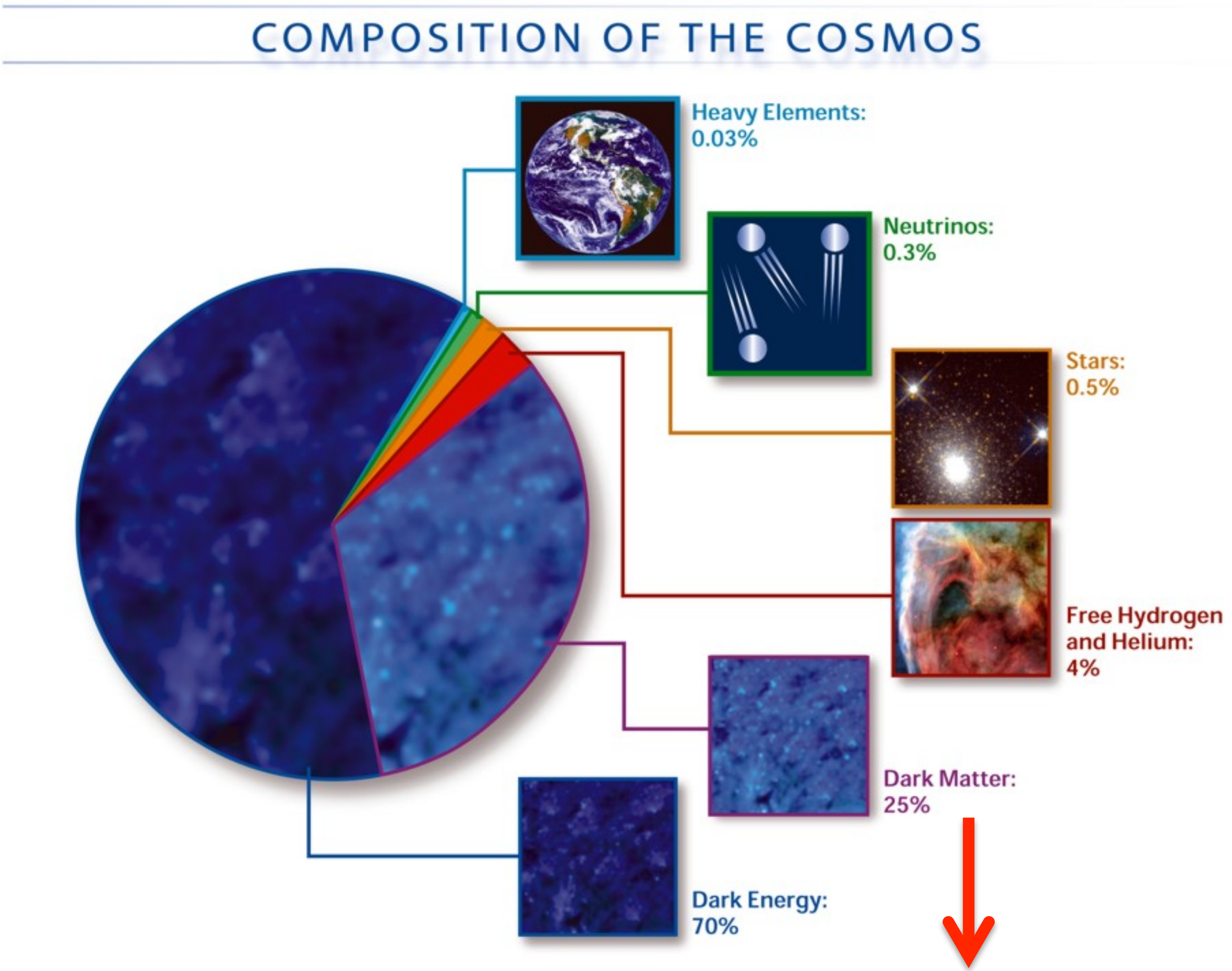
Antimatter production for studying dark matter

Fiorenza Donato
Torino University and INFN

2nd EMMI Workshop
University of Torino, 07.11.2017

The composition of the Universe



One hypothesis: the solution is a particle,
a WIMP (weakly interacting massive particle)

SIGNALS from RELIC WIMPs

Direct searches: elastic scattering of a WIMP off detector nuclei
Measure of the recoil energy
Annual modulation and directionality of the measured rate

Indirect searches: in cosmic rays (CRs)

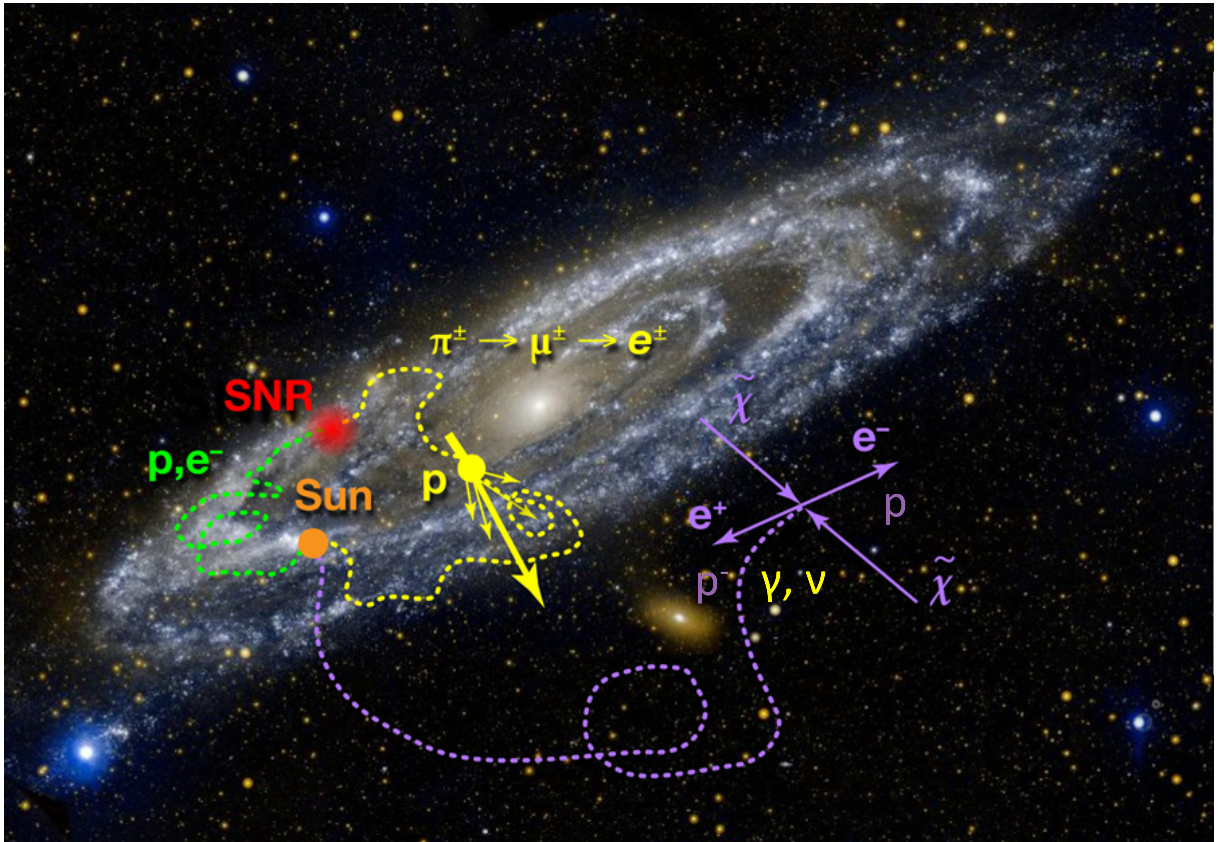
- signals due to annihilation of accumulated $\chi\chi$ in the centre of celestial bodies (Earth and Sun)

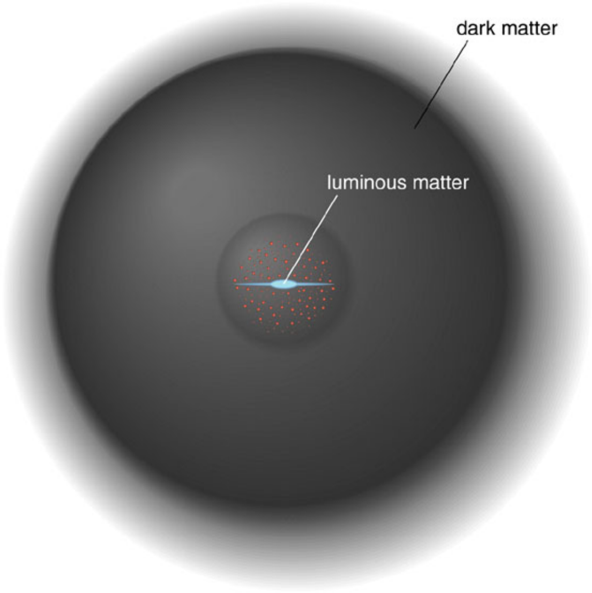
- signals due to $\chi\chi$ annihilation in the galactic halo

N.B. New particles are searched at **colliders** but we cannot say anything about being the solution to the **DM** in the Universe!

Indirect DARK MATTER searches

Dark matter can annihilate in pairs with standard model final states.
Low background expected for cosmic **ANTIMATTER**, and for **NEUTRINOS** and **GAMMA RAYS** coming from dense DM sites





GALACTIC COSMIC RAYS

are charged particles (nuclei, isotopes, leptons, antiparticles)
diffusing in the galactic magnetic field
Observed at Earth with E~ 10 MeV/n – 10^3 TeV/n

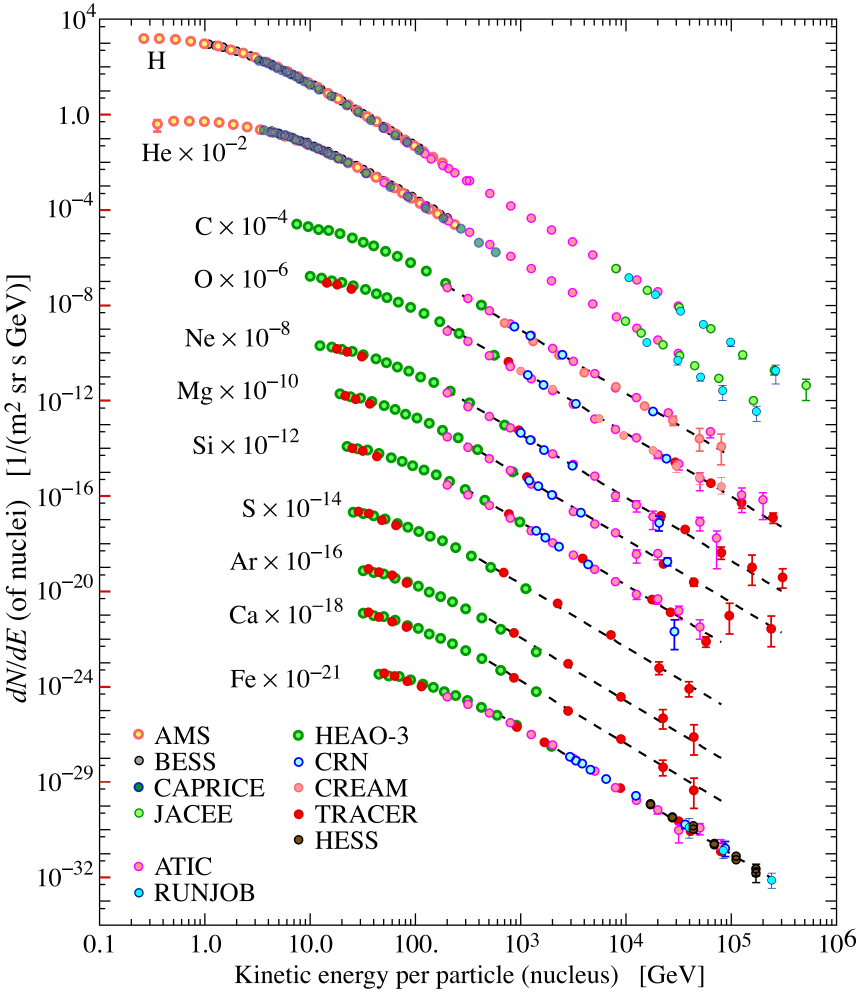
1. **SOURCES**
   PRIMARIES: directly produced in their sources
   Supernova remnants (SNR), pulsars, dark matter annihilation, …
   SECONDARIES: produced by spallation reactions of primaries on the interstellar medium (ISM), made of **H and He**

