INDIRECT DARK MATTER SEARCHES WITH γ-RAYS

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University of Washington Seattle
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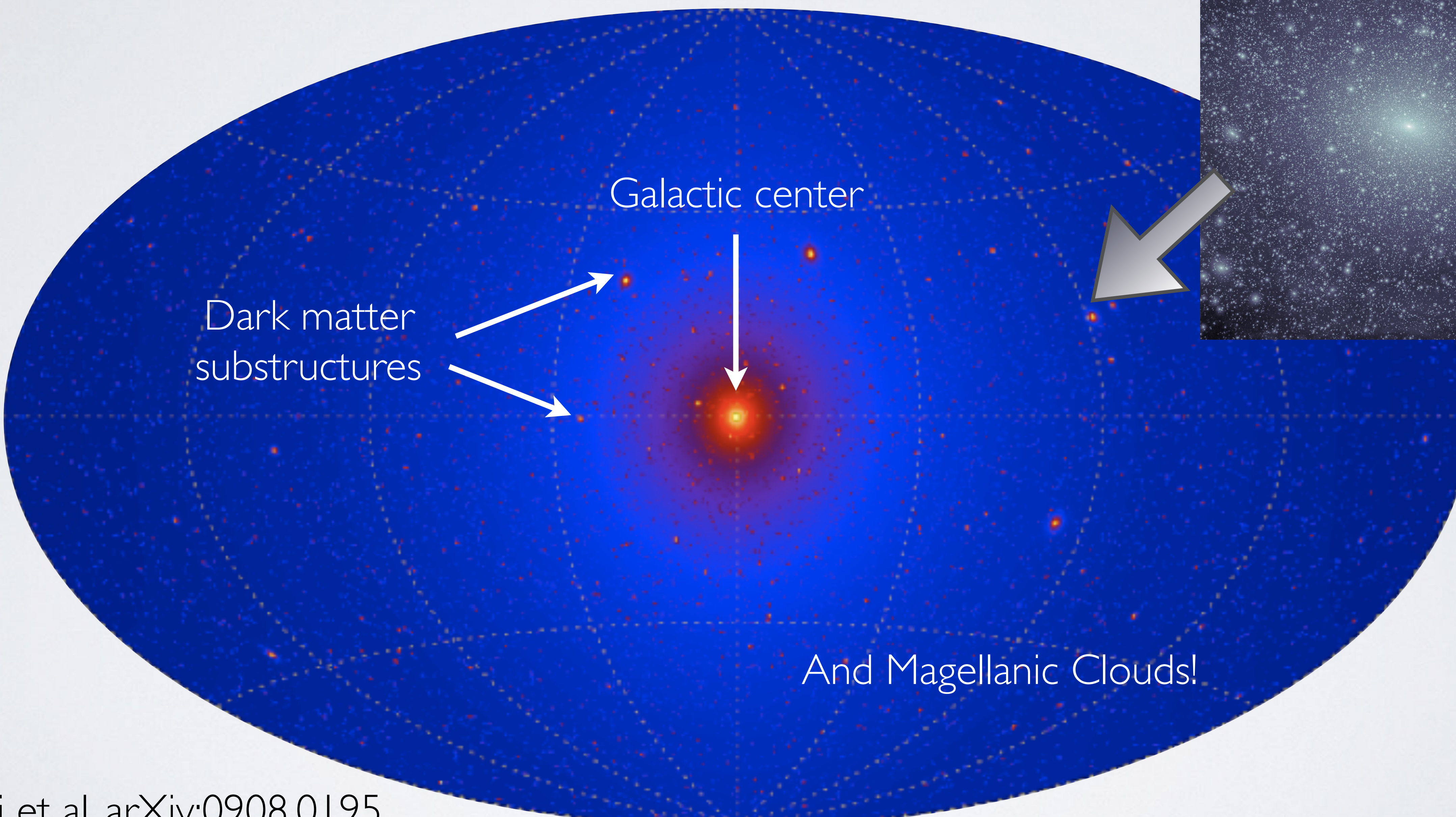
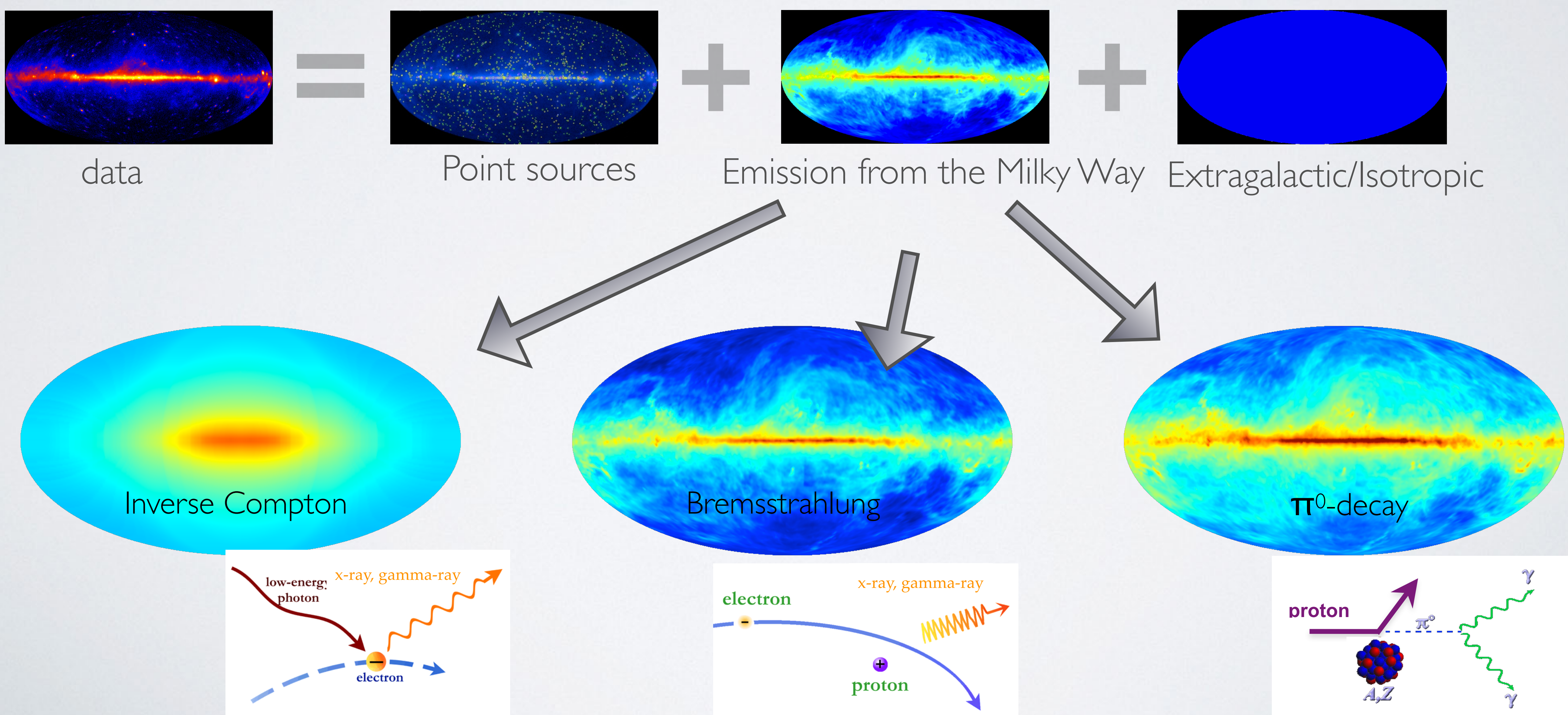
GAMMA RAYS FROM DM ANNIHILATION: MILKY WAY AND ITS SATELLITES



Pieri et al, arXiv:0908.0195

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!



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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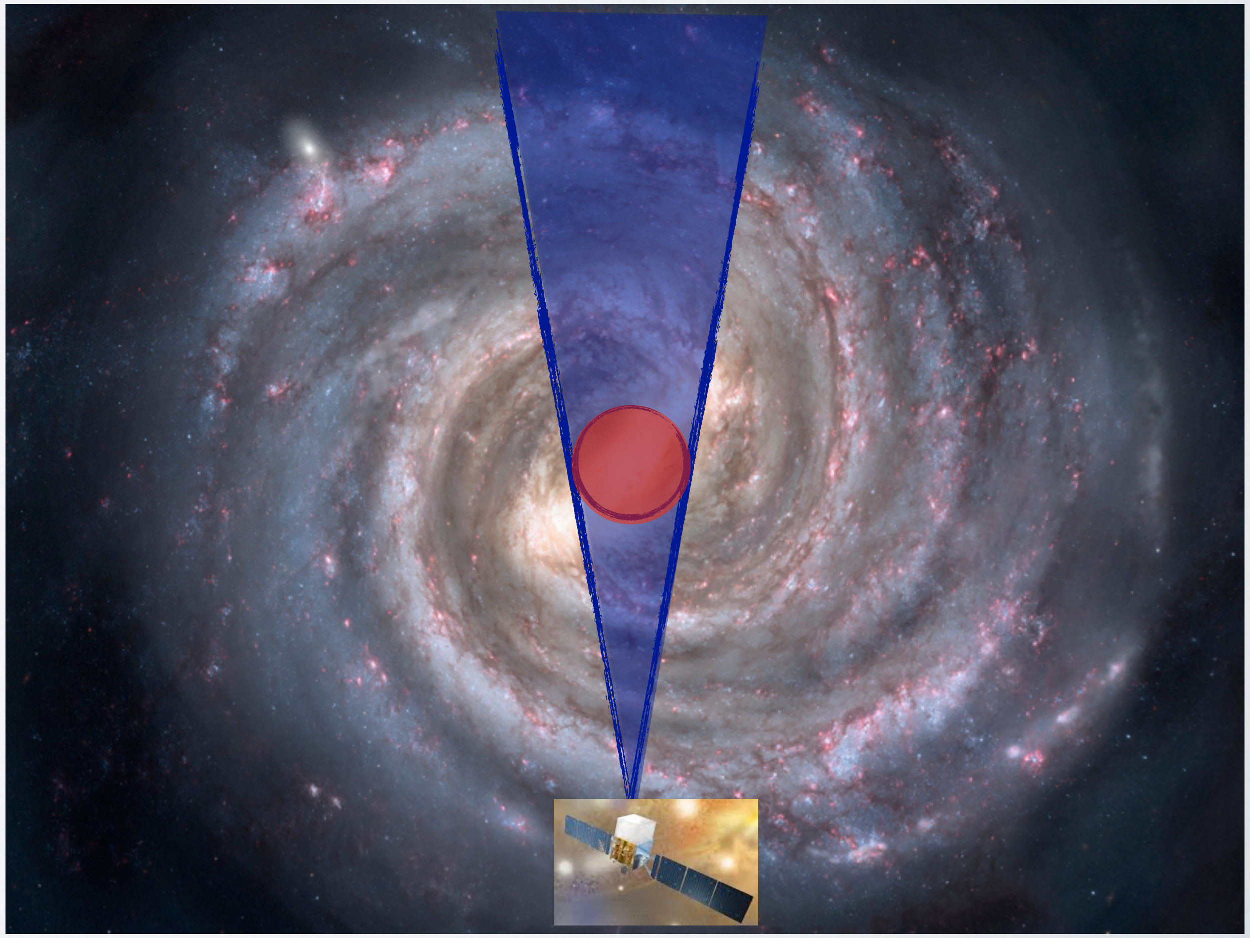

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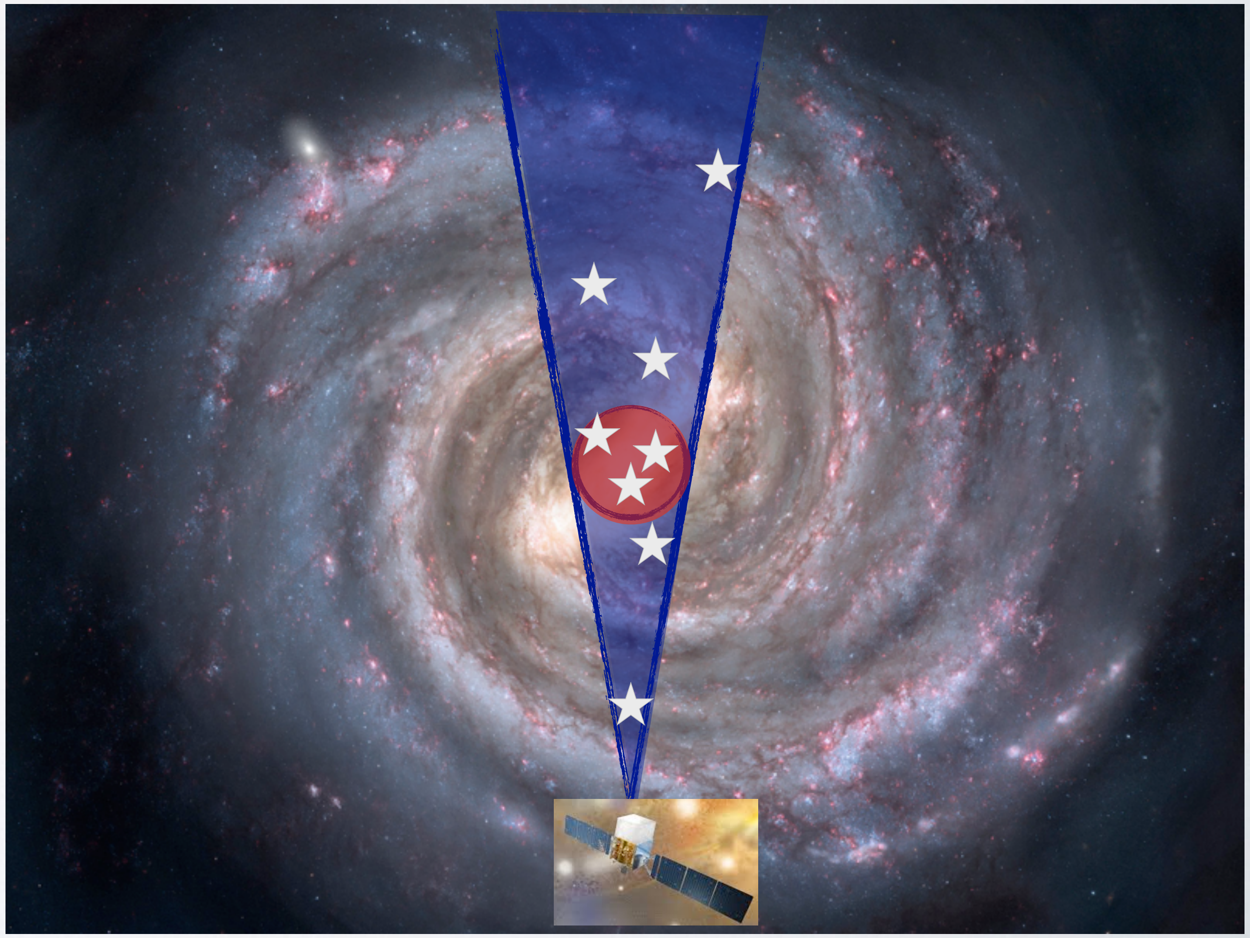

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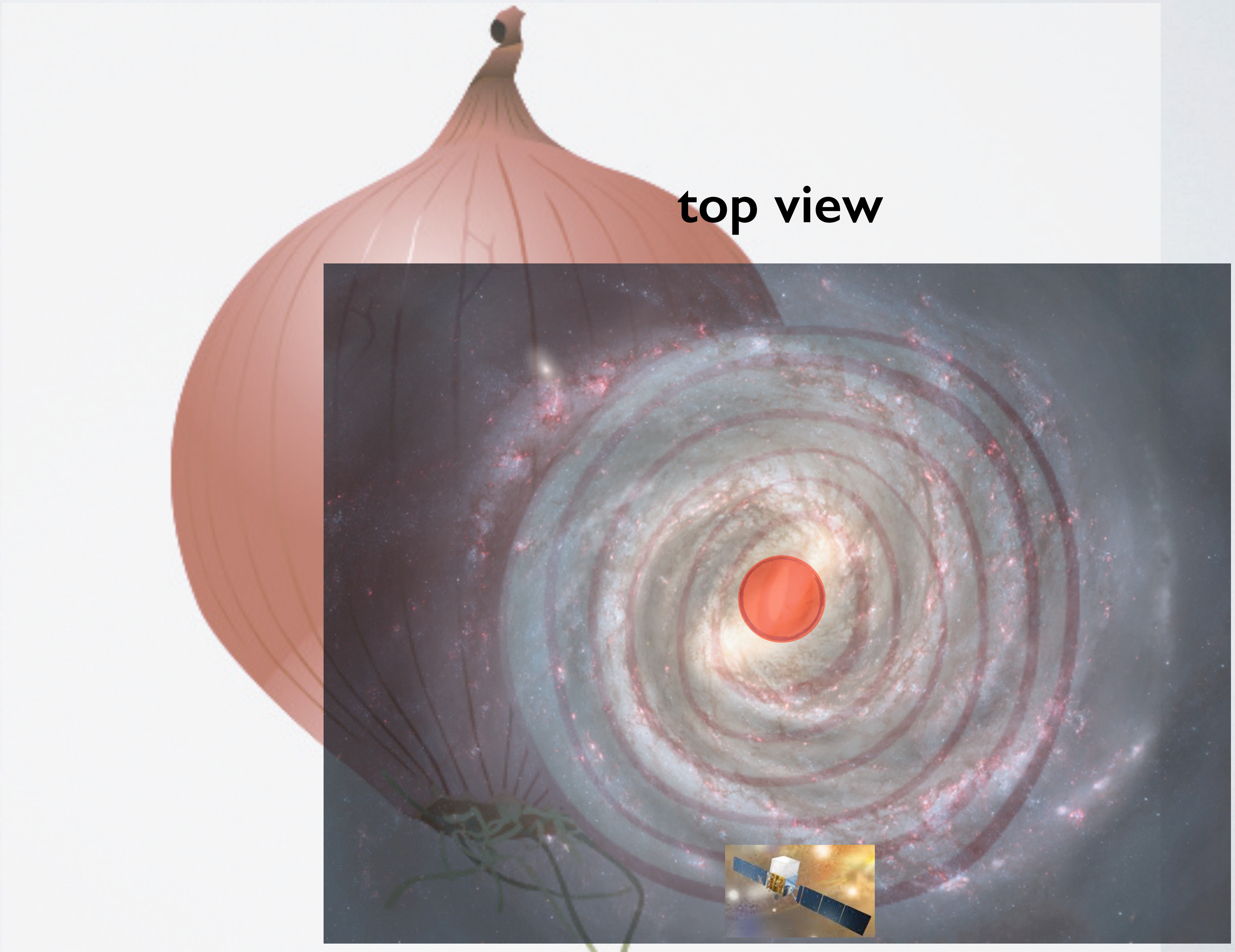
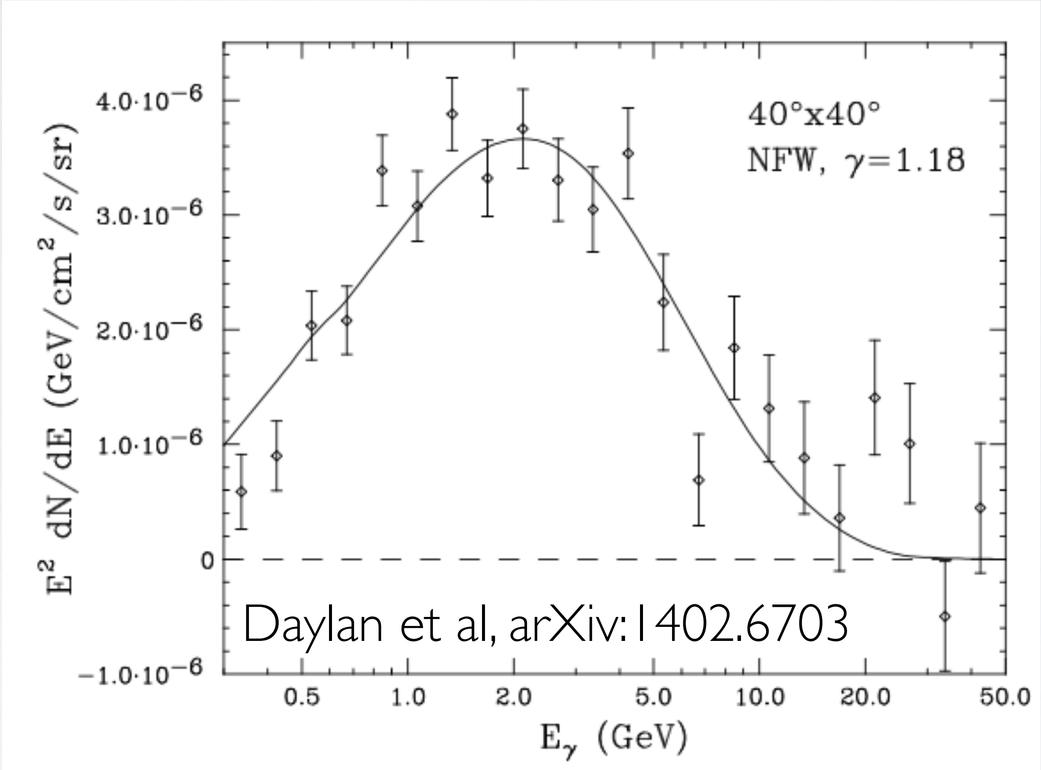
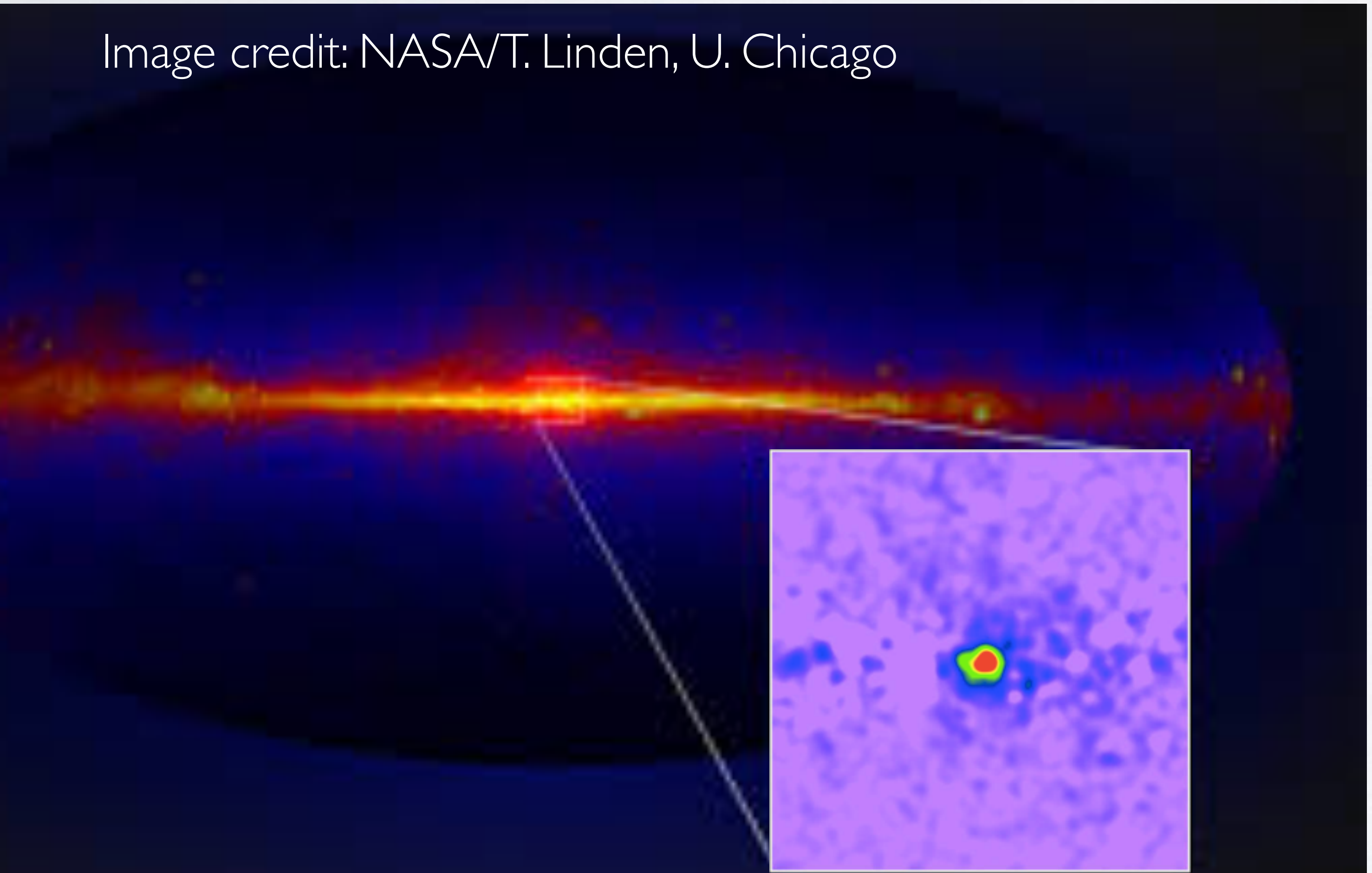
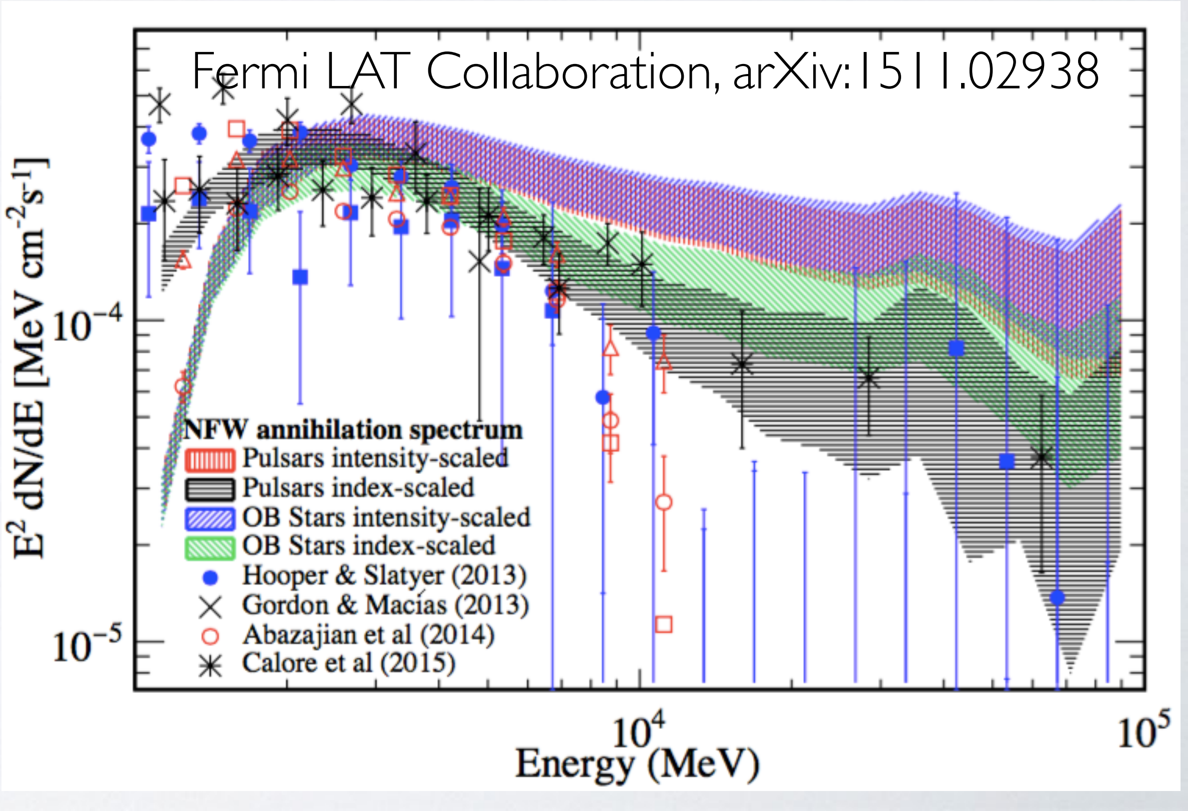


A DARK MATTER SIGNAL FROM THE GALACTIC CENTER?

