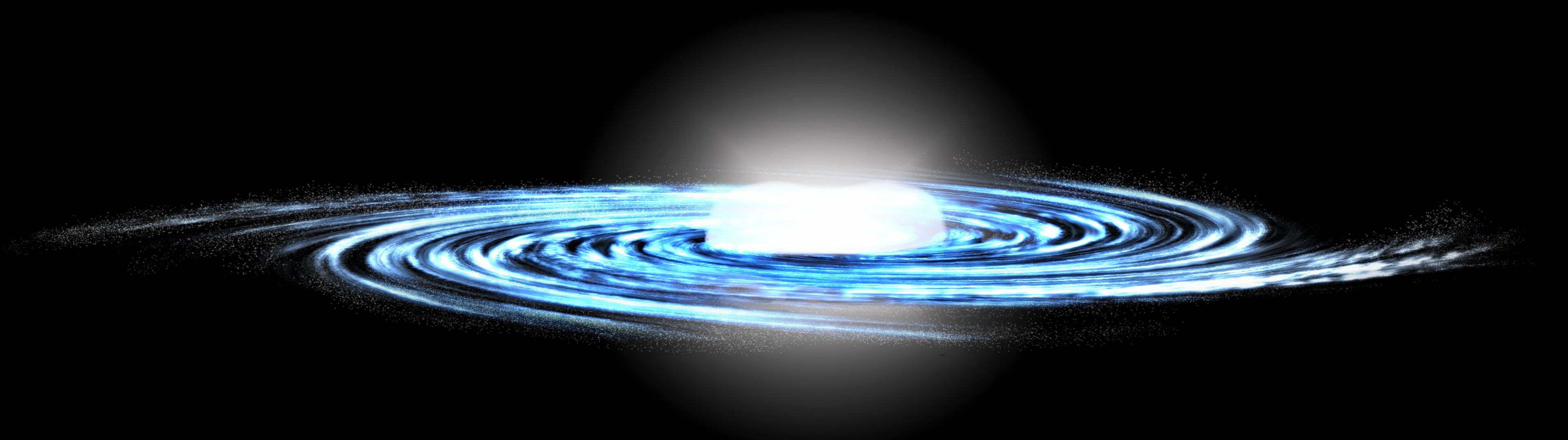
Stronger Evidence that the Galactic Bulge is shining in gamma-rays



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ArXiv:1901.00???

Kavli IPMU – Berkeley Week
Jan 8, (2019)

KAVLI IPMU

GRAPPA
GRavitation AstroParticle Physics Amsterdam

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   Overall consensus that the excess is real but uncertainties are large

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   Millisecond pulsars and new methods to detect them

1. INTRODUCTION TO THE GALACTIC CENTER EXCESS

Galactic Center Excess (GCE)

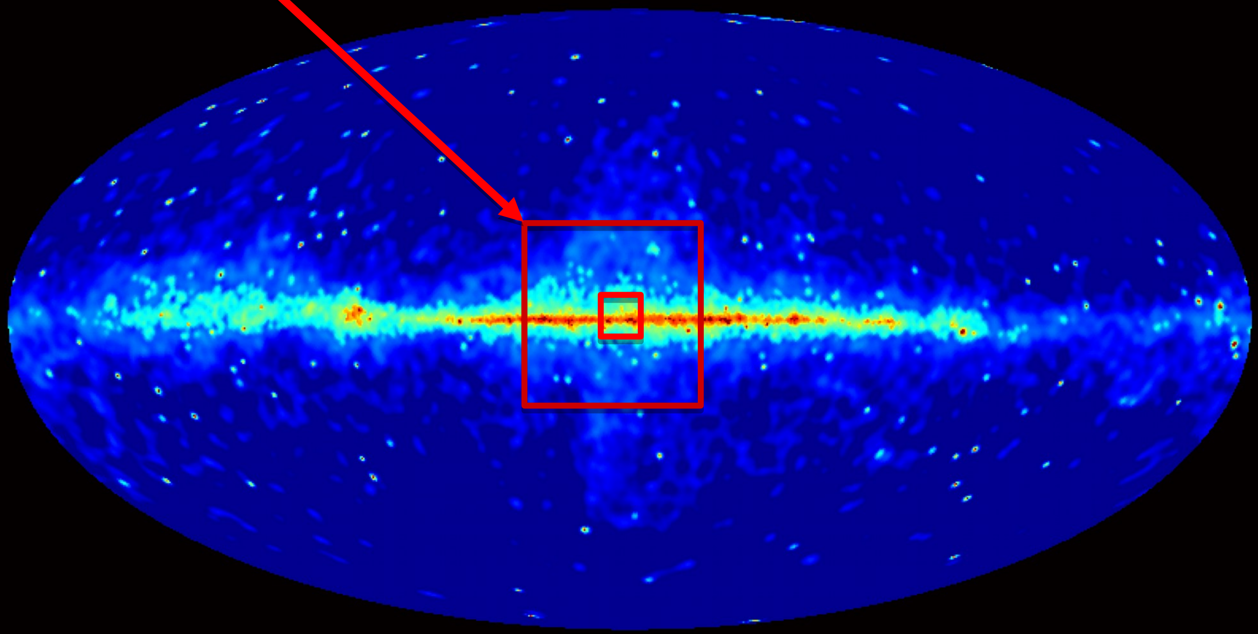
From the Galactic Center out to mid-latitudes

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)
Zhou et al (2014)
Daylan et al (2014)
Selig et al (2015)
Huang et al (2015)
Gaggero et al (2015)
Carlson et al (2015, 2016)
Yand & Aharonian (2016)
Horiuchi et al (2016)
Lee et al (2016)
Bartels et al (2016)
Linden et al (2016)
Ackermann et al (2017)
Ajello et al (2017)
Macias et al (2017)
Bartels et al (2017)
…

(not a complete list)

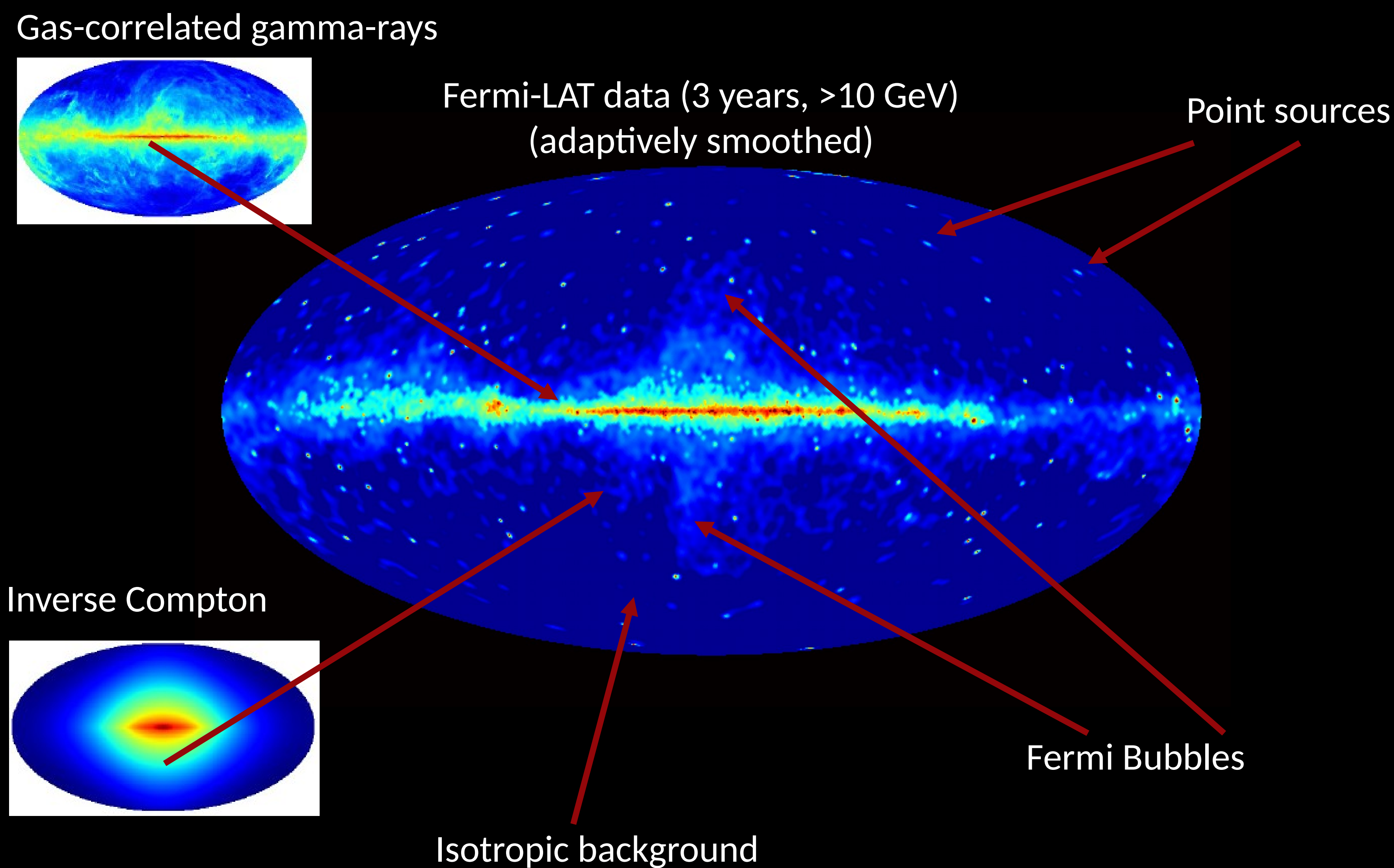
Method

Found by morphological template fitting



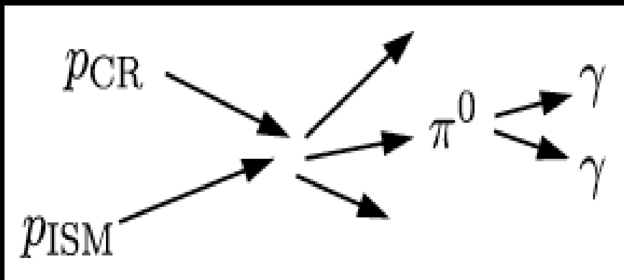
Fermi-LAT data (3 years, >10 GeV)
(adaptively smoothed)

The gamma-ray Sky

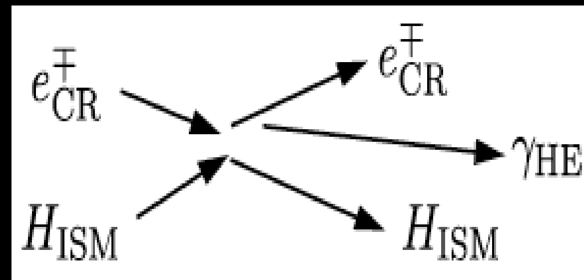


Galactic Diffuse Emission

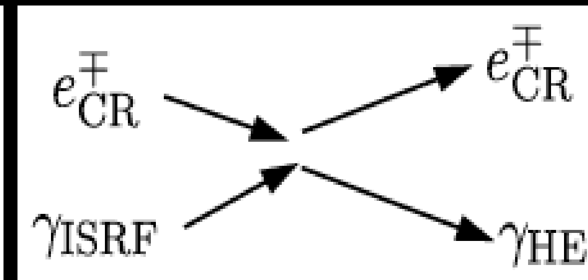
Decay of neutron pions



Bremsstrahlung



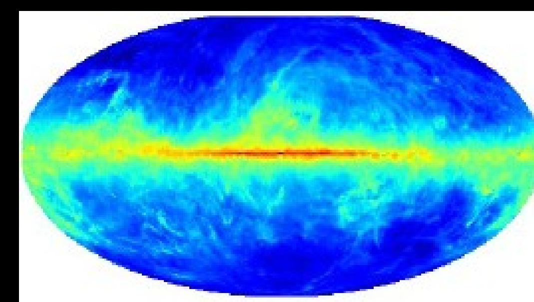
Inverse Compton

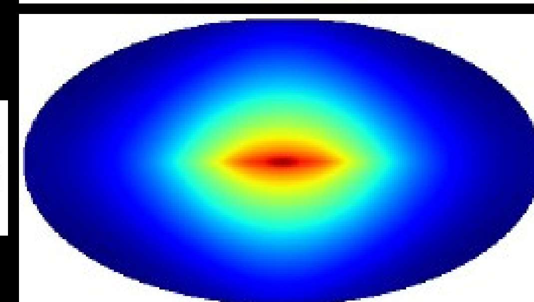


Simulations

Numerically solve the diffusion equation, e.g., Galprop

- ✓ Allows physical parameter choices
- ✓ Can be tuned to the Galactic Center
- ✗ Many parameters not well known
- ✗ Still missing some physics
- ✗ Still poor resolution



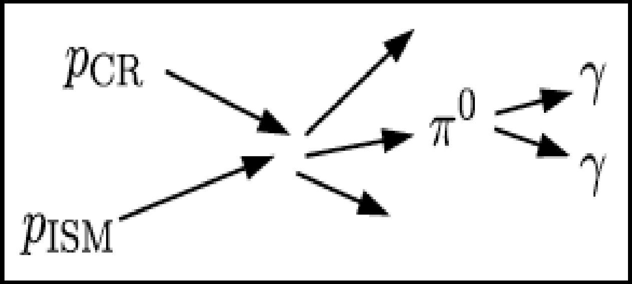


$$\frac{\partial \psi}{\partial t} = q(\vec{r},p) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$

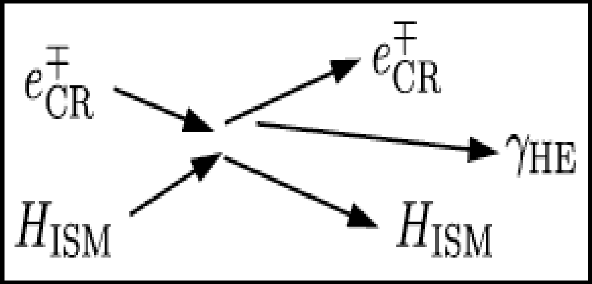
e.g., Galprop; Moskalenko & Strong (1998)

Galactic Diffuse Emission

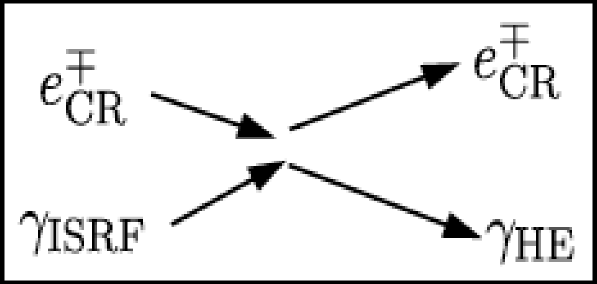
Decay of neutron pions



Bremsstrahlung



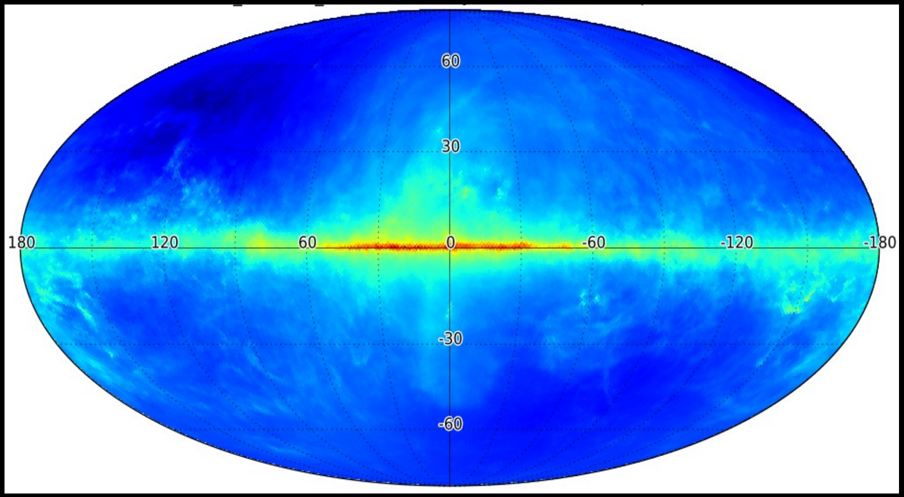
Inverse Compton



Fermi diffuse map

Built for all-sky, starting with many templates split into annuli

- ✓ Simple (hard work already done!)
- ✓ Accounts for some cosmic-ray injection and propagation variations (via annuli)
- ✗ Somewhat of a black box for user
- ✗ Fixed to (usually) older data
- ✗ Construction not dedicated for the Galactic Center

