

What is the Source of the Galactic Center Gamma-Ray Excess?

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The Ohio State University



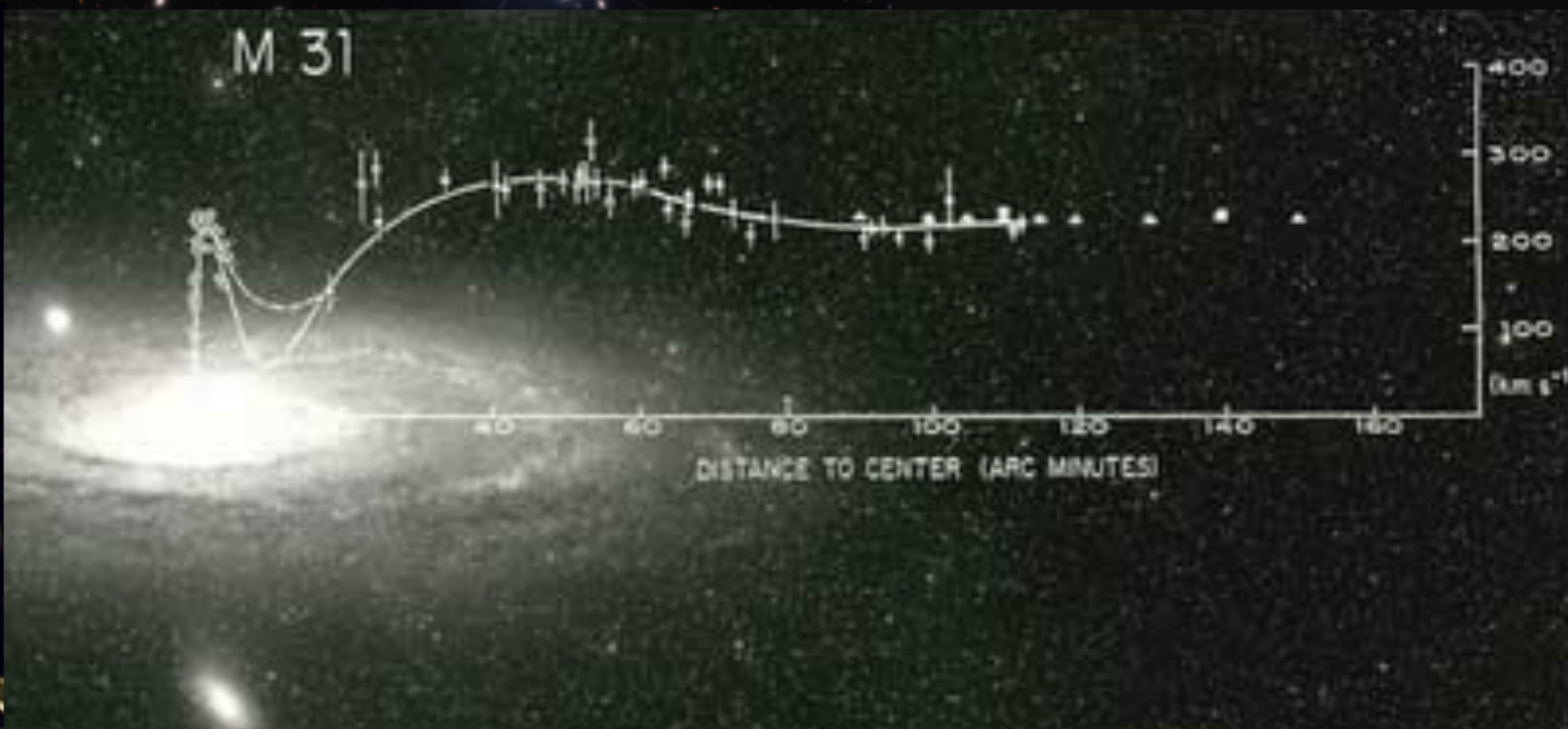
Texas A&M Cosmology Seminar 9/24/15

Gravitational Dark Matter



1933: Zwicky observes dark matter in Coma Cluster

Gravitational Dark Matter



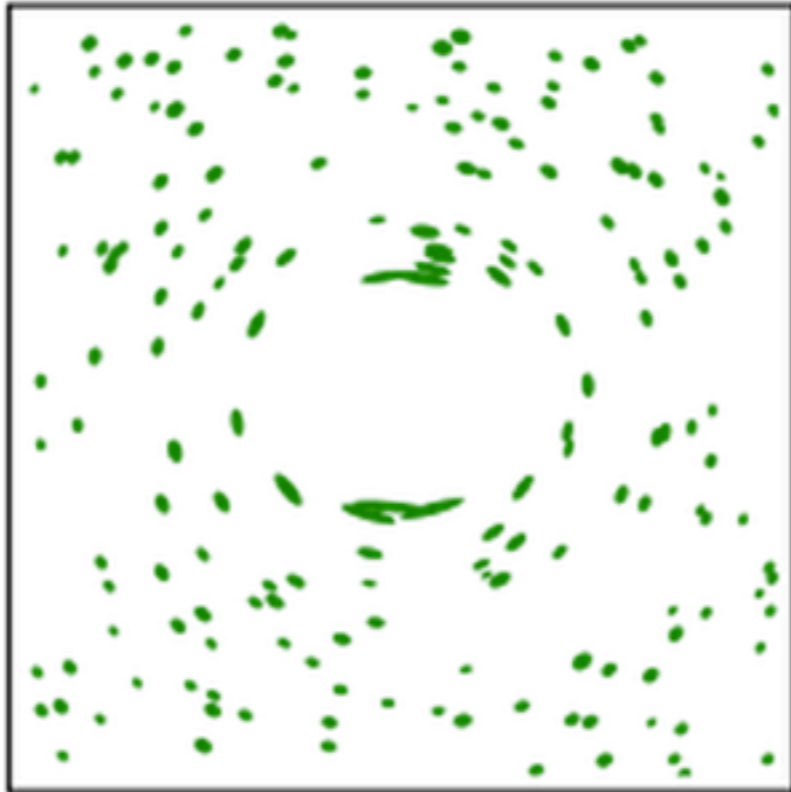
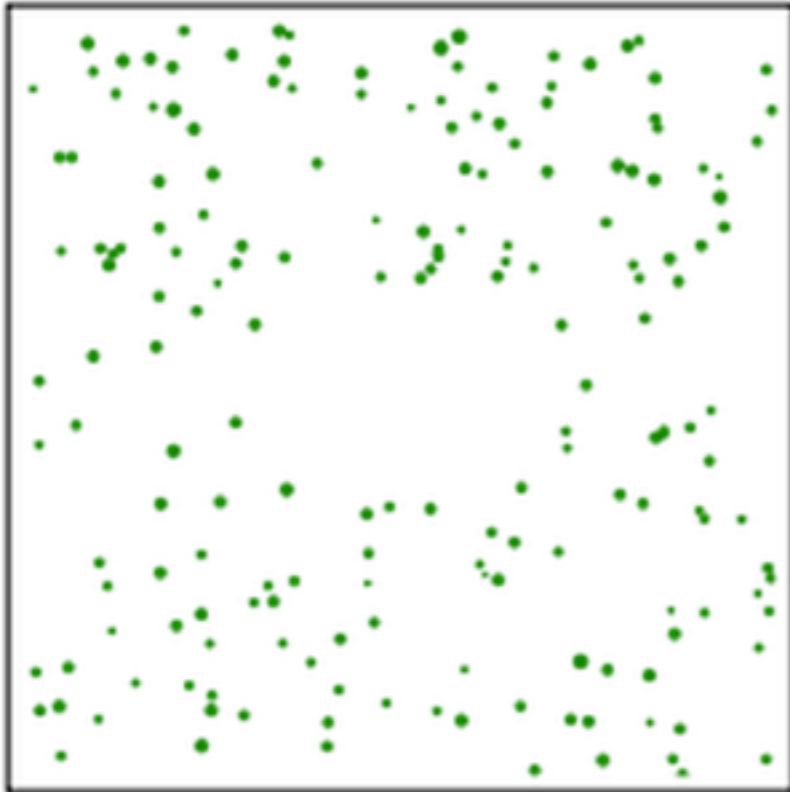
1970s: Vera Rubin observes anomalous rotation velocities in M31

