Status of the Galactic Center Gamma-ray Excess

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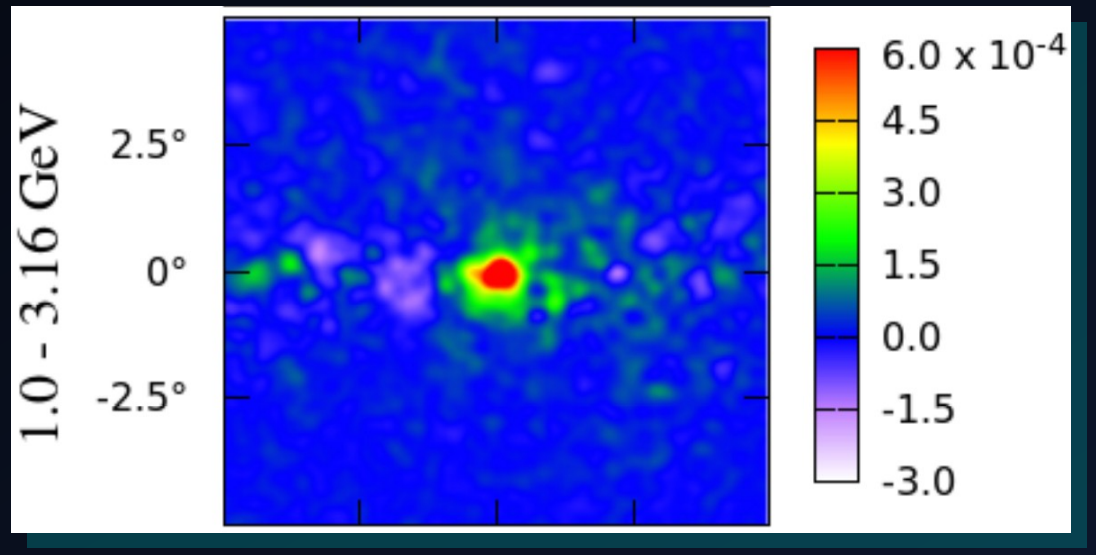
OUTLINE

- Introduction to the Galactic Center Excess (GCE)
  - Brief background and characteristics
- Dark matter vs pulsars?
  - How to tell hypotheses apart
  - Latest developments
- Understanding systematics
  - Subtleties behind GCE analyses
- Ways forward

THE GALACTIC CENTER GEV EXCESS

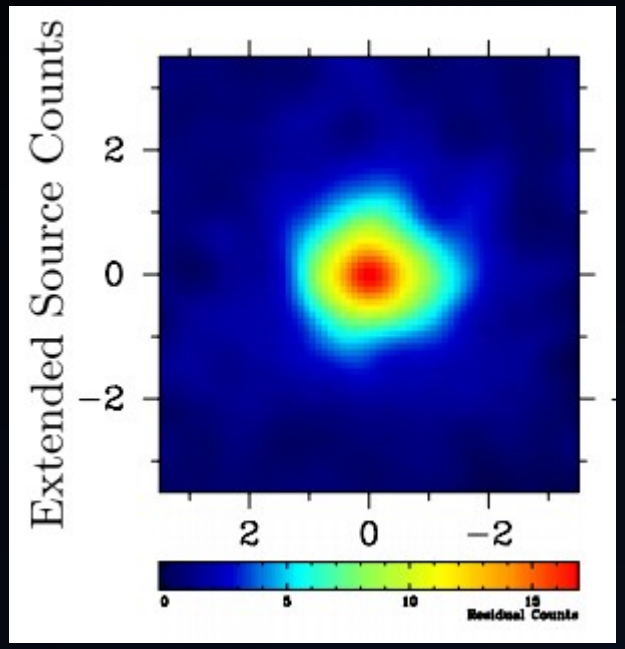
- Highly significant bright excess in gamma rays
- Detected by the Fermi gamma-ray Space Telescope
- Peaked at 1-3 GeV



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

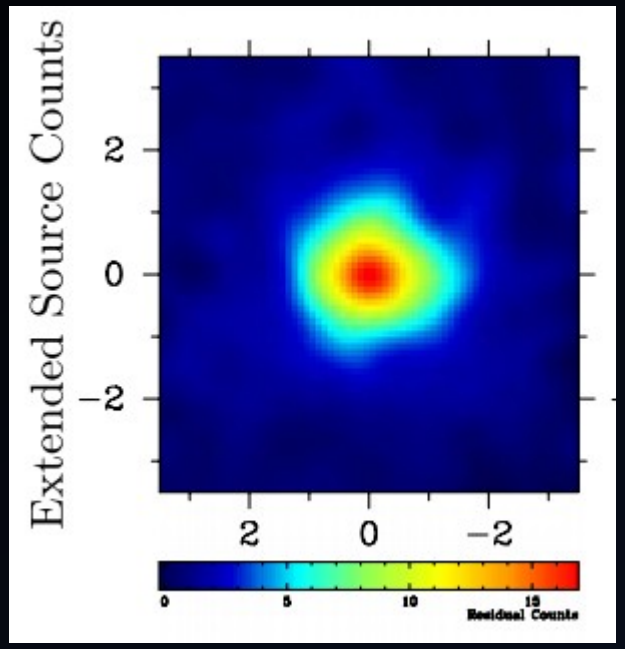


Abazajian+ Kaplinghat ‘12

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

MORPHOLOGY



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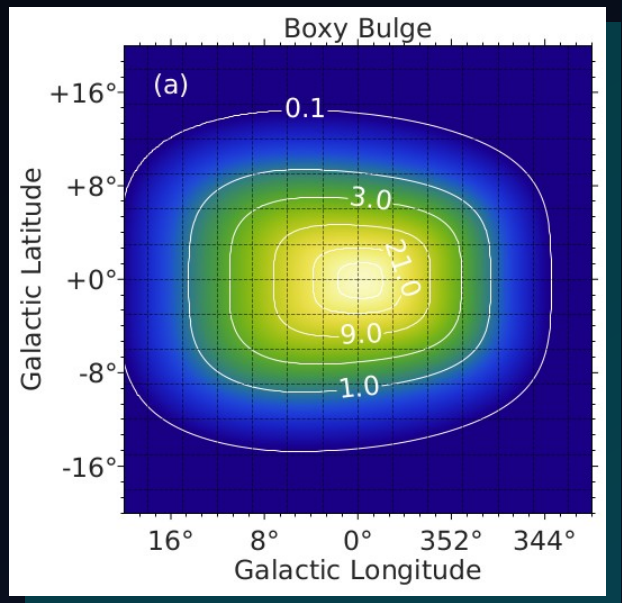

Abazajian+, ‘20

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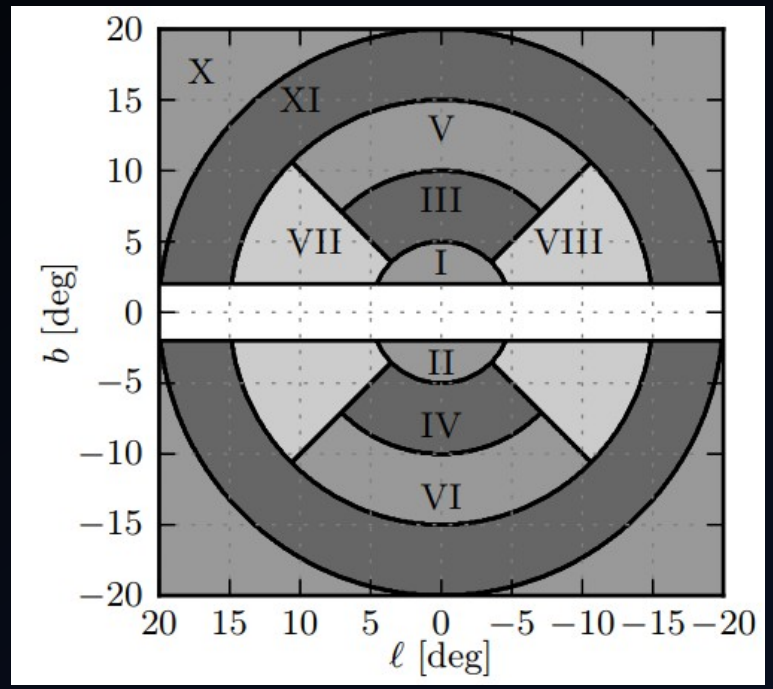
Hooper+Slatyer ‘13

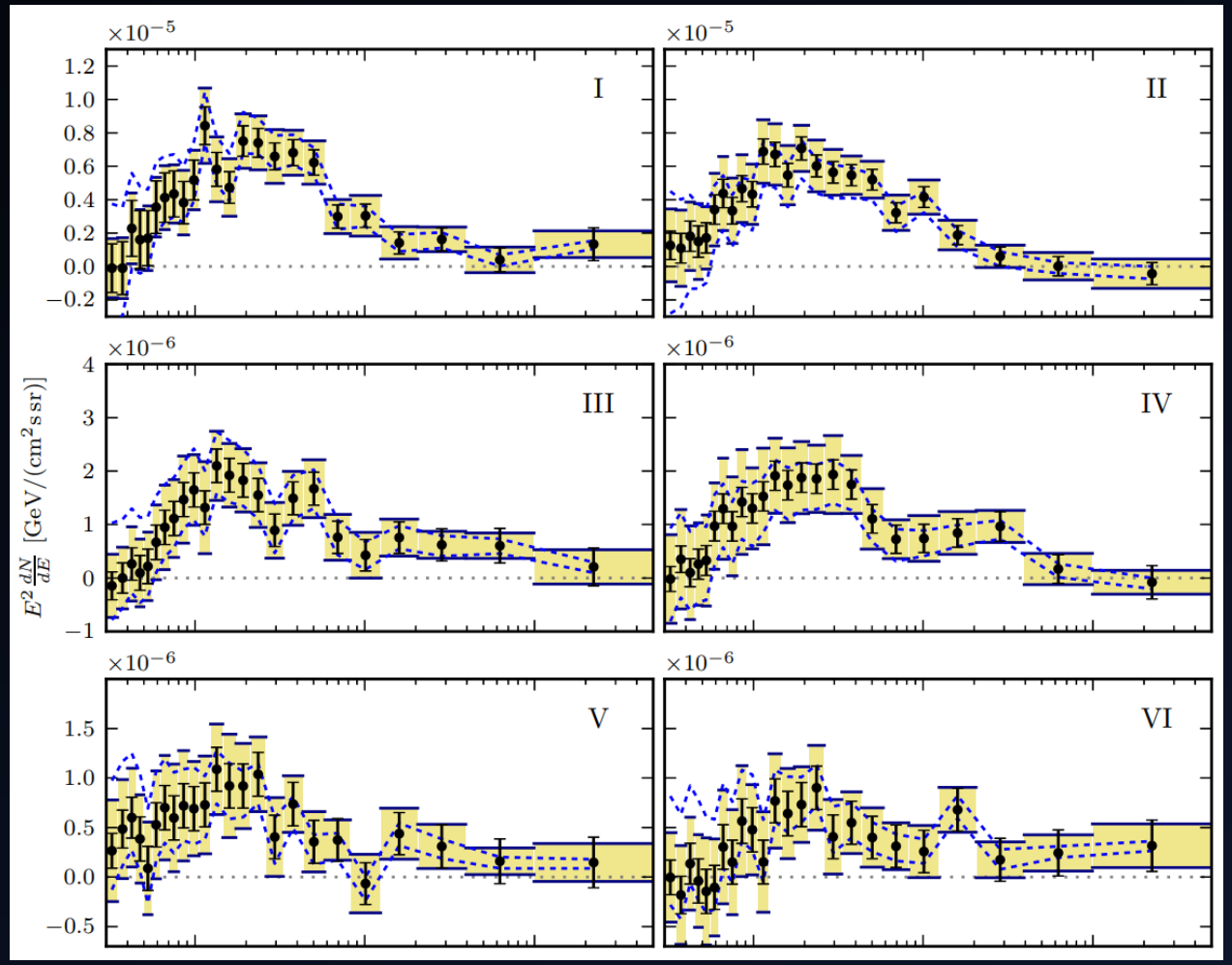
Some recent studies find bulge preference

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

SPECTRUM

- Shape appears to be uniform throughout the Inner Galaxy



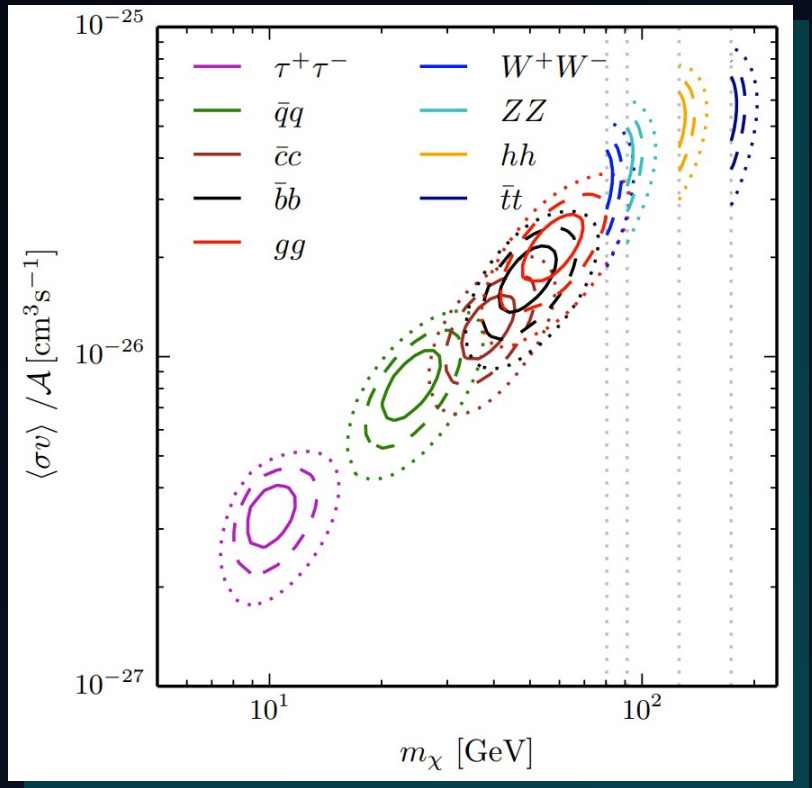


Calore et al ‘14

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

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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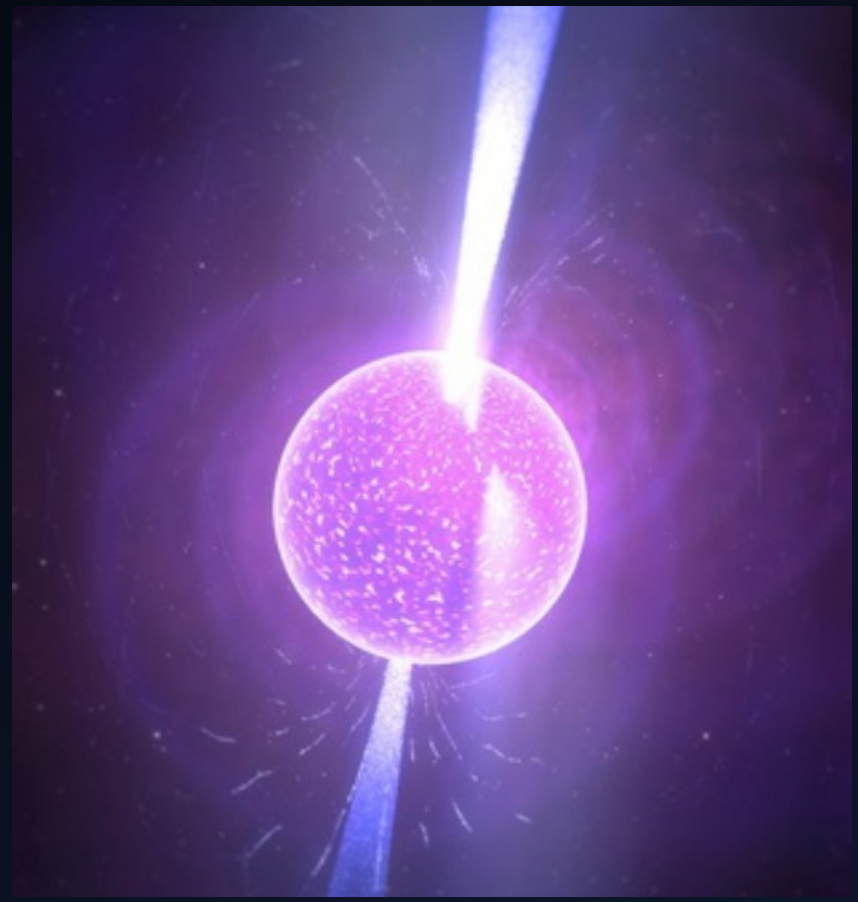
PULSARS AS THE EXCESS

- 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



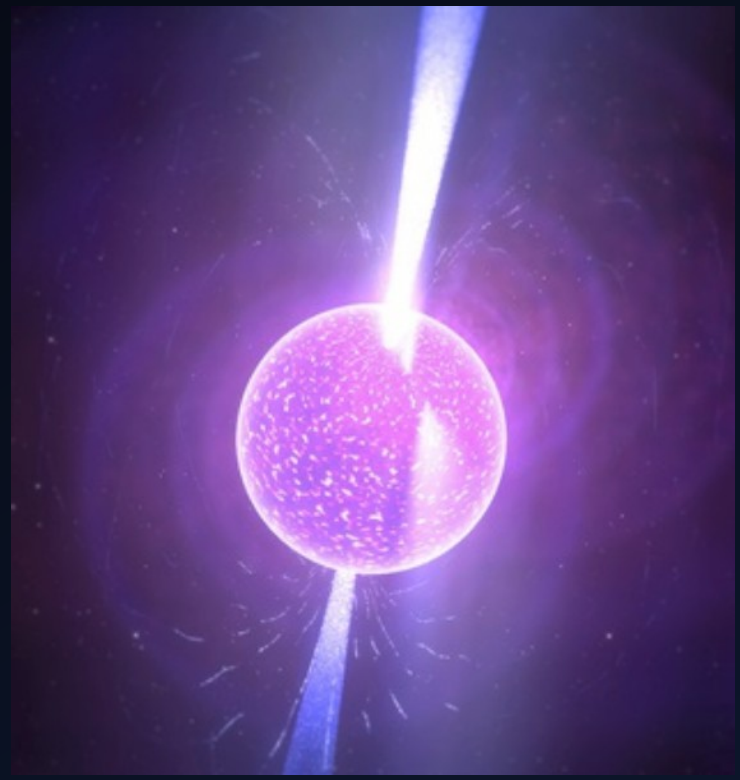
POINT SOURCES AS THE EXCESS

- Resolved Point Sources:

  Bright enough to be individually detected

- Unresolved Point Sources:

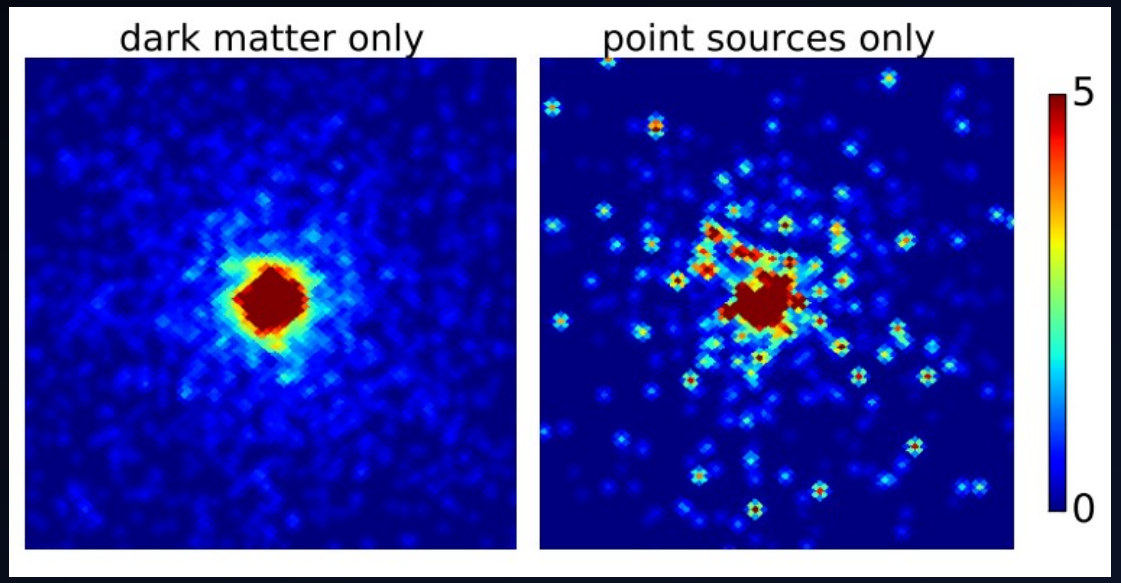
  Too dim to be individually detected, cannot be individually resolved, but collectively could explain GCE



DISTINGUISHING DM vs. POINT SOURCES

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

Lee+ ‘15

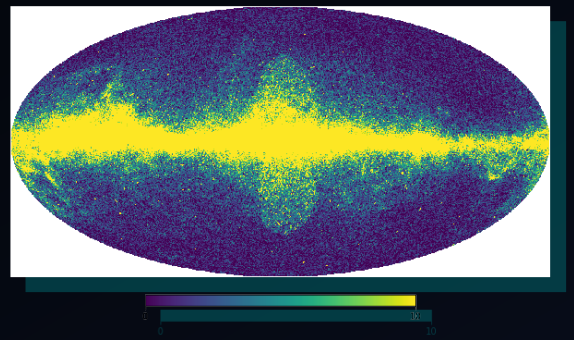


Dark matter: smooth
continuous halo
in the Galaxy

Point Sources: clumpy
individual sources

METHOD 1: TEMPLATE FITTING

Full sky



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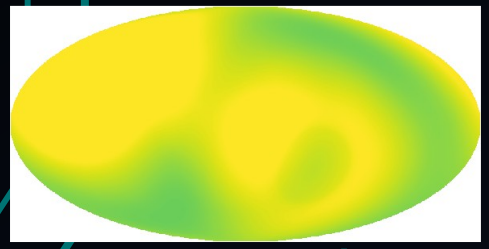
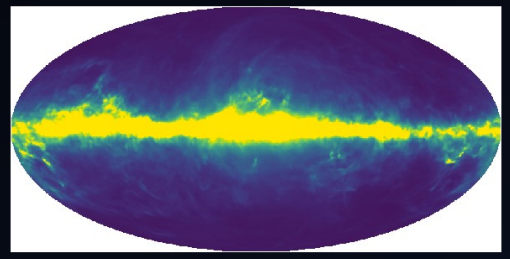
(Example combination)



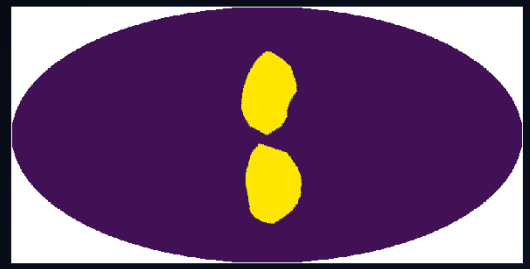
Isotropic

+



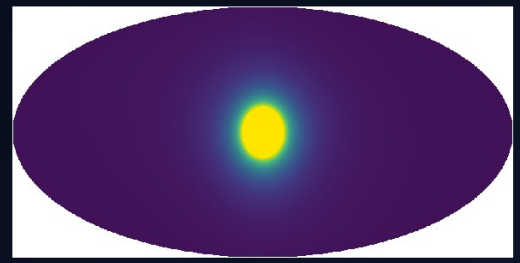
Diffuse

+



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

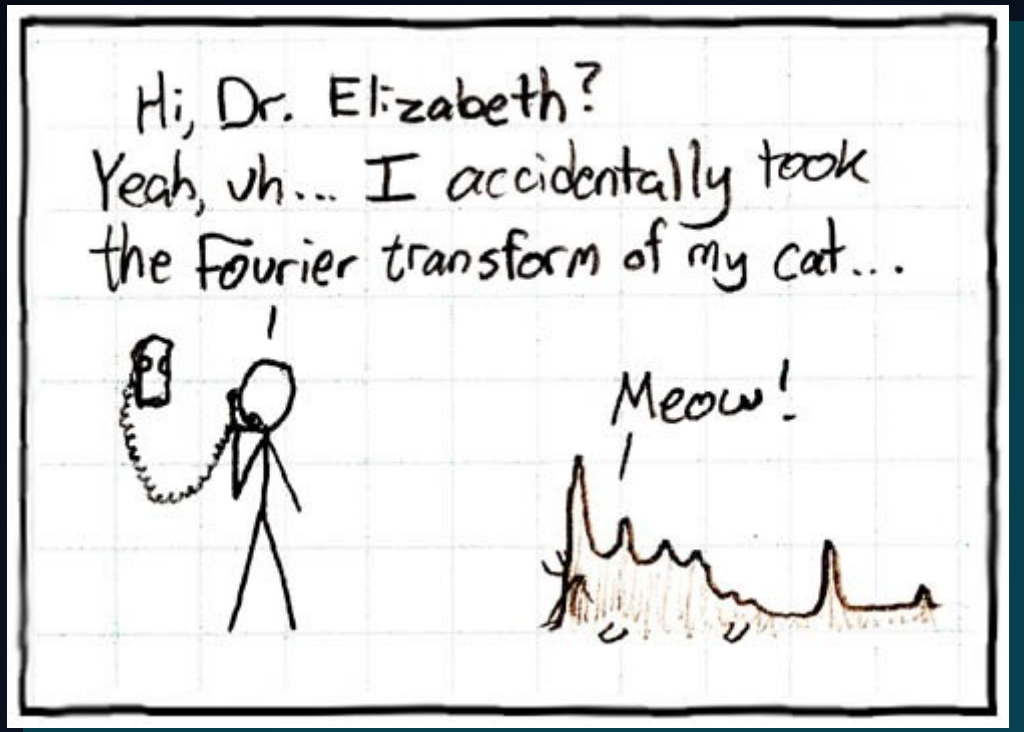
As before,

Clumpy (peaks):

point sources

Smooth (no peaks):

either no point sources,
or very faint point sources

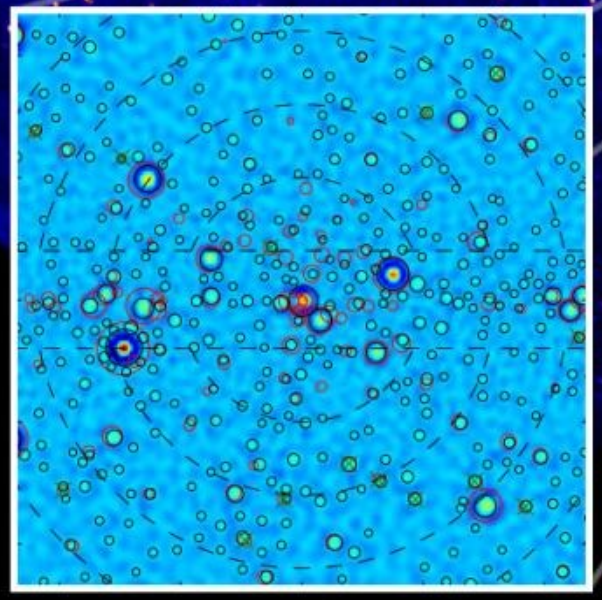


xkcd

POINT SOURCES AT THE GALACTIC CENTER?

2015 Status: **Consensus towards point source explanation, evidence for “clumpy” rather than “smooth” signal**

Wavelet transformation



Bartels et al. 2016

Non-Poissonian noise

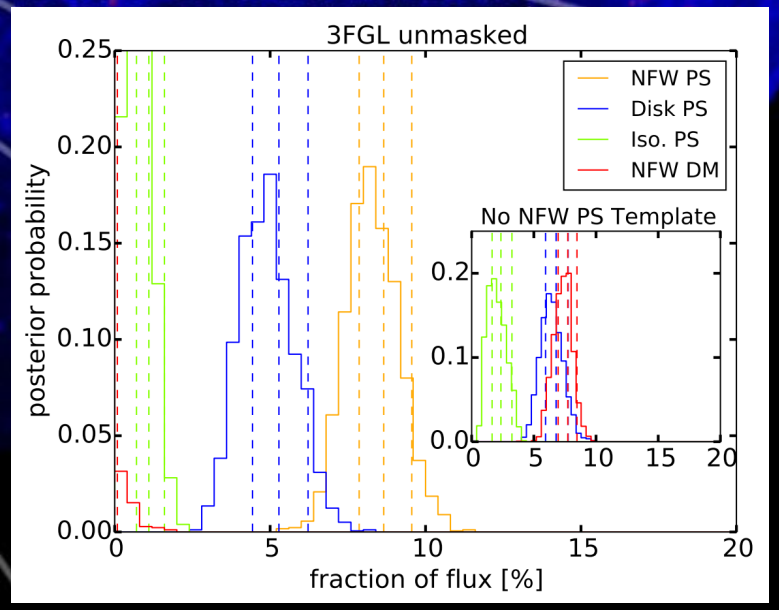


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Image: C.Weniger

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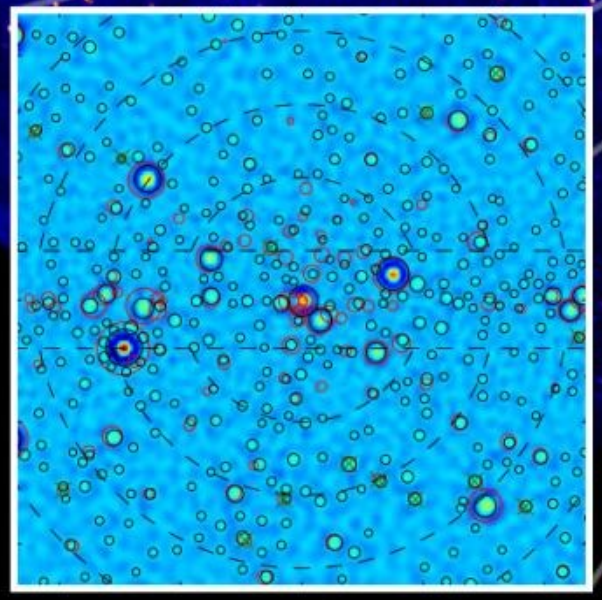

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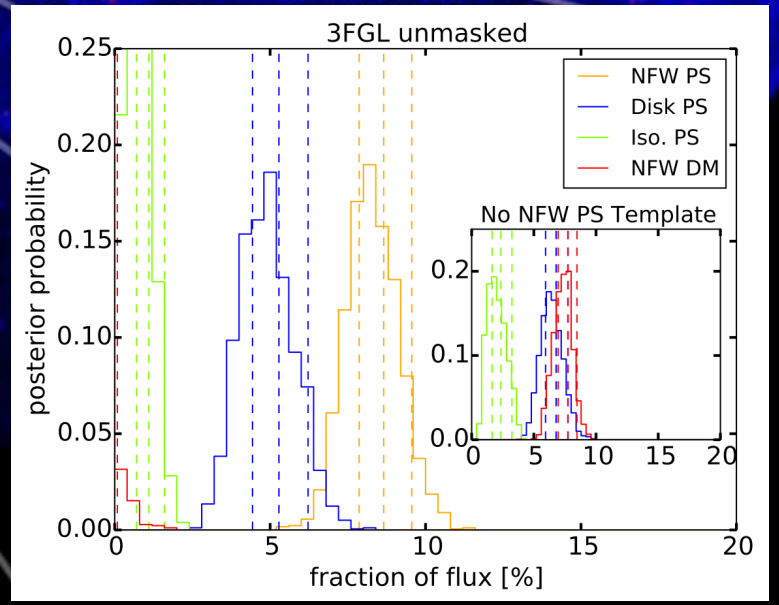


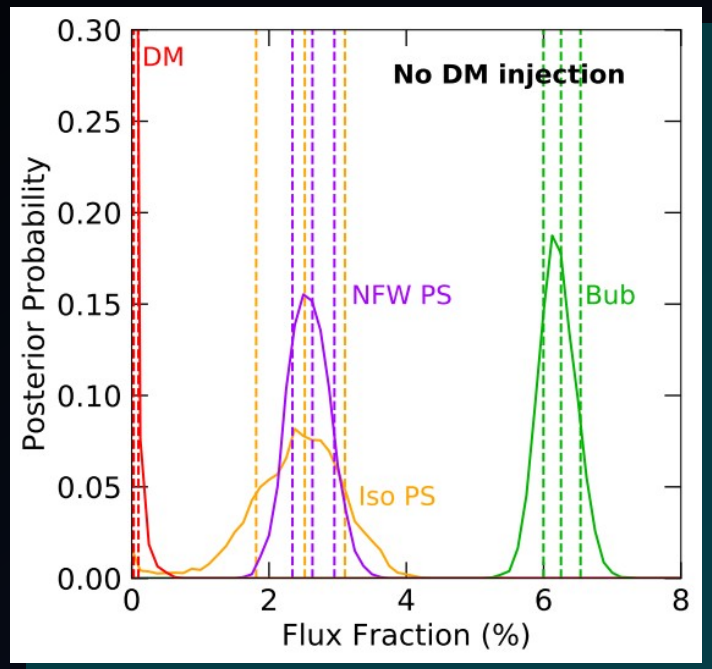
Lee et al. 2016

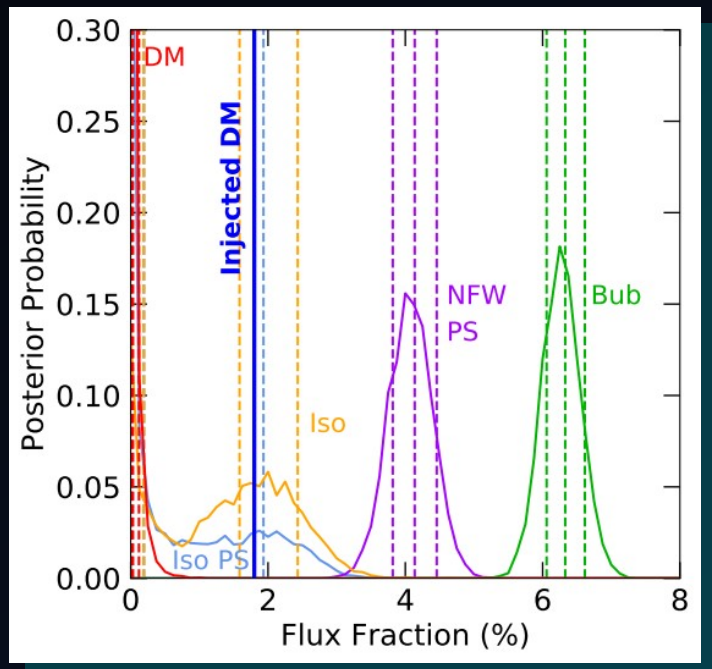
Image: C.Weniger

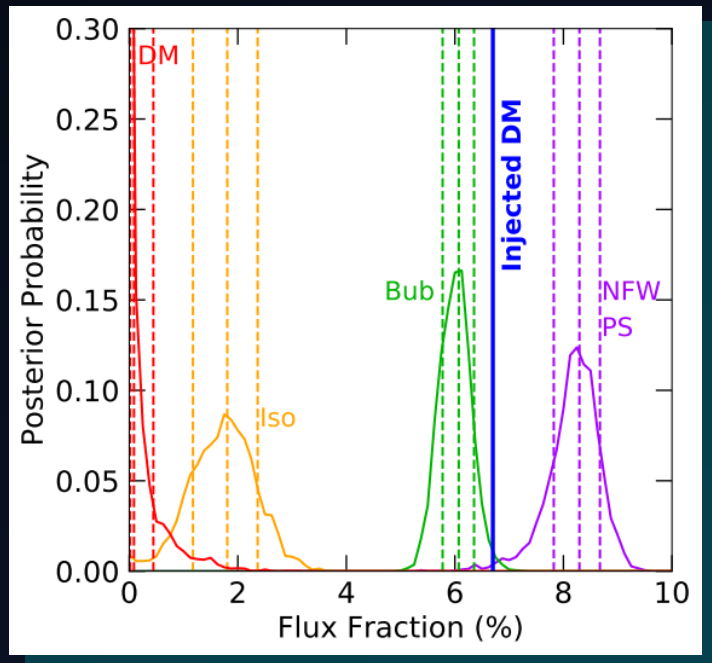
DARK MATTER STRIKES BACK

RL+Slatyer, PRL ‘19

Mismodeling can hide a dark matter signal !



