DARK MATTER ANNIHILATION IN THE GALACTIC CENTER

Dan Hooper – Fermilab and the University of Chicago

UCLA Dark Matter Conference

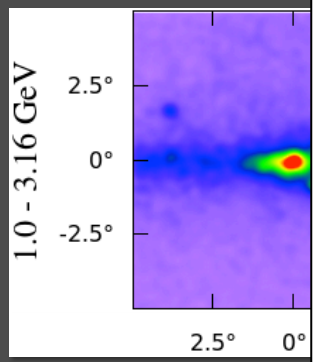
February 18, 2016

Sorry if I sound like a broken record…

Reason 1: Overwhelming Statistical Significance and Detailed Information

- This excess consis
  per year (>1 GeV,

Raw M



UCLA DM 2014

The Dark Matter Interpretation

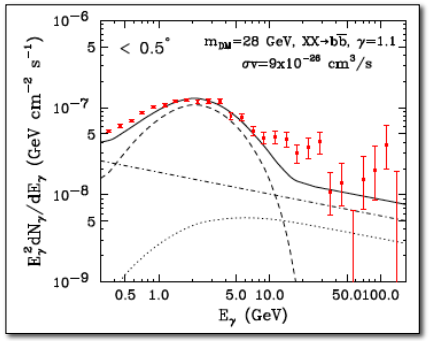
- The spectral shape of the excess can be well fit by a dark matter particle with a mass in the rang 7 to 12 GeV (*similar to that rec by CoGeNT, DAMA, and CRE* annihilating primarily to $\tau^+\tau^-$ (possibly among other leptons)
- The angular distribution of the signal is well fit by a halo profil $\rho(r) \sim r^{-\gamma}$, with $\gamma \sim 1.25$ to 1.4 (in good agreement with expec
- The normalization of the signa cross section within a factor of relic ($\sigma v \sim 3\times10^{-26}$ cm^3/s)

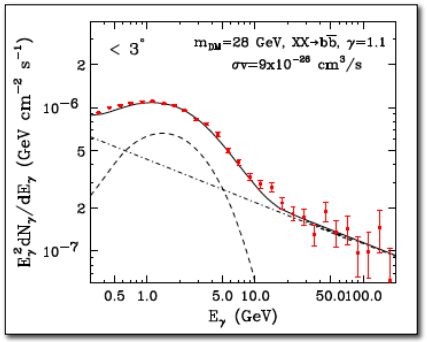
Hooper and Linden, PRD, arXiv:

UCLA DM 2012

Dark Matter In The Galactic Center Region

- The spectrum contains a "bump-like" feature at ~1-5 GeV
- Can be fit quite well by a simple 25-30 GeV dark matter particle, in a cusped distribution (γ~1.1), annihilating to bb with $\sigma v \sim 9 \times 10^{-26}$ cm^3/s





Dan Hooper - *The Hunt For Dark Matter*

L. Goodenough, D. Hooper, arXiv:0910.2998

UCLA DM 2010

The Evolving Nature of the Galactic Center Debate

The Evolving Nature of the Galactic Center Debate

UCLA 2010

There is no Galactic Center excess ("*what are you smoking?*")

The Evolving Nature of the Galactic Center Debate

UCLA 2010

There is no Galactic Center excess ("*what are you smoking?*")

UCLA 2012

Sure there seems to be a Galactic Center excess, but

1) Are we sure that it is spatially extended?
2) Are we mismodeling standard diffuse emission mechanisms?
3) Is there really a Galactic Center excess?

The Evolving Nature of the Galactic Center Debate

UCLA 2010

There is no Galactic Center excess ("*what are you smoking?*")

UCLA 2012

Sure there seems to be a Galactic Center excess, but

1) Are we sure that it is spatially extended?
2) Are we mismodeling standard diffuse emission mechanisms?
3) Is there really a Galactic Center excess?

UCLA 2014

What is generating this excess?

1) A large population of centrally located millisecond pulsars?
2) A series of recent cosmic ray outbursts?
3) Annihilating dark matter?

The Evolving Nature of the Galactic Center Debate

UCLA 2010

There is no Galactic Center excess ("*what are you smoking?*")*

UCLA 2012

Sure there seems to be a Galactic Center excess, but

1) Are we sure that it is spatially extended?
2) Are we mismodeling standard diffuse emission mechanisms?
3) Is there really a Galactic Center excess?

UCLA 2014

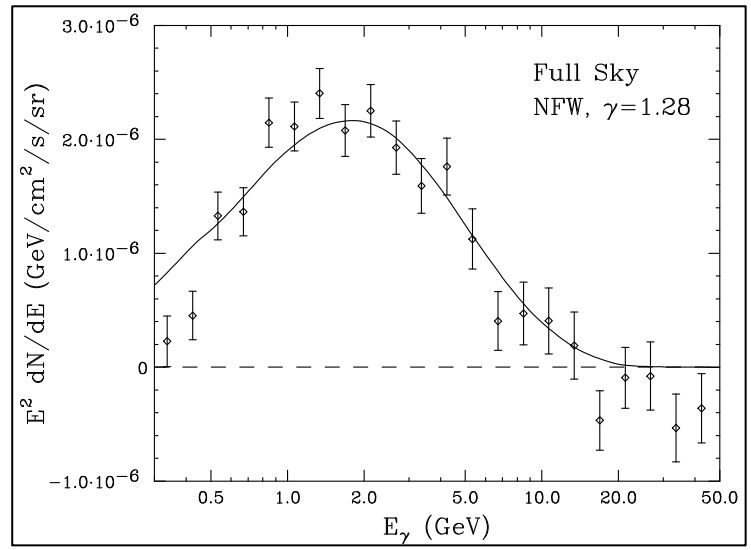
What is generating this excess?

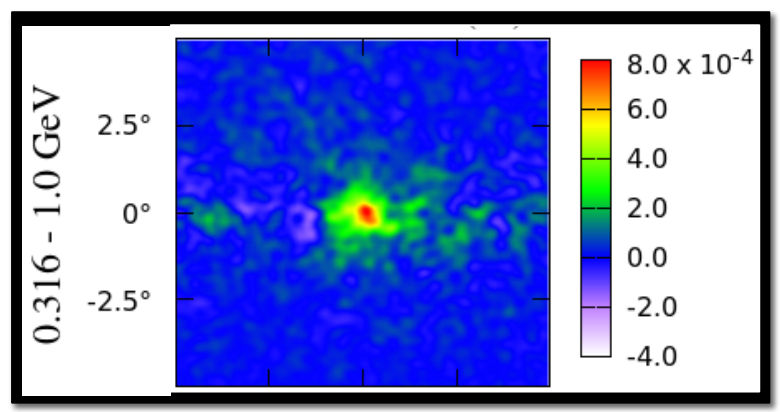
1) A large population of centrally located millisecond pulsars?
2) A series of recent cosmic ray outbursts?
3) Annihilating dark matter?

*Dave Klein was very supportive during this critical time

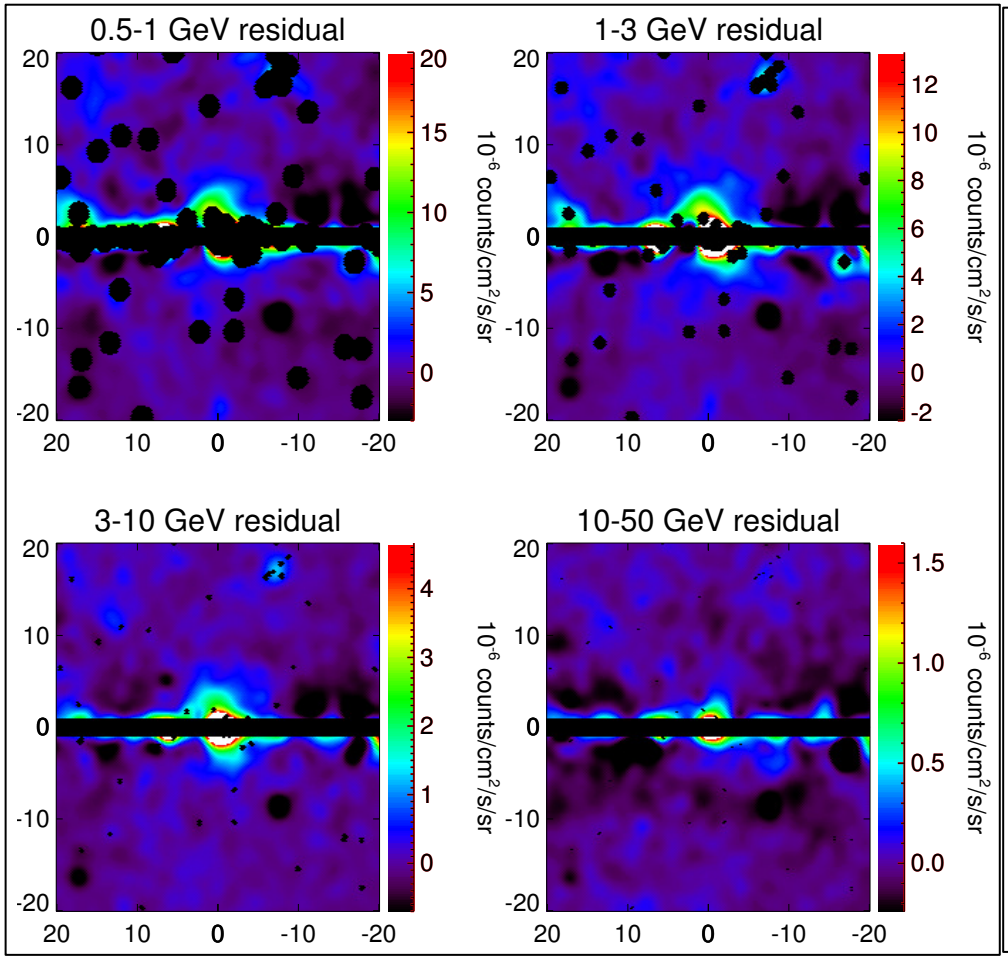
The Basic Features of the GeV Excess

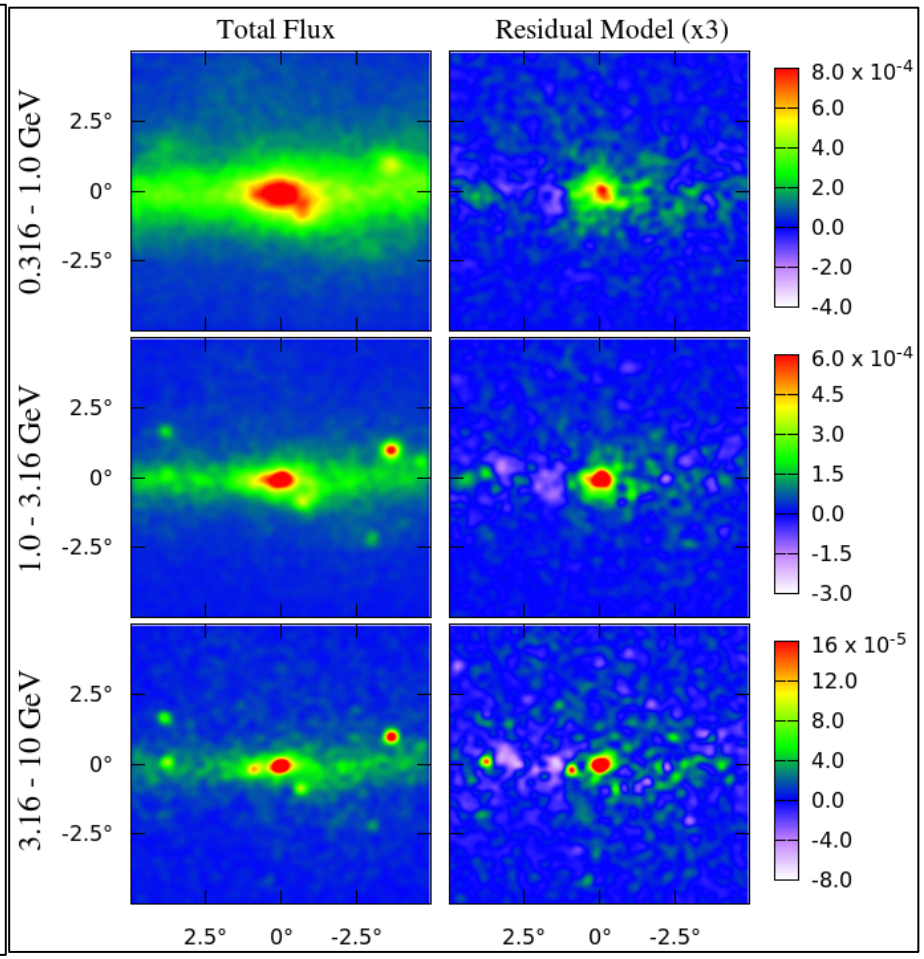
- Bright and highly statistically significant
- Distributed with spherical symmetry about the Galactic Center with a flux that falls as ~$r^{-2.4}$, between ~0.06° and ~10° (if interpreted as annihilating dark matter, $\rho_{DM} \sim r^{-1.2}$ between ~10-1500 pc)
- The spectrum of this excess peaks at ~1-3 GeV, and is in good agreement with that predicted from a ~35-50 GeV WIMP annihilating to $b\bar{b}$ (for example)
- To normalize the observed signal with annihilating dark matter, a cross section of $\sigma v \sim 10^{-26}$ cm^3/s is required