Gravitational Dark Matter



Unlensed

Lensed



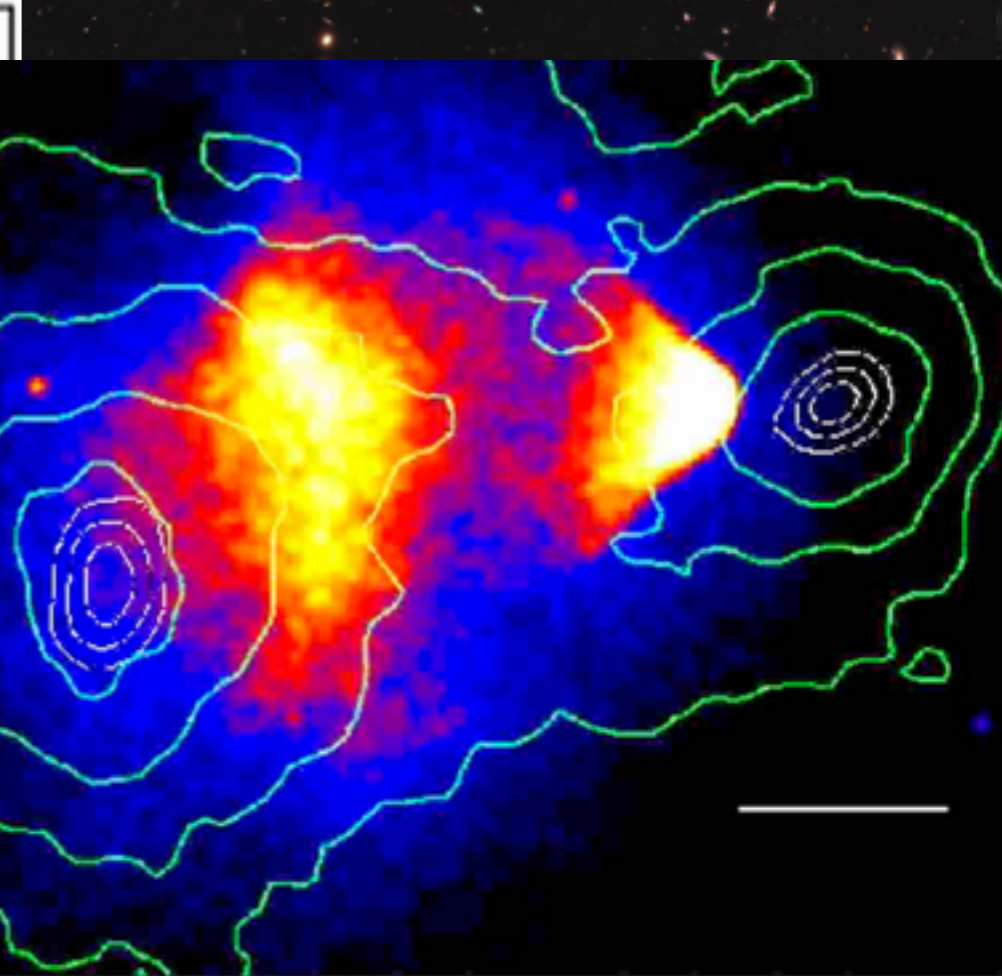
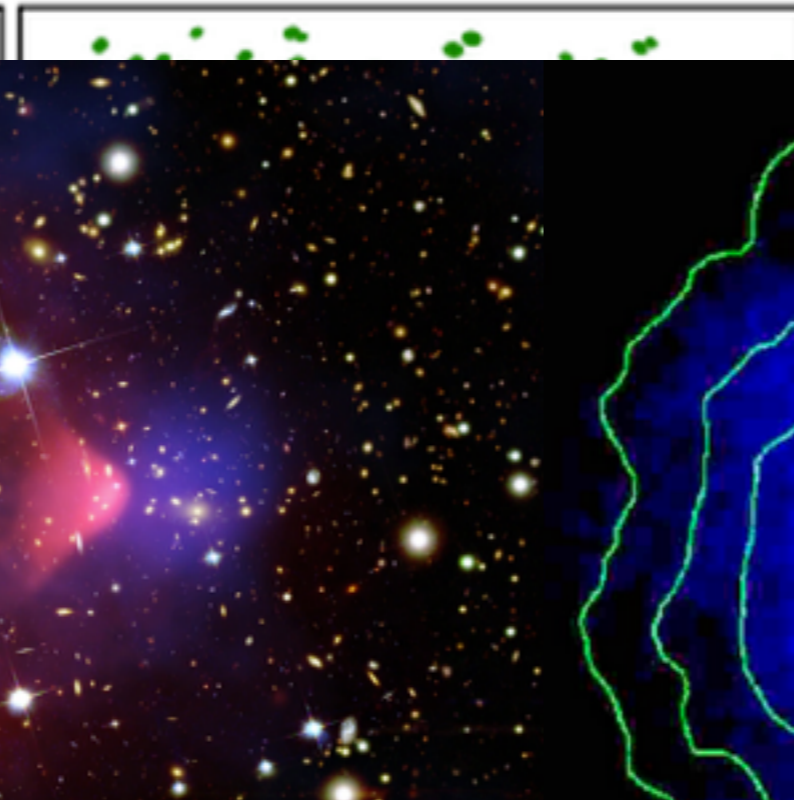
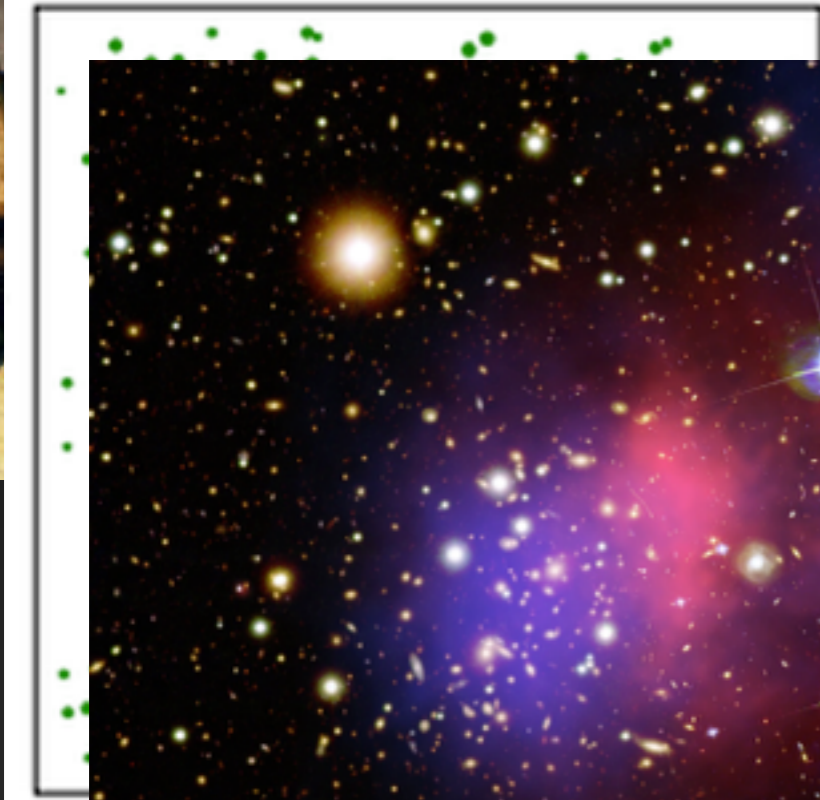
1996: Weak Gravitational Lensing Observed from Dark Matter Halos

