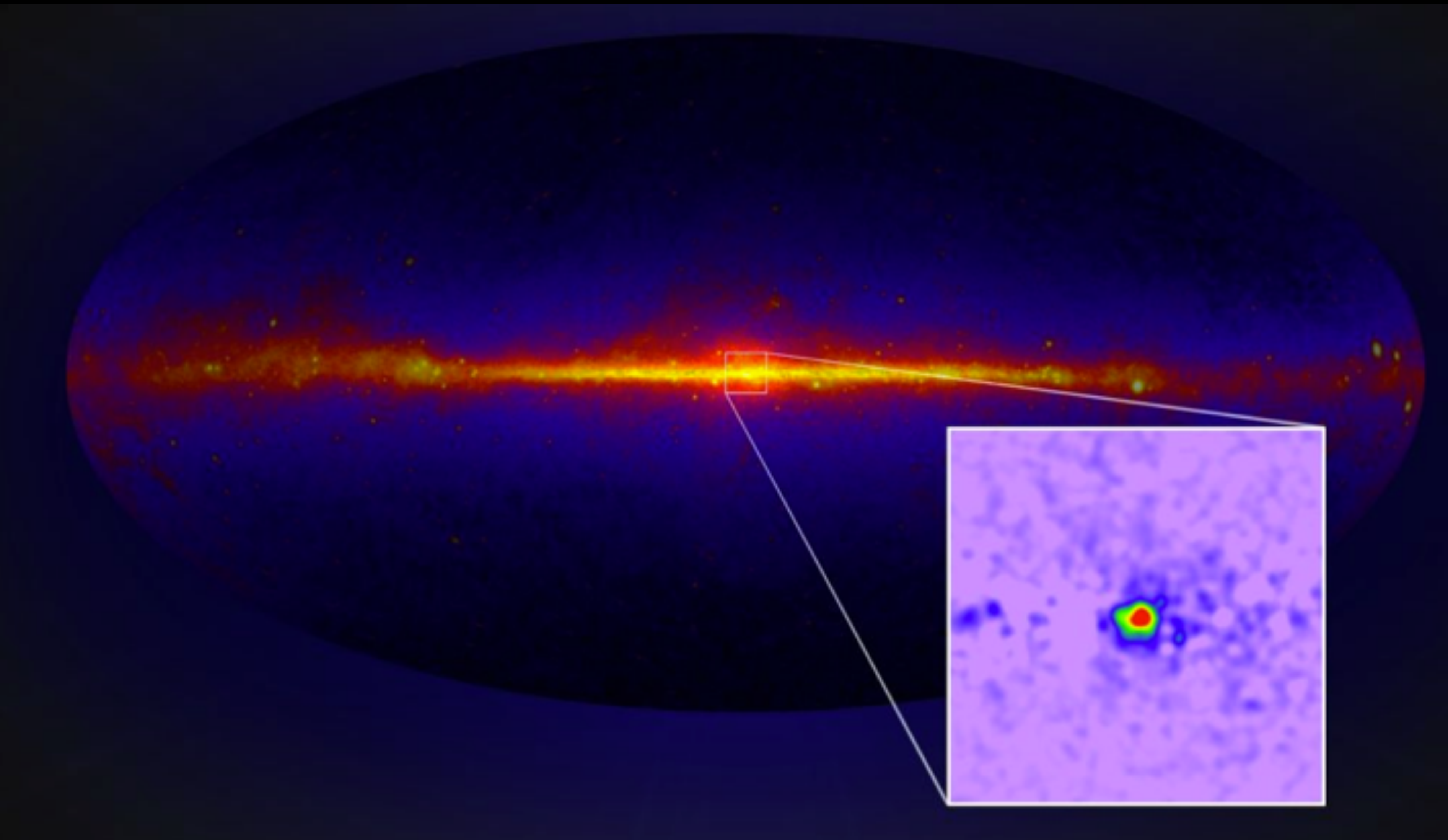

Diffuse Emission Models Confront the Galactic Center Excess

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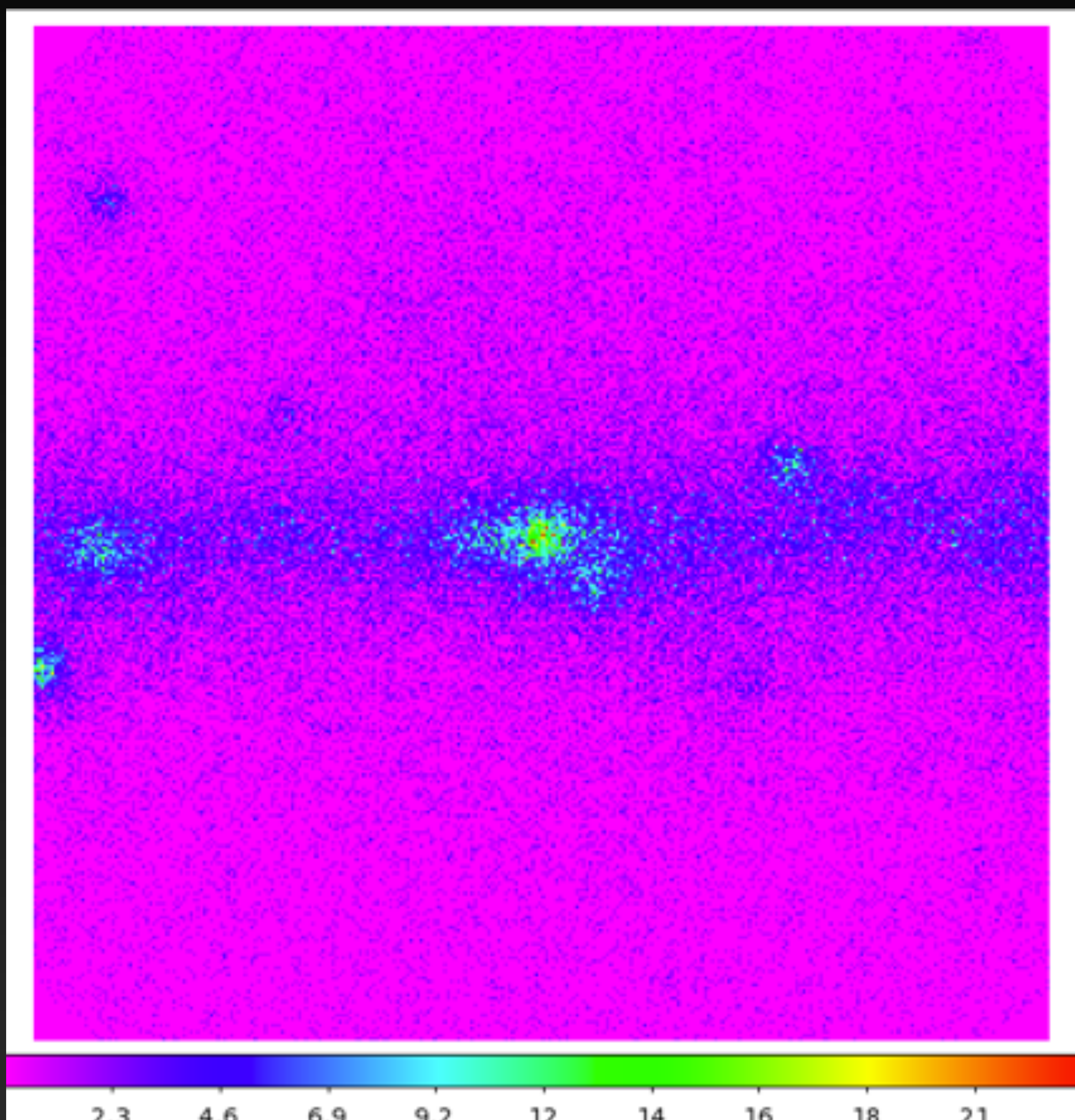
2016 MACROS Workshop

6/22/16

Untangling the spider's web

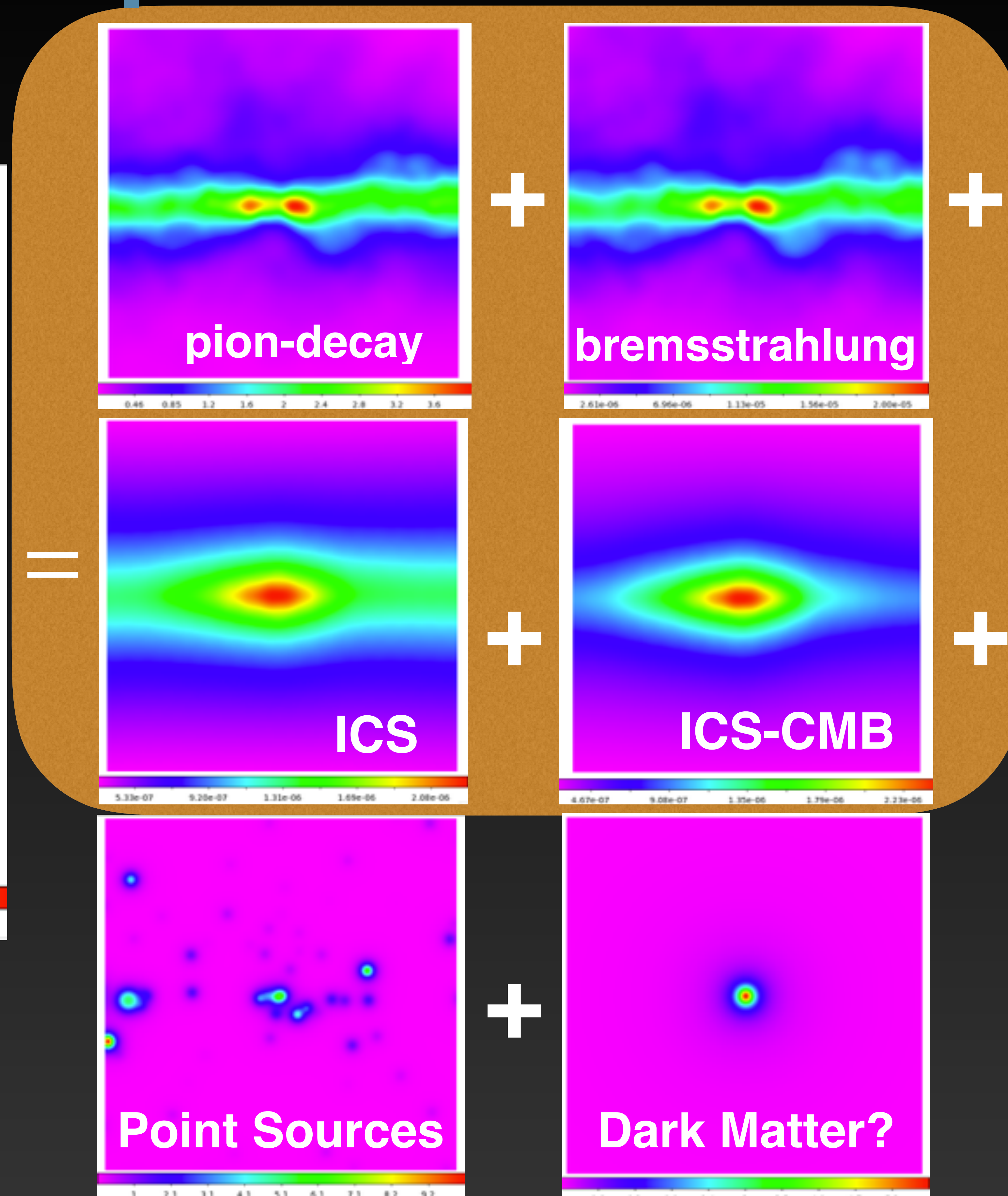


Data

750 — 950 MeV

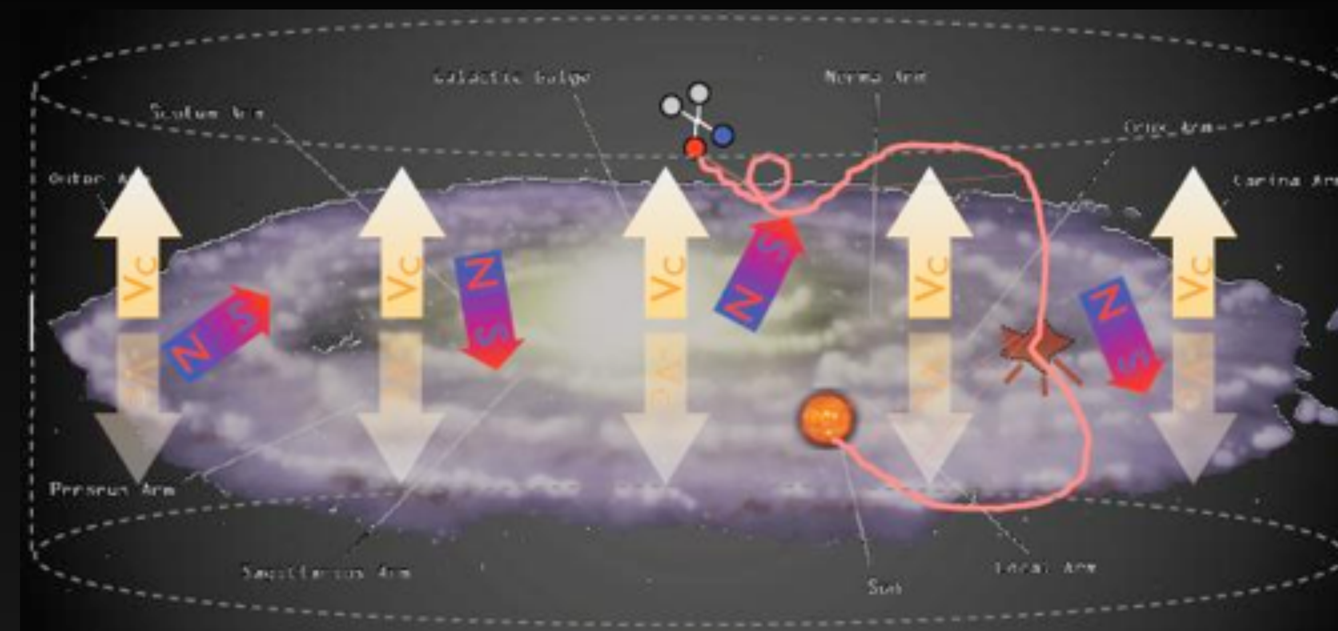
Best Angular Resolution Cut

10° x 10° ROI



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.

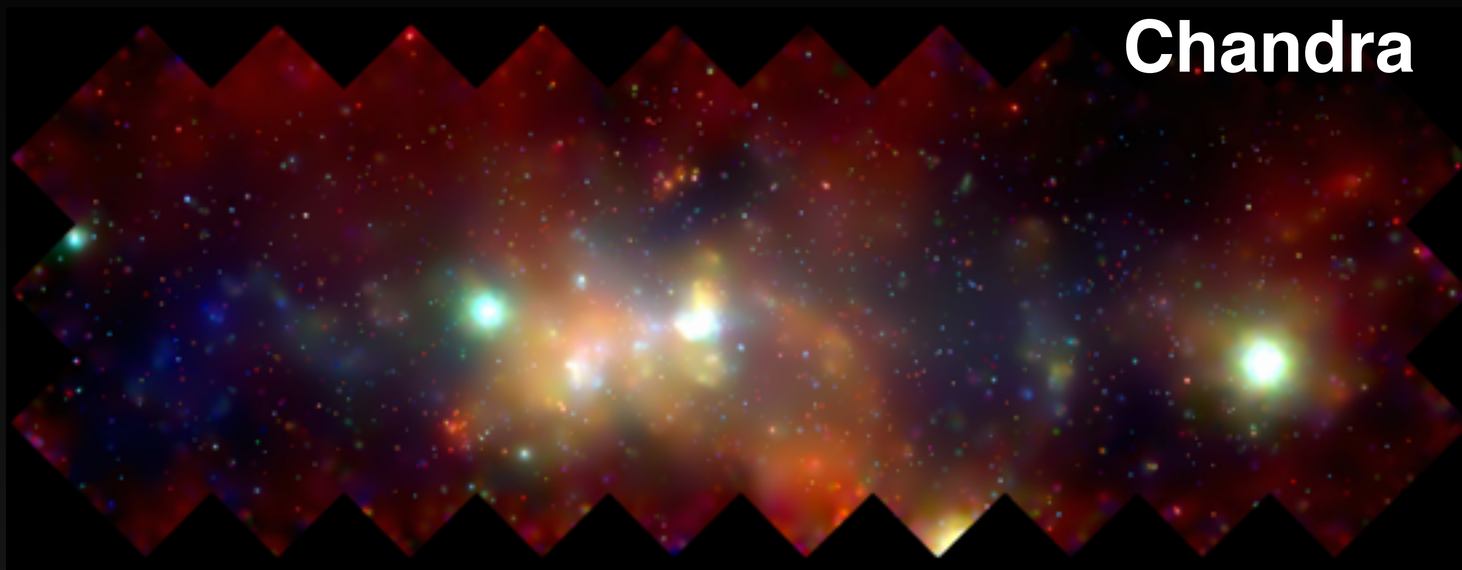
<u>What we need is a catalog of all Galactic supernovae over the past billion years.</u>

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

1.) Observational incompleteness

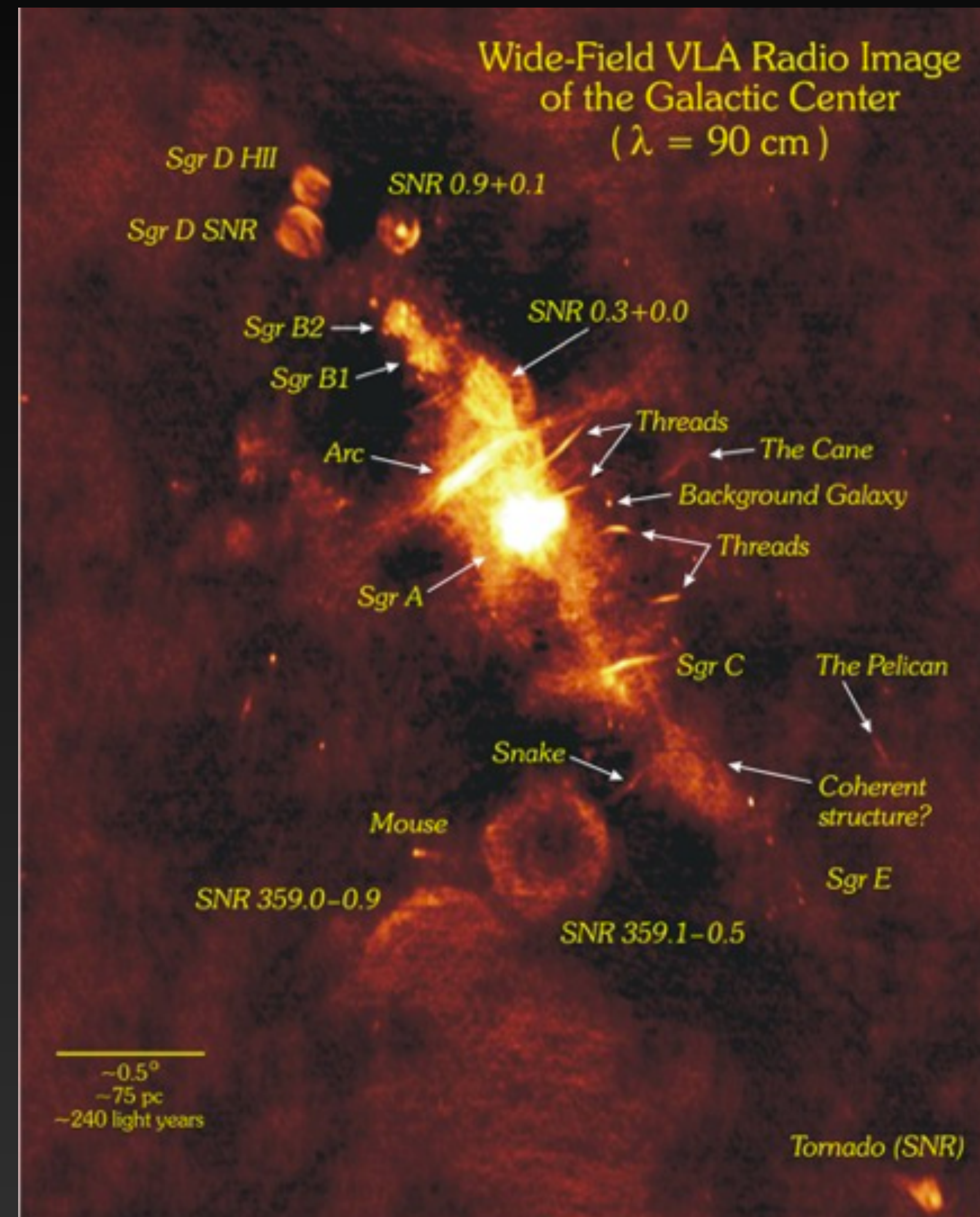
2.) Time variability

The 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.