2. **ACCELERATION**
   SNR are considered the powerhouses for CRs.
   They can accelerate particles at least up to 10^2 TeV

3. **PROPAGATION**
   CRs are diffused in the Galaxy galactic magnetic field (microGauss)

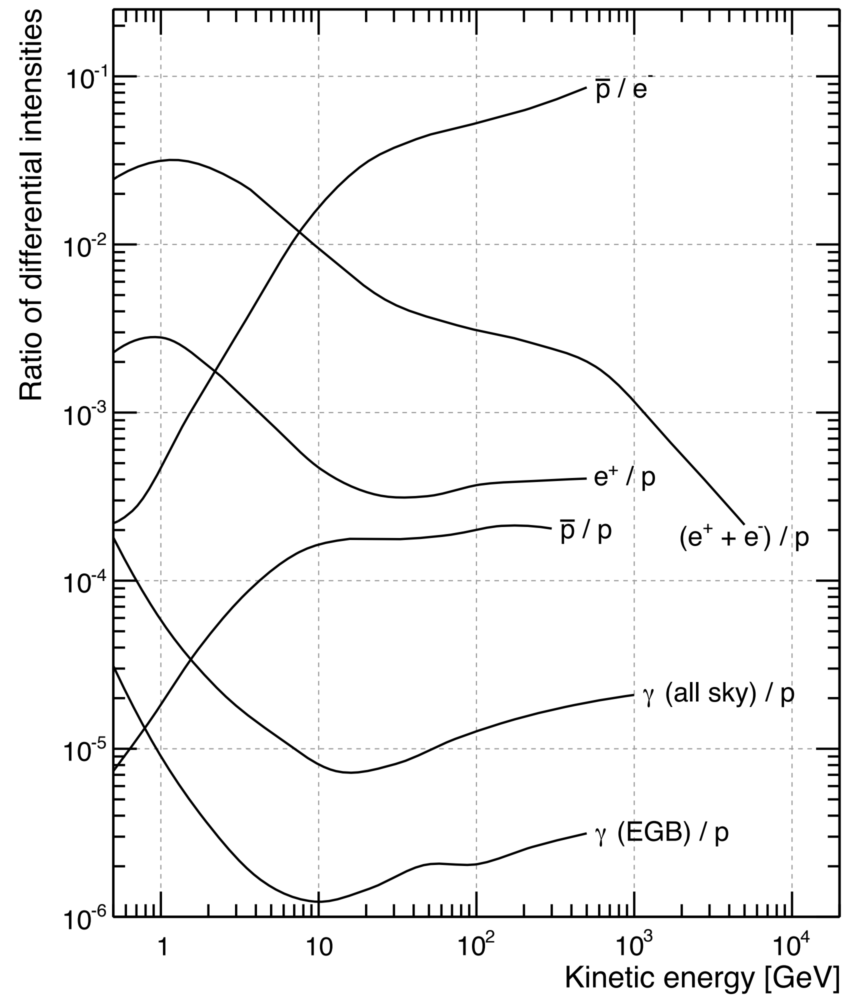
\+ loose/gain energy with different mechanisms

Charged cosmic rays intensity



PDG, Fig. created by
P. Boyler and D. Muller

Rare CRs and γ-rays



L Baldini, 1407.7631

Antimatter sources from DARK MATTER

Annihilation

$$Q_{\rm ann}(\vec{x}, E) = \quad \epsilon \left(\frac{\rho(\vec{x})}{m_{DM}} \right)^2 \sum_f \langle \sigma v \rangle_f \frac{dN^f_{e^\pm}}{dE}$$

Source spectrum, MC (i.e. Pythia)

Decay

Particle physics model

$$Q_{\rm dec}(\vec{x}, E) = \quad \left(\frac{\rho(\vec{x})}{m_{DM}} \right) \sum_f \Gamma_f \frac{dN^f_{e^\pm}}{dE}$$

- $\rho(\vec{x})$ DM density in the halo of the MW
- m_{DM} DM mass
- $\langle \sigma v \rangle_f$ thermally averaged annihilation cross section in SM channel f
- Γ_f DM decay time
- e+, e- energy spectrum generated in a single annihilation or decay event

Antimatter sources from CR spallations

Flux ≈ $$N^j(r,z) = \exp\left(\frac{V_c z}{2K}\right) \sum_{i=0}^{\infty} \frac{\bar{Q}^j}{A_i^j} \frac{\sinh\left[\frac{S_i^j(L-z)}{2}\right]}{\sinh\left[\frac{S_i^j L}{2}\right]} J_0\left(\zeta_i \frac{r}{R}\right)$$

$$\bar{Q}^j \equiv q_0^j Q(E)\hat{q}_i + \sum_k^{m_k>m_j} \tilde{\Gamma}^{kj} N_i^k(0)$$

$$S_i^j \equiv \left(\frac{V_c^2}{K^2} + 4\frac{\zeta_i^2}{R^2} + 4\frac{\Gamma_{rad}^{N^j}}{K}\right)^{1/2}$$

$$A_i^j \equiv 2h\tilde{\Gamma}_{N^j}^{tot} + V_c + K S_i^j \coth\left(\frac{S_i^j L}{2}\right)$$

$\Gamma^{kj} = n_{ISM}\, \sigma^{kj}\, v$

Production

$\Gamma^{kj} = n_{ISM}\, \sigma^{tot}\, v$

Destruction

Production cross sections in the galactic cosmic ray modeling

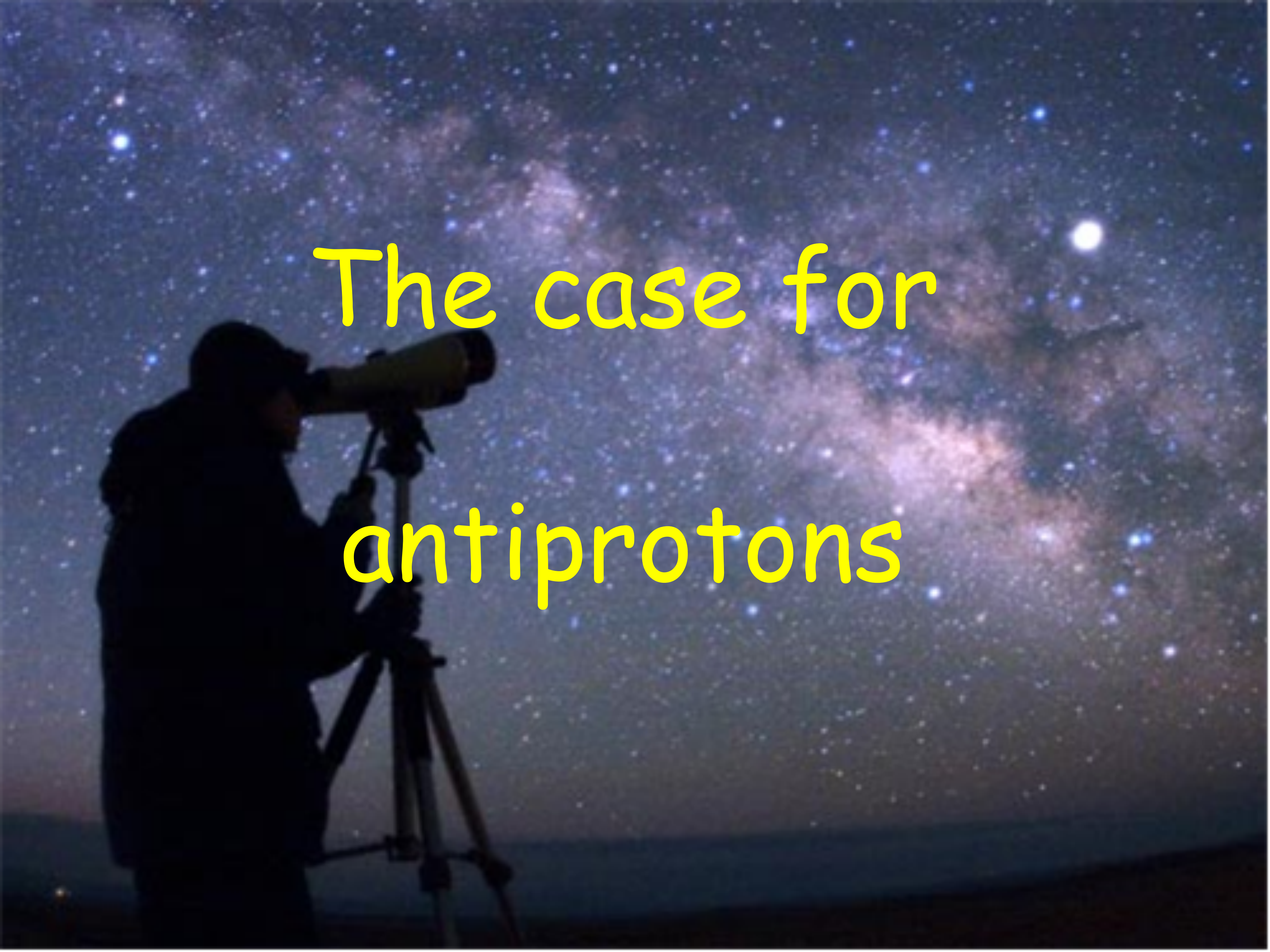
H, He, C, O, Fe,... are present in the supernova remnant surroundings, and directly accelerated into the the interstellar medium (ISM)

All the other nuclei (Li, Be, B, p-, and e+, gamma, ...) are produced by spallation of heavier nuclei with the atoms (H, He) of the ISM

We need all the cross sections σ^{kj} - from Nichel down to proton - for the production of the j-particle from the heavier k-nucleus scattering off the H and He of the ISM

Remarkable for DARK MATTER signals is productions of: antiproton, antideuteron, positron and gamma rays.

The case for antiprotons



Cosmic antiprotons

Antiprotons are produced in the Galaxy by **fragmentation** of proton and He (and marginally heavier nuclei) on the interstellar medium (ISM)

These secondary antiprotons would be the background to an exotic component due to

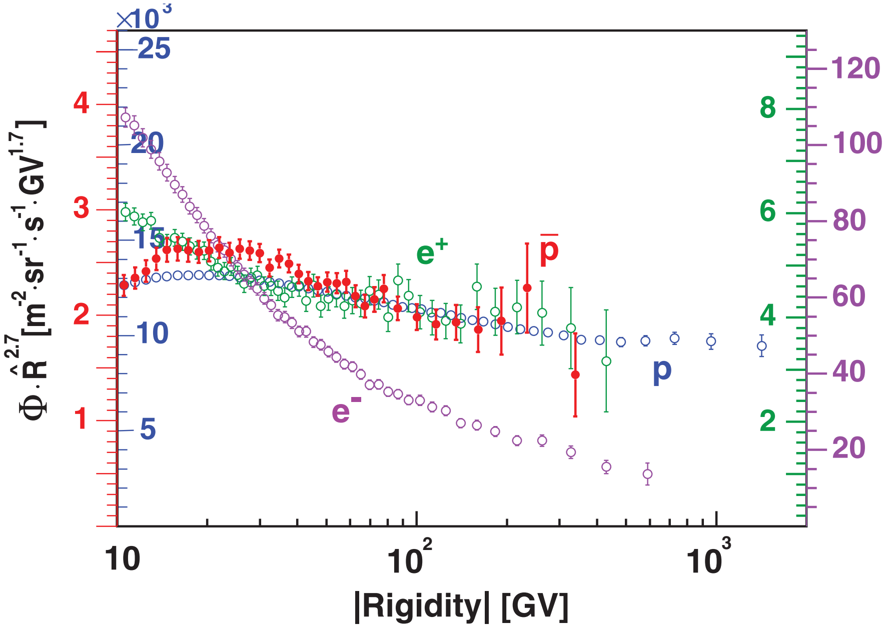
dark matter annihilation

in the galactic halo (**primary antiprotons**).

