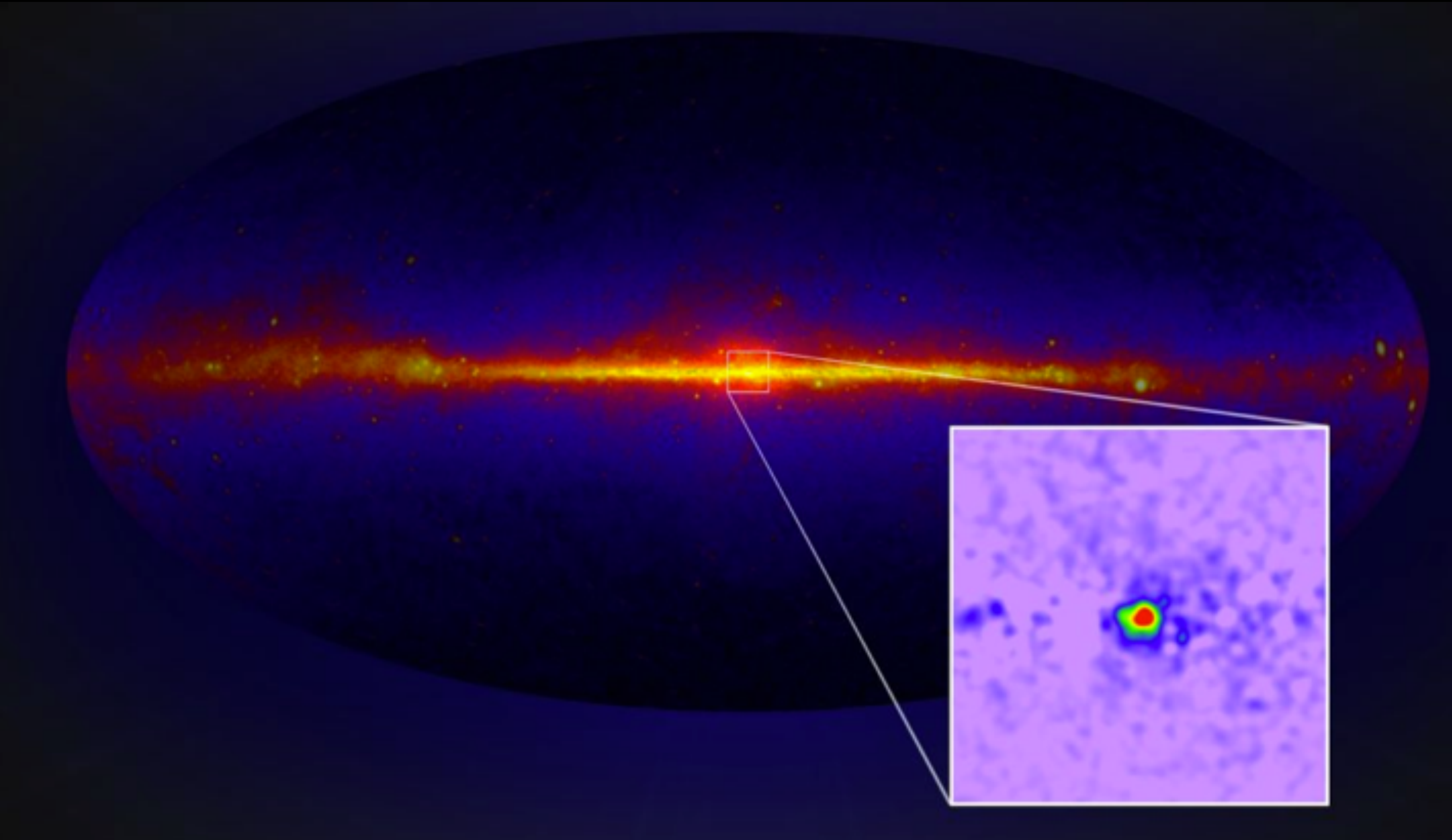

Diffuse Emission Models Confront the Galactic Center Excess

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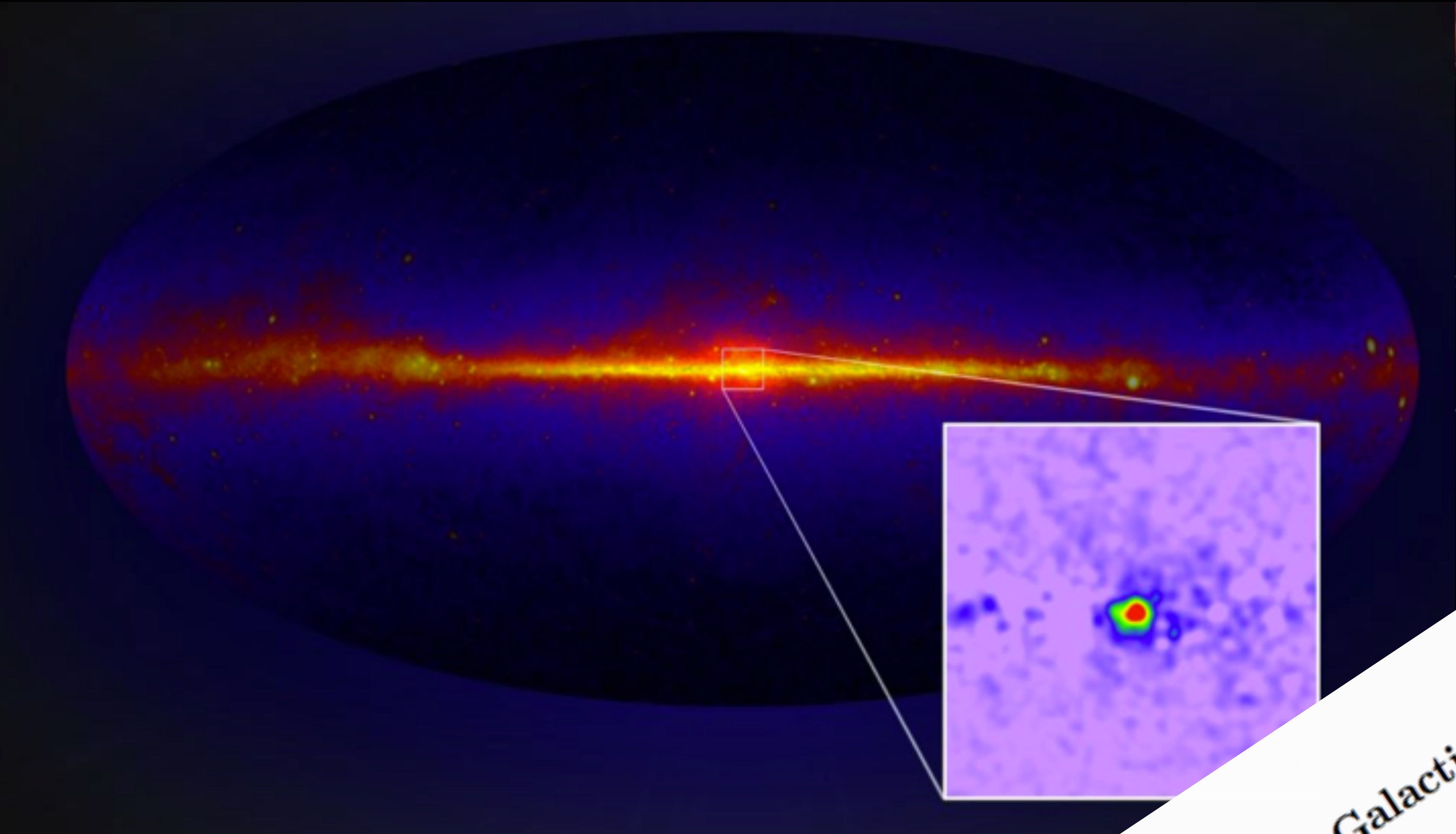
The Ohio State University

12th UCLA Dark Matter Conference

2/18/15



Diffuse Emission

the Galactic

Tim Linden

Einstein Pos

Center f

The Ohio

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

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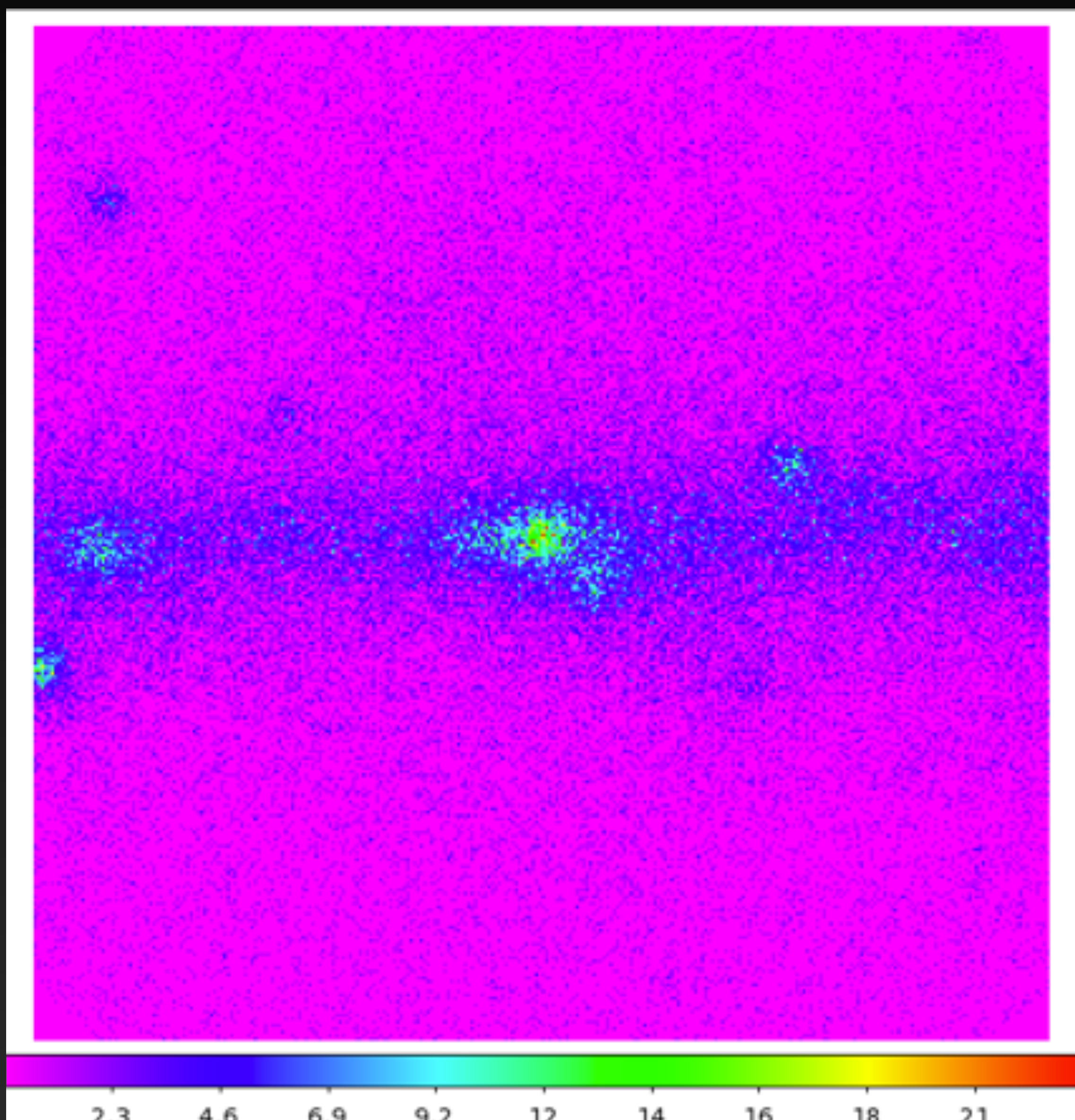
...AT observations of the Milky Way Galactic Center (GC) have revealed a spherically sym-
...of GeV γ-rays extending to at least 10° from the dynamical center of the galaxy. A
...in extracting the intensity, spectrum, and morphology of this excess concerns the
...al diffuse emission models in the GC region. Recently, it has been noted tha
...dels employ a cosmic-ray injection rate far below that predicted based
...Central Molecular Zone. In this study, we add a significant emis
...density determined in three-dimensions, and find that this
...rate with many properties of the γ-ray excess. Specifi
...surrounding the GC) to normalize the best-fitti
...center excess drops considerably and the
...ymmetric. However in models exam
...GC), the normalization of astro
...resilient to changes in
...osmic-rays injected
...ky Way – a r
...excess.