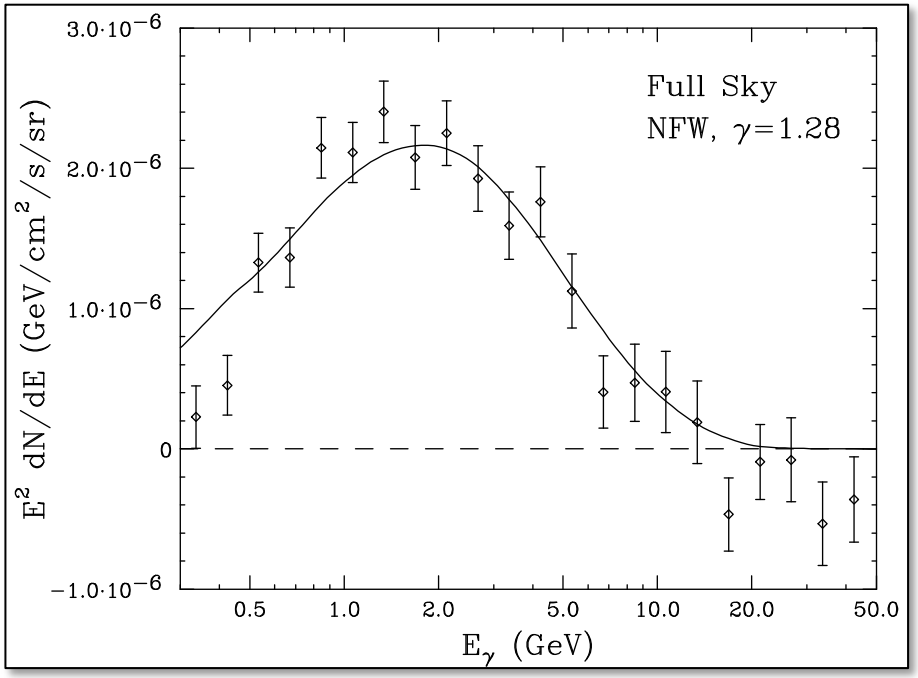


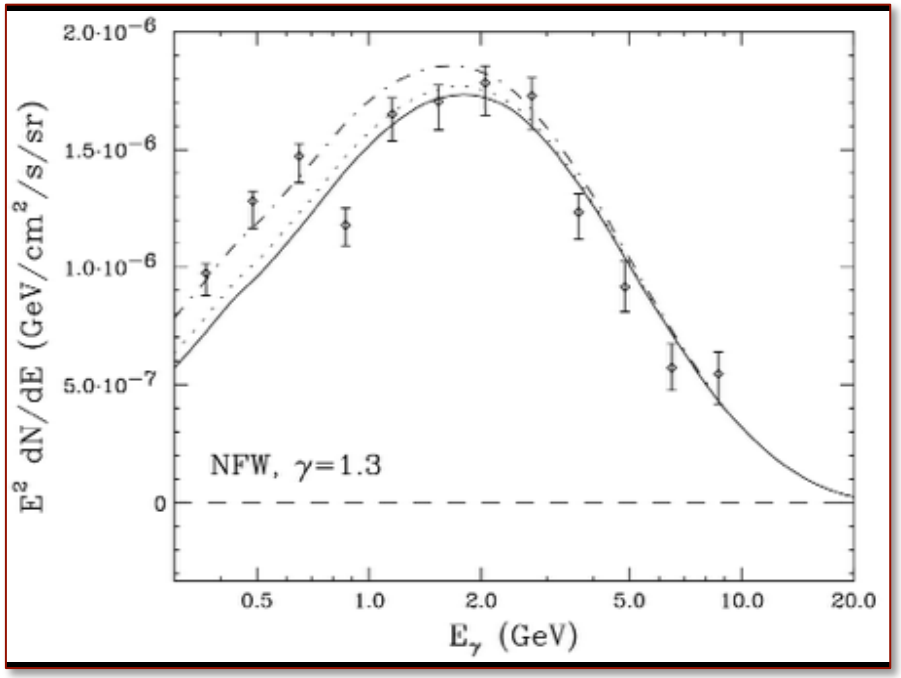
DH, Goodenough (2009, 2010), DH, Linden (2011), Abazajian, Kaplinghat (2012), Gordon, Macias (2013), Daylan et al (2014), Calore, Cholis, Weniger (2014)





Daylan, Finkbeiner, DH, Linden, Slatyer, Rodd (2014)





Daylan, Finkbeiner, DH, Linden, Slatyer, Rodd (2014)

An Excess Relative to What?

Although it is clear at this point that Fermi has observed an excess relative to standard astrophysical background models, it is important and reasonable to be asking to what extent we can trust and rely upon the predictions of such background models

Are there any viable astrophysical models that can explain the excess?

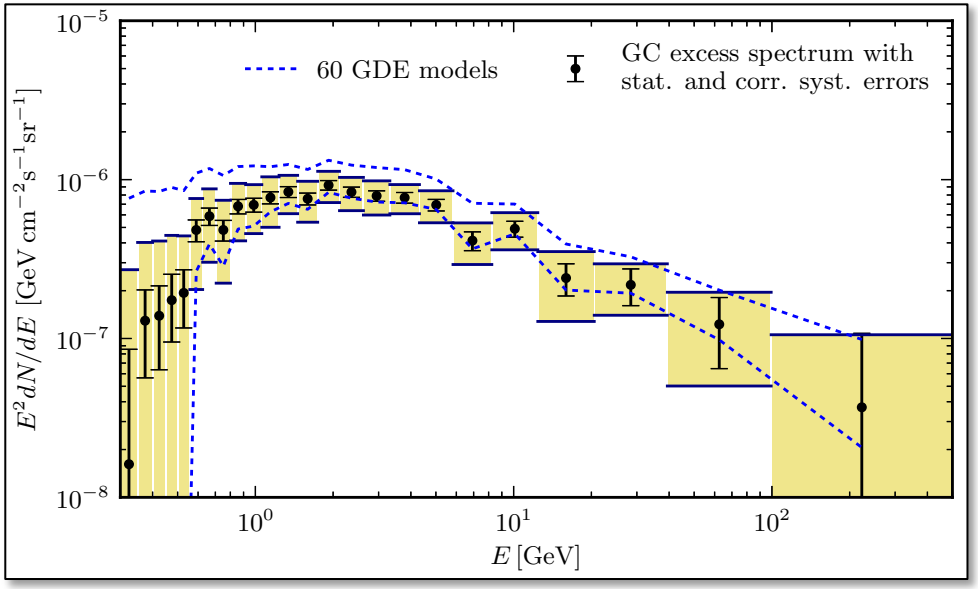
Do variations in the background model significantly impact the characteristics of the residual excess?

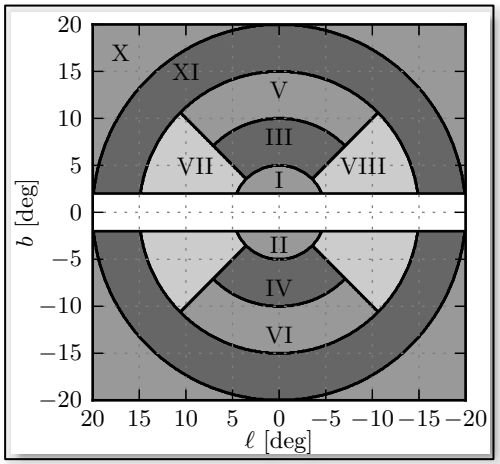
Background model systematics for the Fermi GeV excess

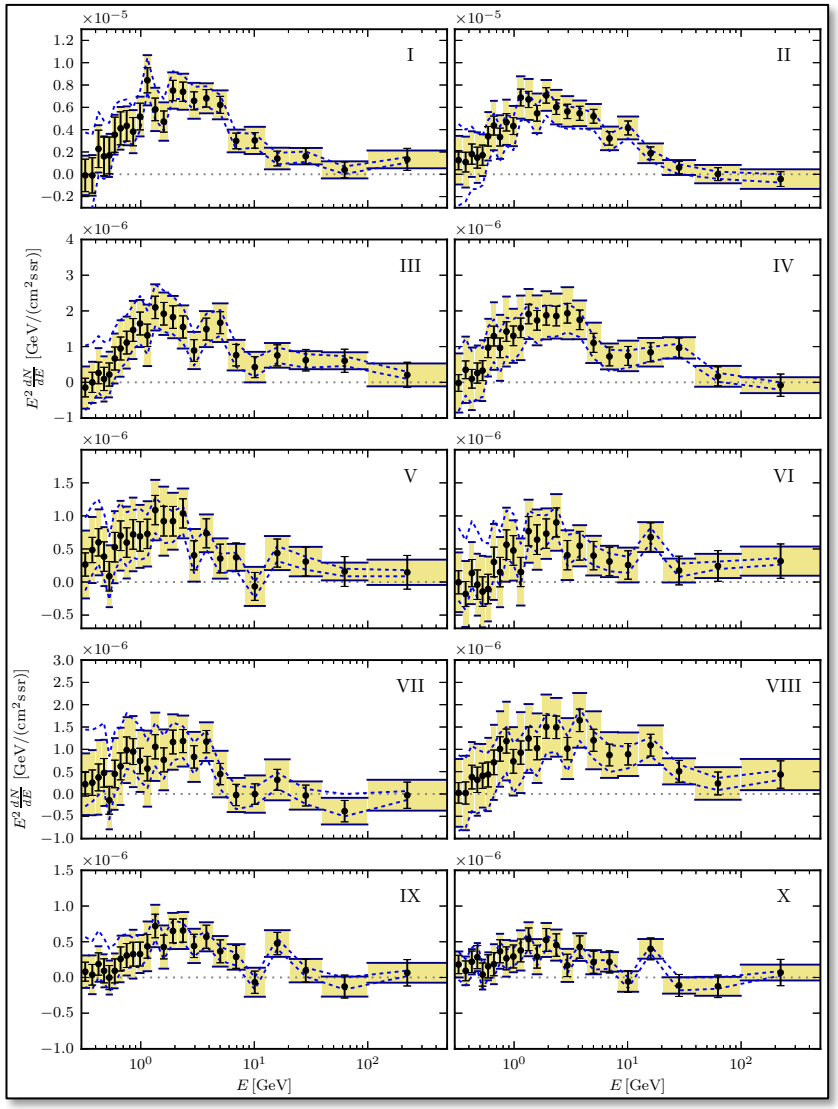
Francesca Calore,[a] Ilias Cholis[b] and Christoph Weniger[a]

arXiv:1409.0042
Highly Recommended!

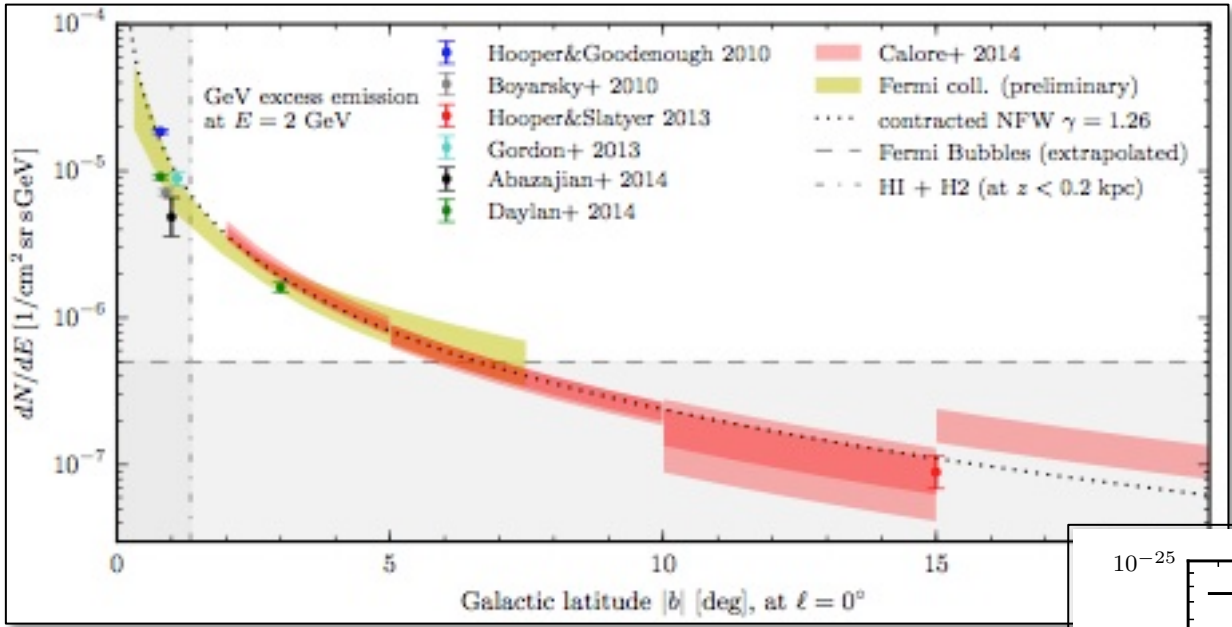
- First comprehensive study of the systematic uncertainties on the relevant astrophysical backgrounds
- Considered a very wide range of models, with extreme variation in cosmic ray source distribution and injection, gas distribution, diffusion, convection, re-acceleration, interstellar radiation and magnetic fields
- Not only does the excess persist for all such background models, the spectral and morphological properties of the excess are “remarkably stable” to these variations
- The excess does not appear to be the result of the mismodeling of standard astrophysical emission processes