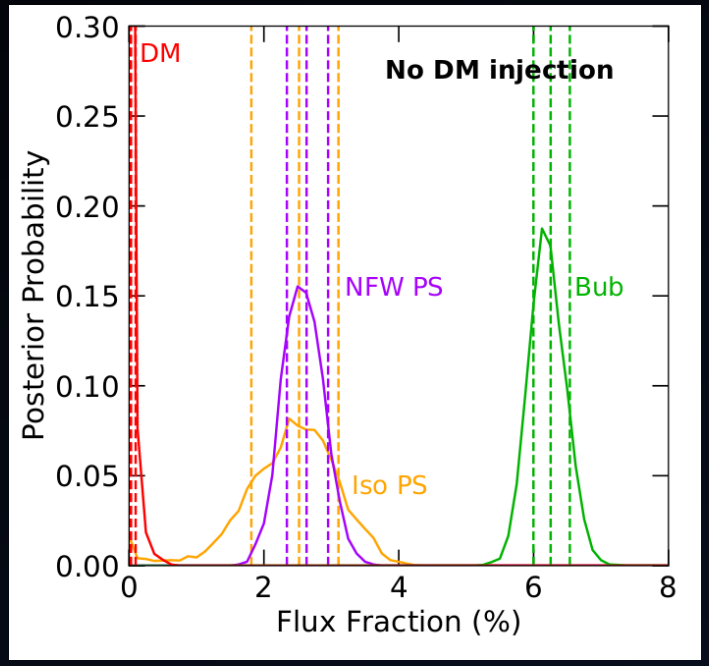


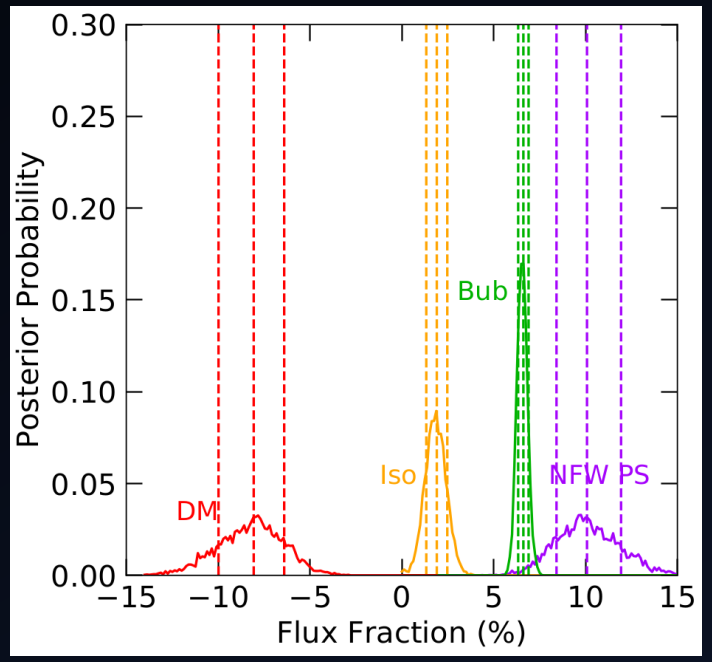


Systematics not under control, need to be understood to claim any robust result

ALTERNATIVE TO INJECTION: GOING NEGATIVE

Prior of DM normalization only allowed to float positive





Prior of DM normalization also allowed to float negative

Shows the degeneracy of smooth signals
(DM vs faint point sources) does not explain this behavior

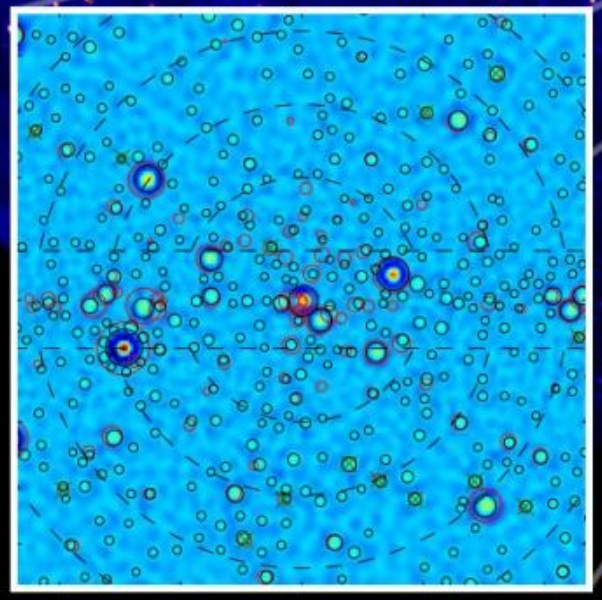
Observed that degree of oversubtraction varied with diffuse models;
effect likely due to diffuse mismodeling

RL+Slatyer, PRL ‘19

POINT SOURCES AT THE GALACTIC CENTER?

2019 Status: **Interpretation of both papers challenged**

Wavelet transformation



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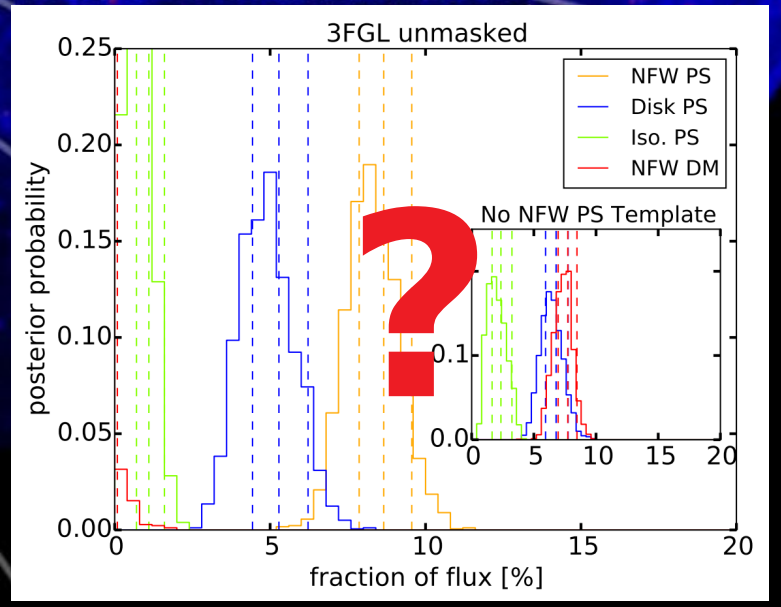

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Image: C.Weniger

POINT SOURCES AT THE GALACTIC CENTER?

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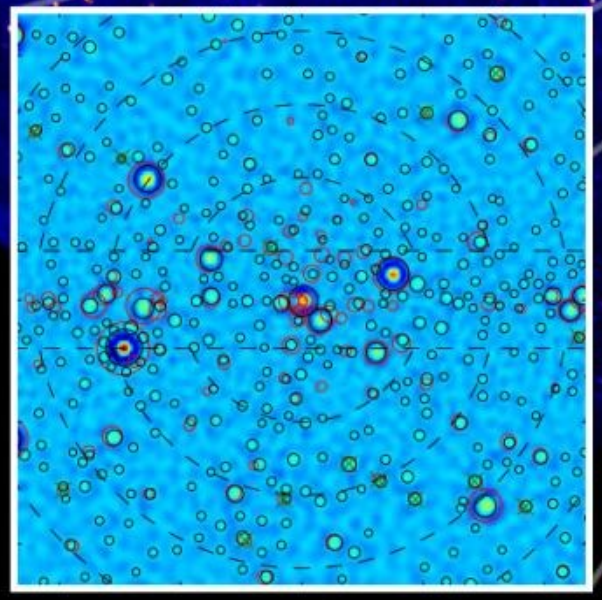

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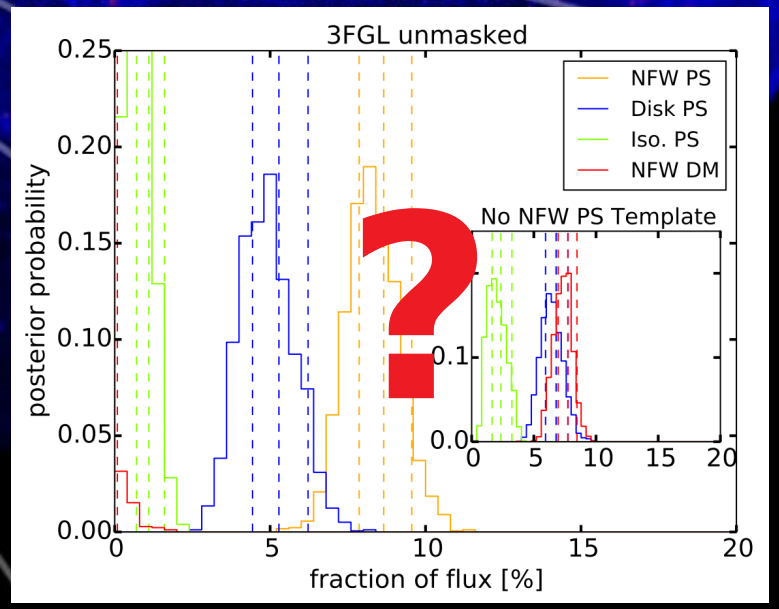

Lee et al. 2016

mage: C.Weniger

WAVELET METHOD RE-EVALUATION

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

Rebecca Leane

WAVELET METHOD RE-EVALUATION

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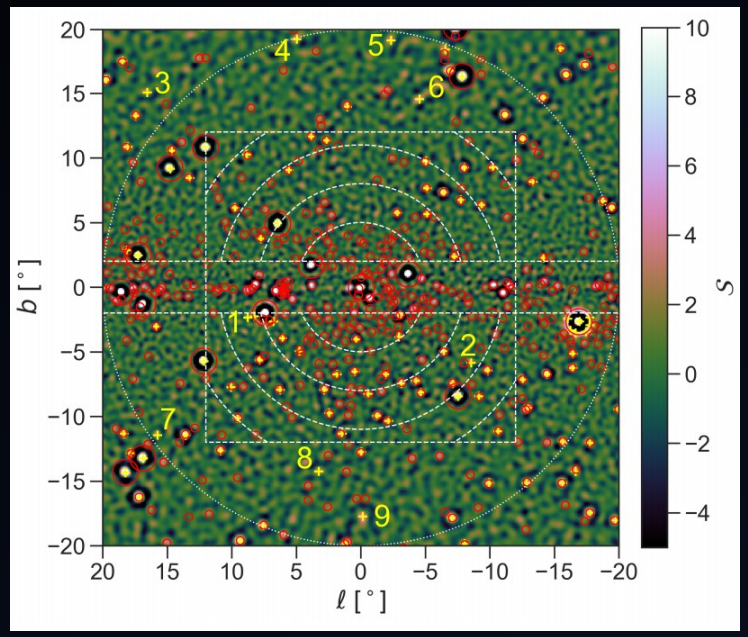

Turns out the 2015 paper correctly found point sources

Zhong, McDermott, Cholis, Fox, PRL '19

WAVELET METHOD RE-EVALUATION

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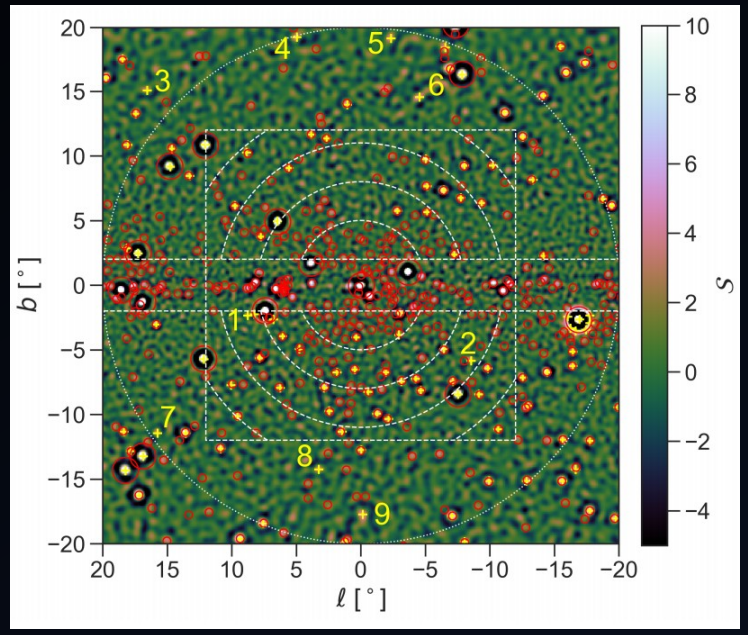

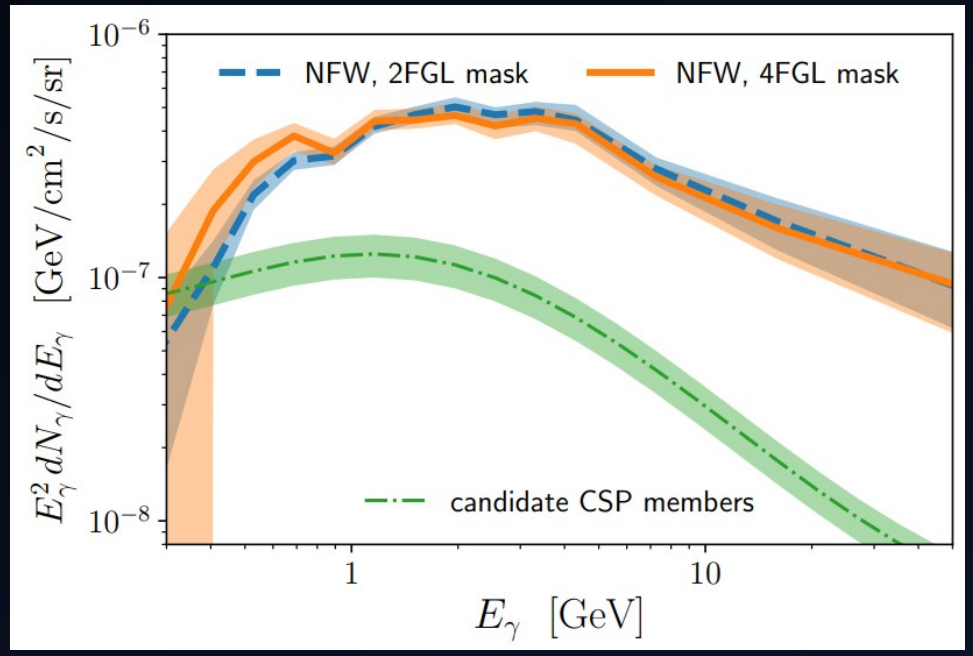

Turns out the 2015 paper correctly found point sources

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

Zhong, McDermott, Cholis, Fox, PRL '19

POINT SOURCES AT THE GALACTIC CENTER?

2019 Status: Interpretation of both papers challenged
No clear evidence for GCE point sources

Wavelet transformation

Bartels et al. 2016

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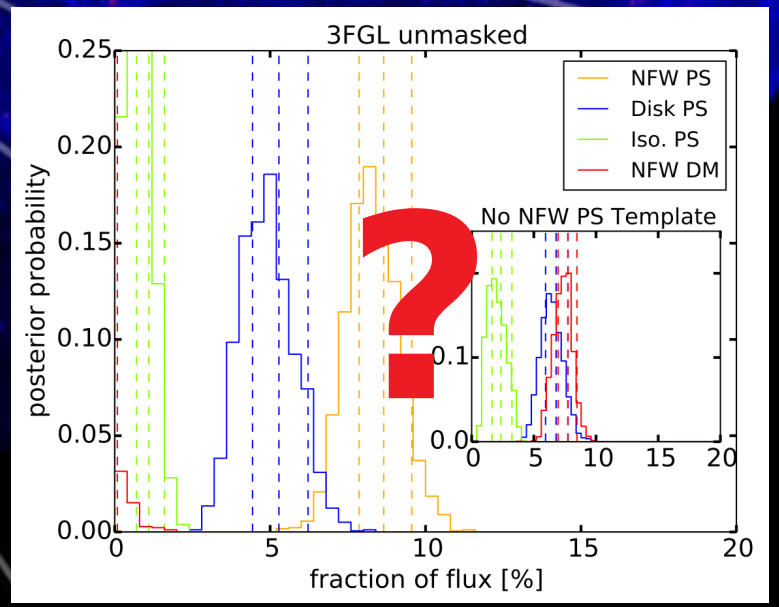
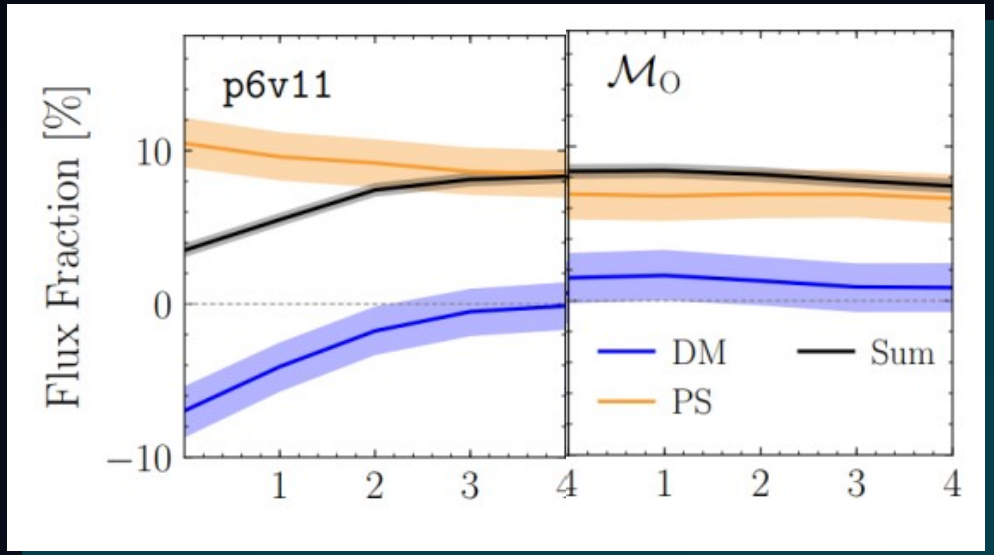


Lee et al. 2016

mage: C.Weniger

GCE: EVEN MORE RECENT DEVELOPMENTS

- Dark matter injection test issue shown indeed likely due to diffuse mismodeling
- Improved diffuse models: new model + spherical harmonics
- Point source preference robust to these specific variations and diffuse models

