Recent updates on the morphology of the Galactic center excess

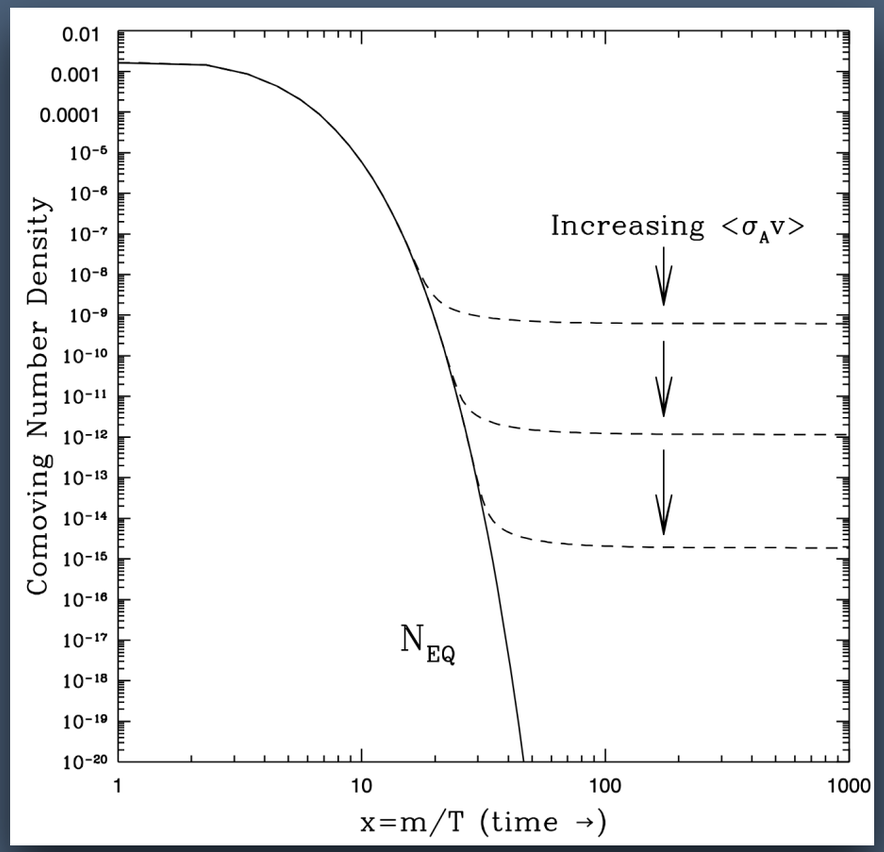
Deheng Song (YITP, Kyoto University)

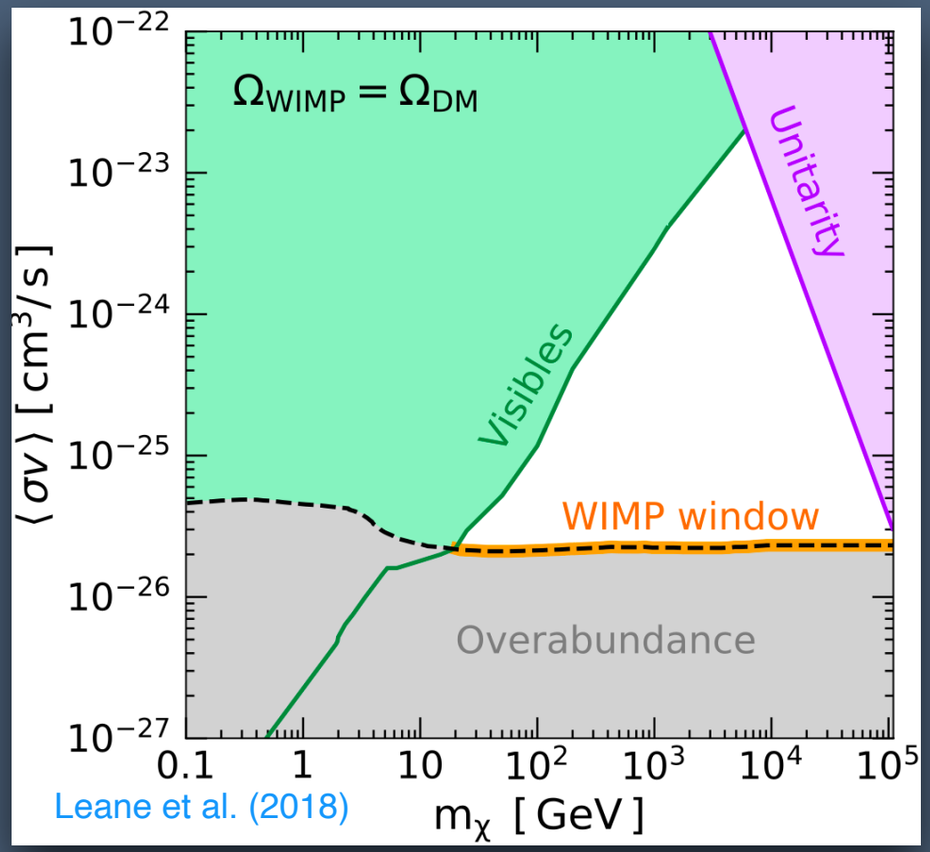
10/17/2024 Cosmic Indicators of Dark Matter 2024

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) and other works

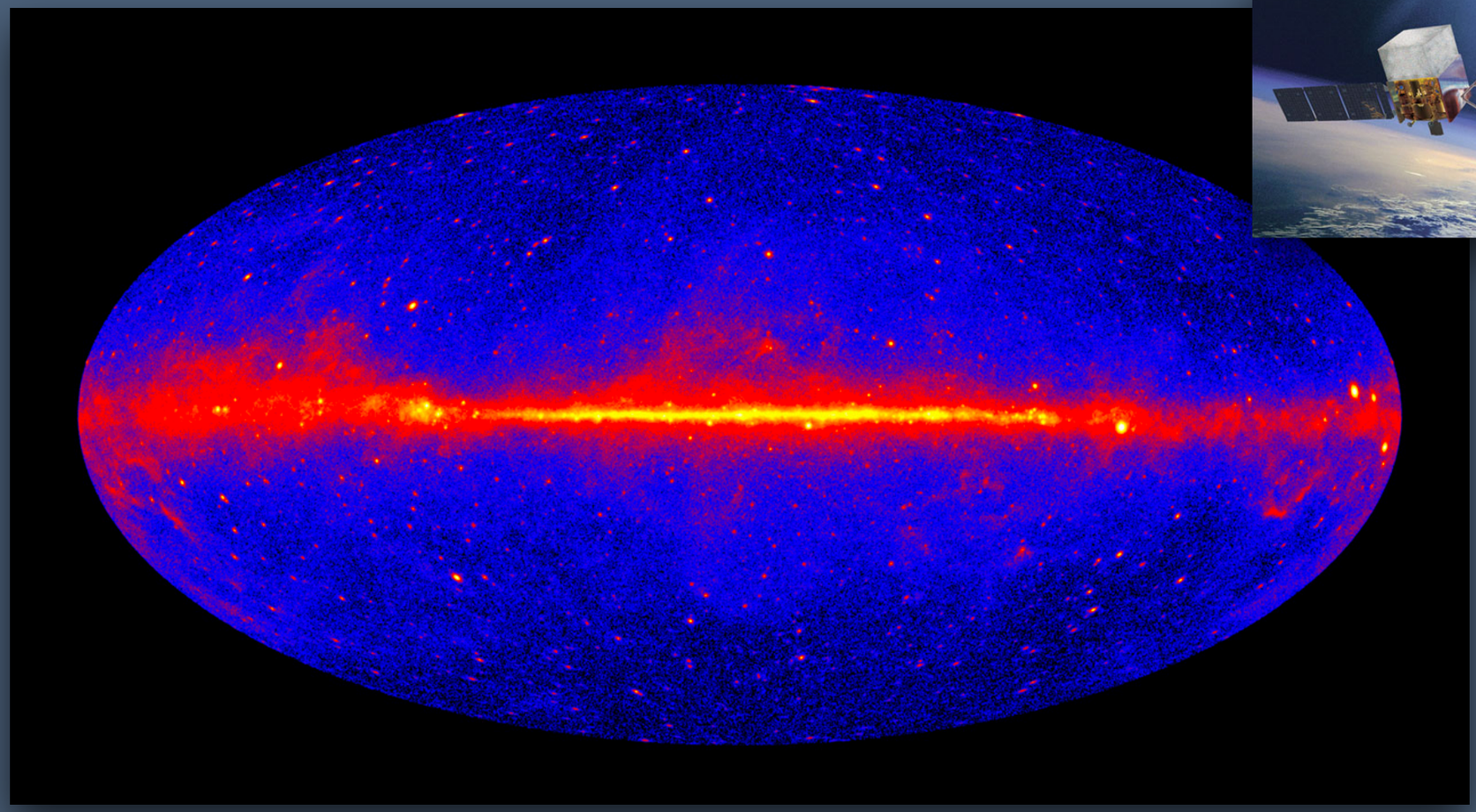
WIMP dark matter

- Motivated by supersymmetry
- Naturally account for the observed DM abundance through the freeze-out mechanism
- Parameter space is getting smaller but still open
- A long lasting GeV gamma-ray excess observed by Fermi LAT



