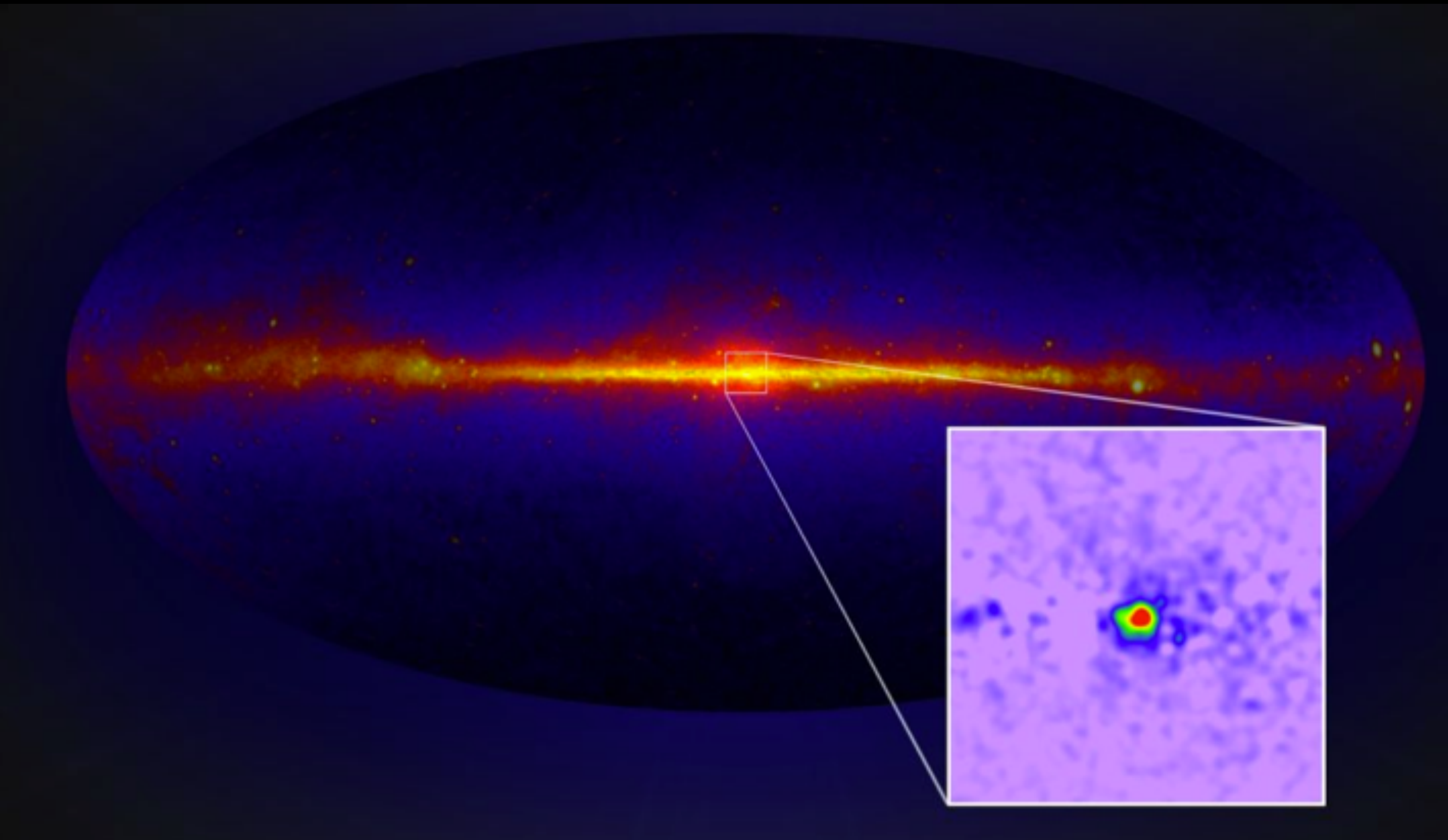

# Diffuse Emission Models Confront the Galactic Center Excess

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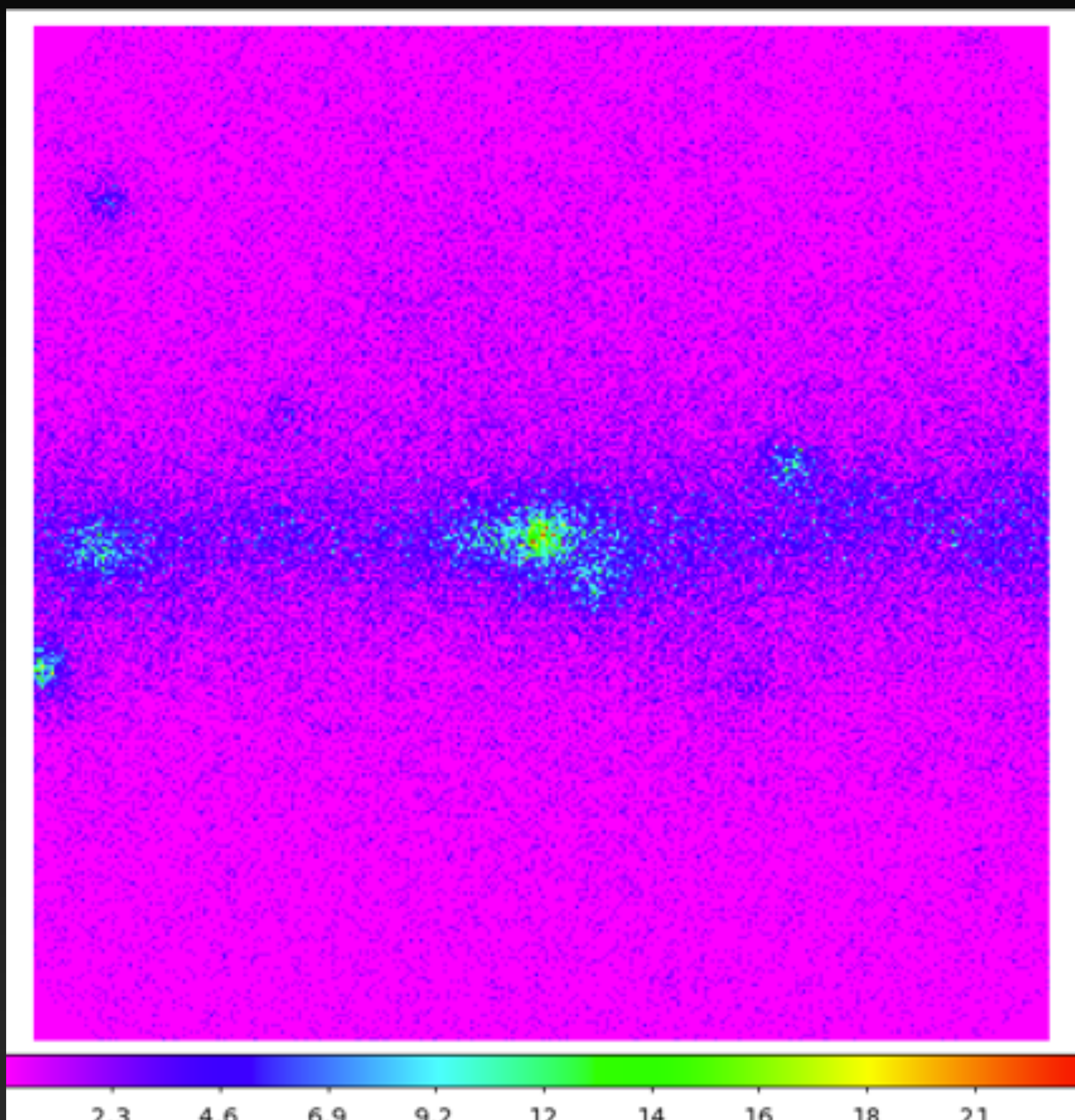
Gamma Rays and Dark Matter 12/08/15