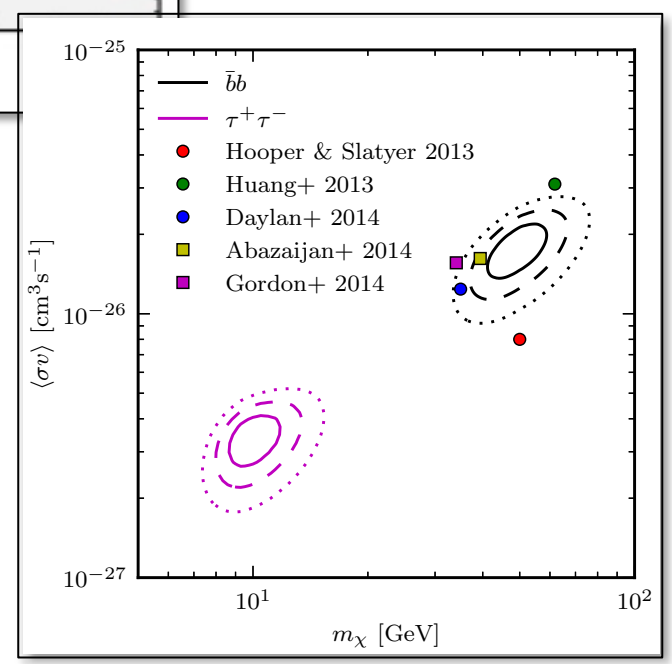






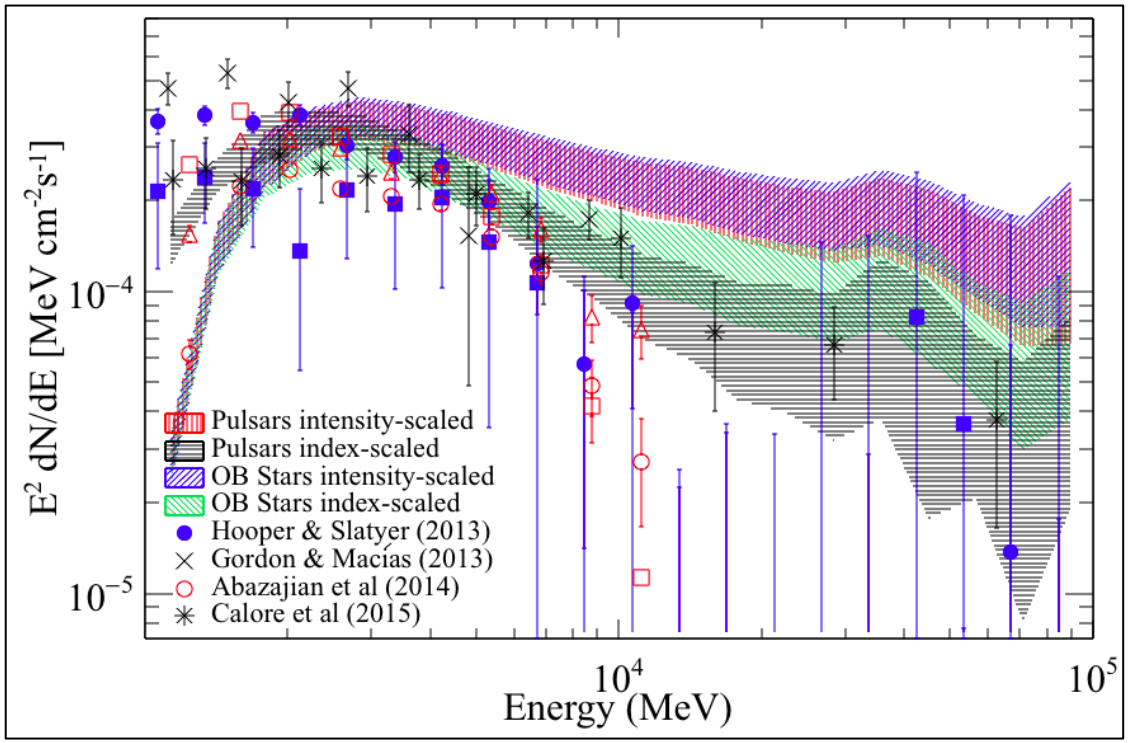
Calore, Cholis, Weniger, arXiv:1409.0042





Calore, Cholis, McCabe, Weniger, 1411.4647;
Calore, Cholis, Weniger, arXiv:1404.0042

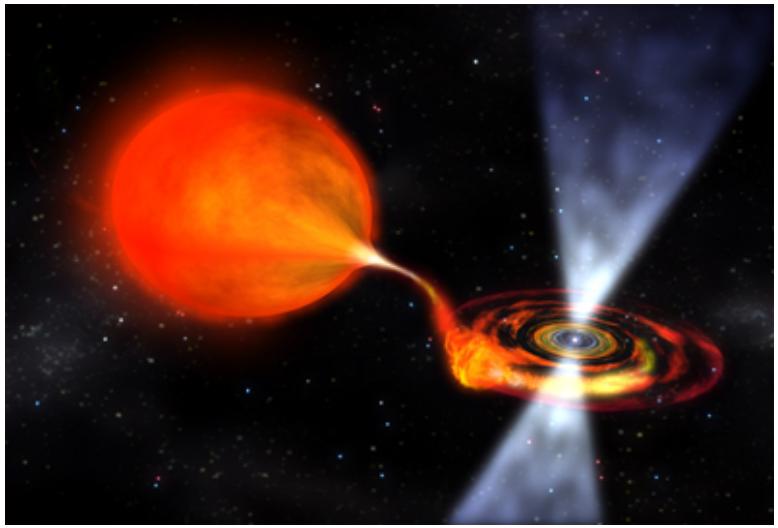
The Fermi Collaboration has recently presented their first paper on this subject (arXiv:1511.02938), reporting an excess with a similar spectrum and morphology to that reported by previous groups



Simona Murgia, et al. (Fermi Collaboration)

What Produces the Excess?

- Non-standard cosmic-ray models?
- A large population of centrally located millisecond pulsars?
- Annihilating dark matter?



Beyond Standard Diffuse Backgrounds

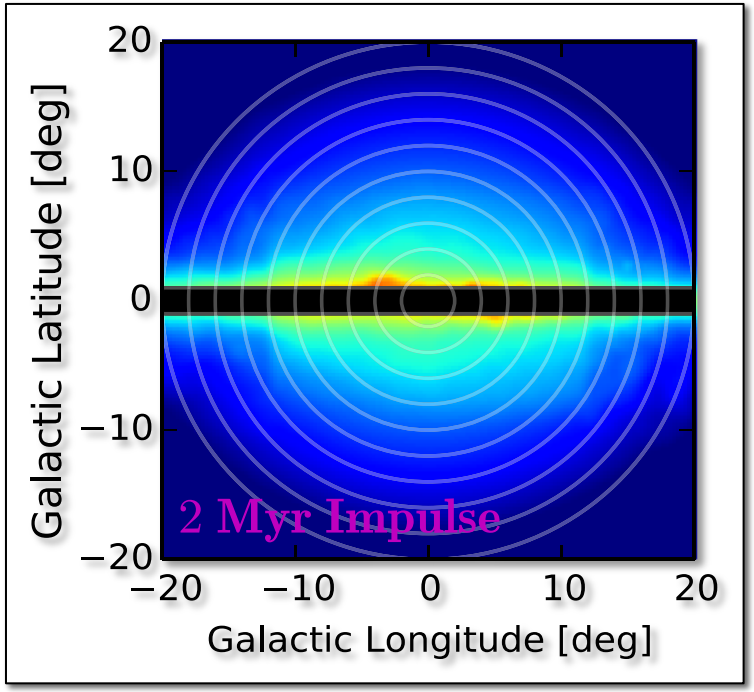
- Although Calore, Cholis and Weinger showed that the excess is robust to standard variations in the diffuse emission model, one might wonder whether a less standard scenarios might work
- To accommodate the morphology of the observed excess, one needs a very strong and steep concentration of cosmic ray sources and/or gas distributed symmetrically about the Galactic Center
- Two main difficulties:

  1) Diffusion broadens the profile of cosmic rays, making it difficult for steady-state models to account for the innermost 1-2° of the excess

  2) The gamma-ray spectra that result from cosmic ray processes are less sharply peaked than the observed excess
- Together, these considerations make it very difficult for steady-state cosmic ray scenario to account for the excess (although such models could plausibly alter the inferred characteristics of the excess)

A Series of Cosmic Ray Outbursts?

- To address these challenges, it has been proposed that recent burst-like injection of cosmic rays might be responsible for the excess
- Hadronic scenarios predict a signal that is more disky than spherical; incompatible with the data
- In more generality, the small-scale structure of the excess does *not* correlate with the distribution of gas (Daylan *et al*. 2014), disfavoring a hadronic cosmic ray origin for the excess



Carlson, Profumo, PRD, arXiv:1405.7685,
Petrovic, Serpico, Zaharijas, arXiv:1405.7928

A Series of Cosmic Ray Outbursts?

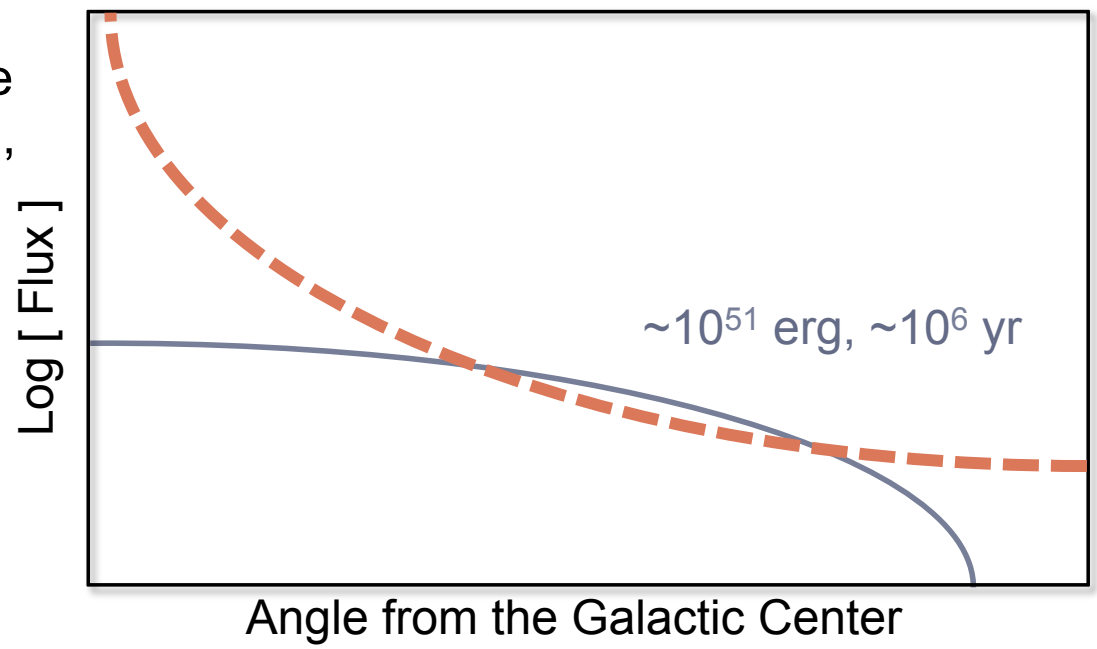
- Leptonic outburst scenarios (Petrovic *et al*.) are more difficult to rule out
- After exploring a wide range of leptonic outburst scenarios, there appear to be two main challenges (among others):

Cholis, Evoli, Calore, Linden, Weniger, DH, arXiv:1506.05104

A Series of Cosmic Ray Outbursts?

