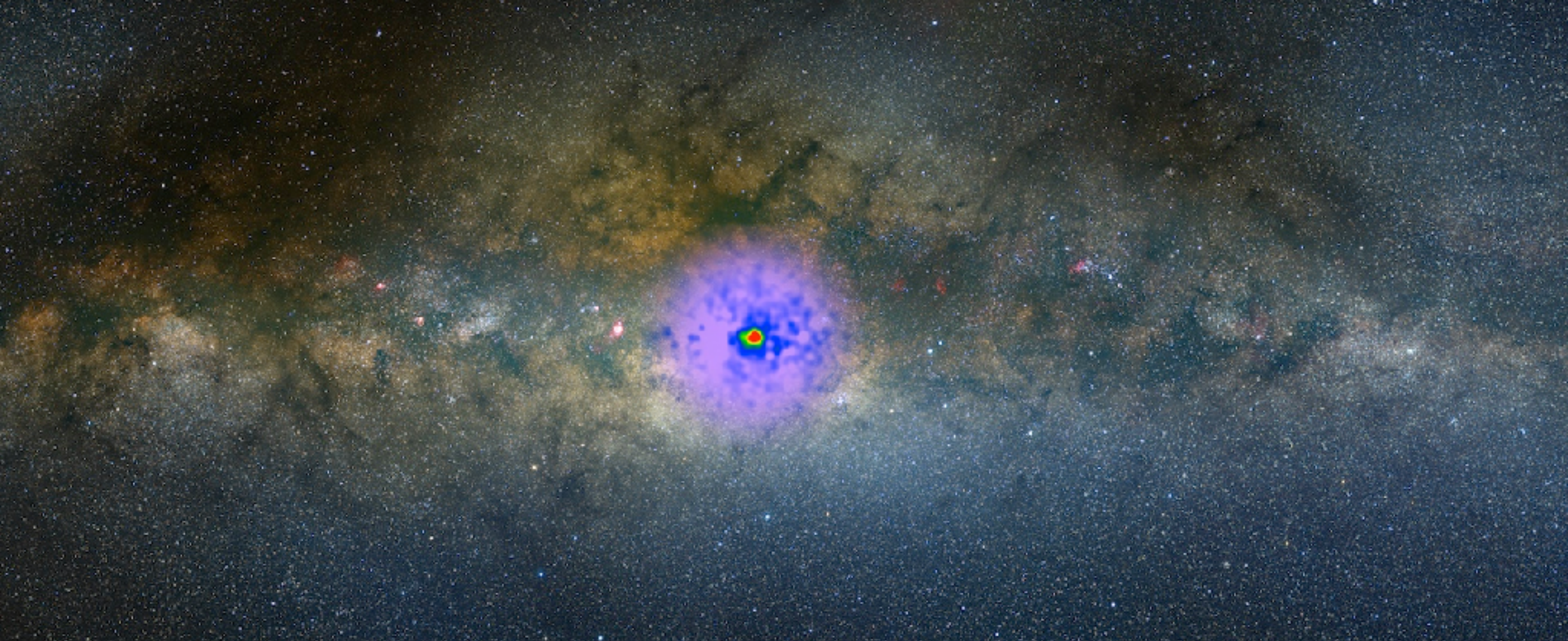


Cosmic-Ray Injection Models and the Galactic Center Excess

Tim Linden

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

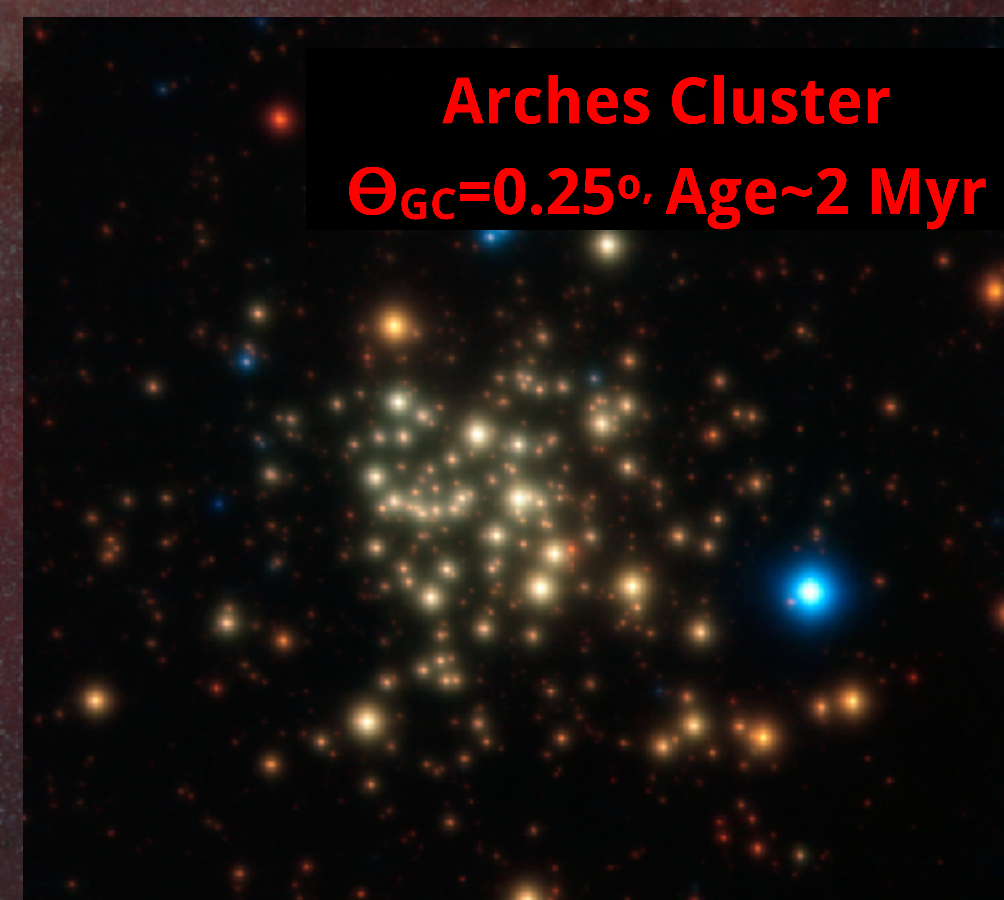
Three Elephants Workshop

10/23/17

An Ominous Problem...

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

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

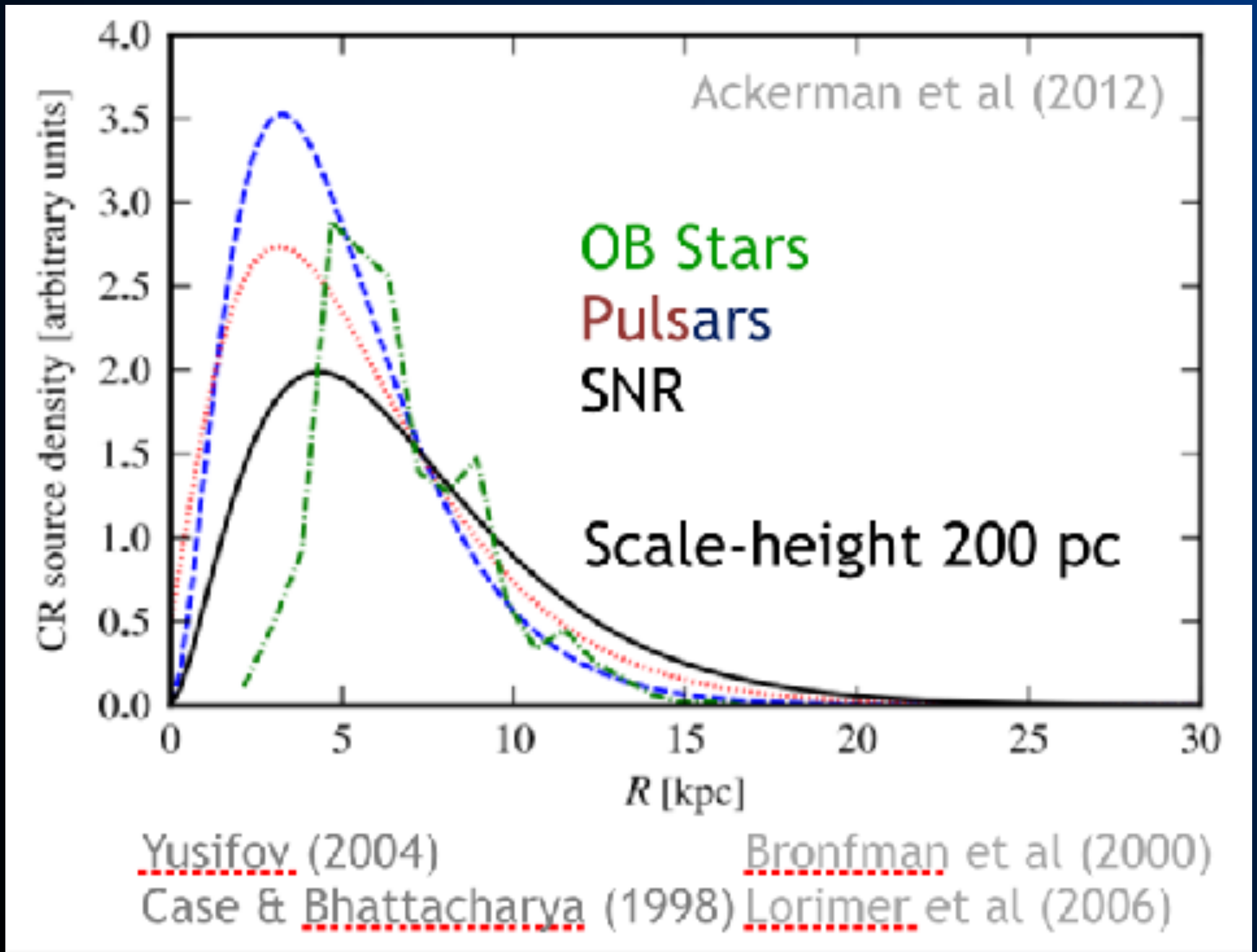


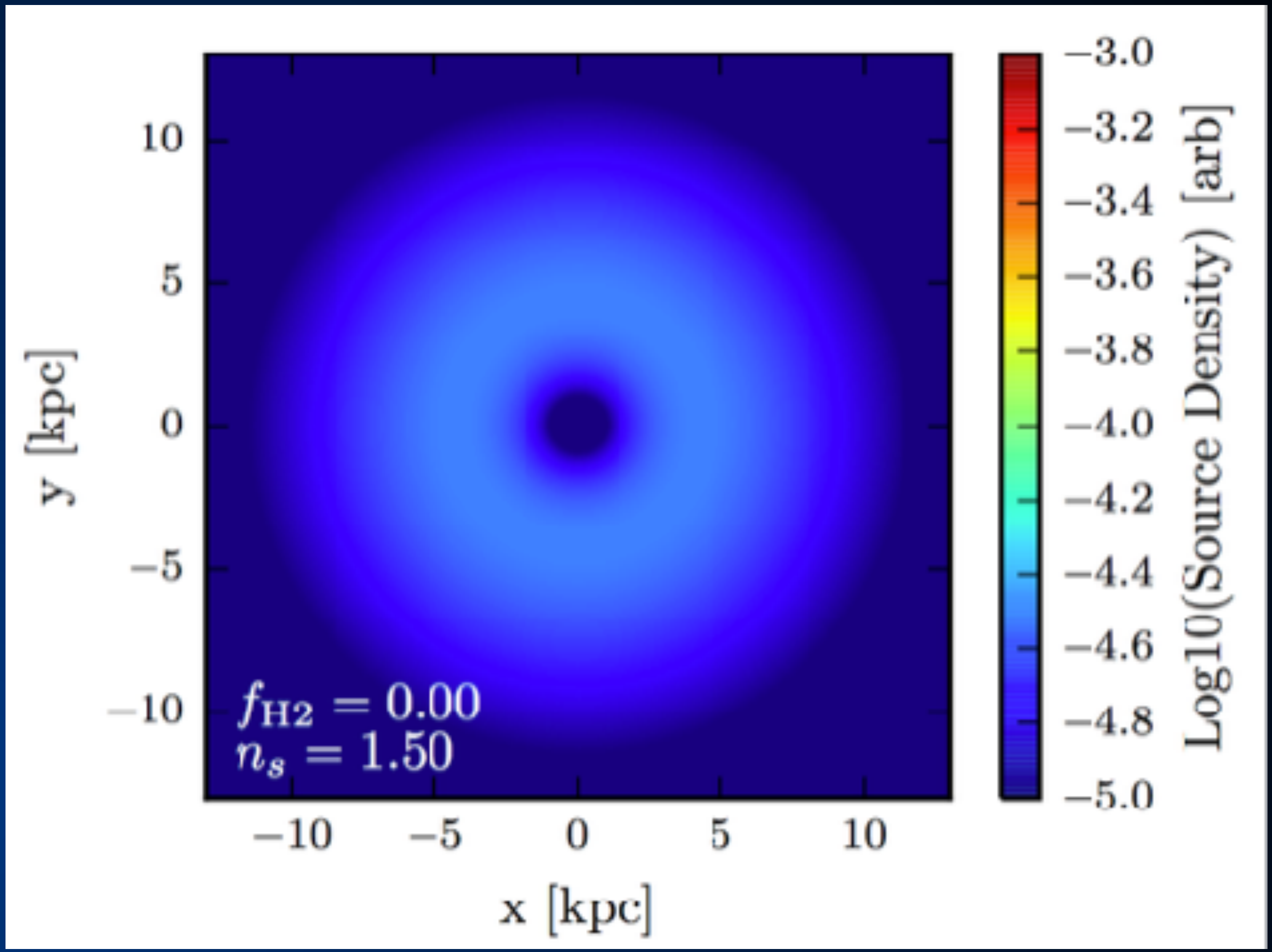
- 2-4% - ISOGAL Survey Immer et al. (2012)
- 2.5-5% - Young Stellar Objects Yusef-Zadeh et al. (2009)
- 5-10% - Infrared Flux Longmore et al. (2013)
- 10-20% - Wolf-Rayet Stars Rosslowe & Crowther (2014)
- 2% - Far-IR Flux Thompson et al. (2007)
- 2.5-6% - SN1a Schanne et al. (2007)

An Ominous Problem...

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

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





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

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

A New Tracer for Cosmic-Ray Injection

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

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

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

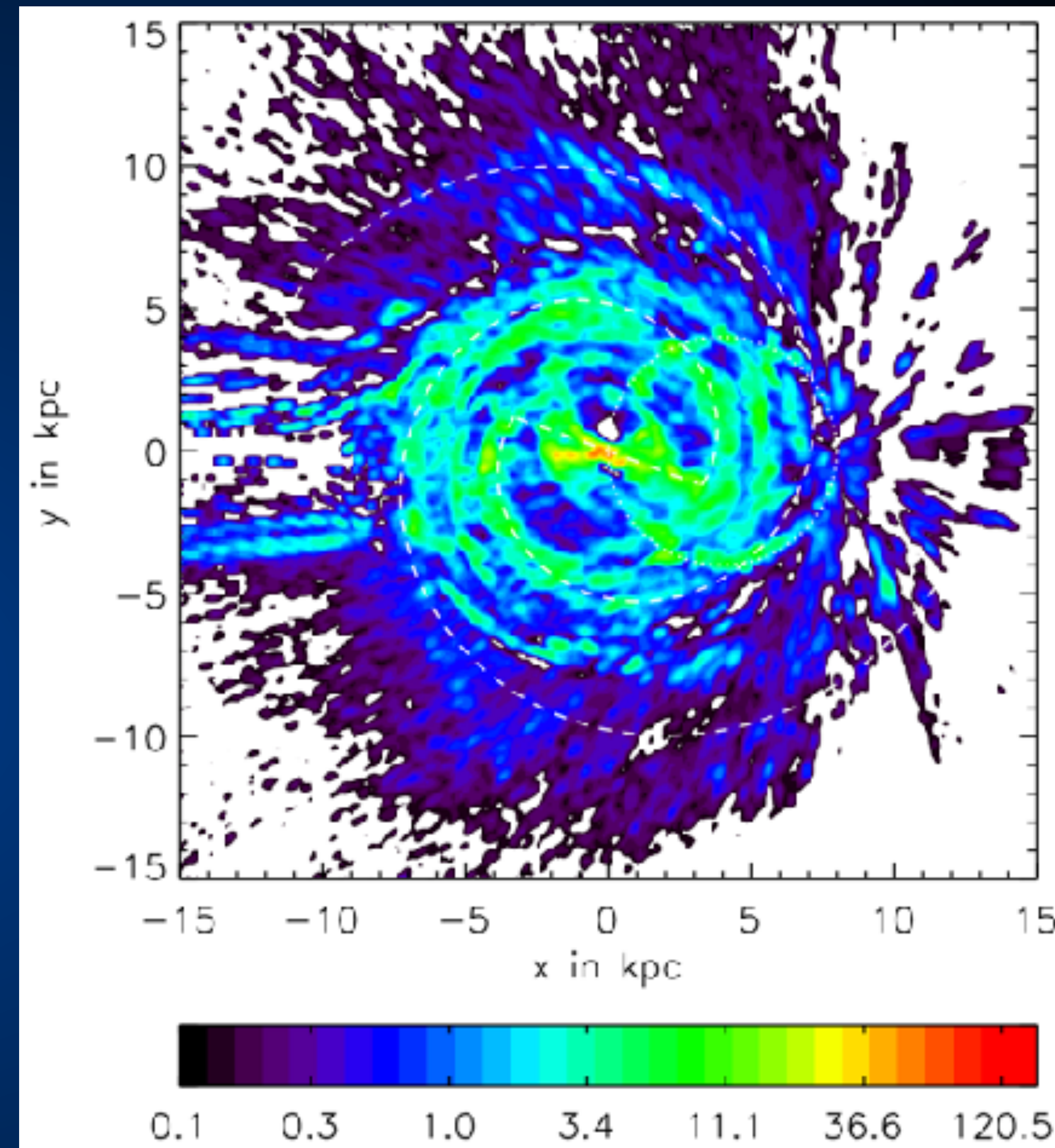
$$\mathrm{Q}_{\mathrm{CR}}(\vec{r}) \propto \begin{cases} 0 & \rho_{\mathrm{H2}} \leq \rho_s \\ \rho_{\mathrm{H2}}^{n_s} & \rho_{\mathrm{H2}} > \rho_s \end{cases}$$

A New Tracer for Cosmic-Ray Injection

In this study we utilize the Pohl, Englmaier & Bissantz (2008; 0712.4264) model.

