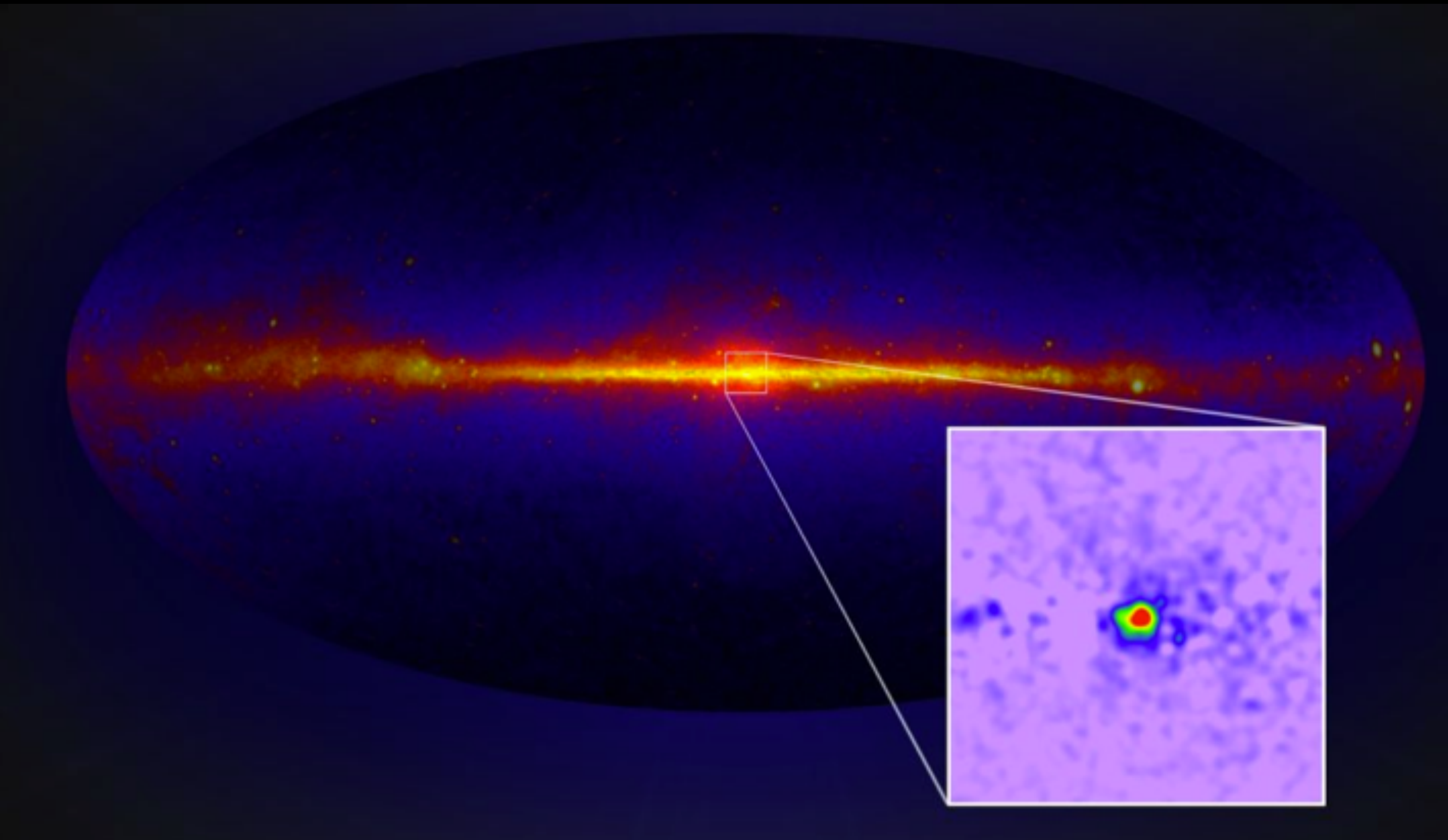


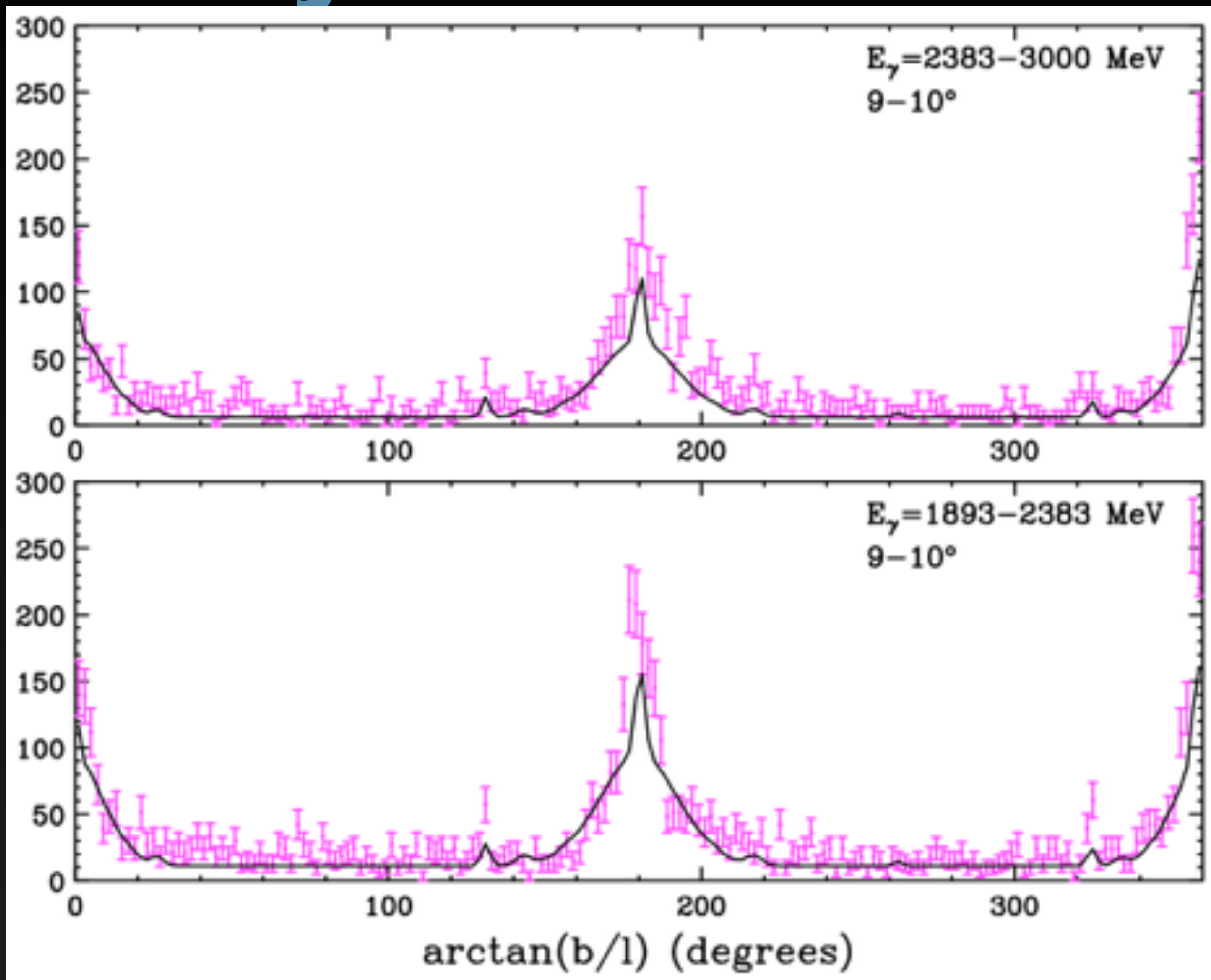
The Galactic Center Excess: Status Updates and a Path Forward

Tim Linden

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

2016 Amsterdam-Paris-Stockholm Meeting 8/30/16

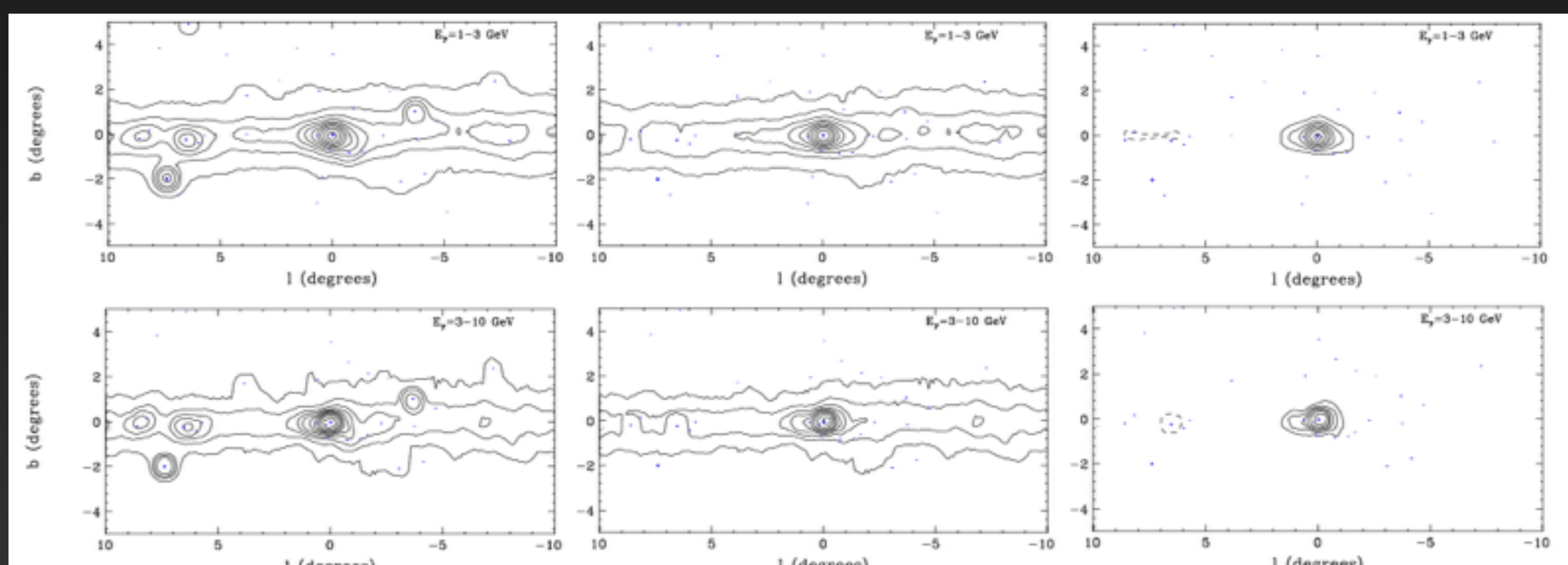
Analyses of the Galactic Center Excess



First analyses of the GCE utilized simple data driven techniques to remove emission tracing gas.

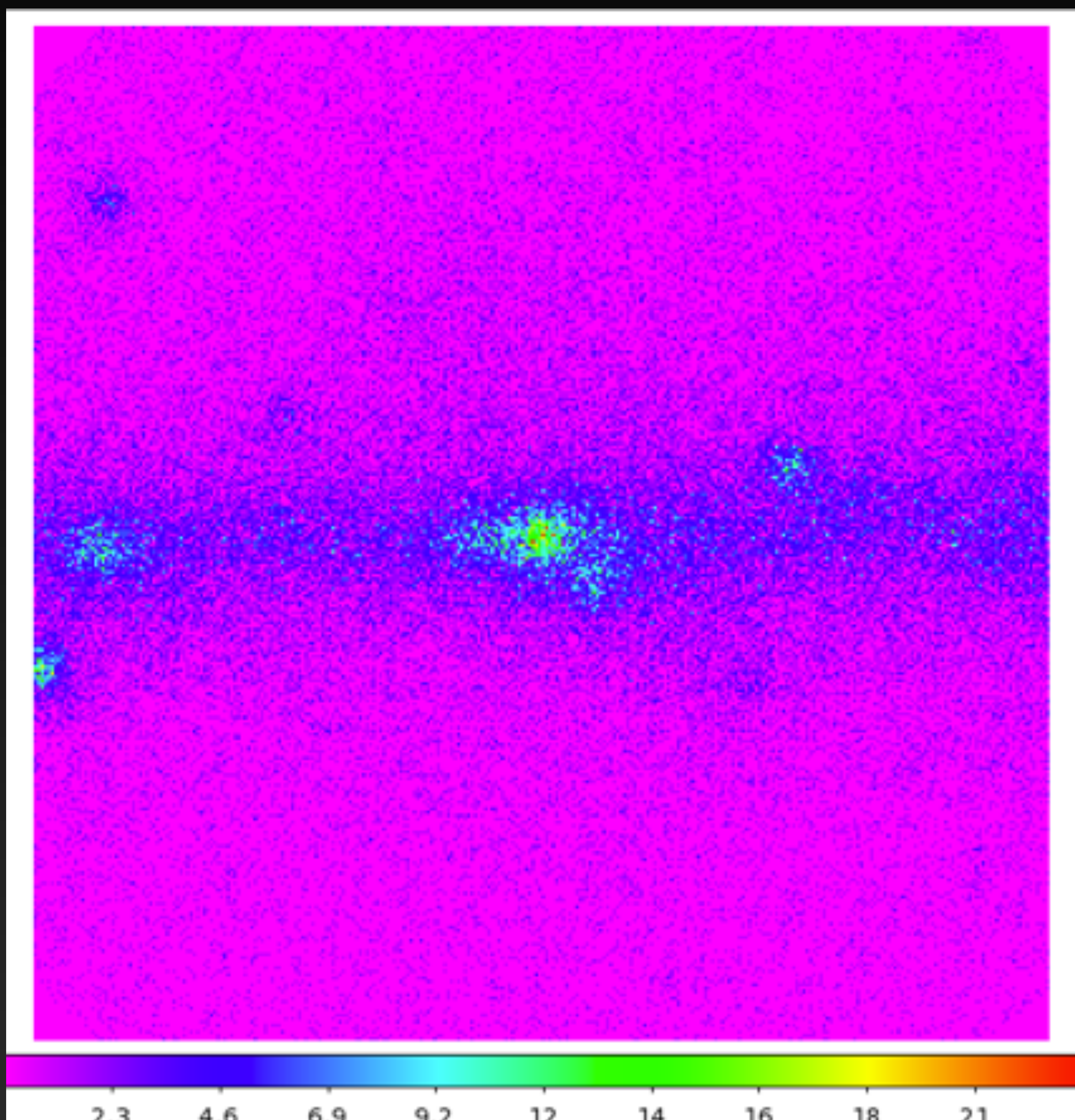
Uncovered a residual excess producing ~10% of the total emission.

Limited to observations of the inner few degrees.

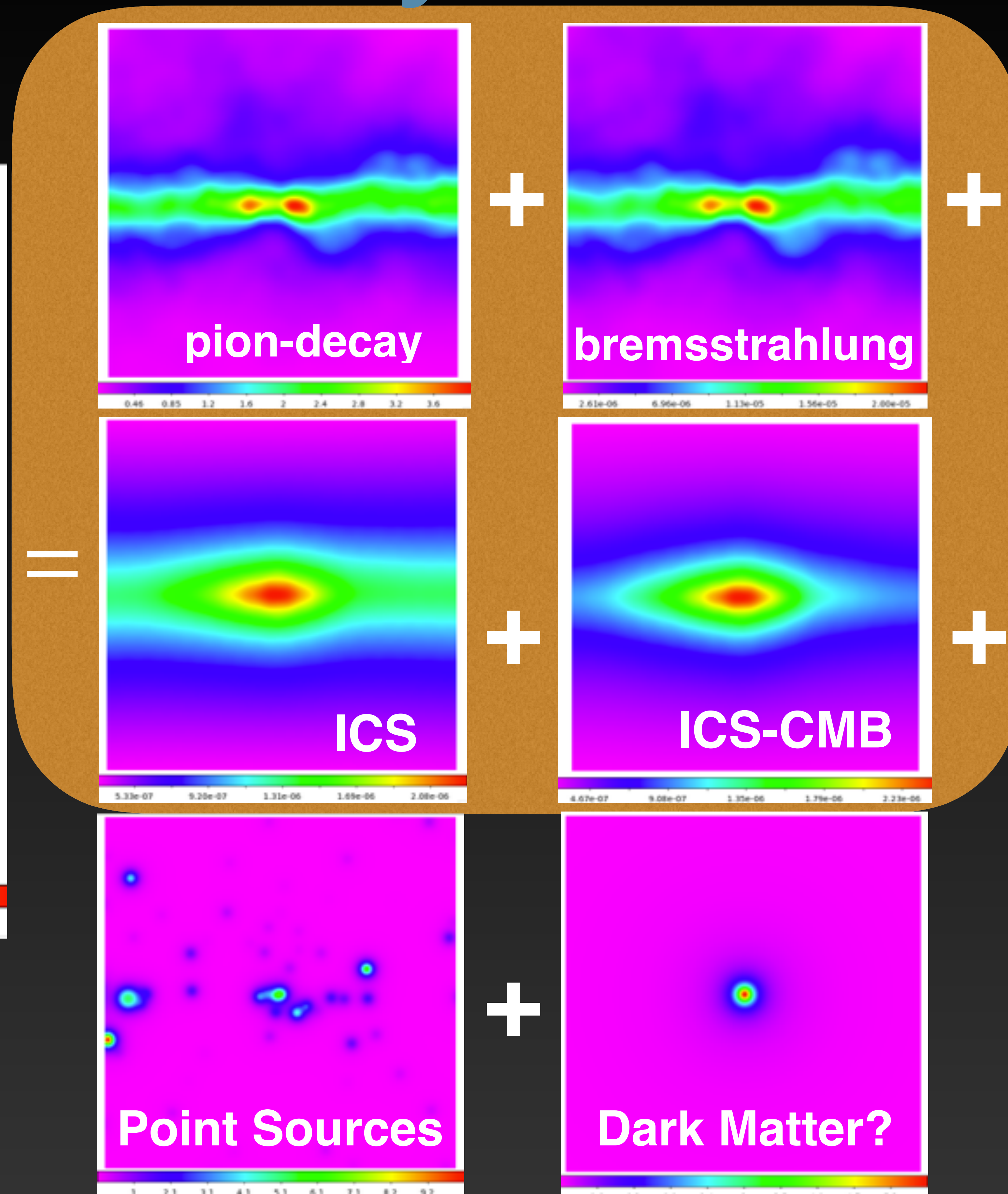


0910.2998
1010.2752
1110.0006

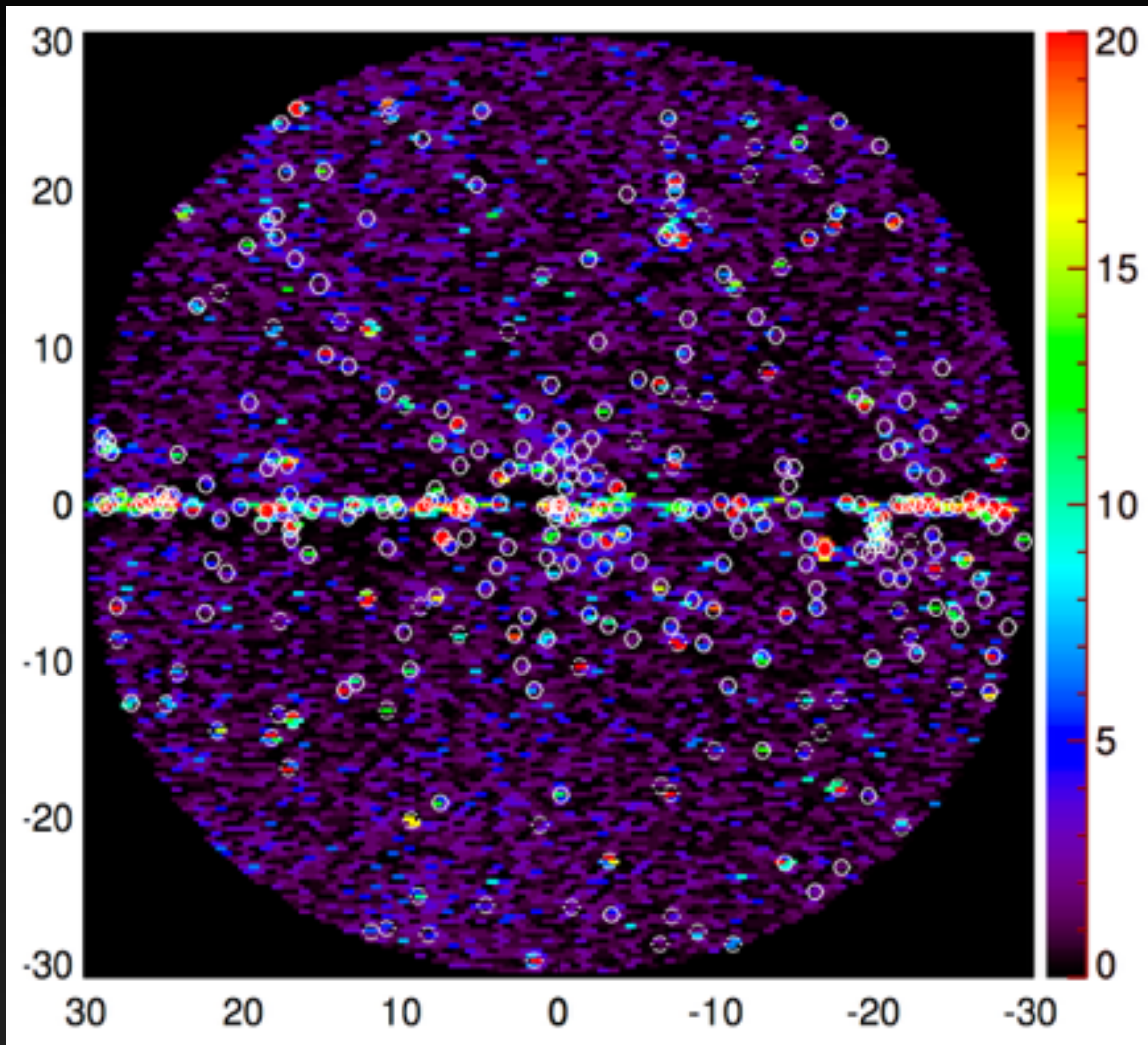
Diffuse Template Analyses

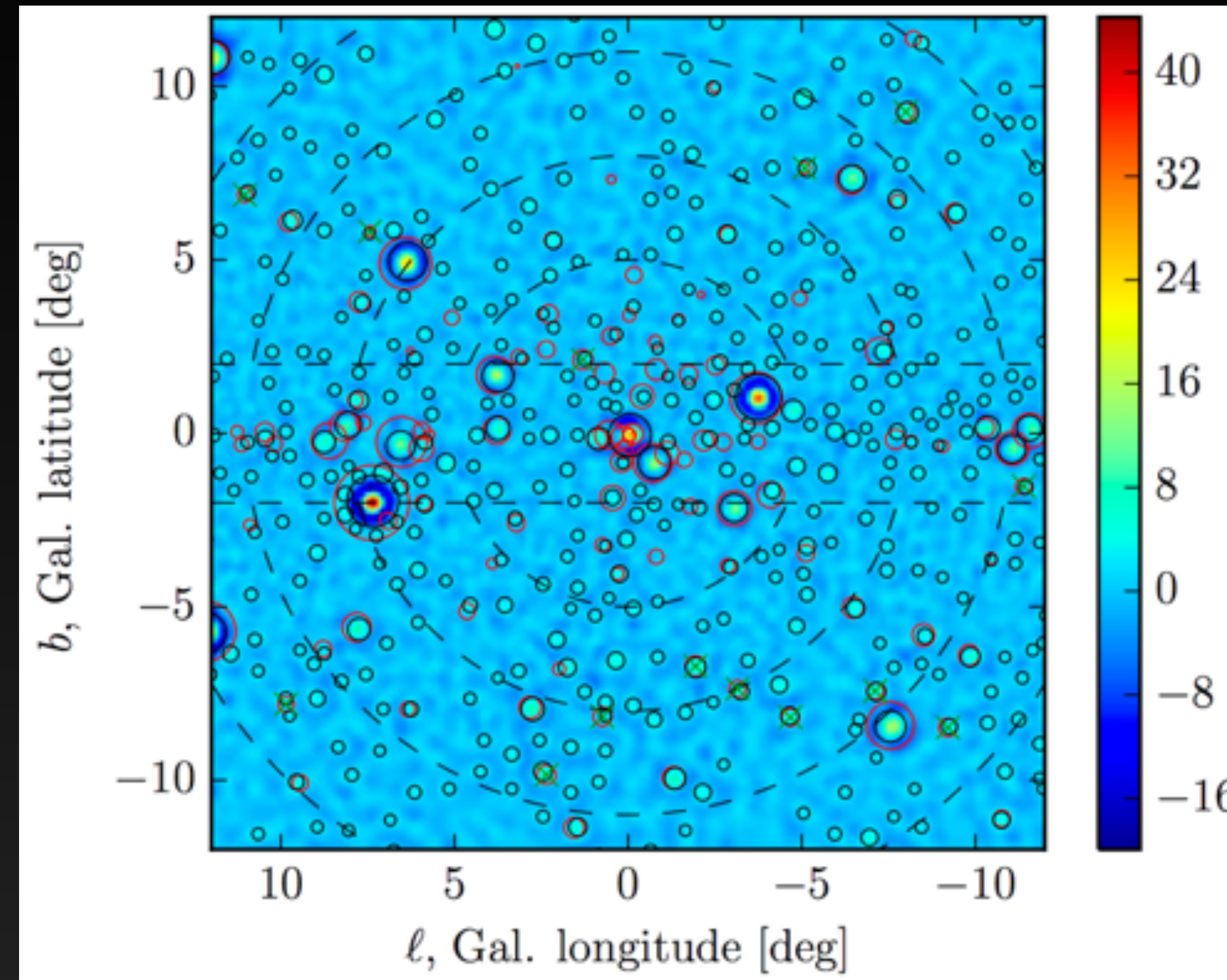


Data
750 — 950 MeV
Best Angular Resolution Cut
10° x 10° ROI



NPTF/Wavelet Analyses



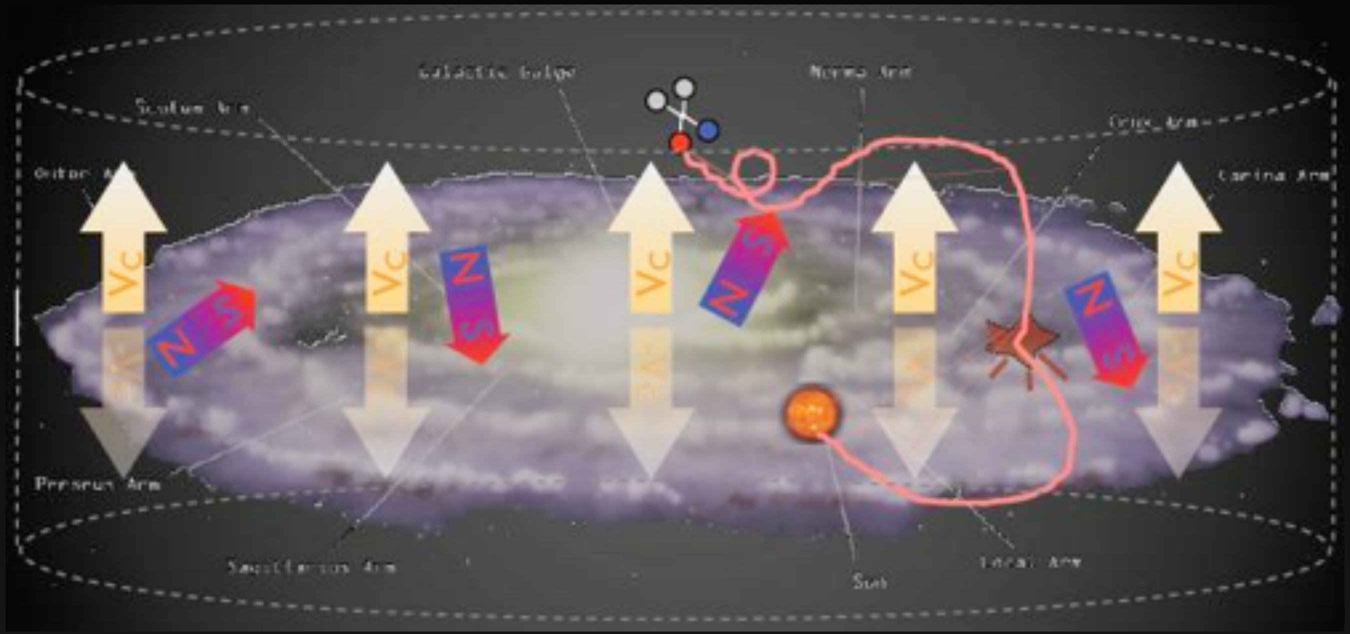


Utilize diffuse models along with an excess model which is capable of absorbing not only a smooth density profile, but is able to adapt its emission intensity in order to capture sub-threshold "point source" fluctuations .

1506.05104
1506.05124

Diffuse Emission Modeling

Models of diffuse gamma-ray emission depend sensitively on the Galactic cosmic-ray distribution.



Cosmic-Rays are thought to be accelerated primarily by supernovae events, and then take ~10^8 — 10^9 years to escape the Milky Way magnetic field.

What we need is a catalog of all Galactic supernovae over the past billion years.

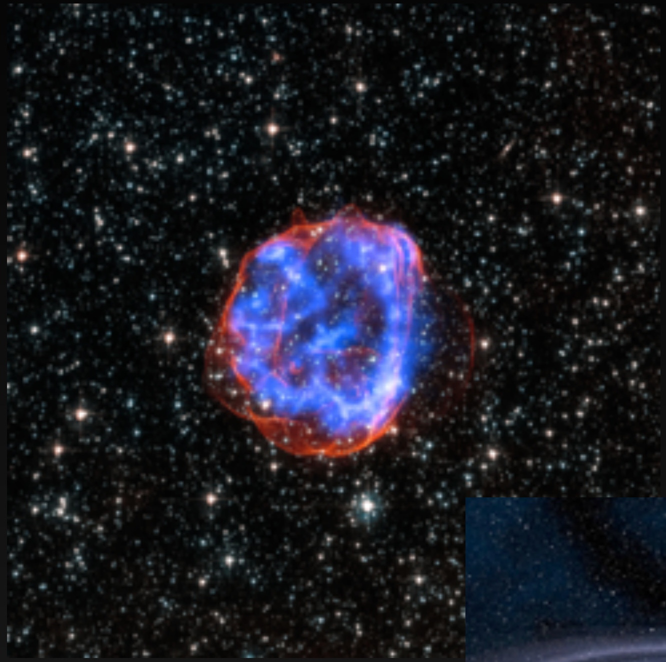
Observations of the historical supernova rate can fail in two ways:

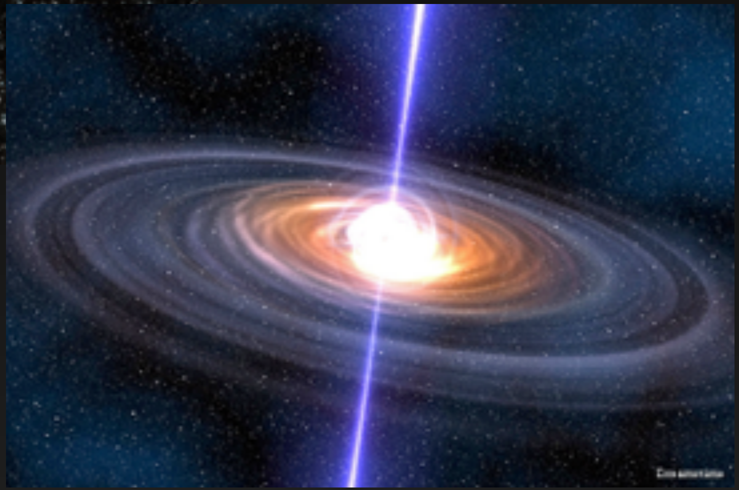
1. **Observational incompleteness**
2. **Time variability**

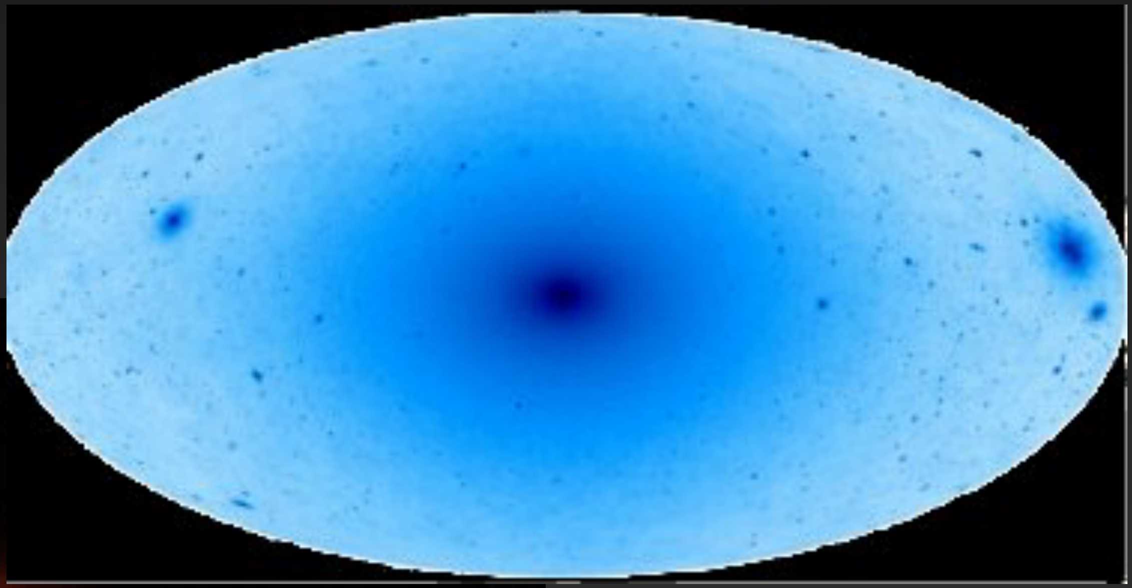
What Generates these Cosmic-Rays?

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

1.) Supernovae
2.) Pulsars
3.) Sgr A*
4.) Reacceleration





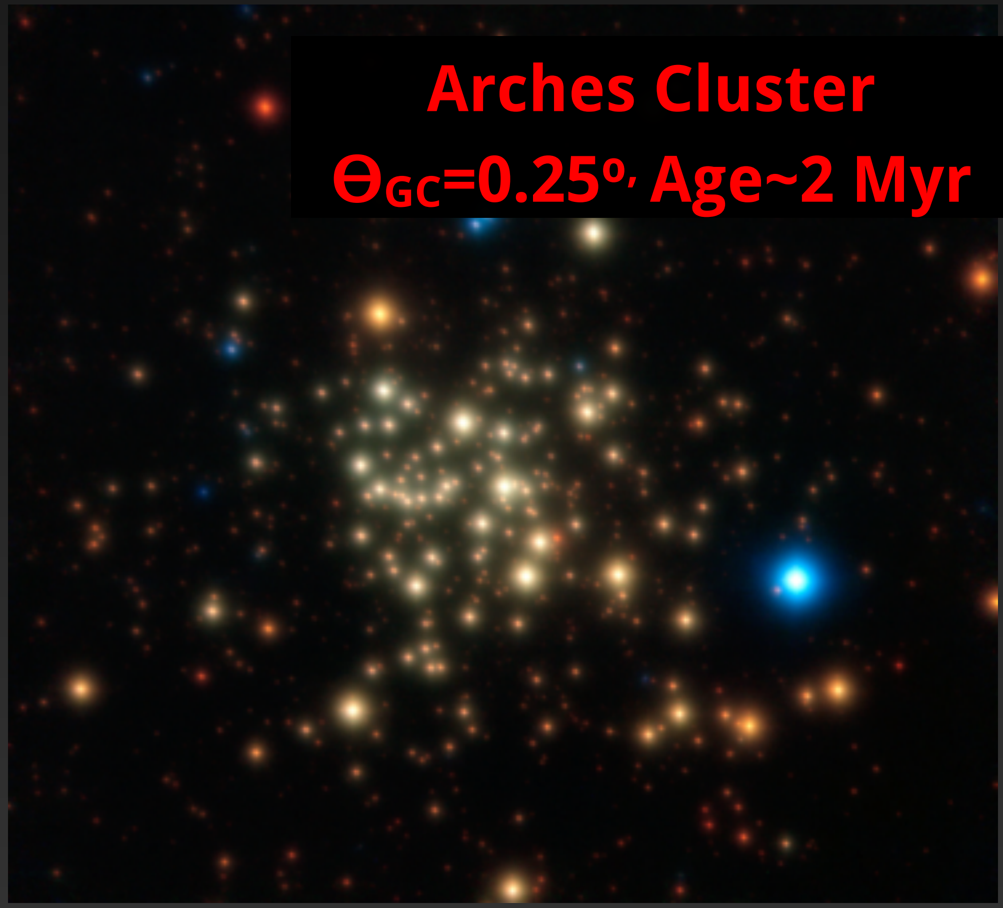


The Galactic Center Supernovae

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)

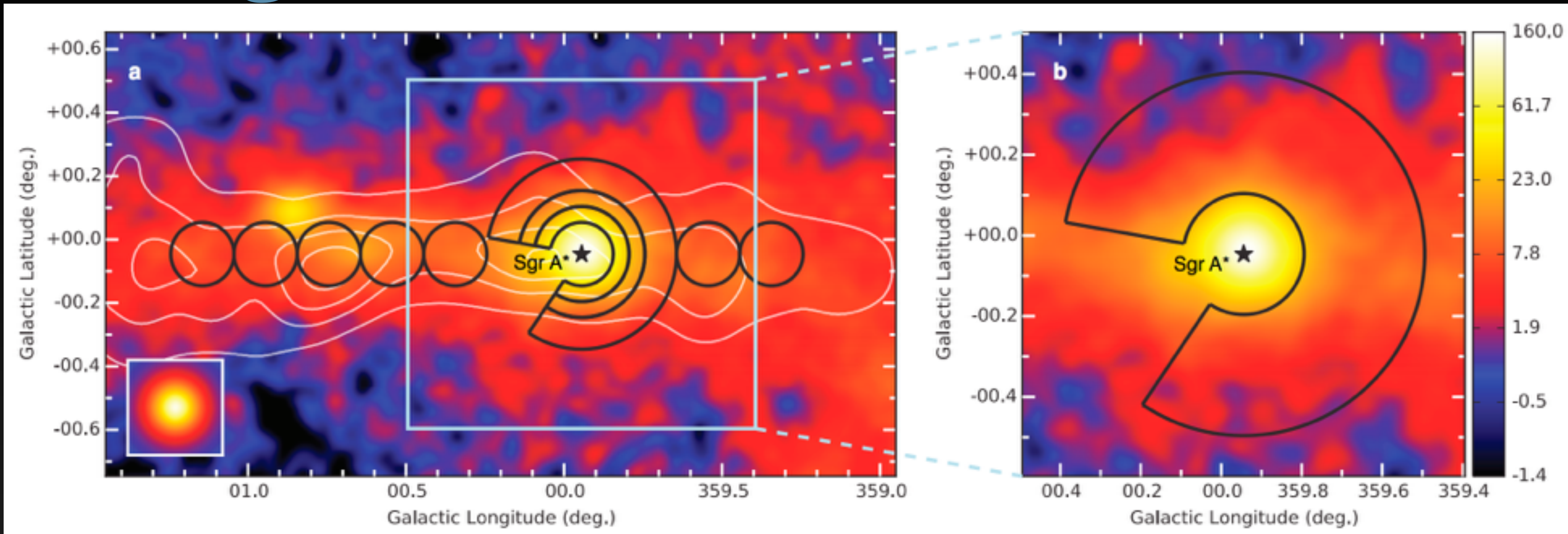


Galactic Center Pulsars

The Galactic Center is expected to host a significant population of both young pulsars (due to its high SFR), and millisecond pulsars (in part from the disruption of Globular Clusters).

Over the lifetime of a young (recycled) pulsar, ~10^{50} erg of energy our released, primarily in the form of relativistic e^+e^- pairs.

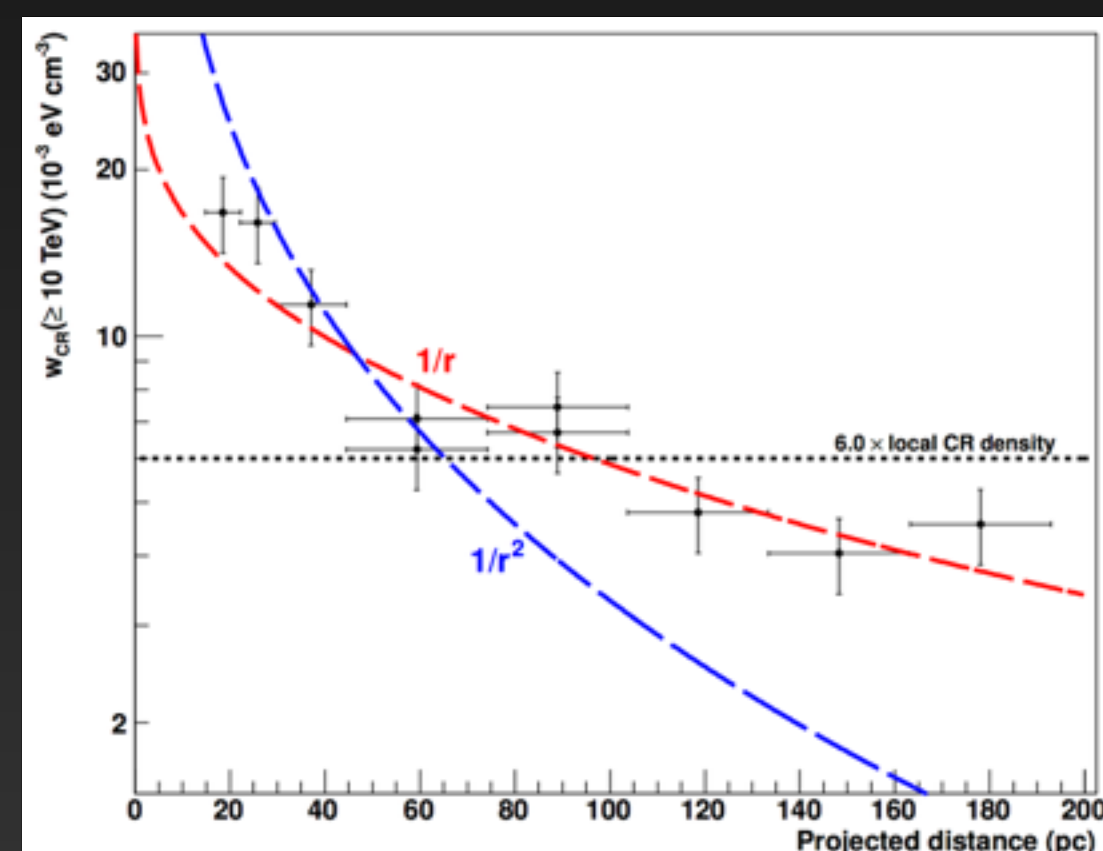
The Sgr A* Source



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.

