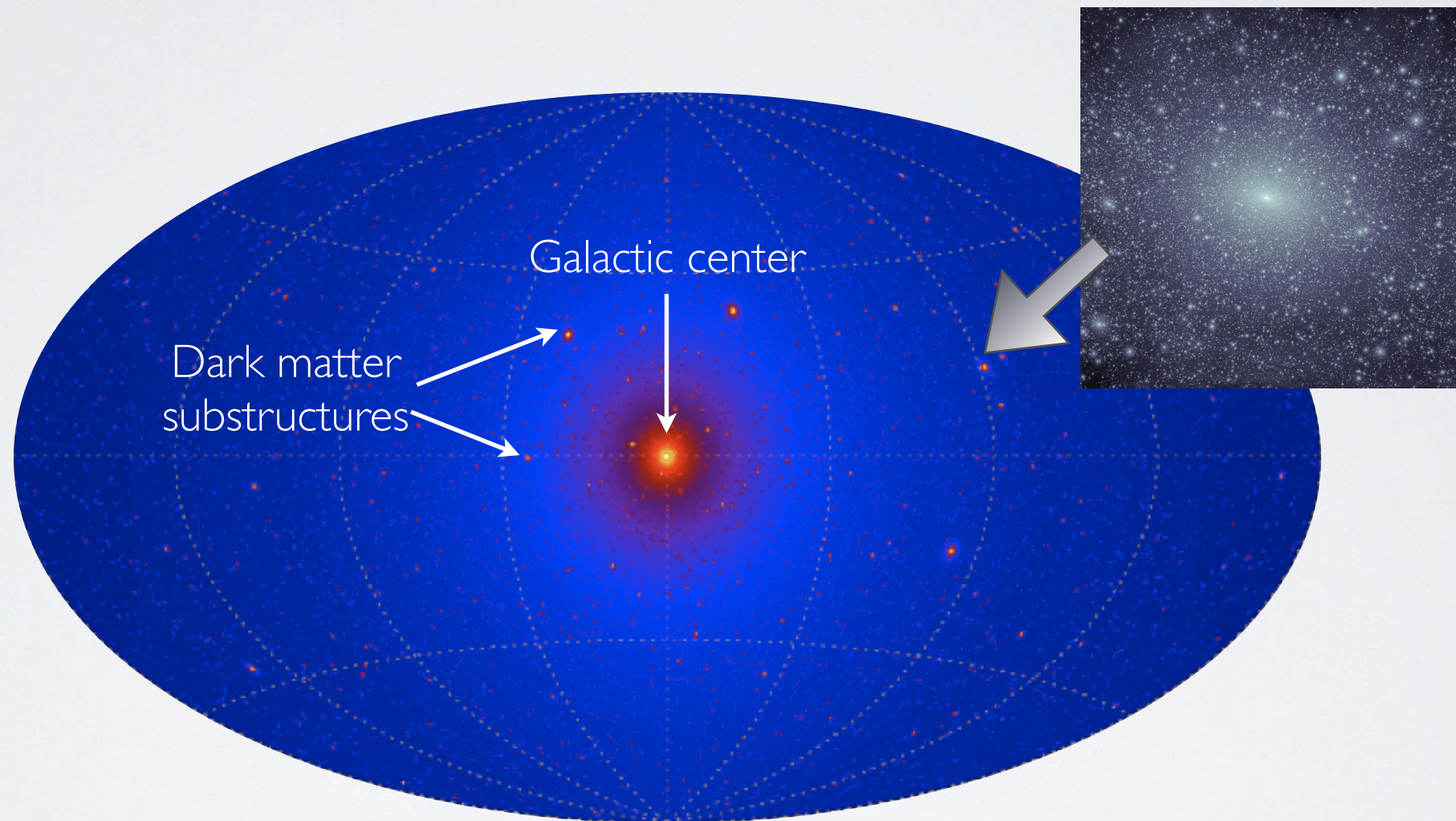


DARK MATTER SEARCHES WITH γ -RAYS: POTENTIAL SIGNALS FROM THE MILKY WAY AND THE LOCAL GROUP

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XIX International Conference on Interconnections between Particle Physics and Cosmology (PPC2026)
Sydney, Australia - 3 September 2026

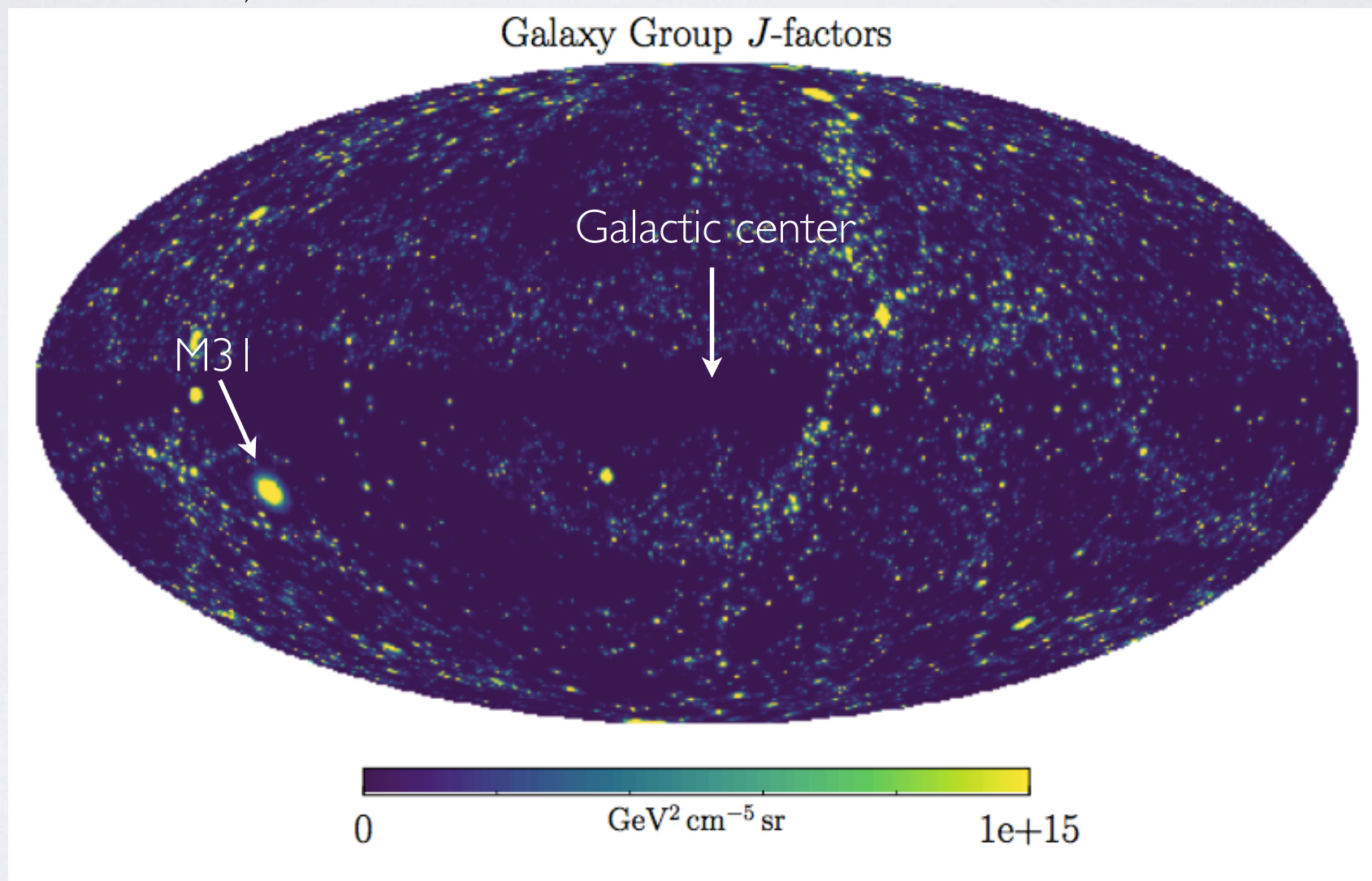
GAMMA RAYS FROM DM ANNIHILATION: MILKY WAY AND ITS SATELLITES DWARF SPHEROIDAL GALAXIES



Pieri et al, arXiv:0908.0195

GAMMA RAYS FROM DM ANNIHILATION: BEYOND THE MILKY WAY: M31

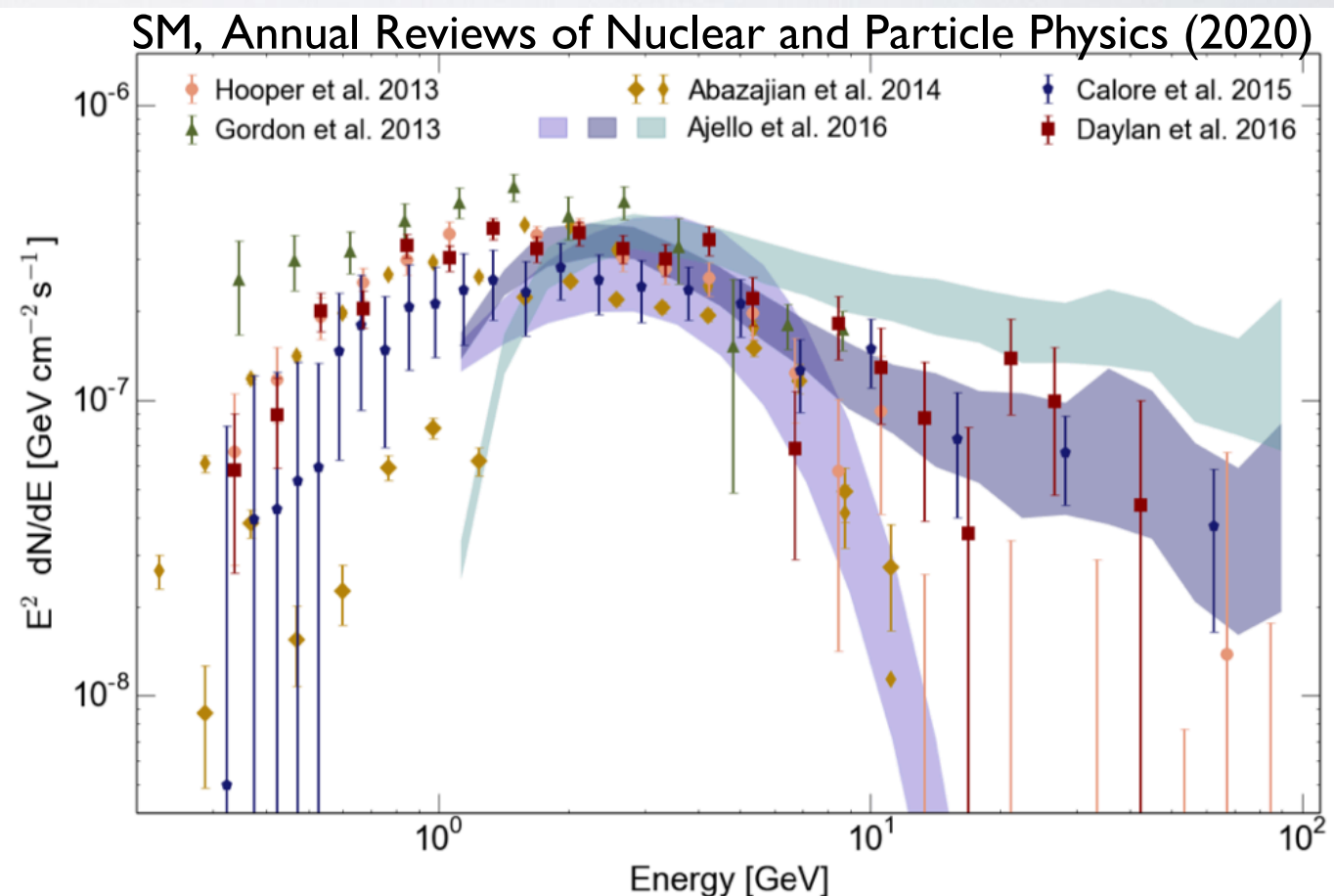
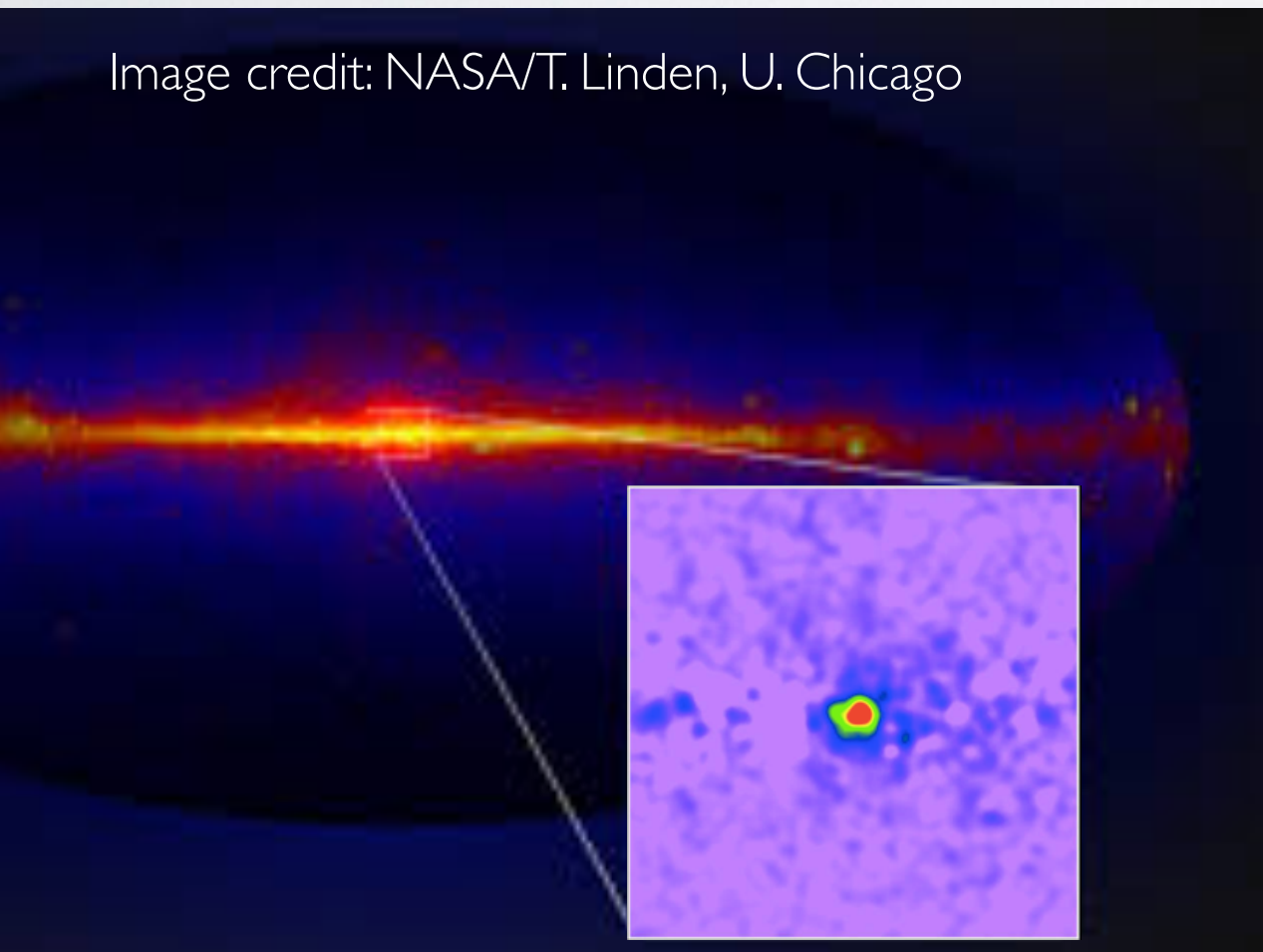
Lisanti et al, arXiv 1708.09385



