CNP Research Day, May 10th 2019

Bulge-correlated gamma rays

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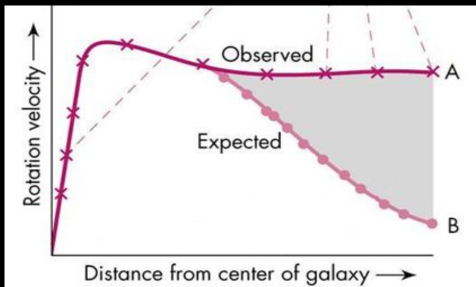
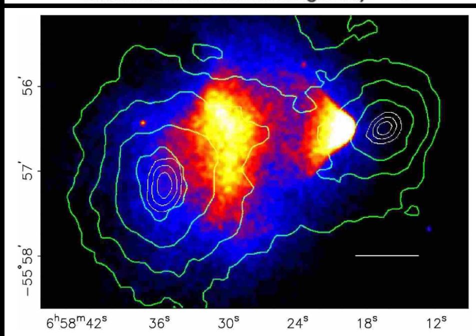
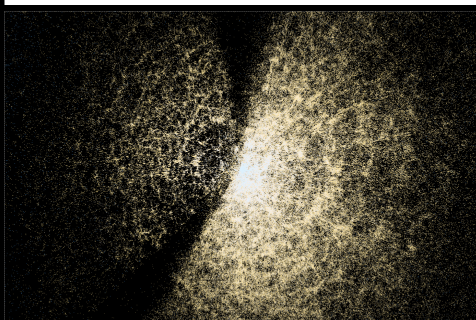
Dark matter: evidence & questions



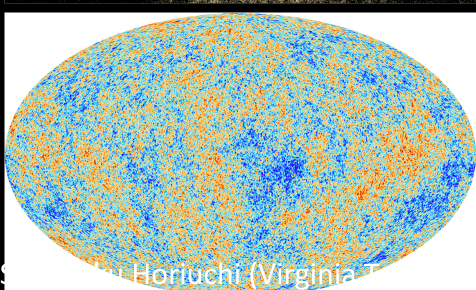
Galaxy rotation curves



Galaxy clusters

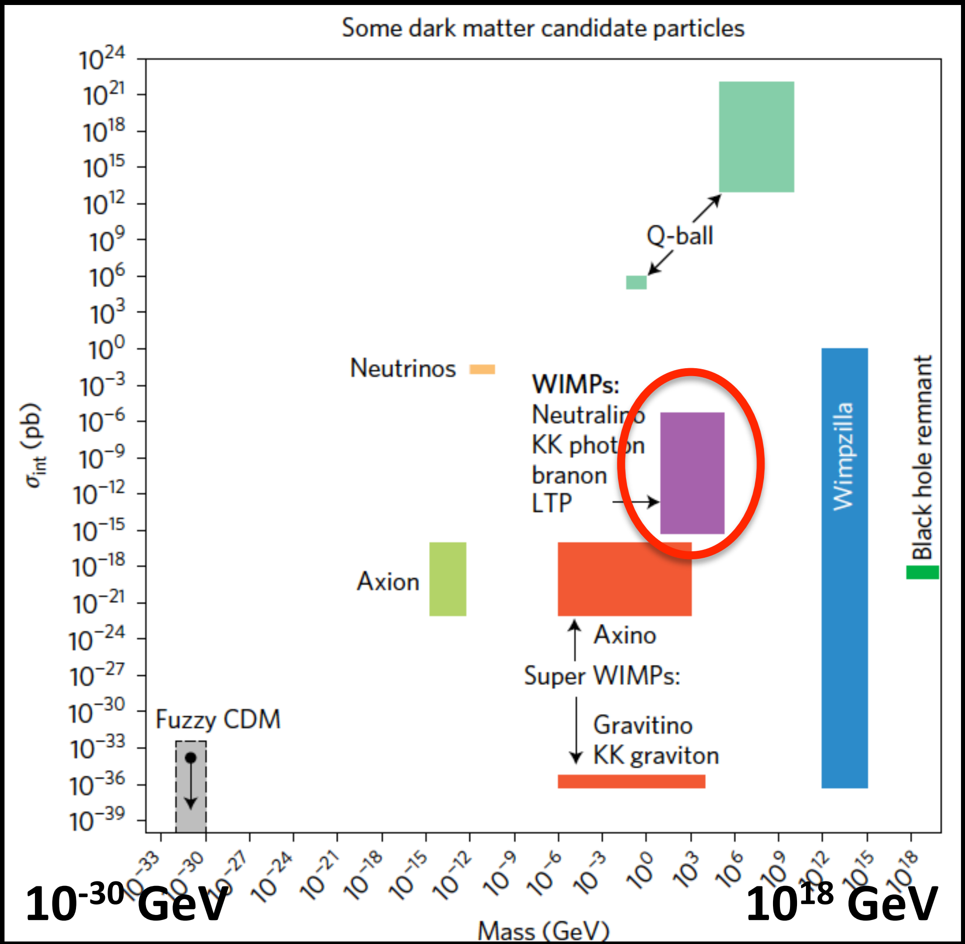


Large scale structure



CMB

The landscape of potential DM particles:



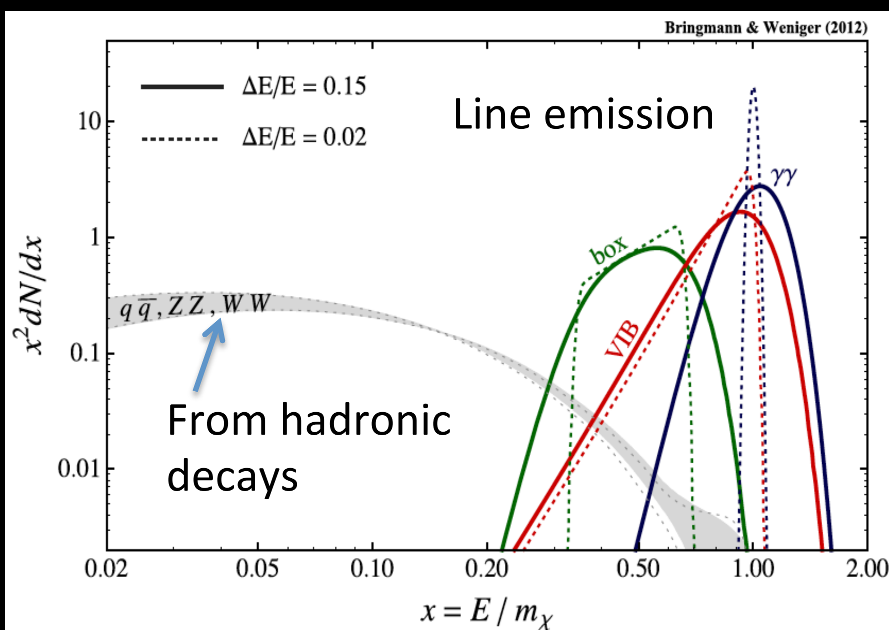
- Input from theory helps define better searches
- Theory is prejudiced by what can be probed by existing / upcoming data

Dark matter gamma-ray emissions

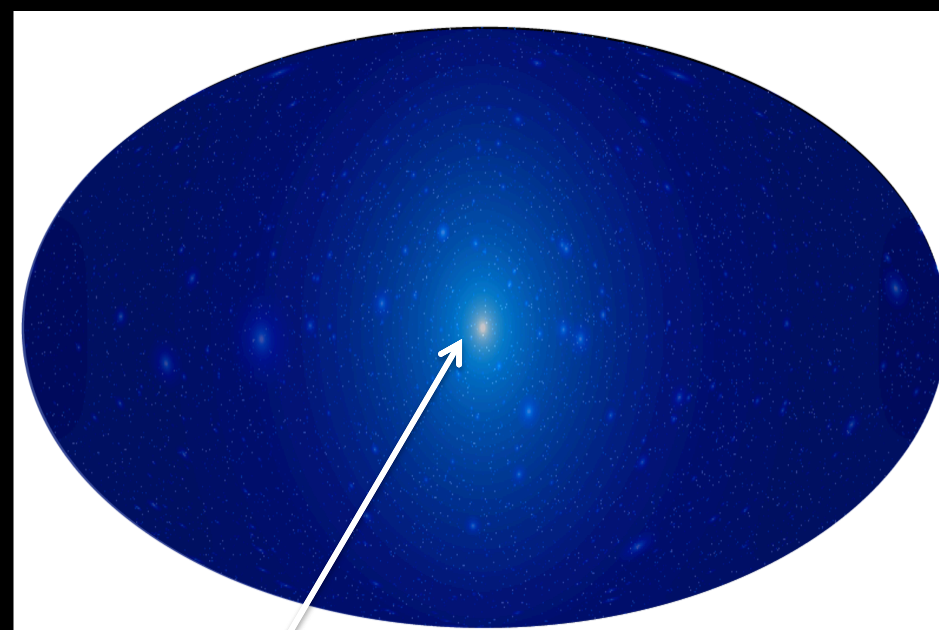
Gamma-ray flux from annihilation of dark matter in the Milky Way halo:

$$\Phi(E,\psi) = \frac{\sigma_A v}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \int d\ell \, \rho \left[r(\ell,\psi)\right]^2$$

Spectral energy distribution per annihilation



Spatial distribution of density (squared)



Strong signal predicted from Galactic Center

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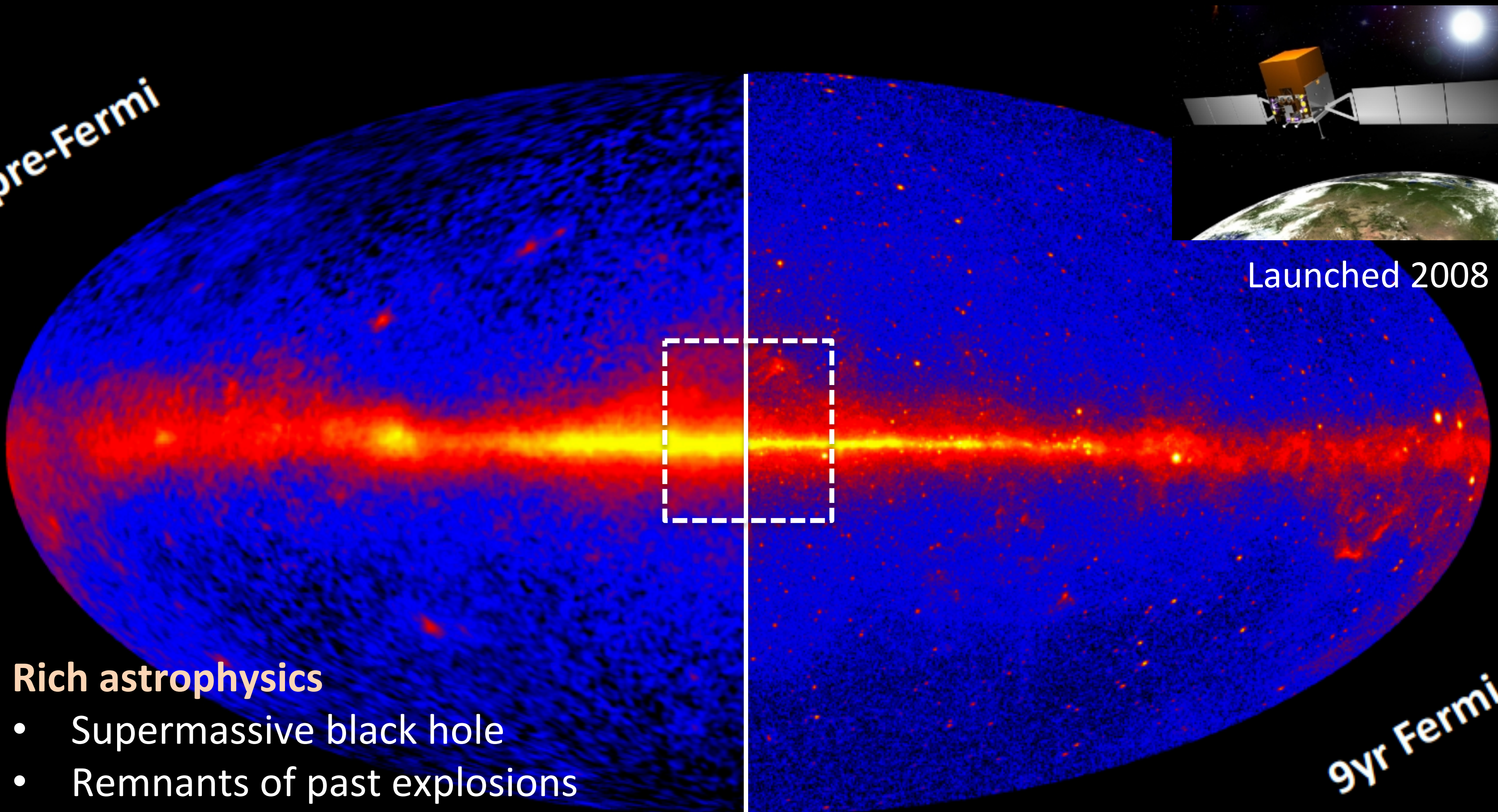
The Galactic Center

