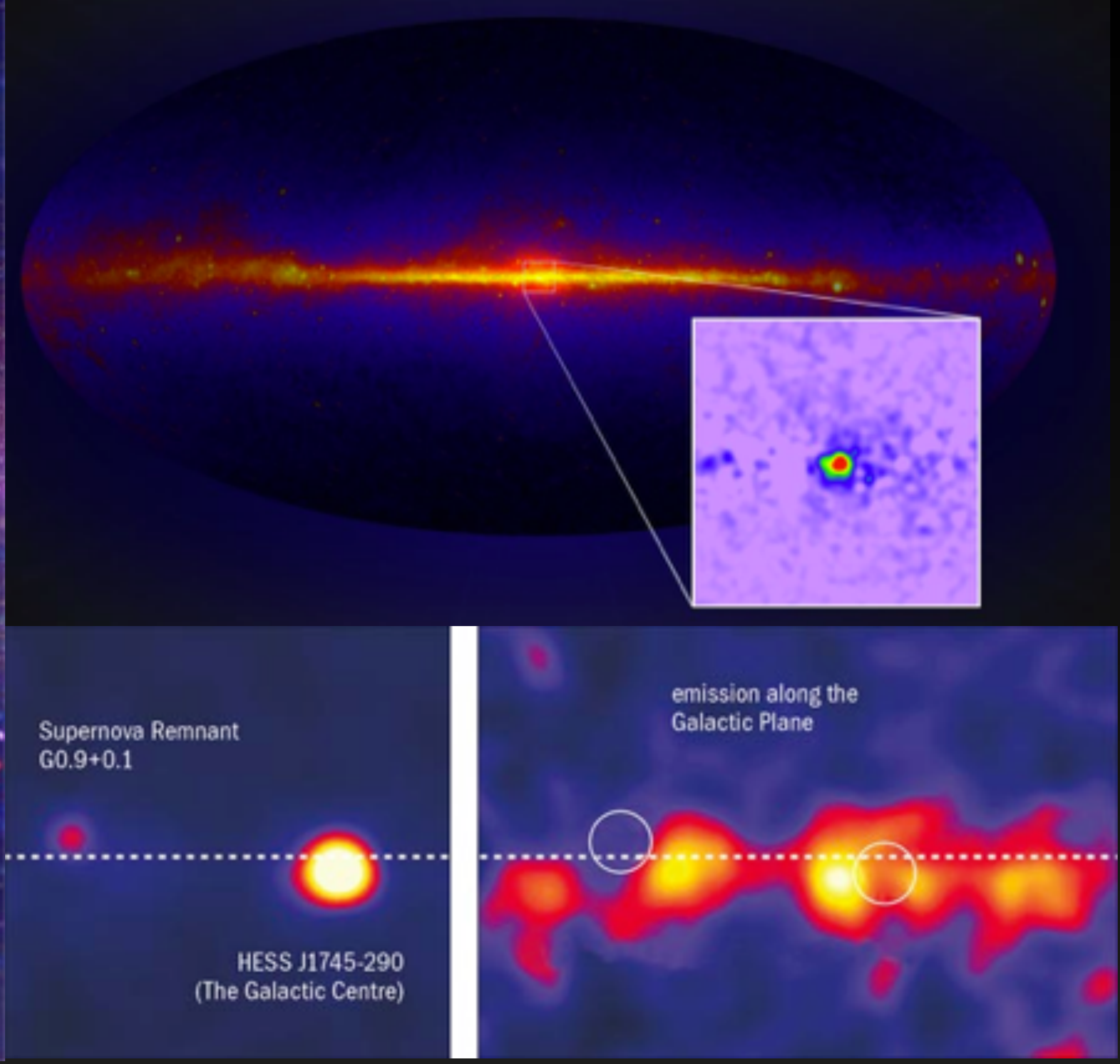


Dark Matter, Pulsar, and Diffuse Emission Models for the Galactic Center Excess

Tim Linden

CCAPP Postdoctoral Fellow
Center for Cosmology and Astro-Particle Physics
The Ohio State University

CCAPP

The Ohio State University

TeVPA 2016

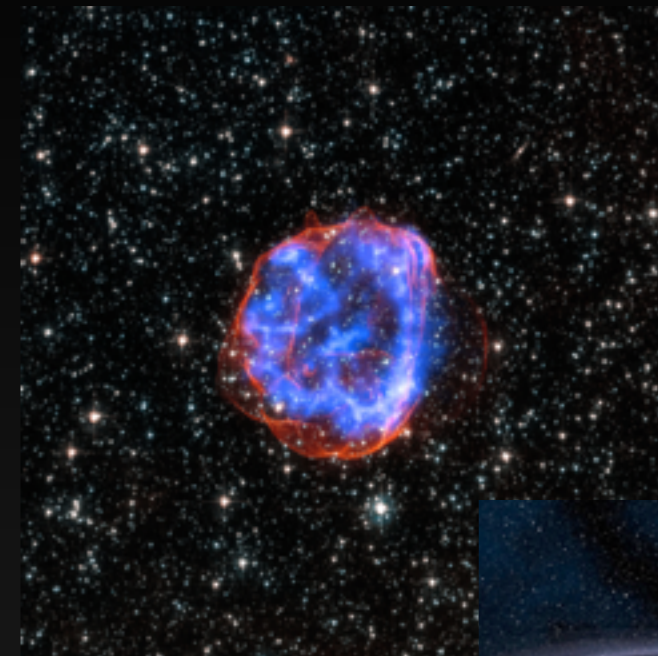
9/15/16

The Central Molecular Zone

- 400 pc x 80 pc
- 10^7 M_o of gas in Molecular Clouds
- Conditions similar to nearby starburst galaxies

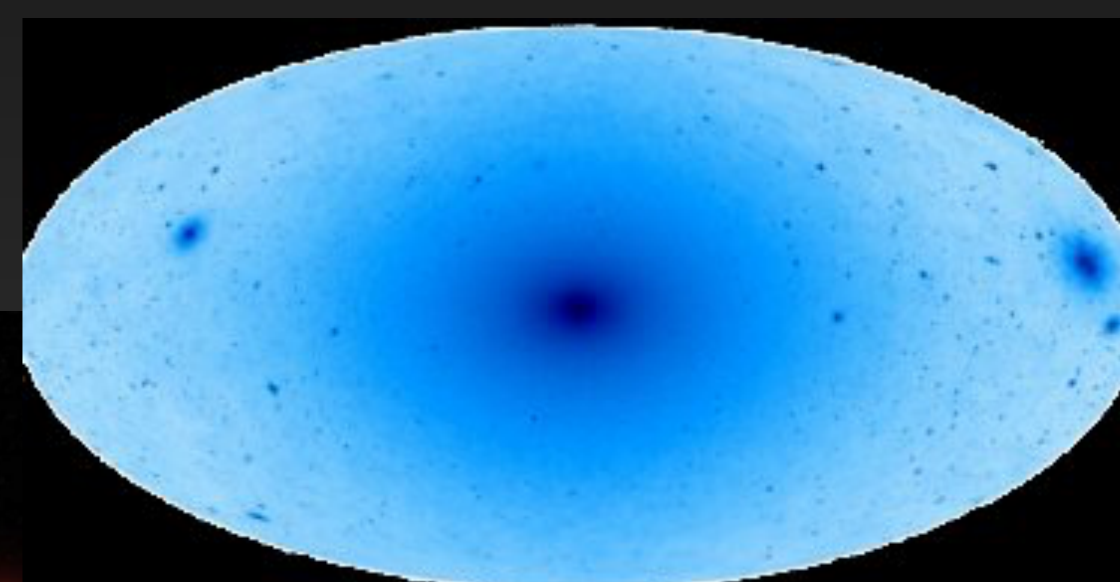
- Molecular Gas clouds in the Central Molecular Zone are hot (~50-100K), which is indicative of heating by a significant cosmic-ray population. (Yusef-Zadeh et al. 2013)

What Generates these Cosmic-Rays?



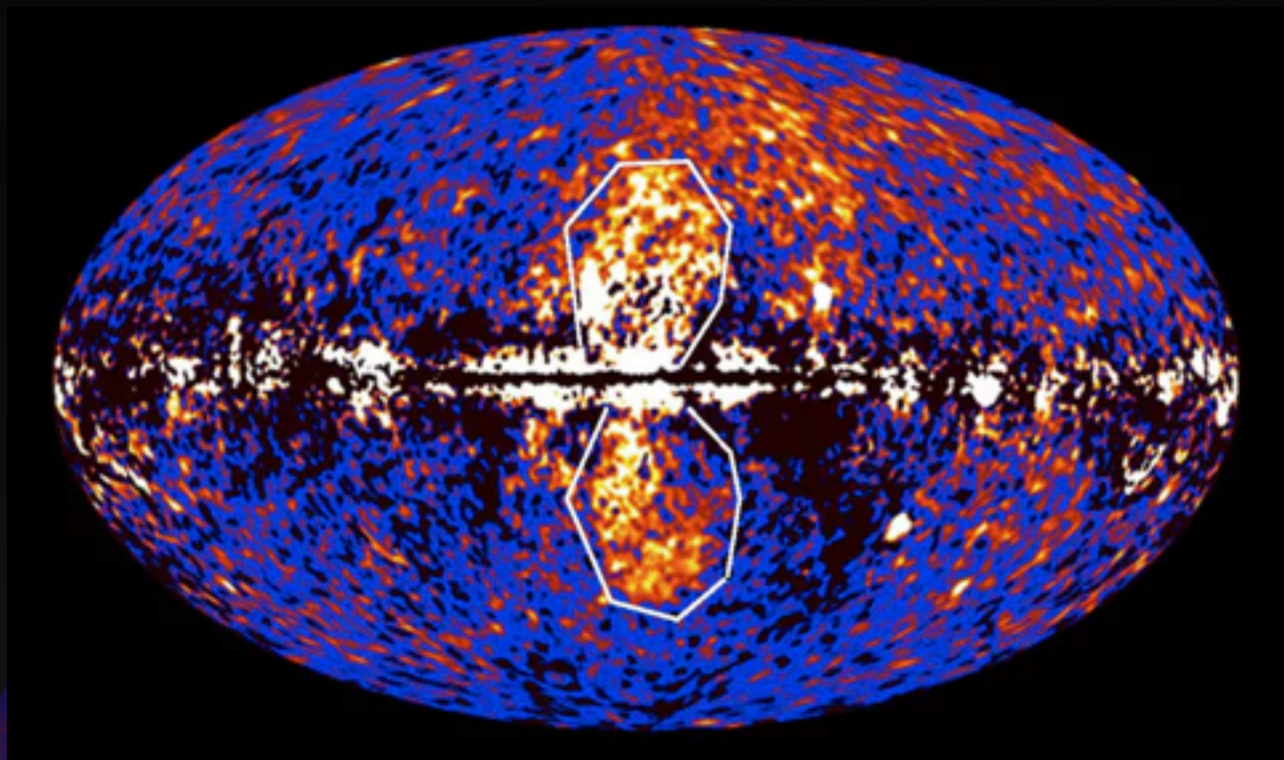
The Galactic center region is known to contain nearly every known cosmic-ray acceleration mechanism.

1.) Supernovae
2.) Pulsars
3.) Sgr A*
4.) Dark Matter Annihilation?

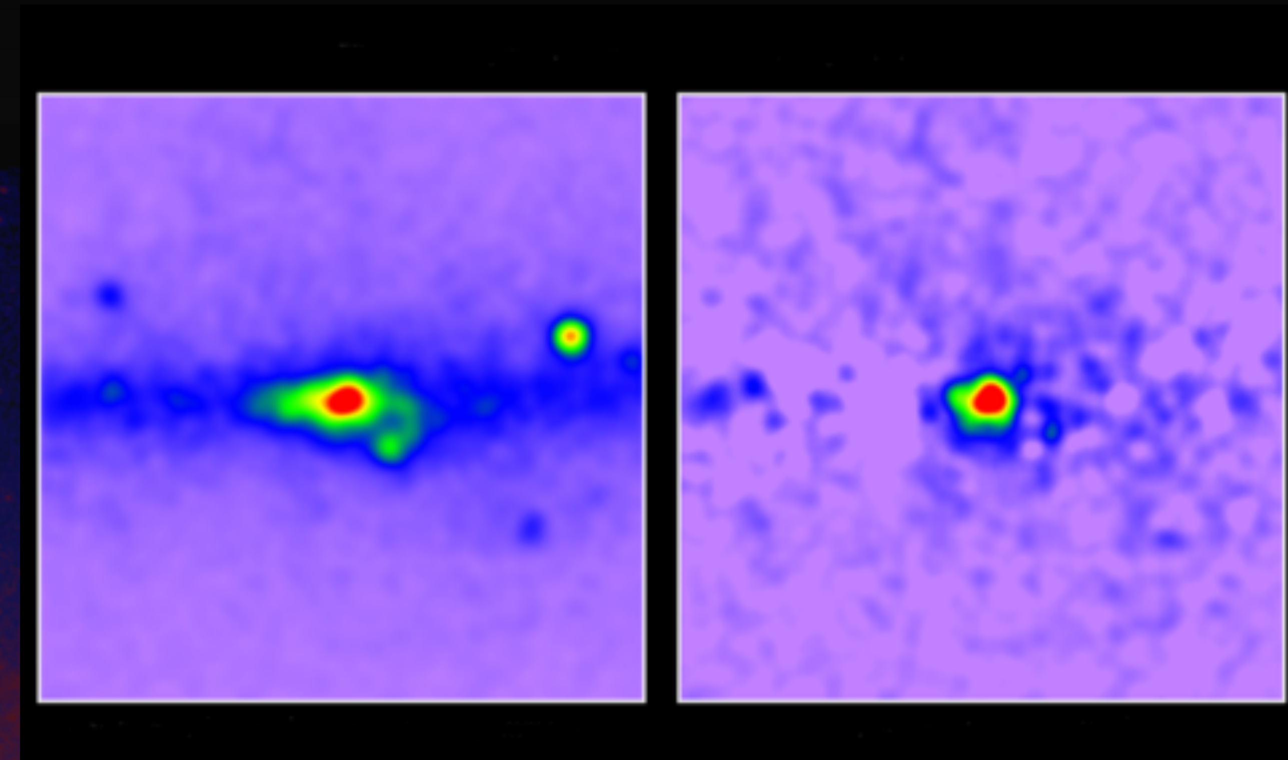


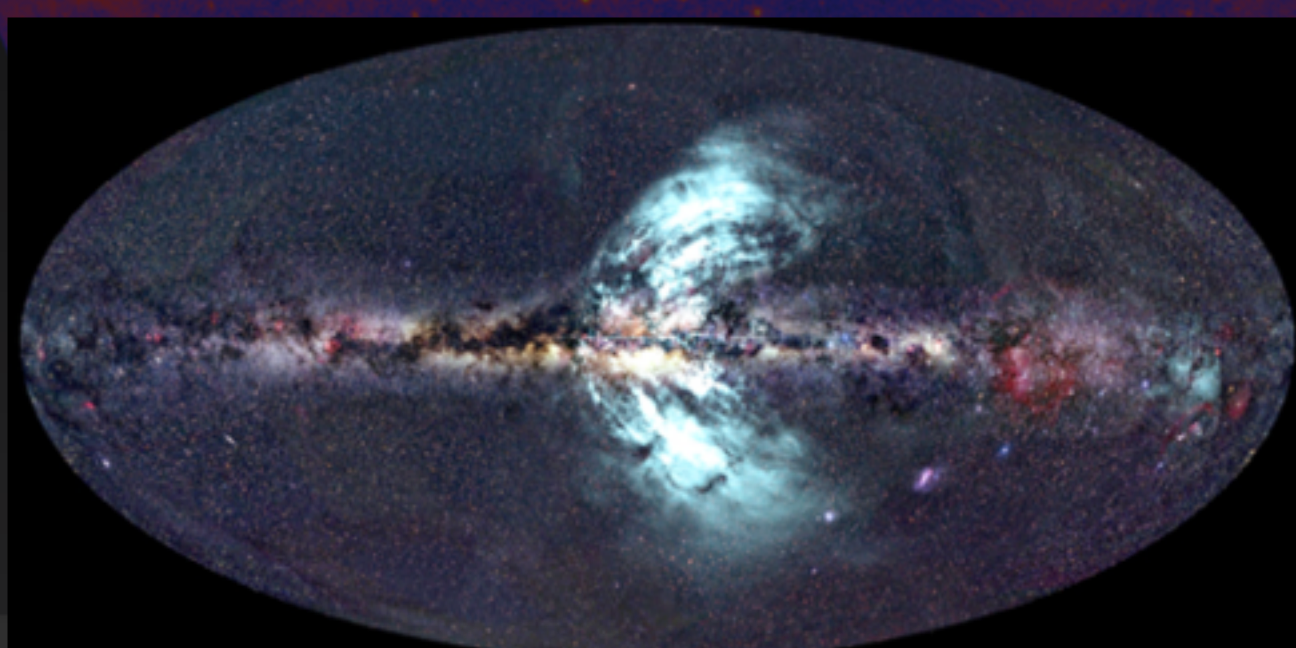
The GC Powers Large Scale Excesses

Fermi Bubbles

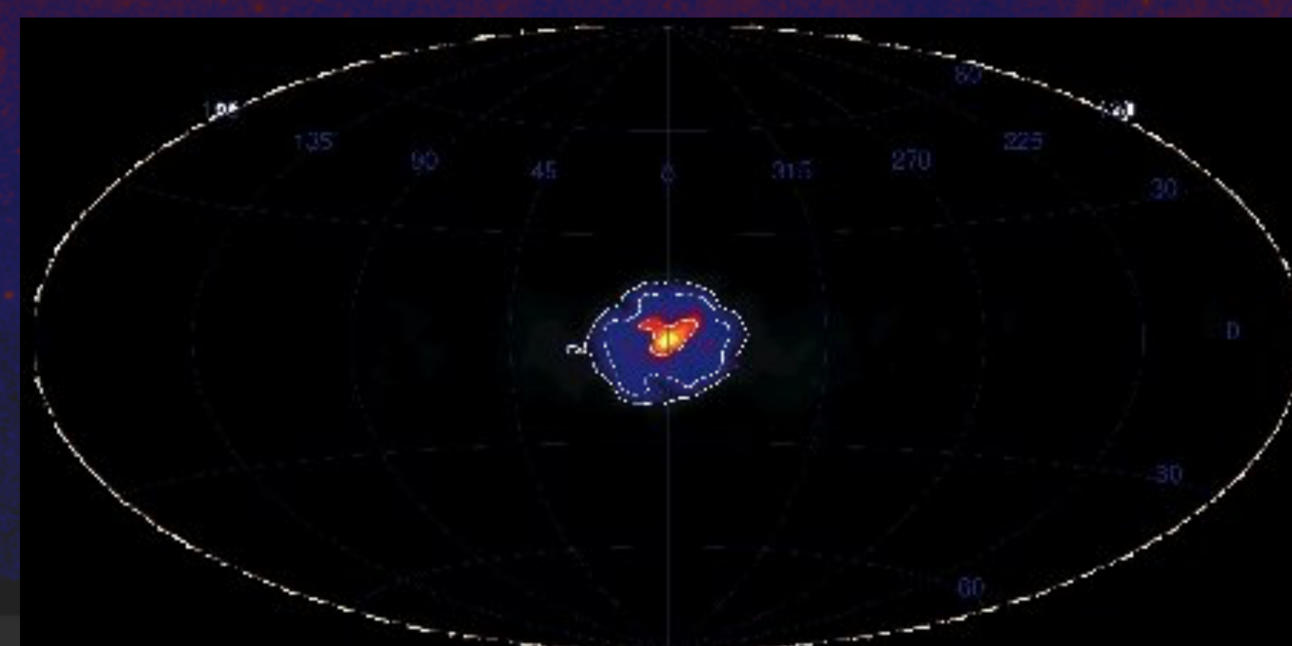


GeV Excess



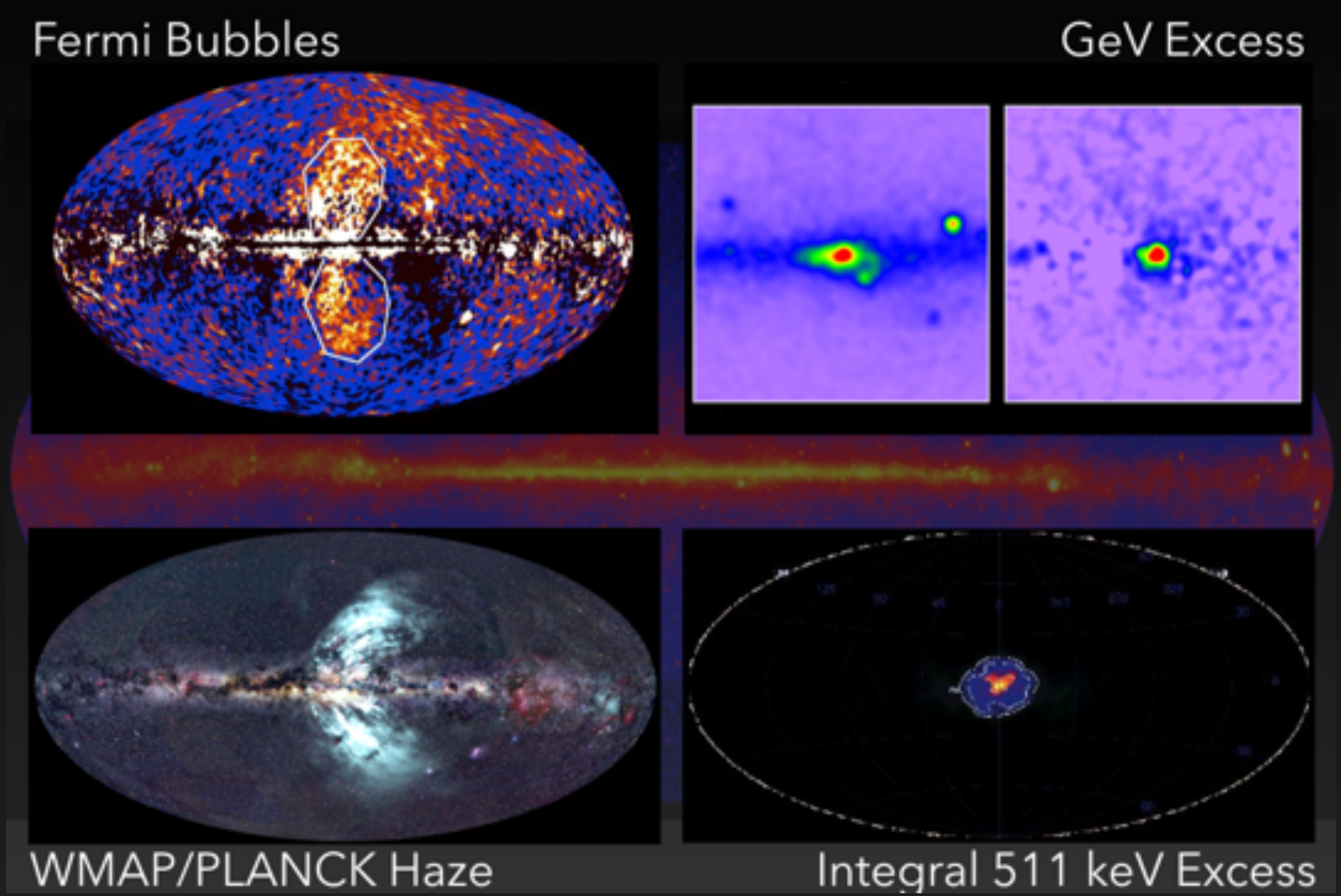


WMAP/PLANCK Haze



Integral 511 keV Excess

Non-Thermal Emission (Observables)



The photon excesses extend very far from the central molecular region!

This:

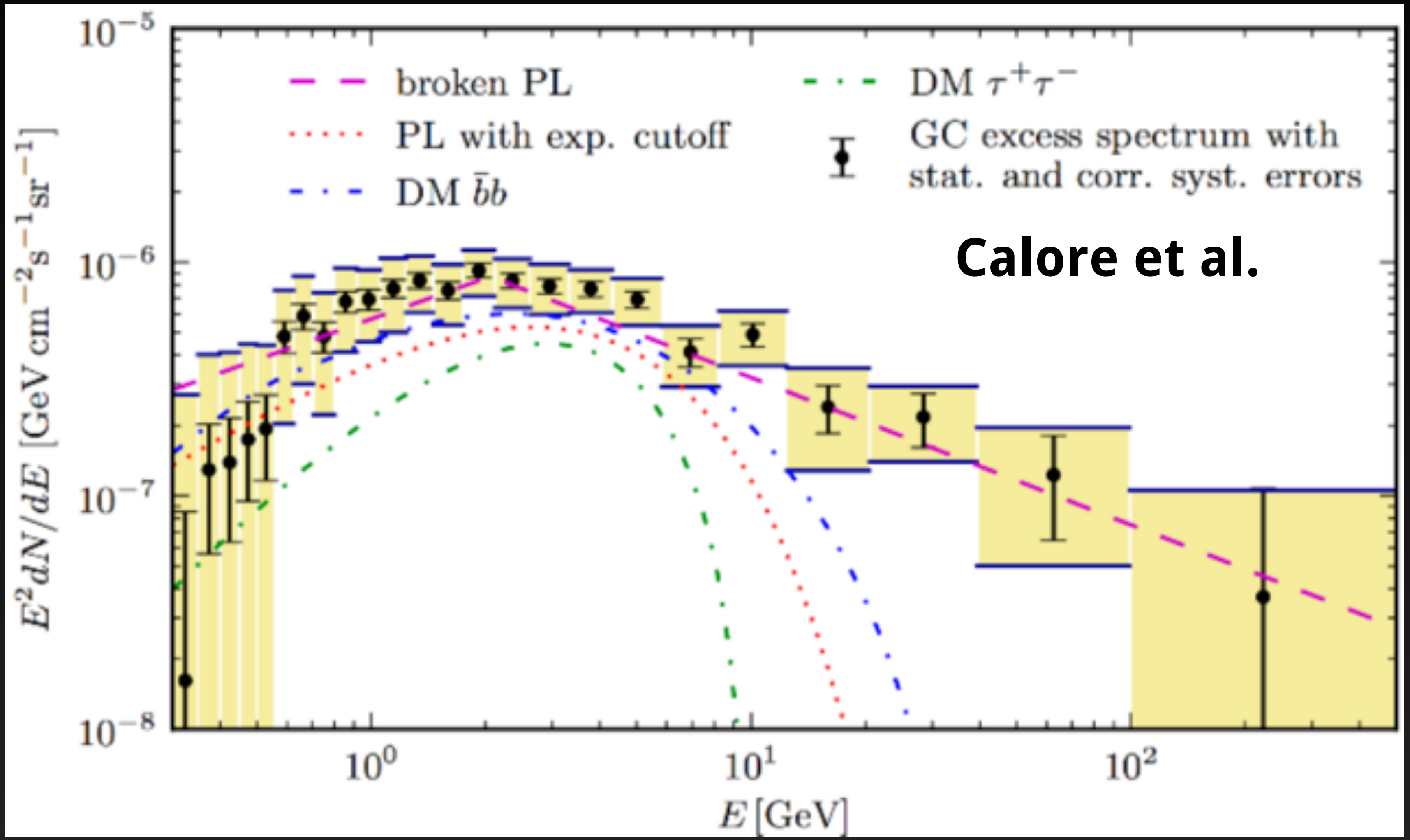
(a) Indicates the relative power of Galactic center accelerators, compared to the Galactic plane.

(b) Provides a large field of view for studies of GC emission.

(c) Implies that propagation is important!

Observational Results

Goodenough & Hooper (2009, 0910.2998)
Hooper & Goodenough (2010, 1010.2752)
Hooper & Linden (2011, 1110.0006)
Abazajian & Kaplinghat (2012, 1207.6047)
Gordon & Macias (2013, 1306.5725)
Gordon & Macias (2013, 1312.6671)
Abazajian et al. (2014, 1402.4090)
Daylan et al. (2014, 1402.6703)
Calore et al. (2014, 1409.0042)
Abazajian et al. (2014, 1410.6168)
Bartels et al. (2015, 1506.05104)
Lee et al. (2015, 1506.05124)
Gaggero et al. (2015, 1507.06129)
Carlson et al. (2015, 1510.04698)
The Fermi-LAT Collaboration (2015, 1511.02938)
Yang & Aharonian (2016, 1602.06764)
Carlson et al. (2016, 1603.06584)
Linden et al. (2016, 1604.01026)
Horiuichi et al. (2016, 1604.01402)



<u>These are the three resilient features of the GeV Excess:</u>

1.) Hard Gamma-Ray Spectrum peaking at ~2 GeV
2.) Spherically Symmetric Emission Morphology
3.) Extension to >10° from the GC.

Astrophysical Models

How could we model this with:

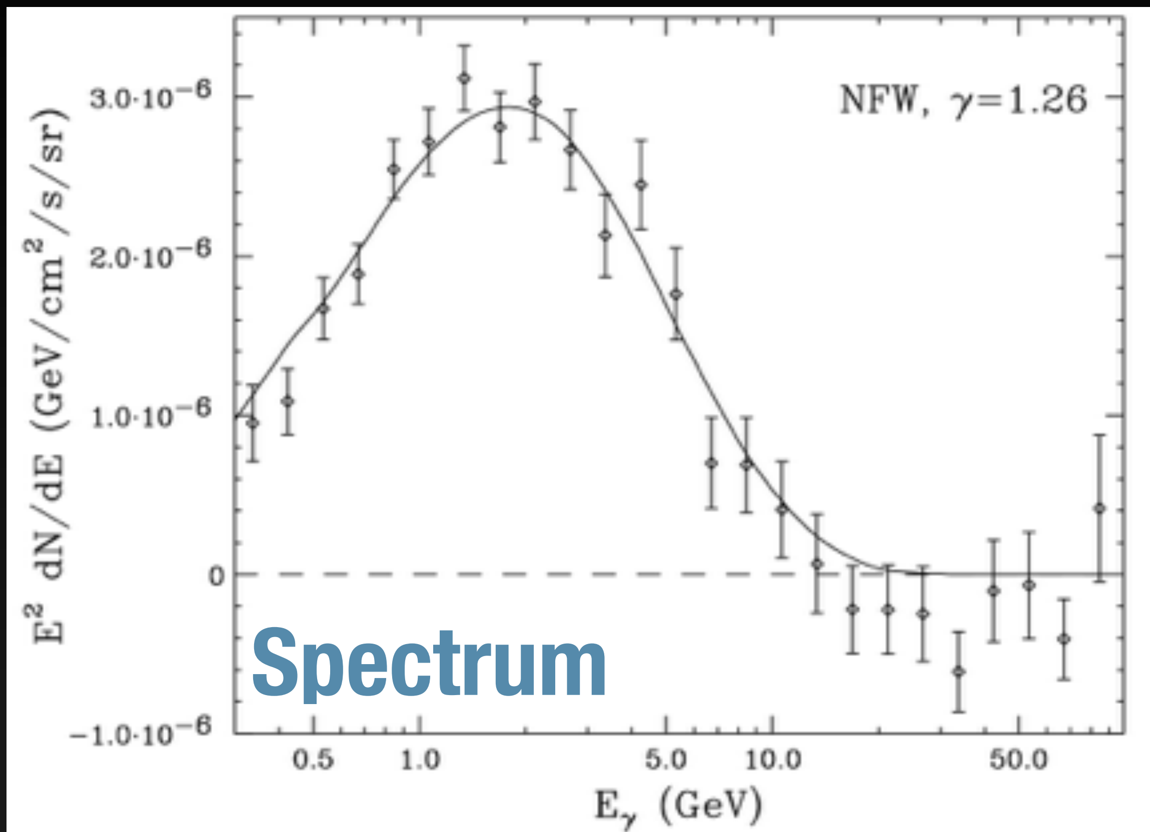
1.) Dark Matter annihilation

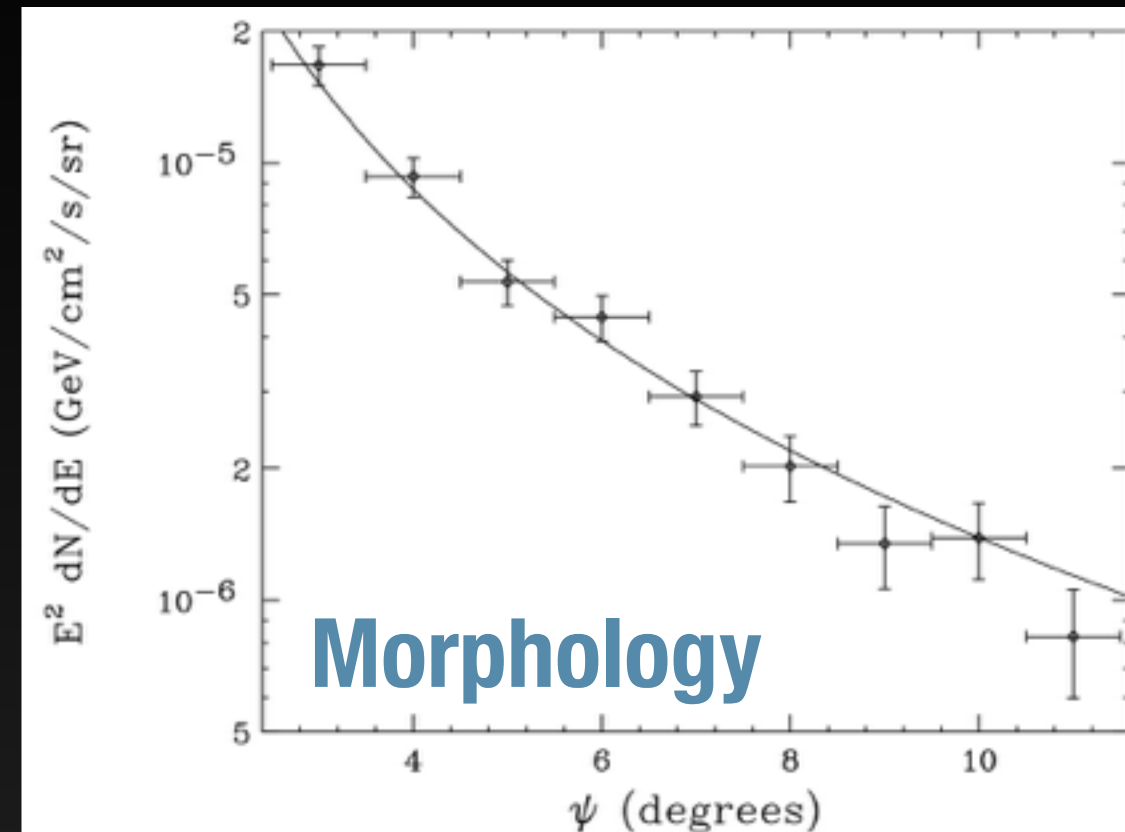
2.) Millisecond Pulsars

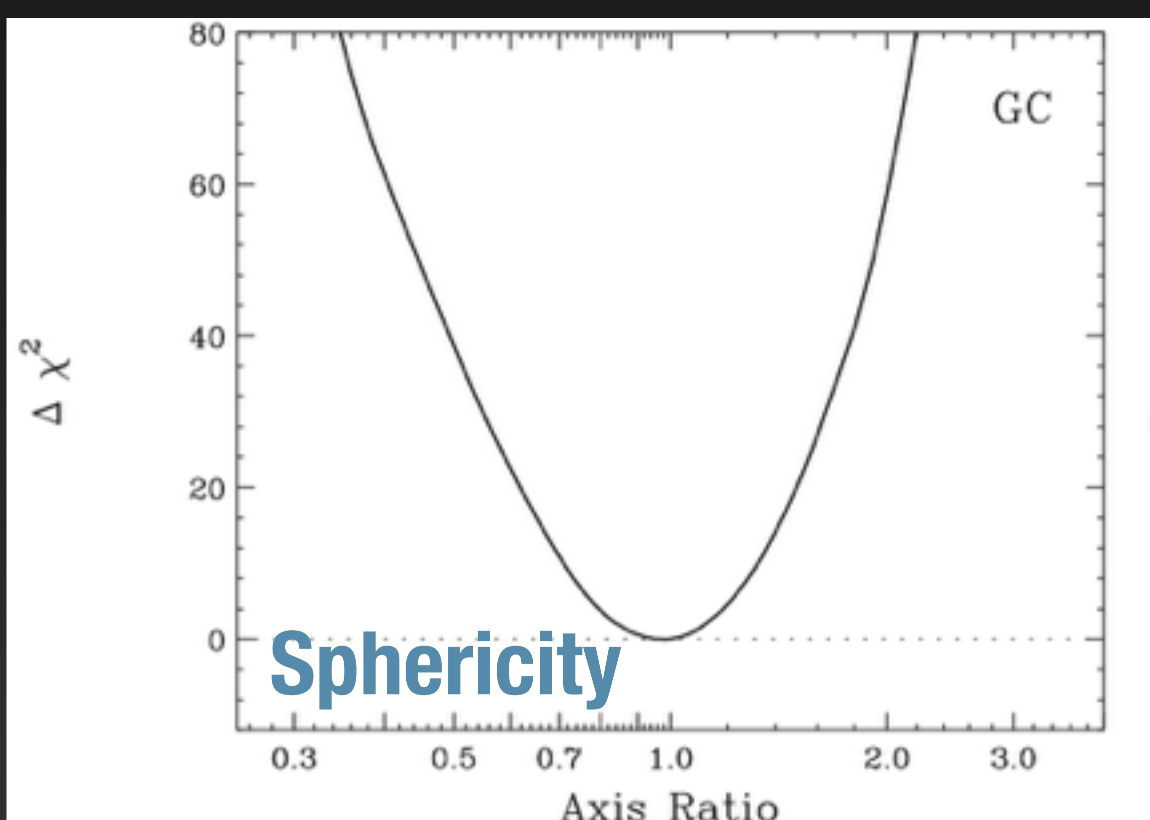
3.) Cosmic-Ray Outbursts

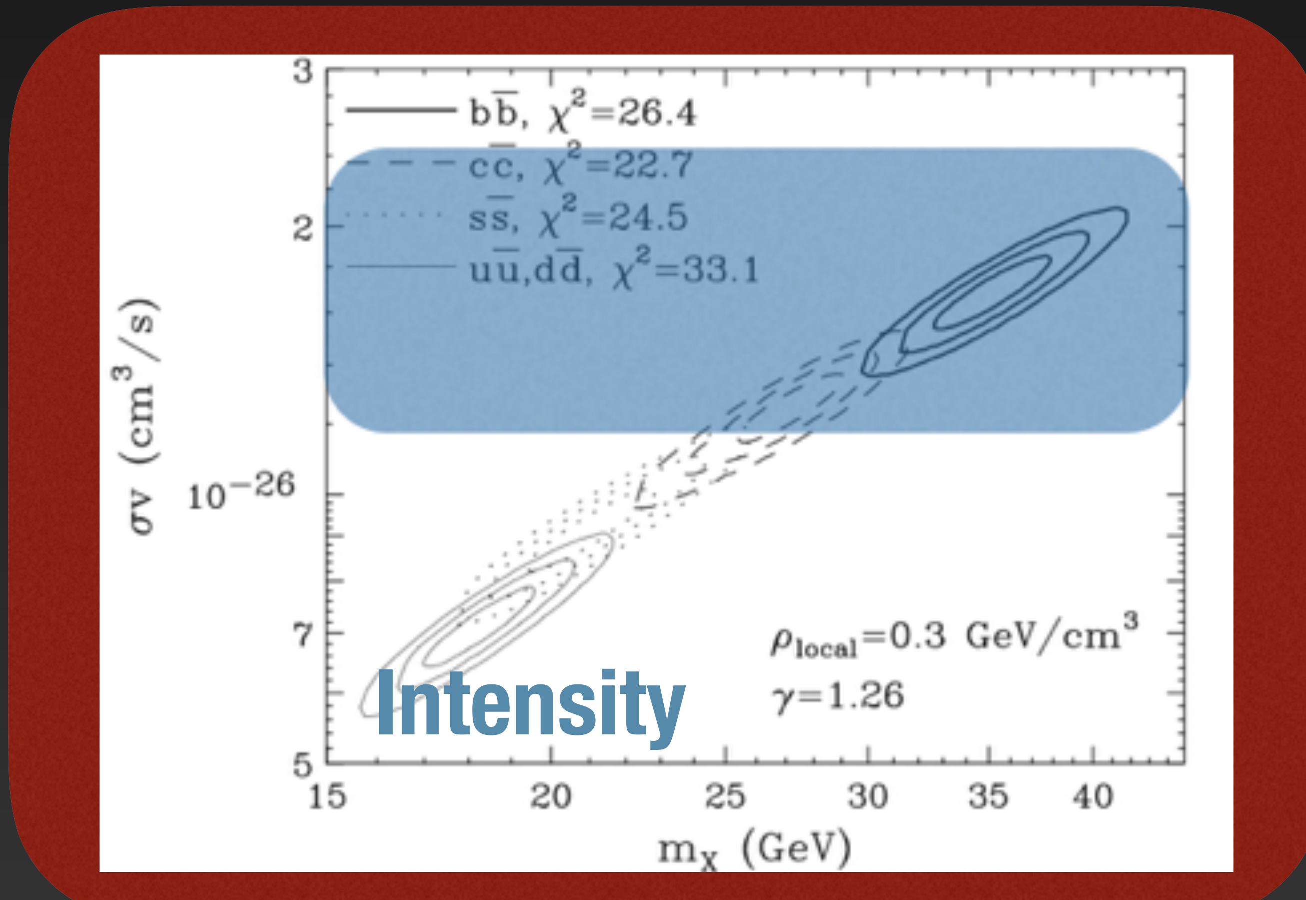
4.) Diffuse Emission Modeling

Dark Matter Model Fitting?





