Indirect Dark Matter detection and the effect of nuclear uncertainties

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The p-He cross sections measurement: a physics case from Cosmic rays

Torino, July 6 2015

Outline

This talk will be about **Dark Matter**

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It will focus on a particular way to look for it, the **indirect detection**, in the **charged cosmic rays** channels

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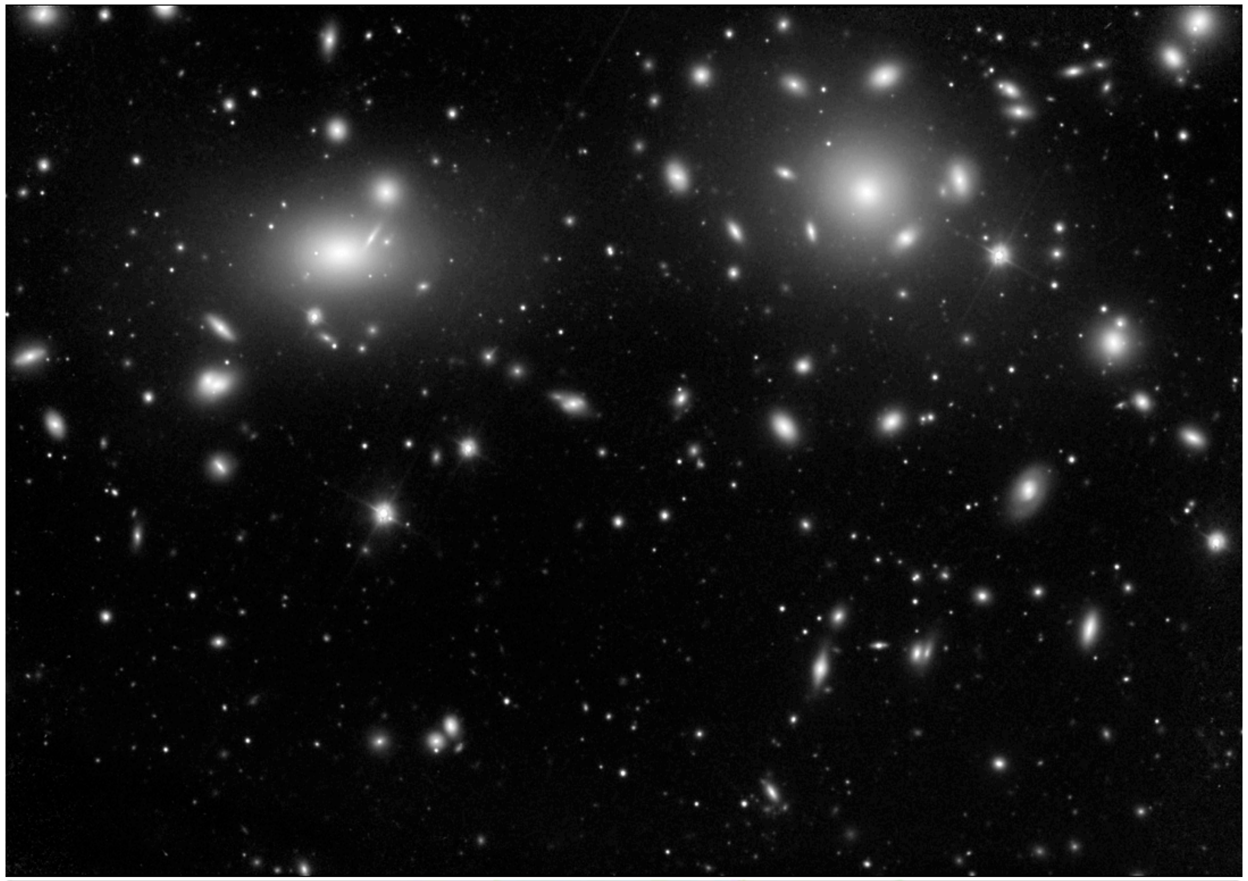
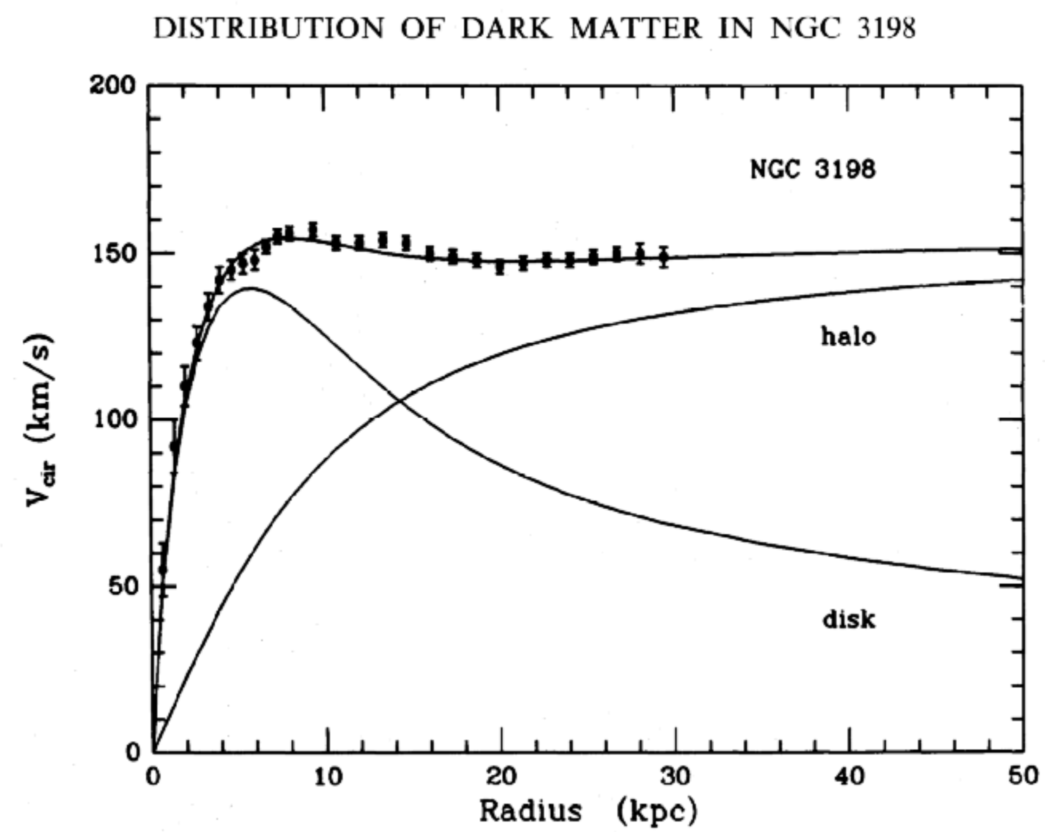
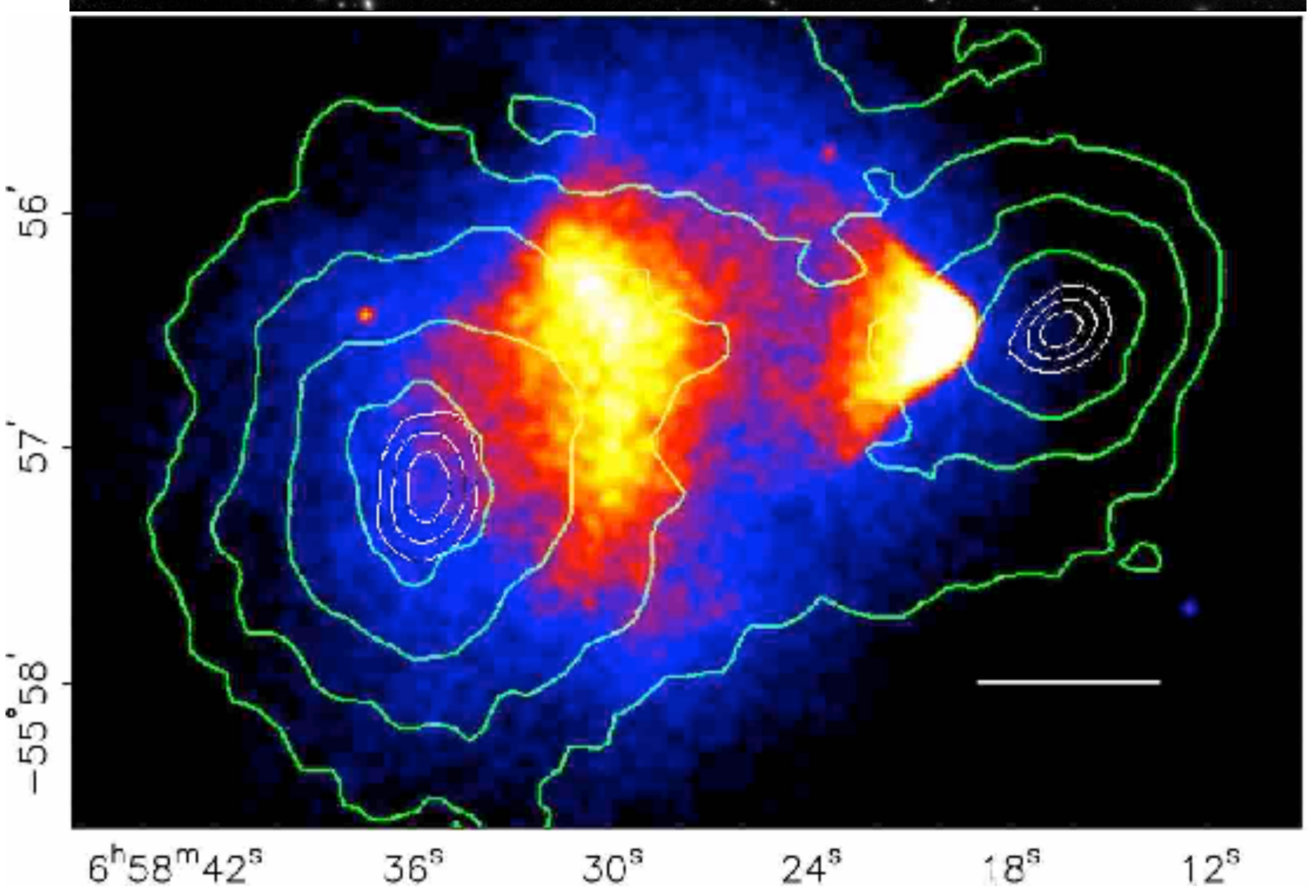
I will investigate the **impact of nuclear uncertainties** on this searching strategy

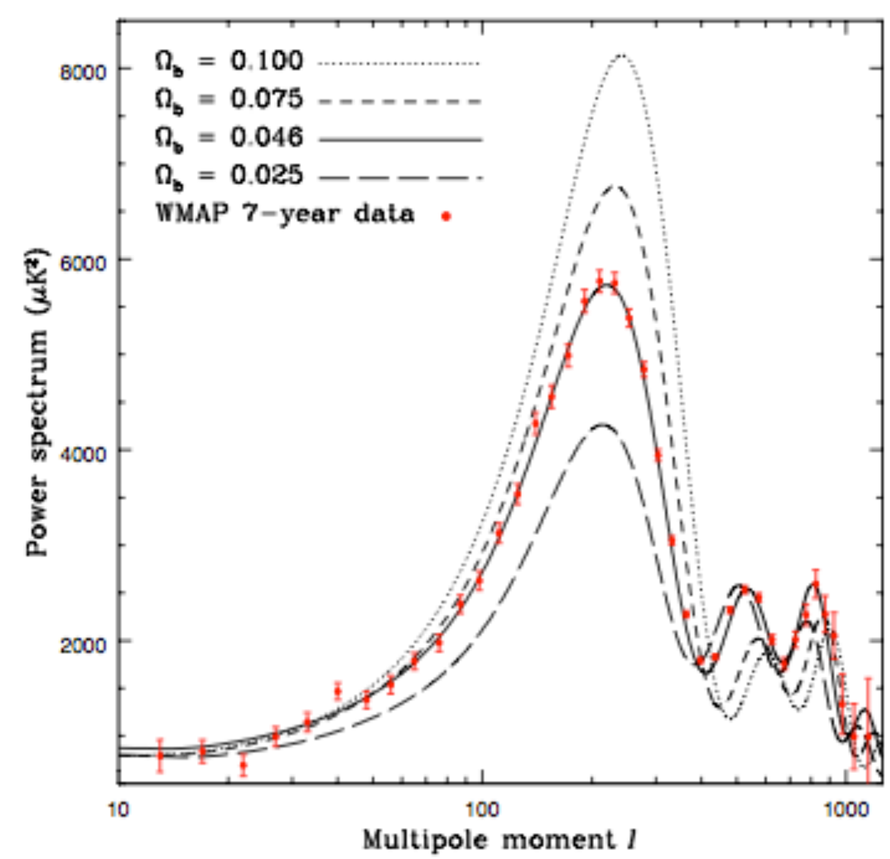
A dark Universe

A dark Universe

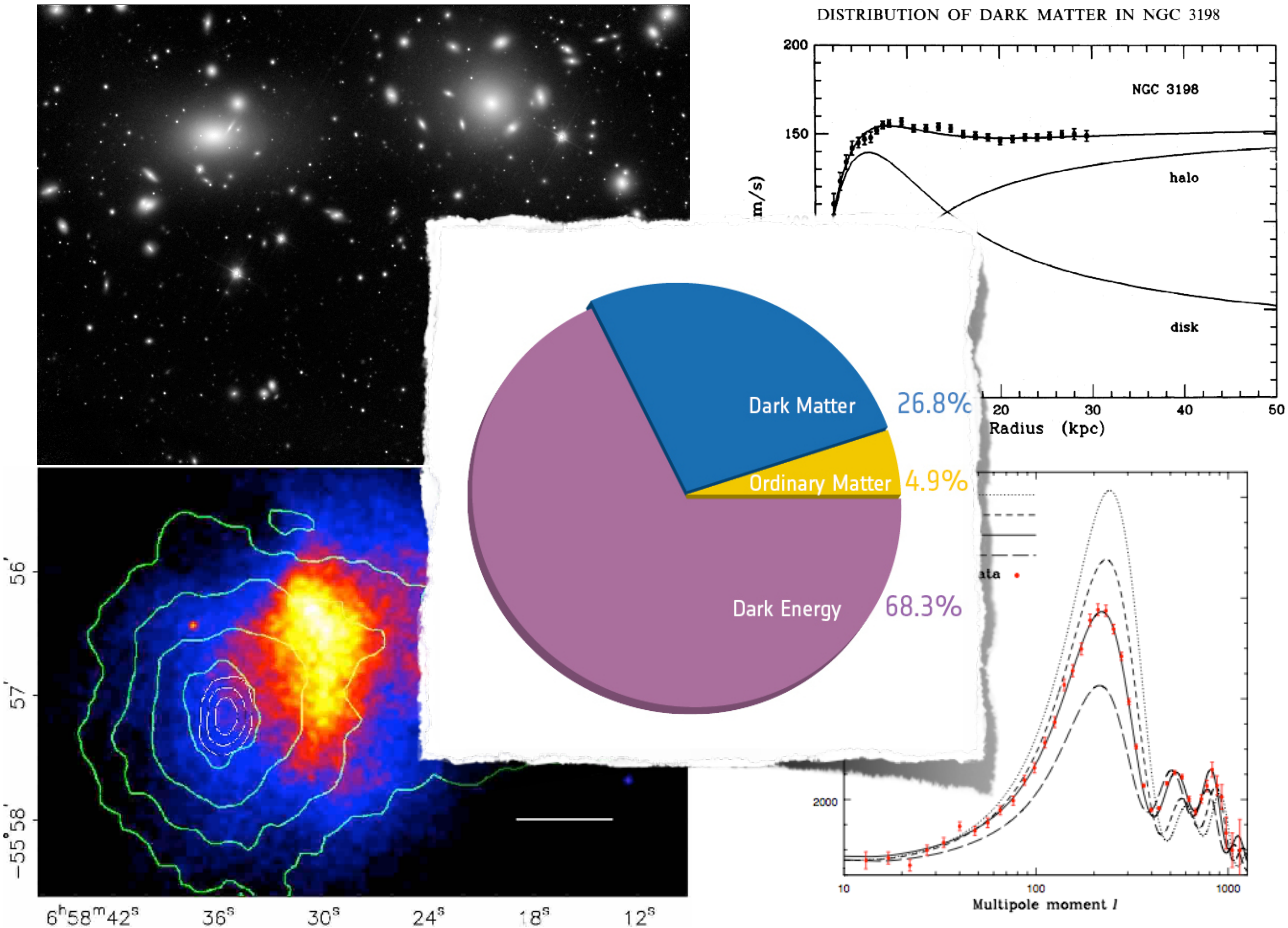








A dark Universe



Dark Matter properties

We know that Dark Matter is:

- **Non-baryonic**
- **Stable** on cosmological scales
- **Invisible** (optically dark)
  - DM particles are ***dissipationless***, i.e. they cannot cool down by emitting photons
- **Collisionless**
  - DM can only interact very weakly with baryons; however, it can be ***self-interacting***
- **Non-relativistic** (or, at most, semi-relativistic) at the time of structure formation
  - If not we would have a ***top-down*** scenario in structure formation

Are there particle candidates with such properties?

Dark Matter candidates

In the Standard Model **we do not have** a good candidate to play the role of the whole DM of the Universe.

Plenty of **good DM particles** lie **beyond the Standard Model** and arise when one tries to solve some of its issues:

- **Hierarchy problem**
  - WIMPs (mostly, but not only, in the context of SUSY)
- **Mass of the neutrinos**
  - Sterile neutrinos
- **Strong-CP problem**
  - Axions

Each one of these candidates has its own **production mechanisms** and **detection signatures**

From now on, we will focus on a **generic cold WIMP**

WIMPs

Why do we look for DM particles at the electroweak scale?

•*The Higgs boson mass is highly fine-tuned. All attempts to solve this issue lead to particles at the weak scale*

•*Particles with masses at the weak scale in thermal equilibrium in the early universe naturally have the correct relic density to be the DM of the Universe*

WIMPs

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$$\Omega_{\rm DM} \propto \frac{1}{\langle \sigma_{\rm ann} v \rangle} \sim \frac{m_{\rm DM}^2}{g_{\rm DM}^4} \Longrightarrow \Omega_{\rm DM} \sim 0.1 \quad \text{if} \quad m_\chi \sim 100 \text{ GeV} \quad \text{and} \quad g_{\rm DM} \sim 1$$

"WIMP miracle"

WIMPs

Why do we look for DM particles at the electroweak scale?

Independently of these motivations (that could be considered theoretical prejudices), WIMPs are the DM scenario that has the best chances of being thoroughly explored by experiments in the near future

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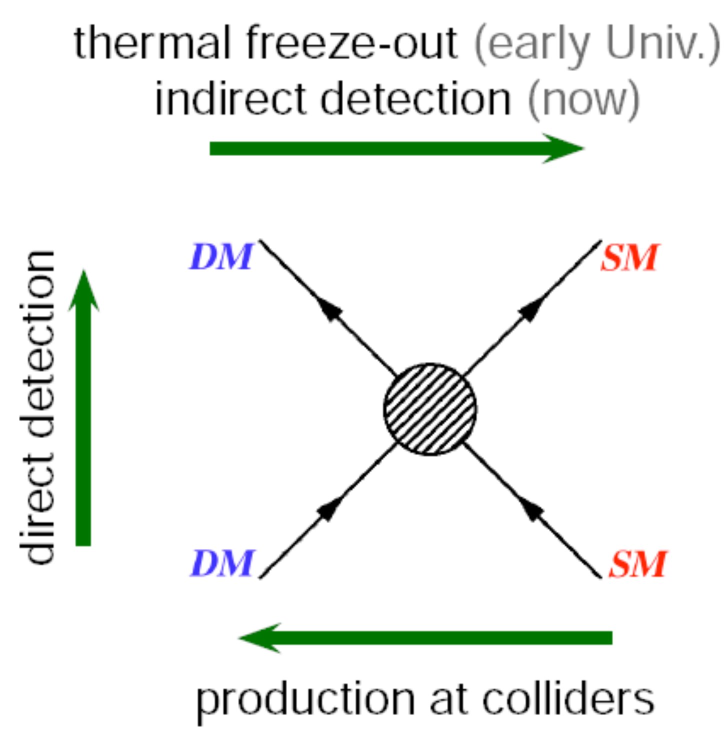
“WIMP miracle”

WIMPs detection

The WIMP miracle requires **efficient annihilation** in the early Universe.
This implies a **DM-DM-SM-SM interaction term.**



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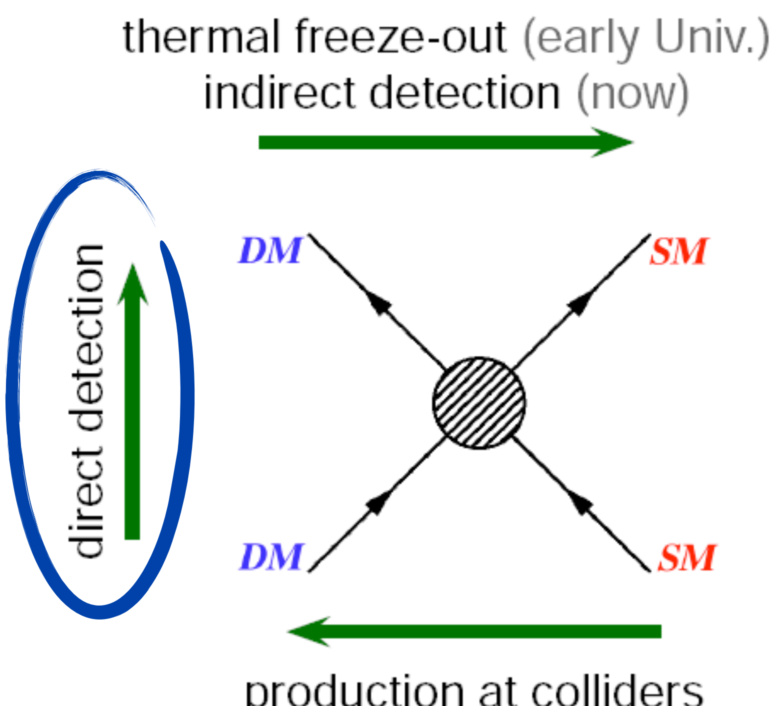
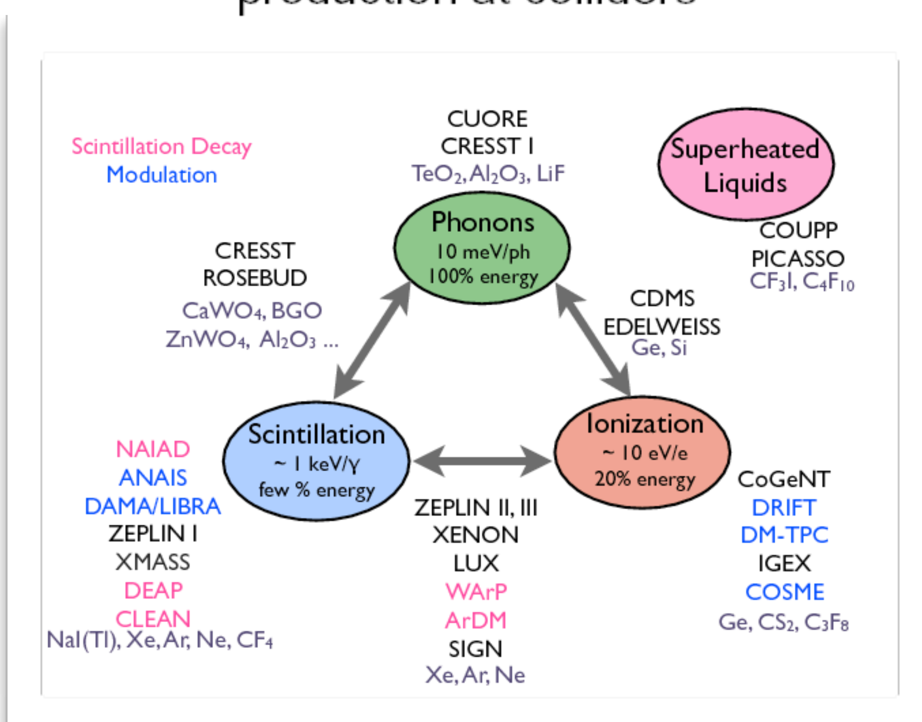
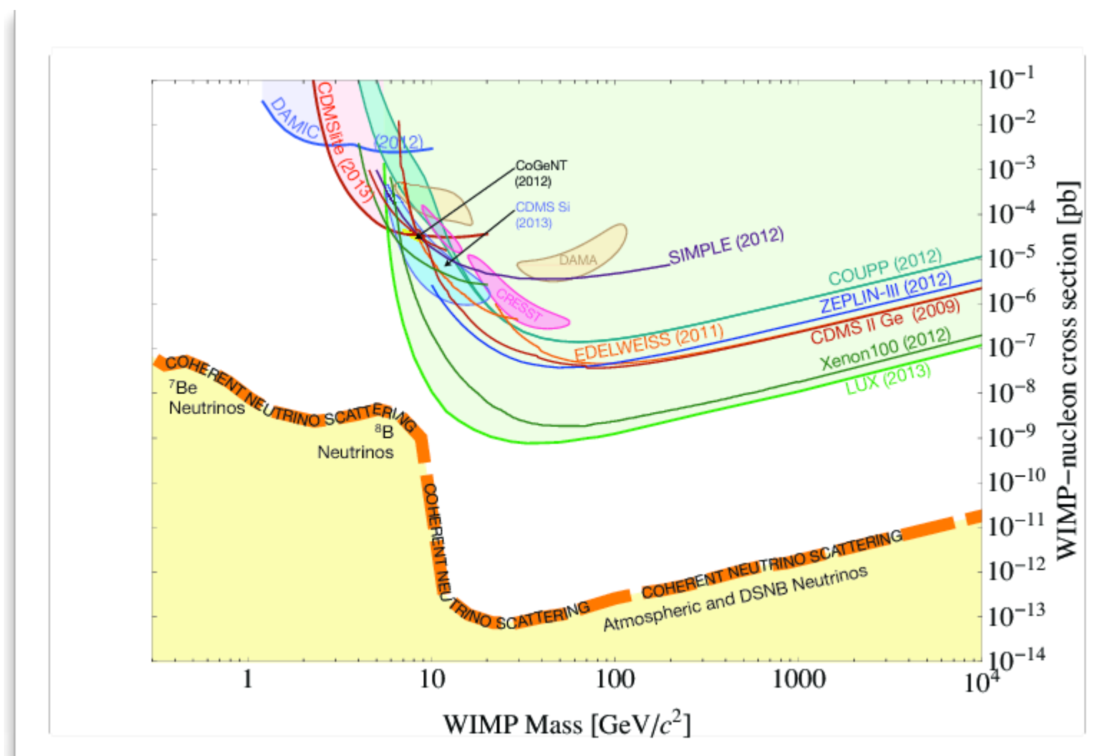


- The idea behind direct detection is that DM particles can be **visible** through their **scattering off SM particles**.
- Several techniques have been developed to separate the **few expected signal events** from the **huge background**.





