Status of the Galactic Center Gamma-ray Excess

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SFB Colloquium, Munich
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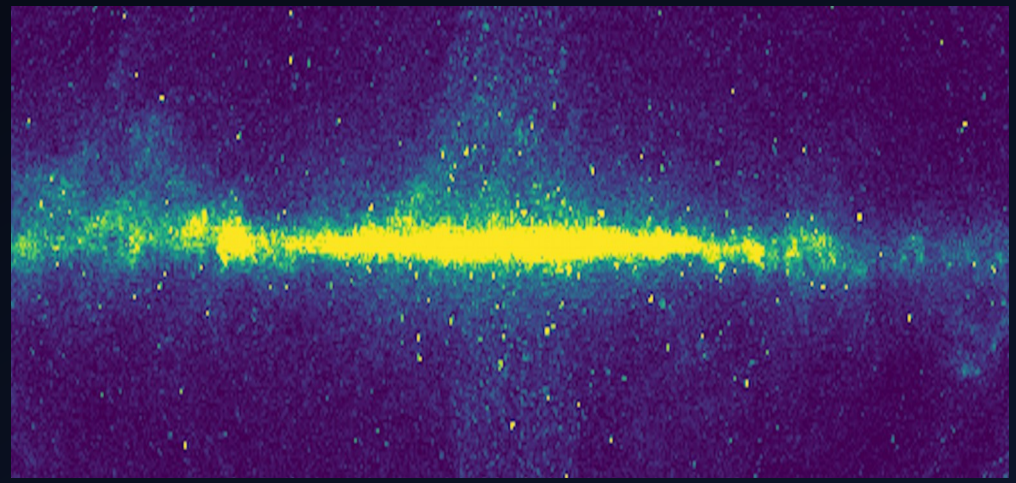
OUTLINE

- Introduction to the Galactic Center Excess
  - Motivation and characteristics
- Dark matter vs pulsars?
  - How to tell hypotheses apart
  - Recent developments
- Understanding systematics
  - Subtleties behind GCE analyses
- Current status and ways forward



Dark Matter Unknowns

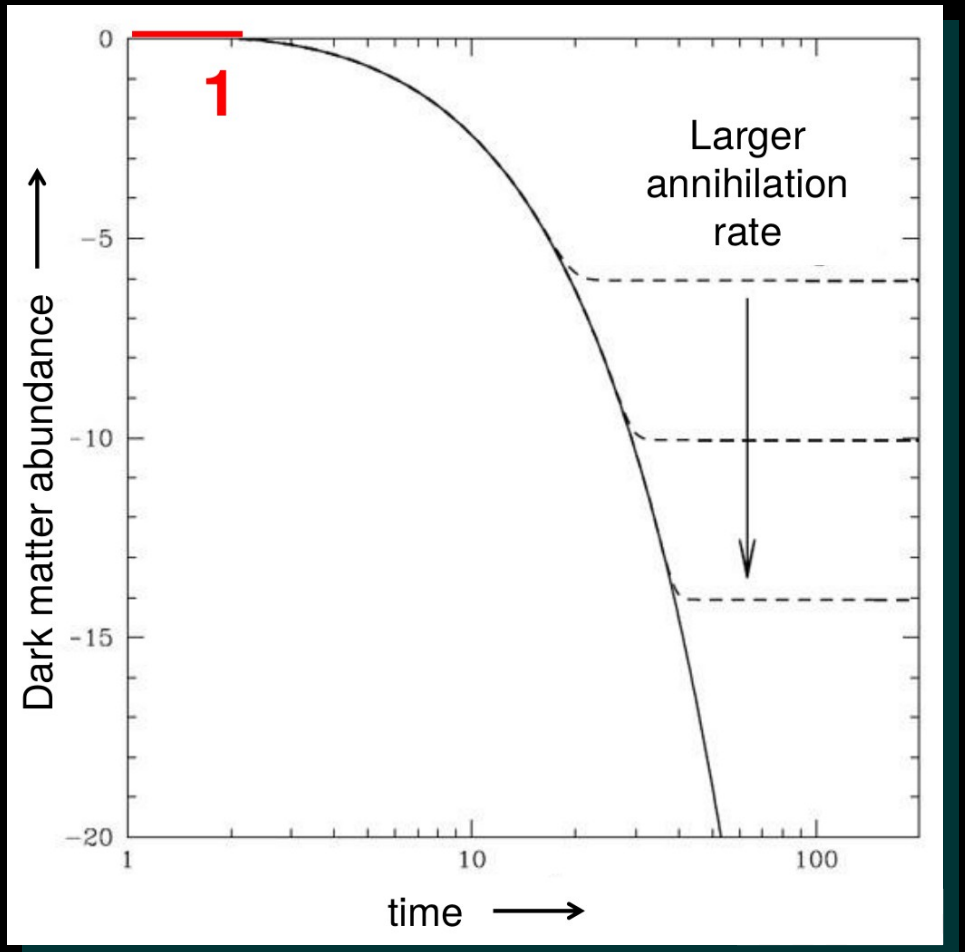
What is it made of?

Where did it come from?

Does it interact with regular matter?

DARK MATTER ABUNDANCE

1) Thermal equilibrium:
DM + DM ⇒ visible particles
Visible particles ⇒ DM + DM



DARK MATTER ABUNDANCE

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2) Universe cools, only
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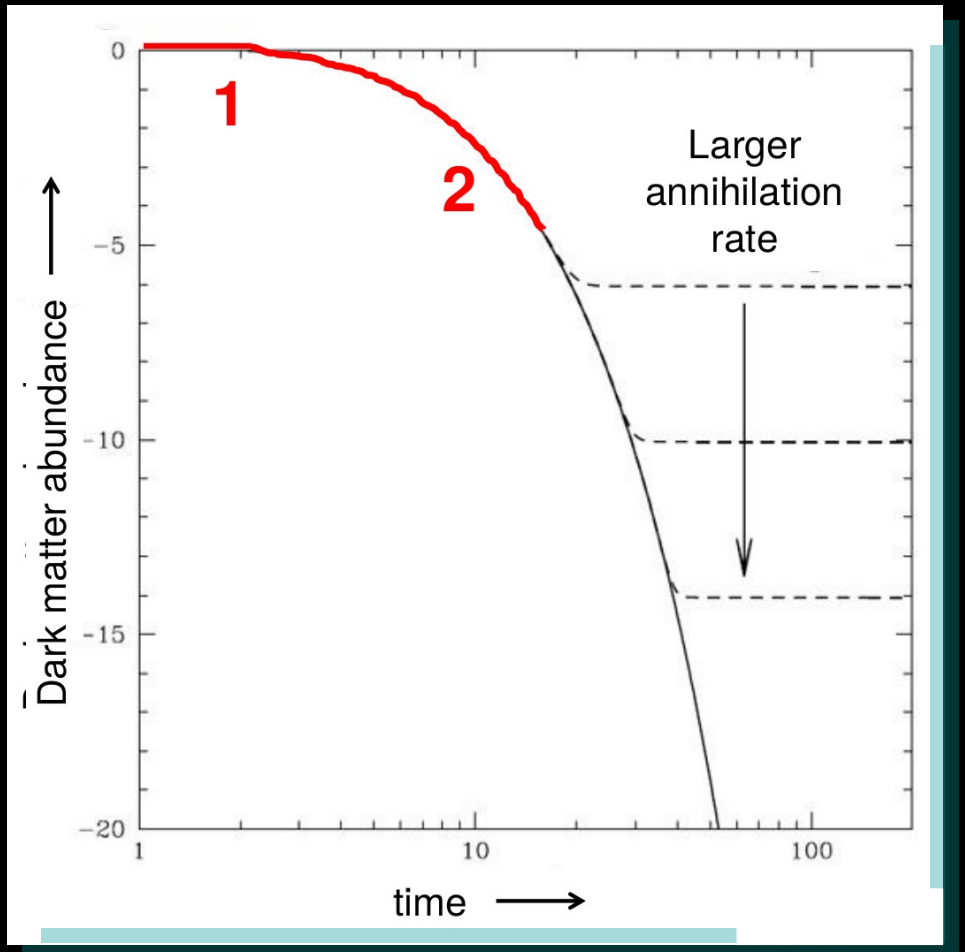

DARK MATTER ABUNDANCE

1) Thermal equilibrium:
DM + DM ⇒ visible particles
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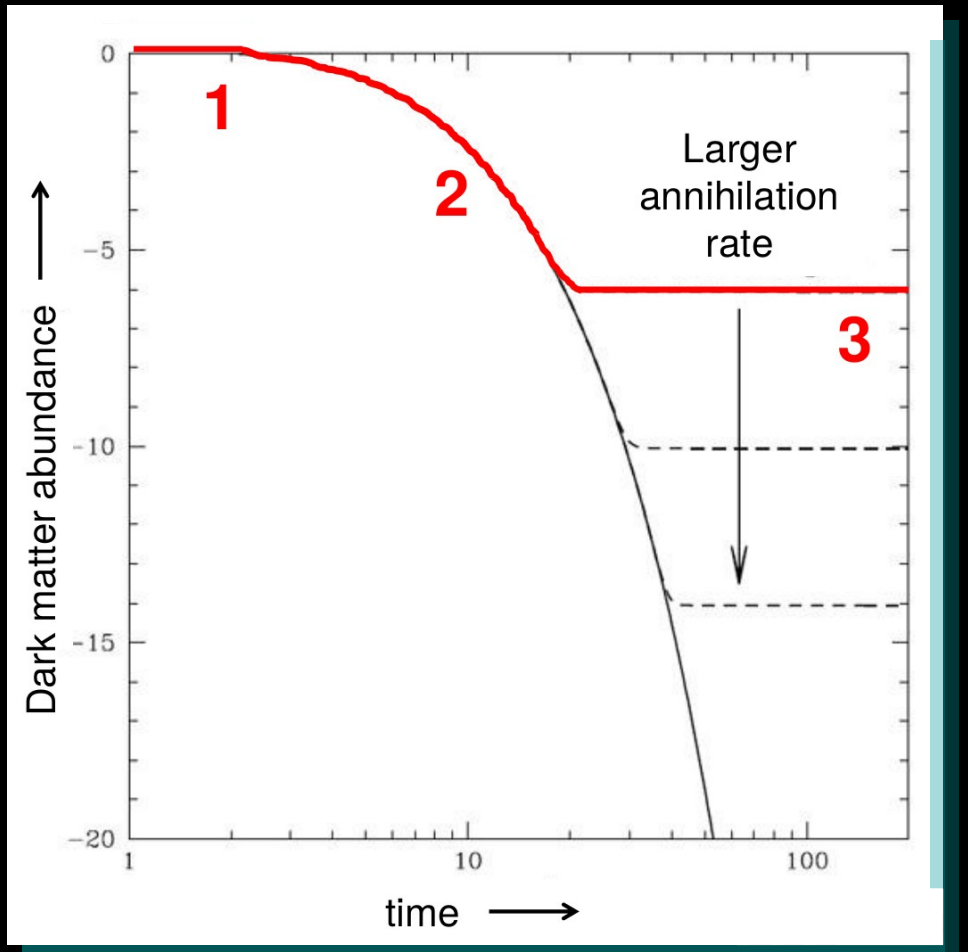
2) Universe cools, only
DM + DM ⇒ visible particles

3) Universe expands too fast.
No more annihilations.
DM abundance is set.

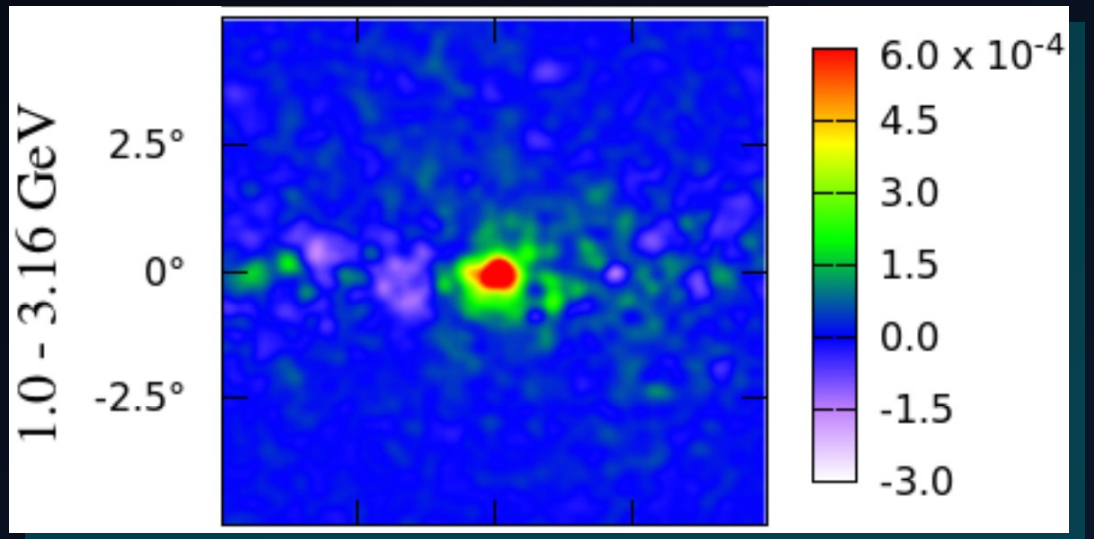
Predicts a particular annihilation rate for dark matter.



A mysterious signal with this intensity has already appeared...

THE GALACTIC CENTER GEV EXCESS

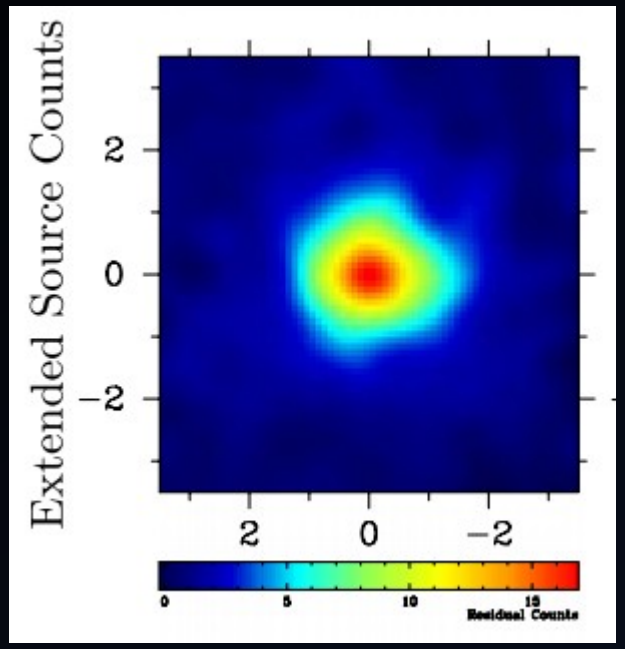
- Highly significant bright excess in gamma rays
- Peaked at 1-3 GeV
- Detected by the Fermi gamma-ray Space Telescope



Daylan+, ‘14

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

MORPHOLOGY



Abazajian+ Kaplinghat ‘12

Spherically symmetric around Galactic Center

Scales like $r^{-2.4}$ extending out to around 10°, roughly fits standard dark matter (NFW) profile
Hooper+Slatyer ‘13

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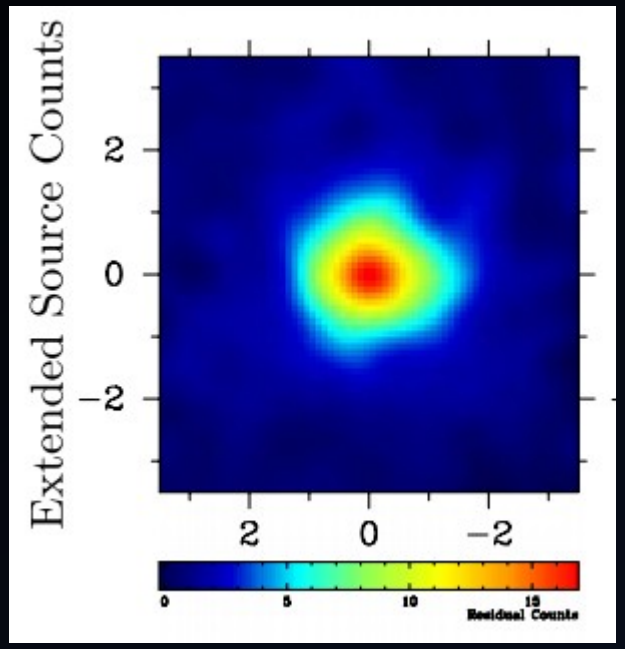

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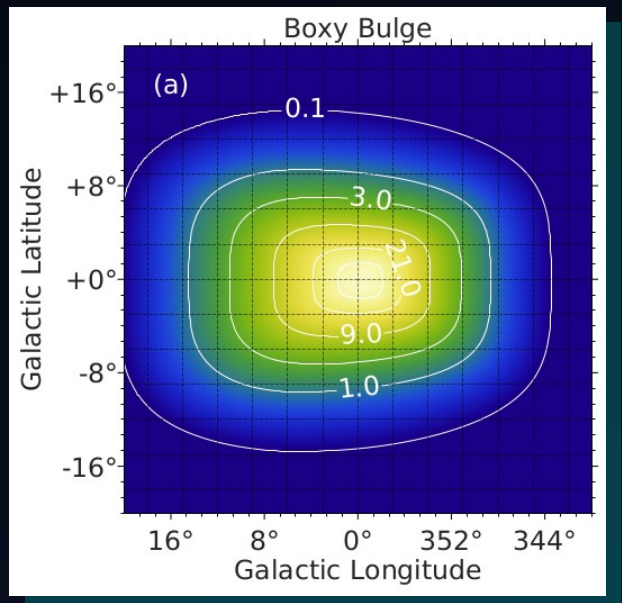