Based on the Dame et al. (2001) composite survey of CO.

Fit XCO to the gamma-ray data during the gamma-ray generation stage.



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}

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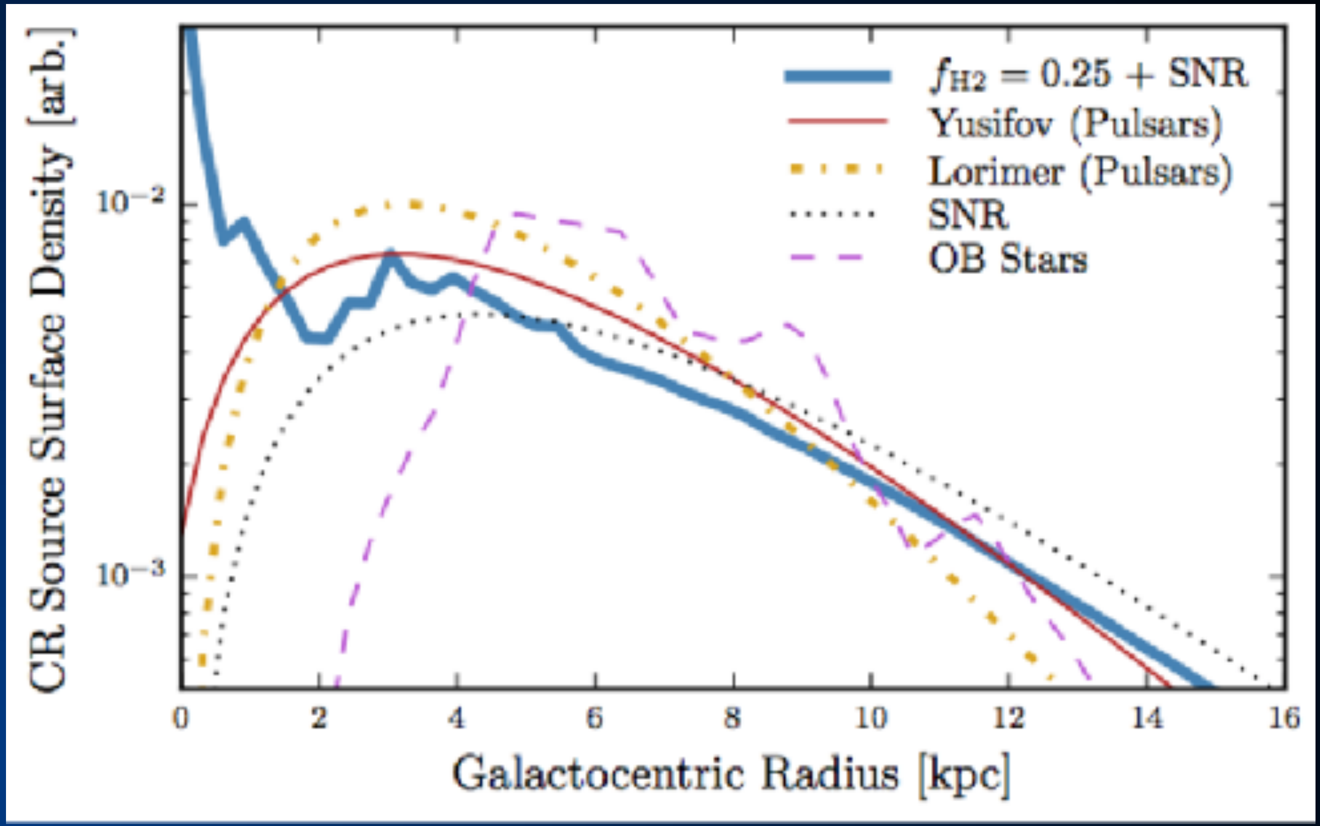

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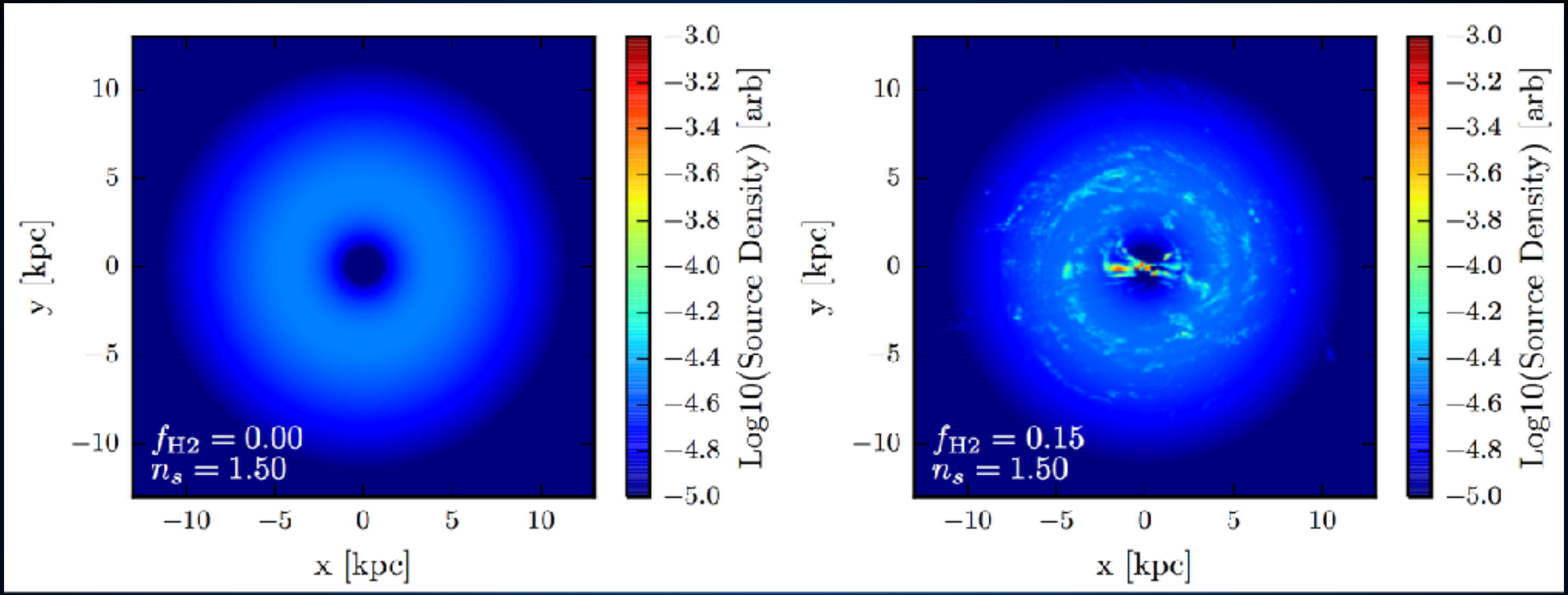


Two features leap out immediately:

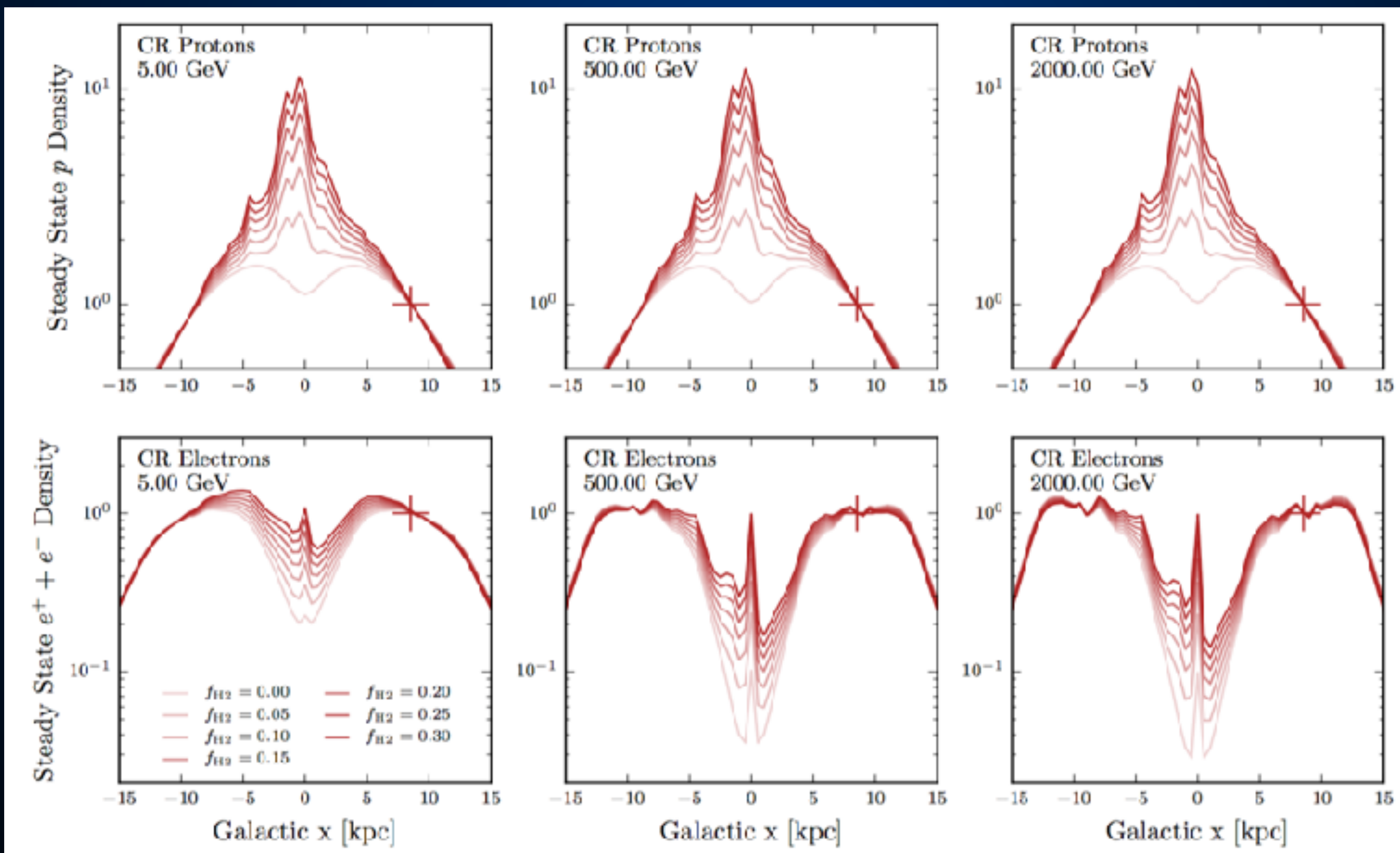
1.) Spiral Arms

2.) A bright bar in the Galactic Center

Simulations!

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

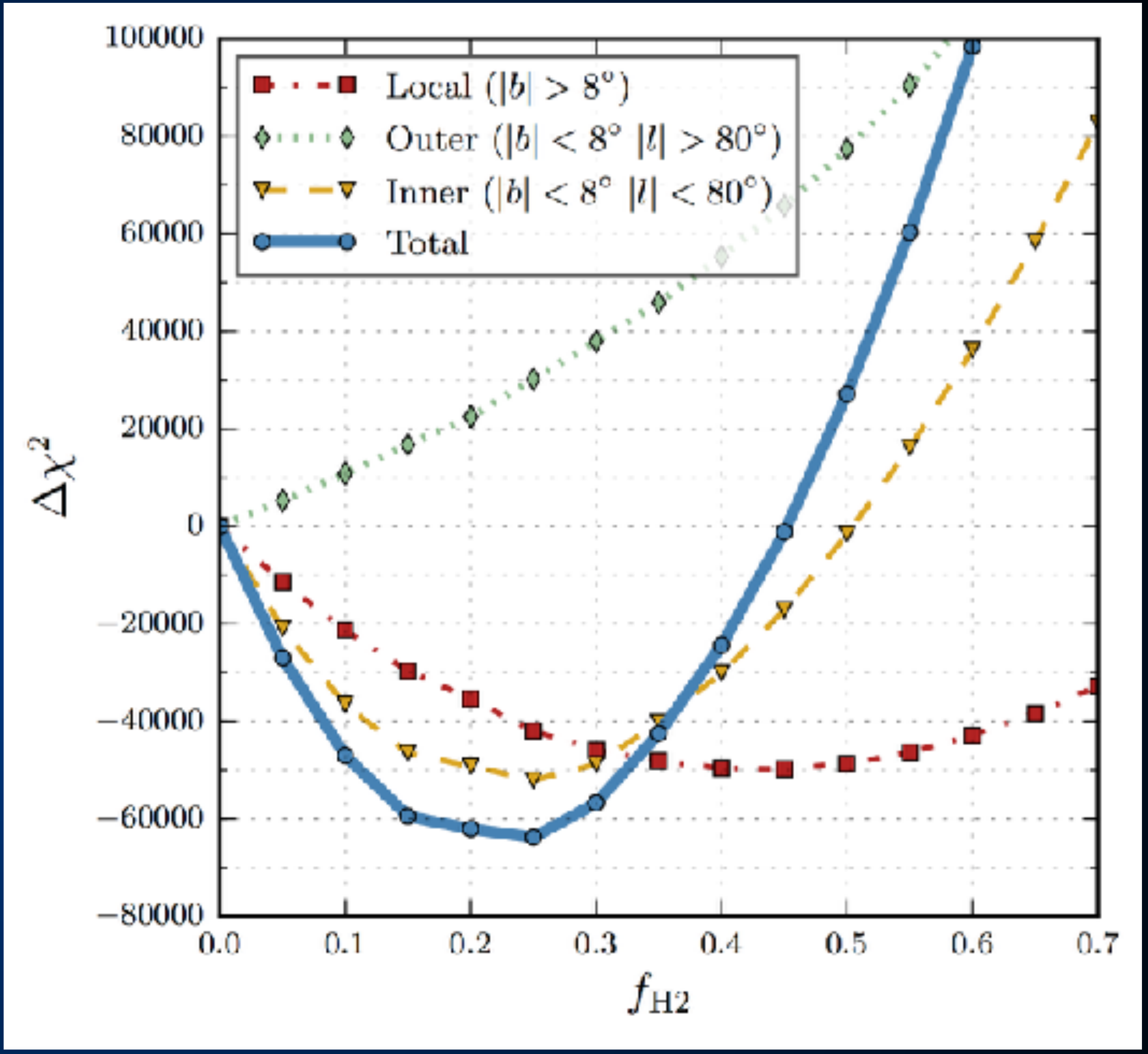
Parameter	Units	Canonical	Mod A	Description
D_0	$cm^2\ s^{-1}$	7.2×10^{28}	5.0×10^{28}	Diffusion constant at $\mathcal{R} = 4$ GV
δ	–	0.33	0.33	Index of diffusion constant energy dependence
z_{halo}	kpc	3	4	Half-height of diffusion halo
R_{halo}	kpc	20	20	Radius diffusion halo
v_a	$km\ s^{-1}$	35	32.7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



A Better fit to the Gamma-Ray Sky

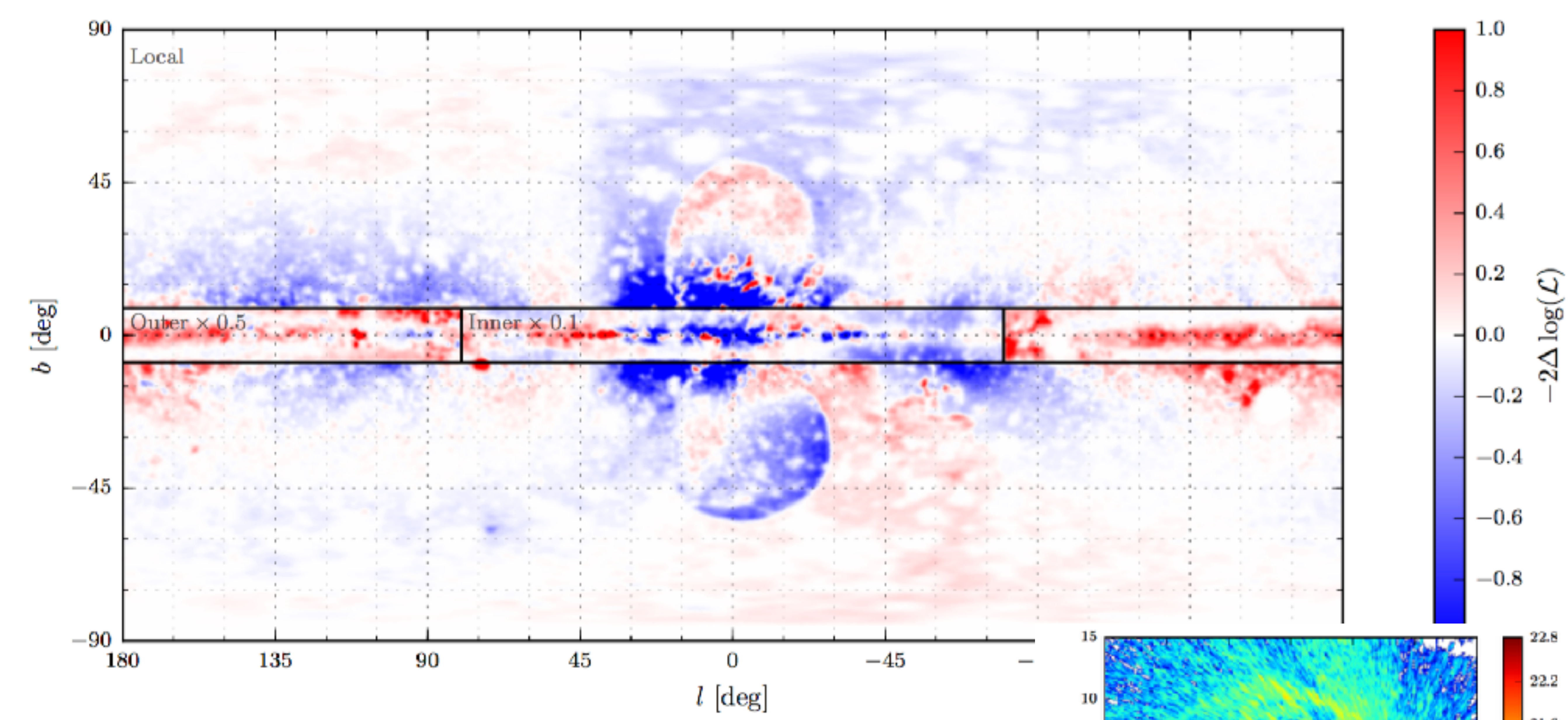
1.) Adding a cosmic-ray injection component tracing f_{H2} improves the full-sky fit to the gamma-ray data.