GALACTIC CENTER EXCESS

- The signal is found in the Fermi LAT data (Goodenough and Hooper, arXiv:0910.2998, confirmed by many analyses since then), compatible with dark matter or collection of pulsars
- **Relatively broad range of possibilities for spectrum and morphology**
 - **Spectrum might cut off at ~ 10 s GeV or extend to ≥ 100 GeV**
 - **The spatial morphology might follow the (square of a) NFW distribution, with $\gamma \sim 1-1.3$, or the stellar distribution in the Galactic bulge**, which is boxy or X-shaped and set strong constraints on dark matter models (e.g. Macias et al, arXiv:1611.06644, Bartels et al, arXiv:1711.04778).
 - ➔ **Some recent magneto-hydrodynamical simulations (HESTIA) predict a non-spherical morphology for a DM signal**, indistinguishable from MSPs (Muru et al arXiv:2508.06314)
- ➔ **Different approaches in modeling the γ -ray interstellar emission from the Milky Way are employed by these analyses and the characterization/properties of the excess depend on these. Increasingly sophisticated modeling over time, but not yet complete or bracketing**

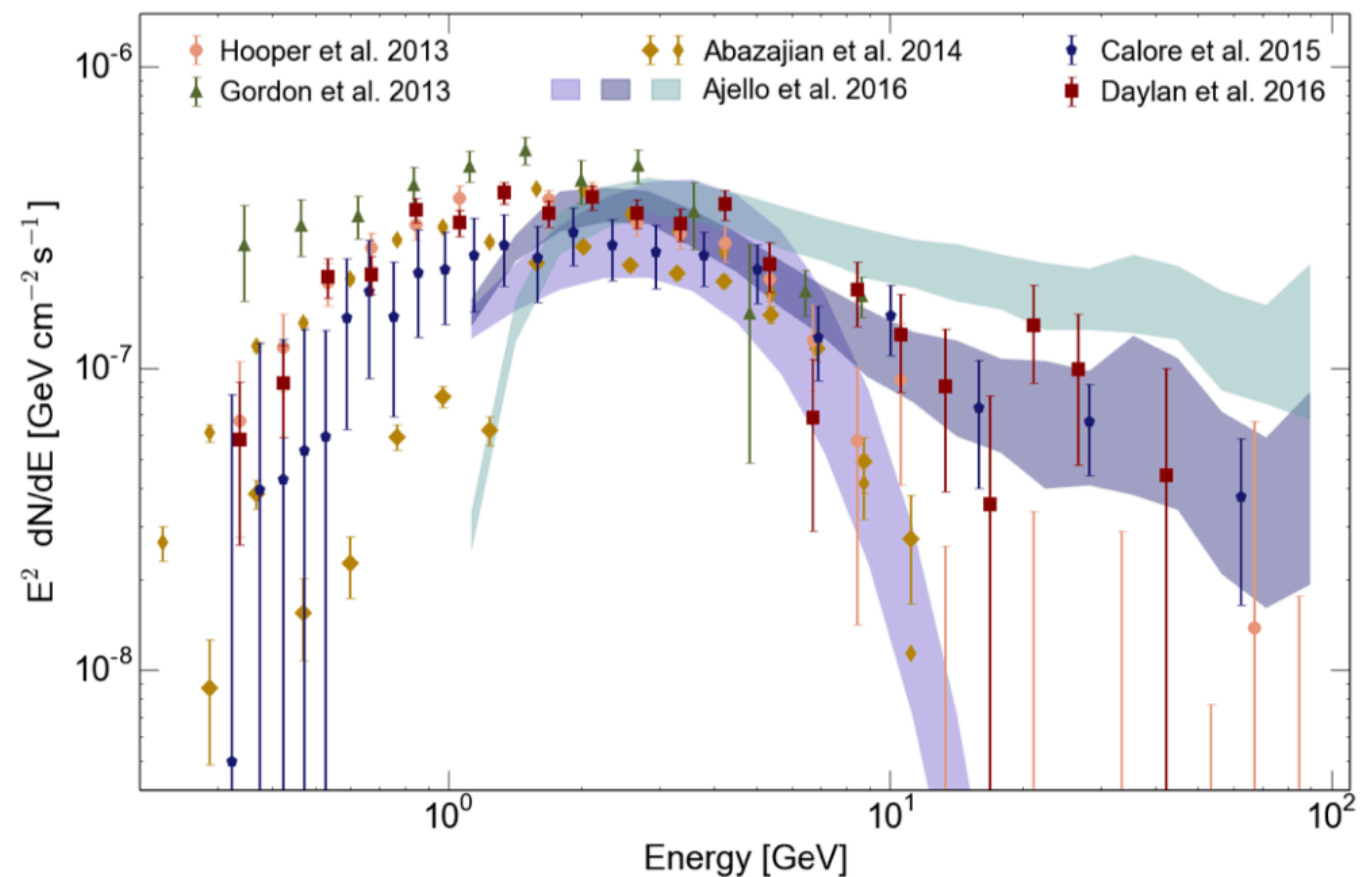
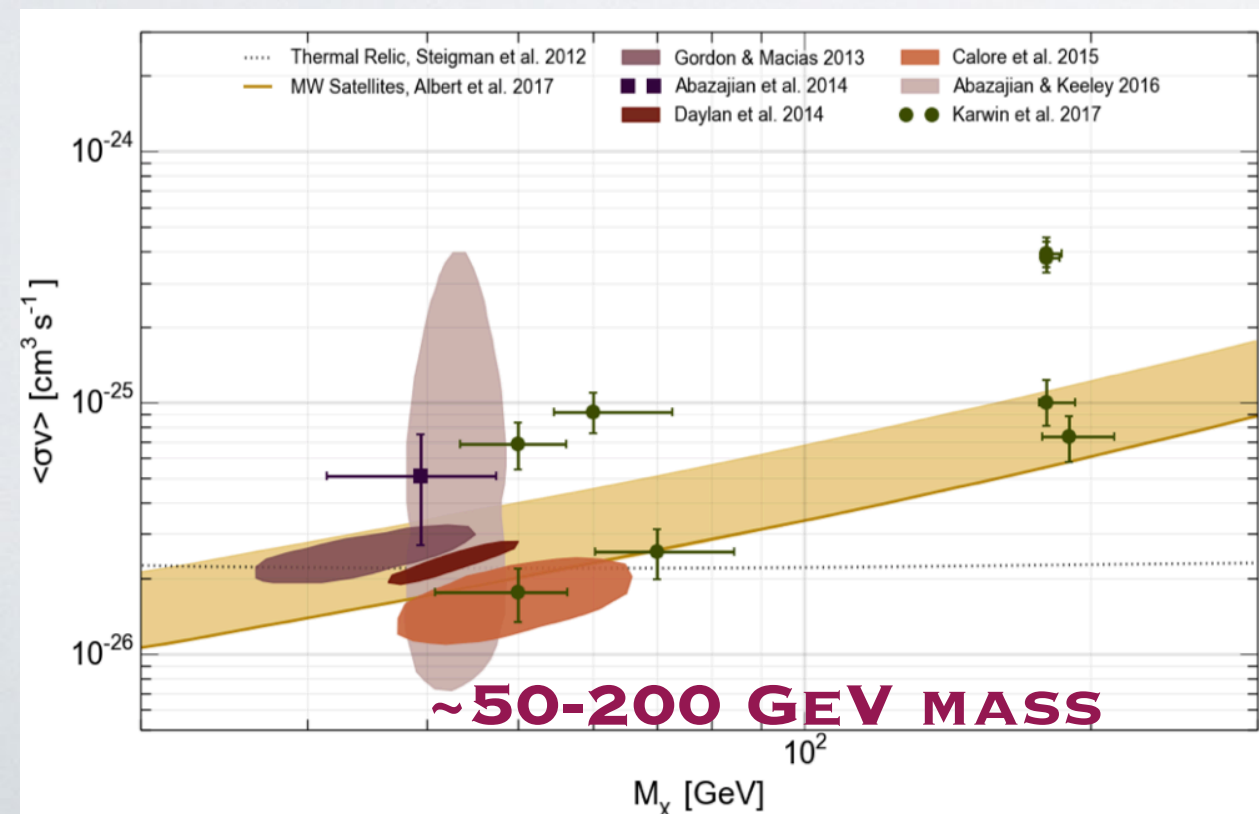
Image credit: NASA/T. Linden, U. Chicago



