Robust inference of the Galactic center excess spatial morphology

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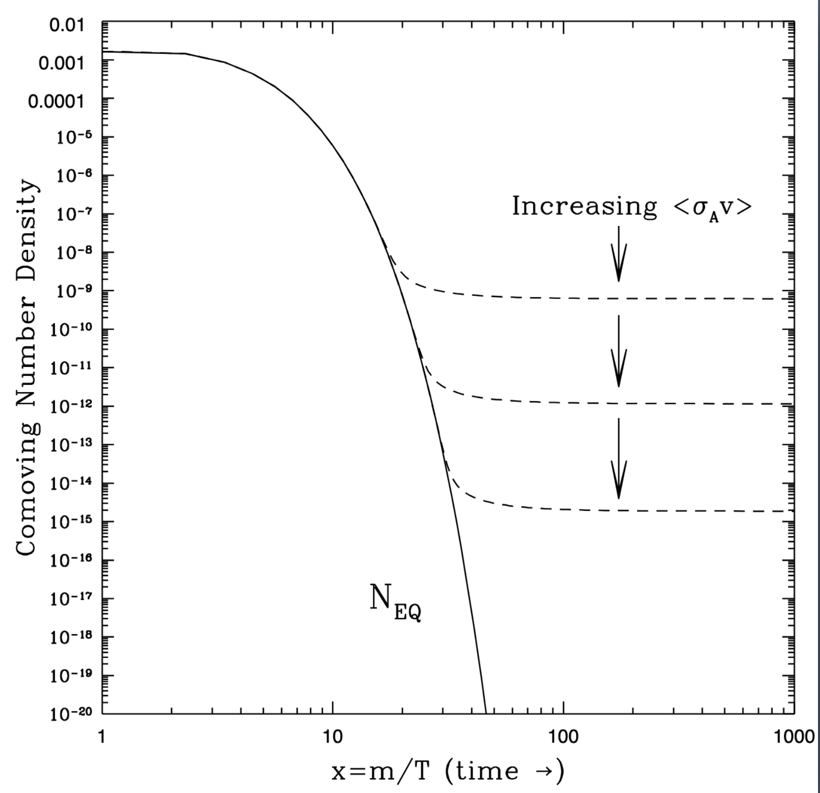
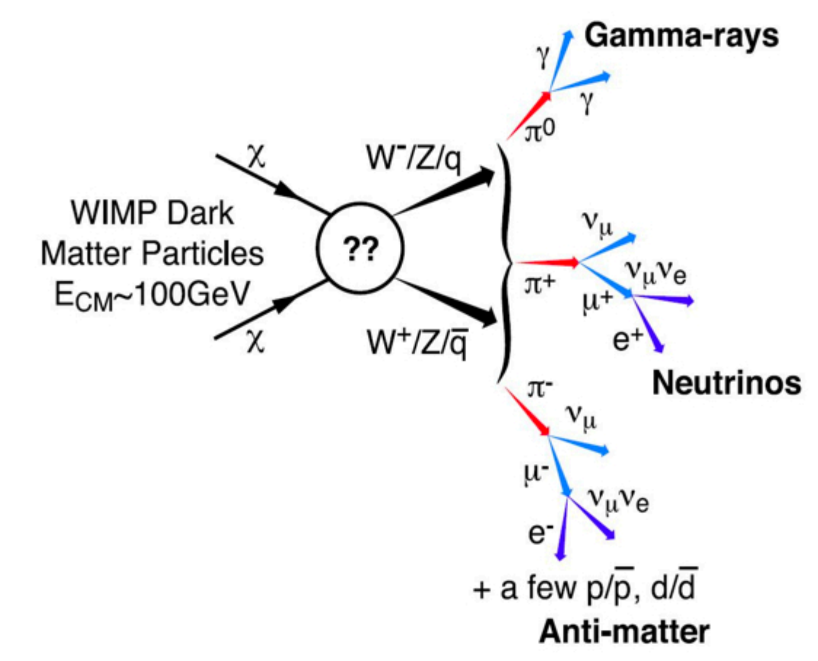
Based on DS, C. Eckner, C. Gordon, F. Calore, O. Macias, K. N. Abazajian, S. Horiuchi, M. Kaplinghat and M. Pohl, MNRAS 530 (2024) no.4, 4395-4411 (arXiv:2402.05449)

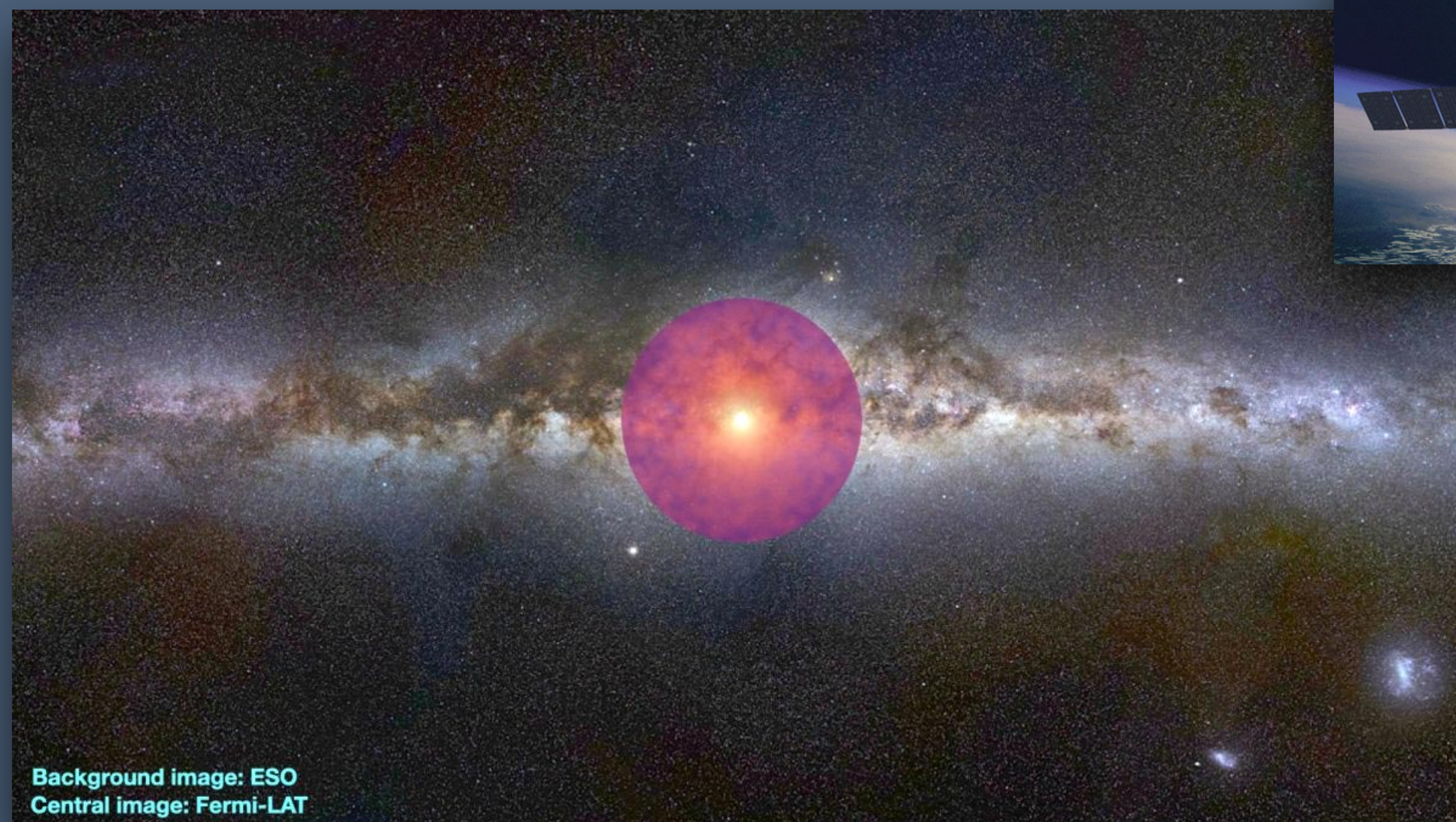
WIMP dark matter

- Weakly Interacting Massive Particles (WIMPs) can naturally account for the observed dark matter abundance through the freeze-out production mechanism
  - A remarkable coincidence between cosmology and particle physics
  - Self-annihilation of dark matter particles is expected to generate late-time signals, including gamma rays





The excess



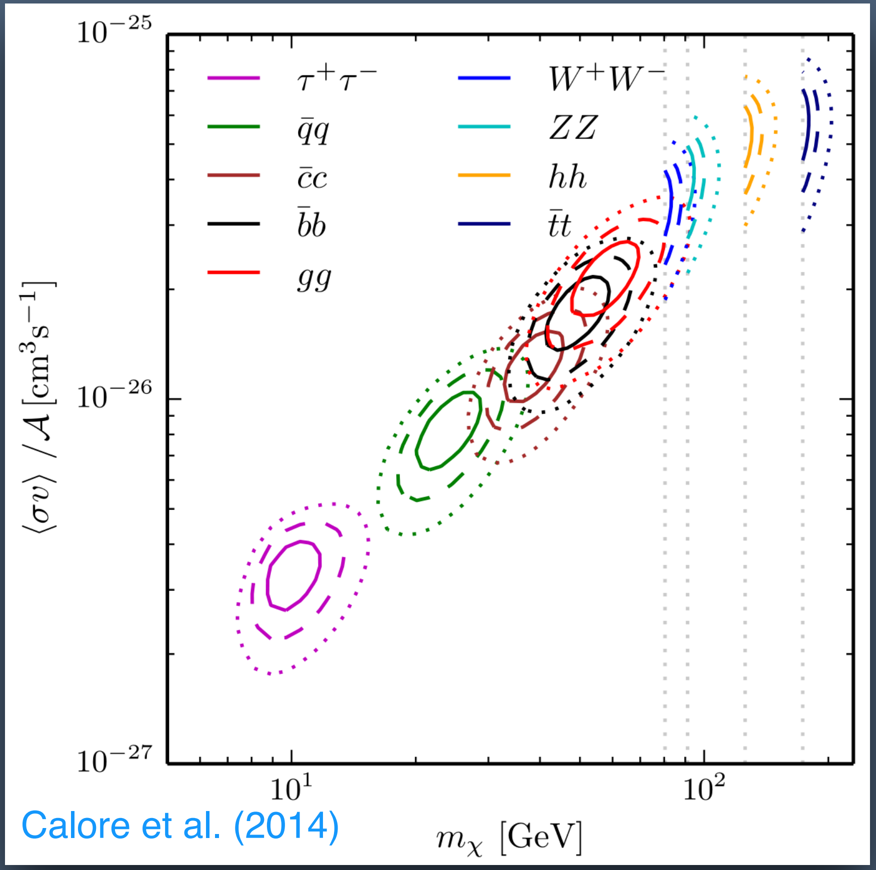
- A Galactic Center Excess (GCE) appears to resemble a WIMP dark matter signal both spatially and spectrally
  - Identified in early Fermi data [Goodenough & Hooper (2009)]
  - Concentrated at the GC and extends to $\sim \pm 20^{\circ}$ in latitude
  - Exhibits a hard spectrum peaking at a few GeV