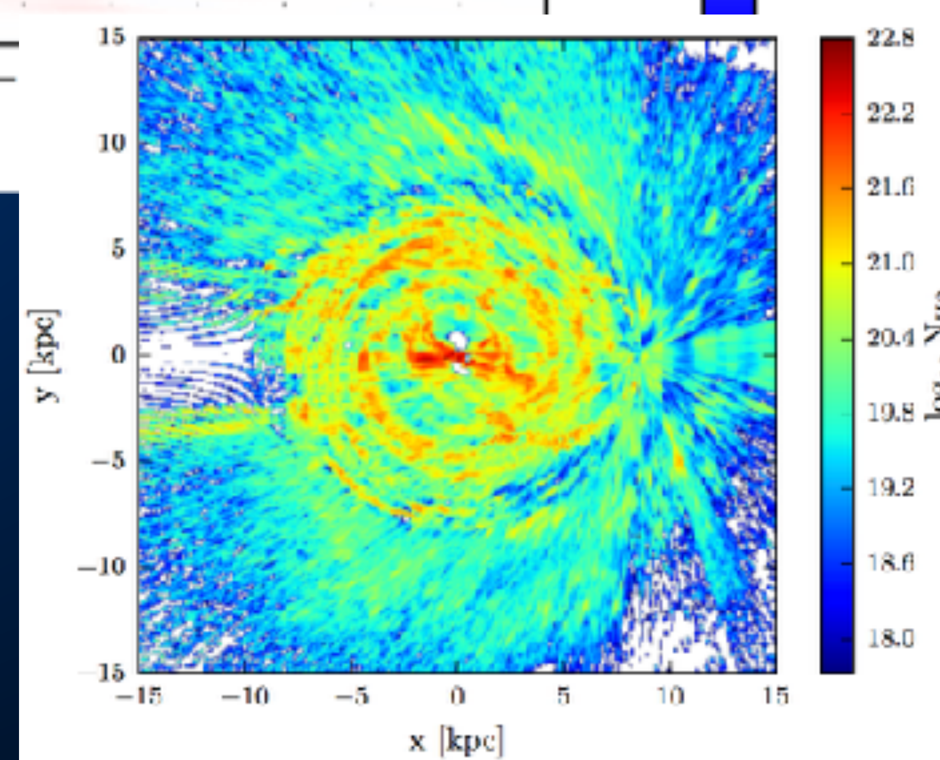
2.) The best fit value over the full sky is $f_{H2} = 0.25$



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

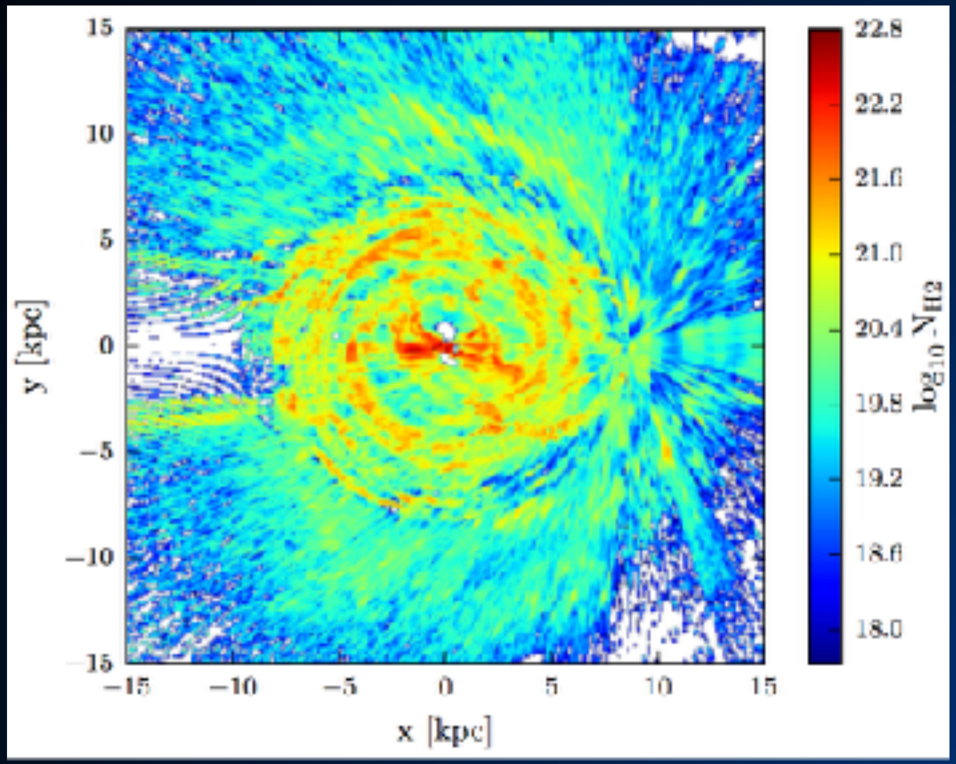
A Better fit to the Gamma-Ray Sky

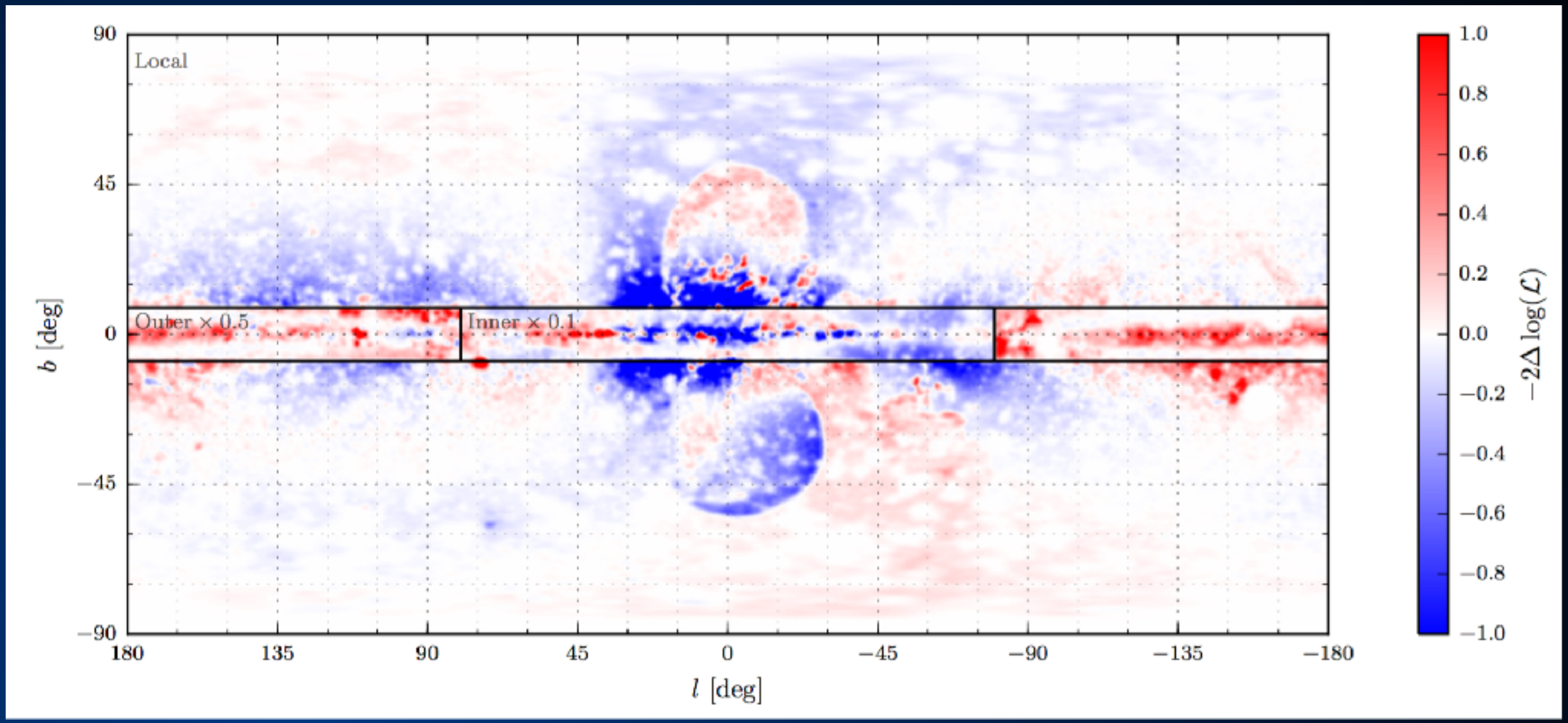




Fits are significantly improved, in particular in regions near the Galactic Center where there is significant kinematic gas information.

A Technical Issue



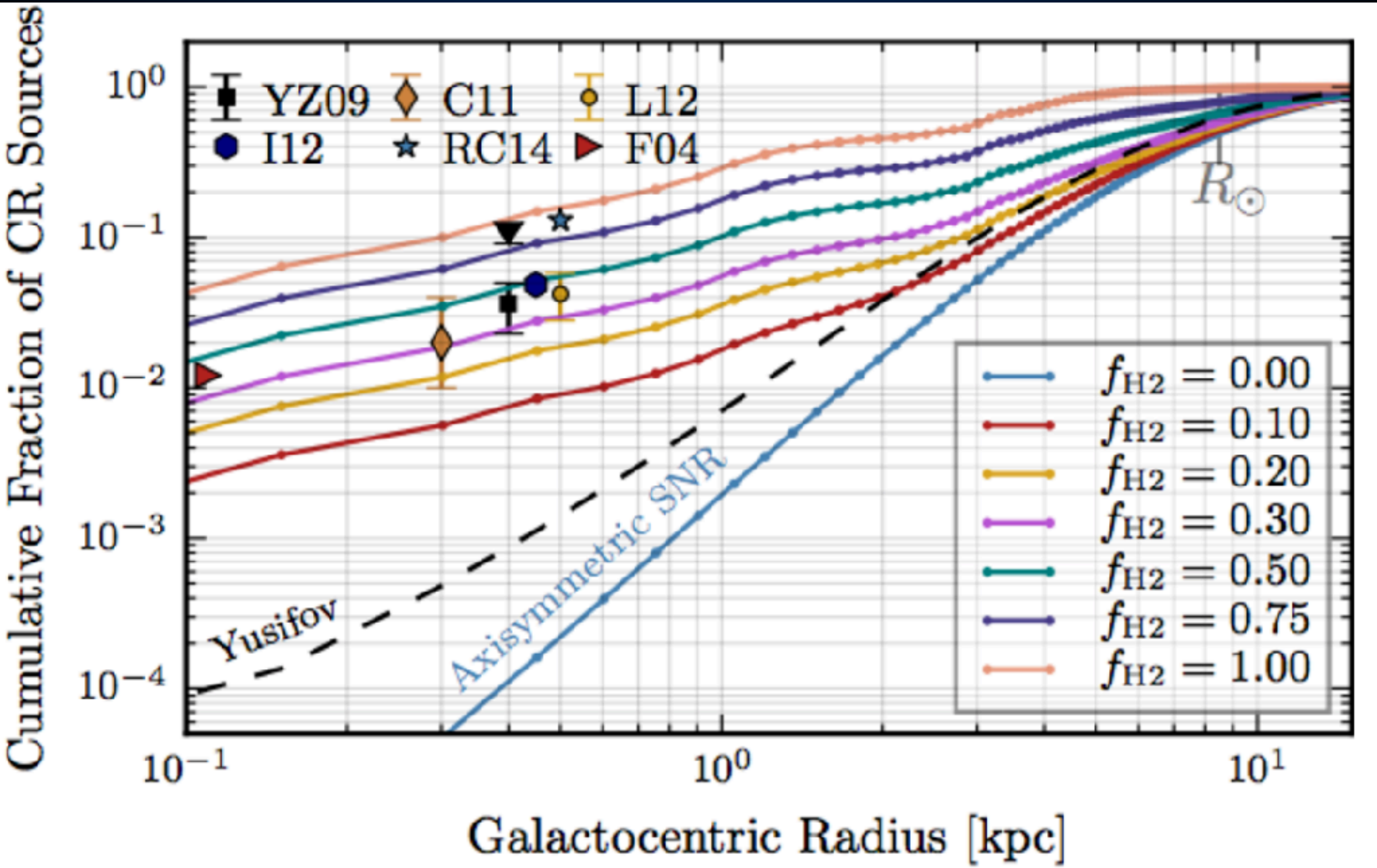


Three Stages of Generating Gamma-Ray Maps

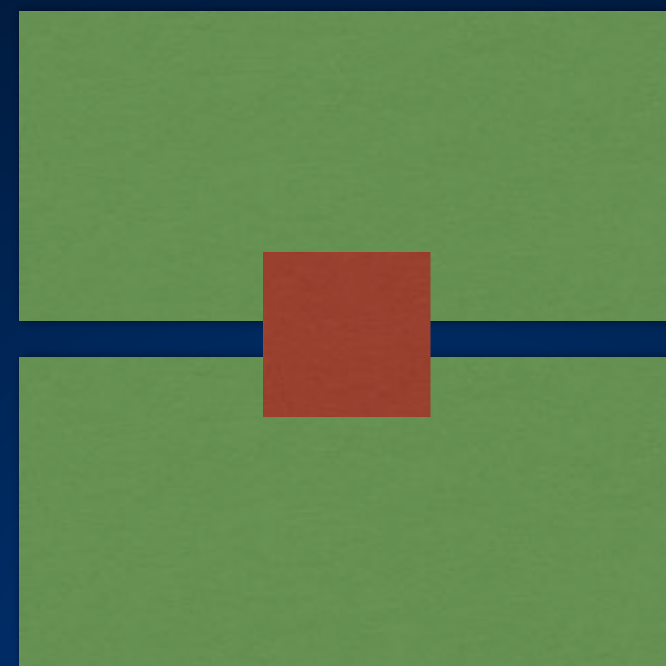
- **Sources**
- **Propagation**
- **Gamma-Ray Generation**

Use enhanced gas maps for cosmic-ray generation, but not for propagation or gamma-ray generation.