INTERPRETATION

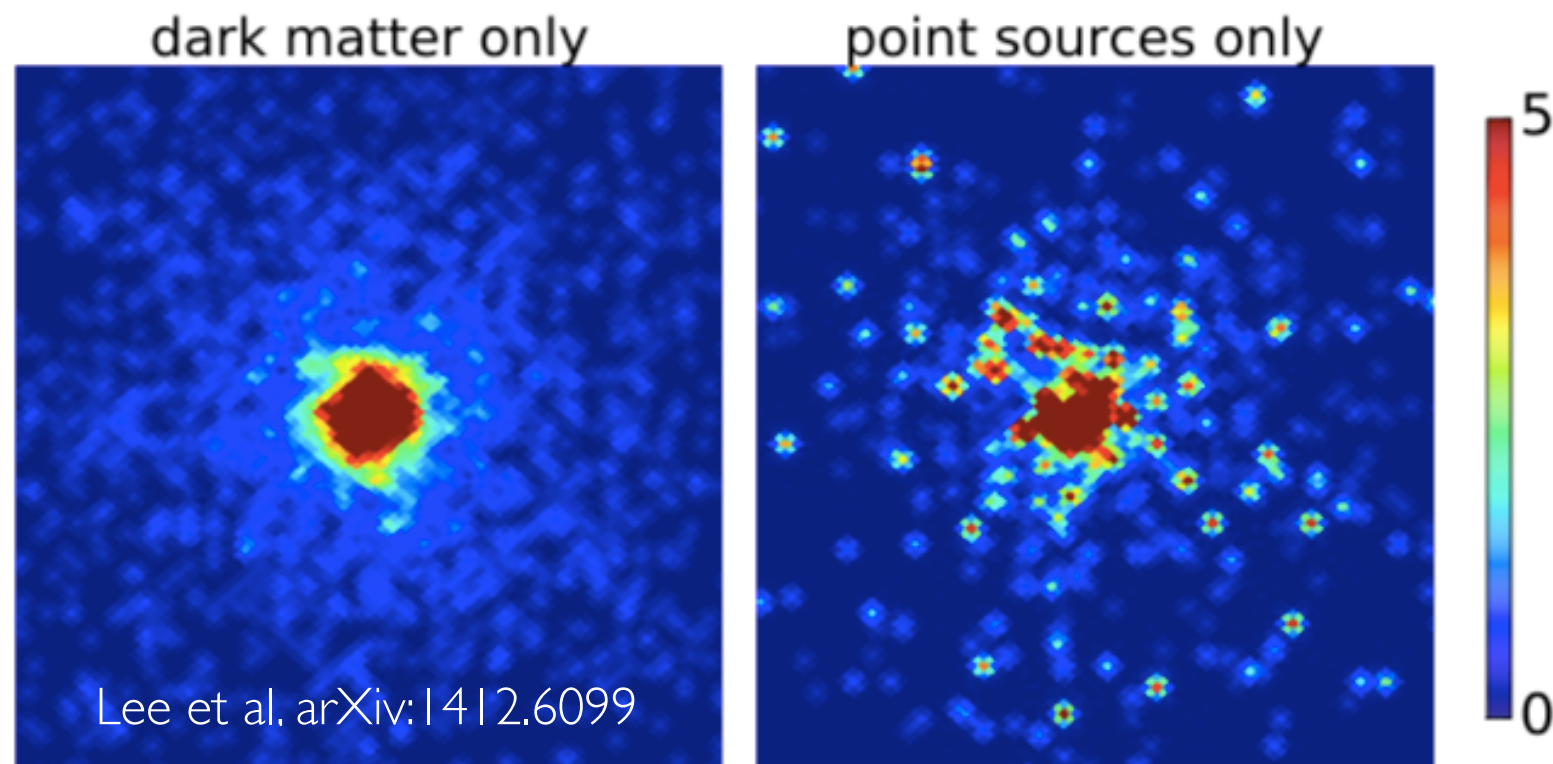
- GC excess spectrum consistent **DM particle with mass in the range ~ 50 (200) GeV**, annihilating mainly into bottom (top) quarks with an annihilation cross section $\sim 10^{-26} \text{ cm}^3/\text{s}$.
- Also compatible with unresolved pulsars**, e.g. $O(1000)$ millisecond pulsars within ~ 1 kpc of GC (Abazajian et al arXiv:1402.4090, but see also, e.g., Hooper et al arXiv:1606.09250 and 2412.05220, the predicted number of MSPs is too small or they are dimmer than predicted).
NB: no accurate a priori prediction for the γ -ray emission from MSPs

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

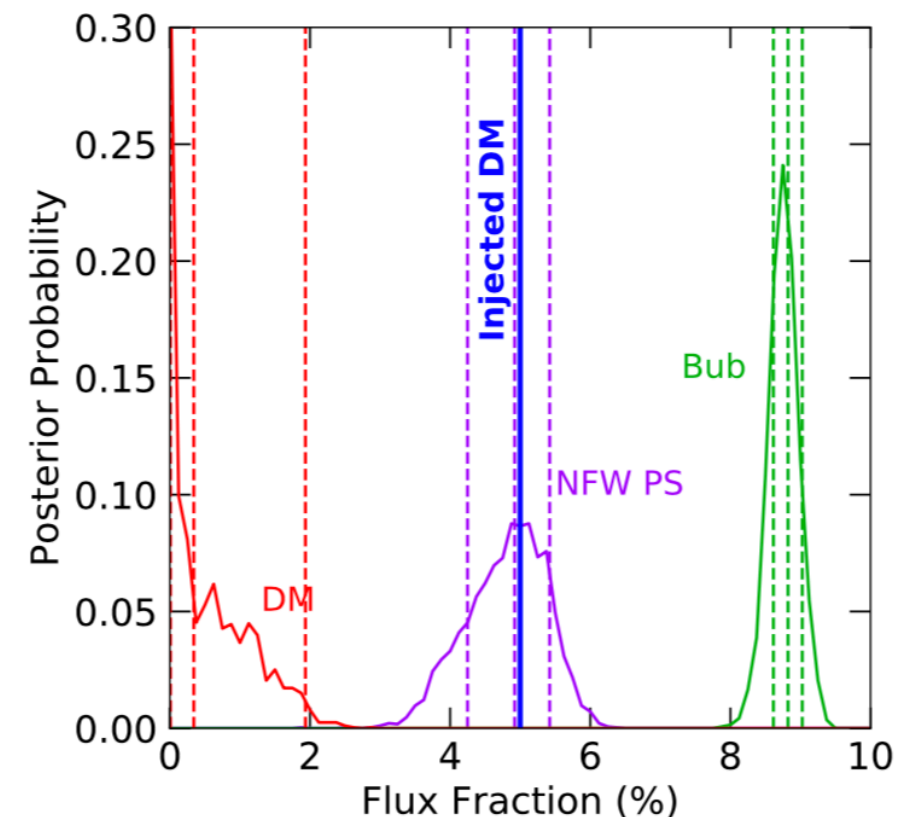


INTERPRETATION

- **Statistical techniques based on non-poissonian photon template fitting (NPTF) and wavelet decomposition** (Lee et al arXiv:1412.6099, 1506.05124; Bartels et al arXiv:1506.05104) **are affected by mismodeling of the Galactic gamma-ray emission**
- **They cannot conclusively prove whether the excess is consistent with a collection of discrete gamma-ray emitters or dark matter**
 - ➔ In 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 are not conclusive (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)

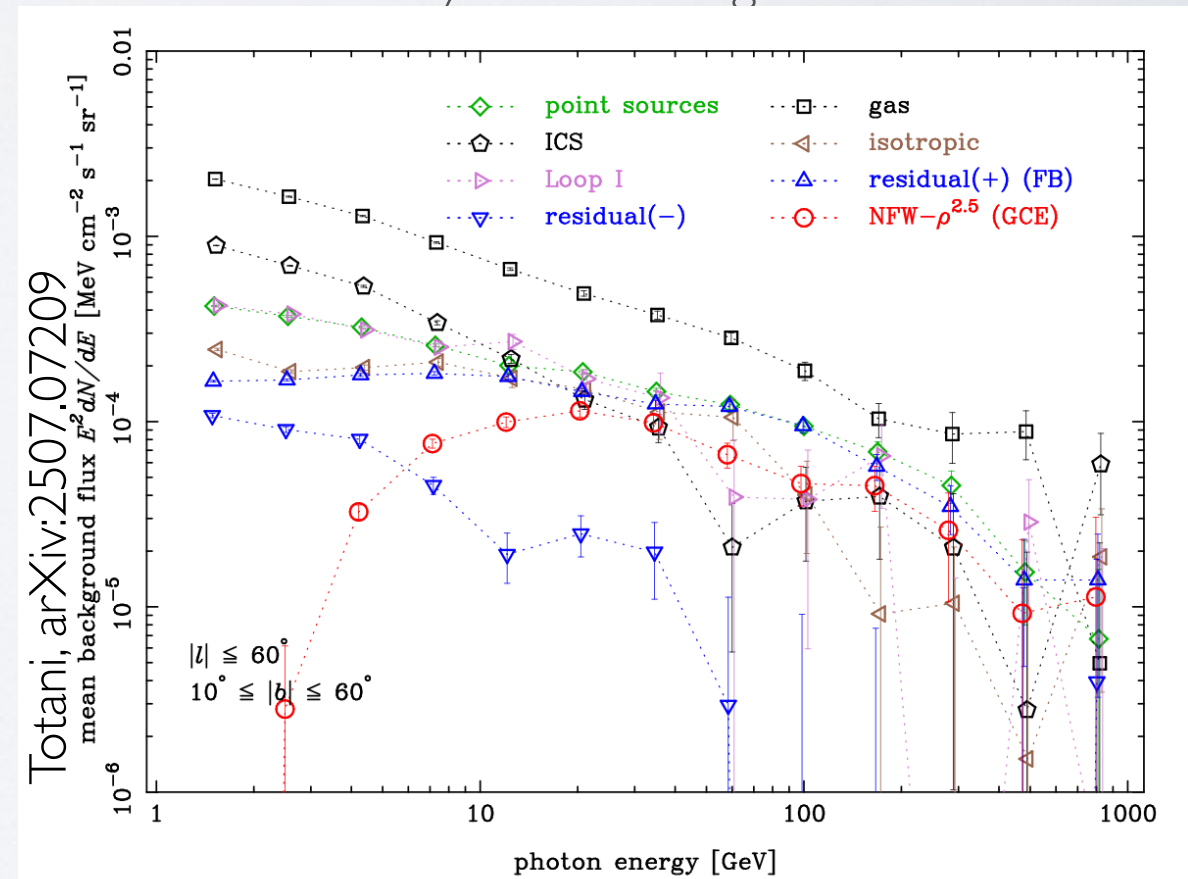
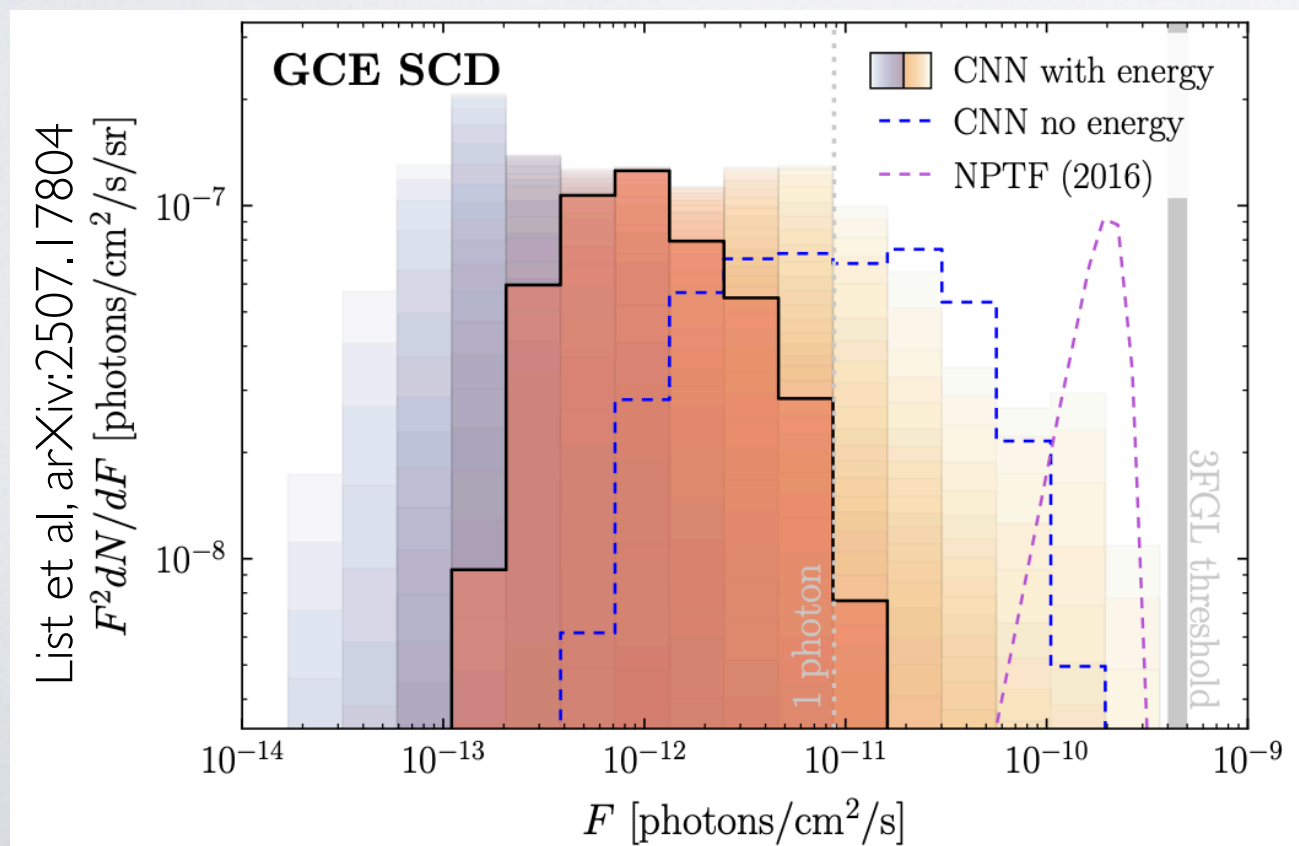