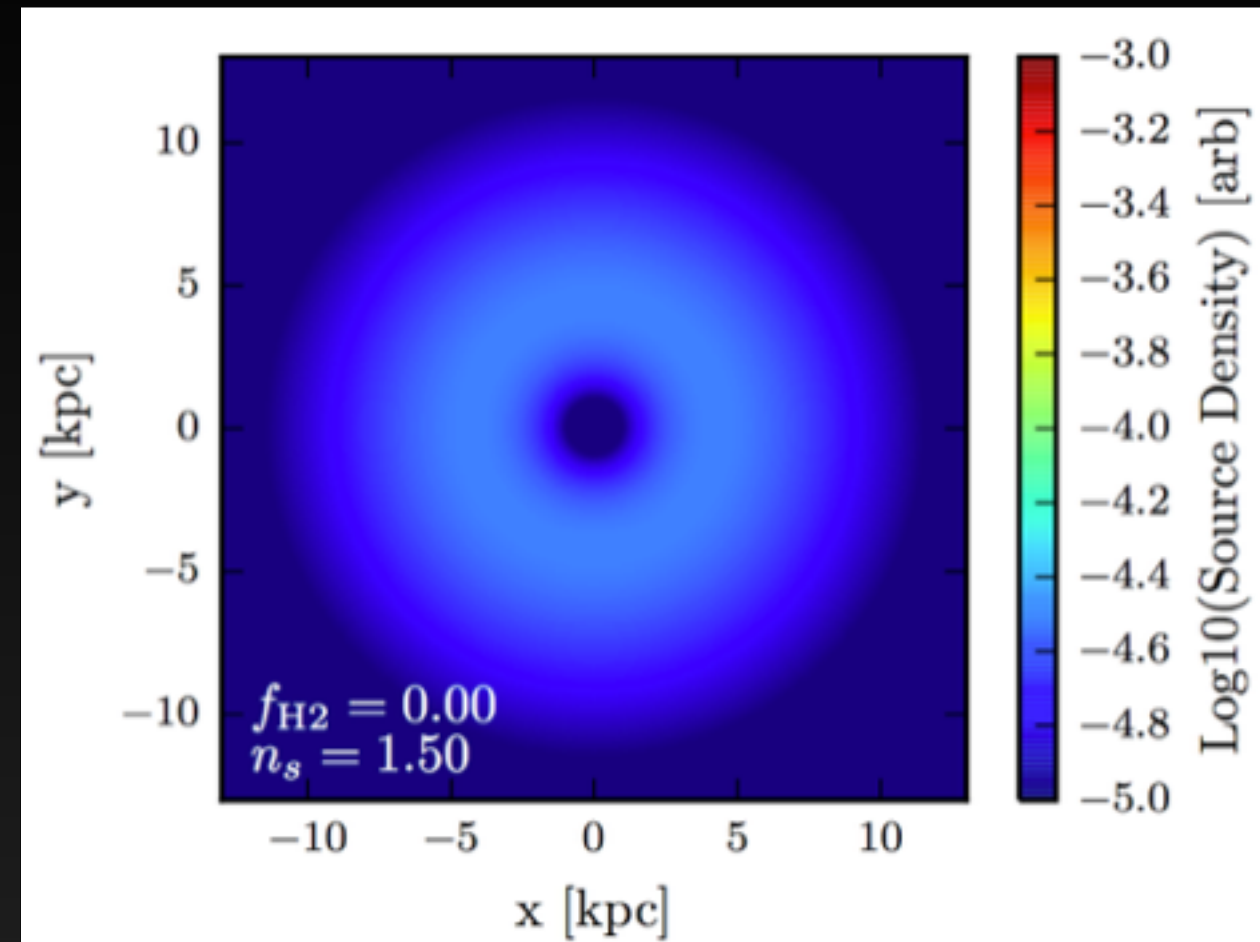
The Problem

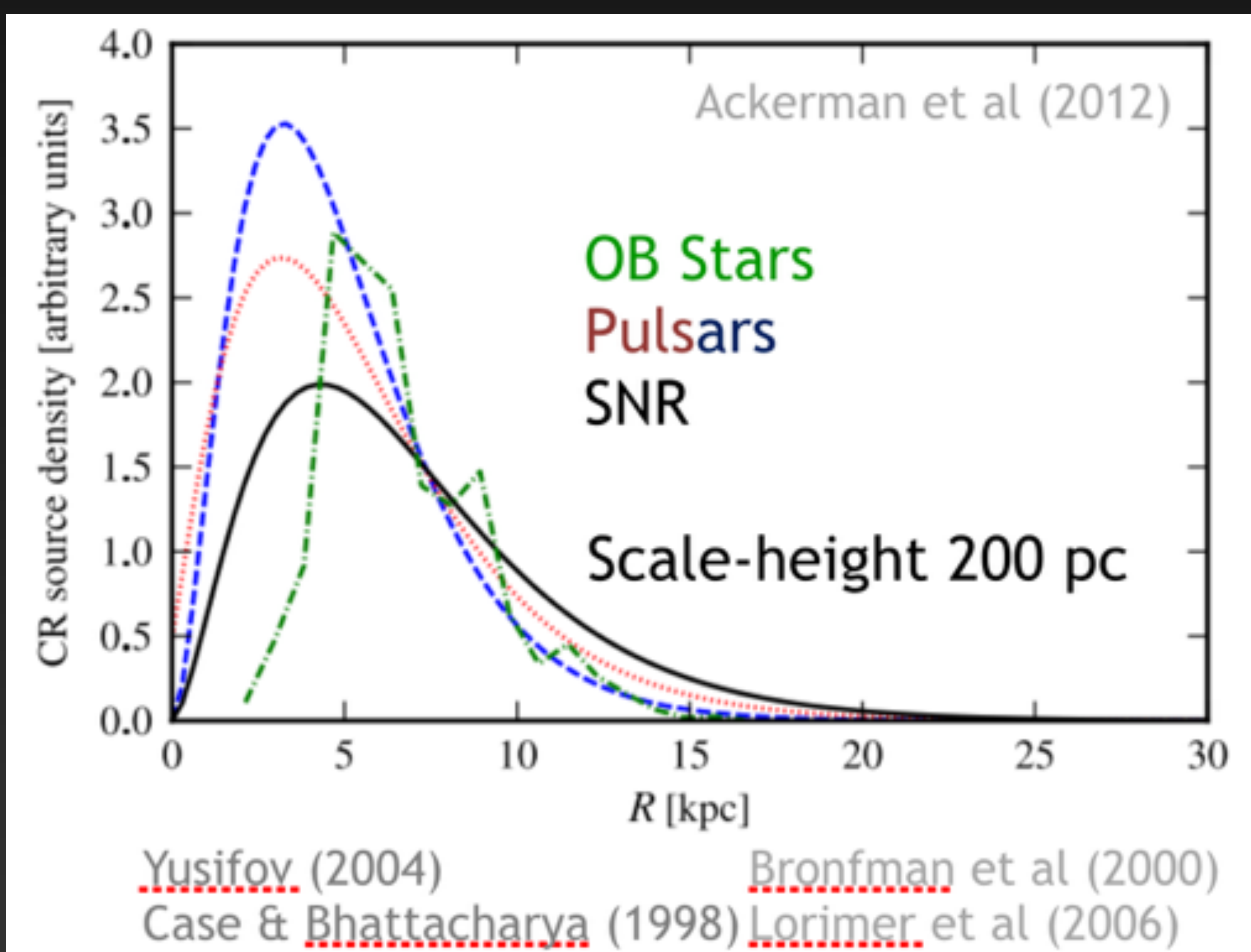
Measurements of Star Formation Rate:

1.) 2-4% - ISOGAL Survey Immer et al. (2012)
2.) 2.5-5% - Young Stellar Objects Yusef-Zadeh et al. (2009)
3.) 5-10% - Infrared Flux Longmore et al. (2013)
4.) 13% - Wolf-Rayet Stars Rosslowe & Crowther (2014)
5.) 2% - Far-IR Flux Thompson et al. (2007)
6.) 2.5-6% - SN1a Schanne et al. (2007)

The Problem

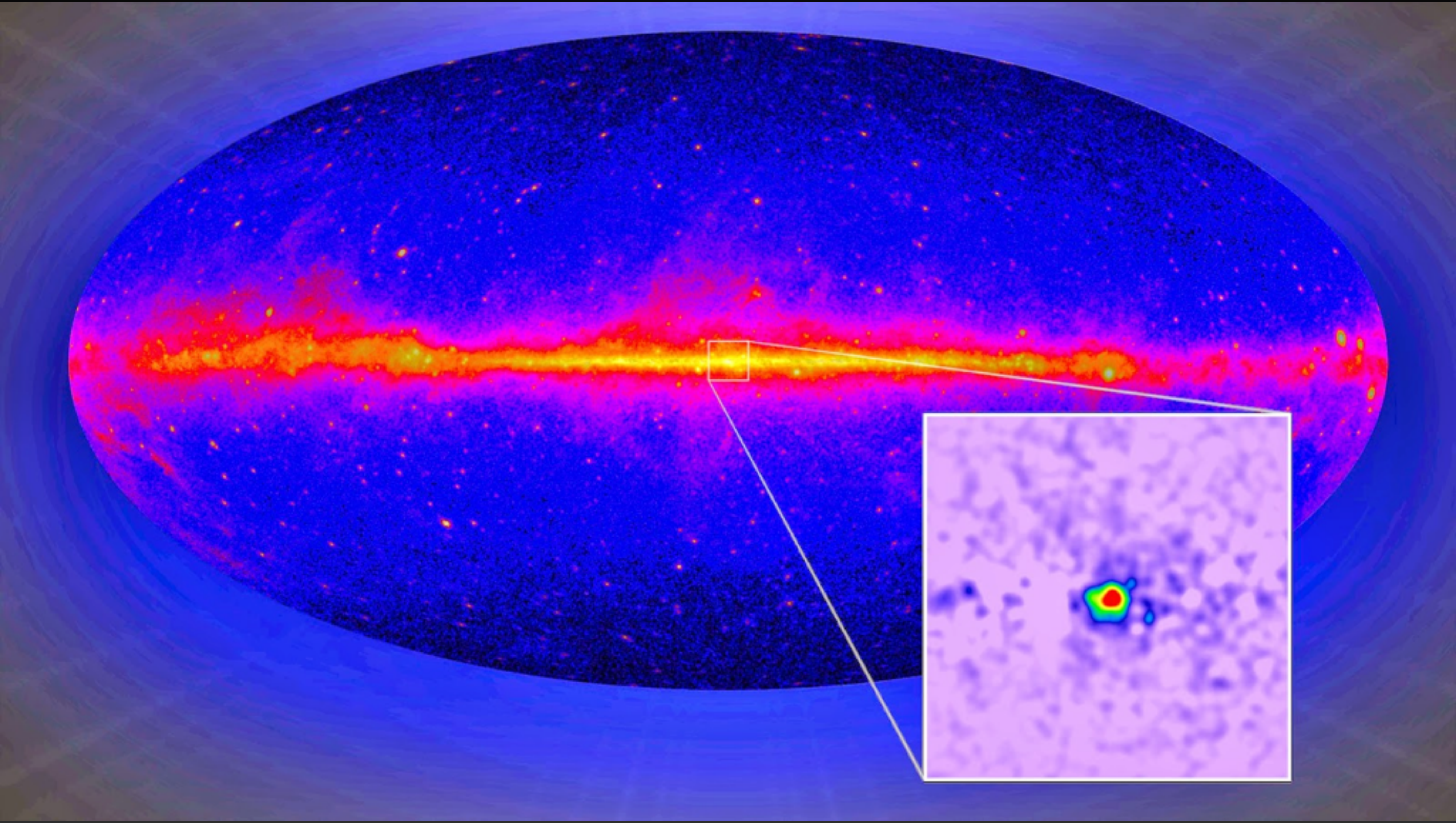
Cosmic-Ray Propagation Codes (e.g. Galprop), generally utilize a cosmic-ray injection rate at the Galactic center that is identically 0.



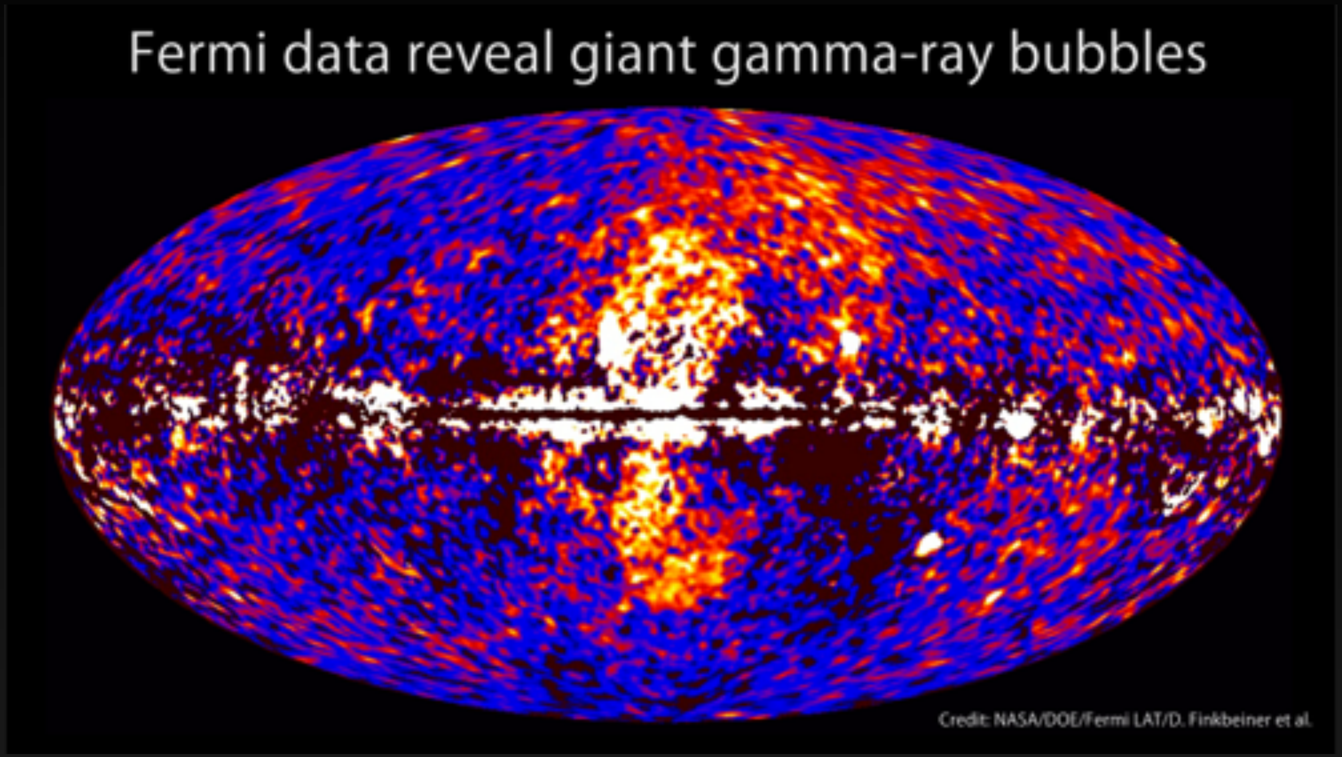


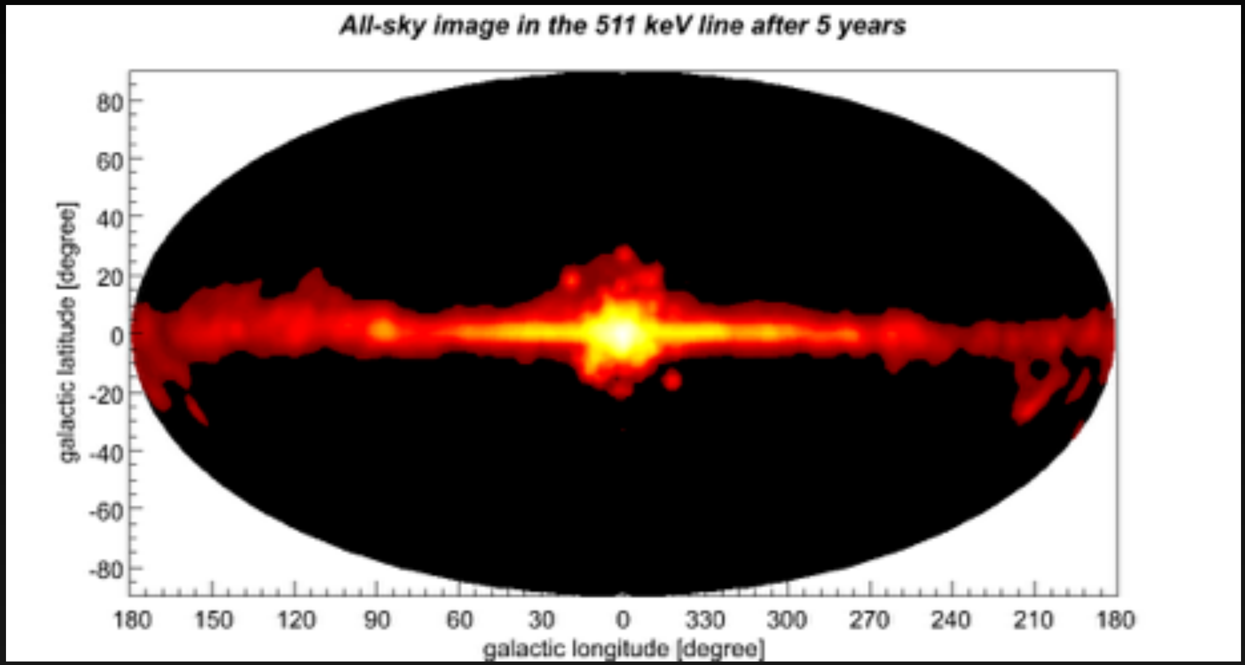
Results from these cosmic-ray propagation codes are used in many analyses of the Galactic center region.

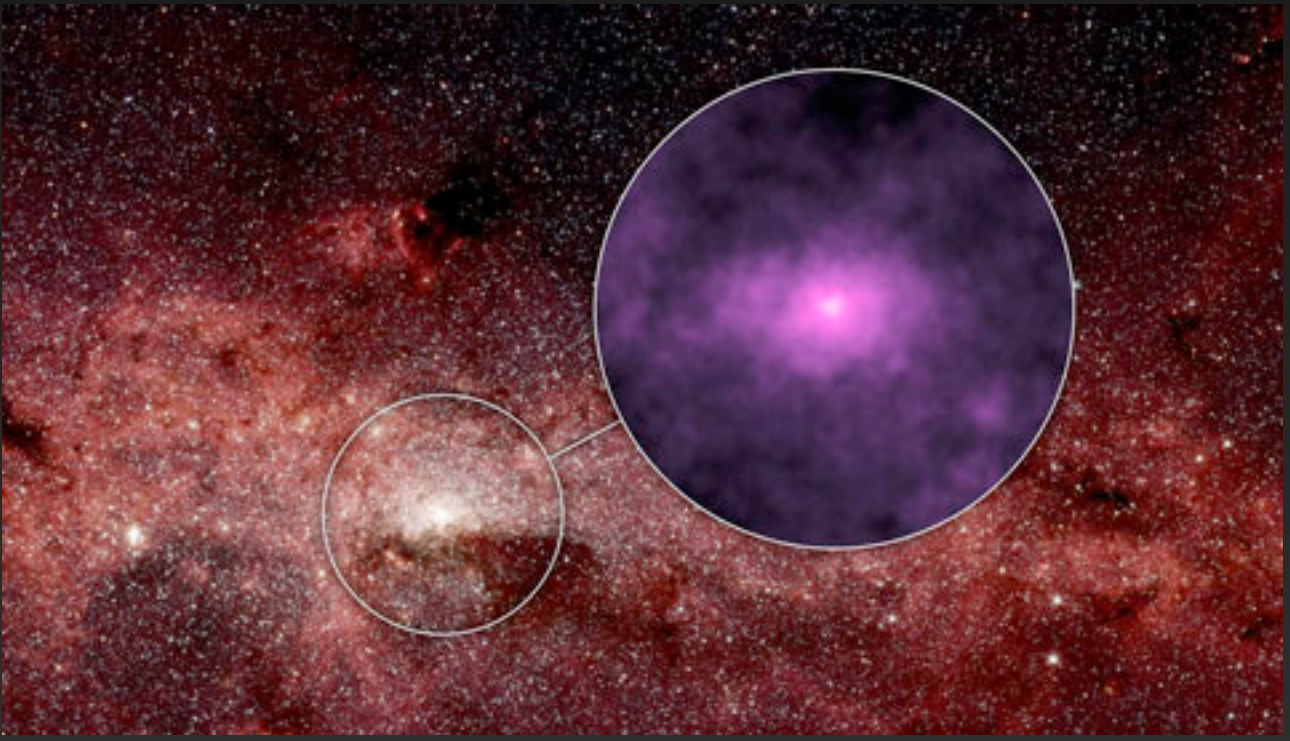
Fool me once, shame on, shame on you...

