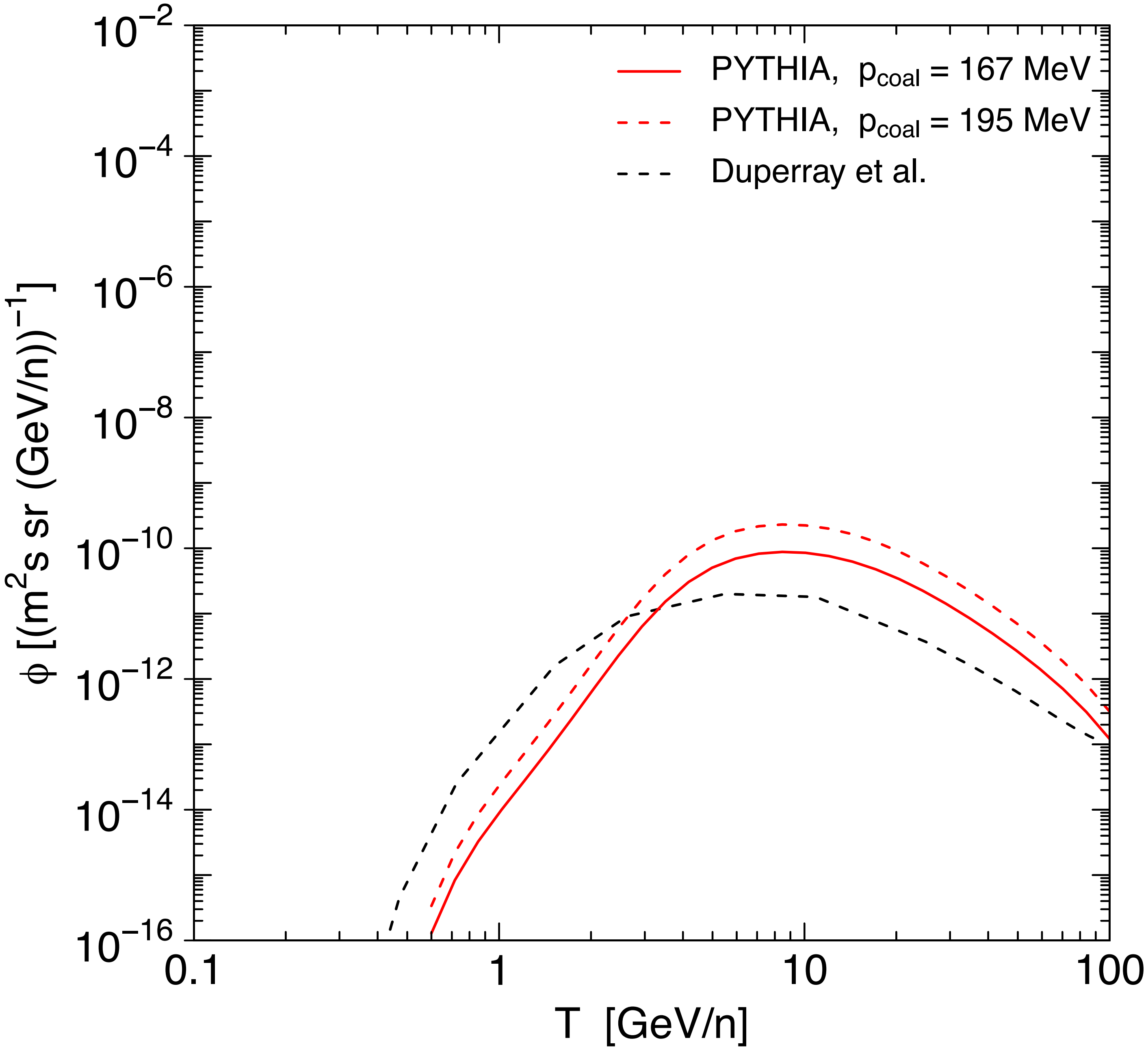
$$\frac{d\sigma_{pp\to\overline{\rm He}+X}}{dE}(E,E') = \sigma_{pp,{\rm tot}}(E,E')\,\frac{dn_{\overline{\rm He}}}{dE}(E,E')$$

consistently with the DM case, p_0 is tuned to reproduce the observed anti-deuteron flux measured in pp collisions (at the ISR experiment)

p_0 = 167 MeV

The anti-helium background

We compare our background flux with the one computed in
Duperray et al. Phys.Rev. D71 2005



