γ-RAY OBSERVATIONS OF THE GALACTIC CENTER AND ANDROMEDA: DARK MATTER IMPLICATIONS

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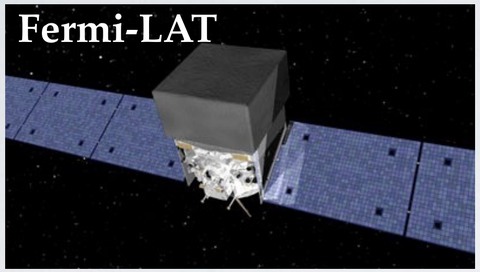
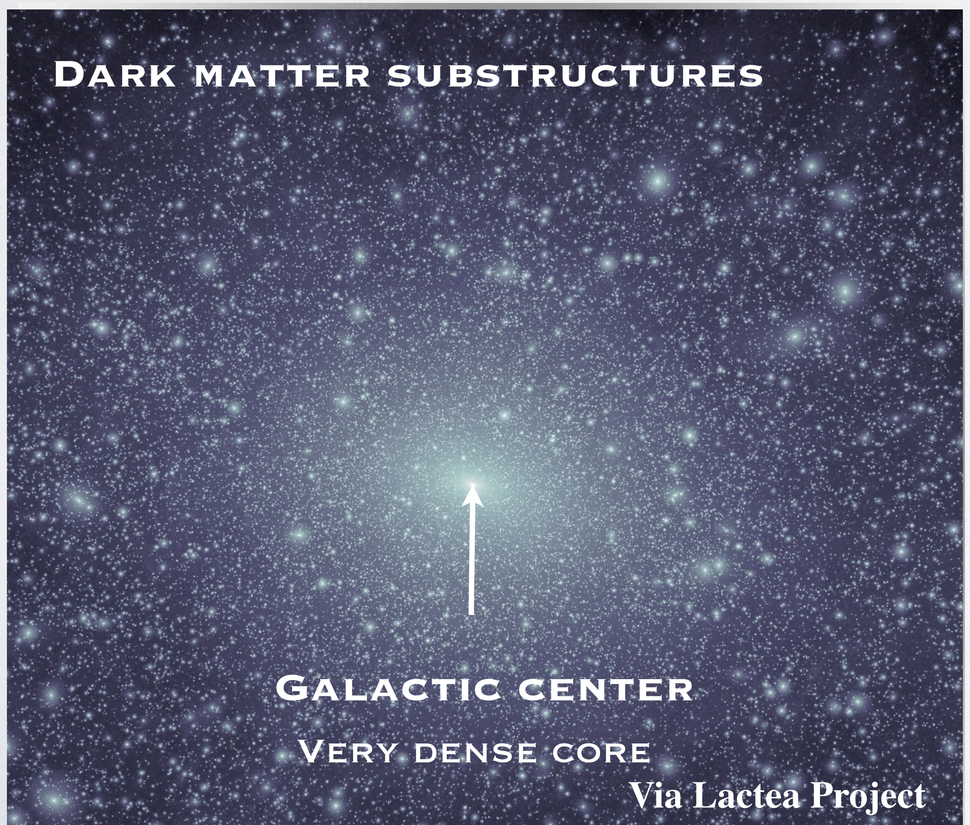
PPC 2021
17 May 2021

INDIRECT DARK MATTER SEARCHES

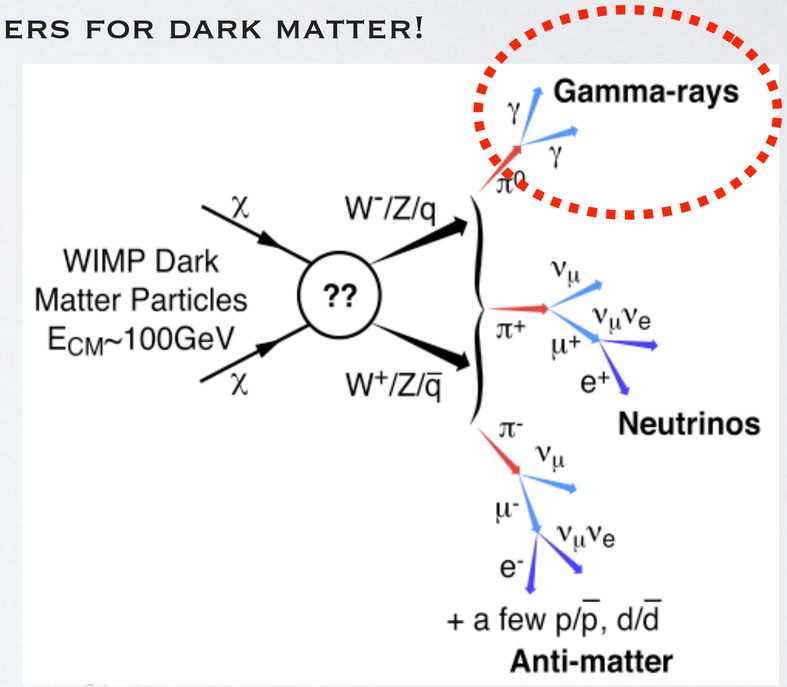


DARK MATTER DISTRIBUTION

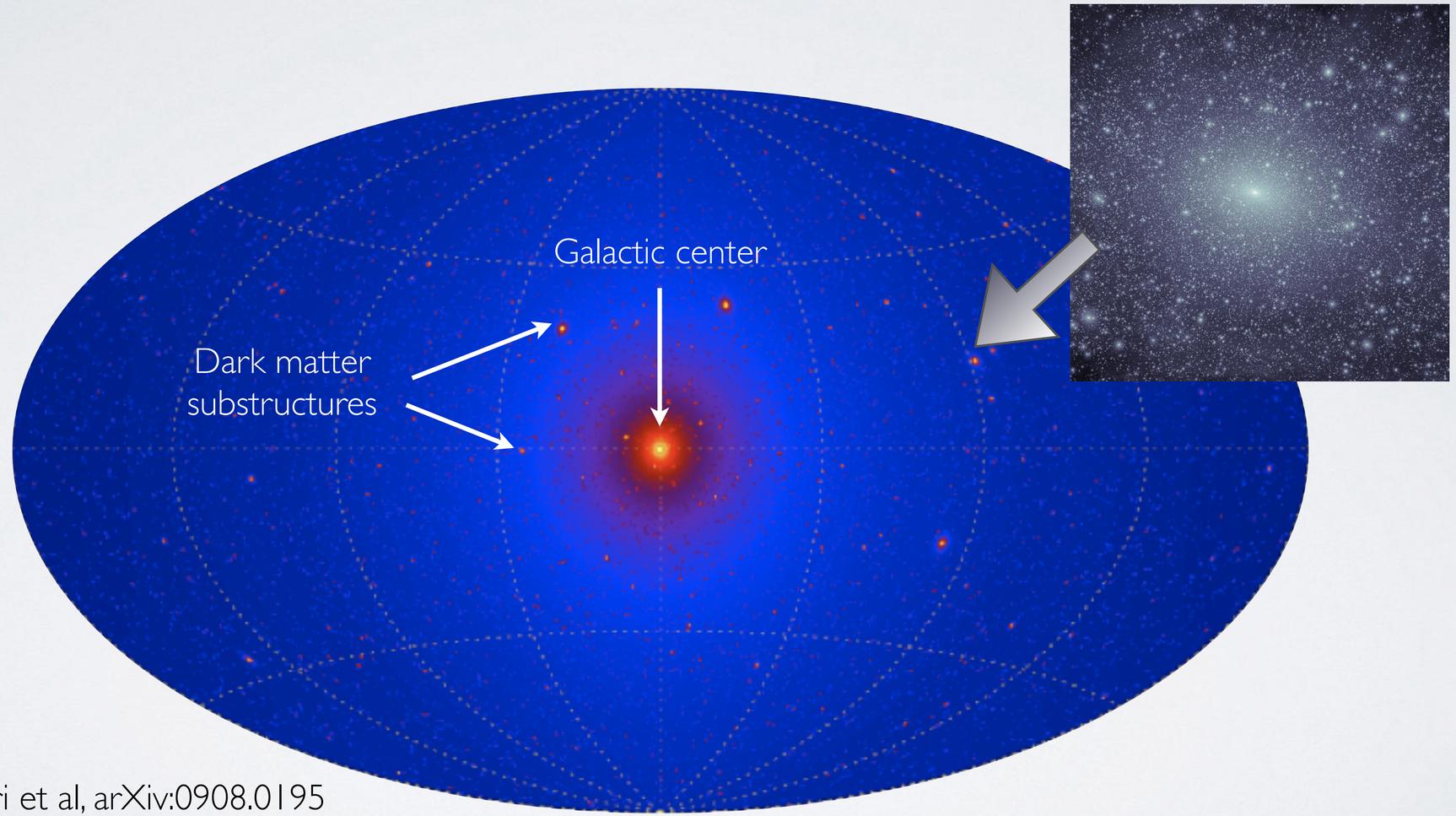


ANNIHILATION PROCESS

Gamma rays are excellent messengers for dark matter!



