New Eras in Astro-Particle Physics

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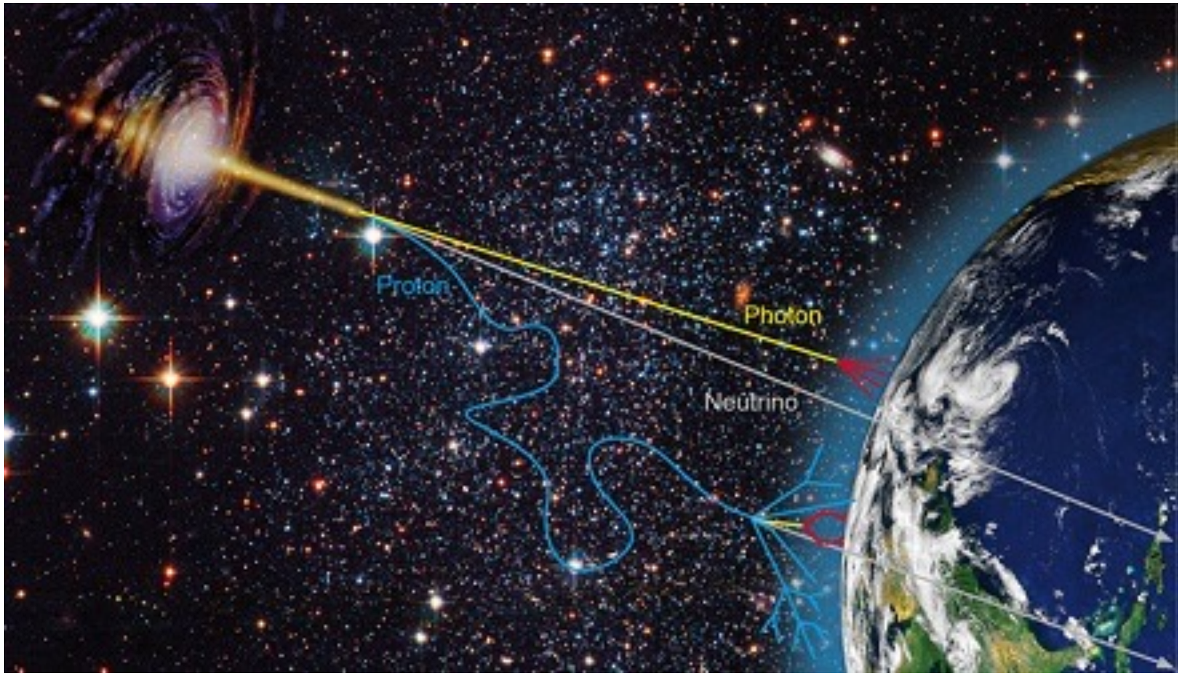
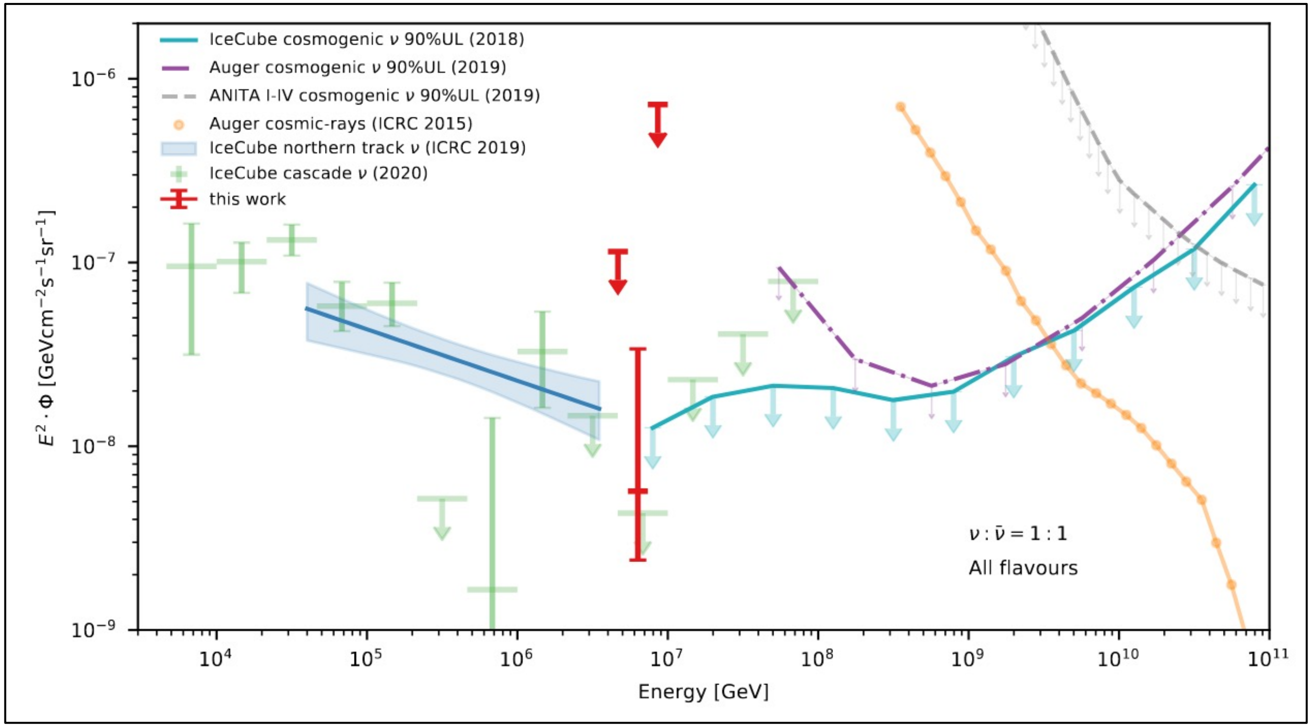
High-Energy Cosmic Particles

- Up until the middle of the 20th century, essentially all of astrophysics was conducted using visible light – today, we use other messengers to collect complementary information
- Energetic cosmic rays, gamma rays and neutrinos each help us to study our universe's most extreme environments
- Despite decades of investigation, the origin of the highest energy cosmic particles remains a mystery



IceCube's High-Energy Neutrinos

- IceCube has measured a diffuse spectrum of astrophysical neutrinos, ranging in energy from several TeV to several PeV (at least)
- Approximately isotropic, with a roughly power-law spectrum $dN/dE \sim E^{-2.3}$
- These particles almost certainly originate from sources of the high and ultra-high energy cosmic rays



IceCube, arXiv:2110.15051

IceCube's High-Energy Neutrinos

Where do these neutrinos come from? Some long-standing hypotheses:

-Gamma-Ray Bursts (GRB)

-Blazars

-Other Active Galactic Nuclei (AGN)

-Star-Forming/Starburst Galaxies

IceCube, arXiv:1702.06868, 1601.06484, 1412.6510, 1204.4219

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- Compared to other source classes, the GRB hypothesis is relatively easy to test
- Individual GRB are very bright and brief, allowing us to search for coincidences in both time and direction
- IceCube data has taught that:

1) GRB are ***not*** efficient producers of high-energy neutrinos

2) GRB do ***not*** appear to be responsible for the acceleration of the ultra-high energy cosmic rays

IceCube, arXiv:1702.06868, 1601.06484, 1412.6510, 1204.4219

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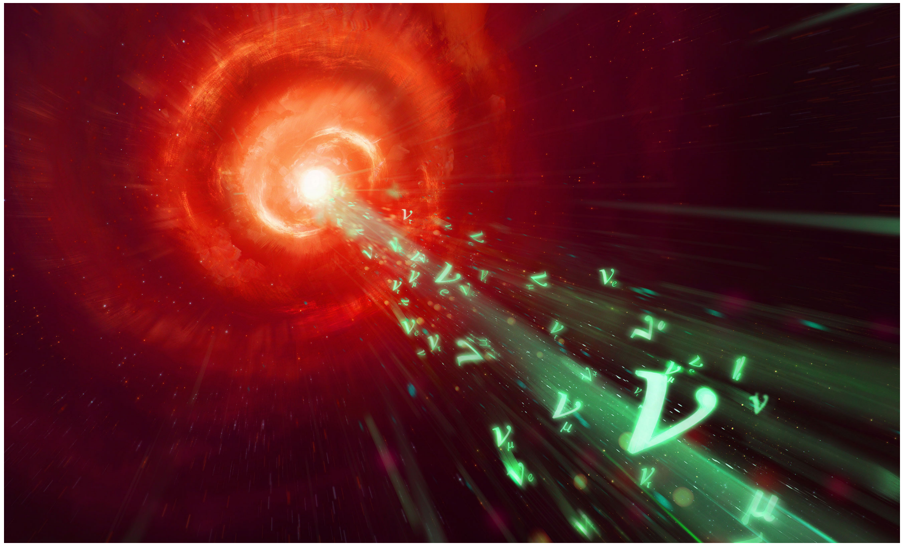

- Blazars (AGN with jets aligned in our direction) have long been considered to be a top candidate for high-energy neutrino production
- In 2018, IceCube reported the detection (~3.5σ) of events in coincidence with a flaring blazar, TXS 0506+056
- While this result is certainly suggestive, it is also hard to explain in terms of standard/simple blazar models
- Personally, I'm skeptical that TXS 0506+056 is responsible for these events (but I could also be wrong)

IceCube, arXiv:1807.08794, 1807.08816

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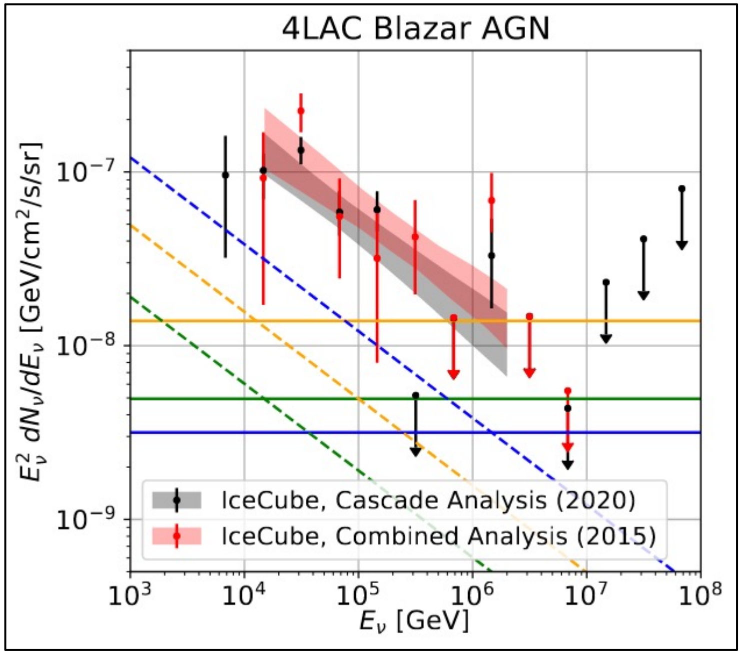
- What we can say with confidence is that ***most*** of IceCube's neutrinos do ***not*** come from blazars
- The lack of spatial correlations between these events and the directions of known blazars show that less than ~5-30% of IceCube's flux can come from this class of objects



Smith, DH, Vieregg (2020)

Kun et al, 2203.14780; Smith et al, 2007.12706; Aartsen et al, 1611.03874

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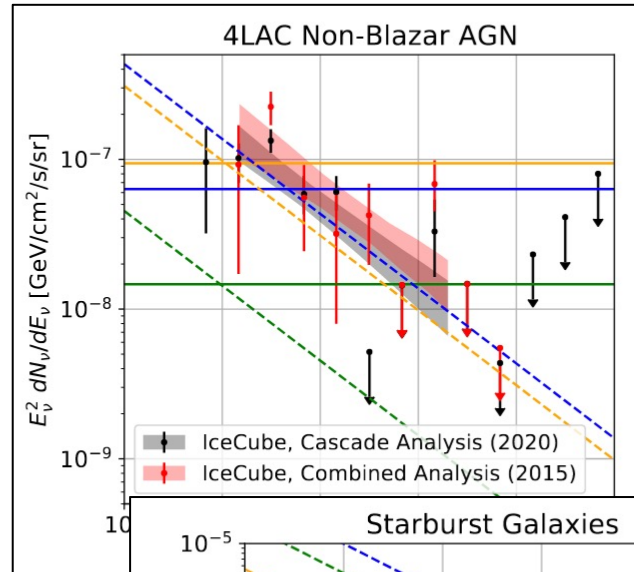

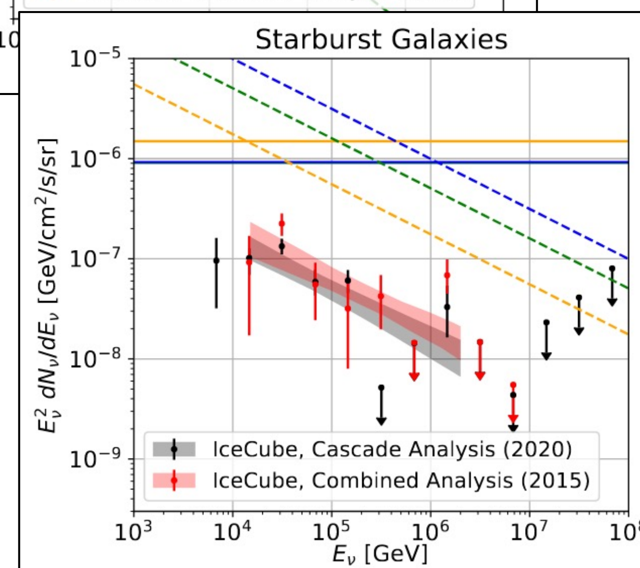

- These results demonstrate that the sources of IceCube's neutrinos are numerous and faint (at least relative to GRB and blazars)
- From this perspective, non-blazar AGN and starforming galaxies remain attractive candidates for IceCube's neutrinos – much harder to test than either GRB or blazars
- Proton-proton collisions taking place in either (or both) of these source classes could provide a reasonable fit and plausible explanation for IceCube's observed neutrinos

Smith, DH, Vieregg (2020)

IceCube's High-Energy Neutrinos

But we're at a particle physics workshop, and some of you are probably asking, "But this is all astrophysics! Why should I care?"