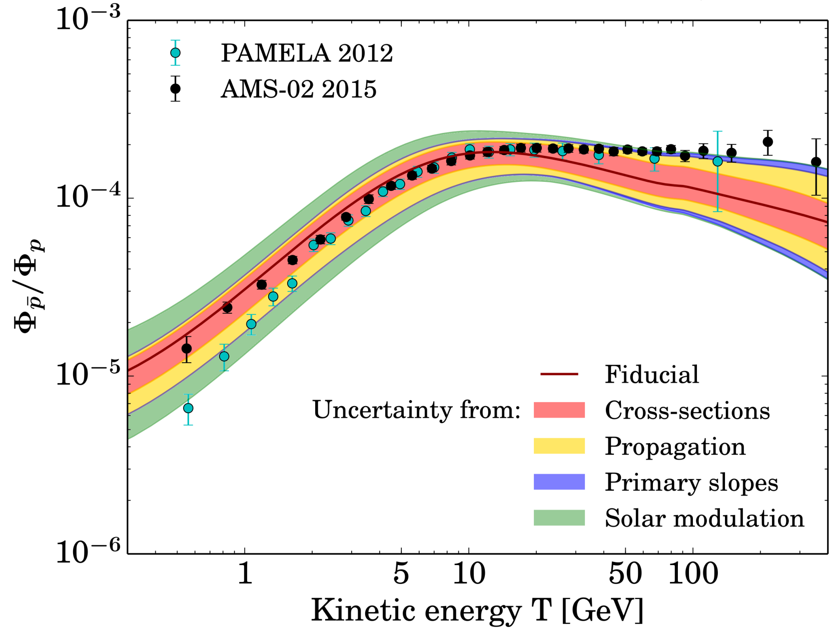
Thousands of cosmic antiprotons have already been detected by balloon-borne (Bess, Caprice,…) or satellite experiments (Pamela), and AMS-01, and 290000 (out of 5.4×10^9 events) from AMS-02 on the ISS

Antiproton data as of 2017

AMS Coll., PRL 2016



Giesen+ 1504.04276

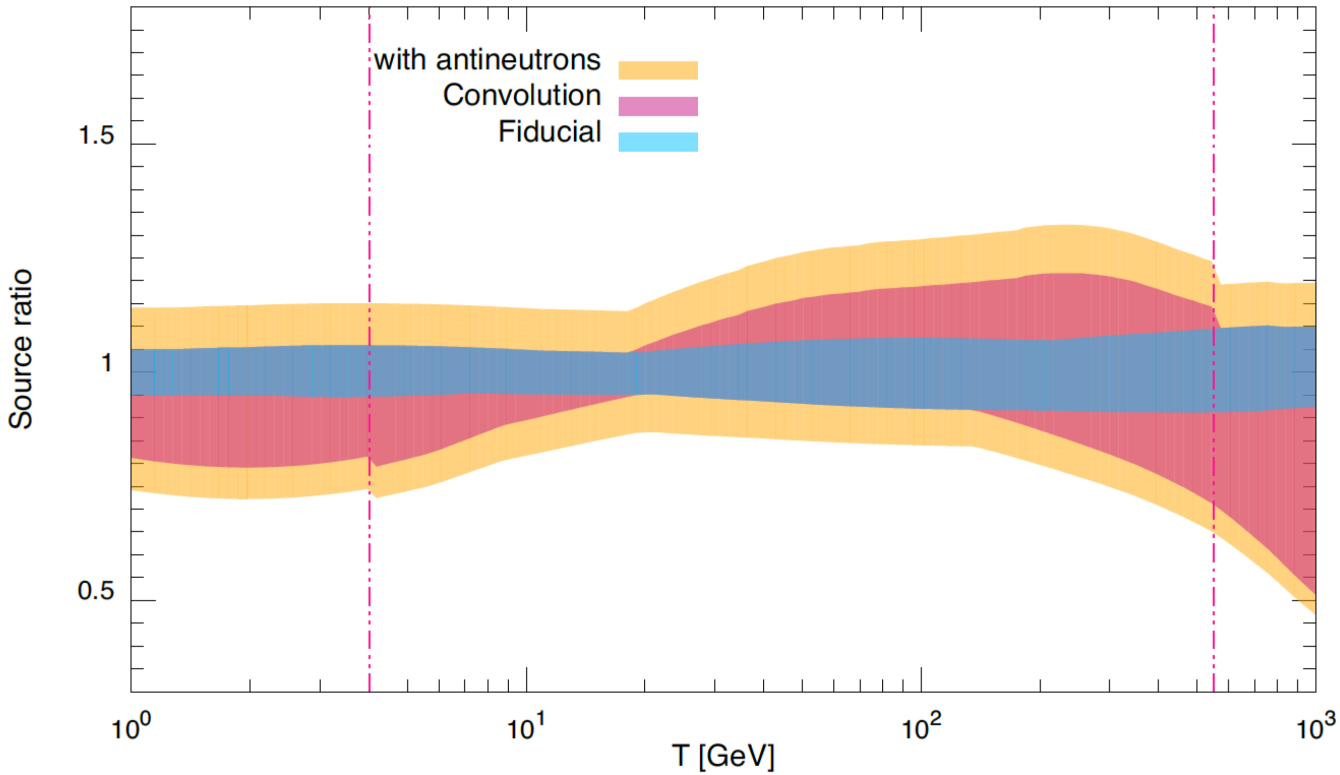


AMS-02 results from below GeV up to 400 GeV
Could be explained by secondary production in the Milky Way

The most relevant theoretical uncertainty is due to production CROSS SECTIONS

Uncertainties due p-p scattering

Di Mauro, FD, Goudelis, Serpico PRD 2014



Uncertainties in the pbar production spectrum from p-p scattering are at least 10%.
Conservative: 20% at low energies (GeV) up to 50% (TeV)
(data expected at least up to ~ 500 GeV)

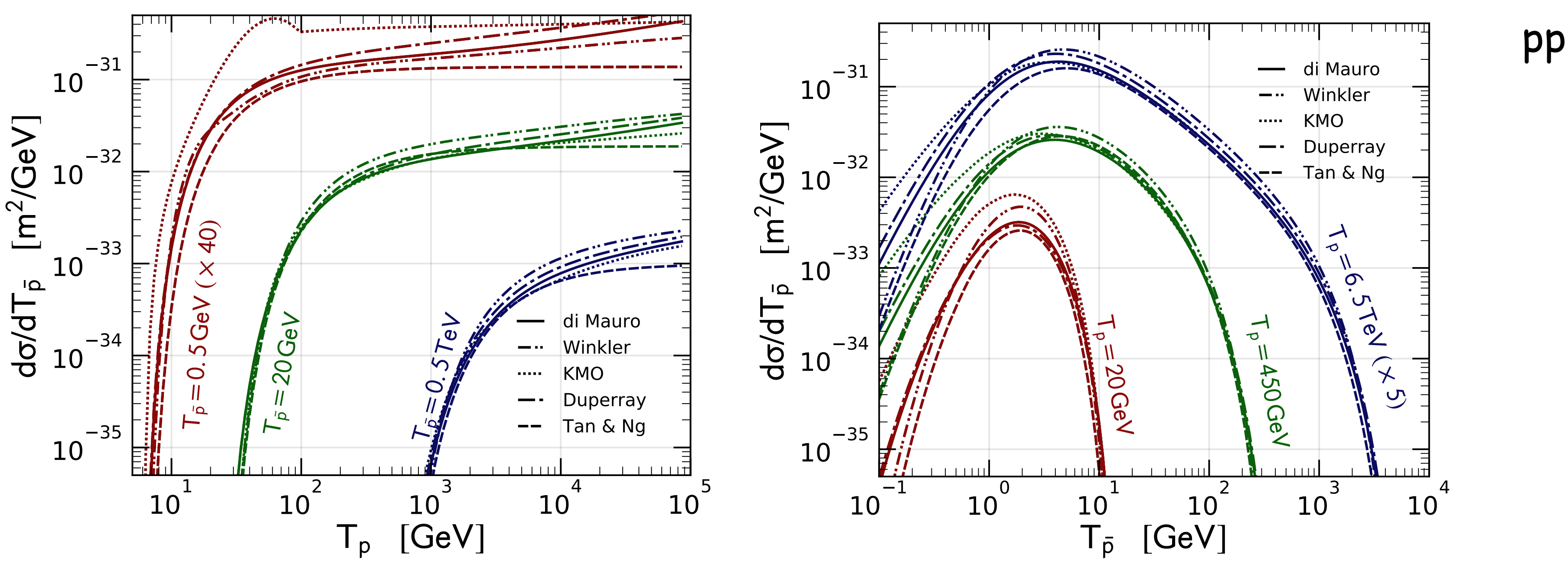
Antiproton production cross sections

FD, Korsmeier, Di Mauro PRD 2017

$$q_{ij}(T_{\bar{p}}) = \int_{T_{\rm th}}^{\infty} dT_i \; 4\pi \, n_{{\rm ISM},j} \, \phi_i(T_i) \, \frac{d\sigma_{ij}}{dT_{\bar{p}}}(T_i, T_{\bar{p}})$$

Source term

i, j = proton, helium
(both in the CRs and in the ISM)



- Reasonable agreement for 10 GeV <T <100 GeV
- Deviations for T<10 GeV

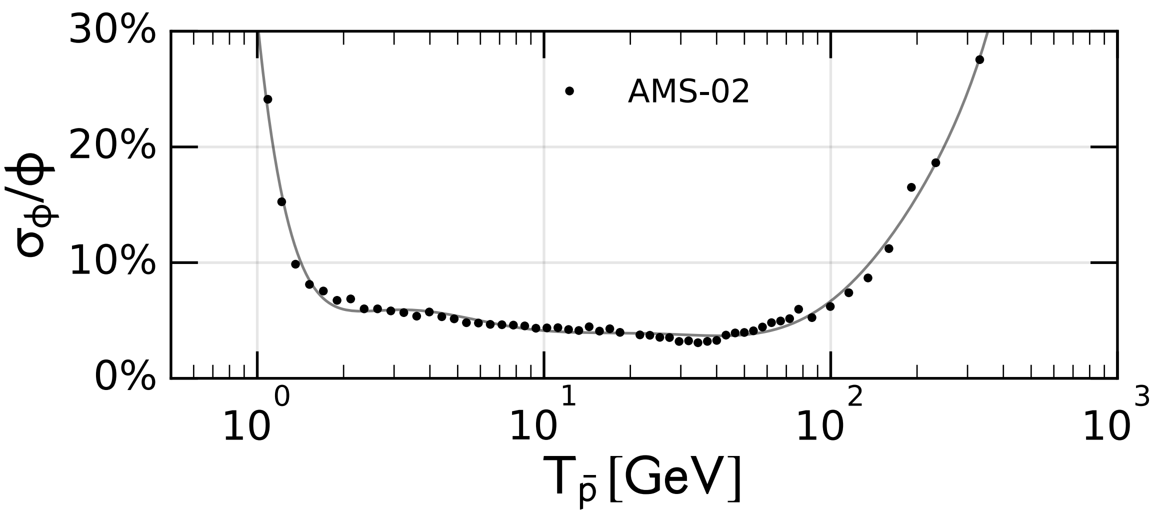
Requirement on phase space for the pp→p- Xcross section