Gravitational Dark Matter



Unlensed

Lensed



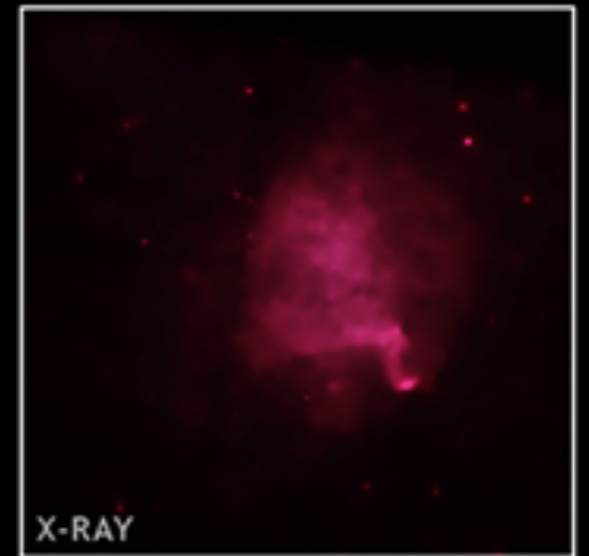
2006: Bullet Cluster Observations Show Offset Between Mass and Hot Gas

Gravitational Dark Matter



Trainwreck Cluster

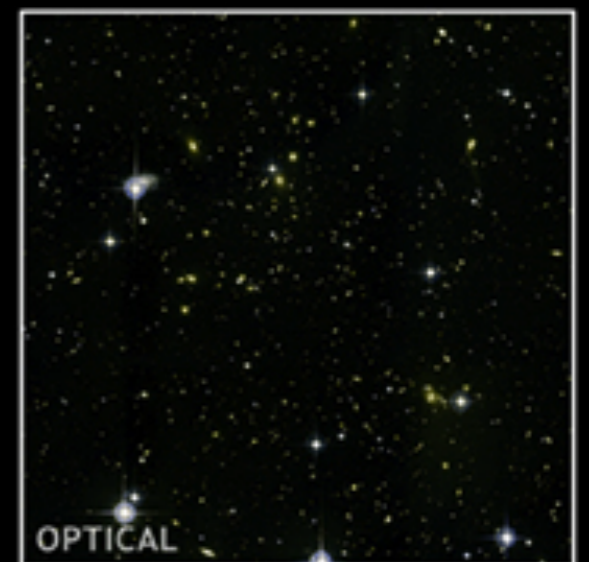
COMPOSITE



X-RAY

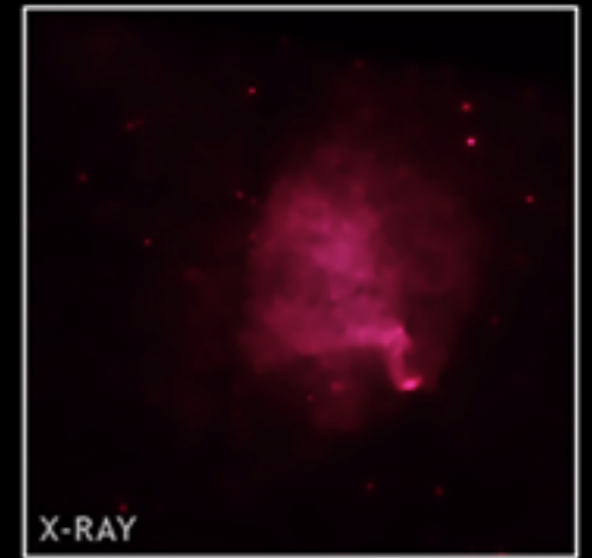


LENSING



OPTICAL

Gravitational Dark Matter