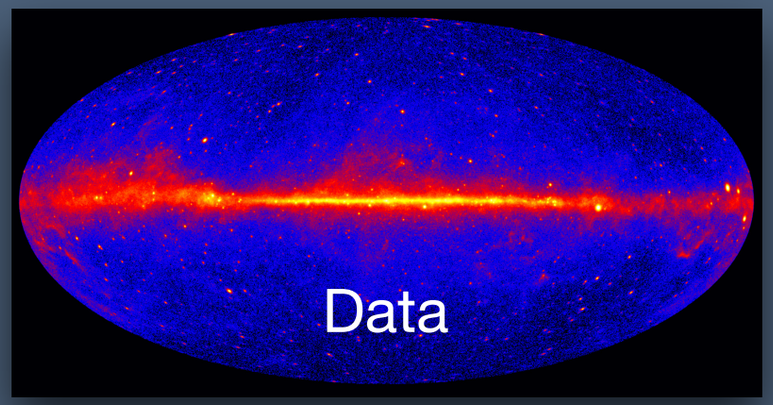


Fermi LAT gamma-ray sky

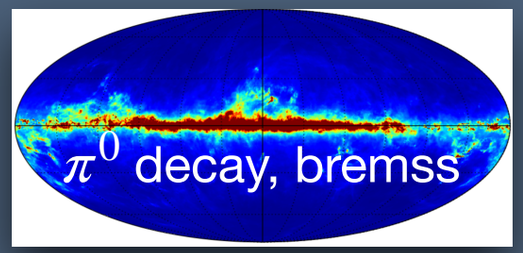


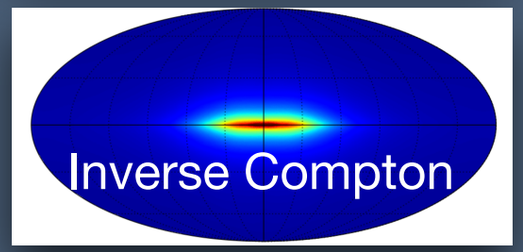
- NASA's Fermi Large Area Telescope (LAT) is currently the most powerful satellite-based gamma-ray telescope available
- Operating in the GeV energy range for more than 16 years
- An excellent tool for WIMP searches

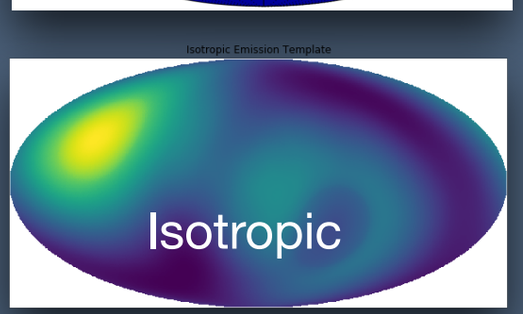
Fermi LAT gamma-ray sky



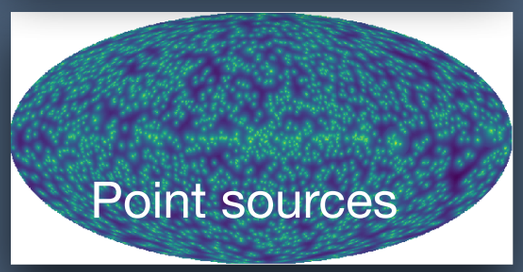
=



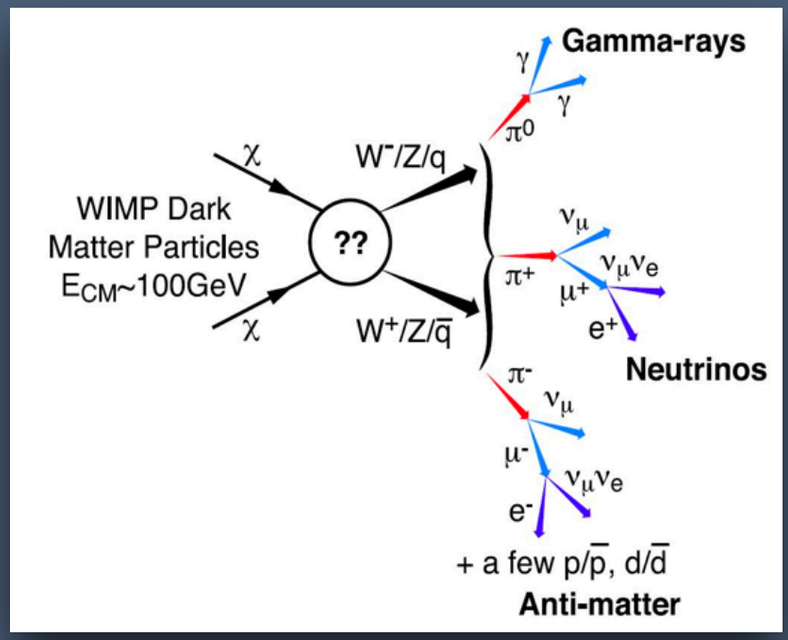




+



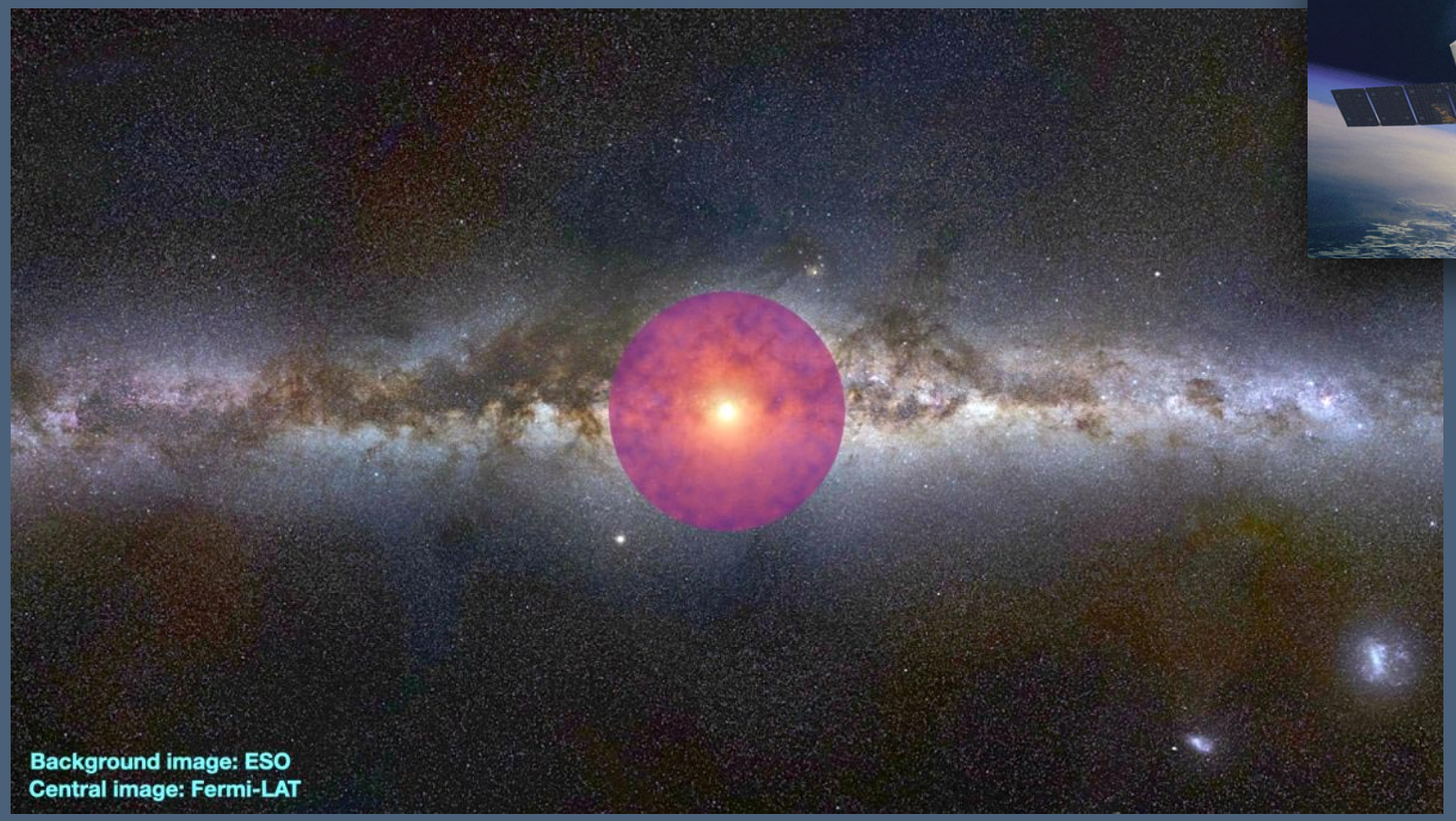
+



WIMP annihilation?

- Diffuse emission and resolved astrophysical sources dominate the observed gamma-ray sky
- Once the backgrounds are well-characterized, we may identify potential dark matter signals