# Template Fitting Analyses

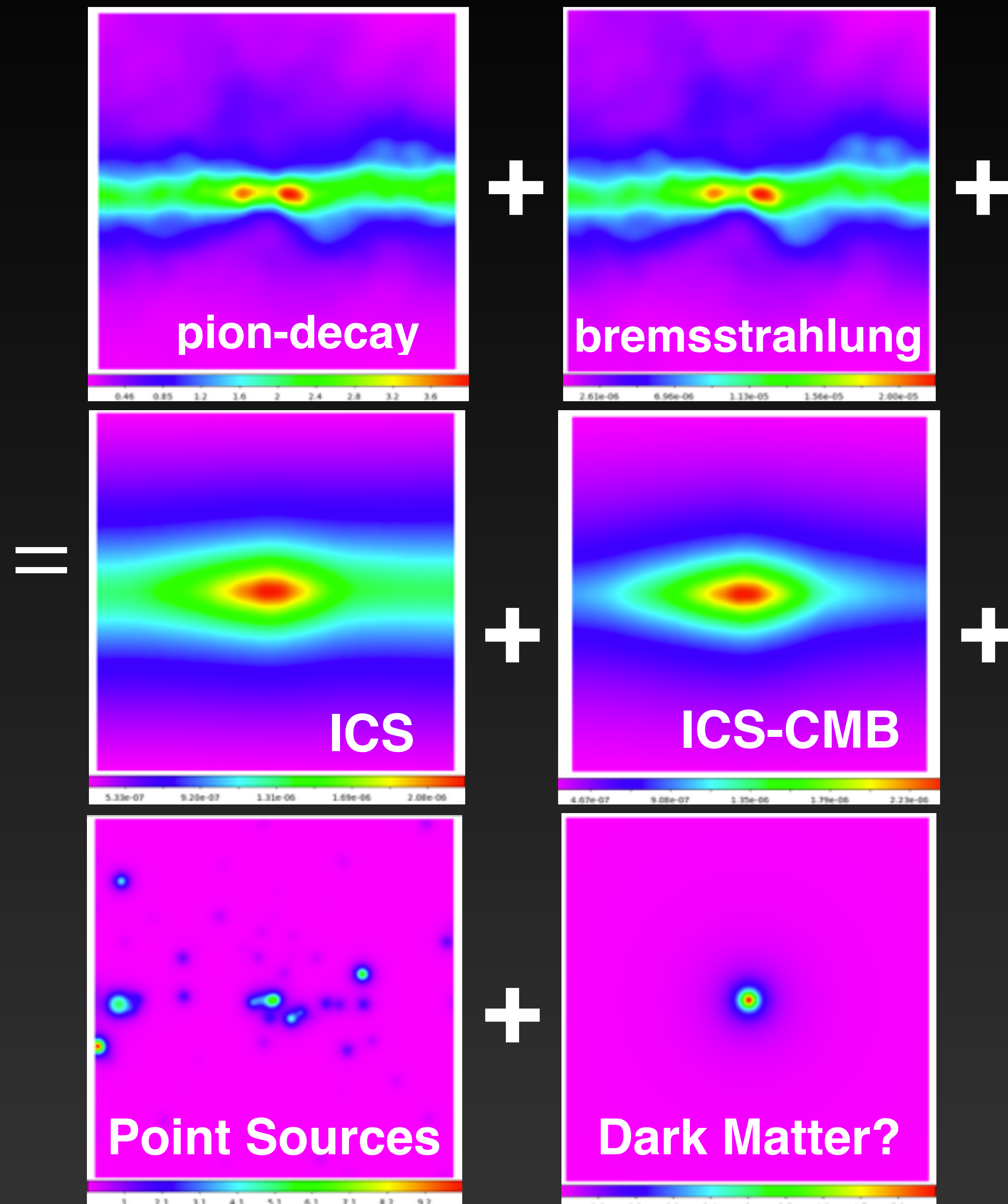



Data

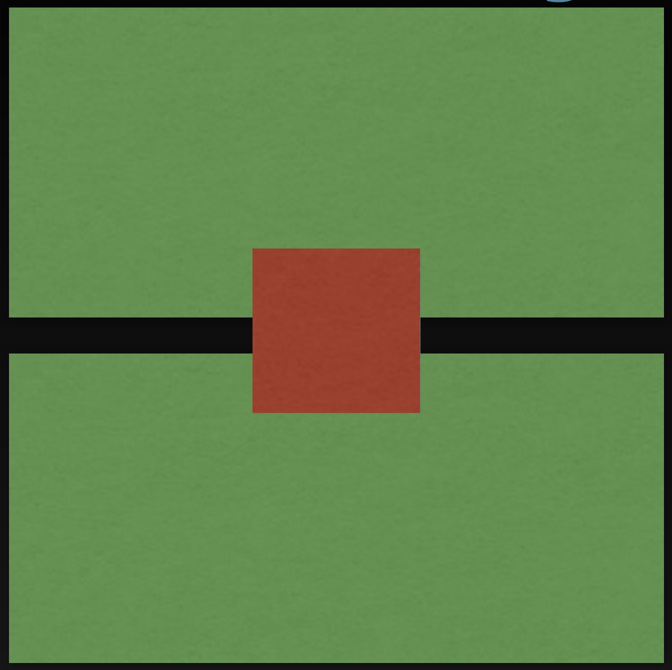
750 — 950 MeV

Best Angular Resolution Cut

10º x 10º ROI



# Two Separate Analysis Regions



## 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

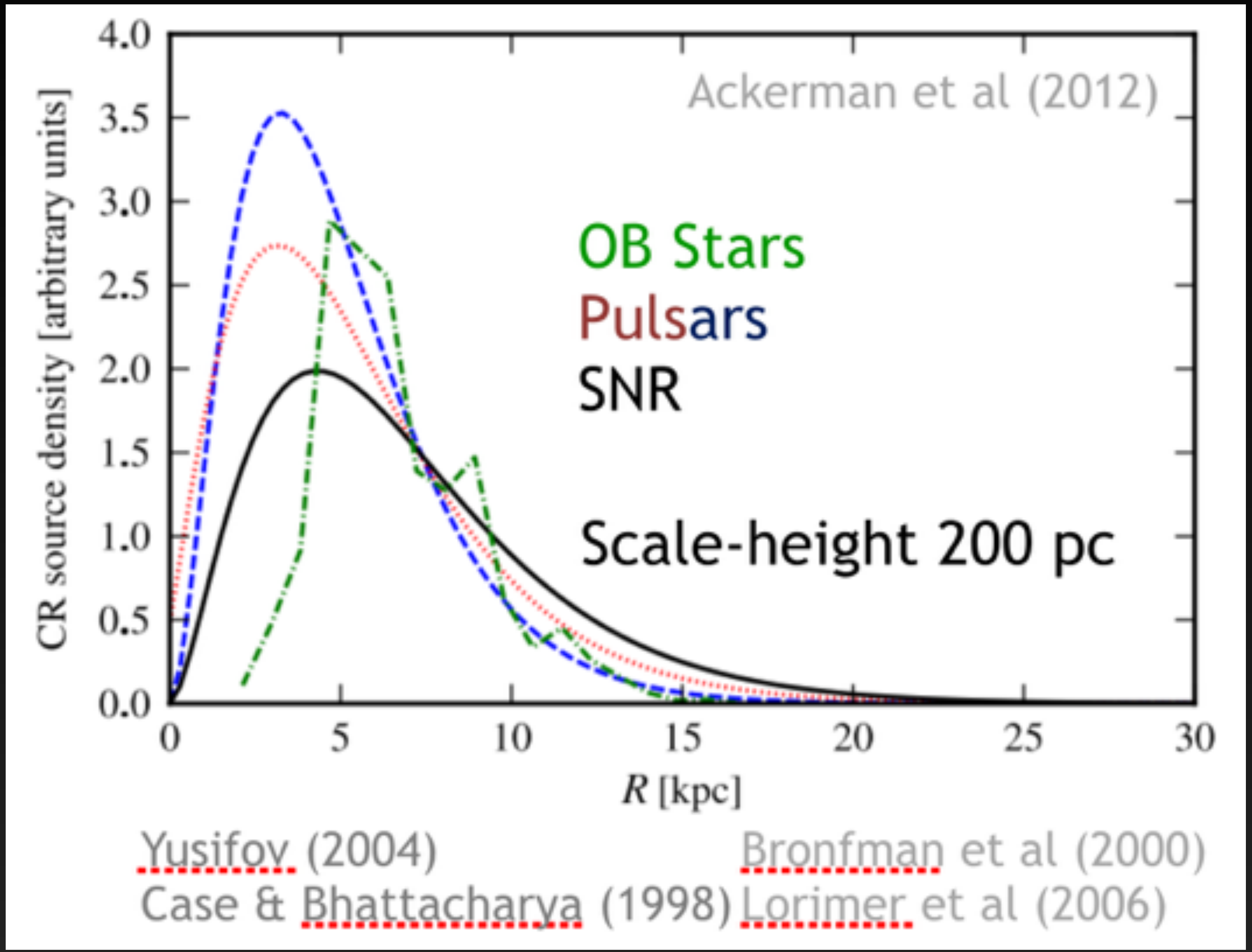
- Box around the GC (10º x 10º)
- Include and model all point sources
- Use likelihood analysis to calculate the spectrum and intensity of each source
- Bright Signal

# Diffuse Emission Modeling

Cosmic-Ray Injection is thought to trace the historic (~$10^9$ yr) supernova rate.

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).

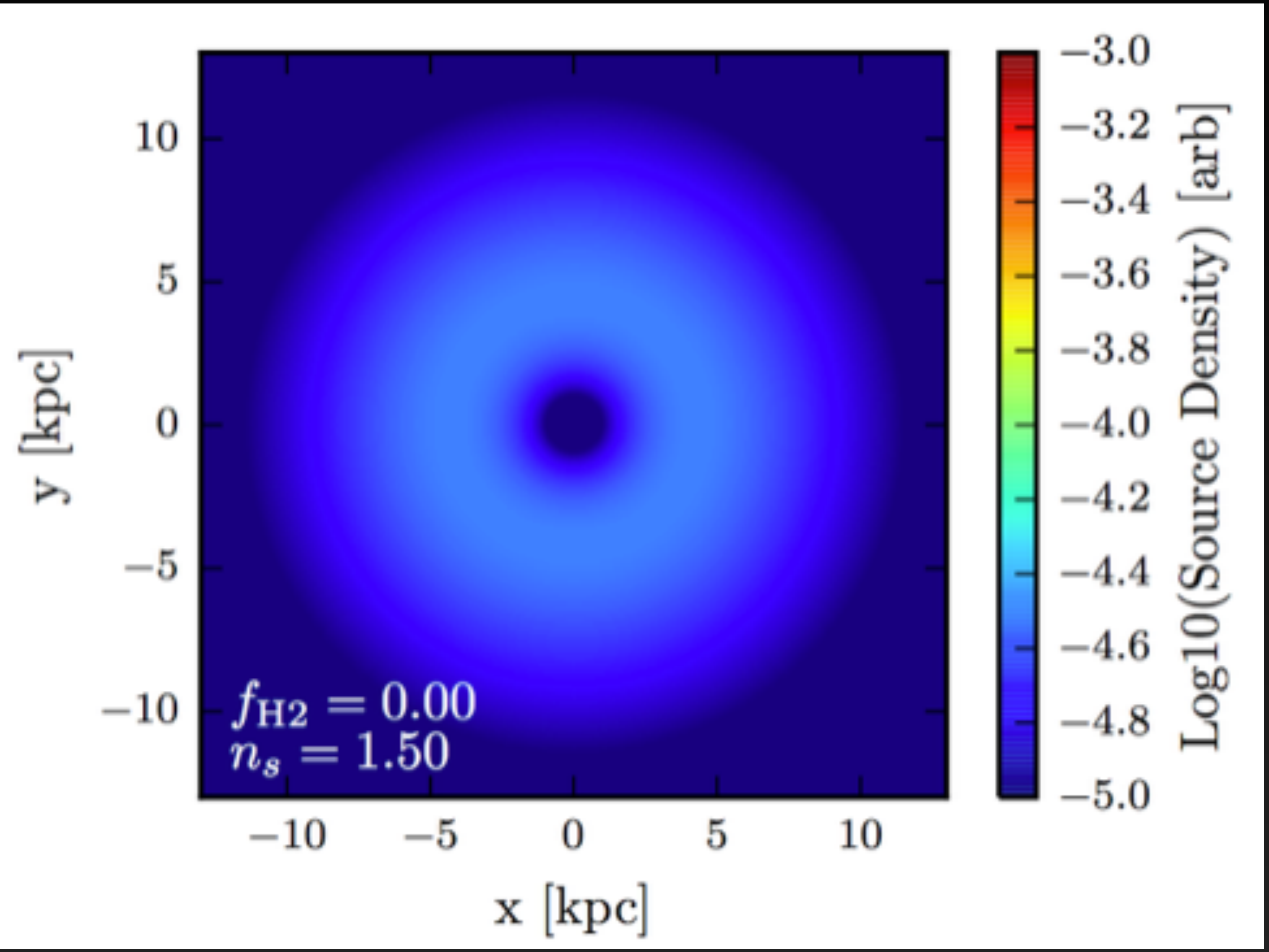
Cosmic-Ray propagation (~30 Myr + 100 Myr)

# Cosmic-Ray Injection Sources

These models can then fail in two ways:

1.) Observational incompleteness

2.) Time variable injection



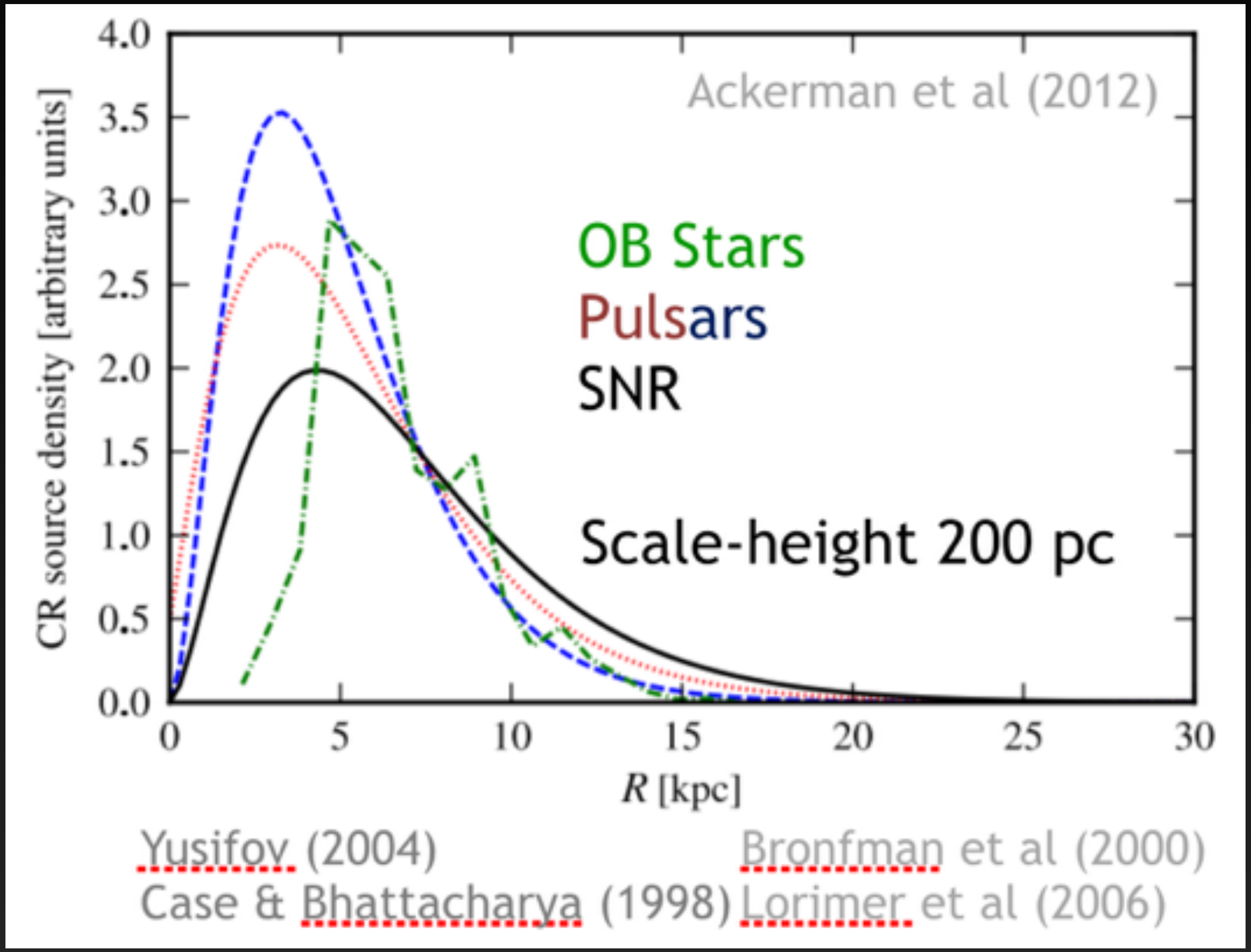

Interestingly the models used for these analyses have extremely small injection rates near the GC (in several cases identically 0).