FD, Korsmeier, Di Mauro PRD 2017

$$\frac{d\sigma}{dT_{\bar{p}}}(T, T_{\bar{p}}) = 2\pi p_{\bar{p}} \int_{-1}^{1} d\cos(\theta)\ \sigma_{\rm inv}$$

$$= 2\pi p_{\bar{p}} \int_{-\infty}^{\infty} d\eta\ \frac{1}{\cosh^2(\eta)}\ \sigma_{\rm inv}$$

$$\{T, T_{\bar{p}}, \cos(\theta)\} \quad \{\sqrt{s}, x_{\rm R}, p_{\rm T}\}$$

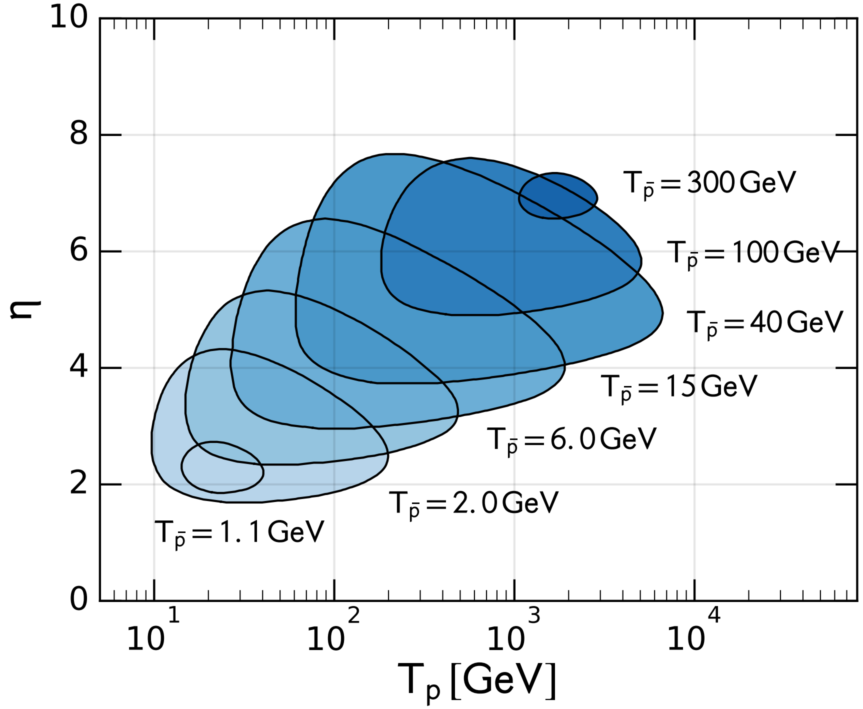


Which level of accuracy on cross sections do we need in order to match (not exceed) the accuracy in CR data?

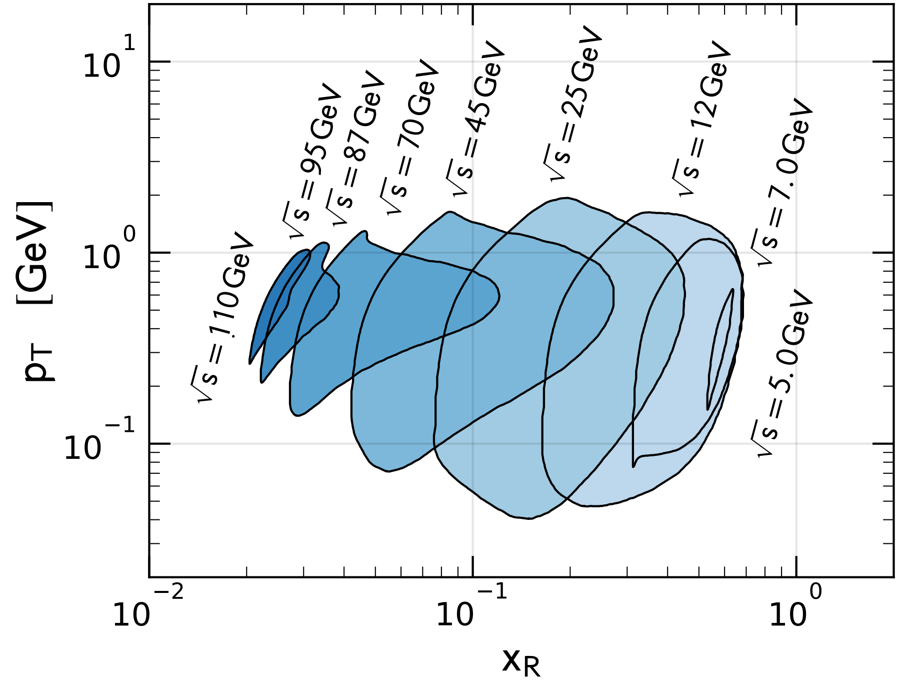
Bias towards AMS-02 data

Parameter space to be covered

Fixed target



Lab frame

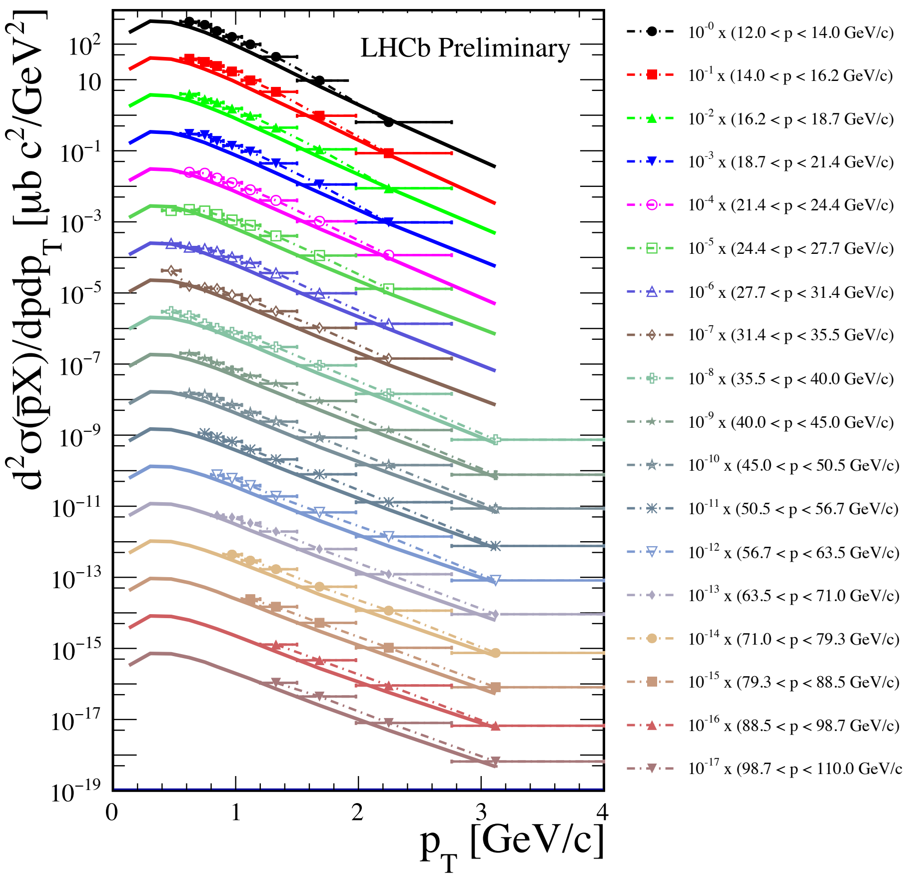


AMS02 accuracy is reached if pp→pbar cross section is measured with 3% accuracy inside the regions, 30% outside.

LHCb pHe → p- cross section data

G Graziani for LHCb, Moriond 2017

First data ever has been collected by LHCb in fixed target mode



Result for **prompt** production (excluding weak decays of hyperons)

The total inelastic cross section is also measured to be

$$\sigma_{inel}^{\mathrm{LHCb}} = (140 \pm 10)\ \mathrm{mb}$$

The EPOS LHC prediction

[T. Pierog at al, Phys. Rev. C92 (2015), 034906]

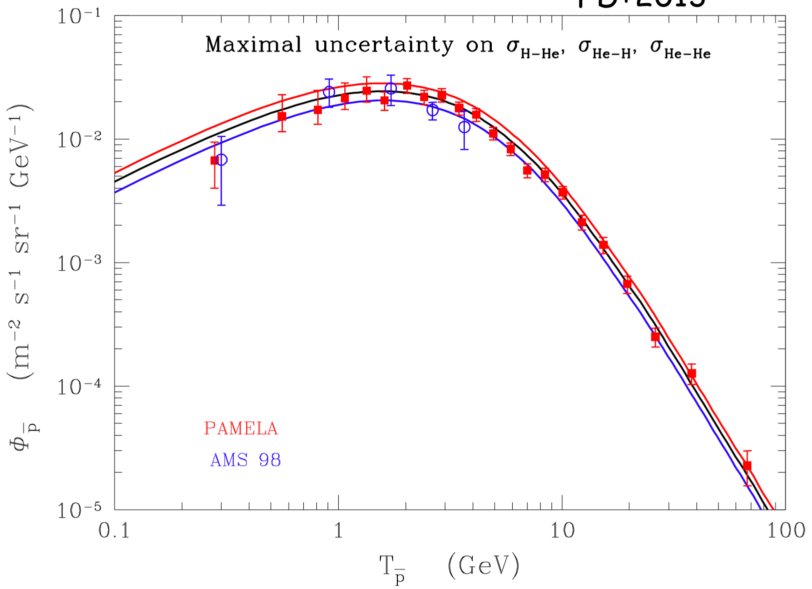
is 118 mb, ratio is 1.19 ± 0.08.