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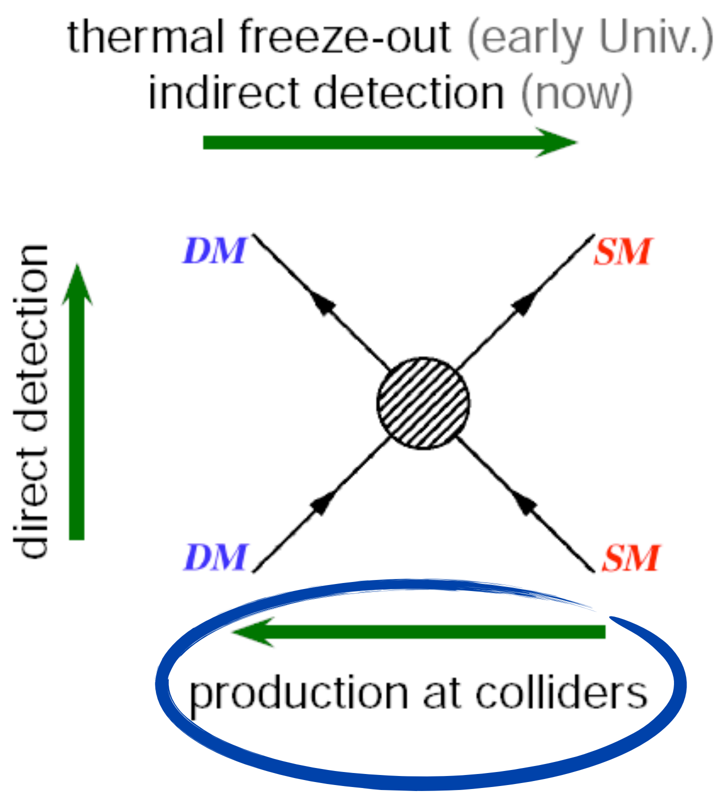

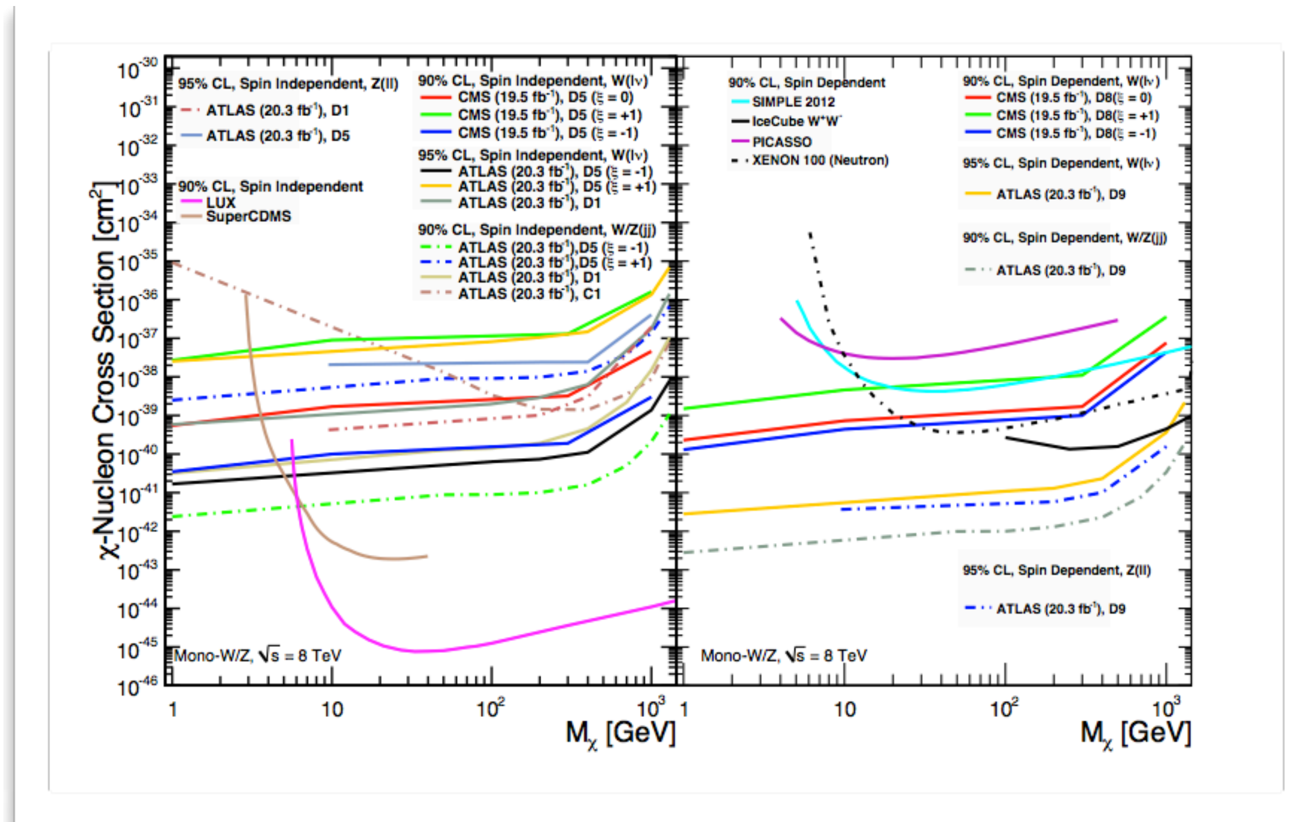

- The main advantage of collider searches is that they **do not suffer from astrophysical uncertainties**.
- Once produced, DM is expected to **leave the detector unseen**, its only possible signature being **missing energy**.
- One can **look for DM imprints** in a collider within a **specific BSM framework** or adopt a **simplified** effective field theory **approach** (as in the searches for mono-jets/photons)

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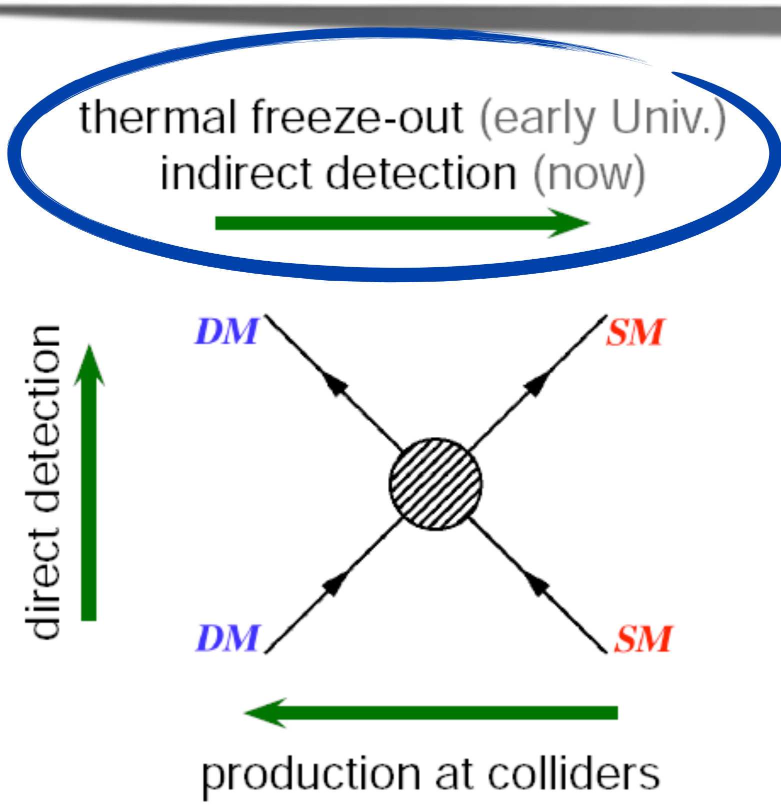
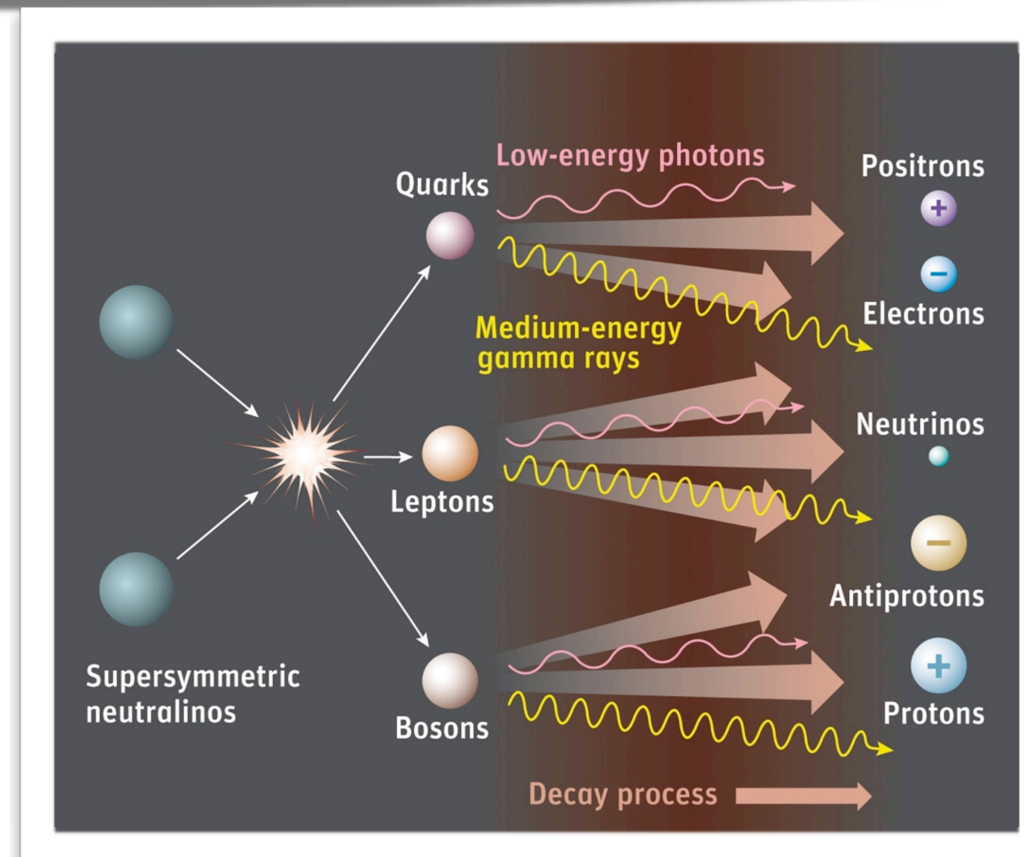




After the freeze-out, **WIMPs can still undergo pair annihilations** (or decays) and **produce SM particles** that can appear in the Cosmic Ray flux:

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

Indirect detection

possible DM imprints

Indirect detection

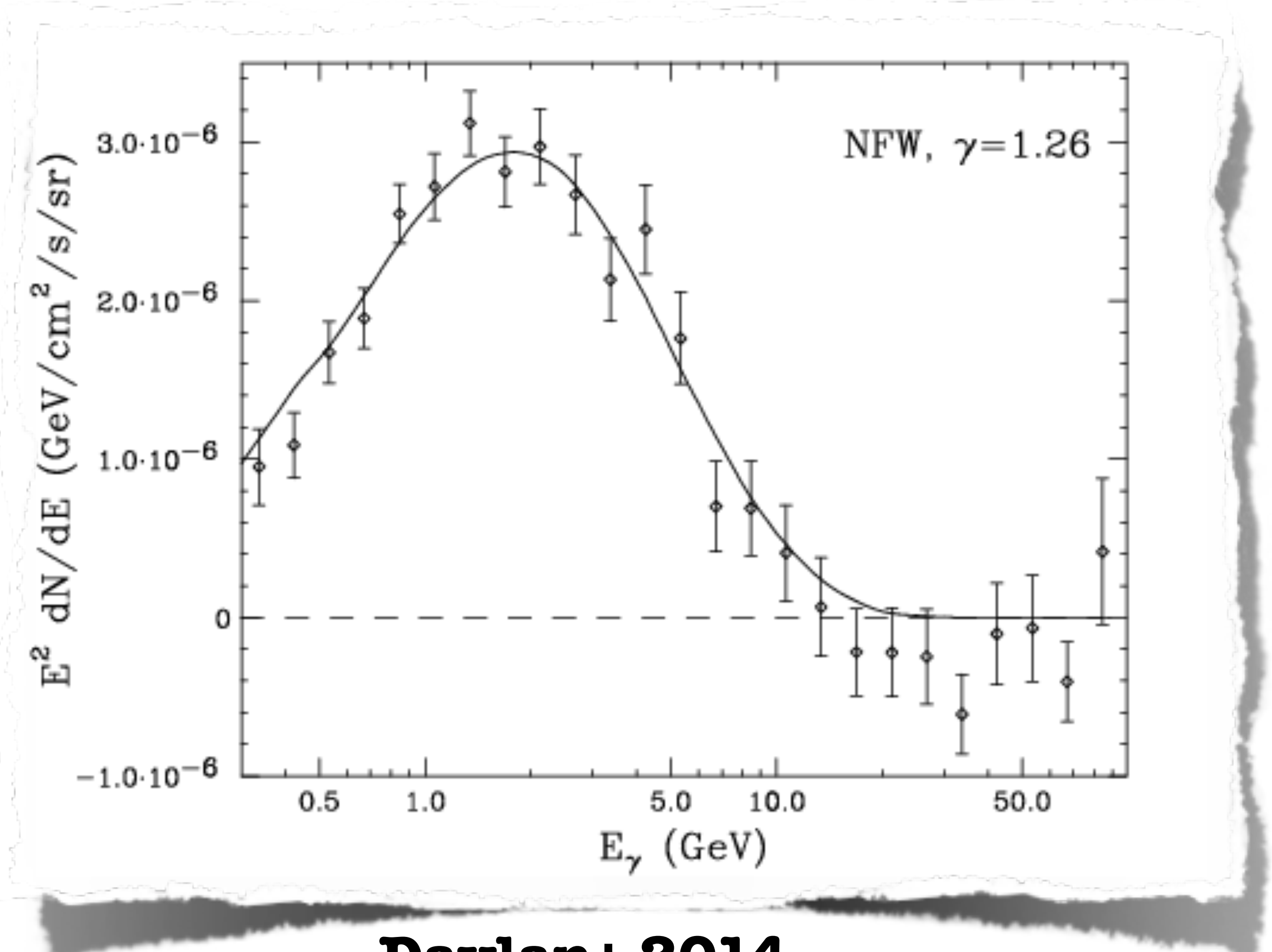
possible DM imprints

photons emitted promptly from DM ann/dec or as products of $e^{\pm}$ synchrotron emission or Inverse Compton Scatterings on ambient light

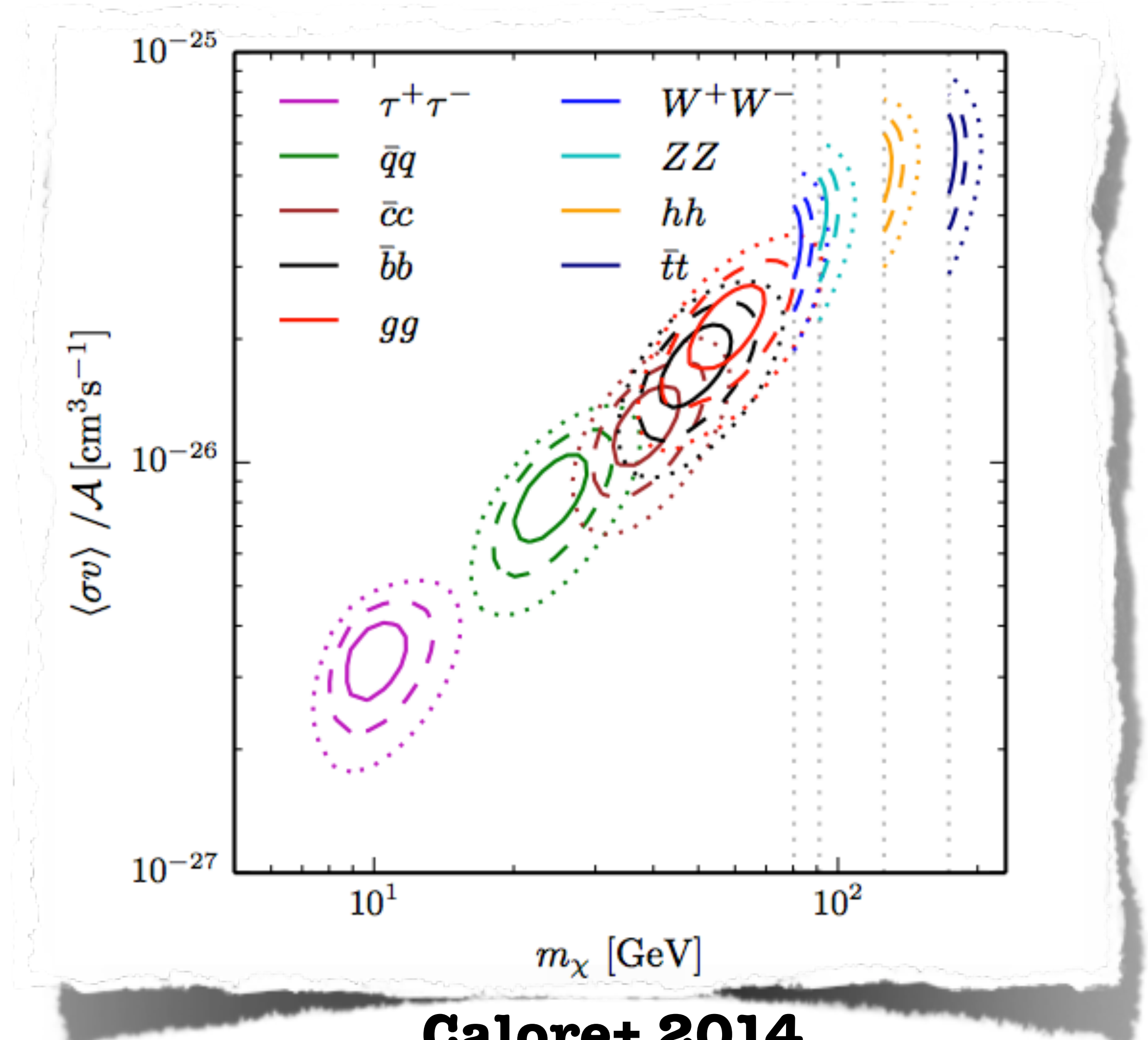
Fermi-LAT
Cherenkov Telescopes
Radio Telescopes

Fermi-LAT GC excess

Fermi-LAT data in the GC region shows a **significant excess** with respect to the expected background



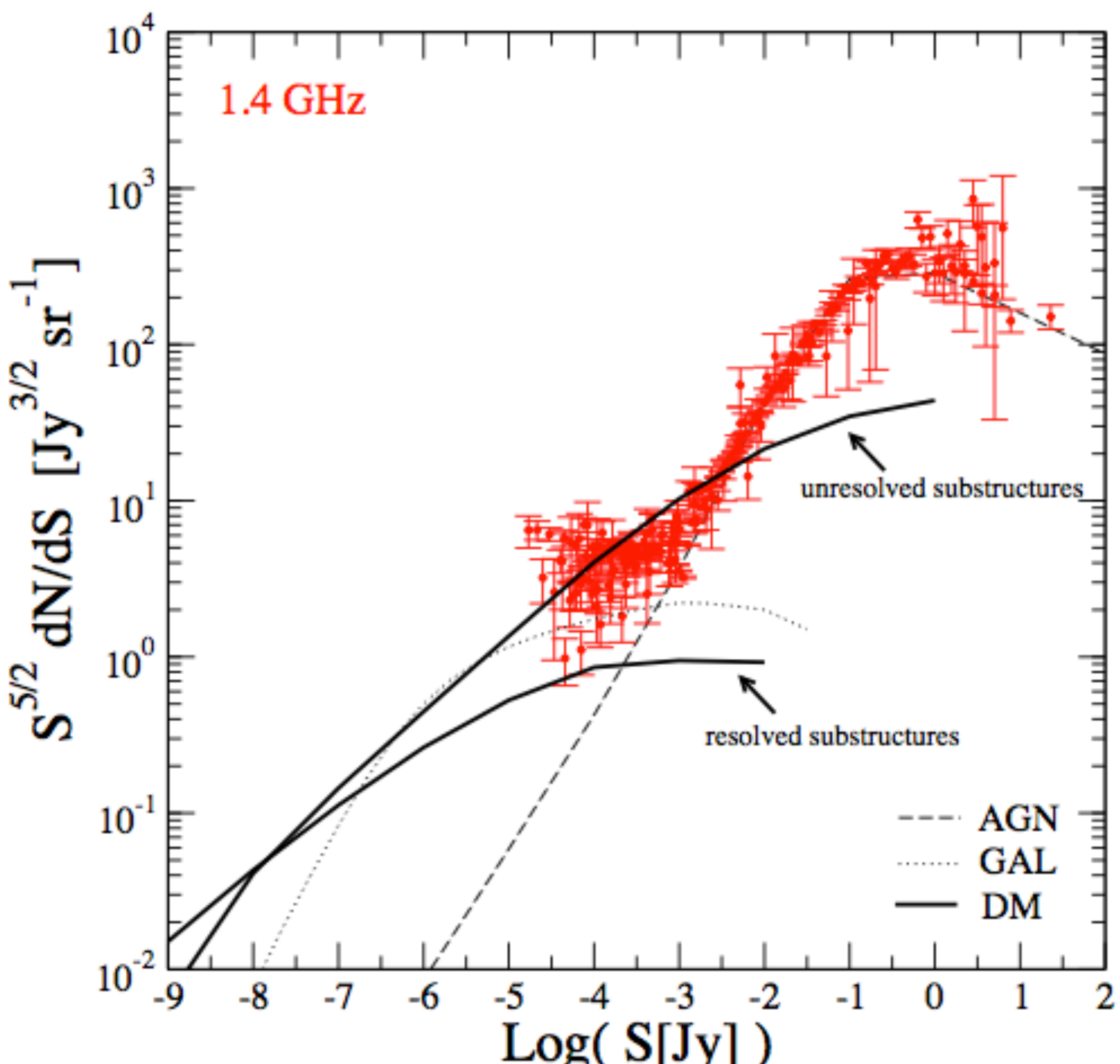
Daylan+ 2014

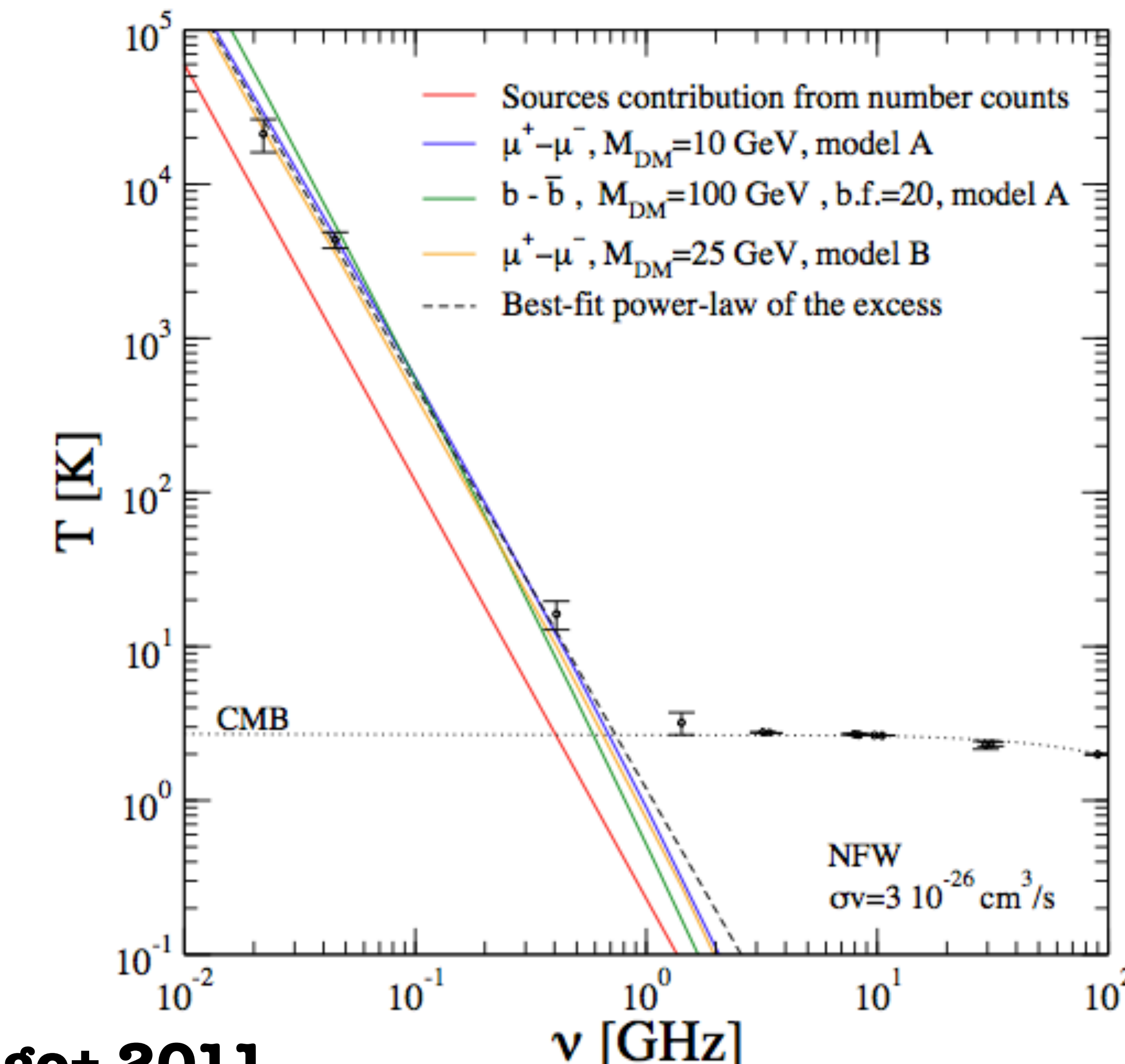


Calore+ 2014

ARCADE excess

Arcade 2 radio measurements at frequencies from 3 to 90 GHz shows an excess compatible with the annihilation of light DM into leptons