- Leptonic outburst scenarios (Petrovic *et al*.) are more difficult to rule out
- After exploring a wide range of leptonic outburst scenarios, there appear to be two main challenges (among others):

1) The morphology from a given outburst is "convex", whereas the data is "concave" – to fit the data, we need several outbursts, with highly tuned parameters

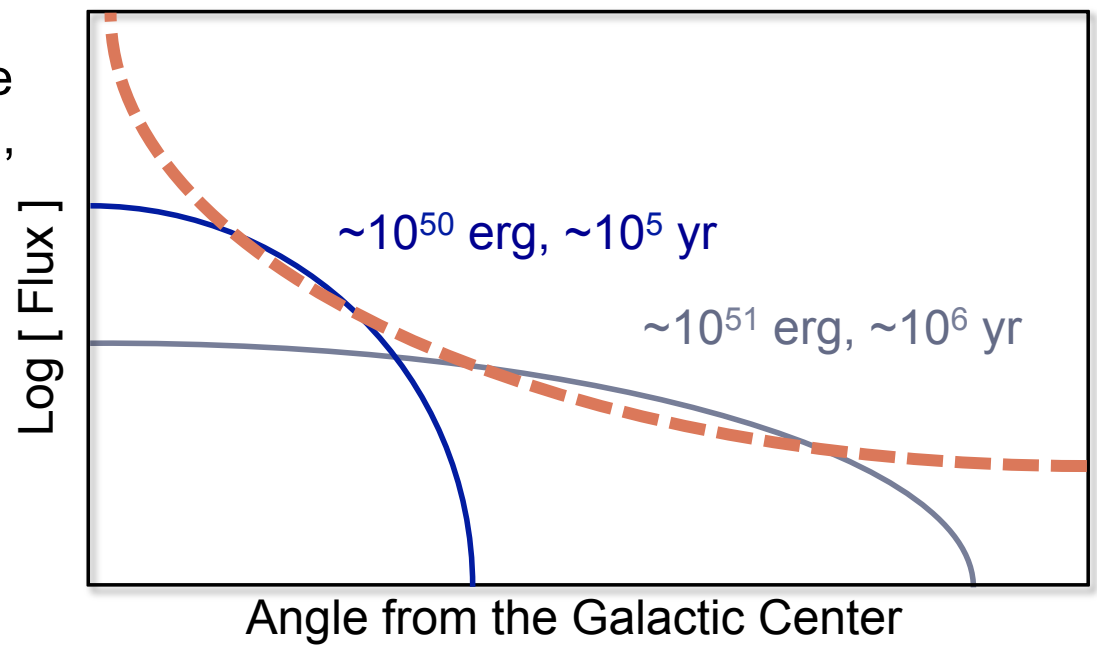


Cholis, Evoli, Calore, Linden, Weniger, DH, arXiv:1506.05104

A Series of Cosmic Ray Outbursts?

- Leptonic outburst scenarios (Petrovic *et al*.) are more difficult to rule out
- After exploring a wide range of leptonic outburst scenarios, there appear to be two main challenges (among others):

1) The morphology from a given outburst is "convex", whereas the data is "concave" – to fit the data, we need several outbursts, with highly tuned parameters

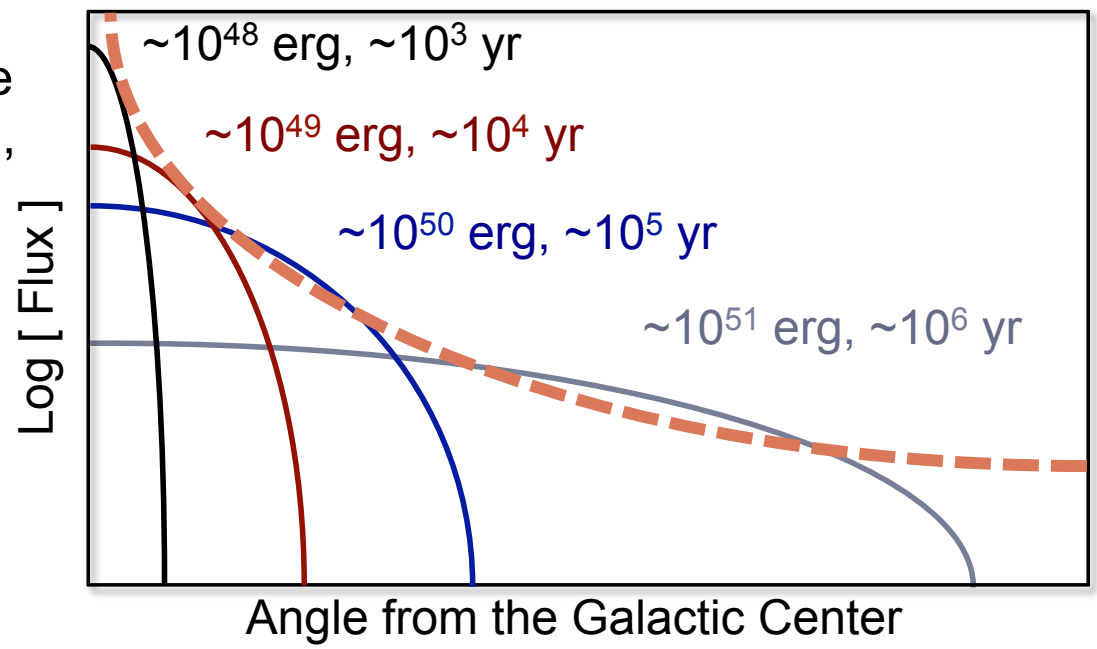


Cholis, Evoli, Calore, Linden, Weniger, DH, arXiv:1506.05104

A Series of Cosmic Ray Outbursts?

- Leptonic outburst scenarios (Petrovic *et al*.) are more difficult to rule out
- After exploring a wide range of leptonic outburst scenarios, there appear to be two main challenges (among others):

1) The morphology from a given outburst is "convex", whereas the data is "concave" – to fit the data, we need several outbursts, with highly tuned parameters



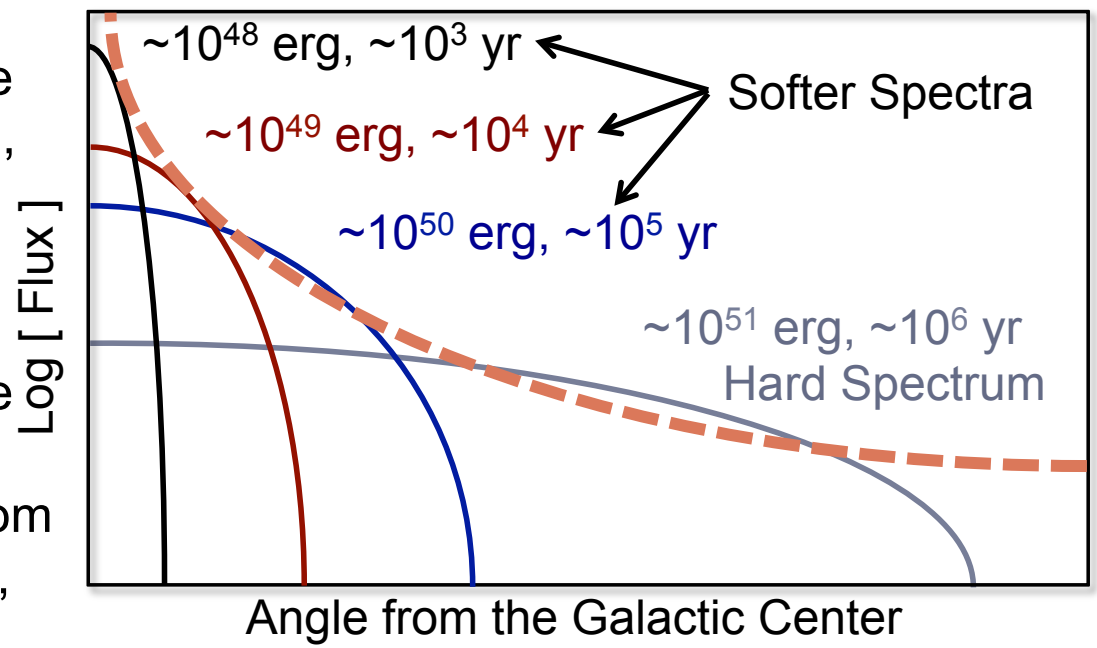
Cholis, Evoli, Calore, Linden, Weniger, DH, arXiv:1506.05104

A Series of Cosmic Ray Outbursts?

- Leptonic outburst scenarios (Petrovic *et al*.) are more difficult to rule out
- After exploring a wide range of leptonic outburst scenarios, there appear to be two main challenges (among others):

1) The morphology from a given outburst is "convex", whereas the data is "concave" – to fit the data, we need several outbursts, with highly tuned parameters

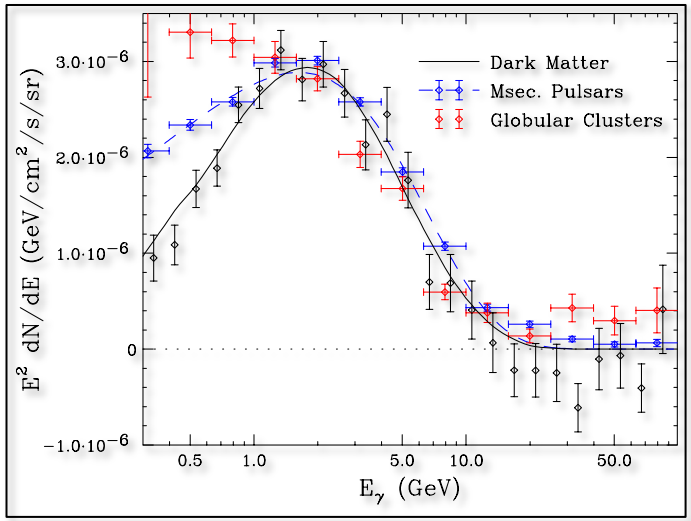
2) The gamma-ray spectrum is approximately uniform across the Inner Galaxy, but energy losses should lead to softer emission from the outer regions – to fit the data, we need the older outbursts to inject electrons with higher energies than more recent outbursts

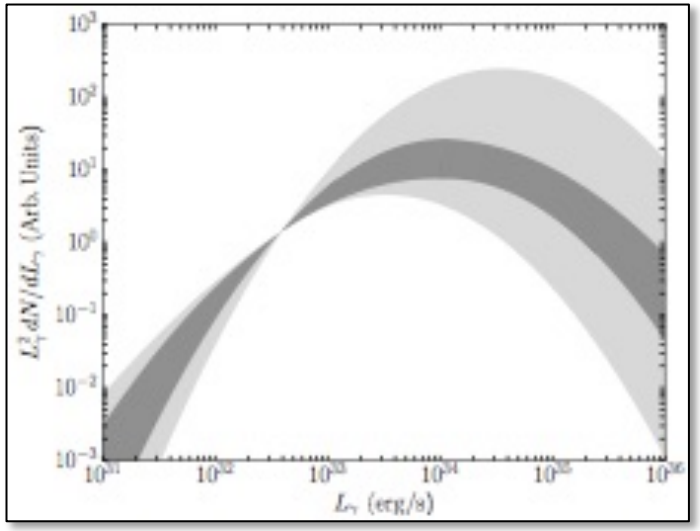


Cholis, Evoli, Calore, Linden, Weniger, DH, arXiv:1506.05104

Gamma-Rays From Millisecond Pulsars

- Although none have been identified near the Galactic Center, it seems plausible that large numbers of MSPs could exist in this region
- Fermi has observed gamma-ray emission from ~75 known MSPs
- The average observed spectra from these sources is similar to that of the Galactic Center excess – this is the main reason that MSPs have been considered as a possible explanation for the excess
- The luminosity function of MSPs has been measured from the observed population (both for those MSPs in the field of the Galaxy and within globular clusters)





Cholis, DH, Linden, arXiv:1407.5625, 1407.5583
DH, Mohlabeng, arXiv:1512.04966

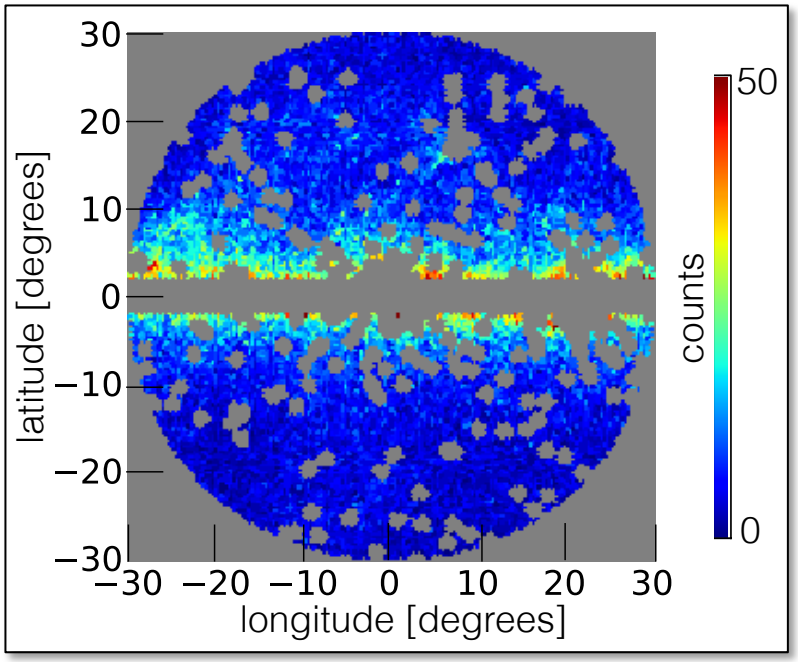
Could Millisecond Pulsars Generate the Galactic Center Excess?

- From the measured luminosity function, we find that approximately 2000 to 15,000 MSPs would be required within a few kpc of the Galactic Center to account for the excess
- Taking into account Fermi's detection threshold, the 3FGL catalog should contain ~20-40 MSPs from this region (in fact, only a few candidates exist)
- Estimates based on the numbers of bright LMXBs observed in globular clusters and in the Galactic Center lead us to expect that MSPs might account for ~1-5% of the observed excess
- If MSPs account for this signal, the luminosity function of this population is very different from that observed elsewhere in the Milky Way, without many bright members
- Perhaps young MSPs continue to be spun-up in both the field of the Milky Way *and* in globular clusters, but not in the Galactic Center, allowing the Galactic Center population to contain fractionally fewer bright MSPs

Cholis, DH, Linden, arXiv:1407.5625, 1407.5583
DH, Mohlabeng, arXiv:1512.04966

Evidence For Unresolved Point Sources?