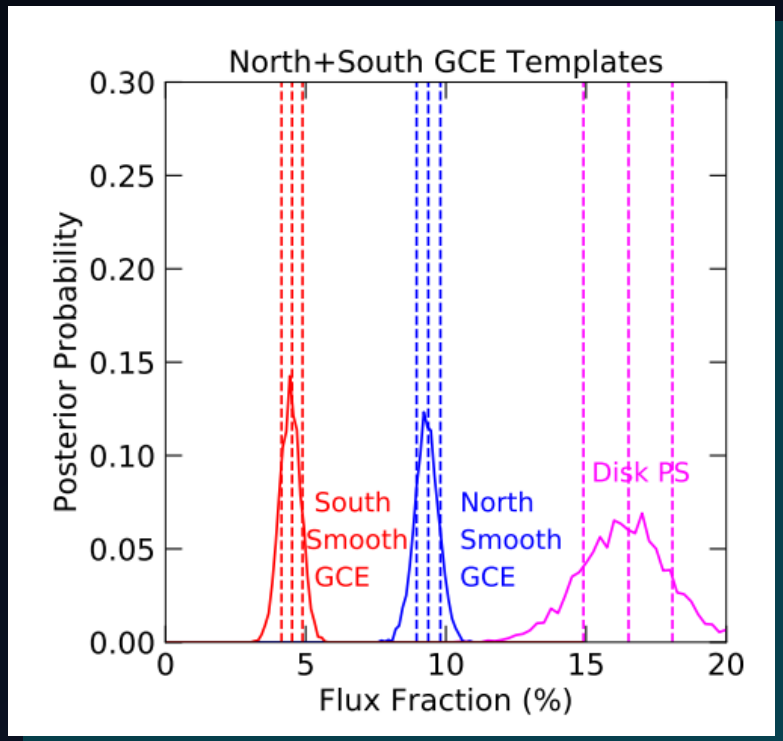


Buschmann+, ‘20

GCE: EVEN MORE RECENT DEVELOPMENTS

- However, point source evidence not robust to all systematics
- 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, ‘20

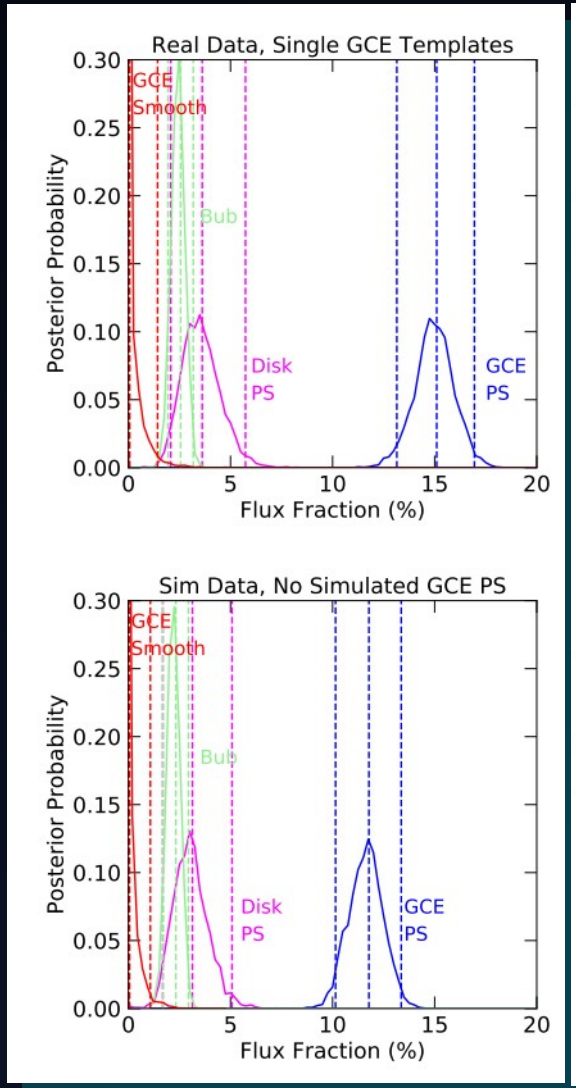
RL+Slatyer, ‘20

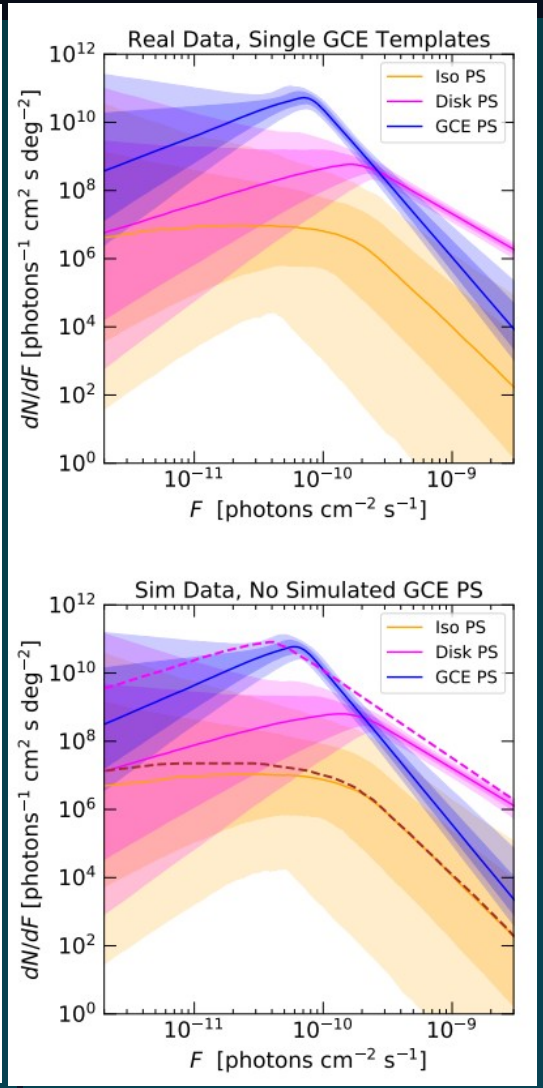
SPURIOUS POINT SOURCES IN THE GCE

- 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, ‘20

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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!

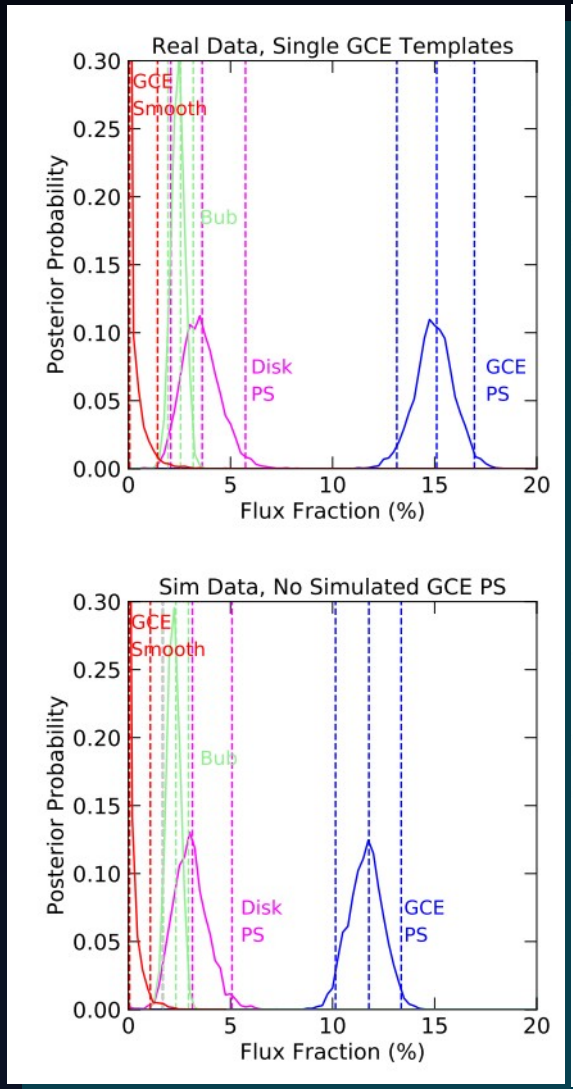
Systematics still not well enough controlled:
Claimed point source evidence for the GCE is still not robust

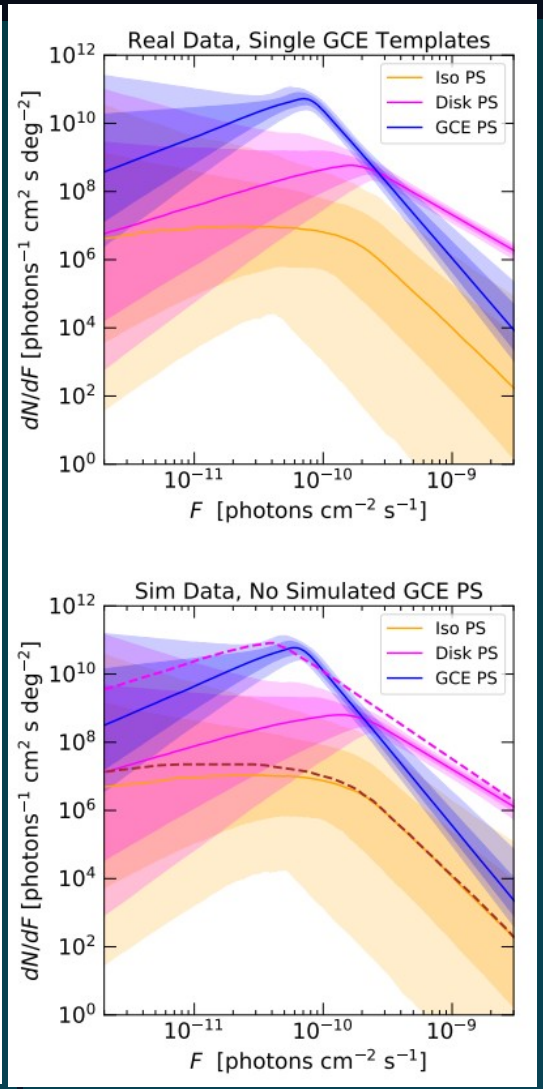
RL+Slatyer, ‘20

RL+Slatyer, ‘20

REAL DATA

SIMULATION



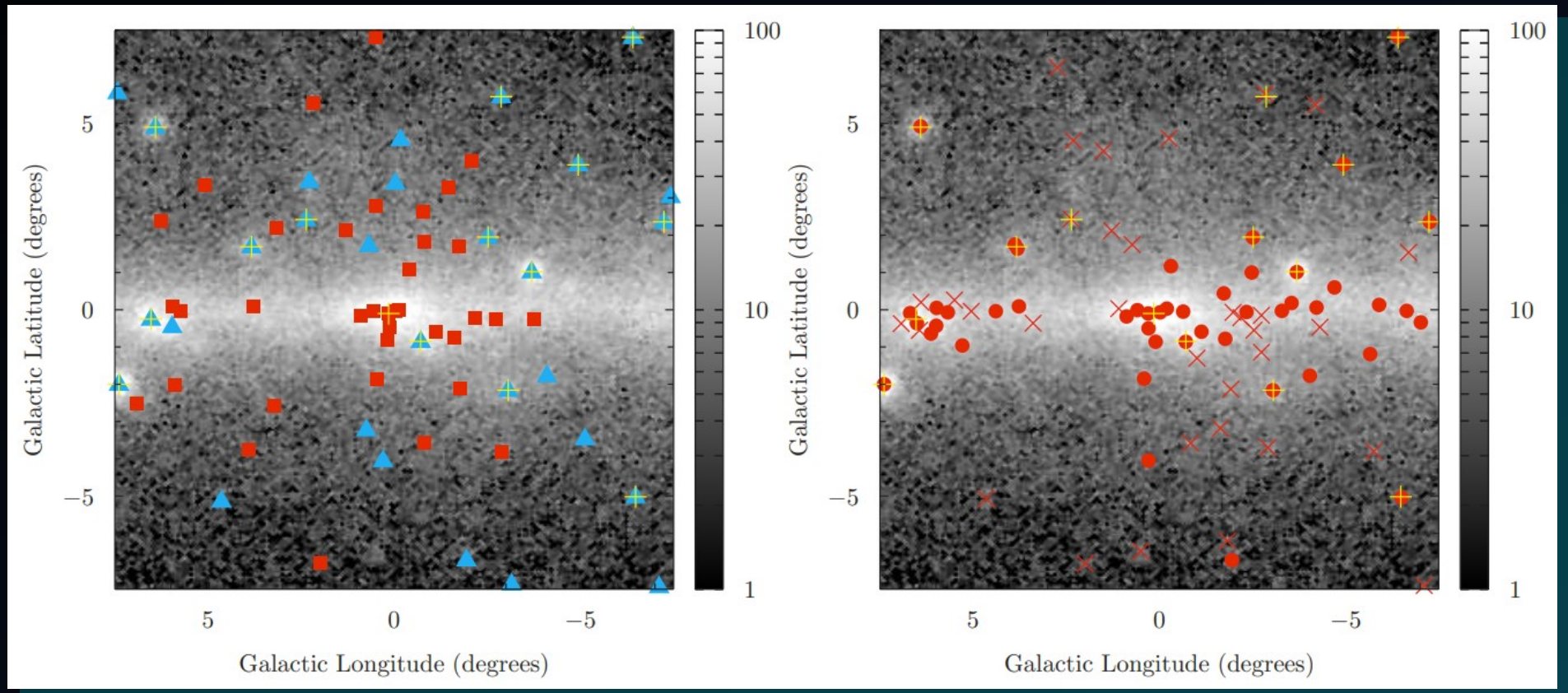


SYSTEMATICS: WHAT IS GOING ON?

Rebecca Leane

SYSTEMATICS: POINT SOURCE ID?

Fermi Collaboration '15

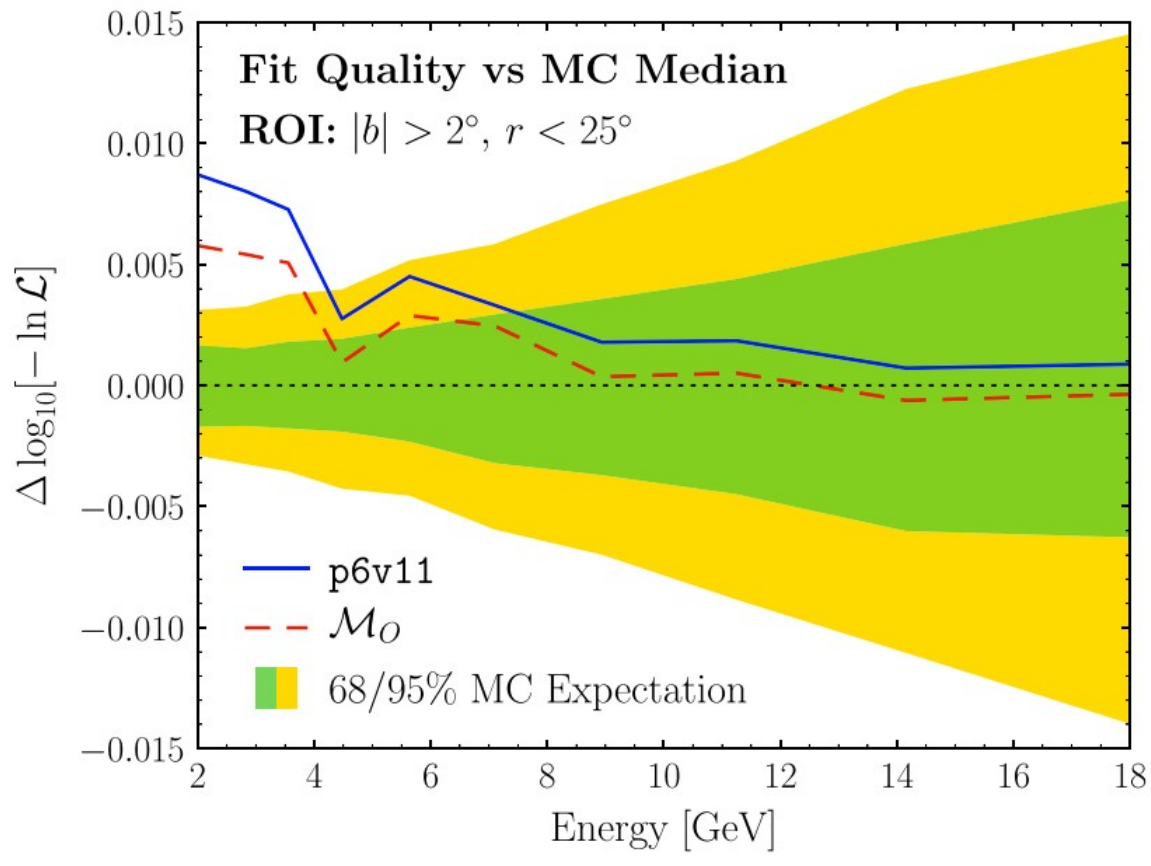


Point source catalog 1 (3FGL)

Point source catalog 2 (1FIG)

Different point sources "found" in different diffuse models!