Injection in the Galactic Center



Two Analyses of the Gamma-Ray Excess



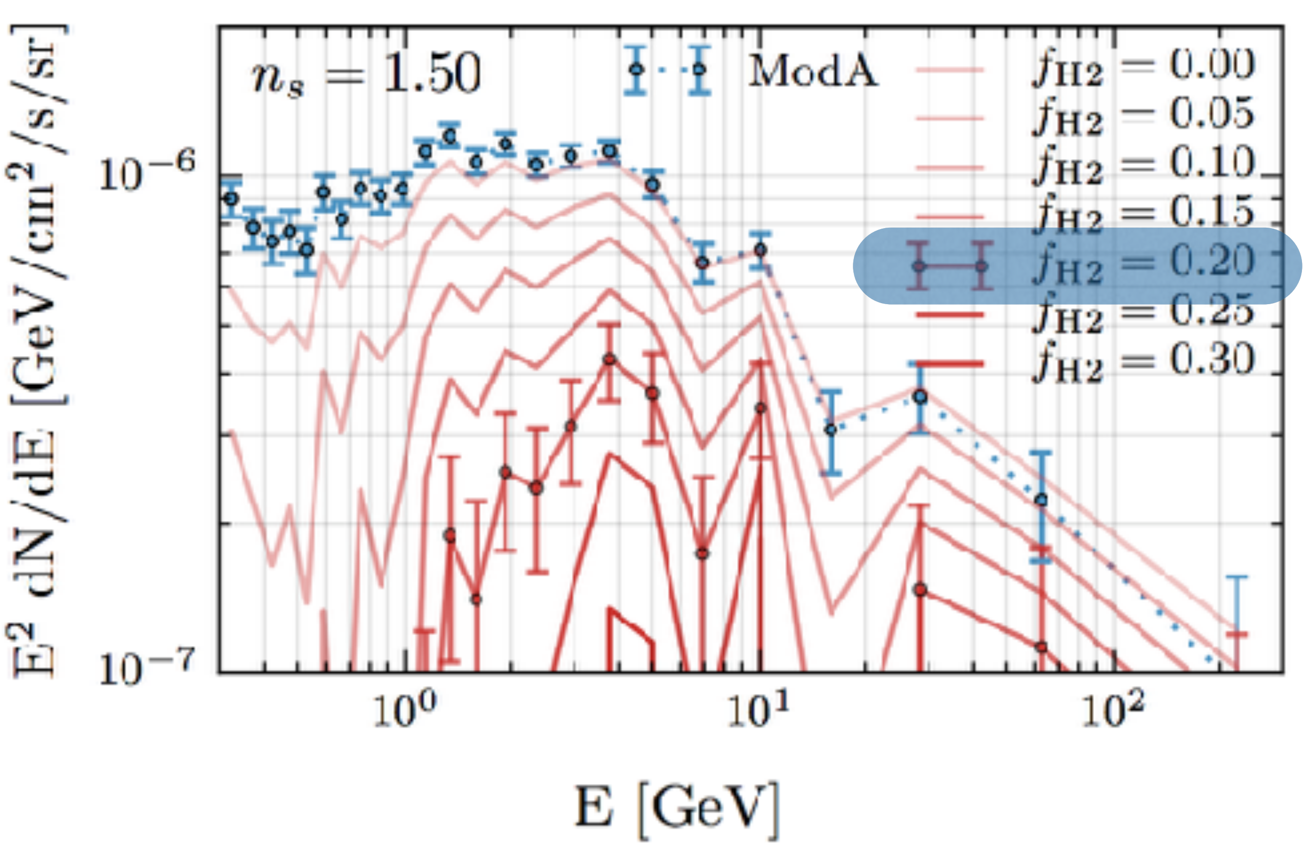
INNER GALAXY

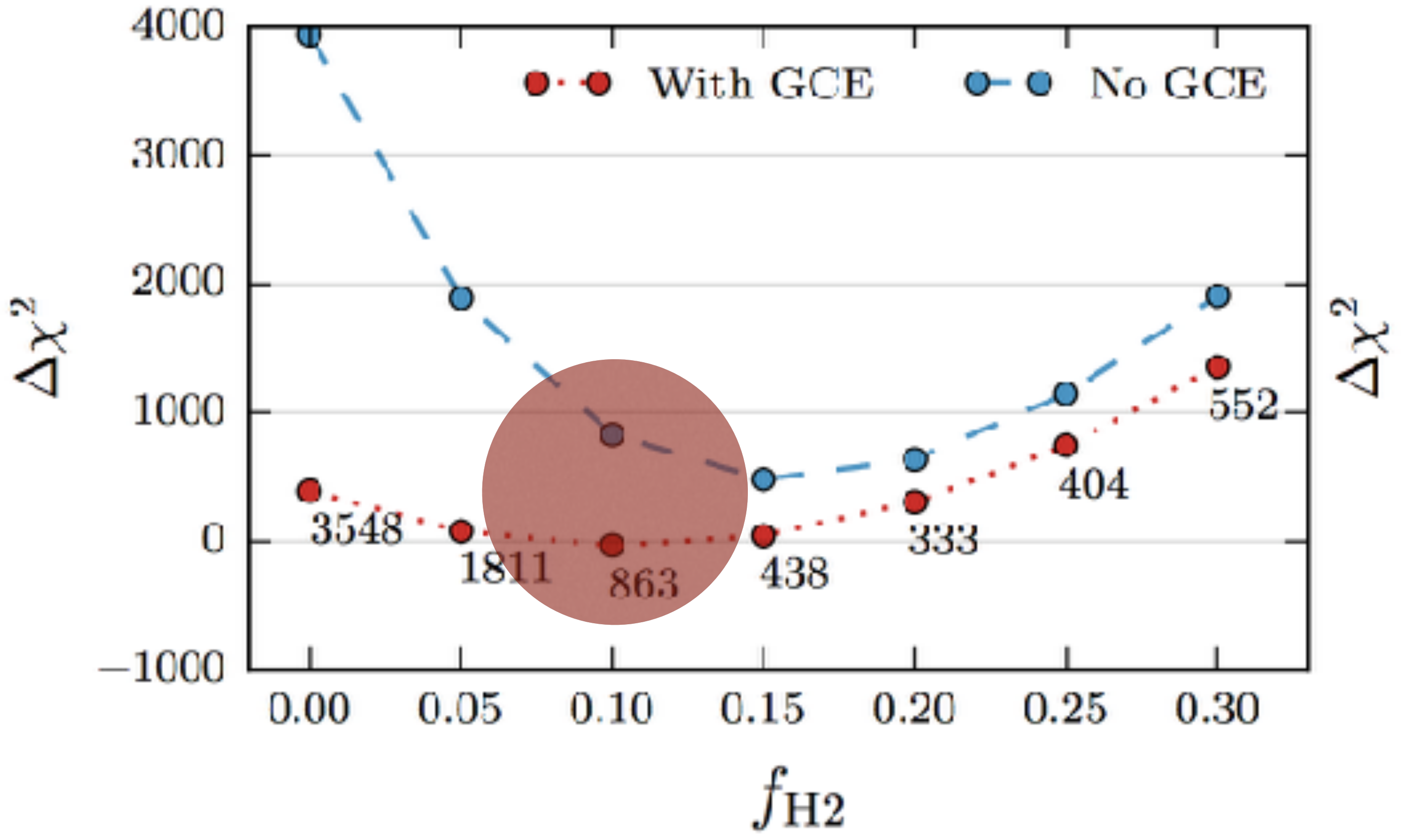
- Mask galactic plane (e.g. |b| > 1^{o}), and consider 40^{o} x 40^{o} box
- Bright point sources masked at 2^{o}
- Use likelihood analysis, allowing the diffuse templates to float in each energy bin
- Background systematics controlled

GALACTIC CENTER

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

Effect on the GC Excess

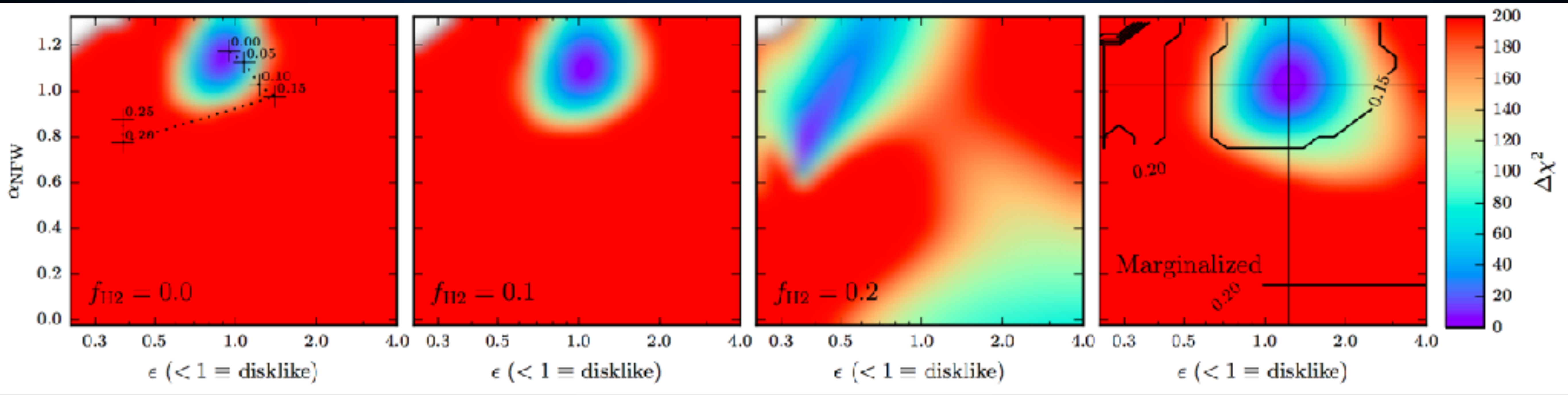




Increasing the value of f_{H2} decreases the intensity of the gamma-ray excess.

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

Effect on the Excess Morphology

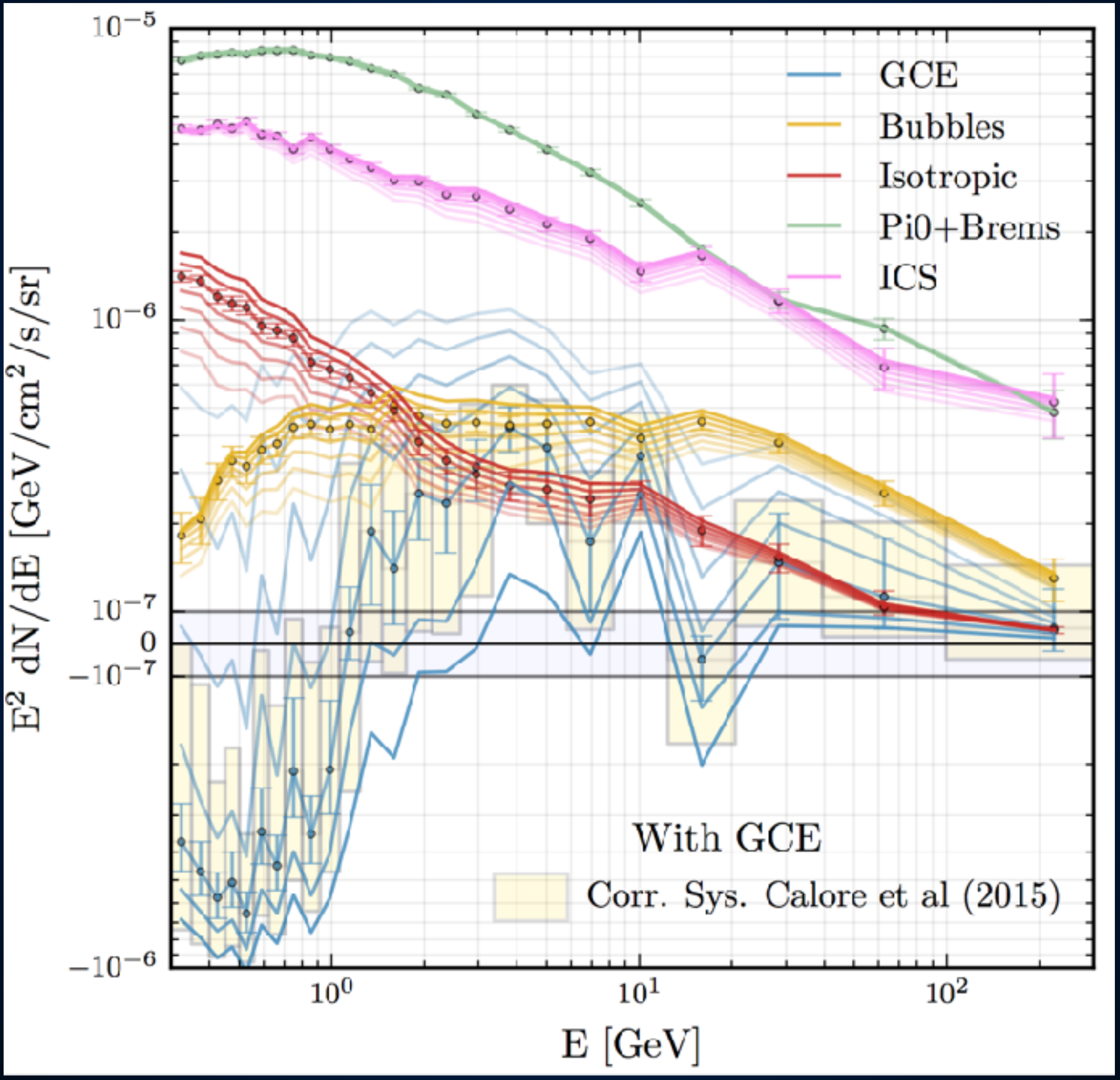


The morphology of the excess is also degenerate with f_{H2}.

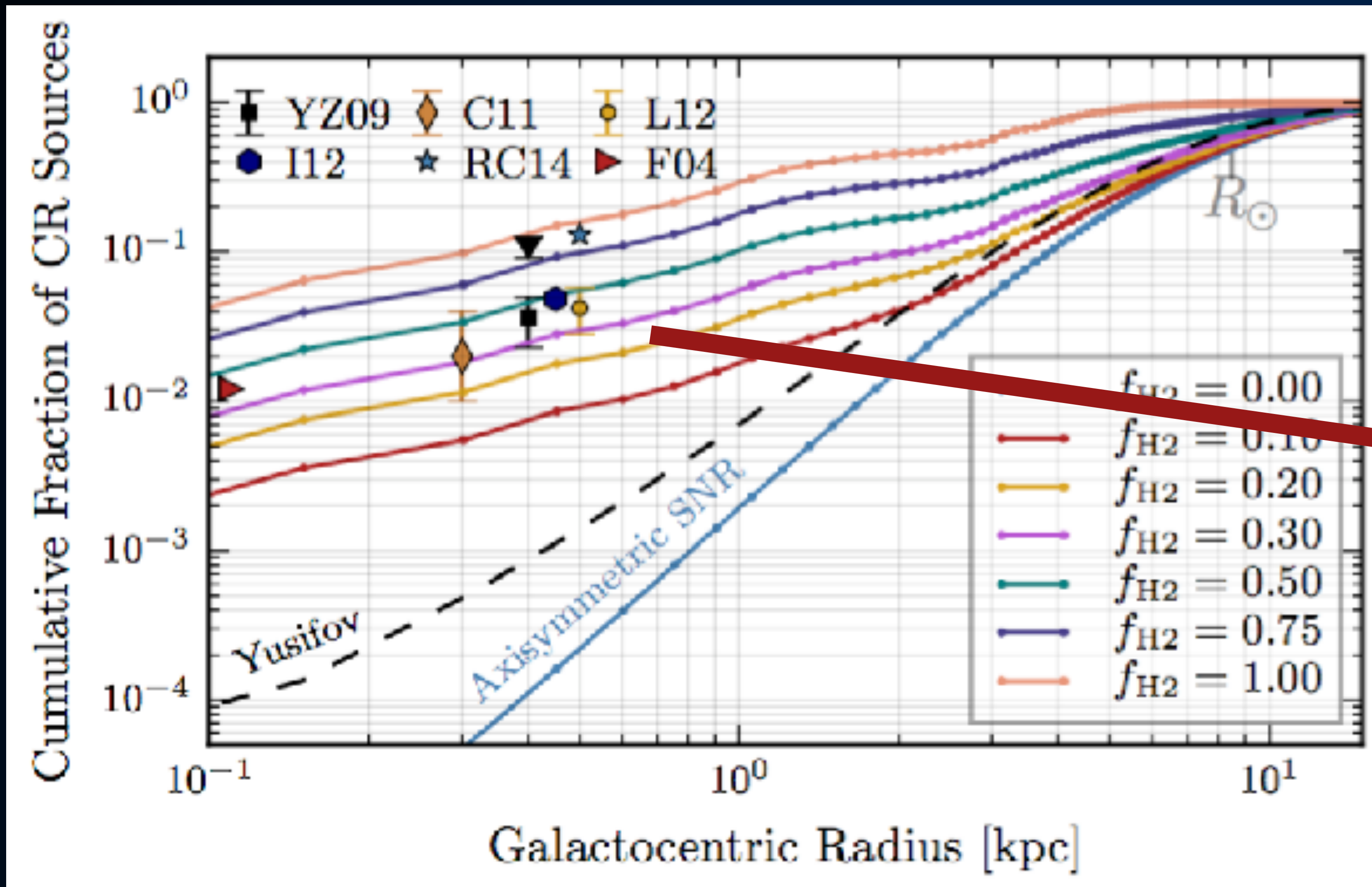
As f_{H2} is increased, the best-fit morphology becomes stretched perpendicular to the galactic plane.

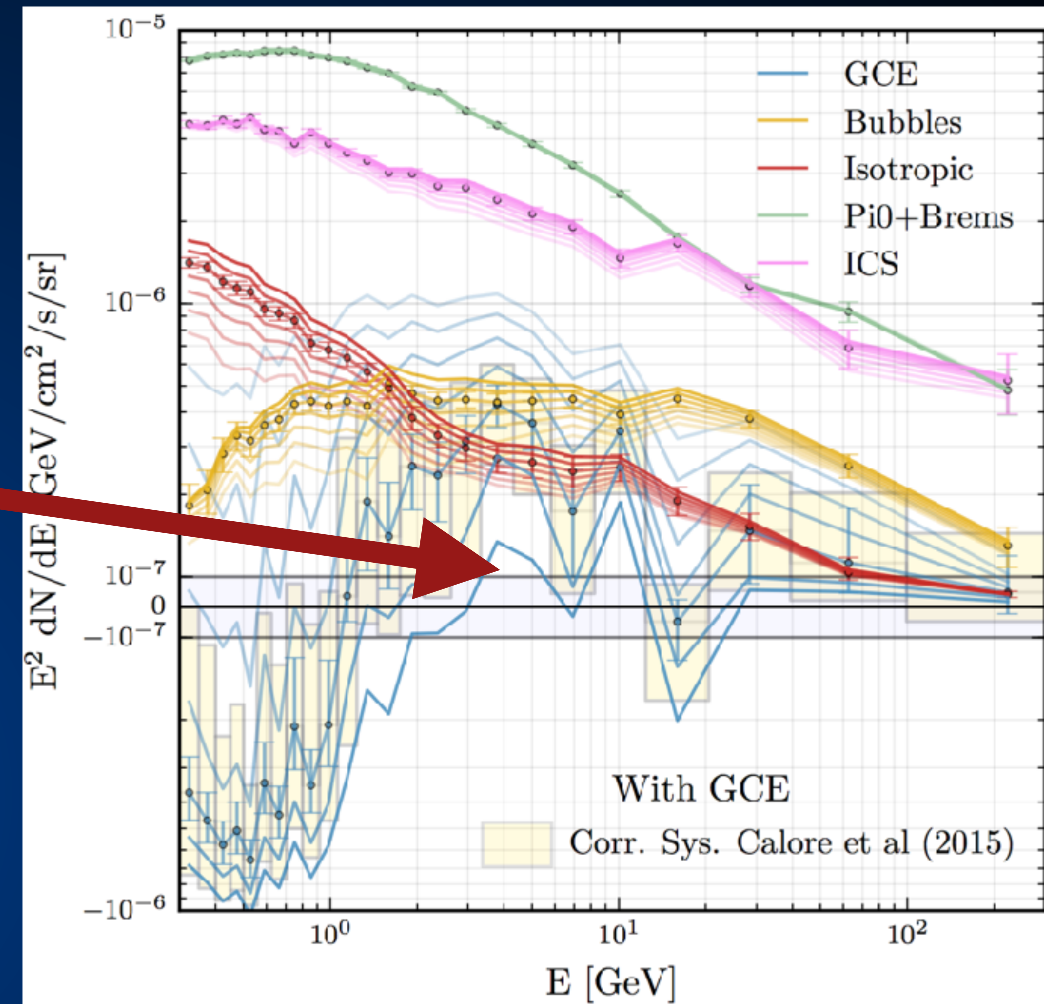
However, marginalized over all values of f_{H2}, the standard NFW template is still consistent with the data.

