Dark Matter searches with charged cosmic rays: status and perspectives

Andrea Vittino (TUM, Munich)

GSSI, L'Aquila, 16 March 2016

Outline

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(more specifically, about **WIMPs**)

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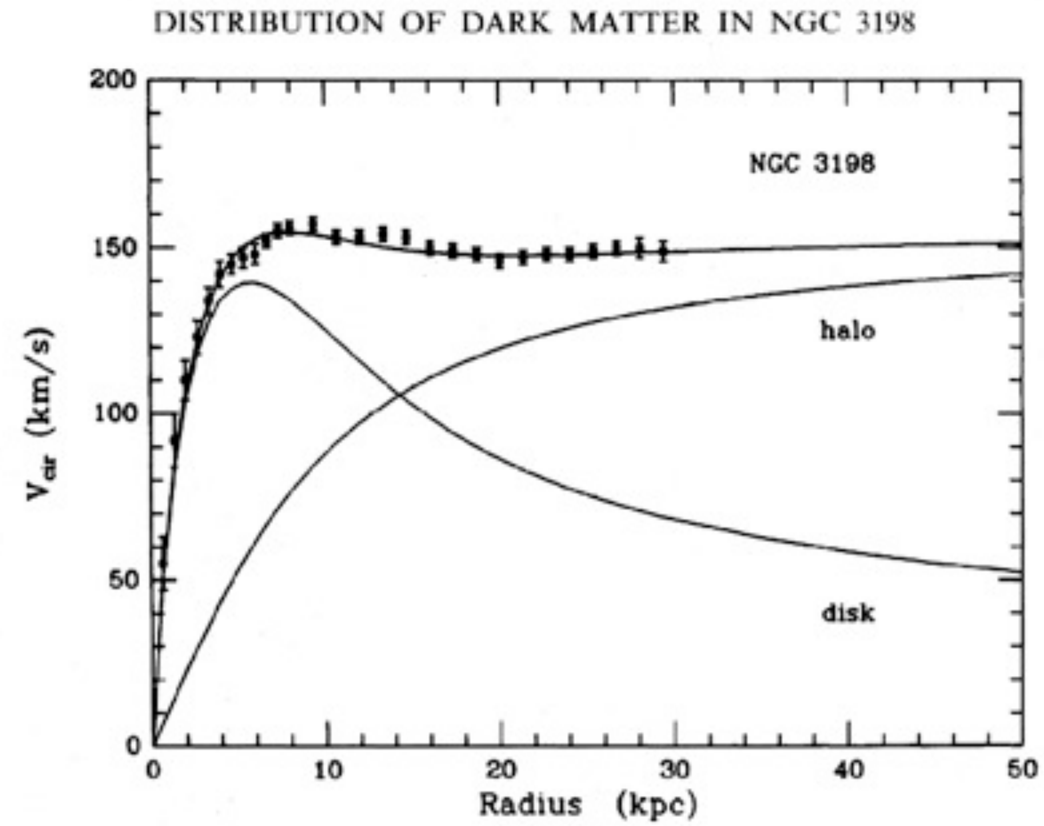
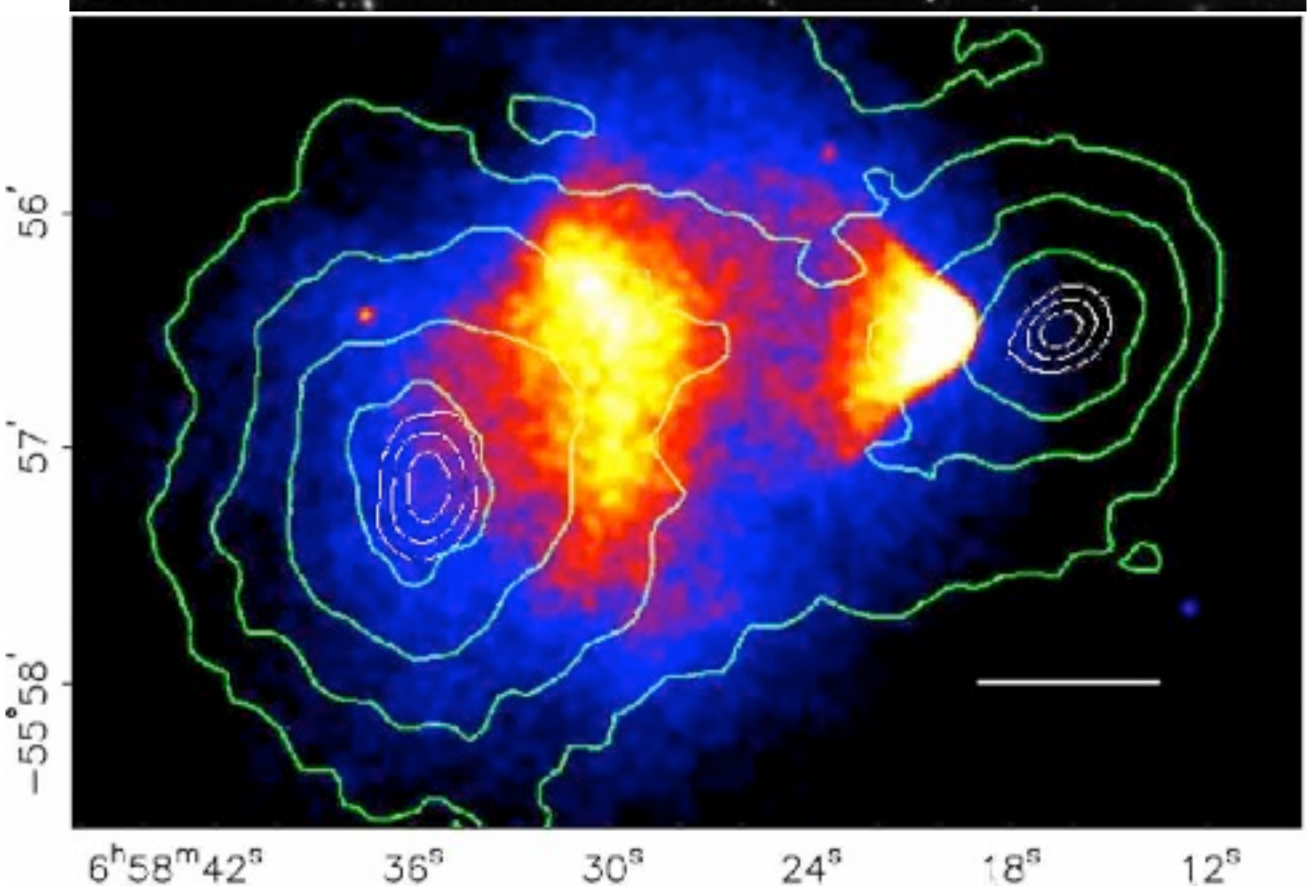
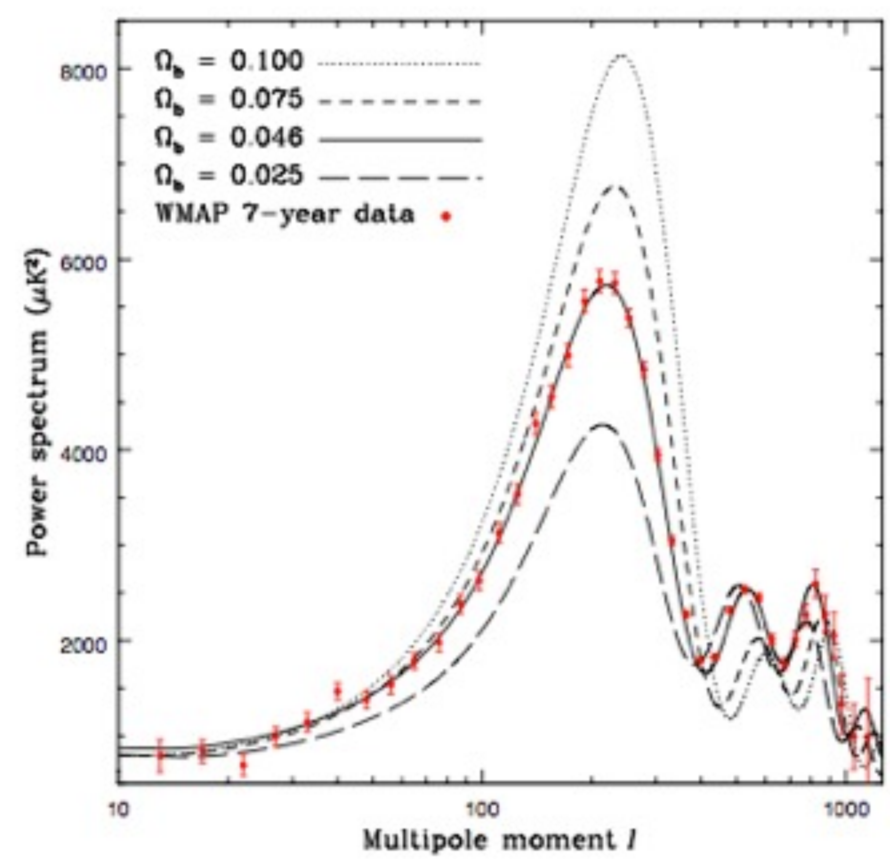
I will discuss indirect detection in **charged cosmic rays**,
namely **antiprotons**, **anti-nuclei** and **positrons**

A dark Universe

A dark Universe







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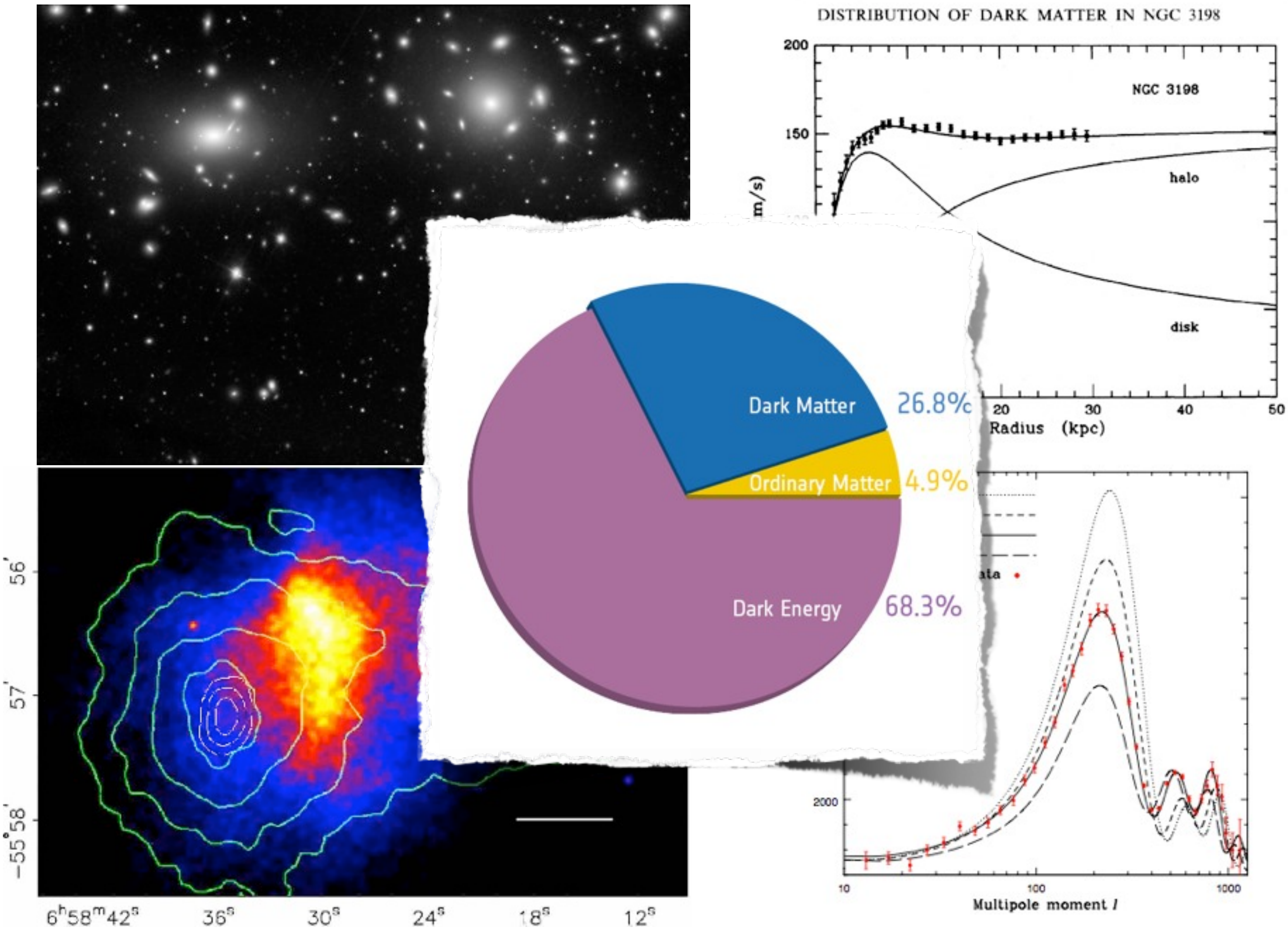
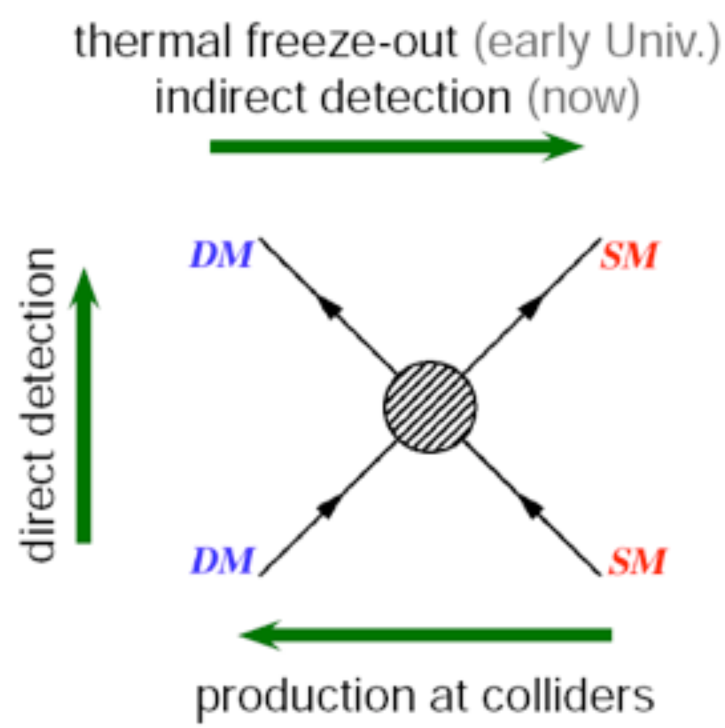


WIMPs detection

In order for the WIMP to have the **correct relic density**, the annihilation in the early Universe must be **efficient**. This implies a **DM-DM-SM-SM interaction term.**



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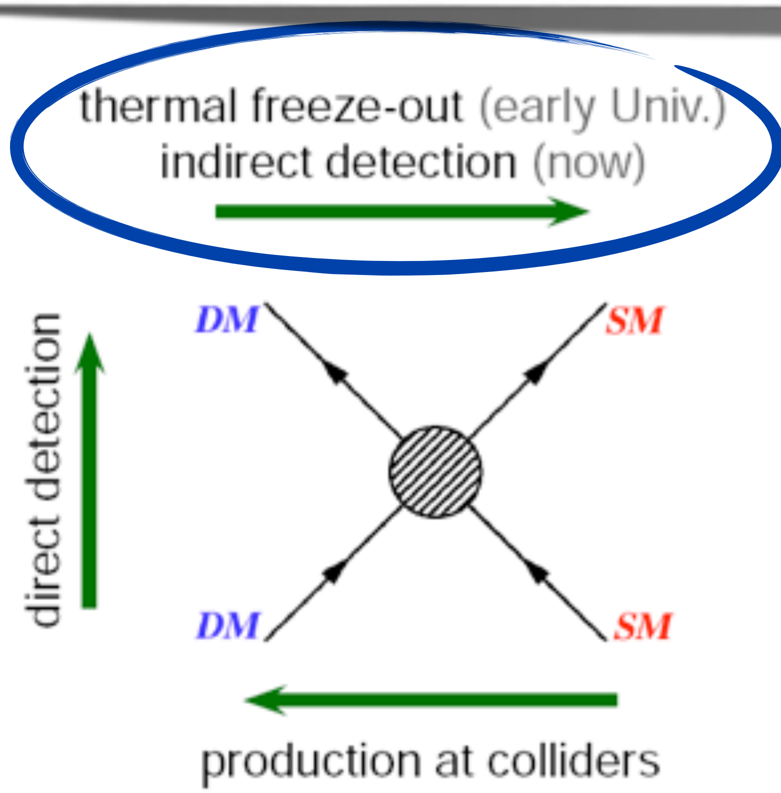

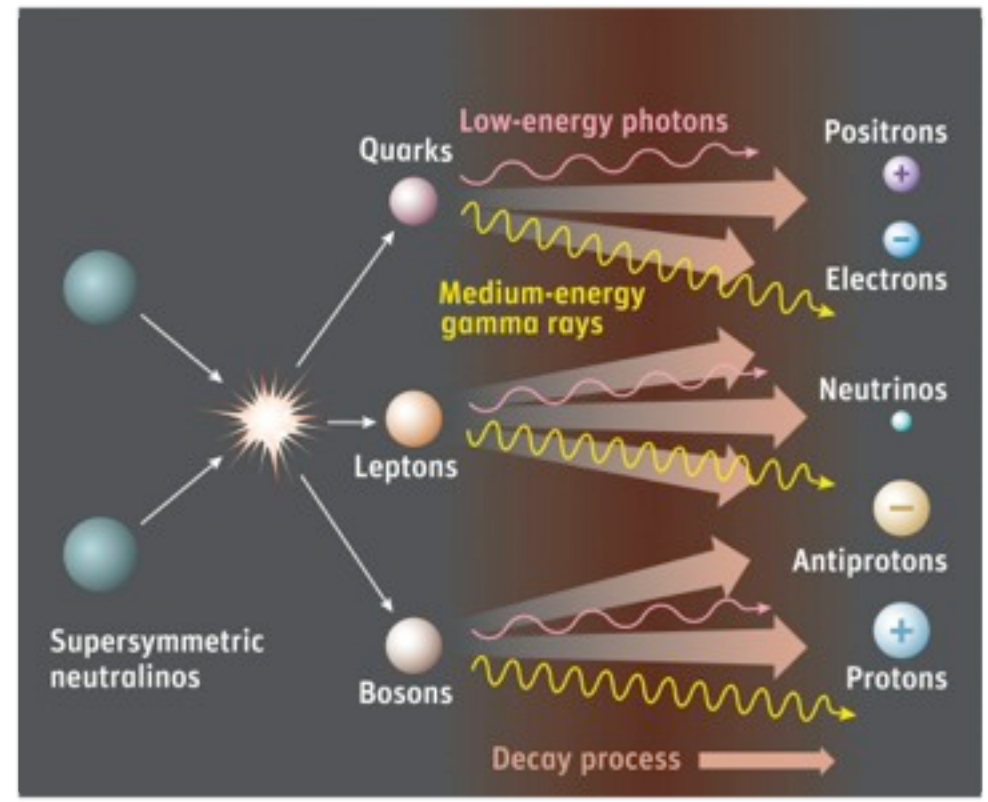

After the freeze-out, **WIMPs can still undergo pair annihilations** (or decays) and **produce SM particles** that can appear in the Cosmic Ray flux:

- **Photons** at various frequencies (from prompt emission or secondary processes)
- **Neutrinos**
- **Charged particles**

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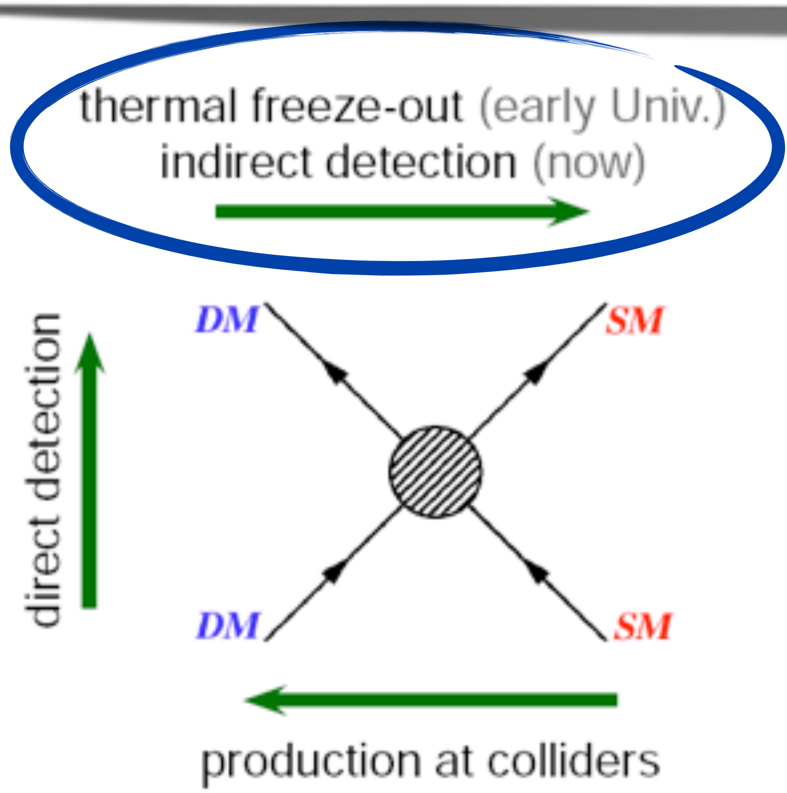

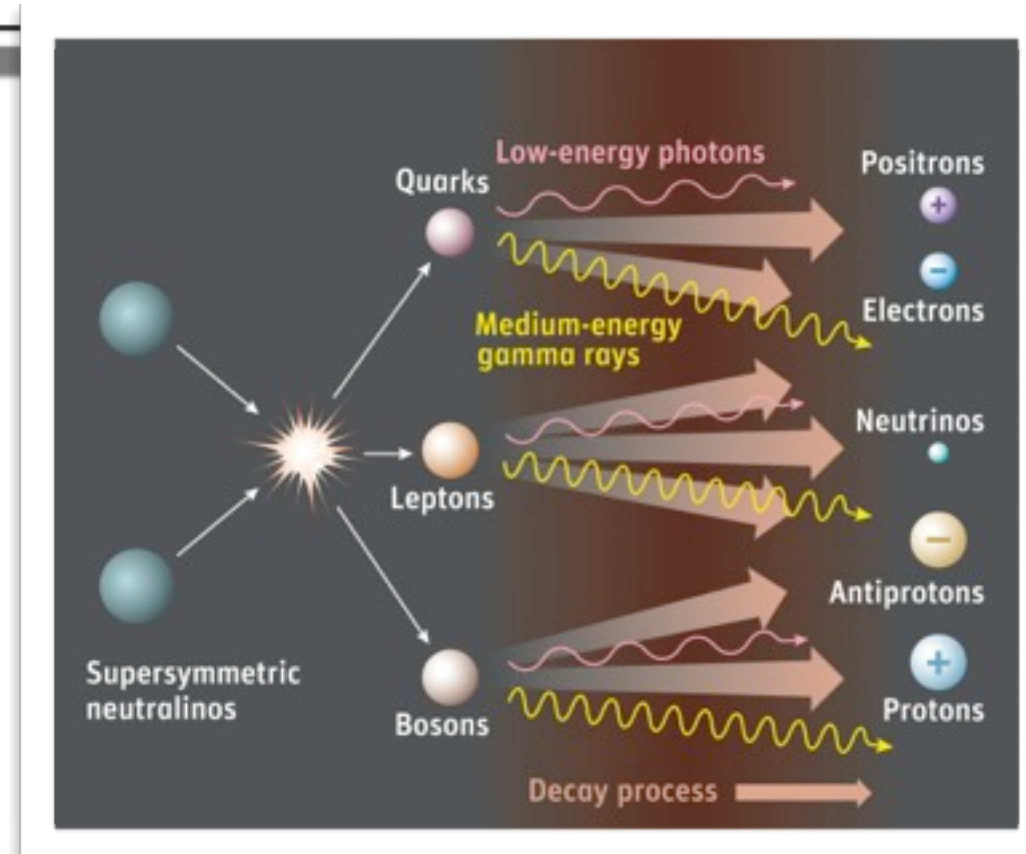

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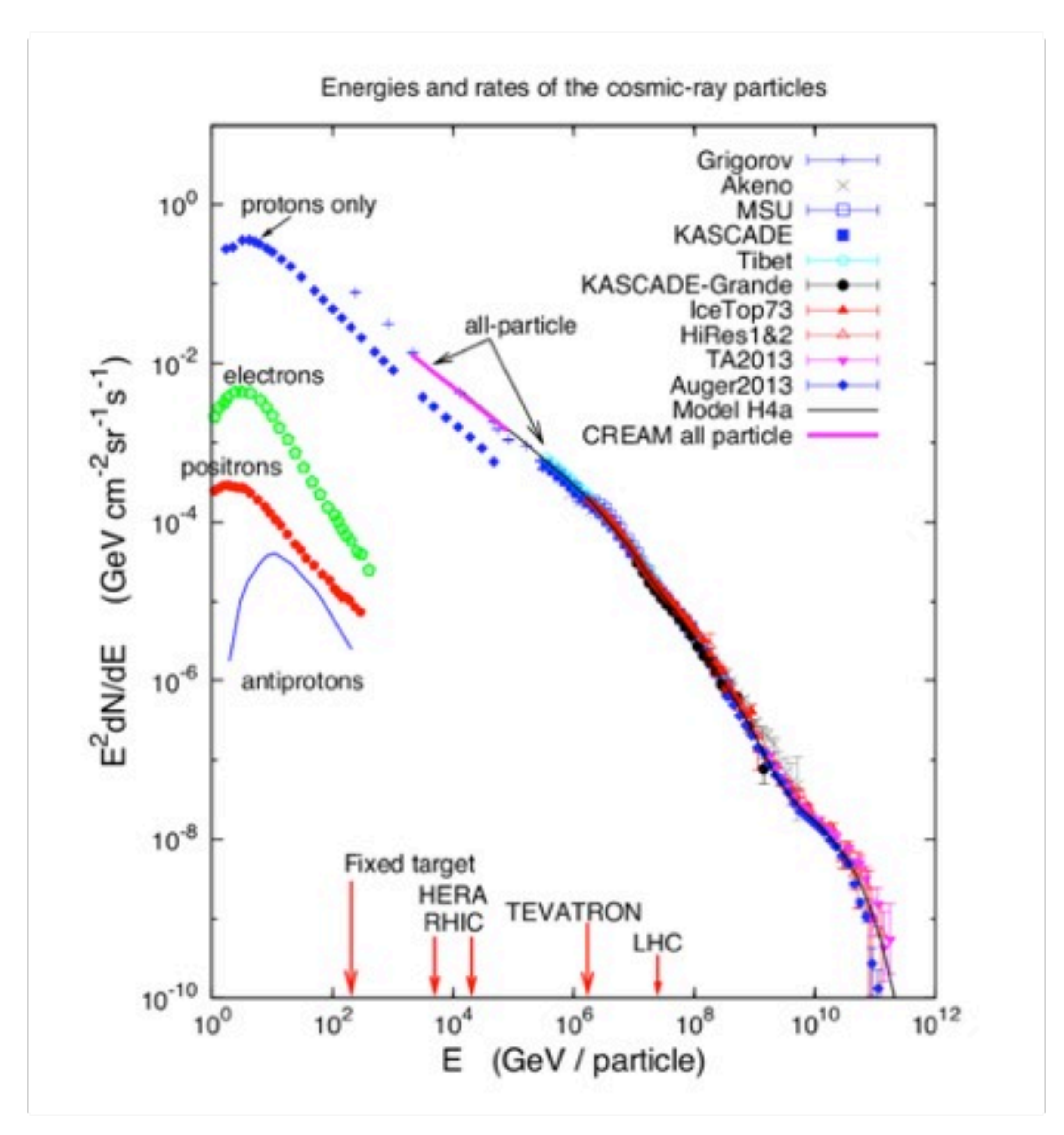
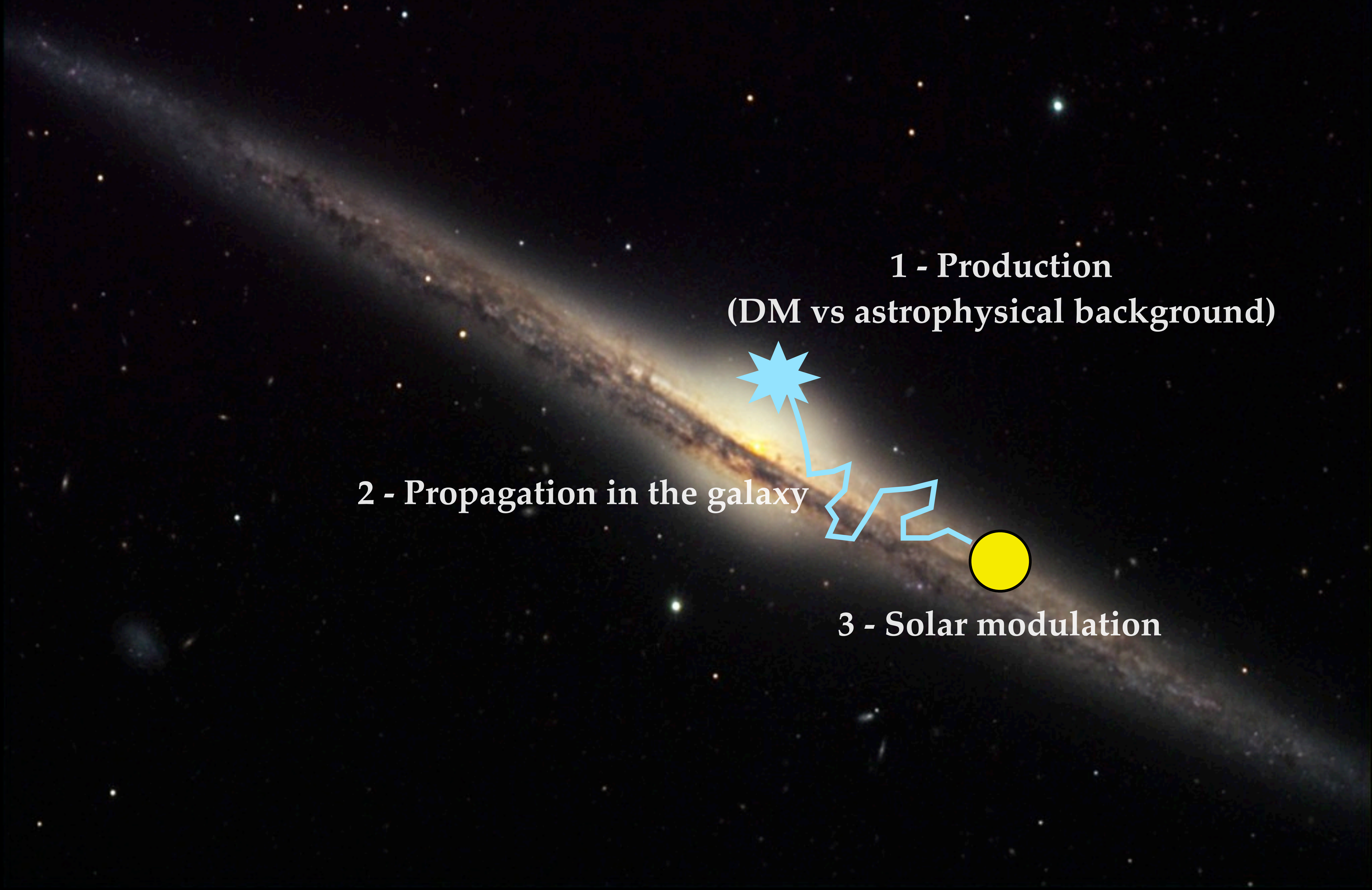
Charged cosmic rays: generalities