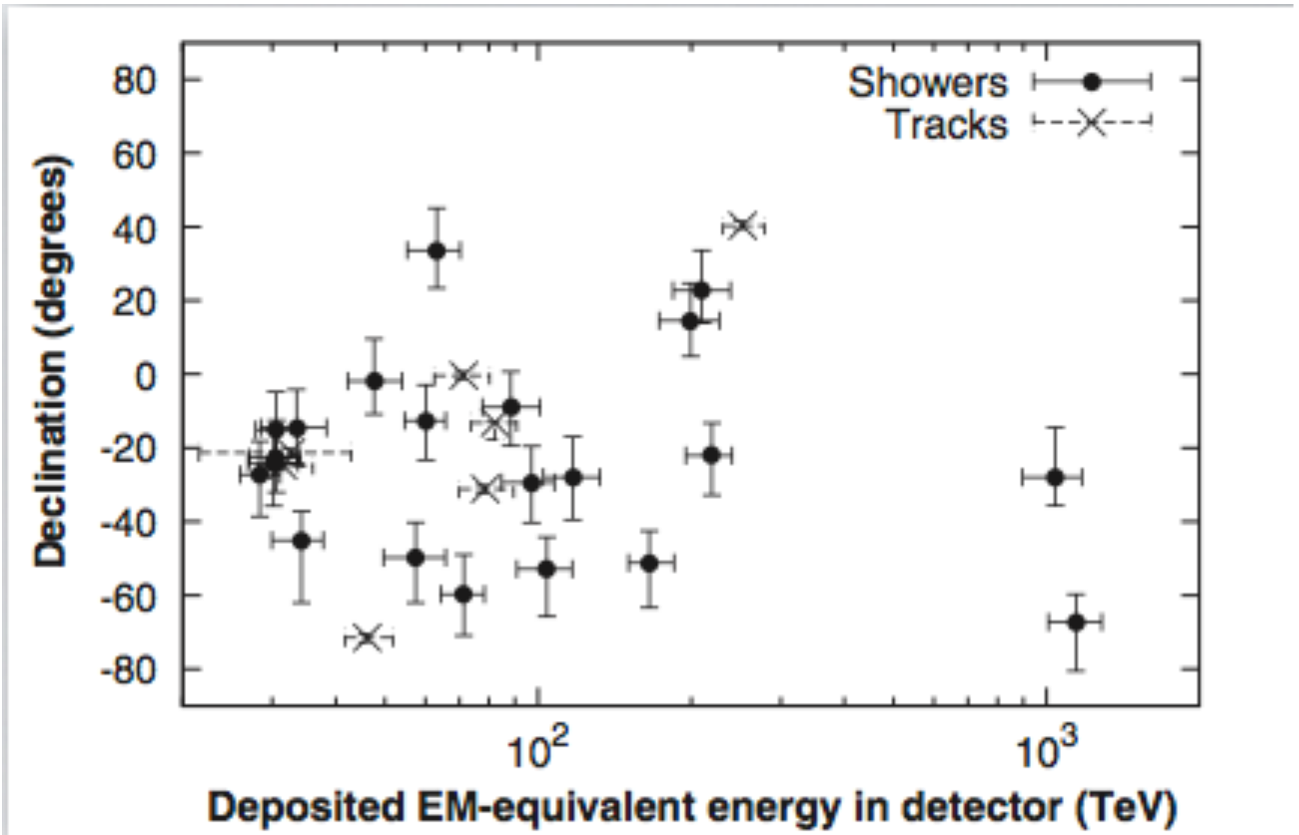
Fornengo+ 2011

Indirect detection

possible DM imprints

- **photons** emitted promptly from DM ann/dec or as products of $e^{\pm}$ synchrotron emission or Inverse Compton Scatterings on ambient light
  - Fermi-LAT
  - Cherenkov Telescopes
  - Radio Telescopes
- **neutrinos** produced in the ann/dec of galactic or extragalactic DM. galactic targets include galactic Center, satellite galaxies or the signal from DM annihilation in massive bodies
  - Neutrino Telescopes (IceCube, Antares, SuperK)

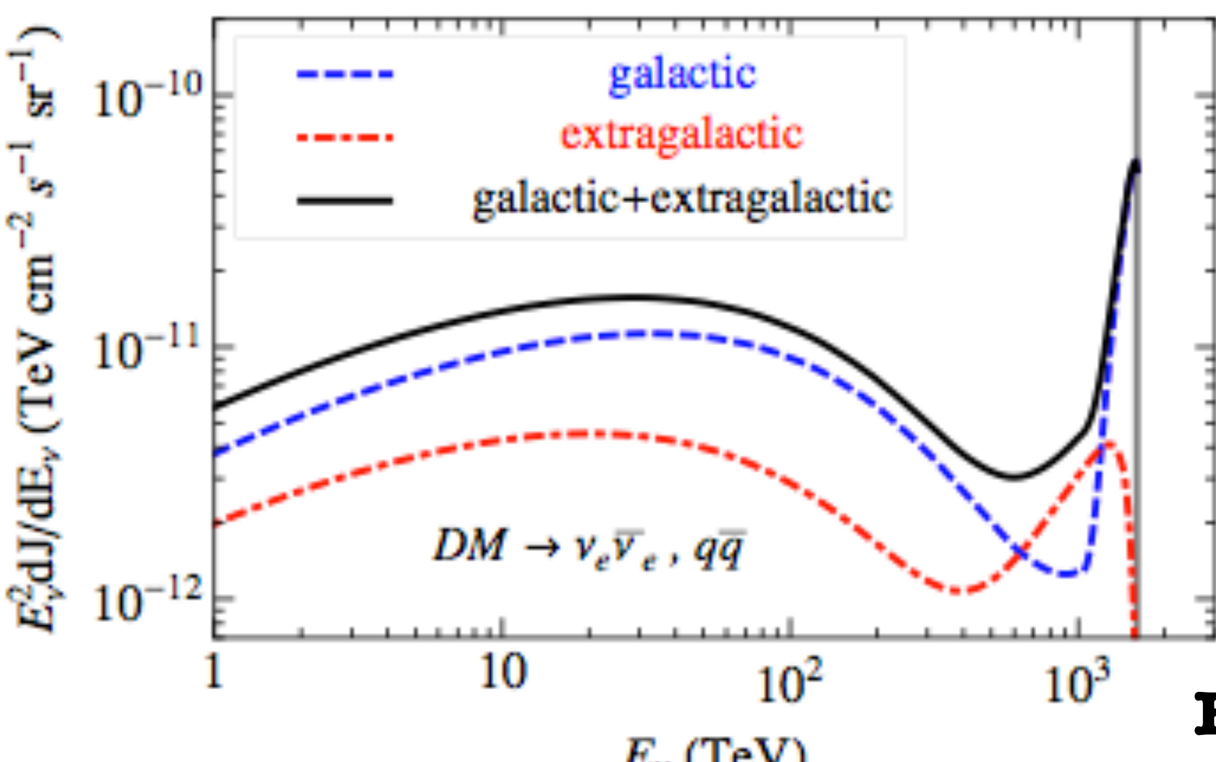
IceCube PeV neutrinos

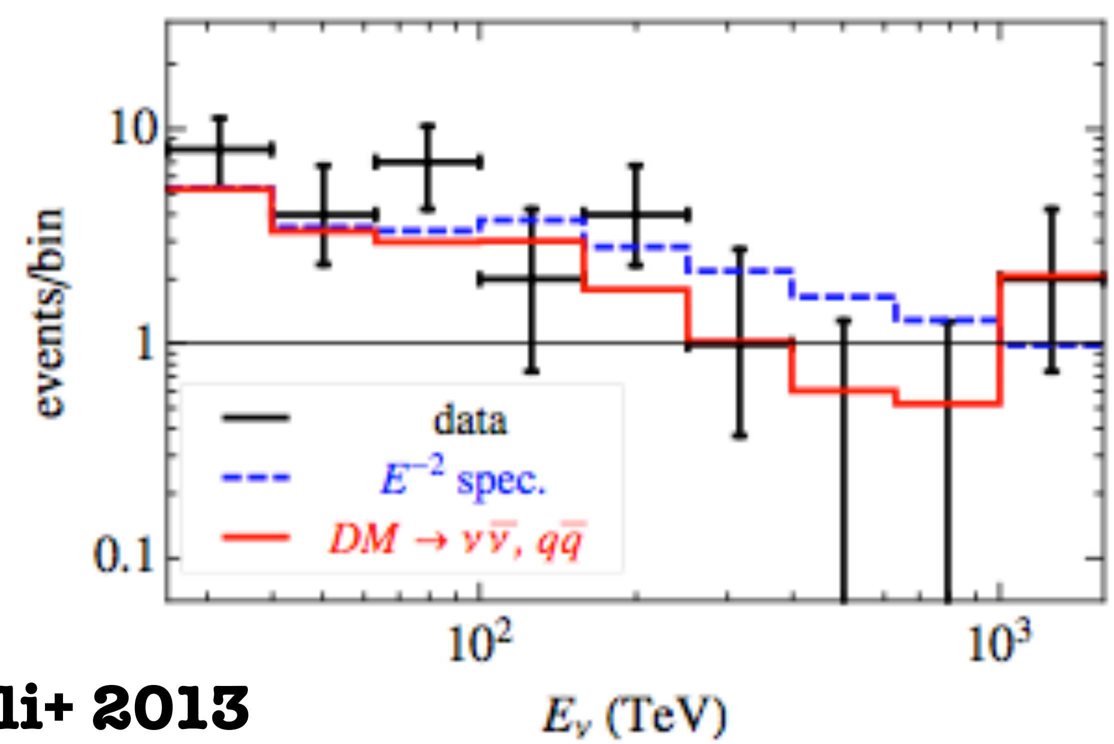


Aartsen+ [Icecube Coll.] 2013

28 events measured in the [30 TeV, 5 PeV] range (expected **background ~10 events**)

signal compatible with the decay of a **DM particle** with **PeV mass**
(obviously, not a WIMP)





Esmaili+ 2013

Indirect detection

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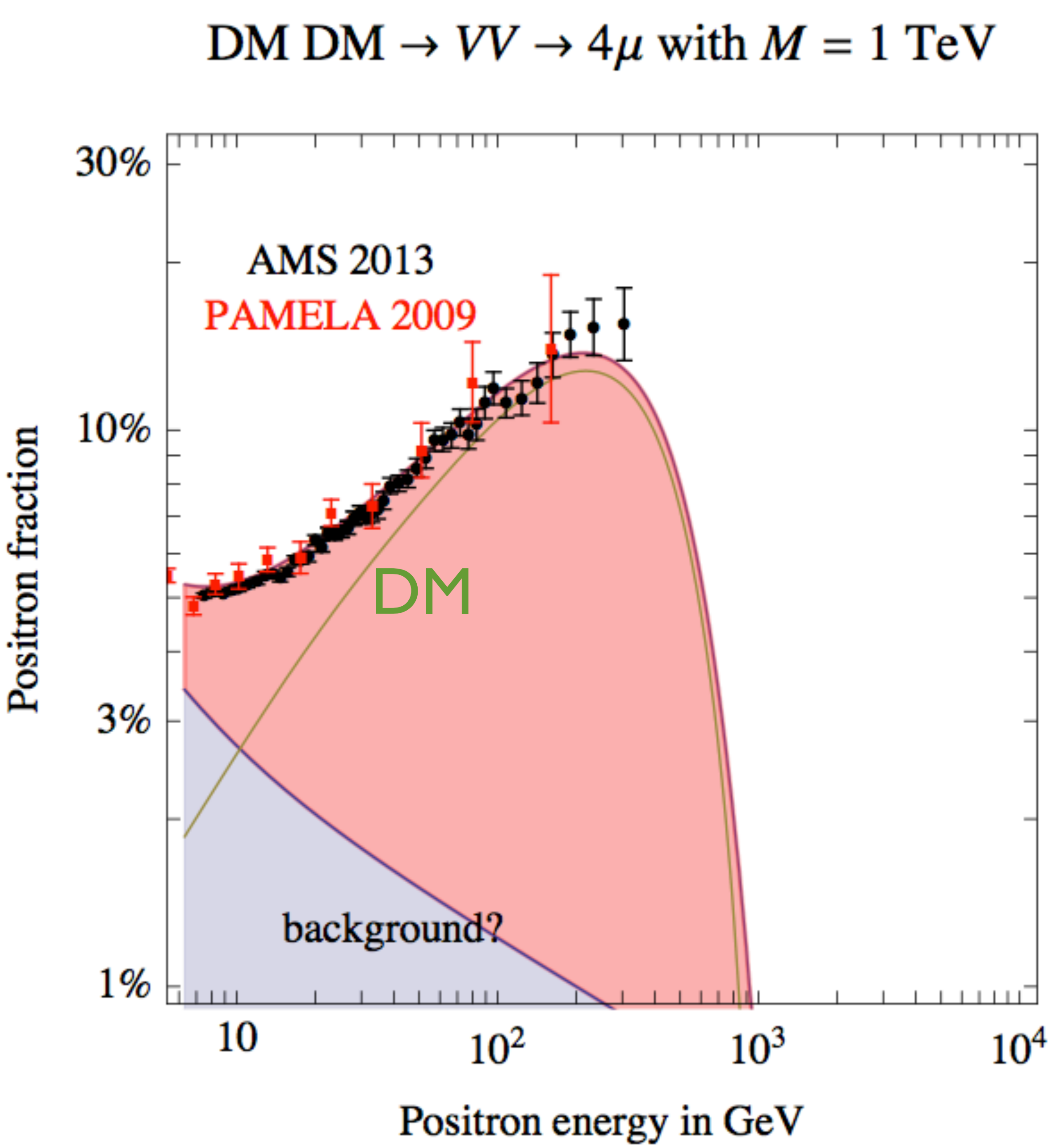
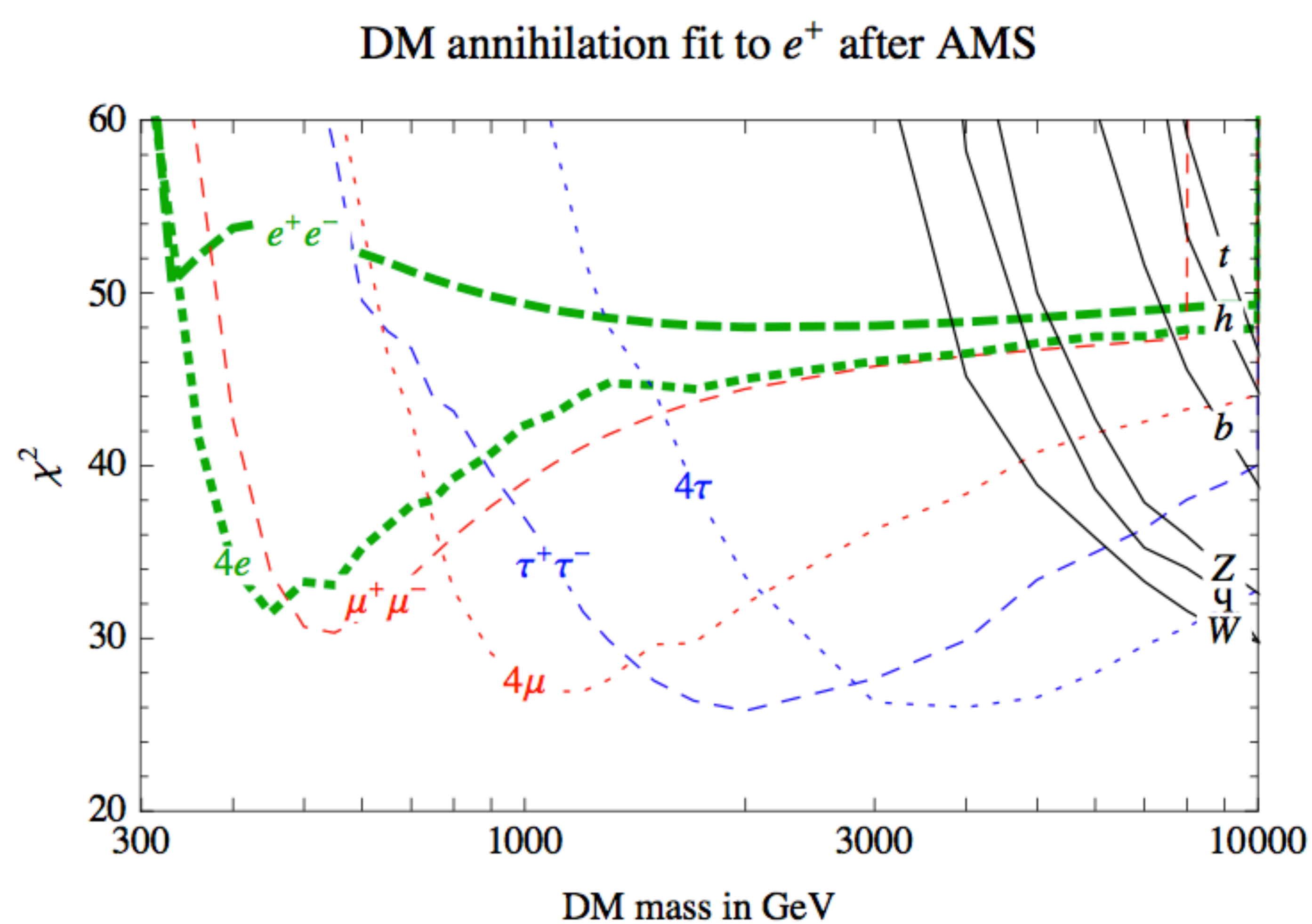
- **charged CRs** produced in DM ann/dec in the galactic halo
  - AMS
  - PAMELA
  - Balloons (GAPS)

PAMELA/AMS excess

The energy spectrum of the positron fraction measured by PAMELA and AMS shows a **steep rise** compatible with the annihilation of TeV-scale WIMP into leptons

Adriani+ [Pamela Coll.] 2008, Accardo+[AMS Coll.] 2013, Accardo+[AMS Coll.] 2014





Cirelli+ 2008,2013

Indirect detection

possible DM imprints

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Cherenkov Telescopes
Radio Telescopes

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charged CRs produced in DM ann/dec in the galactic halo

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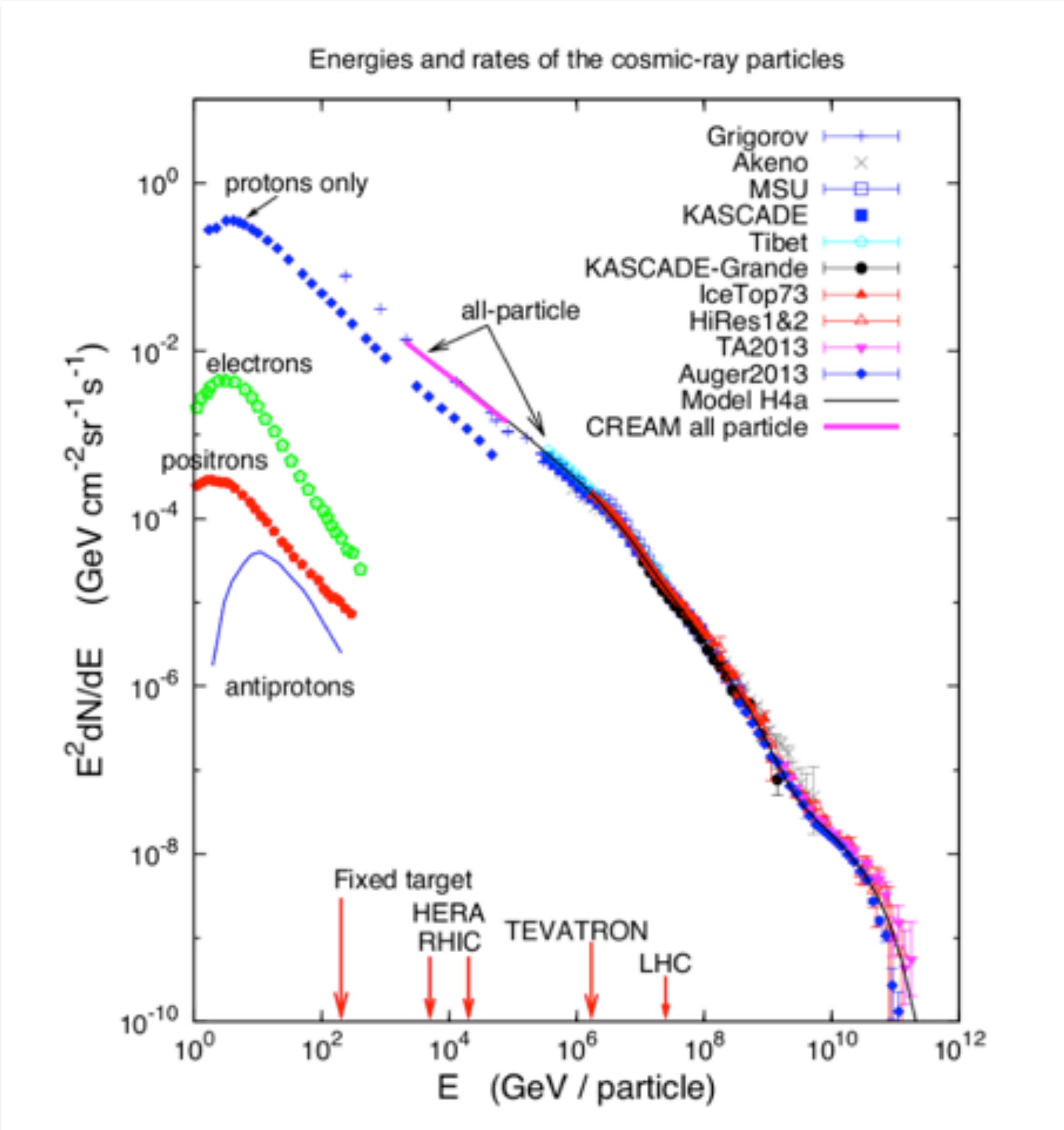
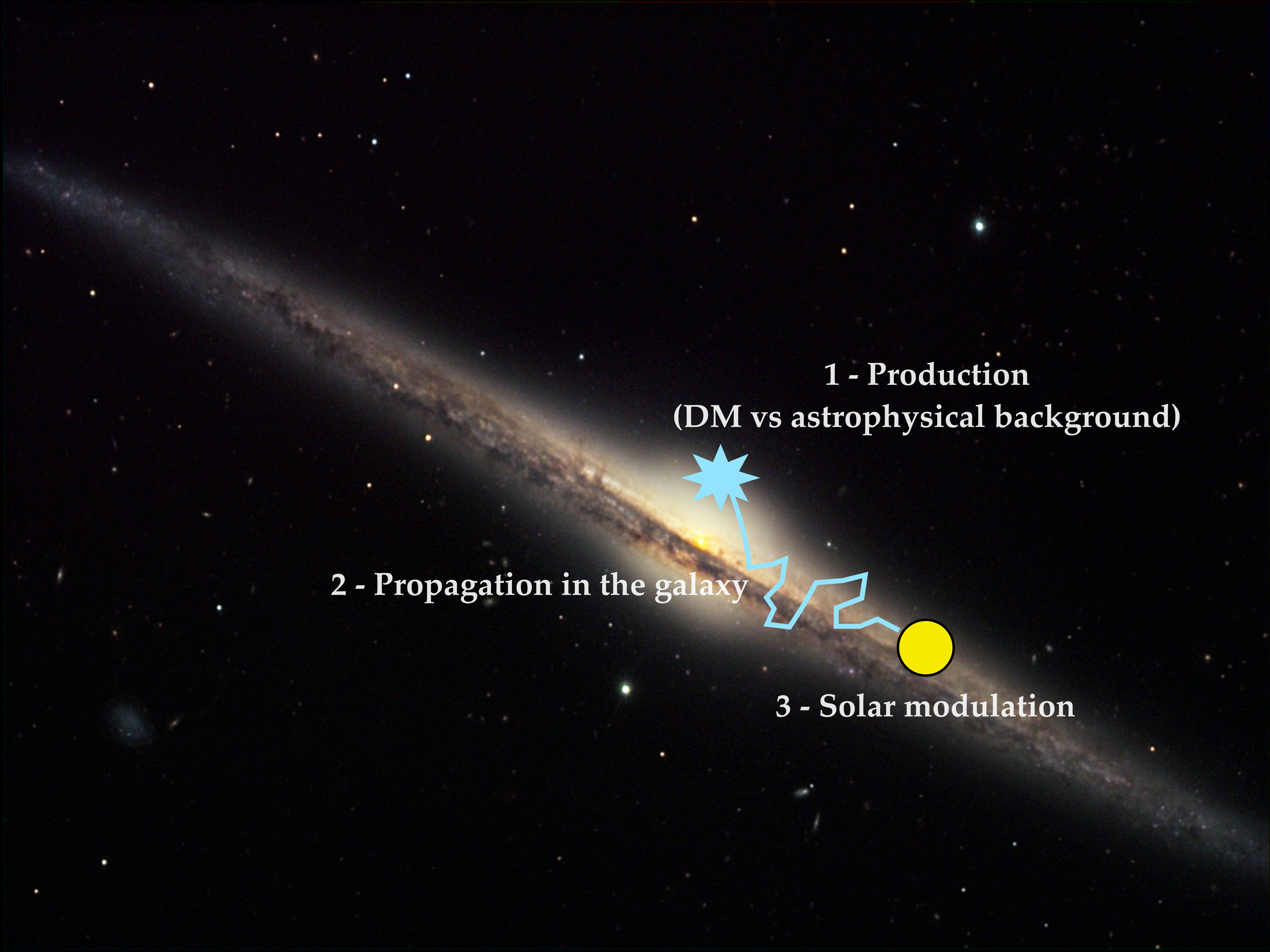
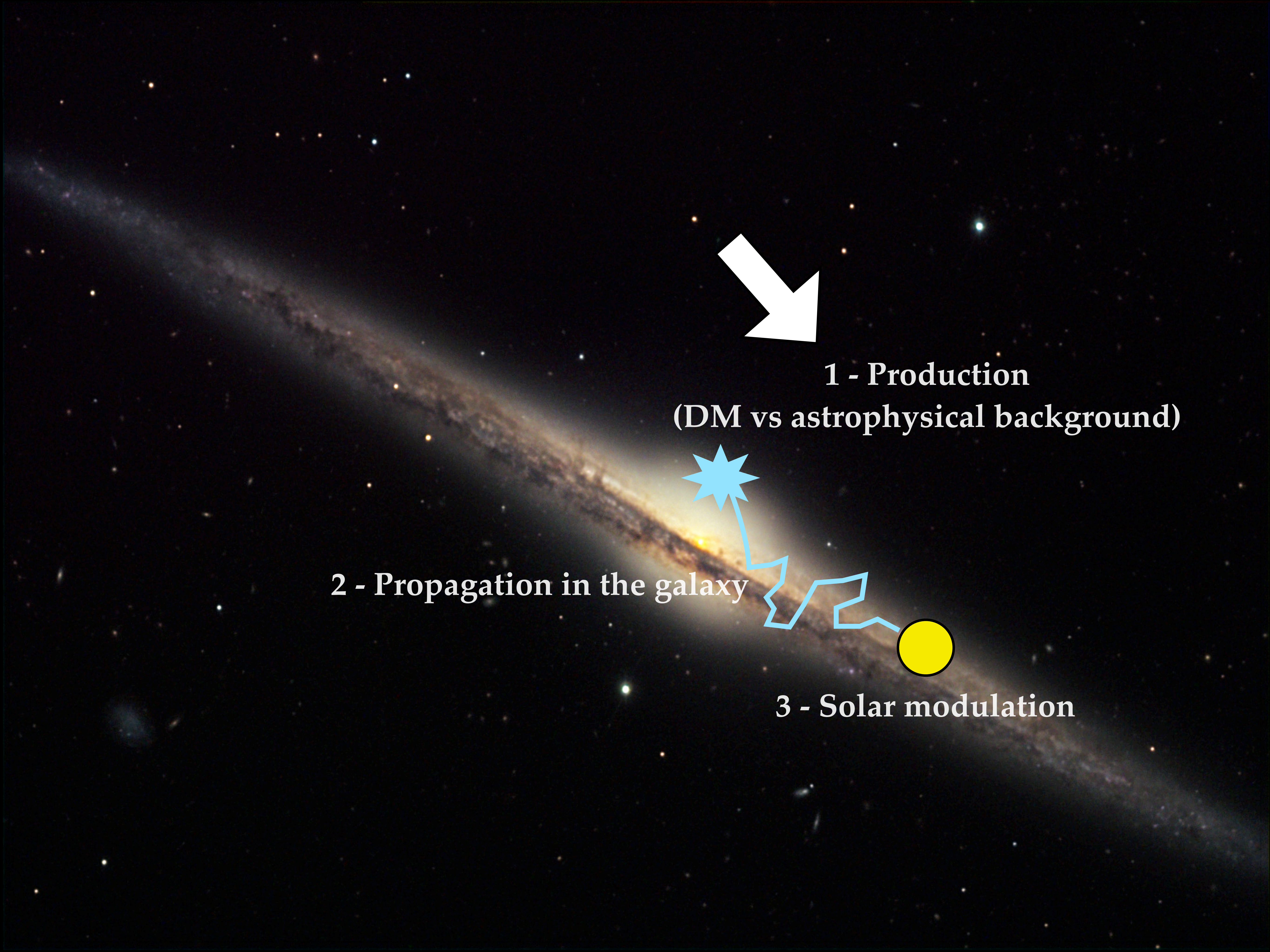
Charged cosmic rays



- 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 extremely rare**
- **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?