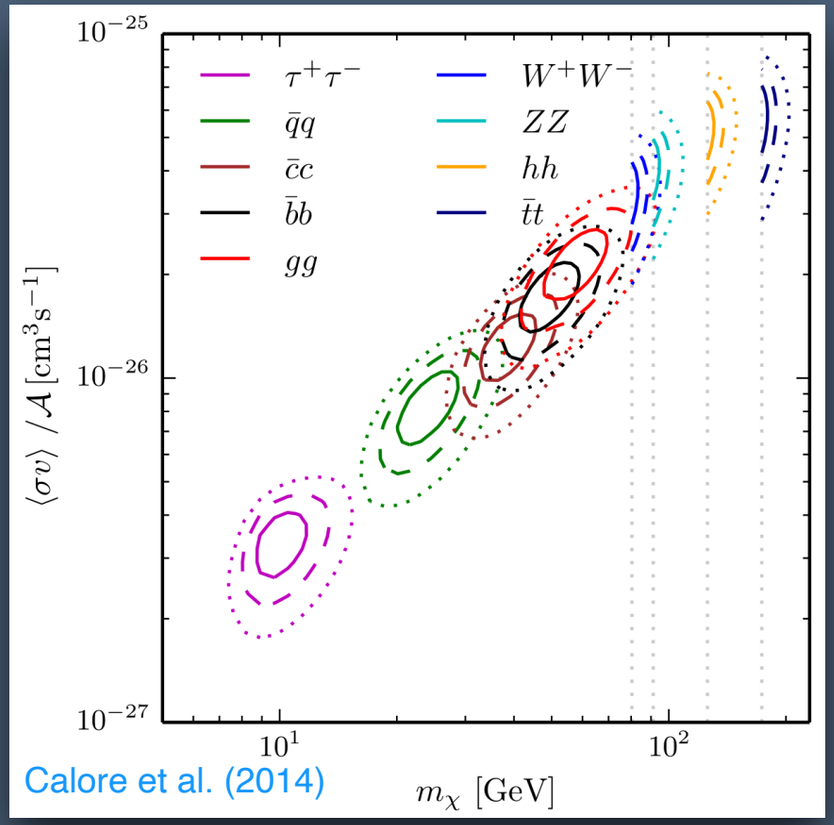
The excess



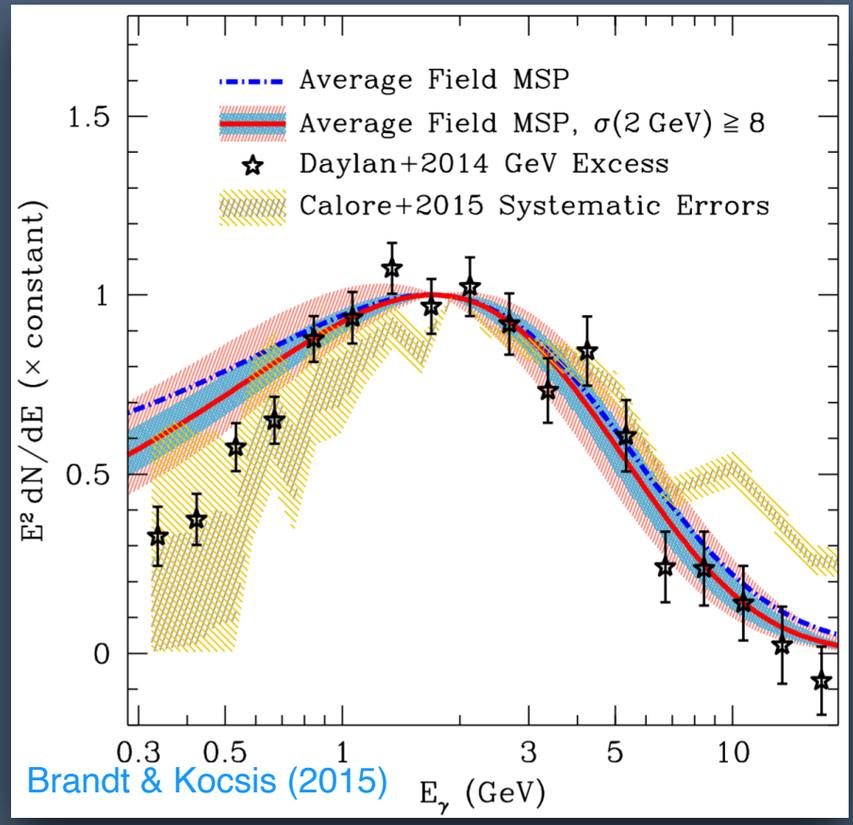
- A Galactic Center Excess (GCE) appears to resemble a WIMP dark matter signal both spatially and spectrally
  - Identified in early Fermi data [Goodenough & Hooper (2009)]
  - Concentrated at the GC and extends to $\sim \pm 20^{\circ}$ in latitude
  - Exhibits a hard spectrum peaking at a few GeV

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.

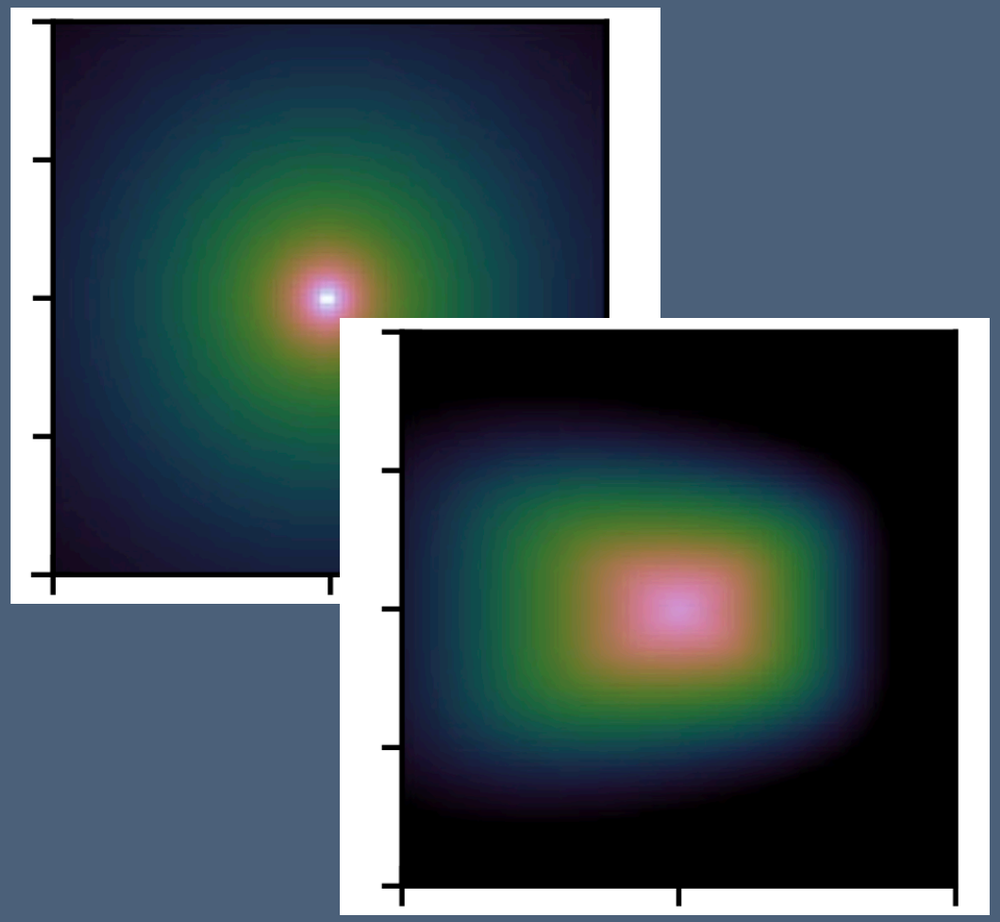


Calore et al. (2014)



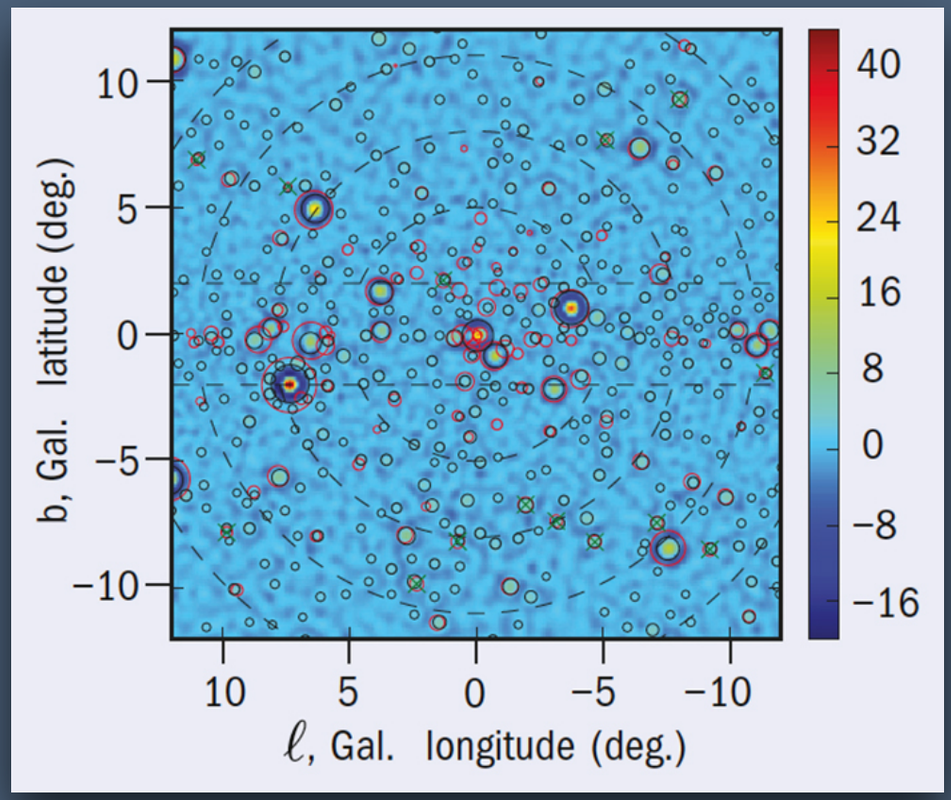
Brandt & Kocsis (2015)

Two frontiers



- Morphology: Does the excess follow the stellar distribution or the dark matter distribution?

This talk

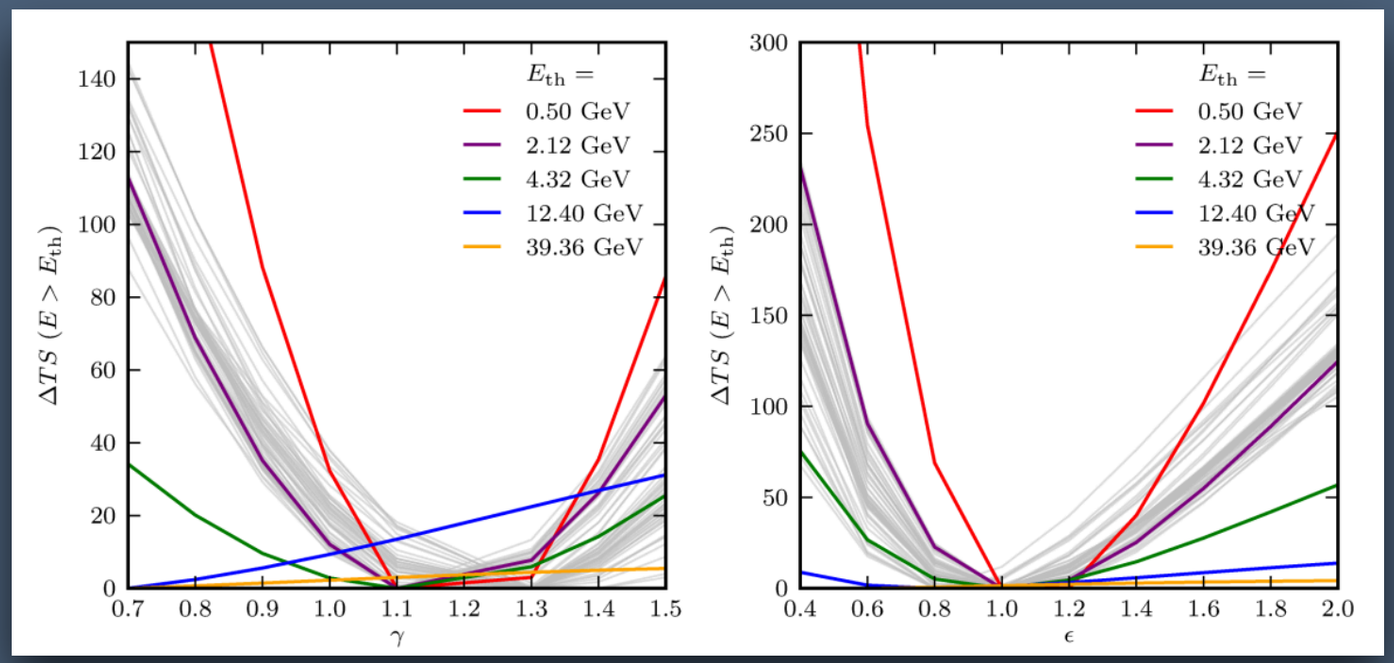


- Photon-Count Statistics: Is the excess of a point-source or diffuse nature?

