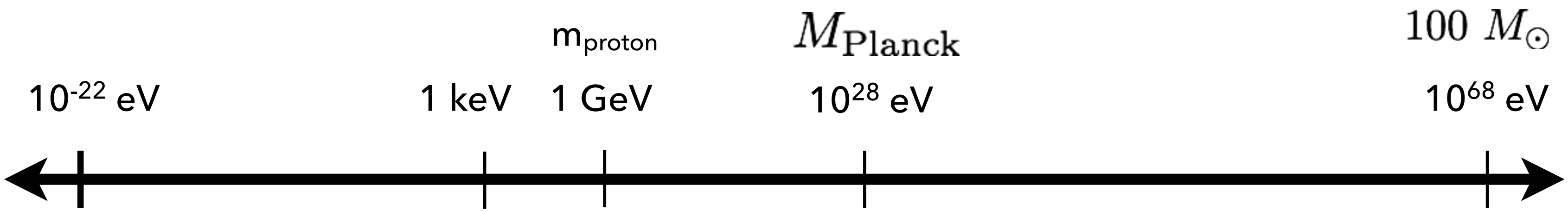
Signals of Annihilating Dark Matter

Dan Hooper – Fermilab and the University of Chicago

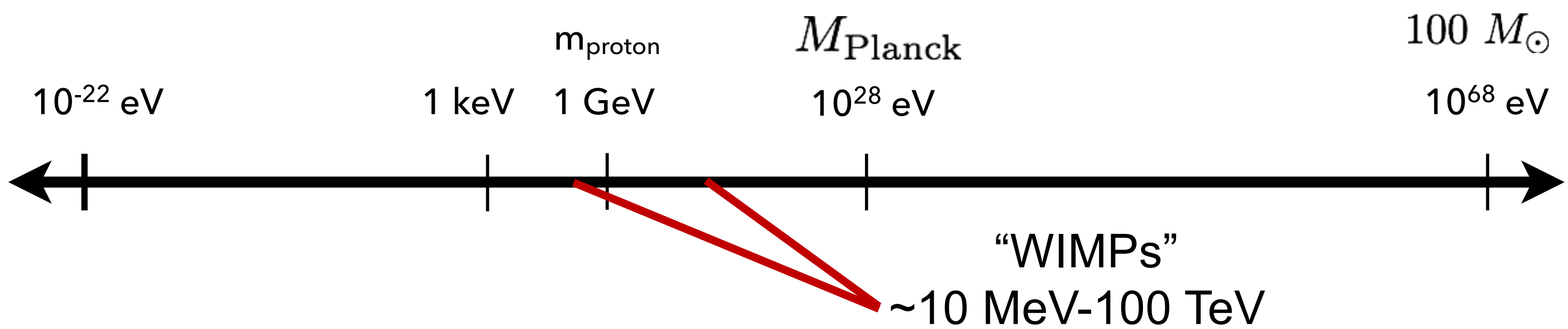
PASCOS 2022, MPI for Nuclear Physics, Heidelberg

July 29, 2022

WIMPs and the Dark Matter Landscape



WIMPs and the Dark Matter Landscape



The Case for WIMPs:

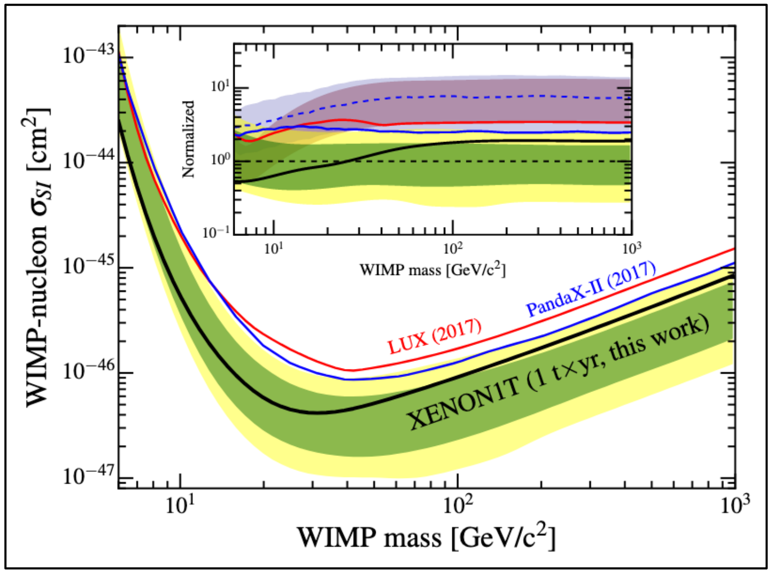
- If we assume that *the dark matter was in thermal equilibrium* at some point in the early universe, and that the early universe was *radiation dominated*, then we can conclude the following:
    1) The dark matter must be heavier than a few MeV (to avoid ruining BBN)
    2) The dark matter must be lighter than ~100 TeV (to avoid overproduction)

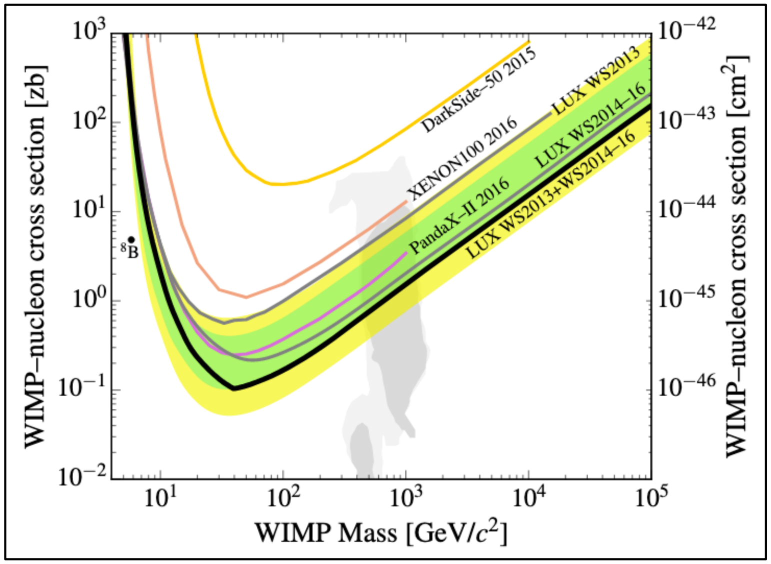
- To freeze-out with the measured dark matter abundance, such a particle must annihilate through something comparable to the weak force – *the "WIMP Miracle"*
- From this perspective, dark matter candidates with roughly weak-scale masses and interactions – "WIMPs" – are particularly well motivated

The Status of Dark Matter

The Fall of the WIMP?

- The thermal relic abundance calculation provided us with a collection of well-motivated benchmarks and experimental targets
- Many of our most attractive WIMP candidates were expected to fall within the reach of planned direct detection and accelerator experiments
- 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
- The LHC has performed beautifully, and yet no compelling signs of dark matter (or other BSM physics) have been discovered



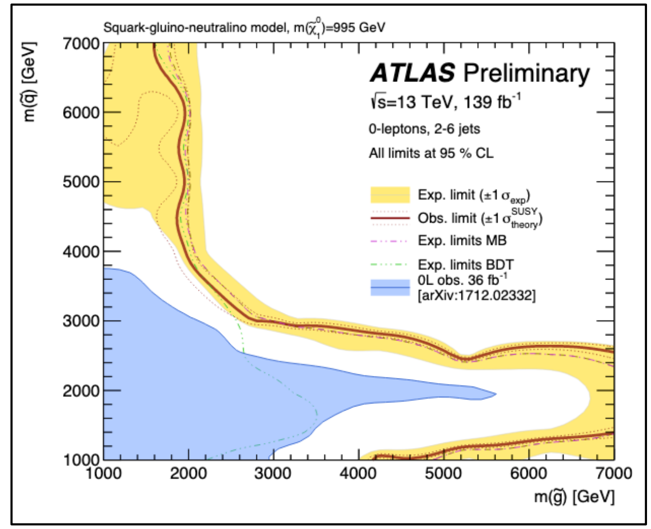


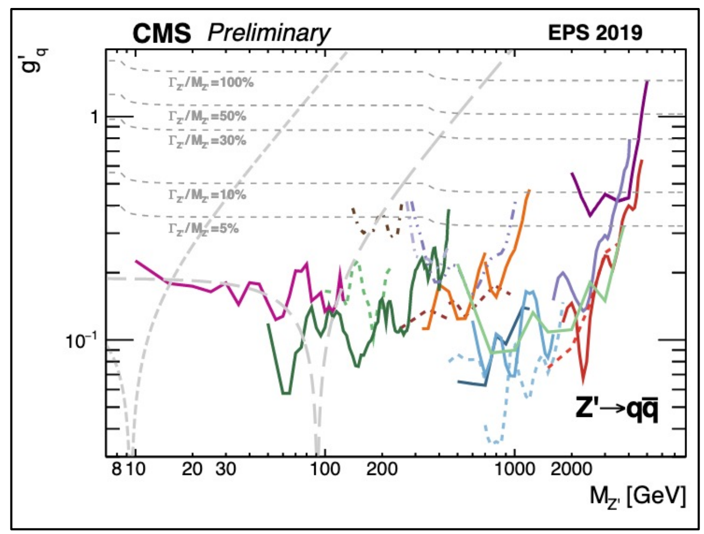
The Status of Dark Matter

So, is the WIMP Dead?

No, not at all.

- The LHC has produced strong constraints on certain classes of new physics, such as particles that can be pair produced with a large cross section (squarks, gluinos, etc.), and particles that can produce a dijet or dilepton resonance (Z', etc), but the constraints on WIMPs remain relatively weak
- The null results of direct DM searches have very meaningfully impacted our understanding of the nature of dark matter; much more so than the LHC, in my opinion
- It is fair to say that most simple WIMP models generally predict scattering rates with nuclei that exceed current bounds

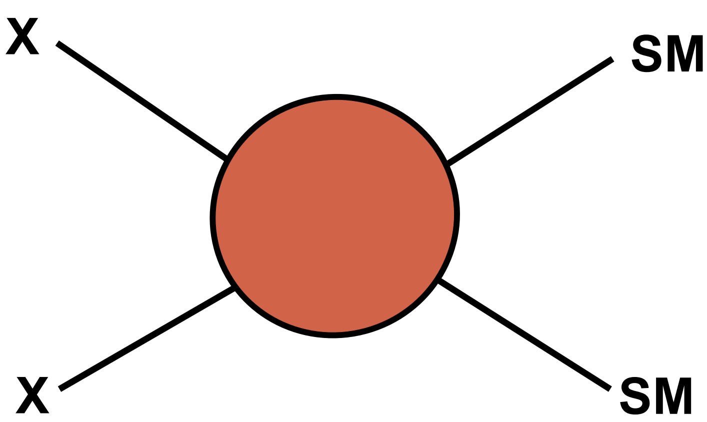




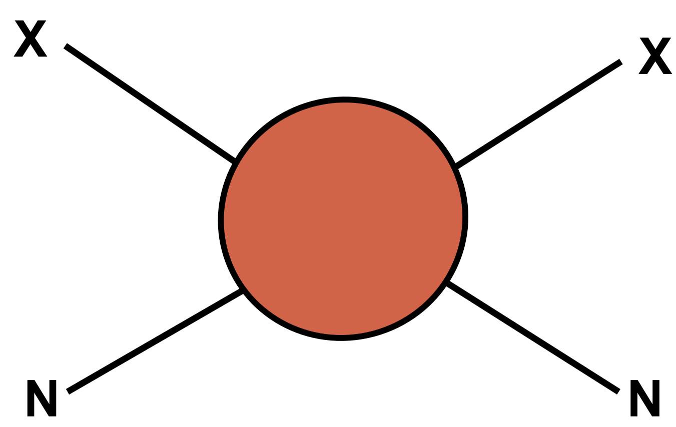
An (Incomplete) List of Ways to Reconcile WIMP Dark Matter With All Current Constraints:

Common Theme: Mechanisms that deplete the dark matter abundance in the early universe without leading to large elastic scattering rates with nuclei or large annihilation rates in the universe today

