Pulsar origins of the Fermi GeV Excess

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U.S. DEPARTMENT OF ENERGY | Office of Science

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Outline

Introduction to the Fermi GeV Excess

- Discovery
- Broad features

Key developments support the millisecond pulsar origin

- Spatial morphology
- Grainy-ness

Implications for millisecond pulsars

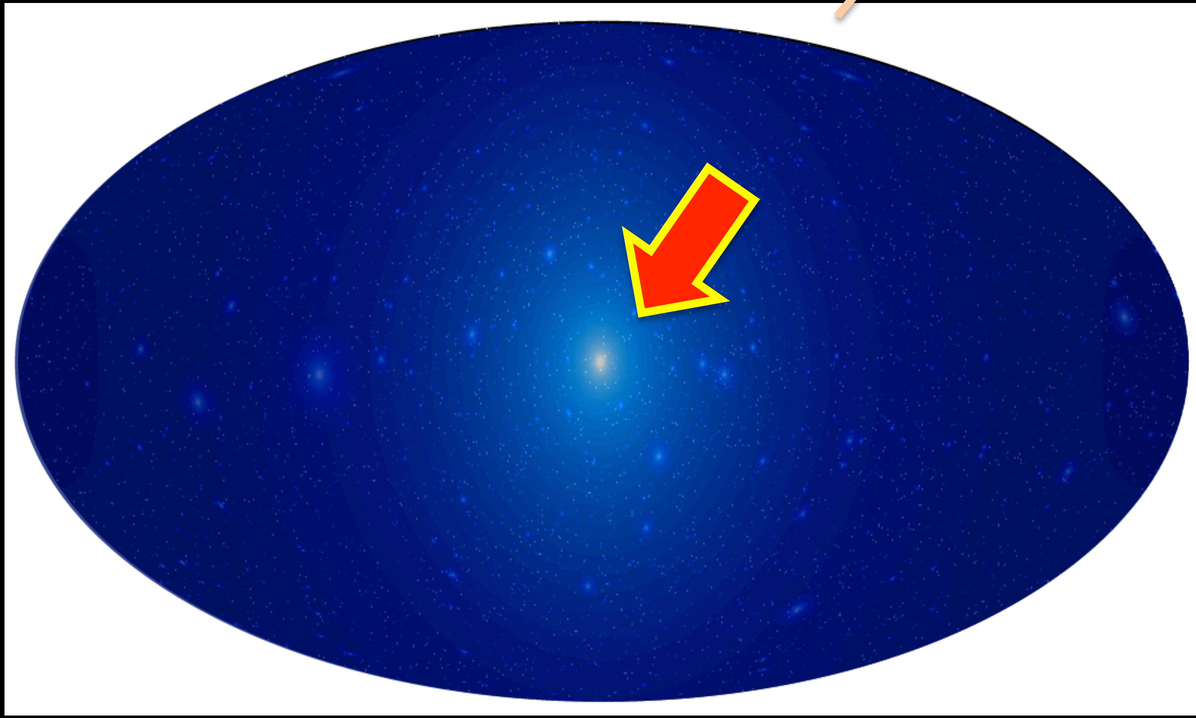
- Comparison with what we know about millisecond pulsars

Dark matter signatures in gamma rays

Fermi Satellite
Launched 2008

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

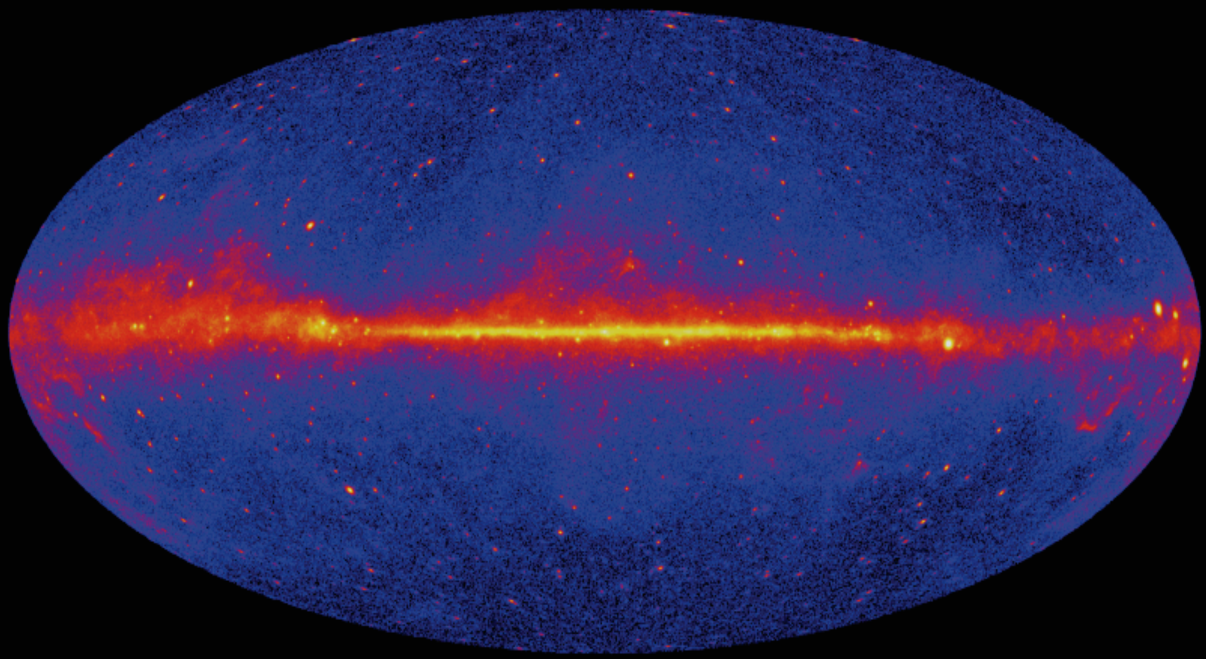
$$\Phi(E,\psi) = \frac{\sigma_A v}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \int d\ell \, \rho \left[r(\ell,\psi)\right]^2$$



Galactic Center Fermi GeV Excess (GCE)

Rich non-thermal phenomena

- Supermassive black hole
- Active star formation
- Pulsars, SNRs
- Base of Galactic bubbles



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Galactic Center Fermi GeV Excess (GCE)

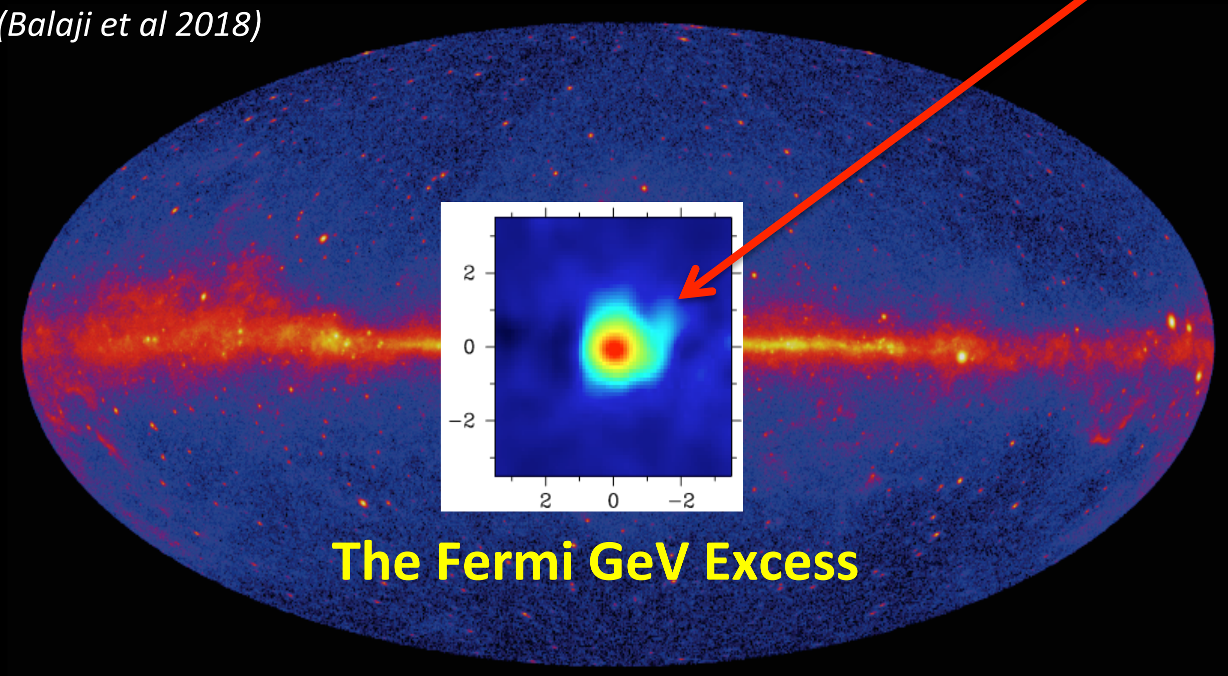
Searches

GCE found by morphological template fitting:

$$\mathrm{data}_i = \sum_j c_{ij}\,\mathrm{template}_{ij}$$

Also new approaches, e.g., wavelets

(Balaji et al 2018)

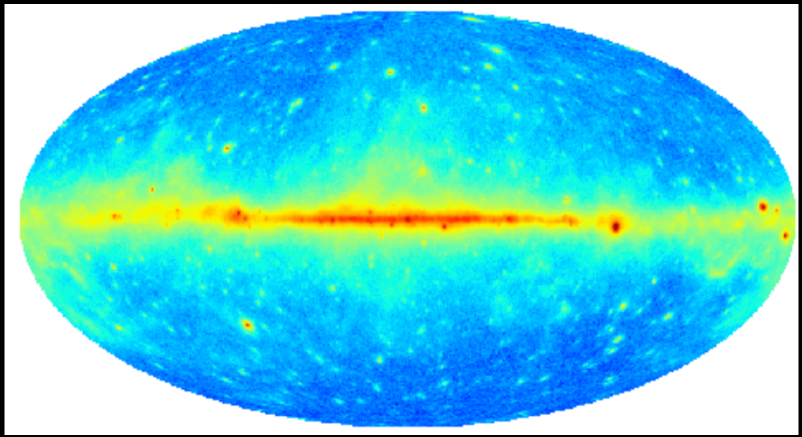


➔ **Confirmed by multiple studies**

Goodenough & Hooper (2009)
Vitale & Morselli (2009)
Hooper & Goodenough (2011)
Hooper & Linden (2011)
Boyarsky et al (2011)
Abazajian & Kaplinghat (2012)
Gordon & Macias (2013)
Hooper & Slatyer (2013)
Huang et al (2013)
Macias & Gordon (2014)
Abazajian et al (2014, 2015)
Calore et al (2014, 2015, 2016)
Daylan et al (2014)
Zhou et al (2014)
Selig et al (2015)
Huang et al (2015, 2016)
Gaggero et al (2015)
Carlson et al (2015, 2016)
Yand & Aharonian (2016)
Ackermann et al (2016, 2017)
Horiuchi et al (2016)
Linden et al (2016)
Macias et al (2016
Ajello et al (2017, 2018)
Macias et al (2018, 2019)
Bartels et al (2018)
Balaji et al (2018)
Zhong et al (2019)
etc

Strategy: templates

Data



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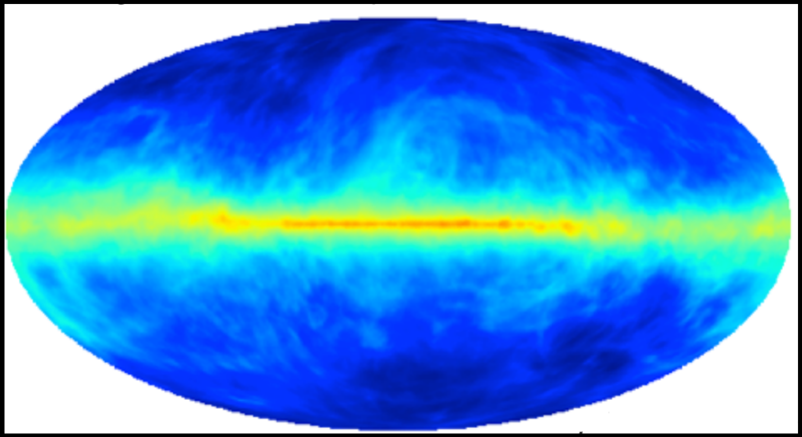
Galactic diffuse



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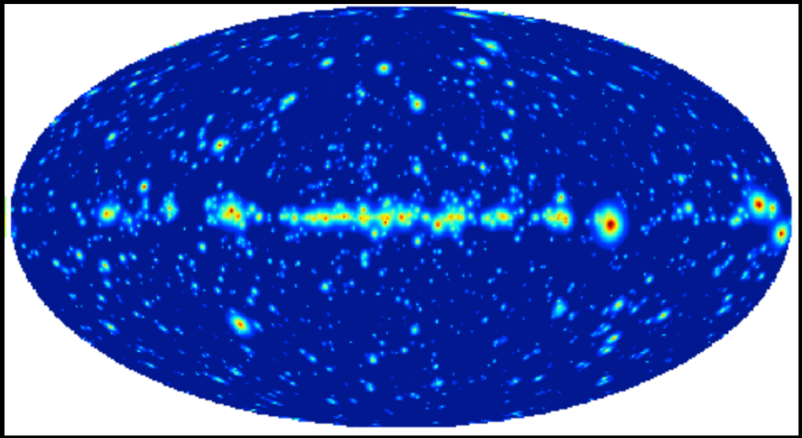
Known sources