Fermi-LAT

Launched 2008



Rich astrophysics

- Supermassive black hole
- Remnants of past explosions
- Evidence for outflows
- Central star formation
- …a lot going on

Galactic coordinates

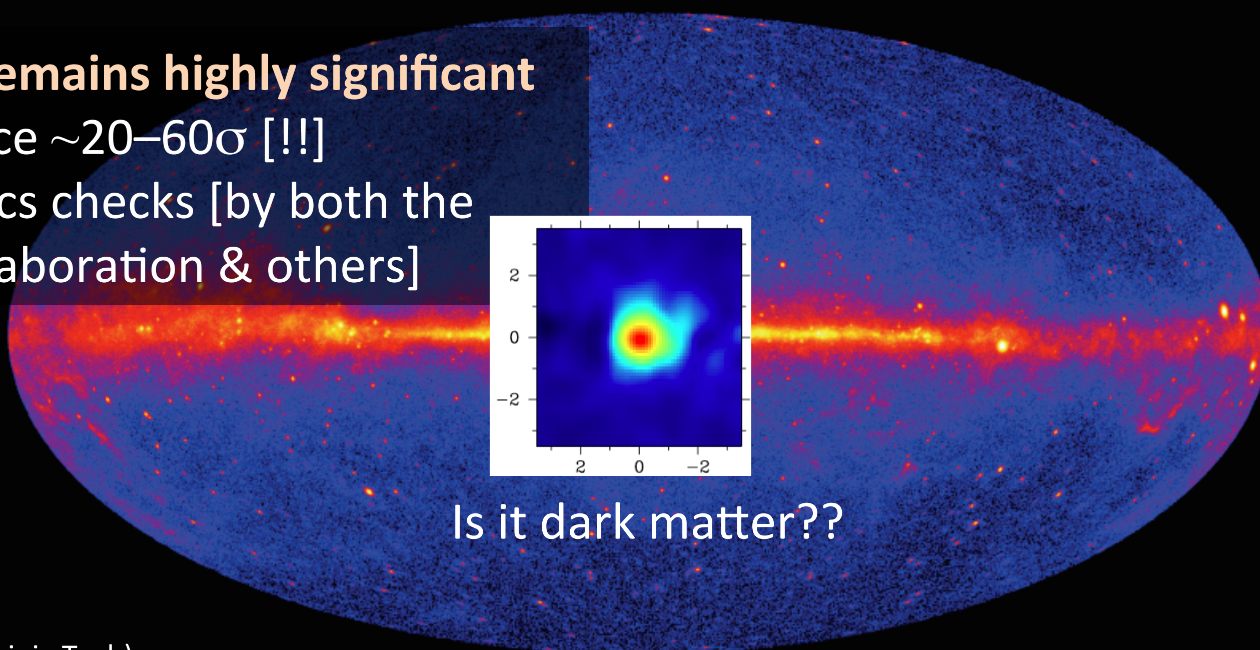
The GeV Galactic Center Excess

Long-lasting anomaly: there exists an excess of GeV photons in the Fermi-LAT data coming from the Galactic Center direction

Goodenough & Hooper (2009)
Vitale & Morselli (2009)
Hooper & Goodenough (2011)
Hooper & Linden (2011)
Boyarsky et al (2011)
Abazajian & Kaplinghat (2012)
Gordon & Macias (2013)
Macias & Gordon (2014)
Abazajian, Horiuchi, et al (2014)
Daylan et al (2014)
Selig et al (2015)
Abazajian, Horiuchi, et al (2015)
Cholis et al (2015)
Gaggero et al (2015)
Carlson et al (2016)
Bartels et al (2016)
Lee et al (2016)
Fermi Coll. (2016)
Kwa, Horiuchi, Kaplinghat (2016)
Horiuchi et al (2016)
Linden et al (2016)
Huang et al (2016)
Ajello et al (2017)
Ackermann et al (2017)
Ajello et al (2018)
Macias et al (2018)
Bartels et al (2018)
…etc…

The excess remains highly significant

- Significance $\sim$20–60σ [!!]
- Systematics checks [by both the Fermi collaboration & others]



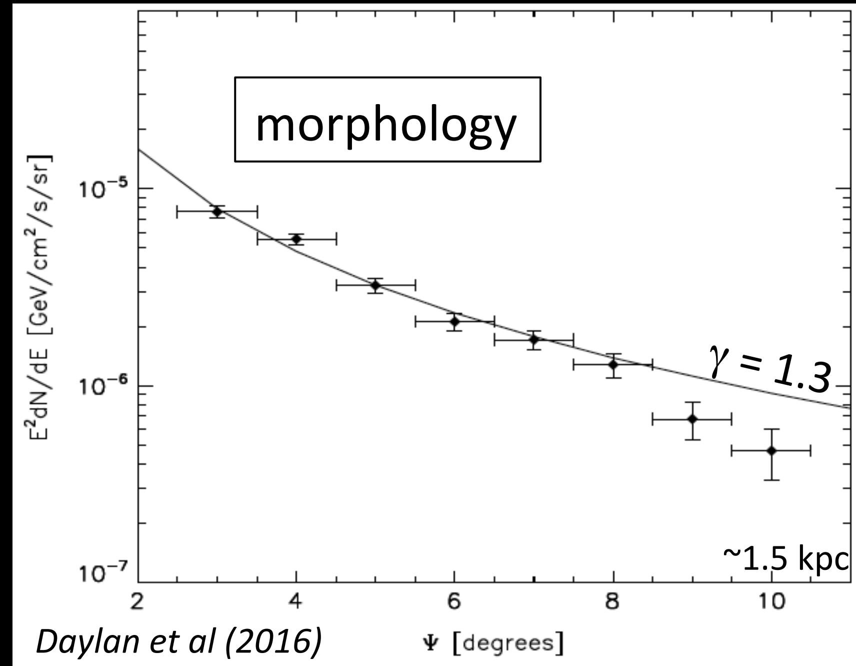
Is it dark matter??

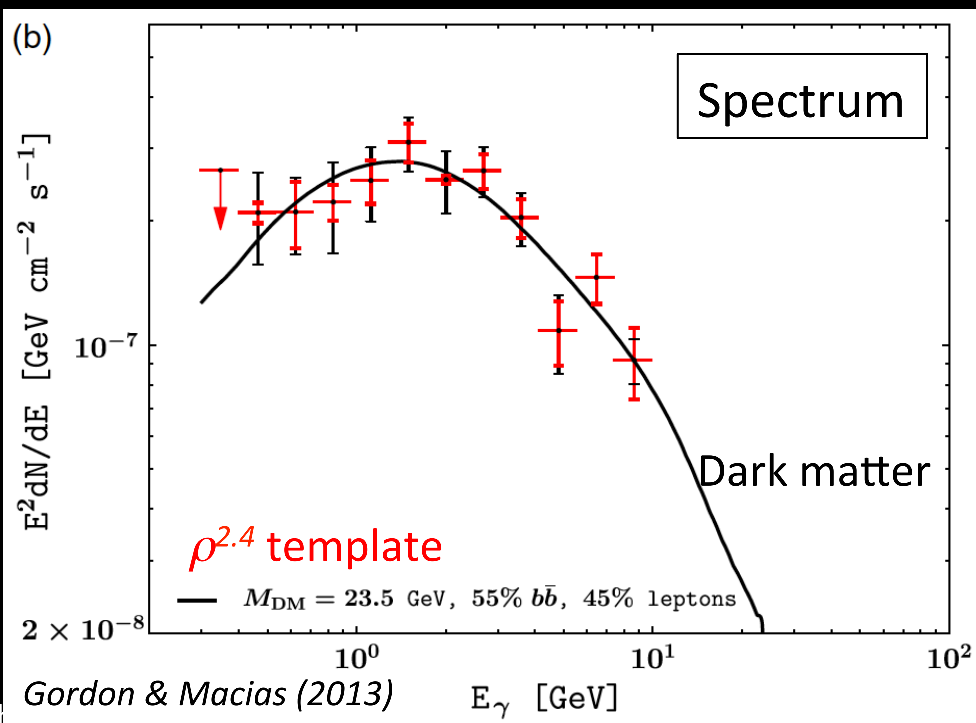
Is it dark matter?

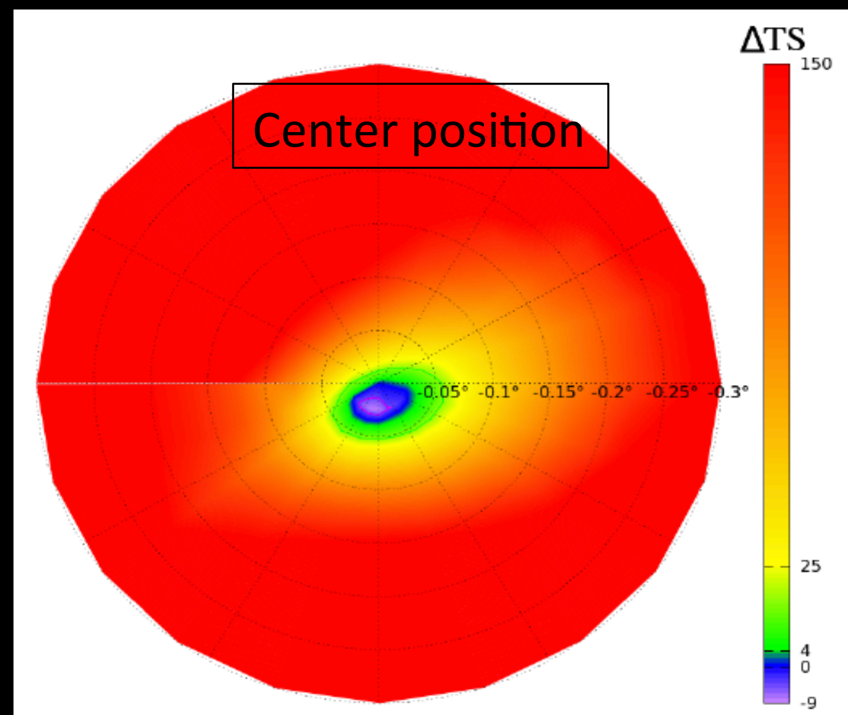
Consistent with dark matter

- Spectrum consistent with thermally produced dark matter annihilations
- Spatial morphology consistent with dark matter (e.g., radial profile, central position, angular deformations)