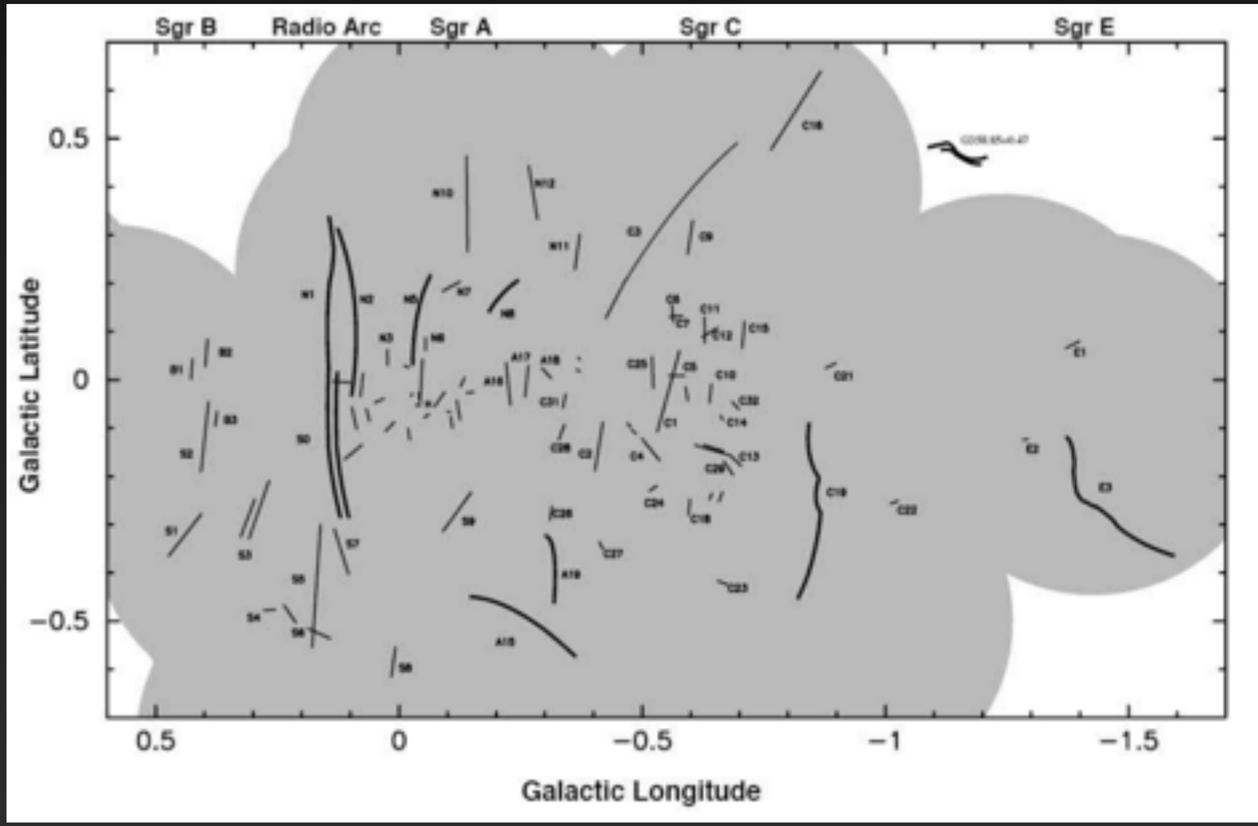


Reacceleration

More than 80 filamentary structures identified in the central 2° x 1° .

The filaments are observed as highly polarized, hard-spectrum synchrotron sources – indicative of strongly ordered magnetic fields and hard injected electron spectra.

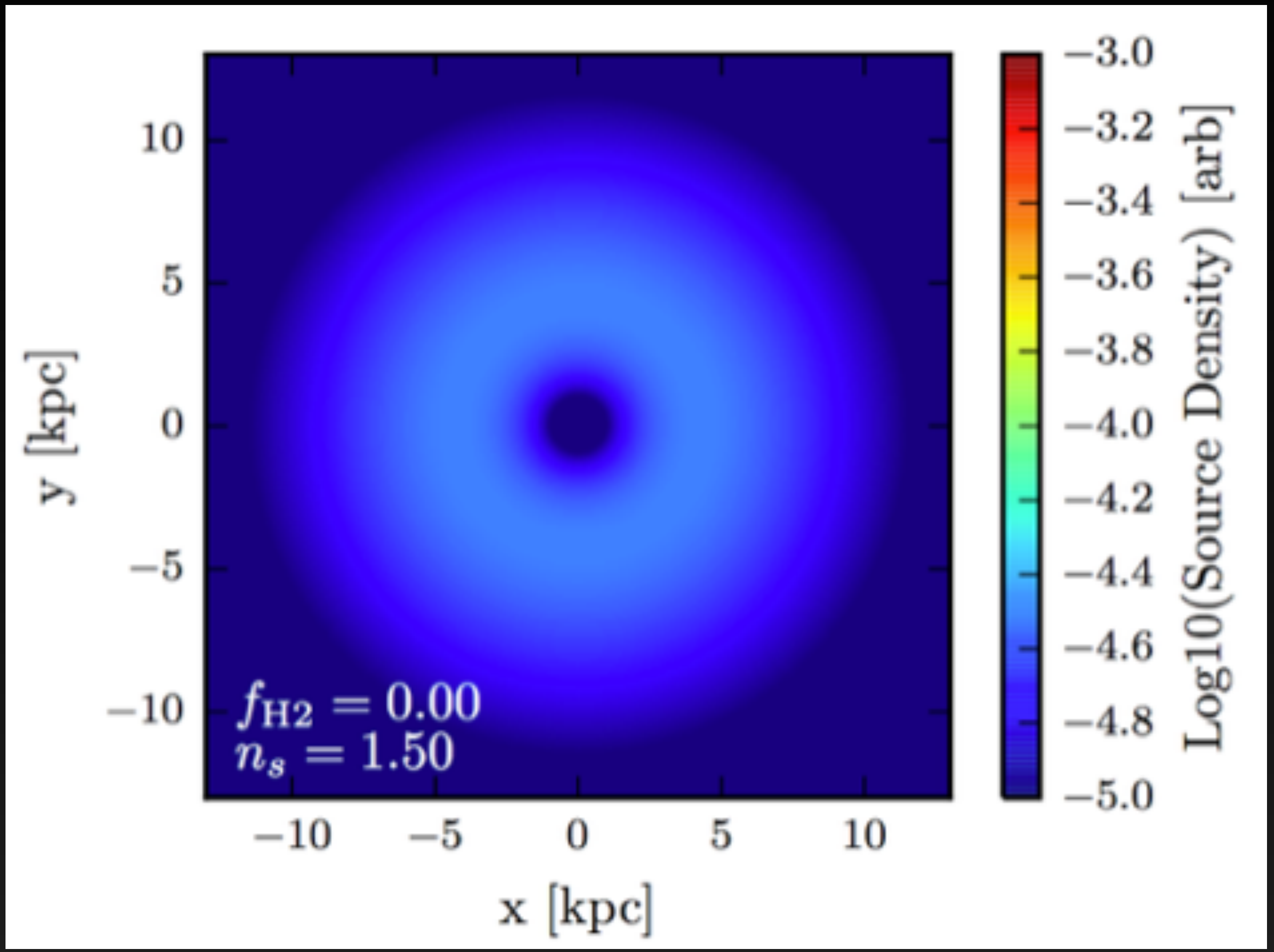
The best astrophysical explanation involves significant re-acceleration via magnetic reconnection (Lesch & Riech 1992, Lieb et al. (2004).



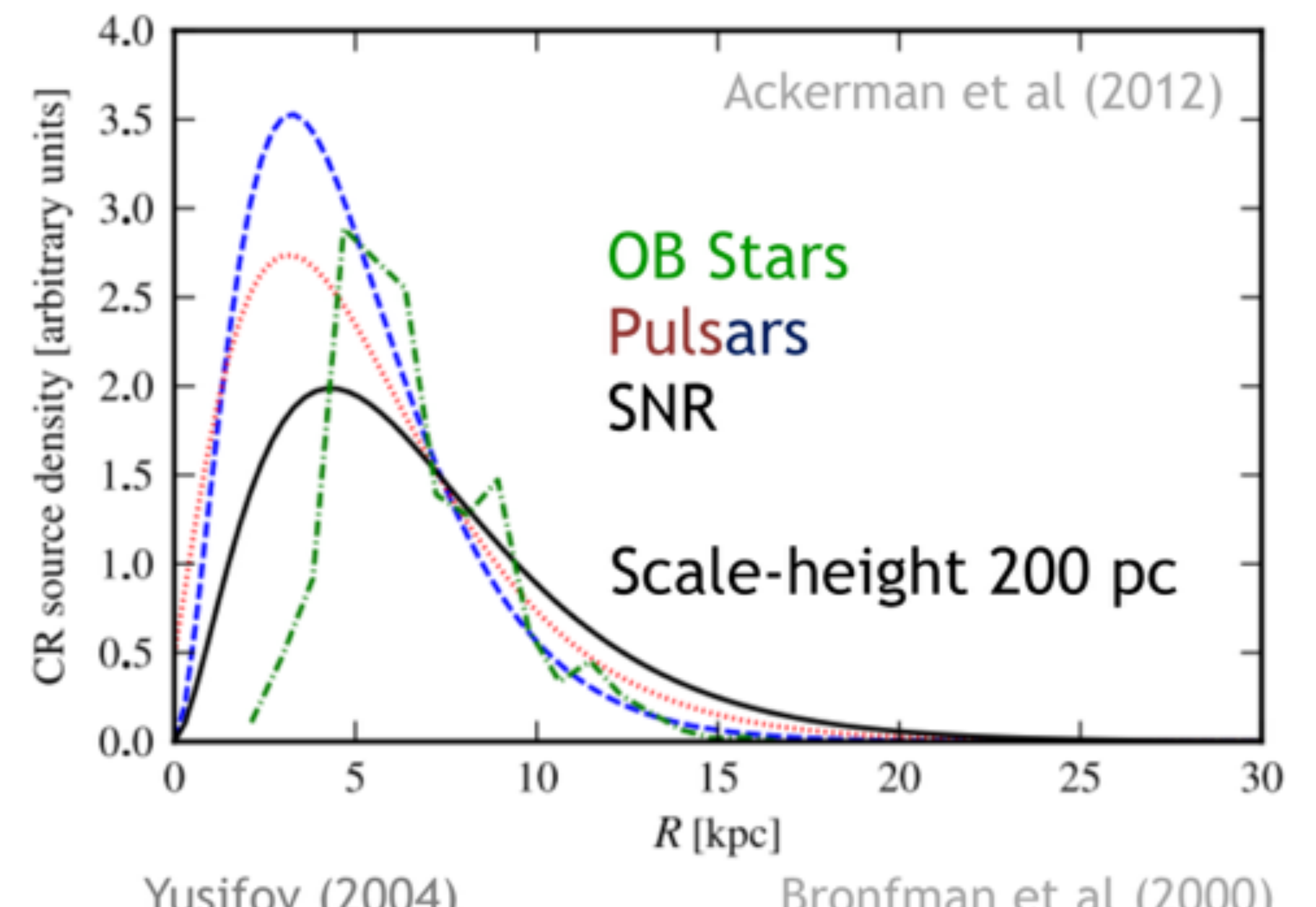
Yusef-Zadeh et al. (2004)

The Problem

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

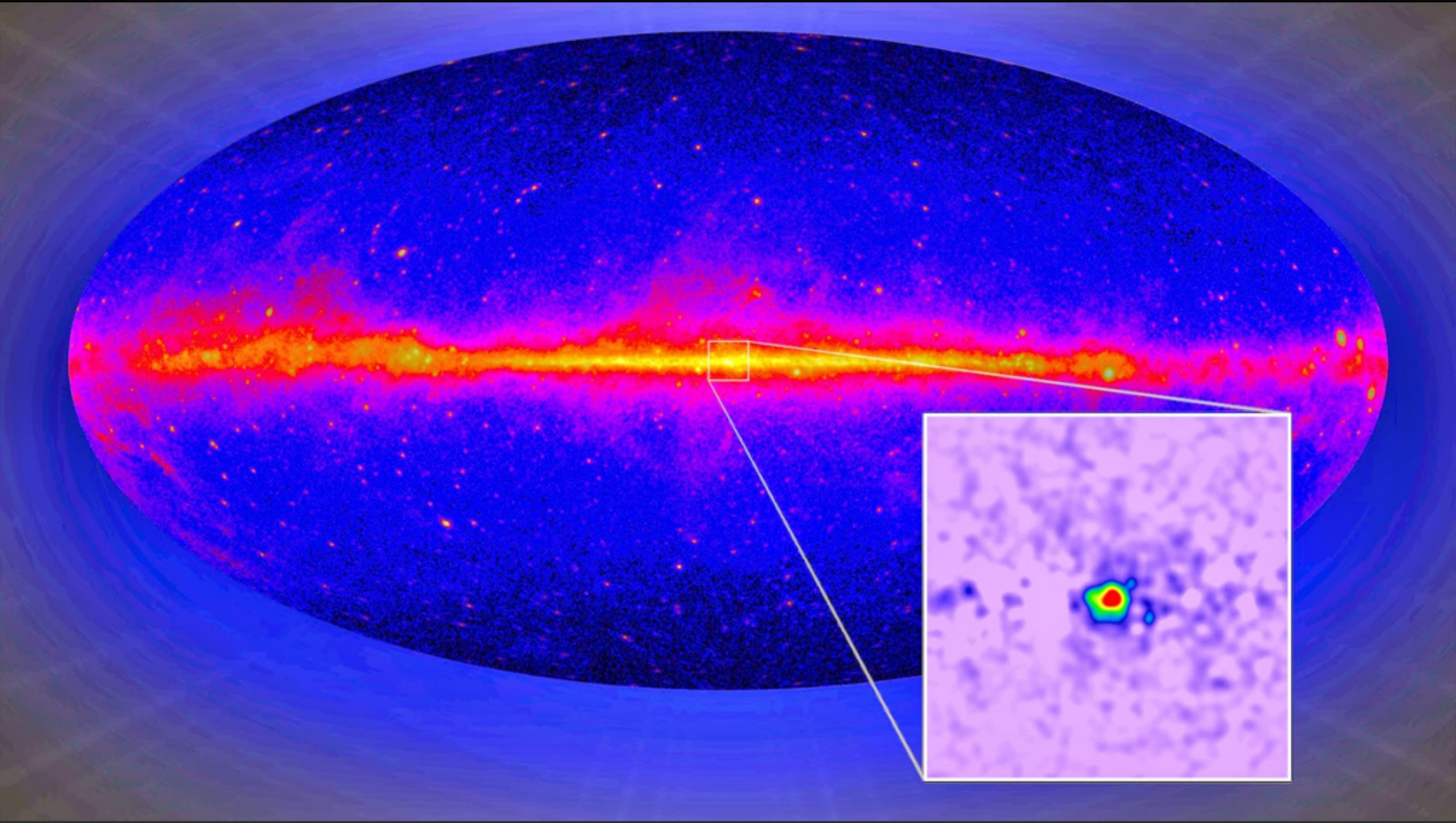


Results from these cosmic-ray propagation codes are used in many analyses of the Galactic center region.



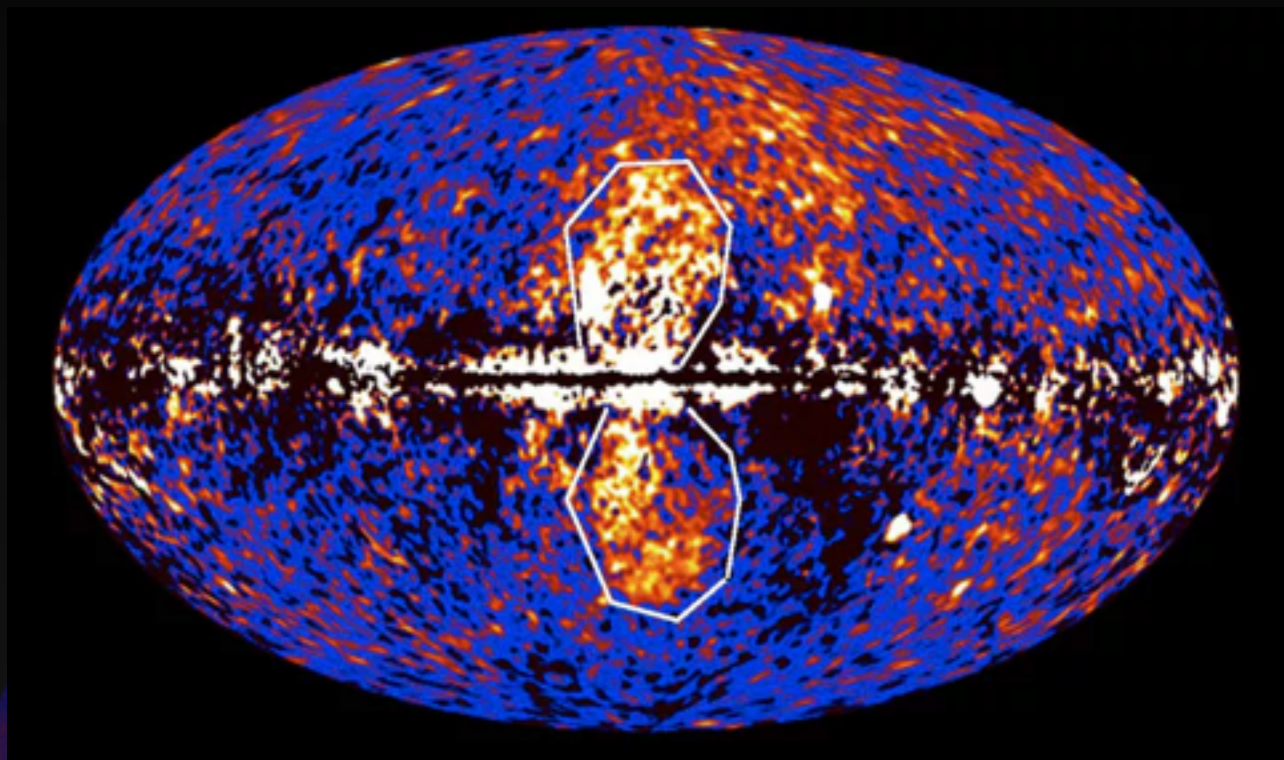
Carlson et al. (2016a, 2016b)
1510.04698
1603.06584

Fool me once, shame on, shame on you...

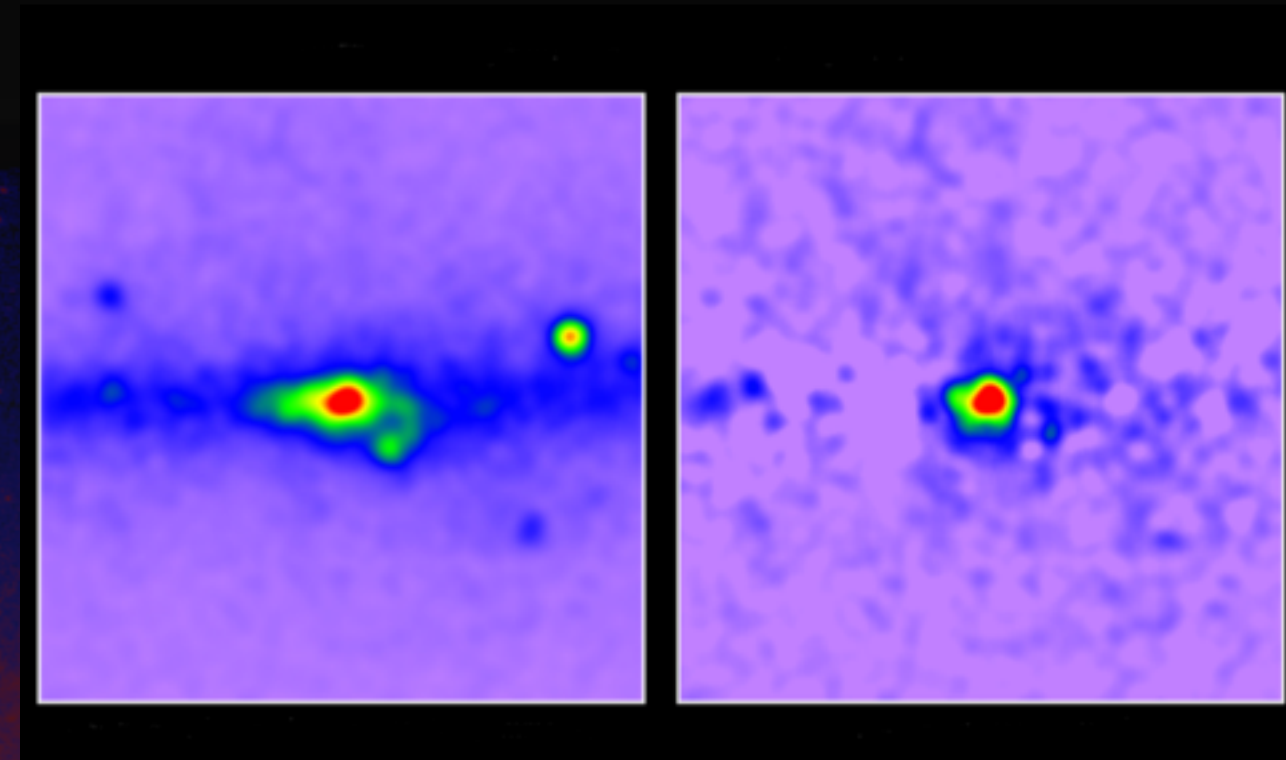


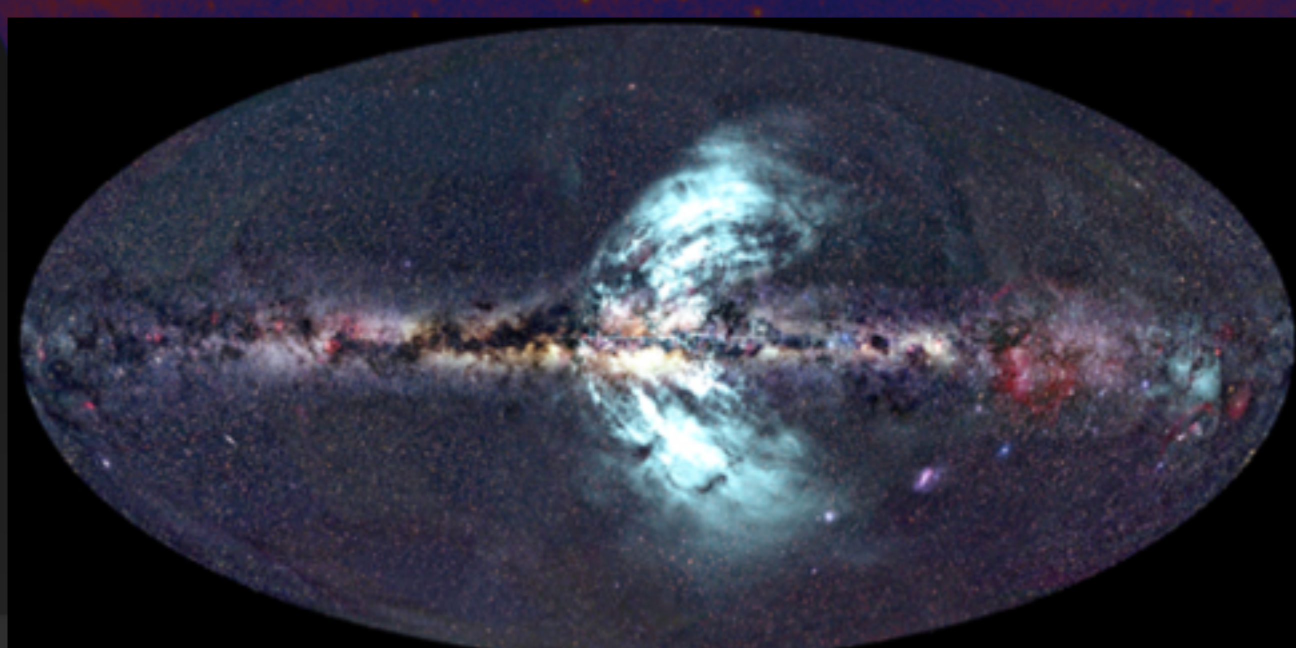
Fool me — you can't get fooled again!

Fermi Bubbles

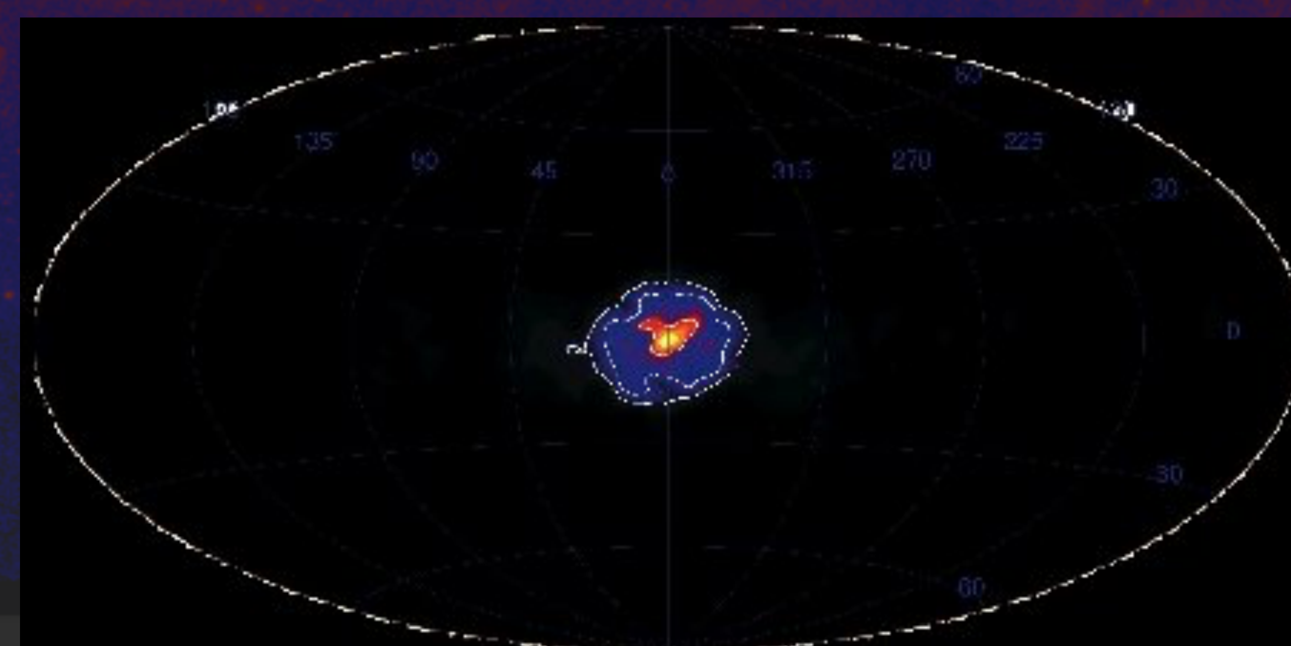


GeV Excess



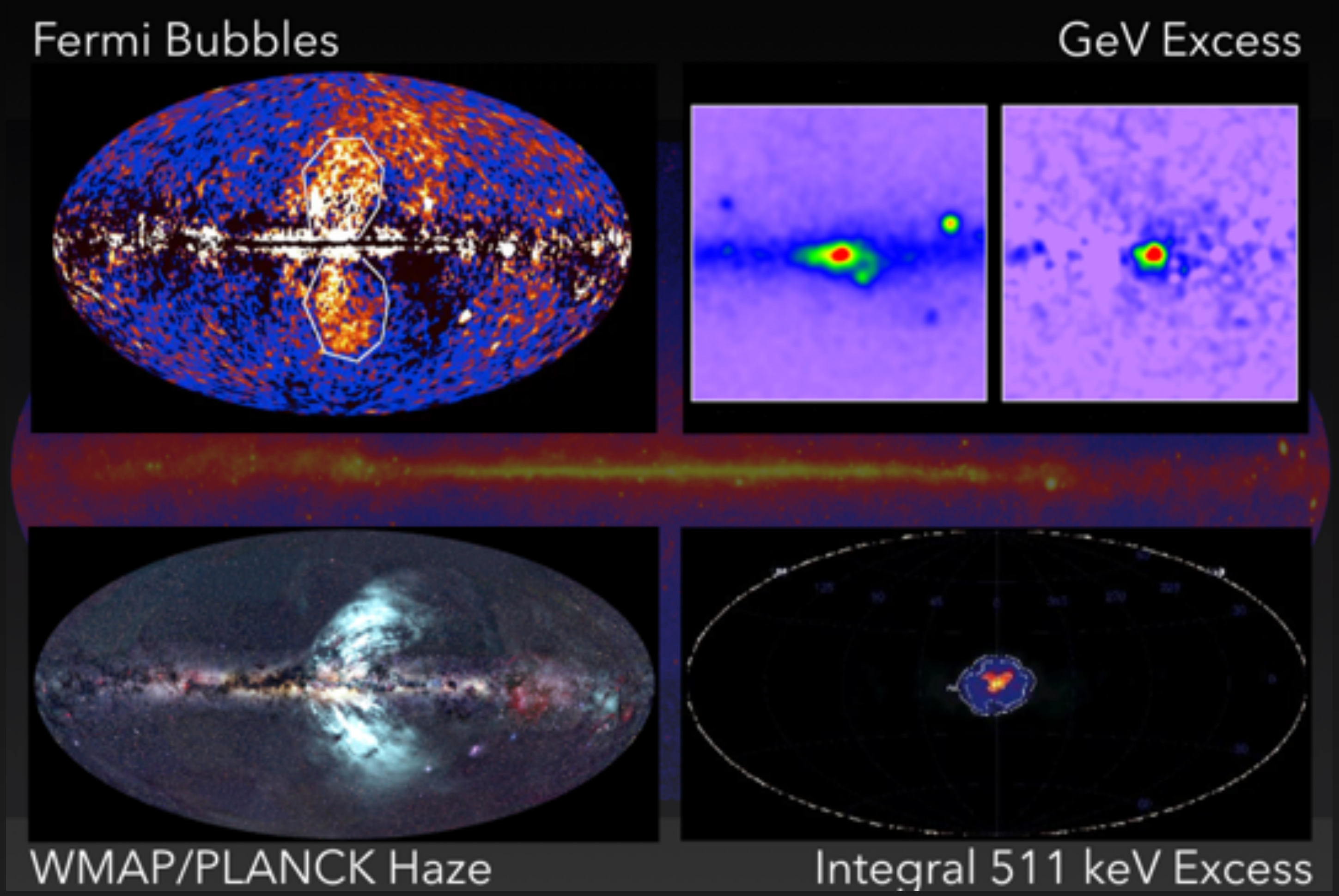


WMAP/PLANCK Haze



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.

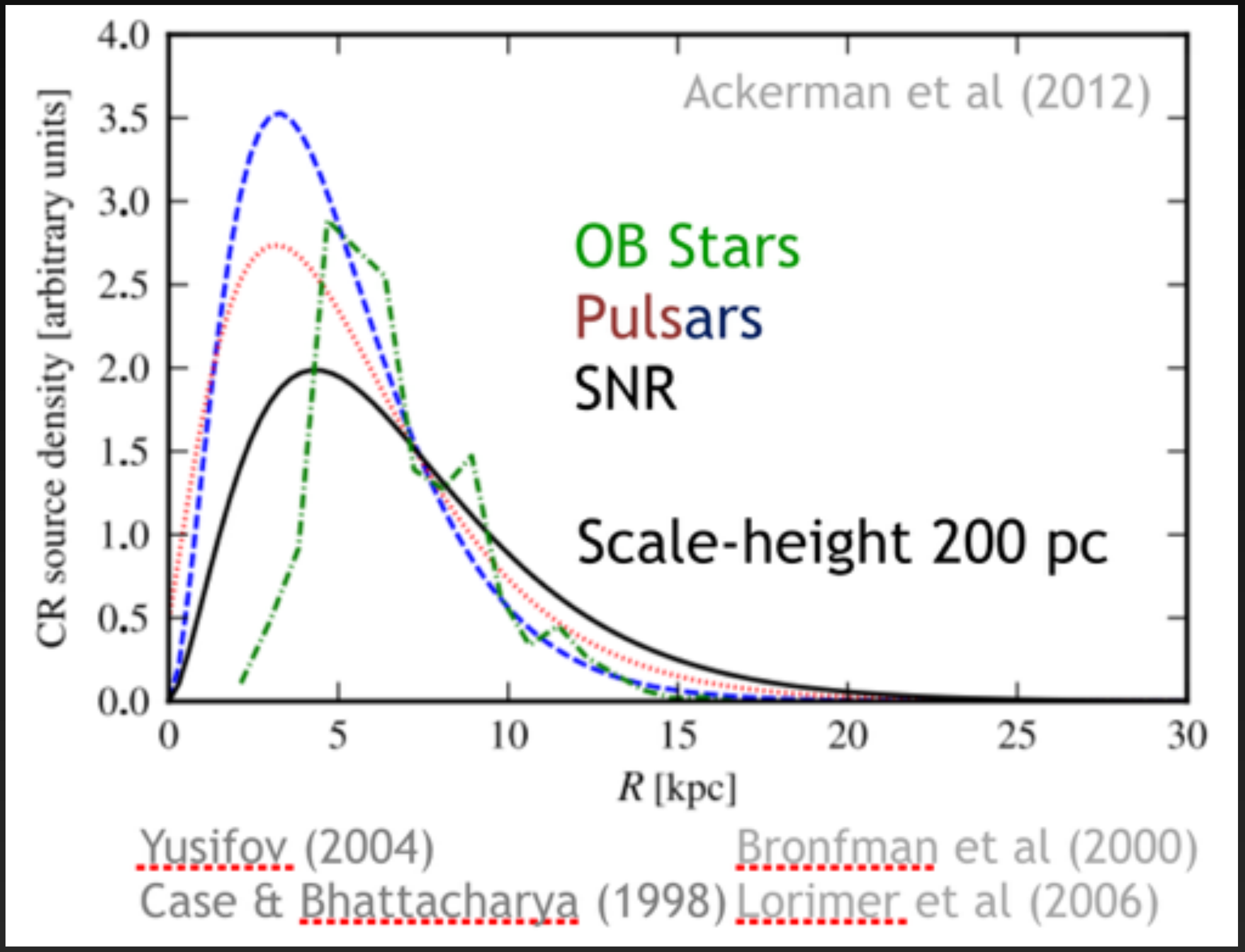
(b) Provides a large field of view for studies of GC emission.

(c) Implies that propagation is important!

What we've got here is a failure to communicate

1.) The Galactic Center star formation rate is based on targeted observations. However, cosmic-ray diffusion models need a equal sensitivity throughout the Galaxy:

- Observed SNR
- Pulsars
- OB Stars



2.) The Galactic center cosmic-ray injection rate does not significantly affect the observed primary-to-secondary cosmic-ray population at Earth.

3.) Computational models (Galprop) are significantly faster if the cosmic-ray injection rate is fit to a simple analytic form.

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

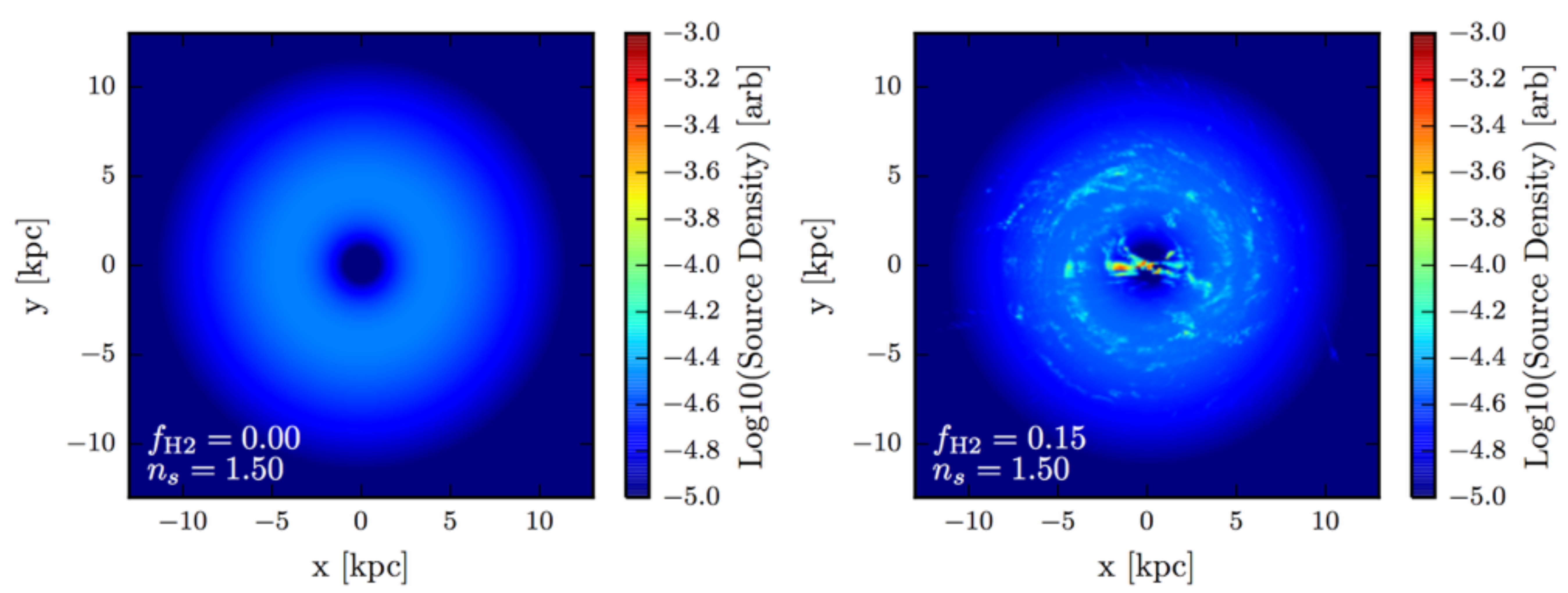
$$\Sigma_{\rm SFR} \propto \Sigma_{\rm Gas}^{1.4\pm.15}$$

Specifically we inject a fraction of cosmic-rays (f_{H2}) 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

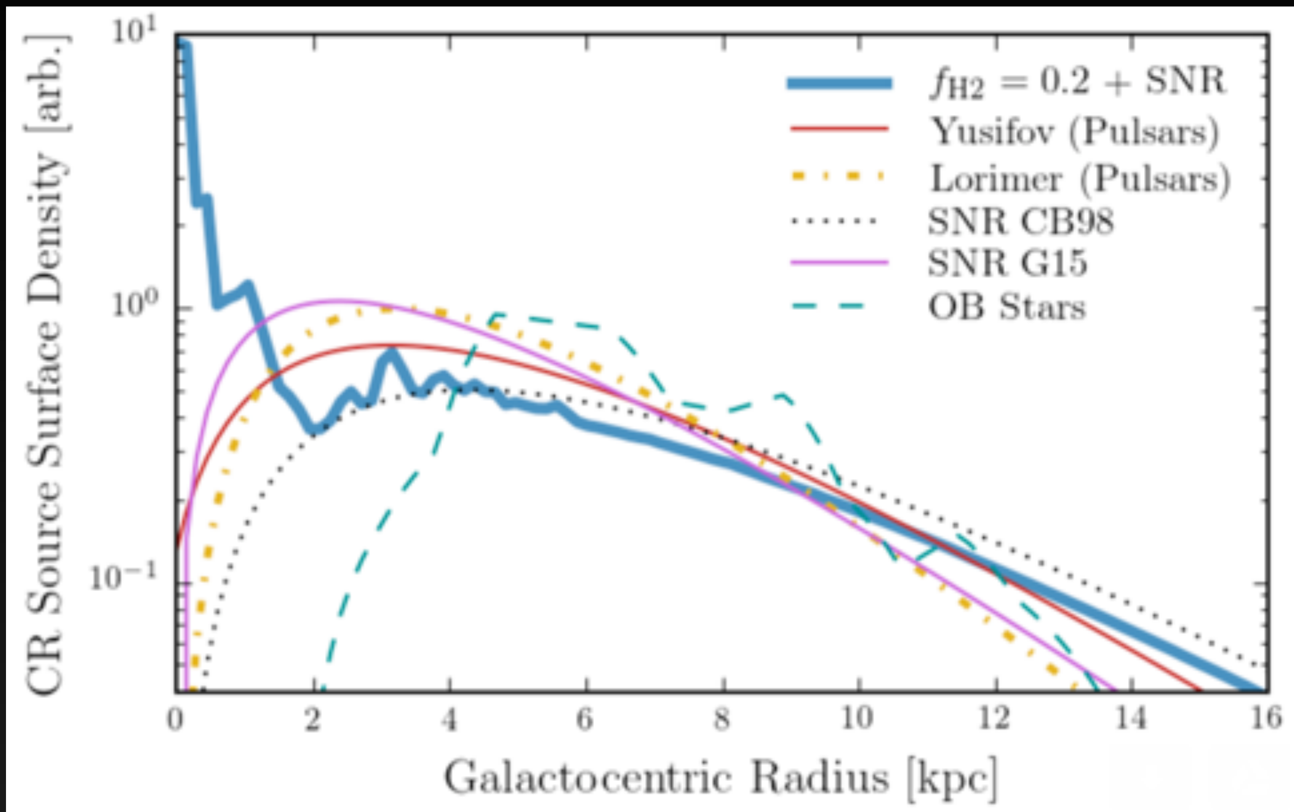


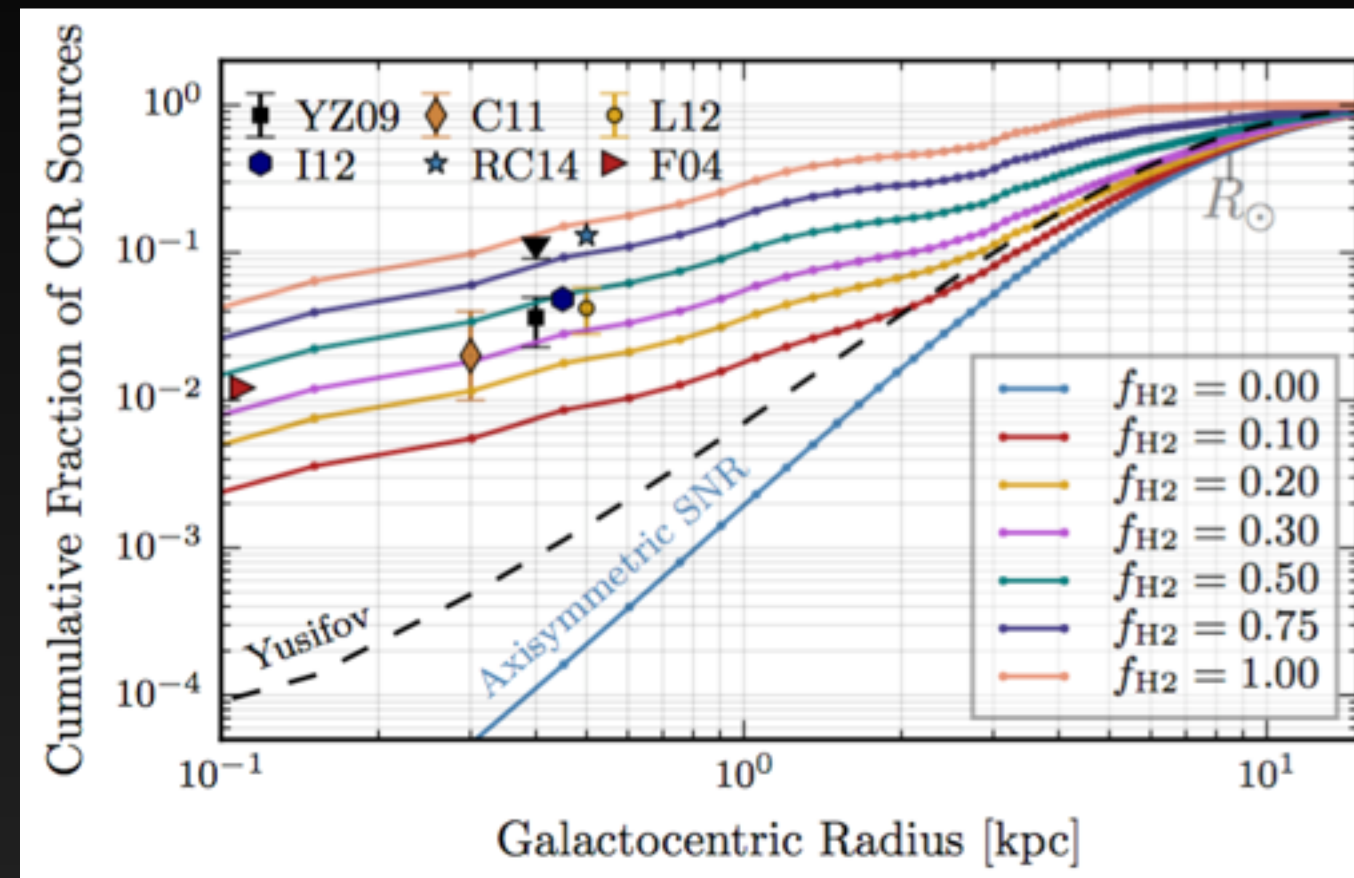
Two features leap out immediately:

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.