- 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!***

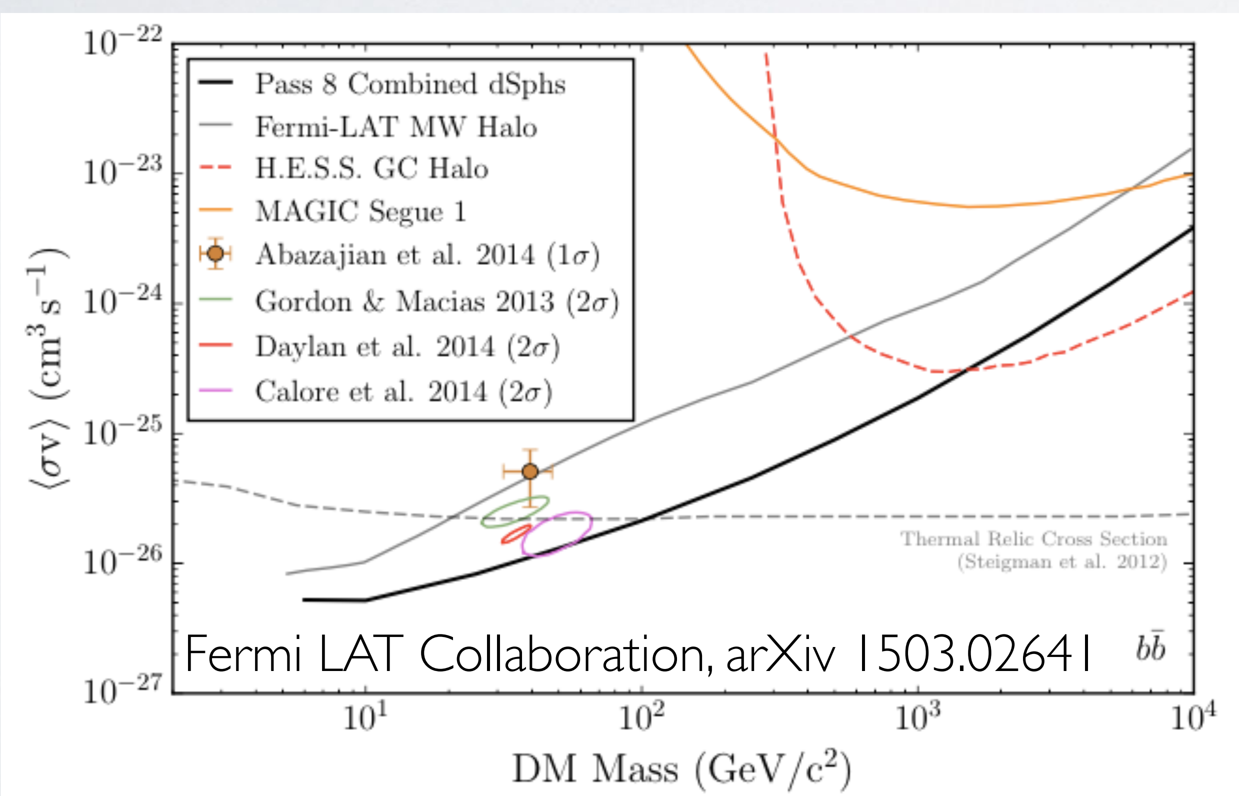






INTERPRETATIONS

- 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.
  - ➡ DM substructures (dwarf spheroidal galaxies) limit the DM interpretation of the GC excess, but don't rule it out



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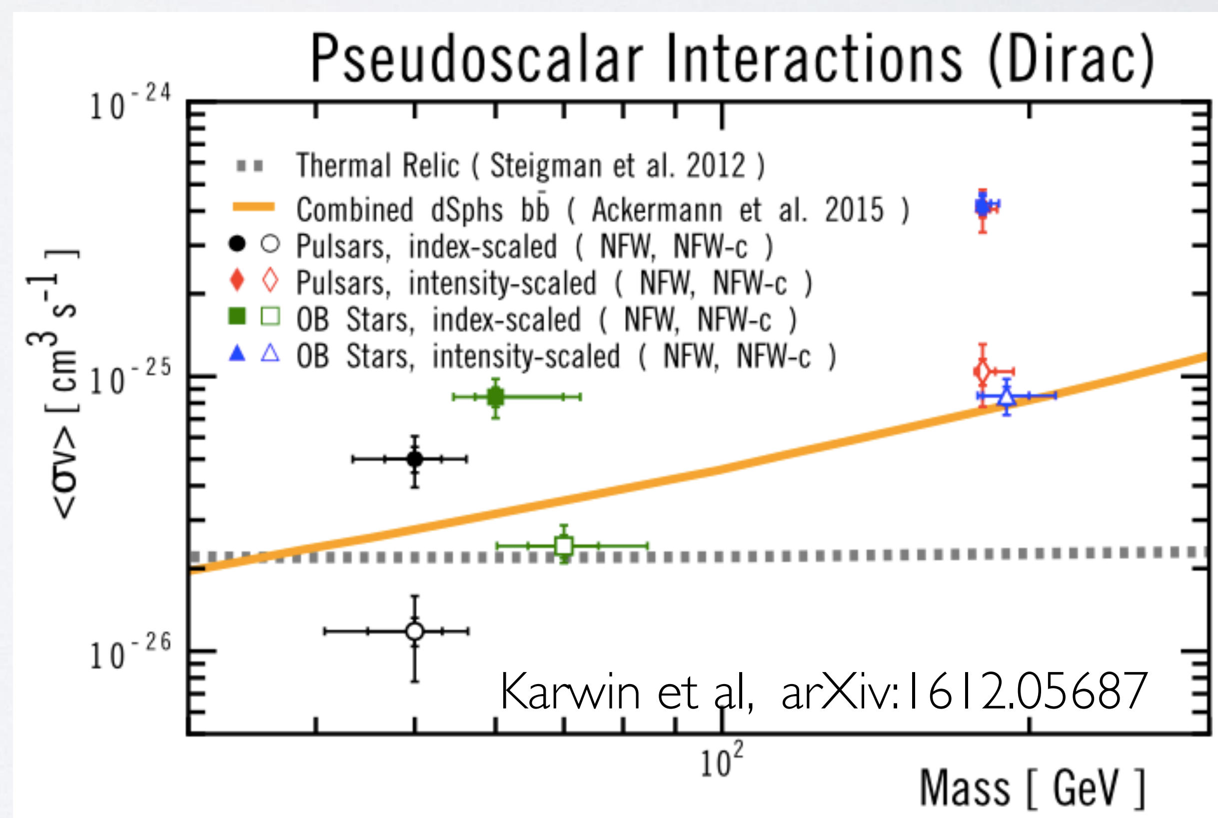

Karwin et al, arXiv:1612.05687

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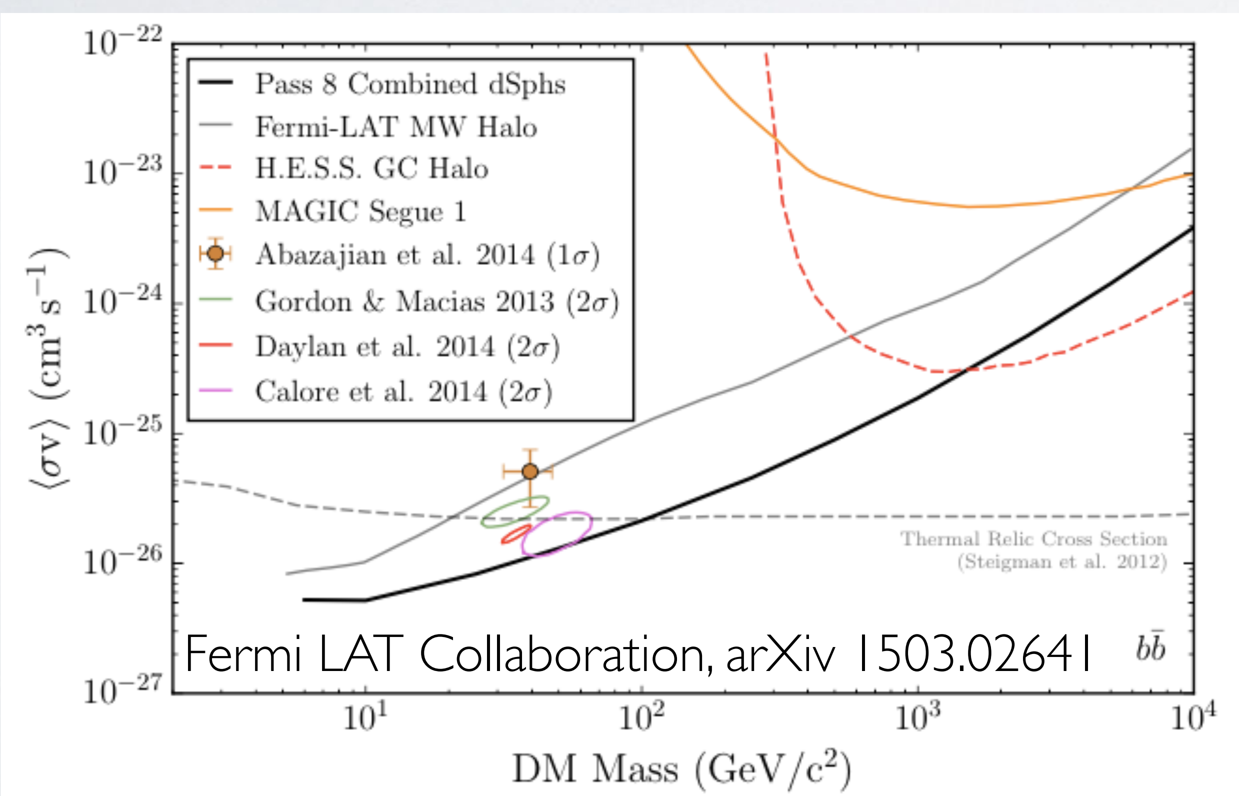

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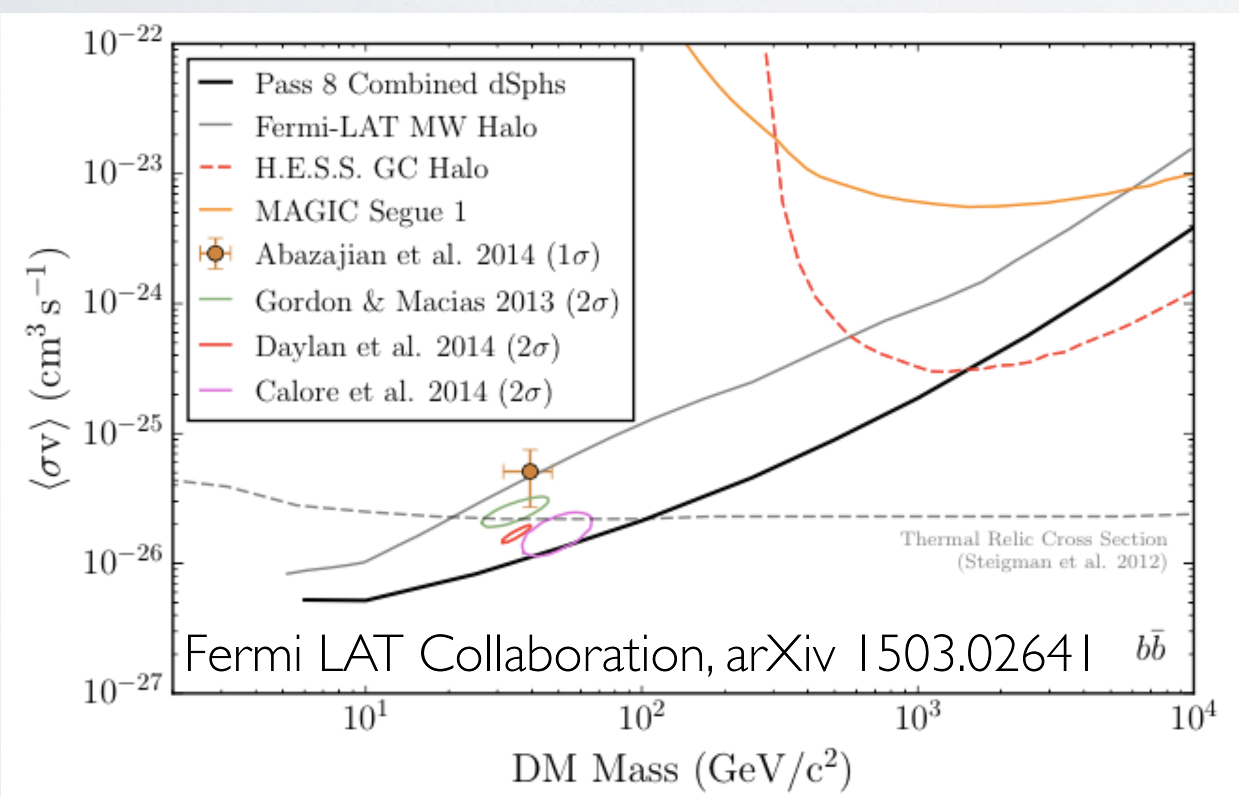

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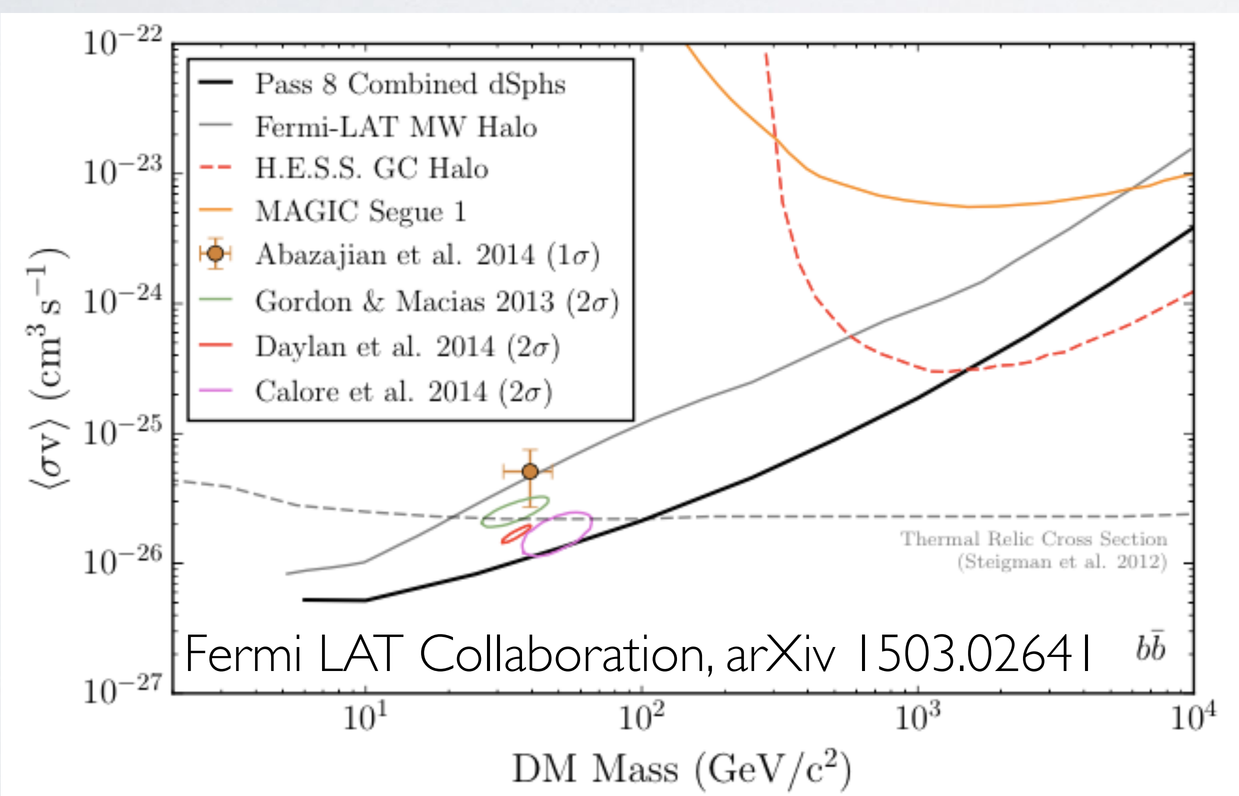

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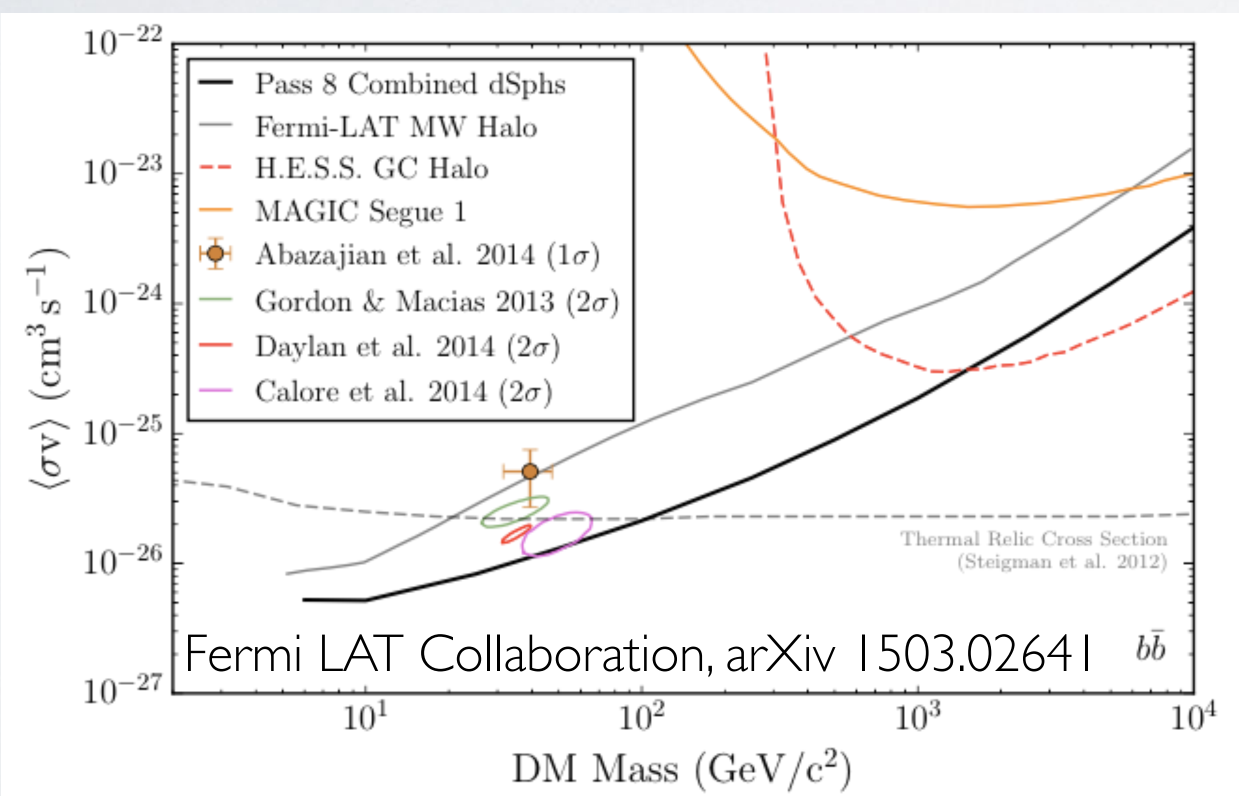

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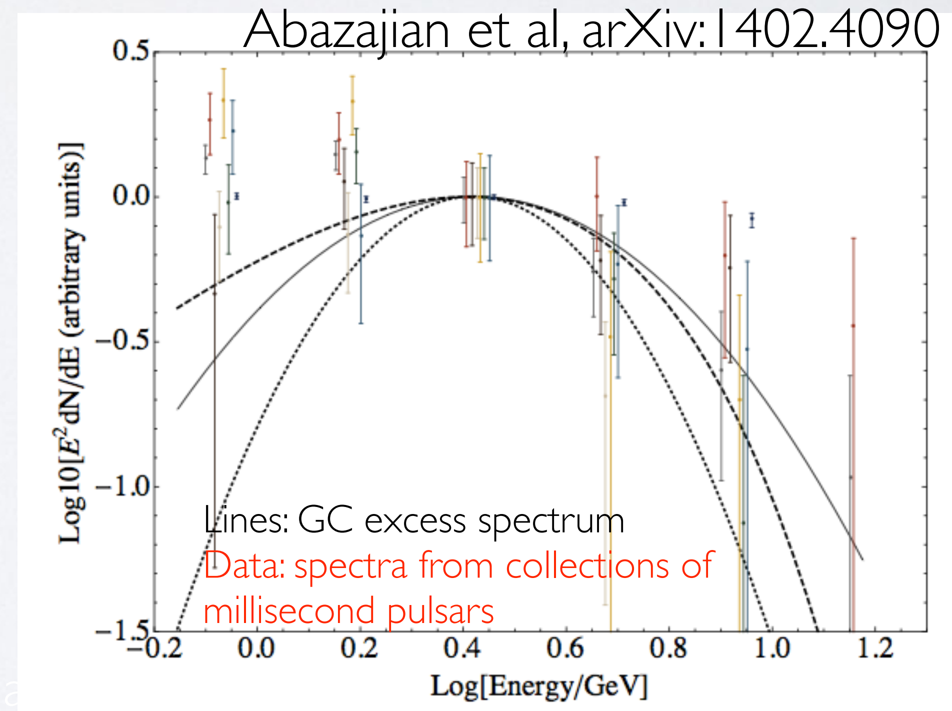

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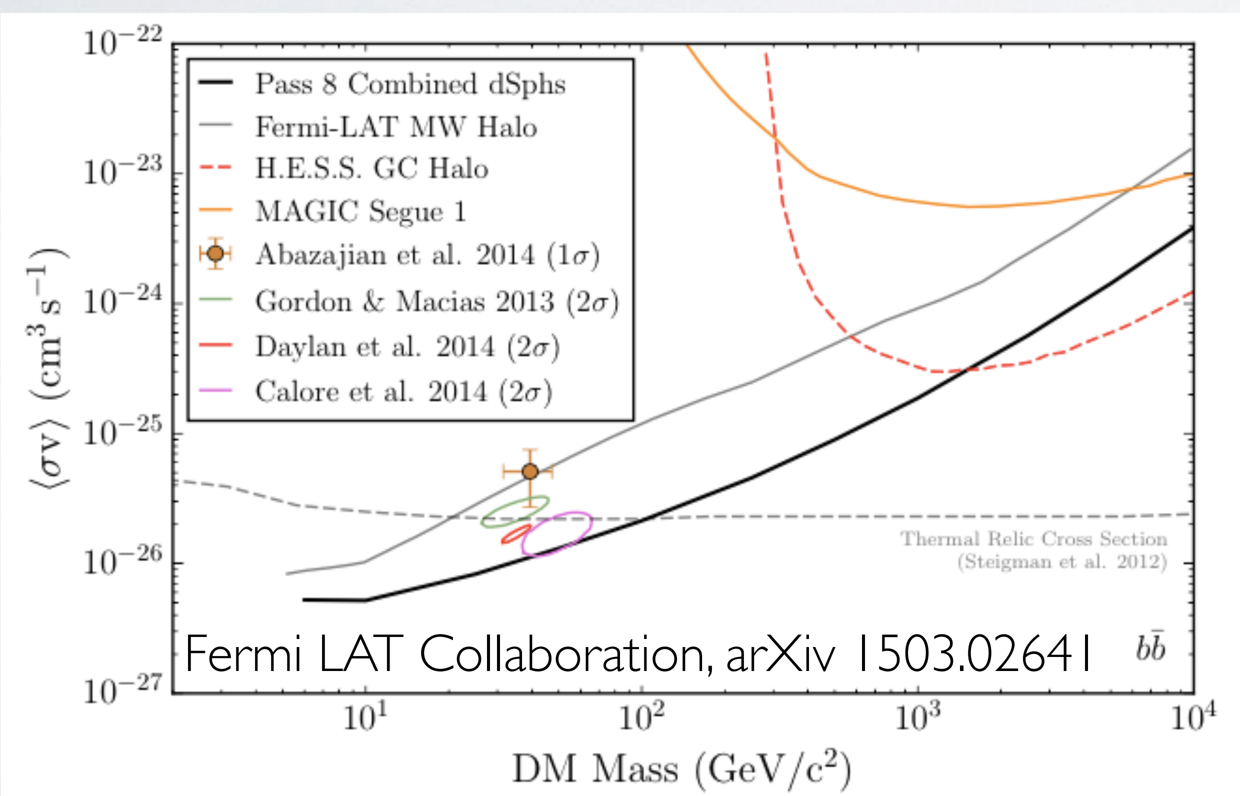

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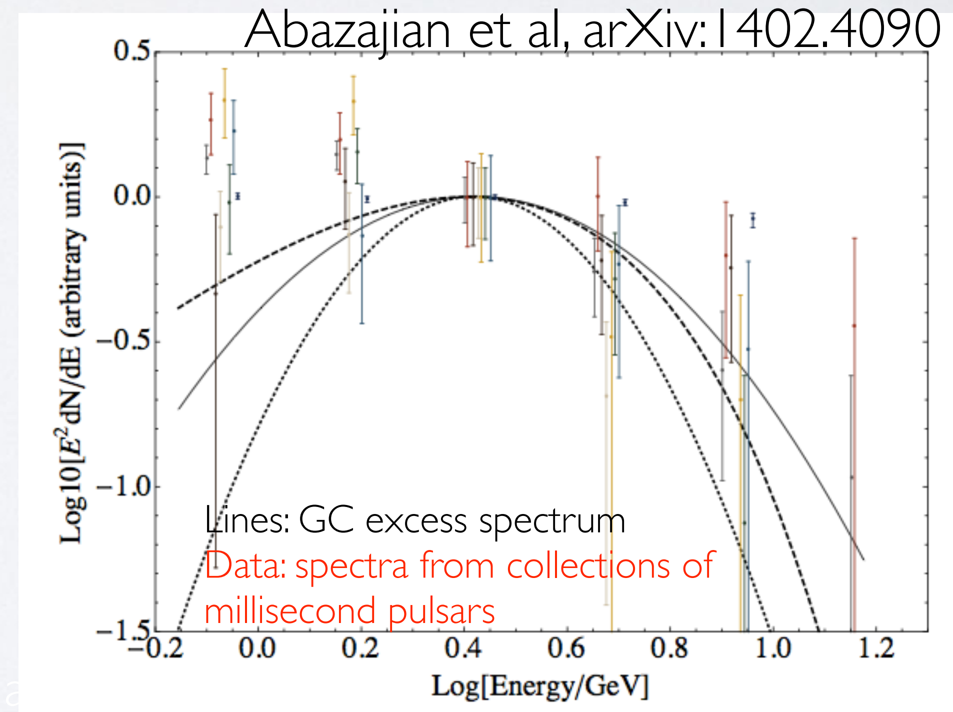

