based on **N.Fornengo, L.Maccione, AV, JCAP 09 2013**
T. Aramaki et al 1505.07785
J.Herms, A. Ibarra, AV, S. Wild, in preparation

Technische Universität München

Dark Matter searches with antideuterons

Andrea Vittino
Technische Universität München

28th Texas Symposium on Relativistic Astrophysics
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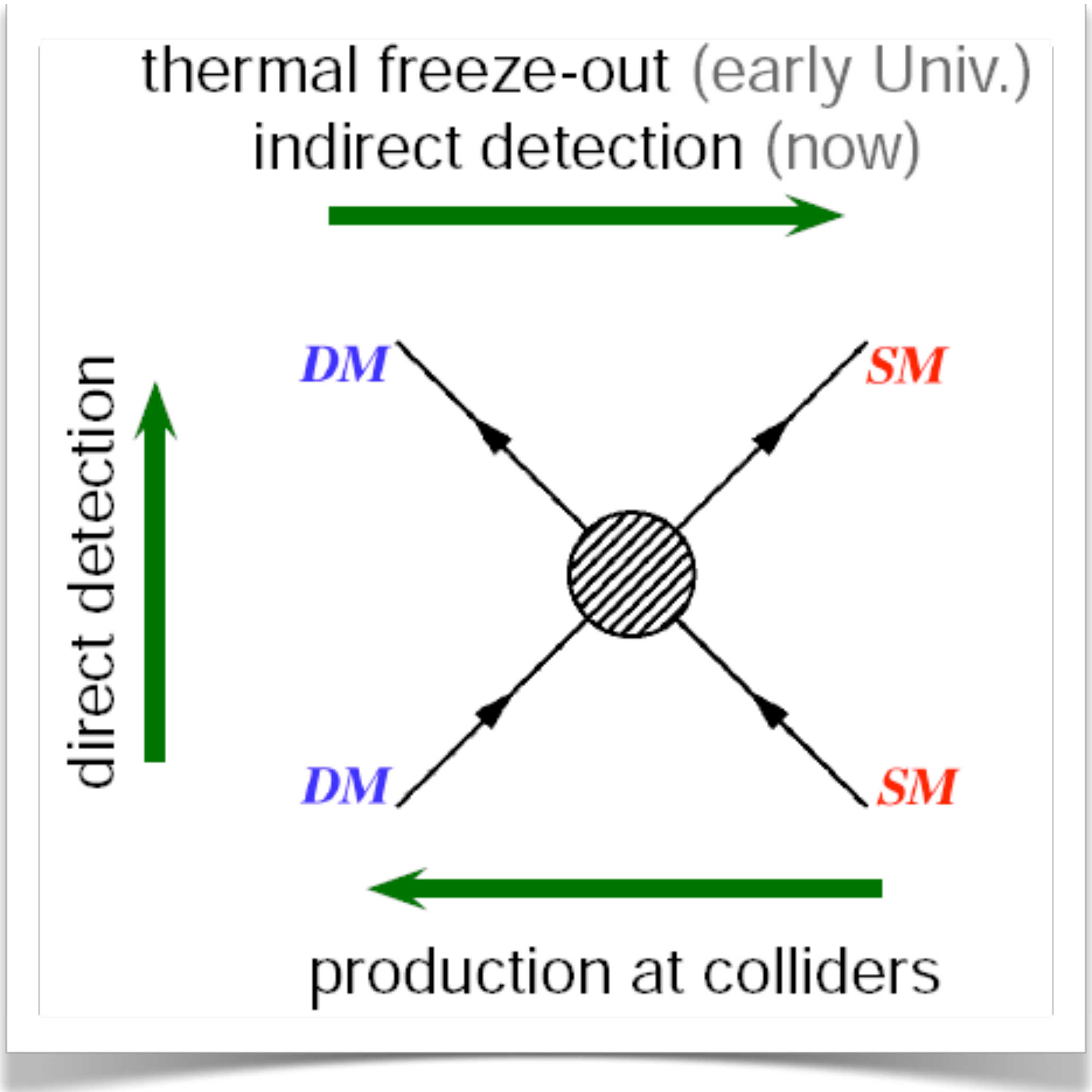
International Conference Center, Geneva

DM indirect detection with charged CRs



This talk will be about DM **indirect detection**, that is realized by looking for **SM (anti)particles** produced by DM annihilation/decay that can appear in the **CR flux**

Concerning **charged** CRs, we have **3 possible channels** for indirect detection :

- Antiprotons
- Positrons

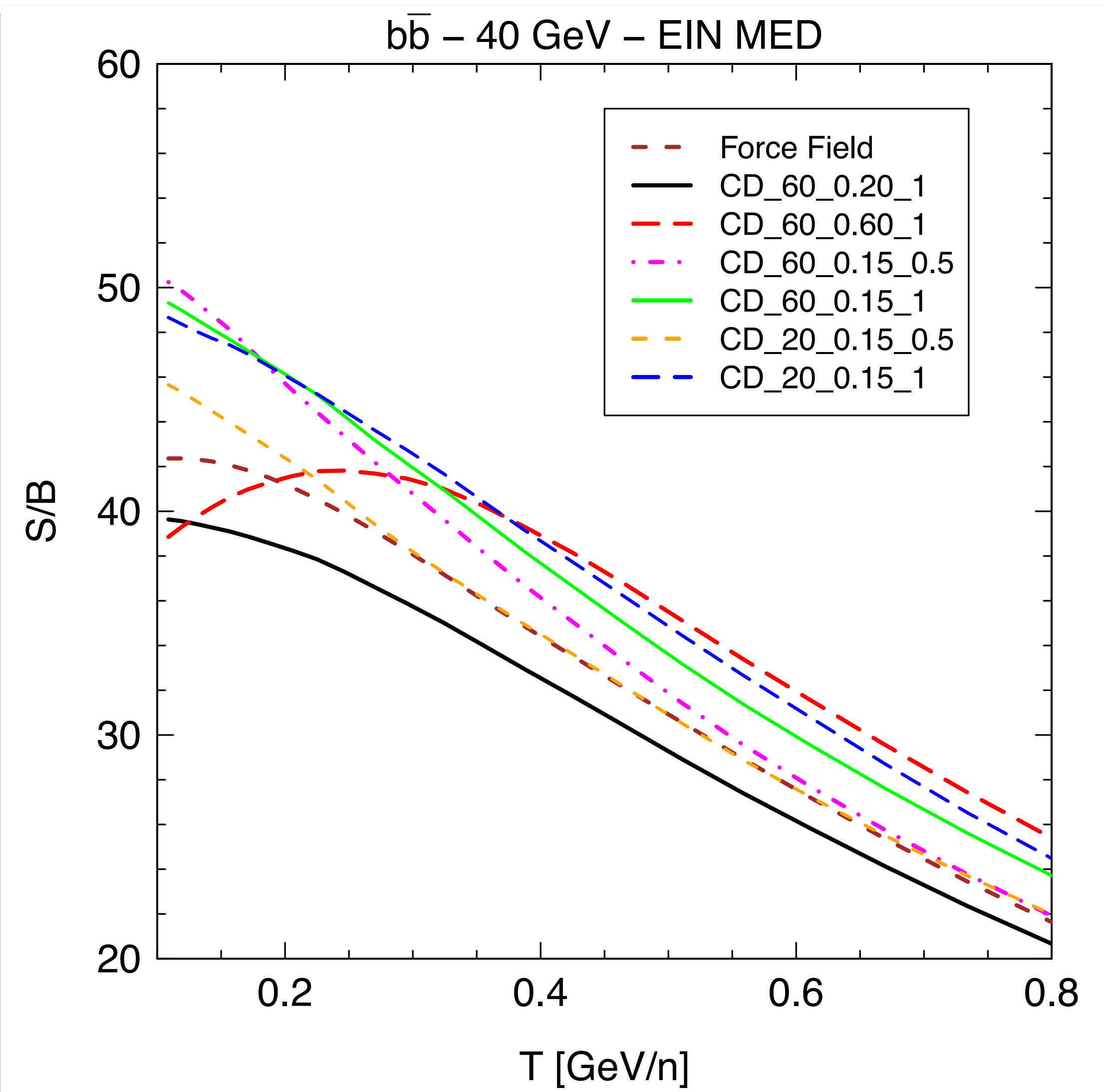
→ **Talk by M. Boudaud**

- Anti-nuclei (**antideuteron** and antiHelium)

Why (and when) should we choose antideuterons?

Why antideuterons?

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



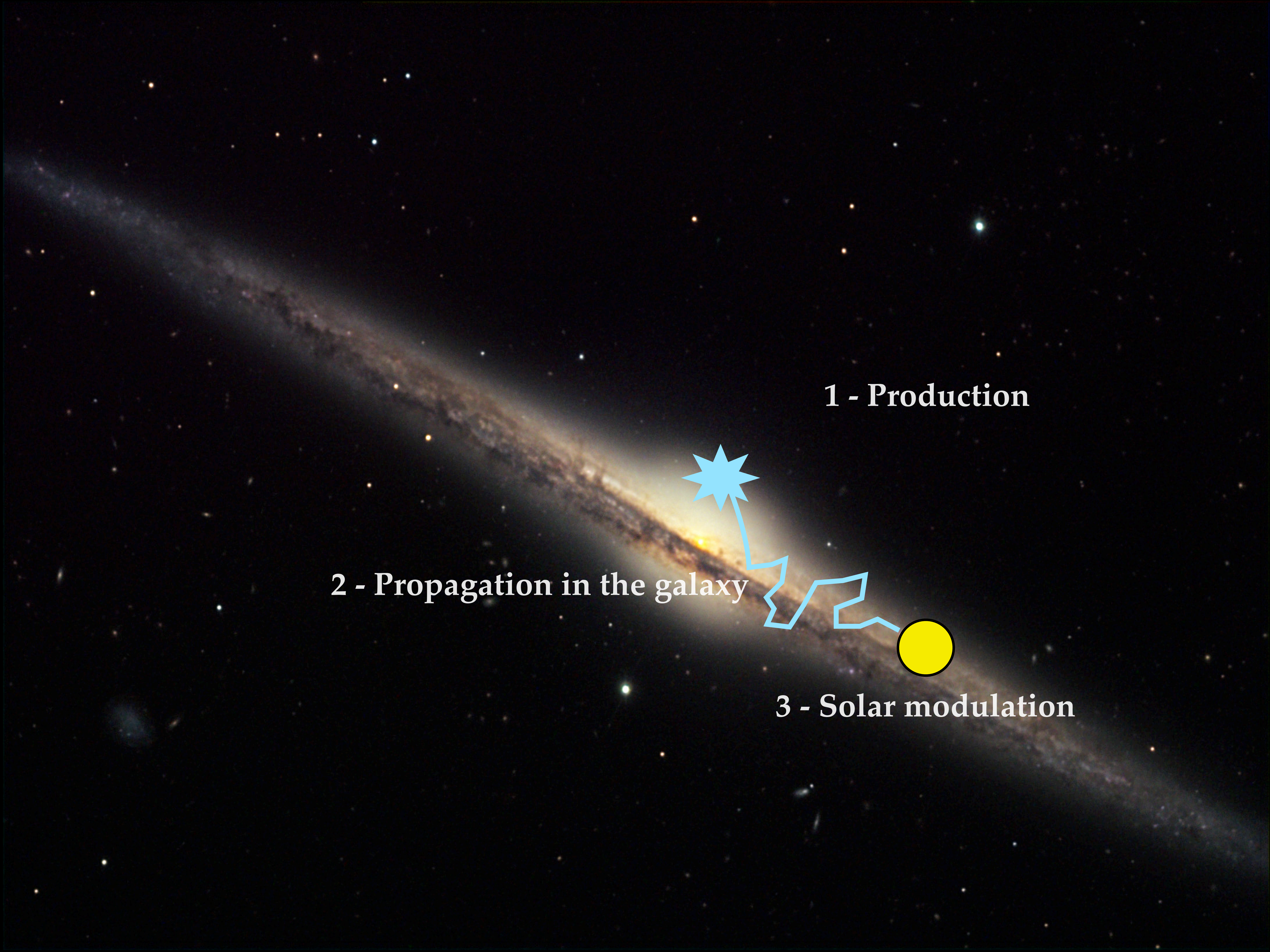
The **background flux is given by spallation** of cosmic ray particles over the interstellar medium

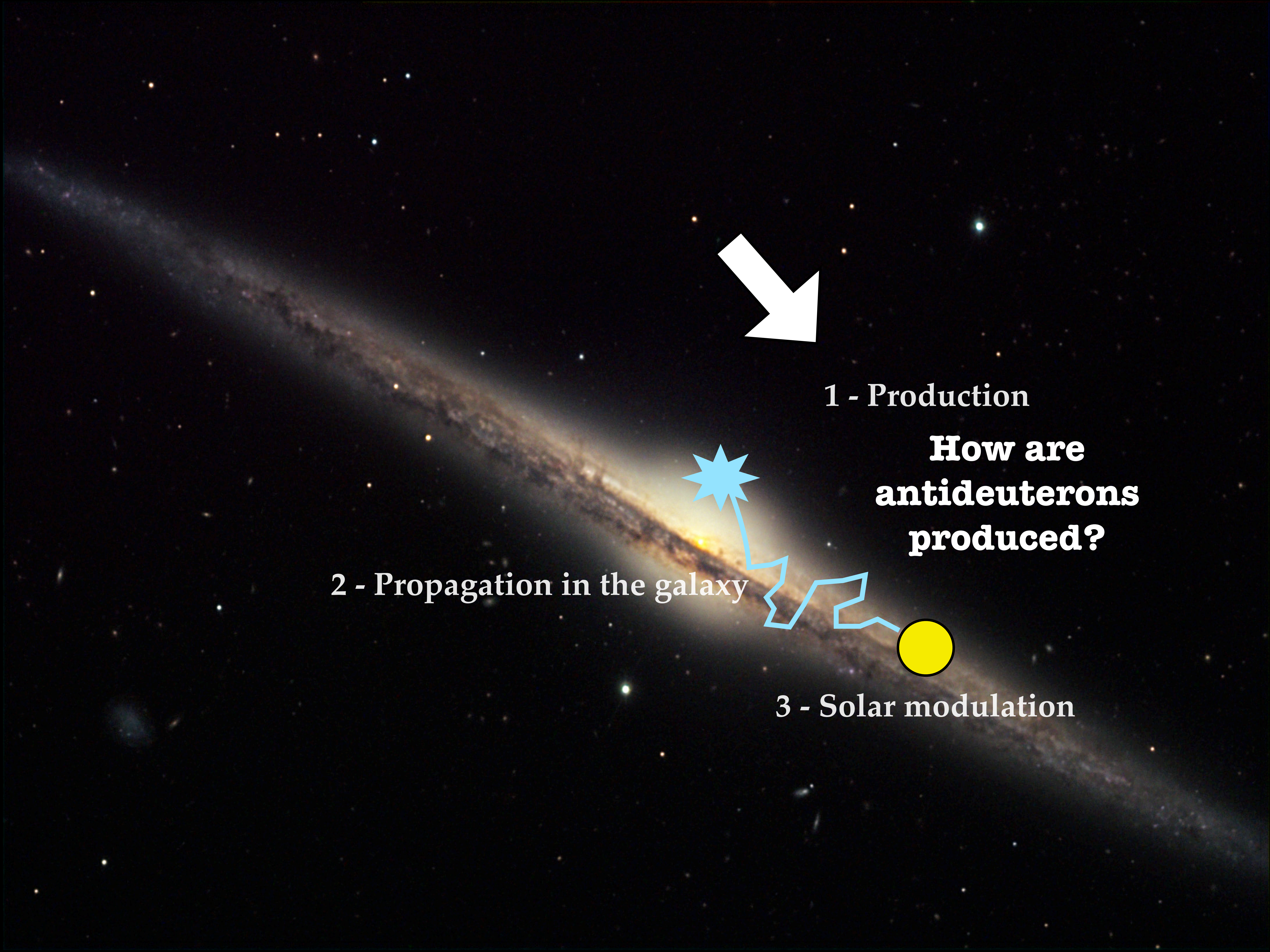
$$\begin{cases} p + p \rightarrow \bar{d} + X & E_{thr} = 17 m_p \\ p + p \rightarrow {}^3\overline{He} + X & E_{thr} = 31 m_p \end{cases}$$