Effect on the GC Excess



The Galactic Center Deficit?





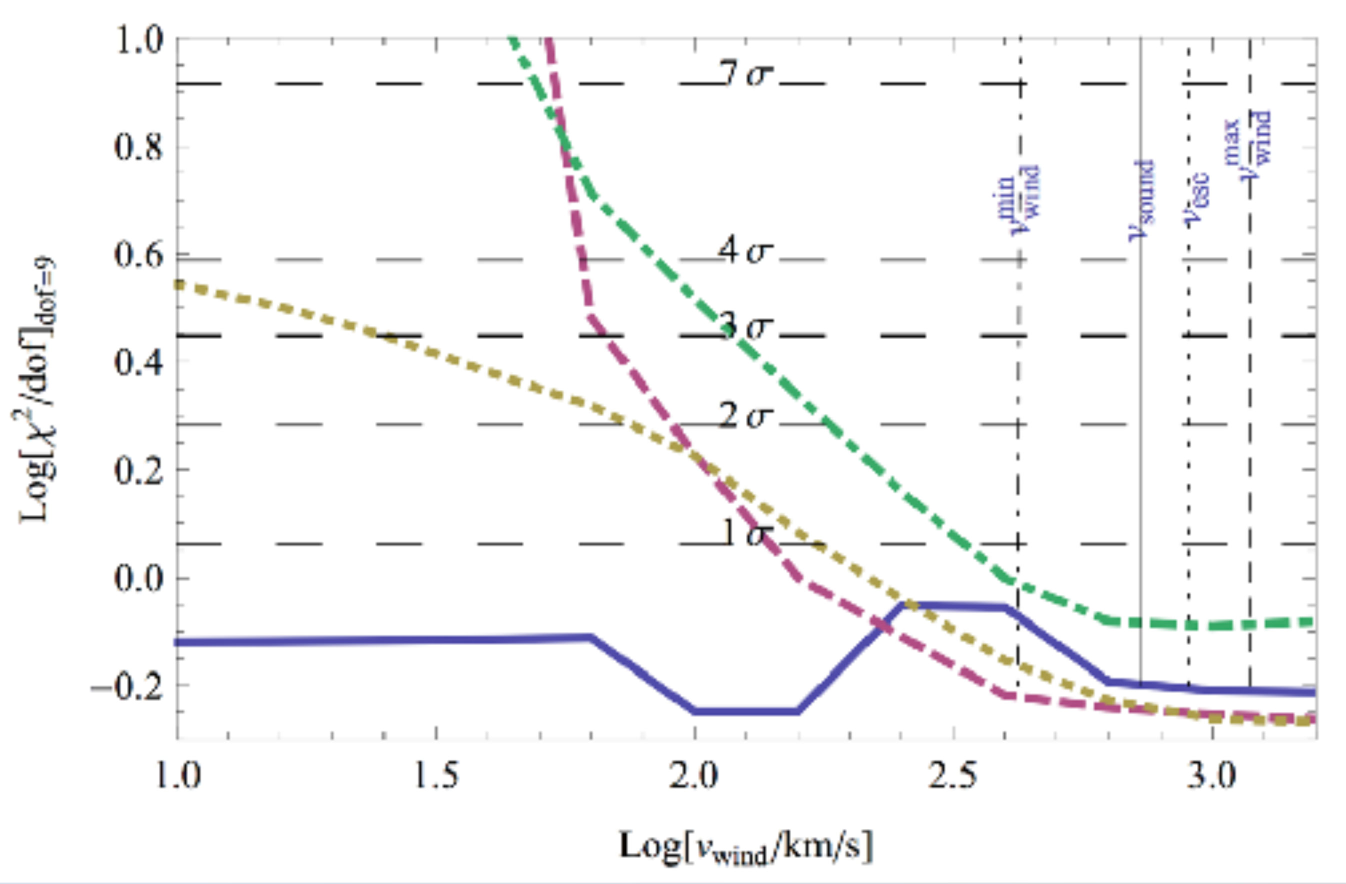
Models which reproduce the SN rate at the Galactic center generally predict a negative gamma-ray excess!

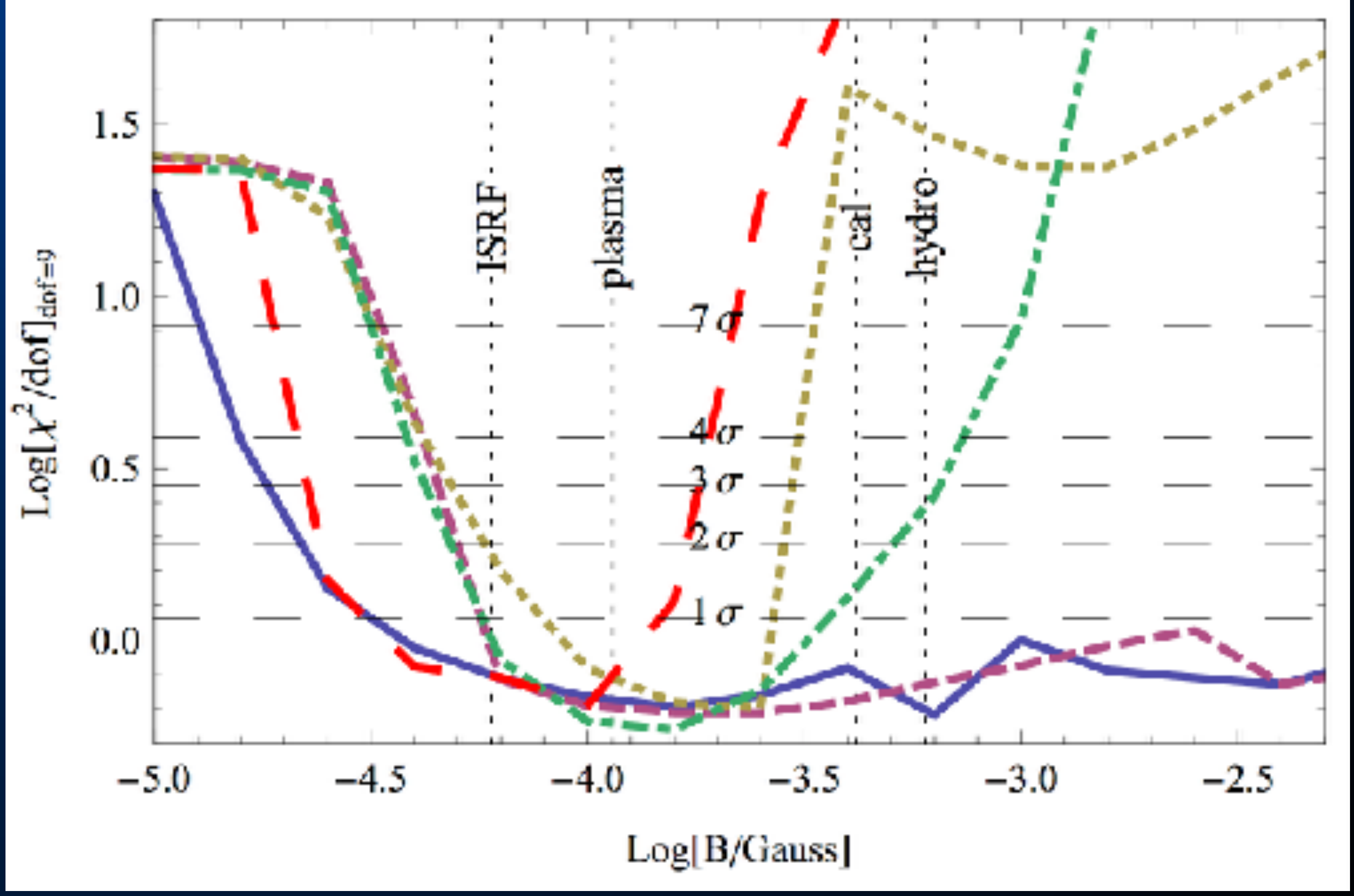
Advection and Convection in the Galactic Center

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

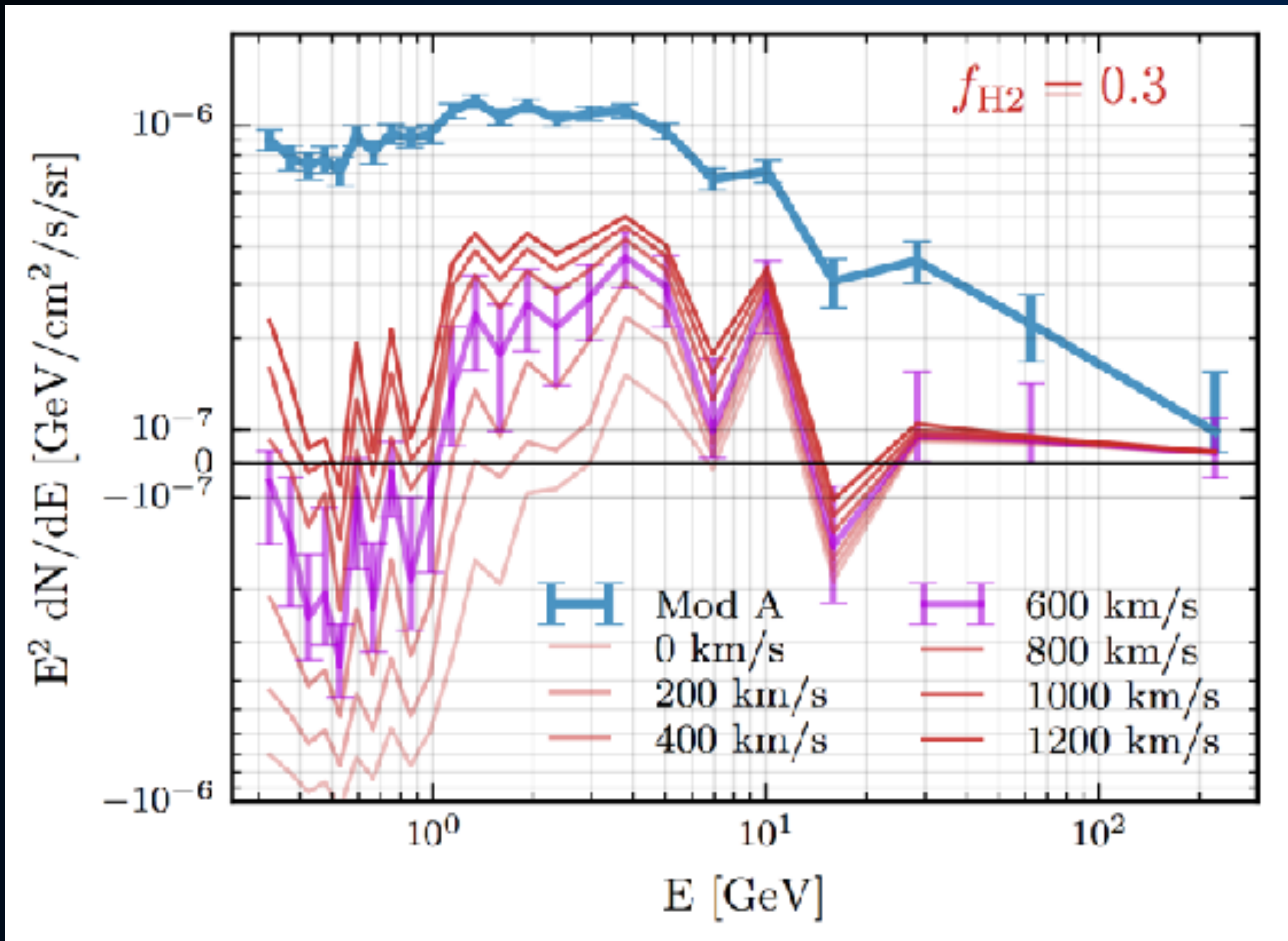
a.) Large Magnetic Fields
b.) Large Convective Winds

Very different from typical Galprop diffusion scenario.





The Low Energy Spectrum

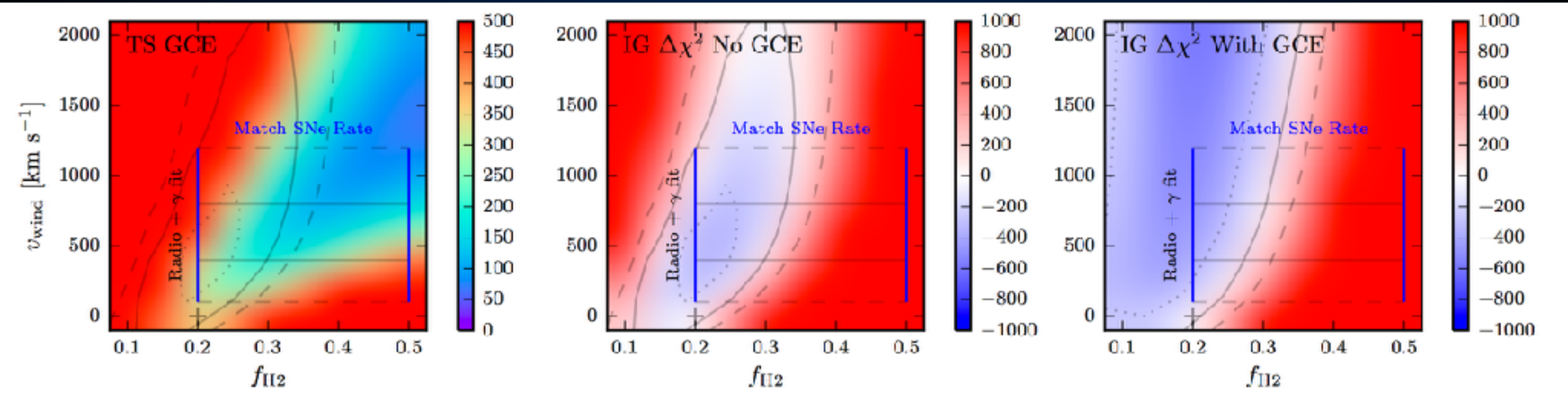


Applying strong convective winds to the diffuse emission model fixes the low-energy over subtraction.

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

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

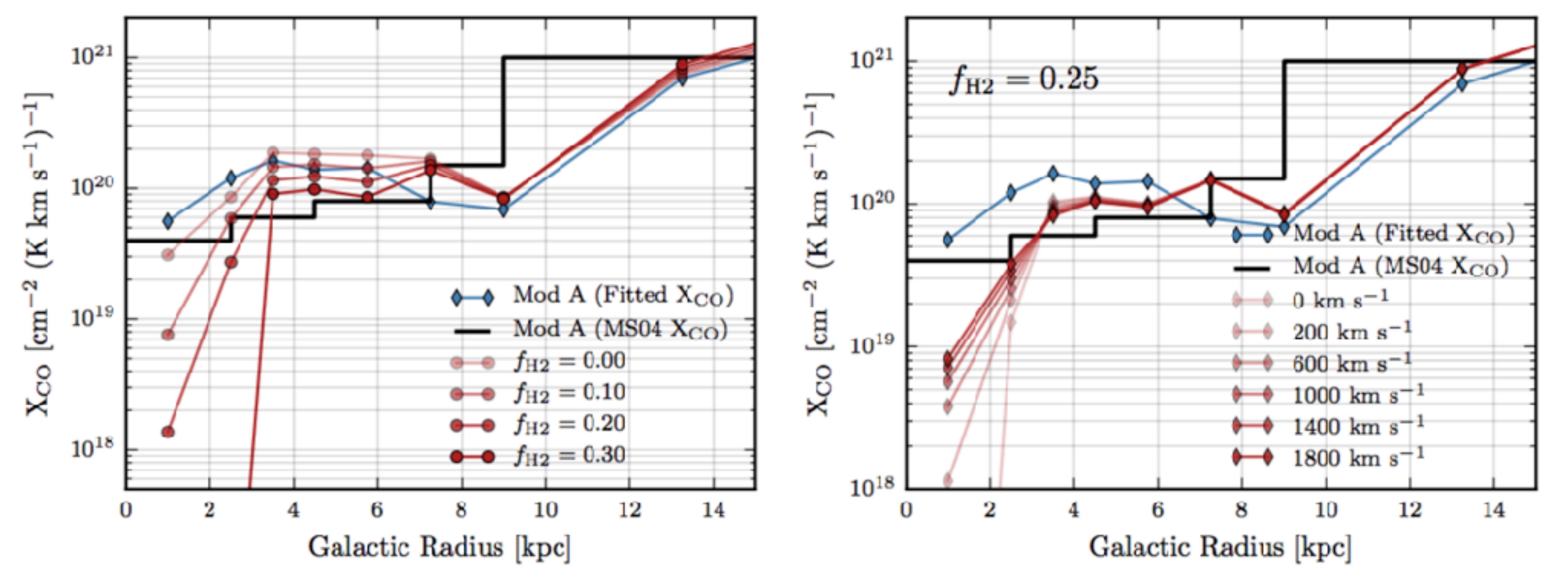
Convection in the Galactic Center



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.