Leane et al, arXiv:1904.08430



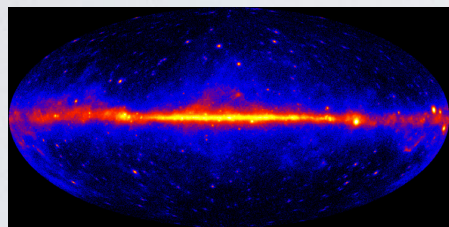
INTERPRETATION

- ➔ **When deep learning is used to reconstruct the spectrum of the point-source population, (too) many, (too) dim point sources are required to explain the excess** (>10000 s point sources needed to explain the excess, i.e. is essentially diffuse) while 100s are preferred by NPTF (Wolf et al, 2401.03336, List et al, arXiv:2507.17804),
 - ➔ Earlier deep learning studies found that excess is consistent with a smooth emission (List et al, arXiv:2006.12504), or still smooth but with $\gtrsim 40\%$ fraction of the originally measured excess due to point sources when ML methods that use simulation-based inference are used (Mishra-Sharma&Cranmer, arXiv:2110.06931)
- ➔ NB: An extended halo component with spectrum peaking at 20 GeV ($|l| \leq 60^\circ$, $10^\circ \leq |b| \leq 60^\circ$) recently claimed, compatible with dark matter annihilation into $b\bar{b}$ for particle mass $\sim 0.5\text{--}0.8\text{ TeV}$ and $\langle\sigma v\rangle \sim (5\text{--}8) \times 10^{-25} \text{ cm}^3 \text{ s}^{-1}$
 - ➔ Could be a distinct component from the GC excess or due to uncertainty in the background model

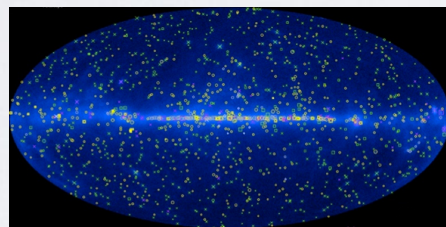


INTERSTELLAR GAMMA-RAY EMISSION

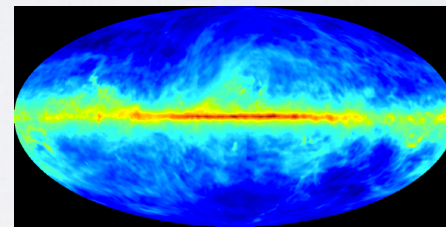
- **Interstellar γ -ray emission (IE)** from the MW is a major background for dark matter searches. It is produced by cosmic rays interacting with the interstellar gas and radiation field



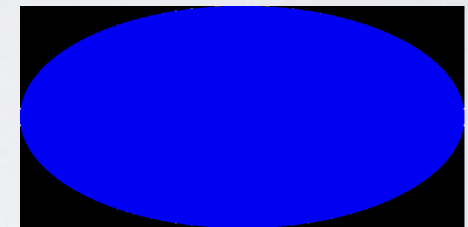
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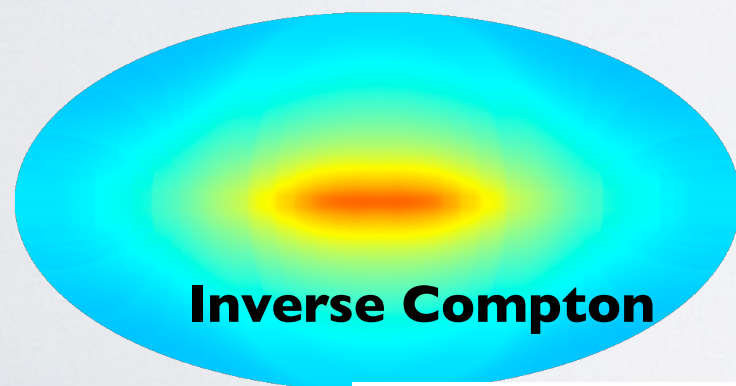
Point sources



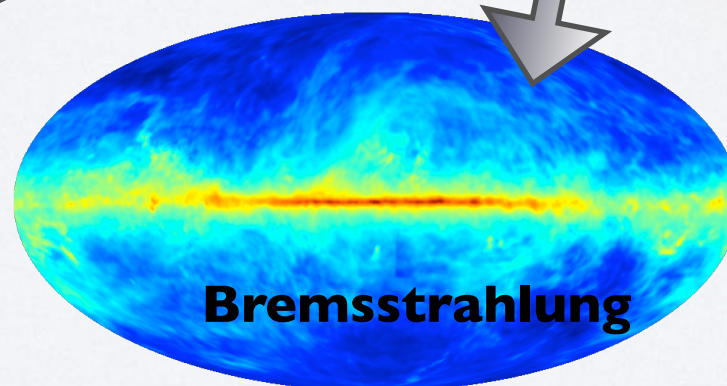
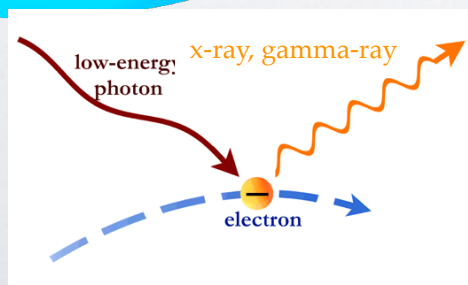
Emission from the Milky Way



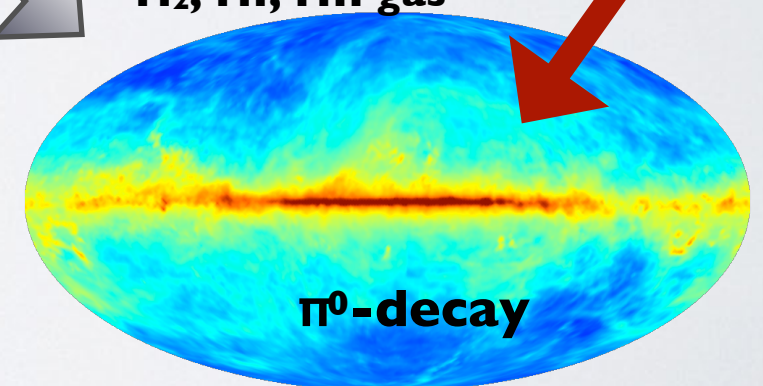
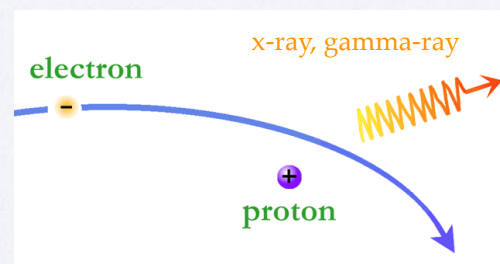
Extragalactic/Isotropic



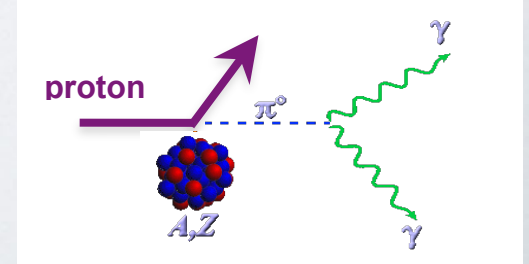
Inverse Compton



Bremsstrahlung



π^0 -decay



IMPROVING IE MODELS

- Improving these models is crucial to settle the origin of the GC excess (short of a complementary signal or improved instruments...) but it isn't easy
 - Here I'll focus on specific IE features/uncertainties that confuse the determination of the excess morphology, i.e. point-like vs smooth, since these could impact the results of statistical techniques
 - This work was triggered by the observation that the distribution of point sources in the inner Galaxy is uncertain, with a significant dependence on the IE model:
 - some of the sources are mismodeled gas clumps!



True σ gas density

INNER GALAXY Fermi LAT Collaboration, arXiv:1511.02938

What does this have to do with the GC excess?

- It is possible that some of the point sources attributed to the GC excess is mis-identified small angular scale structure in the gas!
- If true, we want to determine if there's enough mis-identified small scale structure in interstellar gas to confuse the GC excess characterization by making it appear point-like even if smooth. Not easy to assess this!
- Not arguing that the GC excess is due to gas structure, but that gas structure can disguise it as point-like
- NB: an instrument with better angular resolution would address this issue!