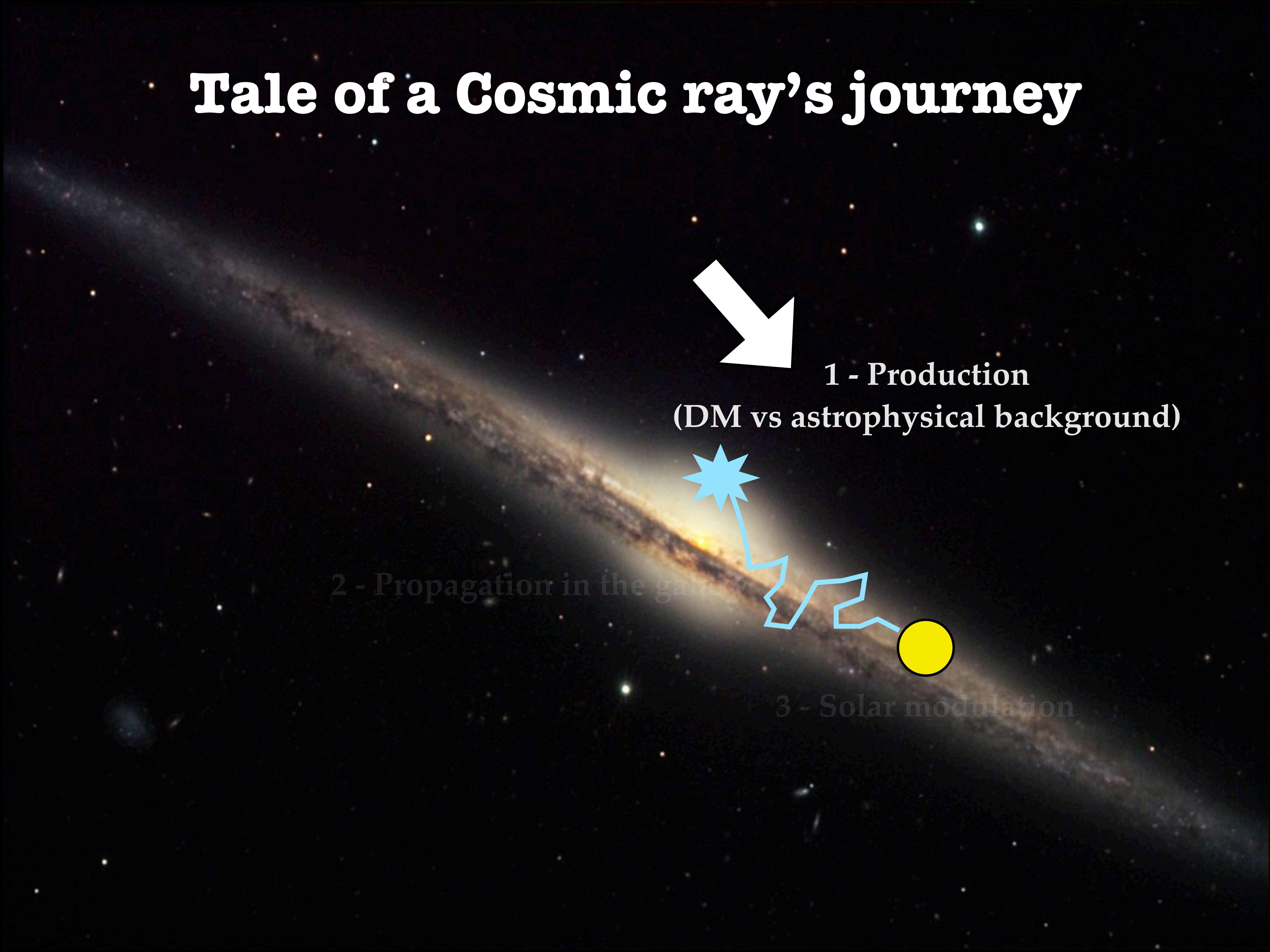


- The CR spectrum can be described by **power law distributions** with shapes varying at fixed points
- CRs are composed for the **98% by nuclei** and for the **2% by electrons**:
  - Among the nuclei: 87% H and 12% He
- **Antimatter** is present but extremely **rare**
  - A good place to look for DM!
- **Primary CRs** are accelerated by astrophysical sources (SNRs)
- CRs generated in **spallation reactions** with the interstellar matter are called **secondary CRs**

How do CRs **propagate** from their source to the observer?

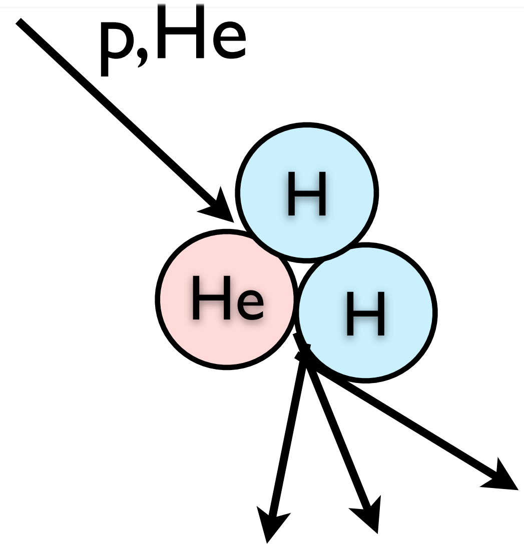
Tale of a Cosmic ray's journey



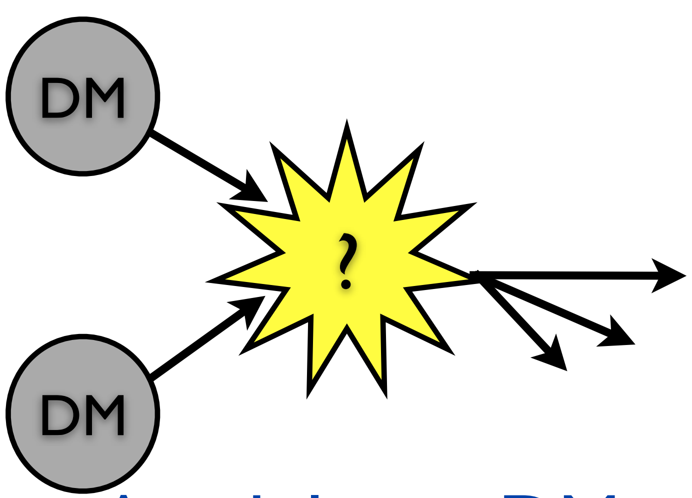

Tale of a Cosmic ray’s journey
1 - Production
(DM vs astrophysical background)
2 - Propagation in the
3 - Solar modulation

Charged cosmic rays: production

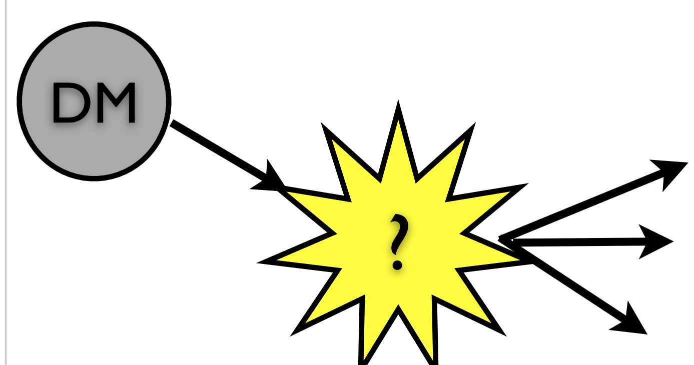
Primary sources (e.g. SNRs)



Secondary CRs



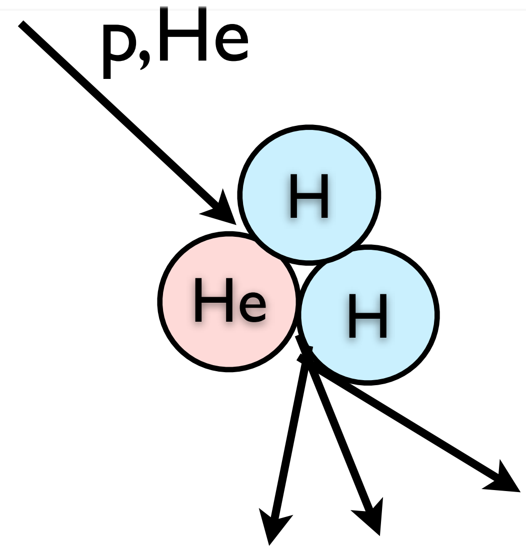
Annihilating DM



Decaying DM

Charged cosmic rays: production

Primary sources (e.g. SNRs)



Secondary CRs

Background

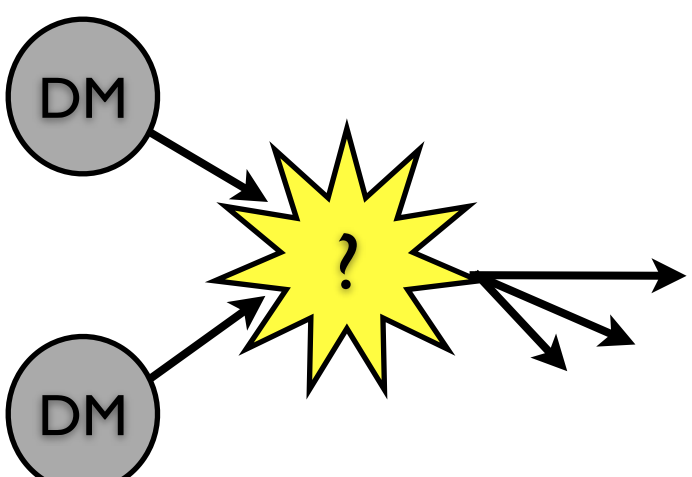
Annihilating DM

Decaying DM

Charged cosmic rays: production

Primary sources (e.g. SNRs)

Secondary CRs



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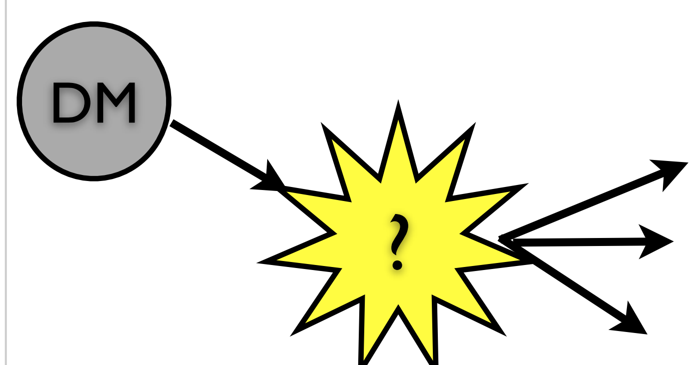
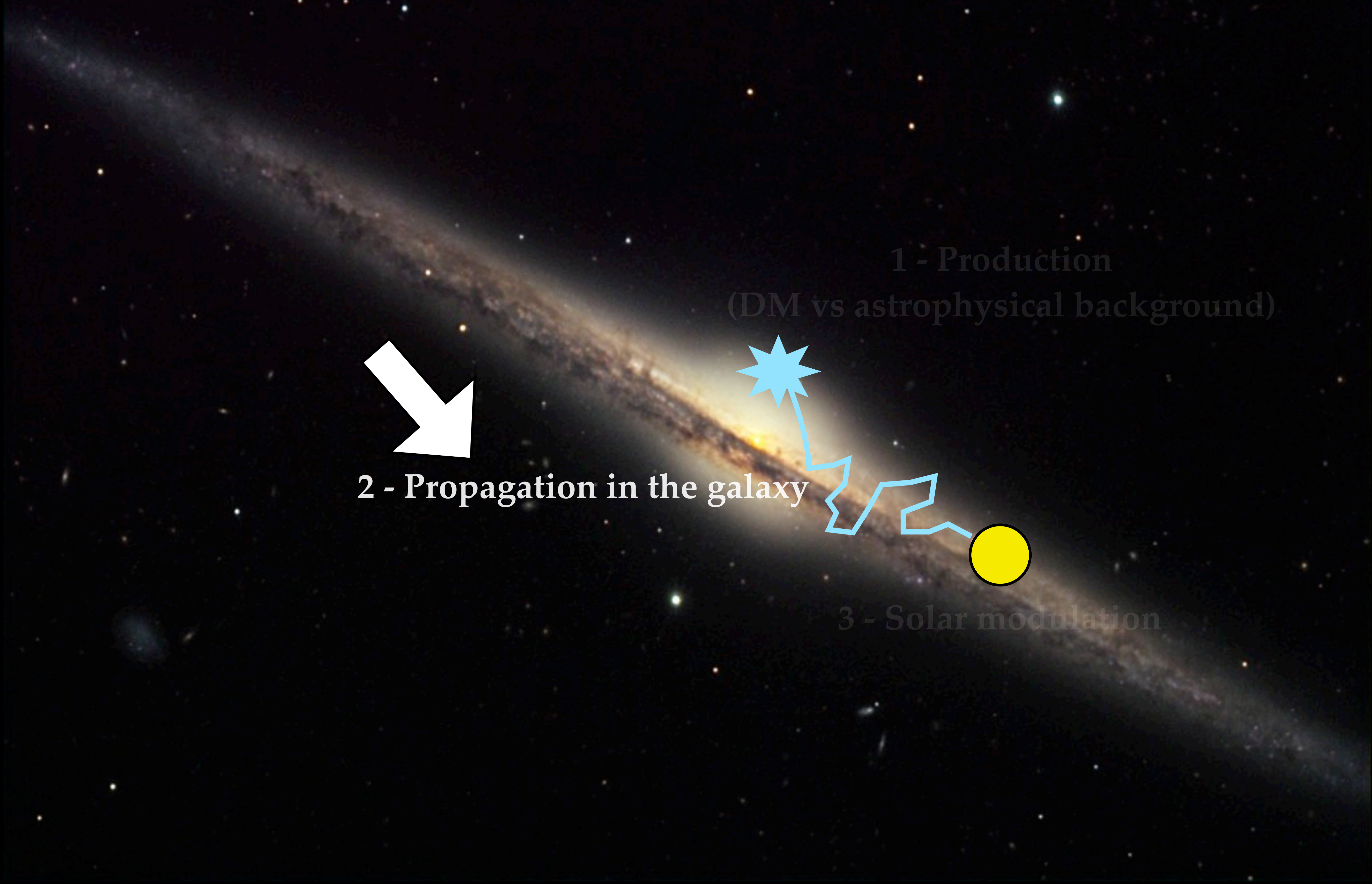


Decaying DM

Signal

Tale of a Cosmic ray's journey



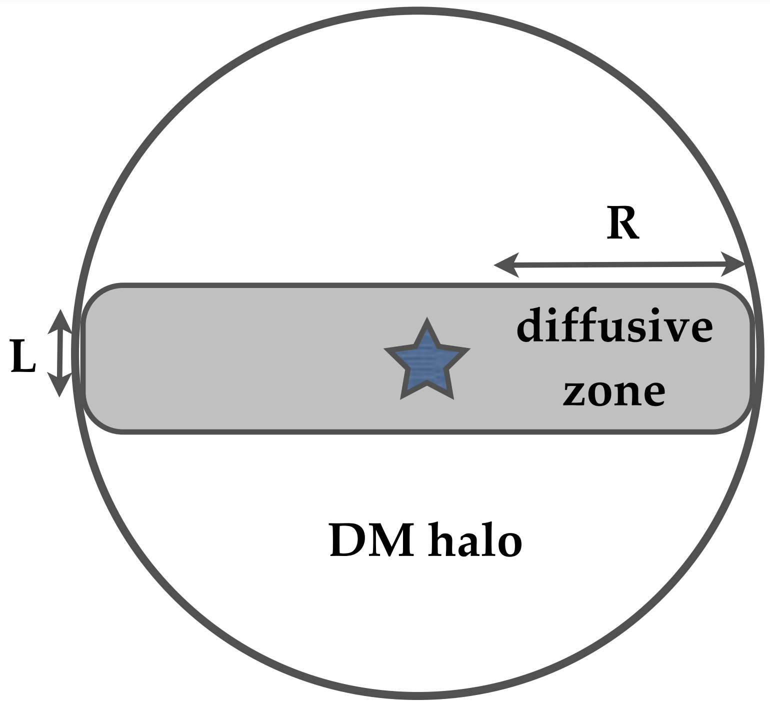
Charged cosmic rays: propagation

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

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

all the information on the production mechanism is here

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

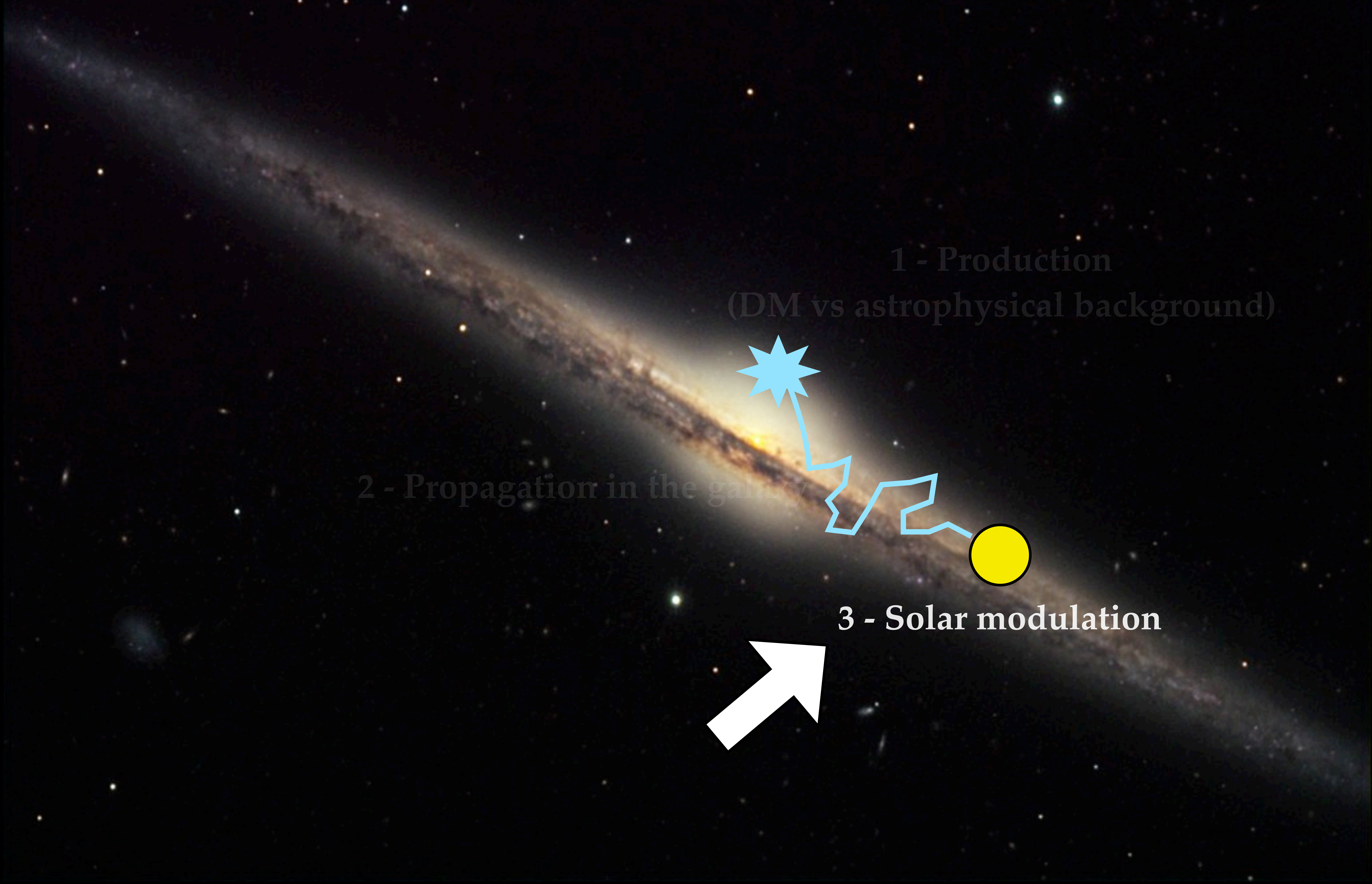
- K_0, V_c, V_a and δ constrained by B/C data
- L can be constrained (L>2kpc) by synchrotron measurements

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

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

F. Donato, N. Fornengo, D. Maurin, P. Salati, PRD 69 (2004) 063501

Tale of a Cosmic ray's journey

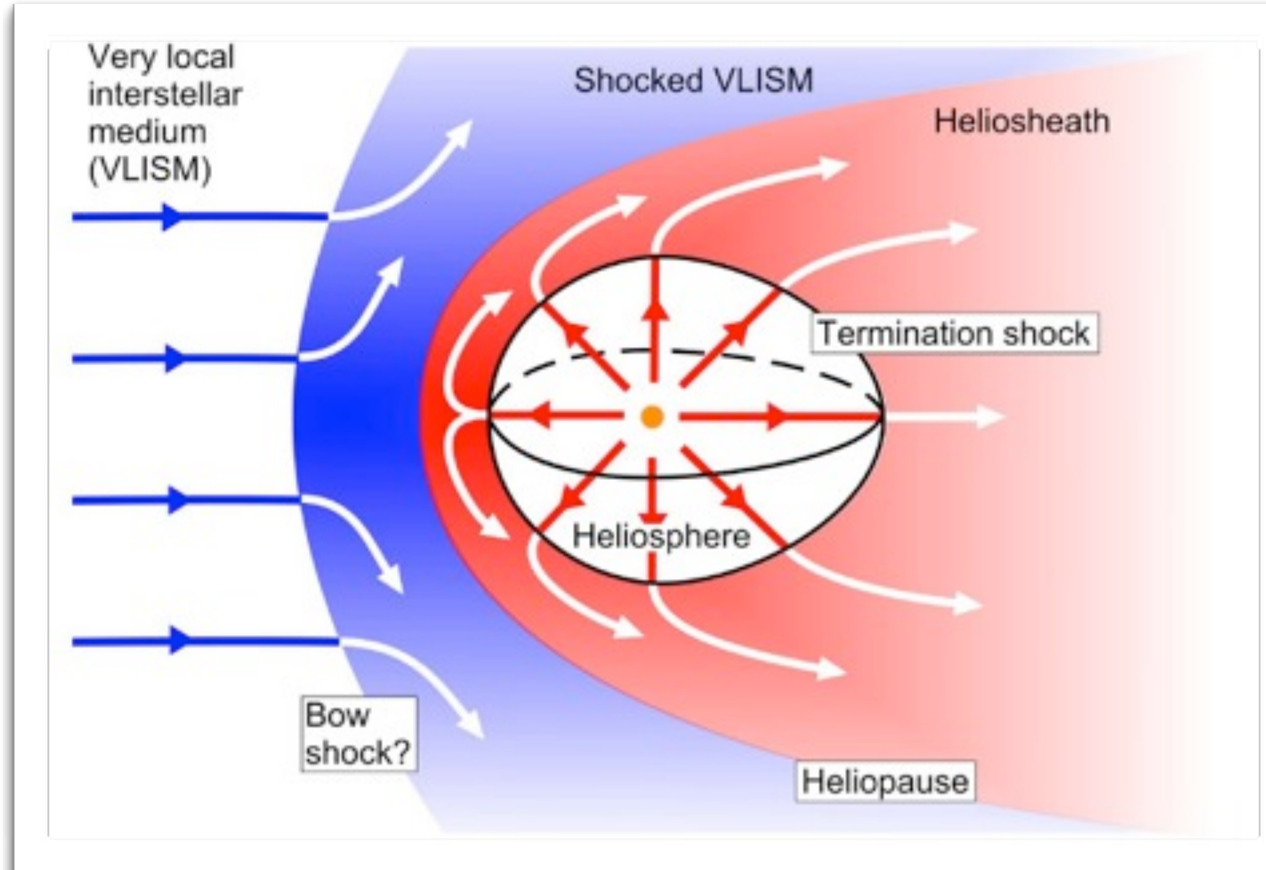


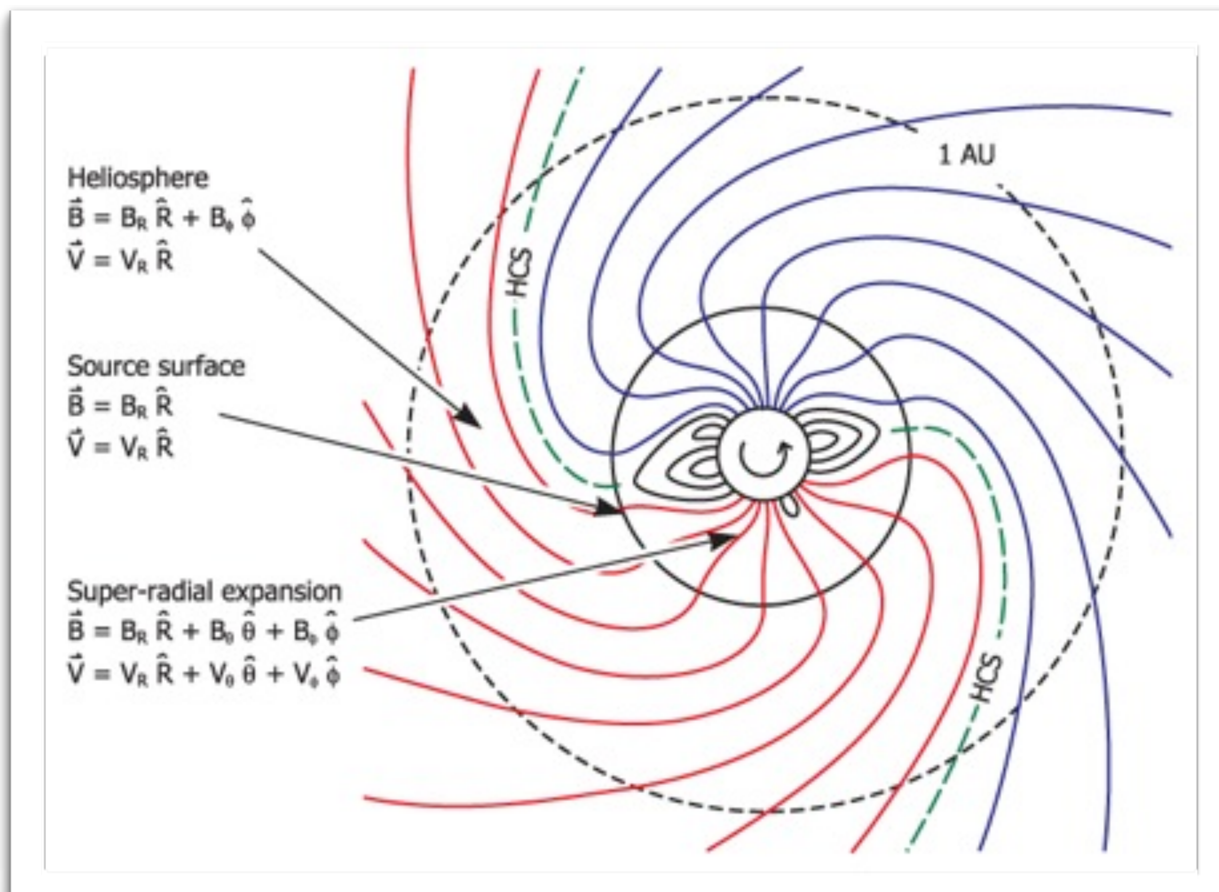
Charged CRs in the heliosphere

•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

Propagation in the heliosphere is described by a **continuity equation**:

$$\frac{\partial f}{\partial t} + \nabla \cdot \left(-\frac{1}{3}\frac{\partial \ln f}{\partial \ln p}\vec{V}_{\mathrm{sw}} f - K \nabla f\right) - \frac{1}{3p^2}\frac{\partial}{\partial p}\left(p^3 \vec{V}_{\mathrm{sw}} \cdot \nabla f\right) = \mathcal{Q}$$

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Steady state

No adiabatic momentum losses

No sources

One can solve it by using **Force Field Approximation**

$$\frac{1}{3}\frac{\partial \ln f}{\partial \ln p}\vec{V}_{\rm sw} f + K\nabla f = \text{const} = 0 \Longrightarrow \frac{\partial f}{\partial r} + \frac{V_{\rm sw}\mathcal{R}}{3k}\frac{\partial f}{\partial \mathcal{R}} = 0$$

Which gives:

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

TOA = Top of Atmosphere (after solar modulation)
IS = interstellar (before solar modulation)

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Steady state

No sources

One can solve it by using **Numerical methods**

One can use 3D models in which the full complexity of the HMF can be taken into account.