They have a simpler coalescence model
but
They compute the background by taking into account also other contributions (pHe, HeHe collisions, etc...) and they have a more detailed treatment of the galactic propagation

Conclusions

- ★ Anti-nuclei can be considered a powerful tool that can help us to shed some light on the DM mystery.
- ★ Despite the strong bounds that we can derive from the antiproton measurements, an anti-deuteron signal can be on the reach of current and future experiments.
- ★ To detect an imprint of DM in the anti-helium channel a much larger sensitivity (a dedicated innovative experiment?) is needed.

Conclusions

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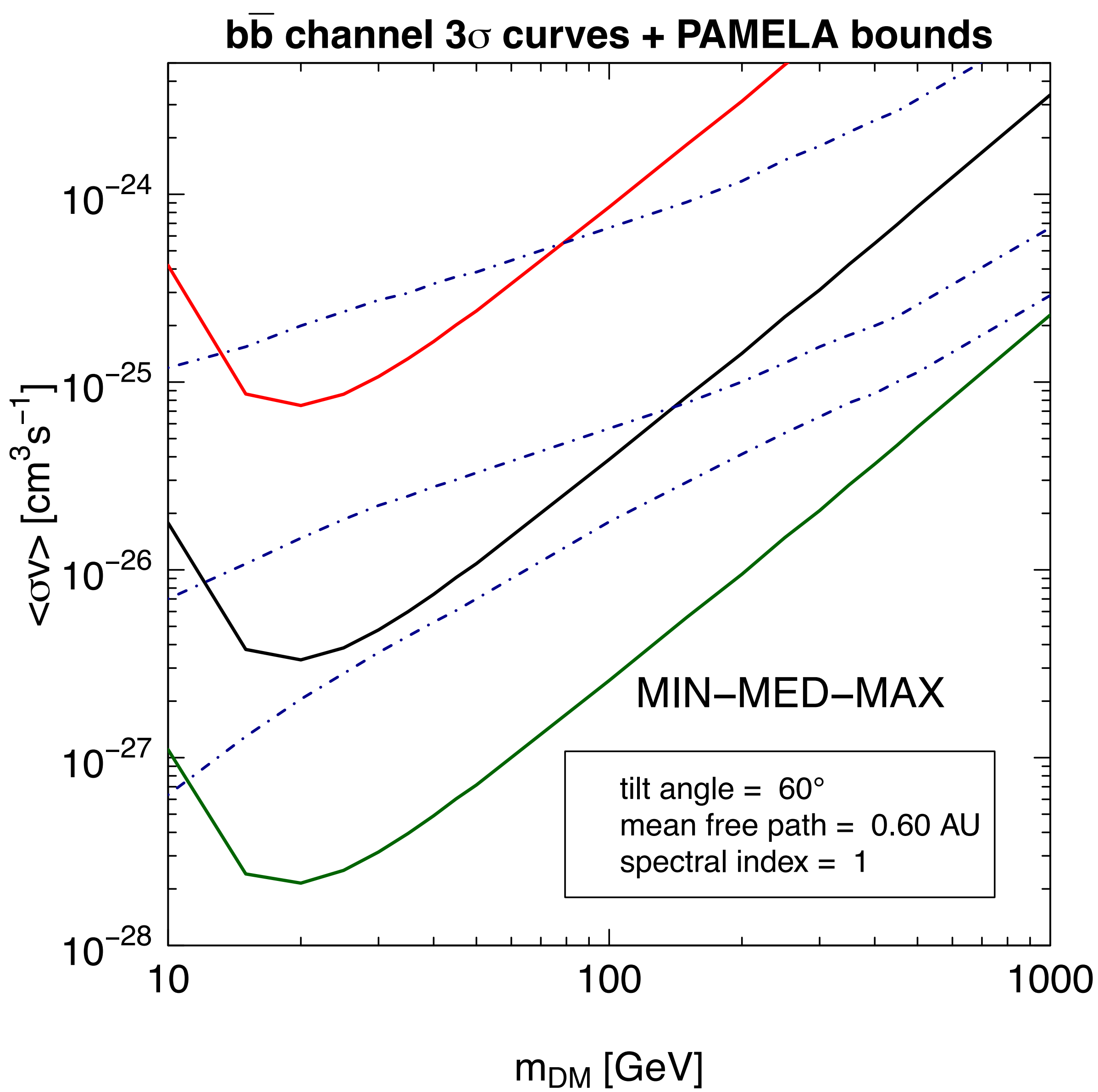
- ★ To detect an imprint of DM in the anti-helium channel a much larger sensitivity (a dedicated innovative experiment?) is needed.