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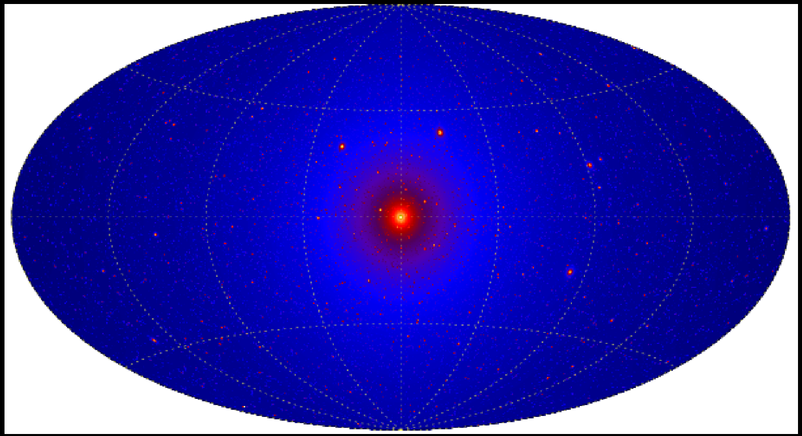
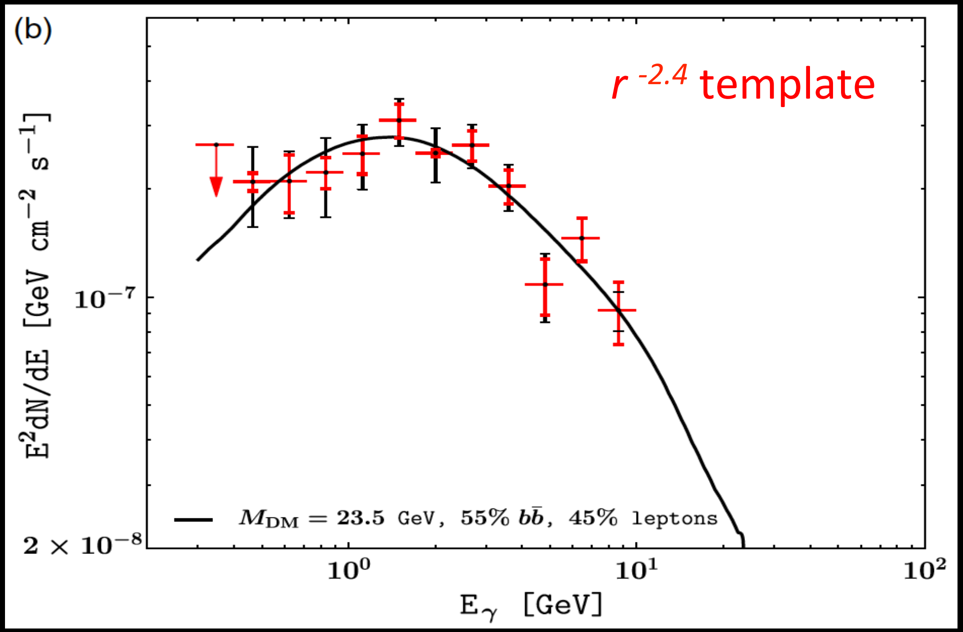
New sources, e.g., dark matter



GCE main features

Gordon & Macias (2013)



GCE as an excess

Dark matter template (NFW^2) is found in addition to:

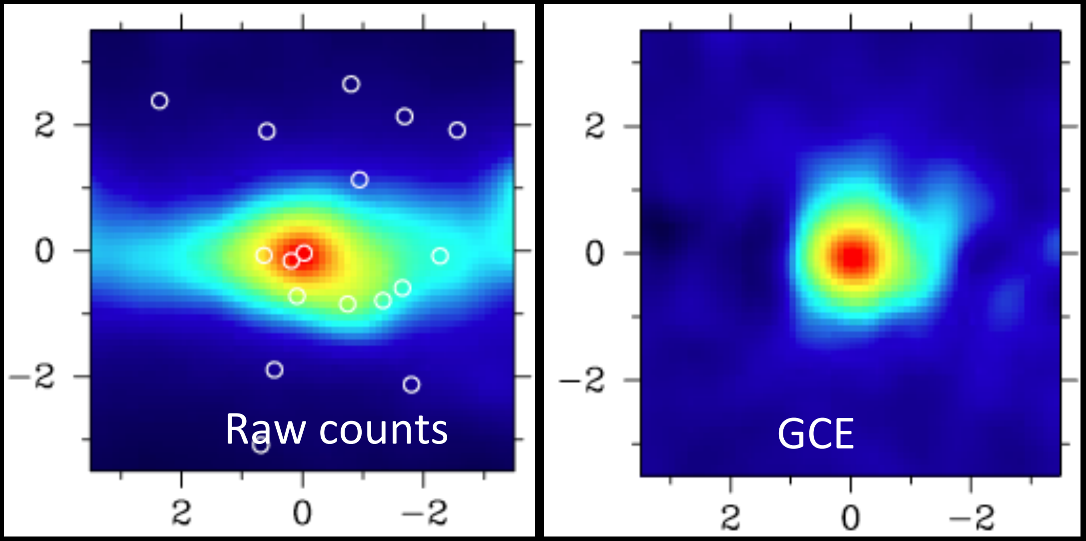
- Galactic diffuse emission
- Fermi bubbles
- Gamma-ray sources

Main features:

- Spectrum peaks at ~GeV
- Flux ~$10^{-(6\text{-}7)}$ GeV cm^{-2} s^{-1} (→ ~10^{36}–10^{37} erg/s)
- Peaked morphology, $r^{-2.4}$

Significance

Statistical significance is ~20–60σ depending on setup



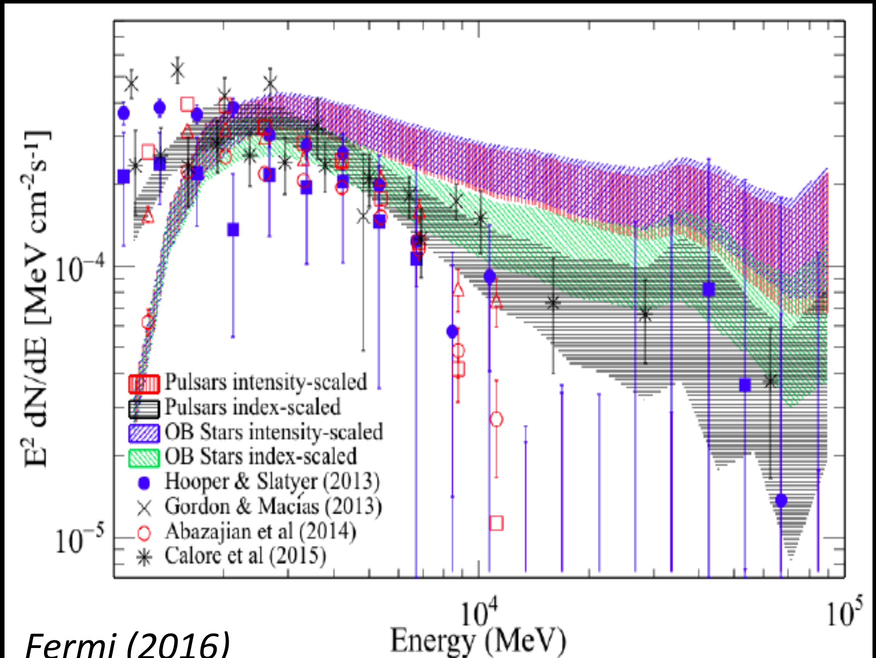
Abazajian & Kaplinghat (2012)

GCE uncertainties

Dedicated systematic studies, eg:

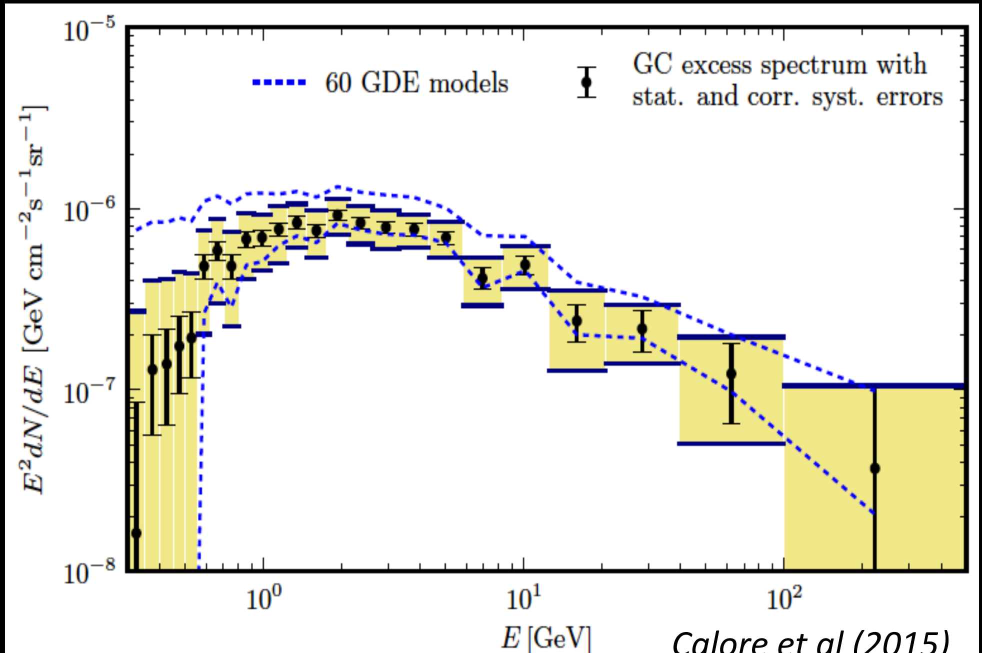
- Galprop model scans
- Data-driven background model building
- Inclusion of on-going SF in the CMZ
- ICS models (photon fields, Bfields)

→ **Despite efforts, the excess remains needed by the data**



Fermi (2016)

Calibrated by the Fermi collaboration to the Galactic Center region



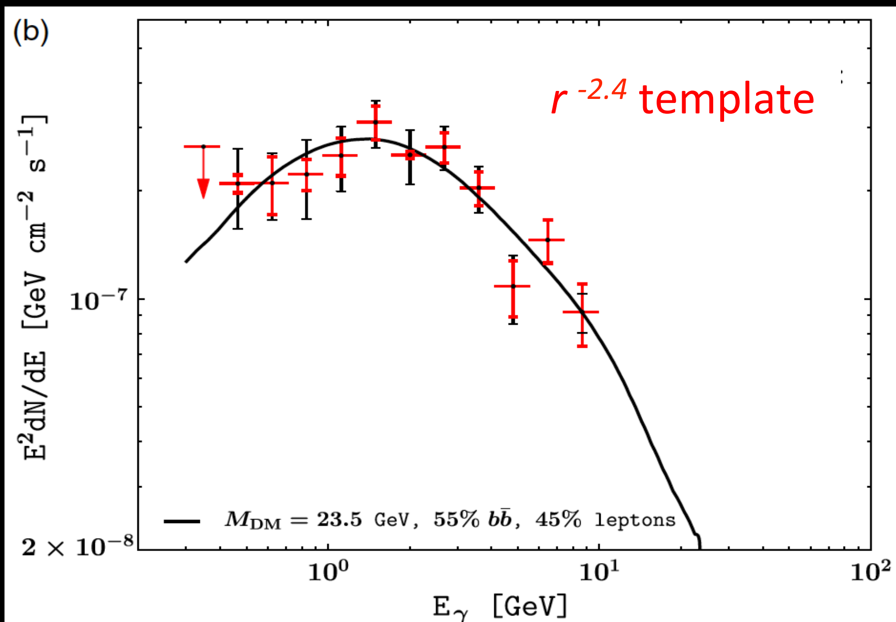
Calore et al (2015)

Galprop: scan diffusion parameters, B-fields, ISRF, CR injection, etc…

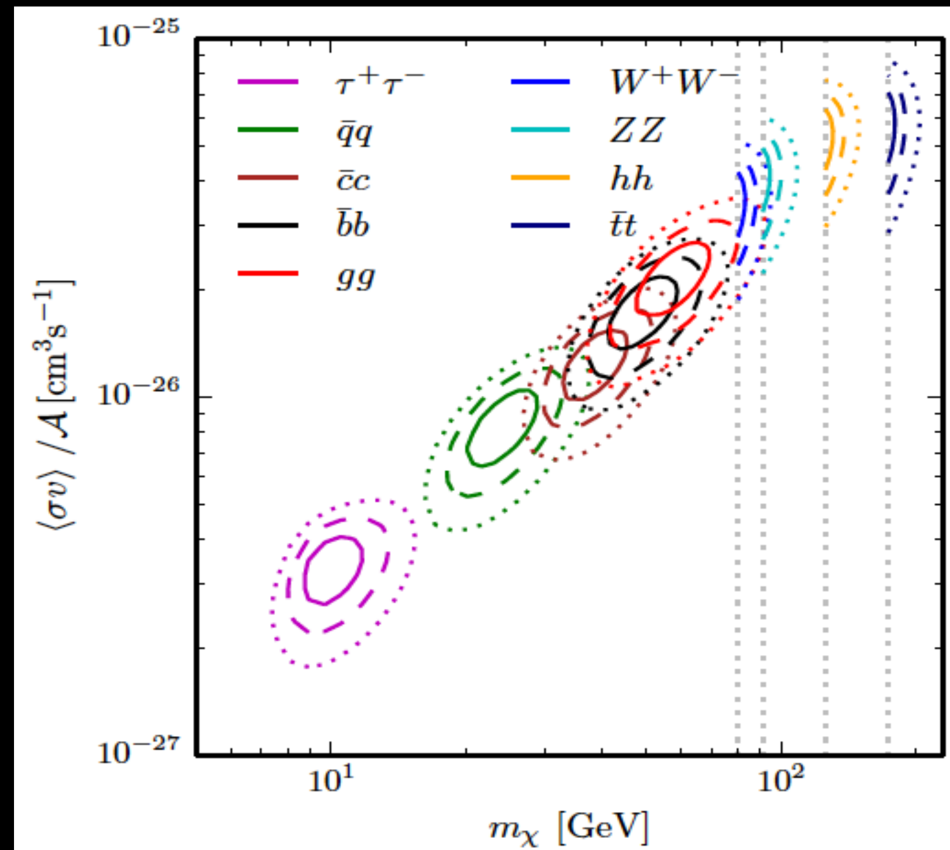
Dark matter interpretation

Tantalizing match with WIMP

All main features consistent with a vanilla WIMP
(annihilation of ~thermally produced WIMP to two-body final states)



Gordon & Macias (2013)



Calore et al (2015)