➔ **Hundreds of papers**



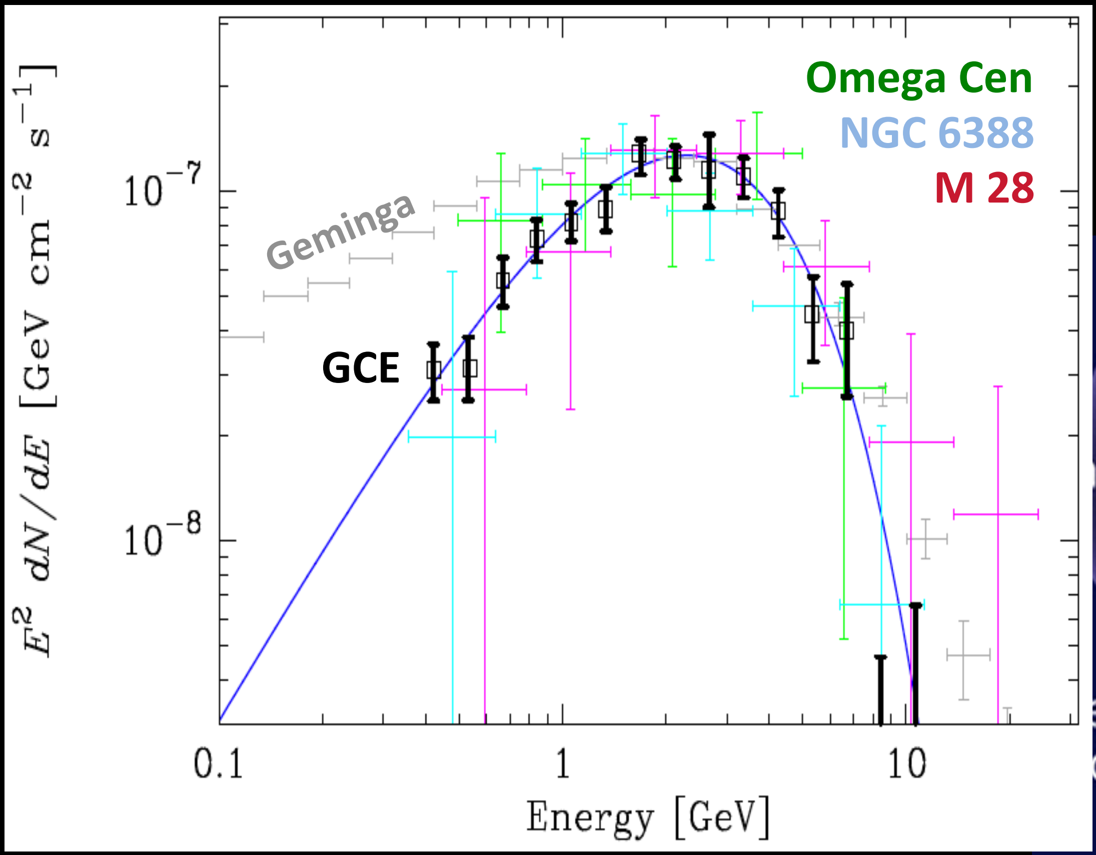




Is it millisecond pulsars?

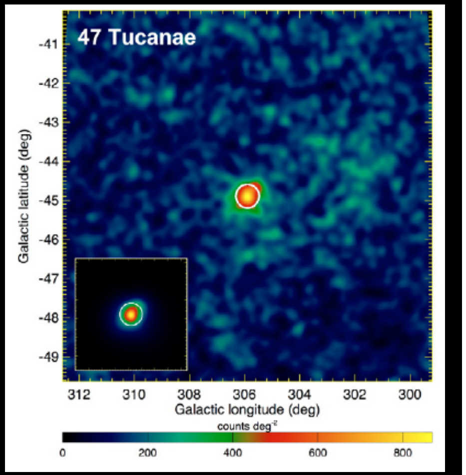
Millisecond pulsars

- Millisecond pulsars are gamma-ray sources with similar spectra to the GCE.
- *O*(5,000) needed in the Galactic Center

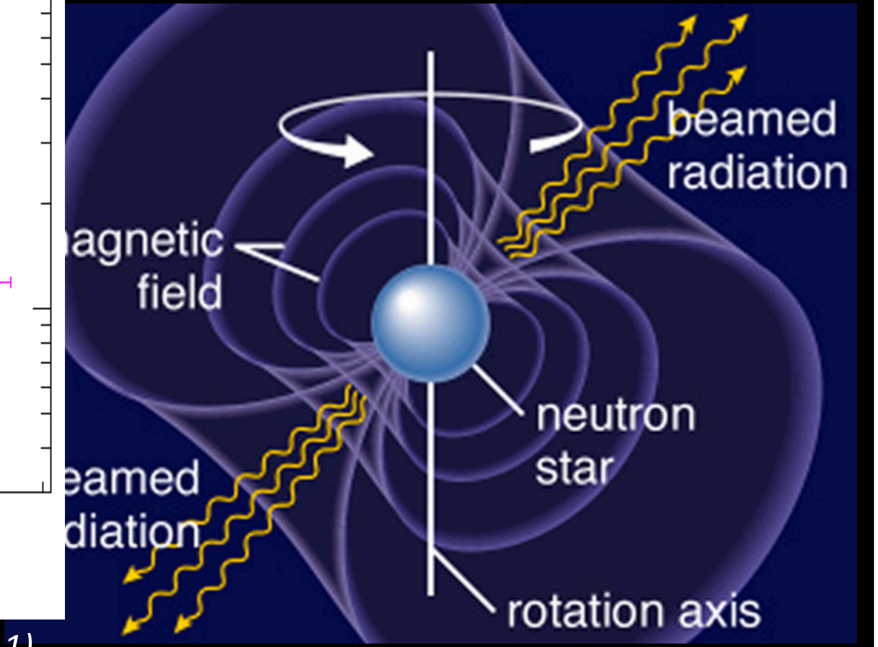


Abazajian (2011)

Globular clusters detected in gamma rays



Fermi (2010)



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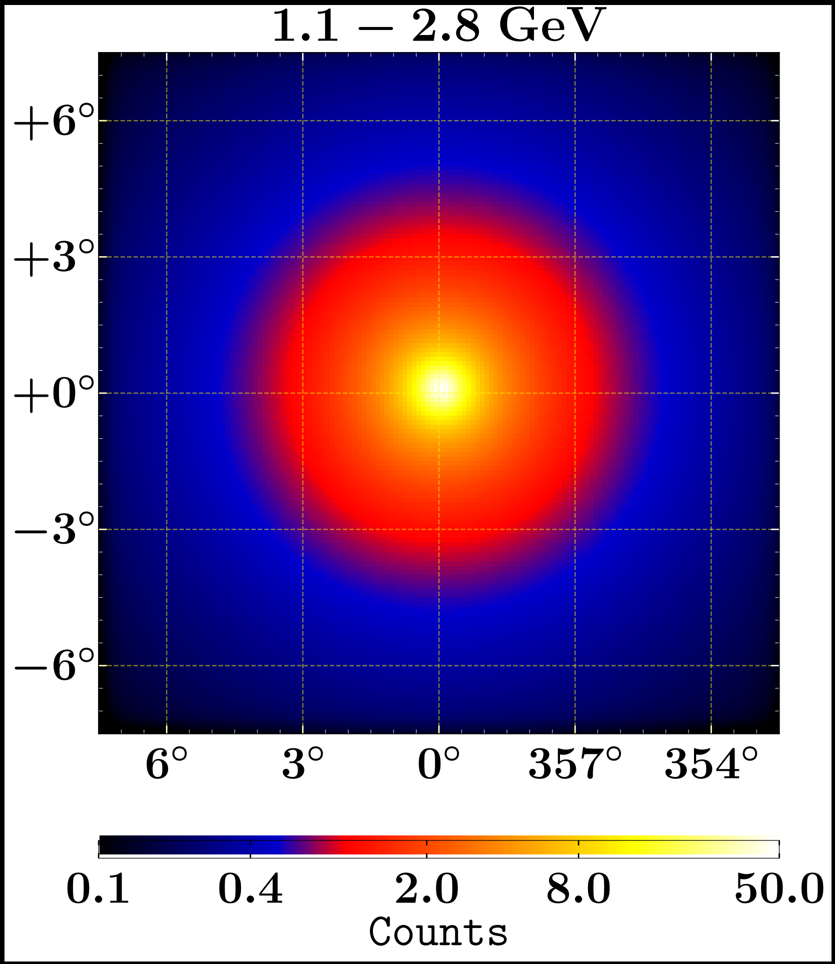
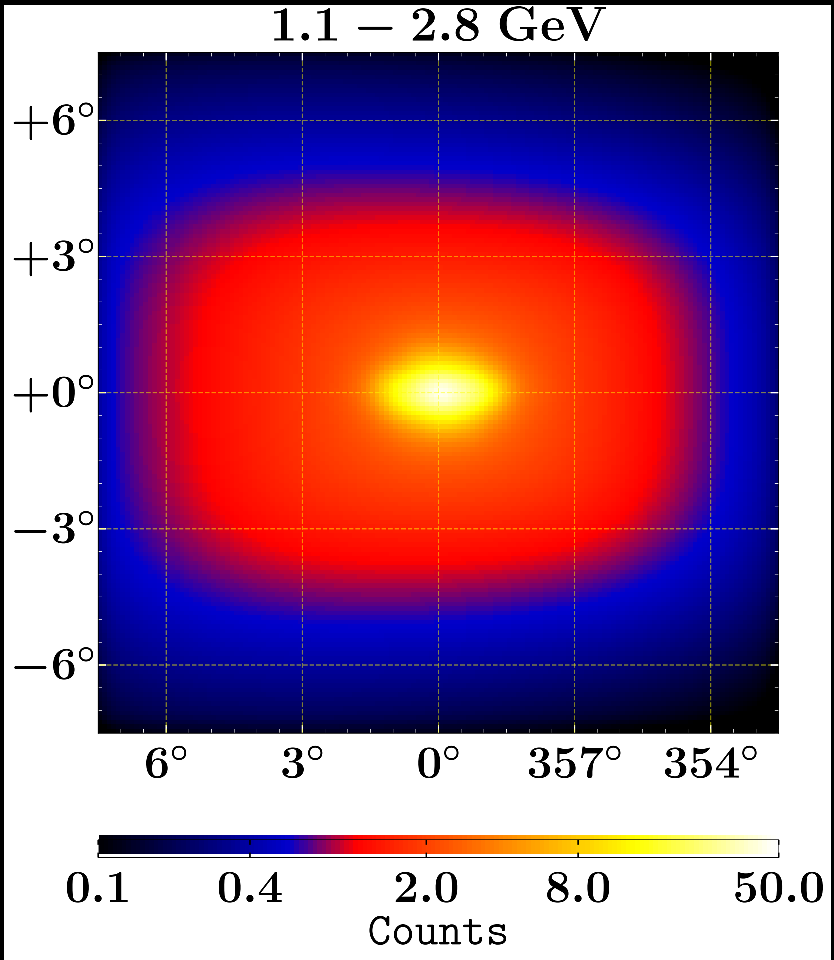
spherical symmetry vs bulge shape

Dark matter annihilation



VS

Astrophysics (pulsar)