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**

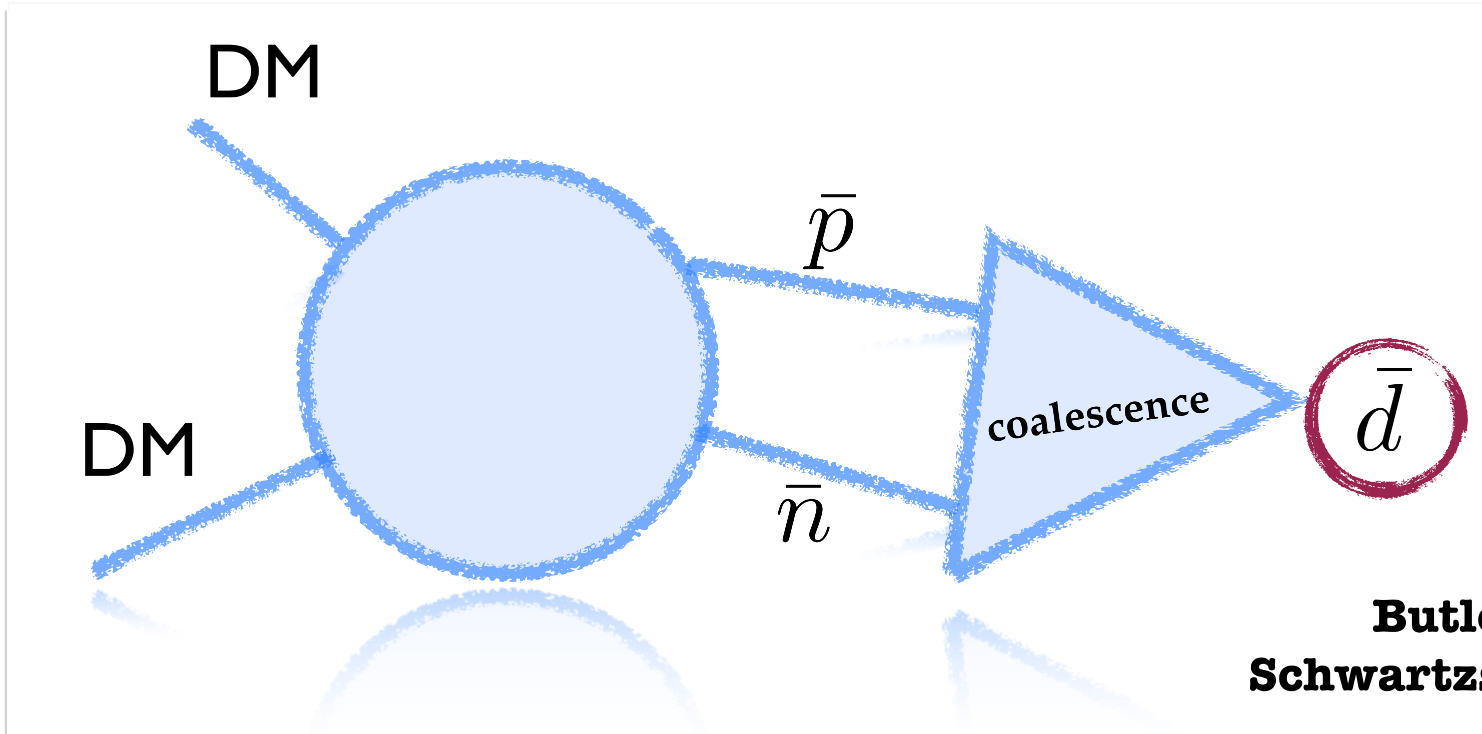
Donato, Fornengo, Salati, 2000


1 - Production
2 - Propagation in the galaxy
3 - Solar modulation


1 - Production
How are antideuterons produced?
2 - Propagation in the galaxy
3 - Solar modulation

Antideuteron production

An antideuteron is the result of the merging (**coalescence**) of a $\bar{\mathrm{p}}\bar{\mathrm{n}}$ pair



Butler and Pearson, 1961
Schwartzschild and Zupancic, 1963

A **simple idea**: the two antinucleons merge if they are **close enough** in the **phase space**

How is coalescence implemented in practice?

Antideuteron production

The spectrum can be written as:

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

$F_{(\bar{p}\bar{n})}$ 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**:

$$C(\Delta p, \Delta r) = \theta(\Delta p^2 - p_0^2)\theta(\Delta r^2 - r_0^2)$$

p_0 is a **free parameter**. Which is its value?

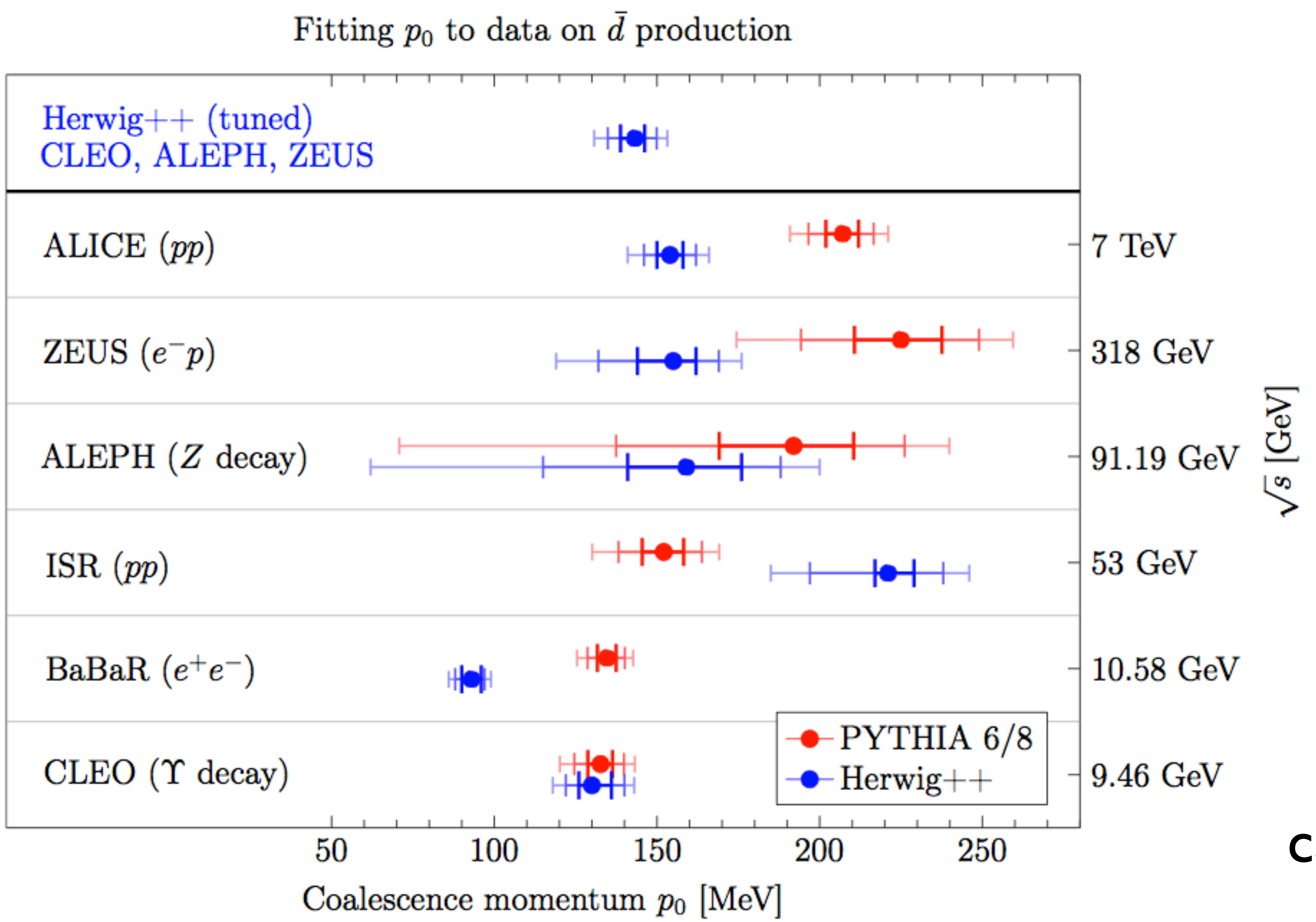
We take $r_0 \approx 2 \text{ fm}$ (radius of the anti-deuteron)

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

Kadastik, Raidal, Strumia 2010 Ibarra, Wild 2013

Antideuteron production

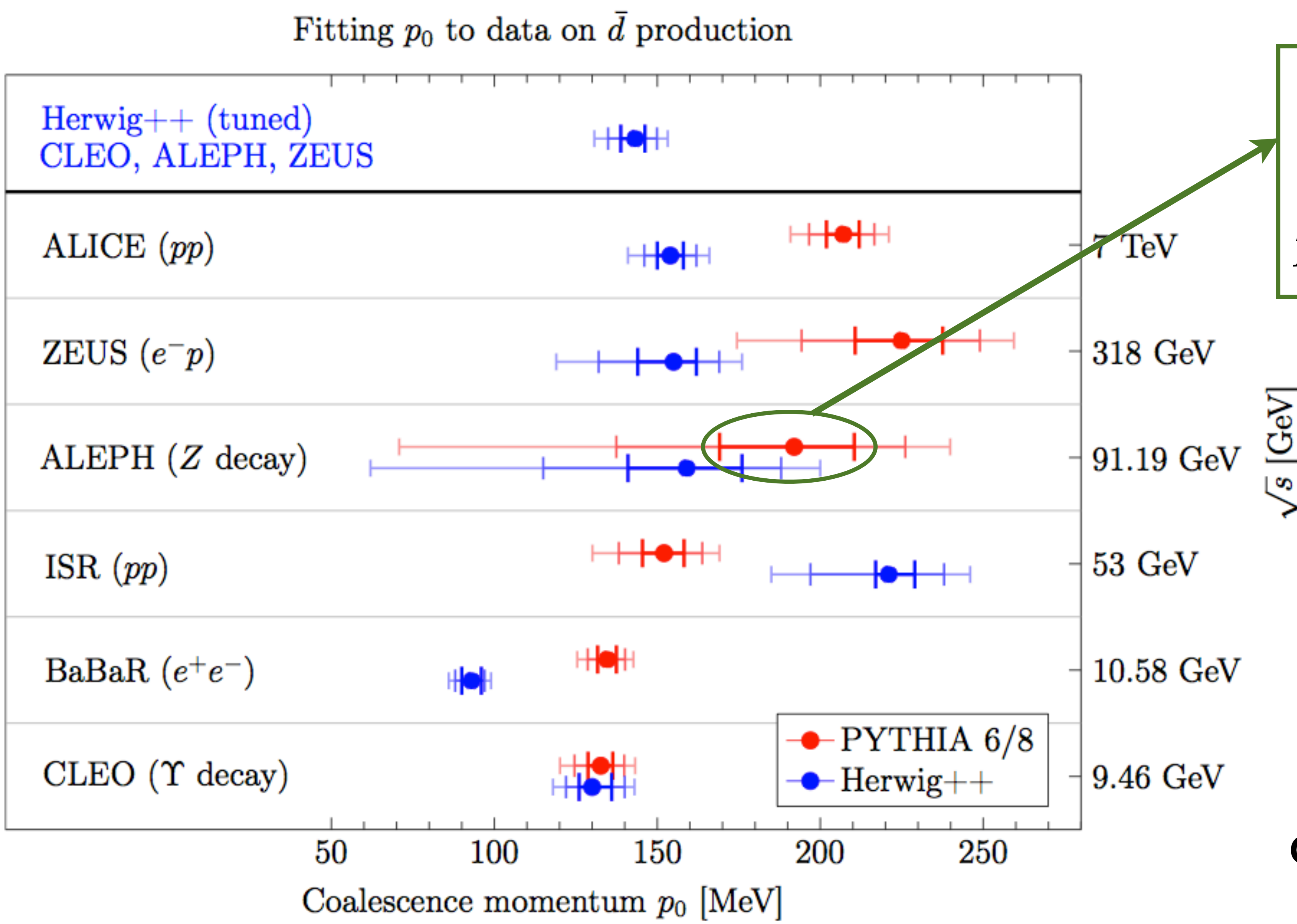
The coalescence momentum p_0 **cannot be calculated** from first principles and should be determined from **fitting** MonteCarlo **event-by-event** predictions to **experimental measurements**



No value of p_0 can **simultaneously** fit all the data!