Note: many constraints exist but cannot rule out entire parameter space

1. Energy spectrum
2. Spatial morphology
3. Grainy-ness

MILLISECOND PULSAR ORIGIN

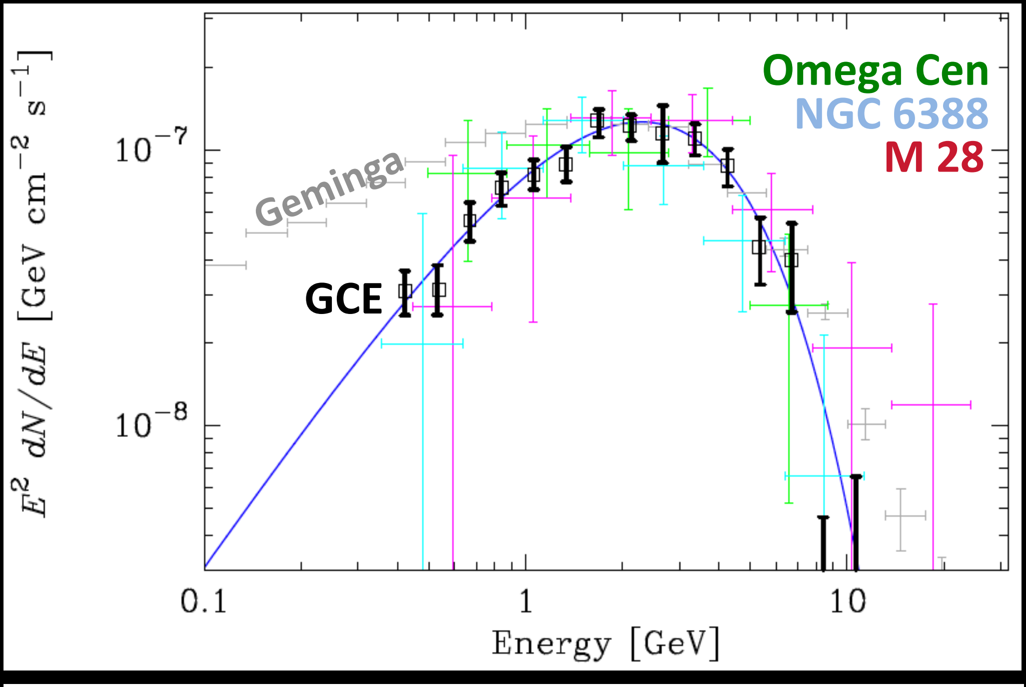
1. Spectra

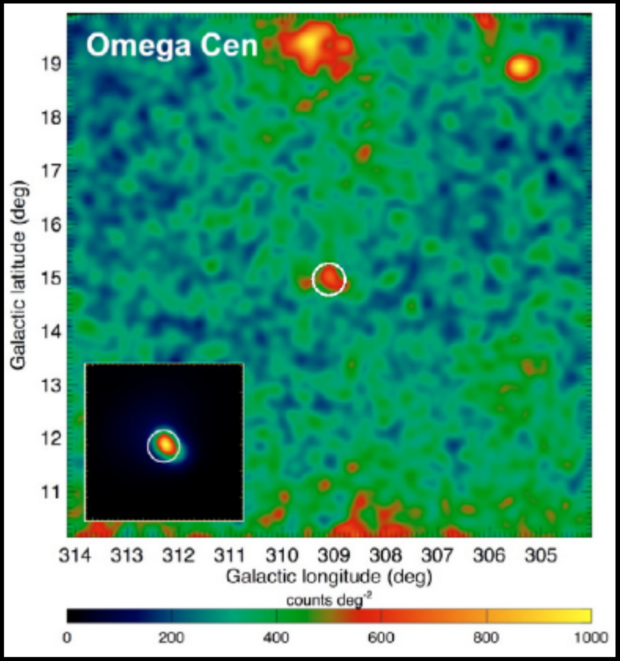
Energy spectrum

Millisecond pulsars and globular clusters observed in gamma rays

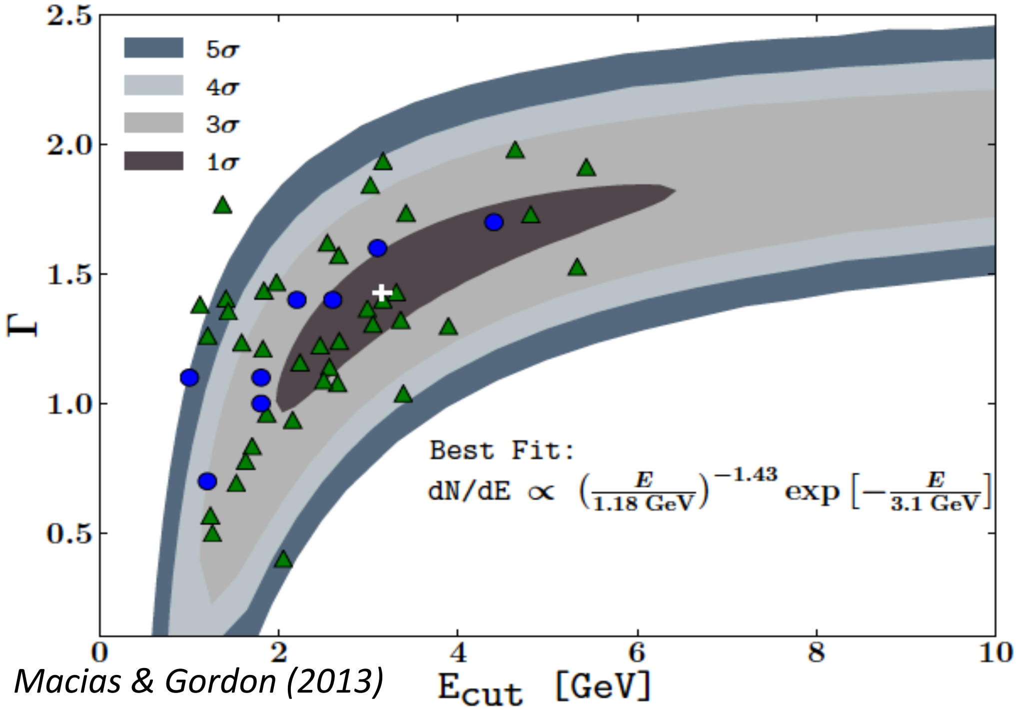
They have similar spectra to the GeV excess

Abazajian (2011)





Fermi (2010)



Macias & Gordon (2013)

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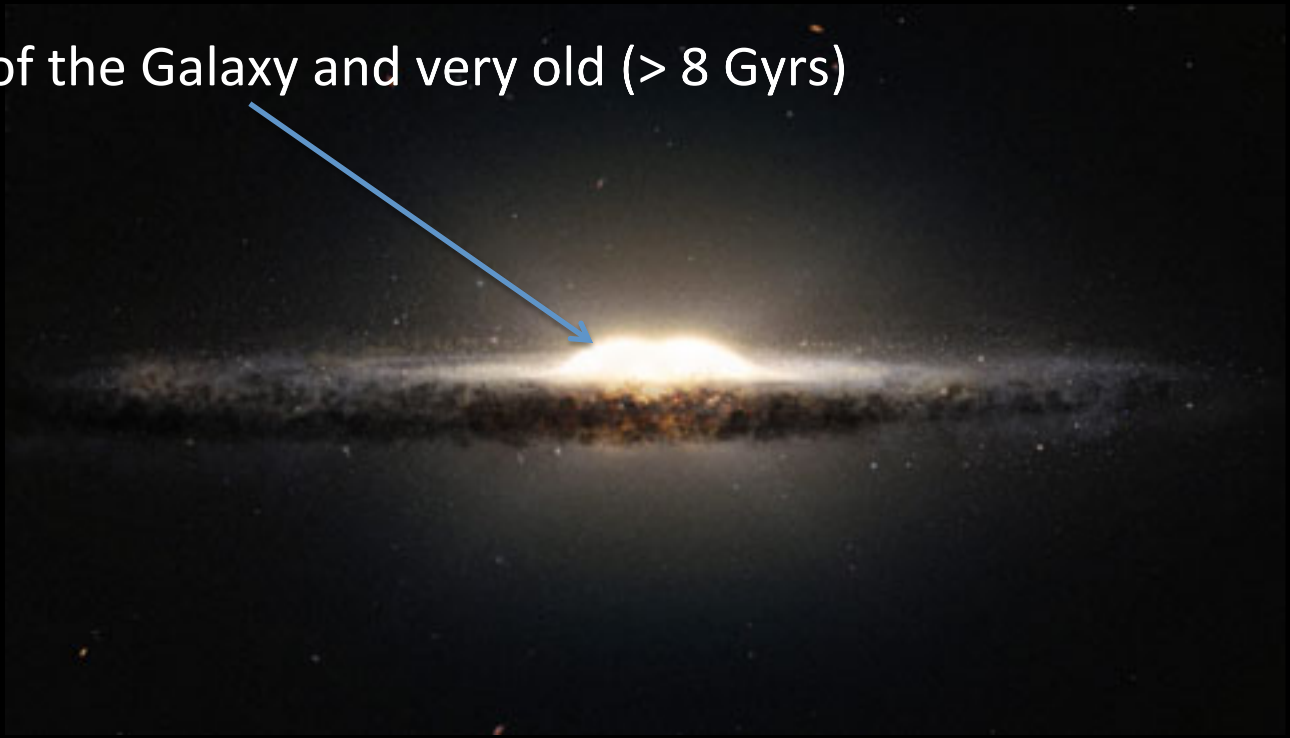
2. Spatial morphology

Dark matter: centrally concentrated, largely spherical, few features
Pulsars: if formed in-situ, should have departures from sphericity

~1/3 mass of the Galaxy and very old (> 8 Gyrs)



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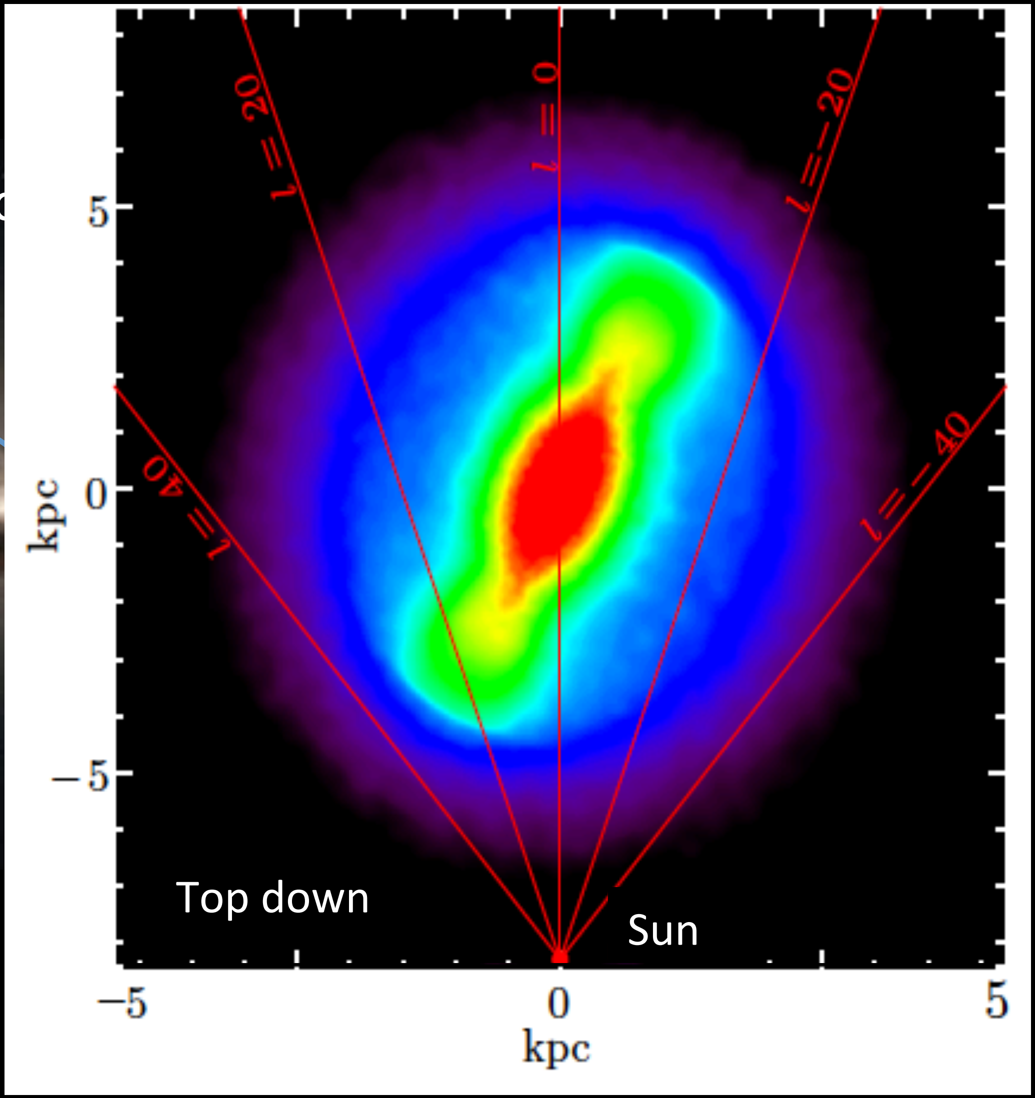

Bland-Hawthorn & Gerhard (2017)

