Antimatter Cosmic Rays and Dark Matter

IC, Hooper, Linden, Phys. Rev. D 93, 043016 (2016)
IC, Linden, Hooper, Phys. Rev. D 102, 103019 (2020)

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Ilias Cholis, 8/25/2021
**The AMS-02 experiment on ISS**

Lunched on May 2011, will collect data for 20 yrs. Measuring all CR nuclei species up to Ni.

**positron fraction, positrons, electrons spectra, antiproton/proton anti-nuclei? B/C, Be10/Be9**
eleven parameters in the fit. They, thus, include the uncertainties in the CR source spectra. For comparison we display the thermal cross section (dashed horizontal line).

The parameterization from \( \text{DM} \) corresponds to a significance of 4.5, although such an

Adding a DM component significantly improves the global fit of the CR antiproton data.

We use as benchmark antiproton production cross section the default in Fermi/WMAP...

Signals of thermal DM

The points are placed at \( \frac{\Phi^\bar{p}}{\Phi^p} \) flux ratio, AMS has simultaneously

AMS Coll. PRL.117.091103 (2016)

Could we have an additional contribution?
AMS-02 pbar/p ratio and Dark Matter (& Fermi Galactic Center excess?)

First discussions on the connection between the two indirect probes:

Bringmann et al. 2014: NO!

Cirelli et al. 2014: TOO DIFFICULT TO SAY

Hooper, Linden, Mertsch JCAP 2015: YES?

Cuoco, Kramer, Korsmeier PRL 2017:

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What about the Antiproton to Proton Ratio Uncertainties?

Antiprotons *background uncertainties are very large.*

They are associated with:

i) the antiproton production cross-section from CR protons and heavier nuclei collisions with the ISM gas

ii) the propagation of CRs through the ISM

iii) Solar Modulation (the propagation of CRs through the Heliosphere)
I) Antiproton production cross-section uncertainties

There are significant uncertainties on the antiproton production cross-section directly from p-p collisions. Most parametrizations have only used data from the 70s.

Also one has to include the production of antiprotons from collisions with heavier nuclei (mainly He), which can contribute \( \sim 40\% \) more antiprotons than the p-p collisions alone. In addition the contribution from antineutrons produced first at p-p collisions must be modeled.

**FIG. 8.** Estimate of the uncertainties in the antiproton source term from inelastic \( pp \) scattering. The blue band indicates the \( 3\sigma \) uncertainty band due to the global fit with Eq.(13), while the red band corresponds to the convolution of the uncertainties brought by fits to the data with Eq.(13), Eq.(12) and with the spline interpolation (see Fig.6.). The orange band takes into account the contribution from decays of antineutrons produced in the same reactions. Vertical bands as in Fig.6. See text for details.
II) Accounting for ISM galactic propagation uncertainties for Cosmic Rays

\[ \frac{\partial \psi(r, p, t)}{\partial t} = q(r, p, t) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi) \]

\[ + \frac{\partial}{\partial p} \left[ p^2 D_{pp} \frac{\partial}{\partial p} \left( \frac{\psi}{p^2} \right) \right] + \frac{\partial}{\partial p} \left[ \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right] \]

Voyager 1 (ISM) proton flux:

We use GALPROP a numerical solver build by Moskalenko, Strong et al. as a starting point and build several models that are in agreement with CR measurements.
B/C from PAMELA and AMS-02; Sets the time scale for CRs to diffuse away from the galactic disk. Also sets constraints on the combination of convection and re-acceleration.
III) Dealing with Solar Modulation Uncertainties


There is Charge Dependence

*Figure 7.* Three-dimensional spatial representation of the particle trajectories shown in Figure 1. Two representative particle trajectories (black and gray lines) are shown for the $A > 0$ (left panel) and $A < 0$ (right panel) HMF polarity cycles. In the $A < 0$ cycle, the pseudo-particles (galactic electrons) are transported mainly toward higher latitudes, while in the $A > 0$ cycle, the particles remain confined to low latitudes and drift outward mainly along the HCS. This illustration is consistent with the results of galactic electrons shown in the previous figure.
III) Dealing with Solar Modulation Uncertainties


Drifts Can NOT be ignored

Diffusion is not isotropic

IC, Hooper, Linden, PRD 2016

There is Charge Dependence

There is Time Dependence AND Energy Dependence

Figure 7. Three-dimensional spatial representation of the particle trajectories shown in Figure 1. Two representative particle trajectories (black and gray lines) are shown for the $A > 0$ (left panel) and $A < 0$ (right panel) HMF polarity cycles. In the $A < 0$ cycle, the pseudo-particles (galactic electrons) are transported mainly toward higher latitudes, while in the $A > 0$ cycle, the particles remain confined to low latitudes and drift outward mainly along the HCS. This illustration is consistent with the results of galactic electrons shown in the previous figure.

