

Diffuse Emission Models Confront the Galactic Center Excess

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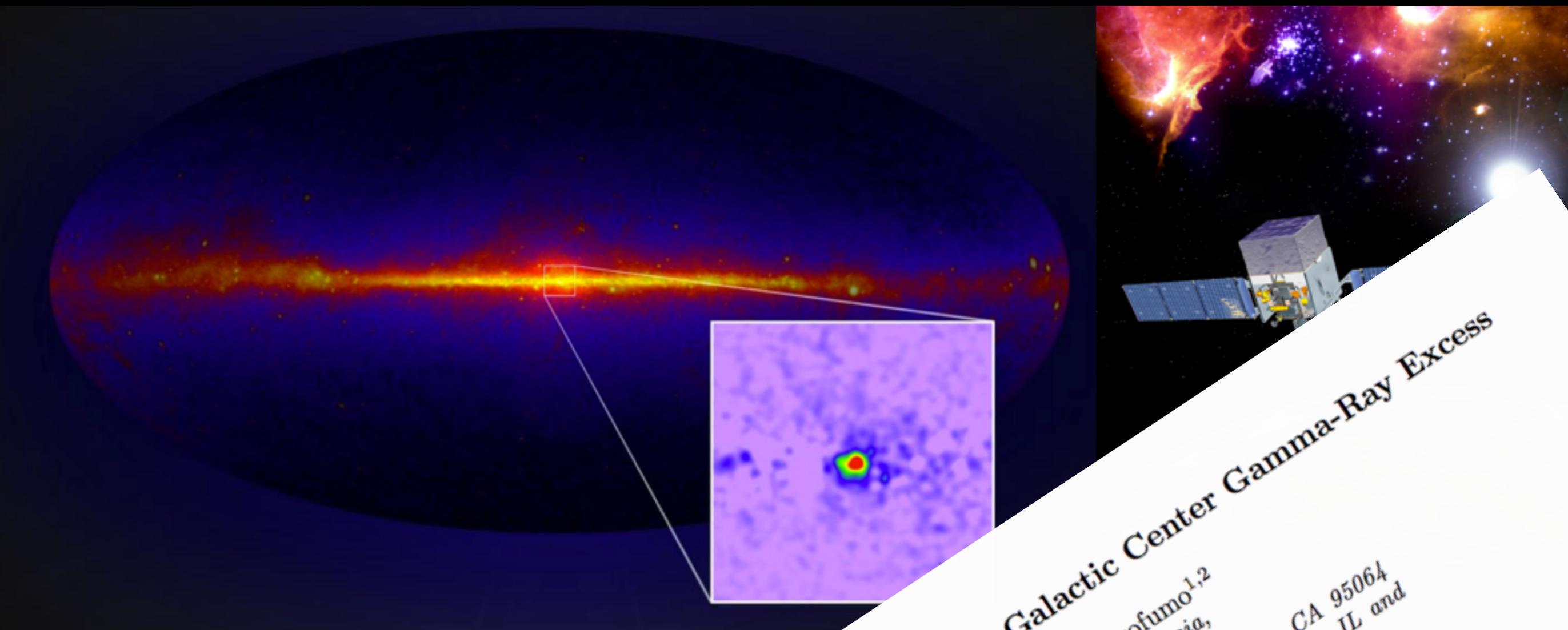
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Diffuse Emission the Galactic

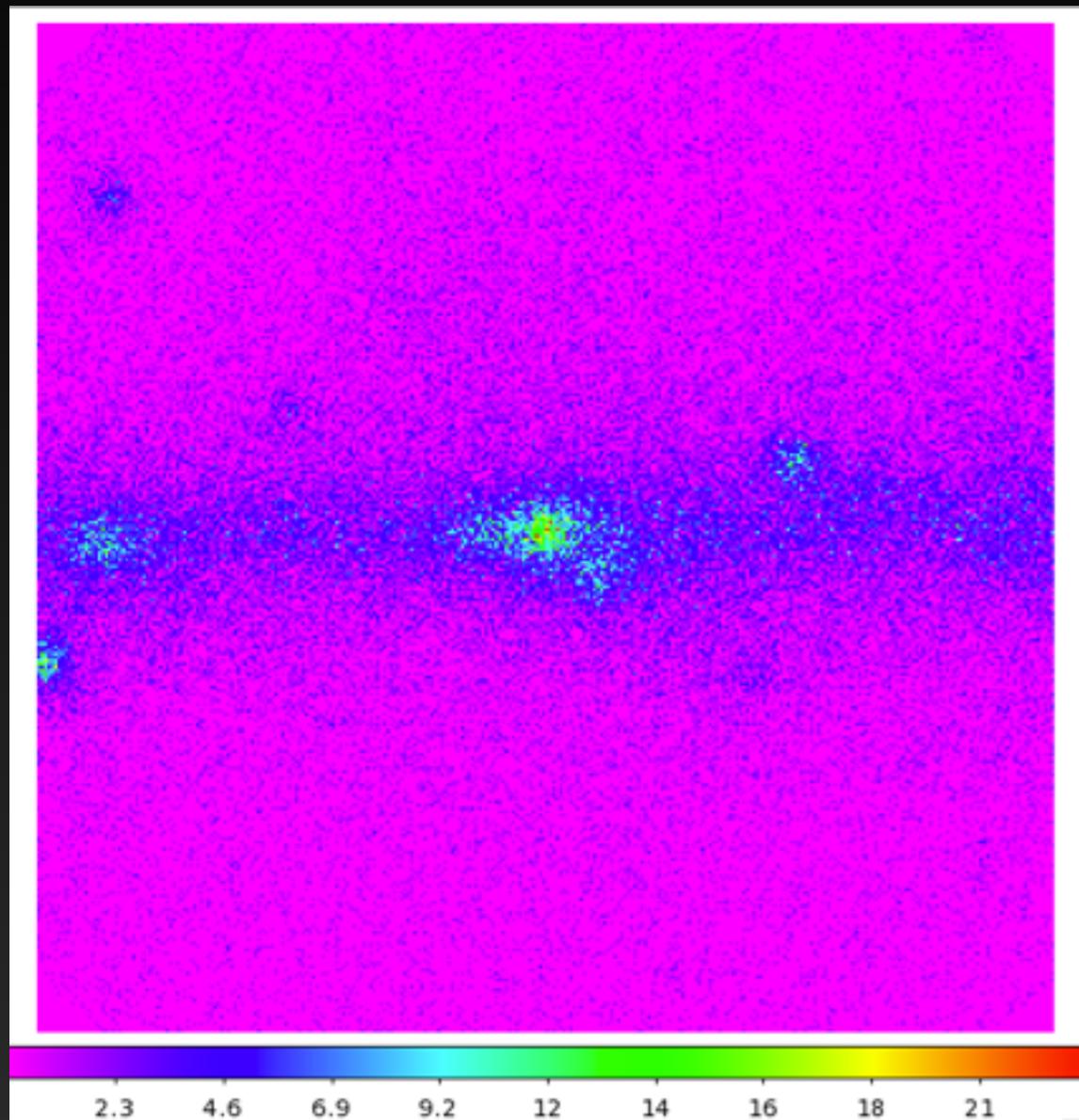
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Novel Cosmic-Ray Injection Models Confront the Galactic Center Gamma-Ray Excess

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AT observations of the Milky Way Galactic Center (GC) have revealed a spherically symmetric excess of GeV γ -rays extending to at least 10° from the dynamical center of the galaxy. A model in extracting the intensity, spectrum, and morphology of this excess concerns the diffuse emission models in the GC region. Recently, it has been noted that models employ a cosmic-ray injection rate far below that predicted based on the Central Molecular Zone. In this study, we add a significant emission rate with many properties of the γ -ray excess, and find that this rate surrounding the GC) to normalize the best-fitting model. However, the normalization of astronomical observations of the GC) is resilient to changes in the injection rate of cosmic-rays injected into the Milky Way – a result of the diffuse emission models.

Template Fitting Analyses



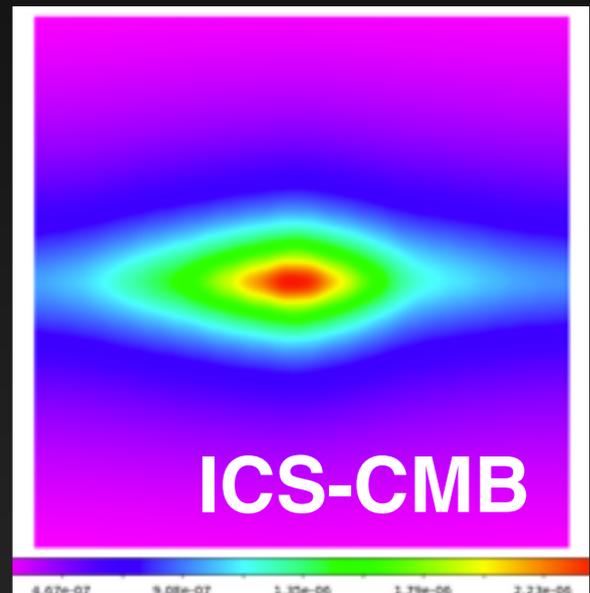
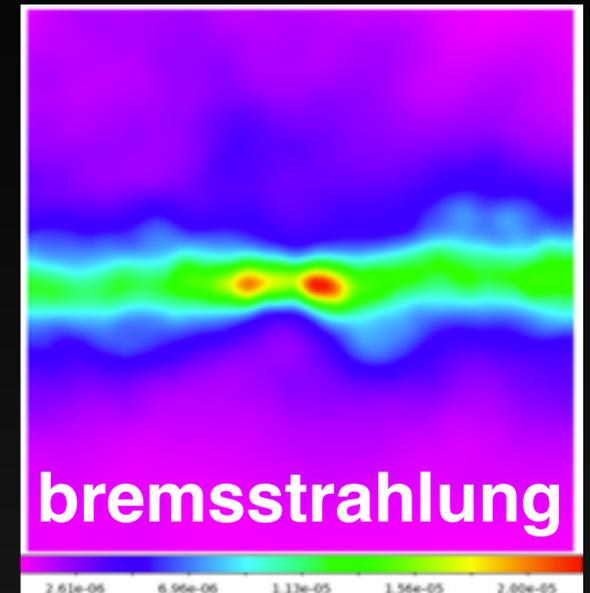
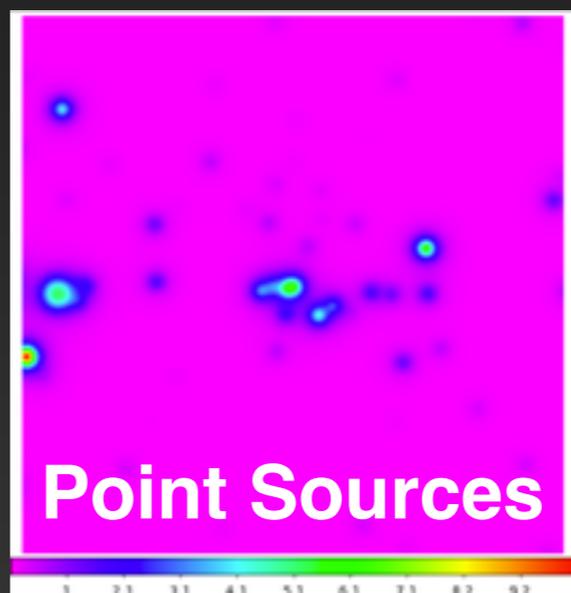
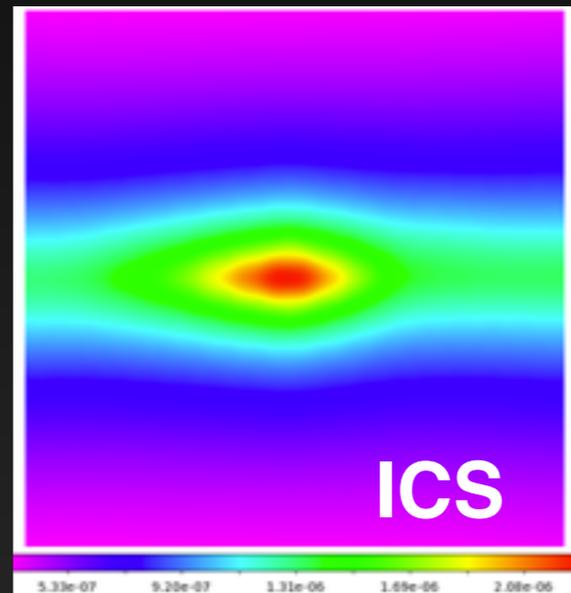
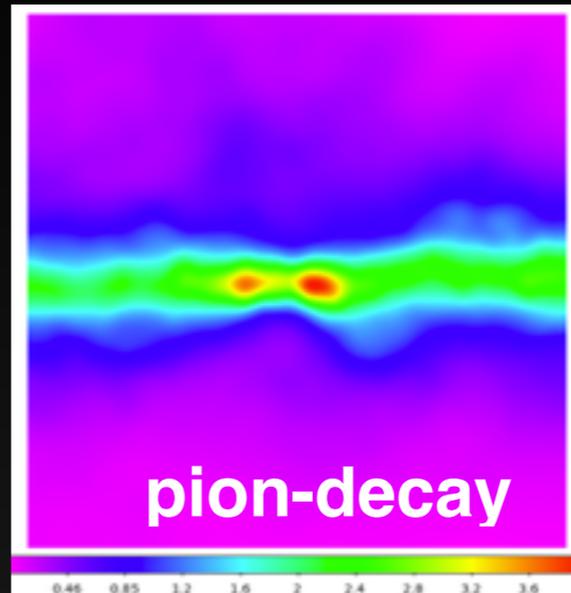
Data