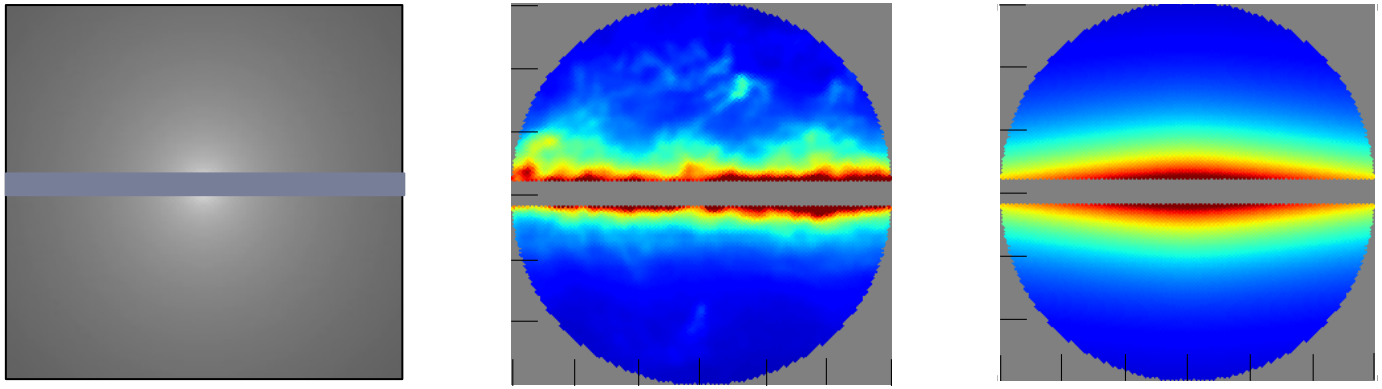
- Two recent studies find that ~1-10 GeV photons from the direction of the Inner Galaxy are more clustered than expected, suggesting that the GeV excess might be generated by a population of unresolved point sources



Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124
(see also Bartels, Krishnamurthy, Weniger, arXiv:1506.05104)

Evidence For Unresolved Point Sources?

- Lee *et al*. use smooth and point source population templates that trace the following morphologies:
  1) The dark matter density squared (tracing the excess)
  2) The (default) Fermi diffuse model
  3) The Galactic Disk



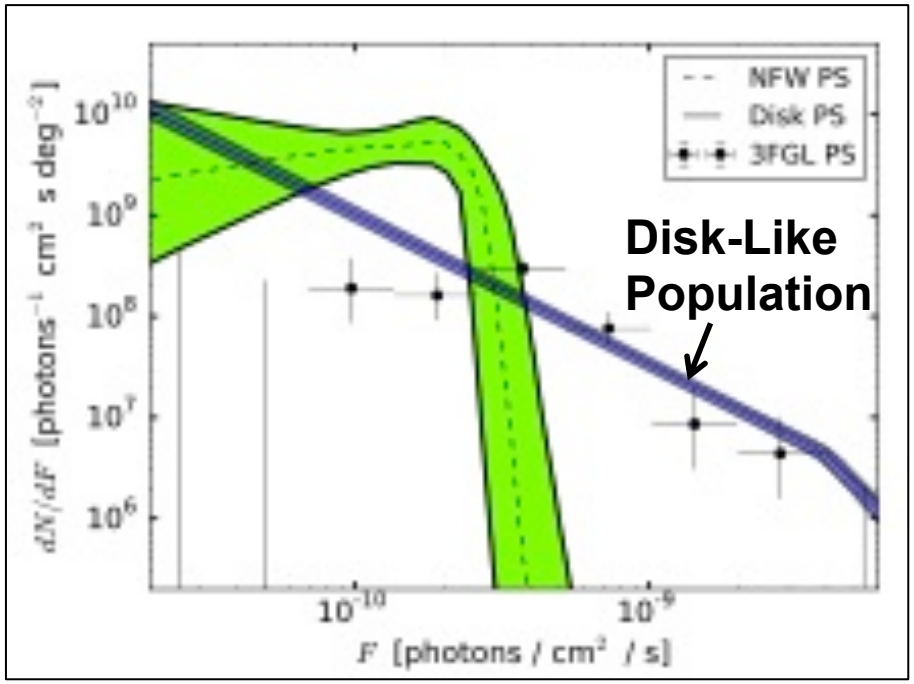
- The question their analysis asks is this: Which of these distributions do any observed gamma-ray clusters most closely trace?

Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124
(see also Bartels, Krishnamurthy, Weniger, arXiv:1506.05104)

Evidence For Unresolved Point Sources?

Lee et al.'s Conclusions include the following:

1) The brightest sources (including those contained in source catalogs) are distributed along the disk – not tracing the excess



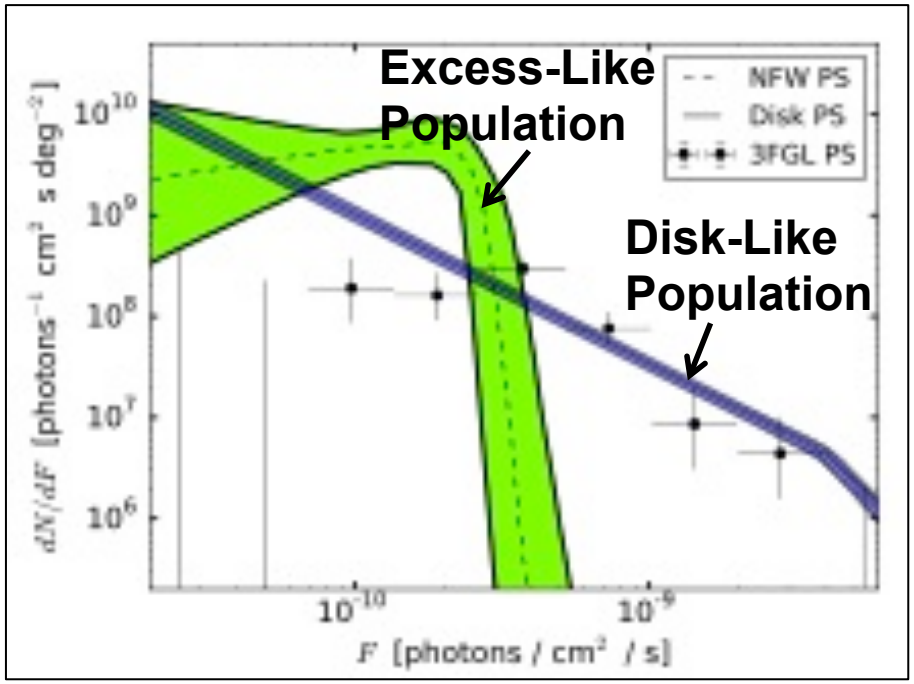
Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124
(see also Bartels, Krishnamurthy, Weniger, arXiv:1506.05104)

Evidence For Unresolved Point Sources?

Lee et al.'s Conclusions include the following:

1) The brightest sources (including those contained in source catalogs) are distributed along the disk – not tracing the excess

2) The fit suggests that the GeV excess could be generated by ~10^3 unresolved sources, most with a flux that is just slightly below Fermi's threshold for point source detection



Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124
(see also Bartels, Krishnamurthy, Weniger, arXiv:1506.05104)

Evidence For Unresolved Point Sources?

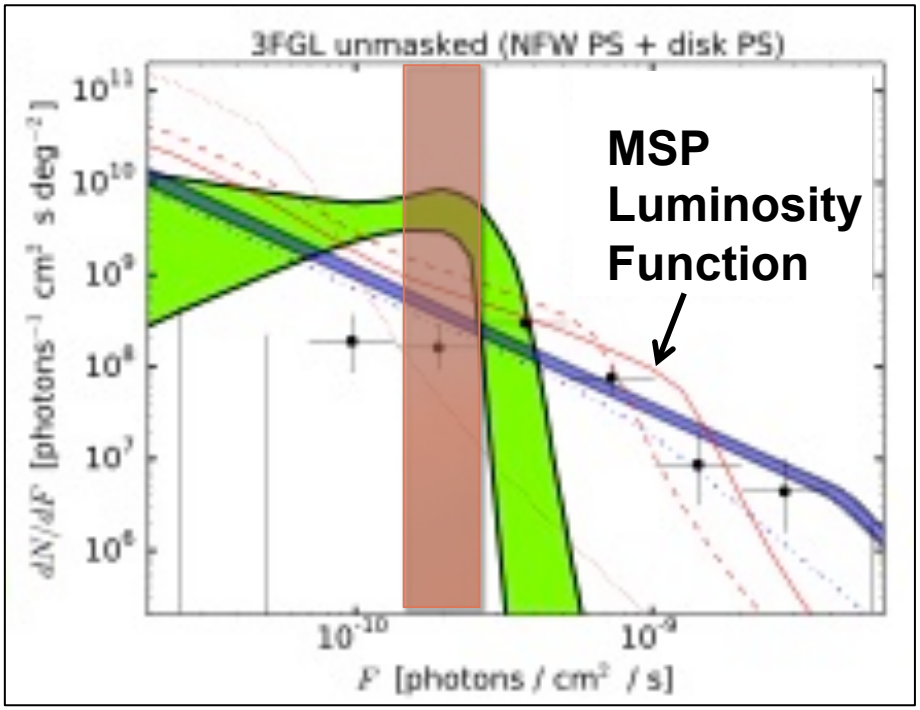
A few comments of my own:

- 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
- Keep in mind that these clusters consist of only a few photons each, on top of large and imperfectly known backgrounds
- These studies do not make use of any spectral information (they use only a single energy bin); whether these putative sources have a spectrum that matches that of the excess will be an important test

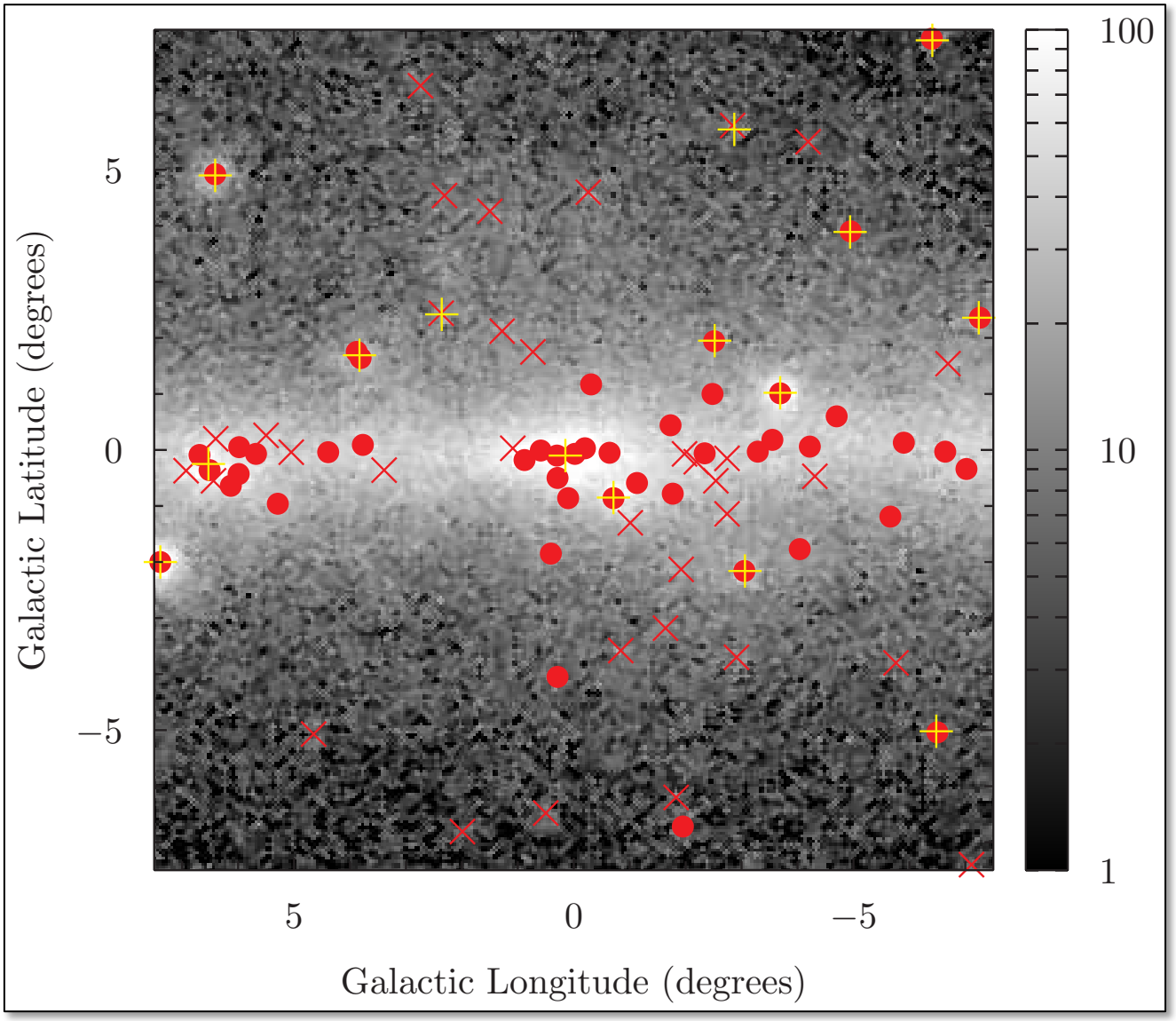
Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124
(see also Bartels, Krishnamurthy, Weniger, arXiv:1506.05104)

Could These Be Millisecond Pulsars?

