1933: Zwicky observes dark matter in Coma Cluster
Gravitational Dark Matter

1970s: Vera Rubin observes anomalous rotation velocities in M31
1933: Zwicky observers dark matter in Coma Cluster

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1996: Weak Gravitational Lensing Observed from Dark Matter Halos
1933: Zwicky observes dark matter in the Coma Cluster.

1996: Weak gravitational lensing observed from dark matter halos.

2006: Bullet Cluster observations show offset between mass and hot gas.

Gravitational Dark Matter
Gravitational Dark Matter

1970s: Vera Rubin observes anomalous rotation velocities in M31

1996: Weak Gravitational Lensing Observed from Dark Matter Halos

2006: Bullet Cluster Observations Show Offset Between Mass and Hot Gas

Table 6. Cosmological Parameter Summary

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>WMAP-only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters for Standard $\Lambda$CDM Model $^a$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age of universe</td>
<td>$t_0$</td>
<td>$13.89 \pm 0.13$ Gyr</td>
</tr>
<tr>
<td>Hubble constant</td>
<td>$H_0$</td>
<td>$71.9^{+2.6}_{-2.7}$ km/s/Mpc</td>
</tr>
<tr>
<td>Baryon density</td>
<td>$\Omega_\text{b}$</td>
<td>$0.0441 \pm 0.0030$</td>
</tr>
<tr>
<td>Physical baryon density</td>
<td>$\Omega_\text{b} h^2$</td>
<td>$0.02273 \pm 0.00062$</td>
</tr>
<tr>
<td>Dark matter density</td>
<td>$\Omega_\text{c}$</td>
<td>$0.214 \pm 0.027$</td>
</tr>
</tbody>
</table>
Gravitational Dark Matter

1996: Weak Gravitational Lensing Observed from Dark Matter Halos
2006: Bullet Cluster Observations Show Offset Between Mass and Hot Gas

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Planck</th>
<th>Planck+lensing</th>
<th>Planck+WP</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Best fit</td>
<td>68% limits</td>
<td>Best fit</td>
</tr>
<tr>
<td>$\Omega_m h^2$</td>
<td>0.12029 ± 0.00031</td>
<td>0.11805 ± 0.00031</td>
<td>0.12038 ± 0.00027</td>
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<tr>
<td>$\Omega_b h^2$</td>
<td>0.022068 ± 0.000033</td>
<td>0.022242 ± 0.000033</td>
<td>0.022032 ± 0.000028</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.0925 ± 0.0038</td>
<td>0.0949 ± 0.0038</td>
<td>0.0925 ± 0.0014</td>
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<tr>
<td>$n_s$</td>
<td>0.9624 ± 0.0094</td>
<td>0.9675 ± 0.0094</td>
<td>0.9619 ± 0.0073</td>
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<tr>
<td>$\ln(10^{10} A_s)$</td>
<td>3.098 ± 0.072</td>
<td>3.098 ± 0.057</td>
<td>3.098 ± 0.024</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Planck</th>
<th>Planck+lensing</th>
<th>Planck+WP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Best fit</td>
<td>68% limits</td>
<td>Best fit</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>0.3175 ± 0.020</td>
<td>0.3175 ± 0.019</td>
<td>0.3183 ± 0.015</td>
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<tr>
<td>$\Omega_b$</td>
<td>0.8344 ± 0.027</td>
<td>0.8344 ± 0.027</td>
<td>0.8347 ± 0.012</td>
</tr>
</tbody>
</table>

<table>
<thead>
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<th>Description</th>
</tr>
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<tbody>
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Gravitational Dark Matter

Table 1: Description

- Age of universe
- Hubble constant
- Baryon density
- Physical baryon density
- Dark matter density

Large Scale Structure
Gravitational Dark Matter

Baryonic Acoustic Oscillations

Galaxy map 3.8 billion years ago
Galaxy map 5.5 billion years ago
CMB 13.7 billion years ago
Particle Dark Matter - The Present

$10^{-25}$ GeV
$R_{DM} > R_{UFD}$

$10^{62}$ GeV
$M_{DM} > M_{UFD}$

slide concept courtesy of Asher Berlin
Can We Eliminate Classes of Dark Matter Models?

Yes!
Can We Eliminate Classes of Dark Matter Models?

Yes!

Ahlen et al. (1987; Physics Letters B 195 4)
Thermal Dark Matter

artist: Sarah Szabo
Thermal Dark Matter Density

Present density inversely proportional to the strength of the interaction.

Almost independent of particle mass.

Weak-Interaction Produces the right density!
Thermal Dark Matter Density

Present density inversely proportional to the strength of the interaction.

Almost independent of particle mass.

Weak-Interaction Produces the right density!