750 — 950 MeV

Best Angular Resolution Cut

$10^\circ \times 10^\circ$ ROI

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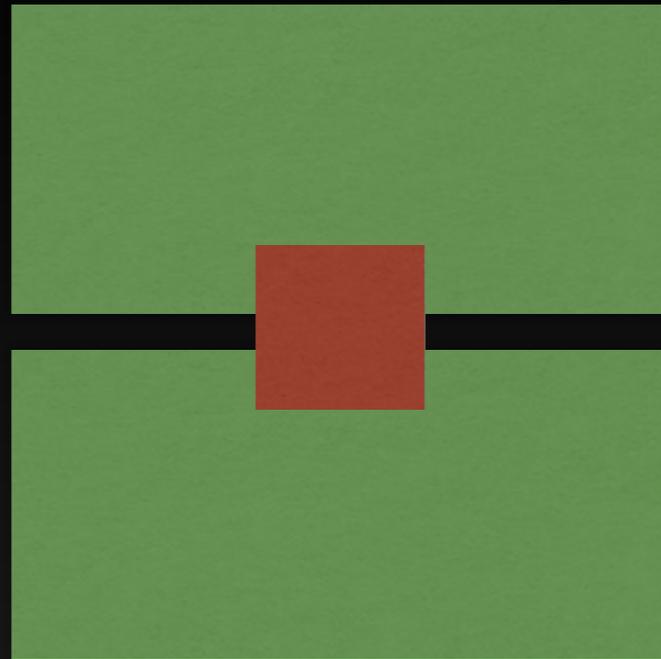
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Two Separate Analysis Regions



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**

Powerful Evidence for the Excess

Previous analyses showed that the evaluation of the excess was:

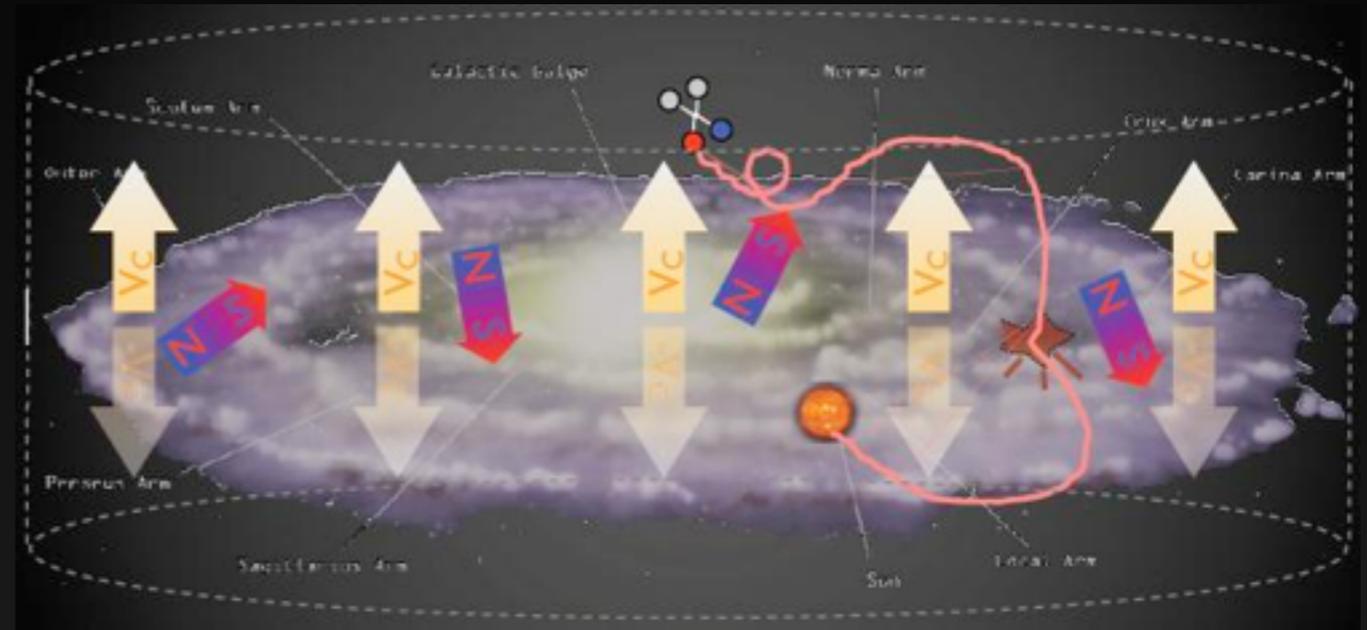
1.) independent of ROI (Daylan et al.)

2.) independent of diffuse emission model (Calore et al.)

If these findings hold, then we can immediately start producing explanations for the excess: dark matter, MSPs, leptonic cosmic-ray outbursts, etc.

Diffuse Emission Modeling

Cosmic-Rays are thought to be accelerated primarily by supernovae events.



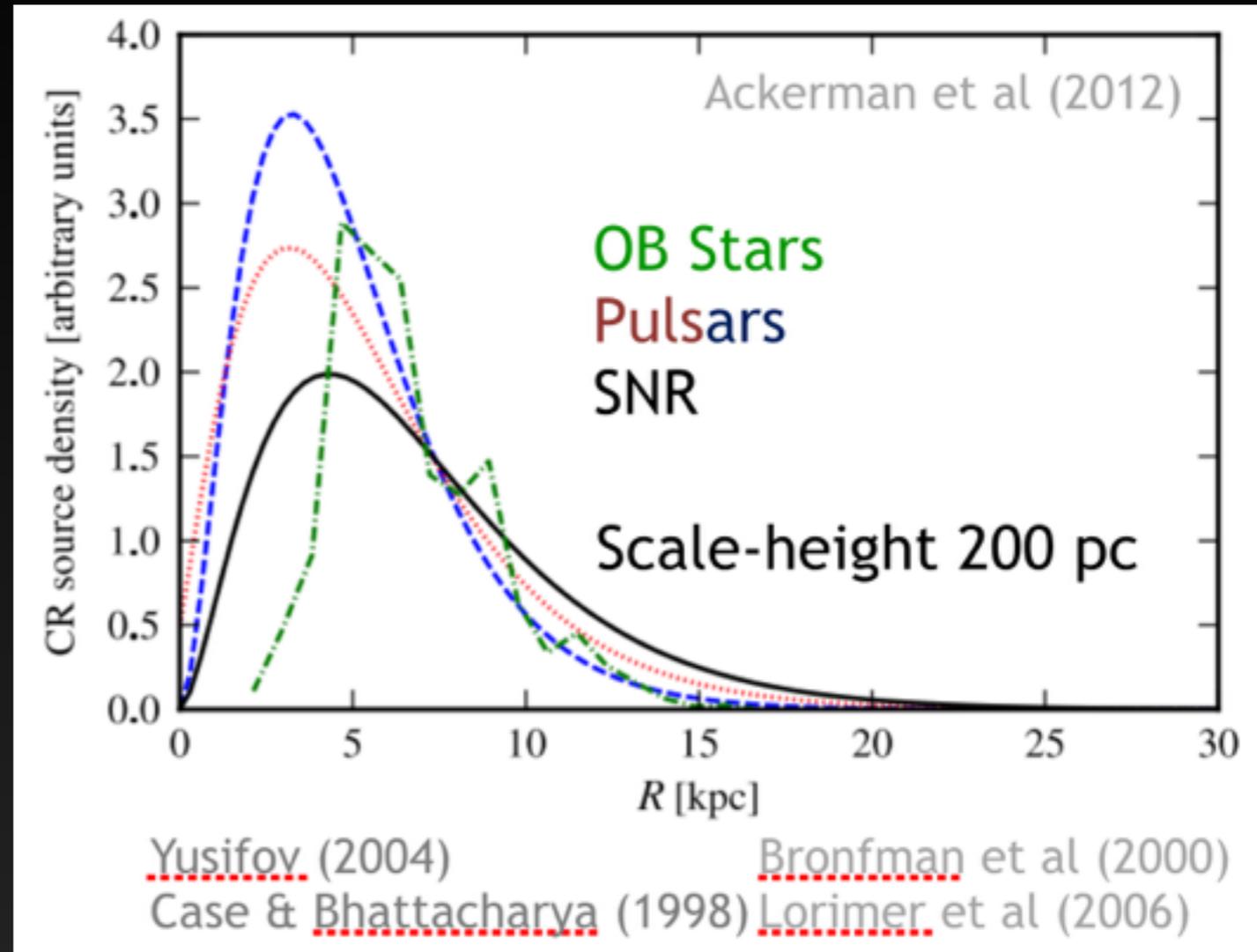
Cosmic-Rays take about 10^8 — 10^9 years to escape the Milky Way magnetic field.

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

Diffuse Emission Modeling

Need tracers of current and past supernovae rate:

- + **Observed SNR**
- + **Pulsars**
- + **OB Stars**



**All of these models observe relatively recent star formation events:
Pulsars (~30 Myr + 100 kyr), SNR (~30 Myr + 10 Myr), OB Stars (~30 Myr).**

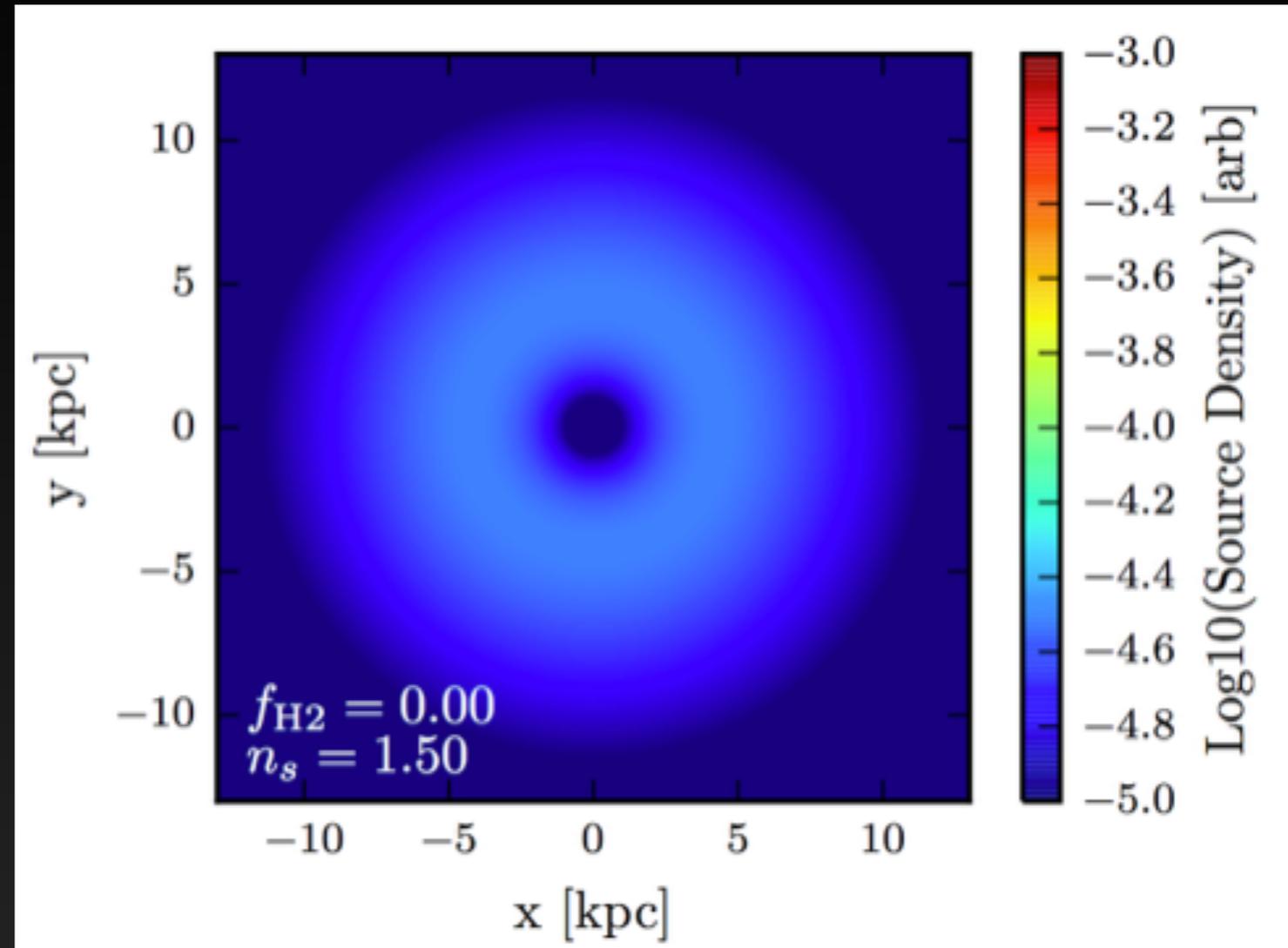
Cosmic-Ray propagation (~30 Myr + 100 Myr)

Cosmic-Ray Injection Sources

These models can then fail in two ways:

1.) Observational incompleteness

2.) Time variable injection



Interestingly the models used for these analyses have extremely small injection rates near the GC (in several cases identically 0).

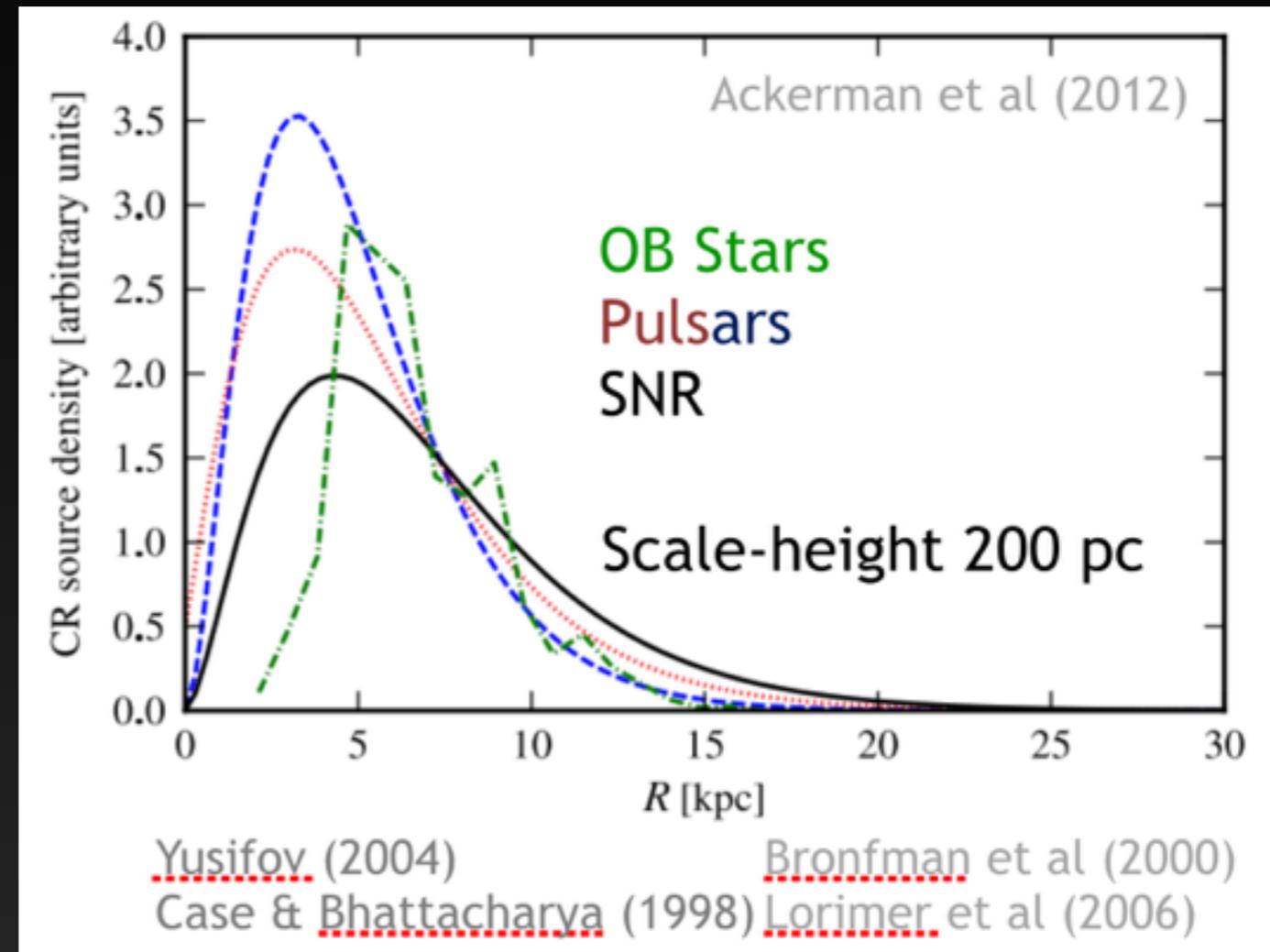
Cosmic-Ray Injection in the GC

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.