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

Drifts (result of the interaction with gradients and curvatures of the HMF) make the solar modulation **charge dependent**

Outline of the talk

Three channels will be discussed:

- **Antiprotons**
  - *N. Fornengo, L. Maccione, AV, JCAP 04 (2014) 003, arXiv:1312.3579*
- **Anti-nuclei**
  - *N. Fornengo, L. Maccione, AV, JCAP 09 (2013) 031, arXiv:1306.4171*
  - *M.Cirelli, N. Fornengo, M.Taoso, AV, JHEP 08 (2014) 009, arXiv: 1402.0321*
  - *T. Aramaki et al. PHYS. REPT. 618 (2016) 1-37, arXiv: 1505.07785*
  - *J. Herms, A. Ibarra, AV, S. Wild, in preparation*
- **Positrons**
  - *M. Di Mauro, F. Donato, N.Fornengo, R.Lineros, AV, JCAP 04 (2014) 003, arXiv:1401.4017*
  - *M. Di Mauro, F. Donato, N.Fornengo, AV, arXiv:1507.07001*

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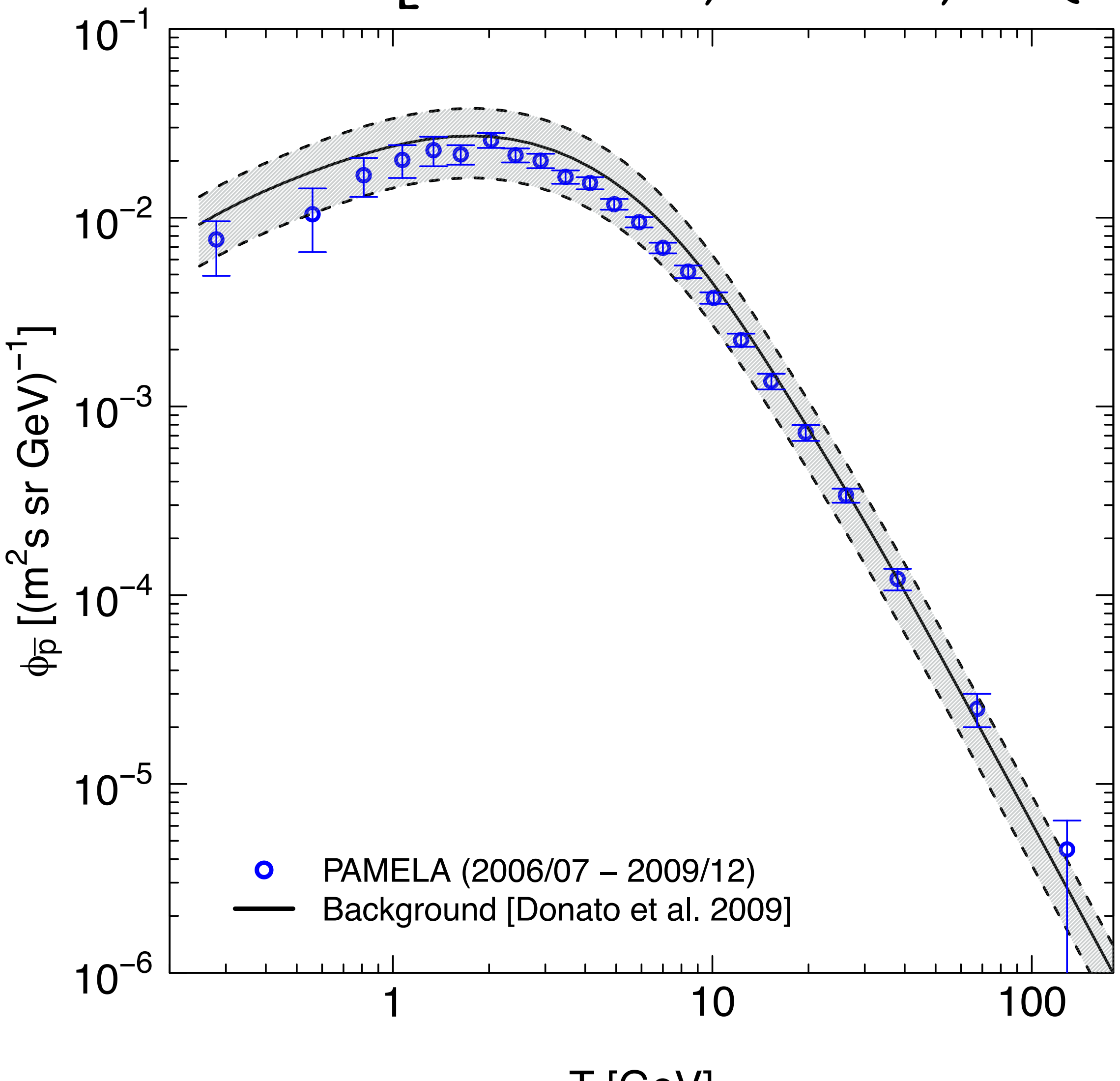
DM searches with antiprotons

The astrophysical **background** is usually assumed to be of purely **secondary origin**. The dominant contribution to this flux comes from **proton-proton** collisions:

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

PAMELA data [**Adriani et al., JETPL 96, 621 (2012)**]



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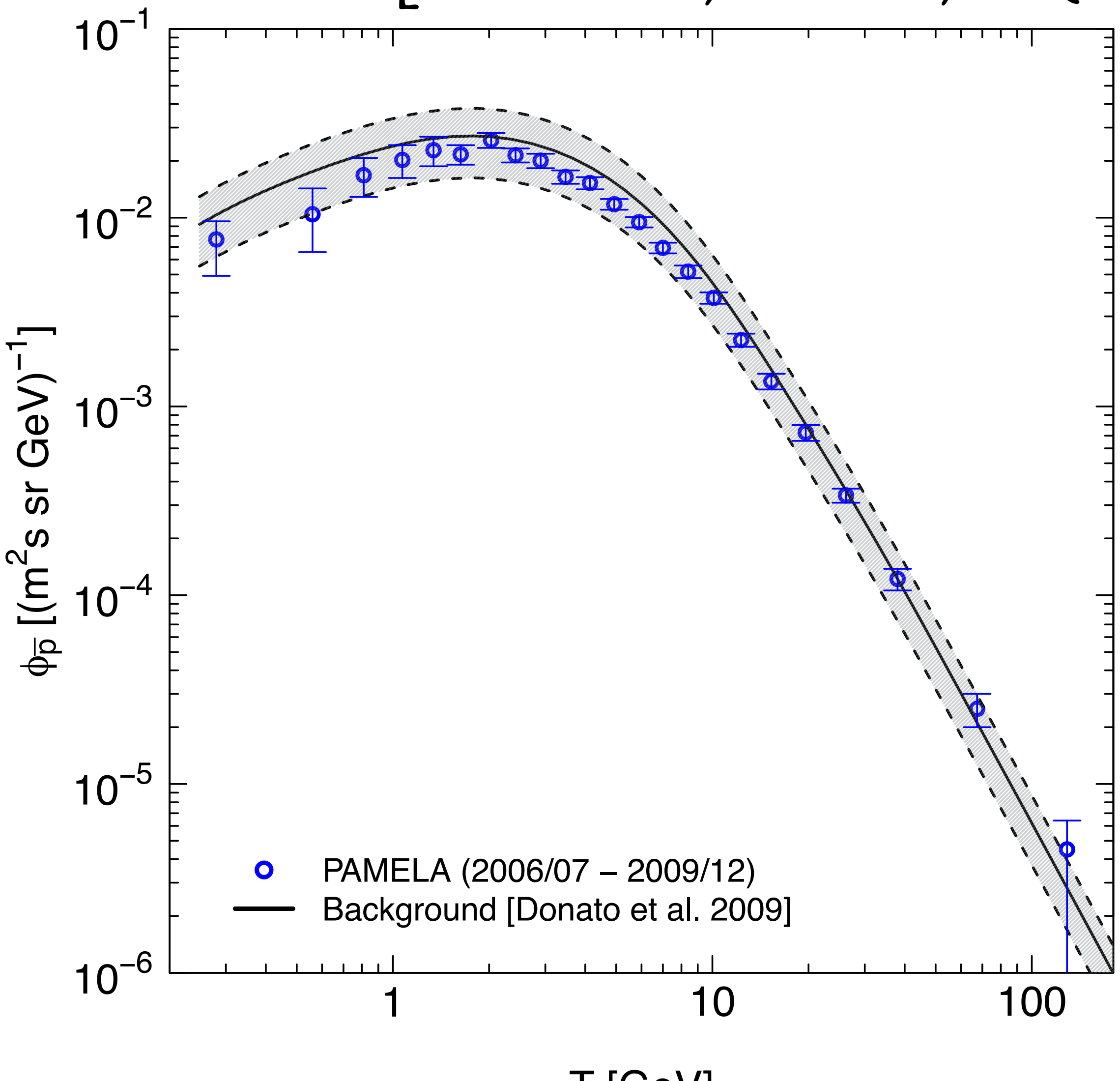

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spallation cross section

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primary flux

H density in the ISM

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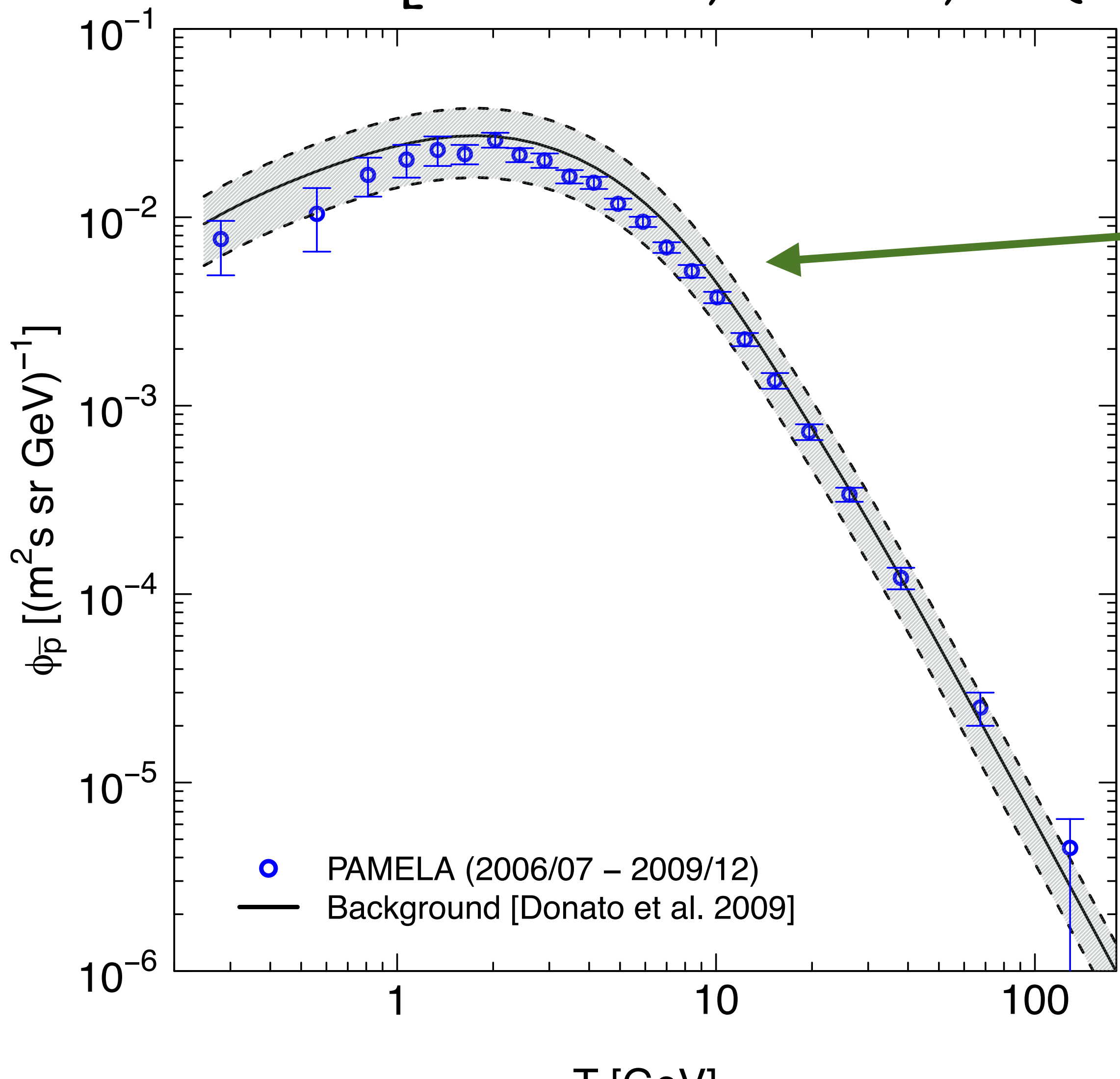

uncertainty related to spallation cross sections (approx. 40% of the flux)

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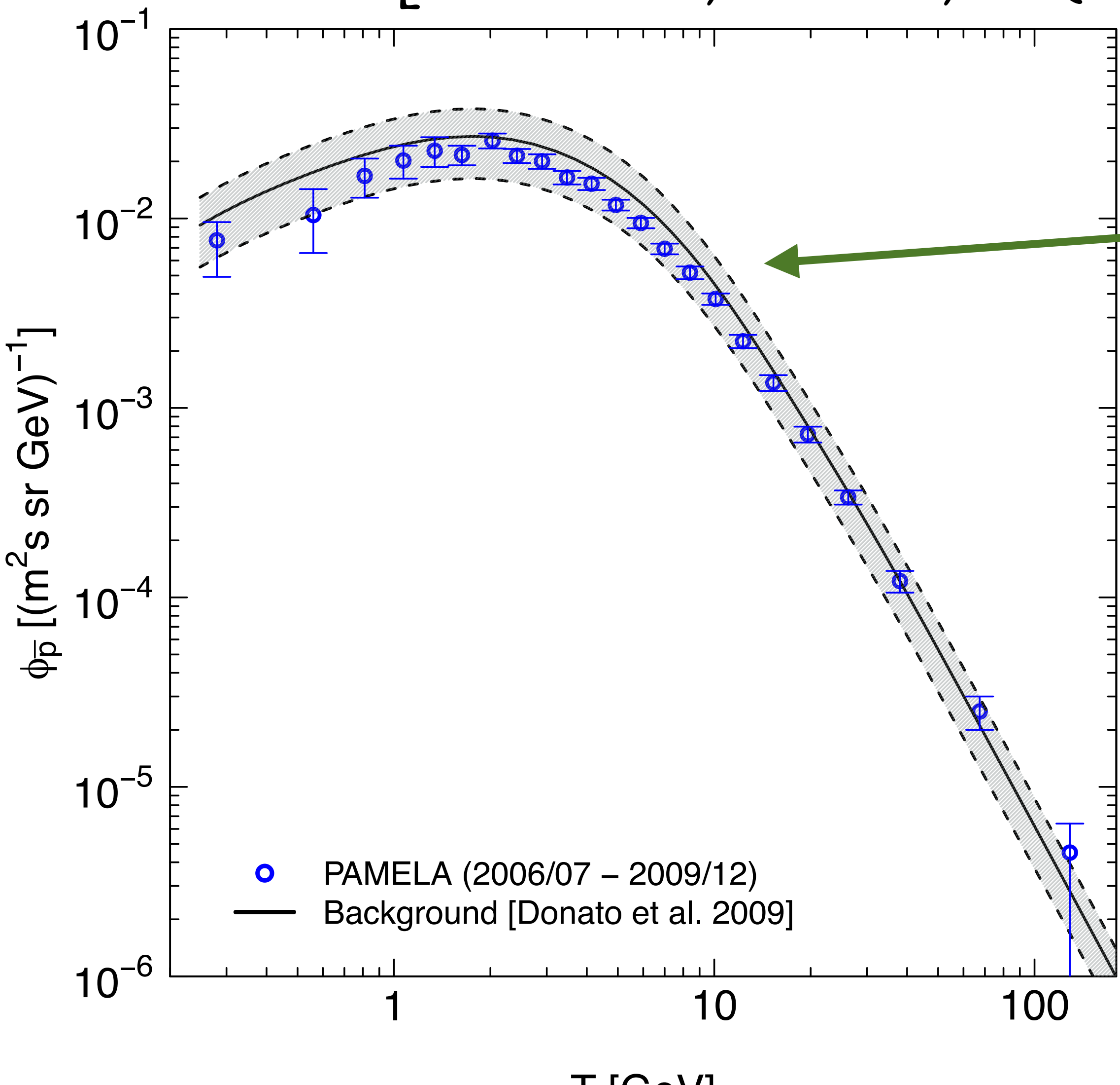
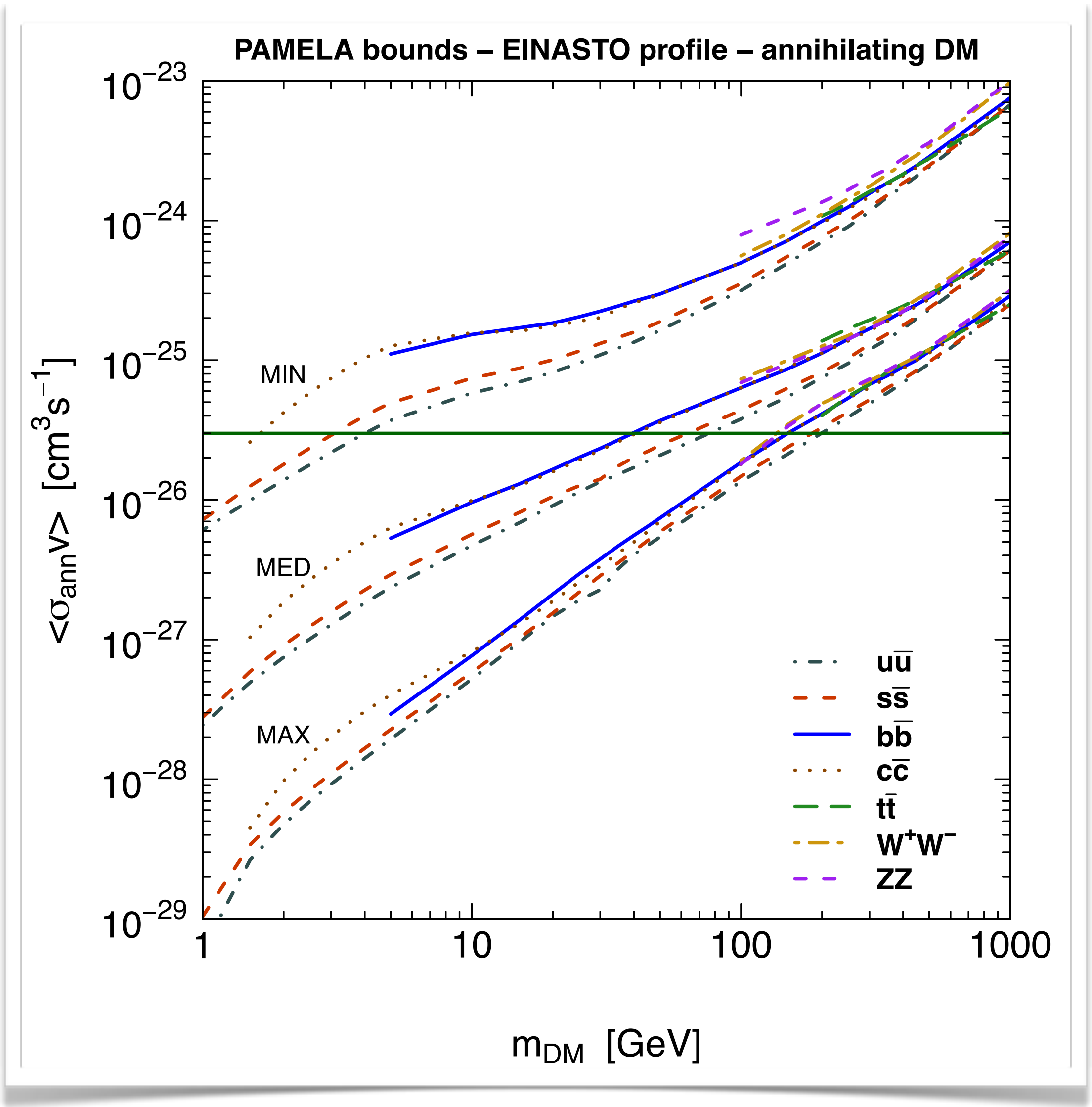
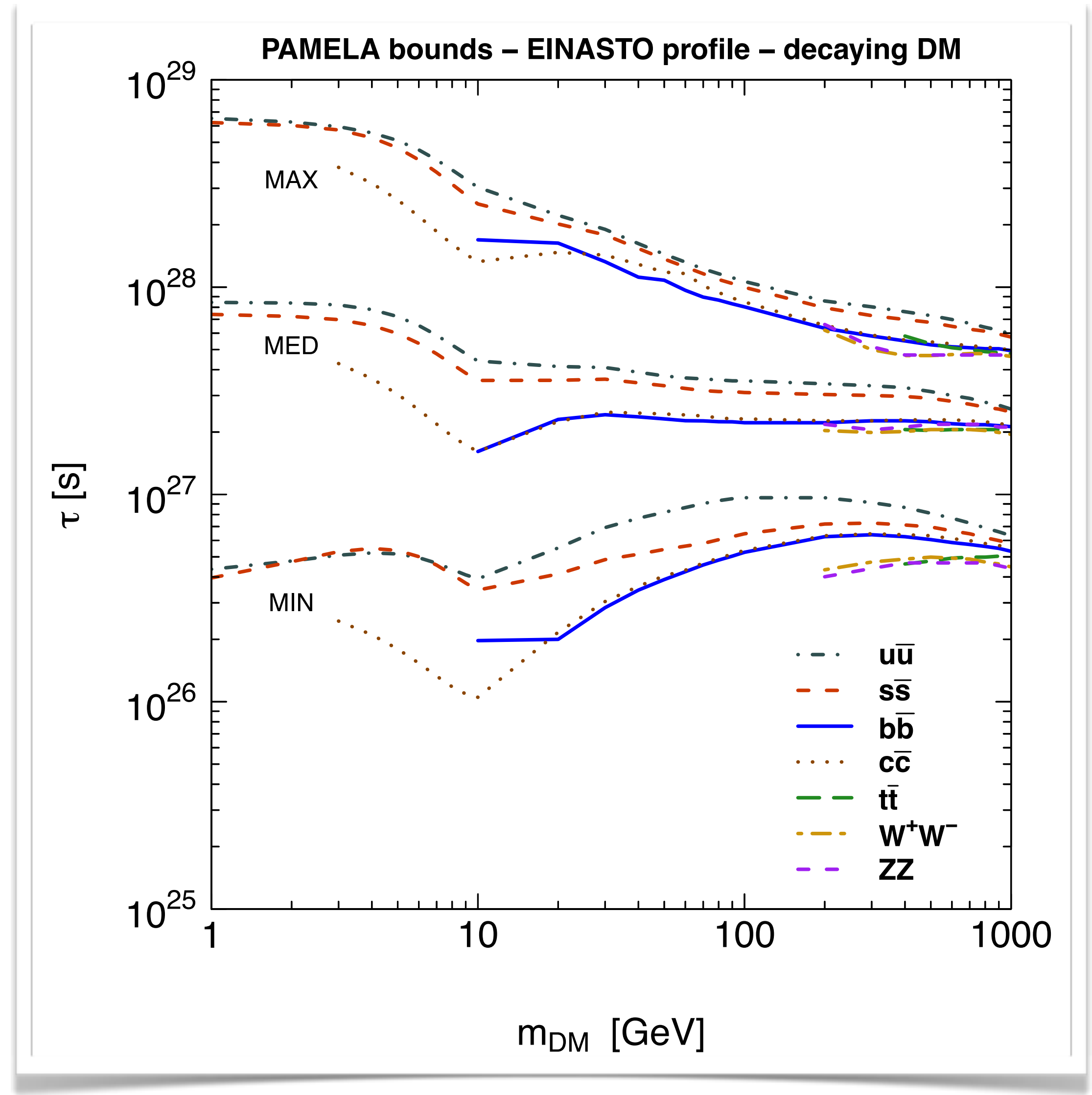


uncertainty related to spallation cross sections (approx. 40% of the flux)

There seems to be very little room left for Dark Matter!

DM searches with antiprotons



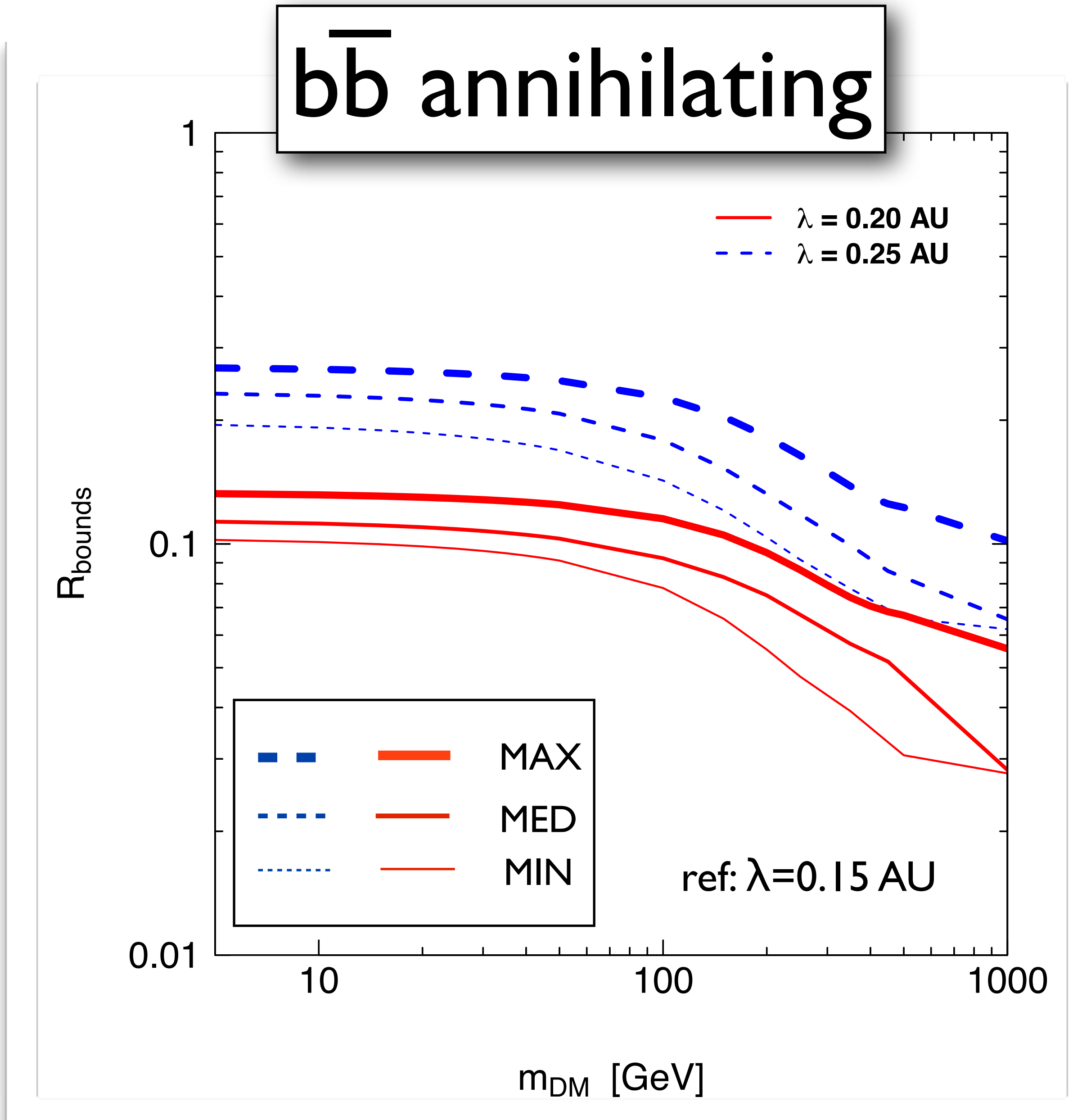


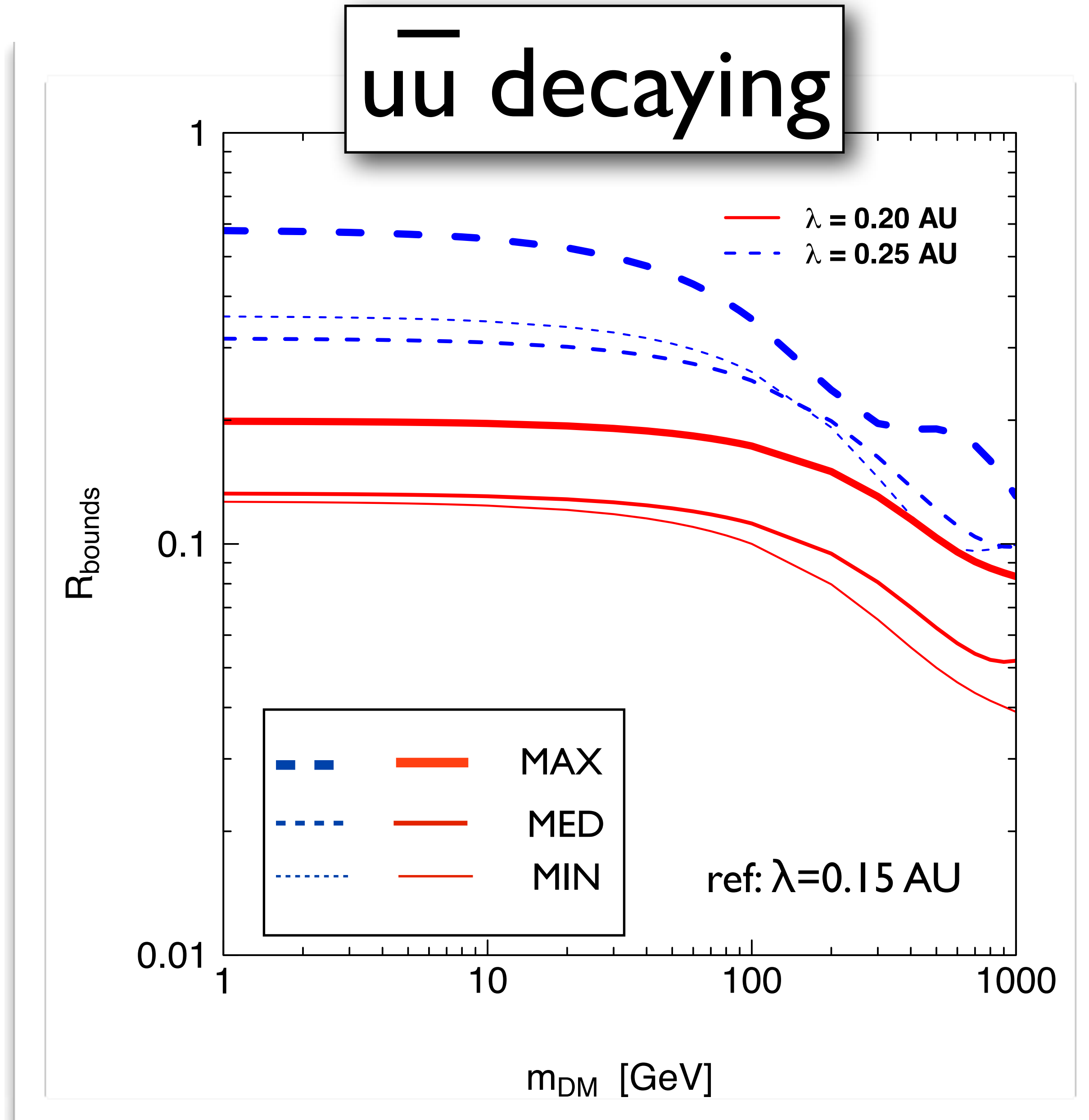
N. Fornengo, L. Maccione, AV, JCAP 04 (2014) 003, arXiv:1312.3579

- As expected, the choice of the **propagation model** is related to the **largest uncertainty**
- The solar modulation used here is **charge dependent** and its parameters are compatible with PAMELA data taking period. What happens if we **change their values**?