Antideuteron production

The coalescence momentum p_0 **cannot be calculated** from first principles and should be determined from **fitting** MonteCarlo **event-by-event** predictions to **experimental measurements**



For the results shown here we use $p_0 = (195 \pm 22)$ MeV

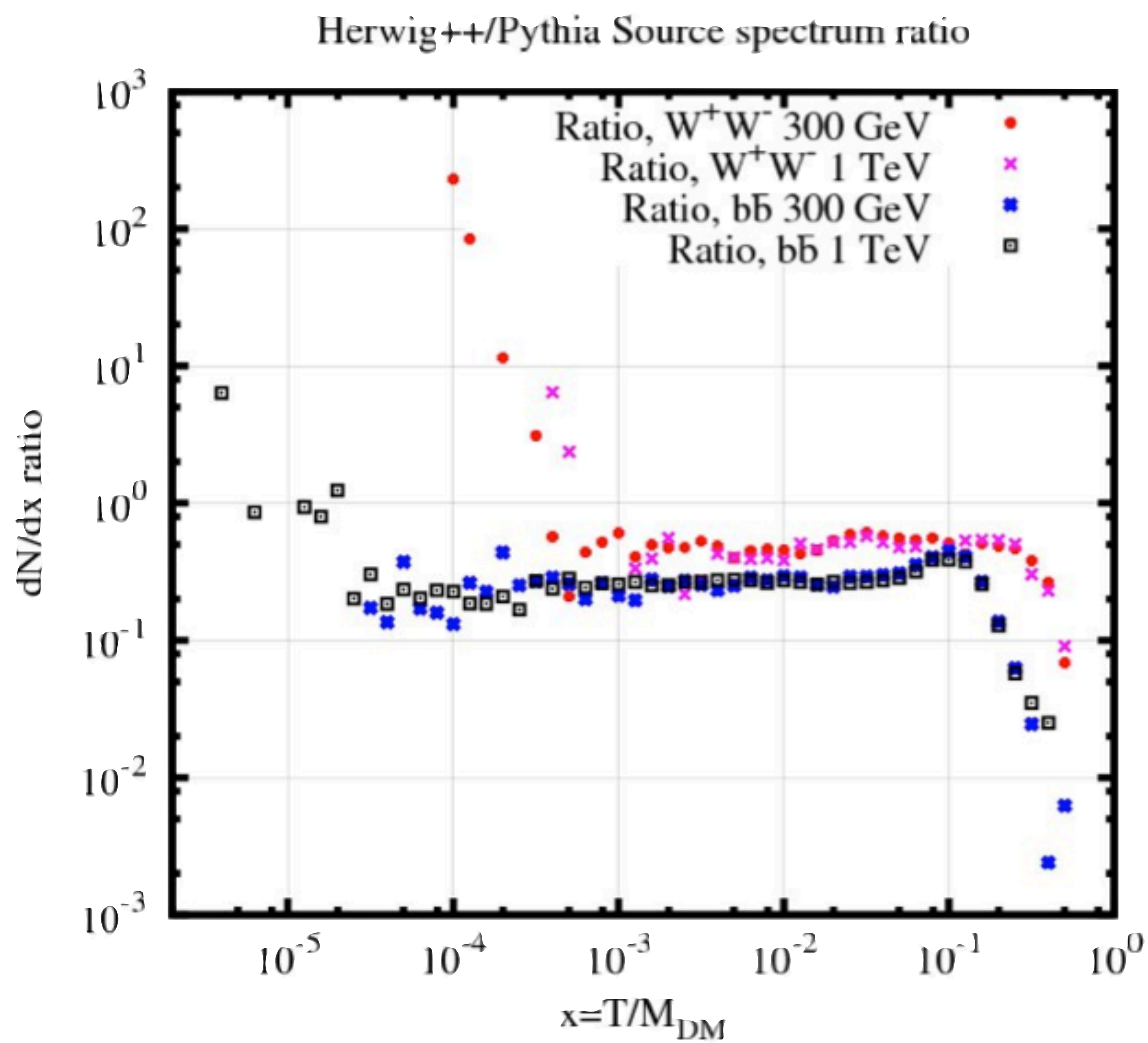
No value of p_0 can **simultaneously** fit all the data!

Antideuteron production

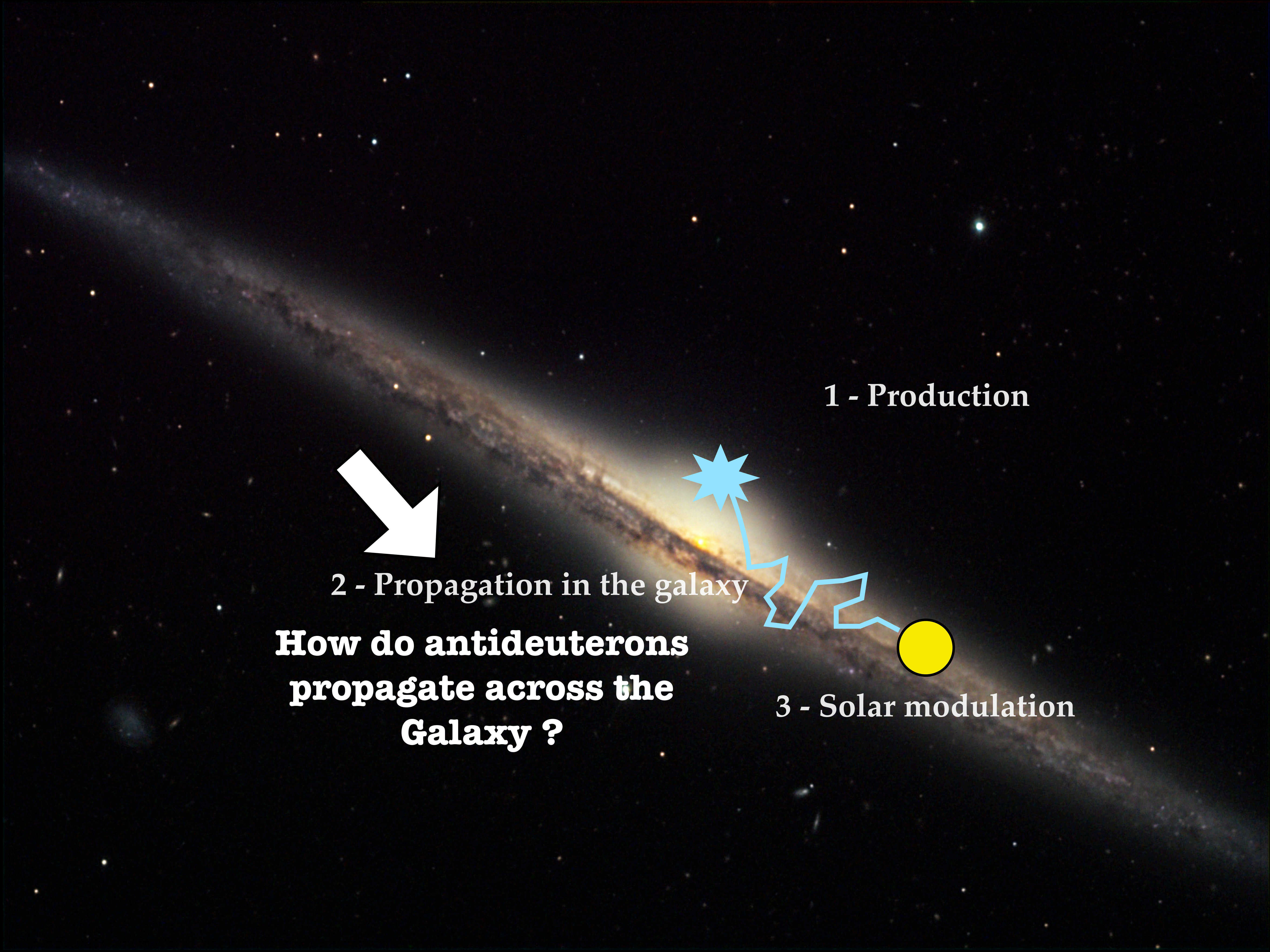
Dal, Kachelriess 2012
Dal, Raklev 2014

The large uncertainty on the coalescence momentum arise from **two factors**:

- p0 is **smaller or comparable to Λ_{QCD}** and therefore coalescence is sensitive to **non-perturbative effects** of the hadronization model of the MC event generator
- p0 is highly sensitive to **two-particle correlation** between the antinucleons, and MC event generators **are not tuned** to reproduce this observable



The uncertainty on p_0 has a large impact on our results, since the DM yield is proportional to p_0^3



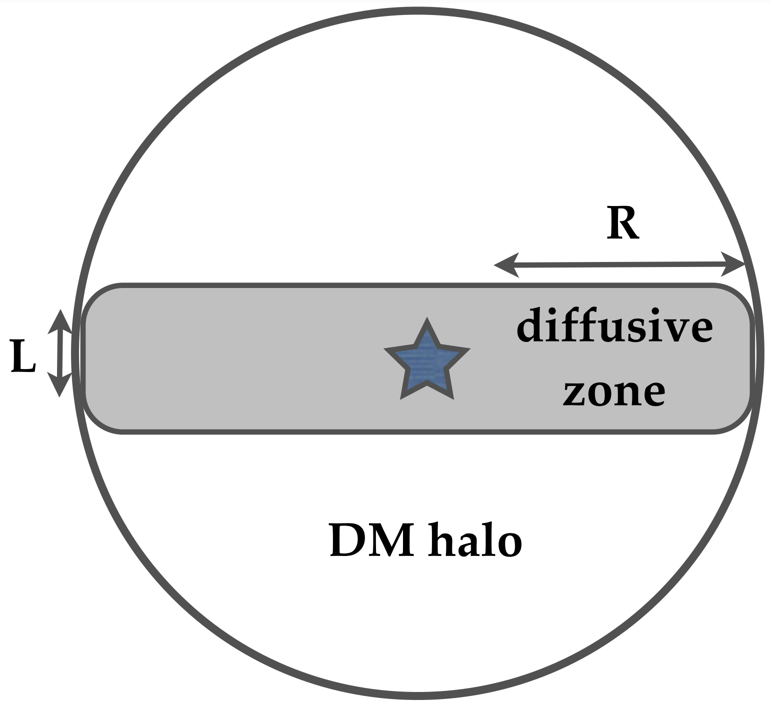
1 - Production
2 - Propagation in the galaxy
How do antideuterons propagate across the Galaxy ?
3 - Solar modulation

Galactic propagation

Spatial diffusion · Convection · Annihilation in the ISM · Reacceleration · Energy losses · Source Term

$$-\nabla[K(r,z,E)\nabla\mathcal{N}(r,z,E)] + V_c(z)\frac{\partial}{\partial z}\mathcal{N}(r,z,E) + 2h\delta(z)\Gamma^{\rm ann}\mathcal{N}(r,z,E) +$$
$$2h\delta(z)\partial_E(-K_{EE}(E)\partial_E\mathcal{N}(r,z,E) + b_{tot}(E)\mathcal{N}(r,z,E)) = \mathcal{Q}(r,z,E)$$

Two-zone diffusion model



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

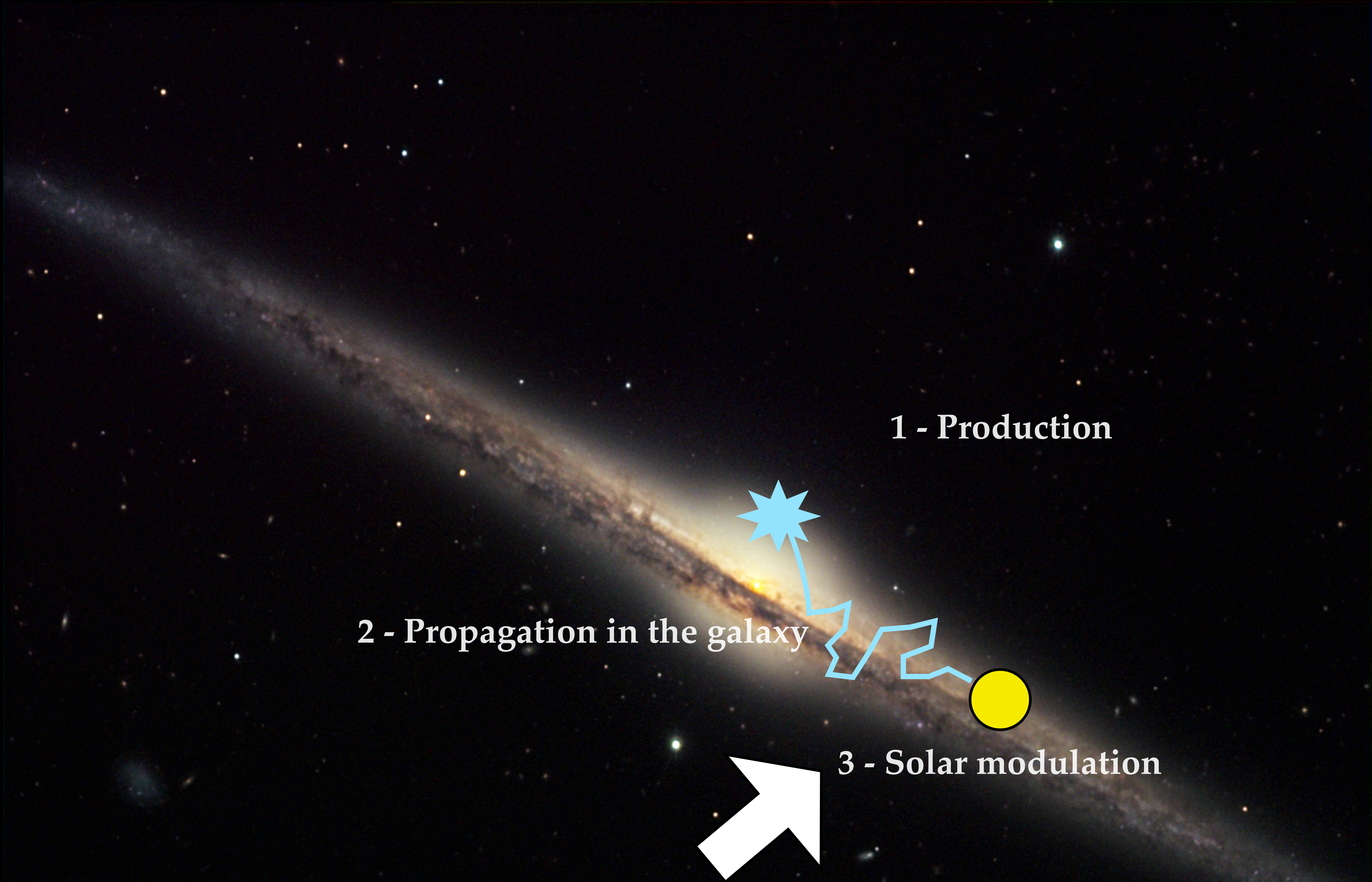
Solution is generally found by expanding the function in the transport equation in **Bessel functions**

The model is defined by these parameters:

	δ	K_0 (kpc^2/Myr)	L (kpc)	V_c (km/s)	V_a (km/s)
Min	0.85	0.0016	1	13.5	22.4
Med	0.70	0.0112	4	12	52.9
Max	0.46	0.0765	15	5	117.6