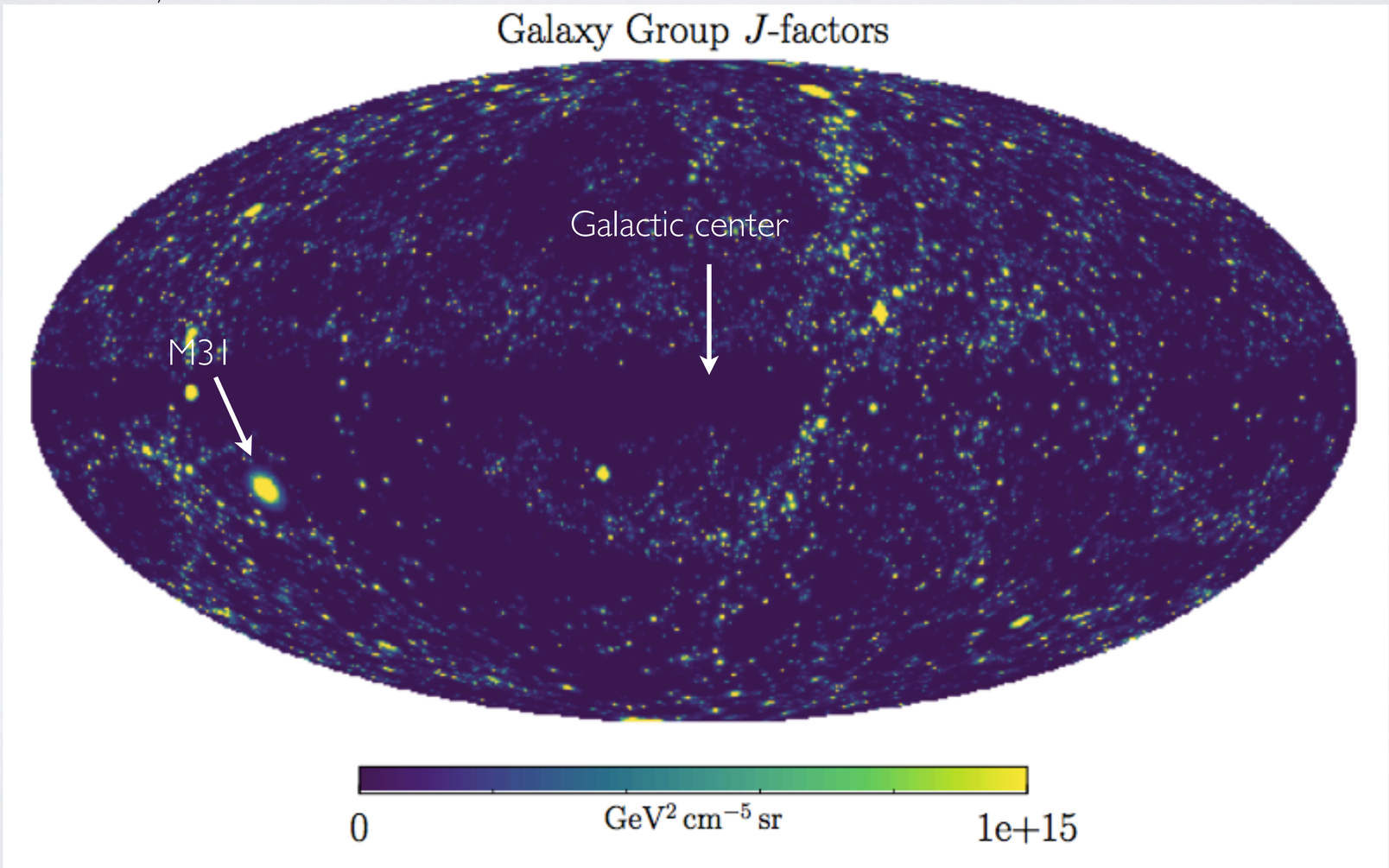
GAMMA RAYS FROM DM ANNIHILATION: MILKY WAY AND ITS SATELLITES



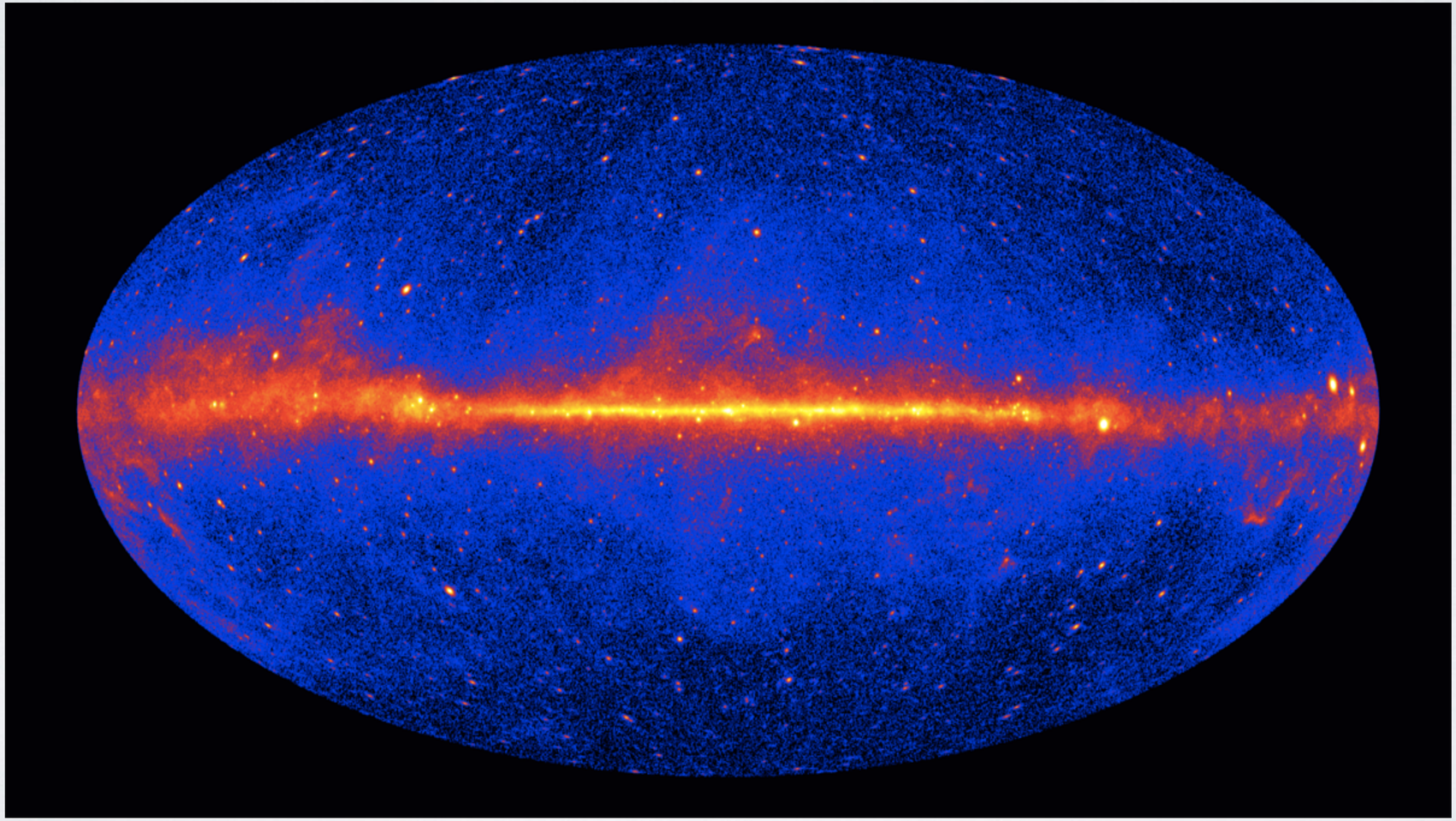
Pieri et al, arXiv:0908.0195

GAMMA RAYS FROM DM ANNIHILATION: BEYOND THE MILKY WAY

Lisanti et al, arXiv1708.09385



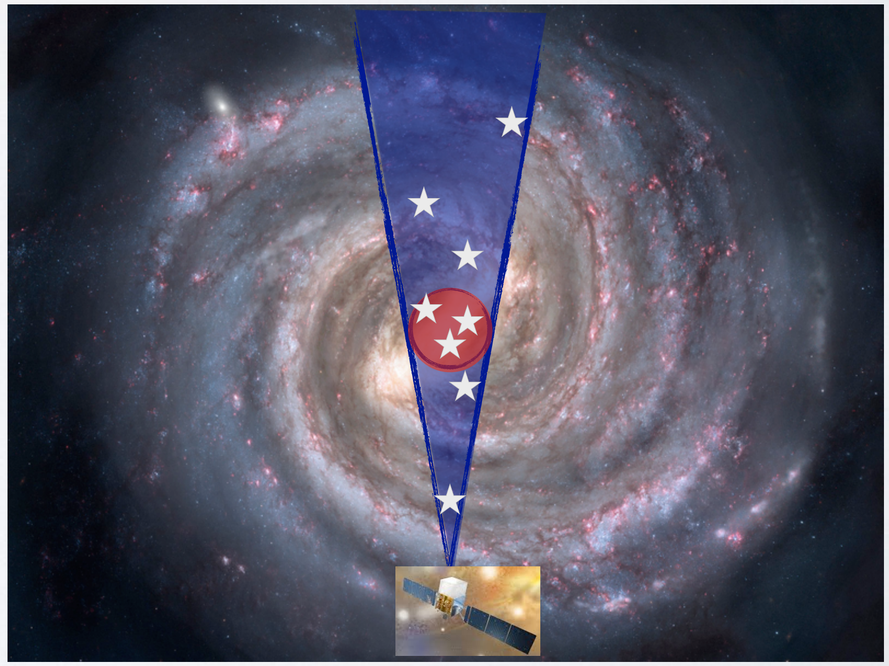
THE FERMI LAT GAMMA-RAY SKY



THE GALACTIC CENTER

Galactic center region: a dark matter signal is predicted to be largest here, where modeling of the gamma-ray emission from the Milky Way (and sources) is difficult!

top view



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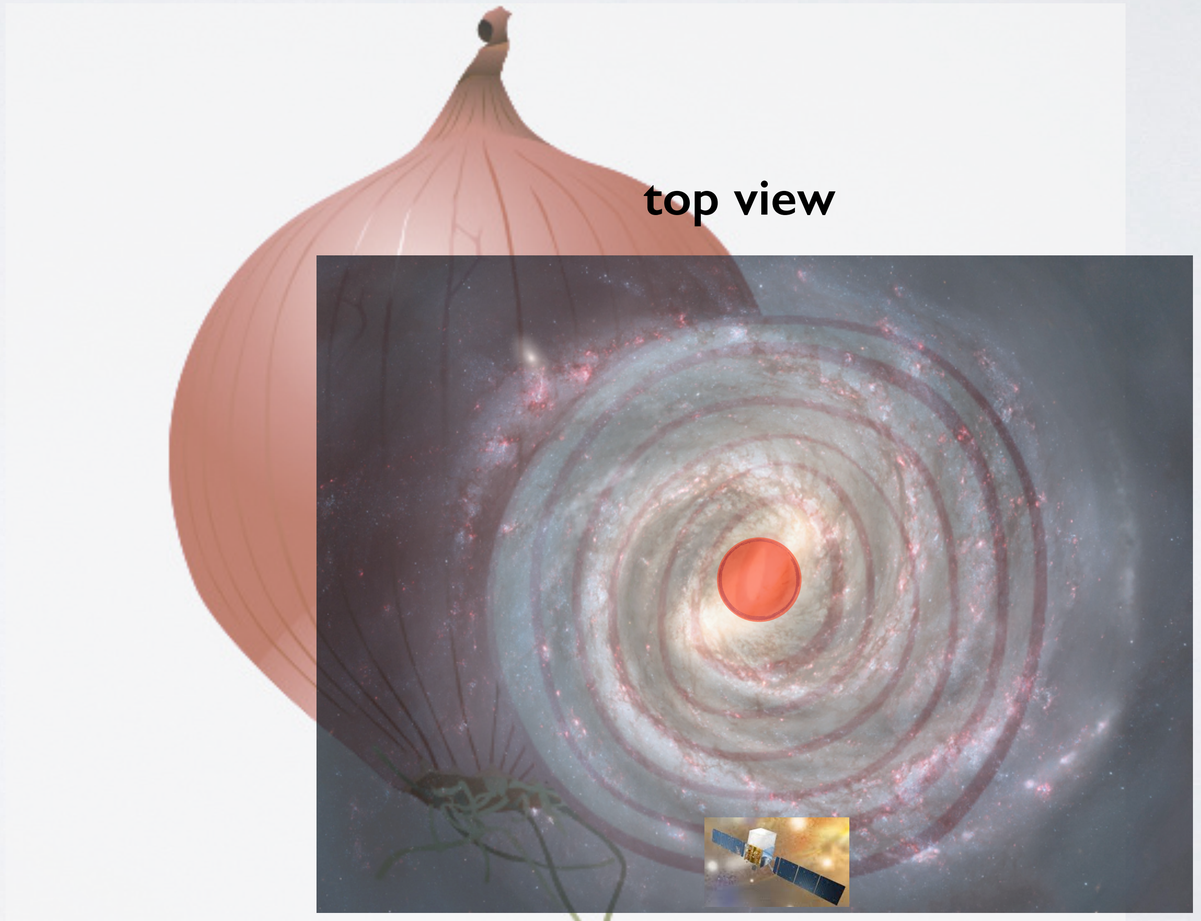
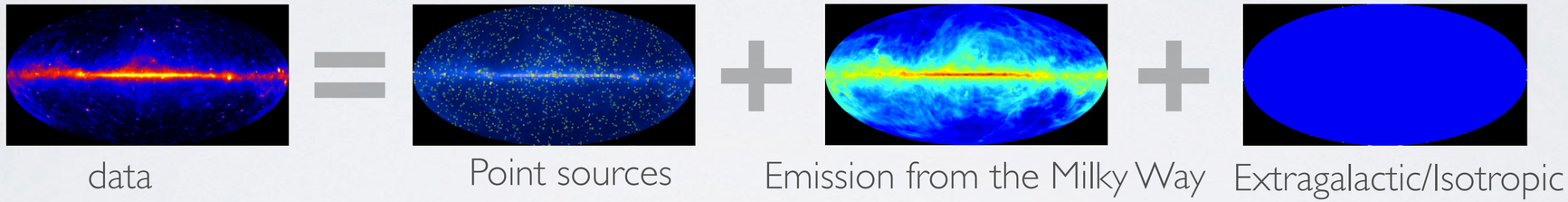
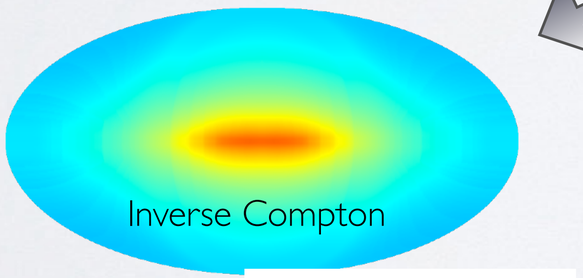
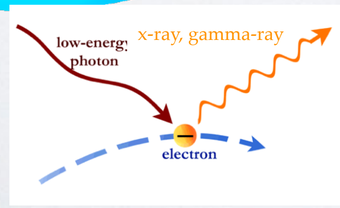