2. Spatial morphology

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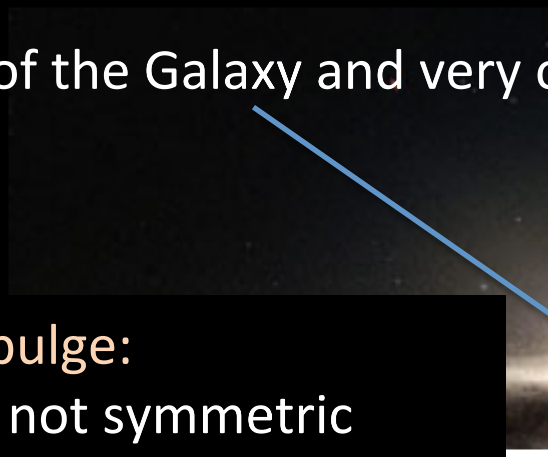
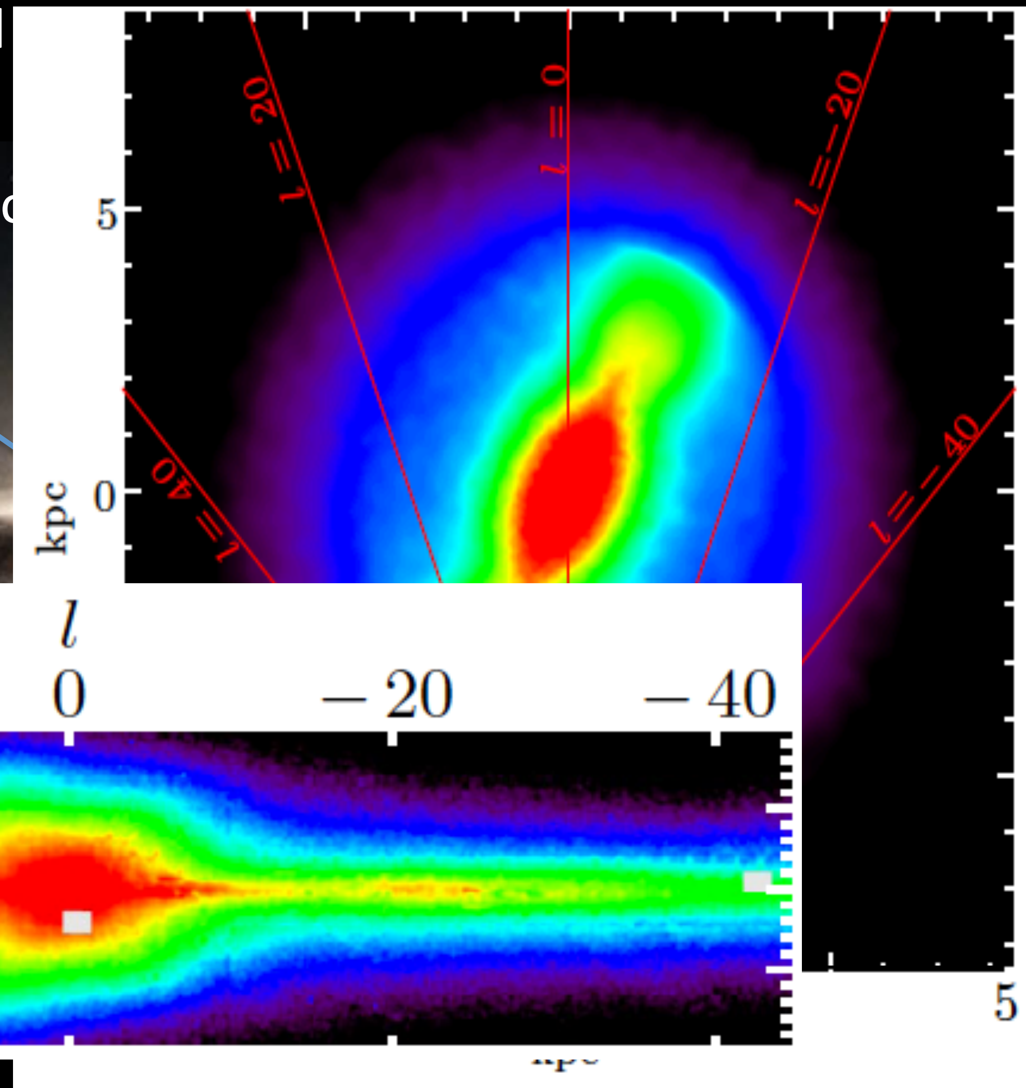
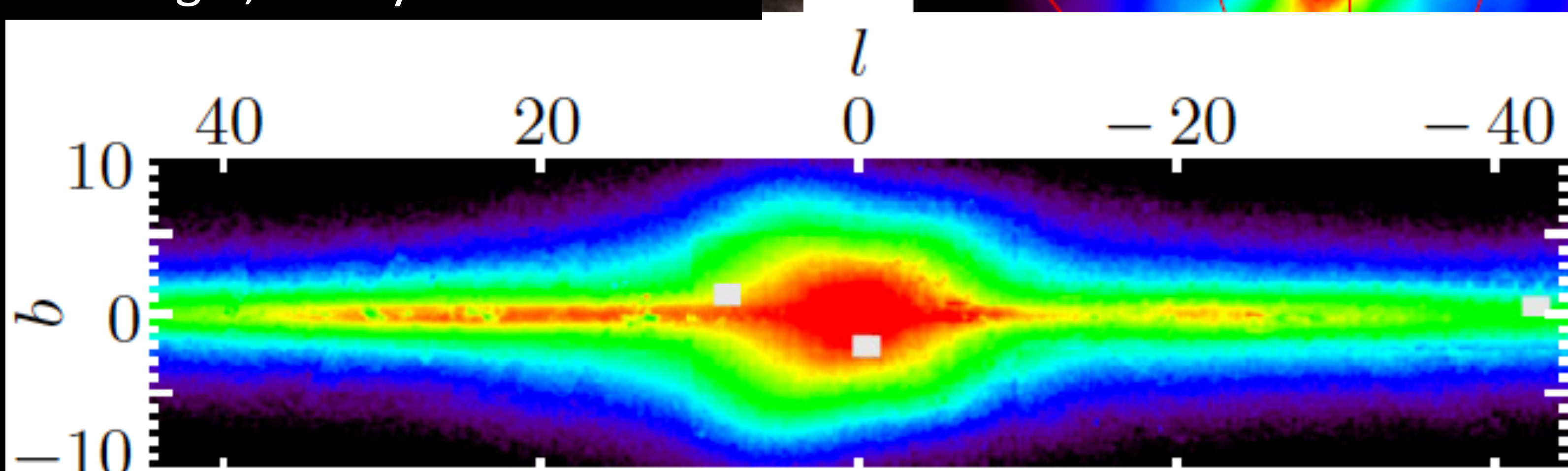


~1/3 mass of the Galaxy and very c

The boxy bulge:
rectangle, not symmetric

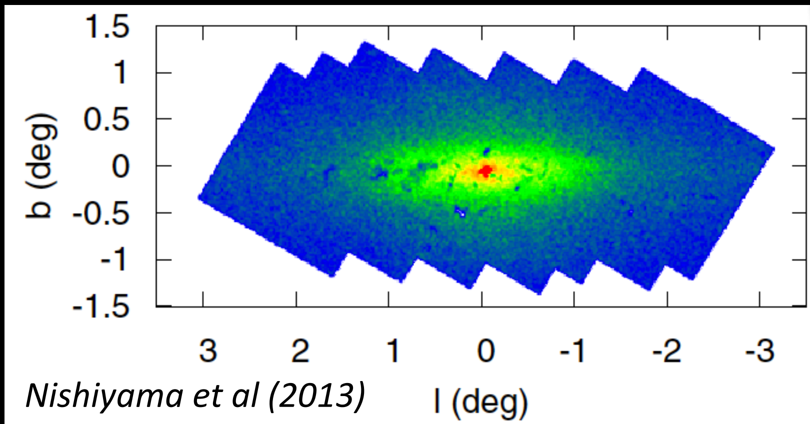




Bland-Hawthorn & Gerhard (2017)

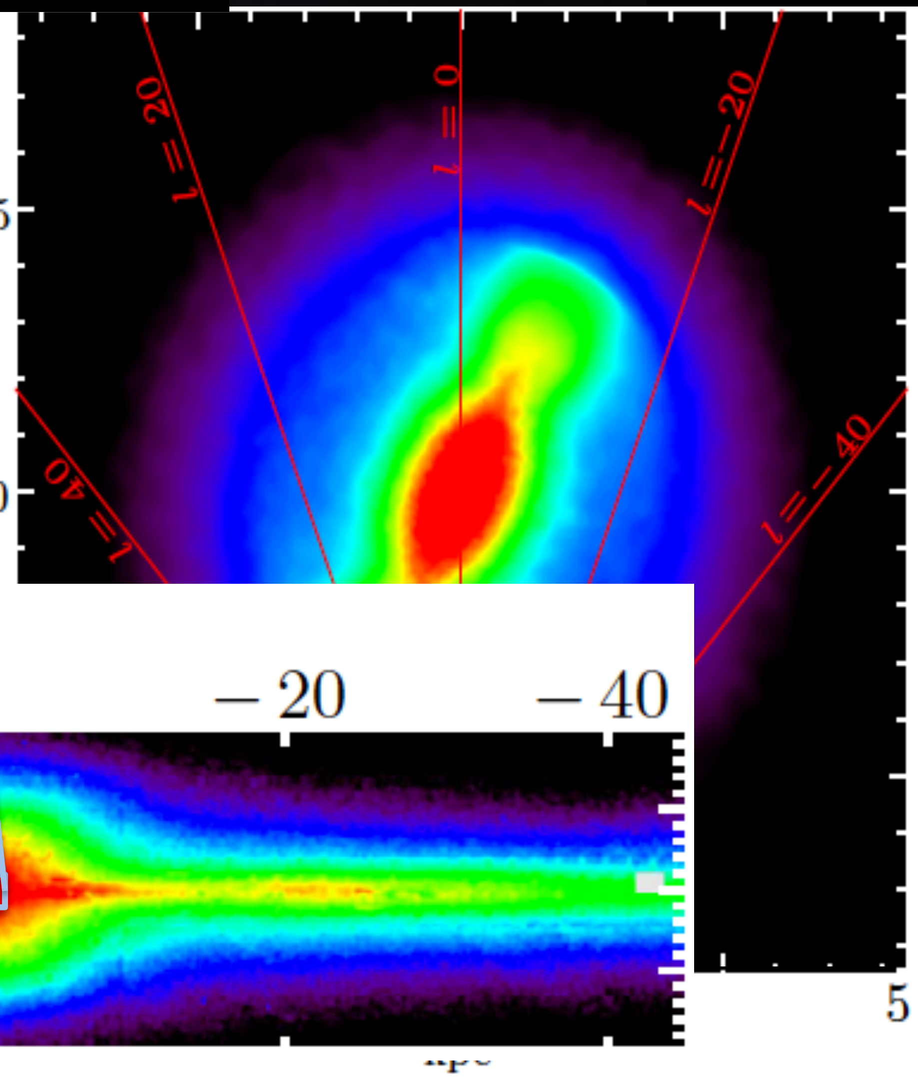
2. Spatial morphology

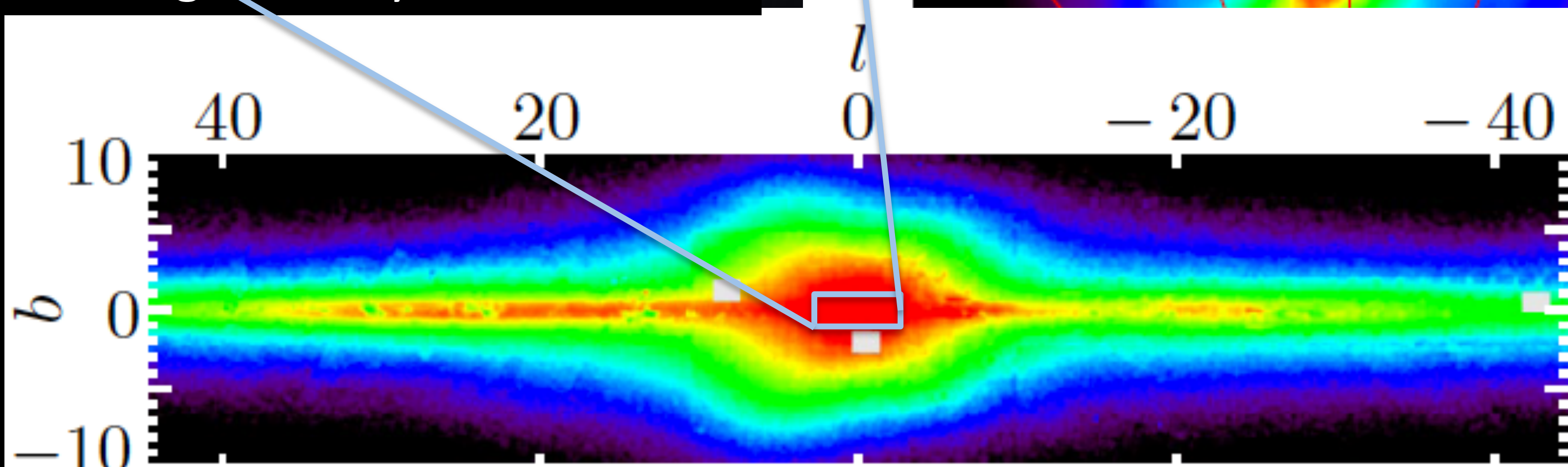
Nuclear Bulge: stellar cluster + stellar disk



Nishiyama et al (2013)