- K_0, V_c, V_a and δ constrained by B/C data
- L can be constrained (L>2kpc) by synchrotron measurements

Maurin+ 2001, Donato+ 2002
Donato+ 2004



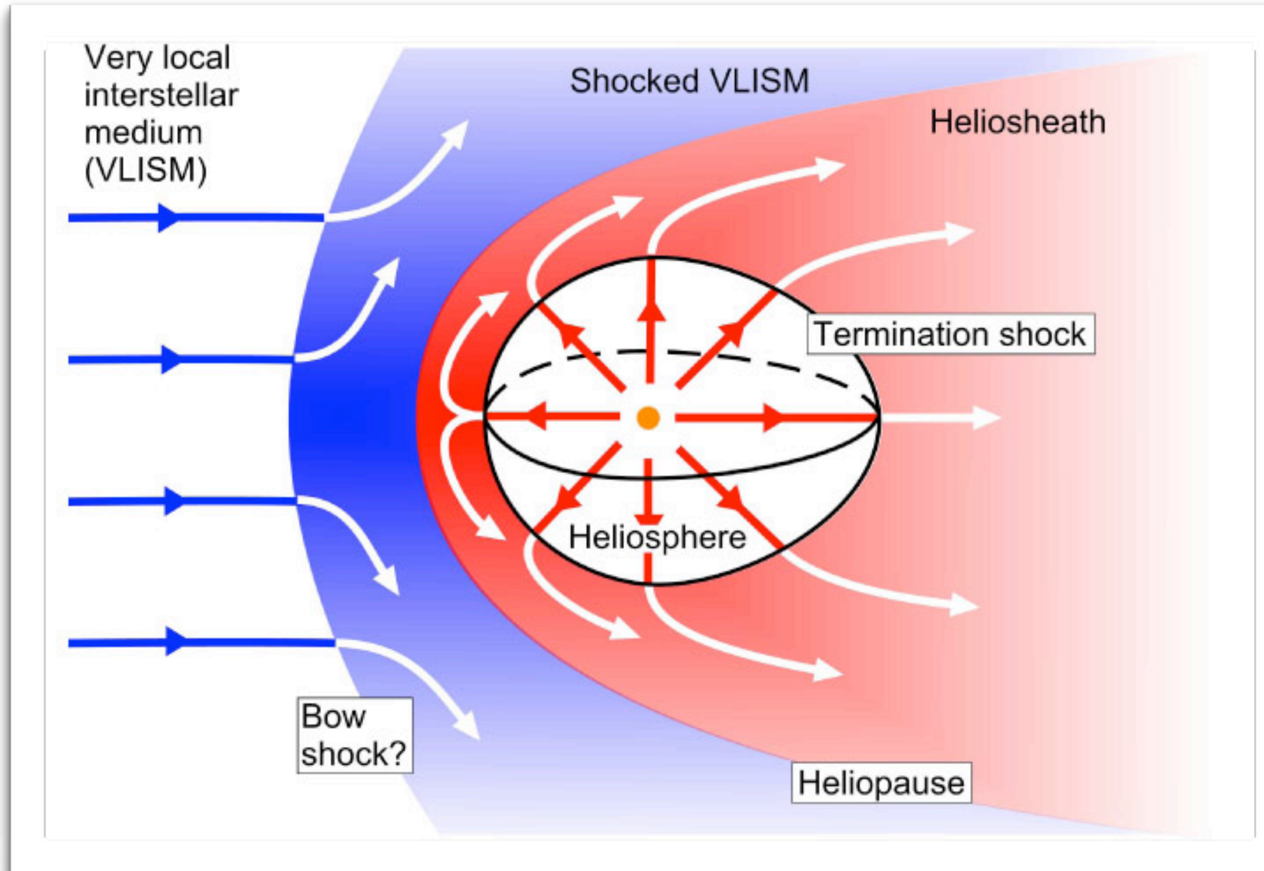
Since we are interested in low-energy antideuterons, solar modulation is extremely relevant

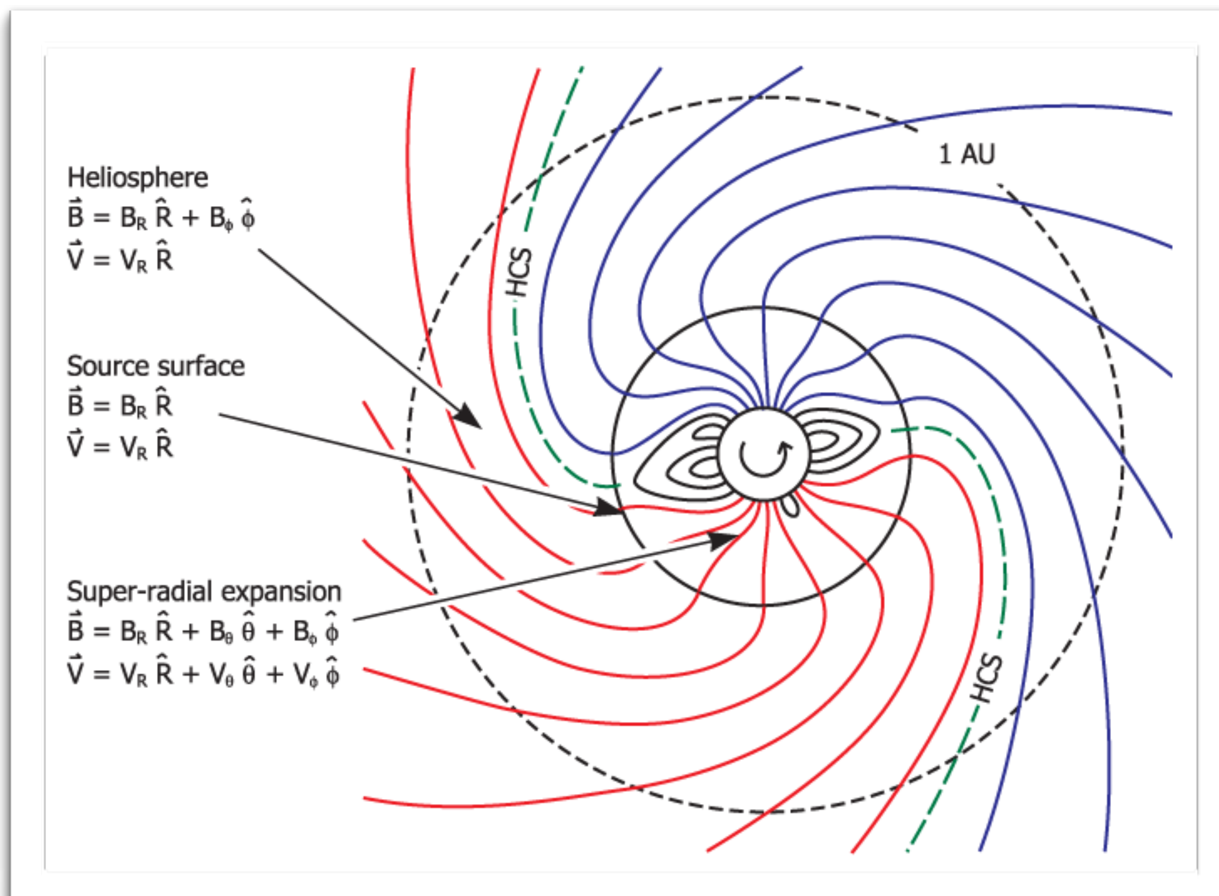
Charged CRs in the heliosphere

•The Sun is surrounded by the **heliosphere** that extends up to 100 AU

•The heliosphere hosts the **solar wind**, originated by the expansion of the hot plasma generated by the solar corona

•This wind of charged particles determines the existence of the **Heliospheric Magnetic Field** (HMF)





•HMF appears as an **Archimedean spiral**

•In the heliosphere, charged CRs **interact** with the HMF and with the solar wind

This mechanism is the **solar modulation**

Solar modulation

two possible approaches:

1) Force field approximation

$$\Phi_{\rm TOA}(T_{\rm TOA}) = \frac{T_{\rm TOA}(T_{\rm TOA}+2m)}{T_{\rm IS}(T_{\rm IS}+2m)}\Phi_{\rm IS}(T_{\rm IS}) \qquad \frac{T_{\rm TOA}}{A} = \frac{T_{\rm IS}}{A} - \frac{|Z|}{A}\varphi$$

Gleeson, Axford, 1967

φ is a **free parameter** tuned to reproduce the observed fluxes

2) Numerical solution of the transport equation in the heliosphere

$$-(\vec{V}_{\rm sw} + \vec{v}_{\rm d})\cdot\nabla f + \nabla\cdot(\vec{K}\cdot\nabla f) + \frac{p}{3}(\nabla\cdot\vec{V}_{\rm sw})\frac{\partial f}{\partial p} = 0$$

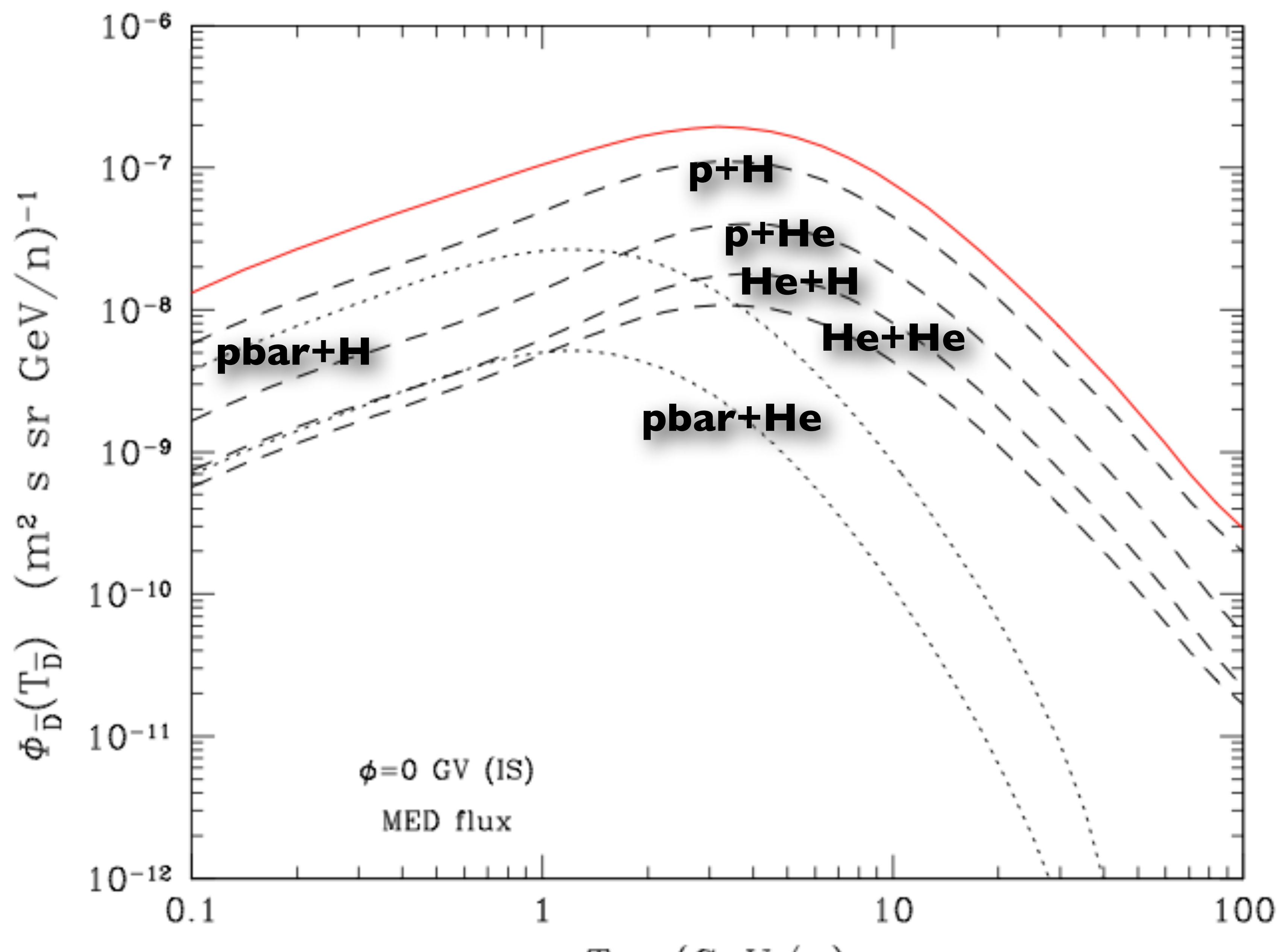
Parker, 1965

In this way, we allow for a **charge dependence**
(we use the Helioprop code **Maccione, 2013**)

Astrophysical background

The background is assumed to be of purely secondary origin:

$$Q^{\rm sec}(T_{\bar{d}}) = \sum_{i\in\{p,{\rm He},\bar{p}\}}^{\rm Cosmic\ Rays} \sum_{j\in\{p,{\rm He}\}}^{\rm ISM} 4\pi n_j^{\rm ISM} \int_{T_{\rm min}}^{\infty} dT_i \Phi_i(T_i) \frac{d\sigma(T_i, T_{\bar{d}})}{dT_{\bar{d}}}$$