Abazajian+, ‘20

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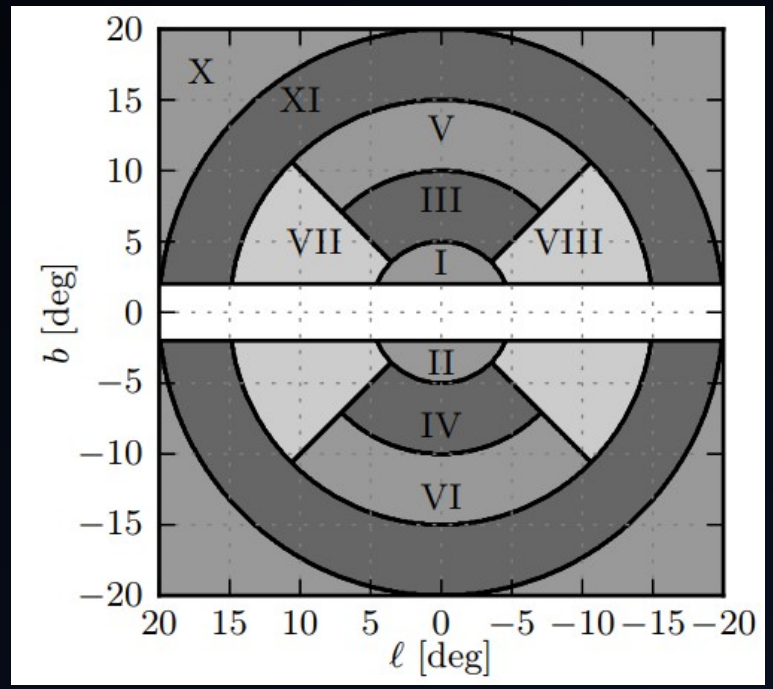
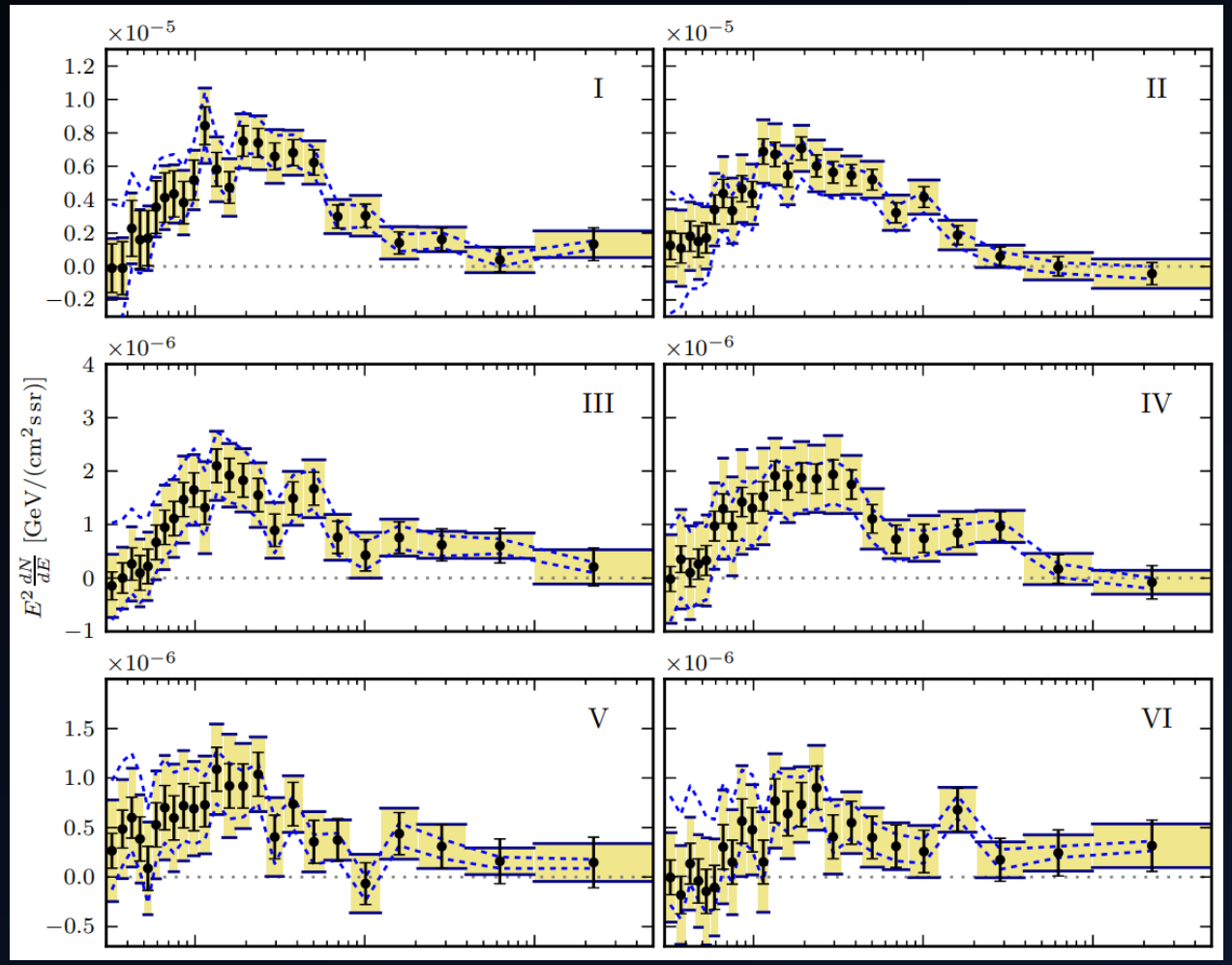
Some recent studies find bulge preference

- Macias+, ‘16
- Bartels+, ‘17
- Macias+, ‘19
- Abazajian+, ‘20
- Calore+, ‘21
- Pohl+, ‘22

SPECTRUM

- Shape appears to be uniform throughout the Inner Galaxy





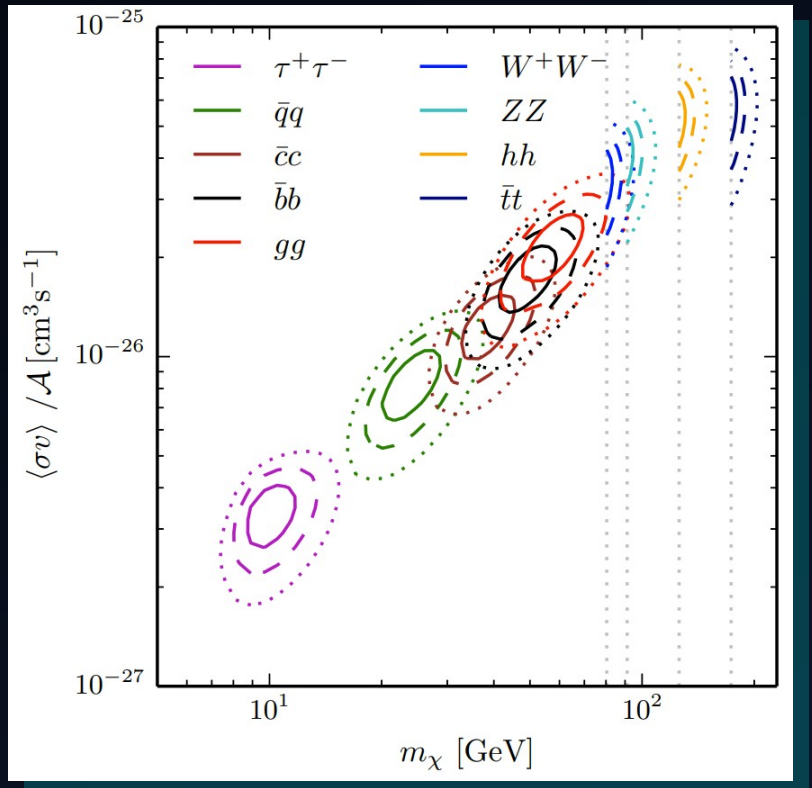
Calore et al ‘14

See also Di Mauro ‘21

INTENSITY+SPECTRUM

Spectrum well fit by a ~20-60 GeV dark matter particle annihilating to hadronic final states

...with the intensity expected of thermal particle dark matter



Calore et al '14

Also see Di Mauro '21

SIGNAL OF ANNIHILATING DARK MATTER?

- Morphology consistent?
  - approximately spherical
  - extending well out of the center
- Intensity of thermal particle dark matter
  - can match thermal relic annihilation cross section
- Spectrum consistent: invariant with position and shape

If dark matter, first evidence of DM – SM interactions:
want to get to the bottom of this!

DARK MATTER vs PULSARS

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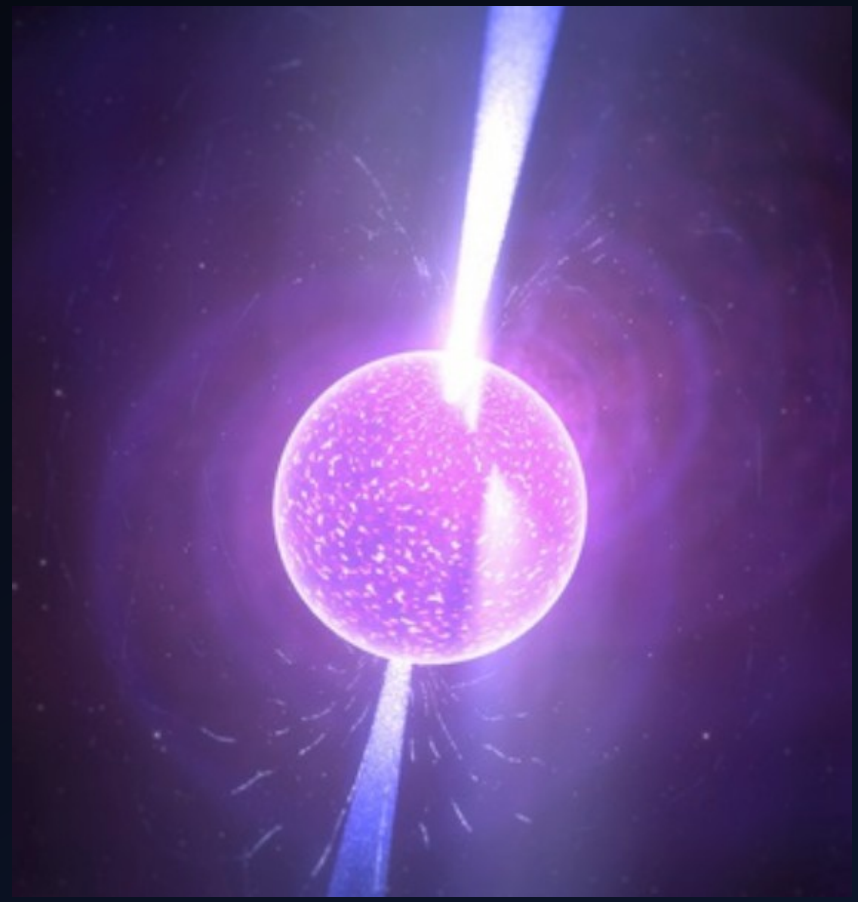
PULSARS AS THE EXCESS

- Pulsars are rapidly spinning neutron stars
- Pulsars also match the gamma-ray energy spectrum
- Pulsars appear as point sources to Fermi, which mean they have angular extent below detector thresholds



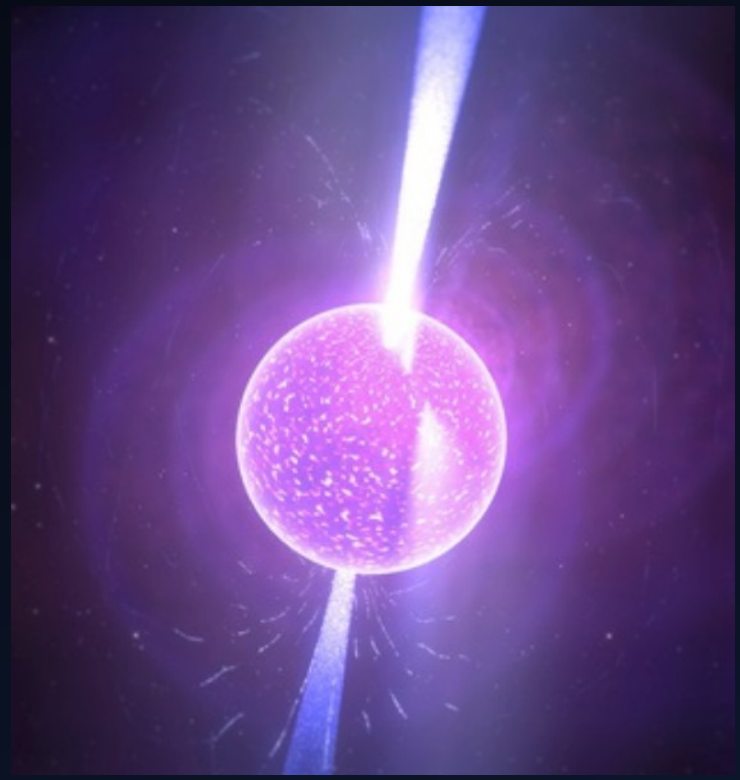
POINT SOURCES AS THE EXCESS

- Resolved Point Sources:

  Bright enough to be individually detected

- Unresolved Point Sources:

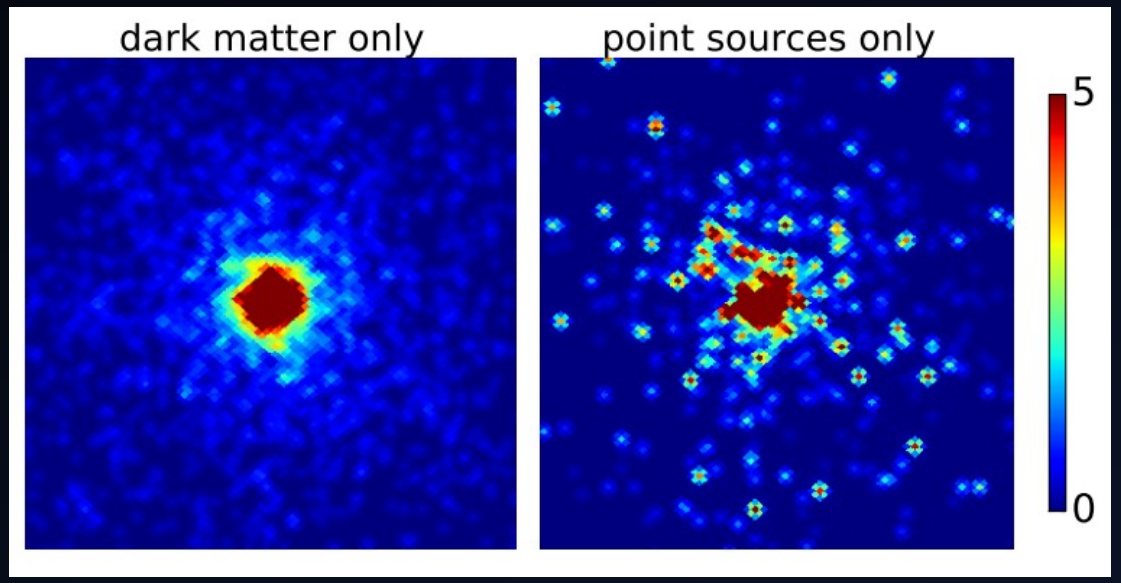
  Too dim to be individually detected, cannot be individually resolved, but collectively could explain GCE



DISTINGUISHING DM vs. POINT SOURCES

Counts of gamma rays from point sources exhibit different statistical behavior compared to those from annihilating DM:

Lee+ ‘15

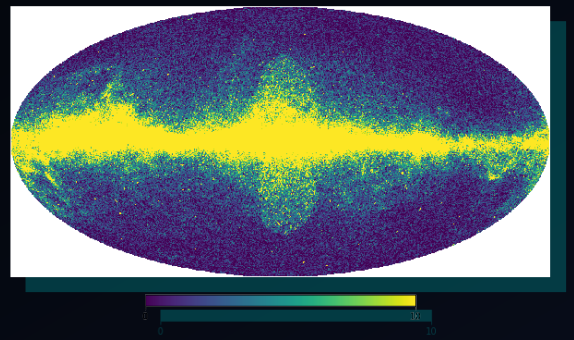


Dark matter: smooth
continuous halo
in the Galaxy

Point Sources: clumpy
individual sources

METHOD 1: TEMPLATE FITTING

Full sky



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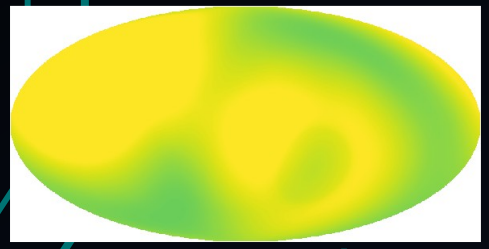
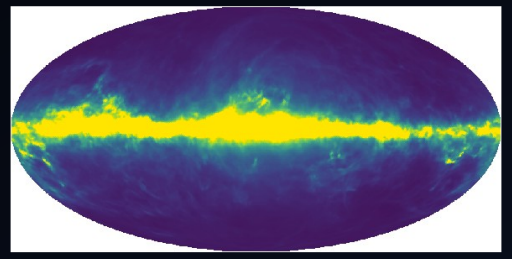
(Example combination)



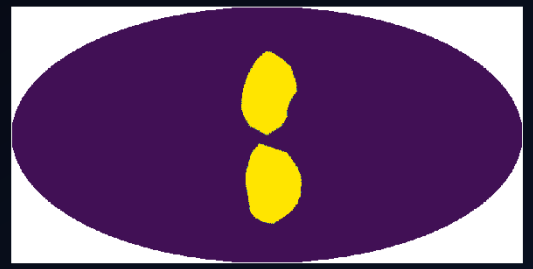
Isotropic

+



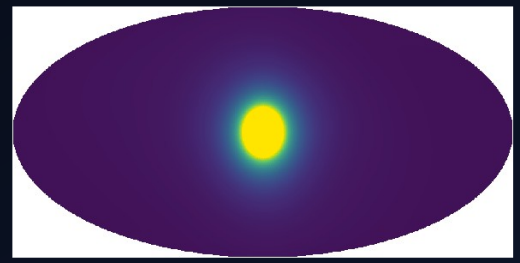
Diffuse

+



Bubbles

+



GCE

Build up picture of gamma ray sky by modeling individual components

Allow all components, or “templates” to float, see if smooth or clumpy is preferred for the GCE template (Lee+ 15)

METHOD 2: WAVELETS

Use wavelet transform to look for peaks in the data

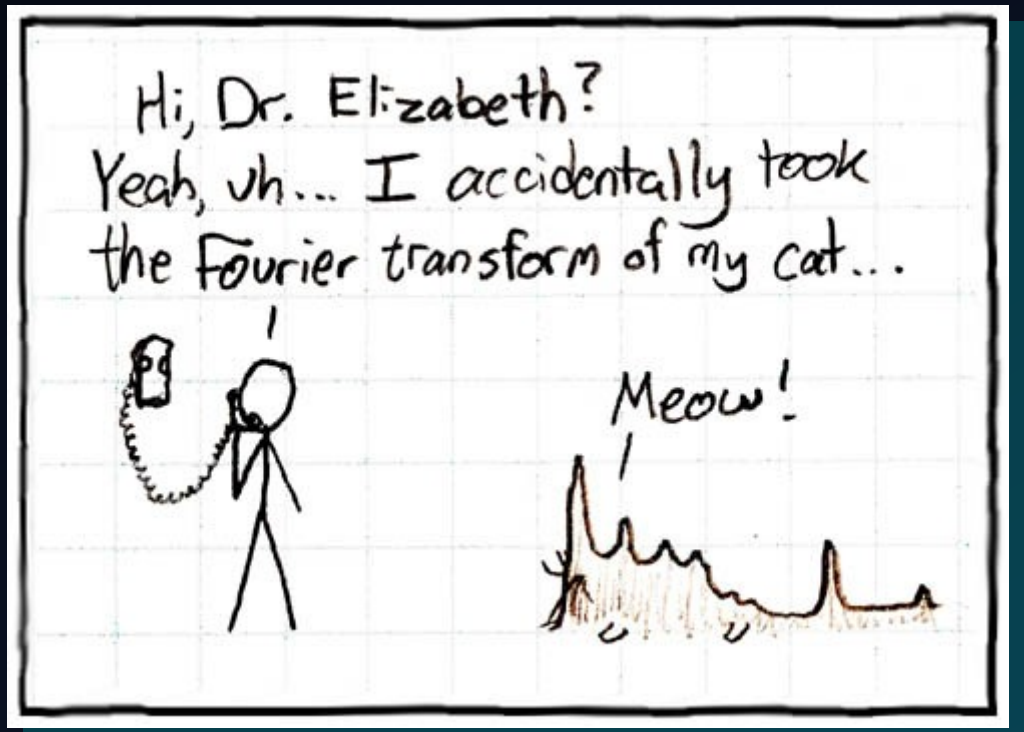
As before,

Clumpy (peaks):

point sources

Smooth (no peaks):

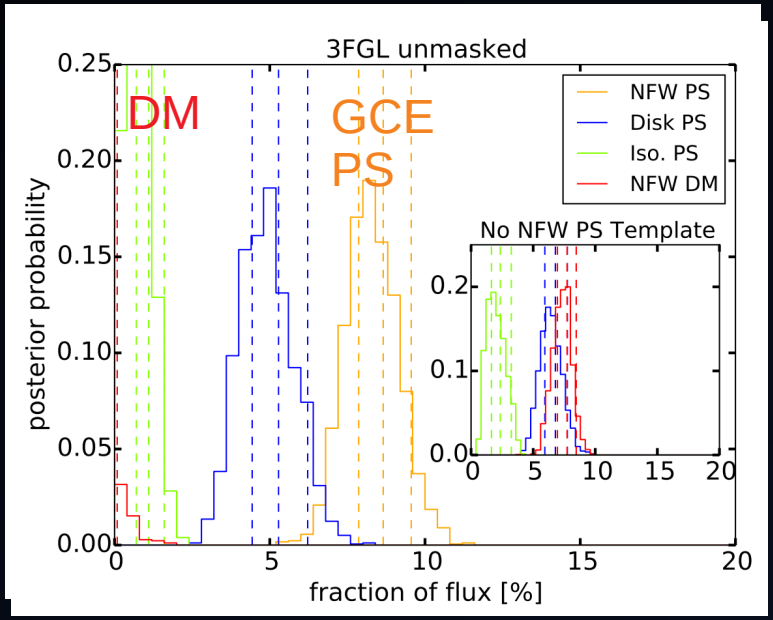
either no point sources,
or very faint point sources



xkcd

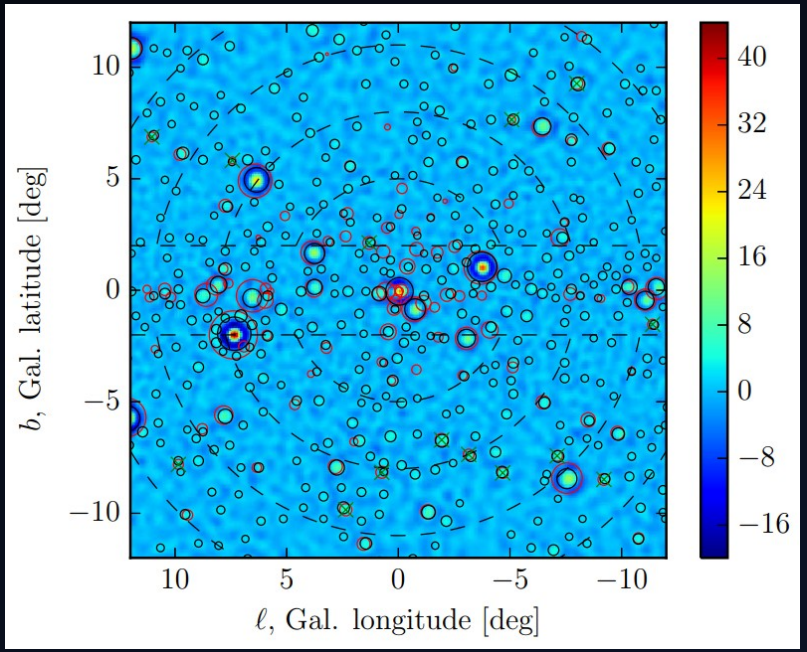
Evidence for Point Sources at the Galactic Center: 2015 Status

1. Template Fitting



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

2. Wavelets



Bartels, Krishnamurthy, Weniger (PRL ’15)

Consensus towards point source explanation,
evidence for “clumpy” rather than “smooth” signal

The Double Plot Twist of 2019...