Template Fitting Analyses



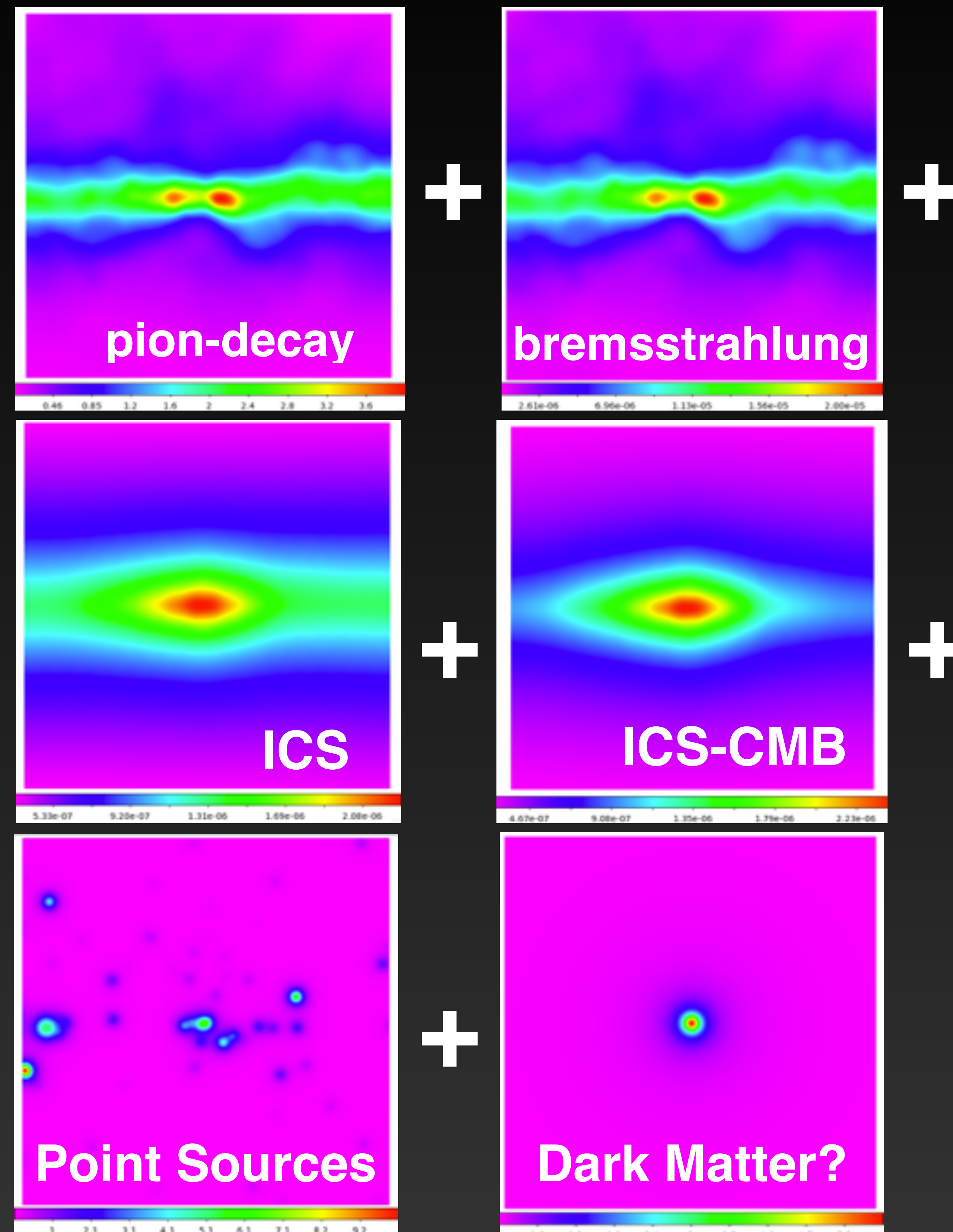
Data

750 — 950 MeV

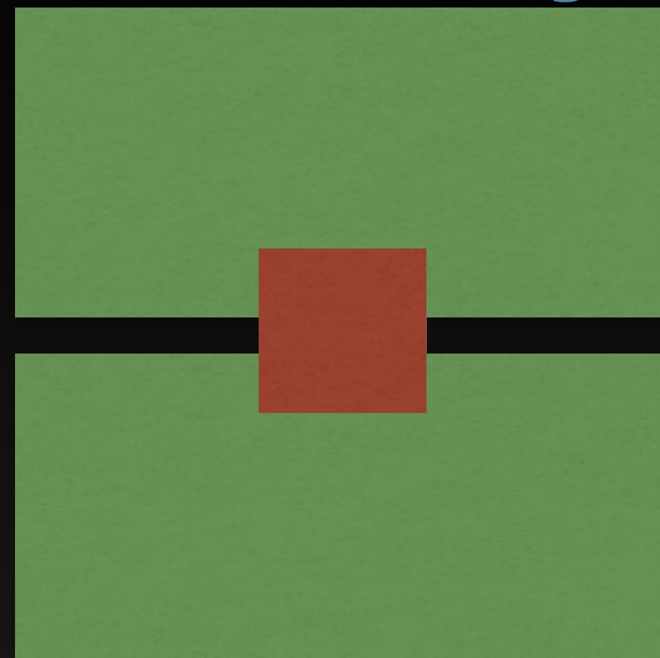
Best Angular Resolution Cut

10^o x 10^o ROI

=



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:

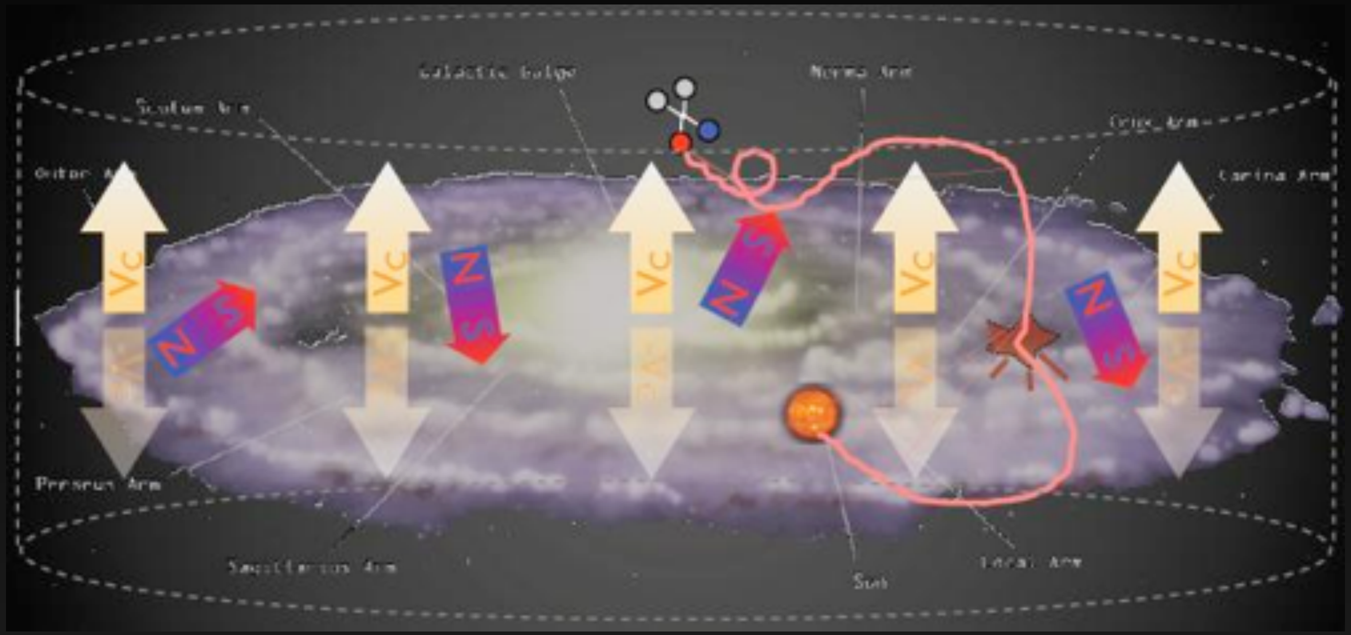
1.) independent of ROI (Daylan et al.)

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.



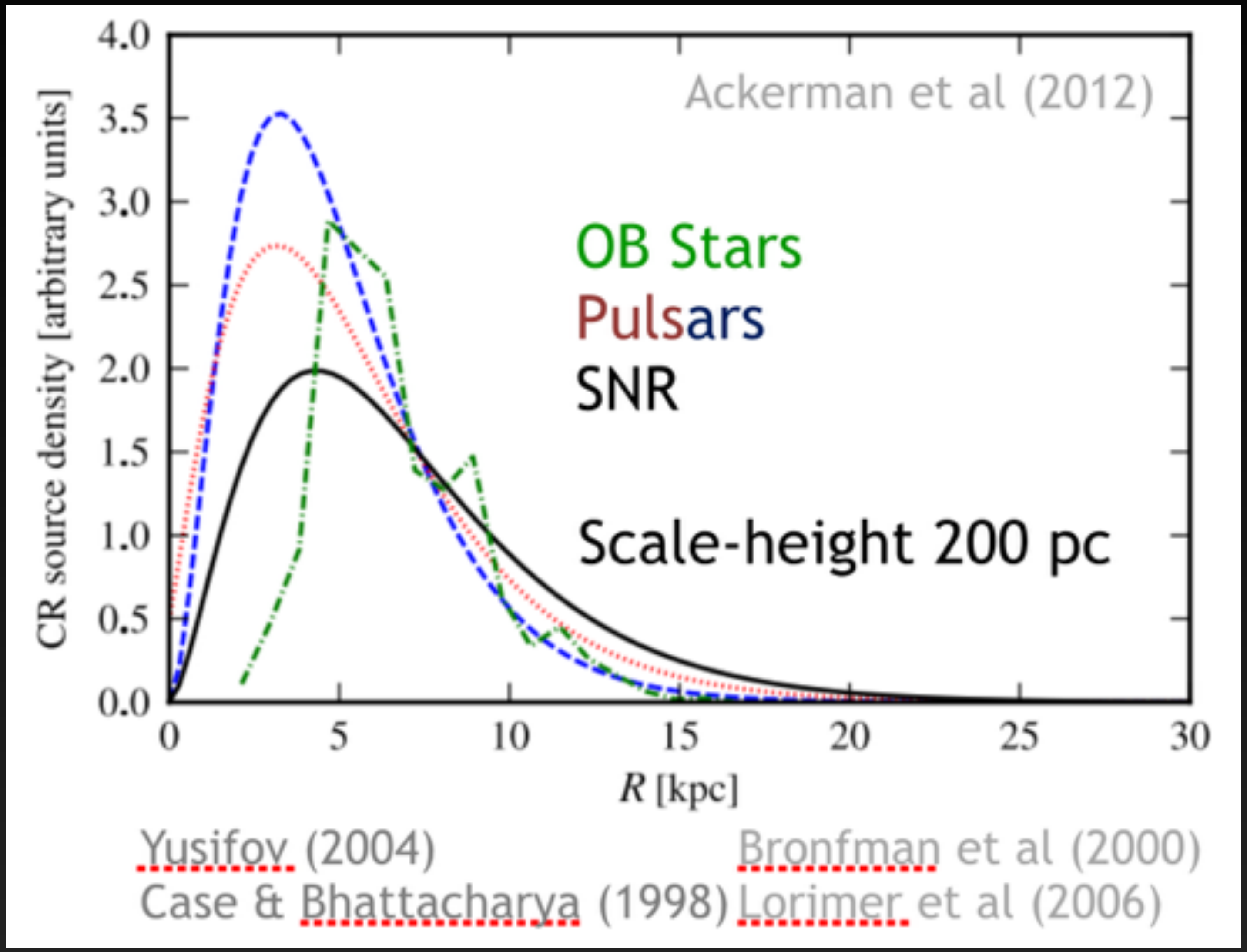
Cosmic-Rays take about 10^8 — 10^9 years to escape the Milky Way magnetic field.

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).

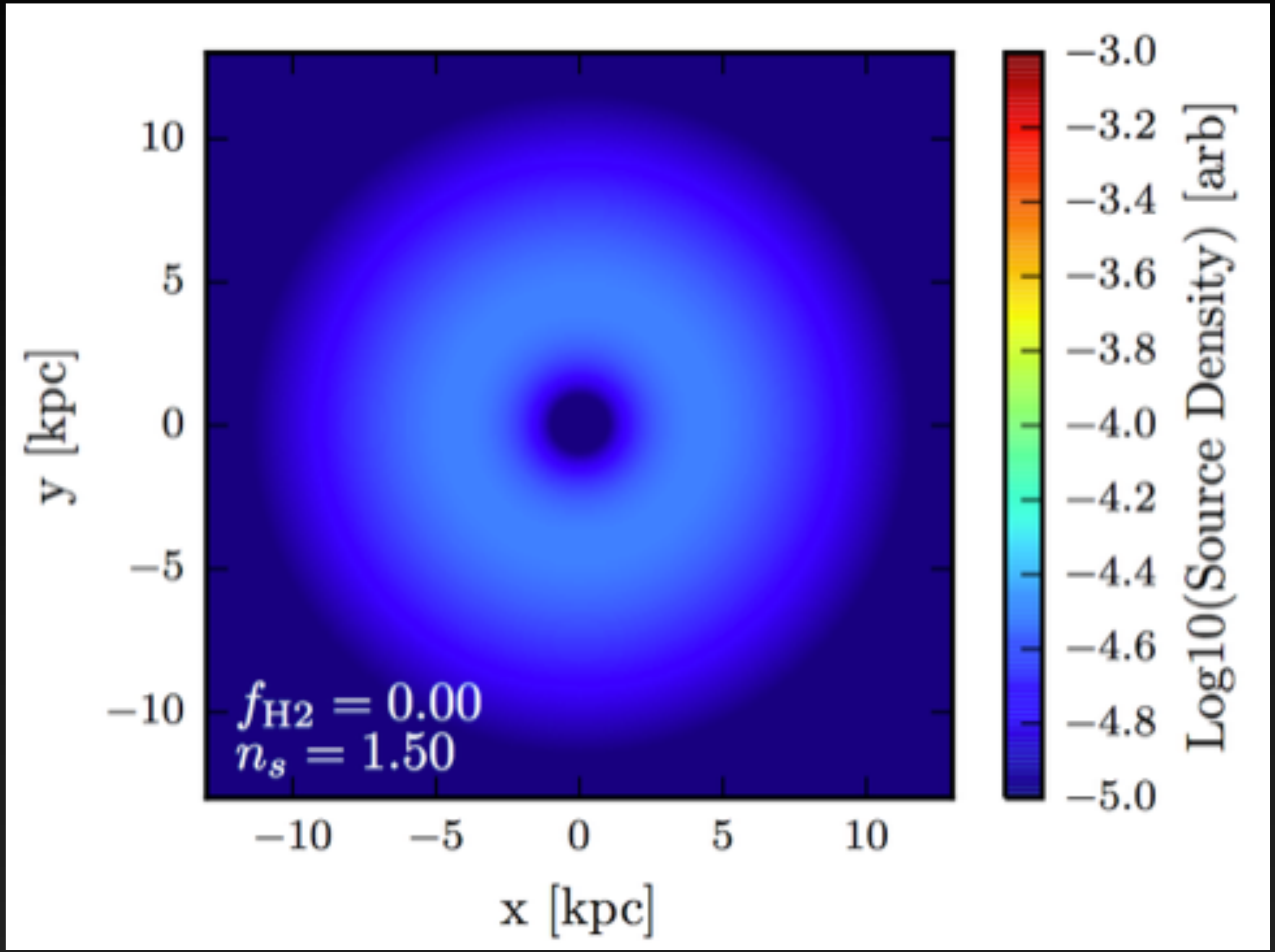
Cosmic-Ray propagation (~30 Myr + 100 Myr)

Cosmic-Ray Injection Sources

These models can then fail in two ways:

1.) Observational incompleteness

2.) Time variable injection



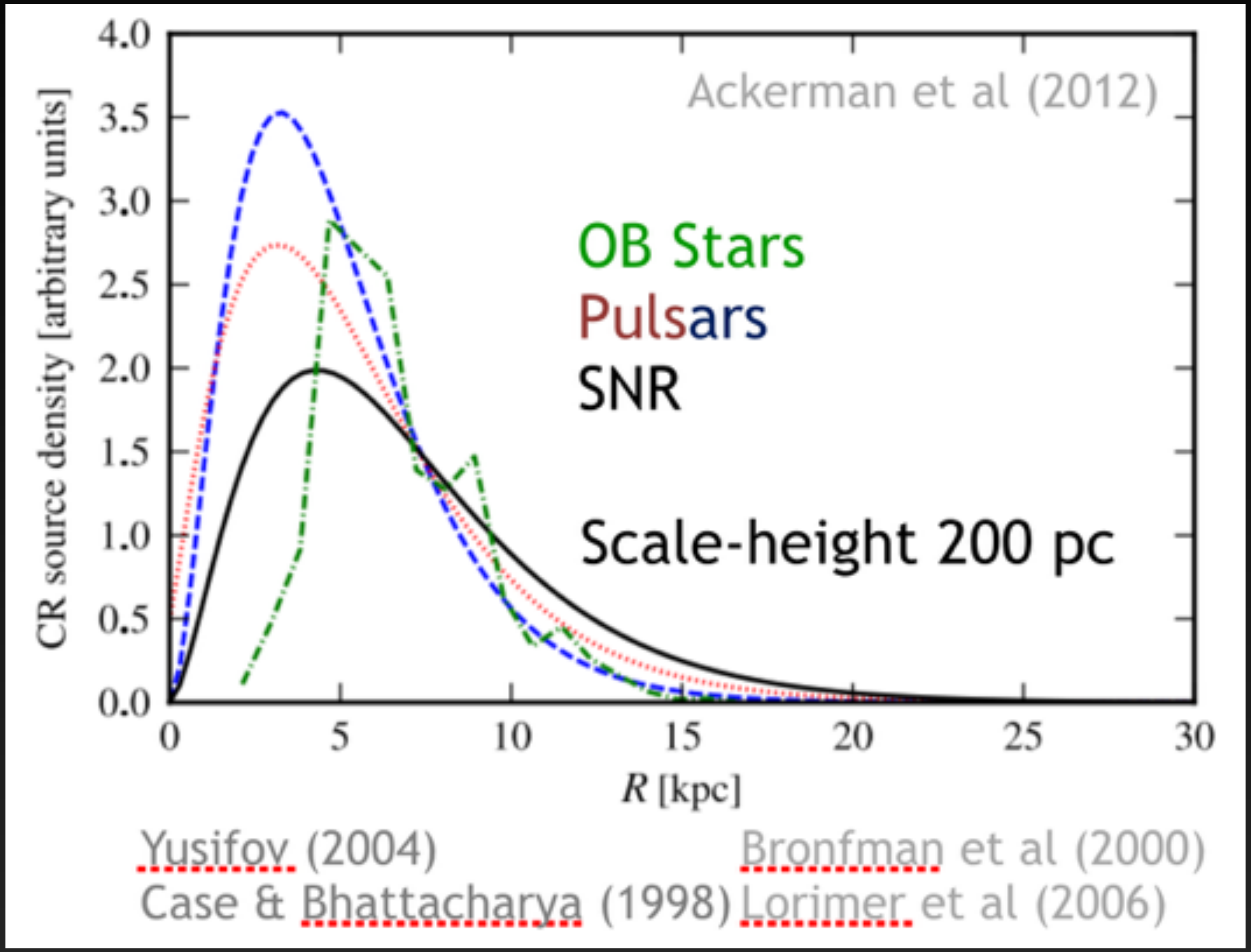
Interestingly the models used for these analyses have extremely small injection rates near the GC (in several cases identically 0).

Cosmic-Ray Injection in the GC

Why Is this Done?

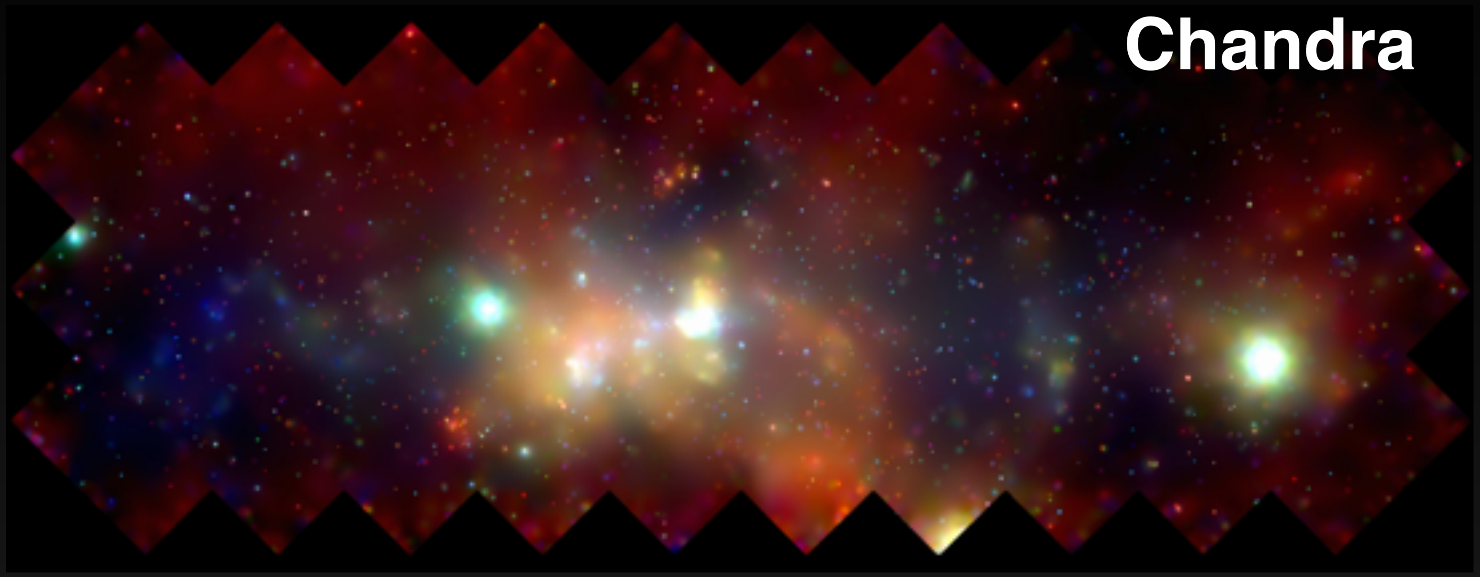
1.) Want to fit a simple analytic form to a profile that peaks at 4 kpc.

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



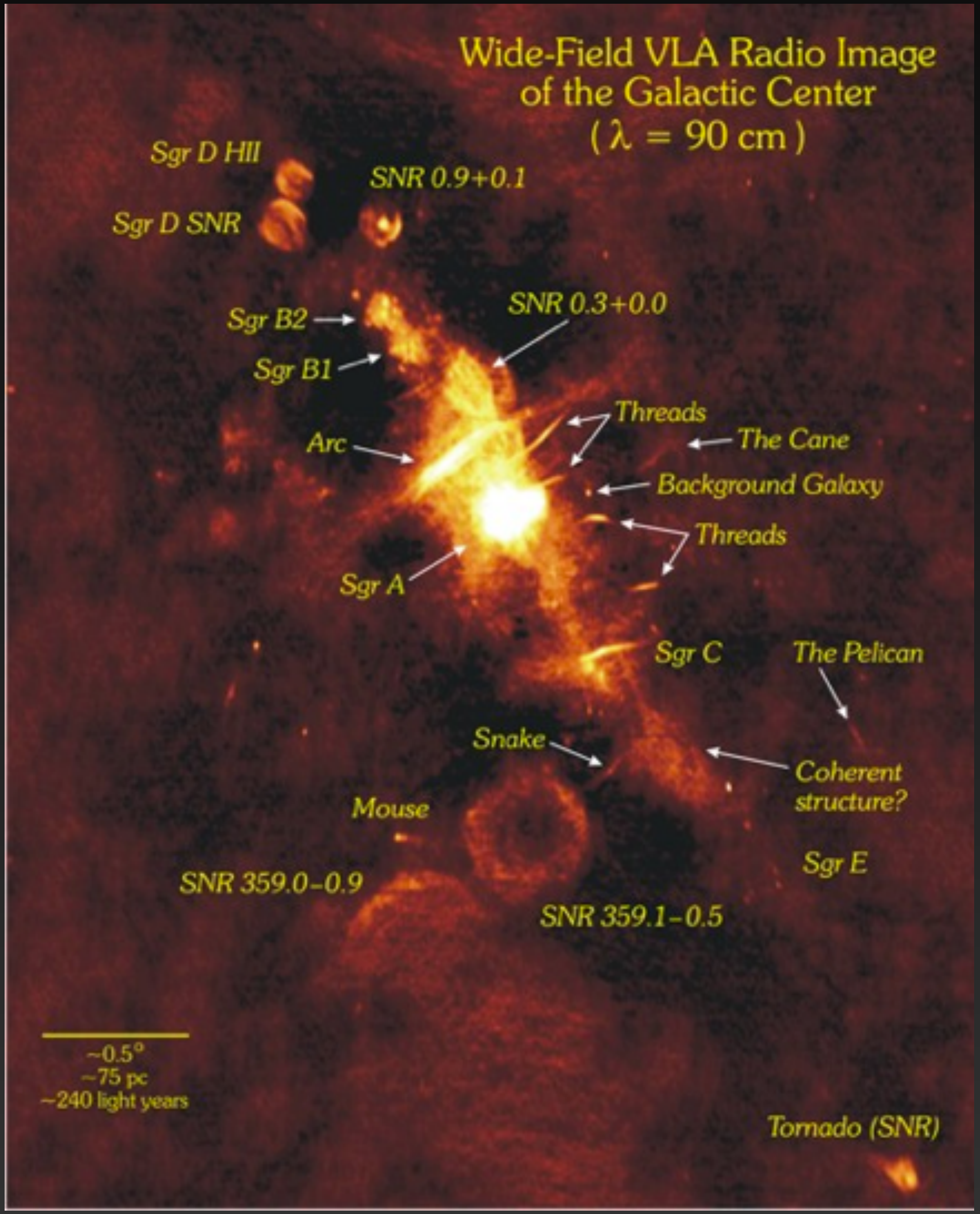
3.) Model of GC is unimportant for cosmic-ray propagation studies.

Current Observations of GC

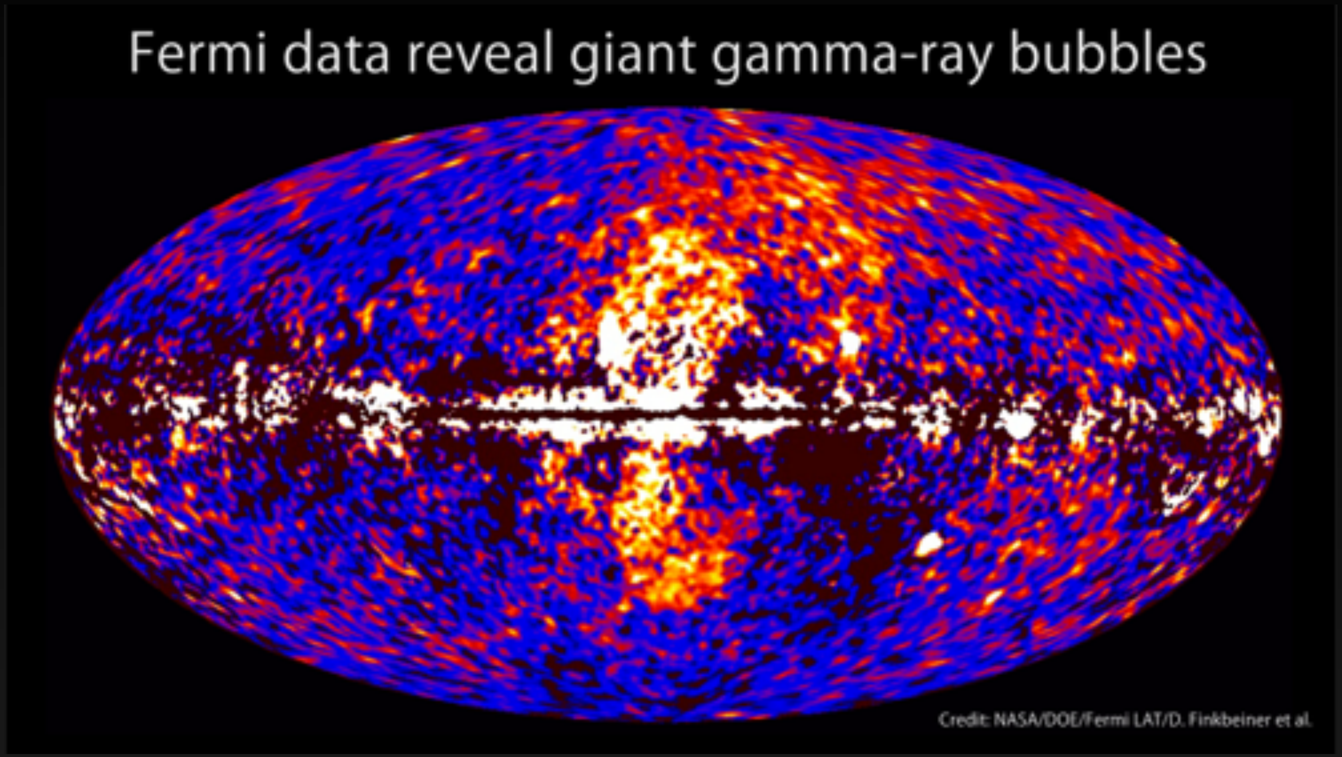


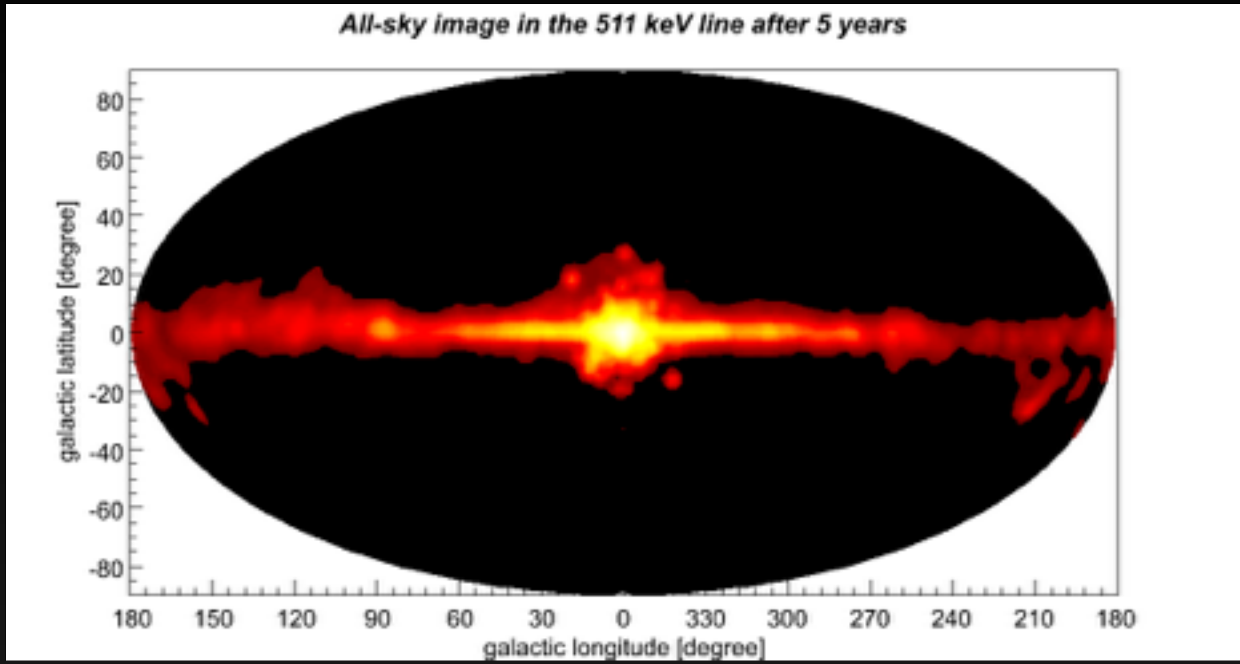
However, observations of the GC find intense star formation and many supernovae remnants.

