Indirect Searches for Dark Matter

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Identification of Dark Matter Workshop, L'Aquila, Italy

July 11, 2024

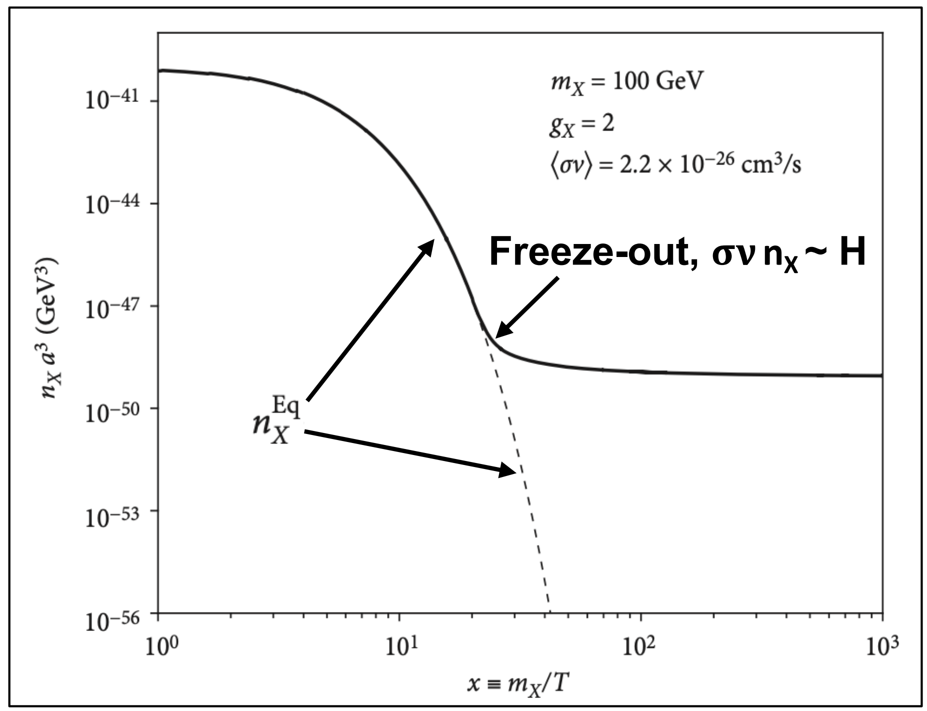
The Motivation for Indirect Searches

- Consider a stable particle species that was in equilibrium with the thermal bath in the early universe; the abundance of these particles will evolve according to the following Boltzmann equation:

$$\frac{dn_X}{dt} = -3Hn_X - \langle \sigma v \rangle \left[n_X^2 - (n_X^{\rm Eq})^2 \right]$$

- The number density of these particles will be held near their equilibrium value until their production/annihilation rate falls below the rate of Hubble expansion – *thermal freeze out*
- After a particle species has frozen-out, it is no longer created or destroyed in significant numbers
- The resulting abundance of such a relic is set by the temperature at which it froze out of equilibrium, which is directly related to its annihilation cross section:

$$\boldsymbol{\Omega}_X \sim 0.27 \times \left(\frac{2.2 \times 10^{-26}\,{\rm cm}^3/{\rm s}}{\langle \sigma v \rangle} \right)$$



The Motivation for Indirect Searches

If we make the following two quite reasonable assumptions:

1) The dark matter was in equilibrium at some point in the early universe
2) The early universe was radiation dominated

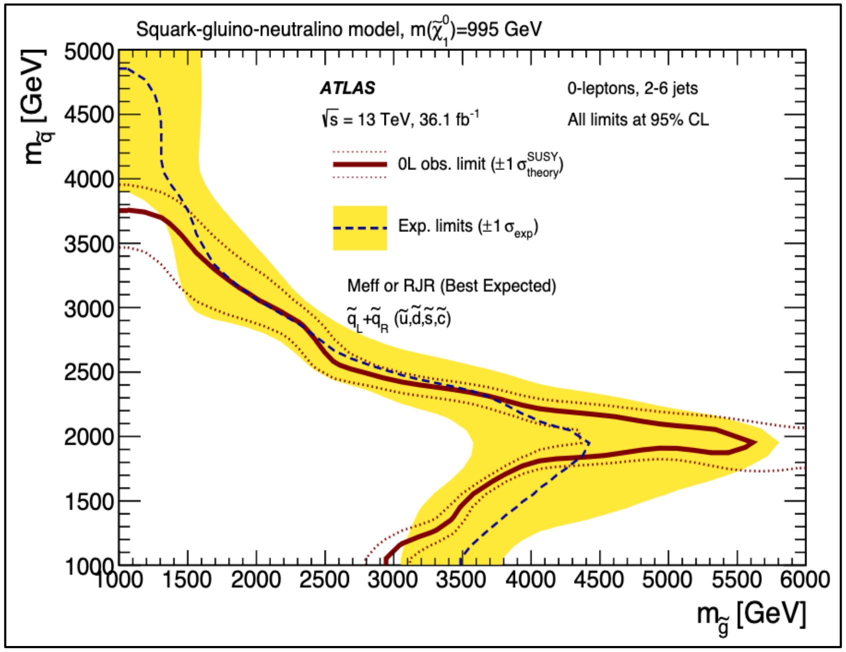
Then we can conclude that the dark matter must be:

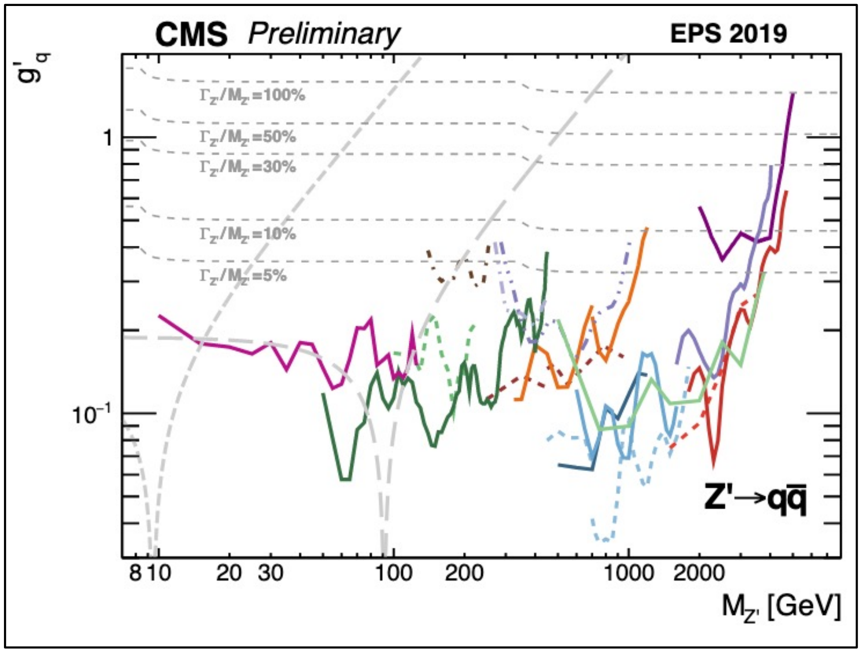
1) Heavier than ~1 MeV (to avoid ruining BBN)
2) Lighter than ~100 TeV (to avoid overproduction)

- To freeze-out with the measured dark matter abundance, such a particle must annihilate through an interaction comparable in strength to the weak force – this is sometimes referred to as the *"WIMP Miracle"*
- From this perspective, dark matter candidates with roughly weak-scale masses and interactions – "WIMPs" – are particularly well motivated

The Impact of the LHC on WIMPs

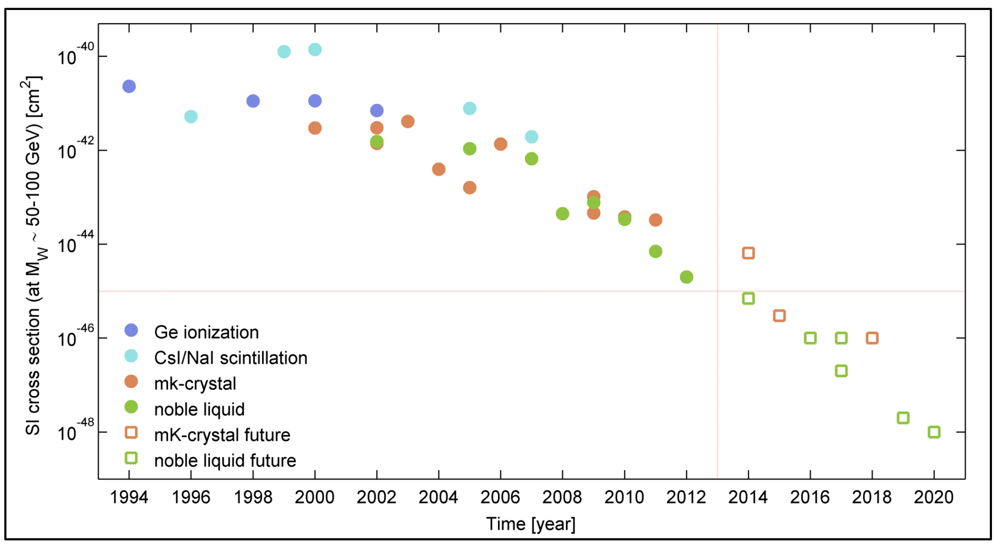
- The LHC has performed beautifully, and yet no compelling signs of dark matter (or any other BSM physics) have been discovered
- This machine has led to very strong constraints on certain classes of new physics, such as particles that can be produced with large cross sections (squarks, gluinos, etc.), and particles which lead to particularly distinctive signatures (such as dijet or dilepton resonances from a Z')
- In contrast, the constraints on WIMPs from the LHC remain quite weak

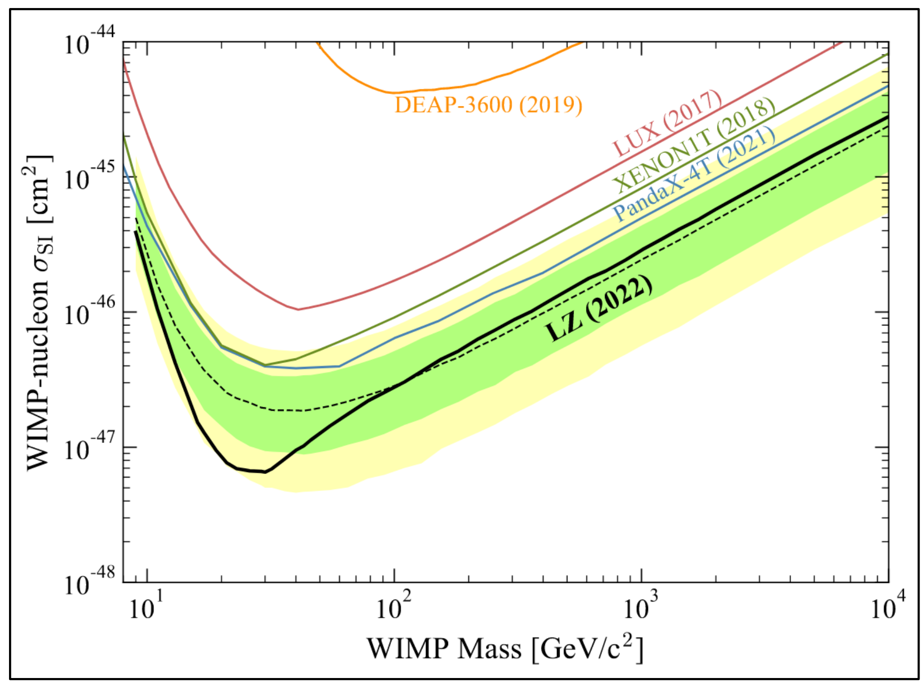




The Impact of Direct Searches on WIMPs

- The null results of underground experiments searching for evidence of dark matter scattering with nuclei have very meaningfully impacted our understanding of dark matter; much more so than the LHC, in my opinion
- Over the past two decades, direct detection experiments have performed better than we had any right to expect, improving in sensitivity at a rate faster than Moore's Law – and yet no WIMPs have appeared
- It is fair to say that most – although certainly not all – simple WIMP models predict scattering rates with nuclei that exceed current bounds





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No, not at all.