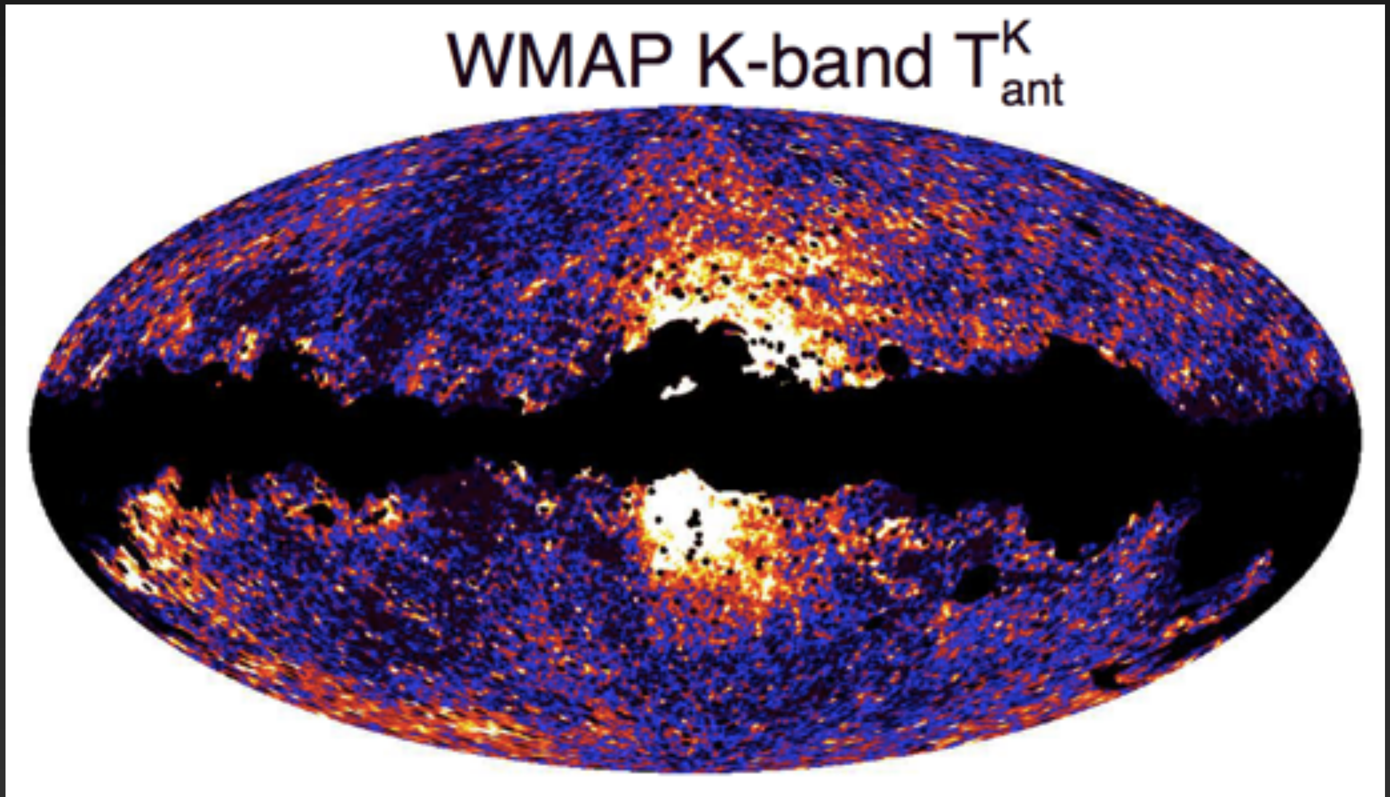


Fool me —- you can't get fooled again!





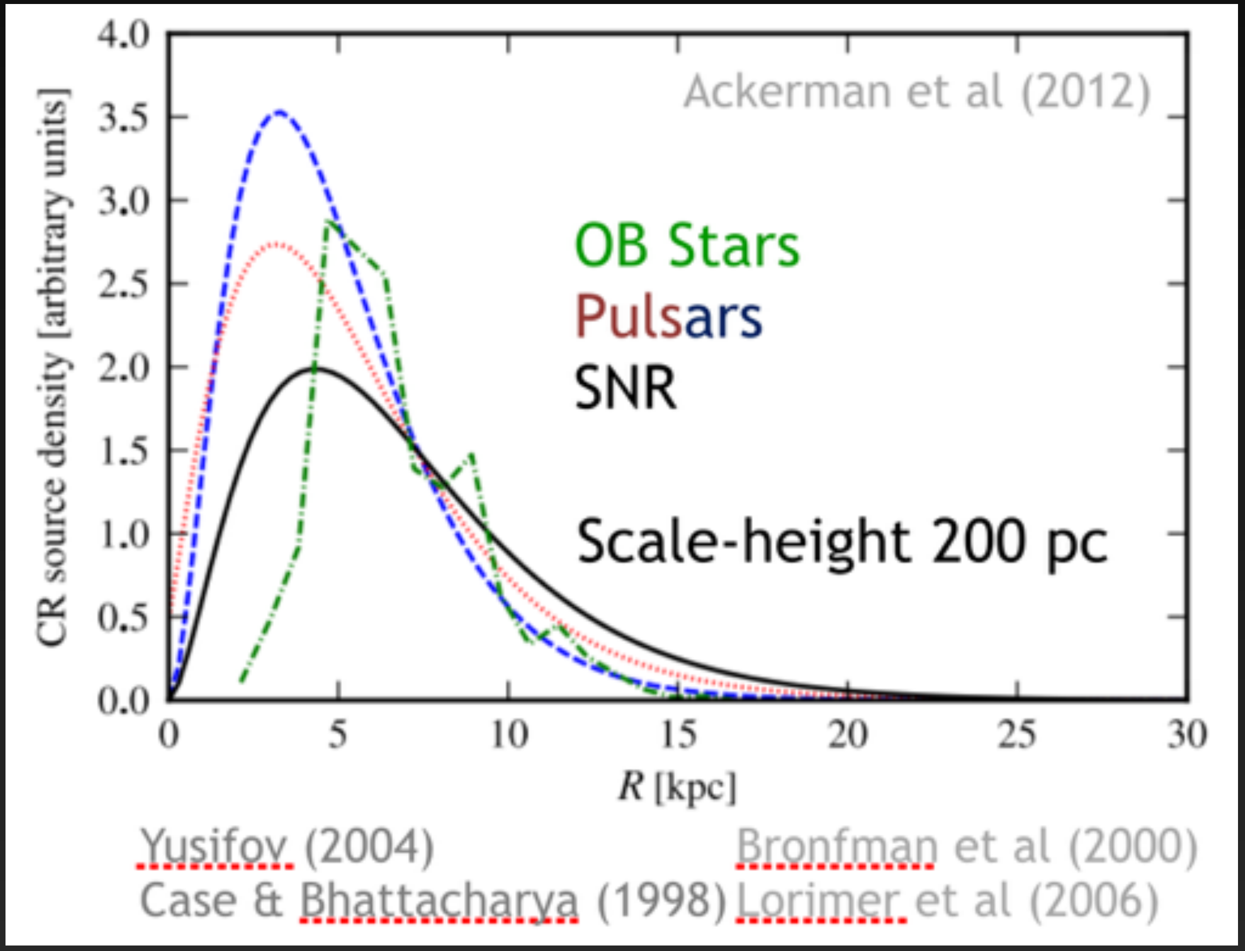




What we've got here is a failure to communicate

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**

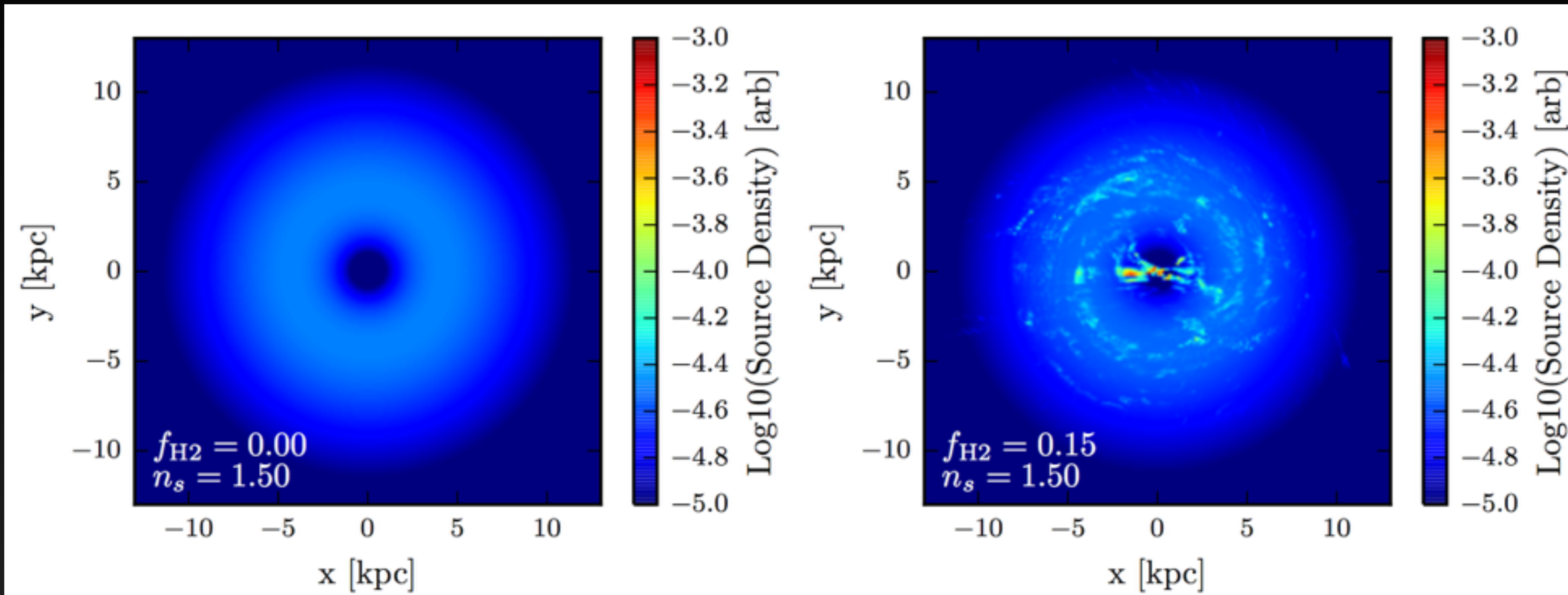
$$\Sigma_{\rm SFR} \propto \Sigma_{\rm Gas}^{1.4 \pm .15}$$

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

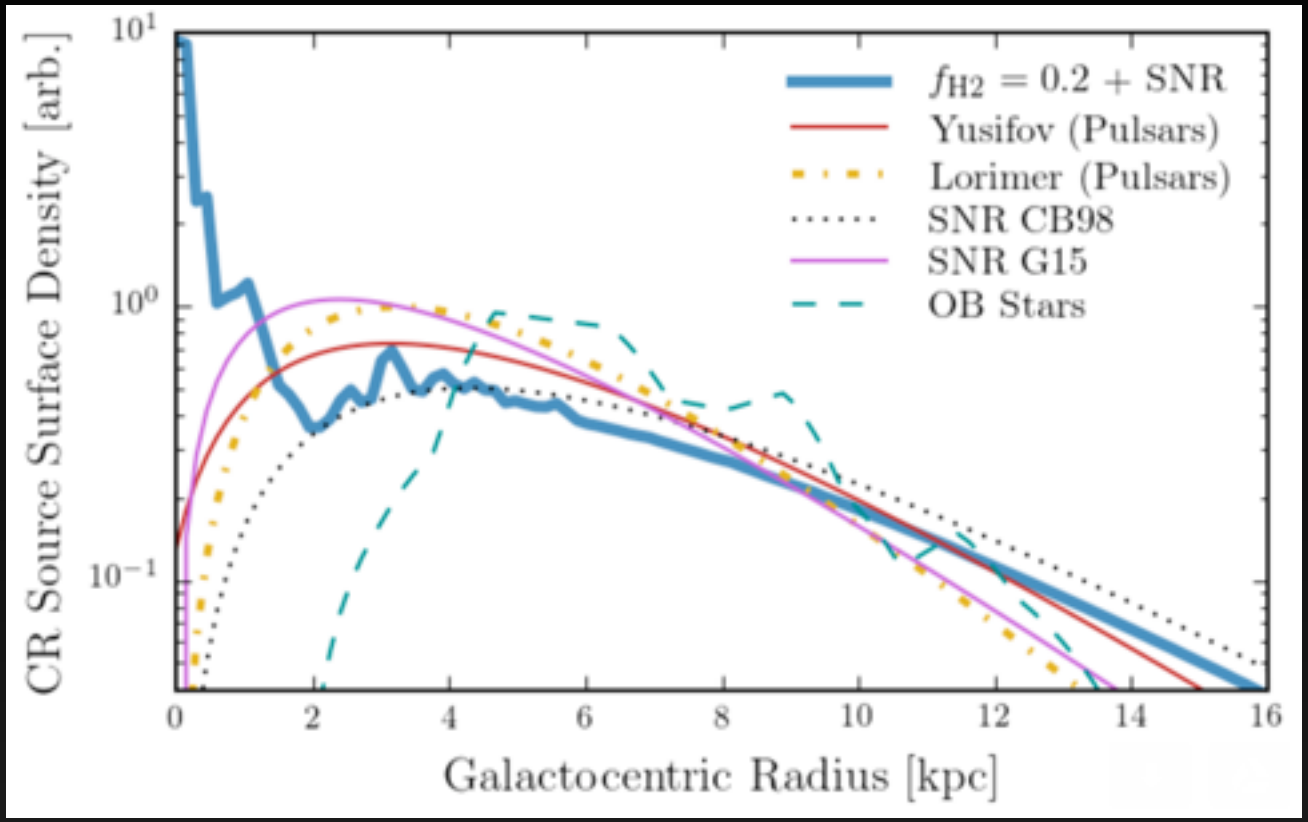


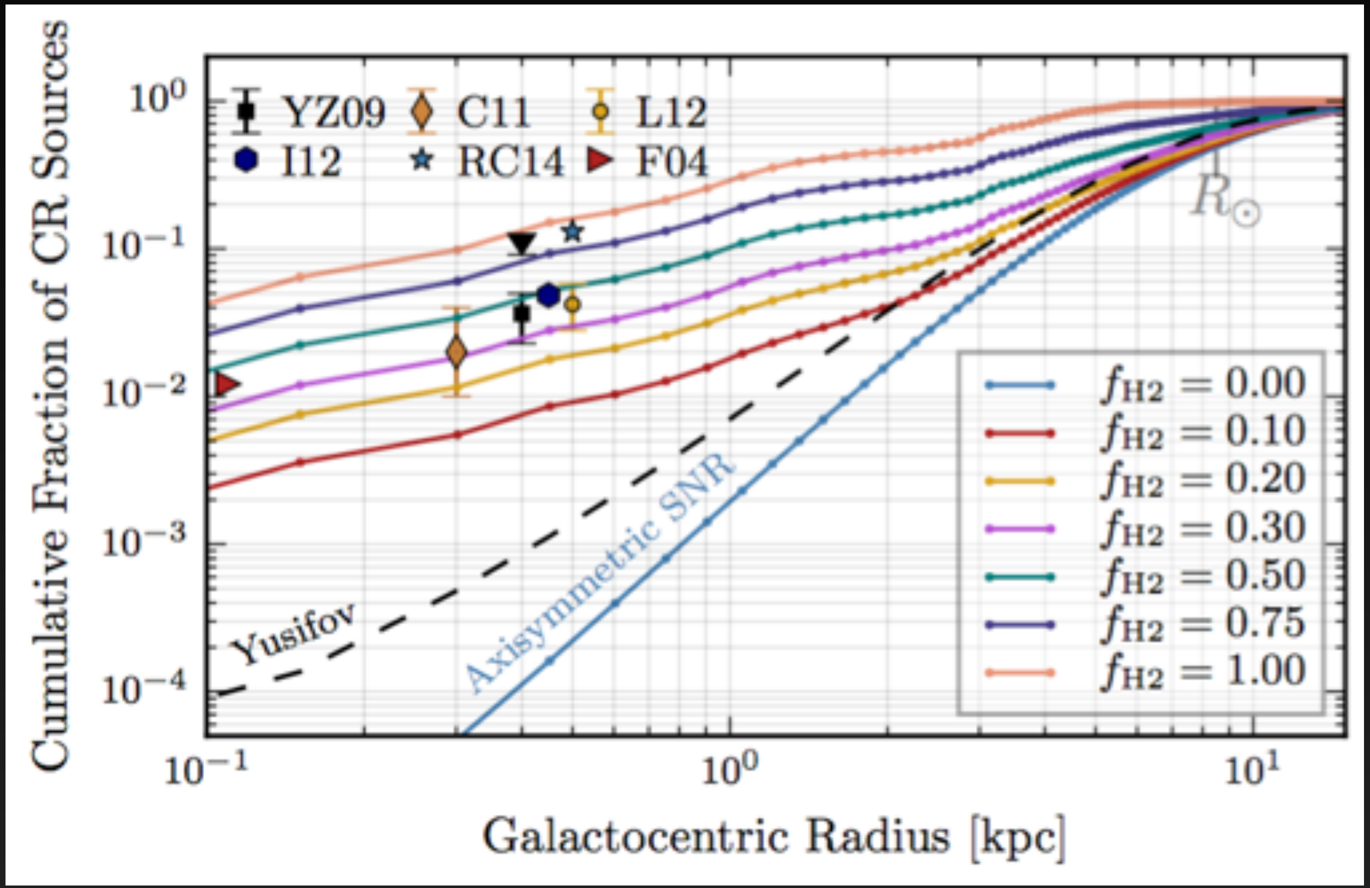
Two features leap out immediately:

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!