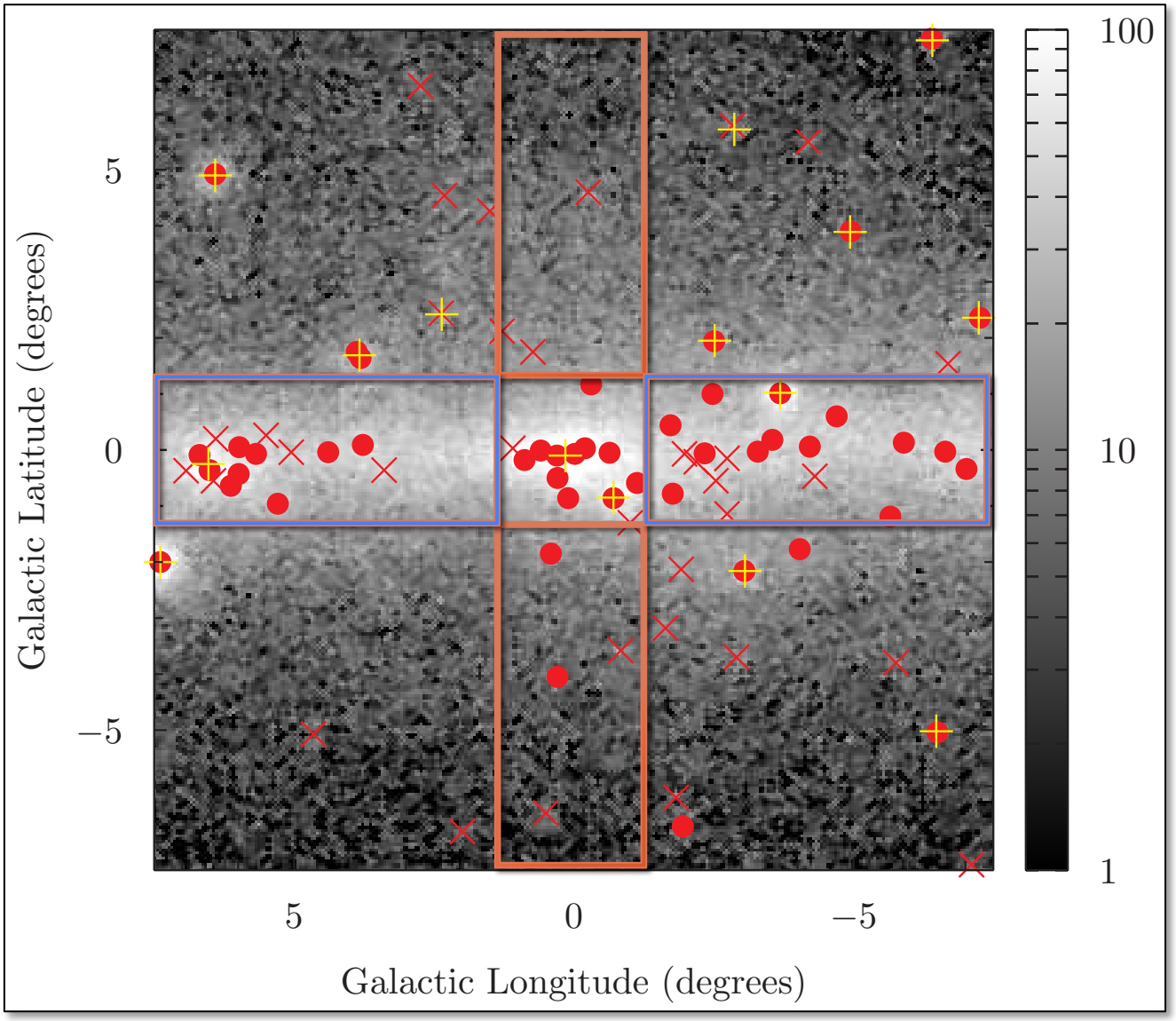
- The measured luminosity function of MSPs extends well above the threshold for detection by Fermi; very different than this new putative source population
- Where are all of the bright MSPs? (bright sources are disk-like, not DM-like)
- If these are point sources, they are very weird point sources
- A new class of standard candles?! – 68% possess luminosities within a factor of 2 ($\Delta M \sim 0.4$)



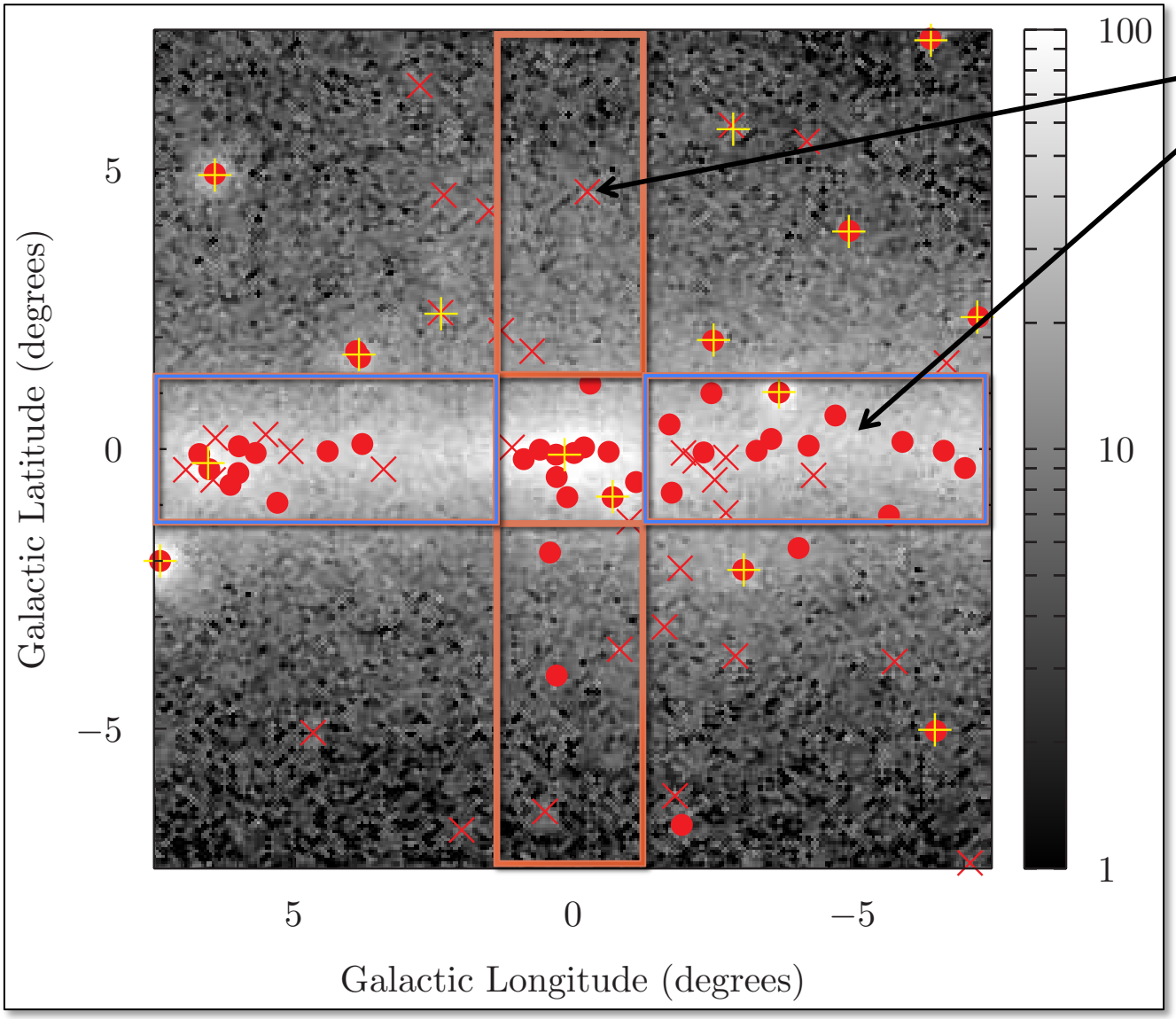
Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124
(see also Bartels, Krishnamurthy, Weniger, arXiv:1506.05104)



1FIG Catalog, Fermi Collaboration (Murgia, *et al.*)
arXiv:1511.02938



1FIG Catalog, Fermi Collaboration (Murgia, *et al.*)
arXiv:1511.02938



6 N+S Sources
34 W+E Sources

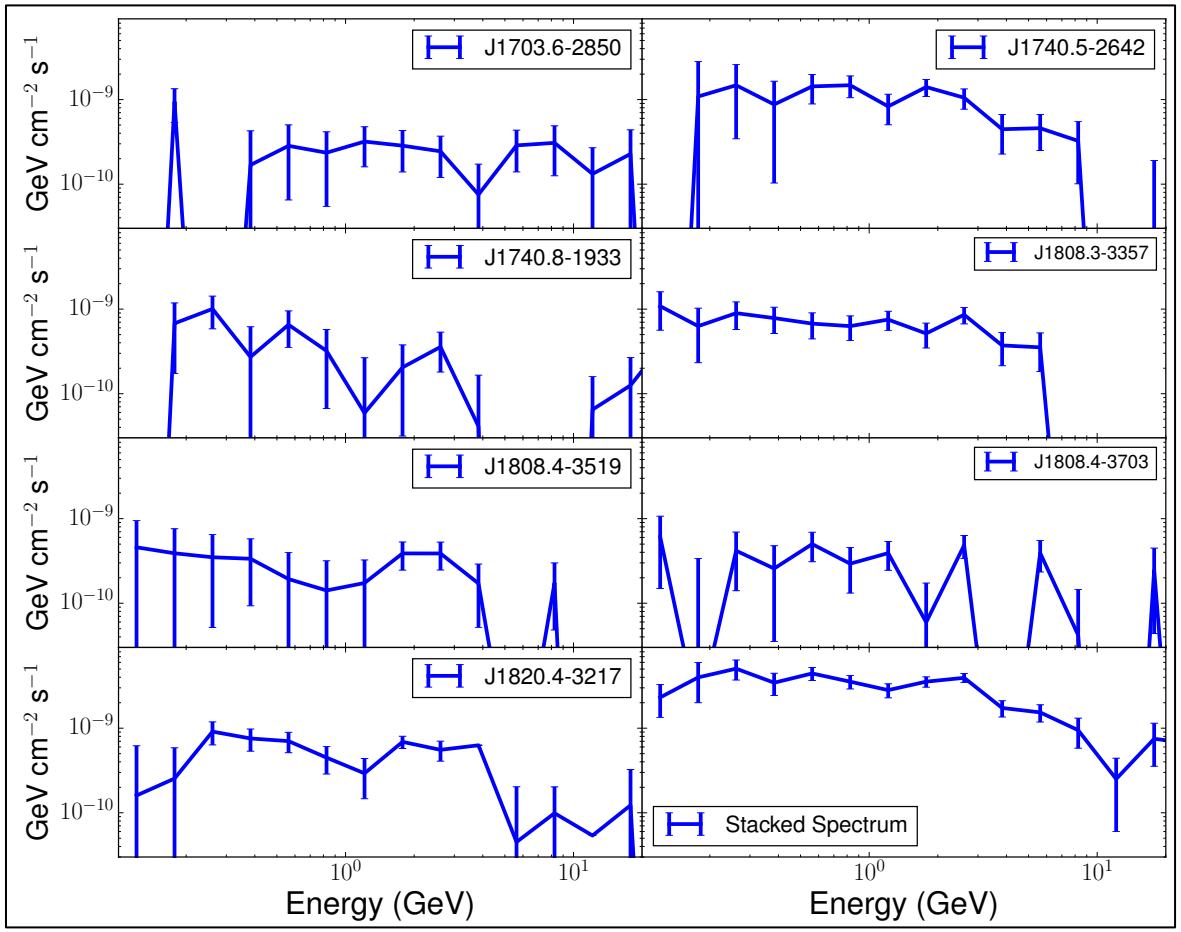
-Fermi's resolved sources are not at all spherical, but are instead concentrated along the disk

-If anything, one expects that sources in the plane would be *more* difficult to detect

1FIG Catalog, Fermi Collaboration (Murgia, *et al.*)
arXiv:1511.02938

Are These Sources Millisecond Pulsars?