Unsuppressed

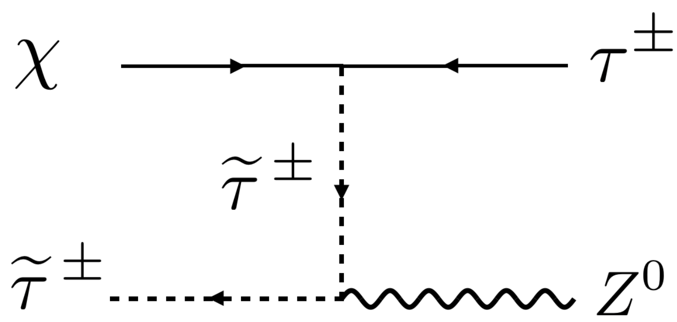


Suppressed



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

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

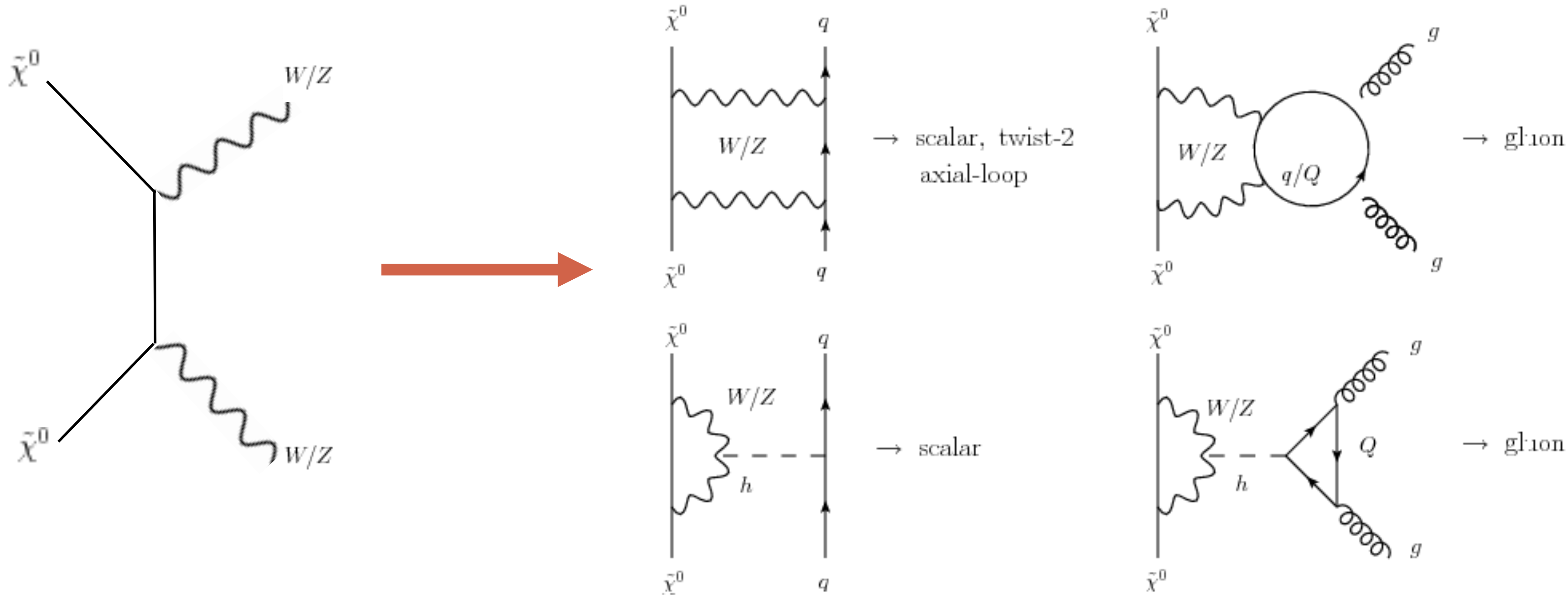


- Roughly speaking, coannihilations can be effective in setting the dark matter's relic abundance (without appreciable annihilation) if the mass splitting between the dark matter and the coannihilating state is less than ~10%
- If the dark matter's relic abundance is set by coannihilations, then we would expect the scattering rate of dark matter with nuclei to be highly suppressed

Griest, Seckel (1991)

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

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



- Well-motivated examples are wino-like or higgsino-like neutralinos, which predict σ_{SI}~2×10^{-46} to ~2×10^{-47} cm^2

Hisano, et al., arXiv:1007.2601, 1104.0228, 1504.00915;
Hill, Solon, arXiv:1309.4092, 1409.8290;
Berlin, DH, McDermott, arXiv:1508.05390

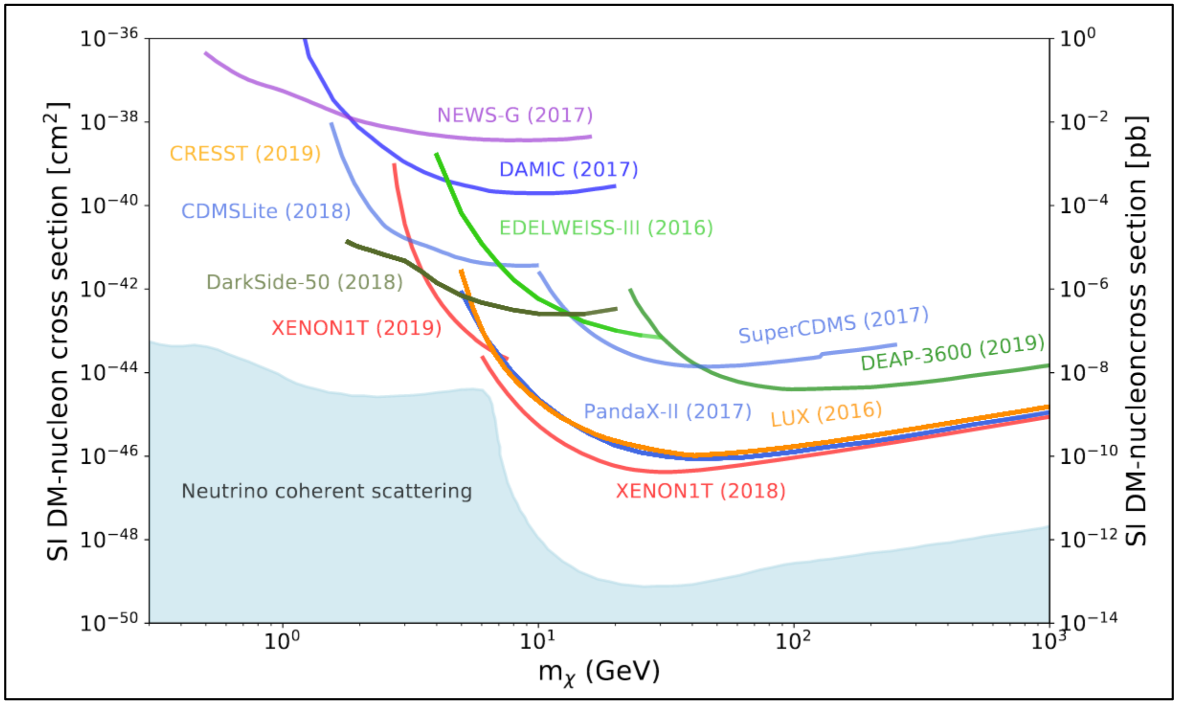
An (Incomplete) List of Ways to Reconcile WIMP Dark Matter With All Current Constraints:

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

- There are numerous examples of dark matter models in which the scattering cross section with nuclei is suppressed by factors of v^2, q^2, or q^4
- This translates to the rates at direct detection experiments being suppressed by factors of ~10^{-6} to 10^{-12}, for velocities present in the galactic halo

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

4) Dark matter that is lighter than a few GeV



- WIMPs can be as light as a few MeV (lighter thermal relics conflict with the successful predictions of BBN)
- The ~MeV-GeV mass range (3 orders of magnitude!) is relatively unconstrained by direct detection

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

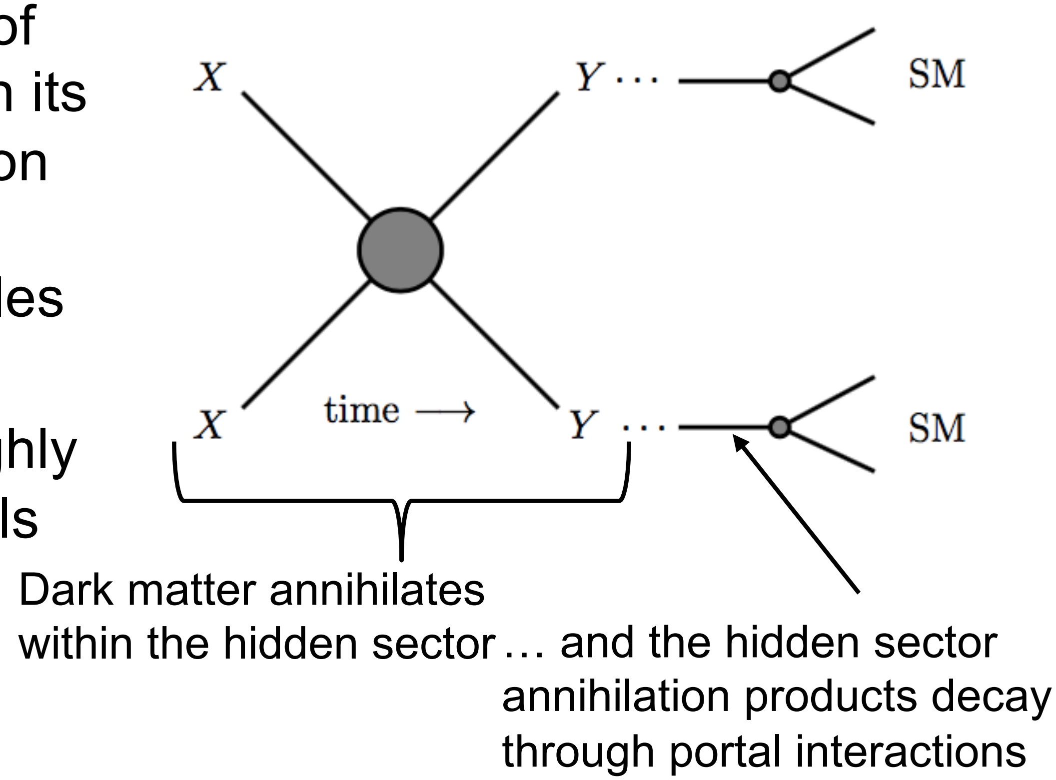
5) Departures from radiation domination in the early universe

- We have no direct observations that tell us what forms of matter or energy dominated the energy density of the universe prior to BBN
- A wide range of viable and well-motivated scenarios have been proposed in which the early universe included a matter-dominated era, and underwent a period of late-time reheating
- Such departures from the standard assumption of a radiation dominated early universe can alter the relic abundance of dark matter candidates, reducing our expectations for their elastic scattering cross section with nuclei

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

6) The dark matter is part of a hidden sector

- The dark matter could be one of several particle species within a hidden sector, which is entirely uncharged under the Standard Model
- Even without any direct couplings between these two sectors, small "portal" interactions could allow them to interact (feebly)
- The dark matter, *X*, freezes-out of thermal equilibrium entirely within its own hidden sector; the annihilation products, *Y*, then decay through portal interactions into SM particles
- Elastic scattering with nuclei and production at colliders can be highly suppressed in this class of models



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)

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)

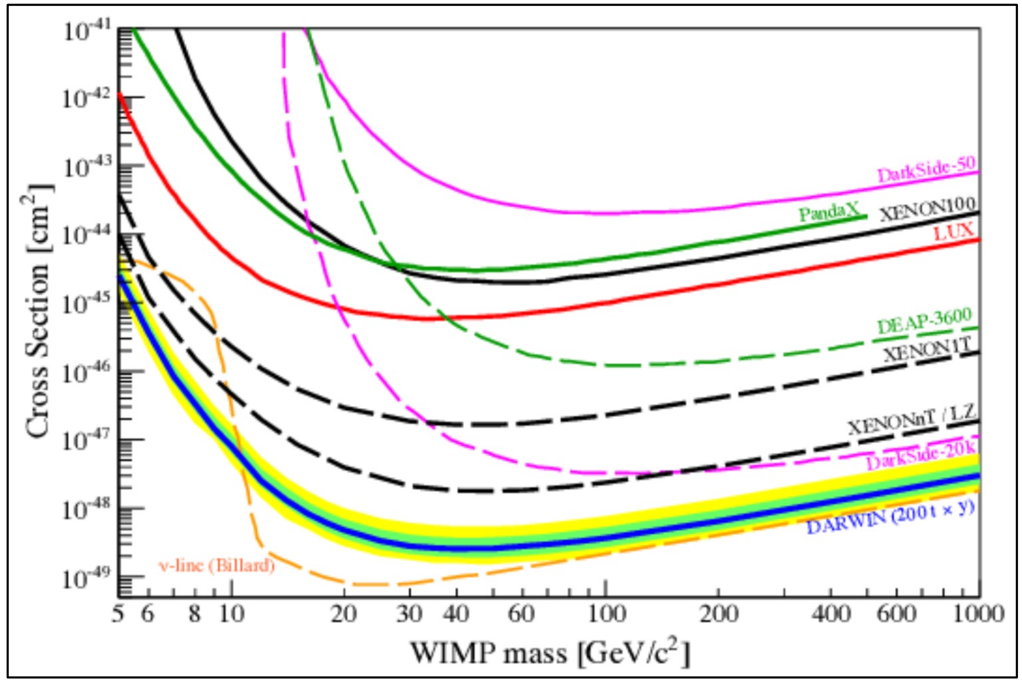
5) Departures from radiation domination in the early universe (early matter domination; late-time reheating, etc.) which result in the depletion of the dark matter's relic abundance

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

So, where do we go from here?