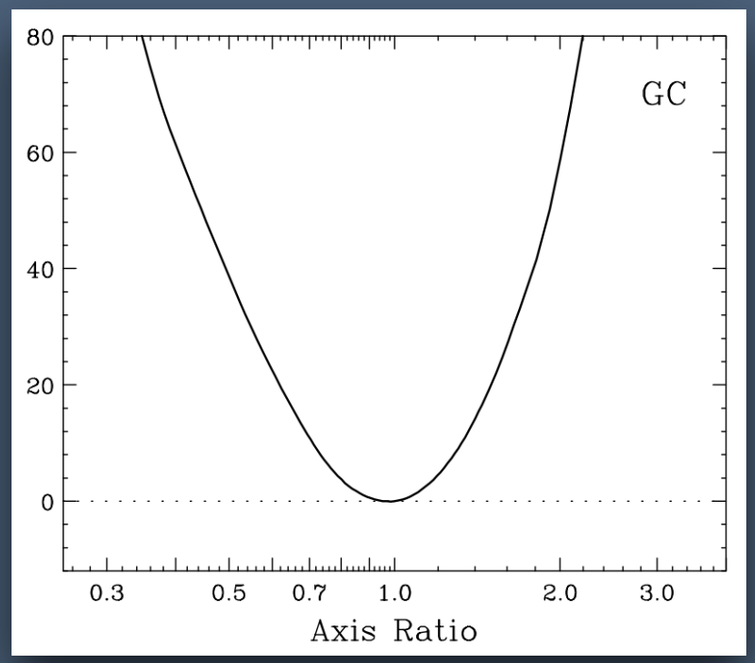
Significant progress has been made, with machine learning playing a key role

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.

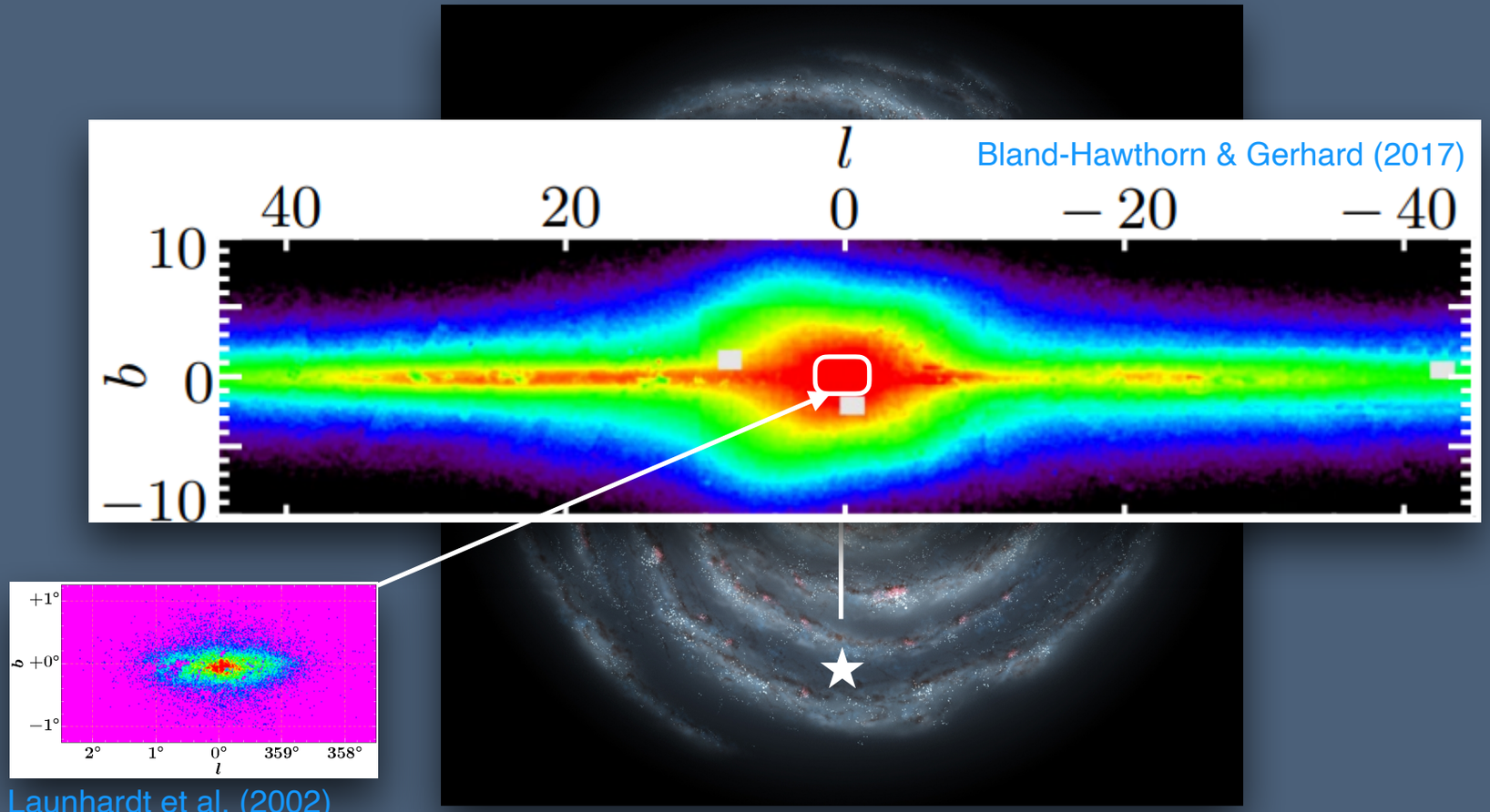
$$\rho(r) = \rho_0 \left(\frac{r}{R_s}\right)^{-\gamma} \left(1 + \frac{r}{R_s}\right)^{\gamma-3}$$

- 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 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

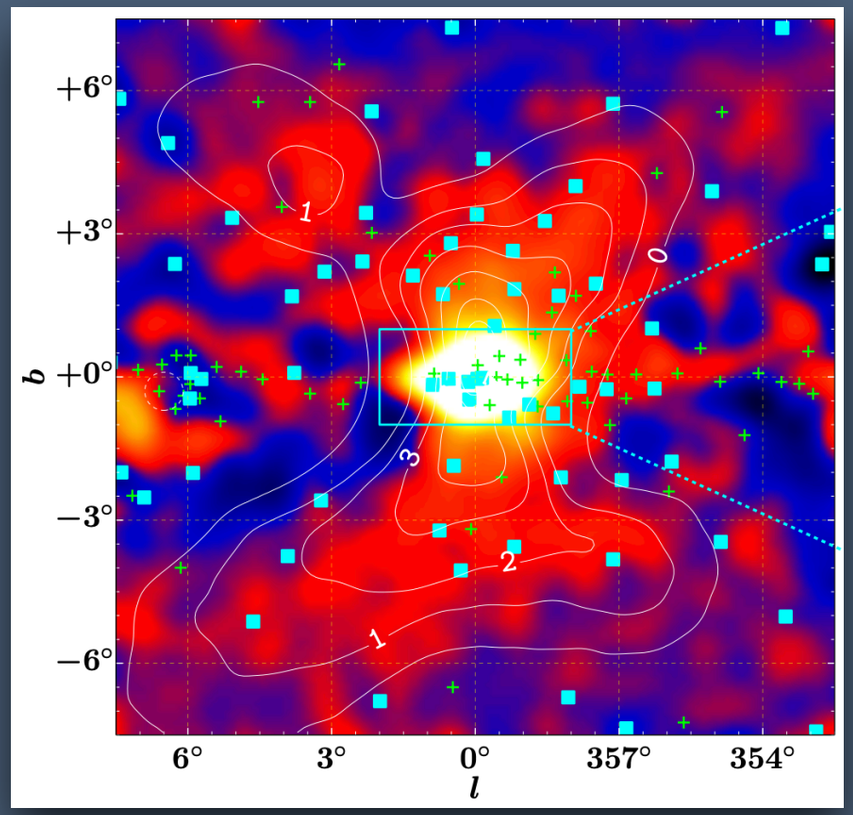


Launhardt et al. (2002)

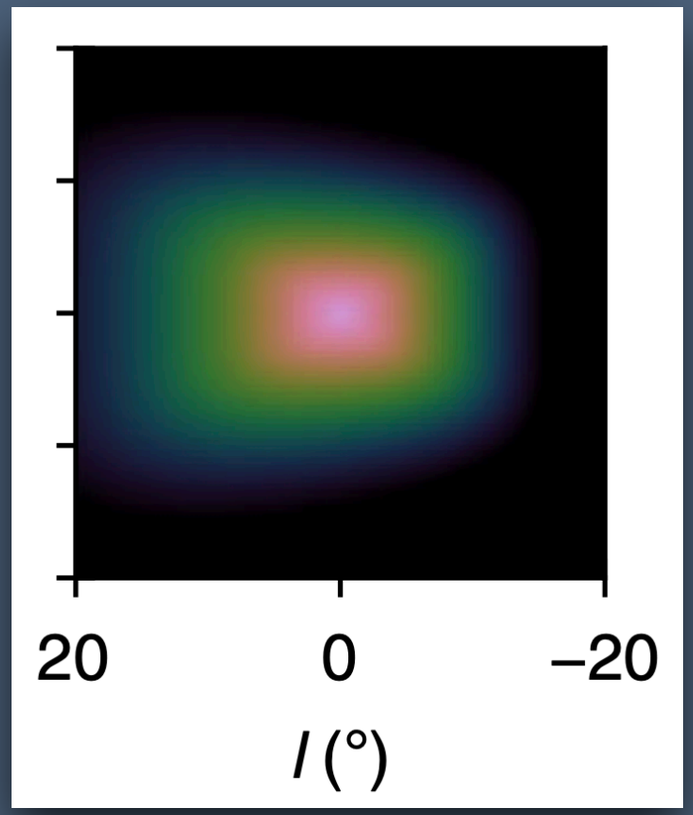
Test of bulge templates

- 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)