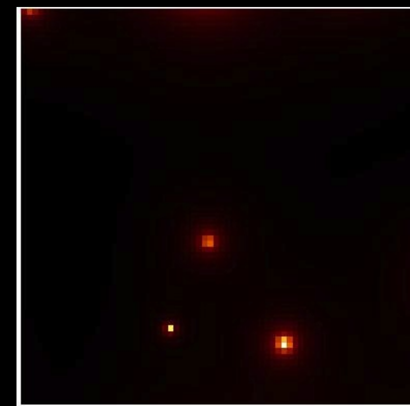


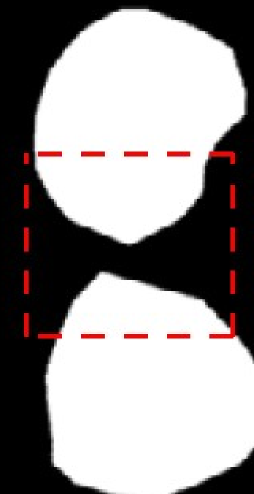
Acero et al (2016)

Modeling strategy: template fitting

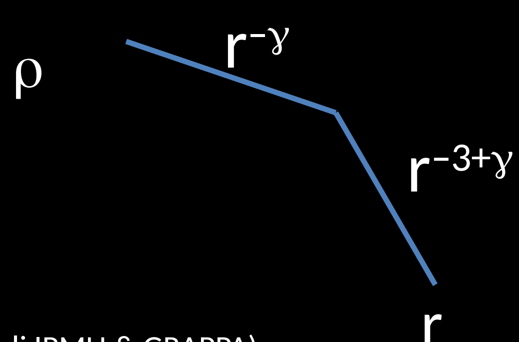
Background and foreground:
List of known point and extended sources, e.g., gas-correlated, Inverse Compton, Fermi bubbles, …

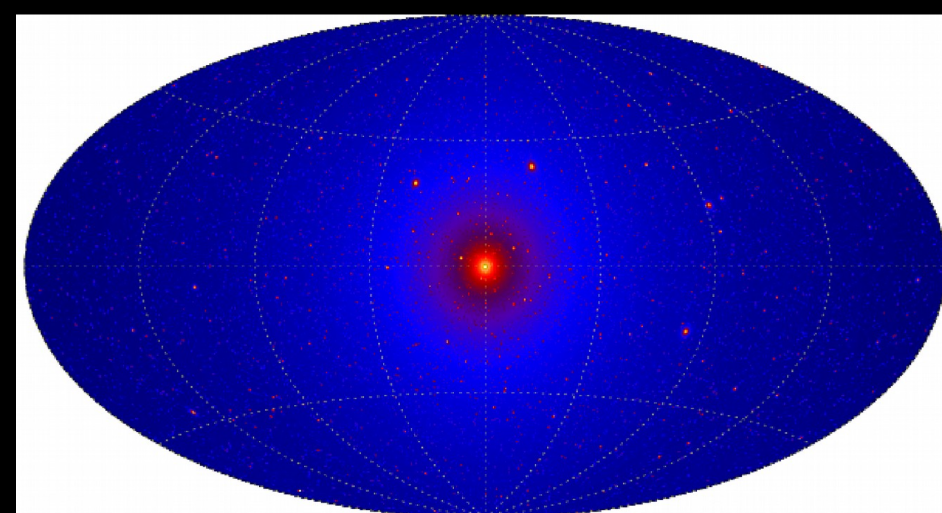
New physics template:
"generalized" NFW-squared template, which allows for cosmological simulation info with parameterized contraction effects





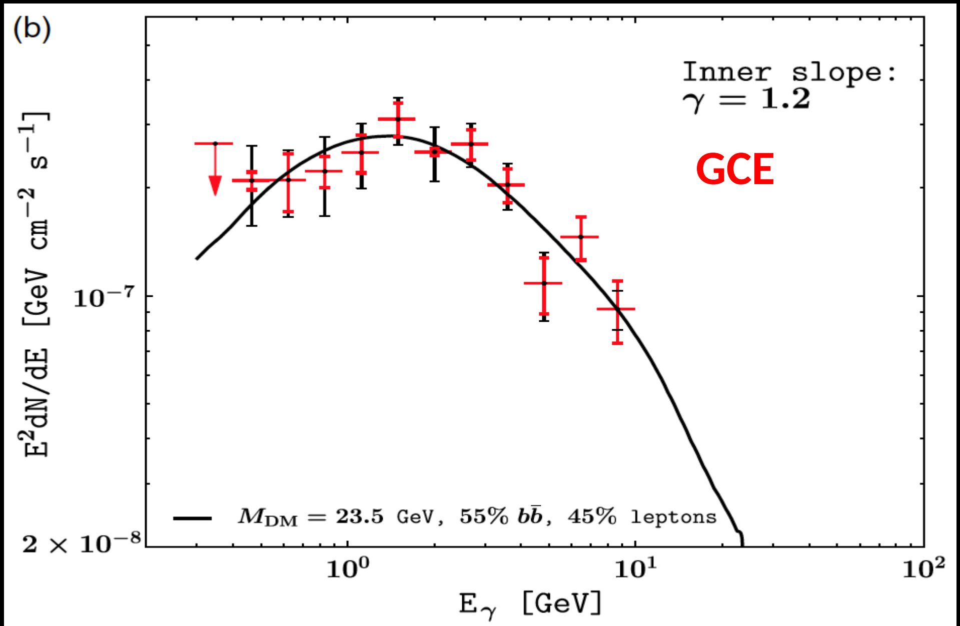
$$\rho \propto \left(\frac{r}{r_s}\right)^{-\gamma} \left(1 + \frac{r}{r_s}\right)^{-3+\gamma}$$





Results

Gordon & Macias (2013)



The dark matter template is detected in excess wrt to

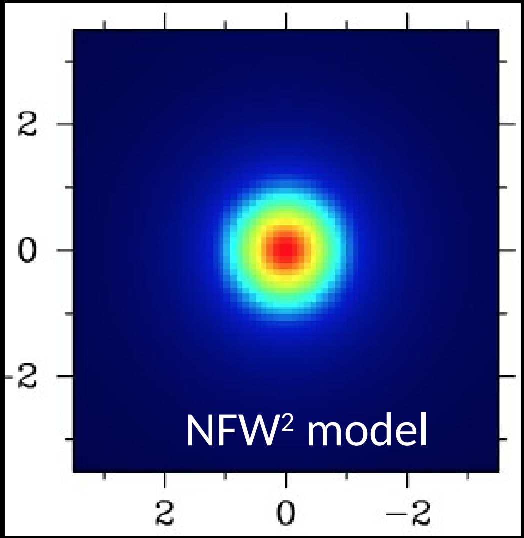
- Galactic diffuse models
- Point source catalog

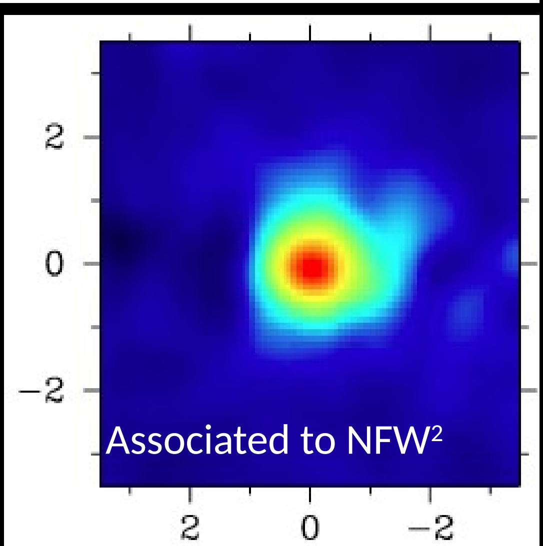
Main features:

- Spectrum peaks at a ~GeV
- Peak flux ~$10^{-(6-7)}$ GeV cm^{-2} s^{-1}
- Gamma-ray luminosity is ~10^{37} erg/s
- Spatial morphology ~$r^{-2.4}$

Significance

Statistical significance is ~20–60σ depending on the data and templates used.



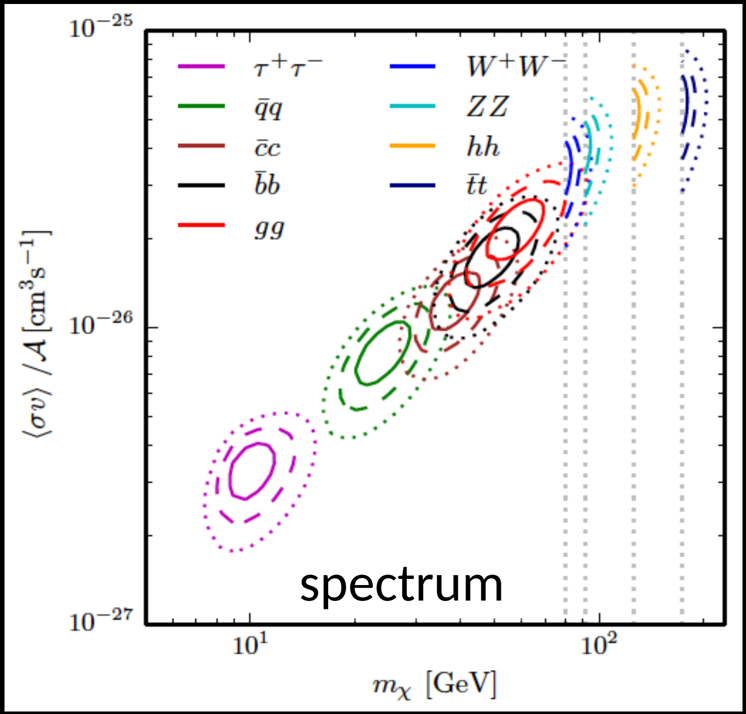


Abazajian & Kaplinghat (2012)

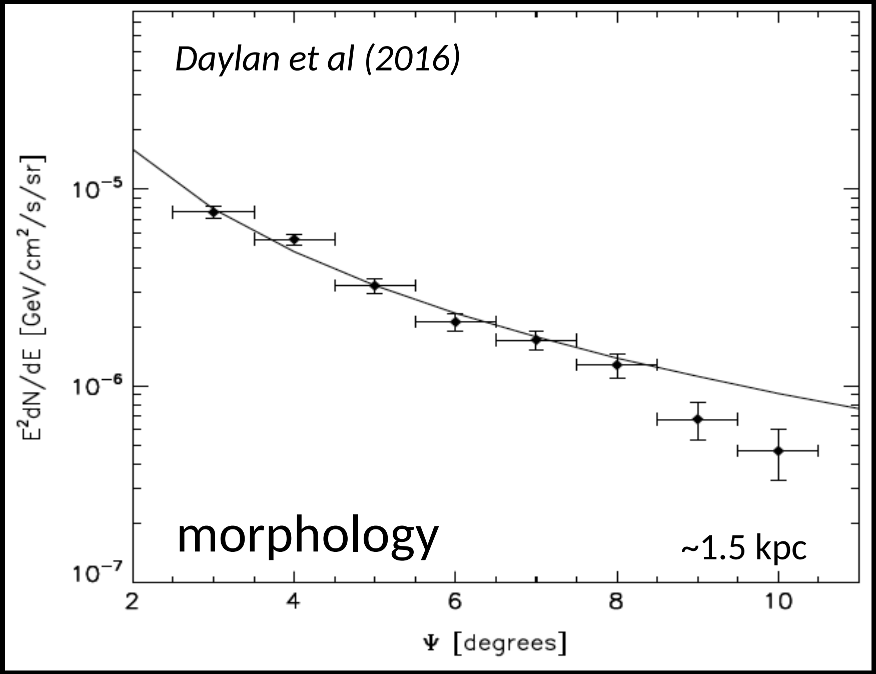
Dark Matter

Earlier studies showed that Dark matter can explain the observations

Annihilation of thermally produced WIMPs explains the spectrum and morphology well.



Calore et al (2014)

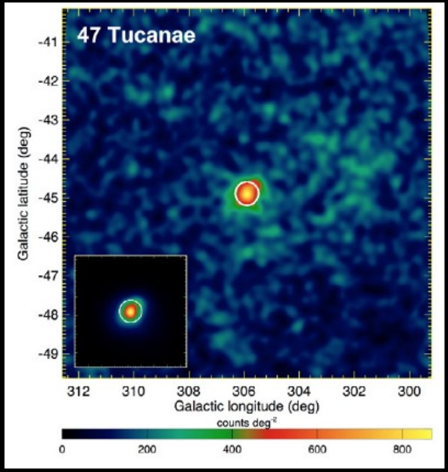


Spectral similarity with millisecond pulsars

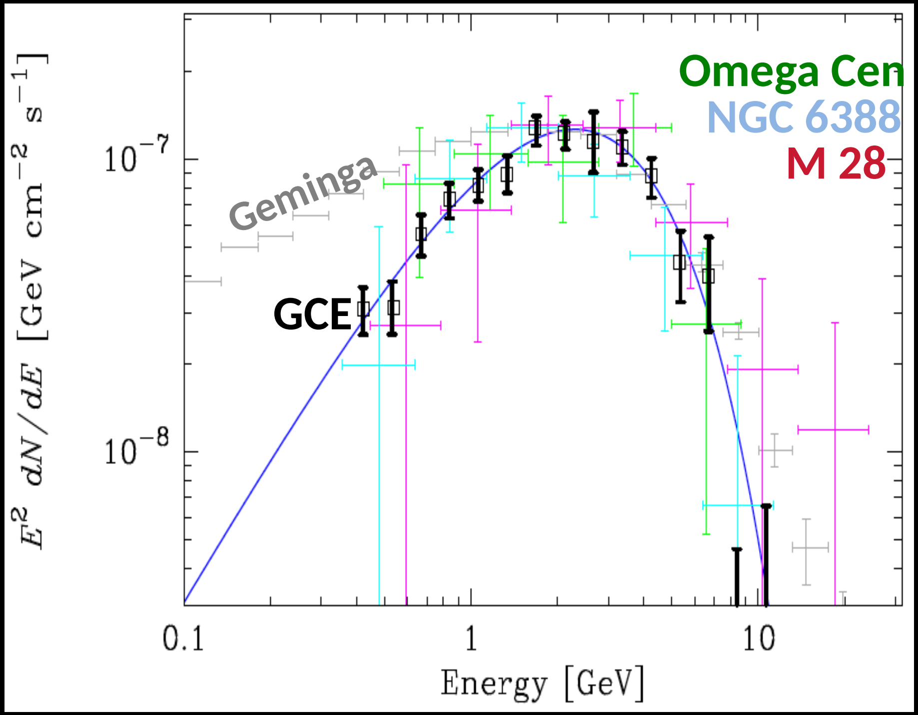
Millisecond pulsars

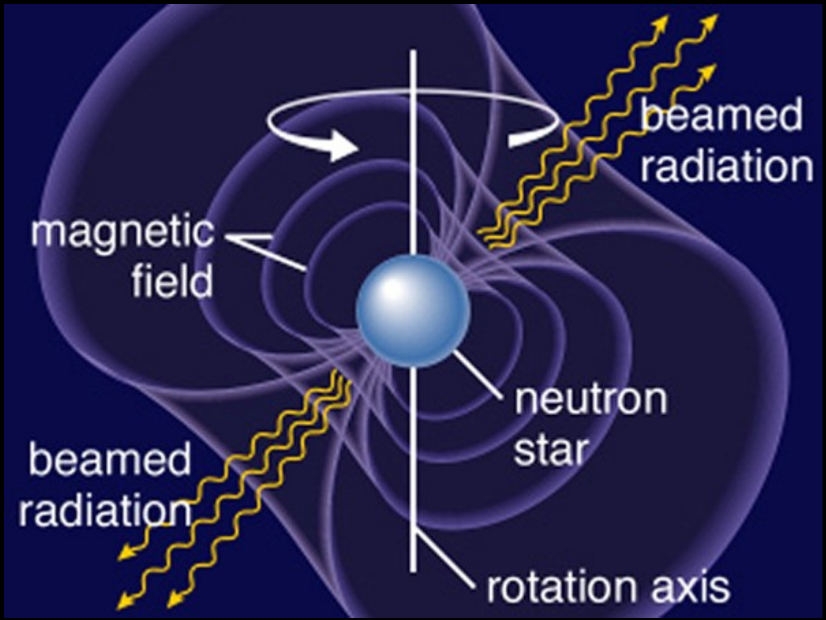
- Millisecond pulsars are gamma-ray sources with similar spectra to the GCE.
- *O*(5,000) needed in the Galactic Center