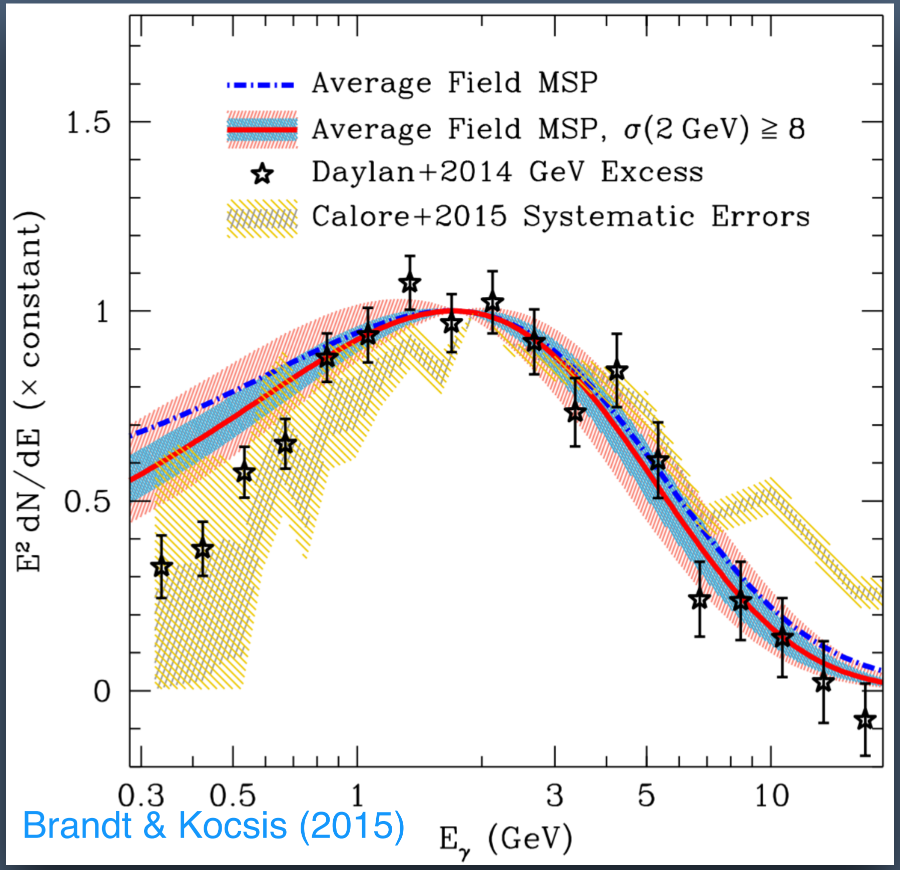
See also talks of Ben, Silvia & Joanna

Two candidates

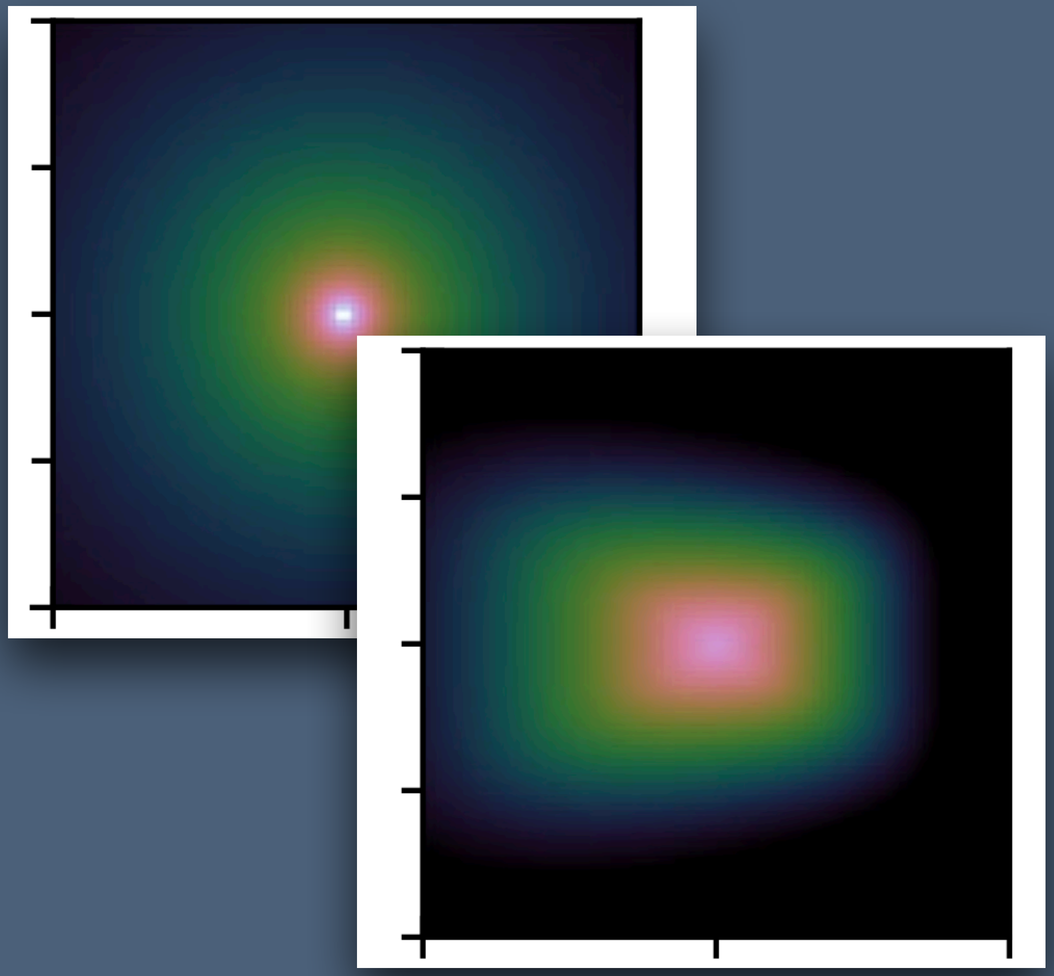
- Dark Matter: The GCE is consistent with the annihilation spectrum and cross section of thermal WIMP dark matter.

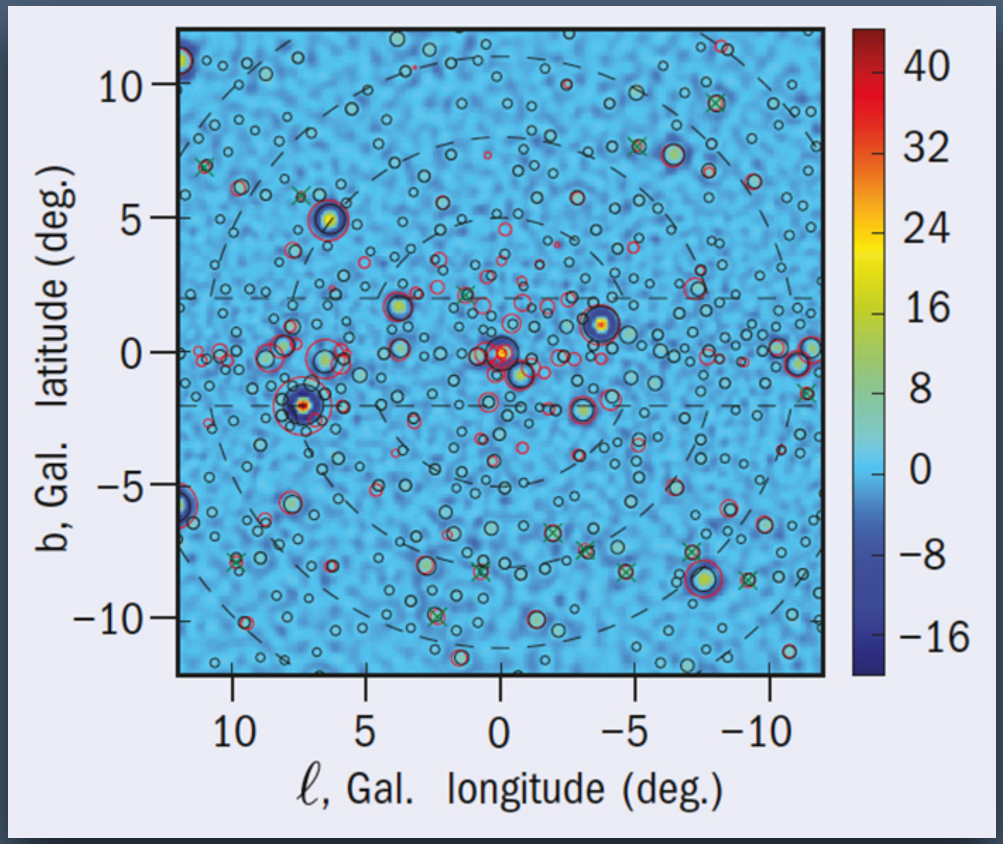
- Millisecond Pulsars: Their average gamma-ray spectrum is also consistent with the GCE.





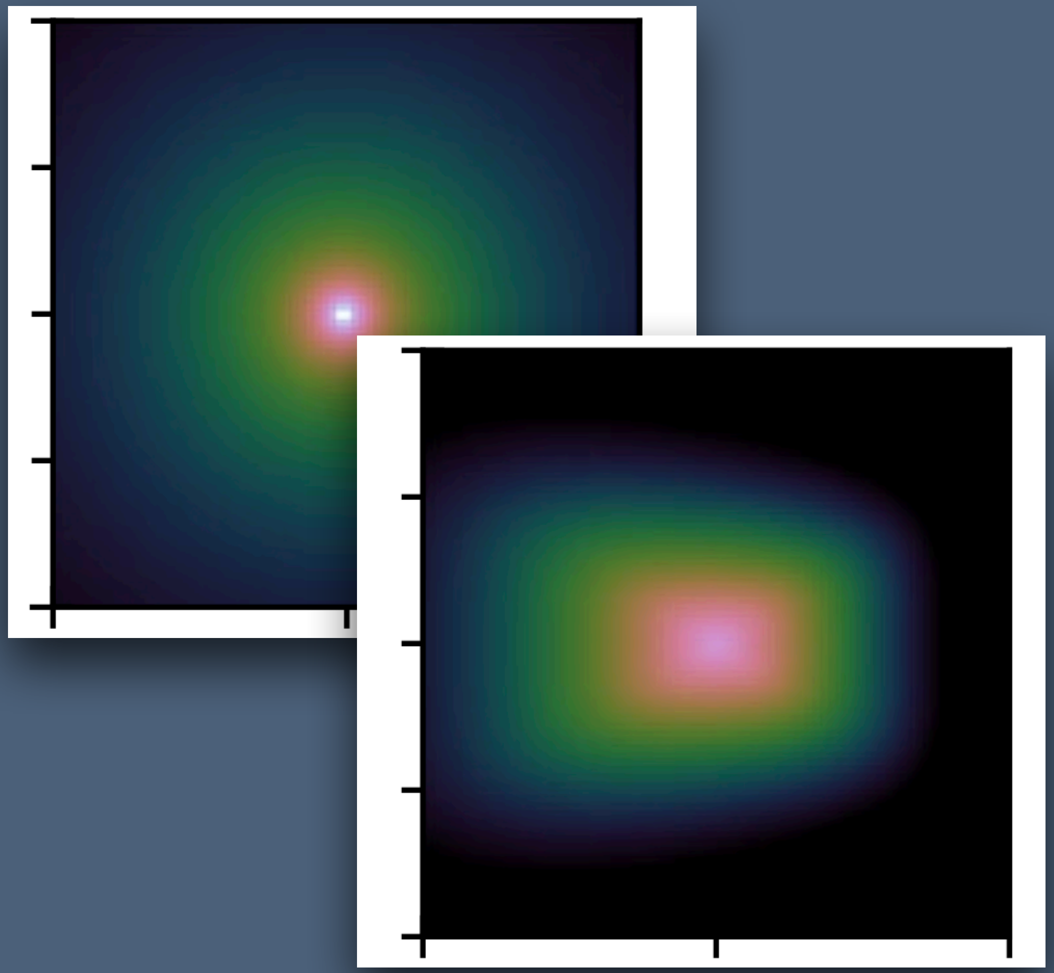
Two frontiers

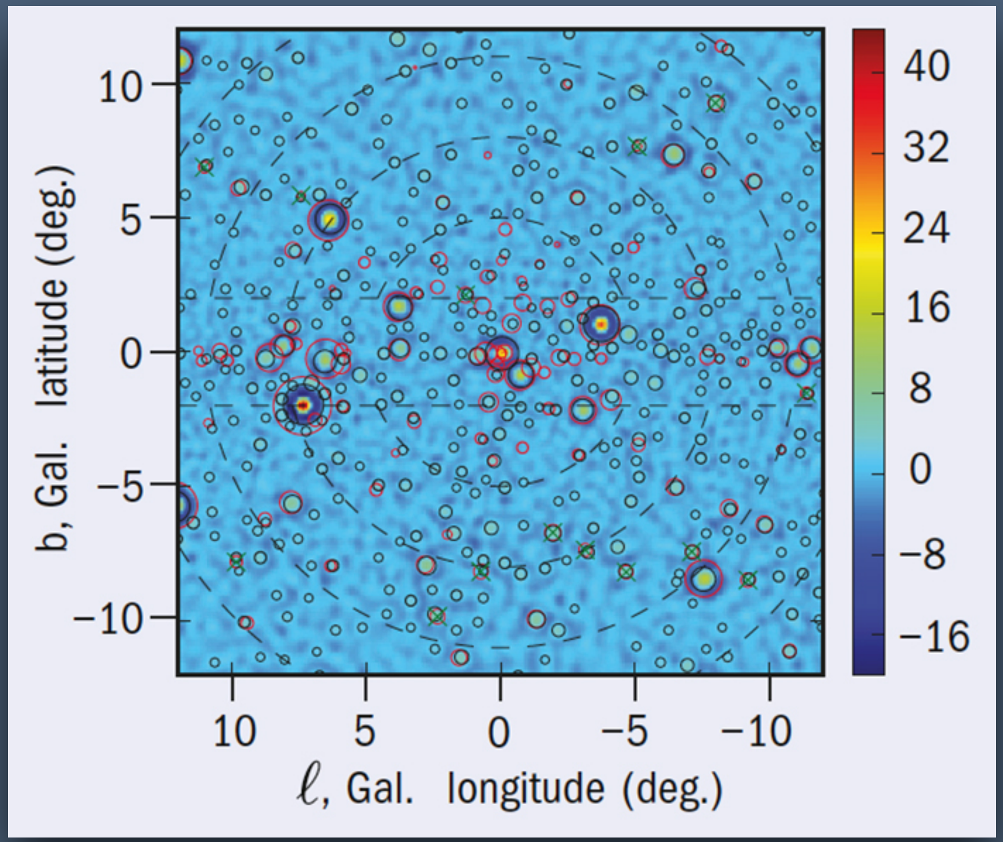




- Morphology: Does the excess follow the stellar distribution or the dark matter distribution?
- Photon-Count Statistics: Is the excess of a point-source or diffuse nature?