Despite the very stringent constraints that have been placed on the nature of dark matter, there remain many viable options for WIMP model building

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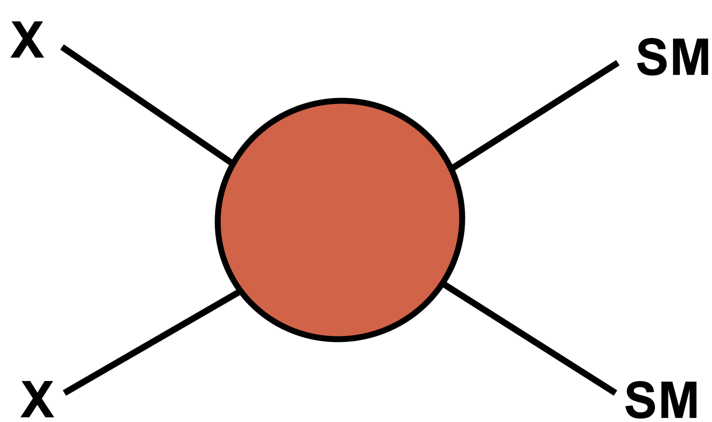
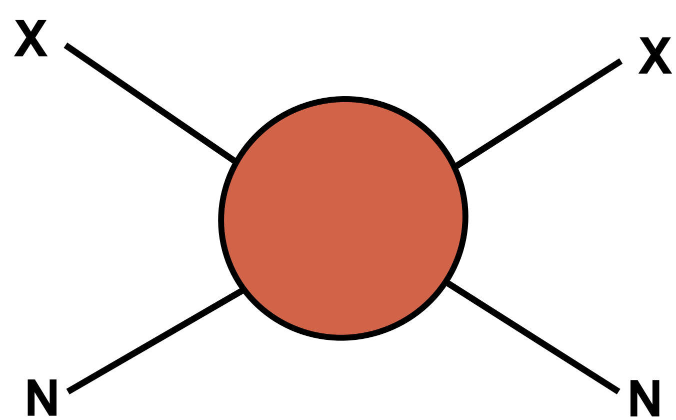
Unsuppressed



Suppressed



An (Incomplete) List of Ways to Reconcile WIMP Dark Matter With All Current Constraints:

1) Co-annihilations between the dark matter and another state

2) Annihilations to W, Z and/or Higgs bosons; scattering with nuclei only through highly suppressed loop diagrams

3) Interaction which suppress elastic scattering with nuclei by powers of velocity or momentum

4) Dark matter that is lighter than a few GeV (relaxing direct constraints)

5) Departures from radiation domination in the early universe (early matter domination; late-time reheating, etc.) which result in the depletion of the dark matter's relic abundance

6) The dark matter annihilates to unstable non-Standard Model states (*ie*. hidden sector models)

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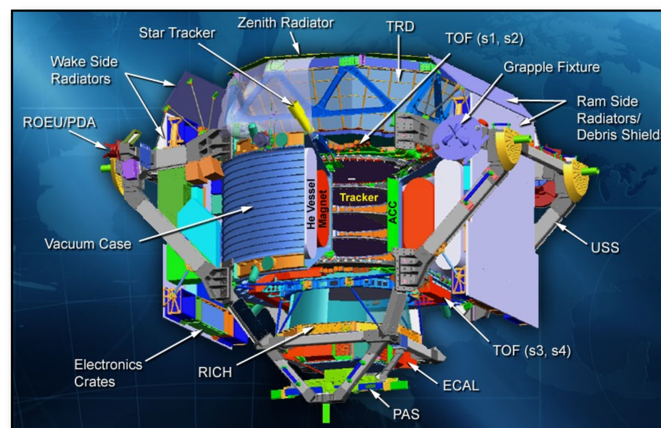
Although these scenarios can be invisible to both underground detectors and colliders, many are testable with indirect searches

The Motivation for Indirect Searches

- To account for the observed dark matter abundance, a thermal relic must have an annihilation cross section (at freeze-out) of $\sigma v \sim 2\text{x}10^{-26}\,\text{cm}^3/\text{s}$
- Although many model-dependent factors can cause the dark matter to possess a somewhat lower or higher annihilation cross section today, most models predict current annihilation rates that are within an order of magnitude or so of this estimate
- Indirect detection experiments that are sensitive to dark matter annihilating at approximately this rate will be able to test a significant fraction of WIMP models

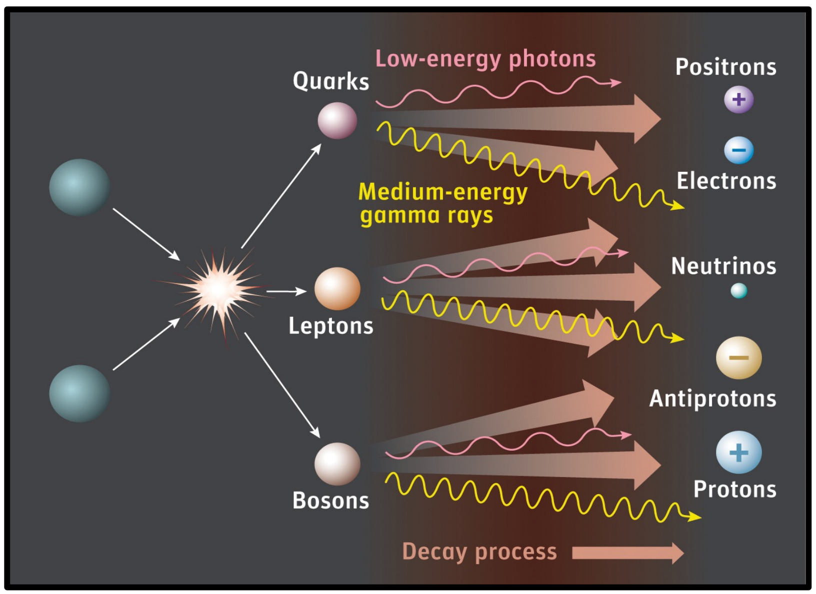
Fermi

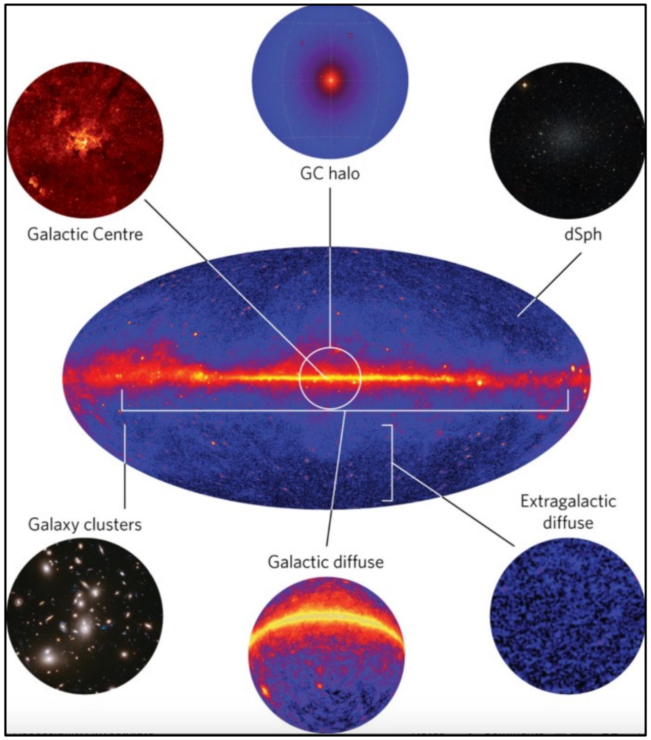
AMS-02



The Many Paths Toward Indirect Detection

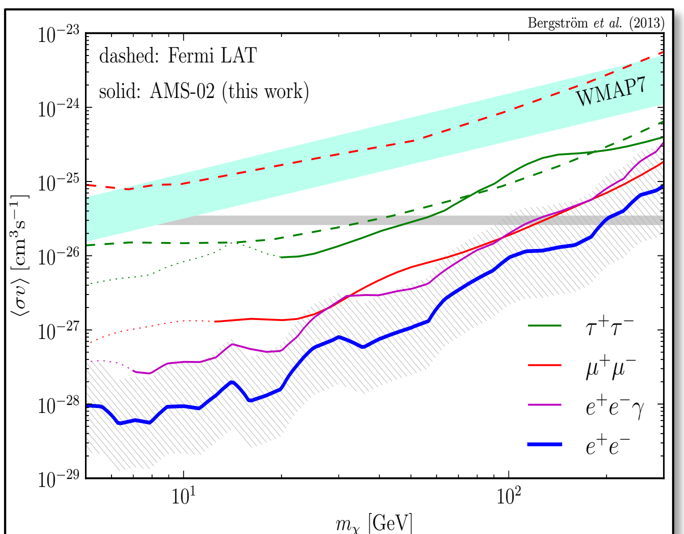
- Dark matter could produce a variety of different potentially observable annihilation/decay products, each of which feature various advantages and disadvantages; there is a great deal of complementary between these different indirect detection signals
- Searches with gamma rays and neutrinos employ many different search strategies, targeting different parts of the sky; again, bringing a great deal of complementary to the problem