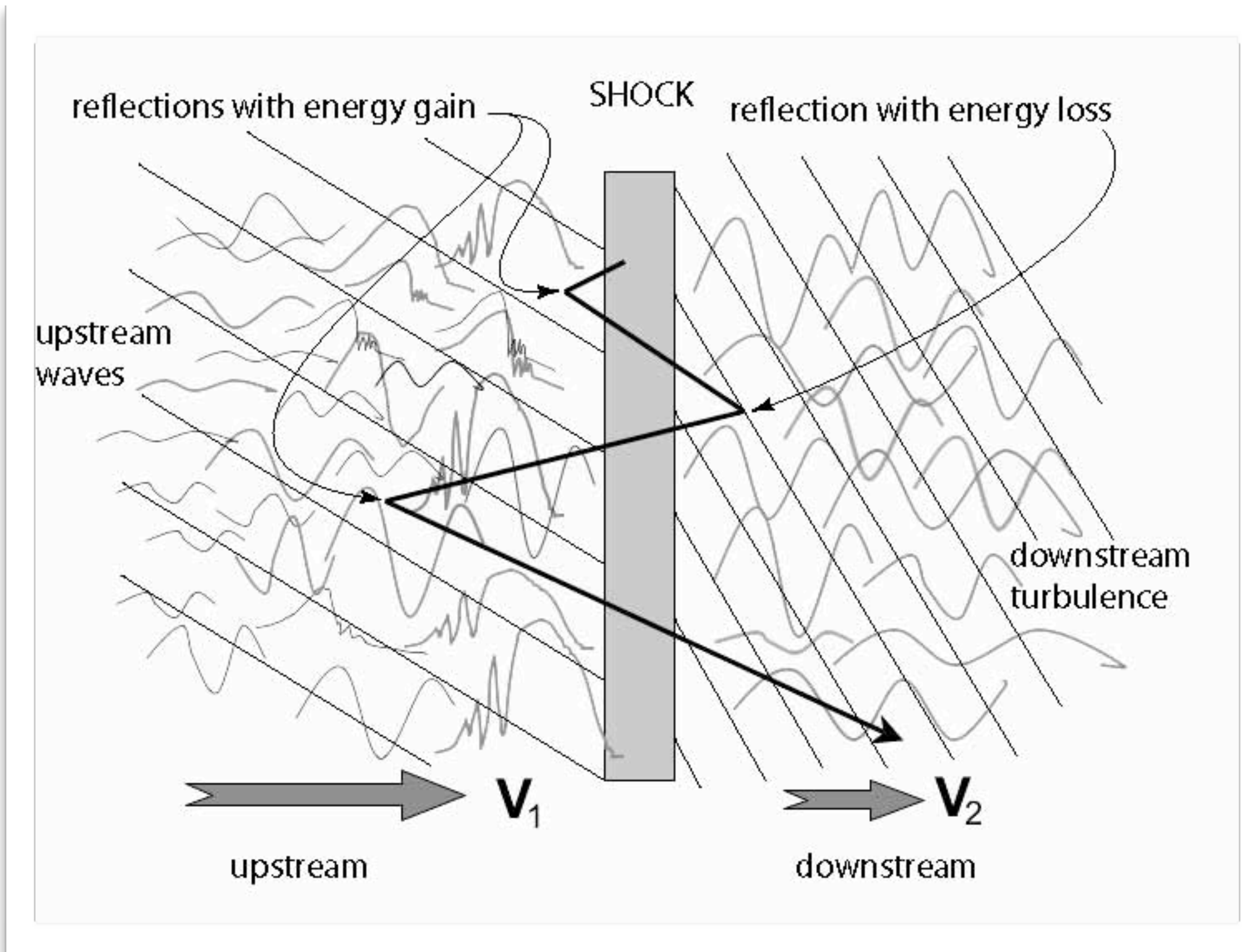


Donato+ 2008
Ibarra, Wild 2013

Astrophysical background
-additional contributions-

An example: secondary antideuterons accelerated **within** SNRs

J. Herms, A. Ibarra, AV, S. Wild, in preparation



Diffusive shock acceleration (DSA) is the mechanism through which **CRs are accelerated**

As a possible interpretation of the **rise in the positron fraction** observed by PAMELA, it has been suggested that DSA can accelerate also particles created by **pp collisions** that take place **inside** the shock region

Blasi 2009, Blasi, Serpico 2009
Ahlers, Mertsch, Sarkar 2009
Donato, Tomassetti 2012 ...

Antideuterons from SNRs

propagation within the shock region:

J. Herms, A. Ibarra, AV, S. Wild, in preparation

$$u\frac{\partial f}{\partial x} = D\frac{\partial^2 f}{\partial x^2} + \frac{1}{3}\frac{du}{dx}p\frac{\partial f}{\partial p} - \Gamma f = Q$$

Solution:

$$f(x,p) = f_0(p) + \left[\frac{q_2(p)}{u_2} - \Gamma f_0(p)\right]x$$

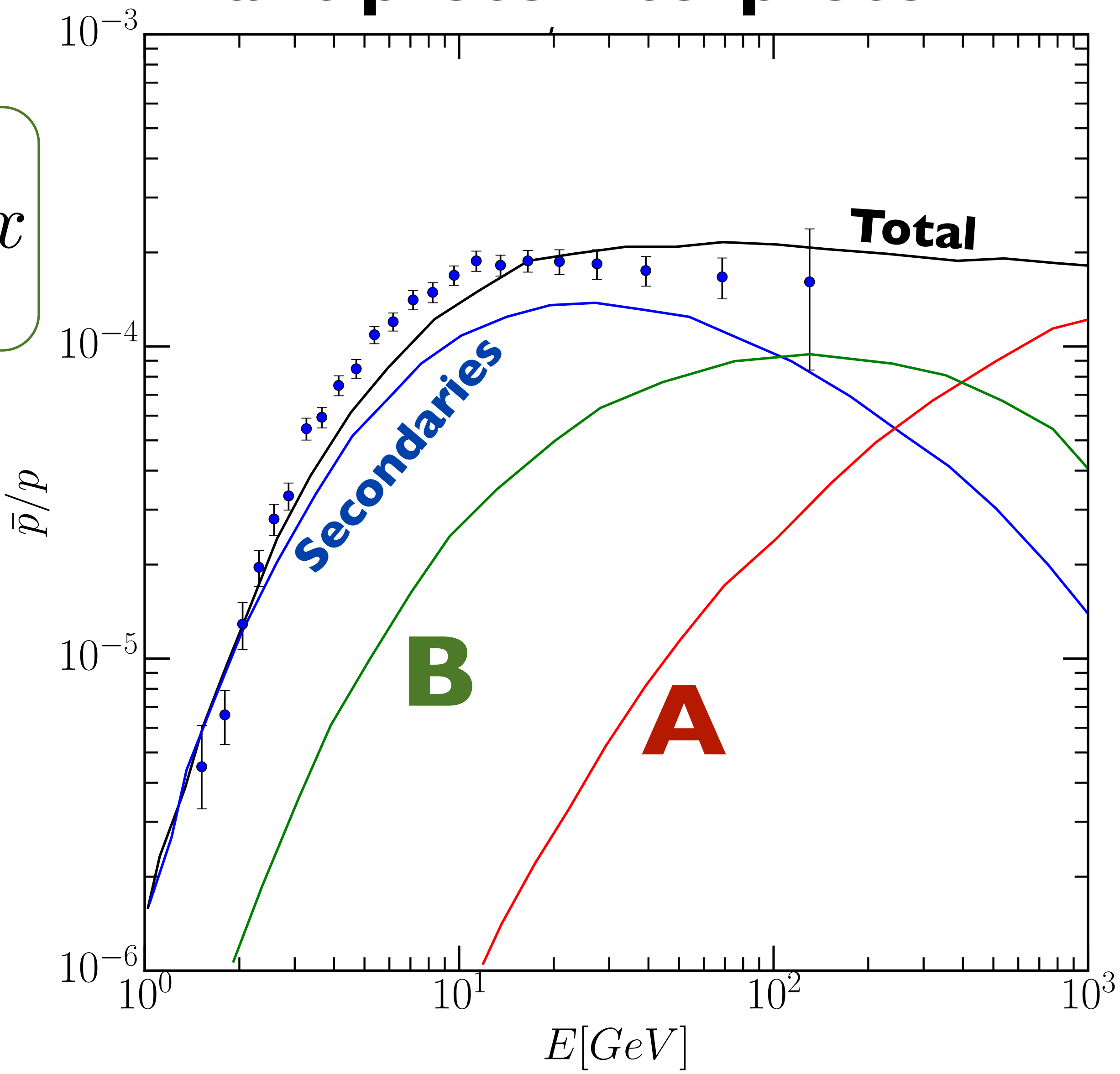
A B

Blasi, Serpico 2009

$$f_0(p) = \gamma \int_0^p \frac{dp'}{p'}\left(\frac{p'}{p}\right)^\gamma \frac{D(p')q_1(p')}{u_1^2}\left(\frac{1}{\xi(p)} + r^2\right)$$

$$r = \frac{u_1}{u_2} \quad \gamma = \frac{3r}{r-1} \quad \xi = \frac{p_{\bar{d}}}{p_p}$$

antiproton-to-proton

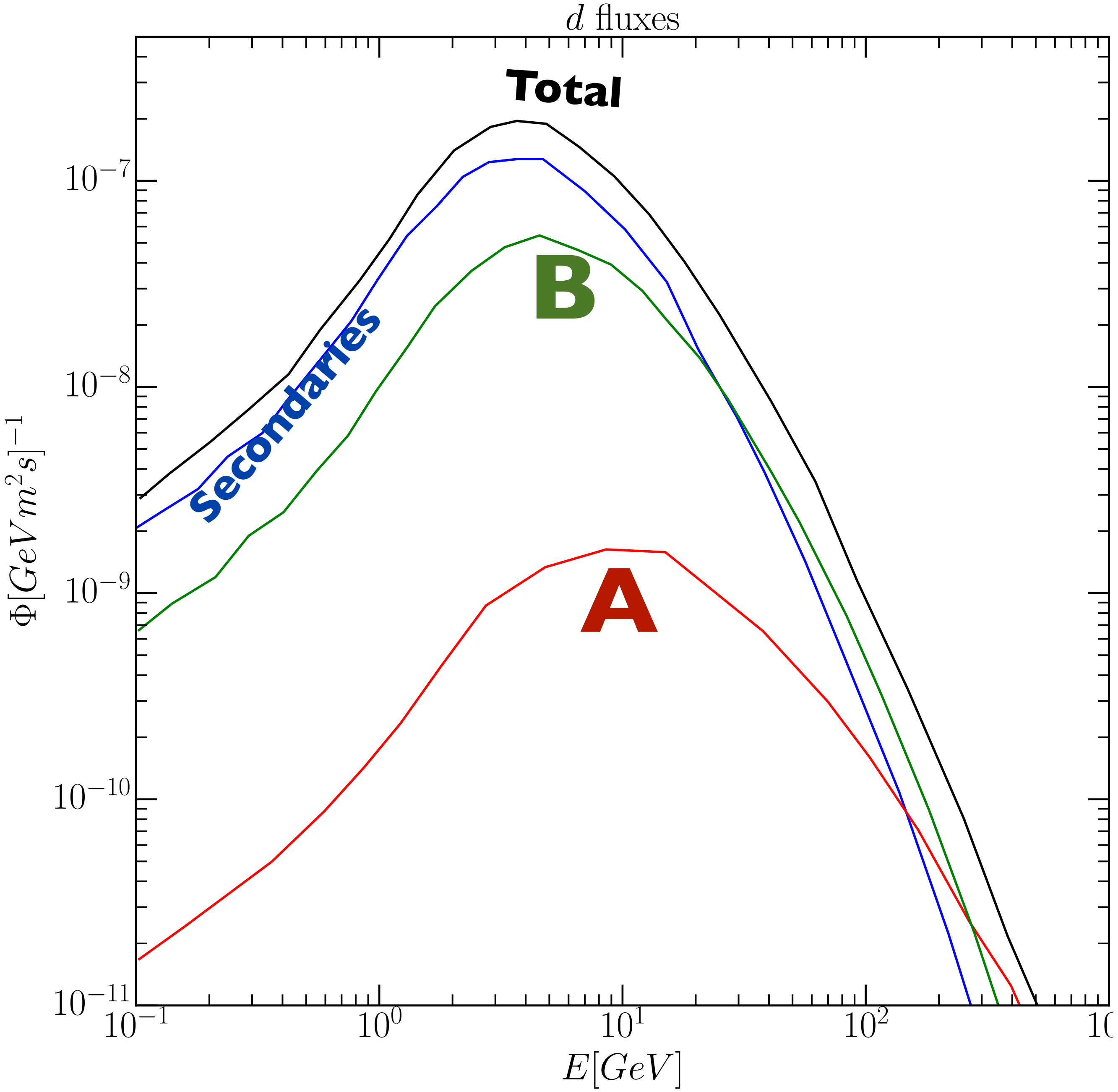


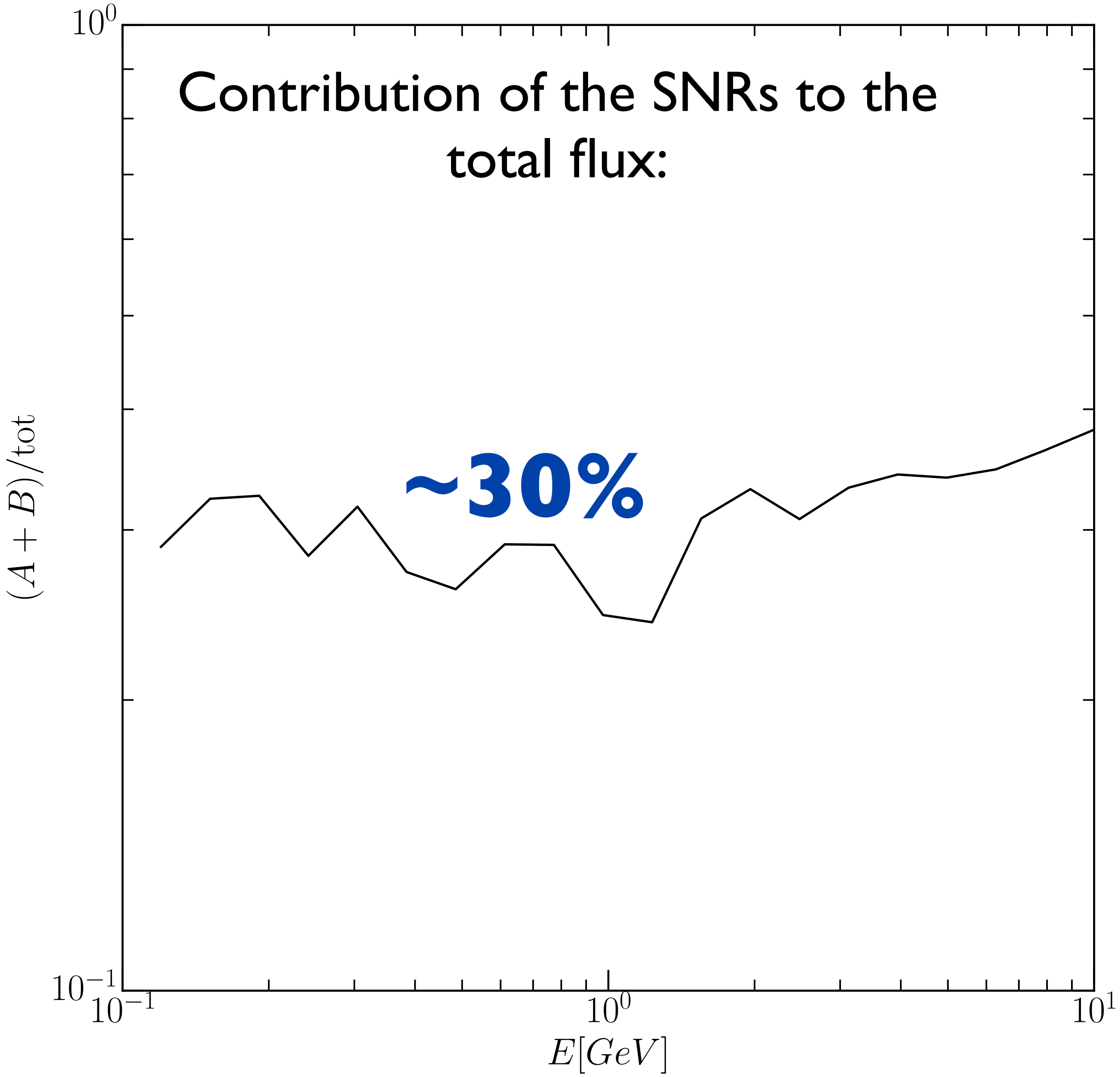
Antideuterons from SNRs

J. Herms, A. Ibarra, AV, S. Wild, in preparation

Prediction for antideuteron fluxes:

very preliminary!