Globular clusters detected in gamma rays



Fermi (2010)





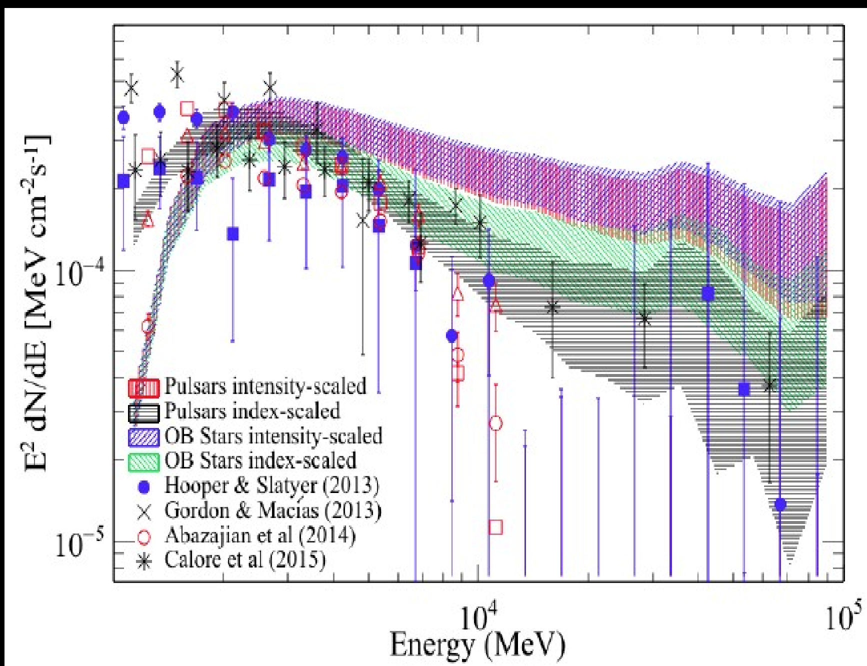
Abazajian (2011)

Background model uncertainties

More relevant is systematic uncertainty.

Dedicated diffuse models

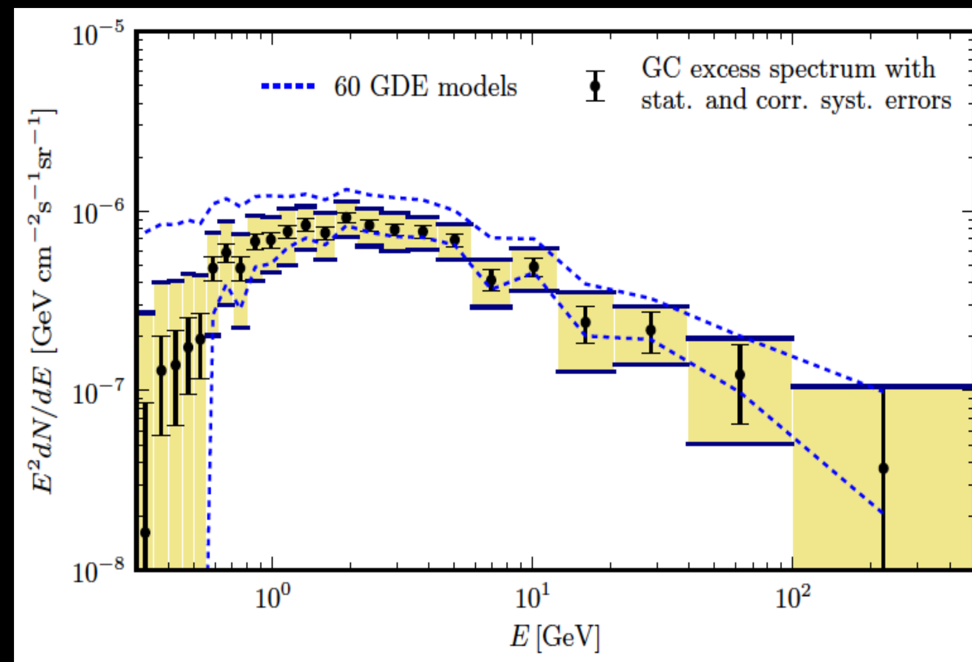
Calibrated by the Fermi collaboration for Galactic Center analysis



Fermi (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

2. REVISION OF THE MAIN SOURCES OF SYSTEMATICS

- ✓ **Interstellar gas and dust templates:**
- ✓ Use hydrodynamic gas maps.

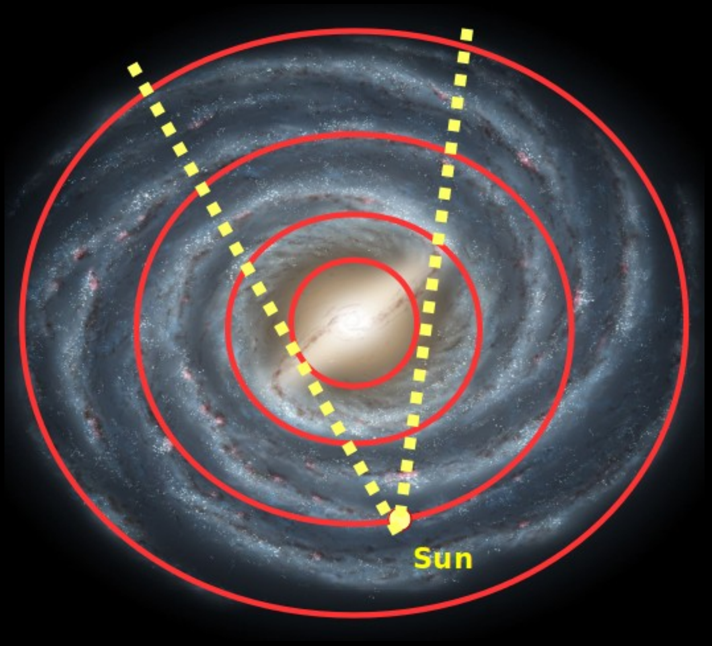
- ✓ **Inverse Compton emission models**
- ✓ Use 3D Inverse Compton maps

- ✓ **Fermi bubbles template**
- ✓ Use improved low-latitude Fermi bubbles maps

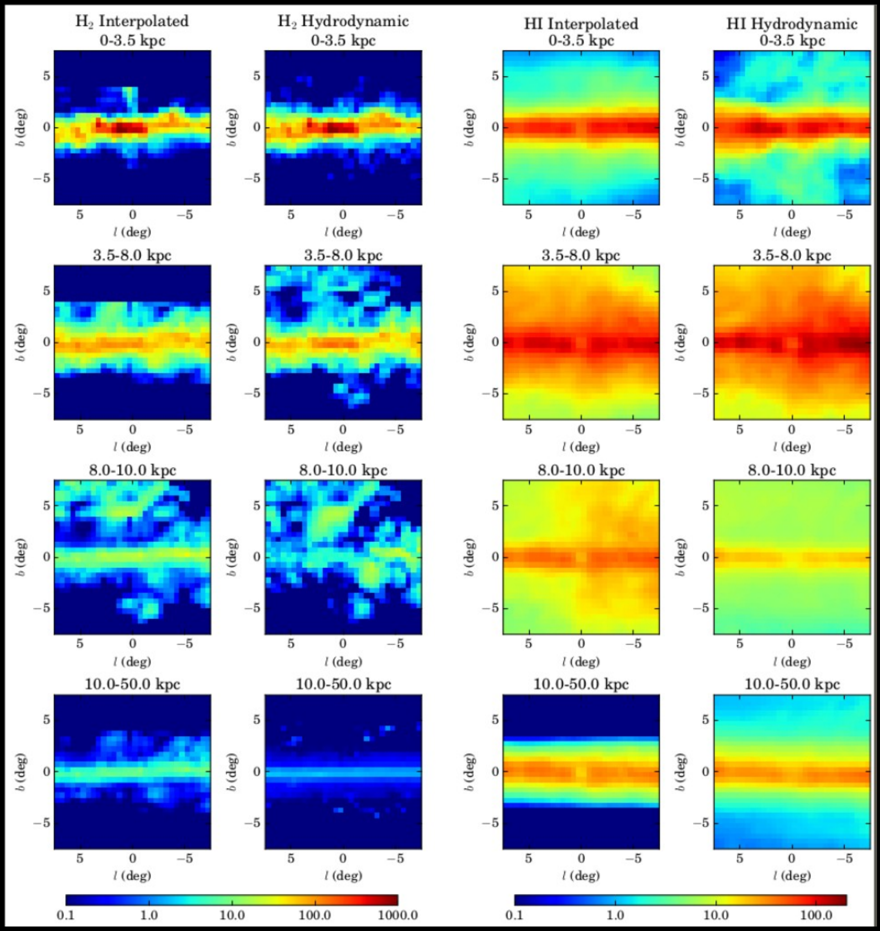
(A) Interstellar gas and dust maps

Hydrodynamic gas maps avoid bias from interpolated method

- *Fermi diffuse emission model uses interpolated gas maps*
- *Hydrodynamic gas maps are preferred by the GC data*



Macias et al. Nat. Astr. (2018)



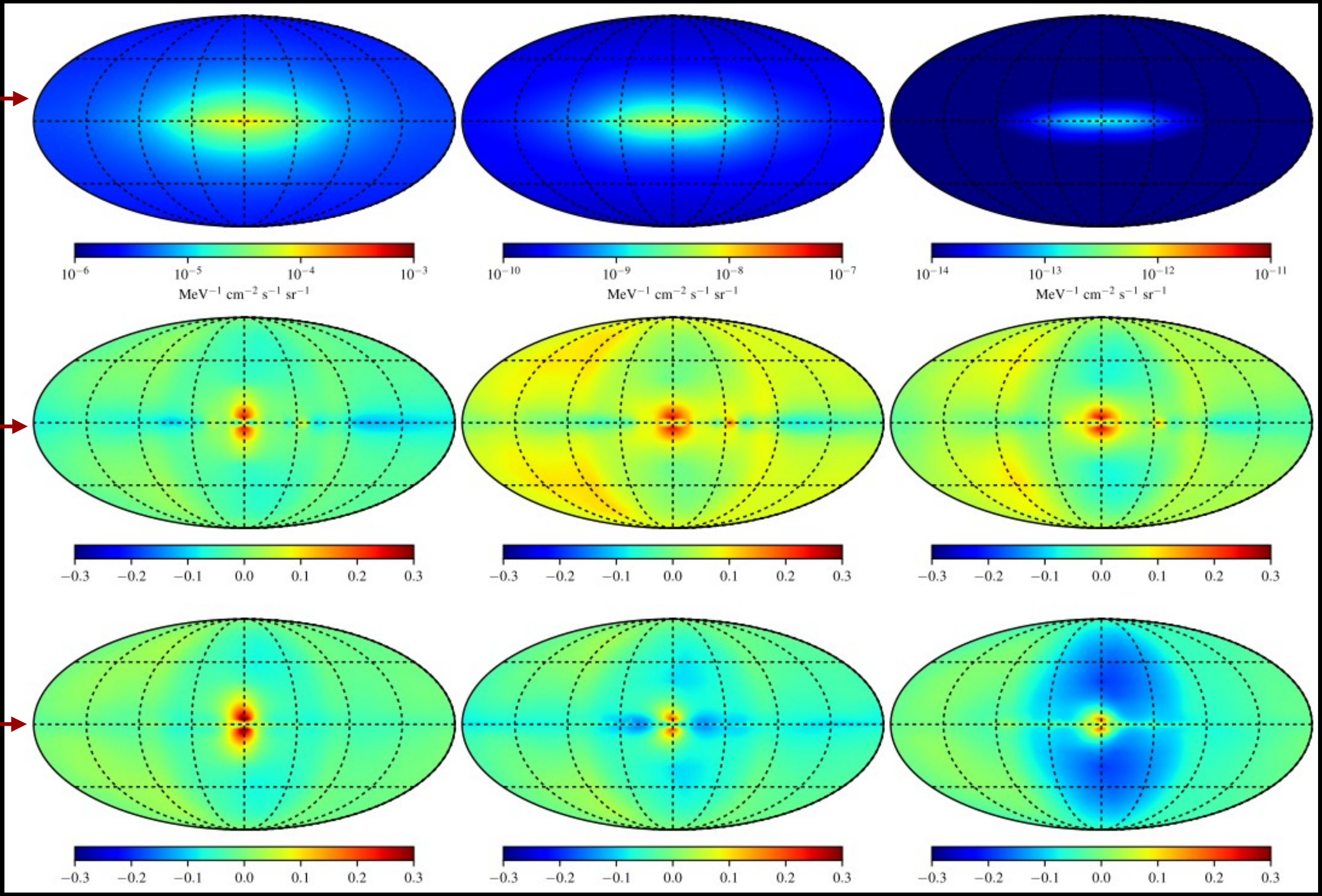
(B) New 3D Inverse Compton Maps

10.6 MeV | 1.2 GeV | 79 GeV

Standard 2D IC

New 3D IC:
Fractional residual for
R12 Model

New 3D IC:
Fractional residual for
F98 Model

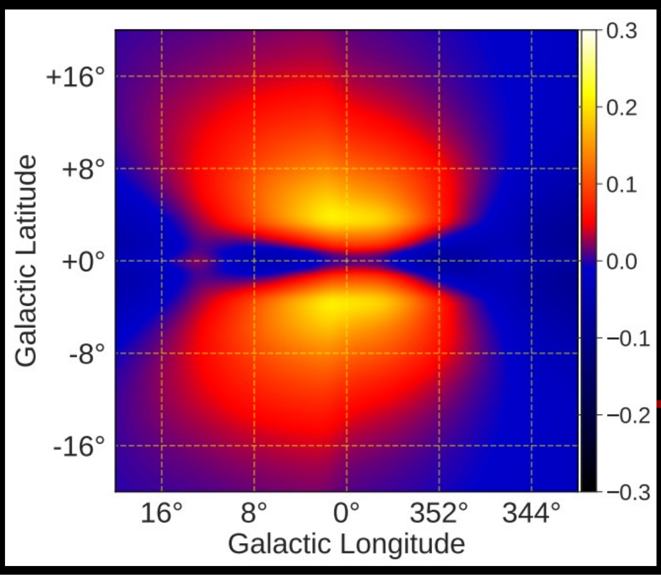


Porter et al. ApJ. (2017)

