Cosmic-ray Antinuclei: New Inputs on Dark Matter

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A Worldwide Hunt for Dark Matter

Focus on novel signatures of astrophysical dark matter processes…

Direct Detection

Particle Colliders

The Large Hadron Collider

Indirect Detection

Beyond the Standard Model (BSM) Physics

Standard Model

Dark Matter

K. Perez - MIT
The challenge of astrophysical searches...

Common challenge = minimize/constrain astrophysical background, maximize predicted dark matter signal

- $\sigma v$, dark matter profile/density, boost factors, galactic/solar propagation...
- Background (choice of target, signature)
- Dark Matter annihilation

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The challenge of astrophysical searches...

γ-rays, X-rays...

Flux: \( \Phi_i \propto \frac{dN_i}{dE} \langle \sigma_X \bar{X} \nu \rangle \frac{1}{m_X} J(\Delta\Omega)\Delta\Omega \)

Annihilation: \( J(\Delta\Omega) \propto \langle \int_{l.o.s.} dl \ \rho_X^2 \rangle \Omega \)

Choose high J-factor (GC, dwarf galaxies), low or well-constrained predicted astrophysical background

Charged (anti)particles

Choose low or well-constrained predicted background signature, need precise modelling of cosmic-ray propagation.

There have been tantalizing possible detections!
But vulnerable to poorly-constrained astrophysical backgrounds
Current status: The “GeV excess”

- An excess of gamma-rays at the Galactic Center, with spectrum, morphology, intensity consistent with annihilating dark matter
  

- Non-detection limits from dwarf galaxies weakened by Galactic and dwarf halo profiles, astrophysical background models – compatible with dark matter interpretation of Galactic Center excess
  
  e.g. Agrawal+ 1411.2592, Karwin+ 1612.05687, Hayashi+ 1603.08046, Klop+ 1609.03509, Abazajian+ 1510.06424, Benito+ 1612.02010

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Current status: The “GeV excess”

- Spectrum also consistent with millisecond pulsars
- Evidence for sub-threshold point-source contribution
- Could indicates a population of MSPs with a luminosity function and low-mass X-ray binary progenitor population quite different from those in the Milky Way disk or globular clusters

Interpretation depends on poorly-understood Galactic source (MSP) population

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Current status: The “positron excess”

- Rising positron fraction observed since PAMELA 2008, confirmed to higher energies by AMS-02
- Implies heavy TeV-scale dark matter. Need enhanced annihilation cross section and leptophilic annihilation (to avoid antiproton bounds).
- Or local pulsars...

See also: DAMPE e⁺e⁻, Ambrosi+ 1711.10981 Nature (2017)
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↓ HAWC – if Galactic diffusion similar to diffusion in regions of nearby pulsars, excess cannot be due to Geminga and PSR B0656+14

↩ Likely implies that diffusion not uniform throughout local interstellar medium.

Interpretation depends on poorly-understood Galactic propagation (diffusion)
Current status: an antiproton excess?

A. Cuoco+ (2016), M-Y. Cui+ (2016)

~10 GeV dark matter, consistent with GeV excess?
TeV-scale Wino dark matter?
Current status: an antiproton excess?

- Interpretation depends on poorly-understood Galactic and Solar propagation
- Can instead be used to constrain propagation models: favors MED-MAX scenario

\[ \sim 10 \text{ GeV dark matter, consistent with GeV excess?} \]

TeV-scale Wino dark matter? 

K. Perez - MIT
1. Cosmic rays are full of surprises!
2. Surprises are difficult to interpret due to uncertain astrophysical backgrounds
3. Need cross-correlation with different signatures

If interpreted conservatively, much parameter space remains for standard thermal WIMP dark matter

See parallel talk, R. Leane
New physics in cosmic-ray antideuterons

A generic new physics signature with essentially zero conventional astrophysical background

- Probes a variety of dark matter models that evade or complement collider, direct, or other cosmic-ray searches
- GAPS first experiment optimized specifically for low-energy antinuclei signatures
- First GAPS Antarctic flight: late 2020

T. Aramaki et al., Astropart. Phys. 74, 6 (2016)
Complementary sensitivity to viable DM signatures

- Sensitive to ~10s of GeV mass DM models, *as invoked to explain gamma-ray and antiproton observations*

See also: Korsmeier, Donato, Fornengo 1711.08465 (2018), Aramaki+ 1505.07785 (2016)

- Sensitive to heavy DM models, *as invoked to explain positron observations*
The Experiments: AMS and GAPS

- AMS has been in operation on the ISS since May 2011
- Uses magnetic spectrometry for anti-p, anti-D, anti-He detection

- GAPS scheduled for initial Antarctic balloon flight late 2020
- Uses exotic atom capture and decay to identify antinuclei

Rare event search and first-time measurement!
Need multiple experiments with complementary systematics
The Experiments: AMS and GAPS

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Ting, CERN May 2018: https://indico.cern.ch/event/729900/

Anti-deuterons have never been observed in space

First anti-Helium event in the cosmos:

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The GAPS Team
GAPS detection: exotic atom capture and decay

- **Time-of-flight** system measures velocity
- Loses energy in layers of semiconducting Silicon targets/detectors
- Stops, forming *exotic excited atom*

Aramaki et al., http://arxiv.org/abs/1303.3871
Aramaki et al., Astropart. Phys. 74, 6 (2016)
**GAPS detection**: exotic atom capture and decay

- **Time-of-flight** system measures velocity
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- Stops, forming **exotic excited atom**
- Atom de-excites, emitting **X-rays**
- Remaining nucleus annihilates, emitting **pions and protons**

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GAPS Background Rejection

Combination of time-of-flight + depth-sensing, X-ray, and π detection yield necessary rejection of $>10^6$

T. Aramaki et al., Astropart. Phys. 74, 6 (2016)

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Precision antiproton spectrum

- GAPS will measure >1000 antiprotons per flight, in *unprecedented low energy range*

- Reduces systematic and theoretical uncertainties for antideuteron search

Sensitive to light DM
GAPS also sensitive to anti-He, in complementary energy range to where AMS has reported candidate events. Ongoing work to estimate and optimize sensitivity.