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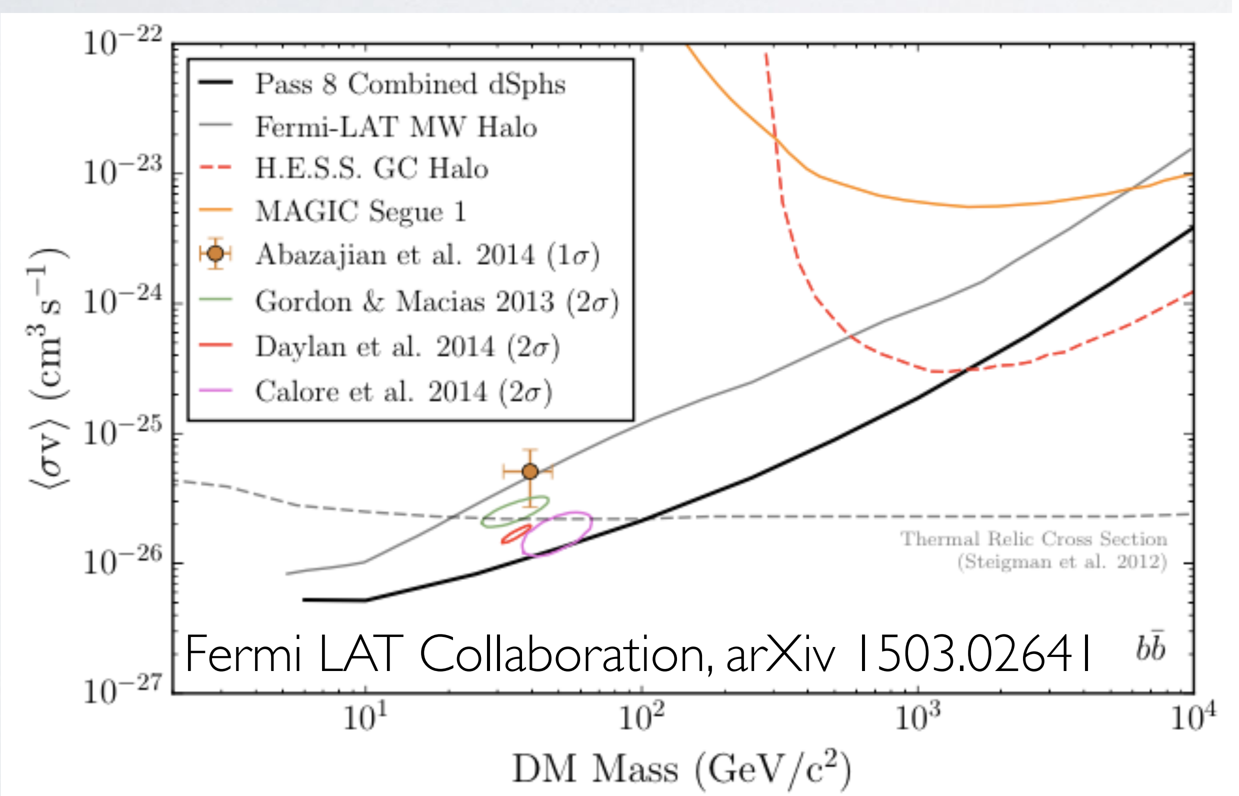

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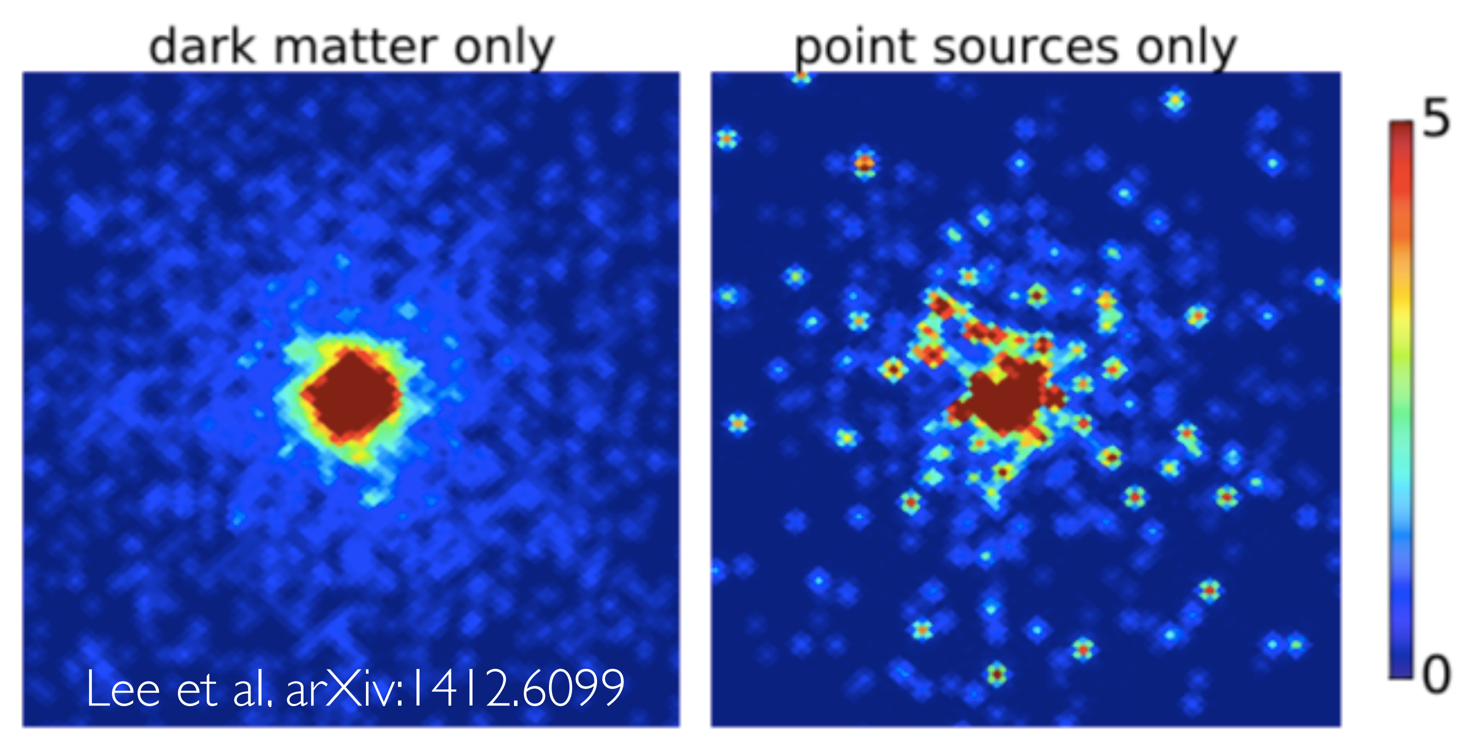

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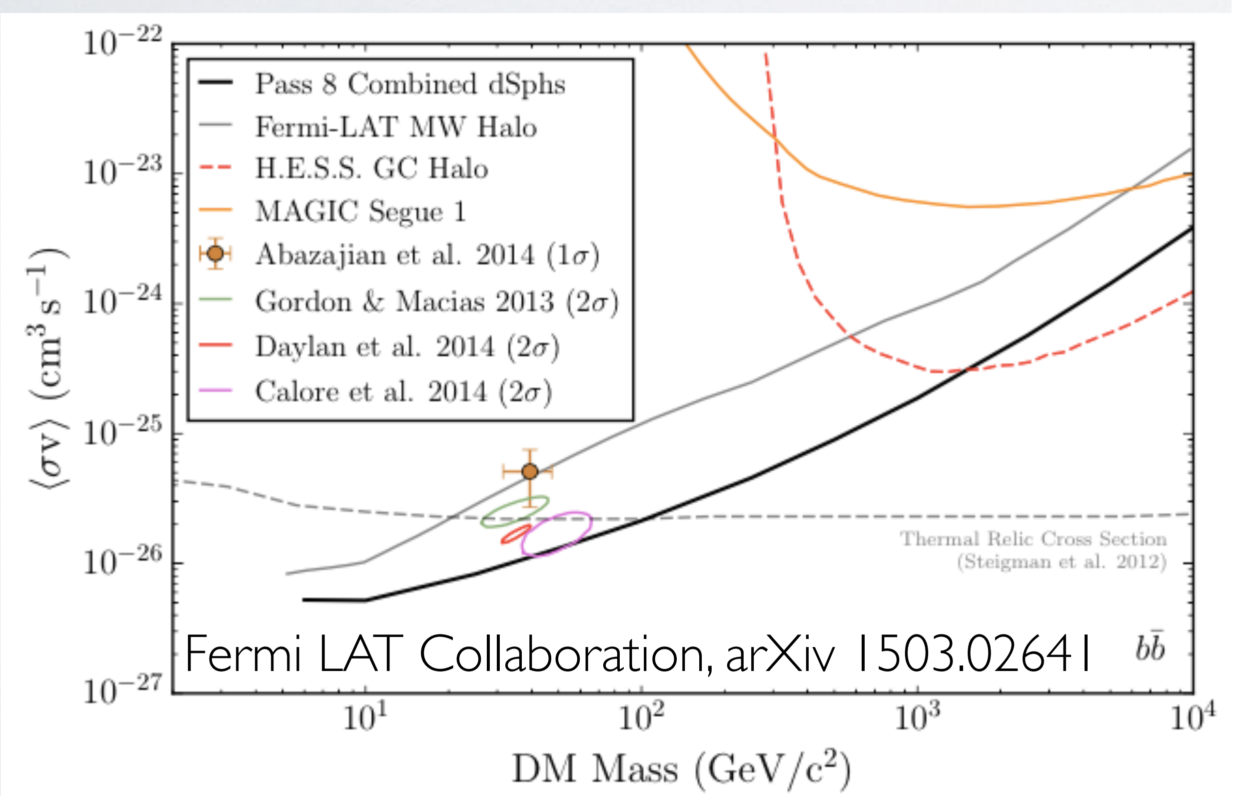
  ➡ **However recent analyses challenge this conclusion (Balaji et al, arXiv:1803.01952 and more recently Leane&Slatyer, arXiv:1904.08430)**



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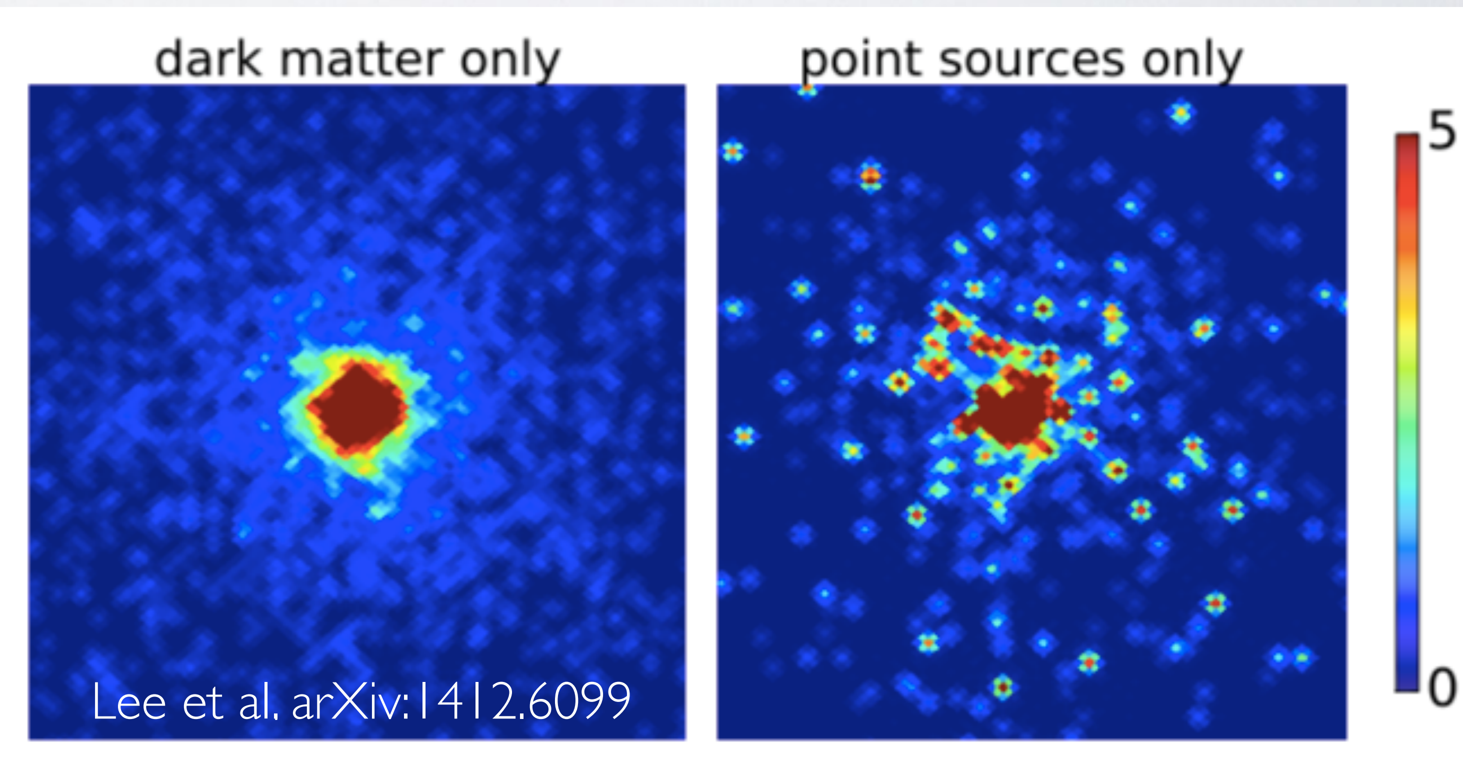

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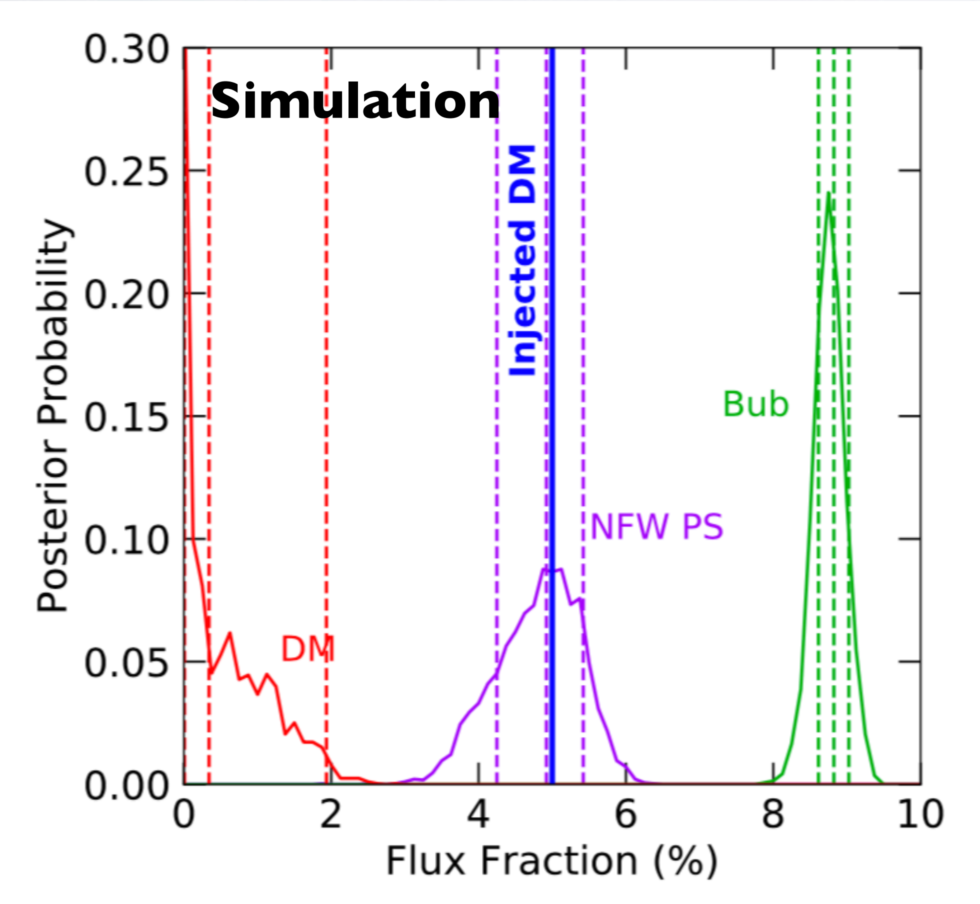
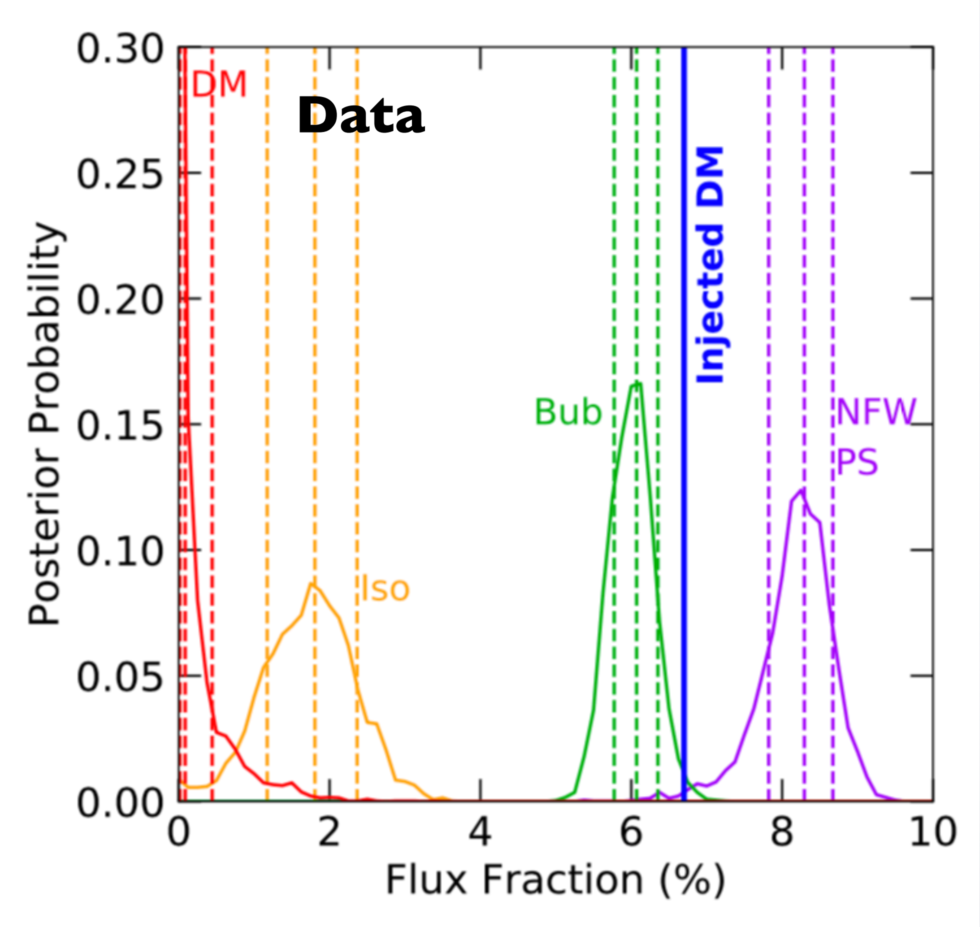
"DARK MATTER STRIKES BACK"

Leane&Slatyer, arXiv:1904.08430

- Test the performance of non-poissonian template fitting in the presence of unmodelled point sources
- Unmodelled point sources could conceal a DM signal!
  - Simulate data including a population of point sources and a GC DM signal, in addition to other components. The DM signal is not recovered if the point sources are mismodeled. The signal is misattributed to point sources instead
  - Inject a GC DM signal into real data. Again, the signal is not recovered and misattributed to point sources instead (unless is very bright, ~10x larger than the GC excess)





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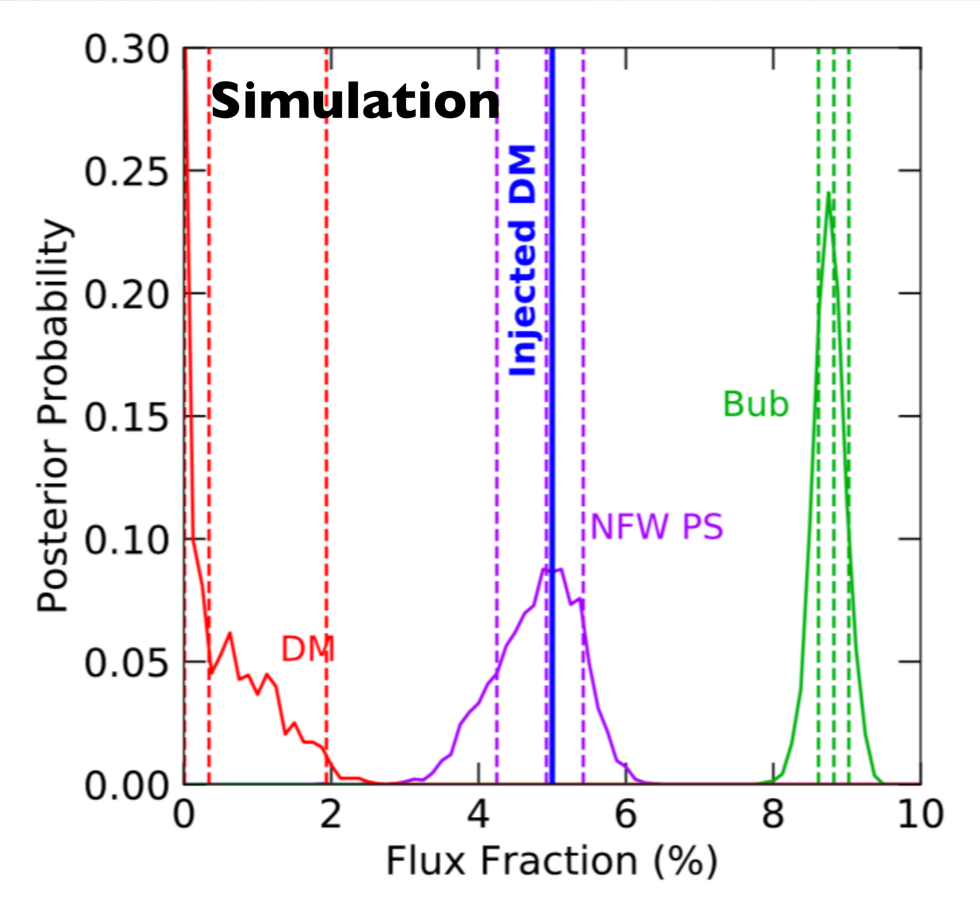
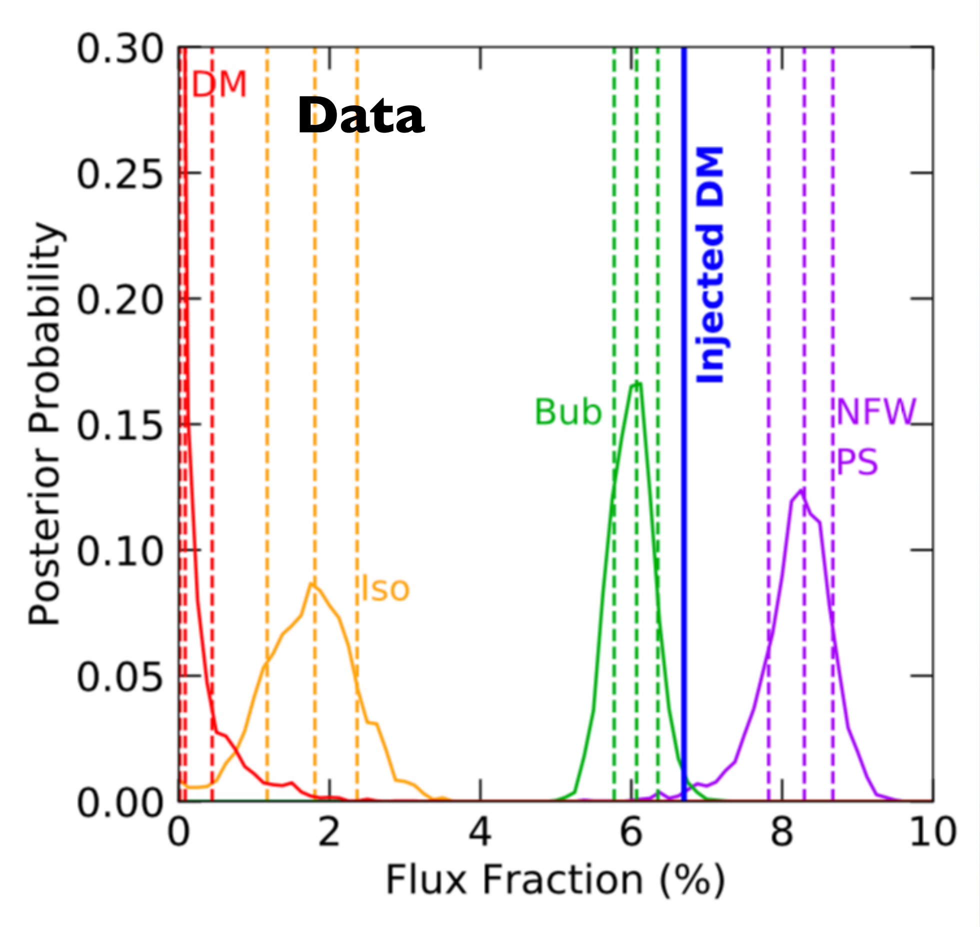
➡ The pulsars must be detected to confirm they generate the GC excess! Crucial is the potential of radio surveys (SKA) to discover millisecond pulsars (Calore et al arXiv:1512.06825)