High-Energy Neutrinos as Probes of New Physics

- Telescopes like IceCube allow us to measure the interactions of neutrinos at ***higher energies*** and over ***longer baselines*** than is possible in any realistic laboratory experiment
- Such measurements can not only be used to learn about astrophysical objects and environments, but can also serve as a probe of physics beyond the SM

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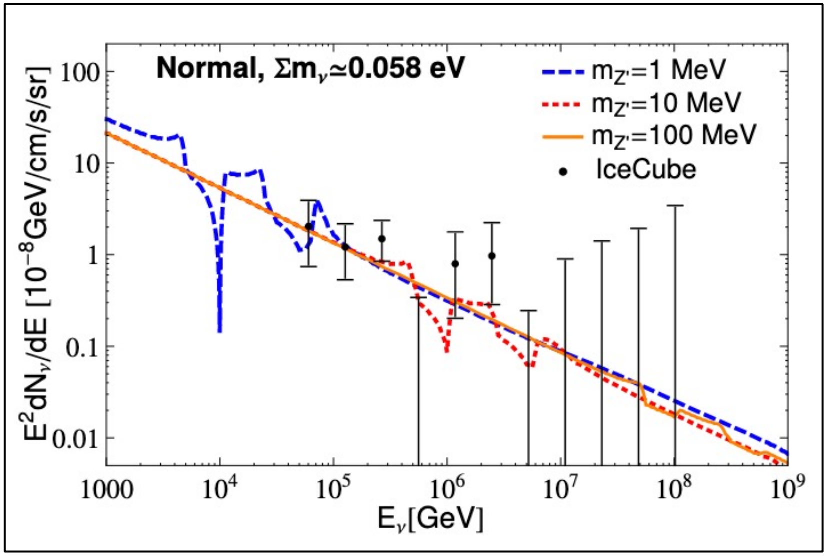
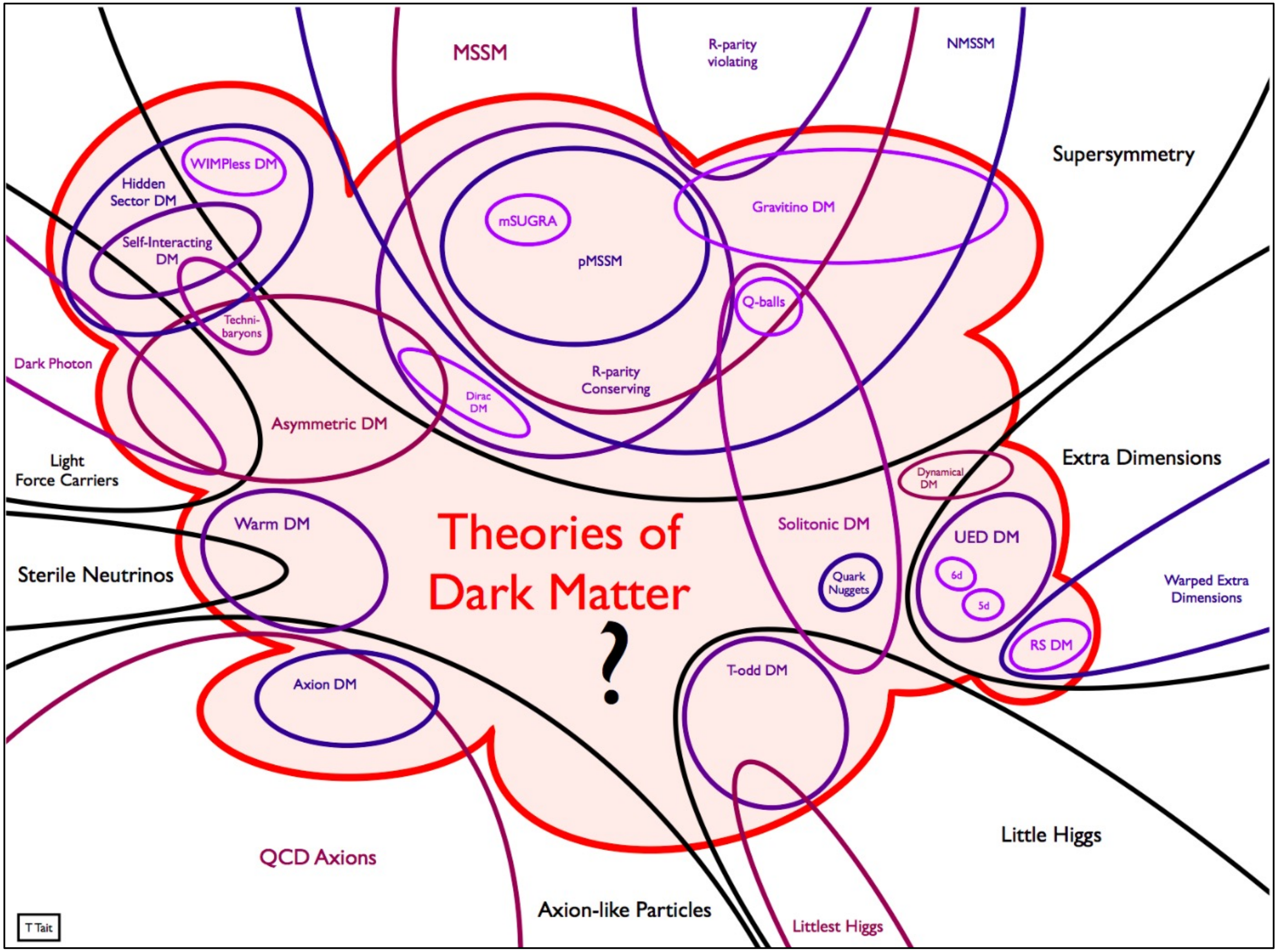
- Such measurements can not only be used to learn about astrophysical objects and environments, but can also serve as a probe of physics beyond the SM
- As an example, consider a light Z' that couples to muons (or muons and taus), with a gauge coupling selected to explain the FNAL/BNL measurements of g_{μ}-2
- Over cosmological distances, such a Z' would cause high-energy neutrinos to scatter with the cosmic neutrino background, leading to potentially observable spectral features
- This is one of many examples of new physics that could be discovered using high-energy astrophysics experiments

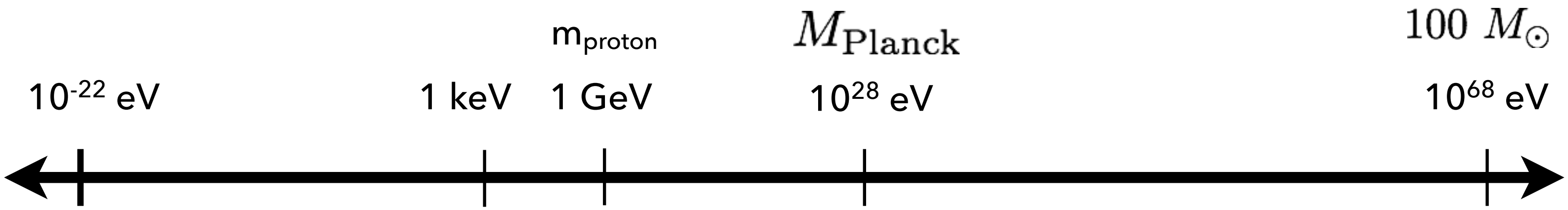


DiFranzo, DH, arXiv:1507.03015
(DH, arXiv:0701194)

The Status of Dark Matter



WIMPs and the Dark Matter Landscape



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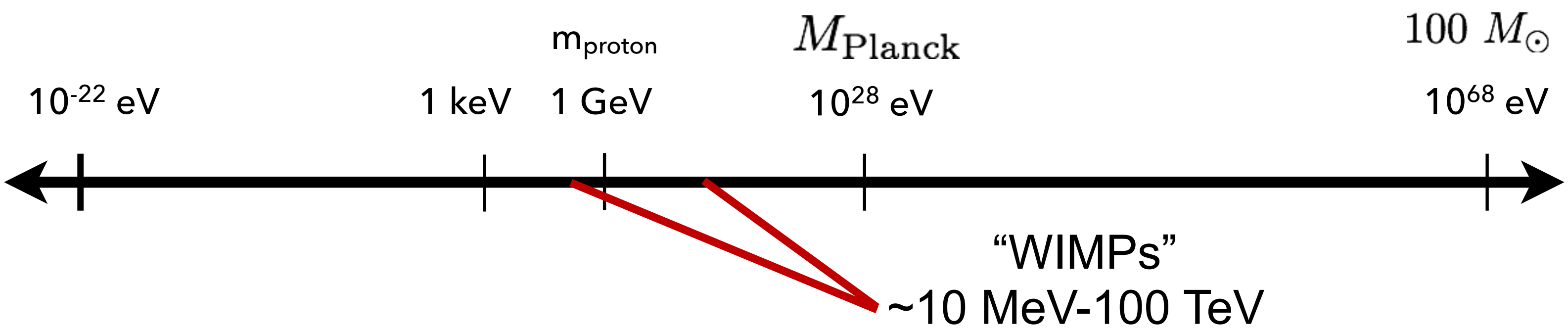


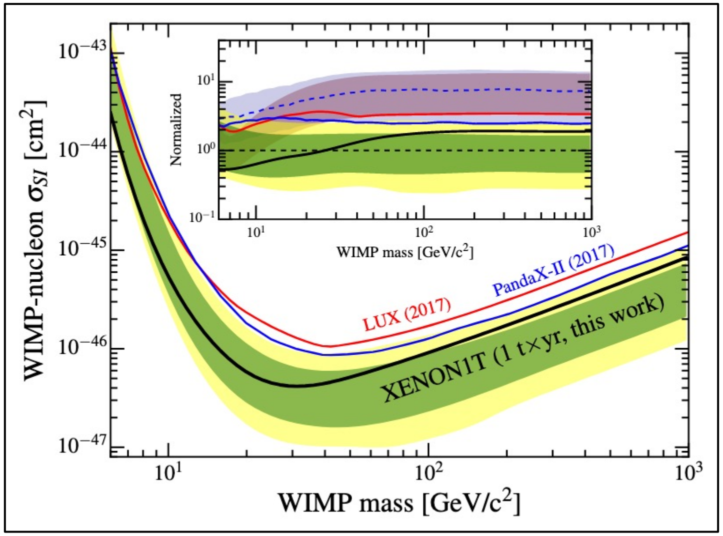
The Case for WIMPs:

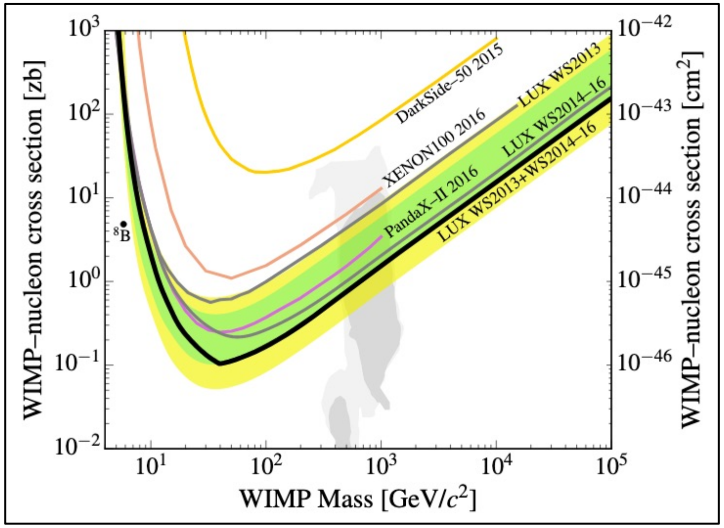
- If we assume that *the dark matter was in thermal equilibrium* at some point in the early universe, and that the early universe was *radiation dominated*, then we can conclude the following:
  1) The dark matter must be heavier than a few MeV (to avoid ruining BBN)
  2) The dark matter must be lighter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



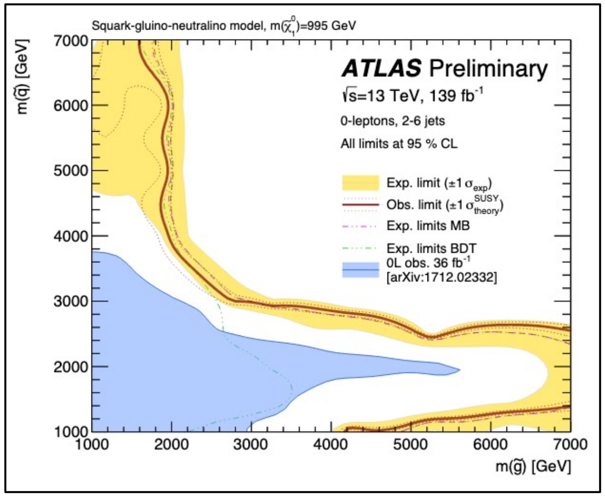


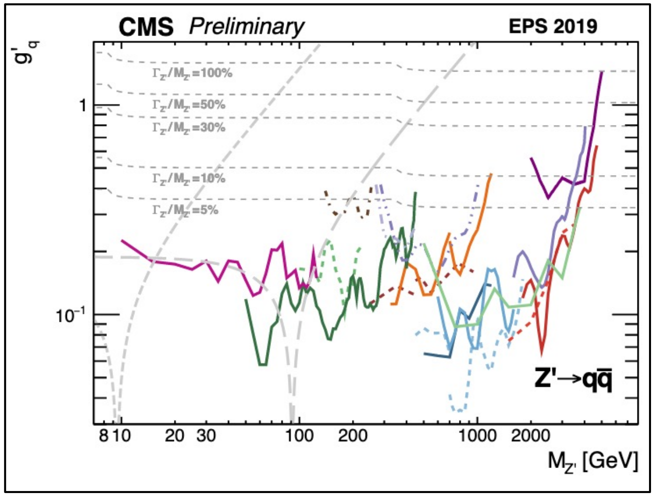
The Status of Dark Matter

So is the WIMP Dead?

No, not at all.

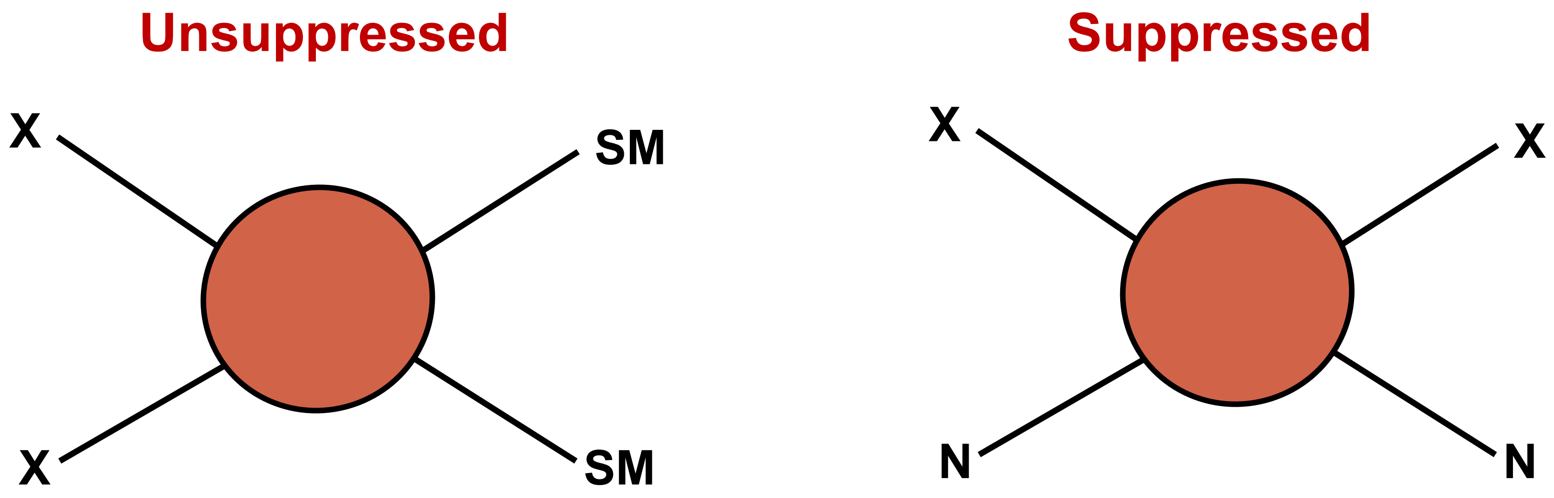
- The LHC has produced strong constraints on certain classes of new physics, such as particles that can be pair produced with a large cross section (squarks, gluinos, etc.), and particles that can produce a dijet or dilepton resonance (Z', etc), but the constraints on WIMPs remain relatively weak
- The 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





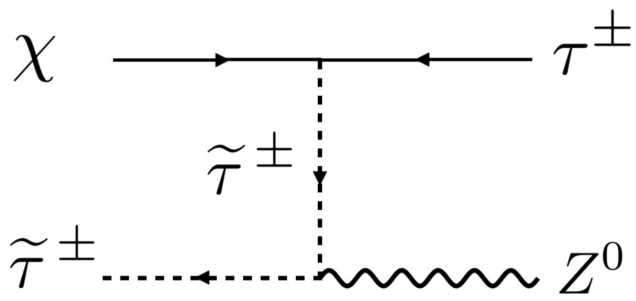
An (Incomplete) List of Ways to Reconcile WIMP Dark Matter With All Current Constraints:

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



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

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

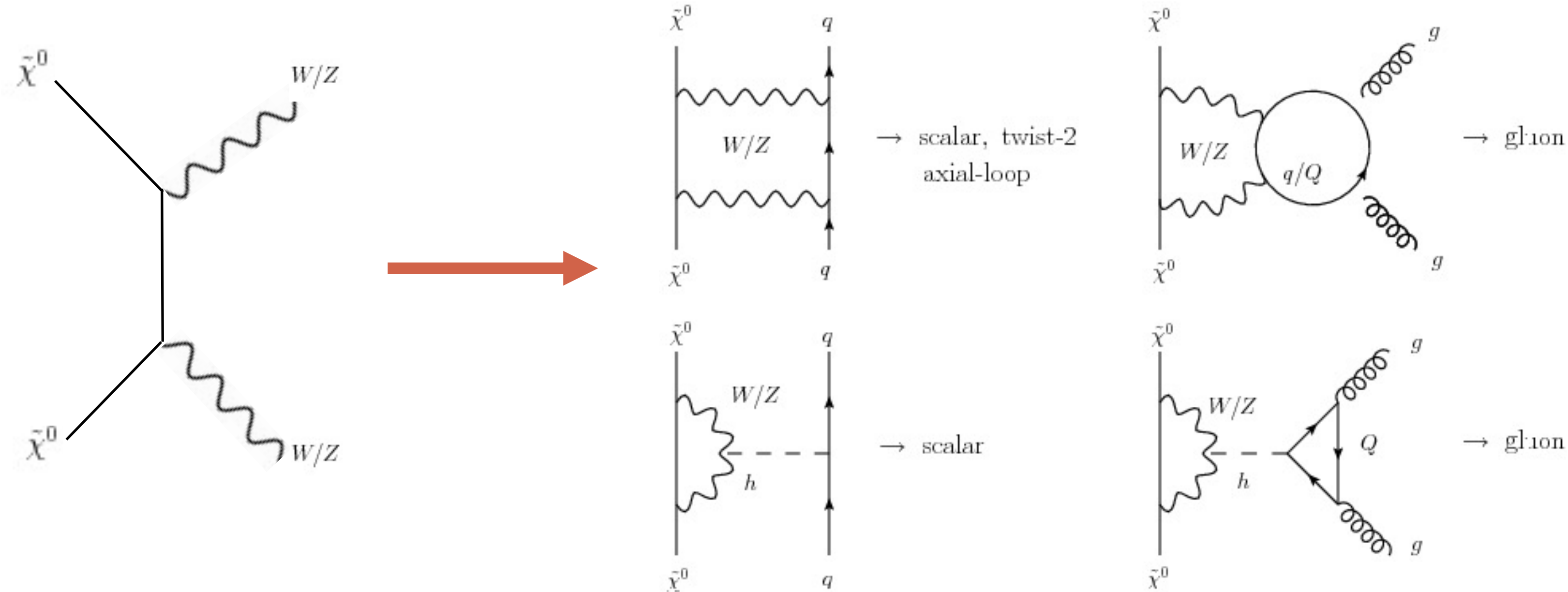


- Roughly speaking, coannihilations can be effective in setting the dark matter's relic abundance (without appreciable annihilation) if the mass splitting between the dark matter and the coannihilating state is less than ~10%
- If the dark matter's relic abundance is set by coannihilations, then we would 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 $\sigma_{SI}\sim 2\times 10^{-46}$ to $\sim 2\times 10^{-47}$ 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

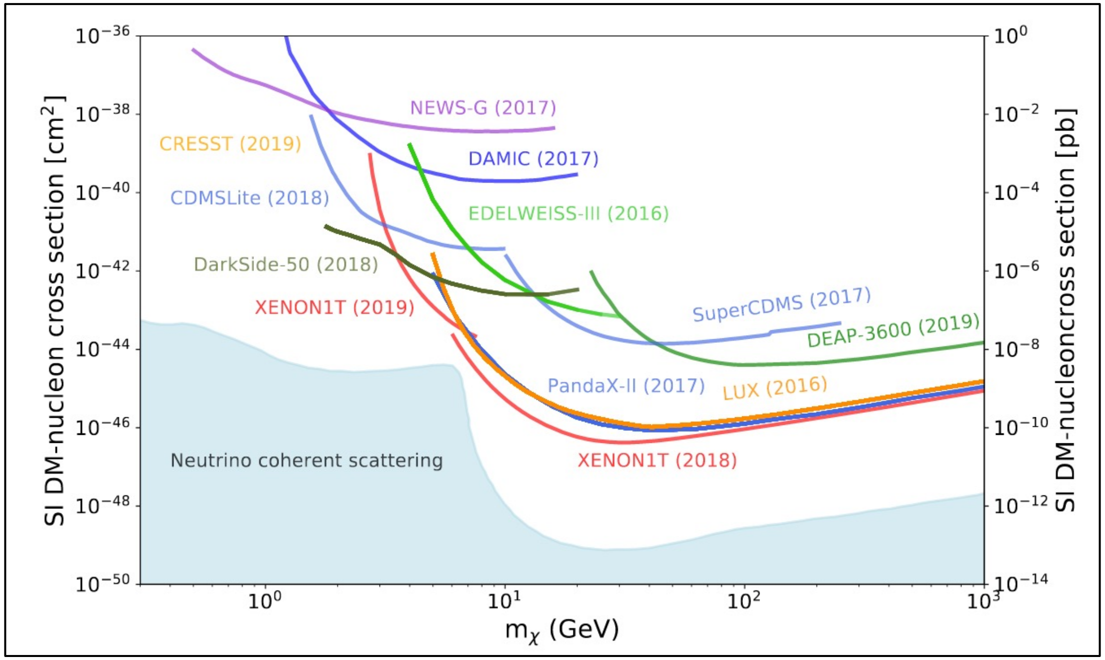
An (Incomplete) List of Ways to Reconcile WIMP Dark Matter With All Current Constraints:

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:

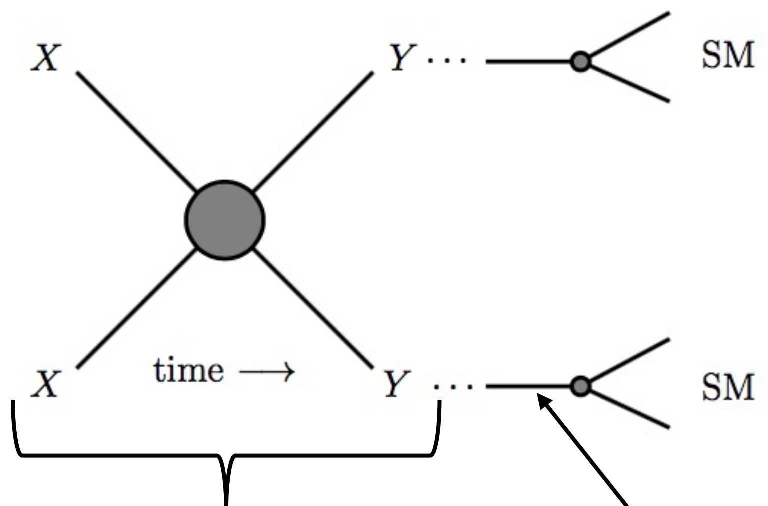
5) Departures from radiation domination in the early universe

- 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



Dark matter annihilates within the hidden sector

... and the hidden sector annihilation products decay through portal interactions

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

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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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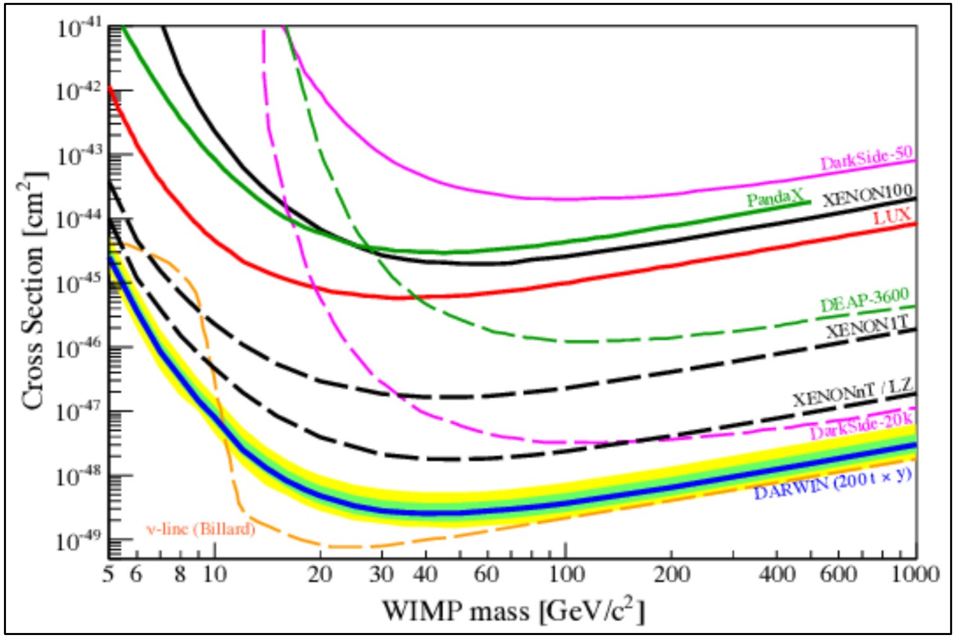
So, where do we go from here?

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 current sensitivity by a factor of ~10^2
- 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

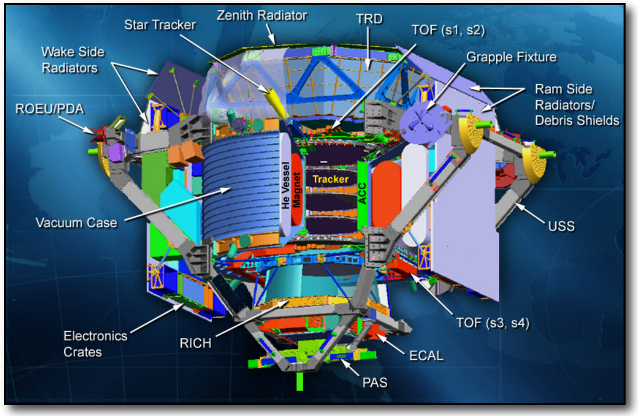


The Motivation for Indirect Searches

- To account for the observed dark matter abundance, a thermal relic must have an annihilation cross section (at freeze-out) of $\sigma v \sim 2\text{x}10^{-26}$ 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

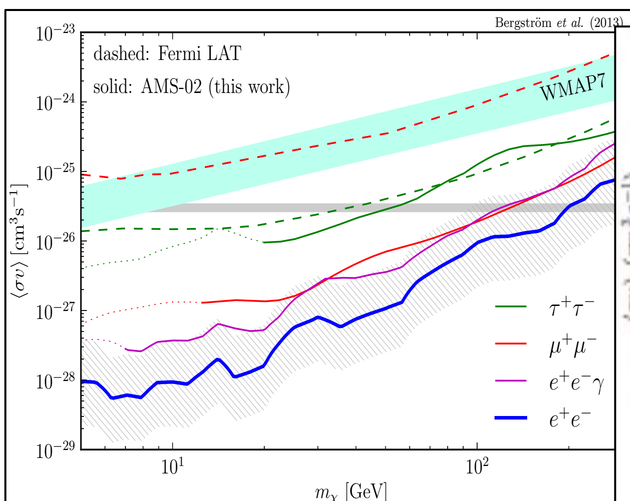
Fermi

AMS-02

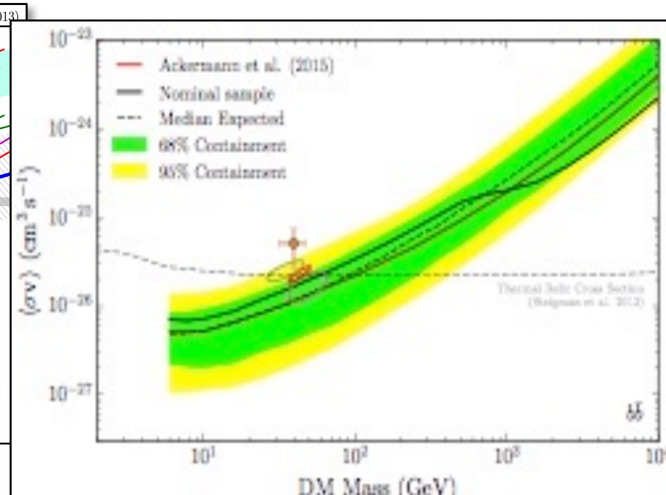


Constraints from Indirect Detection

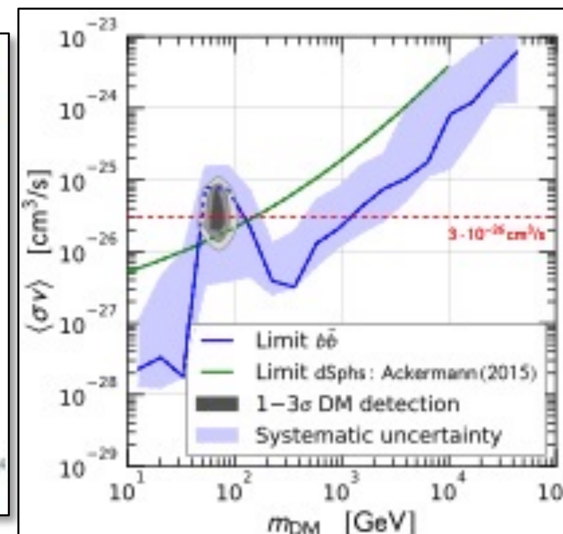
- A variety of gamma-ray strategies (GC, dwarfs, IGRB, etc.) as well as cosmic-ray antiproton and positron measurements from AMS, are currently sensitive to dark matter with the annihilation cross section predicted for a simple thermal relic, for masses up to $\sim\mathcal{O}(100)$ GeV
- This program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



Bergstrom, et al., arXiv:1306.3983



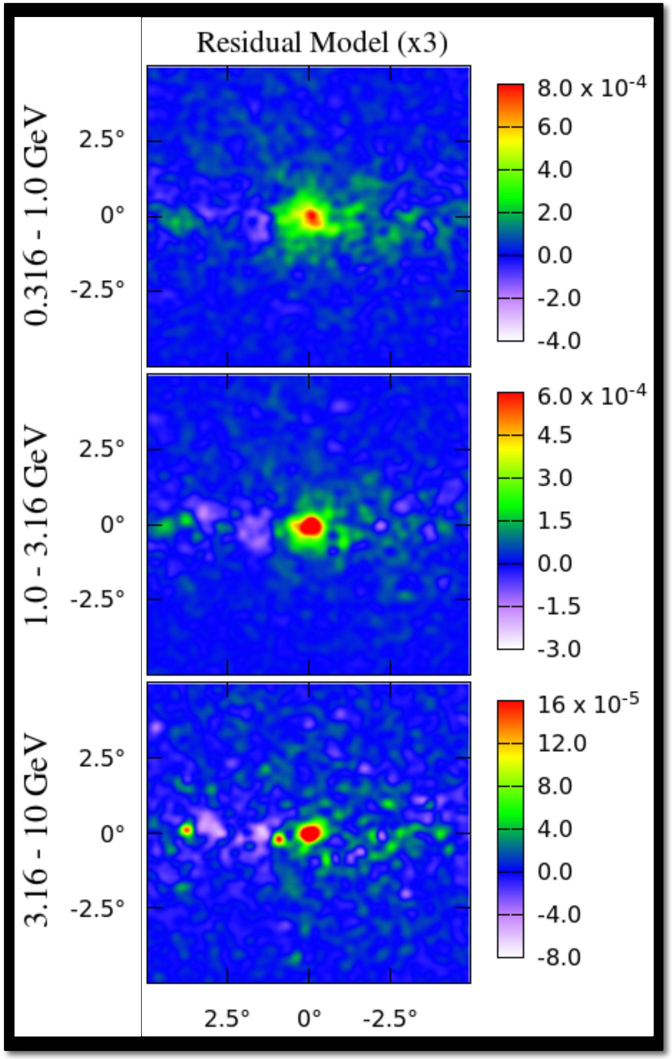
Fermi Collaboration, arXiv:1611.03184



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



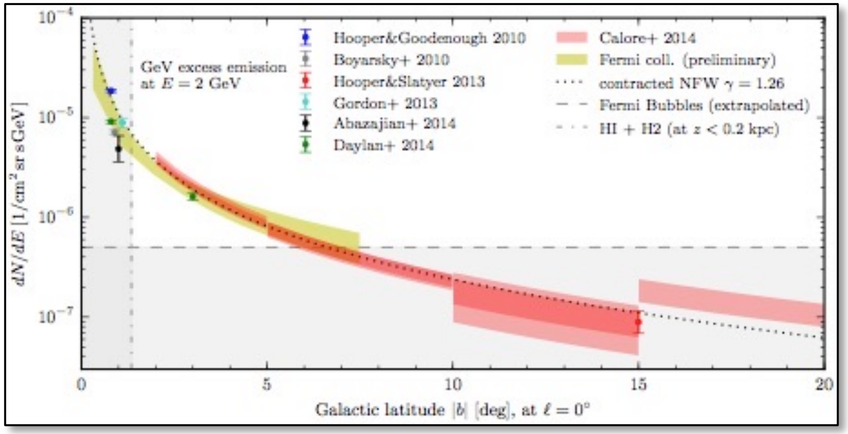
Among other references, see:

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

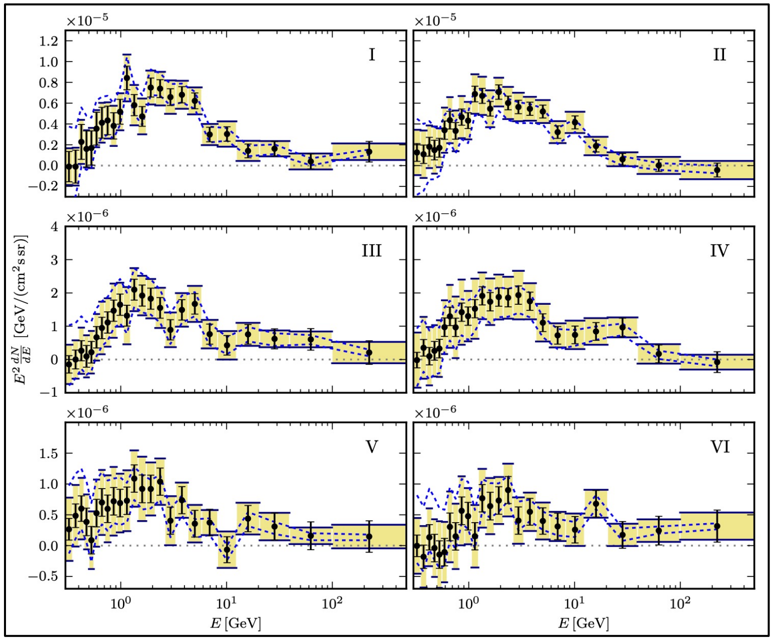
Morphology

- Approximate spherical symmetry about the Galactic Center, with a flux that falls as $\sim r^{-2.4}$ out to at least ~10°
- If from annihilating dark matter, this implies $\rho_{DM} \sim r^{-1.2}$ 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



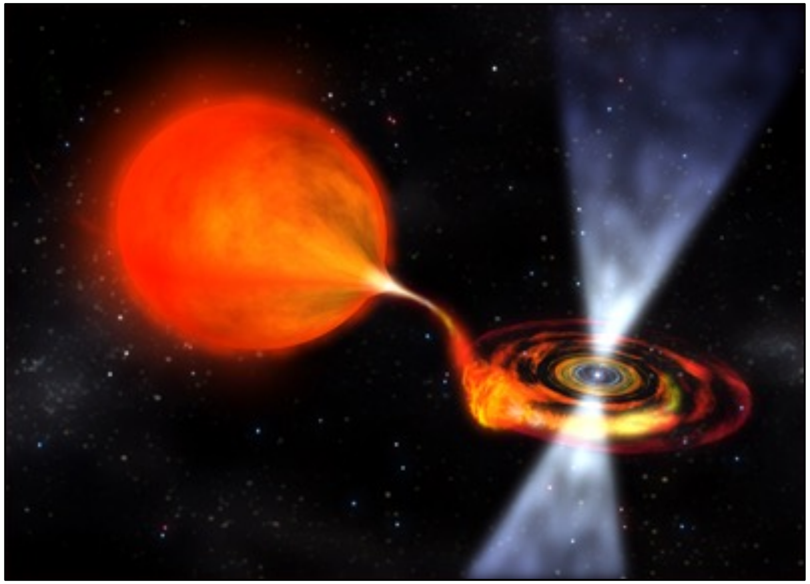
Intensity

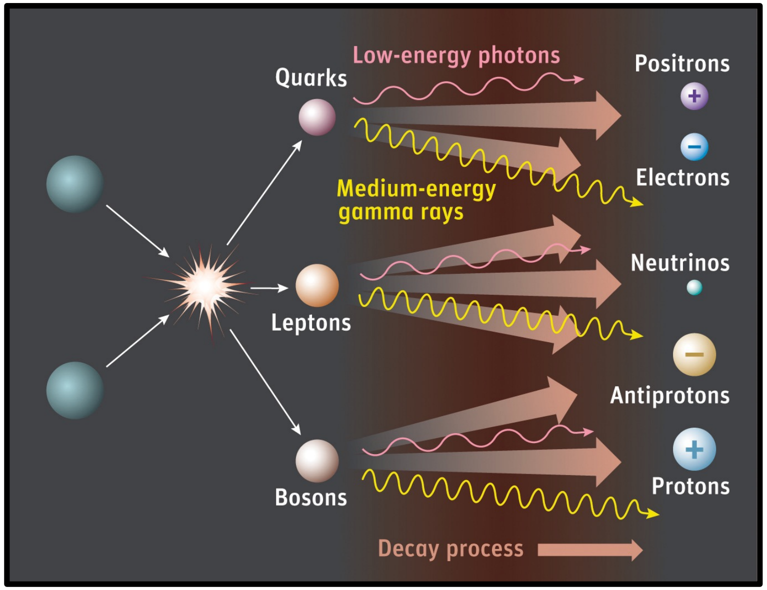
- To normalize the observed excess, the DM particles must annihilate with $\sigma v \sim 10^{-26}$ cm^3/s, approximately equal to the value required to obtain the measured DM abundance

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

What Produces the Excess?

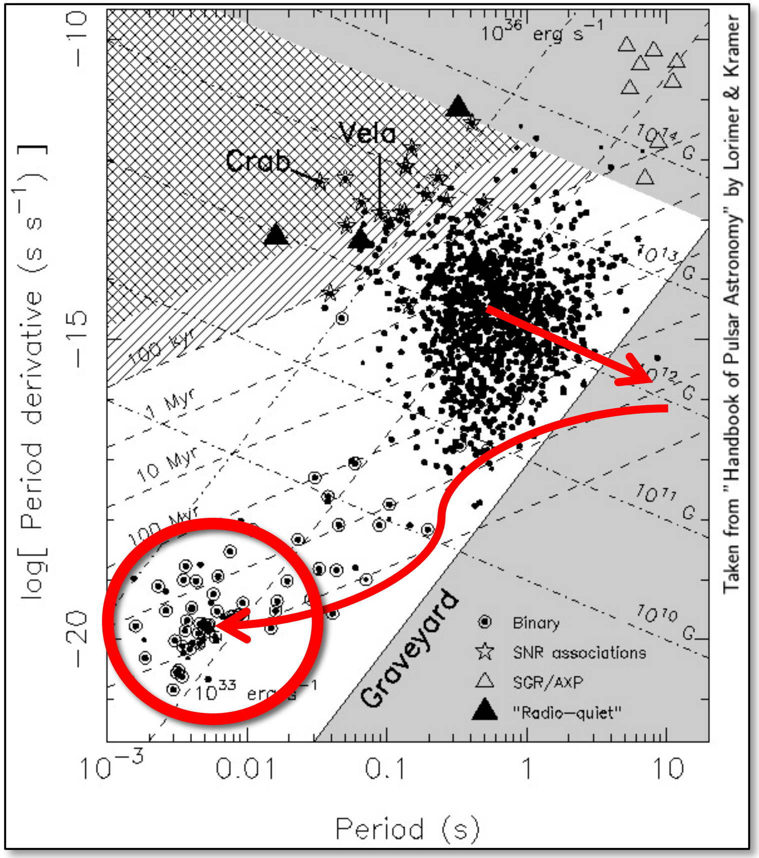
- A large population of centrally located millisecond pulsars?
- Annihilating dark matter?

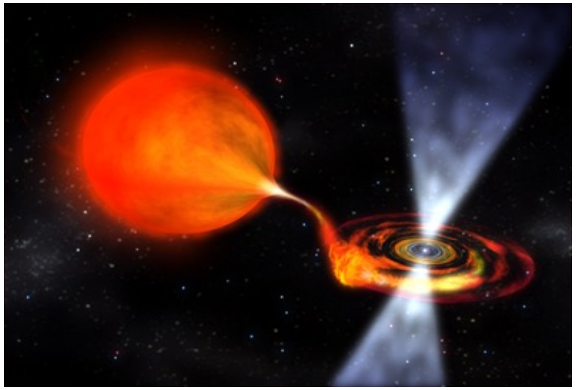




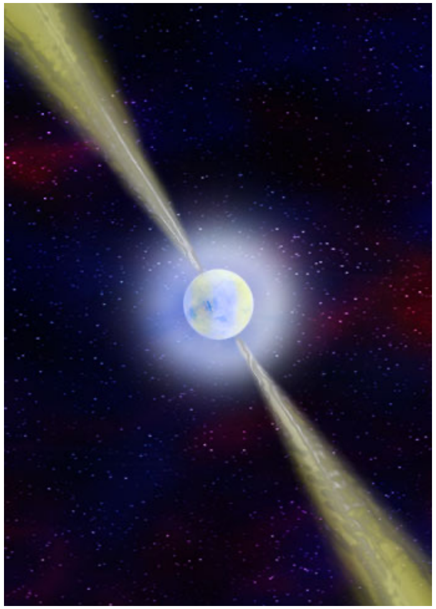
Millisecond Pulsars

- Pulsars are rapidly spinning neutron stars, which gradually convert their rotational kinetic energy into radio and gamma-ray emission
- Typical pulsars exhibit periods on the order of ~1 second and slow down and become faint over $\sim 10^6$ -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 ($\sim 10^8$-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

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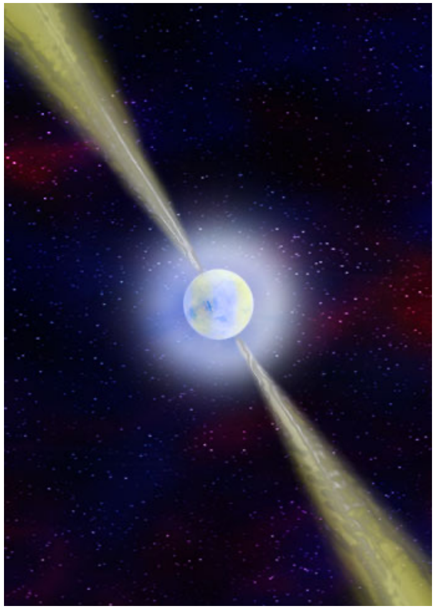

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Evidence of Unresolved Gamma-Ray Sources?

- 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. reach 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