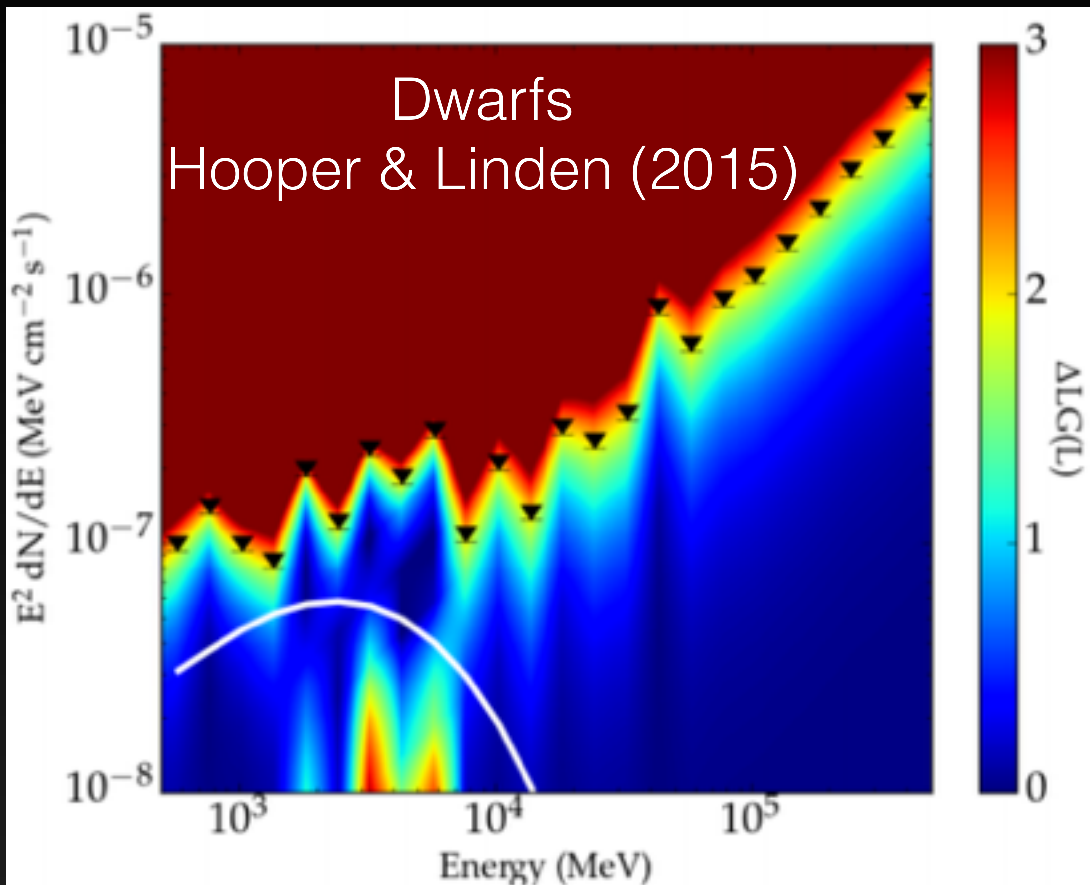


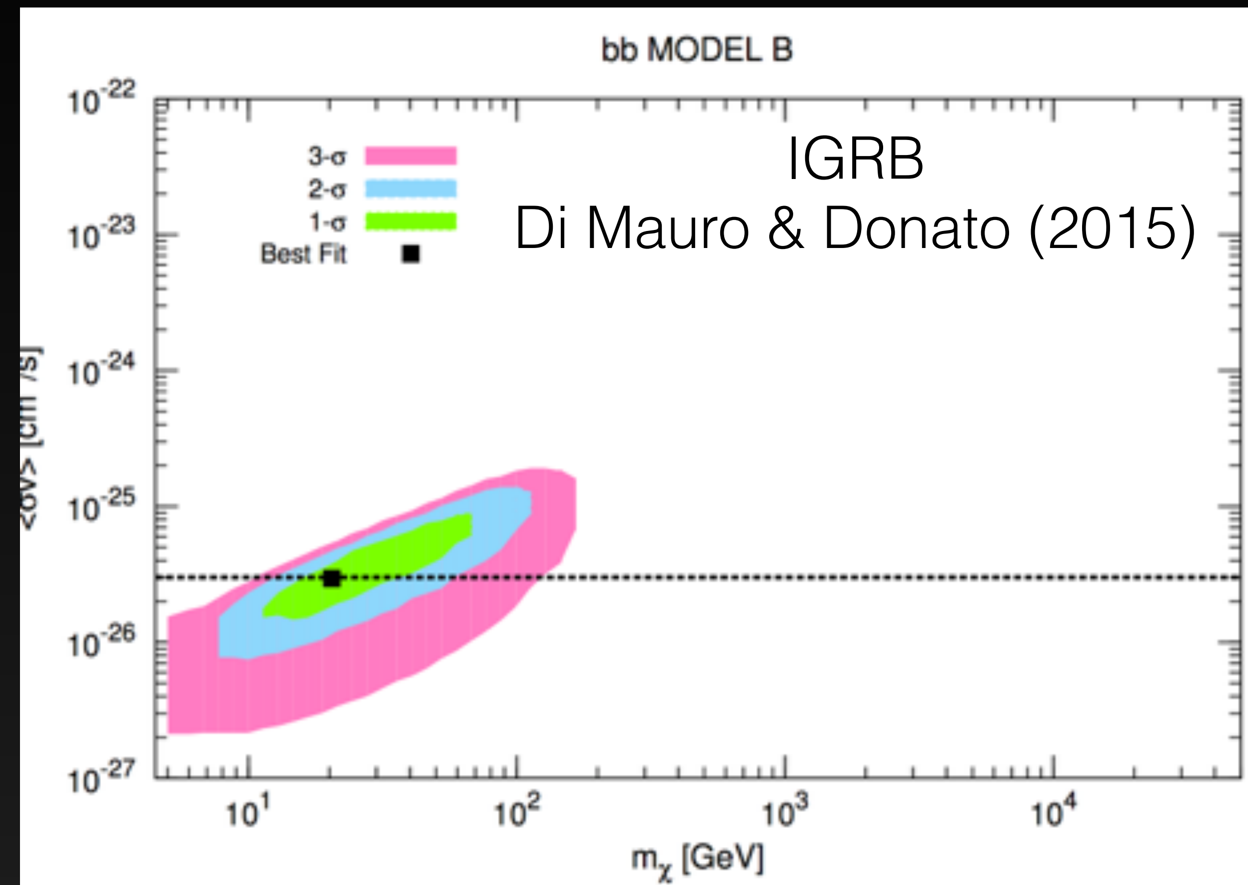


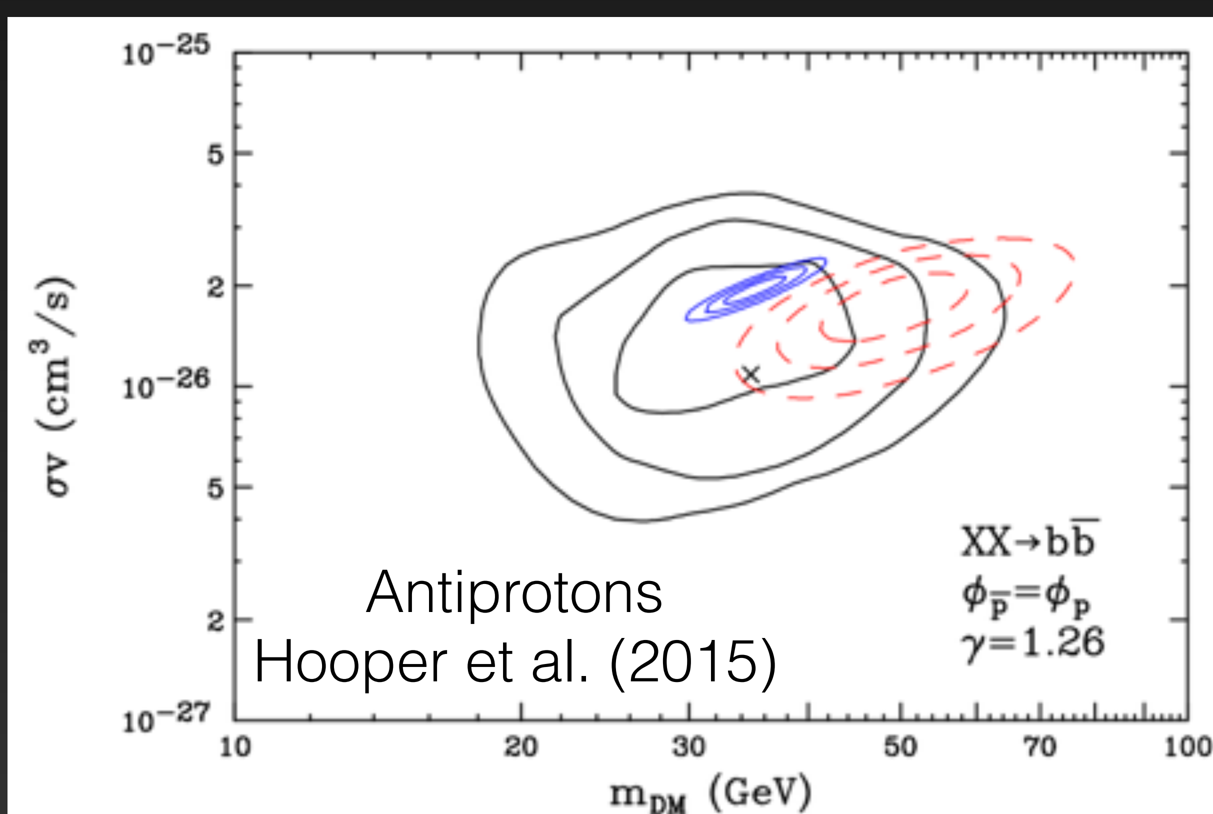
Particle Physics Models Exist...

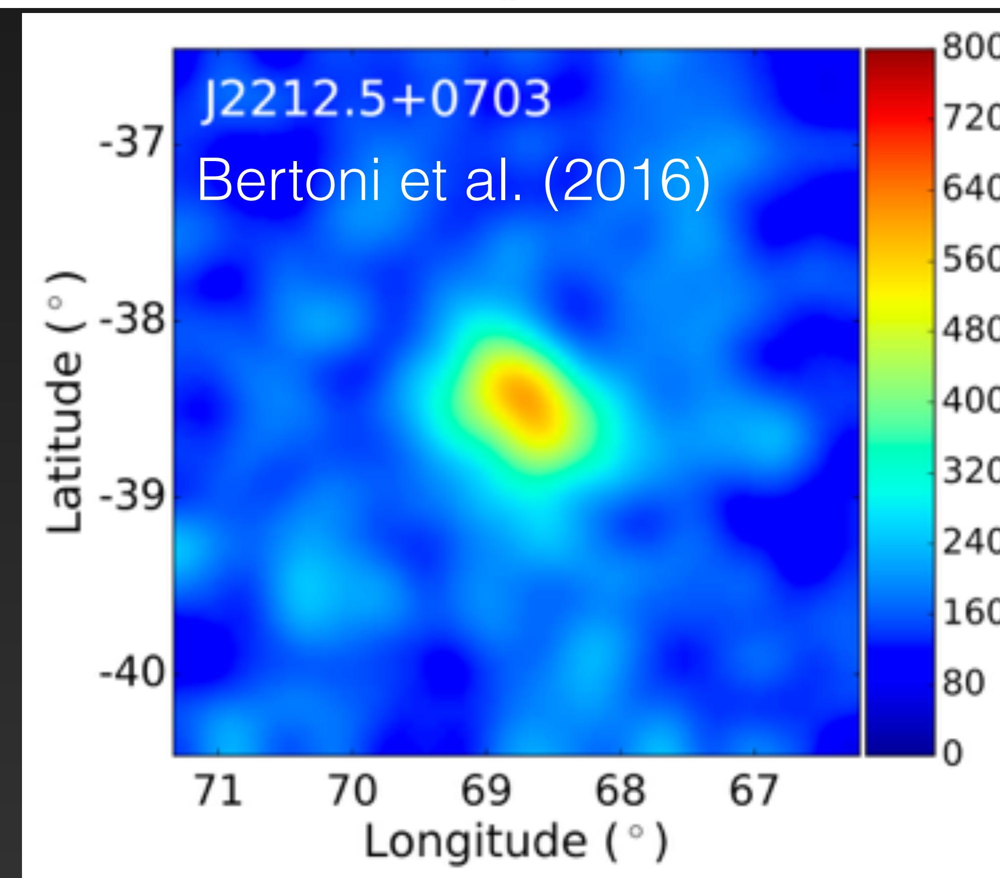
Chan (1607.02246)
Jia (1607.00737)
Barrau et al. (1606.08031)
Huang et al. (1605.09018)
Cui et al. (1605.08138)
Krauss et al. (1605.05327)
Kumar et al. (1605.00611)
Biswas et al. (1604.06566)
Sage et al. (1604.04589)
Choquette et al. (1604.01039)
Cuoco et al. (1603.08228)
Chao et al. (1602.05192)
Horiuchi et al. (1602.04788)
Hektor et al. (1602.00004)
Freytsis et al. (1601.07556)
Kim et al. (1601.05089)
Huang et al. (1512.08992)
Kulkami et al. (1512.06836)
Tang et al. (1512.02899)
Cox et al. (1512.00471)
Cai et al. (1511.09247)
Agrawal et al. (1511.06293)
Duerr et al. (1510.07562)
Drozd et al. (1510.07053)
Arcadi et al. (1510.02297)
Williams (1510.00714)
Cai & Spray (1509.08481)
Freese et al. (1509.05076)
Bhattacharya et al. (1509.03665)
Algeri et al. (1509.01010)
Fox & Tucker-Smith (1509.00499)
Dutta et al. (1509.05989)
Liu et al. (1508.05716)
Berlin et al. (1508.05390)
Fan et al. (1507.06993)
Hektor et al. (1507.05096)
Achterbeg et al. (1507.04644)
Biswas et al. (1507.04543)
Butter et al. (1507.02288)
Mondal et al. (1507.01793)
Cao et al. (1506.06471)
Banik et al. (1506.05665)
Ipek (1505.07826)
Buchmueller et al. (1505.07826)
Balazs et al. (1505.06758)
Medina (1505.05565)
Kim et al. (1505.04620)
Ko et al. (1504.06944)
Ko & Tang (1504.03908)
Ghorbani & Ghorbani (1504.03610)
Fortes et al. (1503.08220)
Cline et al. (1503.08213)
Rajaraman et al. (1503.05919)
Bi et al. (1503.03749)
Kopp et al. (1503.02669)
Elor et al. (1503.01773)
Gherghetta et al. (1502.07173)
Berlin et al. (1502.06000)
Achterberg et al. (1502.05703)
Modak et al. (1502.05682)
Guo et al. (1502.00508)
Chen & Nomura (1501.07413)
Kozaczuk & Martin (1501.07275)
Berlin et al. (1501.03496)
Kaplinghat et al. (1501.03507)
Alves et al. (1501.03490)
Biswas et al. (1501.02666)
Biswas et al. (1501.02666)
Ghorbani & Ghorbani (1501.00206)
Cerdeno et al. (1501.01296)
Liu et al. (1412.1485)
Hooper (1411.4079)
Arcadi et al. (1411.2985)
Cheung et al. (1411.2619)
Agrawal et al. (1411.2592)
Kile et al. (1411.1407)
Buckley et al. (1410.6497)
Heikinheimo & Spethmann (1410.4842)
Freytsis et al. (1410.3818)
Yu et al. (1410.3347)
Cao et al. (1410.3239)
Guo et al. (1409.7864)
Yu (1409.3227)
Cahill-Rowley et al. (1409.1573)
Banik & Majumdar (1408.5795)
Bell et al. (1408.5142)
Ghorbani (1408.4929)
Okada & Seto (1408.2583)
Frank & Mondal (1408.2223)
Baek et al. (1407.6588)
Tang (1407.5492)
Balazs & Li (1407.0174)
Huang et al. (1407.0038)
McDermott (1406.6408)
Cheung et al. (1406.6372)
Arina et al. (1406.5542)
Chang & Ng (1406.4601)
Wang & Han (1406.3598)
Cline et al. (1405.7691)
Berlin et al. (1405.5204)
Mondal & Basak (1405.4877)
Martin et al. (1405.0272)
Ghosh et al. (1405.0206)
Abdullah et al. (1404.5503)
Park & Tang (1404.5257)
Cerdeno et al. (1404.2572)
Izaguirre et al. (1404.2018)
Agrawal et al. (1404.1373)
Berlin et al. (1404.0022)
Alves et al. (1403.5027)
Finkbeiner & Weiner (1402.6671)
Boehm et al. (1401.6458)
Kopp et al. (1401.6457)
Modak et al. (1312.7488)
Alves et al. (1312.5281)
Fortes et al. (1312.2837)
Banik et al. (1311.0126)
Arhrib et al. (1310.0358)
Kelso et al. (1308.6630)
Kozaczuk et al. (1308.5705)
Kumar (1308.4513)
Demir et al. (1308.1203)
Buckley et al. (1307.3561)
Cline et al. (1306.4710)
Cannoni et al. (1205.1709)
An et al. (1110.1366)
Buckley et al. (1106.3583)
Boucenna et al. (1106.3368)
Ellis et al. (1106.0768)
Cheung et al. (1104.5329)
Marshall et al. (1102.0492)
Abada et al. (1101.0365)
Tytgat (1012.0576)
Logan (1010.4214)
Barger et al. (1008.1796)
Raklev et al. (0911.1986)

Testing the Dark Matter Interpretation



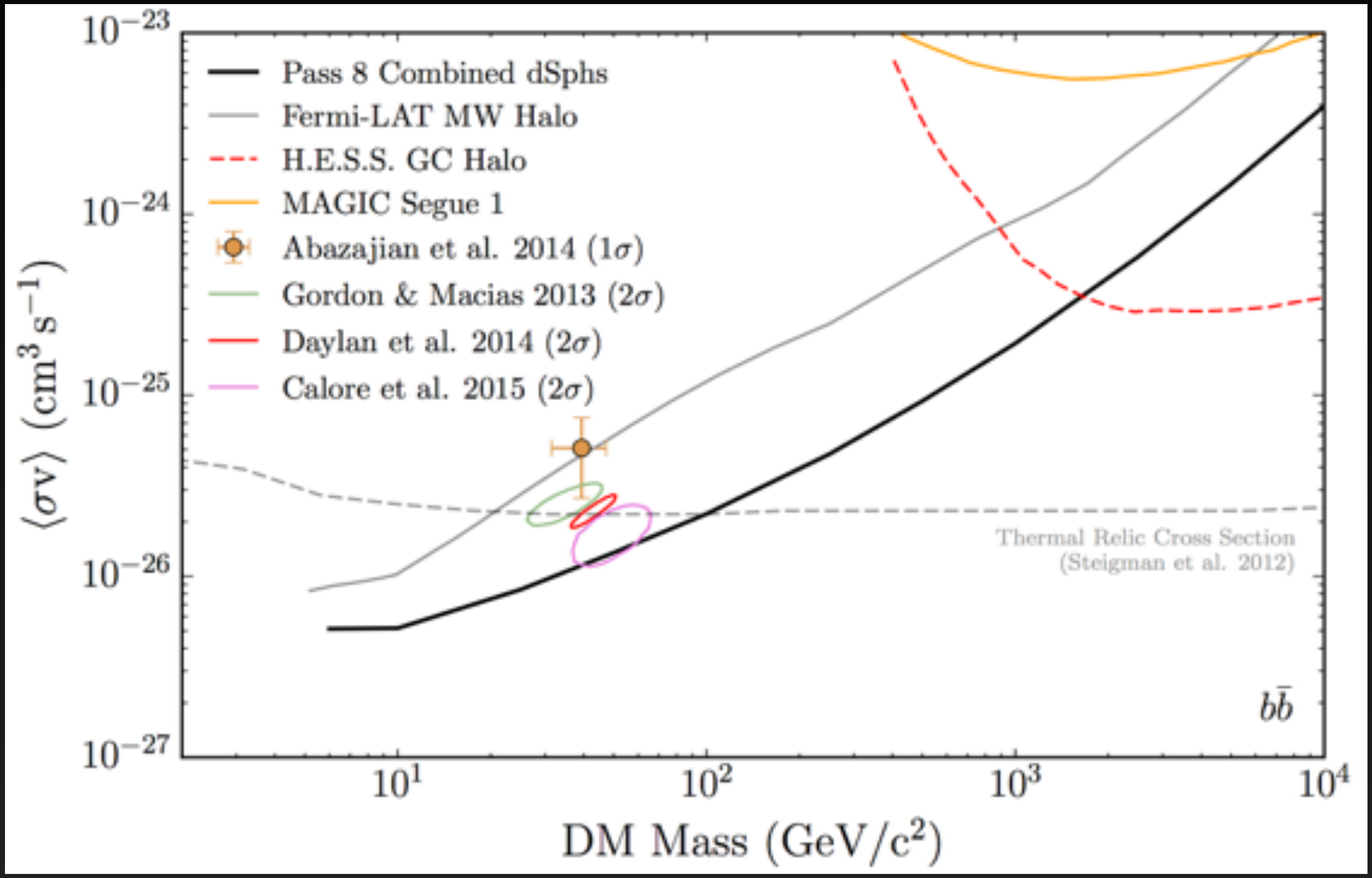






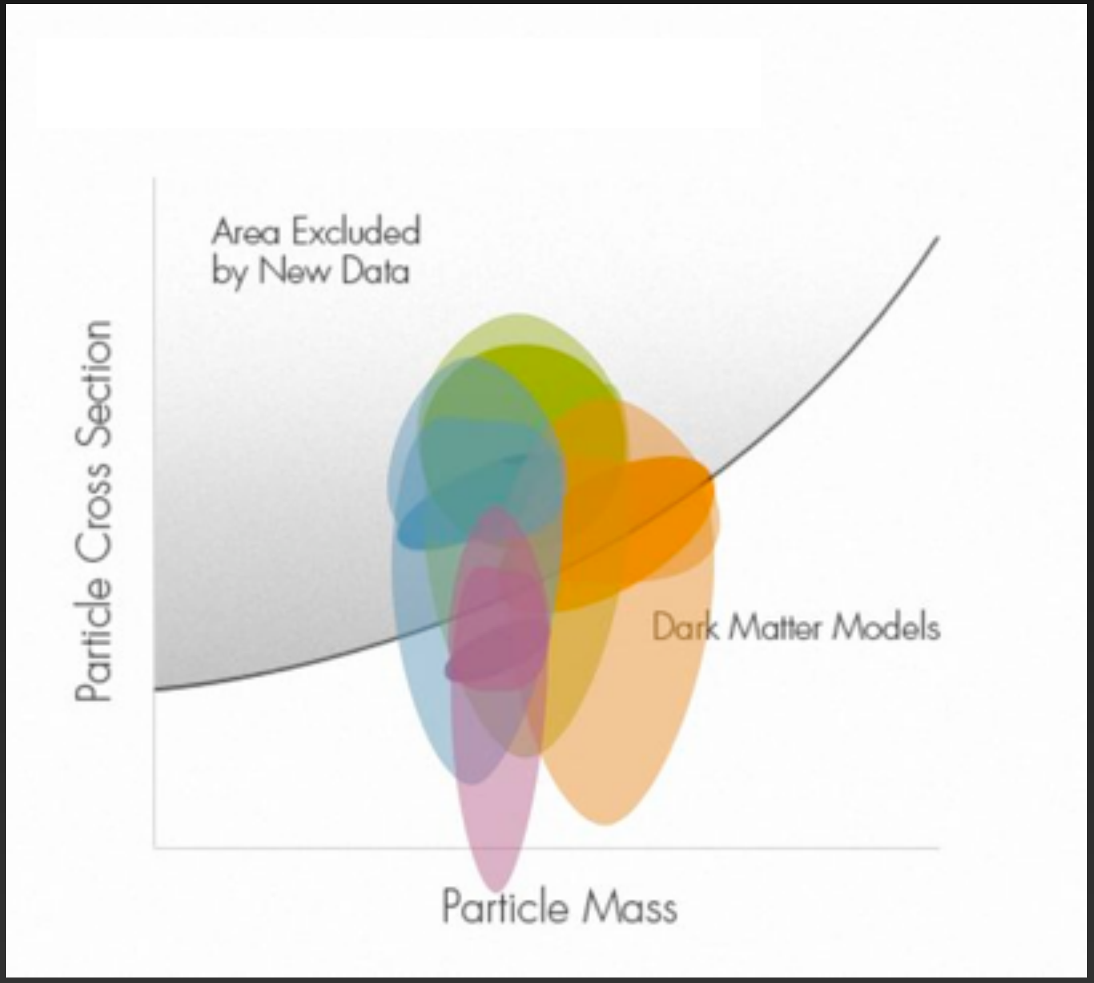
Testing the GCE with Dwarfs

Ackermann et al. (2015)



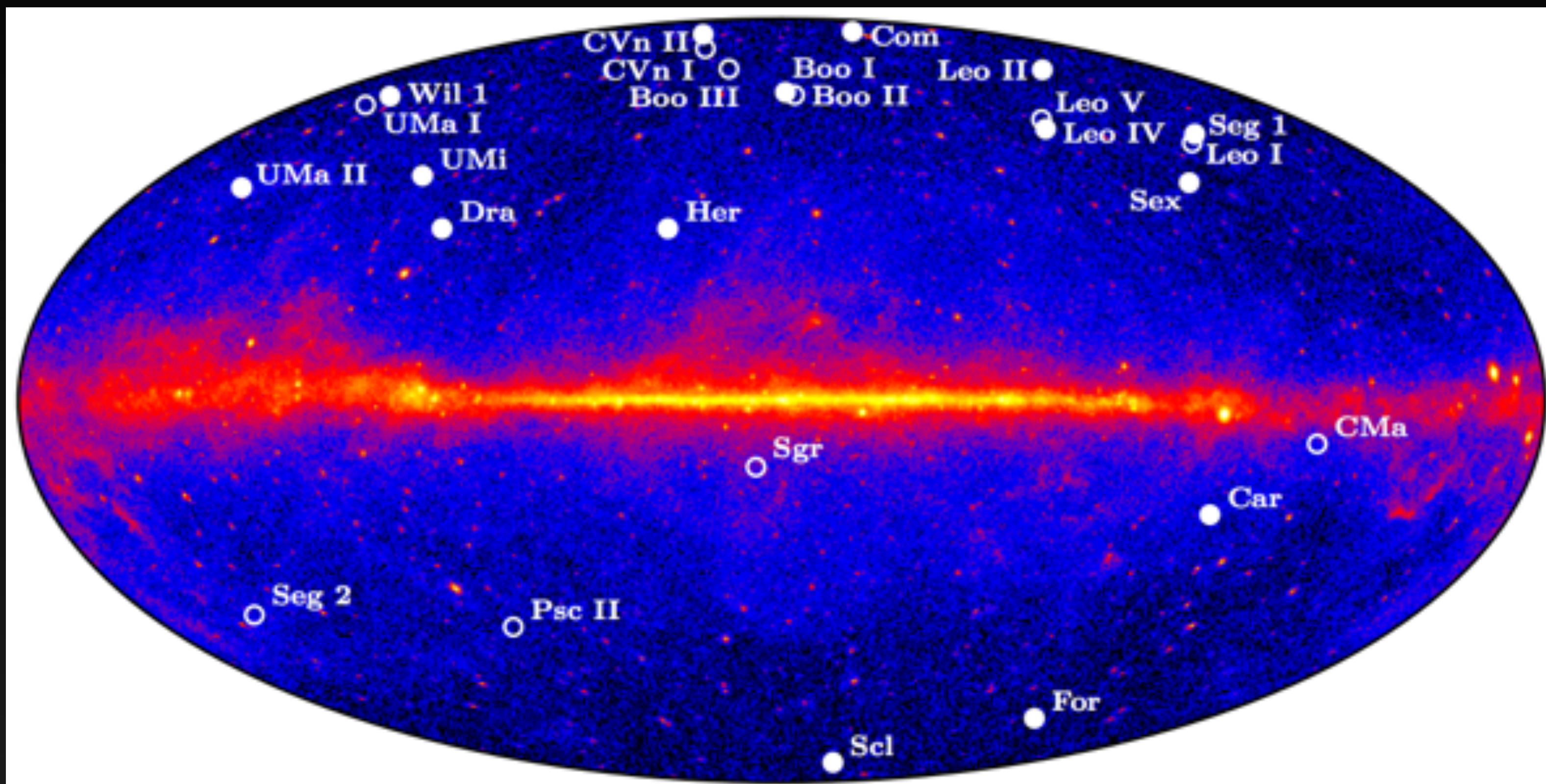
Constraints from dSphs are statistically in 1-2σ tension with the GC excess.

However, uncertainties in the dark matter density profile can easily resolve this tension.

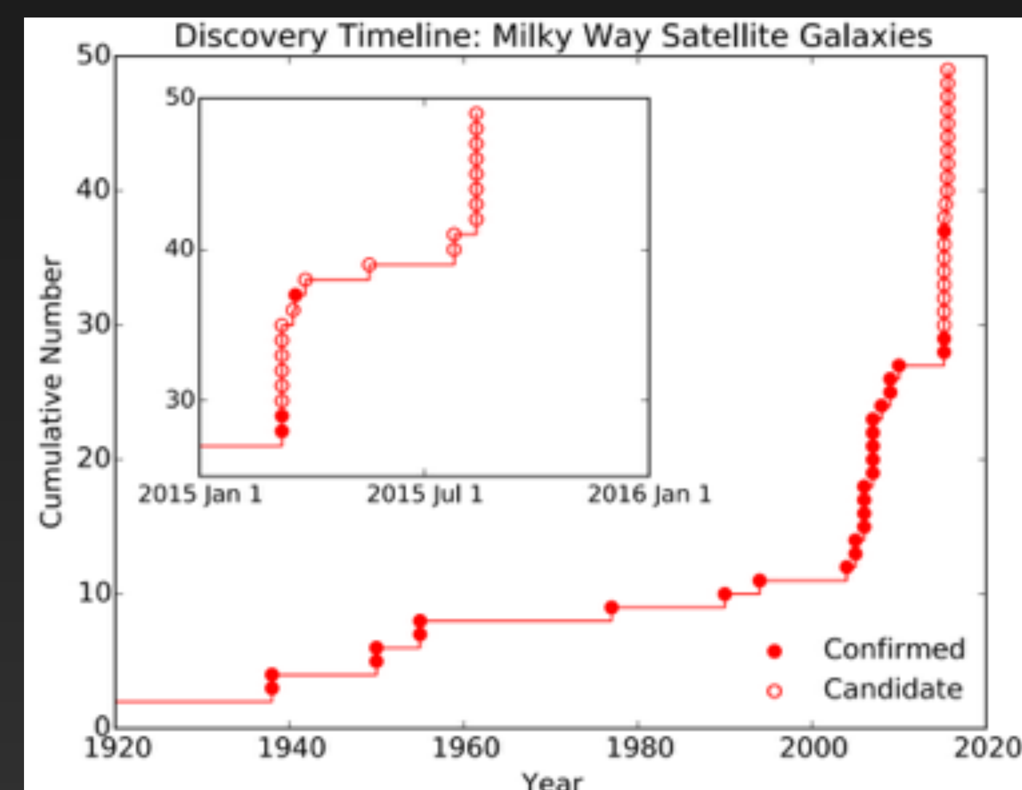


credit: Kev Abazajian (2015)

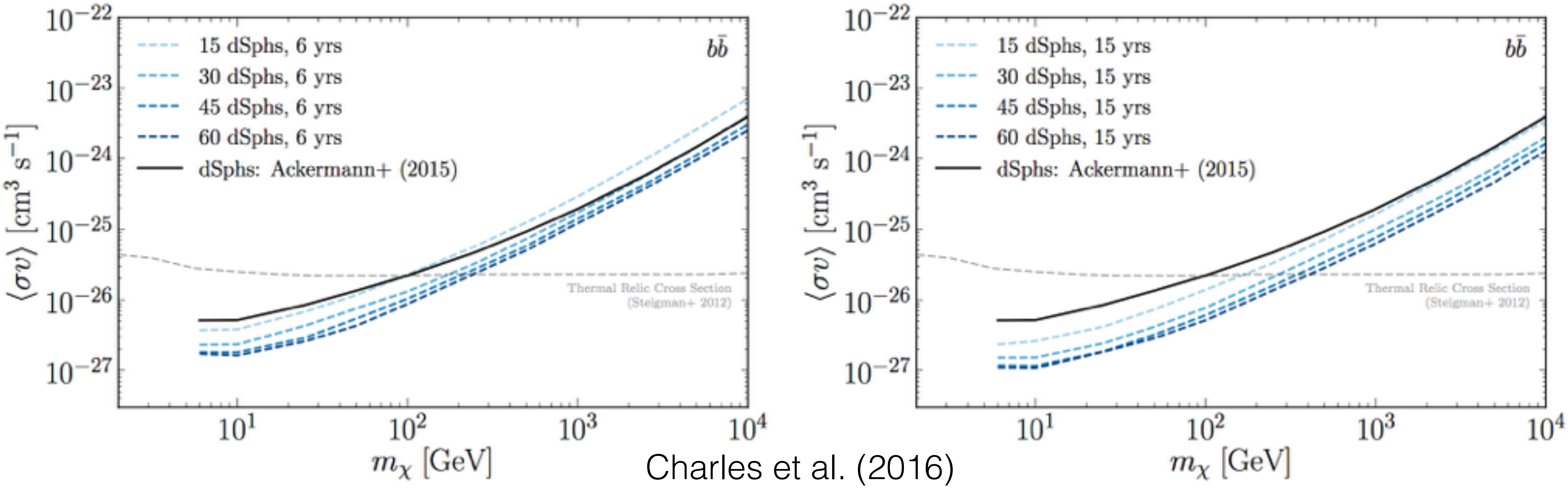
Testing the GCE with Dwarfs



DES, Pan-Starrs (and later LSST) are likely to greatly improve the detection of dwarf spheroidal galaxies in the Southern Hemisphere. Future limits may improve drastically if nearby dwarfs are discovered.