Galactic Longitude (degrees)

Galactic Longitude (degrees)



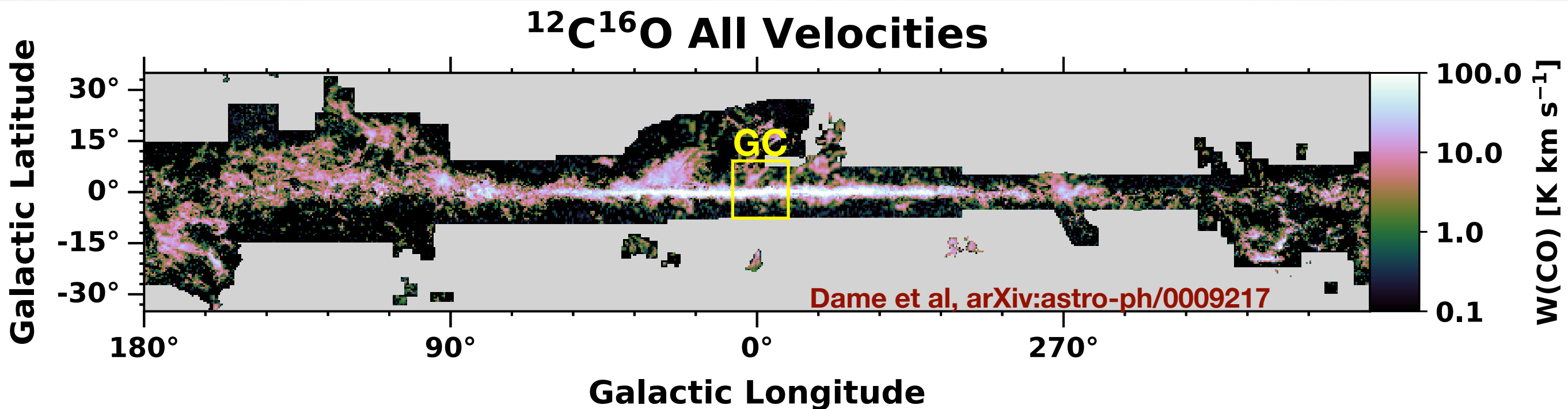
CASE STUDY: H₂

C. Karwin, A. Broughton, S. Murgia, A. Shmakov, M. Tavakoli, P. Baldi, arXiv:2206.02809

→ **We focus on H₂ gas because of its high degree of structure and the availability of additional proxies better suited to trace its small angular scale structure (NB: other components of the γ -ray IE, HI and dark gas, could also contribute)**

- Carbon monoxide as a proxy for H₂: radio surveys trace the distribution of ¹²CO (CO) across the sky (Dame et al is widely used ↓) and the H₂ column density inferred scaling the CO by a conversion factor (X_{CO})
- **However, the CO line emission is typically optically thick in the denser cores of H₂ clouds and it underestimates the total H₂ column density there!**

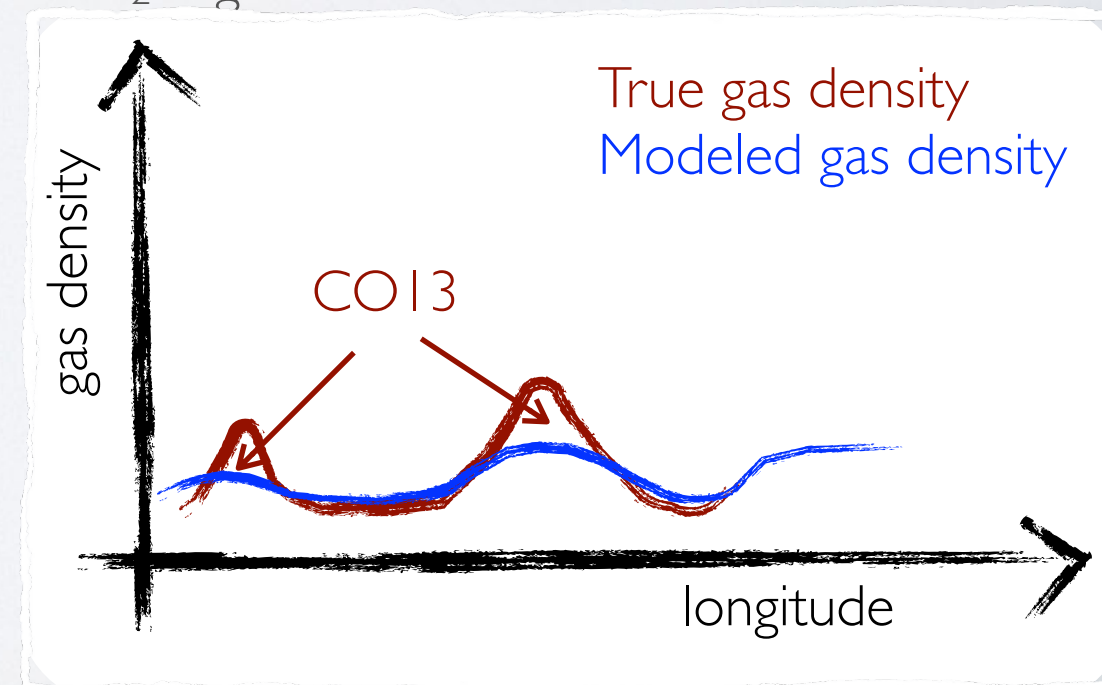
Dame et al



CASE STUDY: H_2

C. Karwin, A. Broughton, S. Murgia, A. Shmakov, M. Tavakoli, P. Baldi, arXiv:2206.02809

- **We focus on H_2 gas because of its high degree of structure and the availability of additional proxies better suited to trace its small angular scale structure (NB: other components of the γ -ray IE, HI and dark gas, could also contribute)**
- Carbon monoxide as a proxy for H_2 : radio surveys trace the distribution of ^{12}CO (CO) across the sky (Dame et al is widely used ↓) and the H_2 column density inferred scaling the CO by a conversion factor (X_{CO})
- **However, the CO line emission is typically optically thick in the denser cores of H_2 clouds and it underestimates the total H_2 column density there!**
 - γ -ray models that employ CO to trace H_2 gas may therefore underestimate its small scale structure.
 - **This limitation can be addressed by exploiting CO isotopologues, ^{13}CO (CO I 3)** and others, also found in H_2 clouds. The line emission from these rarer isotopologues remains optically thin to larger column densities and therefore is more reliable to probe dense H_2 regions.



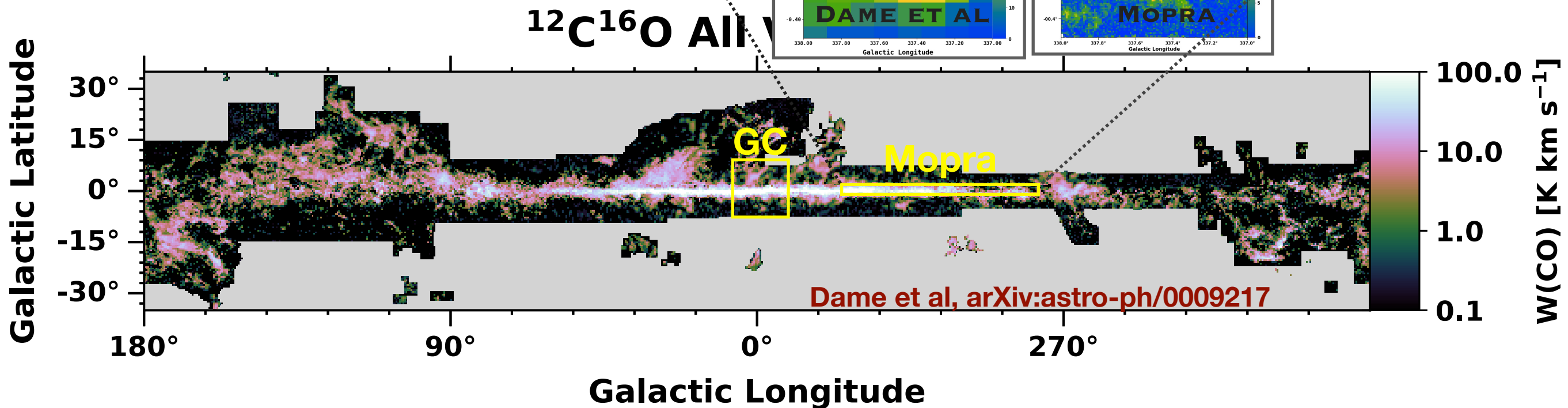
CASE STUDY: H_2

→ We employ the data from the *Mopra Southern Galactic Plane CO Survey* (data release 3) to trace the denser H_2 regions. The survey covers a 50 square degree region, spanning Galactic longitudes $l = 300^\circ$ - 350° and latitudes $|b| \leq 0.5^\circ$ (targets $J = 1-0$ transitions of CO, CO13 (also $C^{18}O$ and $C^{17}O$)

- line strength, $W(CO)$, as a function of Galactic coordinates and local standard of rest velocity

→ In this region, Mopra gives a sharper view of the CO emission compared to Dame al (angular resolution : $8'$ Dame, $0.6'$ Mopra), in addition to probing the rarer H_2 tracers.

Dame et al



GAMMA RAYS FROM H₂ SMALL SCALE STRUCTURE

- We follow standard procedure to determine the γ -ray emission associated with H₂ traced by CO and CO13 in the 50 sq deg Mopra region:



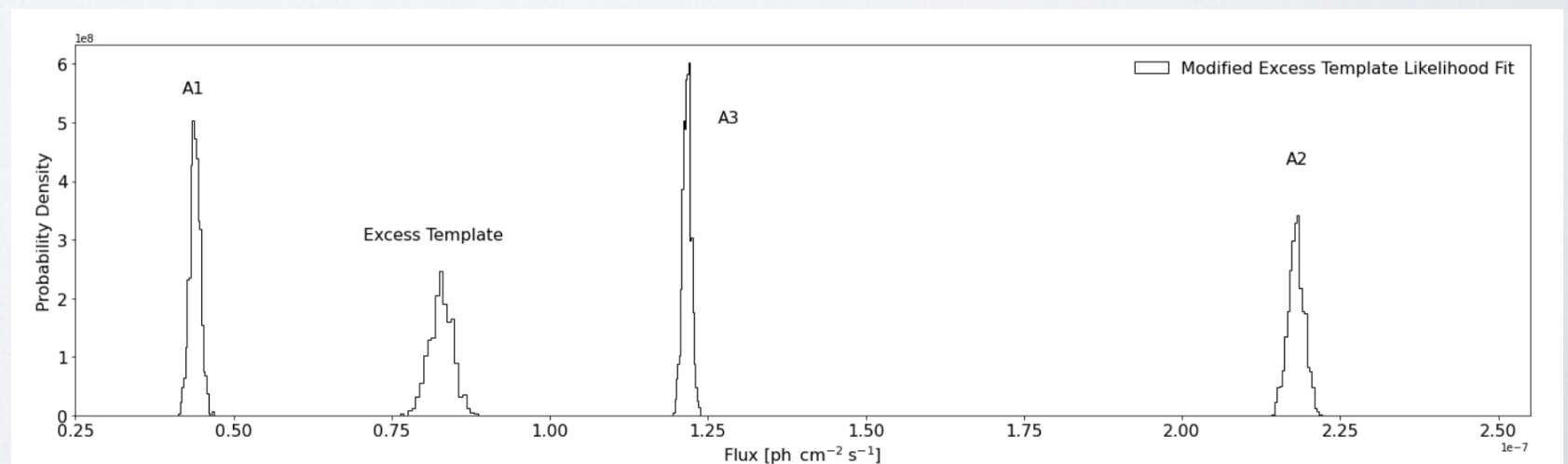
Modified Excess Template: this is an estimate of the small scale H₂ structure the IE models are missing!

- We evaluate the significance of the Modified Excess Template simulating 1000 realizations of ~12 years of Fermi-LAT data

- we assume the optimistic scenario where all other components are satisfactorily modeled

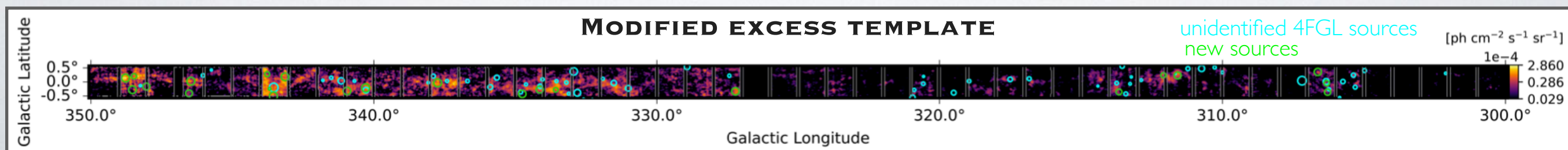
→ The significance is $\sigma \sim \sqrt{TS} \sim 48$, for the 50 sq deg Mopra region, and therefore this contribution is potentially very important

- Overall, the Modified Excess Template accounts for ~15% of the total H₂-related γ -ray emission in this region



IMPLICATIONS

- At this stage, we cannot reliably extrapolate this result to determine this component in the GC region (for the GC excess) since there are very limited CO 13 observations there, however we estimate that:
 - **Assuming the same fraction of H_2 small scale structure in the Mopra region ($\sim 15\%$), this translates into a very rough estimate for the γ -ray from the H_2 small scale structure in the GC region ($15^\circ \times 15^\circ$ region around the GC) of $\sim 30\text{-}50\%$ of the GC excess flux itself!**