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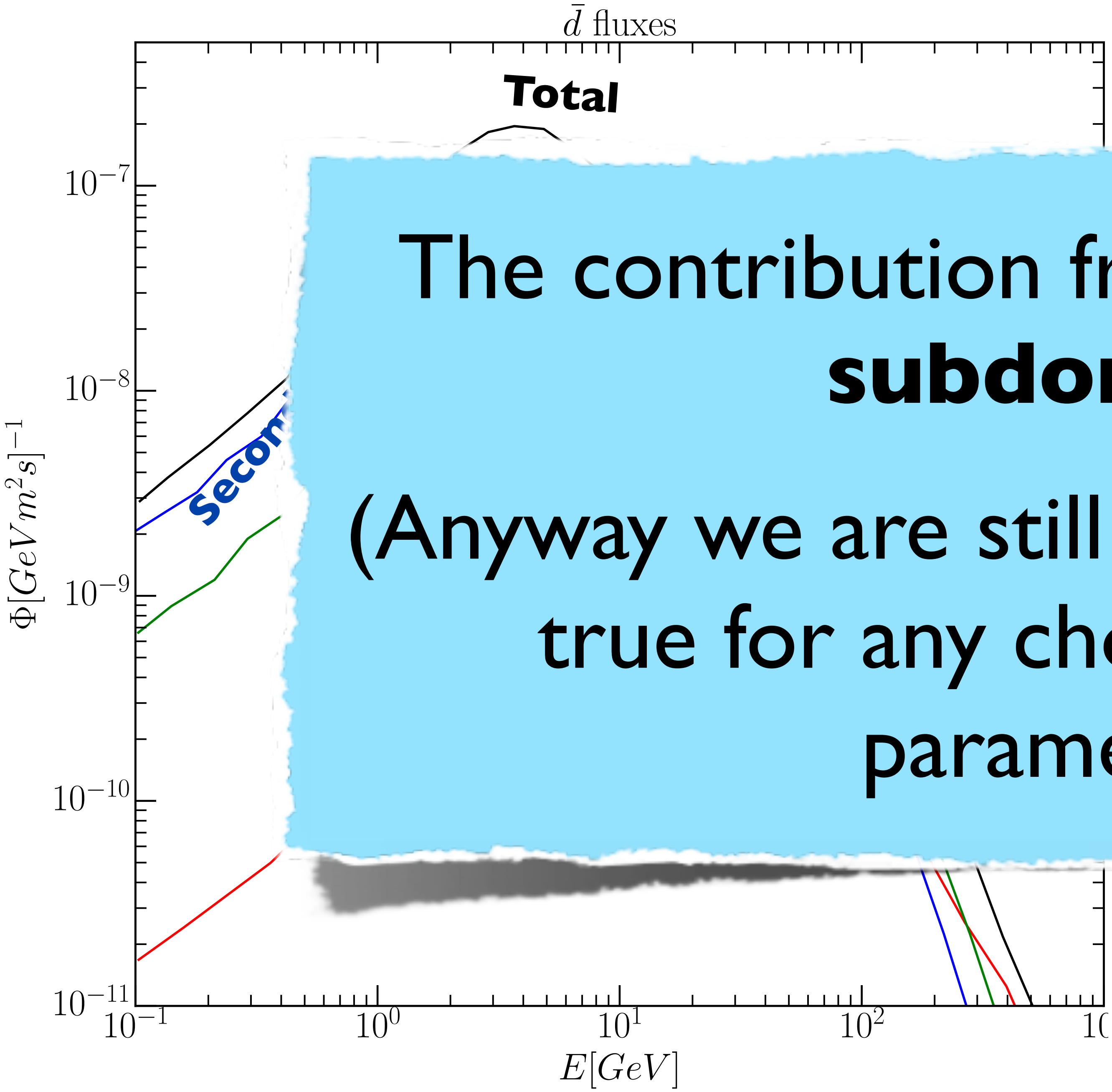
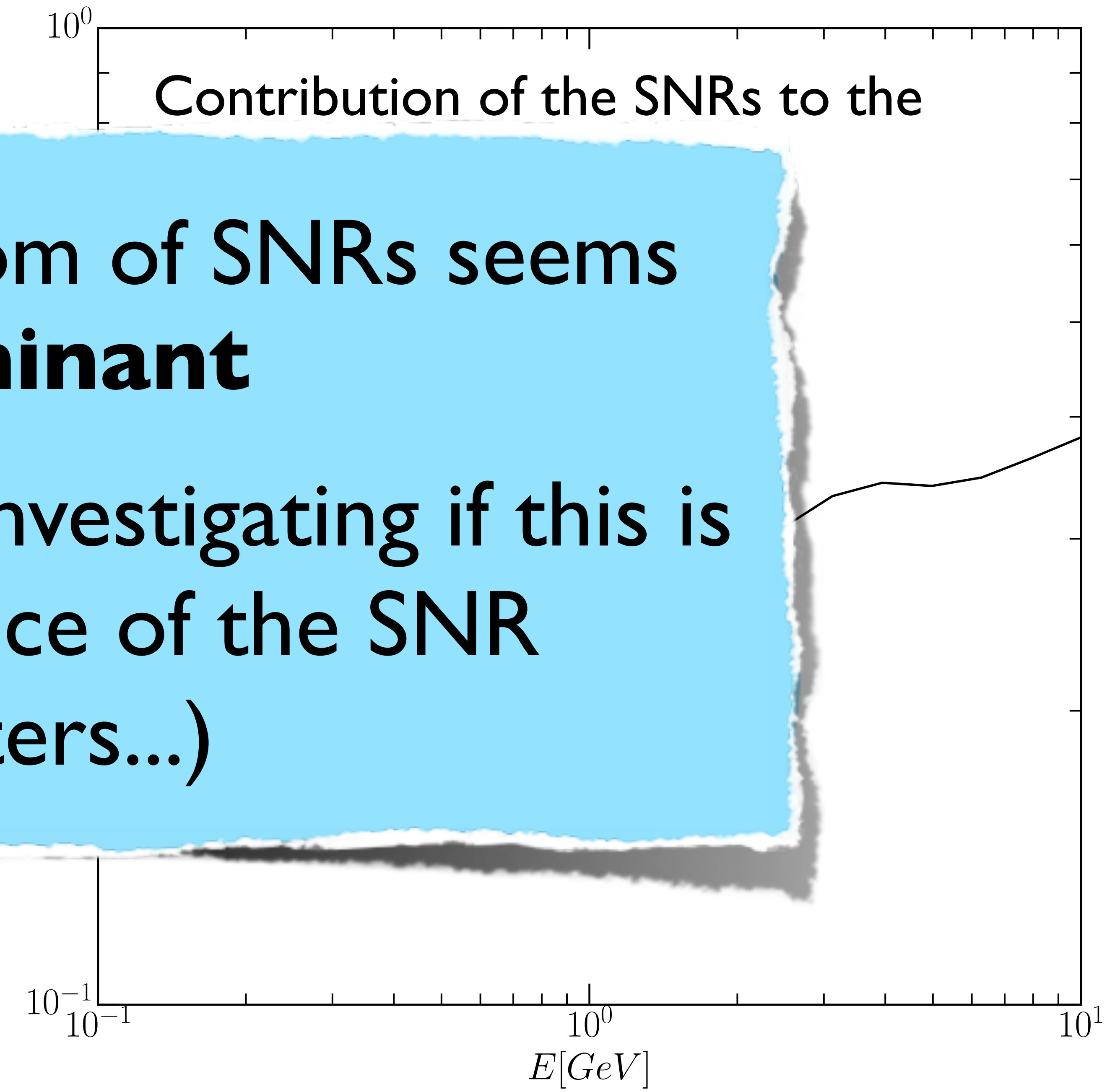




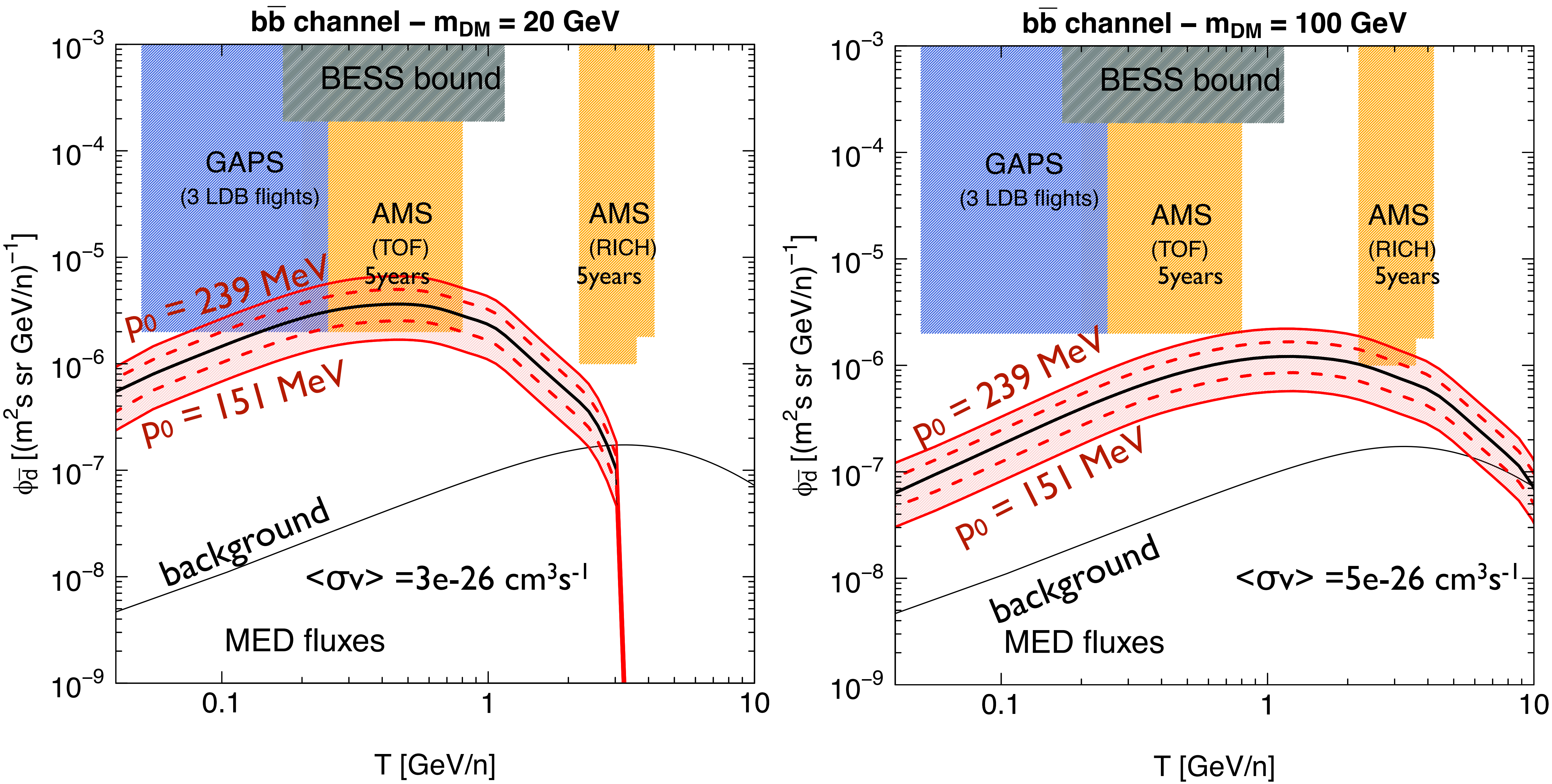
The contribution from of SNRs seems **subdominant**

(Anyway we are still investigating if this is true for any choice of the SNR parameters...)