10 MeV - 100 TeV!
Philosophy:

Constrain the simplest model first
Gamma Rays
Gamma Rays
Cosmic Rays
Radio
Gamma Rays
Thermal WIMPs and the Story of Tantalus

NFW Profile (Mass of Milky Way)

Thermal Cross-Section (Early Universe)

Dark Matter Mass (?)

Annihilation Final State (?)

Gamma-Ray Flux within 10° of Galactic Center

DM Prediction

100 GeV NFW

Energy Flux (GeV cm⁻² s⁻¹)

Energy (GeV)

0.1  1  10  100
Thermal WIMPs and the Story of Tantalus

NFW Profile (Mass of Milky Way)
Thermal Cross-Section (Early Universe)
Dark Matter Mass (?)
Annihilation Final State (?)

Milky Way Star-Formation Rate (Galactic Dynamics)
Diffusion Constant in Galactic Center (Hydrodynamics)
Activity of Supermassive Blackhole (?)

Gamma-Ray Flux within 10° of Galactic Center

Energy Flux (GeV cm⁻² s⁻¹)

Fermi-LAT Data

DM Prediction
100 GeV NFW

Energy (GeV)
Thermal WIMPs and the Story of Tantalus

SMBH Accretion Efficiency (Magnetohydrodynamics)

Blazar Acceleration Mechanisms (Leptonic? Hadronic?)

Radio Galaxy Emission Models

Star-Formation Rates in Starburst Galaxies
Thermal WIMPs and the Story of Tantalus

SMBH Accretion Efficiency (Magnetohydrodynamics)

Blazar Acceleration Mechanisms (Leptonic? Hadronic?)

Radio Galaxy Emission Models

Star-Formation Rates in Starburst Galaxies

dSph Proximity

Substructure Models

Milky Way Merger History
Thermal WIMPs and the Story of Tantalus

Local Dark Matter Density

Thermal Cross-Section (Early Universe)

Dark Matter Mass (?)

Convection of Annihilation Products from GC (Winds?)

Antiproton Flux at Earth

Antiproton Flux (GeV m\(^{-2}\) s\(^{-1}\))

Dark Matter

100 GeV

10

100

Kinetic Energy (GeV)
Thermal WIMPs and the Story of Tantalus

- Local Dark Matter Density
- Thermal Cross-Section (Early Universe)
- Hadronic Component of Dark Matter Final State
- Convection of Annihilation Products from GC (Winds?)

![Antiproton Flux at Earth graph](https://via.placeholder.com/150)

- Local Gas Density
- Local Supernova Rate
Thermal WIMPs and the Story of Tantalus

- Local Dark Matter Density
- Thermal Cross-Section (Early Universe)
- Leptonic Component of Dark Matter Final State
- Convection of Annihilation Products from GC (Winds?)

**Positron Flux at Earth**

![Graph showing positron flux versus kinetic energy.](image)
Thermal WIMPs and the Story of Tantalus

- Local Dark Matter Density
- Thermal Cross-Section (Early Universe)
- Leptonic Component of Dark Matter Final State
- Convection of Annihilation Products from GC (Winds?)

Pulsar Birth Rate

$e^+e^-$ Acceleration Efficiency in Pulsar Magnetospheres

Positron Flux at Earth

- AMS-02 Data

- Dark Matter (100 GeV; $b\bar{b}$)

Positron Flux (GeV m$^{-2}$s$^{-1}$)

Kinetic Energy (GeV)
Anything You Can Do, I Can Do (Slightly) Better

Small Dark Matter Signal
Small Astrophysical Background

Large Dark Matter Signal
Small Astrophysical Background

Small Dark Matter Signal
Large Astrophysical Background

Large Dark Matter Signal
Large Astrophysical Background
Anything You Can Do, I Can Do (Slightly) Better

Anti-Nuclei

Gamma-Rays / Positrons

Antiprotons

Specificity (DM Flux / Astrophysics Flux)

Fraction of Dark Matter Flux
Thermal WIMPs and the Story of Tantalus
Thermal WIMPs and the Story of Tantalus
The Antiproton Excess
The Antiproton Excess

Investigate the Antiproton Fraction!

\[ \frac{\phi\bar{p}}{\phi p} \]

Two Changes:

Ratio is much smaller (don't need to add antiprotons into denominator).