The Future of Direct Detection

- The LZ and XENONnT experiments have each begun collecting data – we should expect new limits (or excesses!) relatively soon
- Ultimately, a DARWIN-like experiment could improve upon the sensitivity of current experiments by ~2-3 orders of magnitude
- In parallel, other technologies will enable us to dramatically increase our sensitivity to ~MeV-GeV scale dark matter particles
- The next years and decade will be very exciting for direct dark matter searches

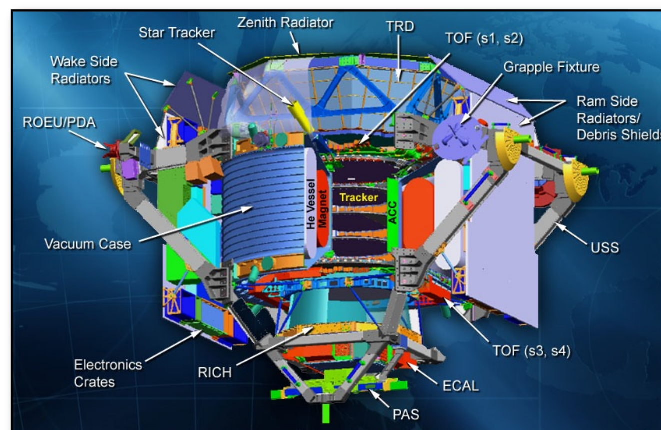


The Motivation for Indirect Searches

- To account for the observed dark matter abundance, a thermal relic must have an annihilation cross section (at freeze-out) of $\sigma v \sim 2\times10^{-26}$ cm^3/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

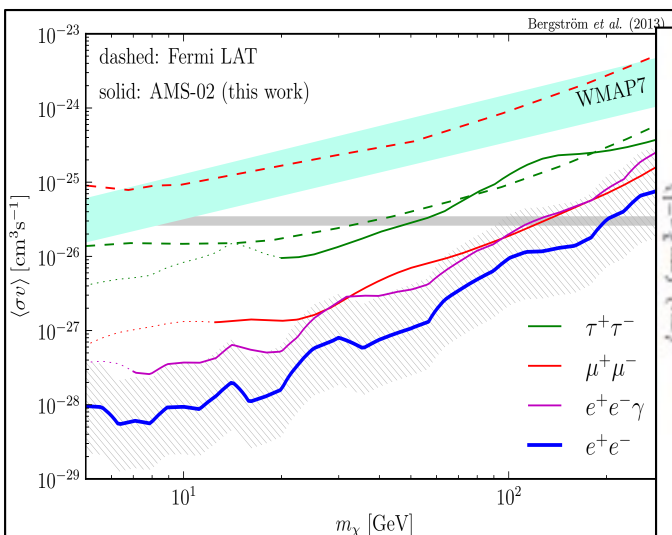
Fermi

AMS-02

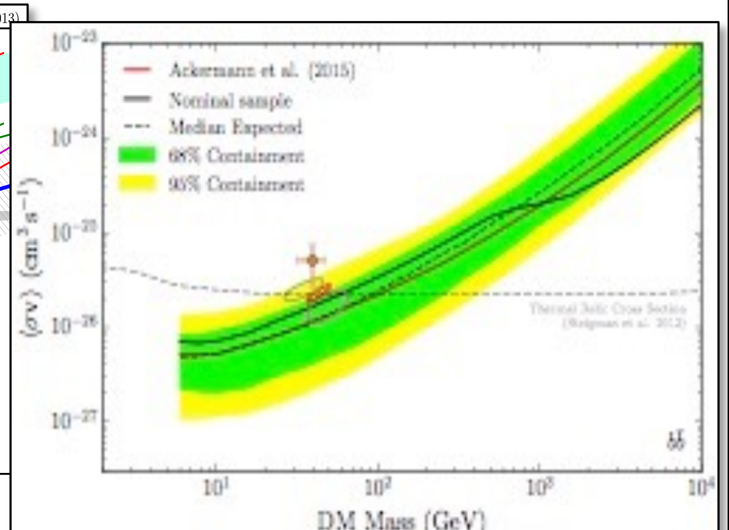


Constraints from Indirect Detection

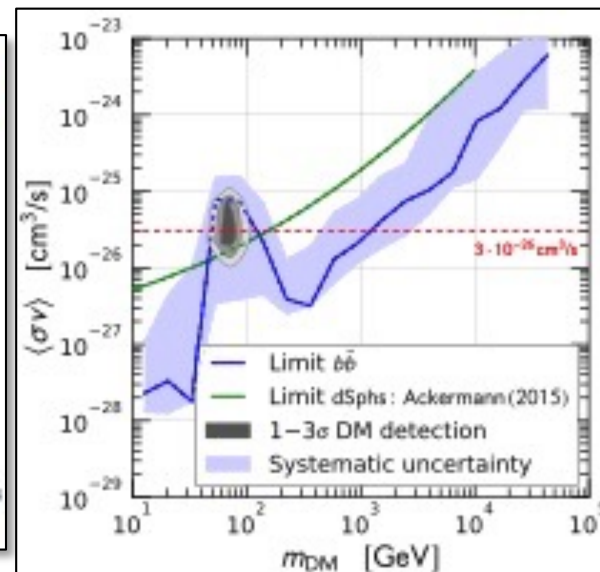
- A variety of gamma-ray strategies (GC, dwarfs, IGRB, etc.) as well as cosmic-ray antiproton and positron measurements from AMS, are currently sensitive to dark matter with the annihilation cross section predicted for a simple thermal relic, for masses up to $\sim\mathcal{O}(100)$ GeV
- This program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



Bergstrom, et al., arXiv:1306.3983



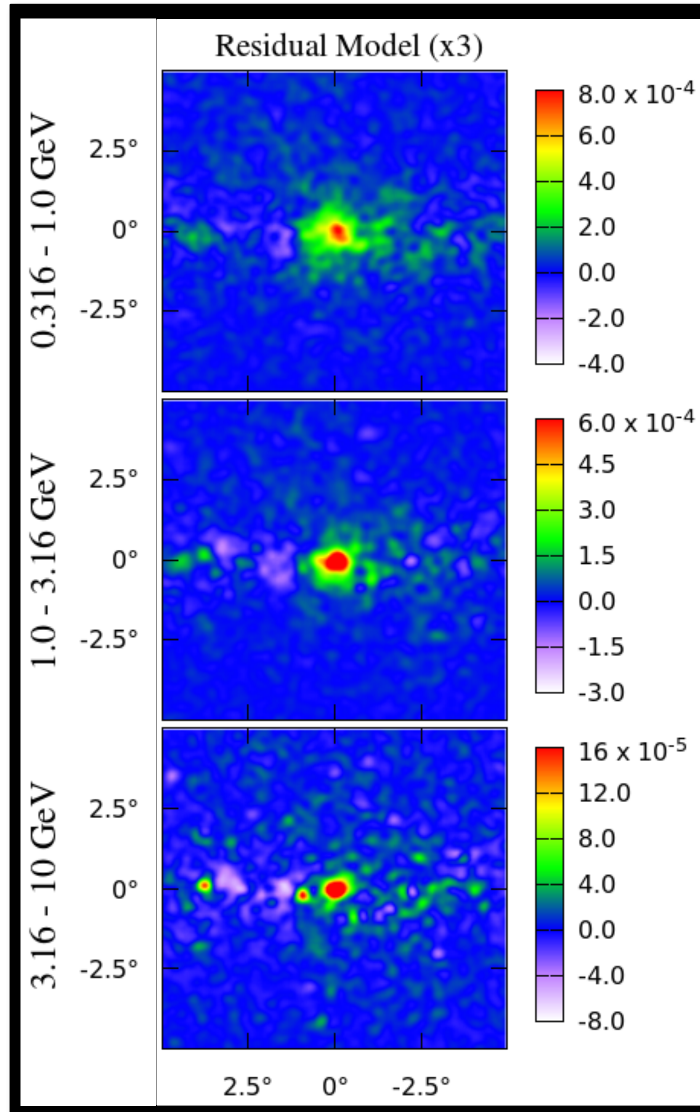
Fermi Collaboration, arXiv:1611.03184



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

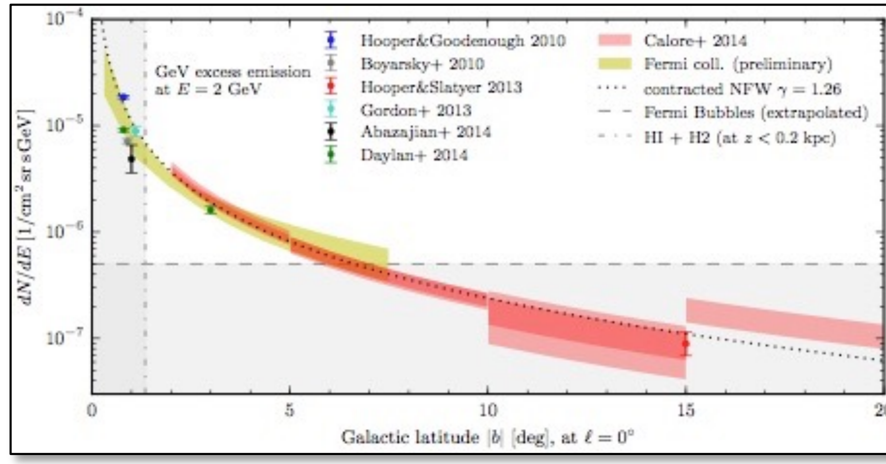
The Galactic Center Gamma-Ray Excess

- A bright and highly statistically significant excess of gamma-rays has been observed from the region surrounding the Galactic Center
- This signal is difficult to explain with astrophysical sources or mechanisms, but is very much like the signal long predicted from annihilating dark matter



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

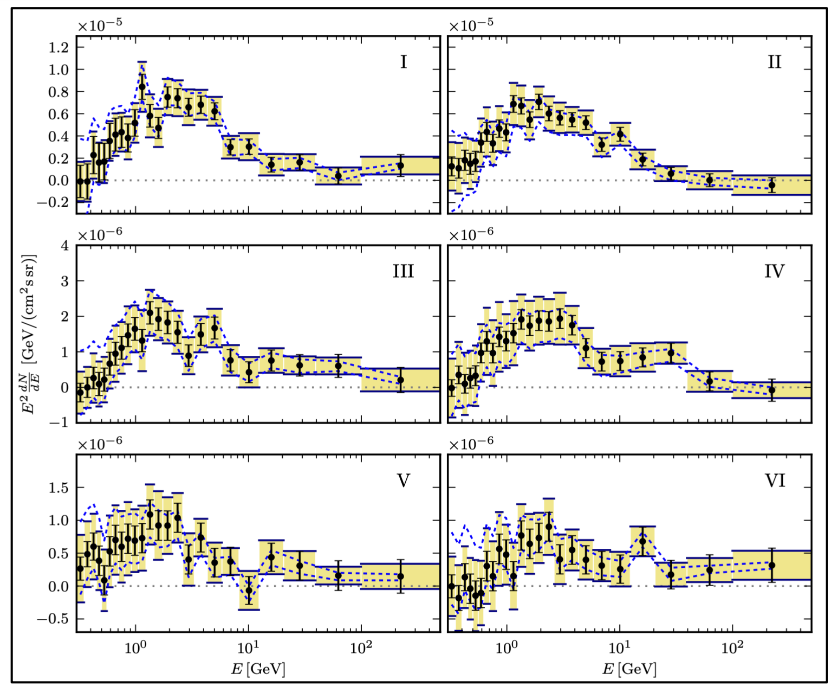
The Galactic Center Gamma-Ray Excess



Morphology

- Approximate spherical symmetry about the Galactic Center, with a flux that falls as ~r $^{-2.4}$ out to at least ~10°
- If from annihilating dark matter, this implies ρ_{DM} ~ r $^{-1.2}$ out to at least ~1.5 kpc, only slightly steeper than the NFW profile

Spectrum



- Well fit by a ~40-60 GeV particle annihilating to quarks or gluons
- Uniform across the Inner Galaxy