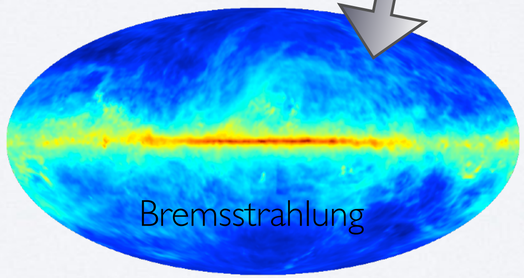
EMISSION FROM THE MILKY WAY

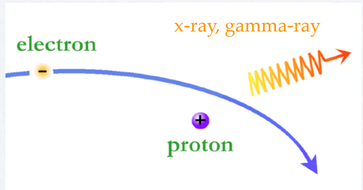
- Interstellar γ-ray emission from the MW is a major background for dark matter searches. It is produced by cosmic rays interacting with the interstellar gas and radiation field
- Need a reliable model of these components to reliably extract a dark matter signal!

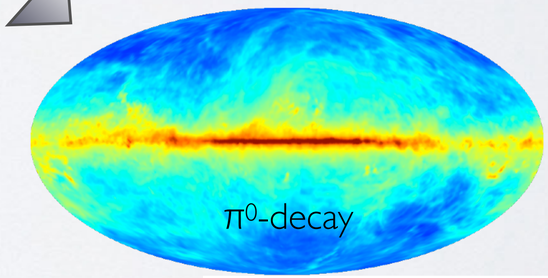


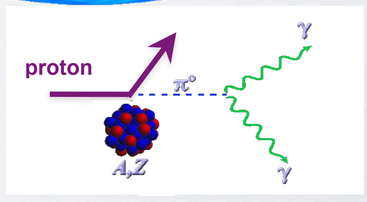






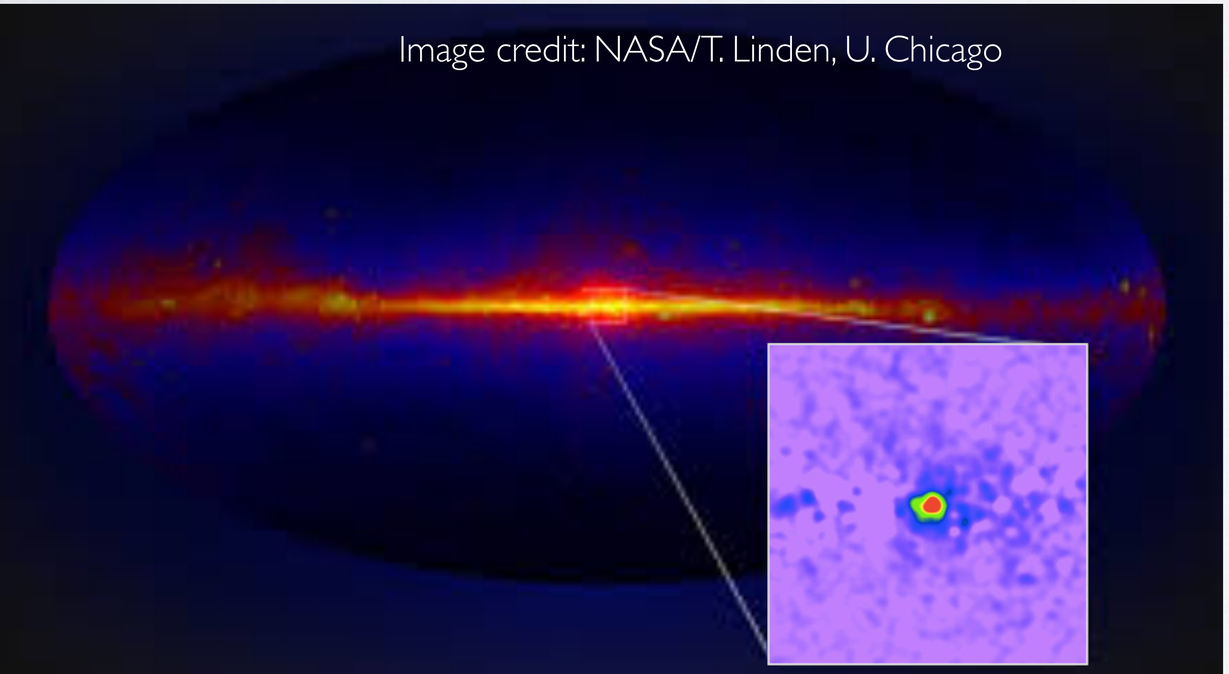




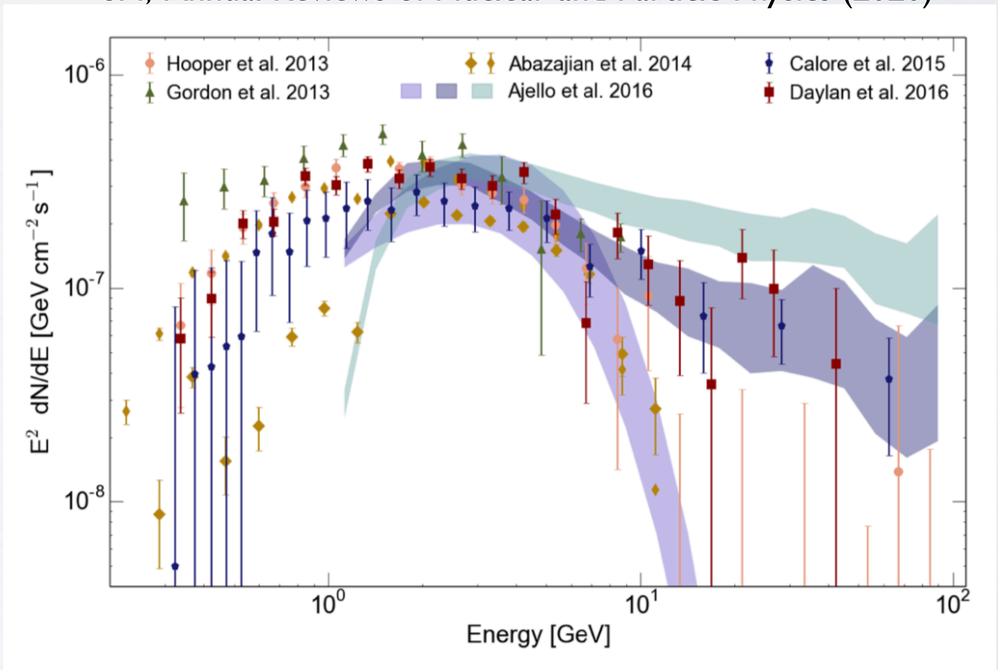


A DARK MATTER SIGNAL FROM THE GALACTIC CENTER?

- A signal consistent with DM annihilation is found in the Fermi LAT data (Goodenough and Hooper, arXiv:0910.2998, confirmed by many analyses since then)
- Different approaches in modeling the γ-ray emission from the Milky Way: ***the characterization of the signal depends on this!***
  - ***relatively broad range of possibilities for spectrum and morphology of the excess depending on model employed for the Galactic γ-ray emission***



SM, Annual Reviews of Nuclear and Particle Physics (2020)



INTERPRETATIONS

- GC excess spectrum consistent DM particle with mass in the range ~**50** (**200**) **GeV**, annihilating mainly into bottom (top) quarks with an annihilation cross section **~ 10^{-26} cm^3/s**. Spatial morphology compatible with the square of NFW distribution, with **γ ~ 1–1.3**

  ➡ DM substructures (dwarf spheroidal galaxies) limit the DM interpretation of the GC excess, but don't rule it out (NB: faint excesses in some dwarfs and LMC)

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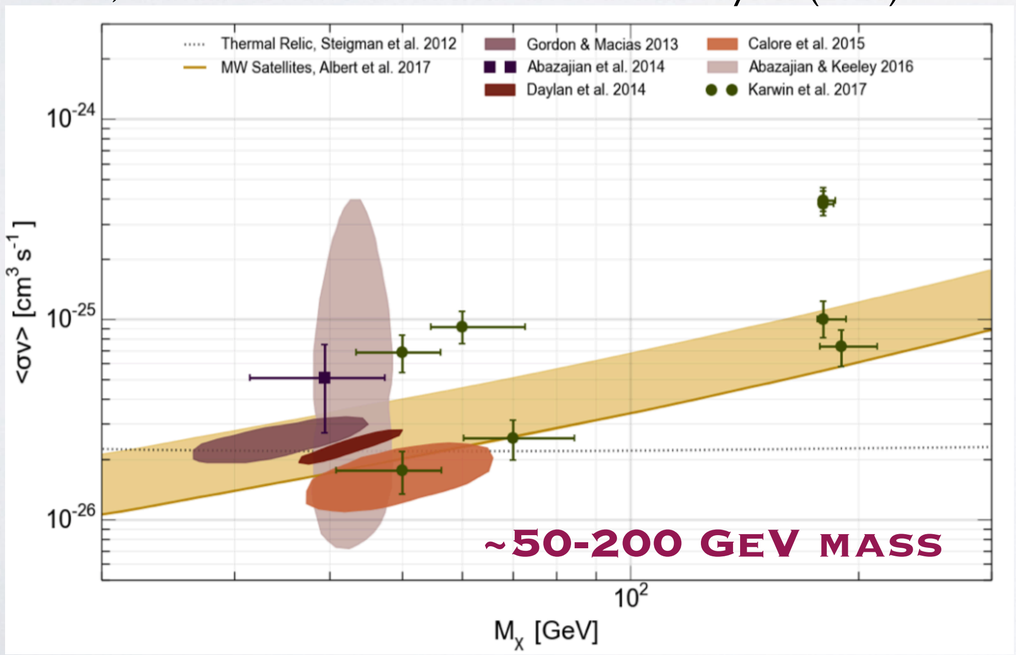