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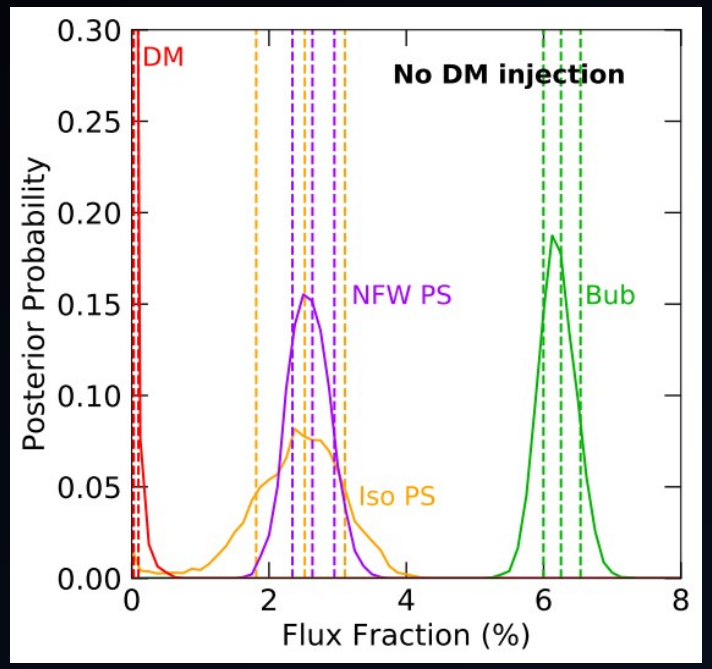
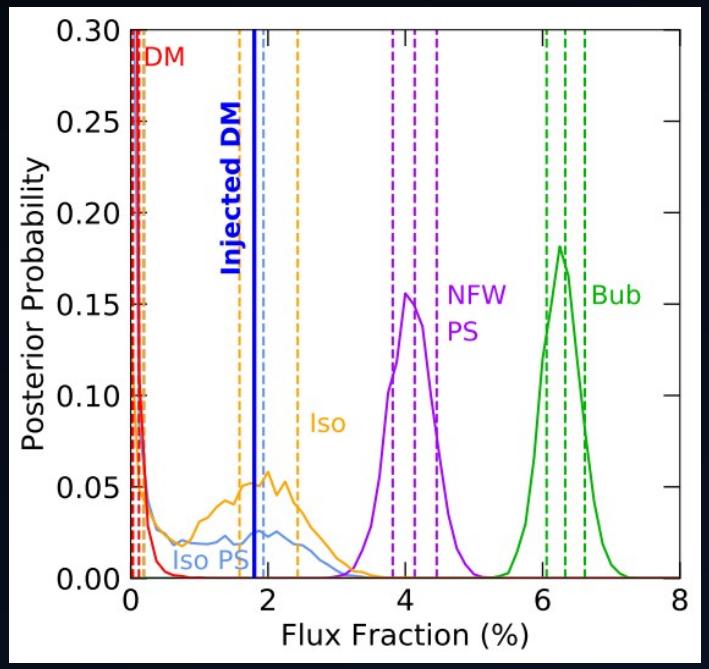
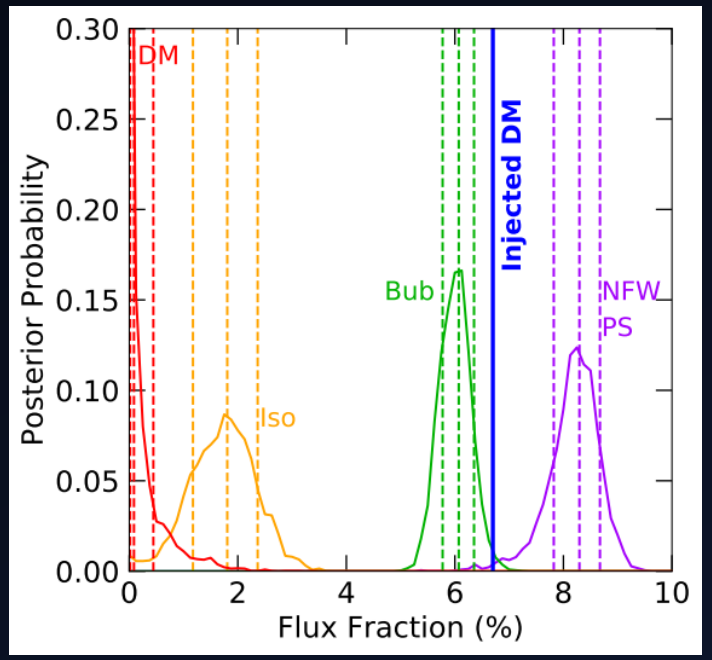
Dark Matter Strikes Back

RL+Slatyer, PRL ‘19

Mismodeling can hide a dark matter signal !



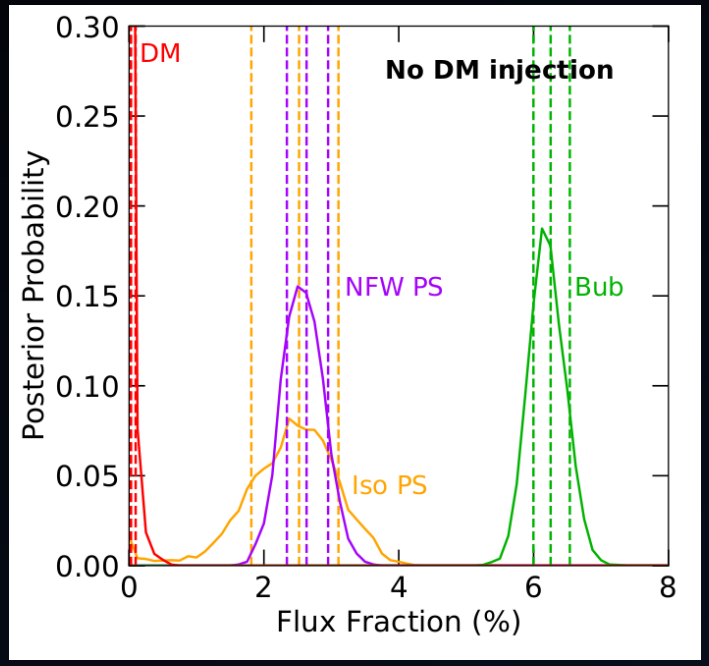


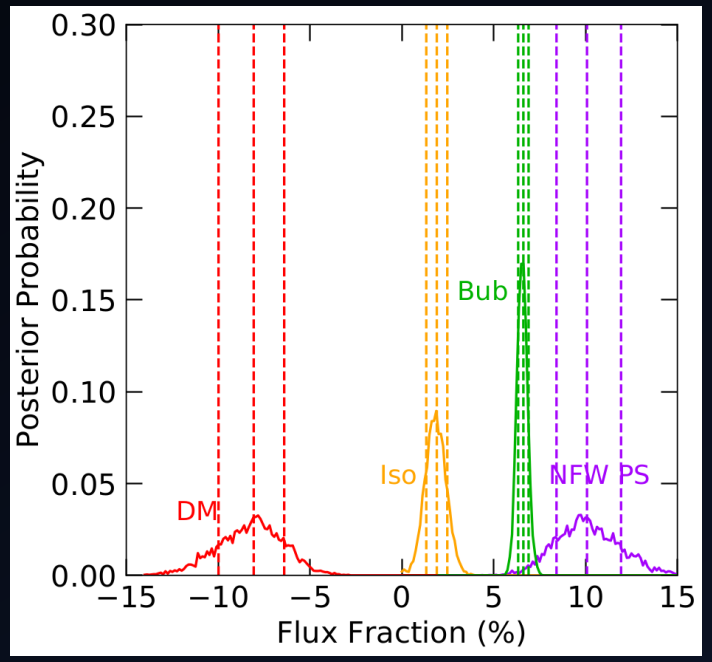


Systematics not under control, need to be understood to claim any robust result

ALTERNATIVE TO INJECTION: GOING NEGATIVE

Prior of DM normalization only allowed to float positive



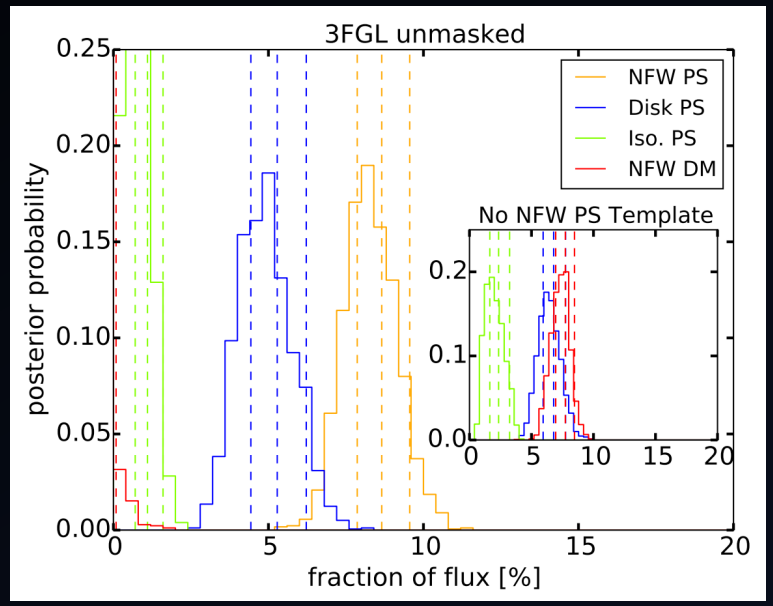


Prior of DM normalization also allowed to float negative

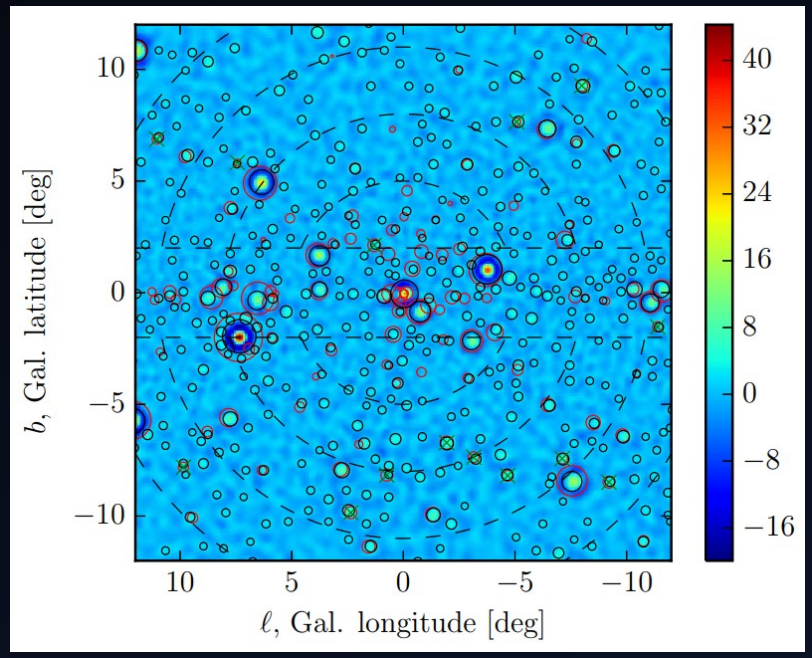
Observed that degree of oversubtraction varied with diffuse models; effect likely due to diffuse mismodeling

RL+Slatyer, PRL ‘19

Evidence for Point Sources at the Galactic Center:



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



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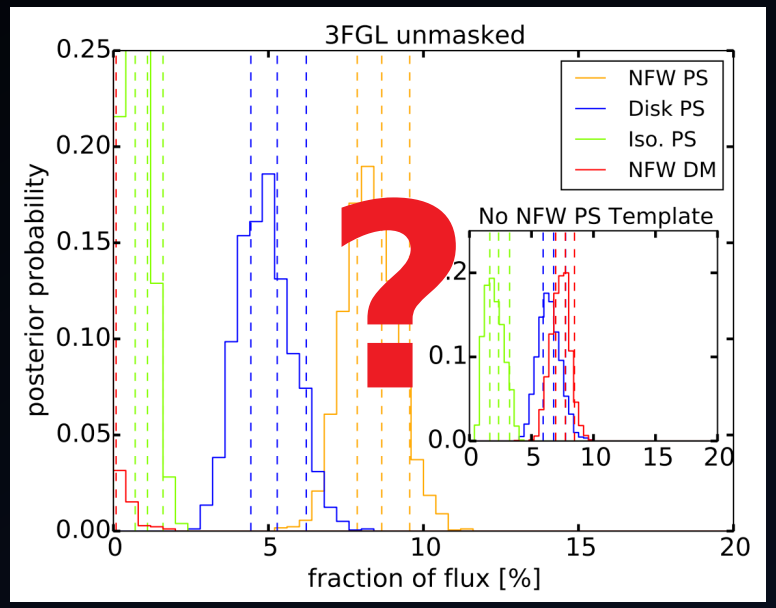

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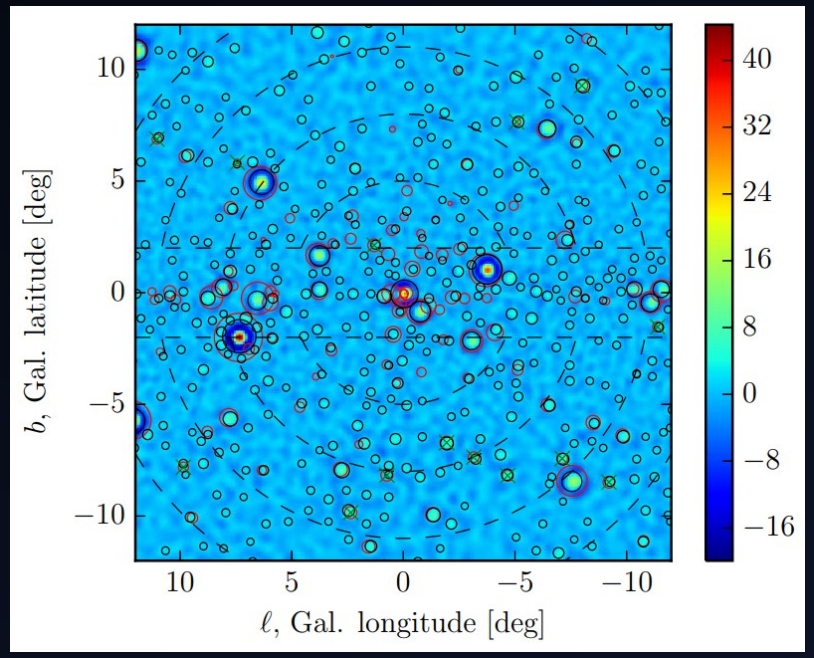

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Systematic Issues
RL+Slatyer (PRL '19)

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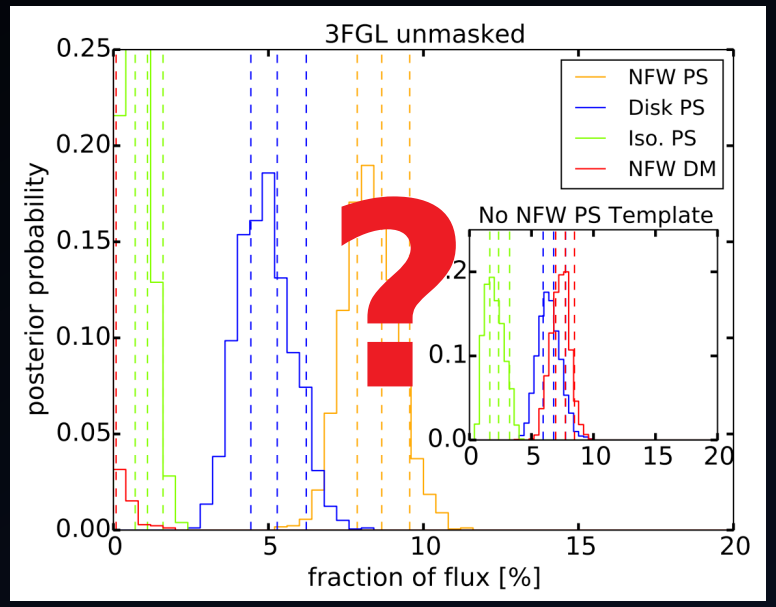

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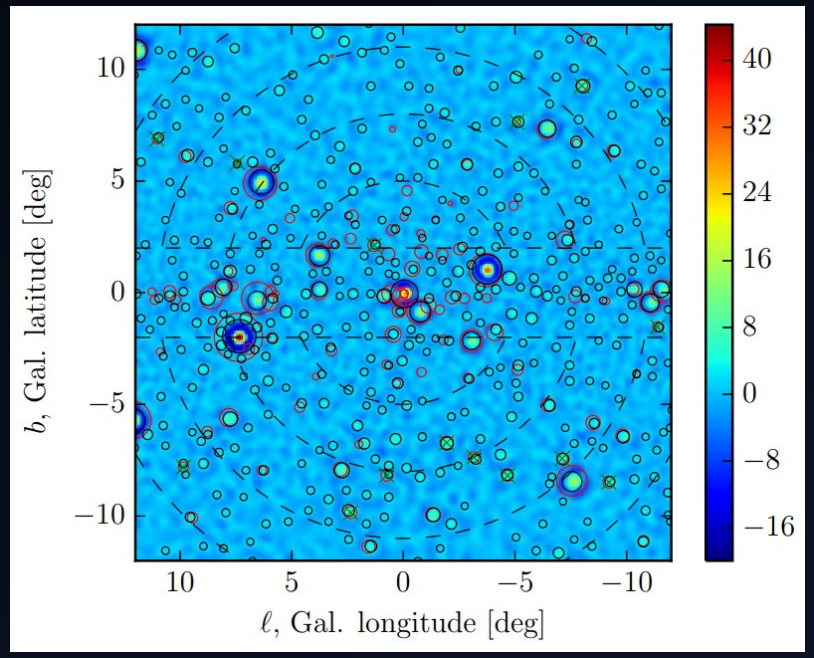

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Wavelet Method Update

Updated to mask out Fermi’s new point source catalog.