Two frontiers





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Discussed in Silvia's talk

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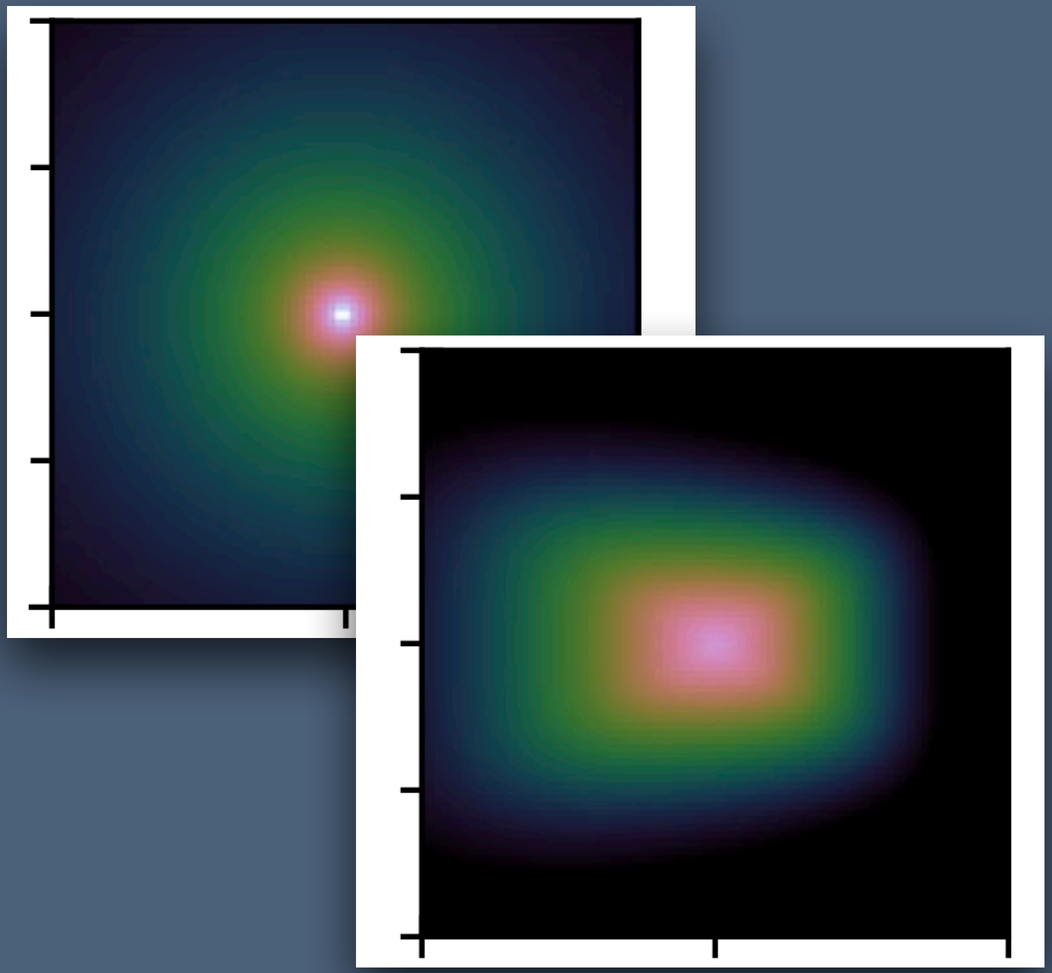

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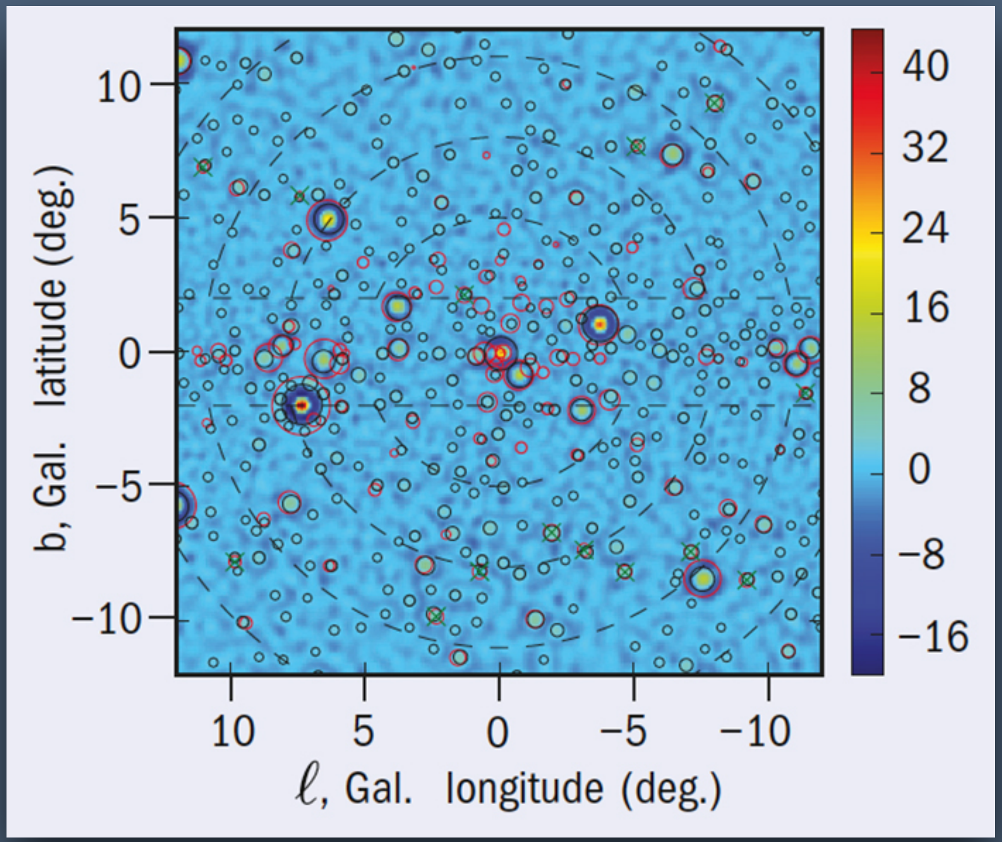
This talk

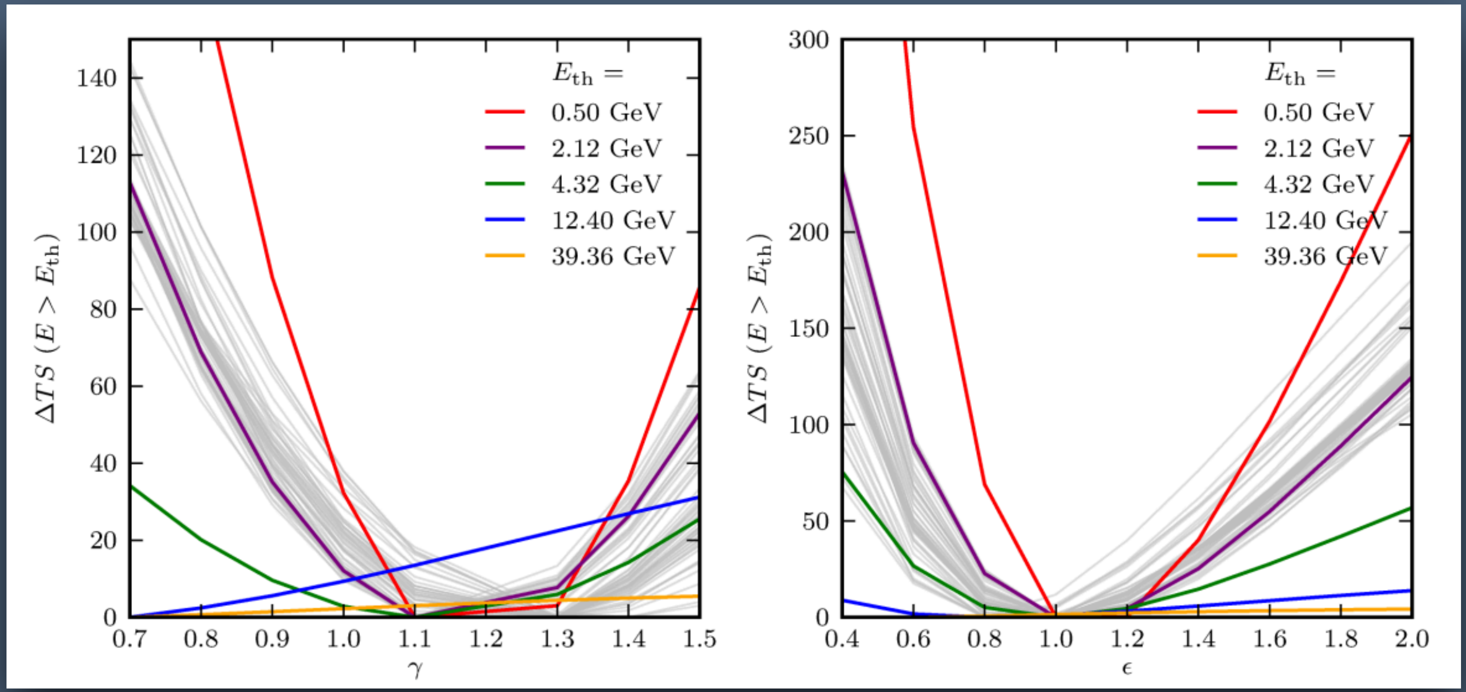


- Photon-Count Statistics: Is the excess of a point-source or diffuse nature?

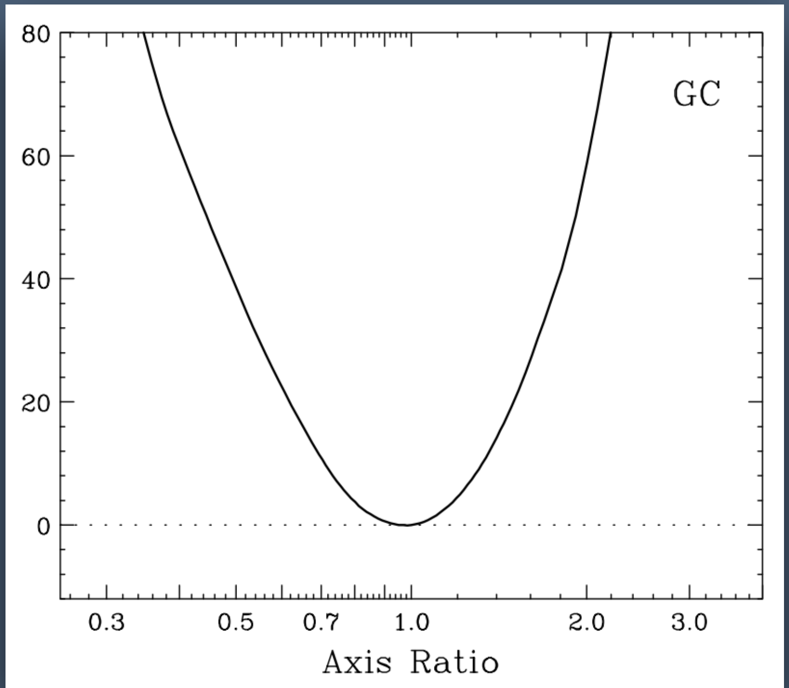
Discussed in Silvia’s talk

Spherical symmetry of GCE

- Early studies on GCE morphology focused on testing its spherical symmetry
  - Consistent with a spherical profile following an $\sim r^{-2.4}$ distribution



Calore et al. (2014)



Dylan et al. (2014)

Interpretation of the sphericity

- Dark Matter: Spherical symmetry is expected for cold dark matter (e.g., NFW profile)
  - An inner slope of $\gamma \sim 1.1$ to 1.3 on the NFW profile is acceptable

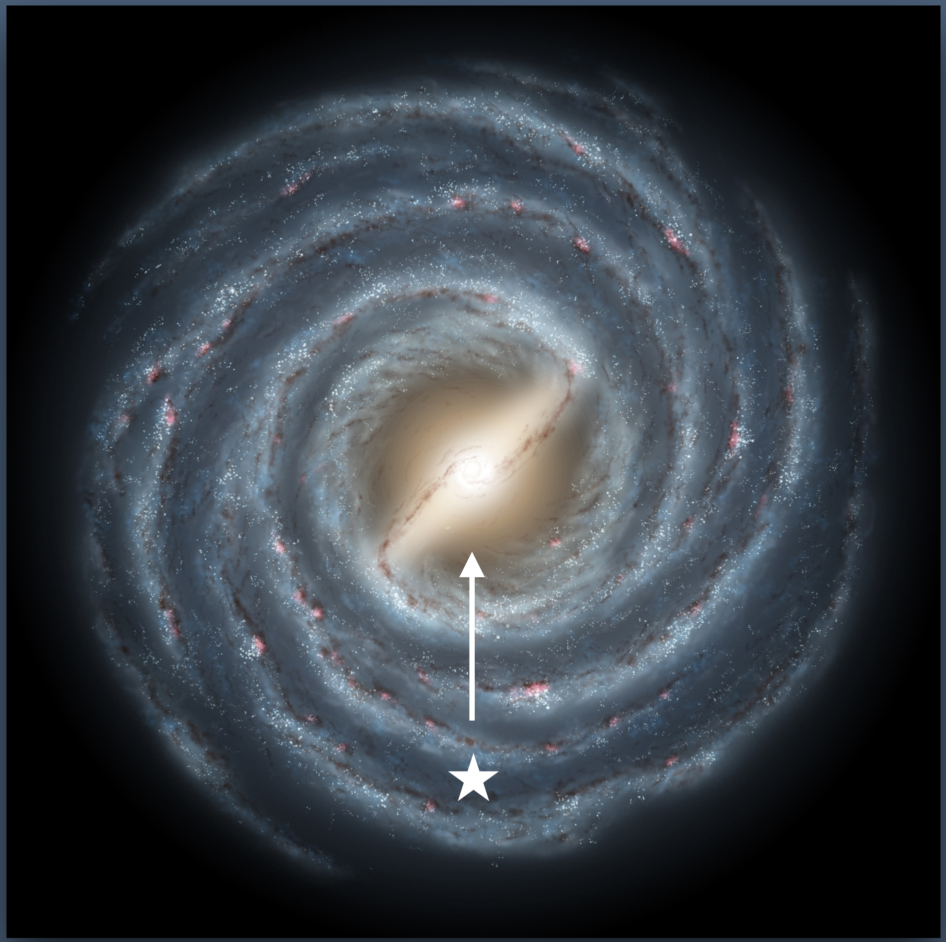
$$\rho(r) = \rho_0 \left(\frac{r}{R_s}\right)^{-\gamma} \left(1 + \frac{r}{R_s}\right)^{\gamma-3}$$