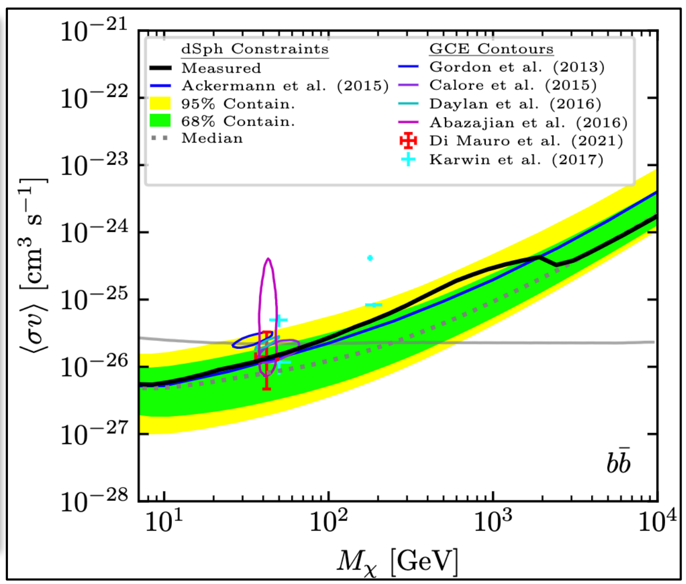


Constraints from Indirect Detection

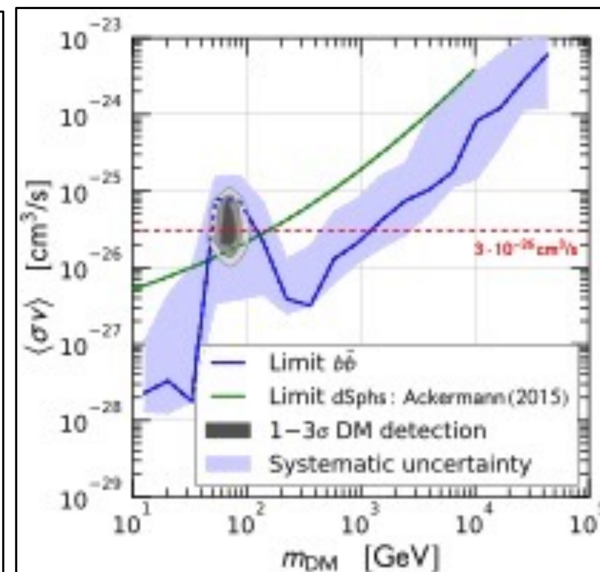
- A variety of gamma-ray searches (GC, dwarfs, IGRB, etc.), as well as cosmic-ray antiproton and positron measurements, are currently sensitive to dark matter with annihilation cross sections in the range predicted for a simple thermal relic, for masses up to $\mathcal{O}(100)$ GeV
- This program is not a fishing expedition, but is testing a wide range of our most well-motivated dark matter models



Bergstrom, *et al.*, arXiv:1306.3983



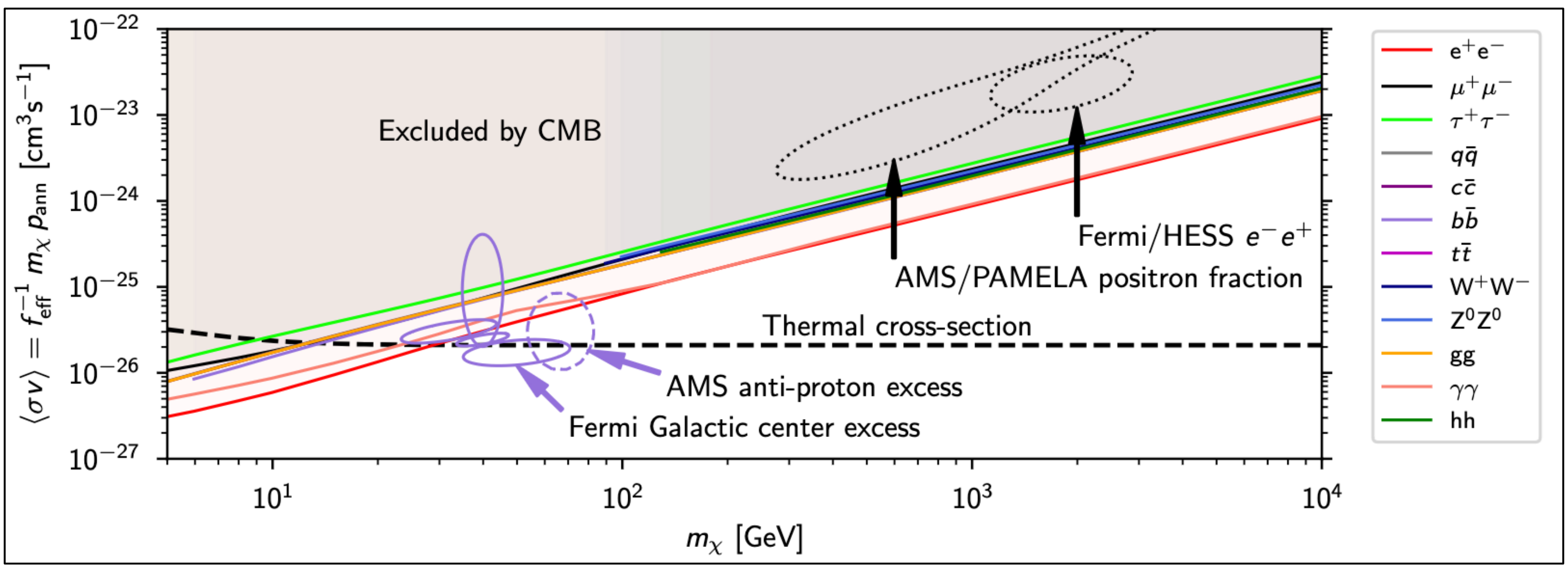
Fermi Collaboration, arXiv: 2311.04982



Cuoco, *et al.*, arXiv:1610.03071
Cui, *et al.*, arXiv:1610.03840

Dark Matter Annihilation in the Era of Recombination

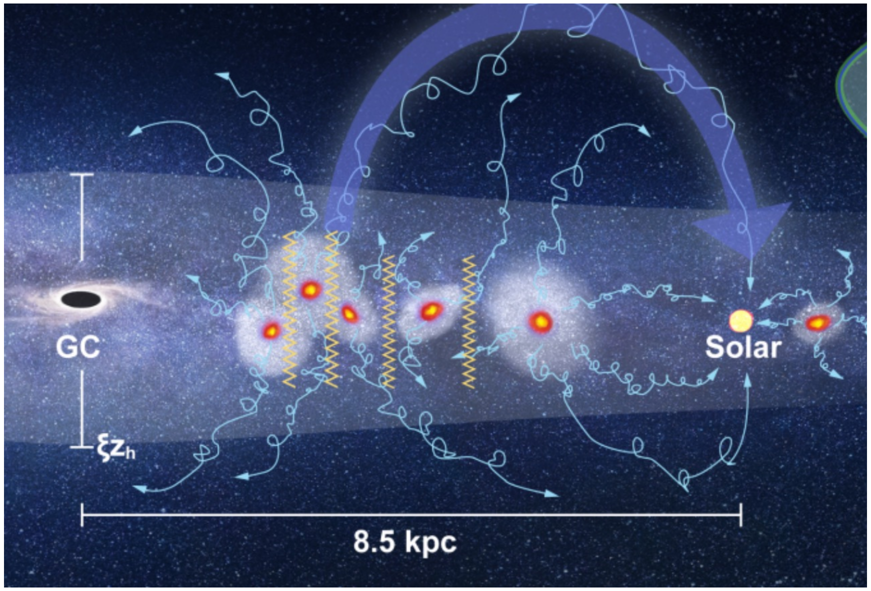
- The angular power spectrum of the CMB is highly sensitive to any energy that may have been injected into the universe during the era of recombination
- Planck data has been used to exclude dark matter candidates with velocity-independent (s-wave) annihilation cross sections lighter than ~10-30 GeV (unless they annihilate mostly to neutrinos)



Planck, arXiv:1807.06209

Dark Matter Searches with Cosmic Ray Antimatter

- Although most astrophysical sources of cosmic rays produce more matter than antimatter, dark matter annihilations/decays produce equal amounts of matter and antimatter (in most models) → excess antimatter in the cosmic ray spectrum could be a signal of annihilating/decaying dark matter
- Unlike gamma ray and neutrinos, cosmic rays do not move in straight lines, but diffuse through the astrophysical magnetic fields → the cosmic rays that reach Earth are almost perfectly isotropic

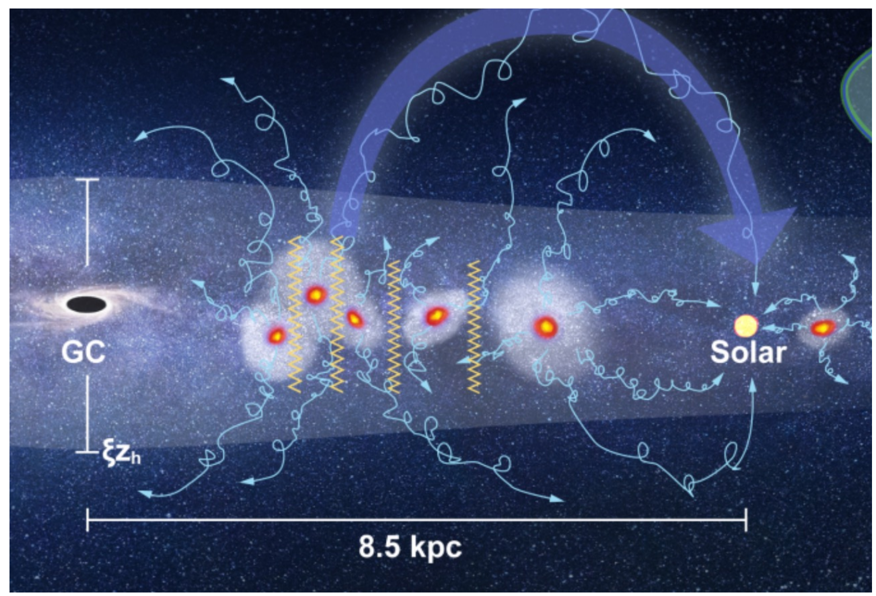


Dark Matter Searches with Cosmic Ray Antimatter

- The process of cosmic-ray propagation is complicated! We typically do our best to model it using equations like this:

$$\underbrace{\frac{\partial \psi(\vec{x},p,t)}{\partial t}}_{\text{Distribution of Cosmic Rays}} = \underbrace{q(\vec{x},p)}_{\text{Source Term}} + \vec{\nabla}\cdot[\underbrace{D_{xx}\vec{\nabla}\psi(\vec{x},p,t)}_{\text{Diffusion}} - \underbrace{\vec{V}_c\psi(\vec{x},p,t)}_{\text{Convection}}] + \underbrace{\frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi(\vec{x},p,t)}_{\text{Diffusive Reacceleration}}$$
$$- \frac{\partial}{\partial p}[\dot{p}\psi(\vec{x},p,t) - \frac{p}{3}(\vec{\nabla}\cdot\vec{V}_c)\psi(\vec{x},p,t)] - \underbrace{\frac{1}{\tau_f}\psi(\vec{x},p,t)}_{\text{Fragmentation}} - \underbrace{\frac{1}{\tau_r}\psi(\vec{x},p,t)}_{\text{Decay}}$$

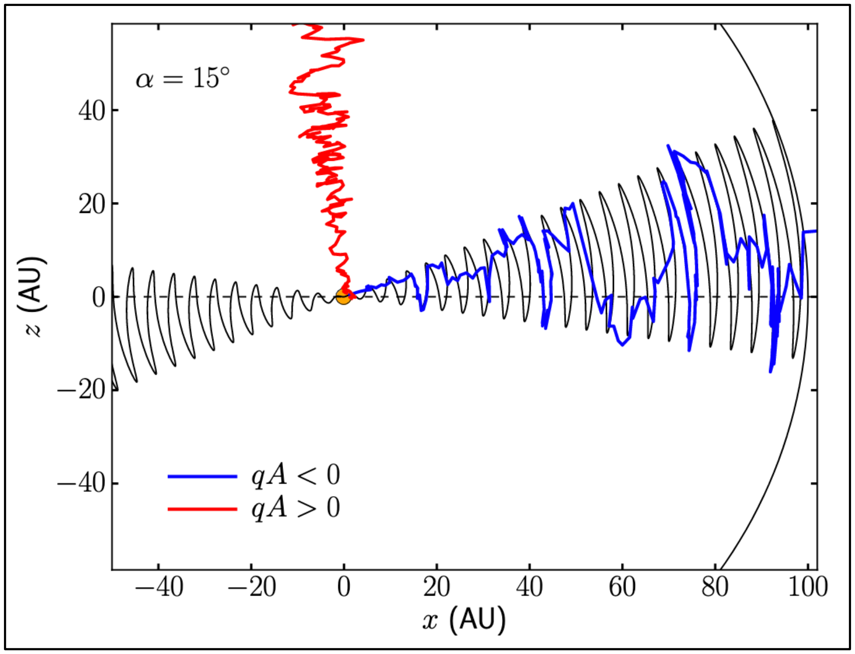
- Lots of free parameters! Constrain with various stable (B/C, etc.) and unstable secondary-to-primary ratios (^{10}Be/^{9}Be)
- To make this problem tractable, we are generally forced to adopt several simplifying assumptions: steady state, spatial uniformity, etc.