Testing the GCE with Dwarfs



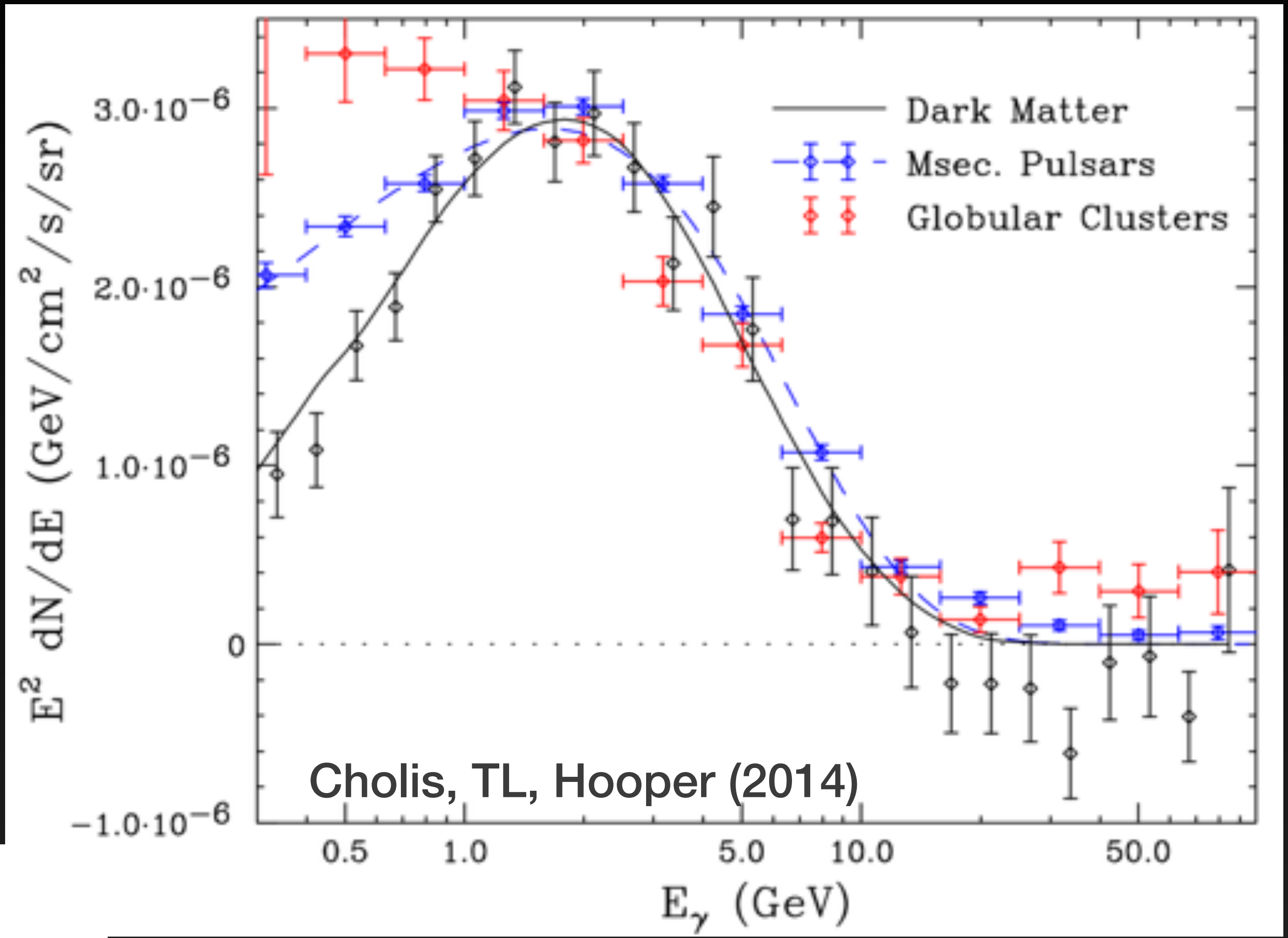
Charles et al. (2016)

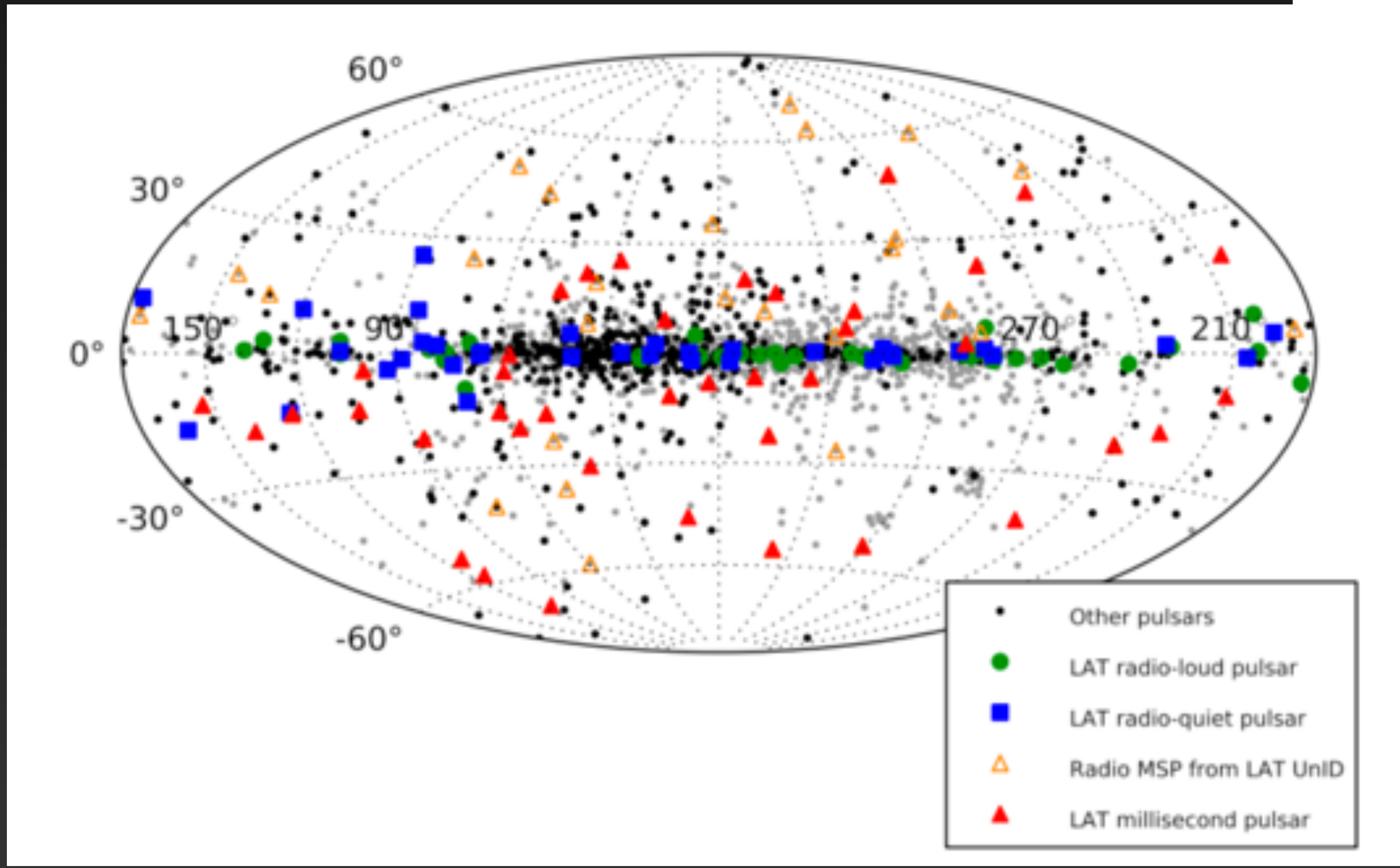
The addition of more dwarfs (in particular, several nearby dwarfs) can significantly strengthen the limits from the Fermi-LAT joint-likelihood analysis.

The Fermi-LAT has already observed all dwarfs in the sky, now we just need to know where they are.

Millisecond Pulsar Fits

- The peak of the MSP energy spectrum matches the peak of the GeV excess

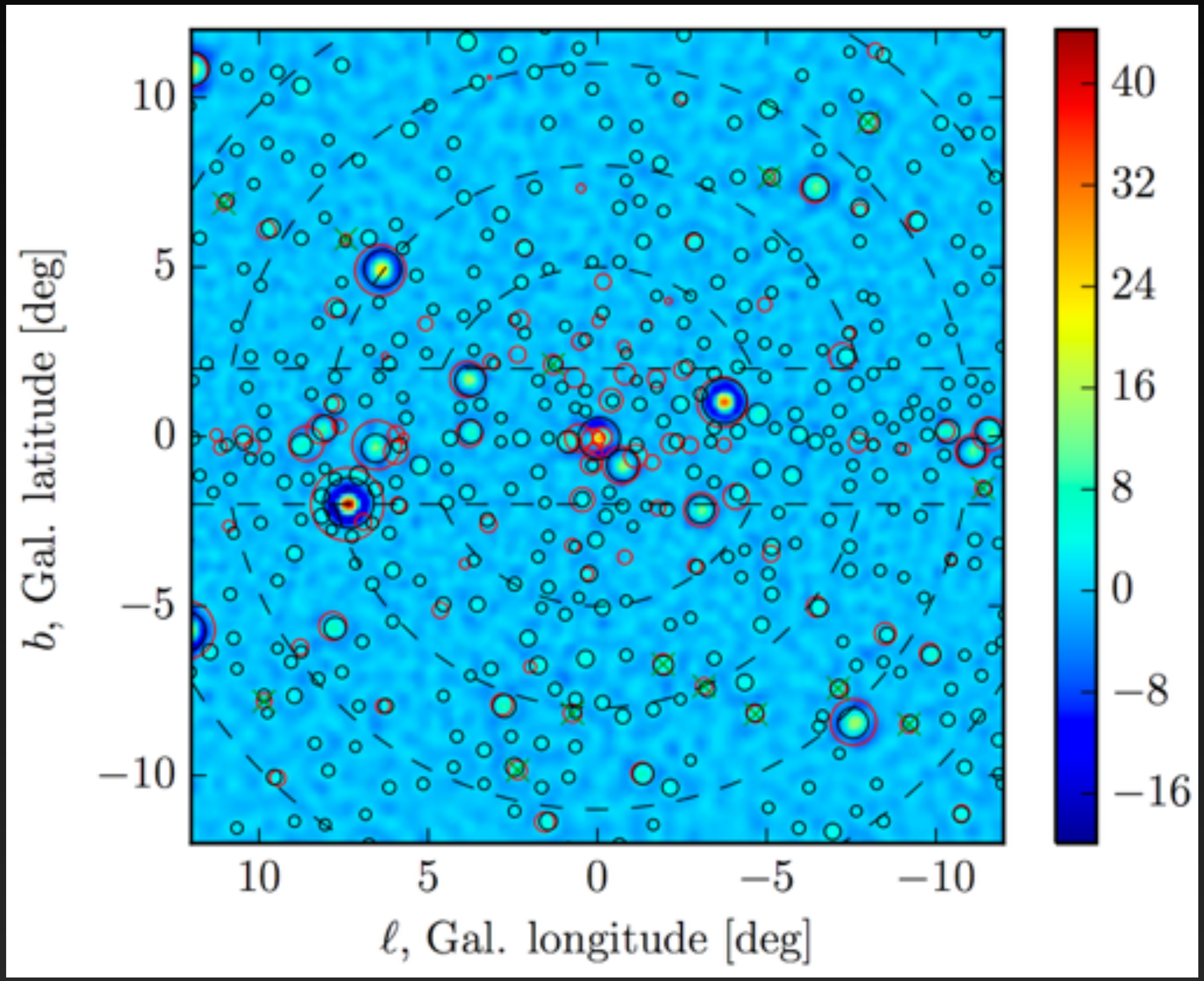




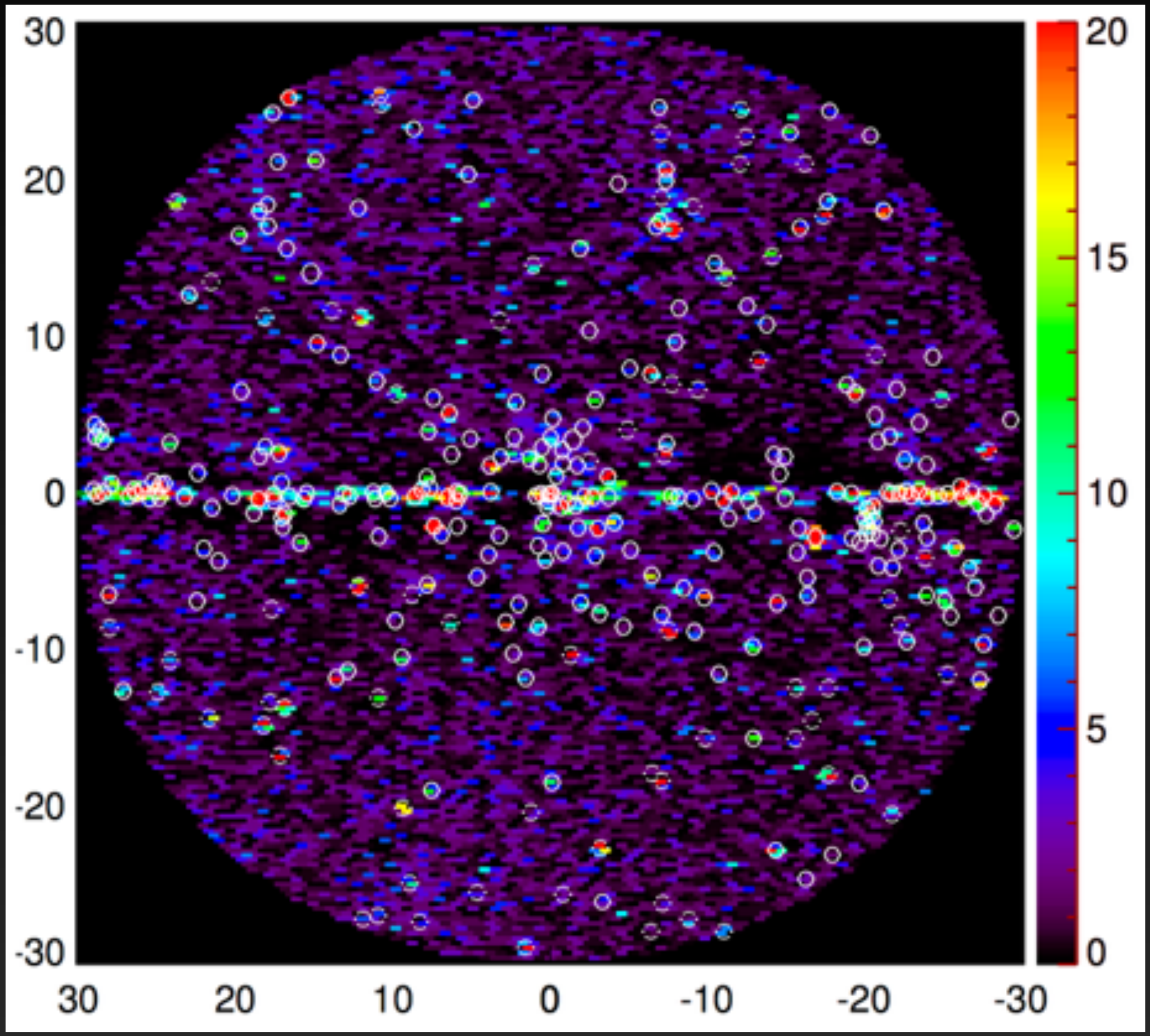
- MSPs are thought to be overabundant in dense star-forming regions like the Galactic Center

Millisecond Pulsar Fits

Bartels et al. (2015)

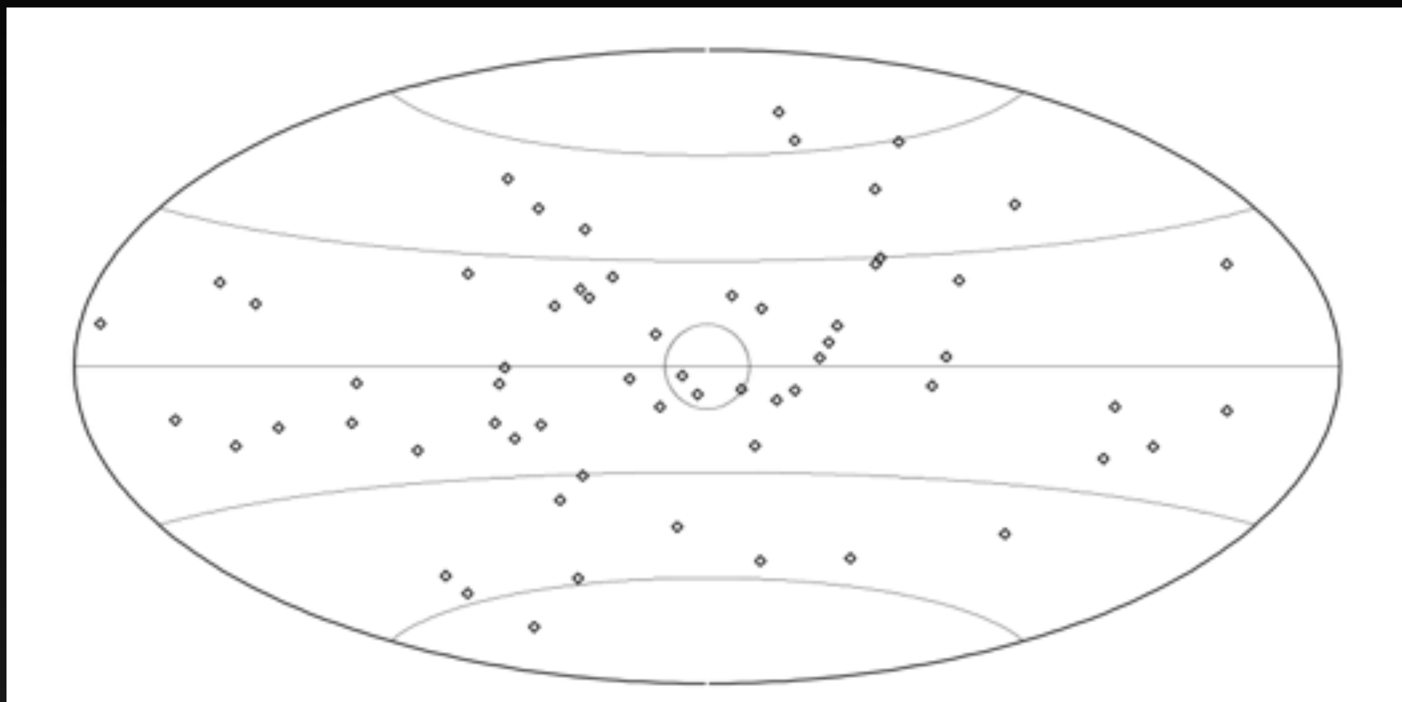


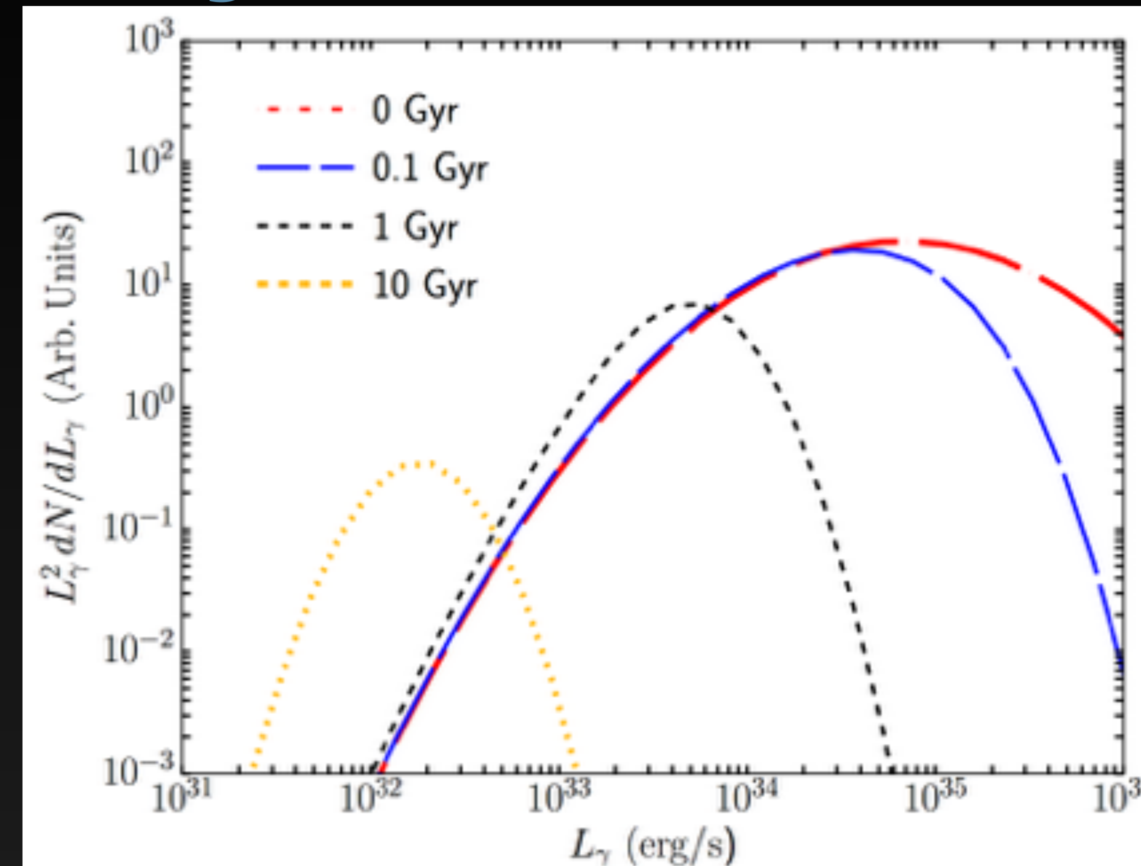
Lee et al. (2015)



- **Recent analyses of hot-spots and cold spots in the GC region find evidence for the presence of a population of sub-threshold point sources.**

Too Bright or Too Many?





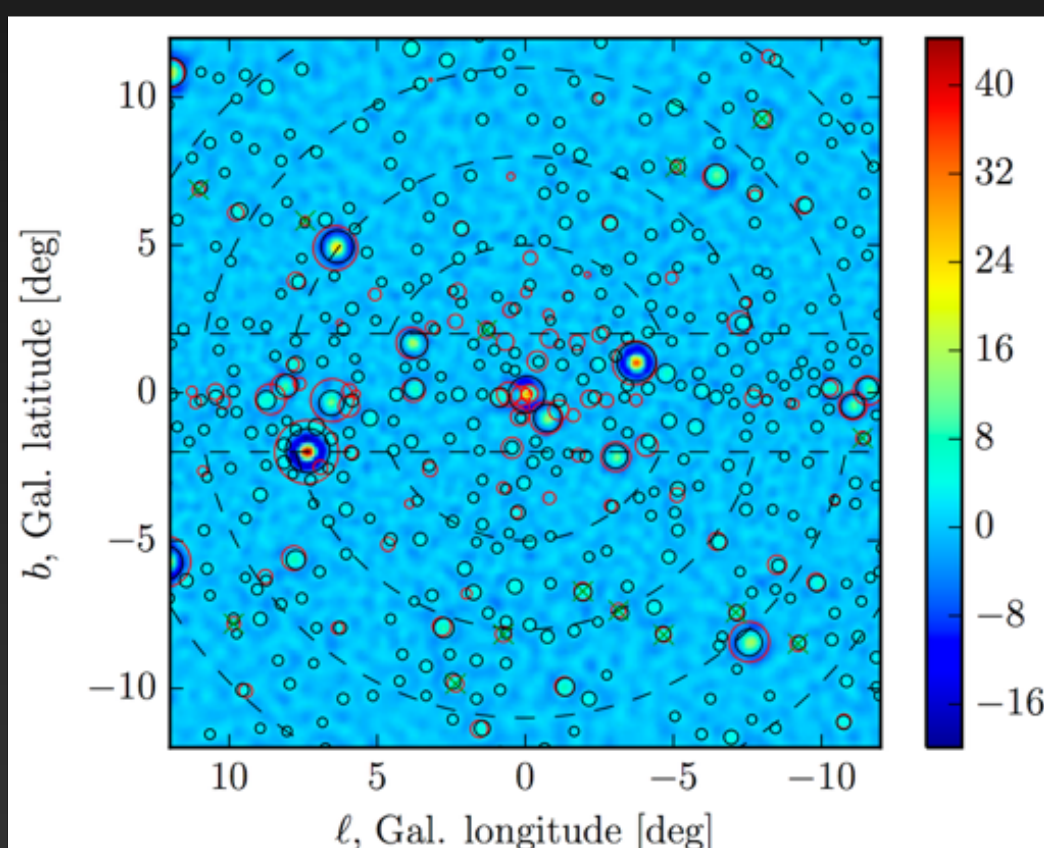
- Utilizing the luminosity distribution of pulsars in the field produces too many bright (detectable) pulsars, compared to observations. (Hooper et al. 2013, 2015)
  - This is also true when normalizing the number of detected pulsars against intermediate sources, such as LMXBs – which avoids many binary evolution uncertainties.
- Evolving the pulsars (compared to the replenished field population) decreases the number of bright pulsars, but requires too many systems to explain the total luminosity. (Hooper & TL 2016)

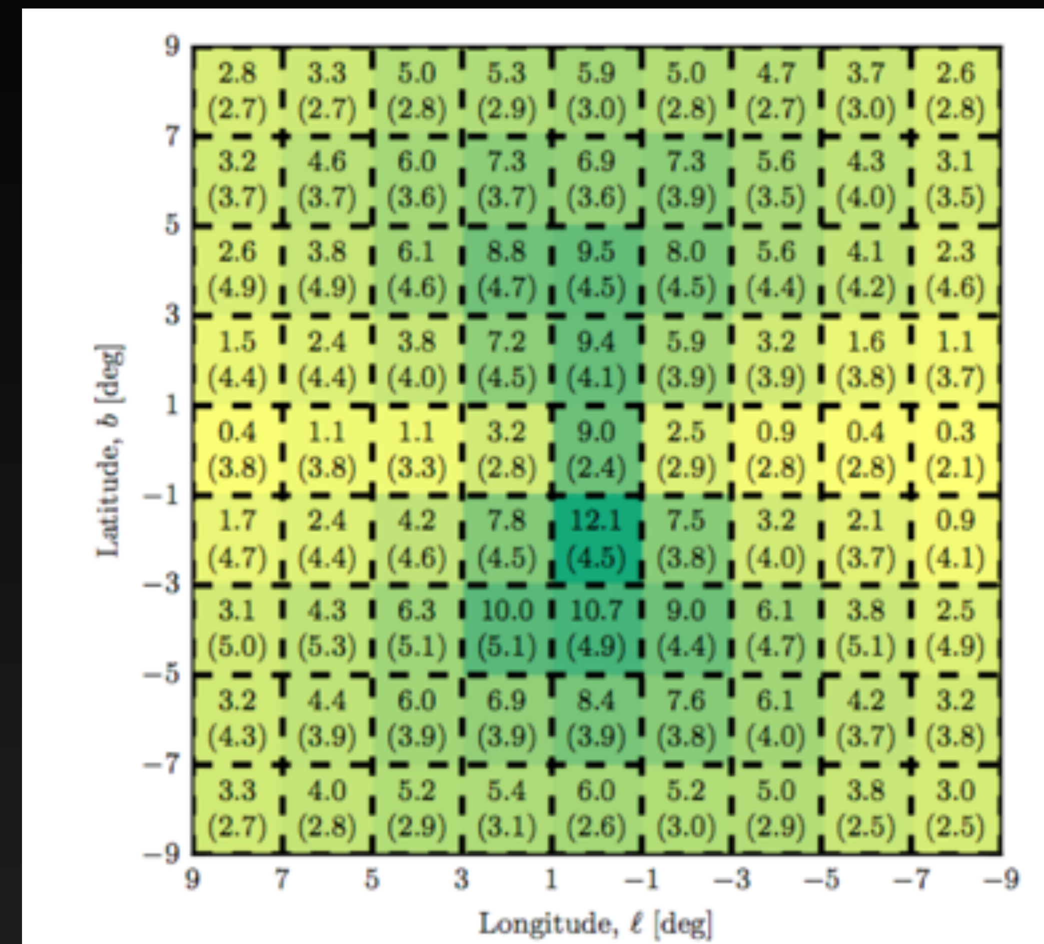
Calore et al. (2015)

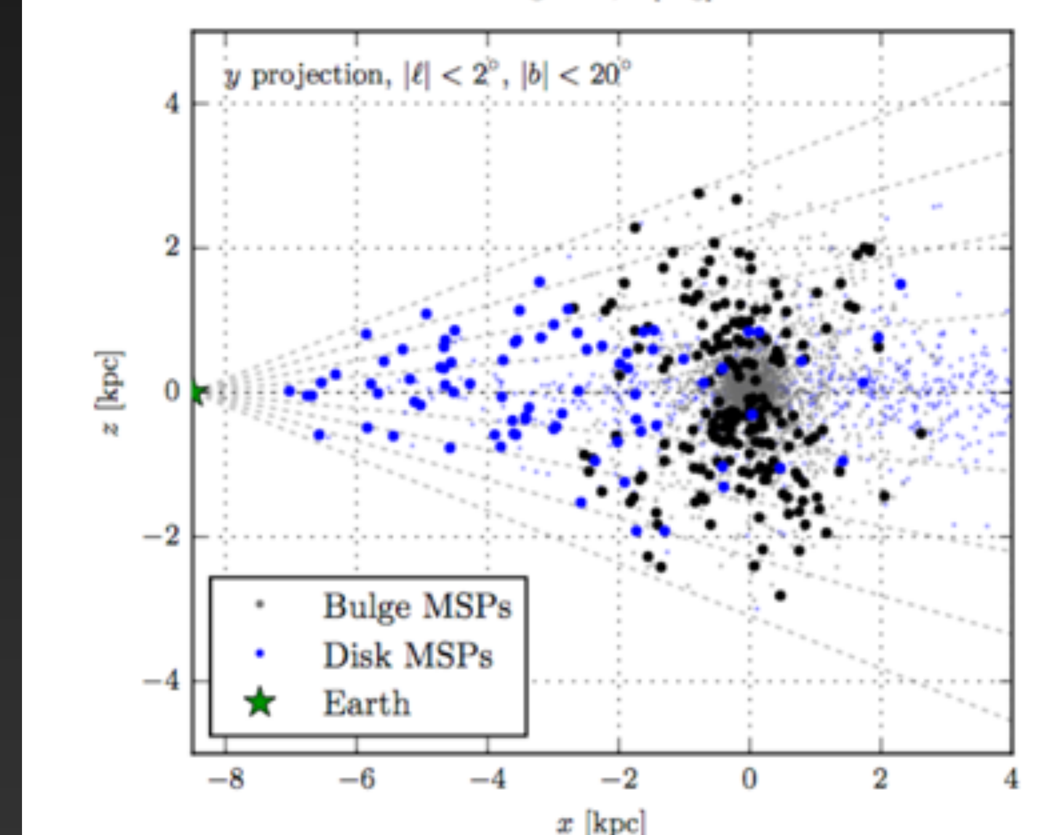
Fortunately the Pulsar Hypothesis is Testable

- Radio Observations with GBT targeted at gamma-ray hotspots would be expected to find ~5-10 MSPs with a 200 hr commitment.

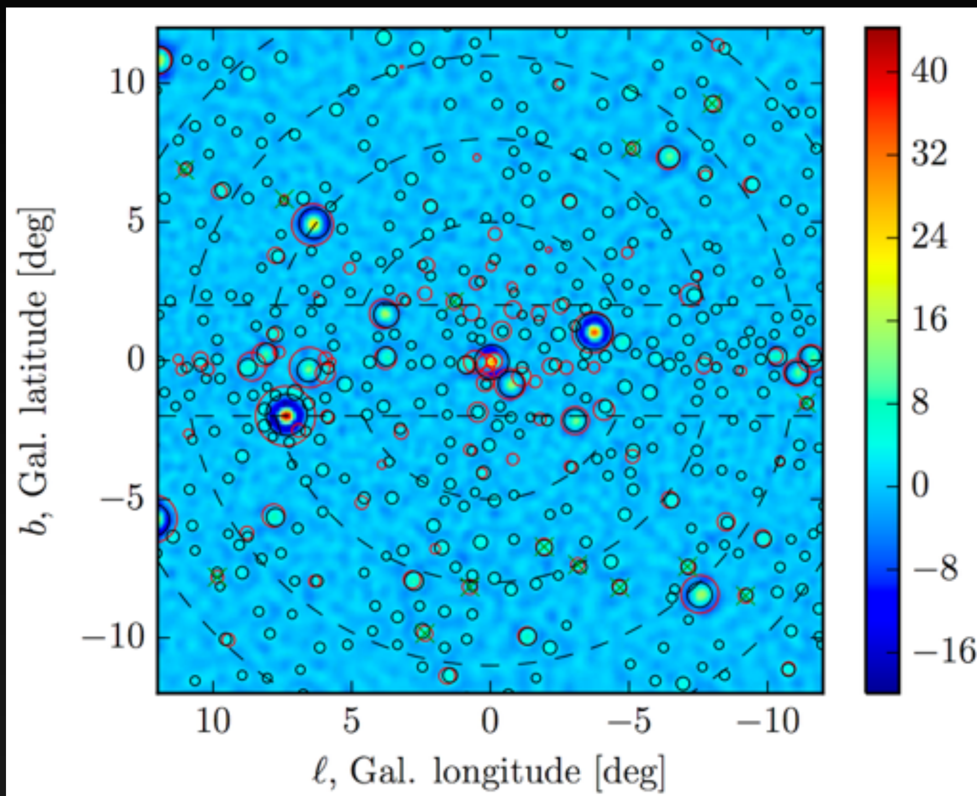
- Fortunately, SKA observations are likely to conclusively find MSPs in the GC, or rule out this scenario.