(B) New 3D Inverse Compton maps

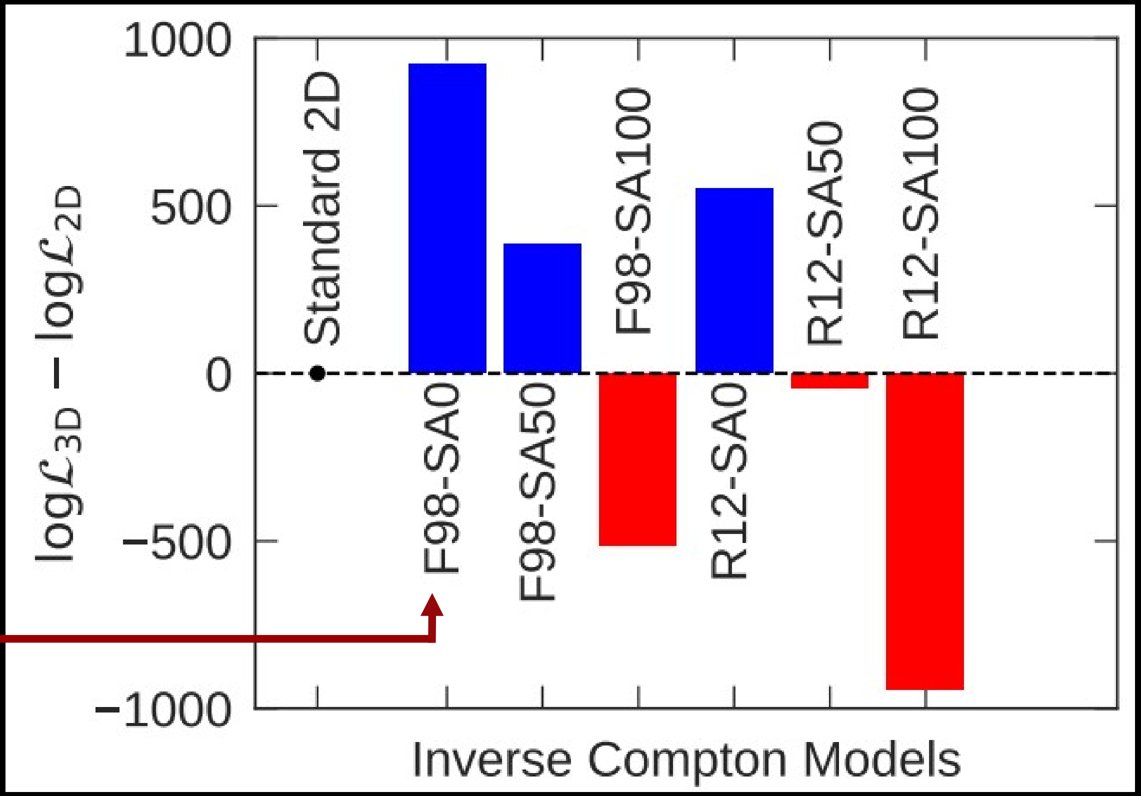
The data highly prefers the new 3D IC map *F98-SA0* to the Standard 2D IC map.

Macias et al. (2019)



Fractional residual for **F98** Model in the Galactic Center

Macias et al. (2019)

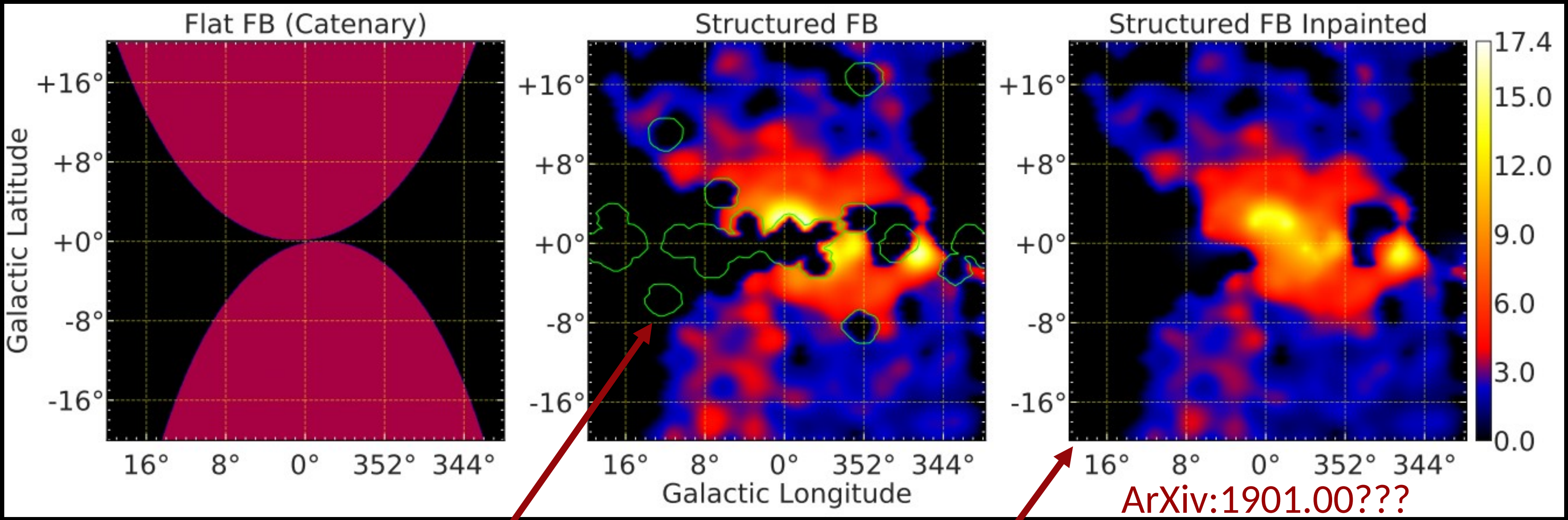


ArXiv:1901.00???

(C) Low-latitude Fermi Bubbles map

Used an inpainting method to correct artifacts in available maps

Acero et al. (2016) Ackermann et al. (2017) Macias et al. (2019)



ArXiv:1901.00???

Artifacts due to point source mask

Correction after inpainting method

(C) Low-latitude Fermi Bubbles map

Inpainted Fermi bubbles map significantly improves the fit

Acero et al. (2016) | Ackermann et al. (2017) | Macias et al. (2019)

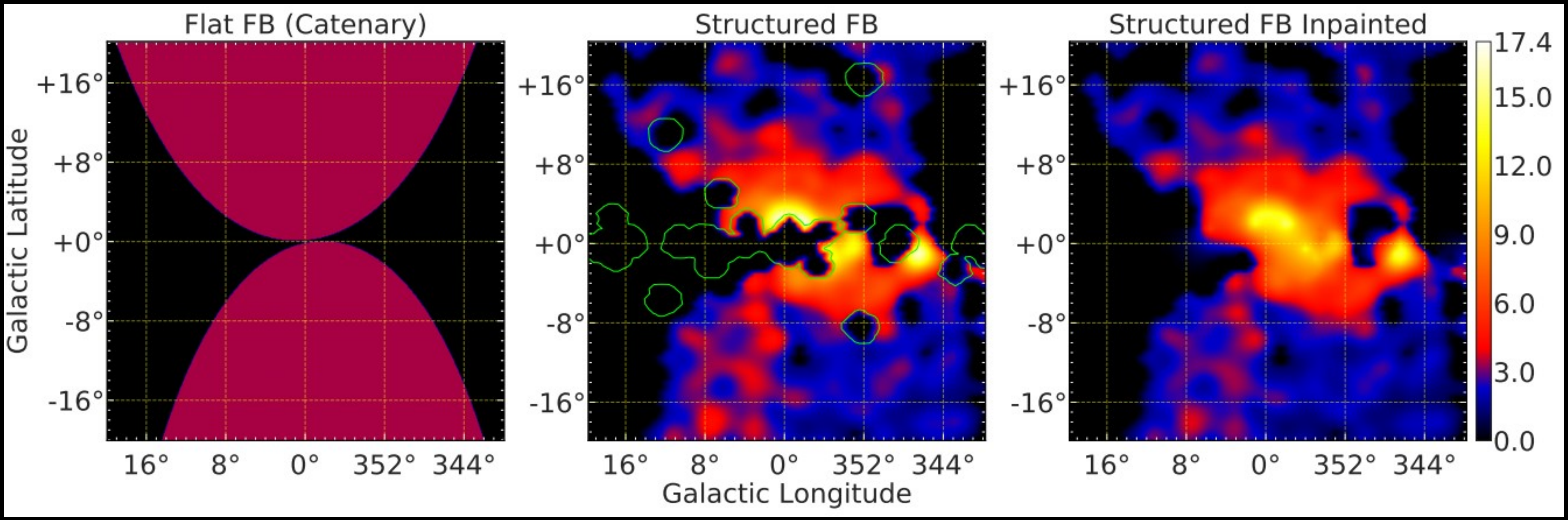


TABLE II. **Summary of the likelihood analyses for 3 alternative *Fermi* bubbles maps.**

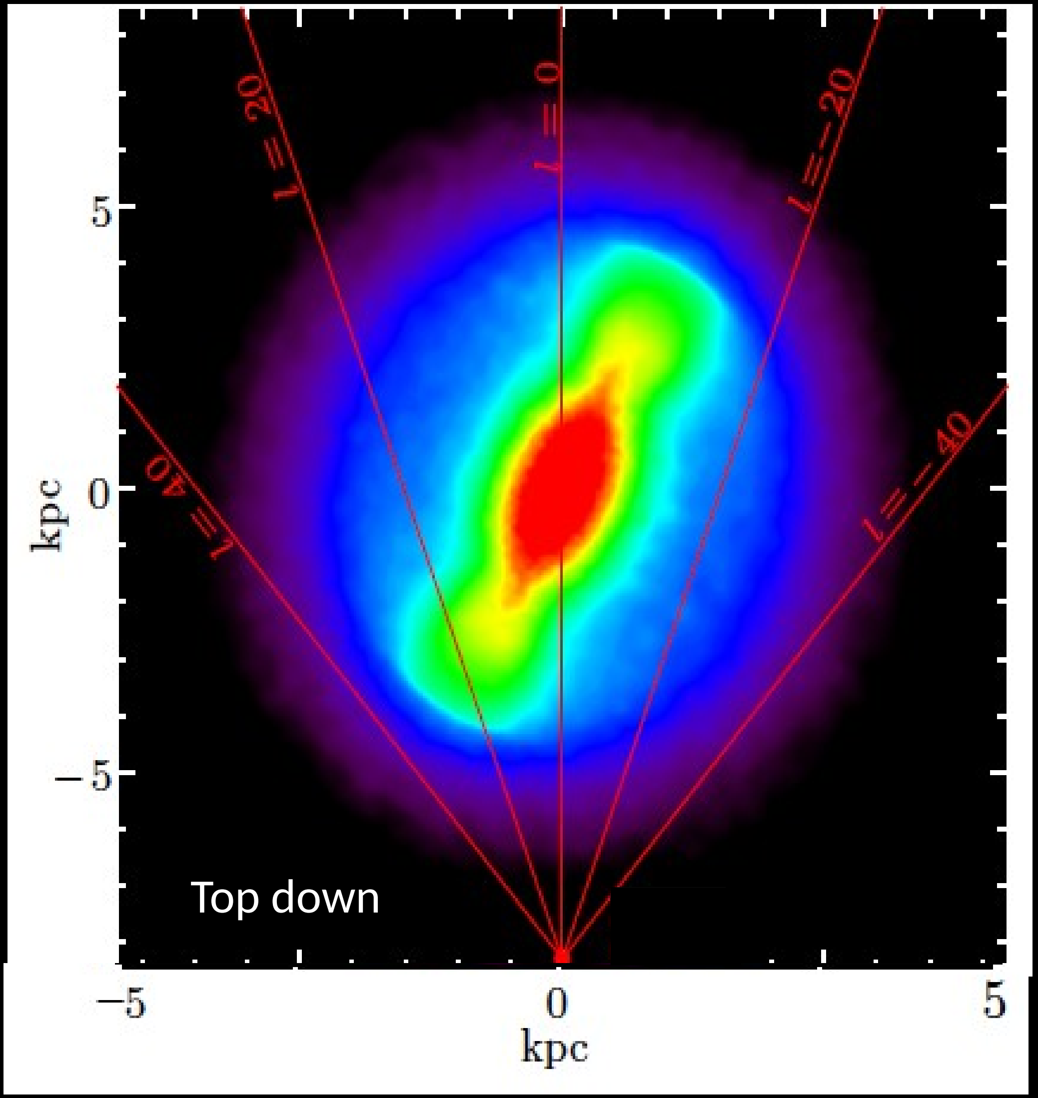
Base	Source	$\log(\mathcal{L}_{\rm Base})$	$\log(\mathcal{L}_{\rm Base+Source})$	$TS_{\rm Source}$	Number of source parameters	Reference for FB template
baseline	Catenary	-2486188.1	-2486753.1	1130	15	[42]
baseline	Structured FB	-2486188.1	-2487322.3	2268	15	[43]
baseline	Structured FB (Inpainted)	-2486188.1	-2487802.1	3228	15	adapted from [43]

ArXiv:1901.00???