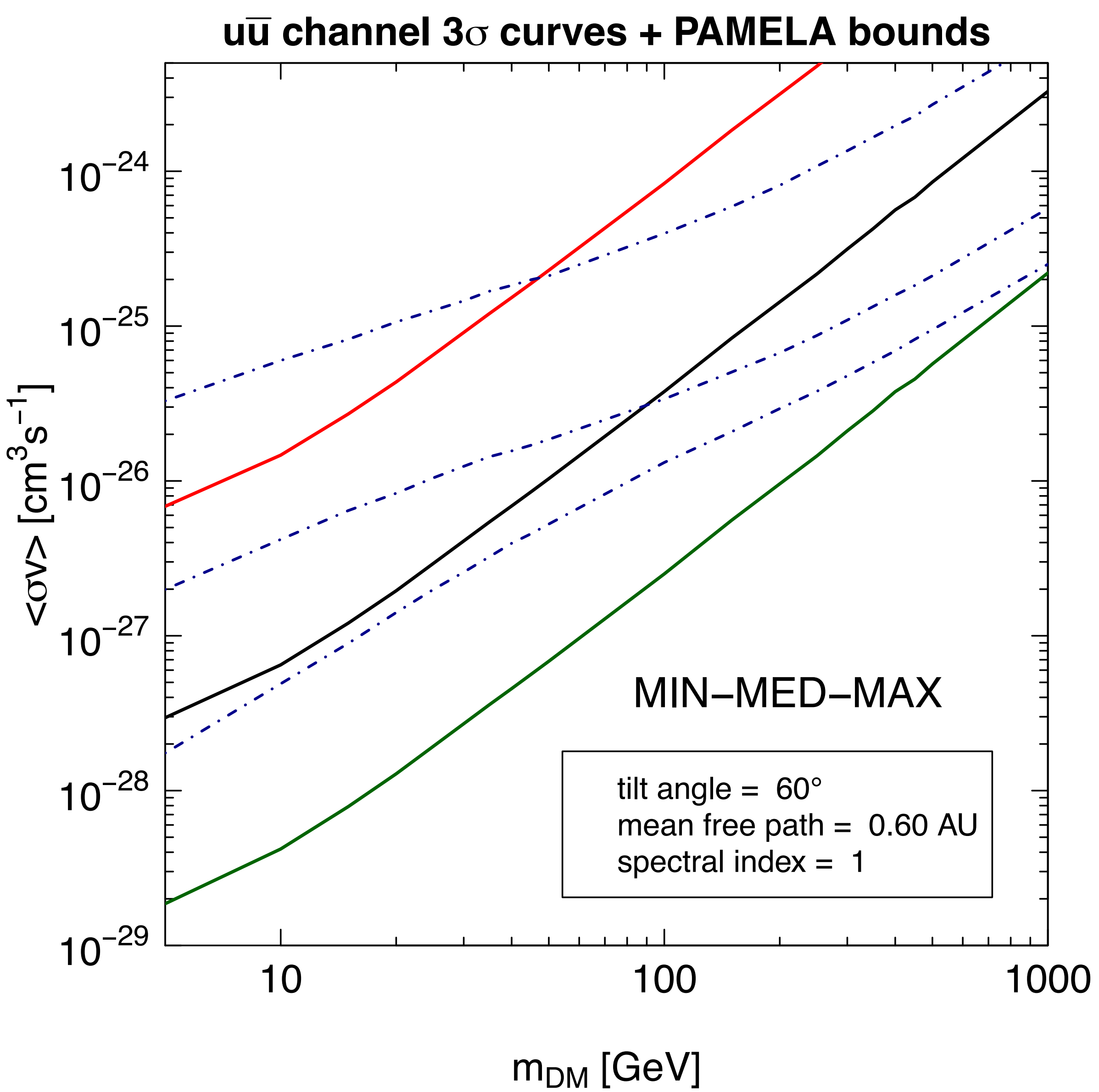
Thank you!