Progress in Understanding Solar Modulation

- The propagation of cosmic rays in the Solar System is impacted by the combined effects of the solar wind and its embedded magnetic field; this is especially important at energies below ~10 GeV
- Until recently, we had little choice but to model this by applying a force field modulation potential, Φ, which was typically taken to be a free parameter:

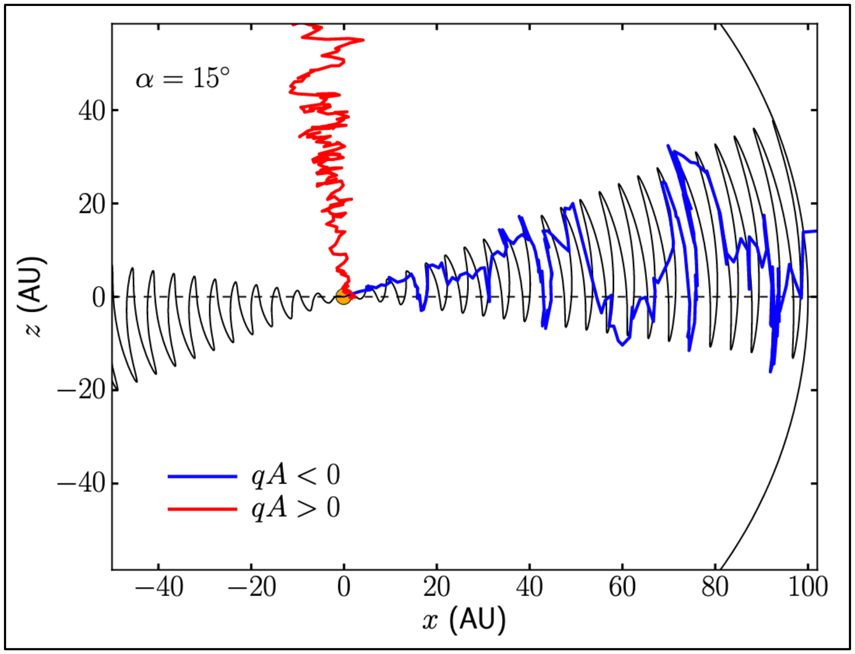
$$\frac{dN^{\oplus}}{dE_{\rm kin}}(E_{\rm kin}) = \frac{(E_{\rm kin}+m)^2 - m^2}{(E_{\rm kin}+m+|Z|e\Phi)^2 - m^2} \times \frac{dN^{\rm ISM}}{dE_{\rm kin}}(E_{\rm kin}+|Z|e\Phi),$$



Cholis, et al., arXiv:1511.01507, 2007.006699

Progress in Understanding Solar Modulation

- Significant progress in our ability to handle the effects of solar modulation has been made possible in recent years by two key developments:
  - Voyager 1 measurements of the cosmic-ray spectrum beyond the heliopause
  - Measurements of the time-dependent cosmic-ray spectrum by PAMELA, AMS
- This new information has made it possible to correlate the modulation potential with measurements of the magnitude of the solar magnetic field, the bulk velocity of the solar wind, and the tilt angle of the heliospheric current sheet
- We can now use these independent observables to predict what the modulation potential will be at a given time, as a function of charge and rigidity
- This allows us to make much greater use of cosmic-ray spectrum, especially at energies below ~10 GeV



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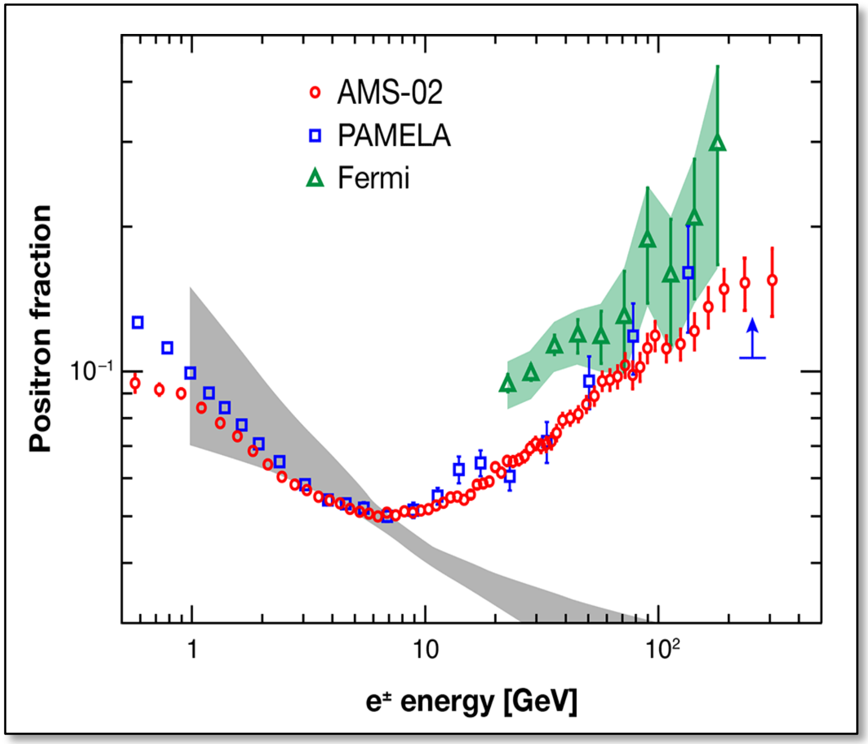
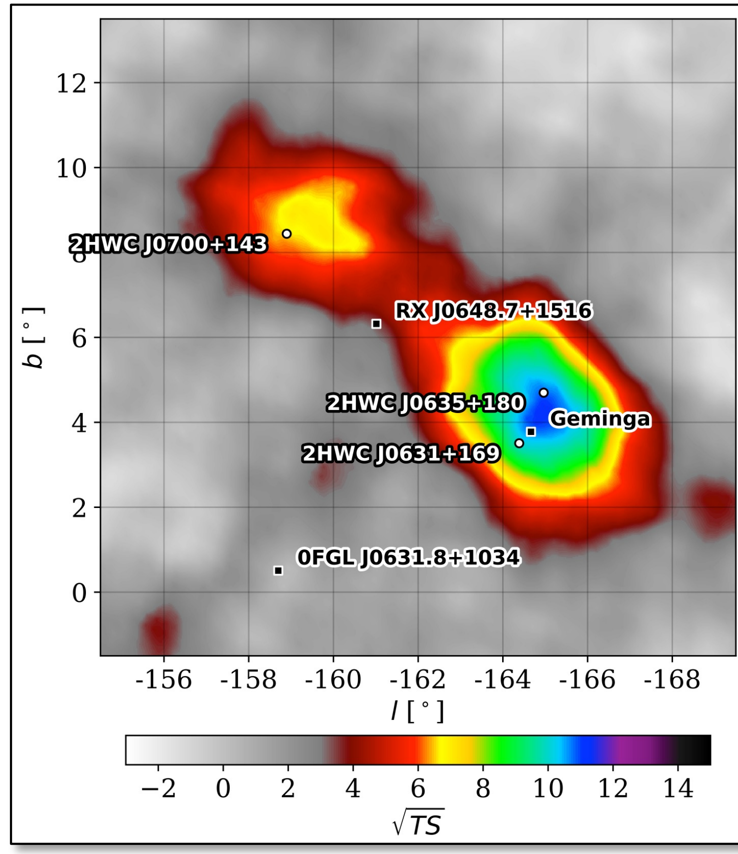
The Cosmic Ray Positron Excess

- A great deal excitement was generated by the measurement of a rising cosmic ray positron fraction by PAMELA and later AMS
- If the positrons are produced in cosmic ray interactions in the ISM, $p_{CR}+p_{gas} \rightarrow \pi^+ \mp X \rightarrow e^+\nu_e\nu_\mu\nu_\mu + X$ (ie. secondary production), the positron fraction should be expect to fall with energy
- The *rising* positron fraction requires the presence of *nearby* ($\lesssim$ kpc) *primary* sources of TeV-scale positrons
- At first, many of us thought these positrons might come from dark matter annihilations, but these interpretations are now in significant conflict with gamma-ray constraints
- So, where do these positrons come from?



Cosmic Ray Positrons From Pulsars

- It has long been appreciated that nearby pulsars could potentially produce the excess positrons
- As early as 2008, it was pointed out that this explanation would work if ~5-10% of. the average pulsar's spin-down power is transferred into the acceleration of very high-energy e^+e^- pairs
- In 2017, the discovery of TeV halos around the Geminga and Monogem pulsars confirmed that this is indeed the case
- Pulsars are almost certainly the main sources of the cosmic-ray positron excess