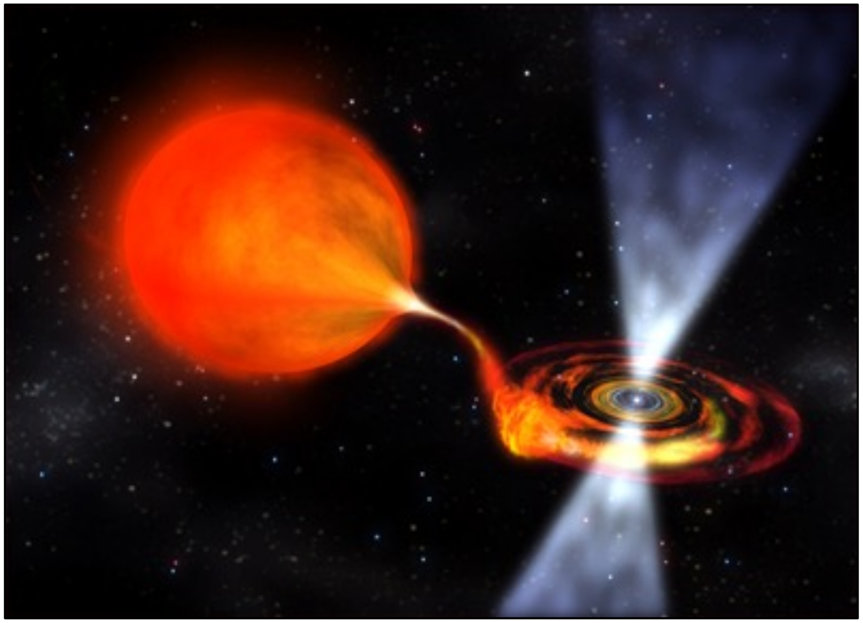
Intensity

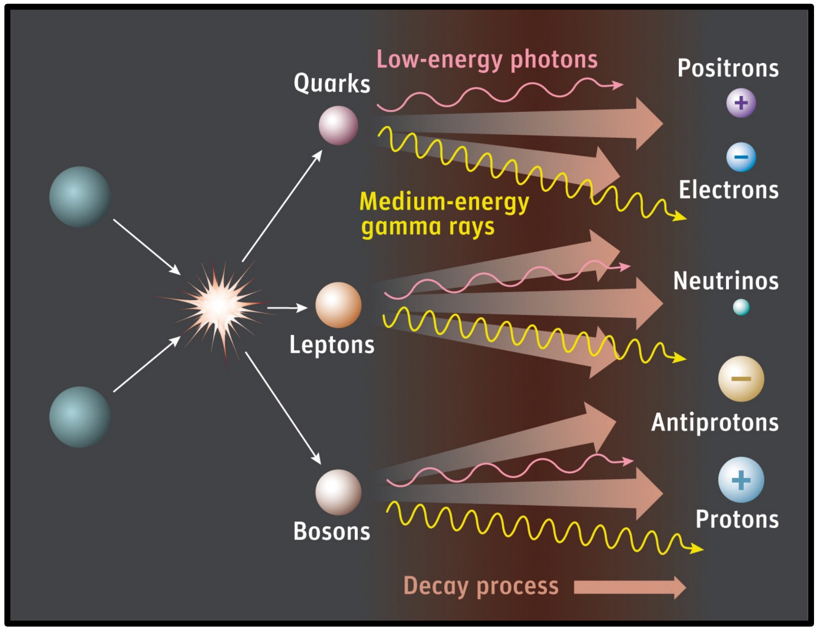
- To normalize the observed excess, the DM particles must annihilate with σv ~ 10^{-26} cm^3/s, approximately equal to the value required to obtain the measured DM abundance

Cholis, Zhong, McDermott, Surdutovich (2021), Calore, Cholis, Weniger (2014)

What Produces the Excess?

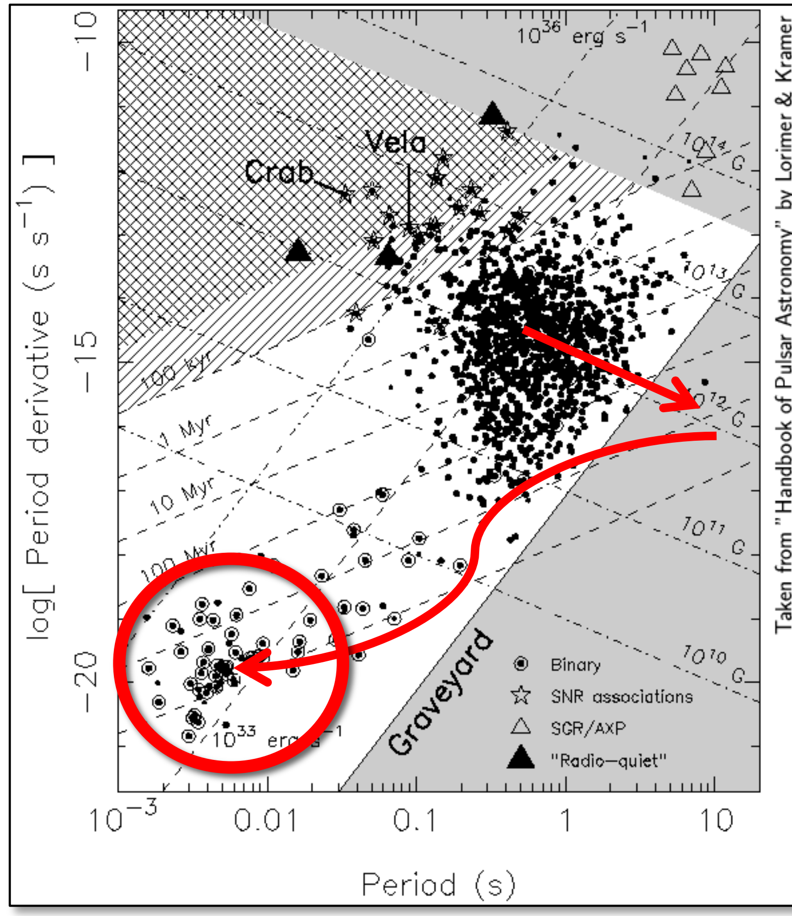
- A large population of centrally located millisecond pulsars?
- Annihilating dark matter?

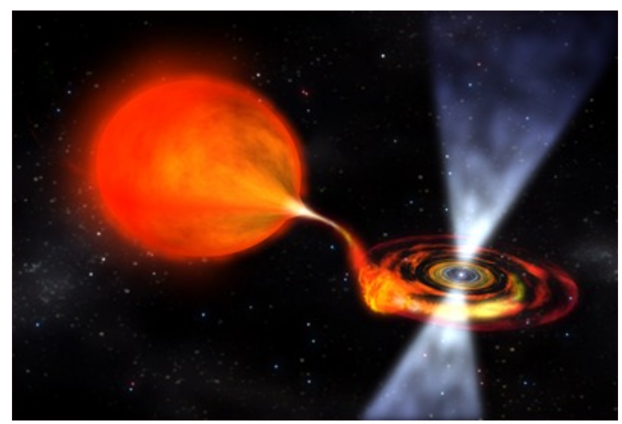




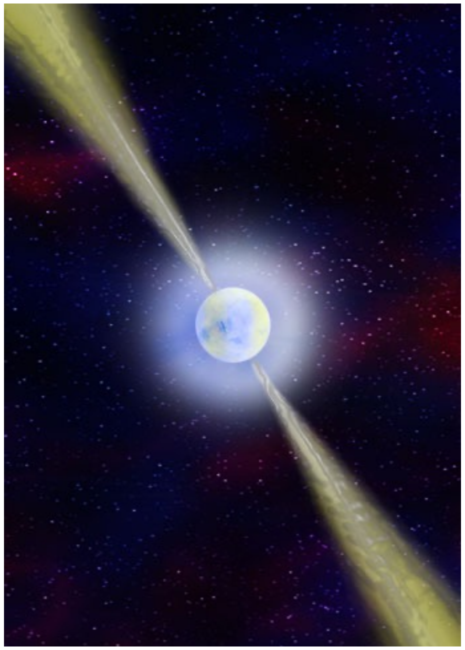
Millisecond Pulsars

- Pulsars are rapidly spinning neutron stars, which gradually convert their rotational kinetic energy into radio and gamma-ray emission
- Young pulsars exhibit periods on the order of ~1 second and slow down and become faint over ~10^6 -10^8 years
- Accretion from a companion star can "spin-up" a dead pulsar to periods as fast as ~1.5 ms
- Such millisecond pulsars have low magnetic fields (~10^8-10^9 G) and thus spin down much more gradually, remaining bright for >10^9 years
- It seems plausible that large numbers of MSPs could exist near the Galactic Center





Millisecond Pulsars and The Galactic Center Gamma-Ray Excess



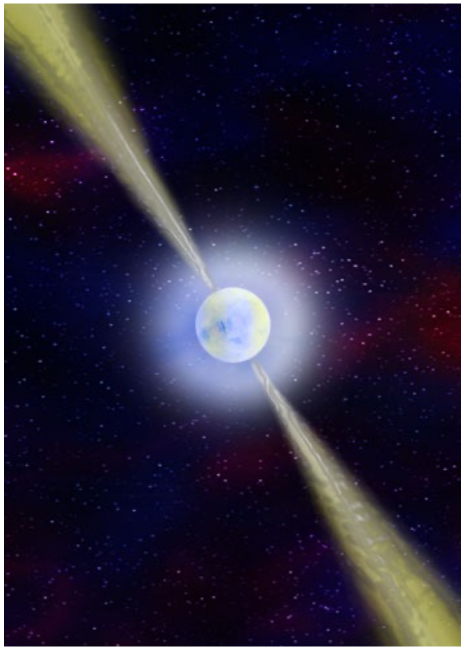
Arguments in Favor of Pulsars:

- The gamma-ray spectrum of observed pulsars
- Claims of small-scale power in the gamma-ray the Inner Galaxy
- Claims that the excess traces the Galactic Bulge/Bar

Arguments Against Pulsars:

- No millisecond pulsars have been detected in the Inner Galaxy, in tension with the measured luminosity function of gamma-ray pulsars
- The lack of low-mass X-ray binaries in the Inner Galaxy
- The relatively low luminosity of the TeV-scale emission from the Inner Galaxy

Millisecond Pulsars and The Galactic Center Gamma-Ray Excess



Arguments in Favor of Pulsars:

- The gamma-ray spectrum of observed pulsars
- ~~Claims of small-scale power in the gamma-ray the Inner Galaxy~~
- ~~Claims that the excess traces the Galactic Bulge/Bar~~

Arguments Against Pulsars:

- No millisecond pulsars have been detected in the Inner Galaxy, in tension with the measured luminosity function of gamma-ray pulsars
- The lack of low-mass X-ray binaries in the Inner Galaxy
- The relatively low luminosity of the TeV-scale emission from the Inner Galaxy

Evidence of Unresolved Gamma-Ray Sources?

- In 2015, two groups found that the ~GeV photons from the direction of the Inner Galaxy are more clustered than predicted from smooth backgrounds, suggesting that the GeV excess might be generated by a population of unresolved point sources
- Lee et al. used a non-Poissonian template technique to show that the photon distribution within ~10° of the Galactic Center (masking within 2° of the Galactic Plane) is *clumpy*, potentially indicative of an unresolved point source population
- Bartels et al. reached a qualitatively similar conclusion employing a wavelet technique

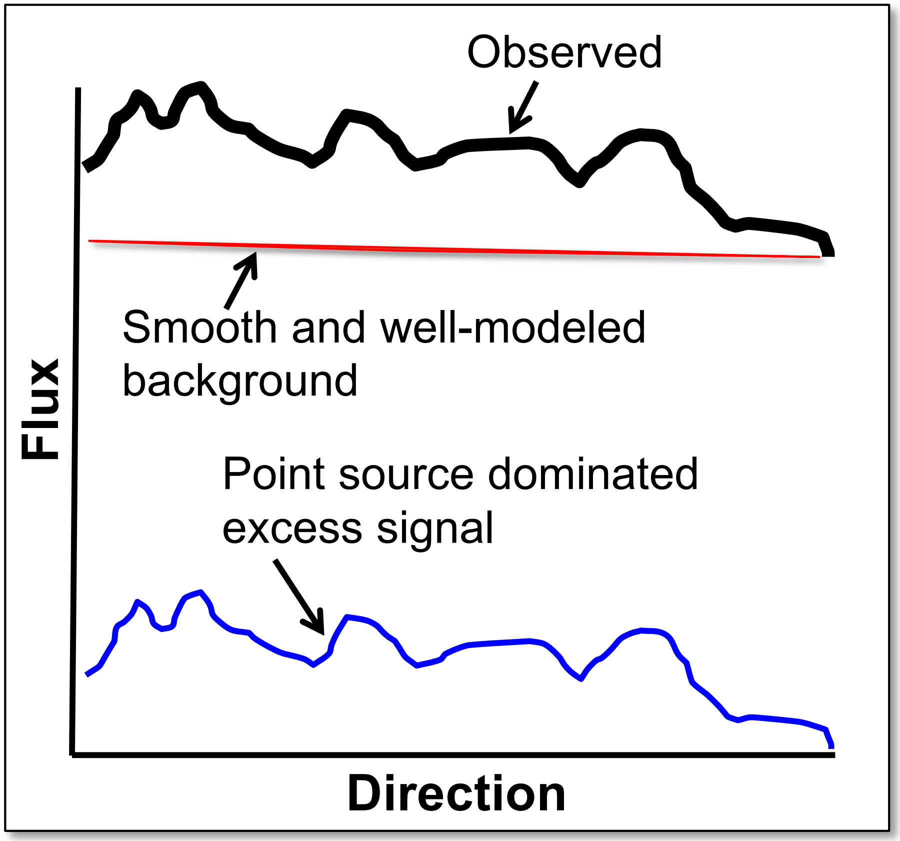
Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124
Bartels, Krishnamurthy, Weniger, arXiv:1506.05104

Evidence of Unresolved Point Sources?