Extra slides

Experimental Reachability

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

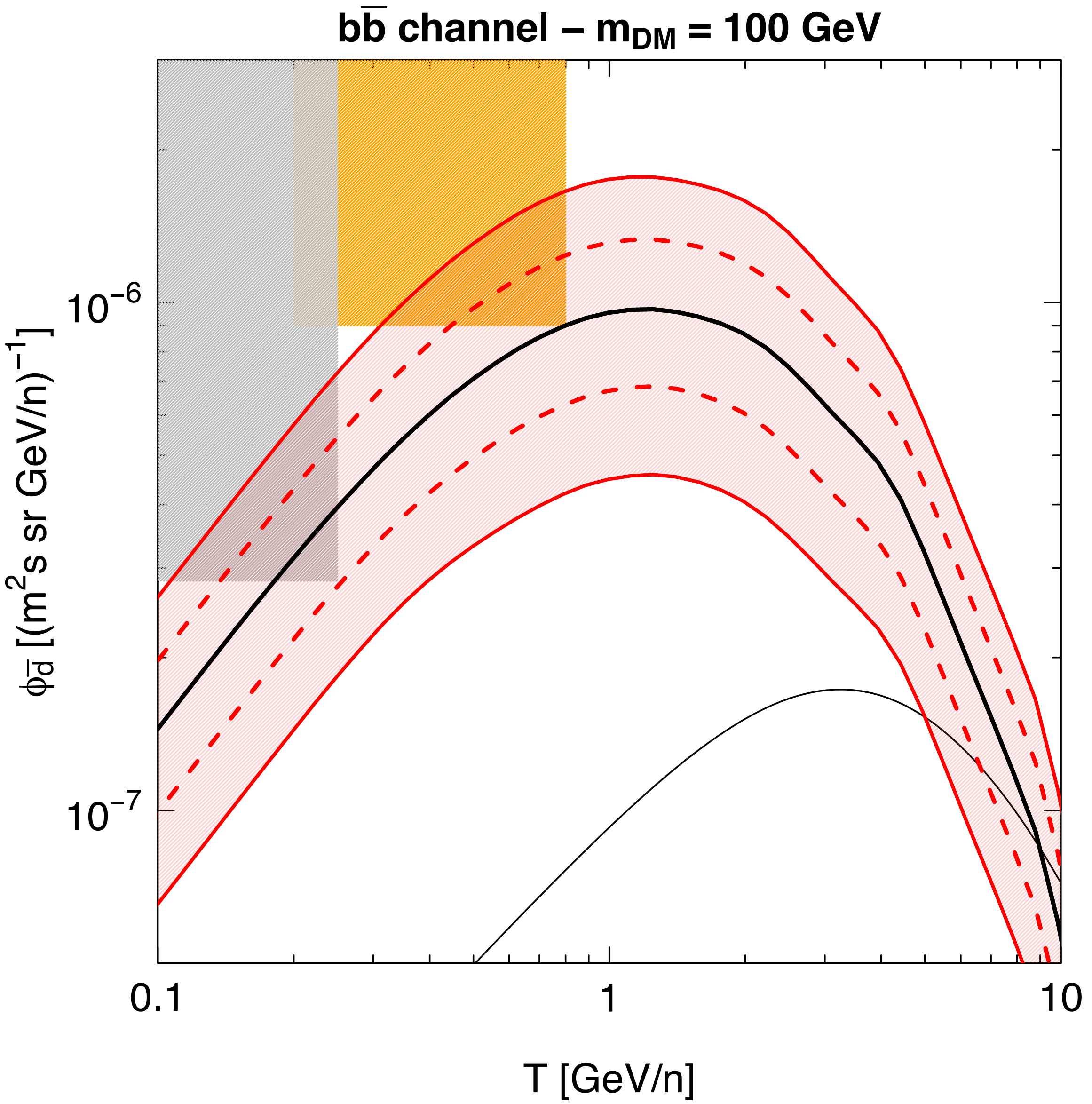