MACHINE LEARNING

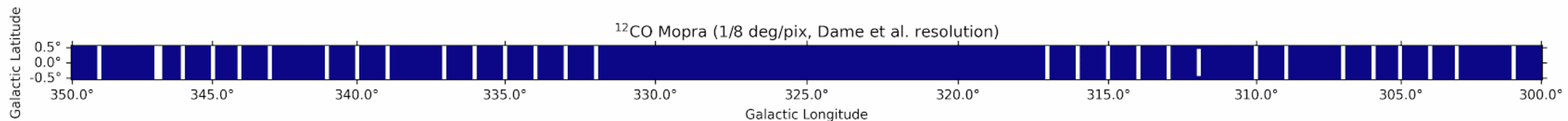
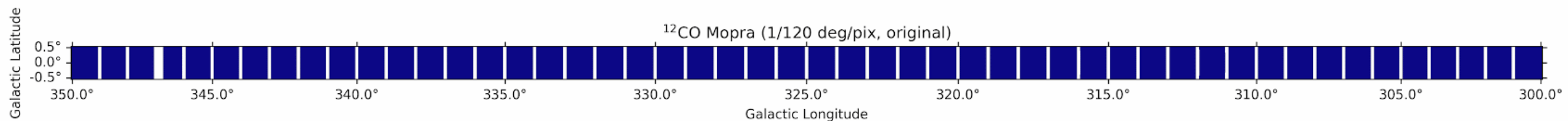
A. Shmakov, M. Tavakoli, P. Baldi, C. Karwin, A. Broughton, S. Murgia arXiv:2206.02819

- **Observations of CO13 (and other isotopologues) are limited to small regions of the sky**
- **To extend our methodology to the rest of the sky, we train a deep learning model to map between CO and CO13 column densities to predict CO13 where only CO observations are available**
 - For now, this study is proof of principle and limited to the Mopra region
- **We determine the CNN analog of the Modified excess template:**
 - **Smart Excess Template: CNN prediction of the γ -ray emission from the small scale H_2 structure not included in the IE models**
- **Result: the Smart Excess Template is in adequate agreement with the Mopra data and can be detected at high statistical significance (based on a full simulation of the γ -ray emission from the Mopra region).**



ONGOING WORK

- **Preliminary results show that we have detected the excess emission traced by Mopra CO I 3 in the Fermi LAT data!**
- **More Mopra data now available, over 2x larger area, crucially closer to the GC and extending to higher latitudes**
- **The main challenge is to extend this procedure to the GC region, where Mopra-like resolution CO I 2 (and CO I 3) surveys are sparse or do not exist**
 - We need a CNN model with additional transfer learning to operate on the lower resolution Dame et al CO map (8' angular resolution compared to 0.6' for Mopra)
 - NB: the gamma-ray resolution is worse than the poorer CO I 2 resolution, so more realistic predictions might still be a significant improvement for the gamma ray gas modeling



CONSTRAINTS FROM DSPHS AND FUTURE PROSPECTS/TELESCOPES

Current dwarf spheroidal (dSphs) constraints from Fermi LAT are in tension with the excess but don't rule it out

- Excesses at $2-3\sigma$ for some dSphs are still present. compatible with a DM particle mass of 100-200 GeV for annihilation into $b\bar{b}$

Future experiments, if realized (e.g. Advanced Particle-astrophysics Telescope, **APT**) might be able to detect the excess or rule it out (**~ 10 years after start of operation**)

Alternatively, **need 10-15 more years from Fermi LAT** and > 35 additional dSphs (e.g. from LSST)

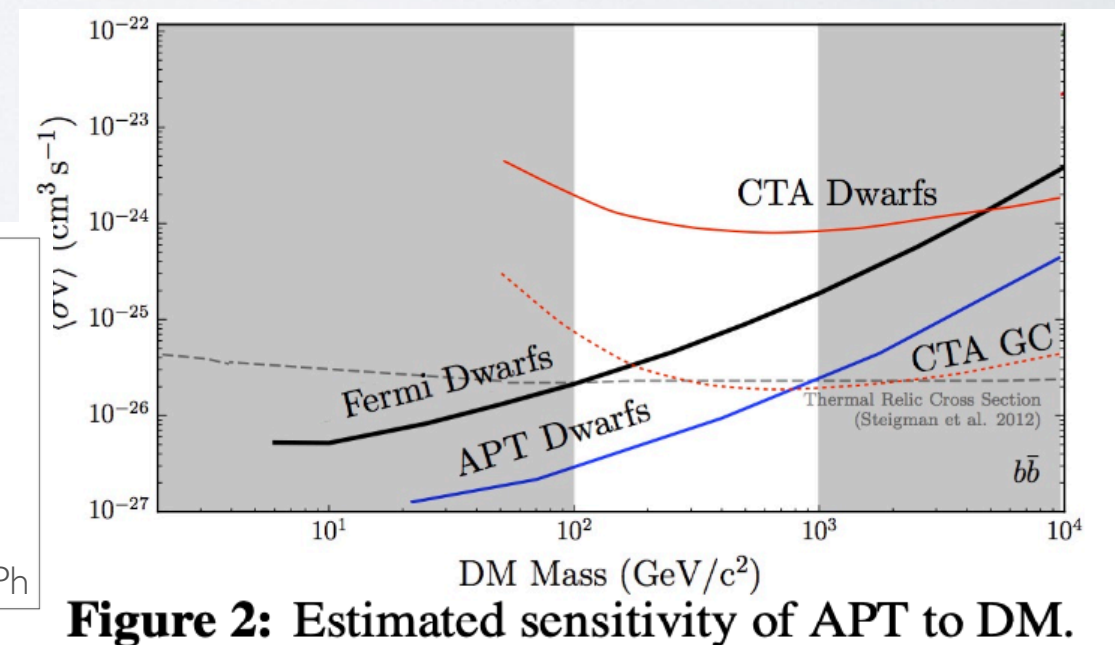
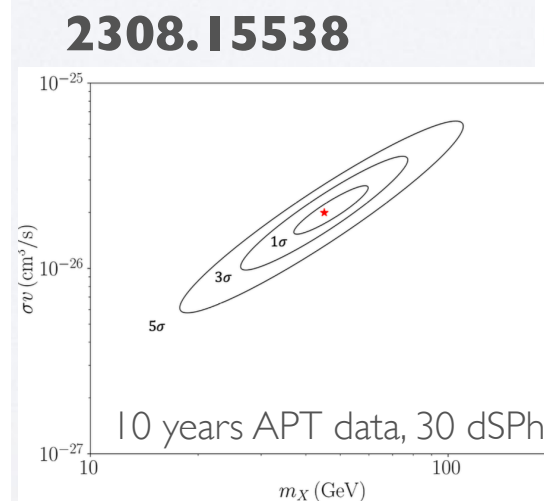
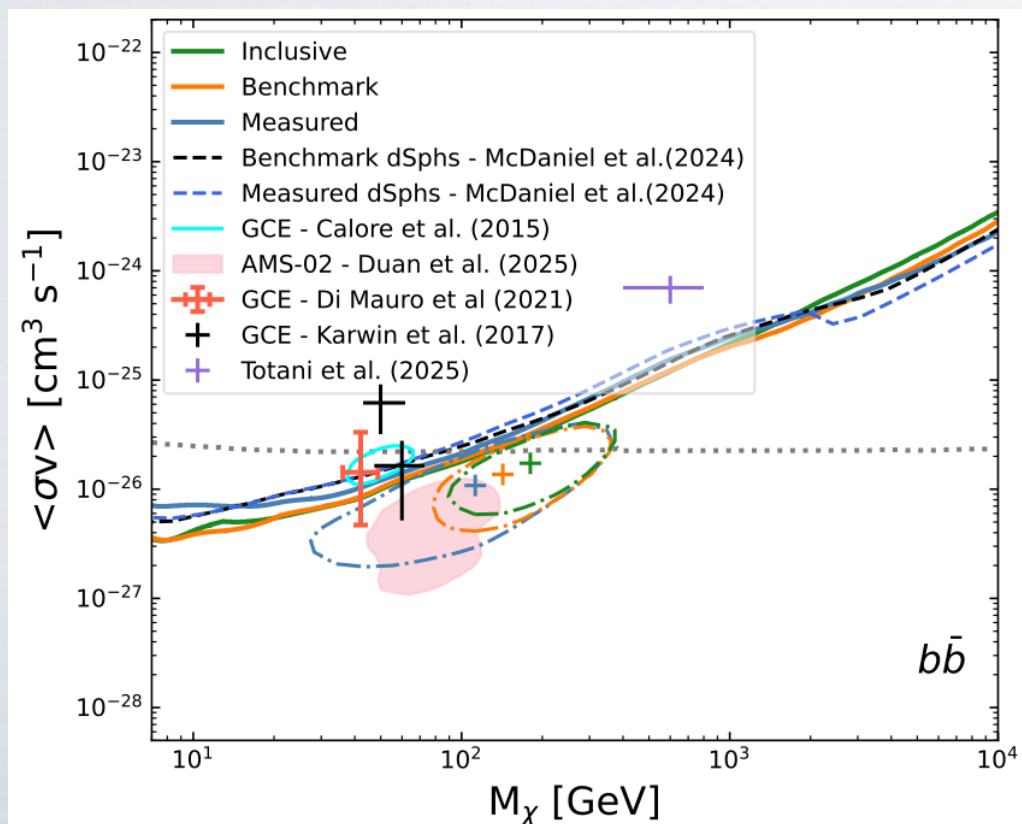
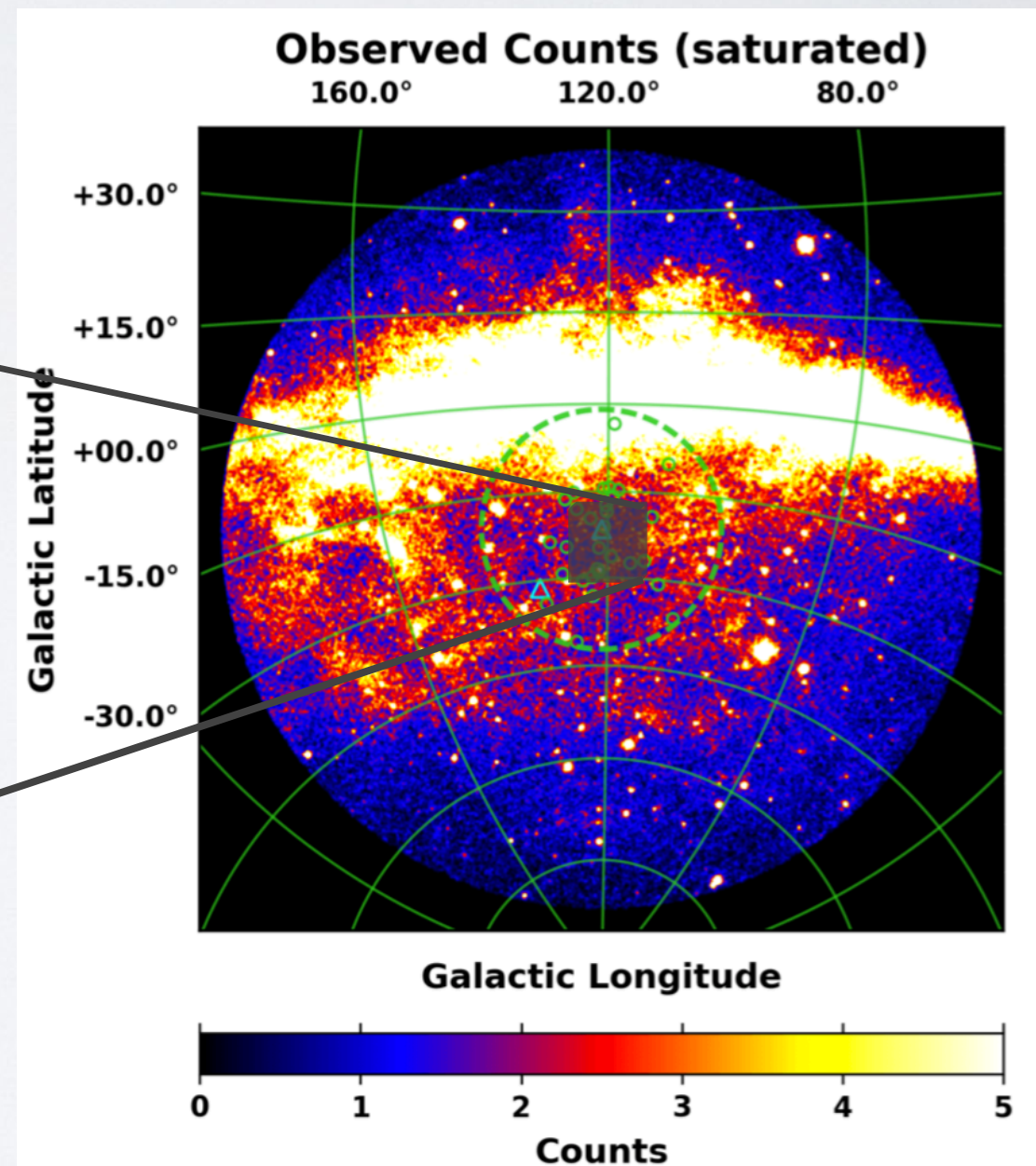
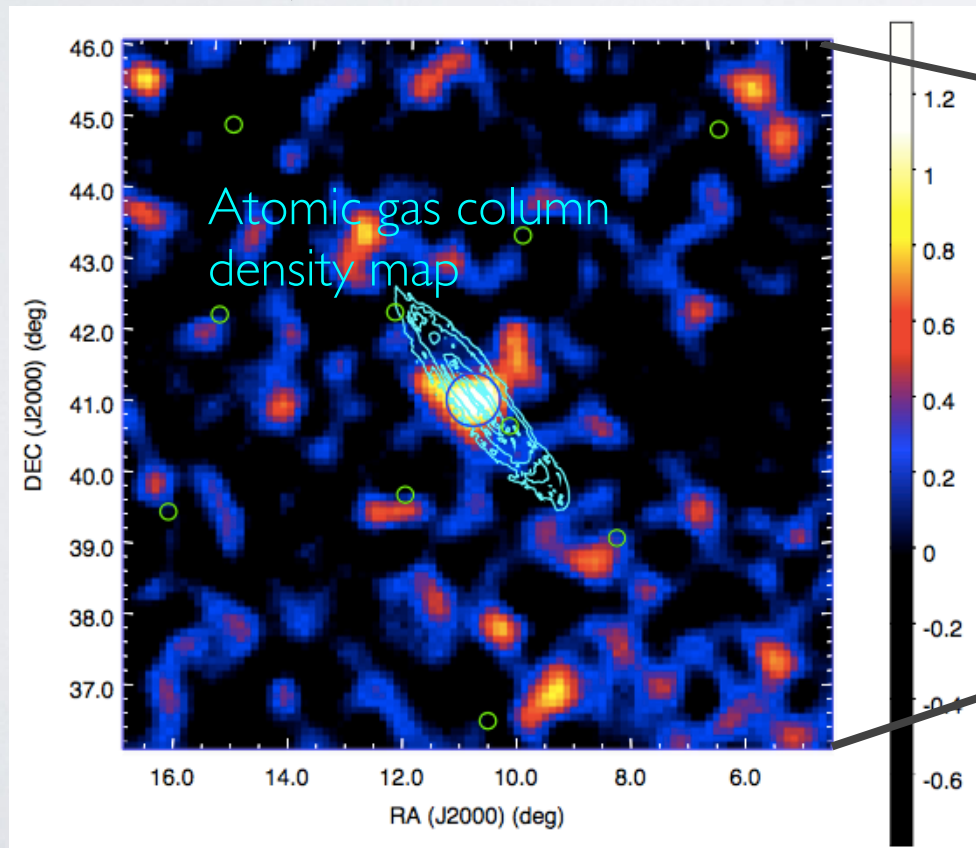