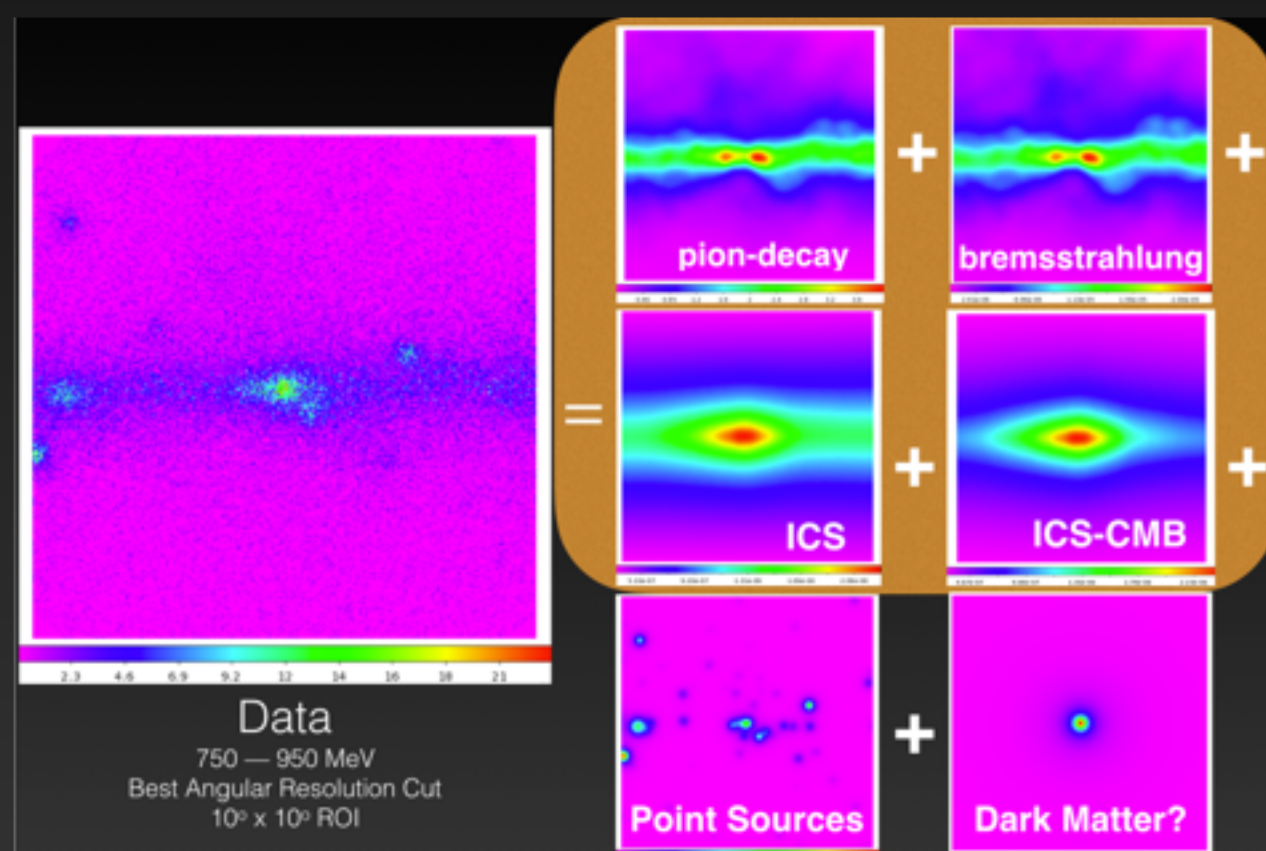




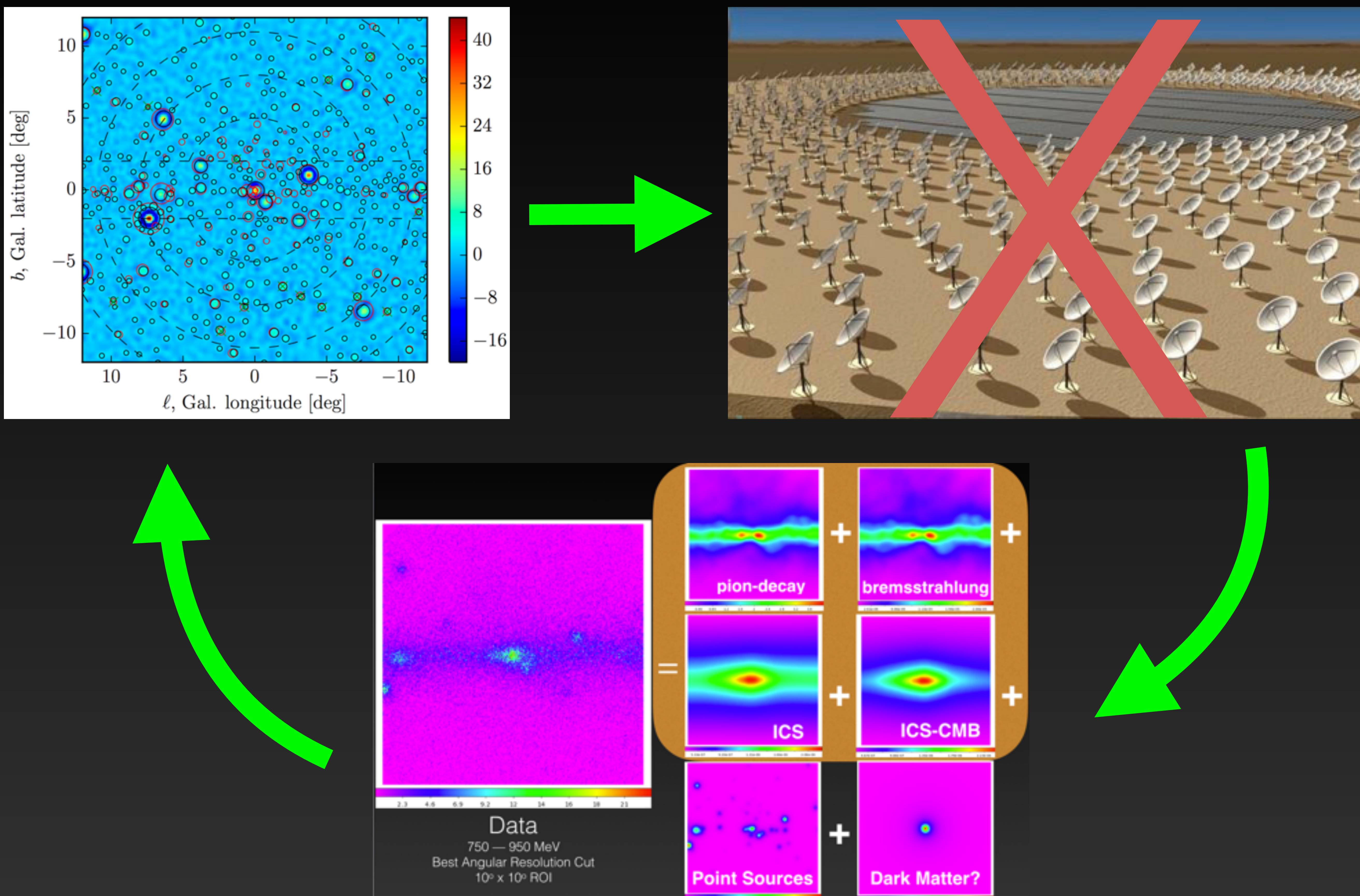


Proving the Pulsar Interpretation



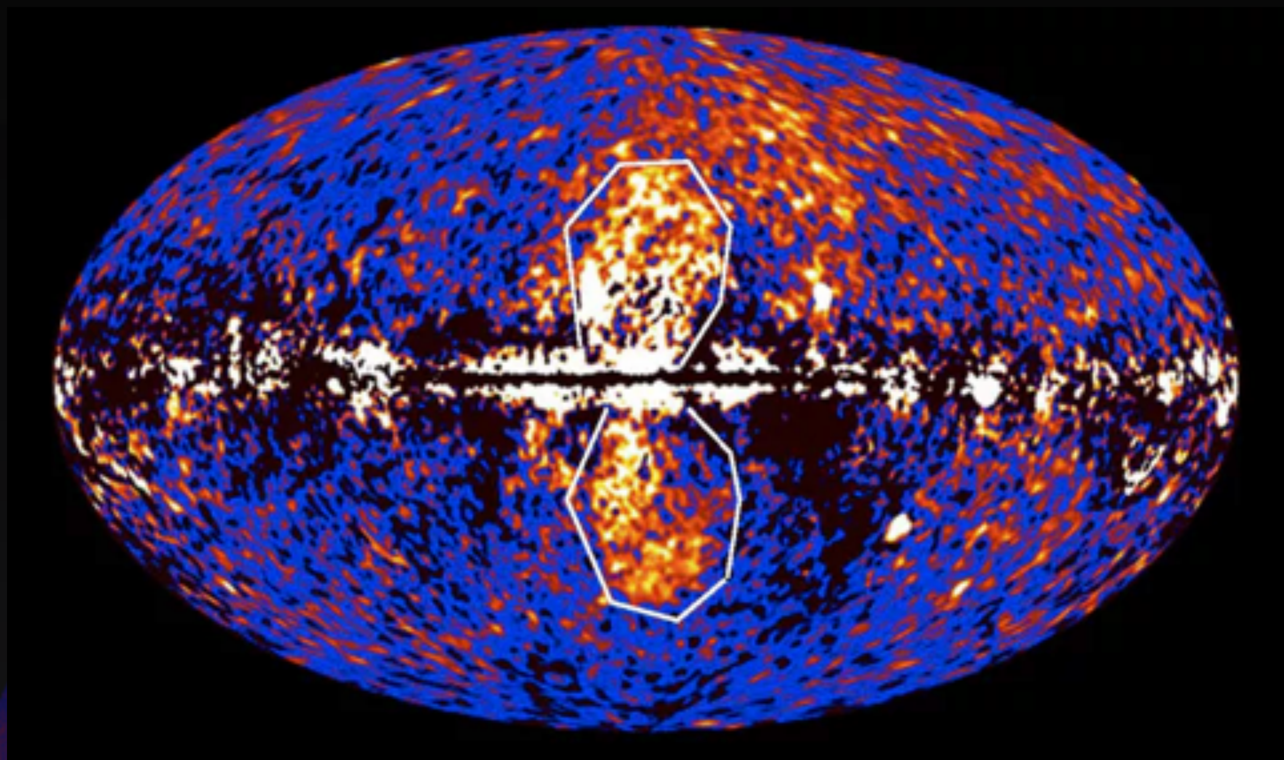


Can this be proven in the negative?

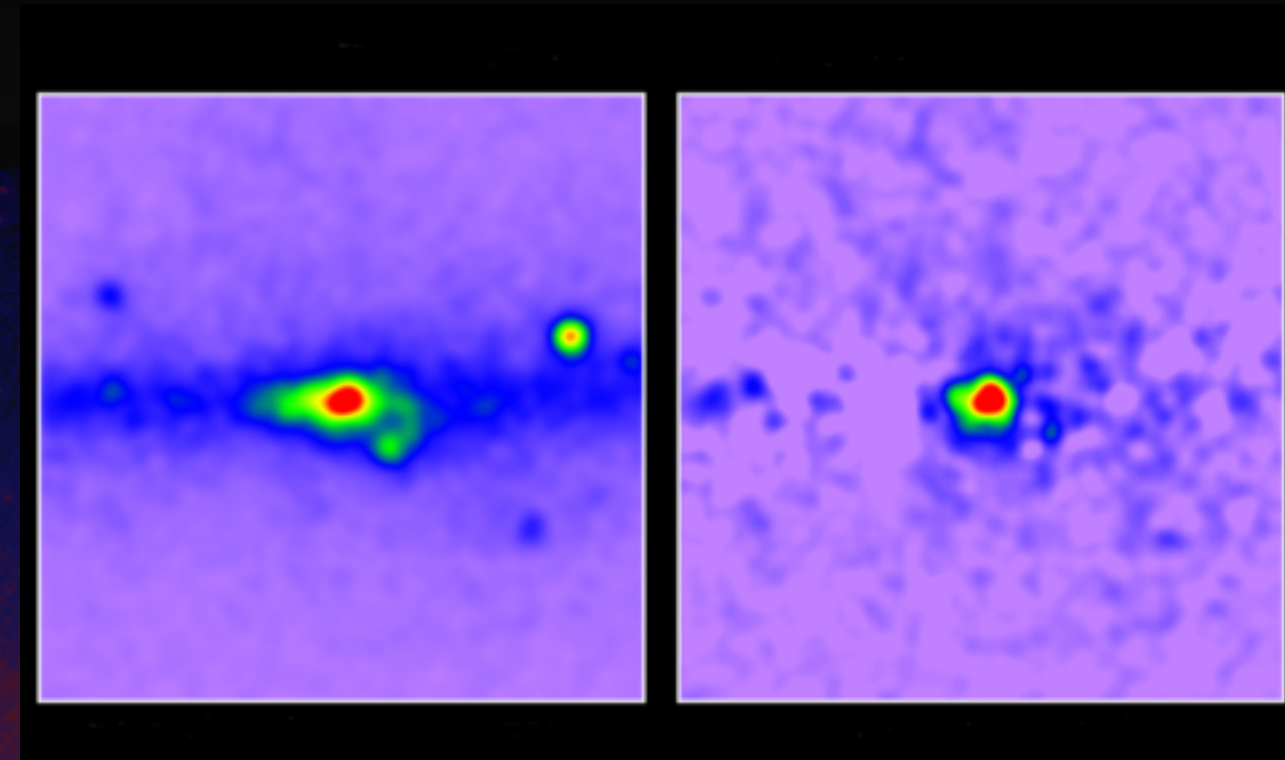


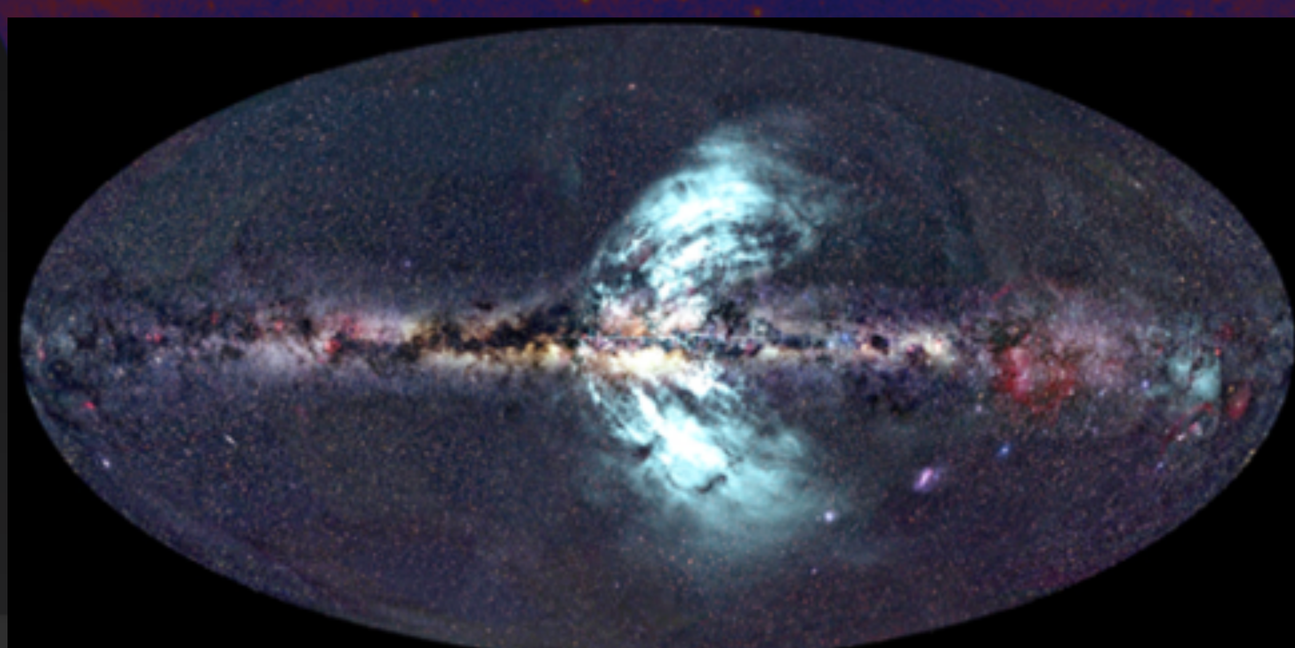
Cosmic-Ray Outbursts are Well-Motivated

Fermi Bubbles

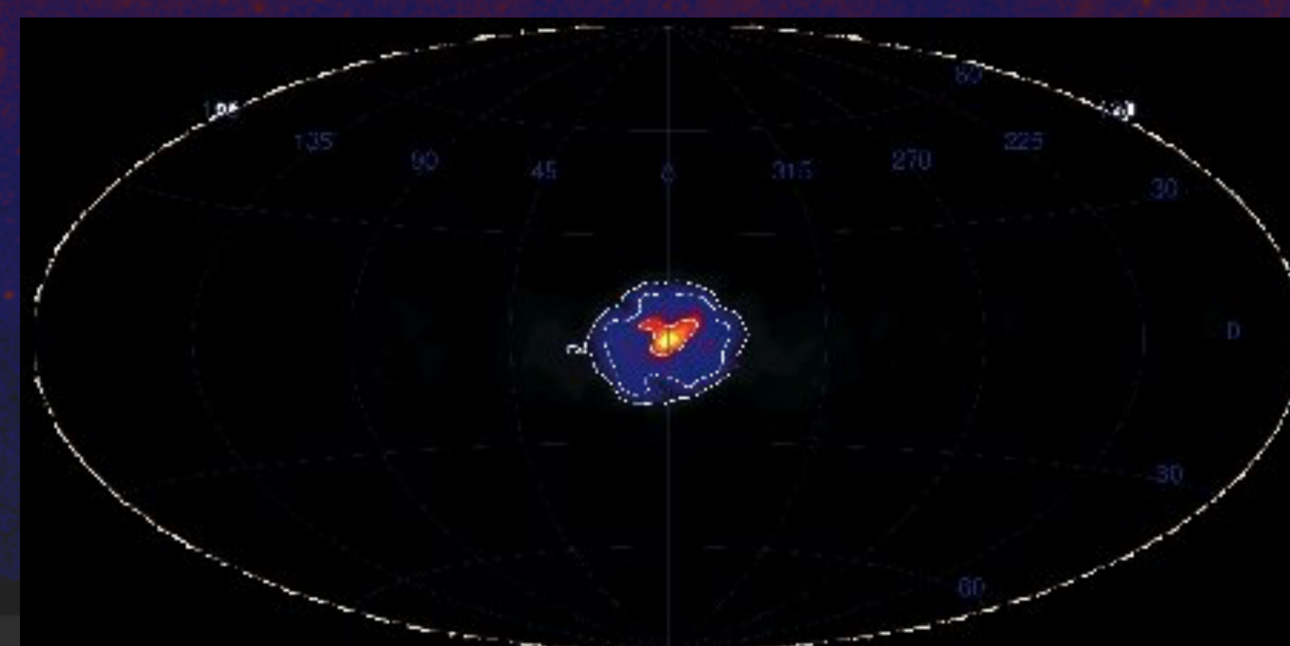


GeV Excess





WMAP/PLANCK Haze

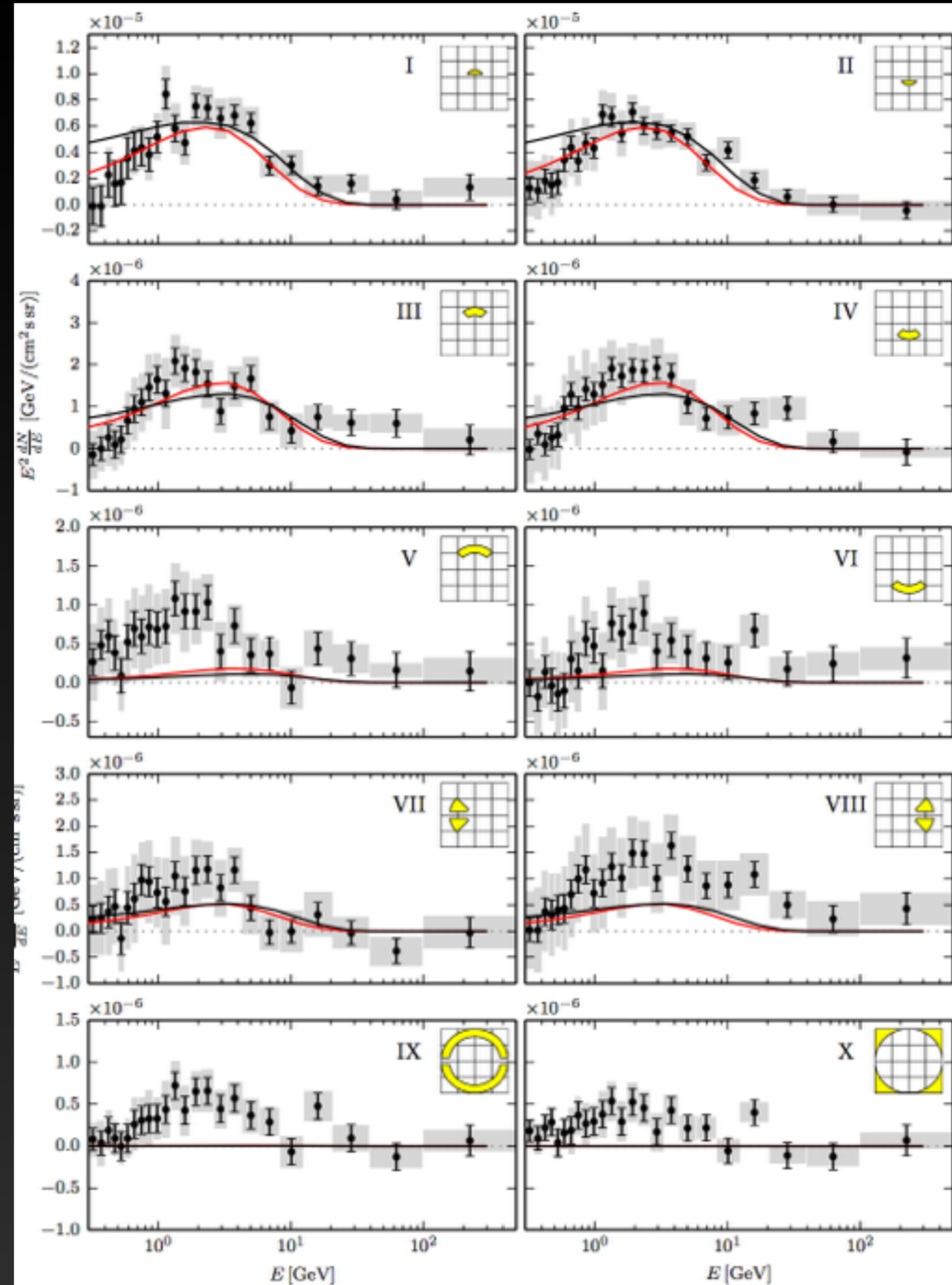


Integral 511 keV Excess

Cosmic-Ray Outbursts

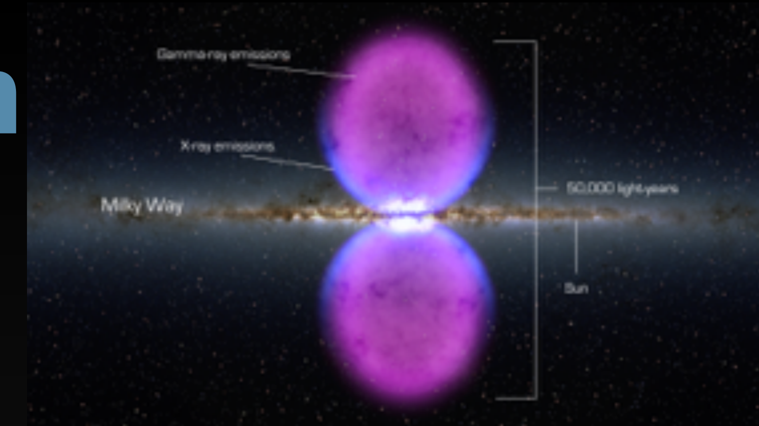
So far, we have only considered steady-state diffuse emission scenarios - but the Galactic center is unlikely to be in steady state (e.g. Fermi bubbles).

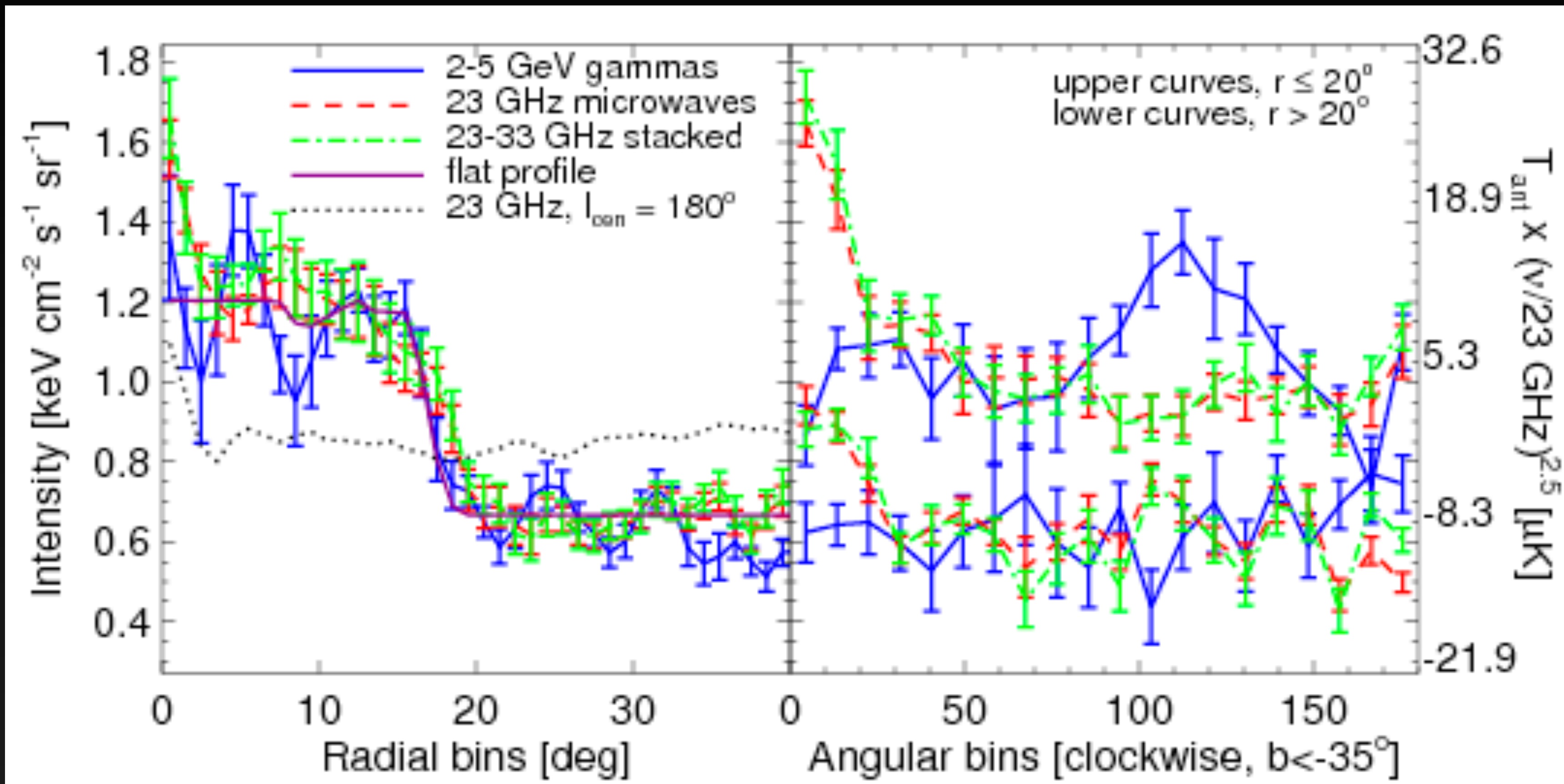
An outburst of leptonic (or possibly hadronic) origin can also produce the gamma-ray excess, but only if the injected electron spectrum is extremely hard (compared to observed blazar spectra).



Cholis et al. (2015, 1506.05119)

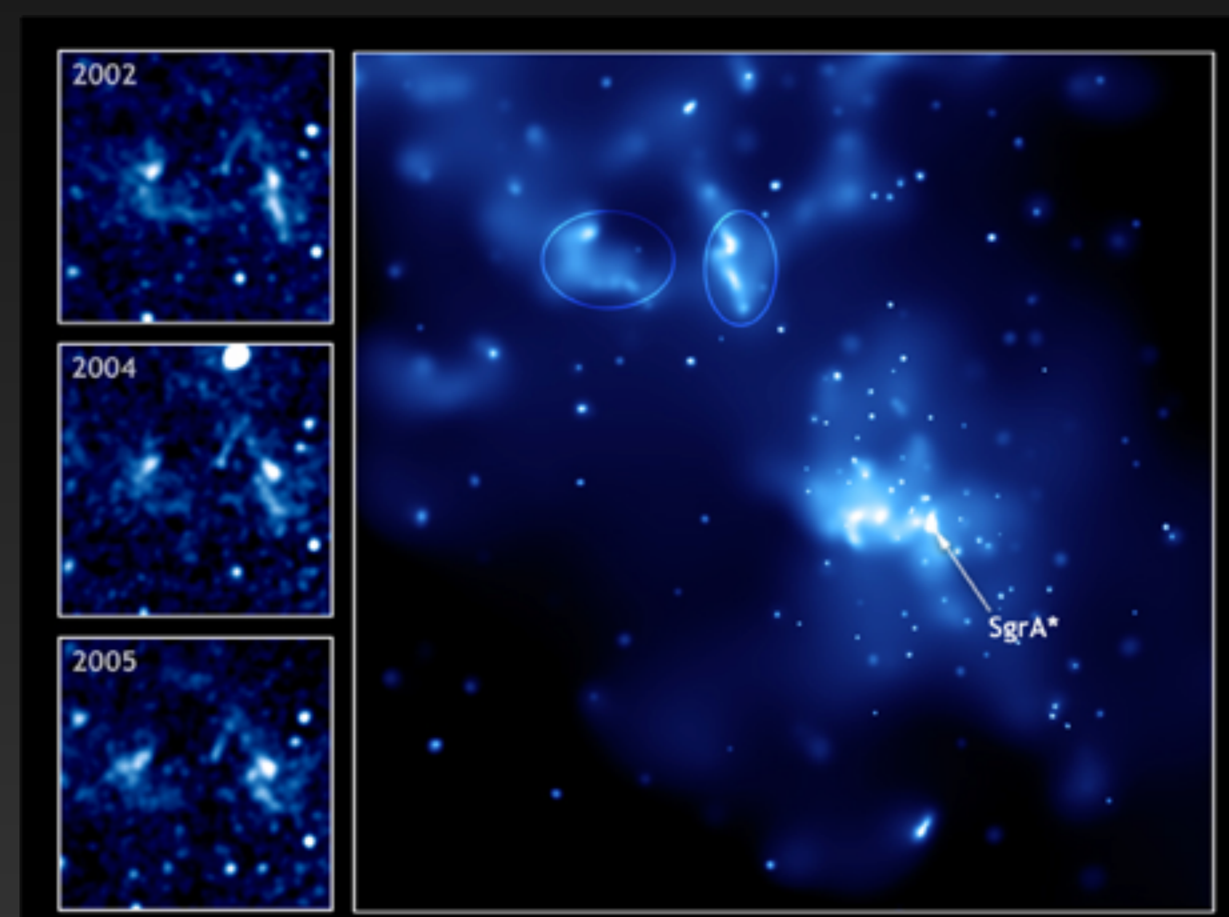
Proving an Outburst Interpretation





The origin of the WMAP haze was determined due to cross-correlation with the Fermi bubbles.

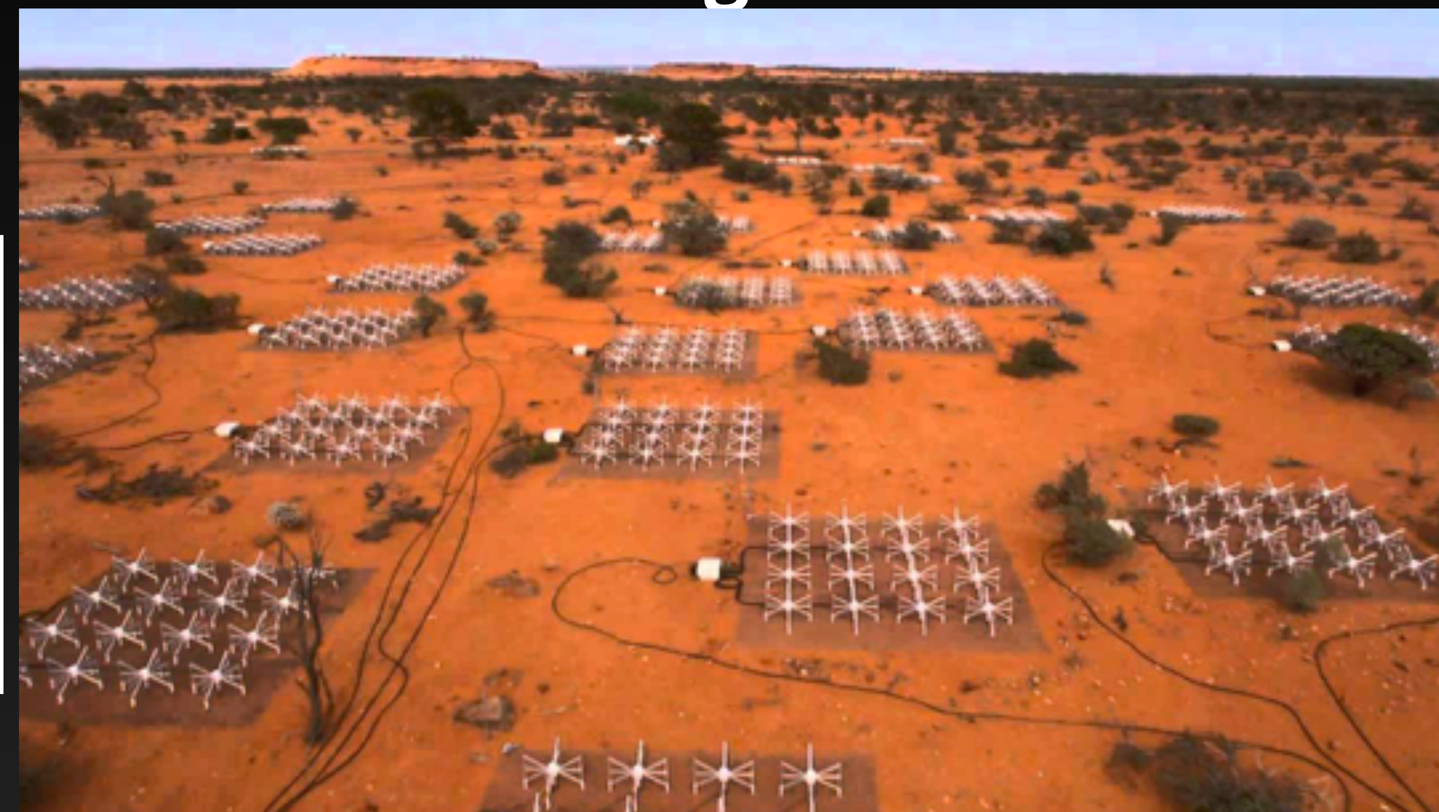
Is a similar cross-correlation (e.g. with X-Ray data) possible?