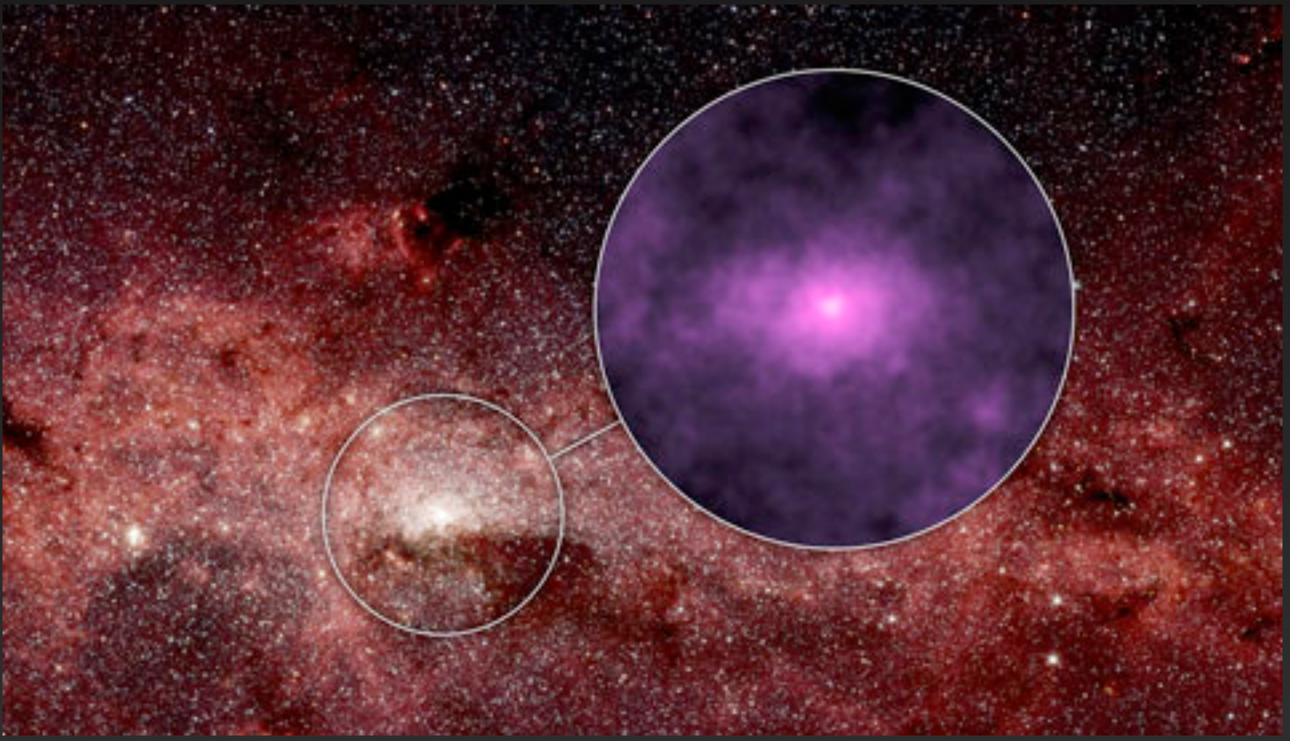
e.g. 5-10% of the total galactic SFR rate occurs in the Central Molecular Zone (Longmore et al. 2012)

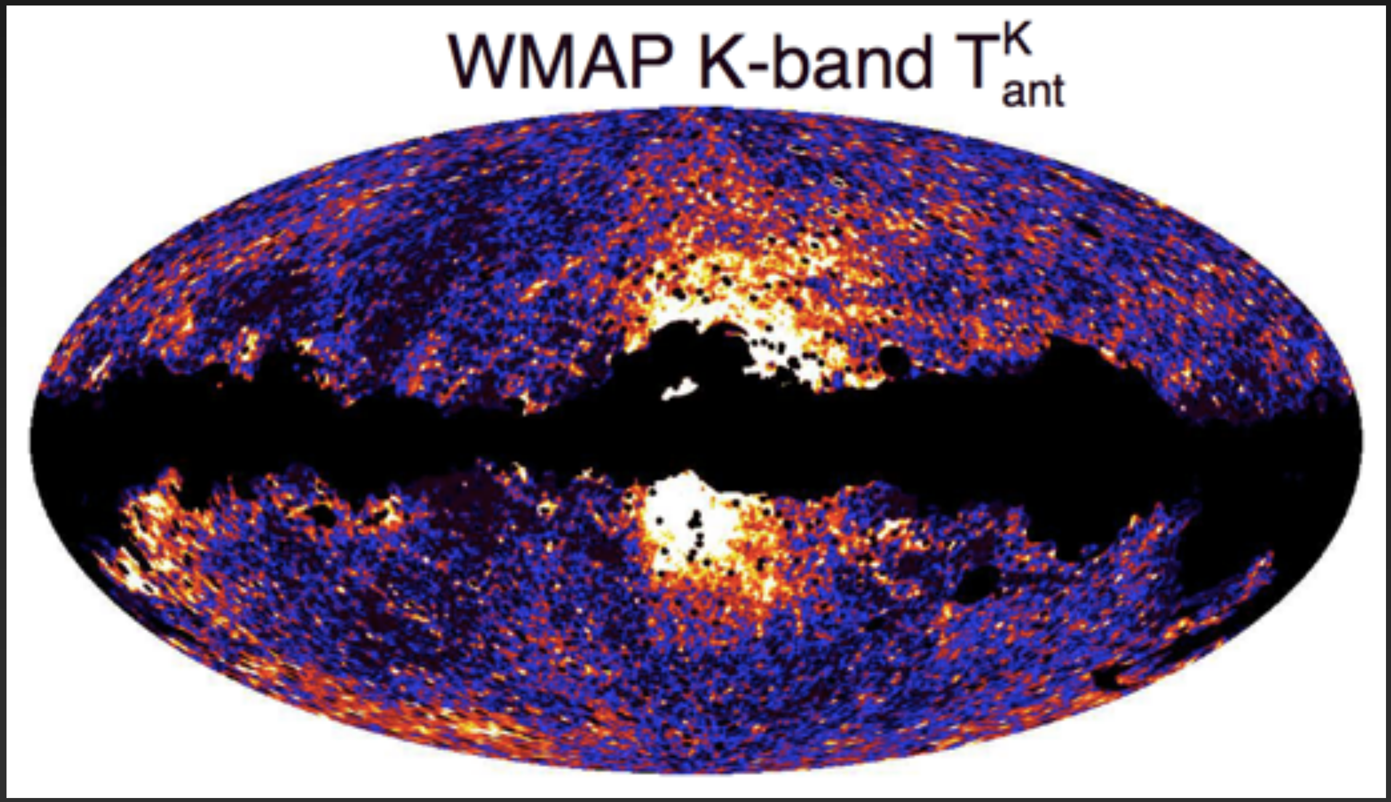


Excesses are not Limited to GeV Energies









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

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

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

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

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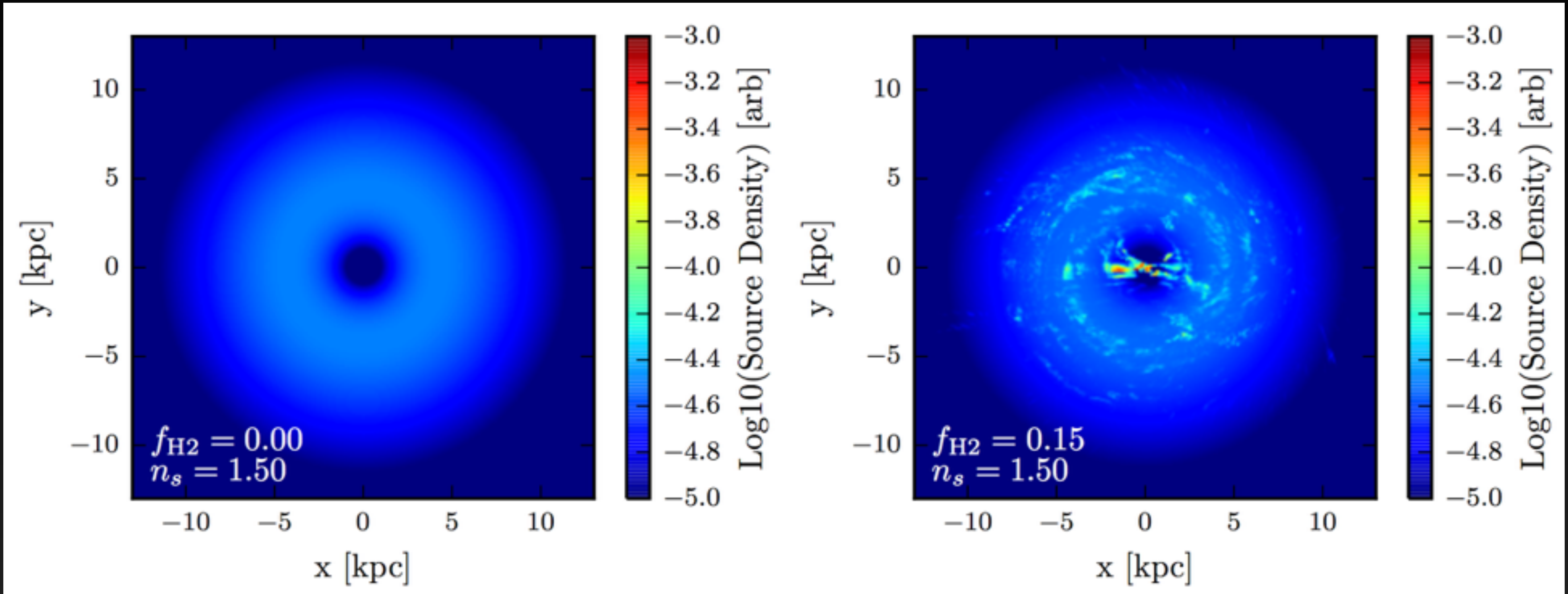
Cosmic-Ray Injection in the GC