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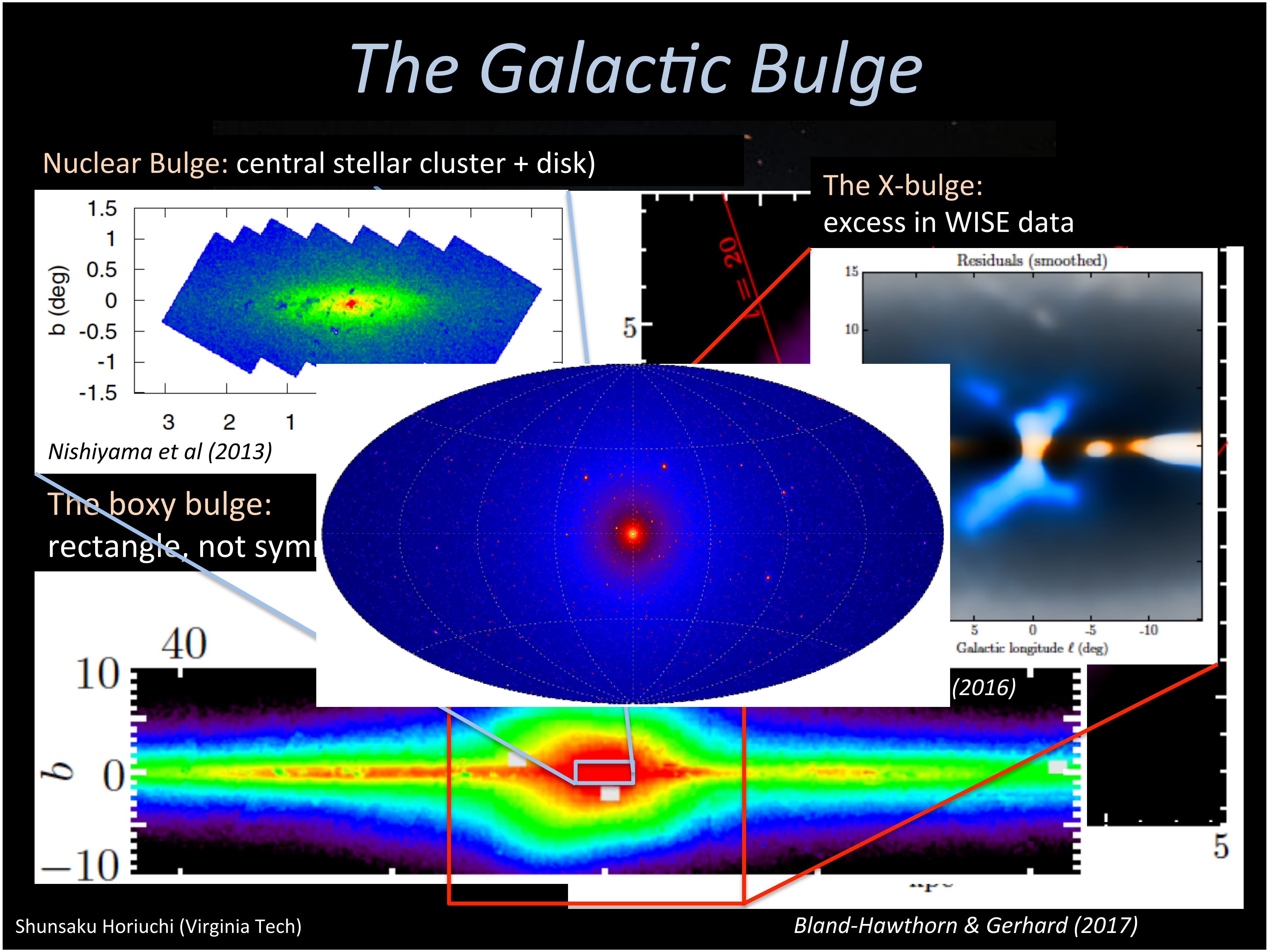
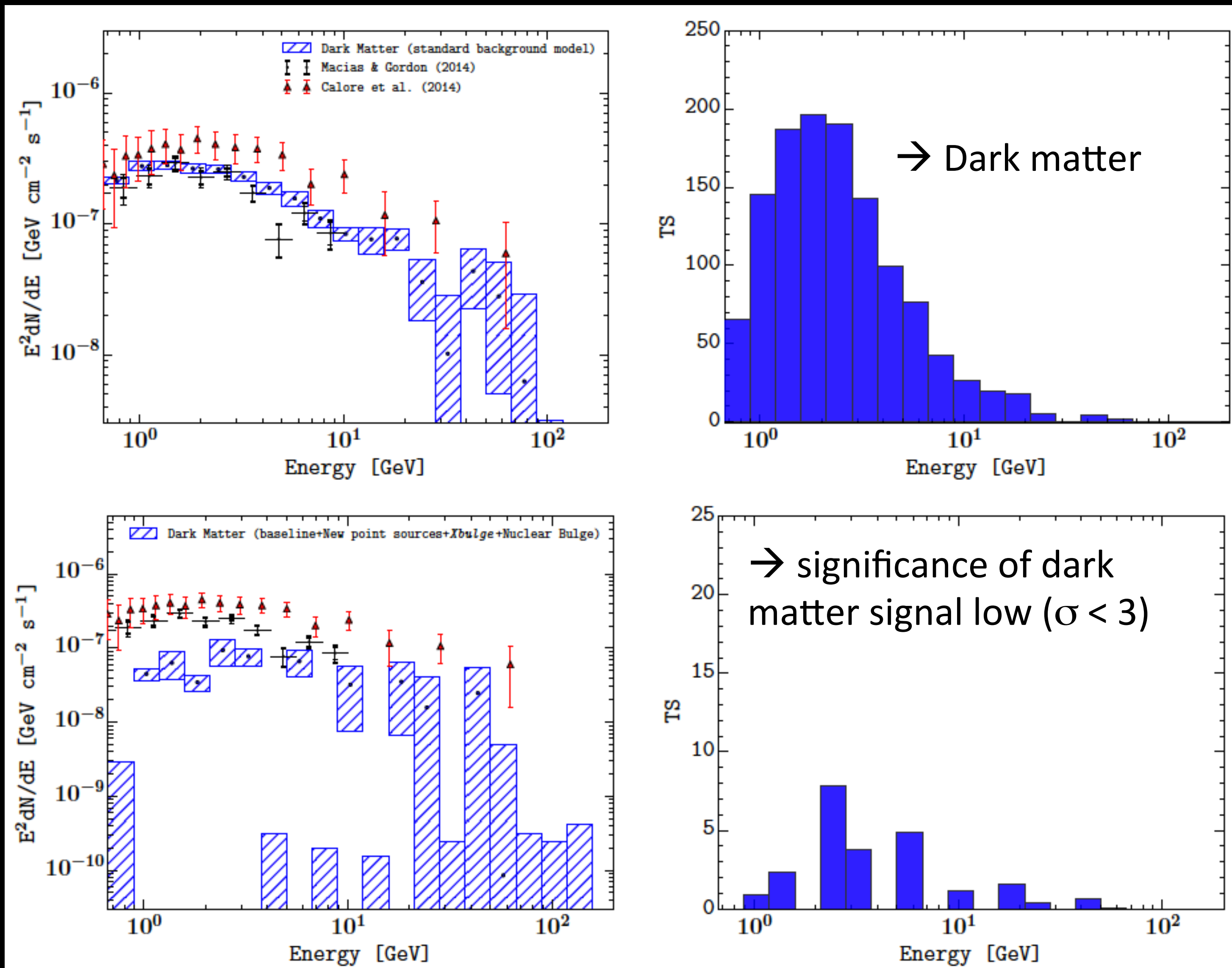

The Galactic Bulge
Nuclear Bulge: central stellar cluster + disk)
b (deg)
1.5
1
0.5
0
-0.5
-1
-1.5
3
2
1
Nishiyama et al (2013)
The X-bulge:
excess in WISE data
Residuals (smoothed)
15
10
5
0
-5
-10
Galactic longitude ℓ (deg)
(2016)
The boxy bulge:
rectangle, not sym
40
10
b
0
−10
5
Shunsaku Horiuchi (Virginia Tech)
Bland-Hawthorn & Gerhard (2017)

No need for dark matter annihilation!



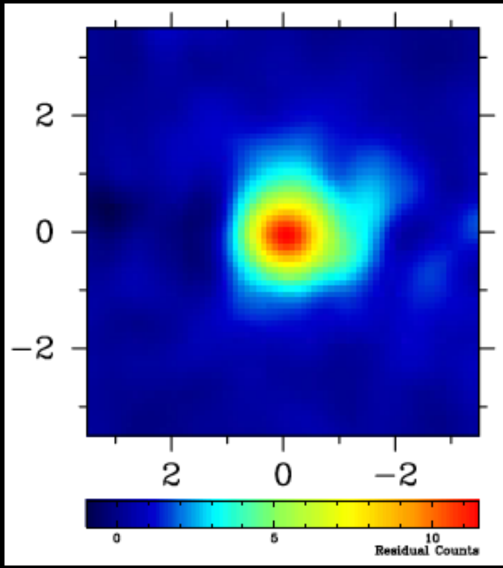
← WITHOUT bulge
Fit without new extended bulge (representative of previous studies)

← WITH bulge
Fit including our new extended bulge, the data no longer needs a NFW component

Macias et al, Nature Astronomy (2018)

Residuals

Including the boxy and nuclear bulges, the gamma-ray residuals do not show obvious large extended excess



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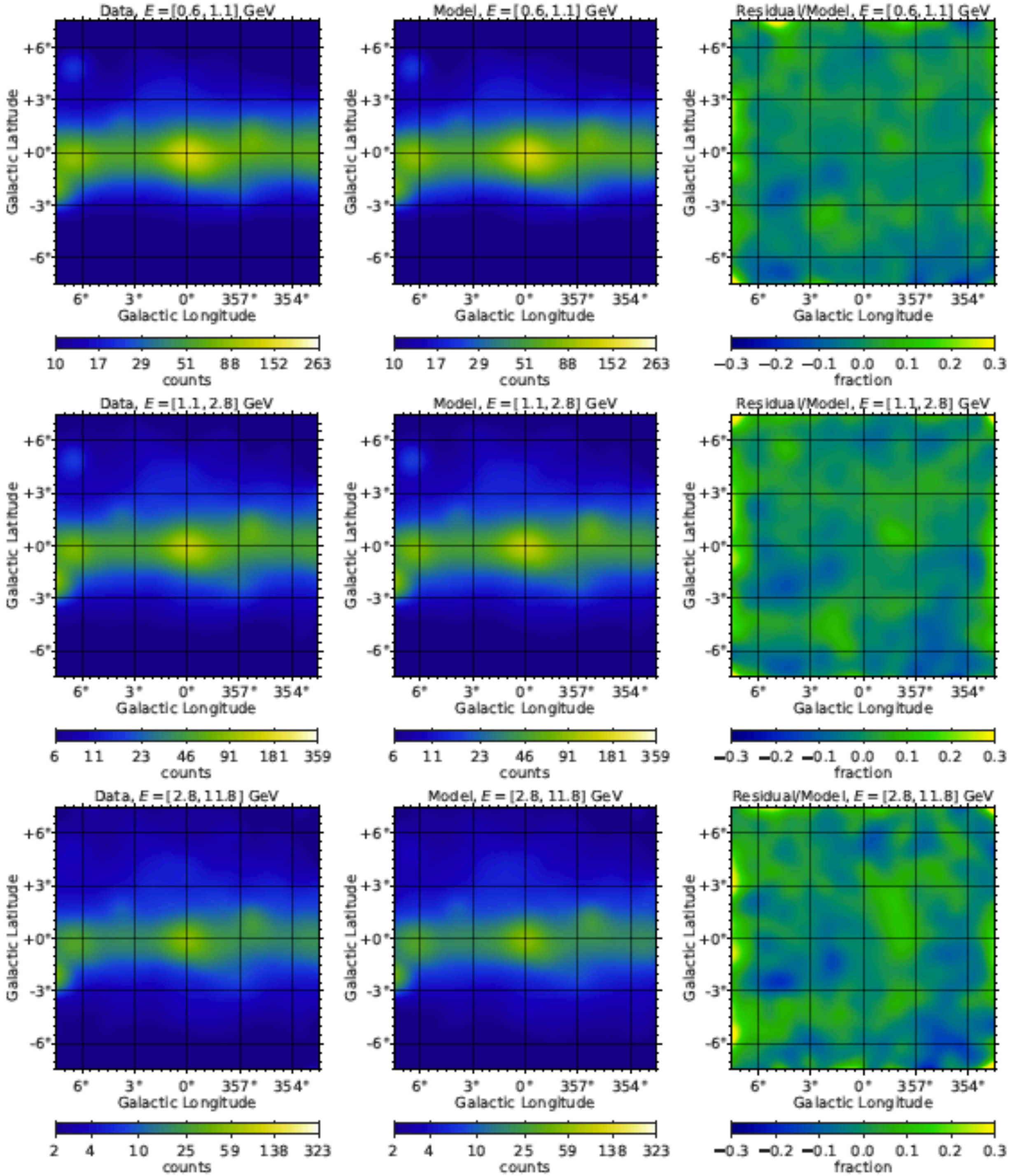