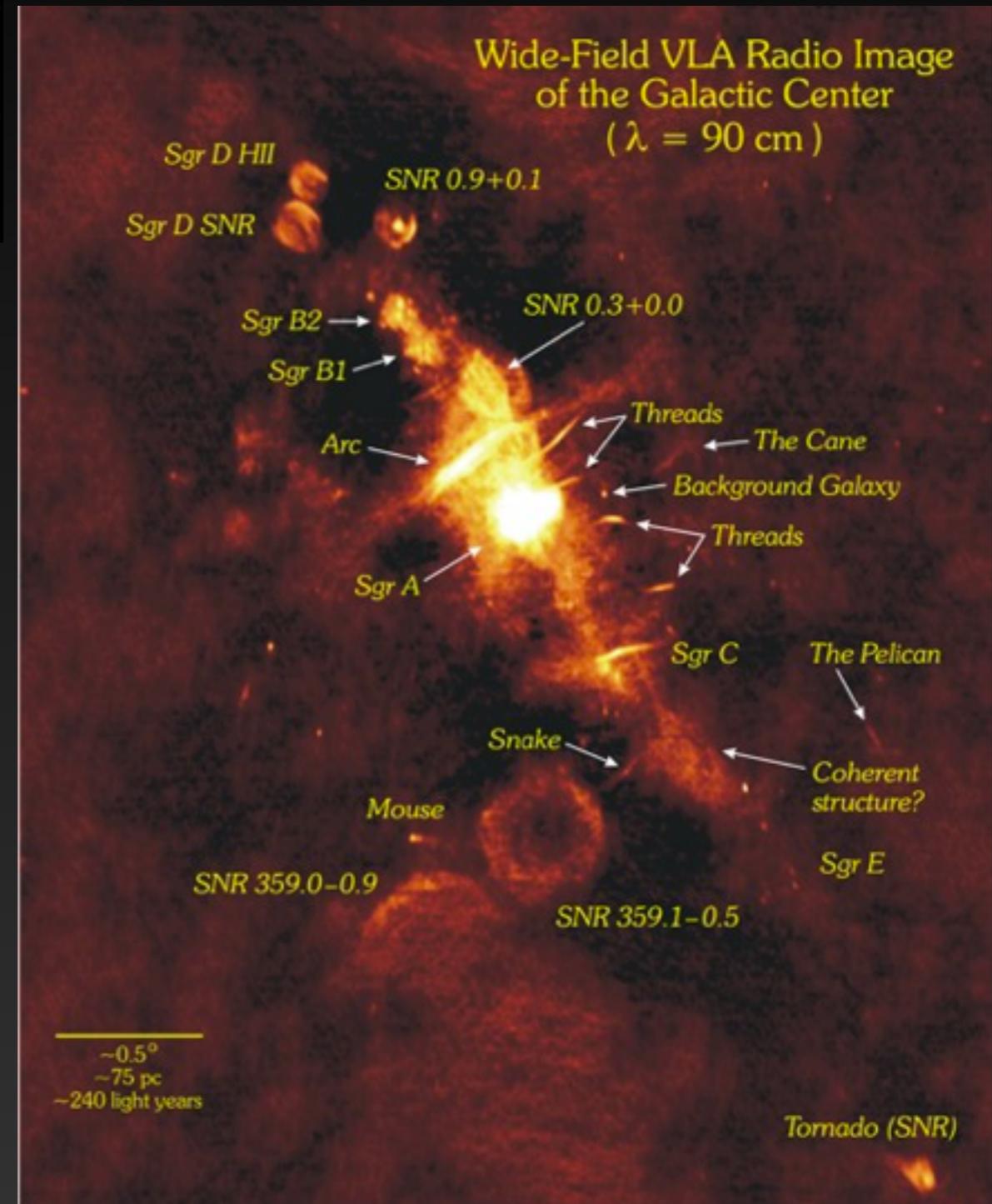


Current Observations of GC



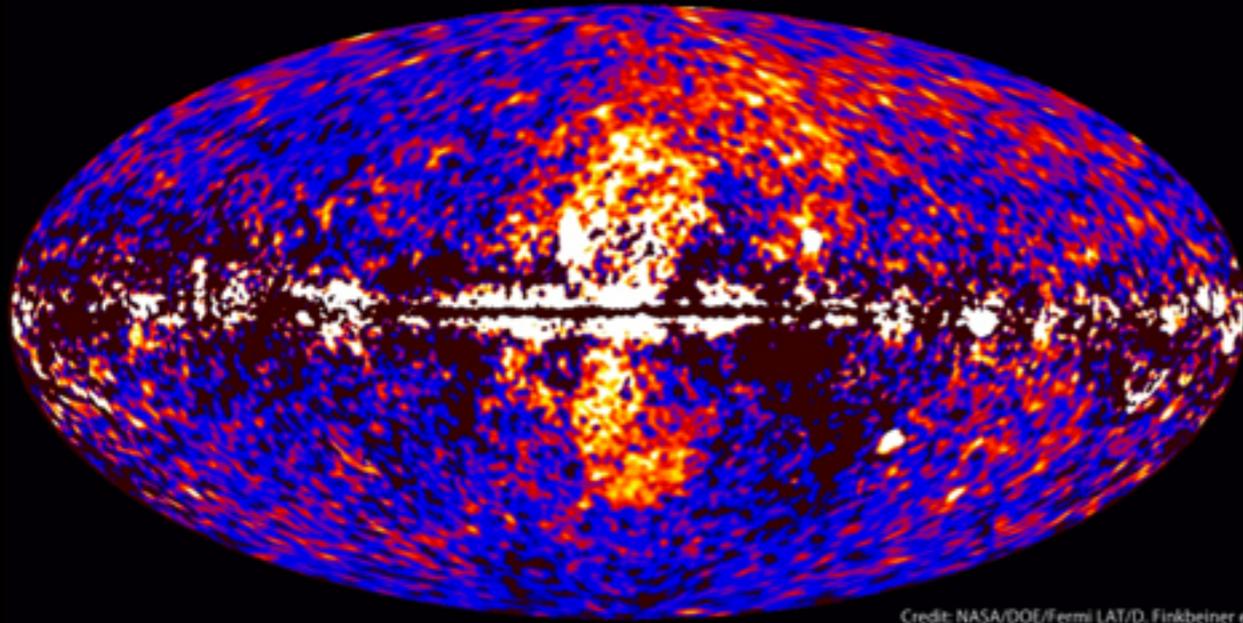
However, observations of the GC find intense star formation and many supernovae remnants.

e.g. 5-10% of the total galactic SFR rate occurs in the Central Molecular Zone (Longmore et al. 2012)

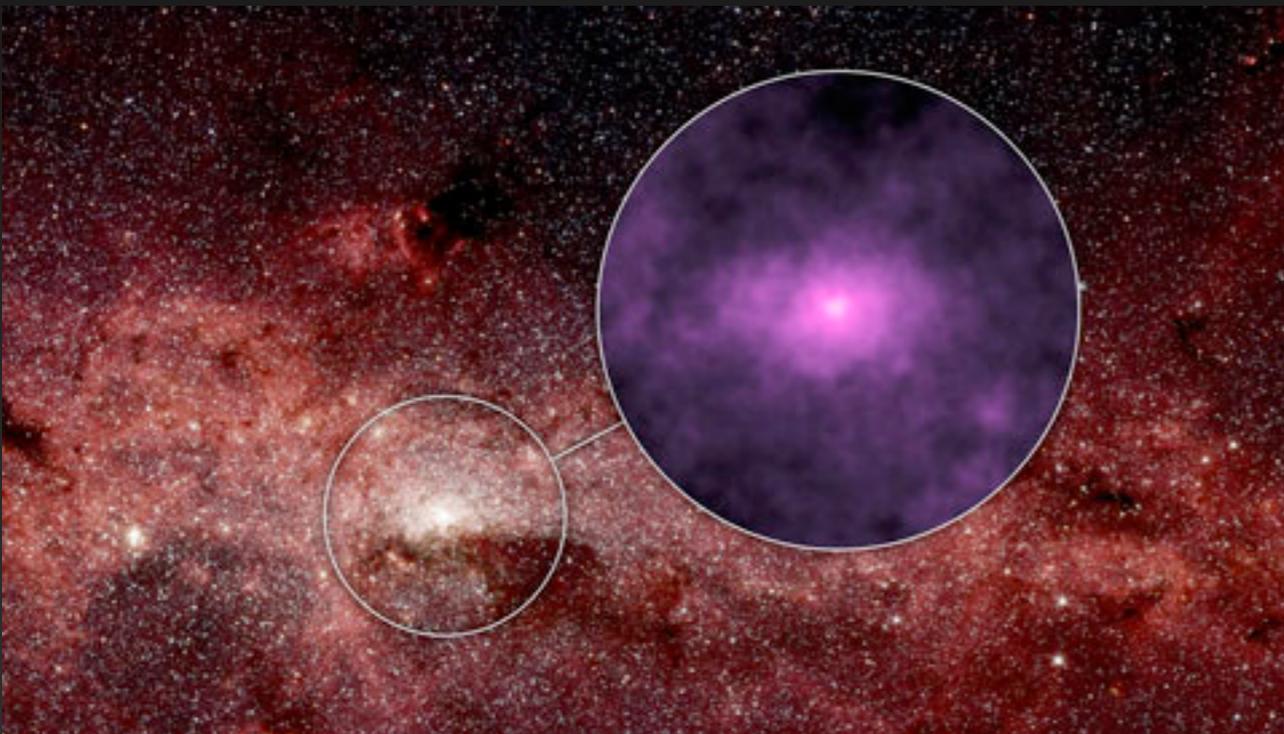
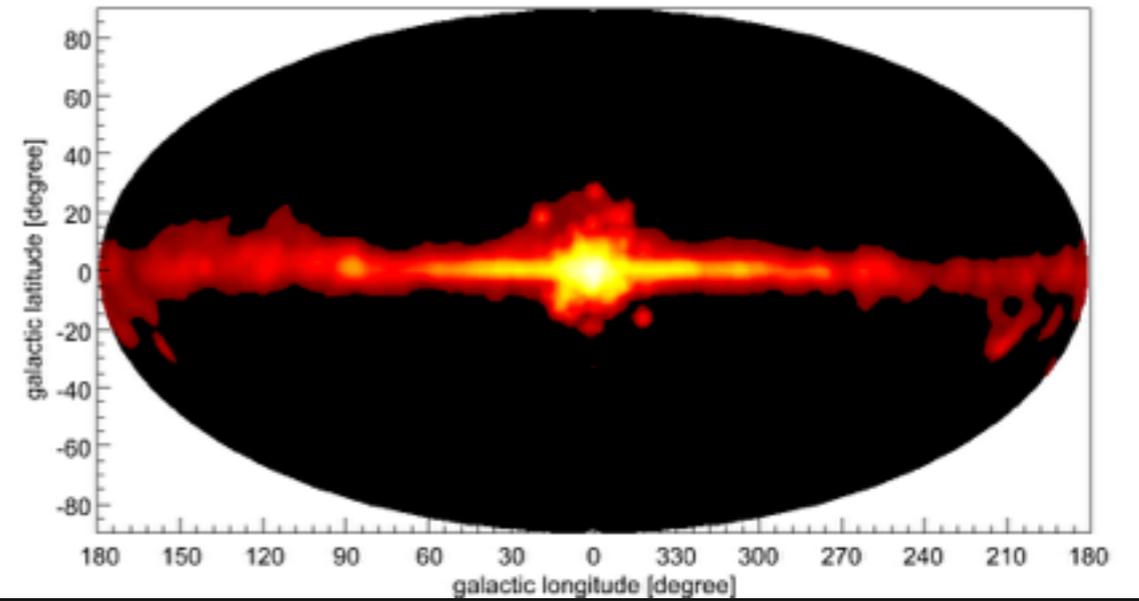