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GAPS Detector Design

**Plastic scintillator TOF**
- high-speed trigger and veto
- 160-180 cm long, 0.5 cm thick
- read out both ends
- ~500 ps timing resolution

**Si(Li) targets/detectors**
- X-ray identification, dE/dx, stopping depth, and shower particle multiplicity
- 2.5 mm thick, 4” diameter
- 4 keV resolution for X-rays
Prototype flight (pGAPS)

100% of flight goals met!
✓ verify stable, low-noise Si(Li) operation at ambient flight pressure
✓ validate the cooling system and thermal model
✓ measure the background levels to validate simulation codes

6 TOF planes + 6 Si(Li) detectors

Mognet et al., Nucl. Instrum. Meth. A735 (2014) 24
von Doetinchem et al., Astropart. Phys. 54 (2014) 93
Development and construction: Si(Li) detectors

GAPS will need ~1000 Si(Li) detectors!

- Low-cost fabrication scheme developed in partnership with Shimadzu Corp.
- Demonstrates required ~4 keV energy resolution at relatively high temp of -35 to -45 C
- Readout via custom ASIC

4”-diameter, 2.5 mm-thick

Development and construction: TOF and cooling

TOF will use 225 scintillation counters, read out on both ends

- evaluating PMT vs SiPM
- custom DRS-4 ASIC @ 2GSp
- optimizing trigger algorithm

Oscillating heat pipe (OHP) validated on pGAPS, developed for GAPS

- small capillary tubes filled with a phase-changing refrigeration liquid
- rapid expansion and contraction of bubbles in liquid create thermo-contraction hydrodynamic waves that transport heat

Exciting coming decade of anti-nuclei searches!

- Indirect astrophysical dark matter searches continue to uncover surprises
- The GAPS design, dedicated to anti-nuclei signatures, is timely, following candidate events from AMS-02
- Low-energy antideuterons offer a new window on dark matter parameter space, providing complementary coverage with direct detection, collider, and other indirect searches
- First GAPS flight will improve current antideuteron limit by ~1.5 orders of magnitude, deliver first precision antiproton flux below 0.25 GeV/n, and provide sensitivity to anti-He with orthogonal detection technique to AMS

- **First GAPS flight in late 2020**
- Subsequent Antarctic flights planned to optimize sensitivity
Backup
A Worldwide Hunt for Dark Matter

Focus on novel signatures of astrophysical dark matter processes…

Charged cosmic-rays

Beyond the Standard Model (BSM) Physics

Photons
Antideuteron Signal of Dark Matter

Dark matter particles annihilate...

...create jets of Standard Model particles...

...some of which can make an antideuteron...
Indirect searches: The “GeV excess”

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Indirect searches: The “GeV excess”

Interpretation depends on poorly-understood Galactic source (MSP) population

- Spectrum also consistent with millisecond pulsars
- Evidence for sub-threshold point-source contribution
- Indicates a population of MSPs would have a luminosity function and low-mass X-ray binary progenitor population quite different from those in the Milky Way disk or globular clusters

Evidence for unresolved point sources
Lee, Lisanti, Safdi, Slatyer, Xue, 1506.05124
Bartels, Krishnamurthy, Weniger, 1506.05104

Comparison with LMXB distribution
Haggard, Heinke, DH, Linden, JCAP, 1701.02726

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Indirect searches: The “positron excess”

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- Implies heavy TeV-scale dark matter. Need enhanced annihilation cross section and leptophilic annihilation (to avoid antiproton bounds).
- …or could be pulsars:

![Graph showing positron distribution](image1)

**Positrons**
AMS (2018)

![Graph showing electron and positron distribution](image2)

**Electrons + positrons**
Indirect searches: The “positron excess”

Interpretation depends on poorly-understood Galactic propagation (diffusion)

↑ HAWC – if Galactic diffusion similar to diffusion in regions of nearby pulsars, excess cannot be due to pulsars

⇐ Likley implies that diffusion not uniform throughout local interstellar medium
Secondary-to-primary ratio 68% and 95% posterior bands from light element (Be–Si) scan (left) The pbar/p ratio (right) indicates that using the same propagation parameters for hydrogen yields a very bad fit to the data.
FIG. 2. Antideuteron flux for secondaries in the ISM and the potential DM signal, corresponding to generic $b\bar{b}$ annihilation from the excess in CuKrKo. We show the different propagation models MED and MAX, which are constrained to fit B/C data in Ref. [41]. CuKrKo corresponds to the propagation parameters obtained from the best fit of $b\bar{b}$ DM in [14]. All fluxes are derived in the analytic coalescence model with $p_C = 160$ GeV (left panel) and $p_C = 248$ GeV (right panel). Solar modulation is treated in the force-field approximation with a potential of $\phi = 400$ MV. Additionally, the current limit by the BESS experiment (95% CL) [55], the AMS-02 sensitivity of [21], and the expected sensitivity for GAPS (99% CL) [20] are displayed.
pGAPS Detector Results

Si(Li) resolution consistent with temperature-dependent predictions
Si(Li) Detector Performance

2”-diameter, 1 mm thick prototype detectors have been produced with the required performance!

Resolution measured with an Am-241 X-ray source

Operational temperature range for 1 mm thick prototype detector