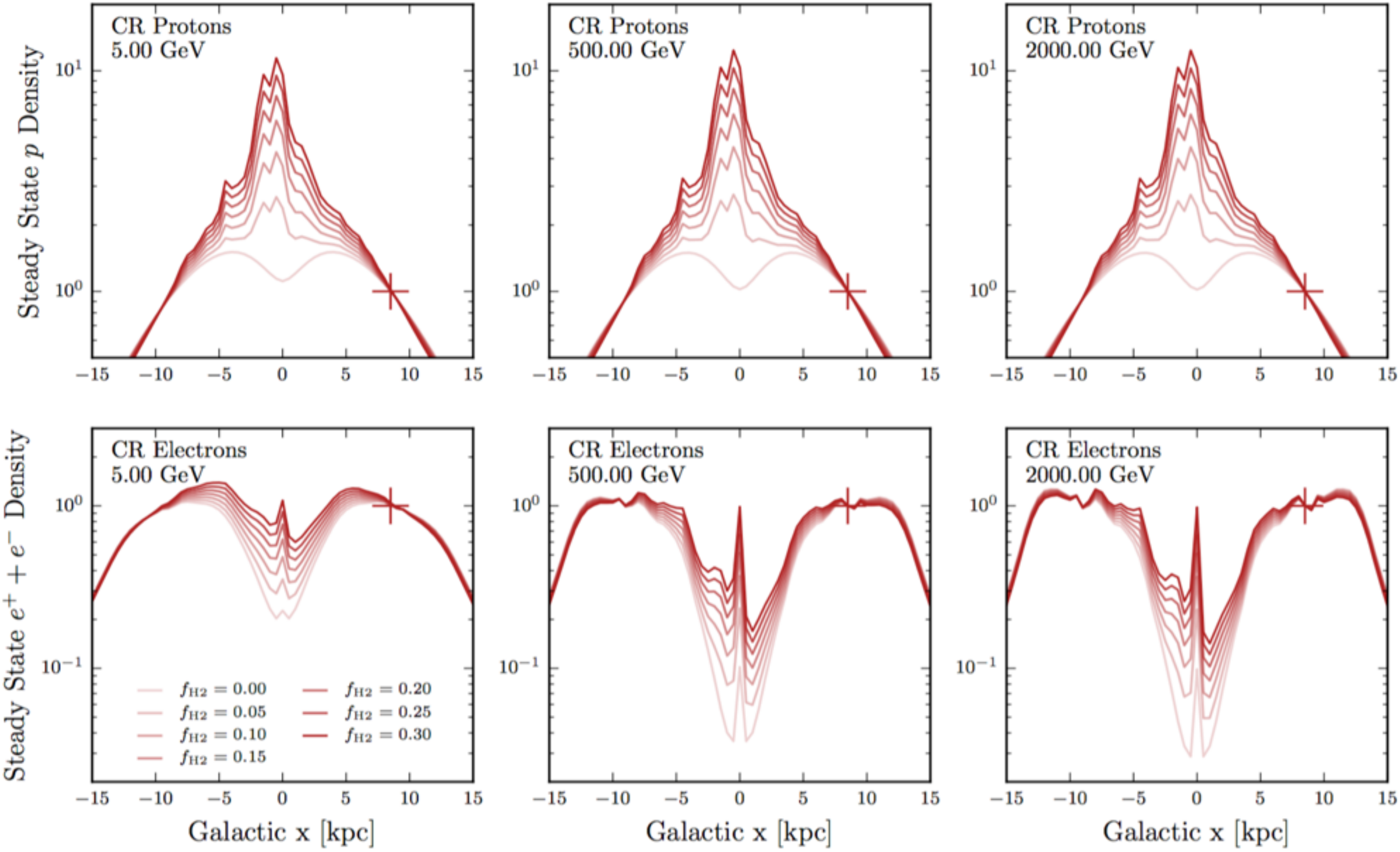
Parameter	Units	Canonical	Mod A	Description
D_0	$cm^2\ s^{-1}$	7.2×10^{28}	5.0×10^{28}	Diffusion constant at $\mathcal{R} = 4$ GV
δ	–	0.33	0.33	Index of diffusion constant energy dependence
z_{halo}	kpc	3	4	Half-height of diffusion halo
R_{halo}	kpc	20	20	Radius diffusion halo
v_a	$km\ s^{-1}$	35	32.7	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

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)

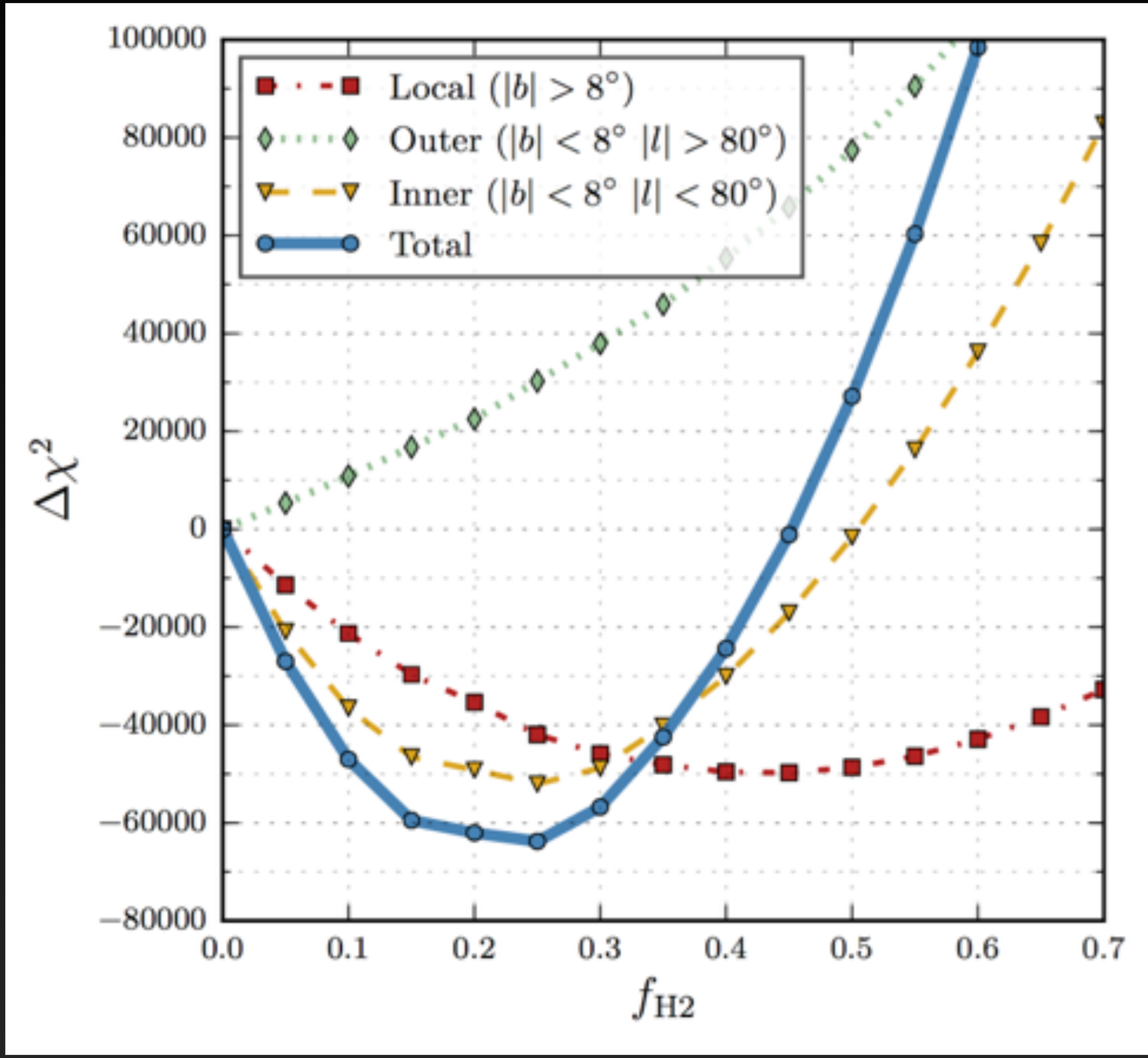
Ring Number	Radius [kpc]	Fit Region	X_{CO} $[cm^{-2}\ (K\ km\ s^{-1})^{-1}]$
1	0 – 2.0	Inner	$1.00 \times 10^{19\dagger}$
2	2.0 – 3.0	Inner	8.42×10^{19}
3	3.0 – 4.0	Inner	1.61×10^{20}
4	4.0 – 5.0	Inner	1.73×10^{20}
5	5.0 – 6.5	Inner	1.72×10^{20}
6	6.5 – 8.0	Inner	1.74×10^{20}
7	8.0 – 10.0	Local	8.61×10^{19}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

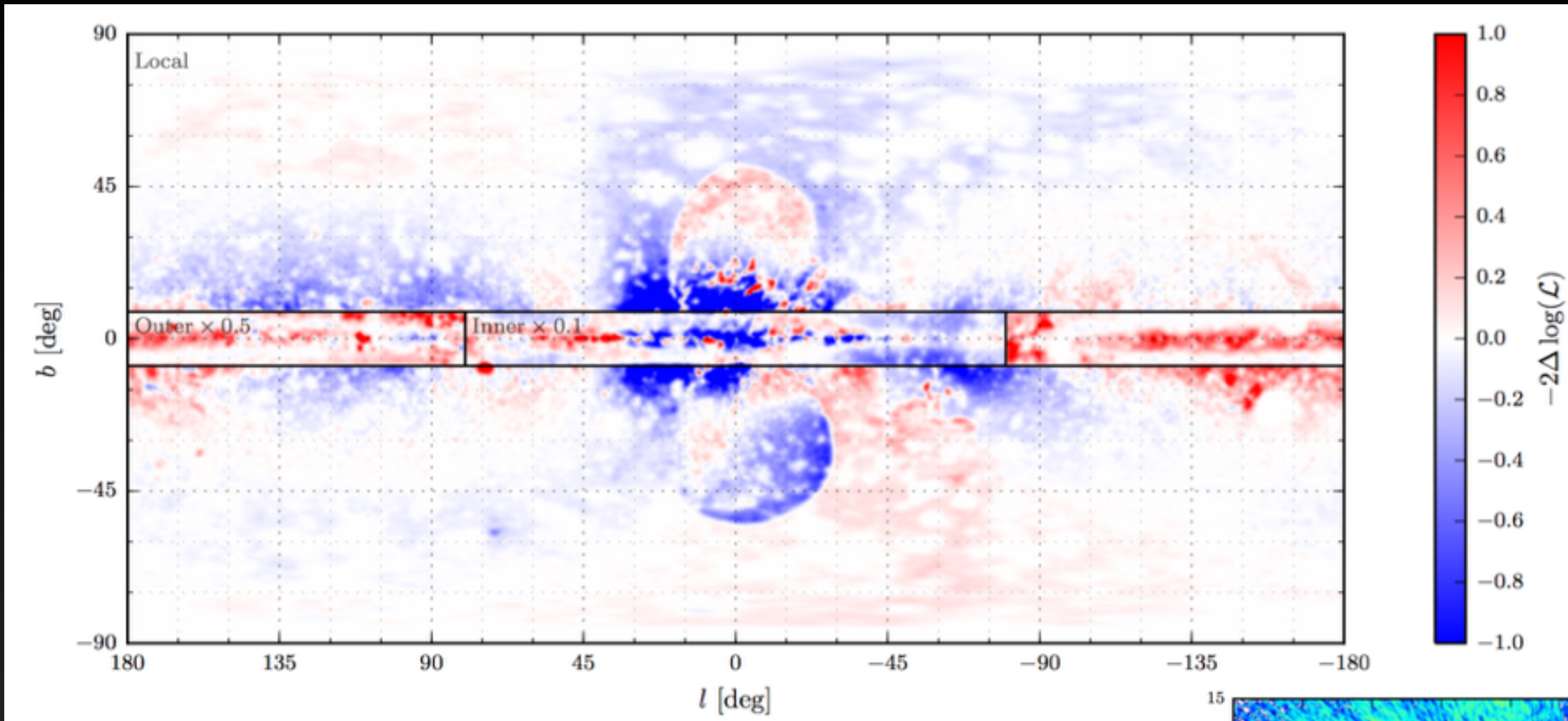
1.) The addition of a new cosmic-ray injection template tracing the 3D H_2 density greatly improves the overall fit to the gamma-ray diffuse emission.

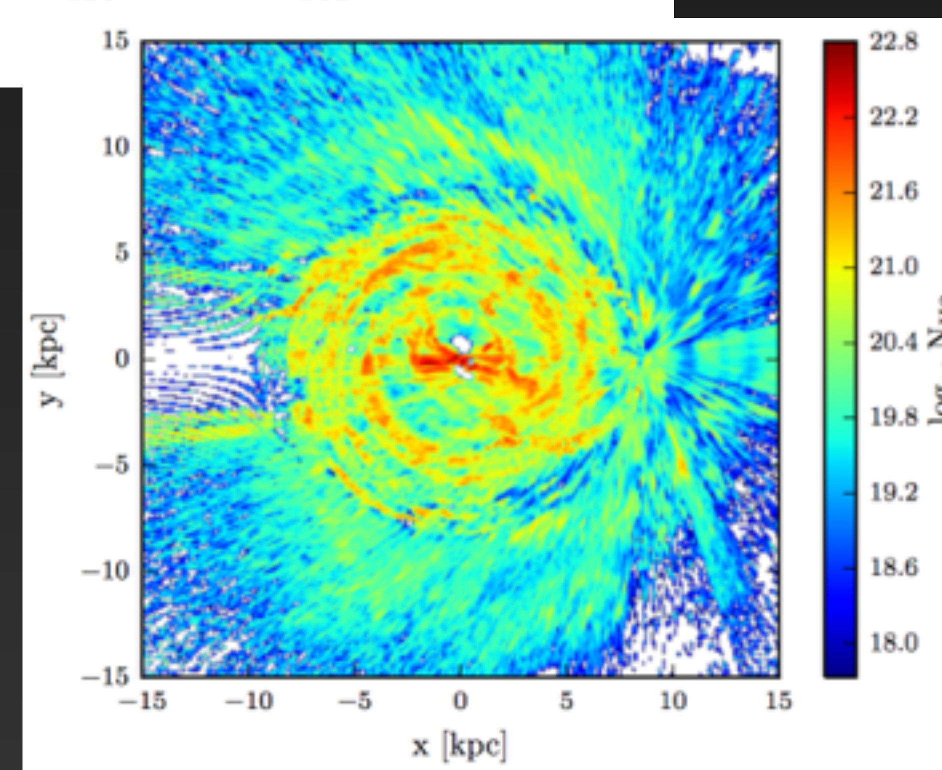


2.) This is an important point on its own, as it offers a new method for improving diffuse models for the gamma-ray sky.