Simulations!

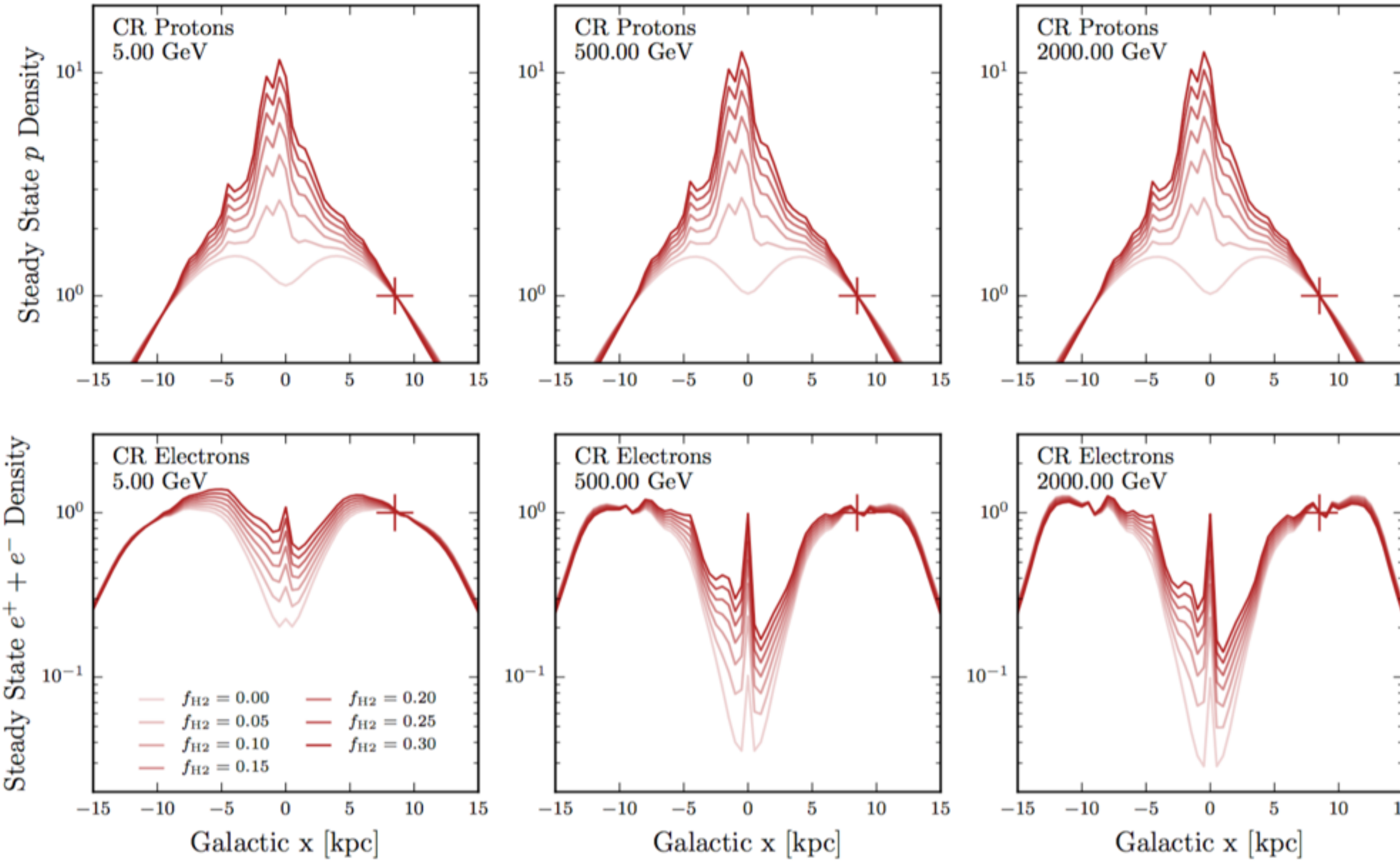
Parameter	Units	Canonical	Mod A	Description
D_0	$cm^2\ s^{-1}$	7.2×10^{28}	5.0×10^{28}	Diffusion constant at $\mathcal{R} = 4$ GV
δ	–	0.33	0.33	Index of diffusion constant energy dependence
$z_{\rm halo}$	kpc	3	4	Half-height of diffusion halo
$R_{\rm halo}$	kpc	20	20	Radius diffusion halo
v_a	$km\ s^{-1}$	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 $(1 - f_{\rm H2})$ primary sources*
$f_{\rm H2}$	–	.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

Add the new cosmic-ray injection models into Galprop.

CO ratios are fitted in galactocentric rings to produce a full sky model (Ackermann et al. 2012)

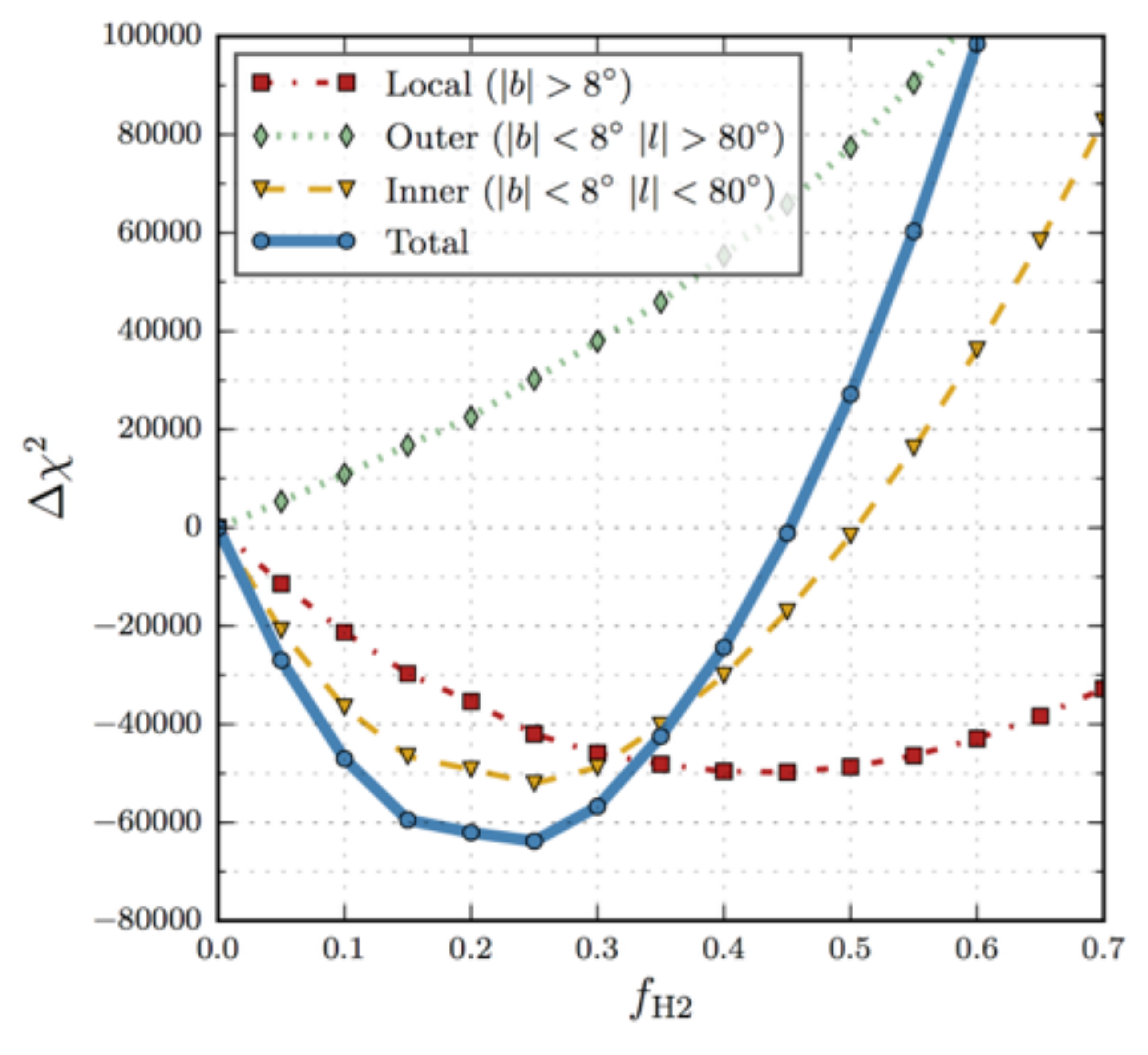
Ring Number	Radius [kpc]	Fit Region	X_{CO} [cm^{-2} (K km $s^{-1})^{-1}$]
1	$0 - 2.0$	Inner	$1.00 \times 10^{19\dagger}$
2	$2.0 - 3.0$	Inner	8.42×10^{19}
3	$3.0 - 4.0$	Inner	1.61×10^{20}
4	$4.0 - 5.0$	Inner	1.73×10^{20}
5	$5.0 - 6.5$	Inner	1.72×10^{20}
6	$6.5 - 8.0$	Inner	1.74×10^{20}
7	$8.0 - 10.0$	Local	8.61×10^{19}
8	$10.0 - 16.5$	Outer	4.29×10^{20}
9	$16.5 - 50.0$	Outer	2.01×10^{21}

Steady State Cosmic-Ray Distribution



A Better fit to the Gamma-Ray Sky

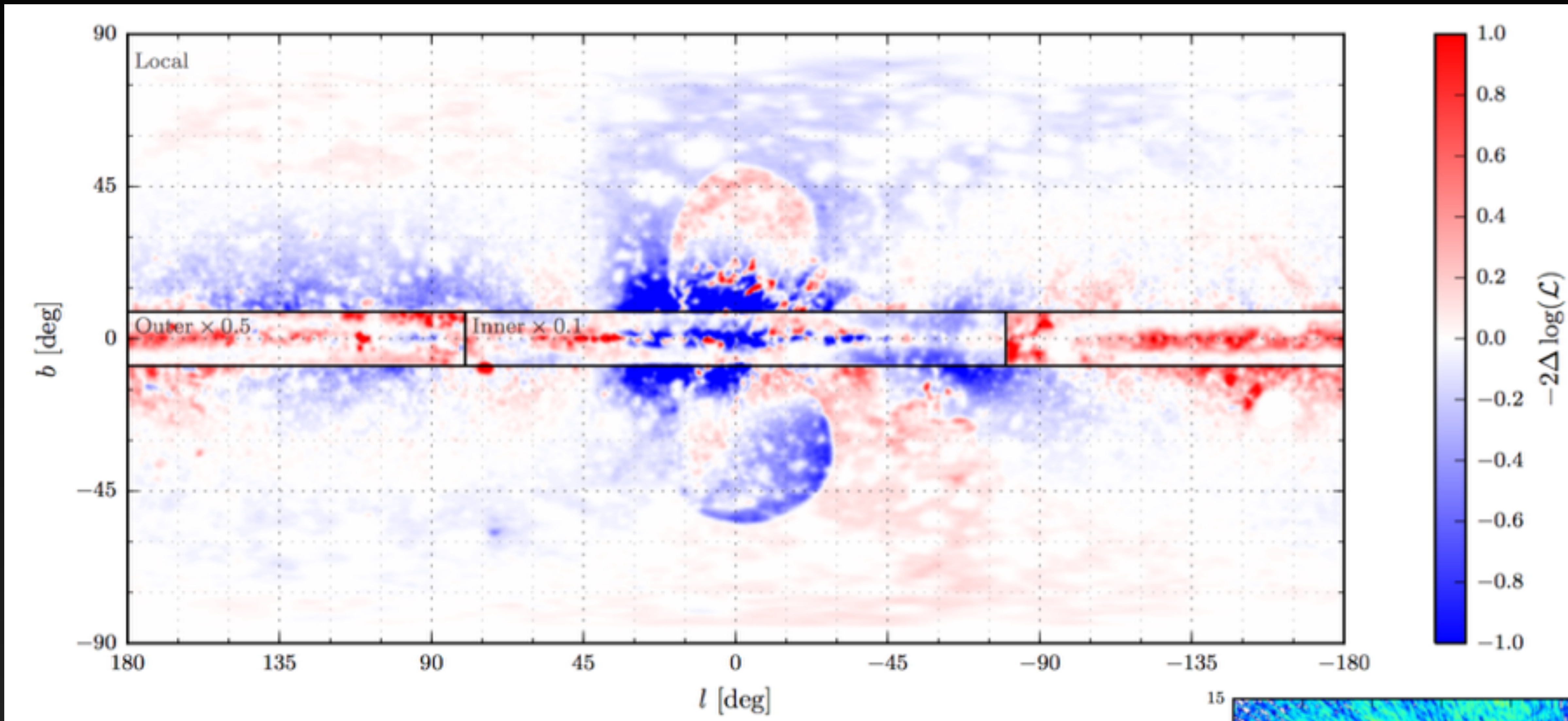
1.) The addition of a new cosmic-ray injection template tracing the 3D H_2 density greatly improves the overall fit to the gamma-ray diffuse emission.

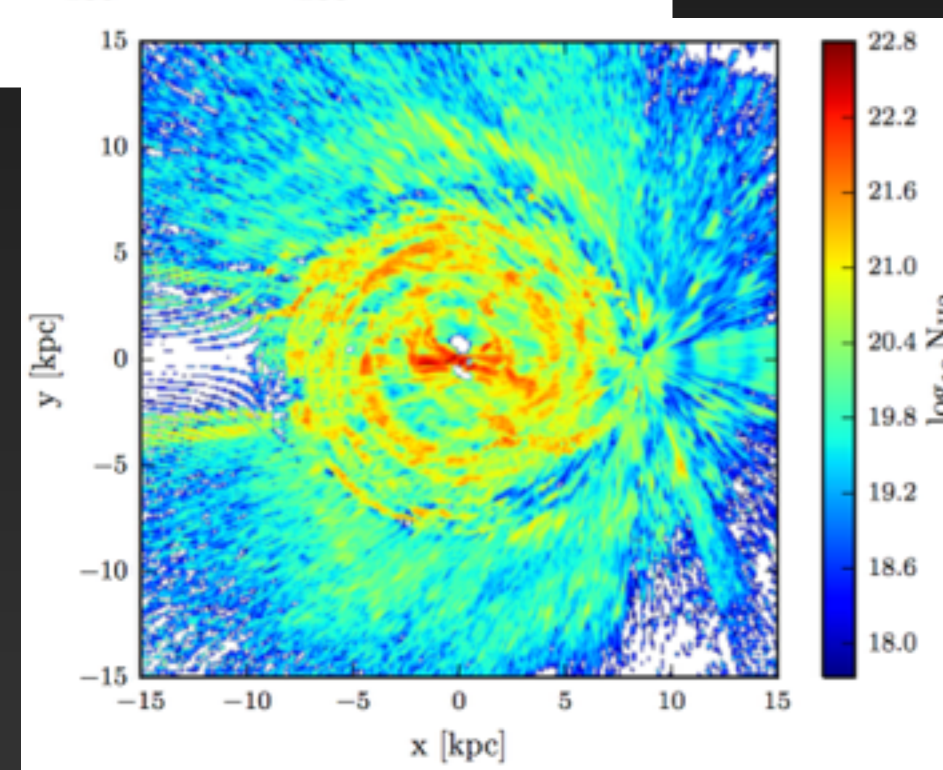


2.) This is an important point on its own, as it offers a new method for improving diffuse models for the gamma-ray sky.

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

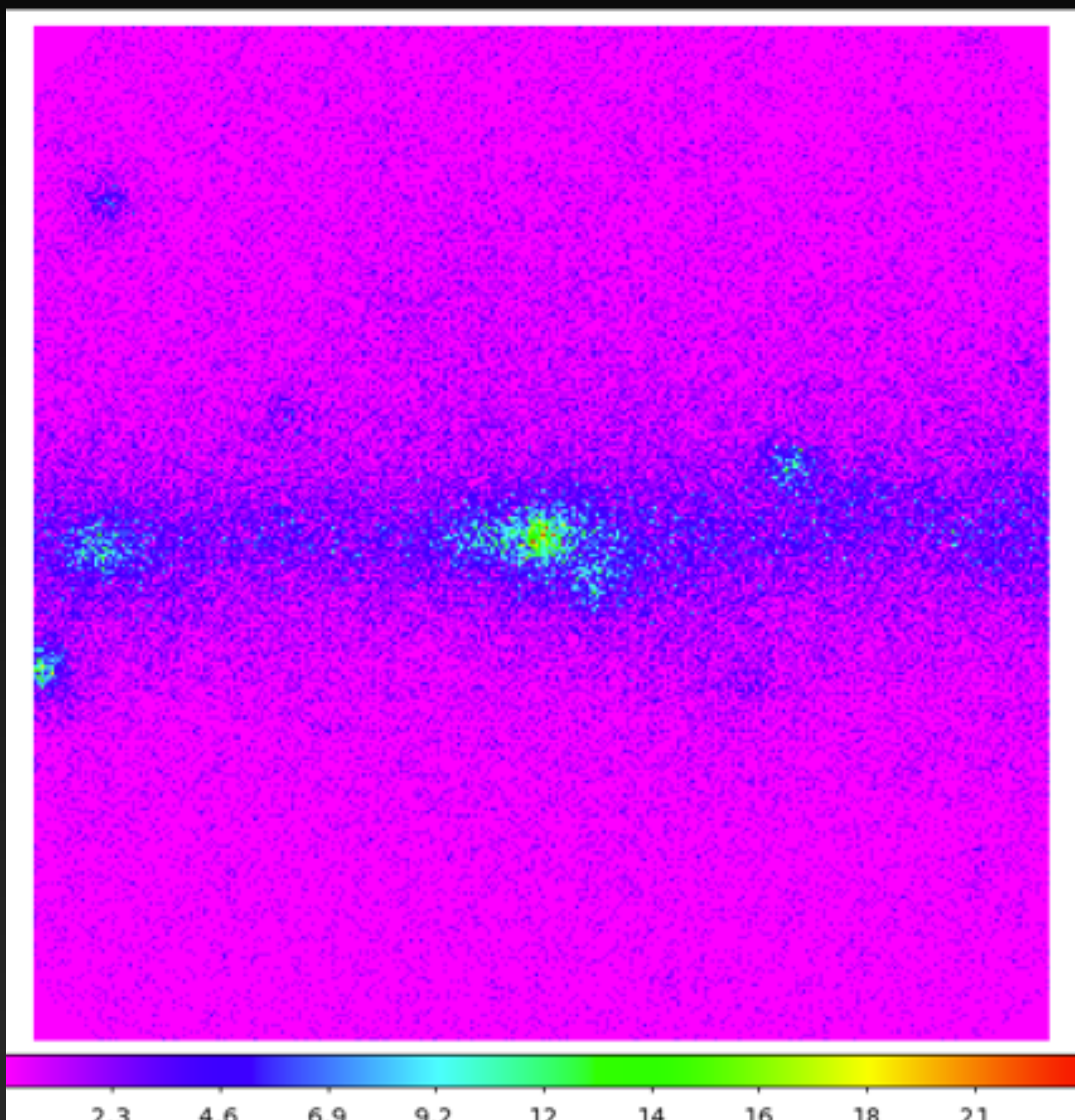
A Better fit to the Gamma-Ray Sky





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

Untangling the spider's web

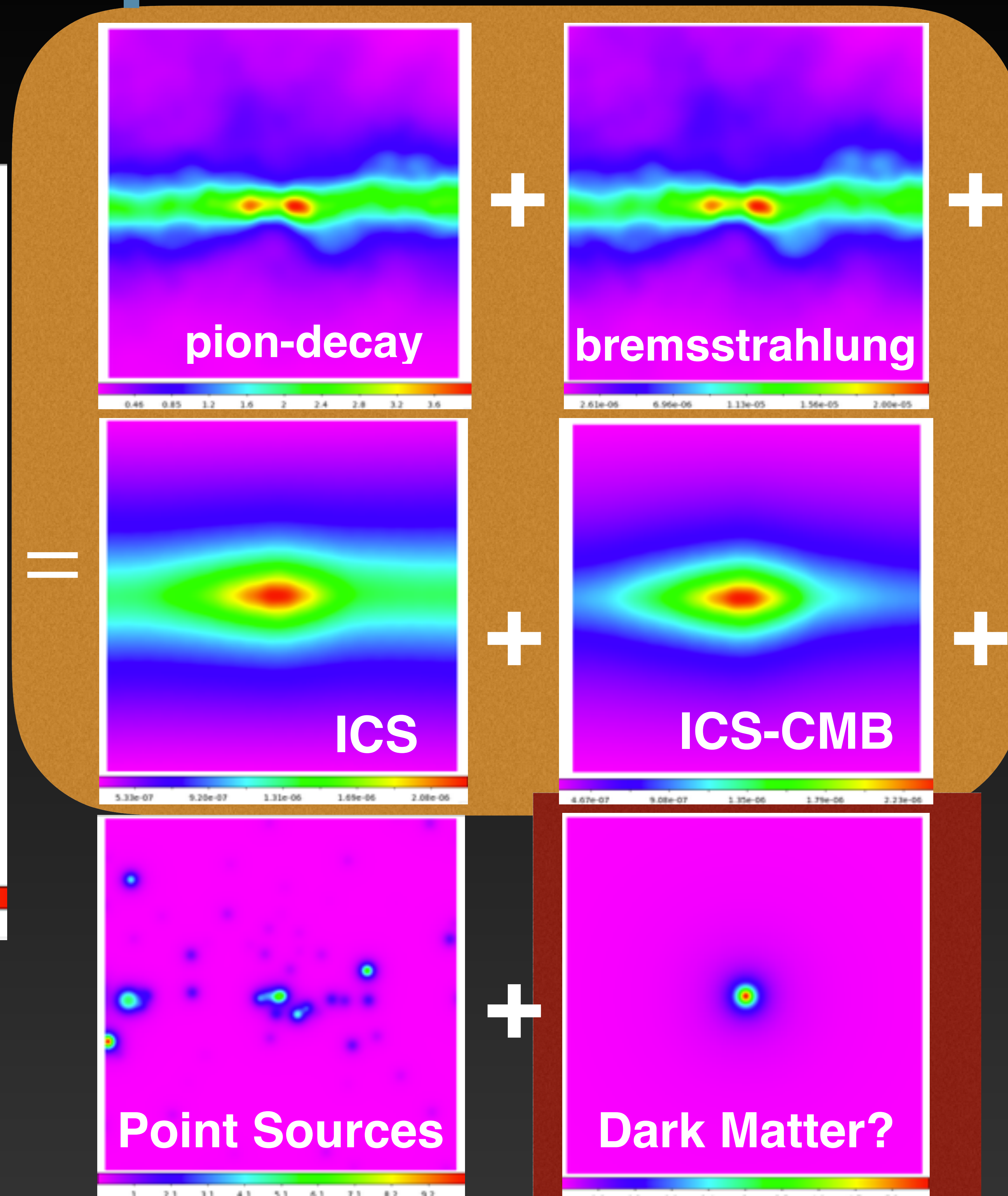


Data

750 — 950 MeV

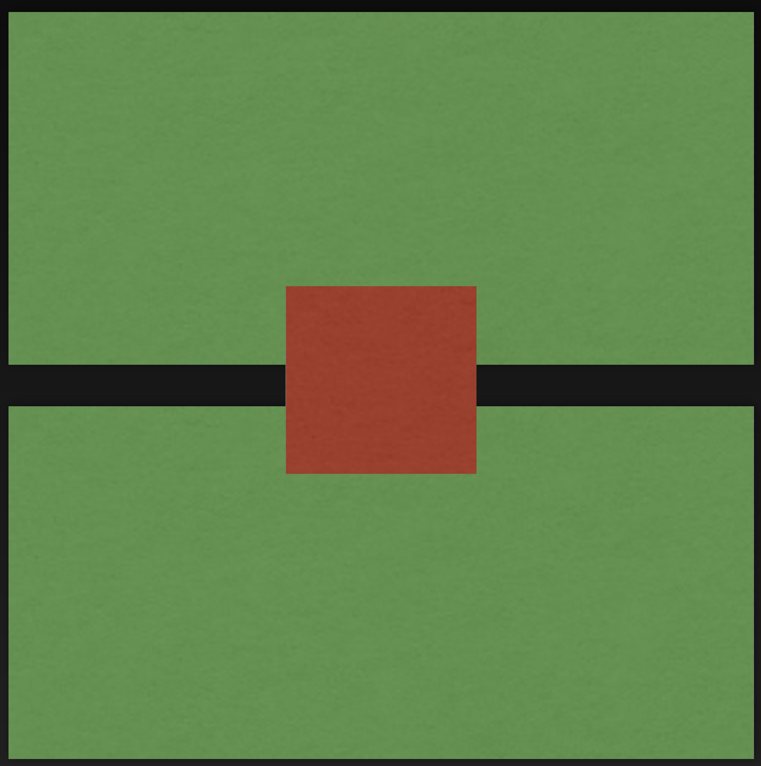
Best Angular Resolution Cut

10º x 10º ROI



An Inner Galaxy Analysis of the GCE

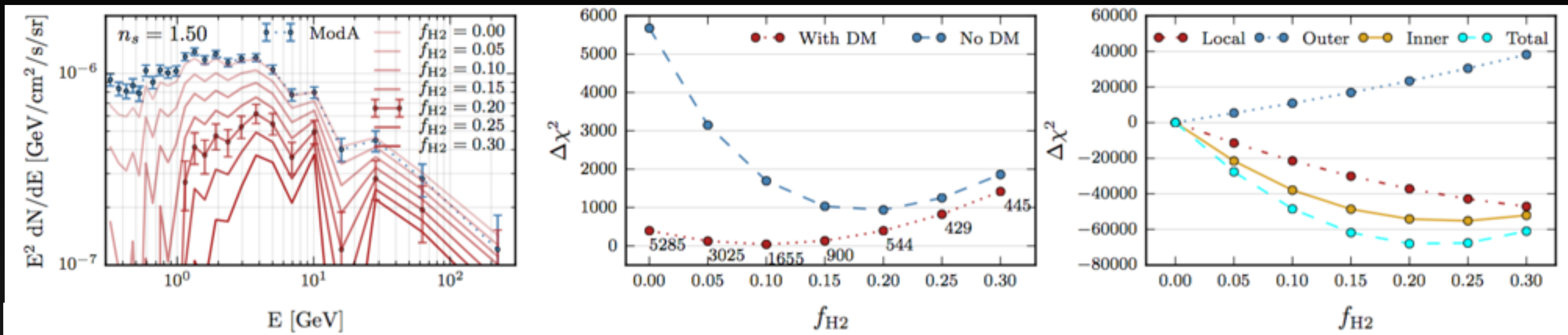
INNER GALAXY



- Mask galactic plane (e.g. $|b| > 2^\circ$), and consider $40^\circ \times 40^\circ$ box
- Energy dependent masking of bright point sources (following Calore et al. 2014)
- Use likelihood analysis, allowing the diffuse templates to float in each energy bin
  - Isotropic energy spectrum fixed via error bars in EGRB analysis (Fermi-LAT 2014)
  - Bubbles fixed via error bars from Su et al.

This creates an analysis with a large sidebands region, where the best fit normalization of the diffuse components is relatively independent of the NFW template.

Effect on the Gamma-Ray Excess



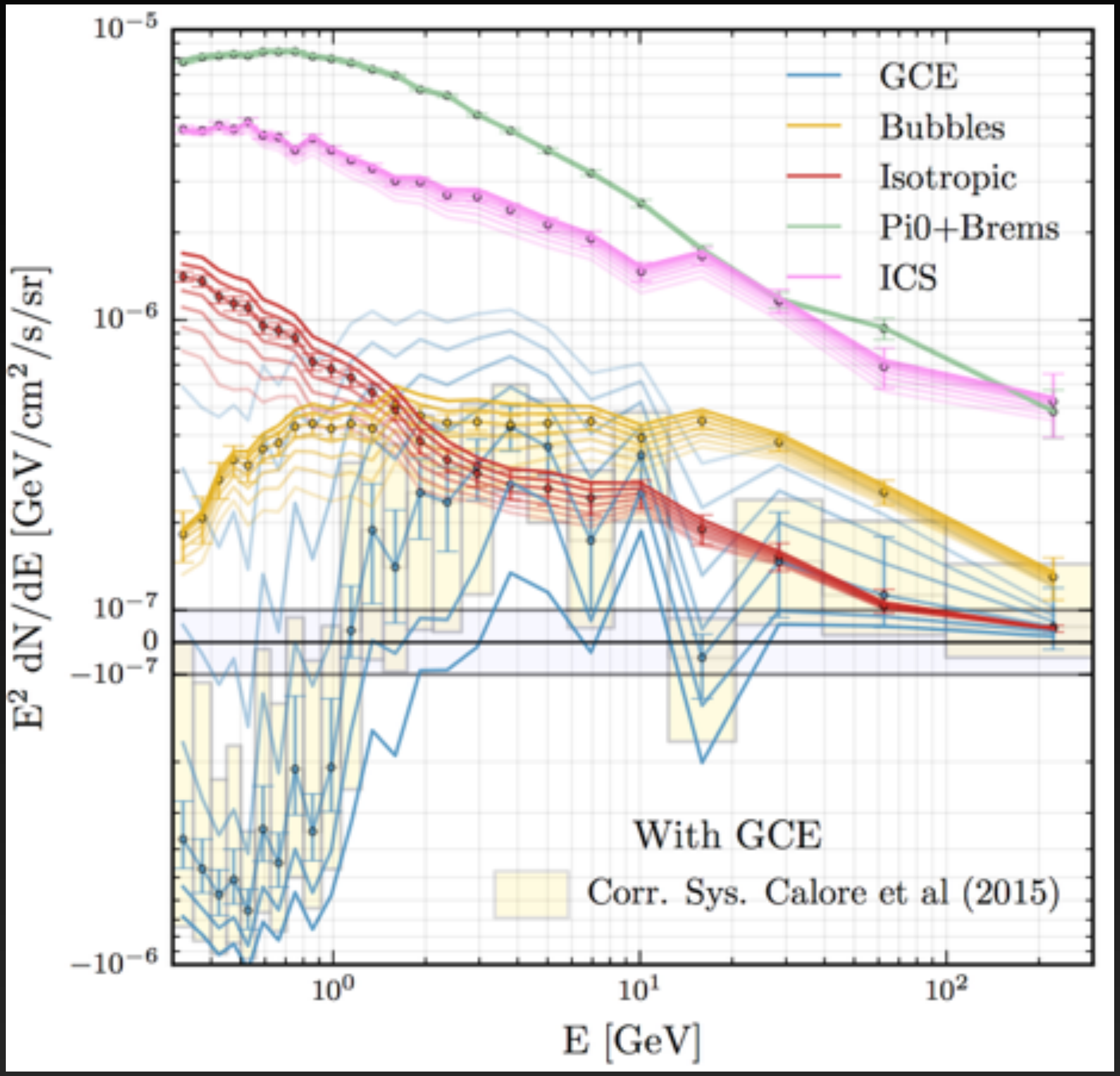
The inclusion of a diffuse emission template tracing the H2 density significantly decreases the intensity of the gamma-ray excess.

However, in the best global fit to the data, the value of f_{H2} decreases to 0.1, and the intensity of the GC excess decreases by only ~30%.

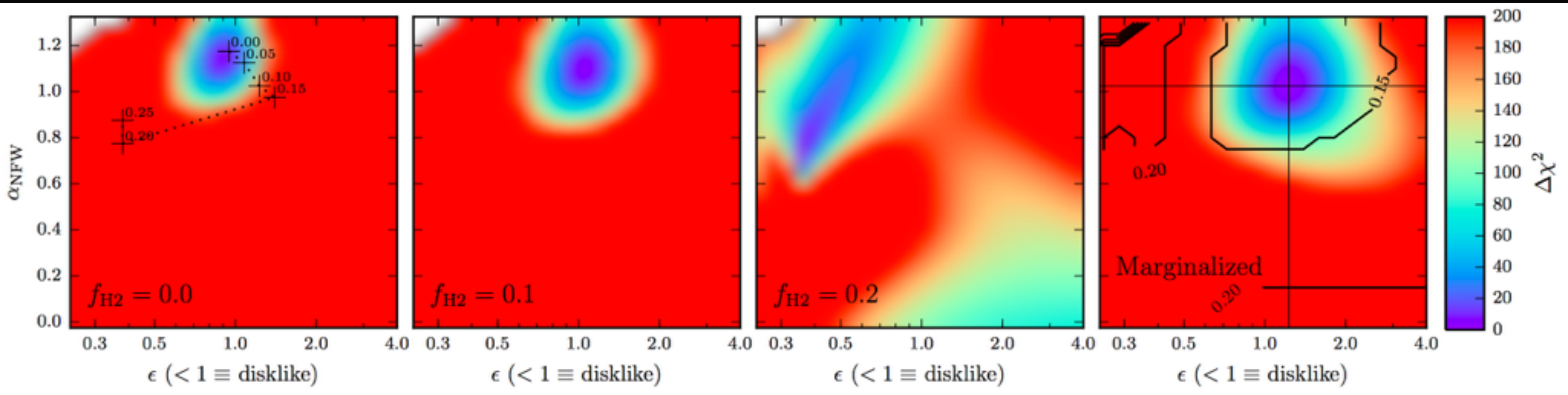
Effect on the Excess Spectrum

Changing the morphology of the excess has a significant effect on the spectrum of the gamma-ray excess.

The spectrum becomes extremely hard as f_{H2} is increased, most likely indicating that the GCE template is picking up mismodeling of some residual.



Effect on the Excess Morphology



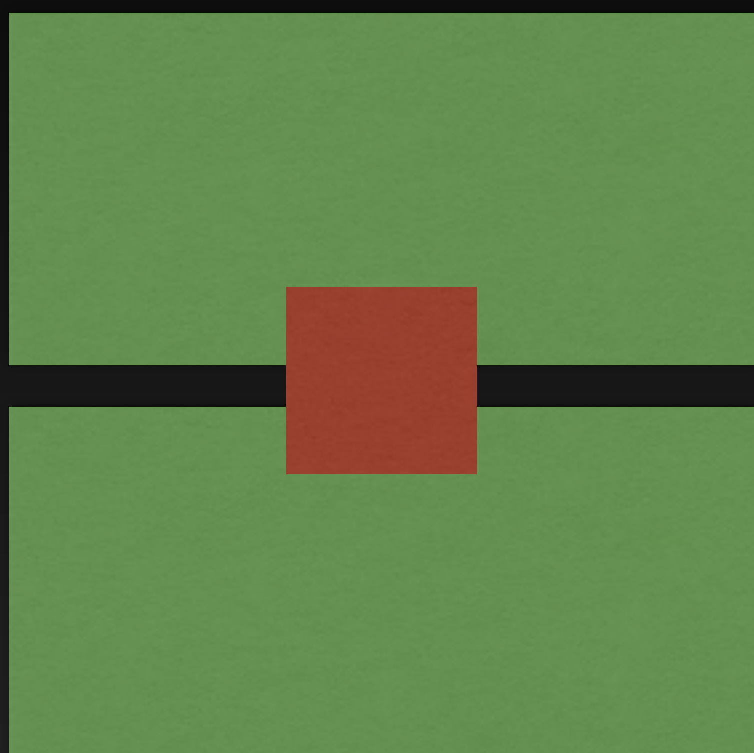
The morphology of the Gamma-Ray Excess is also degenerate with the value of f_{H2}.

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.

A Galactic Center Analysis of the GCE

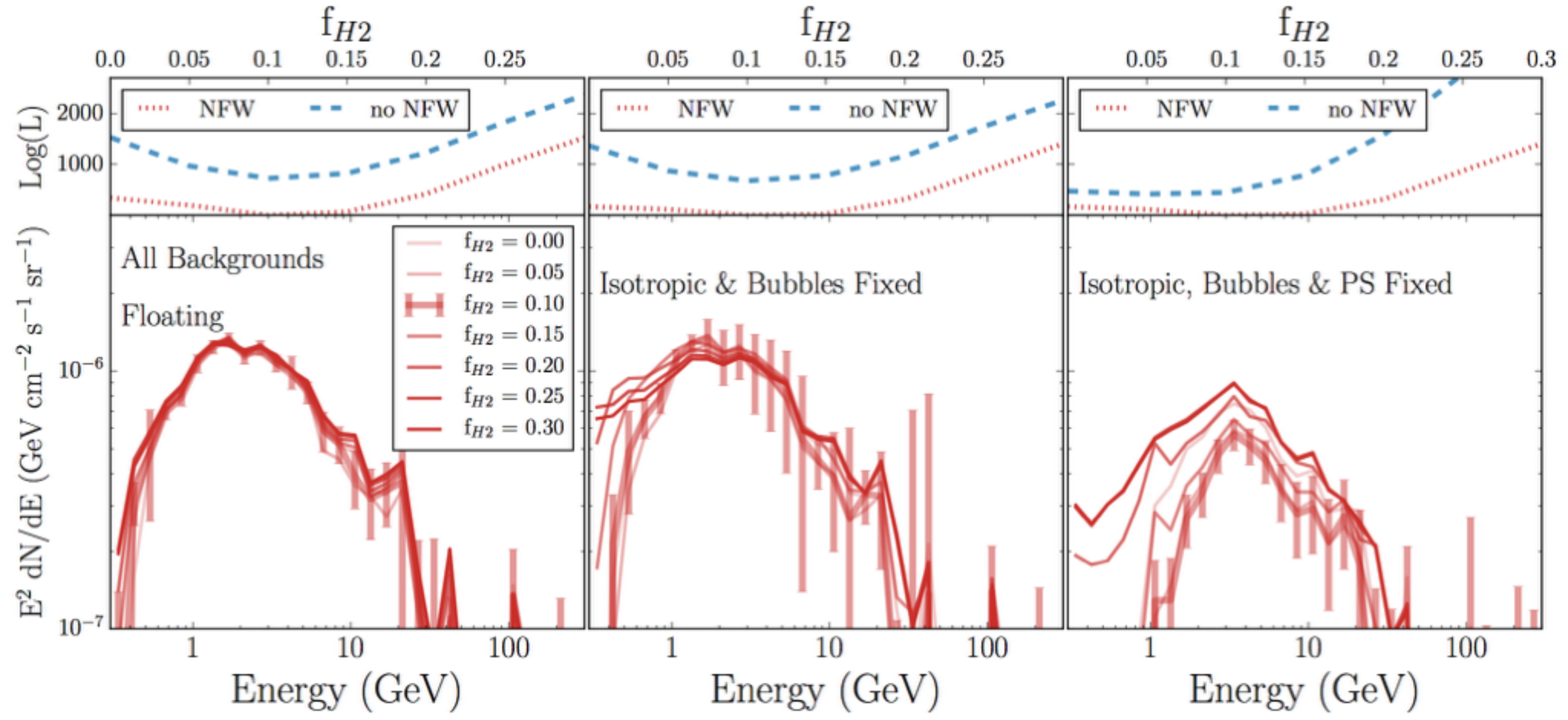
GALACTIC CENTER



- Examine 15° x 15° region surrounding the galactic center.
- No point source masking
- Use likelihood analysis, allowing the diffuse templates and point sources to float in each energy bin.

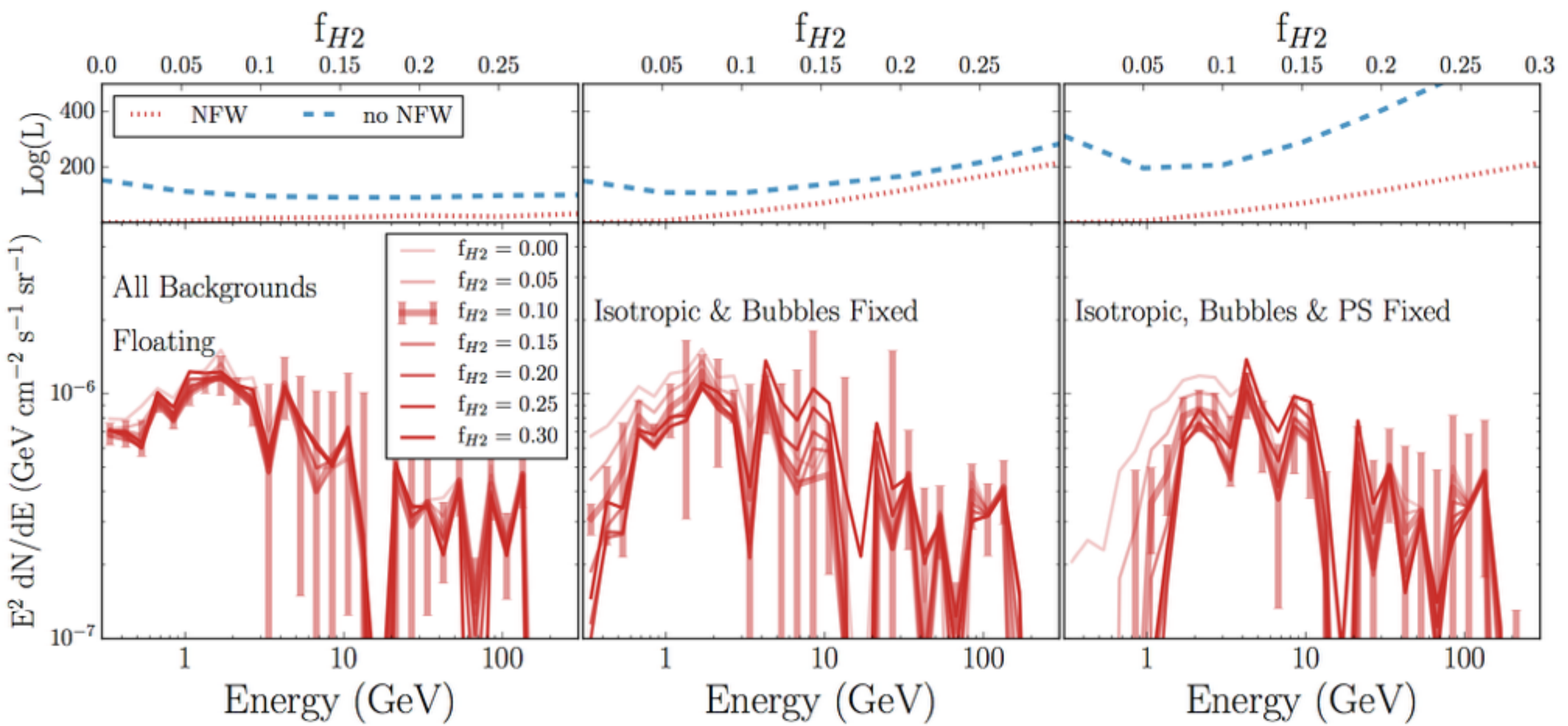
This creates an analysis with no sidebands region, where the NFW template normalization plays a critical role in determining the spectrum and normalization of diffuse components.