# Cosmic-Ray Injection in the GC

## Why Is this Done?

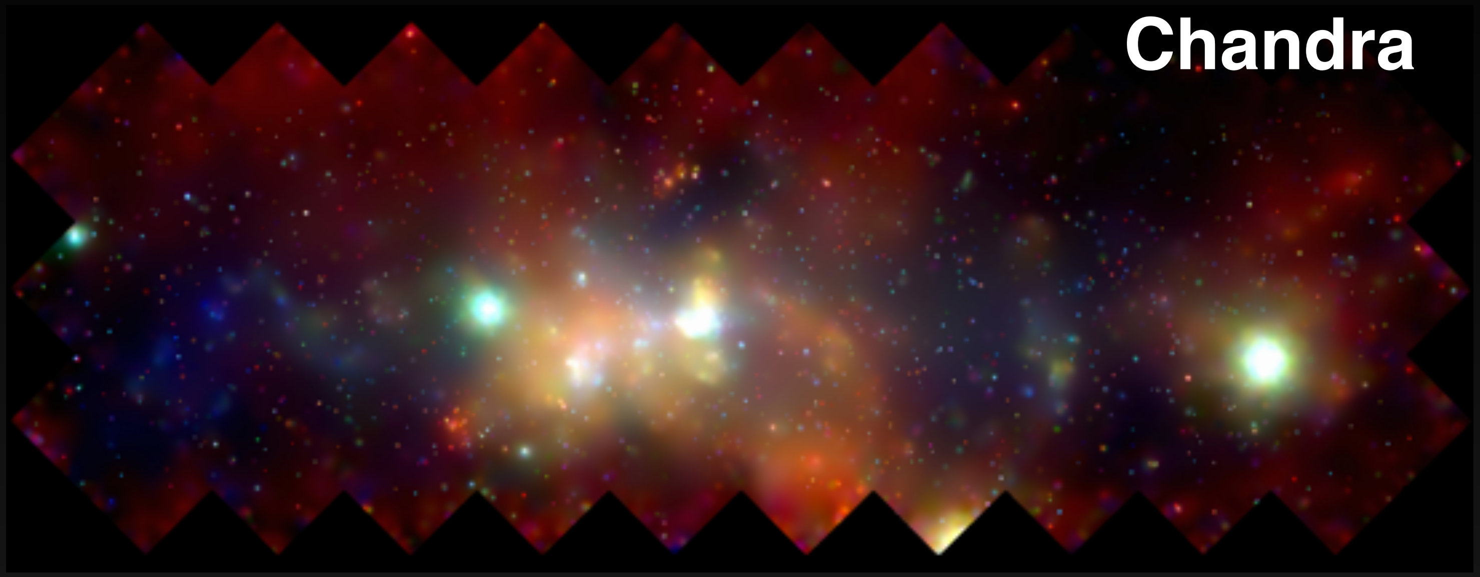
1.) Want to fit a simple analytic form to a profile that peaks at 4 kpc.

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



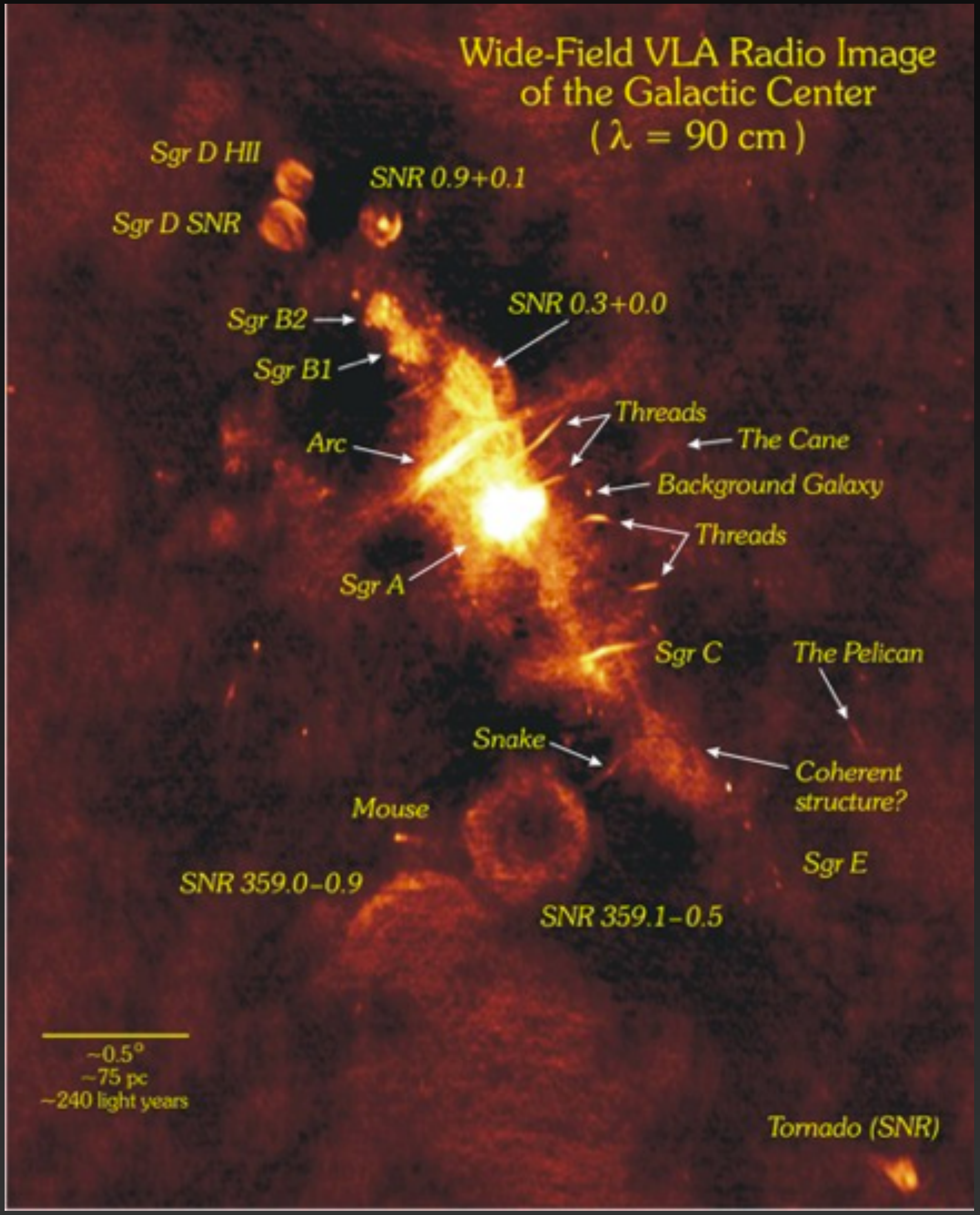

3.) Model of GC is unimportant for cosmic-ray propagation studies.