The role of solar modulation

We can plot the **percentage difference** for different choices of the solar modulation parameters (antiproton mean-free-path λ in the heliosphere)





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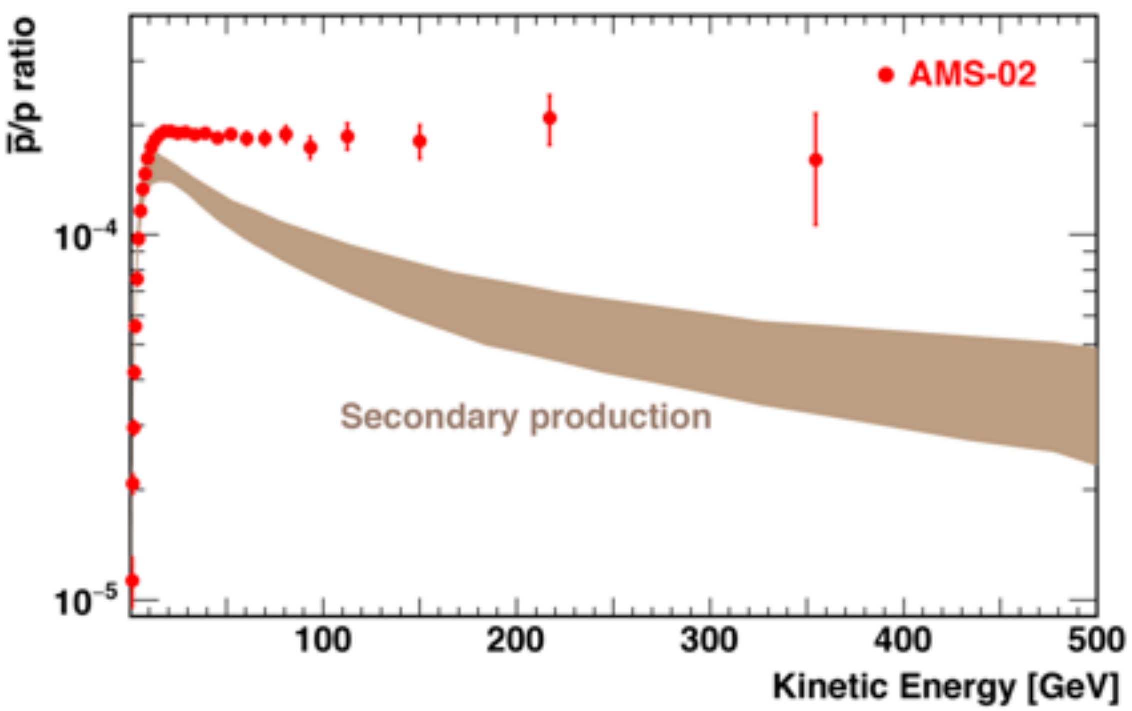
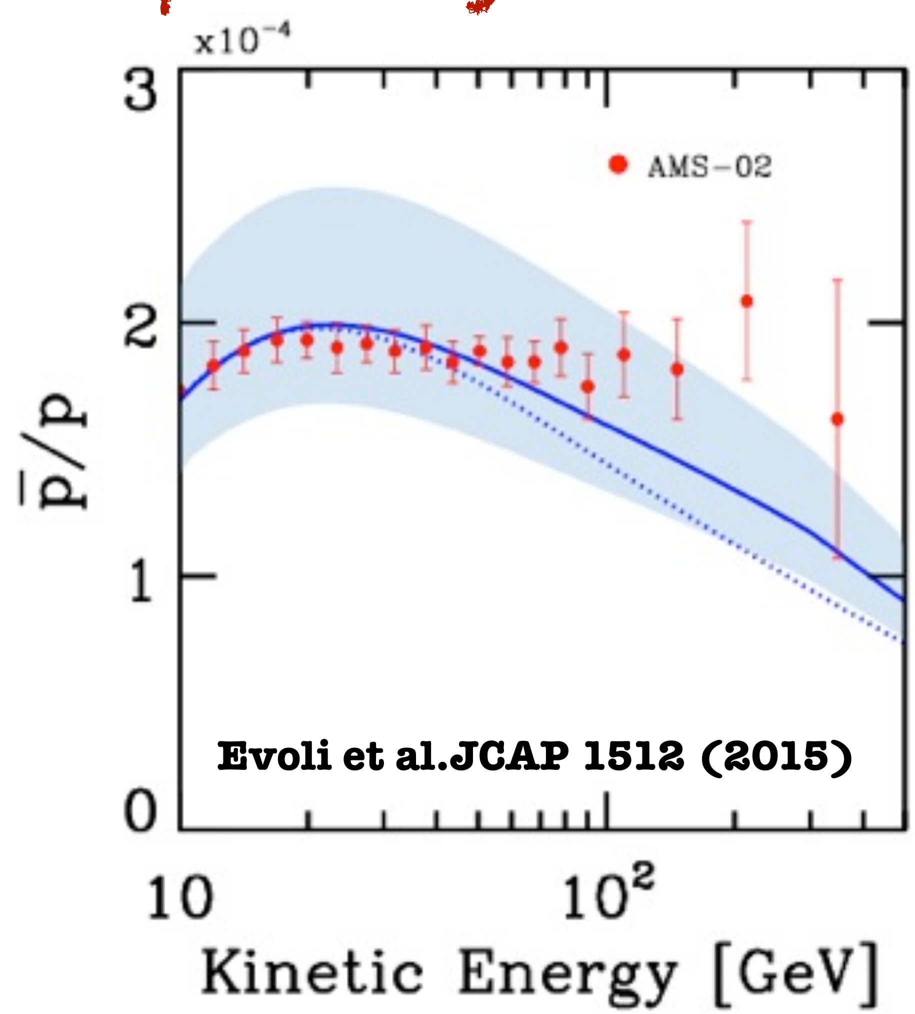
DM searches with antiprotons
-more recent news-

Last year, the AMS collaboration has shown the antiproton/proton ratio up to unprecedented high energies:

What was shown:



What is probably more realistic:



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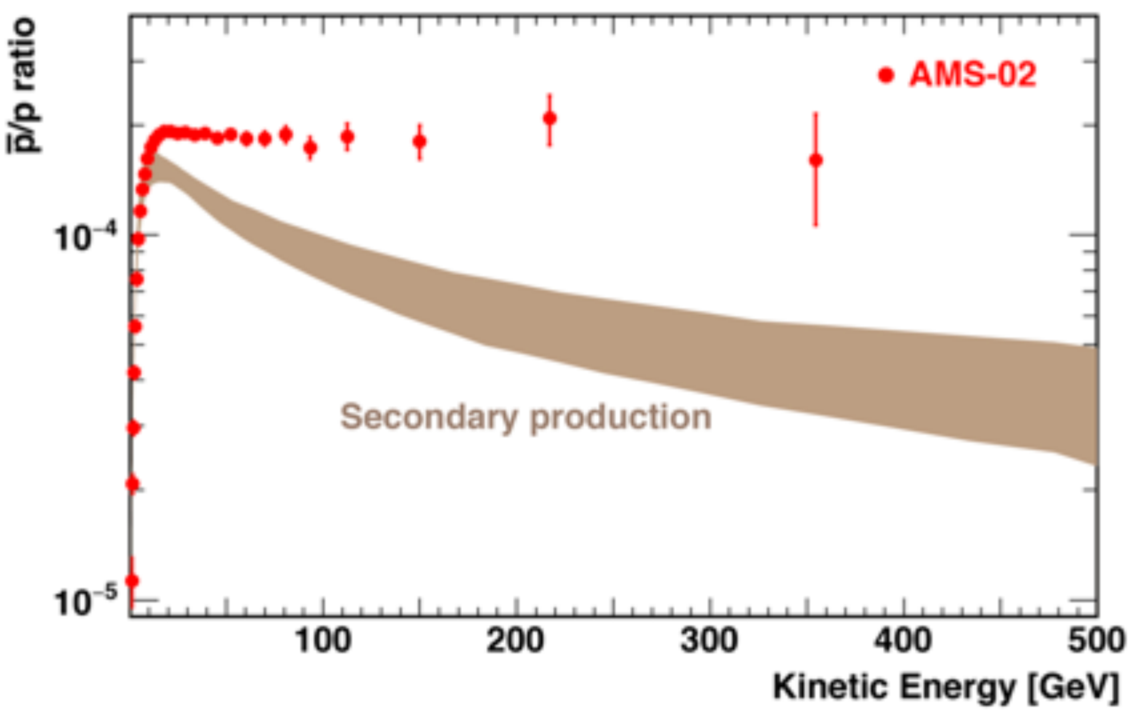

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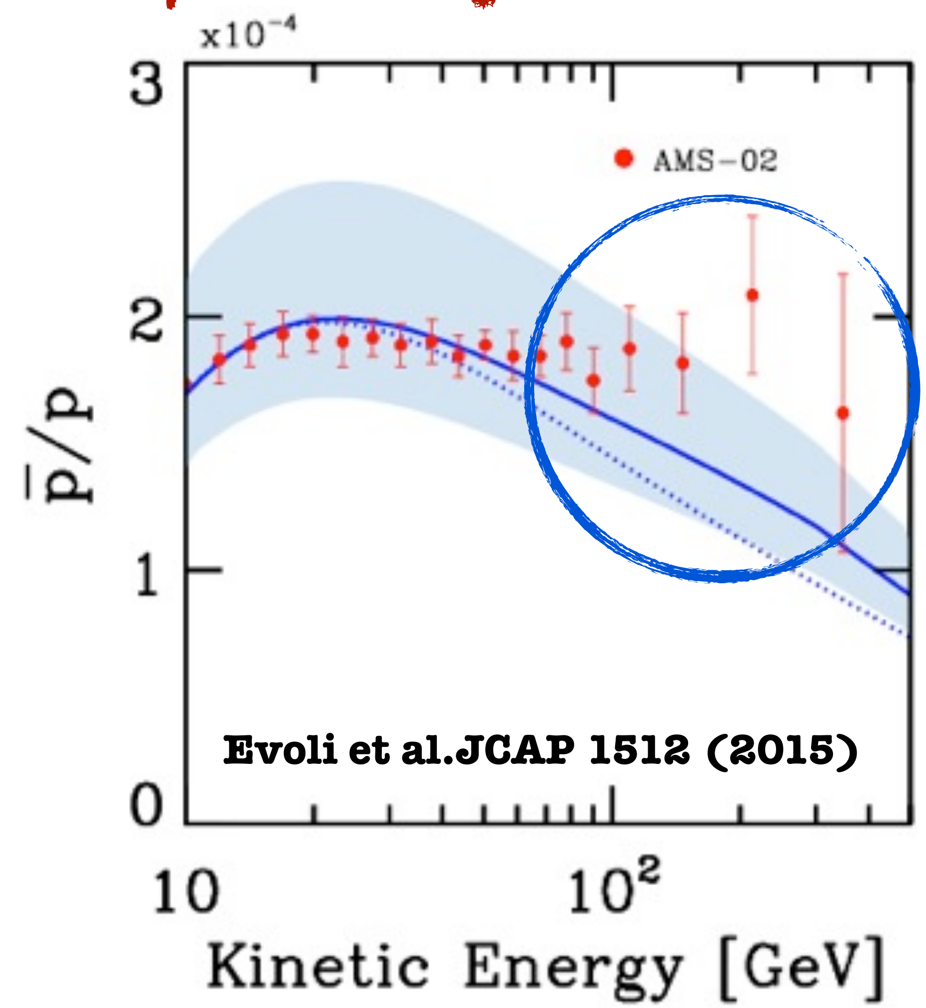
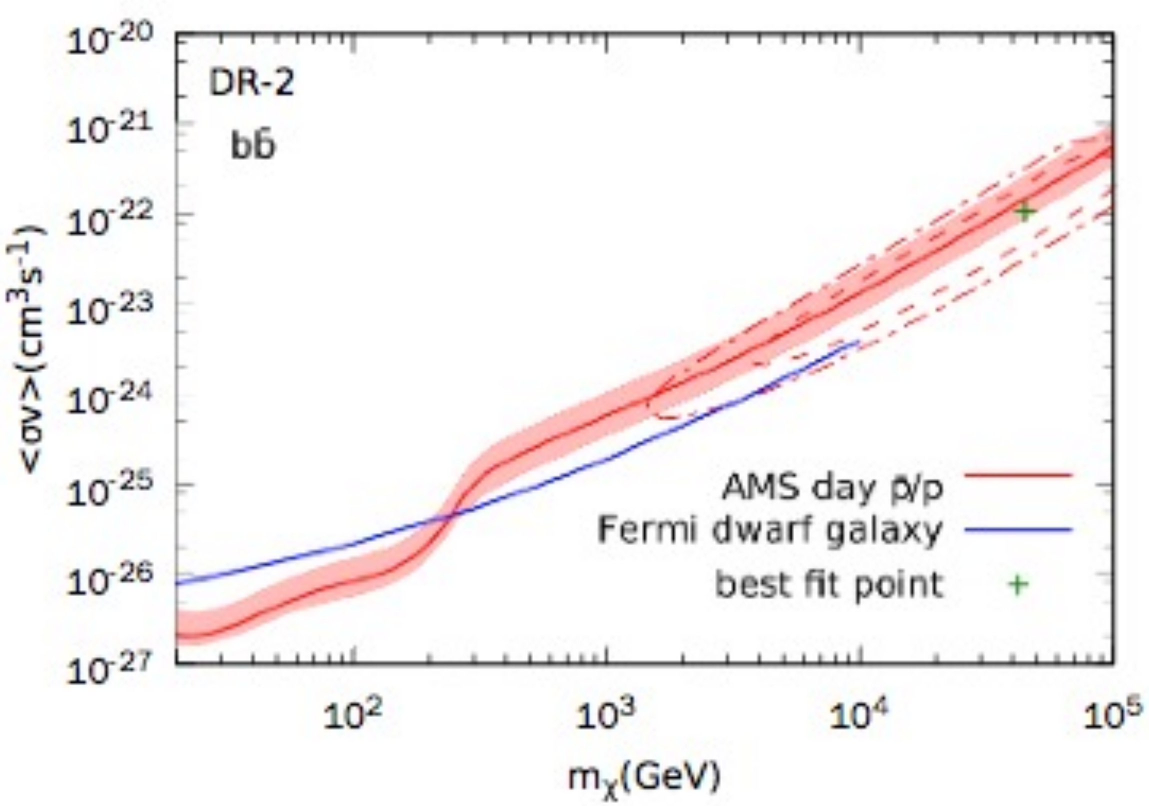


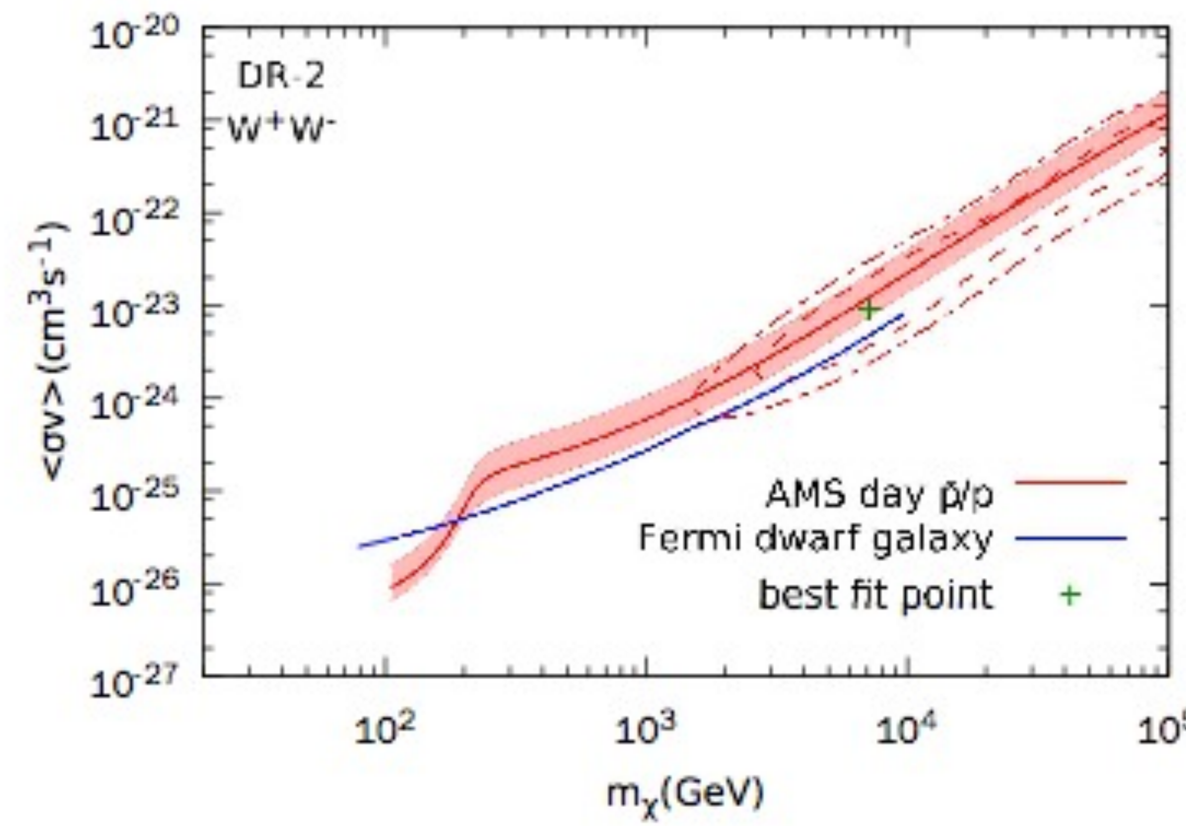
DM searches with antiprotons
-more recent news-

Are we observing an excess of antiprotons?

If **interpreted** in terms of **annihilating DM**, we are around the bounds set by FERMI:

Lin et al. arXiv:1504.07230





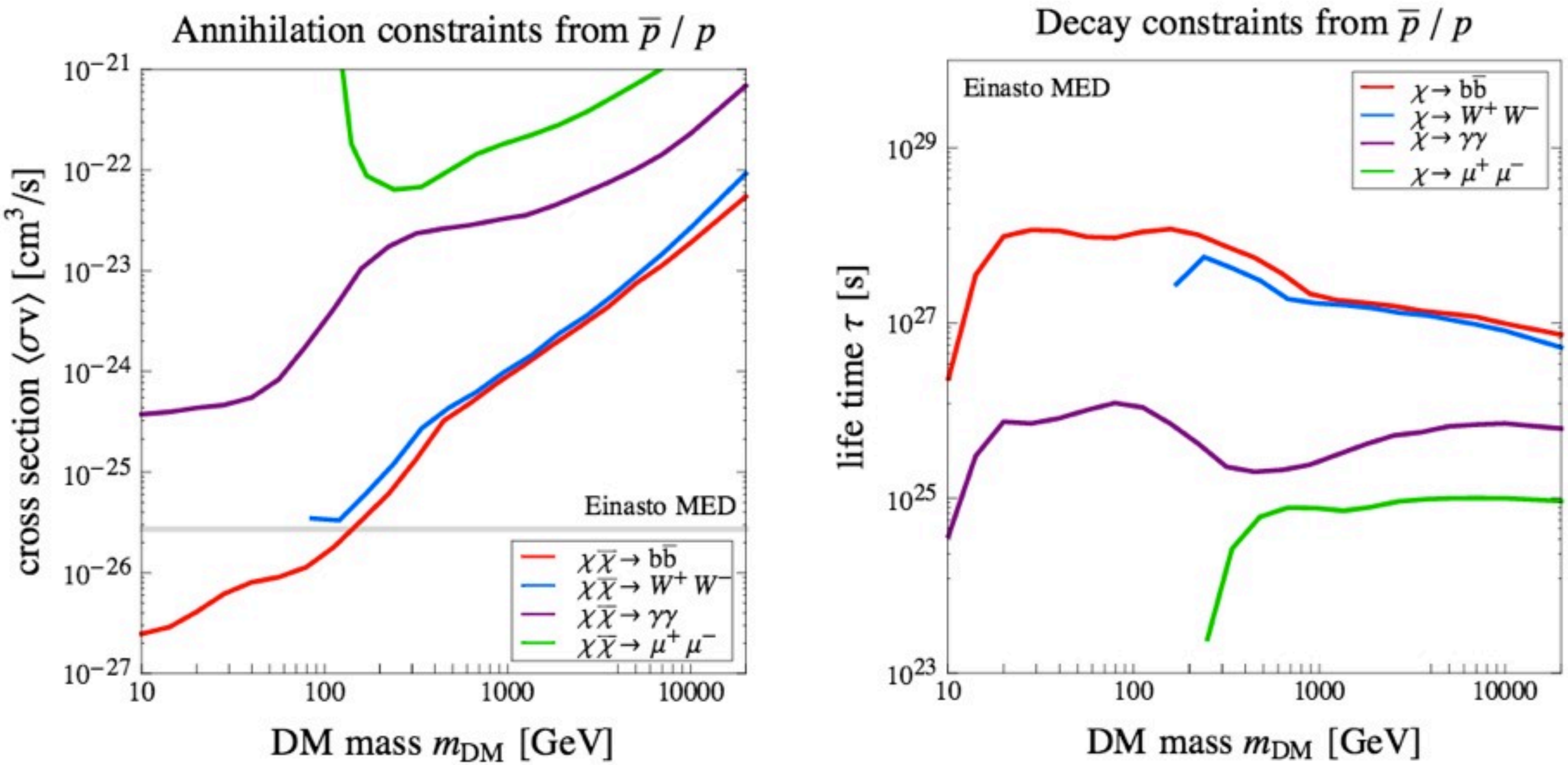
However, some astrophysical sources can fit this excess as well:

- A nearby supernova active in the past (~2Myr ago)
  Kachelriess et al. arXiv:1504.06472
- Secondary production inside the SNR shock region
  Blasi and Serpico, PRL 103 (2009) 081103

They can also be responsible for the rise in the positron fraction!

DM searches with antiprotons
-more recent news-

If the AMS data are used to set constraints on DM properties in the MED propagation model, one finds:



Giesen et al. JCAP 1509 (2015)

What can we say?

•DM candidates annihilating/decaying into quarks are **strongly constrained** by the antiproton measurements of PAMELA and AMS

•The **uncertainties** affecting the computation of the constraints are **many**:

- The **galactic propagation** parameters
- The **spallation cross sections**
- The **Solar modulation**
- The features of the **astrophysical background** (especially at high energies)

•Because of these uncertainties and the limited statistics, it is **very difficult** to say anything unambiguous about the presence of an **excess in AMS** high-energy data.

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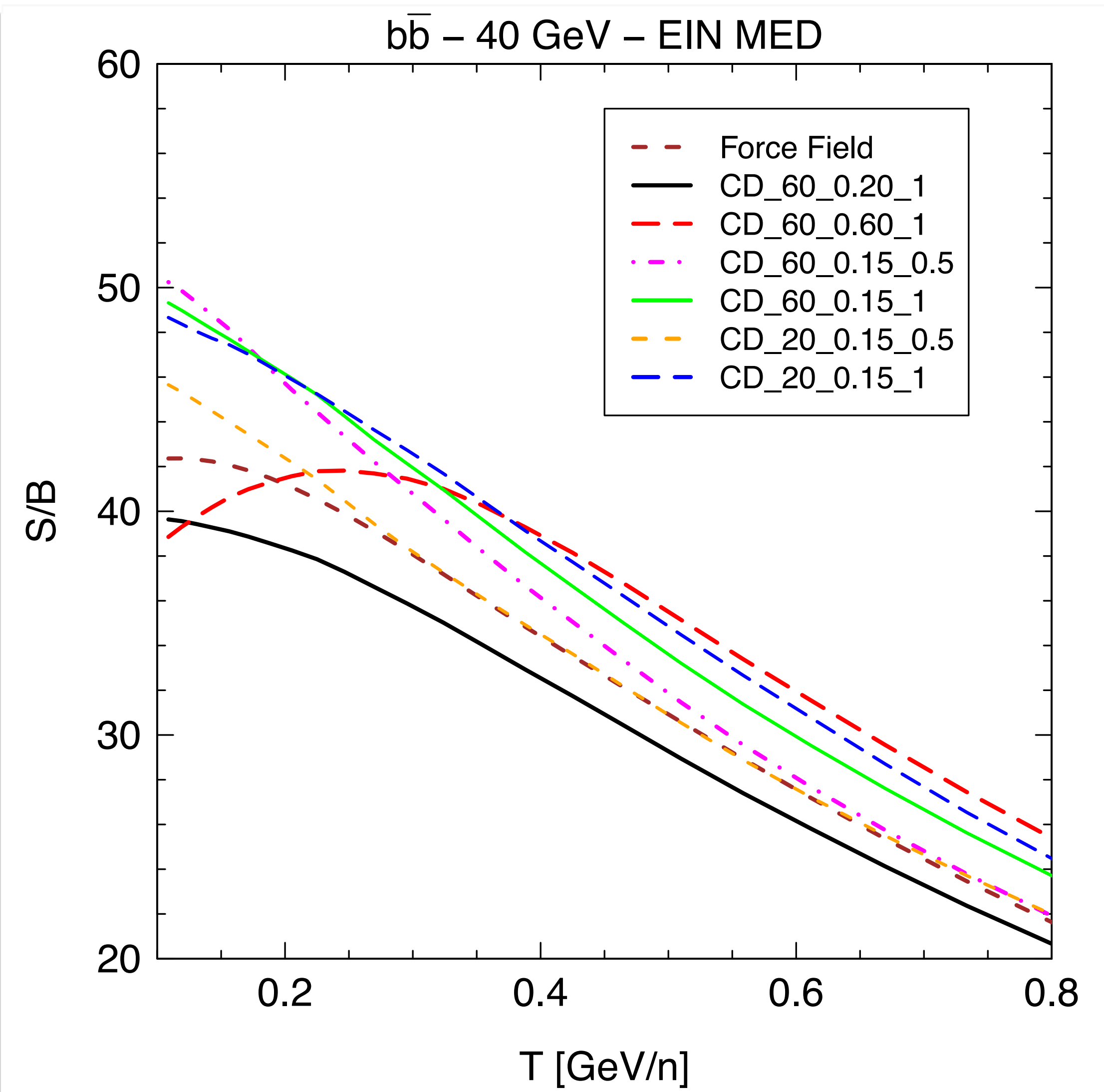
  - *N. Fornengo, L. Maccione, AV, JCAP 04 (2014) 003, arXiv:1312.3579*
- **Anti-nuclei**
  - *N. Fornengo, L. Maccione, AV, JCAP 09 (2013) 031, arXiv:1306.4171*
  - *M.Cirelli, N. Fornengo, M.Taoso, AV, JHEP 08 (2014) 009, arXiv: 1402.0321*
  - *T. Aramaki et al. PHYS. REPT. 618 (2016) 1-37, arXiv: 1505.07785*
  - *J. Herms, A. Ibarra, AV, S. Wild, in preparation*
- **Positrons**
  - *M. Di Mauro, F. Donato, N.Fornengo, R.Lineros, AV, JCAP 04 (2014) 003, arXiv:1401.4017*
  - *M. Di Mauro, F. Donato, N.Fornengo, AV, arXiv:1507.07001*

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

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

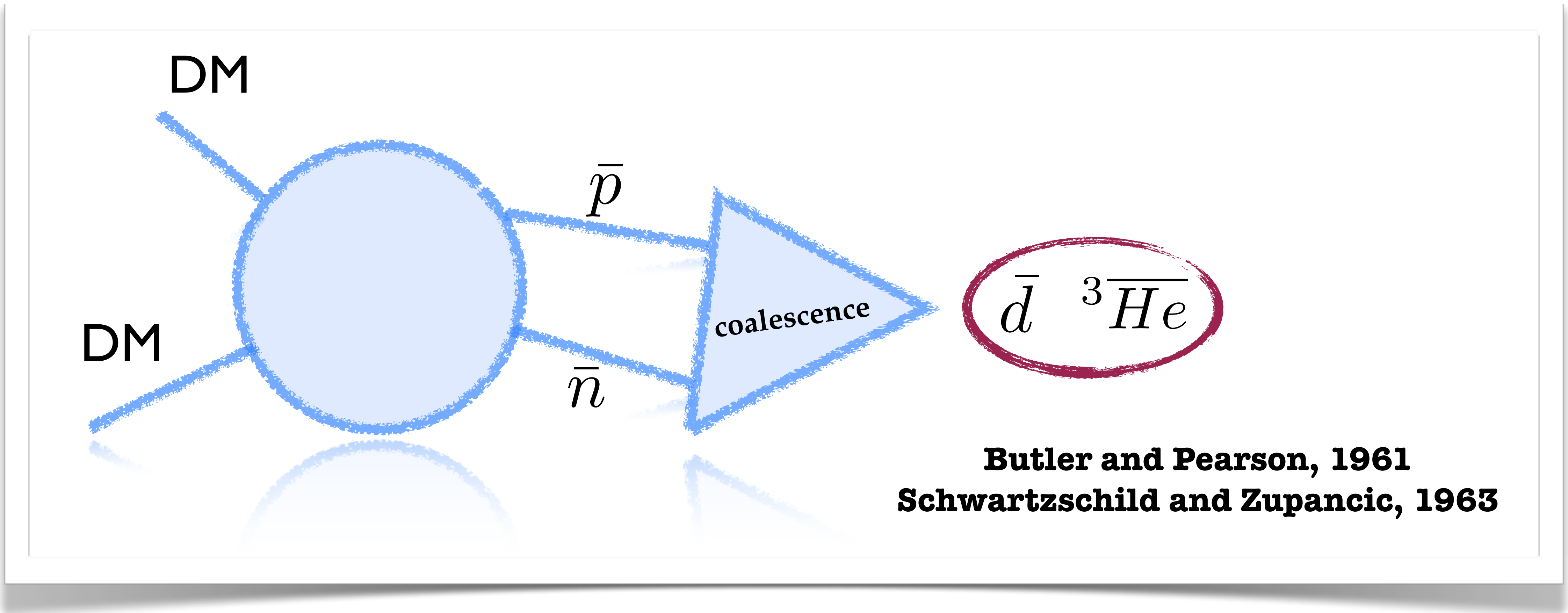
The **large energy thresholds**, together with the steeply falling primary spectra make the astrophysical background **highly suppressed** at low energies