The Effect on the Galactic center Excess



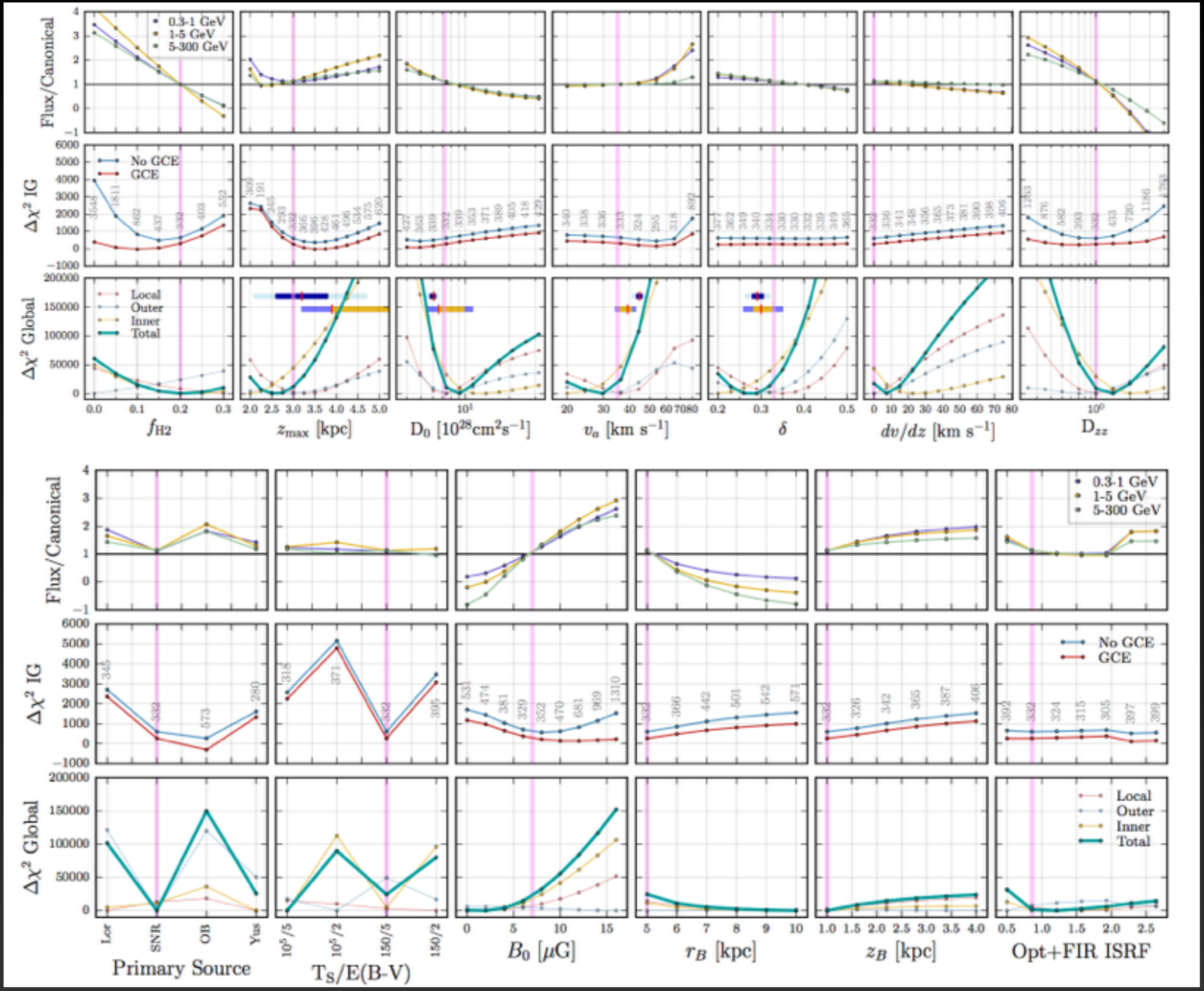
In this smaller region, the excess remains resilient to changes in diffuse emission modeling.

The Effect on the Galactic center Excess (masking |b| < 2º)

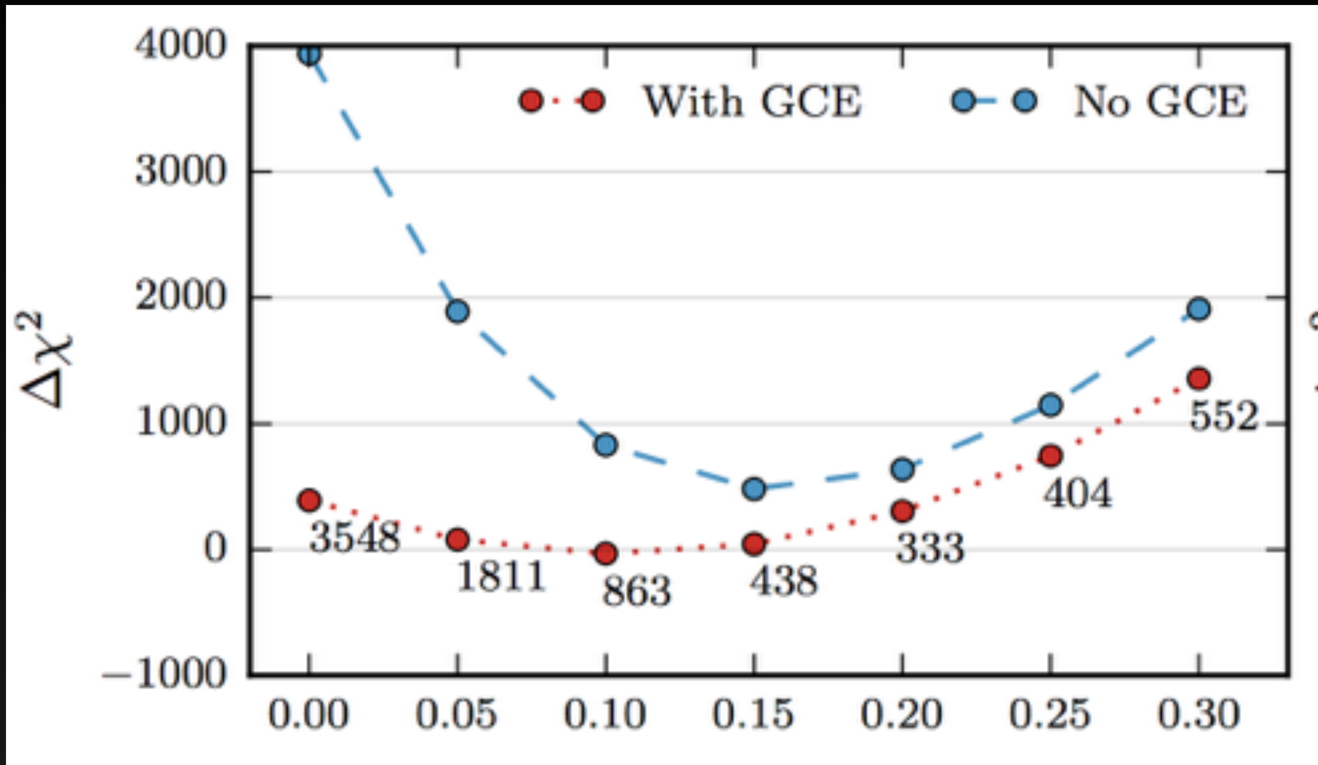


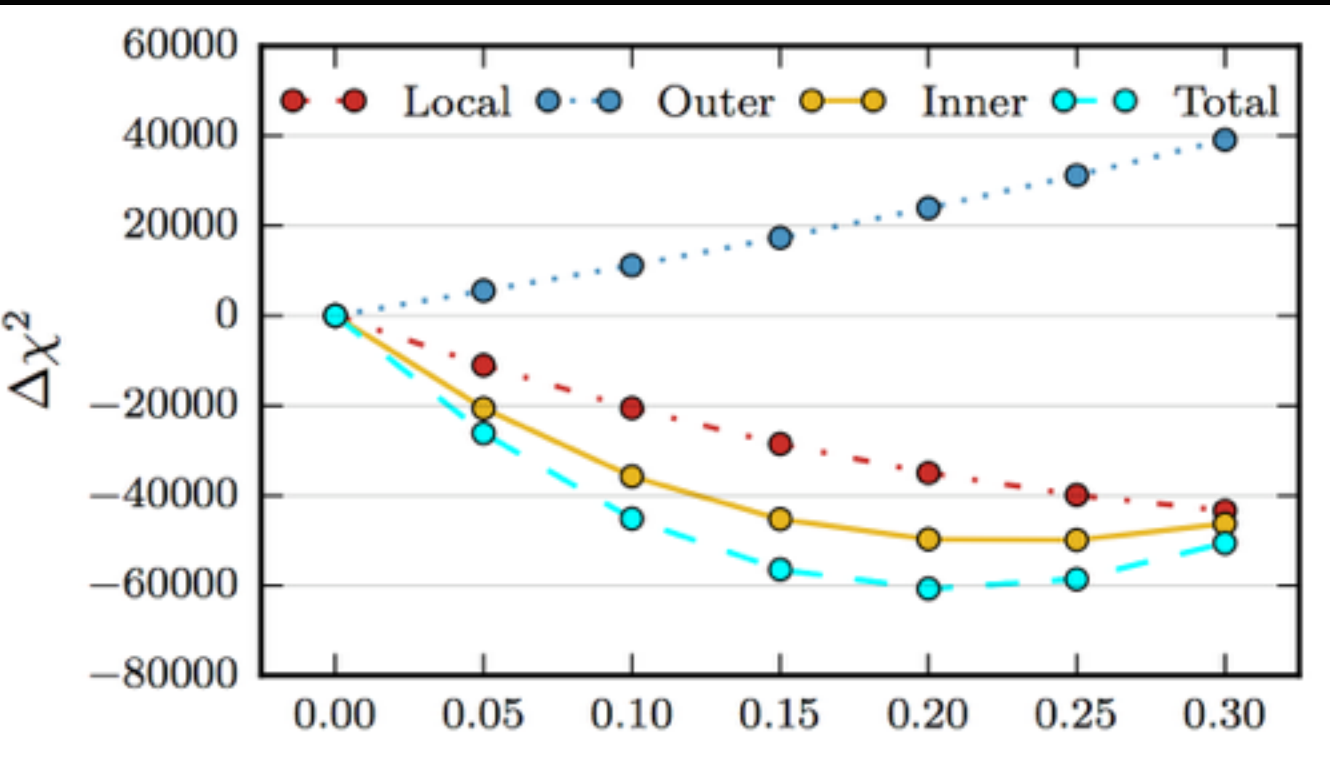
Intriguingly, this persists even when the inner 2º are masked - implying that analyses of small ROIs favors the excess.

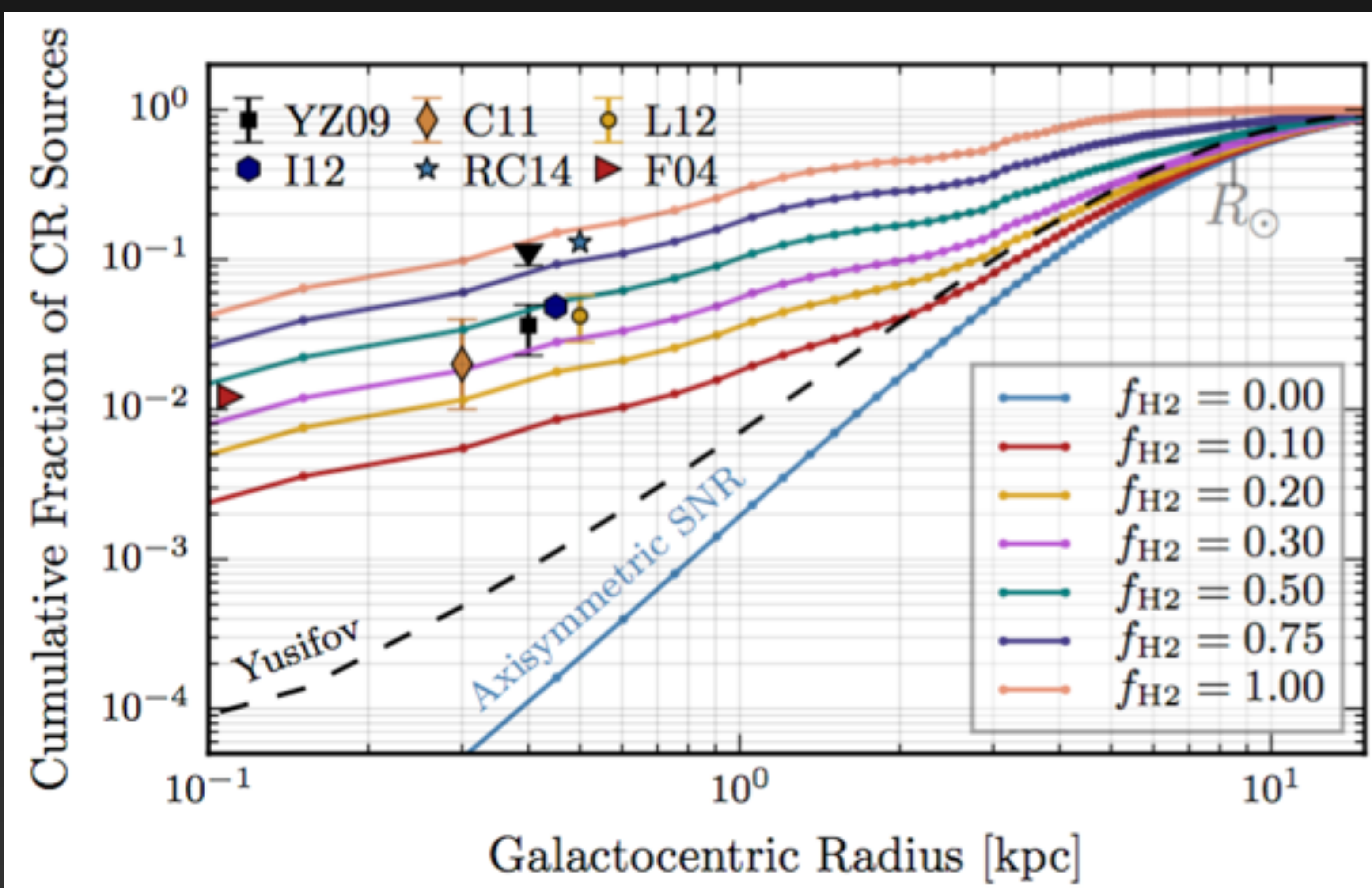
Galactic center excess is resilient to many other parameters….

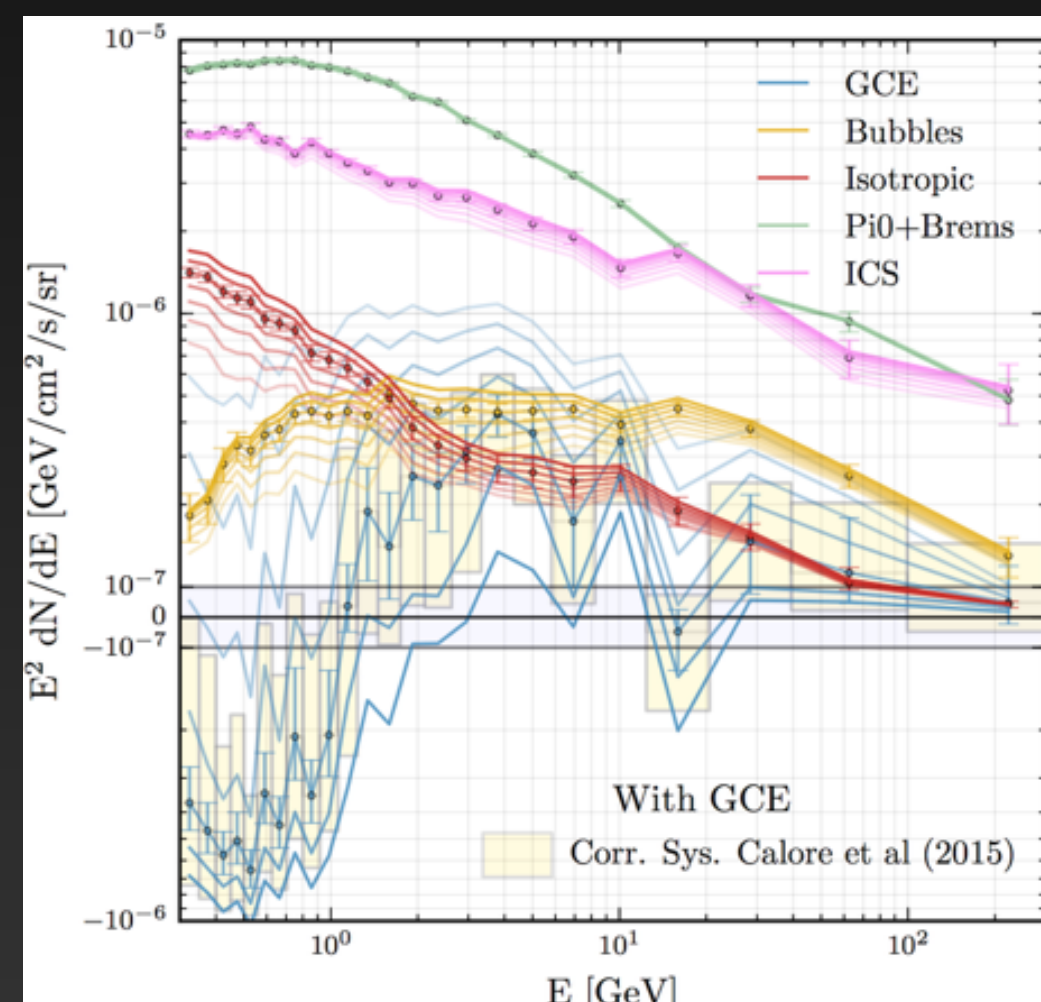


The Galactic Center Deficit?







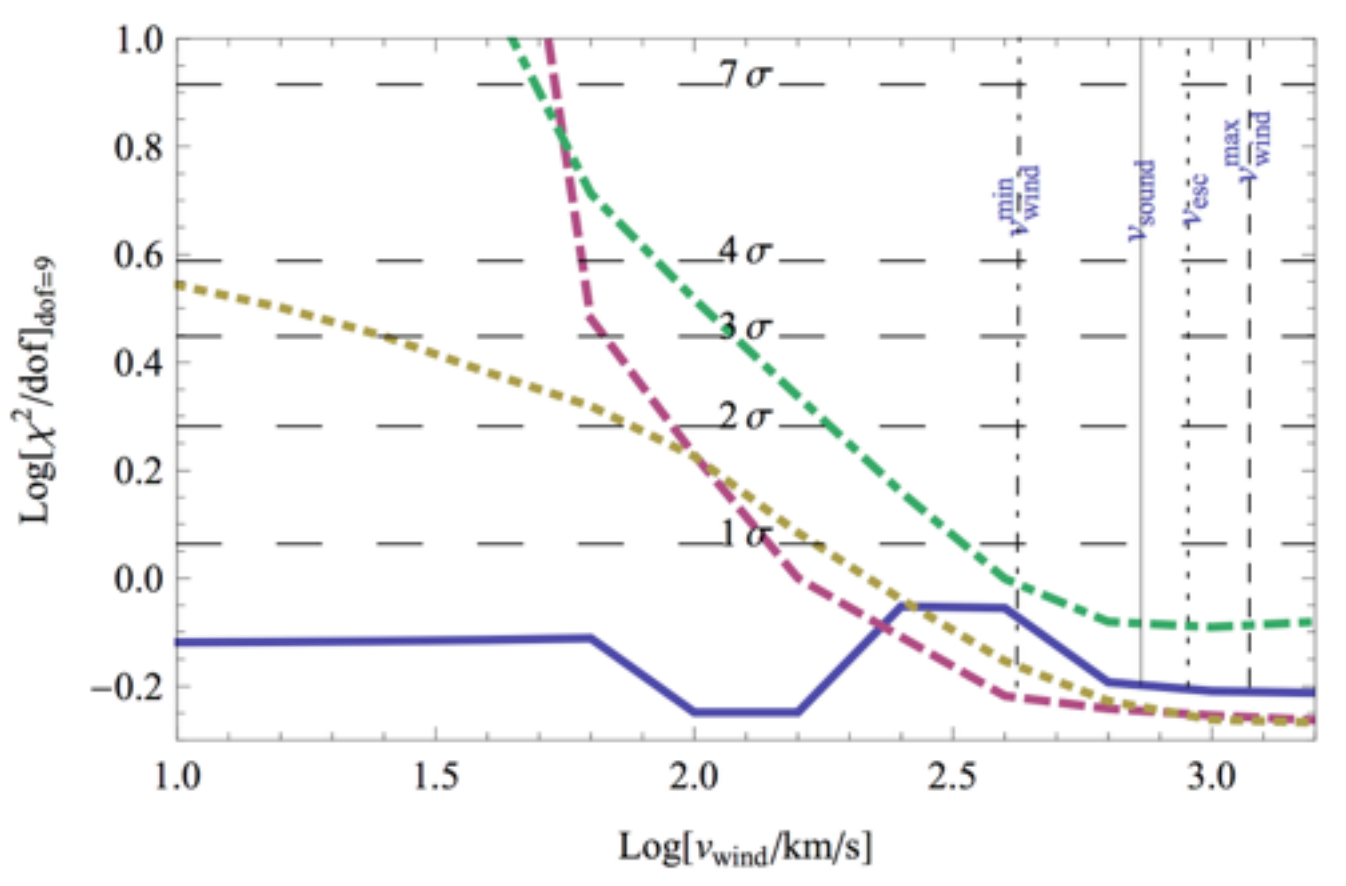


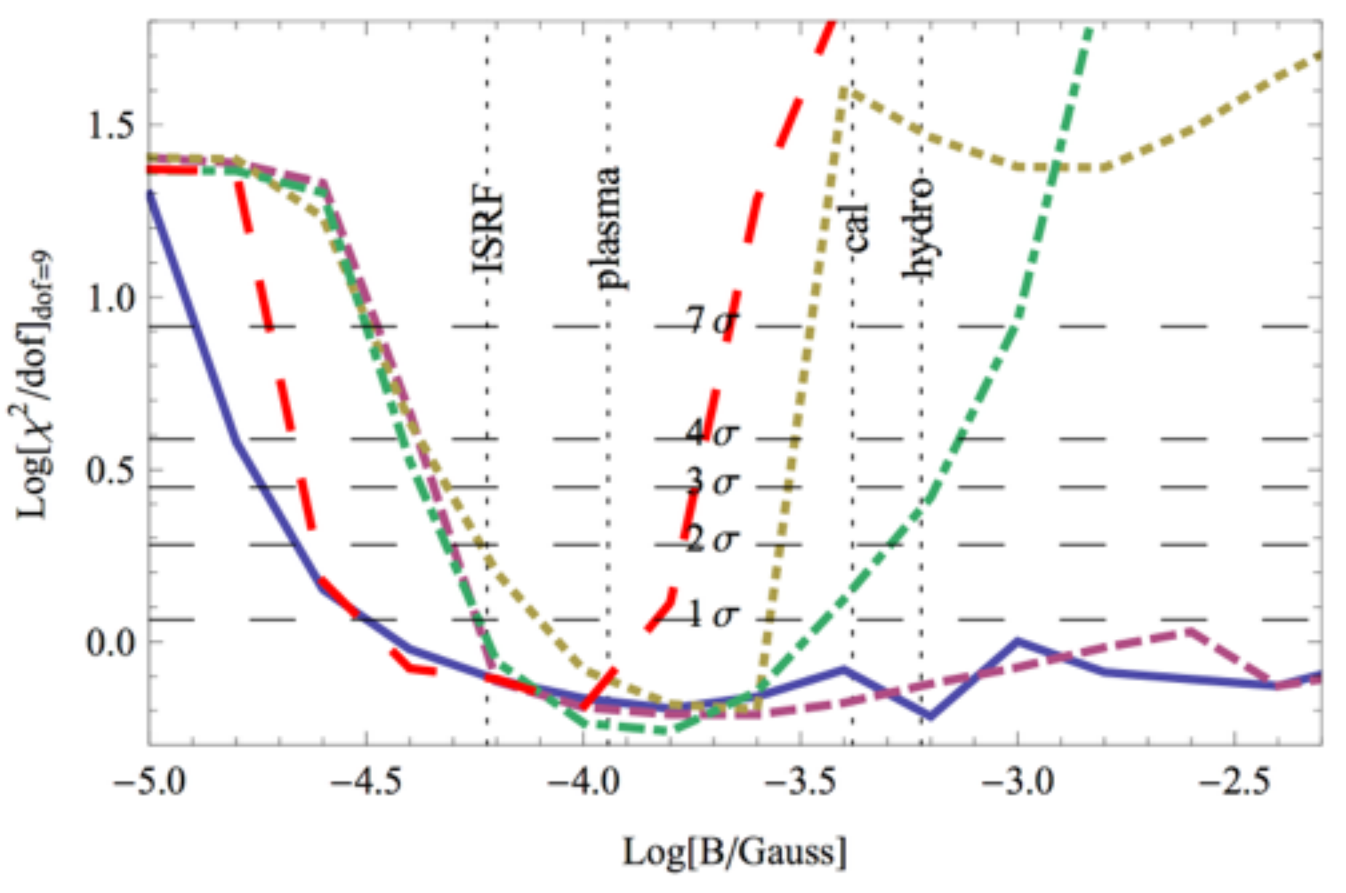
Advection and Convection in the Galactic Center

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

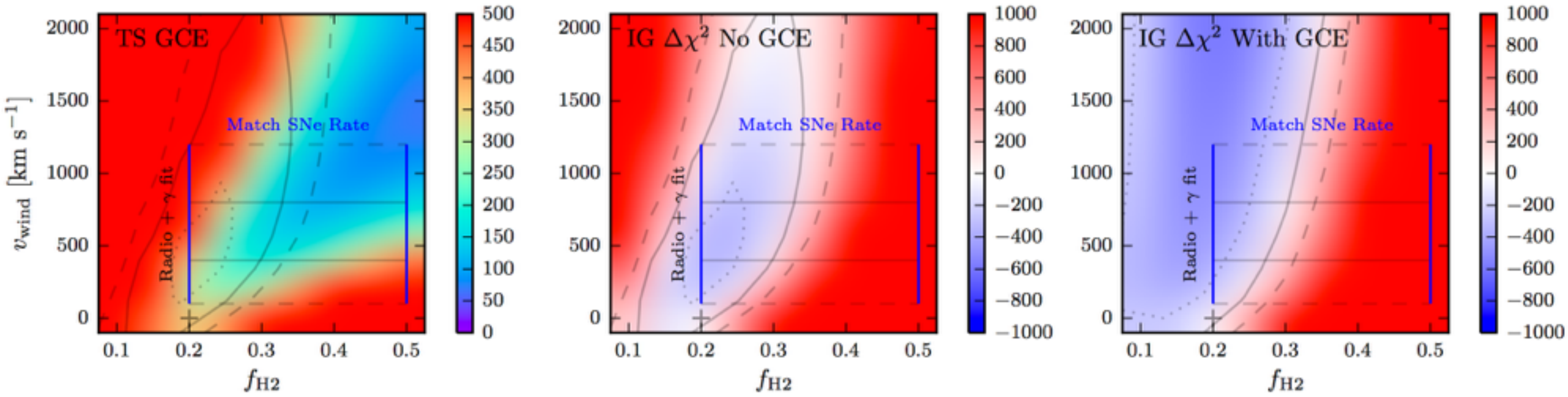
- a.) Large Magnetic Fields
- b.) Large Convective Winds

Very different from typical Galprop diffusion scenario.





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.

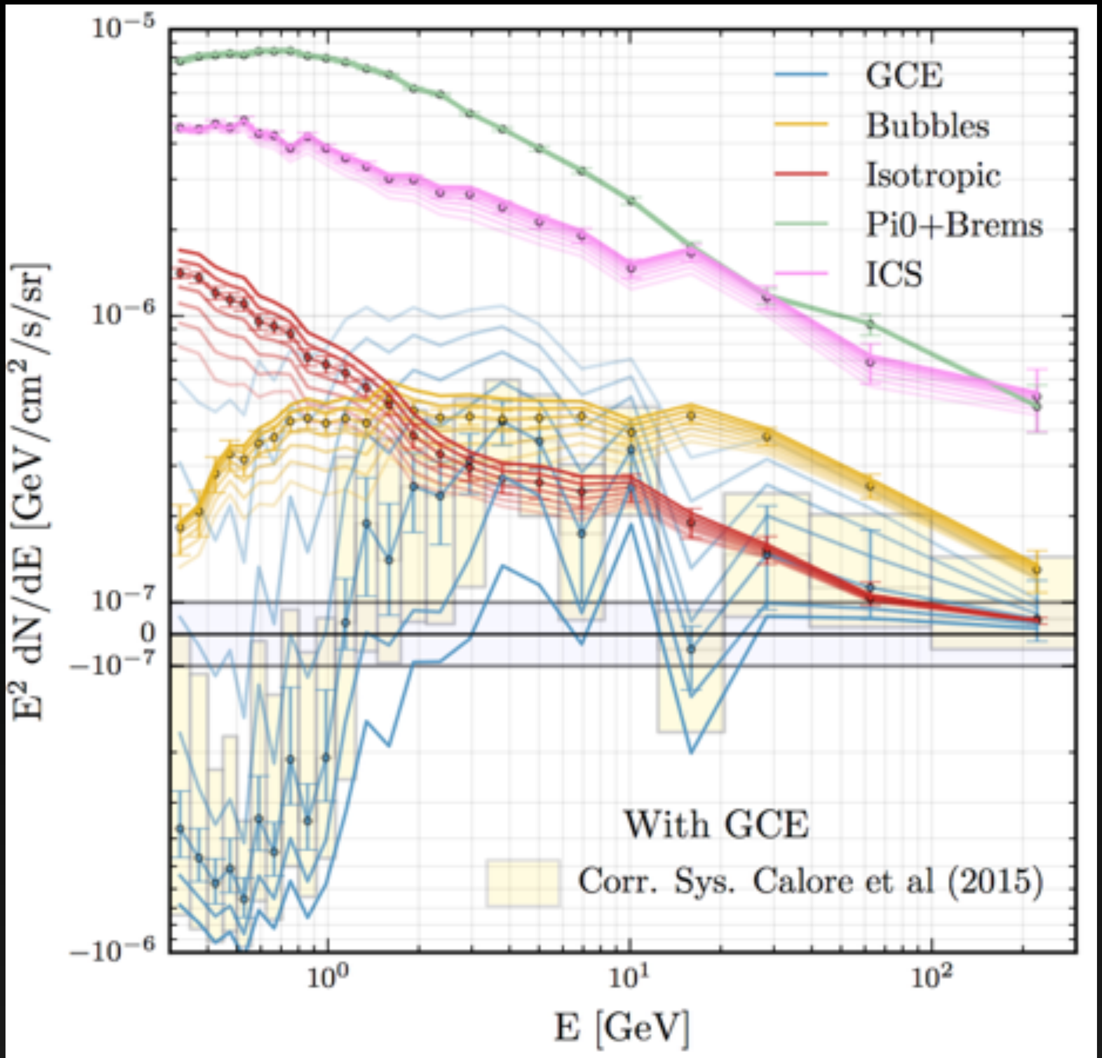
Models with a GCE component still prefer slightly lower values of f_{H2}, but these have increased to 0.2 as well.

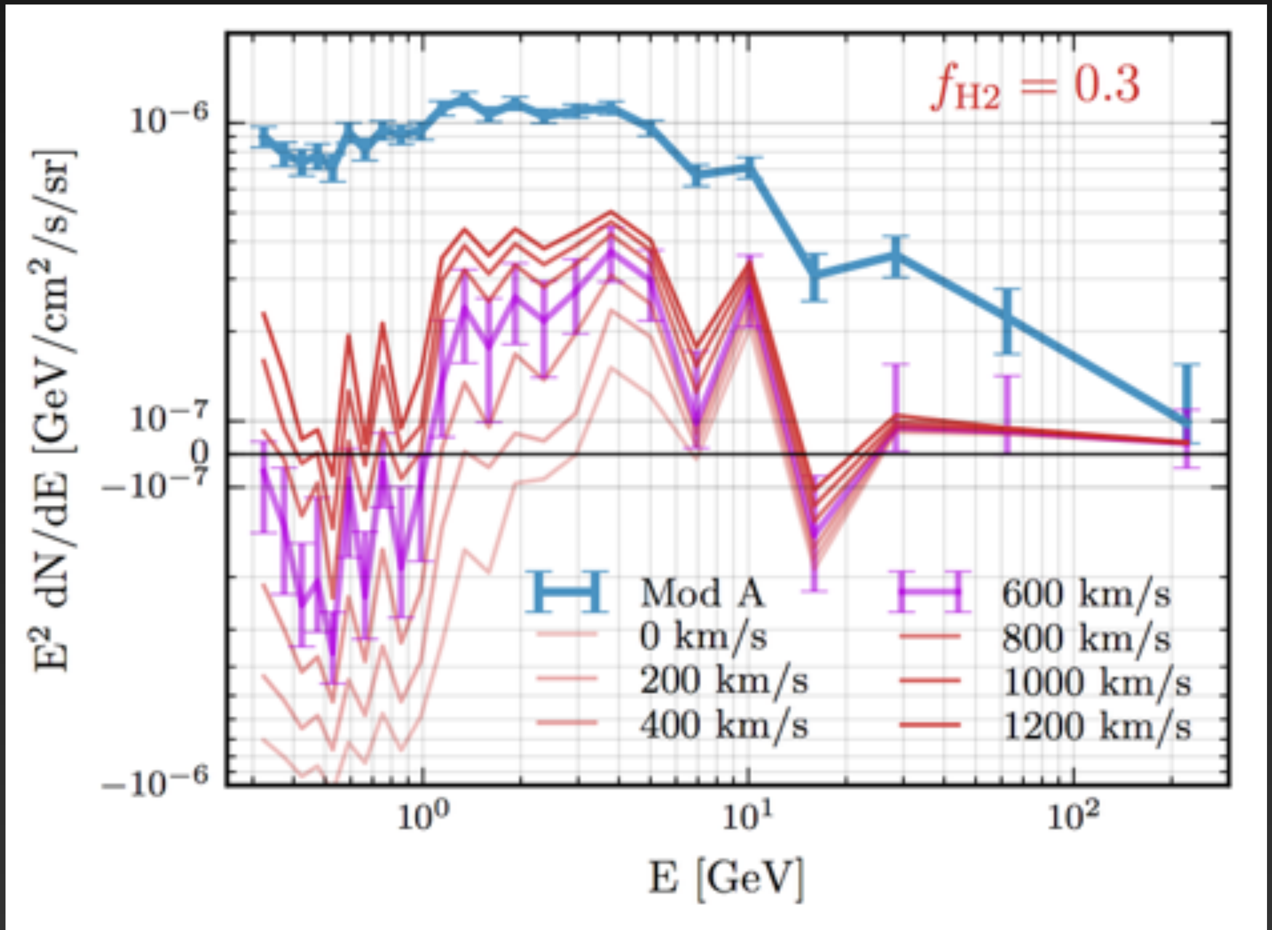
The Low Energy Spectrum

Can apply these to Galprop models by adding a new radial wind.

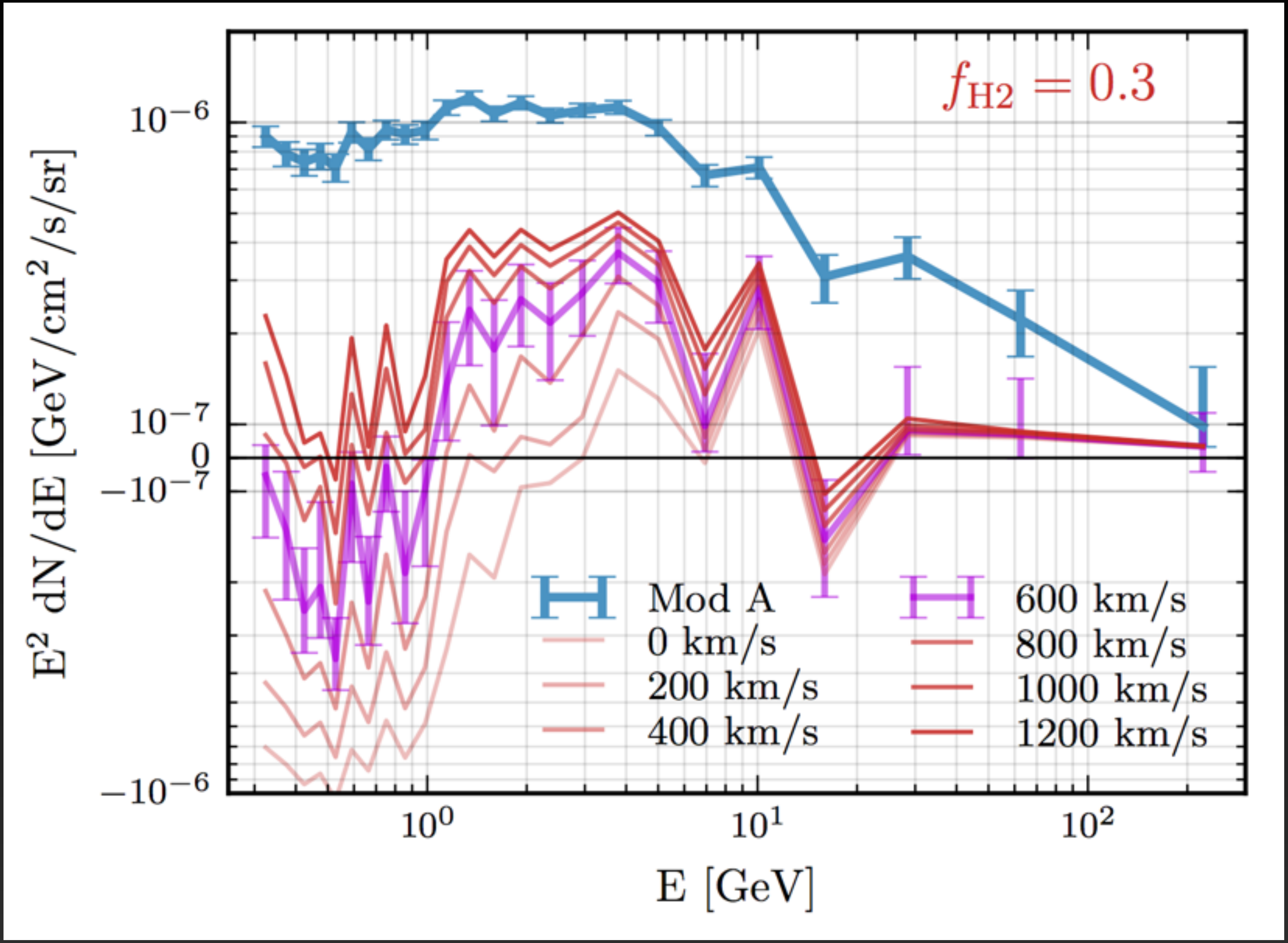
Advective energy losses most important for low-energy cosmic-rays, decreases the astrophysical contribution < 1 GeV.

Peak of the GeV excess returns to more than 50% of initial luminosity.



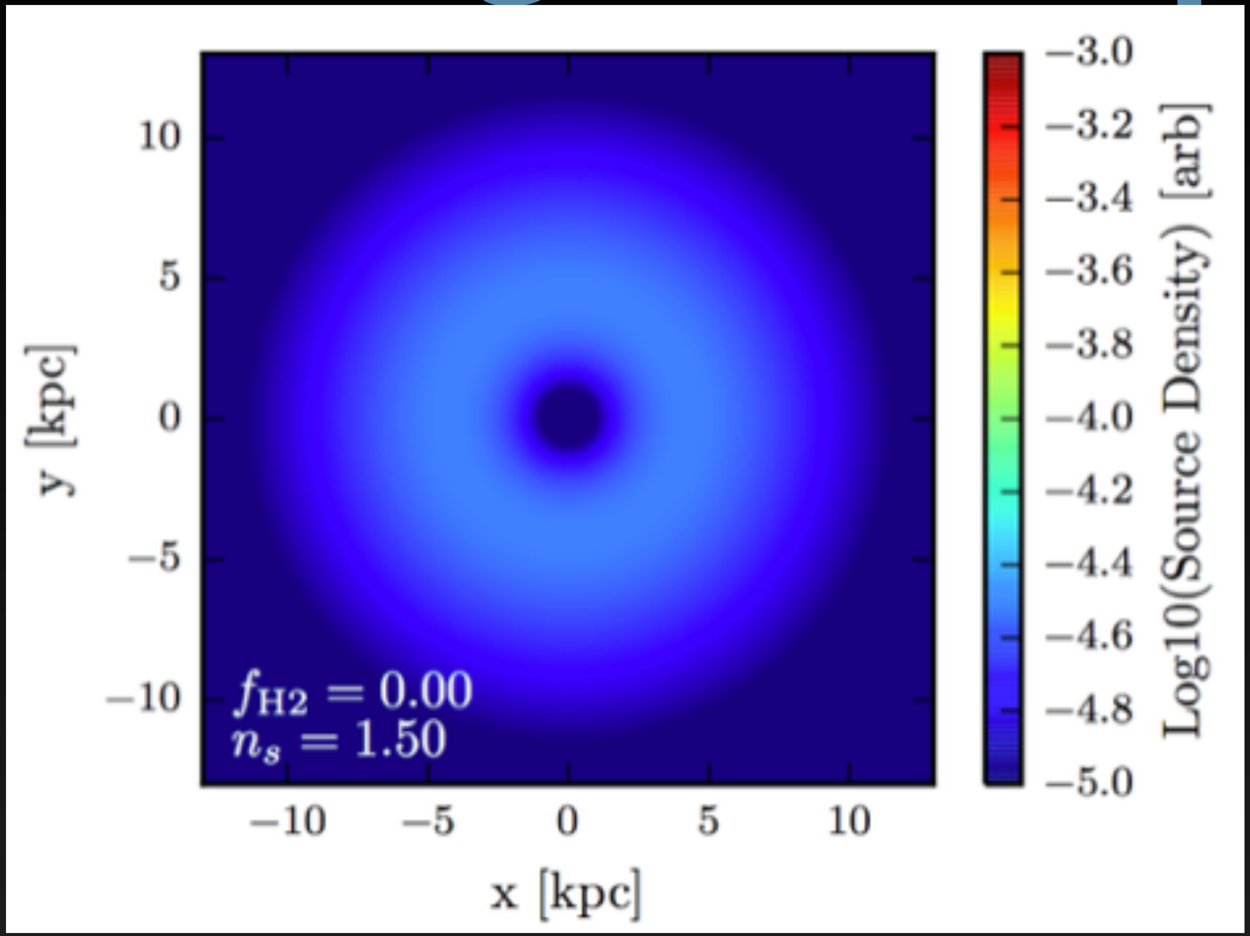


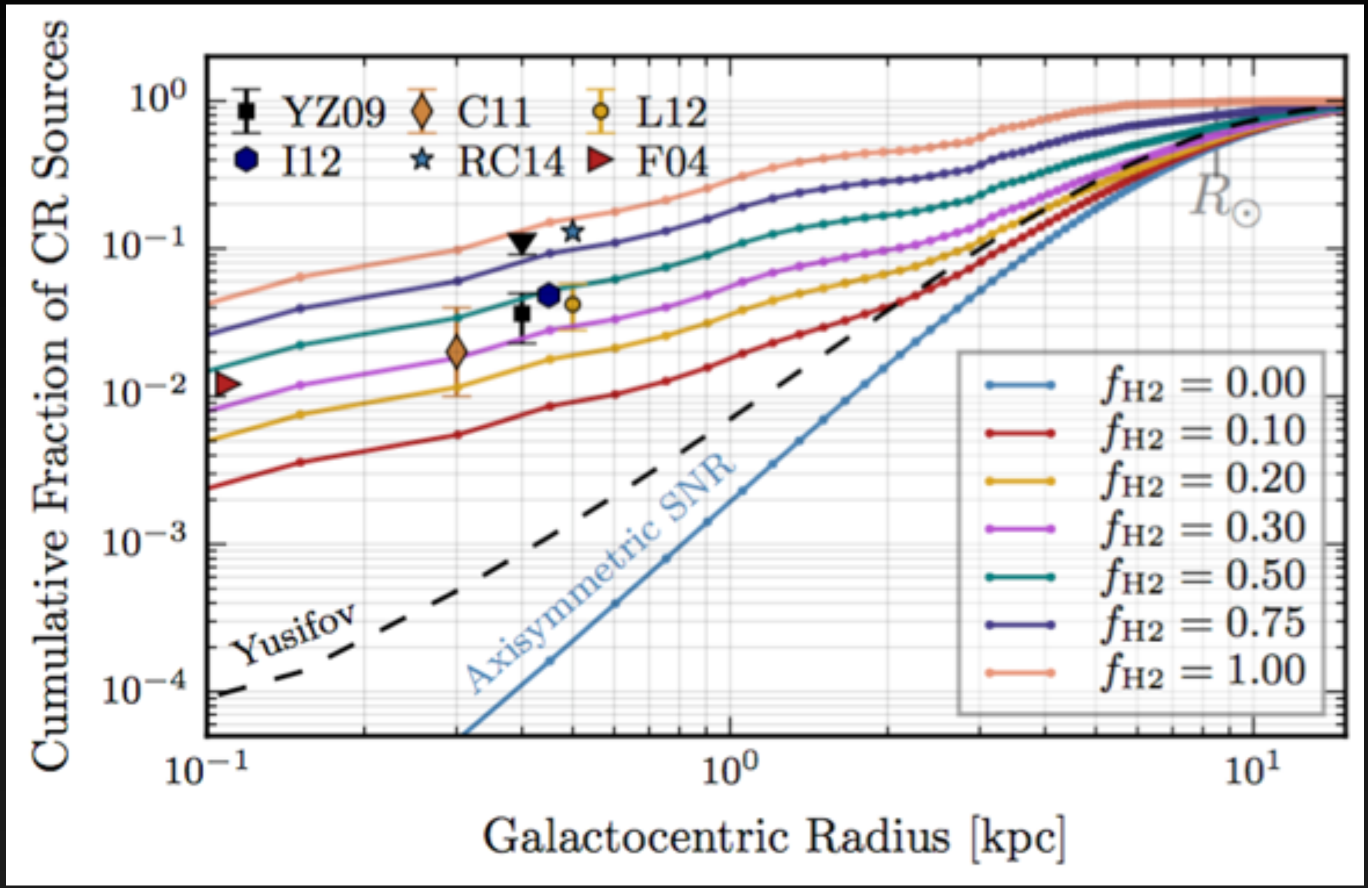
The Low Energy Spectrum



The excess lives!