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

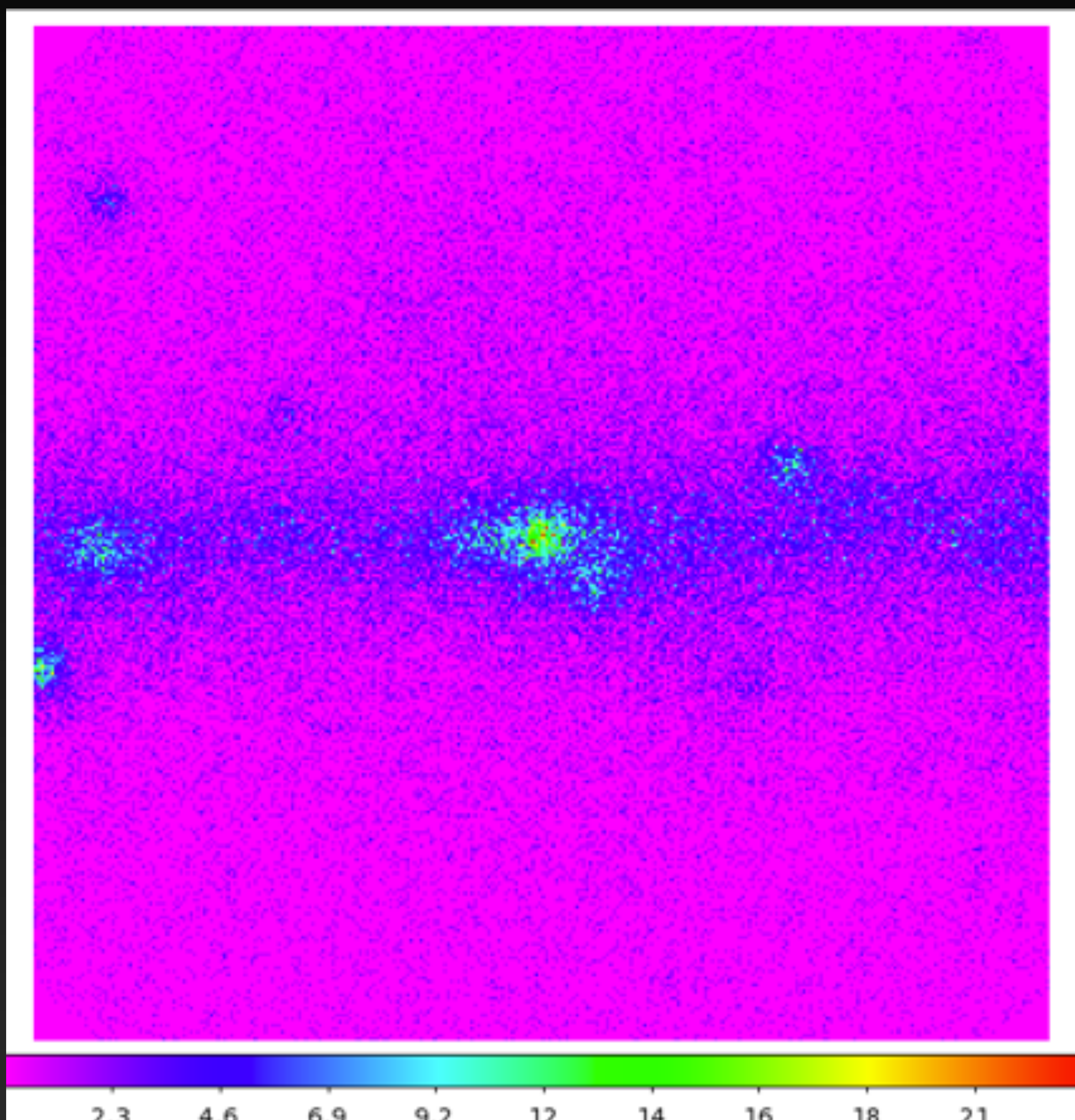
A Better fit to the Gamma-Ray Sky





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

Untangling the spider's web



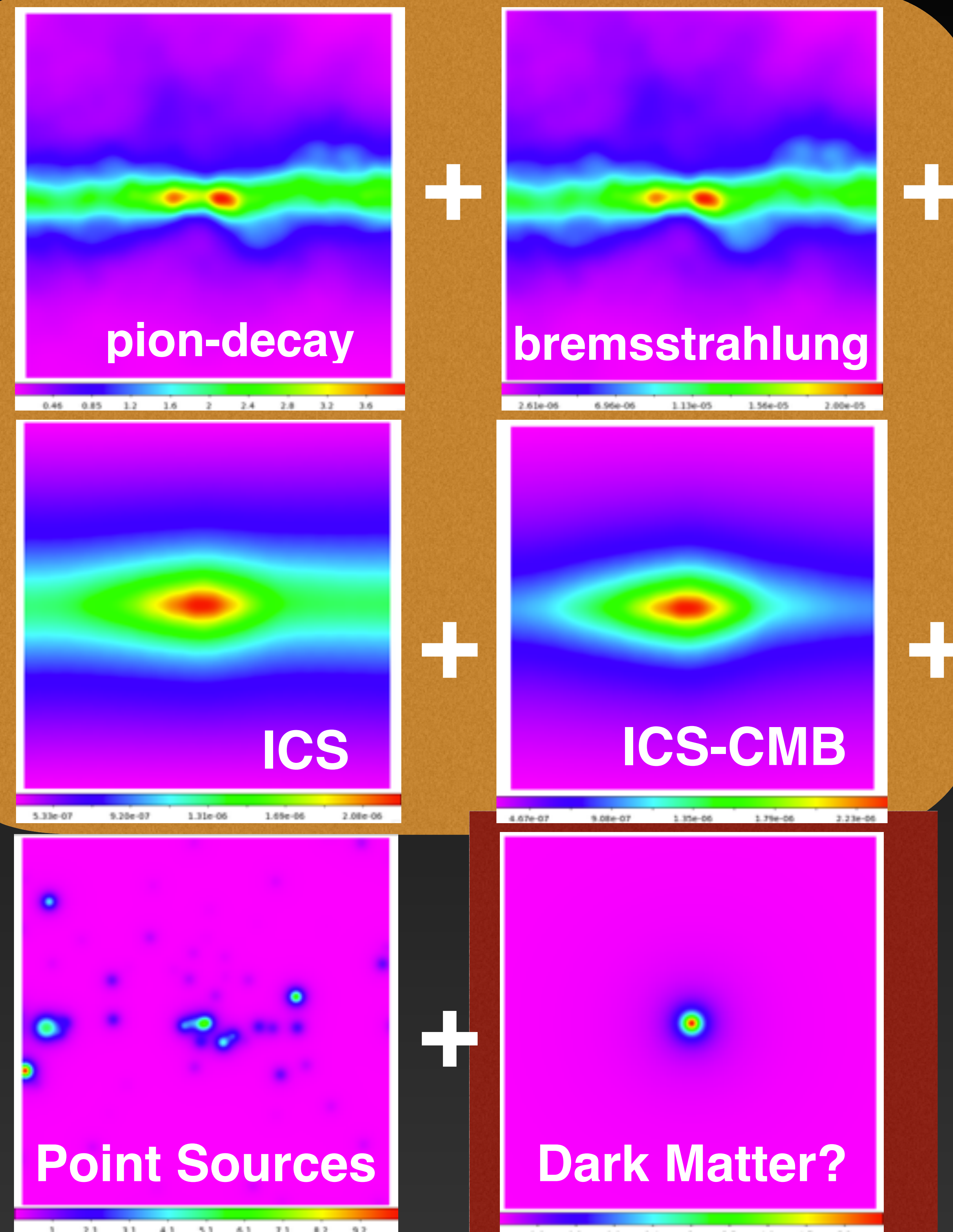
Data

750 — 950 MeV

Best Angular Resolution Cut

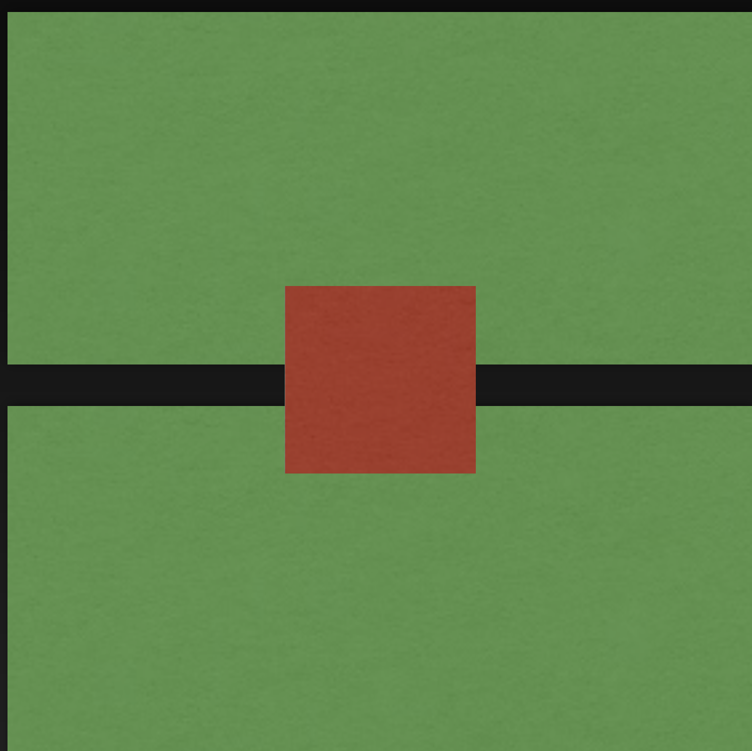
10° x 10° ROI

=



An Inner Galaxy Analysis of the GCE

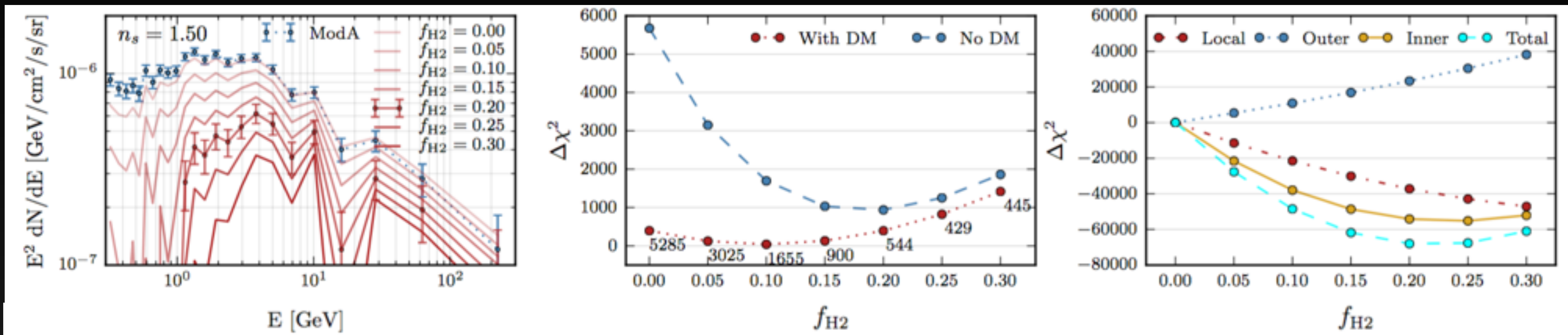
INNER GALAXY



- 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



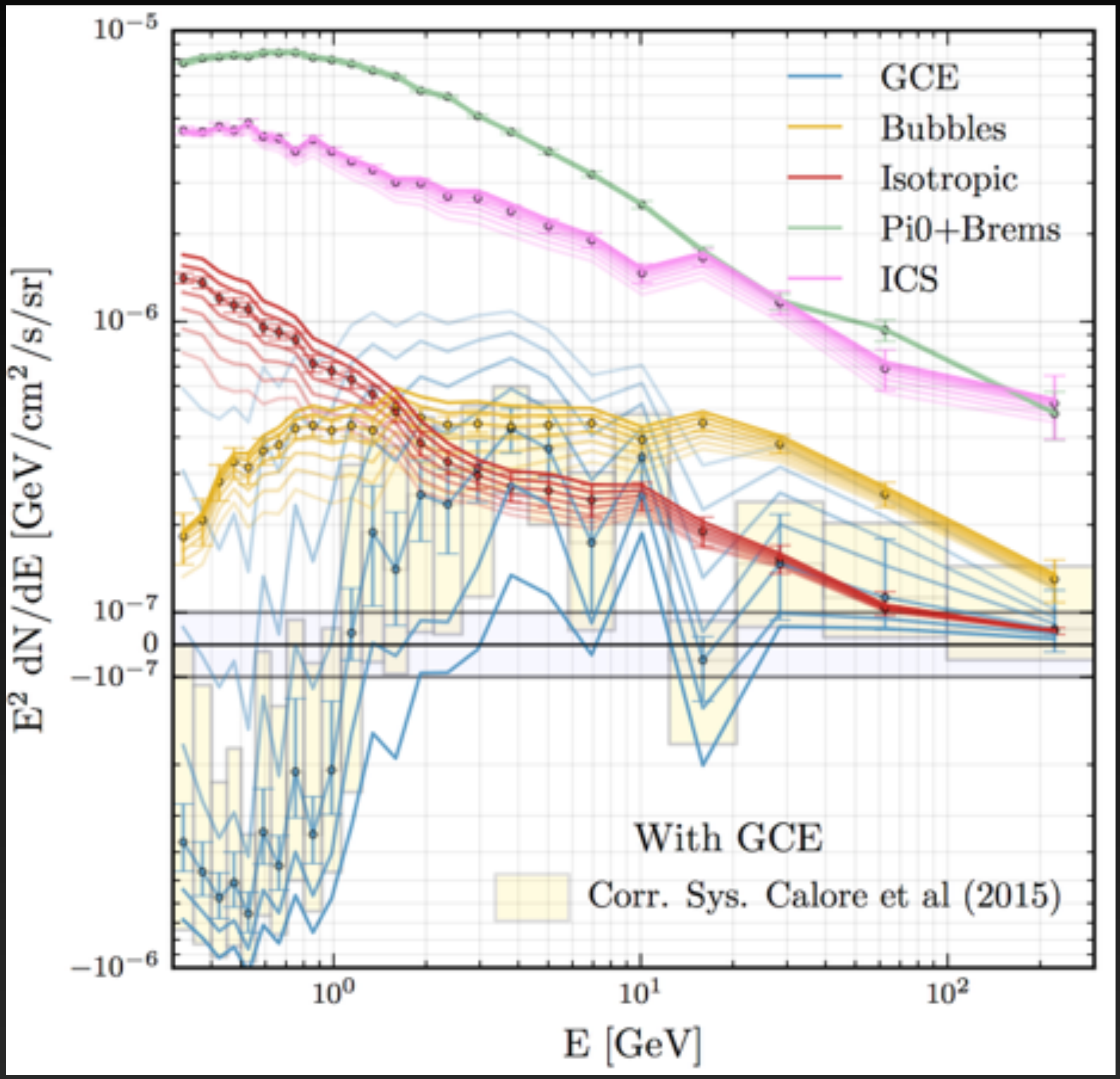
The inclusion of a diffuse emission template tracing the H2 density significantly decreases the intensity of the gamma-ray excess.

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%.

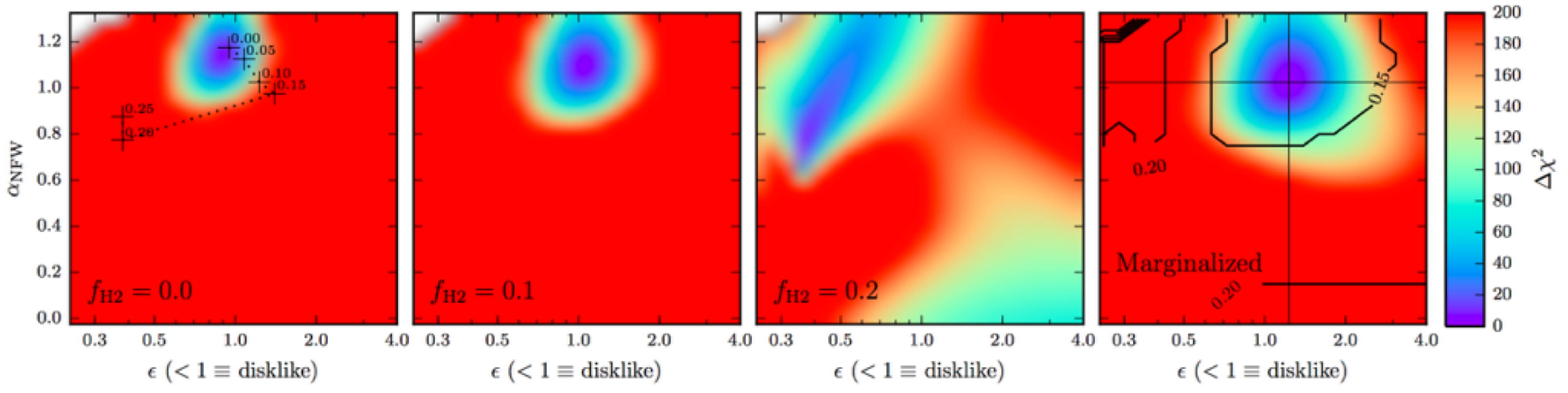
Effect on the Excess Spectrum

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

The spectrum becomes extremely hard as fH2 is increased, most likely indicating that the GCE template is picking up mismodeling of some residual.



Effect on the Excess Morphology



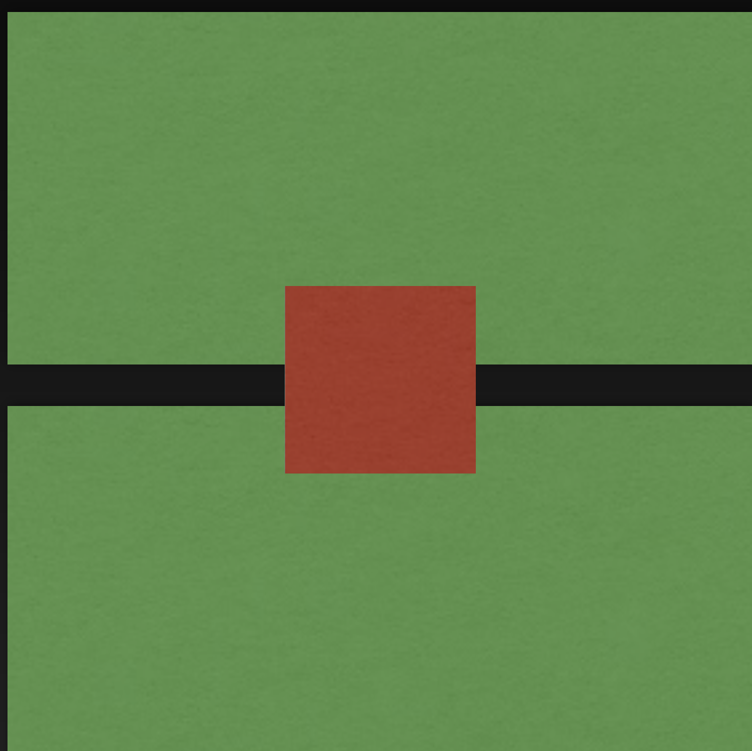
The morphology of the Gamma-Ray Excess is also degenerate with the value of f_{H2}.

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

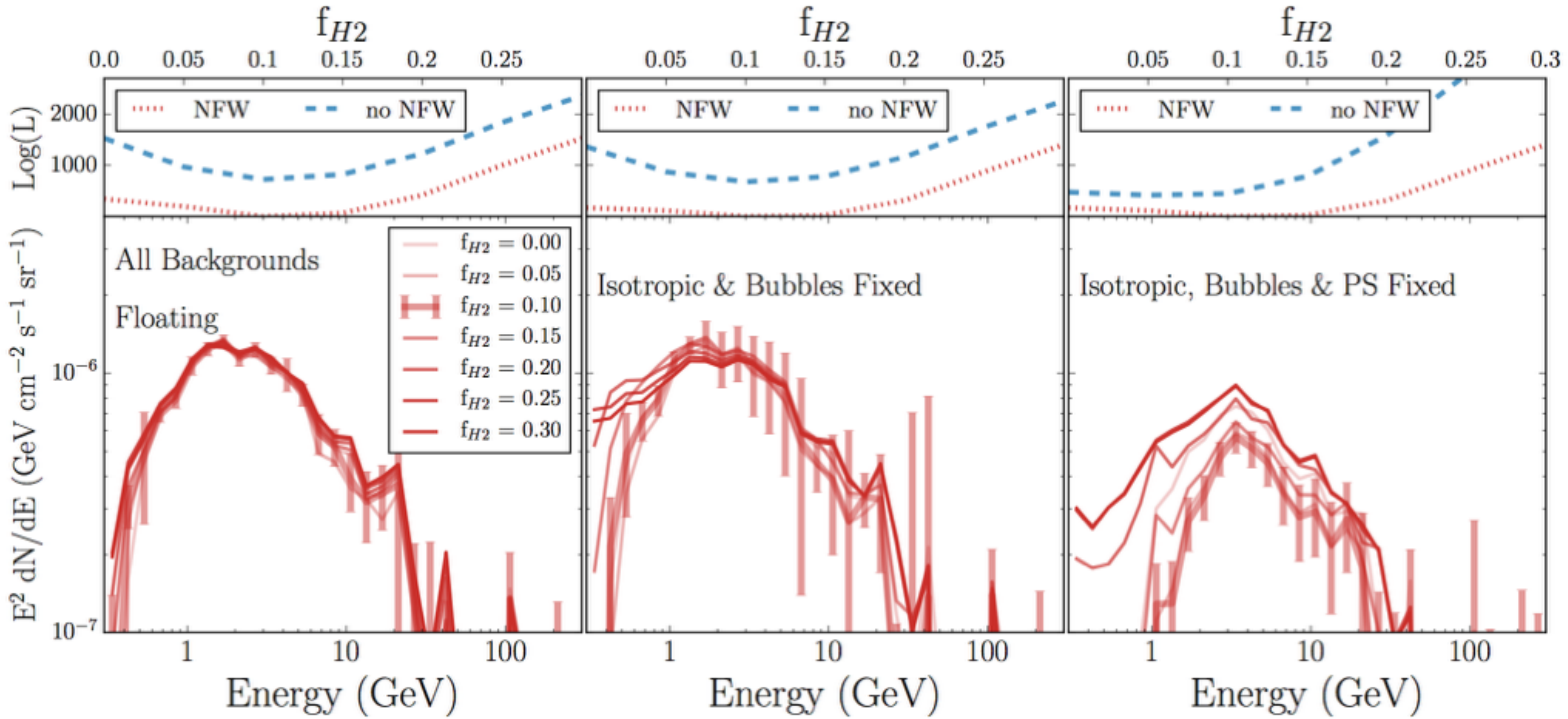
GALACTIC CENTER



- 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.

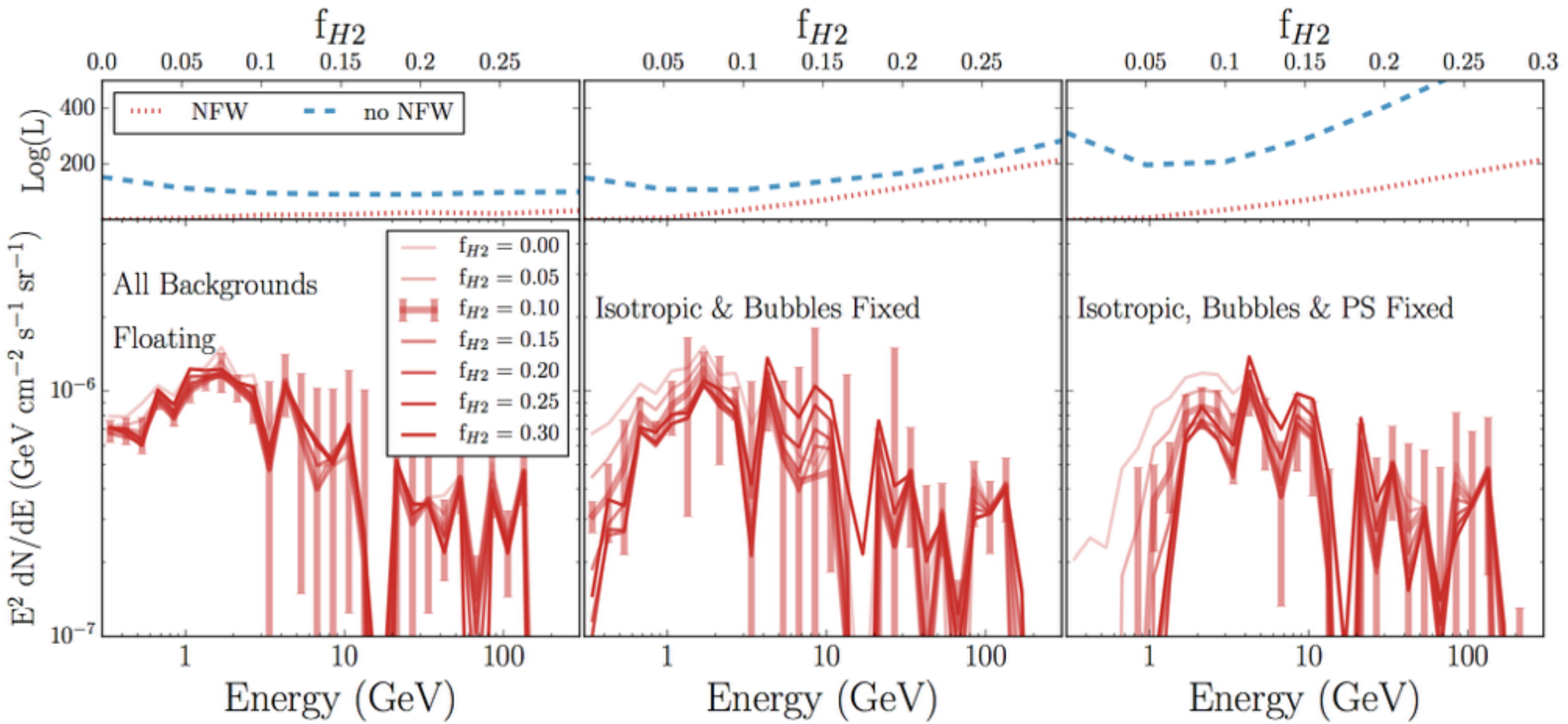
This creates an analysis with no sidebands region, where the NFW template normalization plays a critical role in determining the spectrum and normalization of diffuse components.

The Effect on the Galactic center Excess



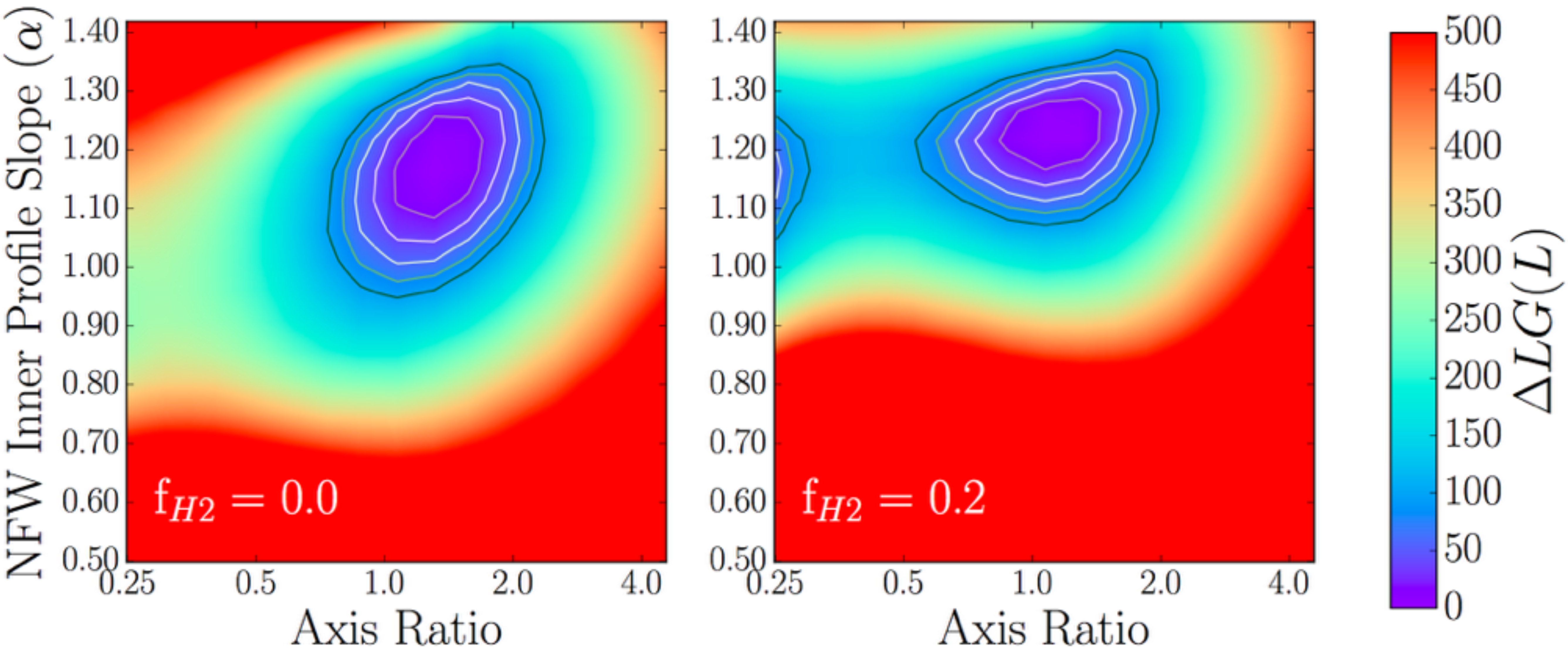
In this smaller region, the excess remains resilient to changes in diffuse emission modeling.