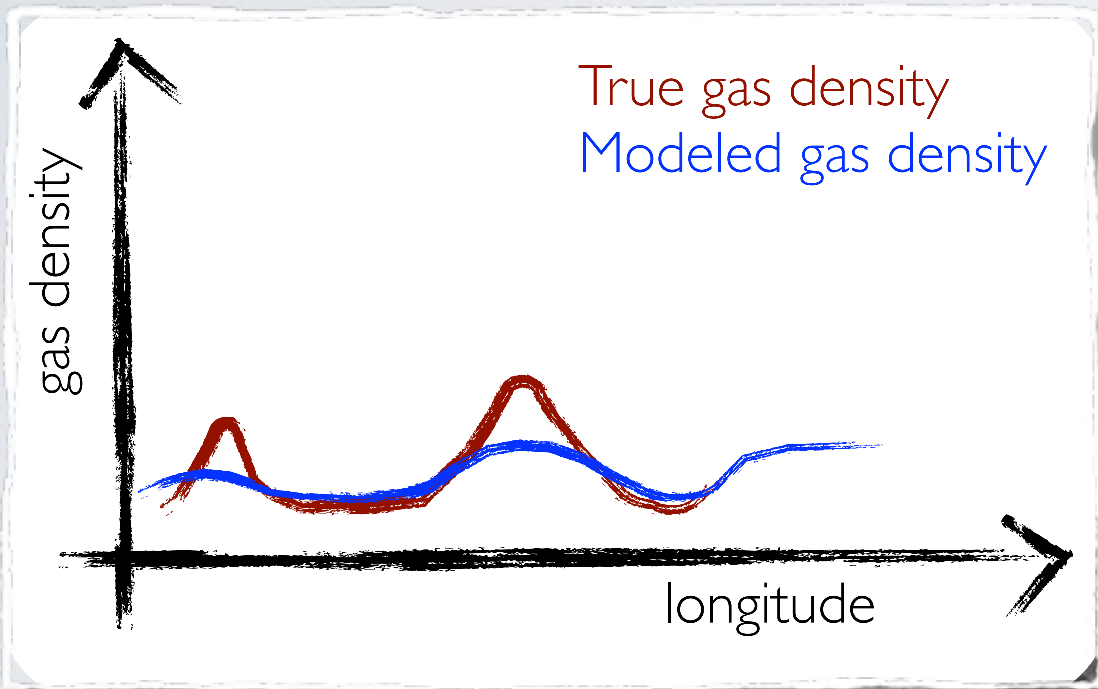




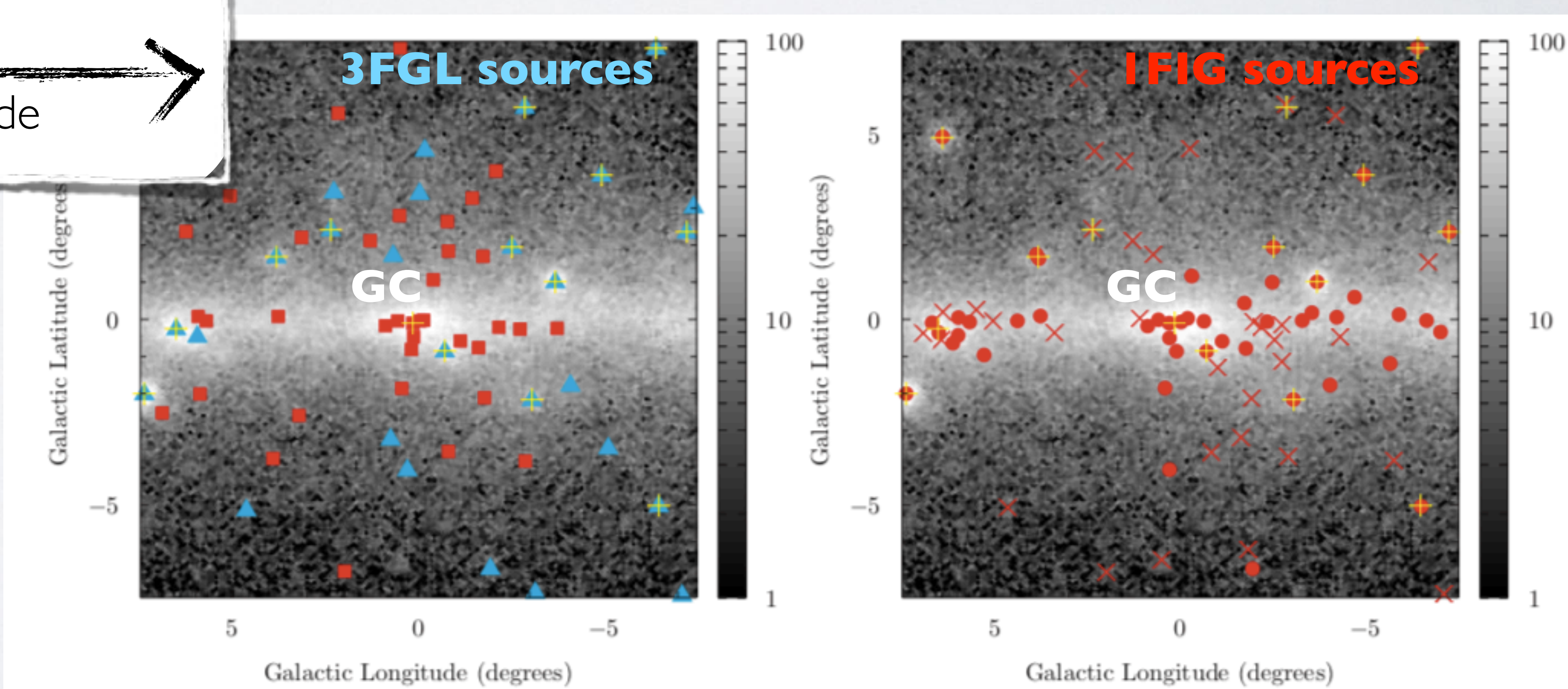
MORE ON POINT SOURCES

- 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 detected point sources in the GC region are mis-identified structured gas emission.

➡ Unmodeled gas features could contribute to the point source population that confounds a DM signal!



Fermi LAT Collaboration, arXiv:1511.02938

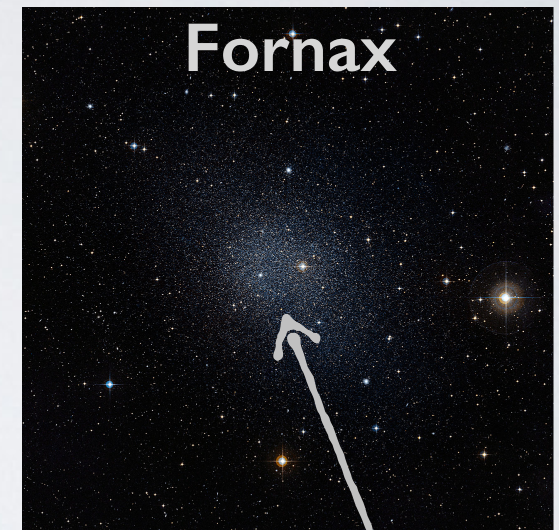


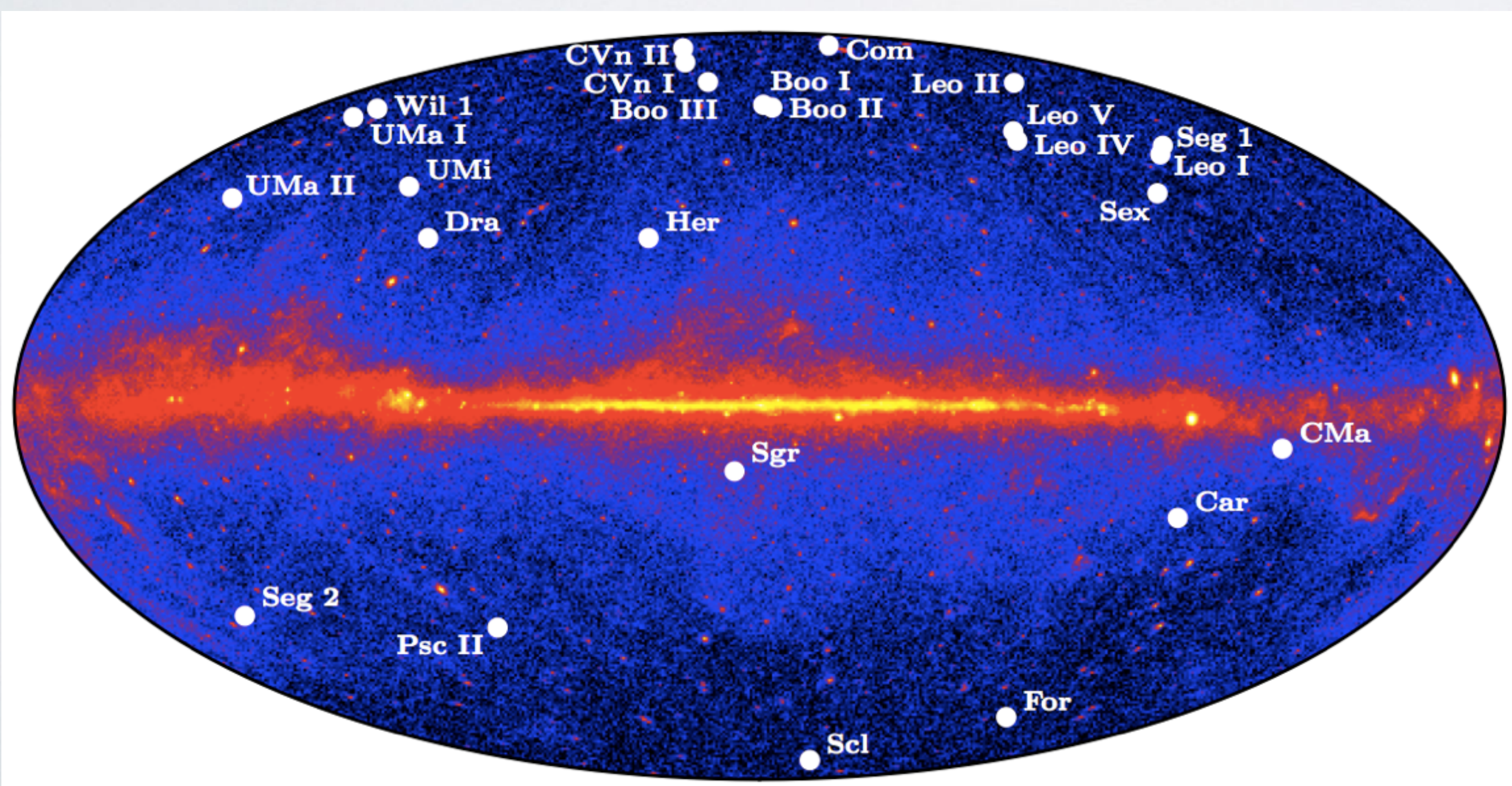
DARK MATTER SUBSTRUCTURES

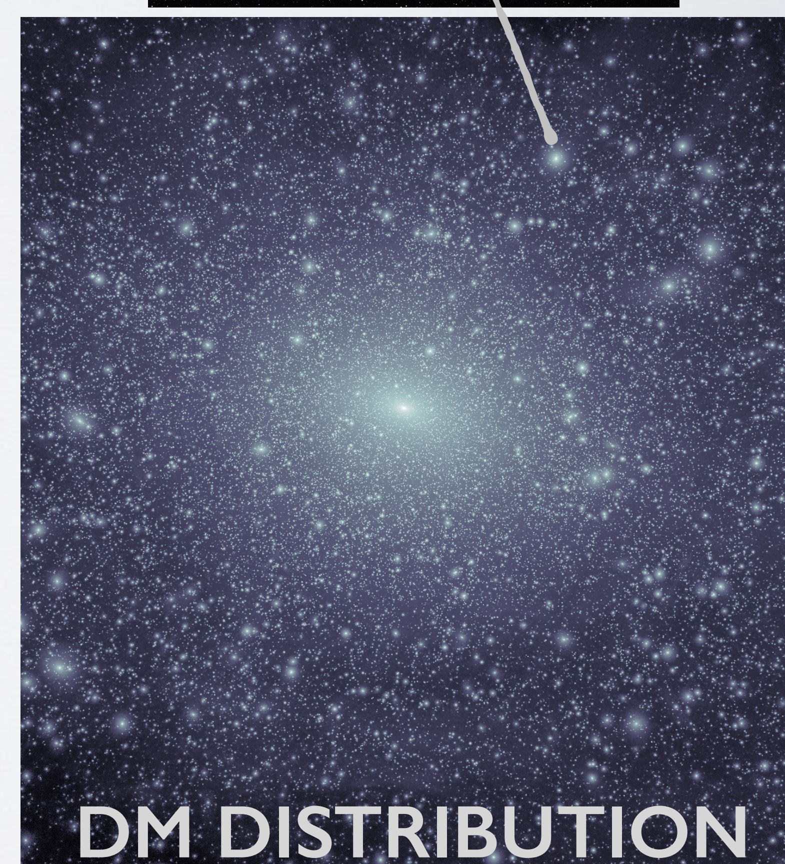
Optically observed dwarf spheroidal galaxies:

Satellite galaxies of the Milky Way largest dark matter substructures predicted by simulations

Excellent targets for gamma-ray dark matter searches, expected to be free from other gamma ray sources







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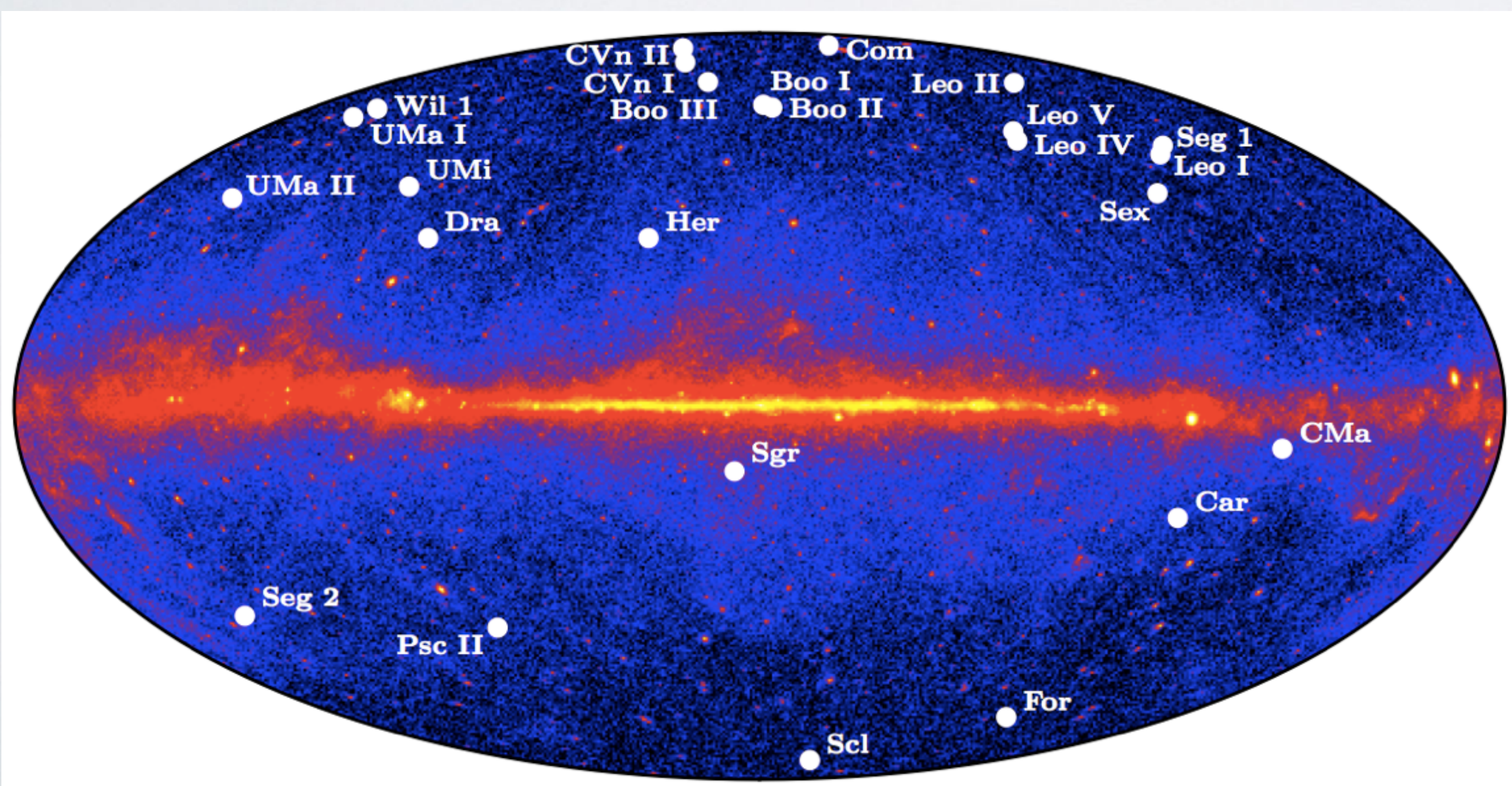

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No significant gamma rays emission is found from dwarf spheroidal galaxies

(but <3σ excesses in Reticulum II and Tucana III, spectrum and annihilation cross section compatible with GC excess, Geringer-Sameth et al arXiv:1503.02320, Albert et al arXiv:1611.03184)

➡ Dwarf spheroidals limit the DM interpretation of the GC excess, but don't rule it out

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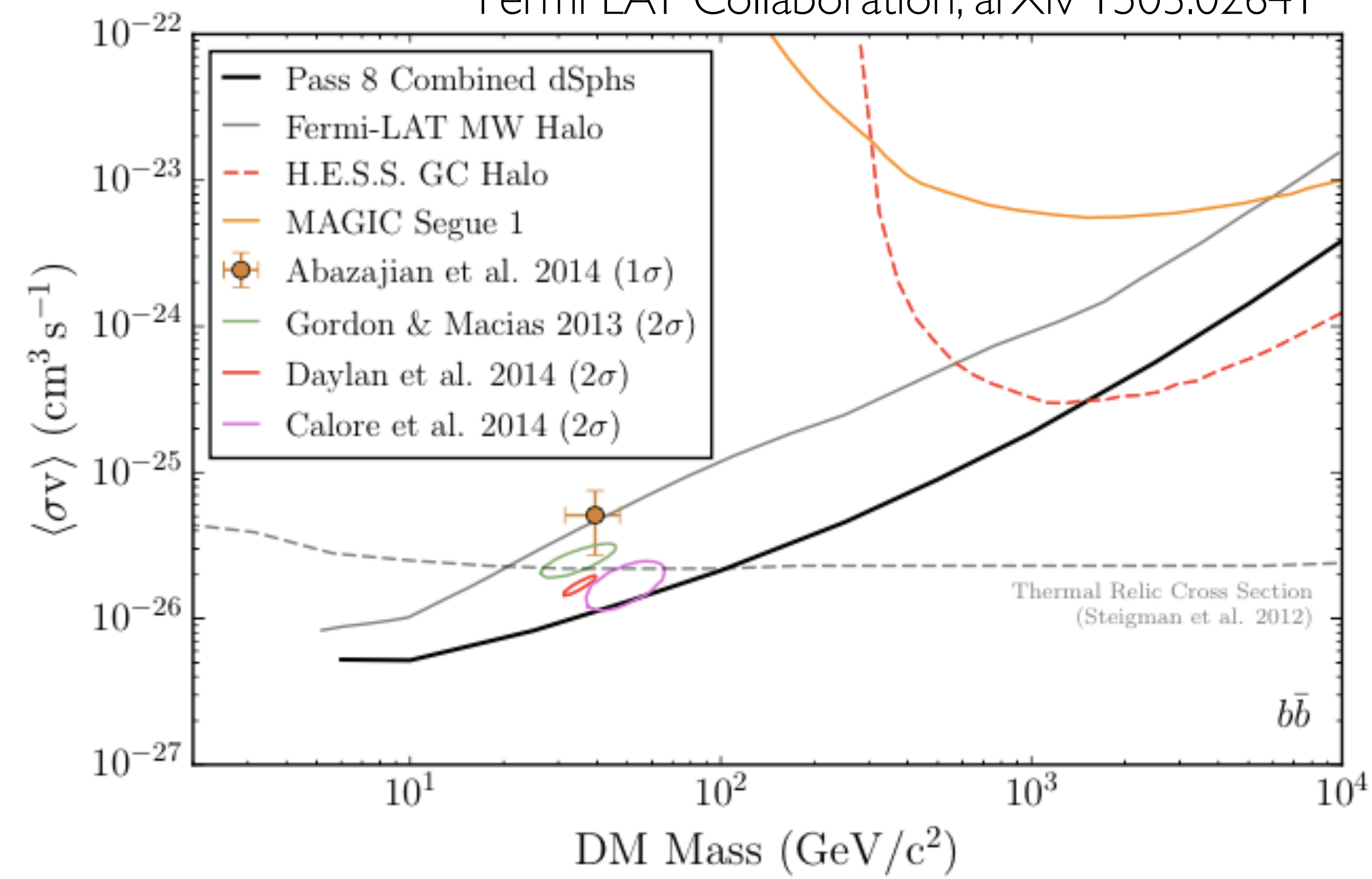

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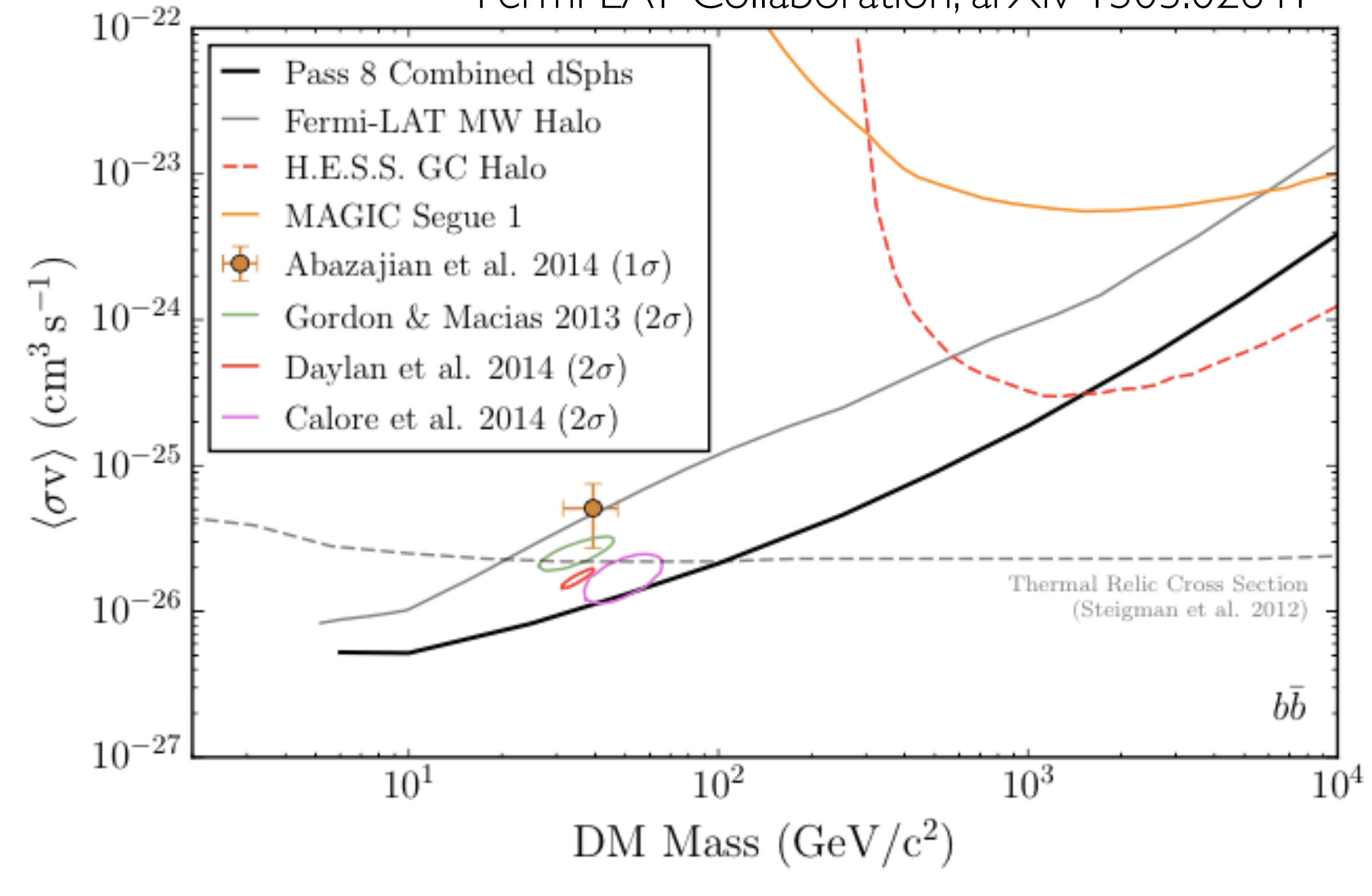

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Broader range of DM masses and annihilation channels (see e.g. Agrawal et al, arXiv:1411.2592, Karwin et al arXiv:1612.05687)

GC excess contours do not fully reflect uncertainties in the DM distribution, might vary by >2x up or down (see e.g. Benito et al arXiv:1612.02010, also see Abazajian et al, arXiv:1510.06424,)

Non-spherical DM halos weaken dSph limits by ~2x (see e.g. Hayashi et al, arXiv:1603.08046, Klop et al, arXiv:1609.03509)

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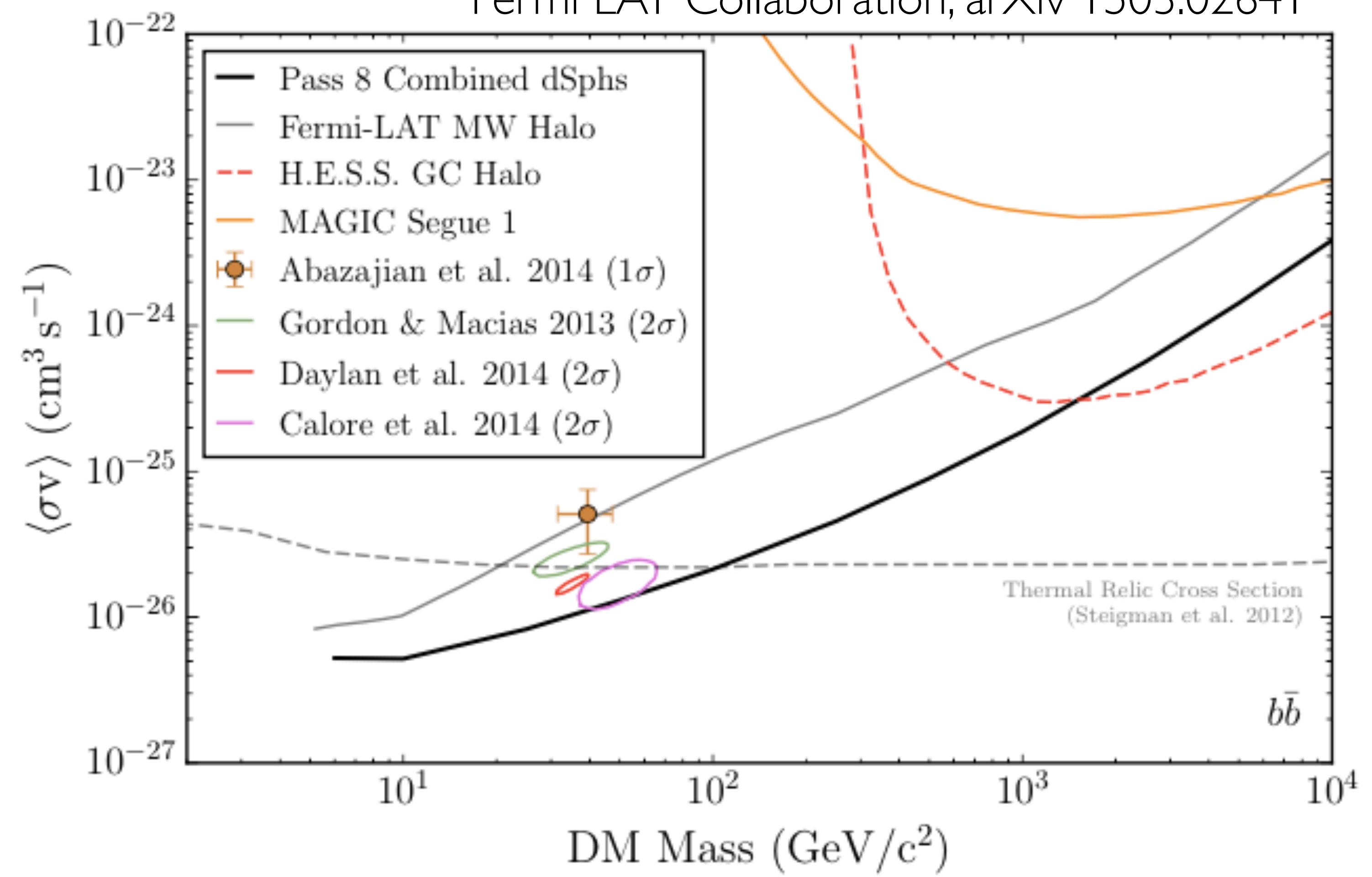