- Millisecond Pulsars: Low-mass X-ray binaries, which are progenitors of MSPs, observed in M31 show a similar sharp rise in the inner region

[Abazajian & Kaplinghat (2012)]

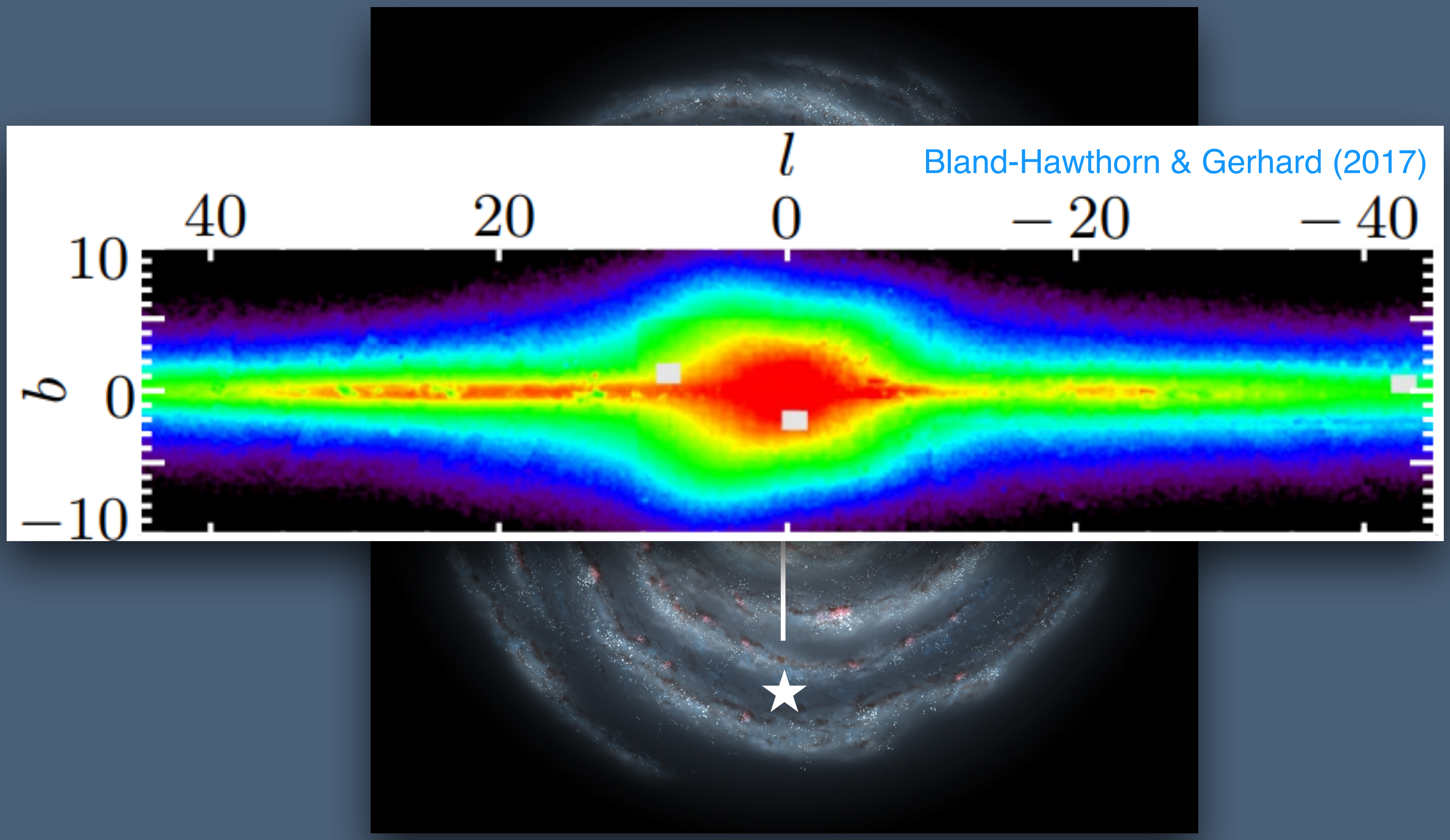
The Galactic bulge

- Unlike our view of M31, we observe the Milky Way edge-on



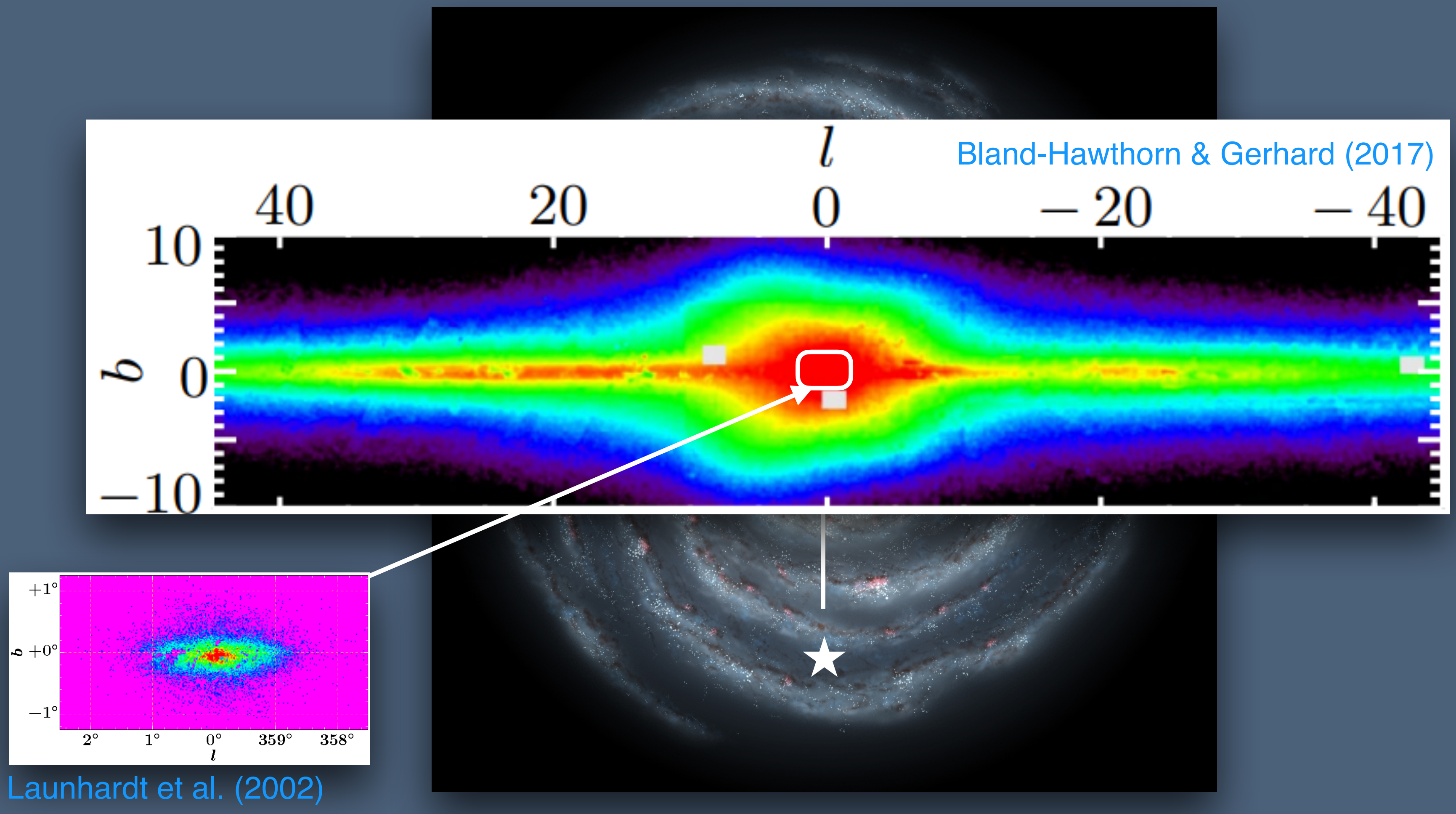
The Galactic bulge

- Unlike our view of M31, we observe the Milky Way edge-on
- The line-of-sight distribution of the stellar population in the inner Galaxy is boxy and asymmetric



The Galactic bulge

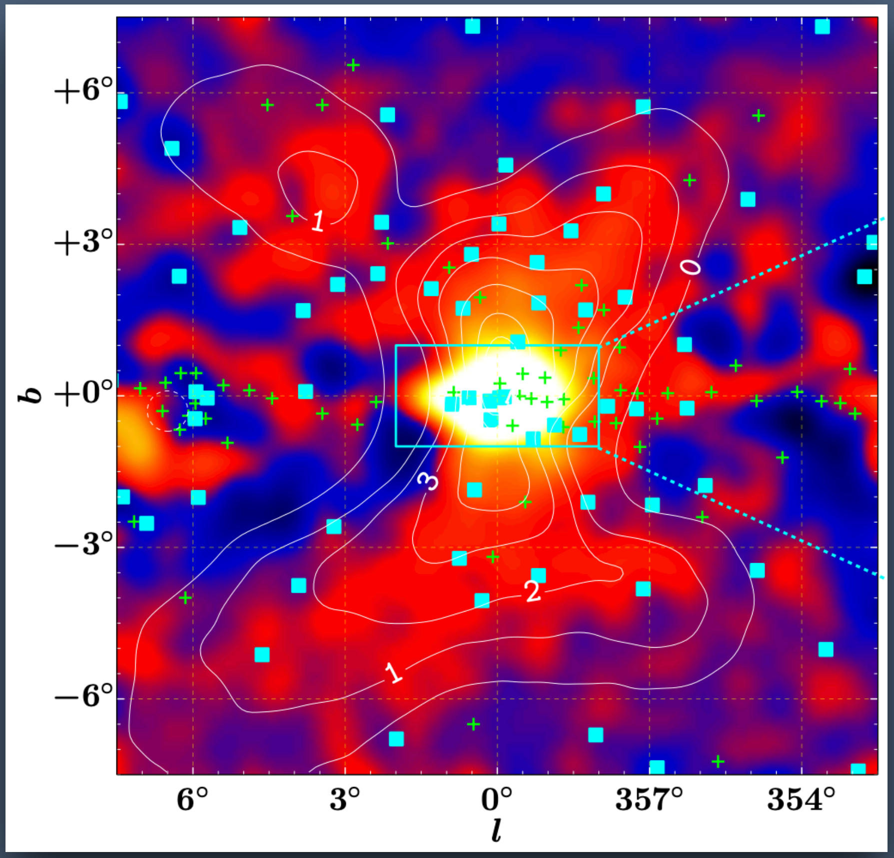
- Unlike our view of M31, we observe the Milky Way edge-on
- The line-of-sight distribution of the stellar population in the inner Galaxy is boxy and asymmetric
  - A nuclear bulge in the innermost region is linked to the Central Molecular Zone