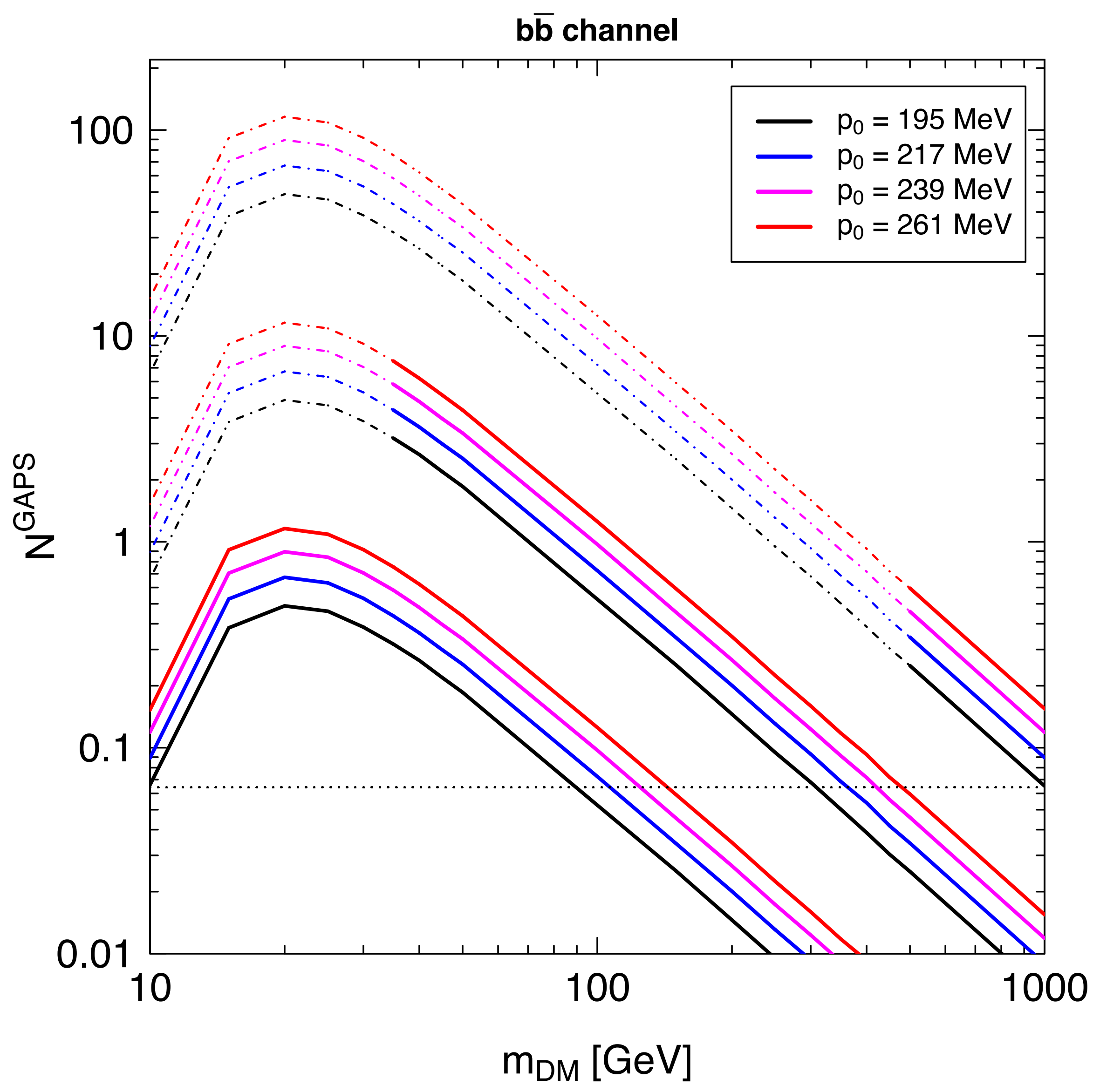


With anti-deuterons we can explore vast regions of the DM parameter space

Number of expected events

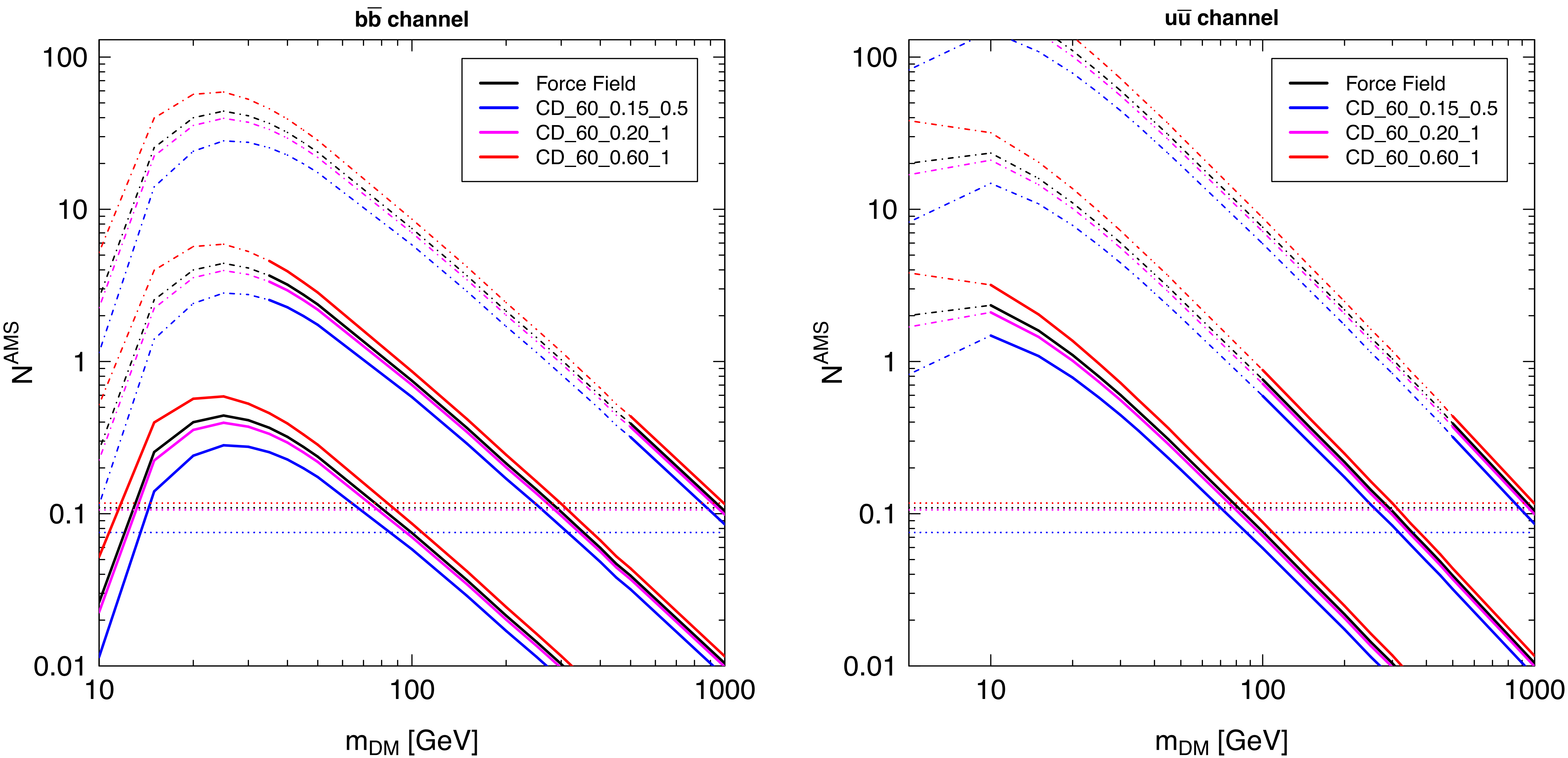
We can vary the coalescence momentum in the 3σ range compatible with the ALEPH measurement





The number of expected events doubles!