- It is difficult to tell whether these clustered gamma-rays result from unresolved sources, or from backgrounds that are less smooth than are being modeled

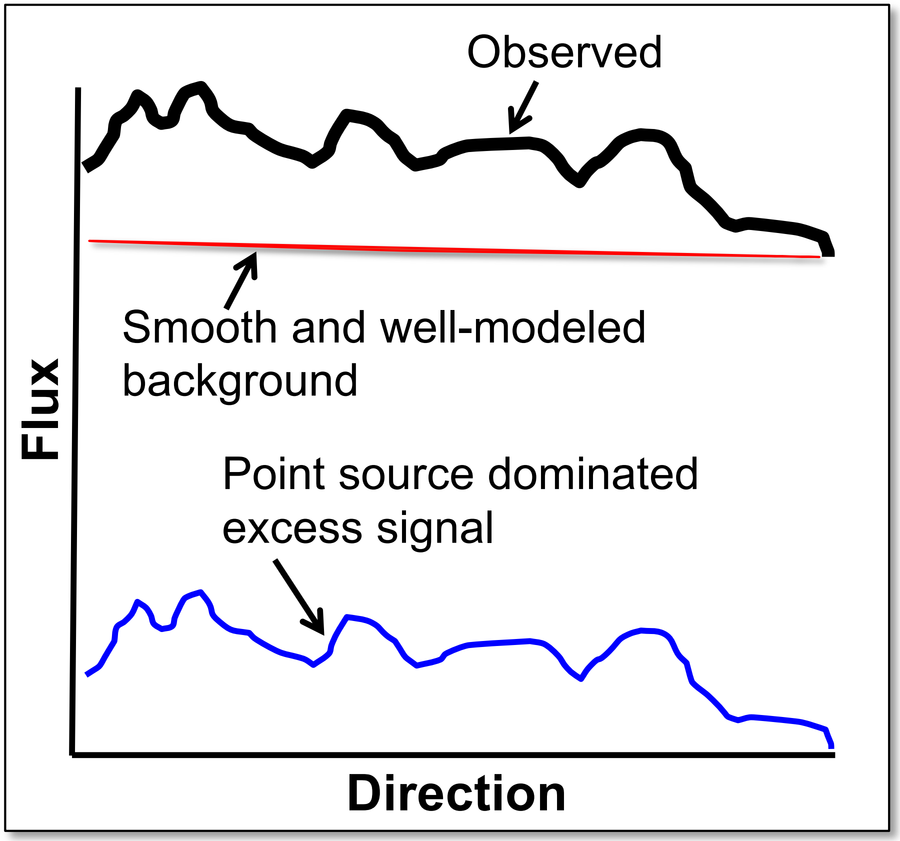
Evidence of Unresolved Point Sources?

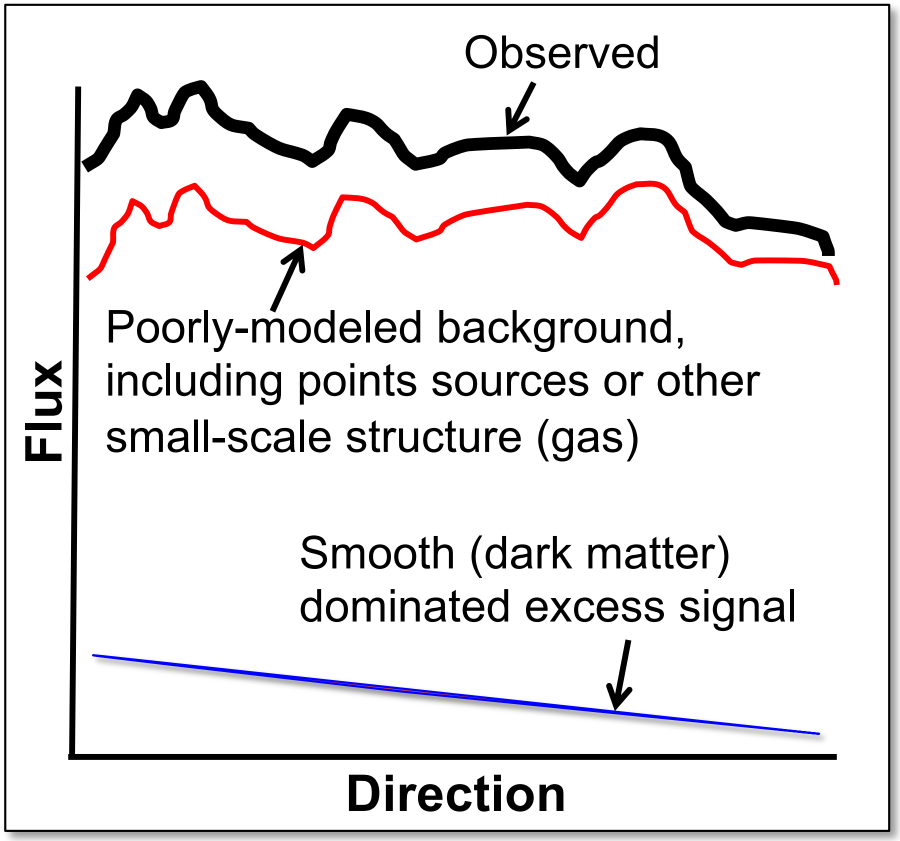
- It is difficult to tell whether these clustered gamma-rays result from unresolved sources, or from backgrounds that are less smooth than are being modeled



Evidence of Unresolved Point Sources?

- It is difficult to tell whether these clustered gamma-rays result from unresolved sources, or from backgrounds that are less smooth than are being modeled





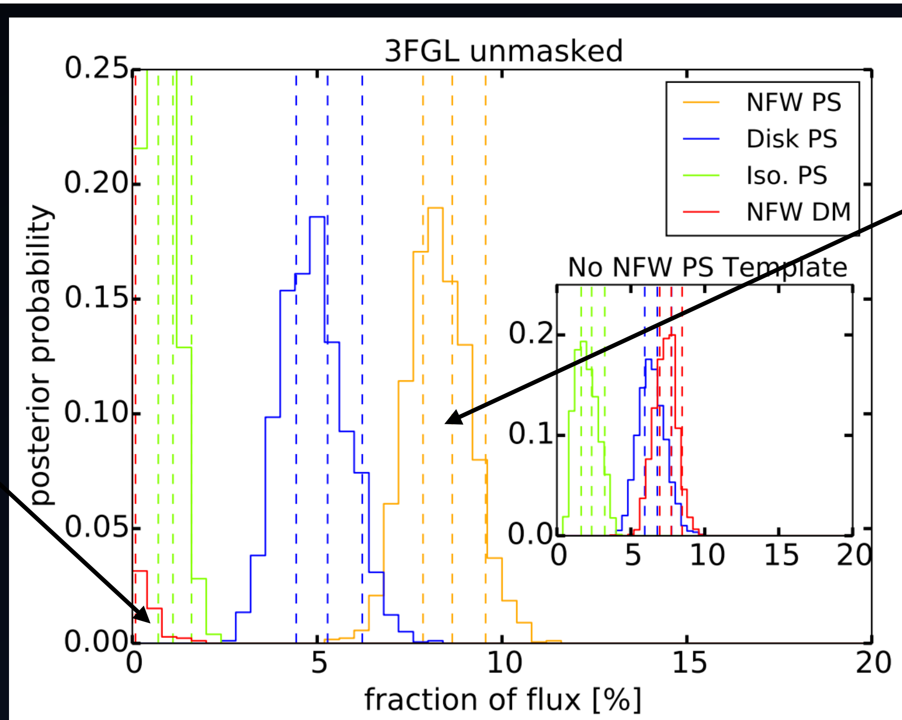
DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

See Leane and Slatyer, arXiv:1904.08430

DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

See Leane and Slatyer, arXiv:1904.08430

Evidence against any significant amount of dark matter annihilation



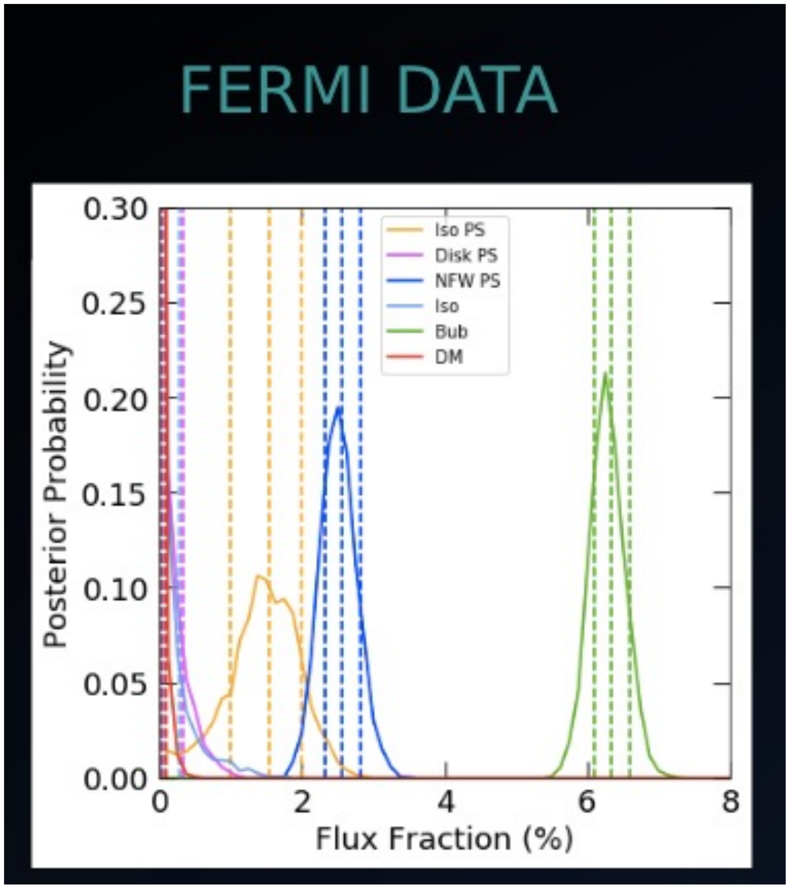
Lee, Lisanti, Safdi, Slatyer, Xue (PRL '15)

Evidence for NFW^2 Distributed Point Sources

To what extent could inadequate templates be biasing these results?

DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

See Leane and Slatyer, arXiv:1904.08430

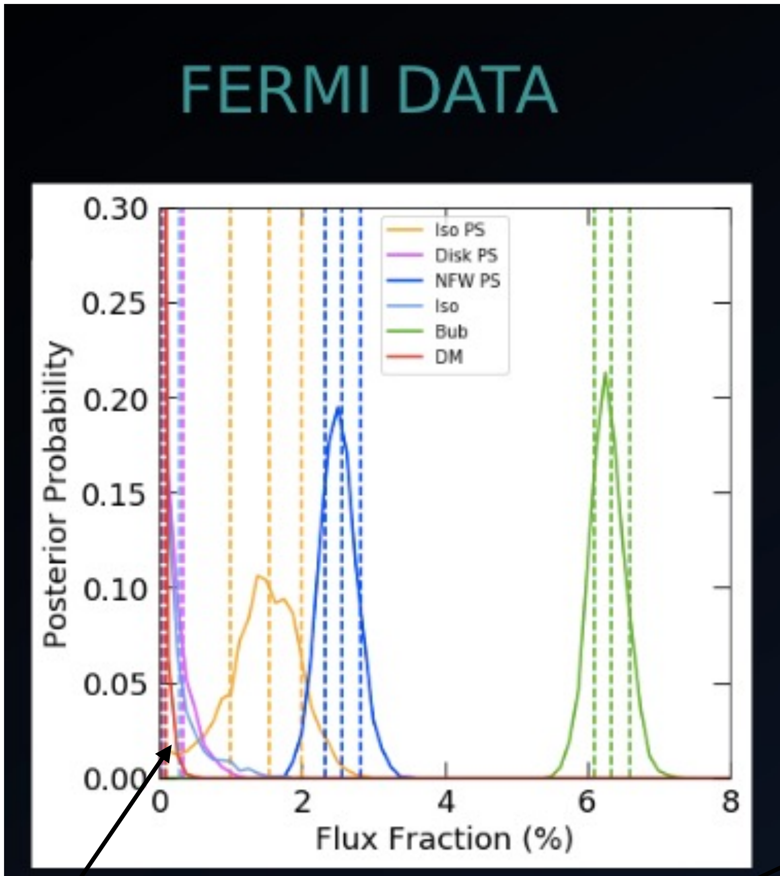


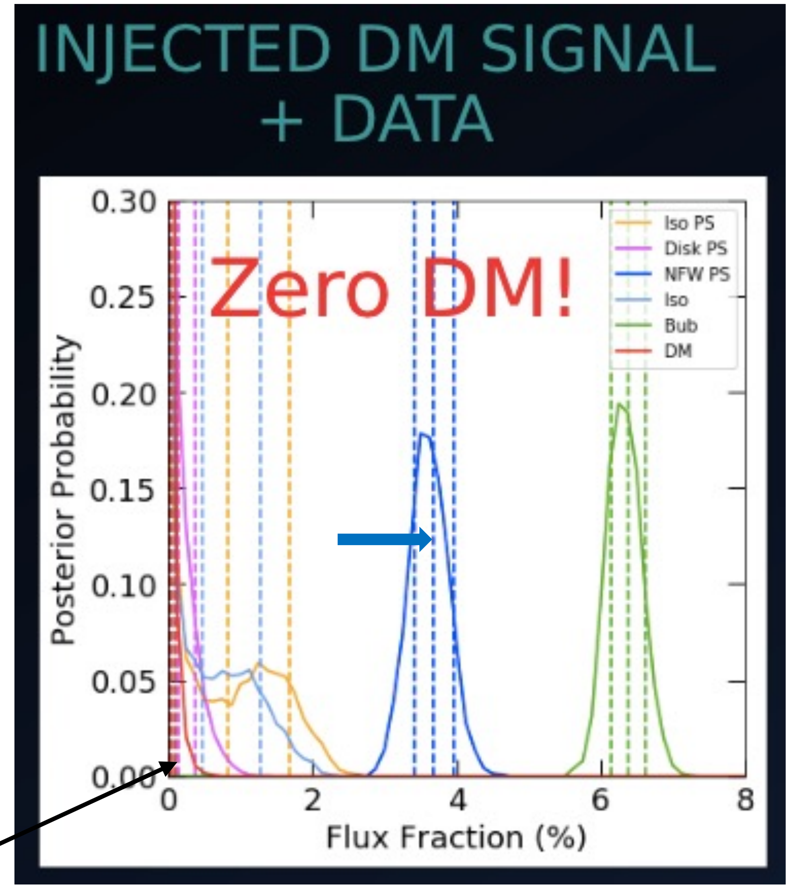
Here is the result that Leane and Slatyer get using the same procedure as Lee *et al.*