# Current Observations of GC

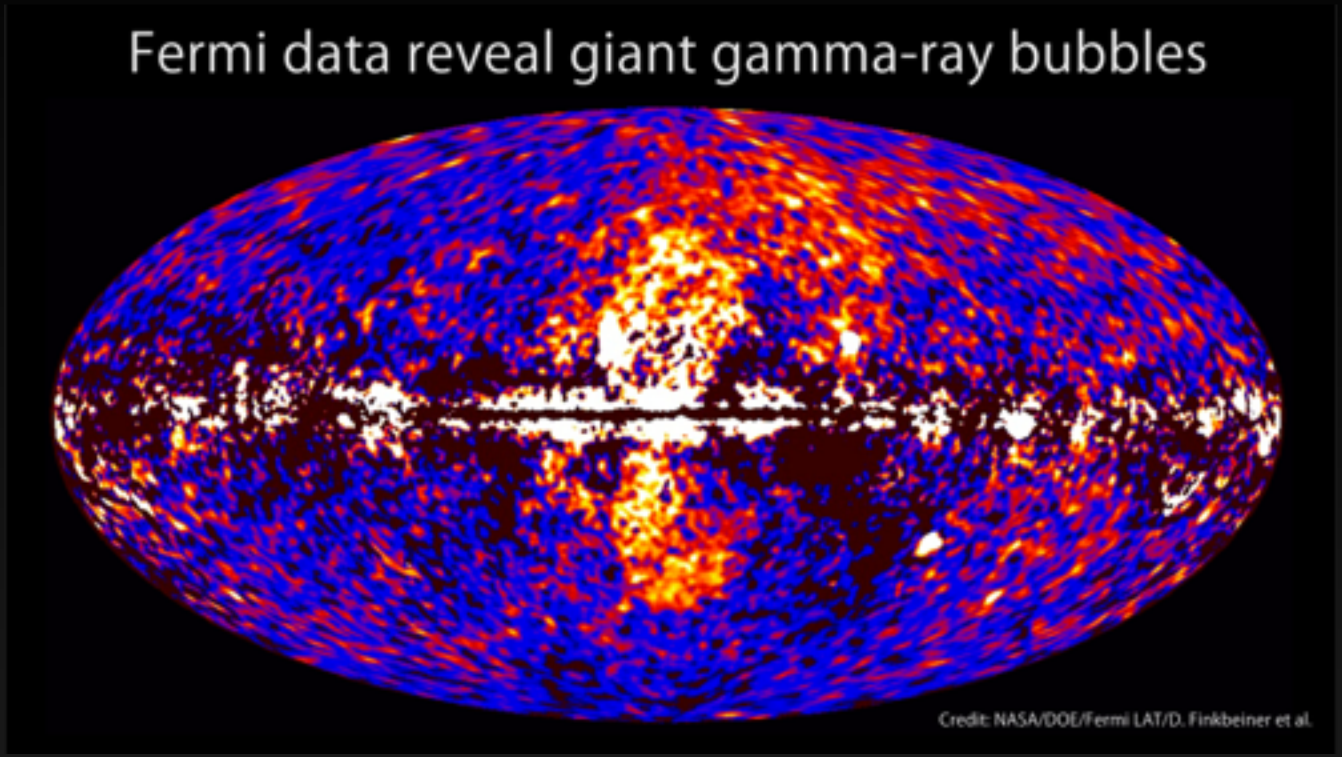


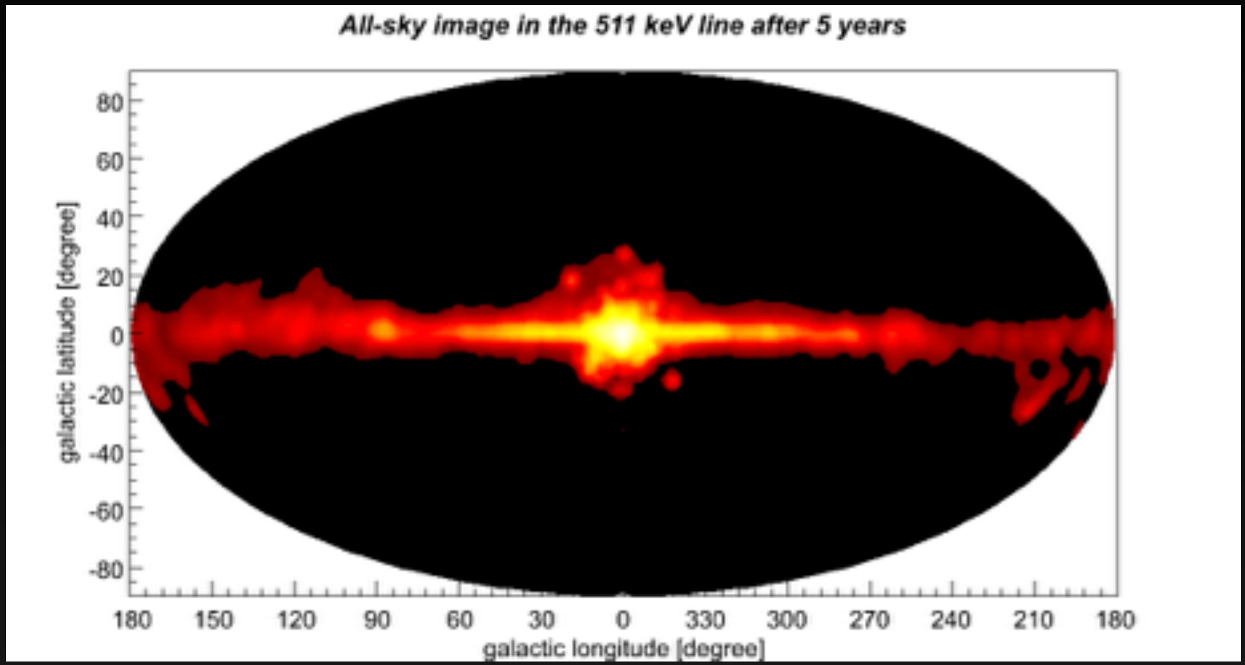

**However, observations of the GC find intense star formation and many supernovae remnants.**

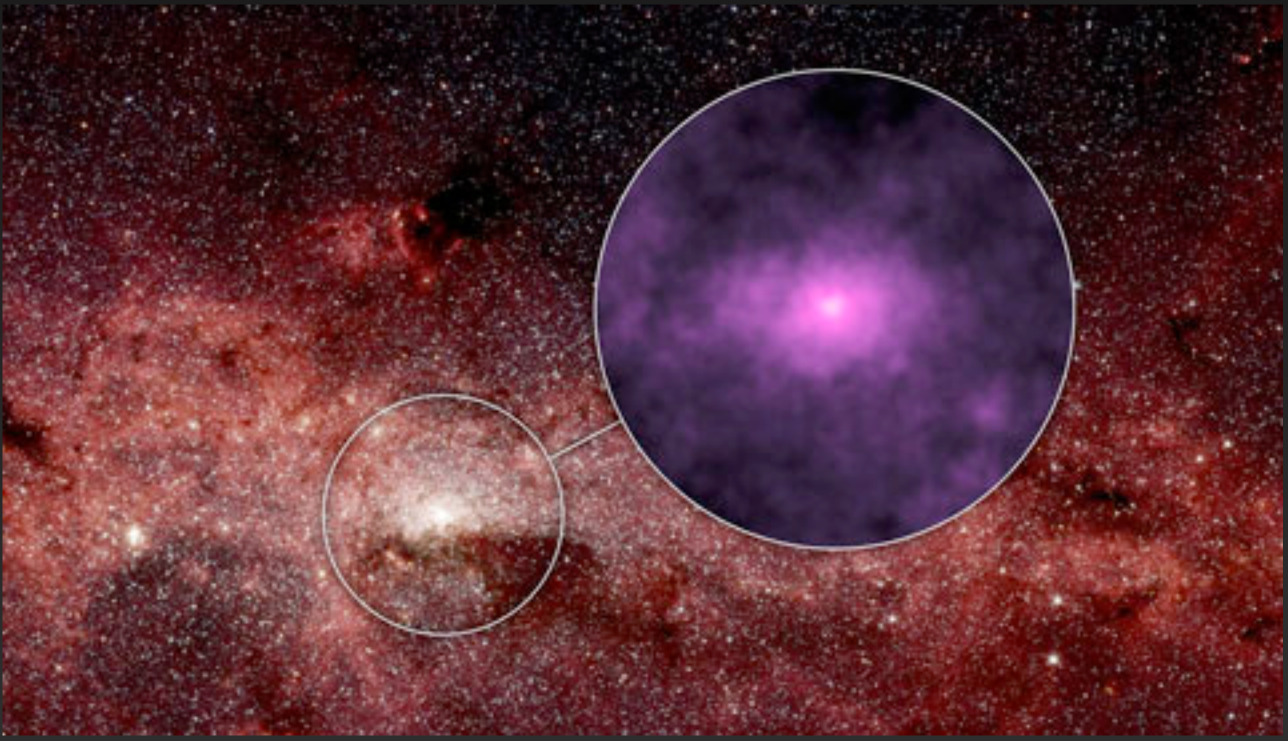
**e.g. 3-6% of the total galactic SFR rate occurs in the Central Molecular Zone (Longmore et al. 2012)**

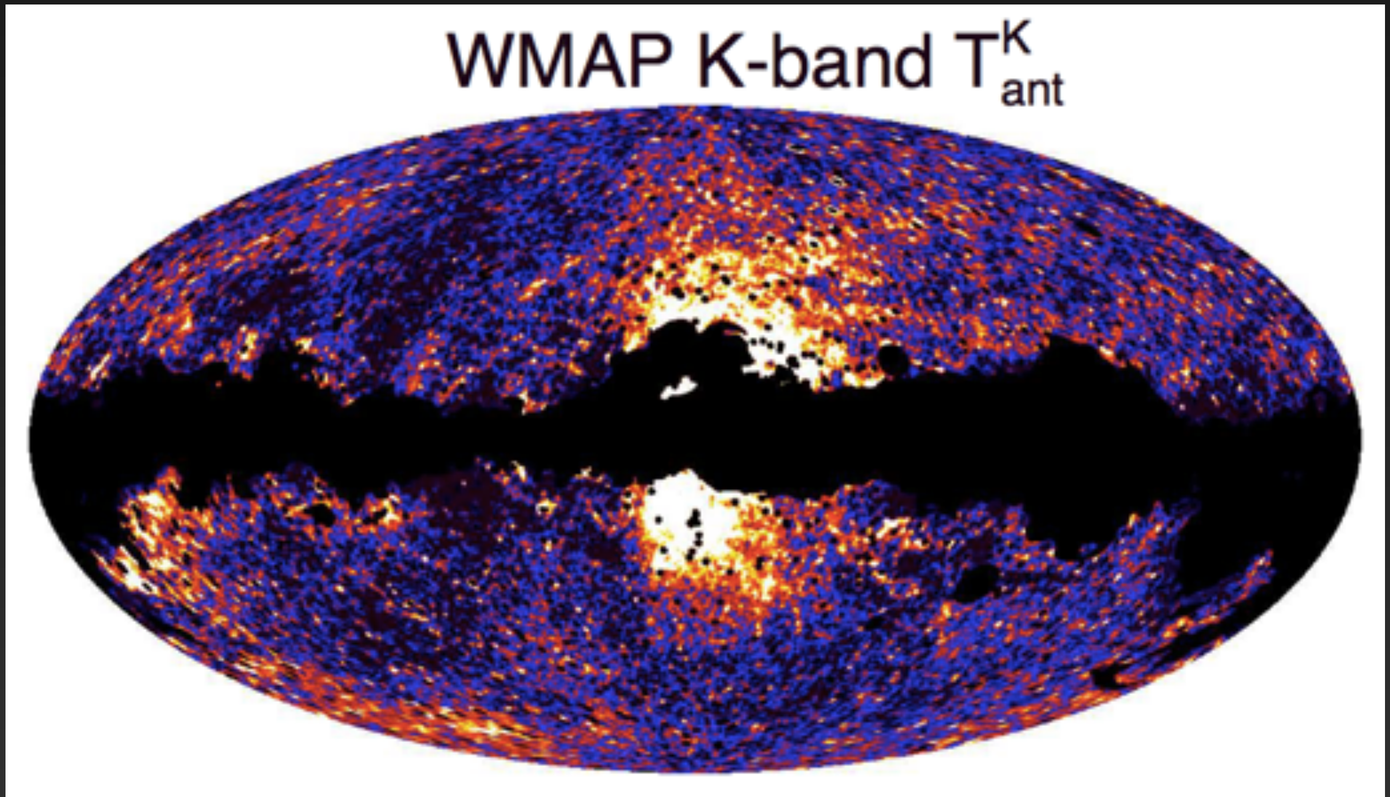


# Excesses are not Limited to GeV Energies





# 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 Kennicutt-Shmidt Law gives

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

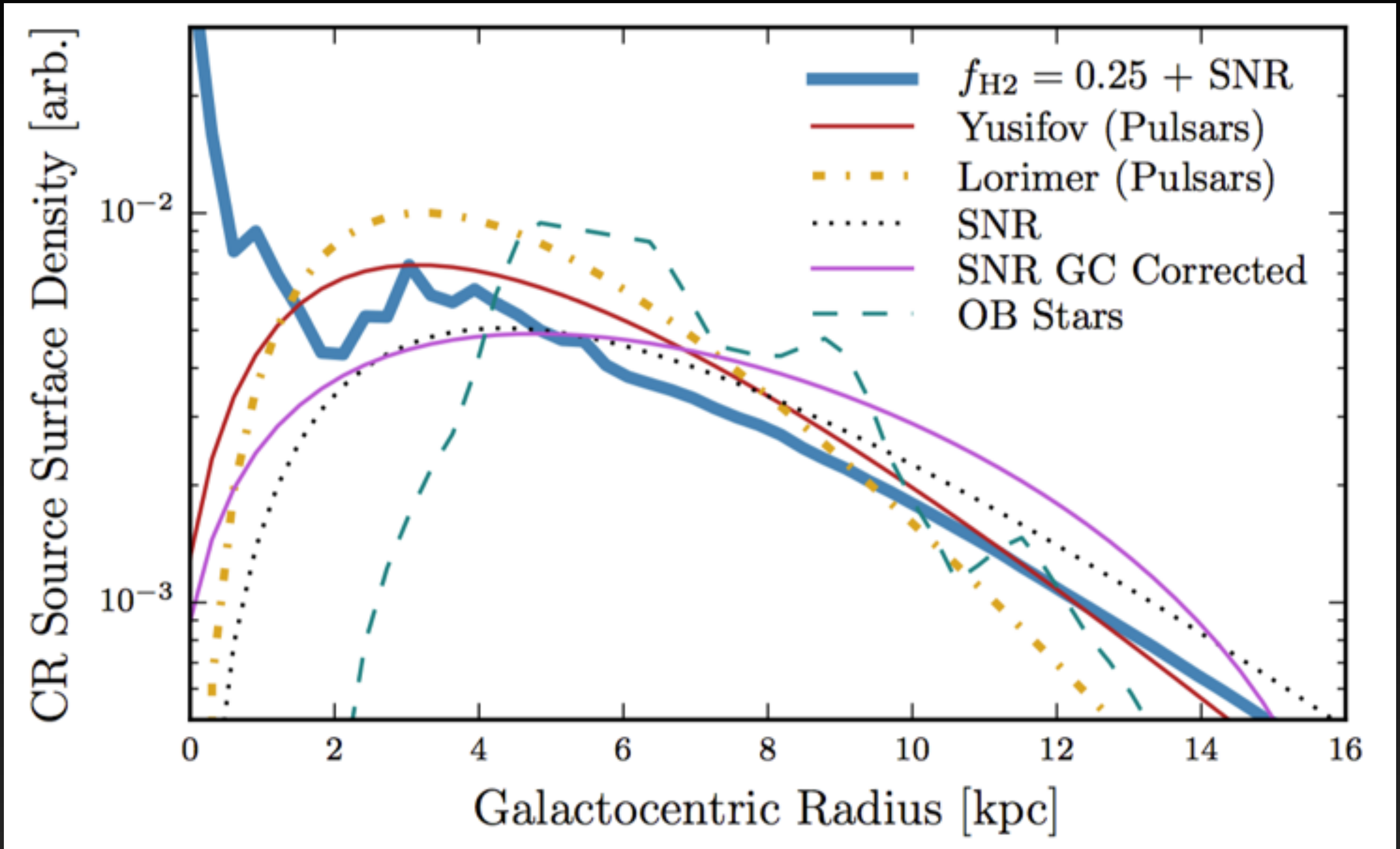
**Specifically we adopt:**

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

1510.04698

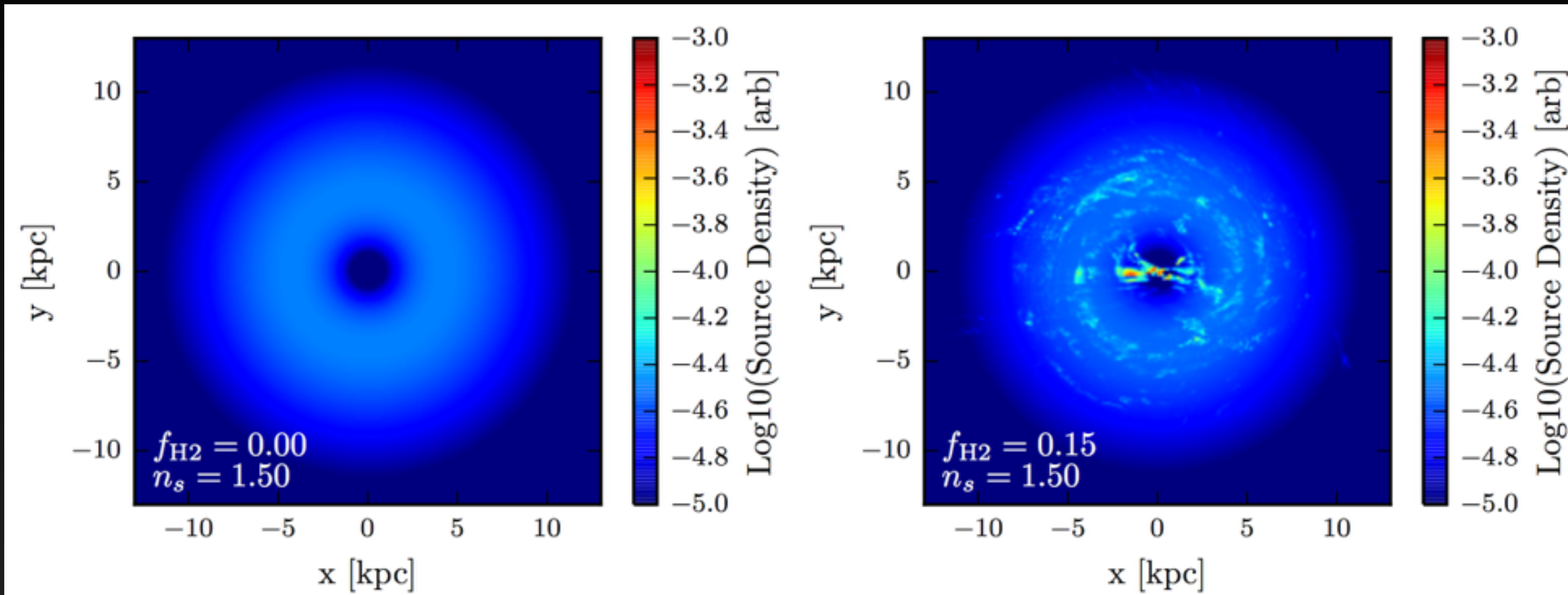
1512.XXXXX?