KEY POINT: ALL DIFFUSE MODELS ARE BAD

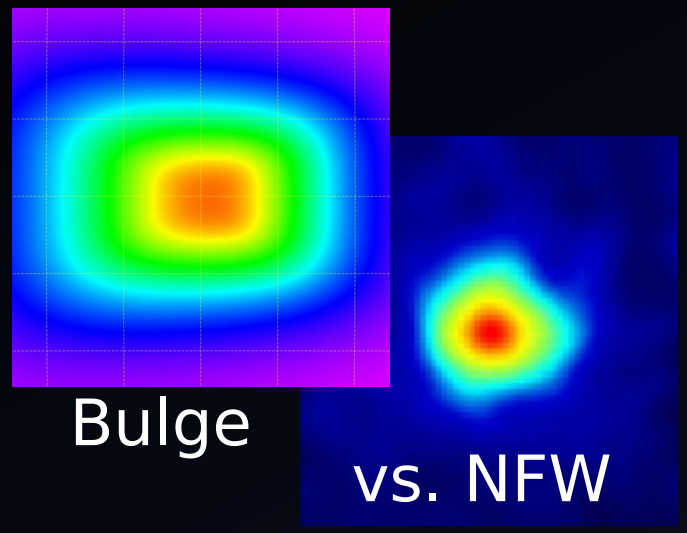


Buschmann+, ‘20

- Even the best diffuse models are far from good fits to the data
- Fitting to real data, and simulating based on best-fit parameters, does not return likelihoods expected within Poisson noise
- There is clearly a systematic here
- Better diffuse models are key to moving forward

CURRENT PICTURE

Morphology

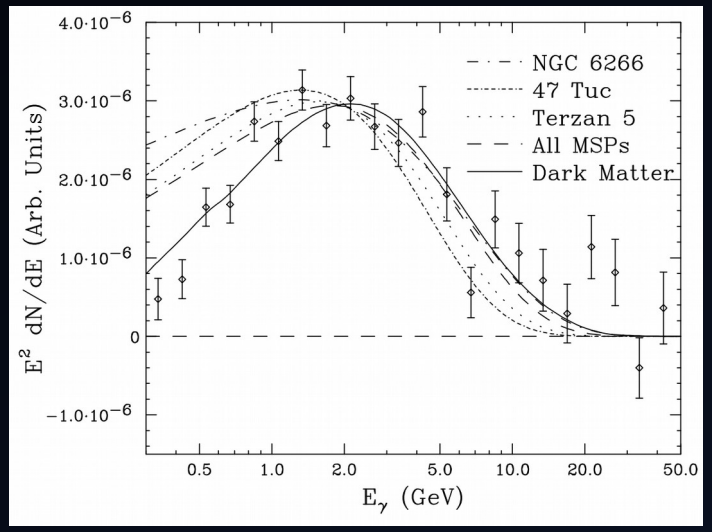


Bulge

vs. NFW

Not robustly known,
but big implications

Energy Spectrum

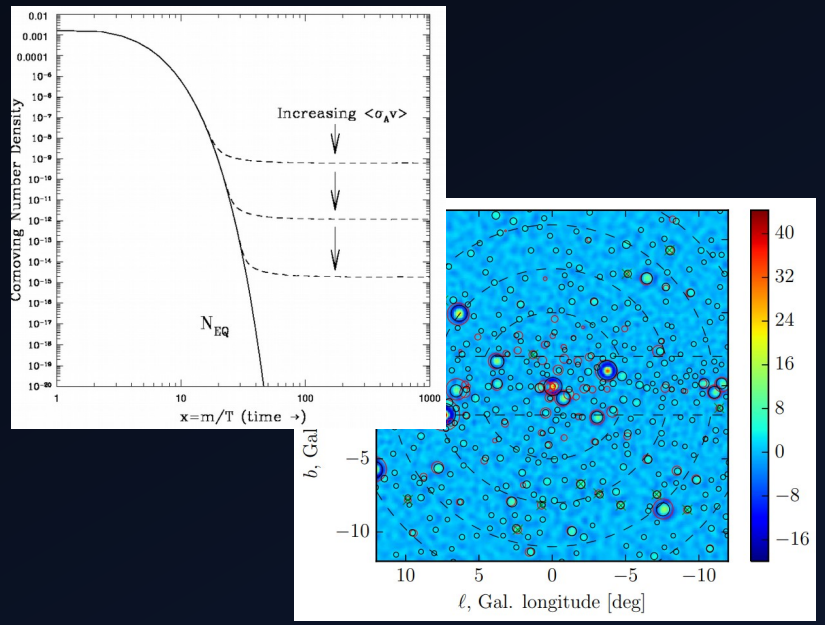


Comparable to
millisecond pulsars

Can be well fit with DM
annihilating to hadrons

Intensity

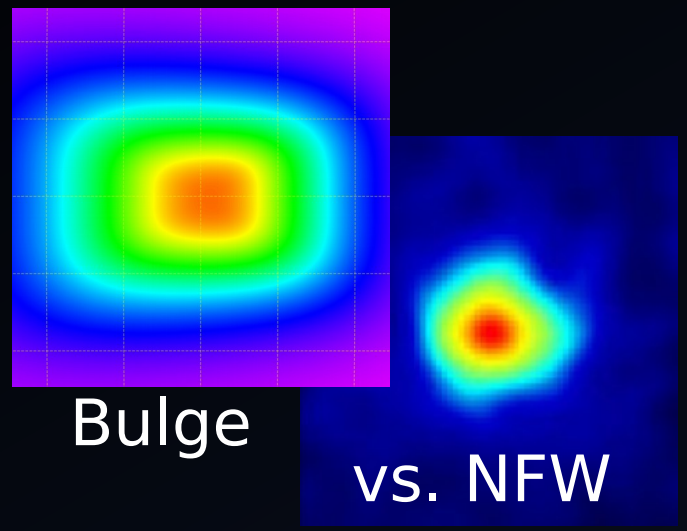
Well-explained by DM
(Predicted by thermal
relic cross section)



Tension for pulsars
strong constraints on
pulsar luminosity function

CURRENT PICTURE

Morphology

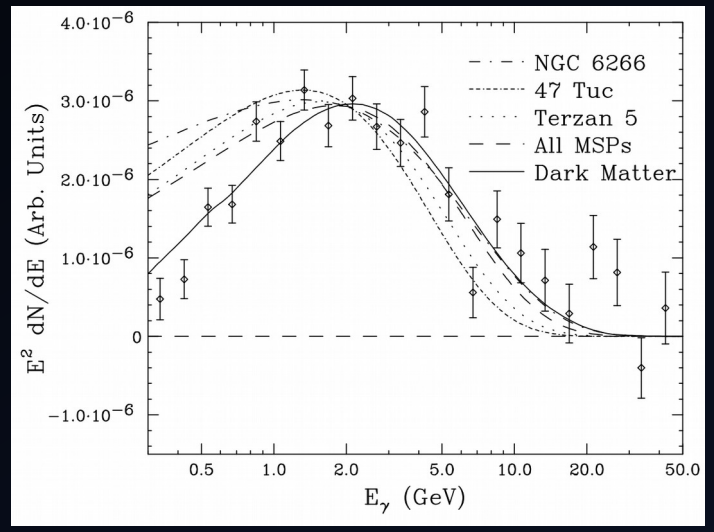


Bulge

vs. NFW

Not robustly known,
but big implications

Energy Spectrum



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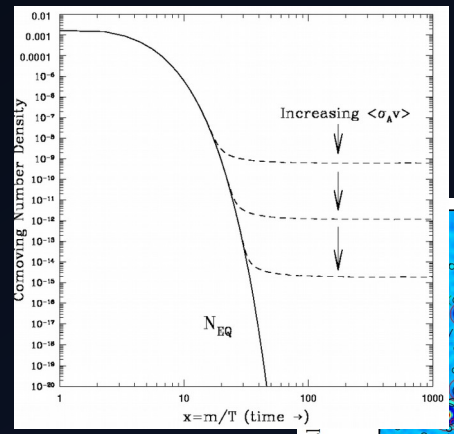

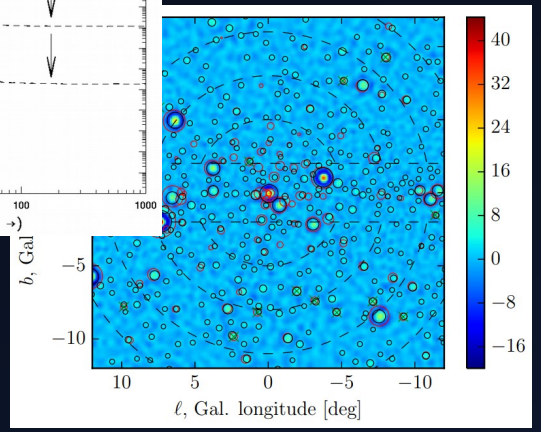

Tension for pulsars
strong constraints on pulsar luminosity function

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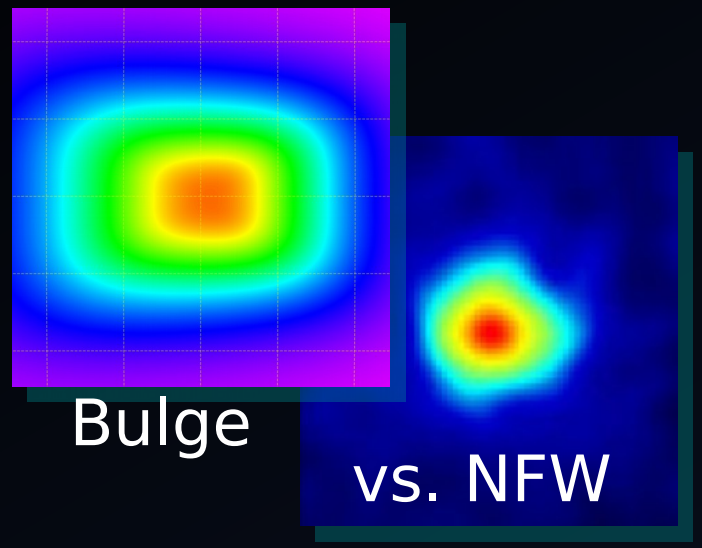
Morphology



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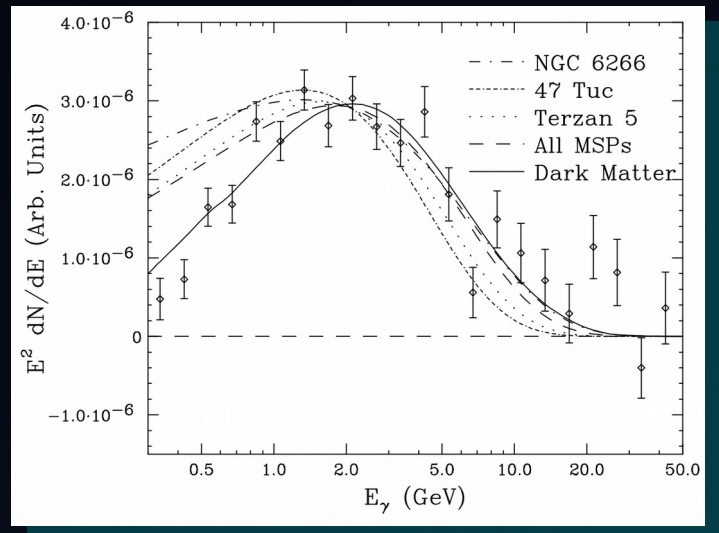

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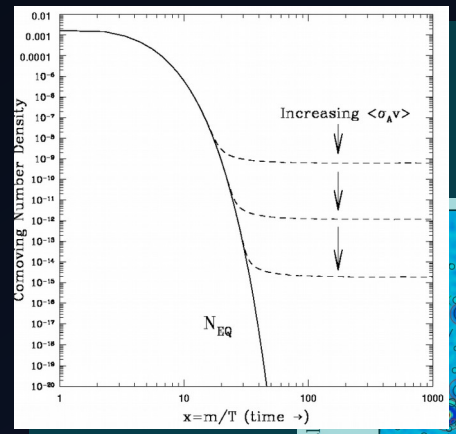
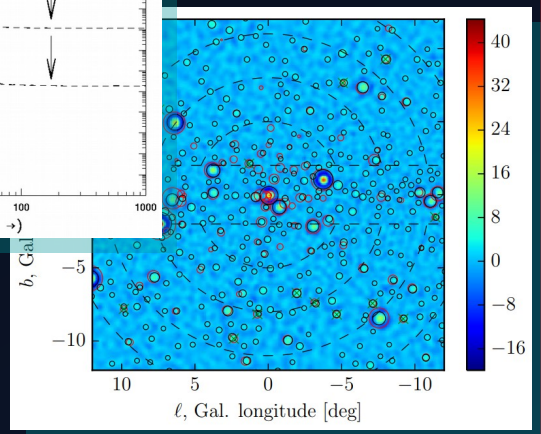




Tension for pulsars
strong constraints on
pulsar luminosity function

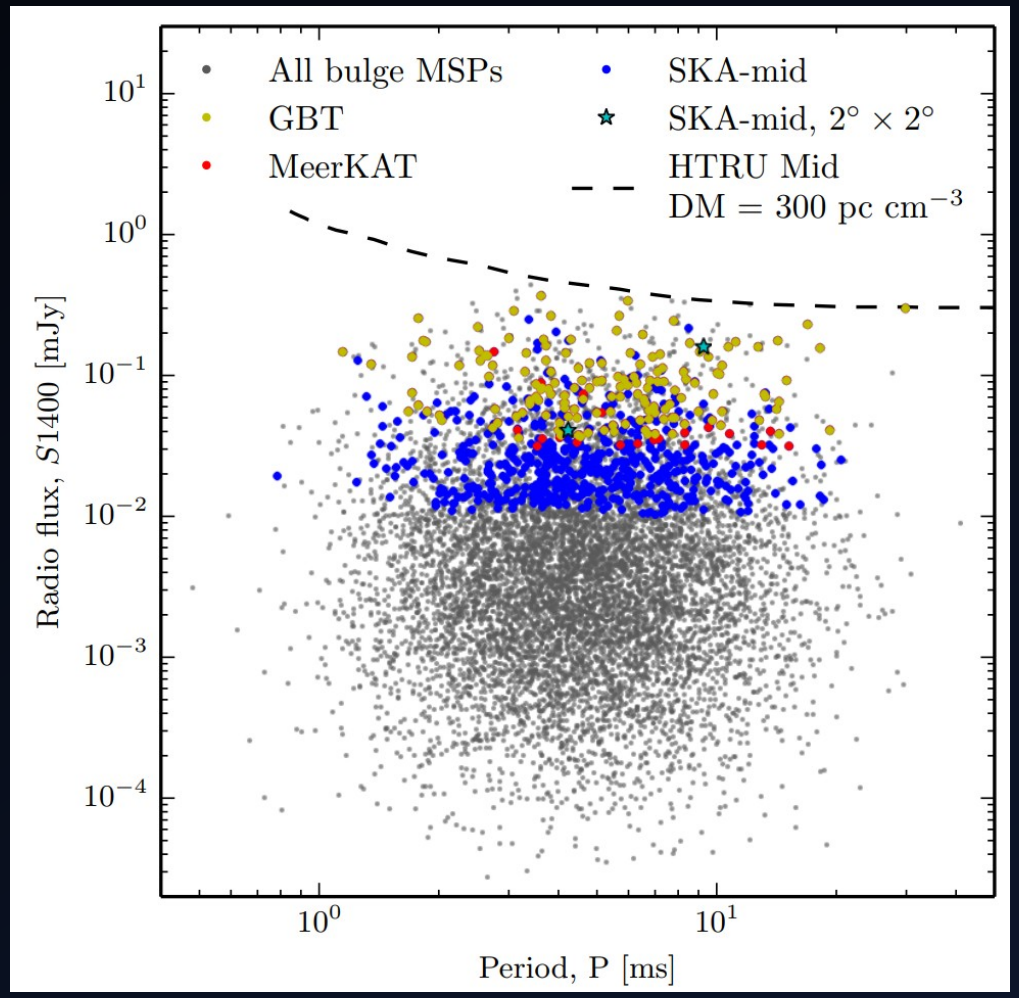
MOVING FORWARD:

DARK MATTER vs PULSARS

Rebecca Leane

PULSARS?

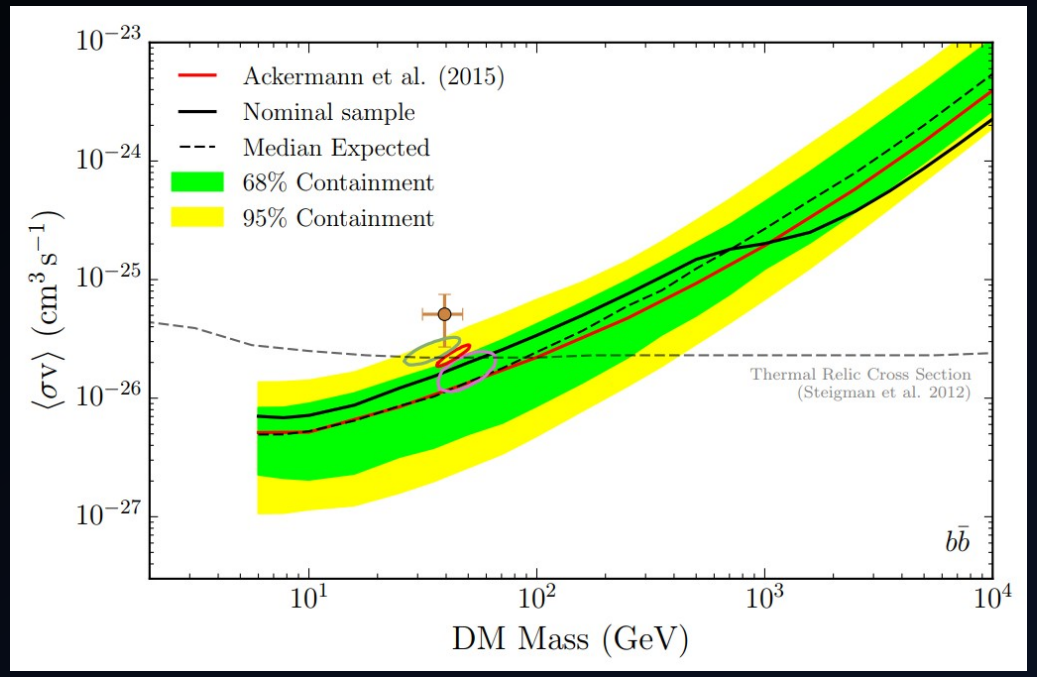
- Future detection of radio emission from pulsars by MeerKat and SKA



Calore+, ‘15

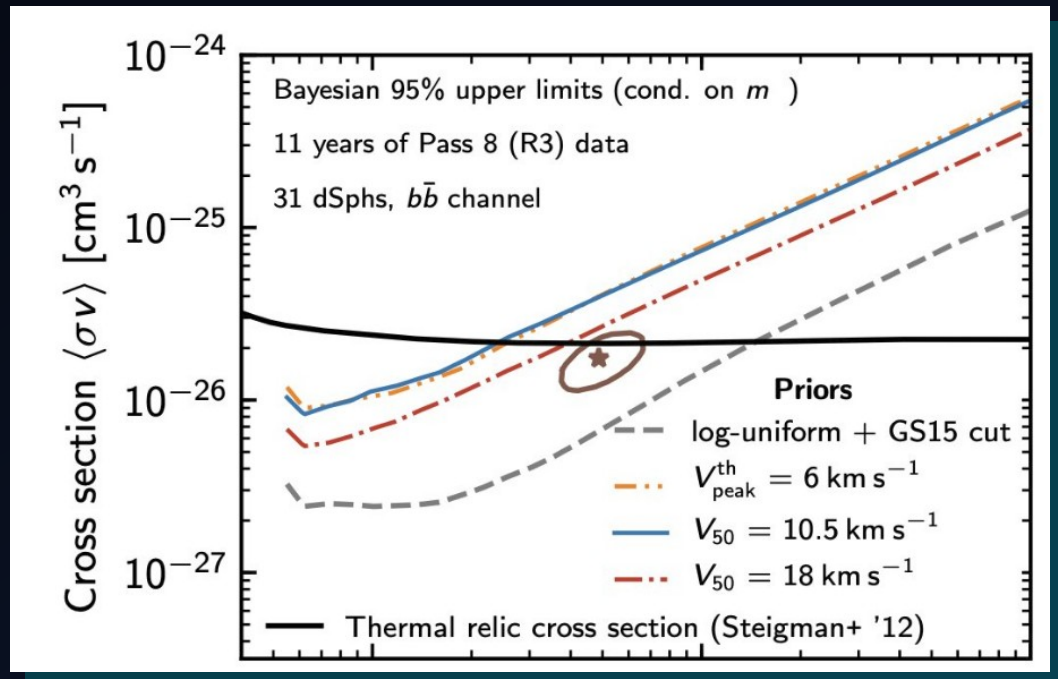
DARK MATTER: WANT A SIGNAL ELSEWHERE

- Dwarf spheroidal observations ideal
- No tension with GCE at the moment, though if the GCE really is DM, signal likely should appear soon