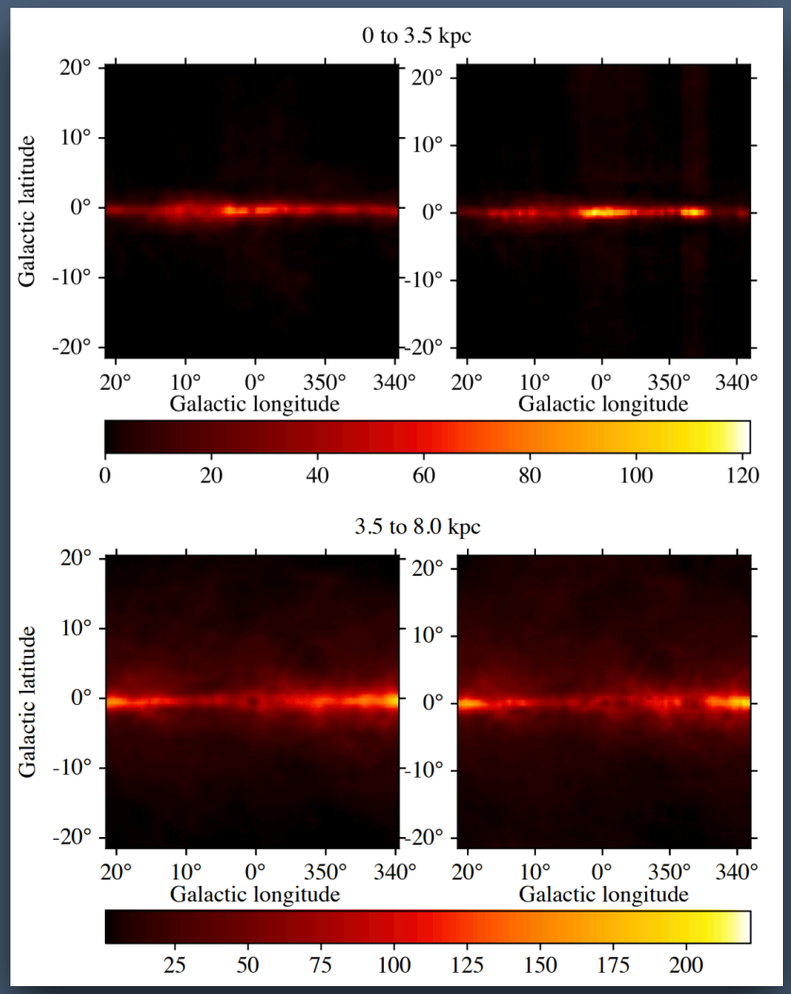
Improved gas maps

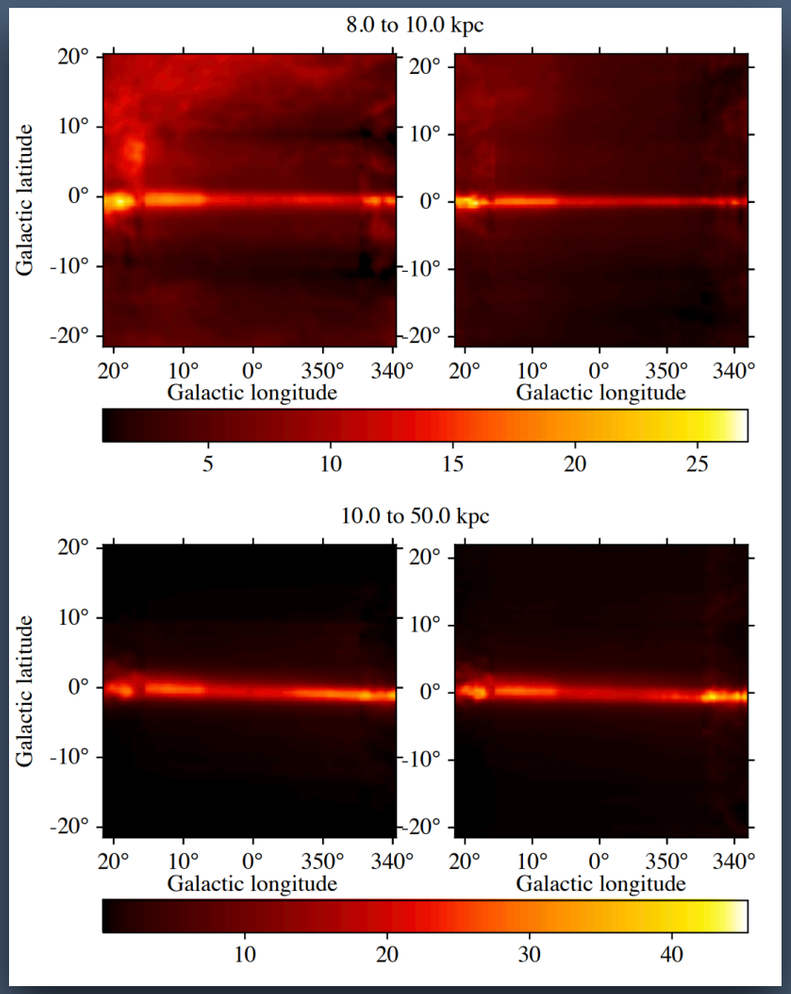
- Hydrodynamic simulations + dividing the Galaxy into rings

[Macia et al. (2017)]

- Including continuum emission to better account for atomic hydrogen

[Phol et al. (2022)]

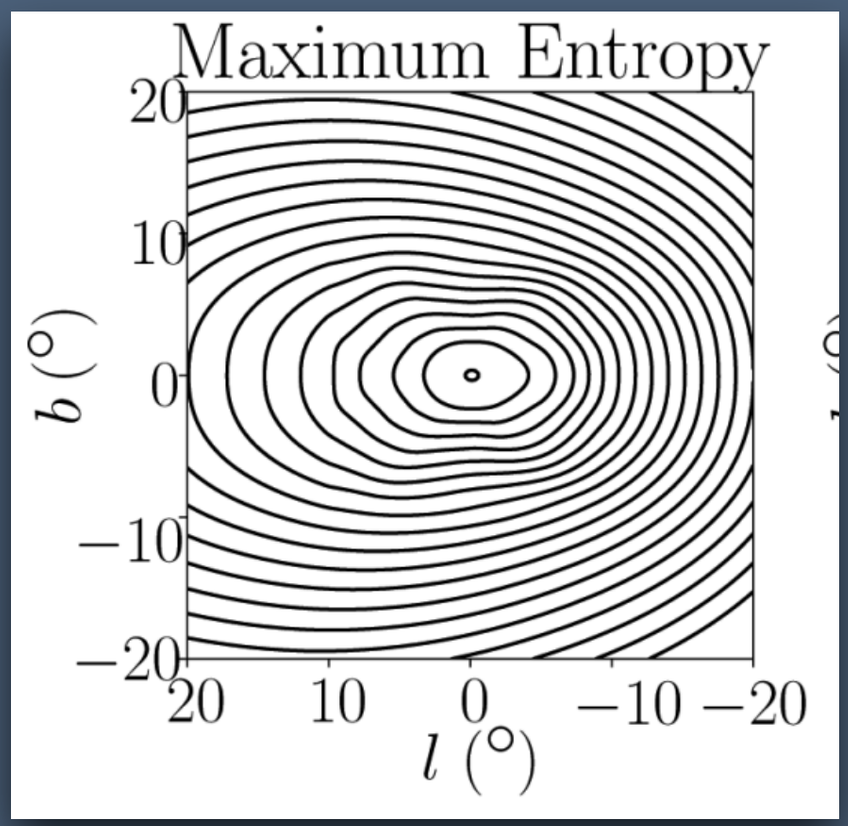


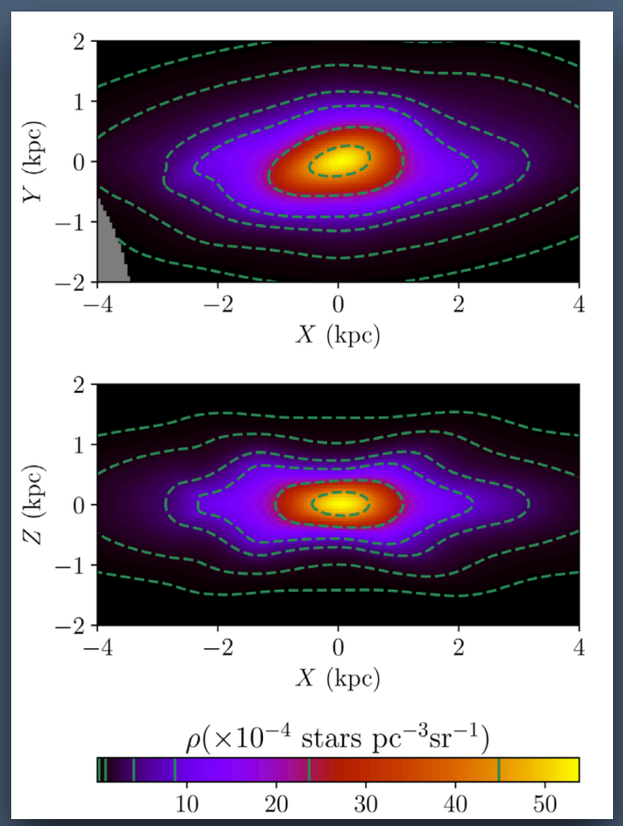


Improved bulge model

- 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

- McDermott et al. (2023) masked the Galactic plane and point sources and tested various GALPROP-based background models.
  - GALPROP-based bkg. model performs much better than the hydro + ring-based model
  - DM (NFW with $\gamma = 1.2$) is preferred in the GALPROP-based bkg. model
- No test of the latest bulge model
- Statement about the ring-based background model is dubious