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- Also compatible with unresolved pulsars, e.g. *O(1000)* millisecond pulsars within ~1 kpc of GC (Abazajian et al arXiv:1402.4090, but see also Hooper et al arXiv:1606.09250)
  - Analyses based on non-poissonian photon template fitting (NPTF) and wavelet decomposition find that the excess is consistent with a collection of discrete gamma-ray emitters (Lee et al arXiv:1412.6099, 1506.05124; Bartels et al arXiv:1506.05104)

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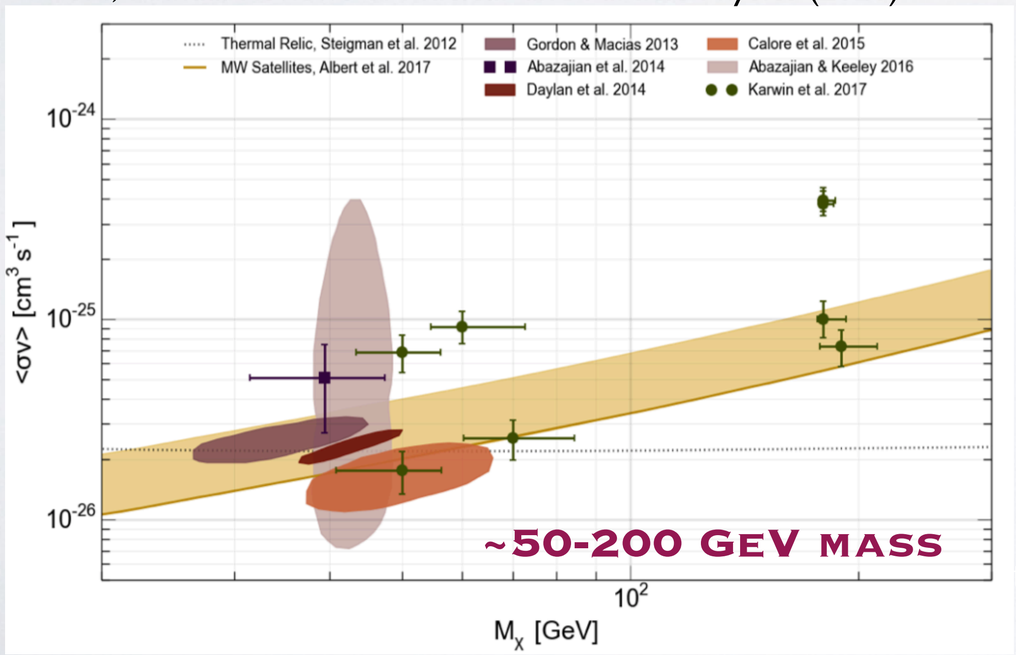
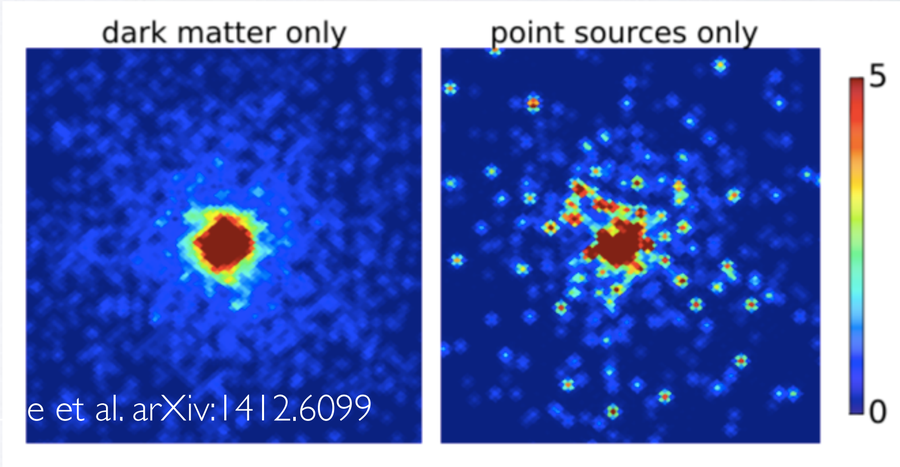
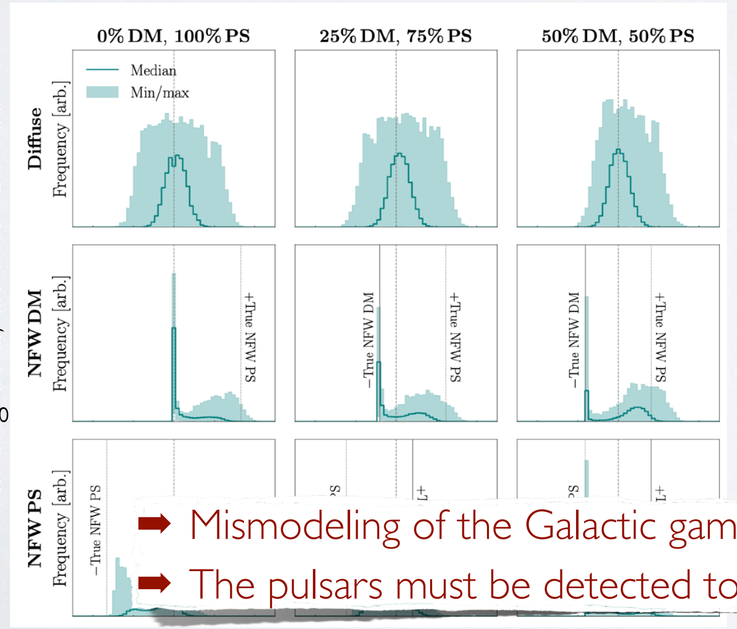




INTERPRETATIONS

- Recent results on NPTF:
  - unmodeled point sources in the data might conceal a dark matter signal (Leane et al, arXiv:1904.08430), and if the excess is spatially asymmetric (but modeled as symmetric) the results of the NPTF technique are not reliable (Leane et al, arXiv:2002.12370, arXiv:2002.12371)
  - the precise mixture of point sources and dark matter might be difficult to disentangle (Chang et al arXiv:1908.10874)
- As for the wavelet technique, not enough power is found at small angular scales to fully explain the excess (Balaji et al arXiv:1803.01952, also Zhong et al, arXiv:1911.12369 with new point source catalog)
- When deep learning is used to distinguish between a point-like and smooth nature, the GC excess is consistent with the smooth emission predicted for a DM signal (List et al, arXiv:2006.12504)

Chang et al, arXiv:1908.10874



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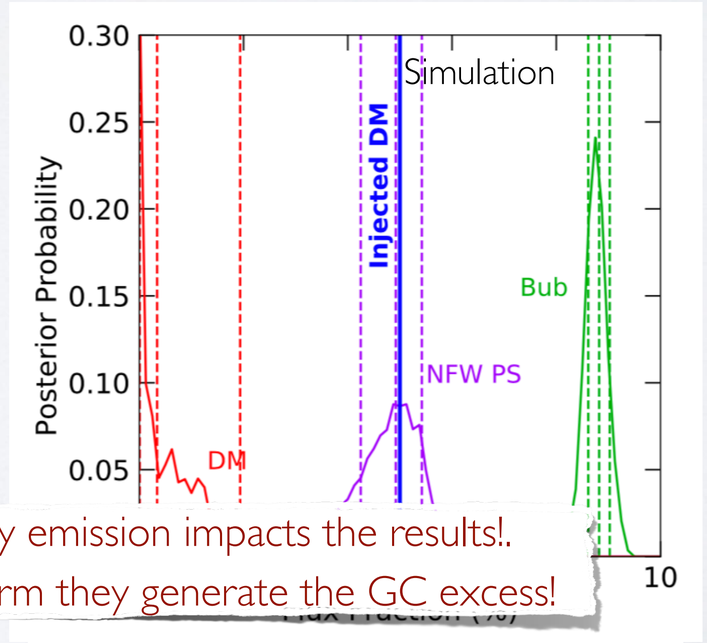


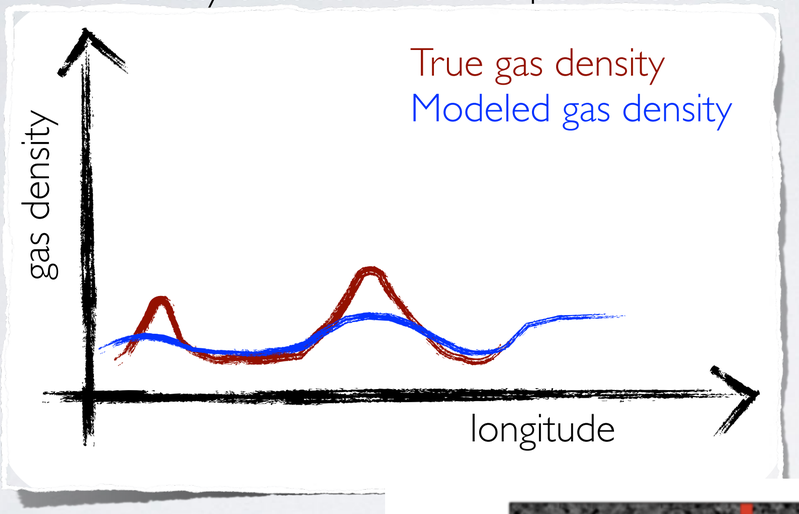
➡ Mismodeling of the Galactic gamma-ray emission impacts the results!.

➡ The pulsars must be detected to confirm they generate the GC excess!