3. ASTROPHYSICAL EXPLANATIONS PREFERRED TO THE DARK MATTER EXPLANATION

- ✓ **Spectral similarity to millisecond pulsars**
- ✓ **Spatial morphology traces the bulge stars**
- ✓ **Spatial morphology is robust to systematic uncertainties**

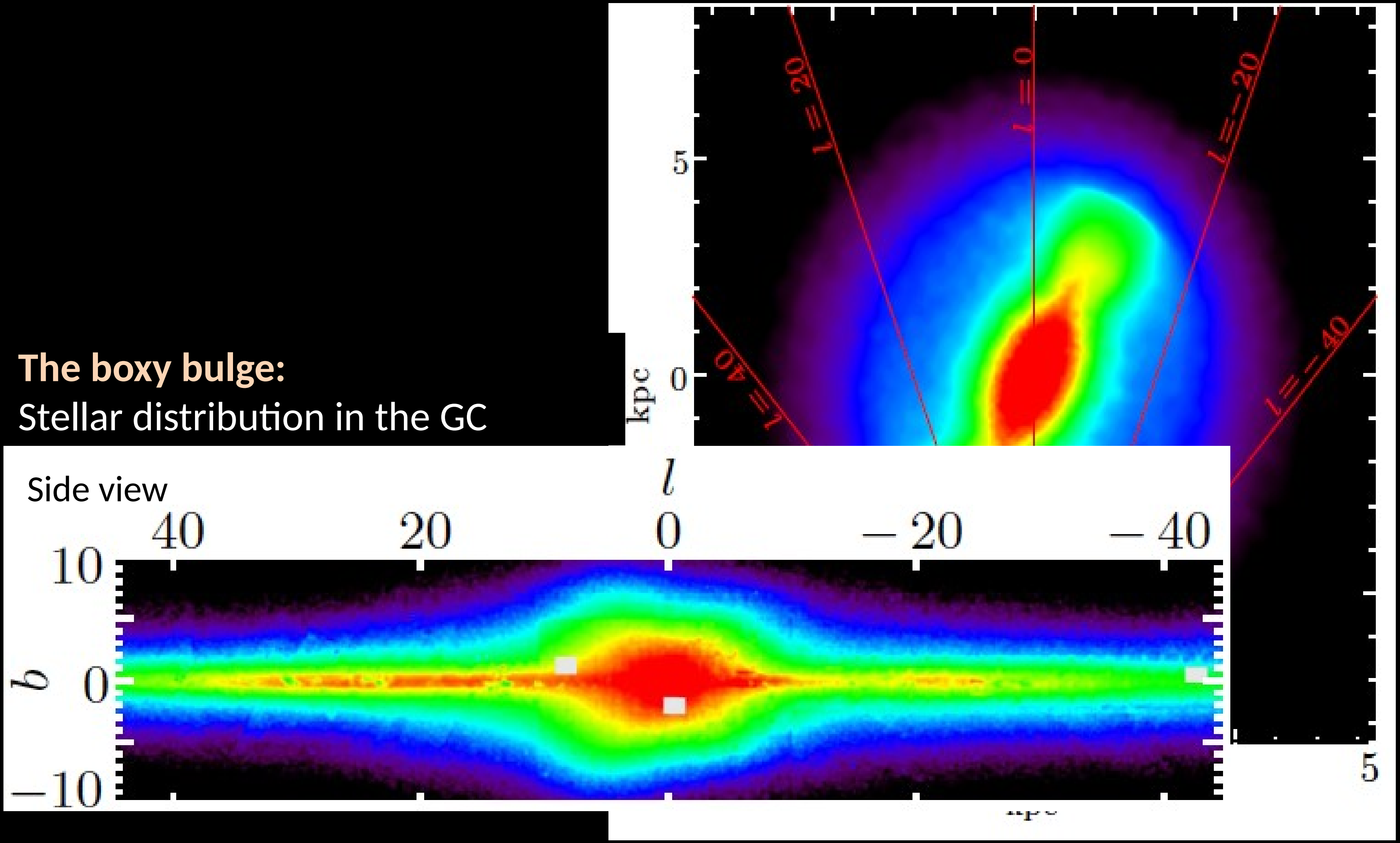
Spatial Morphology: The Galactic Bulge



Bland-Hawthorn & Gerhard (2017)

The Galactic Bulge

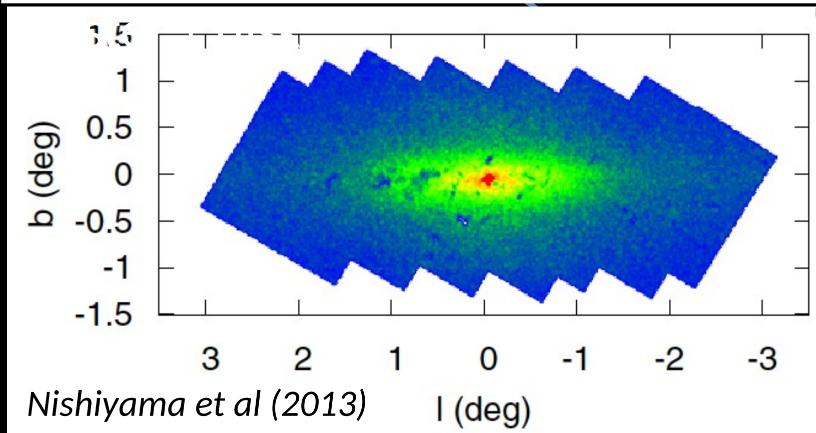
The boxy bulge:
Stellar distribution in the GC



Bland-Hawthorn & Gerhard (2017)

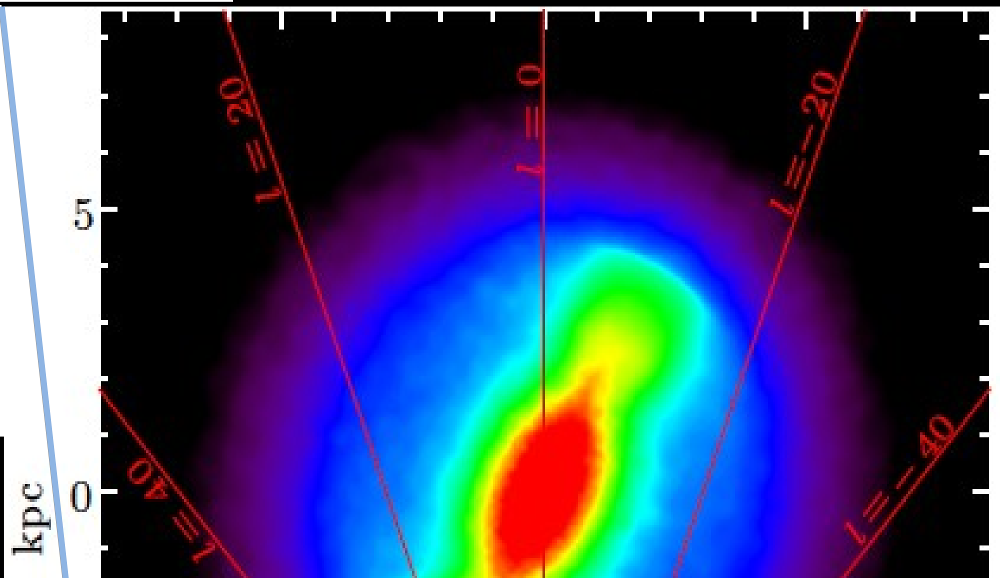
The Galactic Bulge

Nuclear Bulge: inner 200 pc

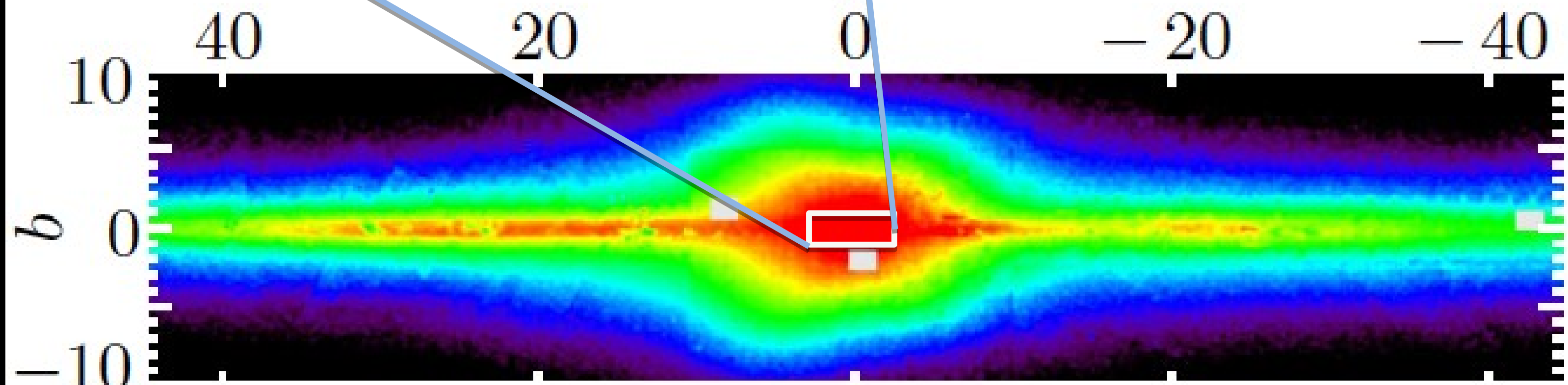


Nishiyama et al (2013)

The boxy bulge:
rectangle, not symmetric

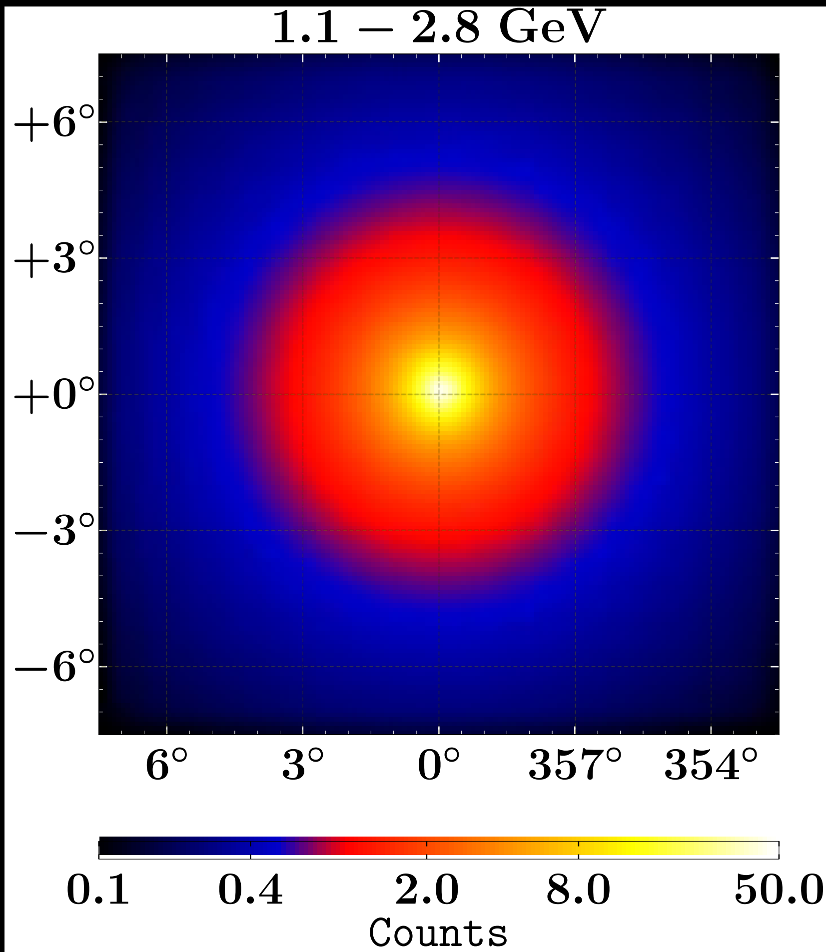


Side view

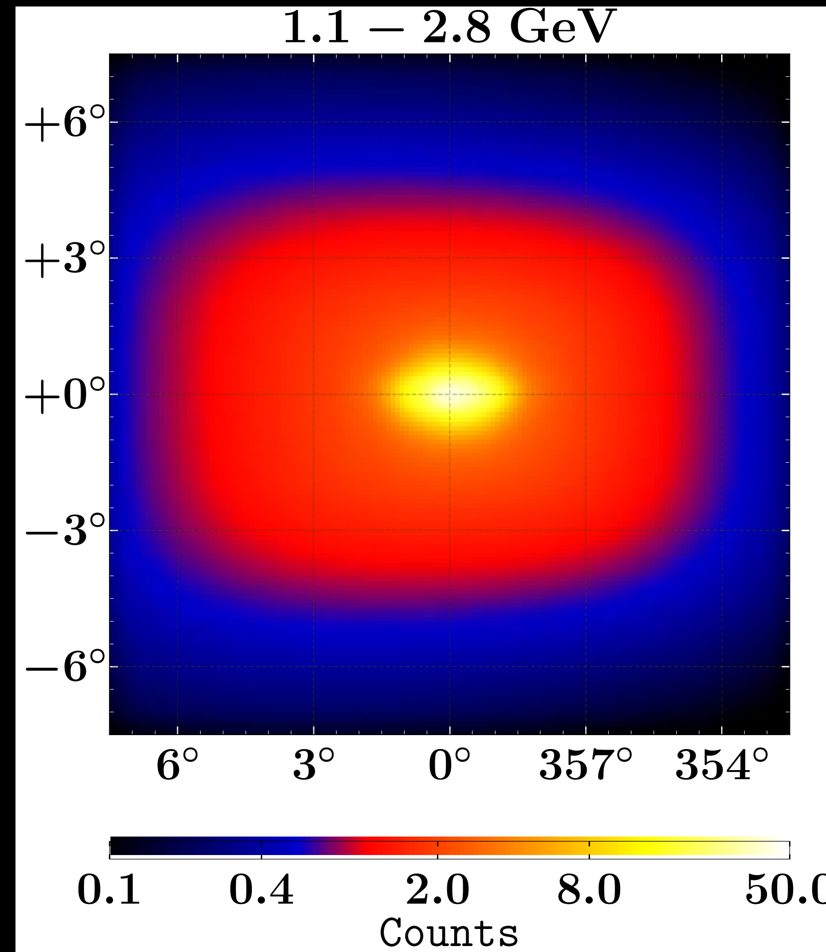


Bland-Hawthorn & Gerhard (2017)