Galprop >> Rings

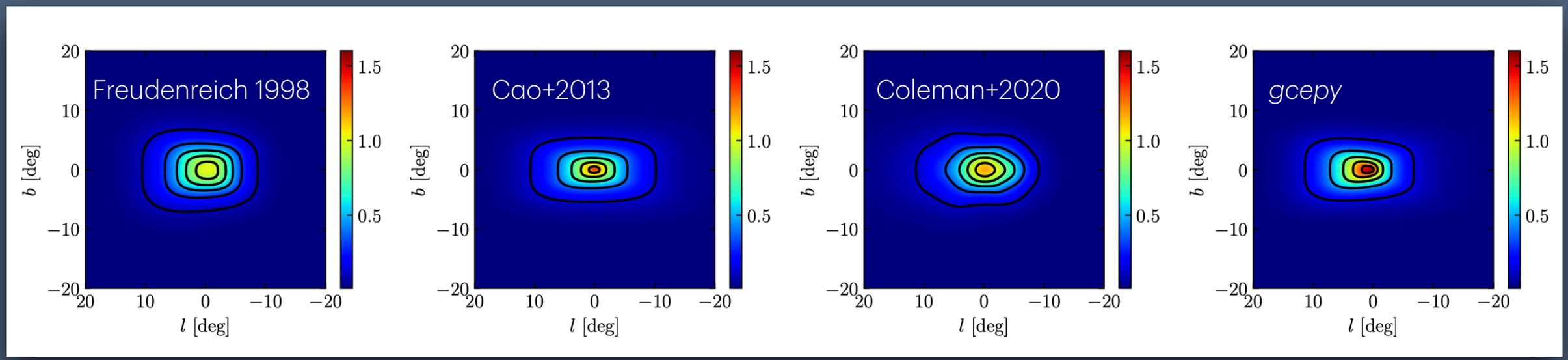
Excess model	Background template	$-2\Delta\ln\mathcal{L}$	$\Delta\ln\mathcal{B}$
No excess	Ring-based	0	0
X-shaped bulge	Ring-based	+30	−190
Dark matter	Ring-based	−237	+12
Boxy & X-shaped bulges	Ring-based	−634	+178
Boxy bulge	Ring-based	−724	+228
Boxy bulge 'plus'	Ring-based	−765	+311
Boxy bulge 'plus' & DM	ring-based	−817	+316
No excess	Astrophysical	−4539	+2933
Boxy bulge	Astrophysical	−6398	+3814
Boxy bulge 'plus'	Astrophysical	−6477	+3853
Dark matter	Astrophysical	−7288	+4268
Boxy bulge 'plus' & DM	Astrophysical	−7401	+4298

DM > Bulge

Testing the findings

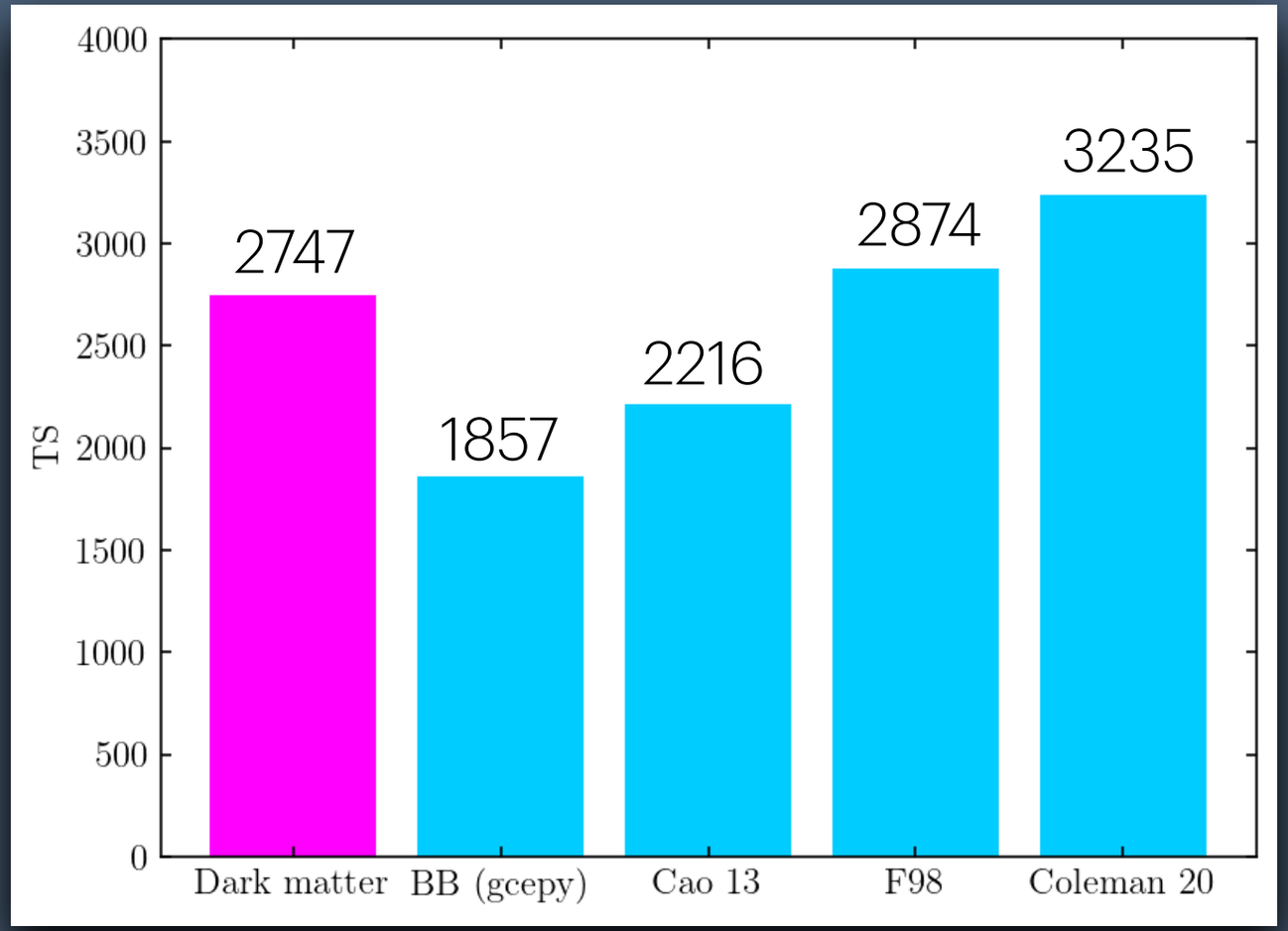
- McDermott et al. have made their data and models public (through the *gcepy* package)
- We've decided to understand the differences by working with their data/models
- We also test additional bulge models

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



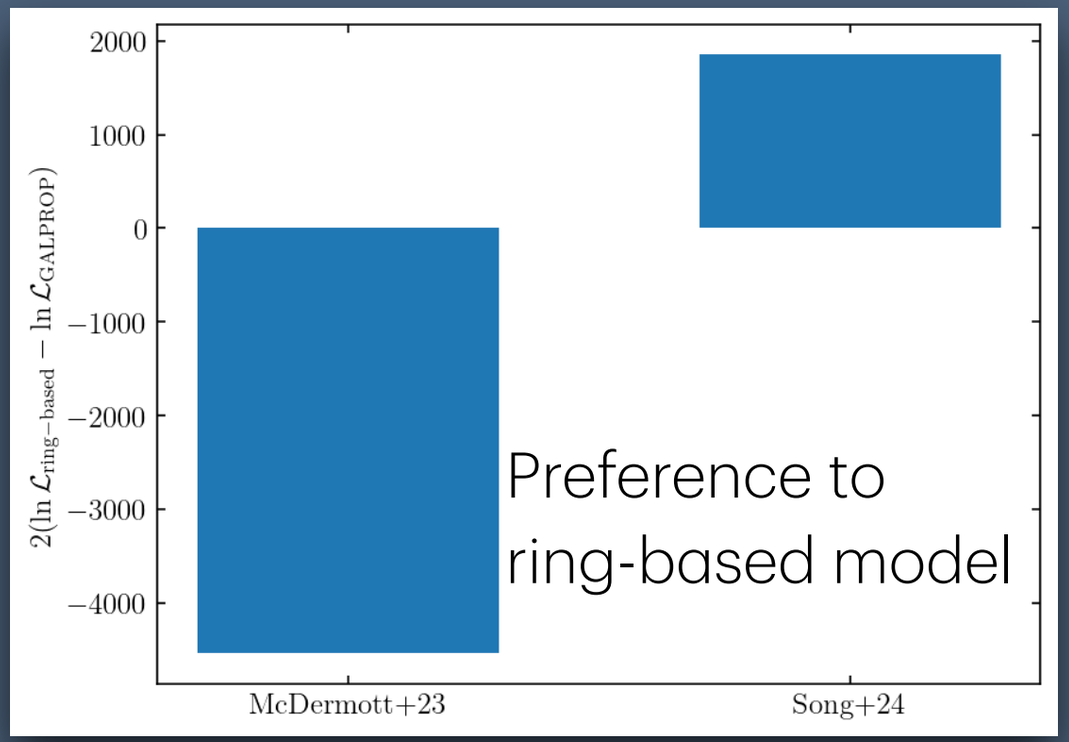
Testing bulge models within GALPROP-based bkg. models

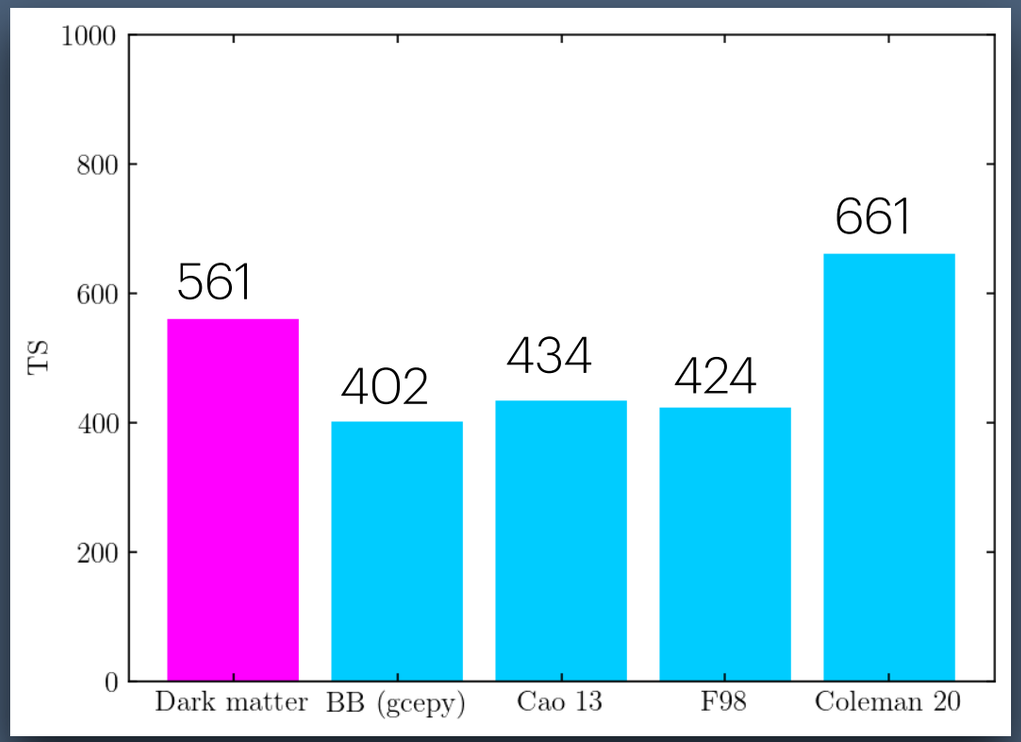
- We can reproduce the results of McDermott et al. using their GALPROP-based background model and bulge model
- The Coleman et al. bulge model is still strongly preferred when tested with the data from McDermott et al.