Figure 2: Estimated sensitivity of APT to DM.

ANDROMEDA (M31)

- **M31 DM halo extends several degrees across the sky ($\sim 40^\circ$ 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, $\sim 1^\circ$ 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

- We searched for extended γ -ray beyond the galactic disk of M31 ($\sim 40^\circ$ for a DM halo 600 kpc across.)

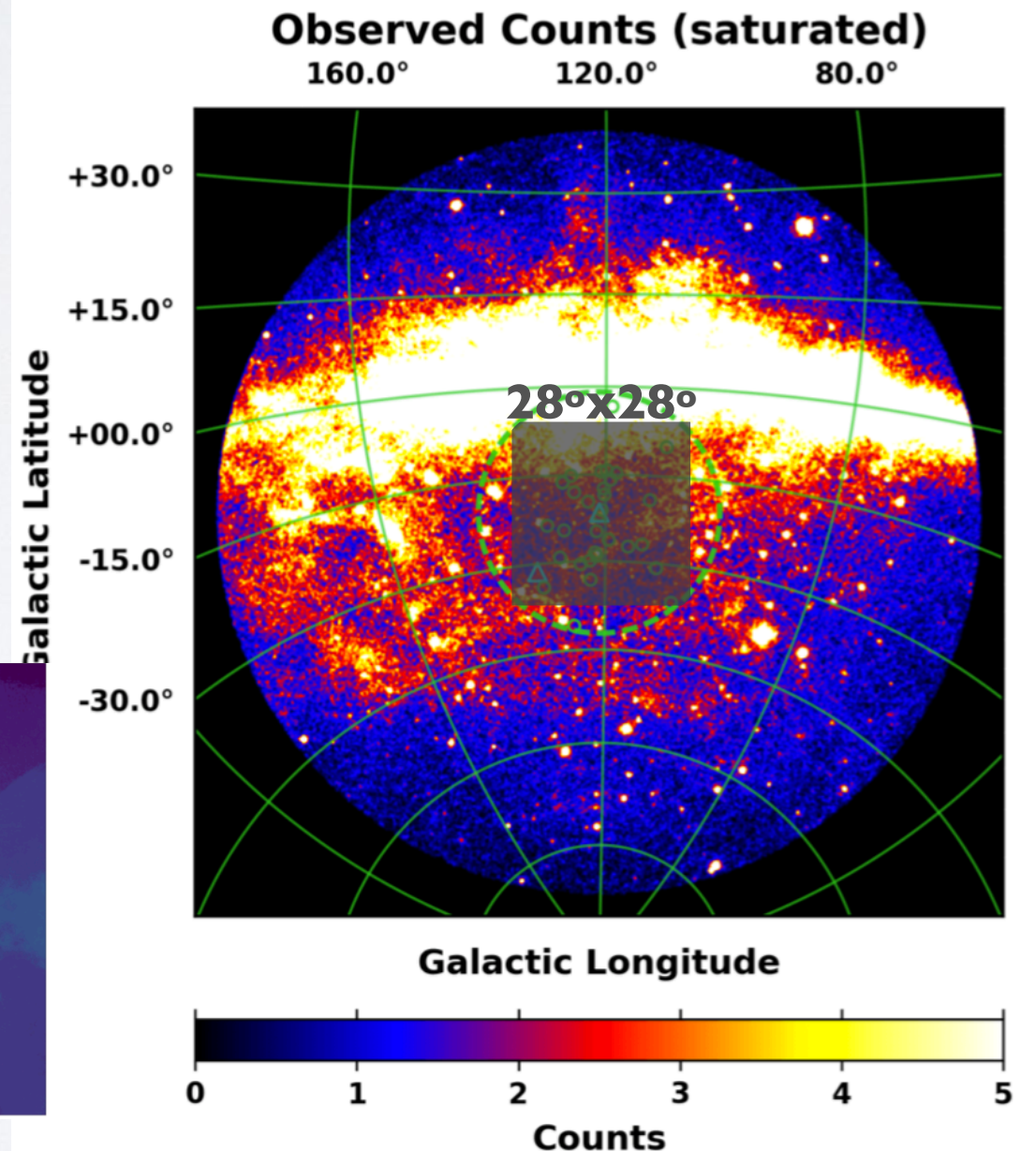
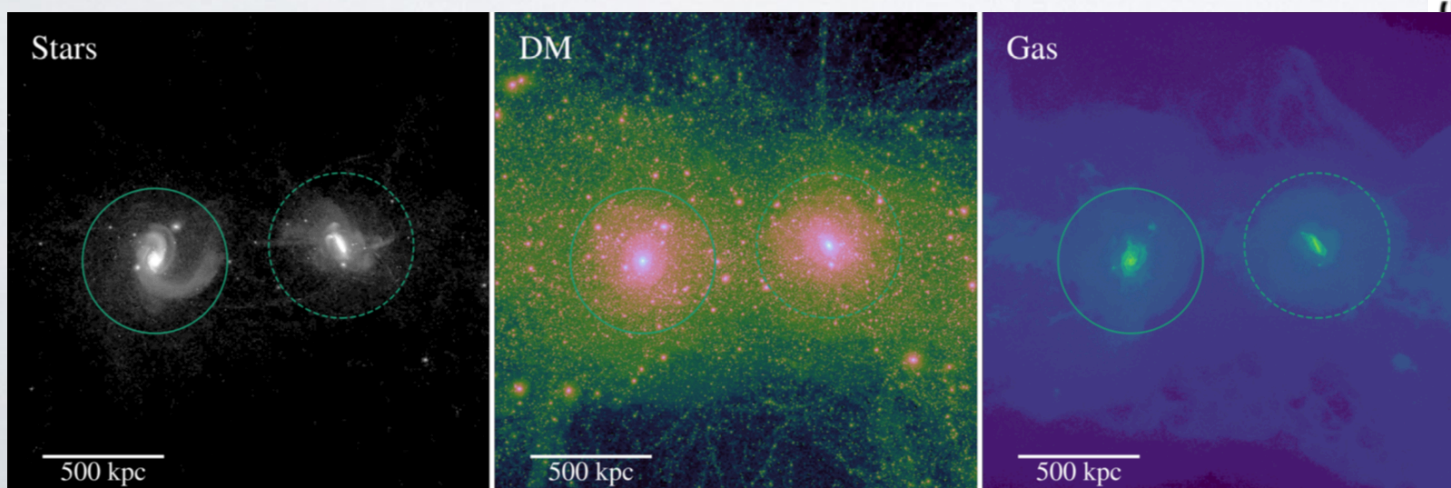
Implications for DM and cosmic rays

- 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**

- NB: DM component in line of sight towards M31 includes M31 halo, MW halo, and possibly local DM filament