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

Donato, Fornengo, Salati, 2000

Anti-nuclei production

Anti-nuclei are the result of the merging (**coalescence**) of 2 or 3 anti-nucleons



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**:

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

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

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

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

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

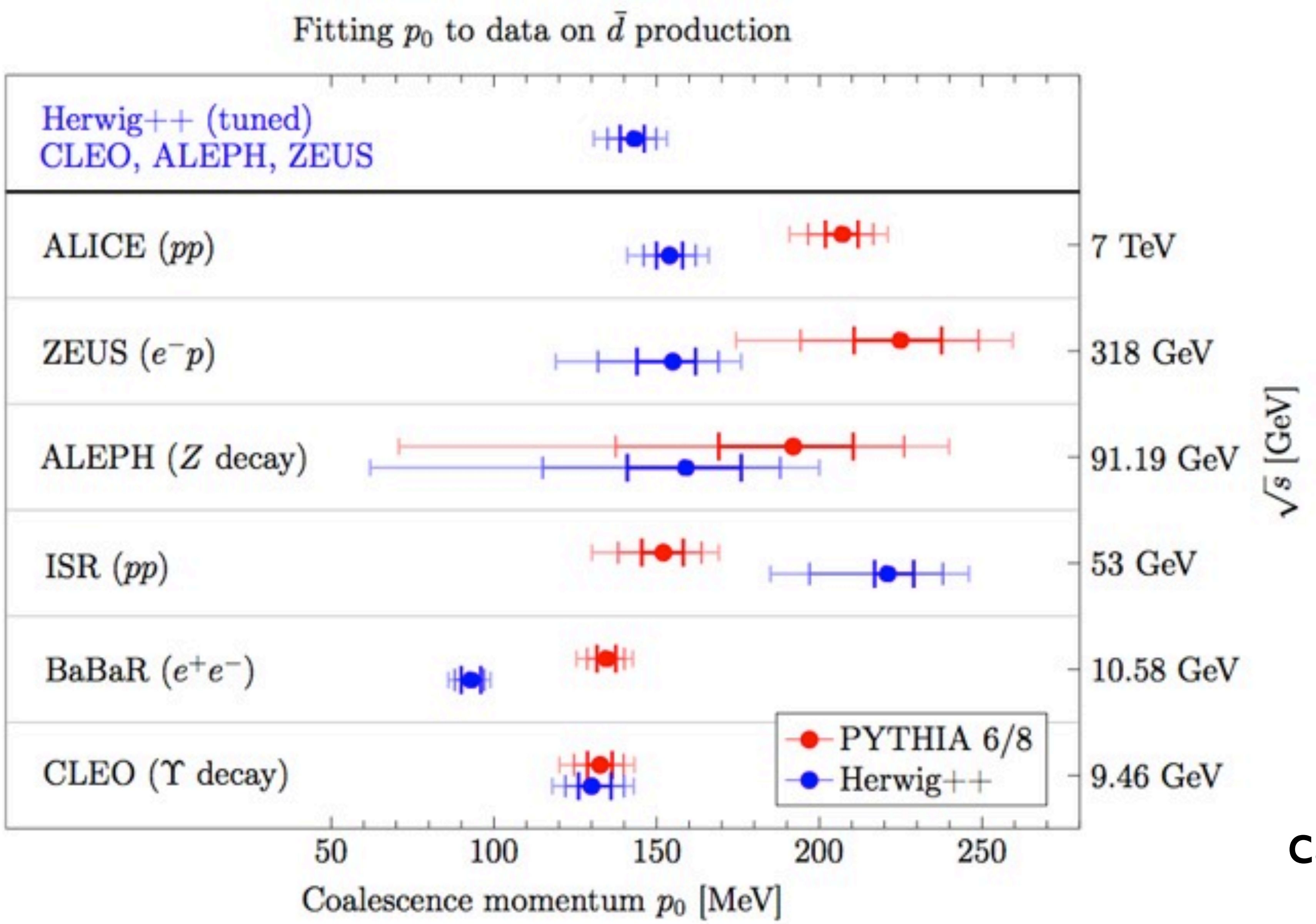
We take $r_0 \approx 2 \text{ fm}$ (radius of the anti-deuteron)

(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

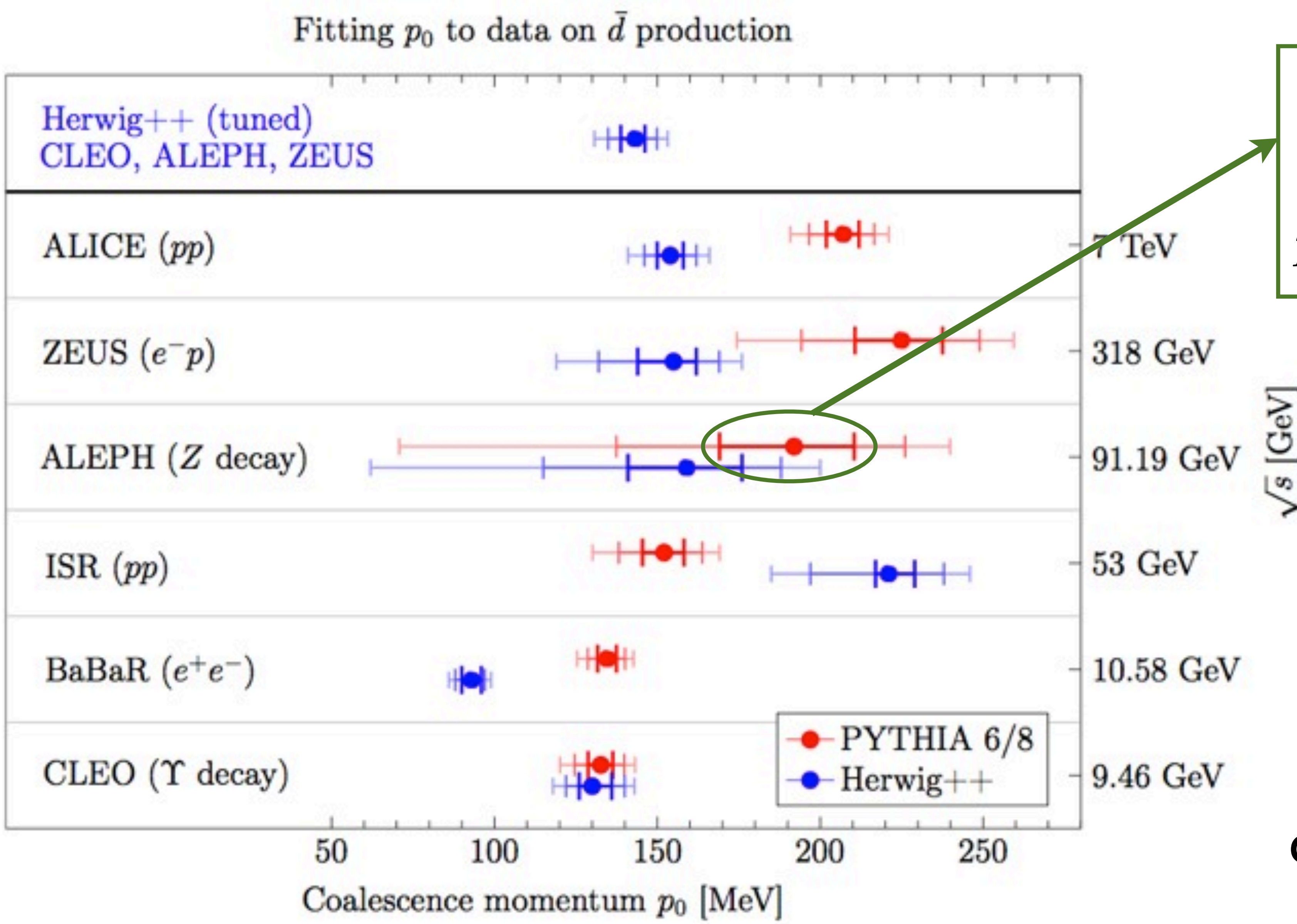
The coalescence momentum p_0 **cannot be calculated** from first principles and should be determined from **fitting** MonteCarlo **event-by-event** predictions to **experimental measurements**



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**



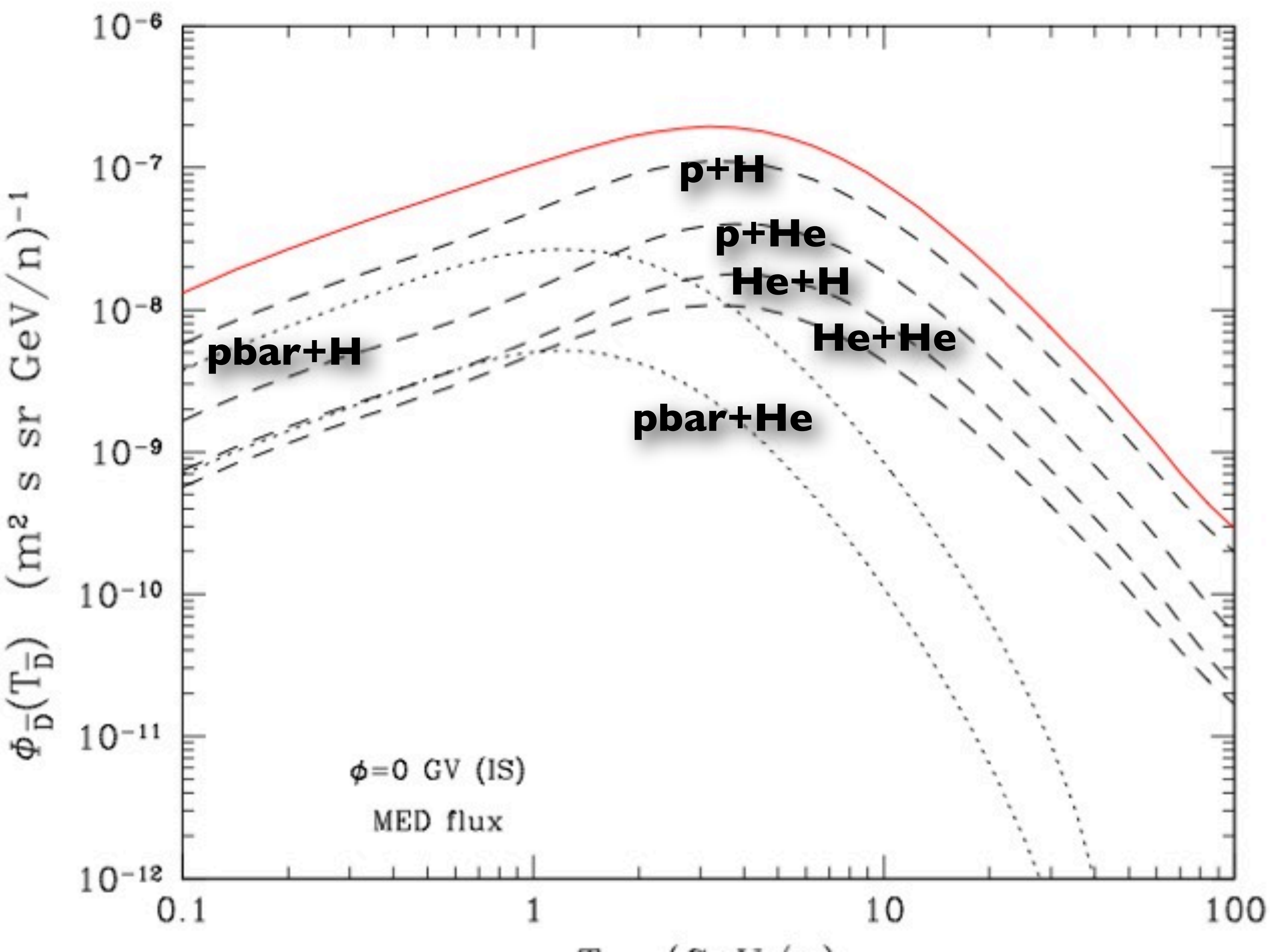
For the results shown here we use $p_0 = (195 \pm 22)$ MeV

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

Astrophysical background

The background is assumed to be of purely secondary origin:

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

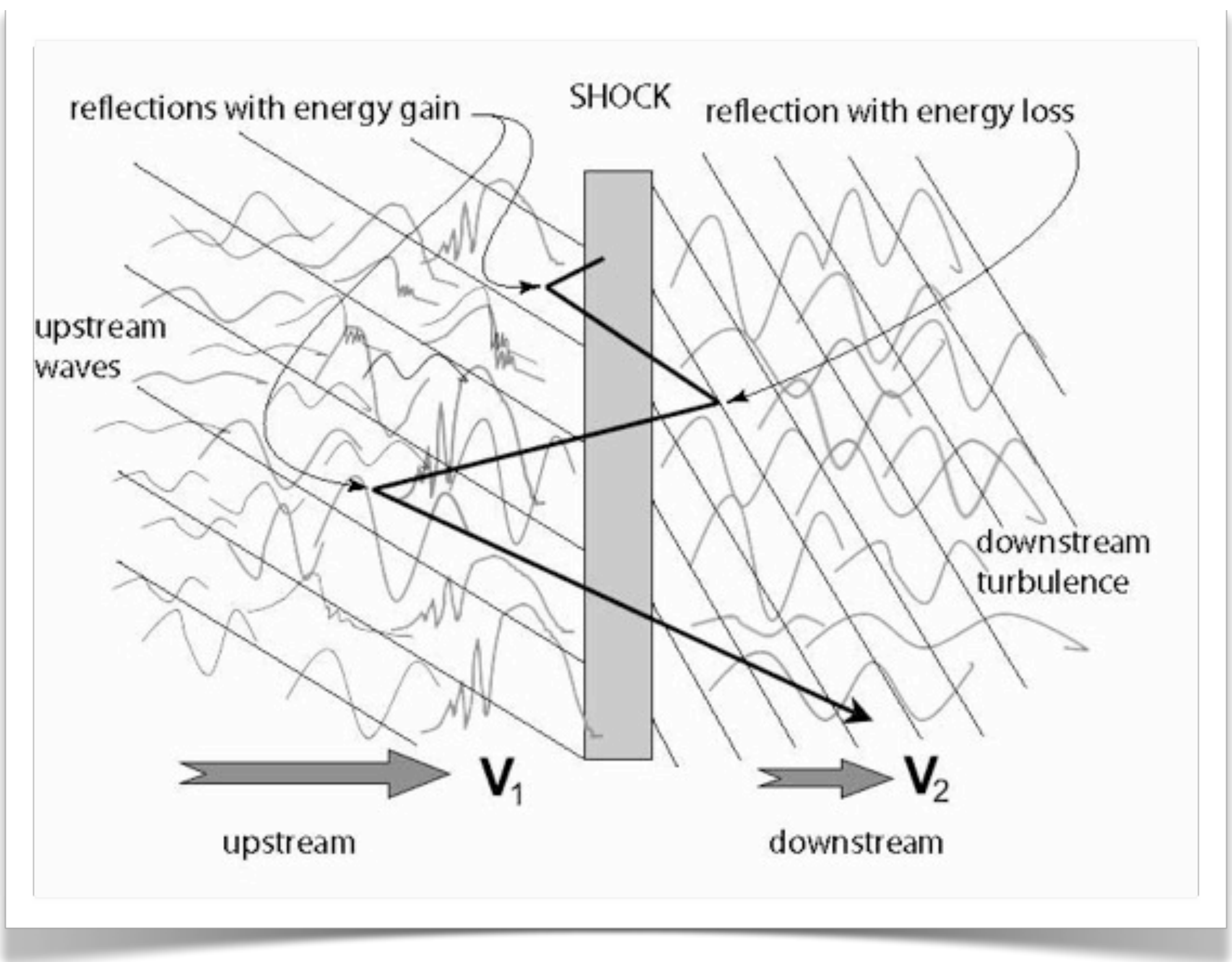


Donato+ 2008
Ibarra, Wild 2013

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:

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

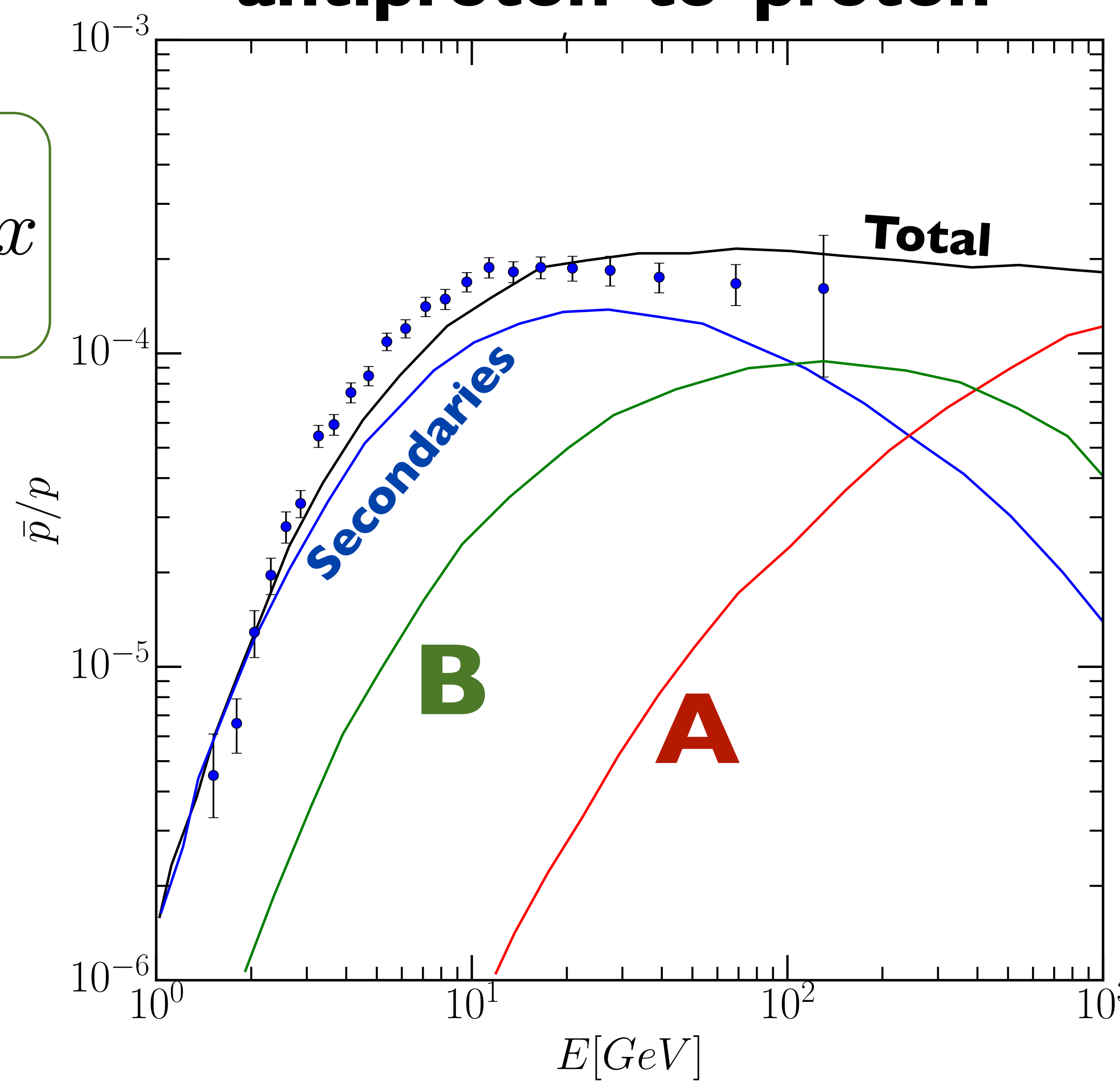
A B

Blasi, Serpico 2009

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

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

antiproton-to-proton

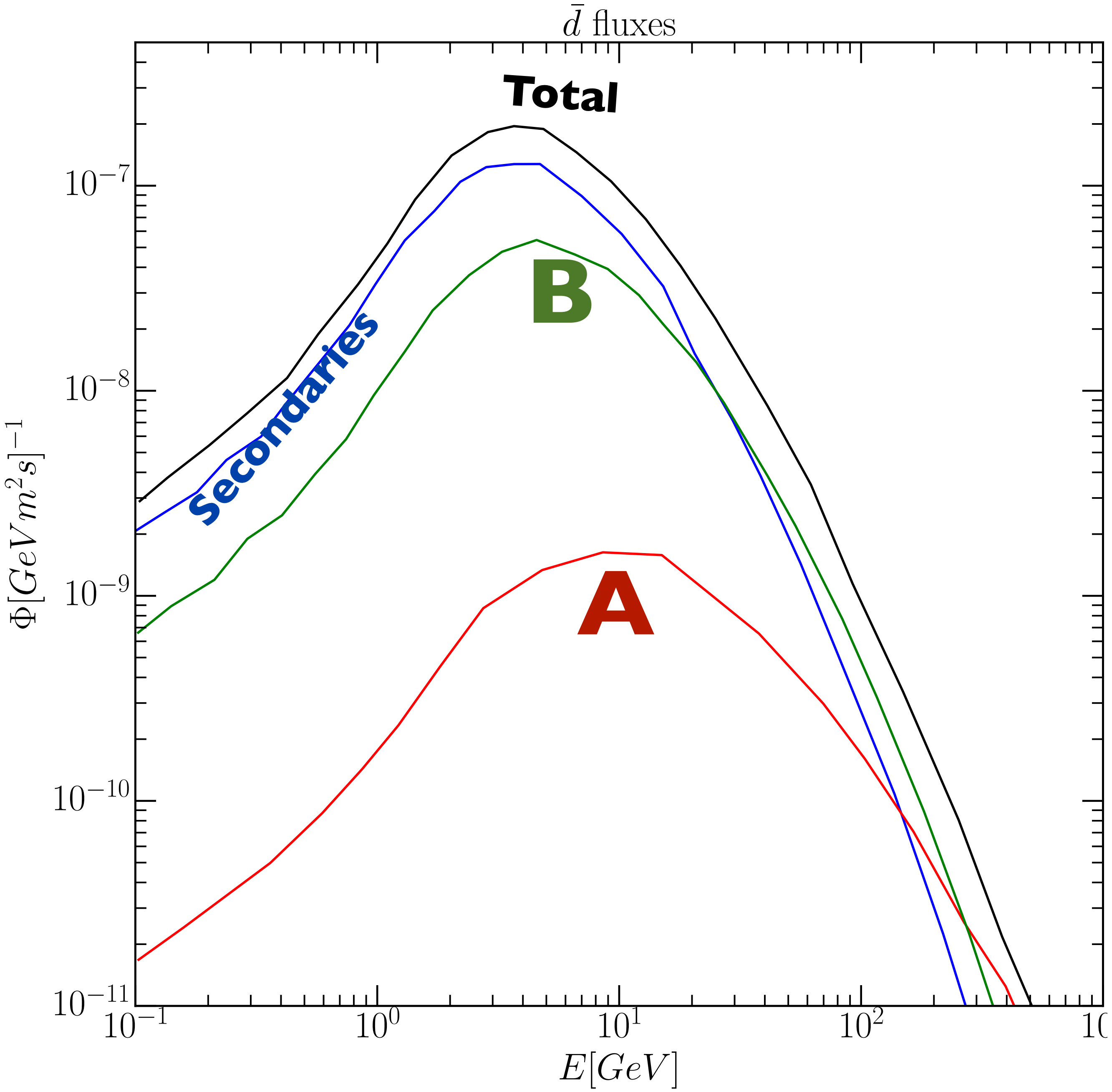


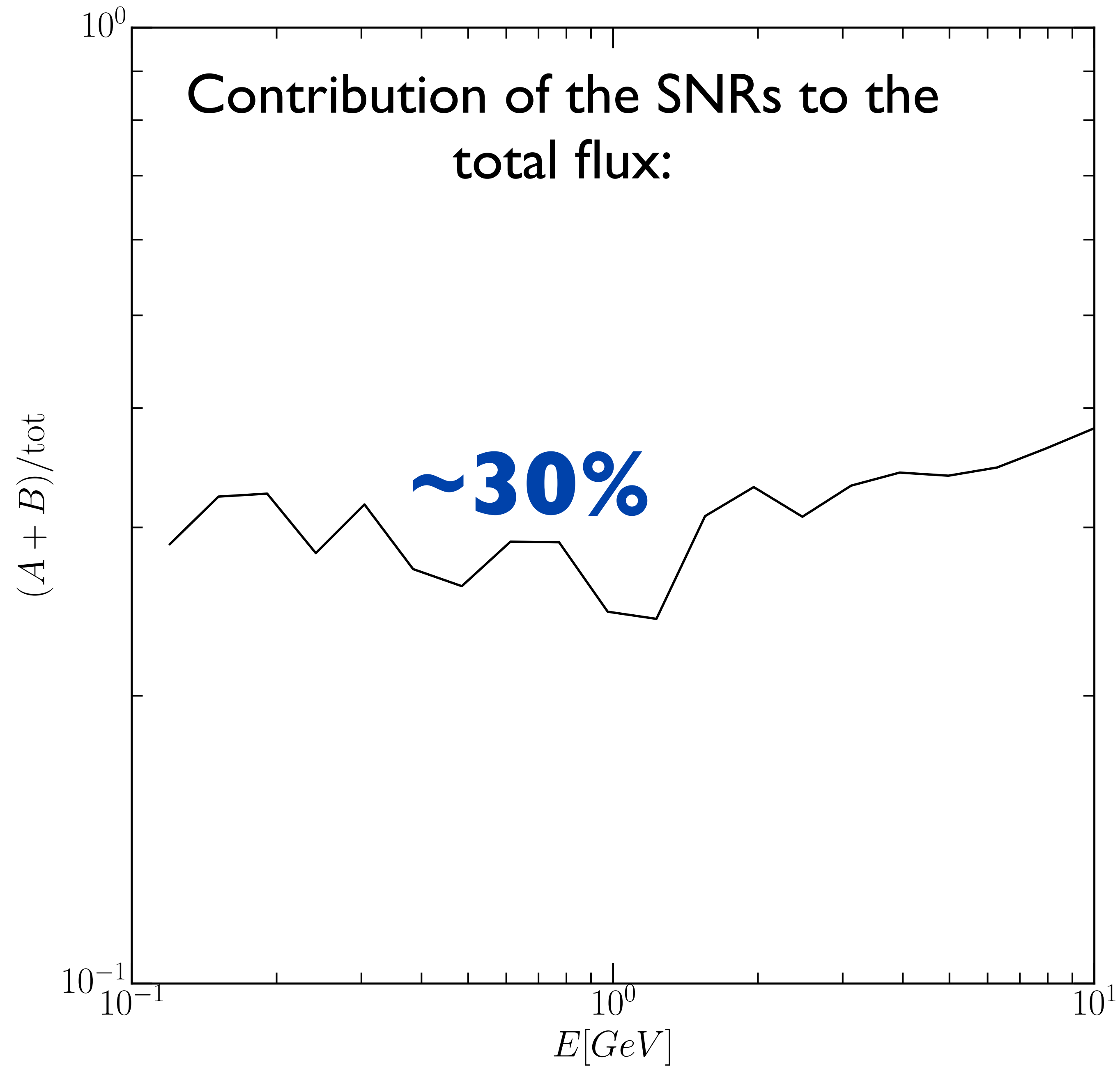
Antideuterons from SNRs

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

Prediction for antideuteron fluxes:

very preliminary!