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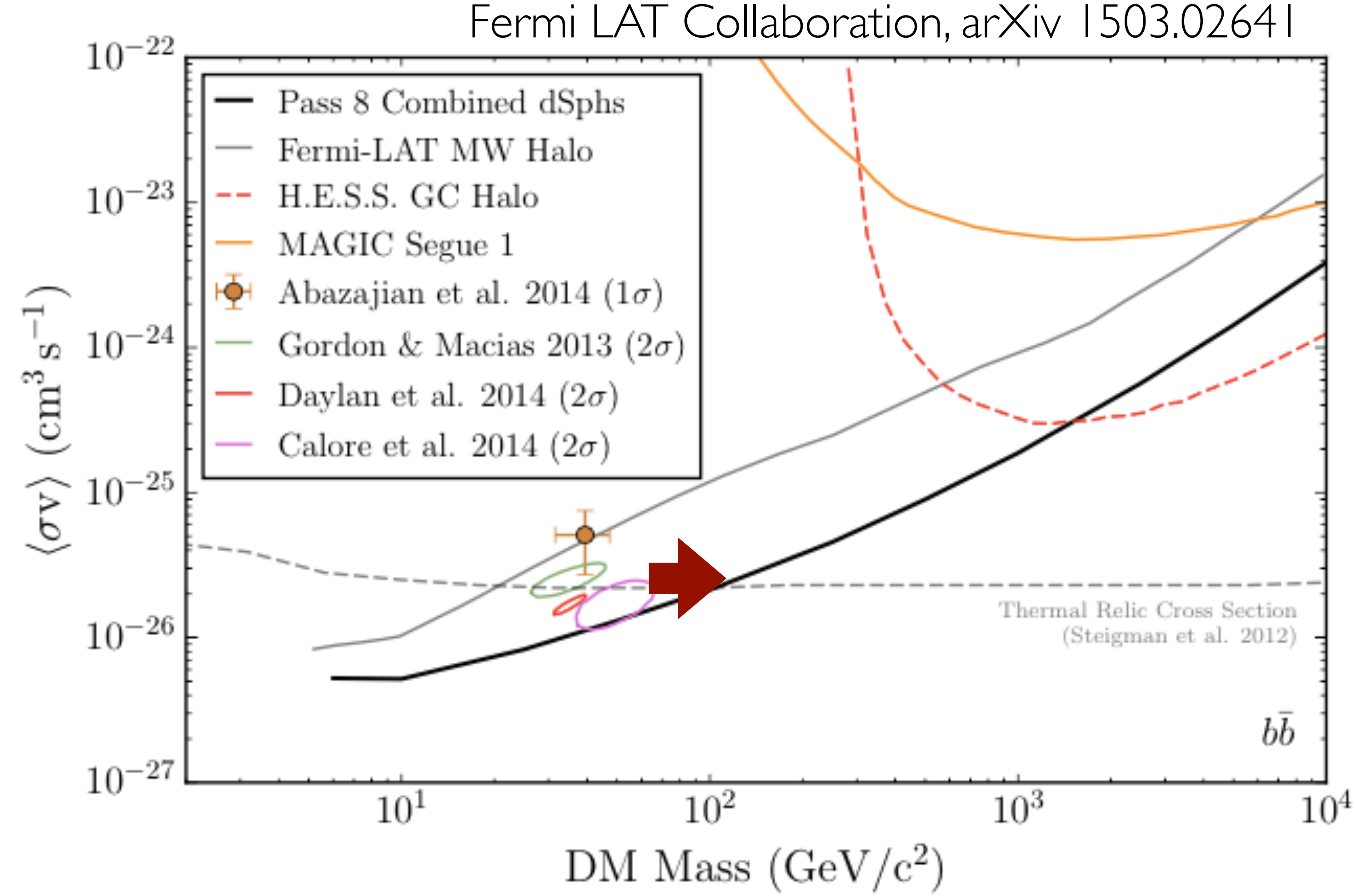

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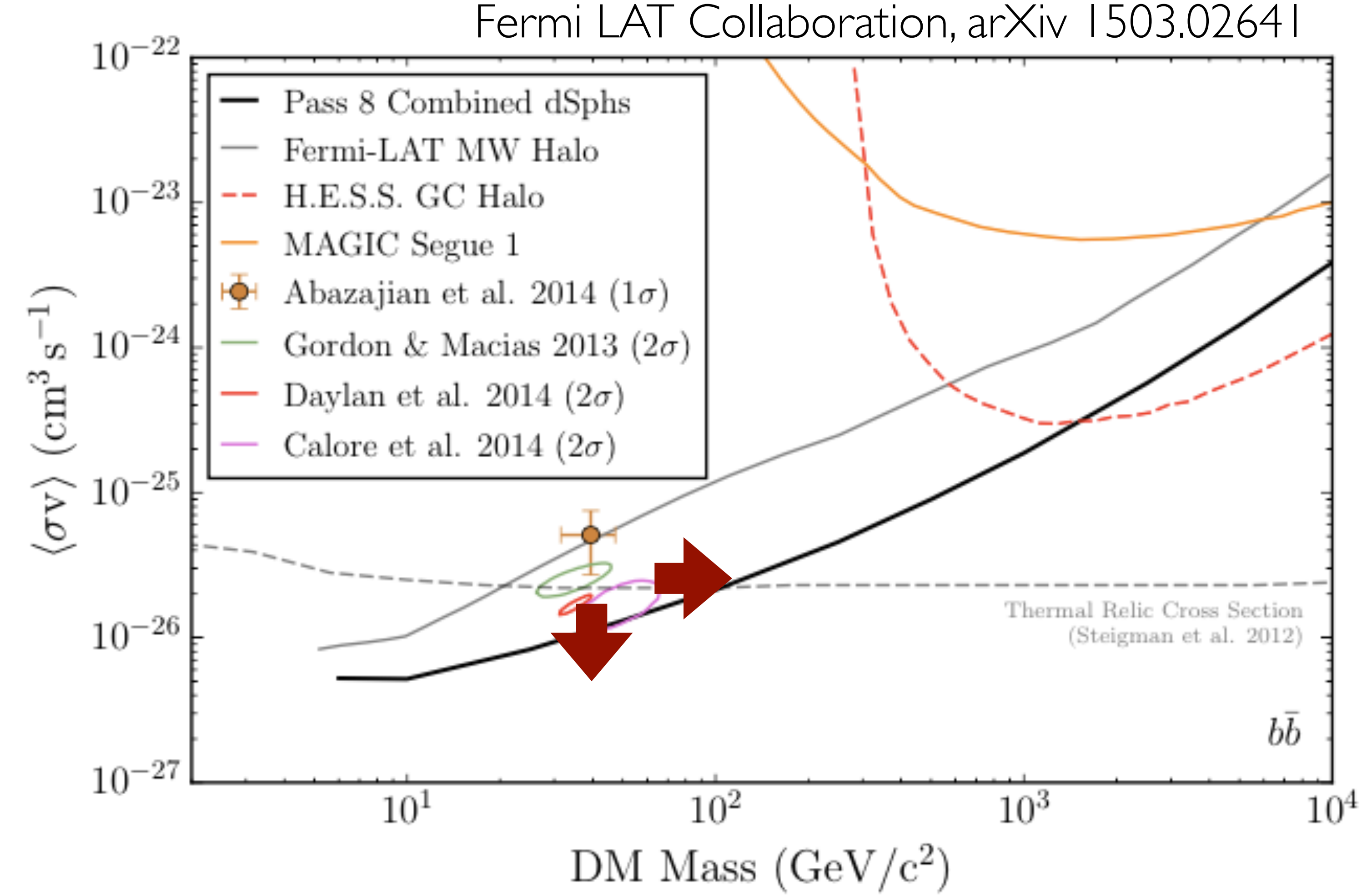

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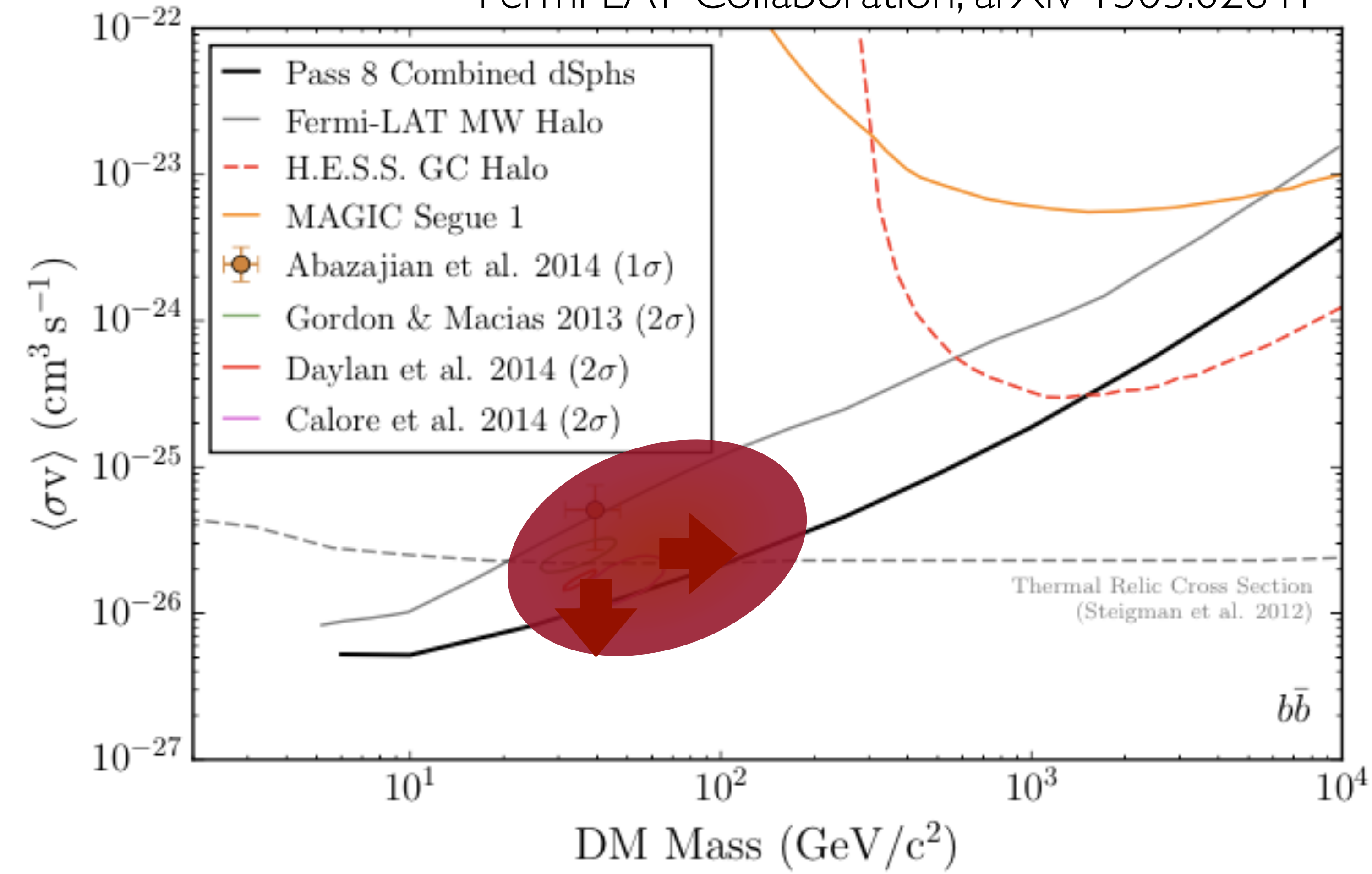

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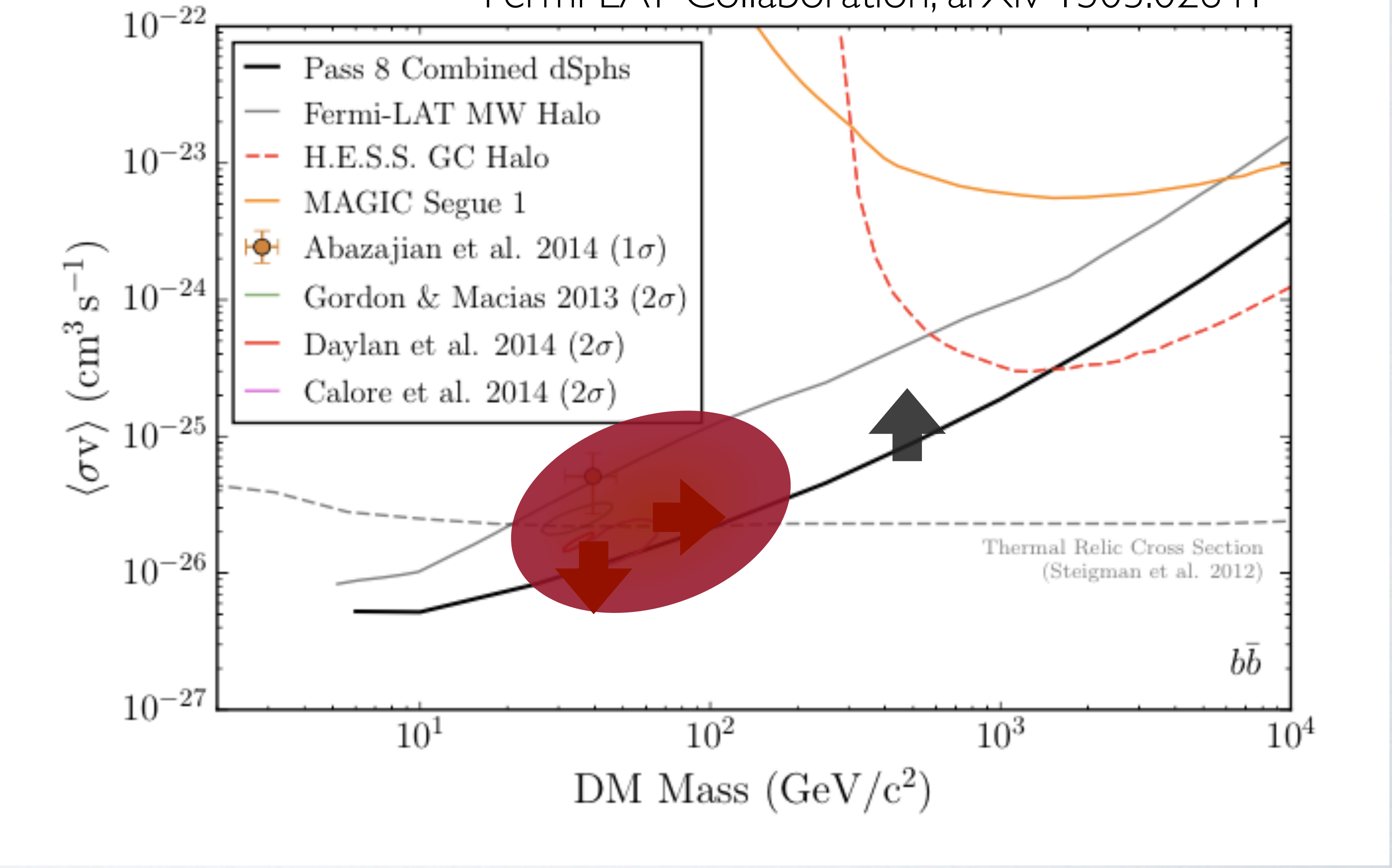

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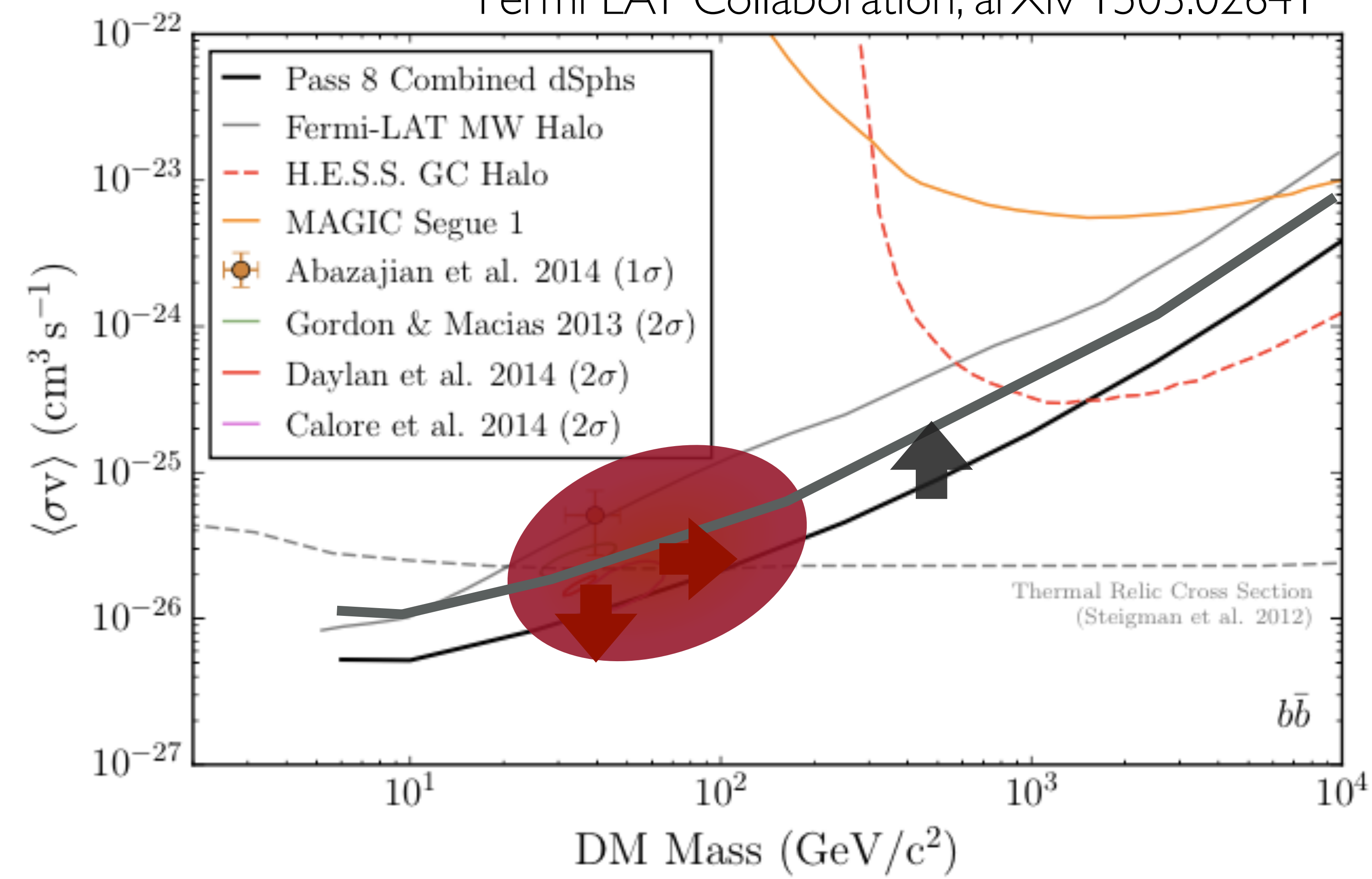
Broader range of DM masses and annihilation channels (see e.g. Agrawal et al, arXiv:1411.2592, Karwin et al arXiv:1612.05687)

GC excess contours do not fully reflect uncertainties in the DM distribution, might vary by >2x up or down (see e.g. Benito et al arXiv:1612.02010, also see Abazajian et al, arXiv:1510.06424,)

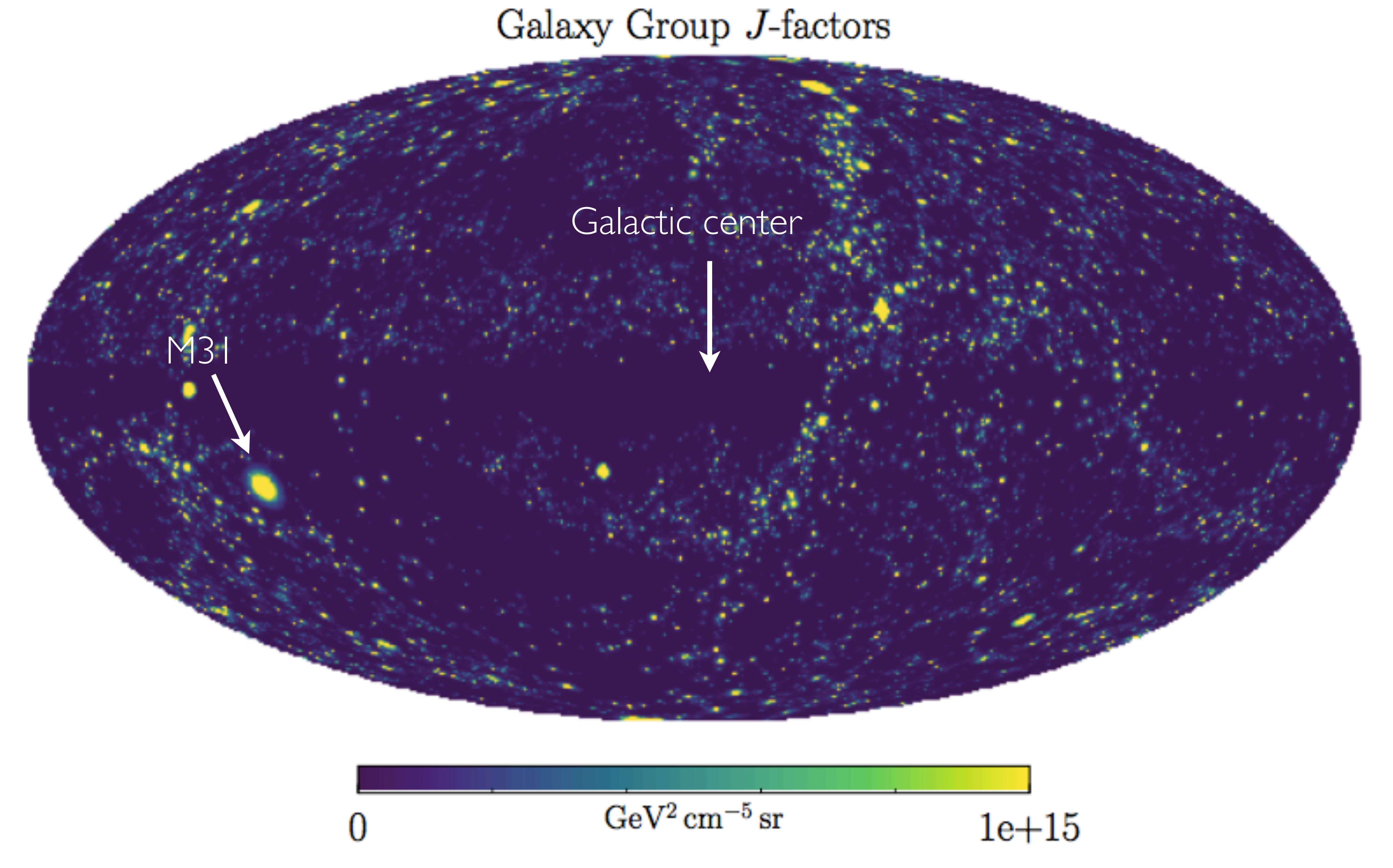
Non-spherical DM halos weaken dSph limits by ~2x (see e.g. Hayashi et al, arXiv:1603.08046, Klop et al, arXiv:1609.03509)

Fermi LAT Collaboration, arXiv 1503.02641



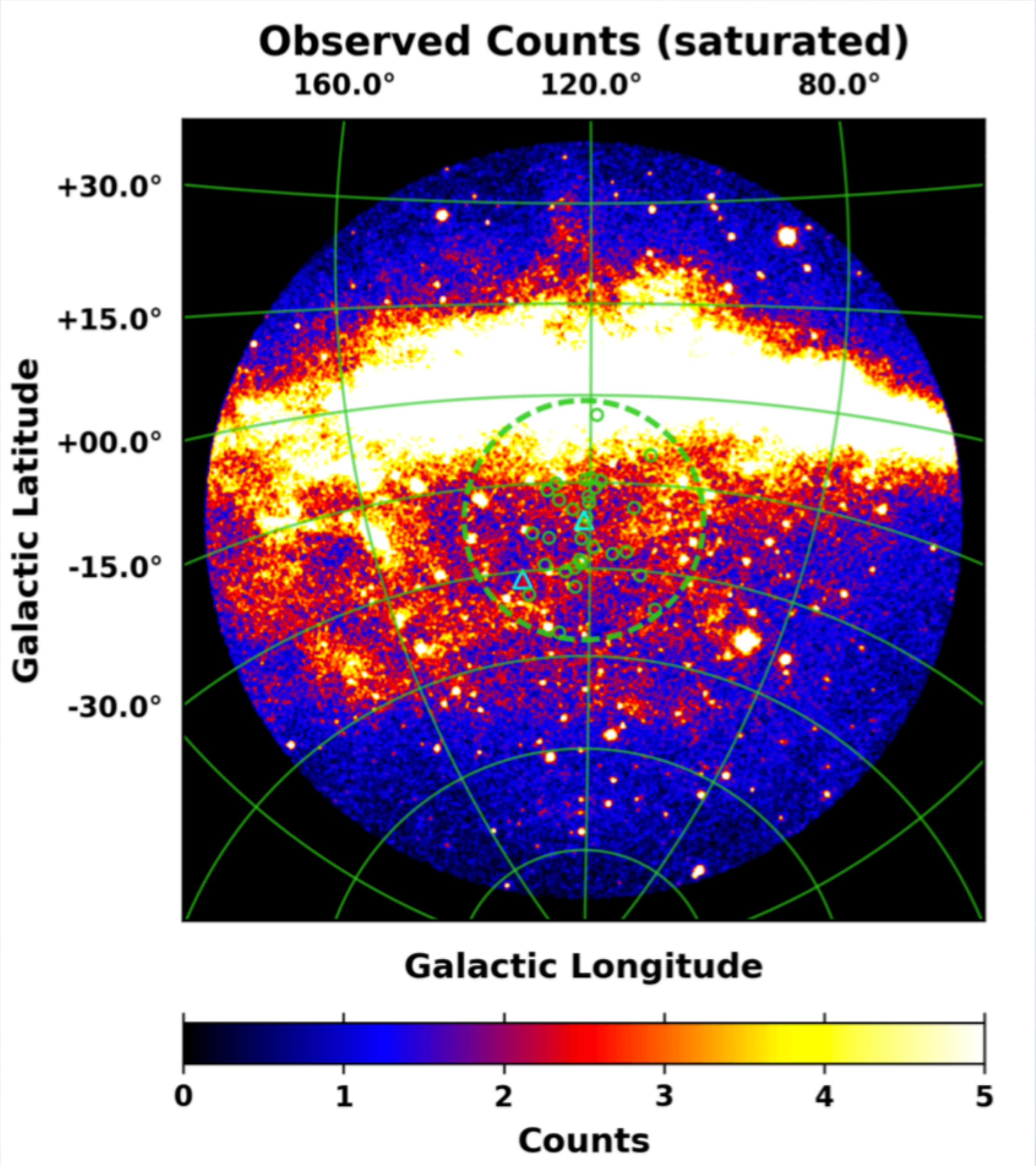
GAMMA RAYS FROM DM ANNIHILATION: BEYOND THE MILKY WAY

Lisanti et al, arXiv1708.09385



ANDROMEDA (M31)