Ackermann+, ‘16

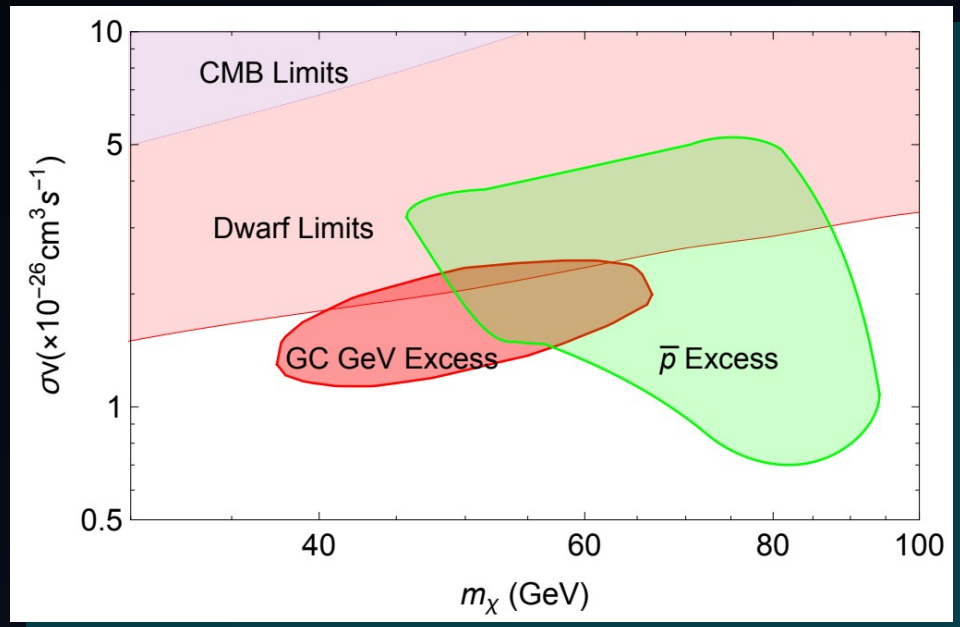
Ando+, ‘20



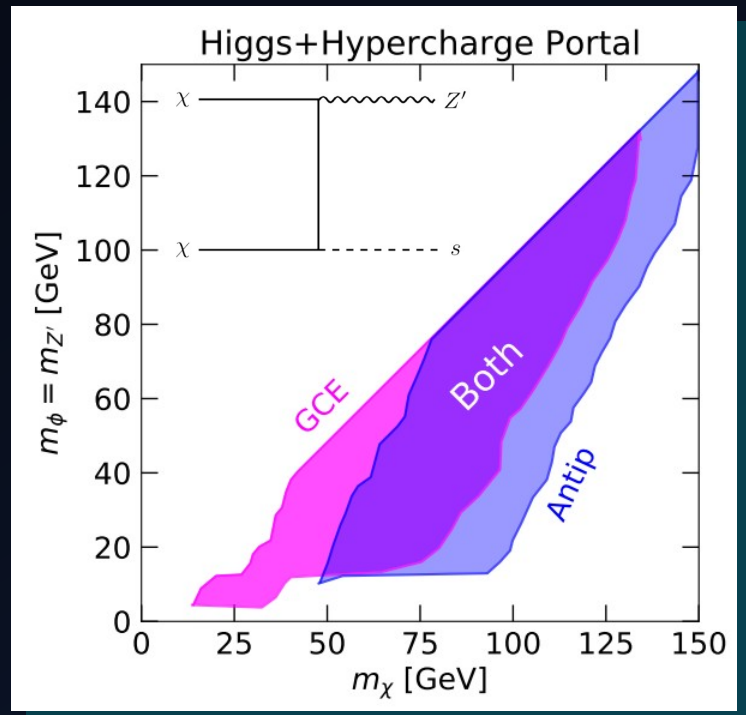
DM density uncertainties weaken limits further

SIGNAL ALREADY ELSEWHERE?

- Antiproton excess measured by cosmic-ray experiment AMS overlaps with GCE, though potentially only systematics
- Can be accommodated by fairly minimal models, not ruled out by collider or direct detection constraints



Cholis+, ‘19



Hooper, RL, Tsai, Wegsman, Witte ‘19

OTHER AVENUES

- Energy spectrum: systematics large for Fermi below a GeV, which is where pulsars and dark matter differ most!
  - Measurements with MeV gamma-ray telescopes can shed light
- Machine learning: List+’20 finds smooth GCE preference
- Better measurements of dark matter density with Gaia
- Better diffuse models!

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
  - Unmodeled asymmetries, or mismodeling more broadly might produce spurious point source signals
  - 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...

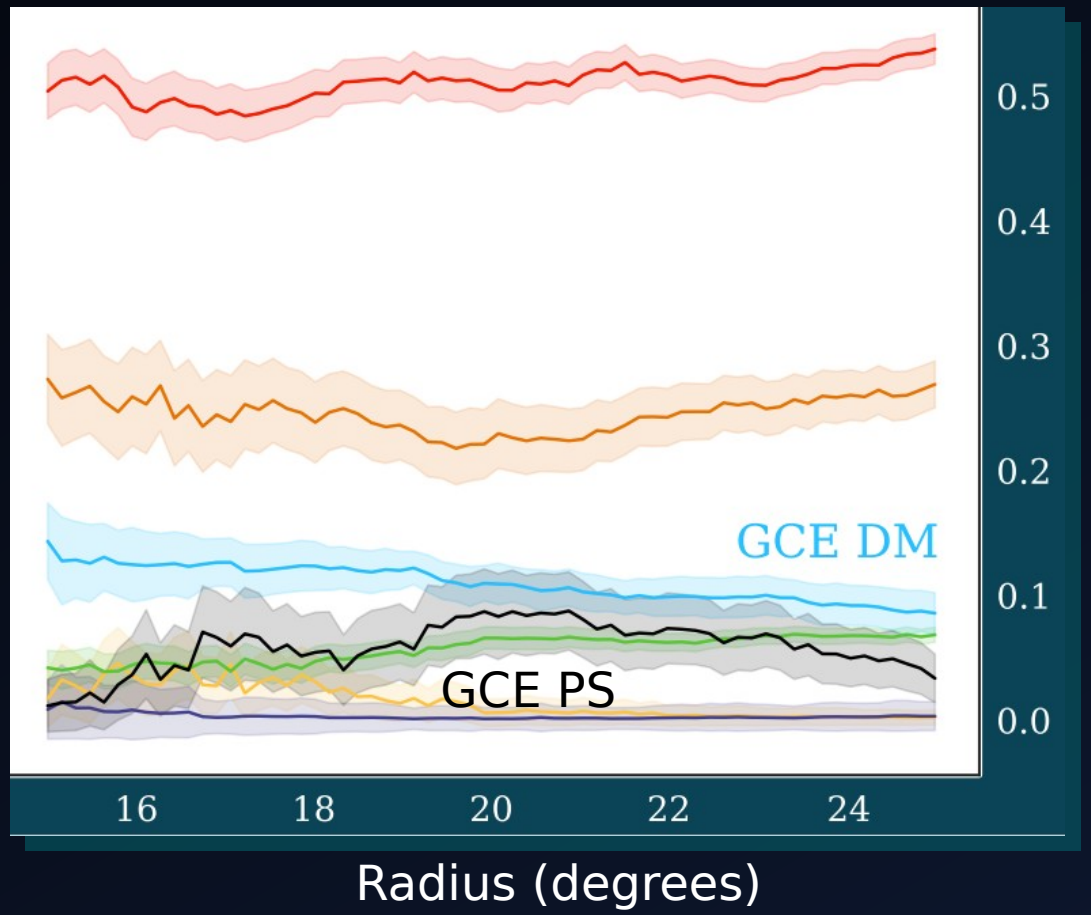
EXTRA SLIDES

Rebecca Leane

ALTERNATE FITTING METHOD

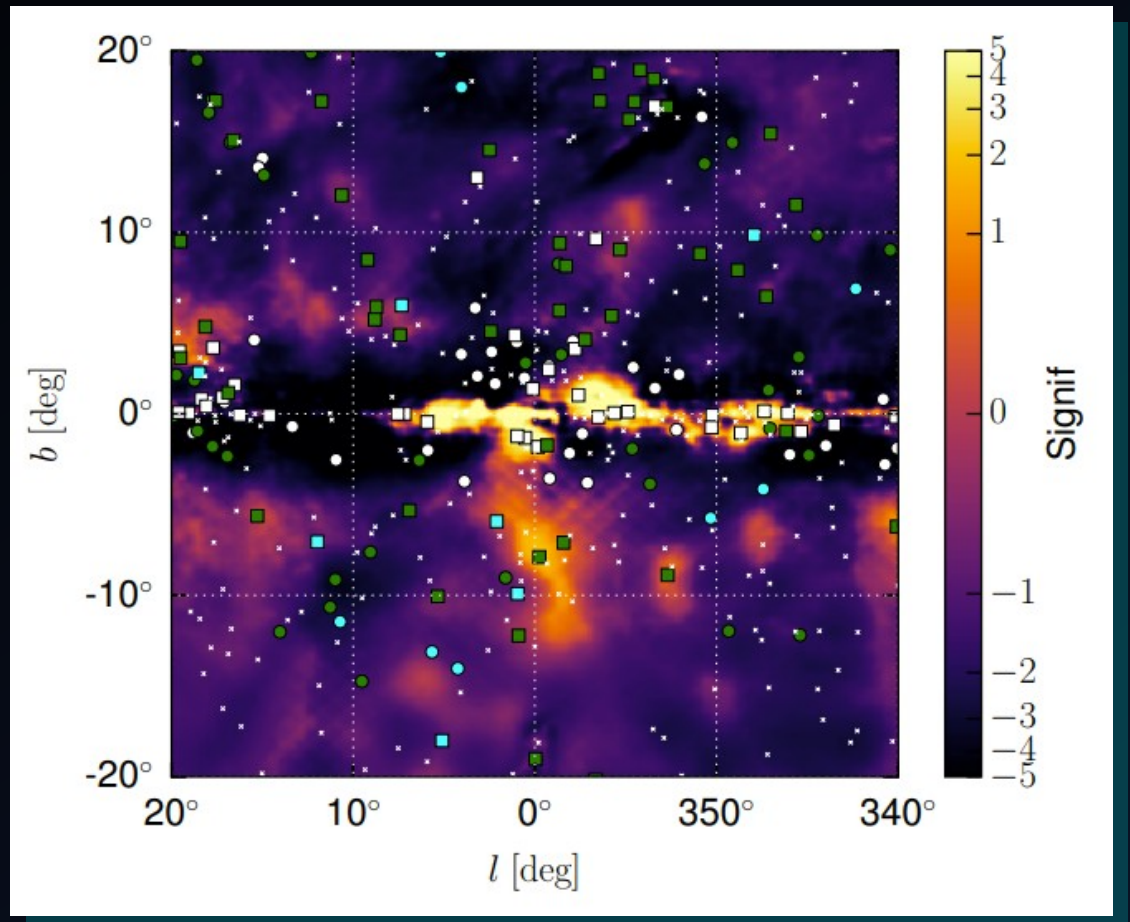
- Train neutral networks on simulated datasets
- Finds same GCE flux fraction as non-Poissonian template fitting, but finds smooth GCE!
- Complementary handle on systematics

List+, ‘20



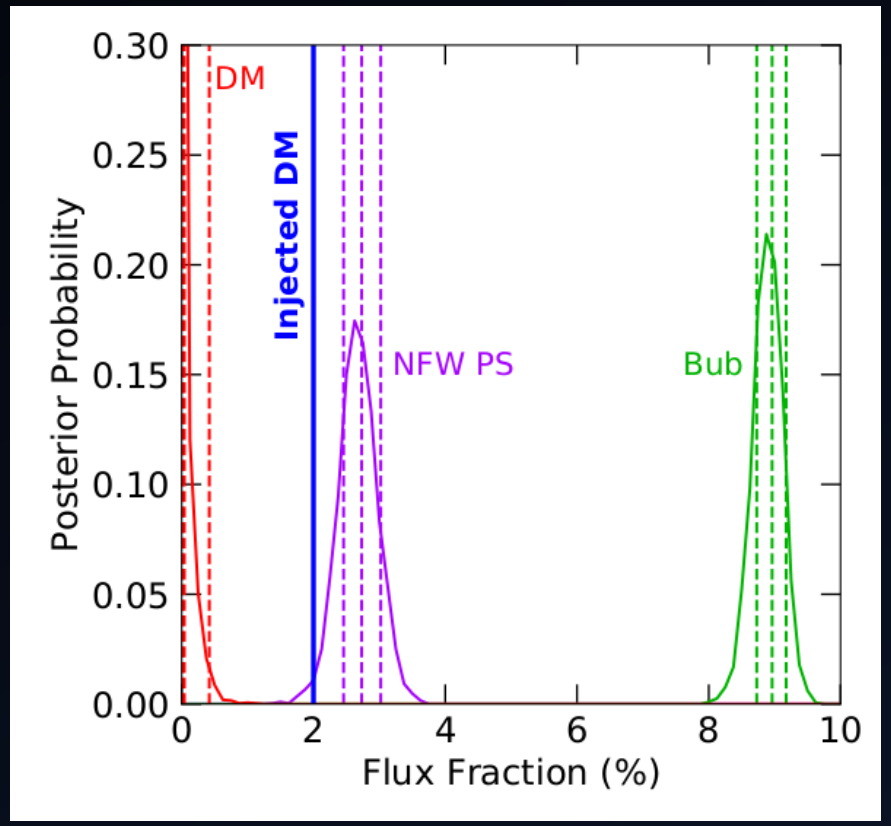
SYSTEMATICS: POINT SOURCE ID?

Fermi Collaboration '17



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

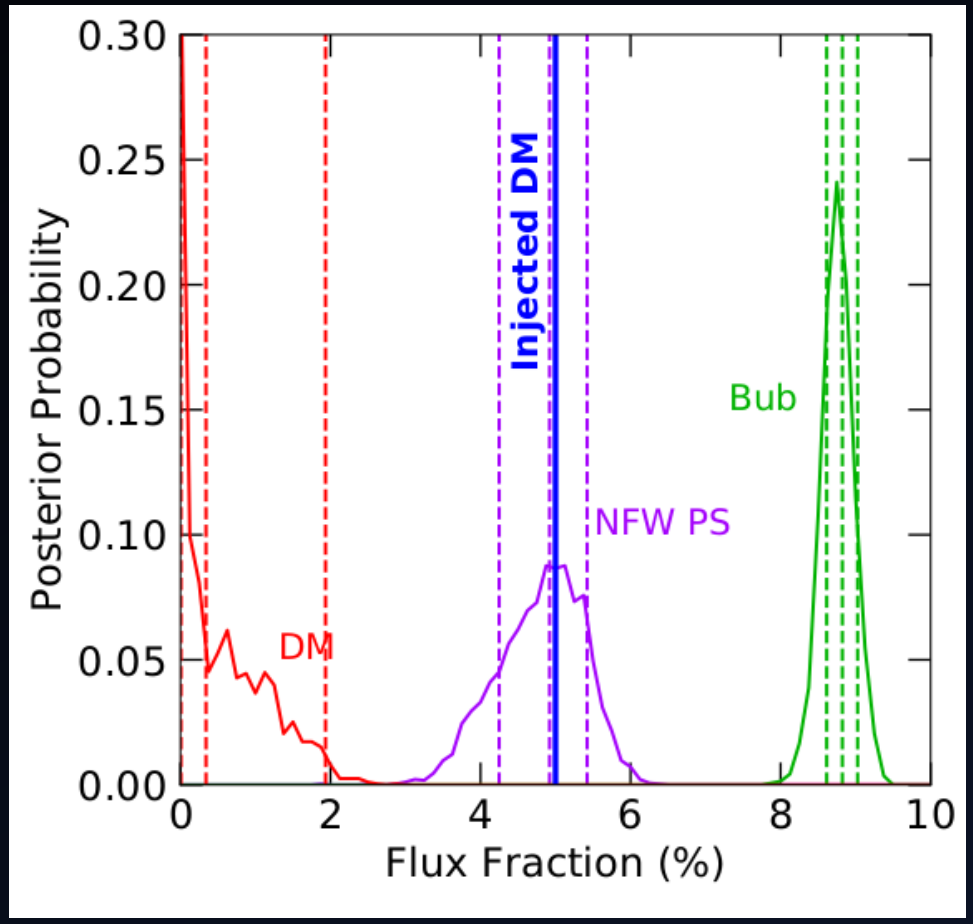
What if we now instead analyze the data with NFW distributed PS instead of the PS bubbles?



The dark matter signal is misattributed to point sources!

RL+Slatyer (PRL ‘19)

Add even more….



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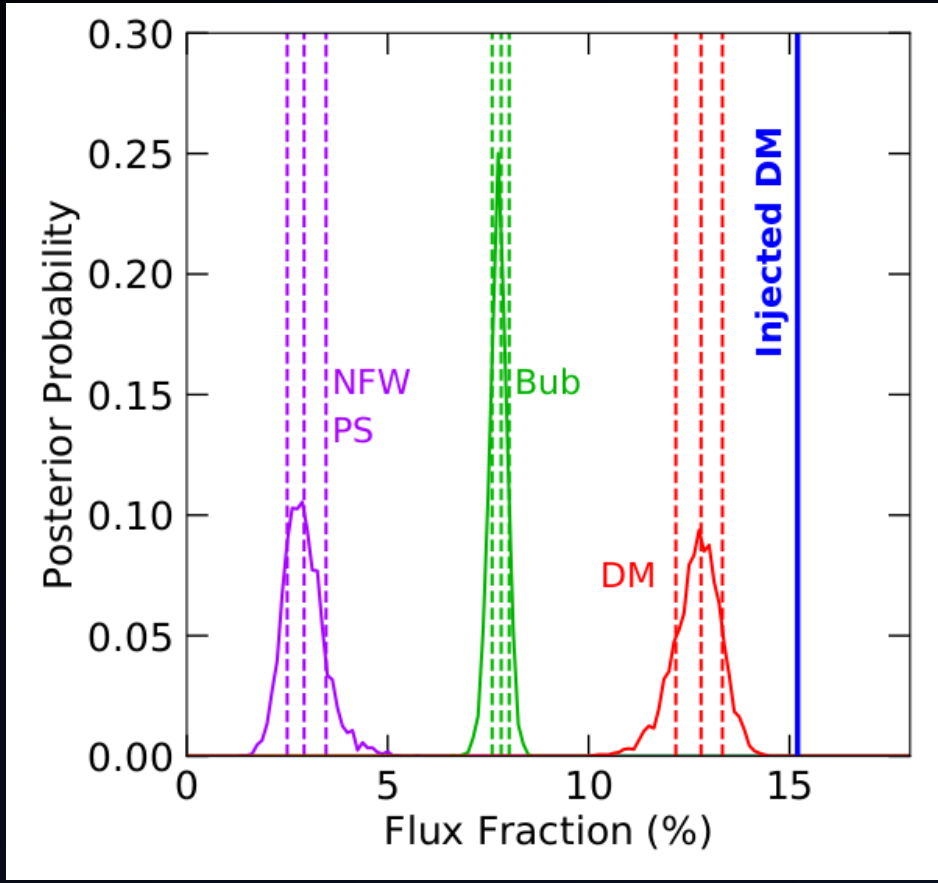
IS THERE A THRESHOLD IN SIMULATIONS?