Musketball Cluster



Gravitational Dark Matter

MACS J0717.5+3745

X-RAY



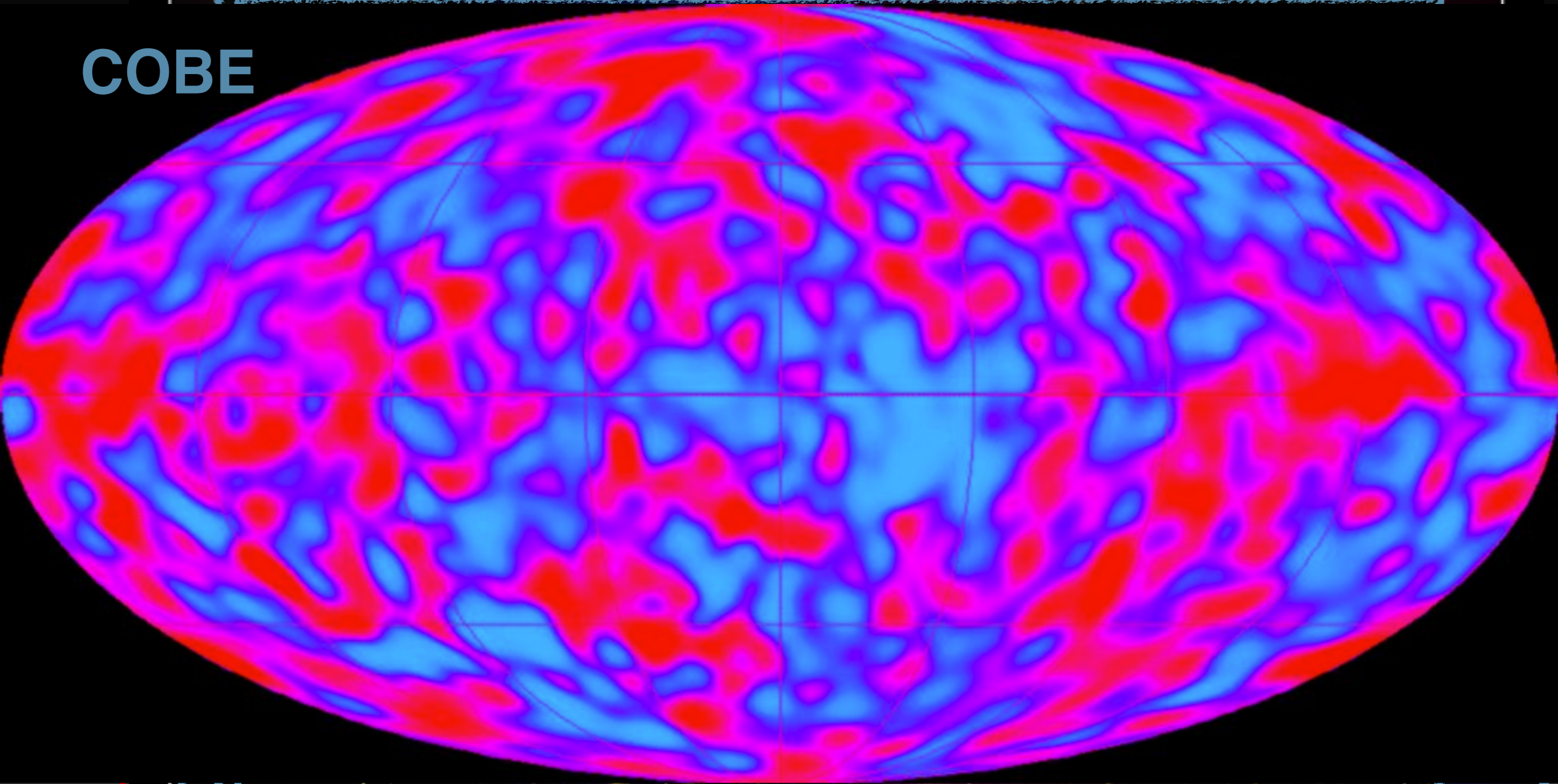
Gravitational Dark Matter

MACS J0025.4-1222



Gravitational Dark Matter

COBE



Gravitational Dark Matter

WMAP

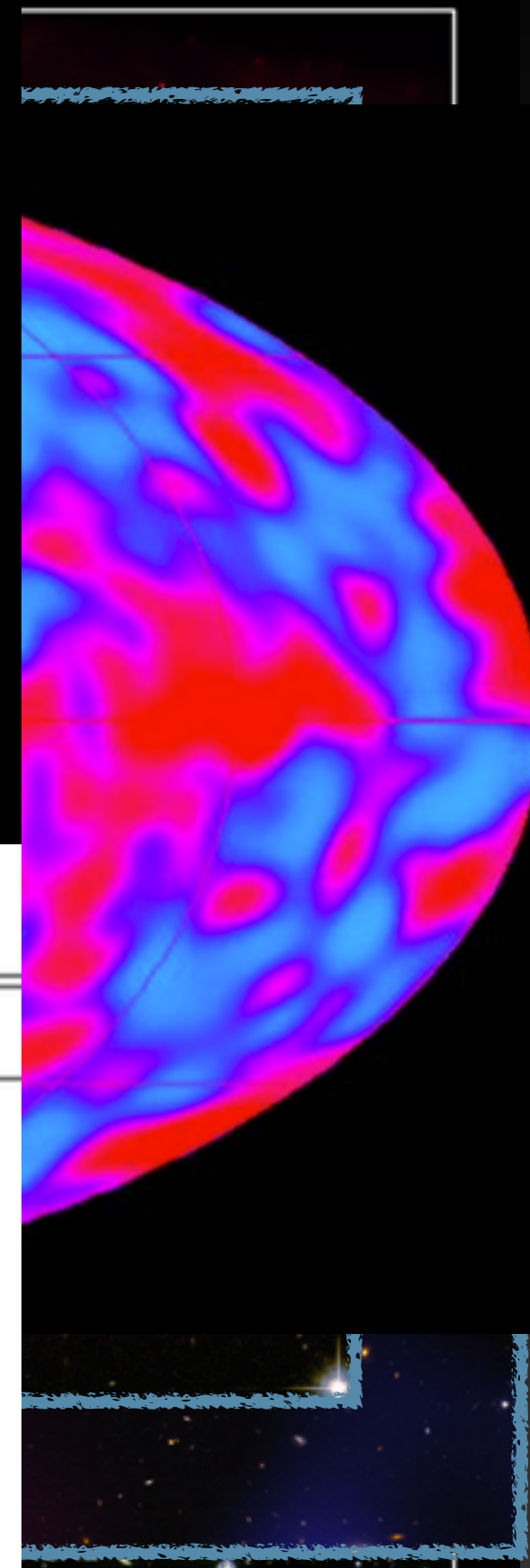
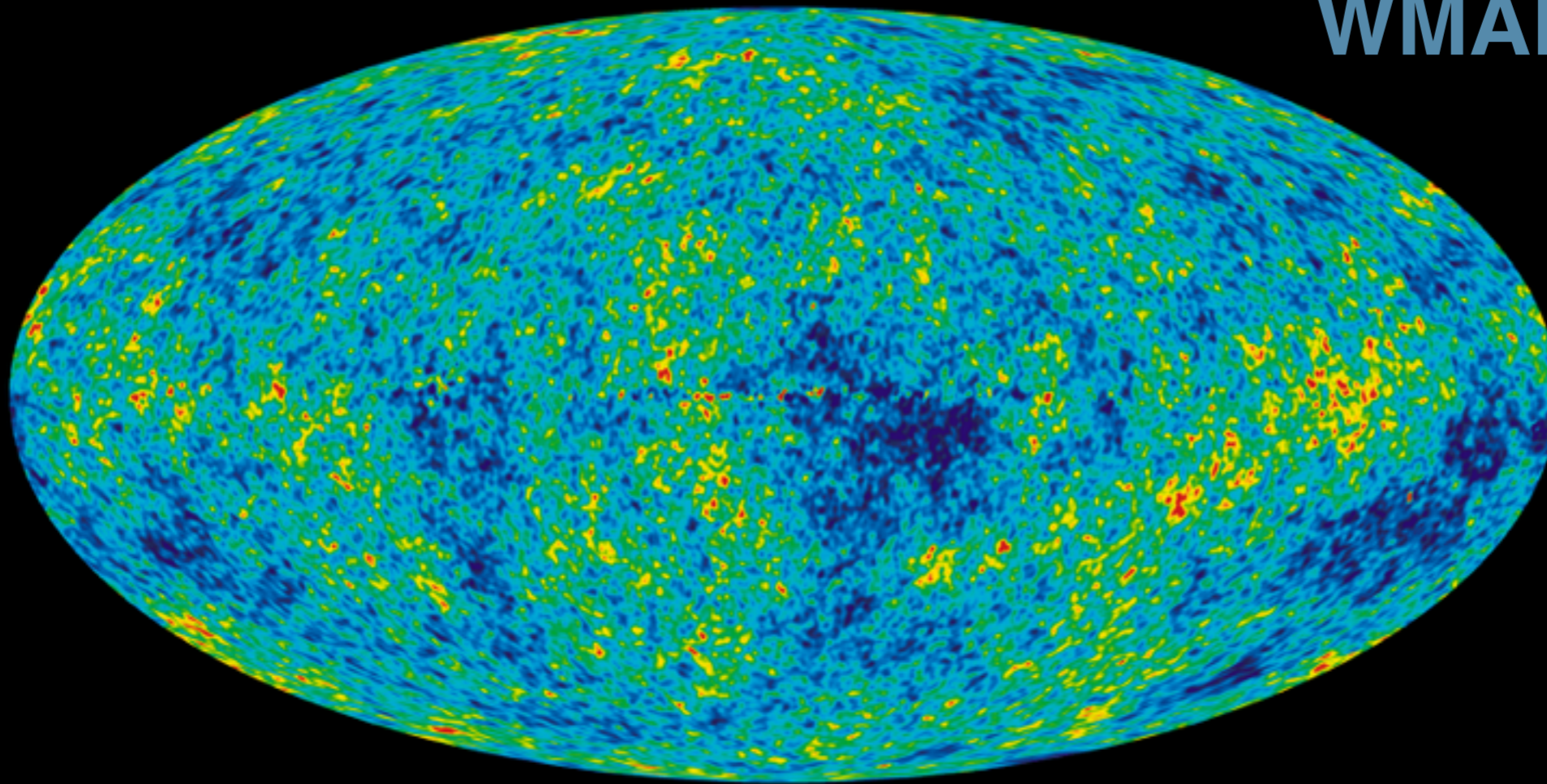
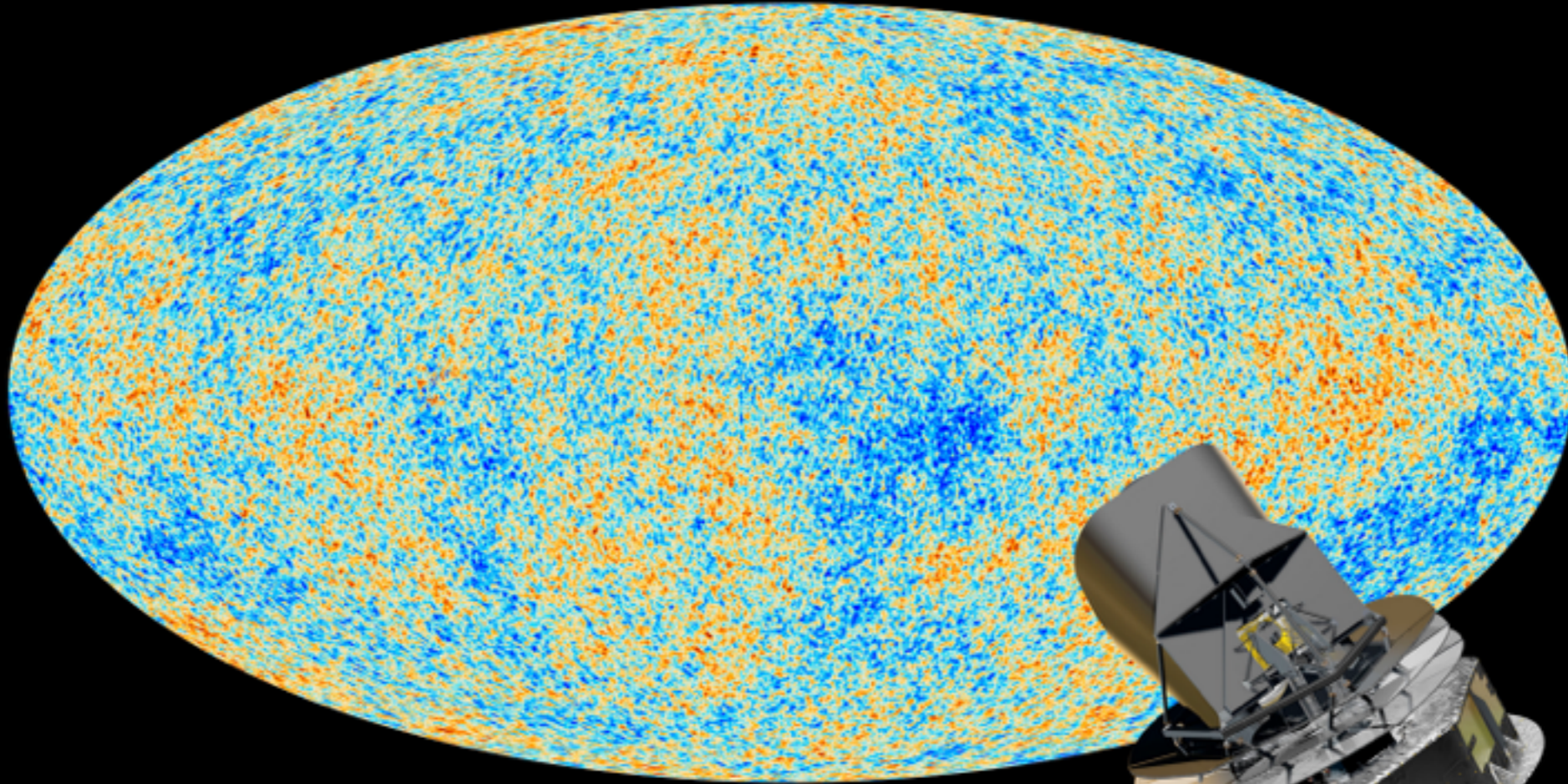