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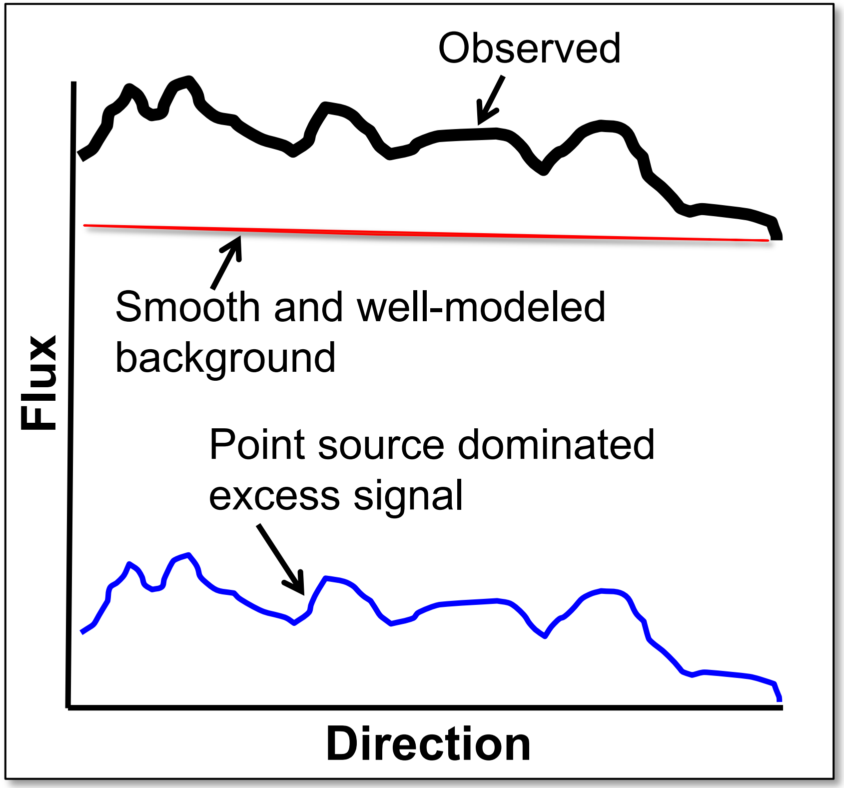
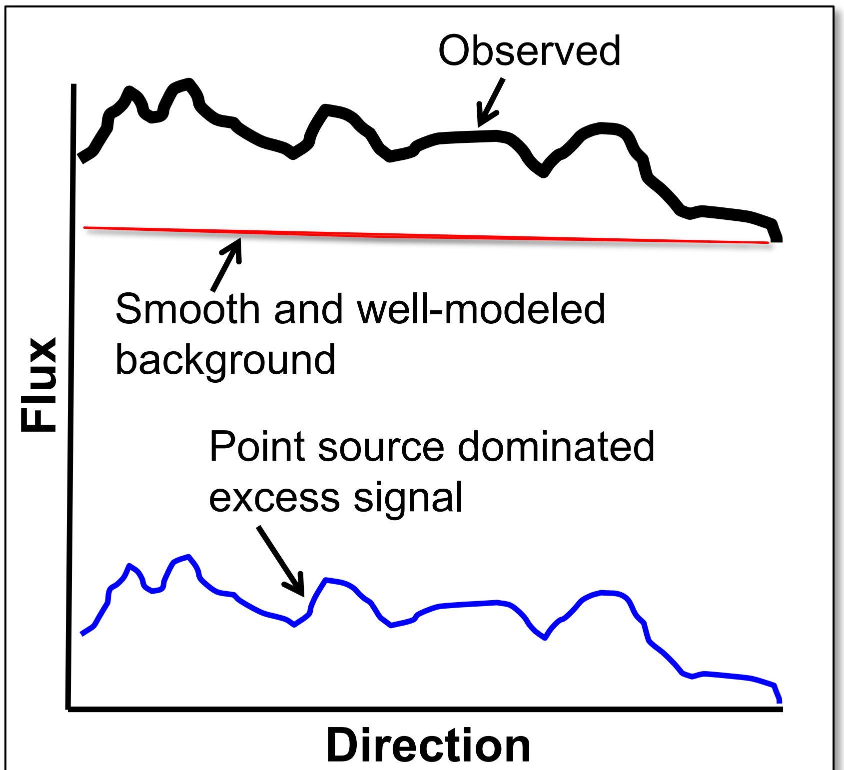
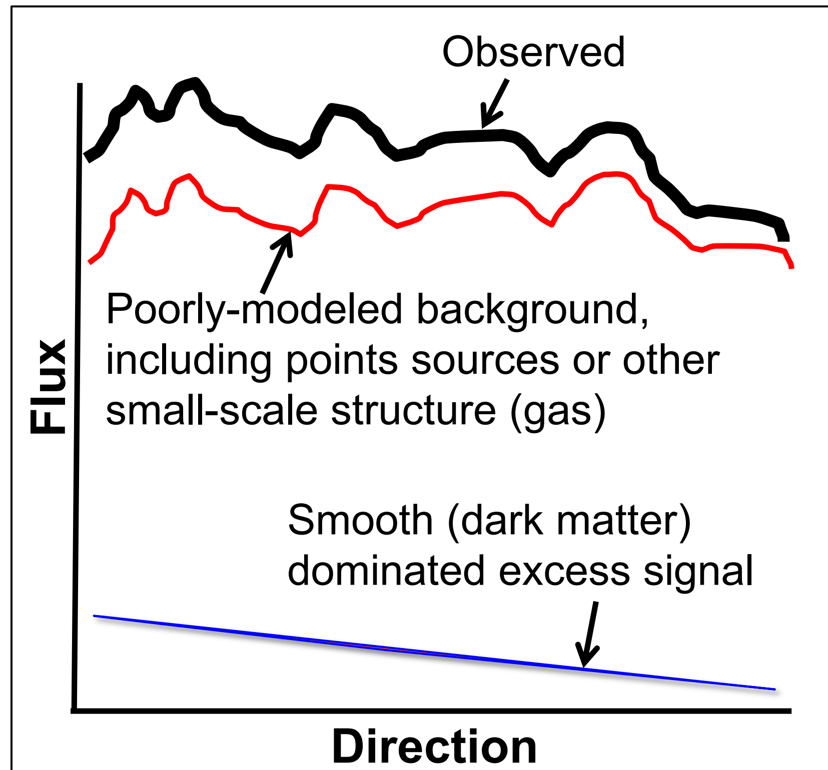


Evidence of Unresolved Point Sources?

- 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





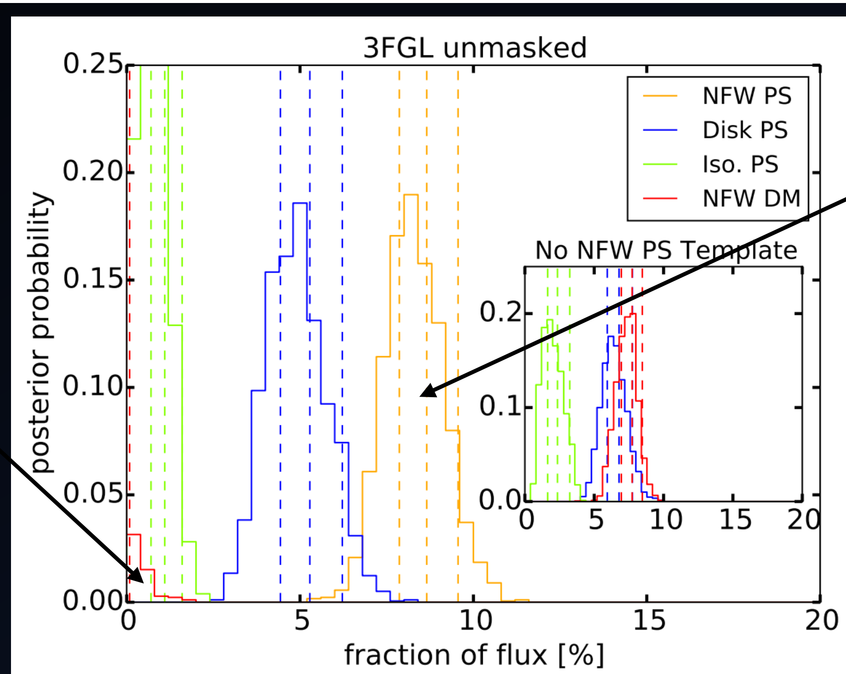
DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

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



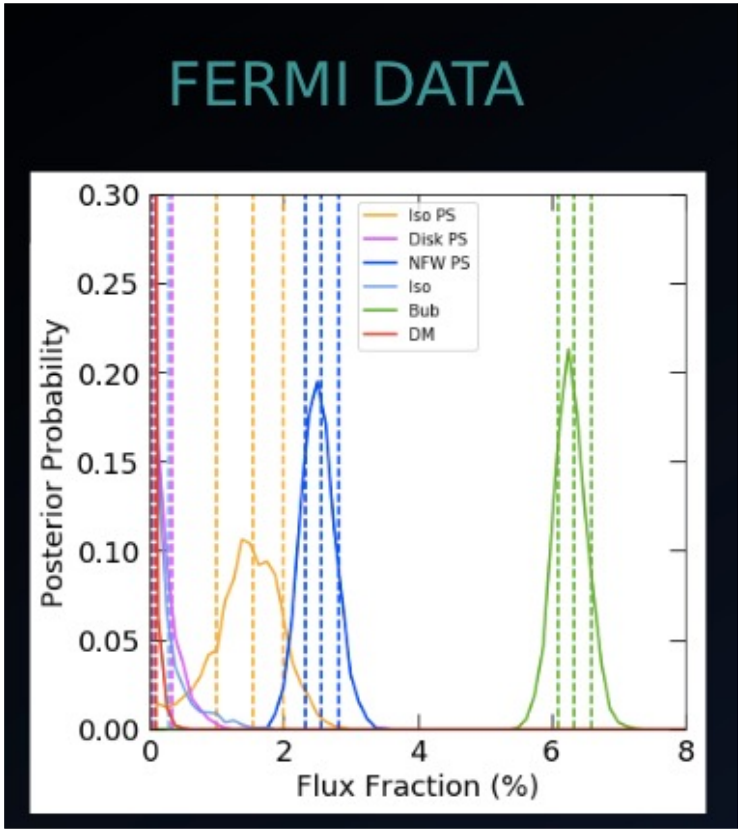
Lee, Lisanti, Safdi, Slatyer, Xue (PRL '15)

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

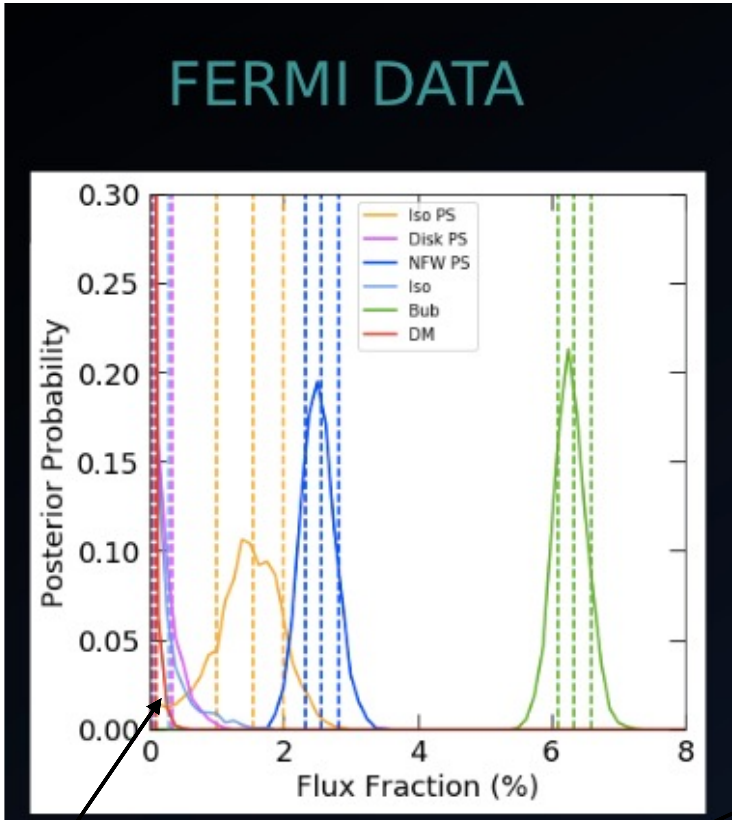


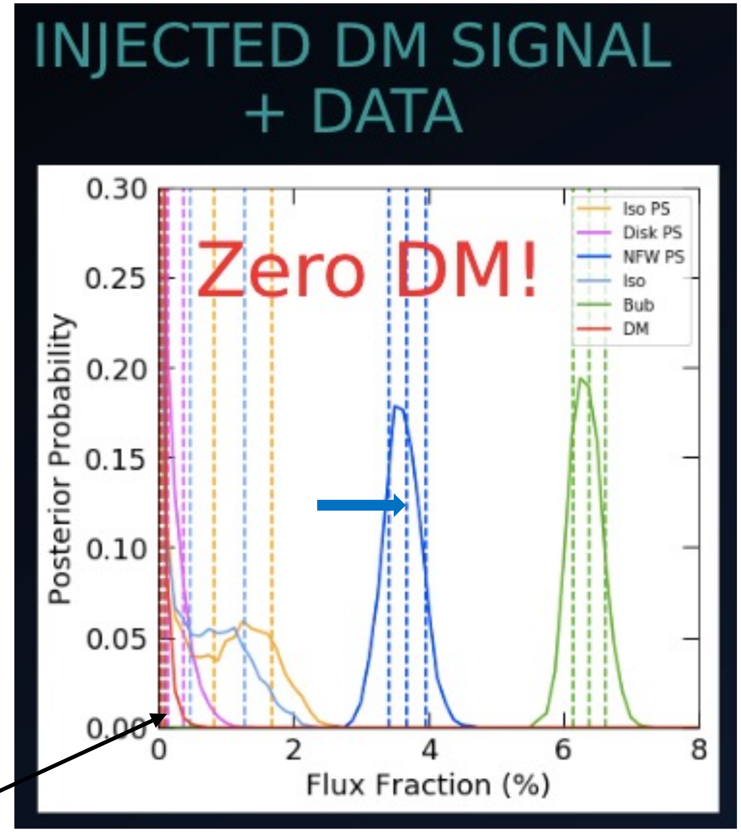
Here is the result that Leane and Slatyer get using the same procedure as Lee *et al.*