Excesses are not Limited to GeV Energies

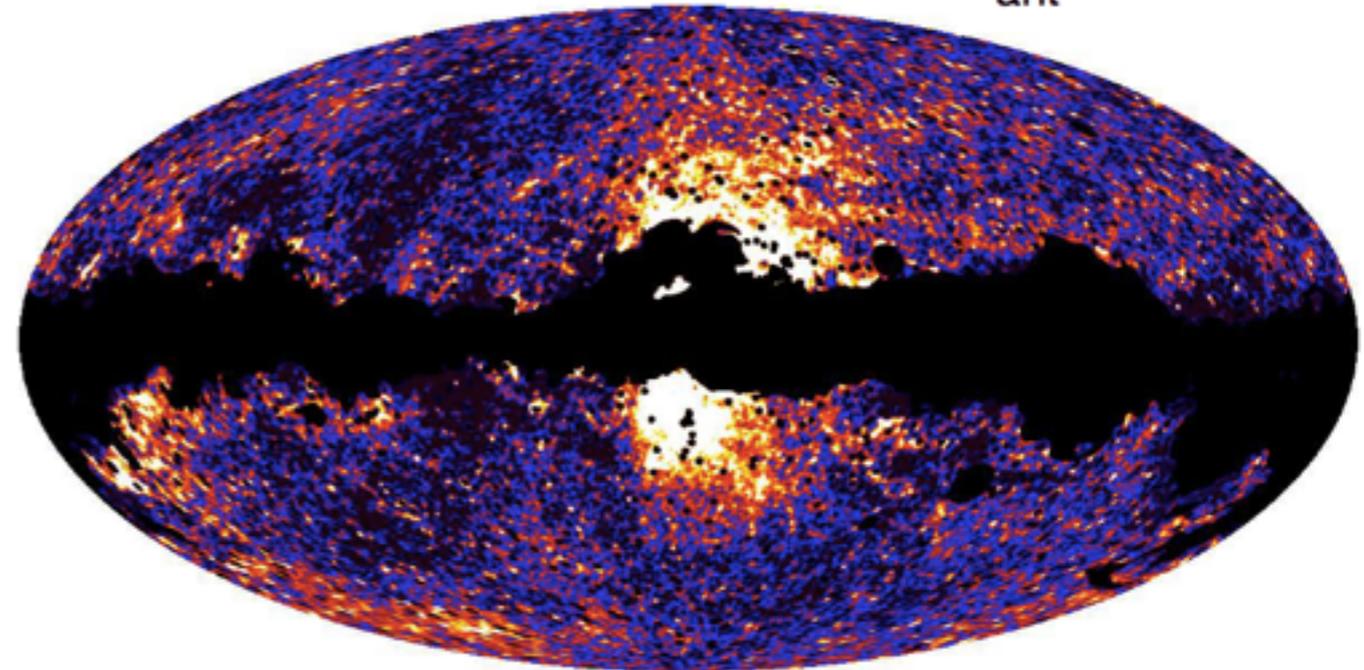
Fermi data reveal giant gamma-ray bubbles



All-sky image in the 511 keV line after 5 years



WMAP K-band $T_{\text{ant}}^{\text{K}}$



Cosmic-Ray Injection Sources

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

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

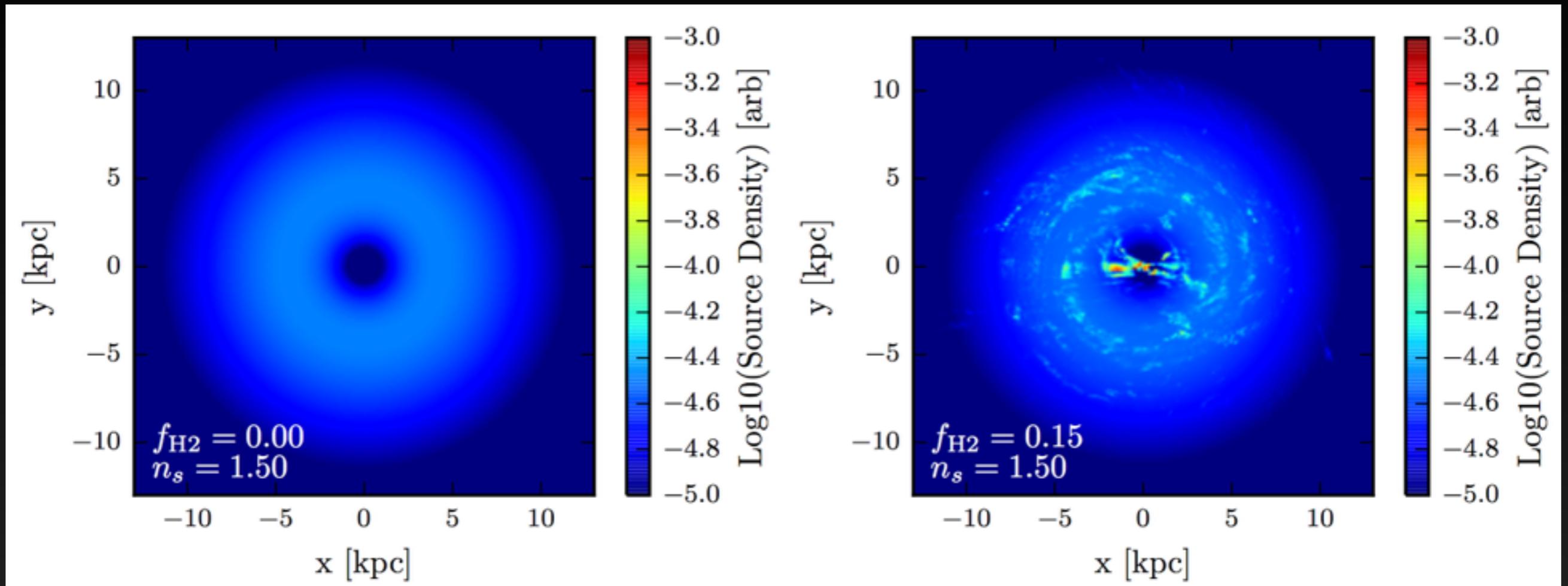
Theoretically Motivated: Molecular Gas is the seed of star formation, the Schmidt Law gives

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

Specifically we inject a fraction of cosmic-rays (f_{H_2}) following:

$$Q_{\text{CR}}(\vec{r}) \propto \begin{cases} 0 & \rho_{\text{H}_2} \leq \rho_s \\ \rho_{\text{H}_2}^{n_s} & \rho_{\text{H}_2} > \rho_s \end{cases}$$

Cosmic-Ray Injection in the GC

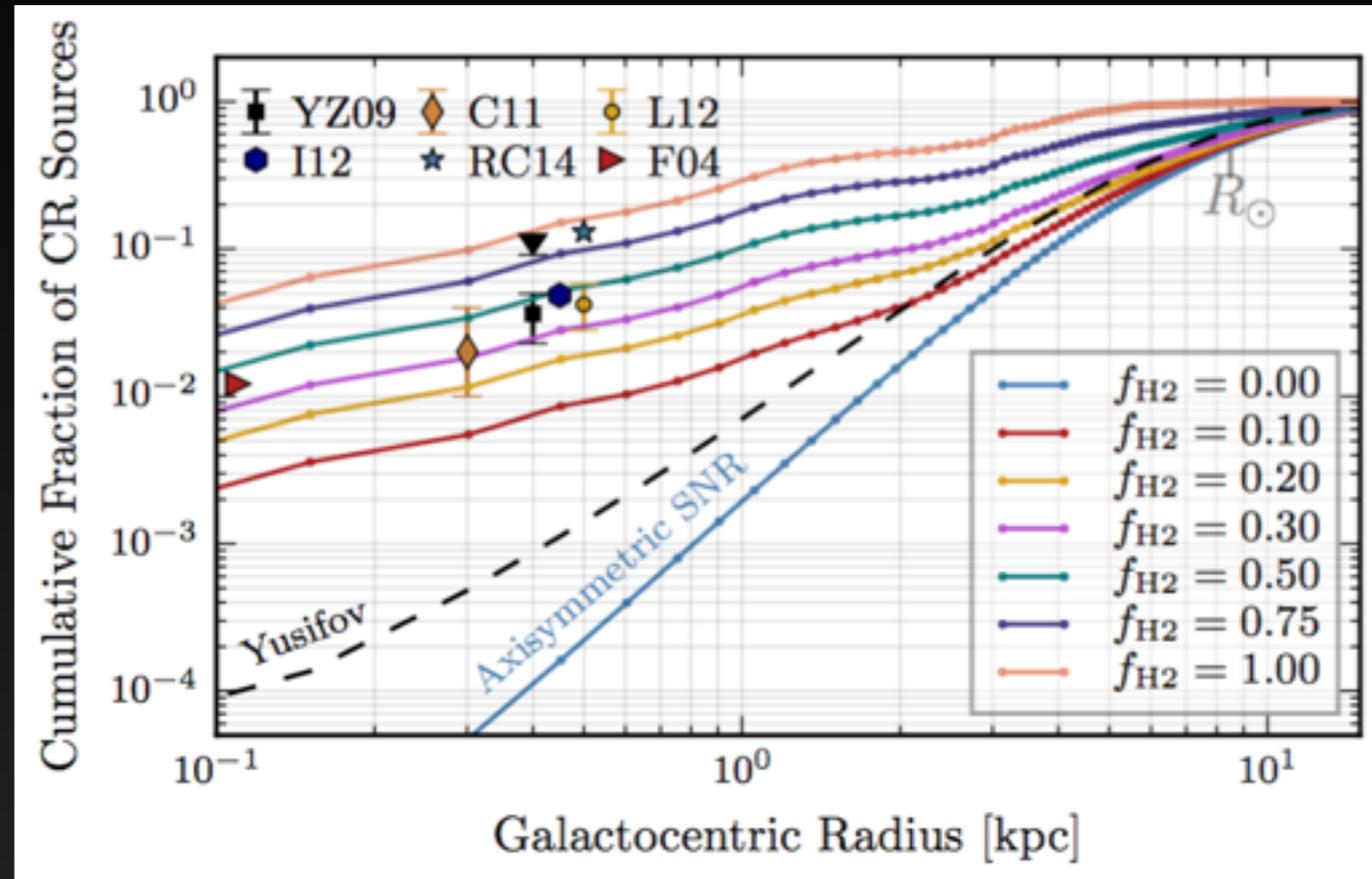
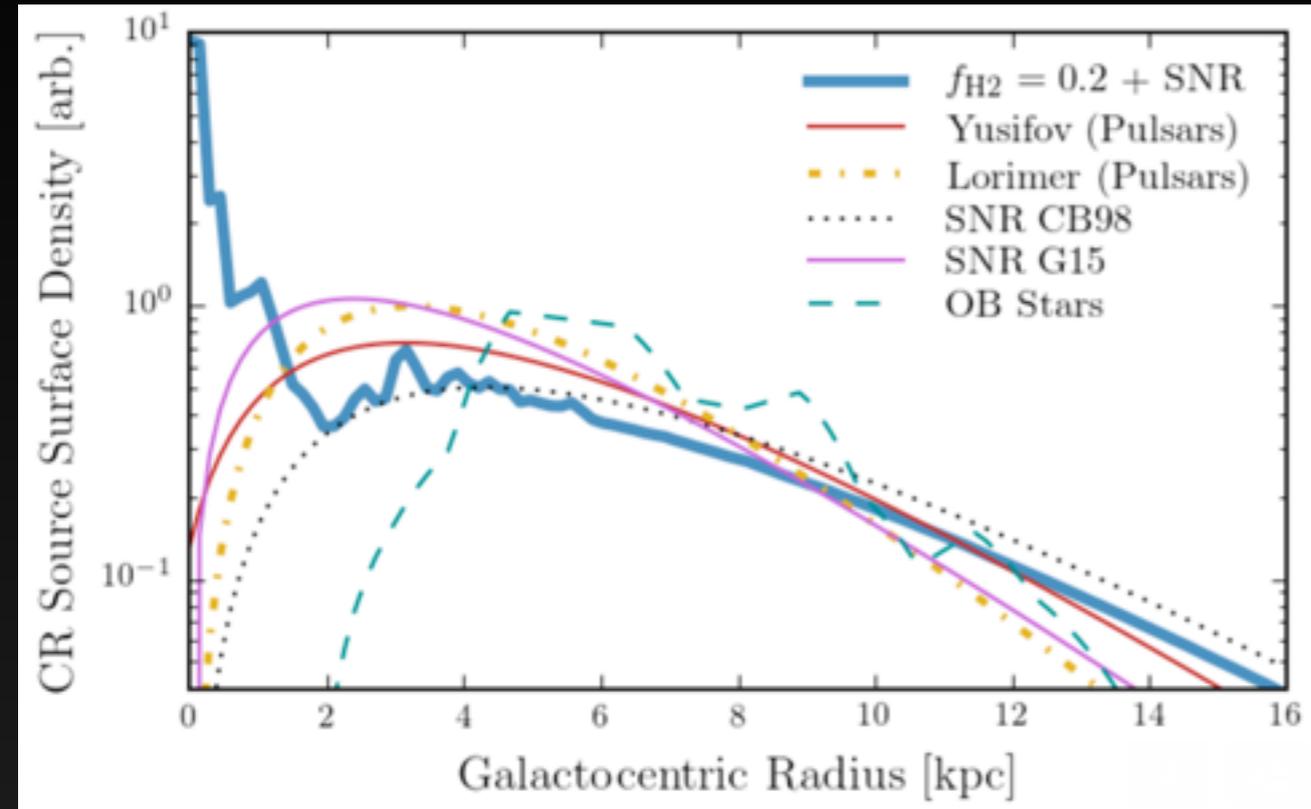


Two features leap out immediately:

1.) Spiral Arms

2.) A bright bar in the Galactic Center

Adding a Molecular Gas Component



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

The cosmic-ray injection rate now matches observational constraints

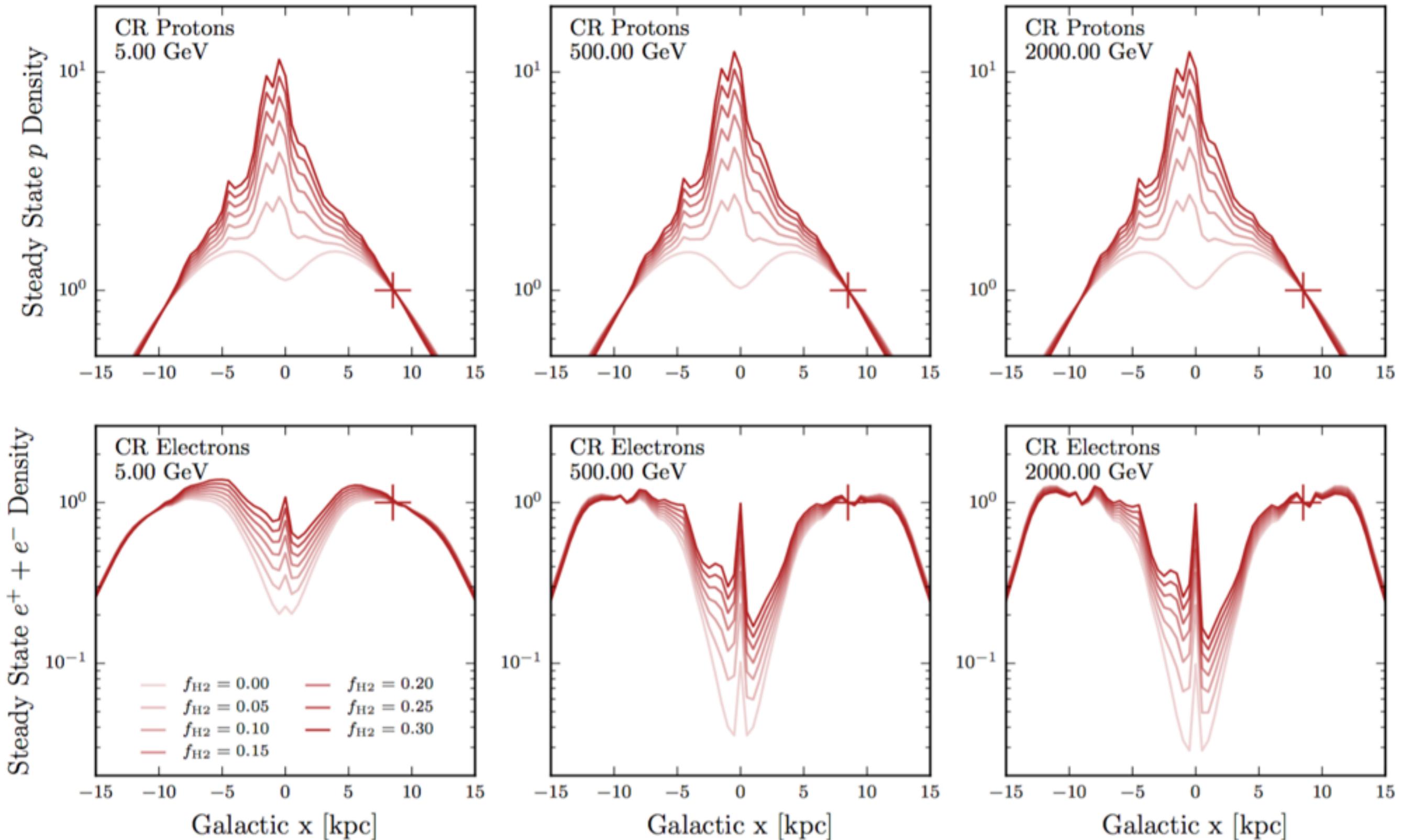
Galprop Simulations

Parameter	Units	Canonical	Mod A	Description
D_0	$\text{cm}^2 \text{s}^{-1}$	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	$\text{km s}^{-1} \text{kpc}^{-1}$	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 $(1 - f_{\text{H}_2})$ primary sources*
f_{H_2}	–	.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

New Cosmic-Ray Injection models are added into a fully-3D realization of Galprop. XCO ratios are fitted in galactocentric rings in order to produce a full diffuse model (e.g. Ackerman et al. 2012)

New models for the 3D galactic gas density are also produced (Carlson 2015, to be submitted).

Steady State Cosmic-Ray Distribution

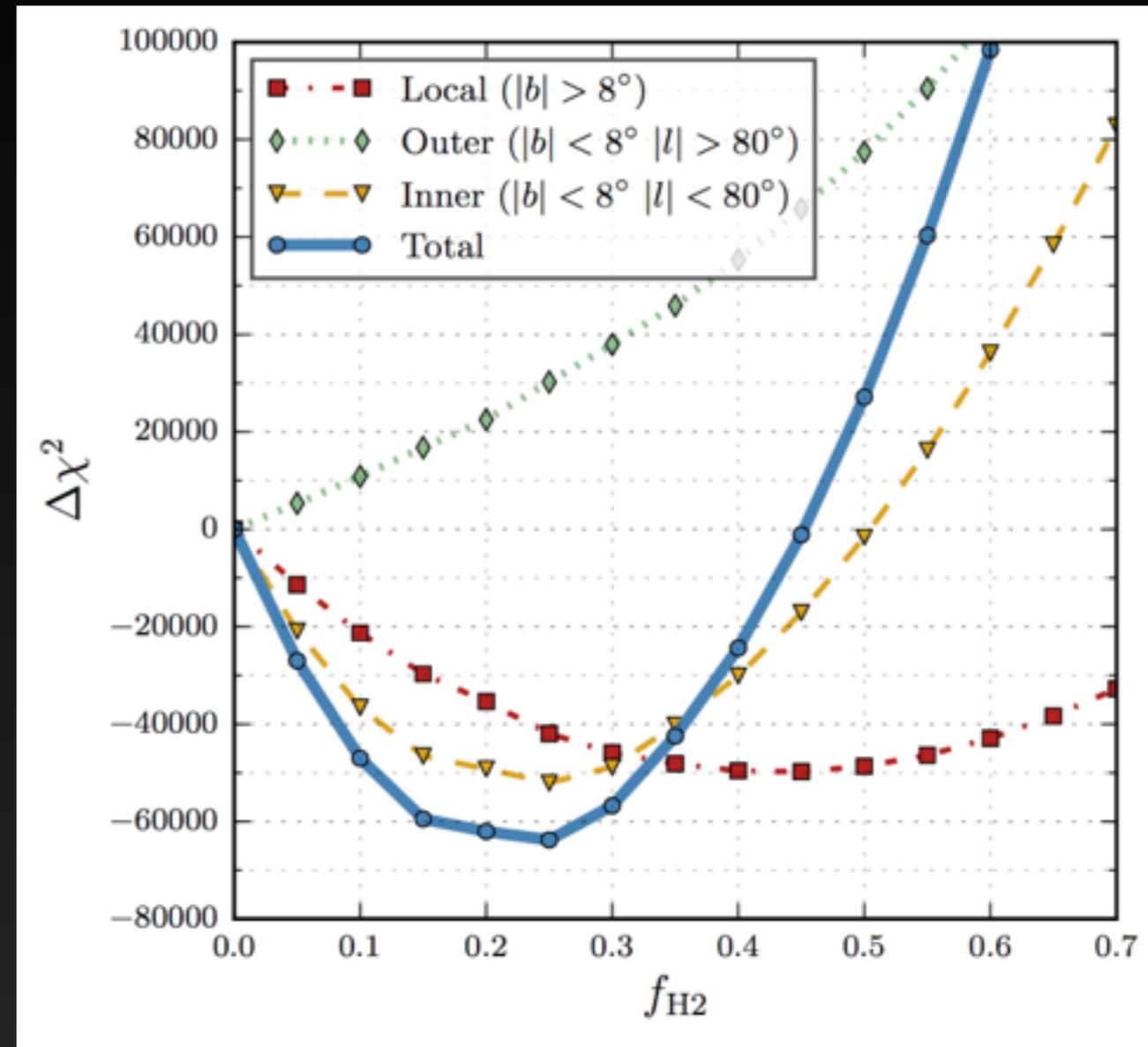


A Better fit to the Gamma-Ray Sky

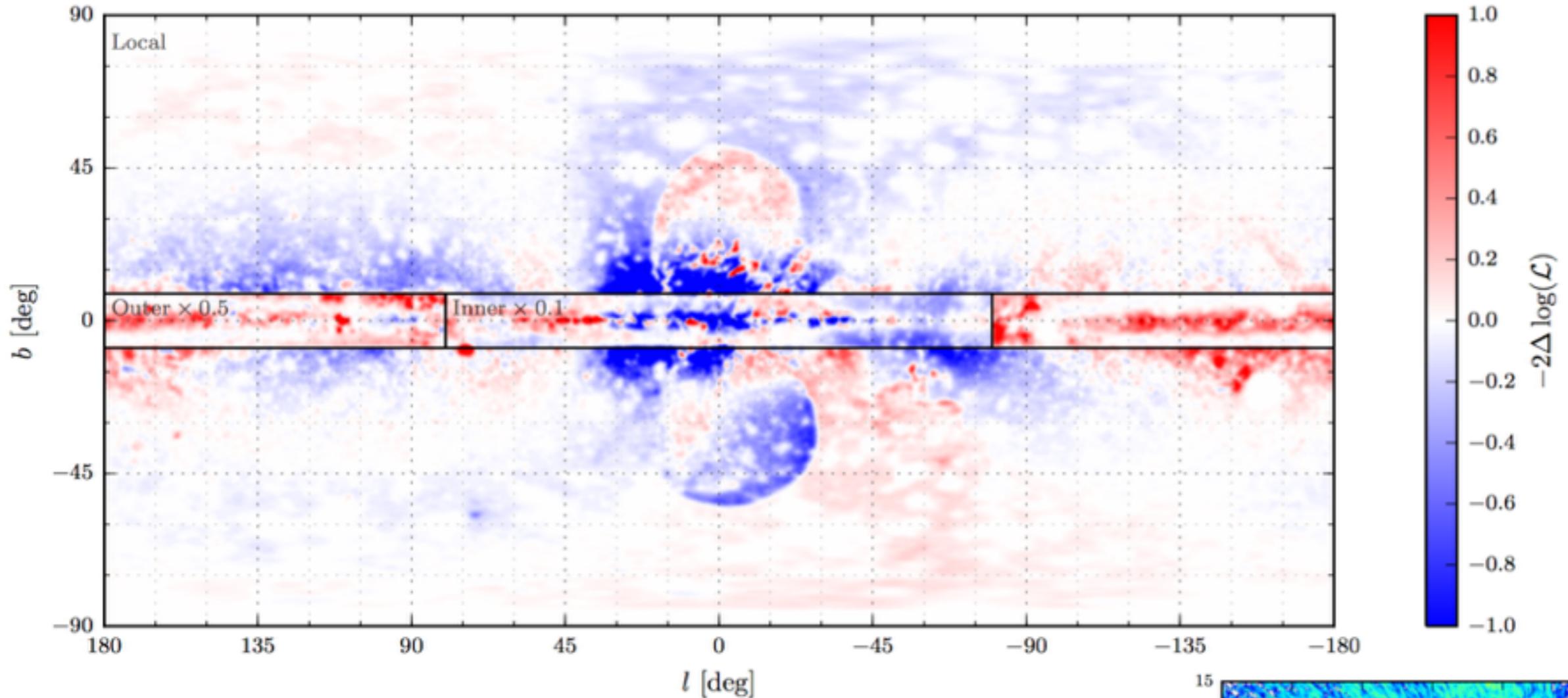
1.) The addition of a new cosmic-ray injection template tracing the 3D H₂ density greatly improves the overall fit to the gamma-ray diffuse emission.

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

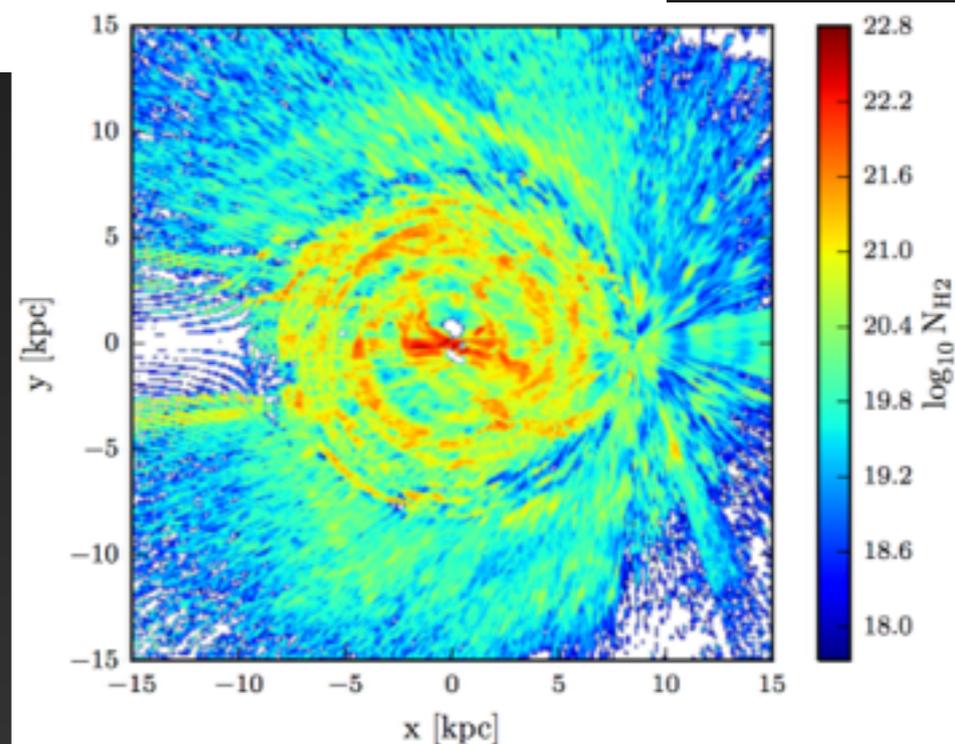
3.) Technique will become more powerful with the introduction of 3D gas and dust maps in the near future.



A Better fit to the Gamma-Ray Sky

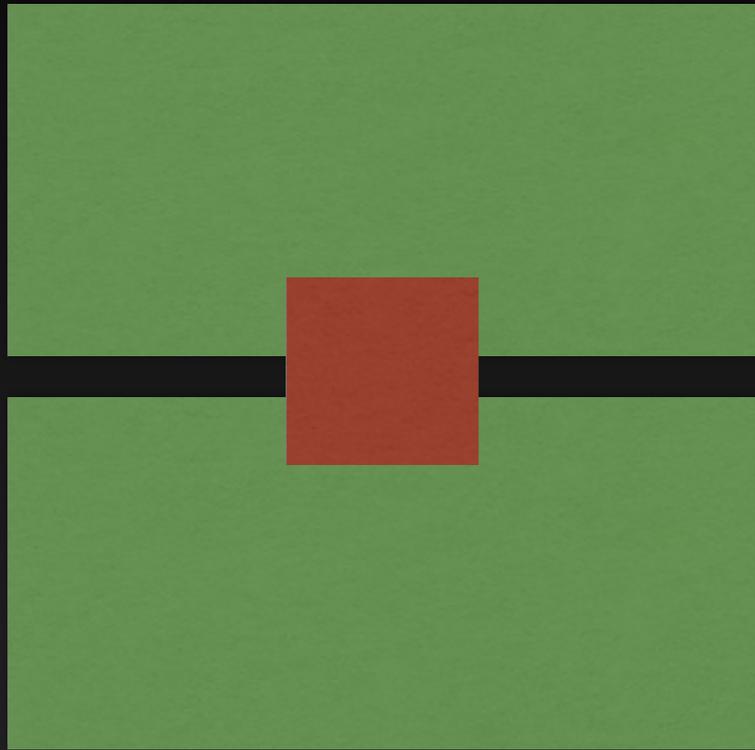


Fits are significantly improved, in particular in regions near the Galactic Center where there is significant kinematic gas information.