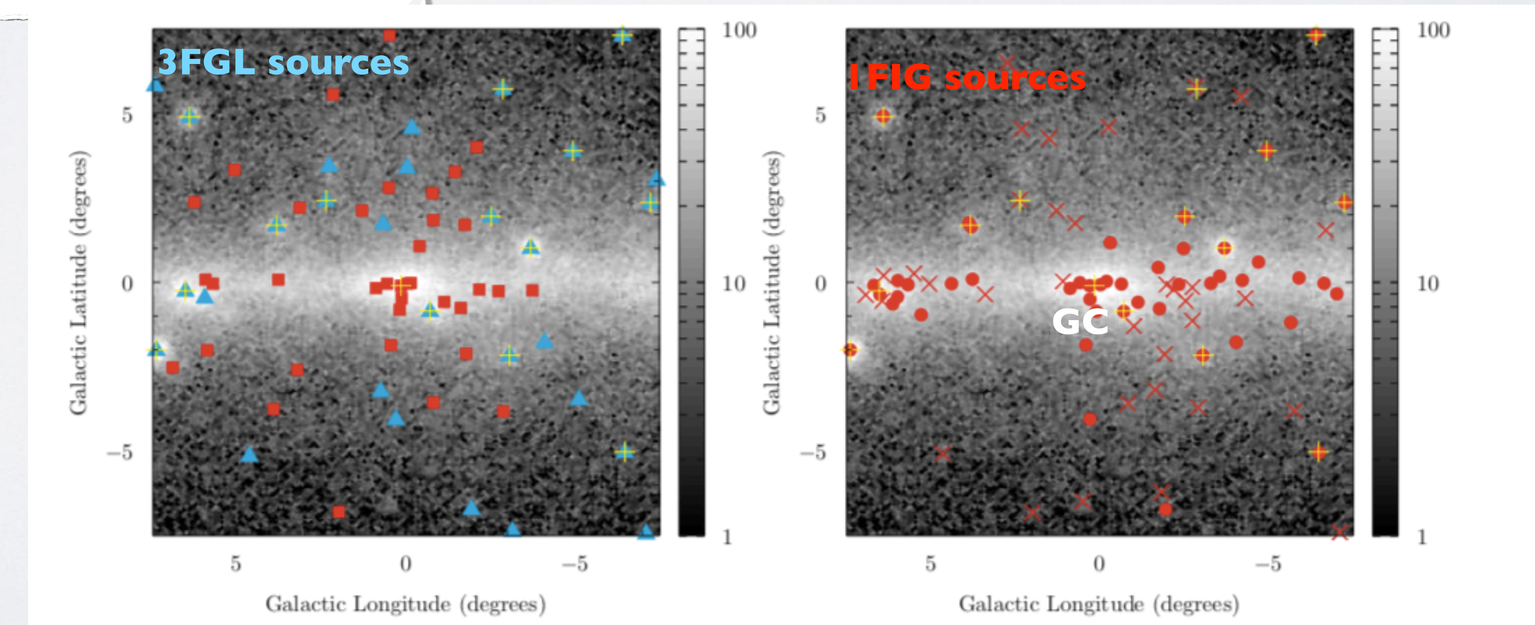
CAVEATS

- The distribution of point sources in the inner Galaxy in uncertain, with a significant dependence on the Milky Way gamma-ray emission model, i.e. some are spurious!

- It is likely that some of the point sources are mis-identified fine/high-density structure in the gas!



Fermi LAT Collaboration, arXiv:1511.02938



IMPROVING MODELS WITH DEEP LEARNING

- We employ gaussian processes and CNNs to learn about the gas in the galaxy and, based on training on the limited available data that traces finer structure in the gas, to generate improved (with finer structure and higher resolution) maps for the rest of the sky!

A. Shmakov, C. Karwin, M. Tavakoli, SM, P. Baldi, in prep

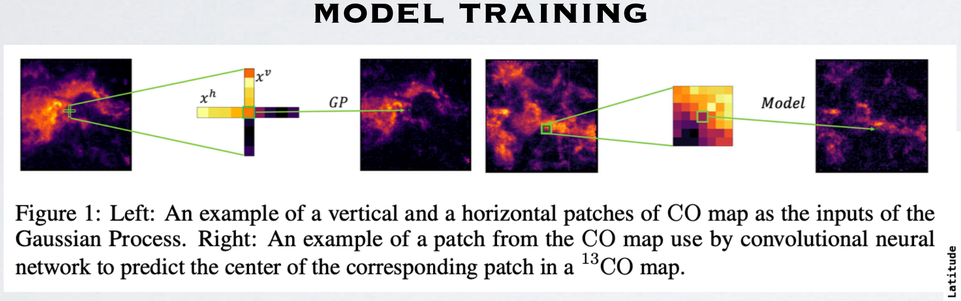
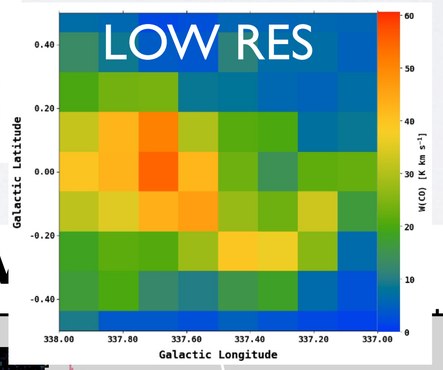
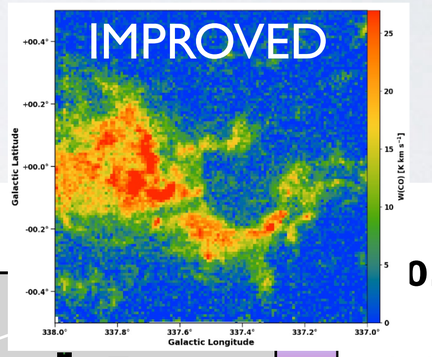
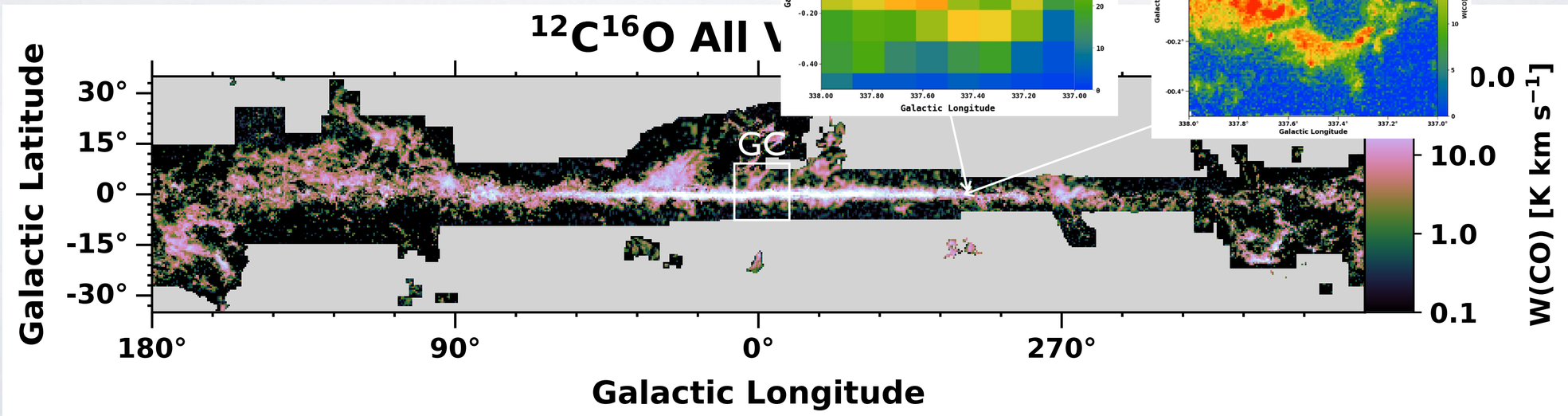


Figure 1: Left: An example of a vertical and a horizontal patches of CO map as the inputs of the Gaussian Process. Right: An example of a patch from the CO map use by convolutional neural network to predict the center of the corresponding patch in a ^{13}CO map.







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- We employ gaussian processes and CNNs to learn about the gas in the galaxy and, based on training on the limited available data that traces finer structure in the gas, to generate improved (with finer structure and higher resolution) maps for the rest of the sky!

- And the corresponding emission in gamma rays

A. Shmakov, C. Karwin, M. Tavakoli, SM, P. Baldi, in prep

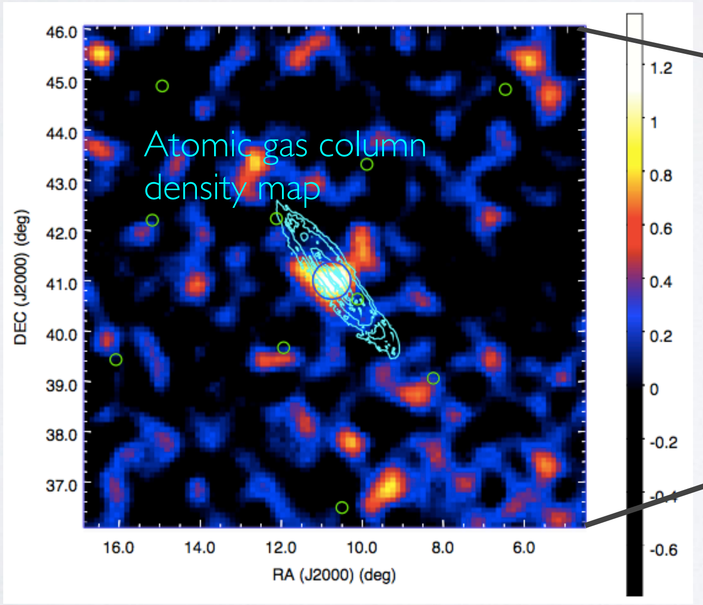
➡ Preliminary results indicate significant contribution from fine/high-density structure in the gas that was missed by models for the Galactic gamma-ray emission and that could be misinterpreted as point sources

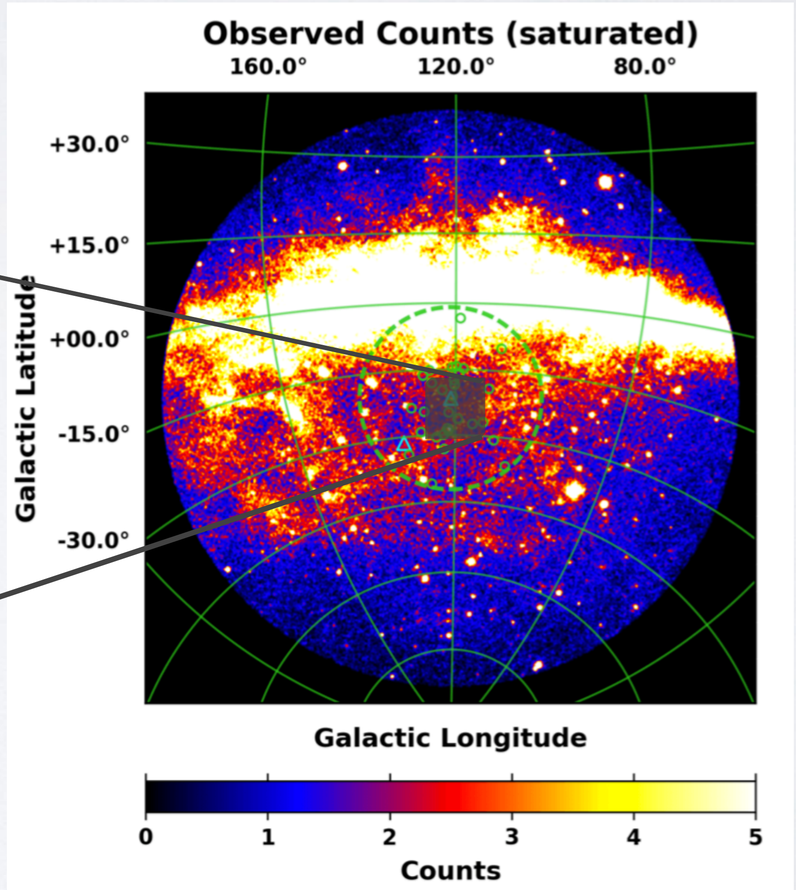
➡ This methodology will be applied the GC data to better resolve whether the GC excess is smooth (DM) or point-like

ANDROMEDA (M31)

- M31 DM halo extends several degrees across the sky (~40° for a DM halo ~600 kpc across). DM density gradient depends on DM distribution, substructures and profile
- Fermi LAT found evidence of a spherical γ-ray halo around M31, ~1° across not correlated with regions rich in gas or star formation activity (Pshirkov et al PoS ICRC2015 867, Fermi LAT Collaboration arXiv:1702.08602)
- DM and/or millisecond pulsars are possible interpretations, also compatible with GC excess