FD, Korsmeier, Di Mauro, in preparation

Reactions involving helium & higher energies

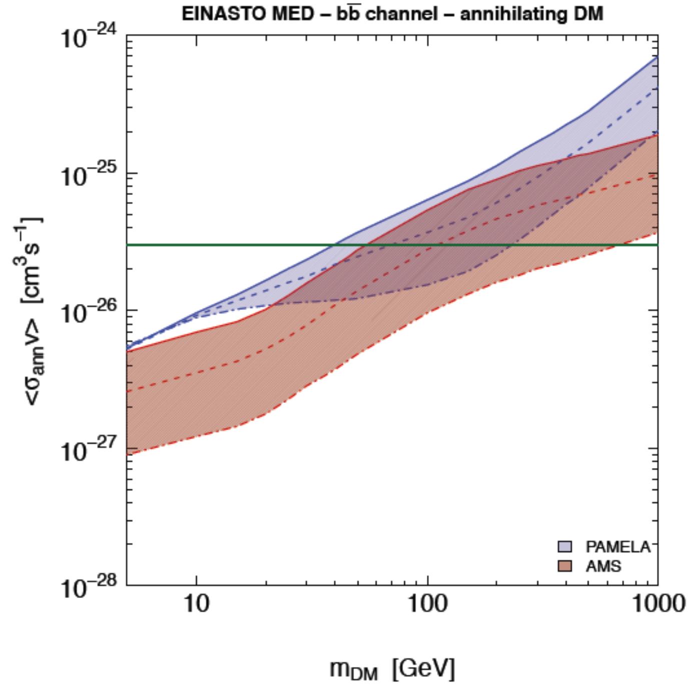
Uncertainties due to helium reactions range 40-50% on Secondary CR flux

FD+2013



Effect of cross section uncertainty on DARK MATTER interpretation

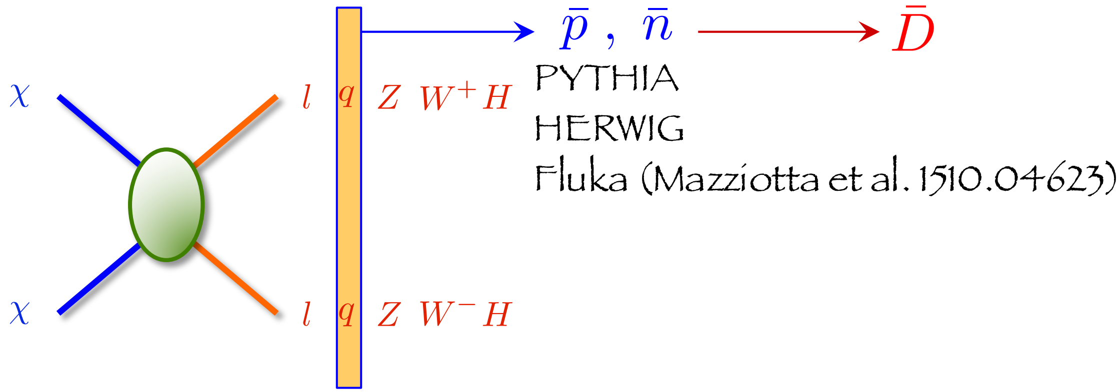
Fornengo, Maccione, Vittino JCAP2014



AMS-02 is providing data with much higher precision up to hundreds of GeV
Their interpretation risks to be seriously limited by nuclear physics


The case for
antideuterons

Antideuteron from Dark Matter particles



$$\frac{dN_{\bar{d}}}{dT_{\bar{d}}} = (4\pi E_{\bar{d}}\, k_{\bar{d}})\, F_{\bar{d}}(\sqrt{s}, \vec{k}_{\bar{d}})$$

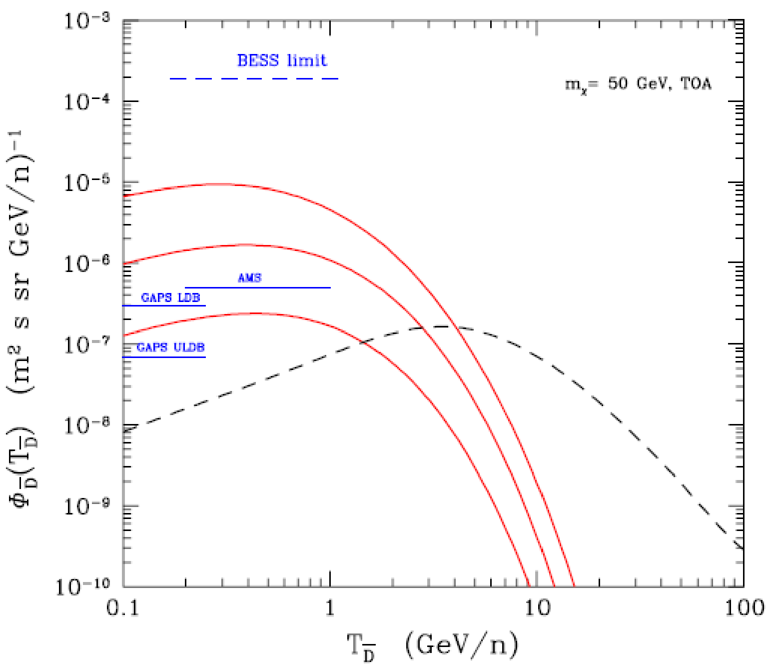
$$F_{\bar{d}}(\sqrt{s}, \vec{k}_{\bar{d}}) = \int F_{(\bar{p}\bar{n})}(\sqrt{s}, \vec{k}_{\bar{p}}, \vec{k}_{\bar{n}})\, \boxed{\mathcal{C}(\sqrt{s}, \vec{k}_{\bar{p}}, \vec{k}_{\bar{n}} | \vec{k}_{\bar{d}})}\, d^3\vec{k}_{\bar{n}}\; d^3\vec{k}_{\bar{n}}$$

Coalescence function

Flux of antideuterons: DM vs secondary one

FD, Fornengo, salati PRD 2001; FD, Fornengo, Maurin PRD 2008;
Kadastik, Raidal, Strumia PLB2010; Ibarra, Wild JCAP2013; Fornengo, Maccione, Vittino JCAP 2013; …

In order for fusion to take place,
the two antinucleons must have low kinetic energy



$$\frac{dN_{\bar{D}}}{dE_{\bar{D}}} = \left(\frac{4\,P_{coal}^{3}}{3\,k_{\bar{D}}}\right)\left(\frac{m_{\bar{D}}}{m_{\bar{p}}\,m_{\bar{n}}}\right)\sum_{F,h} B_{\chi h}^{(F)}\left\{\frac{dN_{\bar{p}}^{h}}{dE_{\bar{p}}}\left(E_{\bar{p}} = \frac{E_{\bar{D}}}{2}\right)\right\}^{2}$$

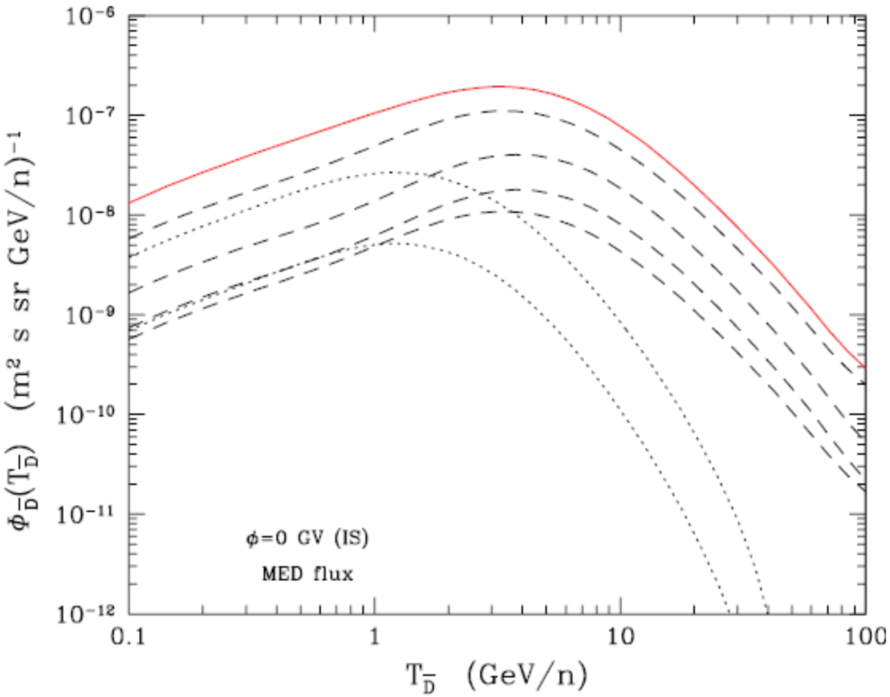
Kinematics of **spallation** reactions prevents the formation of very low antiprotons (antineutrons).

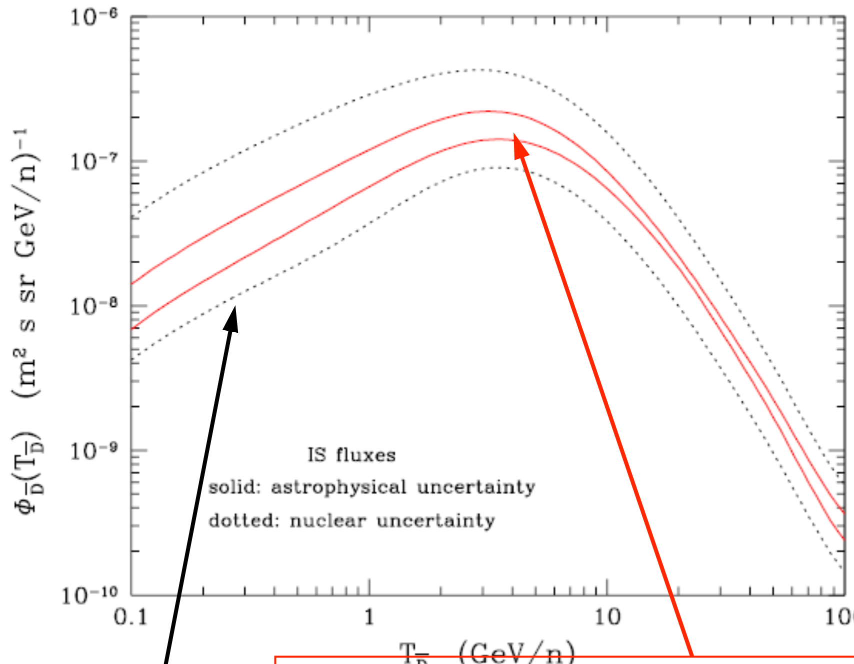
At variance, **dark matter** annihilates almost at rest

Secondary antideuterons

FD, Fornengo, Maurin PRD 2008

Contributions to secondaries





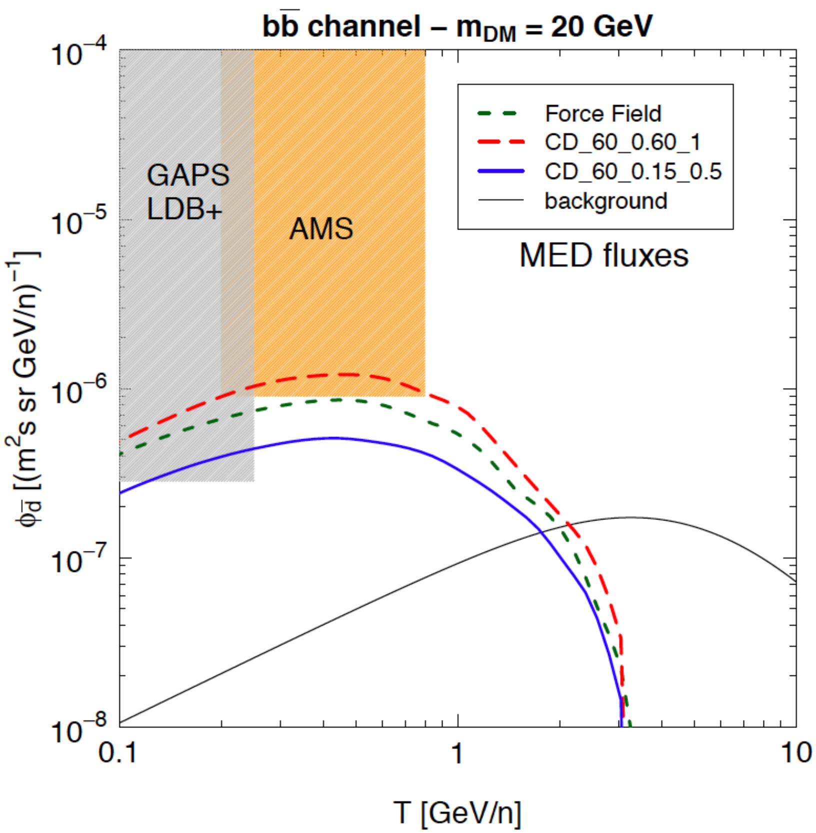
Propagation uncertainties
Compatibility with B/C