1 - Production
(DM vs astrophysical background)
2 - Propagation in the galaxy
3 - Solar modulation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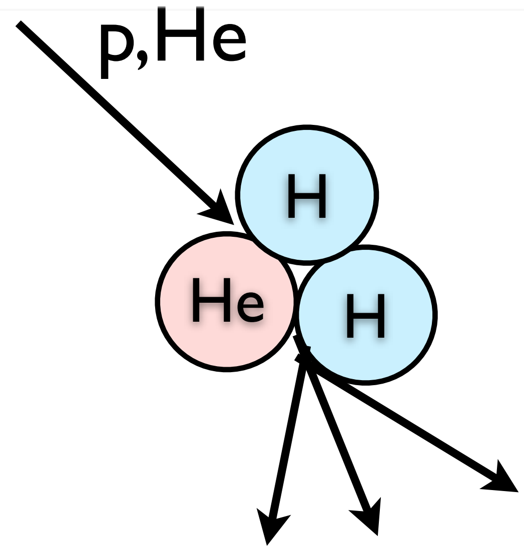
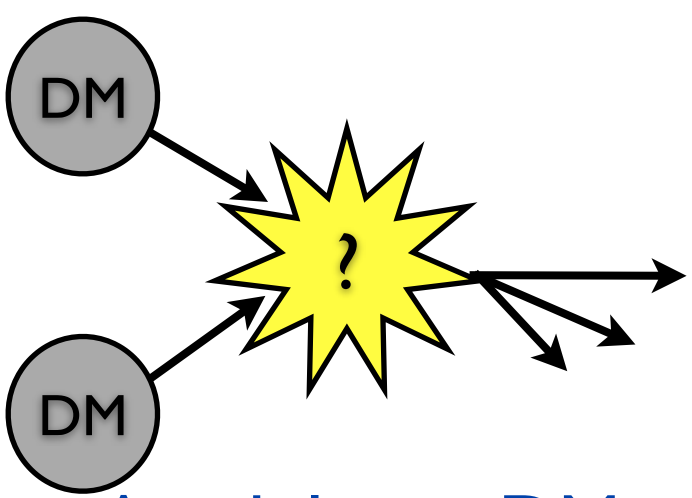
Charged cosmic rays: production

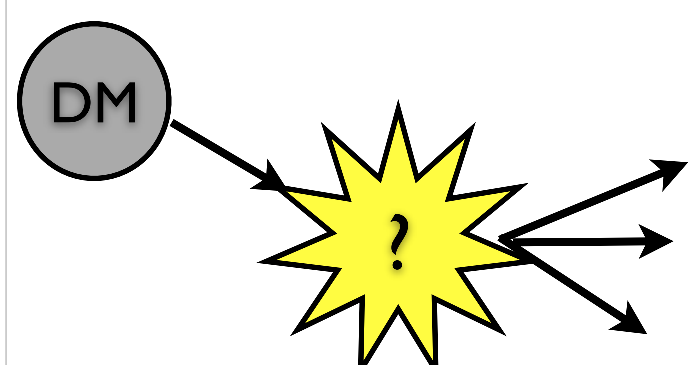

Primary sources (e.g. SNRs)



Secondary CRs



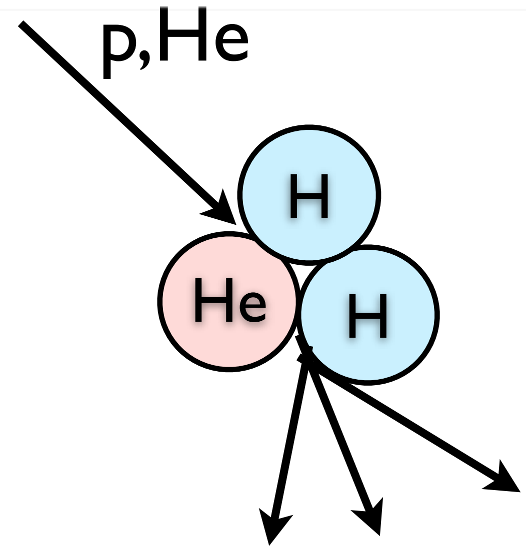
Annihilating DM



Decaying DM

Charged cosmic rays: production

Primary sources (e.g. SNRs)



Secondary CRs

Background

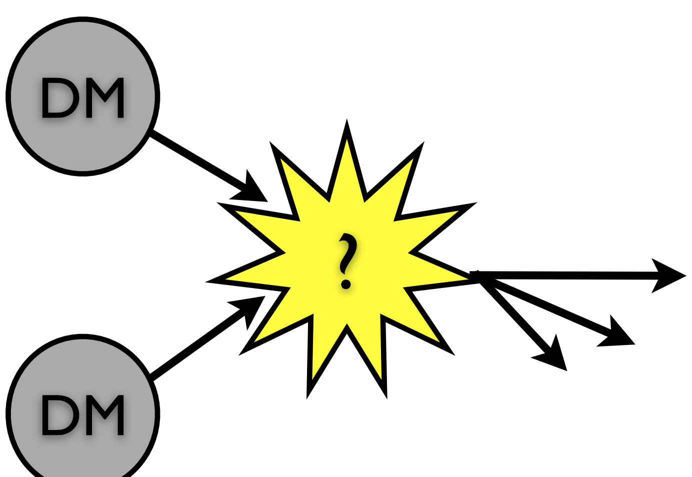
Annihilating DM

Decaying DM

Charged cosmic rays: production

Primary sources (e.g. SNRs)

Secondary CRs



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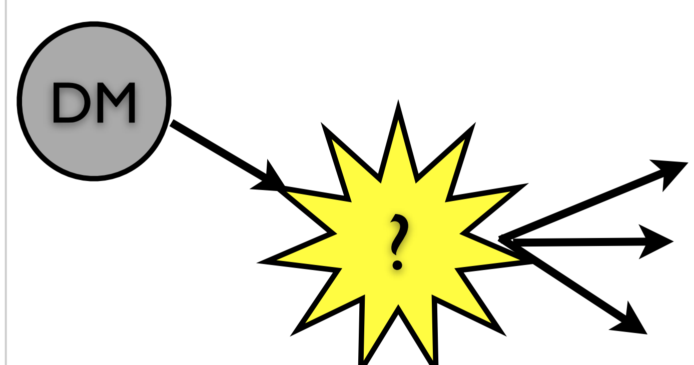
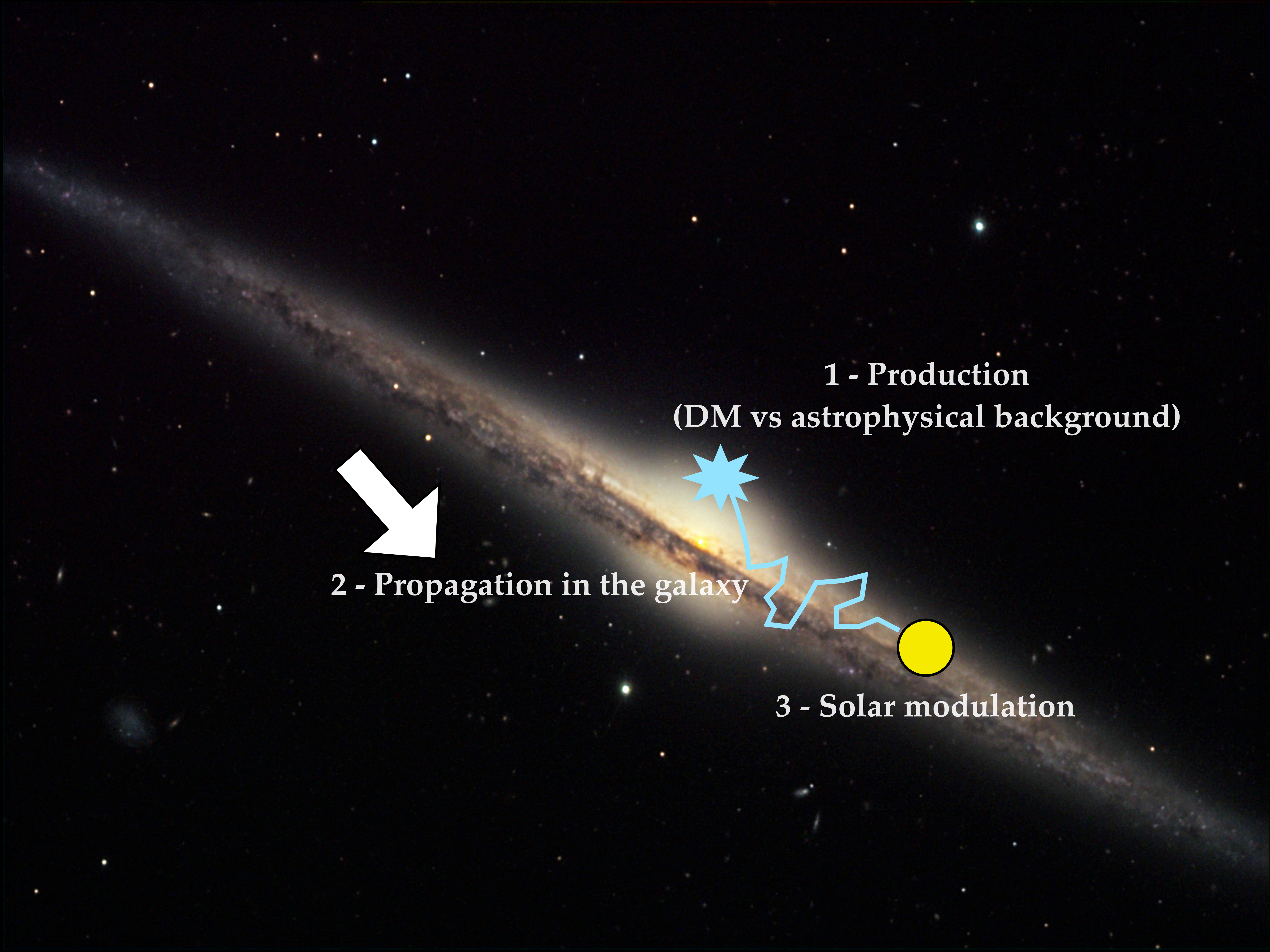


Decaying DM

Signal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Galactic propagation

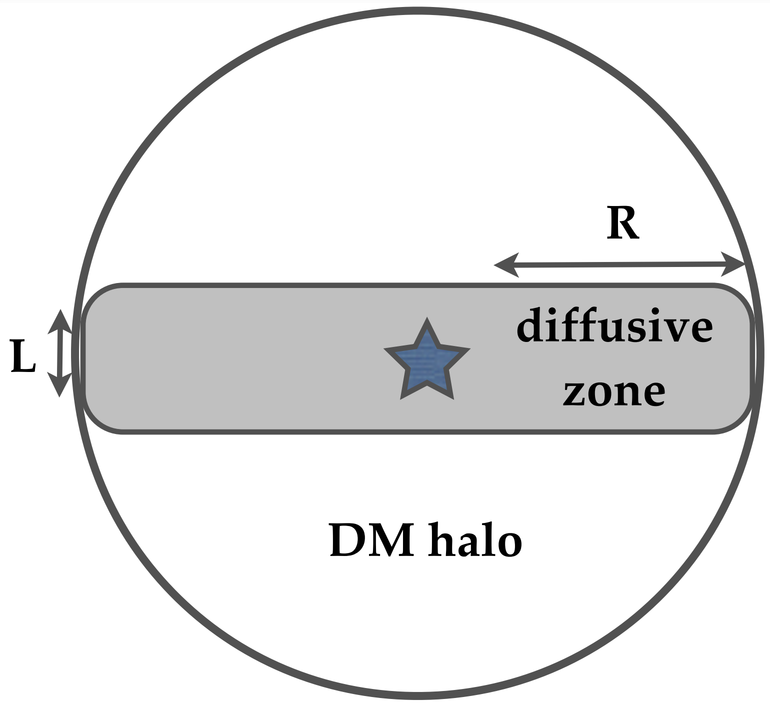
Spatial diffusion | Convection | Annihilation in the ISM

$$-\nabla[K(r,z,E)\nabla\mathcal{N}(r,z,E)] + V_c(z)\frac{\partial}{\partial z}\mathcal{N}(r,z,E) + 2h\delta(z)\Gamma^{\text{ann}}\mathcal{N}(r,z,E)+$$

Reacceleration | Energy losses | Source Term

$$2h\delta(z)\partial_E(-K_{EE}(E)\partial_E\mathcal{N}(r,z,E) + b_{tot}(E)\mathcal{N}(r,z,E)) = \mathcal{Q}(r,z,E)$$

Two-zone diffusion model



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

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

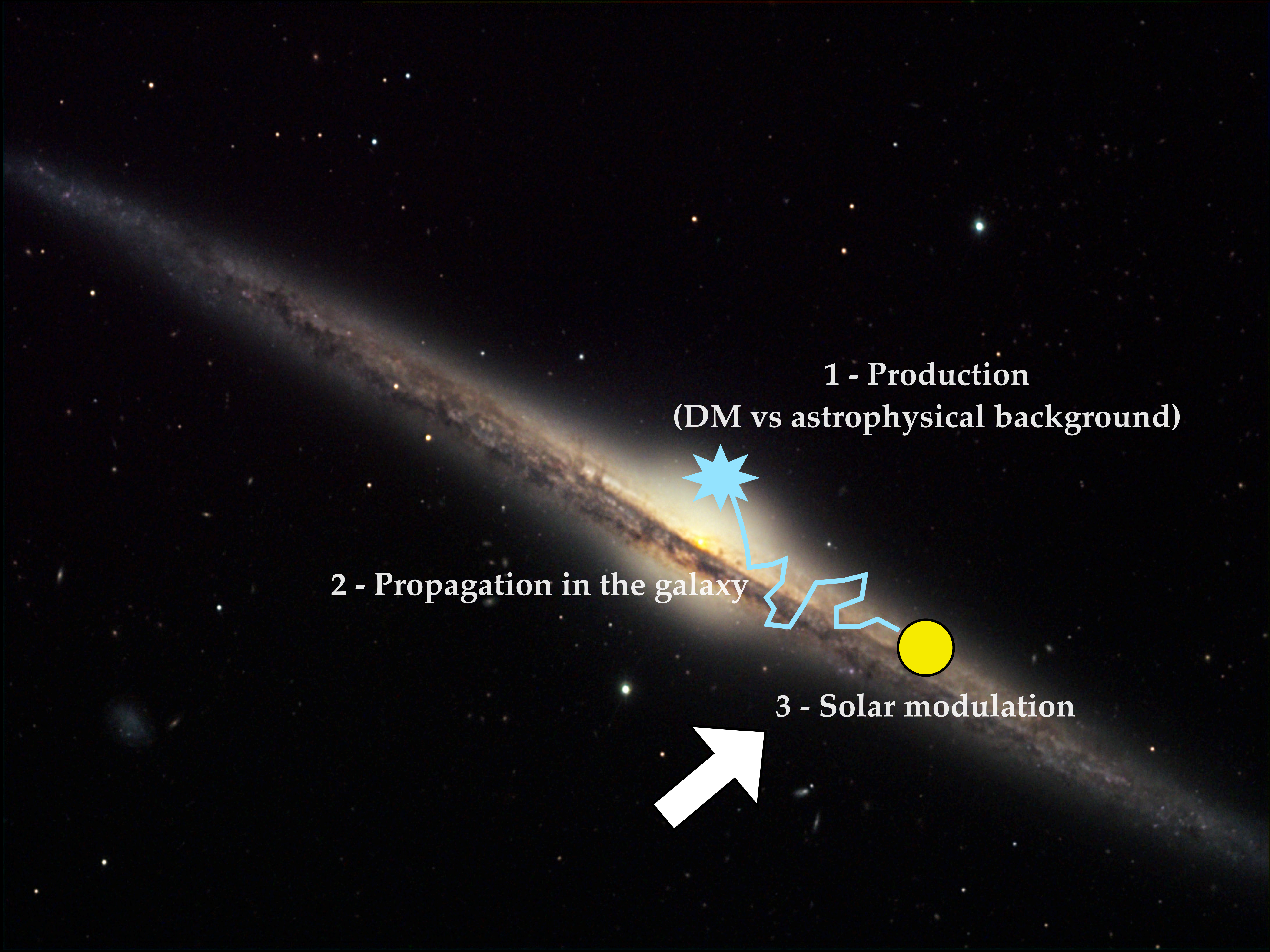
Solution is generally found by expanding the function in the transport equation in **Bessel functions**

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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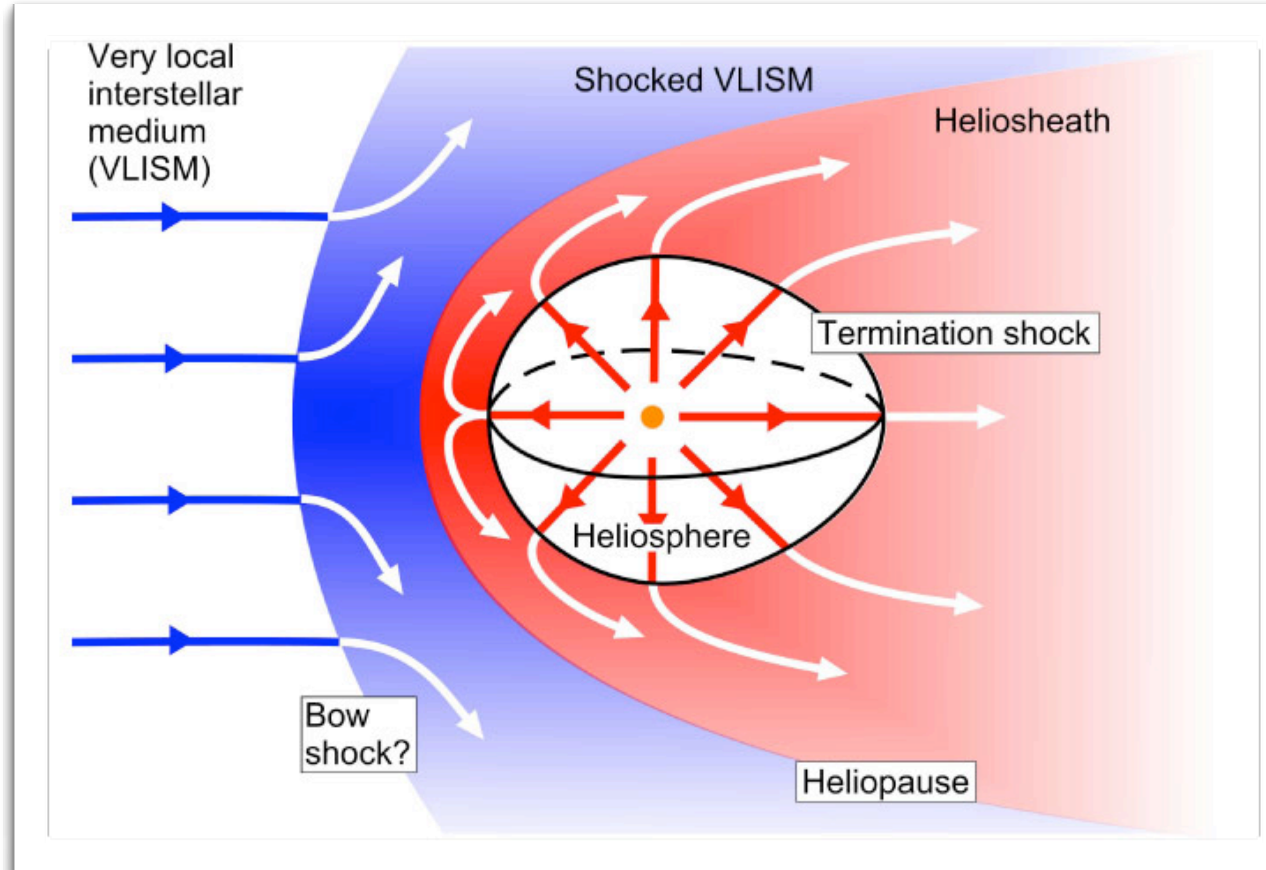
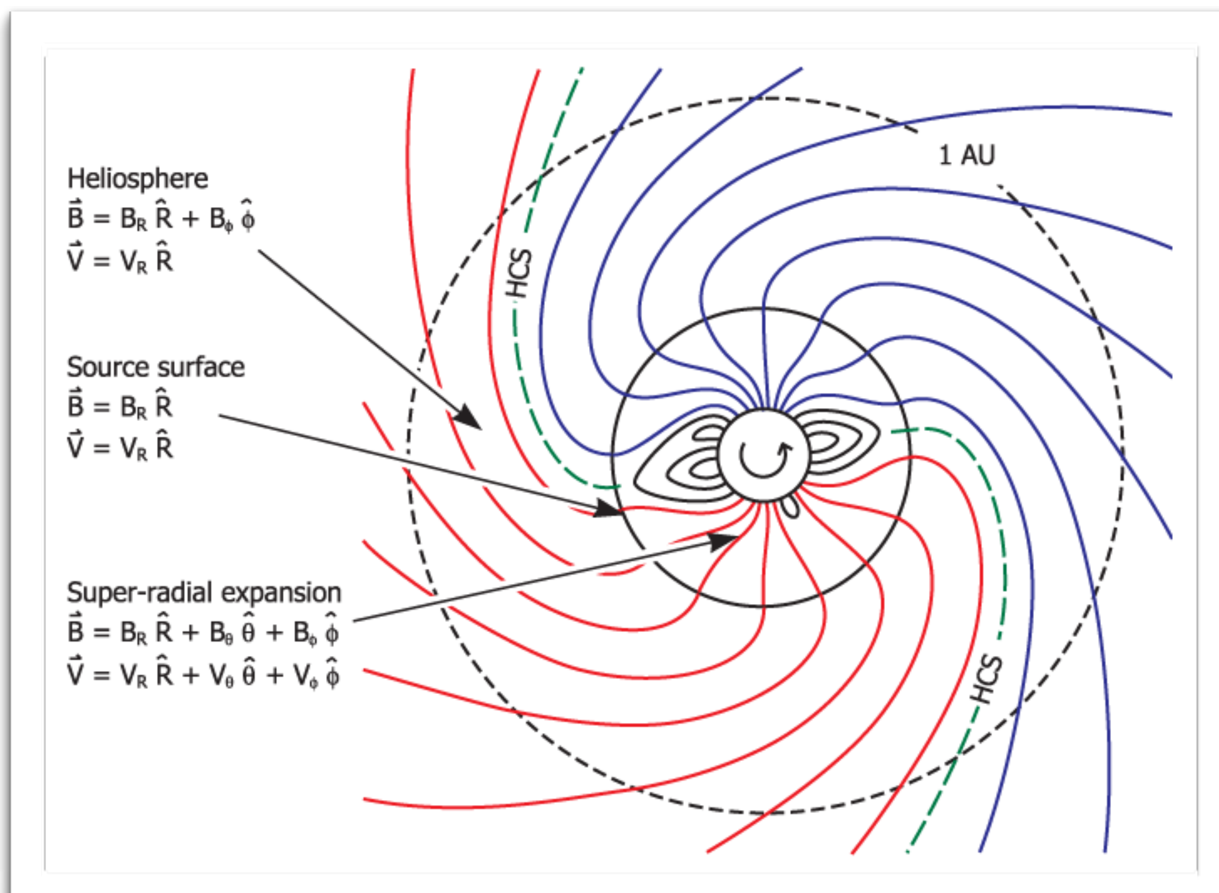
Charged CRs in the heliosphere