Waxing Philosophical.....



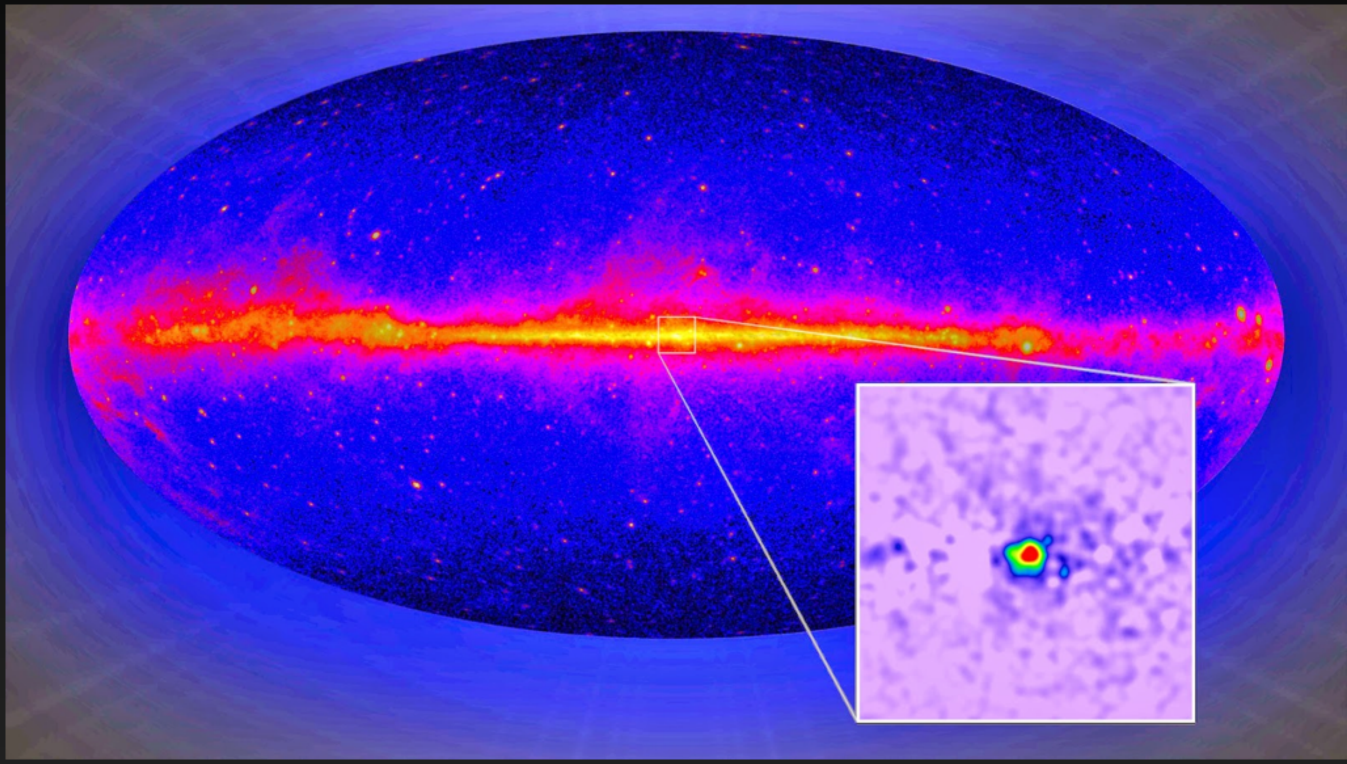


The lack of cosmic-ray injection in the GC should still be slightly disturbing. Especially when we try to answer the question: "excess compared to what?"

On the other hand, it seems clear that we don't have a final answer yet. An optimal diffuse model should remove or produce an excess that is consistent among all ROIs and analysis techniques.

Models of the GCE and Paths Forward

Several Viable Models for the GCE Emission:



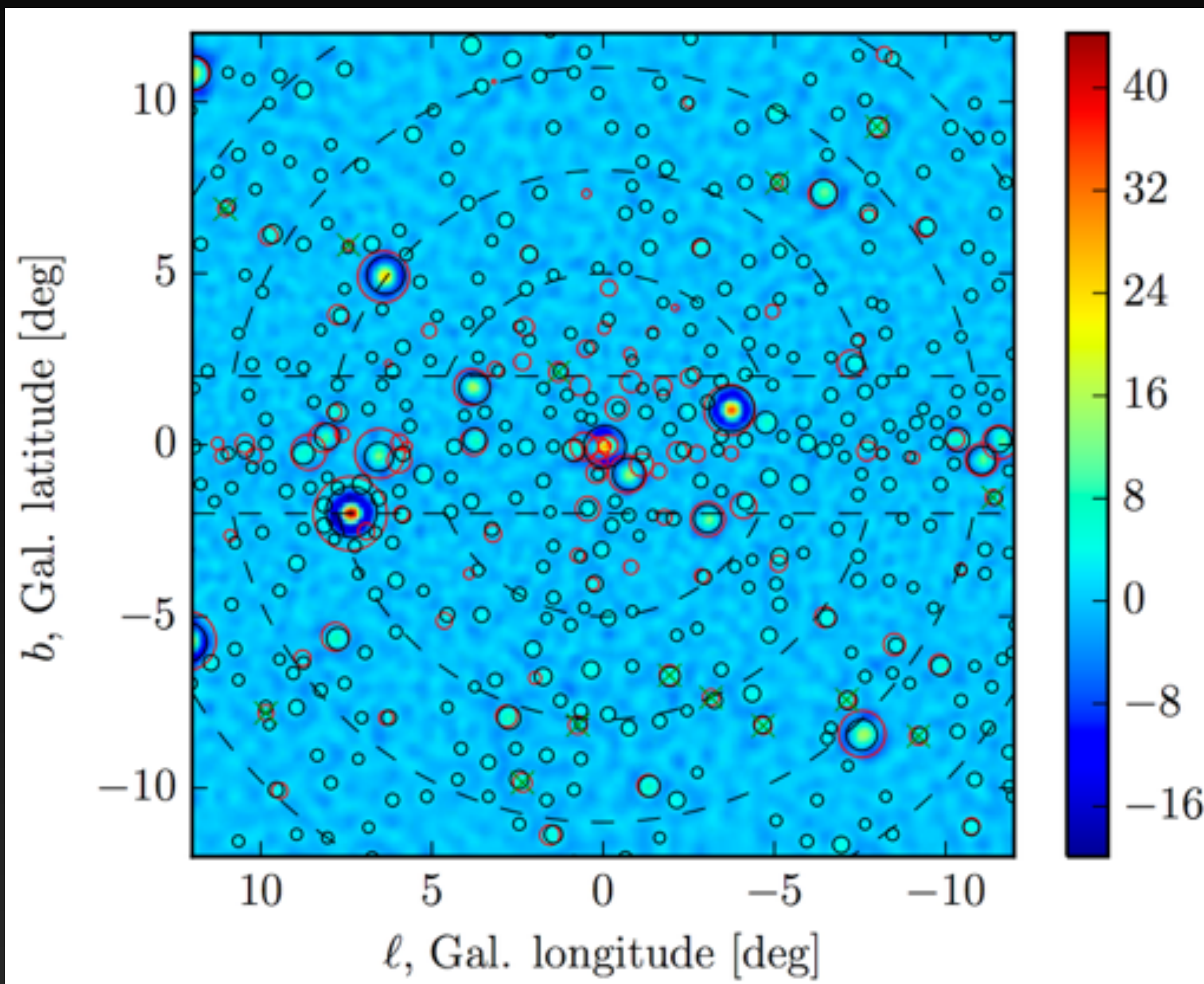
1.) Pulsars (young or recycled)
2.) Leptonic Outbursts
3.) Diffuse Emission Modeling
4.) Dark Matter annihilation

Fermi-LAT has already accumulated 8 years of data —- only marginal improvements are likely in the sensitivity to differences between these models.

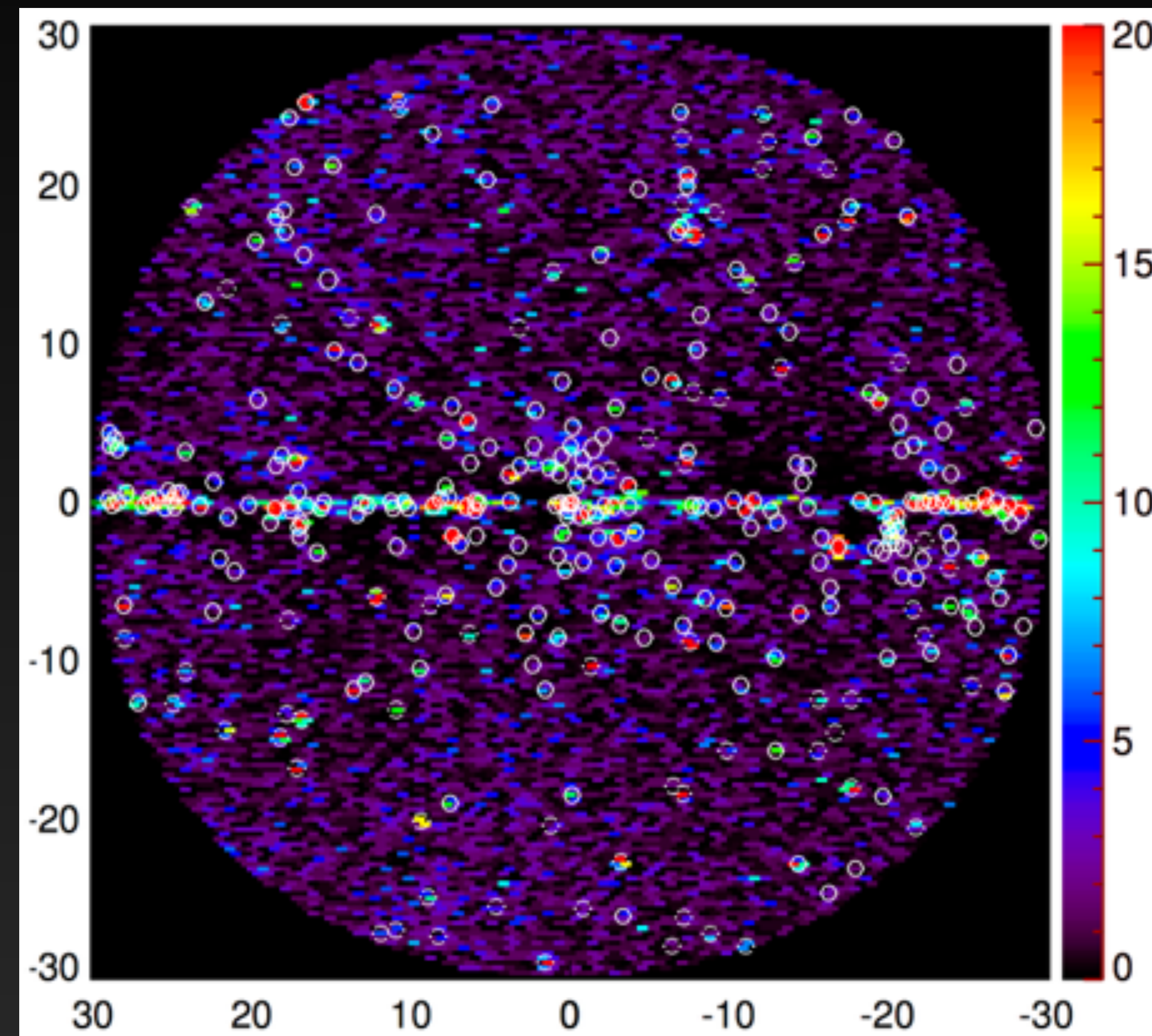
Warning: The remaining slides are intended to be controversial.

Millisecond Pulsar Fits

Bartels et al. (2015)

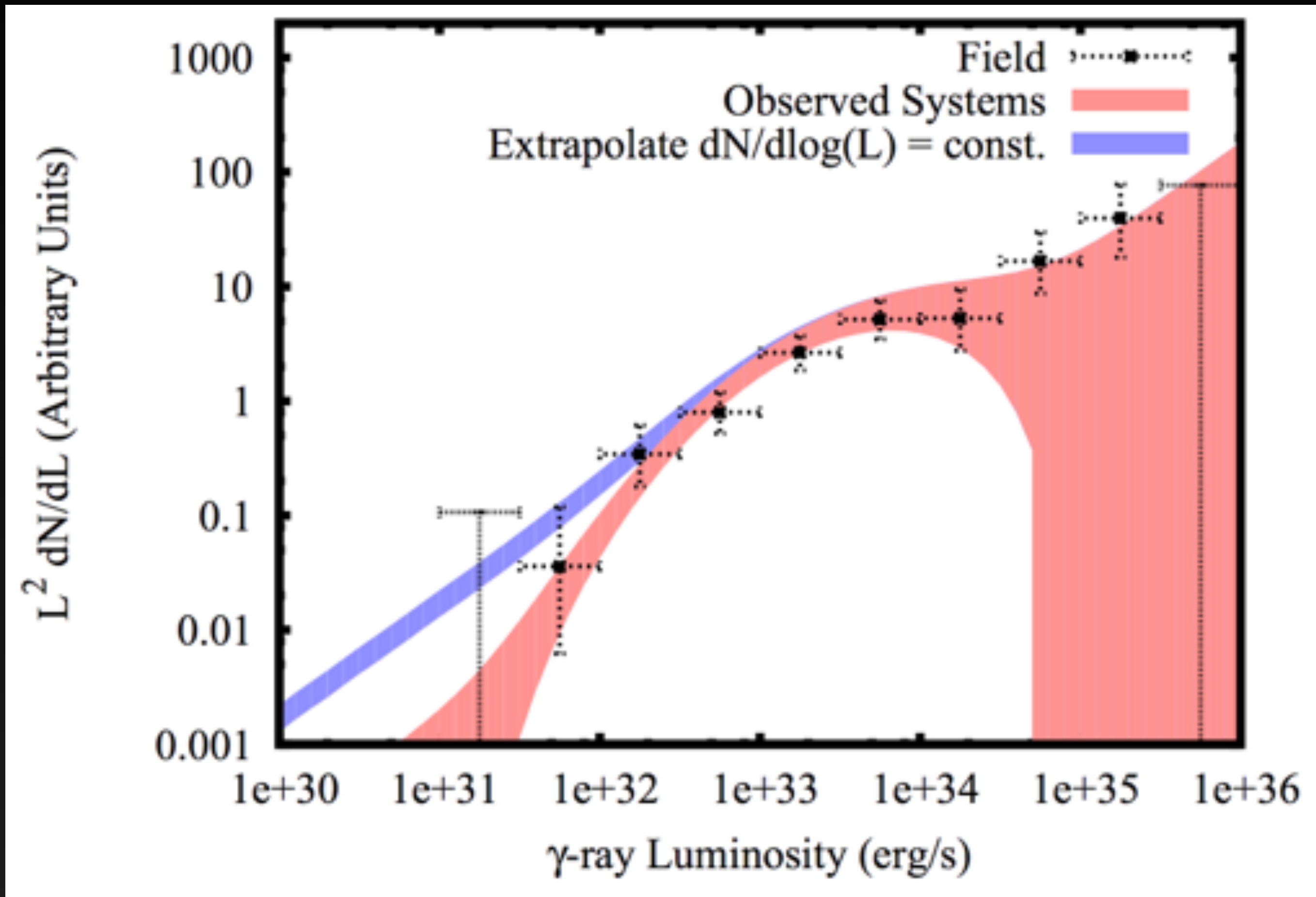


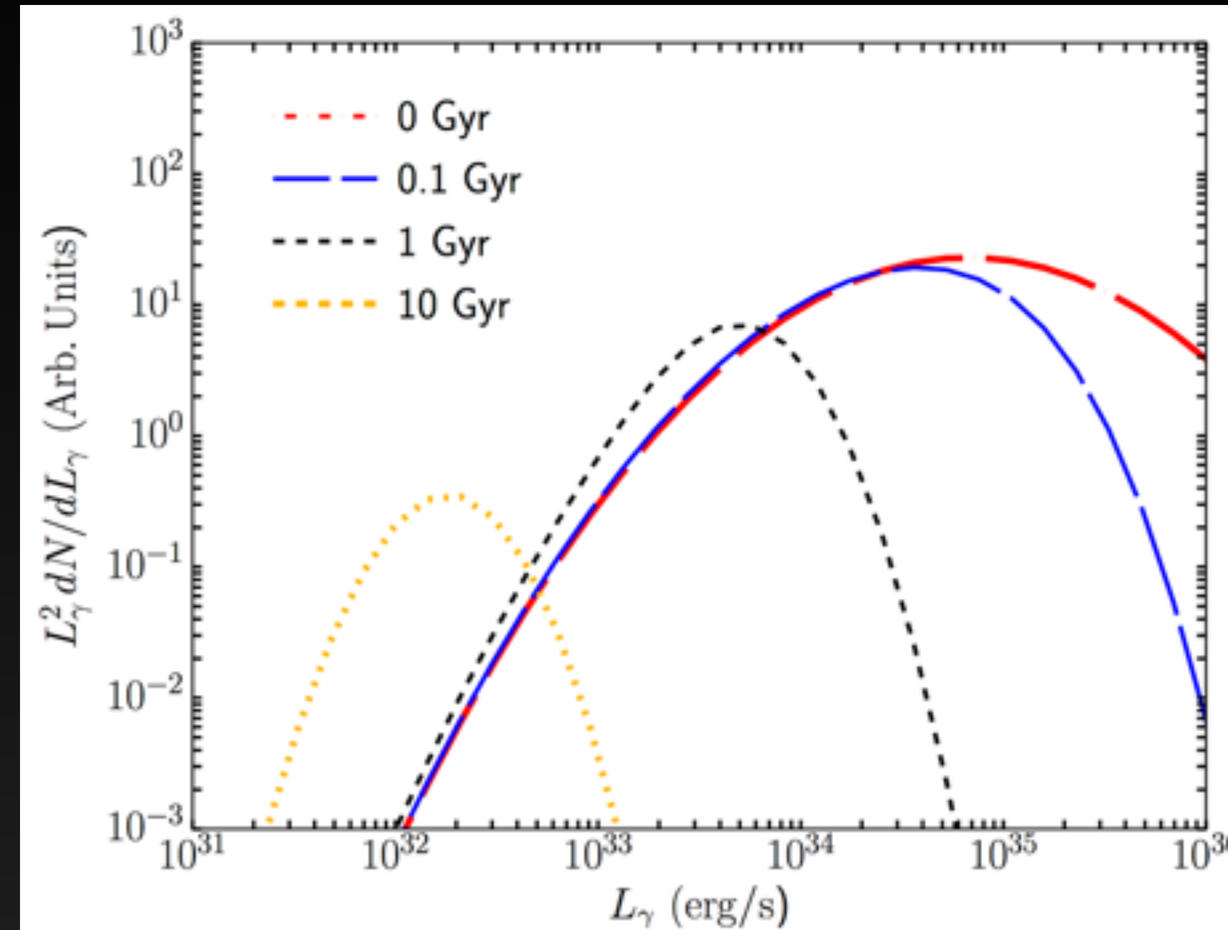
Lee et al. (2015)



- **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)

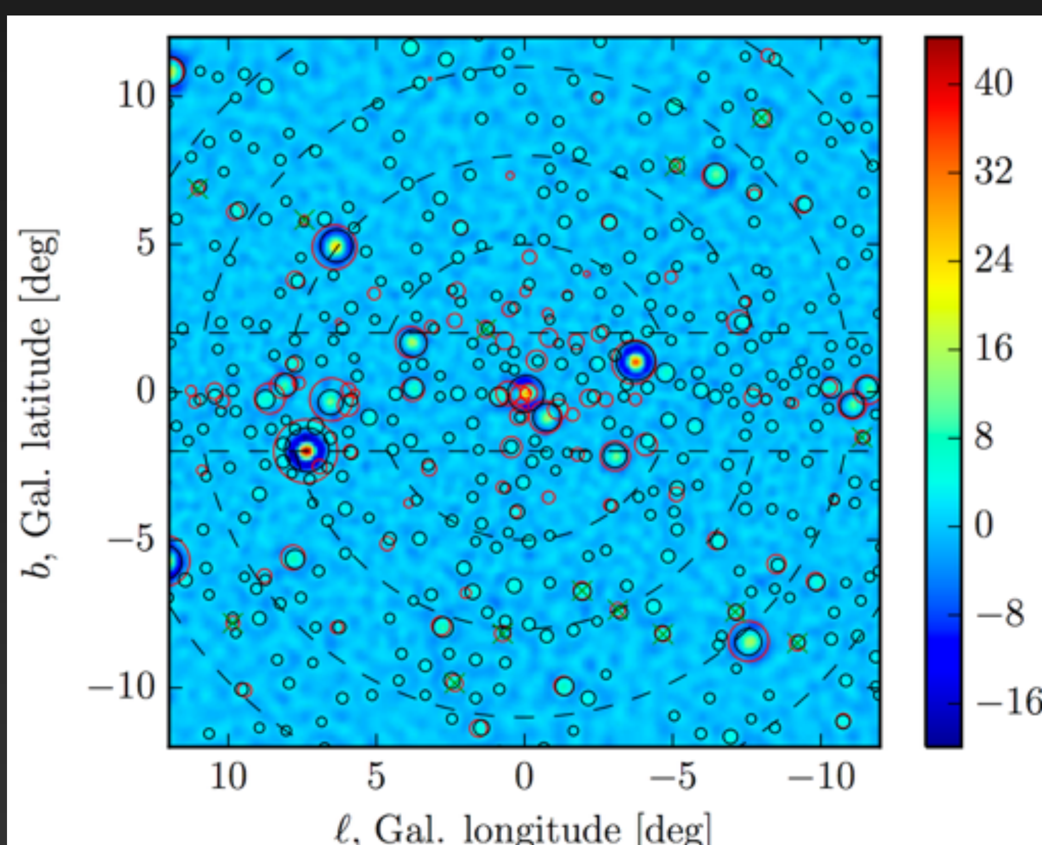
- Evolving the pulsars (compared to the replenished field population) decreases the number of bright pulsars, but requires too many systems to explain the total luminosity. (Hooper & TL 2016)

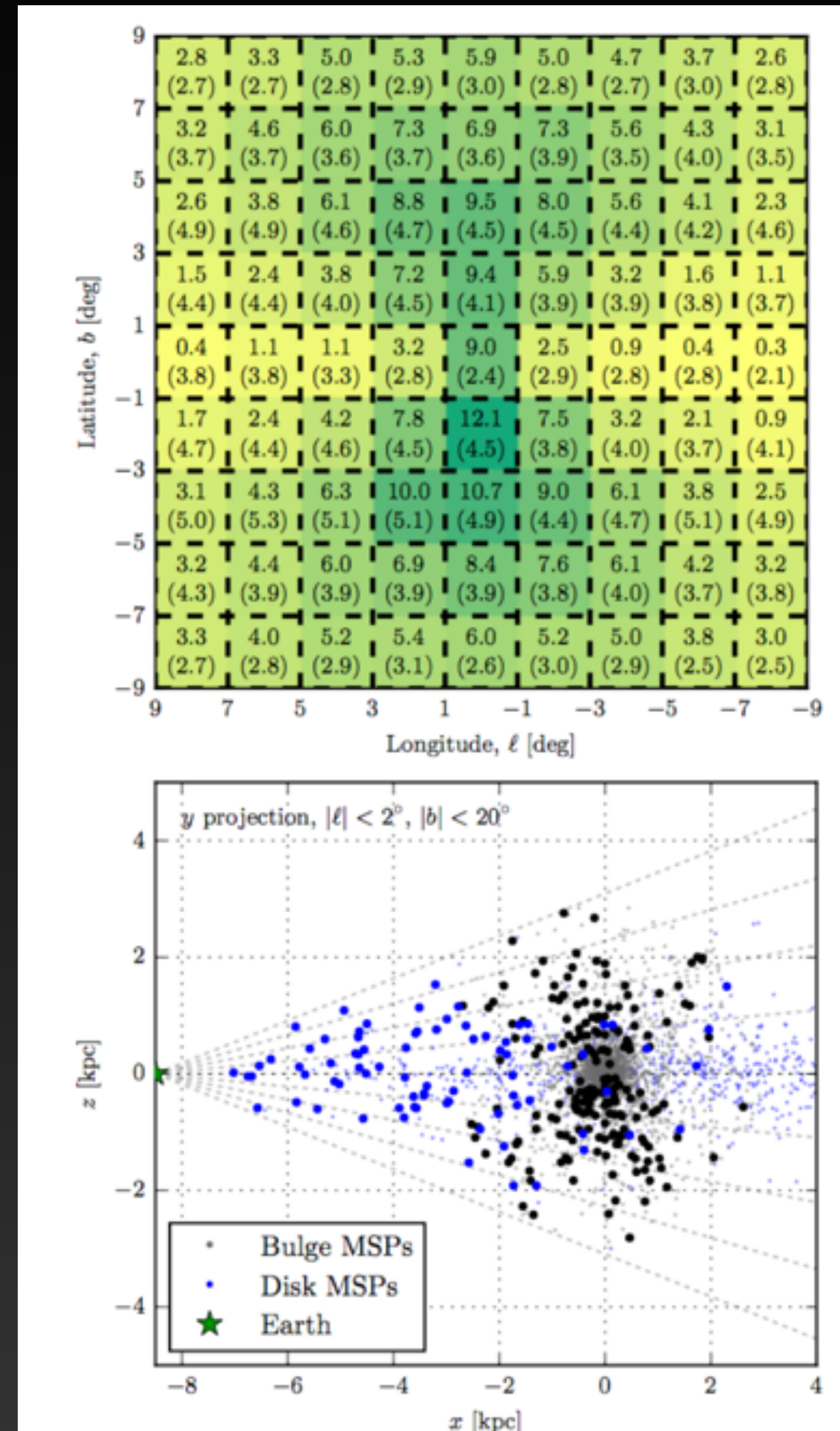
Pulsars

Calore et al. (2015)

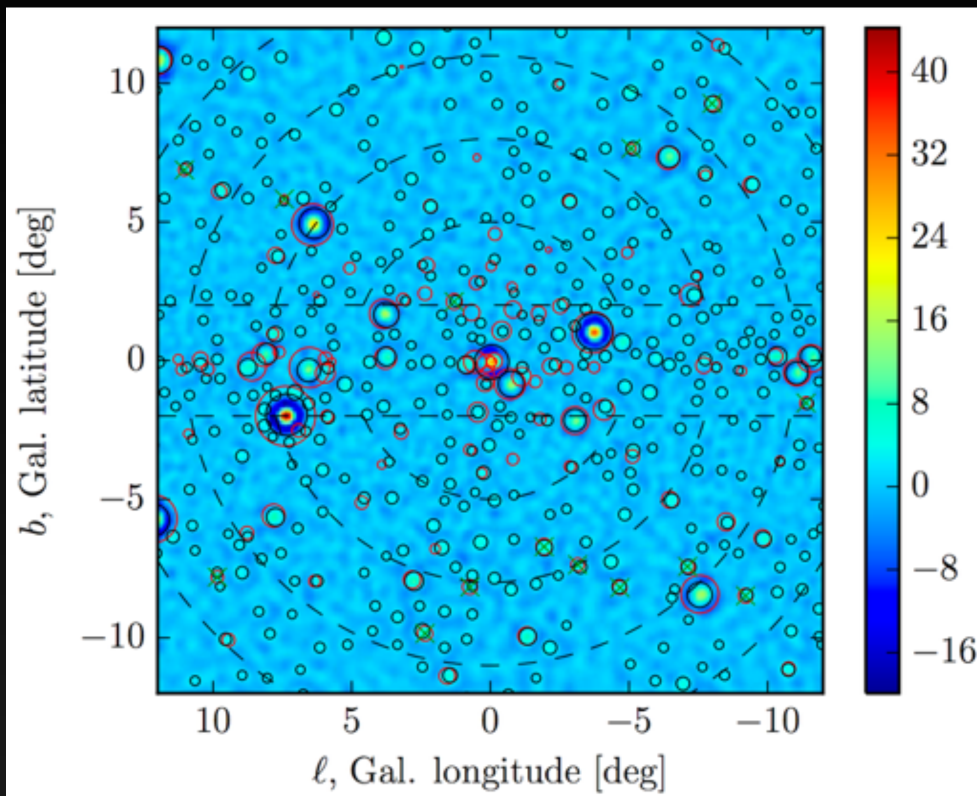
- Radio Observations with GBT targeted at gamma-ray hotspots would be expected to find ~5-10 MSPs with a 200 hr commitment.

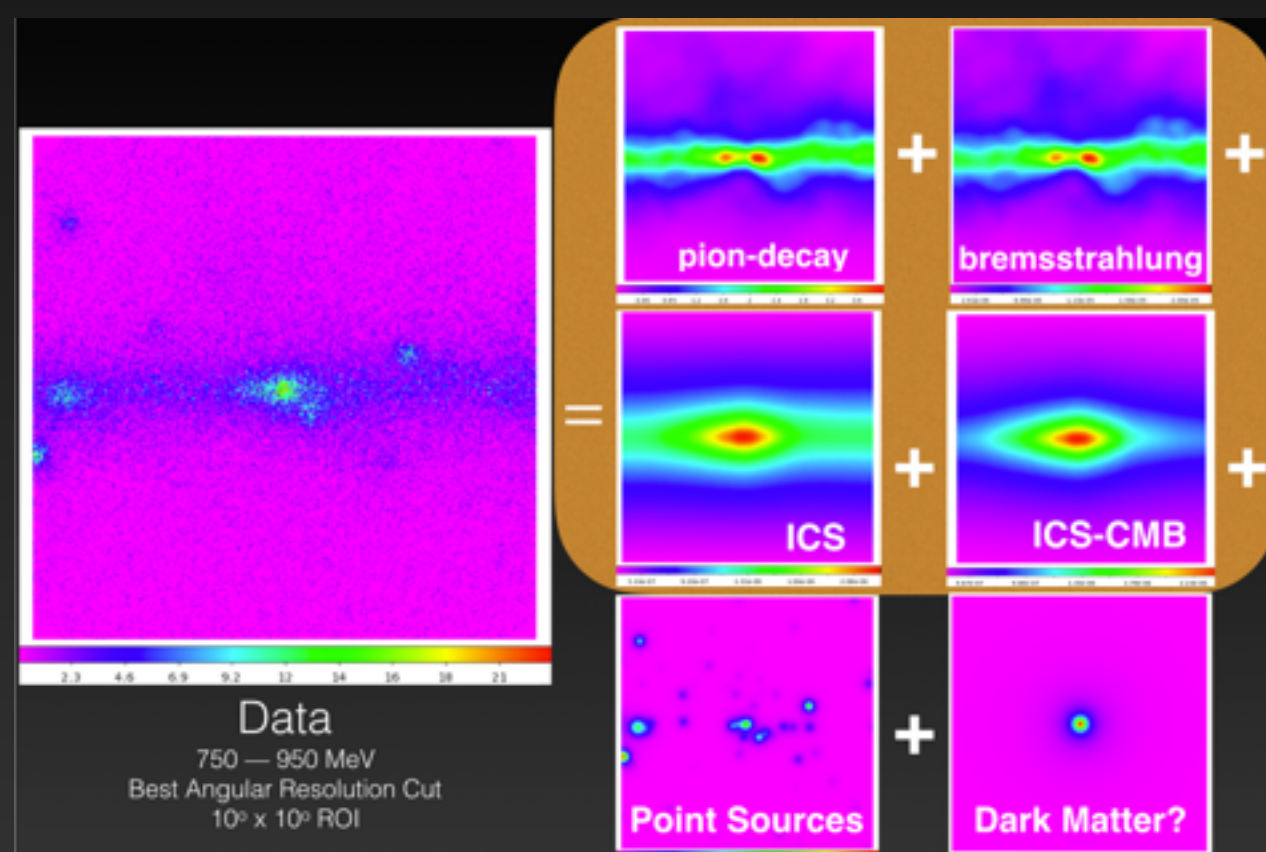
- Fortunately, SKA observations are likely to conclusively find MSPs in the GC, or rule out this scenario.



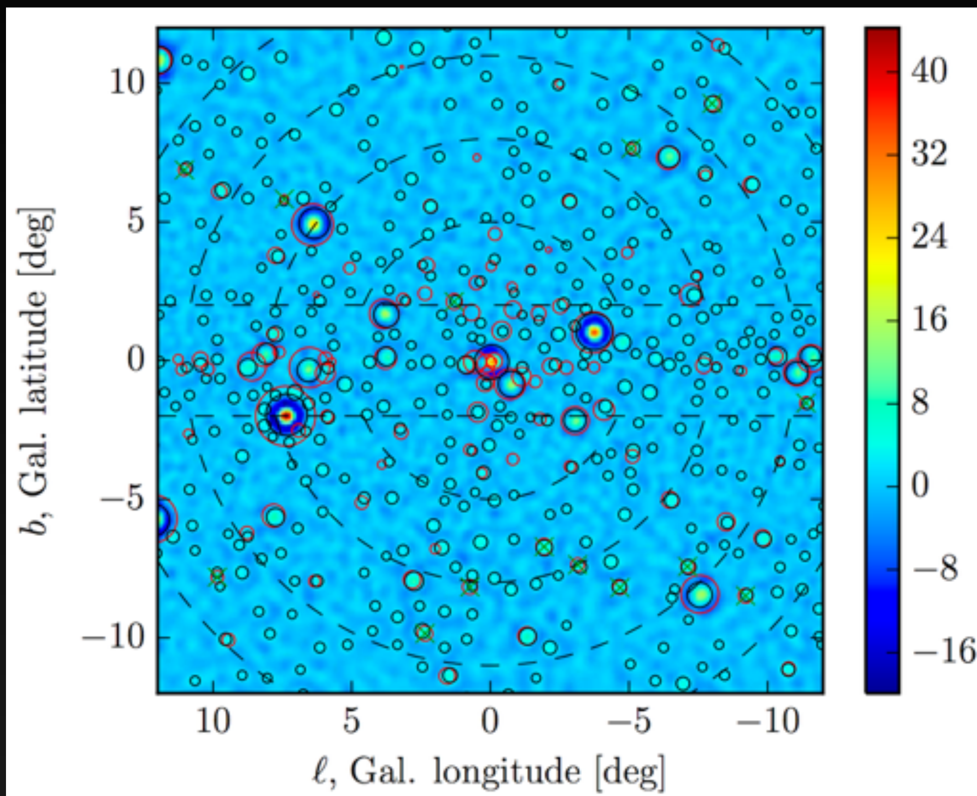


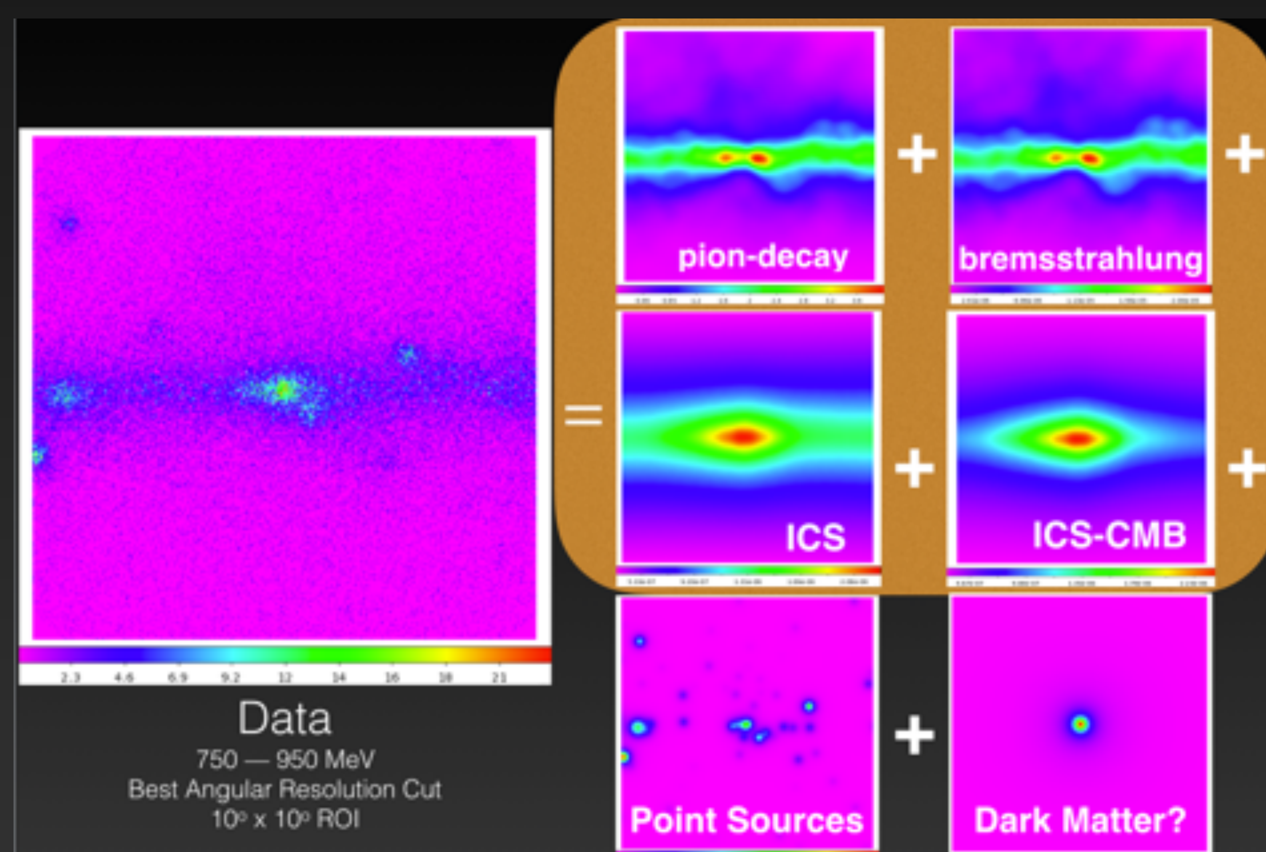
Proving the Pulsar Interpretation





Can this be proven in the negative?