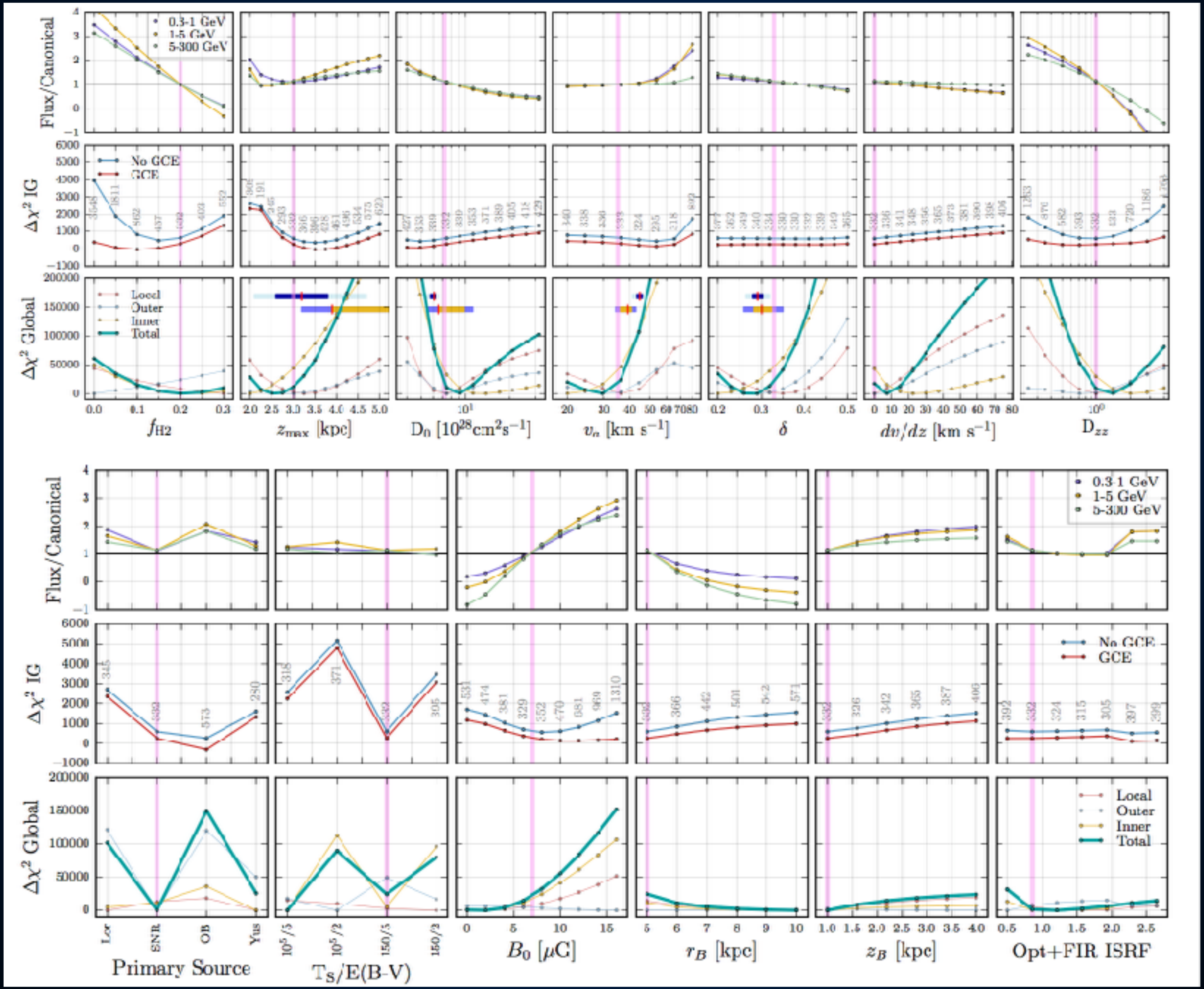
Convection Fixes X_{CO} Values Near the GC



Significant evidence indicates that XCO should be lower near the GC, but models without convection are relatively extreme. (e.g. Sandstrom et al. 2012)

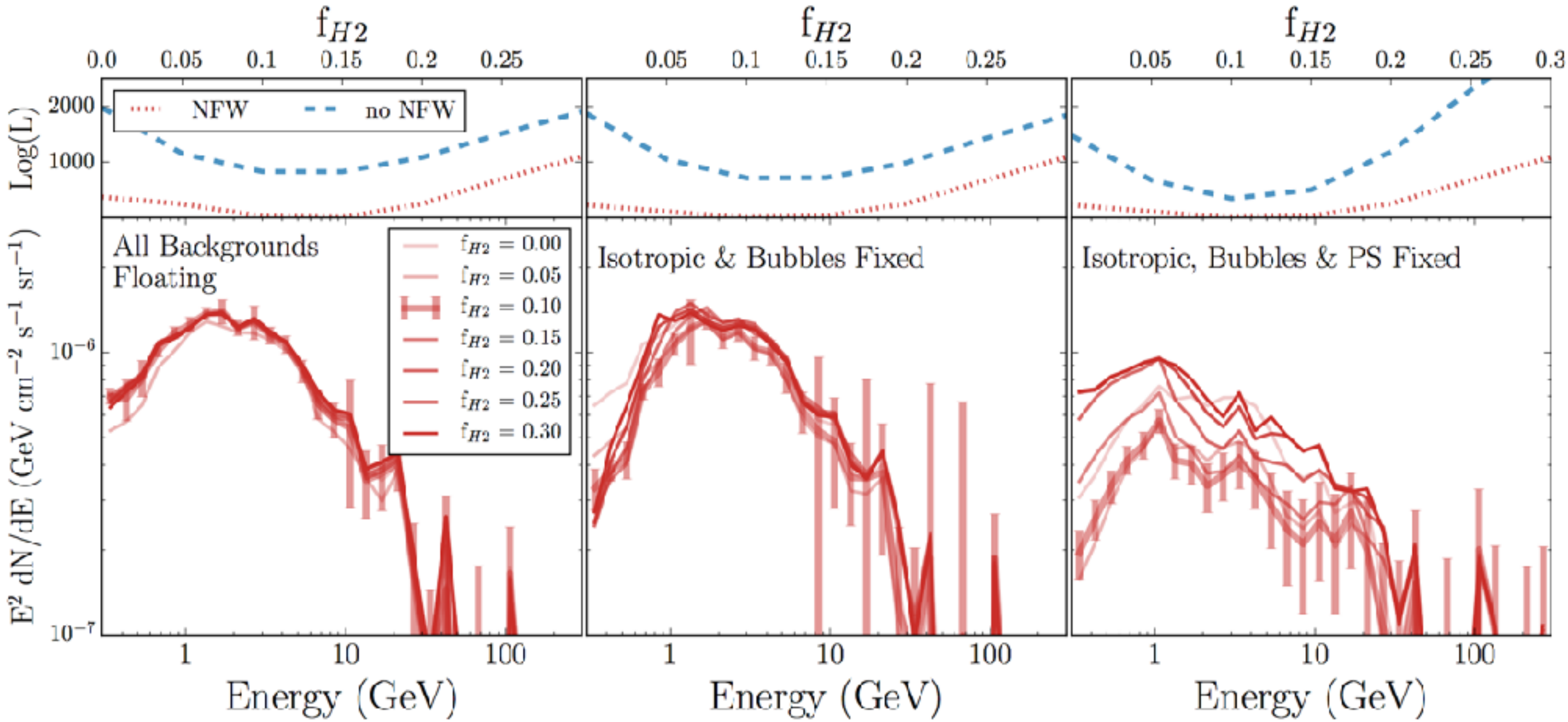
Convection velocities fix XCO, moving it towards a standard 4×10^{19} cm^{-2} (K km s^{-1})$^{-1}$.

Galactic center excess is resilient….