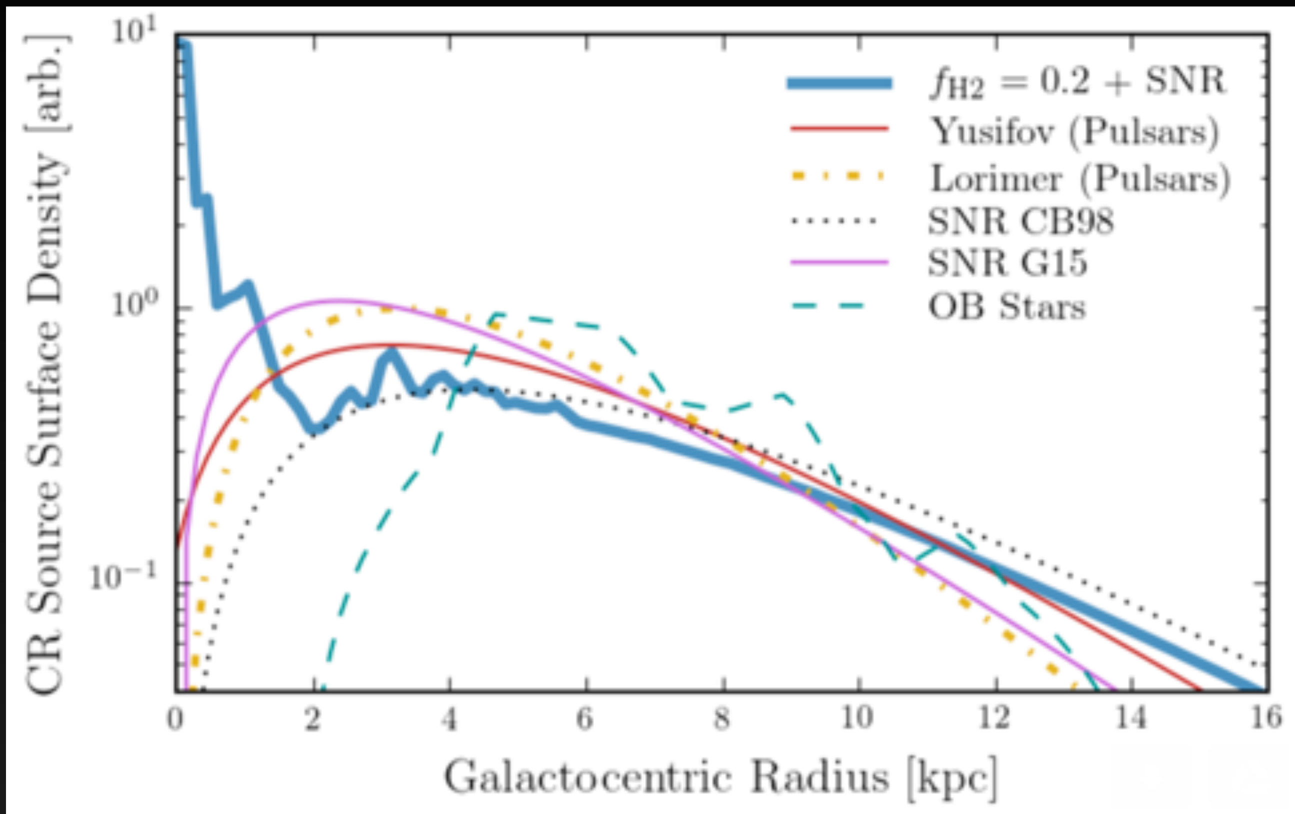


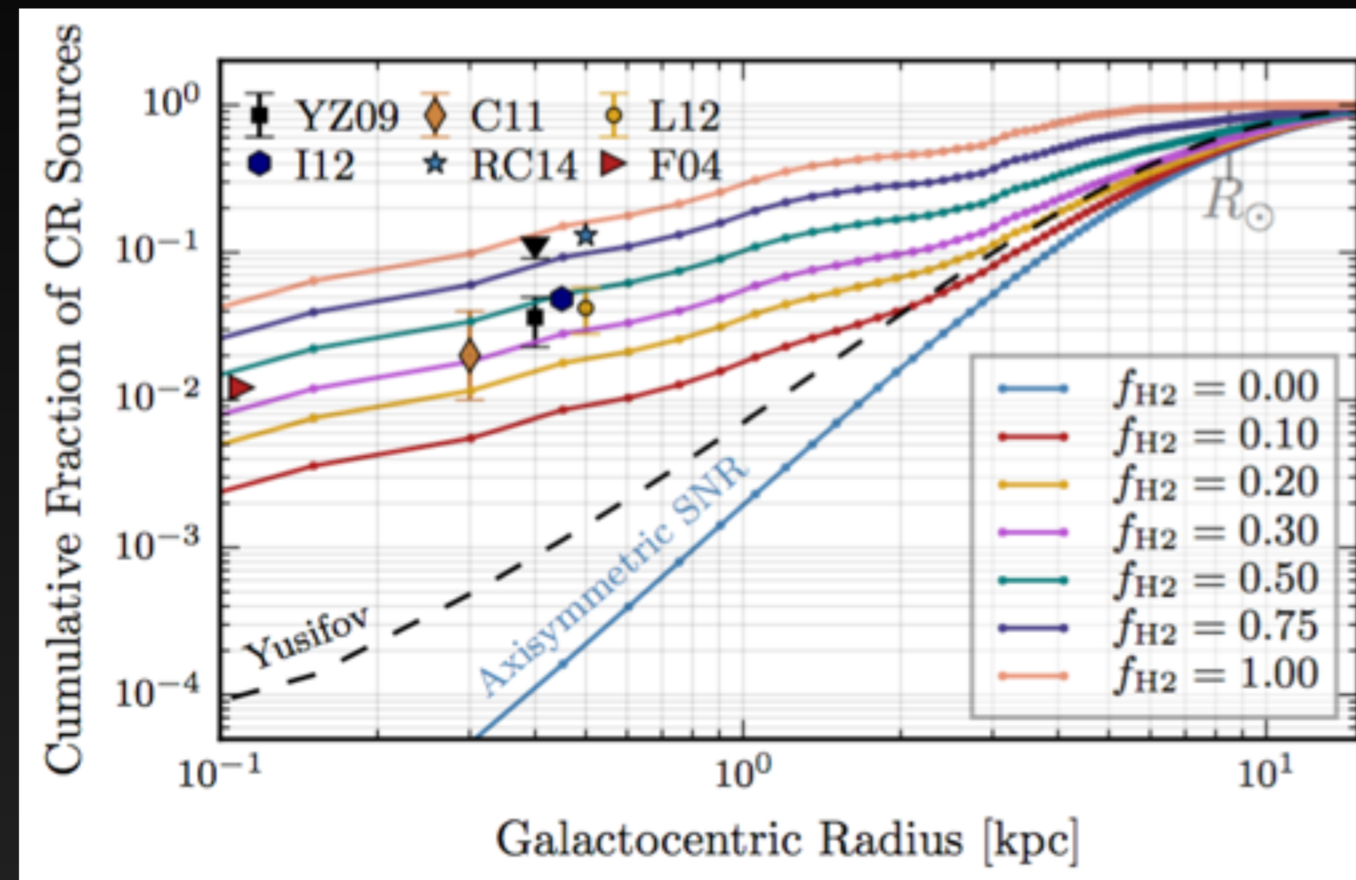
Two features leap out immediately:

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

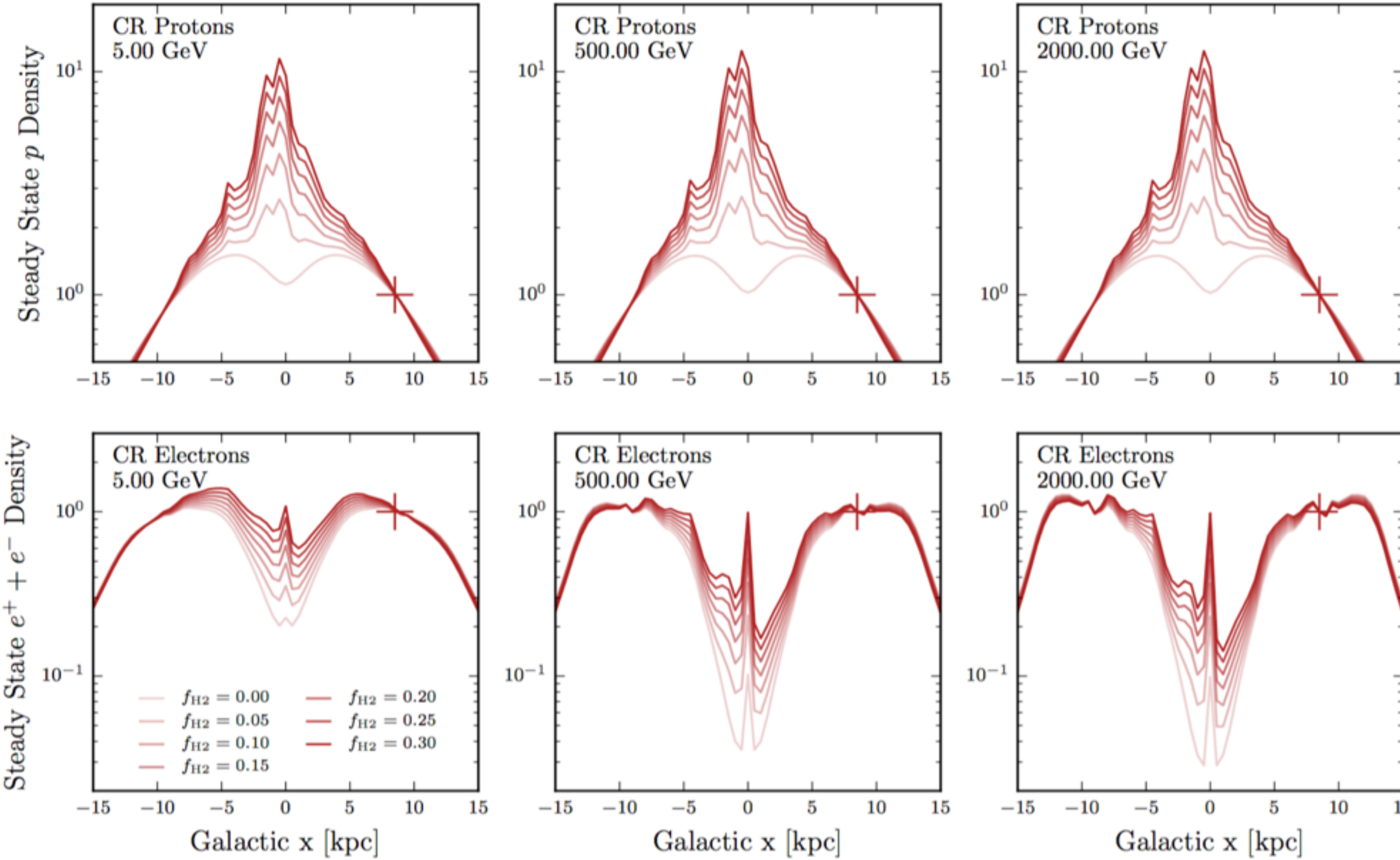
Galprop Simulations

Parameter	Units	Canonical	Mod A	Description
D_0	$cm^2\ s^{-1}$	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

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)

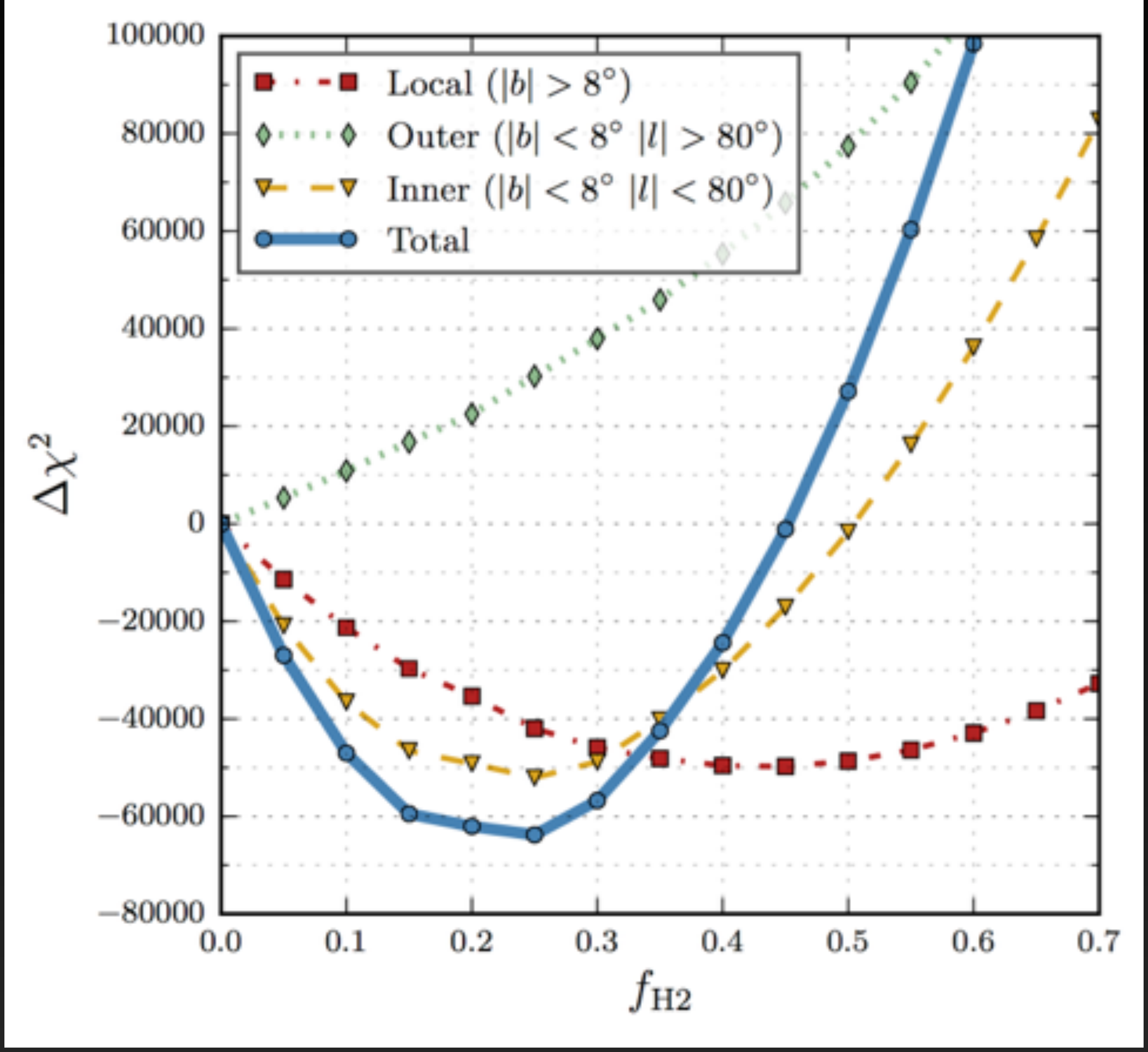
New models for the 3D galactic gas density are also produced (Carlson 2015, to be submitted).

Steady State Cosmic-Ray Distribution



A Better fit to the Gamma-Ray Sky

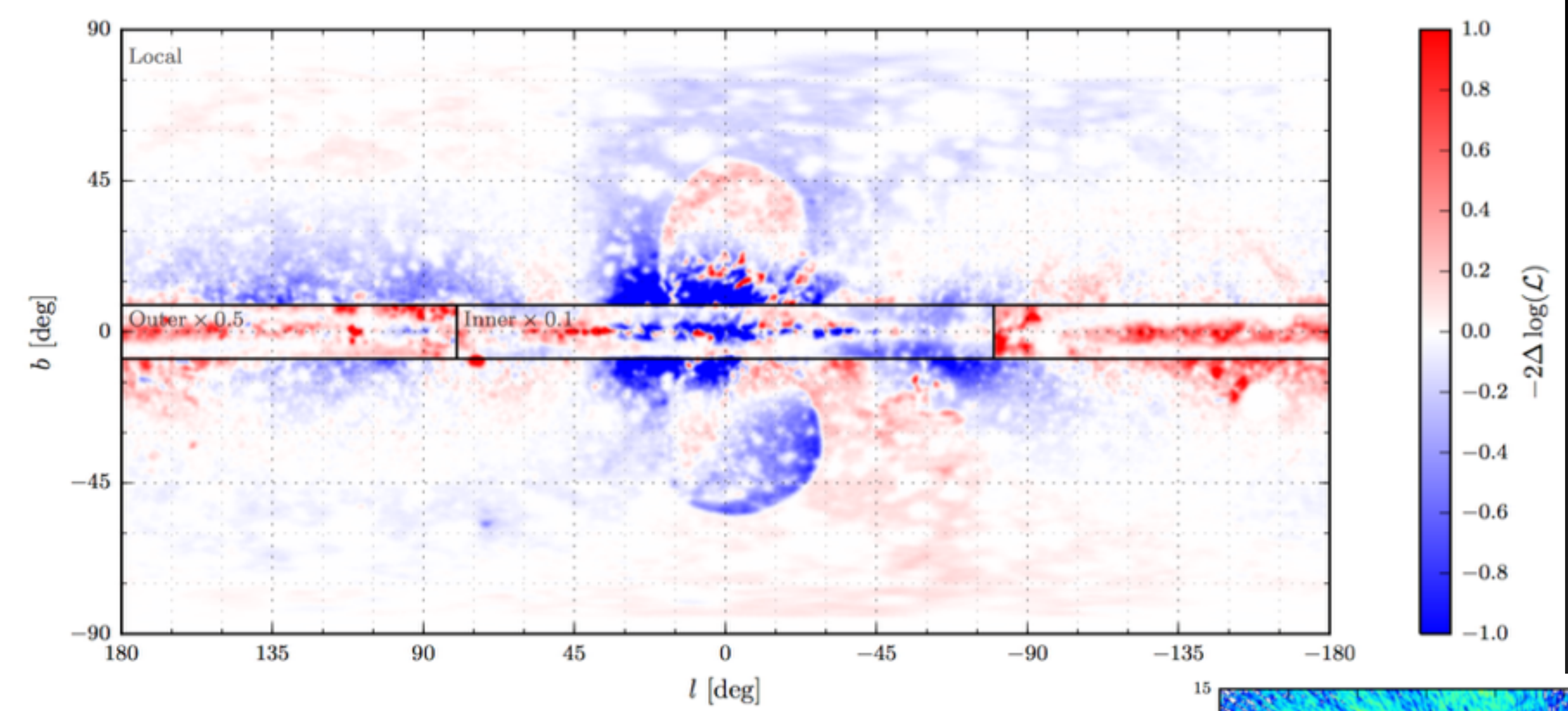
1.) The addition of a new cosmic-ray injection template tracing the 3D H_2 density greatly improves the overall fit to the gamma-ray diffuse emission.