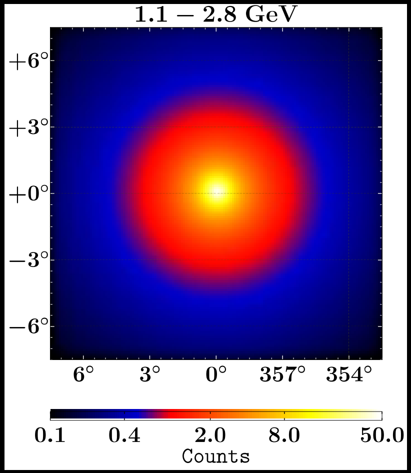
spherical symmetry vs bulge shape



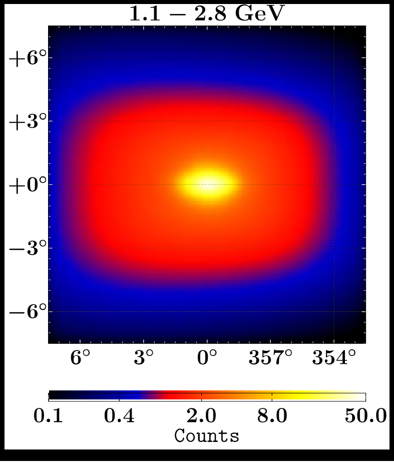
vs

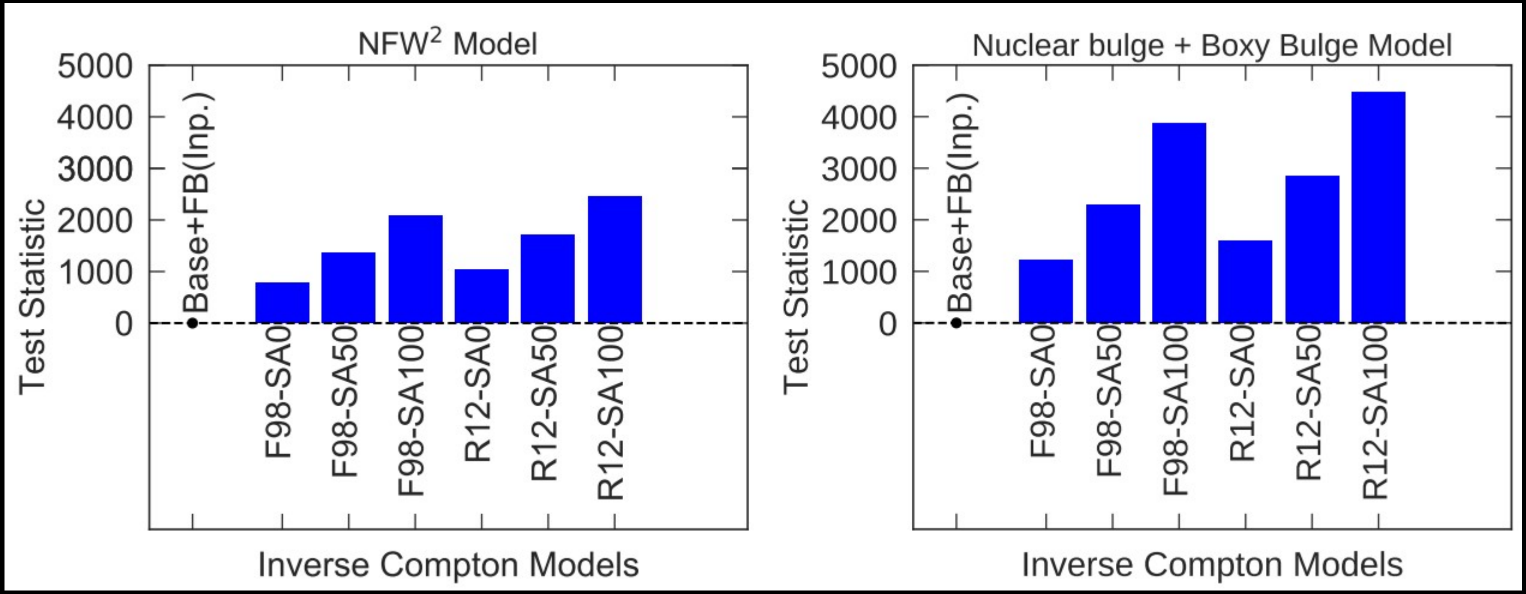


spherical symmetry vs bulge shape



vs



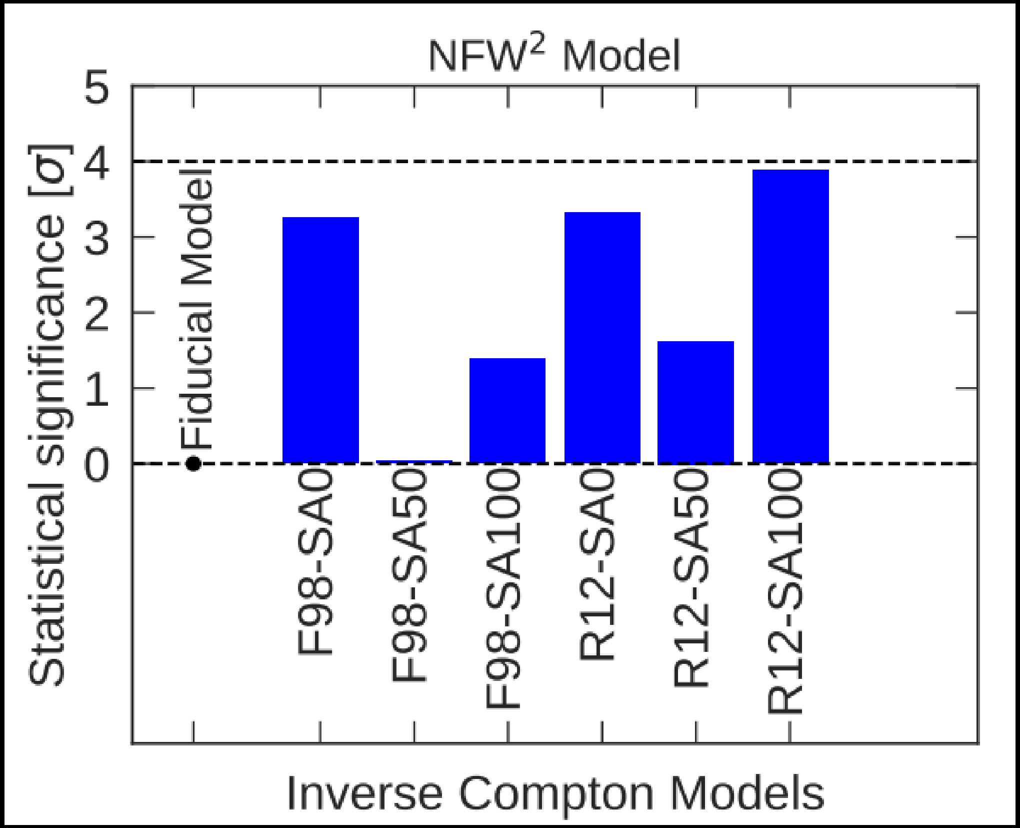


Macias et al. (2019)
ArXiv:1901.00???

Dark Matter explanation is Ruled out

Dark Matter is ruled out when the new 3D Inverse Compton maps and bulge templates are considered in the fit

- ✓ **Robust confirmation of Macias et al. (2018) and Bartels et al. (2018).**
- ✓ **Used state-of-the-art gas maps, 3D Inverse Compton and Fermi bu-bbles maps.**

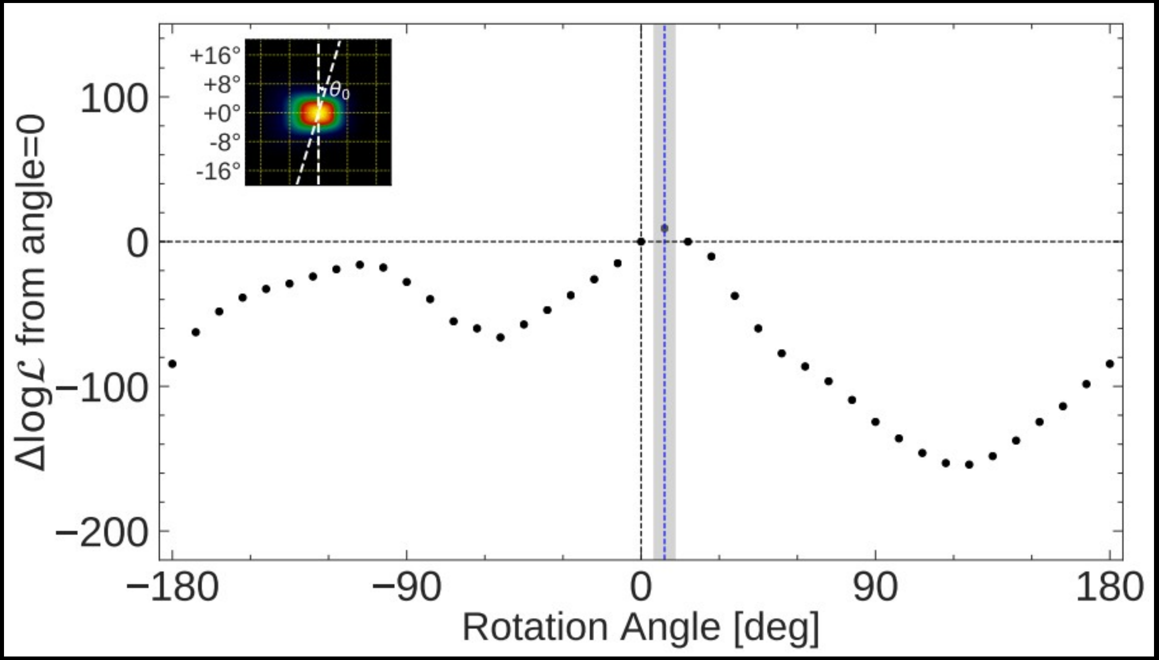


Macias et al. (2019)
ArXiv:1901.00???

Morphological tests to the Bulge

Artificially rotate the original Near Infrared boxy bulge map in steps of 9 deg and compute maximum-likelihood at each step:

- ✓ **Best-fit rotation is 9+/-4 deg with confidence of 2.3σ**
- ✓ **Unrotated boxy bulge image is preferred by the gamma-ray data**

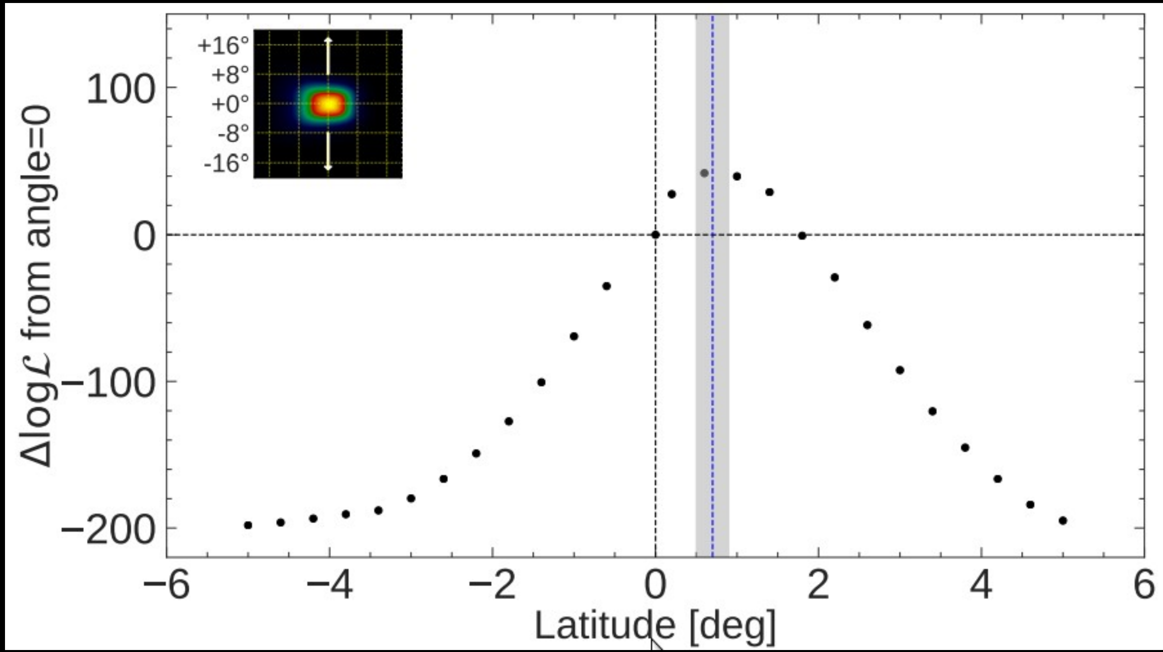


Macias et al. (2019)
ArXiv:1901.00???

Morphological tests to the Bulge

Artificially translate the boxy bulge map along latitude in steps of 0.2 deg and compute maximum-likelihood at each step:

- ✓ **Best-fit translation is b=0.7+/-0.2 deg with confidence of 7.2σ**
- ✓ **Migration of the gamma-ray bulge could be real, but tentative bias introduced by 2FIG catalog of point sources**

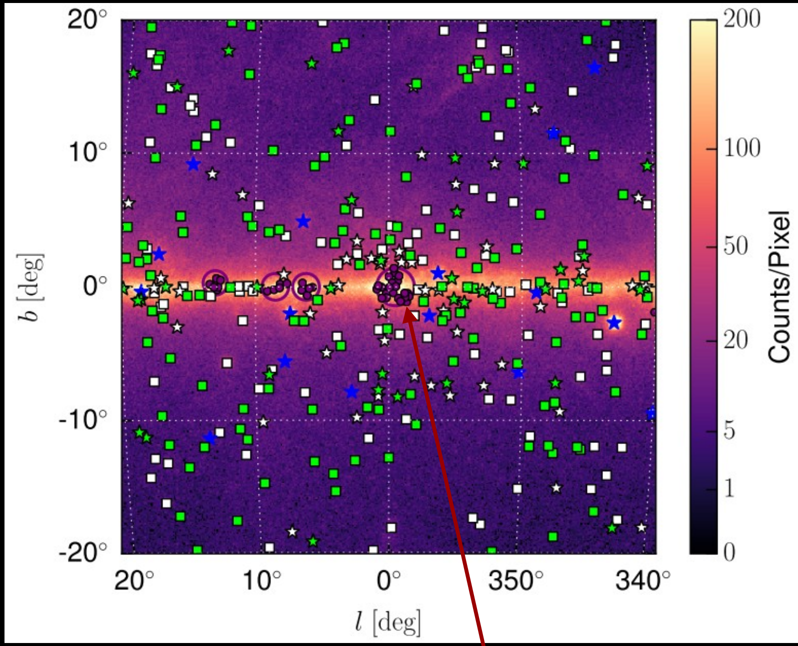


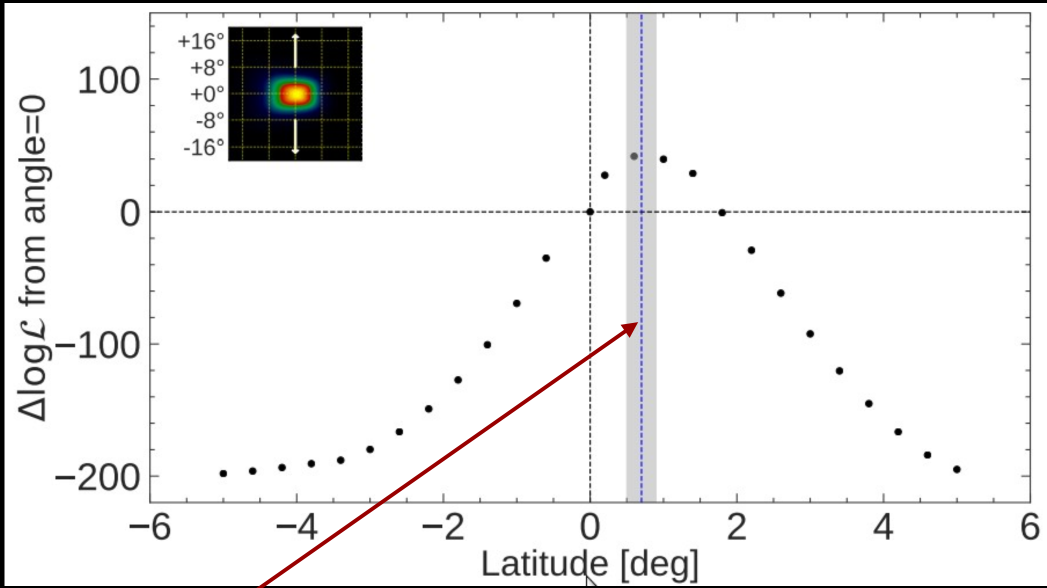
Macias et al. (2019)
ArXiv:1901.00???

Morphological tests to the Bulge

Although a migration of the gamma-ray bulge could be real, there is a tentative bias introduced by the catalog of point sources

Ajello et al. ApJ (2017)





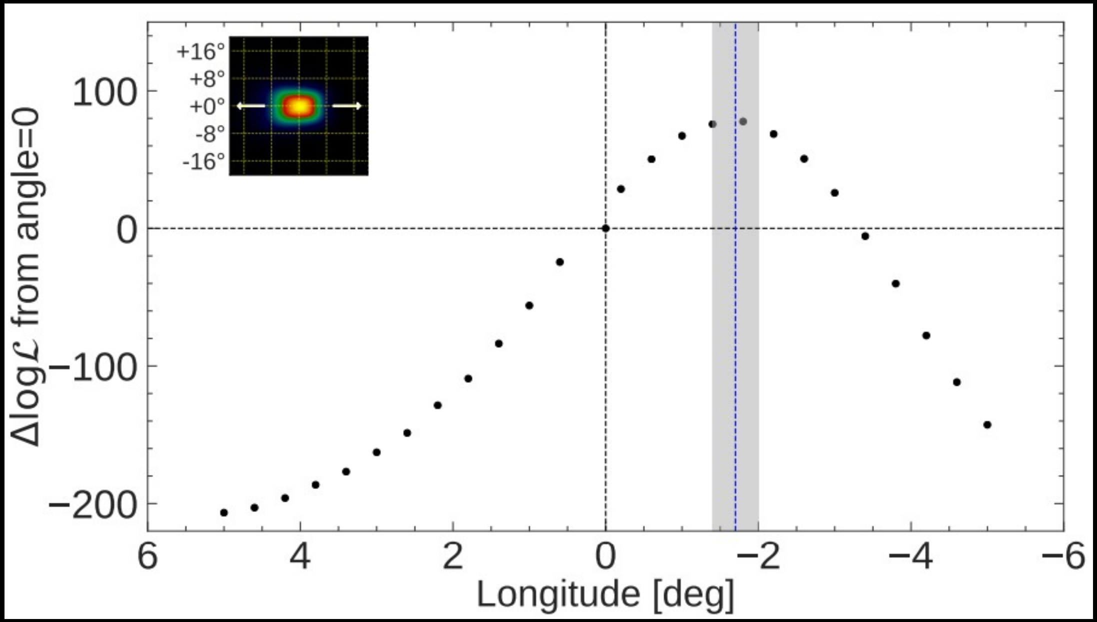
Macias et al. (2019)
ArXiv:1901.00???