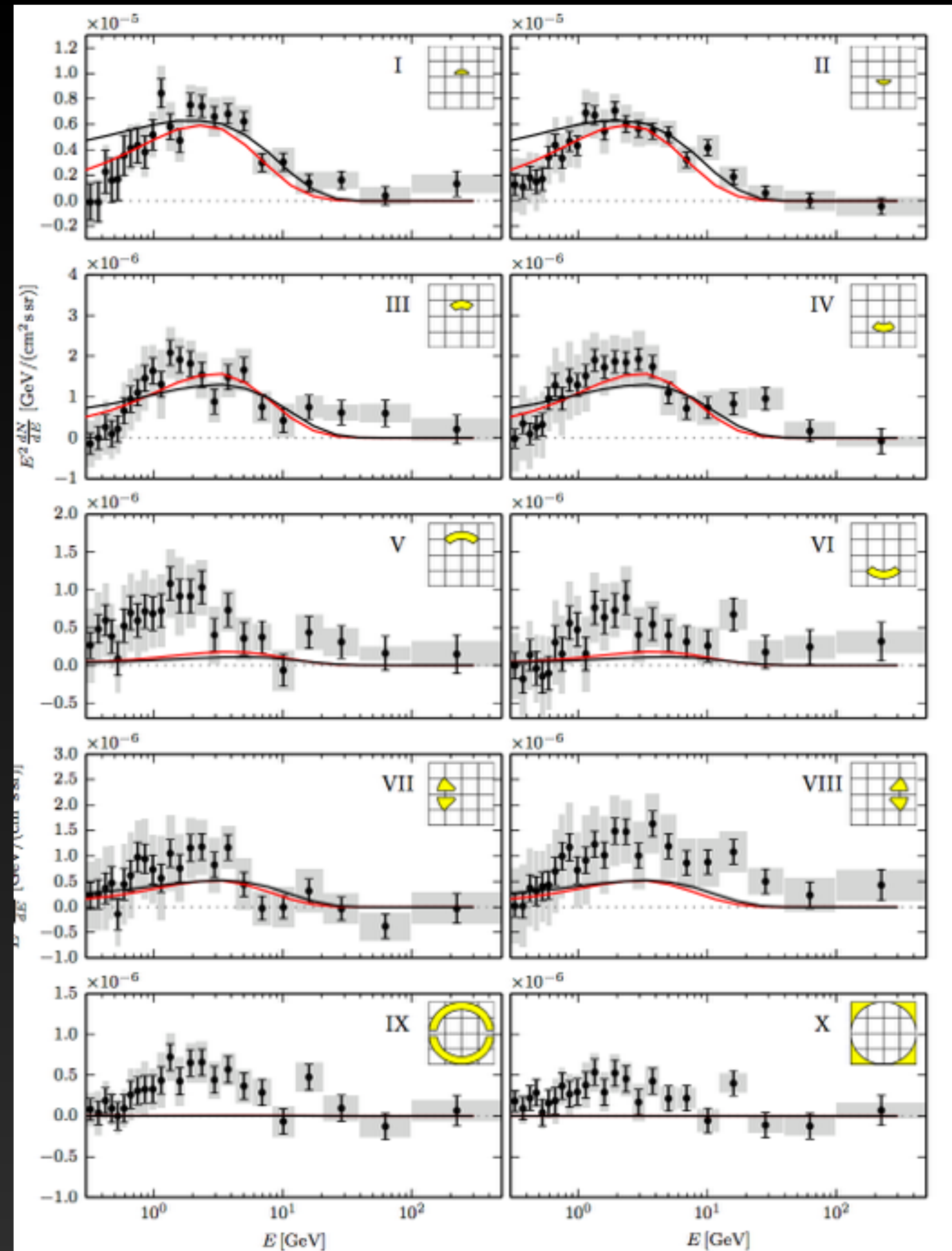




Leptonic Outbursts

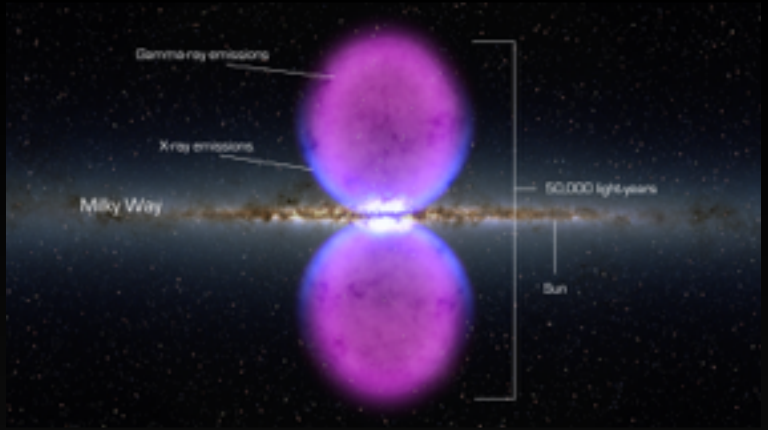
So far, we have only considered steady-state diffuse emission scenarios - but the Galactic center is unlikely to be in steady state (e.g. Fermi bubbles).

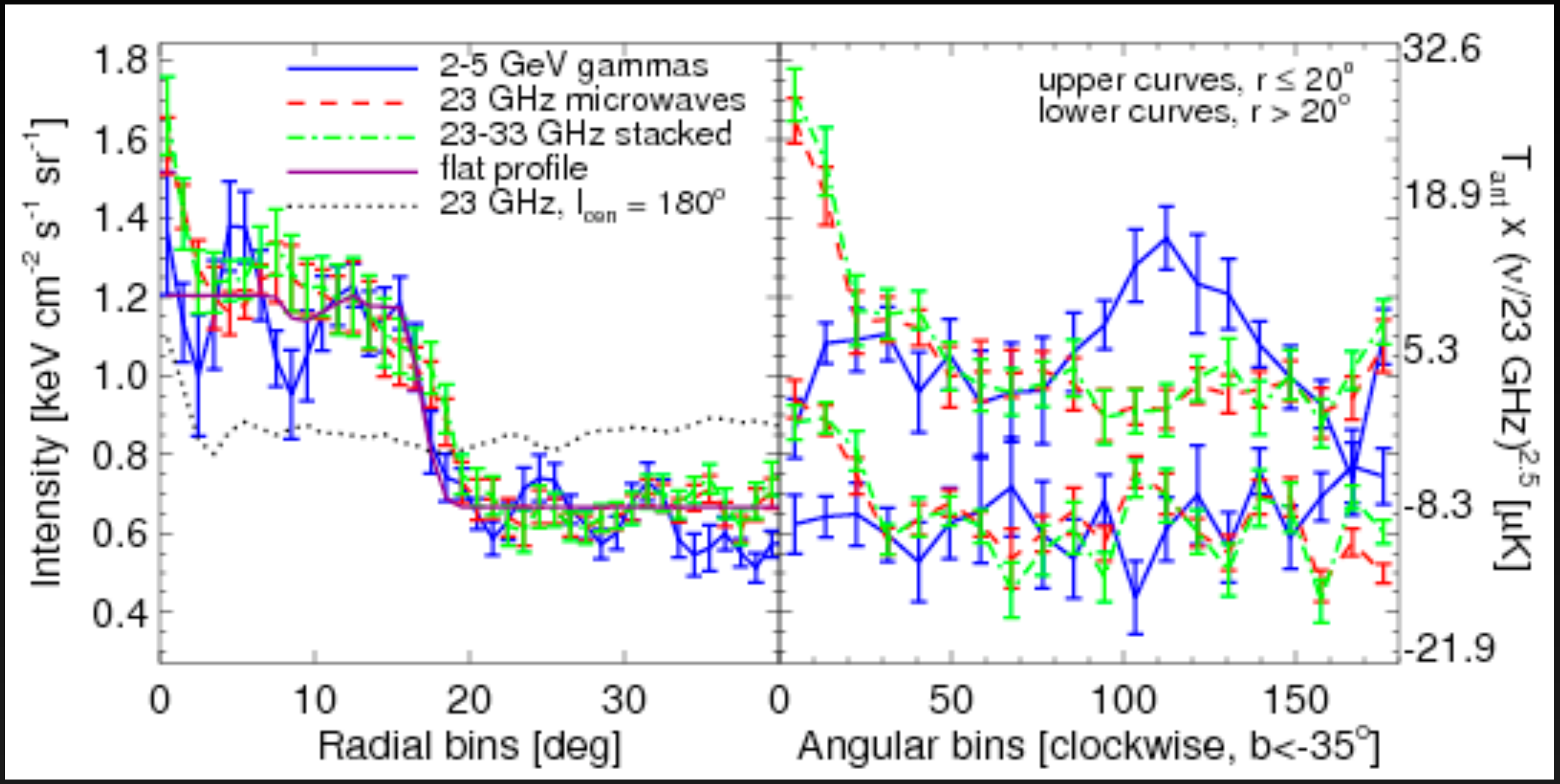
An outburst of leptonic (or possibly hadronic) origin can also produce the gamma-ray excess, but only if the injected electron spectrum is extremely hard (compared to observed blazar spectra).



Cholis et al. (2015, 1506.05119)

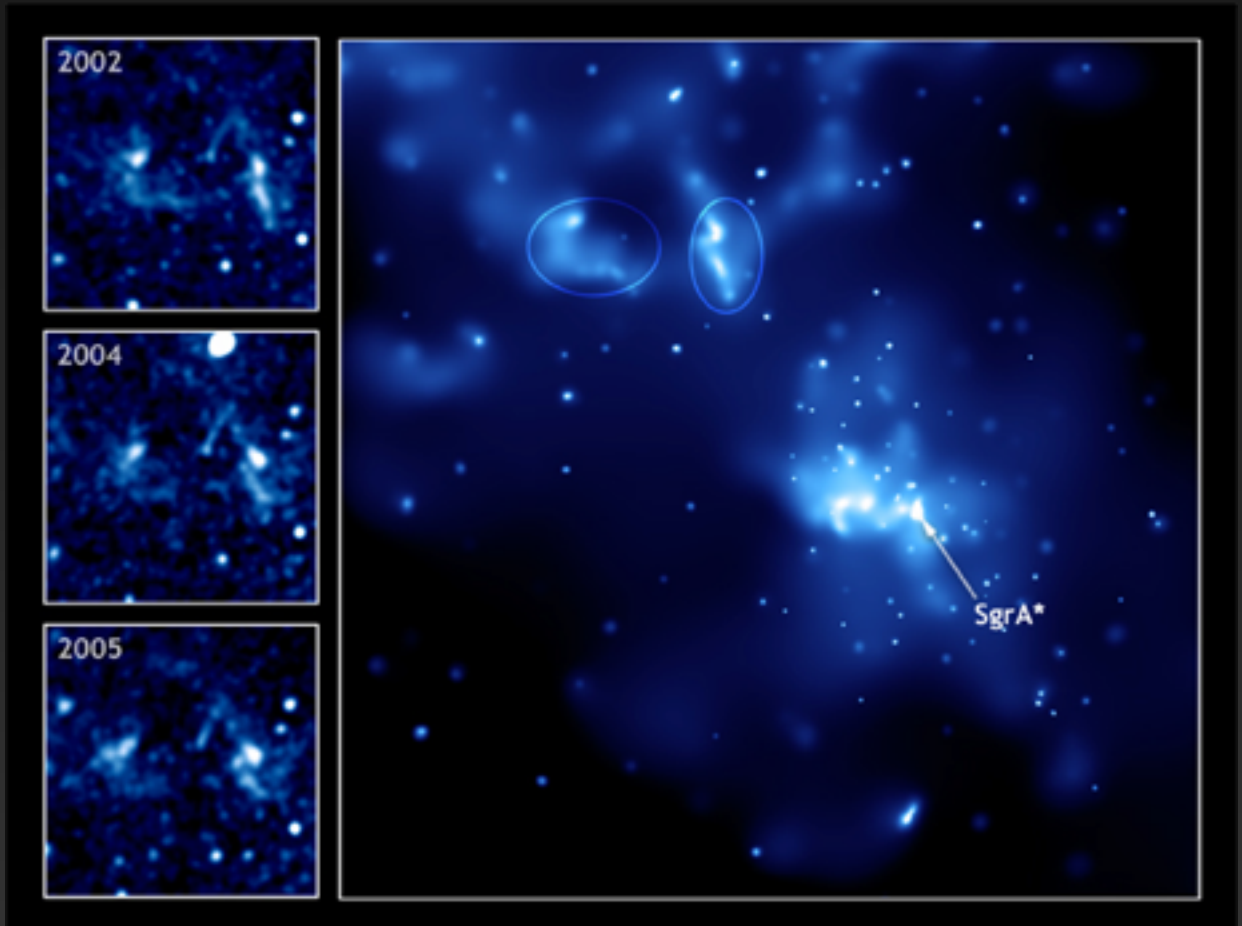
Proving an Outburst Interpretation





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

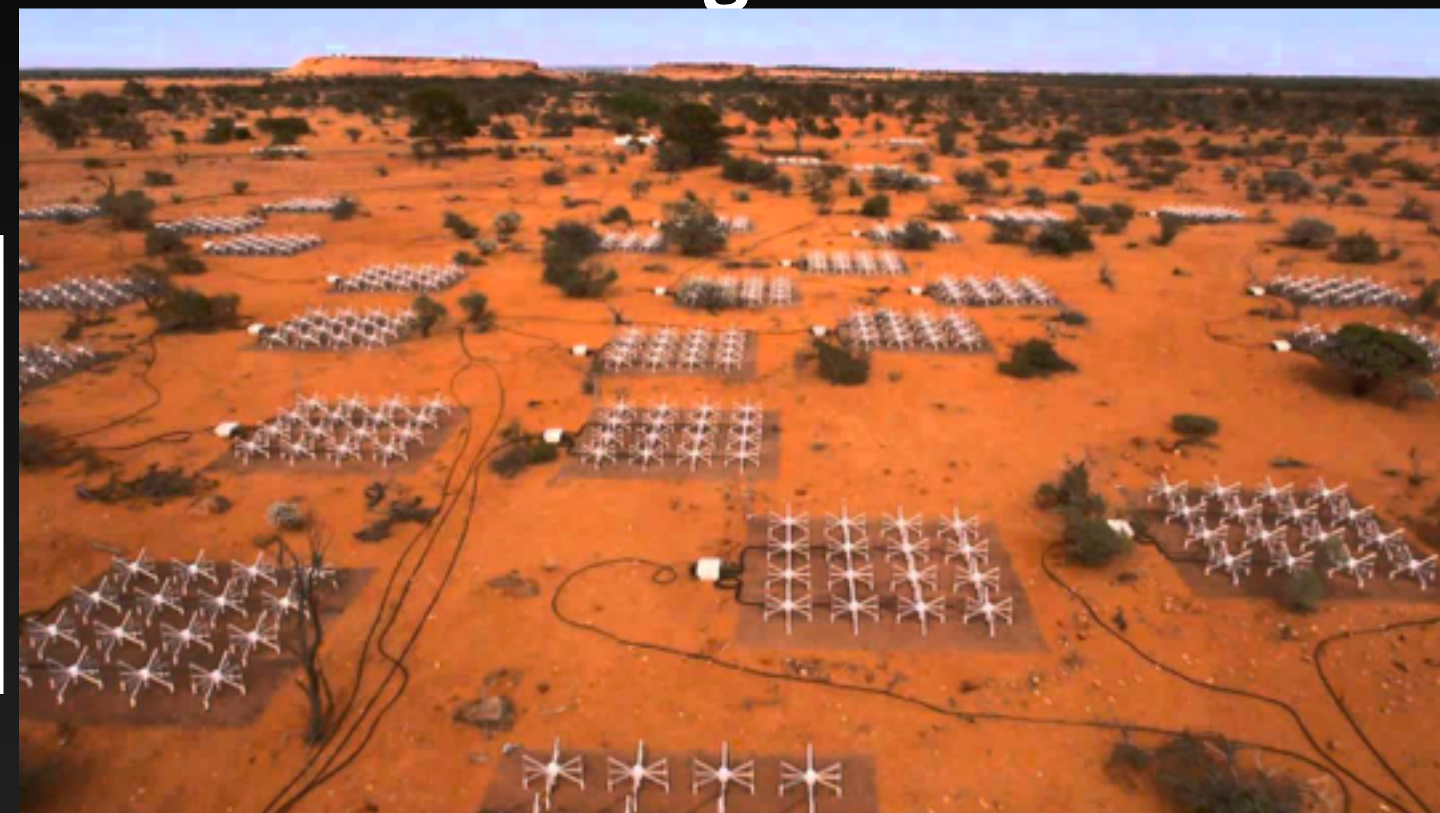
Is a similar cross-correlation (e.g. with X-Ray data) possible?



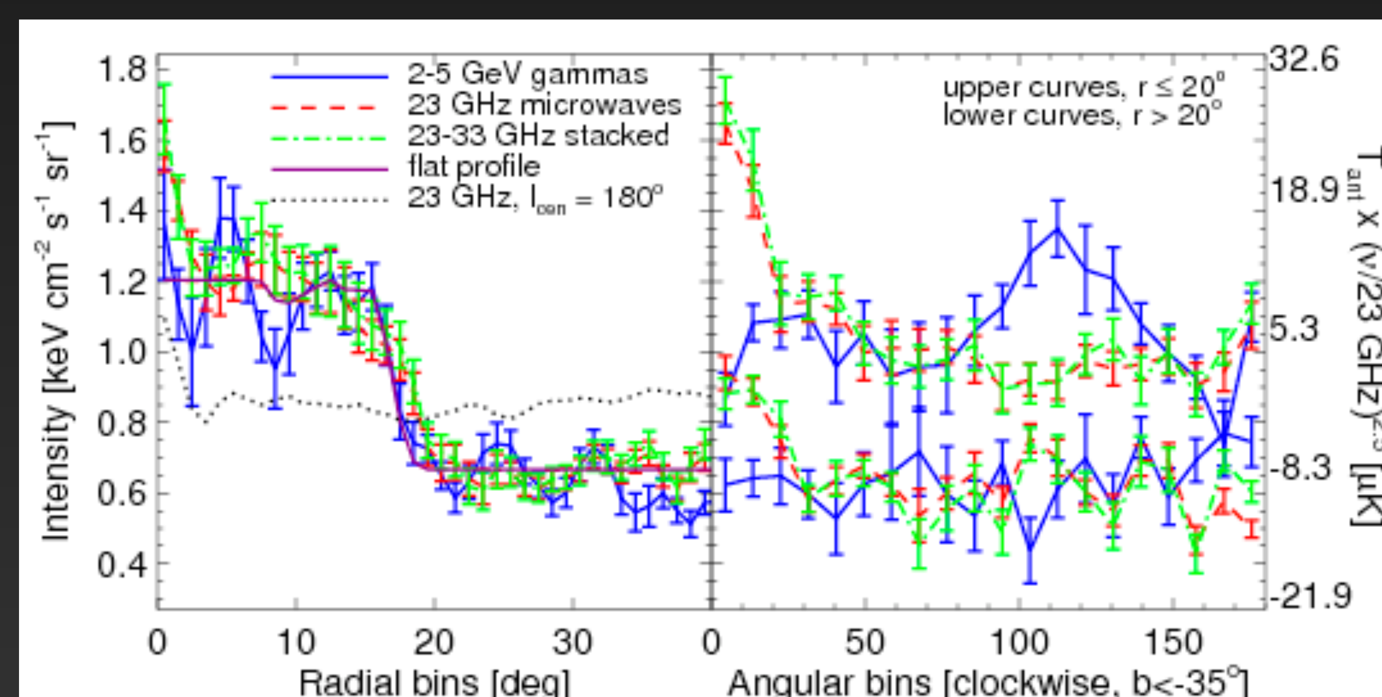
Can Outbursts be Ruled Out?

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

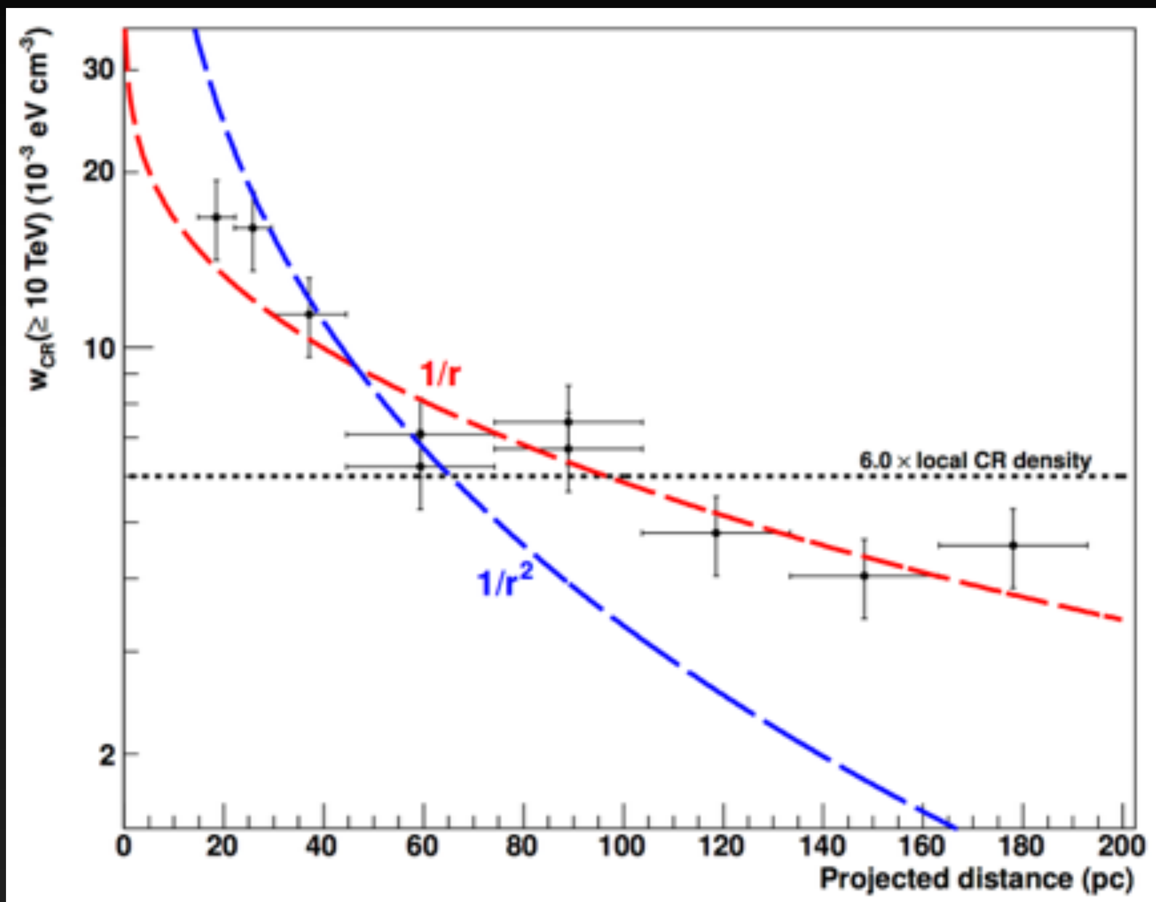
$$\left.\frac{F_{\rm radio}}{F_\gamma}\right|_{\rm DM} = \frac{B_e\left(\frac{\rho_B}{\rho_B+\rho_{\rm rad}}\right)}{B_e\left(\frac{\rho_{\rm rad}}{\rho_B+\rho_B}\right)+B_\gamma}$$

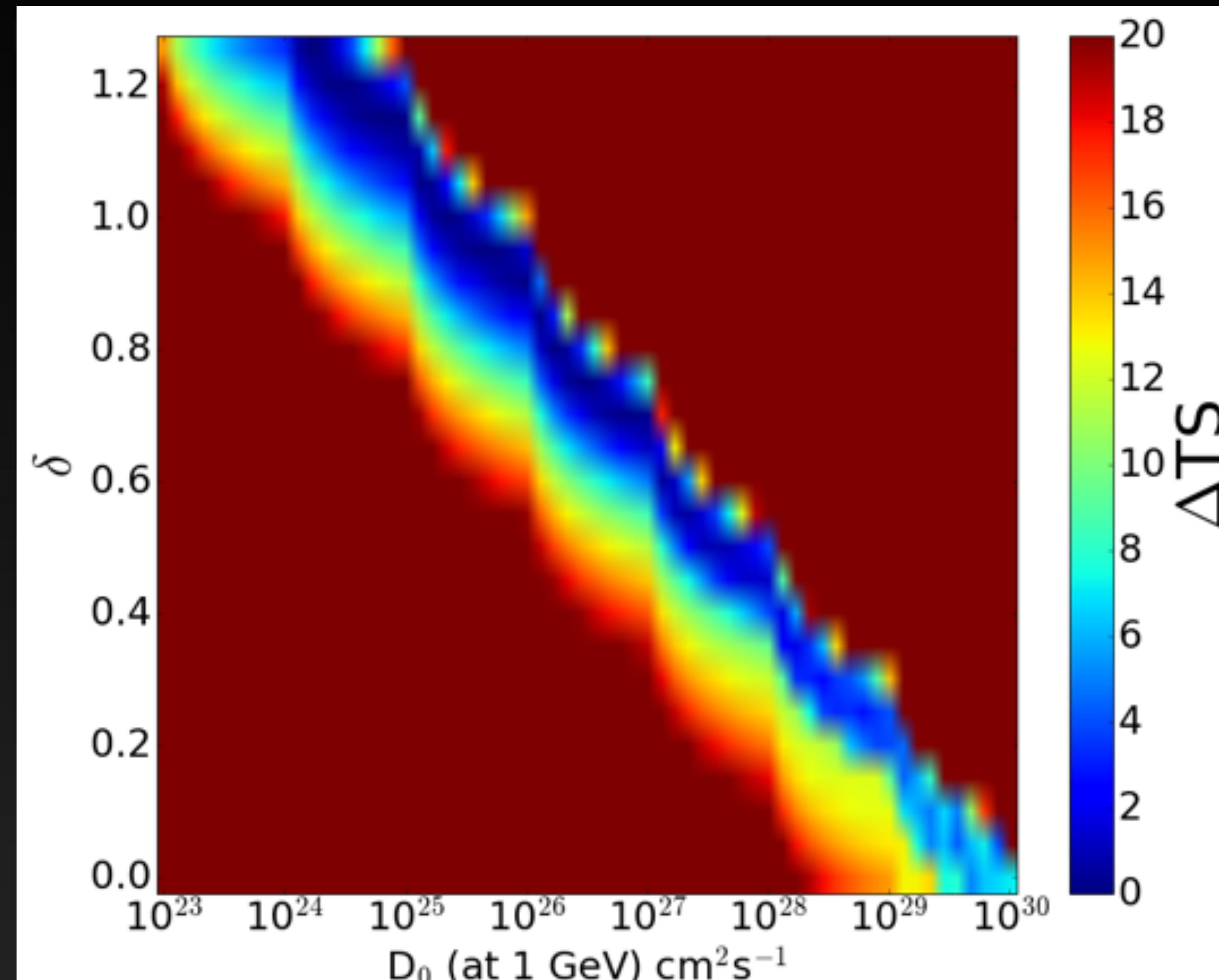


Enhanced measurements of the low-energy synchrotron signal at the Galactic center may rule out any associated synchrotron flux.



Diffuse Emission Models of the Galactic Center



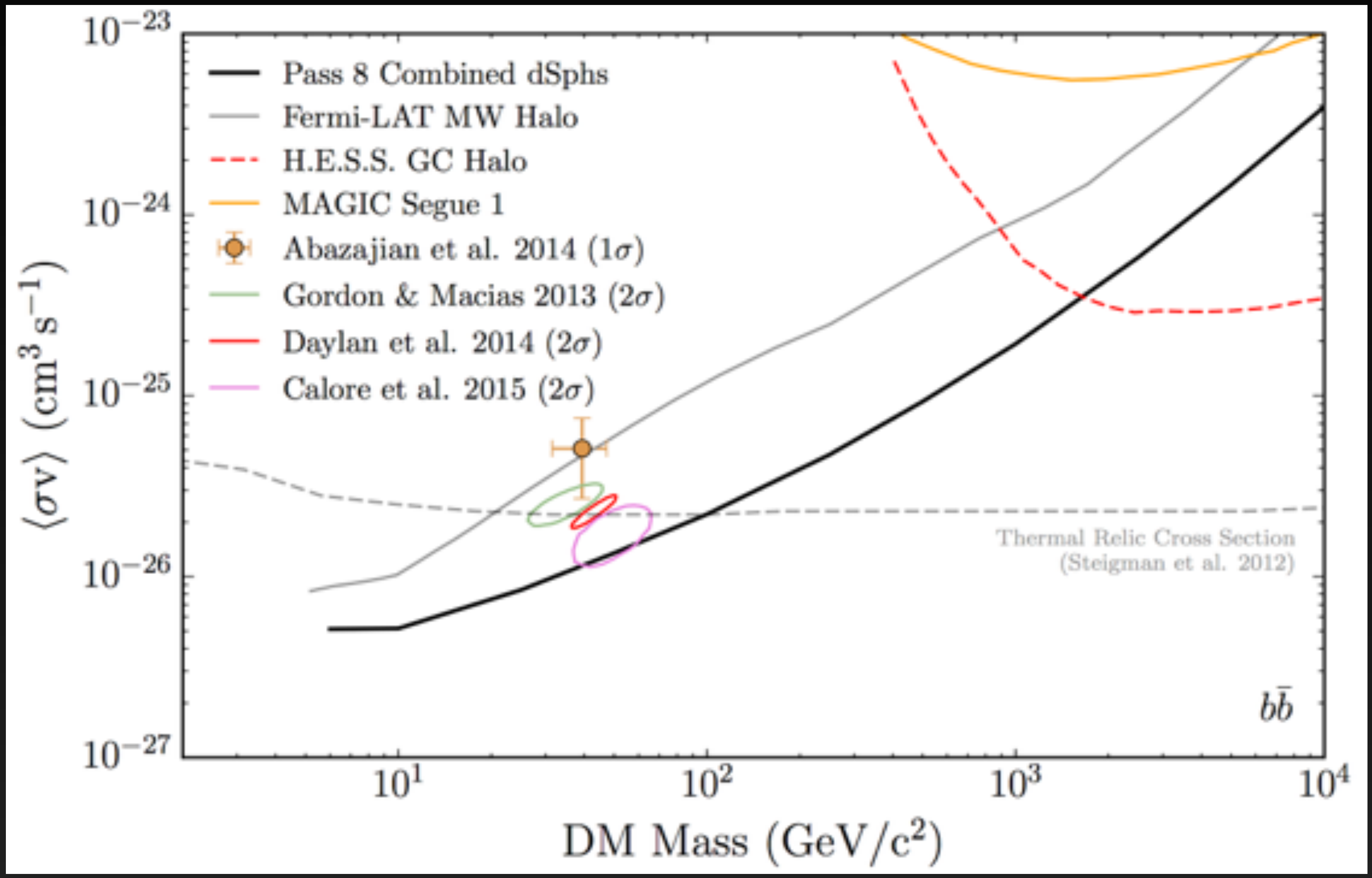


Li, Linden (in prep)

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).

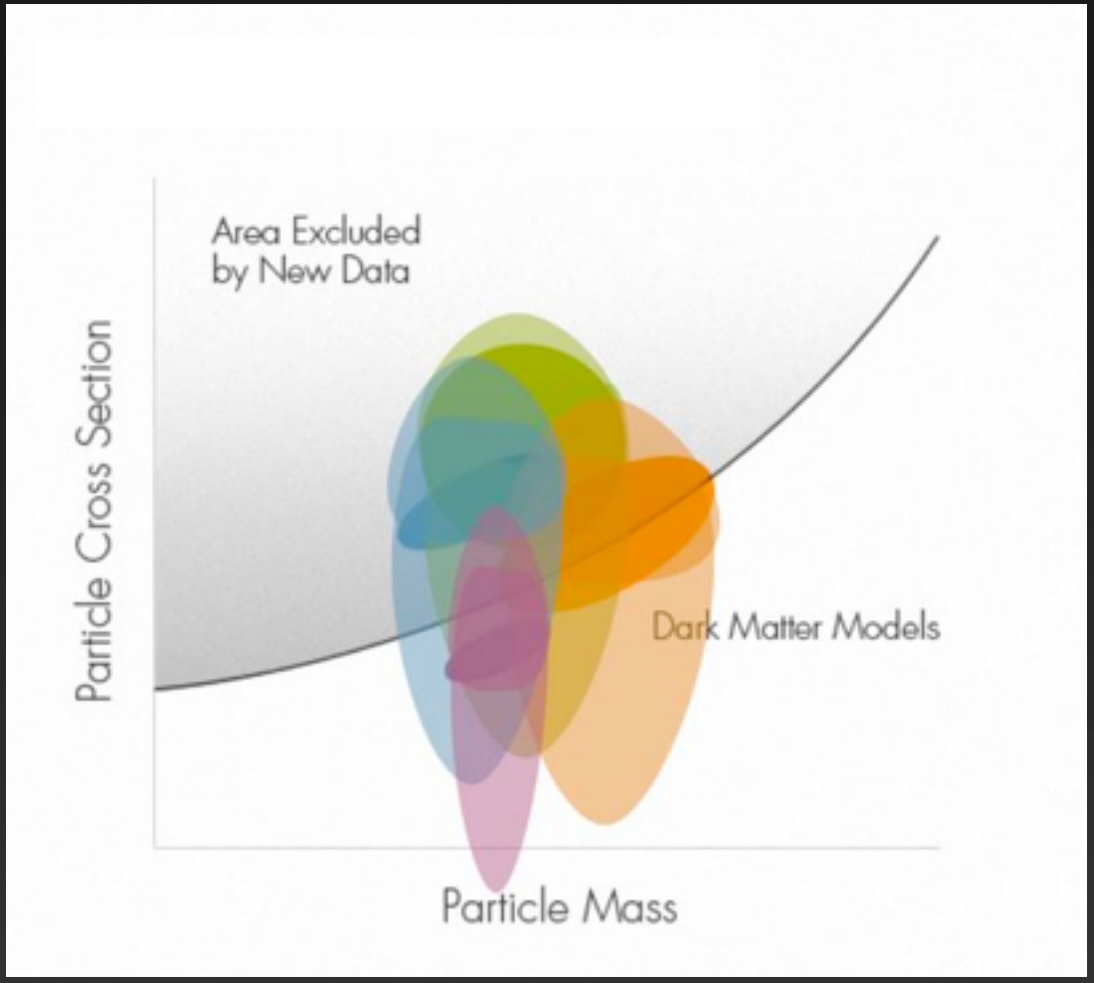
Comparison to Dwarf Constraints

Ackermann et al. (2015)



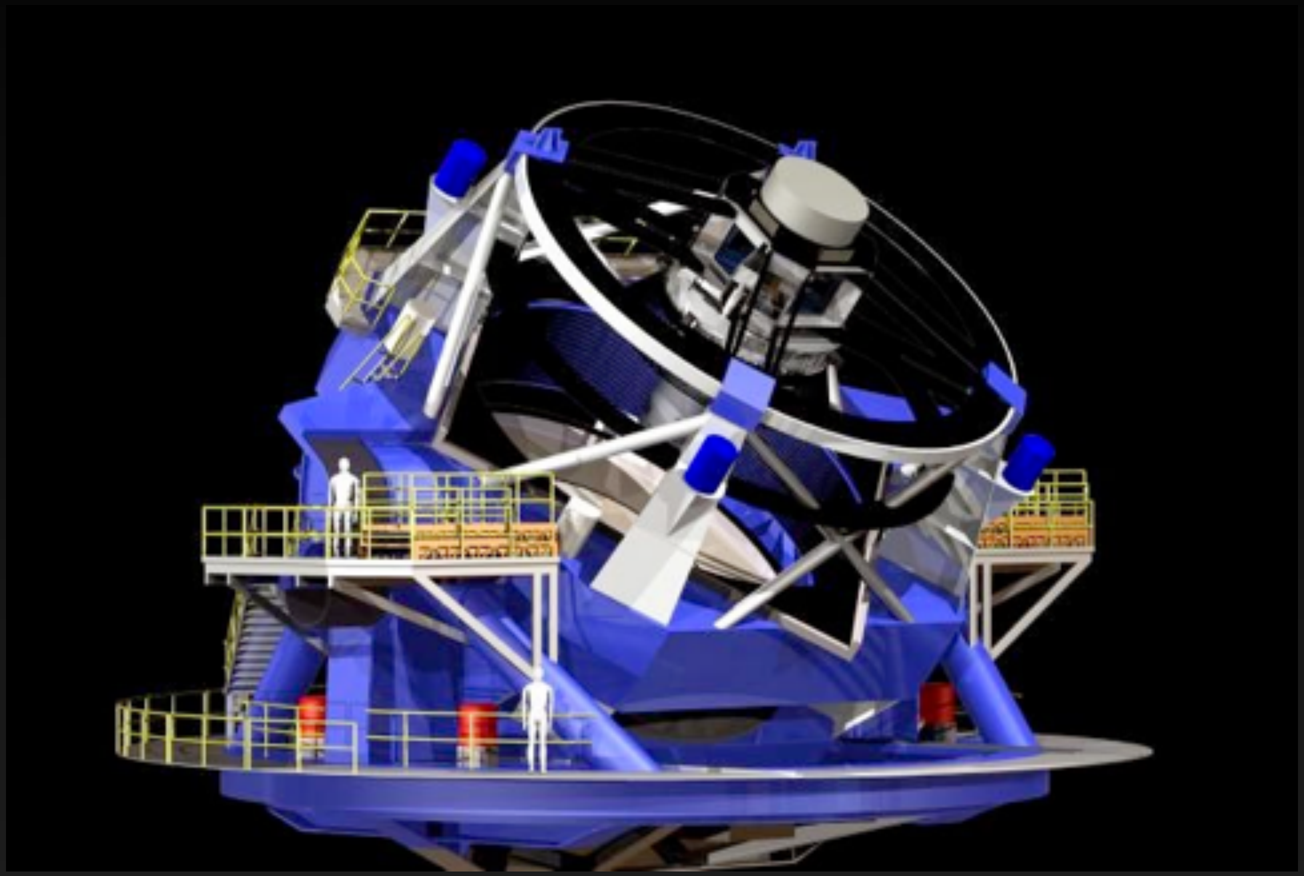
Constraints from dSphs are statistically in 1-2σ tension with the GC excess.

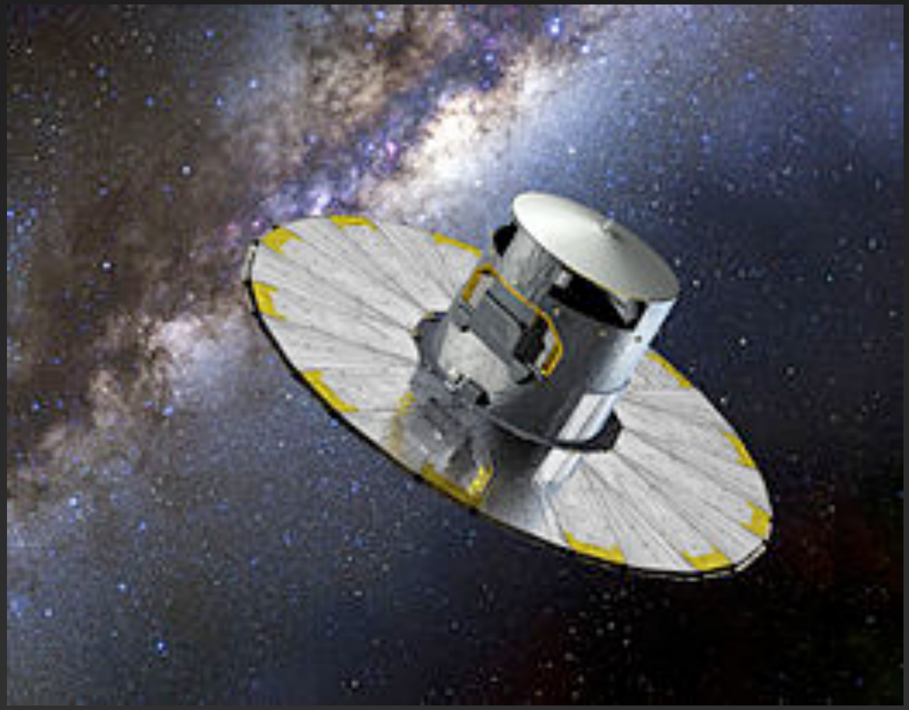
However, uncertainties in the dark matter density profile can easily resolve this tension.

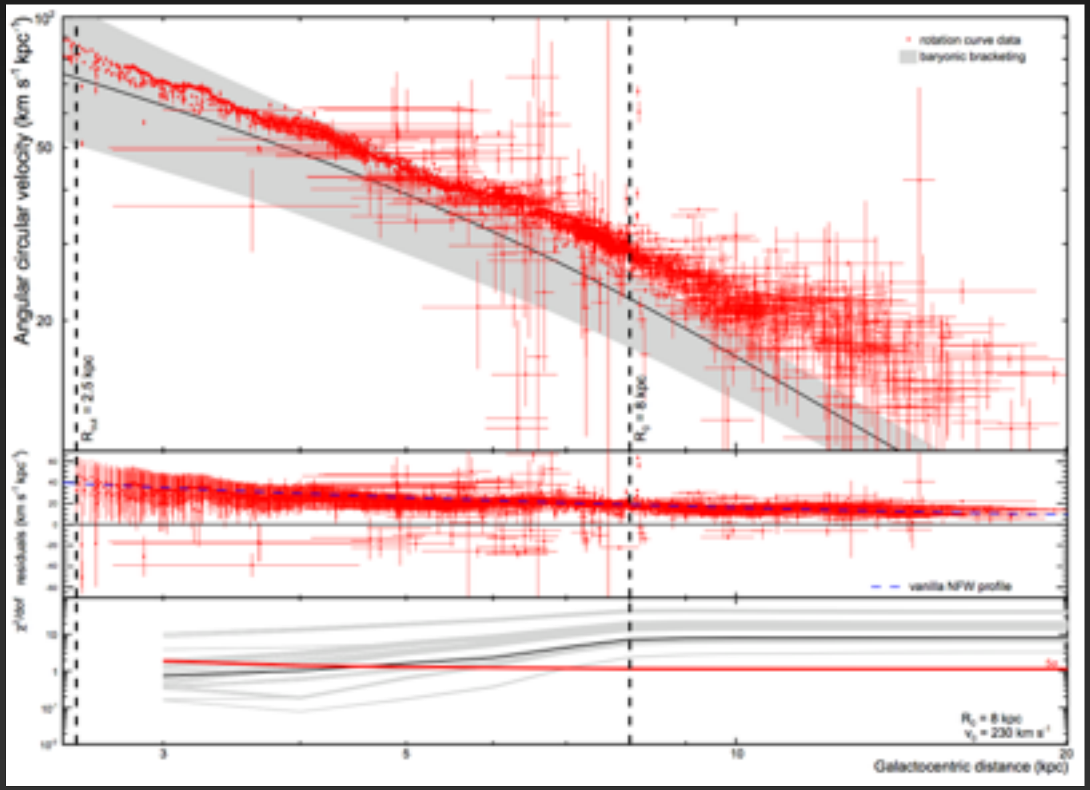


credit: Kev Abazajian (2015)

Comparison to Dwarf Constraints



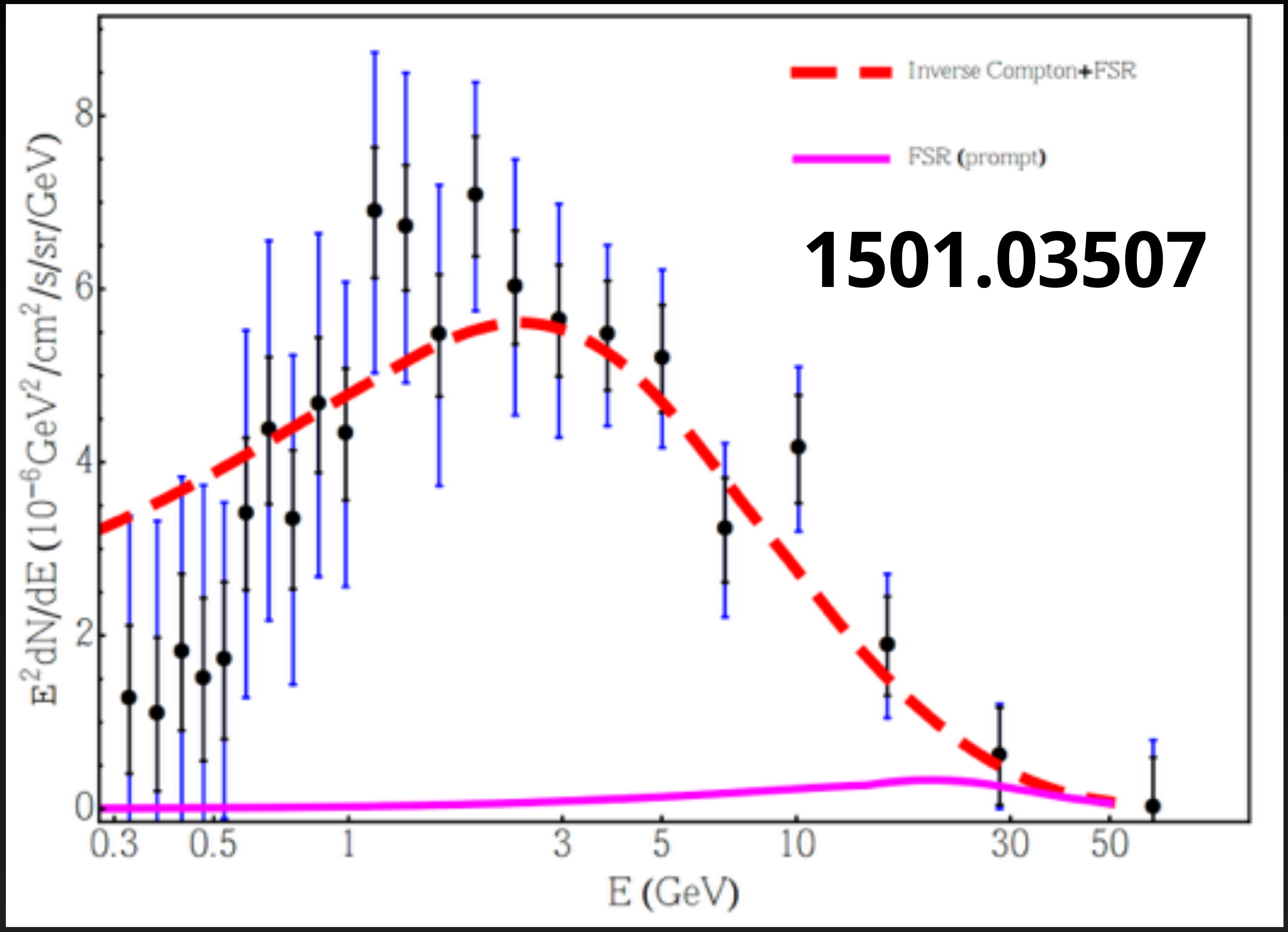




Comparison to Dwarf Constraints

Theorists can fit any set of observations with sufficiently complex models...

e.g. A model where dark matter annihilates to e+e- pairs can reproduce the characteristics of the GC excess while producing no gamma-ray emission in dwarfs.