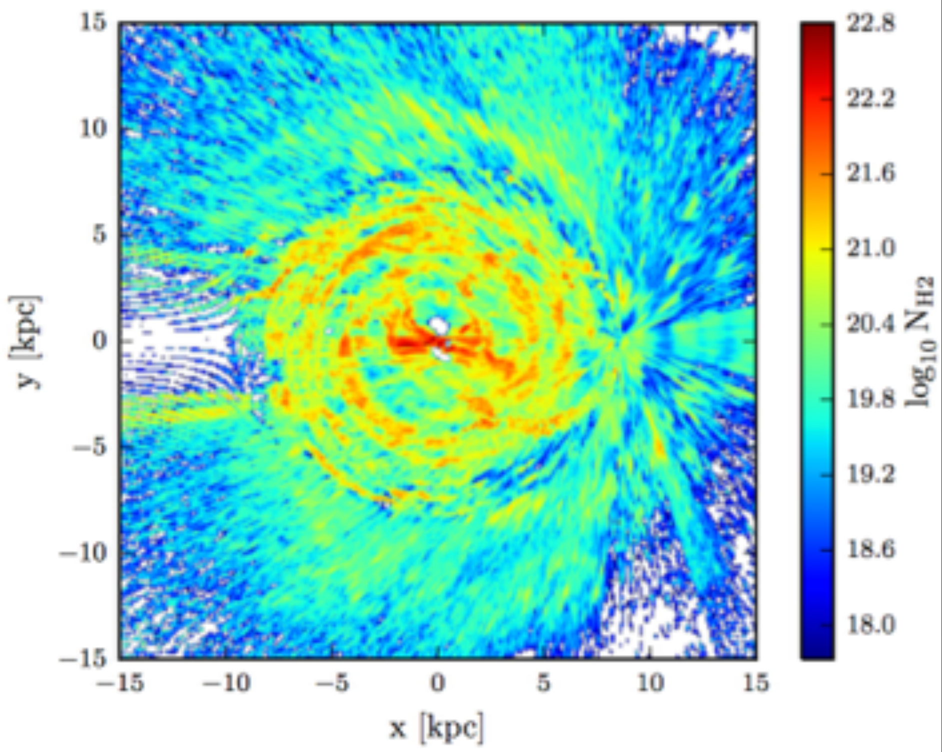
2.) This is an important point on its own, as it offers a new method for improving diffuse models for the gamma-ray sky.

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

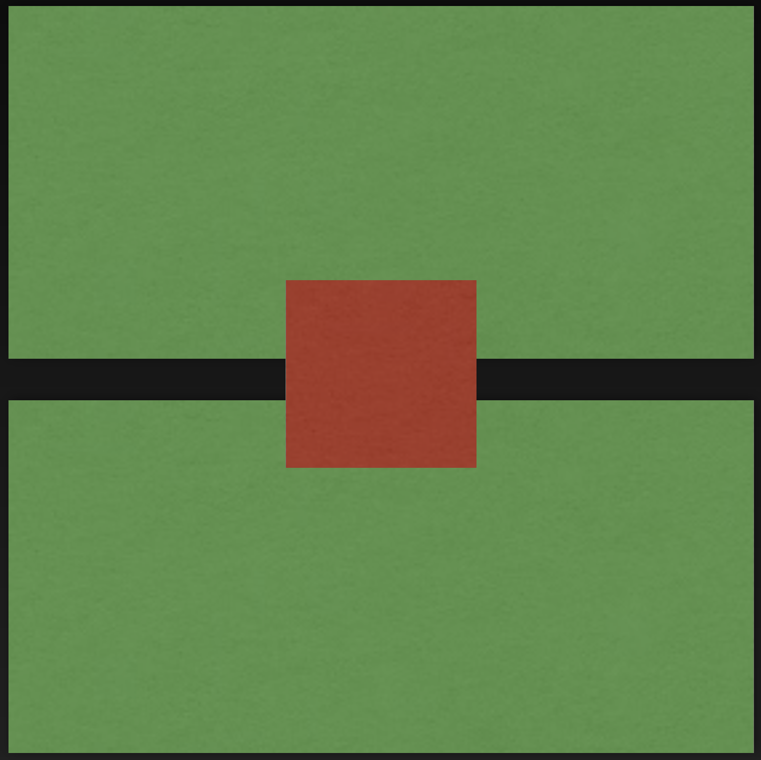


Fits are significantly improved, in particular in regions near the Galactic Center where there is significant kinematic gas information.



An Inner Galaxy Analysis of the GCE

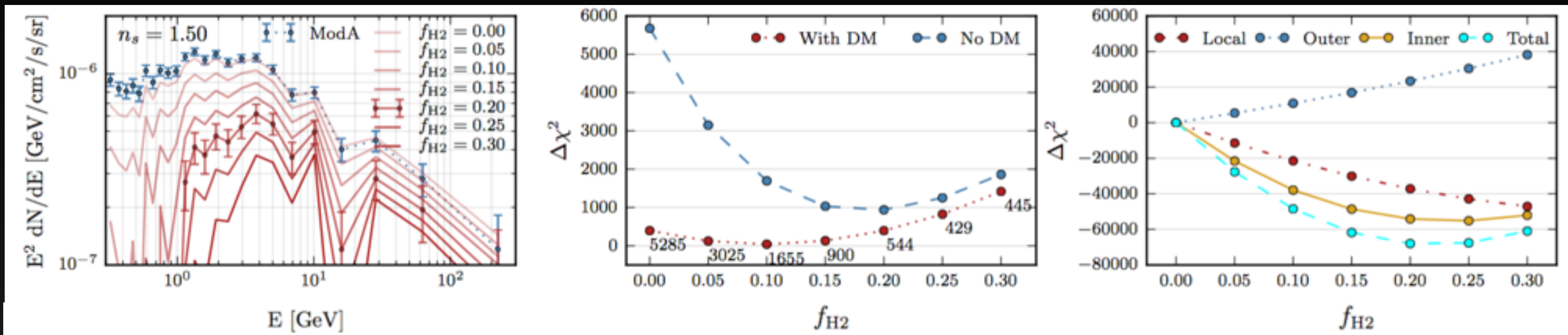
INNER GALAXY



- Mask galactic plane (e.g. $|b| > 2^{\circ}$), and consider 40° x 40° 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.

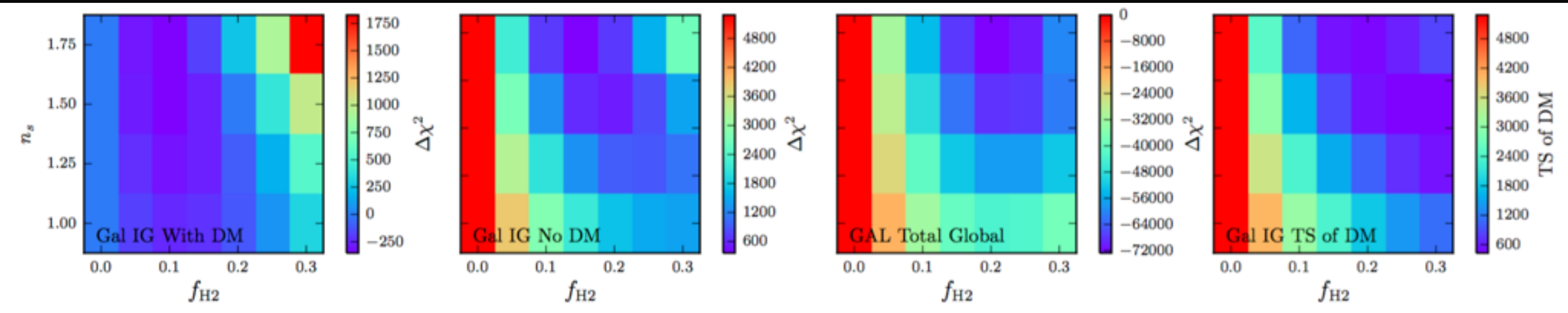
Effect on the Gamma-Ray Excess



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}

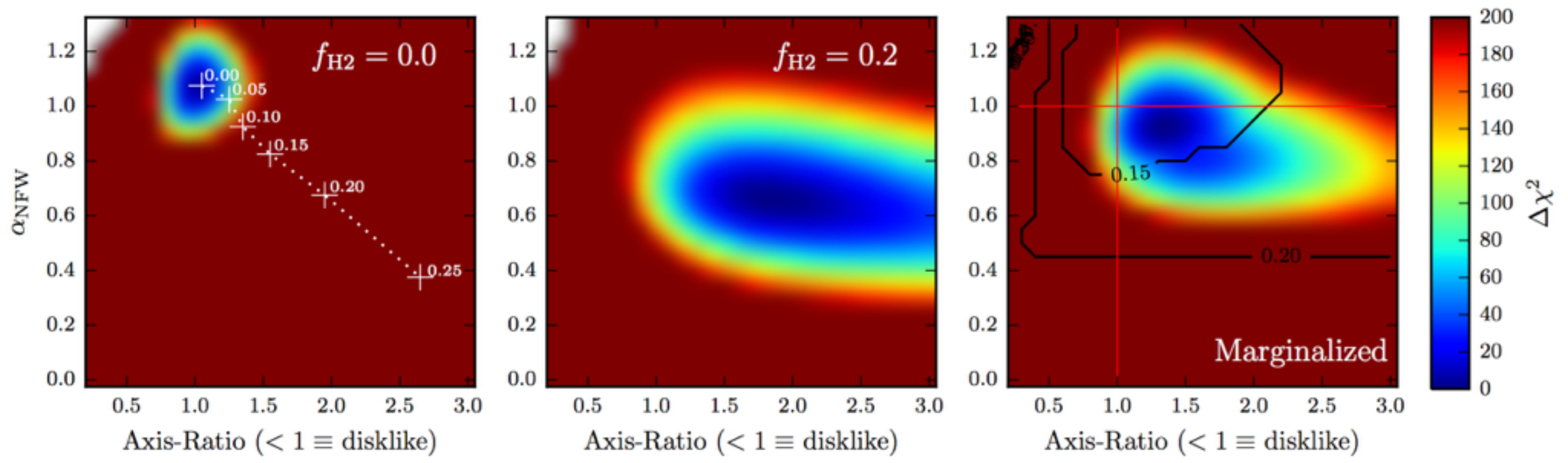


Models with no dark matter universally prefer f_{H2} ~ 0.2 for the 40ºx40º region surrounding the GC.

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.

GC Excess Morphology

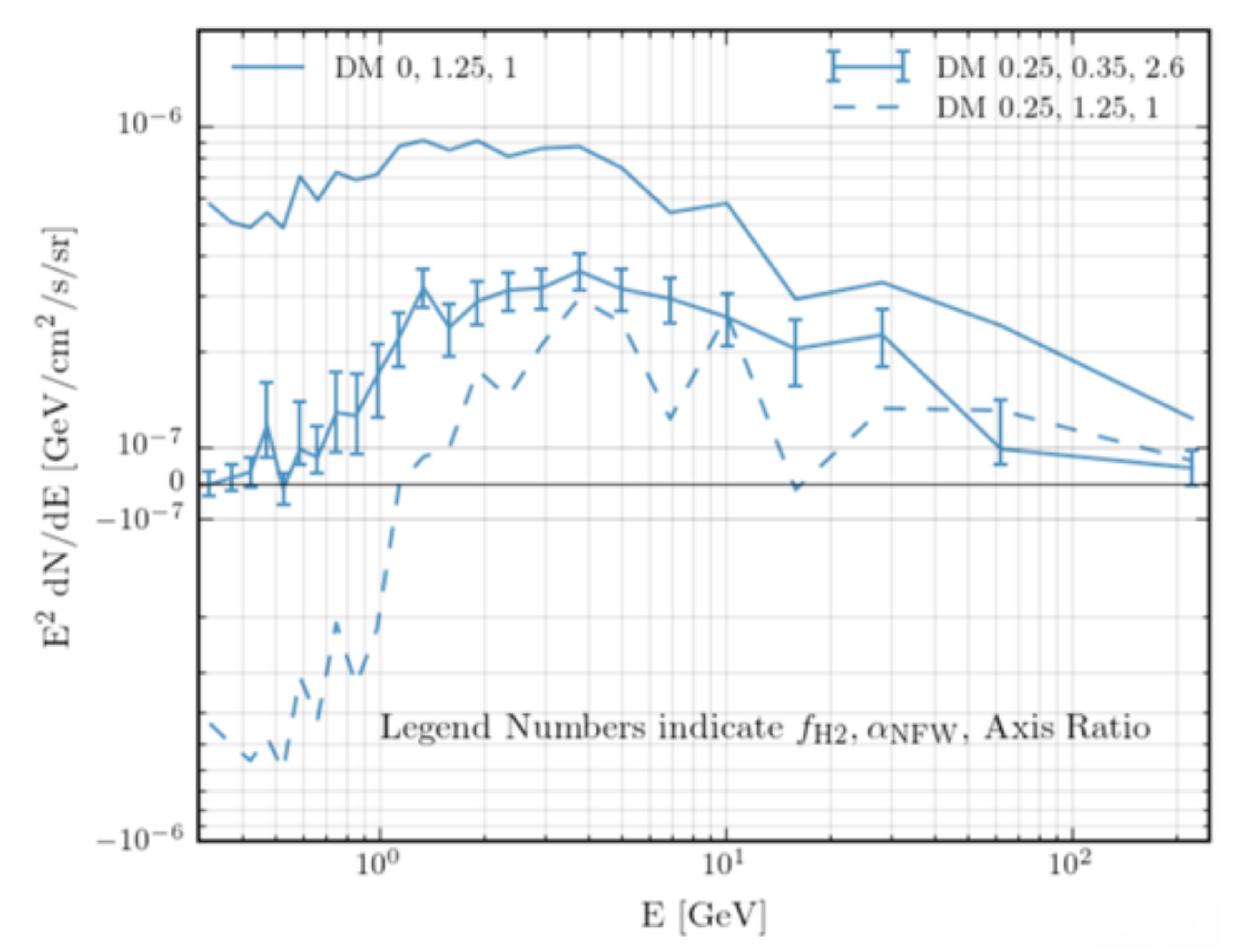


The morphology of the gamma-ray excess is also affected, becoming flatter, and extended perpendicular to the Galactic plane for high values of f_{H2}.

A Fermi Bubbles Component?

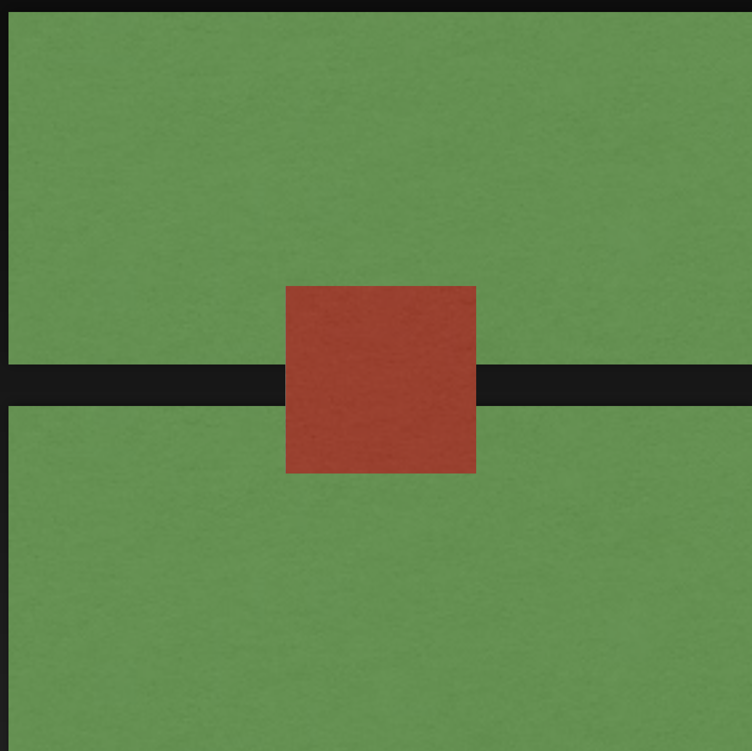
When the excess floats to the best fit morphological configuration, much of the excess intensity returns.