Groups of clustered point sources were removed from the catalog of point sources

Morphological tests to the Bulge

Artificially translate the boxy bulge map along longitude in steps of 0.2 deg and compute maximum-likelihood at each step:

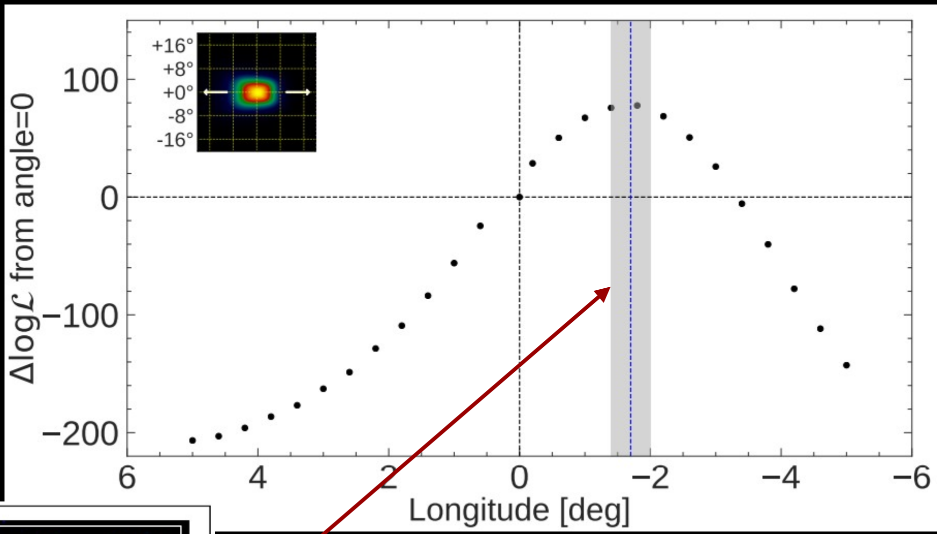
- ✓ **Best-fit translation is lon=-1.7+/-0.2 deg with confidence of 11.0σ**
- ✓ **NIR bulge traces mainly the oldest stars, but there is evidence of star formation activity at lon~[-0.5, -2.5] degrees.**



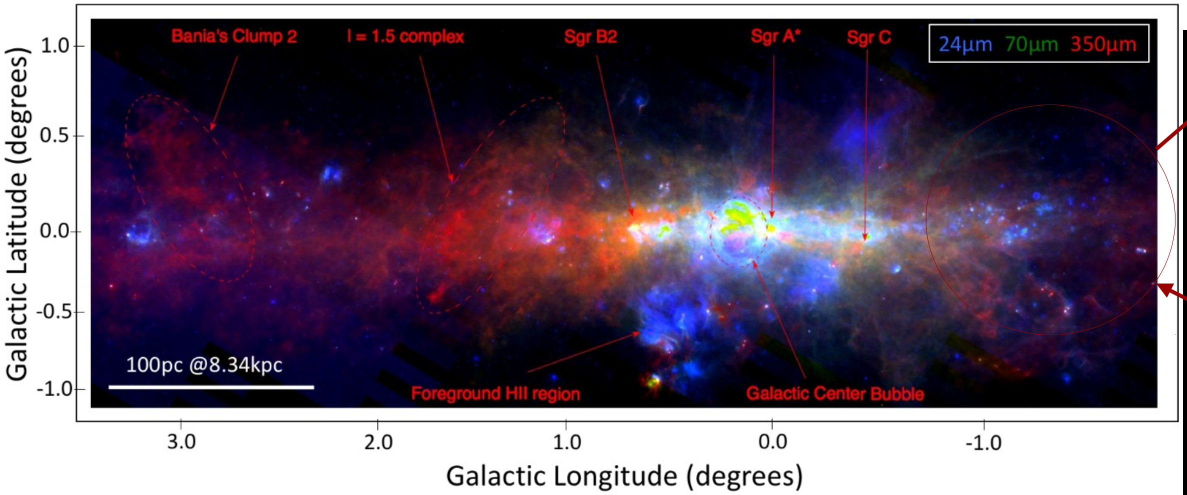
Macias et al. (2019)
ArXiv:1901.00???

Morphological tests to the Bulge

Evidence for star formation activity at lon~[-0.5,-2.5] deg



Longmore & Kruijssen (2018)



Macias et al. (2019)
ArXiv:1901.00???

Blue spots represent star formation sites at longitudes ~-1.7 deg

4. FUTURE DIRECTIONS

- ✓ **Clues in the data about millisecond pulsars formation history**

- ✓ **Mild preference for an admixture scenario in which some of the relevant binaries are formed primordially and the rest dynamically**

- ✓ **Disrupted globular cluster scenario highly disfavored by the data**

The MSPs scenario is rich

MSPs can be formed via a number of channels

- Recycling of old neutron stars
- Accretion induced collapse of O-Ne-Mg white dwarfs
- Merger induced collapse of two white dwarfs

All channels involve binary systems

- Primordial: stars born in binary systems
- Dynamical: captures a companion through encounters

Binary mass transfer and the X-ray connection will be different for different channels.

The relative importance of channels will be environmentally dependent

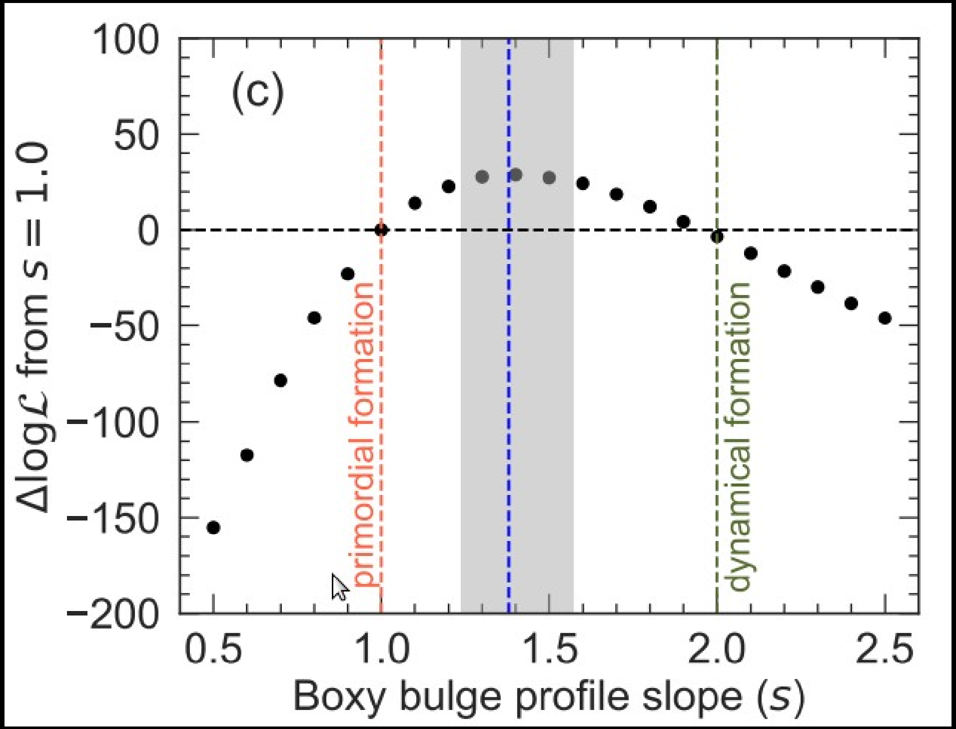
- Stellar age: active star forming (CMZ) to Gyrs old (bulge)
- Stellar density: low (bulge) to high (globular cluster)
- Stellar metallicity: low to solar populations

➔ **No a priori reason MSP population & their connection to LMXB are the same everywhere**

Millisecond pulsars formation history

Modified the 3D triaxial density distribution of stars by adding a slope parameter s and ran our maximum-likelihood procedure:

- ✓ **Primordially formed MSPs are expected to scale linearly with stellar density**
- ✓ **Dinamically formed MSPs scale quadratically with the stellar density**
- ✓ **Mild evidence for an admixture formation scenario in which some of the relevant binaries are primordial and the rest formed through stellar interactions**



Macias et al. (2019)
ArXiv:1901.00???

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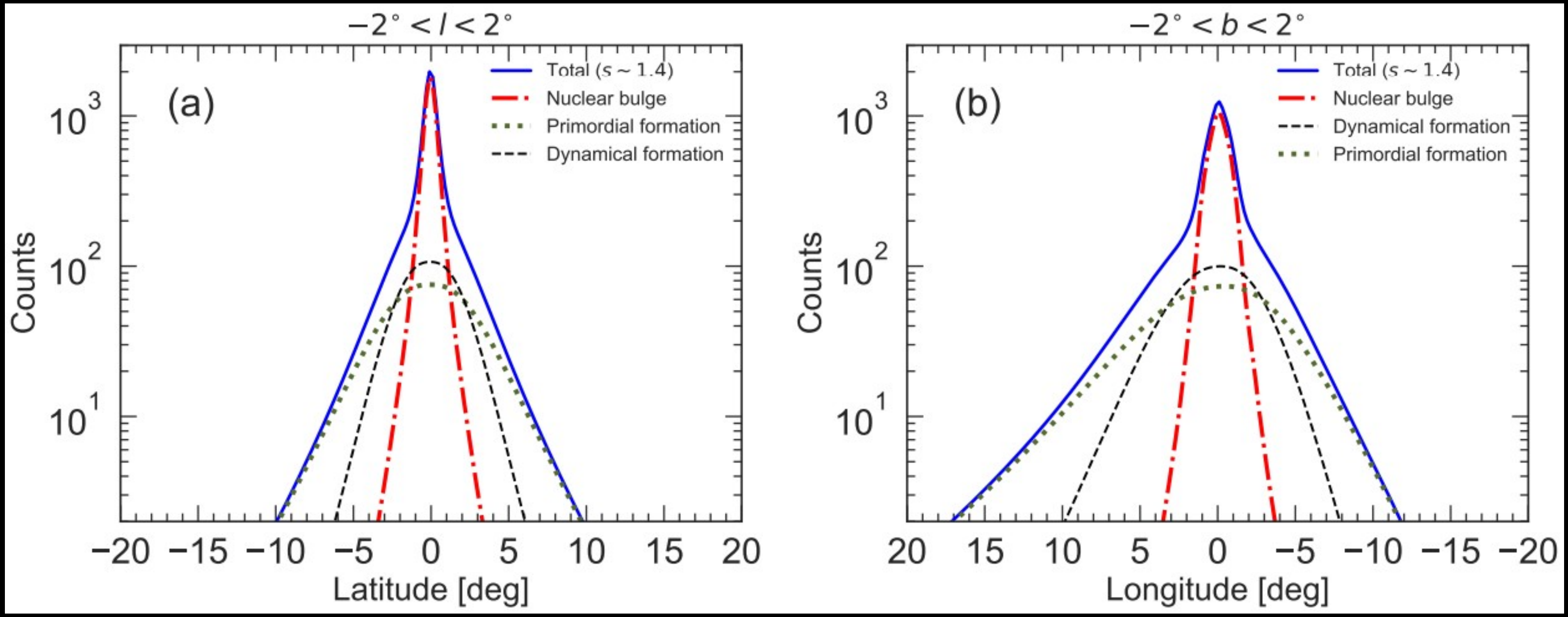
Macias et al. (2019)



Preference for an admixture formation scenario in which ~52% of the MSPs were formed primordially and the rest dynamically

CONCLUSIONS

- ✓ **Used state-of-the-art interstellar gas maps, 3D Inverse Compton maps and improved Fermi bubbles template: *GCE still strongly detected***

- ✓ **Robust confirmation that the morphology of the GCE is correlated with stellar mass in the bulge**

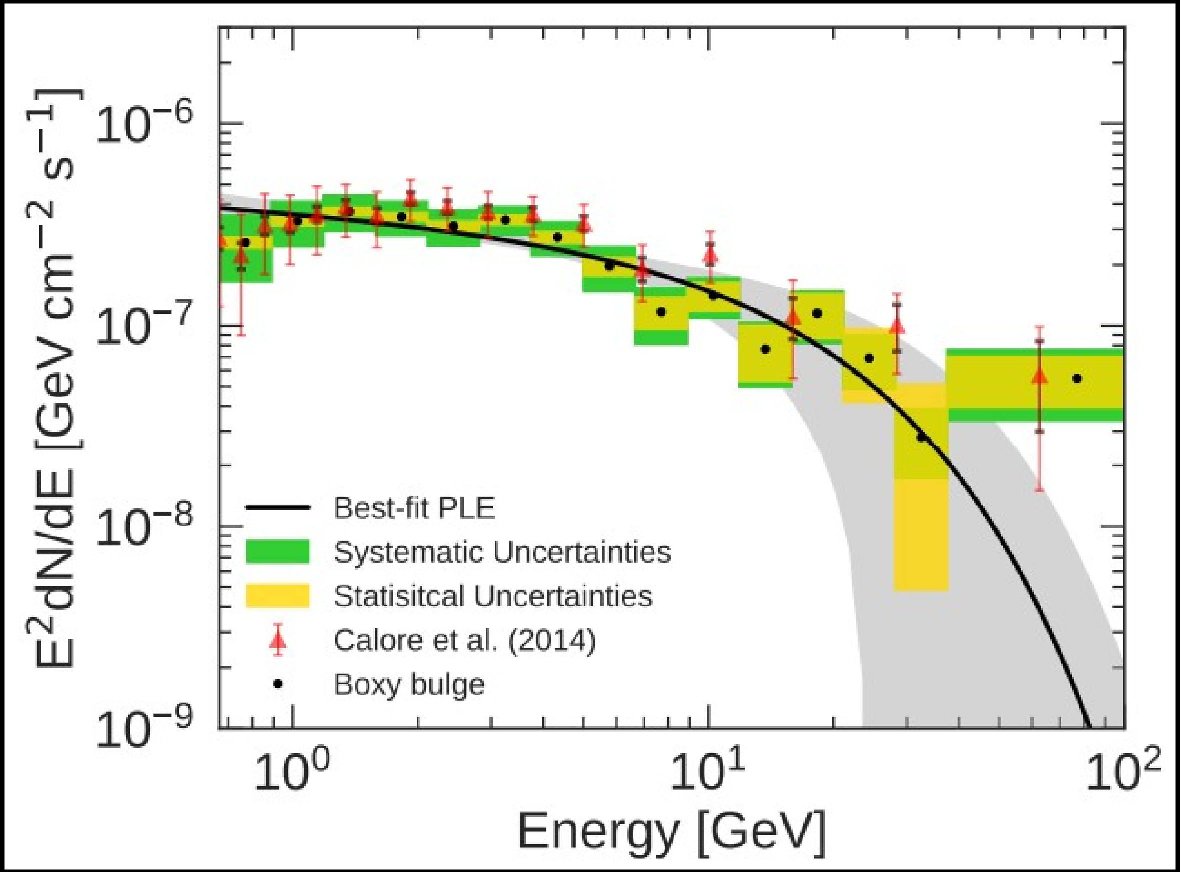
- ✓ **Any model that predicts a spherically symmetric distribution is highly disfavored by the data: e.g. Dark Matter and disrupted globular clusters. Also young pulsars are ruled out as main source of the GCE**