Rebecca Leane

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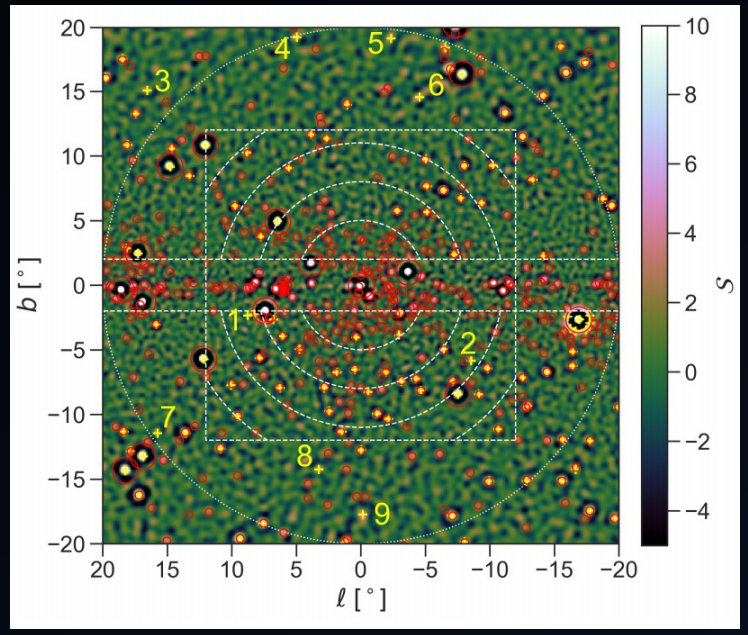

Turns out the 2015 paper correctly found point sources

Zhong, McDermott, Cholis, Fox PRL '19

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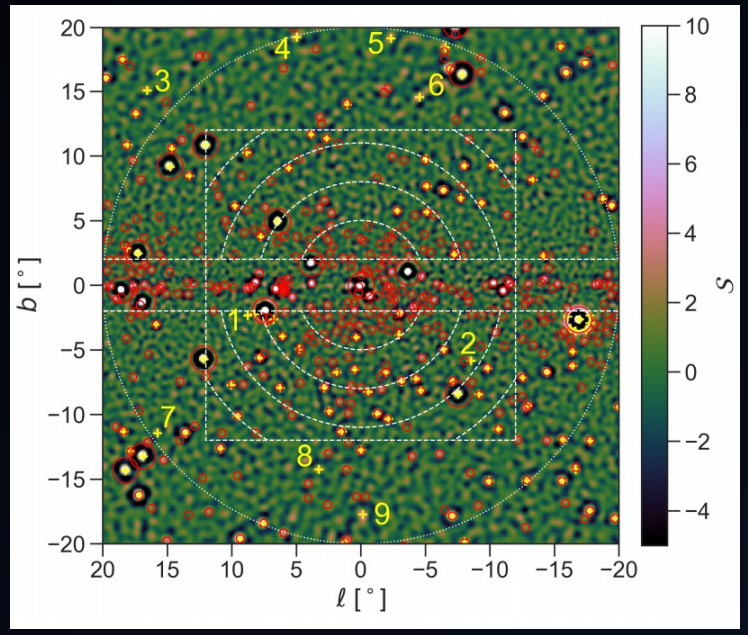

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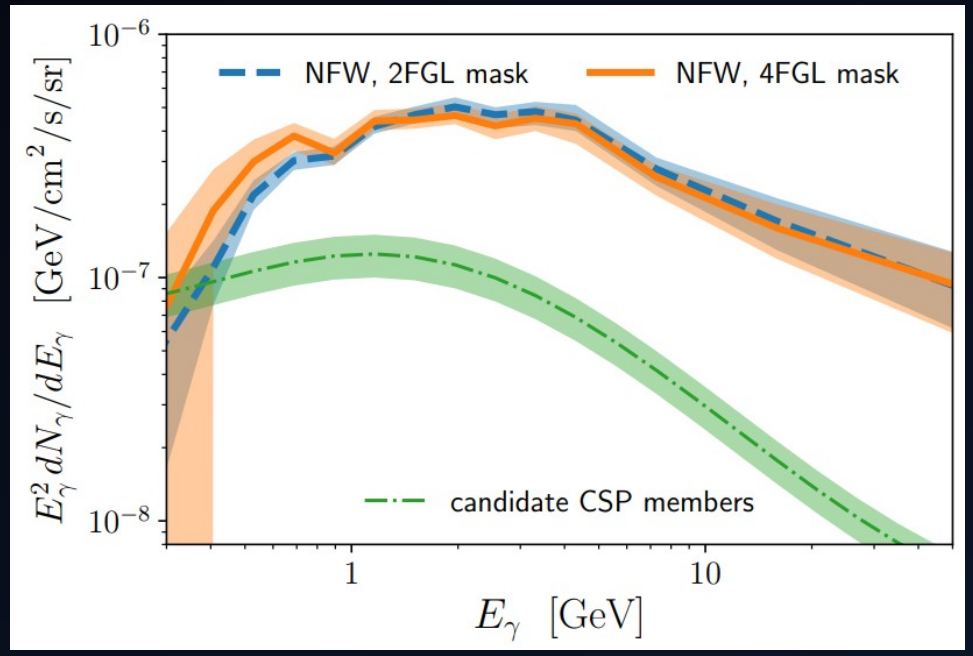

...but **not** point sources that can explain the excess.

Zhong, McDermott, Cholis, Fox PRL '19

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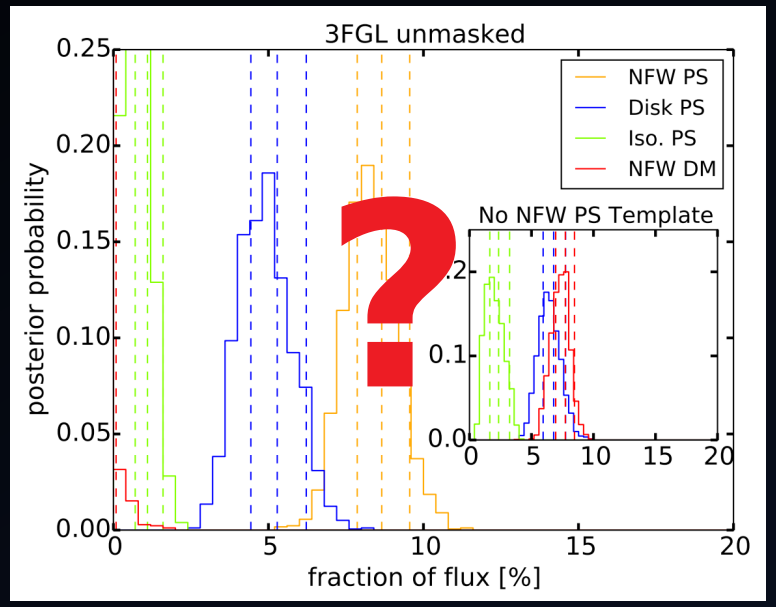

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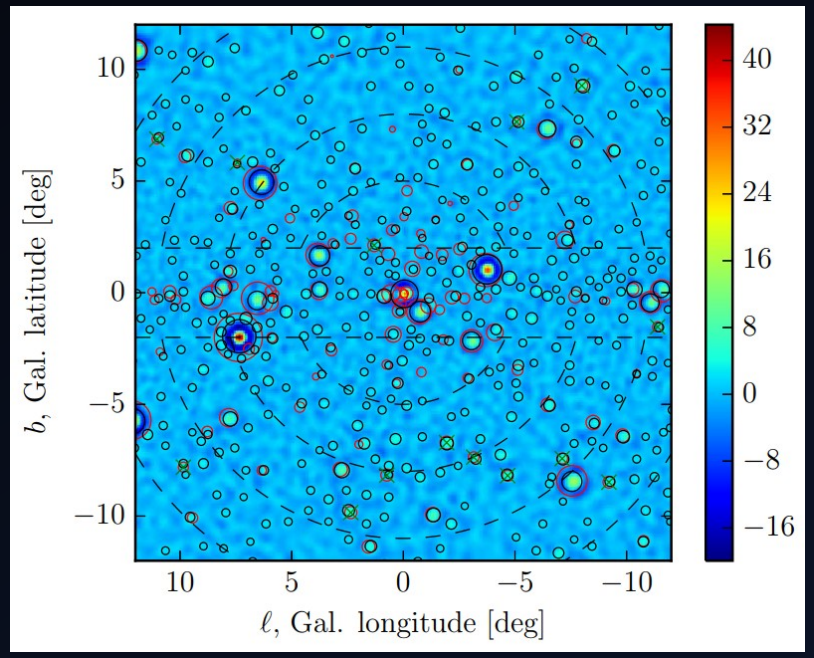

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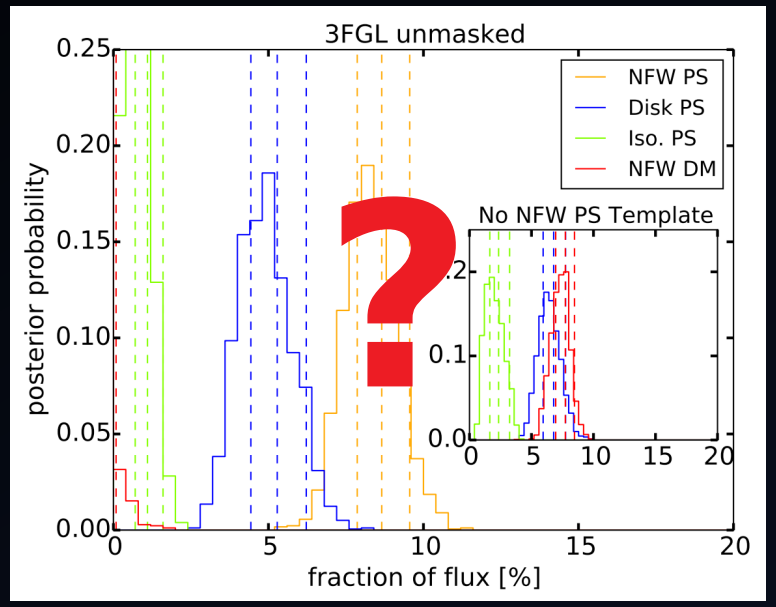

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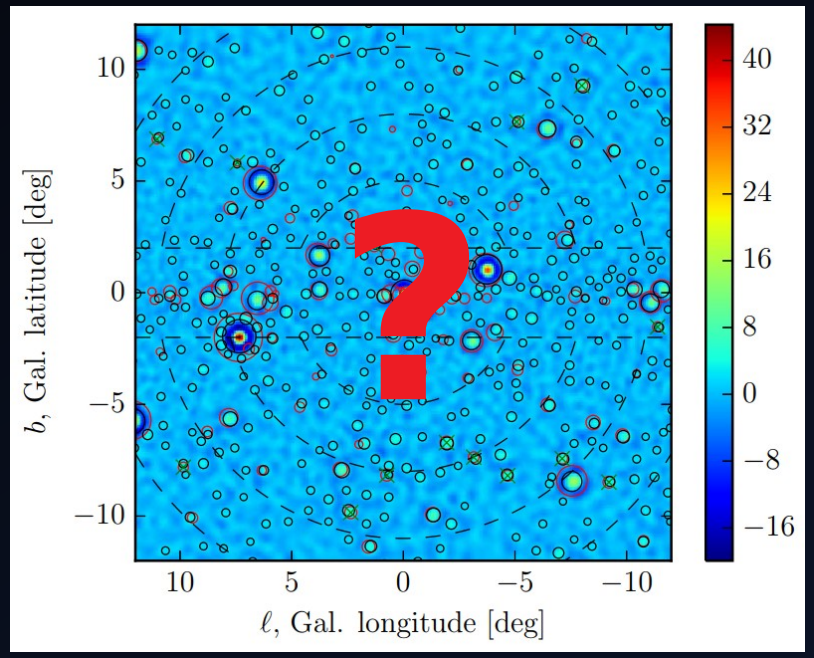

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Systematic Issues
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Shown these point sources are not bulk of excess
Zhong, McDermott, Cholis, Fox PRL '19

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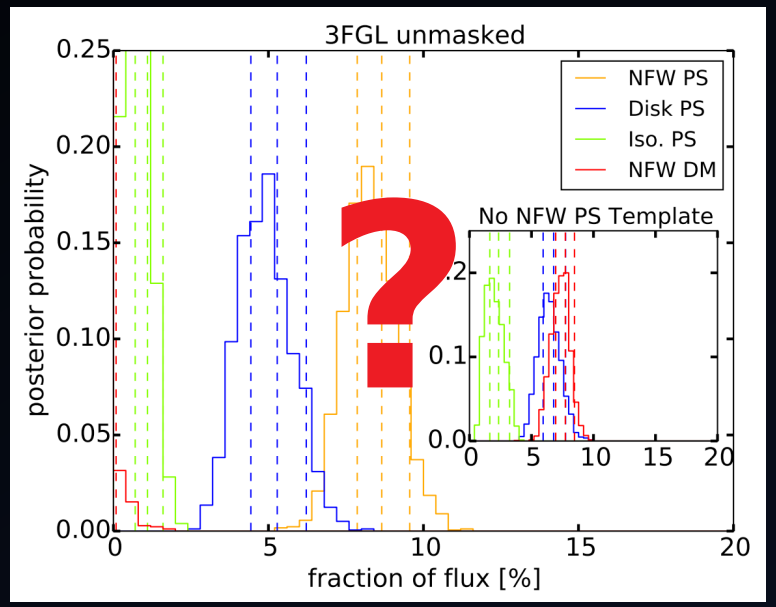

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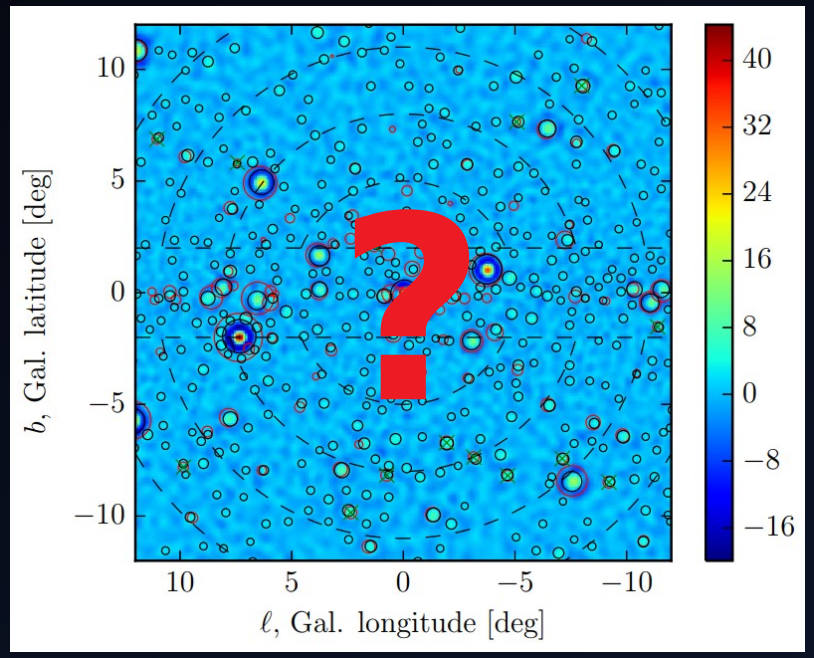

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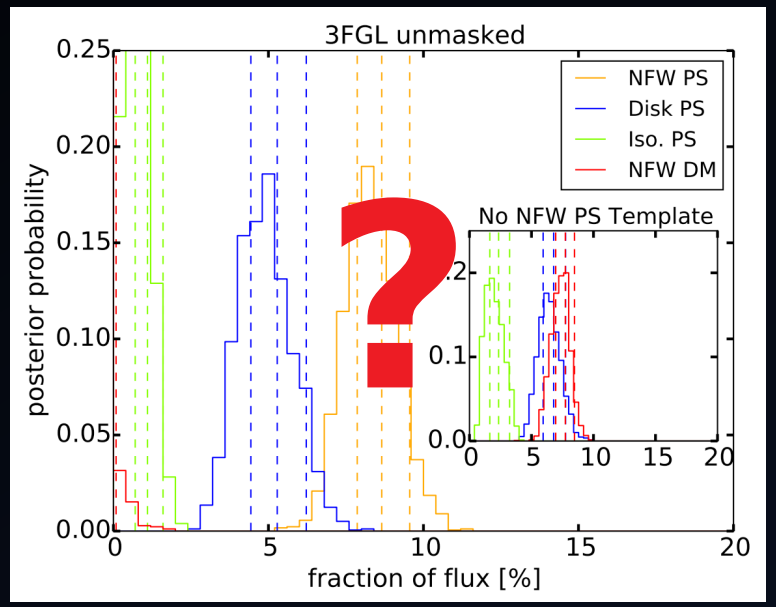

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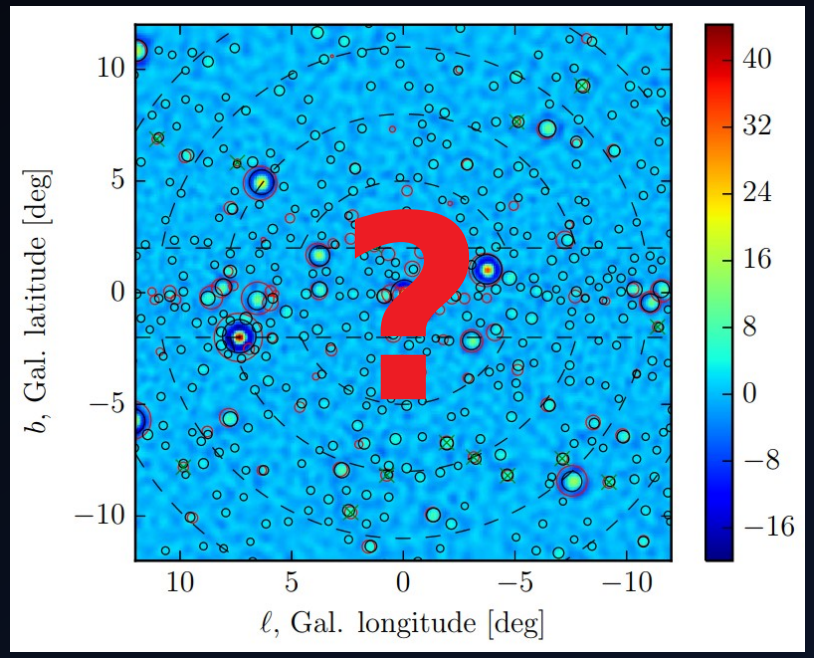

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Zhong, McDermott, Cholis, Fox PRL '19