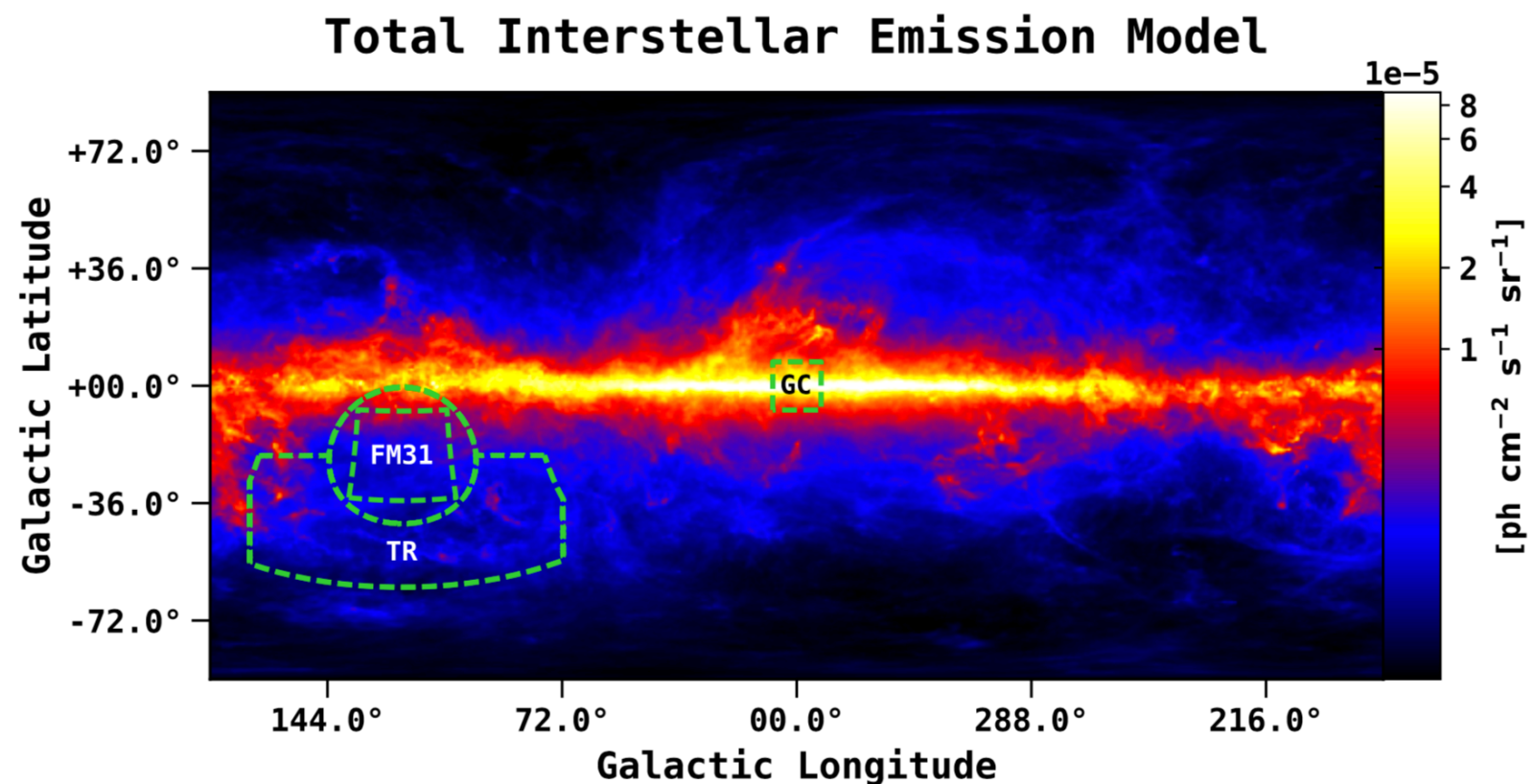
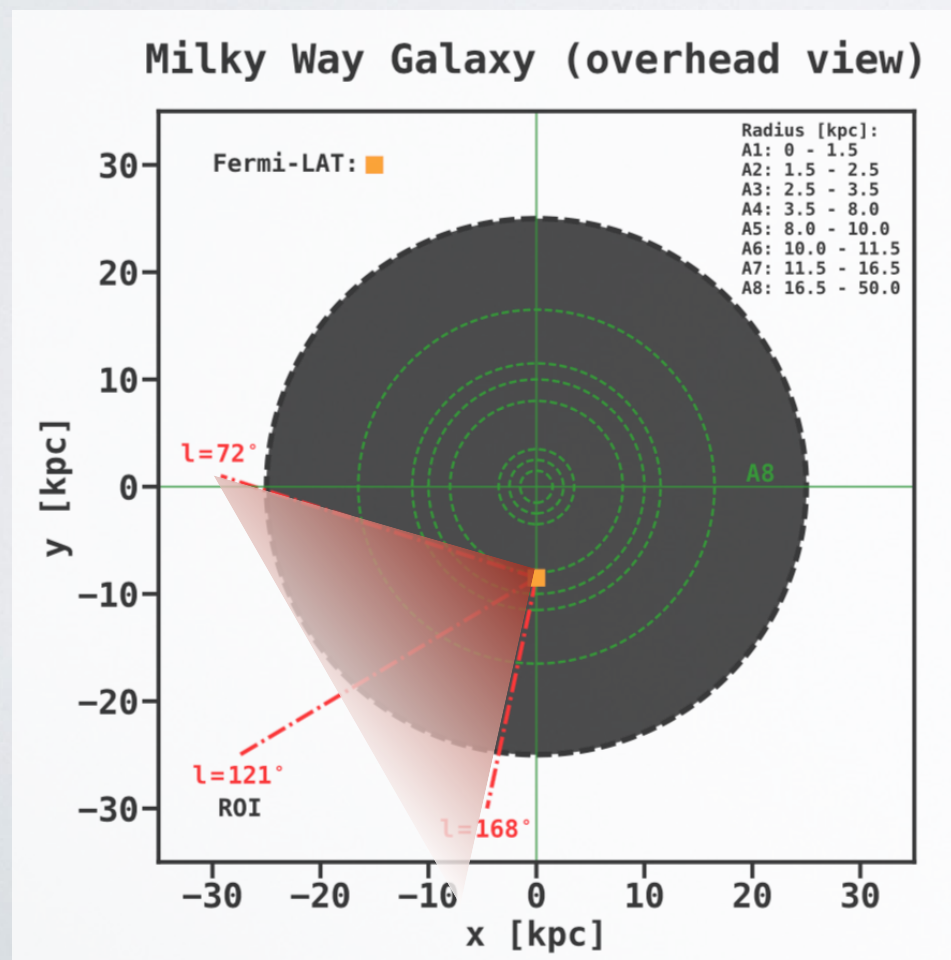
Garrison-Kimmel et al, arXiv:1806.04143



FOREGROUND MODELING

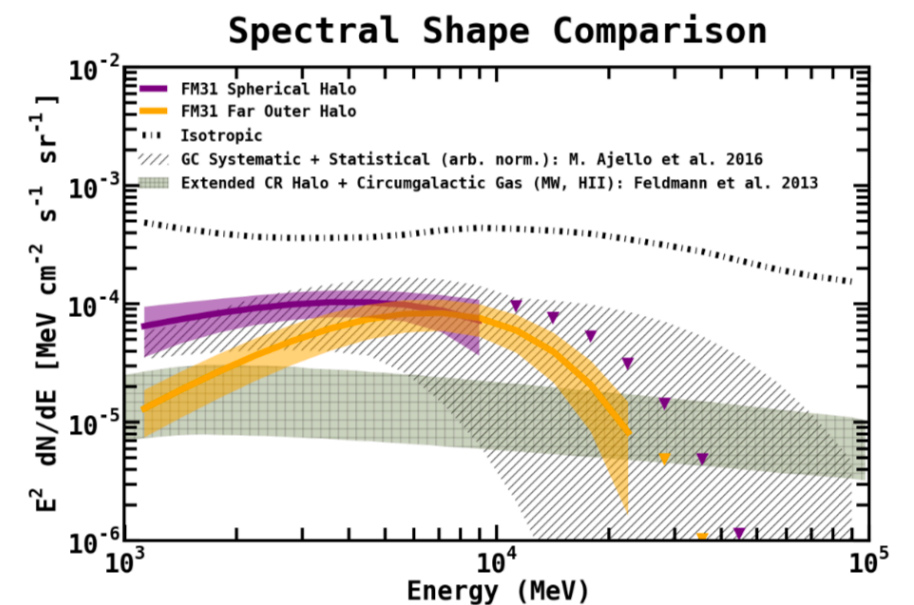
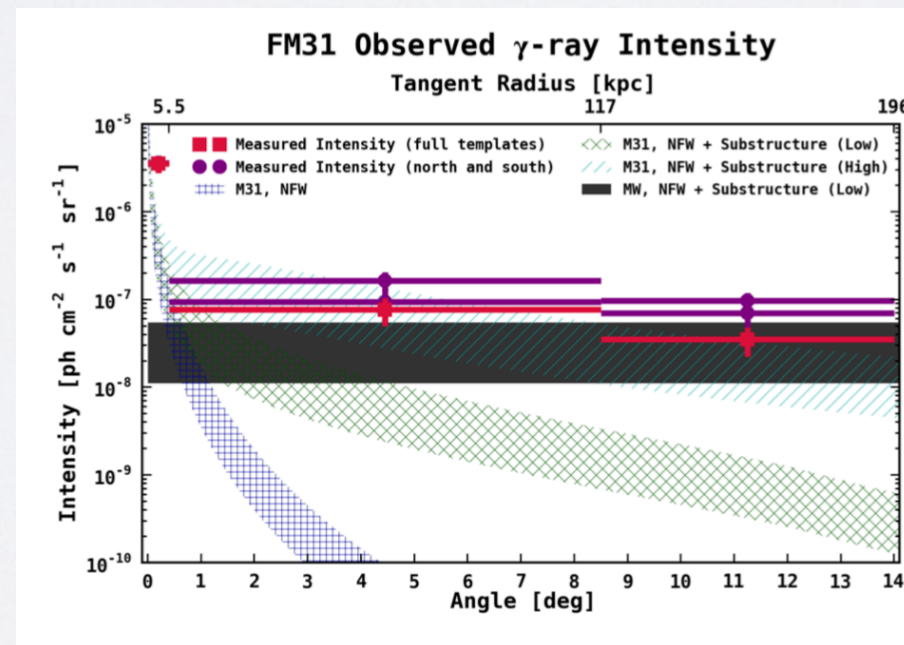
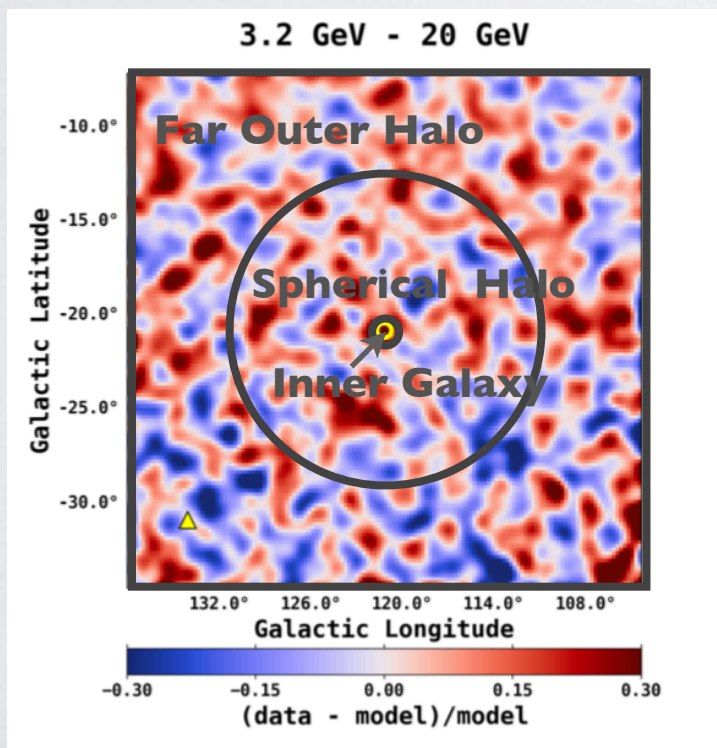
- Caveat: disentangle a potential M31 extended signal from the foreground γ -ray emission from the MW
- We build specialized models (using the GALPROP cosmic ray propagation code) for this emission, tuning them to regions away from M31 (tuning region TR)

Signal region: FM31
Tuning region: TR



ANDROMEDA EXCESS

- We find robust evidence for a significant extended excess in the Fermi LAT data from the direction of Andromeda (Karwin, SM, et al, arXiv:1903.10533)
- The excess significantly decreases outside of the Andromeda region and appears to be distinct from the Milky Way foreground
- The extension is upwards of 120-200 kpc from the center and it has a distinct spectrum that peaks in the 3-20 GeV energy range
- Annihilating DM provides a good description of the extended emission and is consistent with the GC excess dark matter interpretation, though it requires a large substructure contribution to explain the full signal.



CONCLUSIONS

- Gamma ray observations continue to provide very strong and important constraints on dark matter
- Observations of the Local Group by Fermi LAT yielded crucial results to constrain dark matter properties and unveiled intriguing excesses
 - ➡ The jury is still out on the origin of the GC excess: an independent detection of a consistent dark matter signal from another target or of the pulsars could settle it
 - ▶ Alternatively, an instrument that significantly improves over Fermi LAT in the GC excess energy range would likely settle its origin
 - ▶ In the meanwhile, improving models of the Galactic gamma-ray emission might shed light on smooth vs point-like nature of the excess
- Andromeda is a complementary target to these searches: an extended excess in the Fermi LAT data from the direction of Andromeda which appears to be distinct from the Milky Way, out to ~ 120 -200 kpc from Andromeda's center, is still present and its origin not conclusively understood
 - Annihilating dark matter provides a good description of the extended Andromeda emission and is consistent with the GC excess dark matter interpretation
- ➡ Better understanding of the systematic and complementarity with other dark matter searches is crucial to interpret these excesses
- Observations from upcoming optical surveys that probe the distribution of dark matter could also add extremely valuable information (or a discovery!) in unveiling the nature of dark matter

Thank you!