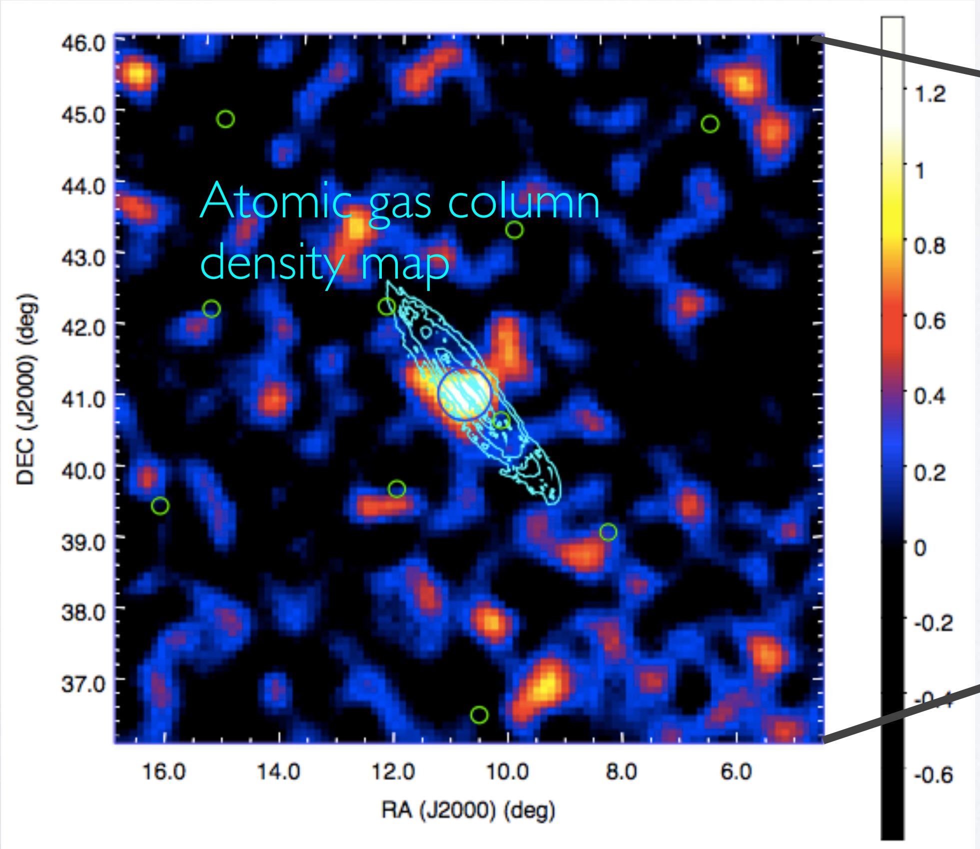
- M31 DM halo extends several degrees across the sky (~40º for a DM halo ~600 kpc across). DM density gradient depends on DM distribution, substructures and profile

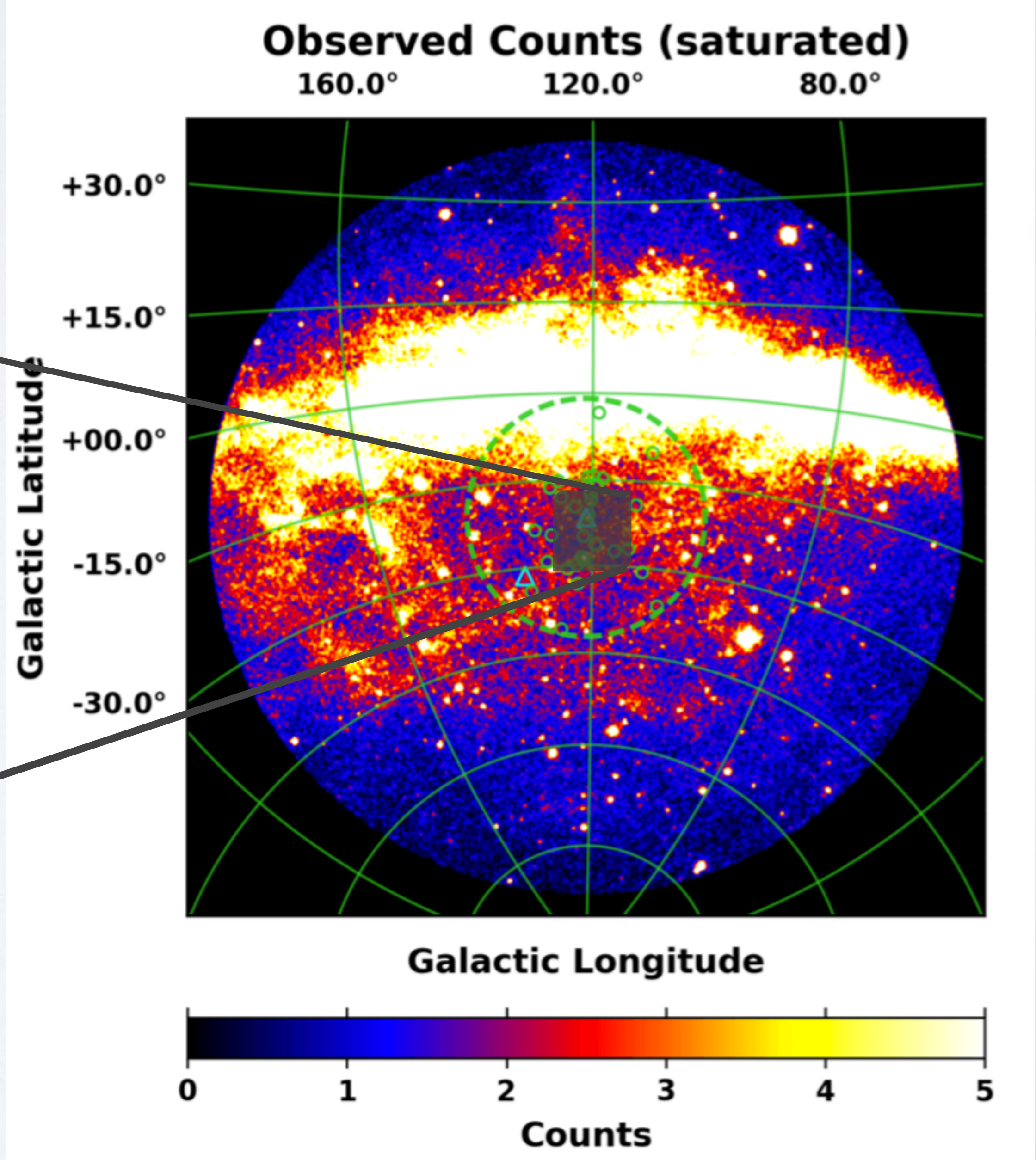


ANDROMEDA (M31)

- M31 DM halo extends several degrees across the sky (~40º 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, ~1º 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

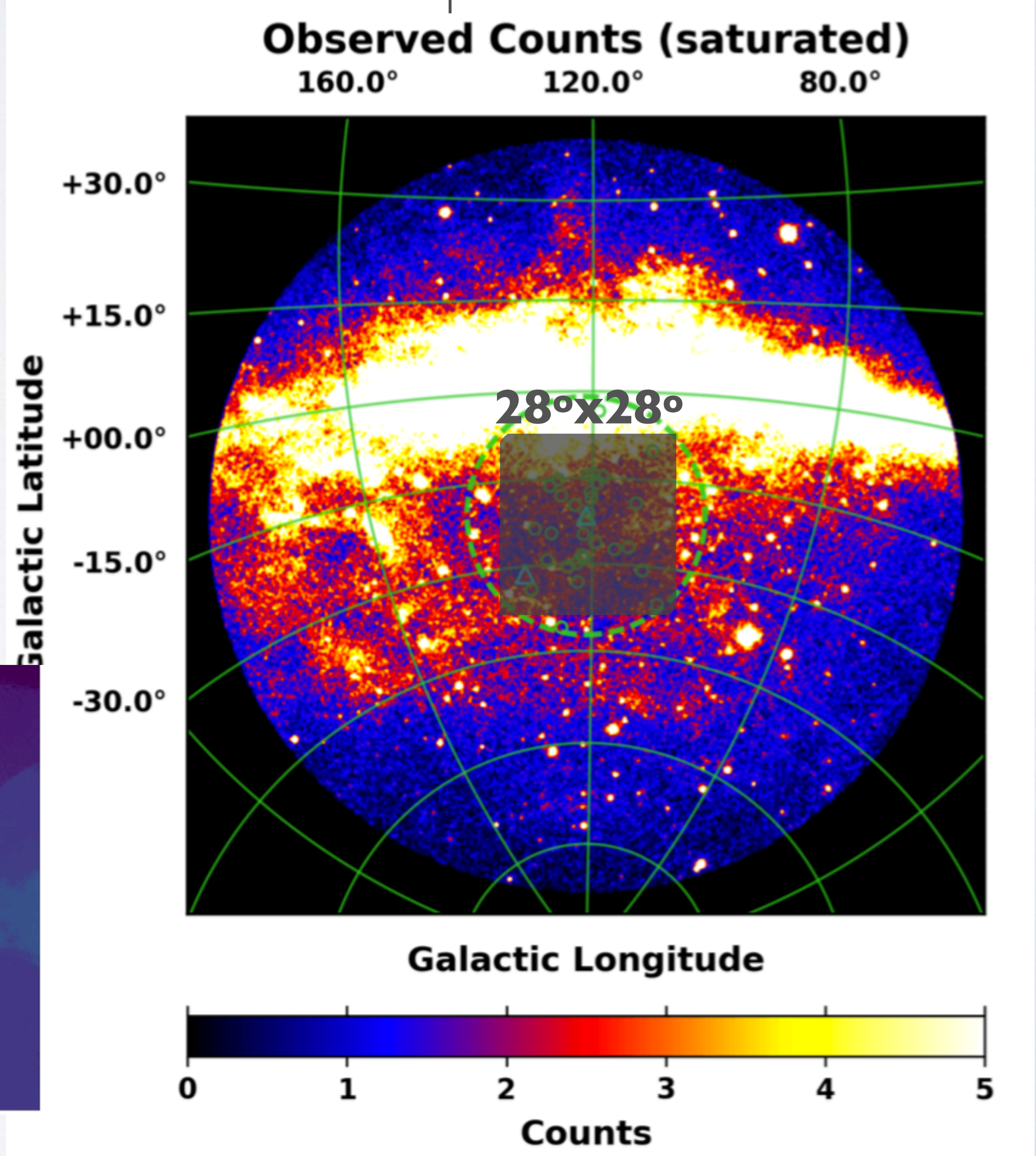




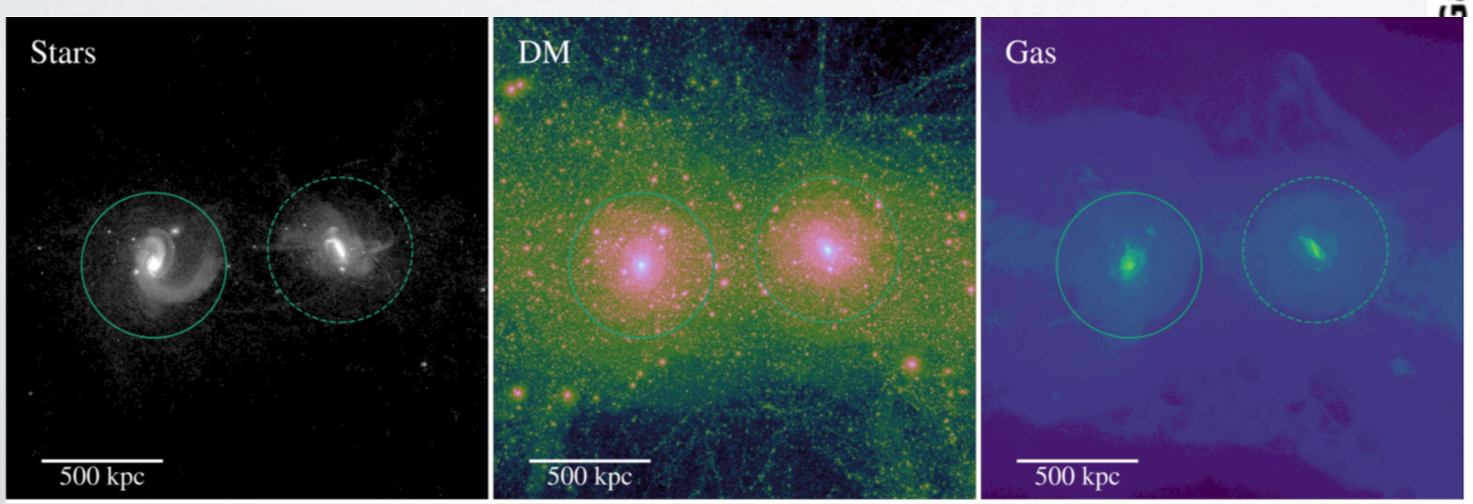
FERMI LAT OBSERVATIONS OF γ-RAY EMISSION TOWARDS THE OUTER HALO OF M31

Karwin 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

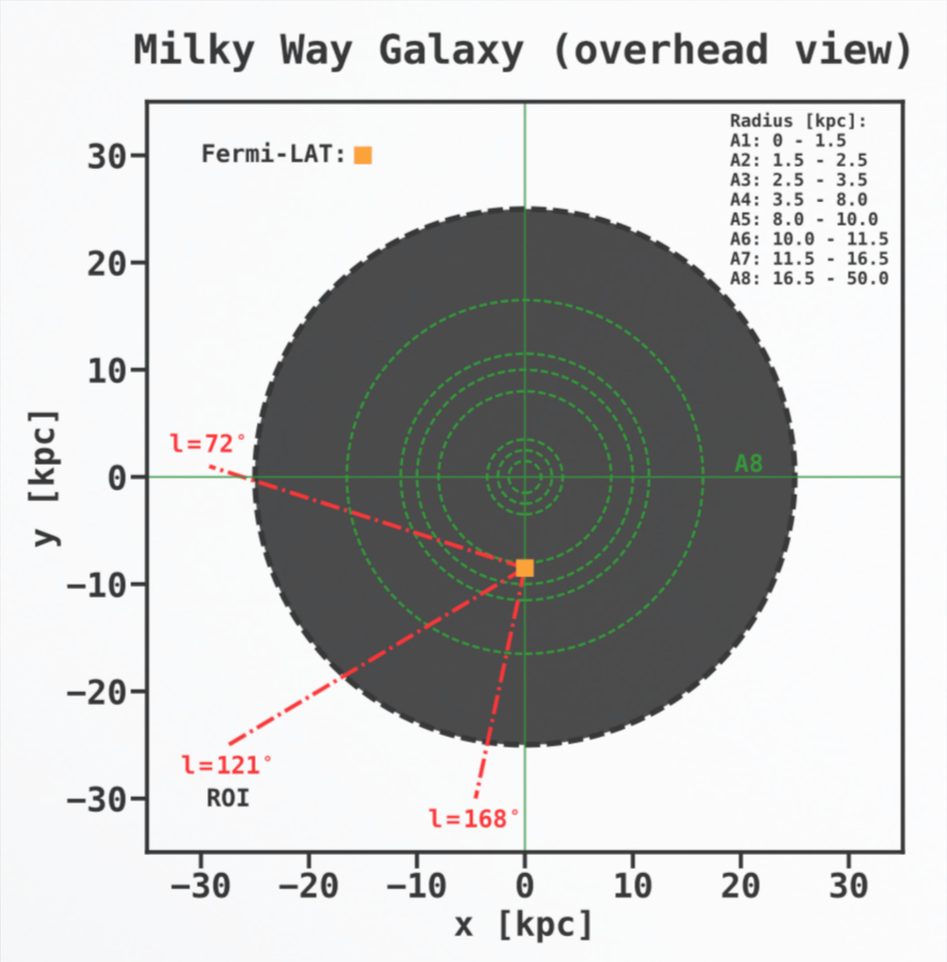


Garrison-Kimmel et al, arXiv:1806.04143



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)



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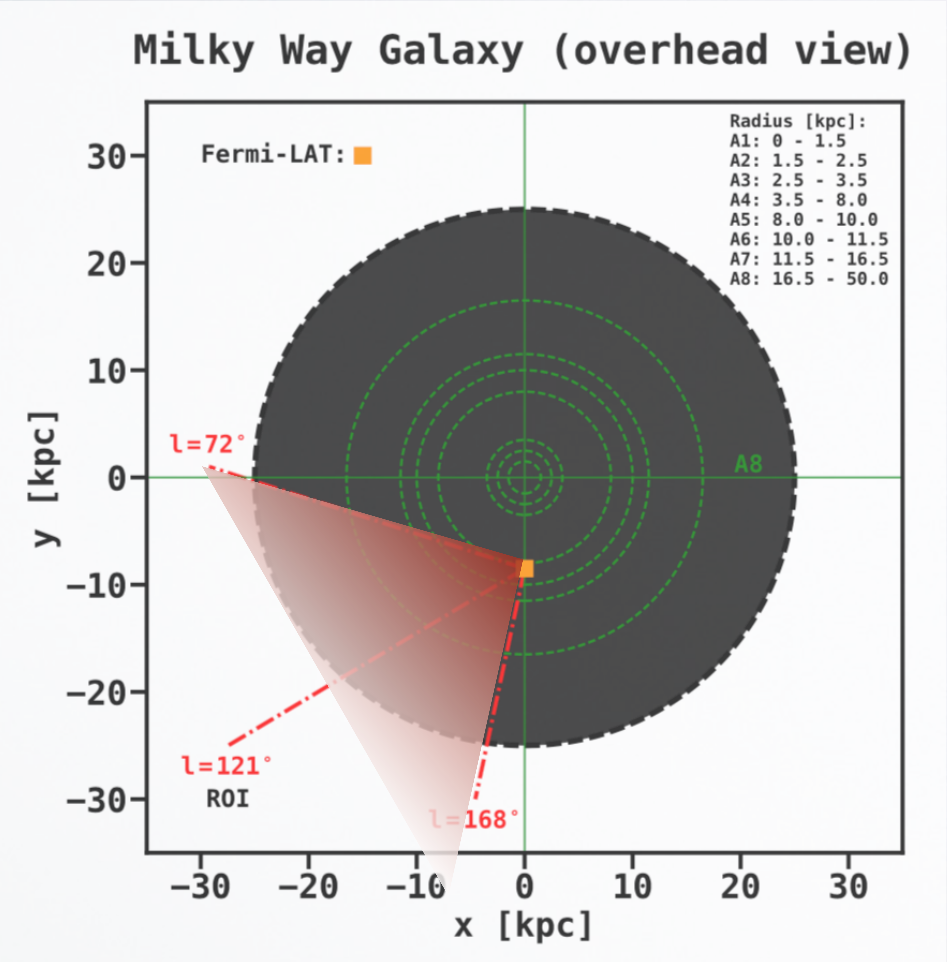

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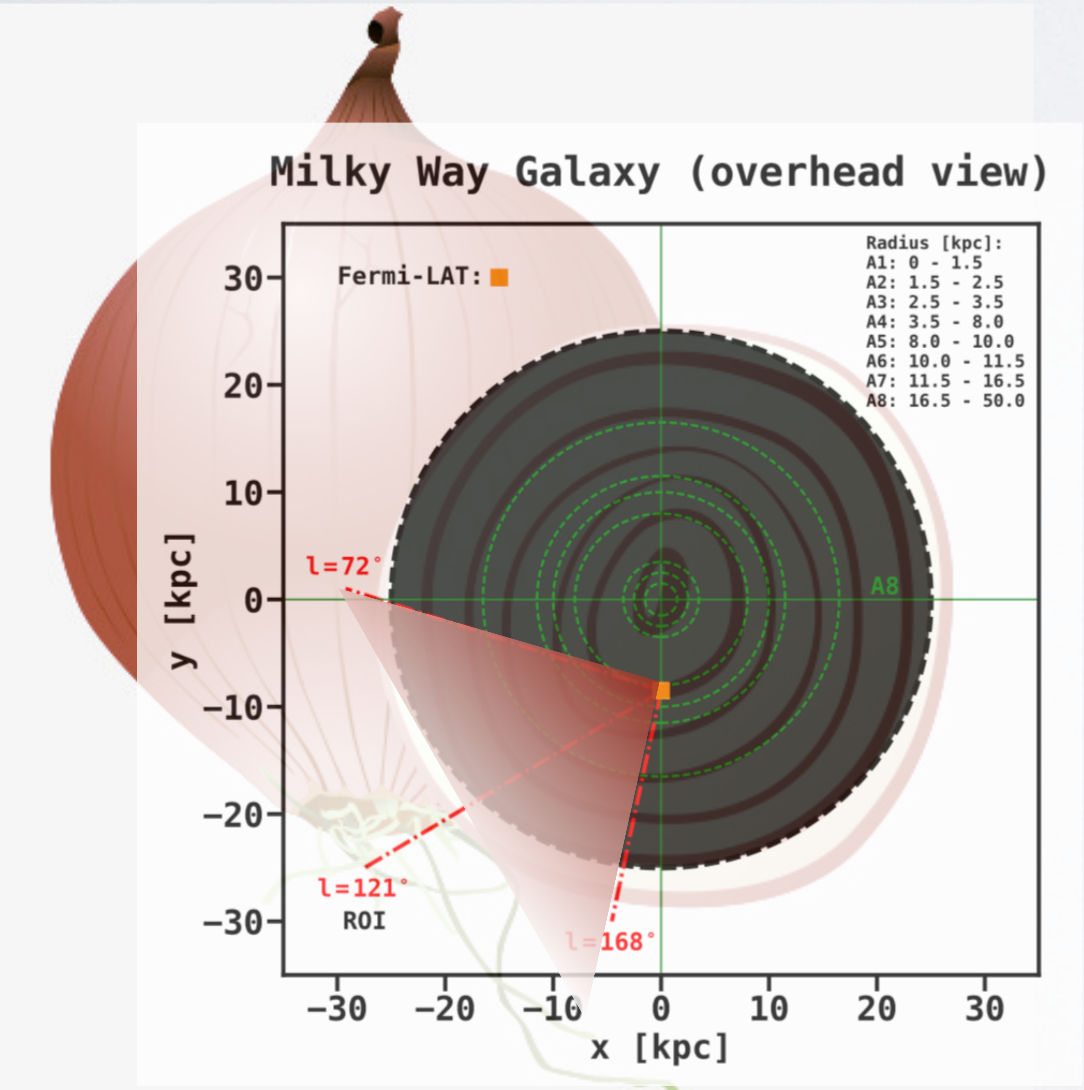

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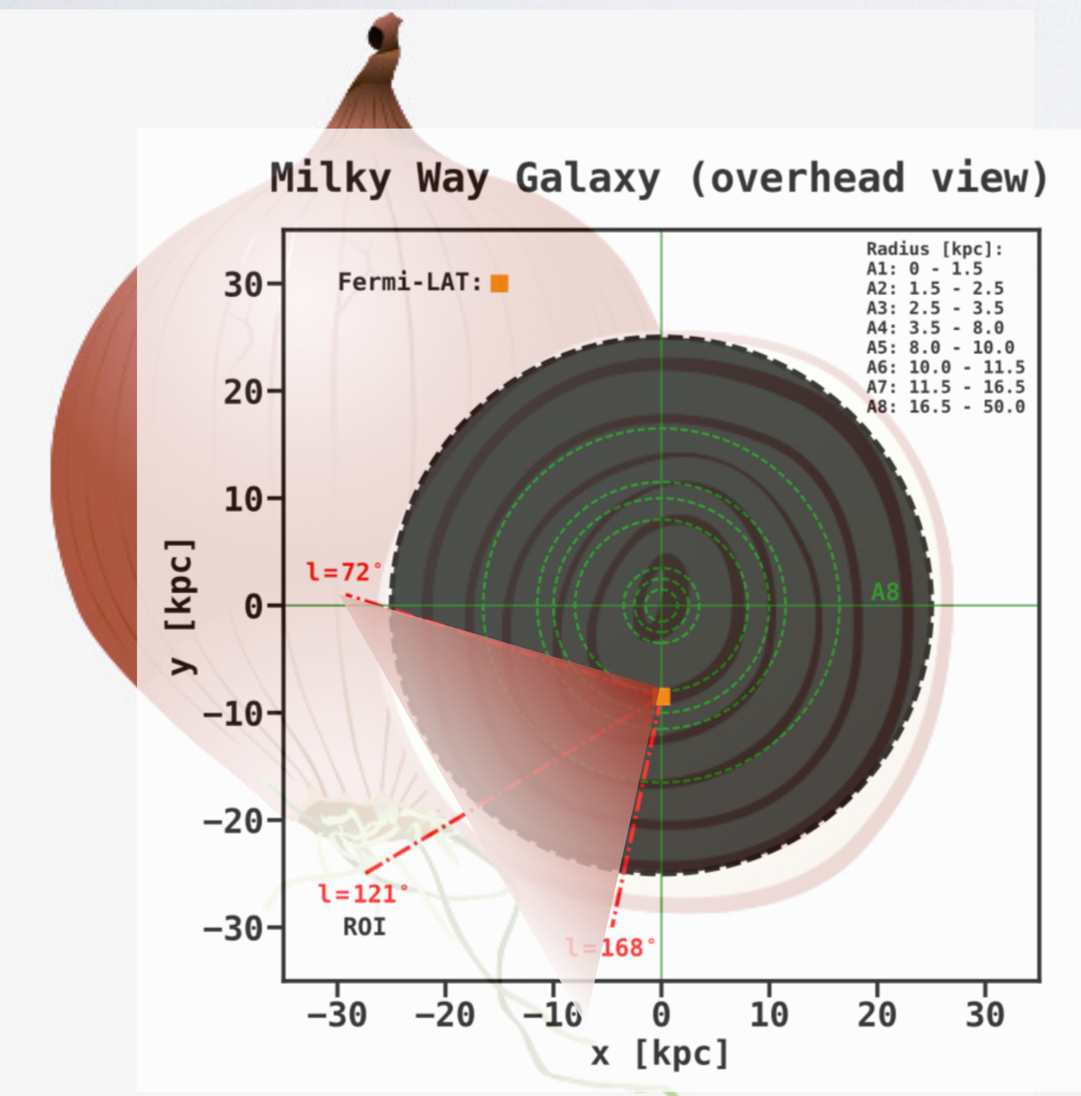
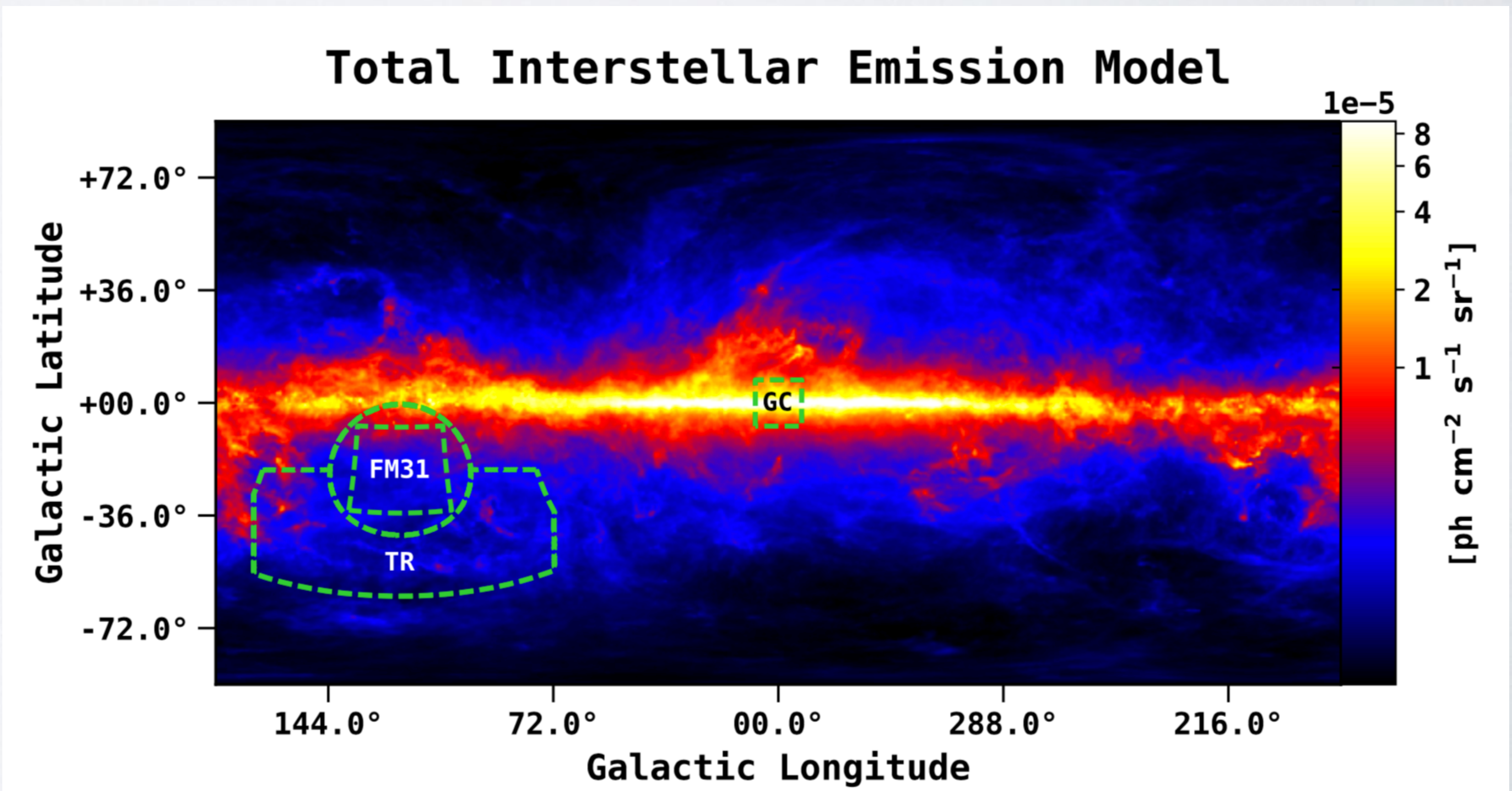