•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

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

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

2) Numerical solution of the transport equation in the heliosphere

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

L. Maccione, 2013

In this way, we allow for a **charge dependence**

I will now discuss **two CRs channels**:

- **antiprotons**

Constraints on particle dark matter from cosmic-ray antiprotons

N. Fornengo[a,b] L. Maccione[c,d] A. Vittino[a,b,e,f]

arXiv:1312.3579
JCAP 1404 (2014) 003

- **antideuterons/anti-Helium**

Review of the theoretical and experimental status of dark matter identification with cosmic-ray antideuterons

T. Aramaki[a,b], S. Boggs[c], S. Bufalino[d], L. Dal[e], P. von Doetinchem[f,*], F. Donato[d,g], N. Fornengo[d,g], H. Fuke[h], M. Grefe[i], C. Hailey[a], B. Hamilton[j], A. Ibarra[k], J. Mitchell[l], I. Mognet[m], R.A. Ong[m], R. Pereira[f], K. Perez[n], A. Putze[o,p], A. Raklev[e], P. Salati[o], M. Sasaki[l], G. Tarle[q], A. Urbano[r], A. Vittino[d,g], S. Wild[k], W. Xue[s], K. Yoshimura[t]

arXiv:1505.07785

Dark matter searches with cosmic antideuterons: status and perspectives

N. Fornengo[a,b] L. Maccione[c,d] A. Vittino[a,b]

arXiv:1306.4171
JCAP 1309 (2013) 031

Anti-helium from Dark Matter annihilations

Marco Cirelli[a], Nicolao Fornengo[b,c], Marco Taoso[a], Andrea Vittino[a,b,c]

arXiv:1401.4017
JHEP 1408 (2014) 009

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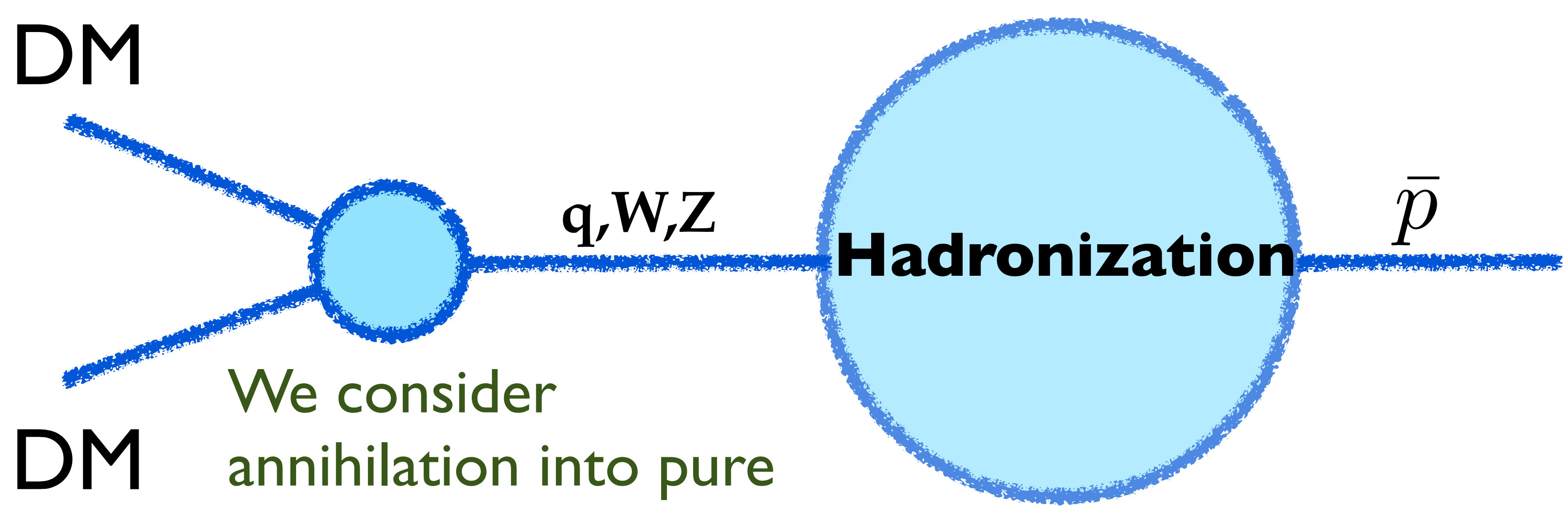
JHEP 1408 (2014) 009

The signal

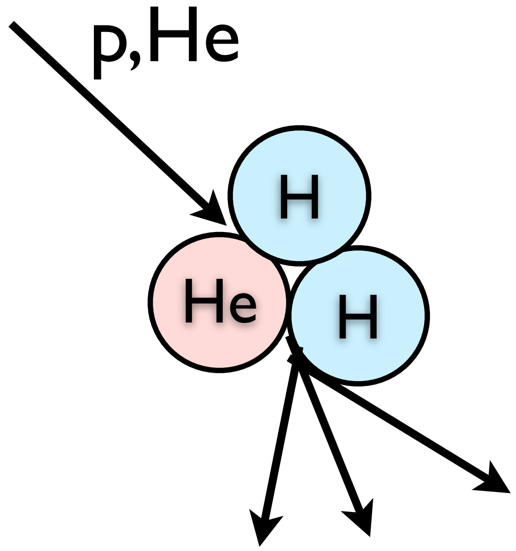


We consider annihilation into pure channels (BR = 1)

Hadronization is modeled with a **MC event generator** (Pythia)

annihilating DM	**decaying DM**
$\mathcal{Q}_{\rm ann}(\vec{r}, z, E) = \epsilon \left(\frac{\rho(\vec{r}, z)}{m_{\rm DM}}\right)^2 \langle \sigma v \rangle \frac{dN_{\rm DM}}{dE}$	$\mathcal{Q}_{\rm dec}(\vec{r}, z, E) = \left(\frac{\rho(\vec{r}, z)}{m_{\rm DM}}\right) \Gamma \frac{dN_{\rm DM}}{dE}$

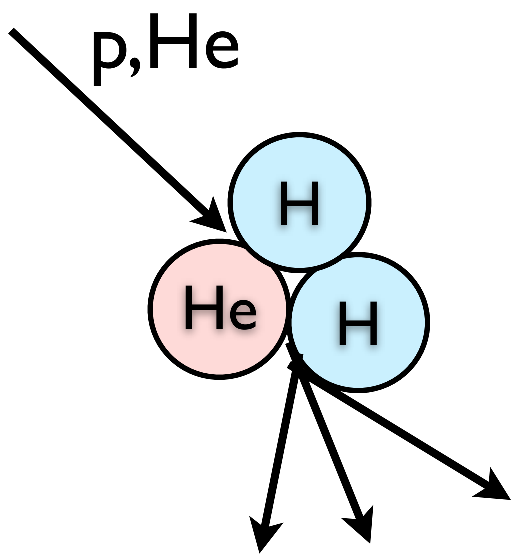
The background



Secondaries are produced by the **spallation** of primary CRs impinging on the nuclei of the Interstellar Medium

$$\mathcal{Q}^{\psi}_{\rm sec}(E_\psi) \;=\; \sum_{i}^{\rm CR}\sum_{j}^{\rm ISM} 4\pi n_j \int_{E_{\rm thr}}^{\infty}\left[dE_i \frac{d\sigma^{i+j\to\psi+X}}{dE_\psi}(E_i, E_\psi)\Phi_i(E_i)\right]$$

The background



Secondaries are produced by the **spallation** of primary CRs impinging on the nuclei of the Interstellar Medium

i,j = p, He

$$Q^{\psi}_{\rm sec}(E_\psi) = \sum_i^{\rm CR} \sum_j^{\rm ISM} 4\pi n_j \int_{E_{\rm thr}}^{\infty} \left[dE_i \frac{d\sigma^{i+j\to\psi+X}}{dE_\psi}(E_i, E_\psi) \Phi_i(E_i) \right]$$

gas density (n_j)

spallation cross section

primary CR flux

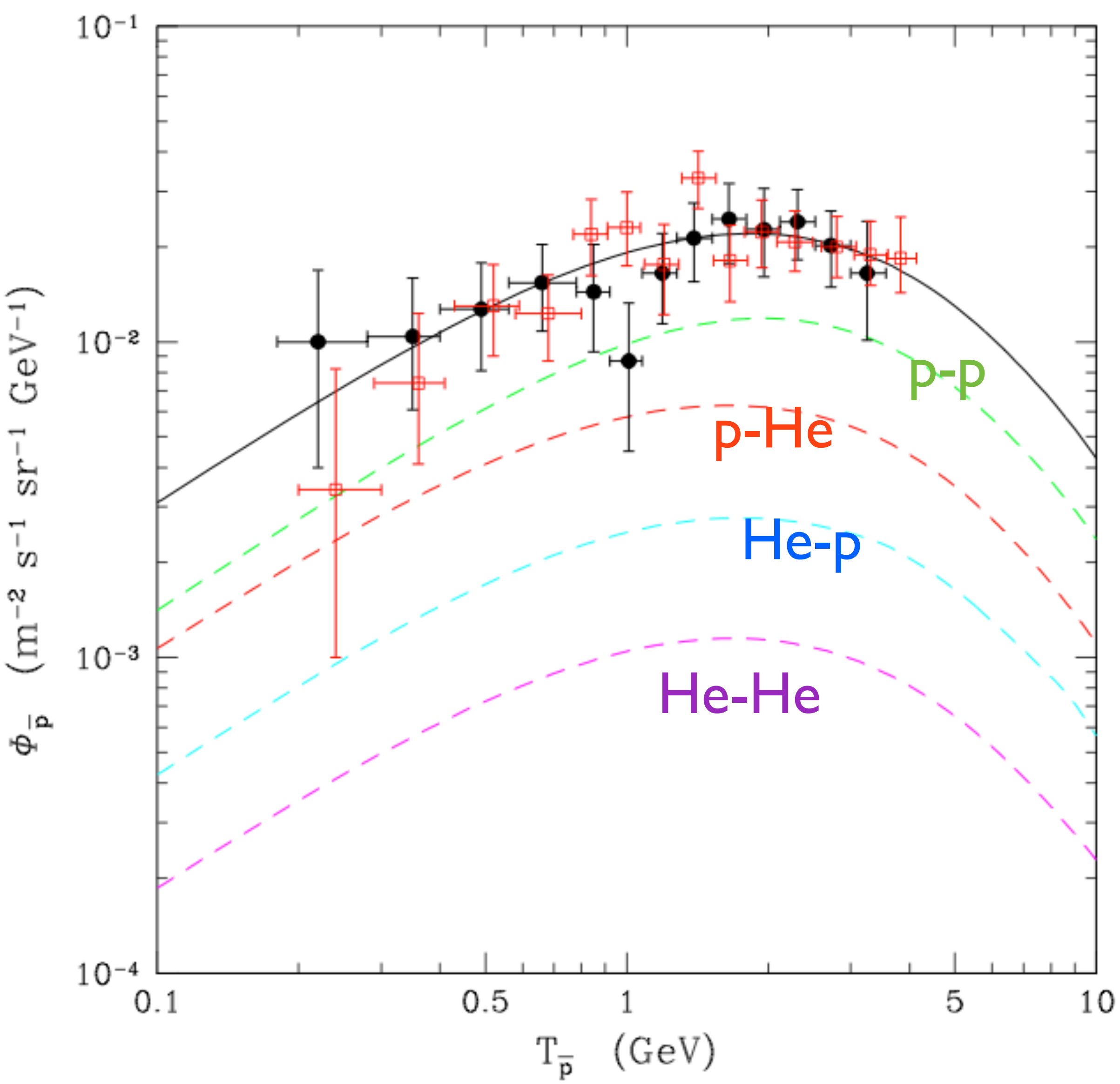
The uncertainty related to the spallation cross sections translates into a 40% uncertainty on the secondary antiproton flux

see talks by **Lipari, Di Mauro** and **Winkler**

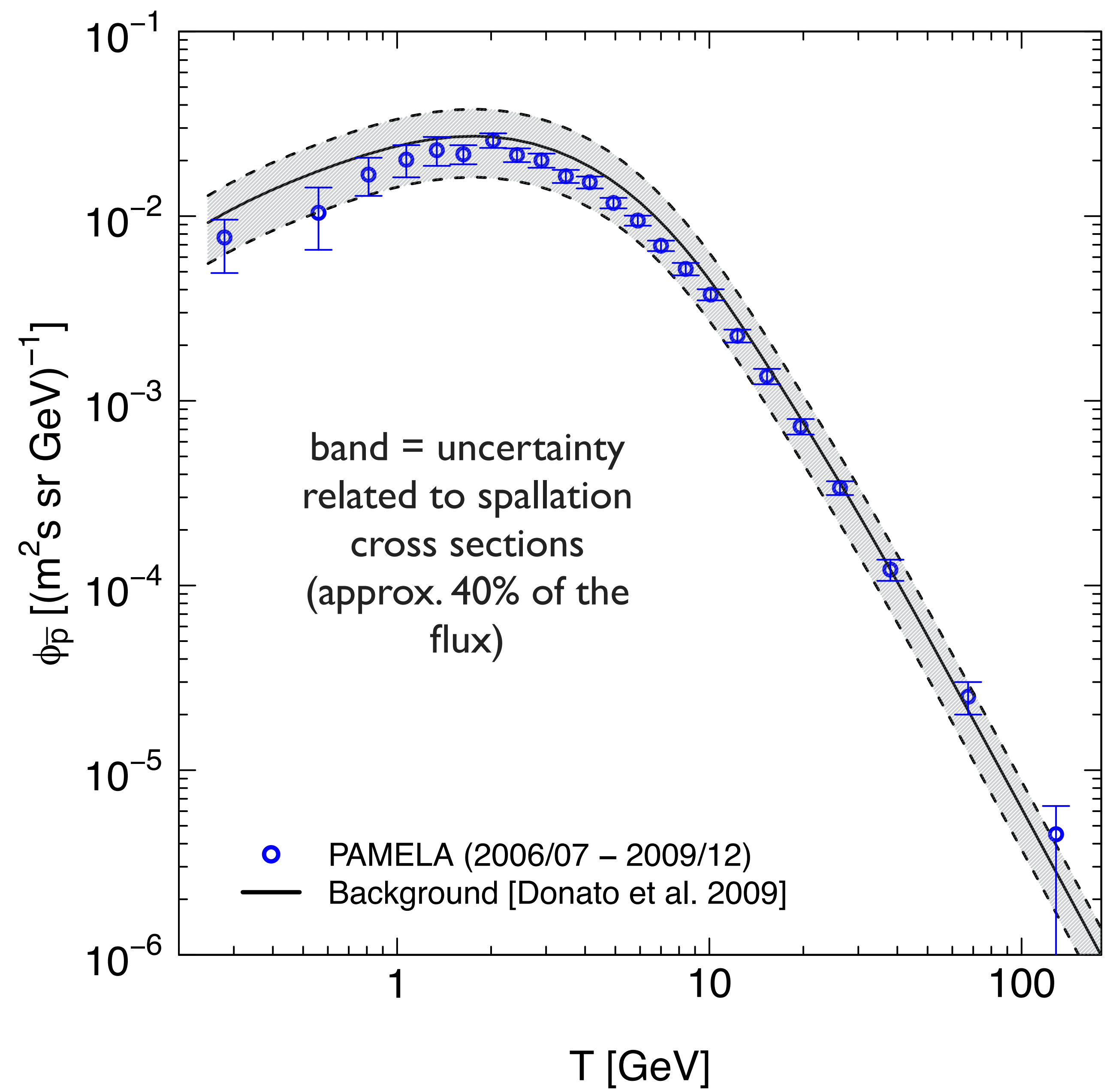
The background

Antiproton flux measured by PAMELA vs. background from cosmic rays spallation over the ISM:

Adriani+ 2012



Donato+ 2001



Antiproton 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

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

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

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

3 sigma confidence level (one sided distribution)

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

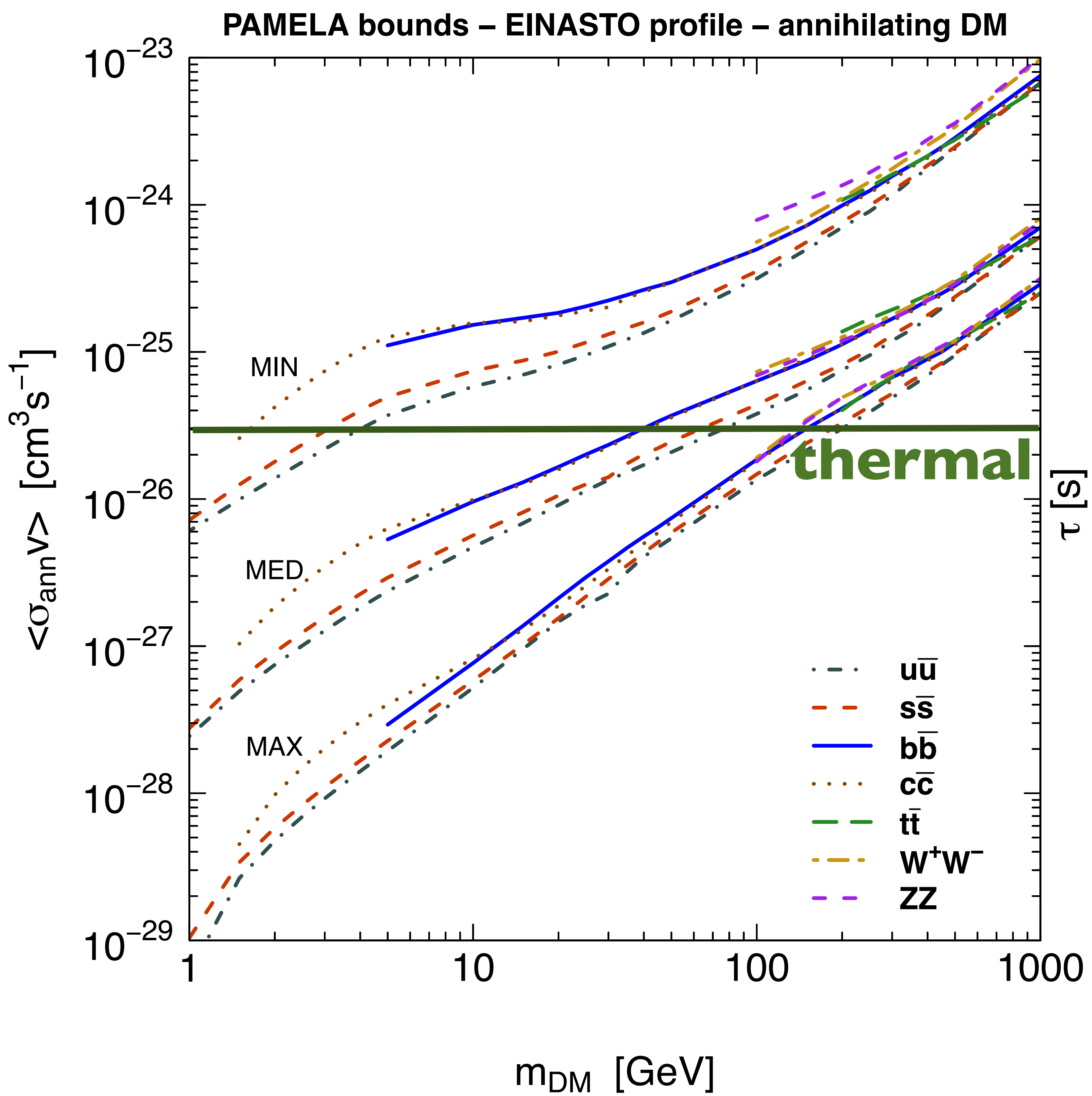
$\sigma^2_{i,exp}$: systematic + statistical error

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

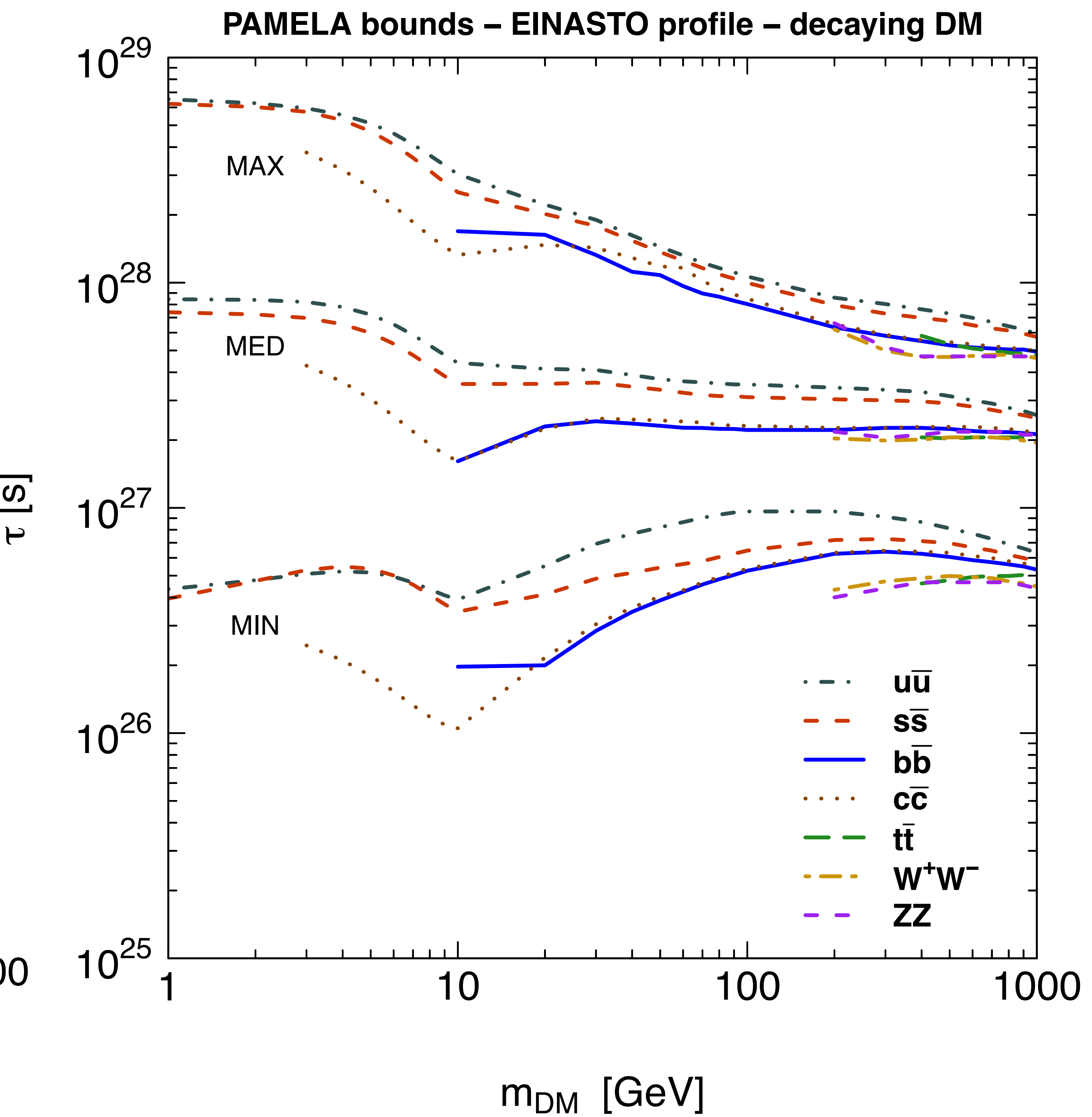
The effect of the theoretical error is to make the upper limits that we find sensibly weaker

Antiproton bounds

Annihilating DM



Decaying DM

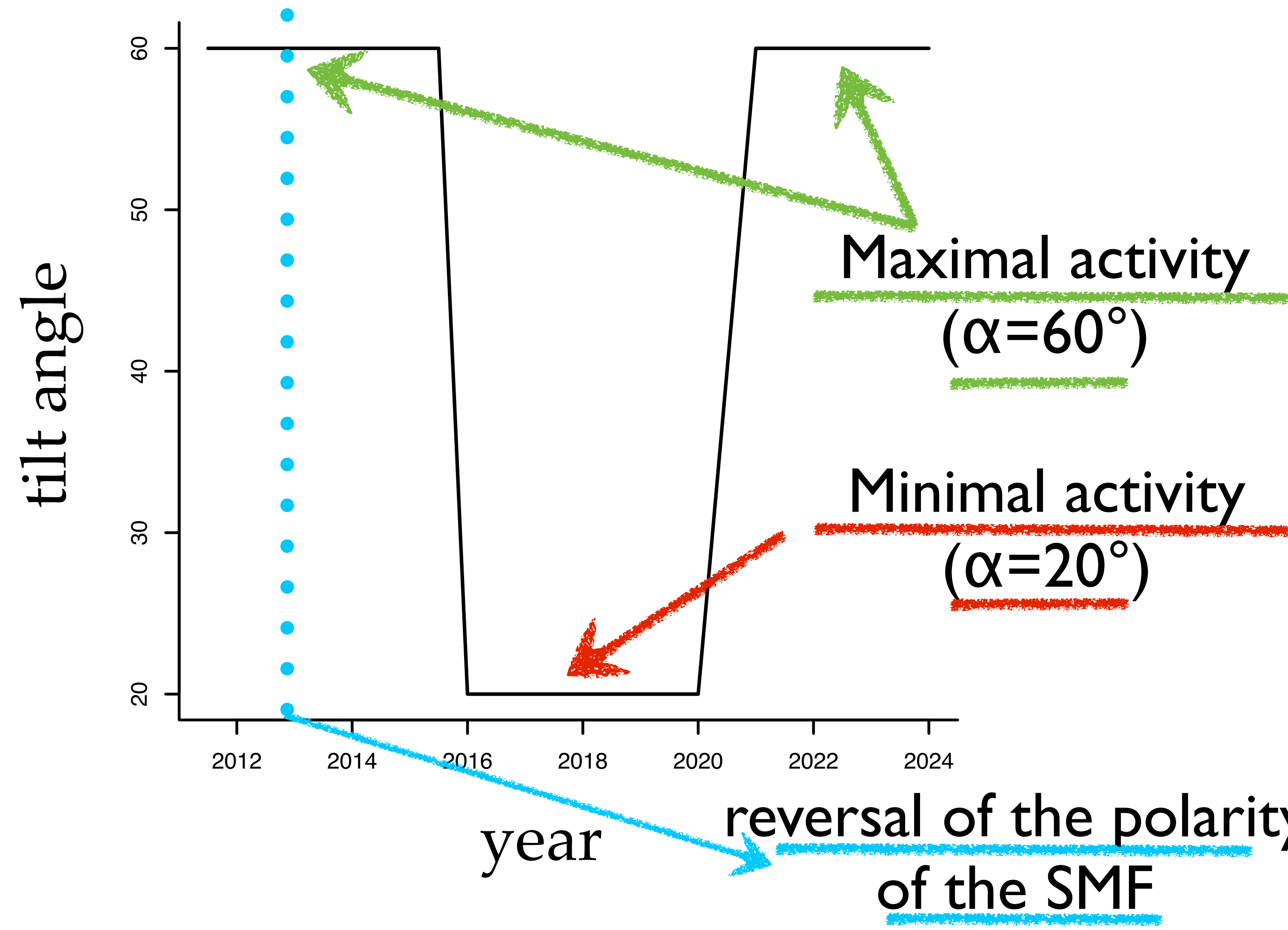


Expected AMS-02 sensitivity

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:

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



How do we generate AMS-02 mock data?