To test the reliability of this result, they then add to the Fermi data a (smooth) dark matter-like signal

DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

See Leane and Slatyer, arXiv:1904.08430

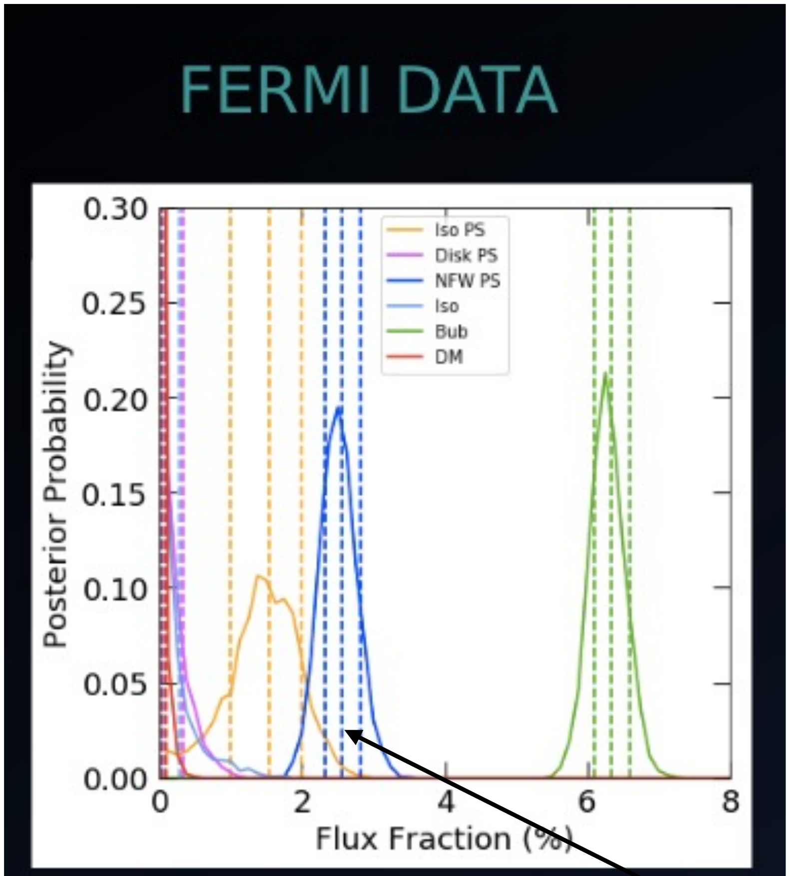


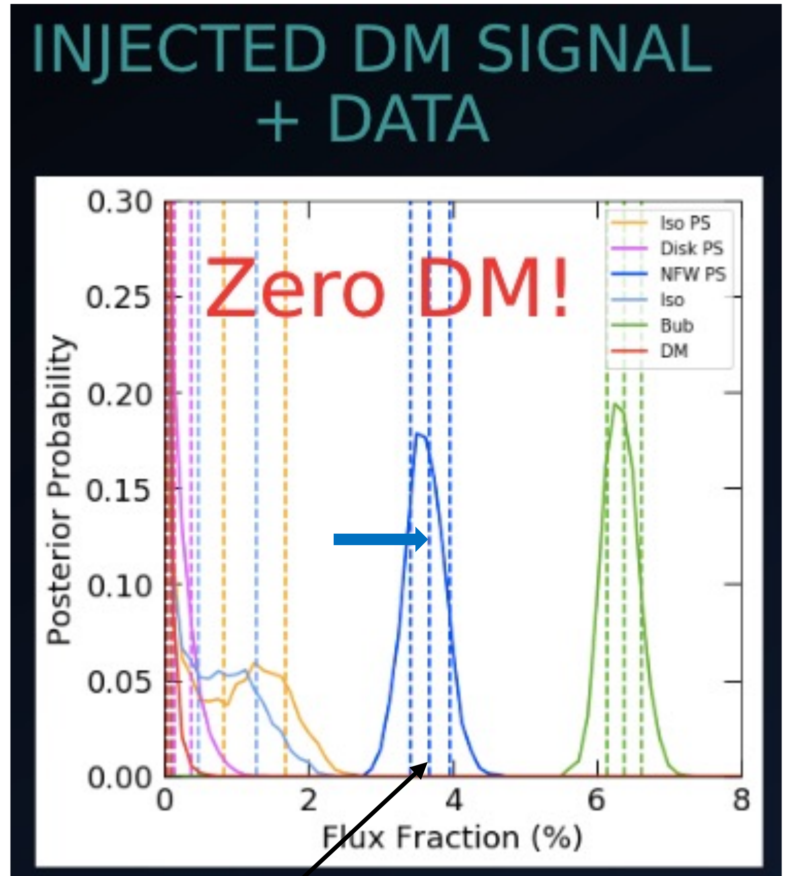


Despite having just added a dark matter-like signal to the data, the fit *does not* ascribe any of it to the dark matter template

Dark Matter Strikes Back at the Galactic Center

See Leane and Slatyer, arXiv:1904.08430





Despite having just added a dark matter-like signal to the data, the fit *does not* ascribe any of it to the dark matter template

Instead, the fit identifies the injected dark matter-like signal as originating from point sources

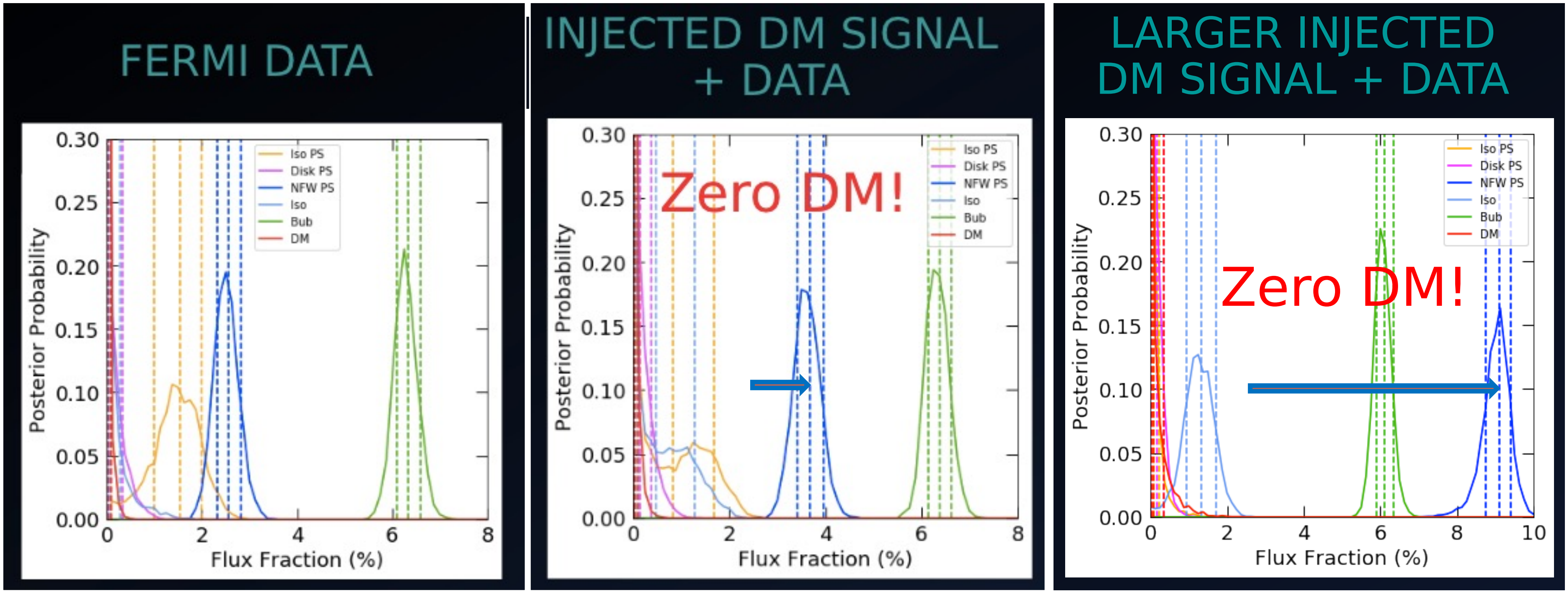
DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

See Leane and Slatyer, arXiv:1904.08430

What happens if an even larger dark matter-like signal is added to the data?

DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

See Leane and Slatyer, arXiv:1904.08430



Even very bright dark matter-like signals are misattributed to the point source templates! (up to an order of magnitude larger than the intensity of the excess)

DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

See Leane and Slatyer, arXiv:1904.08430

Bottom Line:

The non-Poissonian template fit is clearly **misattributing** the dark matter-like signal to point sources, demonstrating that the templates being used are **not adequate to describe the data**, strongly biasing the results of the fit

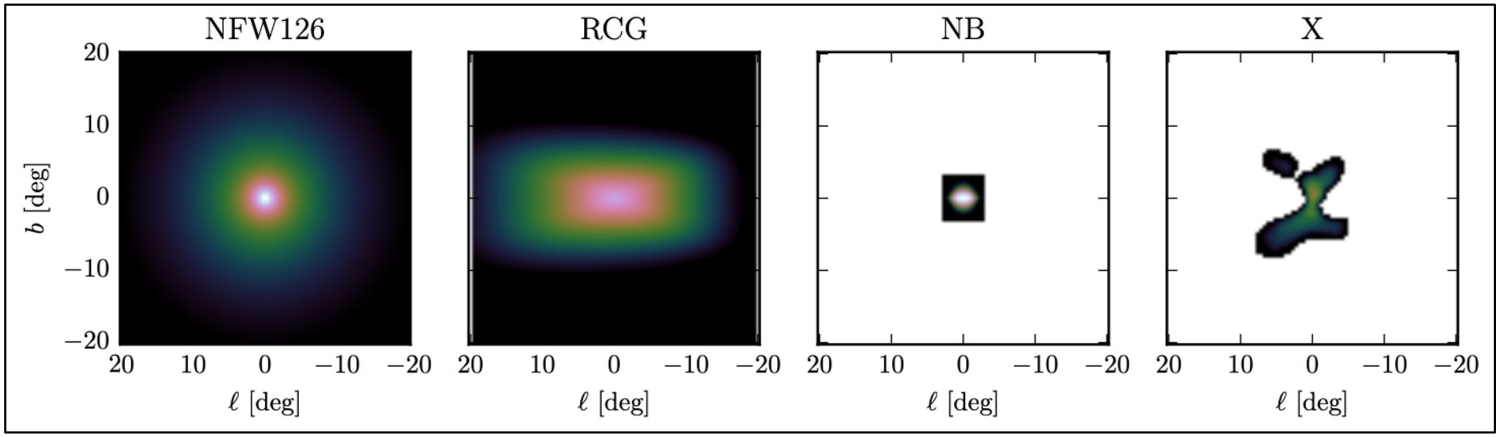
This method does ***not*** provide evidence for point sources over a dark matter interpretation of the excess

In 2019, Zhong, McDermott, Cholis & Fox revisited the wavelet method; after updating the gamma-ray source catalog (4FGL vs 3FGL), they find no evidence that the excess is produced by point sources – if pulsars generate this signal, they must be *very* faint and *very* numerous ($\gtrsim 10^5$)