Signal region: FM31
Tuning region: TR

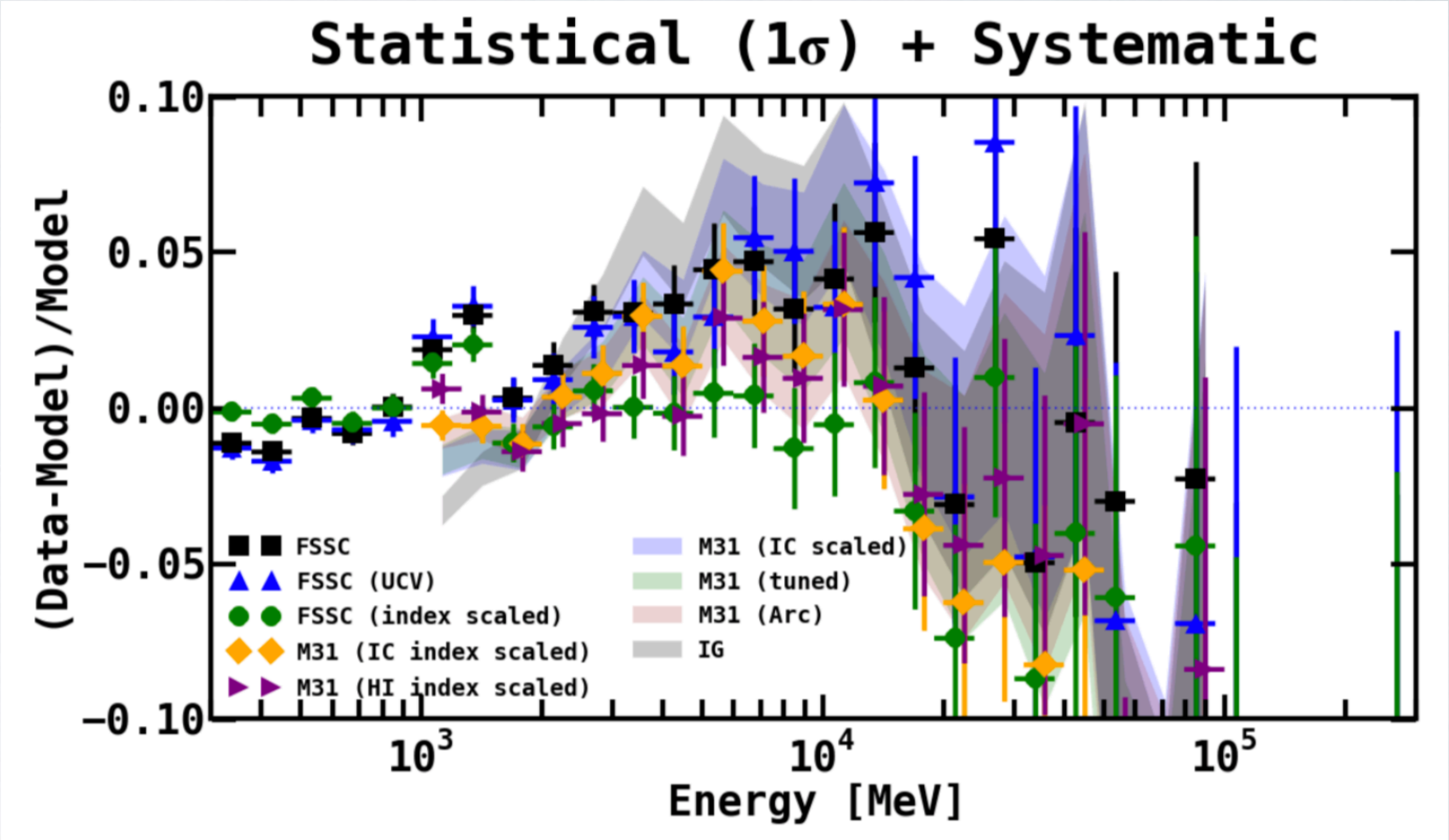


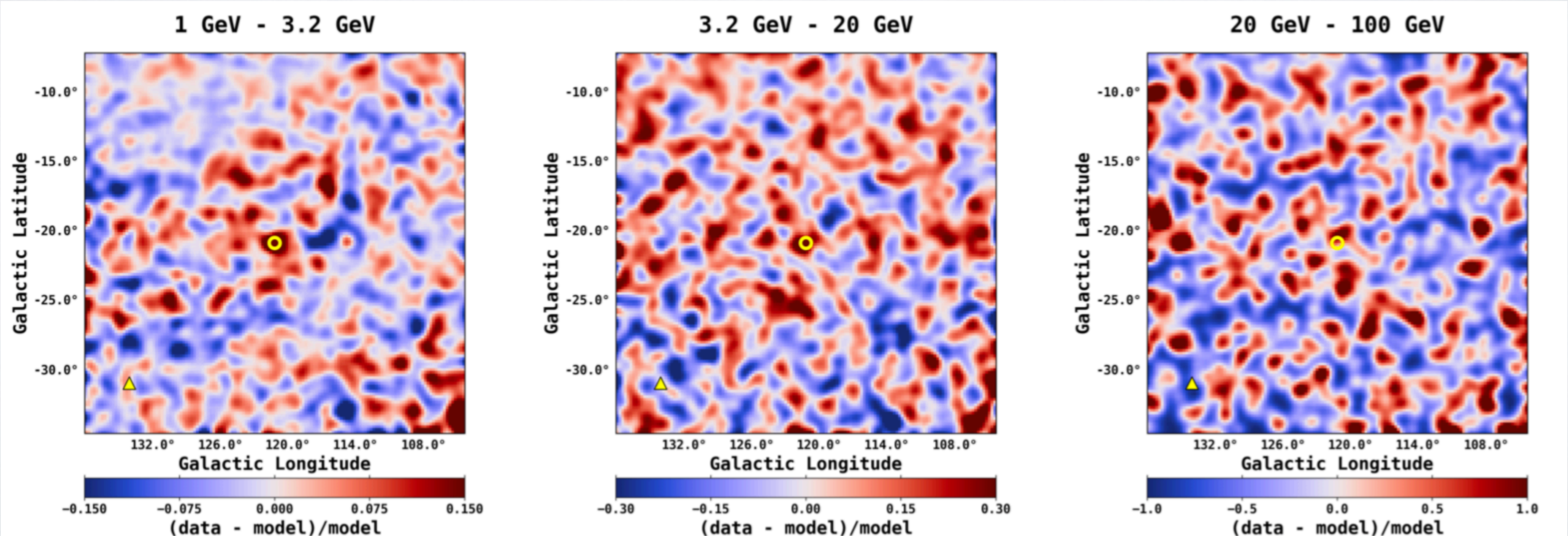
SIGNAL REGION (FM31)

- Fit TR first, find good agreement between data and model
- Fit signal region FM31 using constraints from fit in TR to constrain less structured, extended components. Free other foreground components (and point sources)

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

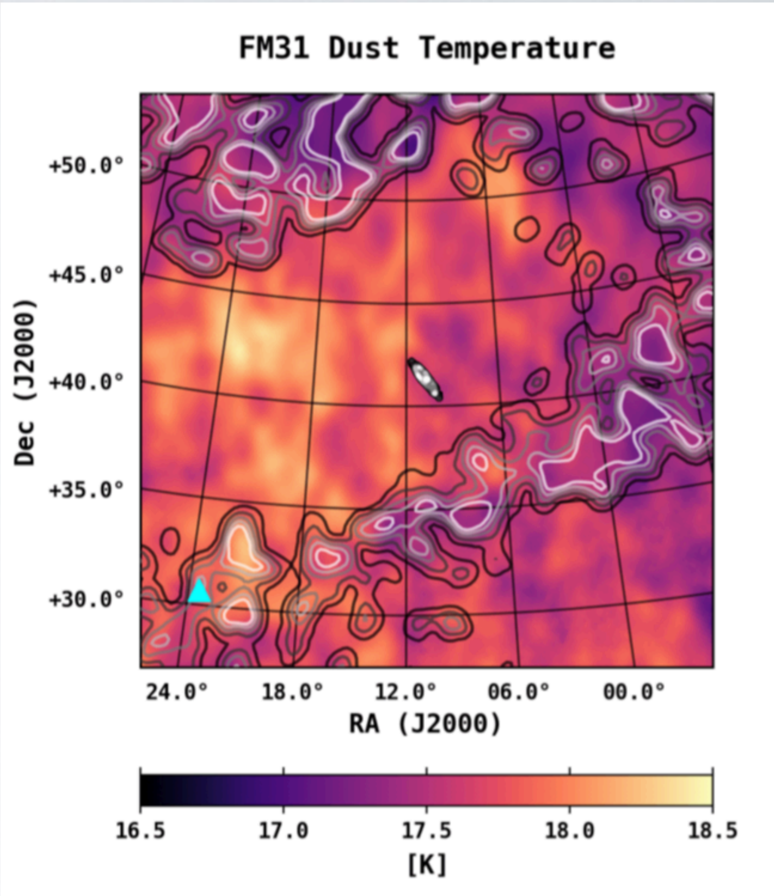
- The features of the residual emission are robust against extensive study of systematics

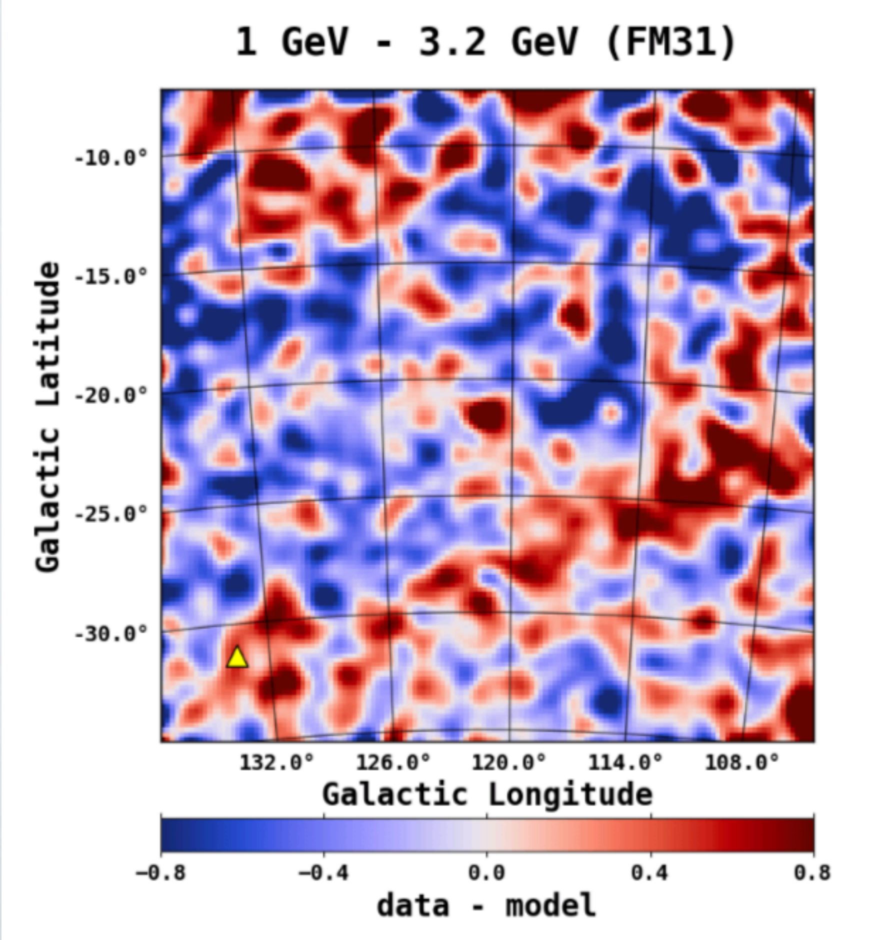


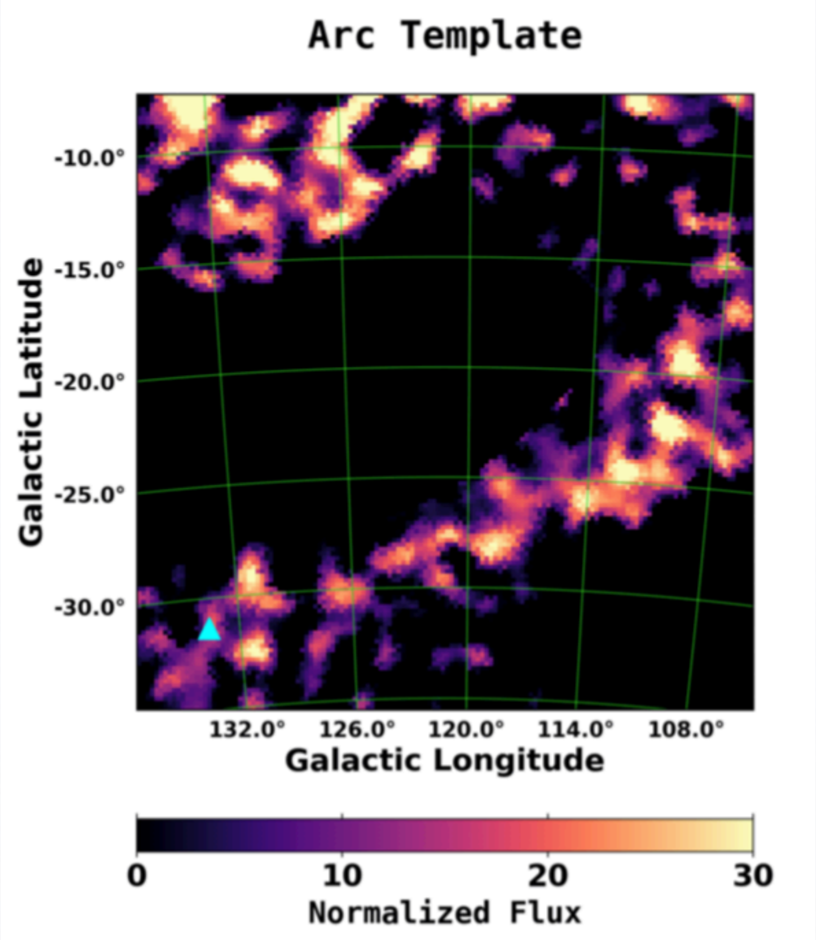


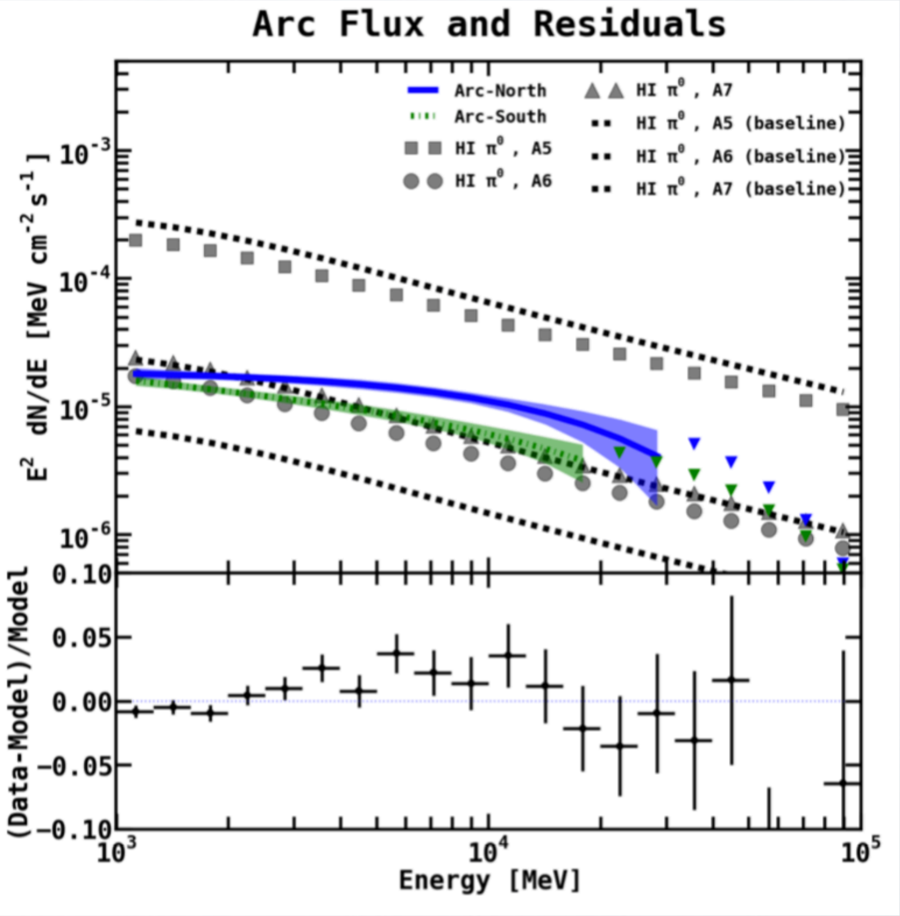
EXAMPLE OF SYSTEMATICS

- We find an arc-like excess correlated with local MW HI column density
- We model it with a specialized template and include in the fit
- The smooth excess emission remains, though arc structure is gone



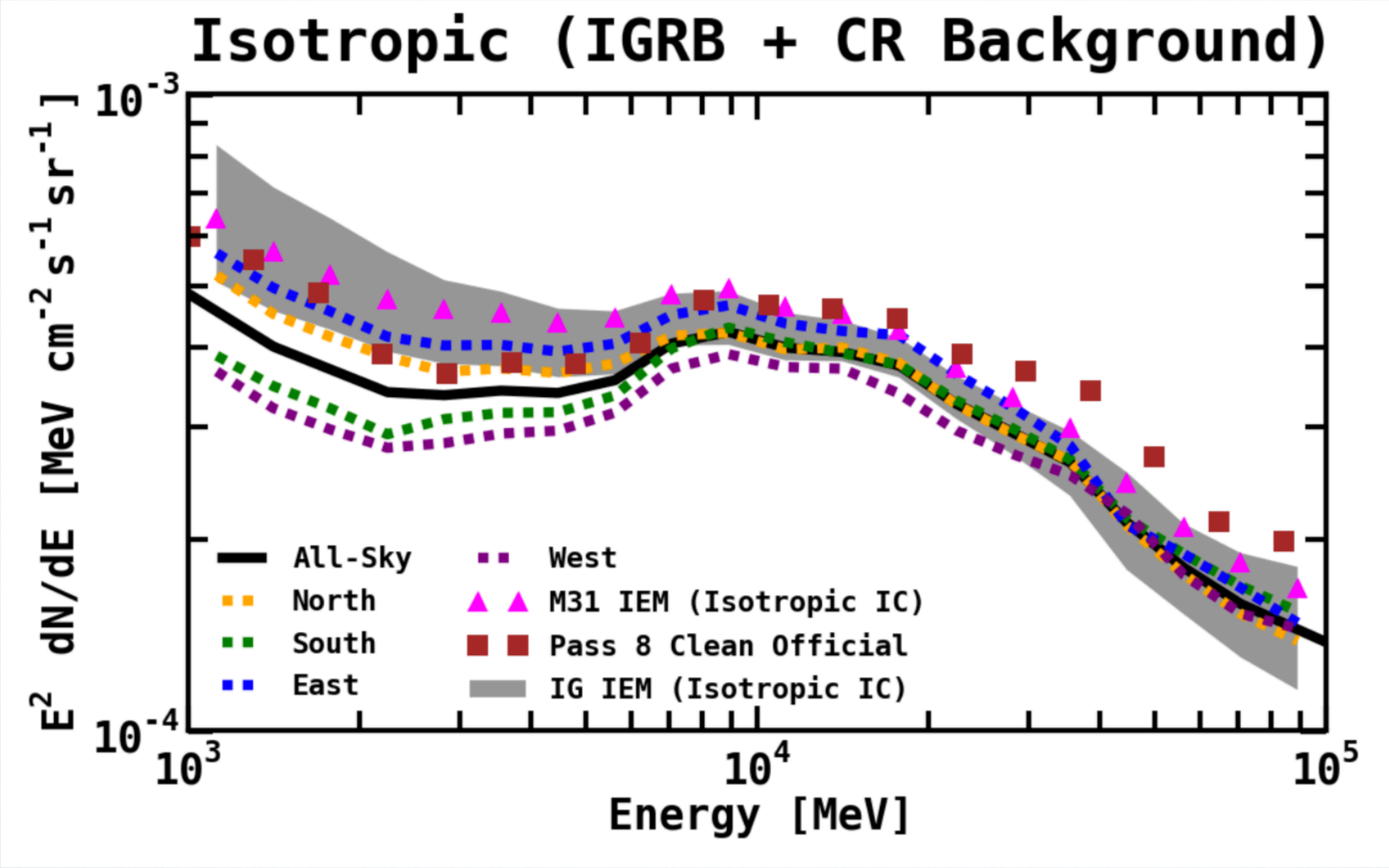






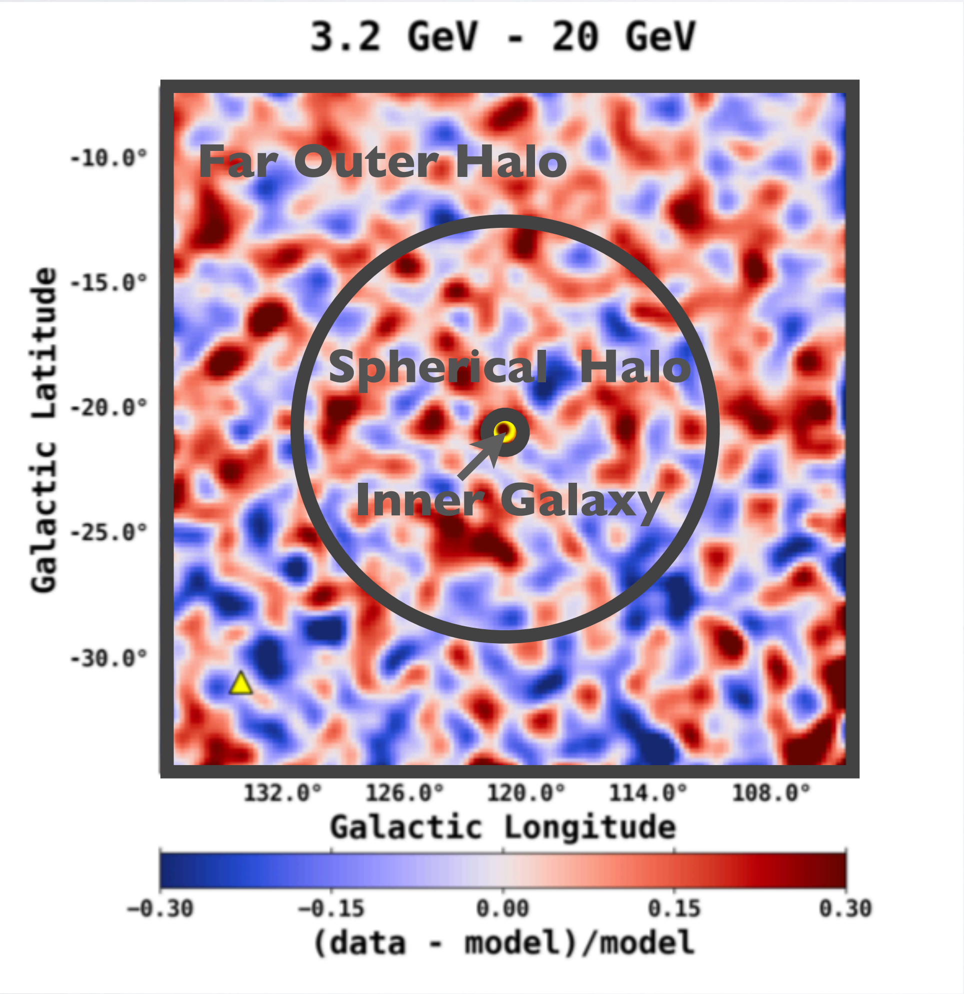
ISOTROPIC EMISSION

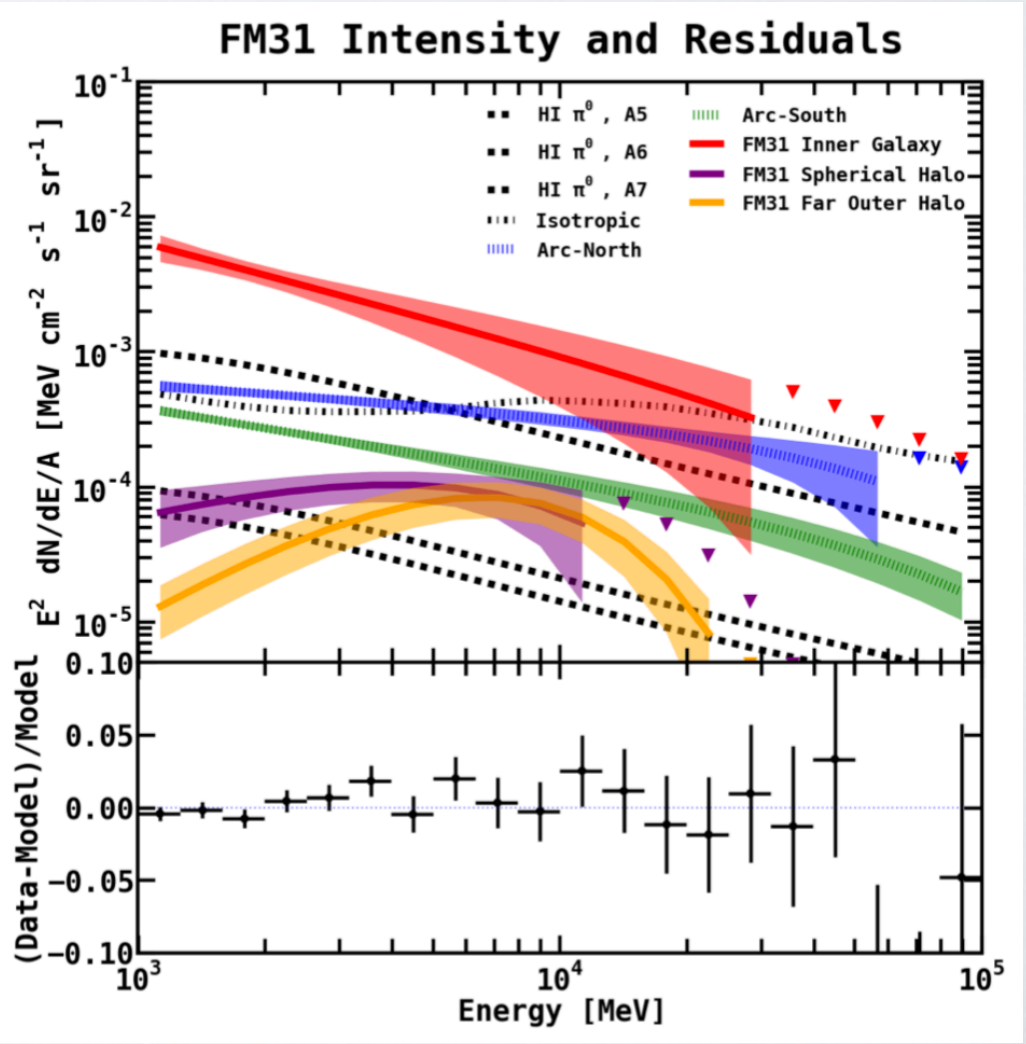
- The isotropic component includes unresolved extragalactic diffuse emission, residual instrumental background, and possibly contributions from other Galactic components
- Included in the model, initially derived in regions away from the Galactic plane and self-consistently with the MW foreground emission