(in prep)

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Millisecond pulsar interpretation

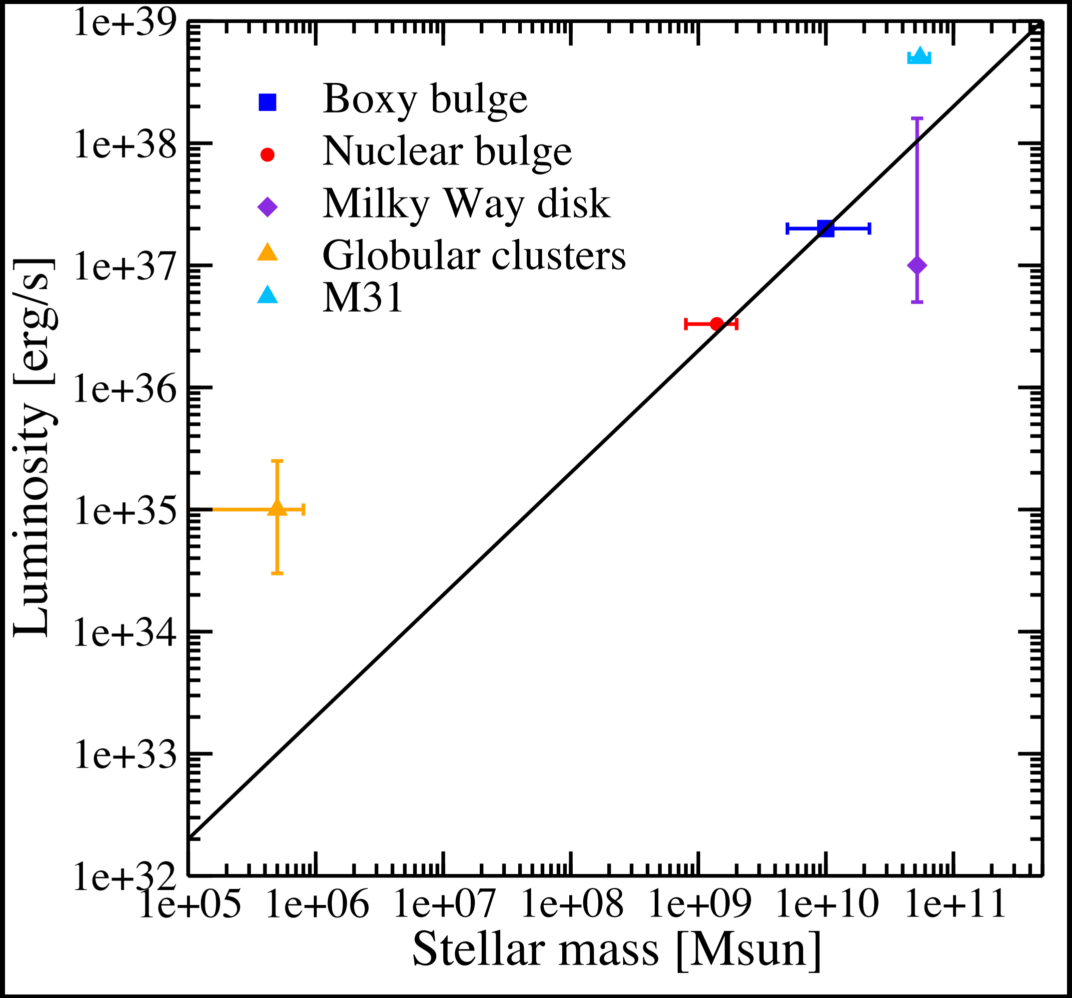
Efficiency:
Consider the mass-to-light ratio.

Milky Way boxy bulge, Milky Way disk: are consistent with a mass-to-light ratio of

$$\sim 3 \times 10^{27}\ \mathrm{erg/s/M_\odot}$$

Source with higher luminosities for their mass

- *Globular clusters*: higher than MW bulge by factor ~10-100
- *M31*: higher by a factor of several



See also Bartels et al (2018)

In-situ millisecond pulsar formation

Millisecond pulsar origins:

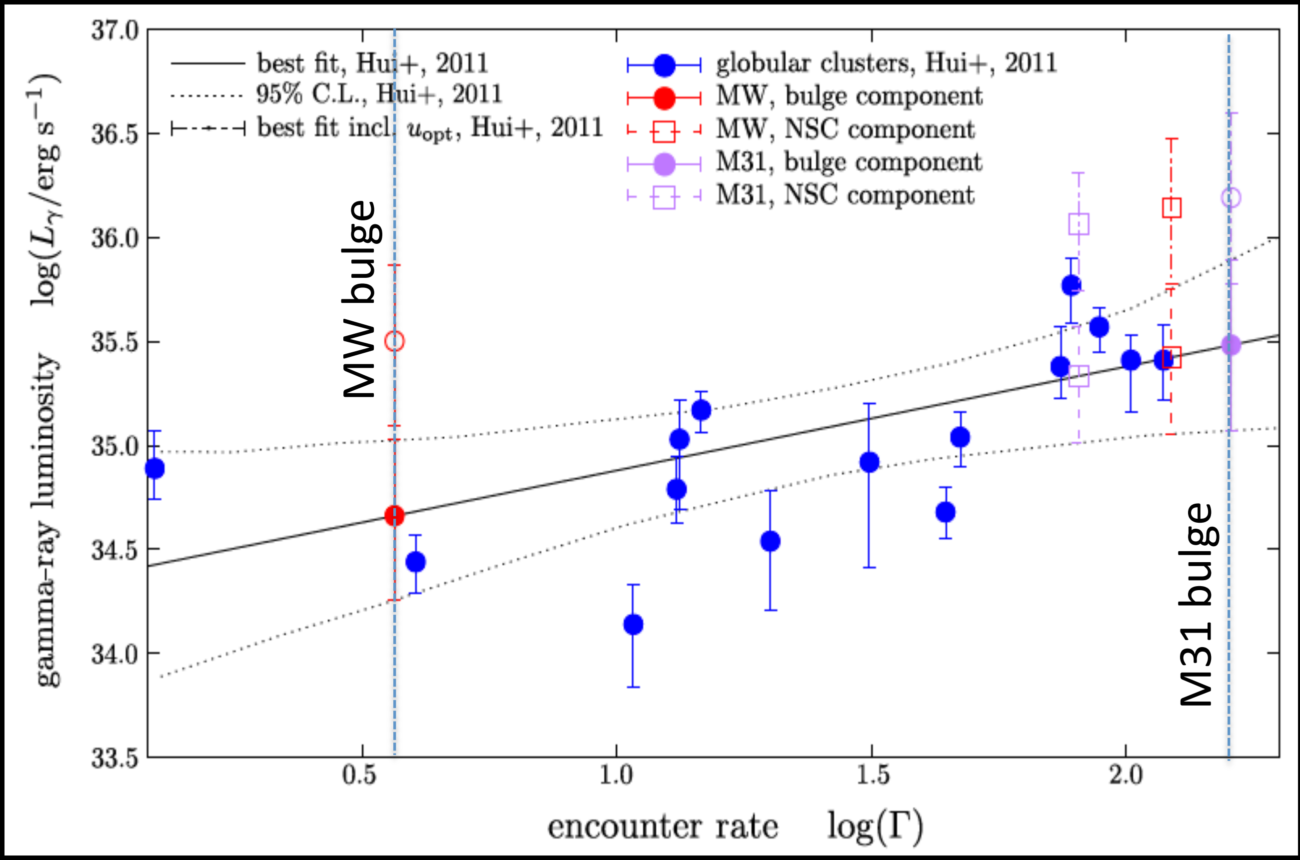
- In-situ formation in the bulge
  1. Primordial binaries scales ~ stellar mass (e.g., x-ray binaries)
  2. Dynamical capture binaries scales ~ encounter rate

Encounter rate:

$$\Gamma \propto \rho_*^2/\sigma$$

Hui et al (2010)
Eckner et al (2017)

MW bulge lower than most globular clusters and also lower than M31 bulge



In-situ millisecond pulsar formation

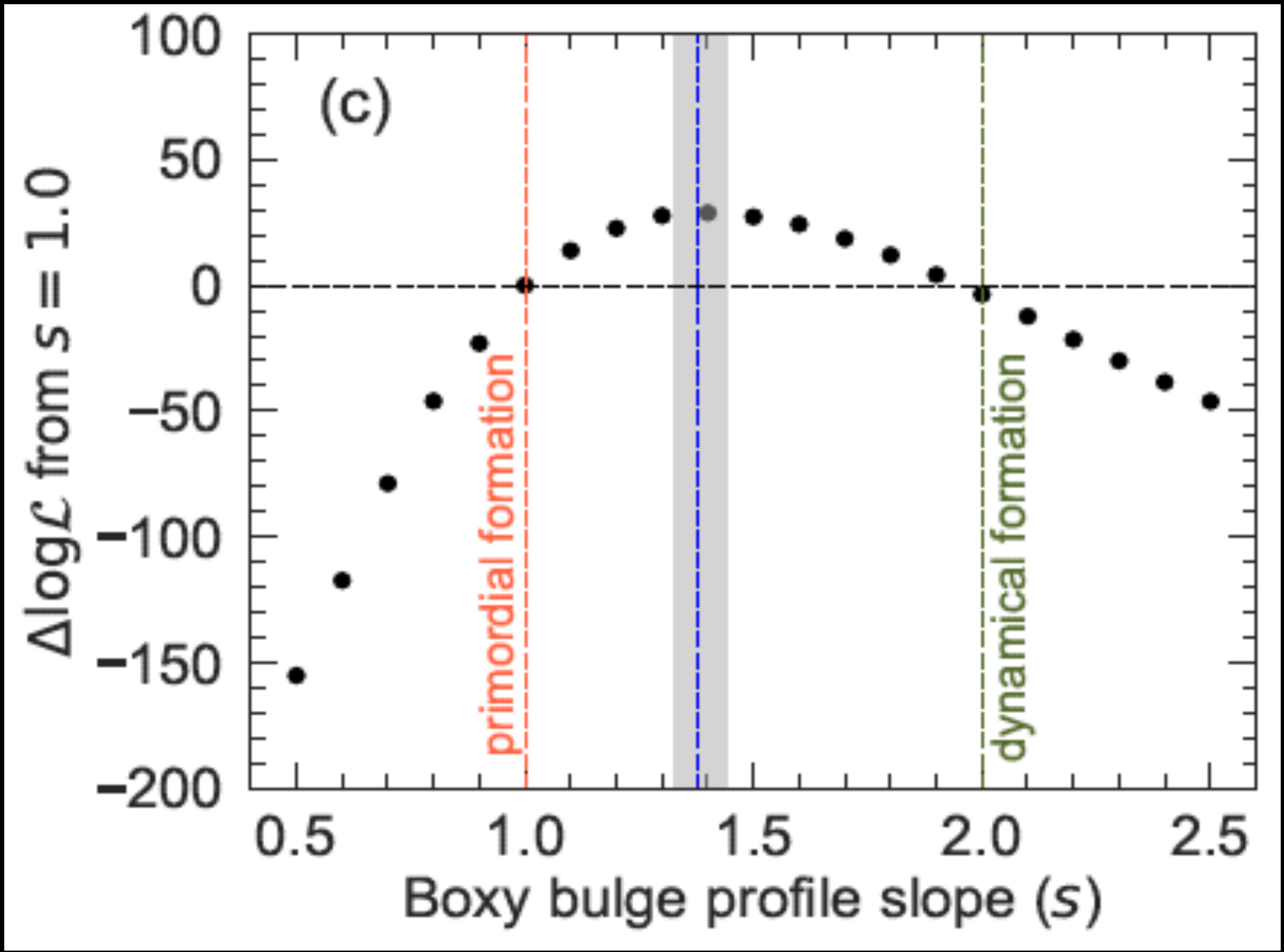
Primordial vs dynamical

Simple search of primordial + dynamical formation channels in the bulge-correlated gamma