Fermi LAT, arXiv:1702.08602

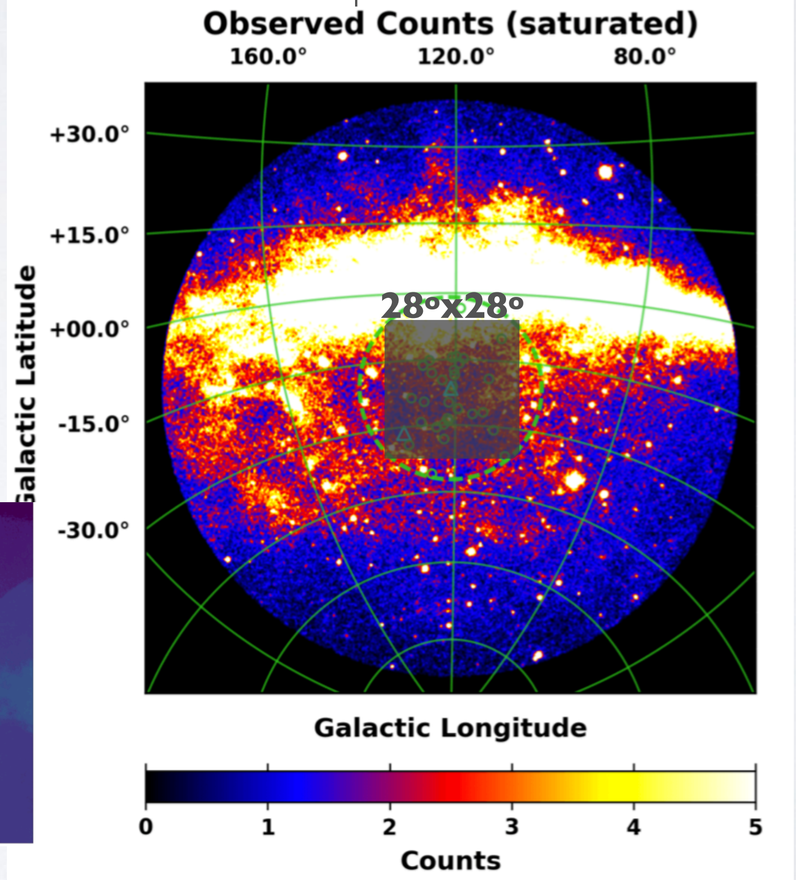




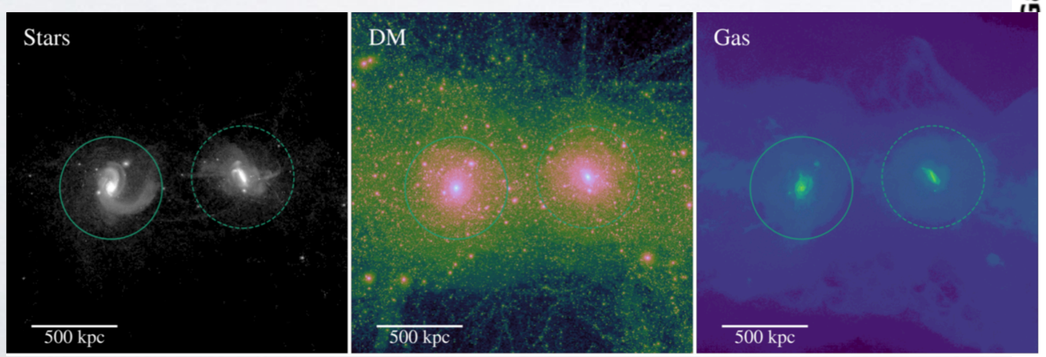
FERMI LAT OBSERVATIONS OF γ-RAY EMISSION TOWARDS THE OUTER HALO OF M31

C. Karwin, SM, et al, arXiv:1903.10533

- Search for extended γ-ray beyond the galactic disk of M31. Implications for DM and cosmic rays
  - annihilating/decaying DM signal (competitive with dwarf spheroidals), also an extended cosmic ray halo interacting with circumgalactic medium (but no pulsars!)
- This study complements previous results on M31 and is the first to explore the farthest reaches of the M31 system in γ rays
- NB: DM component in line of sight towards M31 includes M31 halo, MW halo, and possibly local DM filament

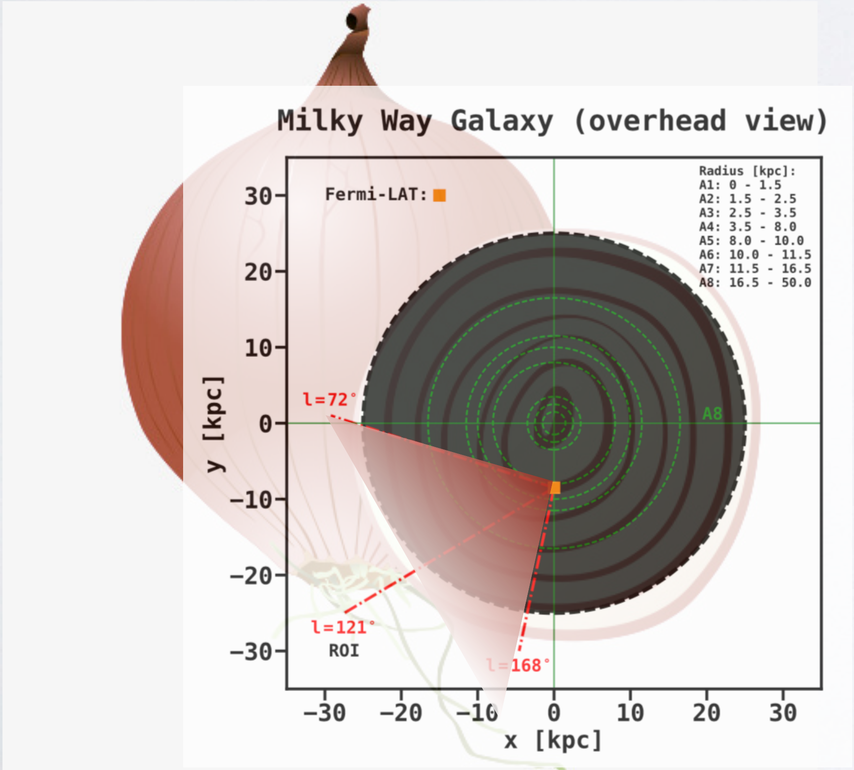


Garrison-Kimmel et al, arXiv:1806.04143

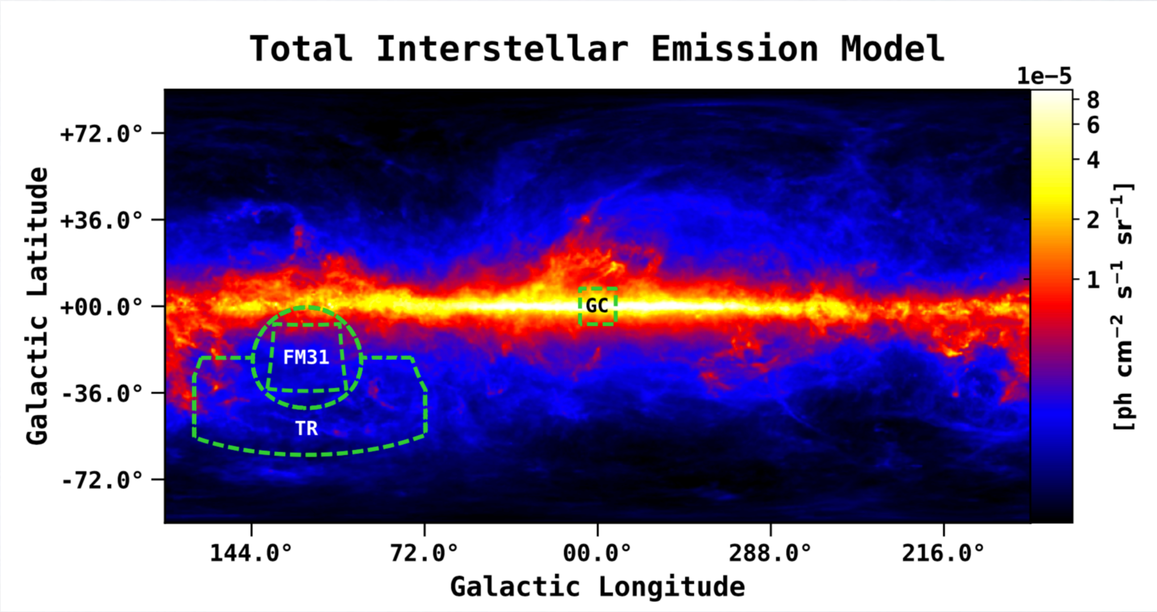


FOREGROUND MODELING

- Caveat: disentangle a potential M31 extended signal from the foreground γ-ray emission from the MW
- We build specialized models (using the GALPROP cosmic ray propagation code) for this emission, tuning them to regions away from M31 (tuning region TR)