CHARACTERIZATION

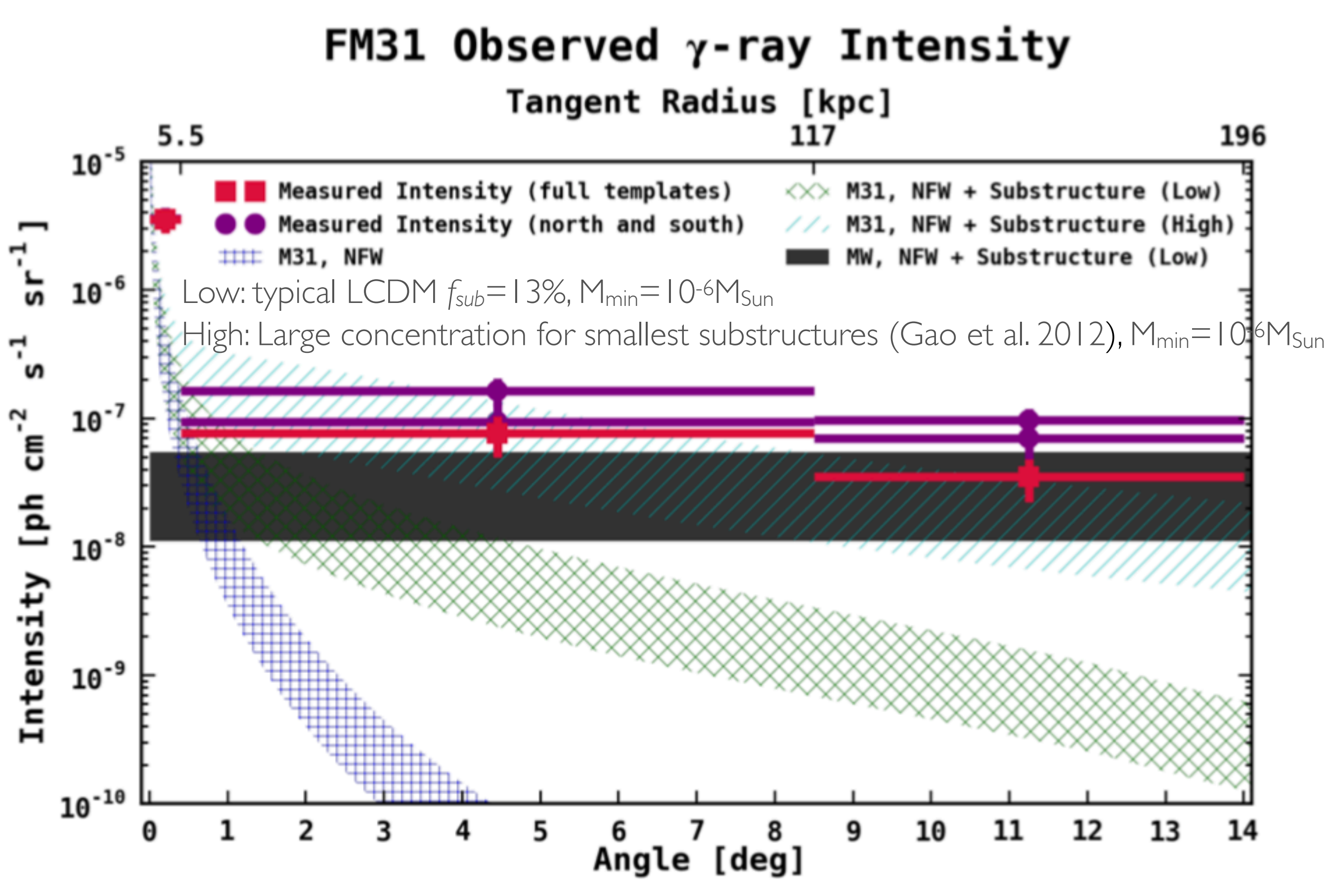
- Model the excess assuming spherical symmetry around M31 and choose templates to test the radial dependence of intensity and spectrum: M31 Inner Galaxy, Spherical Halo, Far Outer Halo. These templates are detected with significance >5σ.
- We conclude there is robust evidence for a significant extended 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 M31 (the Far Outer Halo might have significant contribution from the MW), and the spectrum peaks in the 3-20 GeV energy range

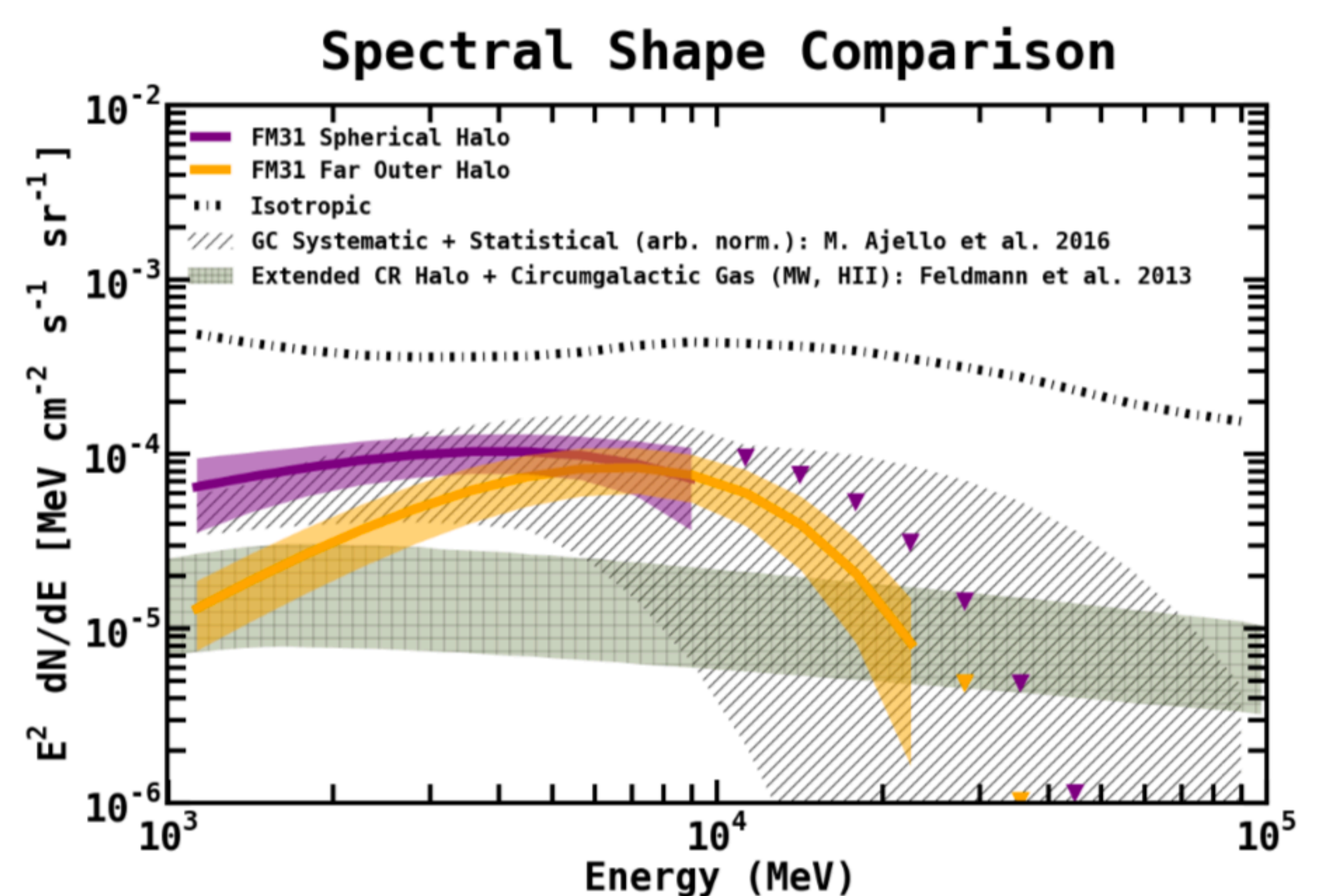




INTERPRETATION

- 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
- 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%)





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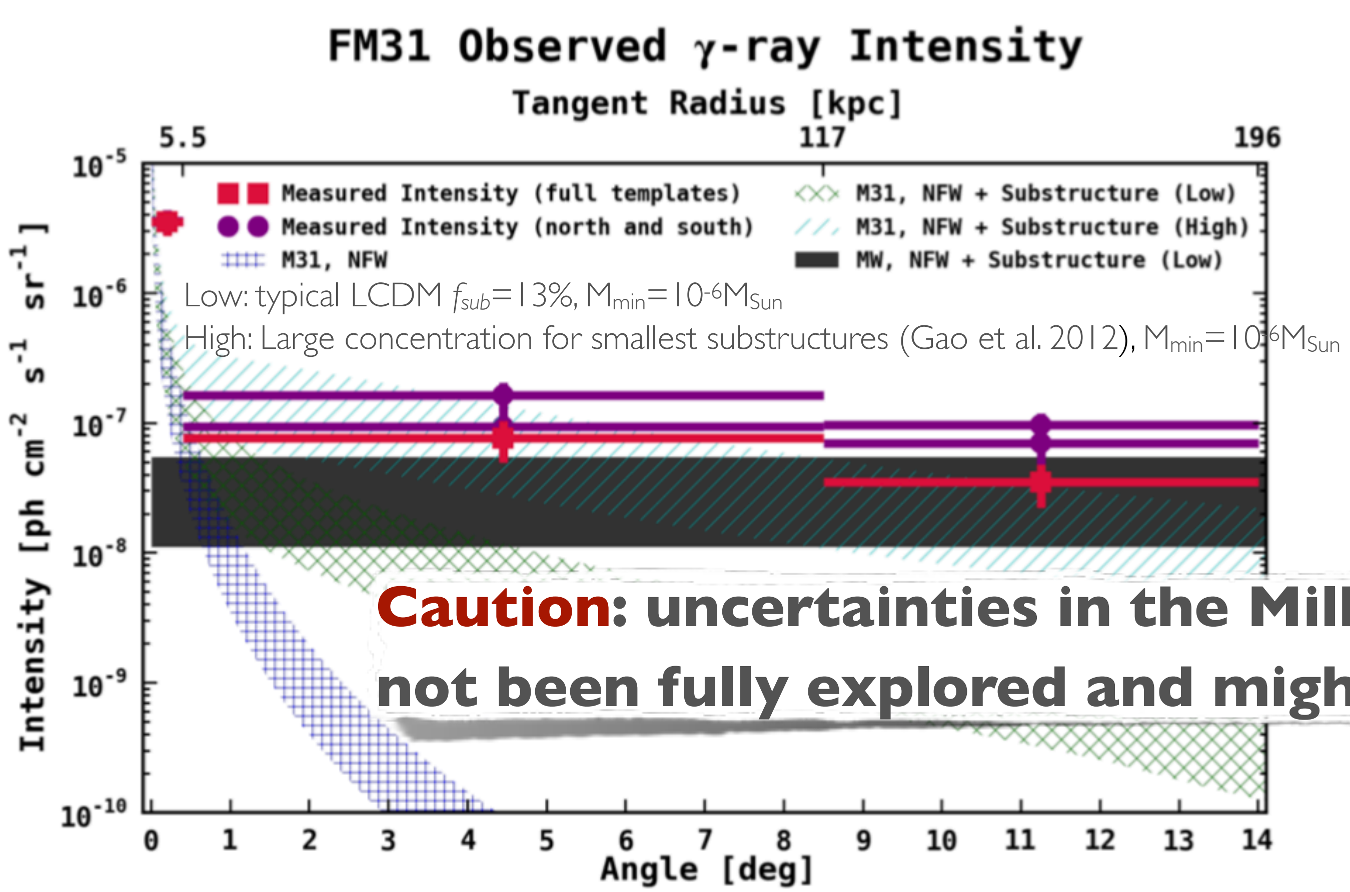
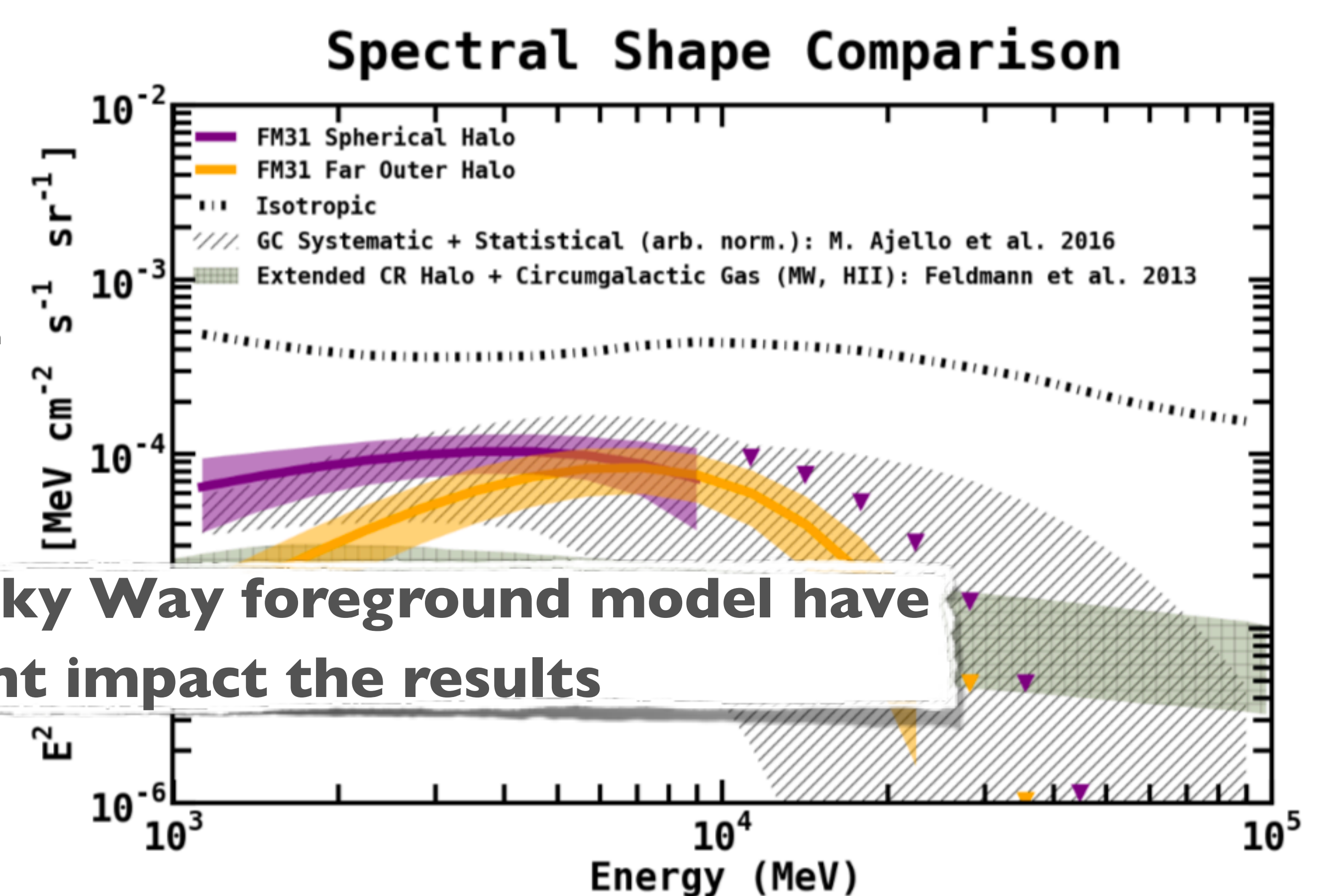
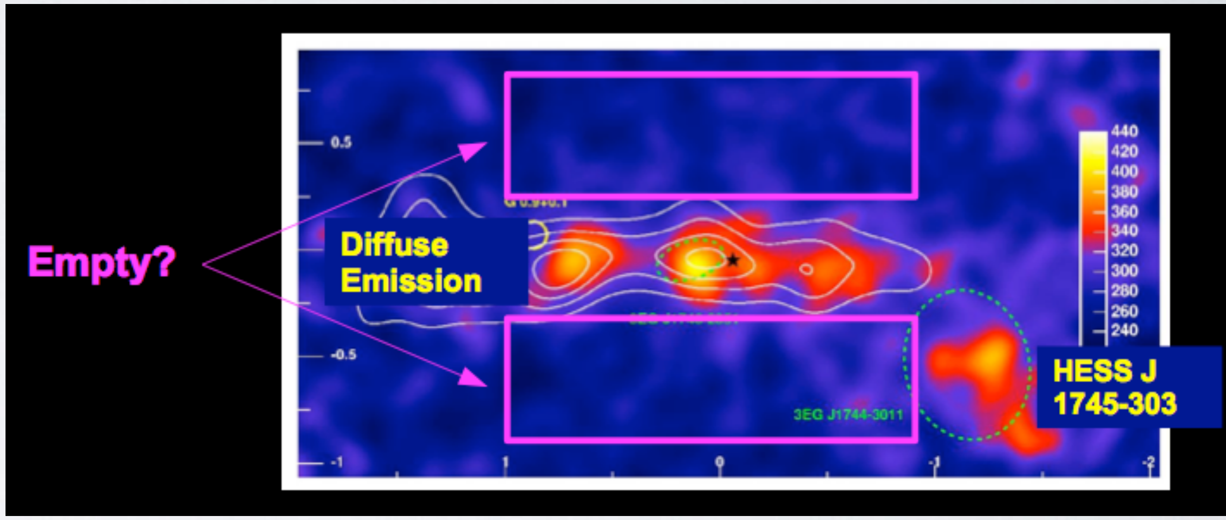




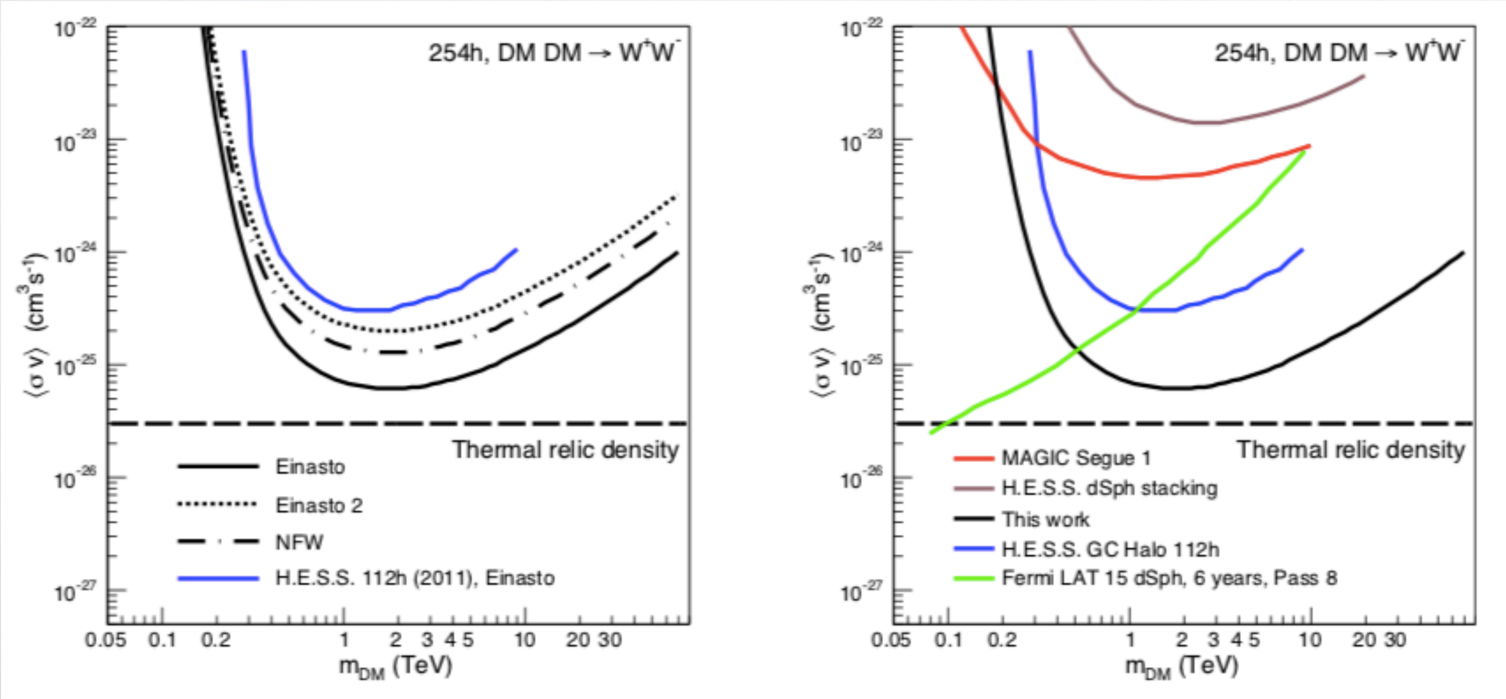
Caution: uncertainties in the Milky Way foreground model have not been fully explored and might impact the results

VHE GAMMA RAYS: H.E.S.S., MAGIC, VERITAS, HAWC

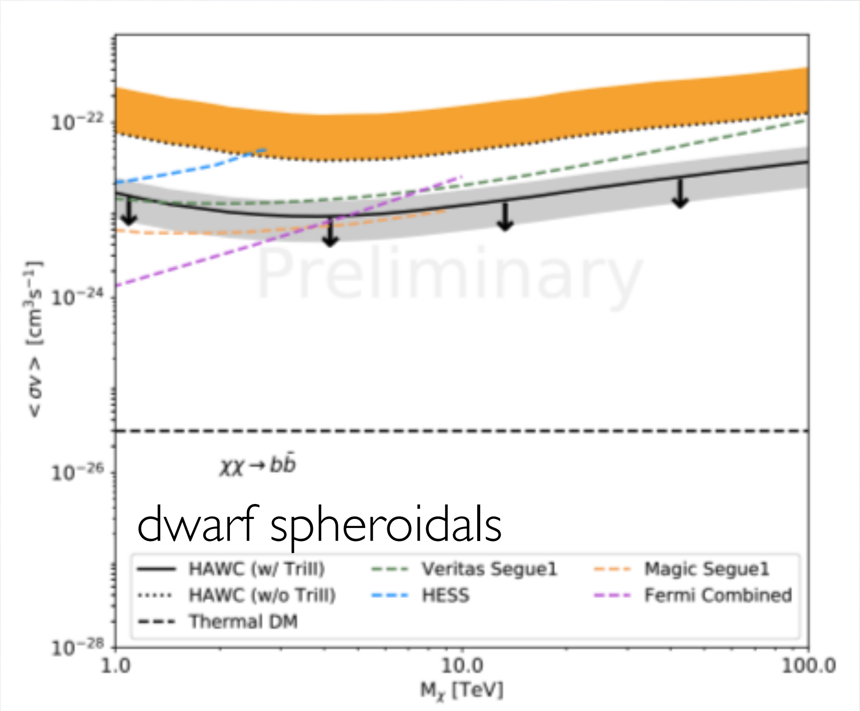
- Higher energy threshold compared to Fermi LAT, sensitive to higher dark matter masses
- No dark matter-like emission is observed
- Dark matter constraints are competitive with Fermi LAT for dark matter particle masses above ~500 GeV (dependence on DM profile)



HESS Collaboration, arXiv:1607.08142



HAWC Collaboration, arXiv:1706.01277



CONCLUSIONS

- DM searches with γ-rays have set stringent constraints on DM models (mainly from dwarf spheroidals) and produced an intriguing excess from the GC, and, more recently, from M31
- Annihilating DM provides a good description of the excesses
- However, better understanding of the systematics and complementarity with other DM searches crucial before claiming a discovery

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Thank you!