Expected AMS-02 sensitivity

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:

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

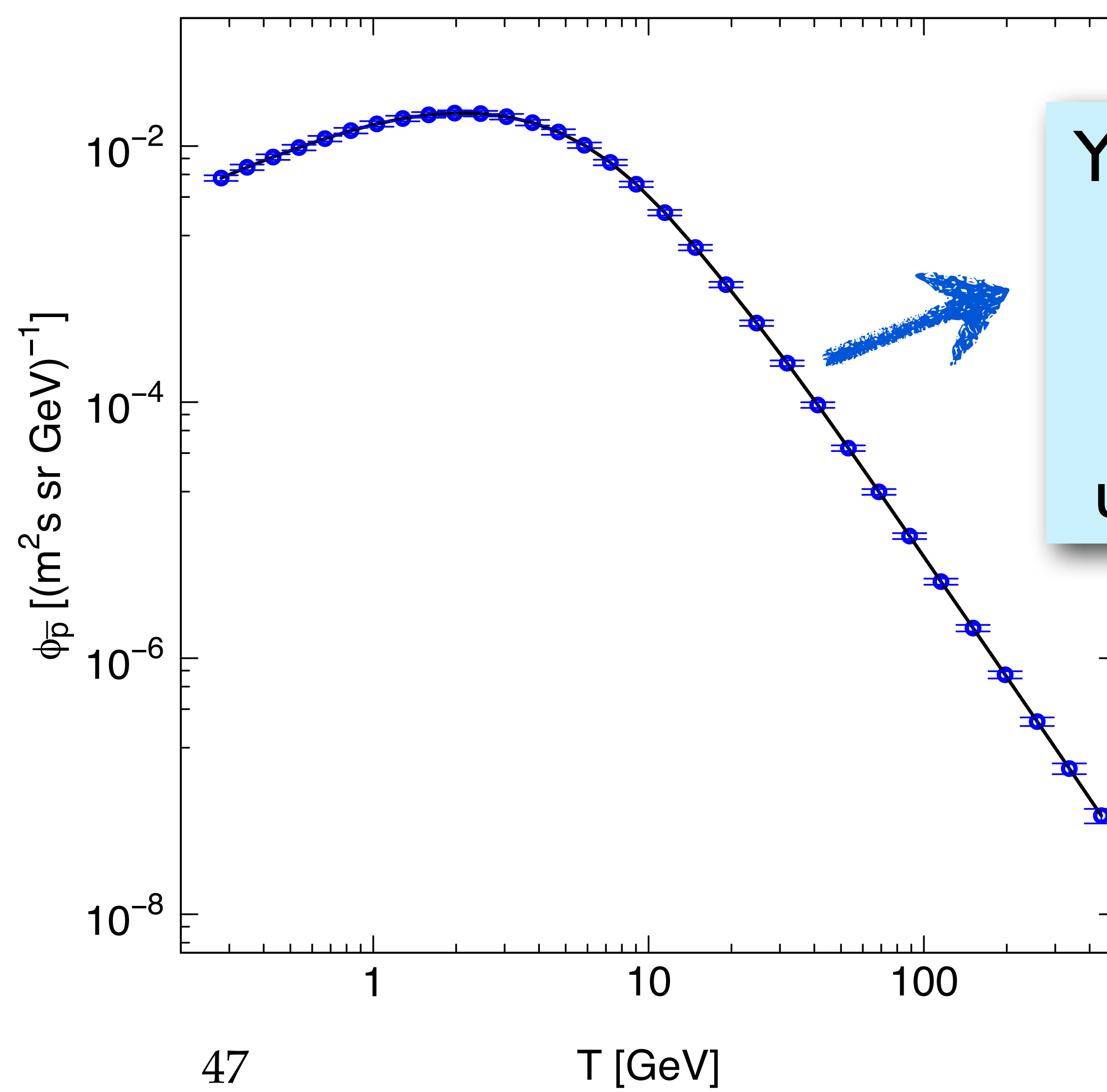
- ϵ is the efficiency:

$$\epsilon(T_i) \;=\; \theta(T_i - T_{min})$$

(geomagnetic effects)

For the acceptance:

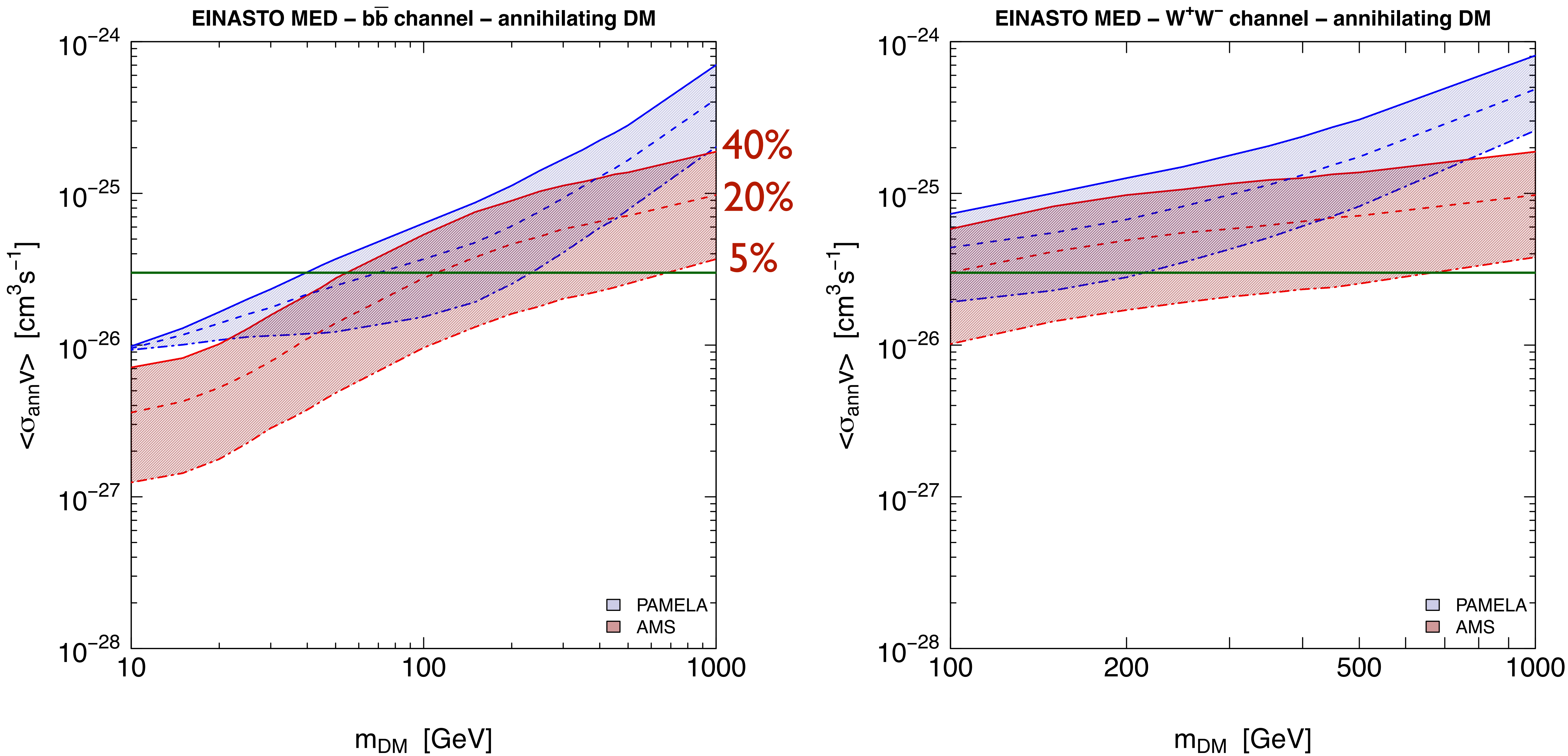
Malinin (AMS Coll.) 2004



You still need to add theoretical uncertainty!

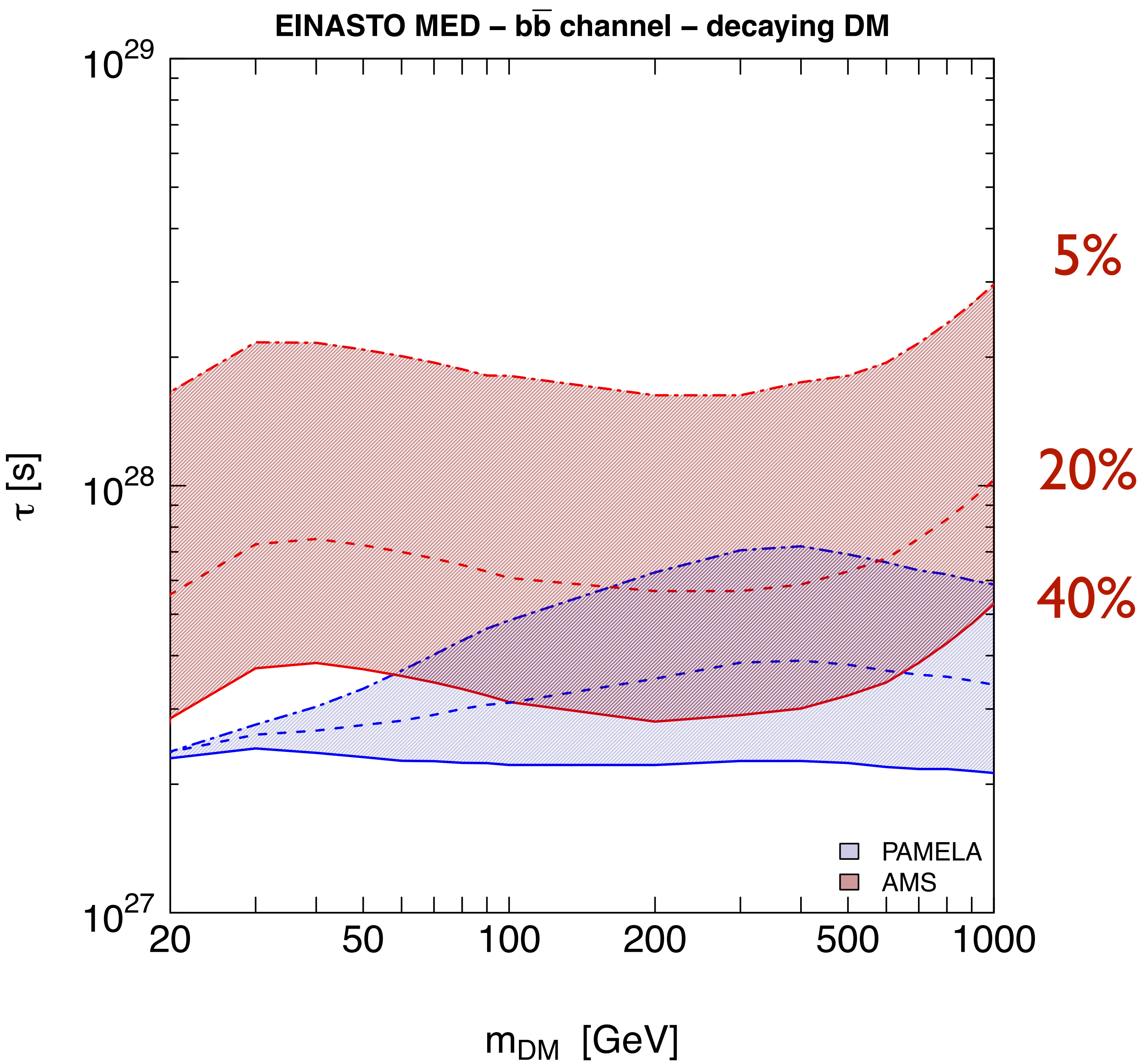
Expected AMS-02 sensitivity

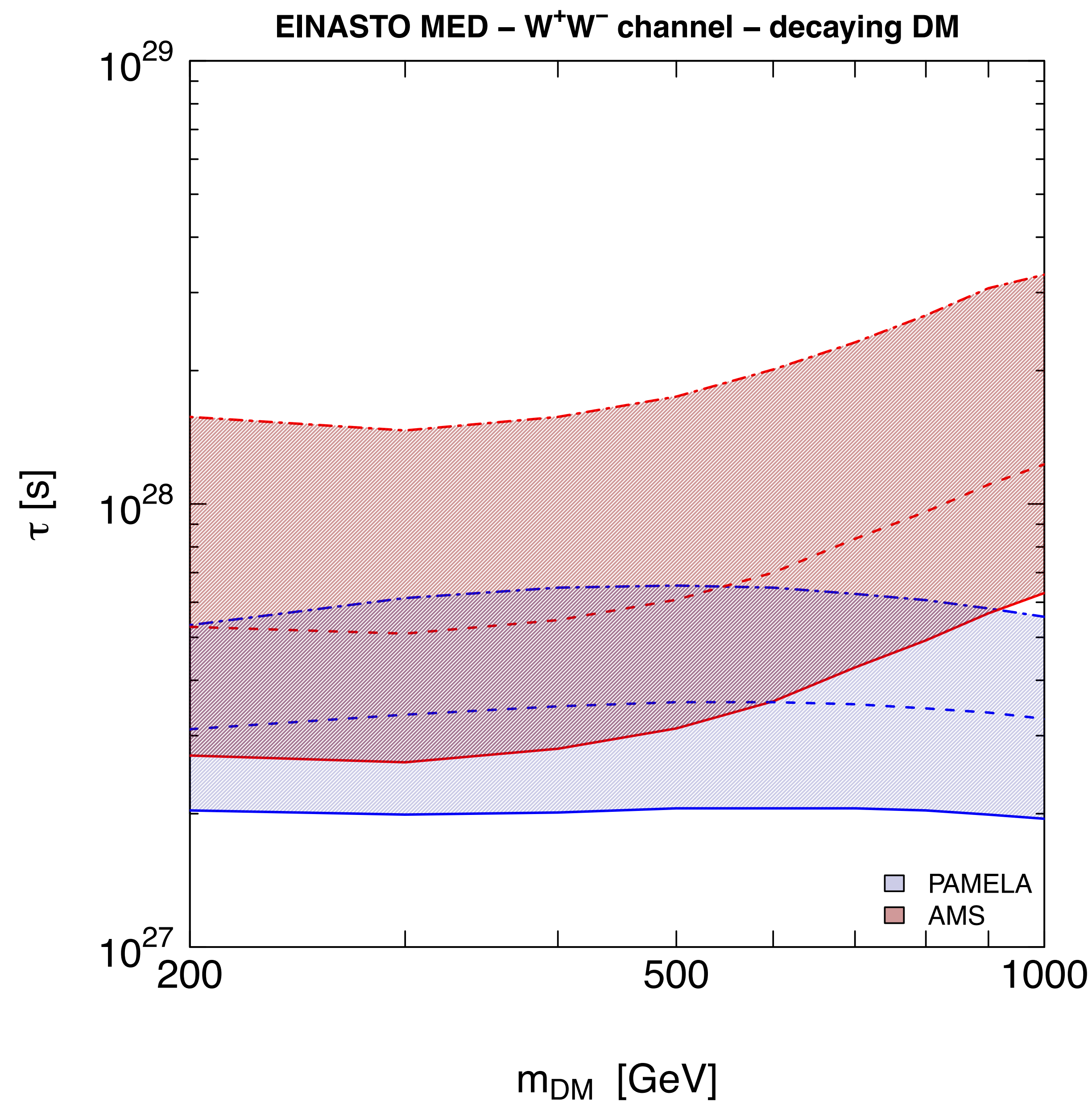
Annihilating case



Expected AMS-02 sensitivity

Decaying case





I will now discuss **two CRs channels**:

- antiprotons

Constraints on particle dark matter from cosmic-ray antiprotons

N. Fornengo[a,b] L. Maccione[c,d] A. Vittino[a,b,e,f]

arXiv:1312.3579
JCAP 1404 (2014) 003

- **antideuterons/anti-Helium**

Review of the theoretical and experimental status of dark matter identification with cosmic-ray antideuterons

T. Aramaki[a,b], S. Boggs[c], S. Bufalino[d], L. Dal[e], P. von Doetinchem[f,*], F. Donato[d,g], N. Fornengo[d,g], H. Fuke[h], M. Grefe[i], C. Hailey[a], B. Hamilton[j], A. Ibarra[k], J. Mitchell[l], I. Mognet[m], R.A. Ong[m], R. Pereira[f], K. Perez[n], A. Putze[o,p], A. Raklev[e], P. Salati[o], M. Sasaki[l], G. Tarle[q], A. Urbano[r], A. Vittino[d,g], S. Wild[k], W. Xue[s], K. Yoshimura[t]

arXiv:1505.07785

Dark matter searches with cosmic antideuterons: status and perspectives

N. Fornengo[a,b] L. Maccione[c,d] A. Vittino[a,b]

arXiv:1306.4171
JCAP 1309 (2013) 031

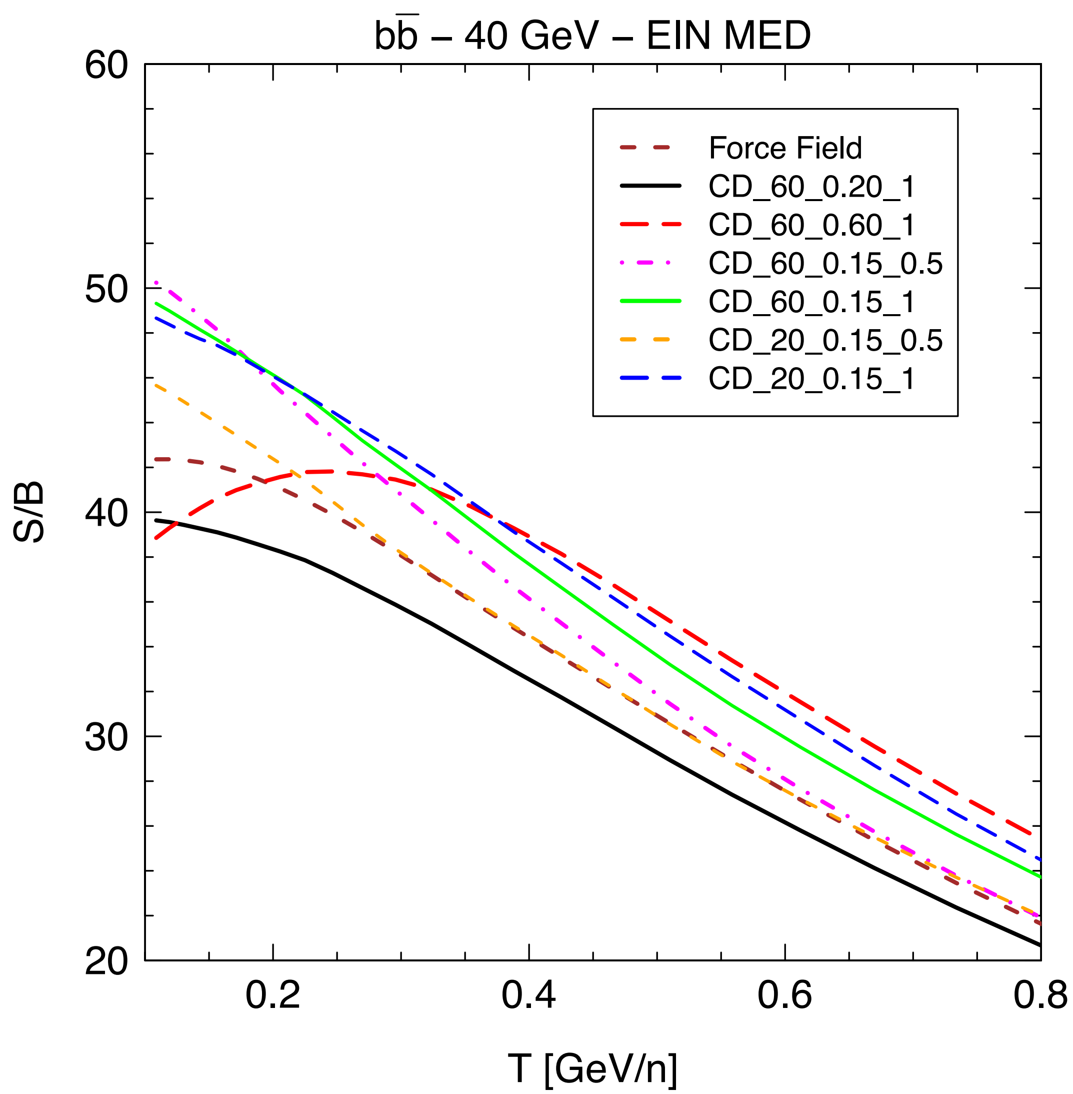
Anti-helium from Dark Matter annihilations

Marco Cirelli[a], Nicolao Fornengo[b,c], Marco Taoso[a], Andrea Vittino[a,b,c]

arXiv:1401.4017
JHEP 1408 (2014) 009

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

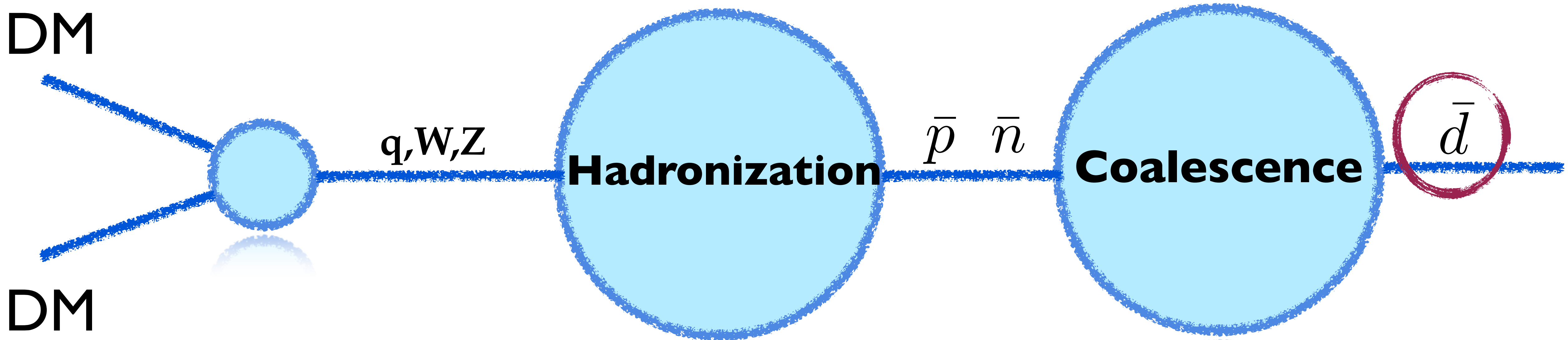
$$\begin{cases} p + p \to \bar{d} + X & E_{thr} = 17 m_p \\ p + p \to {}^3\overline{He} + X & E_{thr} = 31 m_p \end{cases}$$

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, 2000

Antideuteron production



(or spallation reaction)

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?

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?