Discrepancy in ring-based background model

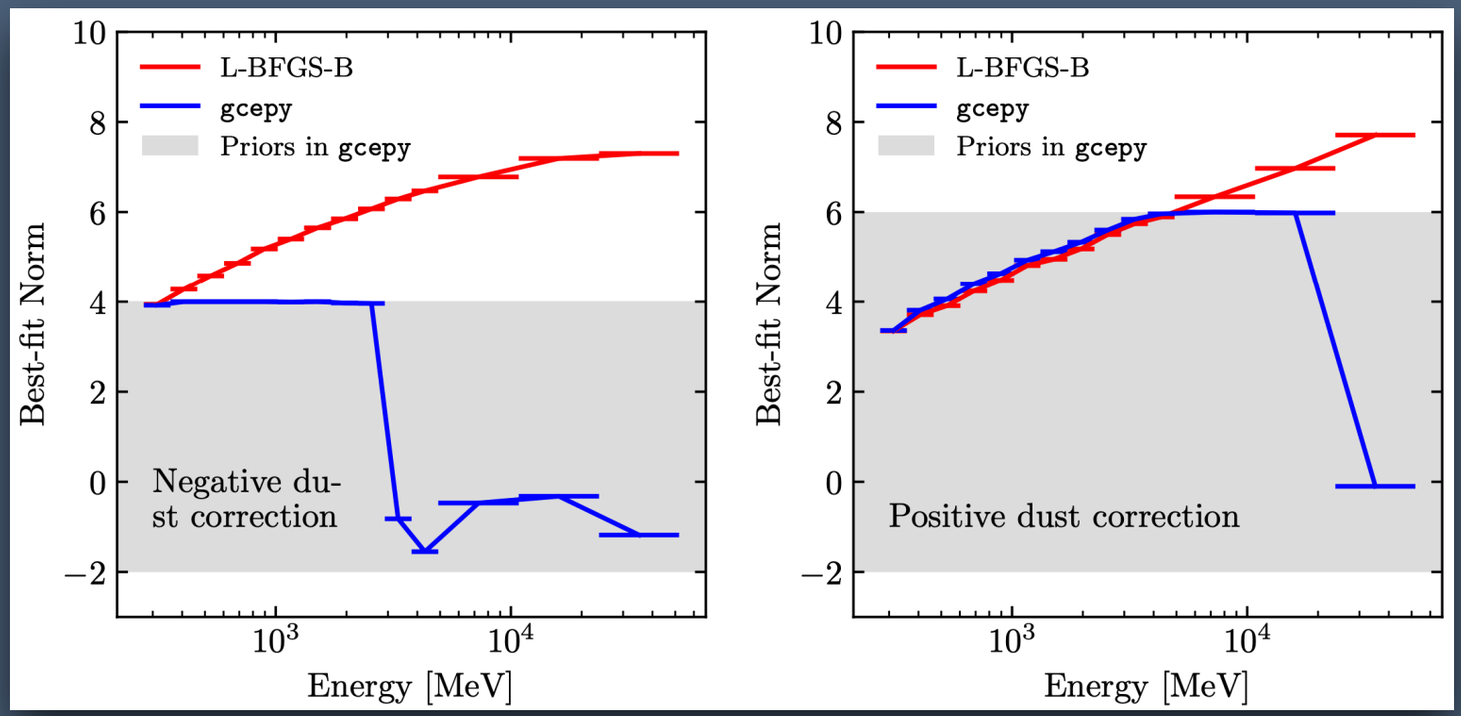
- We find significant discrepancies in testing the ring-based background model
  - The ring-based background model provides a significant improvement in fitting the data compared to the GALPROP-based background model, contradicting McDermott et al.
  - The Coleman et al. bulge model remains the most preferred template for the GCE





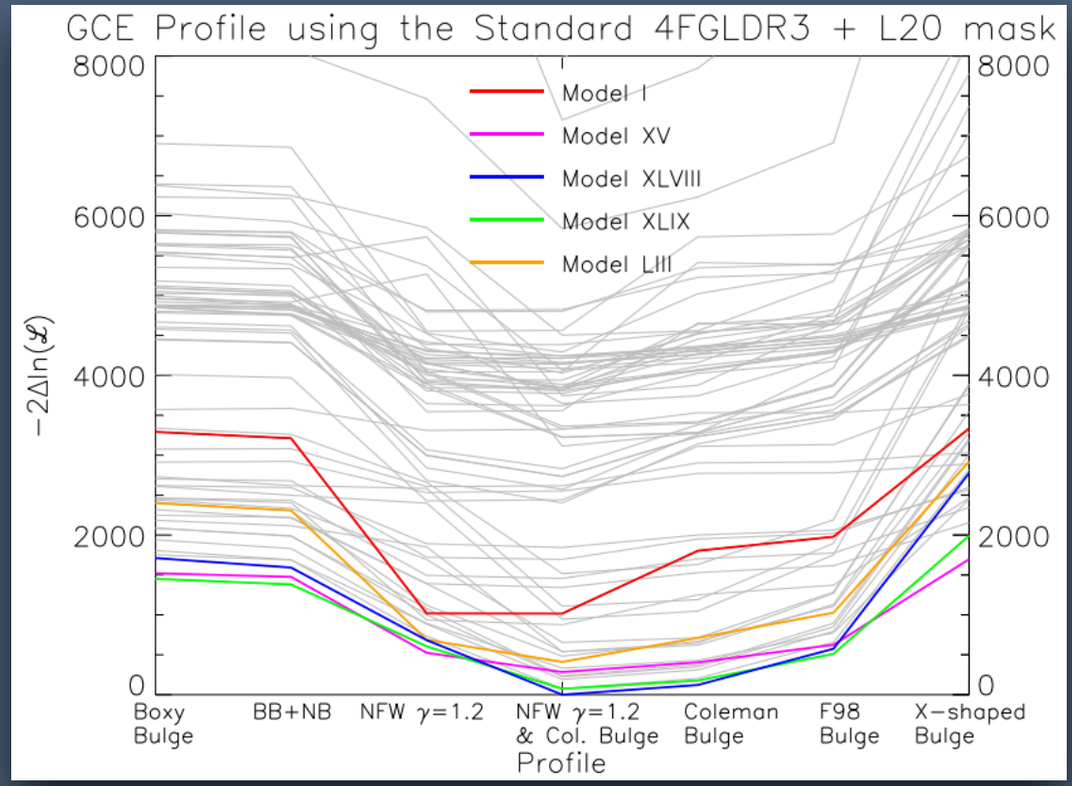
Understanding the discrepancy

- 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



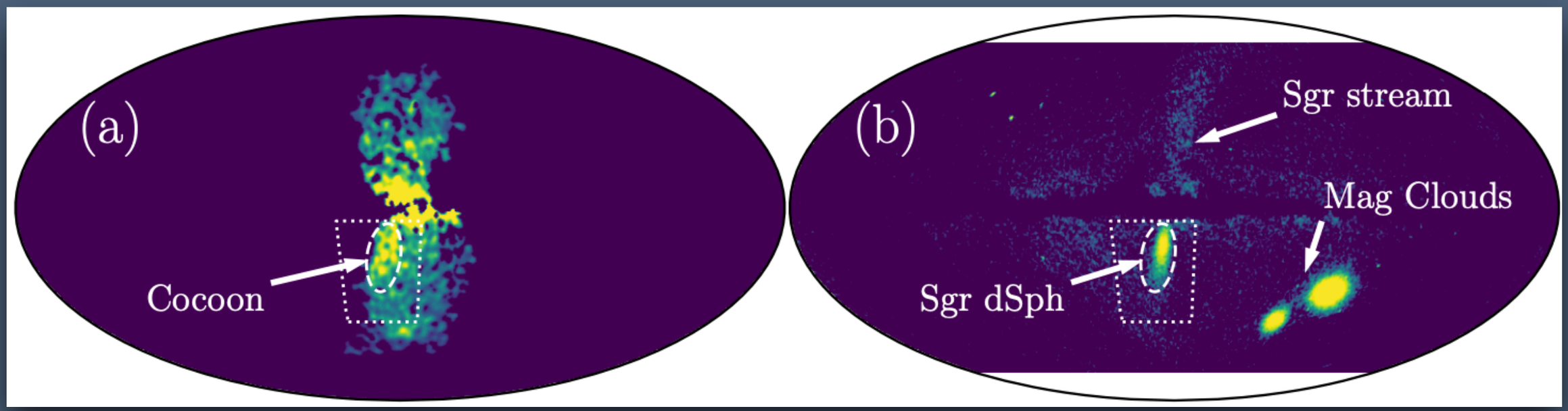
Zhong & Cholis (2024)