The Effect near the GC

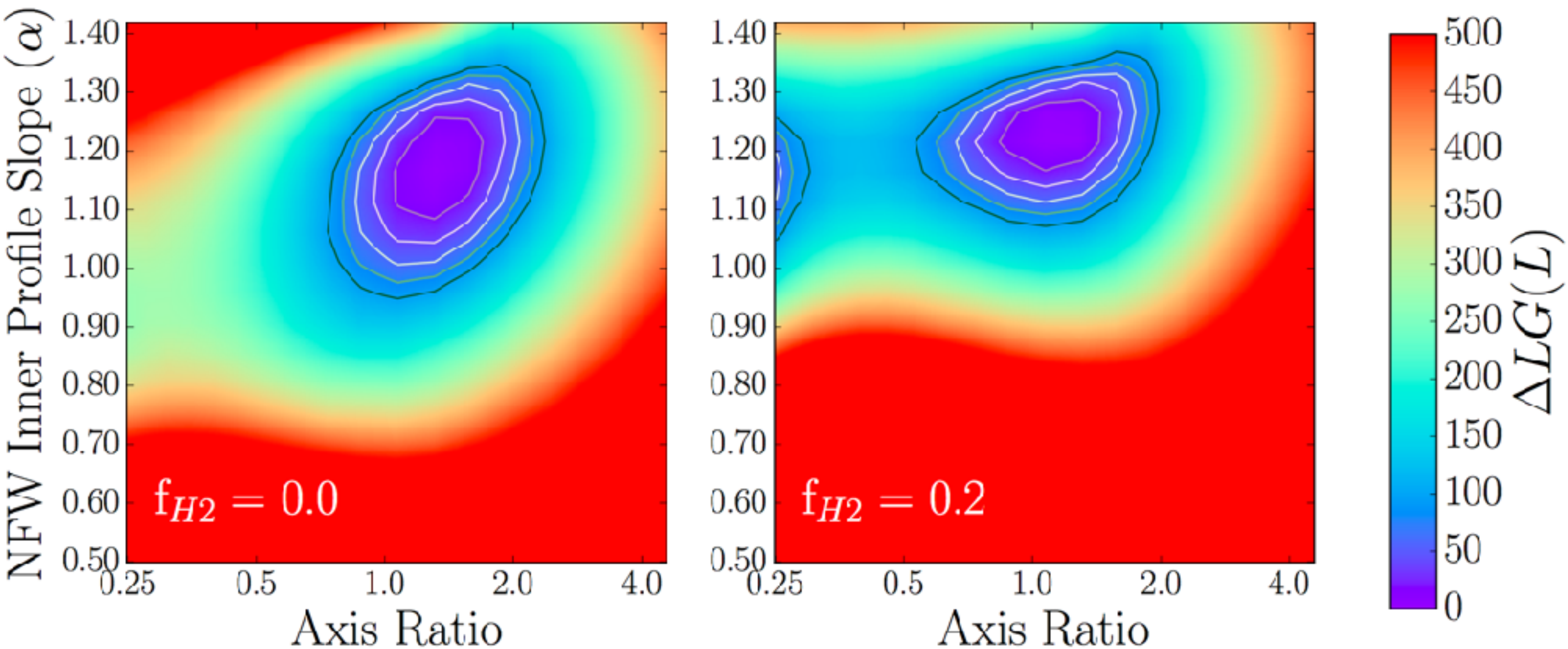
GC



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

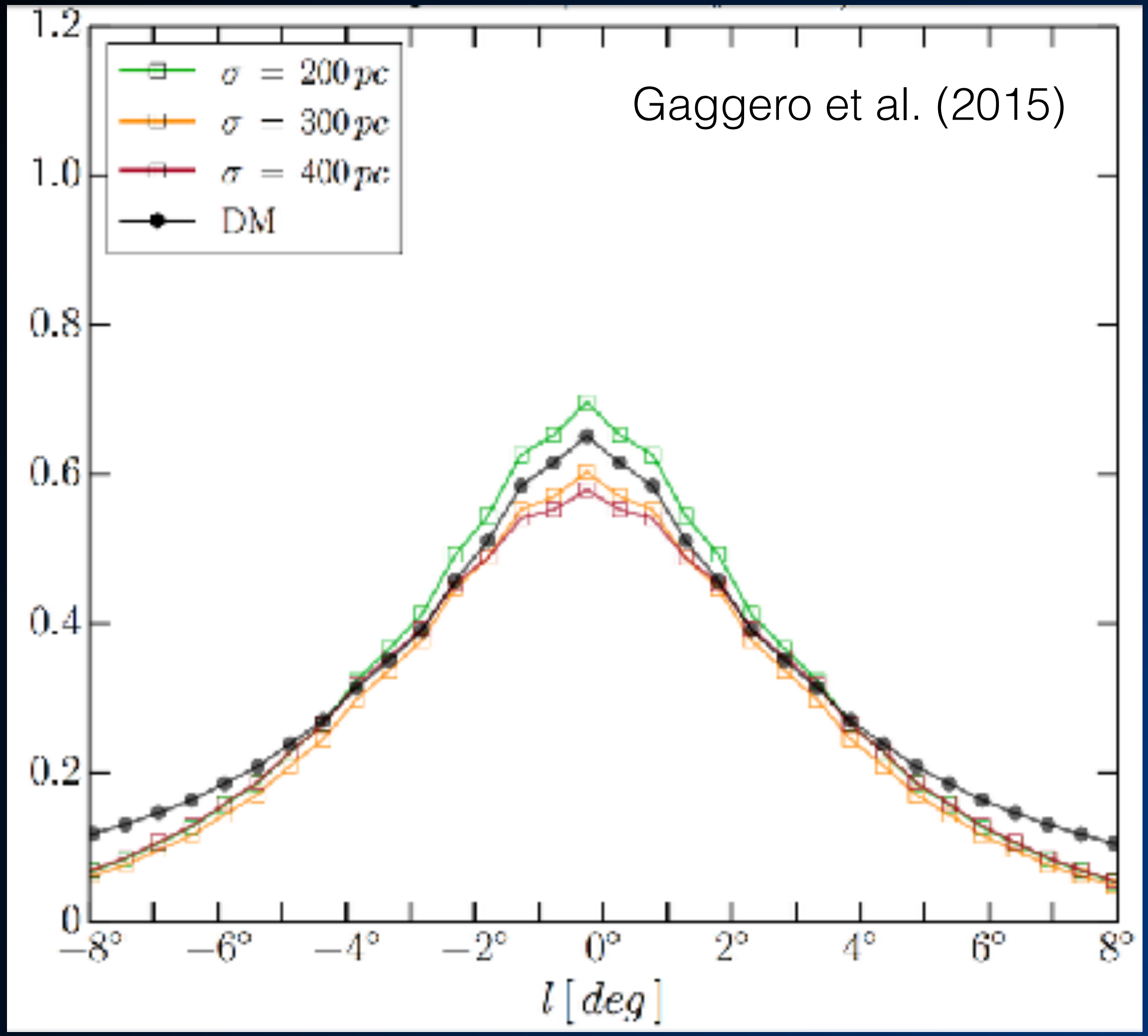
Morphology in the Galactic Center

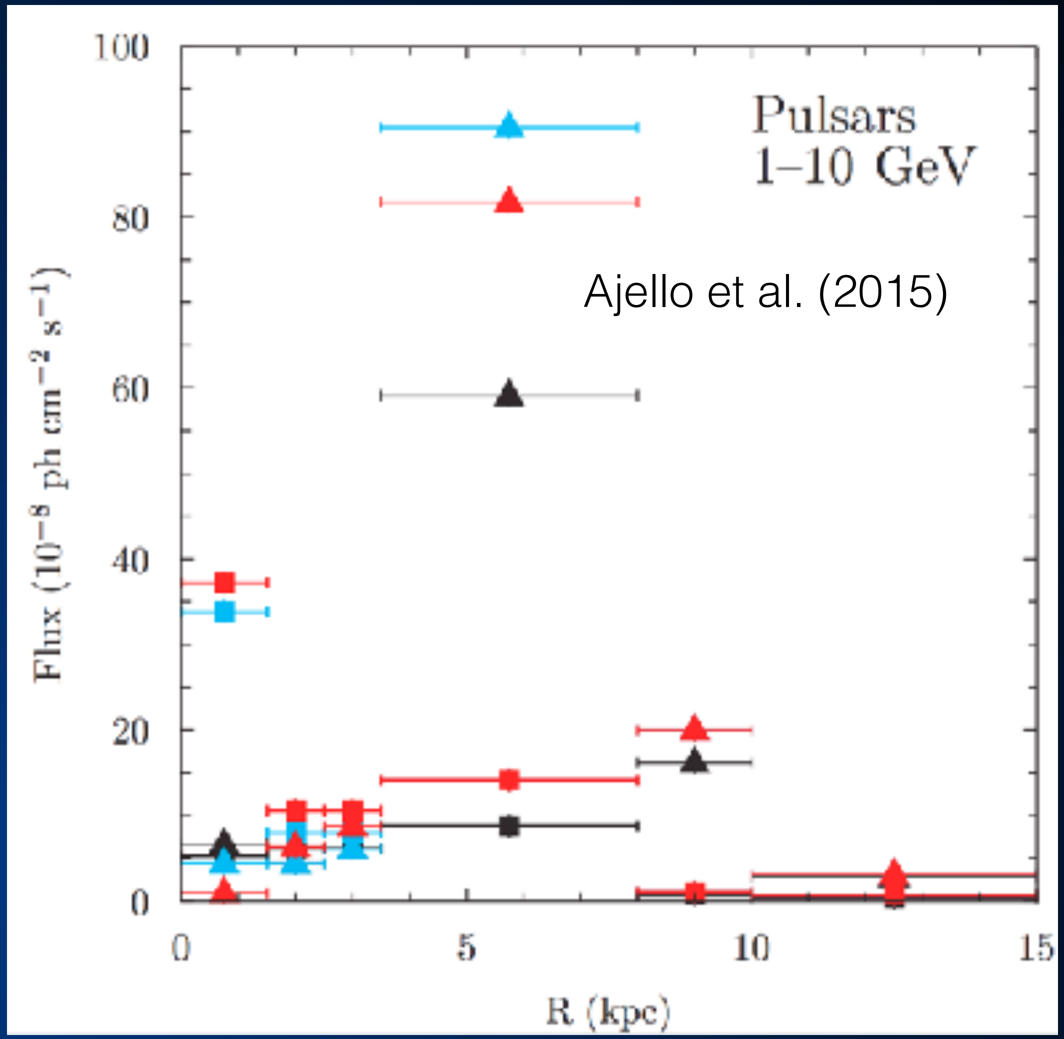
GC

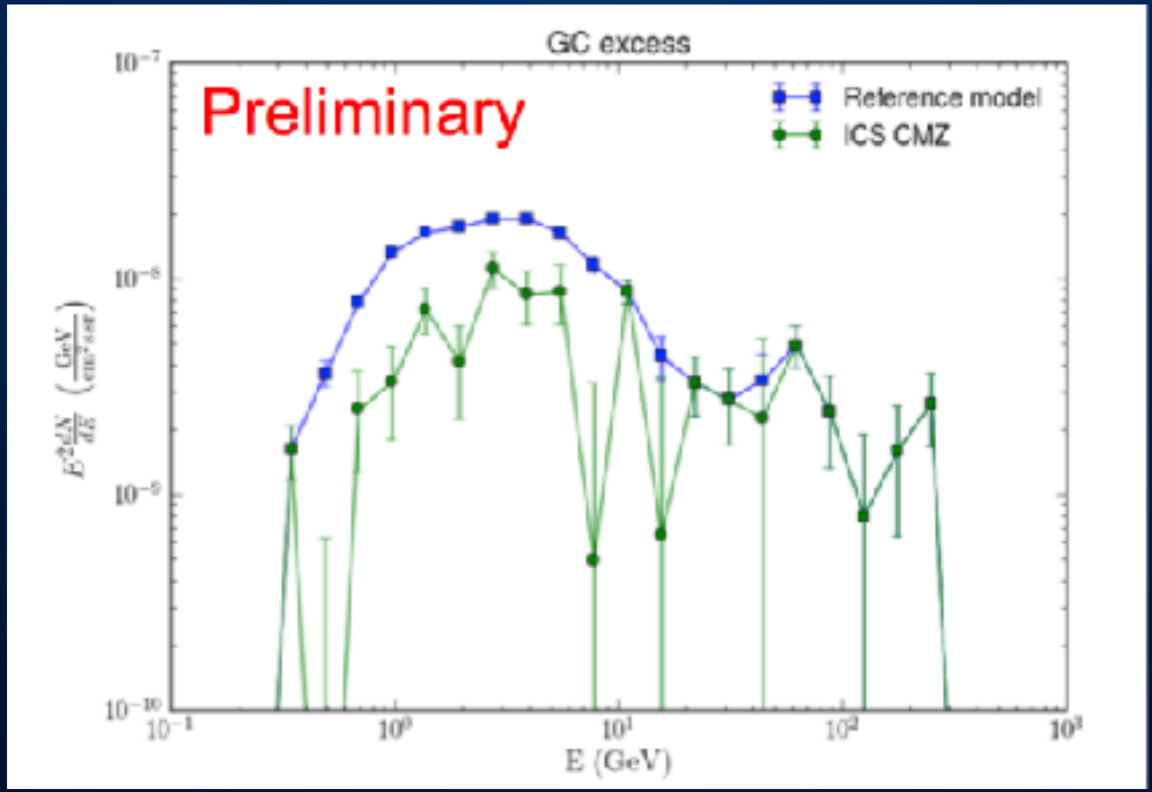


For the Galactic Center analysis, the morphology of the excess component remains relatively robust

A Similar Result with Different Techniques



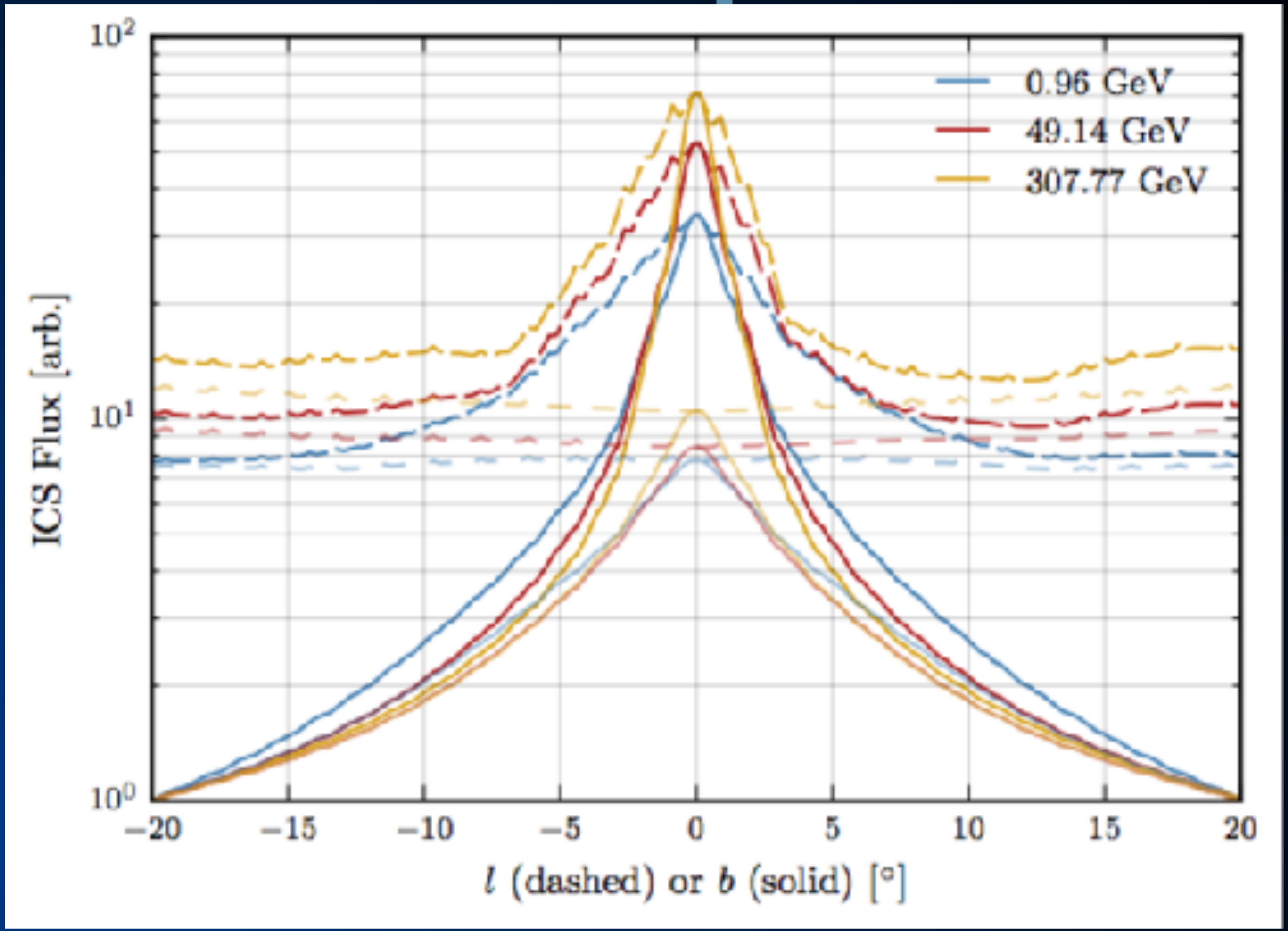


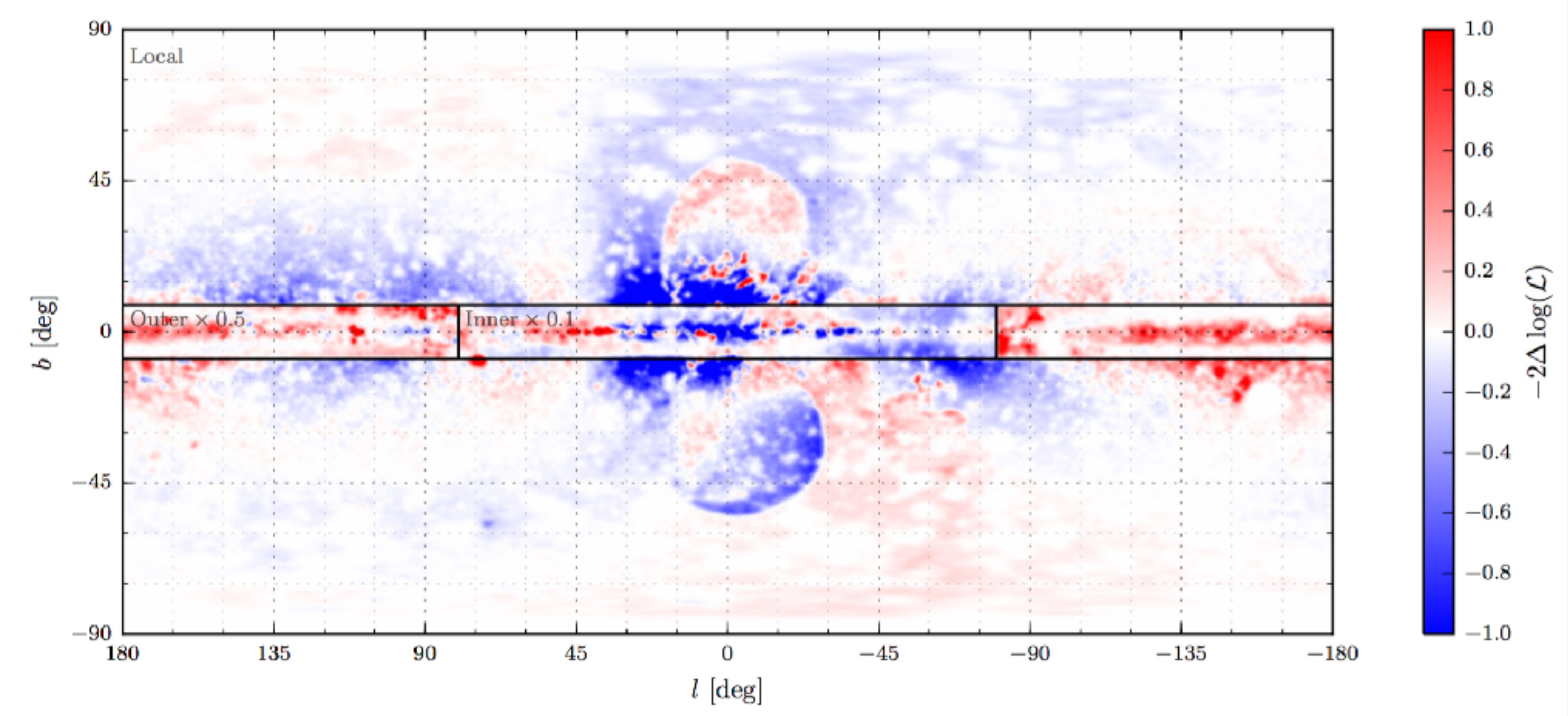


A Similar Result with Different Techniques

Our model effectively results in a significant peak in the ICS template near the galactic center.

However, this is not true everywhere in the model.





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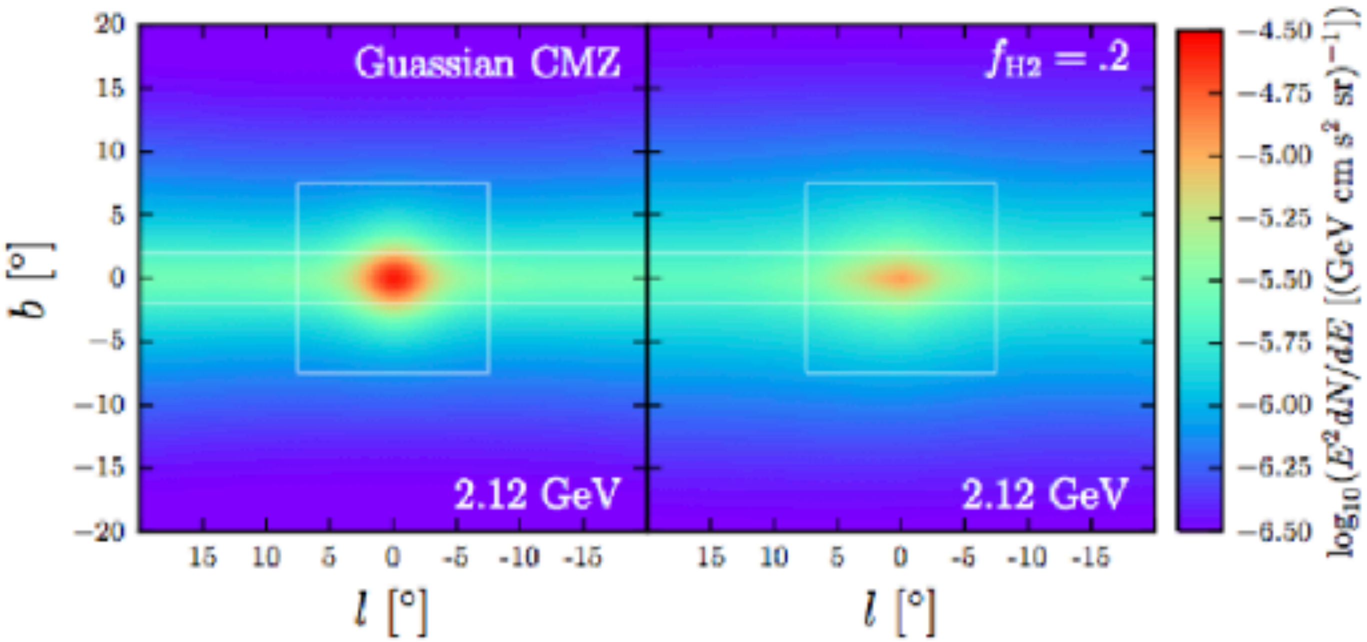
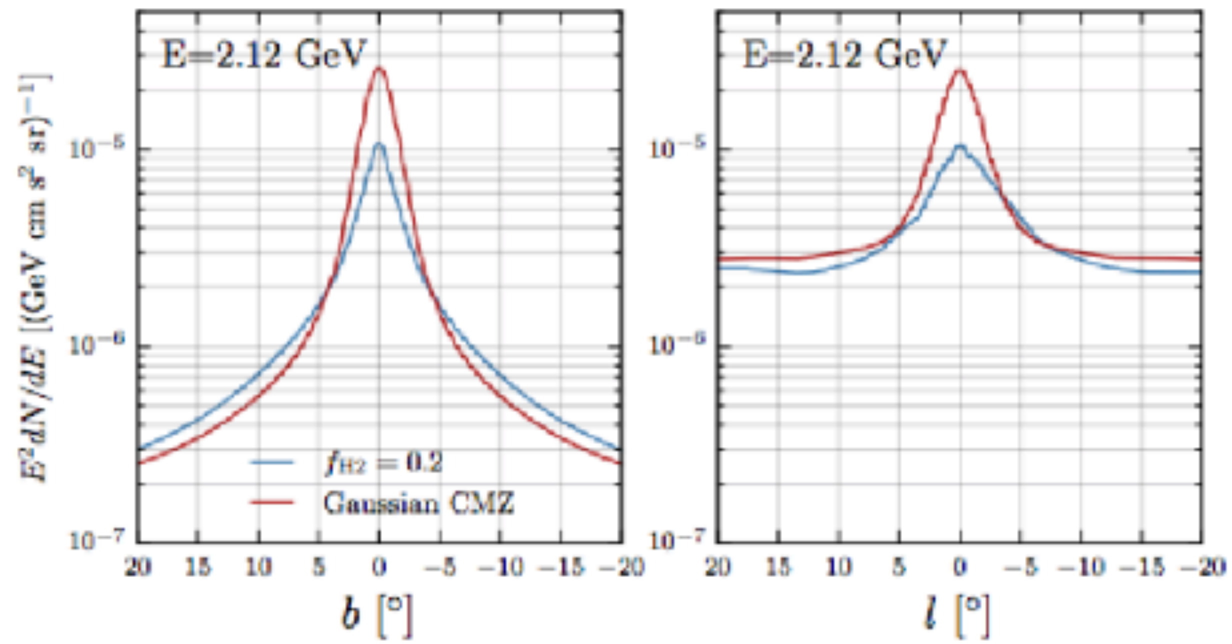
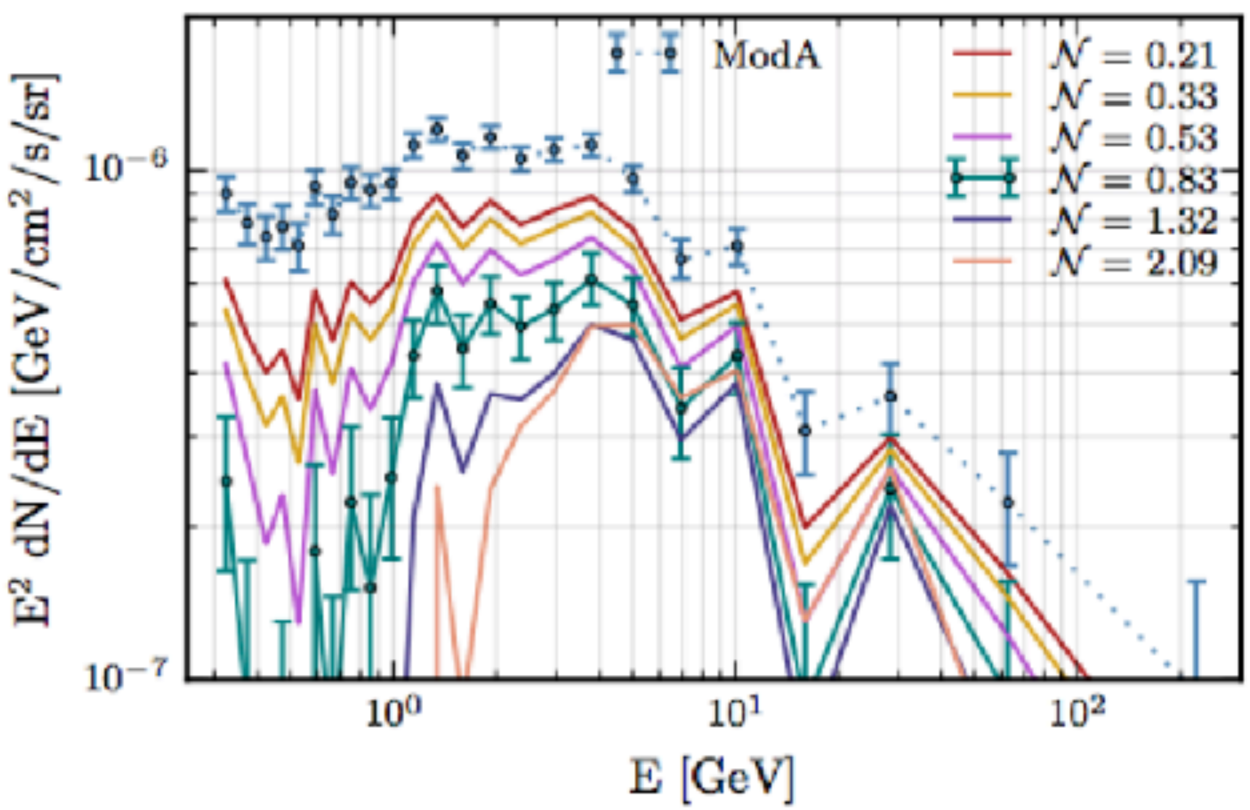
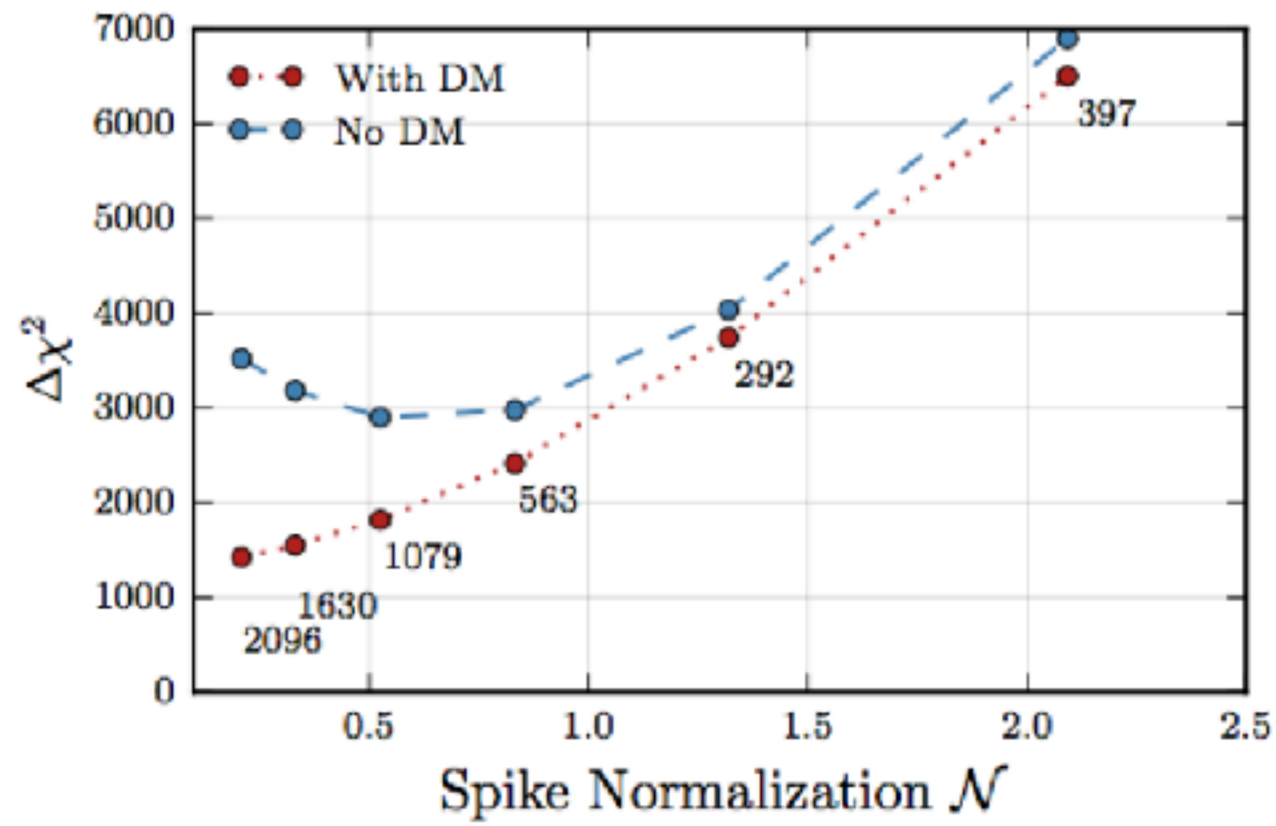