Table 6. Cosmological Parameter Summary

Description	Symbol	WMAP-only
Parameters for Standard Λ CDM Model ^a		
Age of universe	t_0	13.69 ± 0.13 Gyr
Hubble constant	H_0	$71.9^{+2.6}_{-2.7}$ km/s/Mpc
Baryon density	Ω_b	0.0441 ± 0.0030
Physical baryon density	$\Omega_b h^2$	0.02273 ± 0.00062
Dark matter density	Ω_c	0.214 ± 0.027

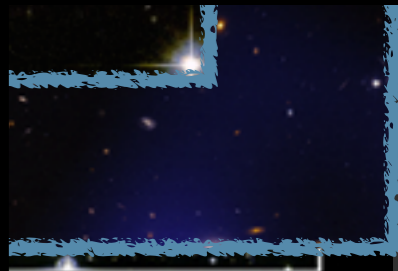
Gravitational Dark Matter

Parameter	Planck		Planck+lensing		Planck+WP	
	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012



PLANCK

Age of u
Hubble c
Baryon c
Physical
Dark ma



Gravitational Dark Matter

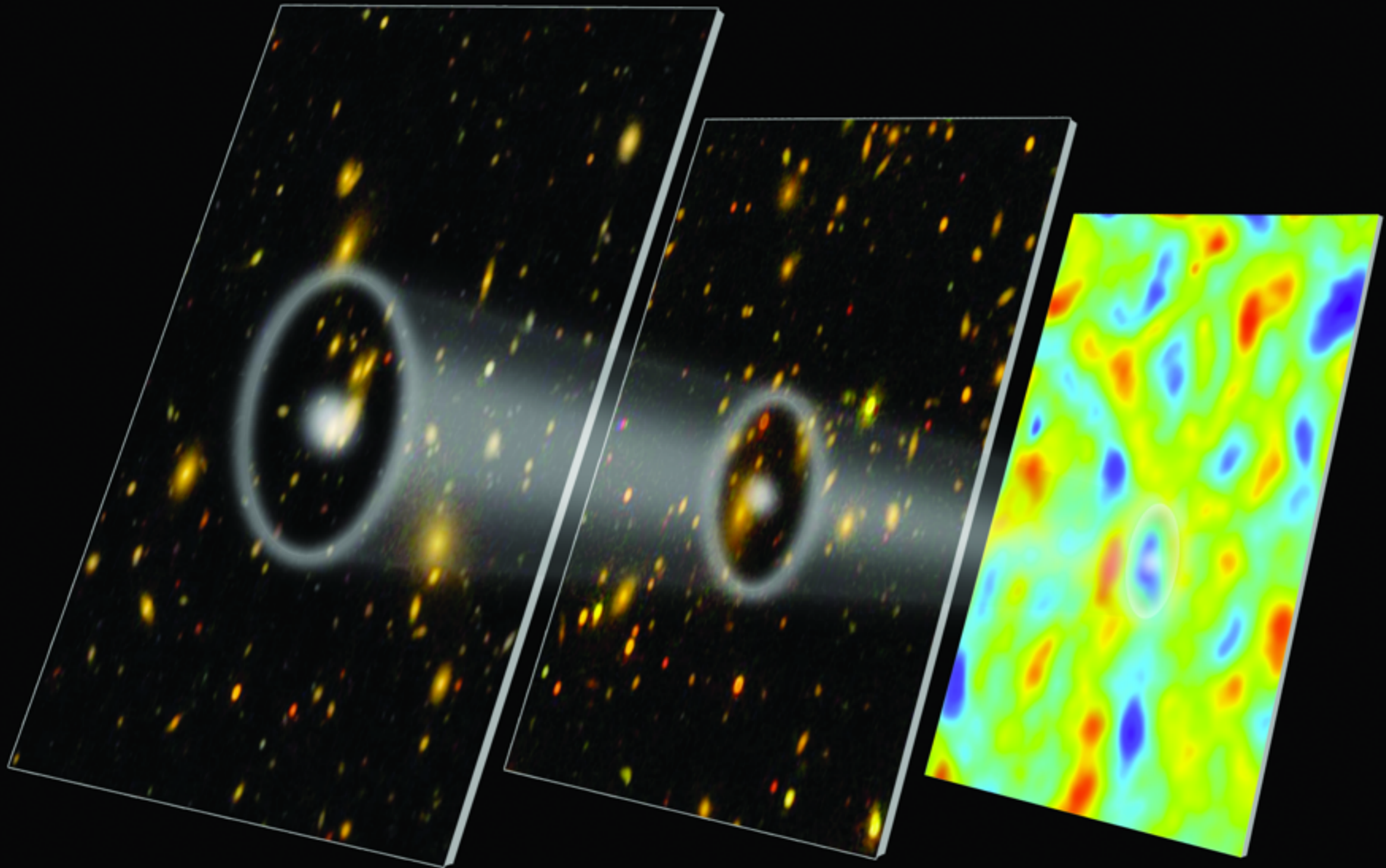


Large Scale Structure

A
H
E
P
D

Gravitational Dark Matter

Baryonic Acoustic Oscillations



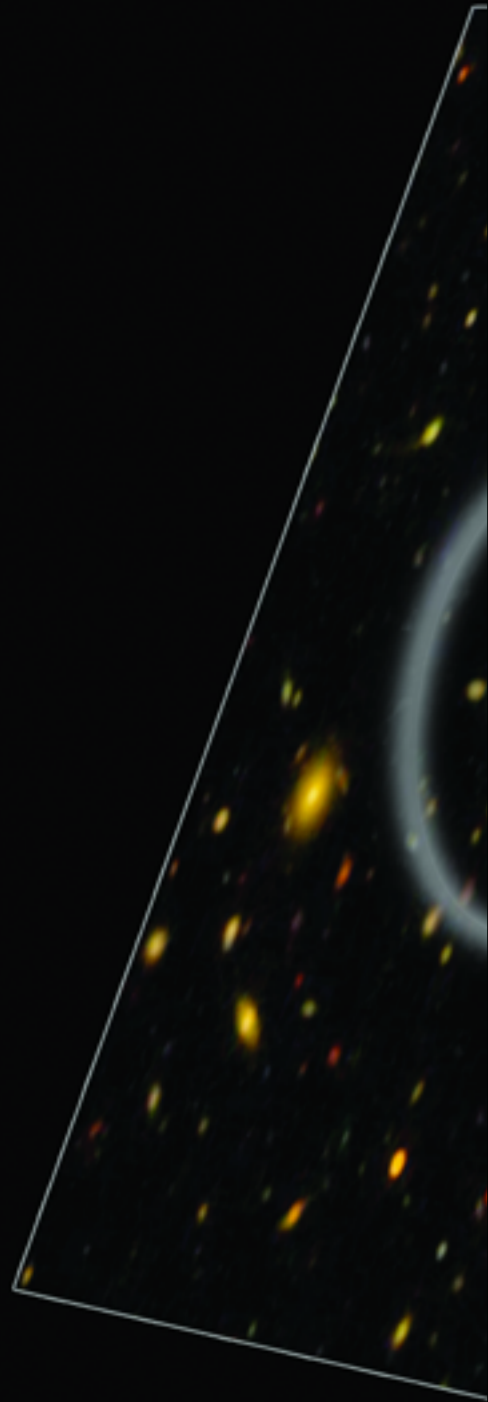
Galaxy map 3.8 billion years ago

Galaxy map 5.5 billion years ago

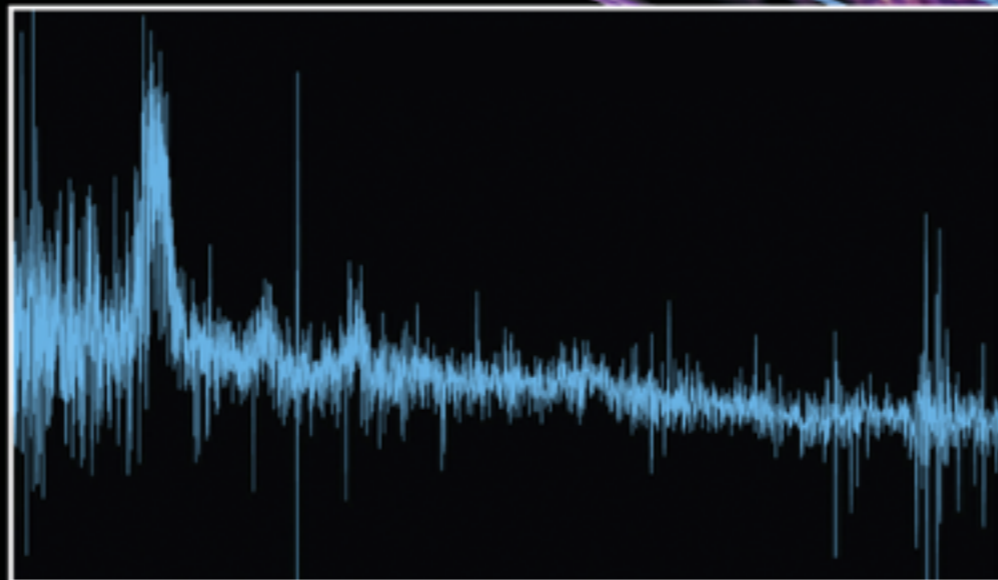
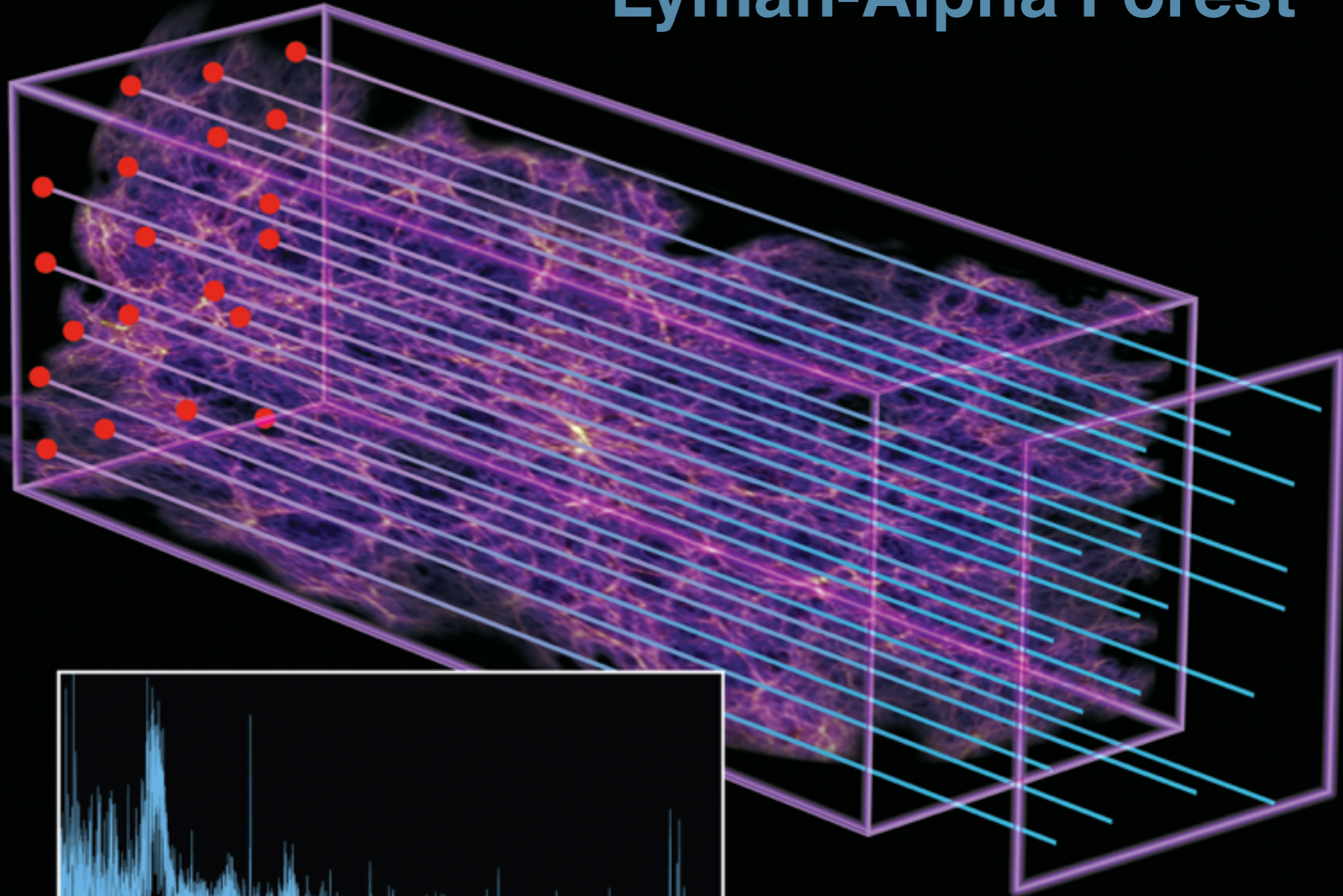
CMB 13.7 billion years ago