An Inner Galaxy Analysis of the GCE

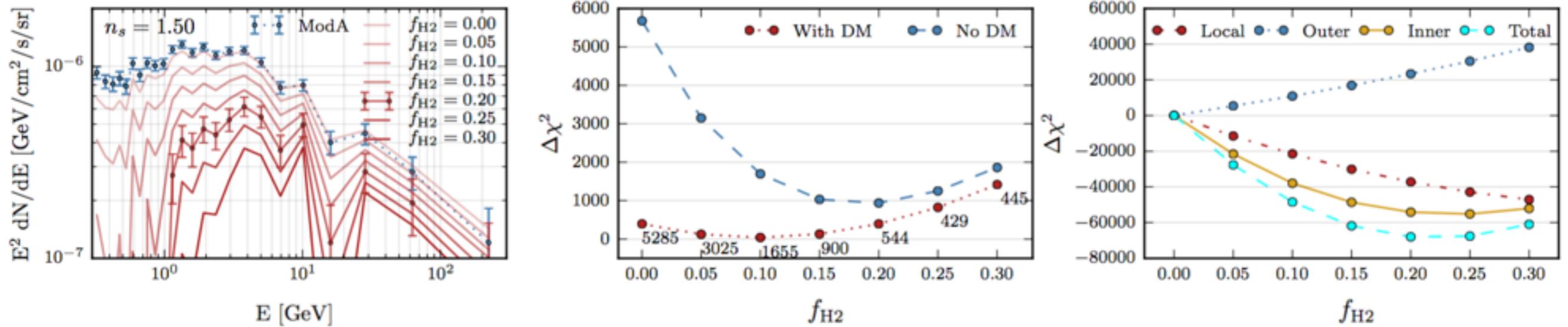
INNER GALAXY



- 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.

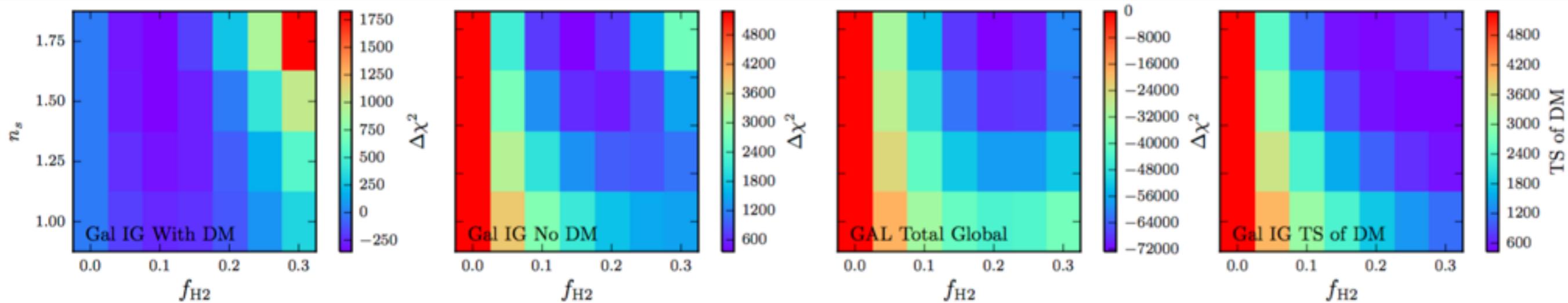
Effect on the Gamma-Ray Excess



Adding cosmic-rays injection tracing the H₂ density significantly decreases the overall normalization of the gamma-ray excess.

However, when dark matter is included, the best fit value of f_{H2} is approximately 0.1

The Excess is Degenerate with f_{H2}

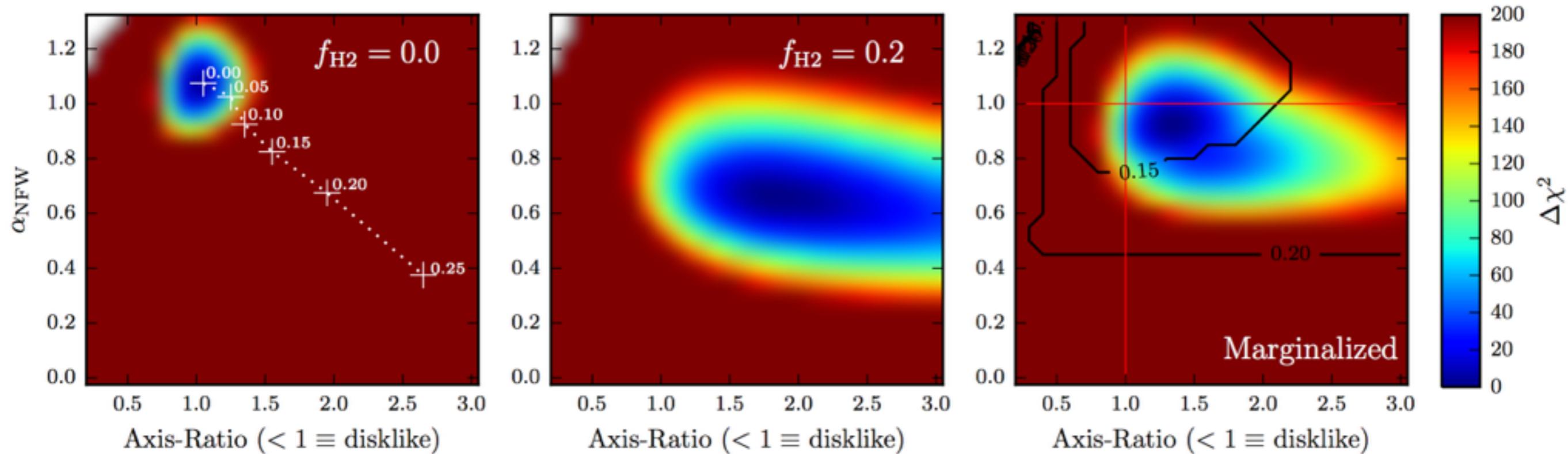


Models with no dark matter universally prefer $f_{H2} \sim 0.2$ for the $40^\circ \times 40^\circ$ region surrounding the GC.

Models with an NFW emission template prefer $f_{H2} \sim 0.1$.

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

GC Excess Morphology

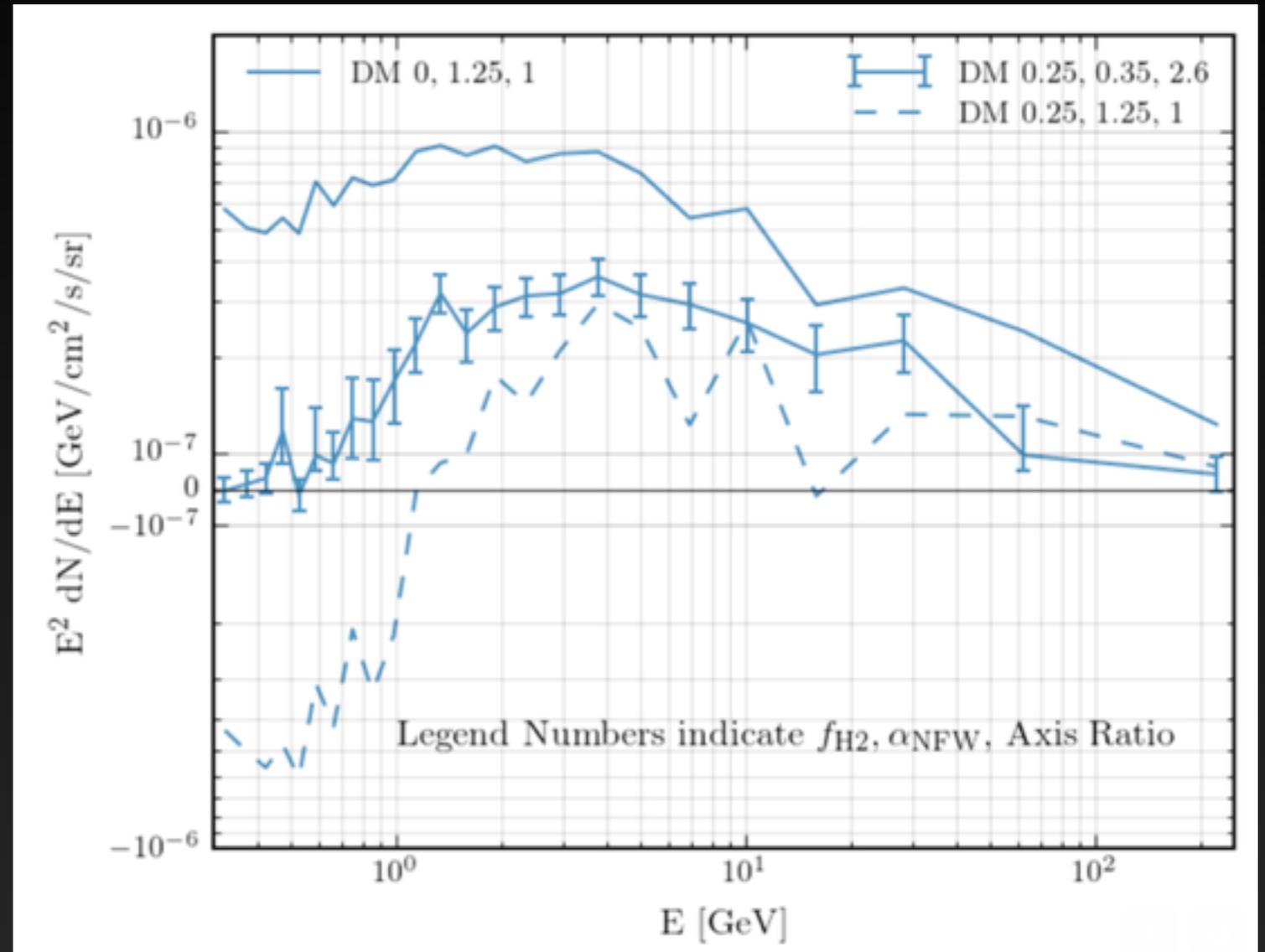


The morphology of the gamma-ray excess is also affected, becoming flatter, and extended perpendicular to the Galactic plane for high values of $f_{\text{H}2}$.

A Fermi Bubbles Component?

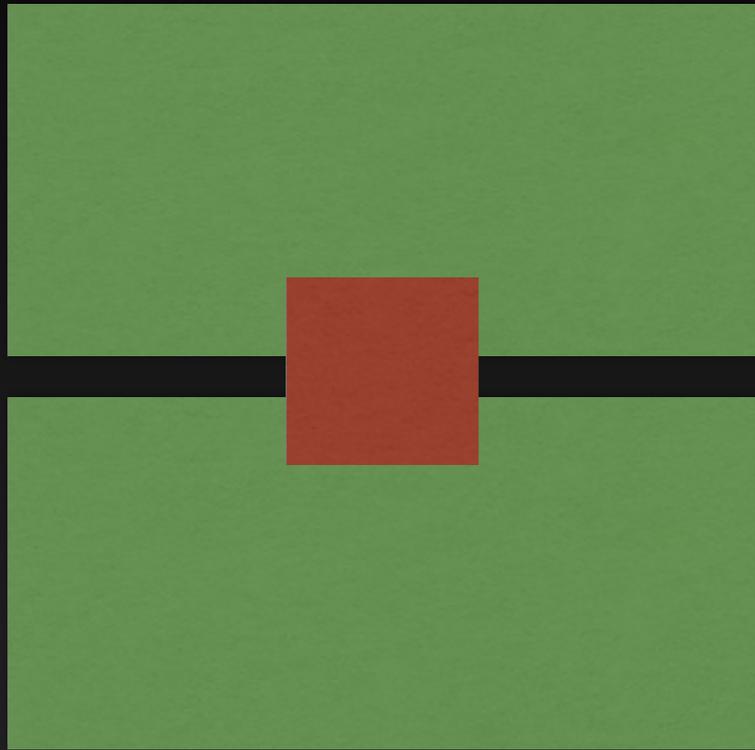
When the excess floats to the best fit morphological configuration, much of the excess intensity returns.

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



A Galactic Center Analysis of the GCE

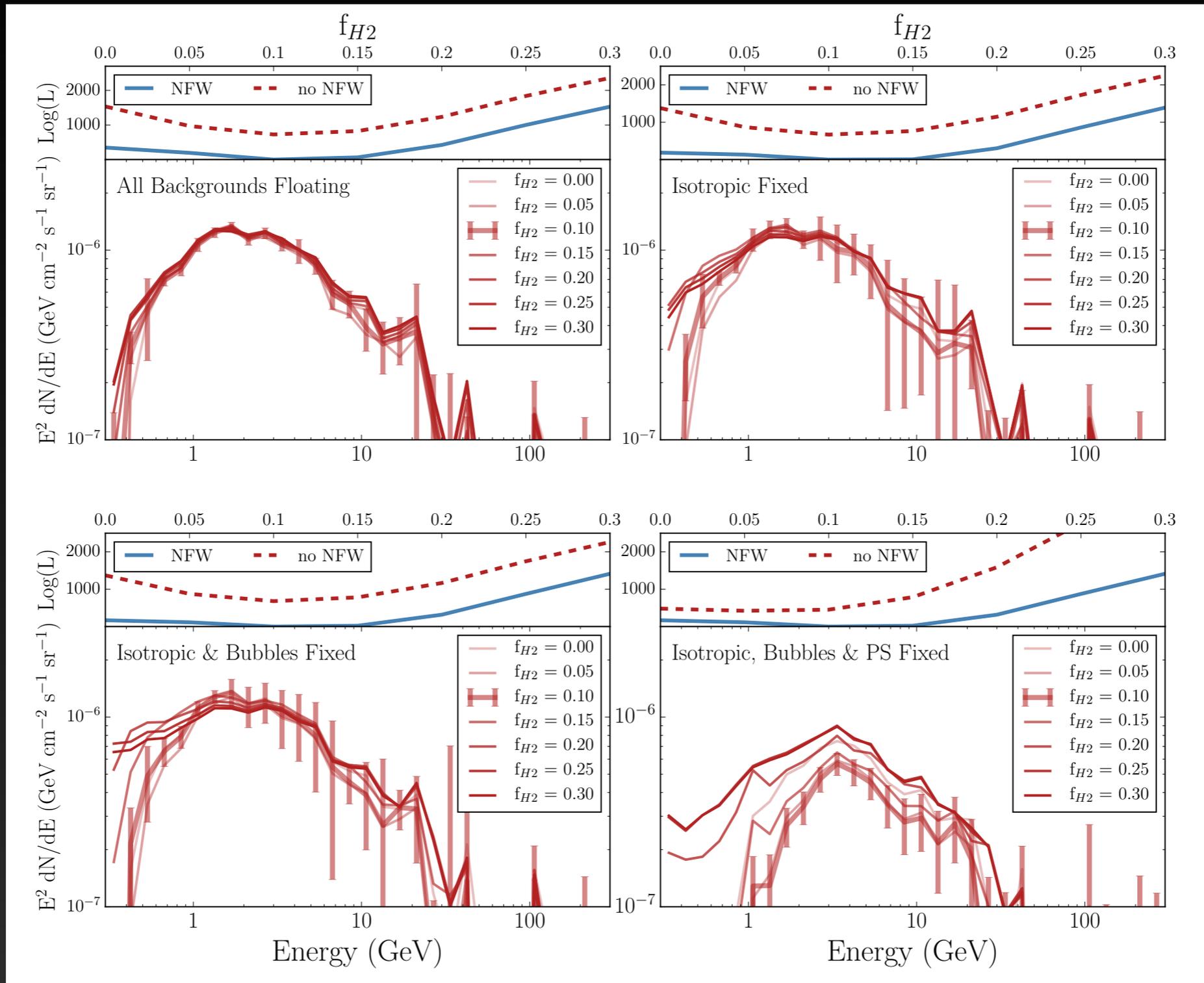
GALACTIC CENTER



- Examine $15^\circ \times 15^\circ$ 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.