Hadronic Energy losses are slower (sensitive to antiproton production throughout the Galaxy).
The Antiproton Excess

Astrophysics - Smooth Profile

Dark Matter - Sharp Bump!
The Antiproton Excess

(Not an exhaustive list of observations)
The Antiproton Excess

(Not an exhaustive list of observations)
The Antiproton Excess

(Not an exhaustive list of observations)
The Antiproton Excess

(Not an exhaustive list of observations)
The Antiproton Excess

(Not an exhaustive list of observations)

**Antiproton Ratio**

**74 GeV**
Arbitrary Normalization

**Kinetic Energy (GeV)**

- **b\bar{b}**

**Astrophysical Model**
- CAPRICE (1994)
- IMAX (1996)
- CAPRICE (1998)
- BESS (1999)
- BESS (2000)
The Antiproton Excess

(Not an exhaustive list of observations)
The Antiproton Excess

(Not an exhaustive list of observations)
The Antiproton Excess

(Not an exhaustive list of observations)
The Antiproton Excess

(Not an exhaustive list of observations)
The Antiproton Excess

(Not an exhaustive list of observations)

Astrophysical Model
CAPRICE (1994)
IMAX (1996)
CAPRICE (1998)
BESS (1999)
BESS (2000)
HEAT (2000)
BESS (2004)
PAMELA (2010)
AMS-02 (2015)
The Antiproton Excess

(Not an exhaustive list of observations)
The Antiproton Excess

Hint of Excess in ~5 GeV antiprotons!

Astrophysical Uncertainties can significantly affect the signal.

Hooper, TL, Mertsch (2014; 1410.1527)
Two papers simultaneously find an excess in the AMS-02 Antiproton Data!

Significance approaching (or past) 5σ!
The Antiproton Excess

With great precision comes great responsibility:

- Antiproton Production Cross-Section
- Galactic Primary to Secondary Ratios
- Inhomogeneous Diffusion
- Solar Modulation
- Instrumental Uncertainties

AMS $\bar{p}/p$ results

AMS-02 (2016; 117 091103)
The Antiproton Excess

With great precision comes great responsibility:

Antiproton Production Cross-Section
Galactic Primary to Secondary Ratios
Inhomogeneous Diffusion
Solar Modulation
Instrumental Uncertainties
The Antiproton Excess

With great precision comes great responsibility:

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See e.g., Weinrich et al. (2002; 2002.11406)
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The Antiproton Excess

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HELMOD Collaboration (2011, 1110.4315)
The Antiproton Excess

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Galactic Primary to Secondary Ratios

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Instrumental Uncertainties
The Antiproton Excess

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**Antiproton Production Cross-Section**

**Galactic Primary to Secondary Ratios**

**Inhomogeneous Diffusion**

**Solar Modulation**

**Instrumental Uncertainties**

AMS-02 (PRL 117 2016)
The Antiproton Excess

With great precision comes great responsibility:

Antiproton Production Cross-Section

Galactic Primary to Secondary Ratios

Inhomogeneous Diffusion

Solar Modulation

Instrumental Uncertainties

Cuoco et al. (2019; 1903.01472)

Boudaud et al. (2019; 1906.07119)

Heisig et al. (2020; 2005.04237)
Antinuclei !?
Antinuclei carry away a significant fraction of the total momentum in a particle collision.

**Astrophysical Antinuclei** - Most be moving relativistically!

**Dark Matter Antinuclei** - Can be slow!
To date, we have observed eight events in the mass region from 0 to 10 GeV with $Z = -2$. All eight events are in the helium mass region.

Currently (having used 50 million core hours to generate 7 times more simulated events than measured events and having found no background events from the simulation), our best evaluation of the probability of the background origin for the eight $^4\text{He}$ events is less than $3 \times 10^{-8}$. For the two $^4\text{He}$ events our best evaluation of the probability (upon completion of the current 100 million core hours of simulation) will be less than $3 \times 10^{-3}$.

Note that for $^4\text{He}$, projecting based on the statistics we have today, by using an additional 400 million core hours for simulation the background probability would be $10^{-4}$. Simultaneously, continuing to run until 2023, which doubles the data sample, the background probability for $^4\text{He}$ would be $2 \times 10^{-7}$, i.e., greater than 5-sigma significance.
AntiNuclei - A Clean Search Strategy?

Antihelium background even cleaner than antideuterons

But the flux is supposed to be much smaller.
AntNuclei - A Clean Search Strategy?

Antihelium background even cleaner than antideuterons

But the flux is supposed to be much smaller.
Astrophysical Enhancements!

The current event rates depend on the detector sensitivity to anti-Helium.

We lose many events because most anti-He are produced at energies that are too small to be detected.

Use re-acceleration to boost the anti-He energies into the detectable range!

Cholis, Linden, Hooper (2020; 2001.08749)
$m_\chi = 67$ GeV $b\bar{b}$

$\sigma v = 2 \times 10^{-26}$ cm$^3$s$^{-1}$

$\#$ of AMS-02 $N$ events (6 years)

$v_A$ (km/s)
Dark Matter Annihilation Can Produce a Detectable Antihelium Flux through $\tilde{\Lambda}_b$ Decays

Martin Wolfgang Winkler$^1$, * and Tim Linden$^1$, †

$^1$Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden

Recent observations by the Alpha Magnetic Spectrometer (AMS-02) have tentatively detected a handful of cosmic-ray antihelium events. Such events have long been considered as smoking-gun evidence for new physics, because astrophysical antihelium production is expected to be negligible. However, the dark-matter-induced antihelium flux is also expected to fall below current sensitivities, particularly in light of existing antiproton constraints. Here, we demonstrate that a previously neglected standard model process — the production of antihelium through the displaced-vertex decay of $\tilde{\Lambda}_b$-baryons — can significantly boost the dark matter induced antihelium flux. This process can triple the standard prompt-production of antihelium, and more importantly, entirely dominate the production of the high-energy antihelium nuclei reported by AMS-02.