Zhong, McDermott, Cholis, Fox, arXiv:1911.12369

Bulge/Bar-Like vs DM-Like Morphology

- An important test of the GC excess' origin is to establish whether the angular distribution of this signal is spherical (DM-like), or instead traces some combination of known stellar populations (*ie*., the Galactic Bulge and Bar)



- In three papers (listed below), it was argued that the Fermi excess is better fit by spatial templates that trace stellar populations than dark matter-like templates, favoring MSP interpretations of the gamma-ray excess

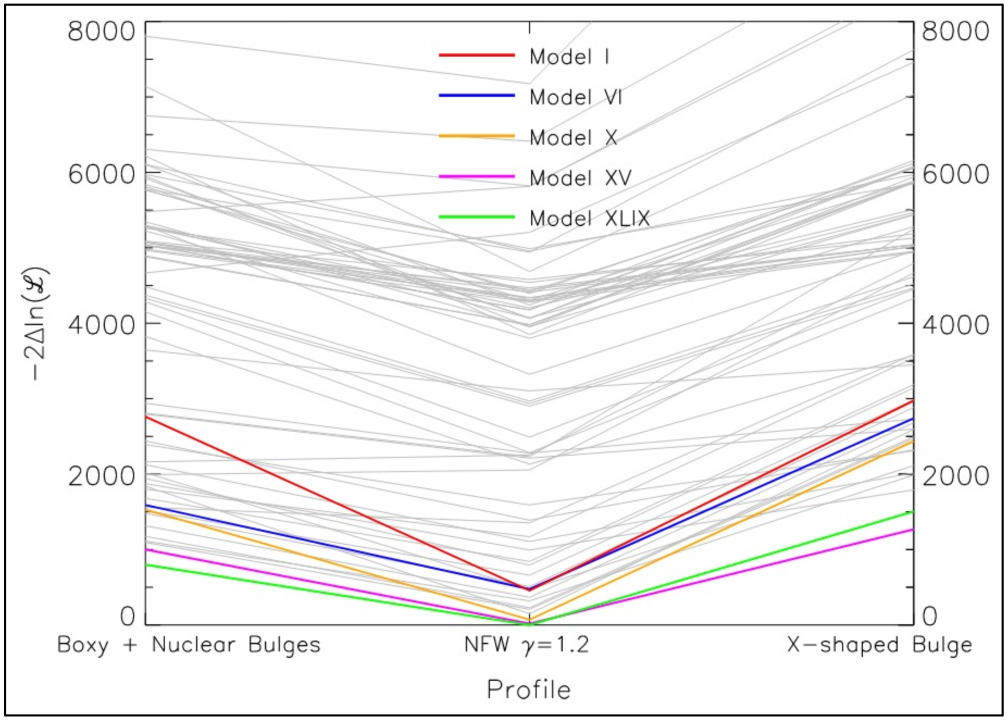
Macias, Gordan, Crocker, Coleman, Paterson, Horiuchi, Pohl, arXiv:1611.06644
Bartels, Storm, Weinger, Calore, arXiv:1711.04778
Macias, Horiuchi, Kaplinghat, Gordan, Crocker, Nataf, arXiv:1901.03822

Bulge/Bar-Like vs DM-Like Morphology

- More recent work, however, has not confirmed these results, but instead finds ***a strong statistical preference for a dark matter-like template*** (Di Mauro, arXiv:2101.04694; Cholis, Zhong, McDermott, Surdutovich, arXiv:2112.09706)

- The differences between these results could be indicative of the systematic uncertainties associated with the choice of astrophysical templates, or might simply reflect a failure of the earlier analyses to identify the true global minimum of this highly multi-dimensional parameter space

- Recent work has consistently favored a spherical morphology for this signal (and thus the DM hypothesis)



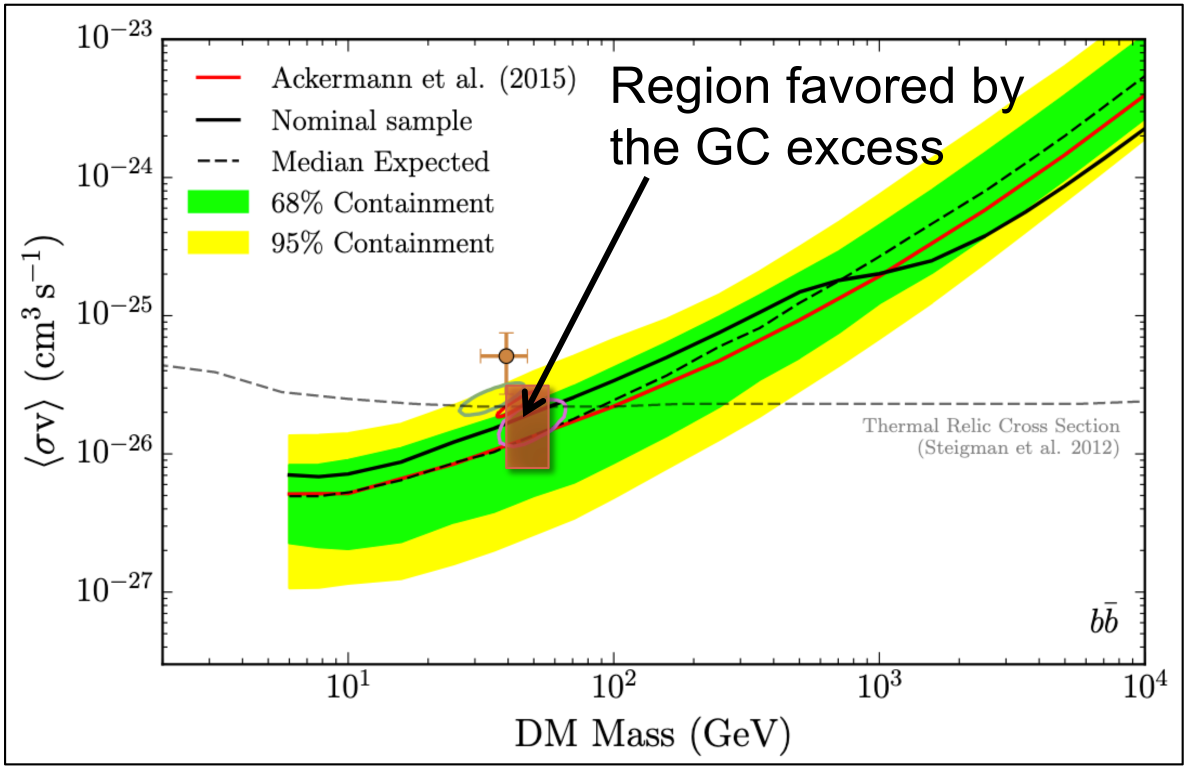
Cholis, et al. (2021)

Macias, Gordan, Crocker, Coleman, Paterson, Horiuchi, Pohl, arXiv:1611.06644
Bartels, Storm, Weinger, Calore, arXiv:1711.04778
Macias, Horiuchi, Kaplinghat, Gordan, Crocker, Nataf, arXiv:1901.03822
Di Mauro, arXiv:2101.04694; Cholis, Zhong, McDermott, Surdutovich, arXiv:2112.09706

If the Galactic Center Excess is the result of annihilating dark matter, where else would we expect to see evidence of this process?

Fermi Observations of Dwarf Galaxies

- Current Fermi dwarf constraints are based on observations of several dozen dwarf galaxies, including many that were discovered in DES and other recent surveys
- Although these constraints are currently compatible with dark matter interpretations of the Galactic Center excess, even modest improvements in sensitivity would shed significant light on this interpretation



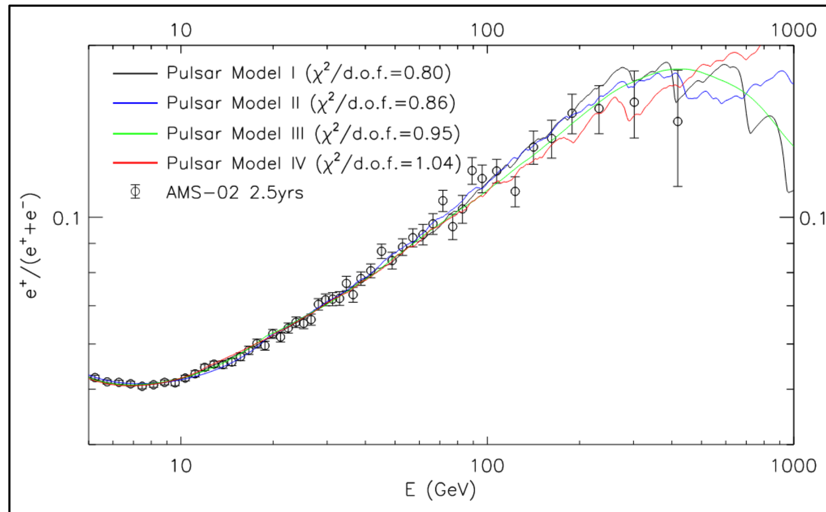
Fermi Collaboration, arXiv:1611.03184

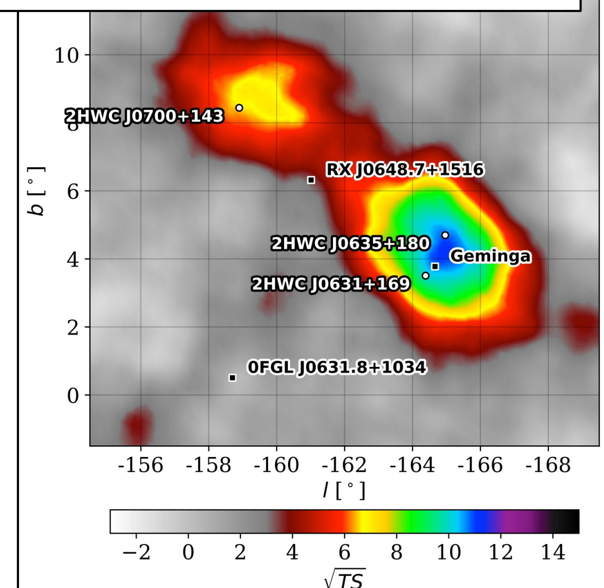
Dwarf Galaxies in the Rubin Era

- The Rubin Observatory (first light in 2023!) is expected to discover ~150-250 new Milky Way dwarf galaxies (compared to ~50 at present)
- Once these new dwarfs are discovered, we can use already existing Fermi data to look for gamma-ray signals from annihilating dark matter
- With Rubin, Fermi's sensitivity to dark matter annihilation in dwarf galaxies could plausibly increase by a factor of ~2-3, finally enabling us to test much of parameter space favored by the Galactic Center excess

Dark Matter Searches Using Cosmic-Ray Anti-Nuclei

- While most astrophysical processes generate far more matter than antimatter, dark matter annihilation (in most models) produces equal fluxes of particles and antiparticles
- Searches for excess antimatter (positrons, antiprotons, anti-nuclei) in the cosmic-ray spectrum can be a powerful probe of DM annihilation in the halo of the Milky Way
- An excess of cosmic-ray positrons generated a great deal of interest in this context, but it is now reasonably clear that these particles originate from nearby TeV halos associated with young and middle-aged pulsars (DH et al, arXiv:1702.08436)