# Adding a Molecular Gas Component




**Adds significant cosmic-ray injection to the inner galaxy, and additionally a large bar structure.**

# Cosmic-Ray Injection in the GC




**Adds significant cosmic-ray injection to the inner galaxy, and additionally a large bar structure.**

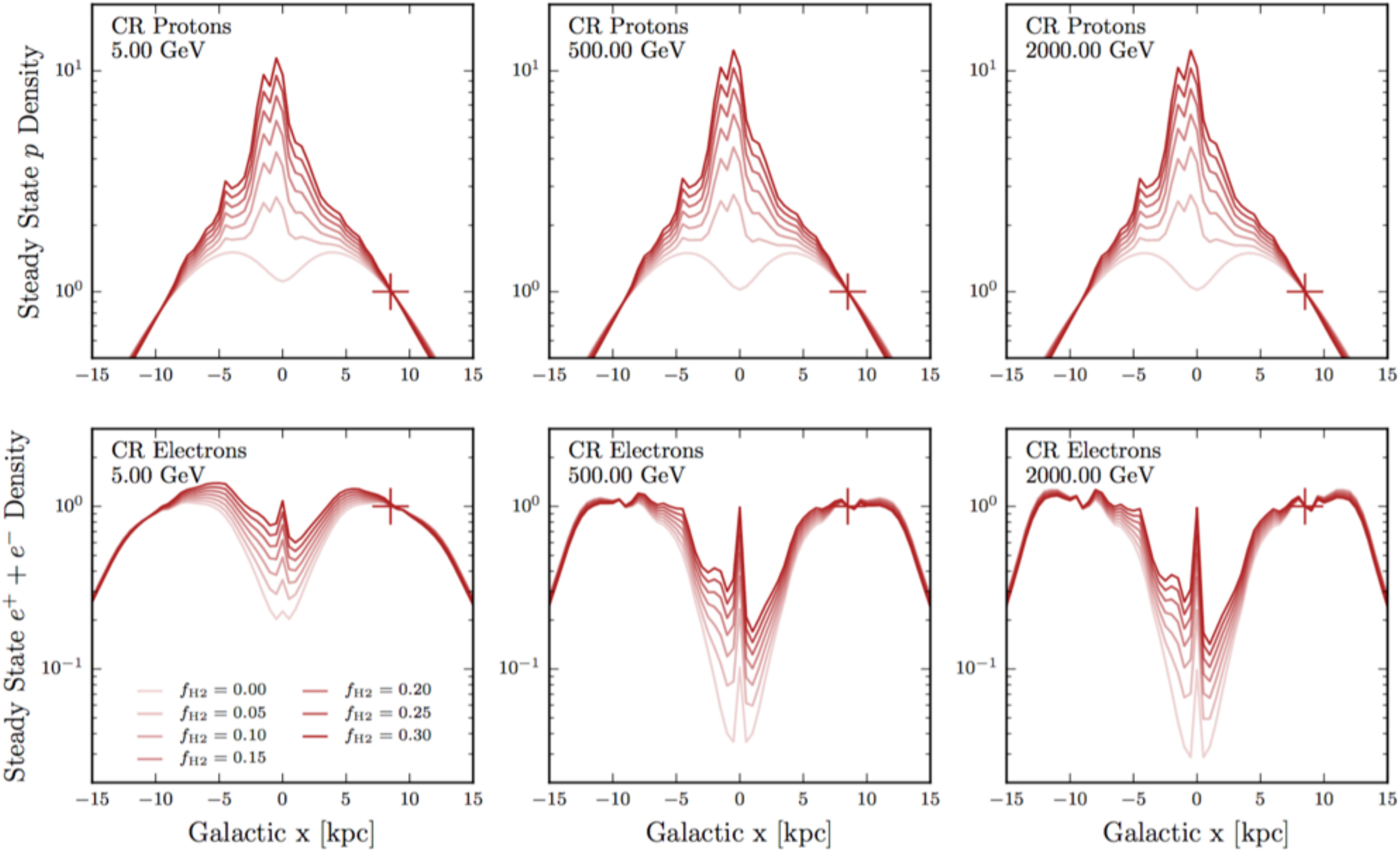
# Galprop Simulations

| Parameter | Units | Canonical | Mod A | Description |
|---|---|---|---|---|
| $D_0$ | $cm^2\ s^{-1}$ | $7.2 \times 10^{28}$ | $5.0 \times 10^{28}$ | Diffusion constant at $\mathcal{R} = 4$ GV |
| $\delta$ | – | 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 |
| $\alpha_p$ | – | 1.88 (2.39) | 1.88 (2.47) | $p$ injection index below (above) $\mathcal{R} = 11.5$ GV |
| $\alpha_e$ | – | 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* |
| $\rho_c$ | $cm^{-3}$ | 0.1 | N/A | Critical $H_2$ density for star formation* |
| $B_0$ | $\mu$G | 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)**

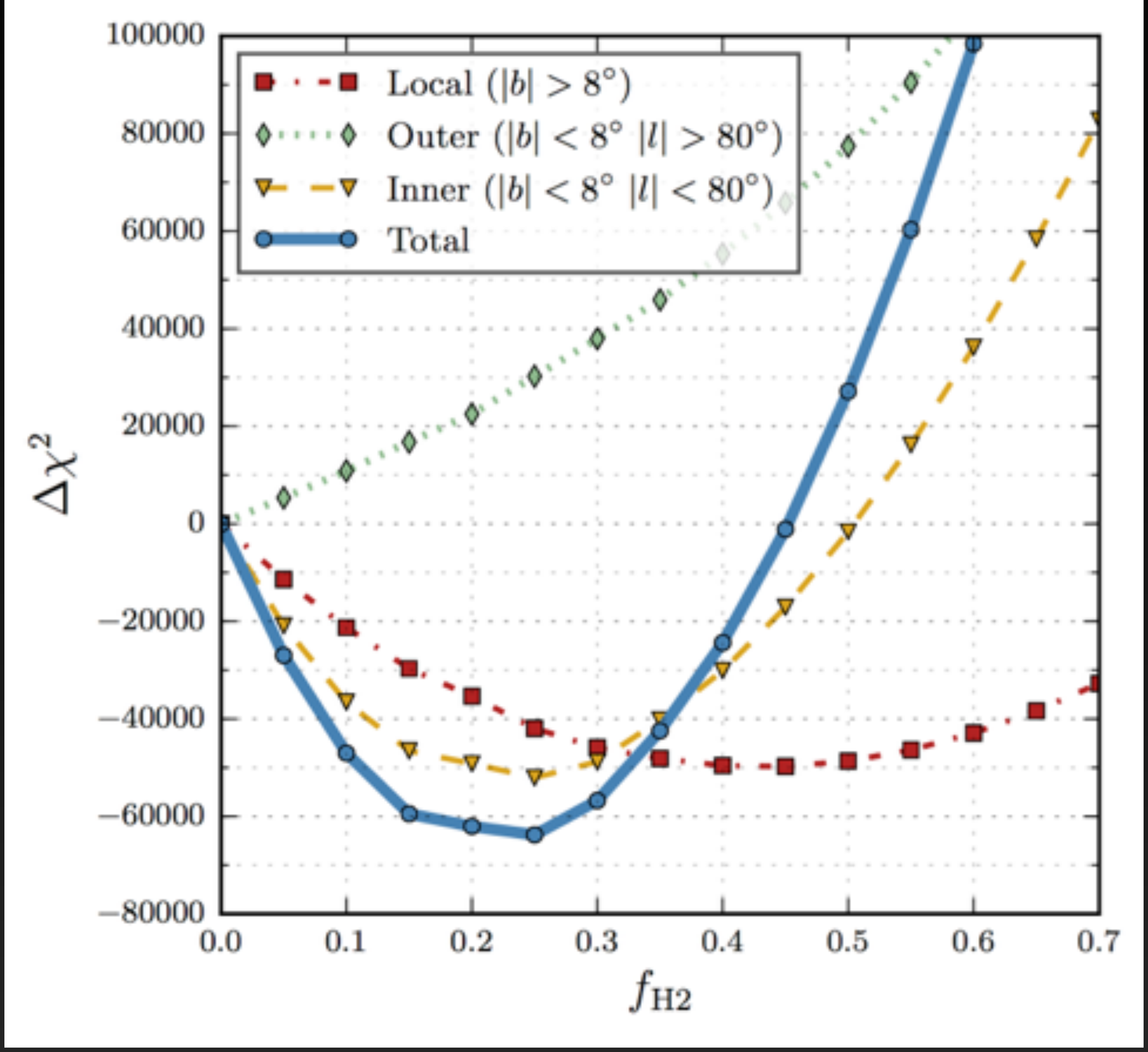
**New models for the 3D galactic gas density are also produced (Carlson 2015, to be submitted).**

# Cosmic-Ray Injection in the GC



# 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.

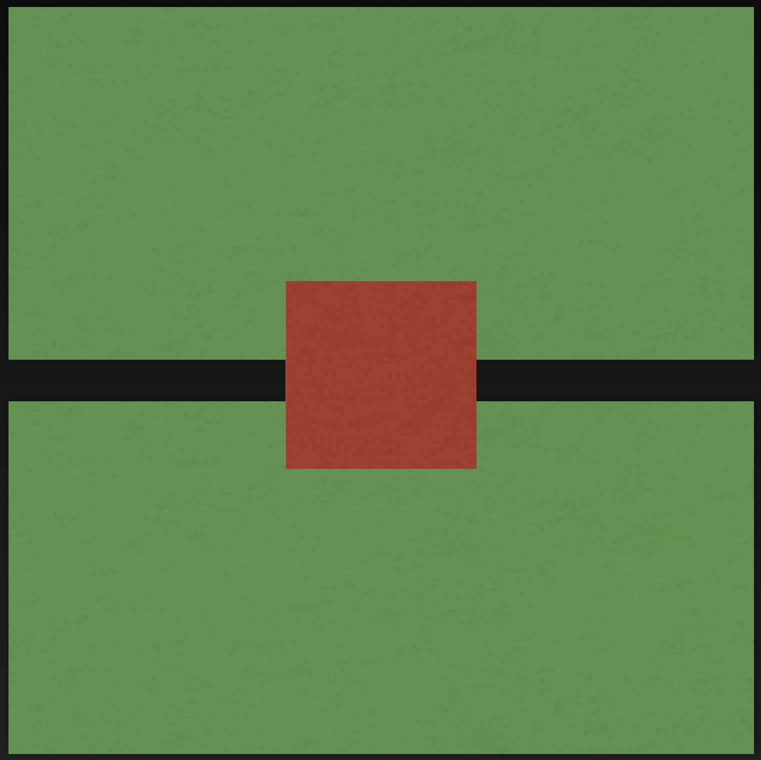



2.) This is an important point on its own, as it offers a new method for improving diffuse models for the gamma-ray sky.