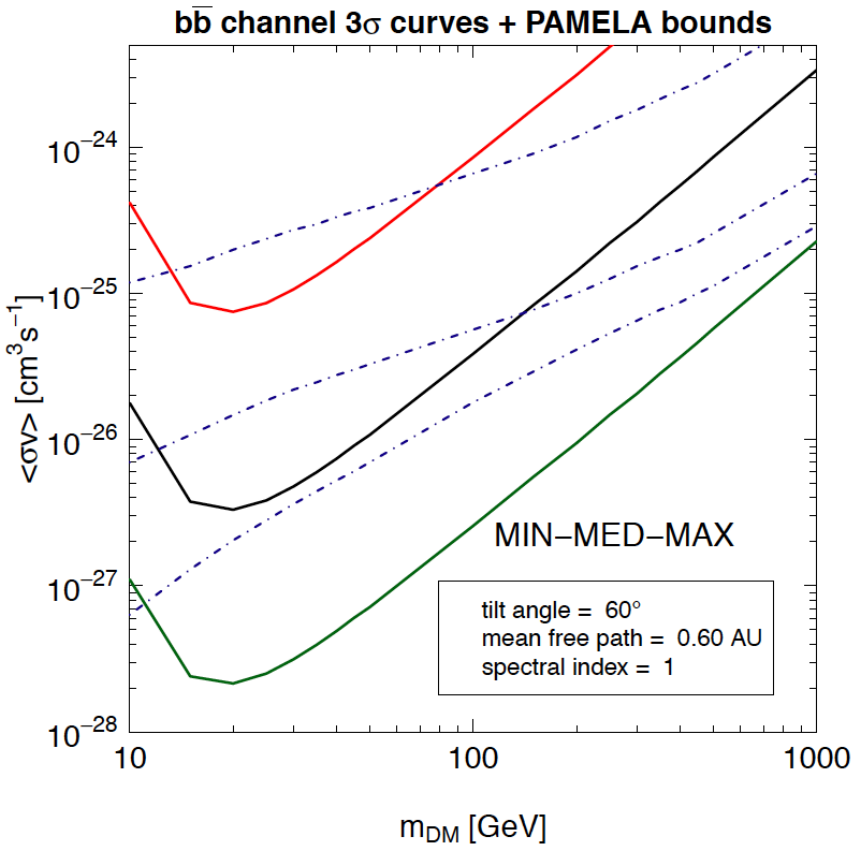
Nuclear uncertainties
Production cross sections & P_{coal}
Production from antiprotons
Non-annihilating cross sections

p-p, p-He,
He-H, He-He
H- pbar, He-pbar

Antideuterons:
Dark matter detection perspectives

Fornengo, Maccione, Vittino JCAP 2013



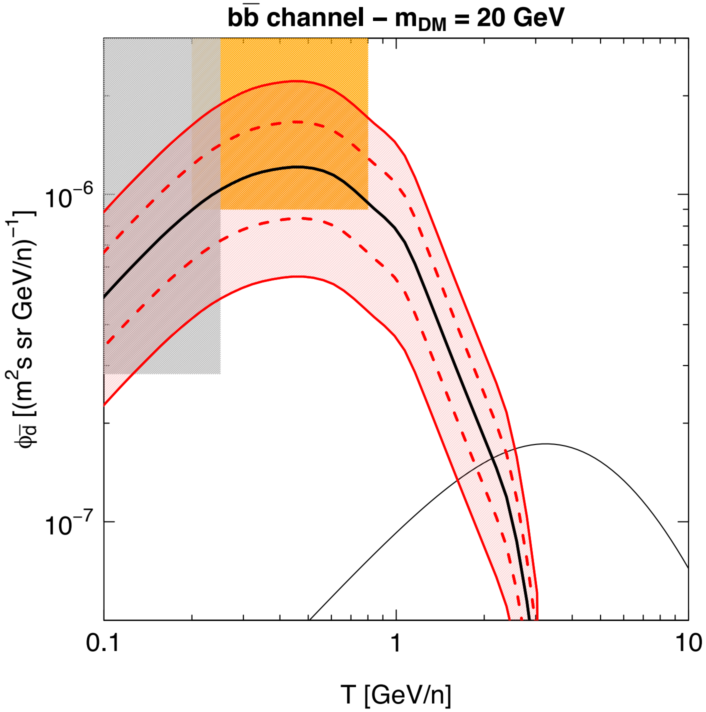


3σ expected sensitivities

Prospects for 3σ detection of antideuteron with GAPS (dotted lines are Pamela bounds from antiprotons)

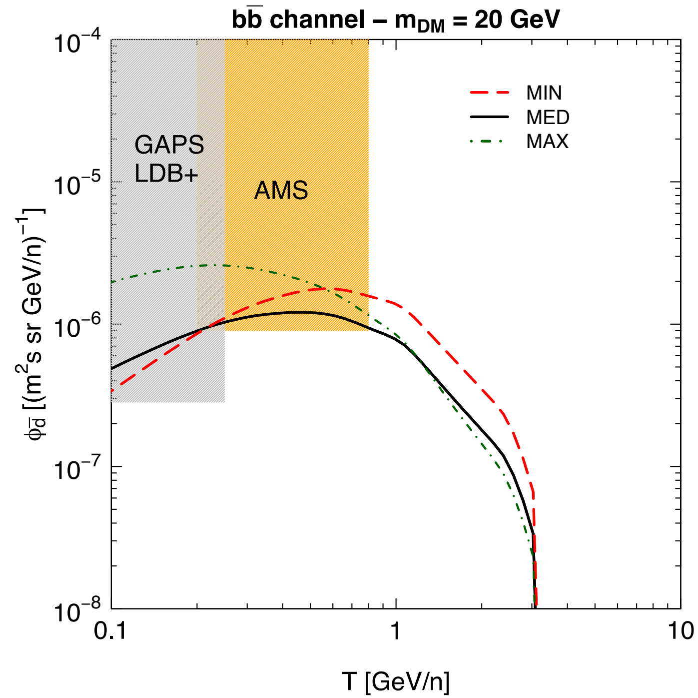
Uncertainties in the D-bar flux

Due to coalescence (p⁻-n⁻ fusion)



$p_0 = (195 \pm 22)$ MeV

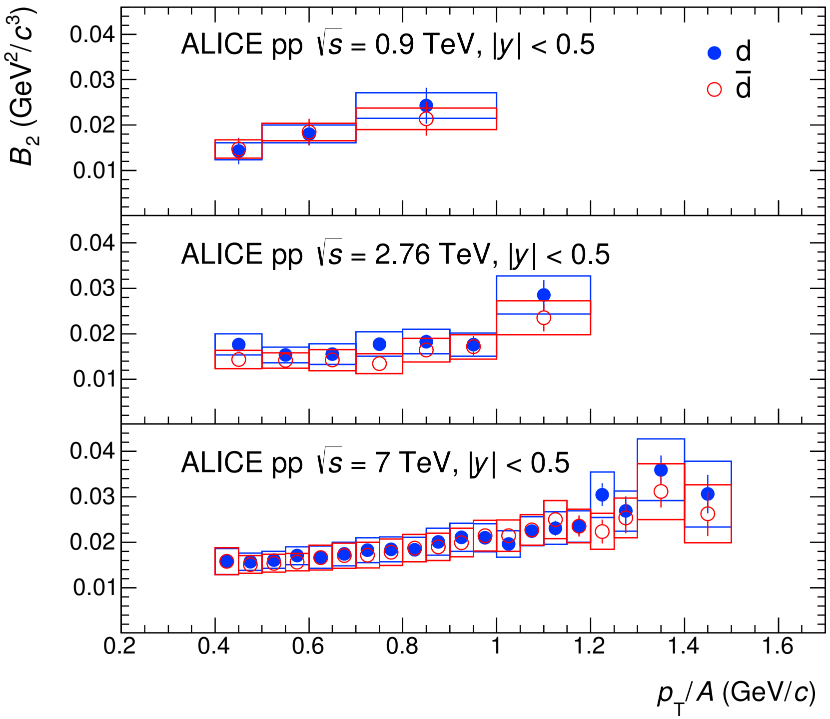
Due to propagation in the Galaxy

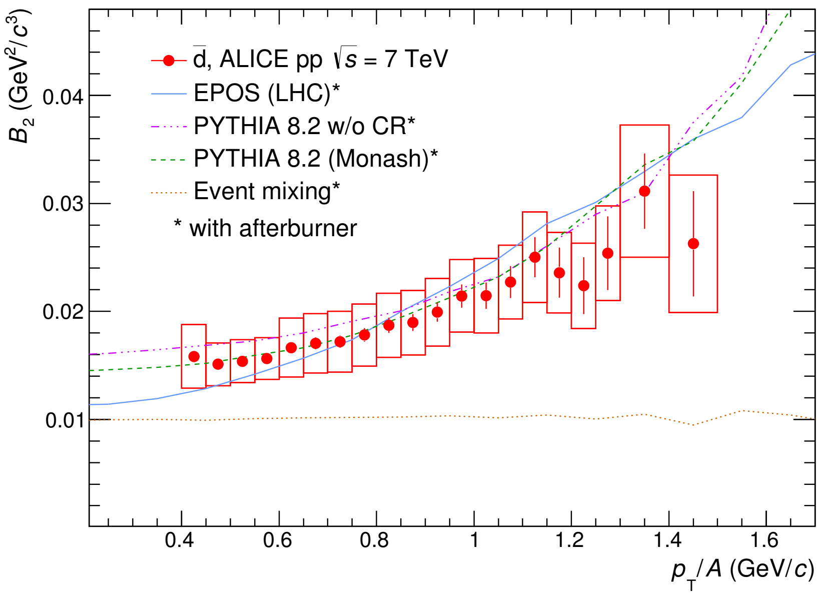


AMS data favor MAX set of propagation parameters

Contribution from ALICE

Alice Coll. 1709.08522, sub. PRC





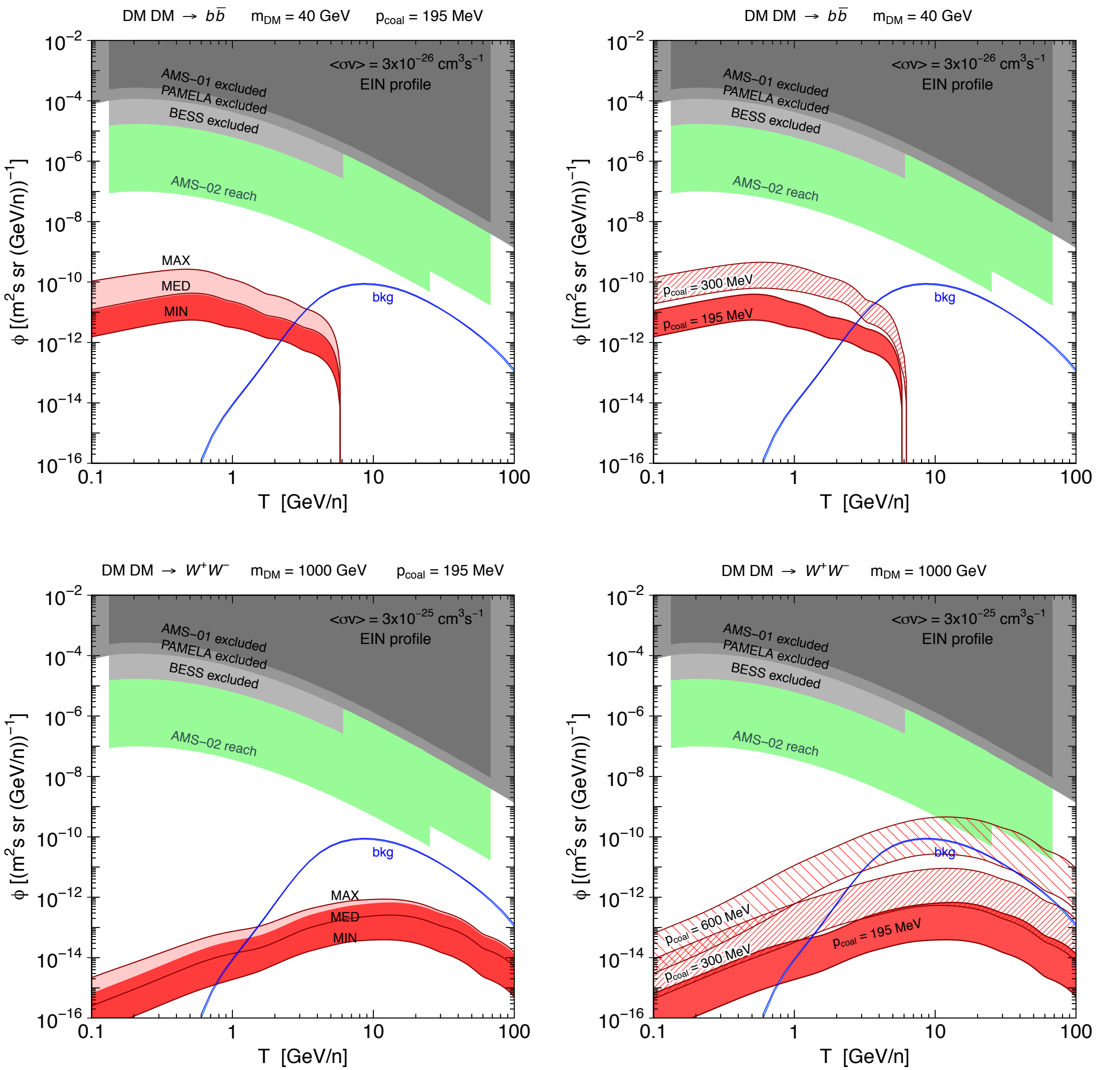
Coalescence parameter measured also at LHC energies