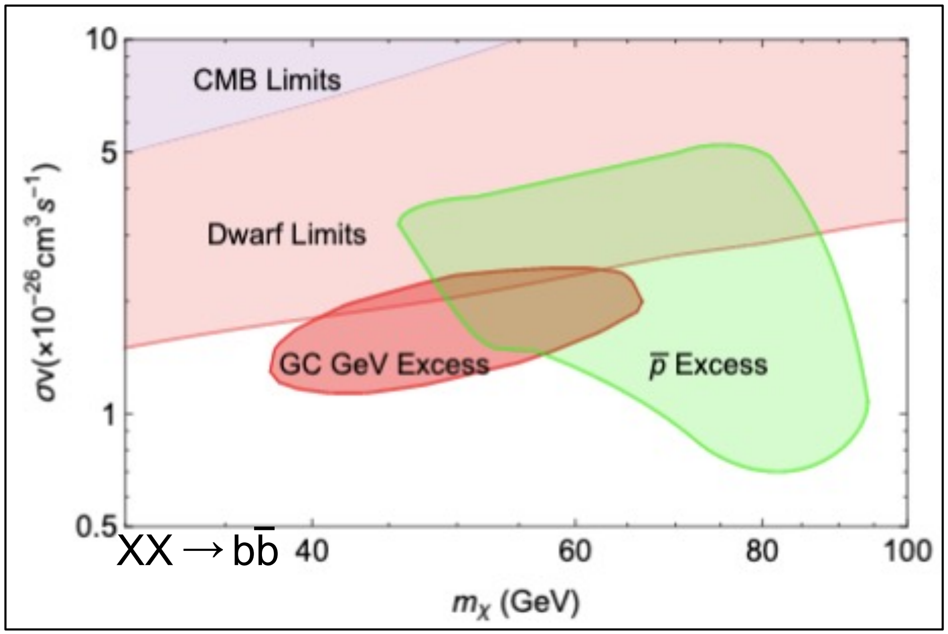


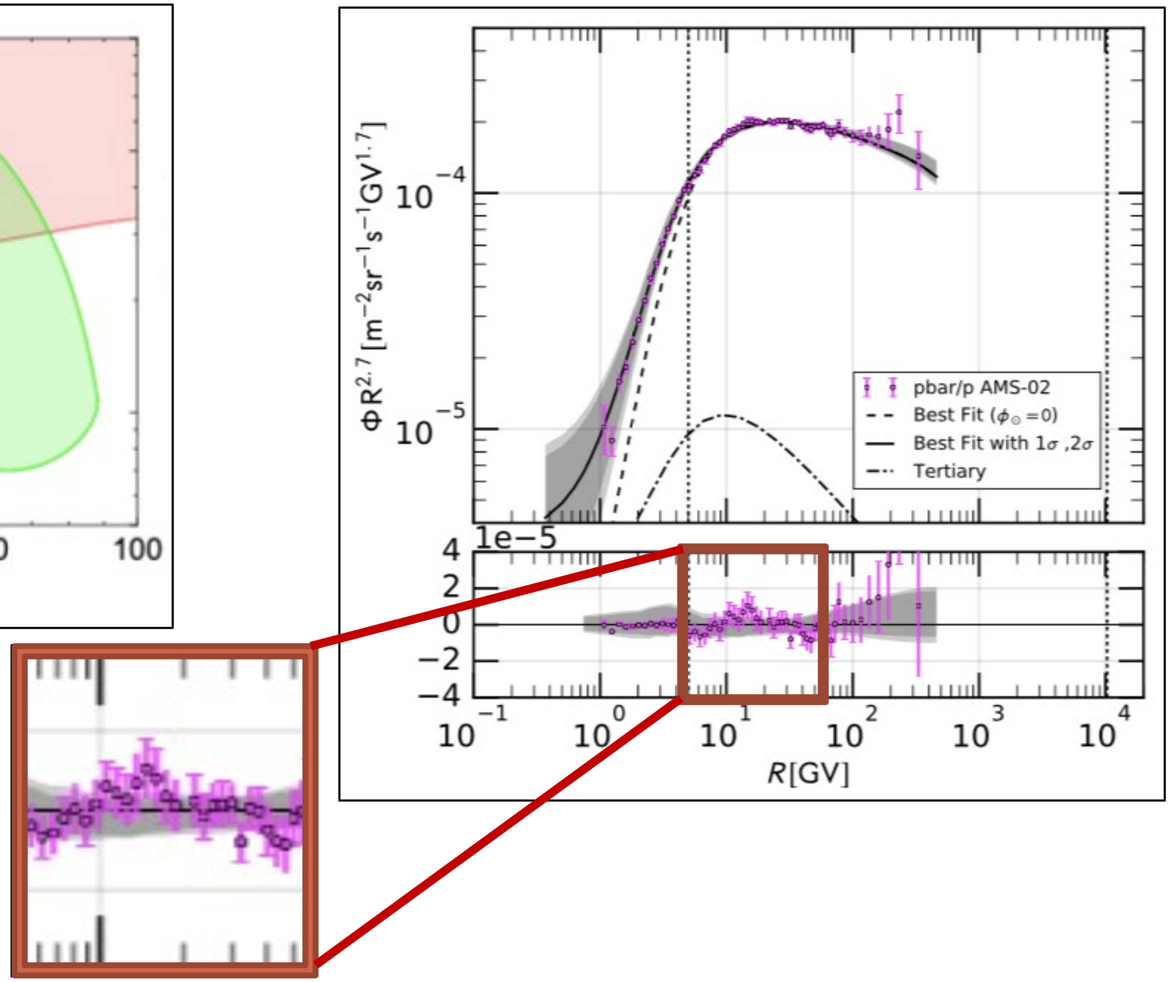


Cholis et al., arXiv:1807.05230;
HAWC Collaboration, arXiv:1702.02992

The Cosmic-Ray Antiproton Excess

- There is a small excess of ~10-20 GeV cosmic-ray antiprotons in the AMS data, which at face value is quite statistically significant, ~4.5**σ** (Cuoco, et al., Cui, et al.)
- This excess is well fit by a ~40-100 GeV WIMP with a ~2x10^{-26} cm^3/s annihilation cross section – a good match to the Galactic Center gamma-ray excess!

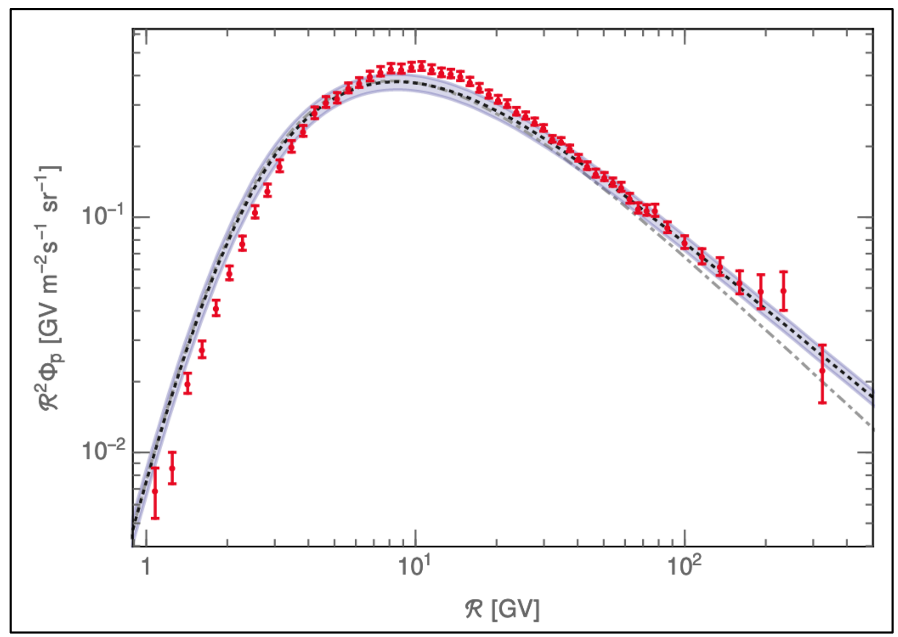




Cuoco et al., arXiv:1610.03071
Cui et al., arXiv:1610.03840
Cholis, DH, Linden, arXiv:1903.02549
Cuoco et al., arXiv:1903.01472
Reinert, Winkler, arXiv:1712.00002

The Cosmic-Ray Antiproton Excess

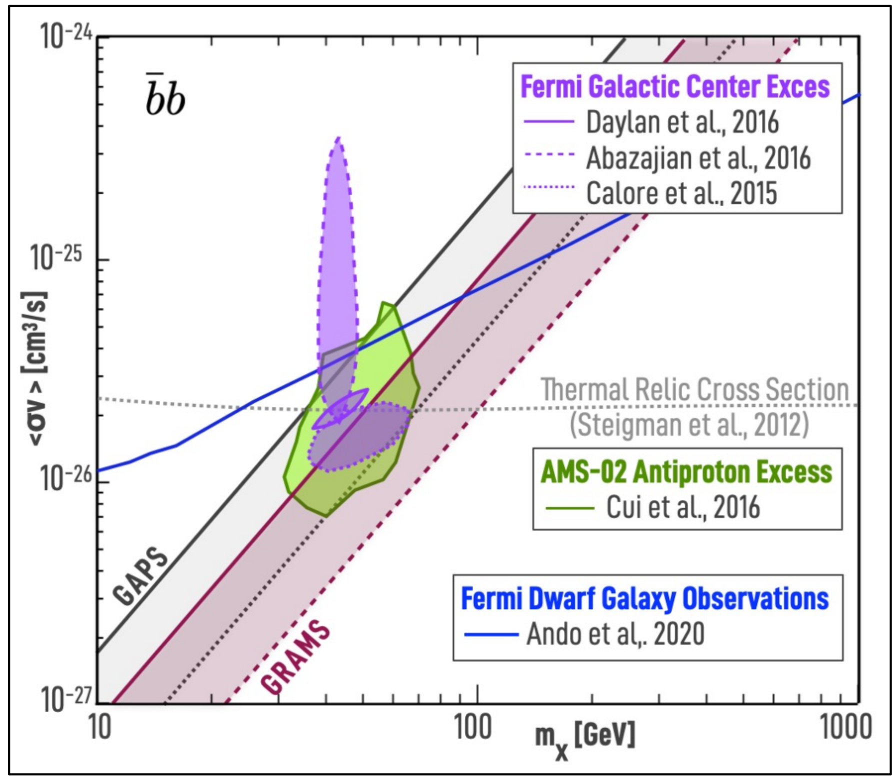
- Although suggestive, many of us in the cosmic-ray community are somewhat skeptical of the anti-proton excess, driven in large part by concerns pertaining to the uncertainties associated with the antiproton production cross section
- To convince us that this excess is real, it is imperative that laboratory measurements of this cross section be improved



M. Winkler, arXiv:1701.04866

Cosmic-Ray Anti-Nuclei

- Searches for cosmic-ray anti-deuterons and anti-helium nuclei are also going to be very exciting in the years ahead
- GAPS (General Anti-Particle Spectrometer), GRAMS (Gamma-Ray and Anti-Matter Survey), and AMS are each projected to be sensitive to the dark matter parameter space favored by the Galactic Center excess
- The first balloon flight for GAPS is scheduled for early 2023
- We could hear more from AMS on this subject at anytime

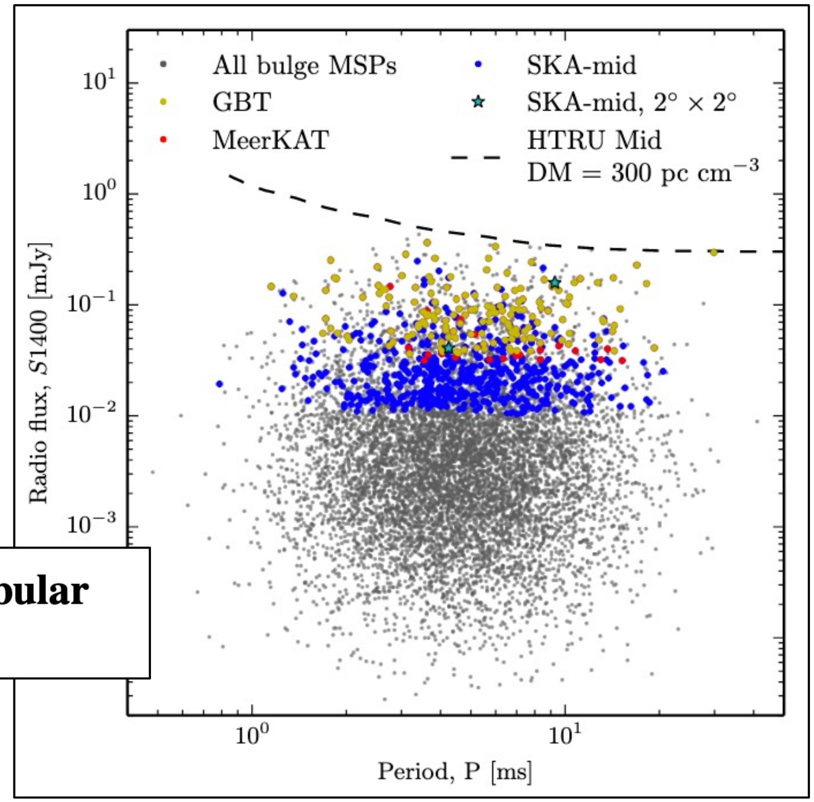


Leane et al., arXiv:2203.06859

Radio Searches for Inner Galaxy MSPs

- If MSPs generate the GeV excess, future deep radio surveys should be able to detect the pulsed radio emission from these objects
- After ~10^2 hours of observation, Green Bank should detect ~1-2 Inner Galaxy MSPs
- Dozens should be detectable with MeerKAT (after a similar exposure)
- Hundreds should be detectable with SKA
- MeerKAT was commissions in 2016, and has already announced their first MSP discoveries (far from Inner Galaxy), arXiv:2103.04800

Eight new millisecond pulsars from the first MeerKAT globular cluster census



- First light for SKA is projected for 2027

Calore, Di Mauro, Donato, Hessels, Weniger, arXiv:1512.06825

Summary

- Direct detection experiments have improved in sensitivity at an exponential rate over the past 2 decades, ruling out many well-motivated dark matter models; many others will be explored over the next decade
- While many WIMP models have been ruled out, many others remain viable; claims that “the WIMP is dead” are sorely premature
- Indirect searches using gamma rays and antimatter 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
- The Galactic Center gamma-ray excess remains compelling as a possible signal of annihilating dark matter, and is difficult to explain with known or proposed astrophysics; future observations (dwarf galaxies, cosmic-ray antimatter) will be critical to establishing the origin of this signal