Gravitational Dark Matter

Lyman-Alpha Forest



Galaxy map 3.8 billion



Gravitational Dark Matter

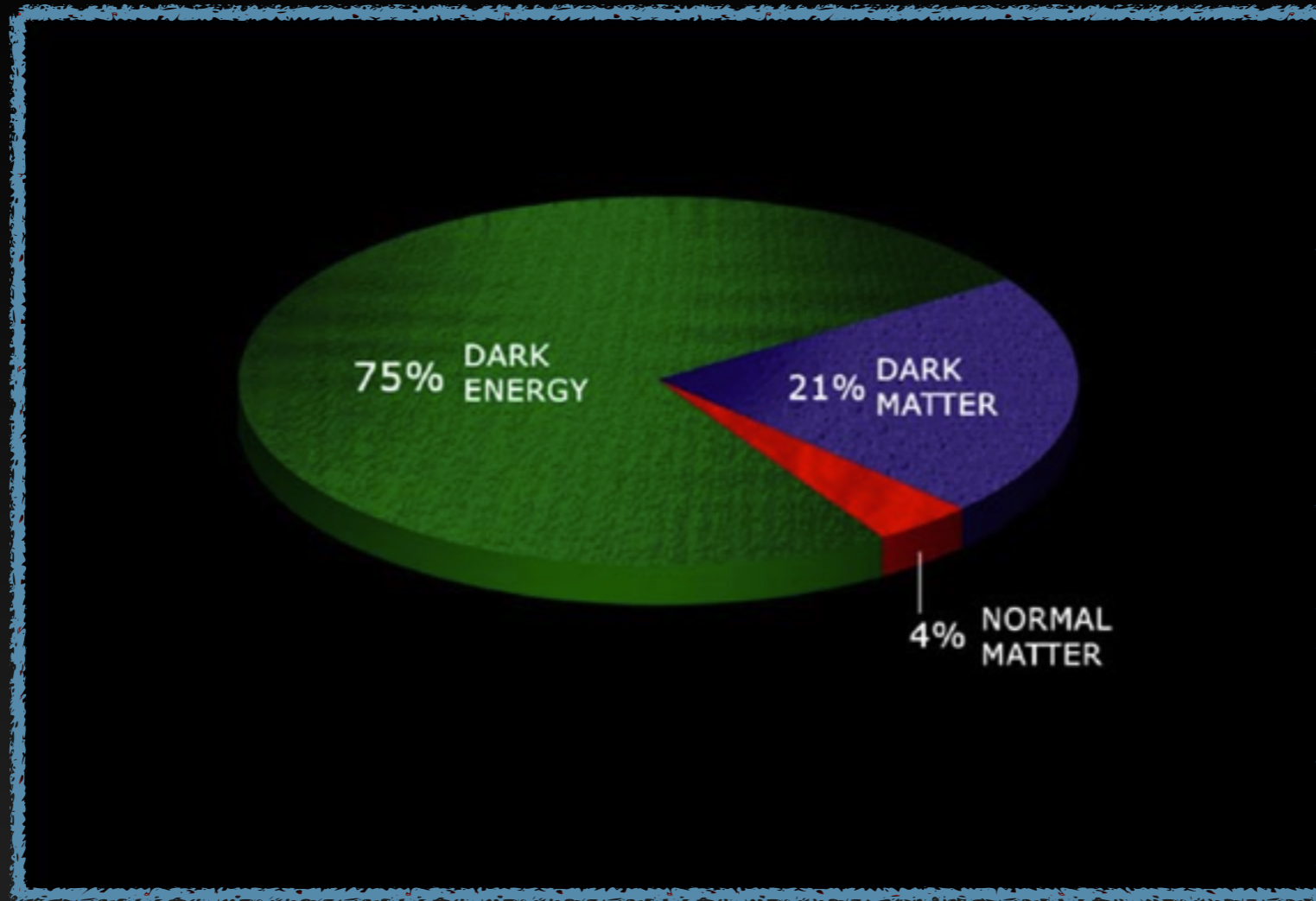
Type 1A Supernove



Galaxy map 3.8 billion



Dark Matter Cosmology

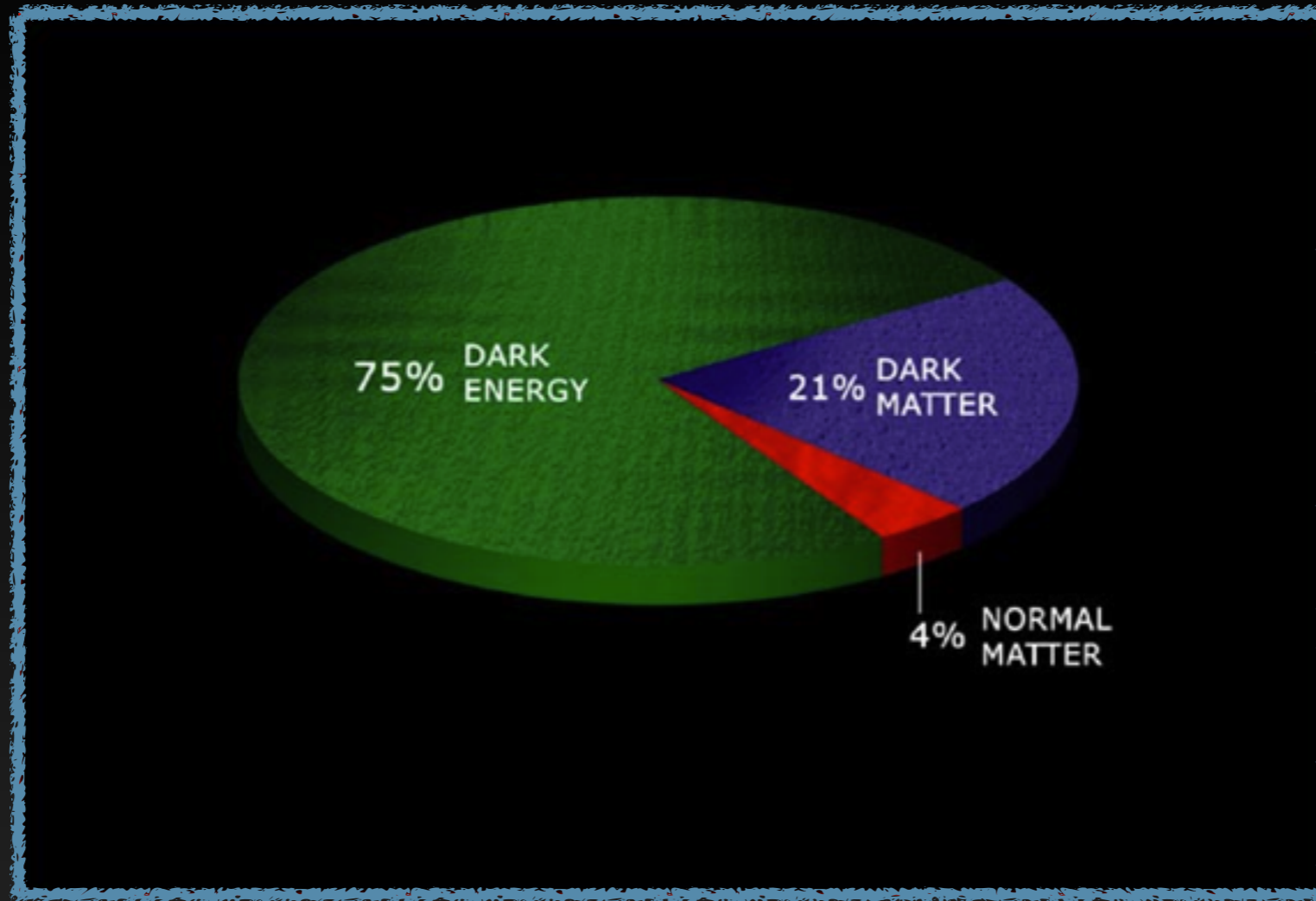


Dark Matter Is:

- 1.) Dark
- 2.) Stable
- 3.) Cold
- 4.) Collisionless

No known particle has these properties!

Particle Dark Matter



The Density of Dark Matter is similar to the density of protons in our universe.