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

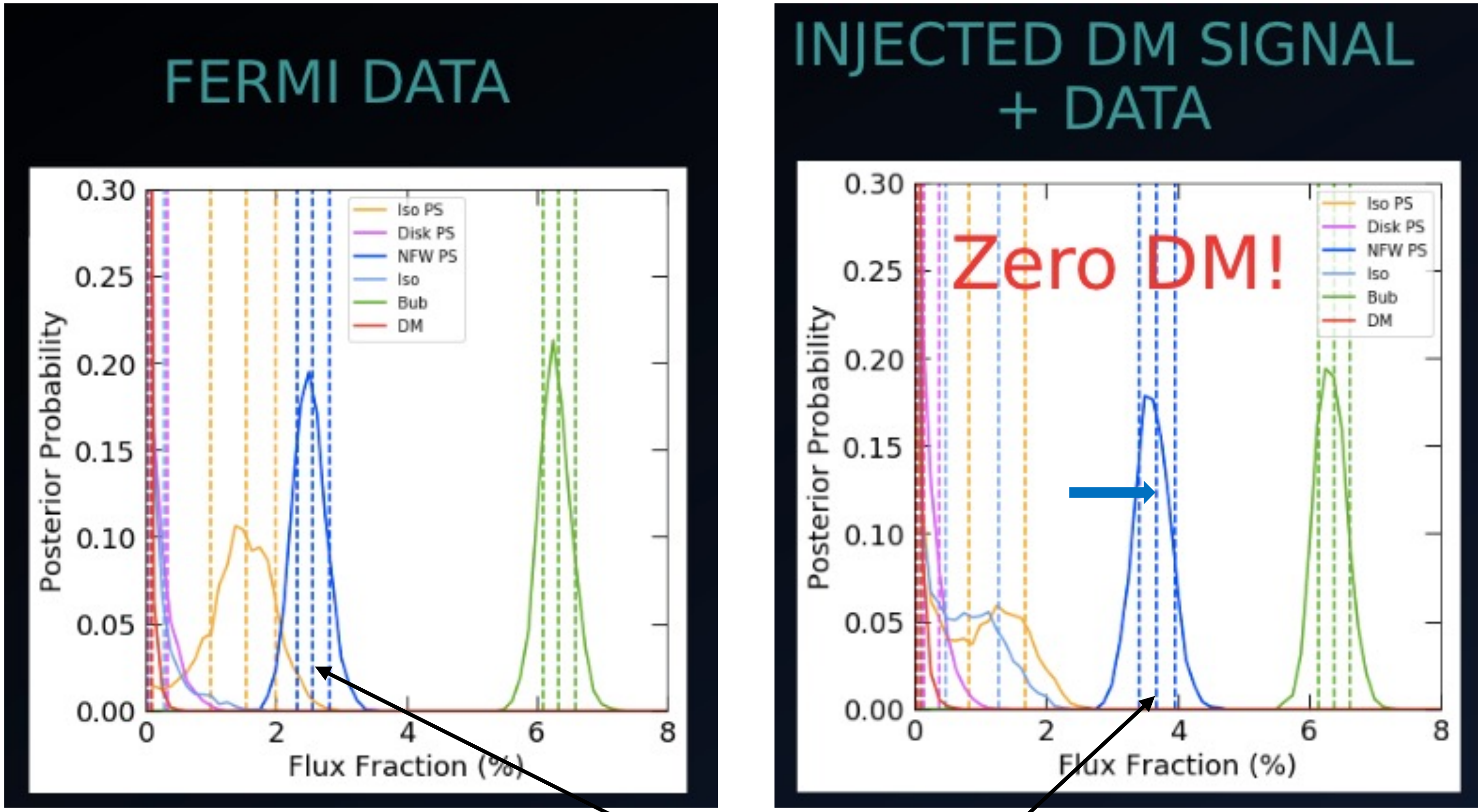




Despite having just added a dark matter-like signal to the data, the fit *does not* ascribe any of it to the dark matter template

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

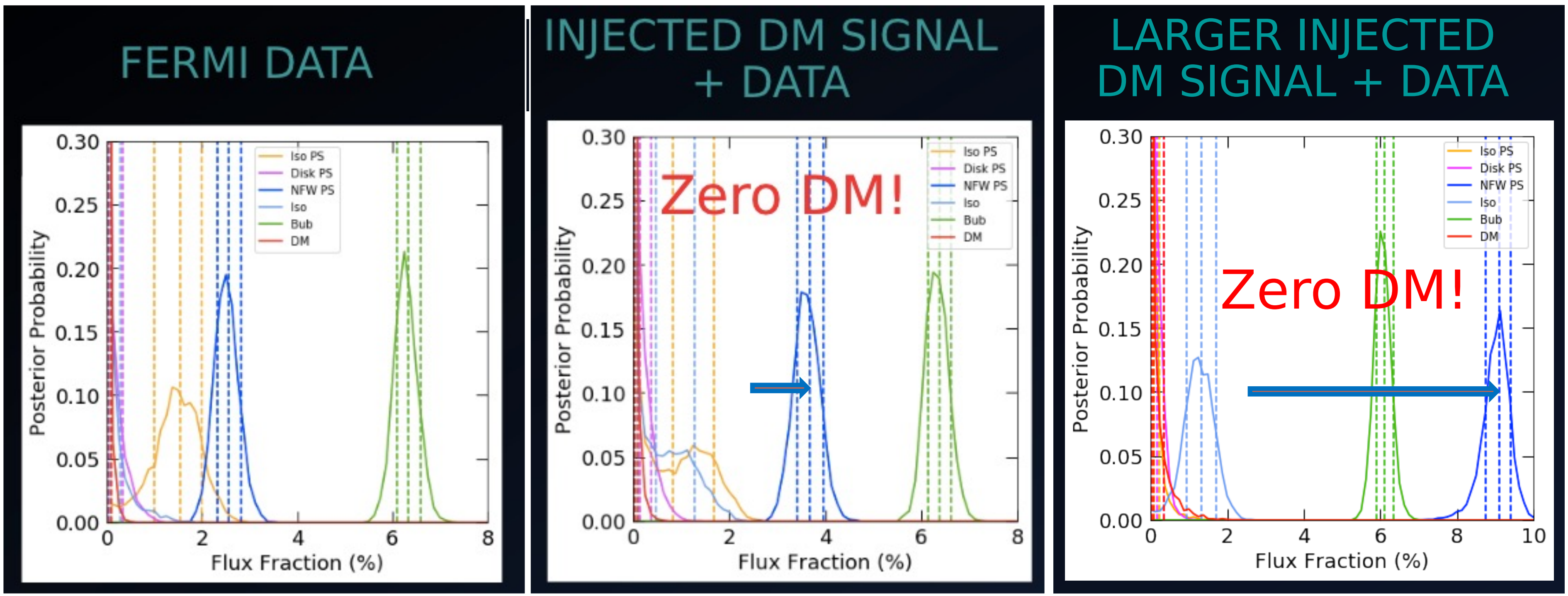
DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

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

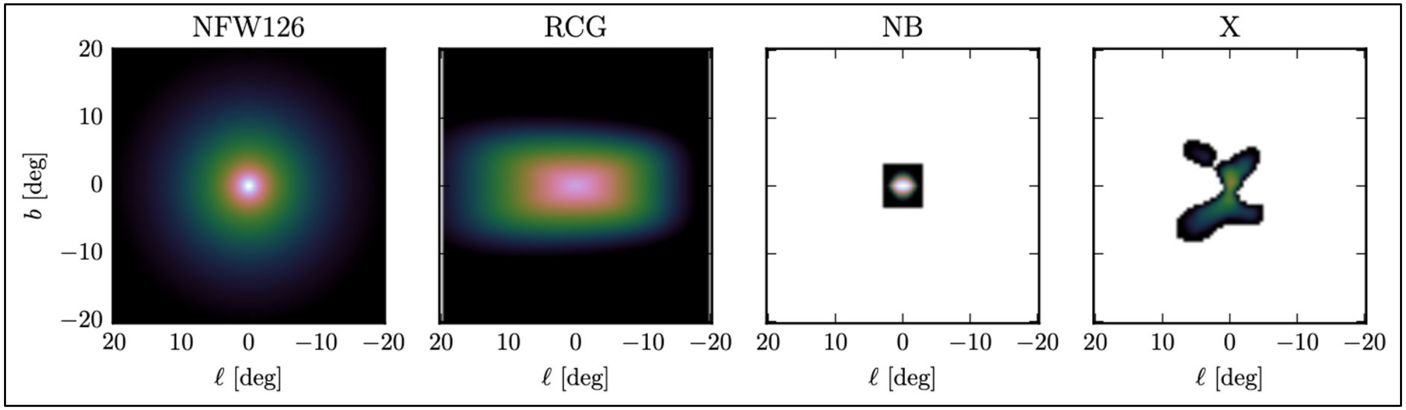
This method does ***not*** provide evidence for point sources over a dark matter interpretation of the excess

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)

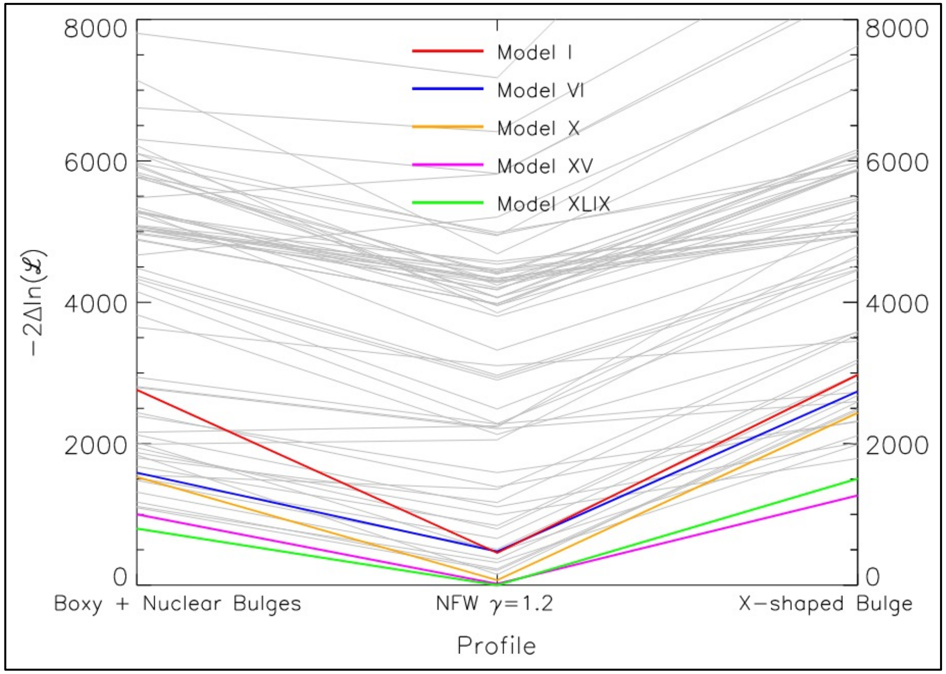


- In three papers (Macias *et al*. 2016, Bartels *et al.* 2017, Macias *et al*. 2017), it was argued that the Fermi excess is better fit by a spatial template that traces stellar populations than one that is dark matter-like, favoring MSP interpretations of the gamma-ray excess

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, hasn't been able to reproduce these results, and 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 early 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)



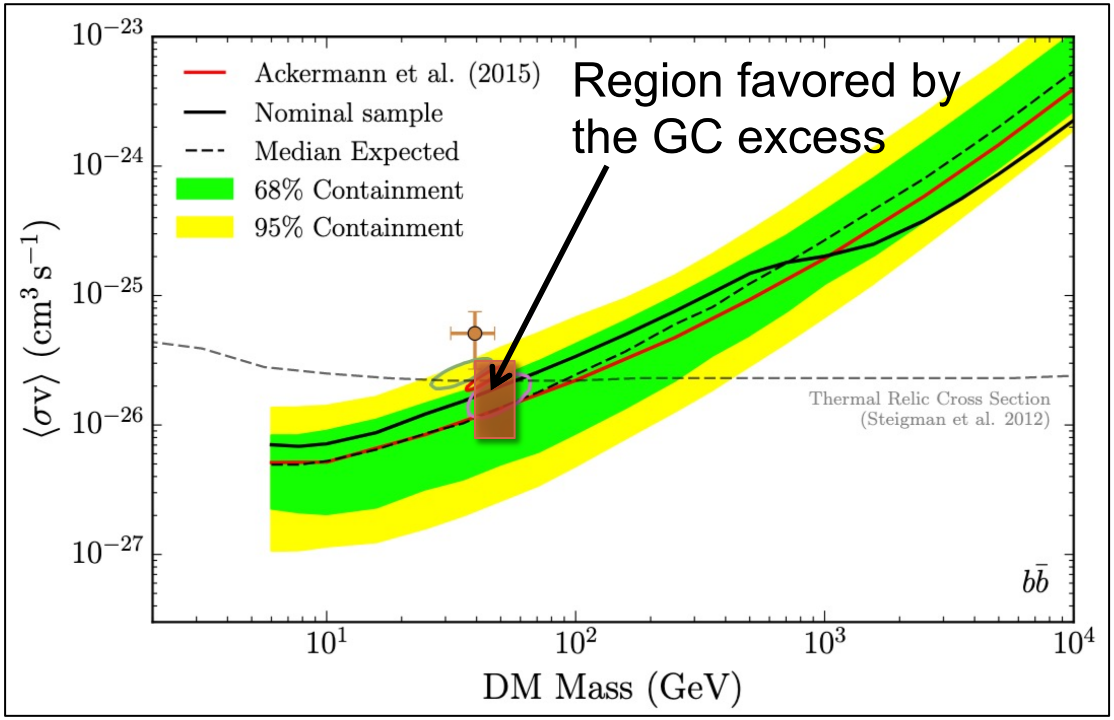
Cholis, et al. (2021)