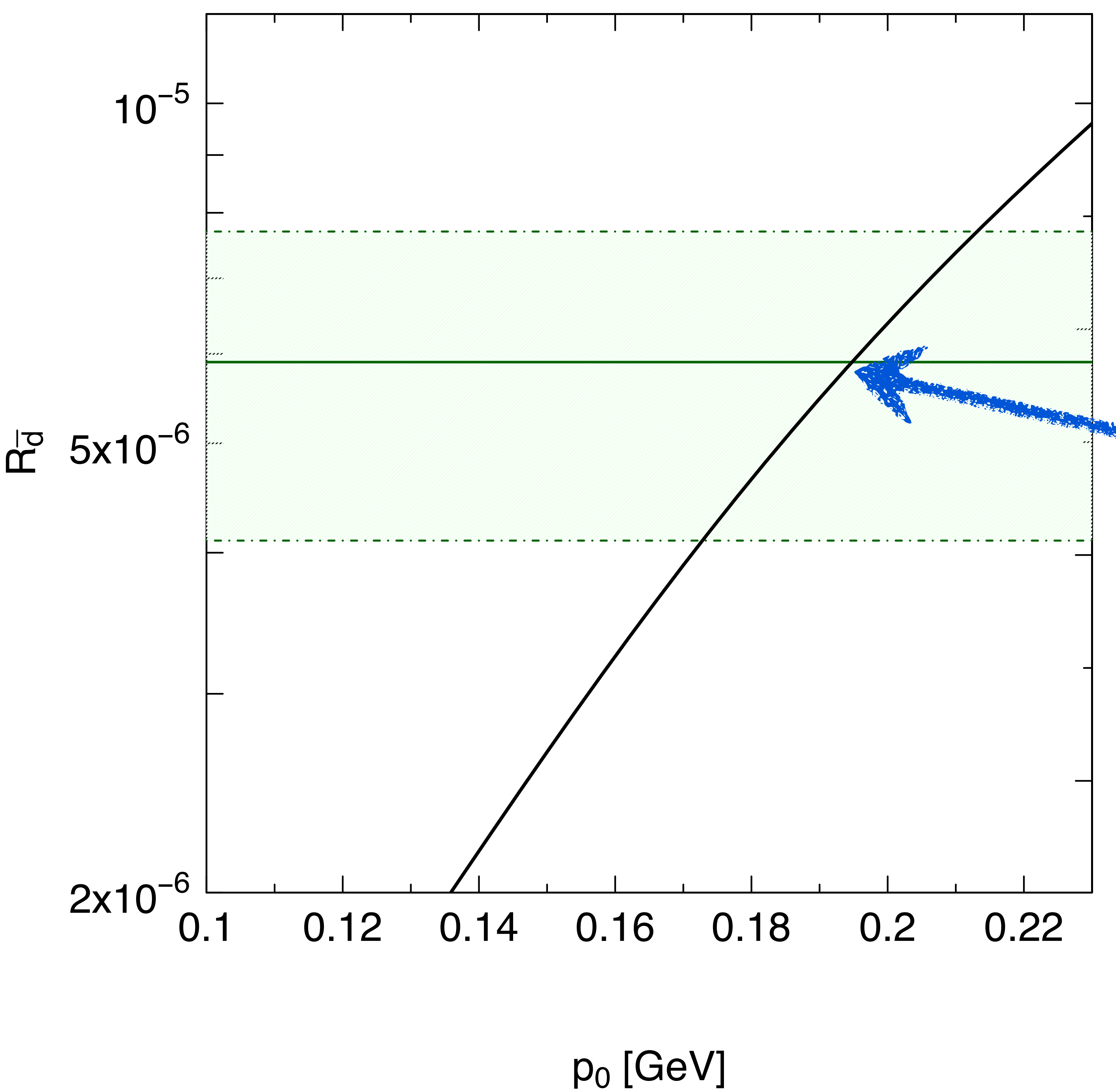
We take $r_0 \approx 2 \text{ fm}$ (radius of the anti-deuteron)

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

Kadastik+ 2010 Ibarra+ 2013

Antideuteron production

We tune p_0 to reproduce ALEPH data:



ALEPH collaboration, 2006

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

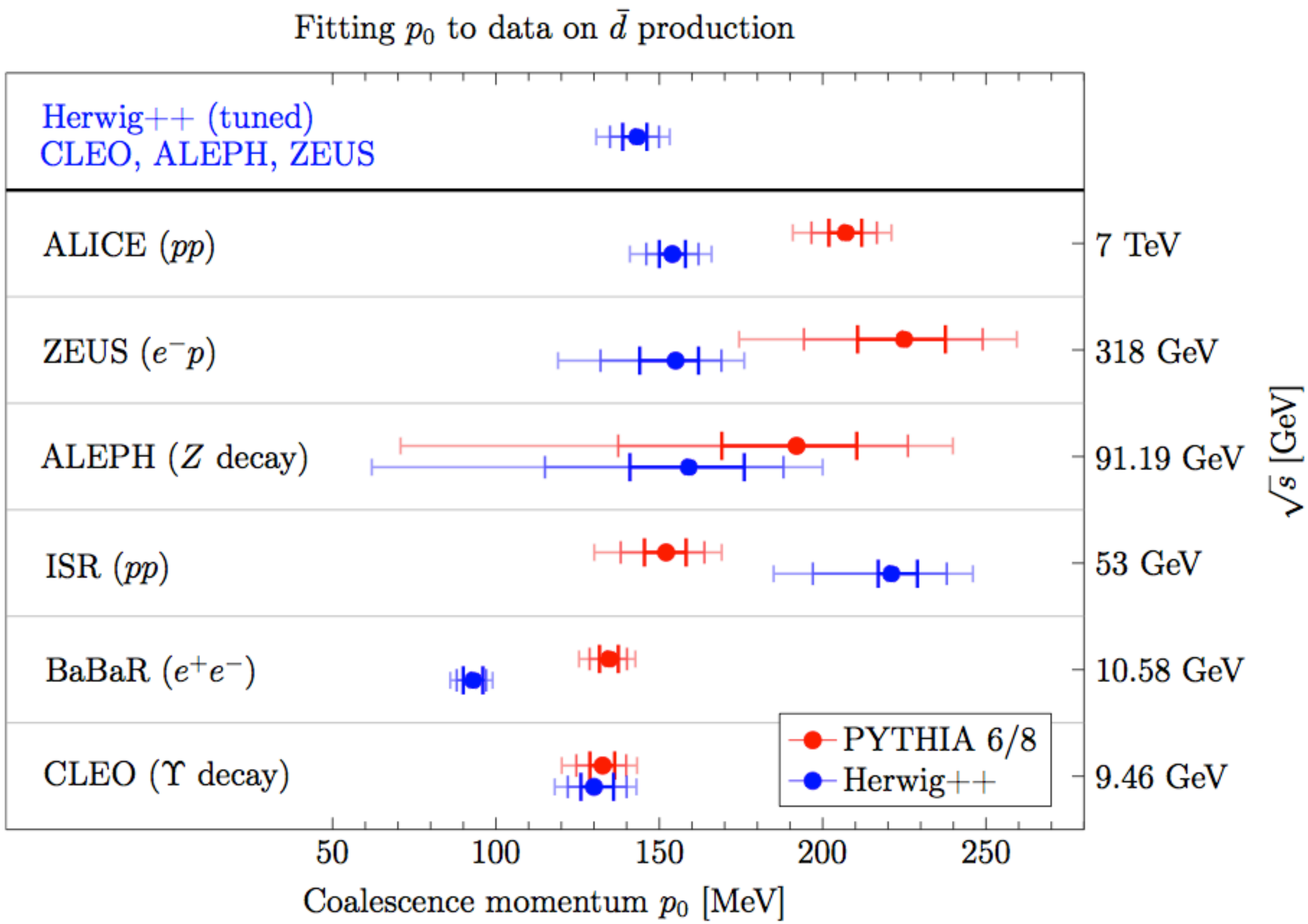
$$p_0 = (195 \pm 22) \text{ MeV}$$

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

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

Antideuteron production

Uncertainty on p_0 is quite large:



see talk by **Von Doetinchem**

Antideuteron production

Approximately, one can write the anti-deuteron yield as:

$$\gamma_{\bar{d}} \frac{dN_{\bar{d}}}{d^3\vec{k}_{\bar{d}}} = \frac{1}{8} \frac{4\pi p_0^3}{3} \gamma_{\bar{p}}\gamma_{\bar{n}} F_{(\bar{p}\bar{n})}(\sqrt{s}, \vec{k}_{\bar{p}} = \vec{k}_{\bar{d}}/2, \vec{k}_{\bar{n}} = \vec{k}_{\bar{d}}/2)$$

Donato+ 2001

Antideuteron production

Approximately, one can write the anti-deuteron yield as:

$$\gamma_{\bar{d}} \frac{dN_{\bar{d}}}{d^3\vec{k}_{\bar{d}}} = \frac{1}{8} \frac{4\pi p_0^3}{3} \gamma_{\bar{p}}\gamma_{\bar{n}} F_{(\bar{p}\bar{n})}(\sqrt{s}, \vec{k}_{\bar{p}} = \vec{k}_{\bar{d}}/2, \vec{k}_{\bar{n}} = \vec{k}_{\bar{d}}/2)$$

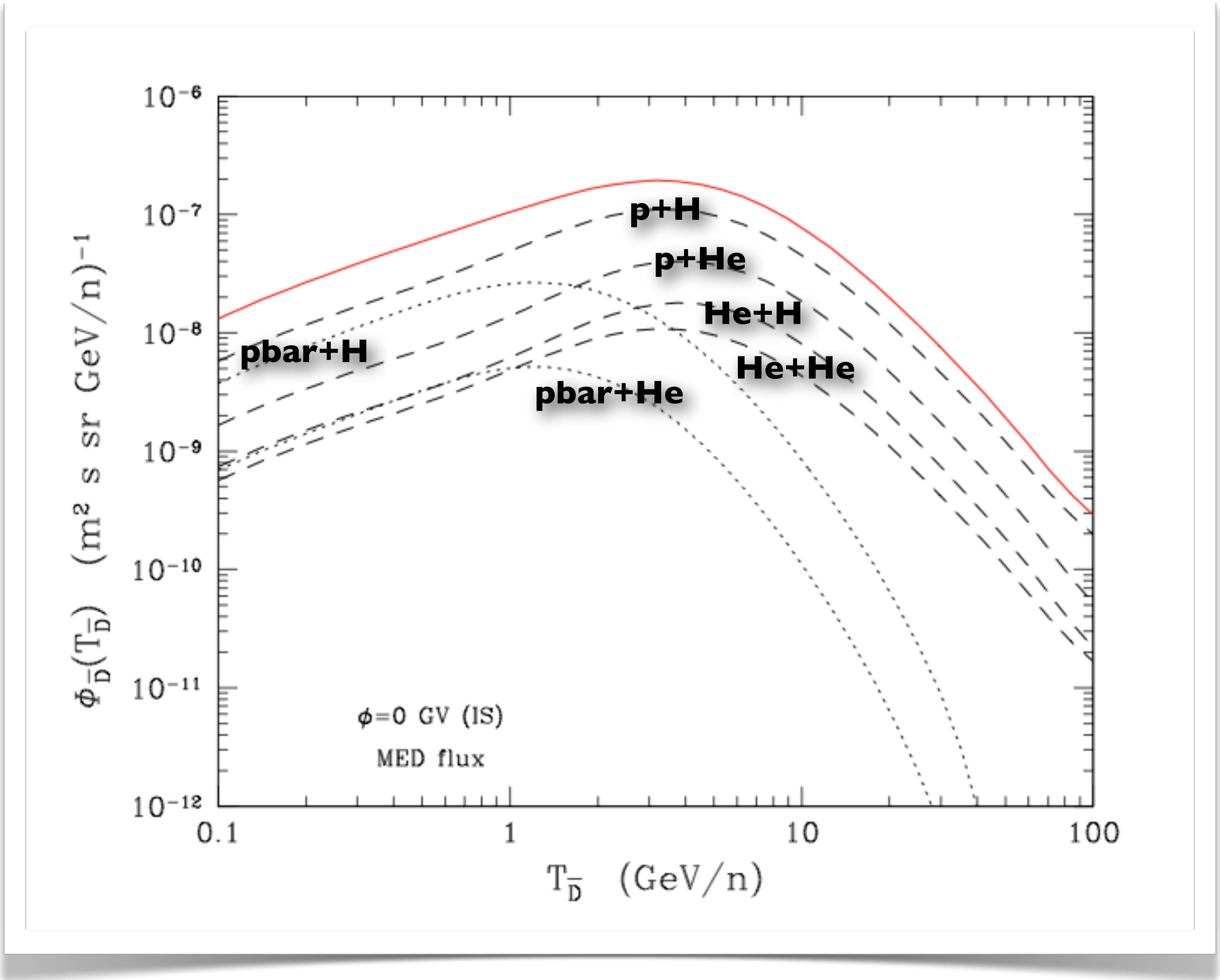
Donato+ 2001

The dependence is strong:

if we go from **p_0 = 0.1 GeV to p_0 =0.3 GeV**

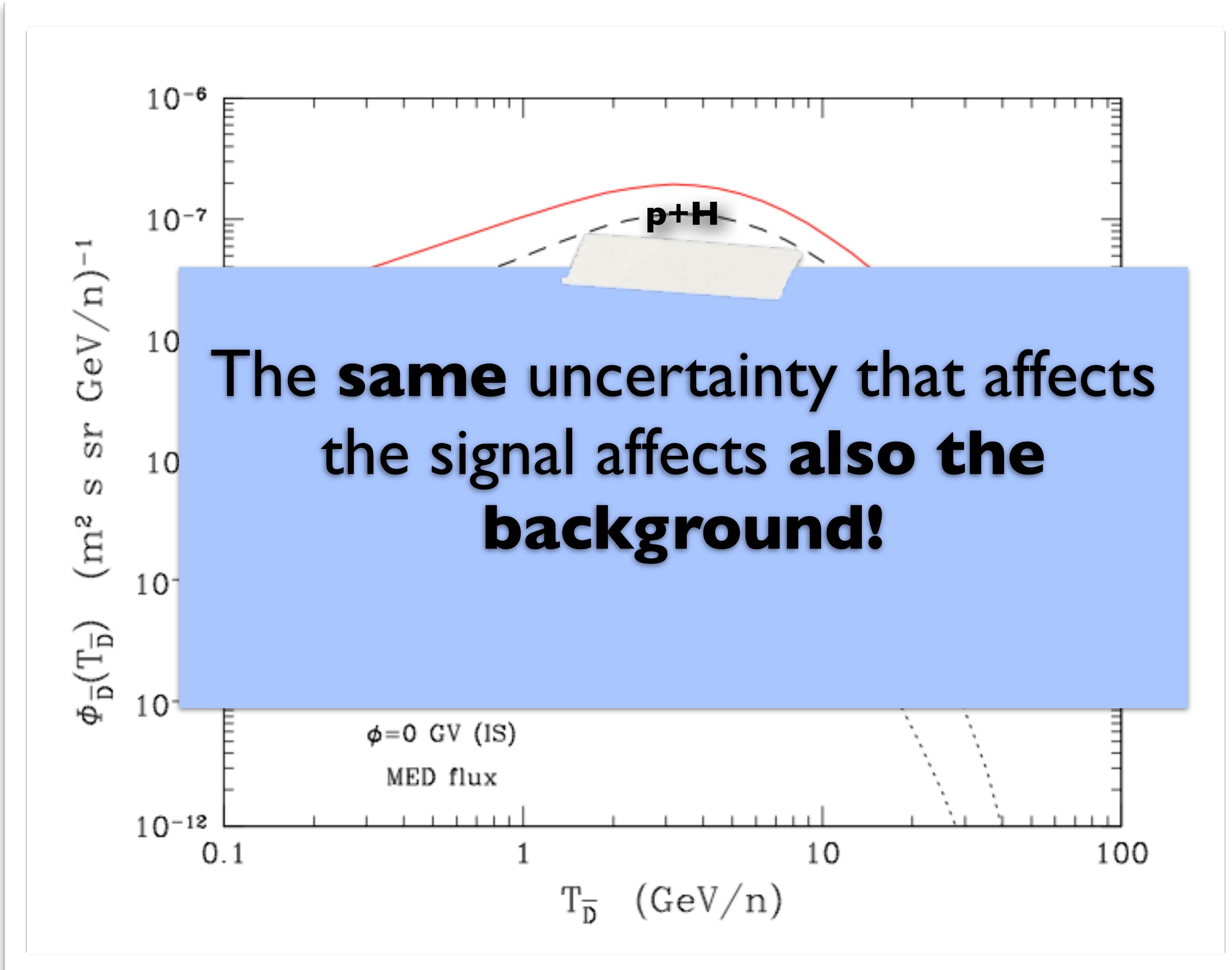
we gain a factor **27 in the flux**

the background



Donato+ 2008

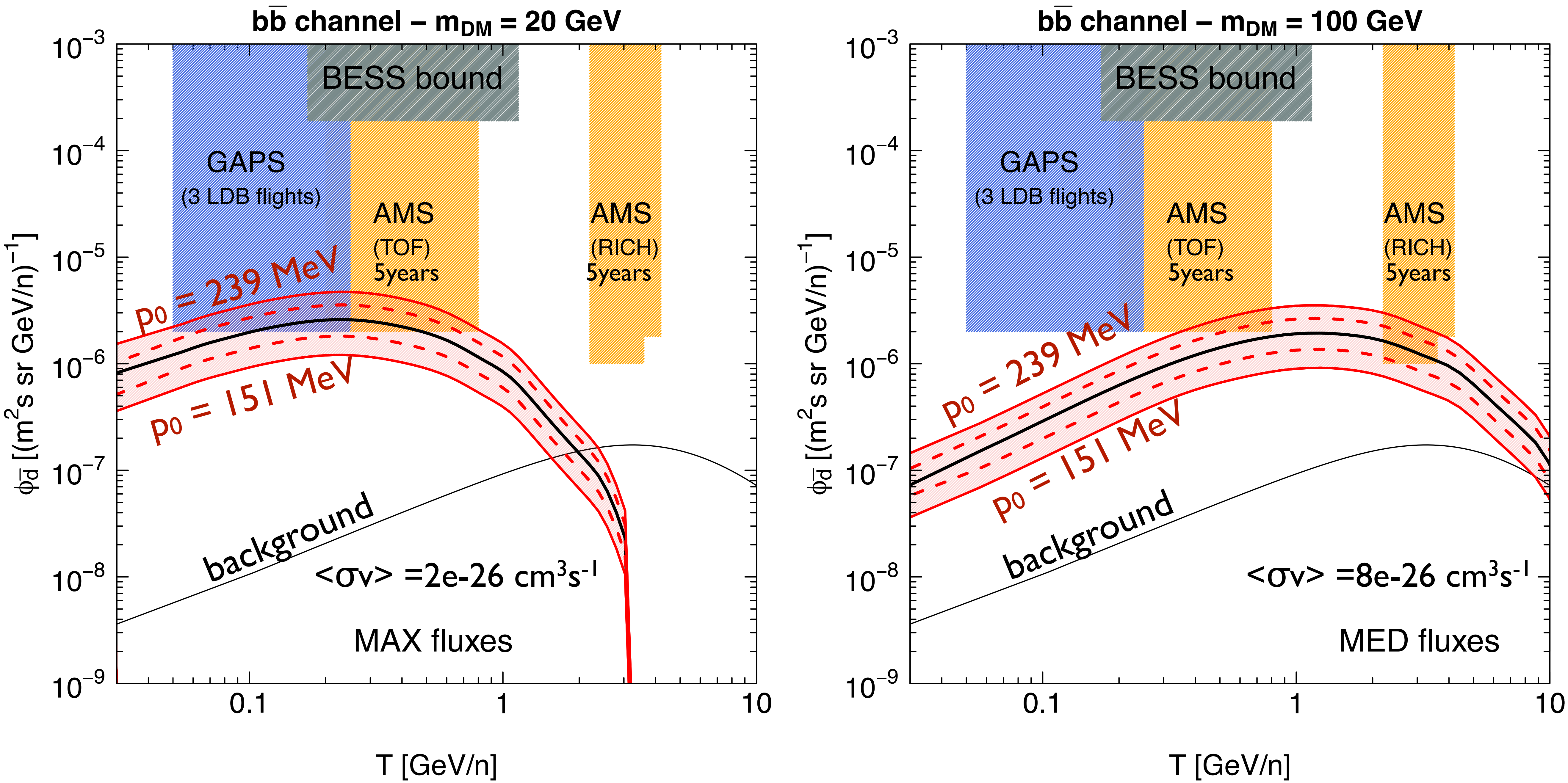
the background



The **same** uncertainty that affects the signal affects **also the background!**

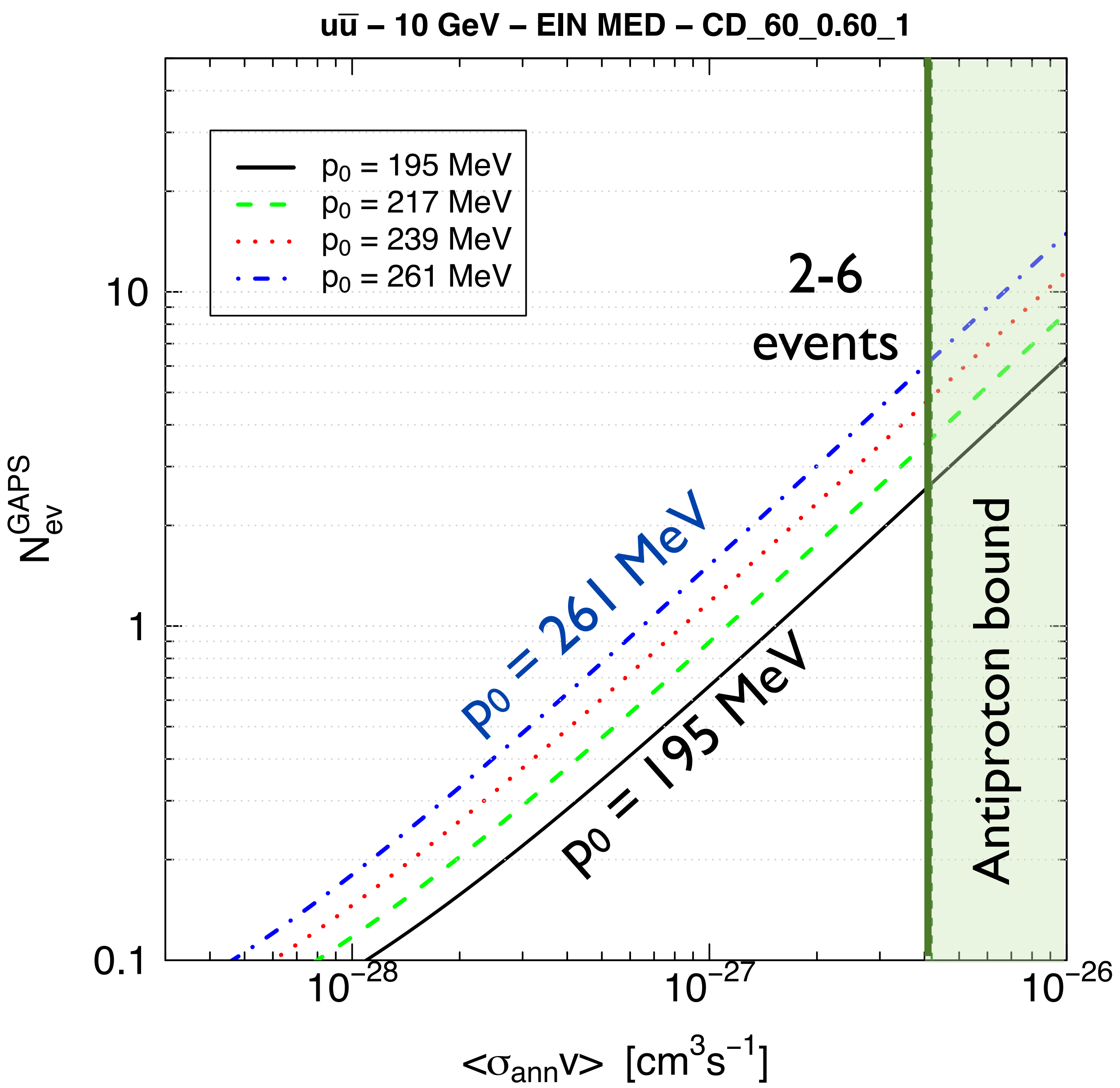
Donato+ 2008

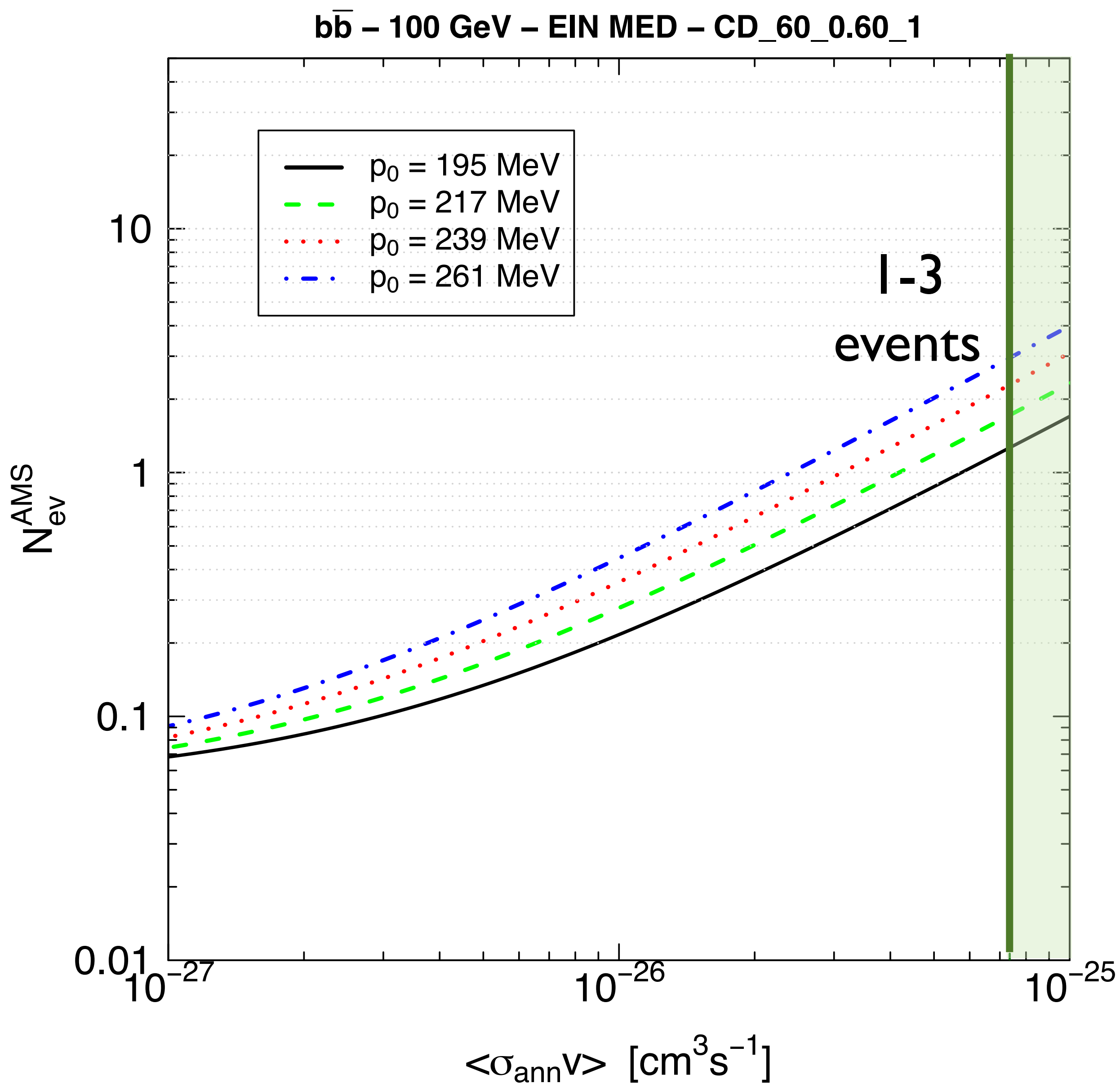
Prospects for antideuteron observation



Annihilation cross sections have to be compatible with antiproton bounds!