See talk by K. BLUM


The case for
antihelium

The case for antihelium

Cirelli, Fornengo, Taoso, Vittino, JCAP2014; Carlson et al. PRD2014



Good signal-to-background ratios

Predictions for most DM models much lower than experimental reach

Nuclear physics brings relevant effects through $(p_{coal})^6$


The case for
positrons

Sources of positrons in the Milky Way

Sources of e^+ and e^- in the Galaxy:

1. Secondary $e^+ e^-$: spallation of cosmic p and He on the ISM (H, He)
   * $p+H(He) \rightarrow p+\Delta^+ \rightarrow p+\pi^0$ & $n+\pi^+$ (mainly below 3 GeV)
   * $p+H(He) \rightarrow p+n+\pi^+$
   * $p+H(He) \rightarrow X + K^{\pm}$

2. Primary e- and e+ from Pulsars (PSR):
   pair production in the strong PULSAR magnetoshpere

3. Primary e- from SNR: 1° type Fermi acceleration mechanism

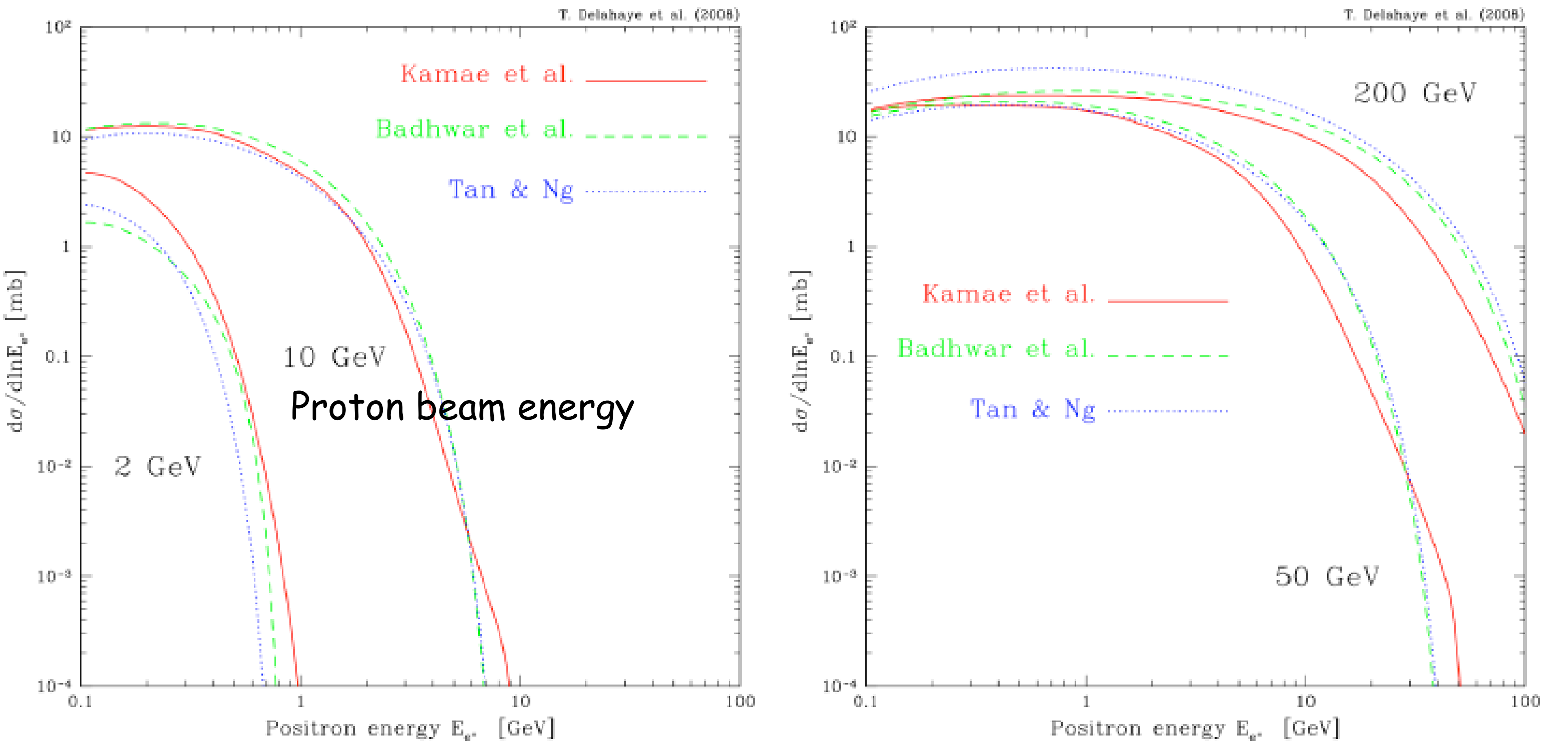
4. Primary $e^+ e^-$ from exotic sources (DARK MATTER)

Secondary positron production

Spallation of proton and helium nuclei on the ISM (H, He)

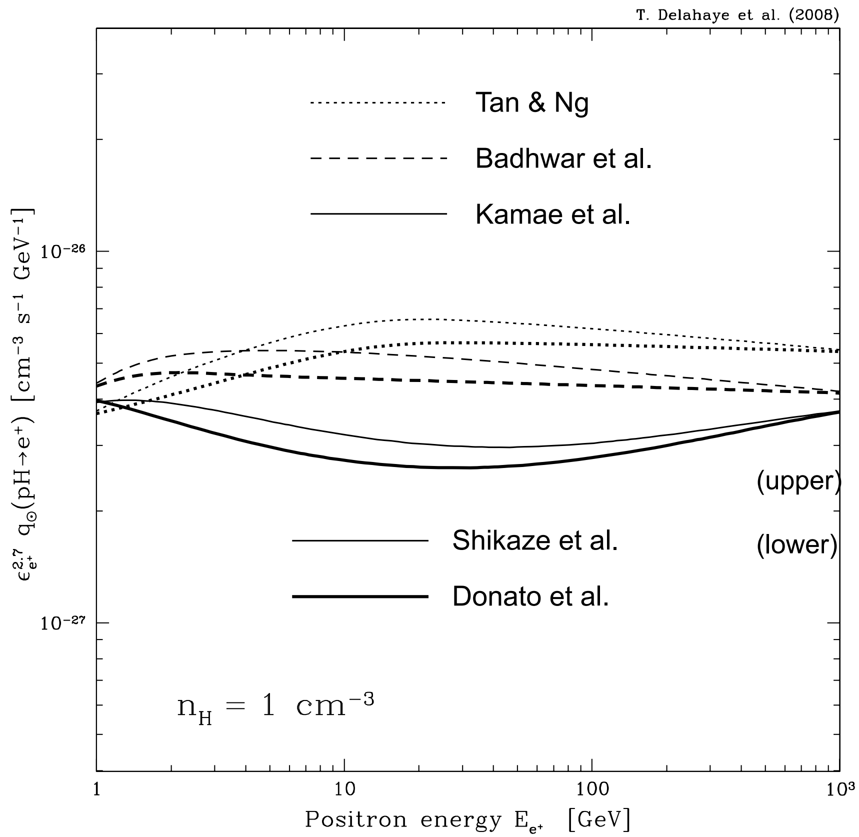
- $p+H \rightarrow p+\Delta^+ \rightarrow p+\pi^0$ & $n+\pi^+$ (mainly below 3 GeV)
- $p+H \rightarrow p+n+\pi^+$
- $p+H \rightarrow X + K^\pm$

Different parameterizations of $p+p \rightarrow e^+ + X$ cross

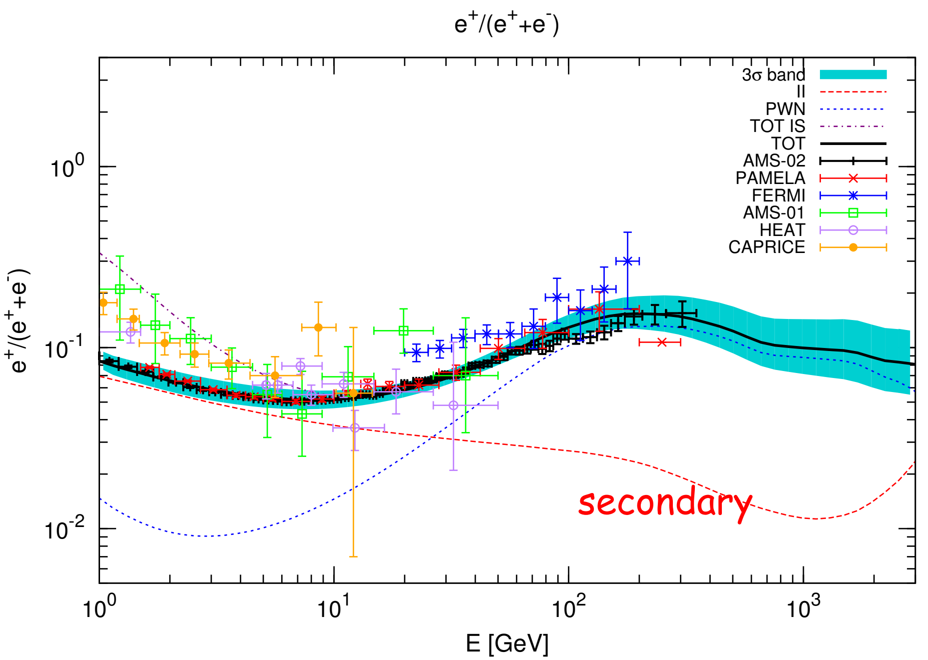


The positron source term

Uncertainties on the production cross sections up to factor 2



Secondary positrons relevant for E < 50 GeV



Data needed for $p+p$ and $p+He \to e^+ + X$

Conclusions

ANTIMATTER (antiproton, antideuterons, positrons) in cosmic rays is a clue ingredient in order search for (or set limits) to **dark matter** annihilating in the halo of the Milky Way