- The spectra of the most promising MSP candidates near the Galactic Center don't look like pulsars – instead look like power-law sources



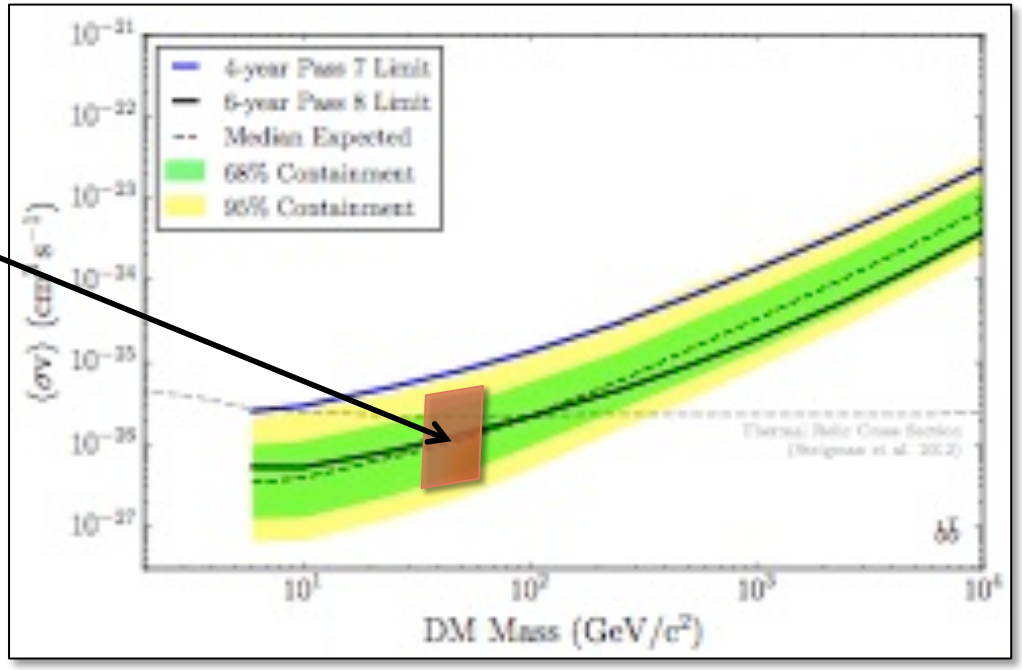
T. Linden, arXiv:1509.02929

What's Next?

- After ~7 years of investigation, the origin of the Galactic Center excess remains unclear – it looks a lot like annihilating dark matter, but we can't rule out other possibilities
- How do we go from establishing an intriguing signal, to being able to claim discovery? (or to rule out a dark matter interpretation)

Dwarf Galaxies

- The constraint from observations of dwarf galaxies remains compatible with a dark matter interpretation of the Galactic Center excess
- That being said, if the Galactic Center signal is coming from annihilating dark matter, one should expect gamma rays from dwarfs to be detected soon



Fermi Collaboration, 1503.02641

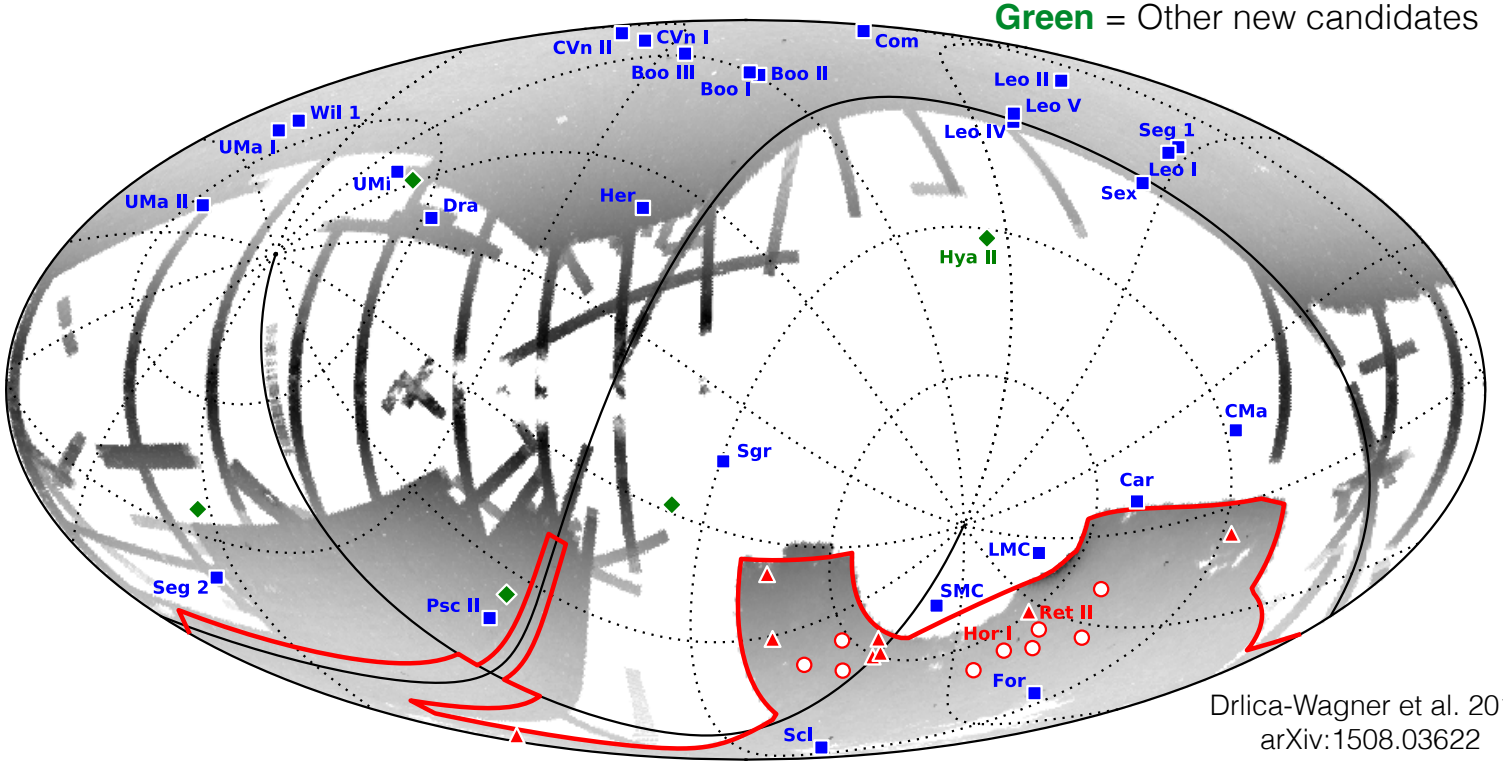
(see Alex Drlica-Wagner's talk for updates)

New Dwarf Galaxies!

- In the past year, 23 new dwarf galaxy candidates have been discovered! (most from Dark Energy Survey data, but also SDSS, and Pan-STARRS)
- Particularly exciting are Reticulum II, Tucana III, and Cetus II which are each nearby (~25-30 kpc) and attractive targets for dark matter searches

Stellar density field from SDSS and DES

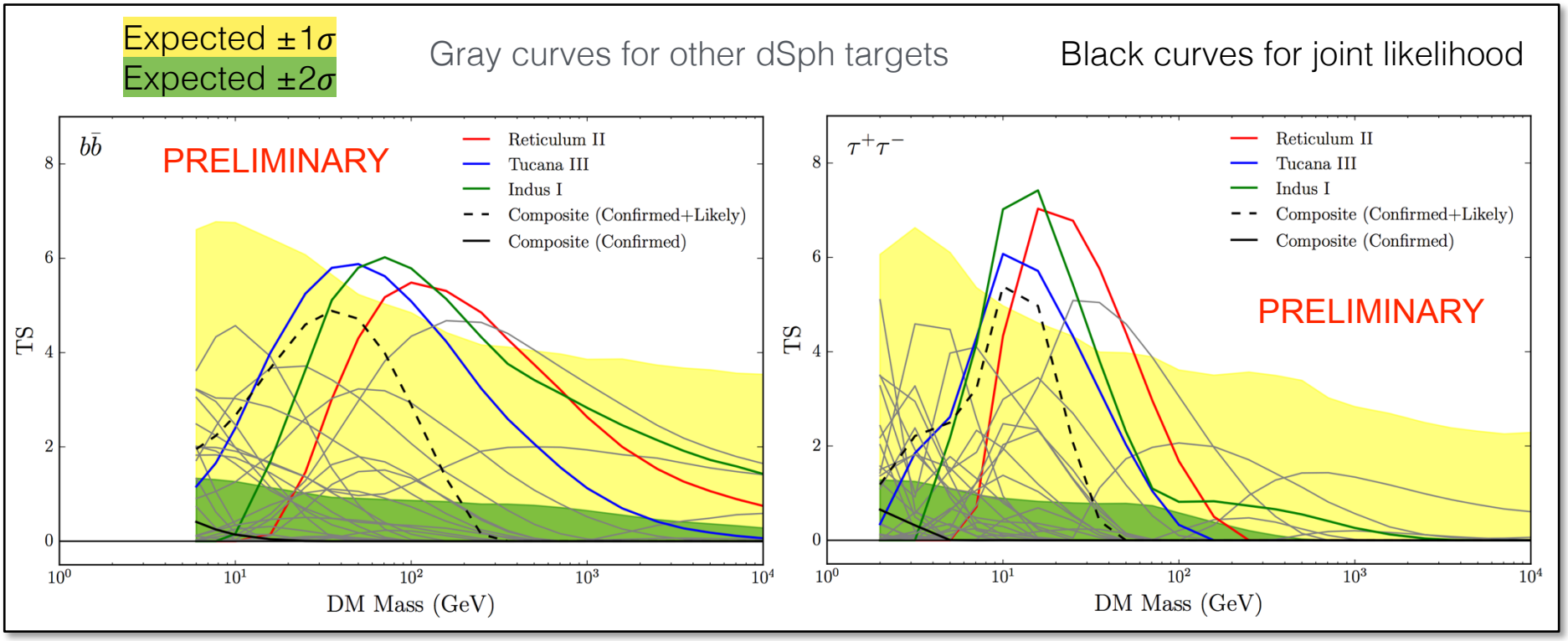
Blue = Known prior to 2015
Red triangles = DES Y2Q1 candidates
Red circles = DES Y1A1 candidates
Green = Other new candidates



Drlica-Wagner et al. 2015
arXiv:1508.03622

Fermi's View of the New Dwarf Galaxies

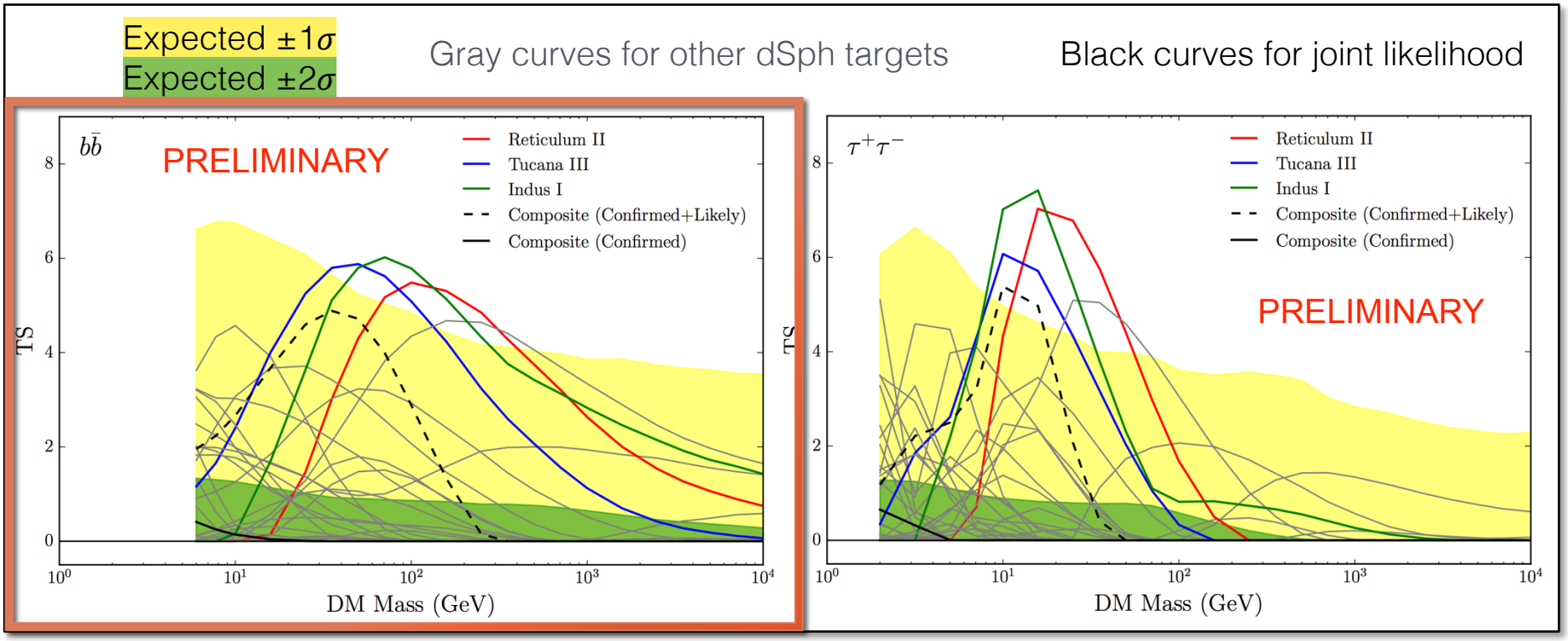
- This spring, three groups reported an excess from Reticulum II, but with only 2.4-3.2σ significance, (Geringer-Sameth et al. Drlica-Wagner, et al, DH & Linden)
- No papers on Tucana III or the other most recently discovered dwarfs yet, but Fermi has recently begun presenting preliminary results in talks:



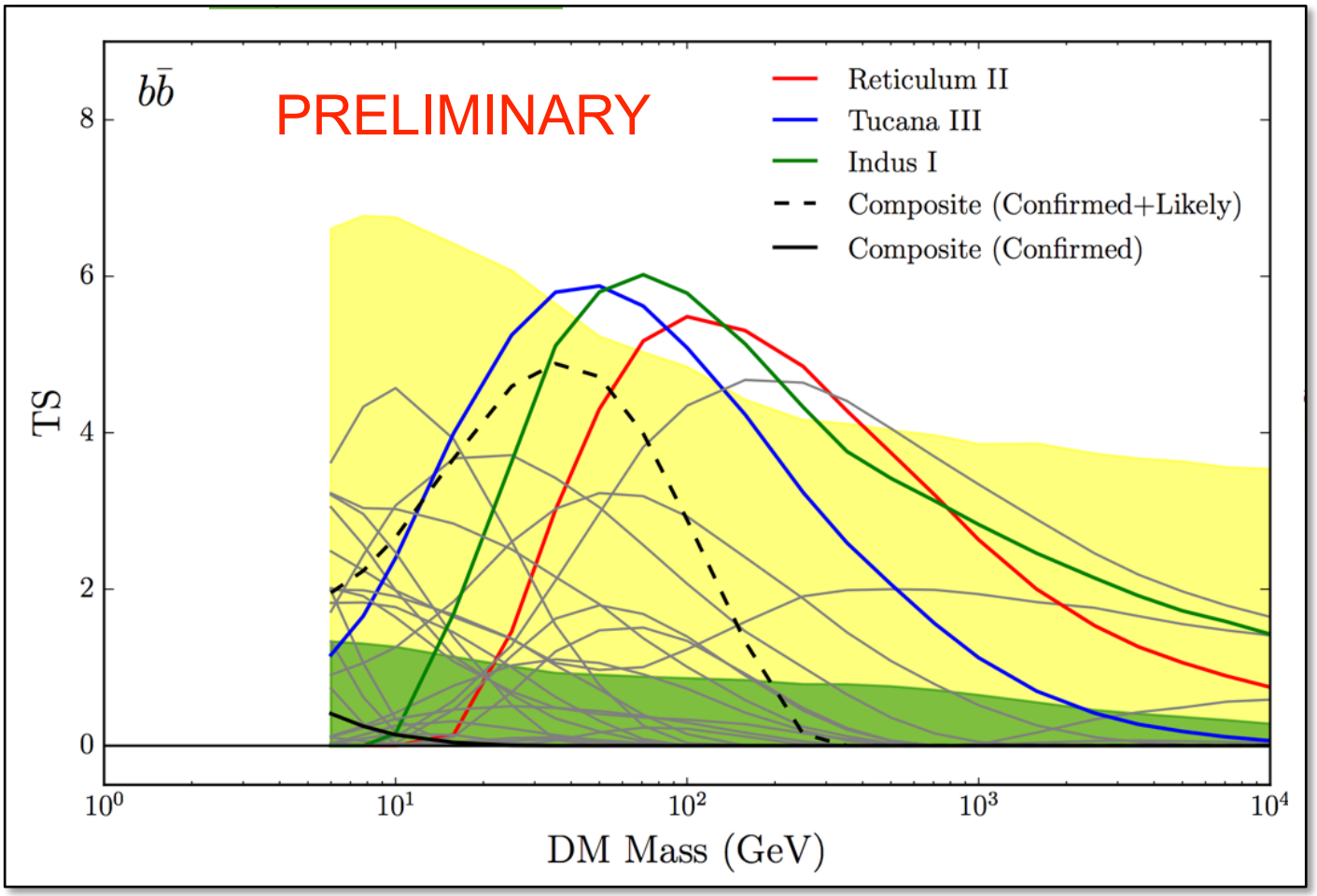
From Keith Bechtol's talk, TAUP 2015 (for the DES and Fermi Collaborations)

Fermi's View of the New Dwarf Galaxies

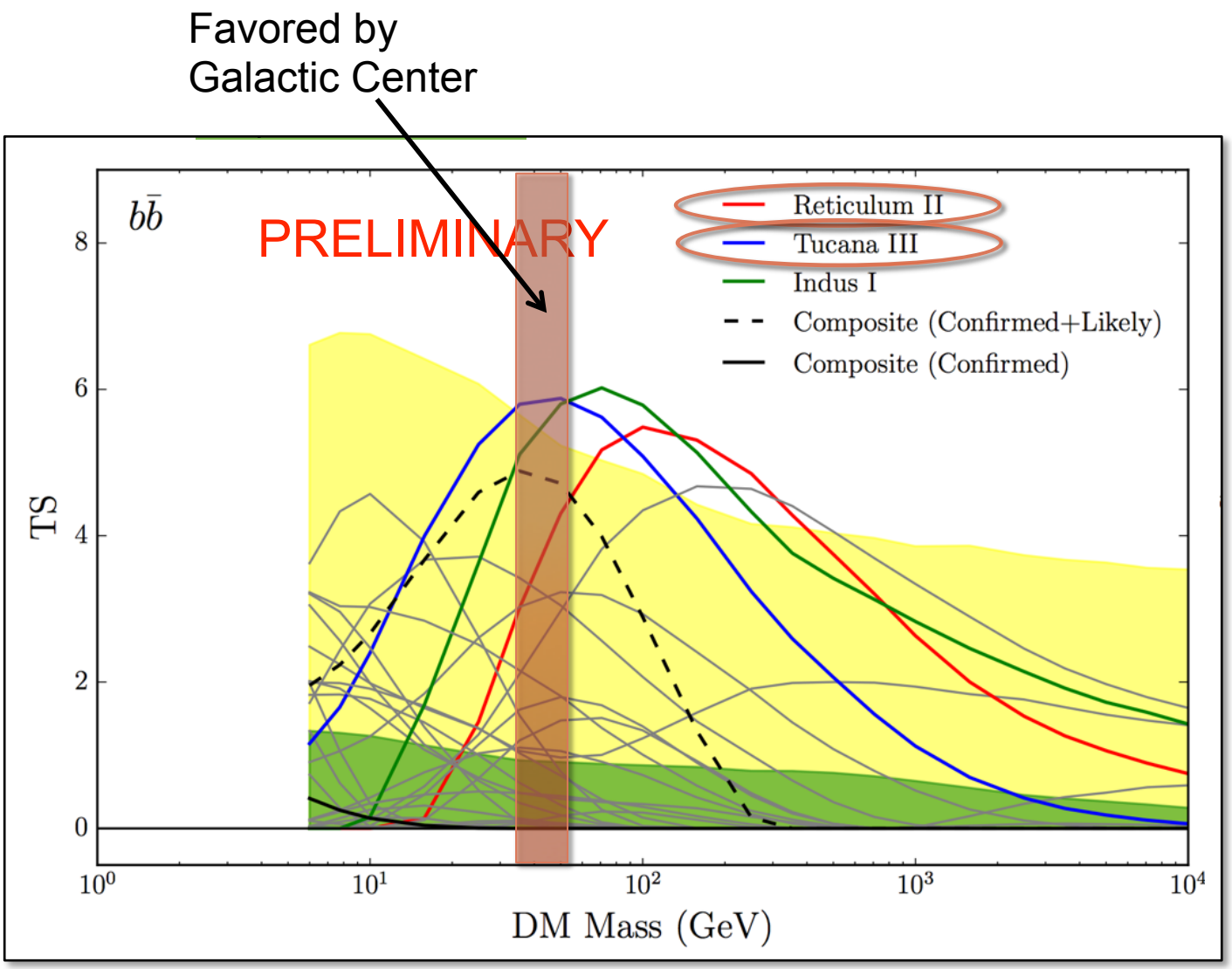
- This spring, three groups reported an excess from Reticulum II, but with only 2.4-3.2σ significance, (Geringer-Sameth et al. Drlica-Wagner, et al, DH & Linden)
- No papers on Tucana III or the other most recently discovered dwarfs yet, but Fermi has recently begun presenting preliminary results in talks:



From Keith Bechtol's talk, TAUP 2015 (for the DES and Fermi Collaborations)



From Keith Bechtol's talk, TAUP 2015 (for the DES and Fermi Collaborations)



From Keith Bechtol's talk, TAUP 2015 (for the DES and Fermi Collaborations)

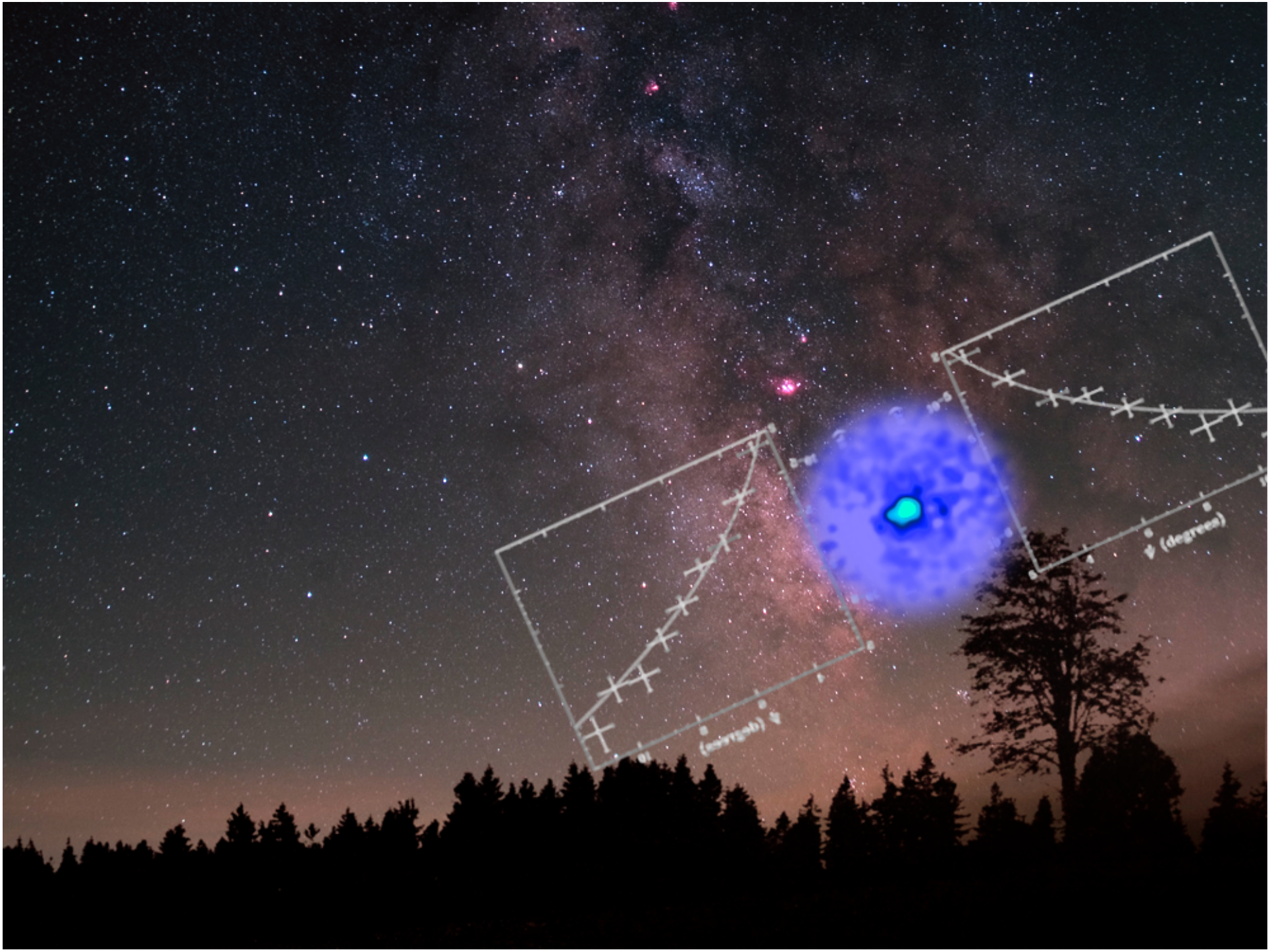
Summary

- The Galactic Center's GeV excess is particularly compelling: highly statistically significant, robust, distributed spherically out to at least 10° from the Galactic Center, and difficult to explain with known or proposed astrophysics
- The spectrum and angular distribution of this signal is very well fit by a ~35-50 GeV WIMP; future observations of dwarf galaxies will provide a critical test of a dark matter origin for this signal
- Fermi's observations of dwarf galaxies – both old, new, and yet to be discovered – seem to be the most promising way forward

  -Fermi's current sensitivity to dwarfs is roughly that needed to test dark matter interpretations of Galactic Center excess

  -A modest excess does exists

  -New dwarf discoveries (DES, LSST), combined with ***more data from Fermi***, could provide significant support for this interpretation or essentially rule out dark matter as the origin of the Galactic Center


(degrees)