Number of expected events - AMS02



Antiprotons 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

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

$$\Delta\chi^2 = \chi^2_{dm+bkg} - \chi^2_{bg} < 10.21$$

$$\chi^2_{bg} \approx \chi^2_{best\ fit}$$

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

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

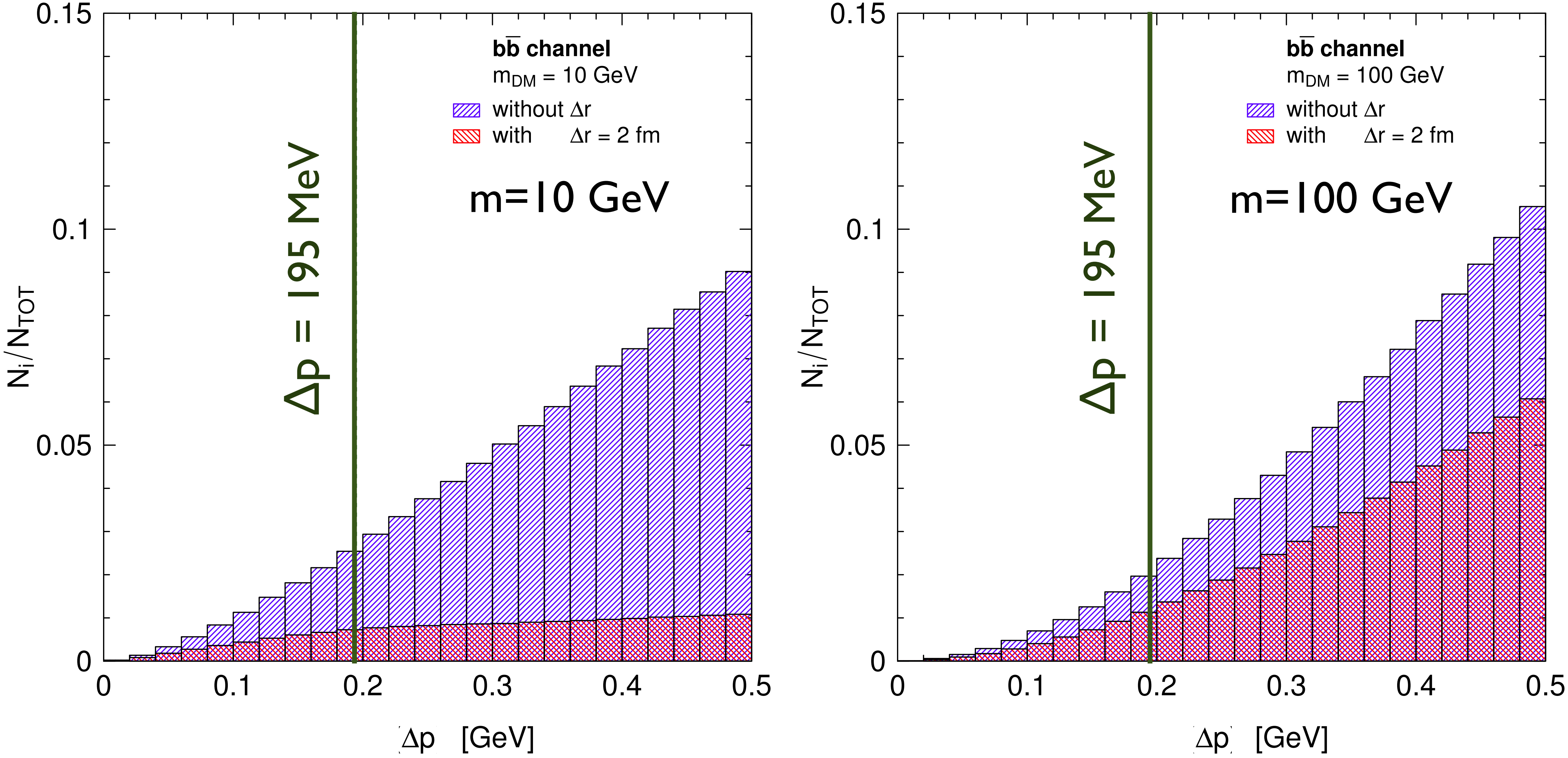
$\sigma^2_{i,theo}$: 40% of the background flux

10.21: 3 sigma confidence level (one sided distribution)