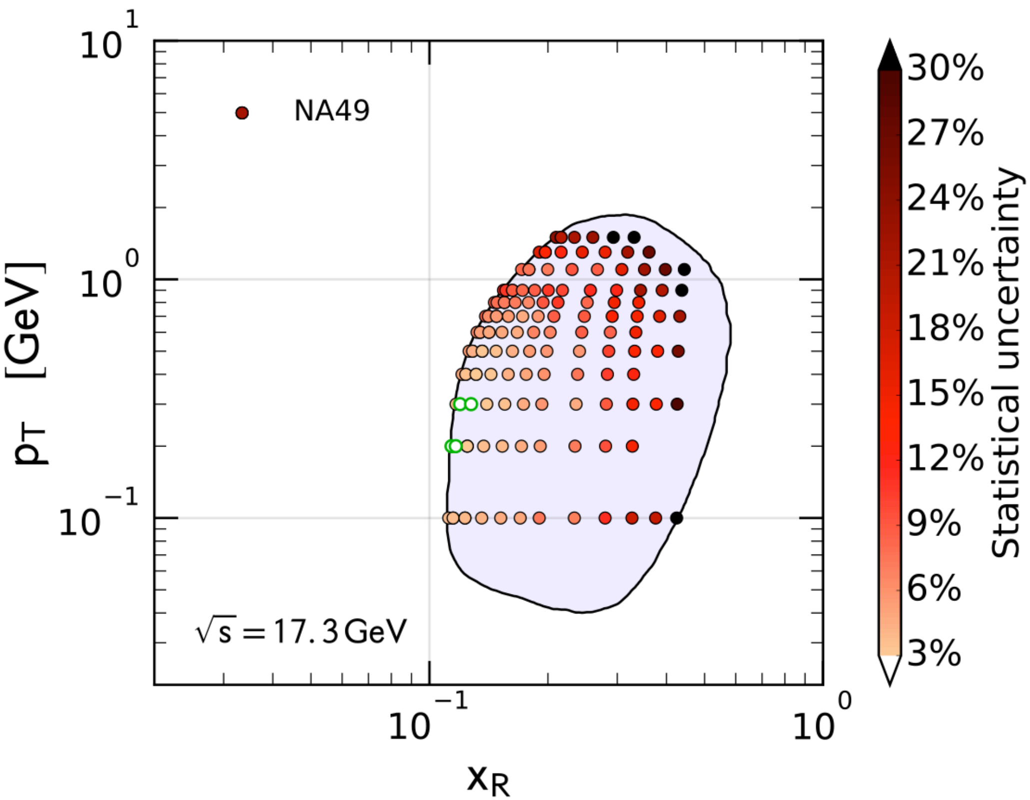
Propagation uncertainties are now confined to <10-20%, and are going to be further reduced by AMS-02 data

Cosmic **antiproton data** are expected with few% errors, while nuclear physics may bring uncertainties ~ 50%

The lack of data on several lab cross section puts **serious limits** in the interpretation of forthcoming cosmic ray data.

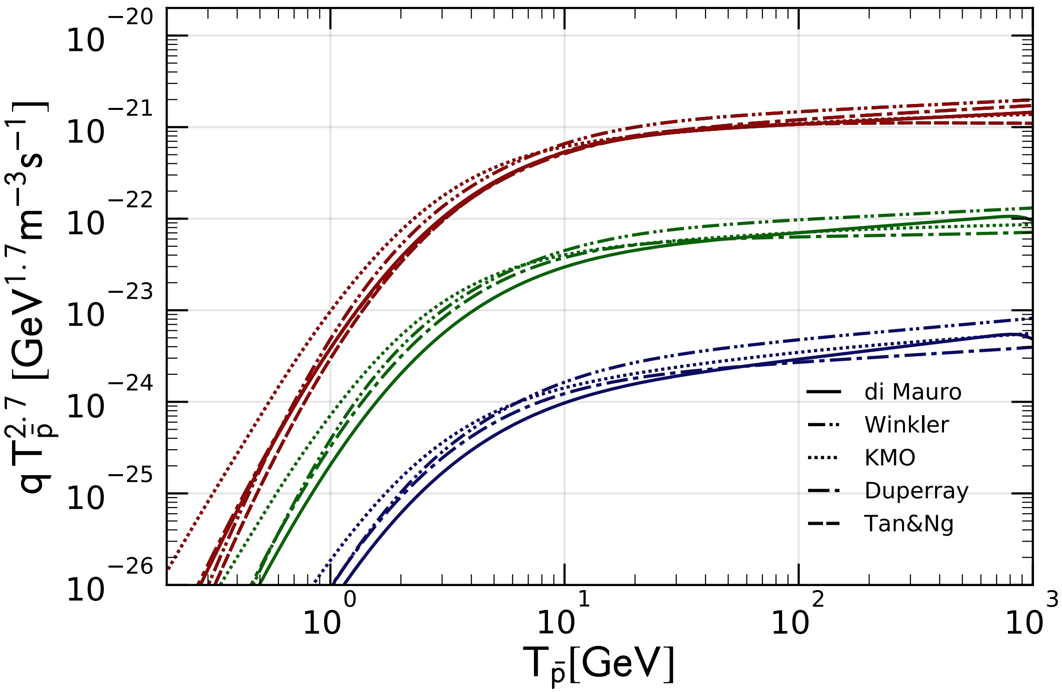
A direct measurement of **p-, γ, e^+, D^- inclusive** production cross section from p + p, and p+He → p- + X, ... is mandatory in order to interpret unambiguously future cosmic ray data.

Comparison with pp data



- The covered parameter space is appropriate
- The level of accuracy is not adequate
- NA61 data are strongly welcome

The antiproton source term



Uncertainty in

the cross sections

reflects directly

on the source term

and then in the flux

predicted at the Earth

WIMP INDIRECT SIGNALS

Annihilation inside celestial bodies (Sun, Earth):

- ν at neutrino telescopes as up-going muons

Annihilation in the galactic halo:

- γ-rays (diffuse, monochromatic line), multiwavelength
- antimatter, searched as rare components in cosmic rays (CRs)

$$e^{+},\ \bar{p},\ \bar{D}$$

ν and γ keep directionality

→ SOURCE DENSITY

Charged particles diffuse in the galactic halo

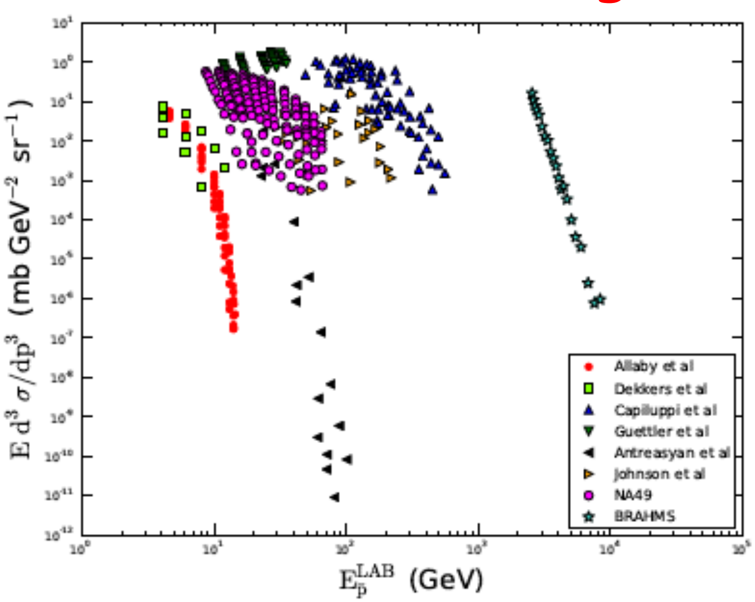
→ ASTROPHYSICS OF COSMIC RAYS!

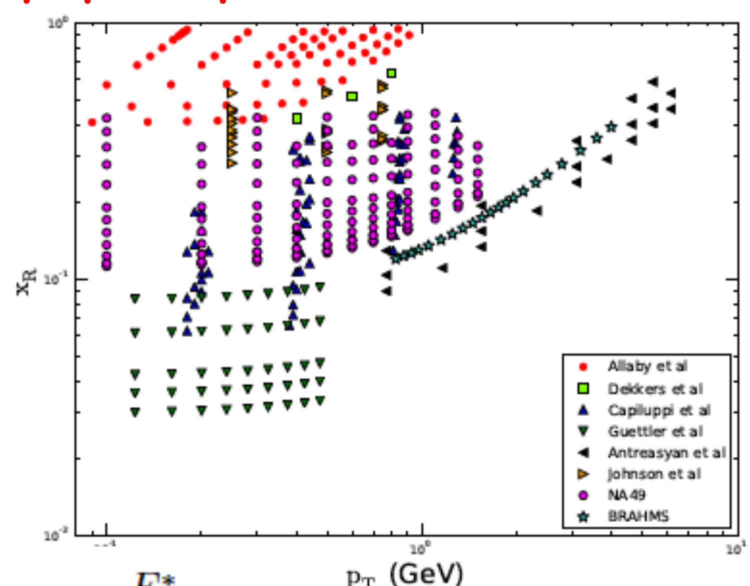
p-p→pbar cross section data

Di Mauro, FD, Goudelis, Serpico PRD 2014, 1408.0288; Kappl, Winkler 1408.0299

$$q_{\bar{p}}^{pp}(E_{\bar{p}}) = \int_{E_{\rm th}}^{+\infty} \boxed{\frac{d\sigma_{p\,p\to\bar{p}}}{dE_{\bar{p}}}(E_p, E_{\bar{p}})} n_H (4\pi\Phi_p(E_p)) dE_p$$

Existing data on p-p → pbar + X





$$x_R = \frac{E^*_{\bar{p}}}{E^*_{\bar{p},\rm max}}$$

4. Antihelium

Zero antihelia measured, Pamela upper limits.
No detection perspectives in a near future

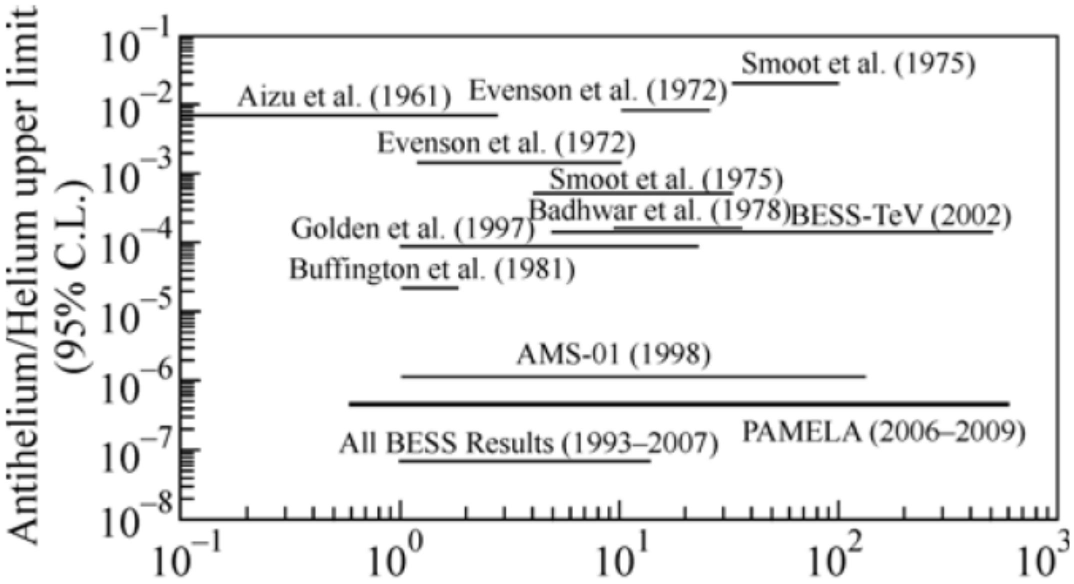


Fig. 5. Upper limit on the $\overline{\mathrm{He}}/\mathrm{He}$ ratio at a 95% confidence level in comparison with other experiments.

Pamela, JETP Lett., 2011