Number of expected events





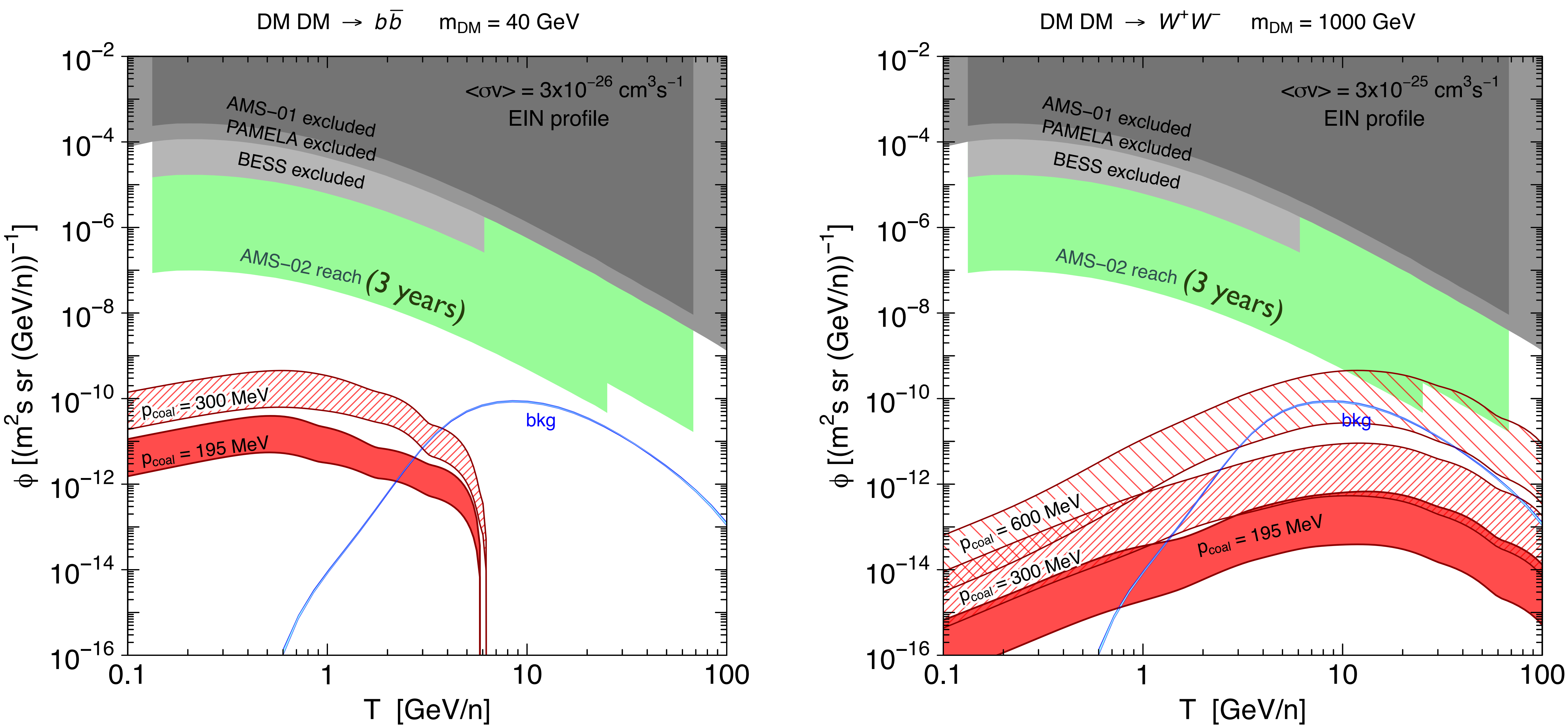
The anti-Helium case

- 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)**

Conclusive remarks

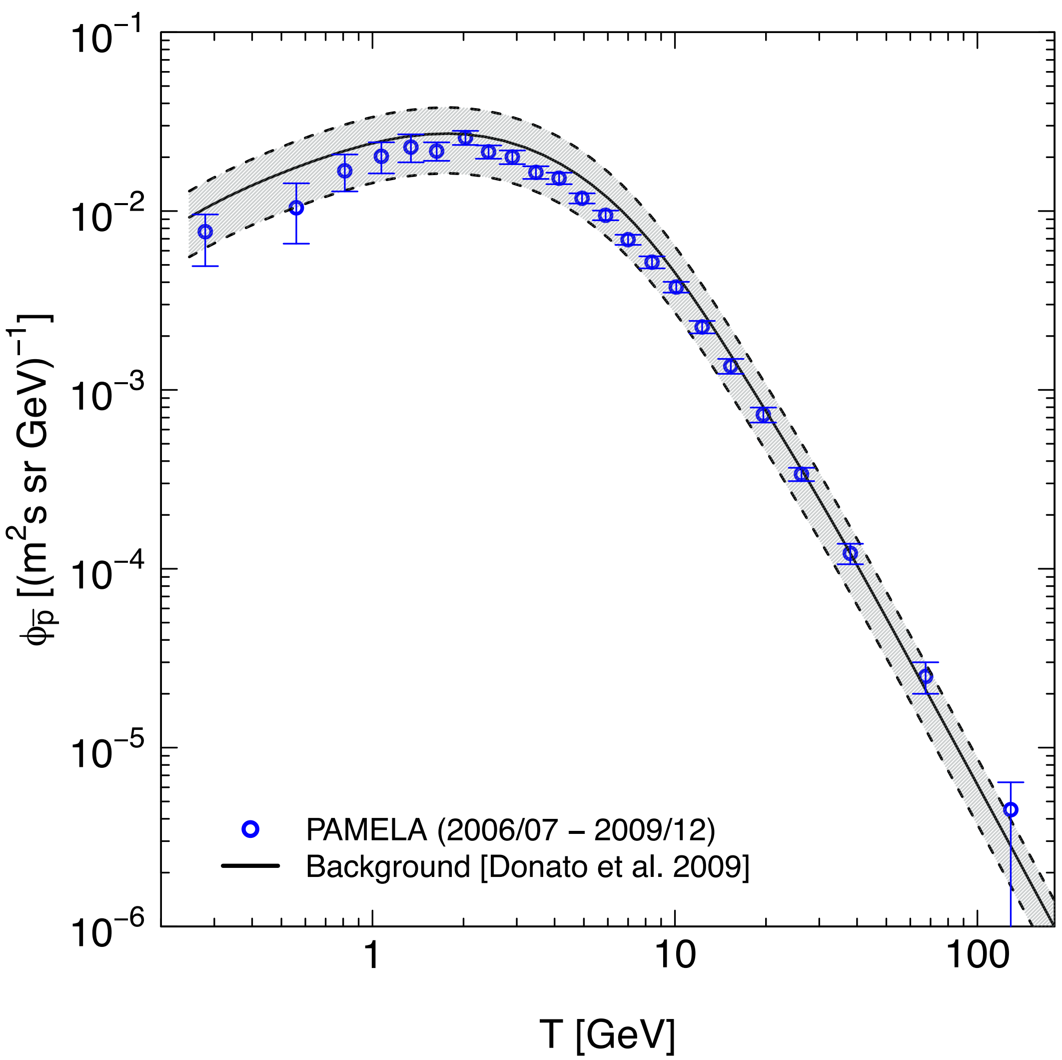
We have explored the role of two messengers: **antiprotons** and **anti-nuclei**

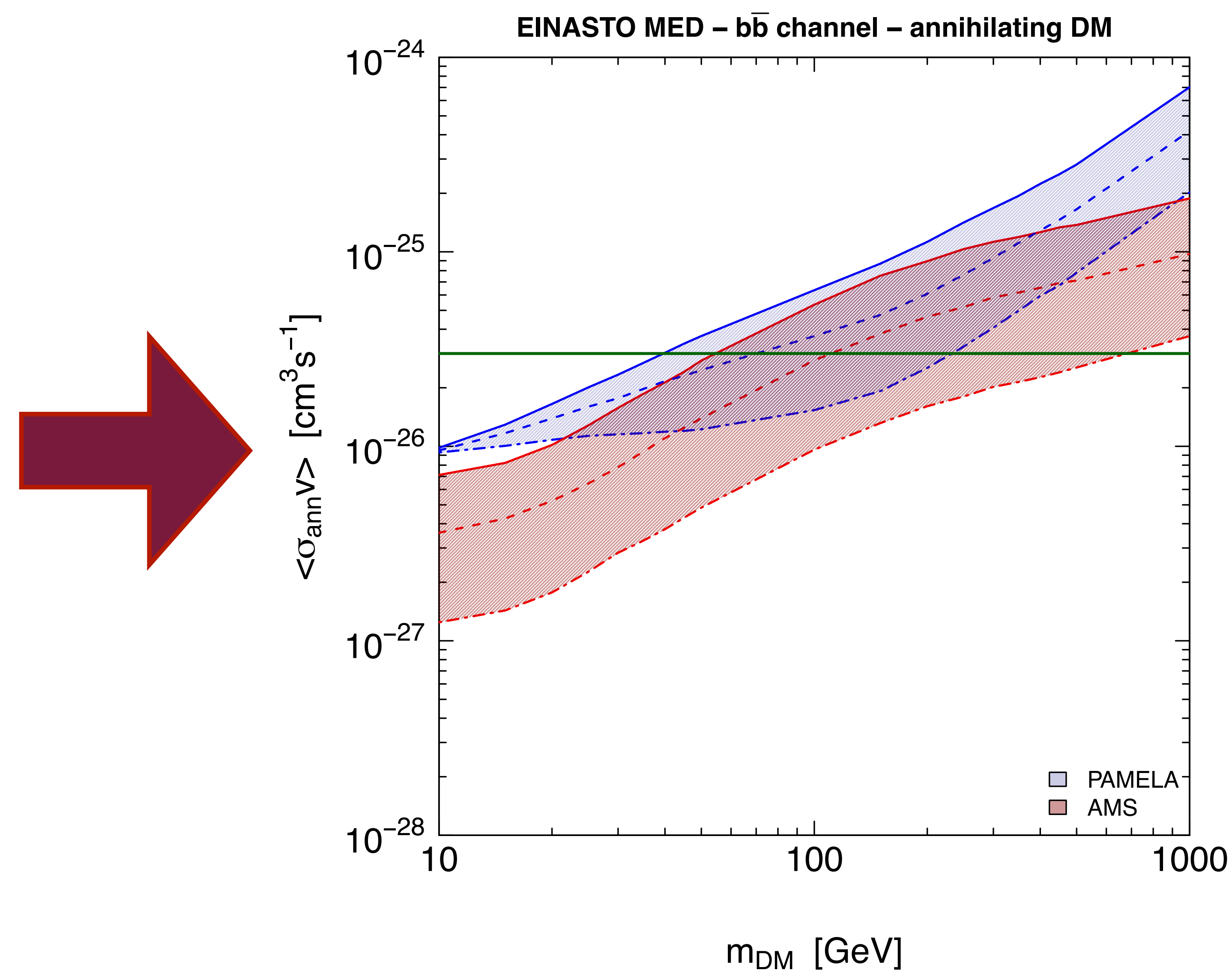
Antiprotons provide **strong constraints**, while **anti-nuclei** are a possible **discovery channel**

However, the **uncertainty** affecting our **theoretical predictions** is a **strong limiting factor** in probing the DM parameters space

Conclusive remarks

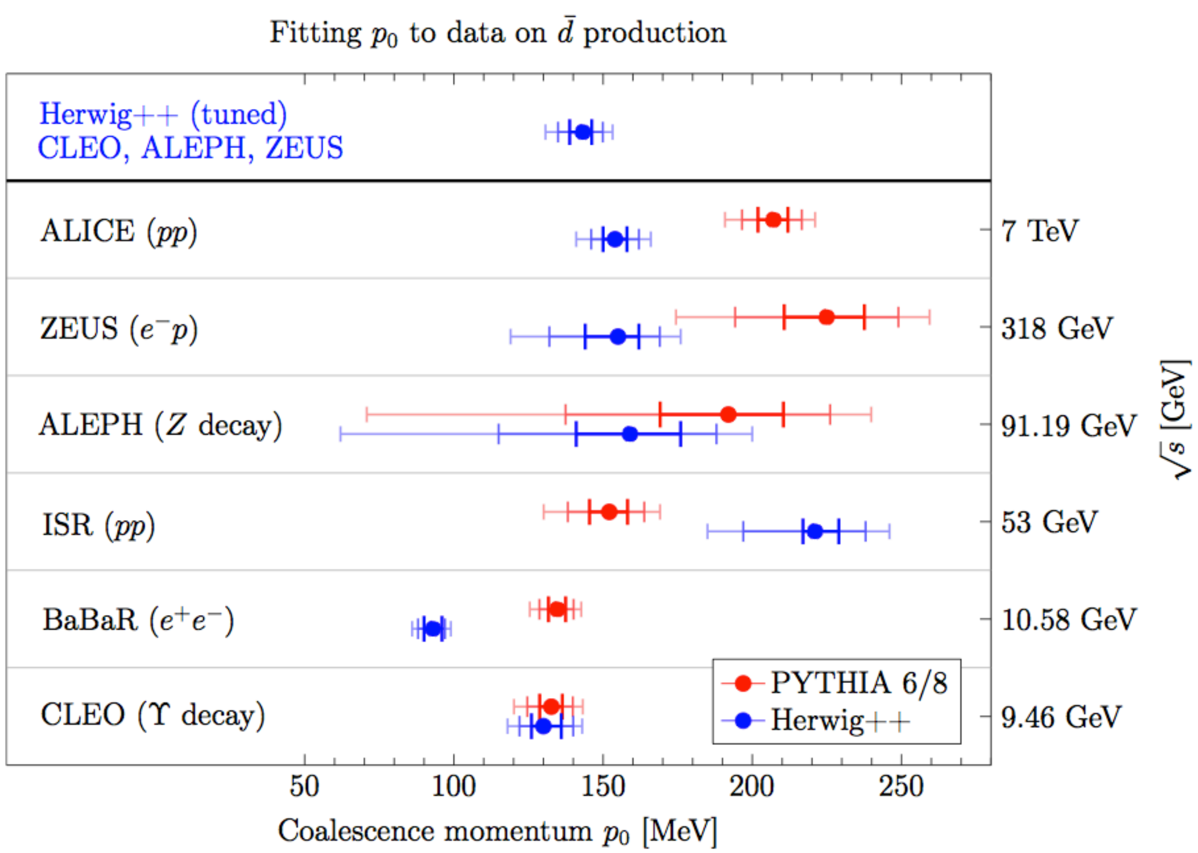
In particular, the **largest** source of uncertainty for the antiproton background is the one that affects **spallation cross sections**

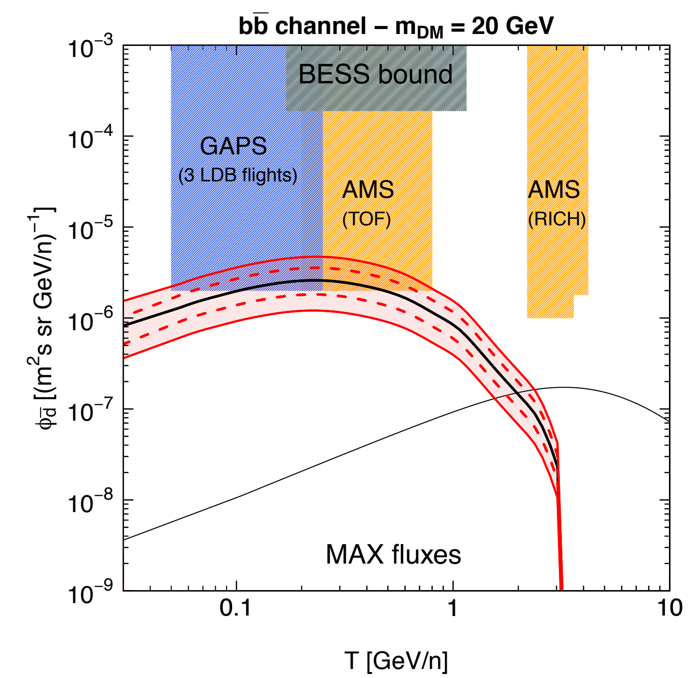


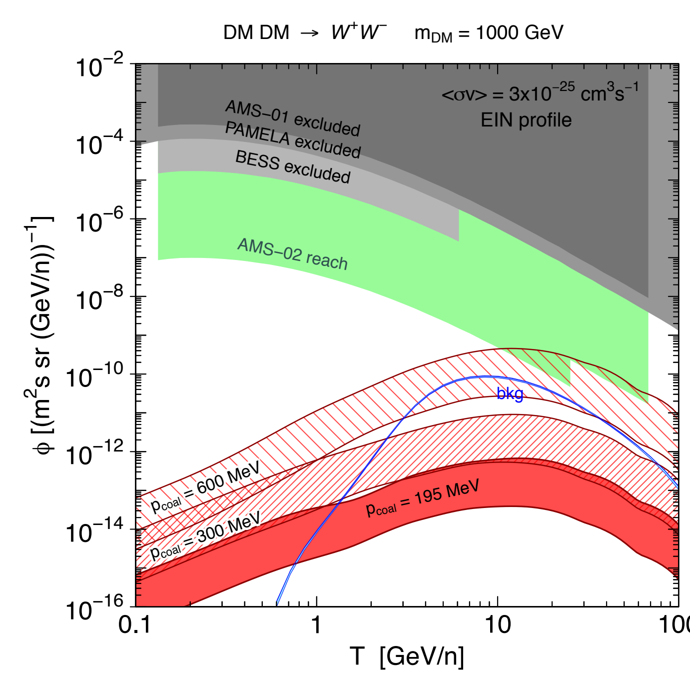


Conclusive remarks

For **anti-nuclei**, the large uncertainty on the **production mechanisms** reflects in a **huge uncertainty** (even more than one order of magnitude!) of the **final fluxes**







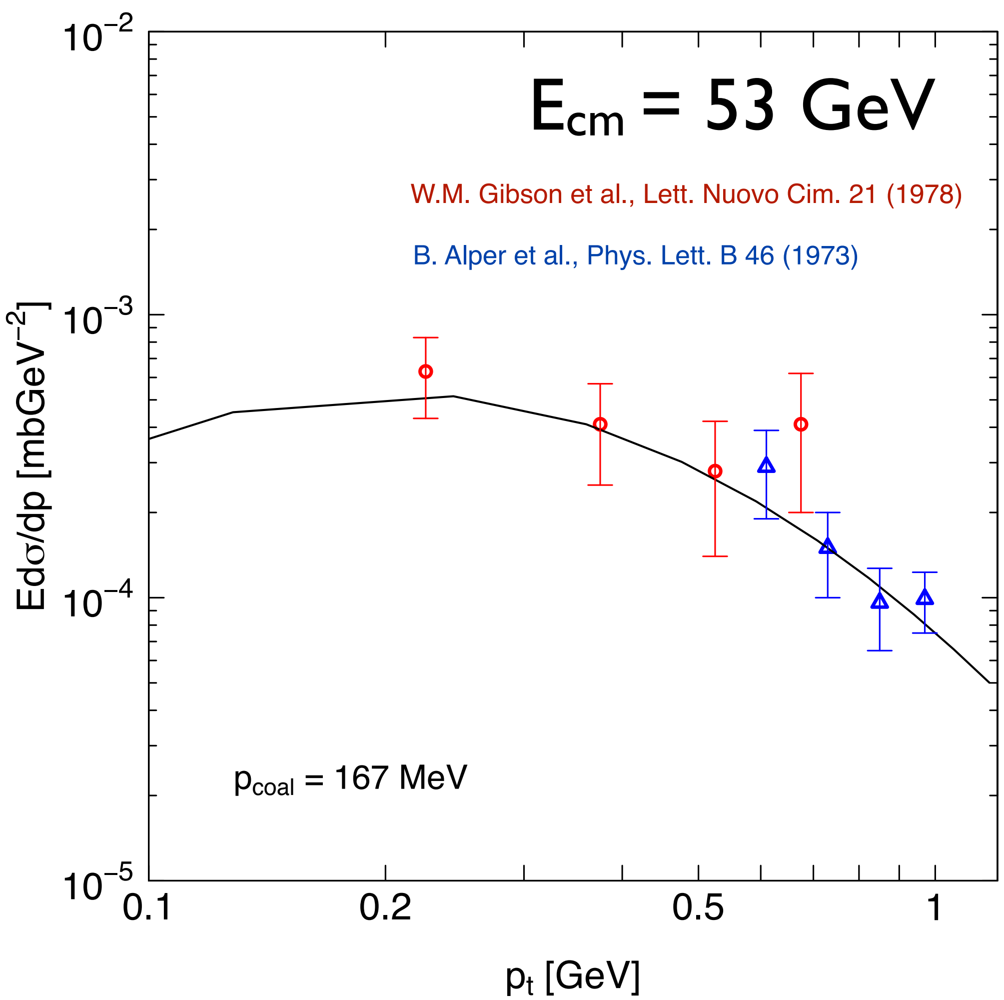

WAIT, HOLD ON. I'M MADE OF THE STUFF THAT 95% OF THE UNIVERSE IS MADE OF, AND YOU CALL ME "DARK MATTER" AND "DARK ENERGY"?
WELL, I MEAN-
YOU'RE THE ONES WHO SHOULD HAVE A SEPARATE IDENTIFIER. YOU'RE THE ONES MADE OF THAT WEIRD MATTER THAT STICKS TO ITSELF AND FORMS GLOBBY CHUNKS.
IN FAIRNESS-
FROM NOW ON, "DARK MATTER" IS JUST "MATTER," AND YOU ARE MADE OF "CLINGY MATTER."
CAN WE TALK ABOUT THIS?
WHOA! GIMME SOME SPACE!
smbc-comics.com

Thank you!

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:

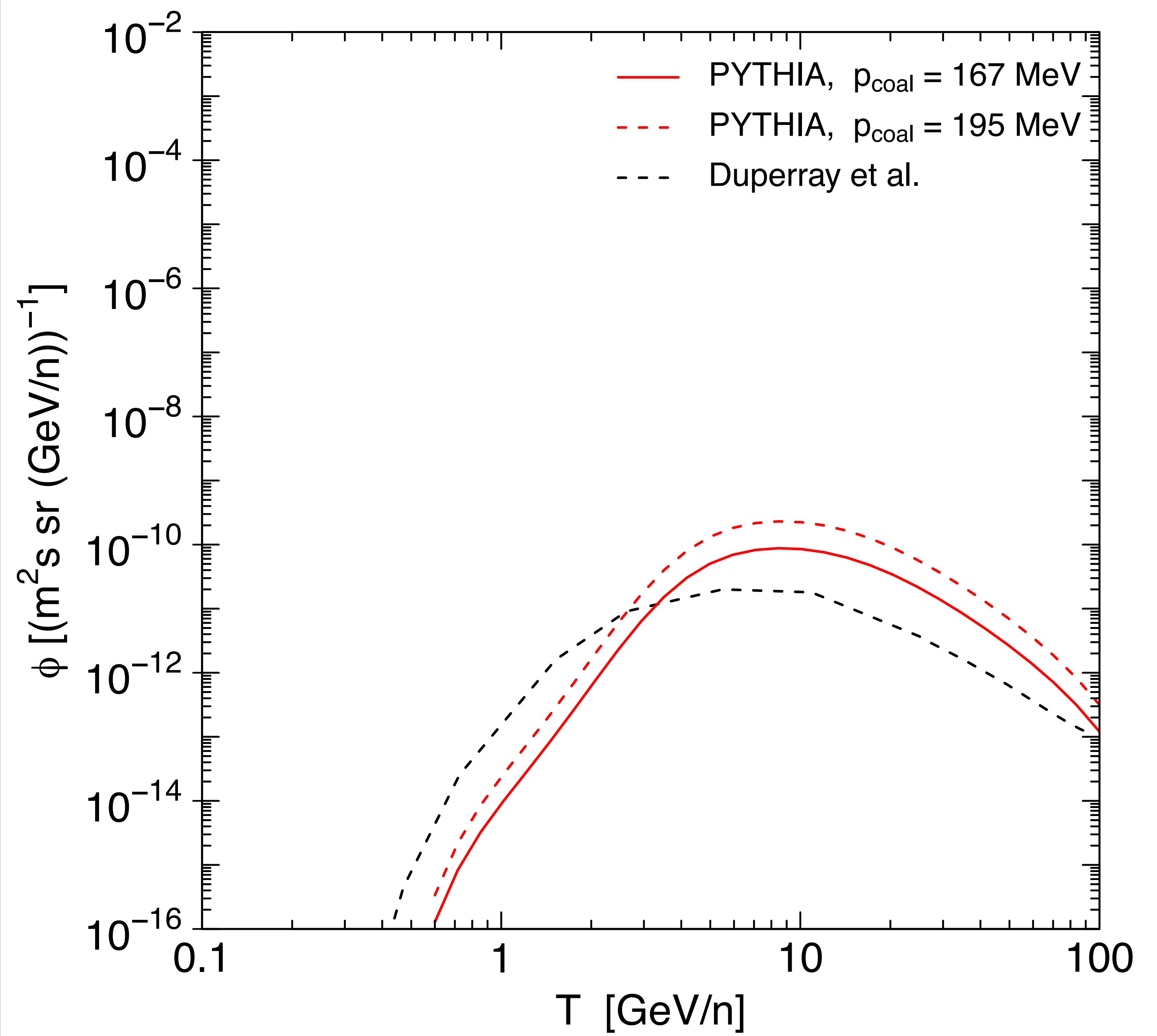
$$\frac{d\sigma_{pp\to\overline{\rm He}+X}}{dE}(E, E') = \sigma_{pp,\rm tot}(E, E') \frac{dn_{\overline{\rm He}}}{dE}(E, E')$$

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

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