Antideuterons from SNRs

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

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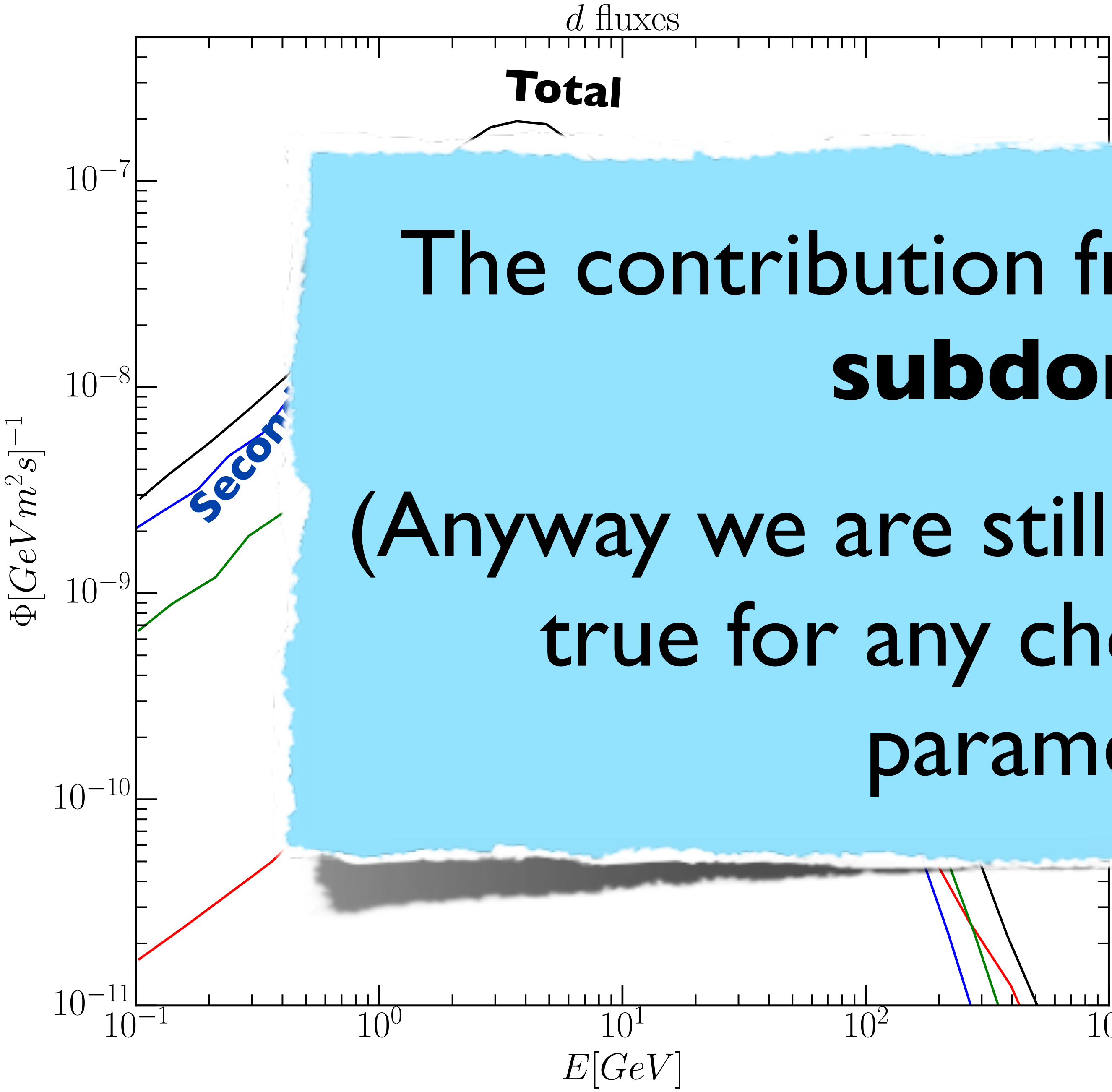
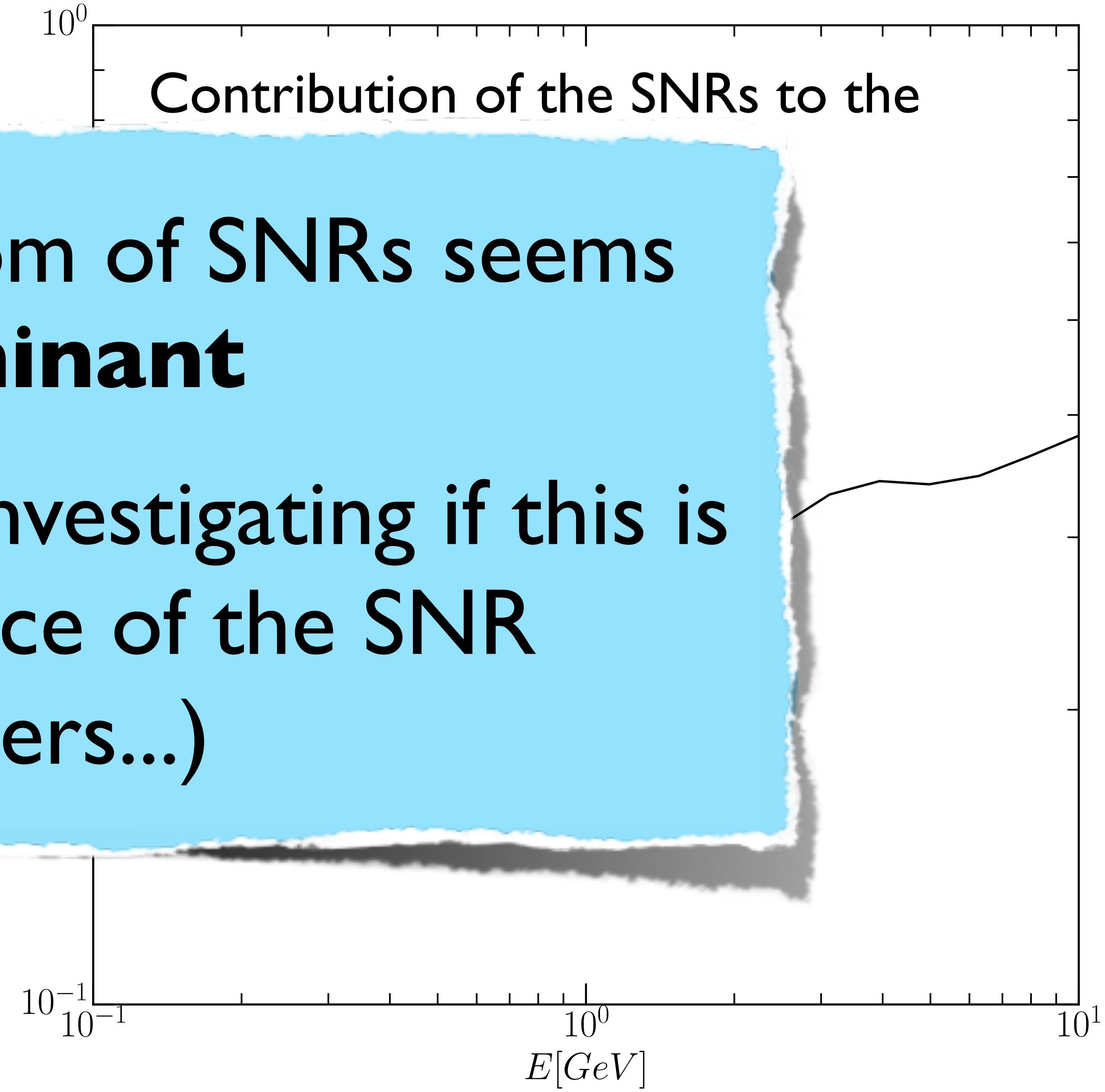




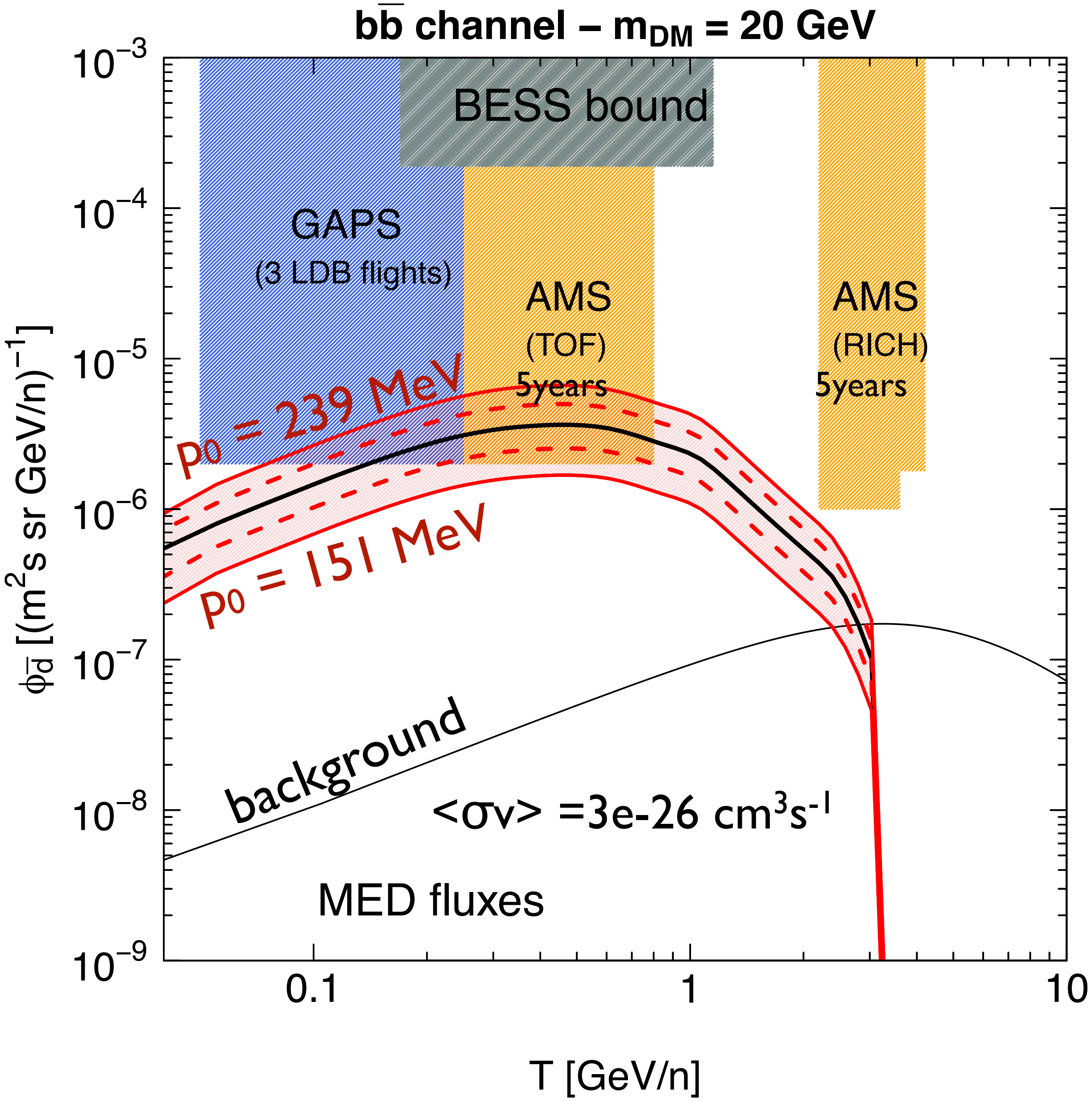
The contribution from of SNRs seems **subdominant**

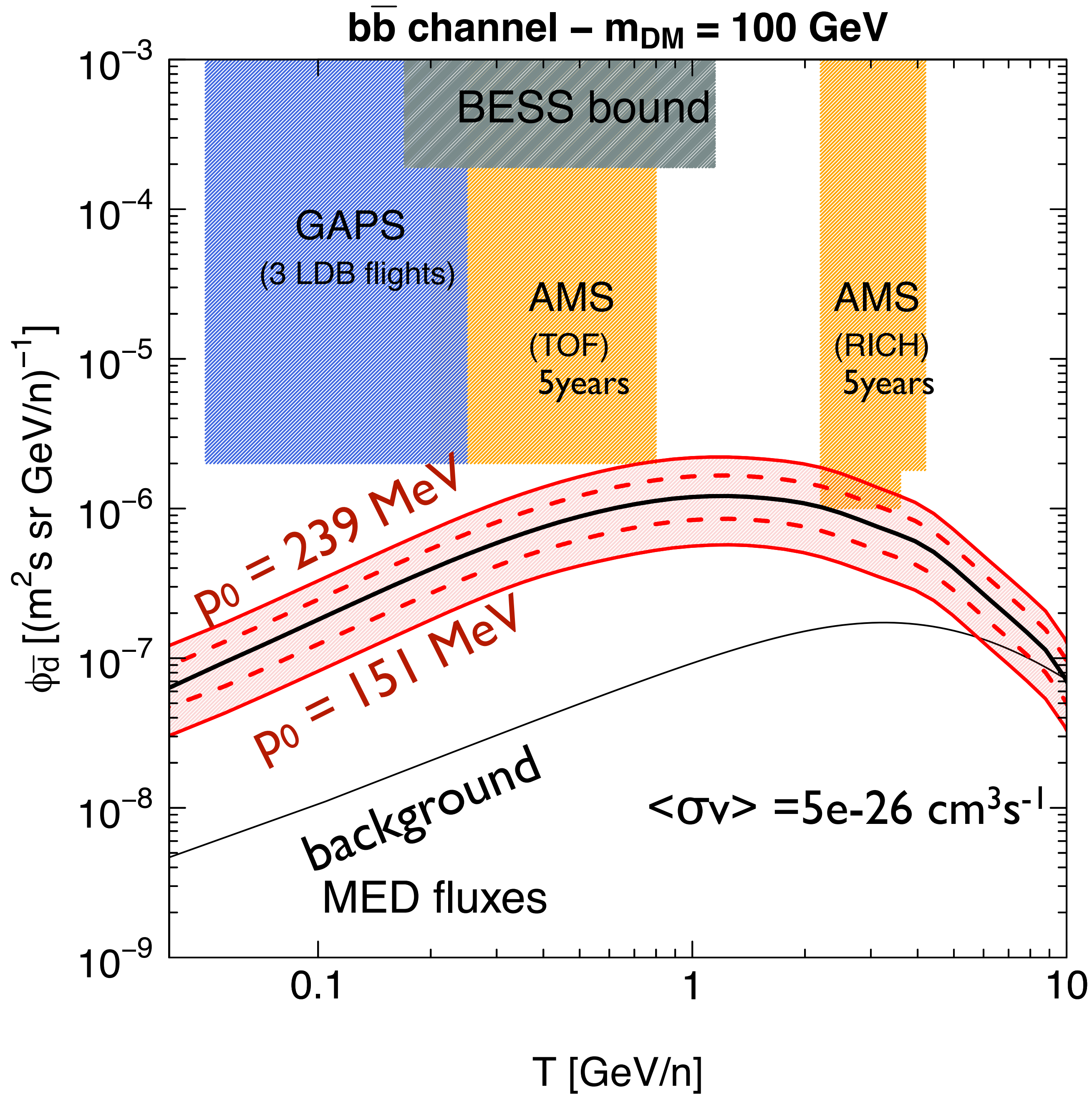
(Anyway we are still investigating if this is true for any choice of the SNR parameters...)

Prospects for DM observation

Prospects for DM observation

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



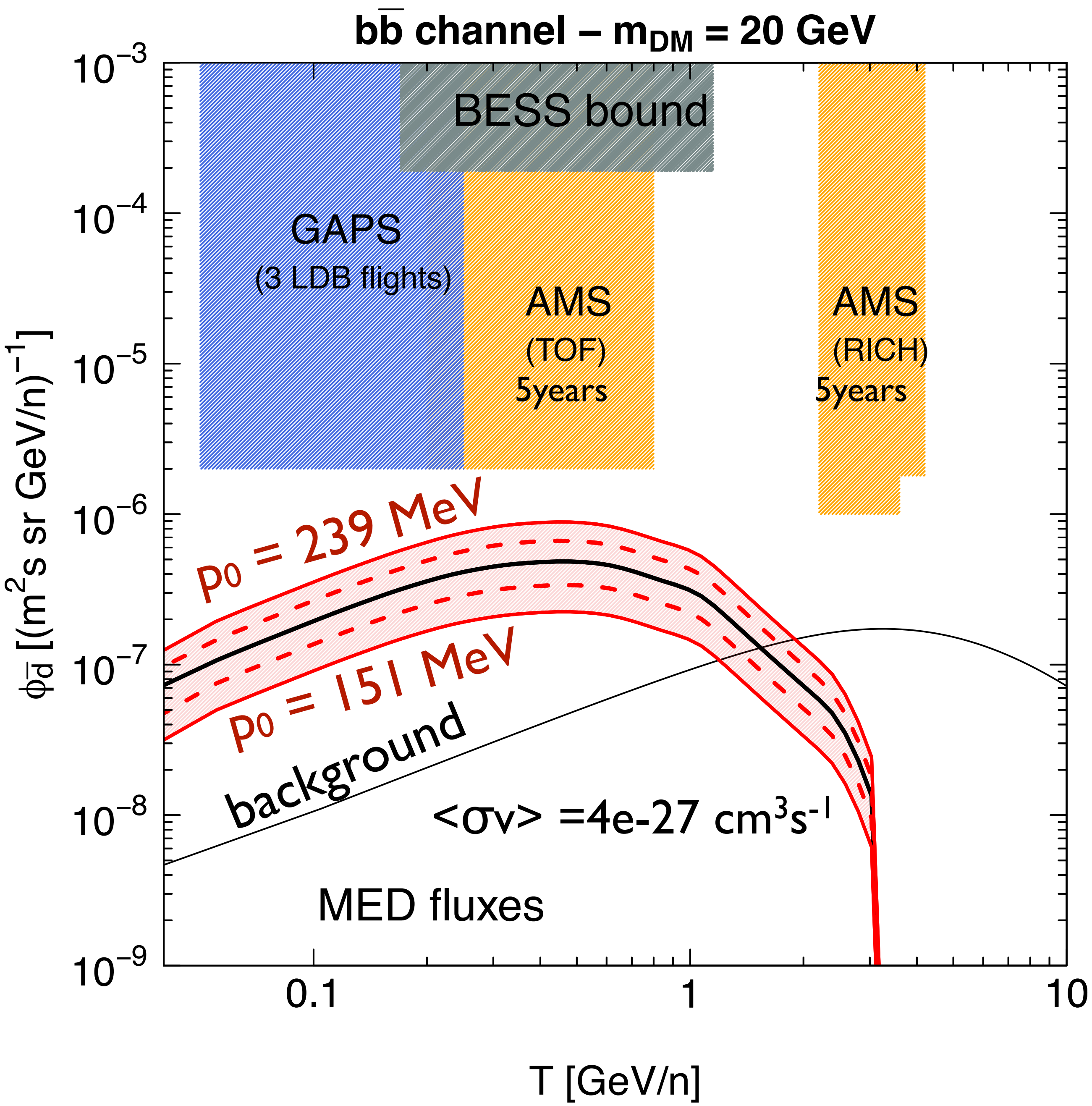


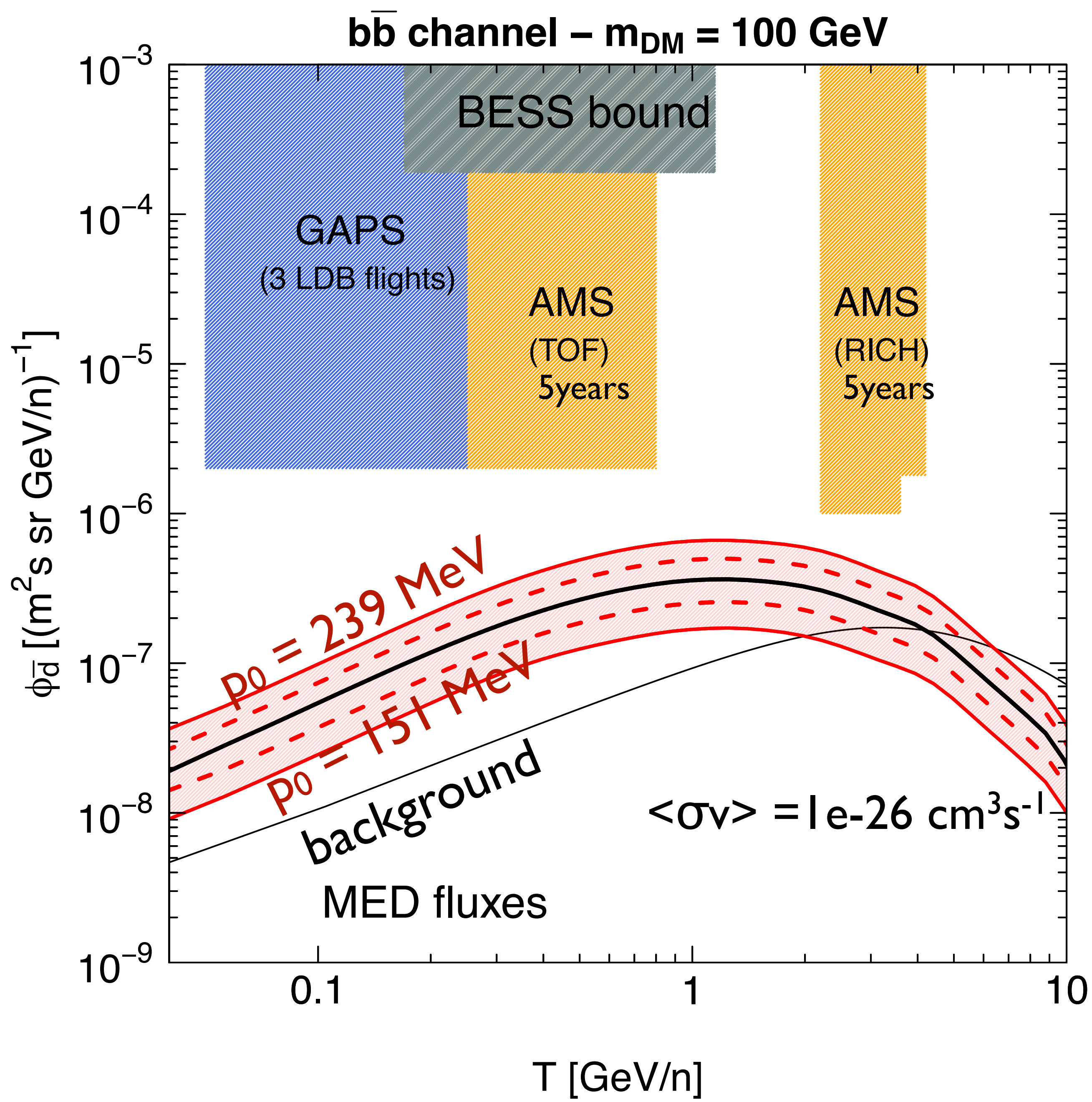
Annihilation cross sections compatible with **PAMELA antiproton bounds**

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

Coalescence for the anti-Helium

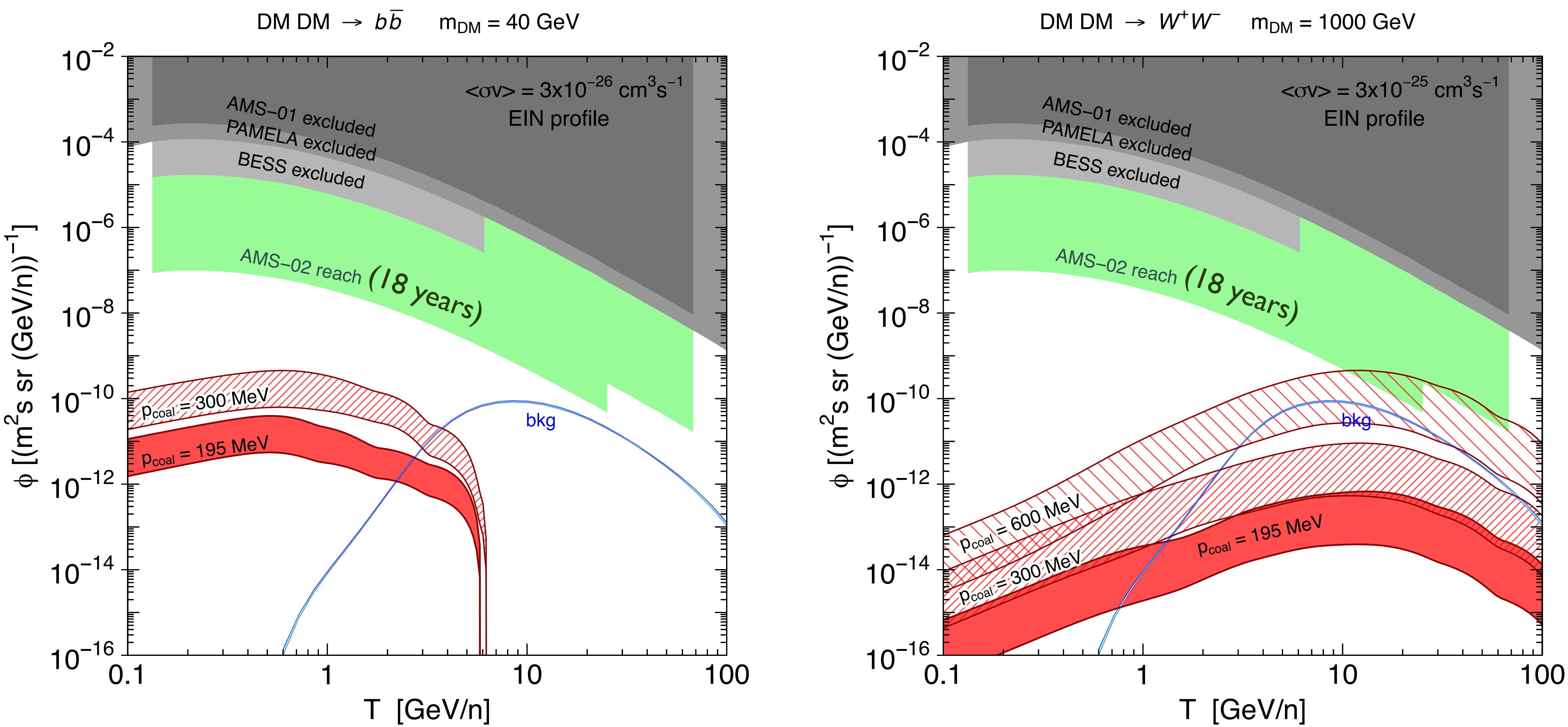
- For the anti-Helium, we have the coalescence of **three anti-nucleons**
- We consider only the pnn case, since for the ppn case we expect to have a suppression due to **Coulombian repulsion**
- Our algorithm is very simple: we compute the relative momentum of every anti-nucleon pair in the rest frame 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** :

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

- 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)

Anti-Helium fluxes at Earth

M.Cirelli, N. Fornengo, M.Taoso, AV, JHEP 08 (2014) 009, arXiv: 1402.0321



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)**

What can we say?

Anti-nuclei 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**.

However, **antiproton constraints** are becoming stronger and stronger.

For the current and future generation of experiments, the **detection of DM** in the anti-nuclei channels will probably be **challenging**

Outline of the talk

Three channels will be discussed:

- **Antiprotons**
  - *N. Fornengo, L. Maccione, AV, JCAP 04 (2014) 003, arXiv:1312.3579*
- **Anti-nuclei**
  - *N. Fornengo, L. Maccione, AV, JCAP 09 (2013) 031, arXiv:1306.4171*
  - *M.Cirelli, N. Fornengo, M.Taoso, AV, JHEP 08 (2014) 009, arXiv: 1402.0321*
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  - *J. Herms, A. Ibarra, AV, S.Wild, in preparation*
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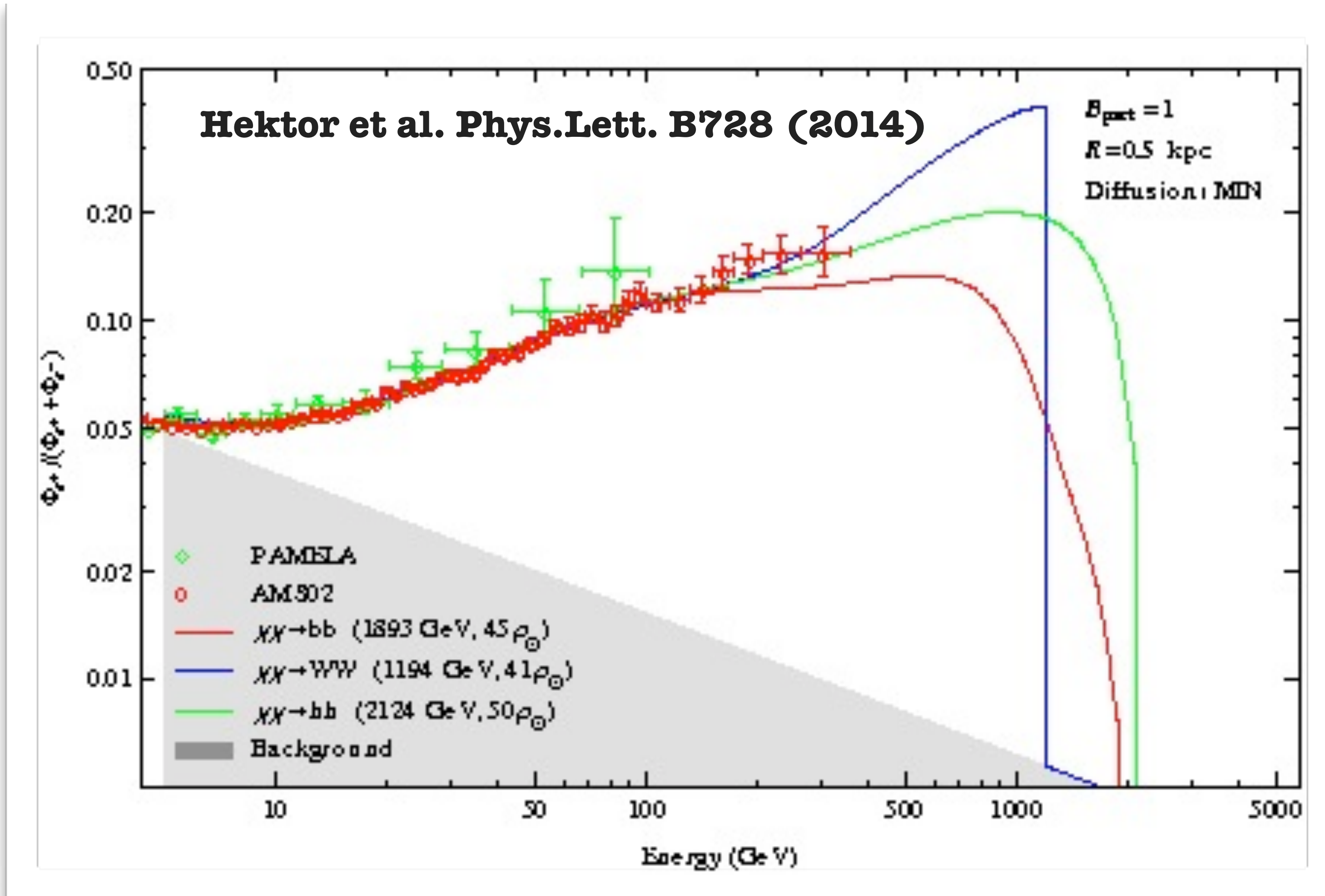
  - *M. Di Mauro, F. Donato, N.Fornengo, R.Lineros, AV, JCAP 04 (2014) 003, arXiv:1401.4017*
  - *M. Di Mauro, F. Donato, N.Fornengo, AV, arXiv:1507.07001*

DM searches with positrons



The observation of a **rise in the positron fraction**, firstly performed by PAMELA in 2009 and then confirmed by AMS-02 has triggered the interest of the community

- The rise is **not compatible** with the hypothesis that all the positrons are of **secondary origin**
- However, this does **not** appear as **a smoking gun for DM**, since it might be due to the **emission** from **primary astrophysical sources**

Supernova Remnants (SNRs)

They accelerate electrons through the **shock acceleration mechanism**. The spectrum is:

$$\boxed{Q(E) = Q_0 \left(\frac{E}{1\ \mathrm{GeV}}\right)^{-\gamma} \exp\left(-\frac{E}{E_c}\right)}$$

The cut-off energy is $\mathbf{E_c = 2\ TeV}$

The value of Q_0 can be derived from radio data:

radio flux

$$Q_0 = 1.2 \cdot 10^{47} (0.79)^\gamma \left[\frac{d}{\mathrm{kpc}}\right]^2 \left[\frac{\nu}{\mathrm{GHz}}\right]^{(\gamma-1)/2} \left[\frac{B}{100\mu\mathrm{G}}\right]^{-(\gamma+1)/2} \left[\frac{B_r^\nu}{\mathrm{Jy}}\right]$$