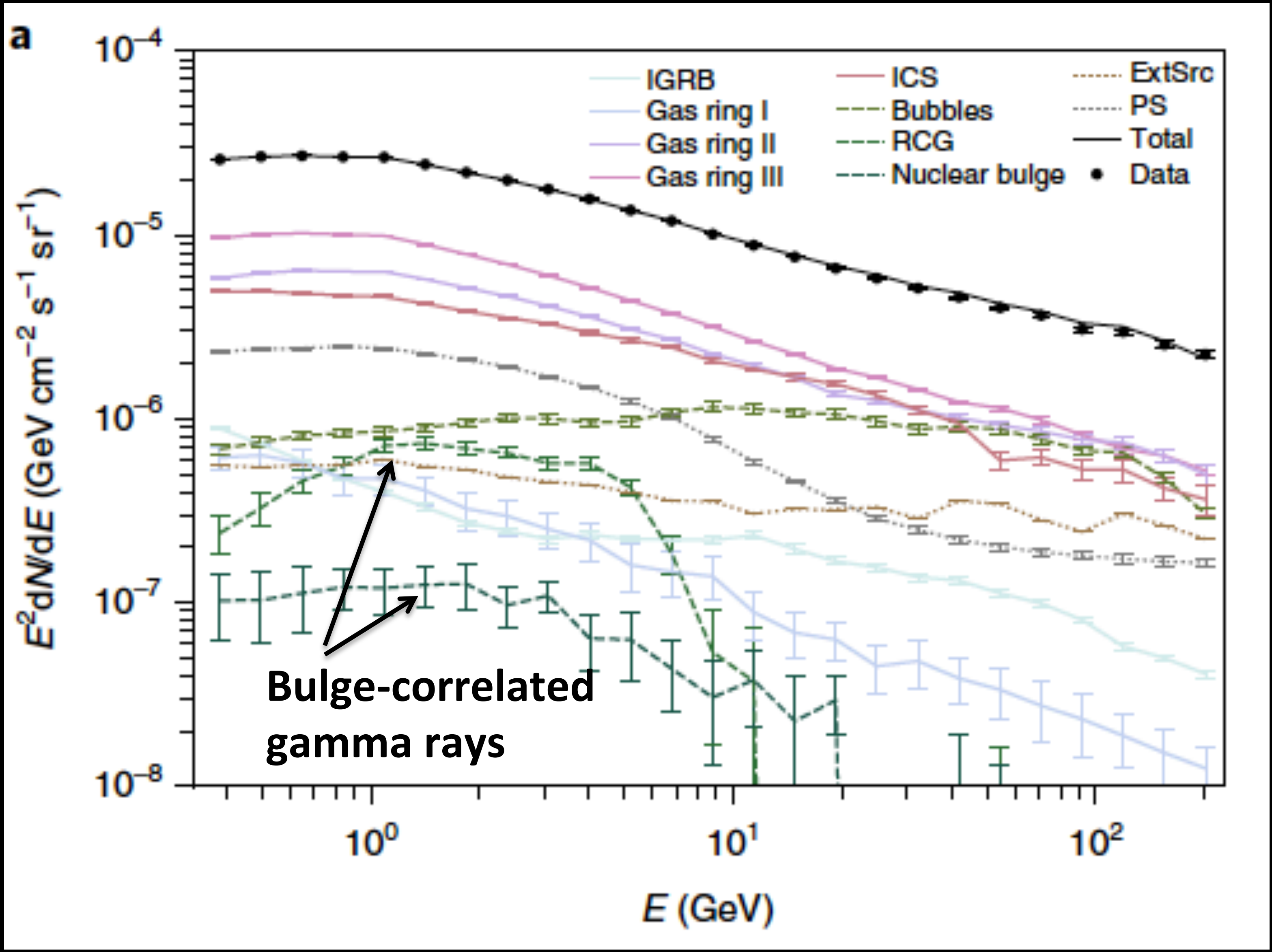
The boxy bulge:
rectangle, not symmetric





Bland-Hawthorn & Gerhard (2017)

Bulge-correlated gamma rays



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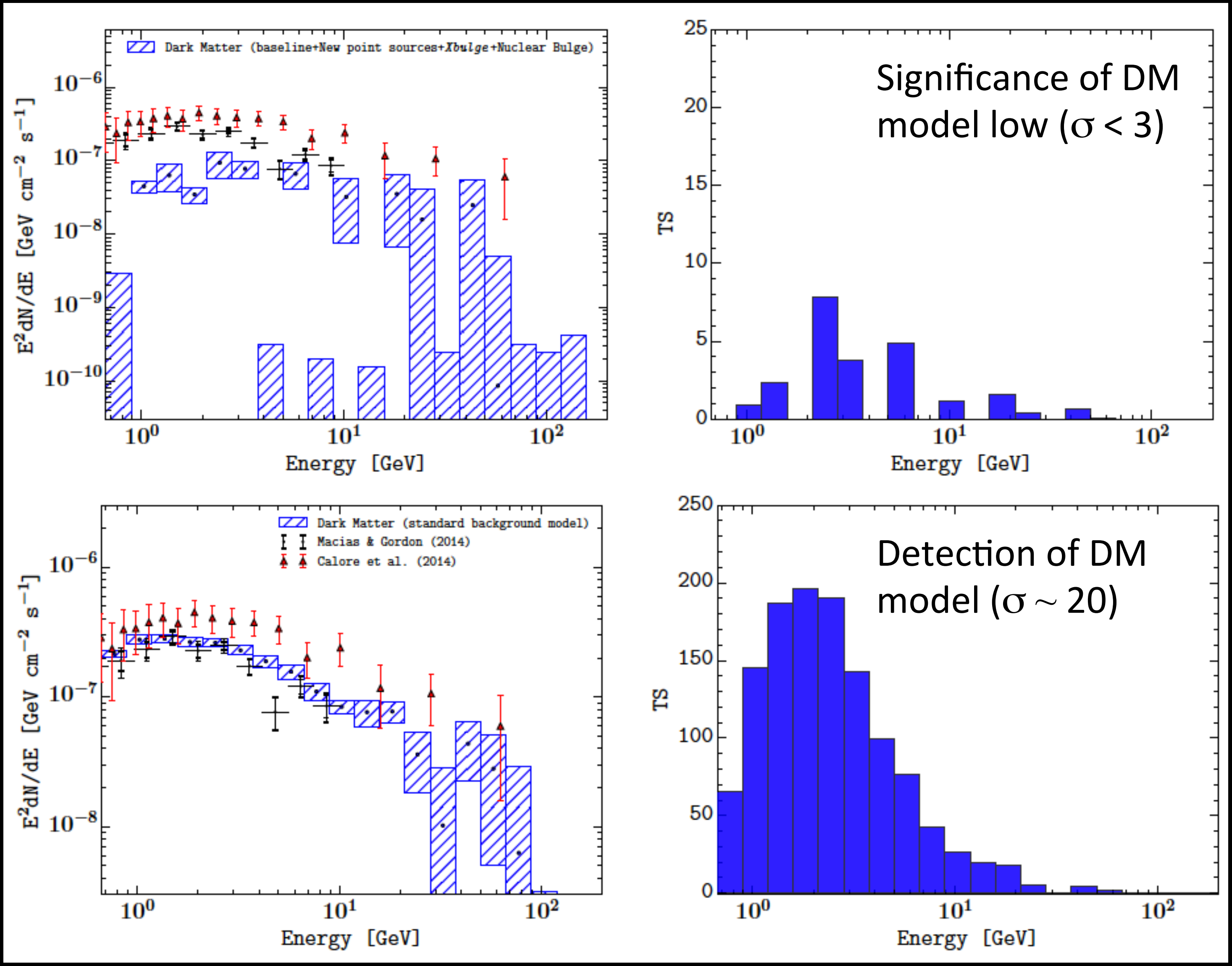
Bartels et al (2018), also Macias et al (2018)

No need for DM excess anymore



← **Bulge AND dark matter**

The data no longer needs a DM (NFW) component!

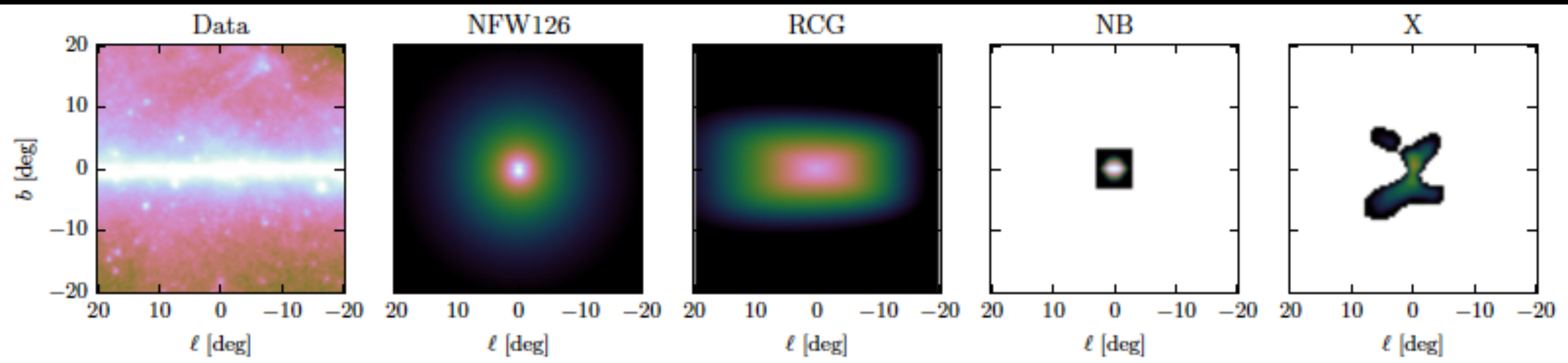
← **Dark matter only**

Representative of previous studies

Macias et al (2018)

SkyFACT : a hybrid approach

SkyFACT = **Sky F**actorization with **A**daptive **C**onstrained **T**emplates
Hybrid method combining adaptive spatial-spectral template regression and image reconstruction to account for small-scale model inaccuracies.

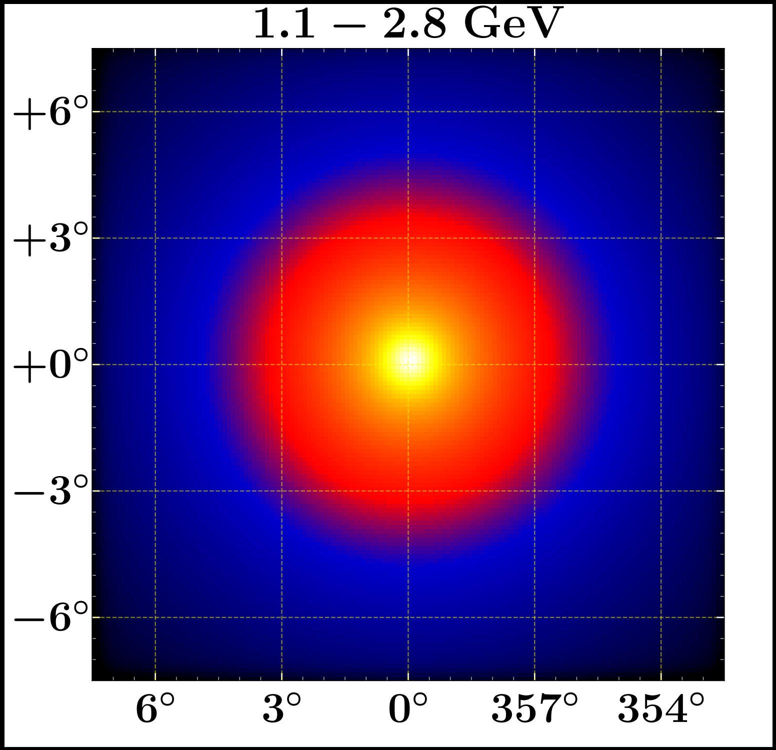


We demonstrated that the stellar bulge model provides a significantly better fit ($> 10\sigma$) to the data than the DM-emission related Einasto or contracted NFW profiles. Hence the GCE appears to simply trace stellar mass in the bulge, not the dark matter density squared (although the actual DM profile is sufficiently uncertain that this possibility cannot be entirely excluded). What

SkyFACT: Storm et al (2017)

Bartels et al (2018)

Spherical symmetric vs bulge



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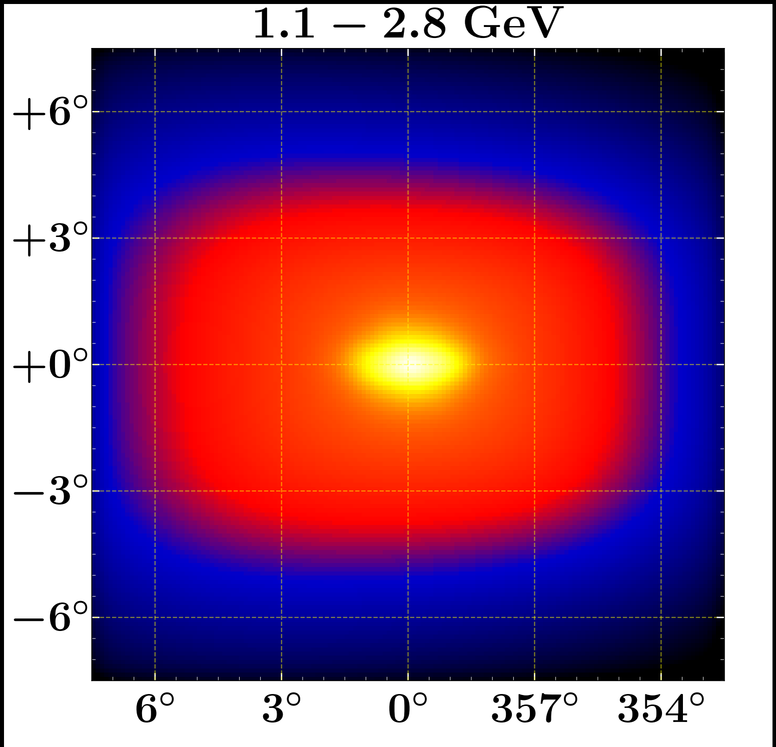

Detailed morphology and impacts
→ C. Gordon's talk Monday

Galactic Bulge Emission ?