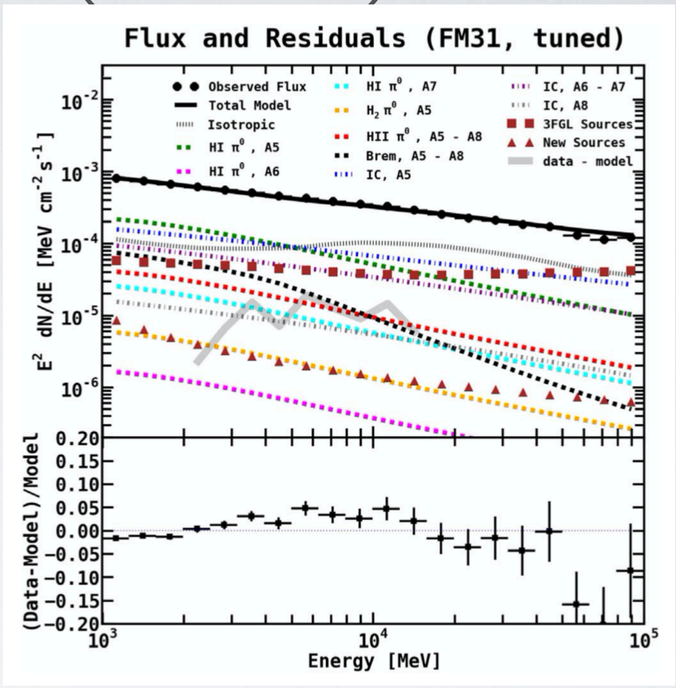
Signal region: FM31
Tuning region: TR

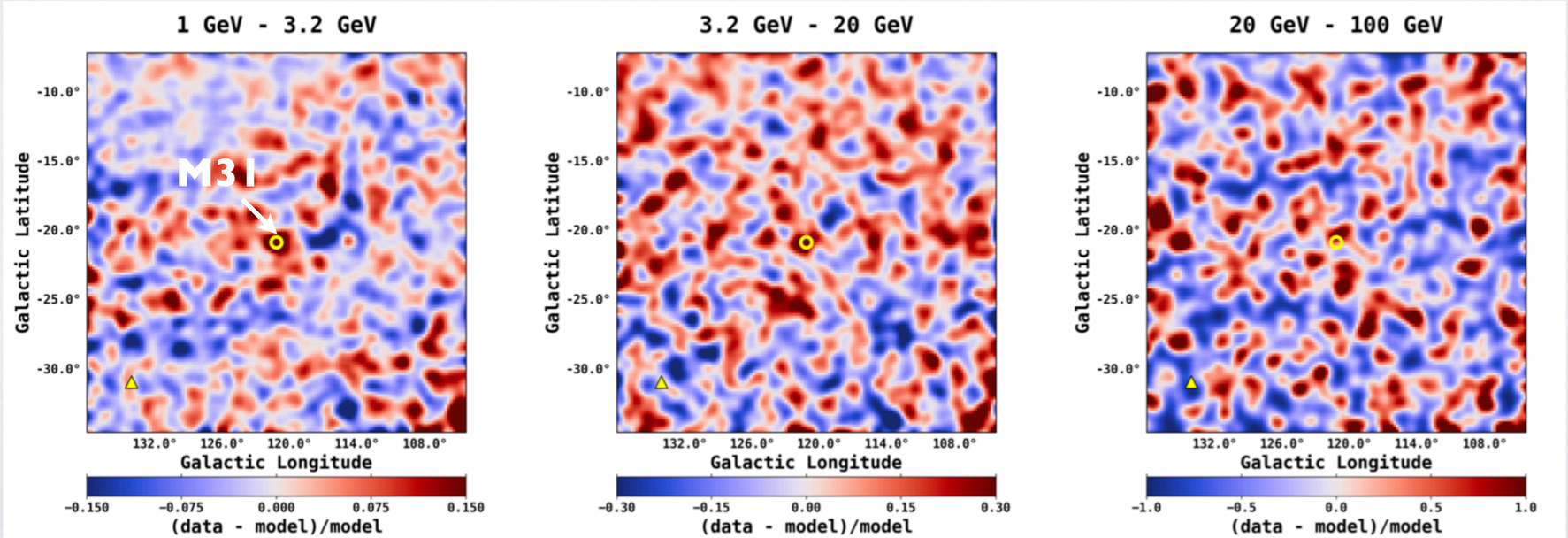


SIGNAL REGION (FM31)

- Use constraints from fit to TR for IC and isotropic. Free other foreground components (and point sources) in FM31
  - Determine additional point sources not in 3FGL (find 4 with TS>25, 17 with 9<TS<25; many correlated with gas)

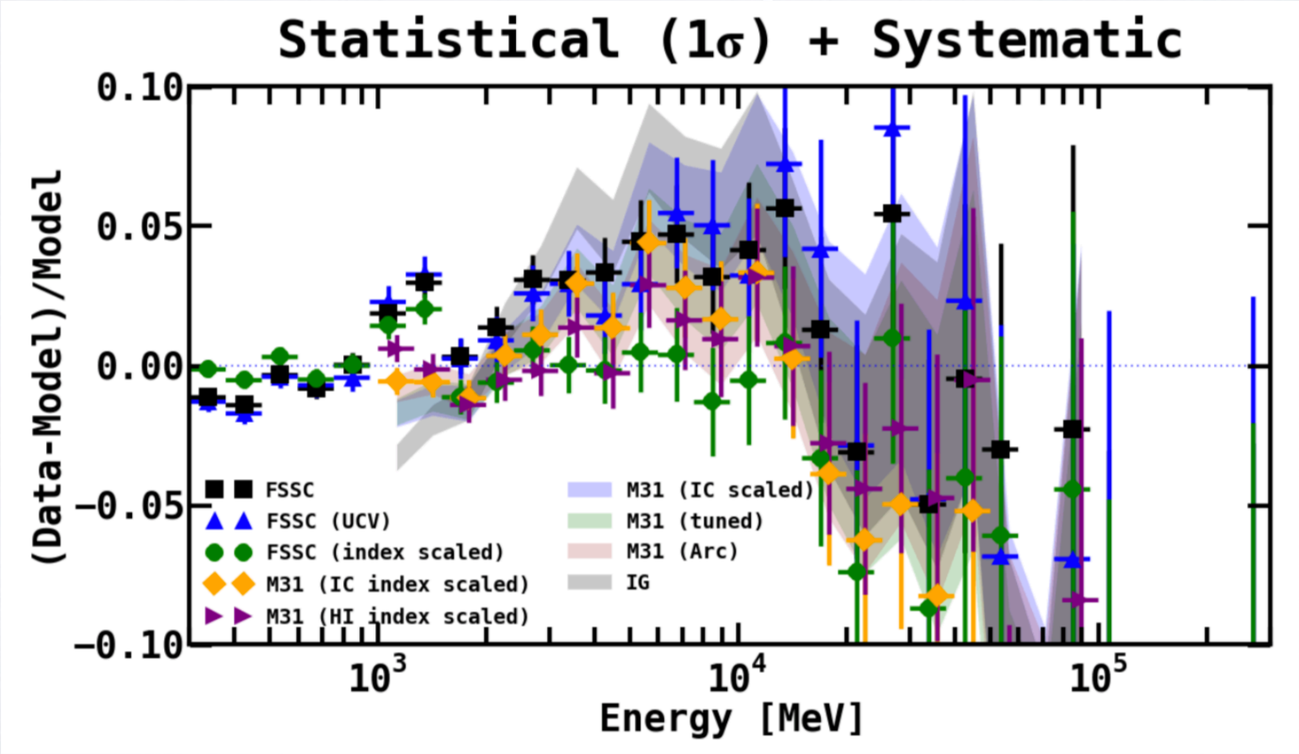
➡ Excess emission is present at the level of ~5% in ~3-20 GeV range ~ smoothly distributed





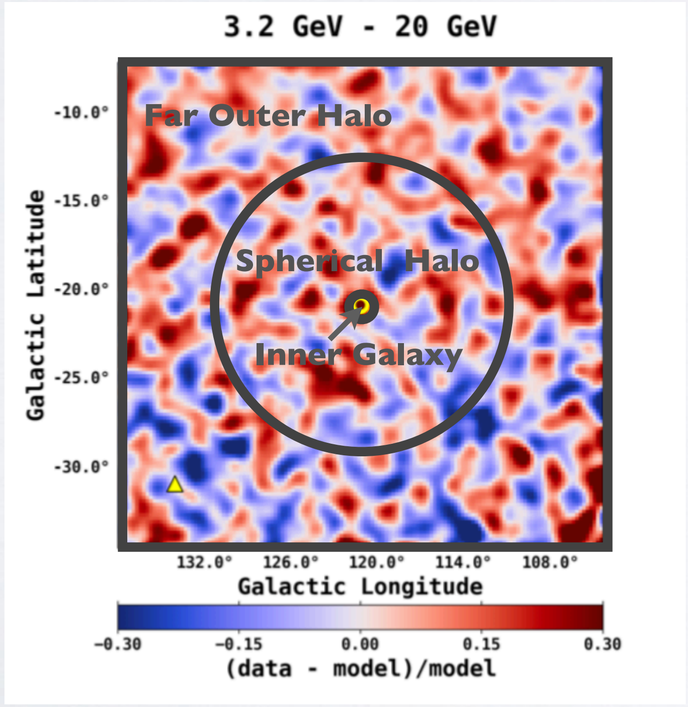
SIGNAL REGION (FM31)

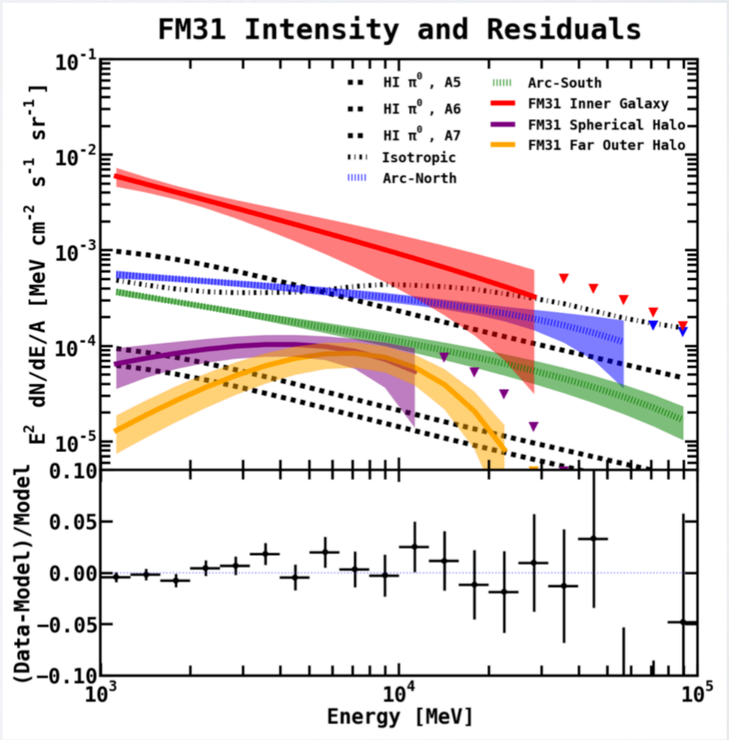
- Perform several more systematic checks: free all foreground components in signal region; allow more flexibility in spectrum and spatial morphology of these components; allow for spatial variation in the CR density, ISRF density, and/or spin temperature; employ different event selection; test alternative MW γ-ray emission models, …). E.g.:
  - free index of IC. Find hardening towards outer galaxy. Excess remains
  - free index of HI-related components. Find unexpected hardening towards outer galaxy, in conflict with other measurements. Some excess remains
- The general features of the residual emission are robust against these variations



CHARACTERIZATION

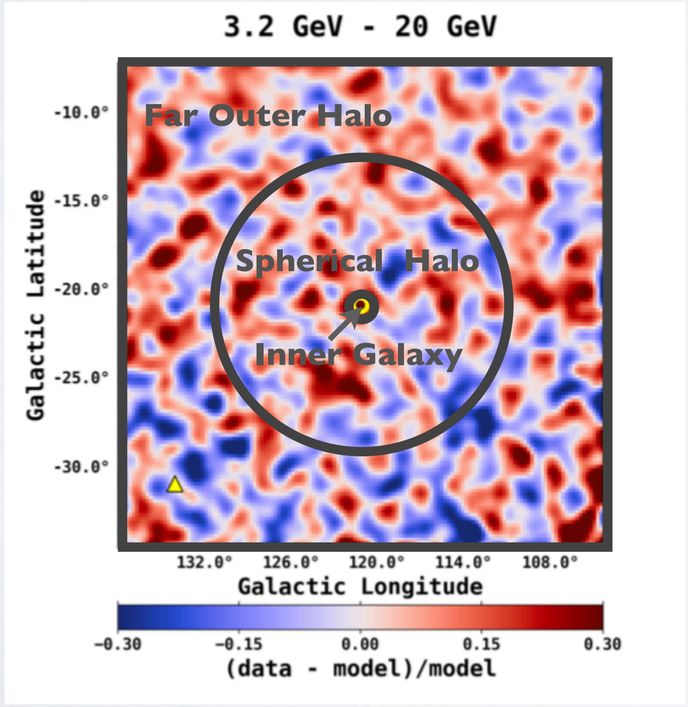
- We model the excess assuming spherical symmetry around M31 and choose templates to test the radial dependence of intensity and spectrum: M31 Inner Galaxy, Spherical Halo, Far Outer Halo
- The addition of these templates significantly improves data-model agreement. These templates are detected with significance >5σ.
- Best fit normalizations for MW foreground in good agreement with GALPROP predictions
- These results are robust against systematic checks