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

# An Inner Galaxy Analysis of the GCE

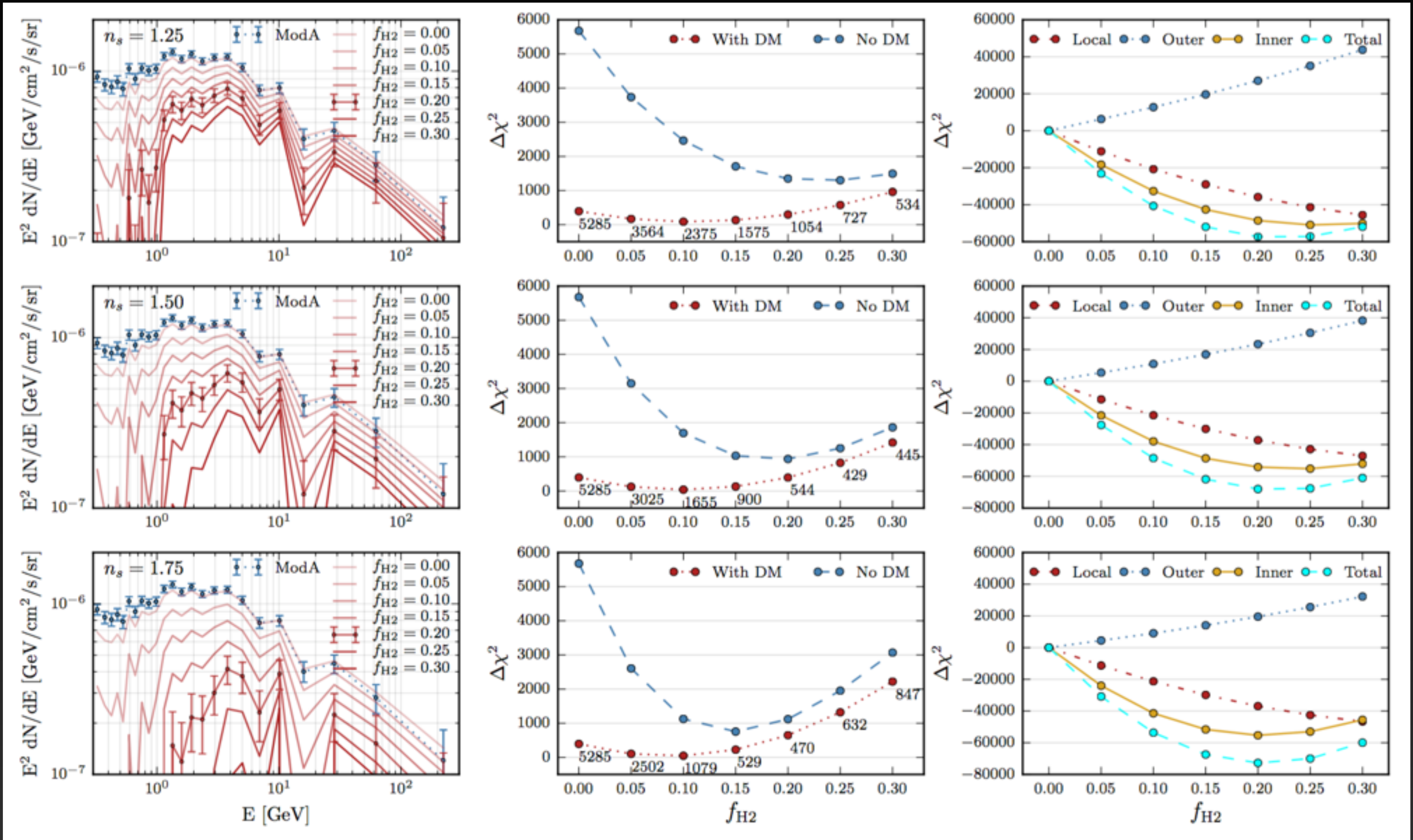
## INNER GALAXY



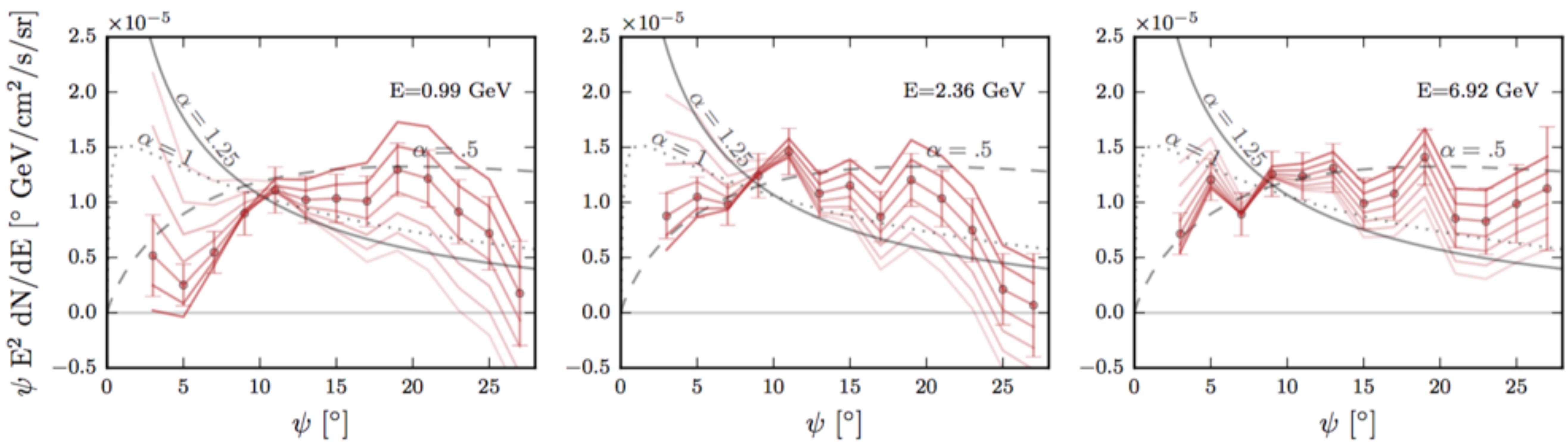
- Mask galactic plane (e.g. |b| > 2º), and consider 40º x 40º box
- Energy dependent masking of bright point sources (following Calore et al. 2014)
- Use likelihood analysis, allowing the diffuse templates to float in each energy bin
  - Isotropic energy spectrum fixed via error bars in EGRB analysis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



# Effects on the Gamma-Ray Excess



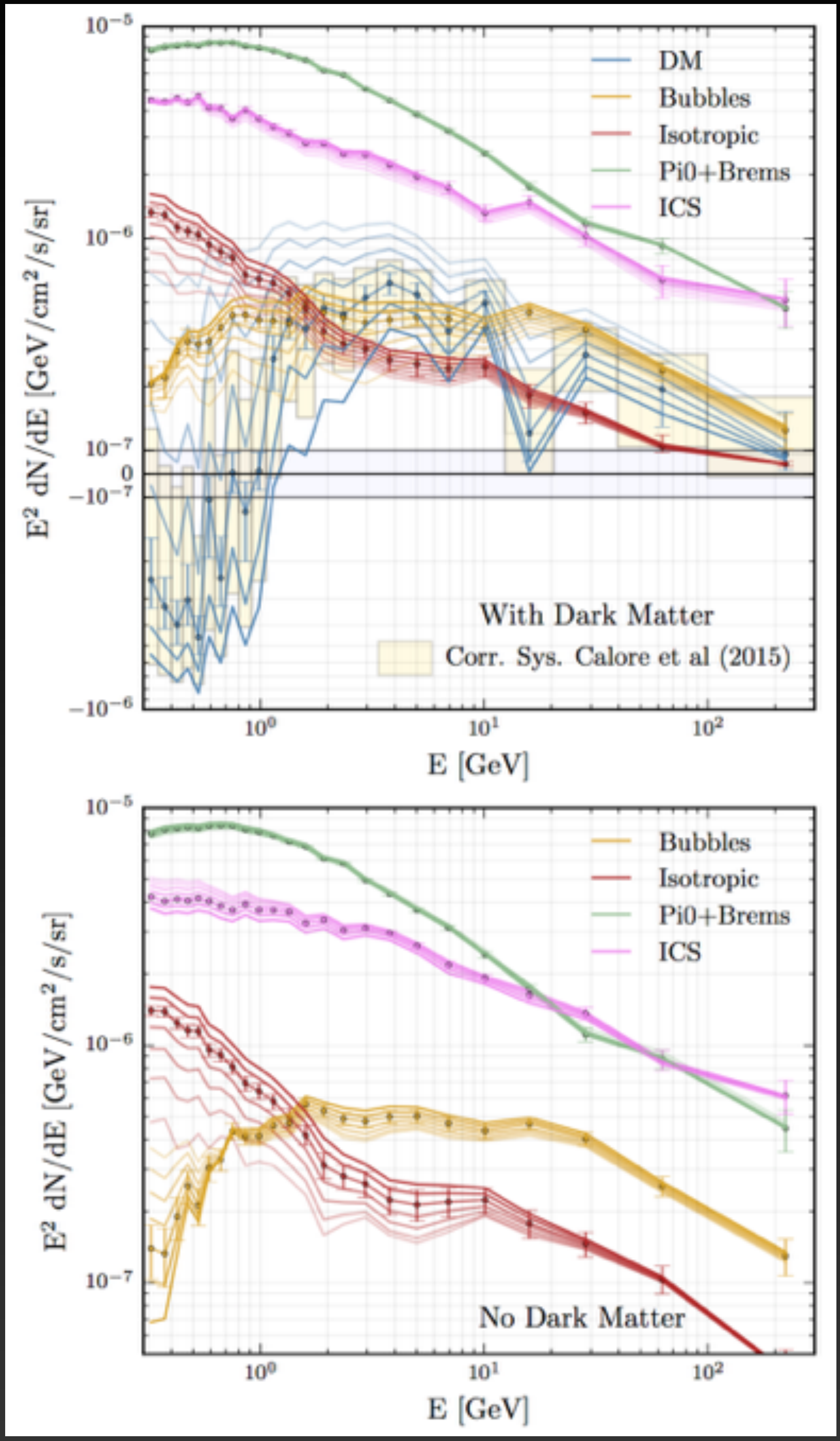

**The addition of the $H_2$ template also significantly flattens and distorts the best fit NFW profile.**

**The addition of the $H_2$ template also significantly flattens and distorts the best fit NFW profile.**

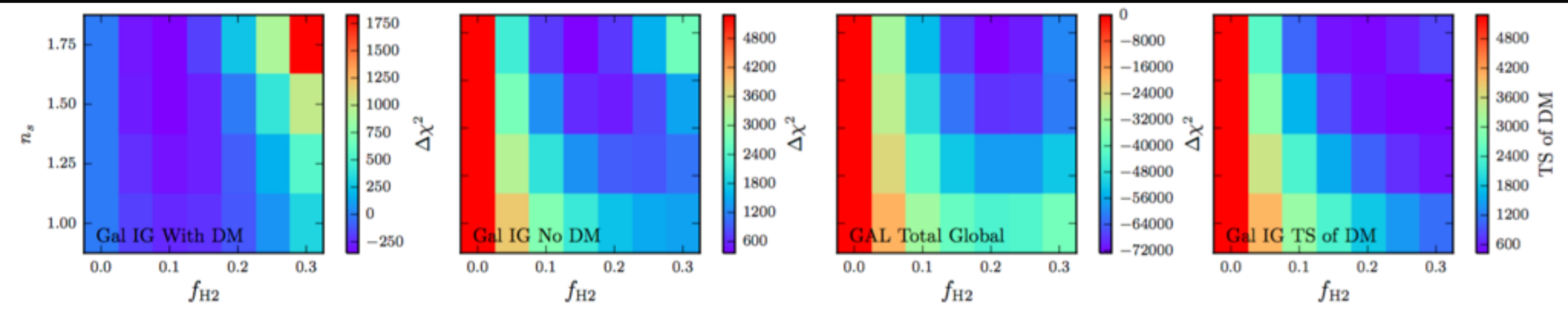
# Effects on the Gamma-Ray Excess

The overall spectrum and intensity of the astrophysical background components is relatively resilient to the emission from the NFW template.

Appears that we may have been premature in arguing that cosmic-ray emission can't spectrally reproduce the excess.