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

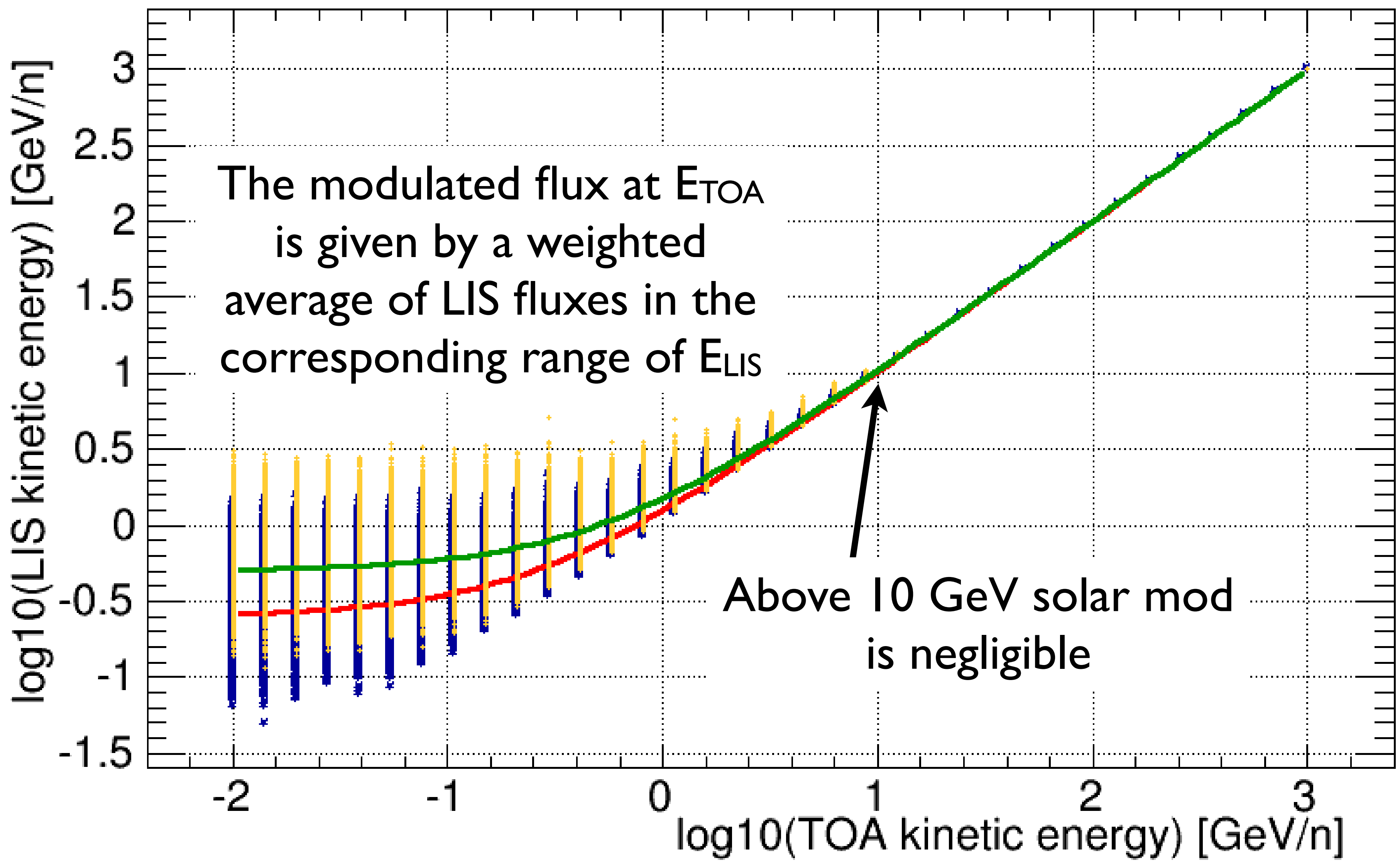
The Coalescence puzzle

What is the impact of the $\Delta r < 2$ fm condition?



Charge dependent solar modulation

In our sample, energy losses vary significantly from particle to particle (they depend on the path):



Solid lines ⟶ Force field approximation (pbar, dbar)

Dots ⟶ CD solar modulation (pbar, dbar)