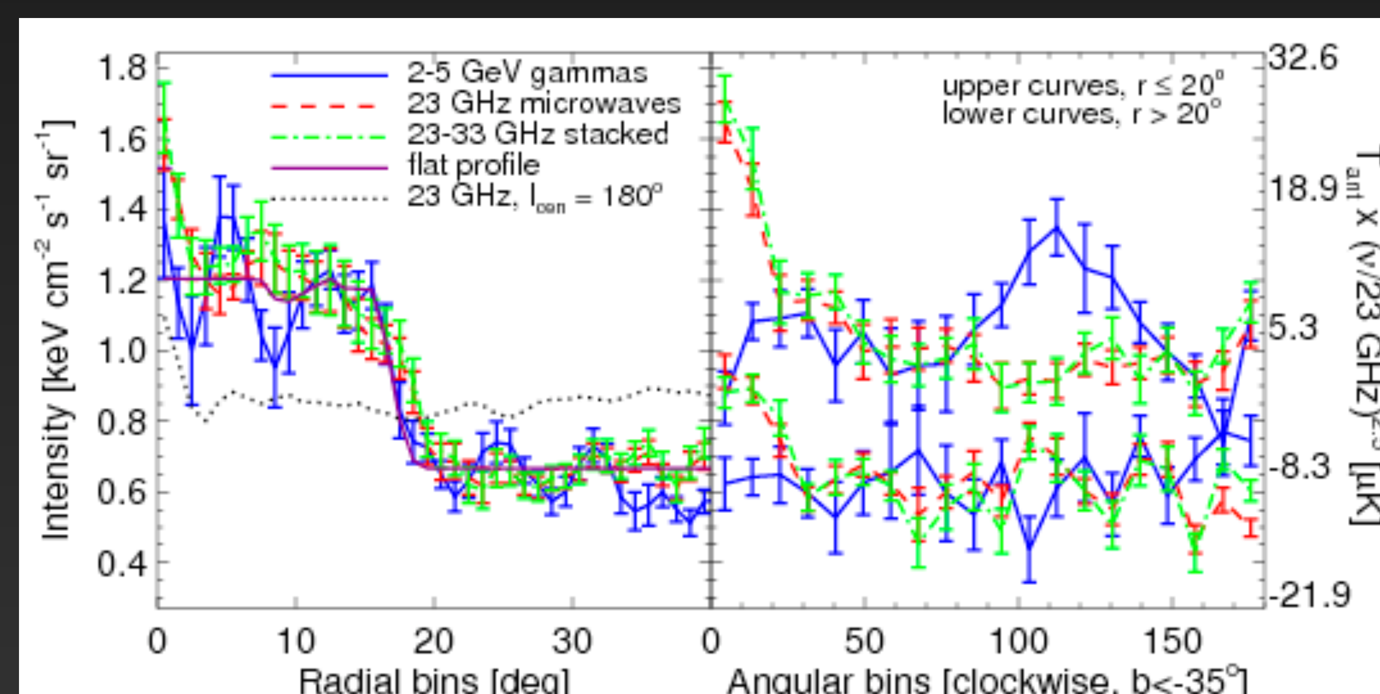
Can Outbursts be Ruled Out?

Leptonic Outbursts at high latitude produce an associated synchrotron flux given by the ratio of the magnetic field and ISRF energy densities.

$$\left.\frac{F_{\rm radio}}{F_{\gamma}}\right|_{\rm DM} = \frac{B_e\left(\frac{\rho_B}{\rho_B+\rho_{\rm rad}}\right)}{B_e\left(\frac{\rho_{\rm rad}}{\rho_B+\rho_B}\right)+B_{\gamma}}$$



Enhanced measurements of the low-energy synchrotron signal at the Galactic center may rule out any associated synchrotron flux.

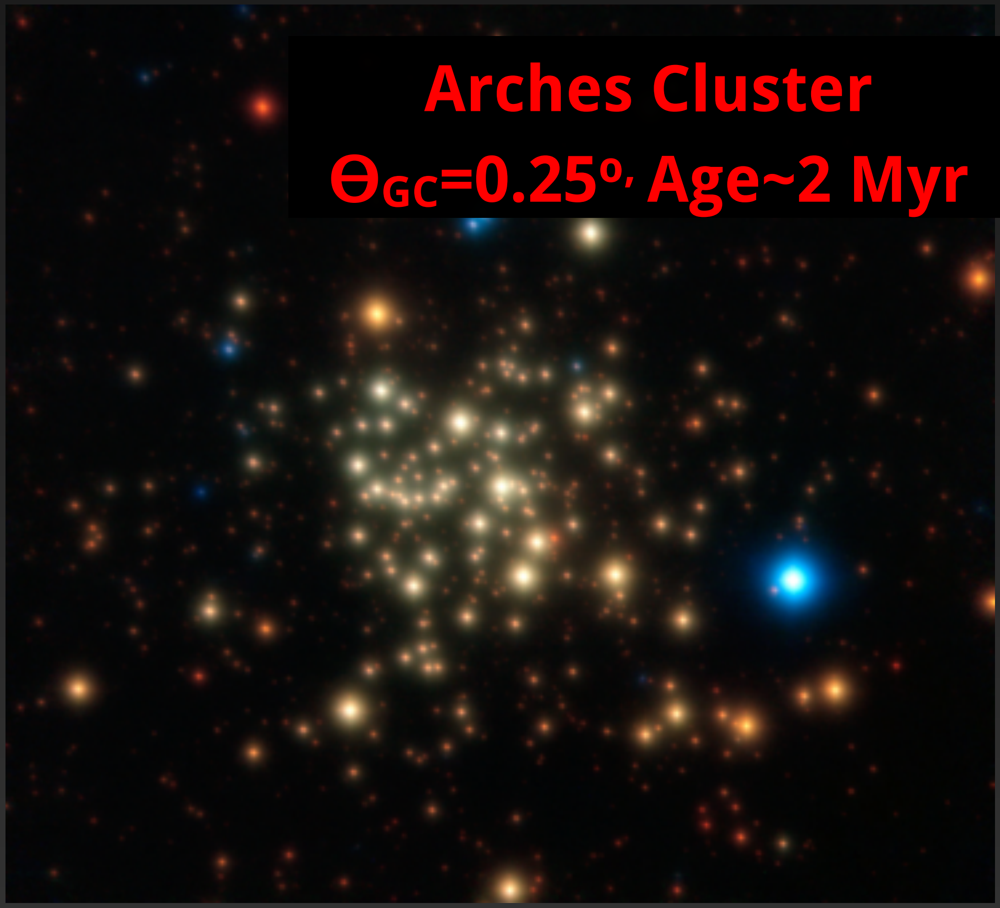


A More Ominous Problem...

Multiwavelength observations indicate that the Galactic Center is a dense star-forming environment.

3-20% of the total Galactic Star Formation Rate is contained within the Central Molecular Zone.

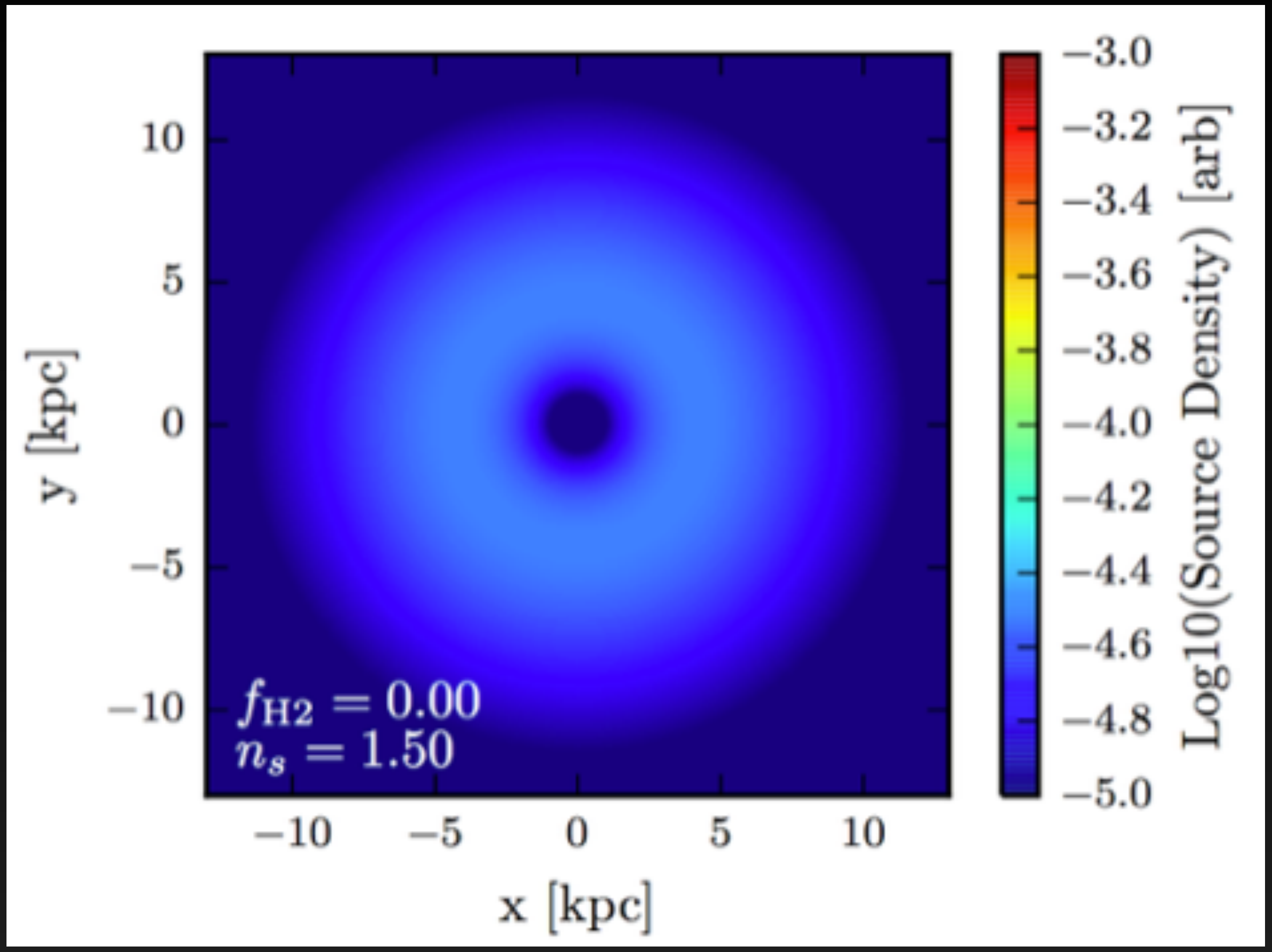
- 2-4% - ISOGAL Survey Immer et al. (2012)
- 2.5-5% - Young Stellar Objects Yusef-Zadeh et al. (2009)
- 5-10% - Infrared Flux Longmore et al. (2013)
- 10-20% - Wolf-Rayet Stars Rosslowe & Crowther (2014)
- 2% - Far-IR Flux Thompson et al. (2007)
- 2.5-6% - SN1a Schanne et al. (2007)

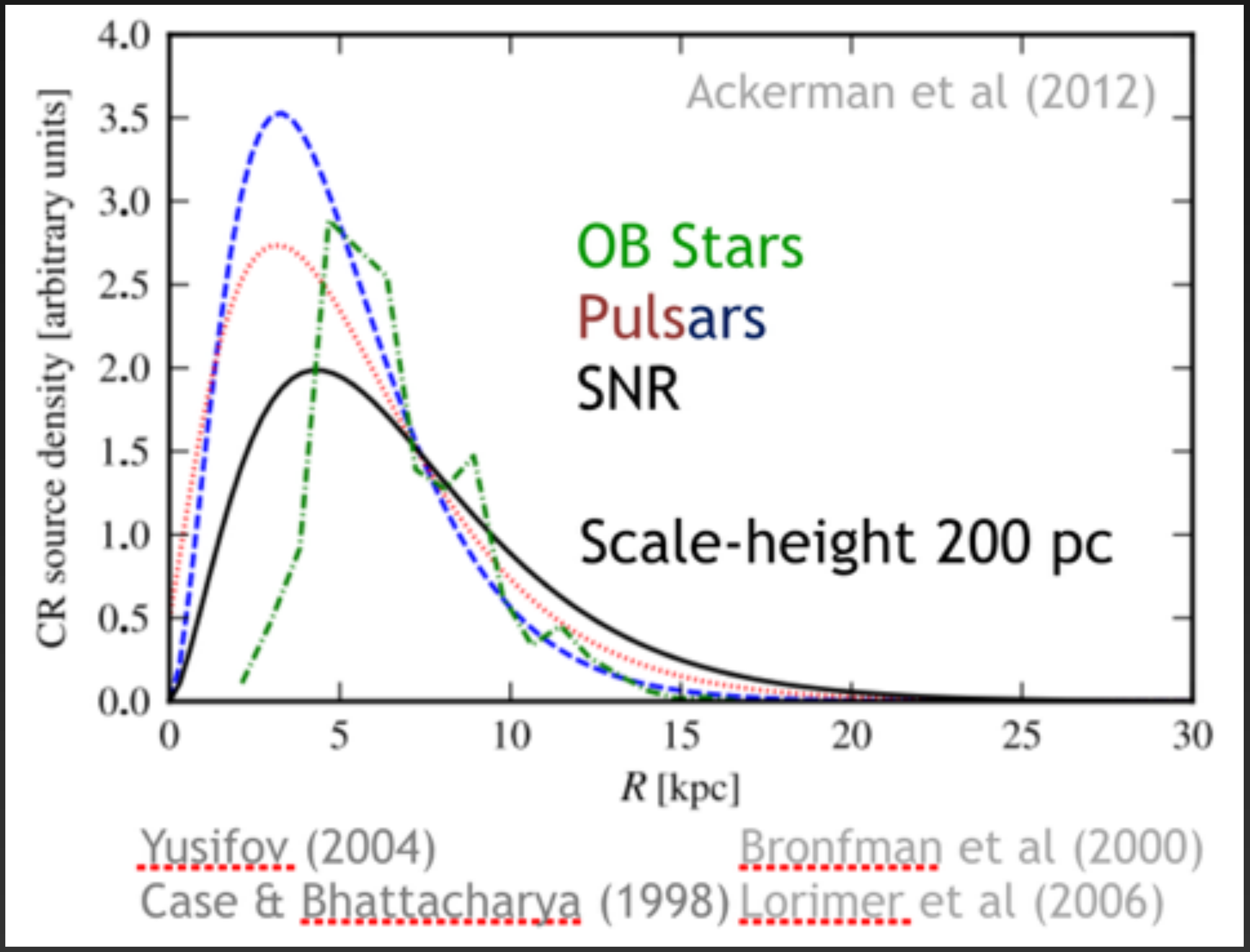


An Excess Compared to What?

Cosmic-Ray Propagation Codes (e.g. Galprop), generally utilize a cosmic-ray injection rate at the Galactic center that is identically 0.

These models were not produced to study the very center of the Galaxy!





Results from these cosmic-ray propagation codes are used in many analyses of the Galactic center region.

Carlson et al. (2016a, 2016b)
1510.04698
1603.06584

The Solution

Solution: Add a new cosmic-ray injection morphology tracing the molecular gas density.

Observationally Resilient: Several tracers of molecular gas are sensitive to the galactic center region.

Theoretically Motivated: Molecular Gas is the seed of star formation, the Schmidt Law gives

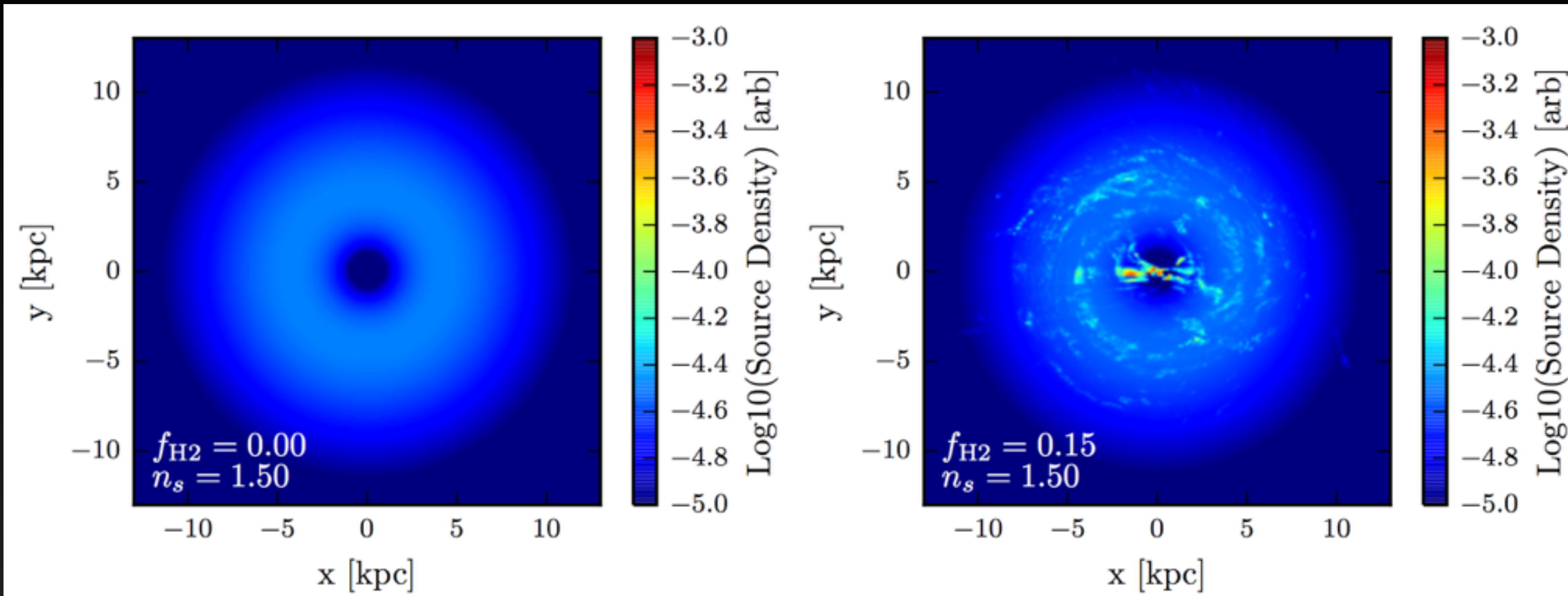
$$\Sigma_{\rm SFR} \propto \Sigma_{\rm Gas}^{1.4\pm.15}$$

Specifically we inject a fraction of cosmic-rays ($0 < f_{H2} < 1$) following:

$$Q_{\rm CR}(\vec{r}) \propto \begin{cases} 0 & \rho_{\rm H2} \leq \rho_s \\ \rho_{\rm H2}^{n_s} & \rho_{\rm H2} > \rho_s \end{cases}$$

1510.04698

The Solution

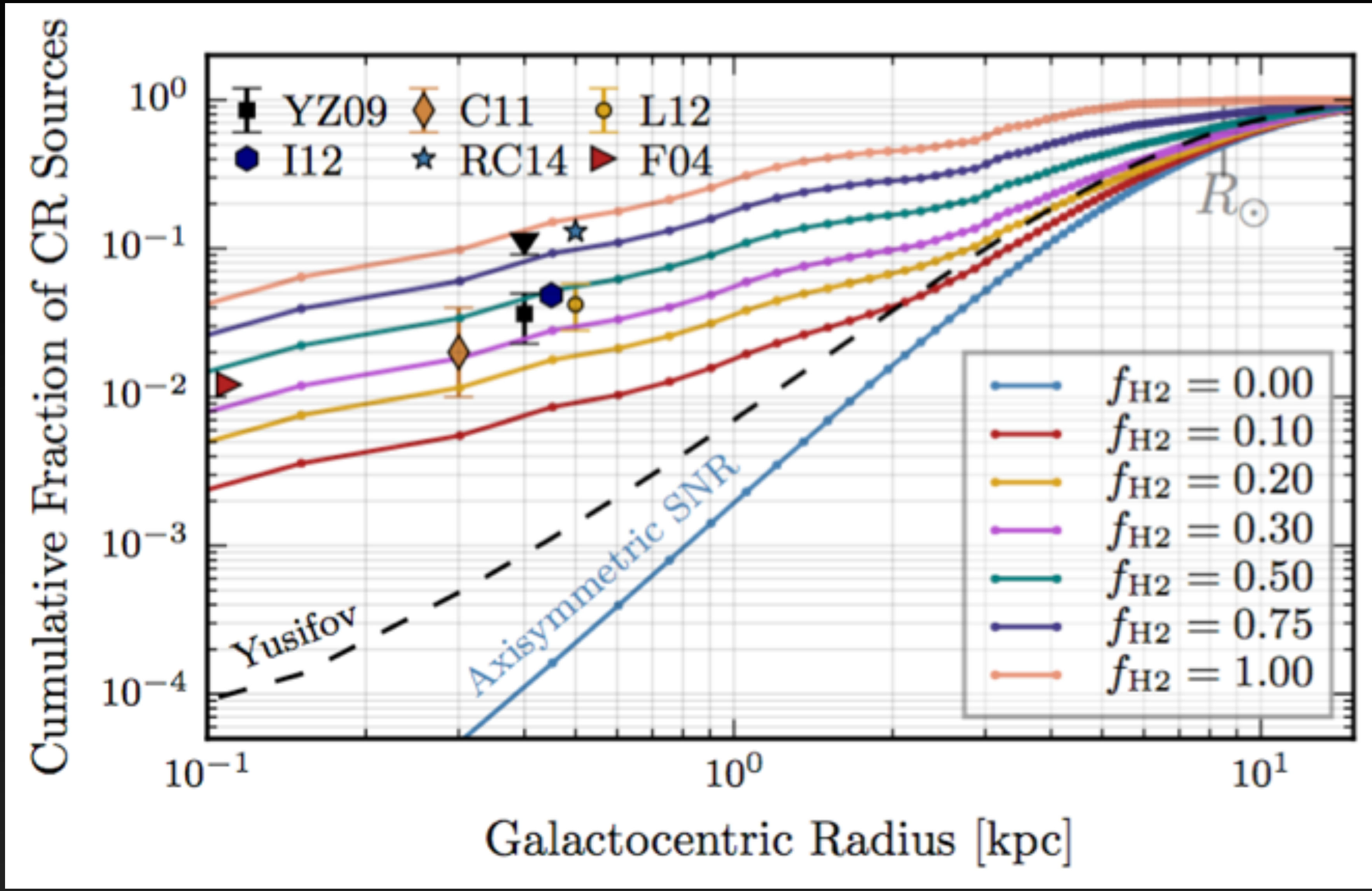


Two features leap out immediately:

1.) Spiral Arms

2.) A bright bar in the Galactic Center

The Solution



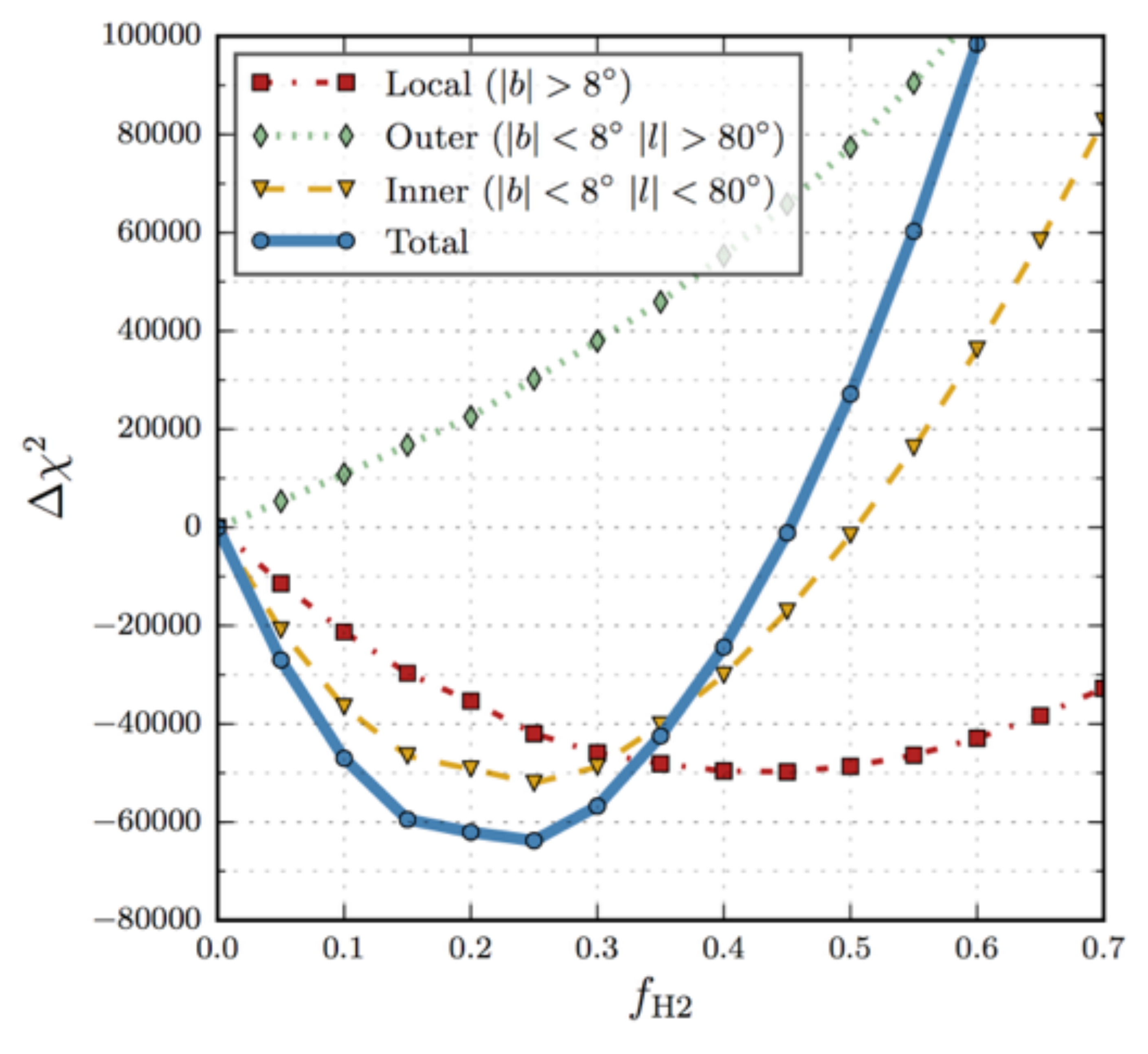
Adds a new, and significant, cosmic-ray injection component, in particular near the Galactic Center.

The cosmic-ray injection rate now matches observational constraints.

A Better fit to the Gamma-Ray Sky

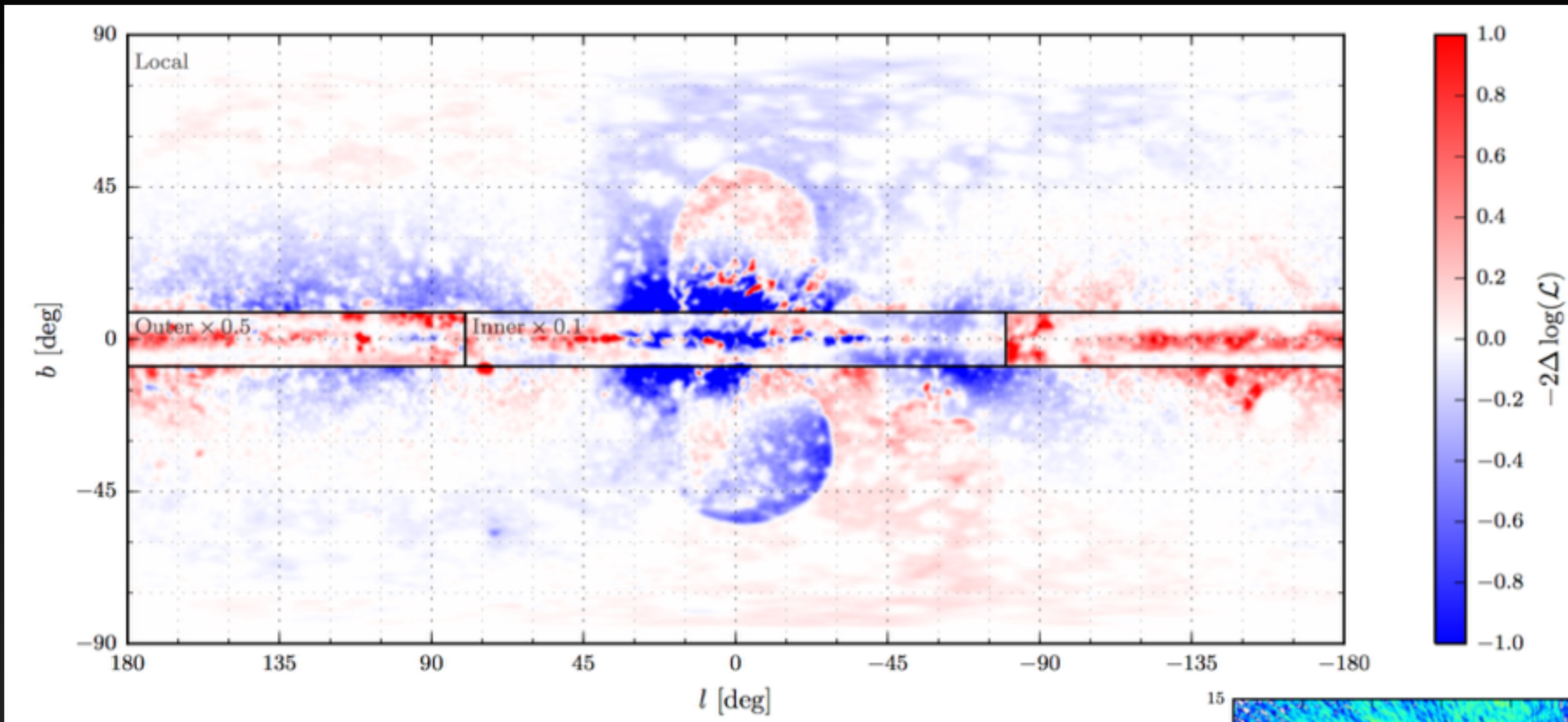
1.) Adding a cosmic-ray injection component tracing f_{H2} improves the full-sky fit to the gamma-ray data.

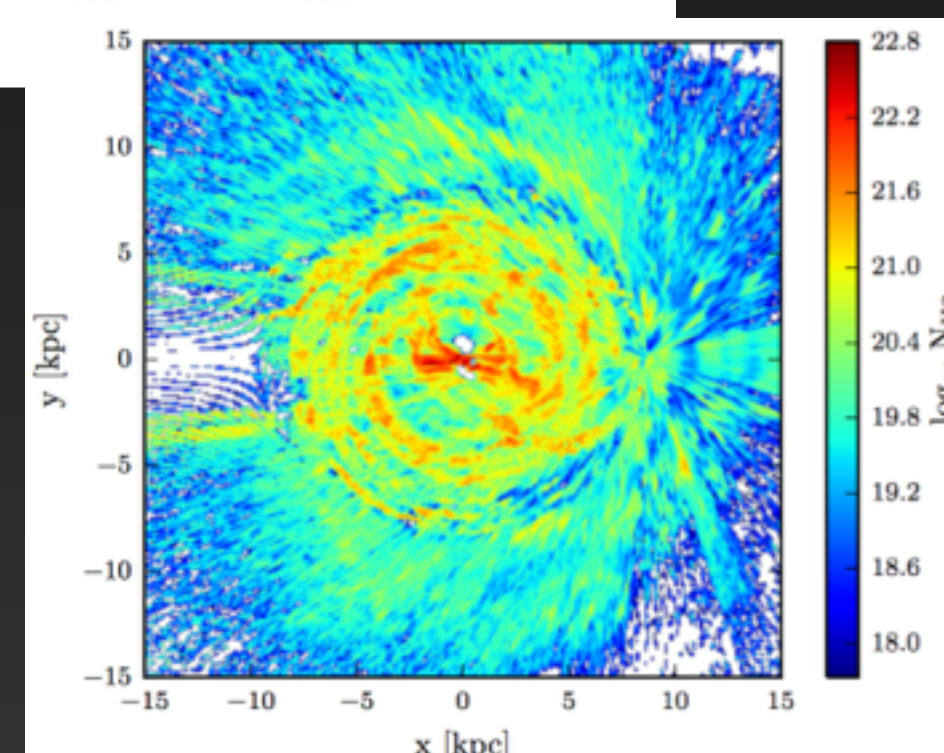
2.) The best fit value over the full sky is f_{H2} = 0.25



3.) Technique will become more powerful with the introduction of 3D gas and dust maps in the near future.

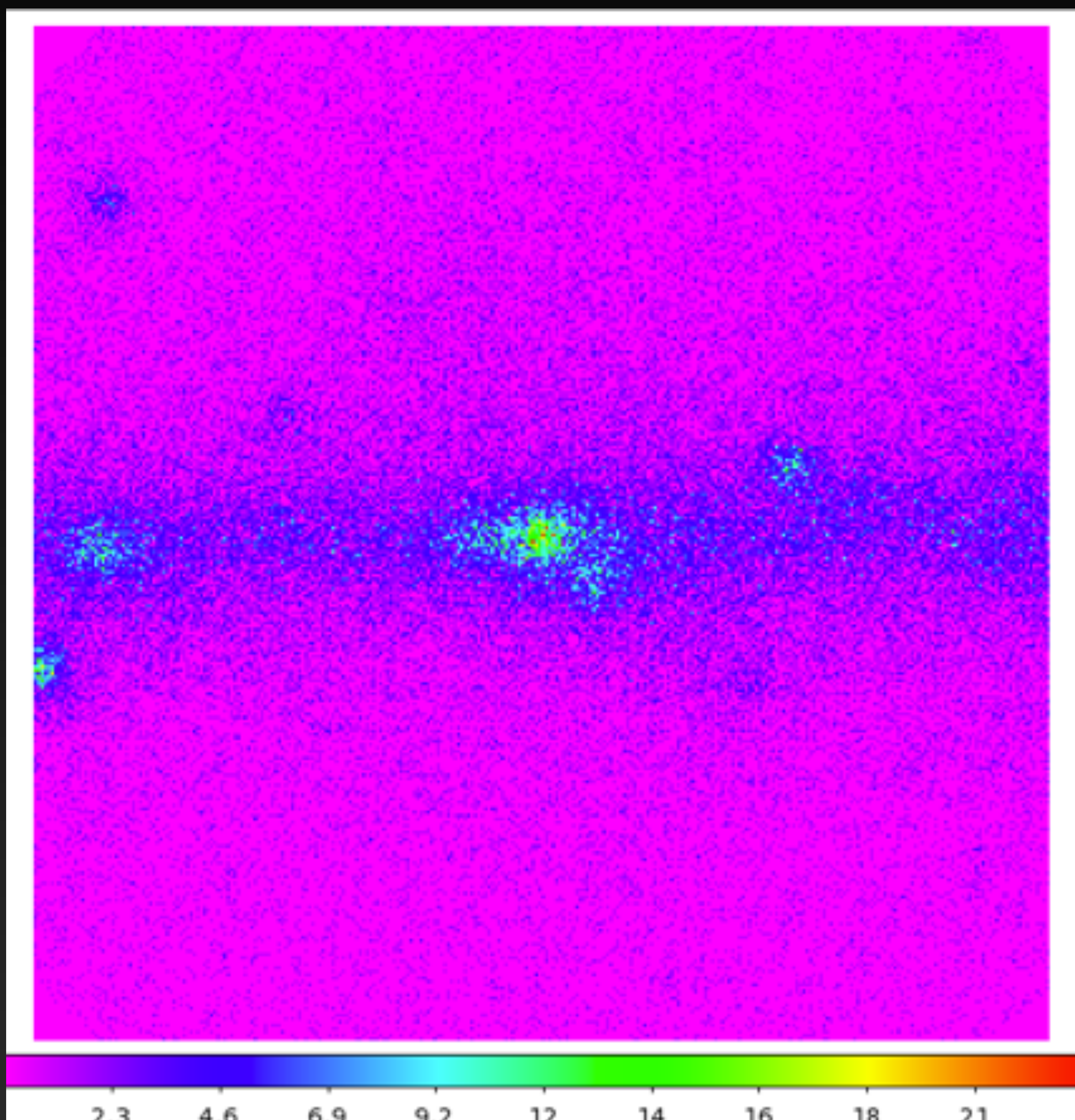
A Better fit to the Gamma-Ray Sky





Fits are significantly improved, in particular in regions near the Galactic Center where there is significant kinematic gas information.