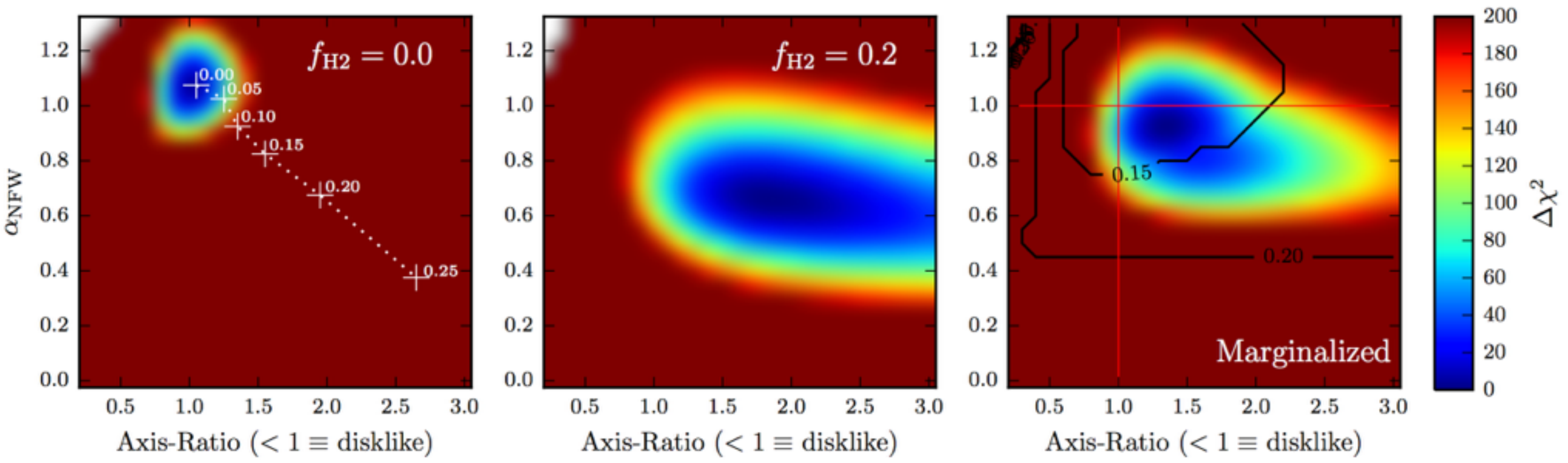
# The Excess is Degenerate with $f_{H2}$




**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.**

# GC Excess Ellipticity



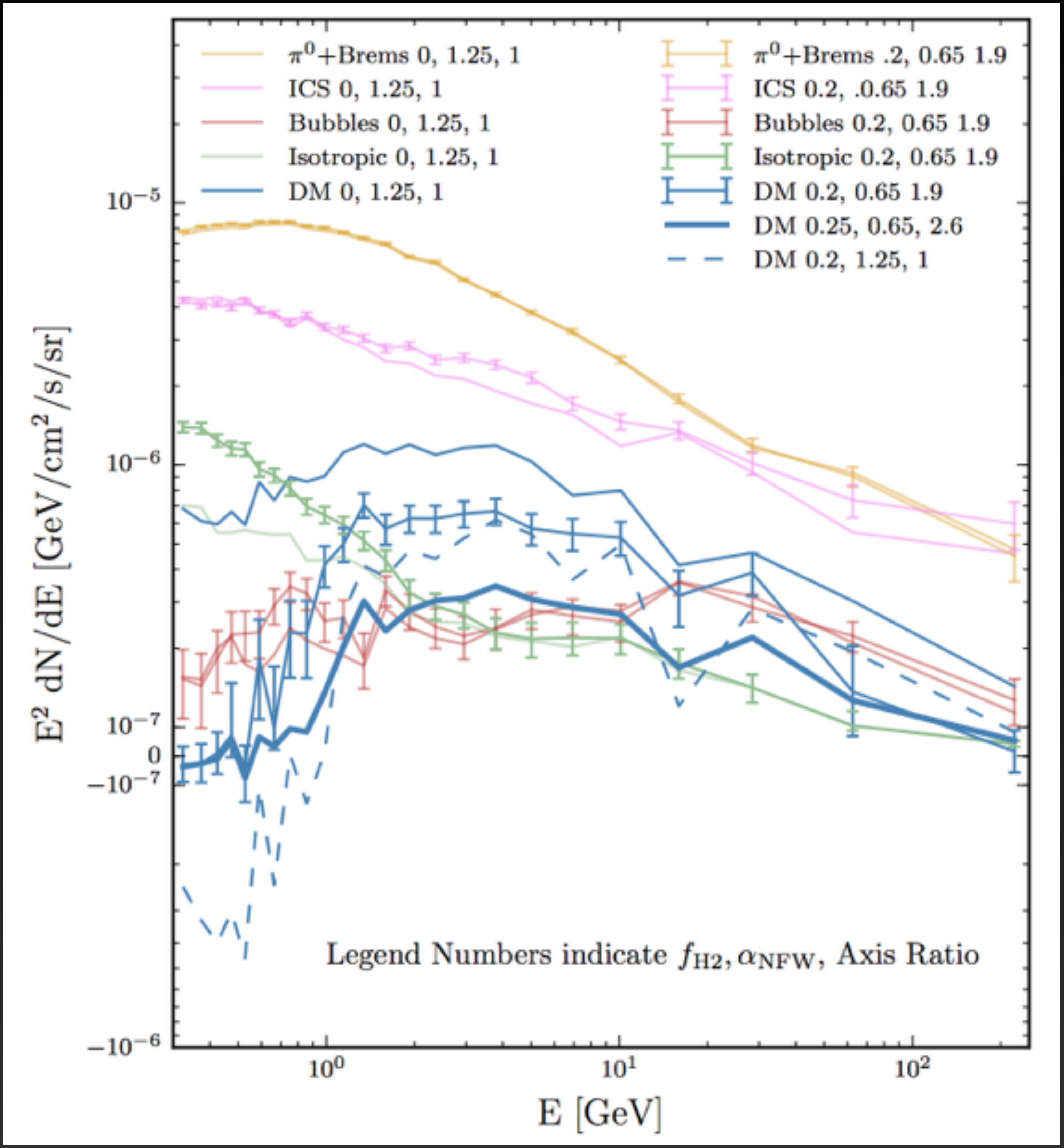

**Interestingly, the intensity of the gamma-ray excess can return, but only if the NFW profile is flattened and stretched perpendicular to the galactic plane.**

**In this case, the NFW component becomes highly degenerate with the Fermi bubbles.**

# A Fermi Bubbles Component?

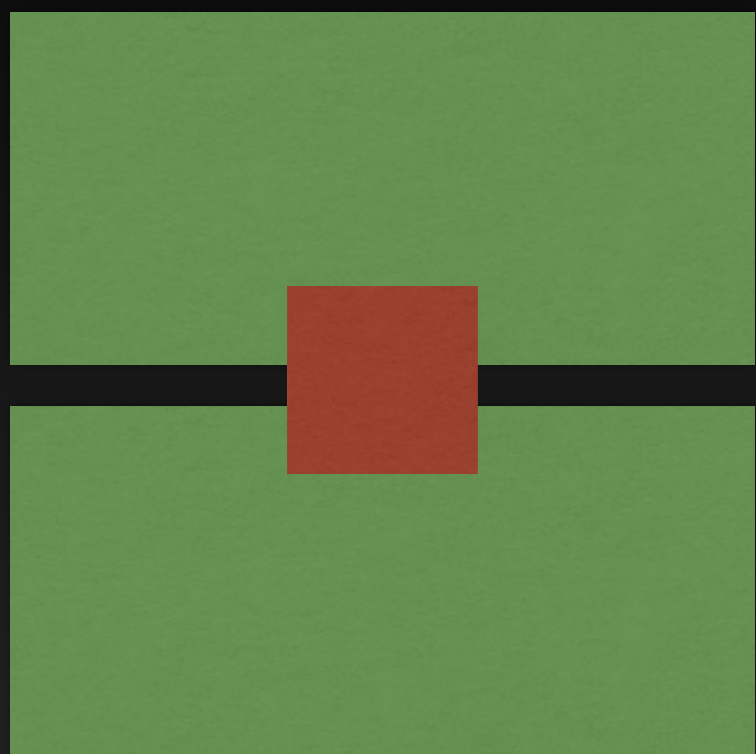
If the best morphological fit to the data is highly elliptical and cored. Is it part of the Fermi bubbles?

The spectra also begins to look similar to the bubbles, suggesting some relation.



# A Galactic Center Analysis of the GCE

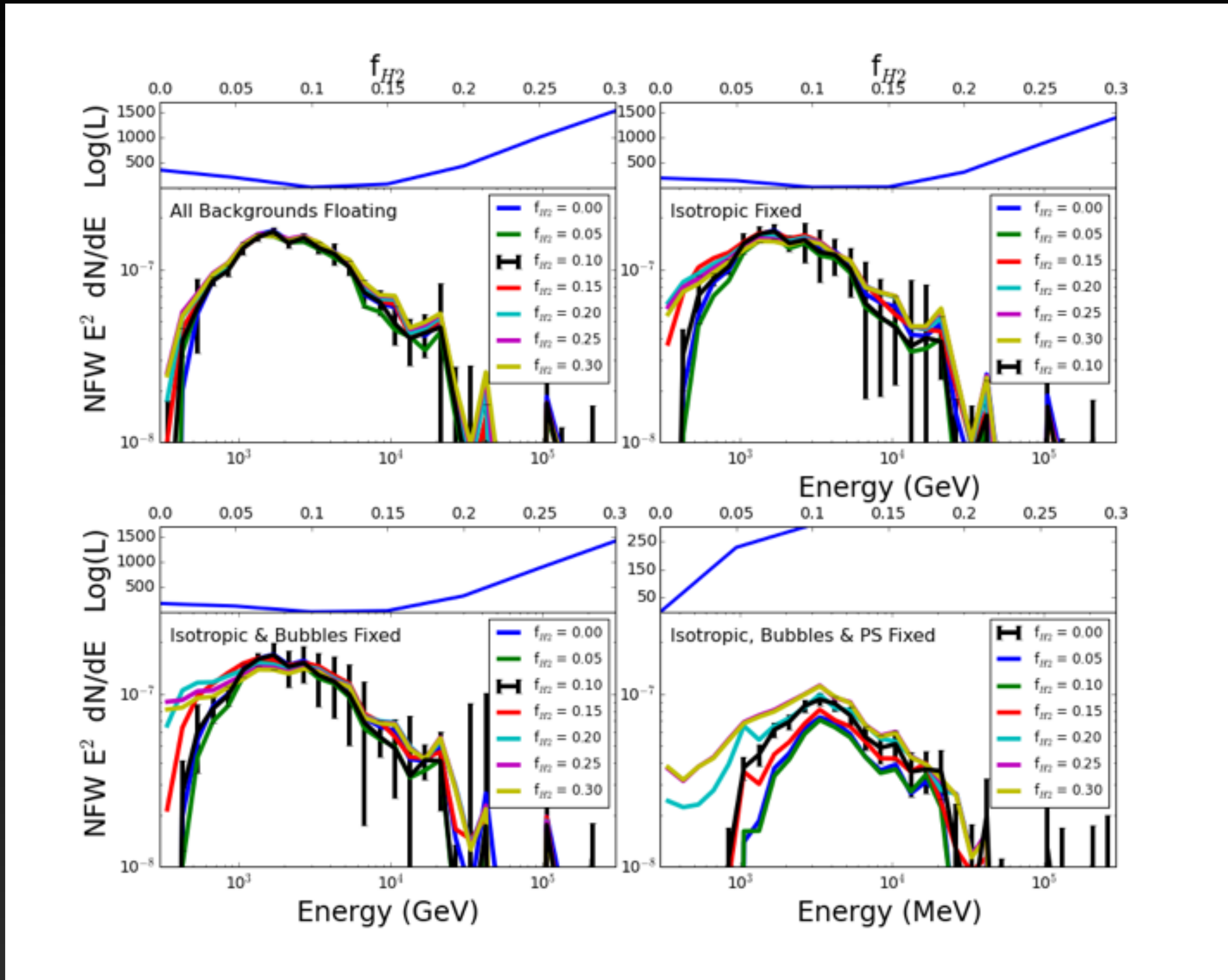
GALACTIC CENTER



- Examine $15^{\circ}$ x $15^{\circ}$ 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.