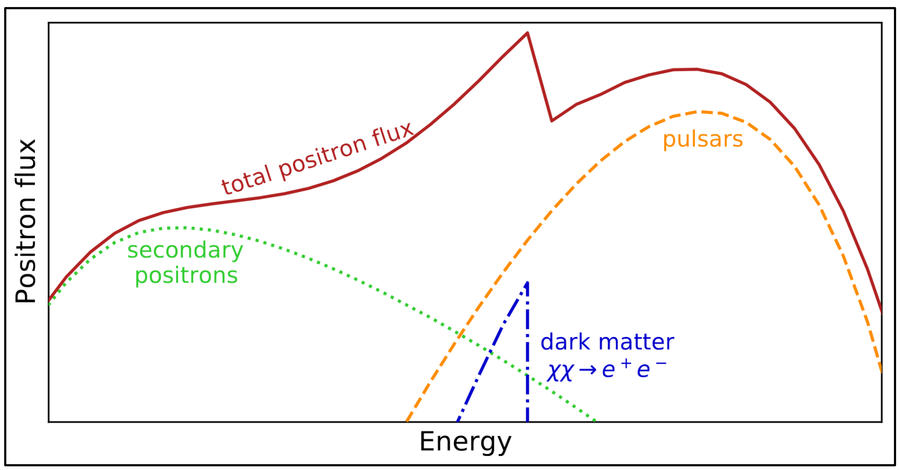


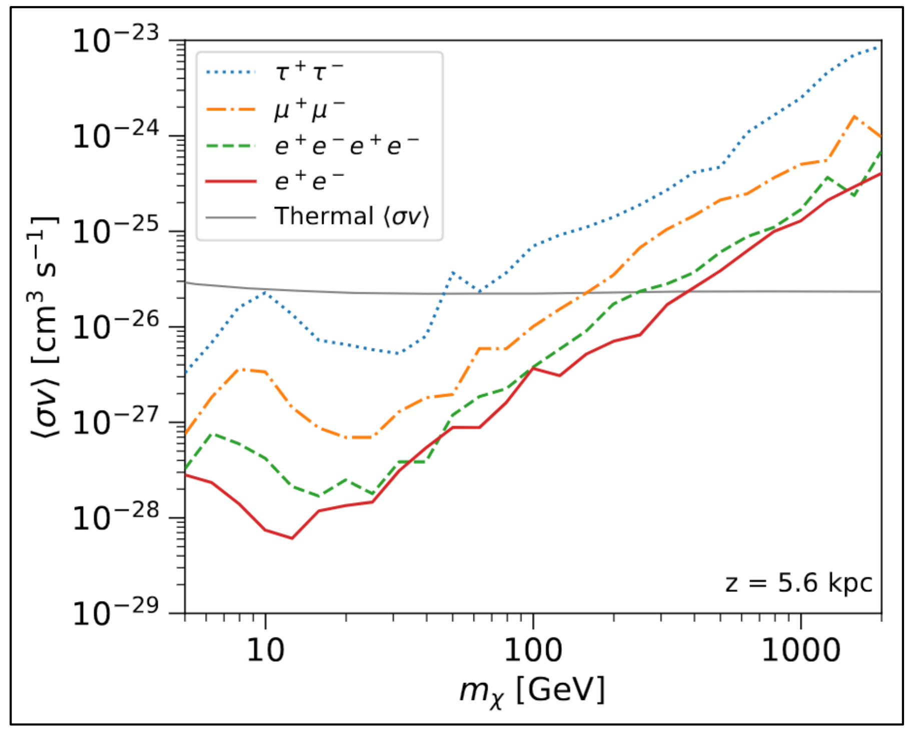
HAWC Collaboration, arXiv:1702.02992

DH, Blasi, Serpico, PRD, arXiv:0810.1527;
Yuksel, Kistler, PRL, arXiv:0810.2784;
DH, I. Cholis, T. Linden, K. Feng, arXiv:1702.08436

Constraining Dark Matter with Cosmic Ray Positrons

- Although we now know that most of the cosmic-ray positrons do not come from dark matter, we can still use these particles to look for the distinctive spectral features that could be produced through dark matter annihilations or decays
- These constraints are particularly strong for leptonic final states





John, Linden, arXiv:2107.10261
Bergstrom et al., arXiv:1306.3983

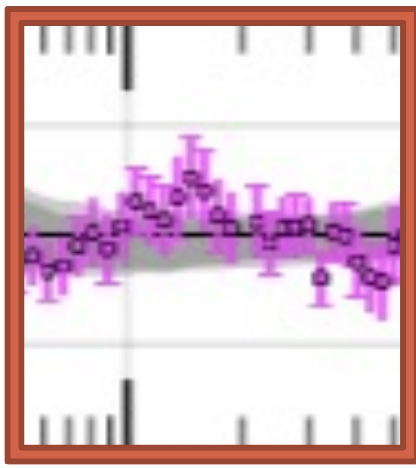
The Cosmic Ray Antiproton Spectrum

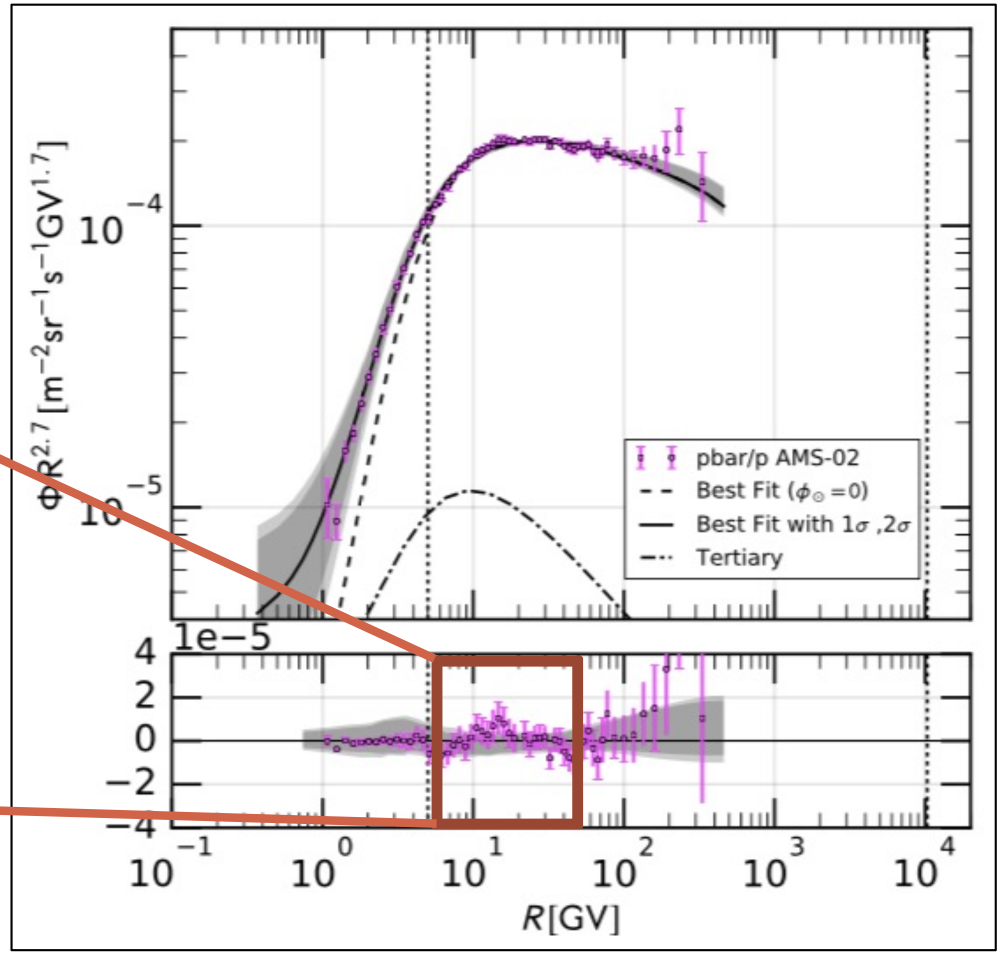
- The AMS-02 Collaboration has provided us with an exquisite measurement of the cosmic-ray antiproton spectrum and antiproton-to-proton ratio
- The precision of this measurement is at the level required to test a wide range of annihilating dark matter models, up to masses of several hundred GeV
- Broadly speaking, the shape and normalization of this spectrum is in good agreement with the expectations of standard cosmic-ray production and transport models
- There is, however, a small but statistically significant departure from these predictions at energies of ~10-20 GeV

AMS Collaboration, PRL 117 (2016)

The Antiproton Excess

- The AMS antiproton excess was identified in 2016 by two independent groups (Cuoco, Krämer, Korsmeier and Cui, Yuan, Tsai, Fan)
- Both papers reported a small, but statistically significant excess (~4.5**σ**)
- These papers made it clear that out-of-the-box GALPROP models could not explain the antiproton spectrum that had been observed by AMS

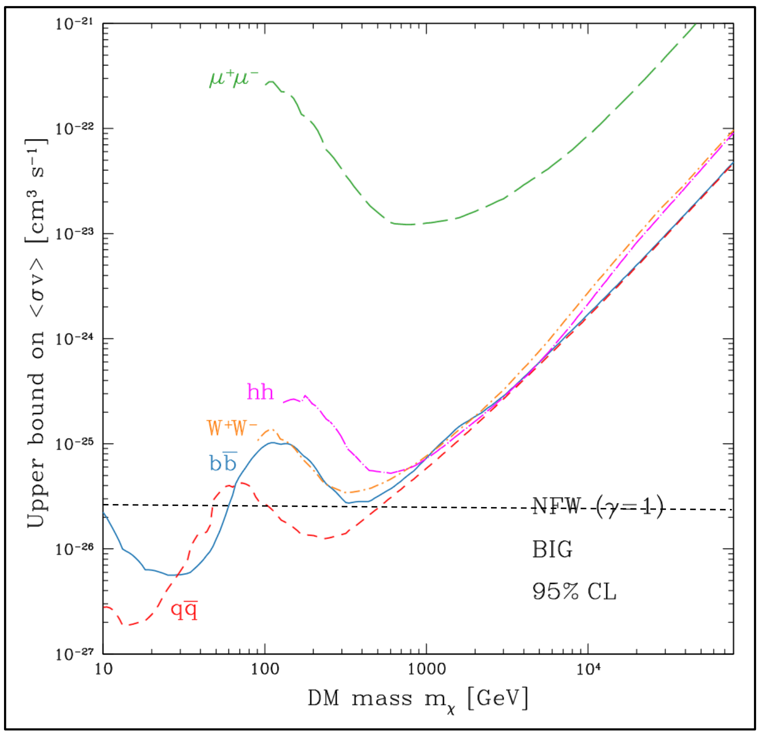




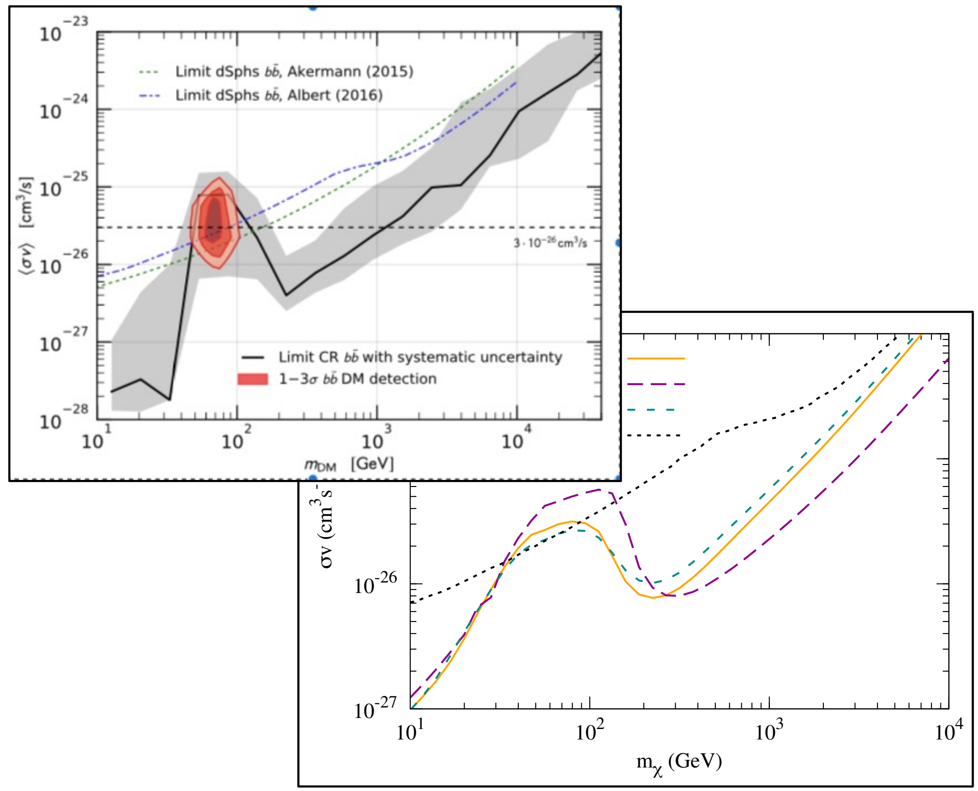
Cuoco et al., arXiv:1610.03071
Cui et al., arXiv:1610.03840