**many checks done: masks, point source changes, rotations, diffuse model, …

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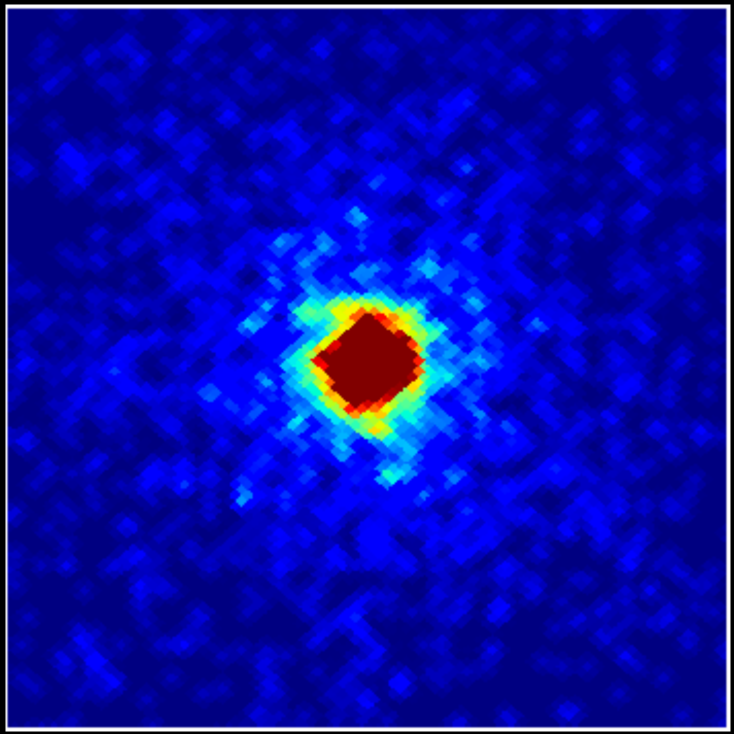
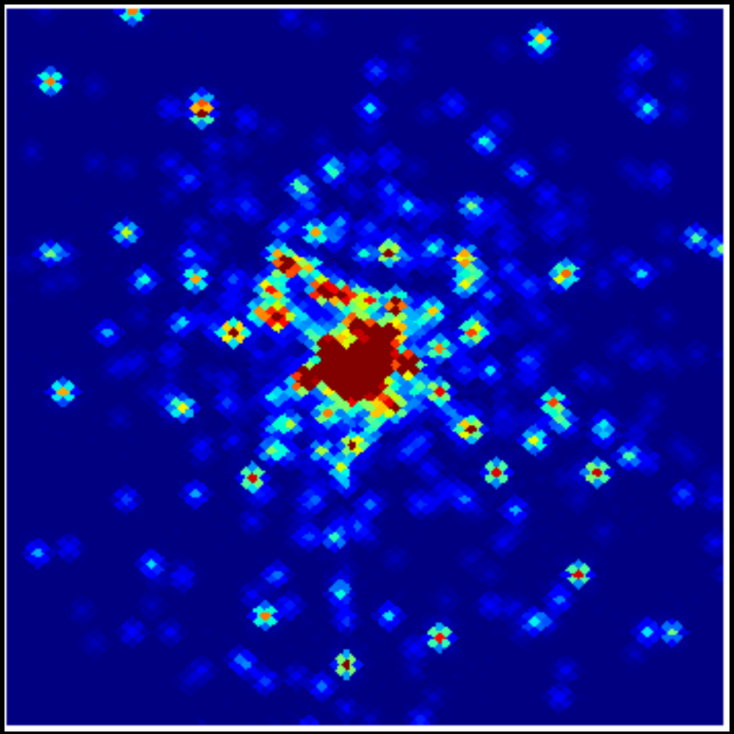
3. point source vs diffuse source



vs



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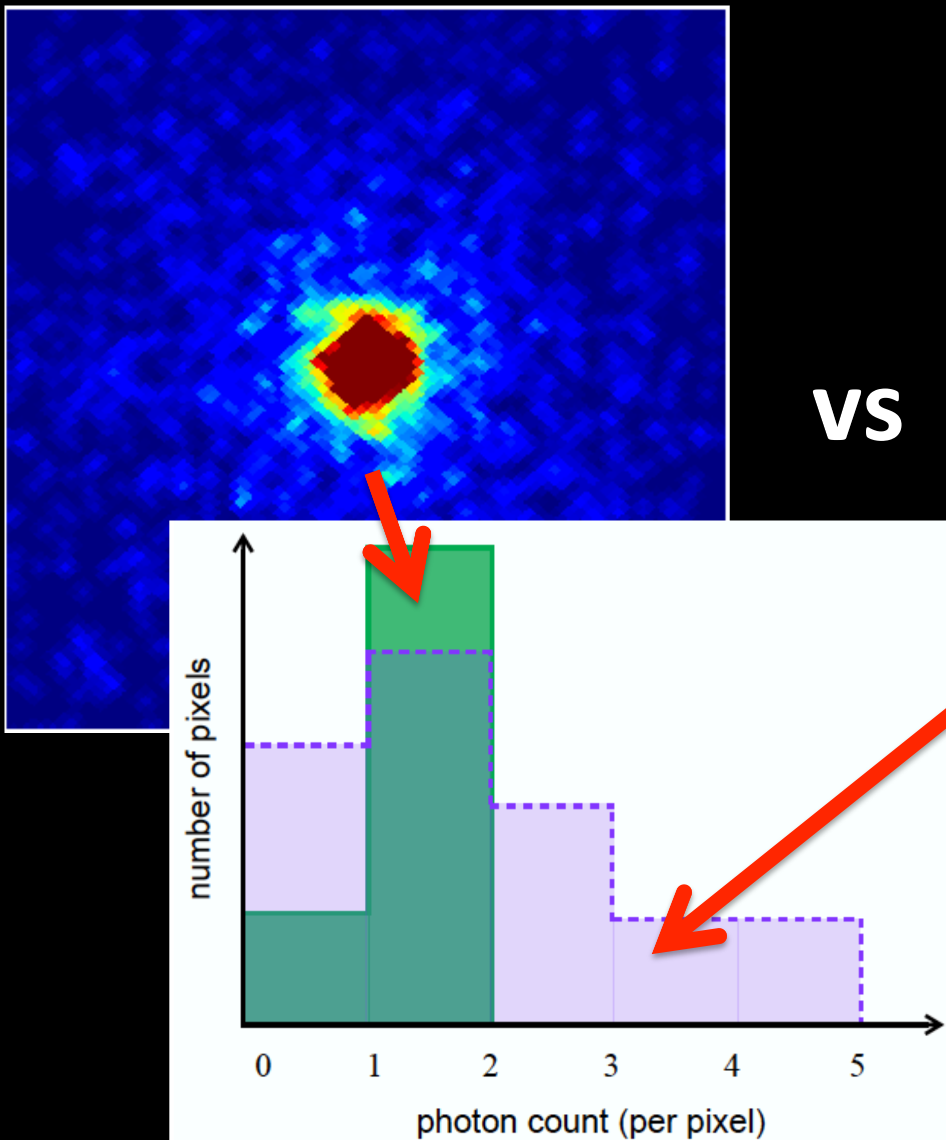
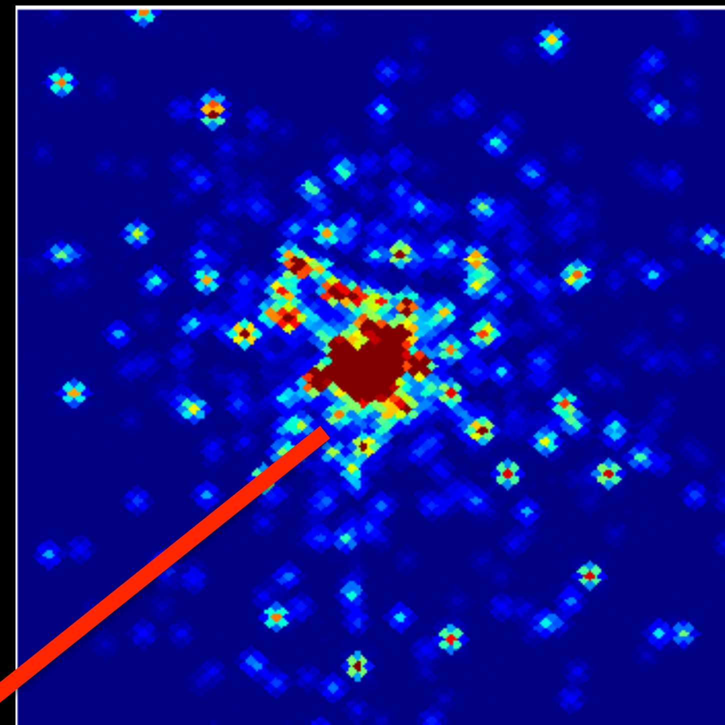
3. *point source vs diffuse source*



vs



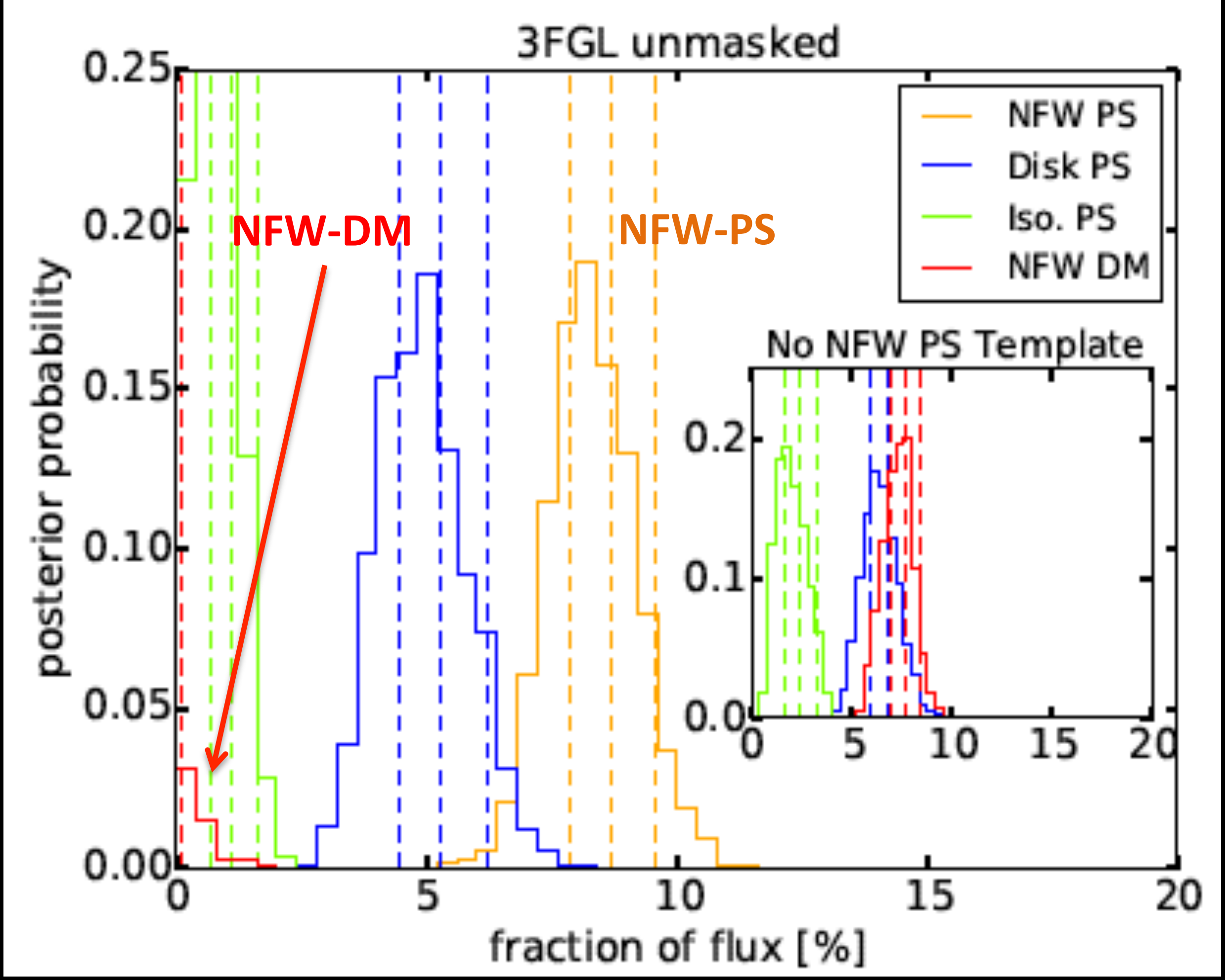
Photon count distribution look different

Lee et al (2016)
also Malyshev & Hogg (2011), *Bartels et al (2016) , Zechlin et al (2016)*

Photon count distribution fit result

- NFW-PS ~8.7% of photons, while NFW-DM is consistent with 0%
  - If NFW-PS is not added, the NFW-DM absorbs the excess
- Background model stays within 1% of high latitude values.

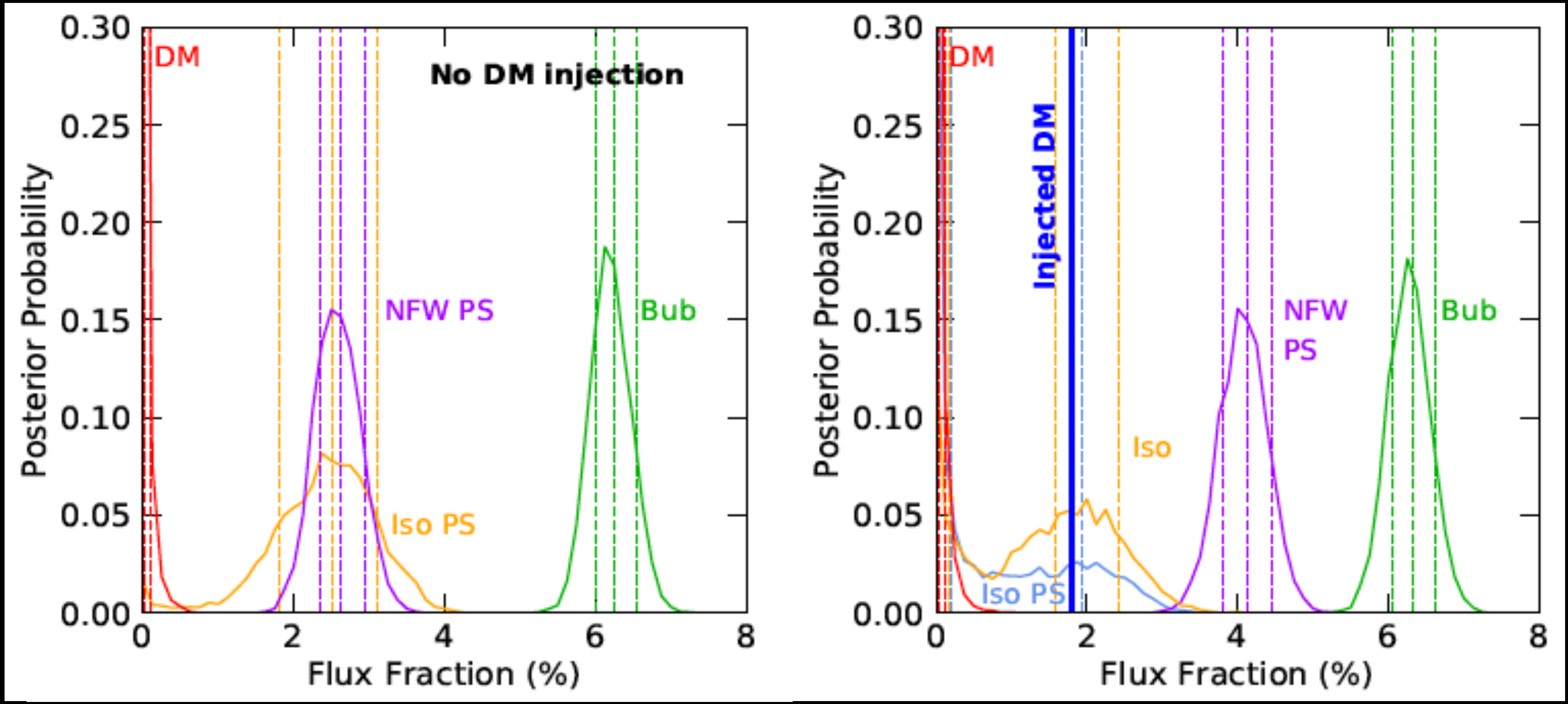
➔ **Strong preference for sub-threshold point sources over a diffuse NFW (dark matter) source**