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



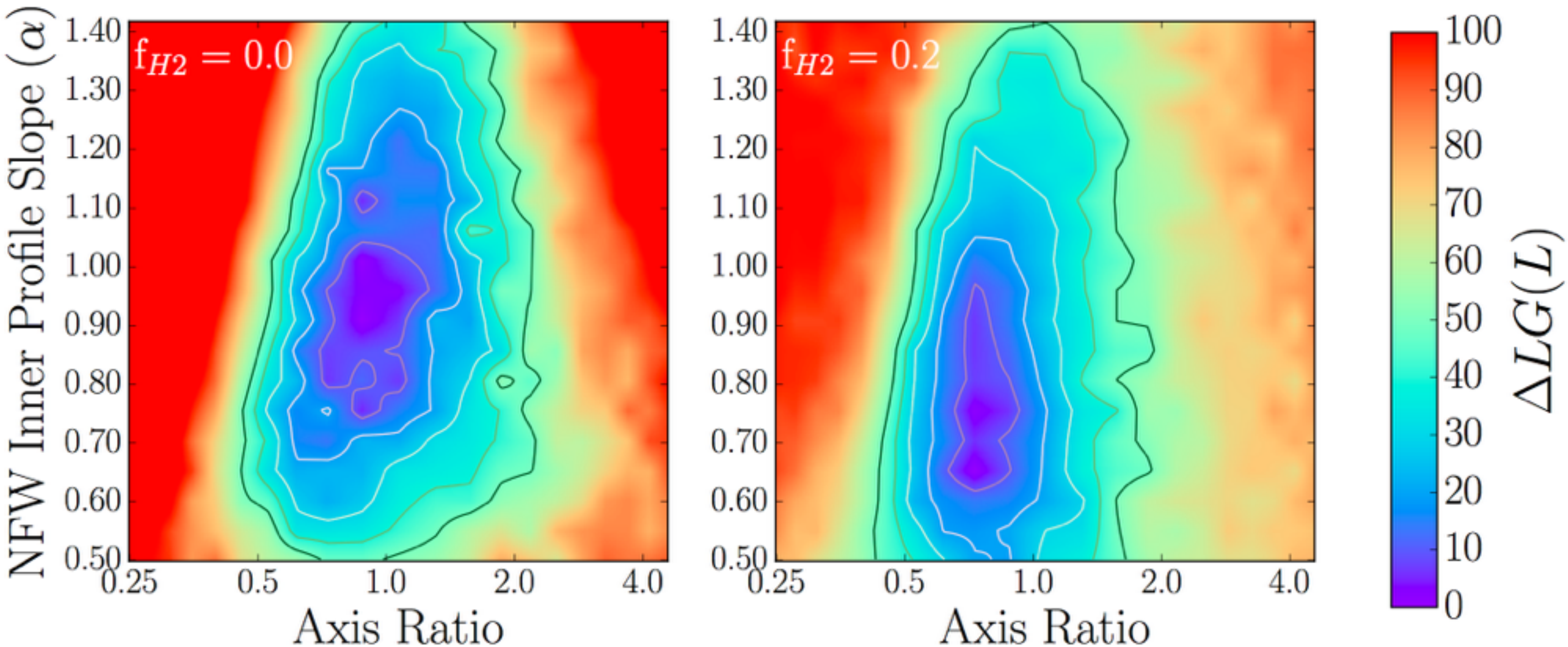
Intriguingly, this persists even when the inner 2º are masked - implying that analyses of small ROIs favors the excess.

The Galactic Center Excess Morphology



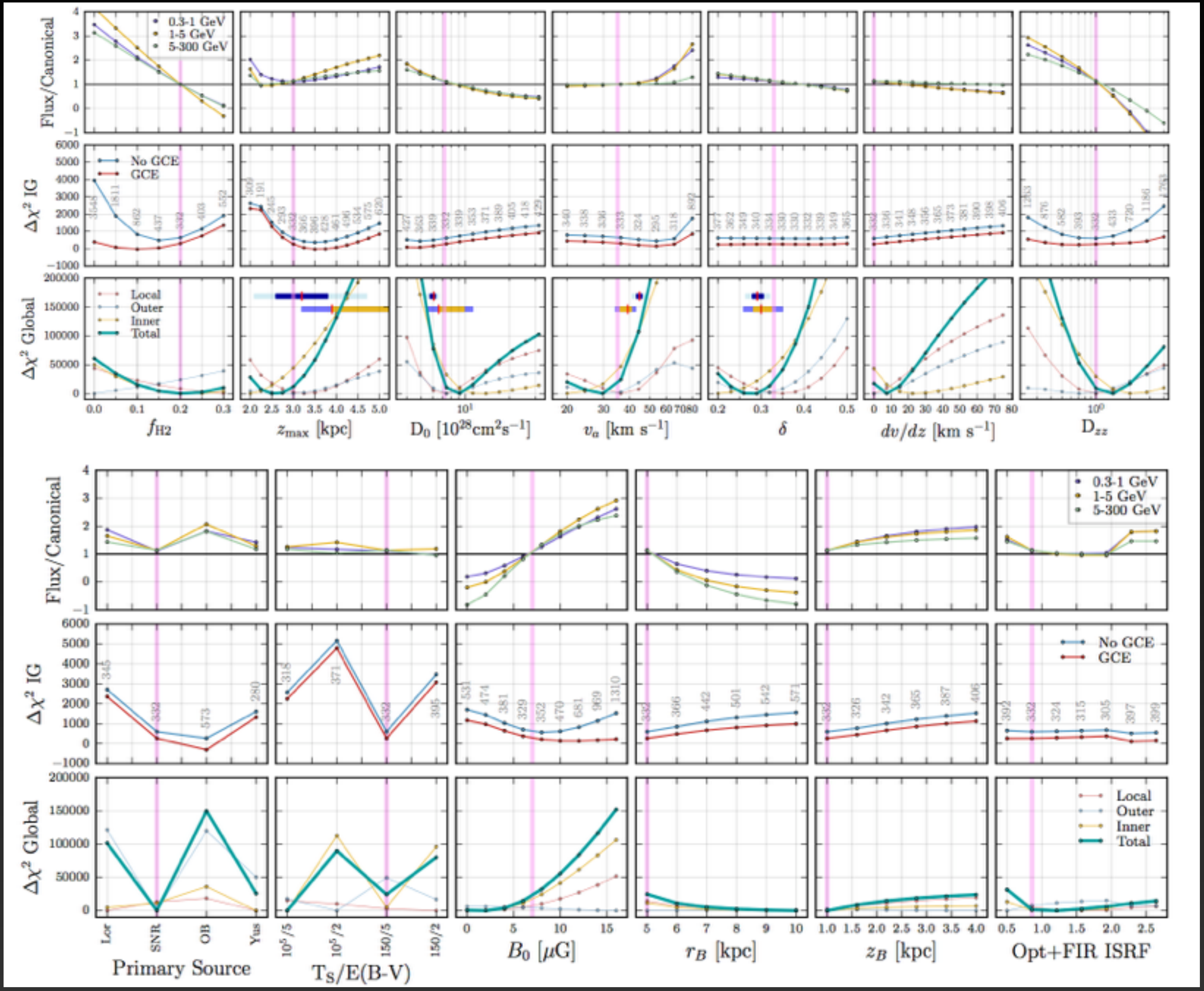
For the Galactic Center analysis, the morphology of the excess component remains relatively robust

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

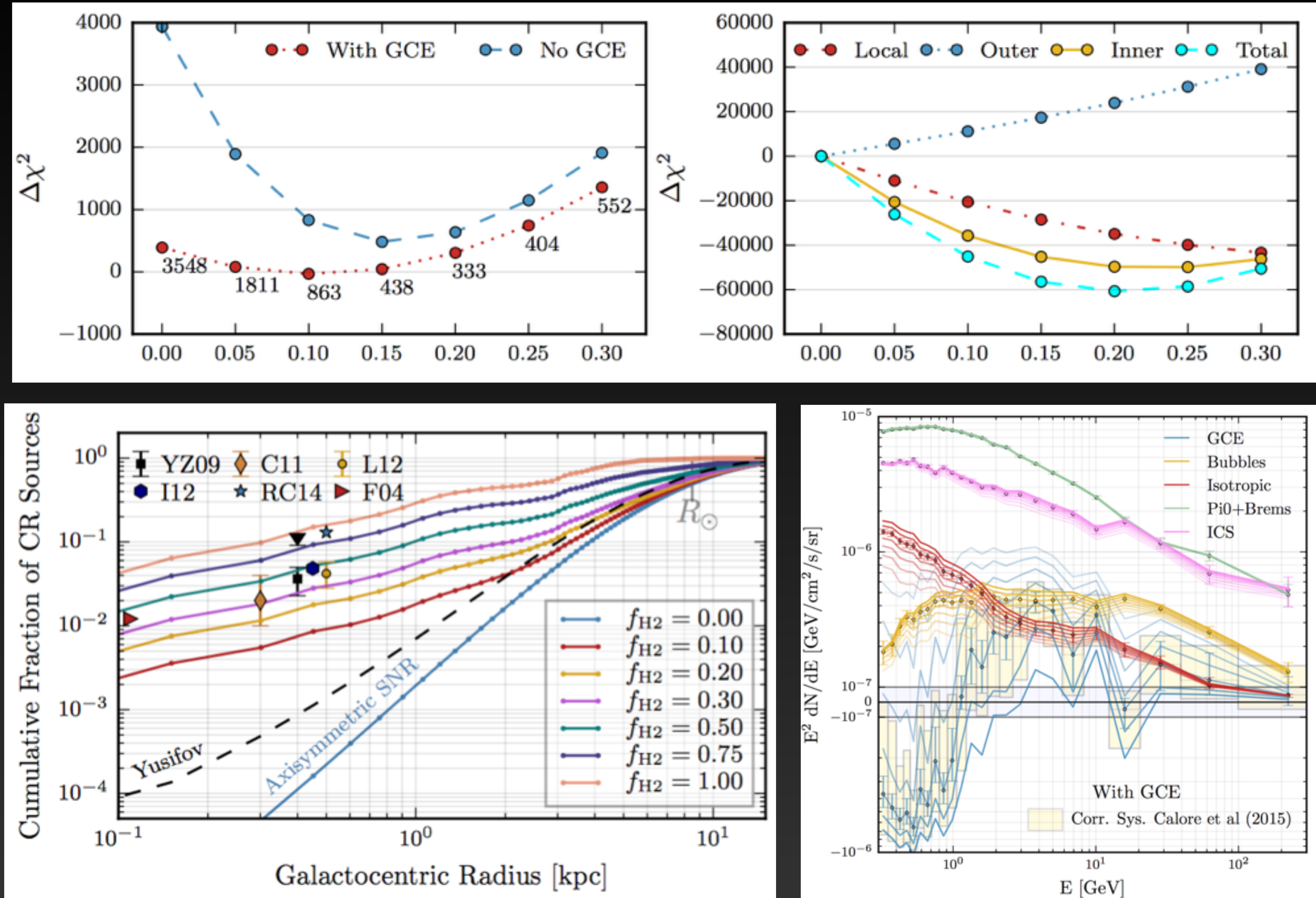


The deviations from typical NFW profiles are more extreme when the |b| < 2º is masked from the analysis, with a shallower emission profile preferred by the data.

Galactic center excess is resilient to many other parameters….



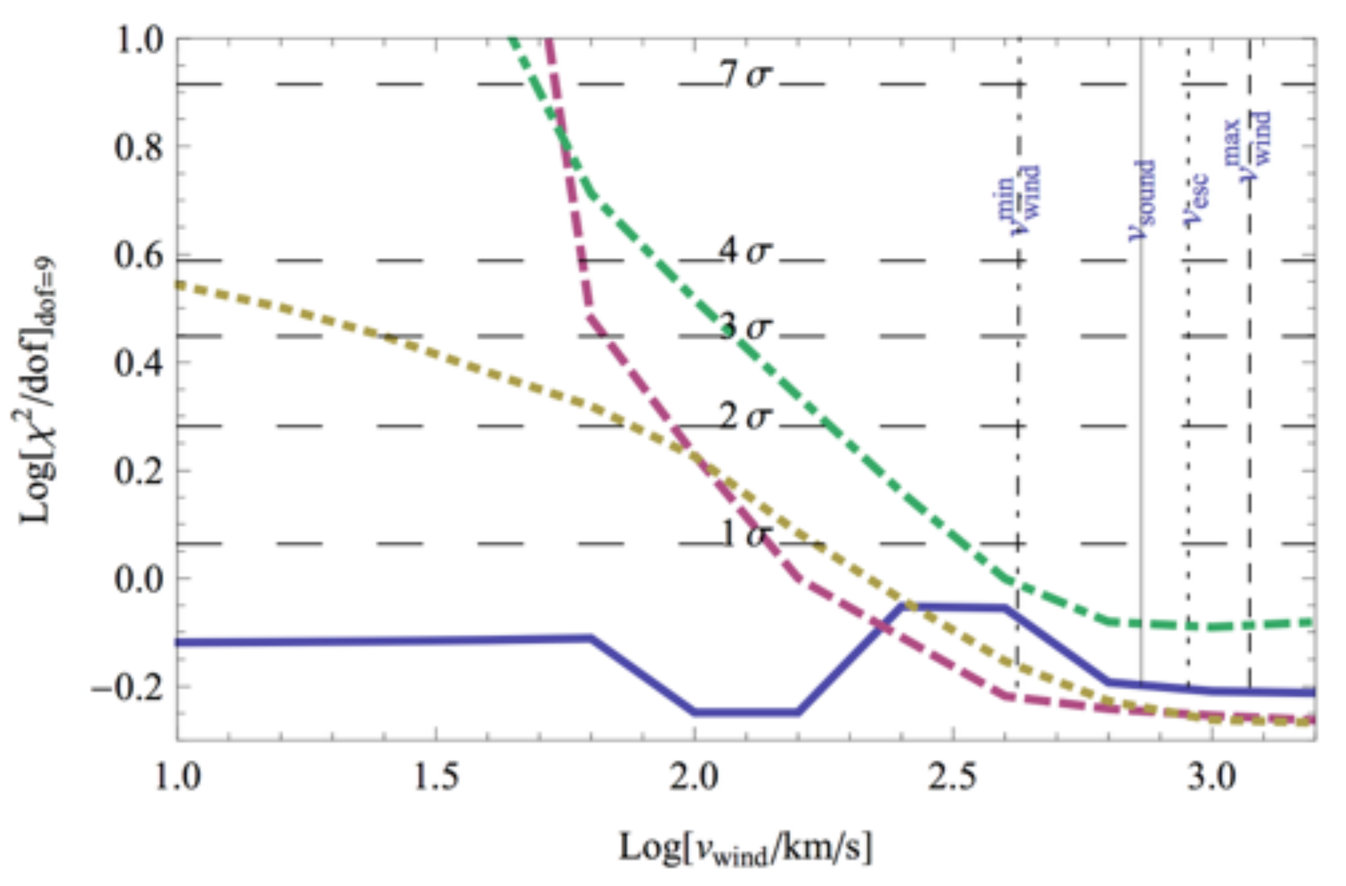
The Galactic Center Deficit?

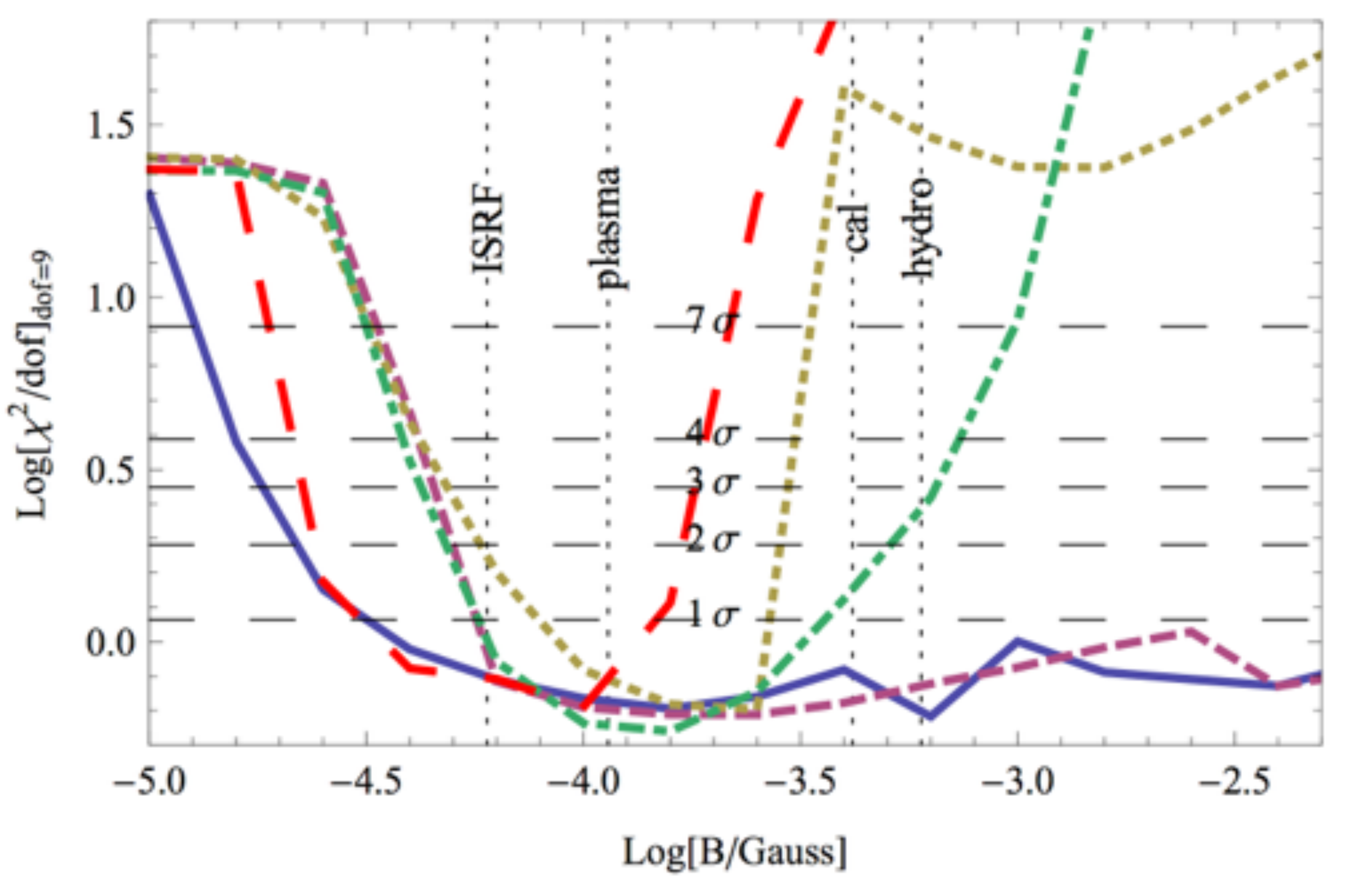


Advection and Convection in the Galactic Center

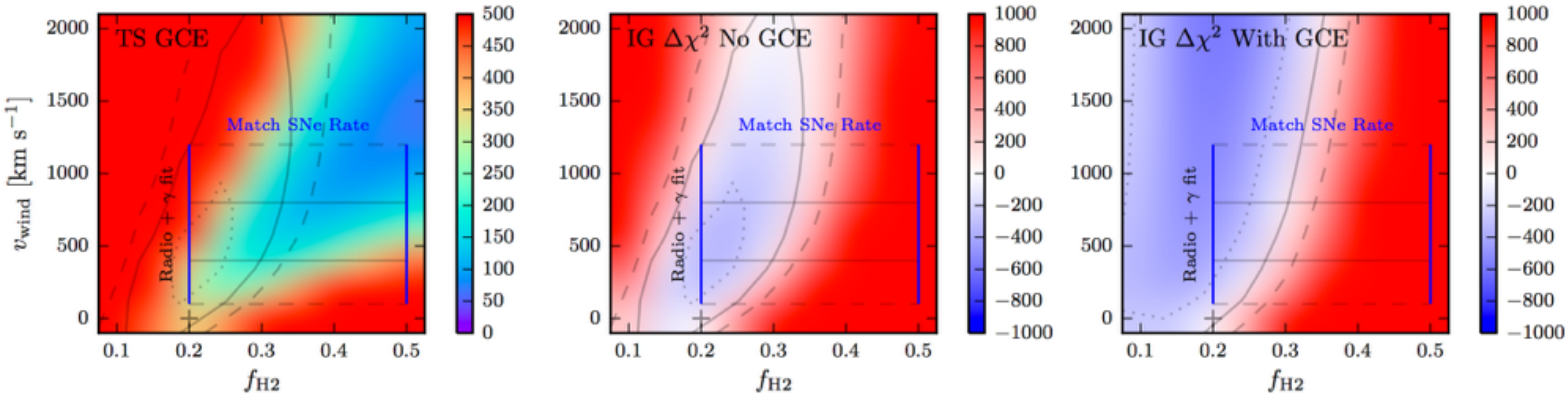
Crocker et al. (2011) demonstrated that the break in the GC synchrotron spectrum is best fit in the regime with:

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





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.