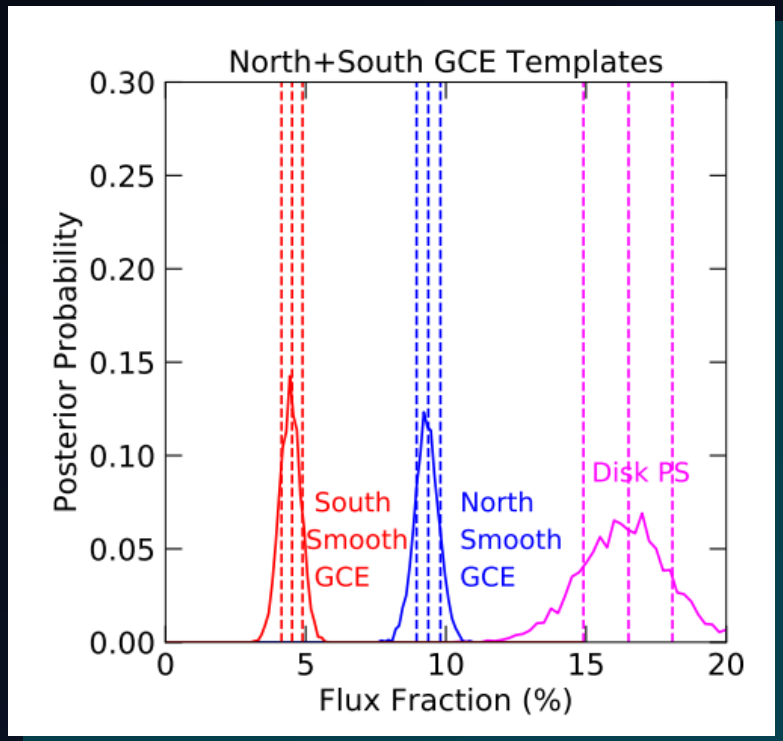
Systematic Issues
RL+Slatyer (PRL '19)
Improvements
Buschmann+, PRD '20

Spurious Point Sources

- Breaking signal template into north and south pieces:

  Removes the point source evidence in our region

- Bonus: smooth asymmetry preferred over point source explanation in some cases



RL+Slatyer, PRL ‘20

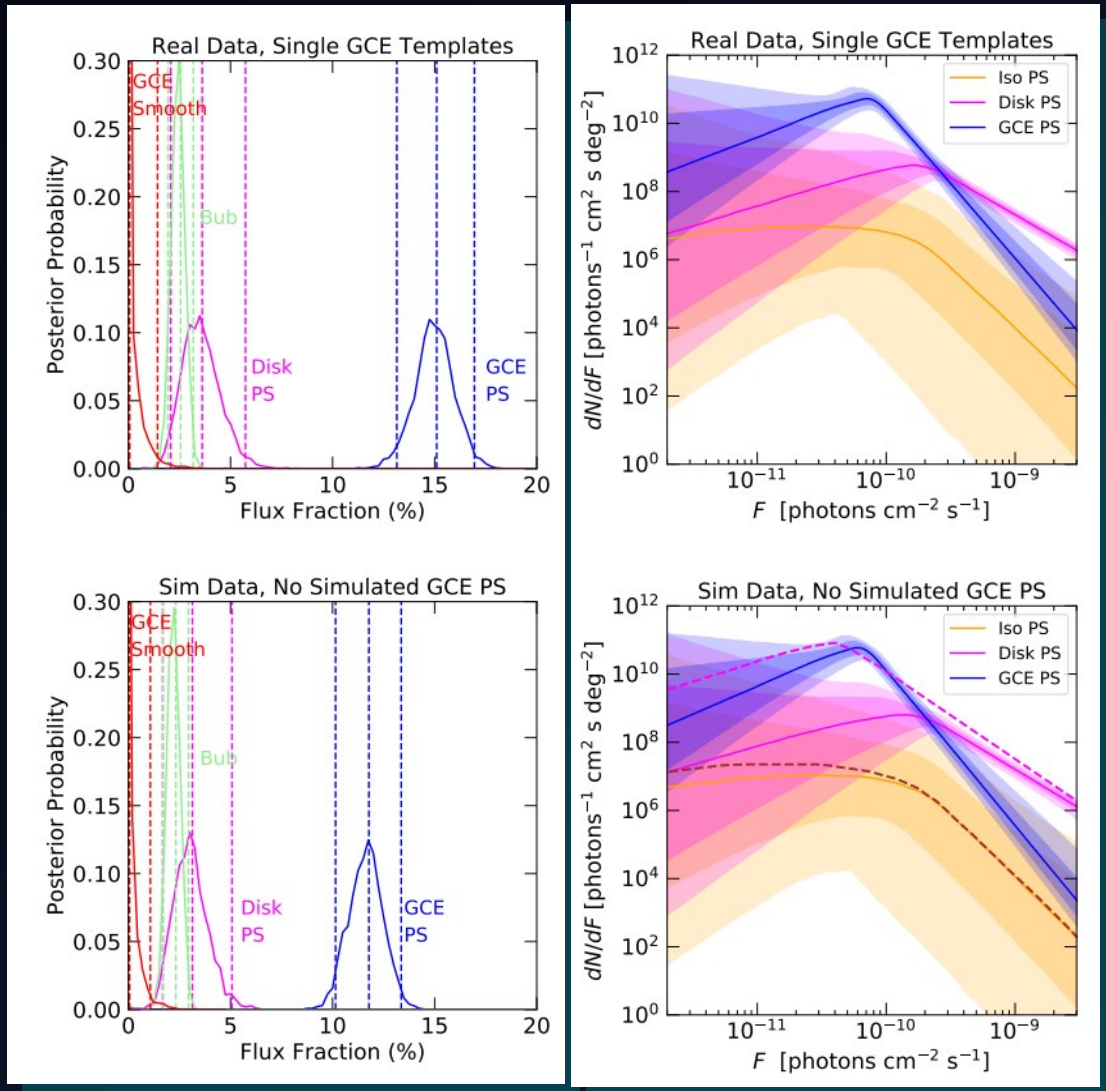
RL+Slatyer, PRD ‘20

SPURIOUS POINT SOURCES IN THE GCE

- Can be explained by an unmodeled asymmetry of the GCE
- Do not claim GCE is intrinsically asymmetric; likely also due to mismodeling

REAL DATA

SIMULATION



RL+Slatyer, PRL ‘20

RL+Slatyer, PRD ‘20

SPURIOUS POINT SOURCES IN THE GCE

- Can be explained by an unmodeled asymmetry of the GCE
- Do not claim GCE is intrinsically asymmetric; likely also due to mismodeling

- More broadly, **any** mismodeling might cause a spurious point source signal:
  - incorrect model leads to increased variance relative to the data
  - This is also a feature of a point source signal!

Systematics still not well enough controlled:
Claimed point source evidence for the GCE is not robust

RL+Slatyer, PRL ‘20

RL+Slatyer, PRD ‘20

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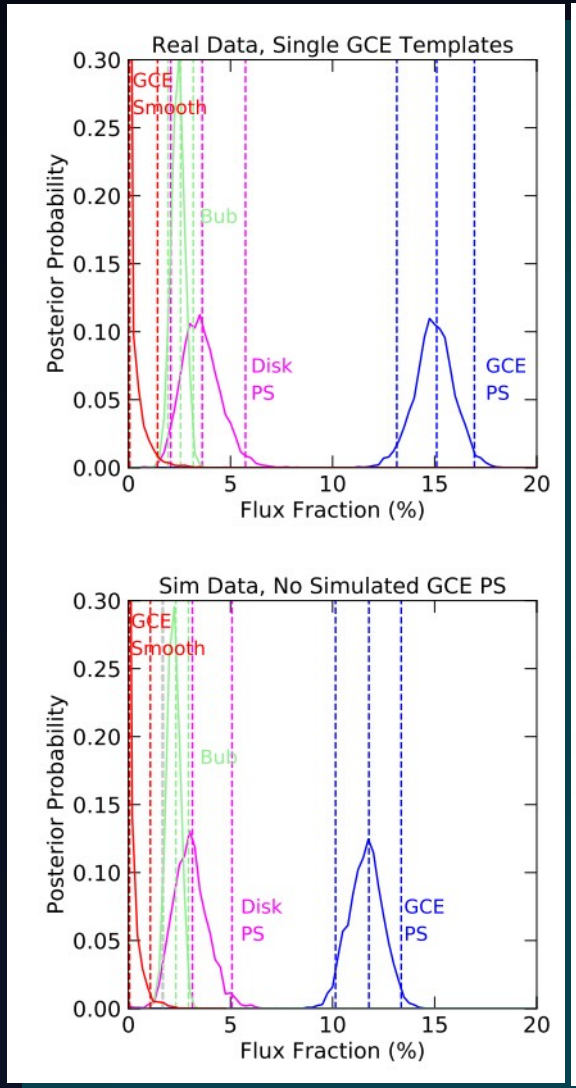
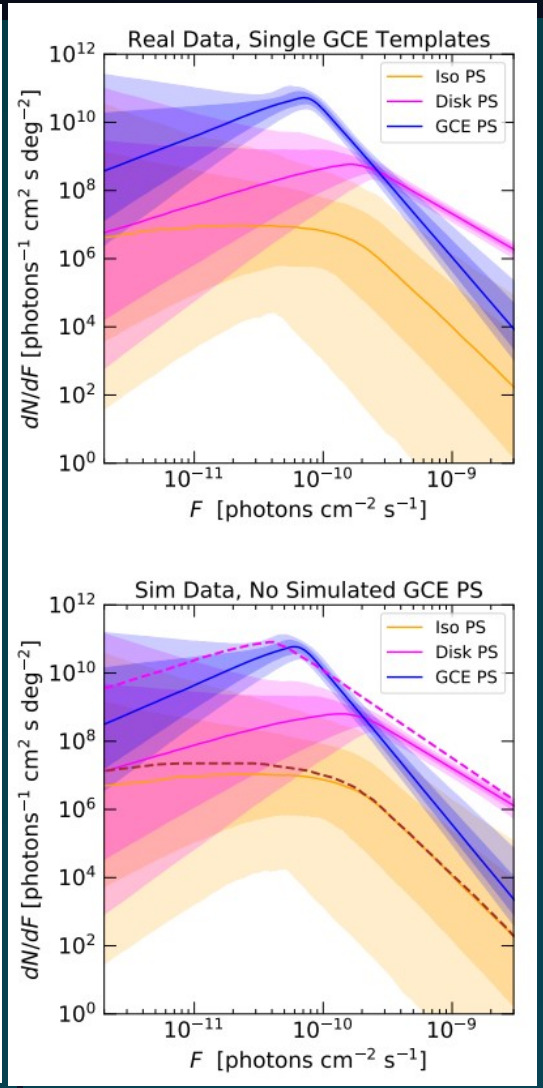


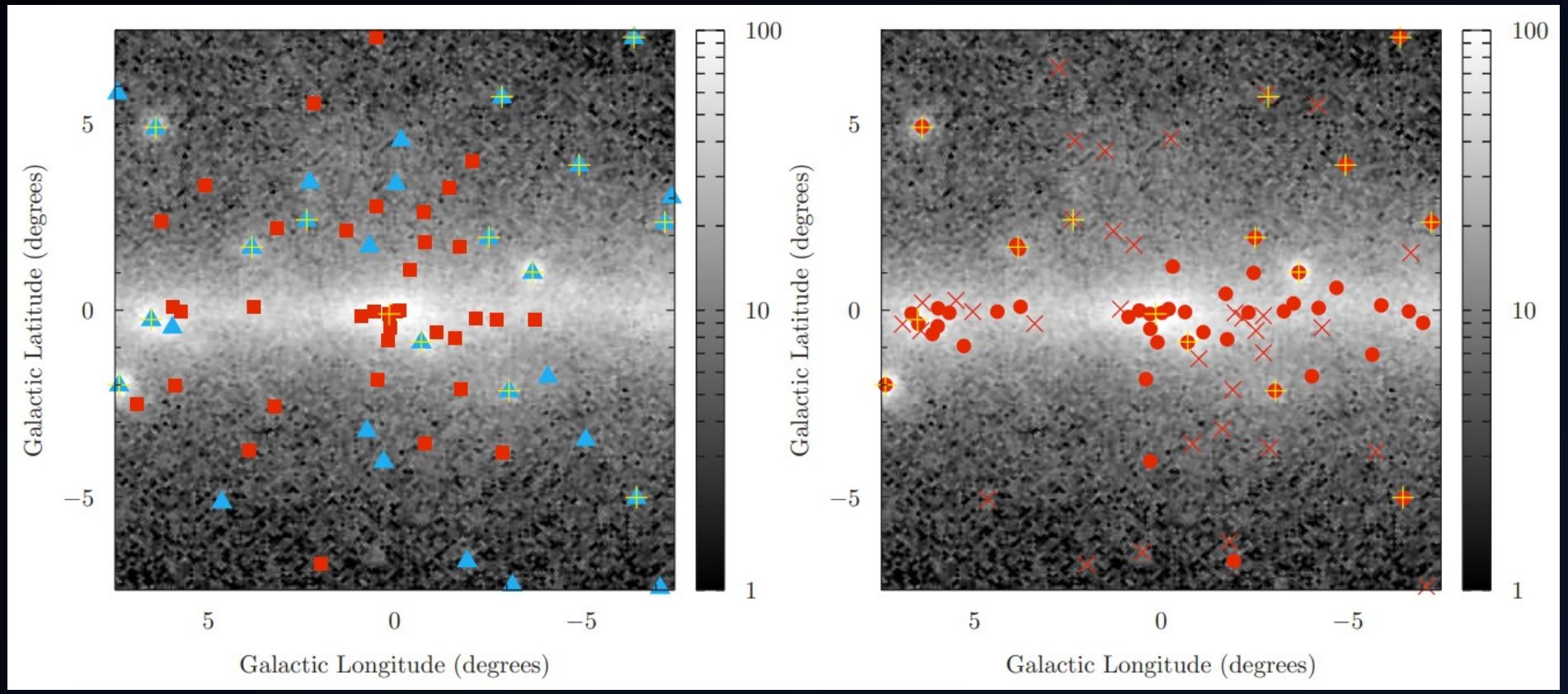


SYSTEMATICS: WHAT IS GOING ON?

Rebecca Leane

Systematics: Point Source ID?

Fermi Collaboration '15



Point source catalog 1 (3FGL)

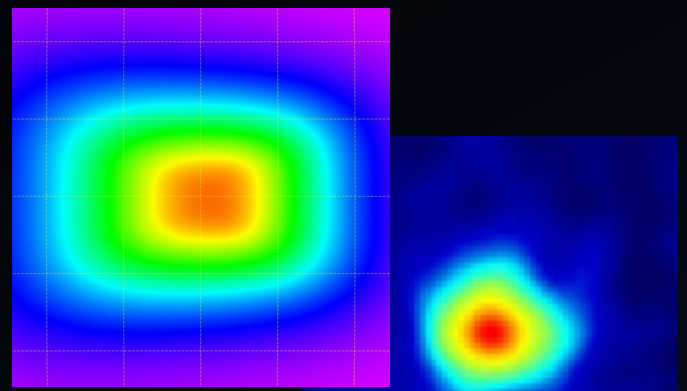
Point source catalog 2 (1FIG)

Different point sources "found" in different diffuse models!

Key point: all diffuse models are not good

Current Picture

Morphology



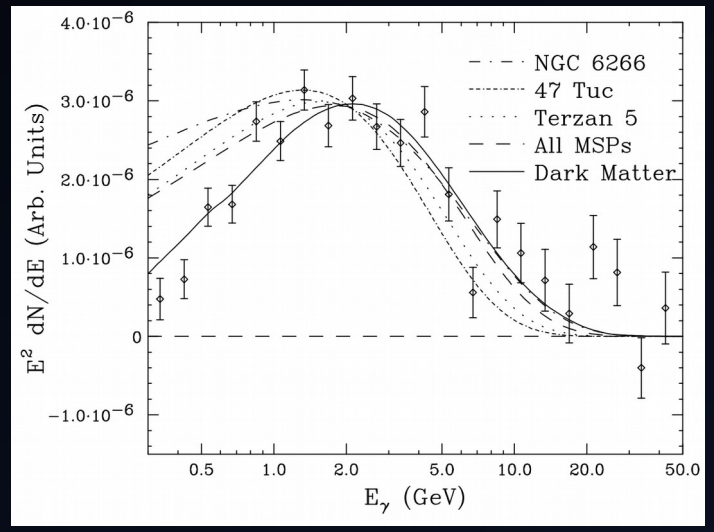
Bulge

vs. NFW

Not robustly known,
but big implications

Bartels+, ‘17
Macias+, ‘19
Calore+, ‘21
Di Mauro, ‘21
Cholis+, ‘21
Pohl+, ‘22

Energy Spectrum

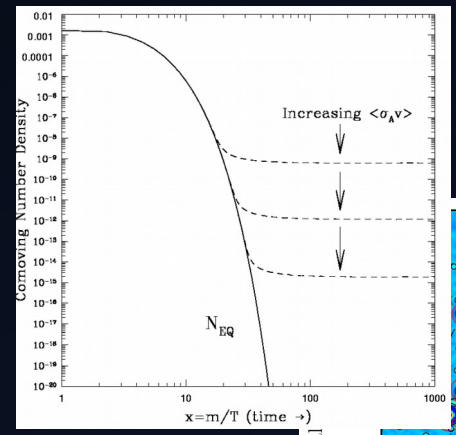


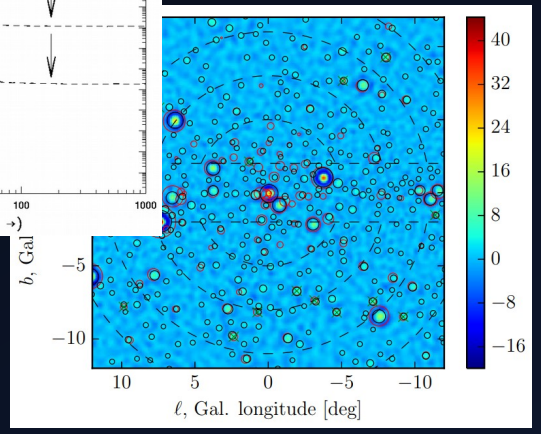
Comparable to millisecond pulsars

Can be well fit with DM annihilating to hadrons

Intensity

Well-explained by DM
(Predicted by thermal relic cross section)

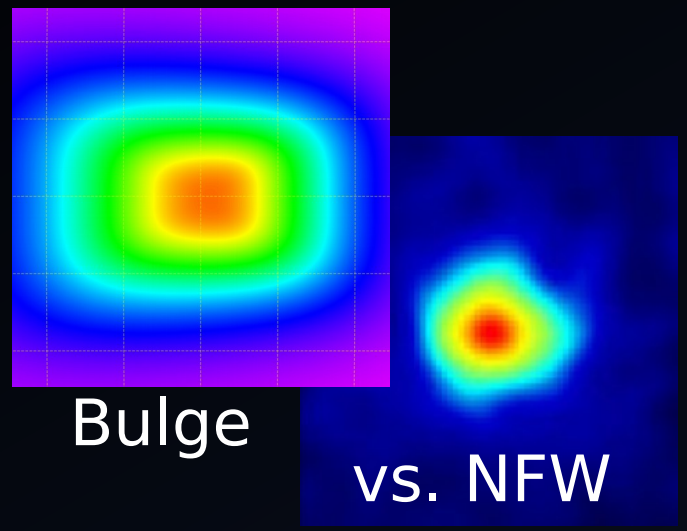




Tension for pulsars
strong constraints on pulsar luminosity function

Current Picture

Morphology



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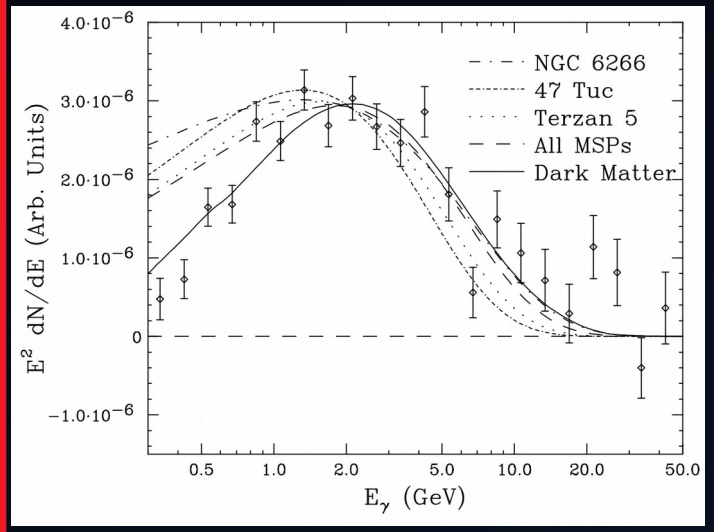