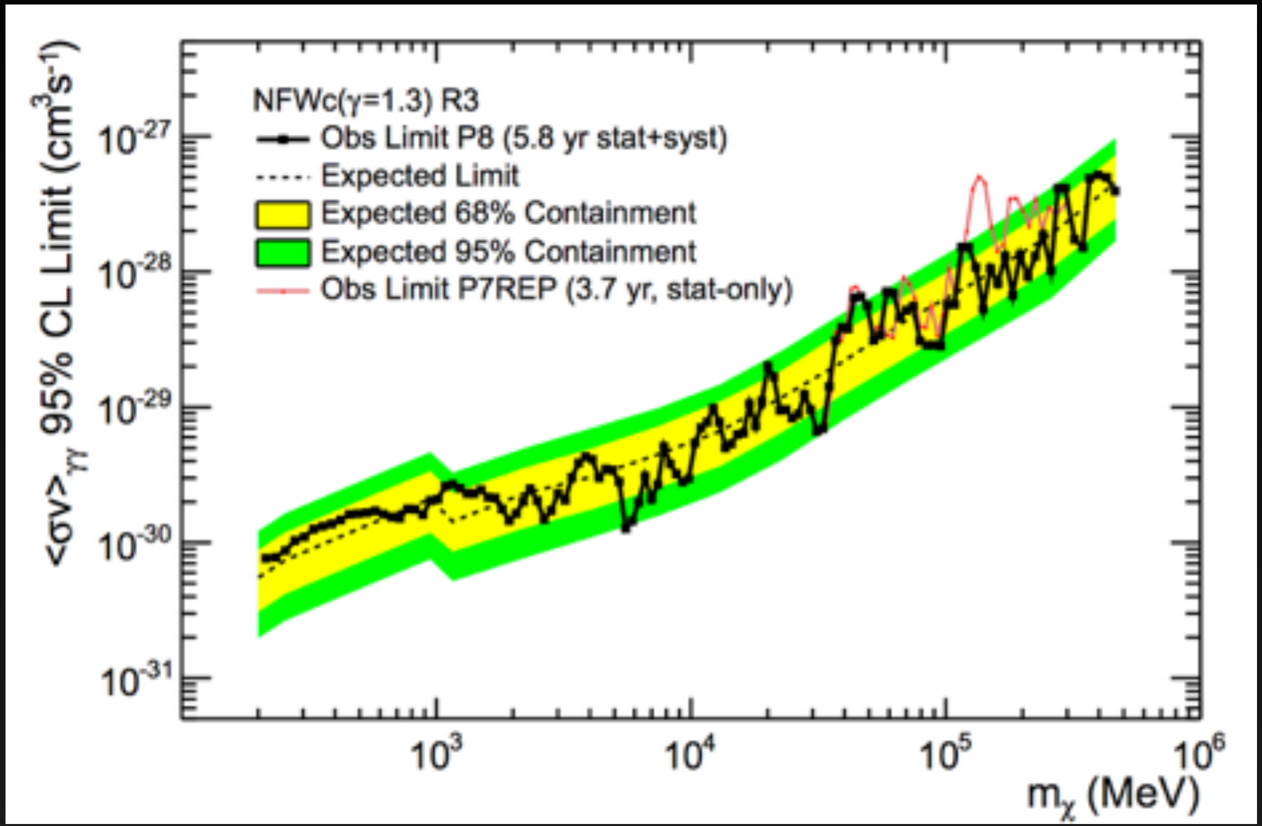


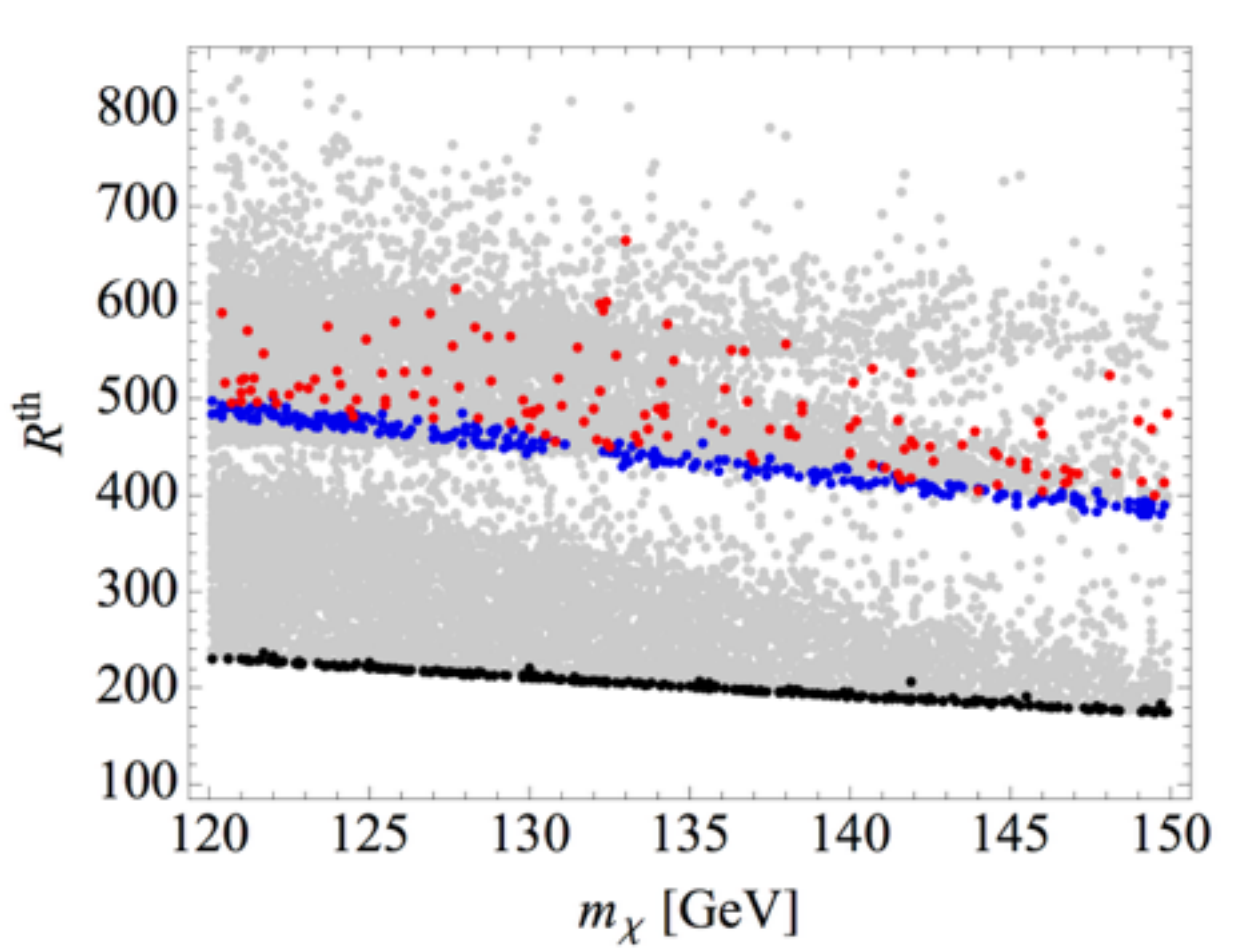
We would like to use GC observations directly to rule out a DM interpretation.

Can DM be Ruled out by GC Observations?

Strong limits exist on the gamma-ray line intensity from the Galactic center.

However different theoretical models predict extremely different line intensities. Unlikely that this can ever constrain DM continuum emission.

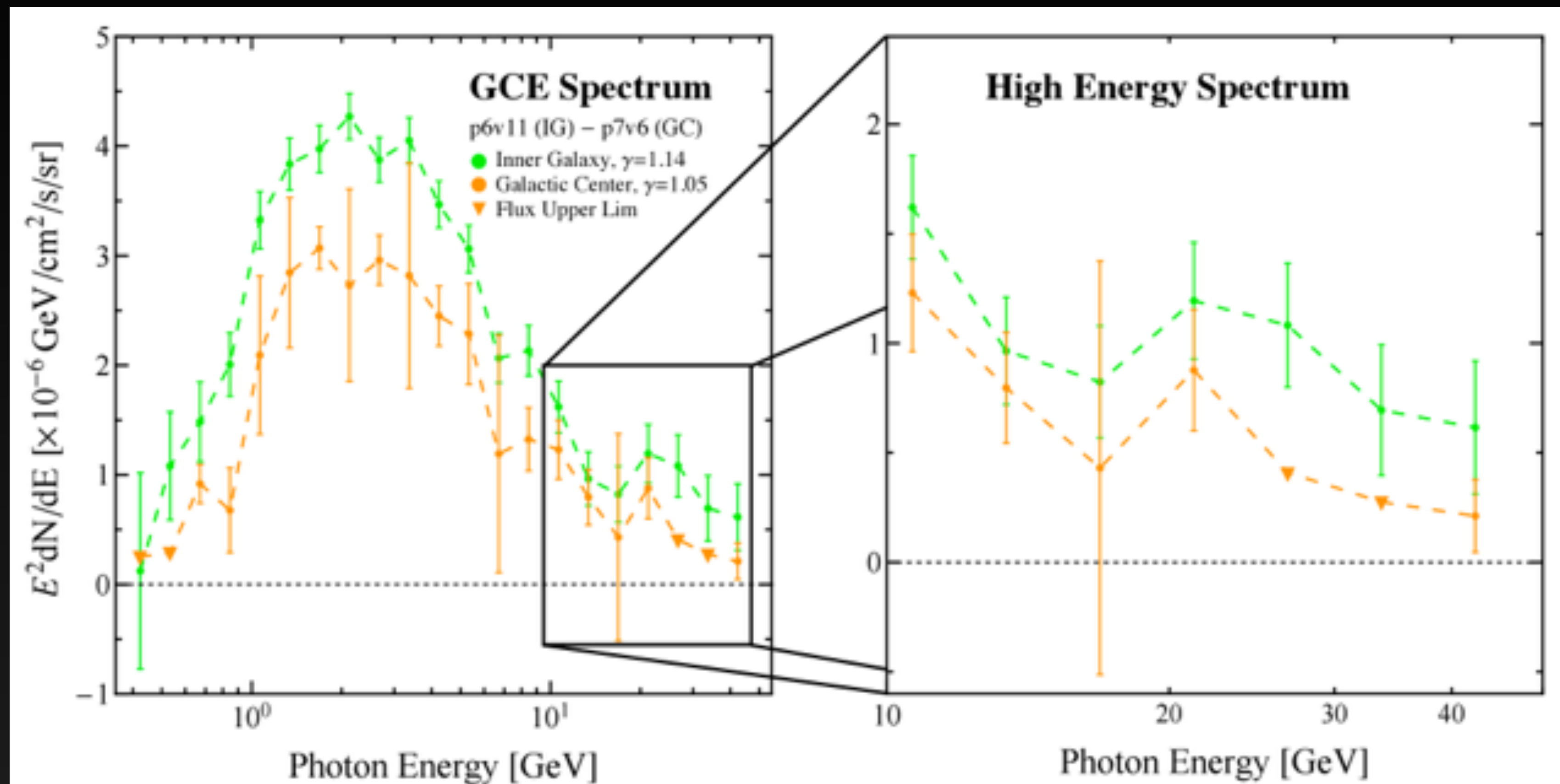


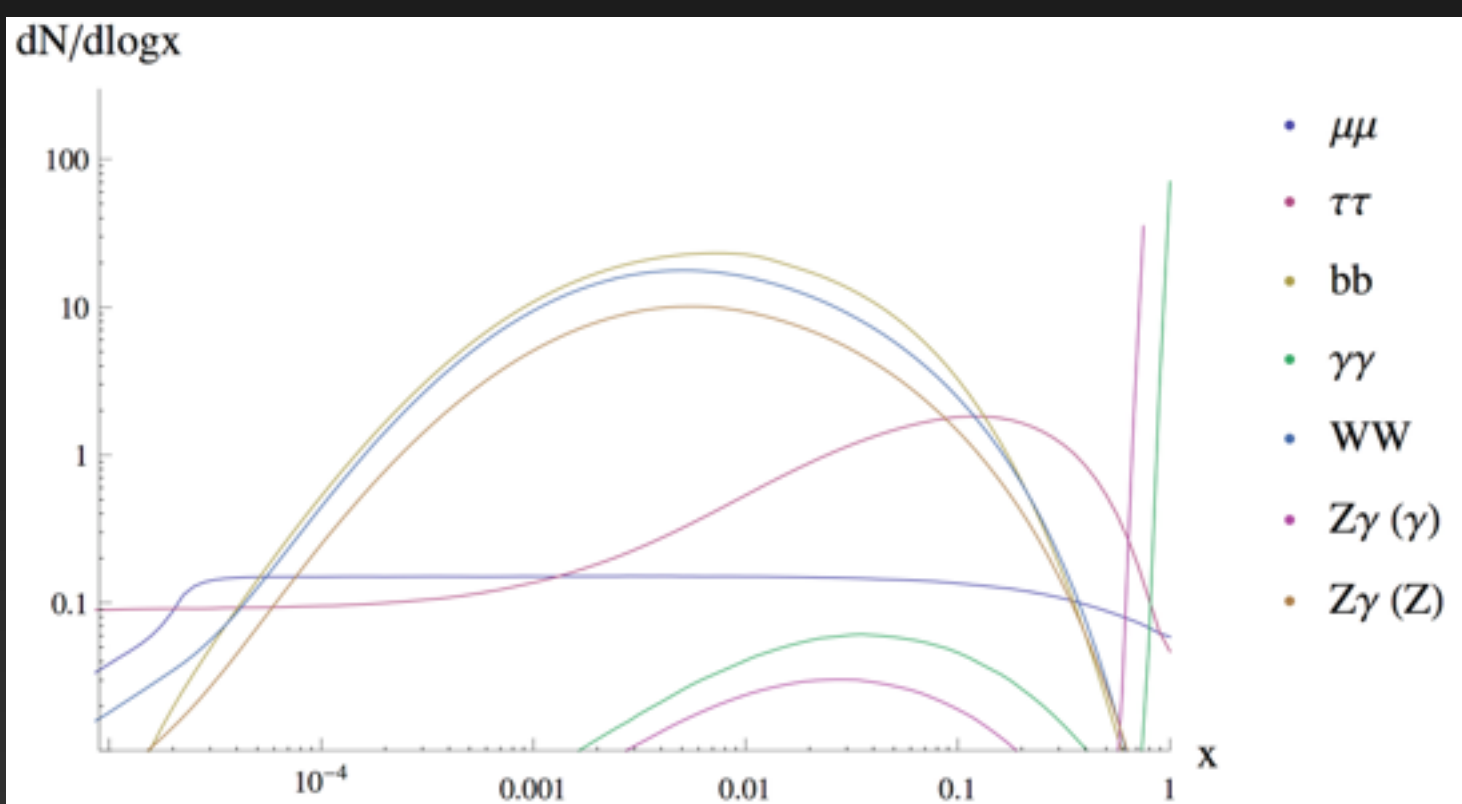


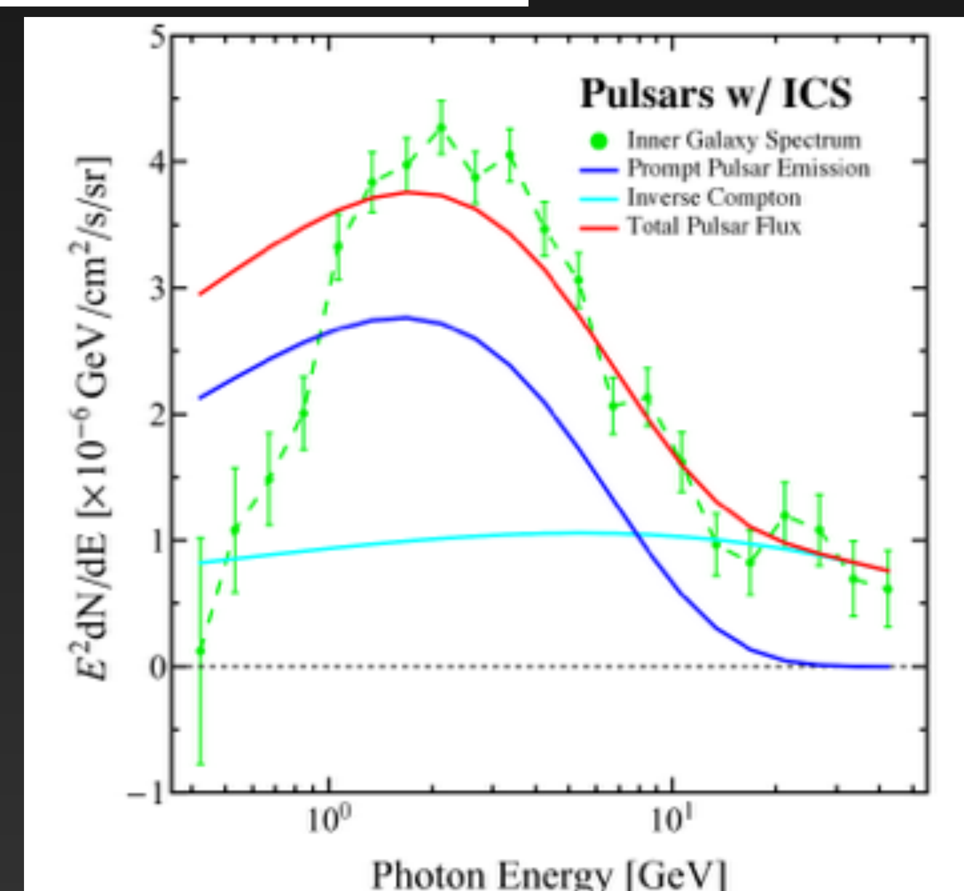
Can DM be Ruled out by GC Observations?

1604.01026

1501.03507



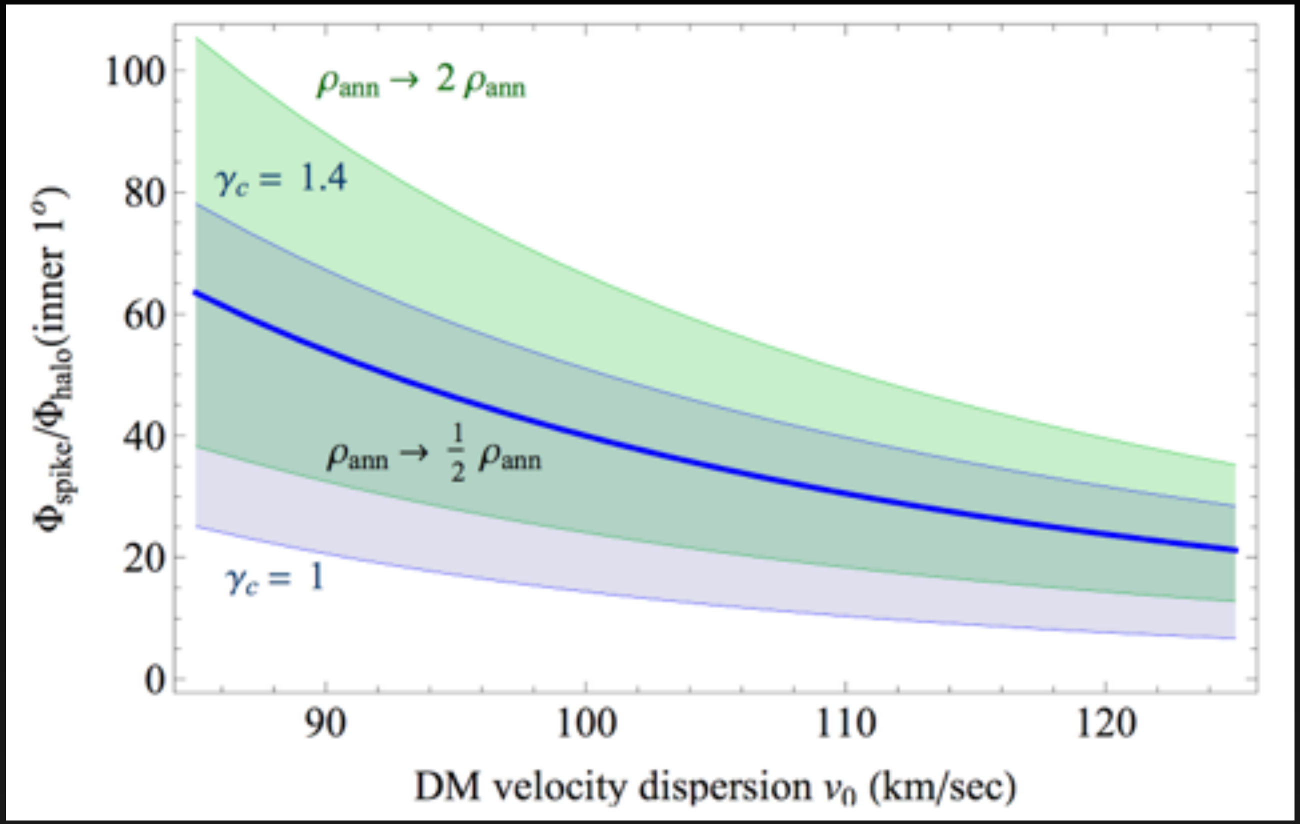


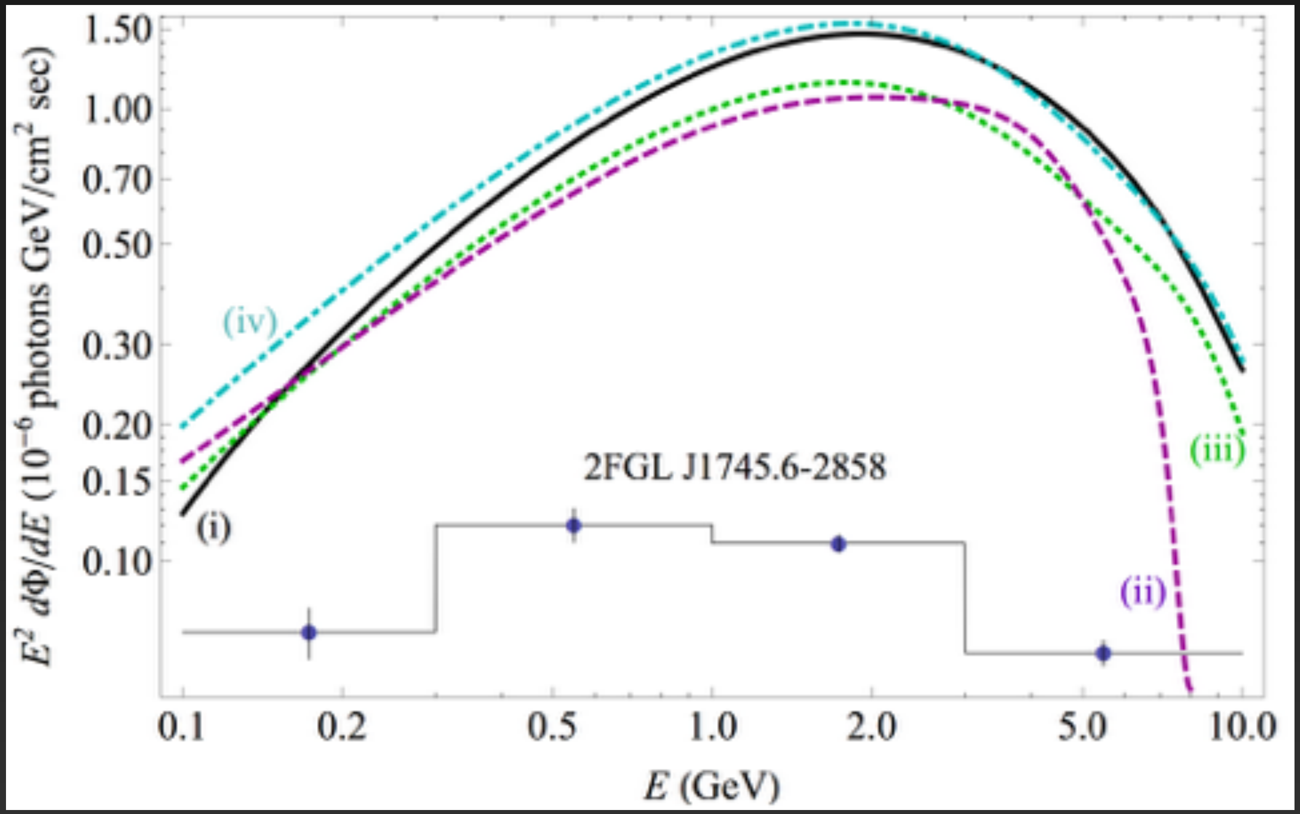


Can DM be Ruled out by GC Observations?

In models with adiabatic BH growth, a significant DM spike is expected near the position of Sgr A*.

This would dominate the total gamma-ray emission, and is currently ruled out by observations of the gamma-ray point source.





1406.4856

Approaching a Conclusion

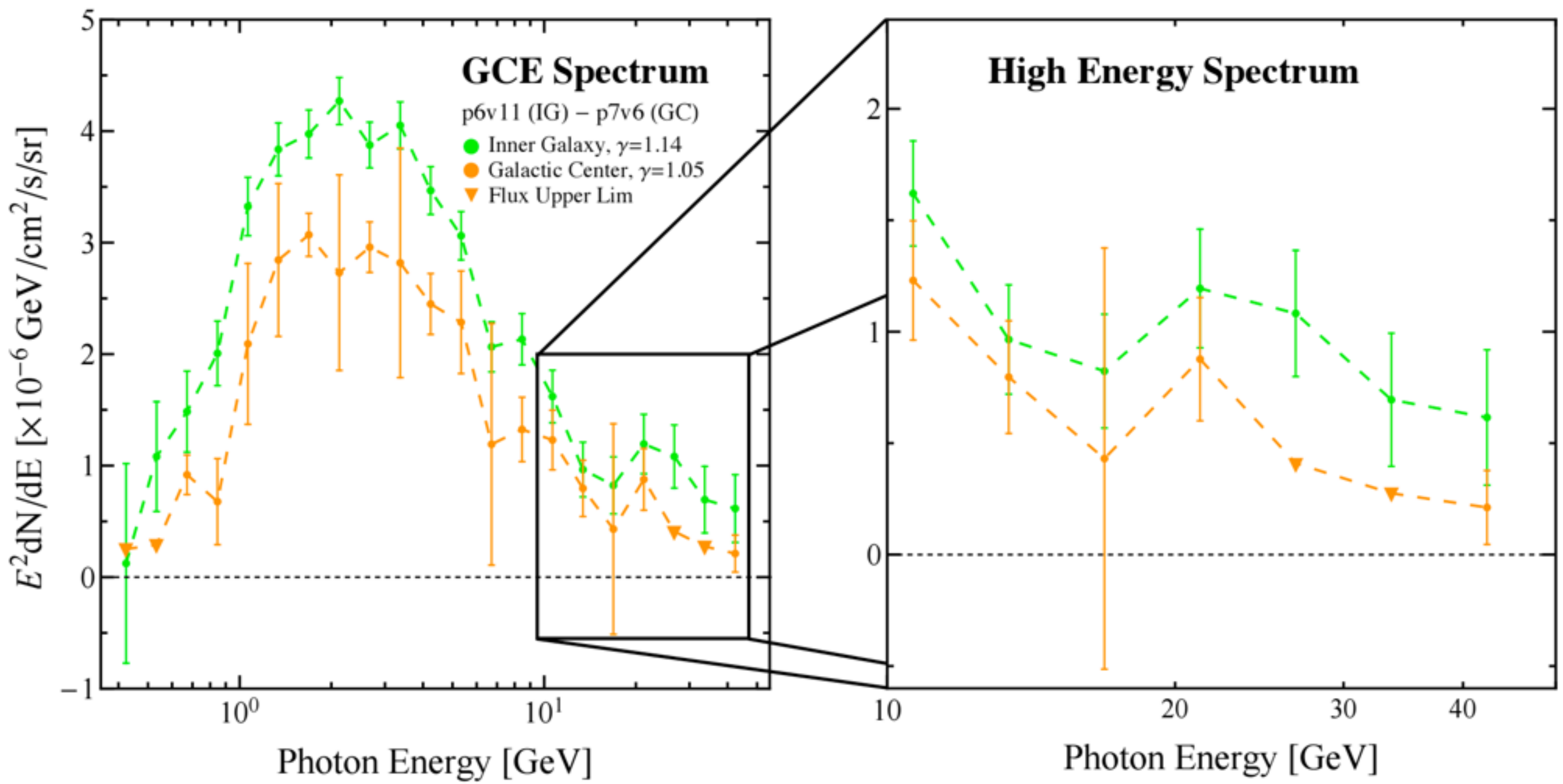
1.) The GCE remains a significant, unexplained, and puzzling excess in the gamma-ray data.

2.) Observations of point-like residuals are currently the most intriguing outlet towards answering this puzzle, but significant work remains.

3.) New multi wavelength models are necessary to conclusively explain this excess.

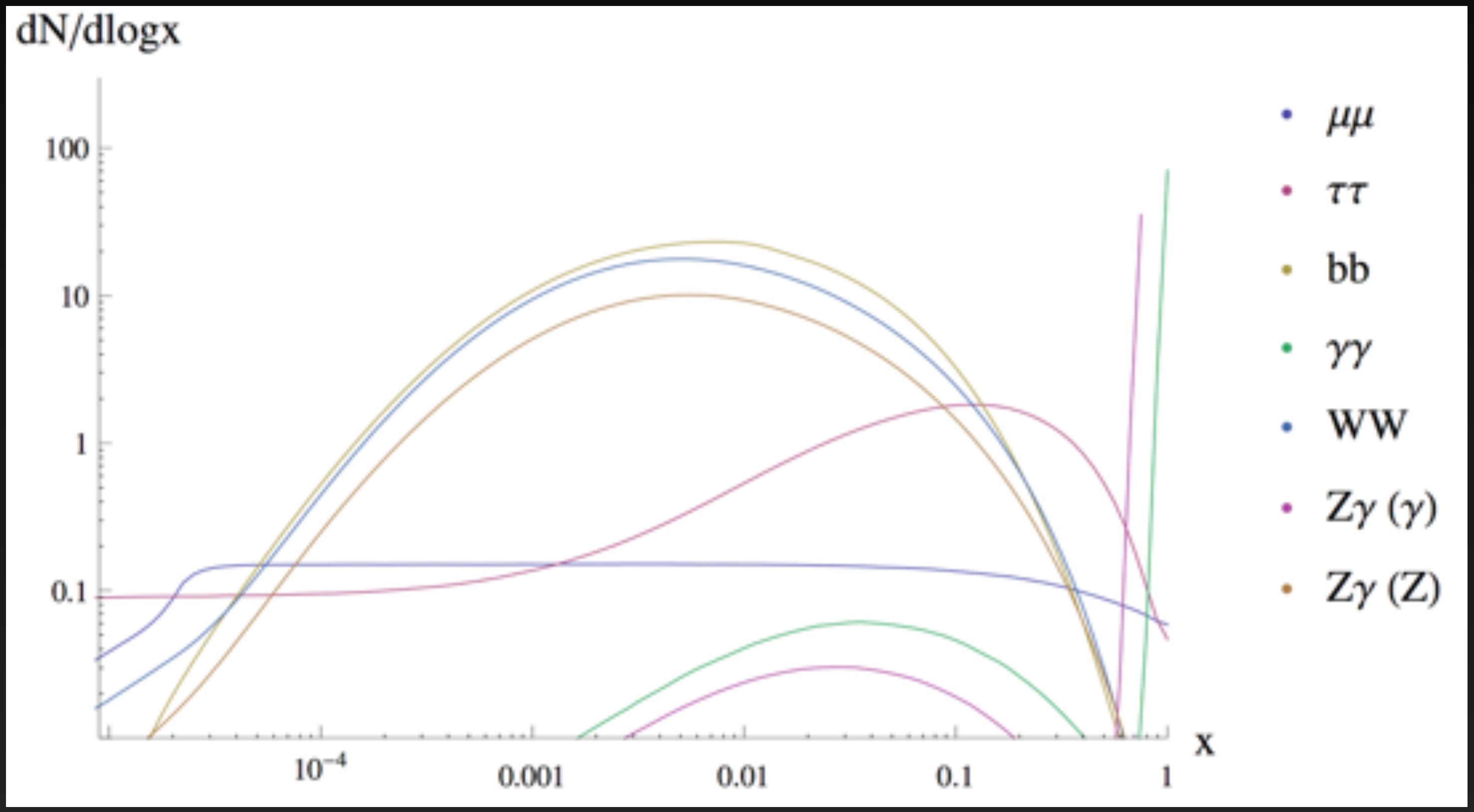
Extra Slides

The High Energy Tail of the Gamma-Ray Excess

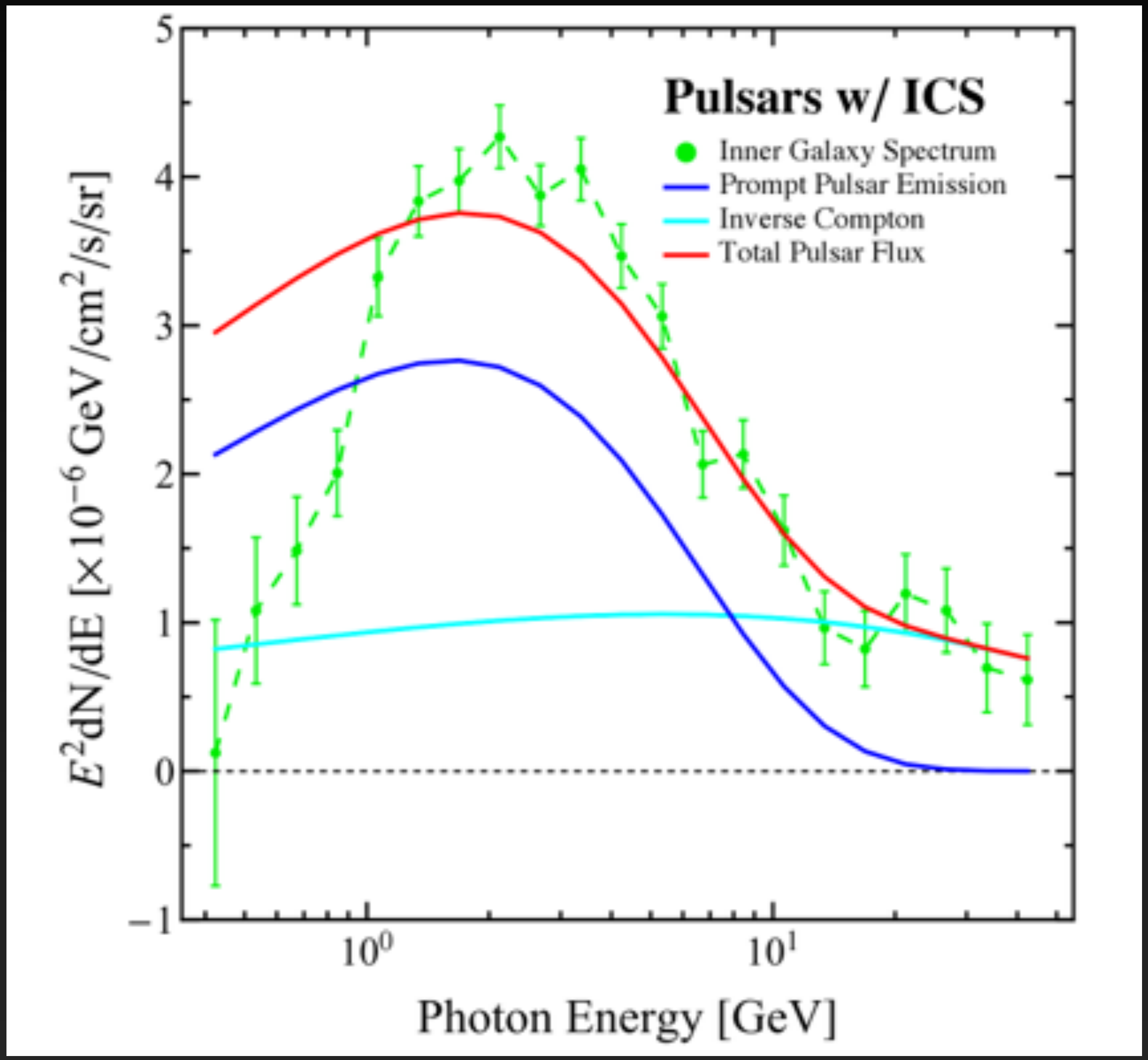


arXiv: 1604.01026

The High Energy Tail of the Gamma-Ray Excess



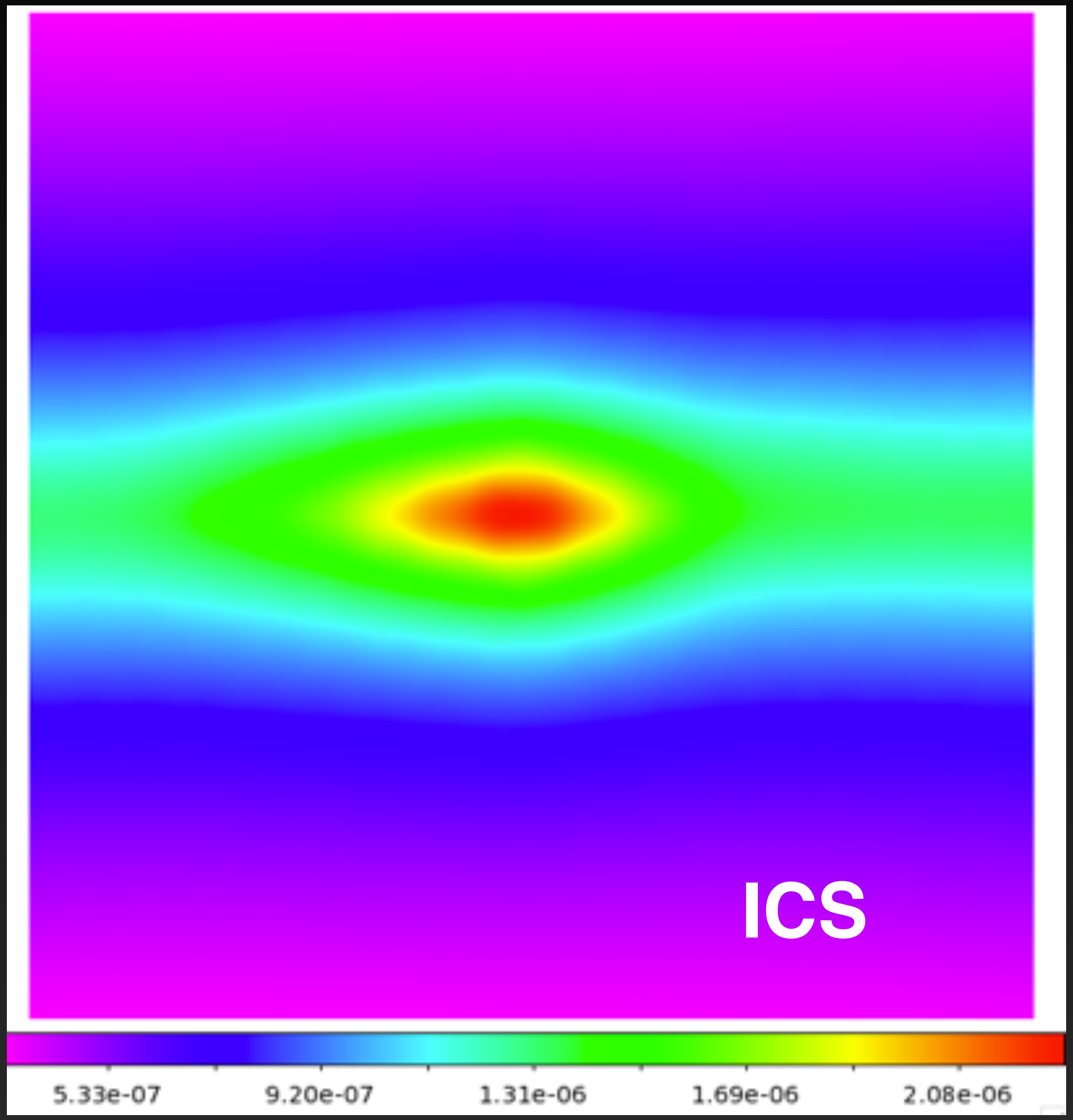
With Dark Matter



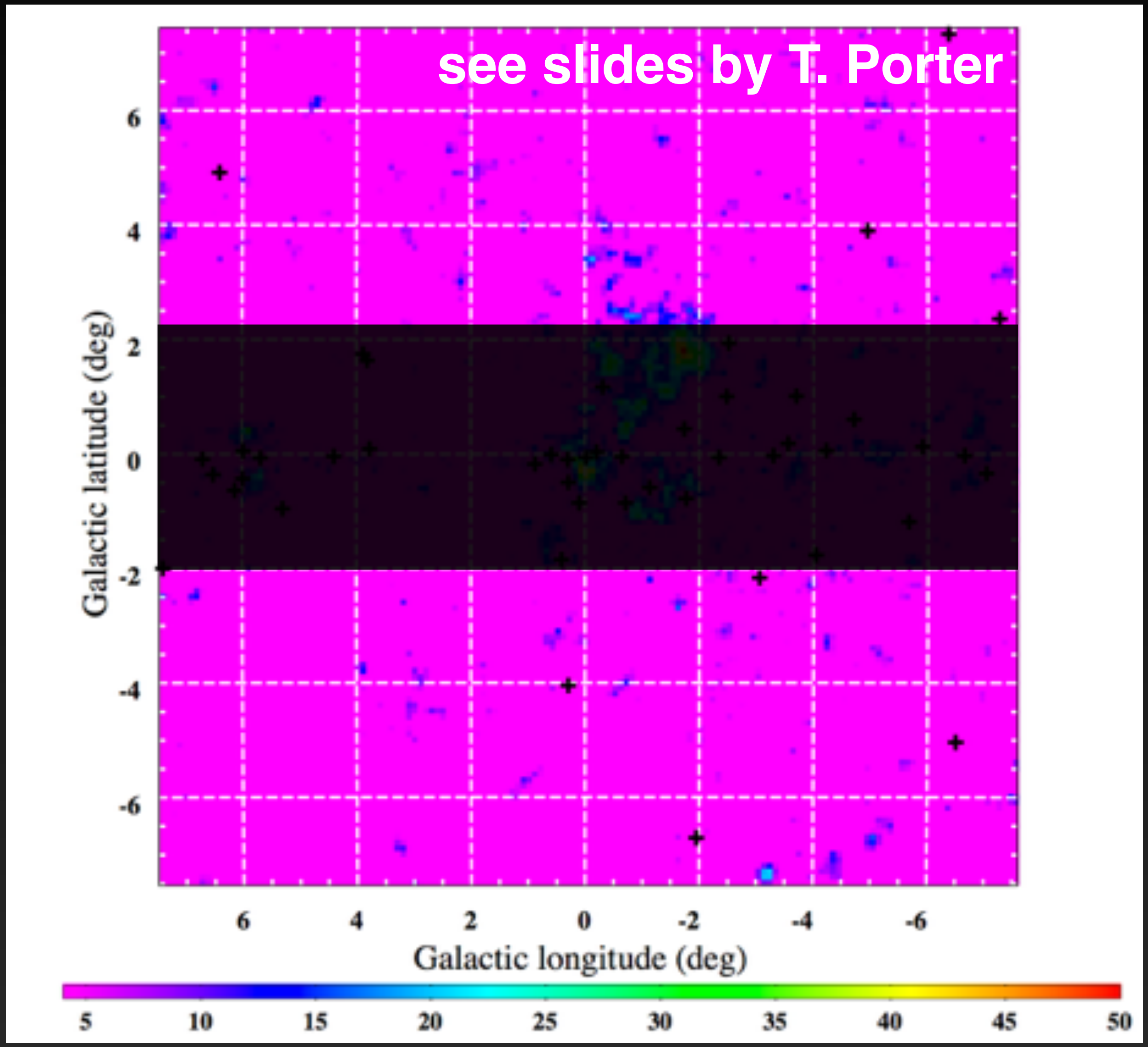
With MSPs

arXiv: 1604.01026

Millisecond Pulsar Fits



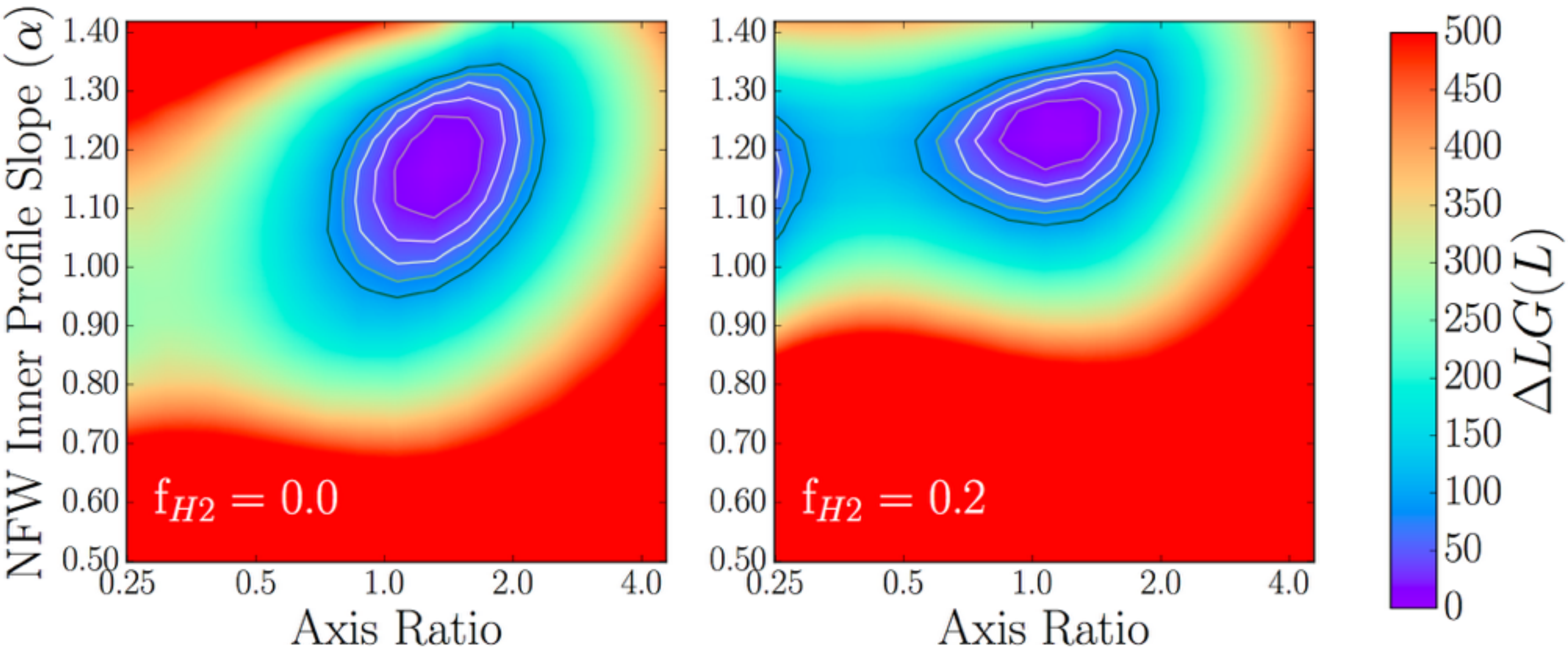
Ajello et al. (2015)



- 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.