Prospects for DM observation

Prospects for DM observation

An update **of N.Fornengo, L.Maccione, AV, 2013**

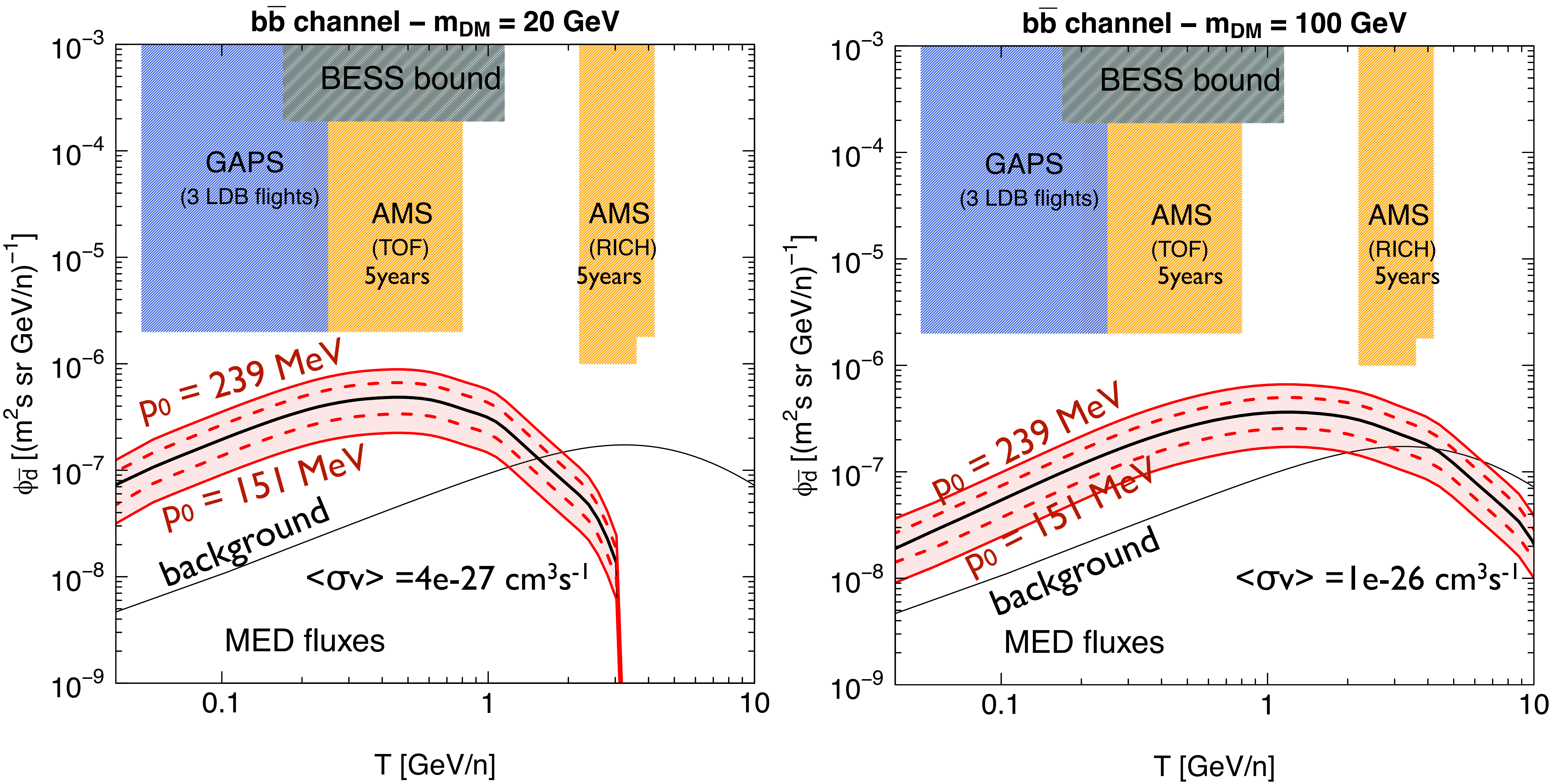


Annihilation cross sections compatible with **PAMELA antiproton bounds**

Boudaud+ 2014

Prospects for DM observation

An update **of N.Fornengo, L.Maccione, AV, 2013**



Annihilation cross sections compatible with **AMS-02 antiproton bounds**

Giesen+ 2015

Conclusions

Anti-deuterons are a **promising channel** for the indirect detection of DM particles with low or intermediate mass. For this DM candidates, in fact, the **signal-to-background** ratio is extremely **large**.

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For the current and future generation of experiments, the **detection of DM** in the antideuteron channel will probably be **challenging**

Conclusions

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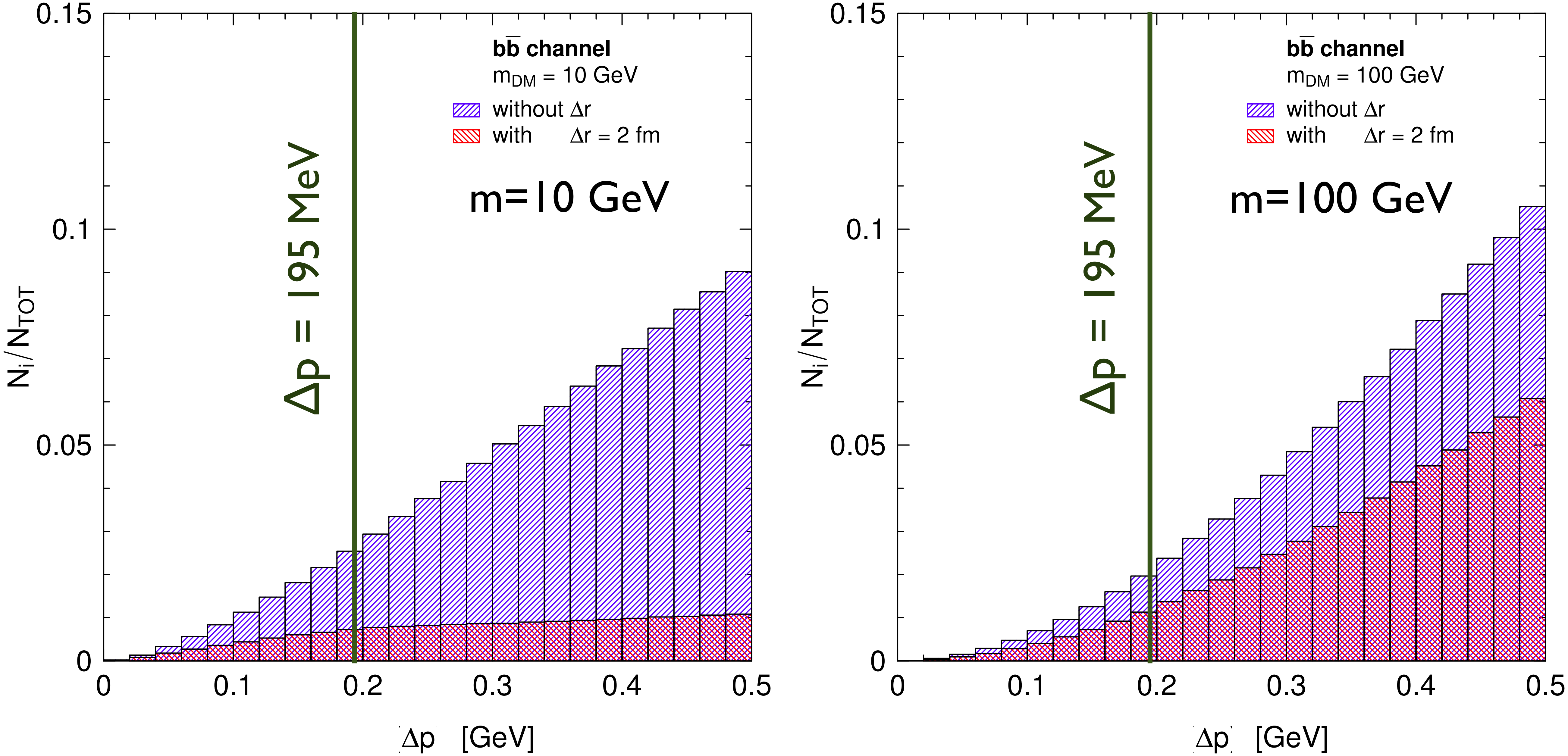
For the current and future generation of experiments, the **detection of DM** in the antideuteron channel will probably be **challenging**

Thank you!

Extra slides

Coalescence - the Δr condition

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



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 ($\alpha \in [20^\circ, 60^\circ]$)

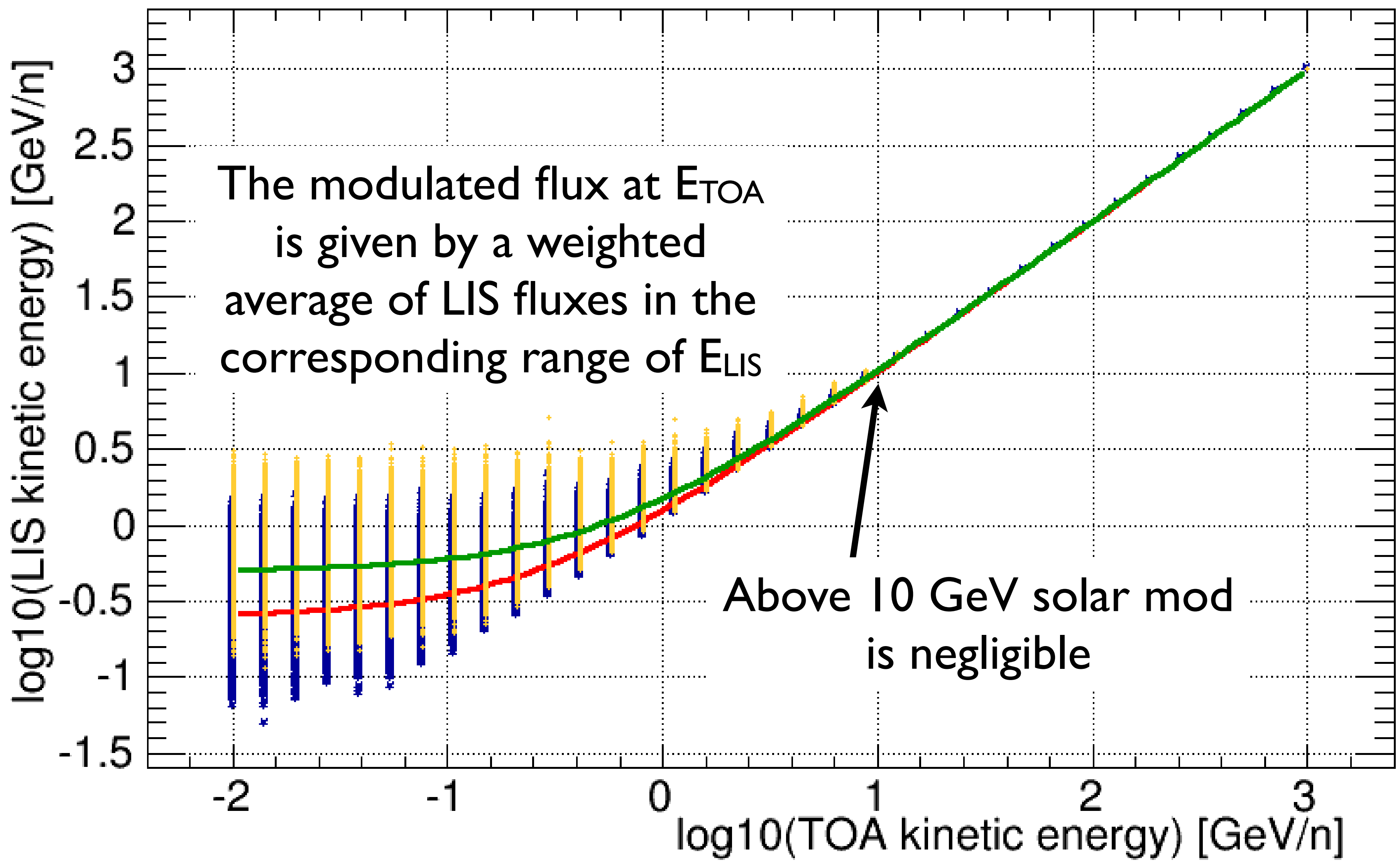
- The mean free path λ of the CR particle along the magnetic field direction

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)

Solar modulation

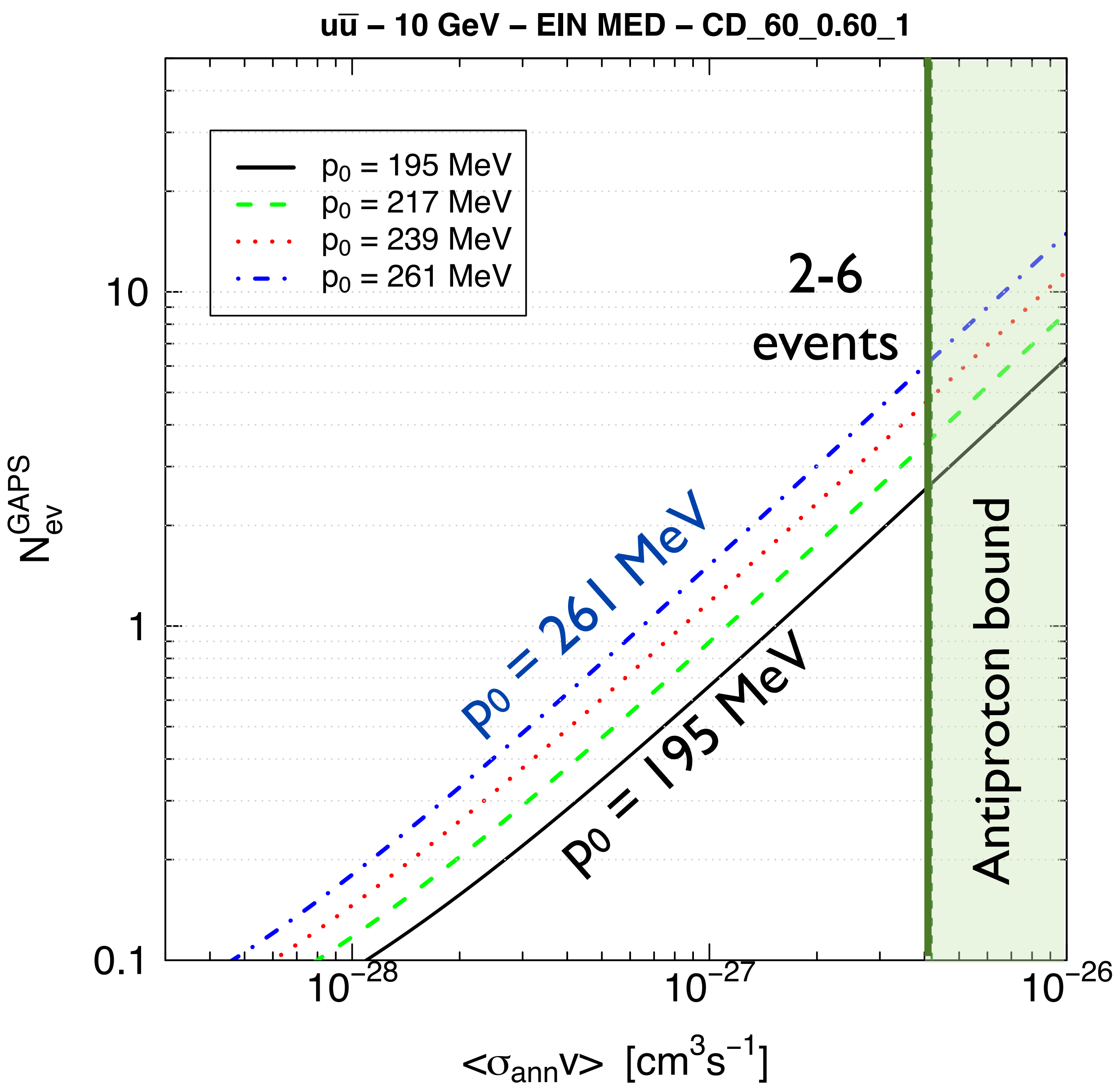
In our sample, energy losses vary significantly from particle to particle (they depend on the path):