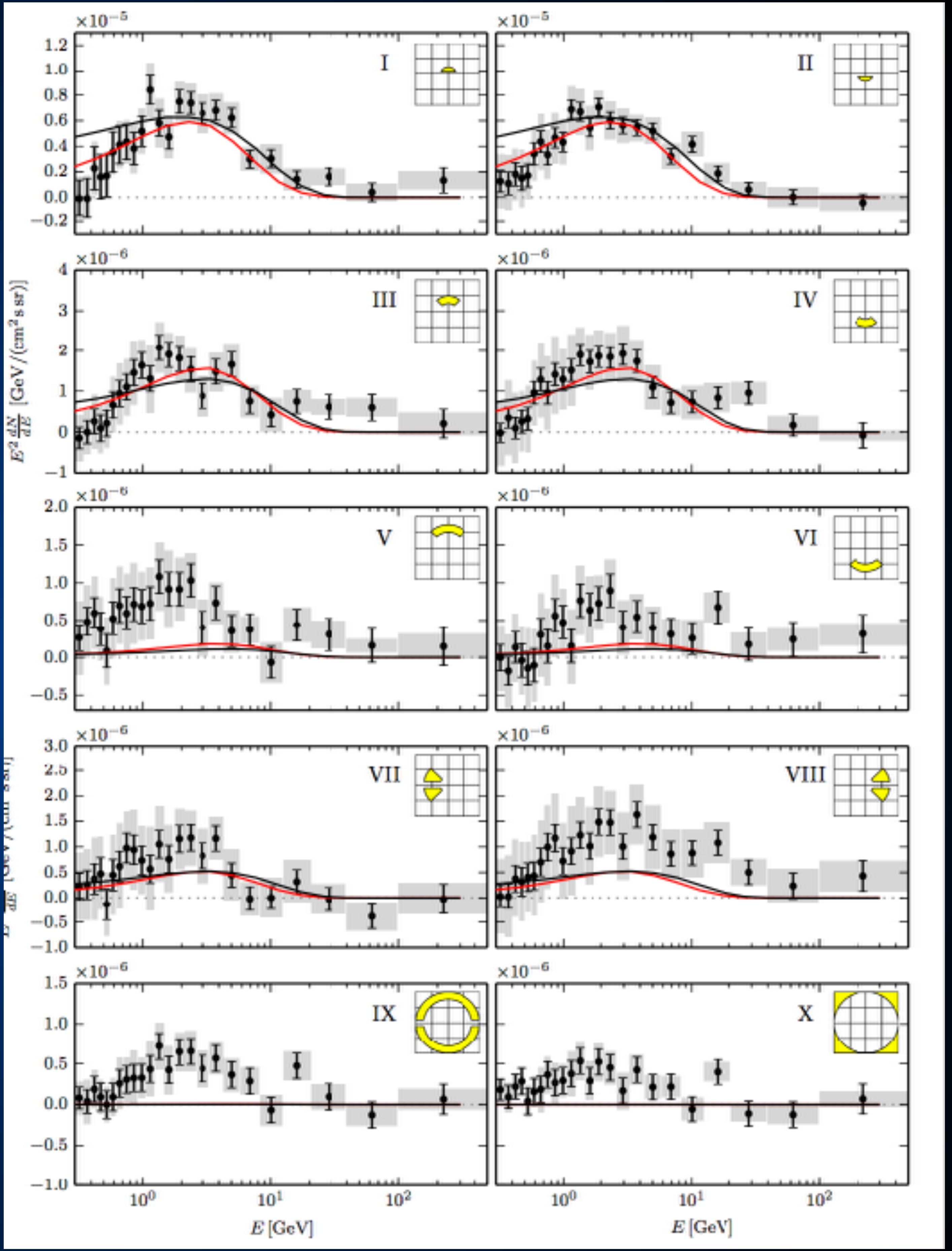




Cosmic-Ray Outbursts

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

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



Cholis et al. (2015, 1506.05119)

My Conclusions (1/2)

Diffuse Galactic emission (as presently modeled) does not account for the excess - but can change its characteristics in a reasonable way.

Future involves:

- **High Resolution modeling of the CMZ region**
- **Addition of new target maps (ISRF/gas) to accompany new proton injection**

Future models of Galactic center gamma-ray emission likely require the addition of a power advective wind.

Our Conclusions

Work shown in many different talks appear to hint at similar conclusions:

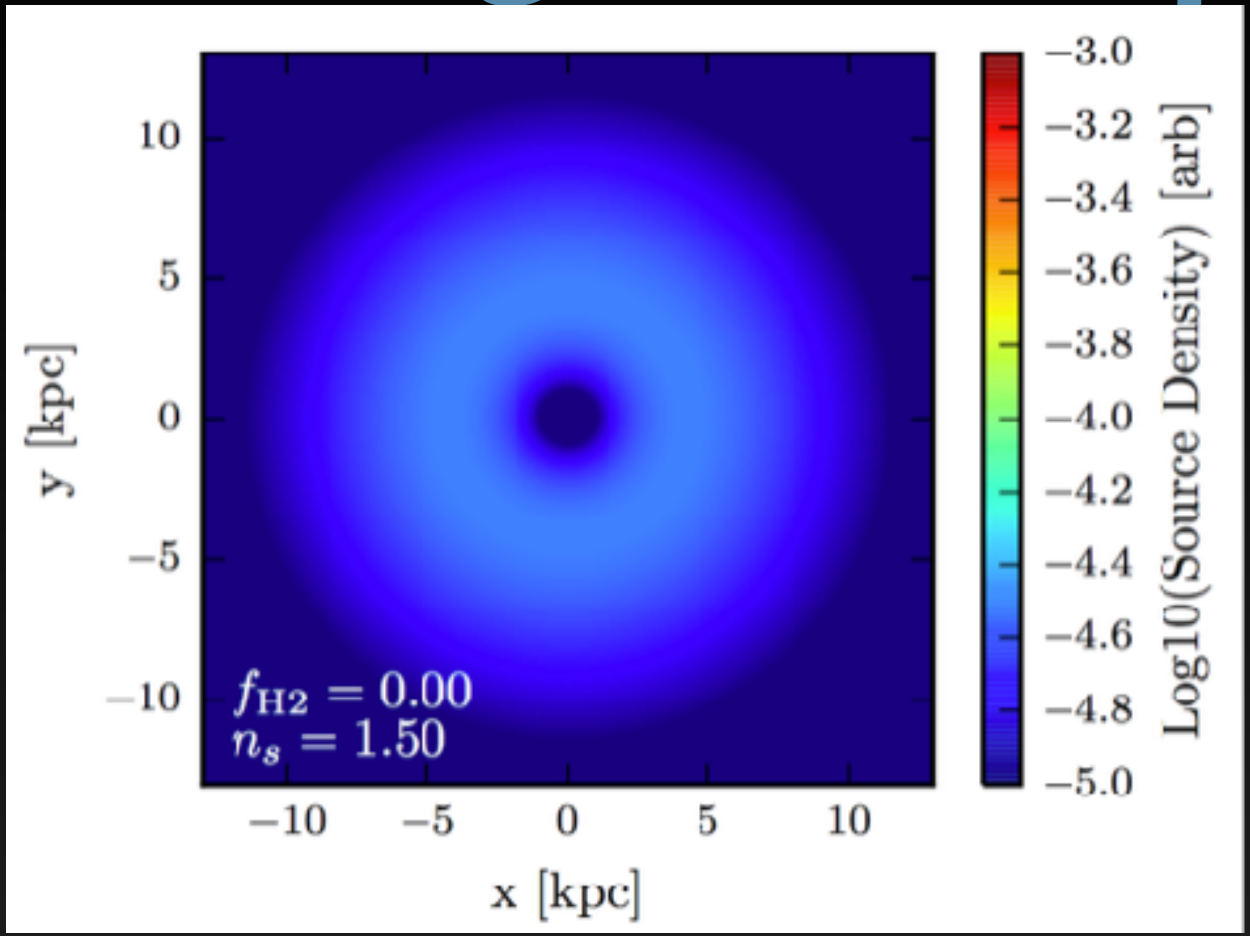
- **3D models of CR injection necessary (Ralf)**
- **Strong Evidence for missing CR injection near GC (Gulli, Fermi bubbles)**

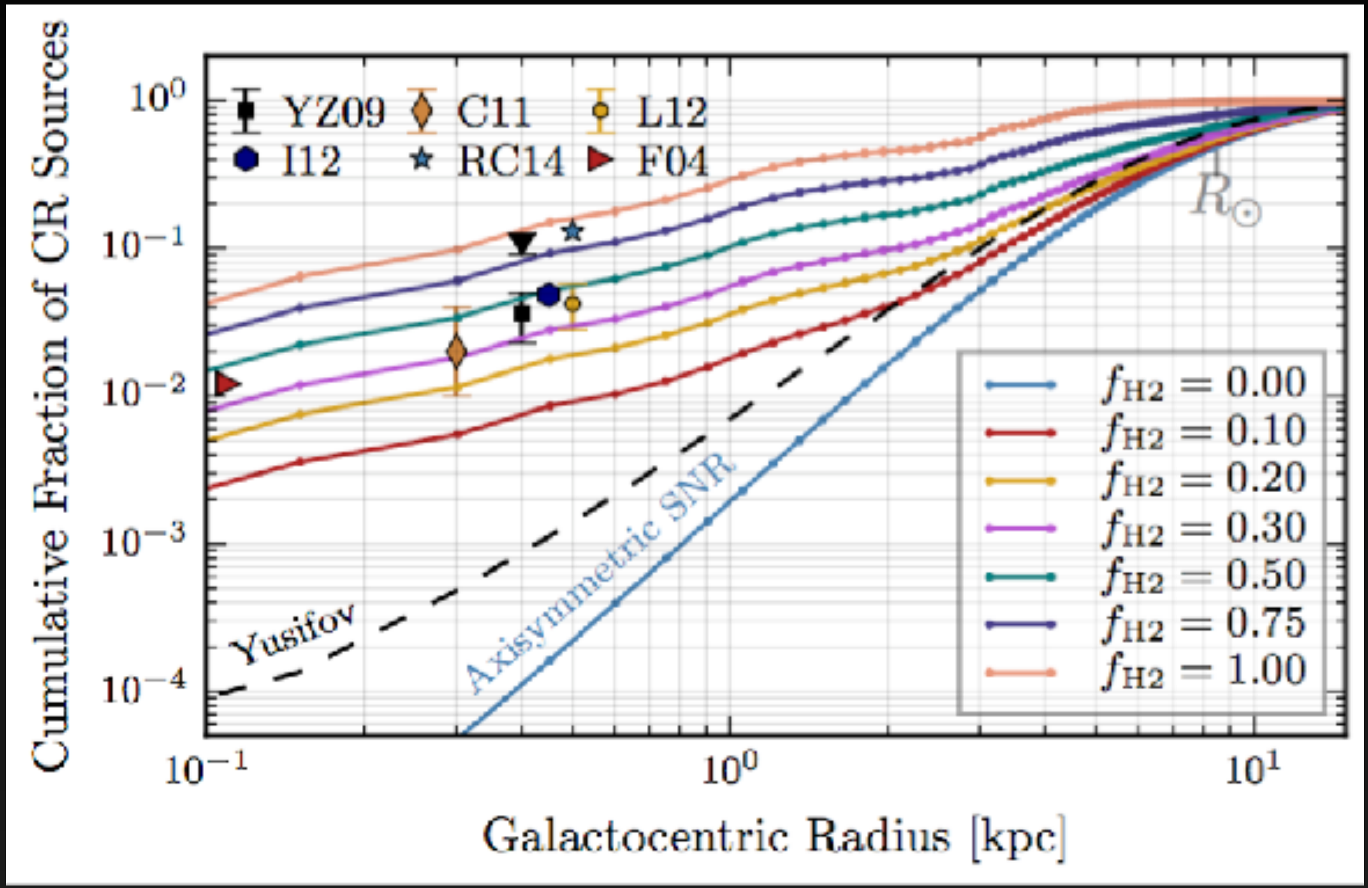
Strong Evidence for advective wind near GC (Bubbles, GCE?, Radio Observations)

Evidence for Anisotropic Diffusion (Andrea, Gulli, Ralf)

Extra Slides

Waxing Philosophical.....





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

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