Application to the Galactic Center

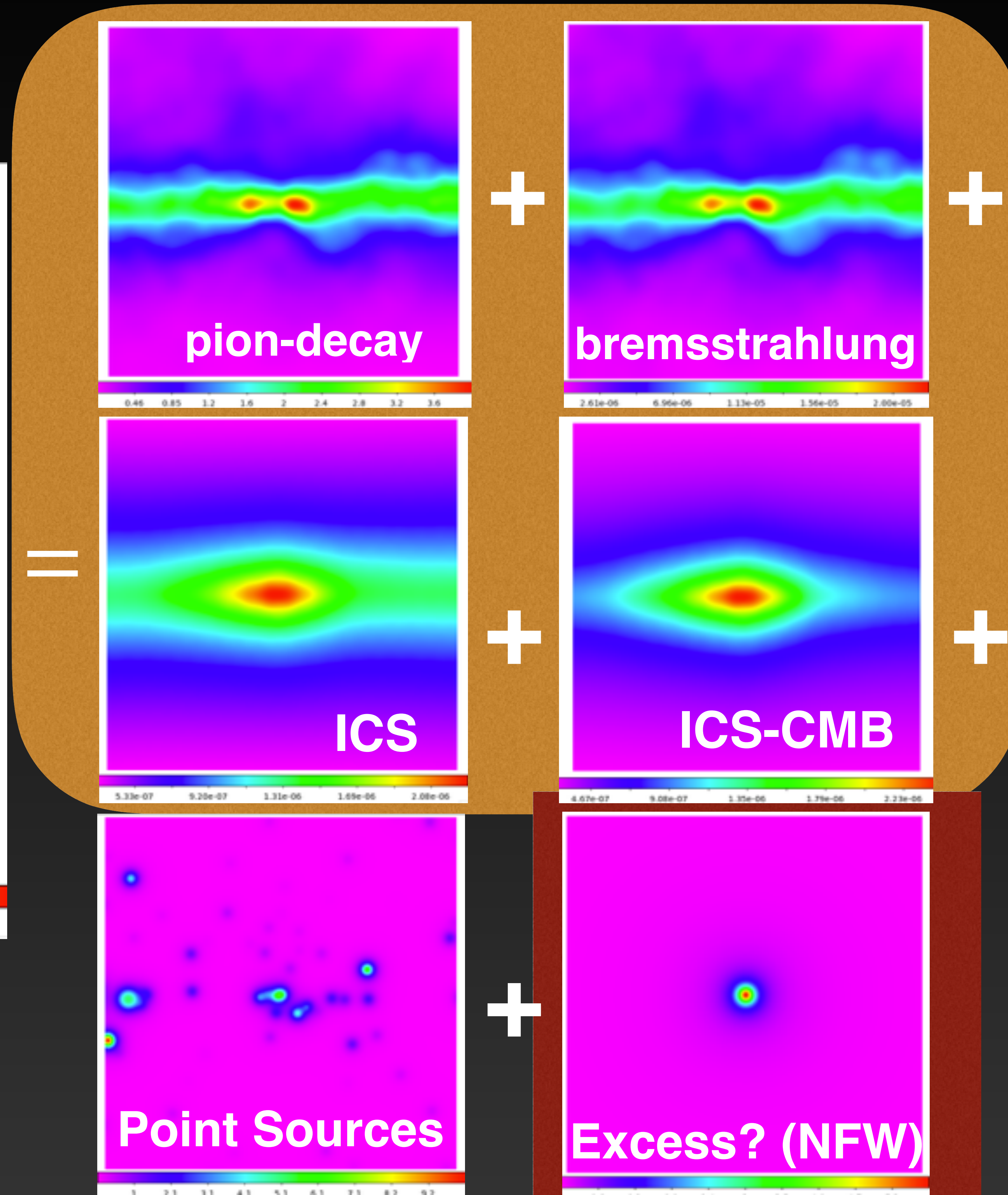


Data

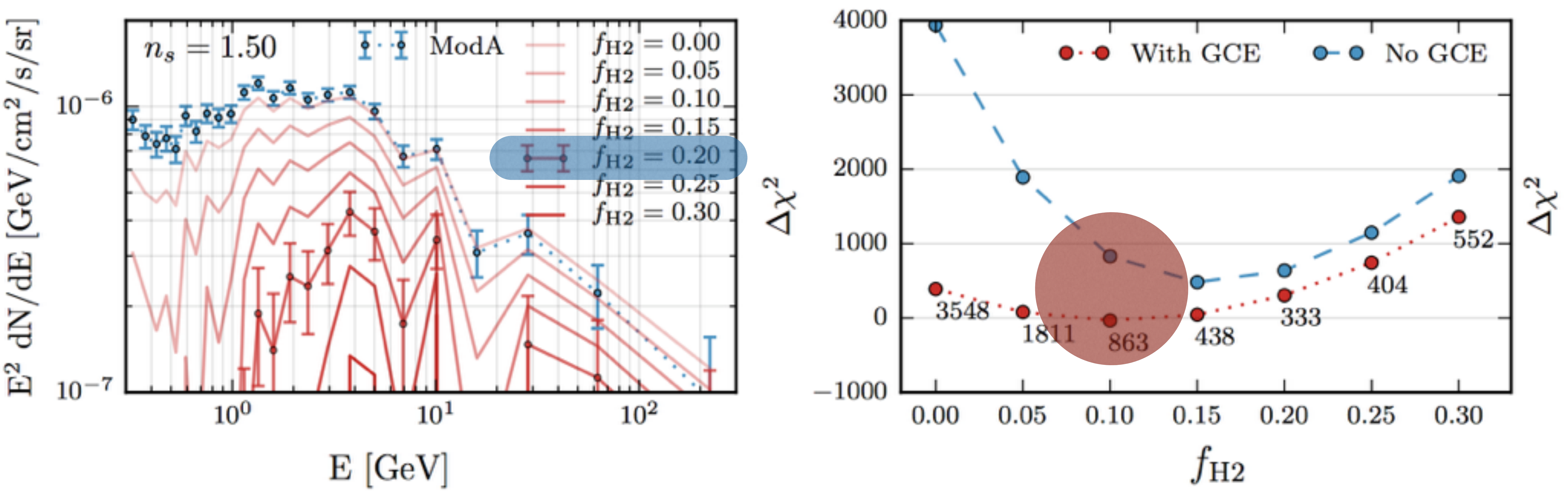
750 — 950 MeV

Best Angular Resolution Cut

10º x 10º ROI



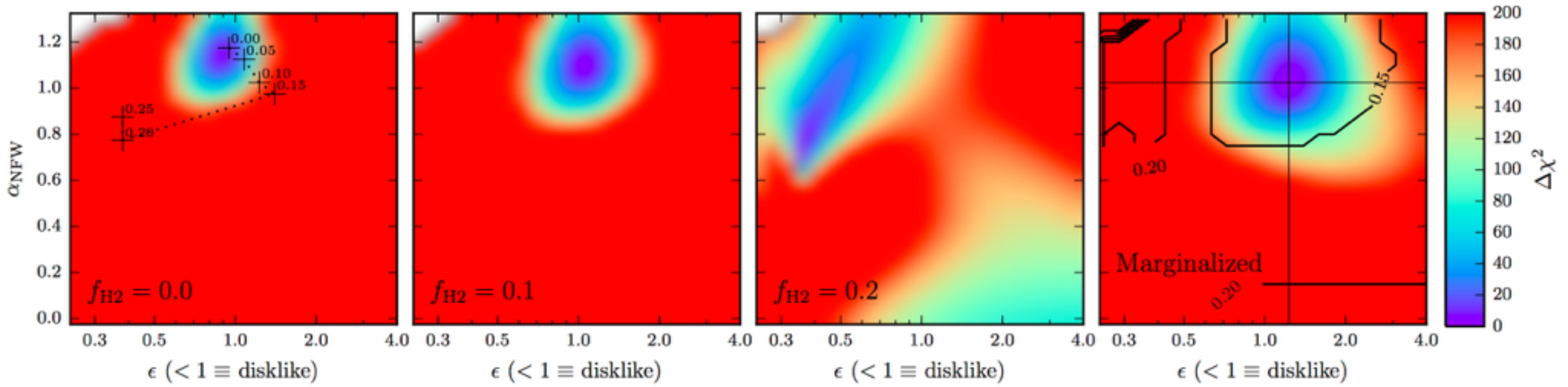
Effect on the GC Excess



Increasing the value of f_{H2} decreases the intensity of the gamma-ray excess.

However, the best global fit is $f_{H2} = 0.1$, with a GC excess intensity that decreases by only ~30%.

Effect on the Excess Morphology

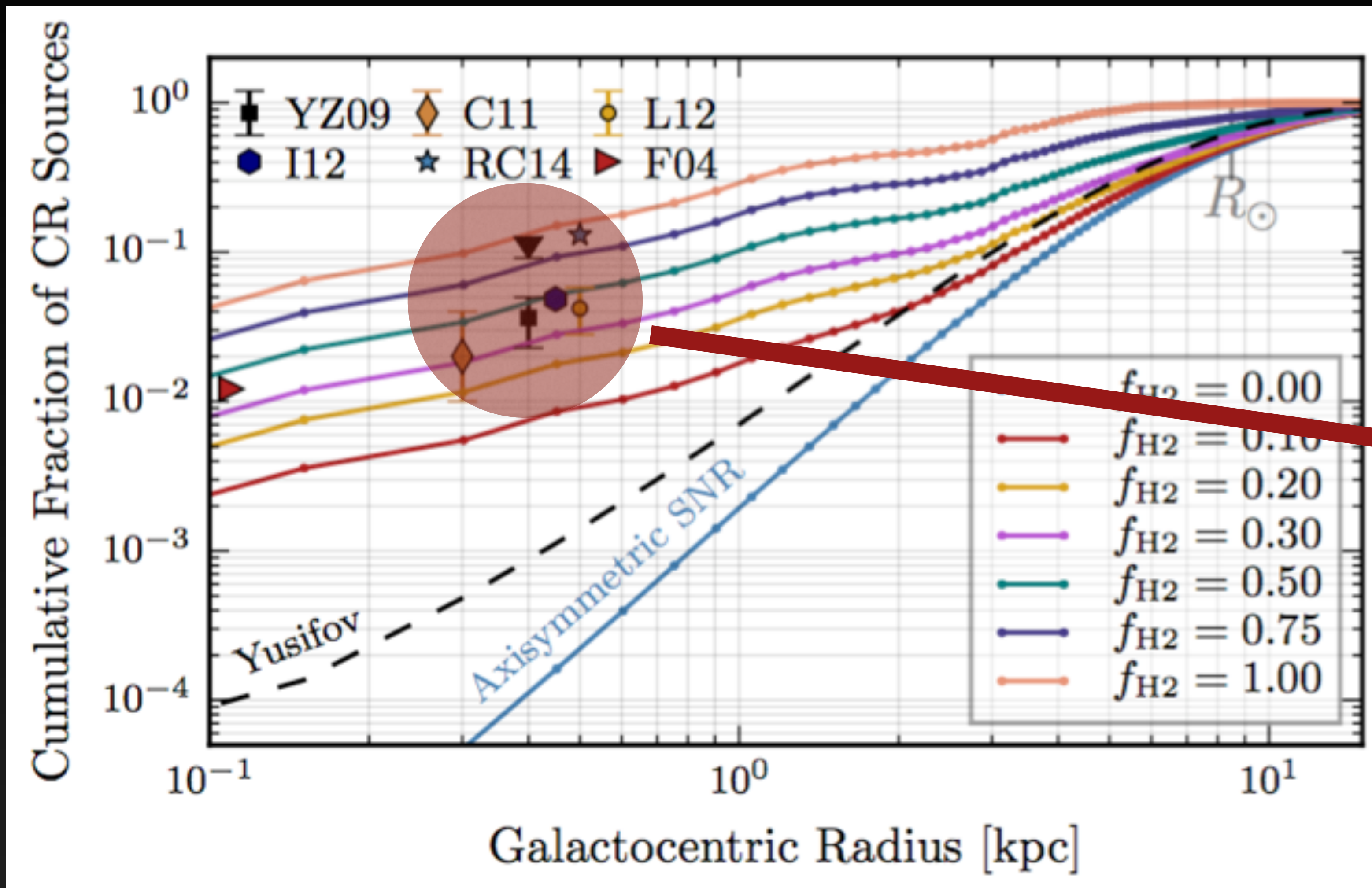


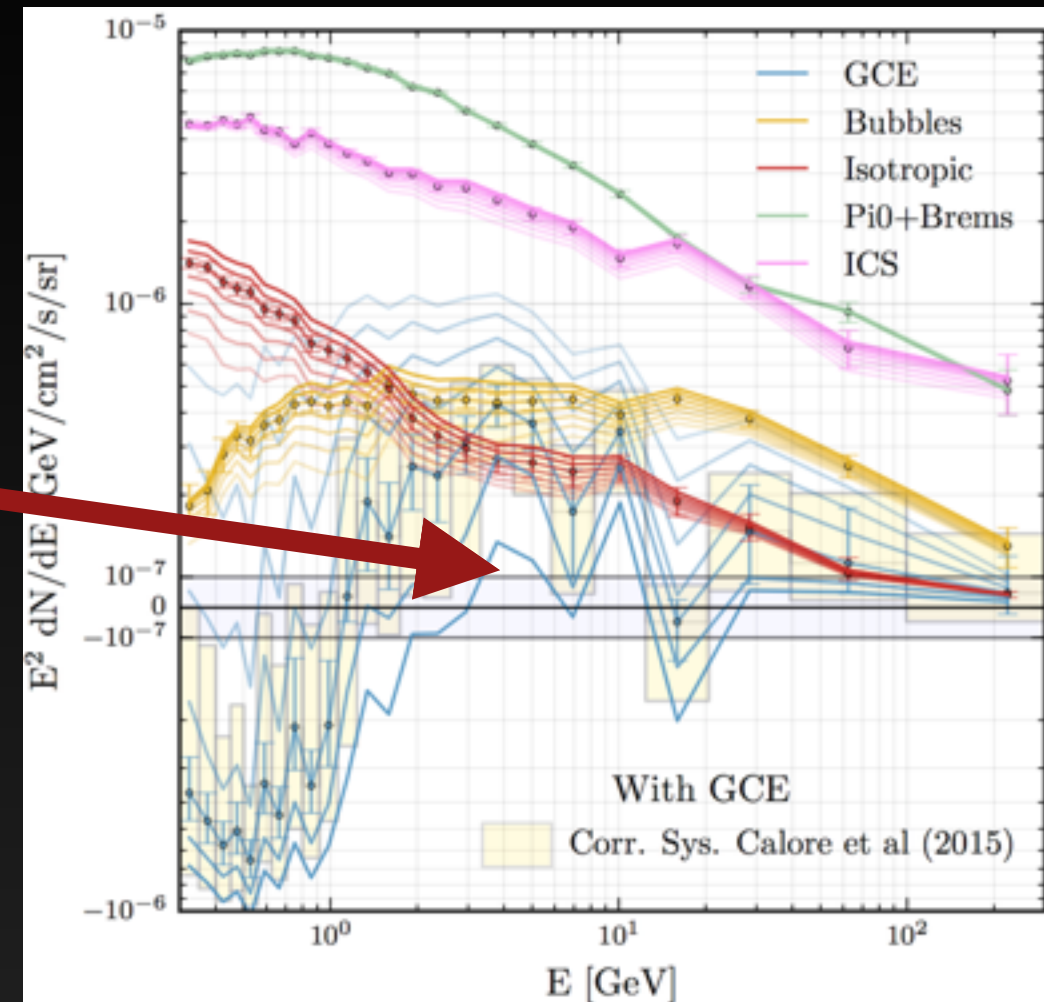
The morphology of the excess is also degenerate with f_{H2}.

As f_{H2} is increased, the best-fit morphology becomes stretched perpendicular to the galactic plane.

However, marginalized over all values of f_{H2}, the standard NFW template is still consistent with the data.

The Galactic Center Deficit?





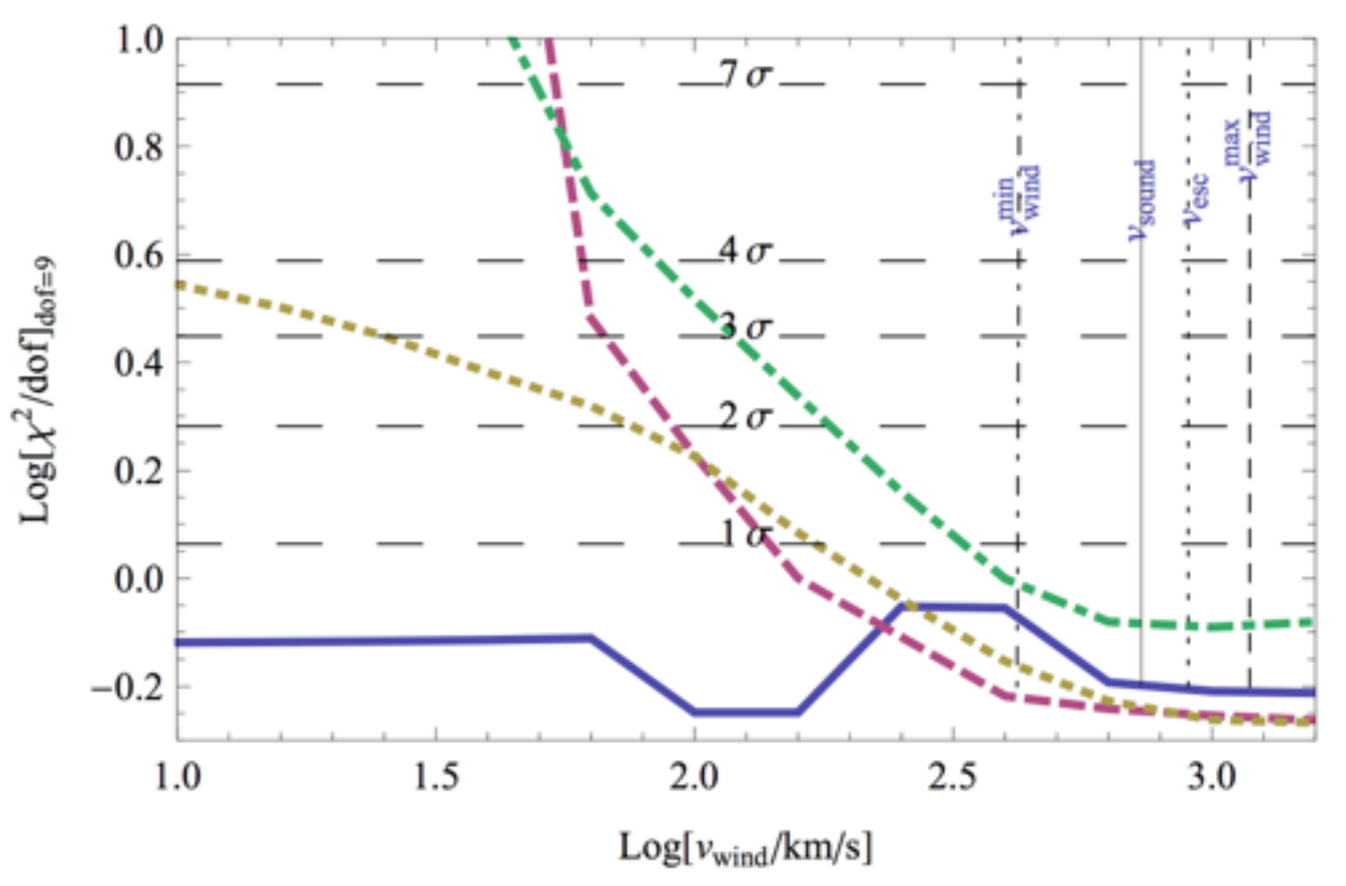
Models which reproduce the SN rate at the Galactic center generally predict a negative gamma-ray excess!

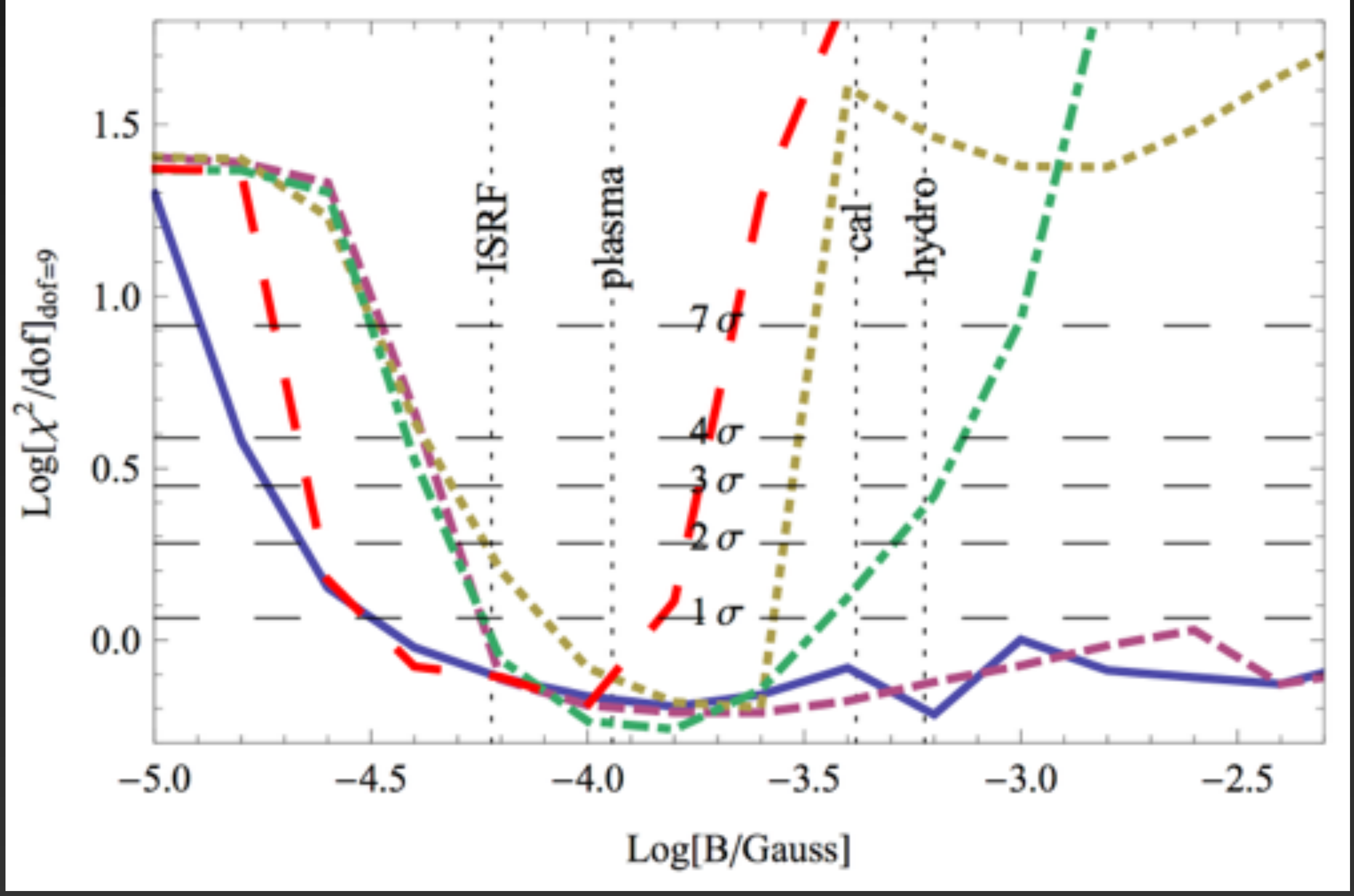
Advection and Convection in the Galactic Center

Crocker et al. (2011) demonstrated that the break in the GC synchrotron spectrum is best fit in the regime with:

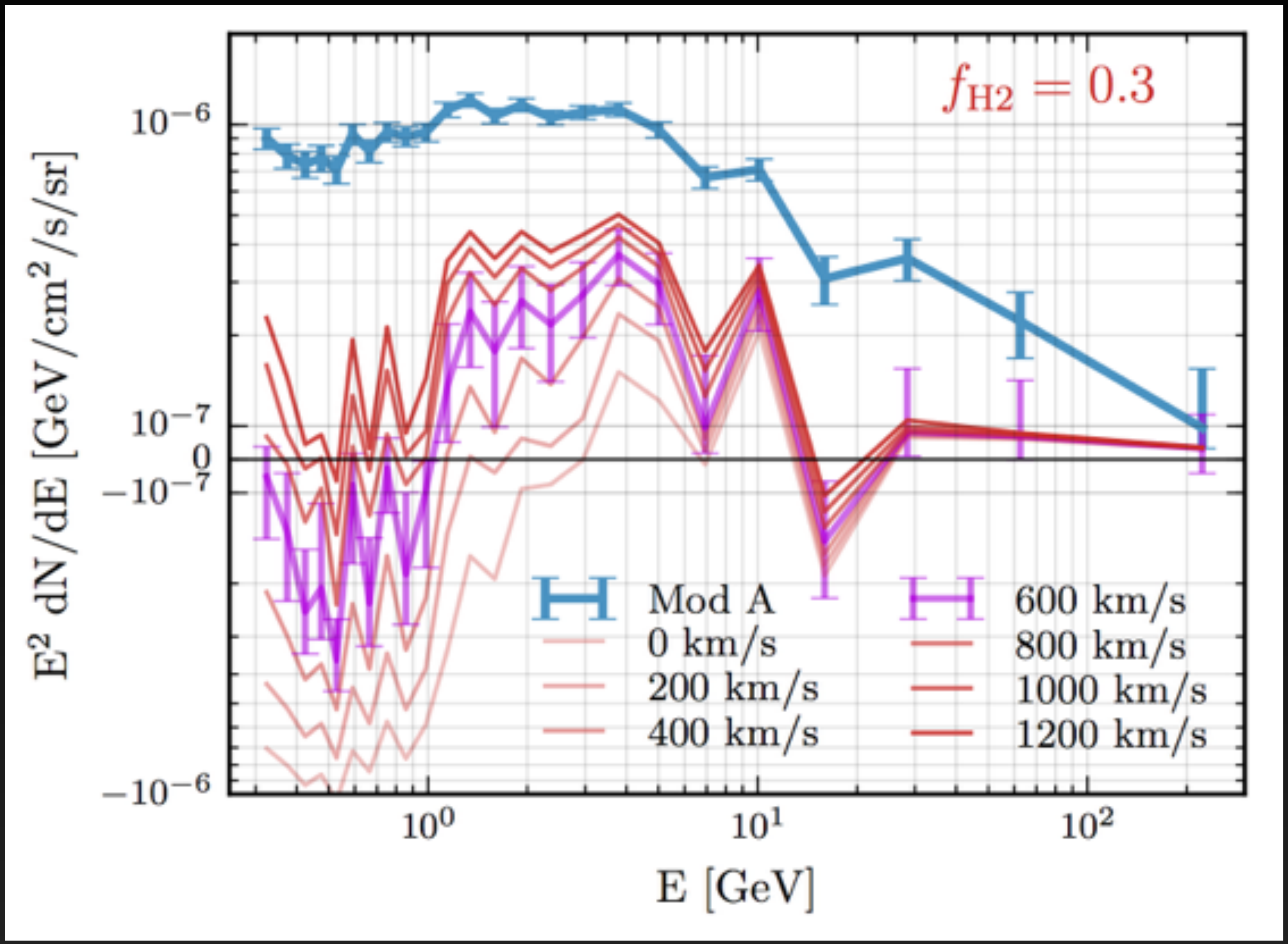
a.) Large Magnetic Fields
b.) Large Convective Winds

Very different from typical Galprop diffusion scenario.





The Low Energy Spectrum

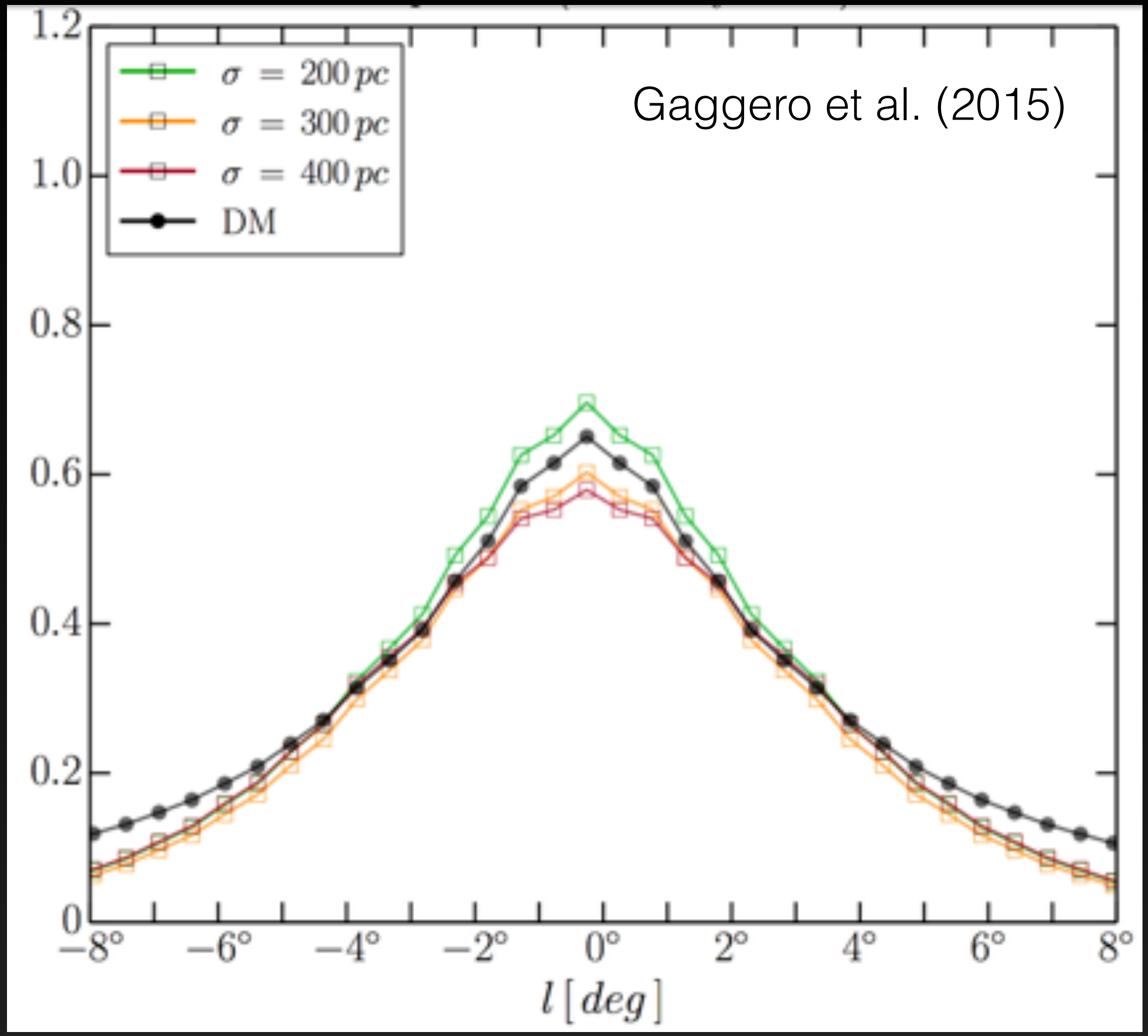


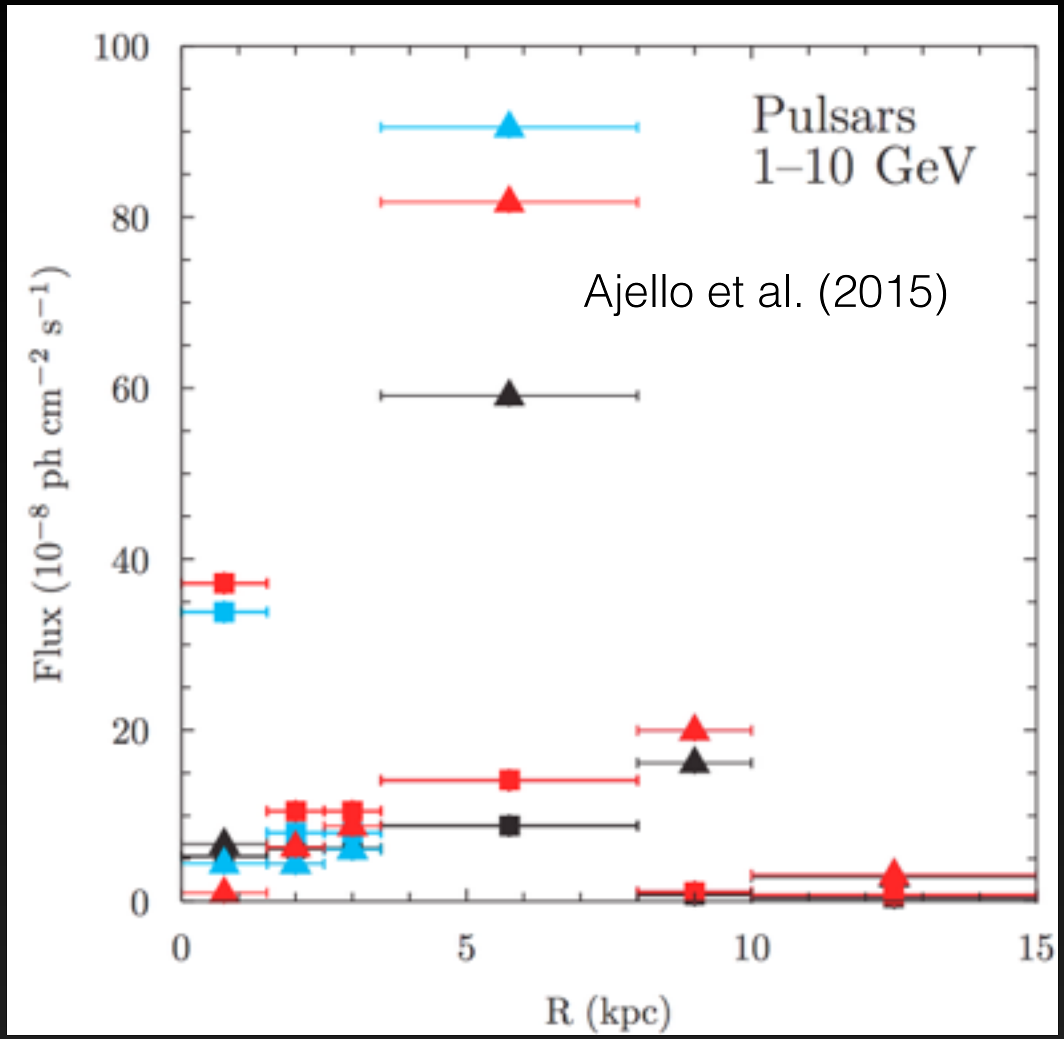
Applying strong convective winds to the diffuse emission model fixes the low-energy over subtraction.

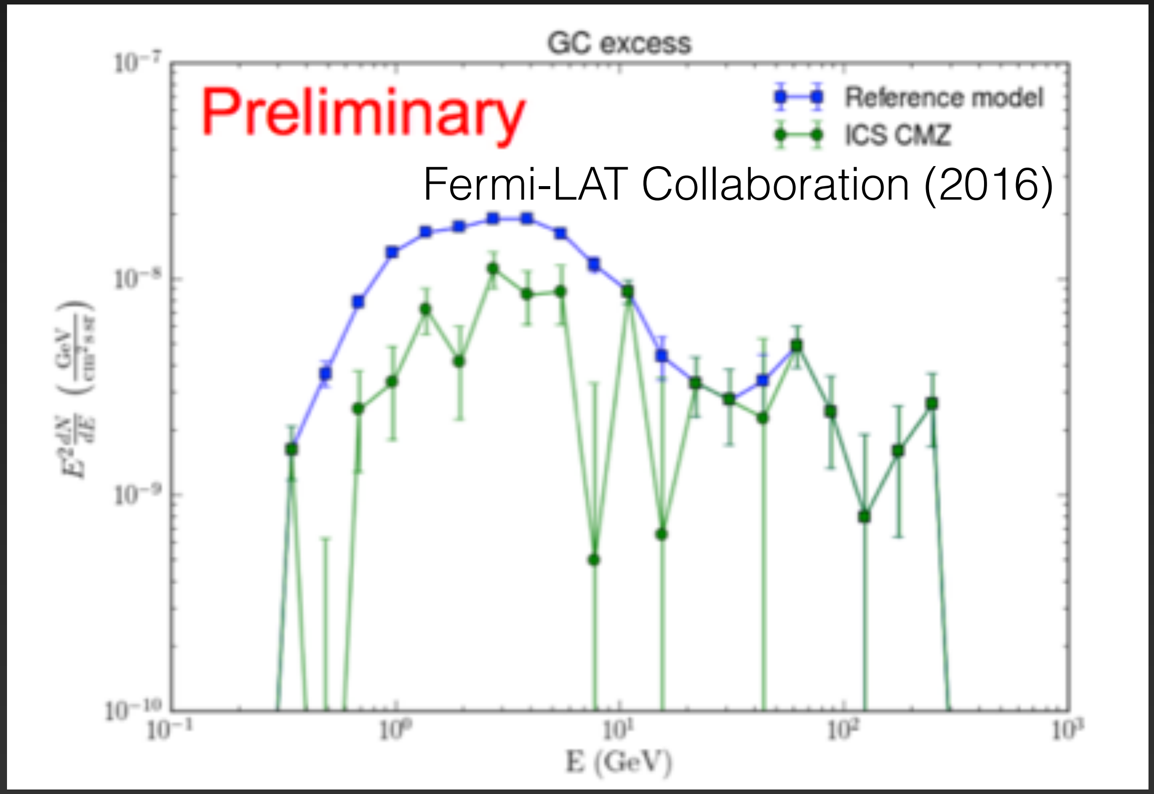
The intensity of the excess near the spectral peak also increases, up to ~50% of its nominal value.

The model produces a significantly better fit to the gamma-ray sky dataset - and also coincides better with multi wavelength data.