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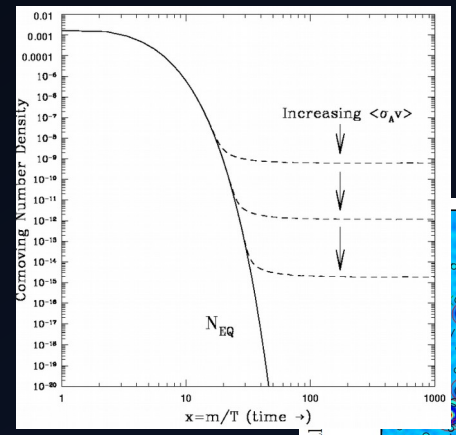

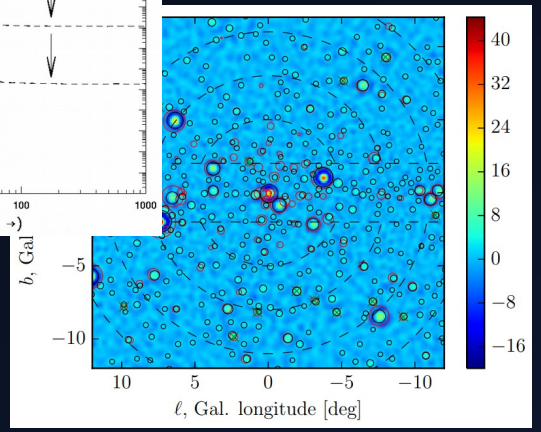

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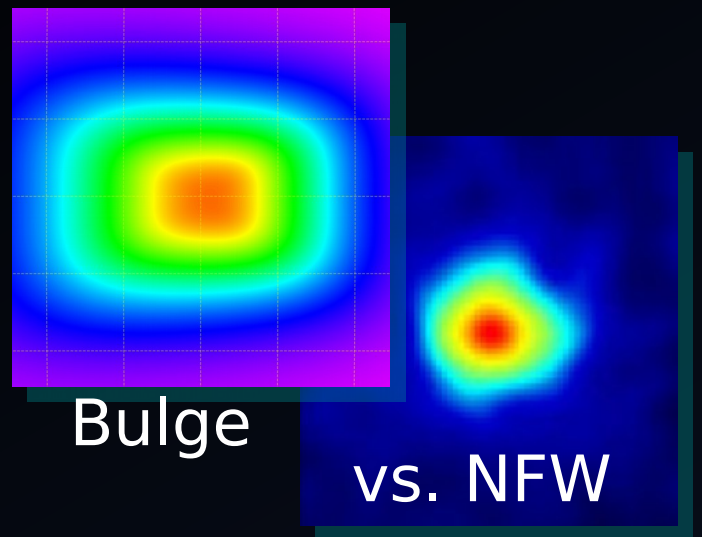

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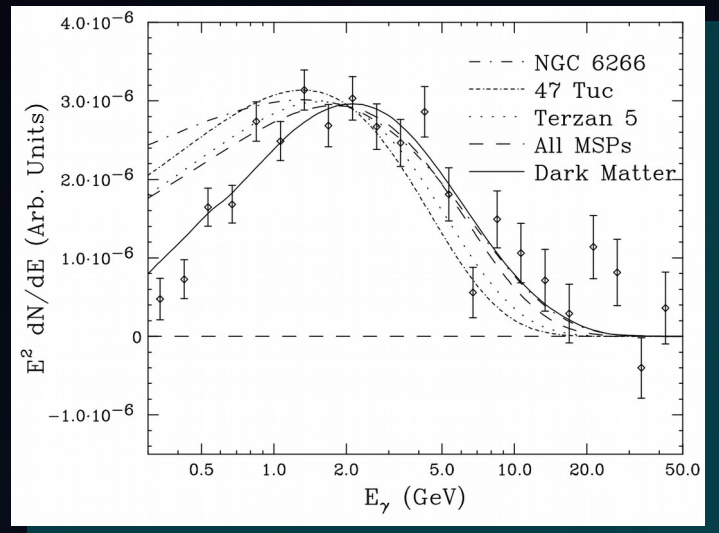

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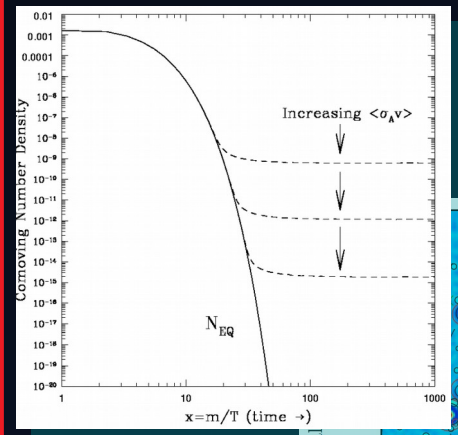
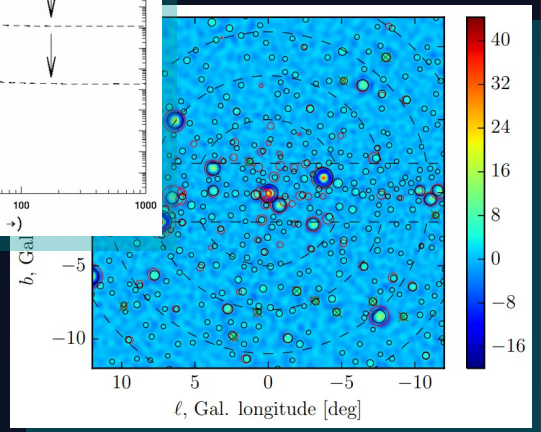


See Gautam+ ‘21



Tension for pulsars
strong constraints on pulsar luminosity function

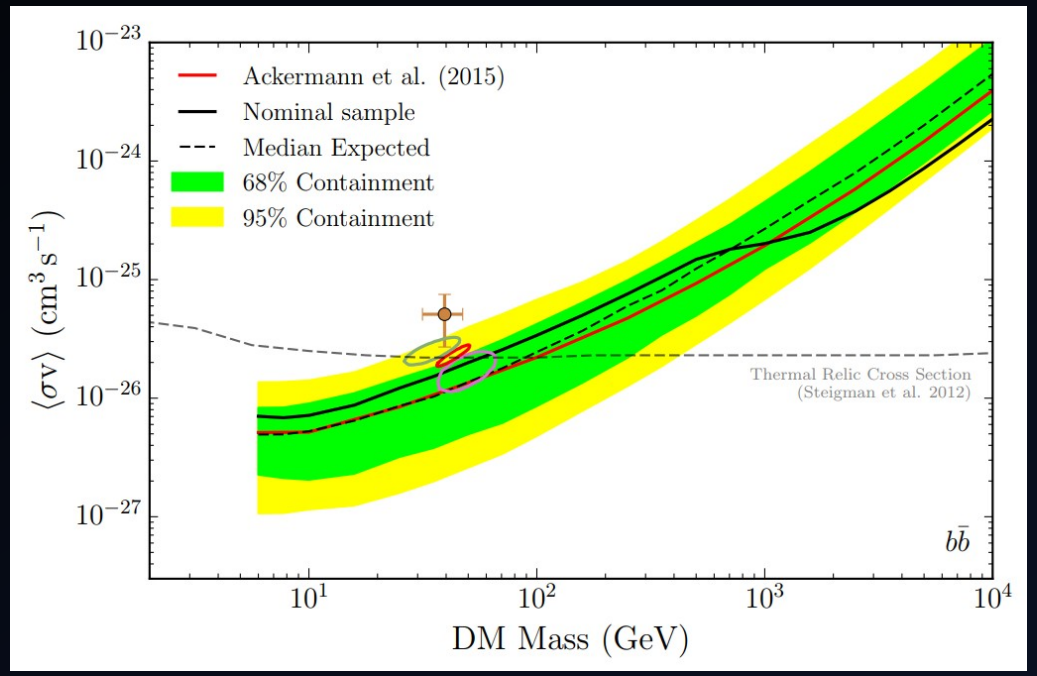
MOVING FORWARD:

DARK MATTER vs PULSARS

Rebecca Leane

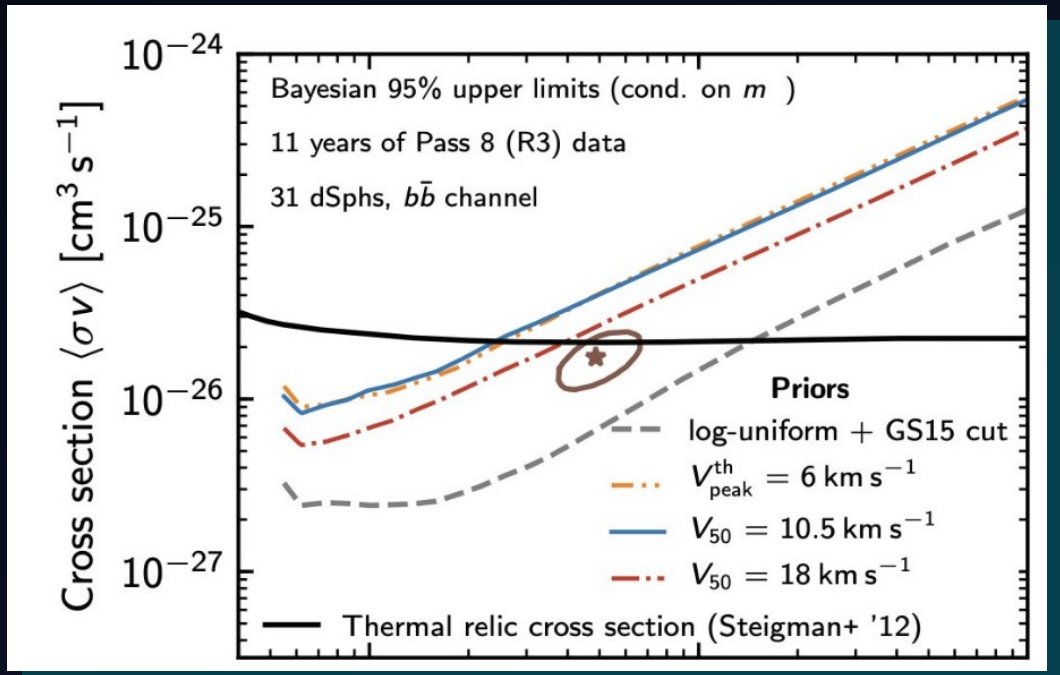
Signals from Dwarf Spheroidals

- No tension with GCE at the moment, though if the GCE really is DM, signal likely should appear soon
- Keep in mind systematics here!



Ackermann+, ‘16

Ando+, ‘20



DM density uncertainties weaken limits further

See also Chang, Necib ‘20

Other avenues for GCE

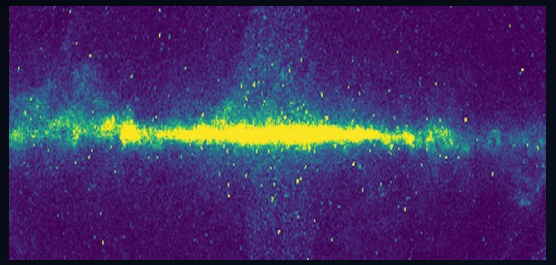
- Detect pulsars directly in radio
- Alternate fitting techniques:
  - SkyFACT+pixel counts: Calore+ ‘21
  - Weighted likelihoods: Di Mauro ‘21
  - Machine learning: List+’20, List+ ‘21, Mishra-Sharma+ ‘21
- Energy spectrum: systematics large for Fermi below a GeV
  - Measurements with MeV gamma-ray telescopes can shed light

Snowmass2021 Cosmic Frontier White Paper: Puzzling Excesses in Dark Matter Searches and How to Resolve Them

Rebecca K. Leane[*1,2], Seodong Shin[†3], Liang Yang[‡4], Govinda Adhikari[4], Haider Alhazmi[5], Tsuguo Aramaki[6], Daniel Baxter[7], Francesca Calore[8], Regina Caputo[9], Ilias Cholis[10], Tansu Daylan[11,12], Mattia Di Mauro[13], Philip von Doetinchem[14], Ke Han[15], Dan Hooper[16,17,18], Shunsaku Horiuchi[19,20], Doojin Kim[21], Kyoungchul Kong[22], Rafael F. Lang[23], Qing Lin[24,25], Tim Linden[26], Jianglai Liu[15,27,28], Oscar Macias[29], Siddharth Mishra-Sharma[30,31,32], Alexander Murphy[33], Meshkat Rajaee[3], Nicholas L. Rodd[34], Aditya Parikh[31], Jong-Chul Park[35], Maria Luisa Sarsa[36], Evan Shockley[18], Tracy R. Slatyer[32], Volodymyr Takhistov[20], Felix Wagner[37], Jingqiang Ye[38], Gabrijela Zaharijas[39], Yi-Ming Zhong[18], Ning Zhou[15], and Xiaopeng Zhou[40]

ArXiv: 2203.06859

SUMMARY



- Excess firmly detected, signal origin is unknown – controversial signal!

- Exciting possibility: we are seeing evidence for annihilating dark matter
  - Main arguments for: signal has consistent intensity, spectrum, and potentially morphology
  - Argument against: potentially morphology, though systematics unclear

- Leading alternative explanation: pulsars
  - Main argument for: energy spectrum looks consistent (could also argue morphology)
  - Arguments against: where are they, and their x-ray binaries? We don't see them in any wavelength. How do you get such a large number of them in the galactic center?

  - If the GCE does arise from pulsars, it must be very different to those we know in the Milky Way

- Previous 2015 point source evidence has been challenged
  - Non-poissonian template fitting results have substantial uncontrolled systematics
  - Updated wavelet study shows the previously found point sources actually cannot be the bulk of the excess

- Lots of ways forward: complementary searches for both dark matter and pulsars, +improving modeling!

The puzzle continues...

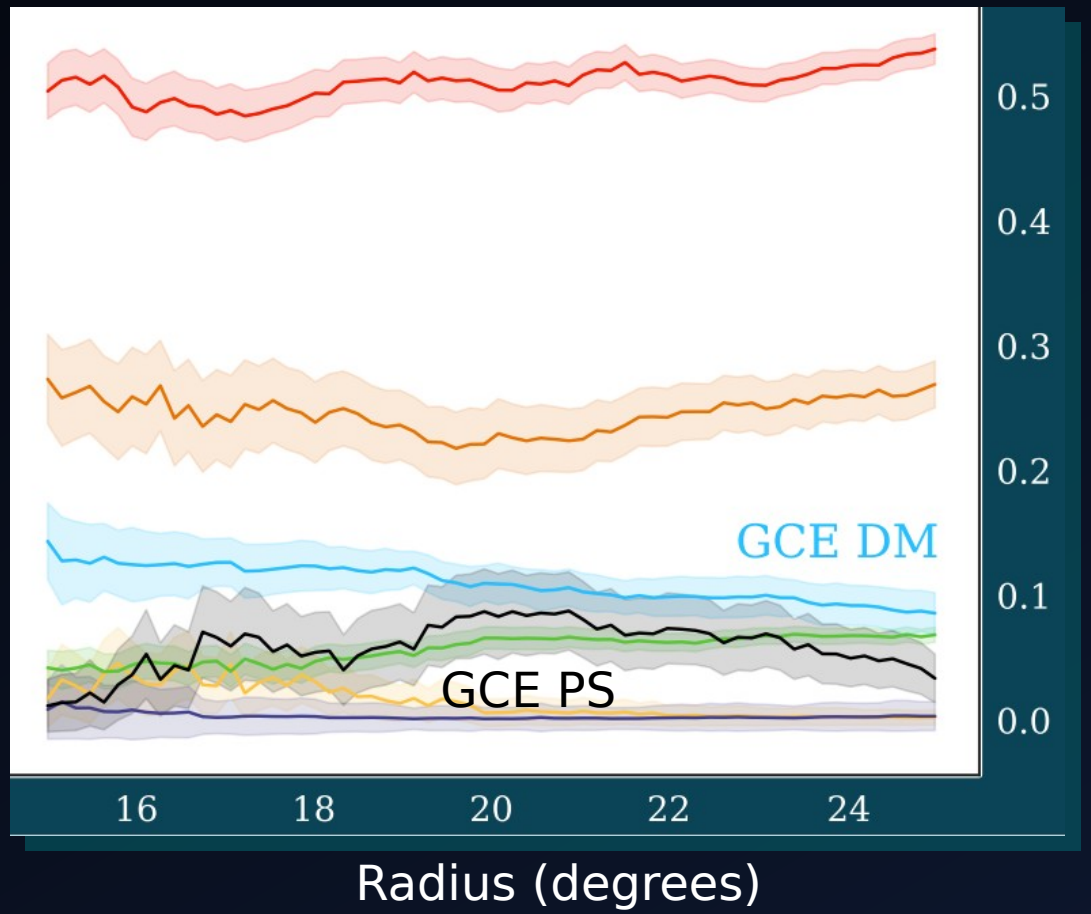
EXTRA SLIDES

Rebecca Leane

ALTERNATE FITTING METHOD

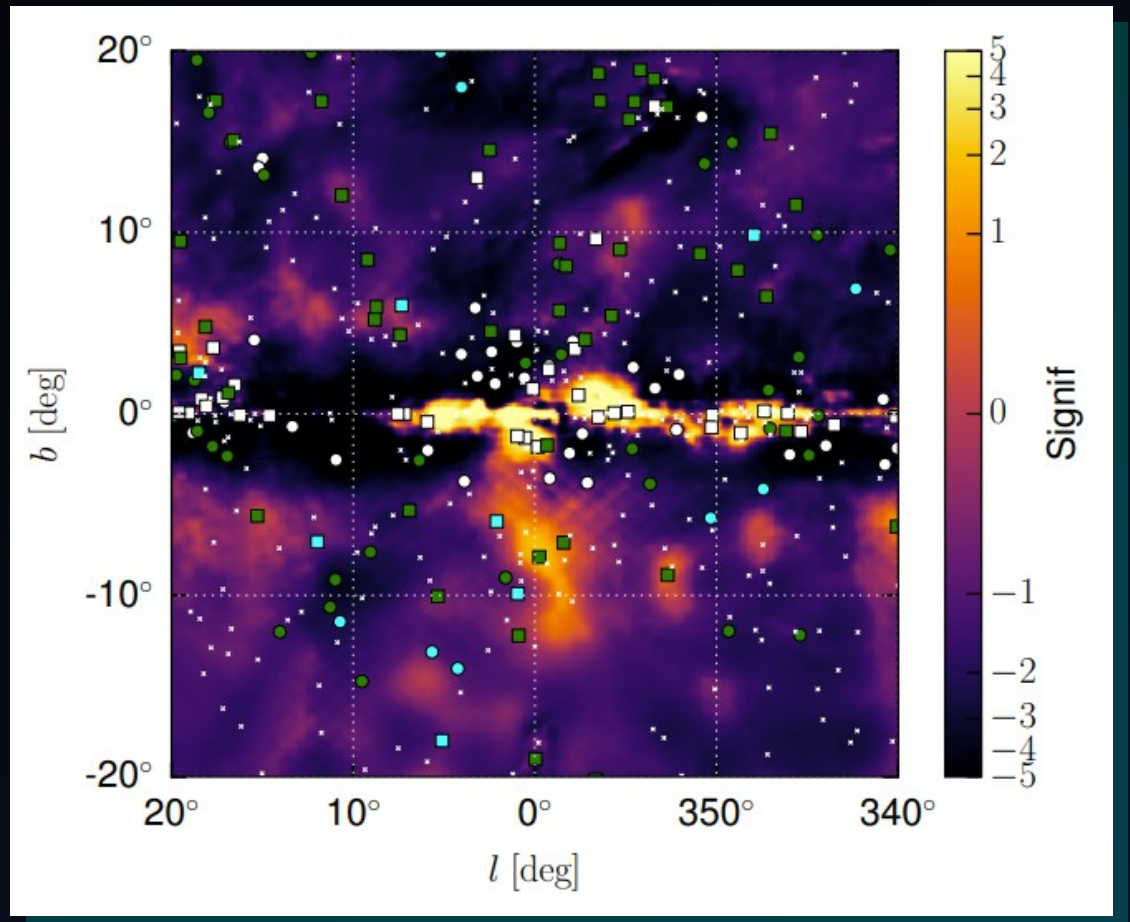
- Train neutral networks on simulated datasets
- Finds same GCE flux fraction as non-Poissonian template fitting, but finds smooth GCE!
- Complementary handle on systematics