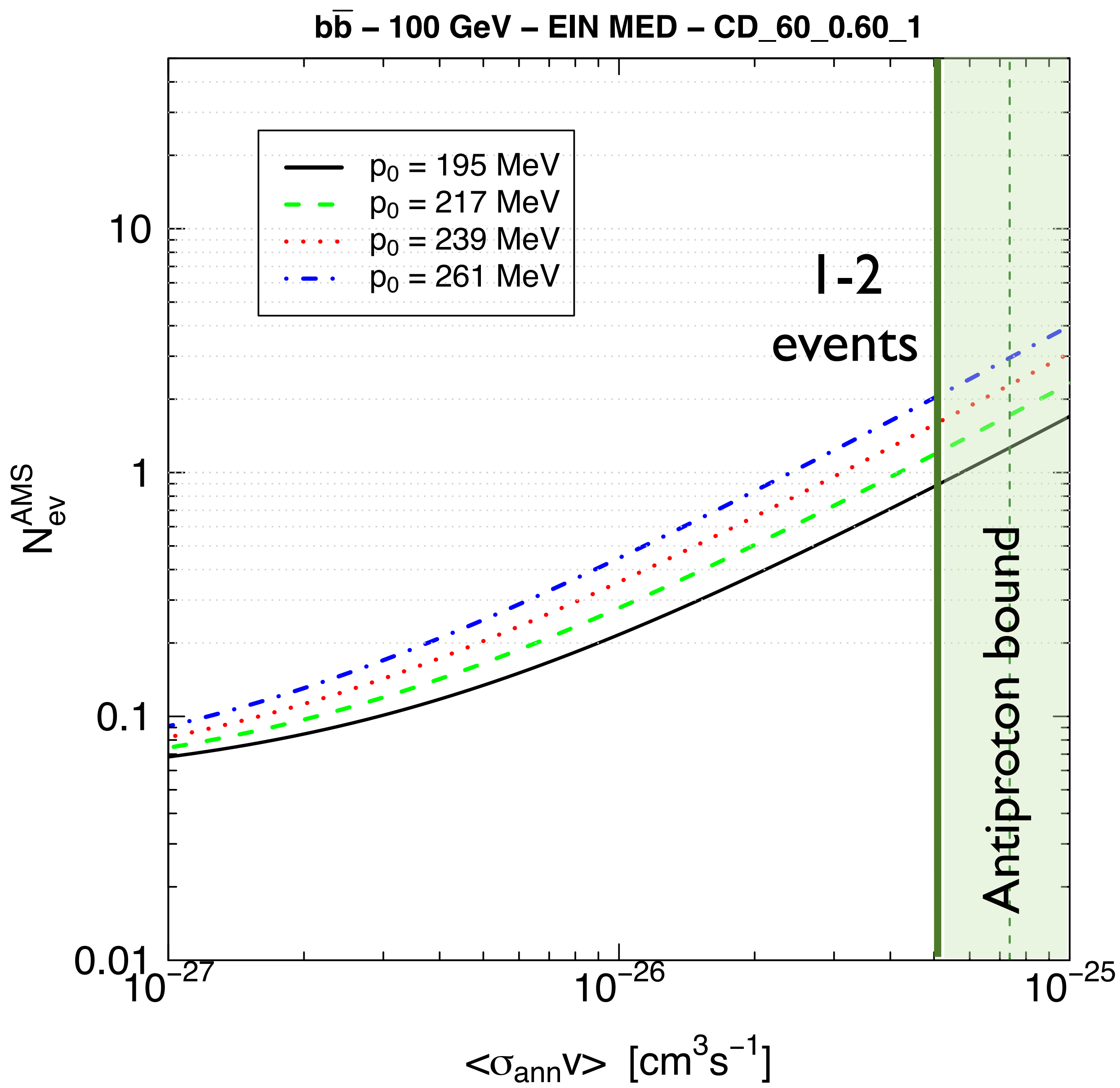


Solid lines ⟶ Force field approximation (pbar, dbar)

Dots ⟶ CD solar modulation (pbar, dbar)

Number of expected events





The anti-Helium case

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

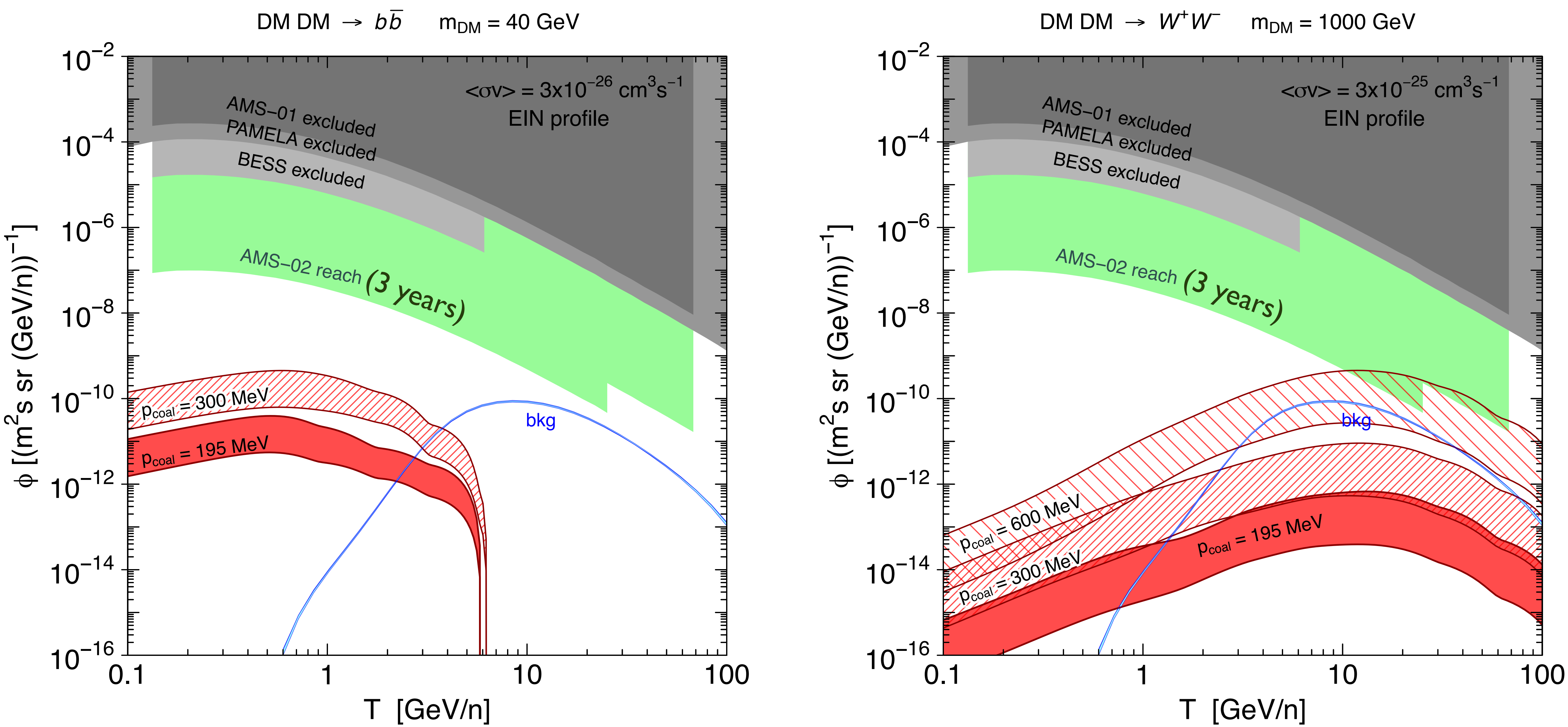
- We consider only the pnn case, since for the ppn case we expect to have a suppression due to **Coulombian repulsion**

- 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** :

$$|\Delta p|_{\max} \leq p_0$$

- 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)

The anti-Helium case



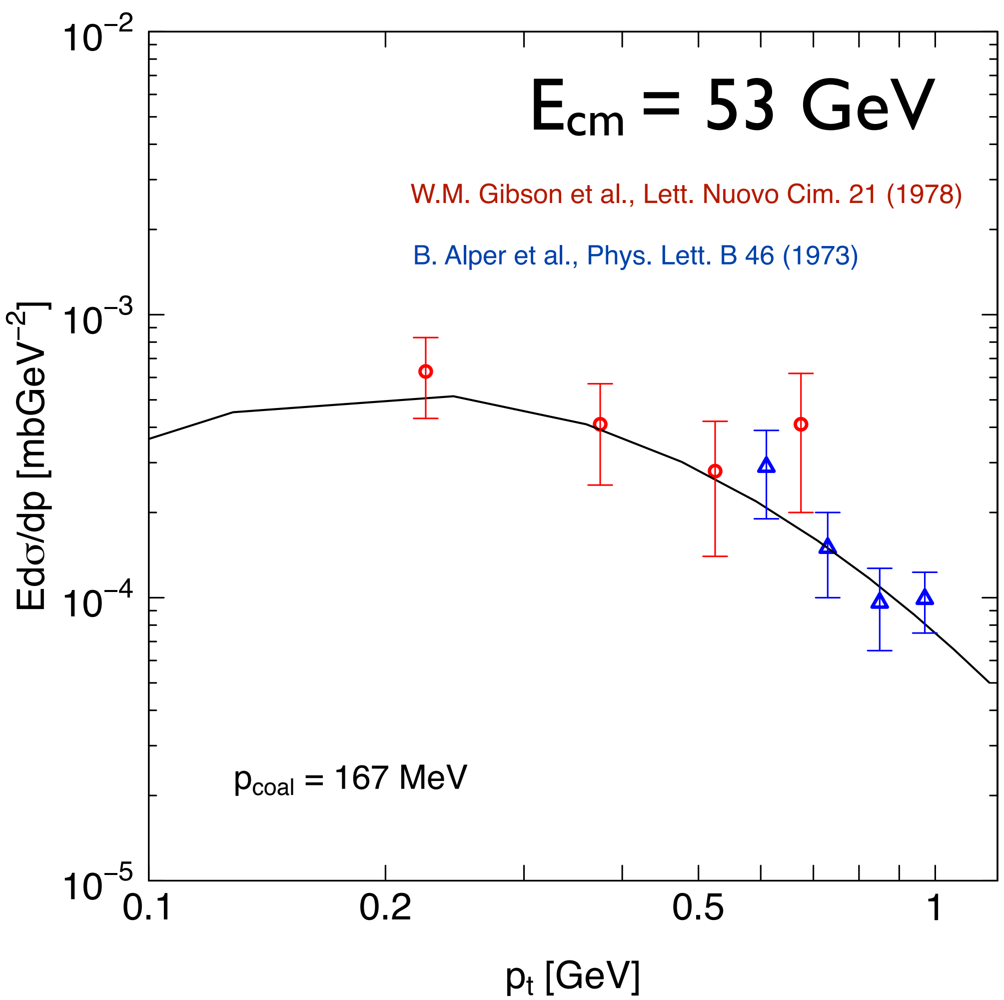
Prospects for detection are **rather weak**, unless the coalescence momentum is really large (~600 MeV)

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:

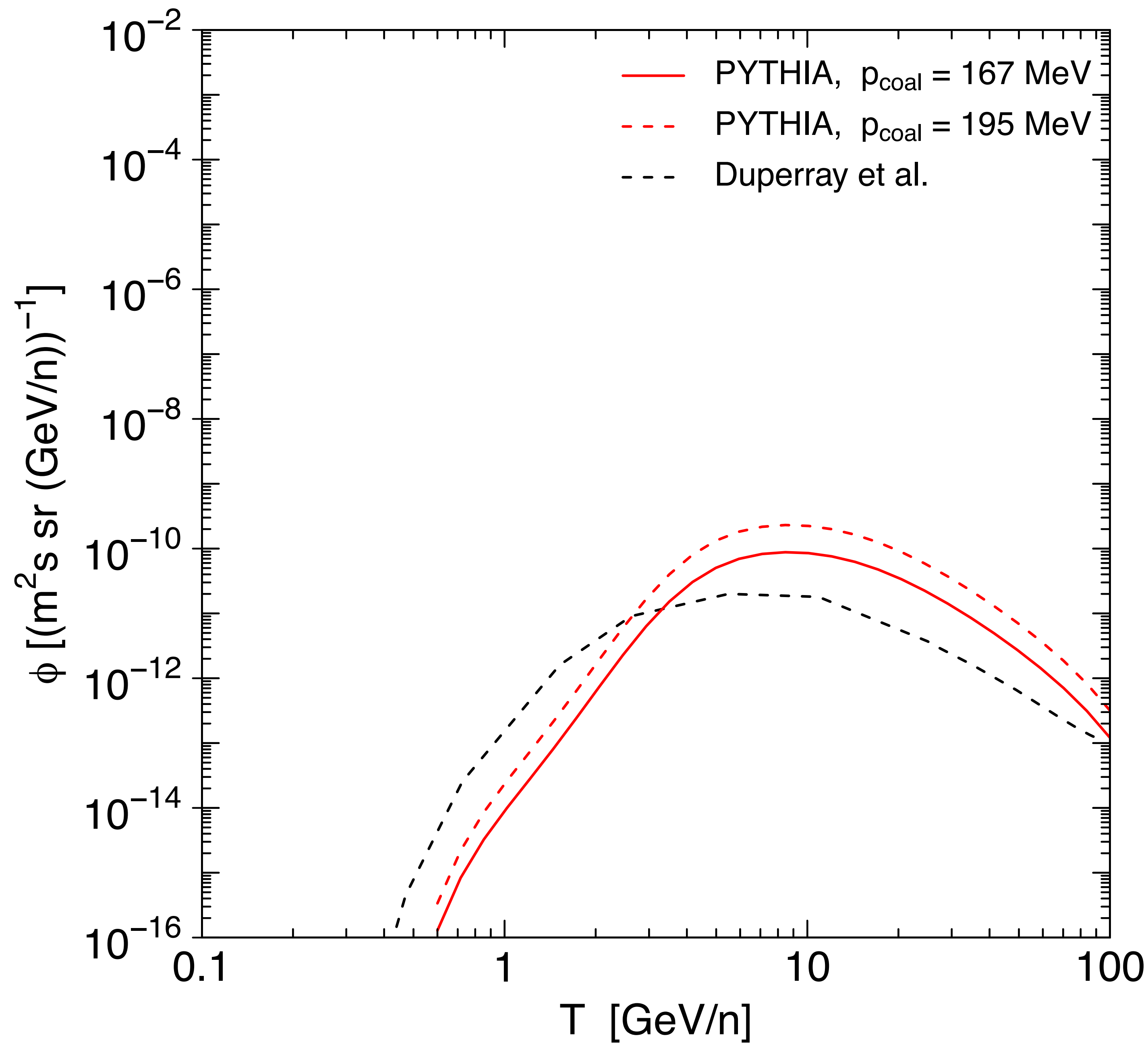
$$\frac{d\sigma_{pp\to\overline{\rm He}+X}}{dE}(E,E') = \sigma_{pp,\rm tot}(E,E')\frac{dn_{\overline{\rm He}}}{dE}(E,E')$$

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