The Antiproton Excess

- If interpreted in terms of annihilating dark matter, this excess favors m_{DM}~50-100 GeV, $\sigma v \sim 10^{-26}$ cm^3/s (for the case of annihilations to $b\bar{b}$)
- This data also provides strong constrains on annihilating dark matter; the most stringent to date across a wide range of masses



Calore et al., arXiv:2202.03076



Cuoco et al., arXiv:1610.03071
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It's All About the Systematics

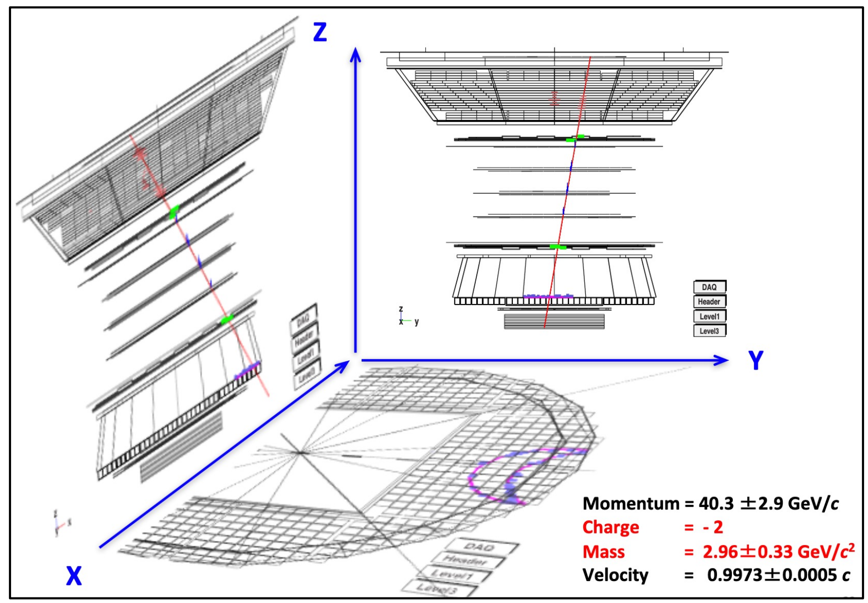
- Compared to other potential signals of dark matter that have been reported in the literature, the AMS antiproton excess has received relatively little attention
- Much of the cosmic-ray community is skeptical of this result, largely due to (reasonable) concerns pertaining to the difficulty in quantifying the systematic uncertainties associated with the antiproton production cross section

The Antiproton Production Cross Section

- Laboratory measurements of the antiproton production cross section have non-negligible uncertainties; error bars on $\sigma_{pp \rightarrow X+p}$ are ~10-15% at GeV-scale energies
- If we allowed this cross section to vary freely within these errors, almost any feature that might be observed could be absorbed
- That being said, bump- and dip-like features in the energy dependance of this cross section are not physically motivated, so we should expect these errors to be strongly correlated in energy
- How one treats these correlations can lead to very different conclusions; some groups find that the excess persists at >4σ significance, while others find that the significance of this feature can disappear almost entirely
- To resolve this situation, we're going to need better laboratory measurements of the antiproton production cross section!

Cosmic Ray Anti-Nuclei

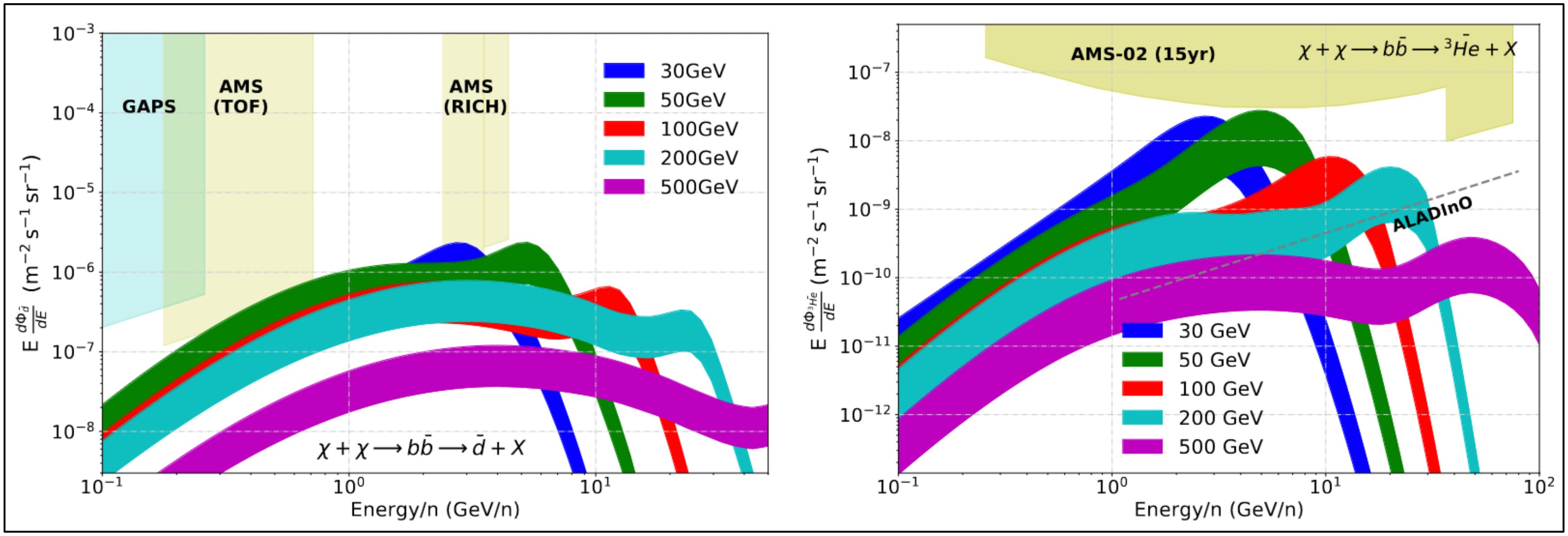
- A very small fraction of dark matter annihilation events could produce an anti-deuteron, or even an anti-^{3}He nucleus
- The astrophysical backgrounds for such events are expected to be very low (in 15 years of AMS data, we expect ~1 $\bar{d}$ event and ~0.1 $^3\overline{\mathrm{He}}$ event)
- To my great surprise, AMS has announced the tentative detection of many anti-deuteron events, ~10 anti-helium events, and even a few anti-^{4}He!!!



From talk by Sam Ting, December 2016

Cosmic Ray Anti-Nuclei

- Dark matter annihilations can produce anti-nuclei, but not nearly as many as AMS has reported
- Setting the dark matter annihilation cross section to its upper limit, one predicts the following fluxes of $\bar{d}$ and $^3\overline{He}$ (Luque, Winkler, Linden, 2404.13114):



- These fluxes are (at best) barely scraping the projected sensitivity of AMS, GAPS
- Dark matter can't explain the large reported number of anti-nuclei events
- But then again, nothing else can either!?!?!

Anomalies and Excesses

- Cosmic-Ray Positron Excess
- Cosmic-Ray Antiproton Excess
- Anti-Deuterons, Anti-Helium at AMS?!?

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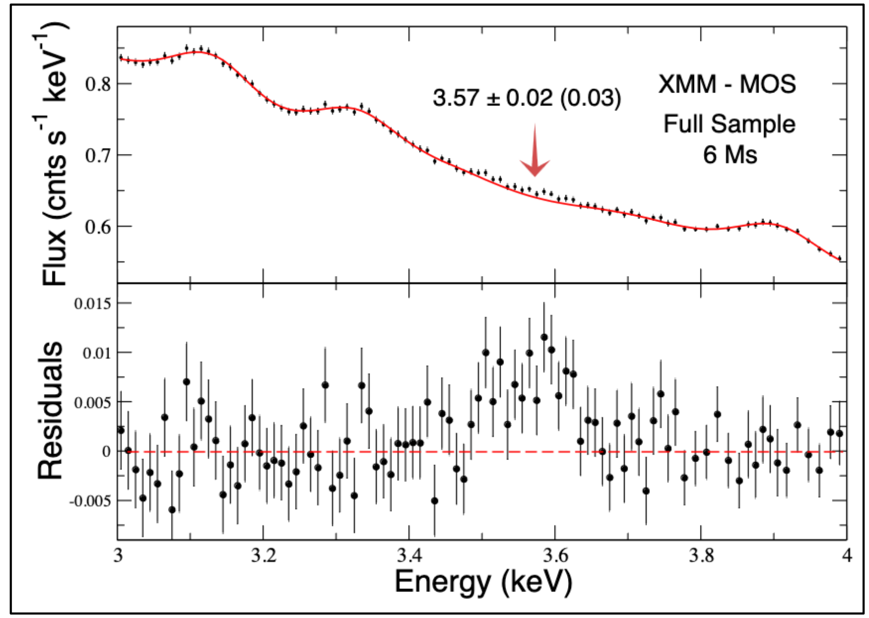
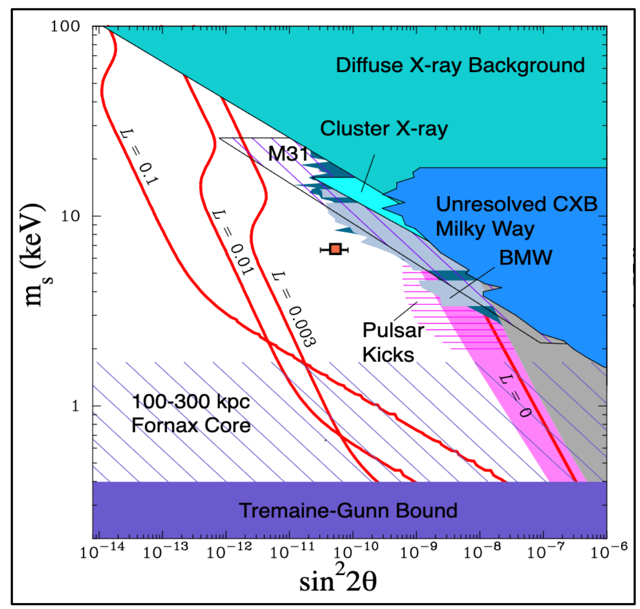
  → Utterly perplexing if true