List+, ‘20



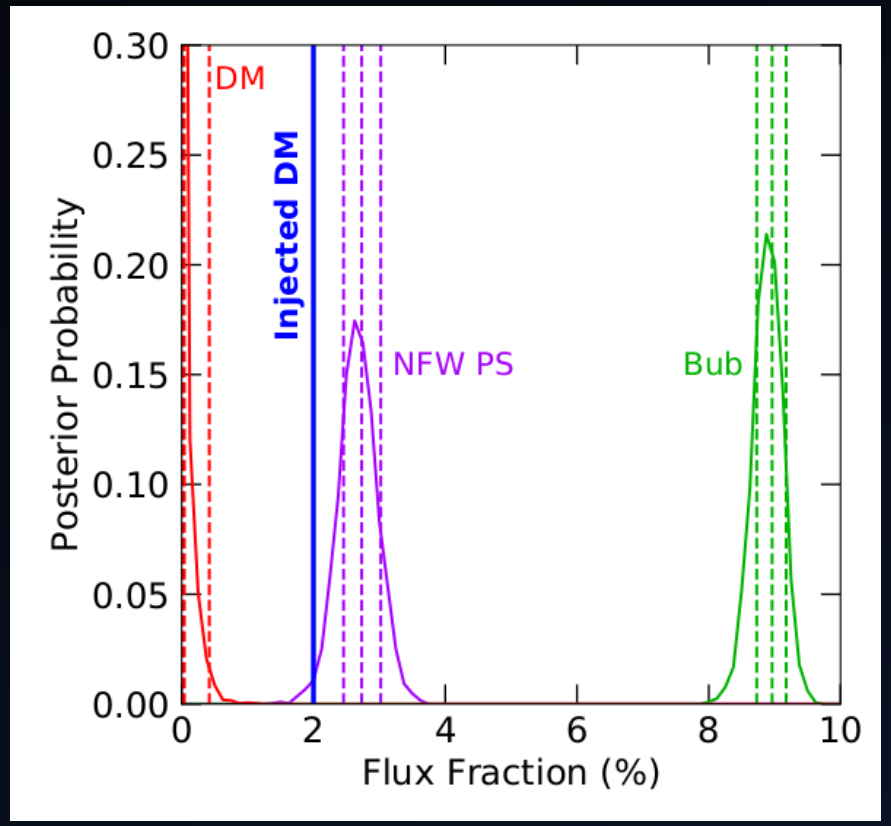
SYSTEMATICS: POINT SOURCE ID?

Fermi Collaboration '17



White dots show point sources that are detected at 7 sigma in one model, but not detected in the other

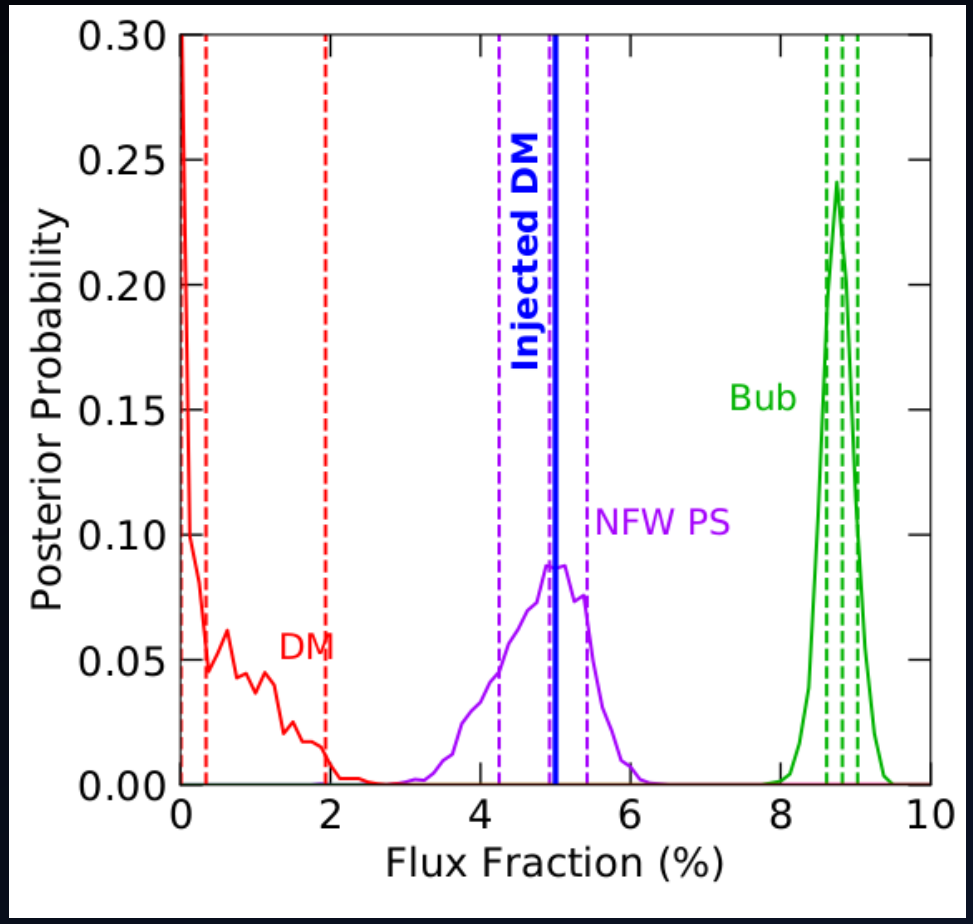
What if we now instead analyze the data with NFW distributed PS instead of the PS bubbles?



The dark matter signal is misattributed to point sources!

RL+Slatyer (PRL ‘19)

Add even more….



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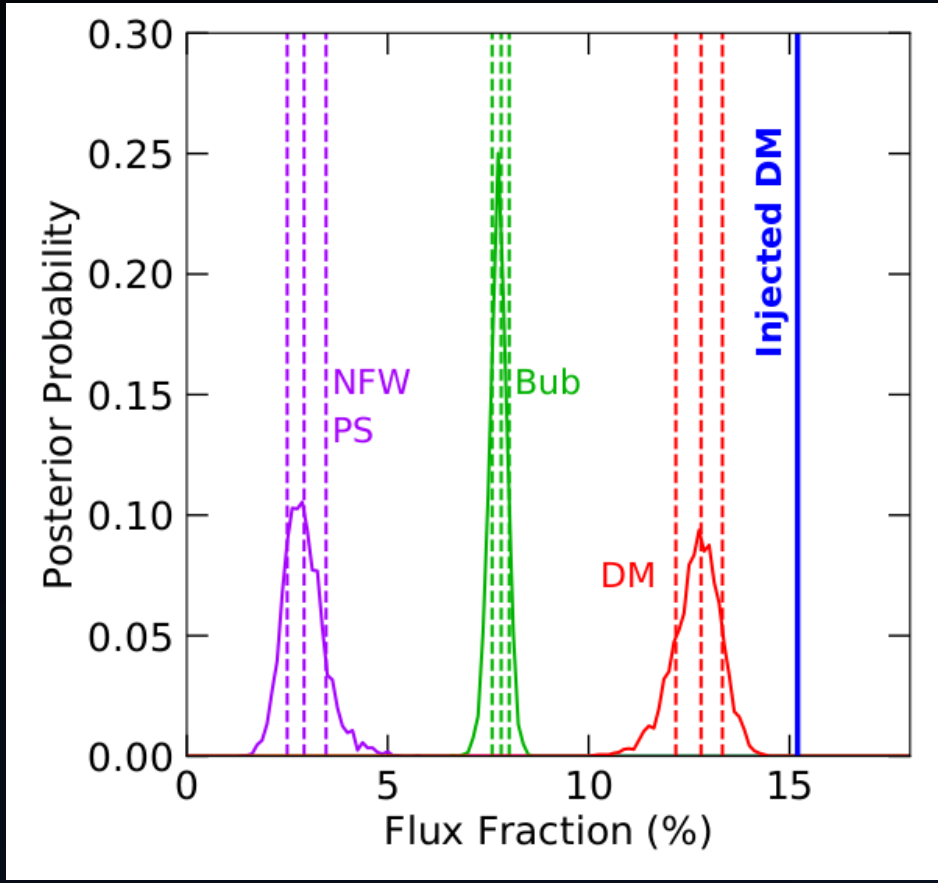
IS THERE A THRESHOLD IN SIMULATIONS?

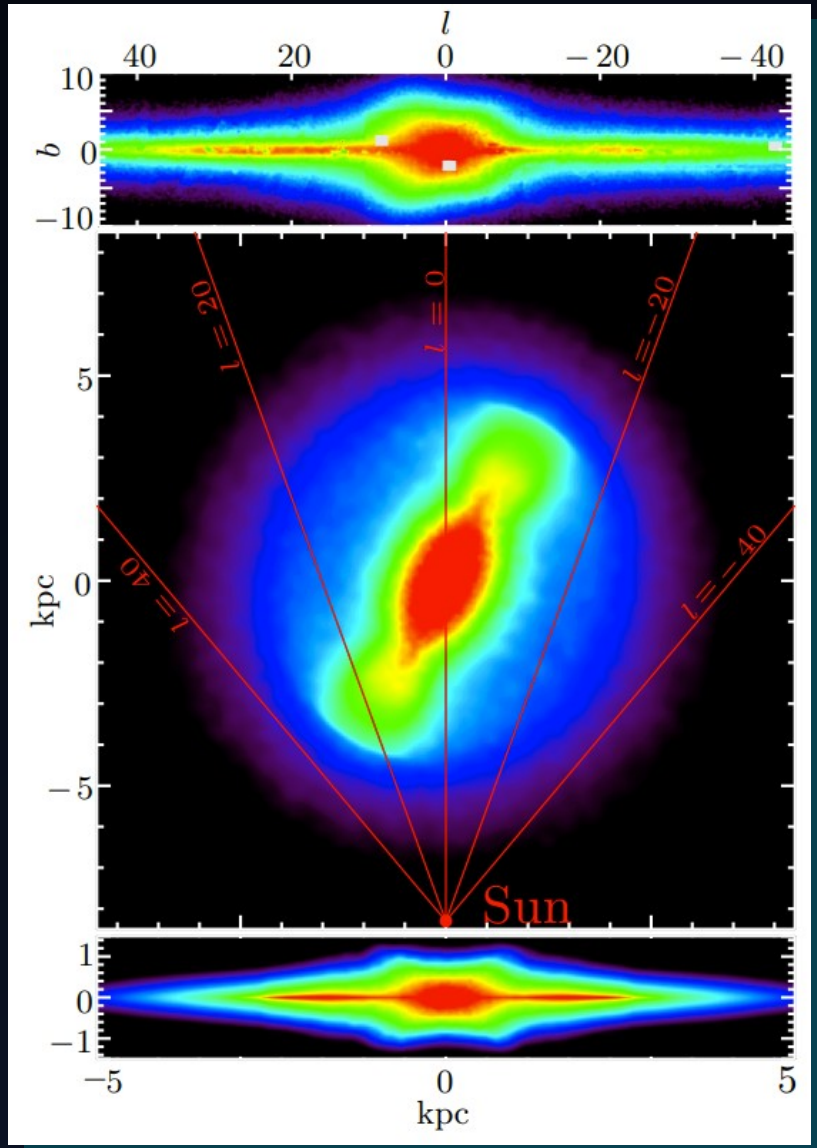


Inject an order of magnitude more DM (~15%)

Takes this much to reconstruct DM, but still not all of it

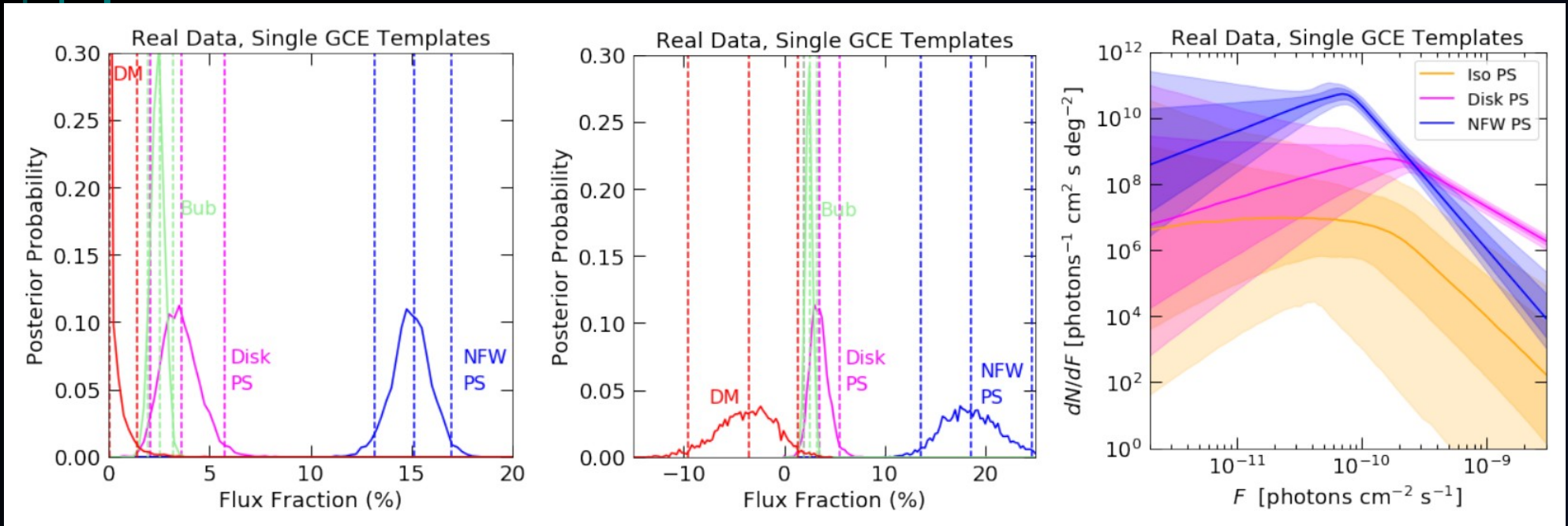
RL+Slatyer (PRL ‘19)

BULGE SHAPE



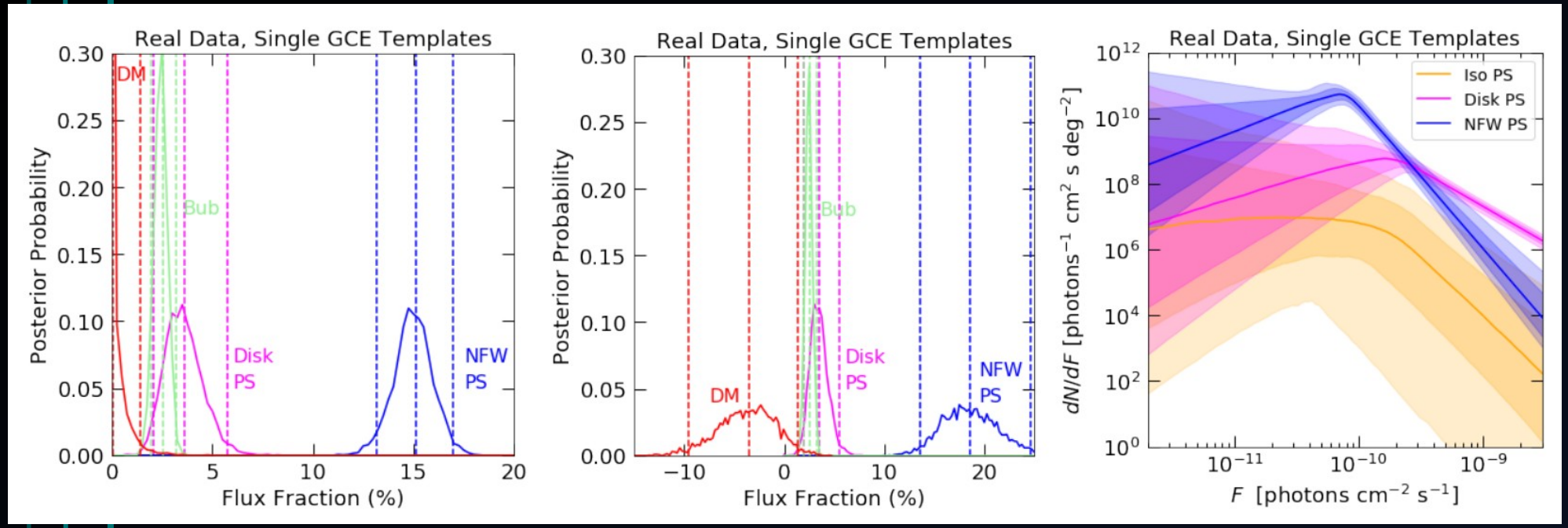
Bland-Hawthorn, Ortwin Gerhard ‘17

RL+Slatyer ’20

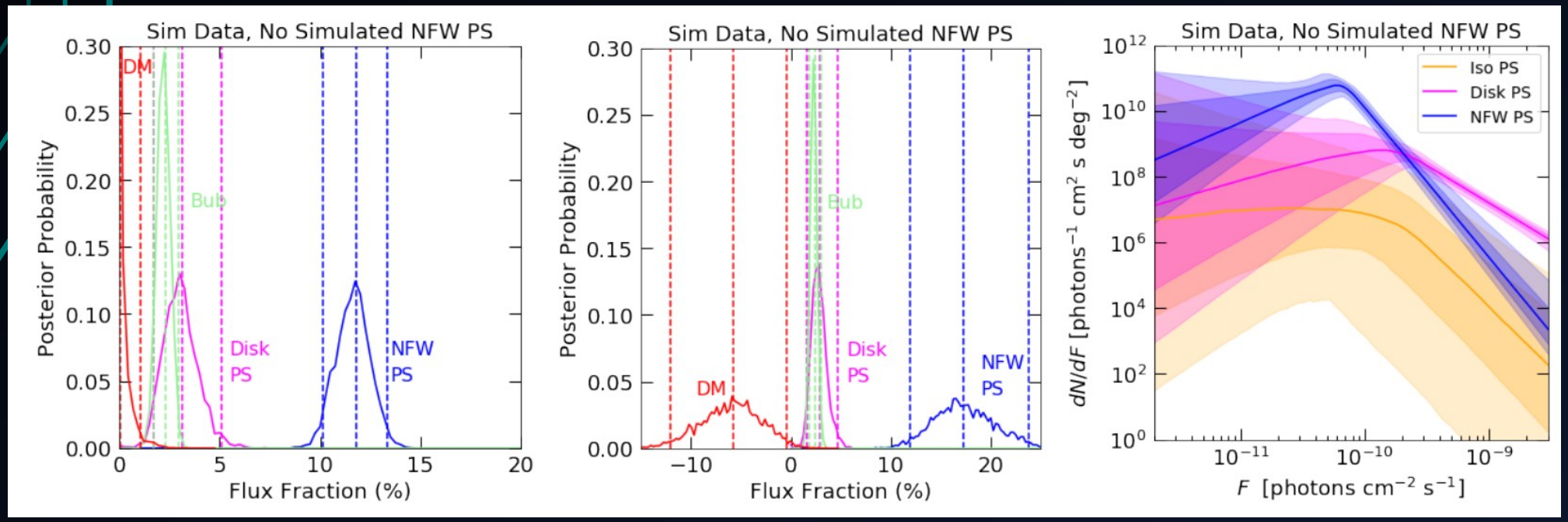


Real data, one excess template

RL+Slatyer '20



Real data, one excess template



Simulated asymmetry, analyzed with one excess template

No simulated point sources

SPURIOUS POINT SOURCES IN THE GCE

- Unmodeled asymmetry leads to a spurious point source signal as the GCE Behavior reproduced in detail in simulations