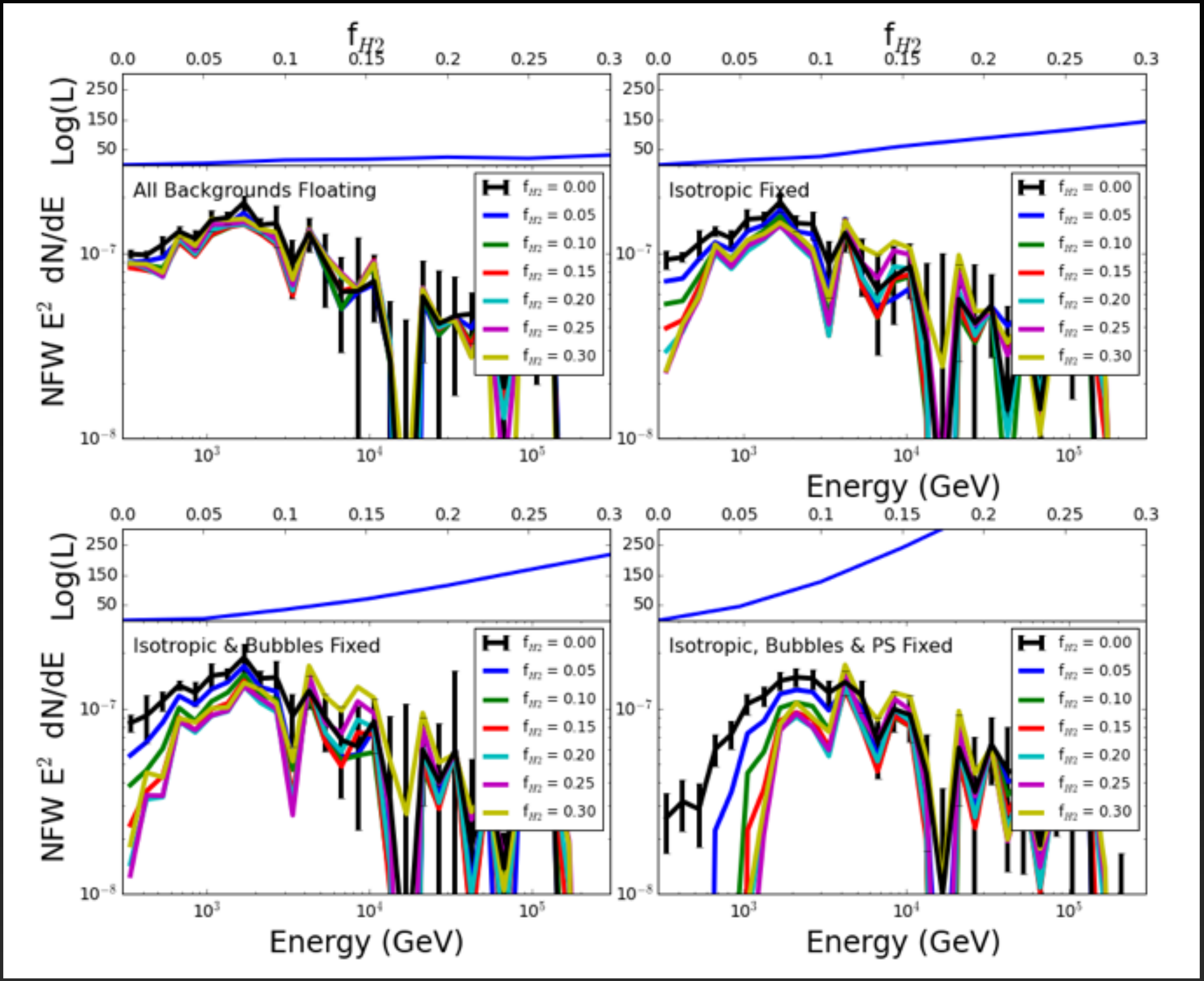
**This creates an analysis with no sidebands region, where the NFW template normalization plays a critical role in determining the spectrum and normalization of diffuse components.**

# Studies of the Galactic Center ($15^o$x$15^o$)



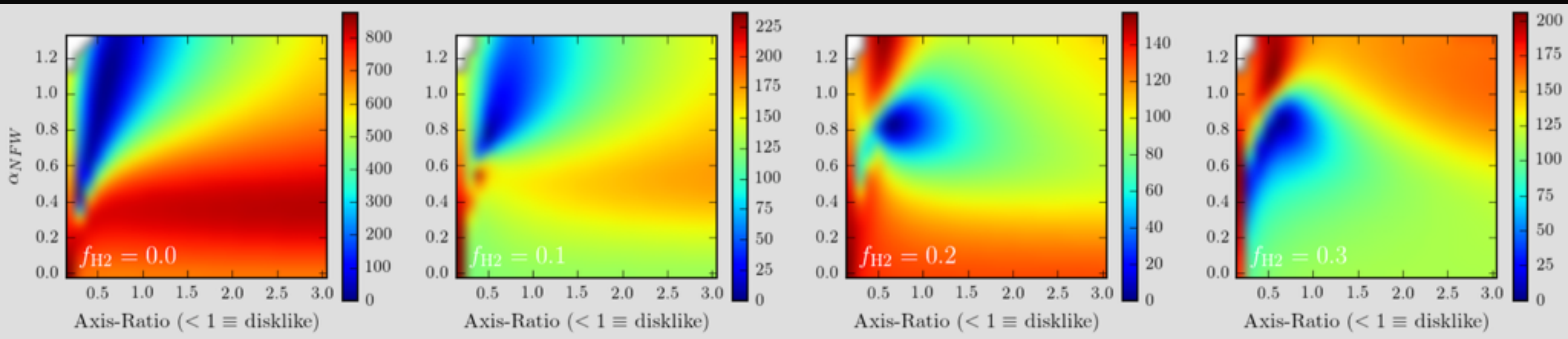

**When the region surrounding the GC is included, the excess remains bright.**

# A 15ºx15º ROI Masking |b| < 2º




**More shockingly, the excess remains relatively bright whenever a small ROI is used, hinting that the excess is reduced primarily due to fits outside the signal region.**

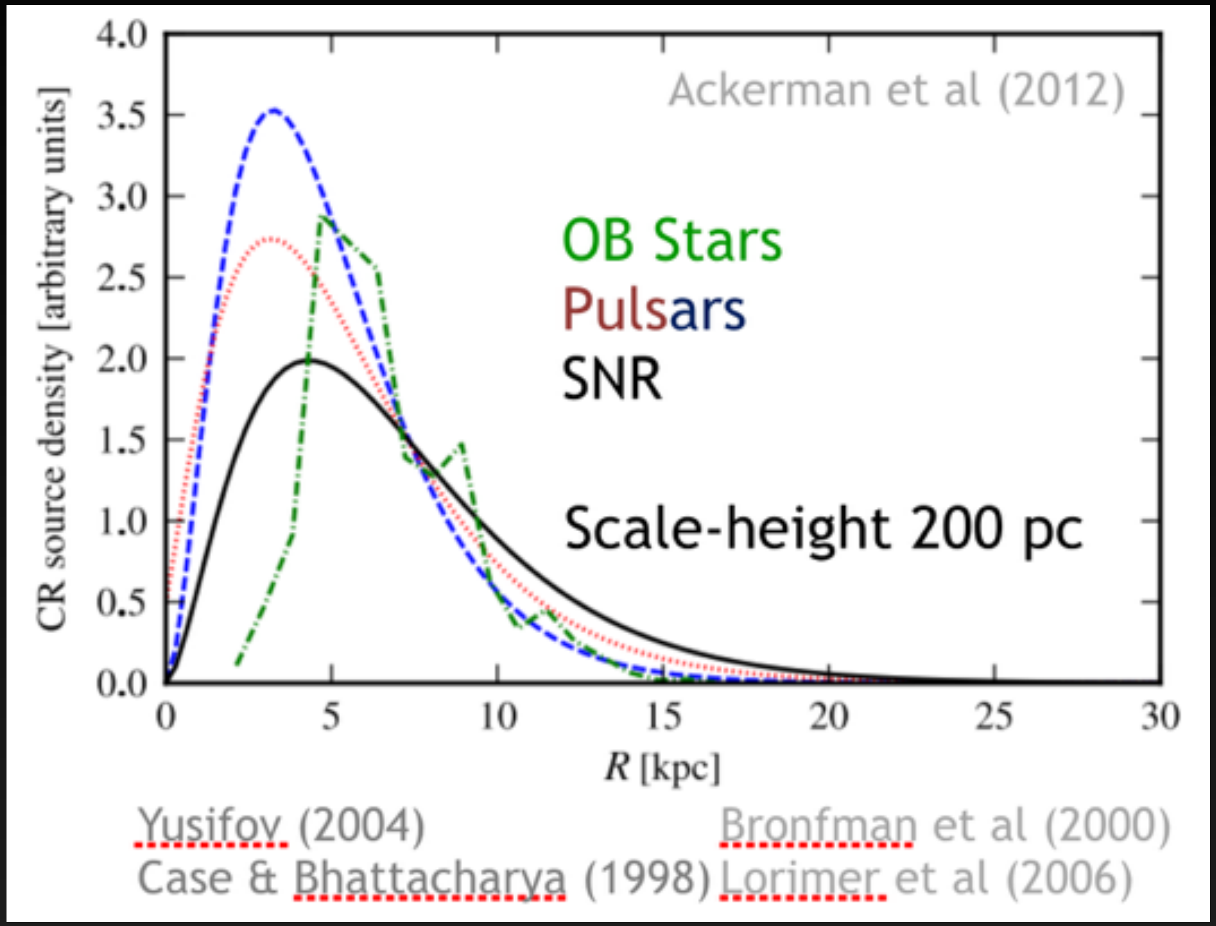
# Ellipticity in the GC Analysis

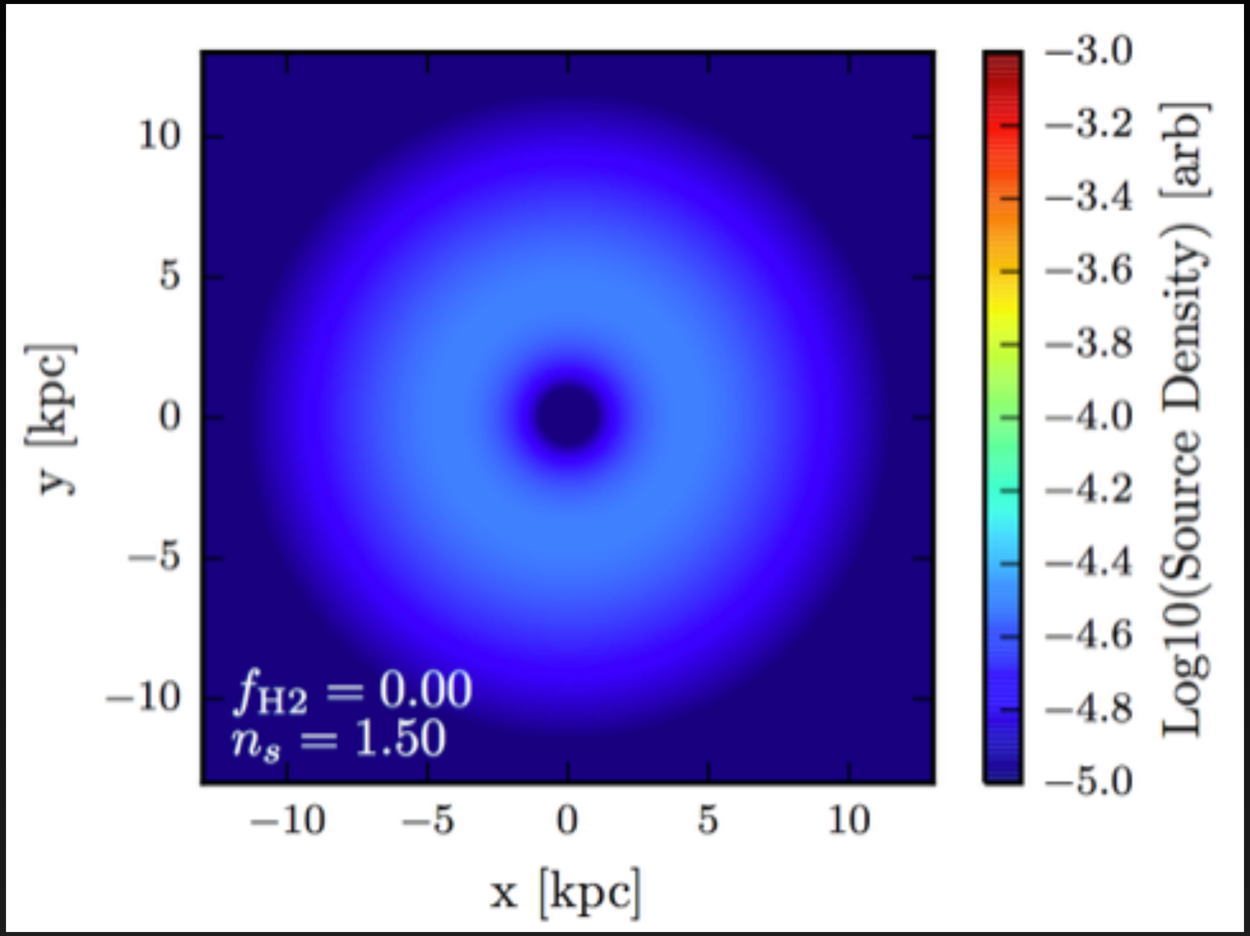



**The addition of a cosmic-ray component tracing the molecular gas density alters the preferred density profile of the dark matter component.**

**For the best fit $f_{H2}$ ~ 0.1, there is a preference for an NFW profile that is slightly cored (0.8) and slightly extended along the galactic plane.**

# 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.