template = ρ_{boxy}^s

Yields $s \sim 1.4$

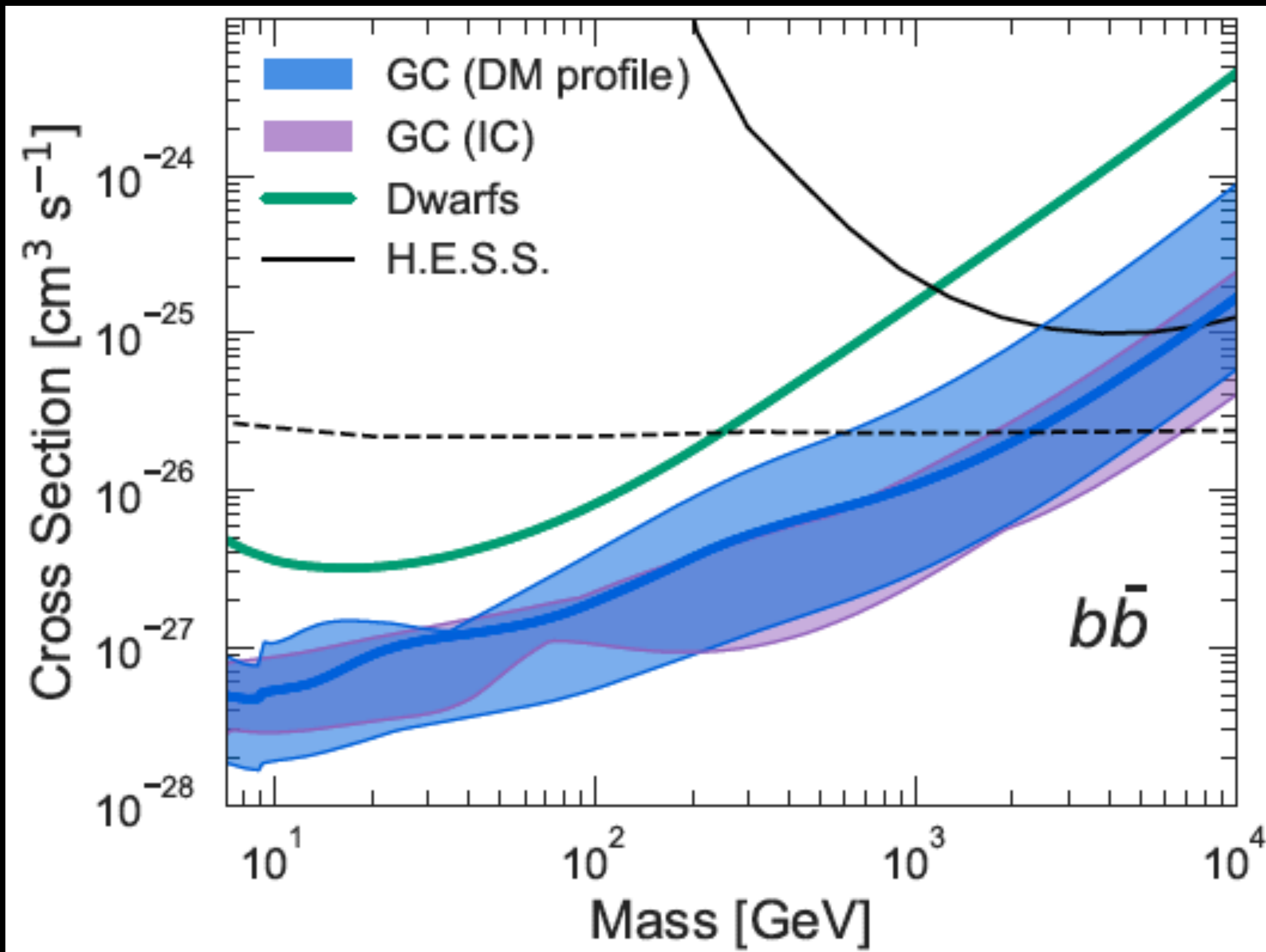
➔ Primordial is 30 – 73% of gamma rays



Macias et al (2019)
see also Eckner et al (2017)

Impact: limits on dark matter

Deliver: beat systematics to tap into the true potential of the Galactic Center



(in prep)

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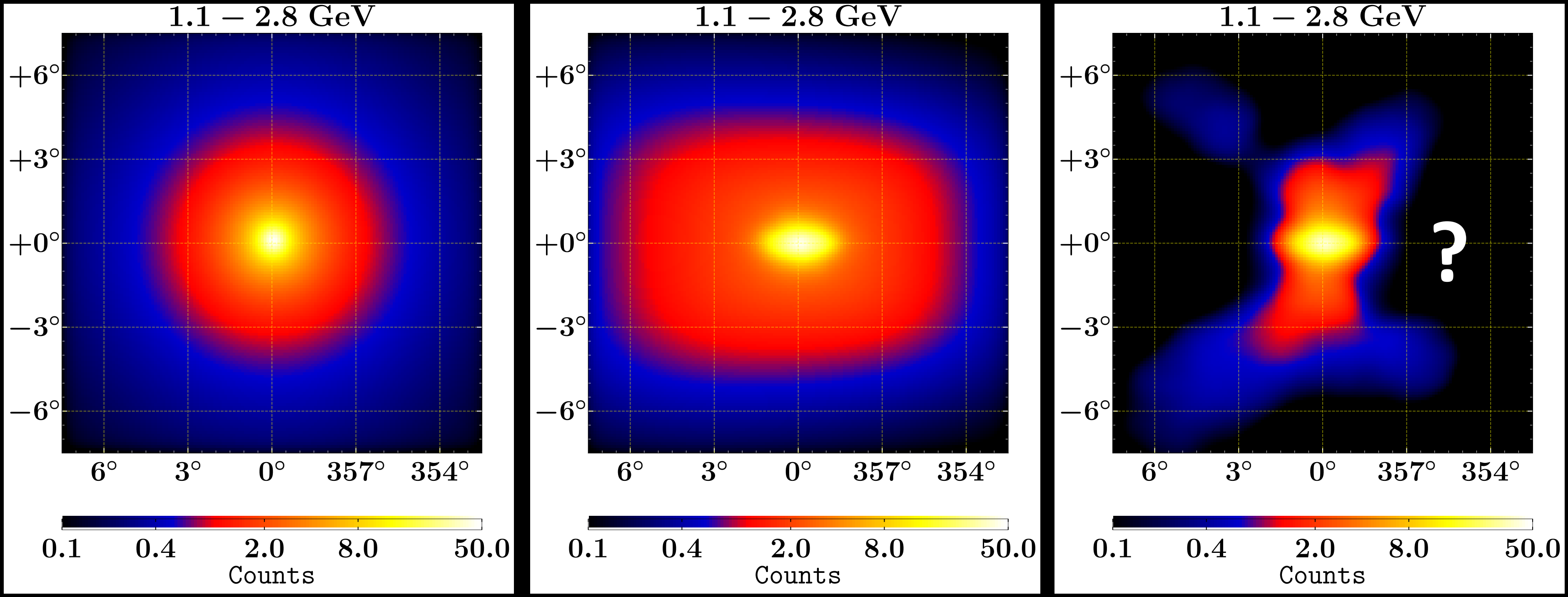
Some future origin tests

1. Look for high-energy counter parts: pulsars predict strong emissions up to TeV energies (not so for dark matter)

➔ Deheng Song's poster: "*Inverse-Compton Emission from Millisecond Pulsars in the Galactic Bulge*"

Song et al (2019)

2. Look for sub-features of the stellar bulge: stars show X-shape (dark matter no)



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Final remarks

Fermi-LAT data reveals an excess of gamma-ray photons arriving from the Galactic Center direction that has persisted 10 years of scrutiny

Origin is being comprehensively tested

1. Spectrum can be explained by both dark matter and pulsars
2. *Spatial morphology traces much better the stellar bulge rather than dark mater*

→ Difficult to explain with standard dark matter scenarios

→ In-situ pulsars do much better

Towards better models & tests

1. Better bulge models (with pulsar formation, emission, migration, etc)
2. Better dark matter models (inner profile, non-simple dark matter morphologies, etc)
3. Better tests (metallicity, radio)

…stay tuned !

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How similar is the gamma-bulge?

Gamma-ray bulge offset?

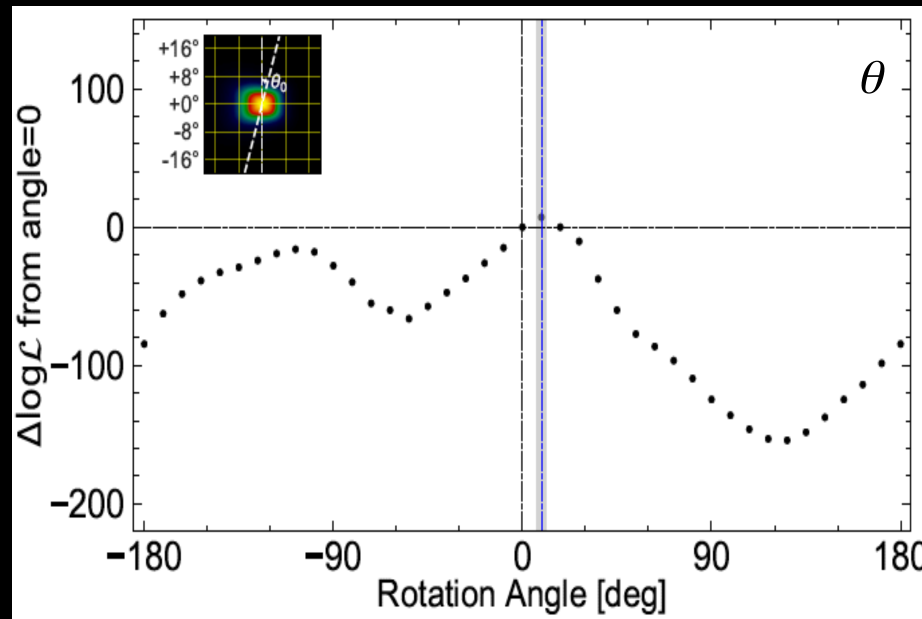
Gammas prefer the bulge model to be:

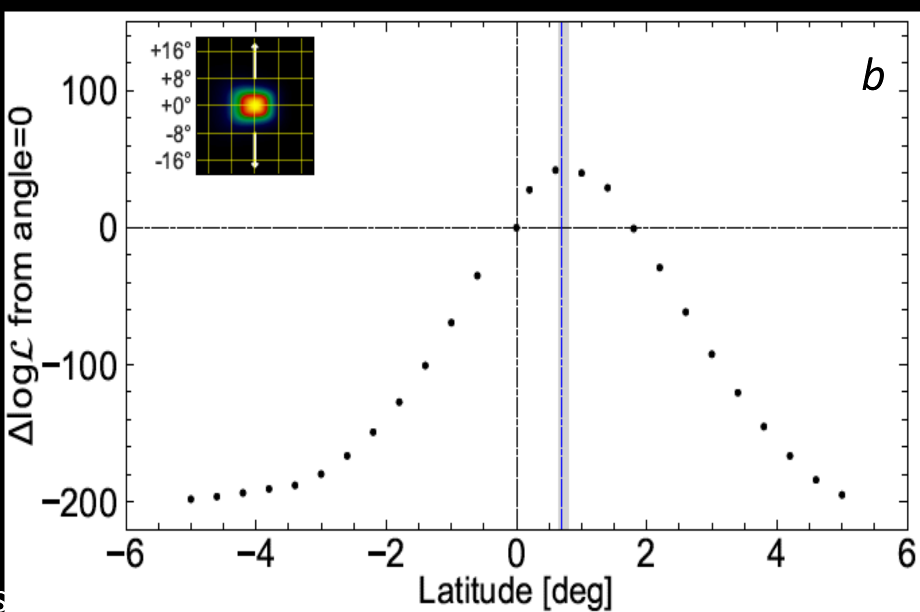
- Oriented close to the stellar bulge
- Within a few degrees of the model bulge center:

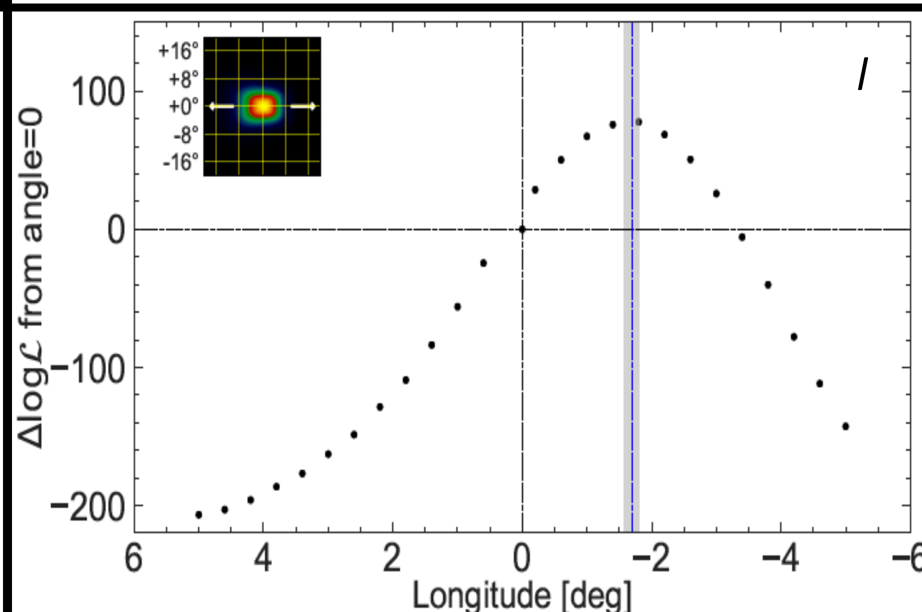
$$\Delta l \sim [0,-3.5],\ \Delta b \sim [0,1.5]$$

➔ Miss-modeling? MSP migration? Center of bulge?

Macias et al (2019)
also Balaji et al (2018)





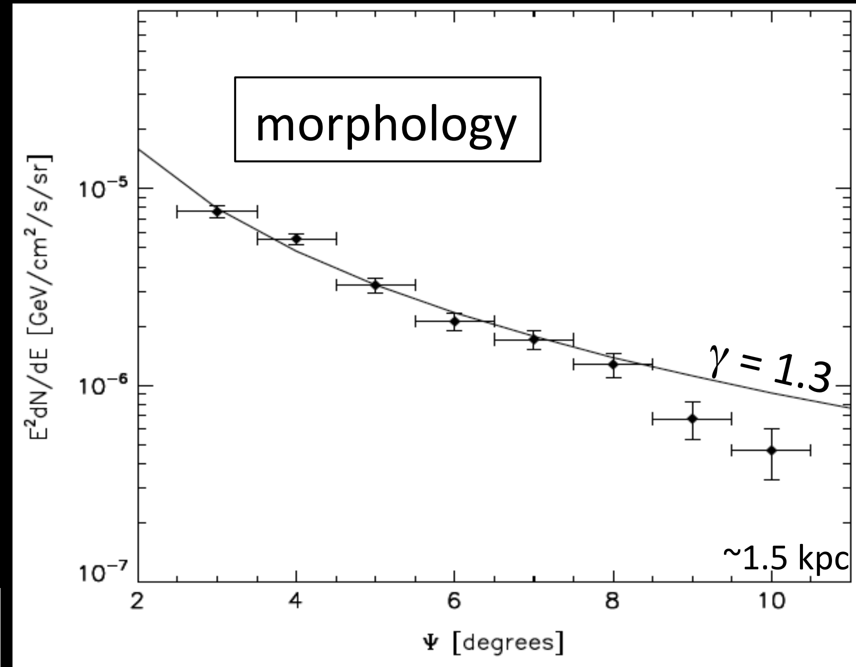


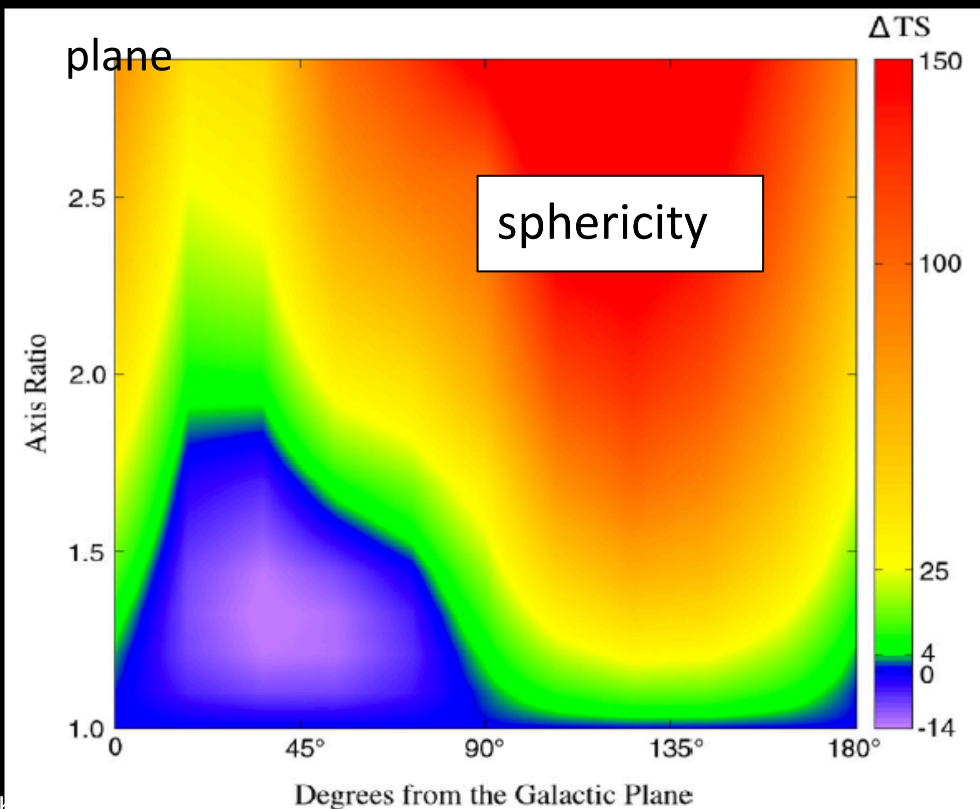
Dark Matter

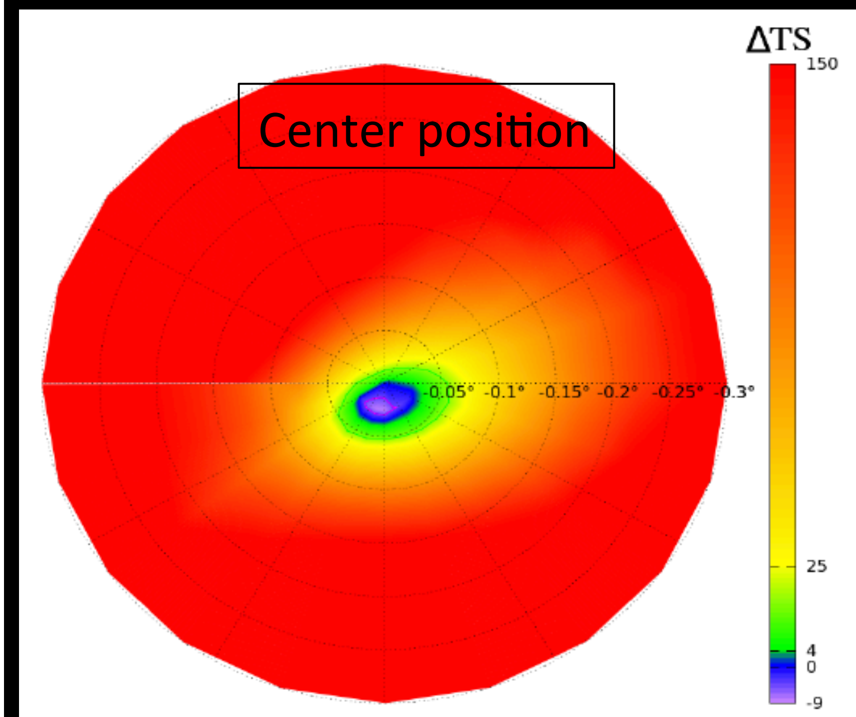
Morphology consistent with dark matter

- DM spatial template was used and detected.
- But modifications reveal the sphericity, morphology, and center position are consistent with WIMP

Daylan et al (2016)



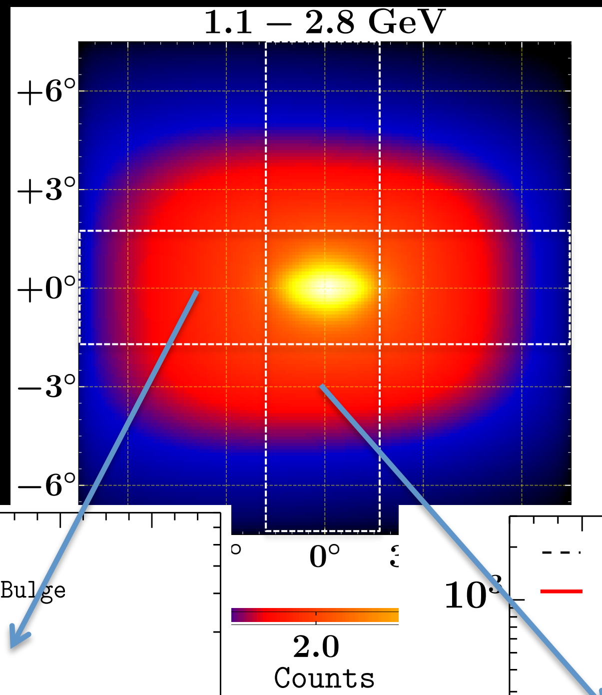




Difficulties for dark matter?