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 compatible with dark matter interpretations of the Galactic Center excess, if the excess is from annihilating dark matter, we should expect to see gamma rays from dwarf galaxies soon



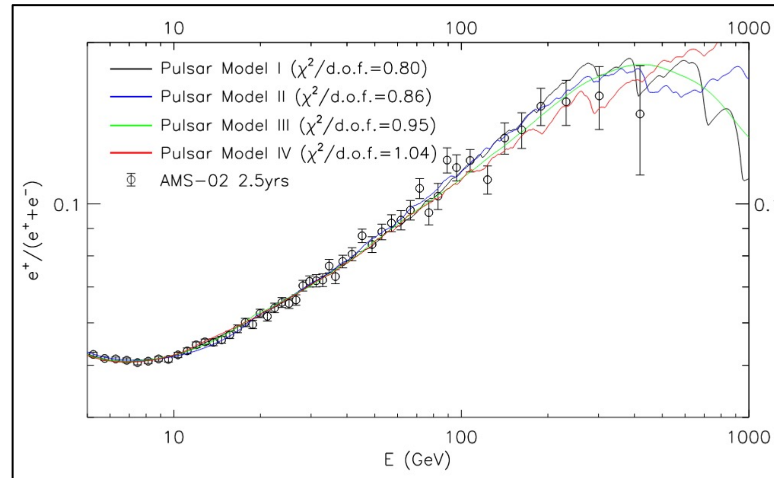
Fermi Collaboration, arXiv:1611.03184

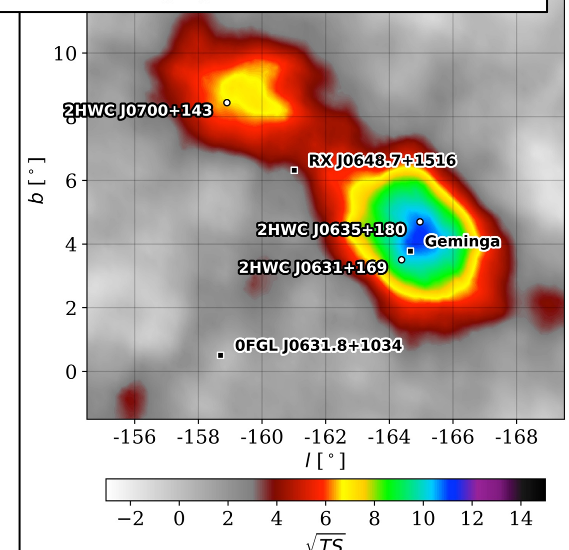
Dwarf Galaxies in the Rubin Era

- 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 testing the region 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)

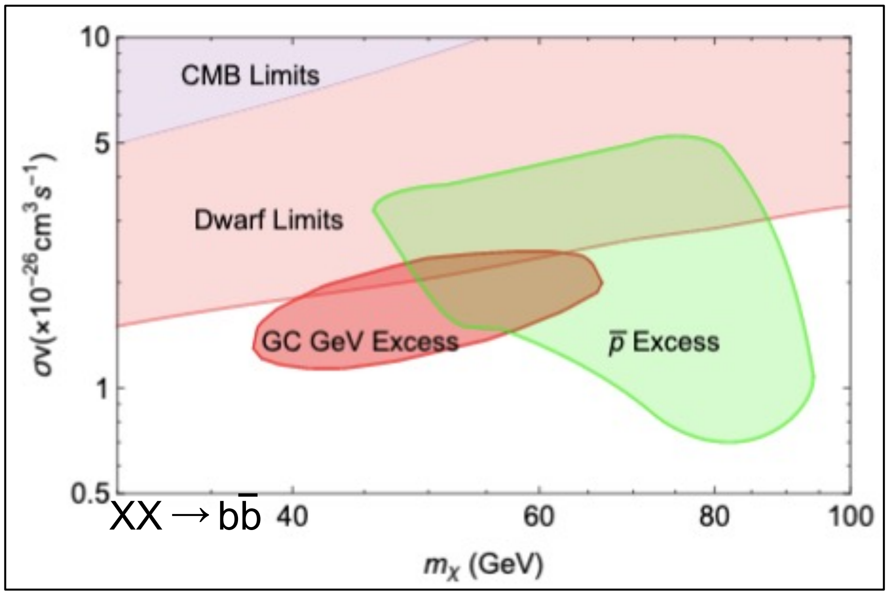


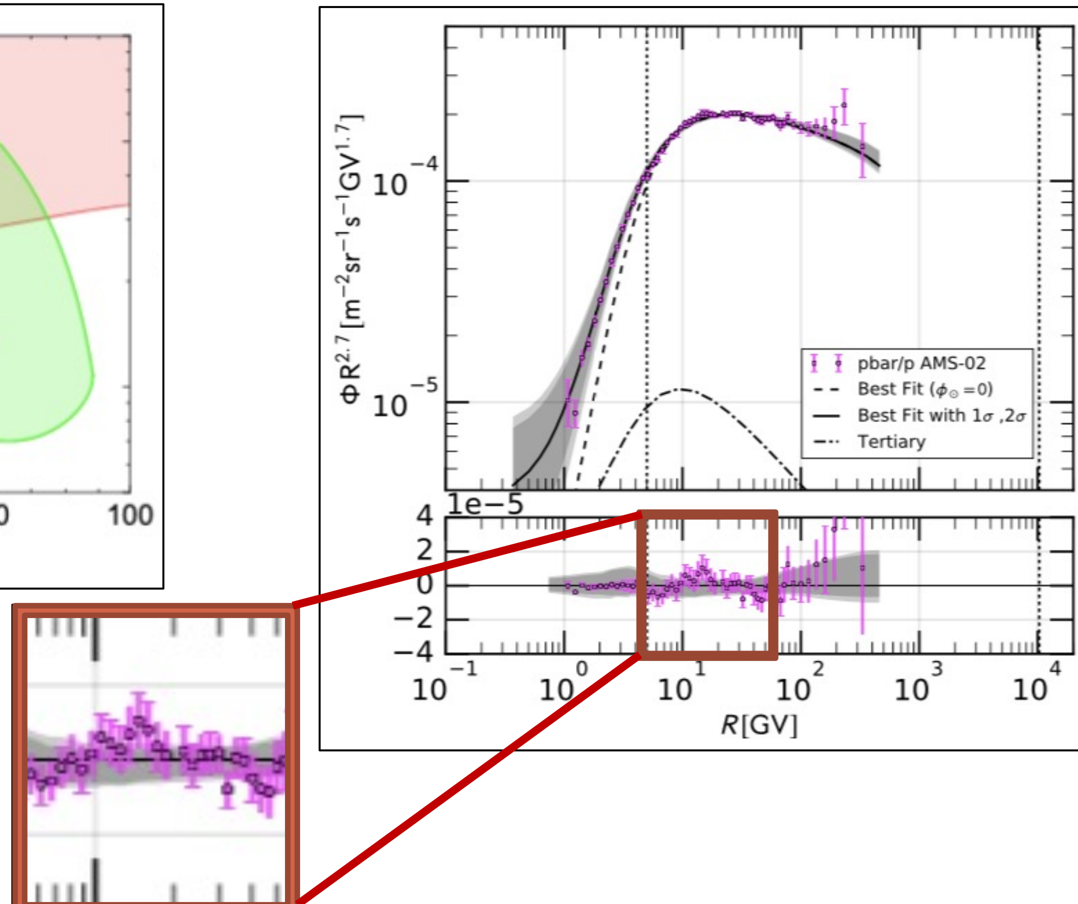


Cholis et al., arXiv:1807.05230;
HAWC Collaboration, arXiv:1702.02992

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!

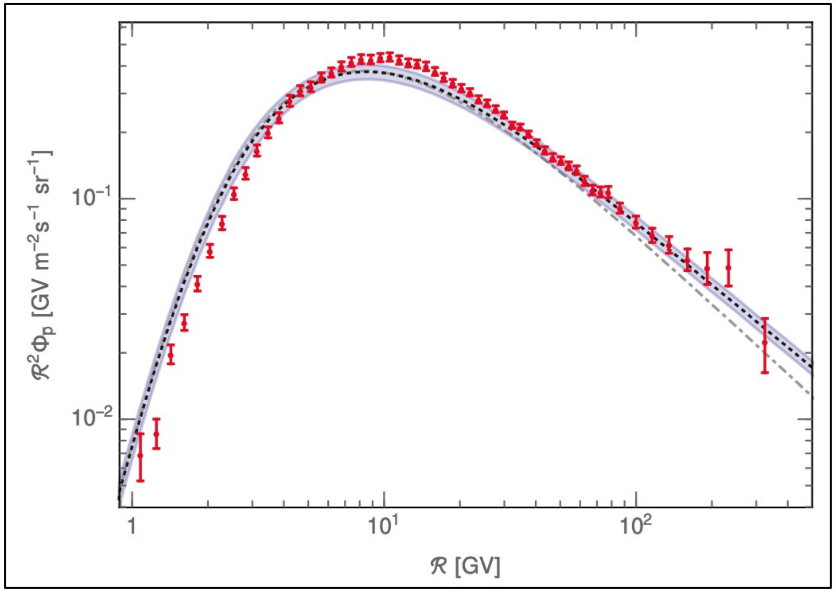




Cuoco et al., arXiv:1610.03071
Cui et al., arXiv:1610.03840
Cholis, DH, Linden, arXiv:1903.02549
Cuoco et al., arXiv:1903.01472
Reinert, Winkler, arXiv:1712.00002

The Cosmic-Ray Antiproton Excess

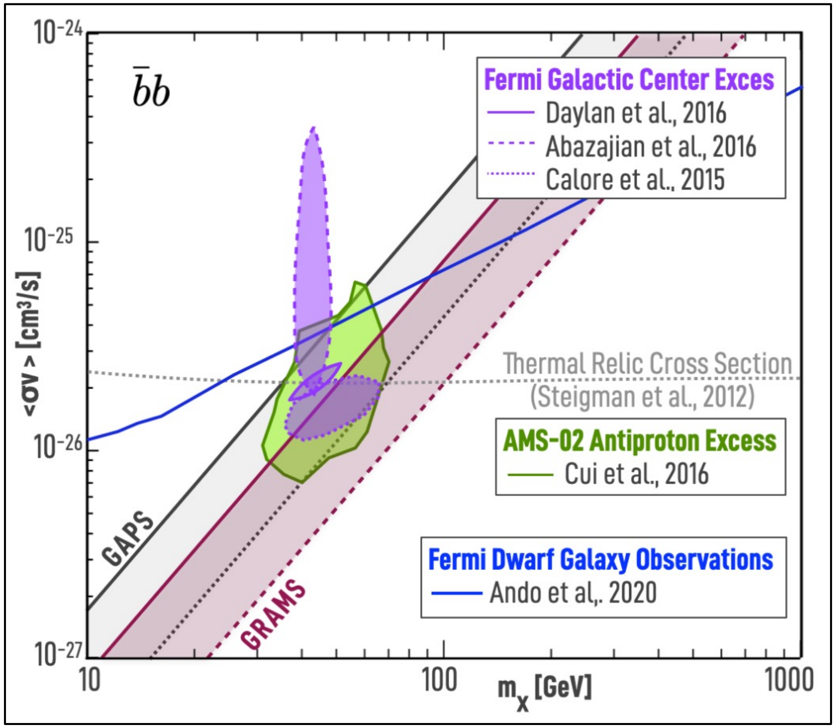
- Many of us in the cosmic-ray community have been somewhat skeptical of the anti-proton excess, driven by concerns pertaining to the systematic uncertainties associated with the antiproton production cross section
- To convince us that this excess is real, it is imperative that laboratory measurements of this cross section be improved – *if you have ideas of how to do this, please talk to me!*



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

Summary

- Exciting activity and new results continue to develop in many areas of astro-particle physics – neutrinos, cosmic rays, gamma rays, and more
- IceCube's neutrinos are ***the key*** to identifying the sources of the high and ultra-high energy cosmic rays; at present some combination of AGN and star-forming galaxies seem most likely
- 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
- 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 ~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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