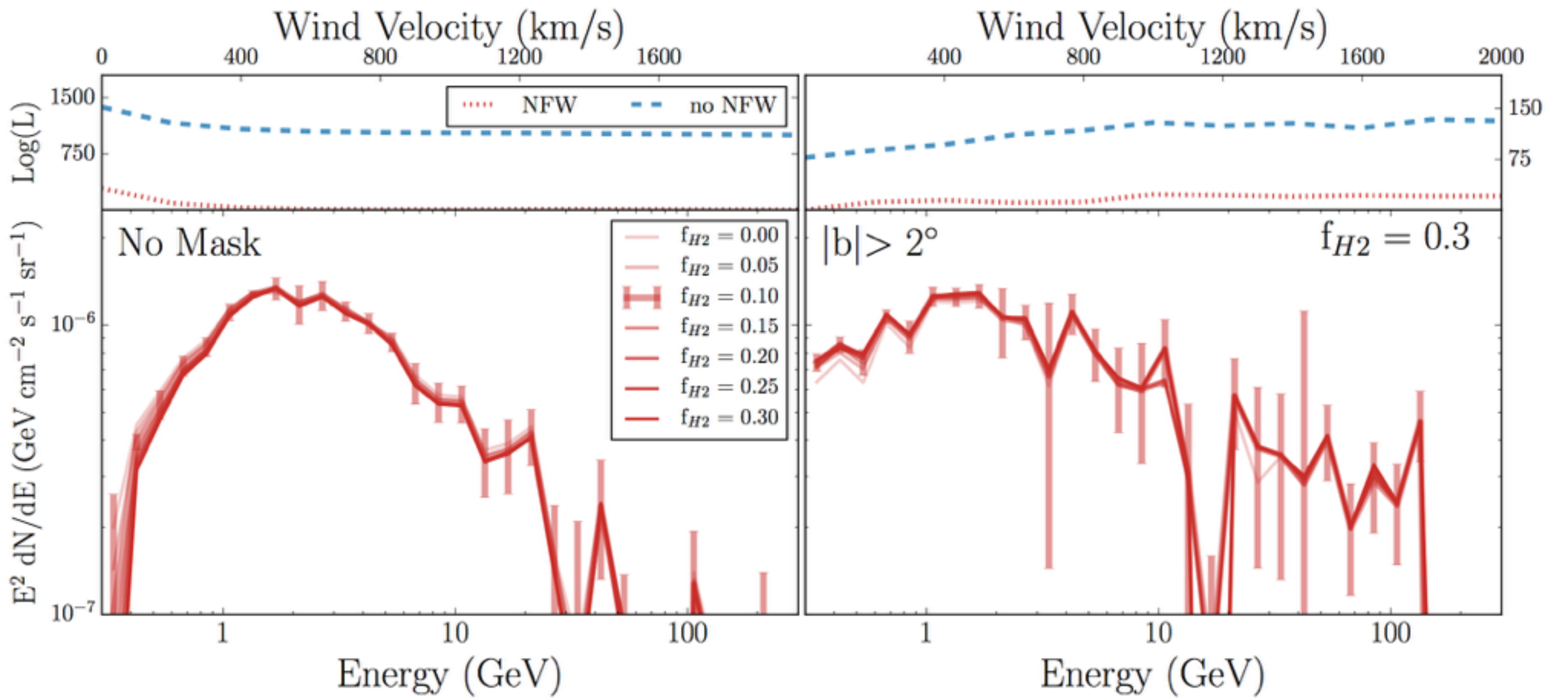
see slides by Christoph Weniger

The Galactic Center Excess Morphology



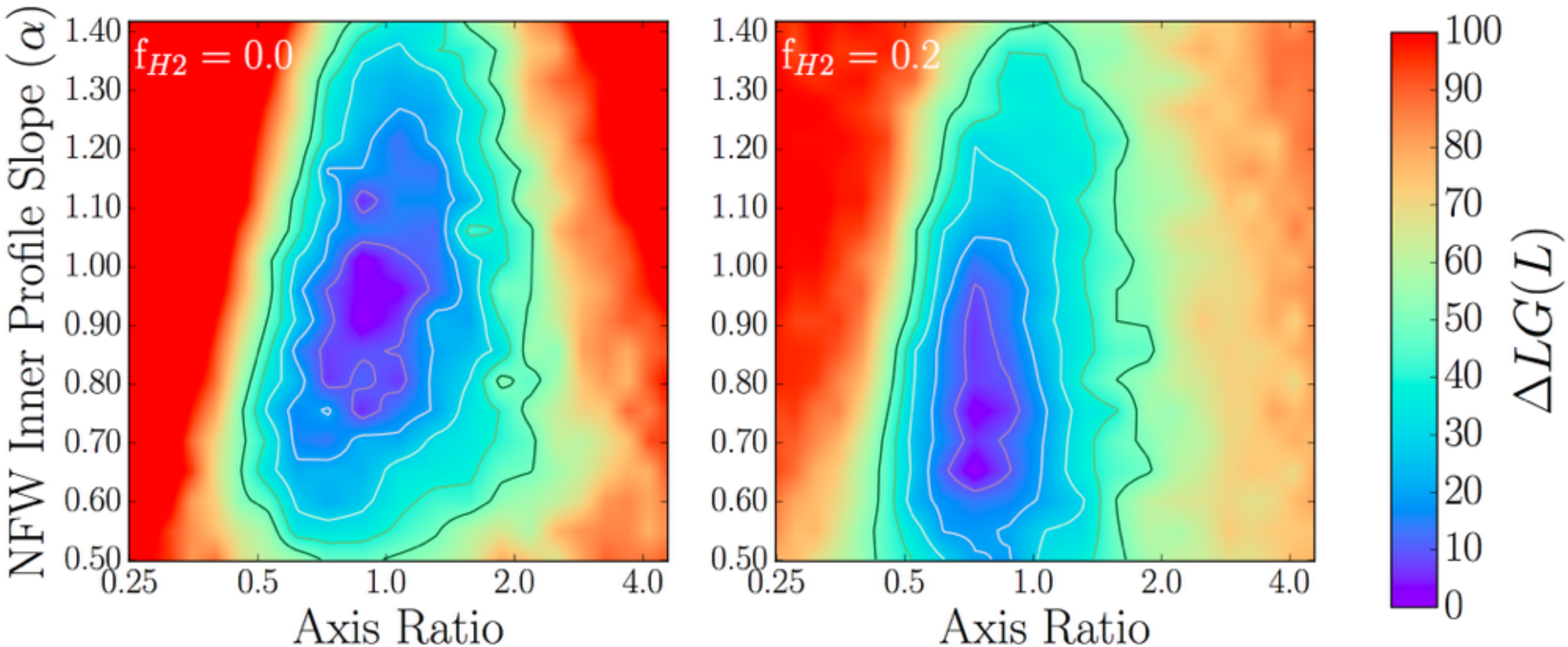
For the Galactic Center analysis, the morphology of the excess component remains relatively robust

The Low Energy Spectrum



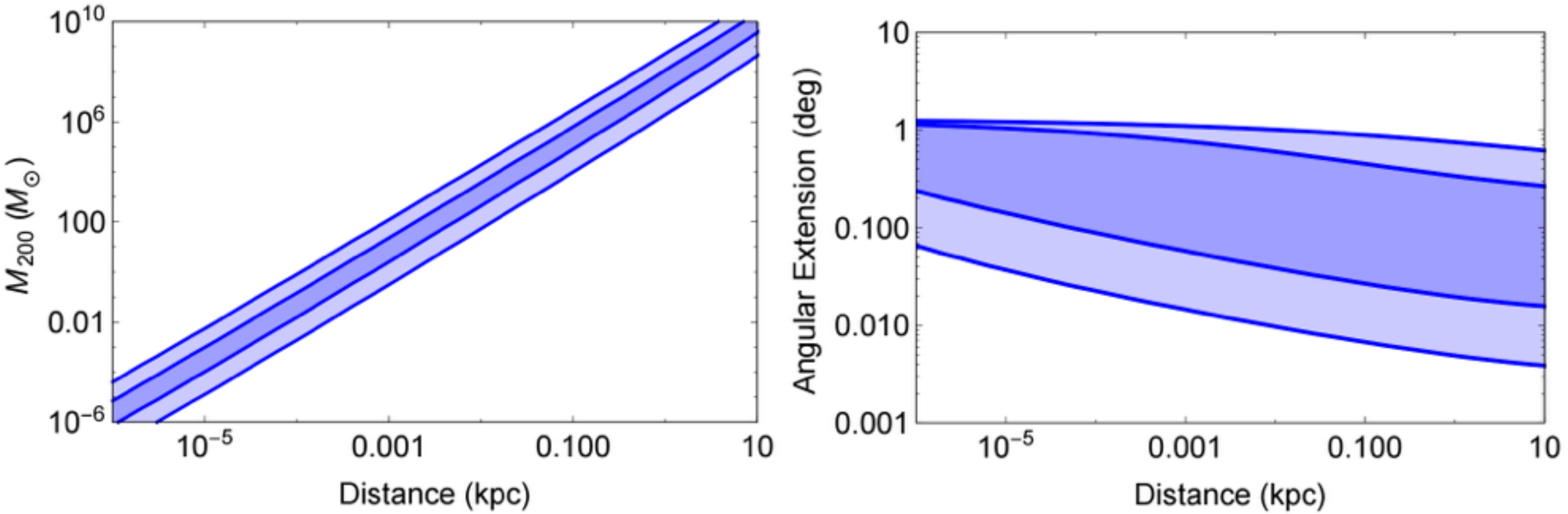
The Galactic Center models contain only a small preference for the convective winds, and the spectrum and intensity of the Galactic center excess component remains resilient.

The Galactic Center Excess Morphology (masking |b| < 2º)



The deviations from typical NFW profiles are more extreme when the |b| < 2º is masked from the analysis, with a shallower emission profile preferred by the data.

Unassociated Point Sources

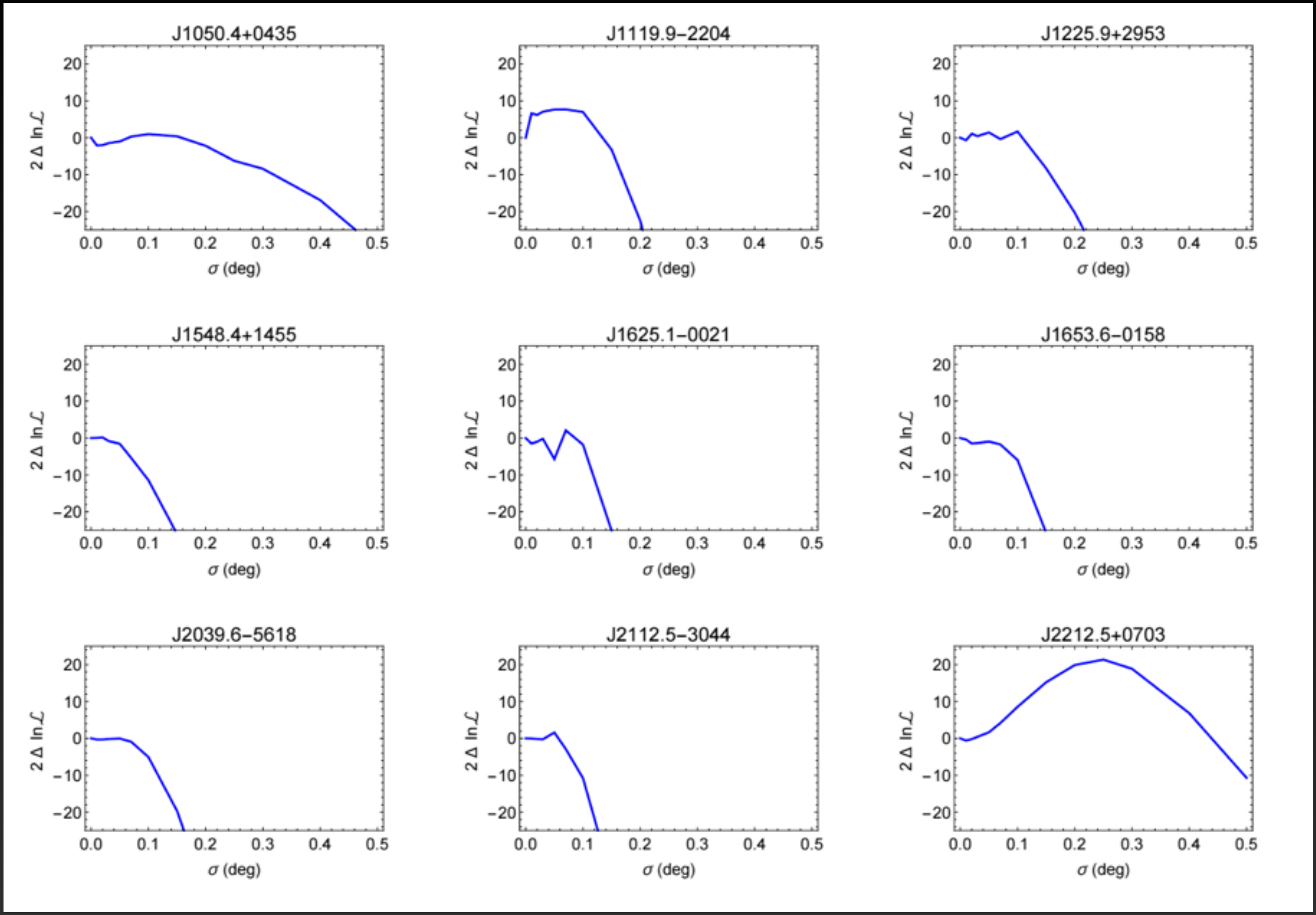


One additional smoking gun signature of dark matter annihilation would be the existence of a spatially extended, but unassociated gamma-ray source.

This could stem from dark matter subhalos of many sizes and distances.

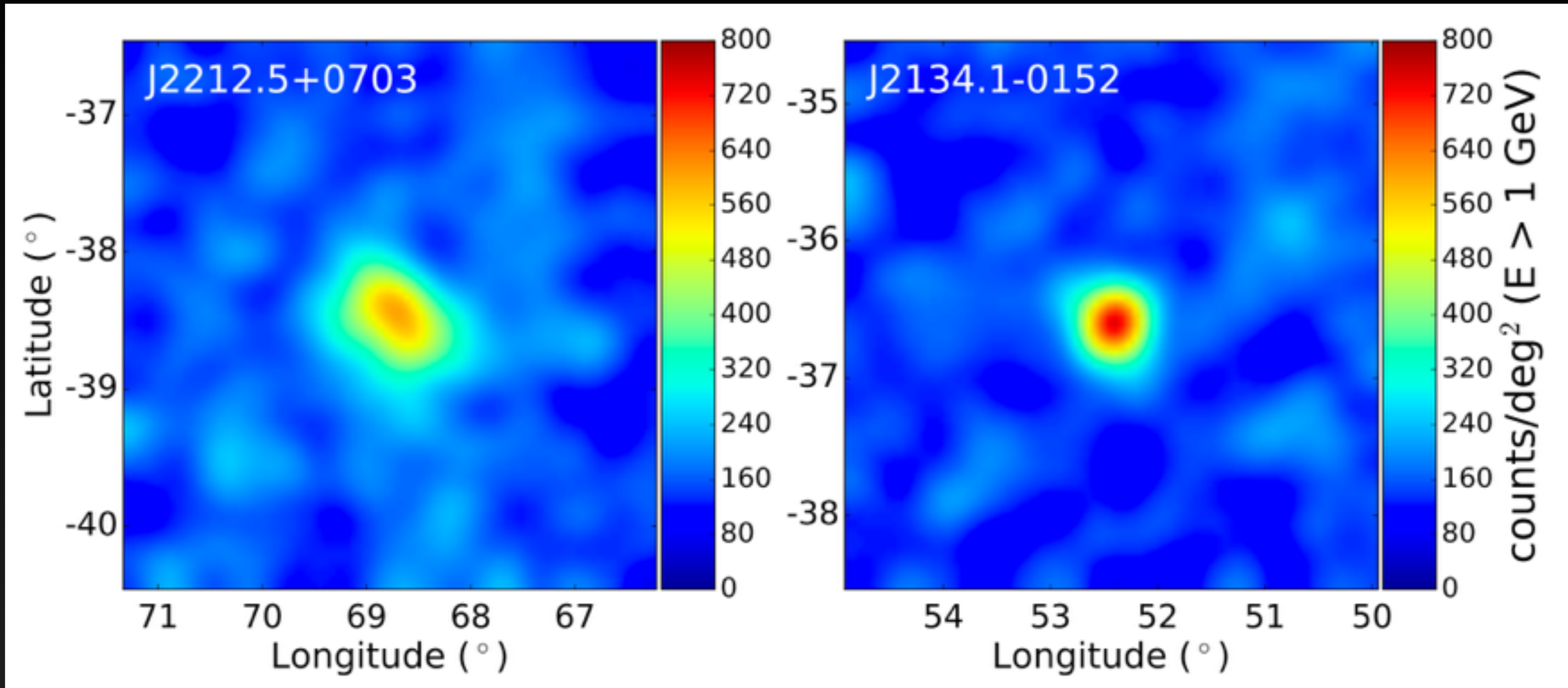
arXiv: 1602.07303

Unassociated Point Sources



arXiv: 1602.07303

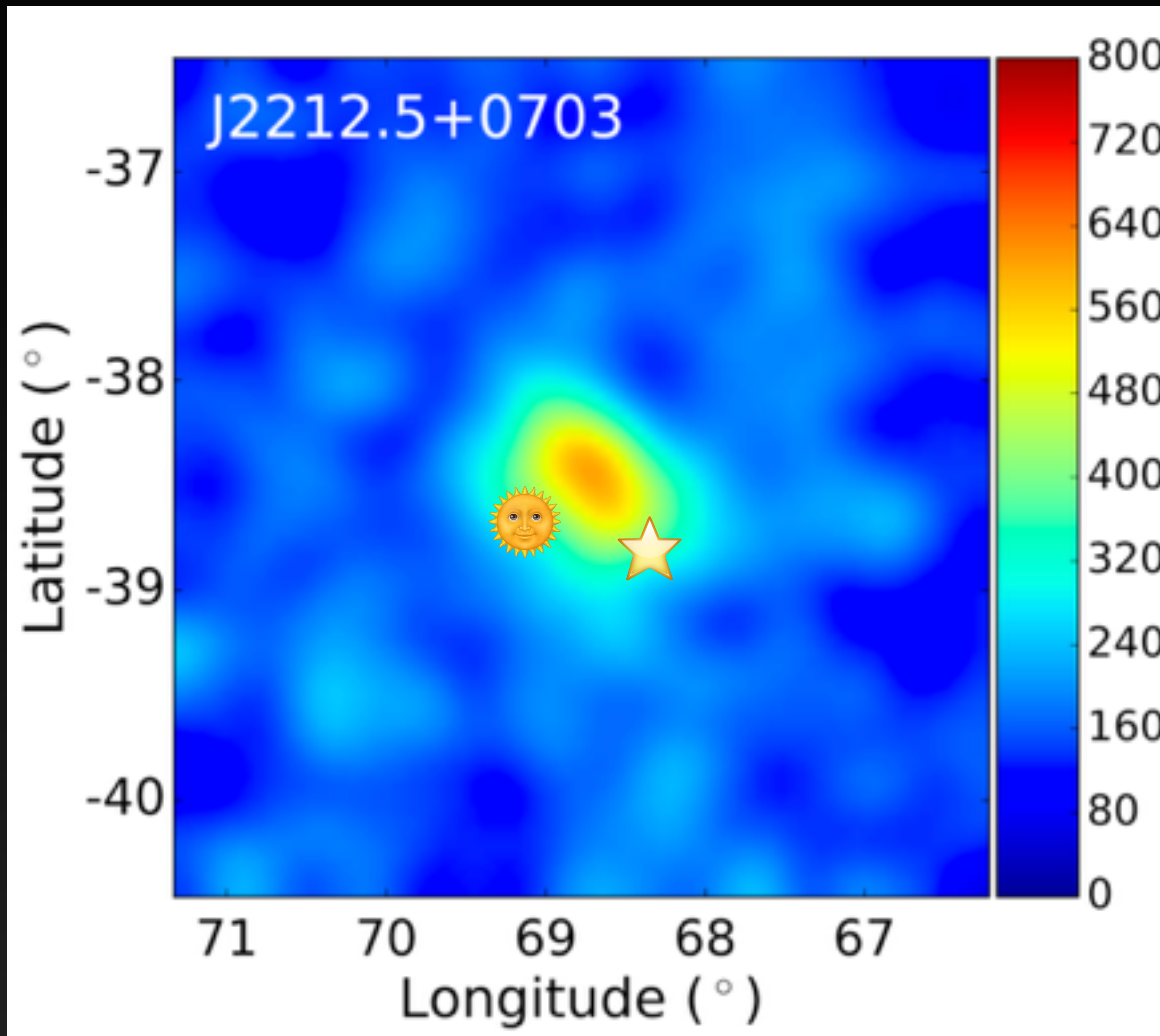
Unassociated Point Sources



The source visually appears to be spatially extended, compared to typical gamma-ray sources, and an extension that is favored at nearly 5σ.

Source Name (3FGL)	σ	$2\Delta \ln \mathcal{L}$
J2212.5+0703	$0.25°$ ($< 0.31°$)	21.4
J1119.9-2204	$0.07°$ ($< 0.12°$)	7.7
J0318.1+0252	$0.15°$ ($< 0.20°$)	5.8
J0953.7-1510	$0.05°$ ($< 0.09°$)	2.5
J1625.1-0021	$0.07°$ ($< 0.10°$)	2.1
J1225.9+2953	$0.10°$ ($< 0.12°$)	1.7
J2112.5-3044	$0.05°$ ($< 0.07°$)	1.6
J0523.3-2528	$< 0.06°$	–
J1050.4+0435	$< 0.21°$	–
J1548.4+1455	$< 0.06°$	–
J1653.6-0158	$< 0.09°$	–
J2039.6-5618	$< 0.09°$	–

Unassociated Point Sources



Unfortunately, it is currently difficult to determine whether the spatial extension results from a population of nearby point sources.

Two (of 14,467) sources are within 0.25º of the J2212 gamma-ray source.

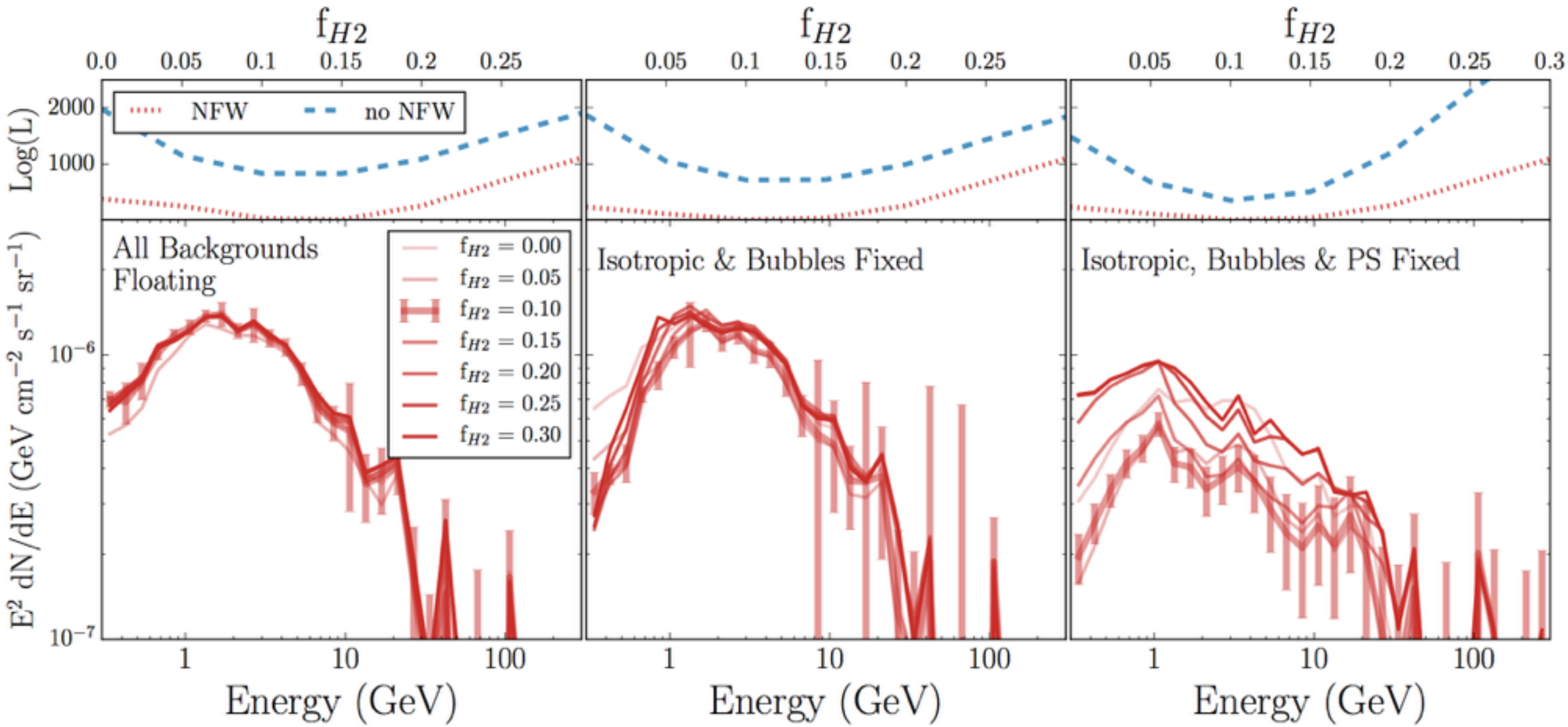
These two point sources do not themselves explain the morphology and spectrum of the source.

However, one source plus an unknown source near the center of the excess does fit.

$$\mathcal{P} = \frac{N(N-1)}{2} \frac{\pi\alpha^2}{4\pi\,[1-\sin 20°]}$$
$$\approx 2.3 \times 10^{-6} \times N(N-1) \times \left(\frac{\alpha}{0.2°}\right)^2$$

$$\mathcal{P} \approx 2.2 \times 10^{-2} \times \left(\frac{\alpha}{0.2°}\right)^2$$

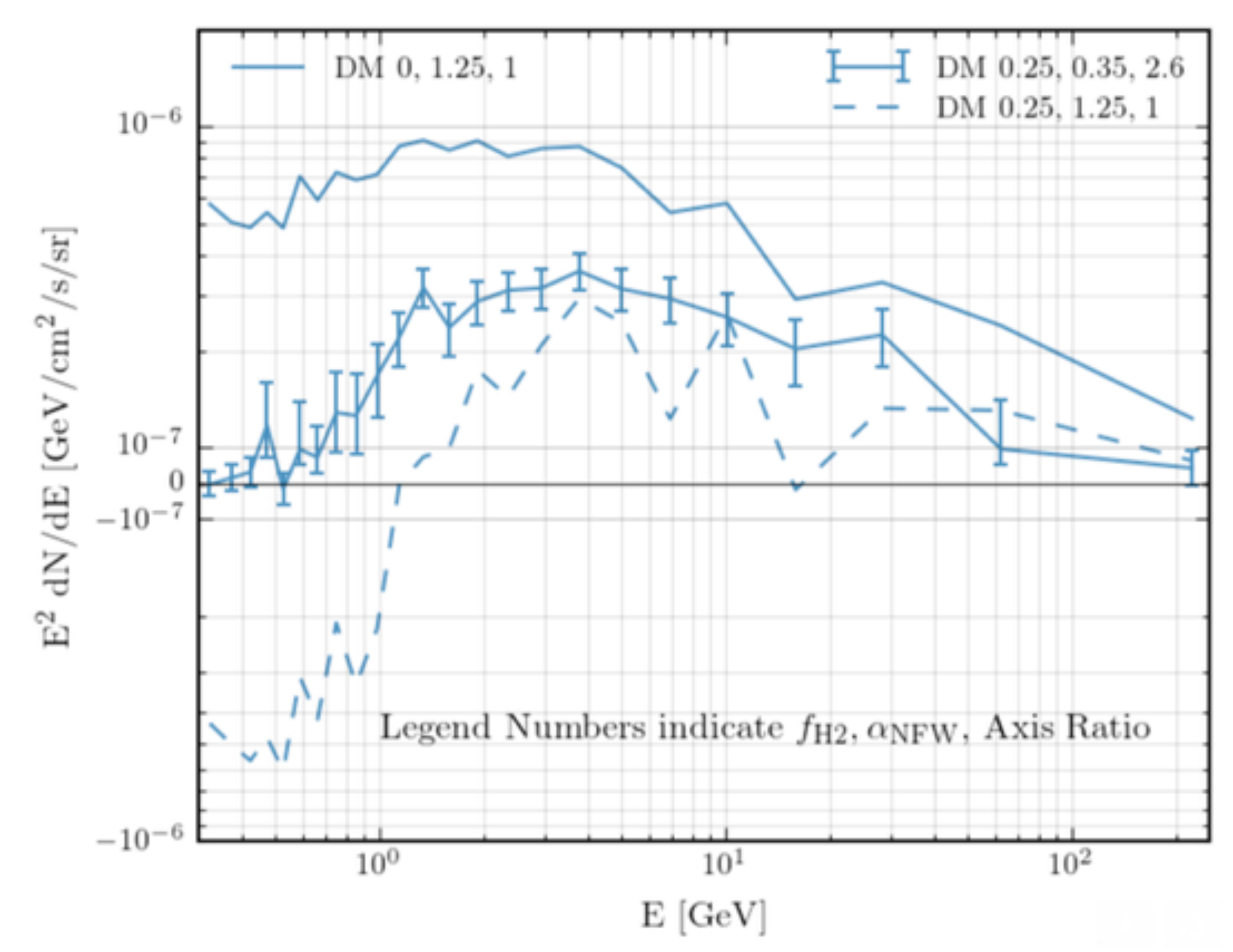
Masking 1FIG Sources in the GC



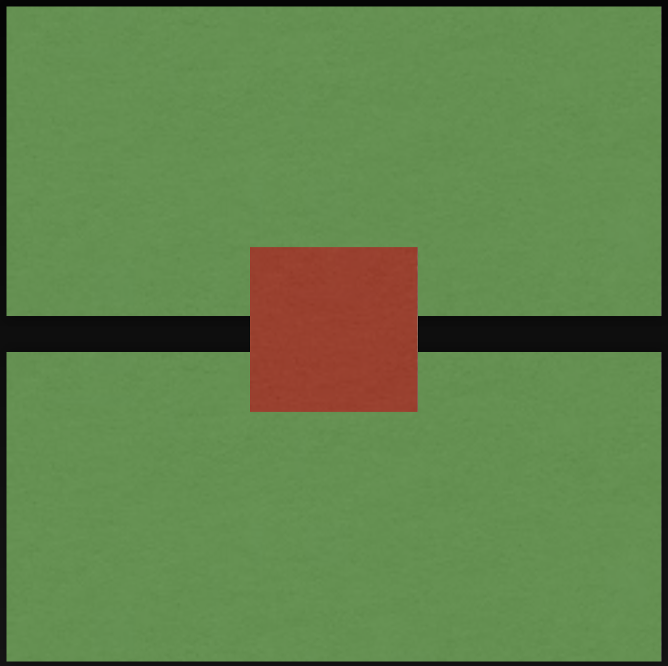
A Fermi Bubbles Component?

When the excess floats to the best fit morphological configuration, much of the excess intensity returns.

Most importantly, the over subtraction issue at low energies is fixed.



Two Analyses of the Gamma-Ray Excess



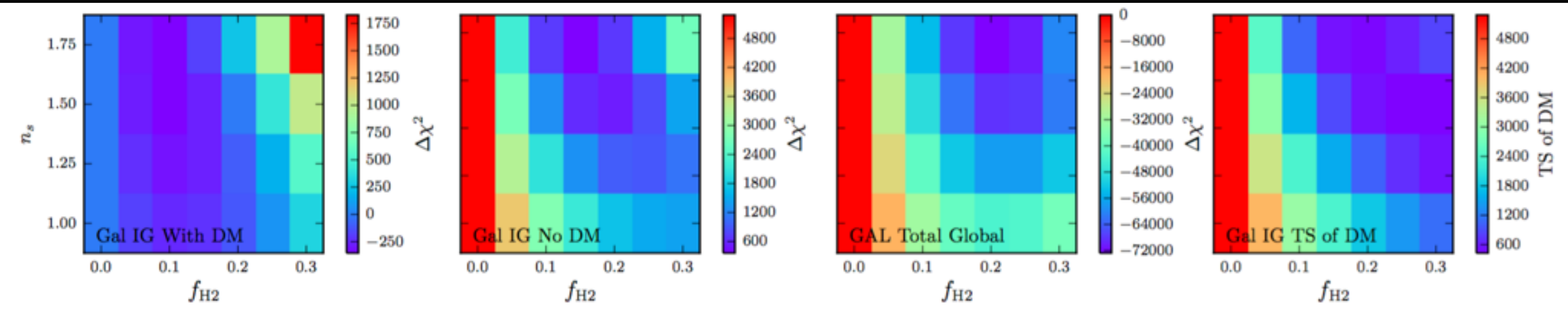
INNER GALAXY

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

GALACTIC CENTER

- Box around the GC (10º x 10º)
- Include and model all point sources
- Use likelihood analysis to calculate the spectrum and intensity of each source
- Bright Signal

The Excess is Degenerate with f_{H2}



Models with no dark matter universally prefer f_{H2} ~ 0.2 for the 40ºx40º region surrounding the GC.

Models with an NFW emission template prefer f_{H2} ~ 0.1.

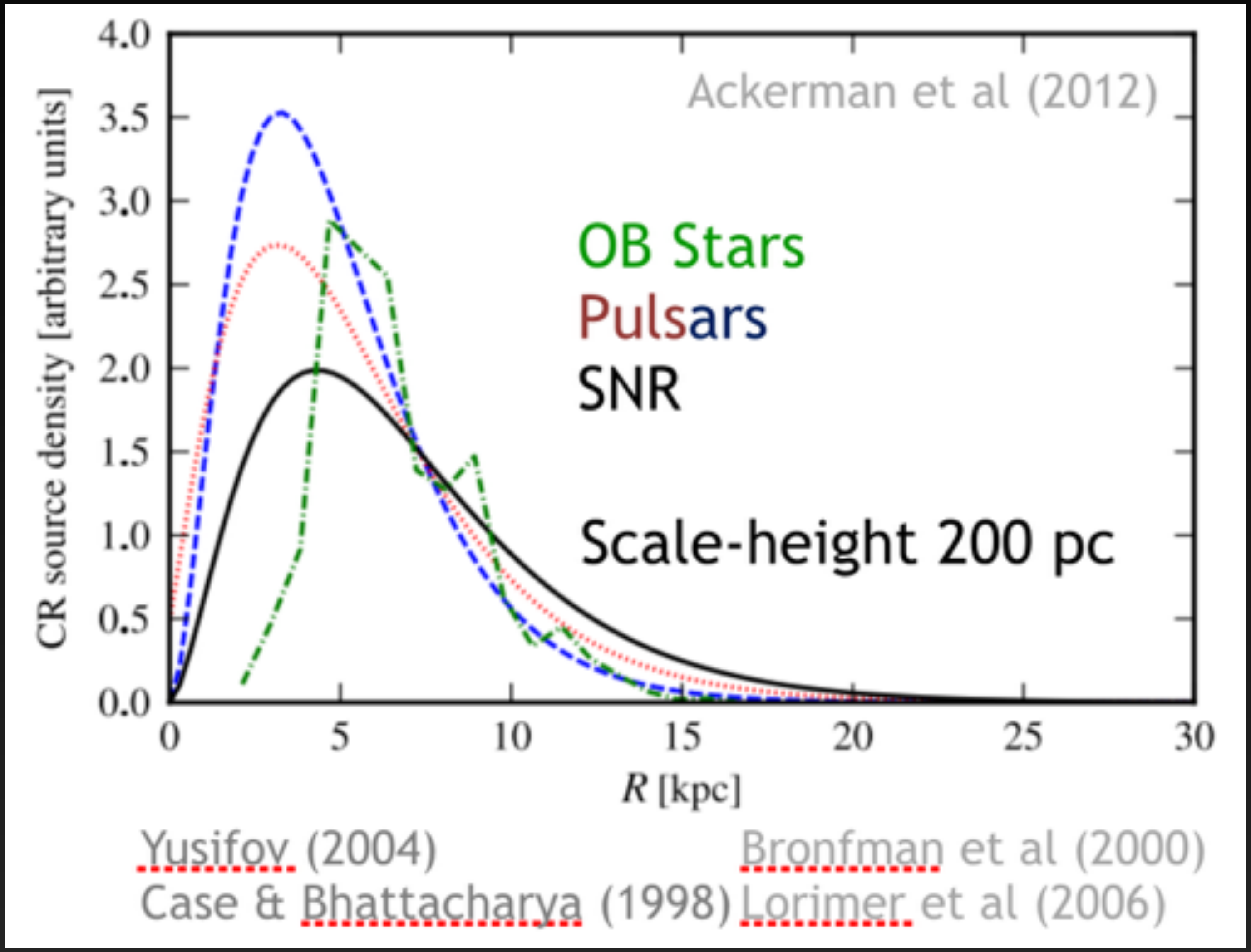
The reduction in the normalization of the NFW template is ~1.5 for f_{H2} ~ 0.1, instead of a factor of 3 at f_{H2} ~ 0.2.

Cosmic-Ray Injection in the GC

Why Is this Done?

1.) Want to fit a simple analytic form to a profile that peaks at 4 kpc.

2.) Small datasets mean error bars near GC are large.



3.) Model of GC is unimportant for cosmic-ray propagation studies.