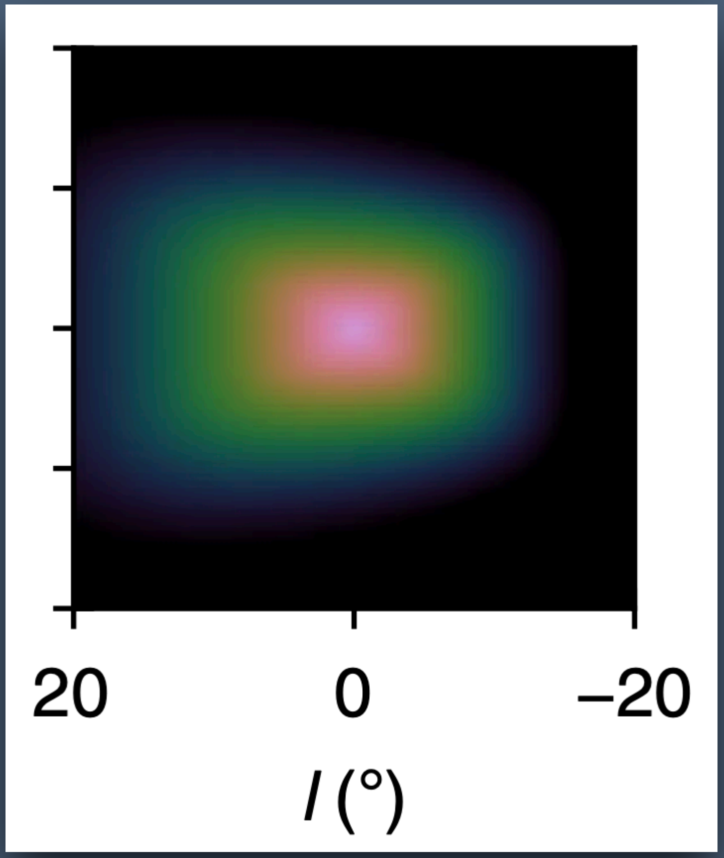
Test of bulge templates

- Galactic bulge templates were first tested by Macias et al. (2017) and Bartels et al. (2017)

- Both studies found a preference for the bulge over dark matter



Macia et al. (2017)



Bartels et al. (2017)

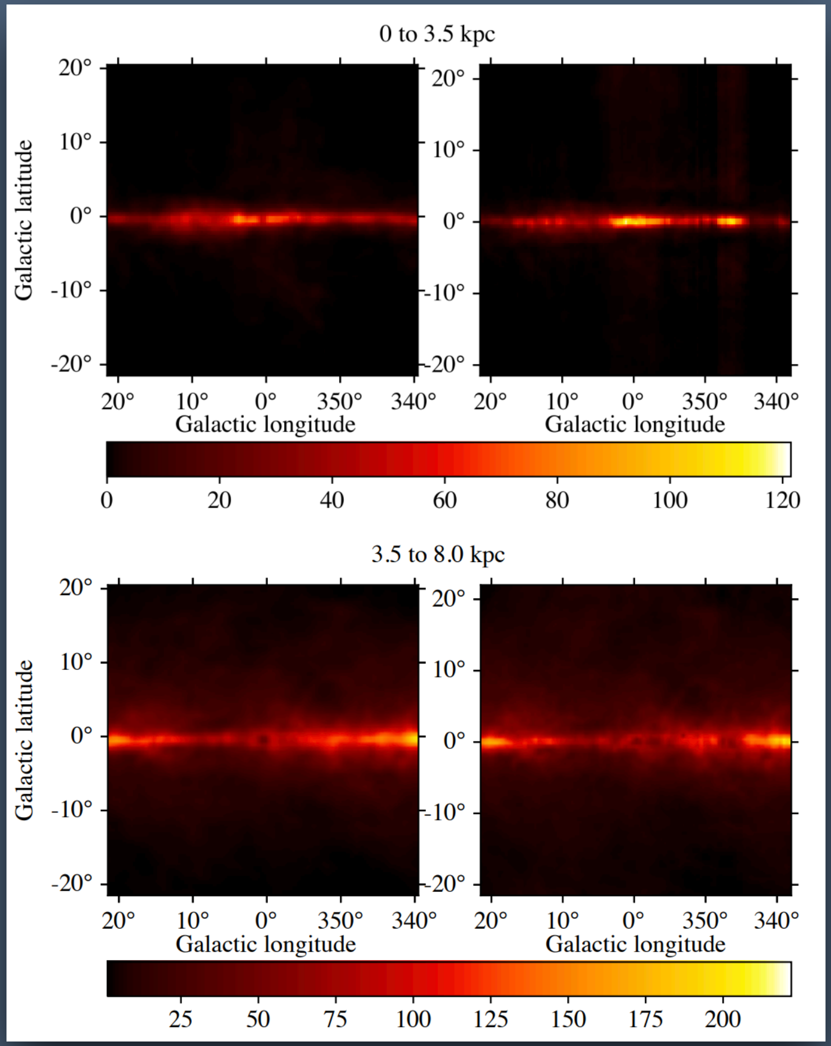
Improved gas maps

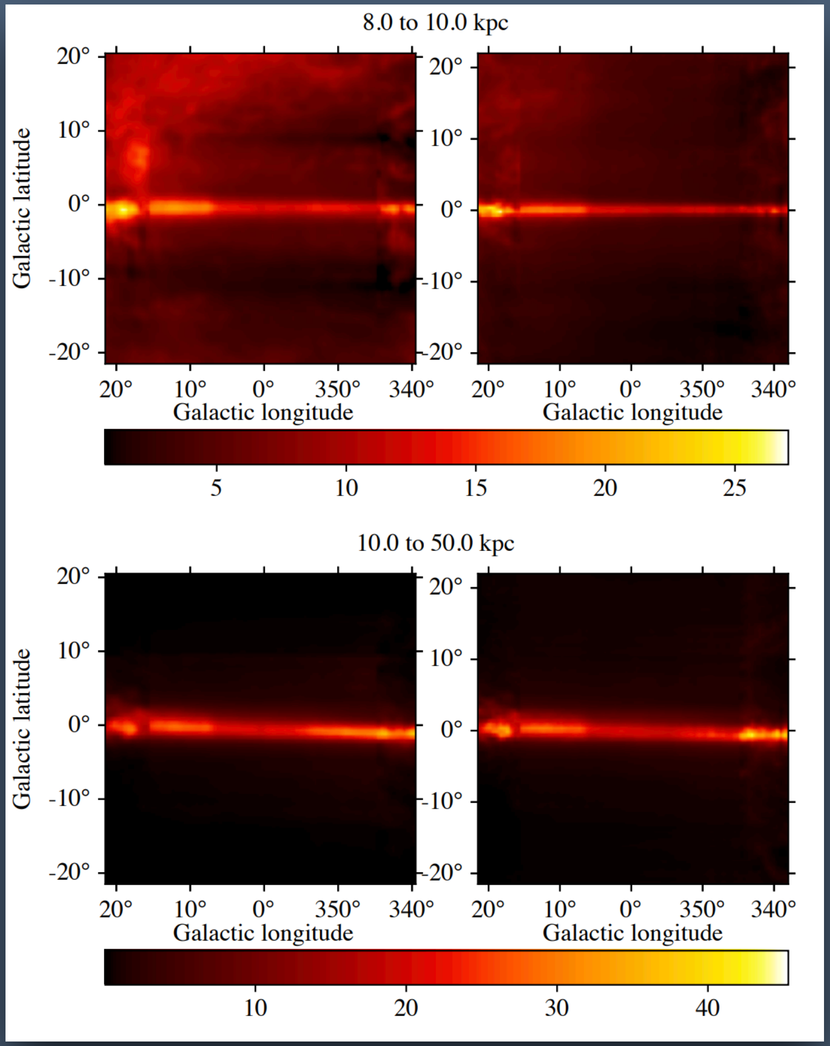
- Hydrodynamic simulations + dividing the Galaxy into rings

[Macia et al. (2017)]

- Including continuum emission to better account for atomic hydrogen

[Phol et al. (2022)]

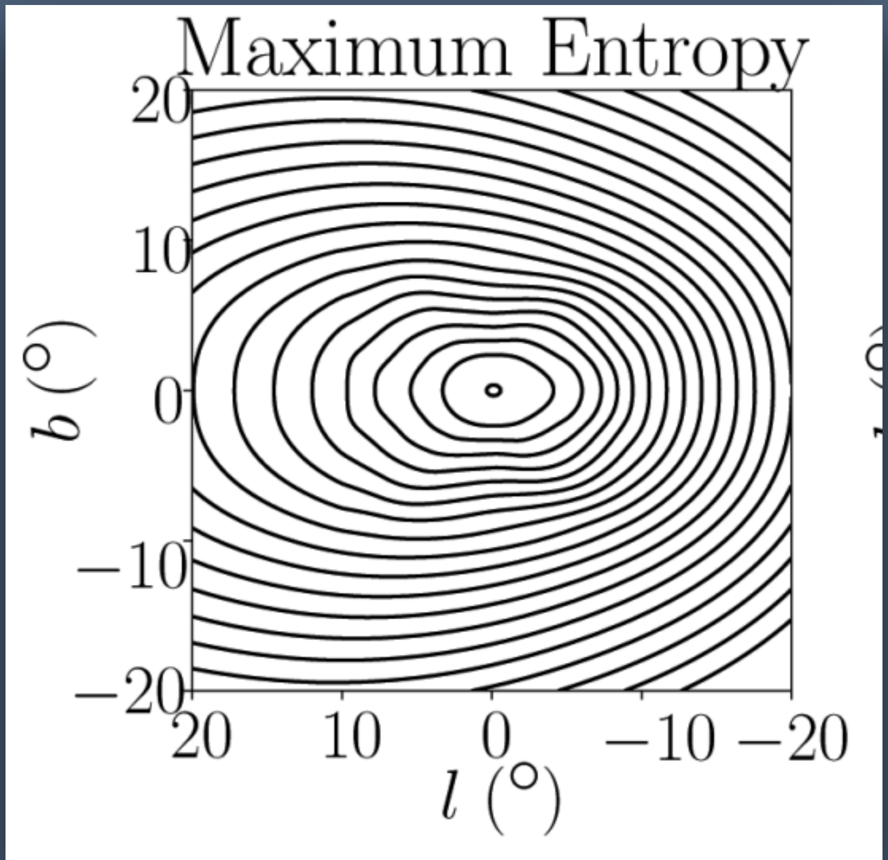


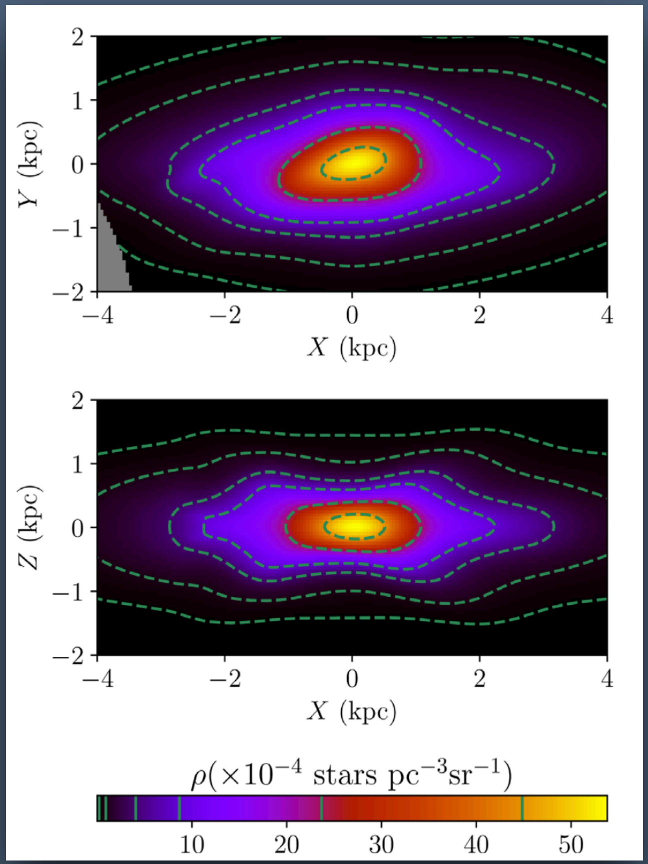


Improved bulge model

- Efforts have been made to improve the bulge model using the latest VVV survey and a non-parametric model based on maximum entropy deconvolution [Coleman et al. (2020)]

- With improved gas maps and bulge model, the preference for the bulge model is persistent





Contradictory results

- Di Mauro (2021) found mixed results

$\mathrm{Log}(\mathcal{L}) - \mathrm{Log}(\mathcal{L}_{\mathrm{DM}})$	Baseline	ICS combined	OB stars	Pulsars	SL ext.	SNR	Yusifov
BB	−1139	−1192	−797	−1434	−543	−826	−1043
DM + NB	+179	+217	+38	+261	+84	+135	+205
BB + NB	+55(−124)	+21(−196)	−34(−72)	+36(−225)	−51(−135)	+15(−120)	+9(−196)

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BB+NB > DM

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  - Only the DM + NB model is preferred over the BB + NB model, but this lacks physical motivation

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Excess model	Background template	$-2\Delta\ln\mathcal{L}$	$\Delta\ln\mathcal{B}$
No excess	Ring-based	0	0
X-shaped bulge	Ring-based	+30	−190
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Boxy bulge ‘plus’ & DM	Astrophysical	−7401	+4298

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Galprop >> Rings

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- No test of the latest bulge model
- Statement about the ring-based background model is dubious

Galprop >> Rings

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DM > Bulge

Testing the findings

- McDermott et al. have made their data and models public (through the *gcepy* package)
- We've decided to understand the differences by working with their data/models
- We also test additional bulge models