The Rise and Fall of the 3.5 keV Line

- In 2014, two groups claimed to detect (at ~4**σ**, ~3.5**σ**) a ~3.5 keV emission line from galaxy clusters (Perseus, and a stacked collection of clusters), using data from XMM-Newton and Chandra; this created a huge amount of interest (~900 citations each!)
- This was further encouraged by claims of a similar line in the Chandra Deep Field
- This line was widely interpreted as evidence of decaying dark matter, and in particular a ~7 keV sterile neutrino

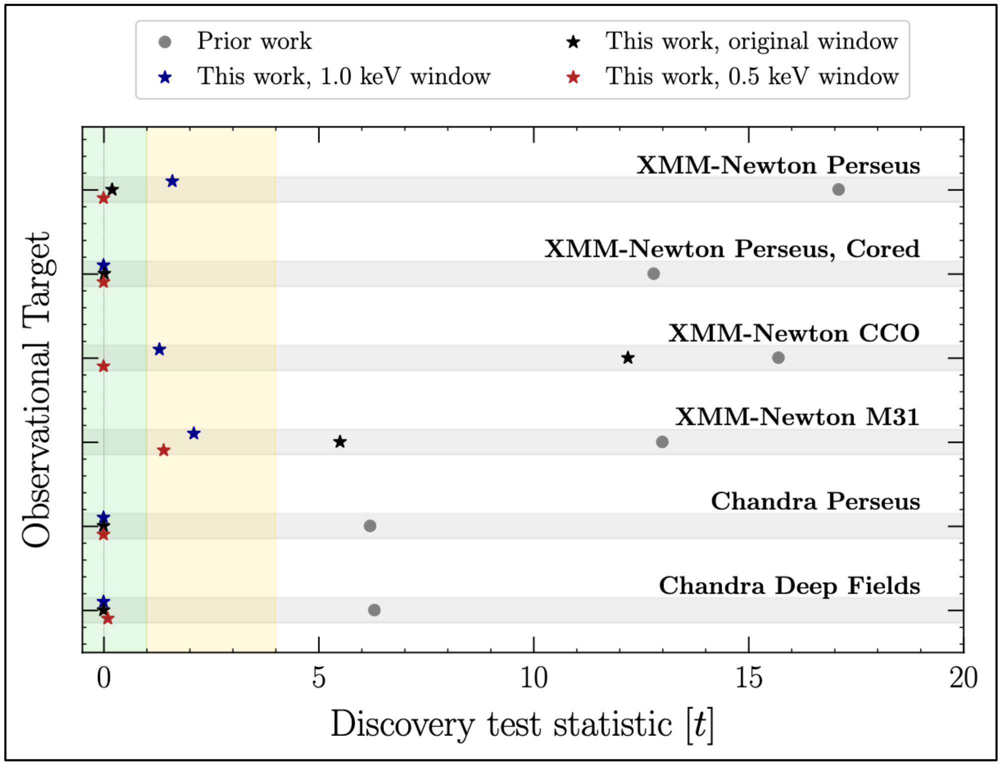




Bulbul, et al., arXiv:1402.2301
Boyarsky, et al., arXiv:1402.4119
Cappelluti, et al., arXiv:1701.07932

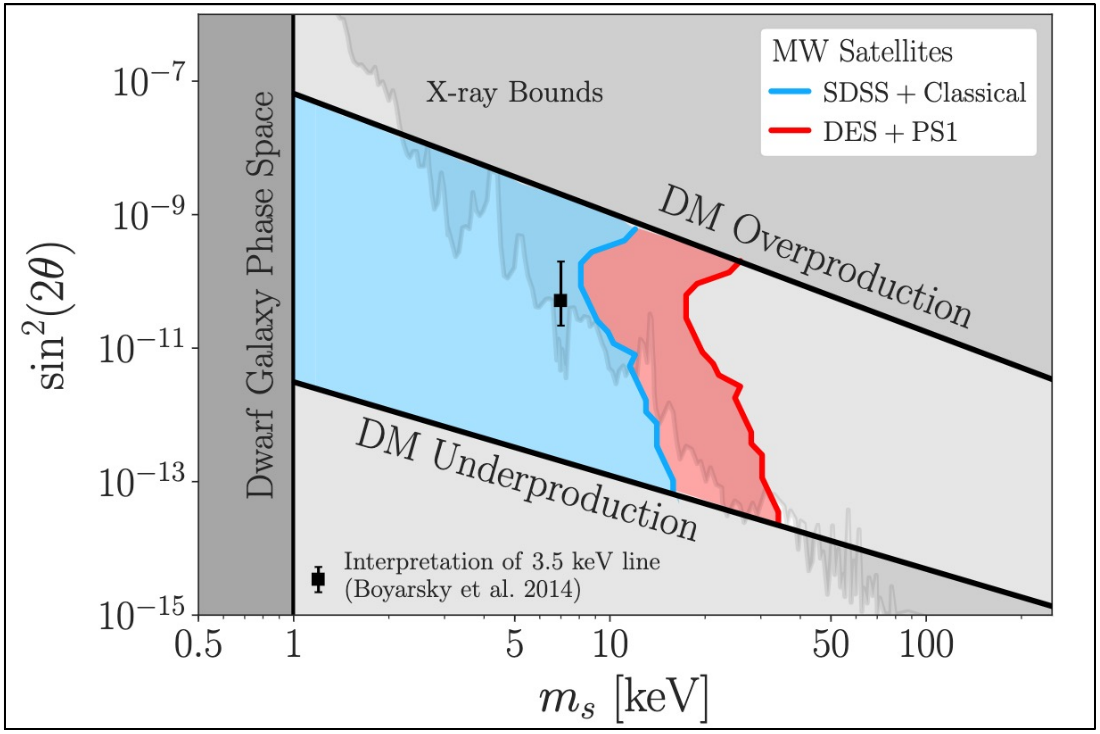
The Rise and Fall of the 3.5 keV Line

- A 2023 study by Dessert, Foster, Park and Safdi placed much doubt on these claims (ApJ., arXiv:2309.03254)
- Many of the results from the previous analyses could not be reproduced, and those that could were shown to not be robust to details of the analysis (such as the width of the energy window adopted)
- It appears that there was never a 3.5 keV line



The Status of Sterile Neutrinos as a Dark Matter Candidate

- Constraints from X-ray line searches and satellite galaxy counts (DES, Pan-STARRS) have *ruled out essentially all of the parameter space* for sterile neutrino dark matter
  (if produced via oscillations; Dodelson-Widrow or Shi-Fuller mechanisms)
- Sterile neutrinos could still be the dark matter, but this would require another production mechanism (such as through out-of-equilibrium decays)



DES Collaboration, arXiv:2008.00022

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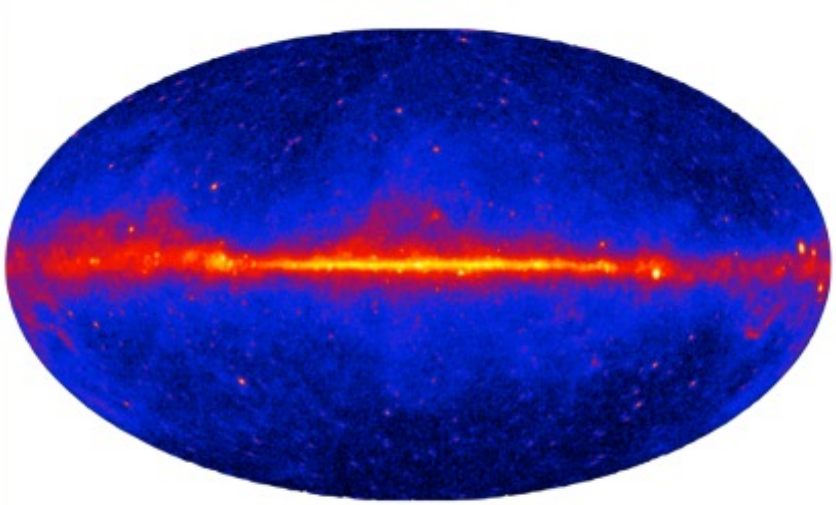
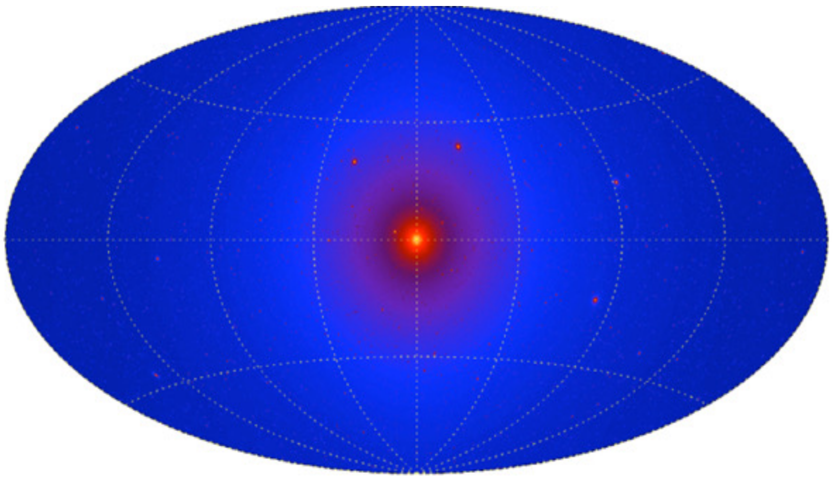
- 3.5 keV Line
  → There is no line.

Gamma Ray Searches for Dark Matter

- The brightest gamma-ray signal from annihilating dark matter is expected to come from the direction of the Galactic Center
- The astrophysical backgrounds are also bright in this region of this sky, and can be difficult to model
- Despite these backgrounds, the signal that would be predicted from a ~1-200 GeV thermal relic was widely expected to be within reach of the Fermi telescope