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



A Galactic Center Analysis of the GCE

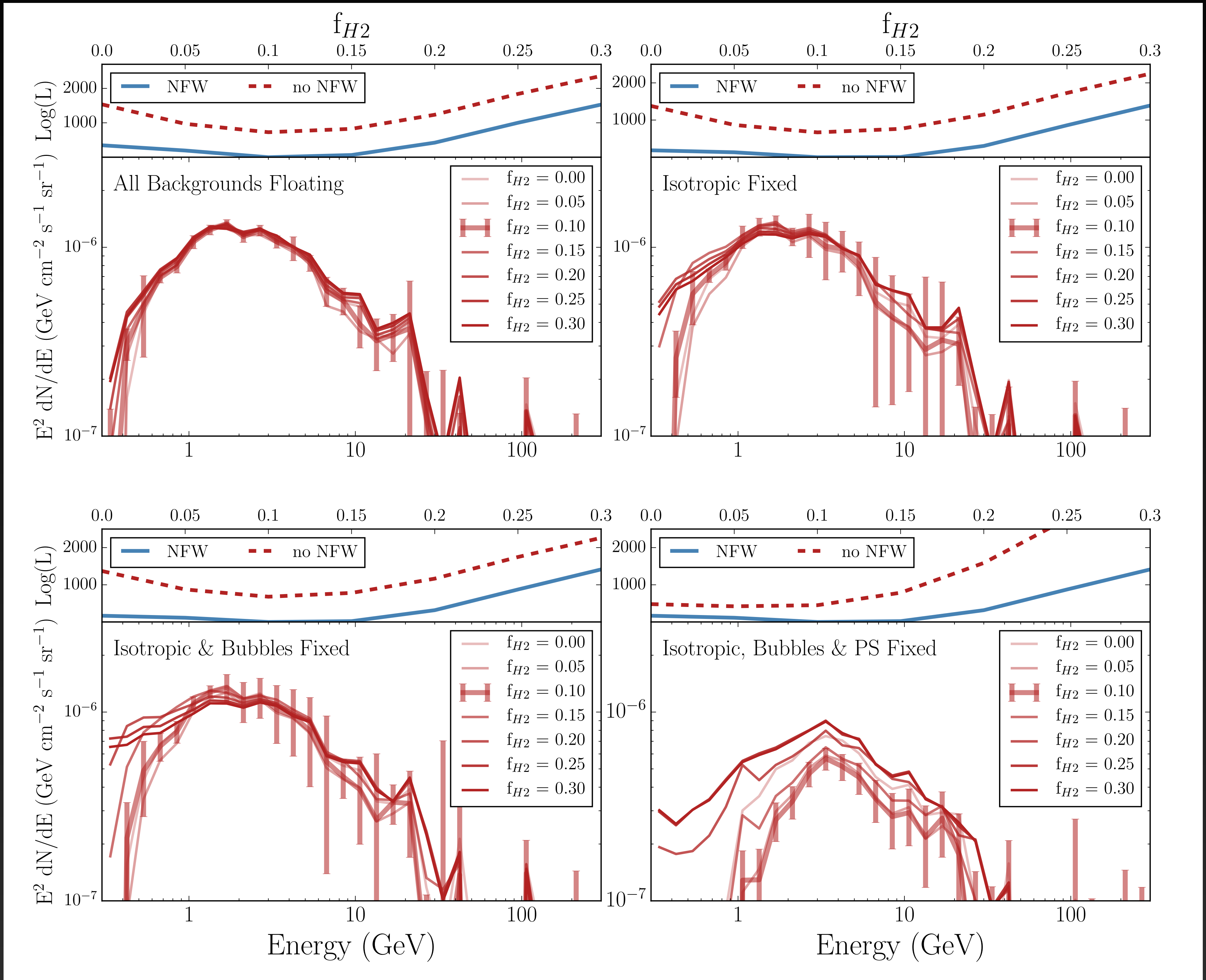
GALACTIC CENTER



- Examine 15° 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.

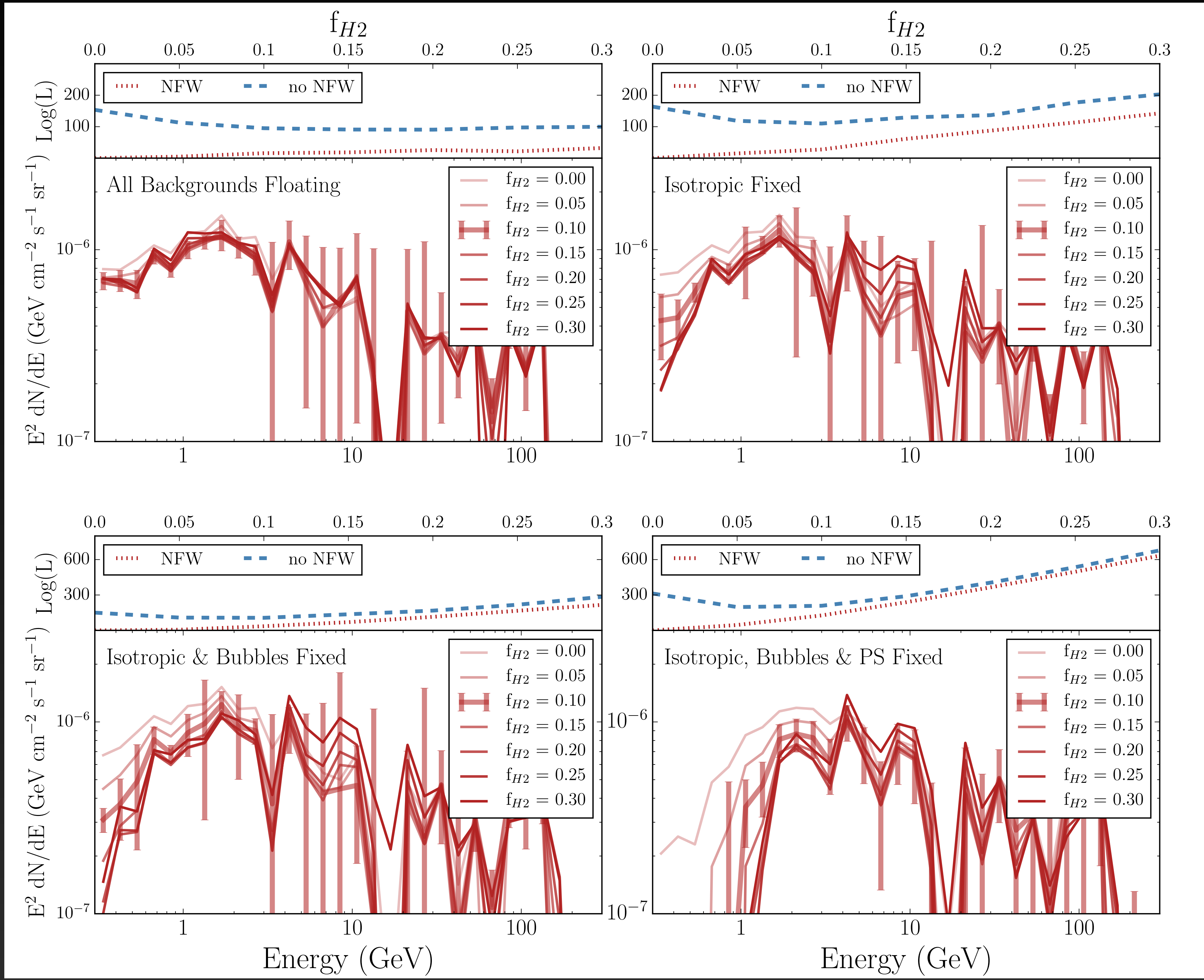
This creates an analysis with no sidebands region, where the NFW template normalization plays a critical role in determining the spectrum and normalization of diffuse components.

Studies of the Galactic Center (15^ox15^o)



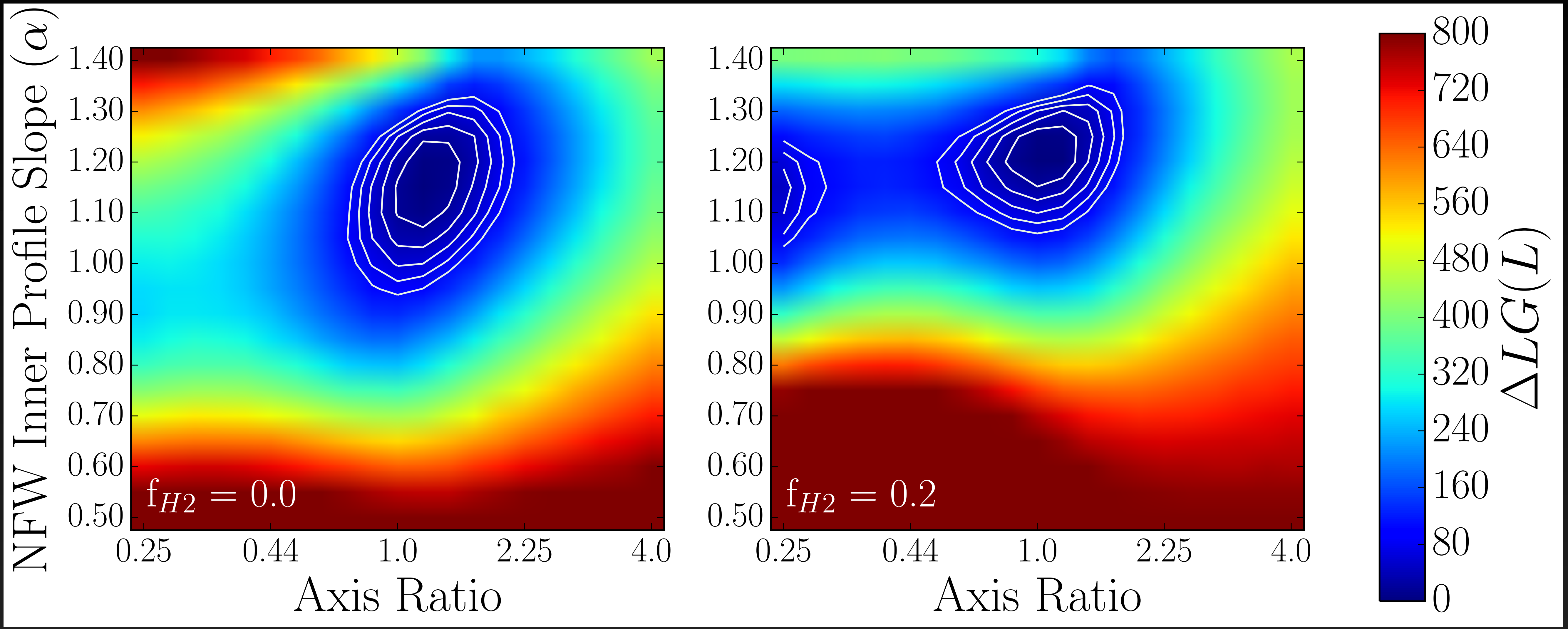
In this smaller region, the excess remains resilient to changes in diffuse emission modeling.

Masking |b| < 2º



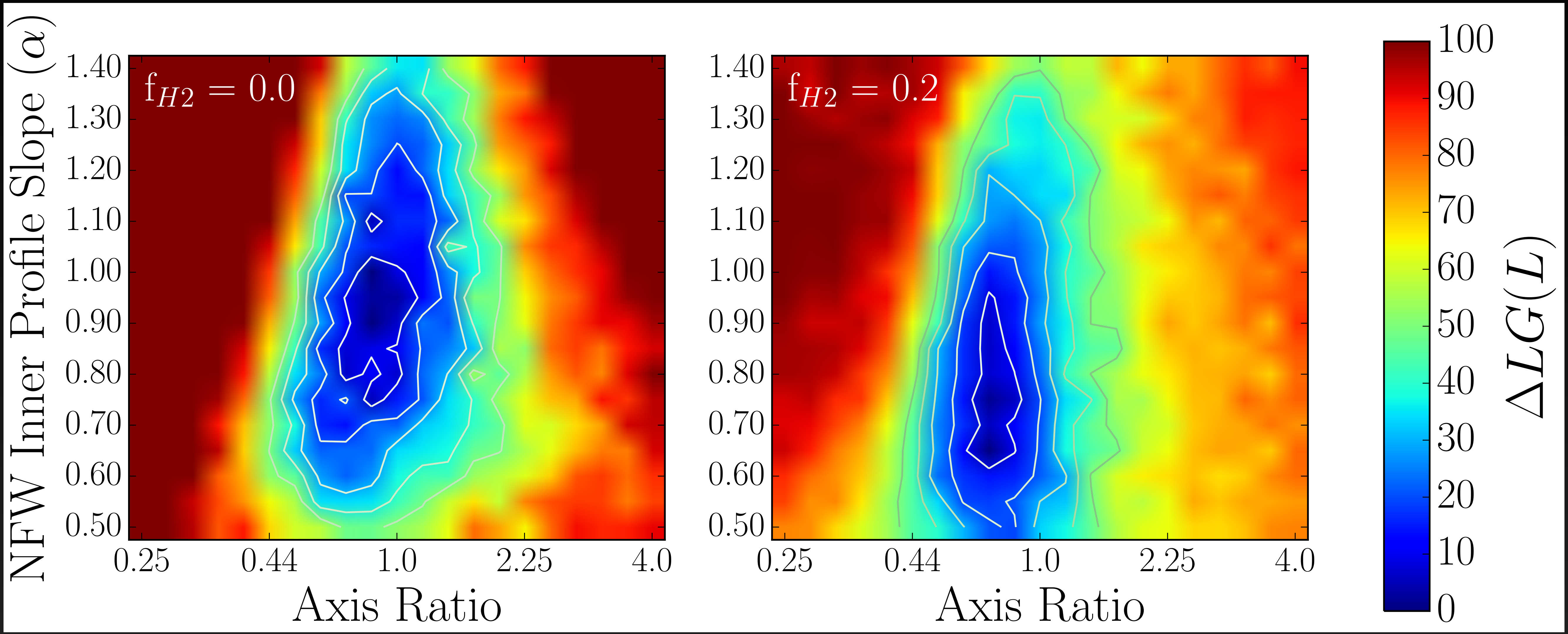
Intriguingly, this persists even when the inner 2º are masked - implying that analyses of small ROIs favors the excess.