DS, C. Eckner, C. Gordon, F. Calore, O. Macias, K. N. Abazajian, S. Horiuchi, M. Kaplinghat and M. Pohl,
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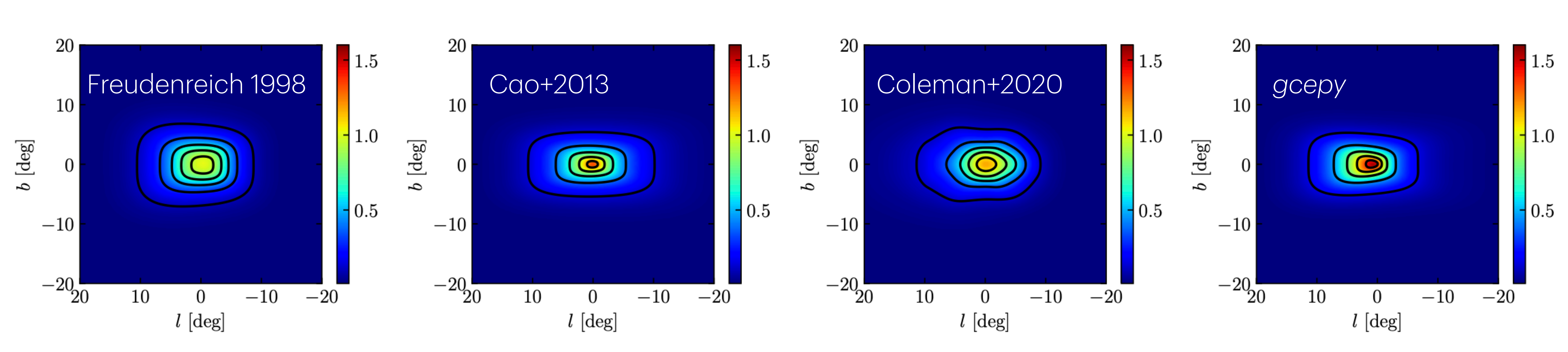
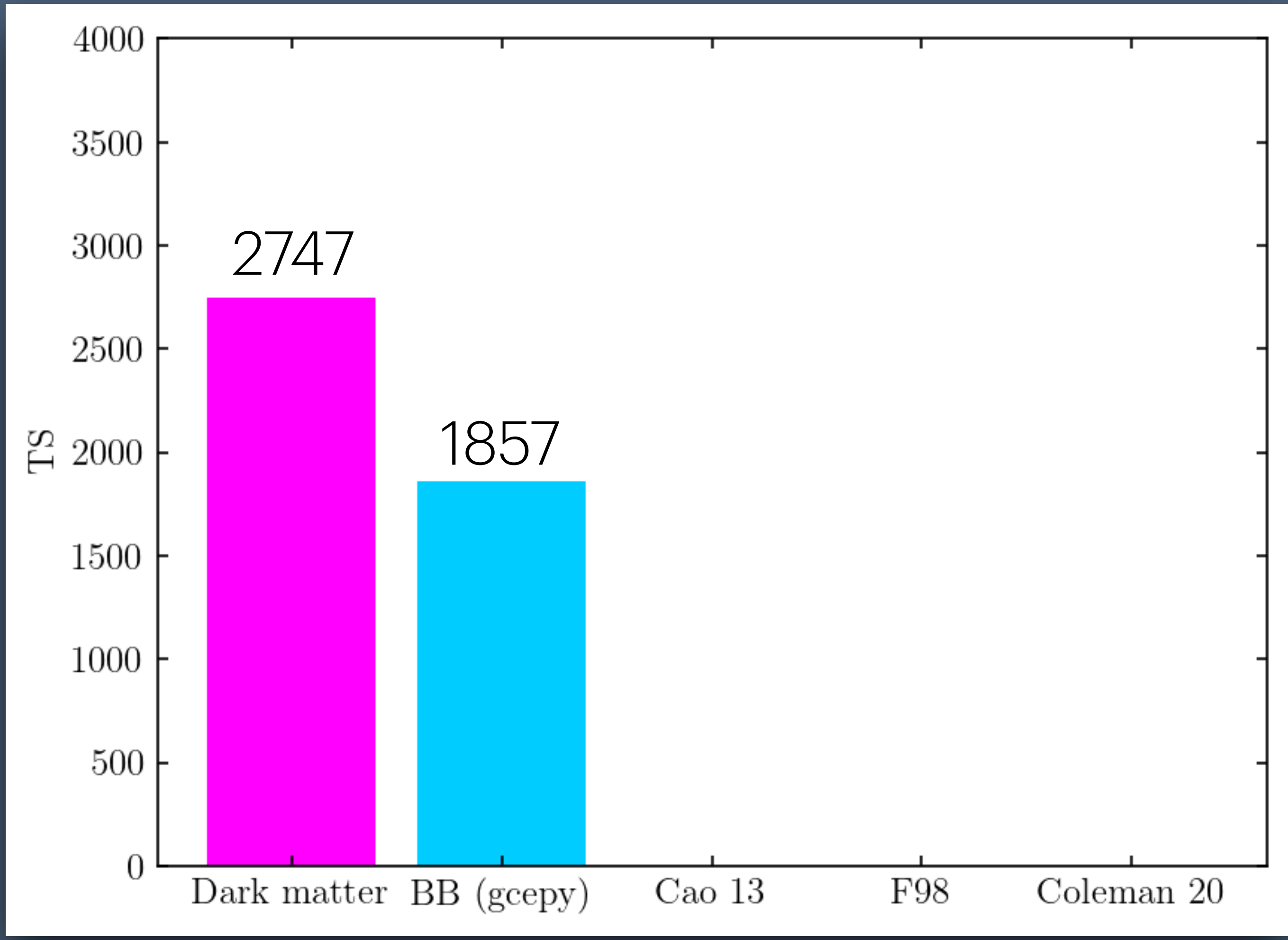


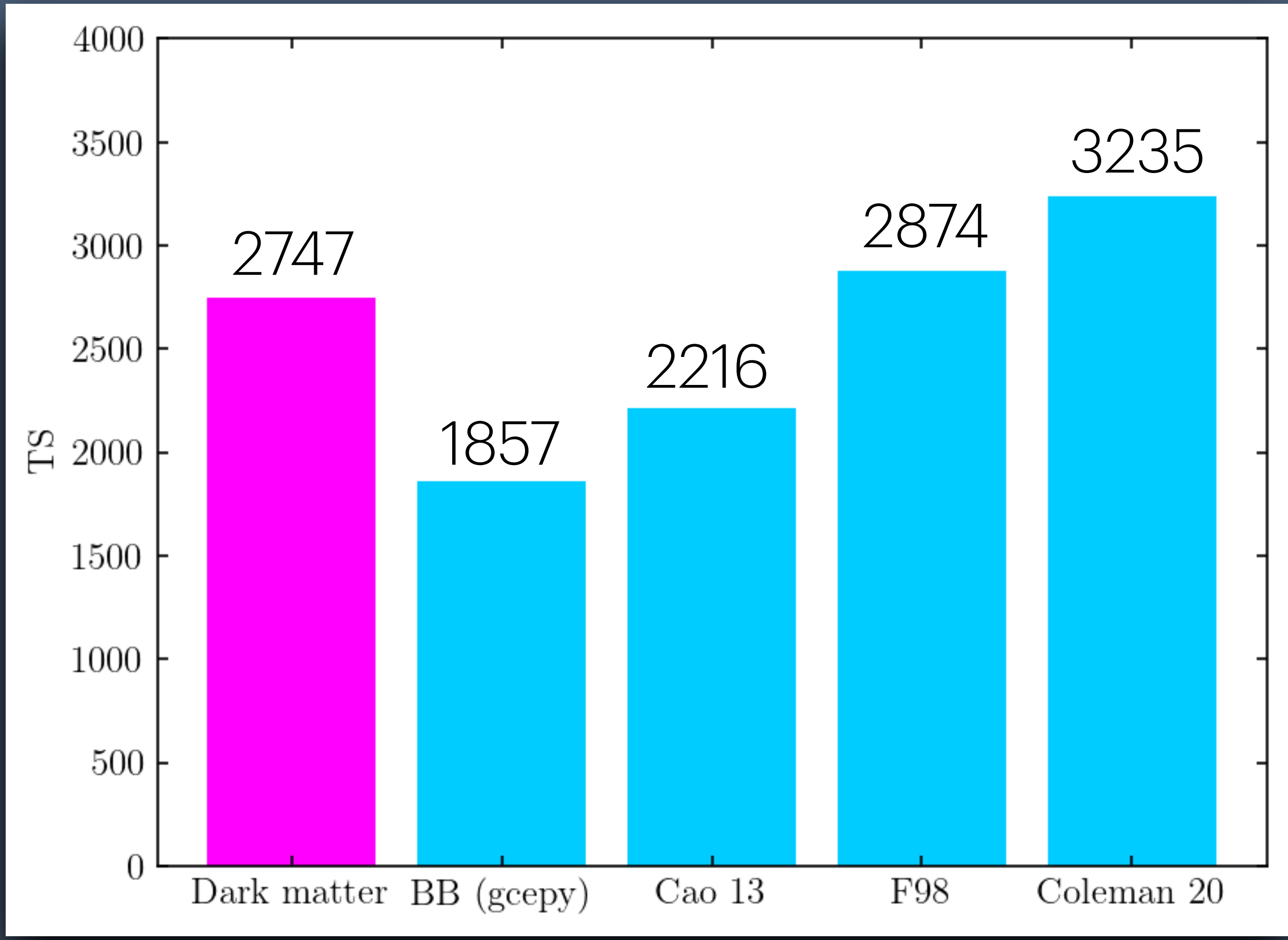
Testing bulge models within GALPROP-based bkg. models

- We can reproduce the results of McDermott et al. using their GALPROP-based background model and bulge model



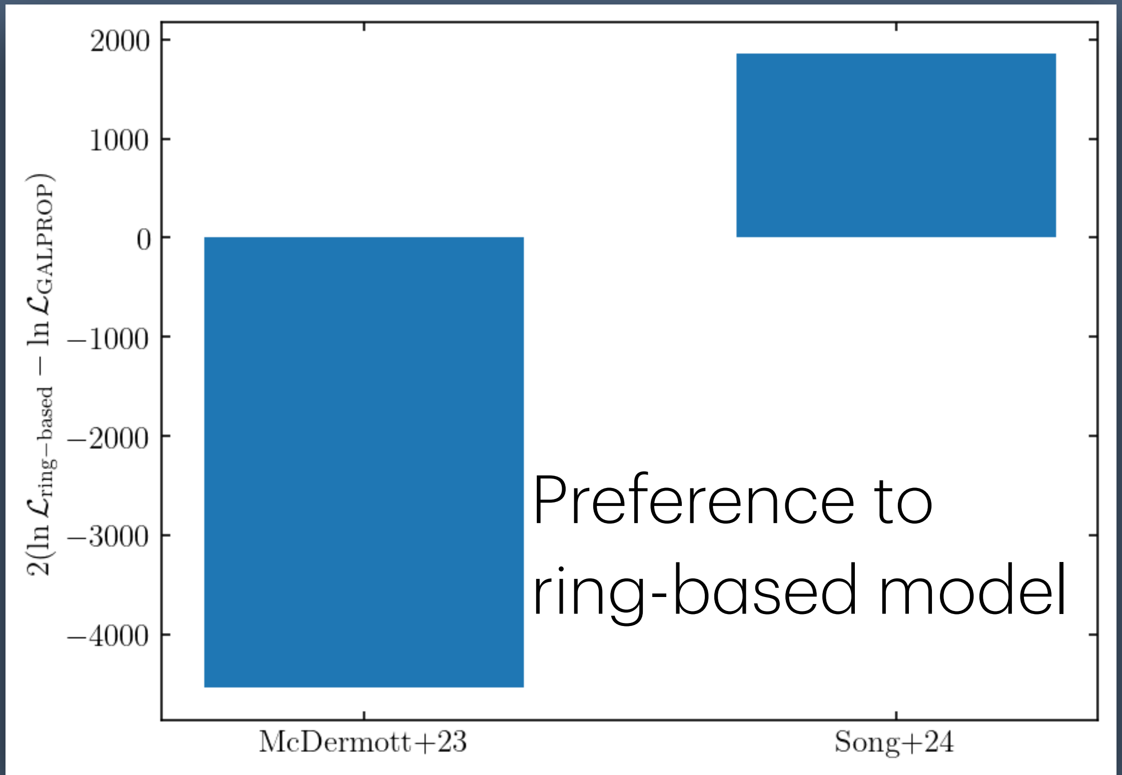
Testing bulge models within GALPROP-based bkg. models

- We can reproduce the results of McDermott et al. using their GALPROP-based background model and bulge model
- The Coleman et al. bulge model is still strongly preferred when tested with the data from McDermott et al.



Discrepancy in ring-based background model

- We find significant discrepancies in testing the ring-based background model
  - The ring-based background model provides a significant improvement in fitting the data compared to the GALPROP-based background model, contradicting McDermott et al.