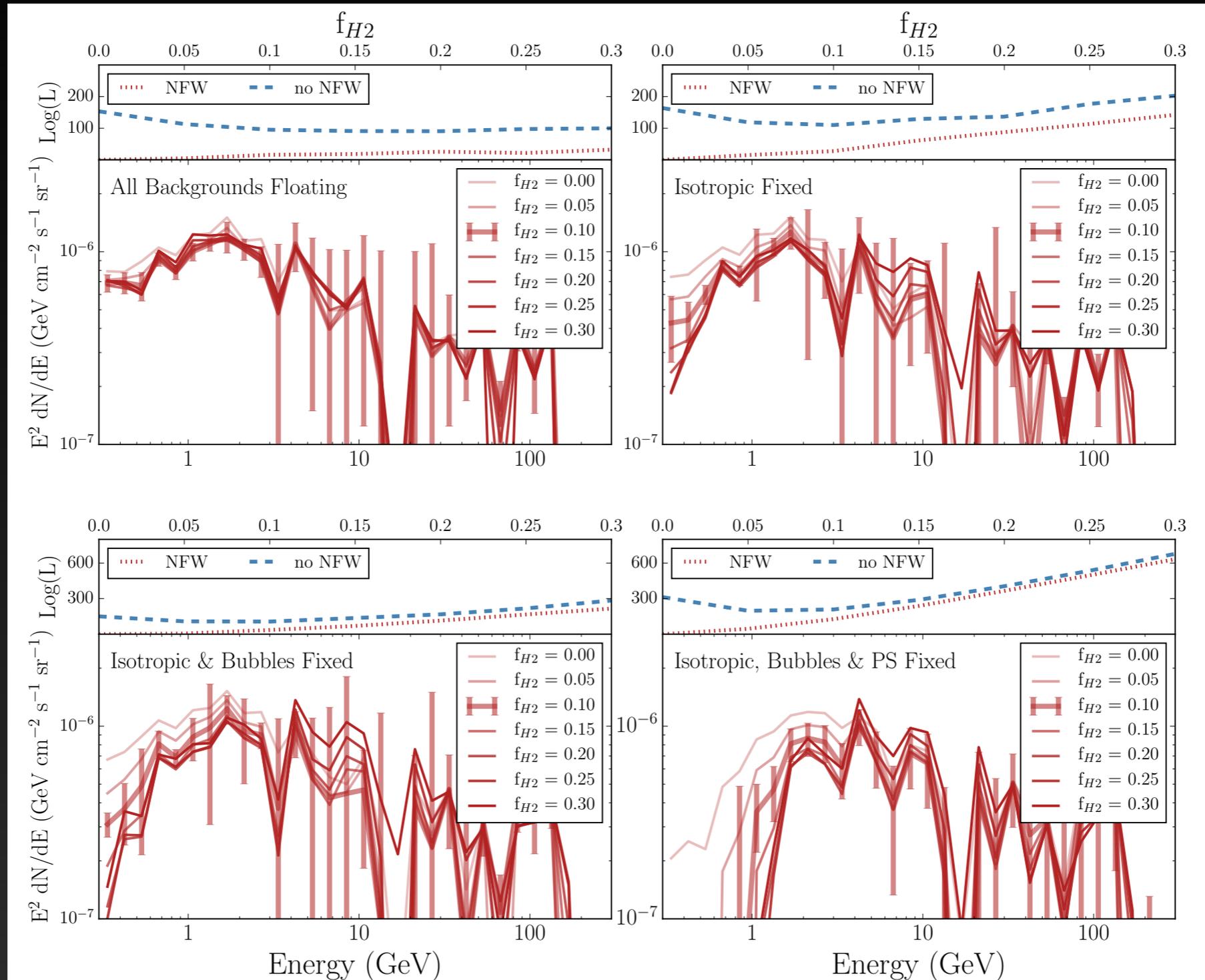
This creates an analysis with no sidebands region, where the NFW template normalization plays a critical role in determining the spectrum and normalization of diffuse components.

Studies of the Galactic Center ($15^\circ \times 15^\circ$)



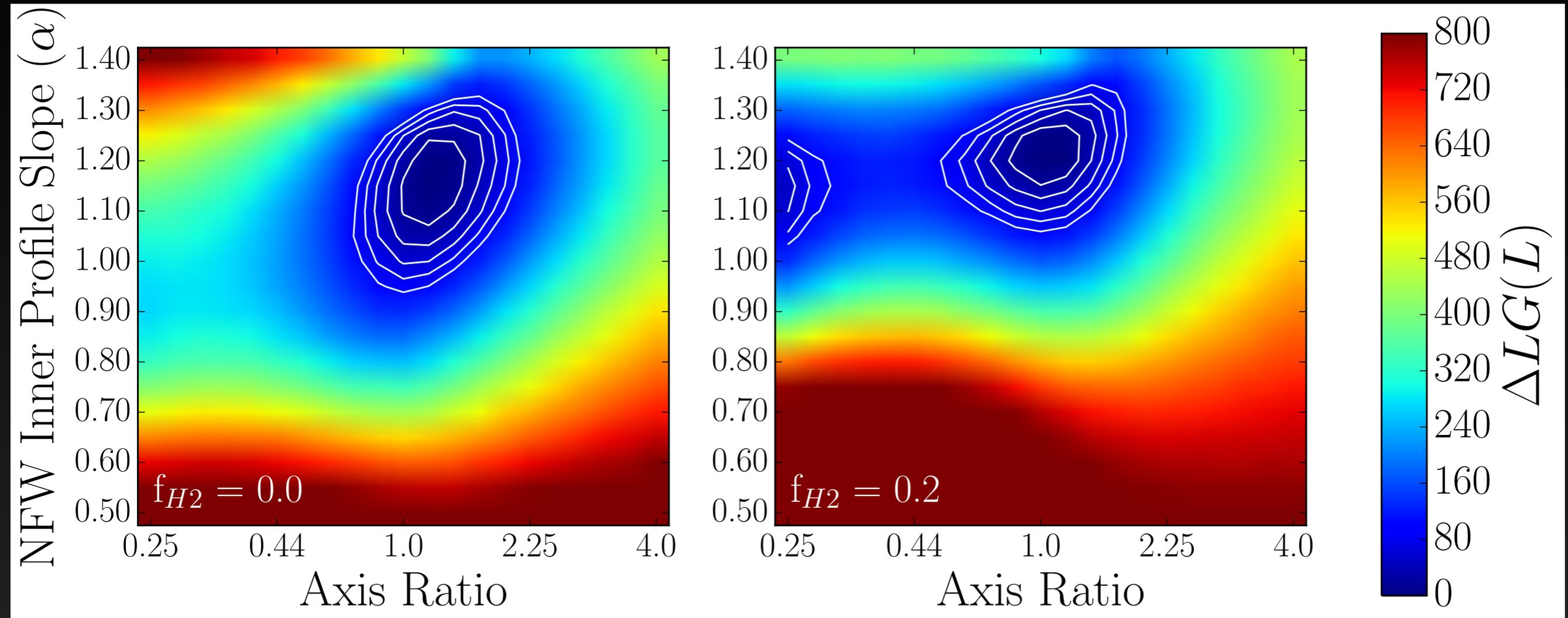
In this smaller region, the excess remains resilient to changes in diffuse emission modeling.

Masking $|b| < 2^\circ$



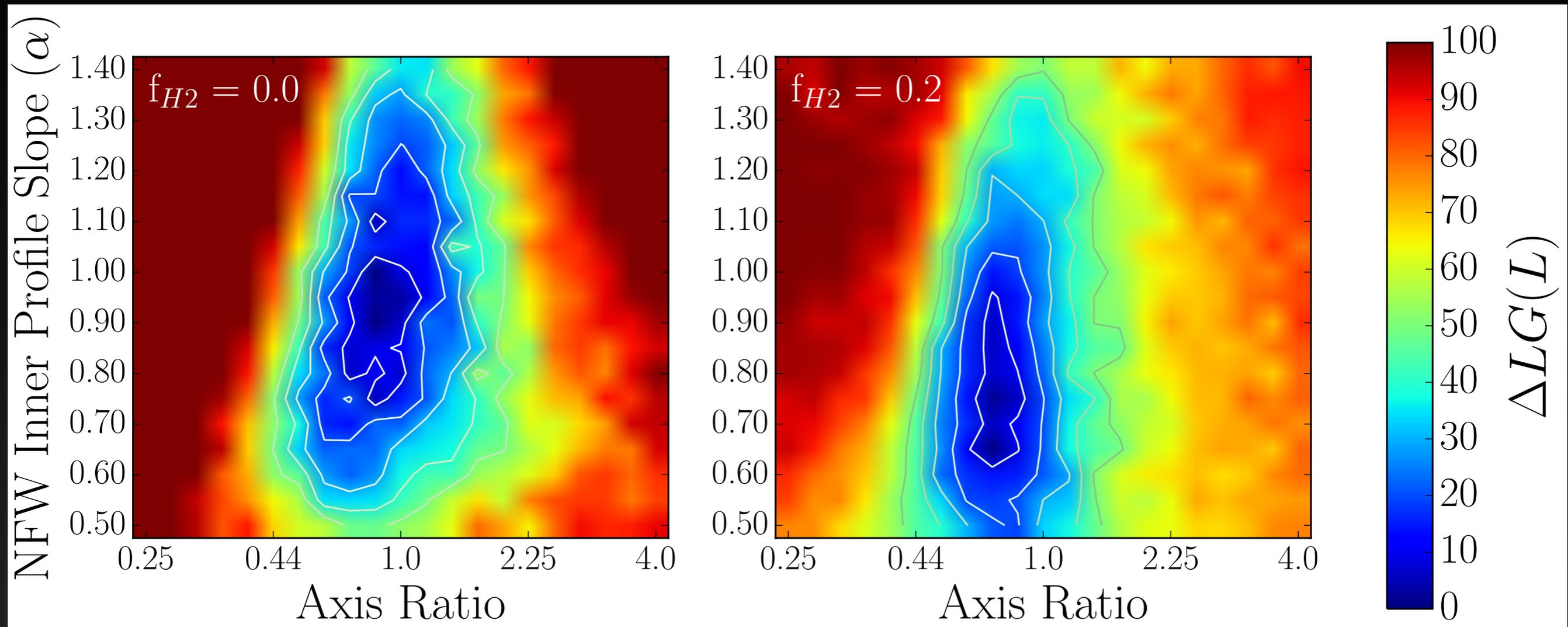
Intriguingly, this persists even when the inner 2° are masked - implying that analyses of small ROIs favors the excess.