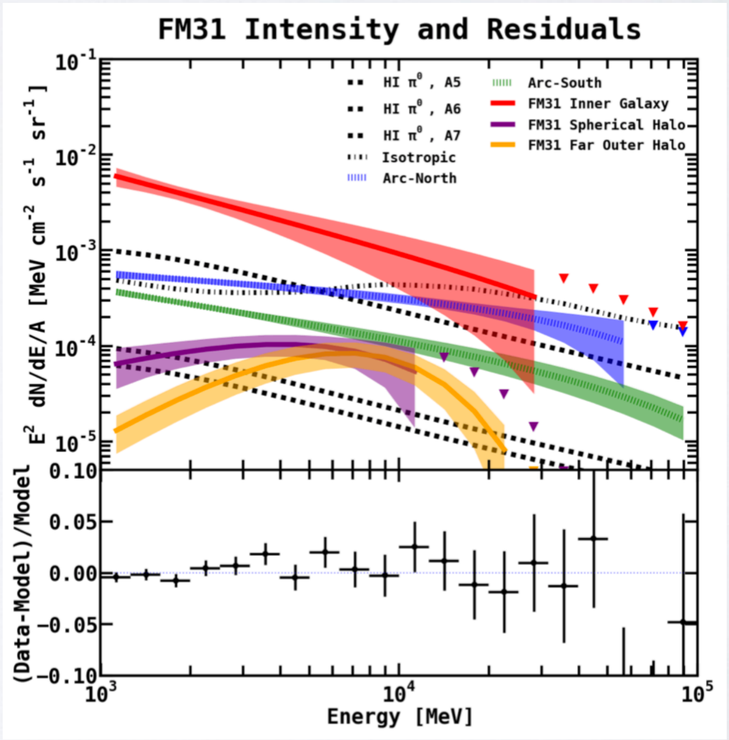




CHARACTERIZATION

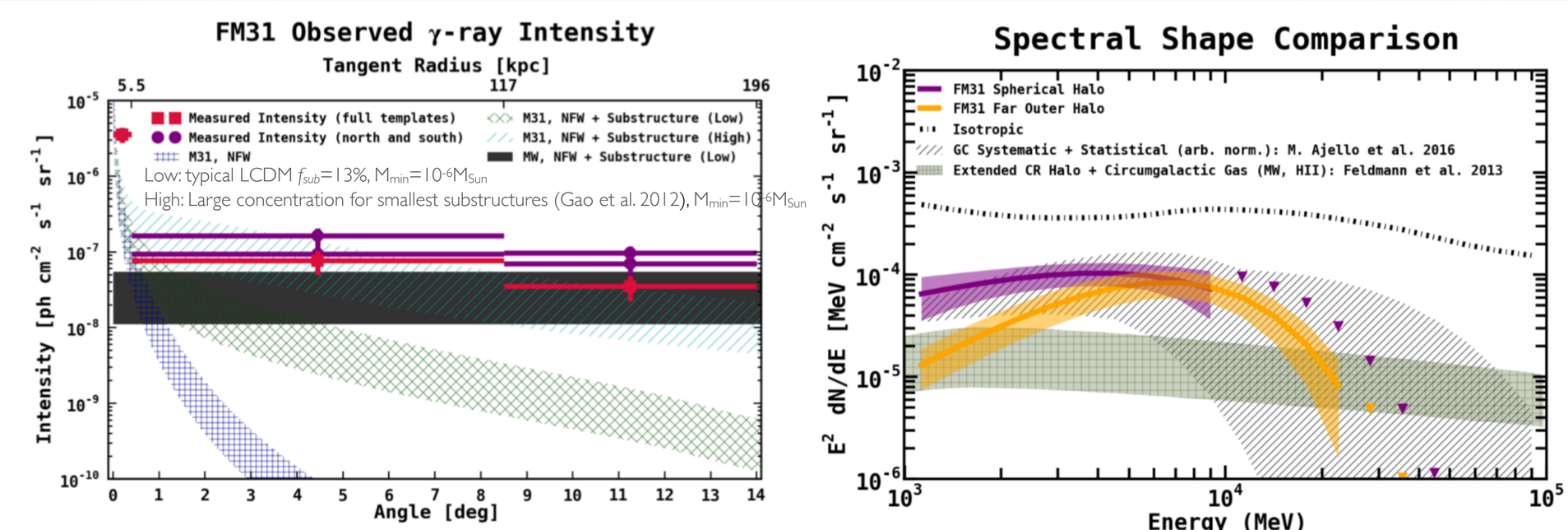
- We conclude that there is robust evidence for a significant extended excess in the Fermi LAT data from the direction of M31
- The excess significantly decreases outside of FM31 and appears to be distinct from the MW foreground
- The extension is upwards of 120-200 kpc from the center of M31and it has a distinct spectrum that peaks in the 3-20 GeV energy range





INTERPRETATION

- Annihilating DM provides a good description of the extended M31 emission and is consistent with the GC excess DM interpretation, though it requires a large substructure contribution to explain the full signal.
  - NB: some residual DM MW and local filament contributions would also be included. The DM MW component has not been explicitly accounted for in this analysis, and may be at least partially embedded in the foreground and isotropic emissions



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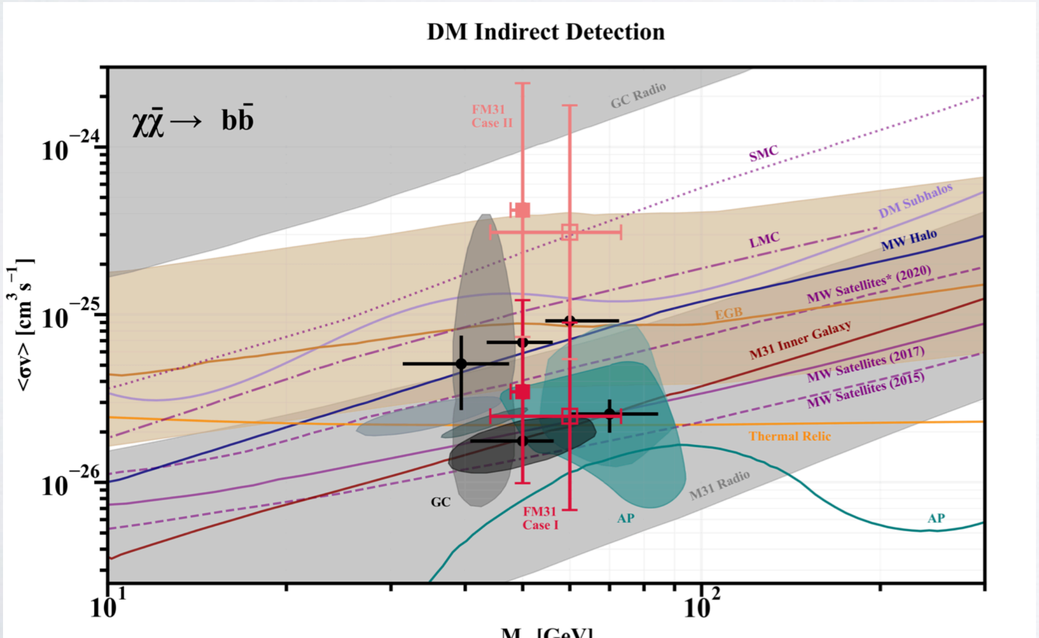

C. Karwin, SM, et al, arXiv:2010.08563

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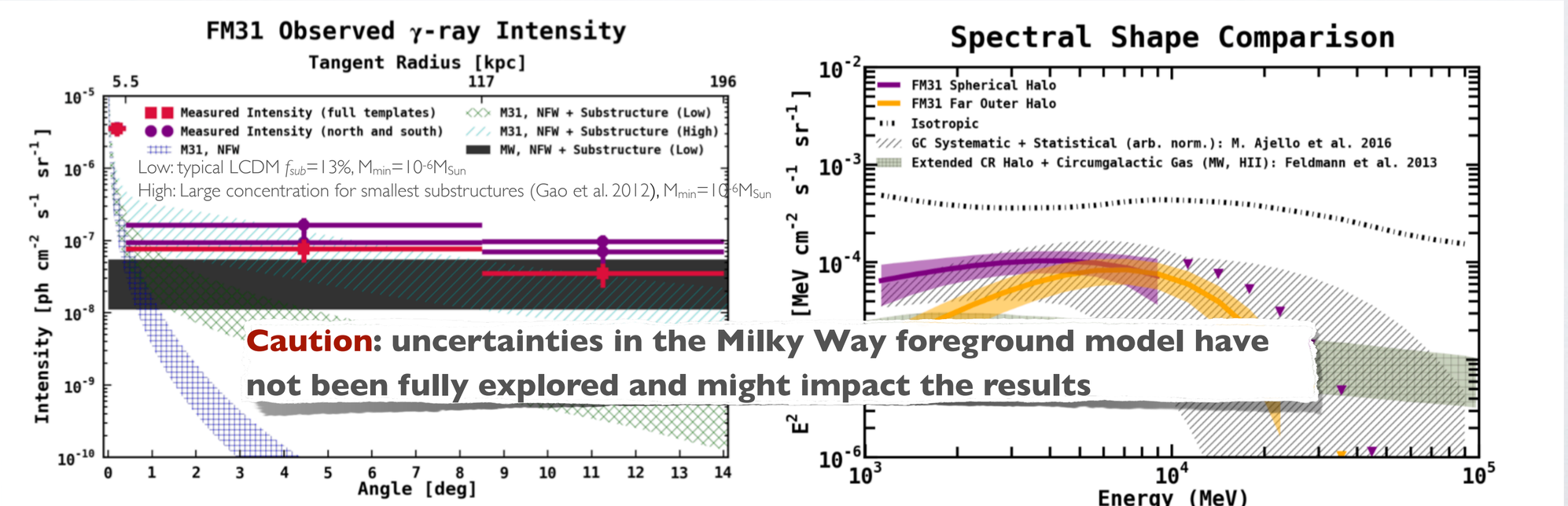
- Another possibility is that the excess arises from CR interactions with the (ionized) gas of M31's circumgalactic medium, but is unlikely
  - This would require CR spectrum and distribution significantly different in M31's outer galaxy than that measured locally in the MW. Other studies have shown that the CR density significantly decreases a few kpc away from the disk (down to ~10%)



CONCLUSIONS

- DM searches with γ-ray have set stringent constraints on DM models (dwarf spheroidals) and produced an intriguing excess from the GC
  - The jury is still out on the origin of the GC excess: an independent detection of a consistent DM signal from another target or of the pulsars is necessary to settle it
- M31 is complementary target to these searches
  - We find an extended excess in the Fermi LAT data from the direction of M31 that appears distinct from the MW, out to ~120-200 kpc from M31's center
  - Annihilating DM provides a good description of the extended M31 emission and is consistent with the GC excess DM interpretation
- Better understanding of the systematic and complementarity with other DM searches is crucial to interpret these excesses

Thank you!