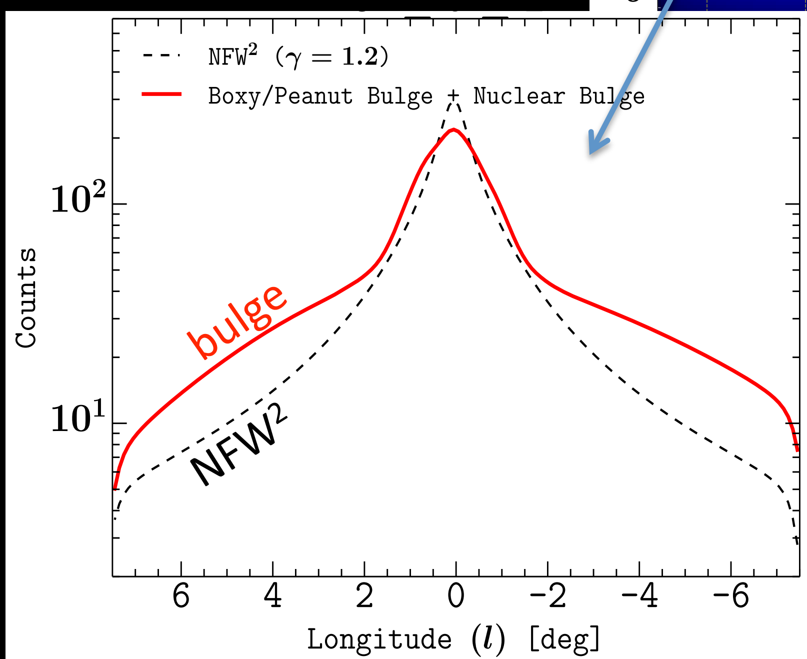
Dark matter profile
DM is largely spherical. (some portion be bar-like but subdominant)

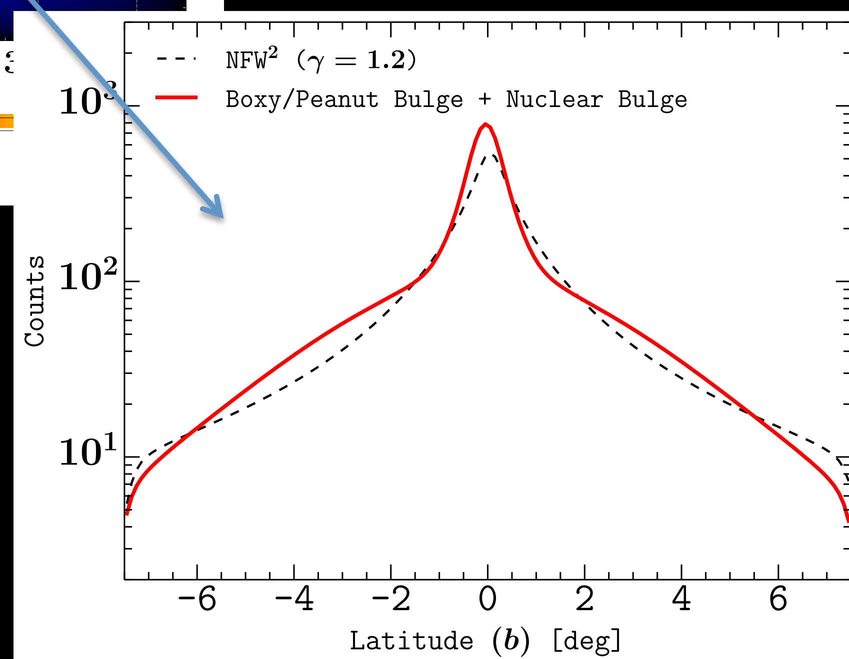
Petersen et al (2016)



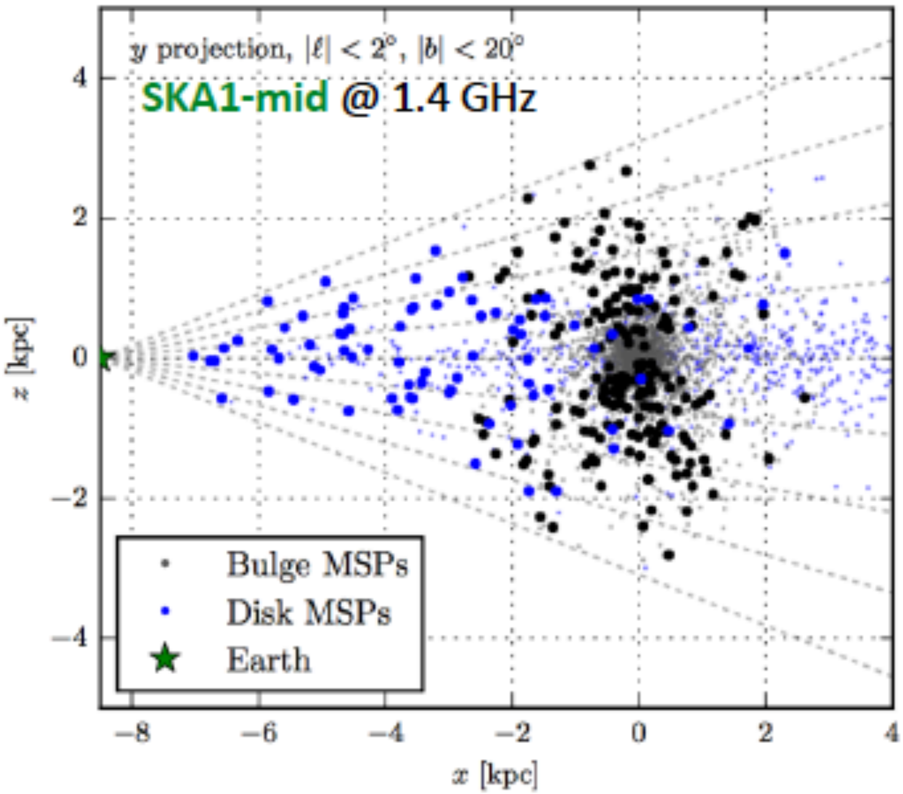
Point-like over diffuse
DM substructure is washed out in the Galactic Center region.

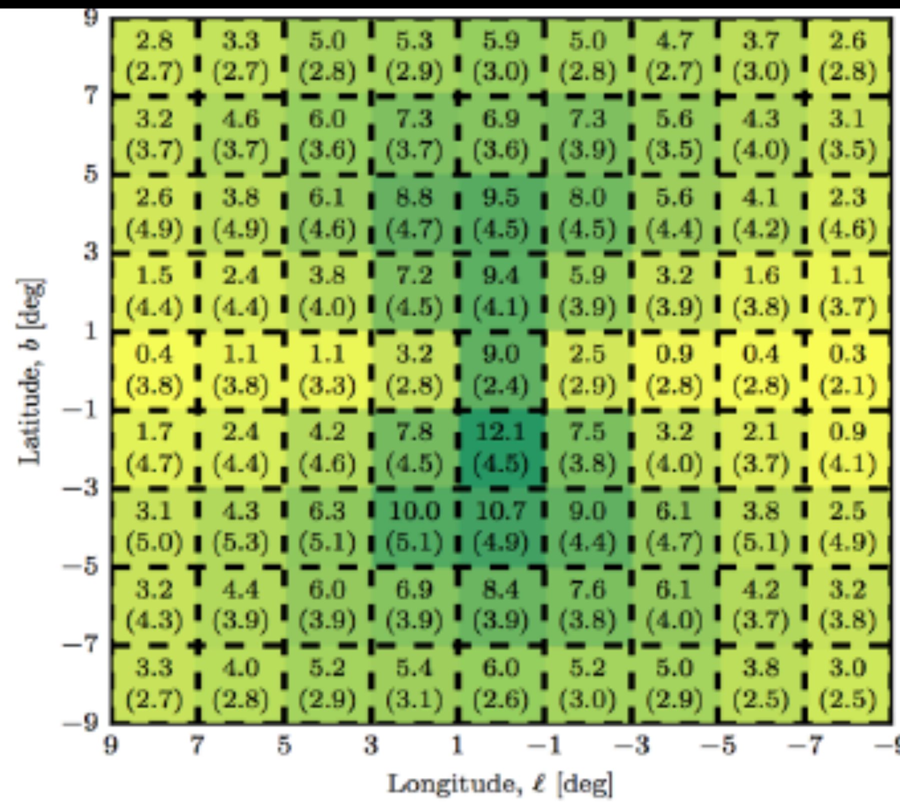
Clark et al (2016)





Future: radio probes of MSPs





Calore et al (2016)

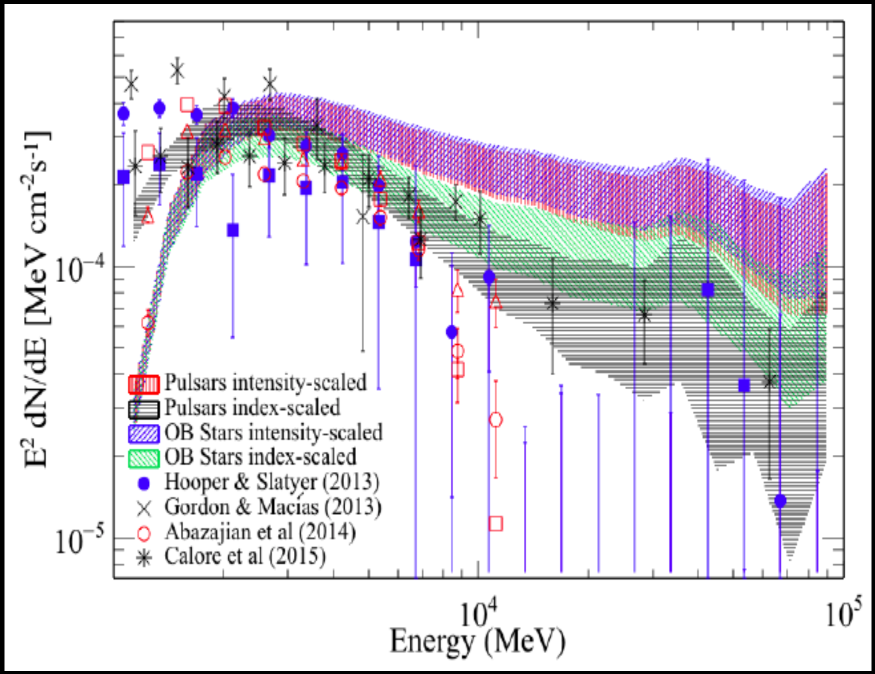
Radio searches for bulge MSP, key points:

1. Bulge population is just below the Parkes HTRU mid-latitude survey
2. Future dedicated searches can discover the bulge MSP population
   - E.g., GBT: ~3 MSP (~100h)
   - E.g., MeerKAT: ~30 MSP (~300 h)

Background model uncertainties

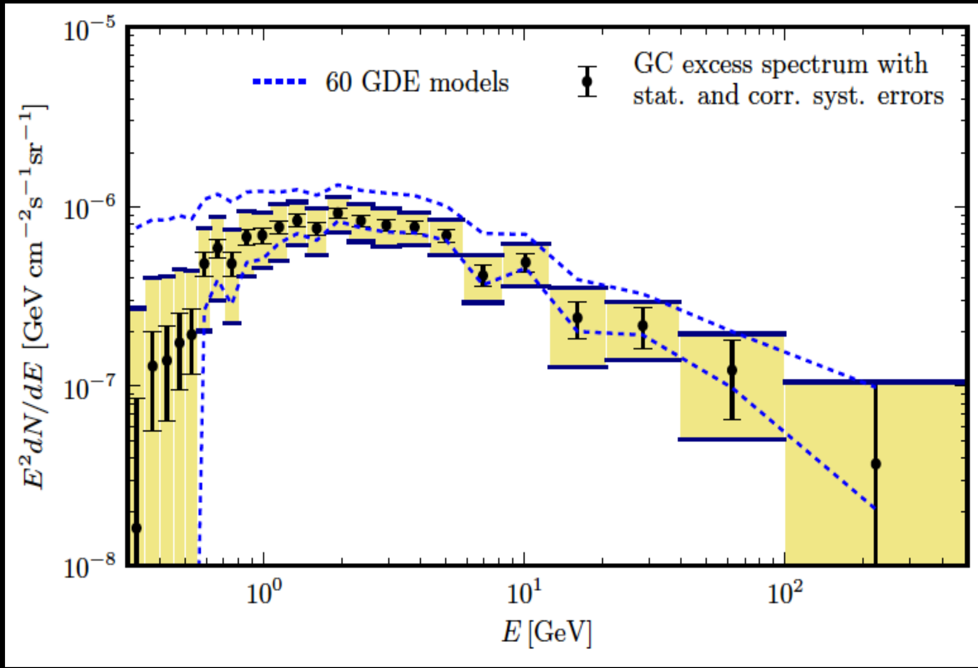
More relevant is systematic uncertainty.

Dedicated diffuse models
Calibrated by the Fermi collaboration to the Galactic Center region



Fermi collaboration (2016)

Galprop models
Scan range of parameters of diffusion, B-fields, ISRF, cosmic-ray injection, etc…



Calore et al (2015)

➔ **Despite efforts, the excess remains**