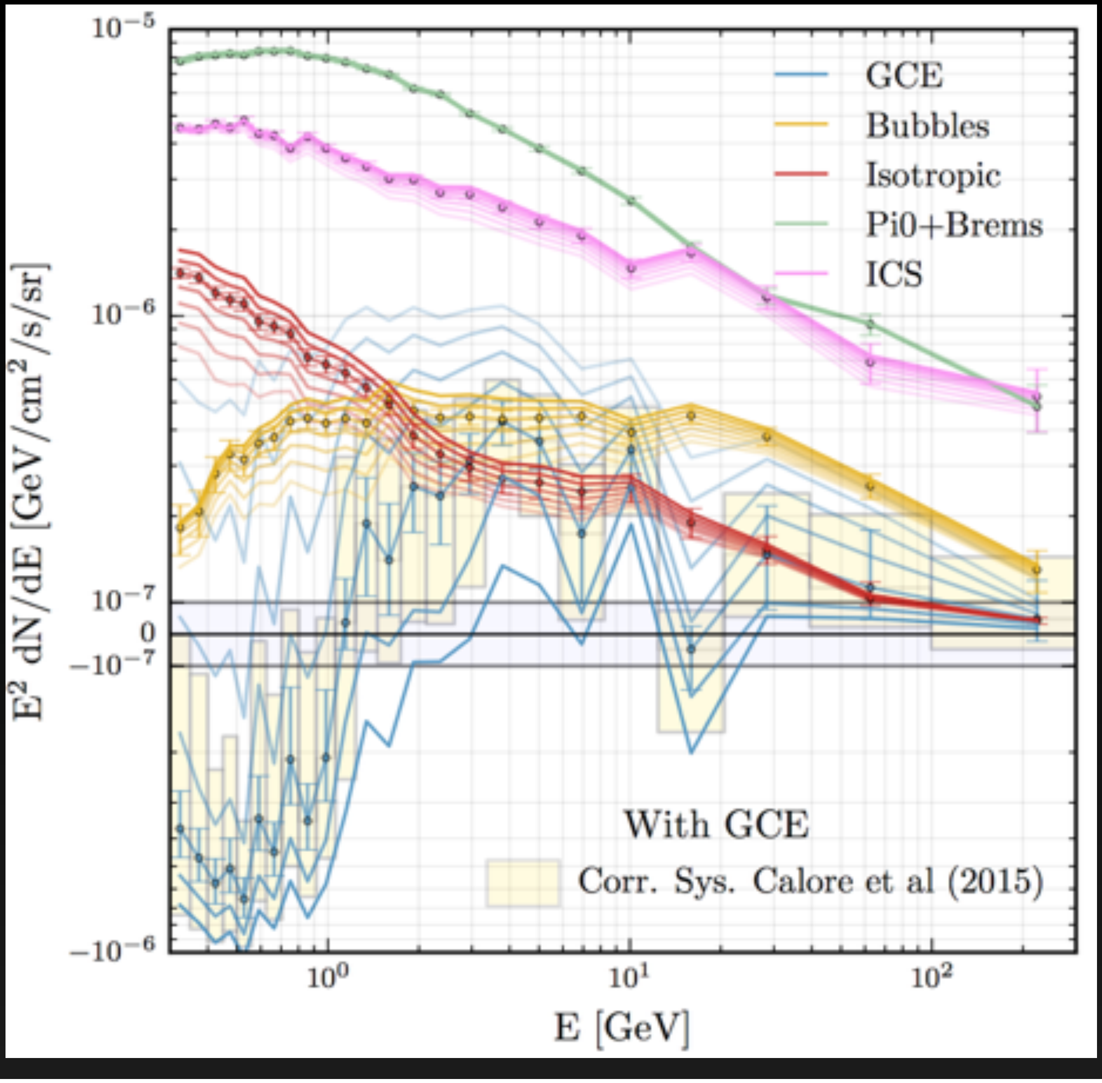
Models with a GCE component still prefer slightly lower values of f_{H2}, but these have increased to 0.2 as well.

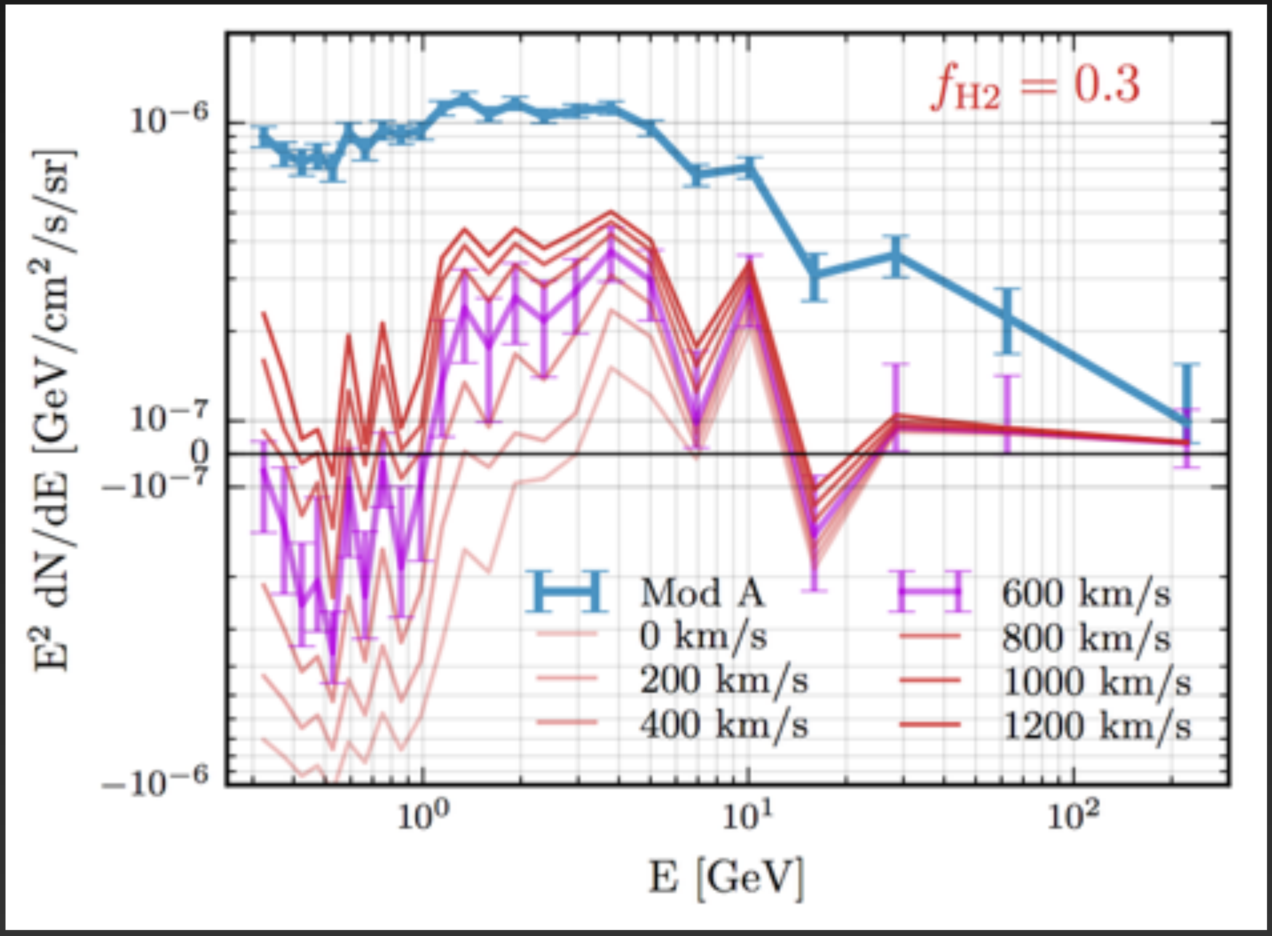
The Low Energy Spectrum

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

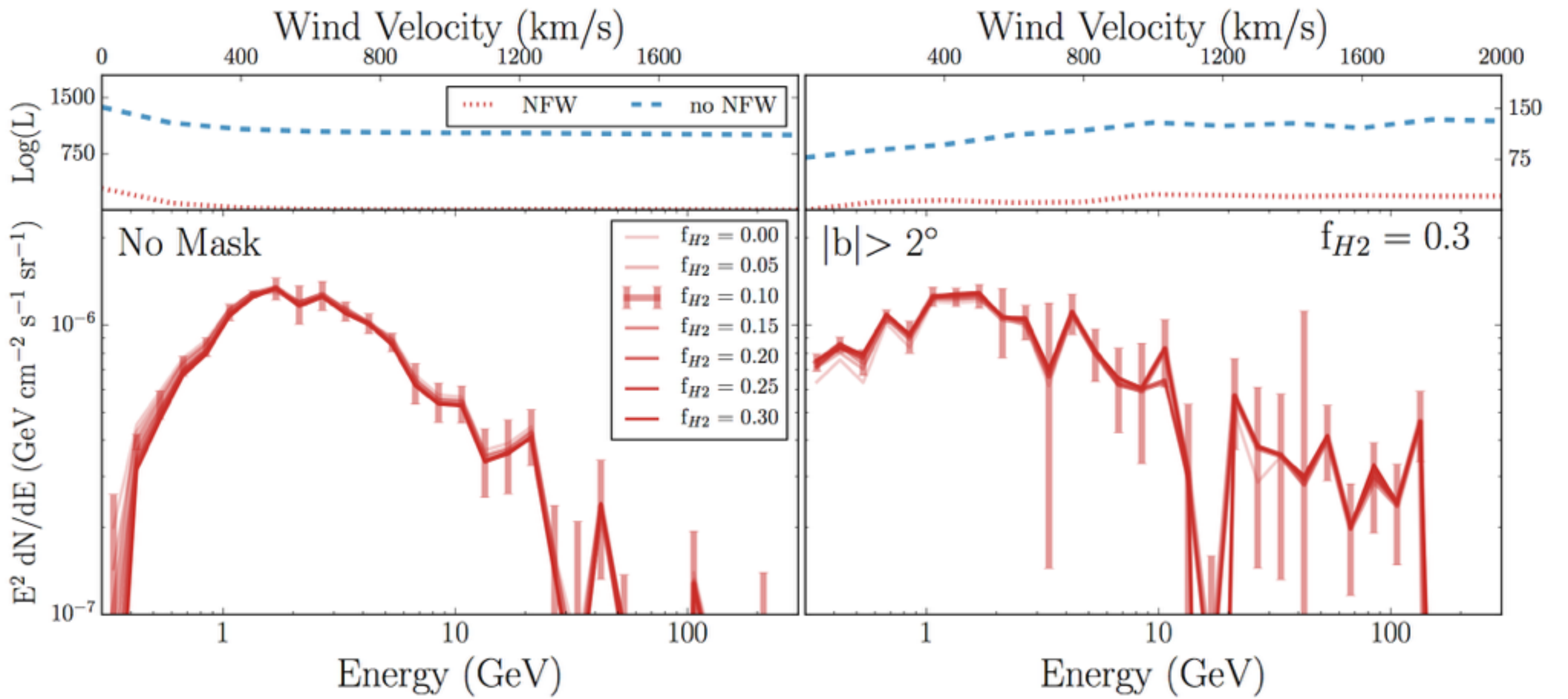
Advective energy losses most important for low-energy cosmic-rays, decreases the astrophysical contribution < 1 GeV.

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



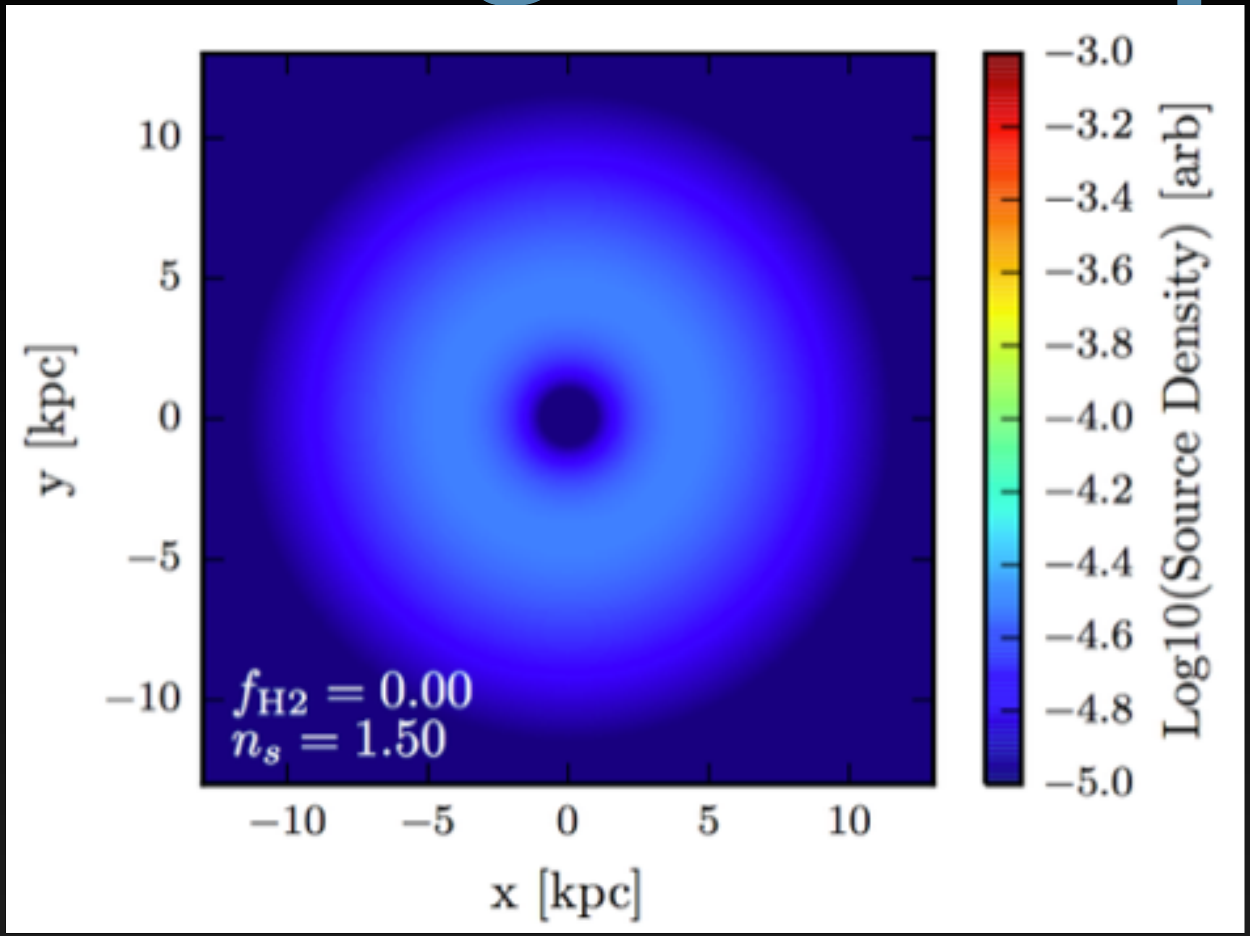


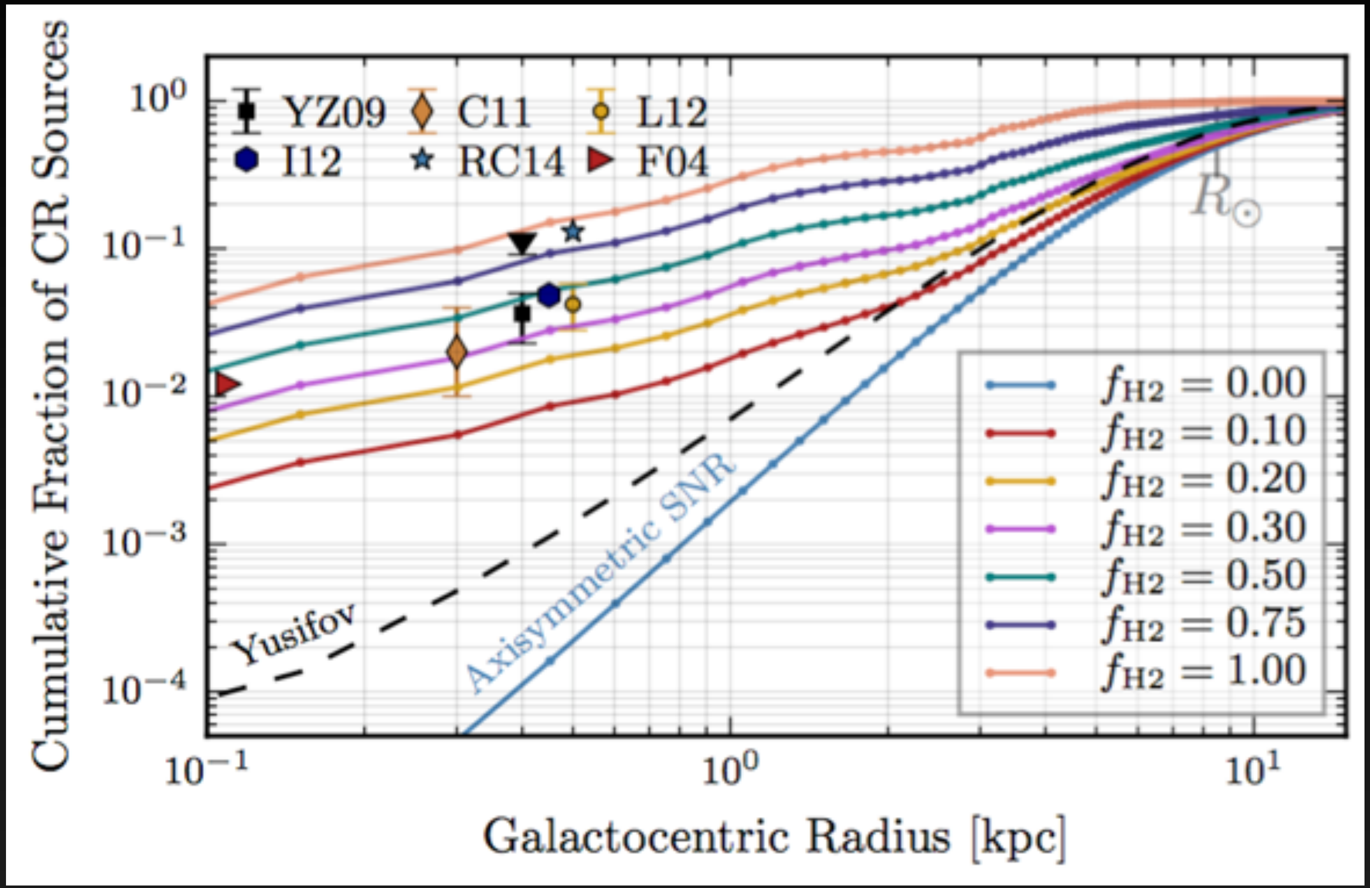
The Low Energy Spectrum



The 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.

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.

Approaching 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 ROI. In signal dominated regions the NFW template produces significant emission, while in side-bands dominated regions, the excess is diminished.