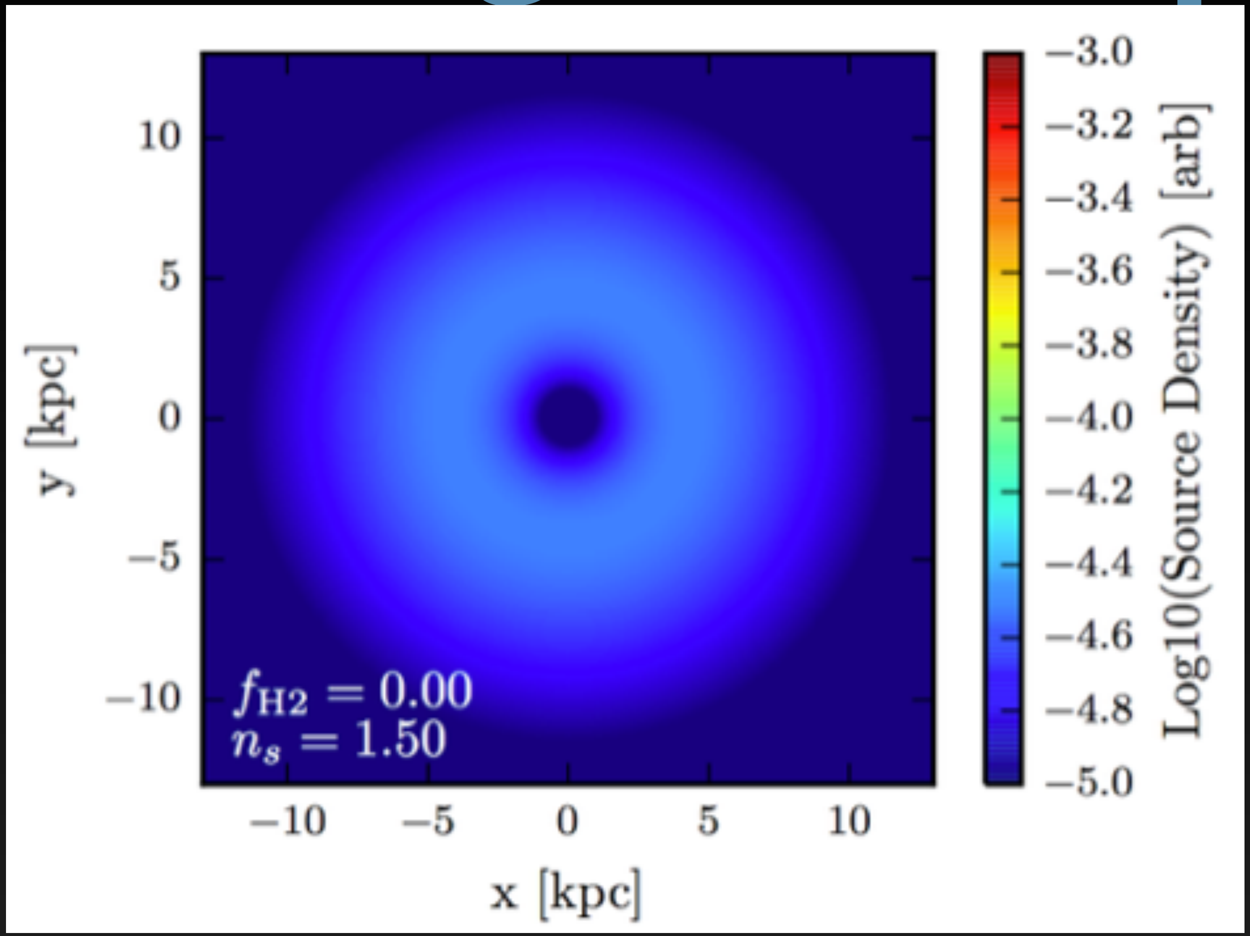
A Similar Result with Different Techniques

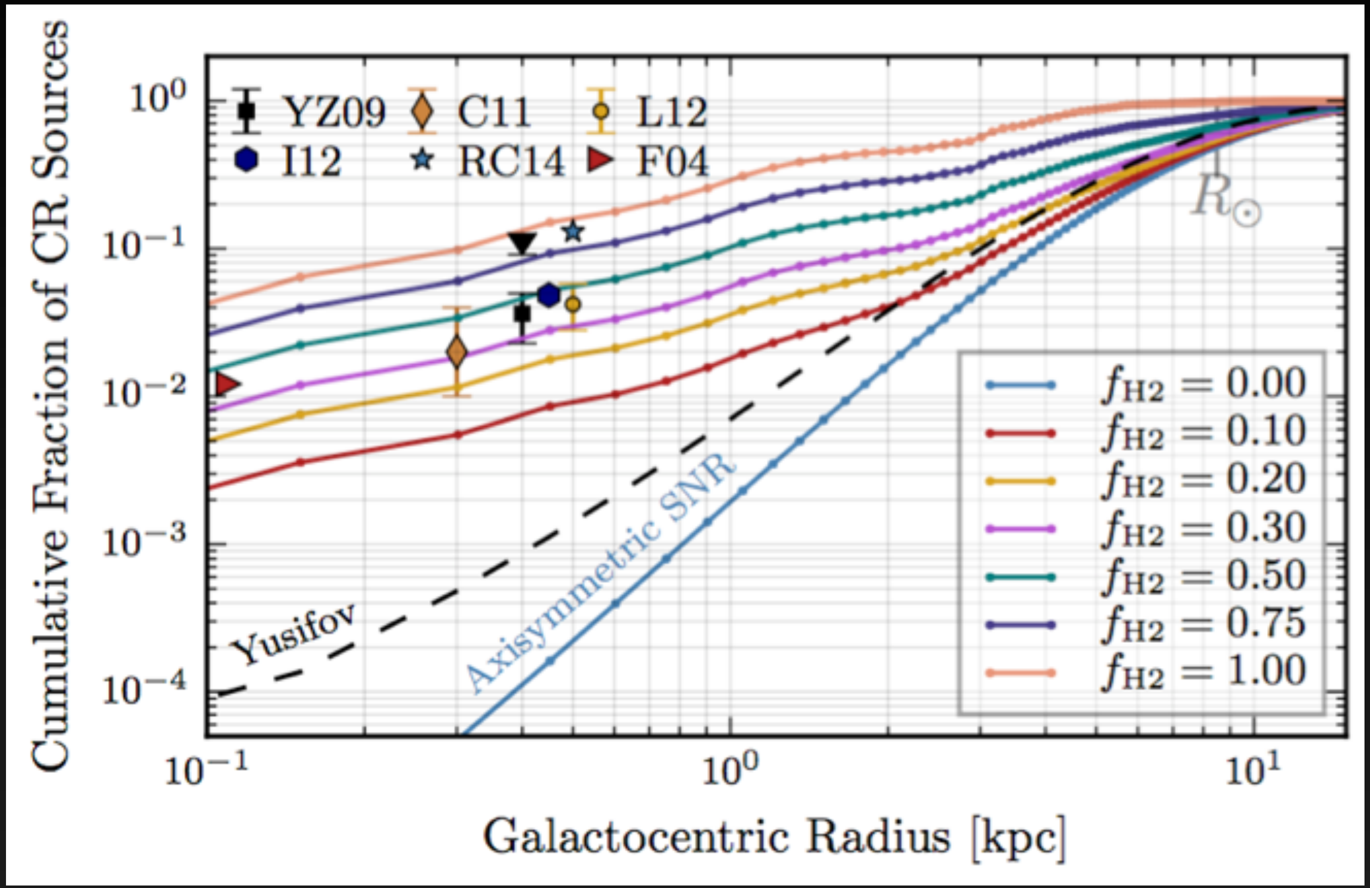






Waxing Philosophical.....



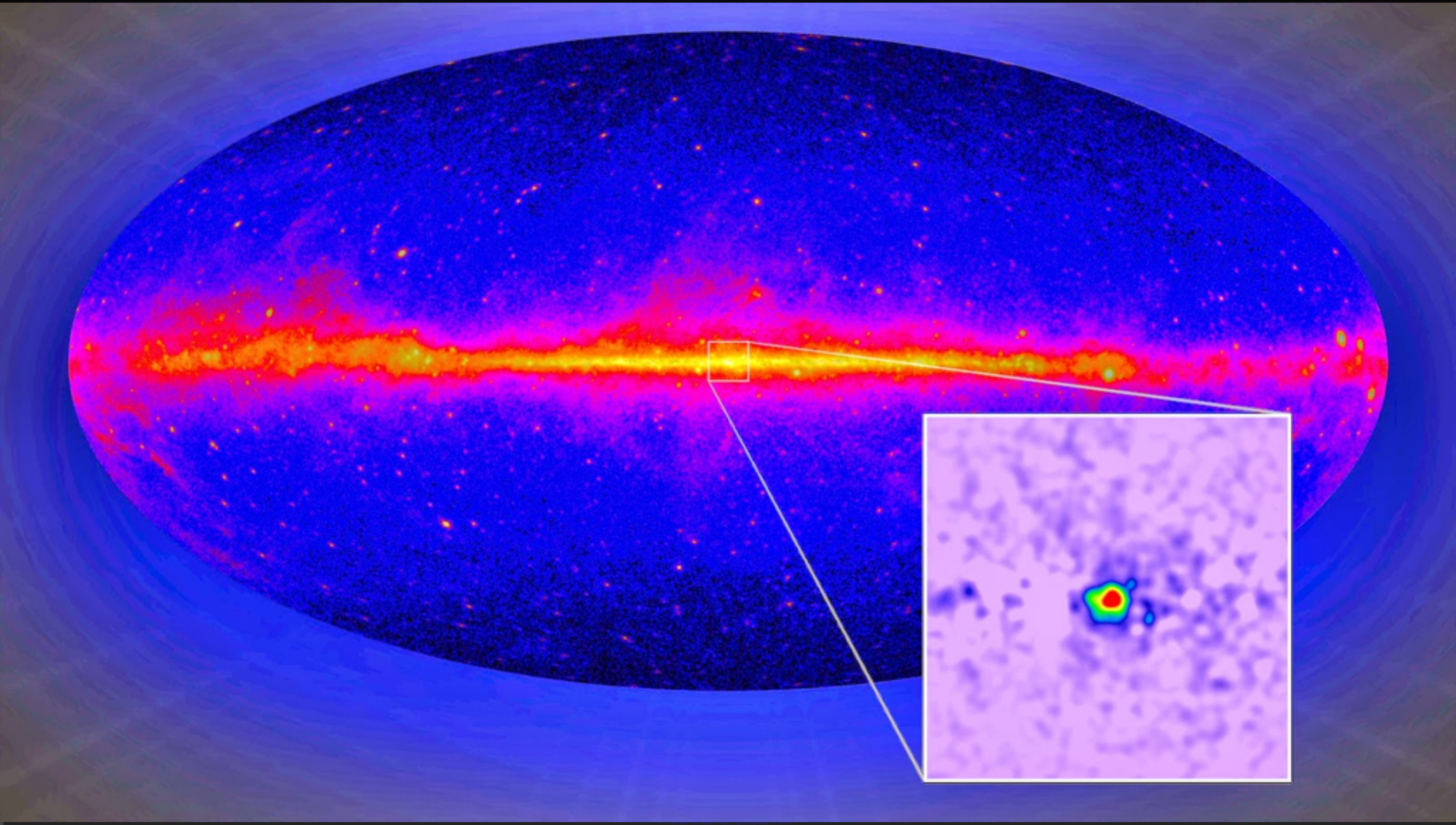


The lack of cosmic-ray injection in the GC should still be slightly disturbing. Especially when we try to answer the question: "excess compared to what?"

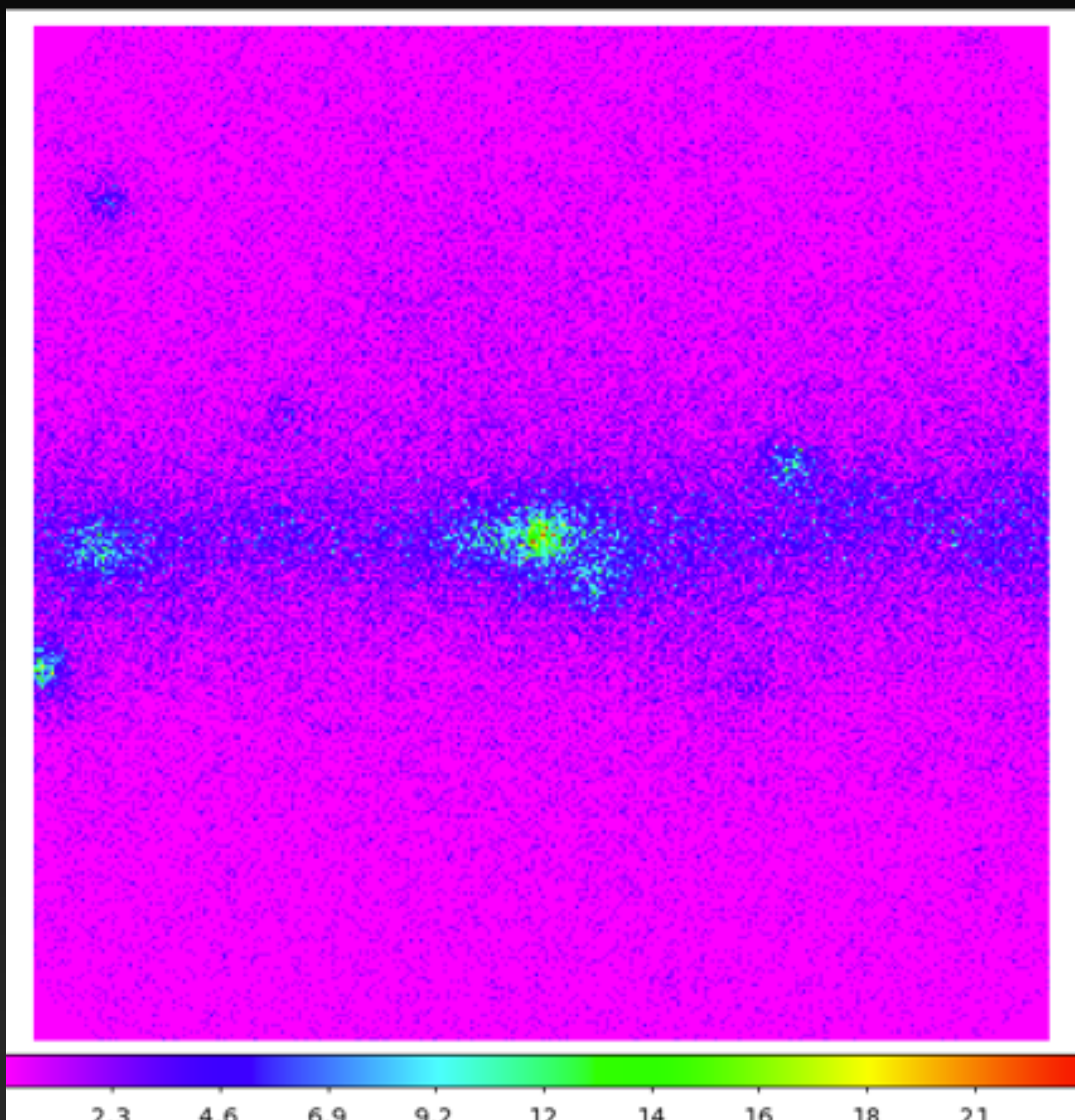
Our models indicate a degeneracy between cosmic-ray injection and the existence of a Galactic center excess template tracing an NFW profile. However, at present the best fit models still include a significant NFW component.

Extra Slides

The GeV Excess



How To Find an Excess

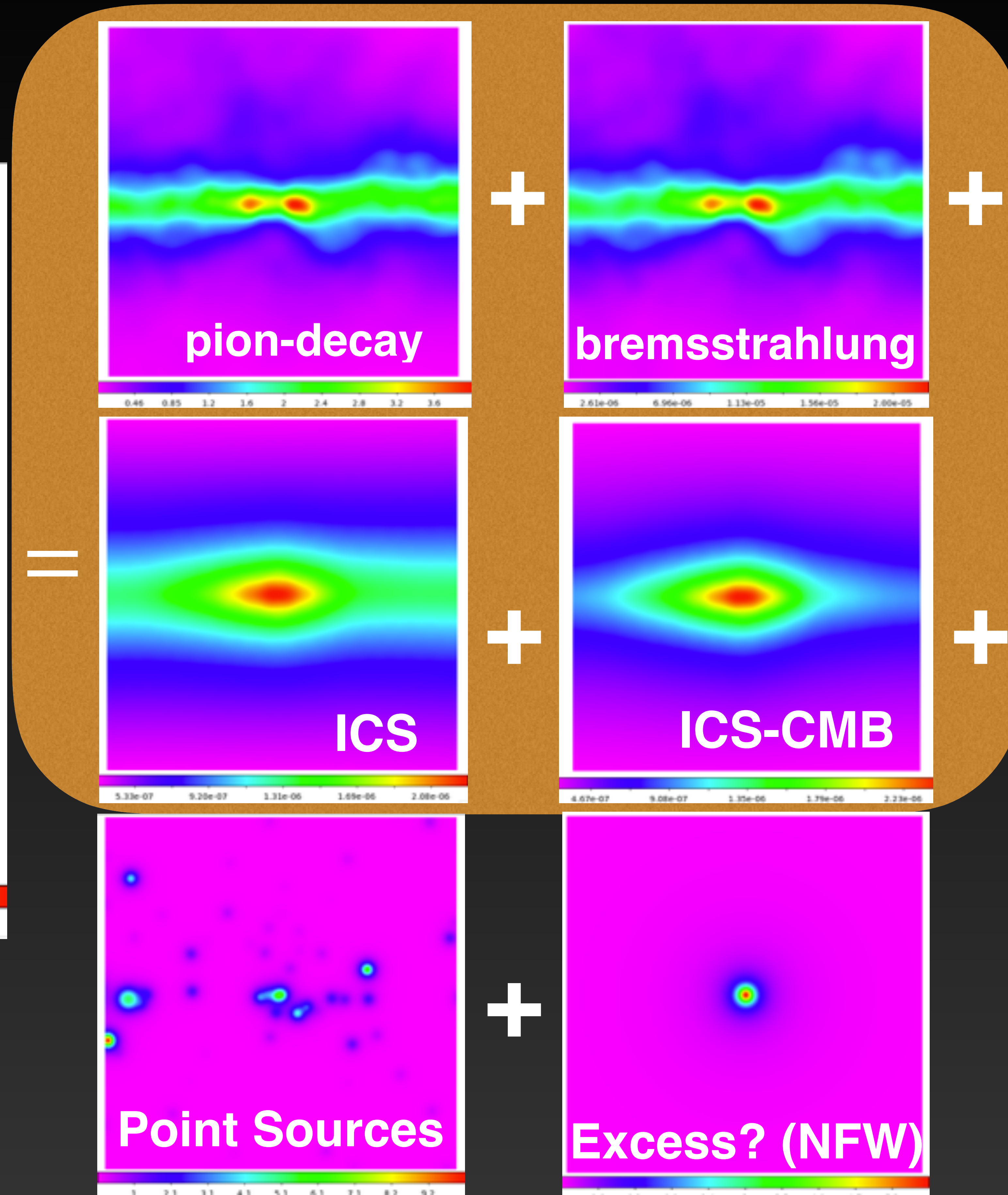


Data

750 — 950 MeV

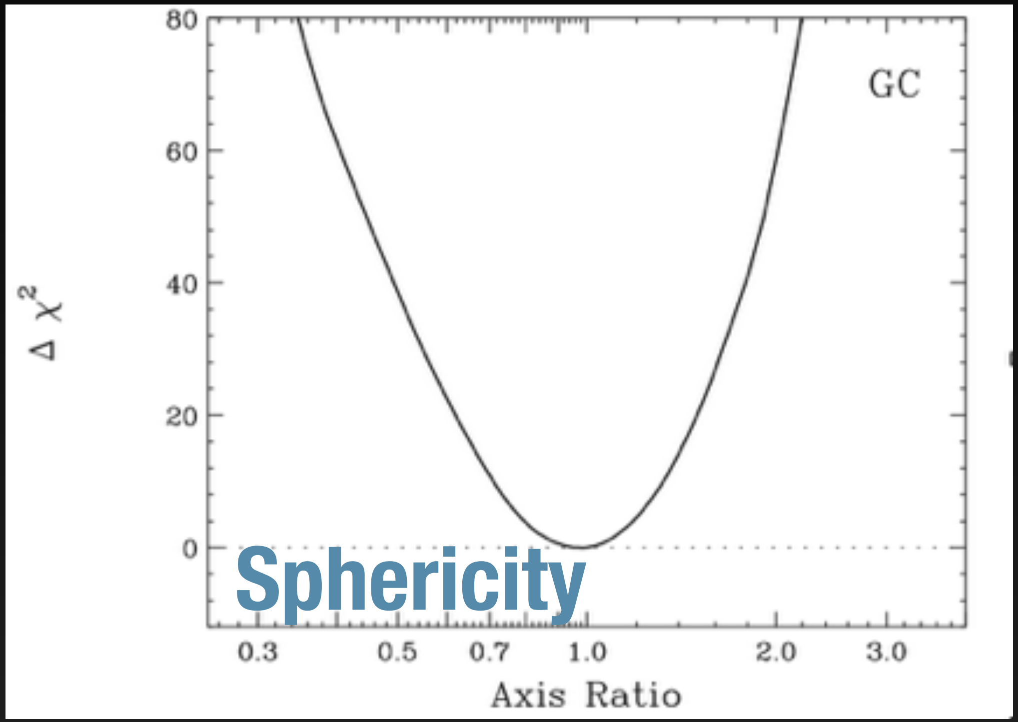
Best Angular Resolution Cut

$10^{o} \times 10^{o}$ ROI

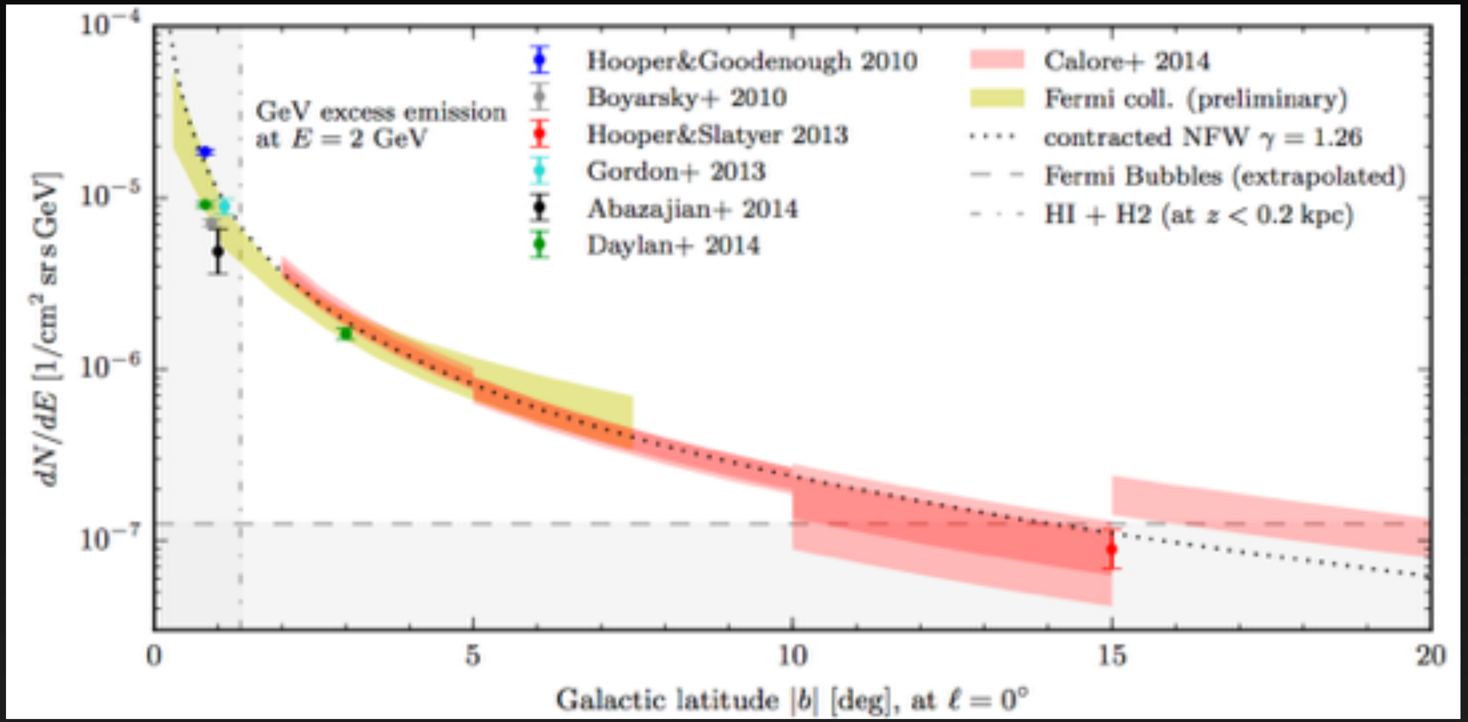


Observational Results

Daylan et al. (2014)



Calore et al. (2014b)



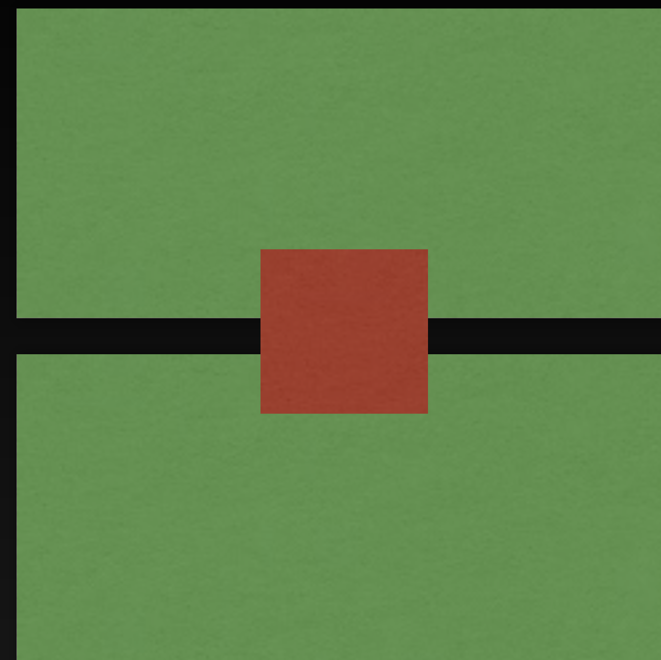
These are the three resilient features of the GeV Excess:

1.) Hard Gamma-Ray Spectrum peaking at ~2 GeV

2.) Spherically Symmetric Emission Morphology

3.) Extension to >10° from the GC.

Two Analyses of the Gamma-Ray Excess



INNER GALAXY

- Mask galactic plane (e.g. $|b| > 1^{\circ}$), and consider $40^{\circ} \times 40^{\circ}$ box
- Bright point sources masked at 2°
- Use likelihood analysis, allowing the diffuse templates to float in each energy bin
- Background systematics controlled

GALACTIC CENTER

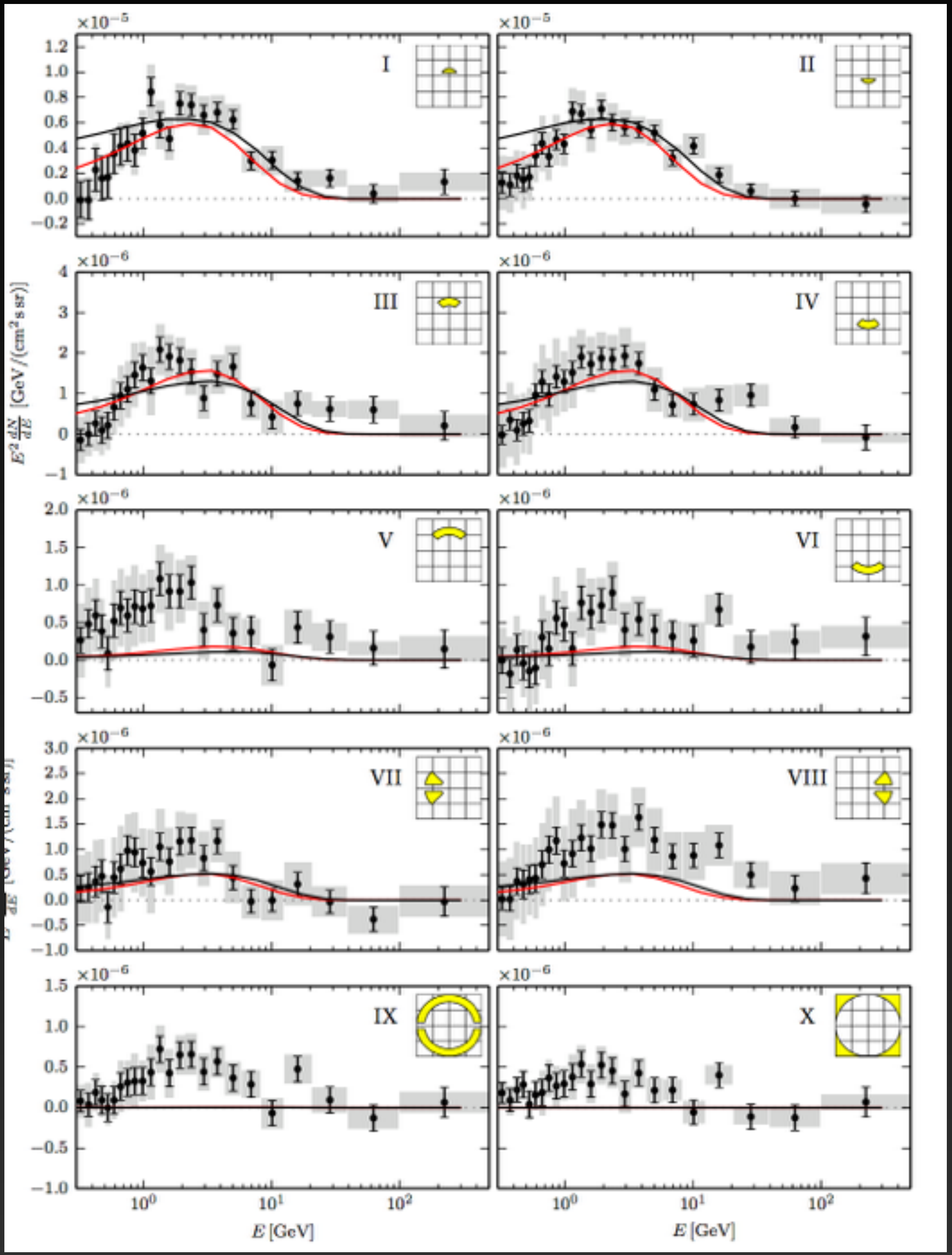
- Box around the GC ($10^{\circ} \times 10^{\circ}$)
- Include and model all point sources
- Use likelihood analysis to calculate the spectrum and intensity of each source
- Bright Signal

Leptonic Outbursts

The Galactic center is unlikely to be in steady state (e.g. Fermi bubbles).

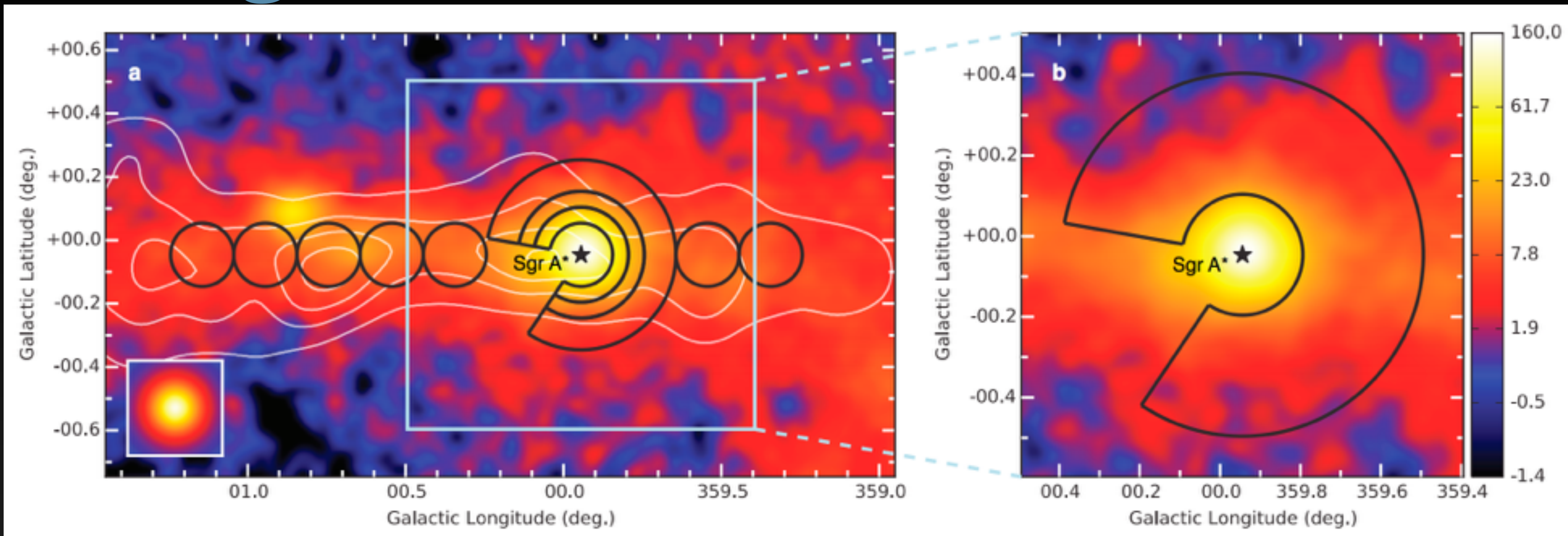
An outburst of leptonic origin can produce the gamma-ray excess, but only if the injected electron spectrum is extremely hard (compared to observed blazar spectra).

Cholis et al. (2015, 1506.05119)



Petrovic et al. (2014, 1405.7928)
Cholis et al. (2015, 1506.05119)

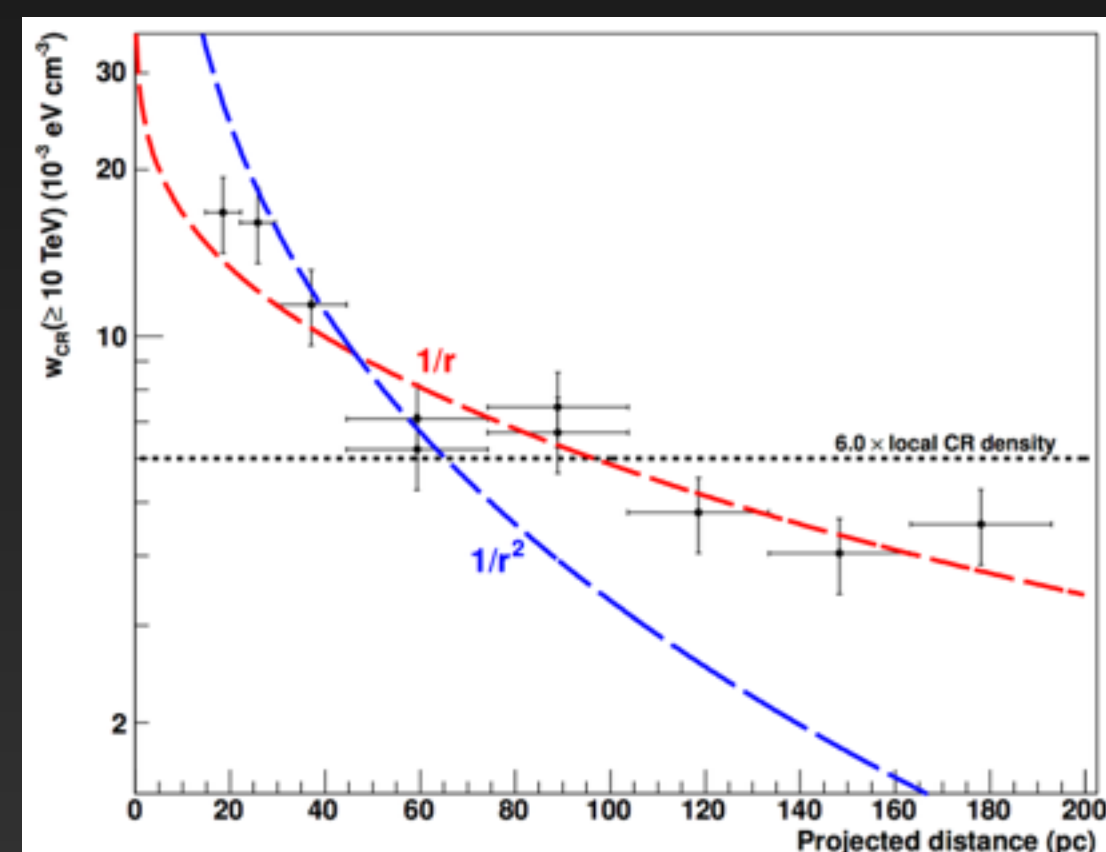
The Sgr A* Source



HESS has detected diffuse gamma-ray emission at energies ~100 TeV.

This is not observed in even the youngest supernova remnants.