- 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



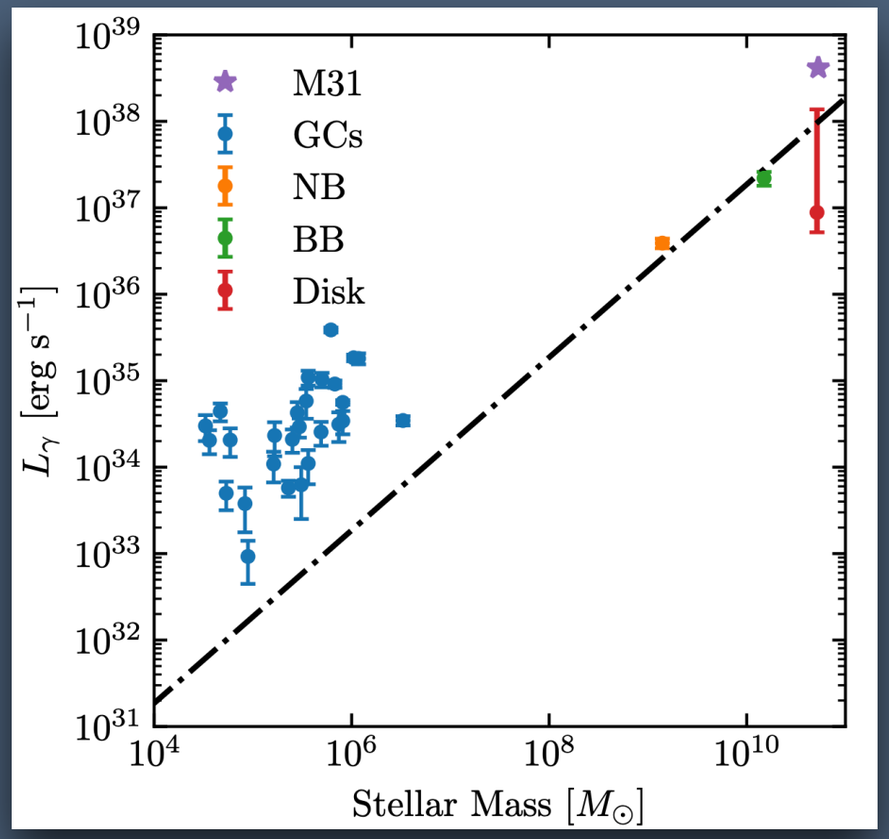
Millisecond pulsars in the Sagittarius dSph

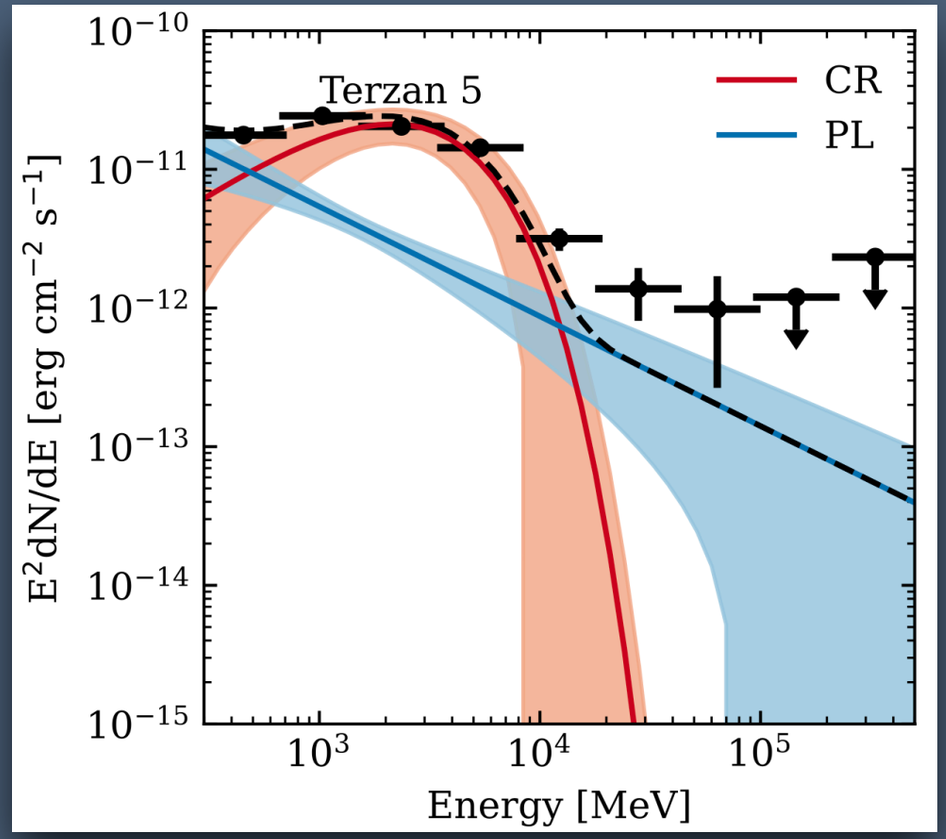
- This connection between stellar populations and gamma-ray emission is not unique
- For example, the cocoon area inside the Fermi bubbles may be linked to millisecond pulsars in the Sagittarius dwarf spheroidal galaxy [Crocker et al. ’22 (*incl.* DS)]



Millisecond pulsars in globular clusters

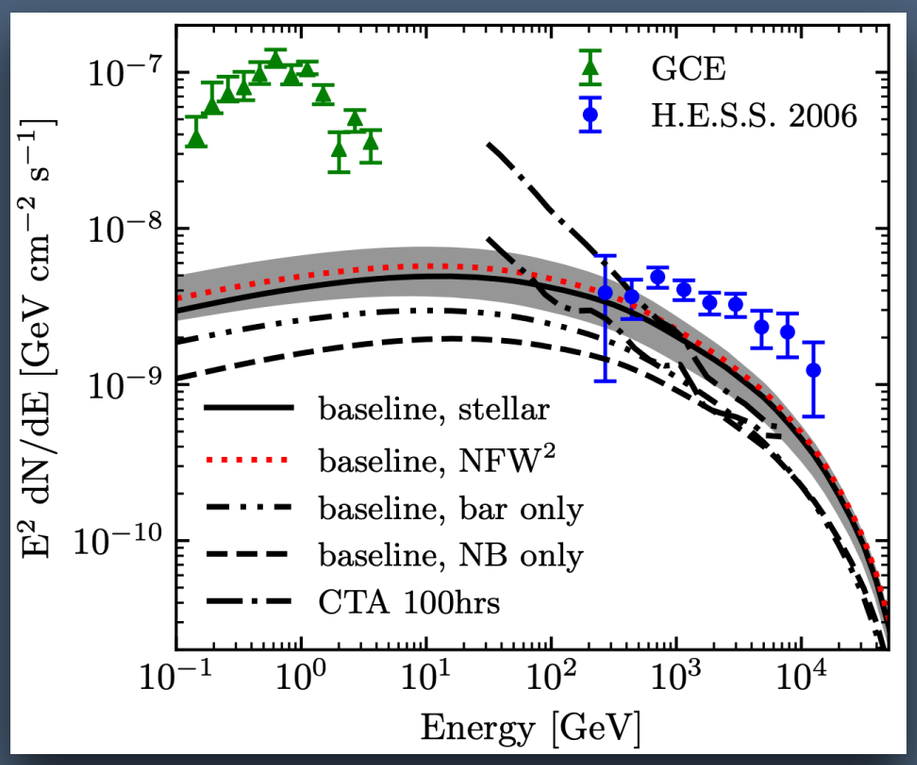
- Globular clusters are gamma-ray bright, most likely due to their population of millisecond pulsars [DS et al. (2021)]
- There is also evidence for inverse Compton scattering in the gamma-ray spectra of globular clusters

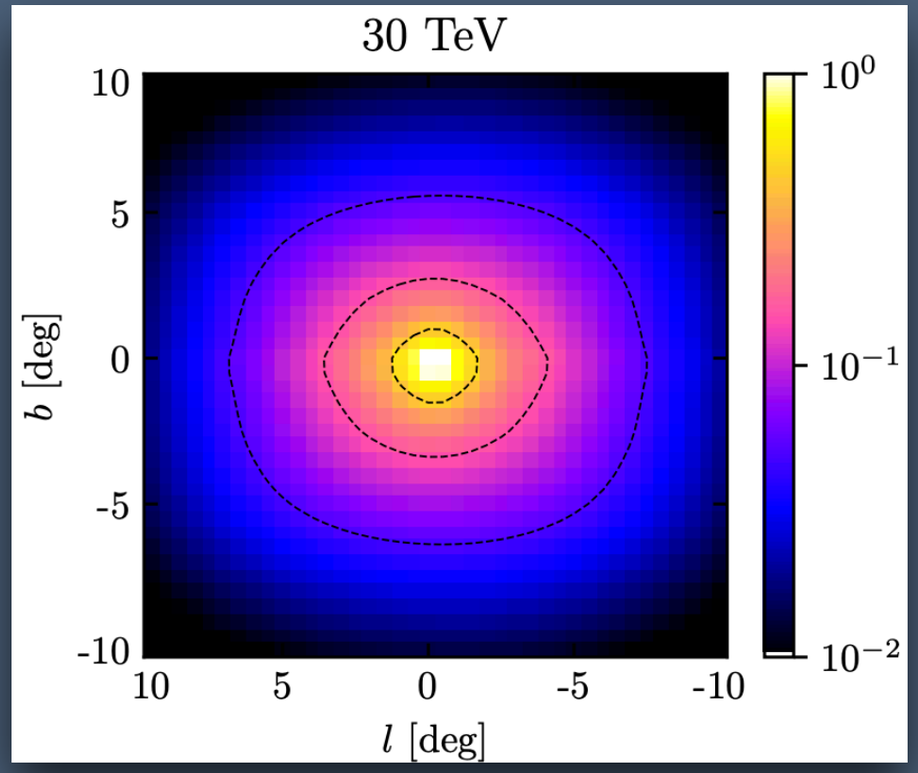




Inverse Compton scattering from millisecond pulsars

- Inverse Compton scattering from MSPs in the Galactic Center provides a unique multiwavelength probe for the origin of the GCE [DS et al. '19]
- The Cherenkov Telescope Array will have the sensitivity to probe this component in the near future [Macias et al. '21 (*incl.* DS)]





Summary

- The morphology of the Galactic Center Excess remains debated. However, we are converging on the preference for the bulge model from the latest VVV survey

  - Further strengthen our motivation to explore dark matter beyond WIMPs.

- A comprehensive picture of millisecond pulsars contributing to the gamma-ray sky

  - GCE, Sagittarius dSph, globular clusters, etc.

  - Future multiwavelength obervations can test this scenario

Thank you!