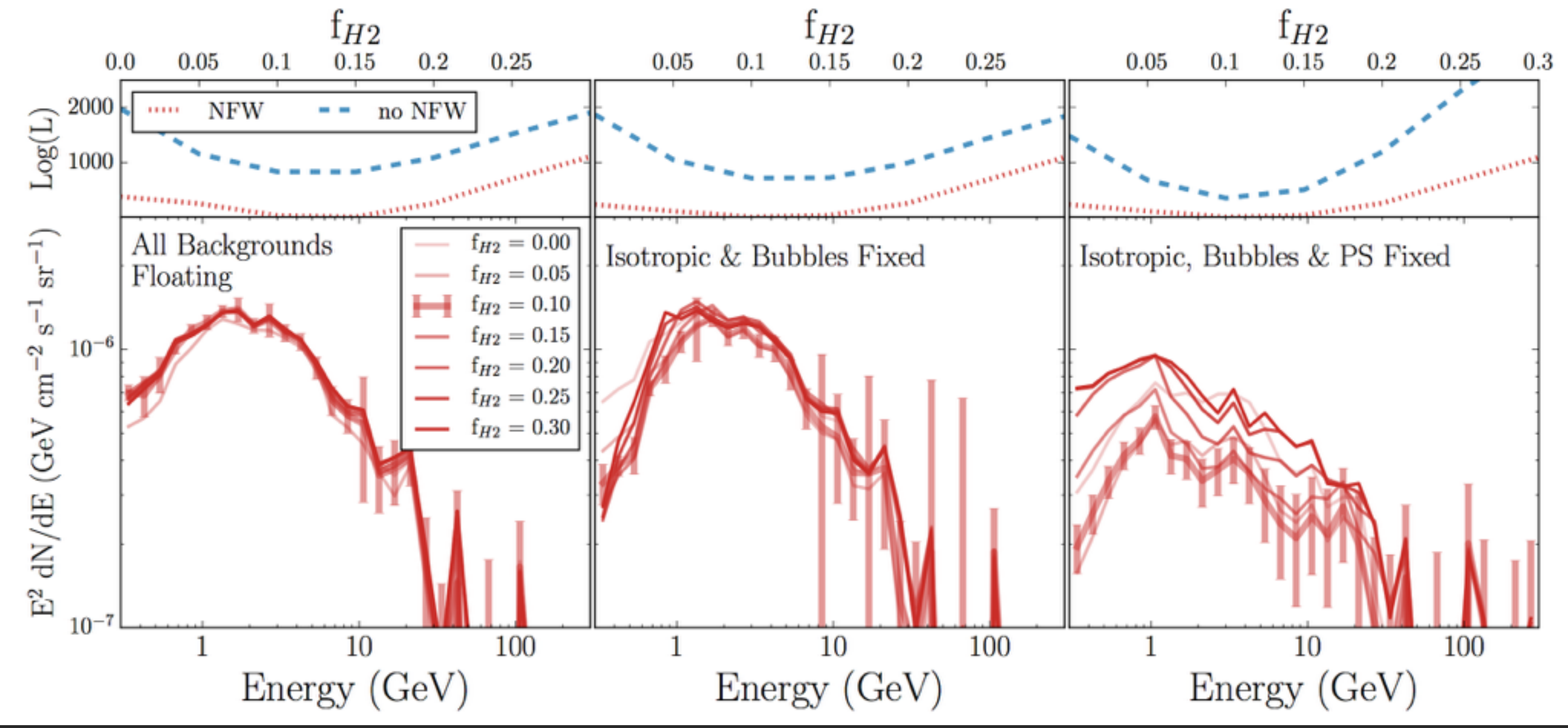
3.) For a preferred value of $f_{H2} \sim 0.1$, the morphology of the excess is significantly altered, producing a slightly elliptical morphology.

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.

arXiv: 1510.04698 1603.06584

Extra Slides

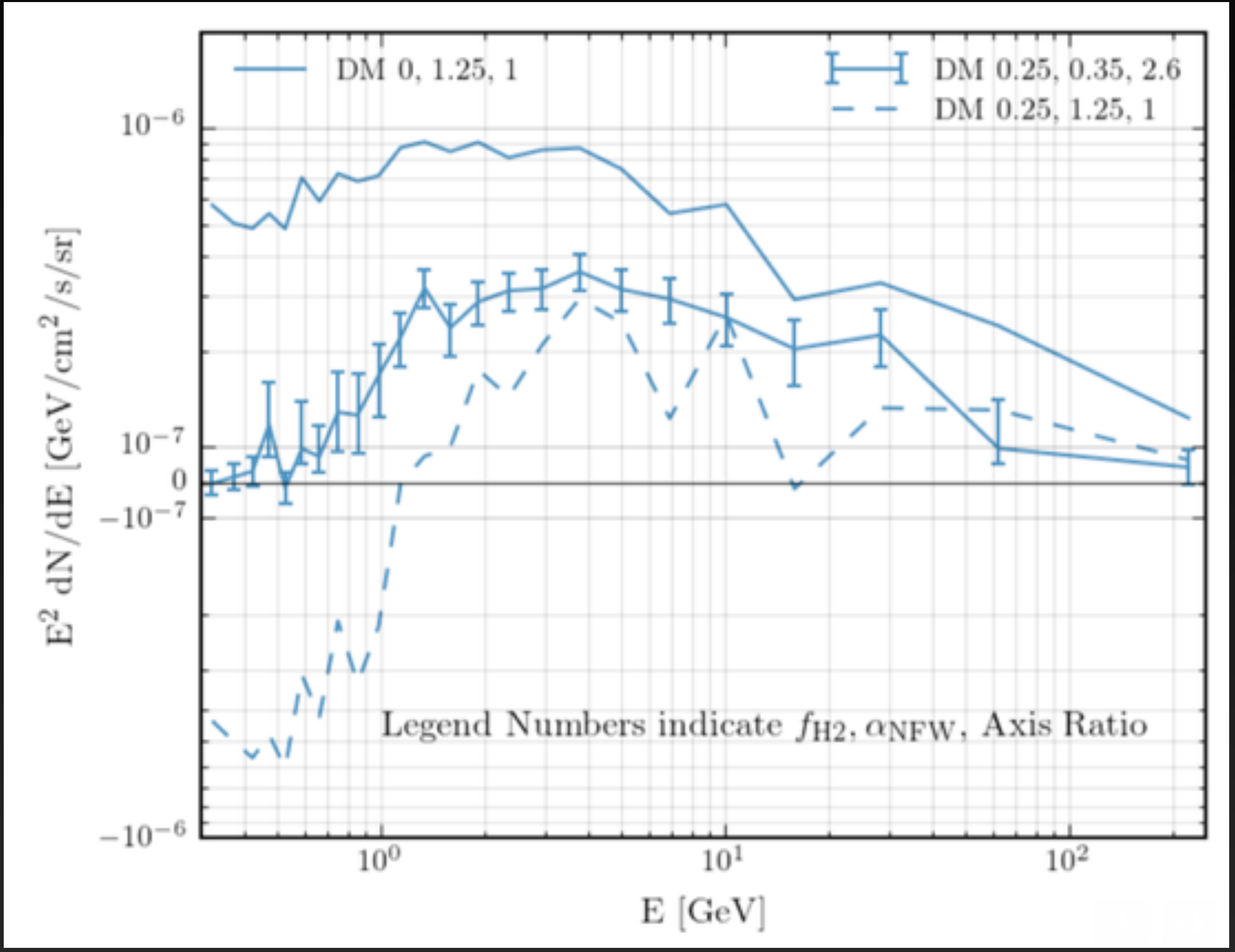
Masking 1FIG Sources in the GC



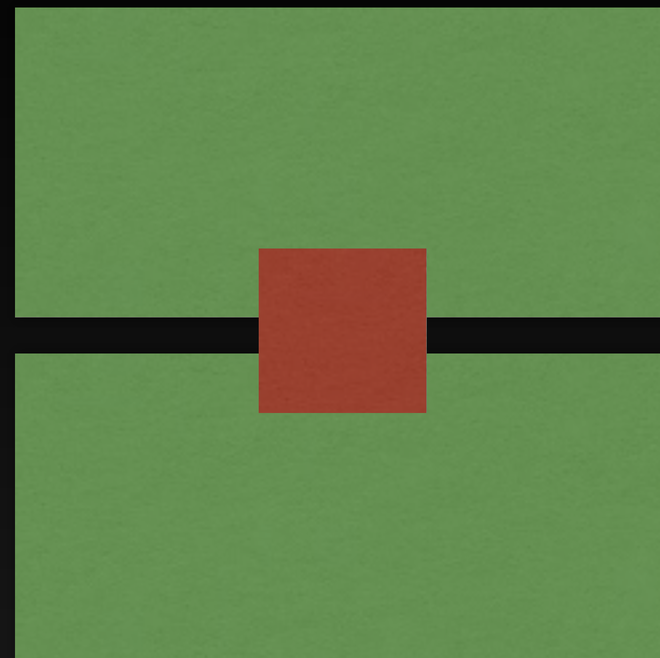
A Fermi Bubbles Component?

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



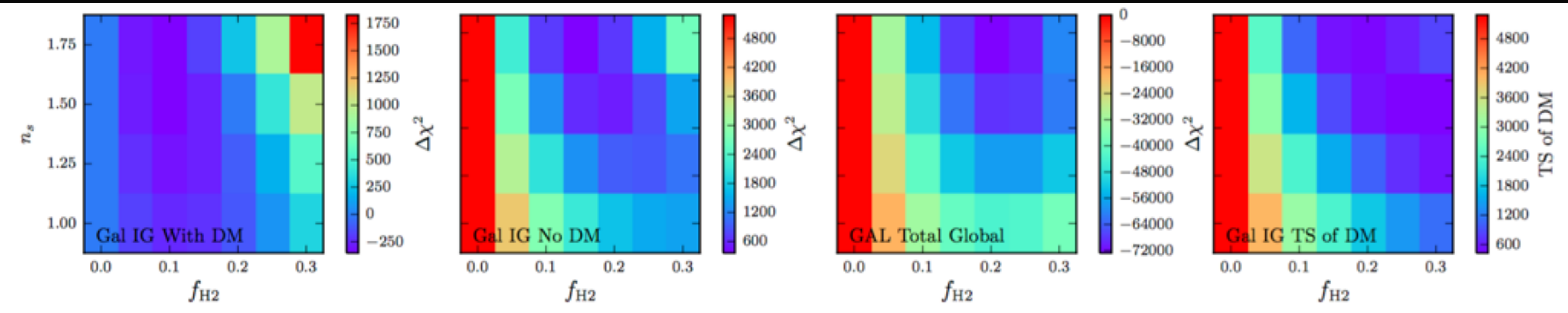
INNER GALAXY

- Mask galactic plane (e.g. $|b| > 1^{\circ}$), 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

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.

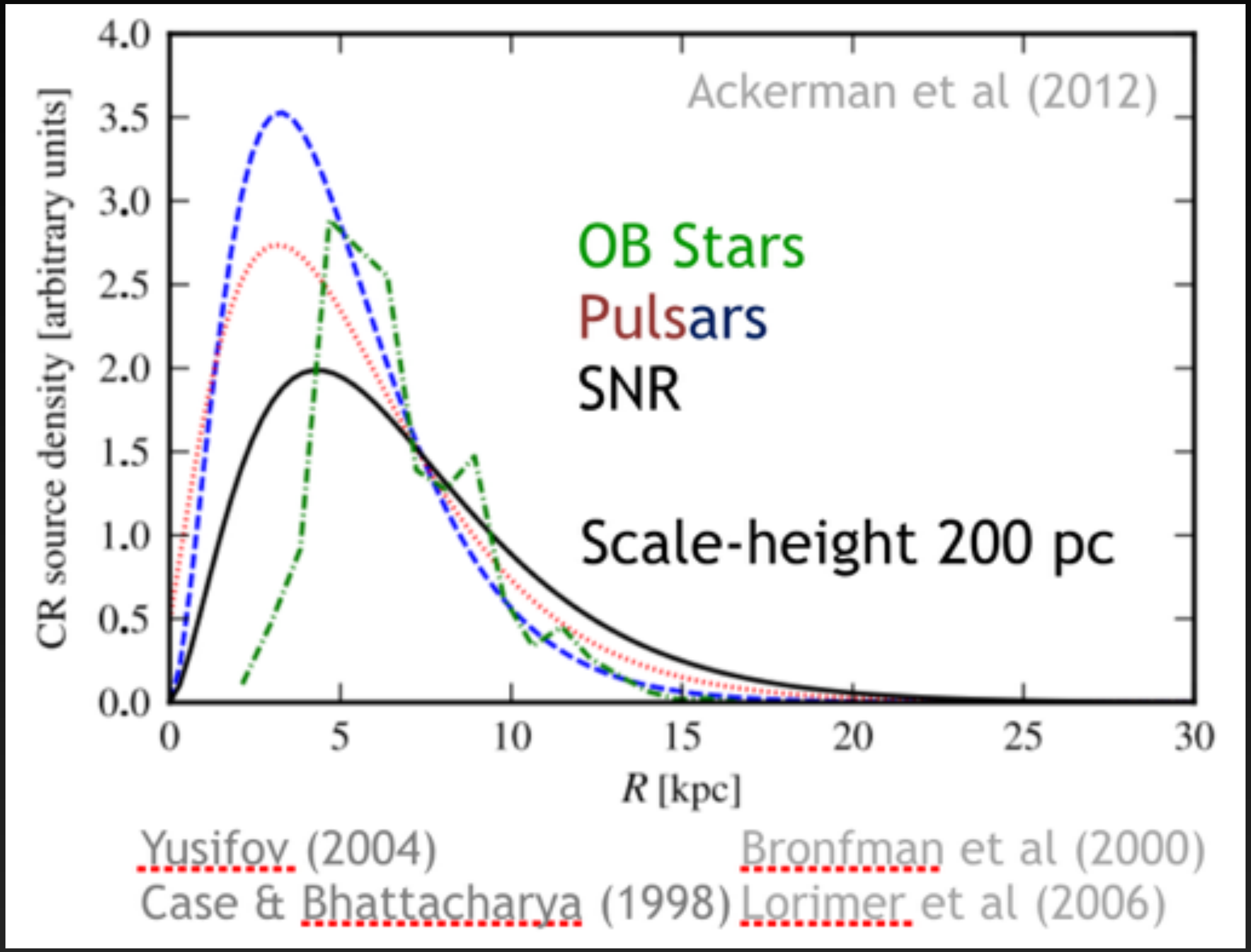
The reduction in the normalization of the NFW template is ~1.5 for f_{H2} ~ 0.1, instead of a factor of 3 at f_{H2} ~ 0.2.

Cosmic-Ray Injection in the GC

Why Is this Done?

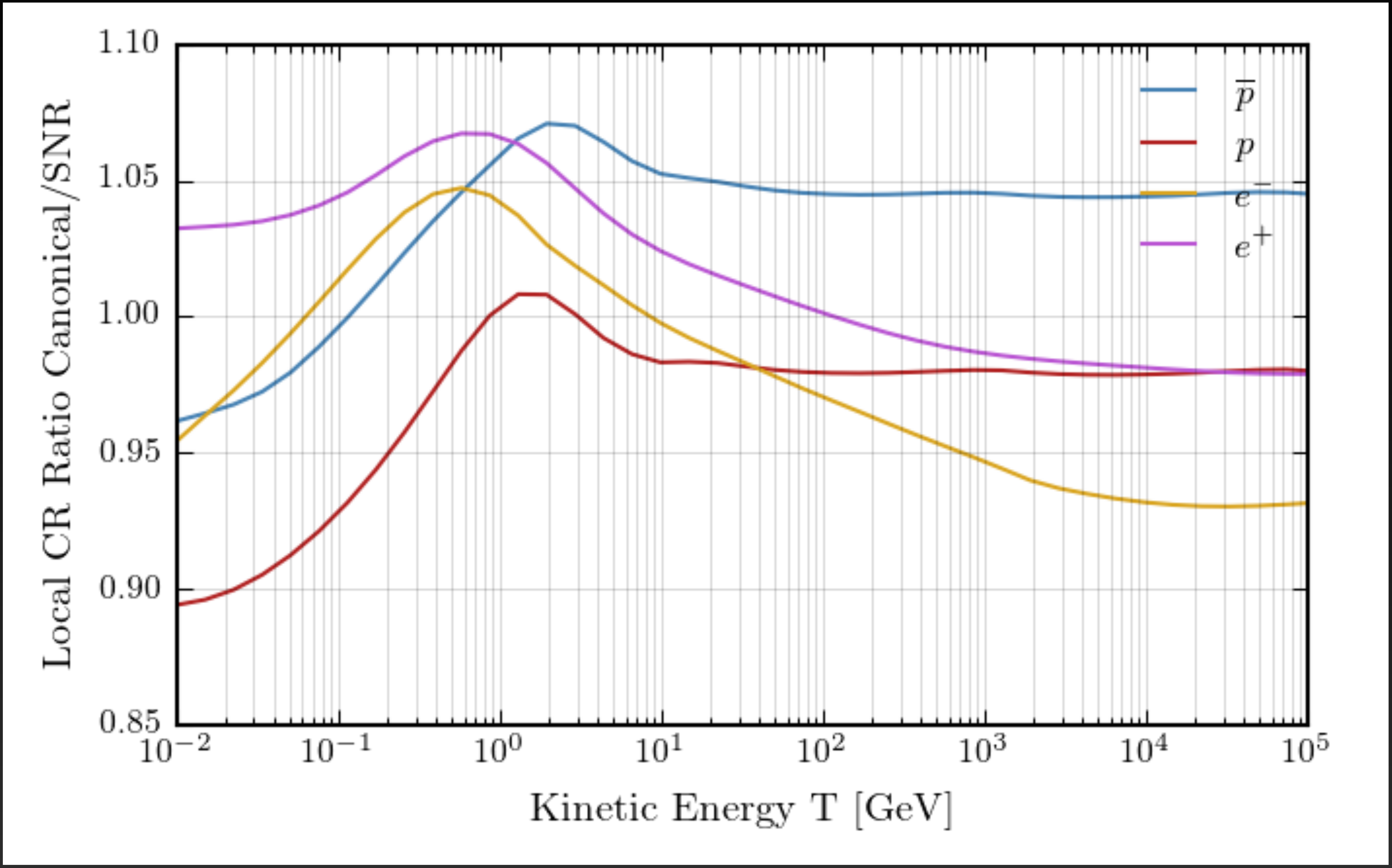
1.) Want to fit a simple analytic form to a profile that peaks at 4 kpc.

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

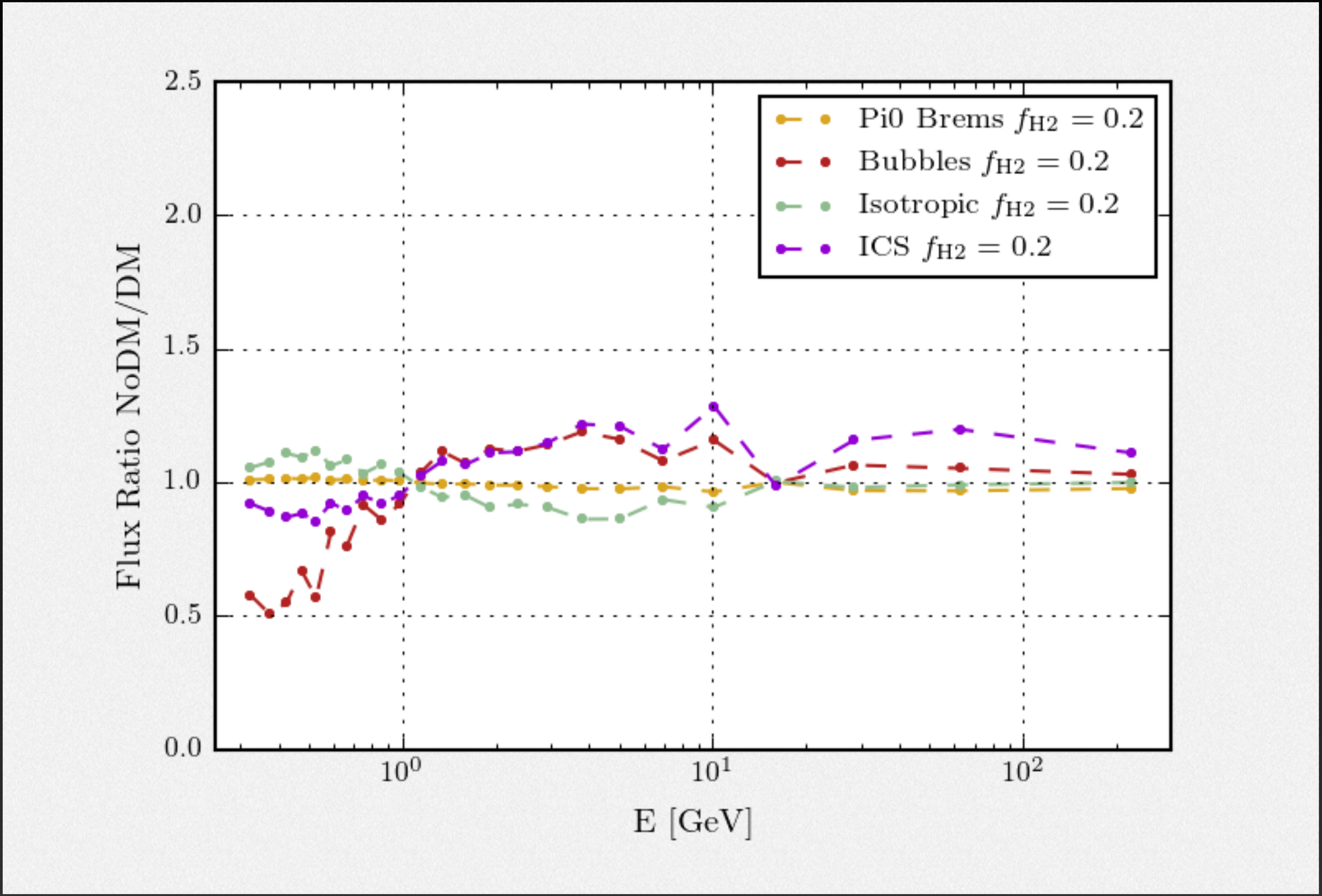


3.) Model of GC is unimportant for cosmic-ray propagation studies.

Local Cosmic-Ray Flux



Changes in IG Spectra



Changes in IG Spectra