- ✓ **Mild evidence that ~52% of the MSPs were formed primordially.**

BACK-UP SLIDES

Galactic bulge spectrum

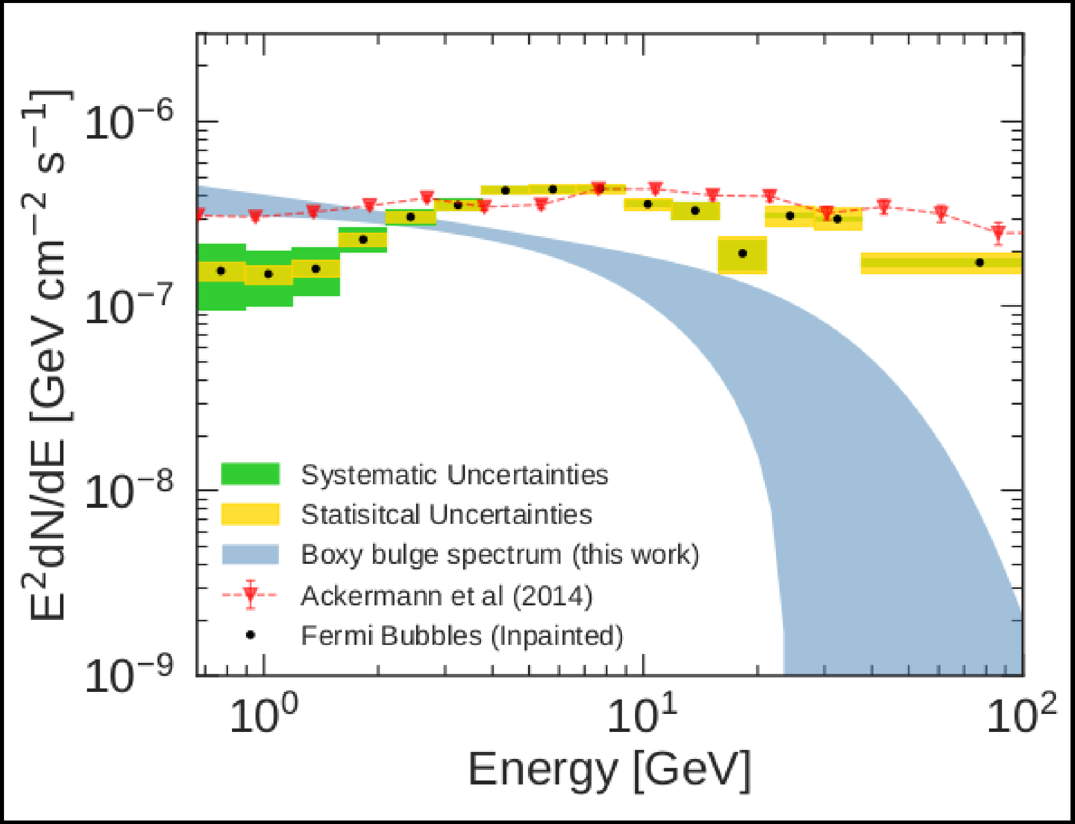
Spectrum agrees well with previously known GCE and is consistent with millisecond pulsars spectrum



Macias et al. (2019)
ArXiv:1901.00???

Spectrum of the Fermi bubbles

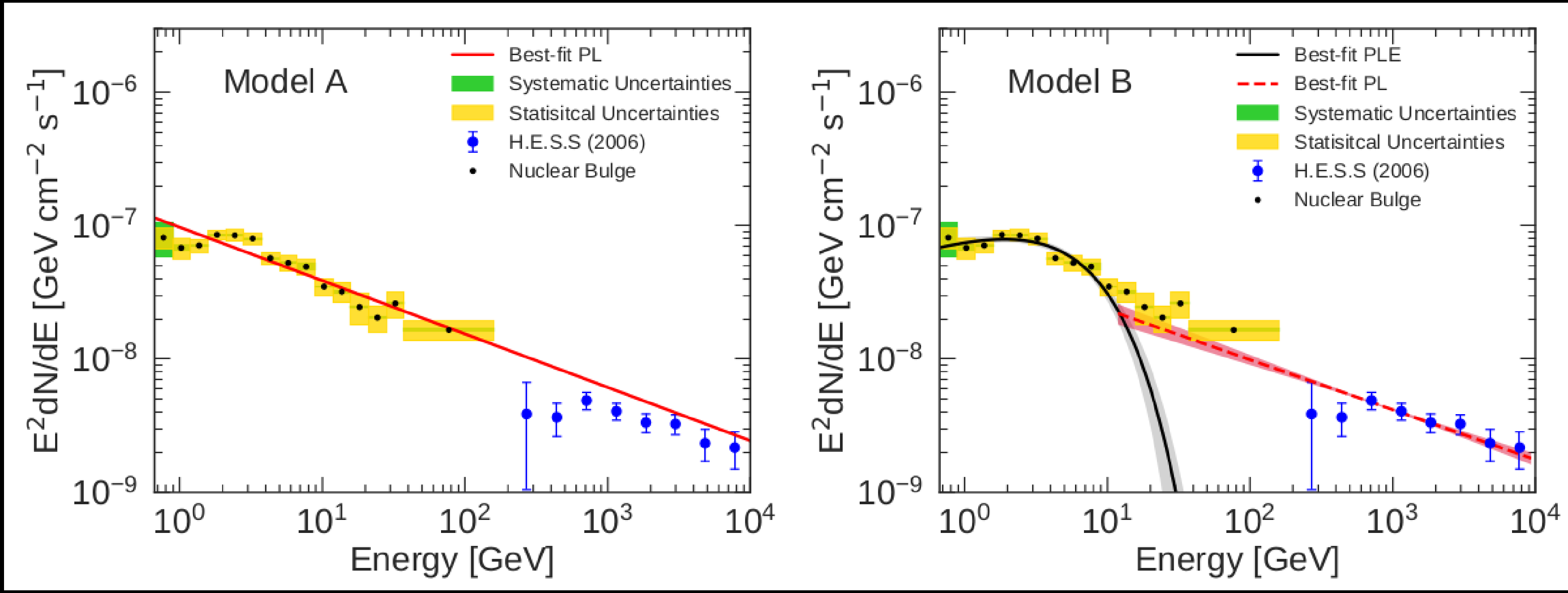
Spectrum of Fermi bubbles is not degenerate with that of the Galactic bulge



Macias et al. (2019)
ArXiv:1901.00???

Spectrum of the Nuclear bulge

Evidence for a high-energy tail in the nuclear bulge spectrum which could be explained electrons from MSPs



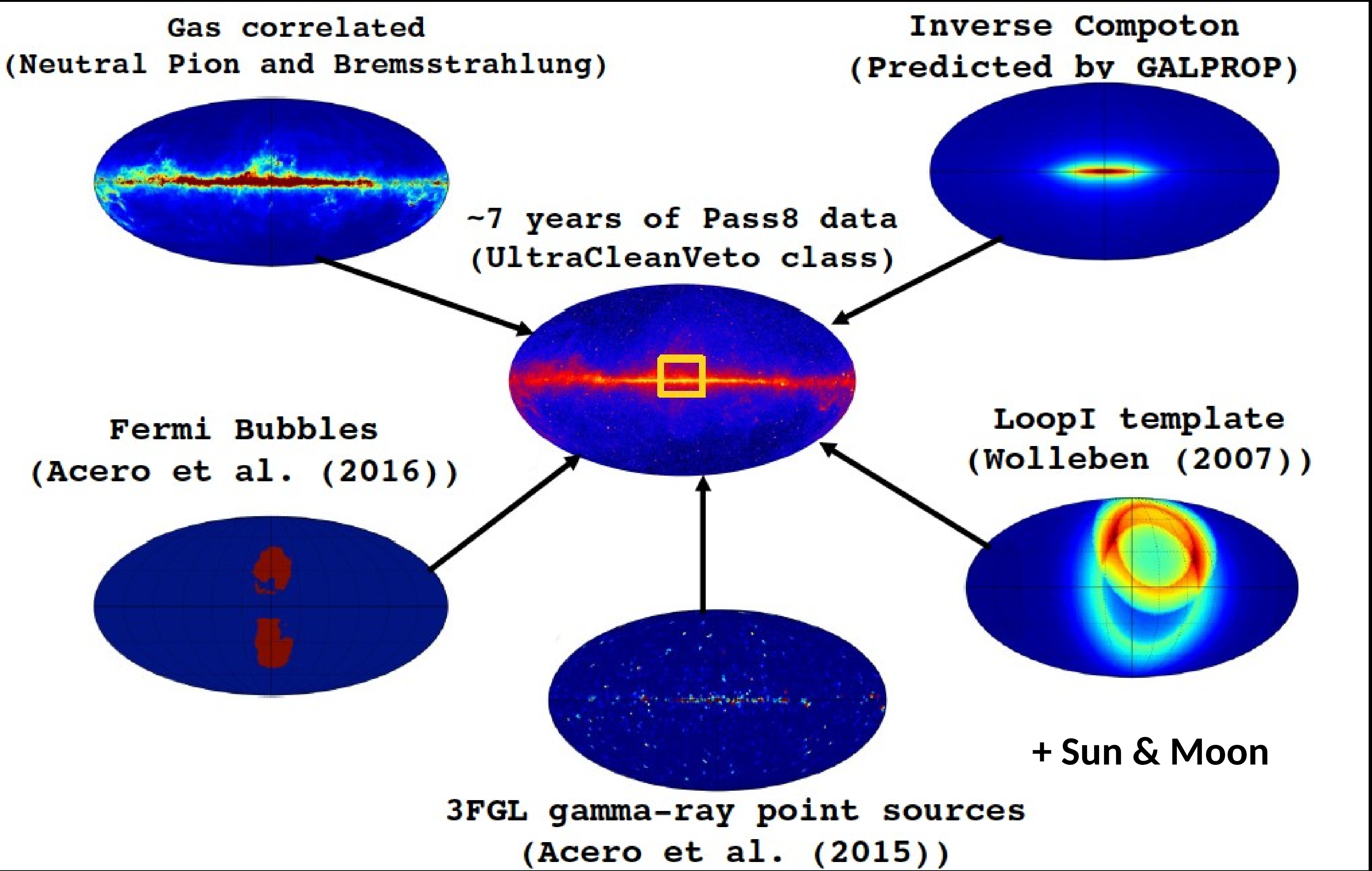
Macias et al. (2019)
ArXiv:1901.00???

Maximum-likelihood results

Macias et al. (2019)

Base	Source	$\log(\mathcal{L}_{\rm Base})$	$\log(\mathcal{L}_{\rm Base+Source})$	$\mathrm{TS}_{\rm Source}$	σ	Number of source parameters
baseline	SFB (Inp.)	-2486188.1	-2487802.1	3228		15
baseline+SFB (Inp.)	NFW^2	-2487802.1	-2488619.8	1635		15
baseline+SFB (Inp.)	X-bulge+NB	-2487802.1	-2488839.6	2075		2×15
baseline+SFB (Inp.)	Boxy bulge+NB	-2487802.1	-2489230.1	2856		2×15
baseline+SFB (Inp.)+Boxy bulge+NB	NFW^2	-2489230.1	-2489233.9	8	0.9	15
$\mathrm{baseline}^1$	SFB (Inp.)	-2487135.2	-2488729.2	3188		15
$\mathrm{baseline}^1$+SFB (Inp.)	NFW^2	-2488729.2	-2489119.4	780		15
$\mathrm{baseline}^1$+SFB (Inp.)	X-bulge+NB	-2488729.2	-2489242.2	1026		2×15
$\mathrm{baseline}^1$+SFB (Inp.)	Boxy bulge+NB	-2488729.2	-2489341.3	1224		2×15
$\mathrm{baseline}^1$+SFB (Inp.)+Boxy bulge+NB	NFW^2	-2489341.3	-2489354.7	27	3.3	15
$\mathrm{baseline}^2$	SFB (Inp.)	-2486191.5	-2488329.8	4276		15
$\mathrm{baseline}^2$+SFB (Inp.)	NFW^2	-2488329.8	-2489004.2	1349		15
$\mathrm{baseline}^2$+SFB (Inp.)	X-bulge+NB	-2488329.8	-2489120.2	1581		2×15
$\mathrm{baseline}^2$+SFB (Inp.)	Boxy bulge+NB	-2488329.8	-2489479.9	2300		2×15
$\mathrm{baseline}^2$+SFB (Inp.)+Boxy bulge+NB	NFW^2	-2489479.9	-2489480.6	1	0.0	15
$\mathrm{baseline}^3$	SFB (Inp.)	-2484807.7	-2487555.6	5496		15
$\mathrm{baseline}^3$+SFB (Inp.)	NFW^2	-2487555.6	-2488596.9	2083		15
$\mathrm{baseline}^3$+SFB (Inp.)	X-bulge+NB	-2487555.6	-2488700.0	2289		2×15
$\mathrm{baseline}^3$+SFB (Inp.)	Boxy bulge+NB	-2487555.6	-2489489.4	3868		2×15
$\mathrm{baseline}^3$+SFB (Inp.)+Boxy bulge+NB	NFW^2	-2489489.4	-2489495.1	11	1.3	15
$\mathrm{baseline}^4$	SFB (Inp.)	-2486304.7	-2488491.0	4373		15
$\mathrm{baseline}^4$+SFB (Inp.)	NFW^2	-2488491.0	-2489006.0	1030		15
$\mathrm{baseline}^4$+SFB (Inp.)	X-bulge+NB	-2488491.0	-2489093.6	1205		2×15
$\mathrm{baseline}^4$+SFB (Inp.)	Boxy bulge+NB	-2488491.0	-2489285.1	1588		2×15
$\mathrm{baseline}^4$+SFB (Inp.)+Boxy bulge+NB	NFW^2	-2489285.1	-2489298.7	27	3.3	15
$\mathrm{baseline}^5$	SFB (Inp.)	-2485197.9	-2488049.6	5703		15
$\mathrm{baseline}^5$+SFB (Inp.)	NFW^2	-2488049.6	-2488901.7	1704		15
$\mathrm{baseline}^5$+SFB (Inp.)	X-bulge+NB	-2488049.6	-2488927.8	1756		2×15
$\mathrm{baseline}^5$+SFB (Inp.)	Boxy bulge+NB	-2488049.6	-2489474.6	2850		2×15
$\mathrm{baseline}^5$+SFB (Inp.)+Boxy bulge+NB	NFW^2	-2489474.6	-2489481.2	13	1.6	15
$\mathrm{baseline}^6$	SFB (Inp.)	-2483983.0	-2487246.5	6527		15
$\mathrm{baseline}^6$+SFB (Inp.)	NFW^2	-2487246.5	-2488472.5	2452		15
$\mathrm{baseline}^6$+SFB (Inp.)	X-bulge+NB	-2487246.5	-2488479.3	2466		2×15
$\mathrm{baseline}^6$+SFB (Inp.)	Boxy bulge+NB	-2487246.5	-2489479.6	4466		2×15
$\mathrm{baseline}^6$+SFB (Inp.)+Boxy bulge+NB	NFW^2	-2489479.6	-2489496.1	33	3.9	15

Define a base model



+ Sun & Moon

The Galactic Bulge: box + X?