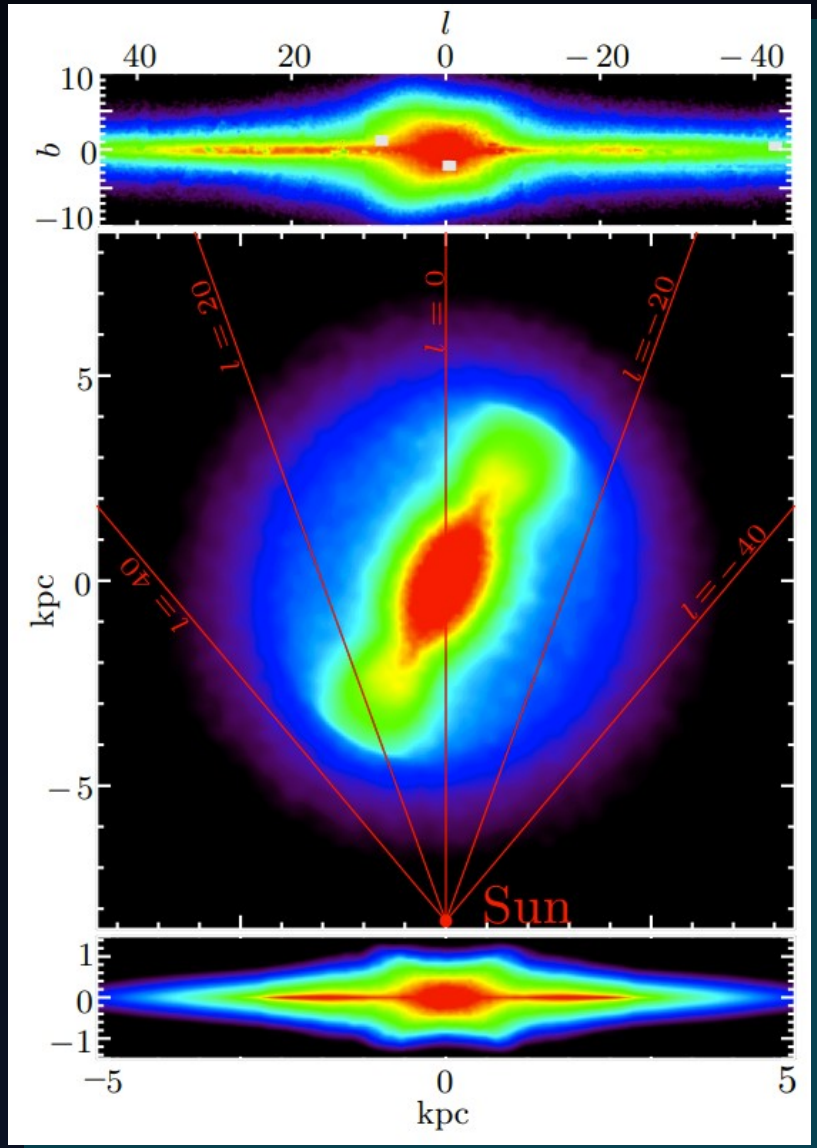


Inject an order of magnitude more DM (~15%)

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

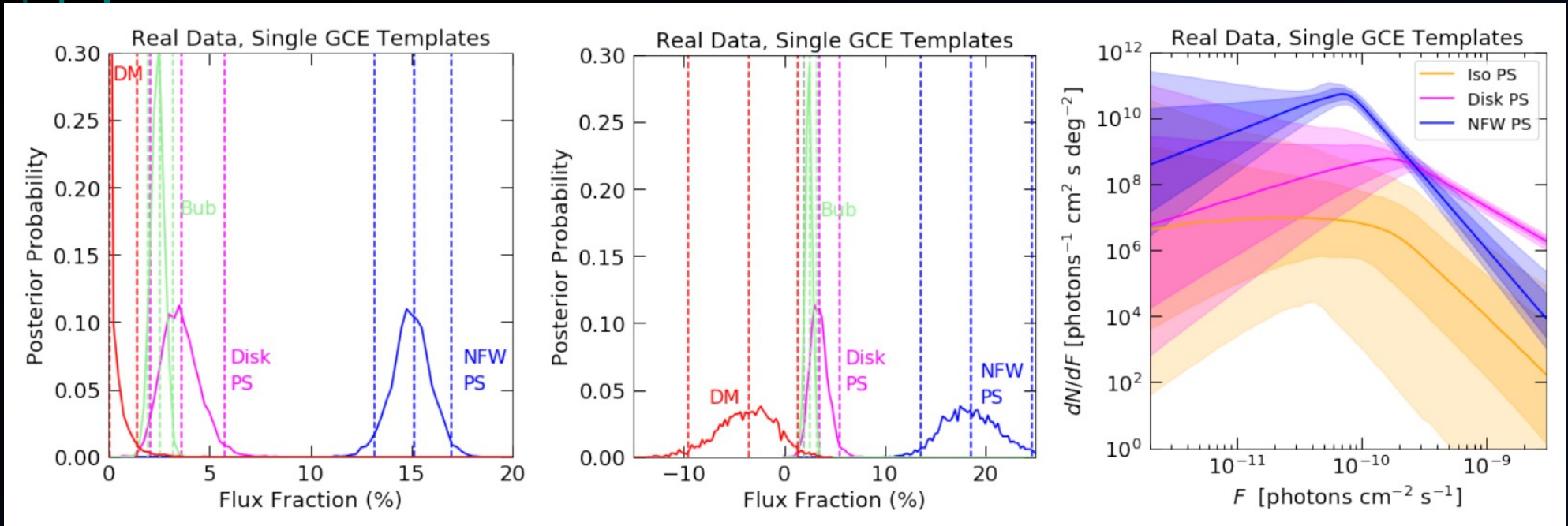
RL+Slatyer (PRL ‘19)

BULGE SHAPE



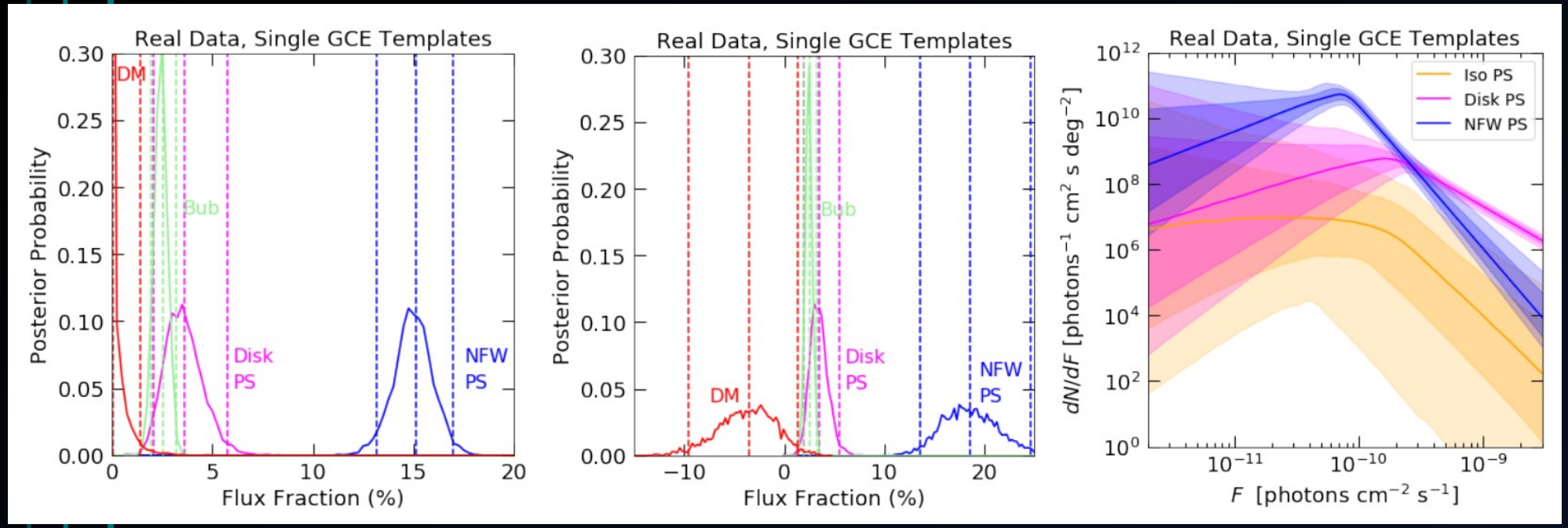
Bland-Hawthorn, Ortwin Gerhard ‘17

RL+Slatyer ’20



Real data, one excess template

RL+Slatyer '20



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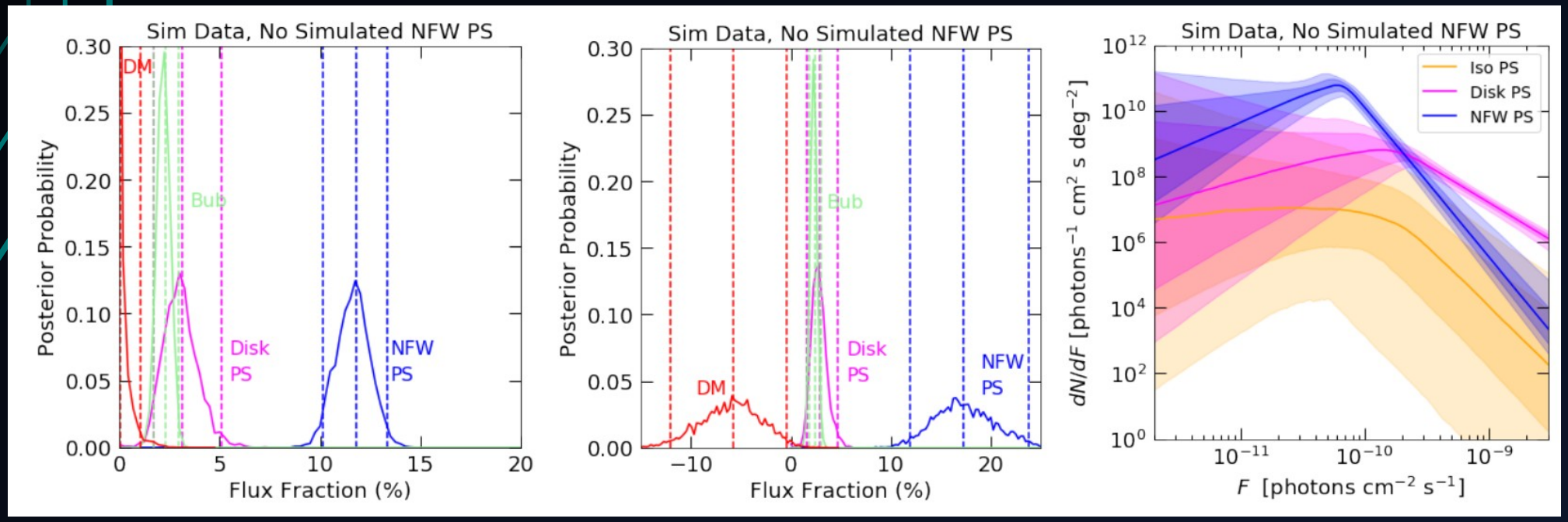

Simulated asymmetry, analyzed with one excess template

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:

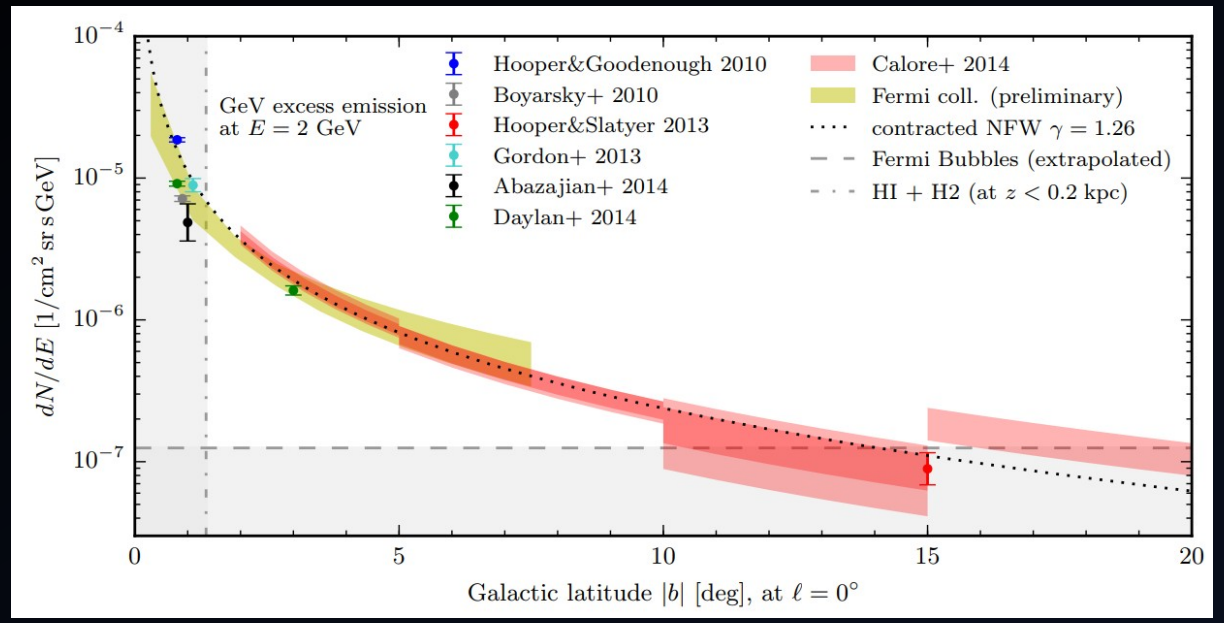
Claimed point source evidence for the GCE is not robust

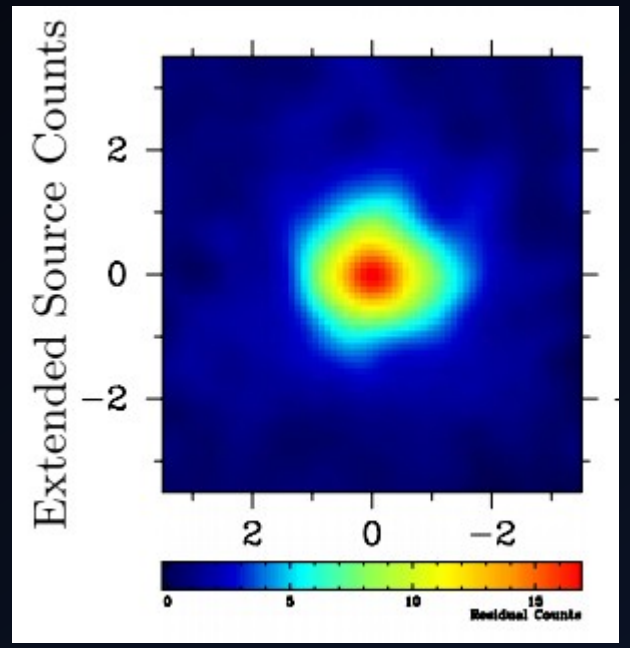
Leane+Slatyer, '20

Leane+Slatyer, '20

MORPHOLOGY

Calore et al ‘14



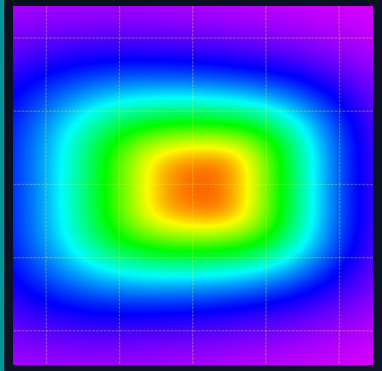


Abazajian+ Kaplinghat ‘12

Spherically symmetric around Galactic Center

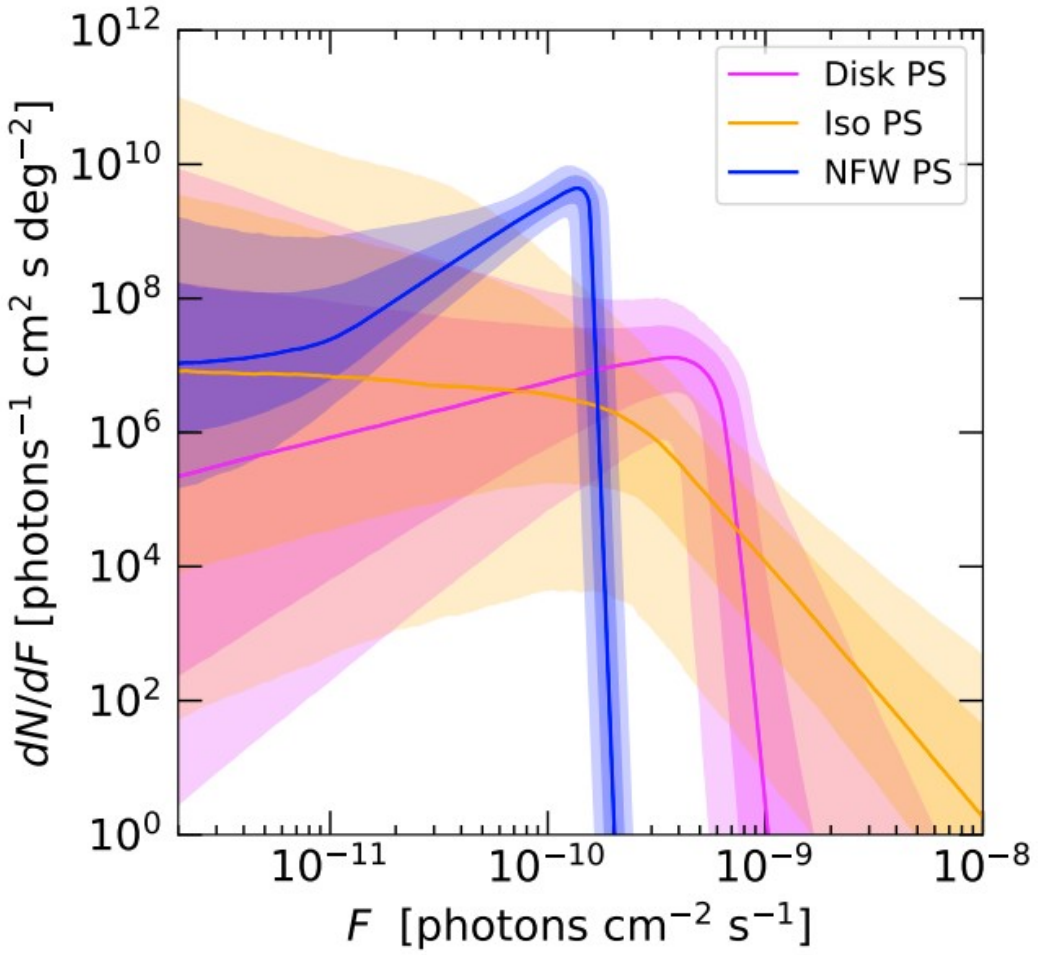
Scales like $r^{-2.4}$ extending out to around 10°, roughly fits standard dark matter (NFW) profile