Ellipticity in the GC Analysis



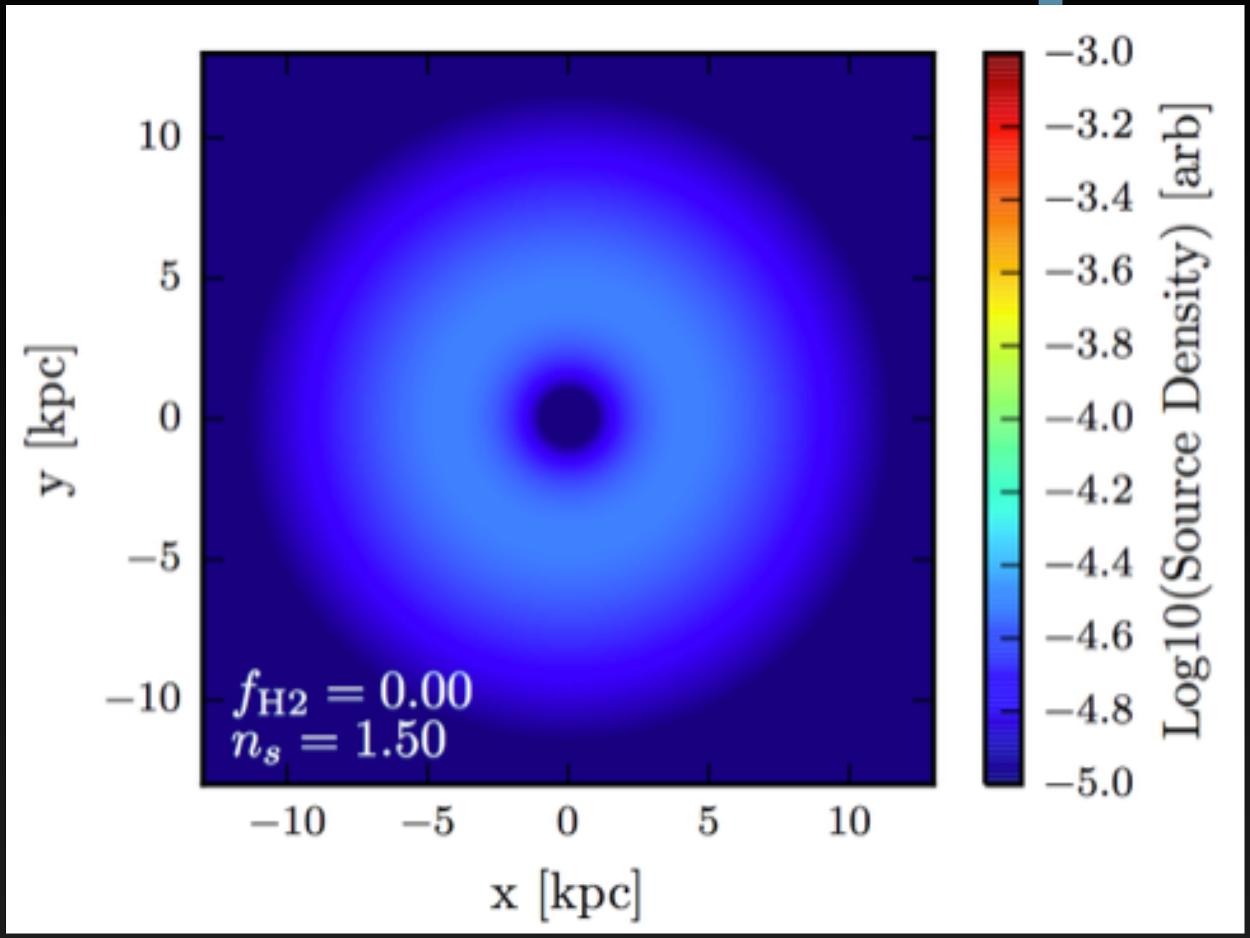
In the galactic center, spherical symmetry and a steep inner profile slope is still preferred by the data.

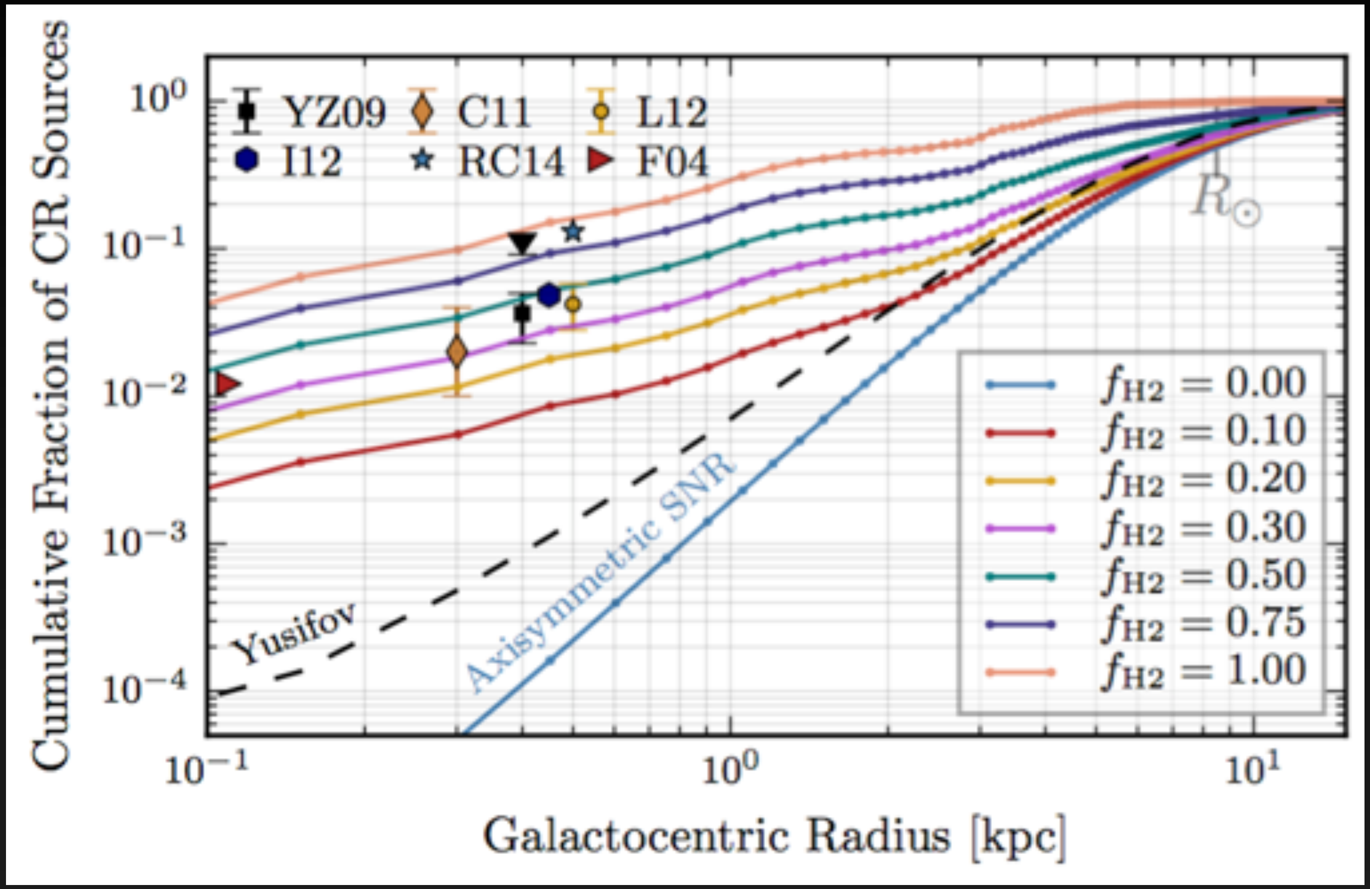
Ellipticity in the GC Analysis



The deviations from typical NFW profiles are more extreme when the |b| < 2° 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

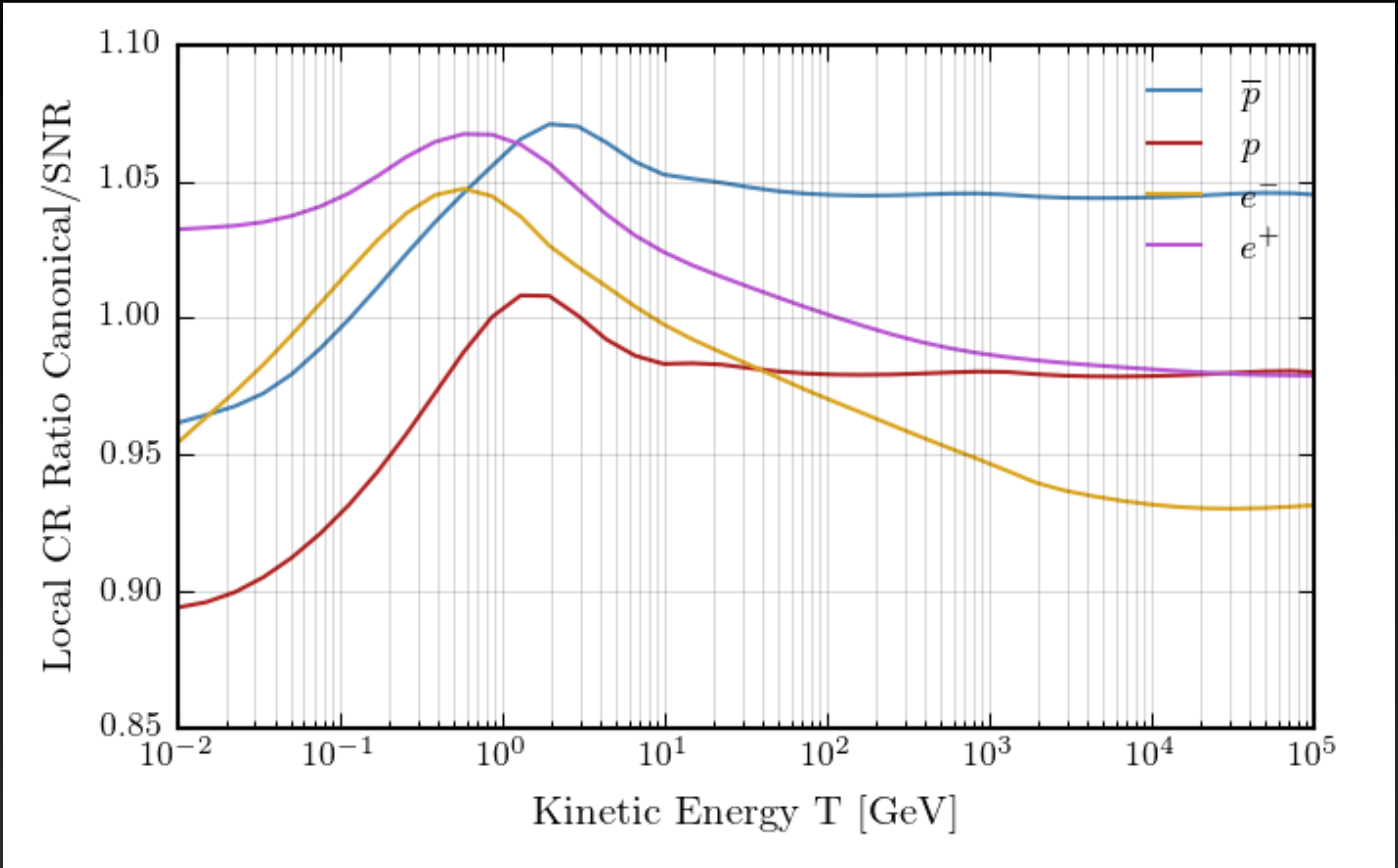
b.) Is degenerate with properties of the gamma-ray excess

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.

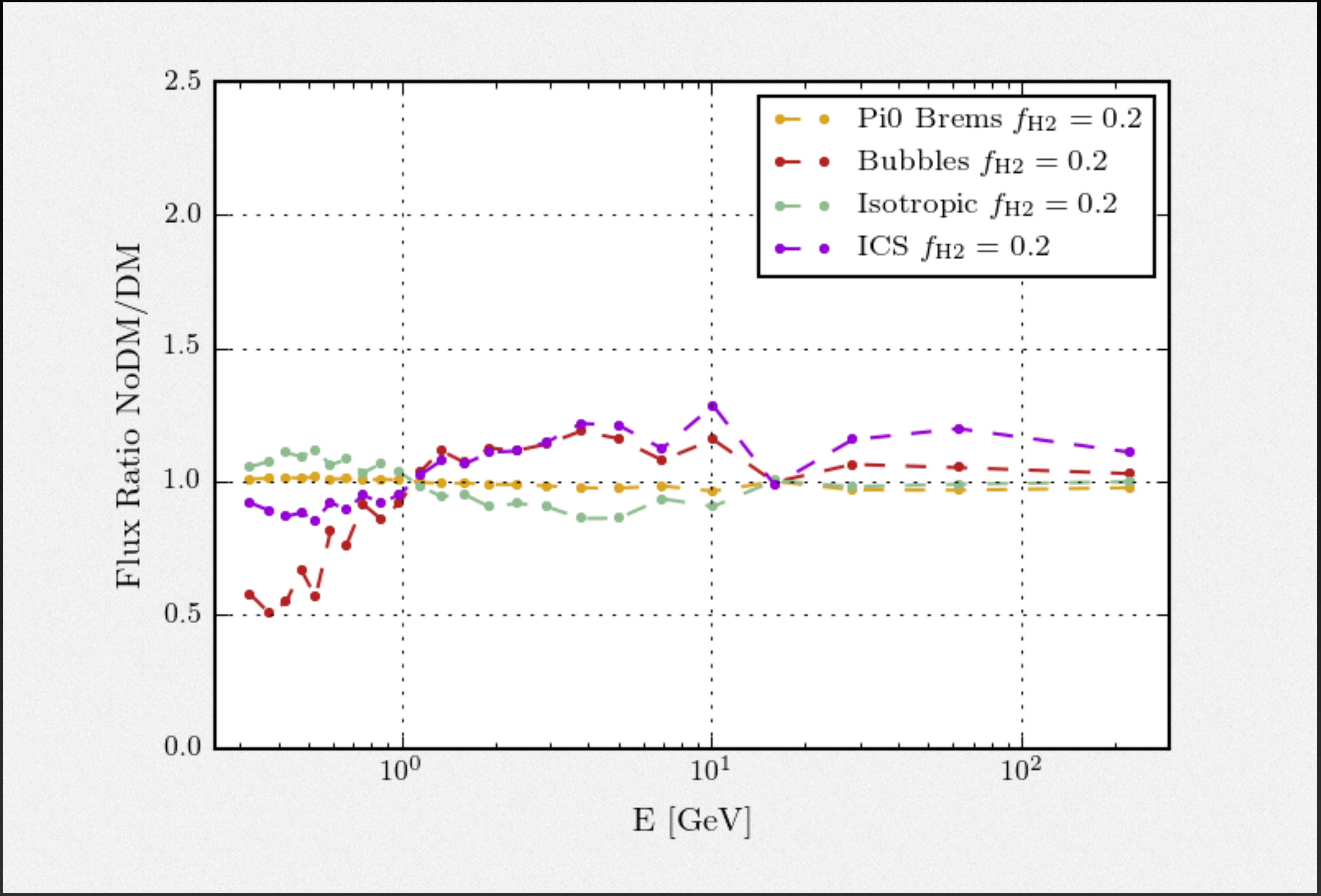
3.) For a preferred value of $f_{H2} \sim 0.1$, the morphology of the excess is significantly altered, producing a more cored, and slightly elliptical morphology.

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