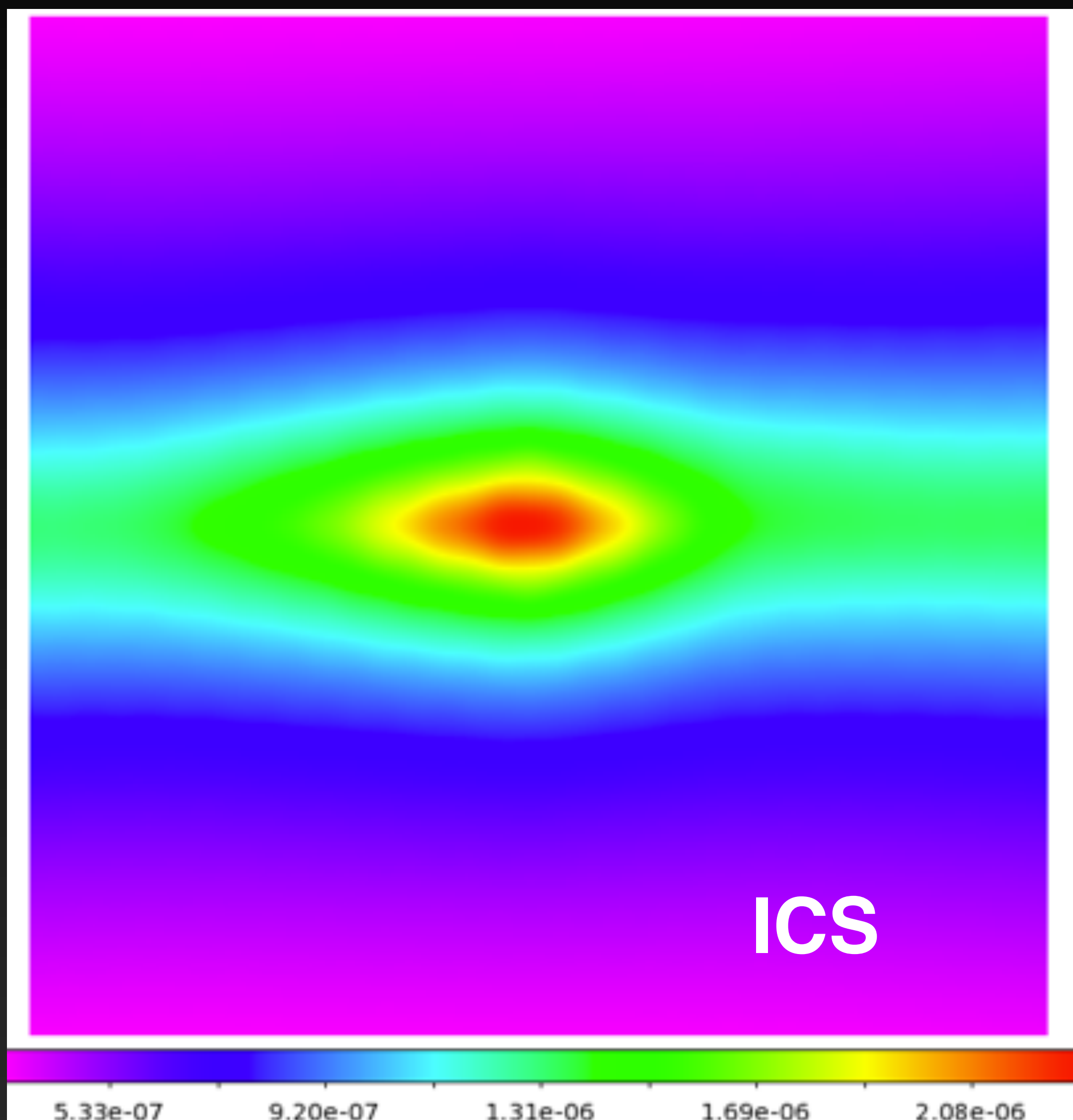
The emission profile is indicative of diffusion from the central BH.

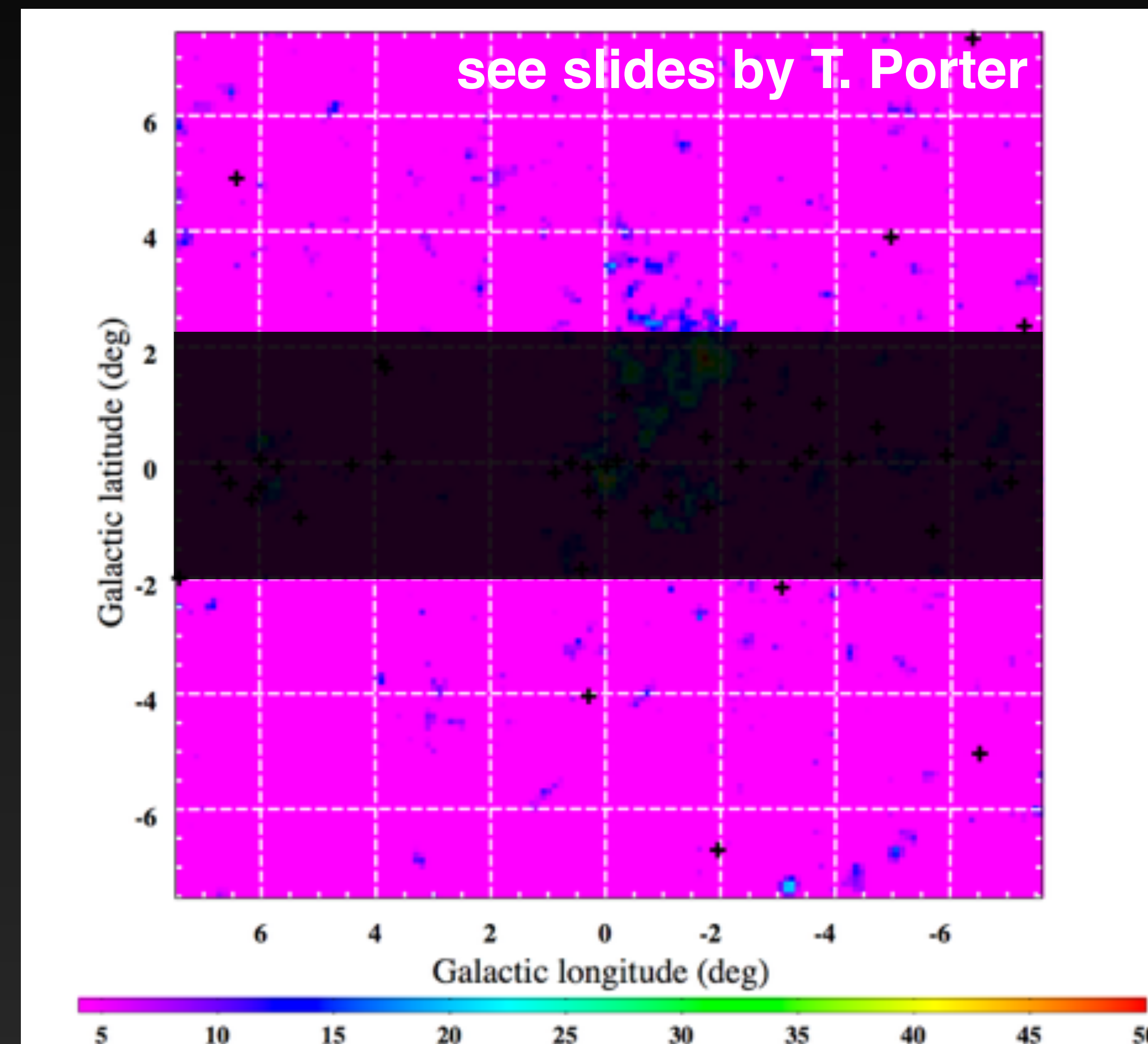


Millisecond Pulsar Fits

IG

Ajello et al. (2015)

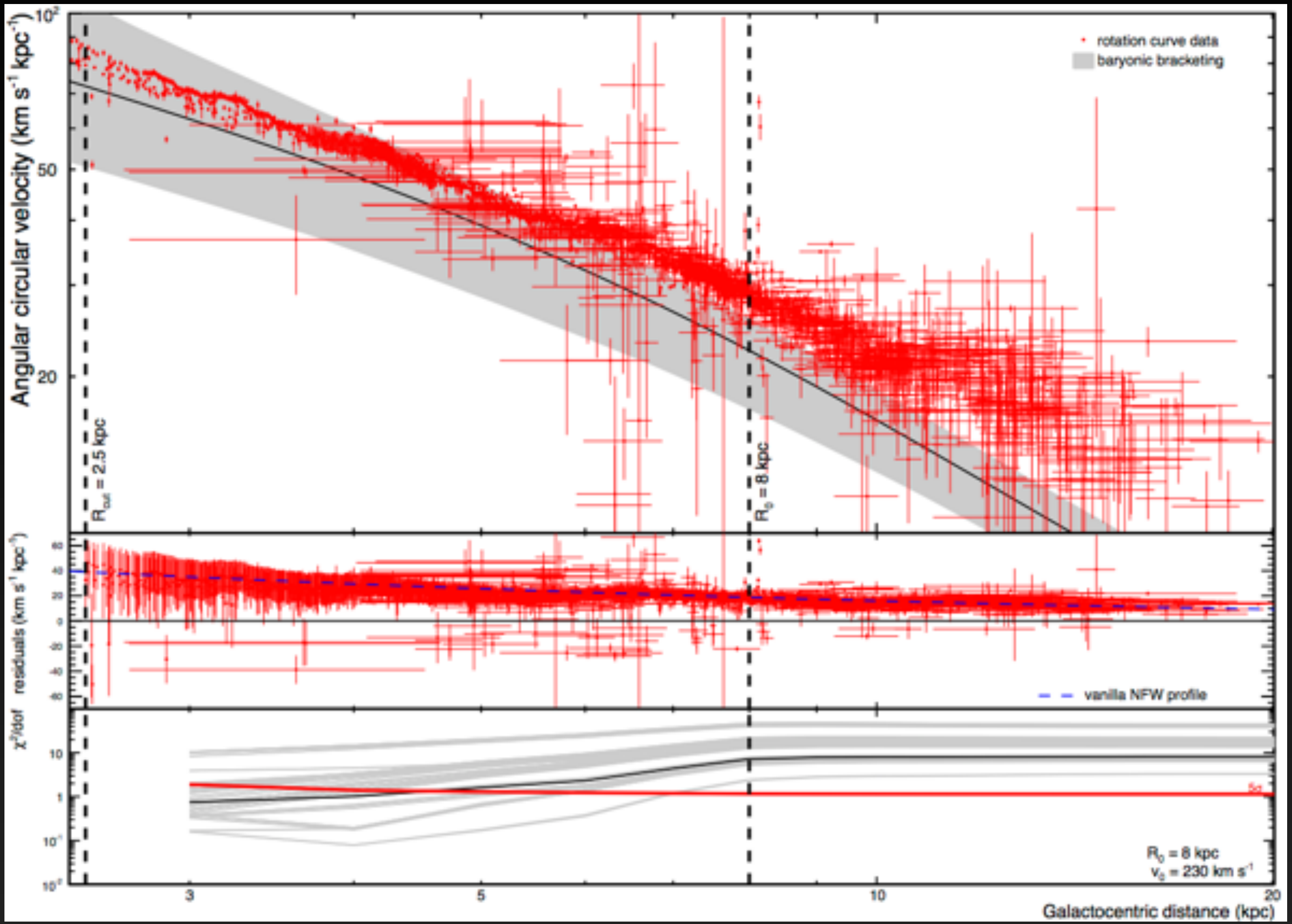




- However, these residuals are found once an extremely smooth diffuse emission model is subtracted - it remains to be seen whether the residuals are resilient to diffuse model changes.

see slides by Christoph Weniger

Dark Matter Annihilation?



Recently, observations by Iocco, Pato & Bertone (2015) have used stellar velocity measurements to directly measure the dark matter density in the Milky Way (to within 3 kpc of the GC).

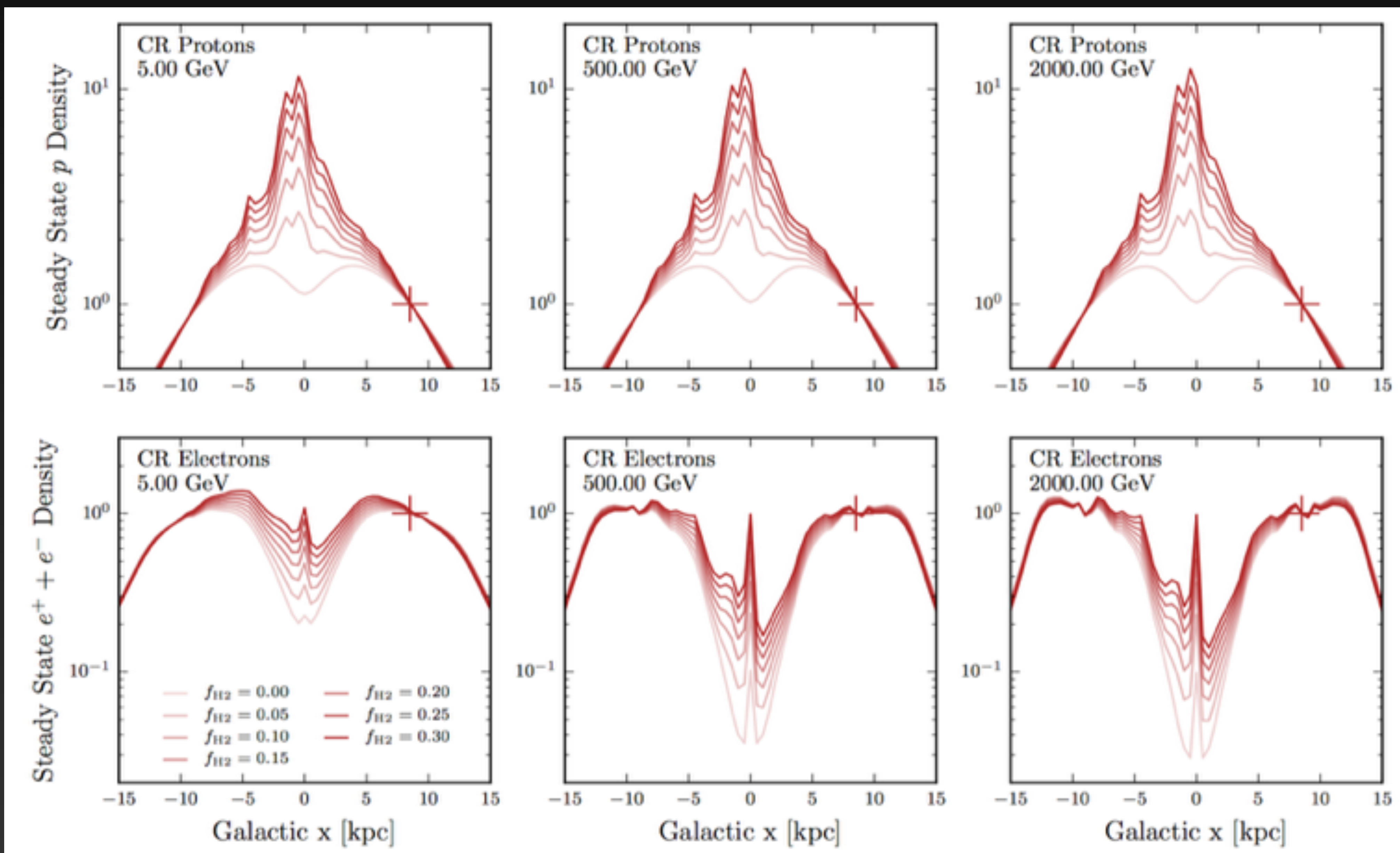
Future measurements (employing Gaia data) will have the ability to significantly improve these measurements.

Iocco, Pato & Bertone (2015)

Simulations!

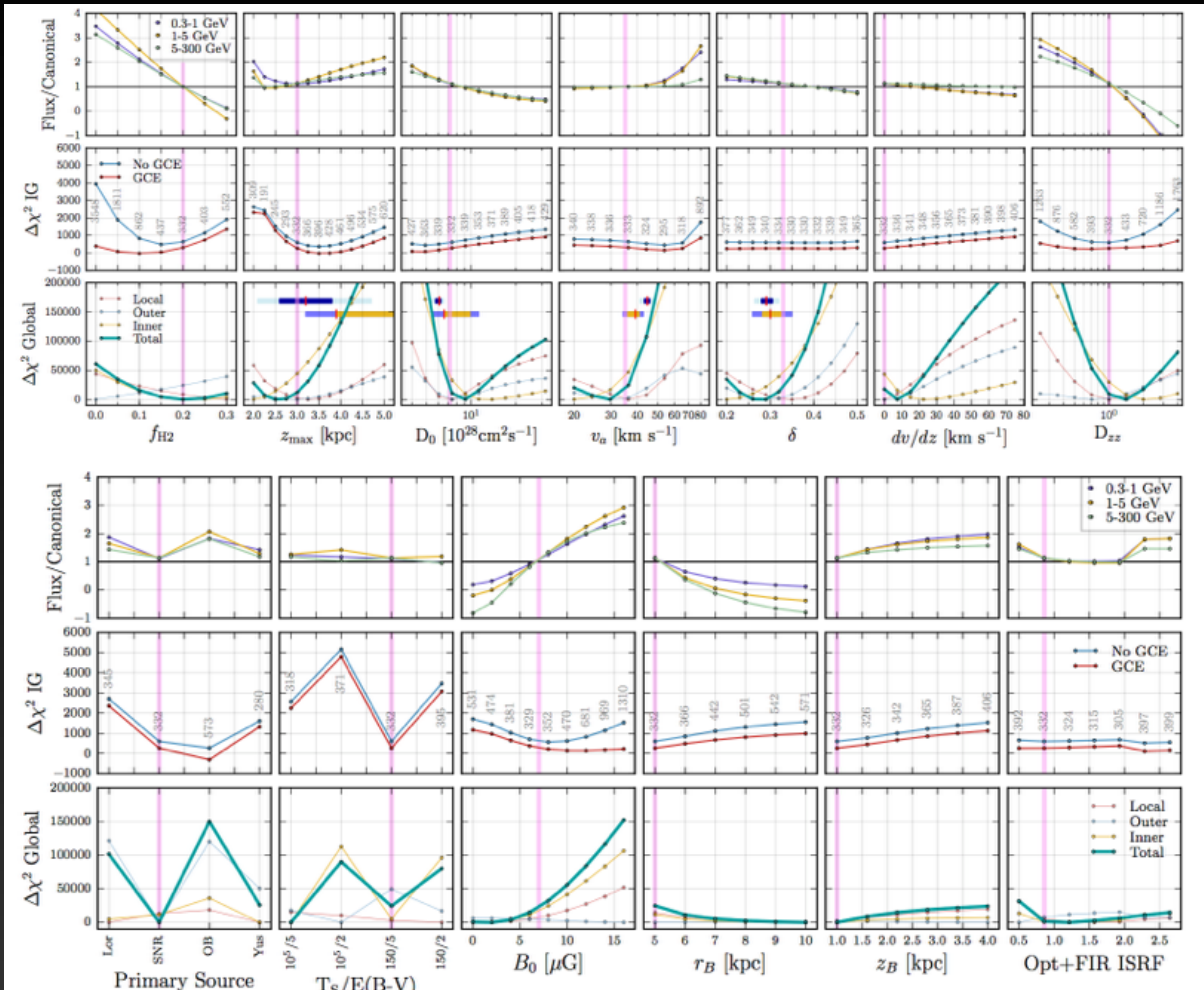
Add the new cosmic-ray injection models into Galprop to produce a new steady-state cosmic-ray distribution.

Parameter	Units	Canonical	Mod A	Description
D_0	$cm^2\ s^{-1}$	7.2×10^{28}	5.0×10^{28}	Diffusion constant at $\mathcal{R} = 4$ GV
δ	–	0.33	0.33	Index of diffusion constant energy dependence
z_{halo}	kpc	3	4	Half-height of diffusion halo
R_{halo}	kpc	20	20	Radius diffusion halo
v_a	$km\ s^{-1}$	35	32.7	Alfvén velocity
dv/dz	$km\ s^{-1}\ kpc^{-1}$	0	50	Vertical convection gradient
α_p	–	1.88 (2.39)	1.88 (2.47)	p injection index below (above) $\mathcal{R} = 11.5$ GV
α_e	–	1.6 (2.42)	1.6 (2.43)	e^- injection index below (above) $\mathcal{R} = 2$ GV
Source	–	SNR	SNR	Distribution of $(1 - f_{H2})$ primary sources*
f_{H2}	–	.20	N/A	Fraction of sources in star formation model*
n_s	–	1.5	N/A	Schmidt Index*
ρ_c	cm^{-3}	0.1	N/A	Critical H_2 density for star formation*
B_0	μG	7.2	9.0	Local ($r = R_\odot$) magnetic field strength
r_B, z_B	kpc	5, 1	5, 2	Scaling radius and height for magnetic field
ISRF	–	(1.0,.86,.86)	(1.0,.86,.86)	Relative CMB, Optical, FIR density
dx, dy	kpc	0.5, 0.5	1 (2D)	x, y (3D) or radial (2D) cosmic-ray grid spacing
dz	kpc	0.125	.1	z-axis cosmic-ray grid spacing

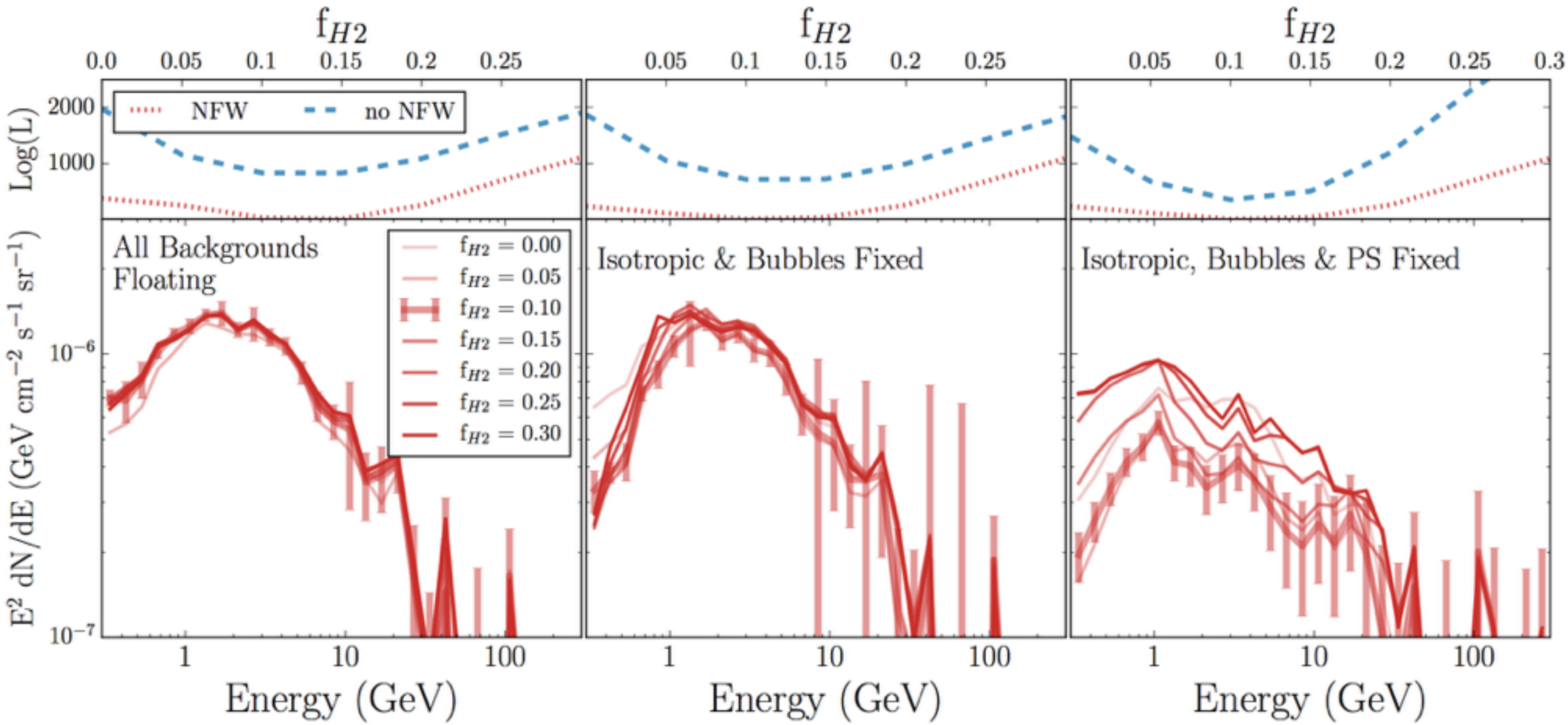


Galactic center excess is resilient....

IG

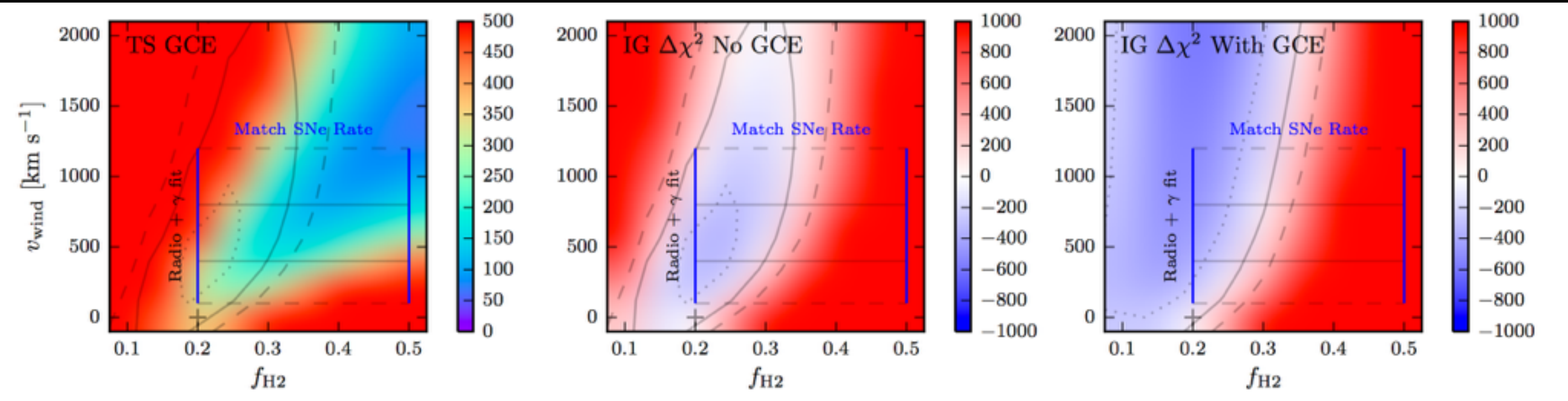


Masking 1FIG Sources in the GC



Changing the point source catalog from the 3FGL to the 1FIG has only a negligible effect on the gamma-ray excess.

Convection in the Galactic Center

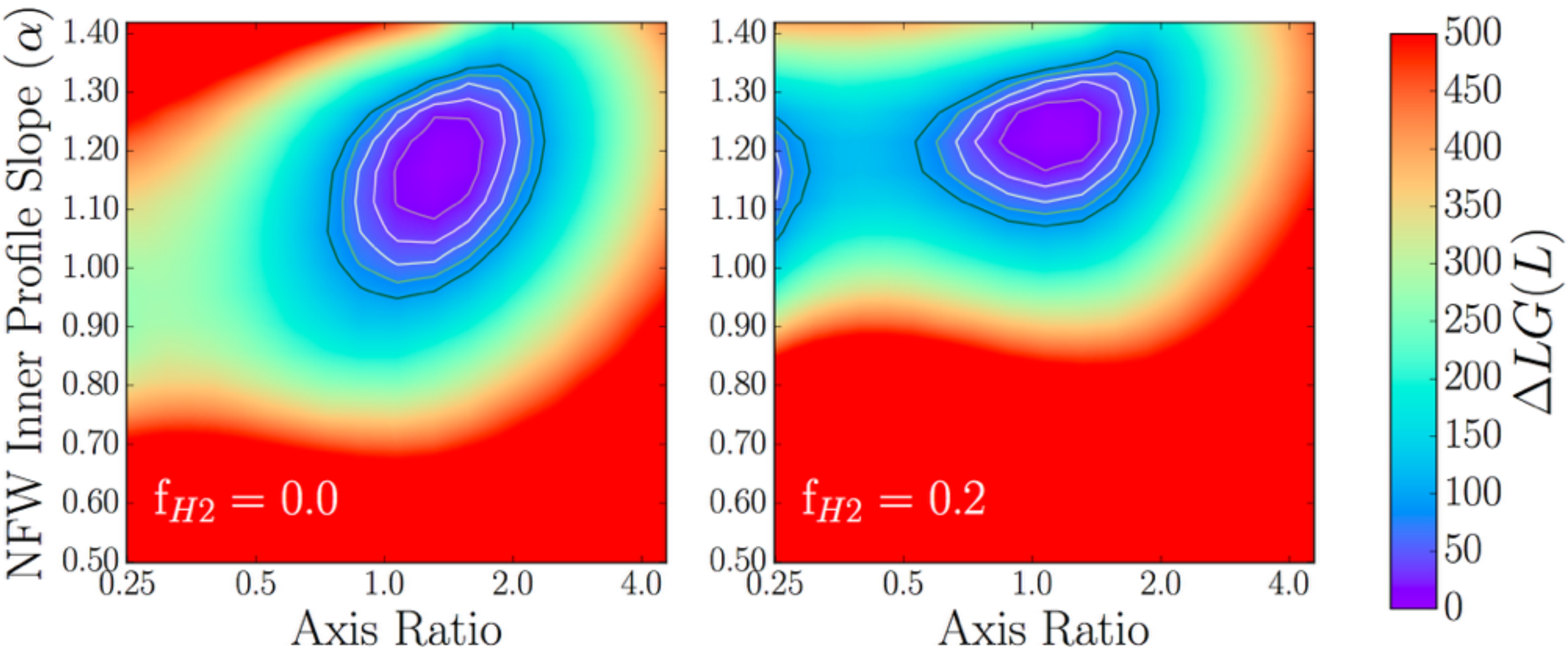


This increases the best fit value of f_{H2} for the GC data, bringing this value into agreement with the global best fit value.

Models with a GCE component still prefer slightly lower values of f_{H2}, but these have increased to 0.2 as well.

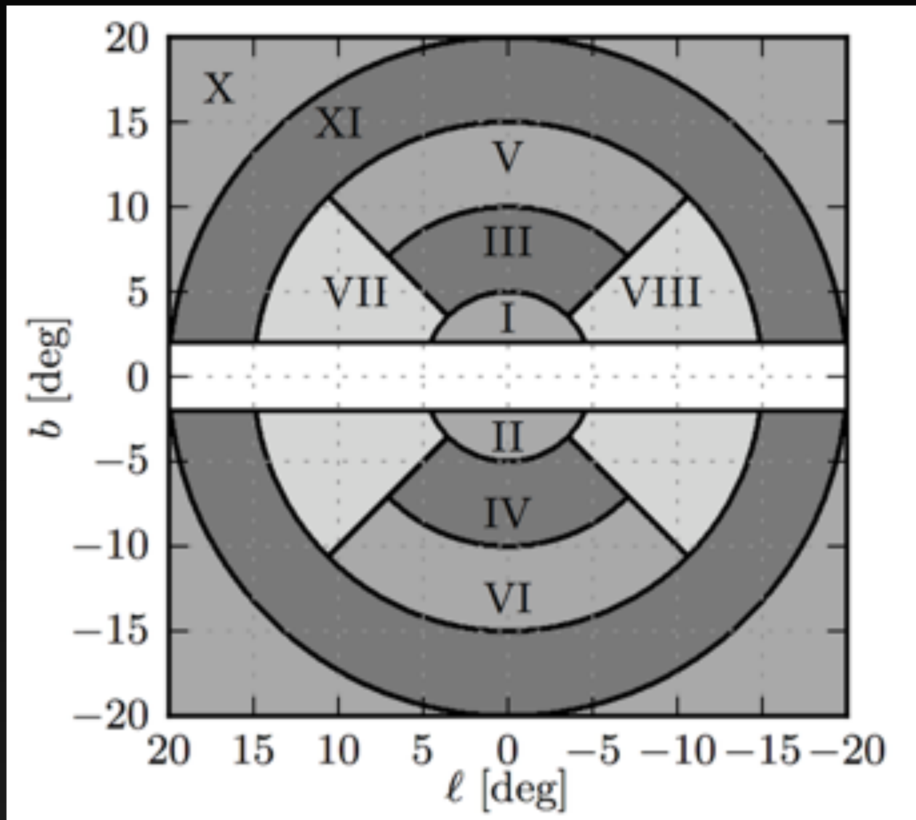
Morphology in the Galactic Center

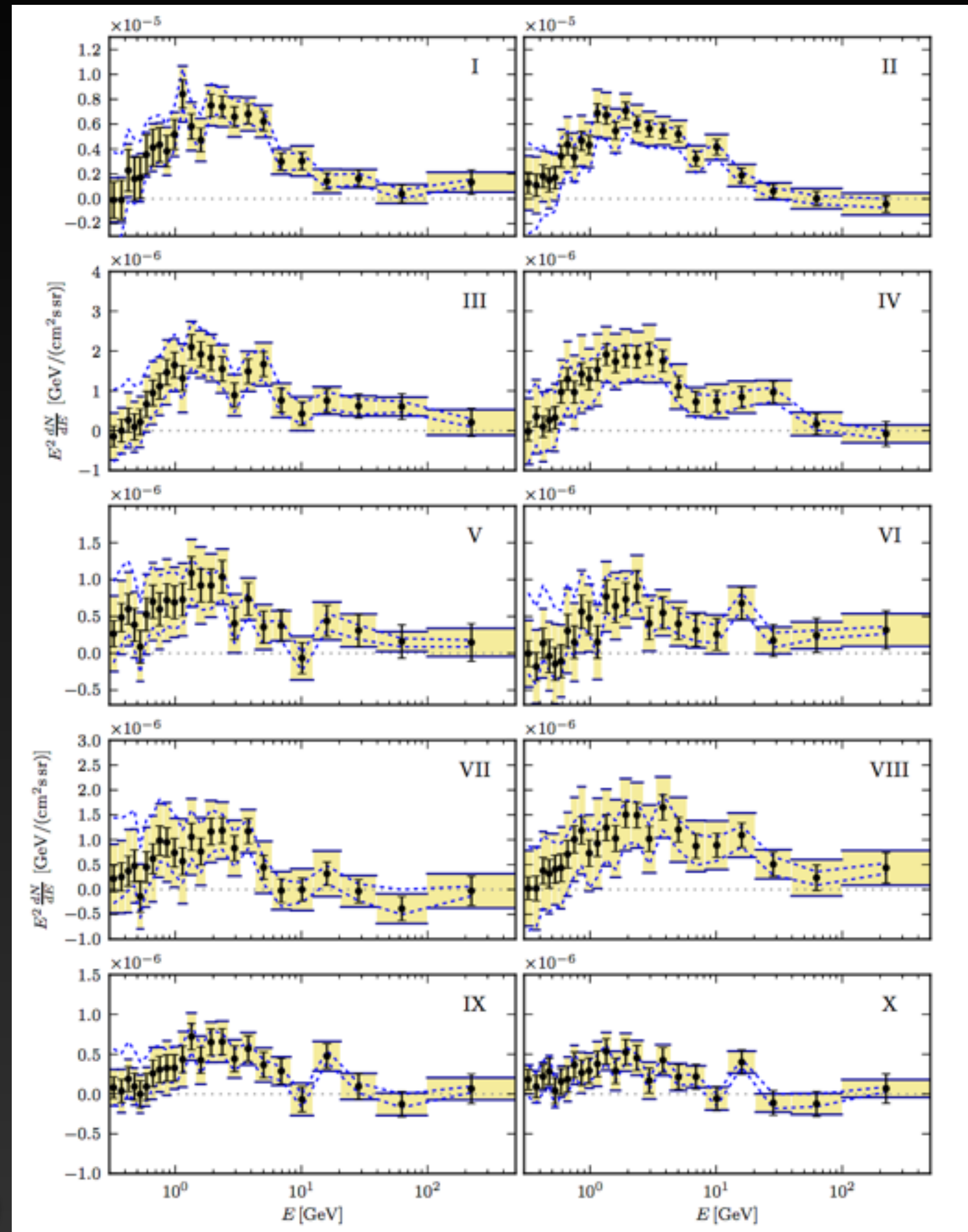
GC



For the Galactic Center analysis, the morphology of the excess component remains relatively robust

Analysis Far from the GC





Analysis regions far from the GC also show an excess – not much star formation occurs a few degrees above the Galactic plane.

Calore et al. (2014, 1409.0042)

Comparison to Cygnus-X