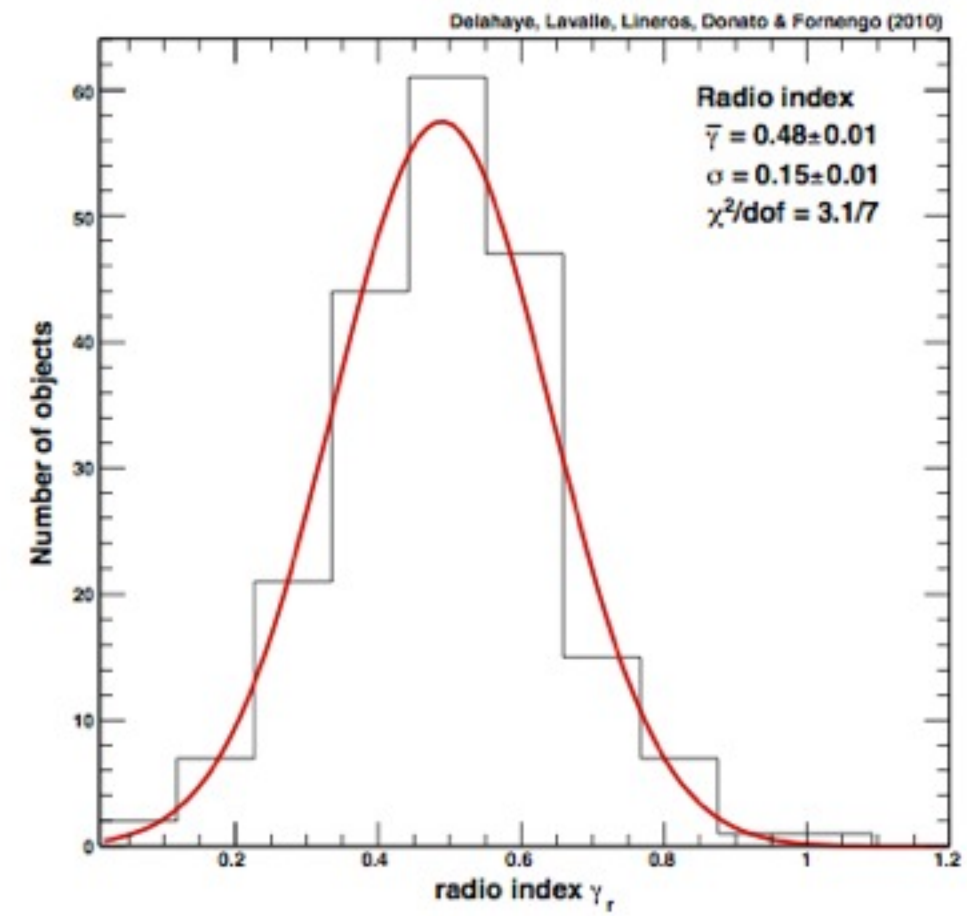
distance from the observer

magnetic field

Supernova Remnants (SNRs)

The **Green catalogue** is the most complete **SNR catalog** (265 sources)

$$\boxed{\langle\gamma\rangle = 2.0 \pm 0.3}$$

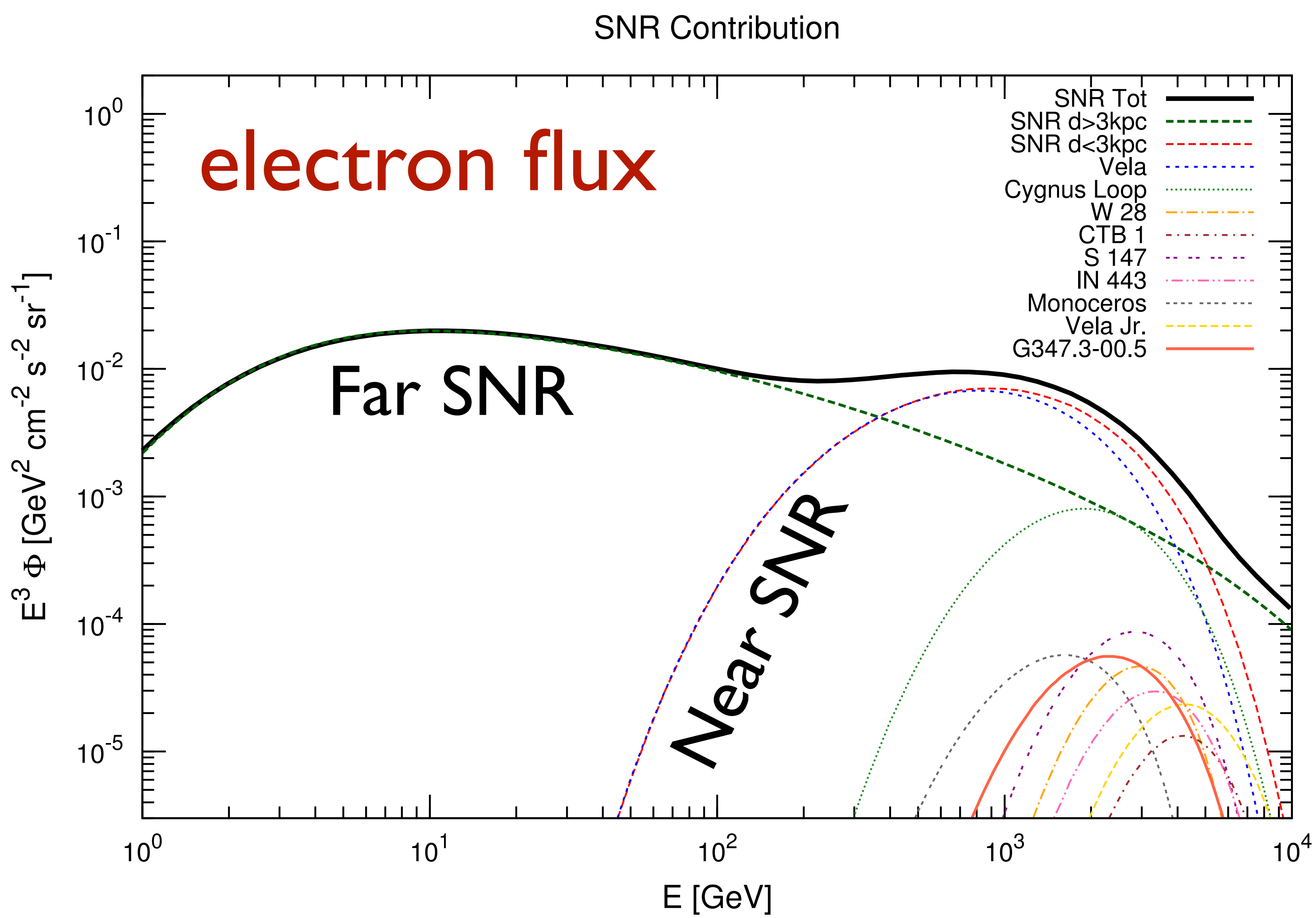


For our analysis, we **divide** the SNRs population in **two classes**:

- **Near SNRs** (d ≤ 3 kpc): their distances and ages are **fixed** to the values of the Green catalogue, we allow a free normalization
- **Far SNRs** (d > 3kpc): treated as an **average population** (which follows a Lorimer radial profile) they share common values for Q_0 and γ, which are **free parameters** of the fit

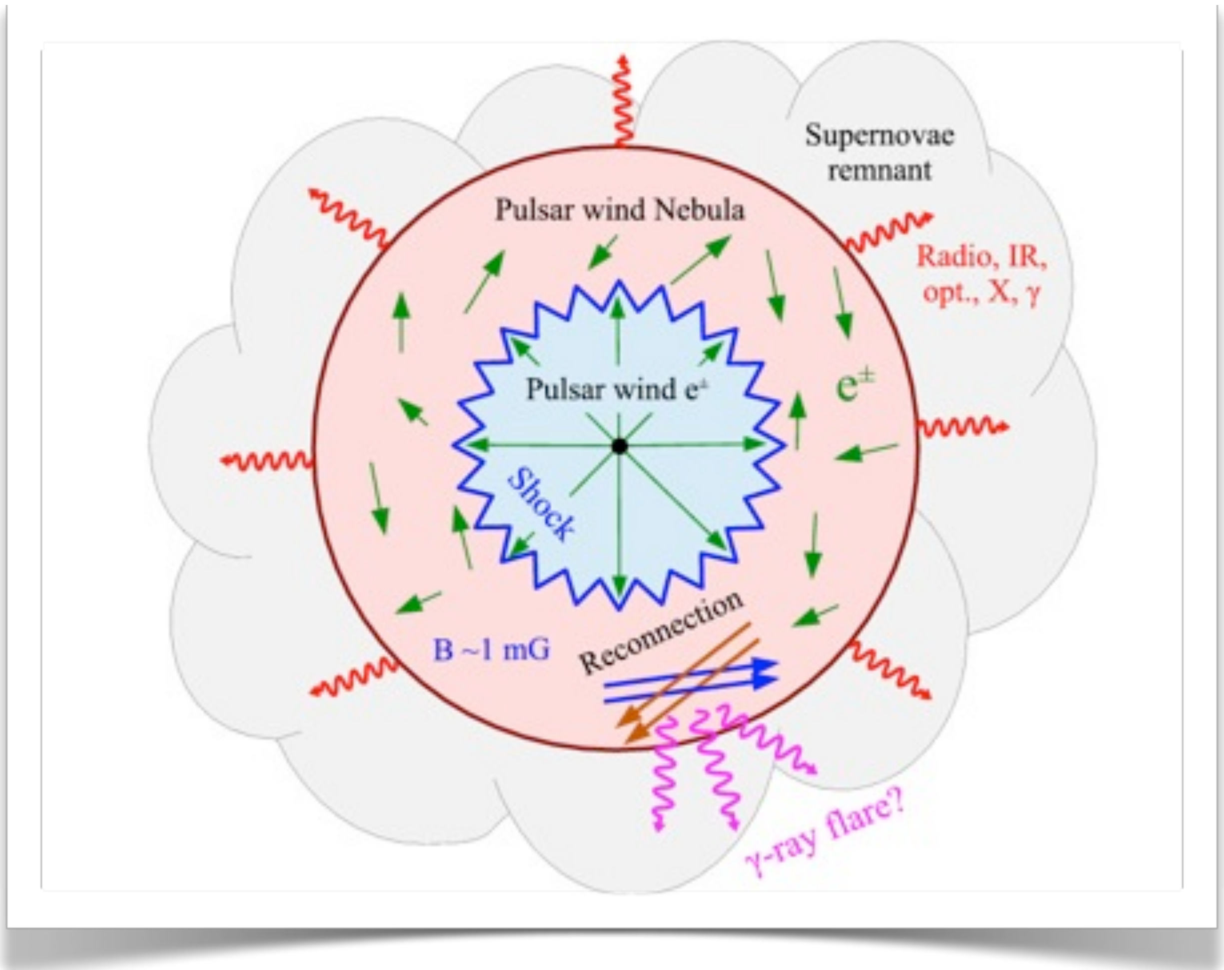
Primary astrophysical sources

Supernova Remnants (SNRs)



Primary astrophysical sources

Pulsar Wind Nebulae (PWNe)



The rotating magnetic field of a pulsar can be so strong to tear particle away from the surface of the star. These particles are **trapped in a nebula**, accelerated (through shock diffusion mechanisms) and **then released in the ISM** (after ~50 kyr).

$$\boxed{Q(E) = Q_0 \left(\frac{E}{1\ \mathrm{GeV}}\right)^{-\gamma} \exp\left(-\frac{E}{E_c}\right)}$$

The cut-off energy is **E_c = 2 TeV**

$$\boxed{Q_0 = \eta W_0}$$

where

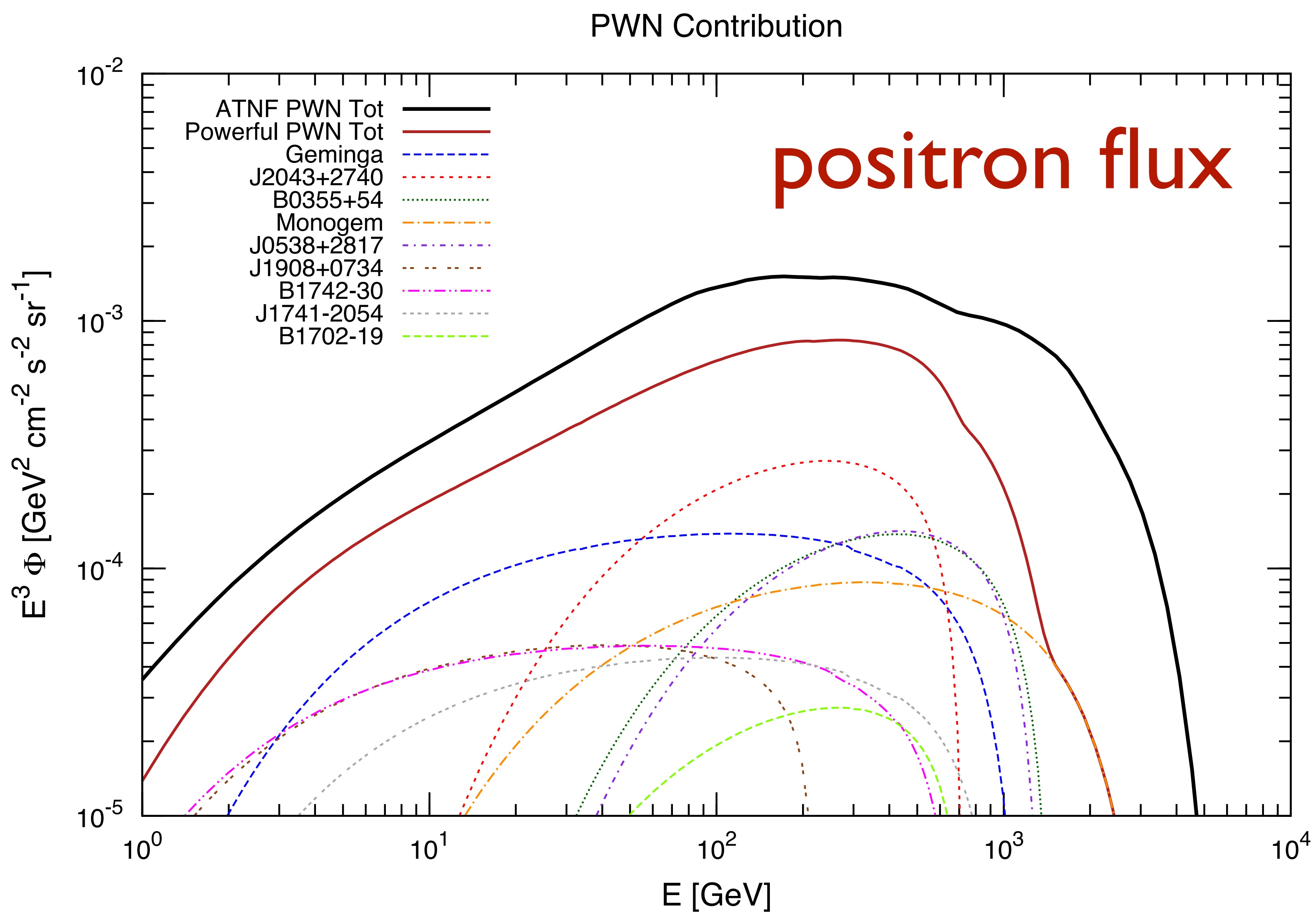
$$\boxed{W_0 \approx \tau_0 \dot{E}\left(1 + \frac{t_\star}{\tau_0}\right)}$$

pulsar spin-down energy
(energy emitted by the pulsar as it slows down)
[ATNF catalogue]

In our fit, pulsars have **2 free parameters**: γ and η

Primary astrophysical sources

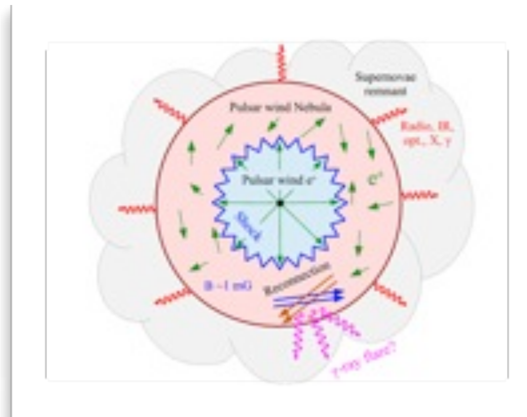
Pulsar Wind Nebulae (PWNe)



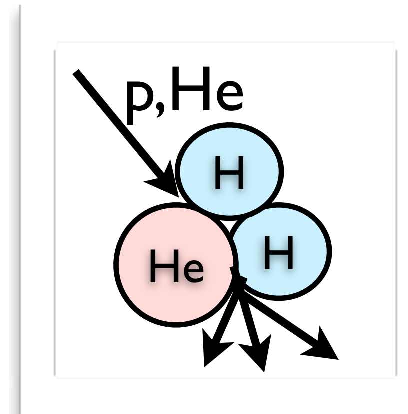
A completely astrophysical model

- Electrons

SNRs

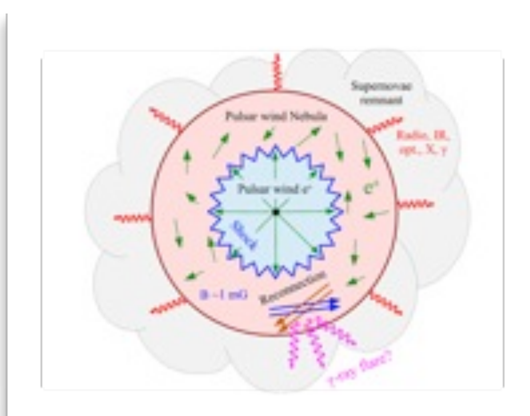


PWNe

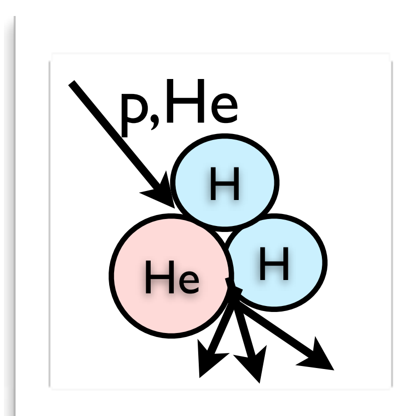


secondaries

- Positrons



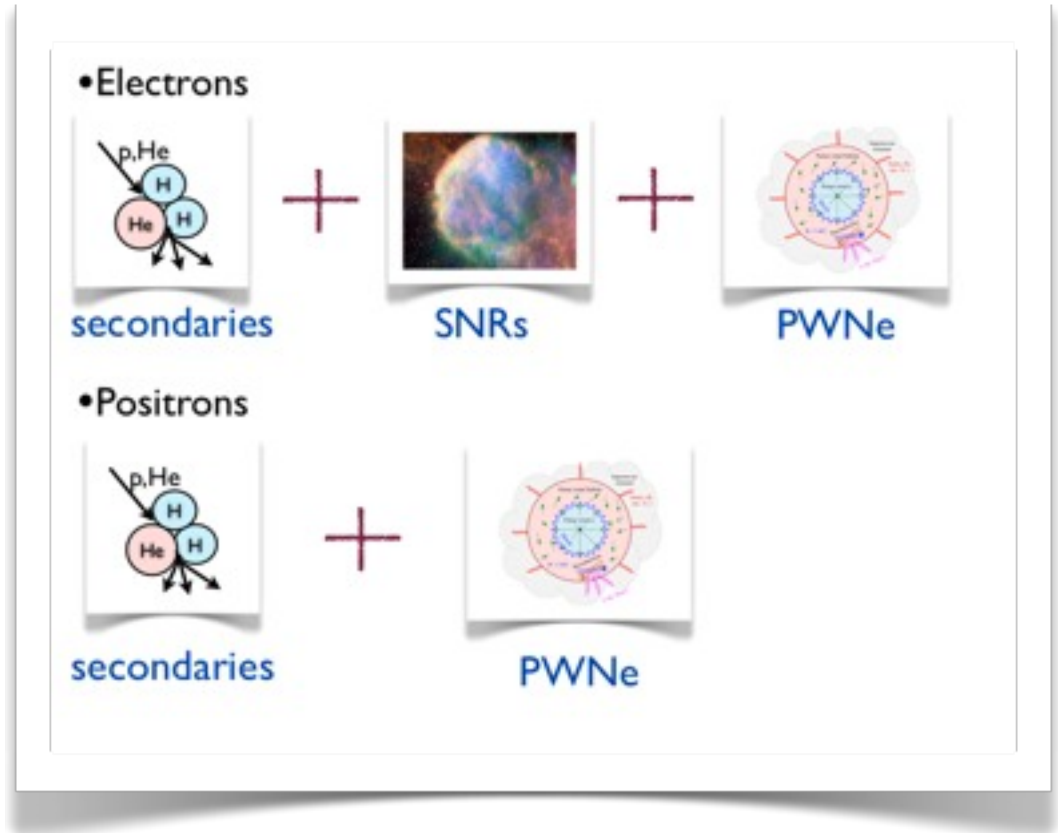
PWNe



secondaries

fit to AMS-02 data

We will now **constrain the properties** of our model by performing a **global fit** to the observables measured by **AMS-02**



We have **6 free parameters**:

- γ
- η

PWNe

- Q_0
- γ_{SNR}

Far SNRs

- φ Fisk potential
- N_{vela} Normalization of near SNRs

We fit the **two independent observables** among the ones measured by AMS-02:

$e^+/(e^+ + e^-)$

$e^+ + e^-$ flux

Fit to AMS data

parameter	best fit ± error
η_{PWNe}	$0.036^{+0.002}_{-0.001}$
γ_{PWNe}	$1.94^{+0.04}_{-0.02}$
$Q_{0,\mathrm{SNRs}}[10^{50}\ \mathrm{erg/s}]$	$1.10^{+0.15}_{-0.05}$
γ_{SNRs}	$2.22^{+0.02}_{-0.01}$
N_{Vela}	$1.00^{+0.23}_{-0.19}$
$\chi^2_{\mathrm{tot}}/\mathrm{d.o.f}$	1.35
χ^2_{pf} (43 data pts)	80.4
χ^2_{sum} (50 data pts)	37.2

Fit to AMS data

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$\eta_{\rm PWNe}$	$0.036^{+0.002}_{-0.001}$
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$\chi^2_{\rm tot}/\rm d.o.f$	1.35
$\chi^2_{\rm pf}$ (43 data pts)	80.4
$\chi^2_{\rm sum}$ (50 data pts)	37.2

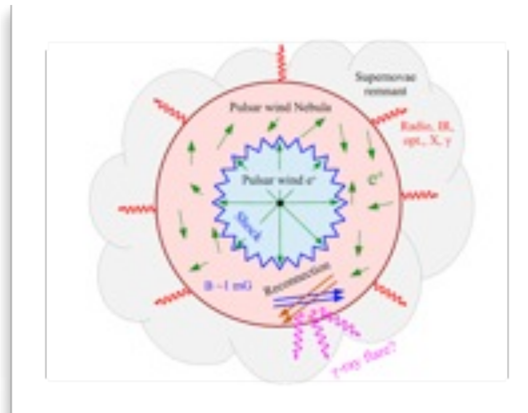
Our model is not able to reproduce the AMS-02 positron fraction!

Adding DM

- Electrons

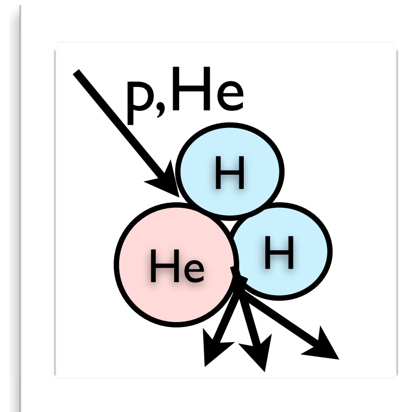
SNRs

+



PWNe

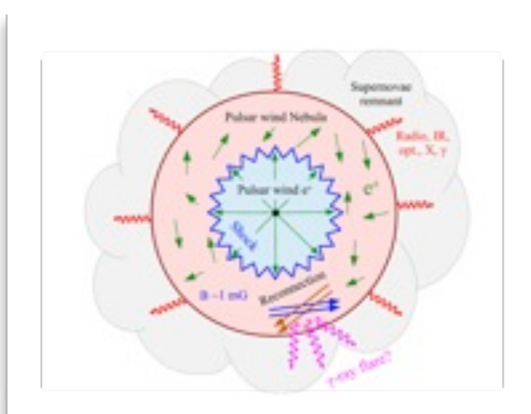
+



secondaries

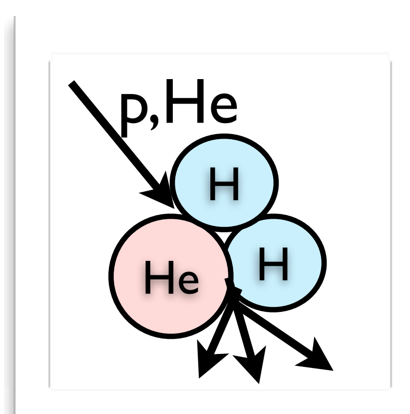
+ DM

- Positrons



PWNe

+

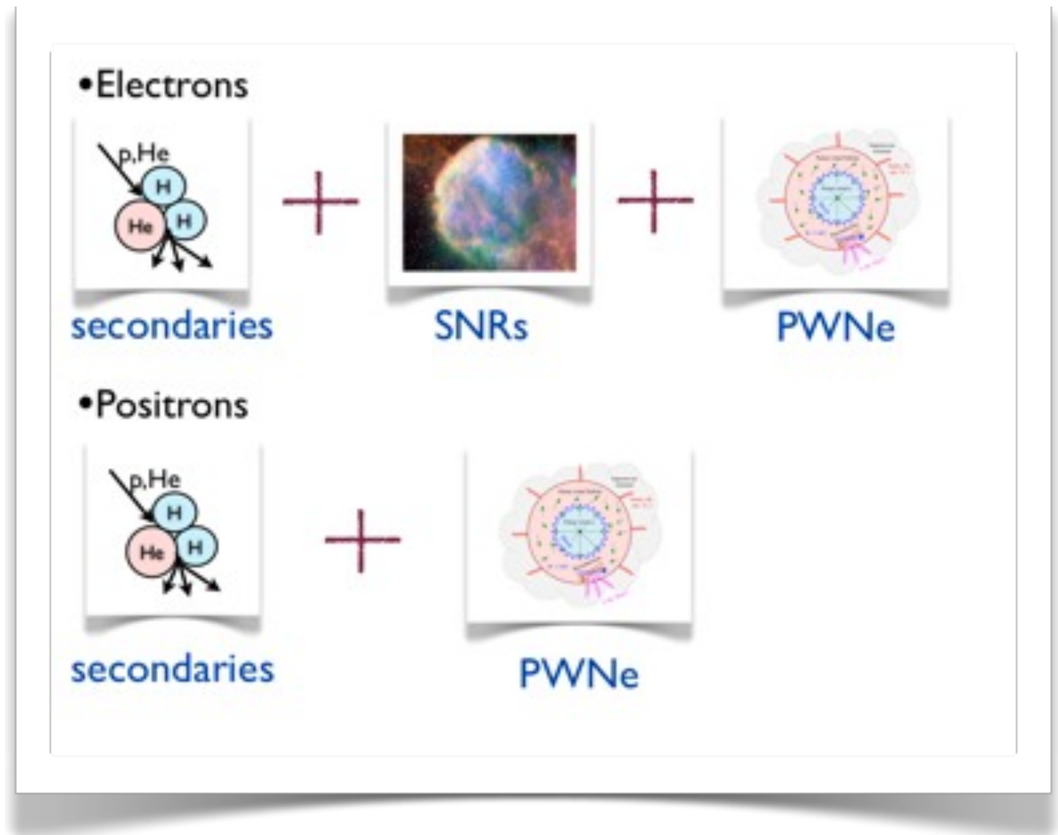


secondaries

+ DM

Adding DM

Our model is now composed by **astrophysical** primary and secondary sources **and Dark Matter**



+ DM

We have **8 parameters**:

- γ
- η

PWNe

- Q0
- γ_{SNR}

Far SNRs

- $\langle\sigma v\rangle$
- mDM

DM

- φ — Fisk potential
- Nvela — Normalization of Vela flux

We fit the **two independent observables** among the ones measured by AMS-02:

$e^+/(e^+ + e^-)$
$e^+ + e^-$ flux

Fit to AMS data

Annihilating DM					
Parameter	$\mathbf{e^+e^-}$	$\mu^+\mu^-$	$\tau^+\tau^-$	$b\bar{b}$	W^+W^-
η_{PWNe}	$0.032^{+0.002}_{-0.002}$	$0.028^{+0.002}_{-0.005}$	$0.011^{+0.005}_{-0.001}$	$0.006^{+0.015}_{-0.001}$	$0.006^{+0.011}_{-0.001}$
γ_{PWNe}	$1.87^{+0.05}_{-0.05}$	$1.76^{+0.09}_{-0.20}$	$1.23^{+0.33}_{-0.23}$	$1.77^{+0.19}_{-0.69}$	$1.72^{+0.27}_{-0.68}$
$Q_{0,SNRs}[10^{50}\ \mathrm{erg/s}]$	$1.13^{+0.12}_{-0.09}$	$1.24^{+0.10}_{-0.18}$	$1.16^{+0.14}_{-0.05}$	$1.40^{+0.11}_{-0.14}$	$1.33^{+0.12}_{-0.11}$
γ_{SNRs}	$2.22^{+0.02}_{-0.01}$	$2.24^{+0.01}_{-0.03}$	$2.23^{+0.02}_{-0.01}$	$2.26^{+0.01}_{-0.02}$	$2.25^{+0.02}_{-0.01}$
N_{Vela}	$0.80^{+0.19}_{-0.17}$	$0.74^{+0.24}_{-0.20}$	$0.88^{+0.14}_{-0.20}$	$0.84^{+0.22}_{-0.15}$	$0.81^{+0.22}_{-0.17}$
m_{DM} [GeV]	50^{+1}_{-4}	88^{+31}_{-9}	635^{+73}_{-195}	39572^{+10351}_{-28792}	24759^{+22964}_{-14907}
$\langle\sigma v\rangle$ [cm^{3}s^{-1}]	$5.6^{+2.2}_{-2.6}\times 10^{-27}$	$7.9^{+12.6}_{-3.4}\times 10^{-26}$	$7.2^{+1.4}_{-3.5}\times 10^{-24}$	$9.5^{+0.5}_{-8.4}\times 10^{-22}$	$7.2^{+11.5}_{-5.7}\times 10^{-22}$
χ^2/85 d.o.f.	1.13	0.98	1.05	1.24	1.18