Ellipticity in the GC Analysis



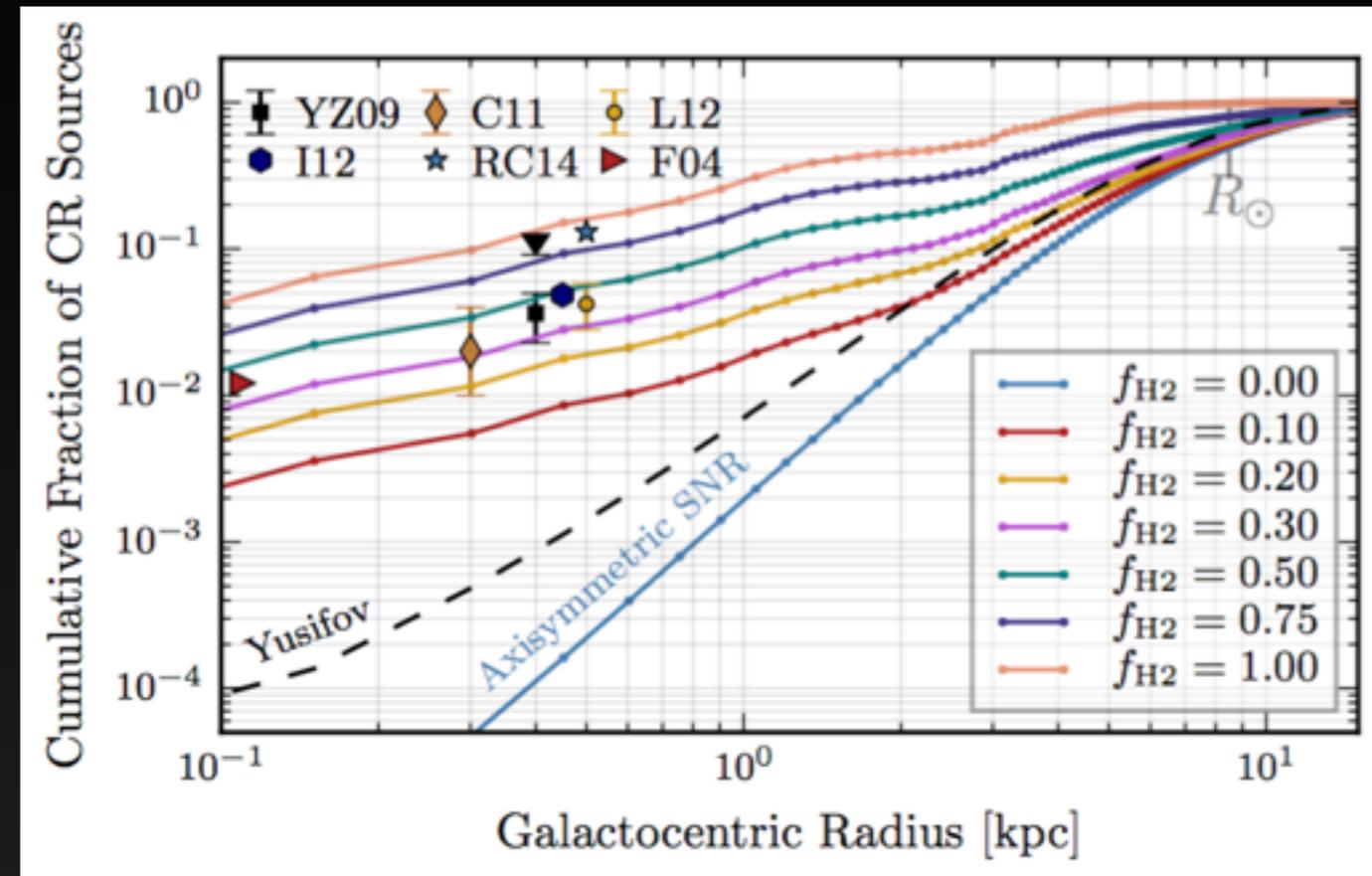
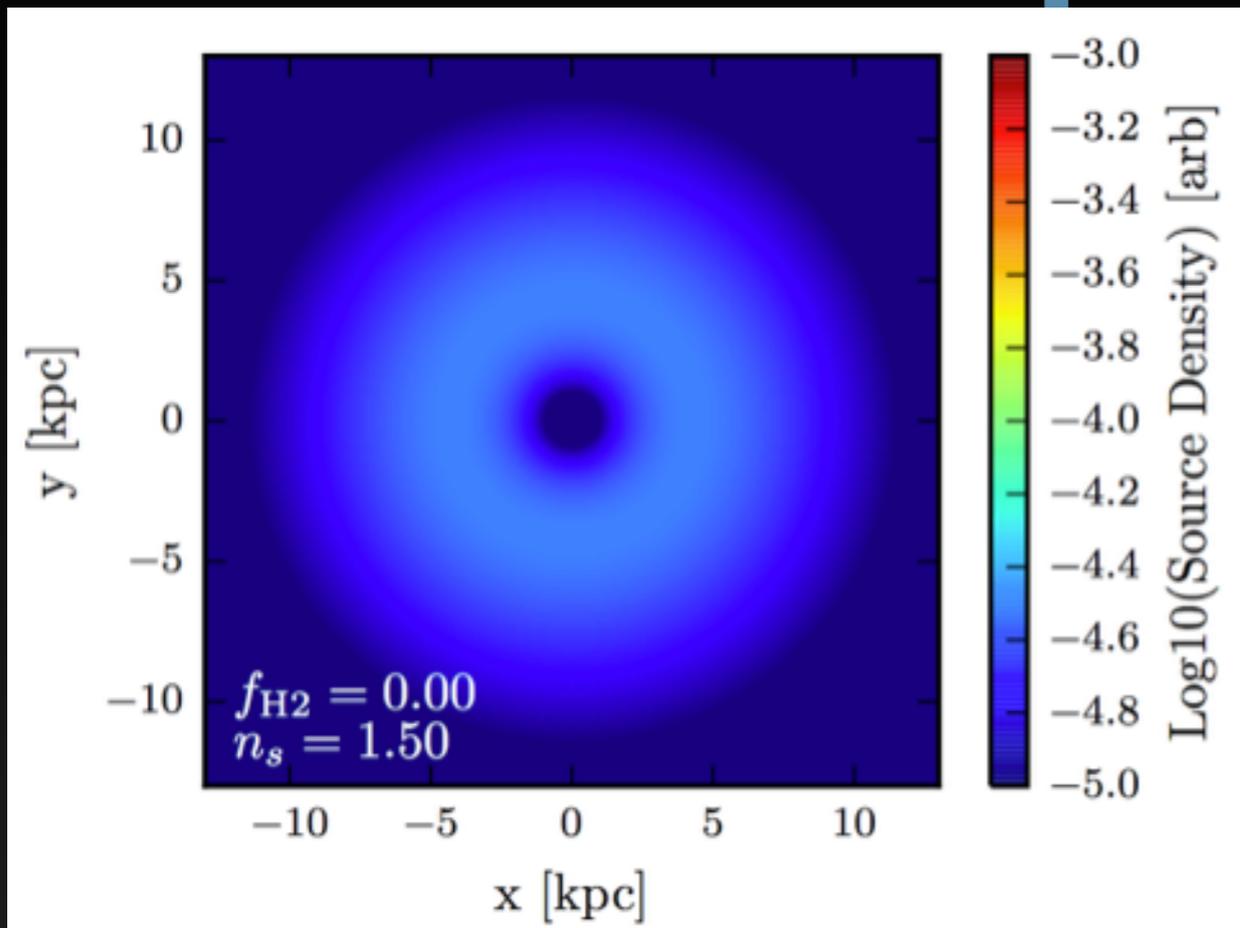
In the galactic center, spherical symmetry and a steep inner profile slope is still preferred by the data.

Ellipticity in the GC Analysis



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

Some Philosophical Rambling



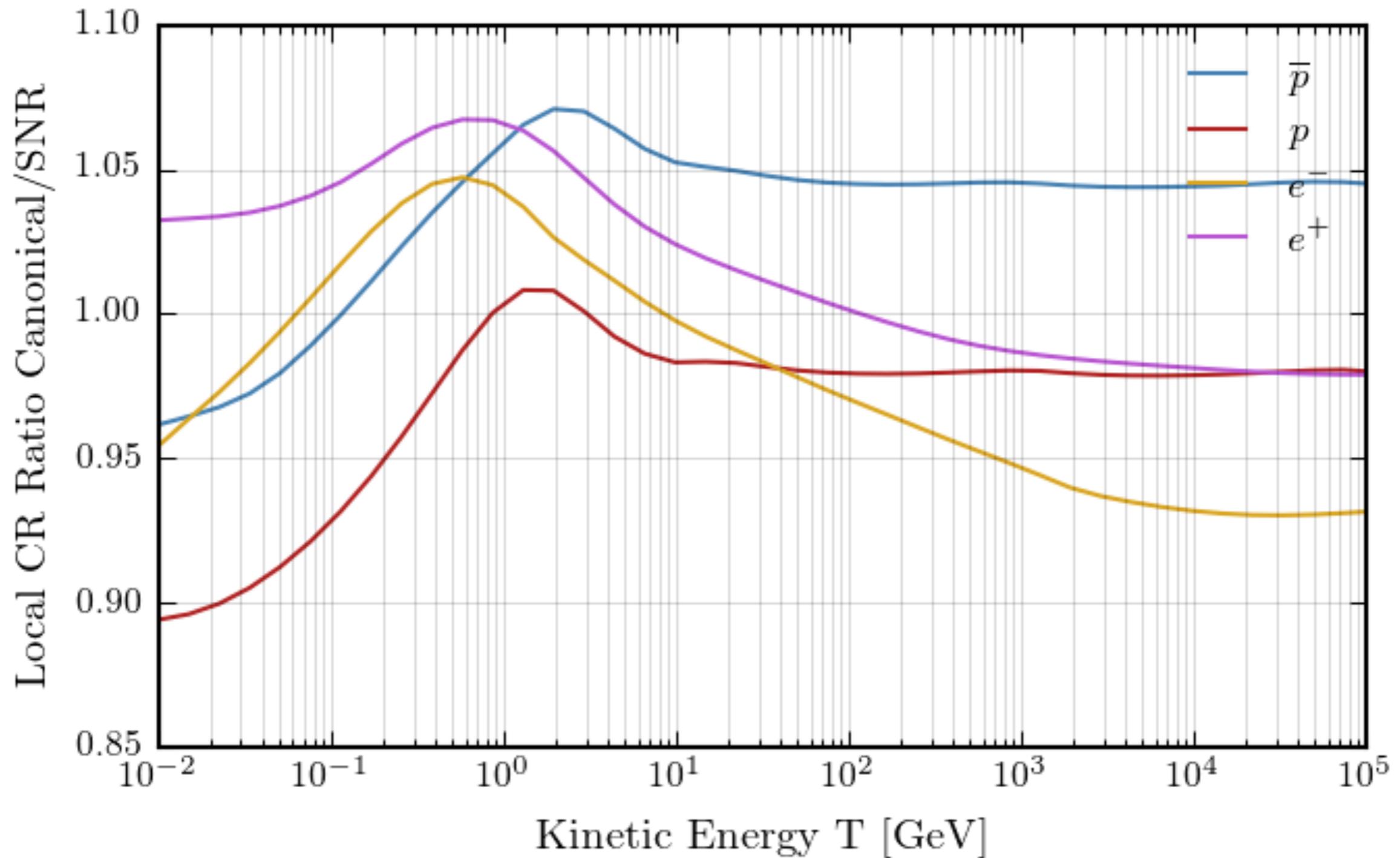
The lack of cosmic-ray injection in the GC should still be slightly disturbing. Especially when we try to answer the question: “excess compared to what?”

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.

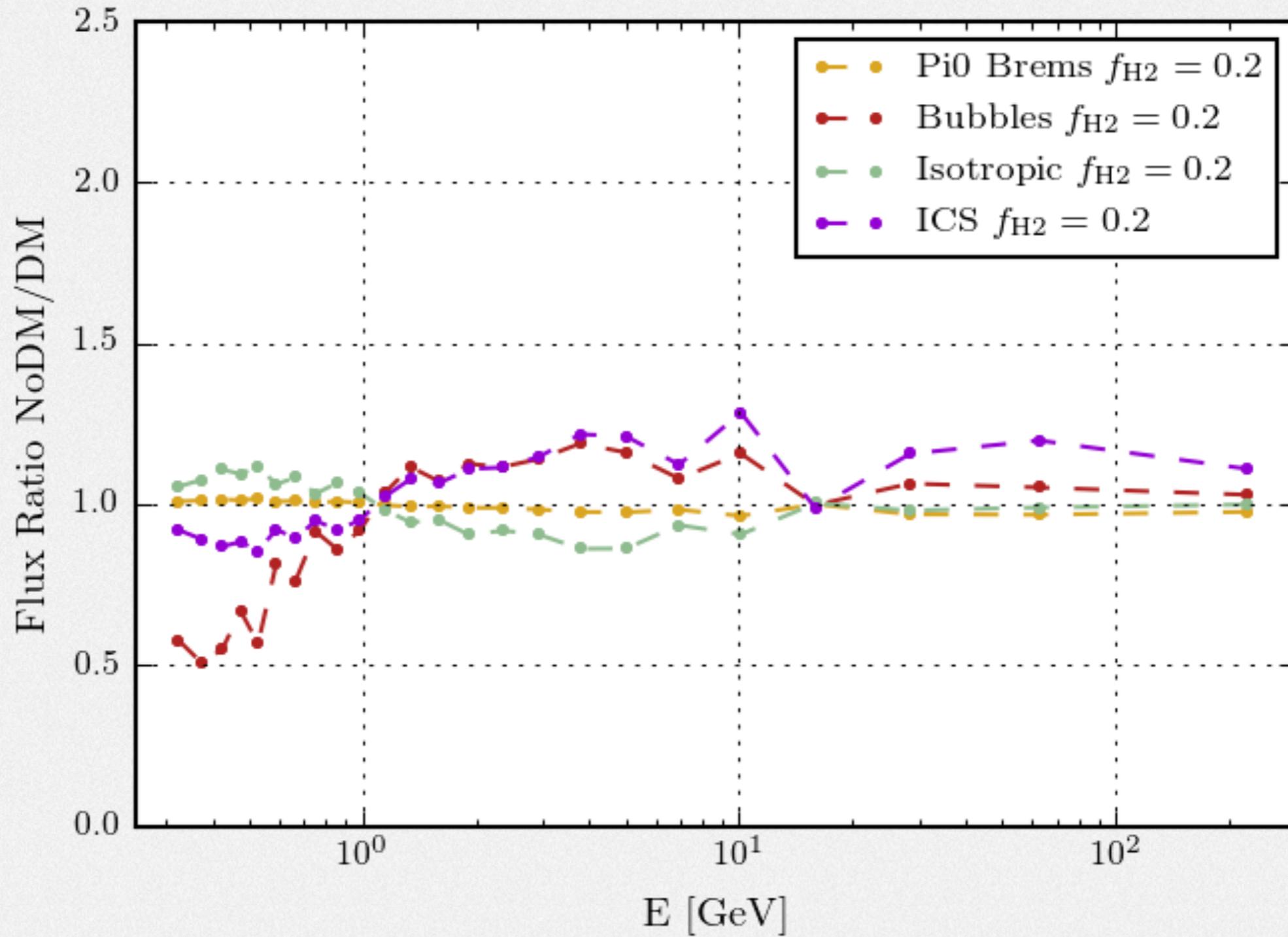
Coming to a Conclusion

- 1.) We introduce a new astrophysical emission tracer which:
 - a.) Improves the overall fit to the gamma-ray sky
 - b.) Is degenerate with properties of the gamma-ray excess
- 2.) The effect on the gamma-ray excess depends on the technique employed. In signal dominated regions the NFW template produces significant emission, while in side-bands dominated regions, the excess is greatly diminished.
- 3.) For a preferred value of $f_{\text{H}_2} \sim 0.1$, the morphology of the excess is significantly altered, producing a more cored, and slightly elliptical morphology.
- 3.) This model space is not yet fully explored, new models of H₂ gas near the GC may greatly improve our fits to the gamma-ray data. There is a clear path forward with enhanced gas observations.

Local Cosmic-Ray Flux



Changes in IG Spectra



Changes in IG Spectra