Lee et al (2016)

Challenges

- Ultra-faint point population degenerate with diffuse source
- Un-modeled small-scale power in the data can erroneously be absorbed by NFW-PS even if NWF-DM injected into data



Leane & Slatyer (2019)
See also Chang et al (2019)

➔ May still allow DM signal, confirms substantial PS (more work ongoing)

MILLISECOND PULSAR IMPLICATIONS

Gamma / mass ratio

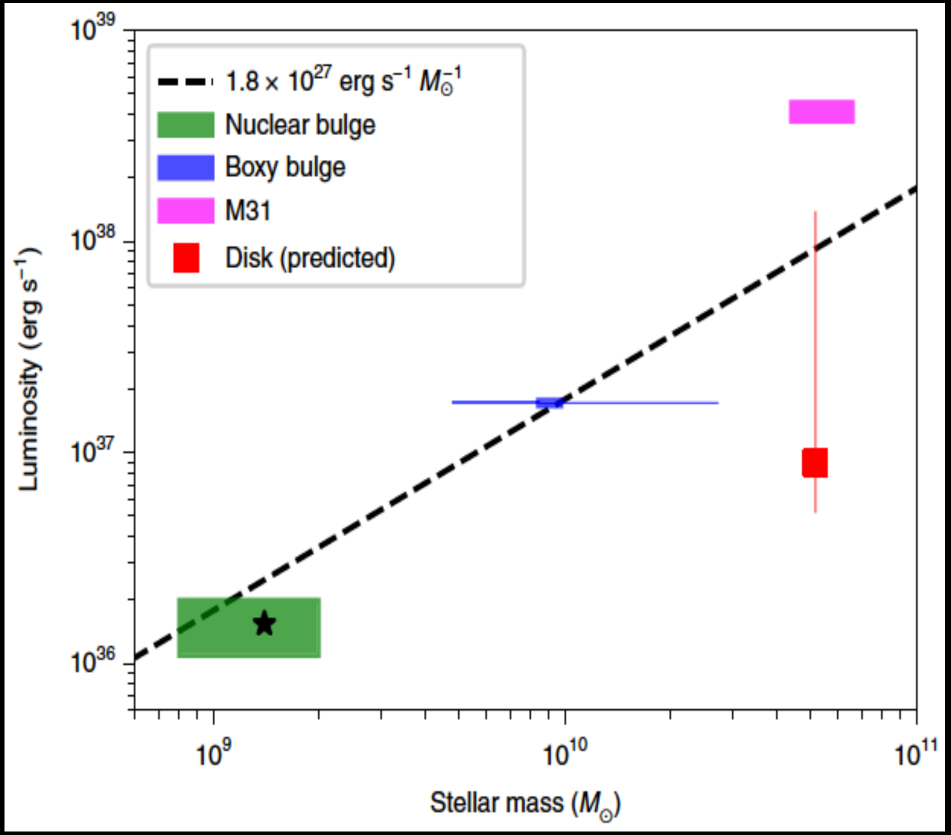
Simple hypothesis:
Gamma-ray luminosity scales linear with stellar mass

Bulge
Both boxy bulge & nuclear bulge

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

MSPs in the disk
~100 MSPS in the Milky Way disk,
but completeness uncertain

e.g., Hooper & Mohlabeng (2016), Winter et al (2016), Ploeg et al (2017), Bartels et al (2018)



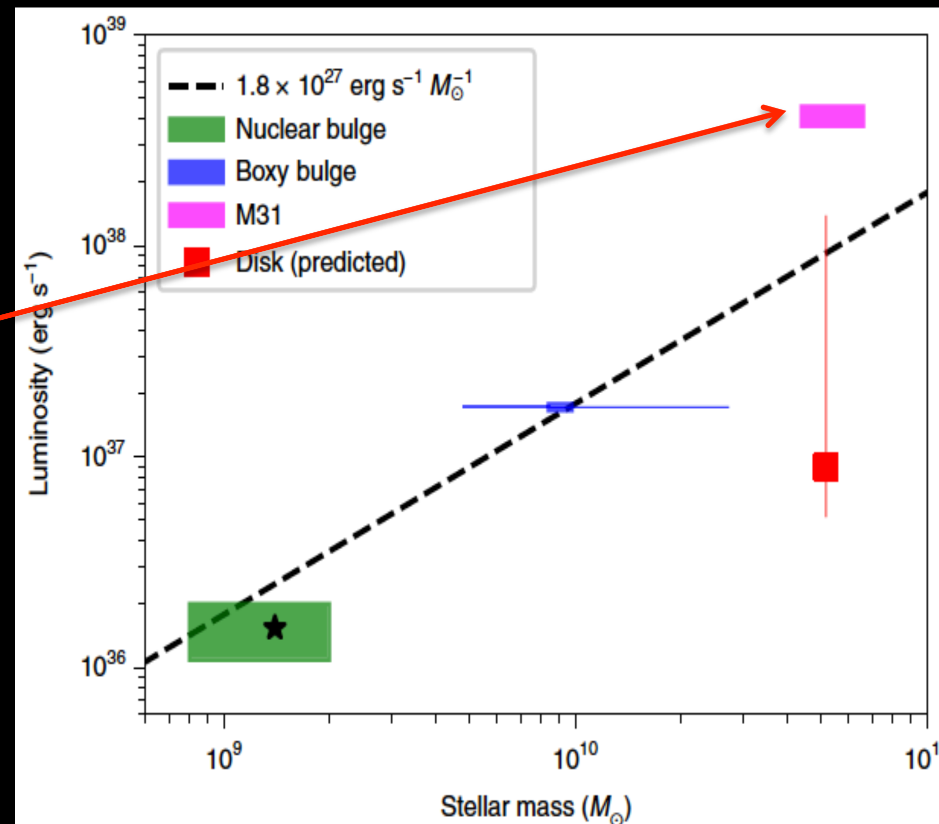
Bartels et al (2018)

**B/D ratio is ~1, cf 511 keV B/D ~ 0.6
Potential connection e.g. Crocker et al (2017), Bartels (2018b)

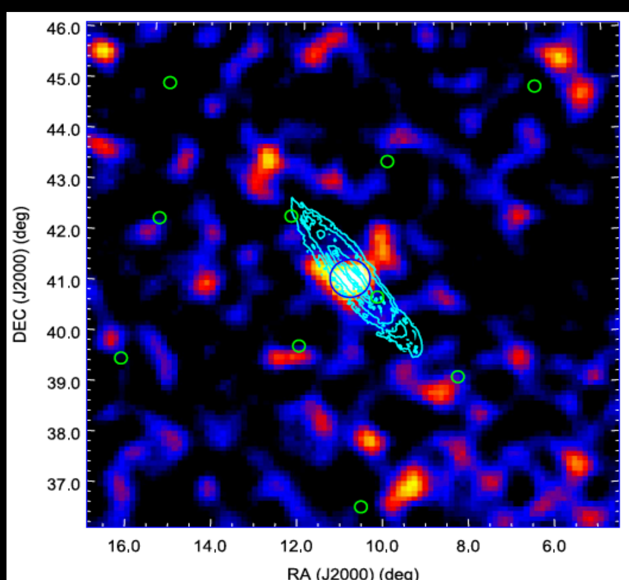
Gamma / mass ratio

Simple hypothesis:
Gamma-ray luminosity scales linear with stellar mass

M31:
Extended (at 4σ) and does not obviously correlate with gas density. Ratio high, but may include some disk emission and sources)



Bartels et al (2018)



Fermi (2017)

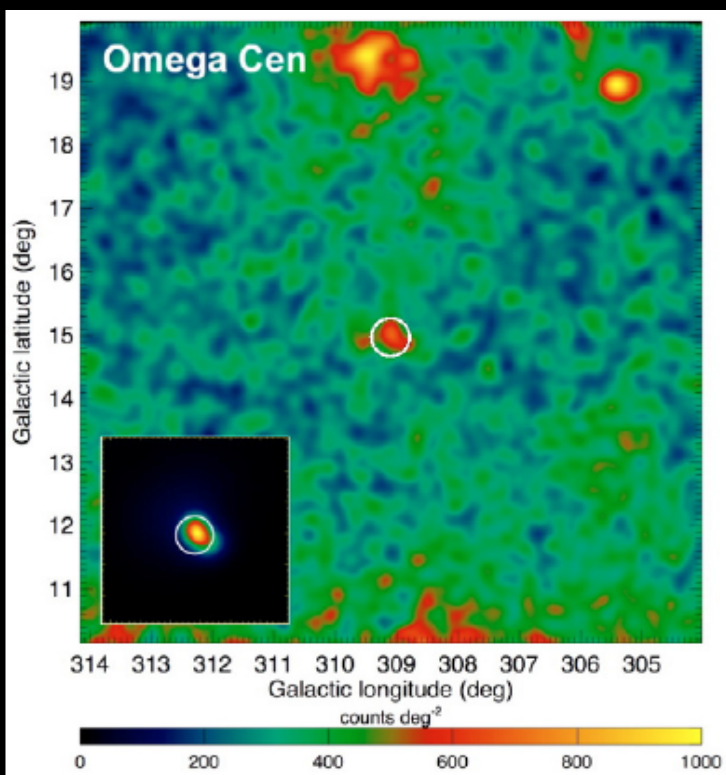
Gamma rays from globular clusters

Fermi:
Some 2 dozen detections, most likely due to MSPs

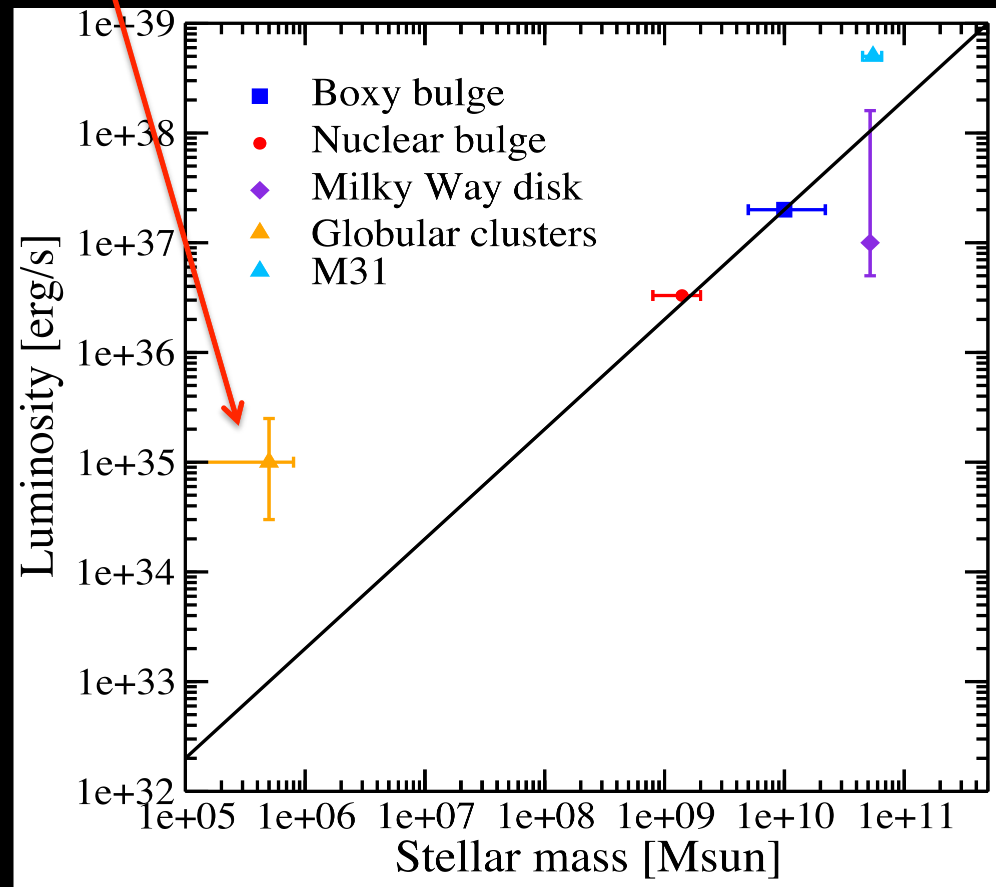
(but, see, *Brown et al 2018, 2019; vs Bartels & Edwards 2019*)

Luminosity/mass ratio:
Higher by factor O(100)

➔ Departure from simple scaling



Fermi (2010)



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MSP formation scenarios

Importance of binaries

MSPs form in binaries, going through a LMXB phase (recycling scenario), and binary can be:

- Primordial ~ stellar mass
- Dynamically captured ~ encounter rate

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

c.f. LMXB

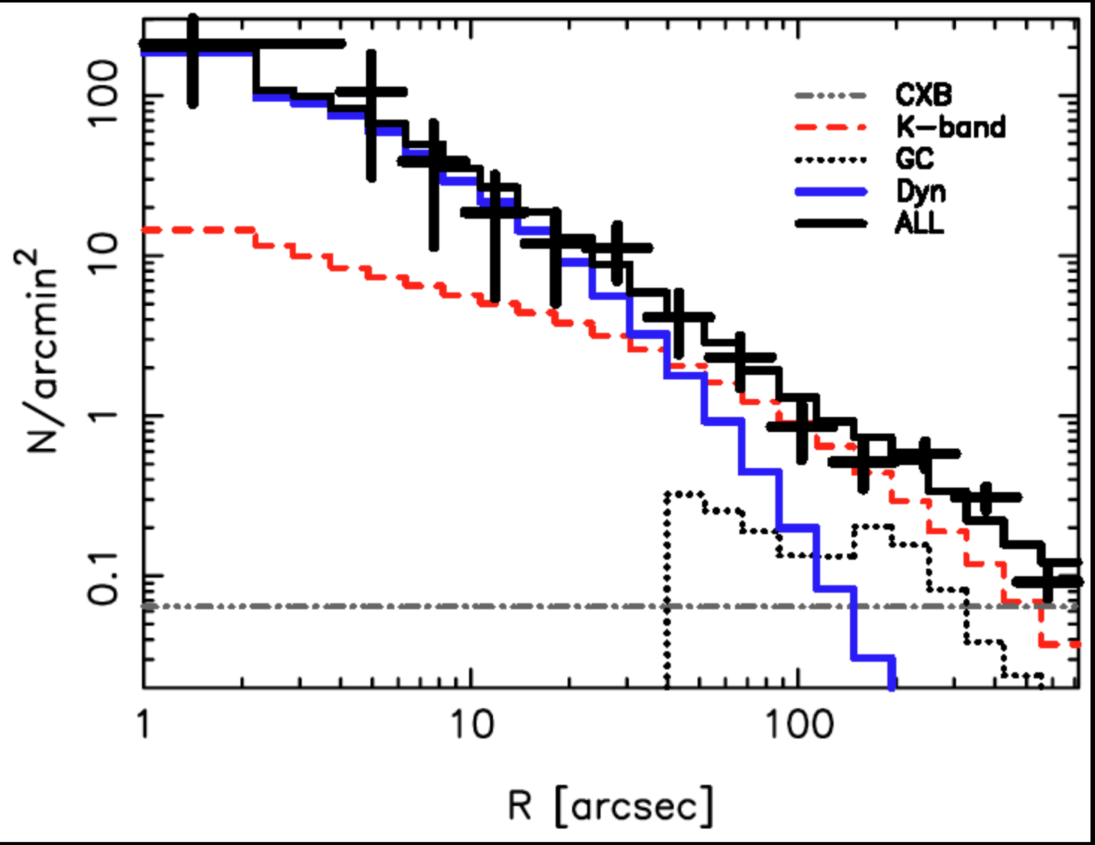
Departure from linear scaling:

- 10—100 times more common in globular cluster than in the disk

Verbunt & Lewin (2006)

- In M31, ~25% show dynamic origin

Voss & Gilfanov (2007)



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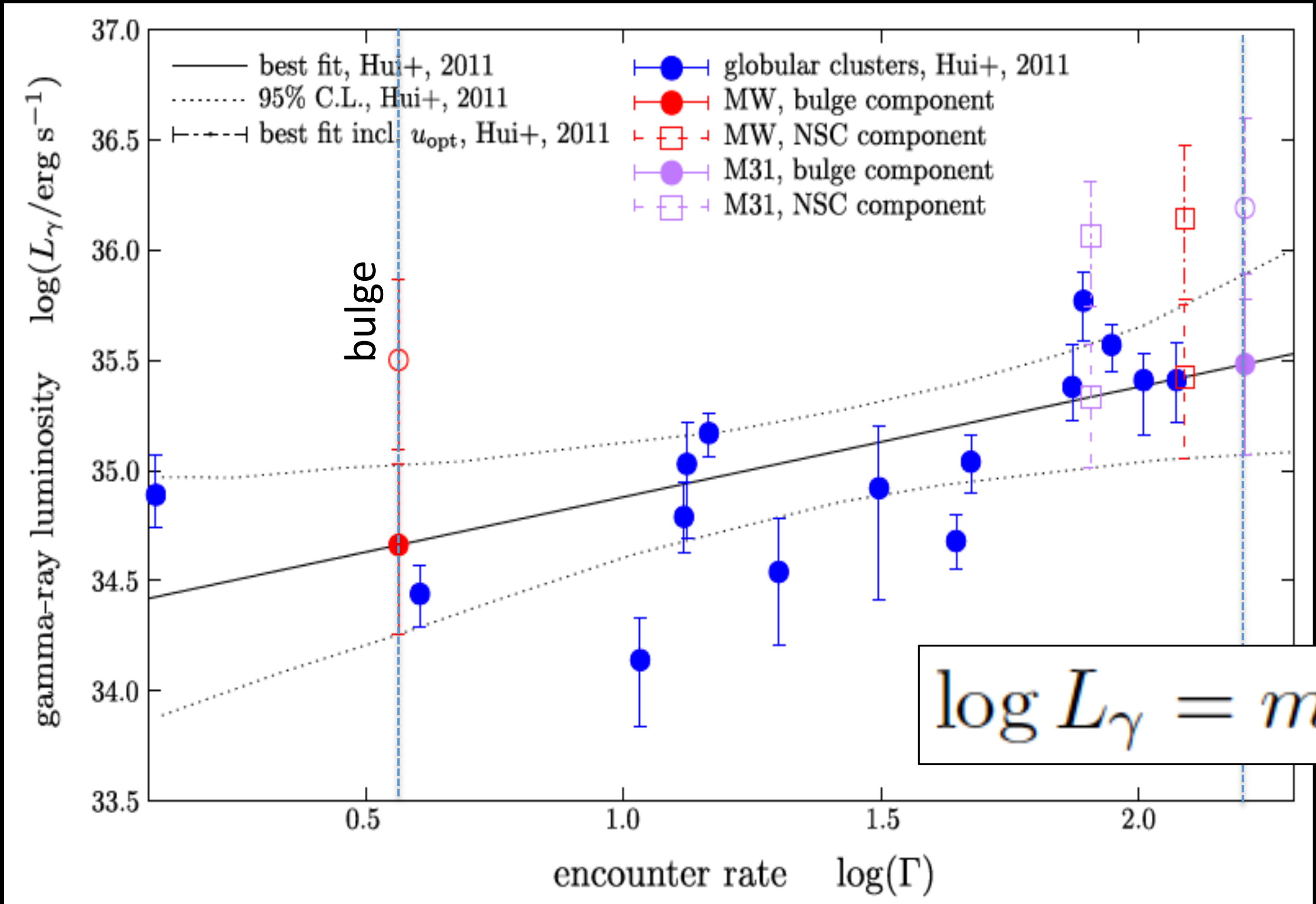
Encounter rates

Encounter rate: $\Gamma \propto \rho_*^2/\sigma$



$$\log L_\gamma = m \log \Gamma_e + c,$$

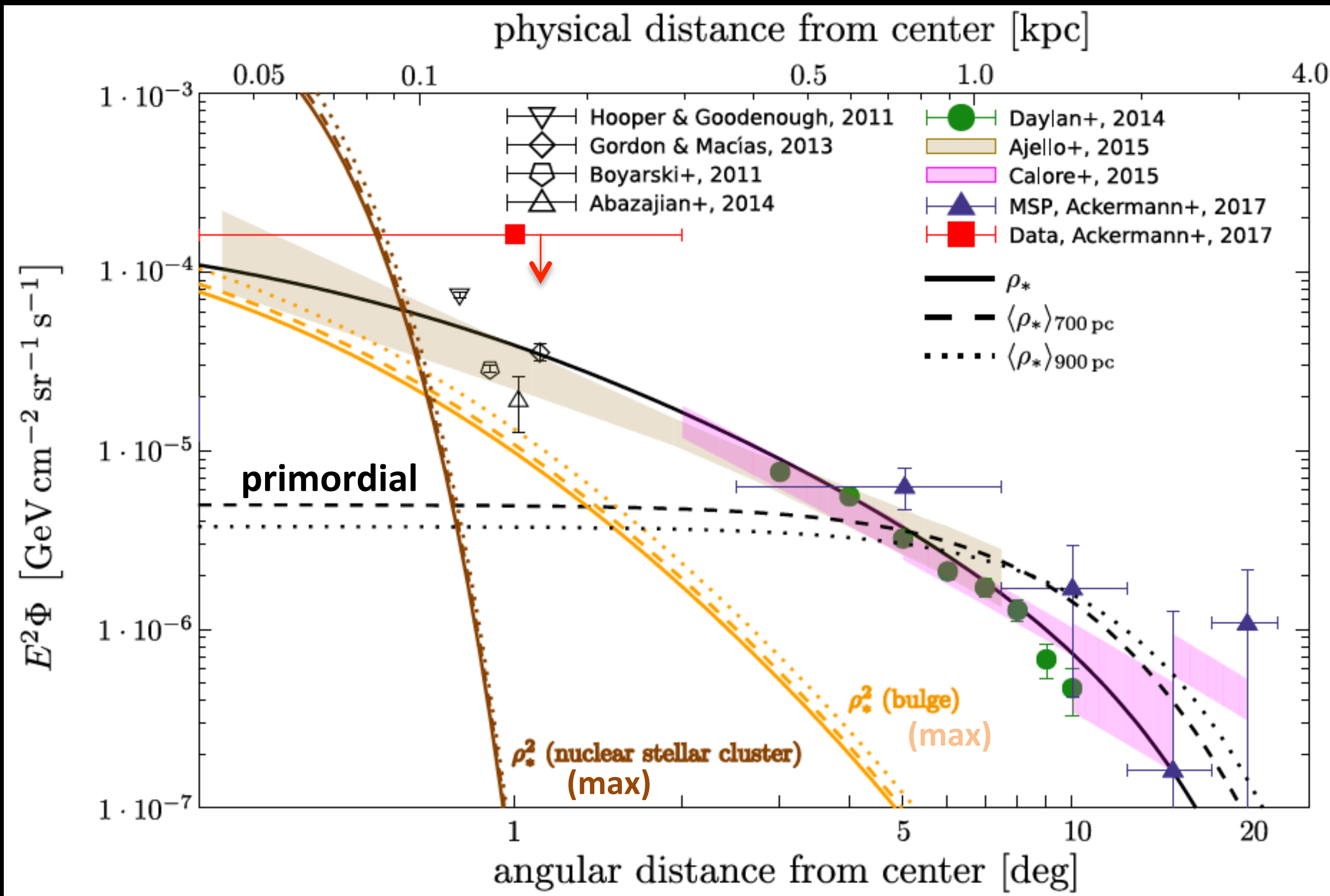
Most γ-ray detected globular clusters have higher encounter rates than Milky Way bulge

Eckner et al (2017); also Hui et al (2011)

Simple addition of dynamical MSPs

MSP in the bulge

In-situ MSP = primordial + dynamical (modeled after globular clusters)



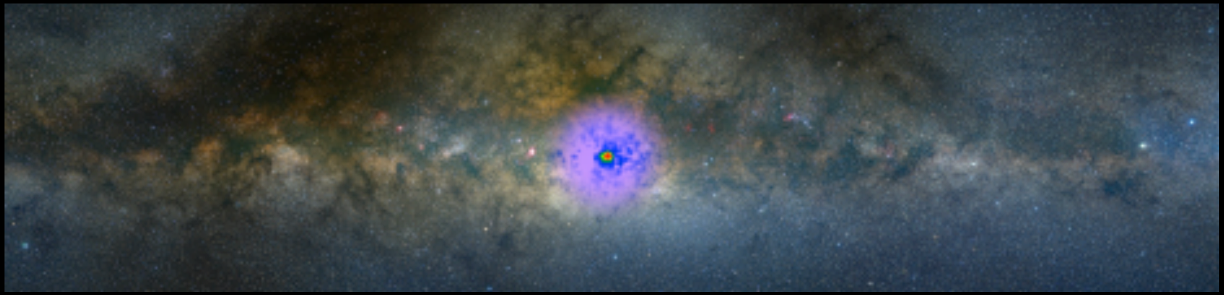
Eckner et al (2017)

Primordial:
Explains most of the GCE outside a few degrees

Dynamical:
Overall small contribution, but important on sub-degree scales

Concluding remarks

- GeV excess found by many groups employing varying techniques



- ***Recent developments favor pulsars***
  - ***The spatial morphology of the excess traces much better the stars of the Galactic bulge rather than annihilating dark matter***
  - ***Photon count statics favor substantial sub-threshold point source***
- Consistent with known millisecond pulsars & formation scenarios
- Many new ideas to test hypothesis → *F. Calore's talk tomorrow*

Rich MSP formation possibilities

LMXB / MSP ratio: Assuming the same ratio with globular clusters

$$L_\gamma^{\rm IG} = L_\gamma^{\rm clusters} \times \left(\frac{N_{\rm LMXB}^{\rm IG}}{N_{\rm LMXB}} \right)$$

MSPs power at most ~22% of GCE

Haggard et al (2017)

$$L_\gamma^{\rm IG} = (2.09^{+0.86}_{-0.71}) \times 10^{36}\,{\rm erg/s}, \quad \text{Only Sources Classified as LMXBs}$$
$$L_\gamma^{\rm IG} = (4.38^{+1.79}_{-1.48}) \times 10^{36}\,{\rm erg/s}, \quad \text{Including All Unclassified Sources}$$

→ MSPs systematically different in bulge & globular clusters?

e.g., accretion-induced collapse (AIC) of white dwarfs scenario:

- ✓ Different relation between X-rays and gamma rays
- ✓ Naturally low kick velocities
- ✓ Naturally low B-fields
- ✓ Could be comparable to the recycling channel in the disk
- ✓ Possible link to 511 keV (e+ source)

Crocker et al (2017), Bartels et al (2018)

Primordial vs dynamical

Simple morphological test:
primordial + dynamical channel with

template = ρ_{bulge}^s

➔ **Primordial 30 – 73% of GCE**

Macias et al (2019)