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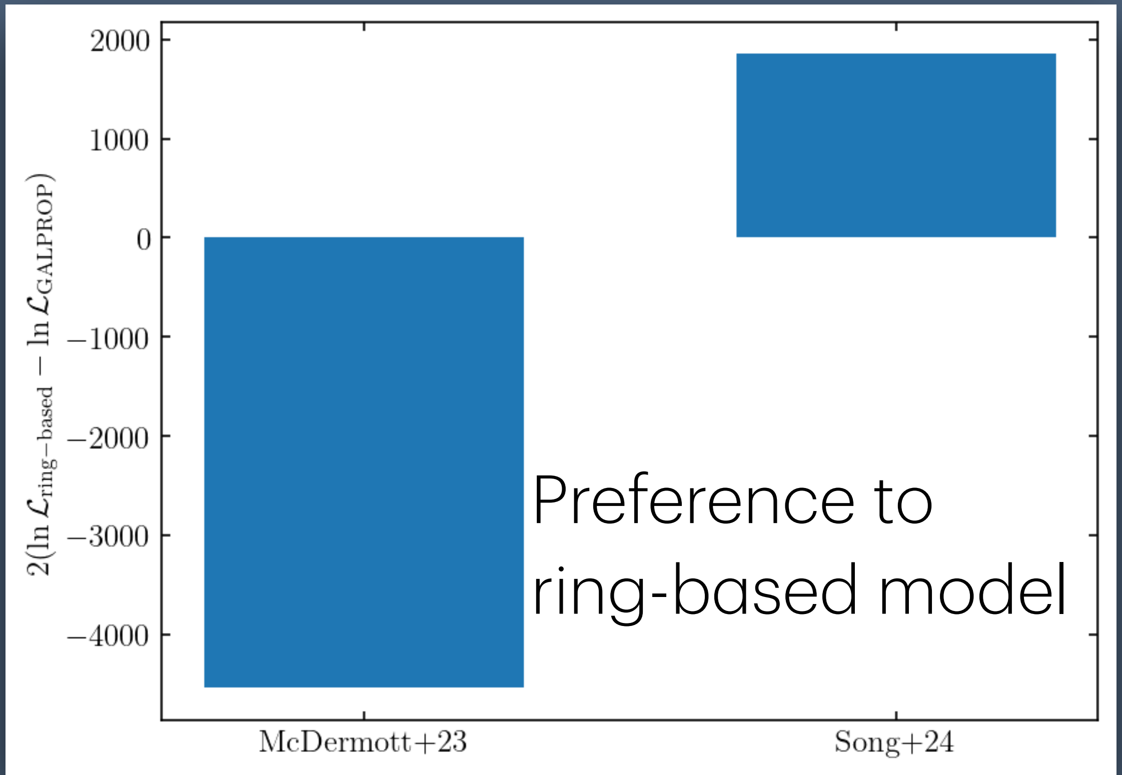
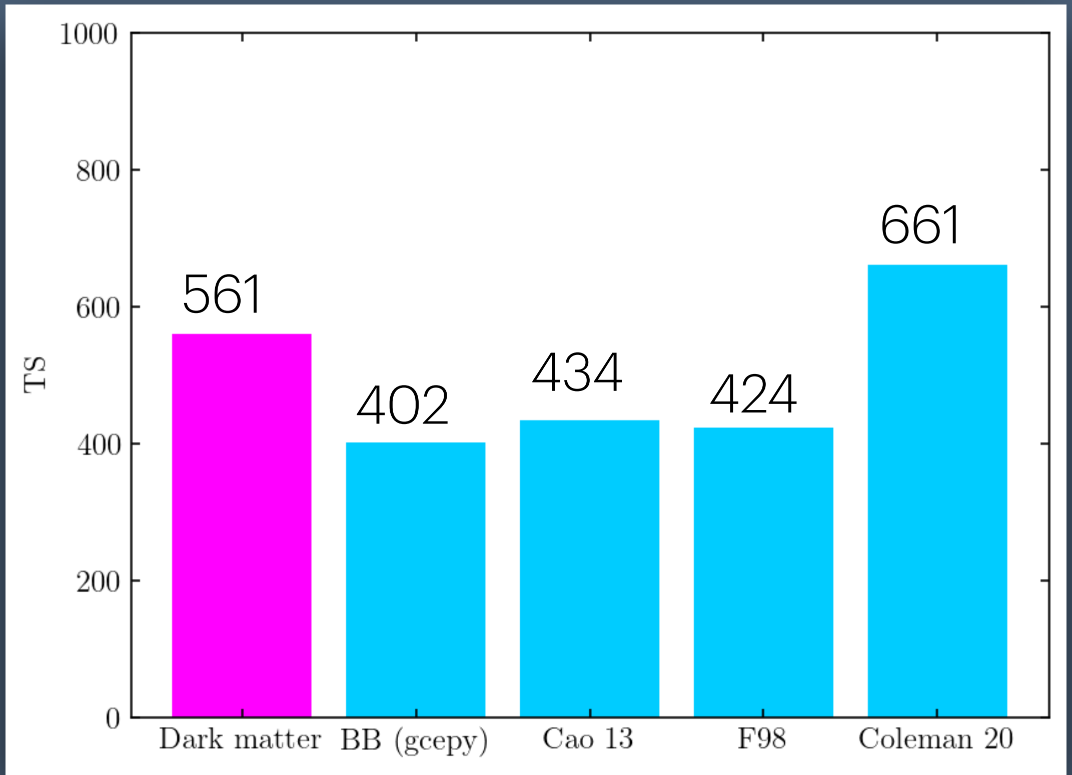
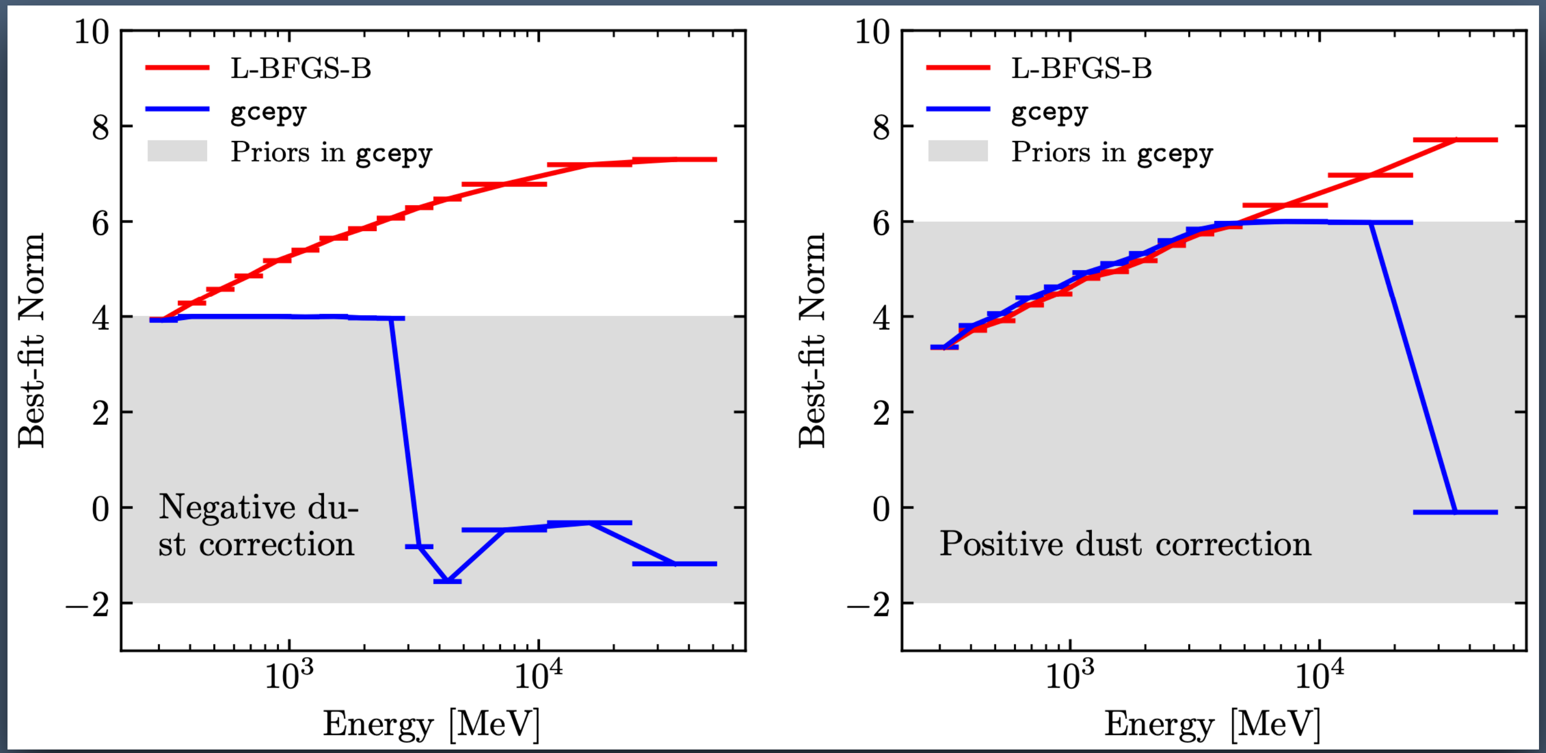
  - The Coleman et al. bulge model remains the most preferred template for the GCE





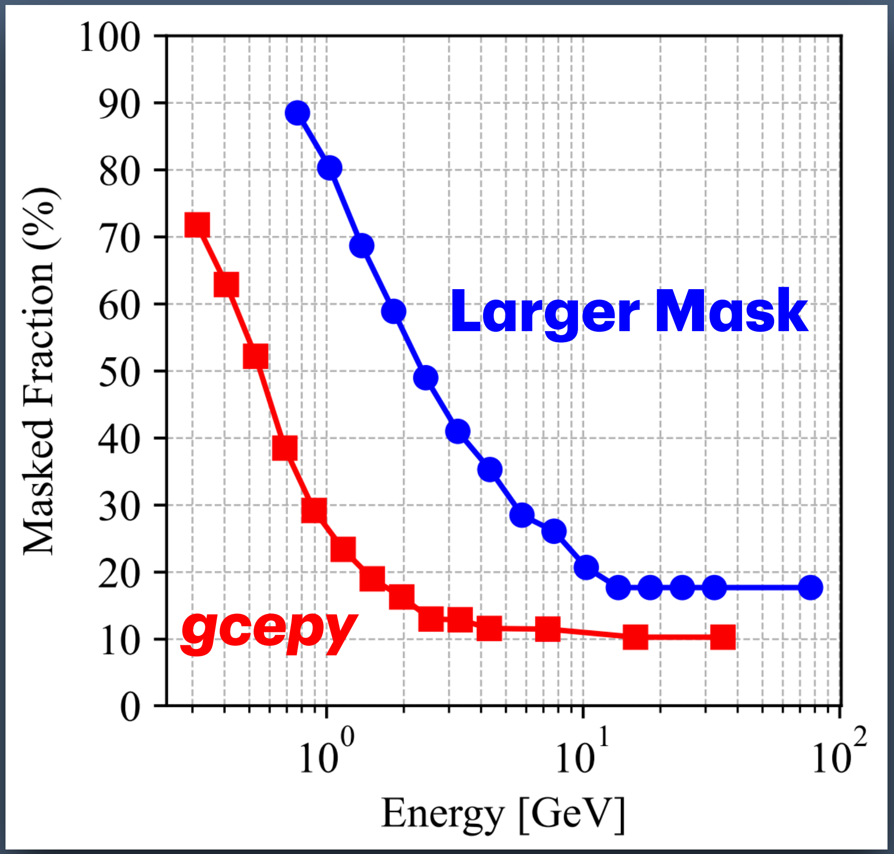
Understanding the discrepancy

- McDermott et al./*gcepy* failed to find the best fit for the ring-based background model due to the use of limited priors for the dust correction maps
  - These maps are corrections for dark neutral medium gas and are also included by the Fermi collaboration in developing the Galactic diffuse model
- *gcepy* also agrees with the superiority of the ring-based background model once broader priors are adopted



Tests including the Galactic plane

- We unmask the galactic plane and include the nuclear bulge
- Also use a larger point-source mask
- On top of ring-based background model + nuclear bulge, Coleman model model is still preferred