PAMELA, Adriani et al. 2013

CR proton flux 4-week intervals
II) & III) Cross-checking every time with all the PROTON data; monthly AND total (i.e. ISM & Solar Modulation):

Constraining the form of the Modulation potential and the ISM p spectrum in a recursive manner. IC, Linden, Hooper (arXiv:2007.00669)
Combining all uncertainties together and marginalizing over them:
We find an the excess at ~3+ sigma!
Can we fit away the excesses? NO (we find them at ~3+ sigma)

\[ \sigma v = 1.3 \times 10^{-26} \text{cm}^3\text{s}^{-1} \]

**Supernova**

\[ \chi \chi \rightarrow b \bar{b} \]

**Gamma-Ray Excess**

**Thermal**

**2\sigma Limit**

**ISM Model I**

**IC, Linden, Hooper PRD 2019**
How about heavier antimatter nuclei?

AMS, has unofficial claims of anti-He CR events (not all at the same year).

$p$ (cosmic-ray proton)

Collision

$p$ (cosmic-ray proton)

target proton (in the ISM)

$p$ $p$ $p$ $p$ $p$ $p$

coalesce (merge) for $p \leq p_0$

$\bar{d}$

cosmic-ray antideuteron
There is an unexpected amplitude on the flux of anti-He
Antideuterons Uncertainties

ISM Model I, $\delta=0.40$, $z_L=5.6$ kpc

At source $\bar{d}$ Spect. (Arb. Norm.)

$E_{\text{kin}} \times \frac{dN_{\bar{d}}}{dE_{\text{kin}}} \quad (\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1})$

0.1 0.5 1 5 10 50 100

$E_{\text{kin}}$ (GeV/n)

IC, Linden, Hooper PRD 2020
Antimatter flux Uncertainties

$E_{\text{kin}} \times dN/dE_{\text{kin}}$ (m$^{-2}$ s$^{-1}$ sr$^{-1}$)

$E_{\text{kin}}$ (GeV/n)

DM 67 GeV

Secondary ISM fluxes

IC, Linden, Hooper  PRD 2020
Diffusive re-acceleration in regions of high turbulence can reshape antimatter cosmic-ray spectra from energies where instruments can not detect them to energies where AMS02 and future GAPS can.

Diffusive re-acceleration in regions of high turbulence can reshape antimatter cosmic-ray spectra from energies where instruments can not detect them to energies where AMS02 and future GAPS can.

\[ \nu_A = 60 \text{ km/s} \]

\[ \nu_A = 20 \text{ km/s} \]

\[ \nu_A = 10 \text{ km/s} \]
Propagation conditions in the ISM do matter. Cosmic-rays can gain energy as they propagate in the ISM (diffusive reacceleration). Also we have to account for convective winds and regular diffusion.

There is complementarity between AMS-02 and GAPS. By comparing their measured antideuteron numbers of detected events we can learn about DM and ISM properties.
Combining all Searches together

$\sigma v (10^{-26} \text{ cm}^3 \text{ s}^{-1})$

$m_\chi \ (\text{GeV})$

$\chi \chi \rightarrow b \bar{b}$

1 $d$ event
1 $^3\text{He}$ event

CMB Limits
Dwarf Limits
$\bar{p}$ Limits
$\bar{p}$ Excess
GC GeV Excess

@ 6 yr of AMS

IC, Linden, Hooper PRD 2020
Thank you
Additional slides
Let the CR archival Data tell us how the CR fluxes have been modulated:

Constraining the $qA>0$ era:

Constraining the $qA<0$ era:

Assuming we know the ISM proton spectrum

IC, Hooper, Linden, PRD 2016
We find that there are two antiproton excesses at $\sim 3.7-6\sigma$ (each) of local significance.

One is a “bump” at $\sim 5-20$ GeV in the anti-proton energies and the other is above $\sim 80$ GeV and is a hardening of the CR spectrum.

From this point on I will focus on the lower energy one. I will work under the hypothesis that it is due to a DM particle of mass 50-90 GeV annihilating to $b\bar{b}$ quarks with a cross-section of $\sim 2 \times 10^{-26}$ cm$^3$/s.
Conclusions

• There is a concrete “additional” component in the AMS antiproton data BOTH at ~GeV energies AND above ~80 GeV.

• The amplitude of the lower energy “additional” component is uncertain at the 50% level.

• To study the pbar/p ratio we have taken into account all basic uncertainties (injection and propagation through the ISM, antiprotons production cross-sections).

• If a dark matter signal it is in agreement with the GeV excess at gamma-rays.

• Anti-nuclei may have been claimed by AMS. These would be very challenging to interpret given the KNOWN coalescence uncertainties.

• Anti-He3 and anti-deuterons events can be in agreement with the GeV excesses in gamma-rays and antiprotons.

• Signals of DM in the Milky Way!?