I. INTRODUCTION

The detection of massive cosmic-ray antinuclei has long been considered a holy grail in searches for WIMP dark matter [1, 2]. Primary cosmic-rays from astrophysical sources are matter-dominated, accelerated by nearby supernova, pulsars, and other extreme objects. The secondary cosmic-rays produced by the hadronic interactions of primary cosmic-rays can include an antinuclei component, but the flux is highly suppressed by baryon number conservation and kinematic constraints [3, 4]. Dark matter annihilation, on the other hand, occurs within the rest frame of the Milky Way and produces equal baryon and antibaryon fluxes [1, 5–7].

The previous attempt for an antinuclei detection has largely obscured the antihelium signal due to the overwhelming antiproton background [8]. In this letter, we challenge the current understanding that standard dark matter annihilation models cannot produce a measurable antihelium flux. Our analysis examines a known, and potentially dominant, antinuclei production mode which has been neglected by previous literature — the production of antihelium through the off-vertex decays of the $\tilde{\Lambda}_b$. Such bottom baryons are generically produced in dark matter annihilation channels involving $b$ quarks. Their decays efficiently produce heavy antinuclei due to their antibaryon number and 5.6 GeV rest-mass, which effectively decays to multi-nucleon states with small relative momenta. Intriguingly, because any $^3$He produced by $\tilde{\Lambda}_b$ inherits its boost factor, these nuclei can obtain the large center-of-mass momenta necessary to fit AMS-02 data [13].
Particle Physics Enhancements!

Previous analyses have missed the (potentially) dominant contribution to anti-Helium production.

The displaced-vertex decays of Lambda\(_b\) baryons potentially boosts the detectable AMS-02 signal by orders of magnitude!

Winkler & Linden (2020; 2020.16251)
Particle Physics Enhancements!

$\chi \chi \rightarrow \bar{b}b \quad m_\chi = 67 \text{ GeV}$

$1 \text{ event} / (10 \text{ GeV/n})$

<table>
<thead>
<tr>
<th>Generator</th>
<th>P</th>
<th>$P [\Lambda_b\text{-tune}]$</th>
<th>H</th>
<th>H+EvtGen</th>
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<tbody>
<tr>
<td>$^3\text{He events}$</td>
<td>0.1 (0.007)</td>
<td>0.9</td>
<td>0.003</td>
<td>0.3</td>
</tr>
<tr>
<td>d events</td>
<td>3.7 (3.5)</td>
<td>4.2</td>
<td>1.7</td>
<td>2.1</td>
</tr>
</tbody>
</table>
WHERE ARE WE NOW?
$\rho_\odot = 0.4 \text{ GeV cm}^{-3}$

- CMB (Planck)
- Dwarfs (Fermi)
- Galactic Center (Fermi)
- Thermal Cross-Section
- Antiproton (AMS)

$\langle \sigma v \rangle$ (cm$^3$s$^{-1}$, x 10$^{-26}$)

Dark Matter Mass (GeV)
\( \rho_\odot = 0.4 \text{ GeV cm}^{-3} \)

CMB (Planck)

Dwarfs (Fermi)

Galactic Center (Fermi)

Thermal Cross-Section

Antiproton (AMS)
$\rho_\odot = 0.5 \text{ GeV cm}^{-3}$

Silverwood et al. (2015; 150708581)

Dwarfs (Fermi)

Galactic Center (Fermi)

Thermal Cross-Section

Antiproton (AMS)
$\rho_\odot = 0.4$ GeV cm$^{-3}$

CMB (Planck)

Dwarfs (Fermi)

Galactic Center (Fermi)

Antiproton (AMS)

$\langle \sigma v \rangle$ (cm$^3$/s$^{-1}$, $\times 10^{-26}$)

Dark Matter Mass (GeV)
Galli et al. (2009; 0905.0003)
see also: astro-ph/0210617, 0810.5952)

\langle \sigma v \rangle (\text{cm}^3 \text{s}^{-1})

\begin{align*}
\text{b\bar{b} (WMAP5)} \\
\text{e^+ e^- (WMAP5)}
\end{align*}

Thermal Cross-Section

\text{Dark Matter Mass (GeV)}

Galli et al. (2009; 0905.0003)
see also: astro-ph/0210617, 0810.5952)