- More broadly, **any** mismodeling might cause a spurious point source signal:
  - An incorrect model leads to increased variance relative to the data
  - Increased variance is also a feature of a point source signal!
  - Thus, variance from mismodeling can be misattributed to variance from point sources (when they don't actually exist)

Leane+Slatyer, '20

Leane+Slatyer, '20

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Systematics still not well enough controlled:

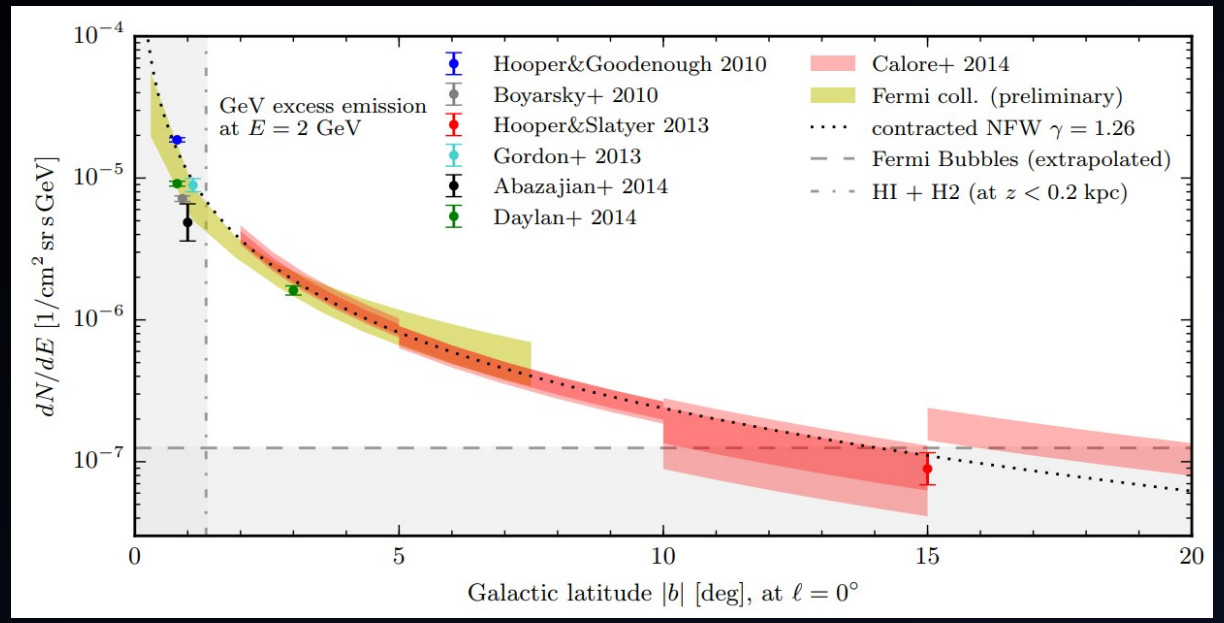
Claimed point source evidence for the GCE is not robust

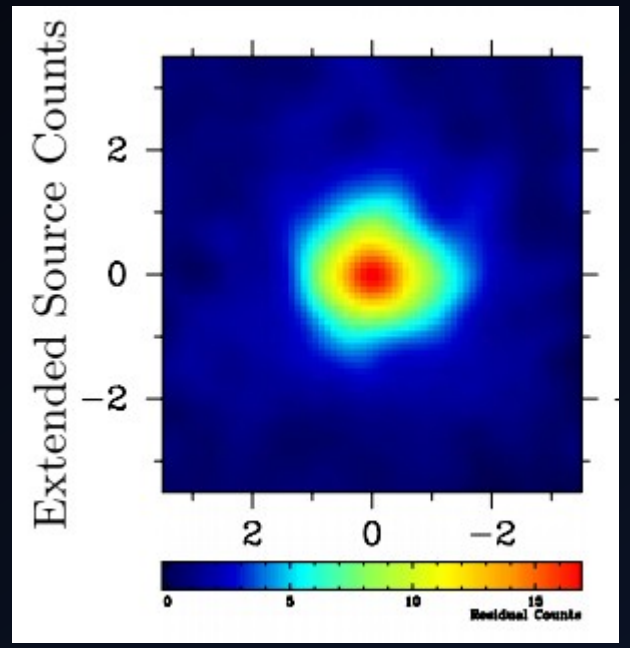
Leane+Slatyer, '20

Leane+Slatyer, '20

MORPHOLOGY

Calore et al ‘14



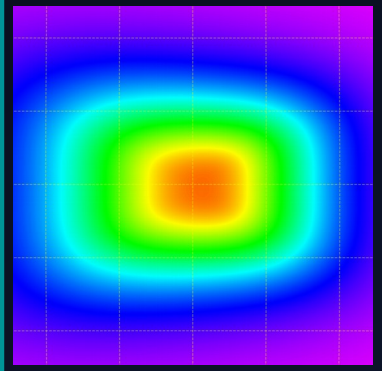


Abazajian+ Kaplinghat ‘12

Spherically symmetric around Galactic Center

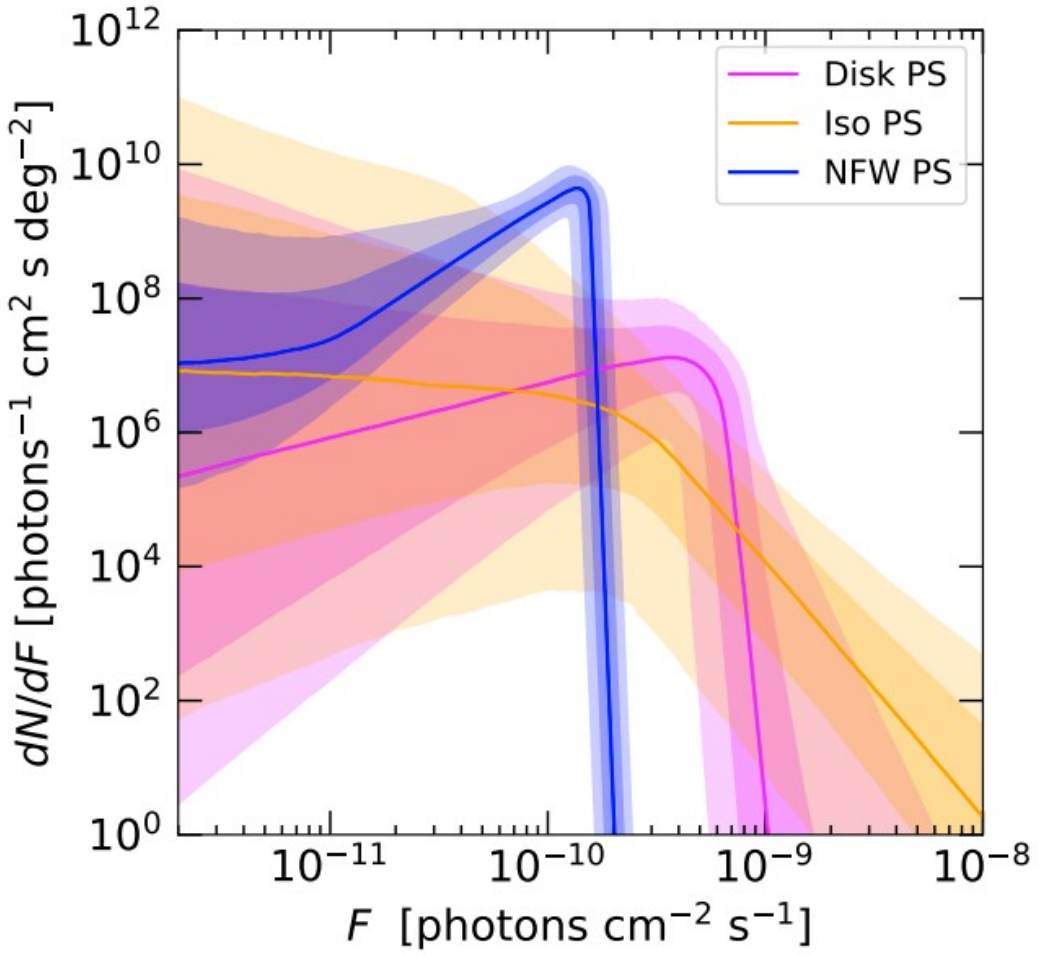
Scales like $r^{-2.4}$ extending out to around 10°, roughly fits standard dark matter (NFW) profile

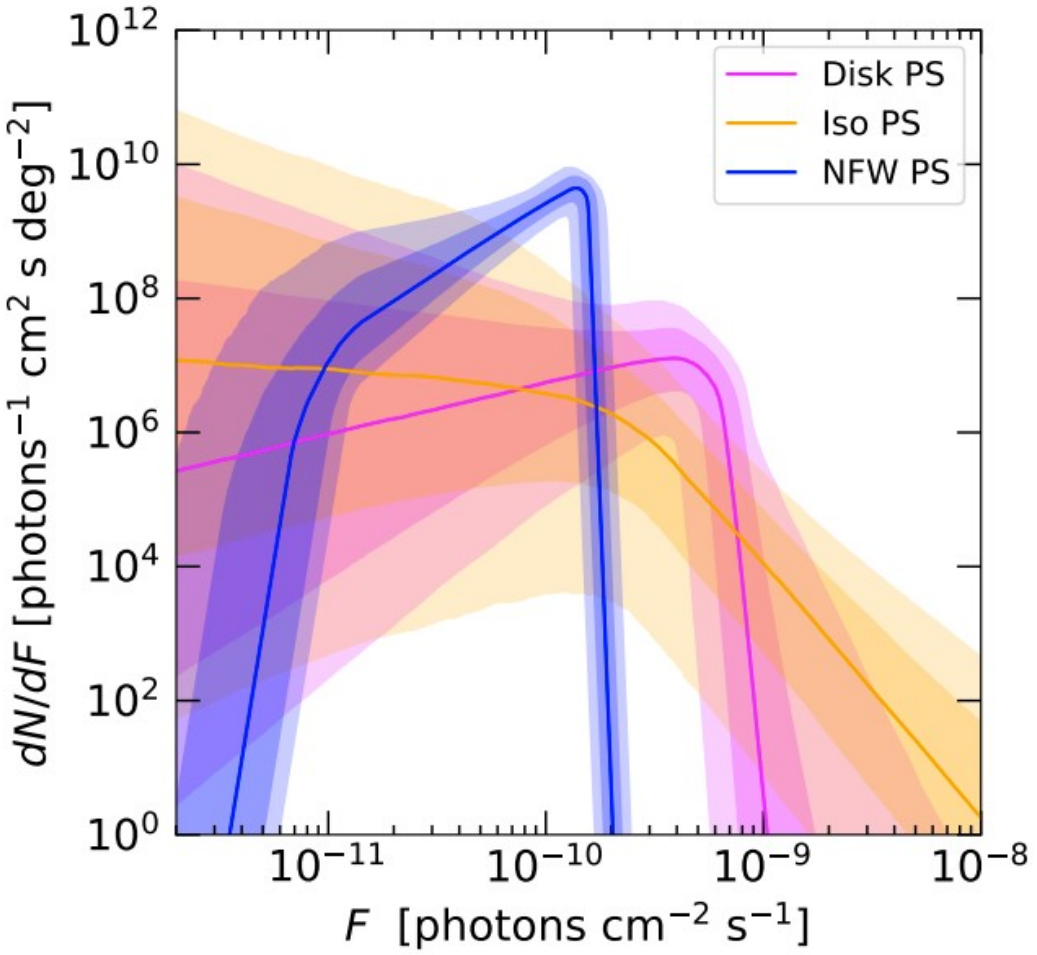
Hooper+Slatyer ‘13



More recent studies find bulge preference

Macias ‘16
Bartels ‘17
Macias ‘19
Abazajian ‘20


Disk PS
Iso PS
NFW PS
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
dN/dF [photons^{-1} cm^{2} s deg^{-2}]
10^{-11}
10^{-10}
10^{-9}
10^{-8}
F [photons cm^{-2} s^{-1}]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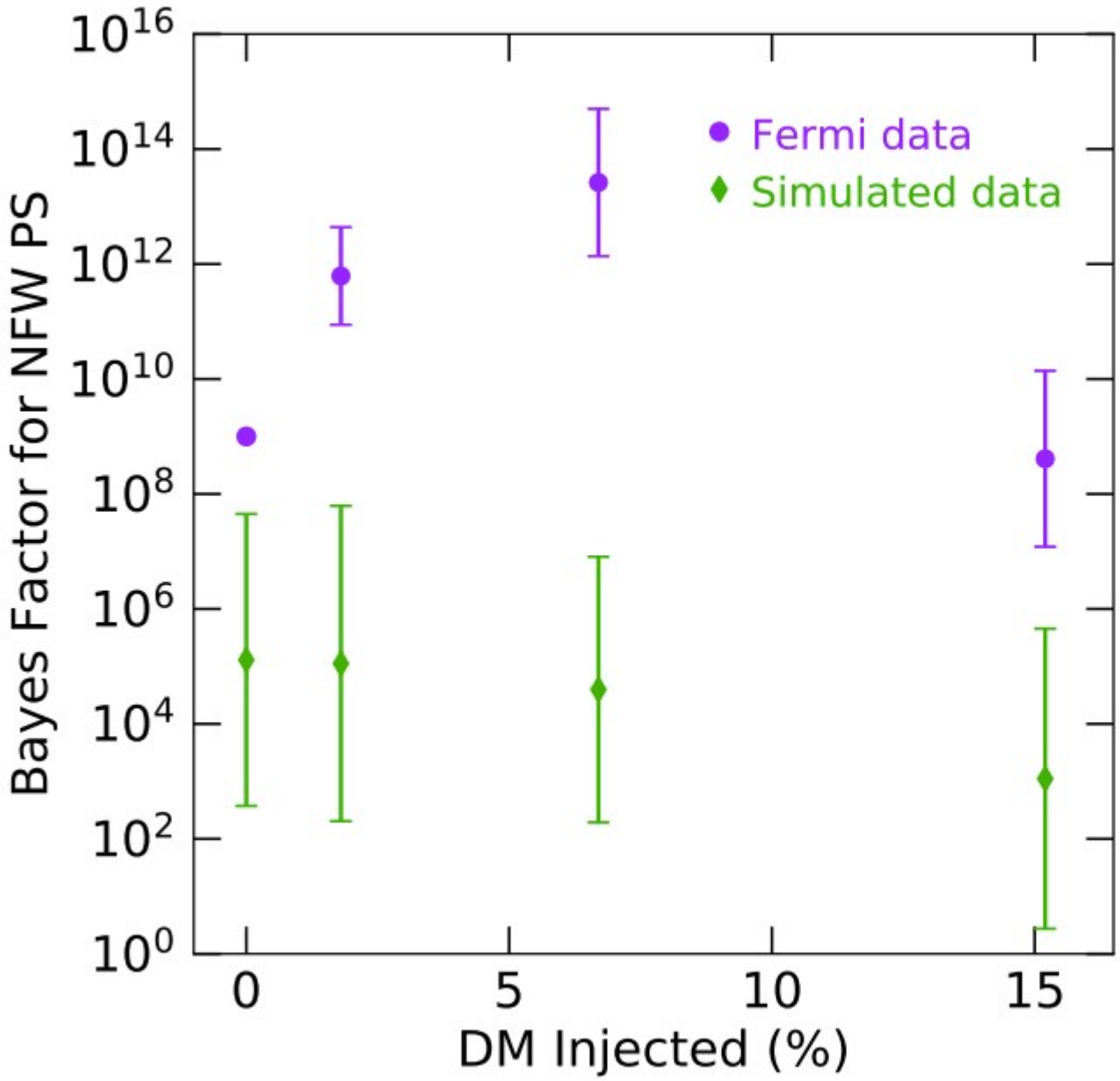
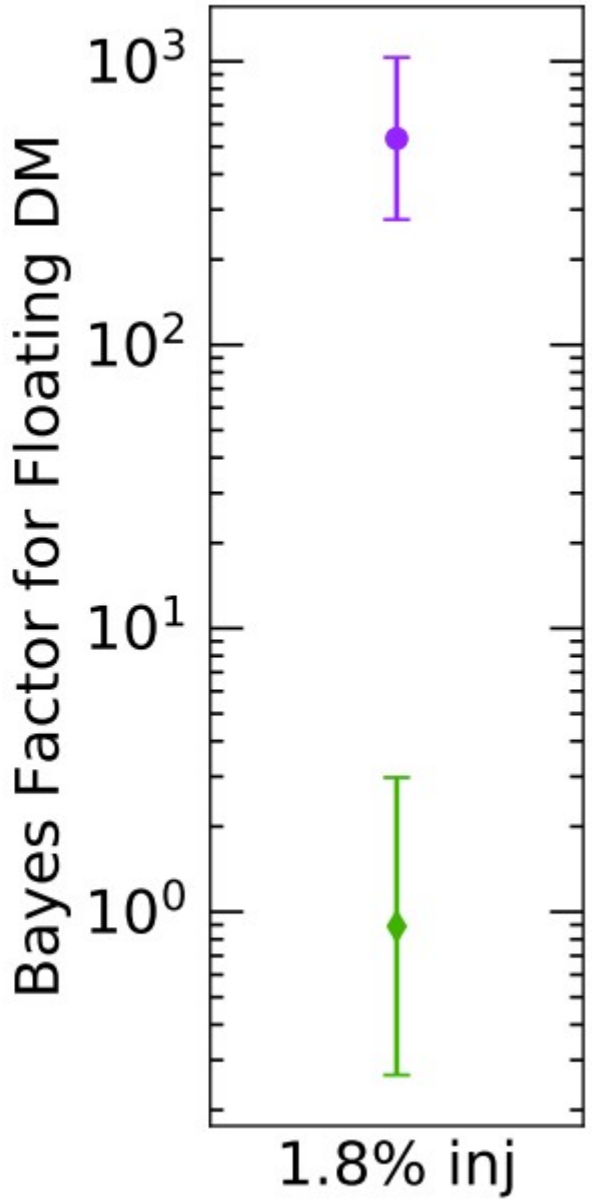
10^{-9}
10^{-8}
F [photons cm^{-2} s^{-1}]


Bayes Factor for NFW PS
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
Fermi data
Simulated data
0
5
10
15
DM Injected (%)


Bayes Factor for Floating DM
10^{3}
10^{2}
10^{1}
10^{0}
1.8% inj

REAL DATA vs SIMULATED DATA