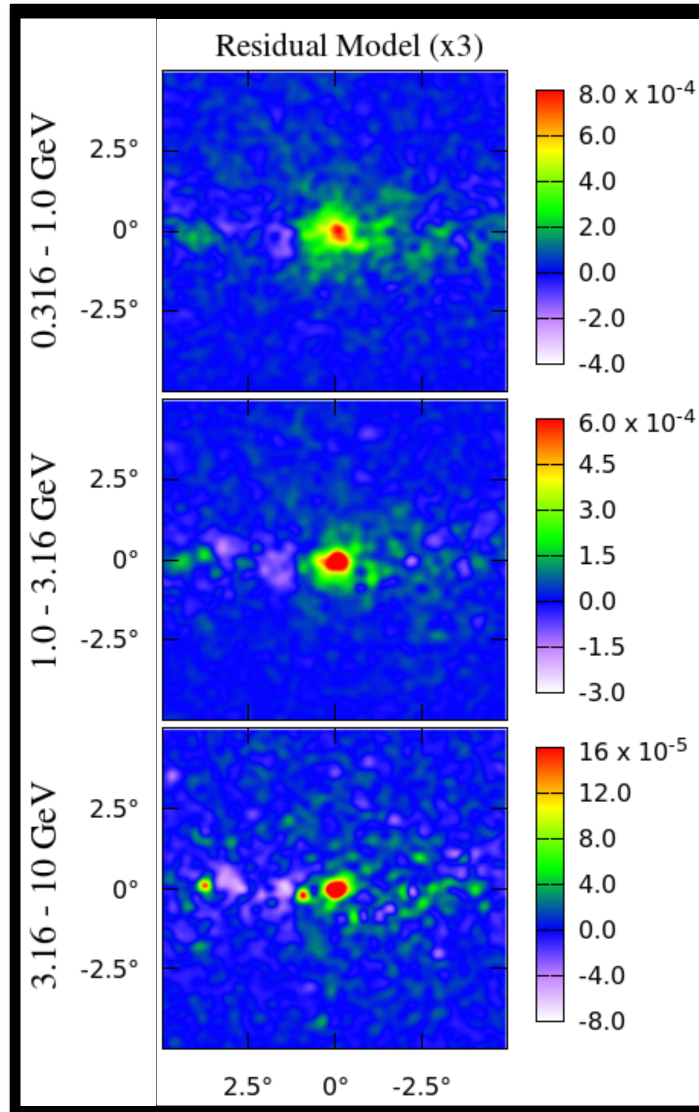
Gamma-Rays Measured by Fermi



Signal Predicted From Dark Matter

The Galactic Center Gamma-Ray Excess

- There is an excess of GeV-scale emission from the direction of the Inner Galaxy in the Fermi data, relative to *all models* of known astrophysical backgrounds
- This signal is bright and highly statistically significant – its existence is not in dispute
- It is very difficult to explain this signal with known astrophysical sources or mechanisms
- The observed characteristics of this signal are consistent with those expected from annihilating dark matter



Among other references, see:

DH, Goodenough (2009, 2010)
DH, Linden (2011)
Abazajian, Kaplinghat (2012)
Gordon, Macias (2013)
Daylan, DH, et al. (2014)
Calore, Cholis, Weniger (2014)
Murgia, et al. (2015)
Ackermann et al. (2017)

The Galactic Center Gamma-Ray Excess

Morphology

-The gamma-ray excess exhibits approximate spherical symmetry about the Galactic Center, with a flux that falls as $\sim r^{-2.4}$ out to at least ~20° (if interpreted as annihilating dark matter, this implies $\rho_{DM} \sim r^{-1.2}$)

Spectrum

-The spectrum of the excess is uniform across the Inner Galaxy and is well fit by a ~30-70 GeV particle annihilating to quarks or gluons

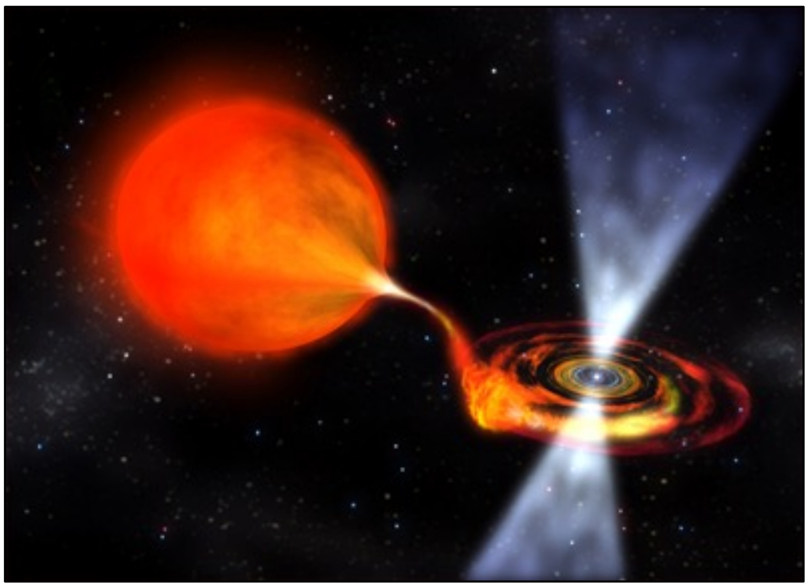
Intensity

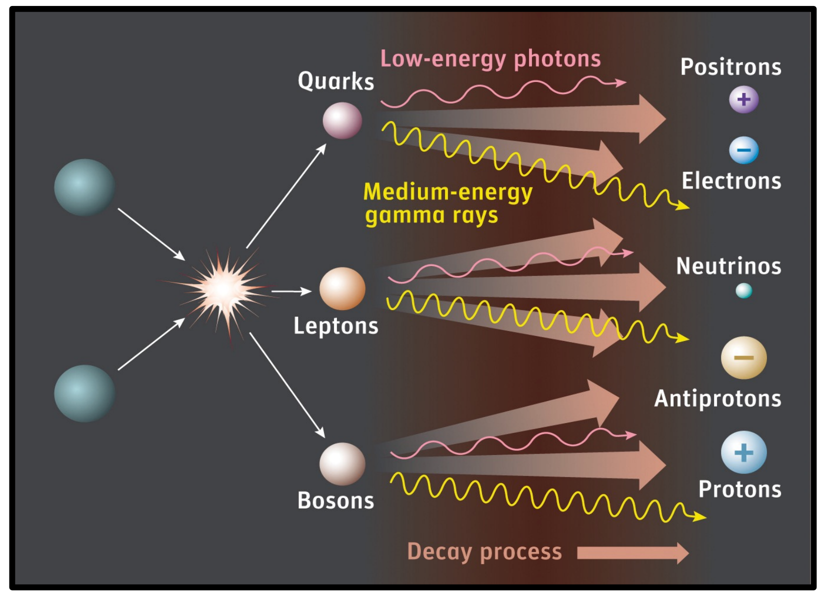
-To produce the observed intensity of the excess, the dark matter particles must annihilate with a cross section of $\sigma v \sim (1\text{-}2) \times 10^{-26}$ cm^3/s, remarkably similar to that expected of a thermal relic

Daylan et al. (2014)
Calore, Cholis, Weniger (2014)
Calore, Cholis, McCabe, Weinger (2014)

What Produces the Galactic Center Excess?

- A large population of centrally located millisecond pulsars?
- Annihilating dark matter?





Anomalies and Excesses

- Cosmic-Ray Positron Excess

  → Very likely produced by pulsars

- Cosmic-Ray Antiproton Excess

  → Subject to significant hadronic uncertainties

- Anti-Deuterons, Anti-Helium at AMS?!?

  → Utterly perplexing if true

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  → There is no line.

- Galactic Center Gamma-Ray Excess

Anomalies and Excesses

- Cosmic-Ray Positron Excess
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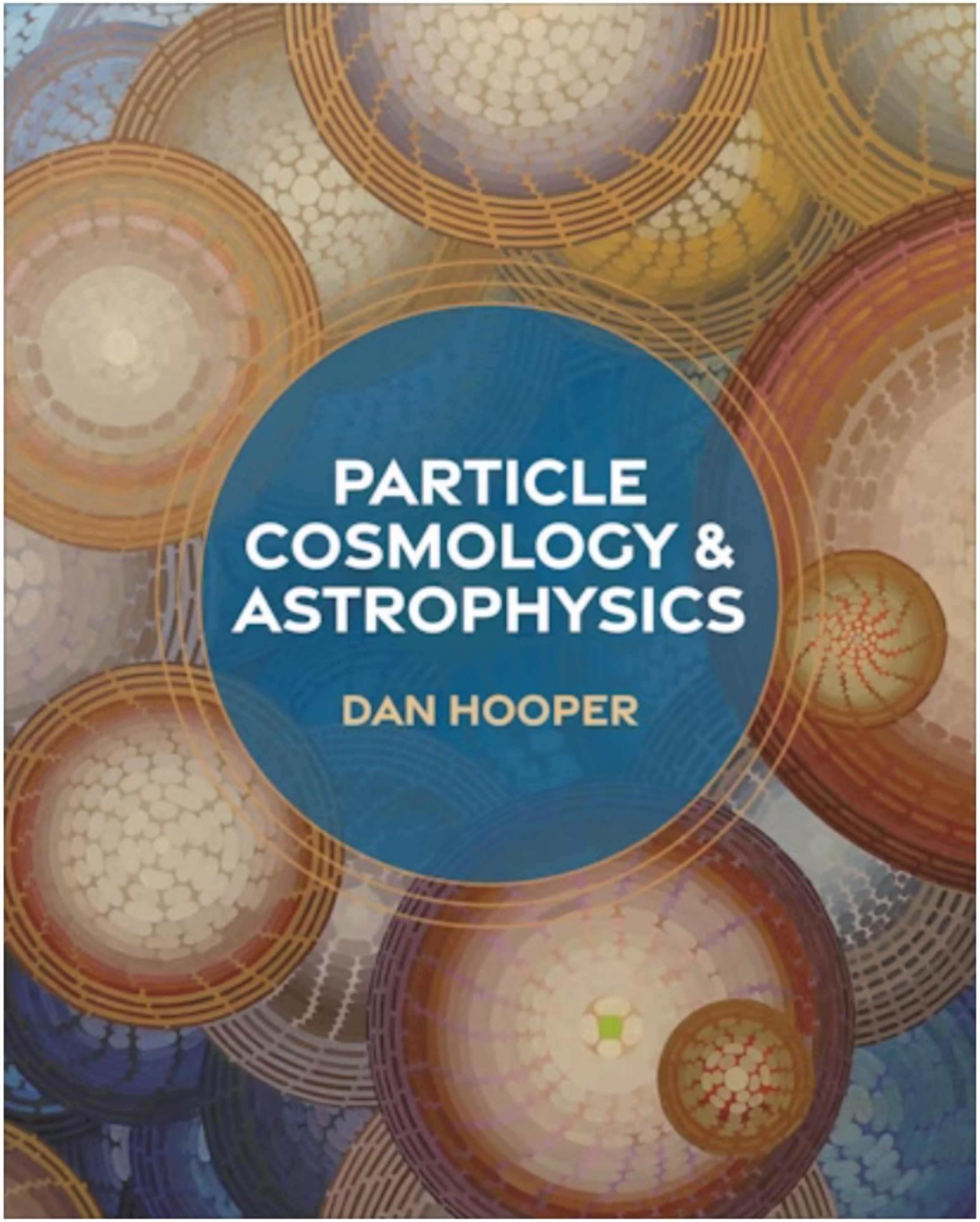
- Anti-Deuterons, Anti-Helium at AMS?!?
  → Utterly perplexing if true
- 3.5 keV Line
  → There is no line.
- Galactic Center Gamma-Ray Excess
  → Consistent with arising from annihilating dark matter or from a large population of exotic pulsars

Summary

- Indirect searches using gamma rays and cosmic rays are currently testing the range of annihilation cross sections that are predicted for a thermal relic, for masses up to $\sim\mathcal{O}(100)$ GeV; this program is testing the WIMP paradigm!
- CMB constraints strongly constrain annihilating dark matter candidates lighter than ~20 GeV
- The cosmic ray positron excess is very likely the result of nearby pulsars, but this data can still be used to derive stringent constraints on dark matter annihilating to leptons
- The AMS antiproton excess could arise from annihilating dark matter, but is subject to sizable hadronic uncertainties
- I have no idea whether AMS' anti-nuclei events are real, or where they might be coming from
- There is no 3.5 keV line
- The Galactic Center's GeV excess remains compelling as a possible signal of annihilating dark matter, but could also be generated by a very large population of exotic pulsars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