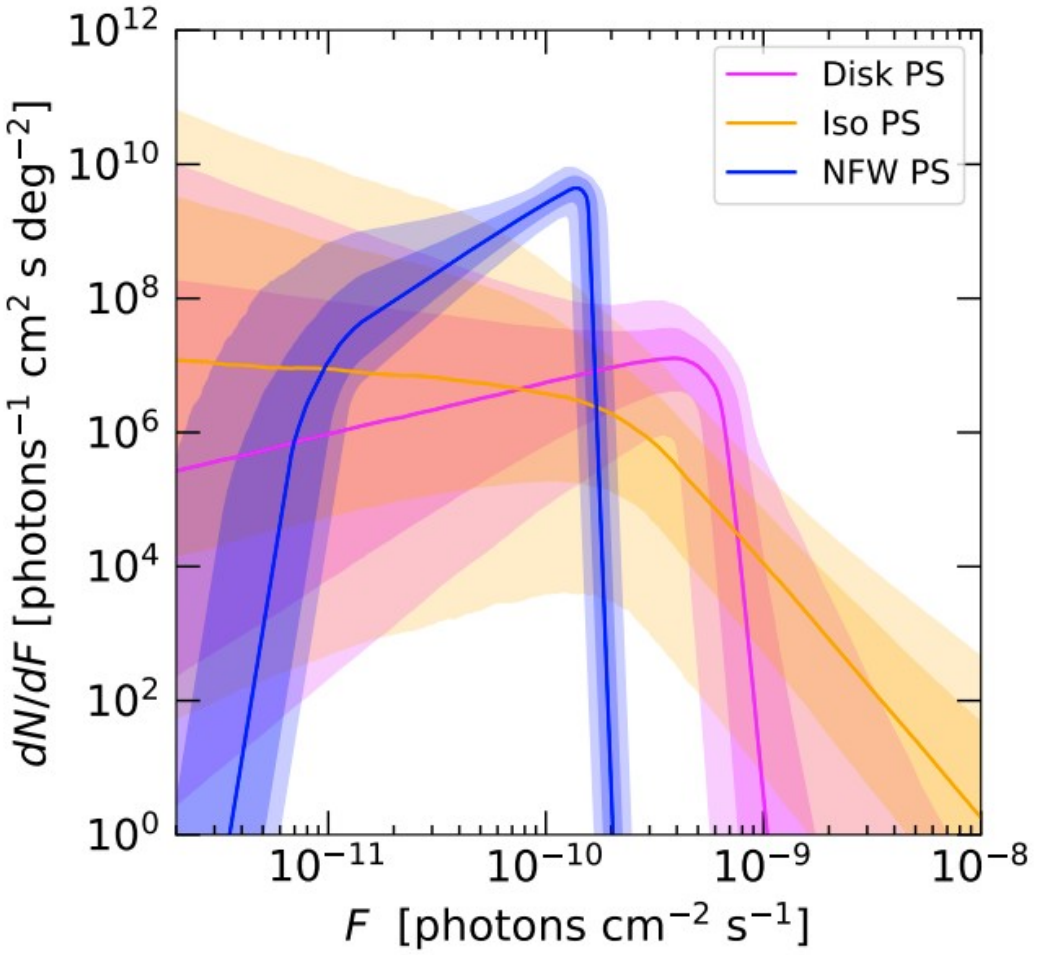
Hooper+Slatyer ‘13



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}]


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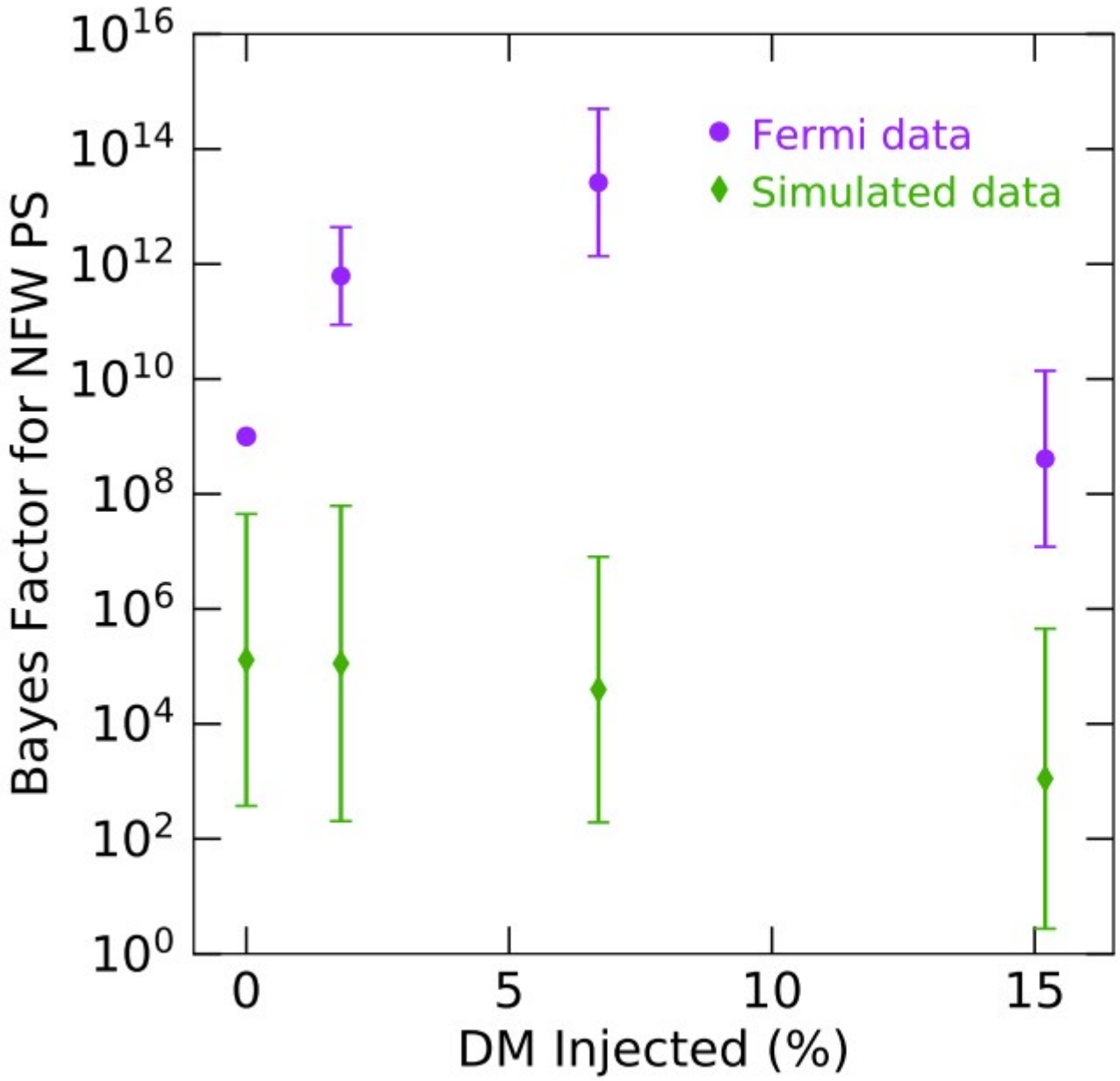
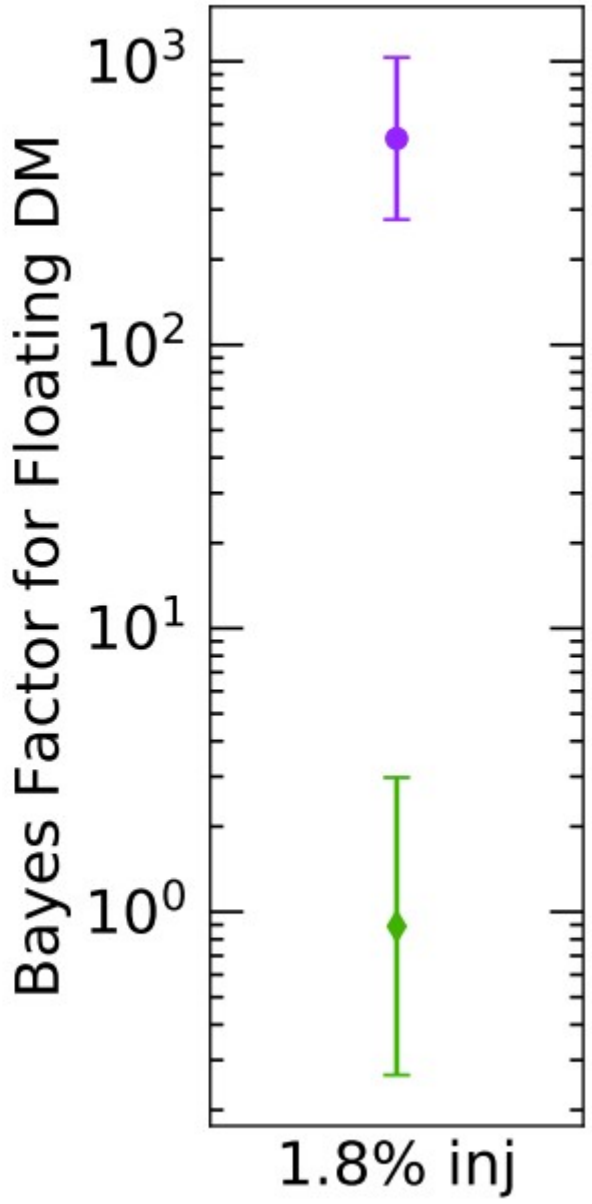
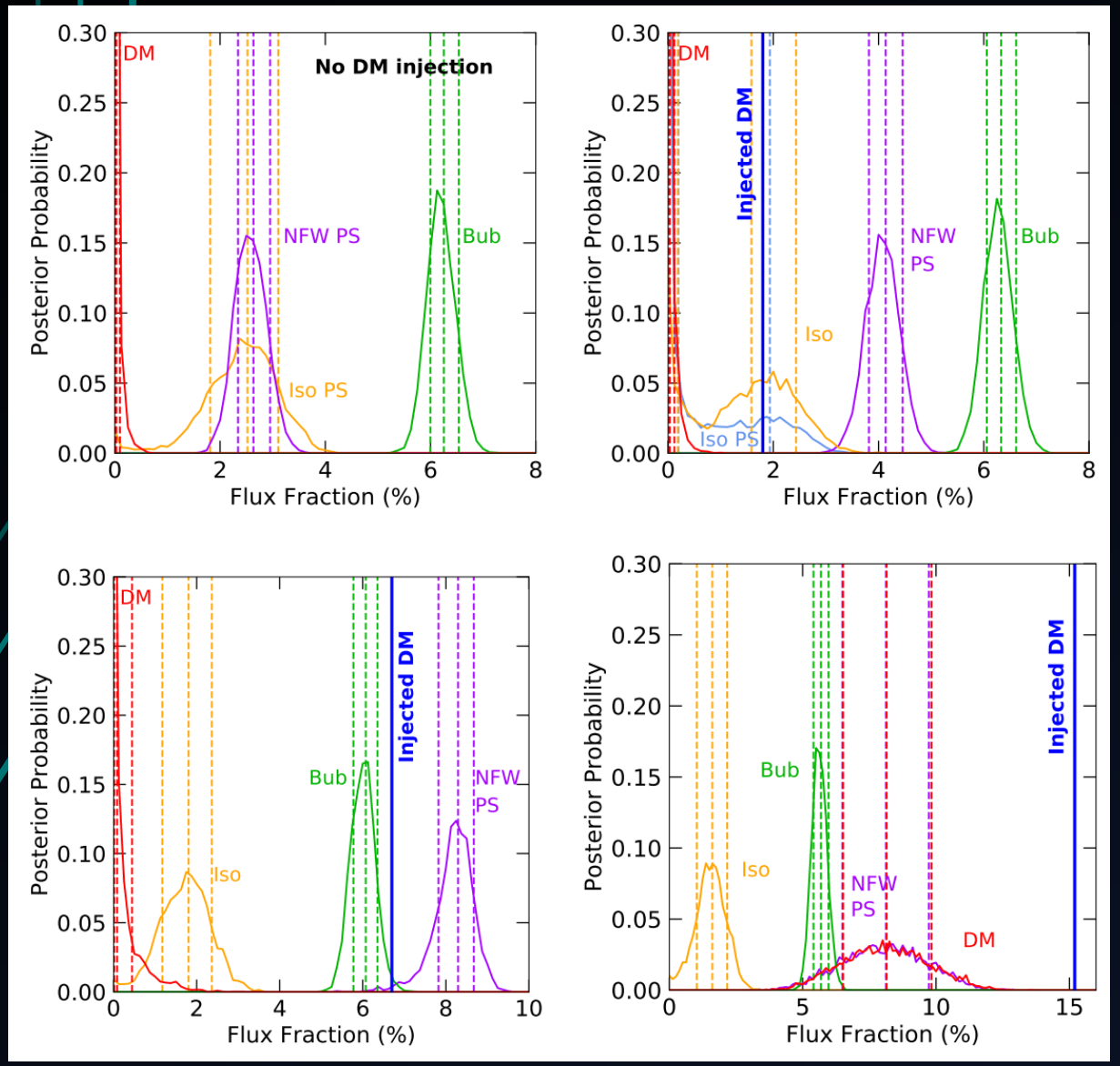
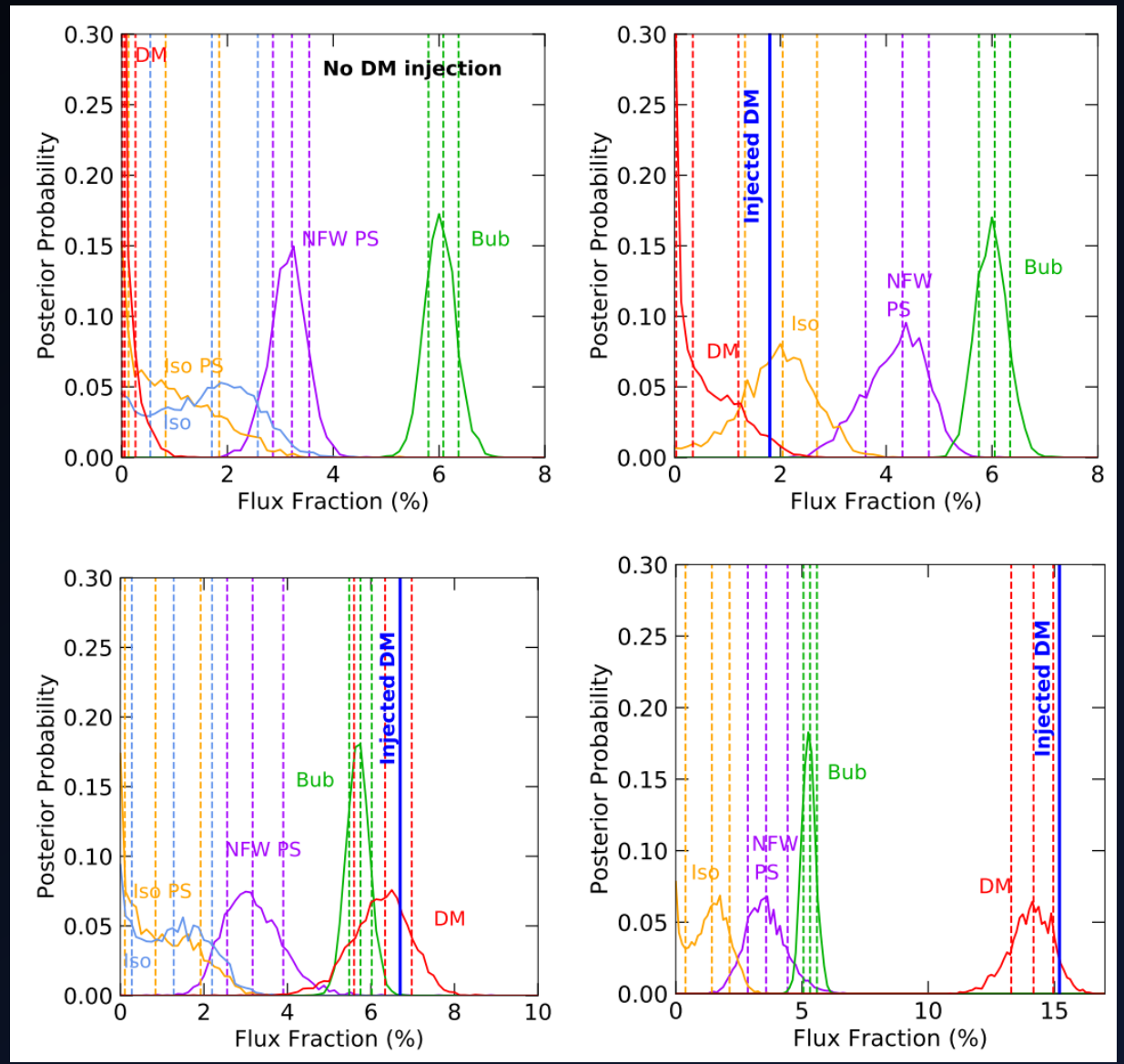
dN/dF [photons^{-1} cm^{2} s deg^{-2}]
10^{-11}
10^{-10}
10^{-9}
10^{-8}
F [photons cm^{-2} s^{-1}]


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