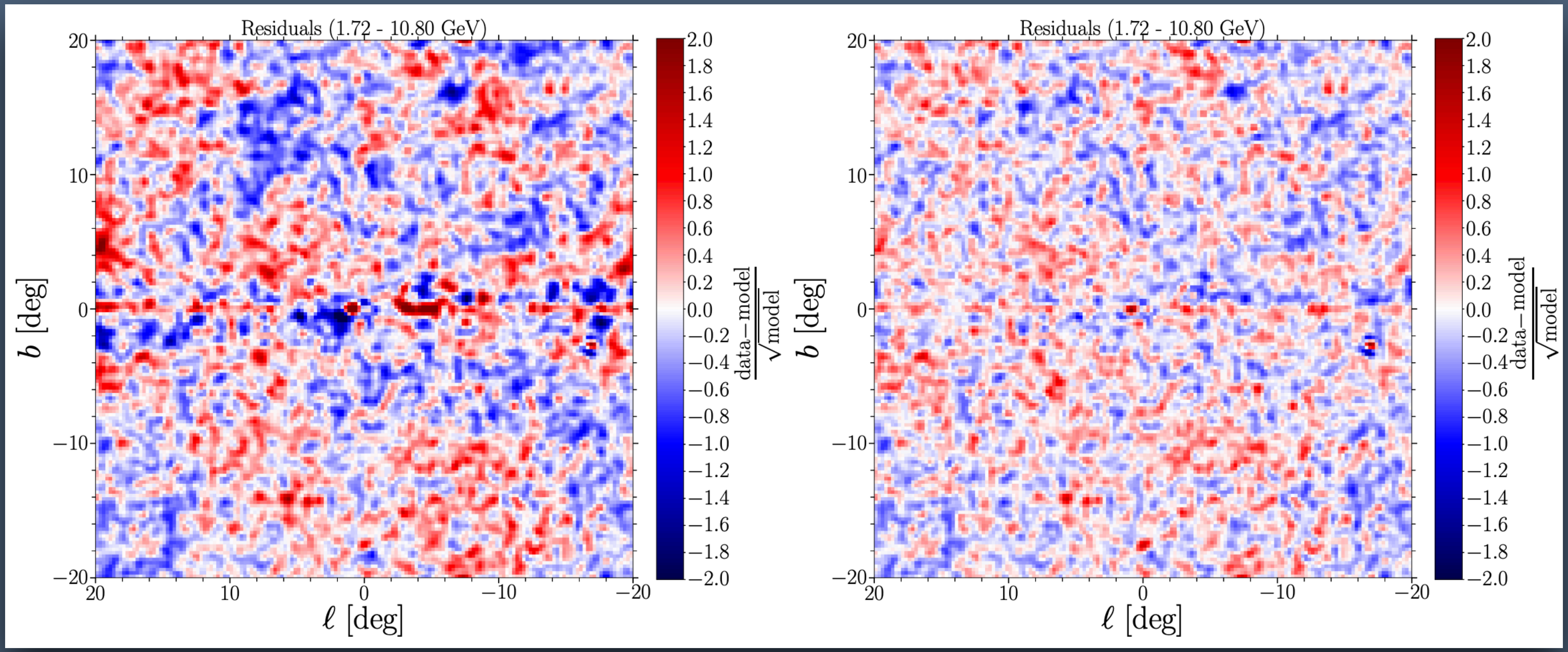
Adaptive template fitting

- We use *skyFACT* code to test adaptive template fitting

[Storm et al. (2017)]

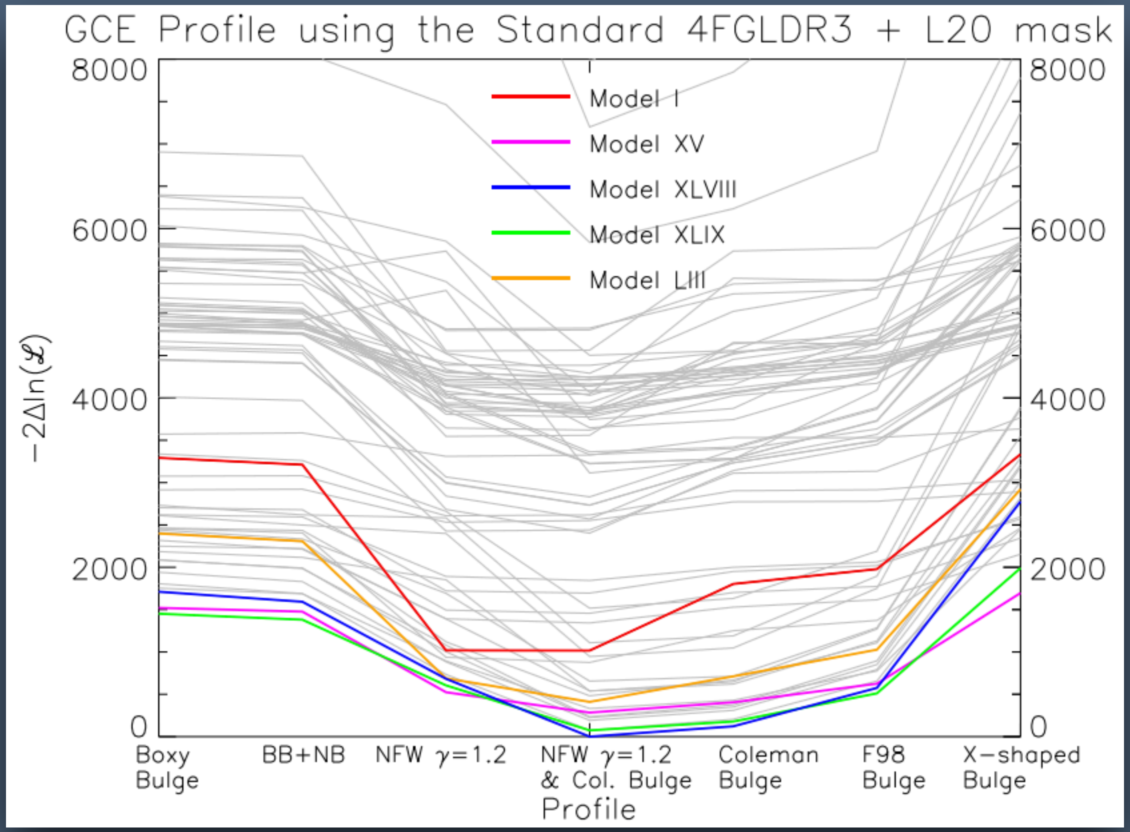
  - Spatial templates are re-modulated and optimized during fitting to reduce residuals

- With ring-based background model + nuclear bulge + Coleman model, no evidence for a dark matter component



Zhong & Cholis (2024)

- Tested additional masks and GALPROP models
- They find that Coleman bulge model is comparable to dark matter (NFW with $\gamma = 1.2$)
- The ring-based background model has not been tested

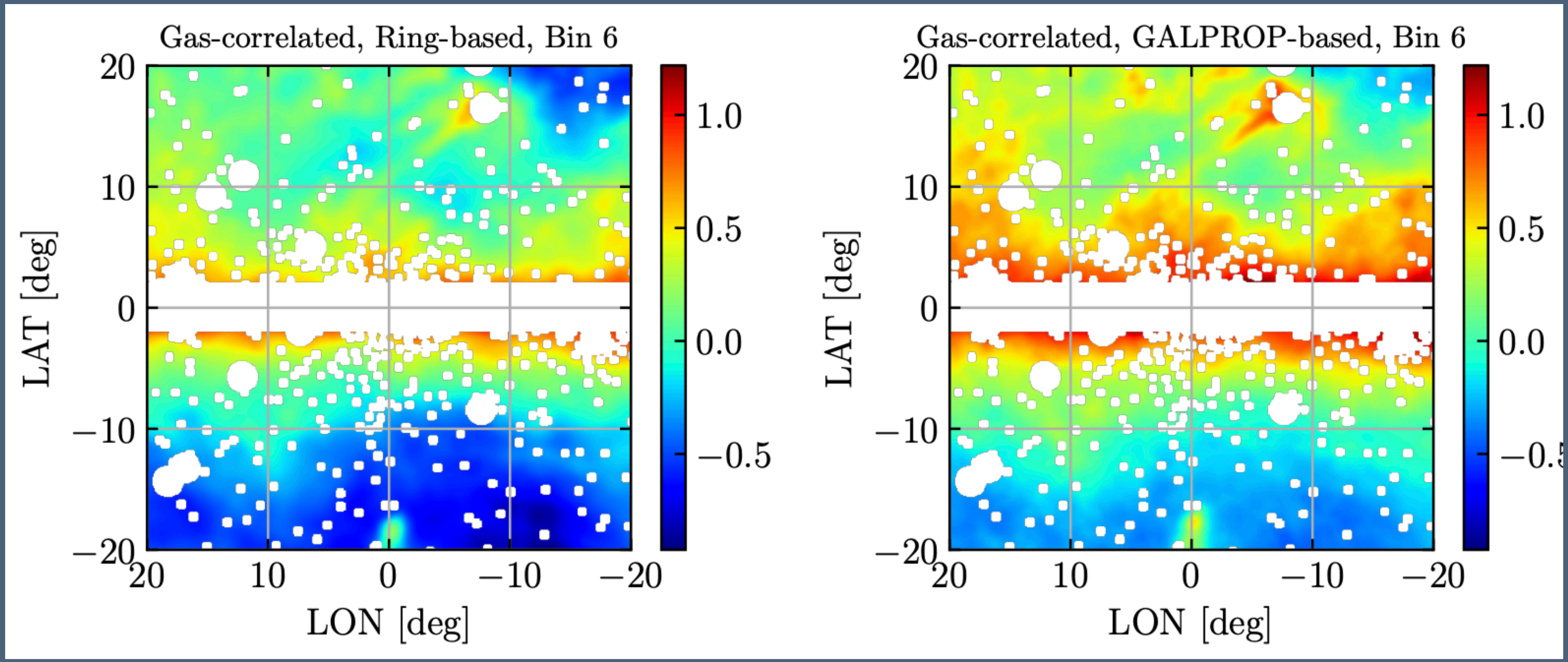


Summary

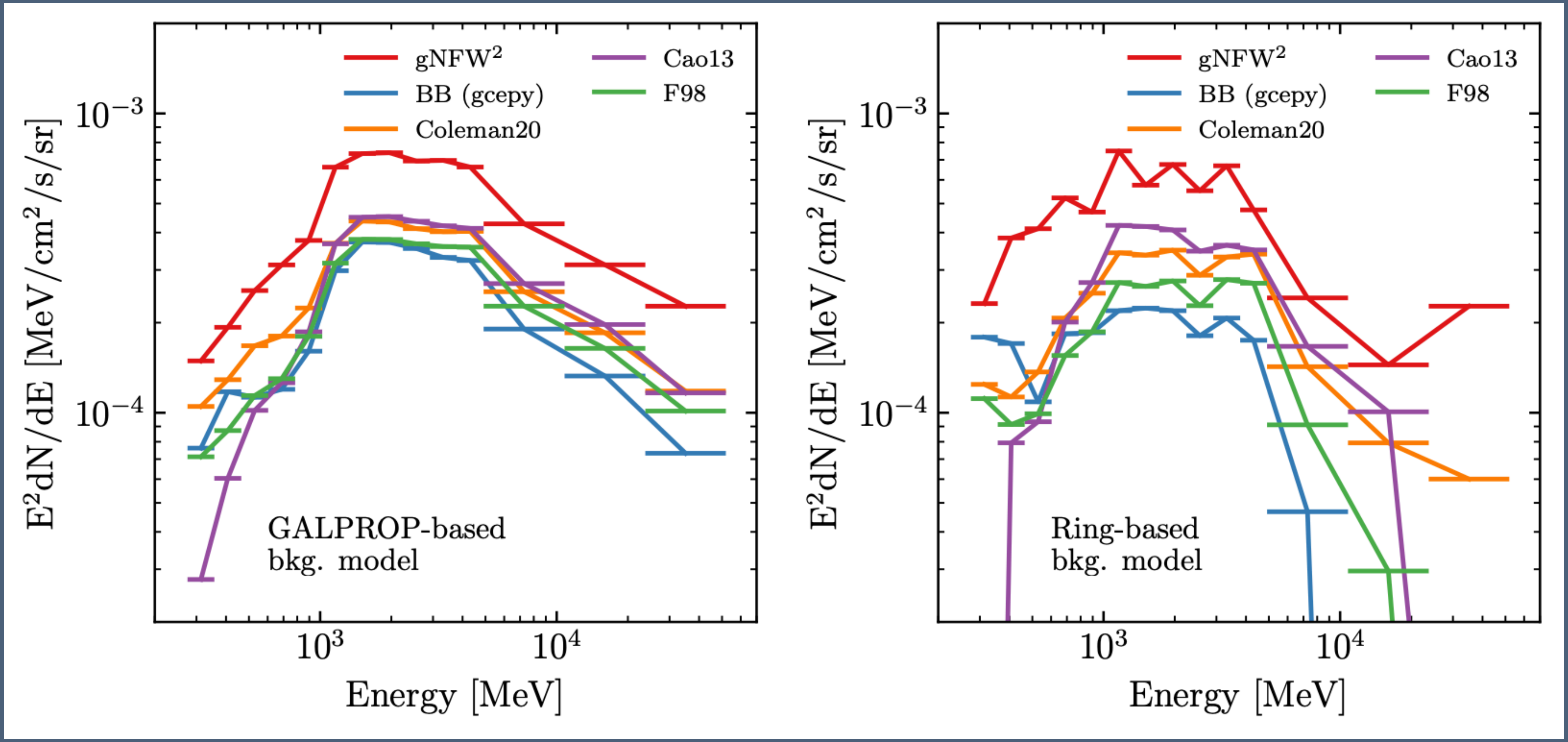
- We test different bulge models in the masked GCE data using various background models
- The ring-based background model fits the data much better than the GALPROP-based models
- The bulge model from the latest VVV survey (Coleman et al. 2020) is consistently the preferred template for the GCE
- Our results are consistent across different masks/ROIs and when using the adaptive template fitting method

Thank you!

Best-fit bkg. Models



GCE spectra


gNFW^2
BB (gcepy)
Coleman20
Cao13
F98
10^{-3}
10^{-4}
E^2dN/dE [MeV/cm^2/s/sr]
GALPROP-based
bkg. model
Ring-based
bkg. model
10^3
10^4
Energy [MeV]