Fit to AMS data

Annihilating DM					
Parameter	$\mathbf{e^+e^-}$	$\mu^+\mu^-$	$\tau^+\tau^-$	$b\bar{b}$	W^+W^-
η_{PWNe}	$0.032^{+0.002}_{-0.002}$	$0.028^{+0.002}_{-0.005}$	$0.011^{+0.005}_{-0.001}$	$0.006^{+0.015}_{-0.001}$	$0.006^{+0.011}_{-0.001}$
γ_{PWNe}	$1.87^{+0.05}_{-0.05}$	$1.76^{+0.09}_{-0.20}$	$1.23^{+0.33}_{-0.23}$	$1.77^{+0.19}_{-0.69}$	$1.72^{+0.27}_{-0.68}$
$Q_{0,SNRs}[10^{50}\ \mathrm{erg/s}]$	$1.13^{+0.12}_{-0.09}$	$1.24^{+0.10}_{-0.18}$	$1.16^{+0.14}_{-0.05}$	$1.40^{+0.11}_{-0.14}$	$1.33^{+0.12}_{-0.11}$
γ_{SNRs}	$2.22^{+0.02}_{-0.01}$	$2.24^{+0.01}_{-0.03}$	$2.23^{+0.02}_{-0.01}$	$2.26^{+0.01}_{-0.02}$	$2.25^{+0.02}_{-0.01}$
N_{Vela}	$0.80^{+0.19}_{-0.17}$	$0.74^{+0.24}_{-0.20}$	$0.88^{+0.14}_{-0.20}$	$0.84^{+0.22}_{-0.15}$	$0.81^{+0.22}_{-0.17}$
m_{DM} [GeV]	50^{+1}_{-4}	88^{+31}_{-9}	635^{+73}_{-195}	39572^{+10351}_{-28792}	24759^{+22964}_{-14907}
$\langle\sigma v\rangle$ [cm^{3}s^{-1}]	$5.6^{+2.2}_{-2.6}\times10^{-27}$	$7.9^{+12.6}_{-3.4}\times10^{-26}$	$7.2^{+1.4}_{-3.5}\times10^{-24}$	$9.5^{+0.5}_{-8.4}\times10^{-22}$	$7.2^{+11.5}_{-5.7}\times10^{-22}$
χ^2/85 d.o.f.	1.13	0.98	1.05	1.24	1.18

Fit to AMS data

	Annihilating DM				
Parameter	$\mathbf{e^+e^-}$	$\mu^+\mu^-$	$\tau^+\tau^-$	$b\bar{b}$	W^+W^-
η_{PWNe}	$0.032^{+0.002}_{-0.002}$	$0.028^{+0.002}_{-0.005}$	$0.011^{+0.005}_{-0.001}$	$0.006^{+0.015}_{-0.001}$	$0.006^{+0.011}_{-0.001}$
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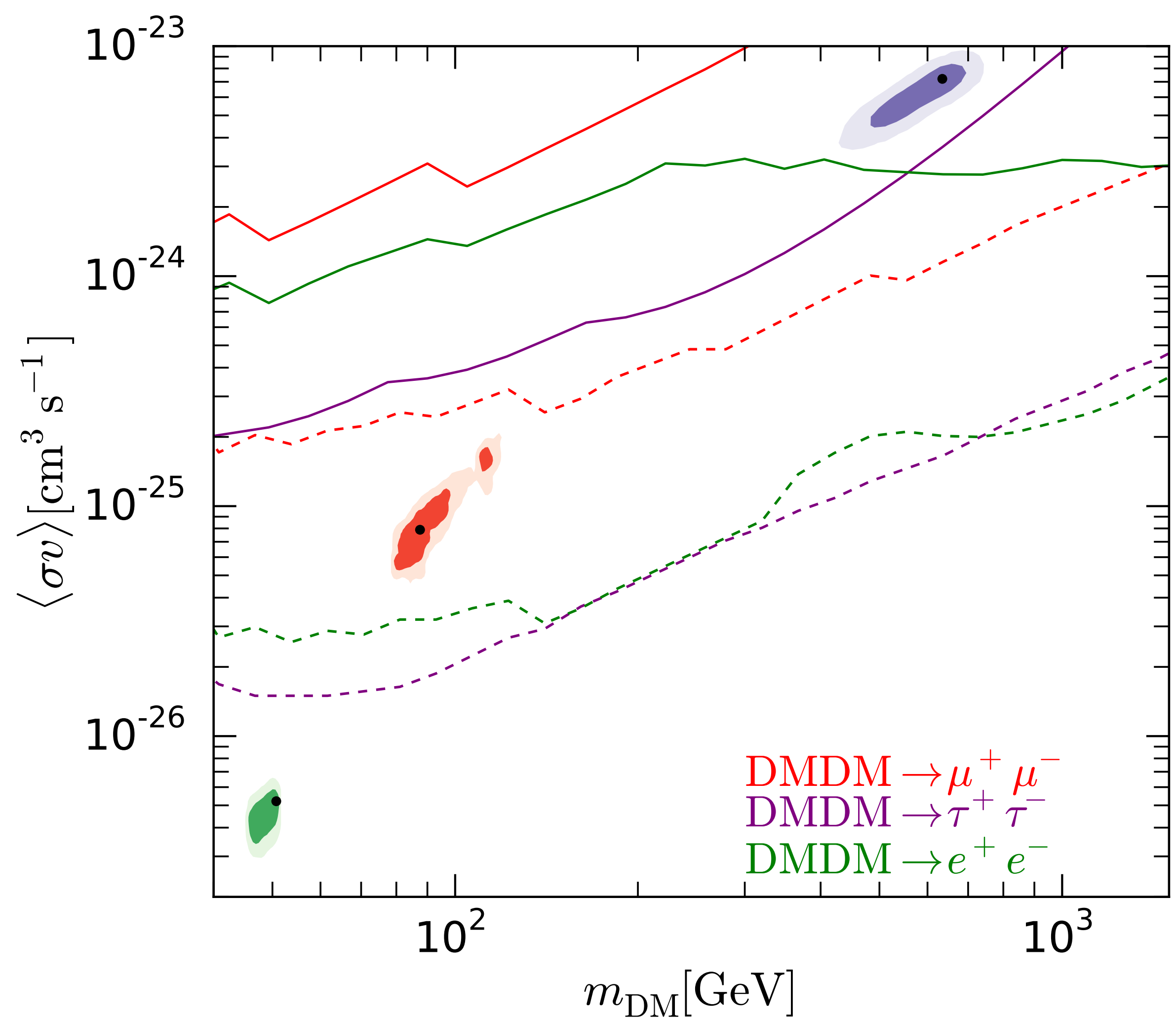


lines are upper limits derived in

Di Mauro, Donato, Phys. Rev. D 91 , 2015

From an analysis of the Isotropic Gamma-ray Background (IGRB) measured by Fermi-LAT

(solid lines = limits based on more conservative assumptions)

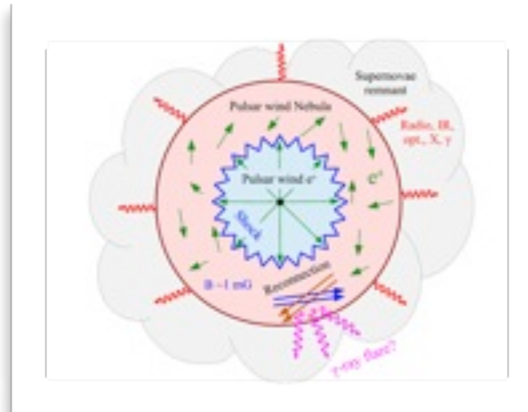
The contour for the μ+μ- channel is compatible with limits derived in the gamma-ray channel!

Alternative scenario

- Electrons

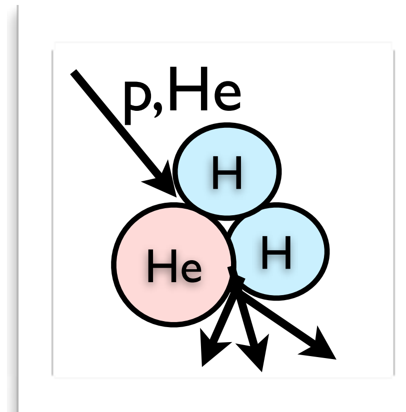
SNRs

+



PWNe

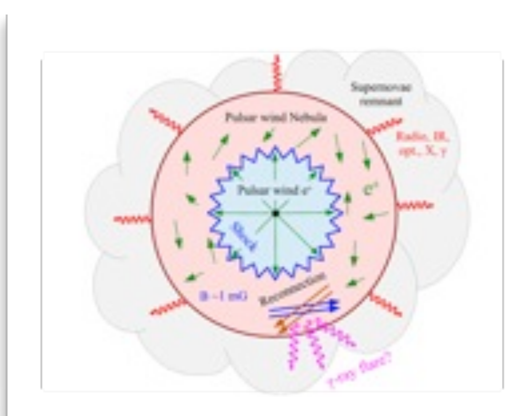
+



secondaries

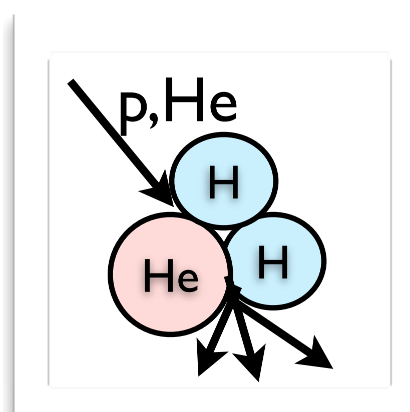
+ DM

- Positrons



PWNe

+



secondaries

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Alternative scenario

- Electrons

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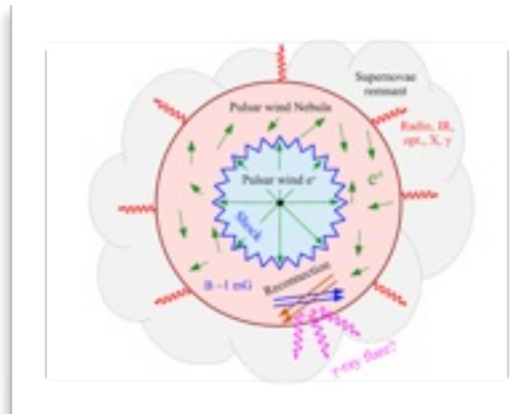

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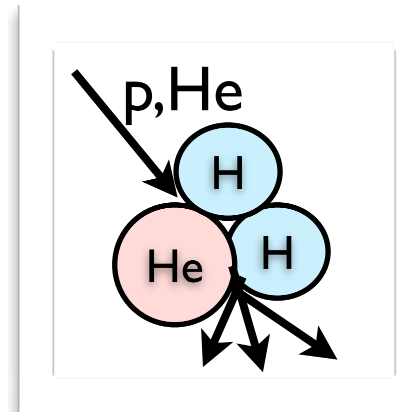
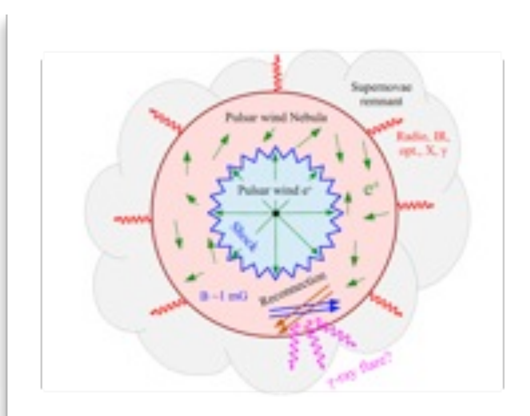


+ ~~DM~~

Additional PWN

SNRs PWNe secondaries

- Positrons



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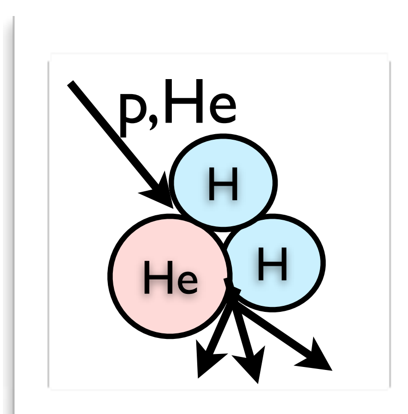


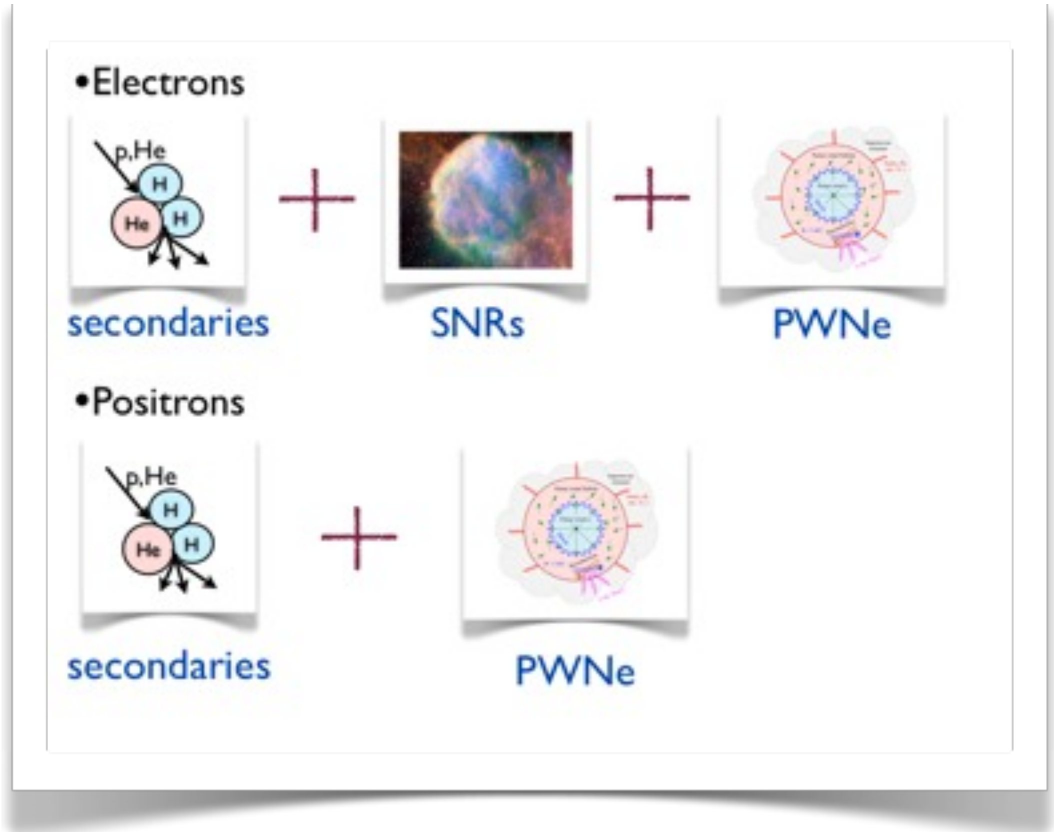
+ ~~DM~~

Additional PWN

PWNe secondaries

Alternative scenario

Our model is now composed by **astrophysical** primary and secondary sources **and an additional PWN**



+PWN

We have **9 parameters**:

- •γ
- •η

PWNe

- •Q0
- •γ_{SNR}

Far SNRs

- •d_{PWN}
- •T_{PWN}
- •η_{PWN}

Additional PWN

- •φ Fisk potential
- •N_{vela} Normalization of Vela flux

We fit the **two independent observables** among the ones measured by AMS-02:

$e^+/(e^++e^-)$
e^++e^- flux

Fit to AMS data

Parameter	central value $\pm 1\sigma$
η_{PWNe}	$0.05^{+0.04}_{-0.03}$
γ_{PWNe}	$2.3^{+0.1}_{-1.0}$
$Q_{0,SNRs}[10^{50}$ erg/s$]$	$1.10^{+0.02}_{-0.06}$
γ_{SNRs}	$2.22^{+0.01}_{-0.02}$
N_{Vela}	$0.8^{+0.2}_{-0.2}$
d_{psr} [kpc]	$0.63^{+0.26}_{-0.24}$
T_{psr} [kyr]	1110^{+873}_{-610}
η_{psr}	$0.47^{+0.23}_{-0.17}$
$\chi^2/84$ d.o.f. $= 0.85$	

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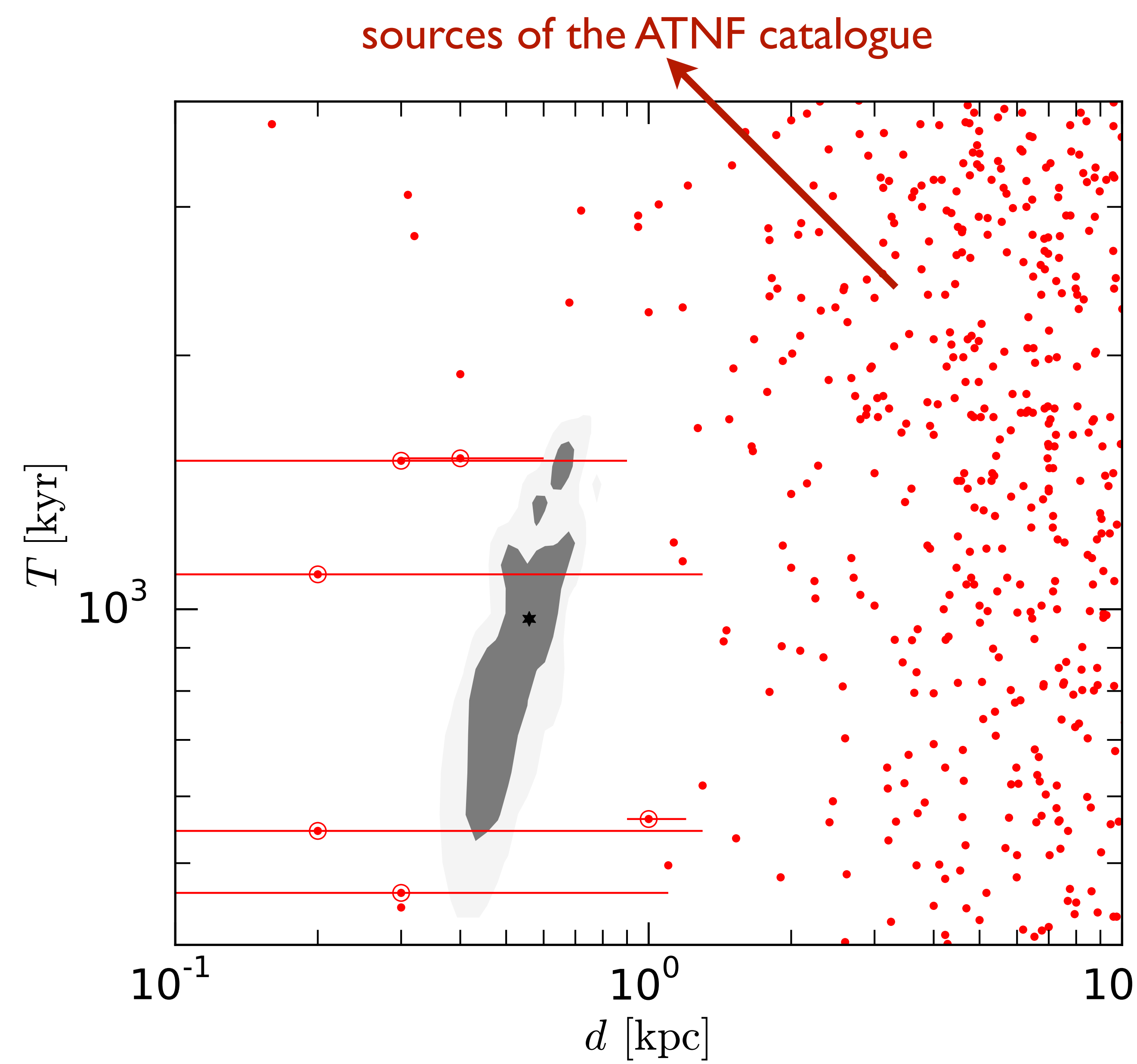

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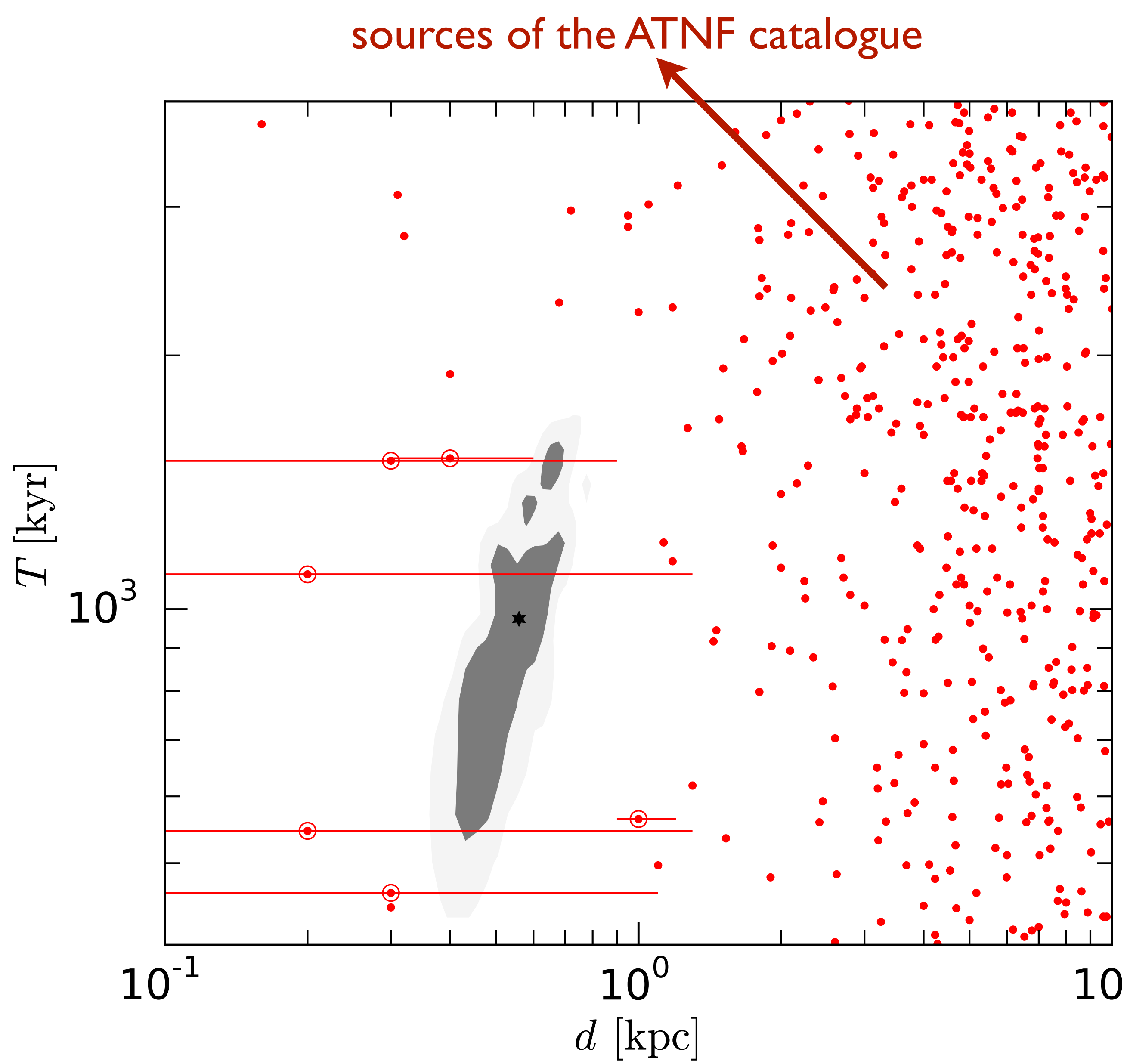


The fit is remarkably good (even better than the one obtained with DM)

The contour region in the (d,T) plane is compatible with the uncertainty on the position of some of the source of the ATNF catalogue

So what?

We have seen that the **simplest astrophysical model** we can think of **fails** in reproducing the **positron fraction**

This can be seen as a hint in favor of **additional positron sources**

However, it is **not an evidence of DM**, since astrophysical explanations are possible as well

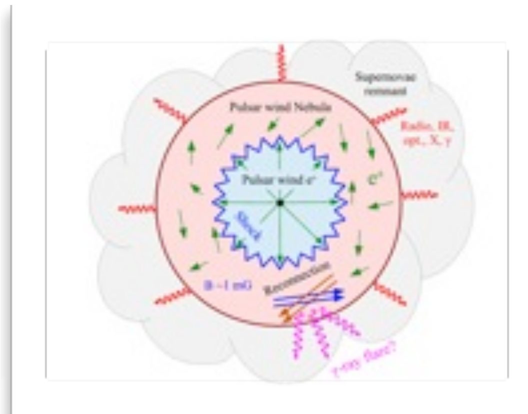
Not everything is lost: we can still use AMS data to put **conservative constraints on DM properties**

Adding DM

- Electrons

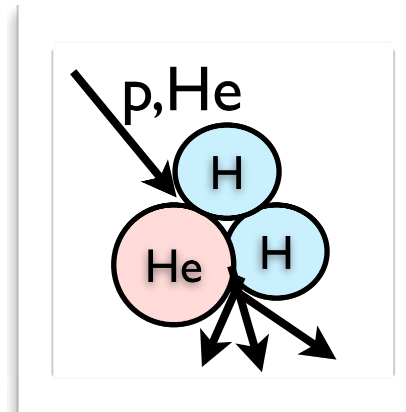
SNRs

$+$



PWNe

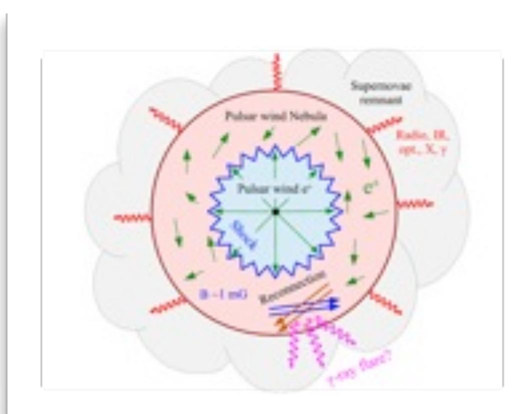
$+$



secondaries

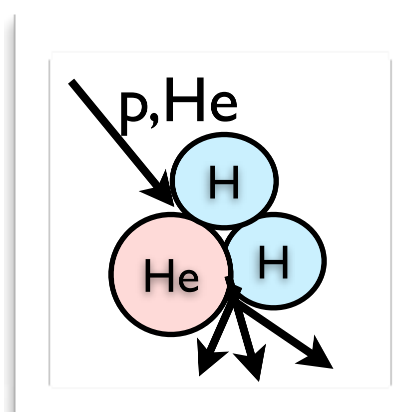
$+$ DM

- Positrons



PWNe

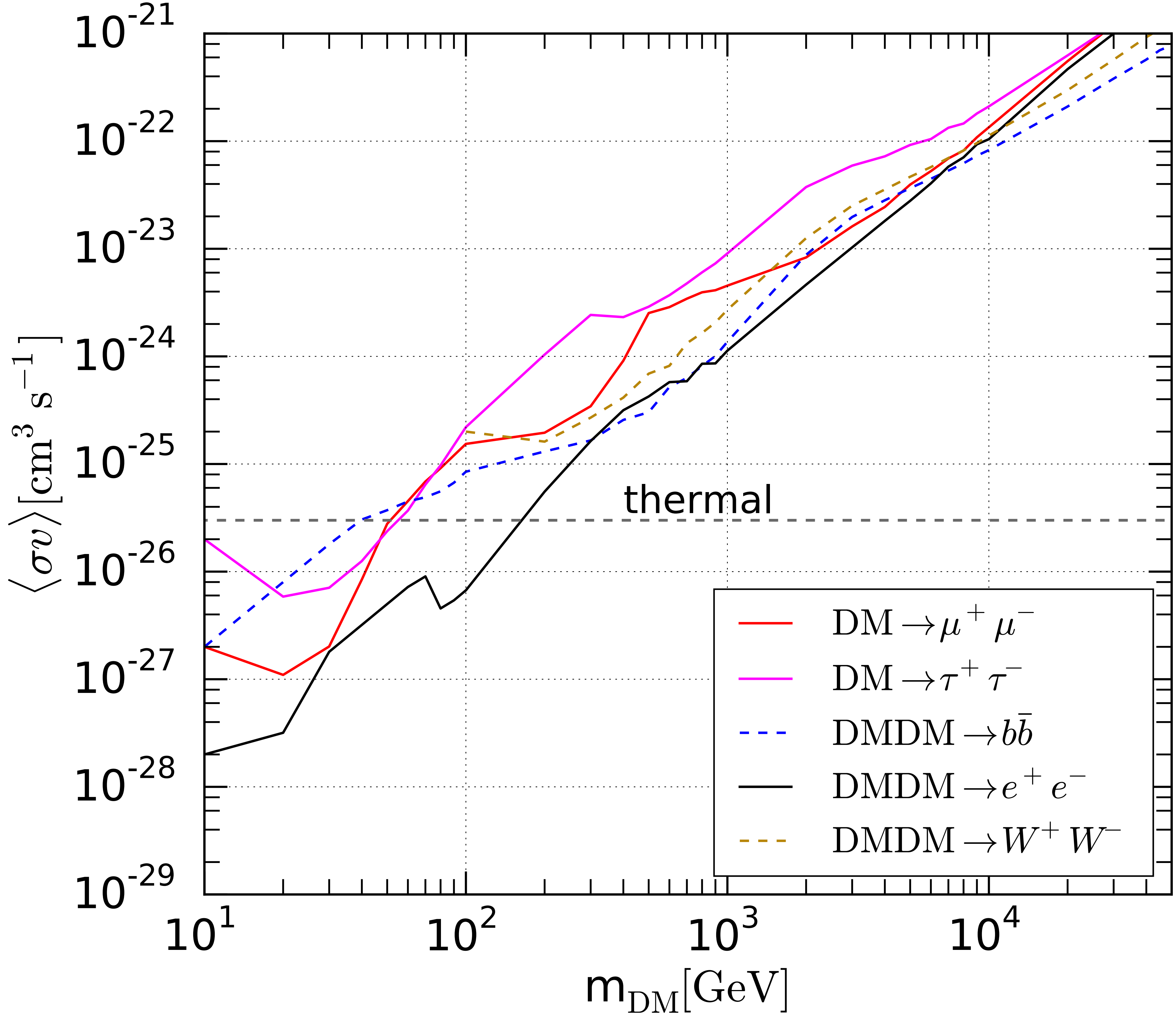
$+$



secondaries

$+$ DM

Constraints on DM properties



Take home message

•We have investigated the role of **three messengers**: antiprotons, anti-nuclei and positrons

•The current **experimental precision** has made indirect DM searches in these channels an invaluable instrument to **explore** configurations of the DM **parameters that are crucial for cold WIMPs**

•Nevertheless, we have seen that the **uncertainties** that can **affect our predictions** are **numerous and varied**. In particular they are represented by the modeling of:

- galactic propagation
- solar modulation
- production mechanisms (for anti-nuclei)
- the astrophysical background (for positrons and antiprotons)

•Achieving a **deep understanding** of these issues is a **mandatory step** if one wants to make **more robust claims** of any kind