This requires either significant fine tuning, or a dynamical interaction - which in QFT must correspond to some force.

Particle Dark Matter

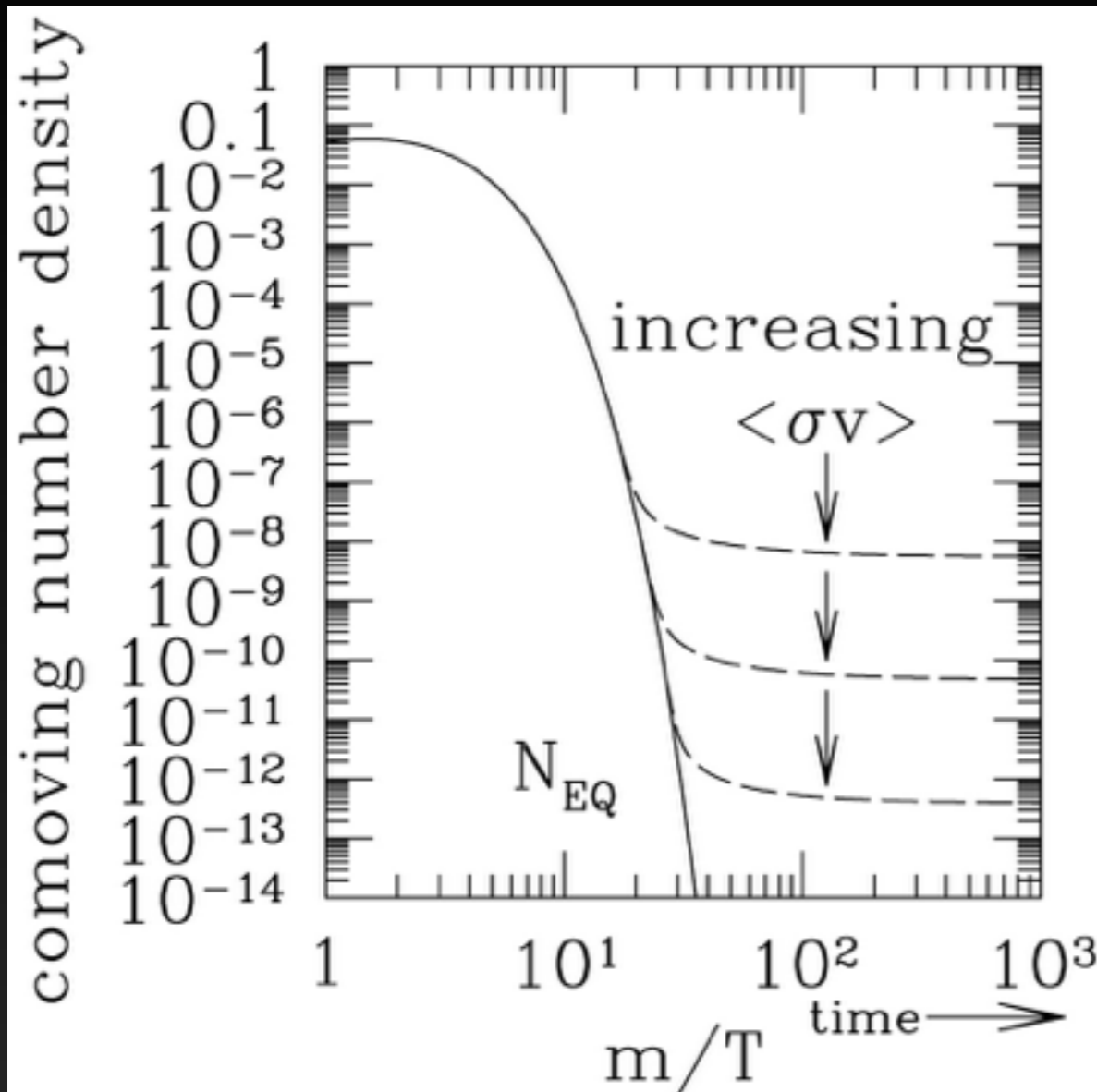
Gravity is Weak!

- The search for a dark matter particle must rely on another force.

Does the dark matter particle have any other interactions?

- Electromagnetic Interactions
- Strong Force Interactions
- Weak Force Interactions
- Planck Scale Interactions
- Something Else?

Dark Matter in Thermal Equilibrium



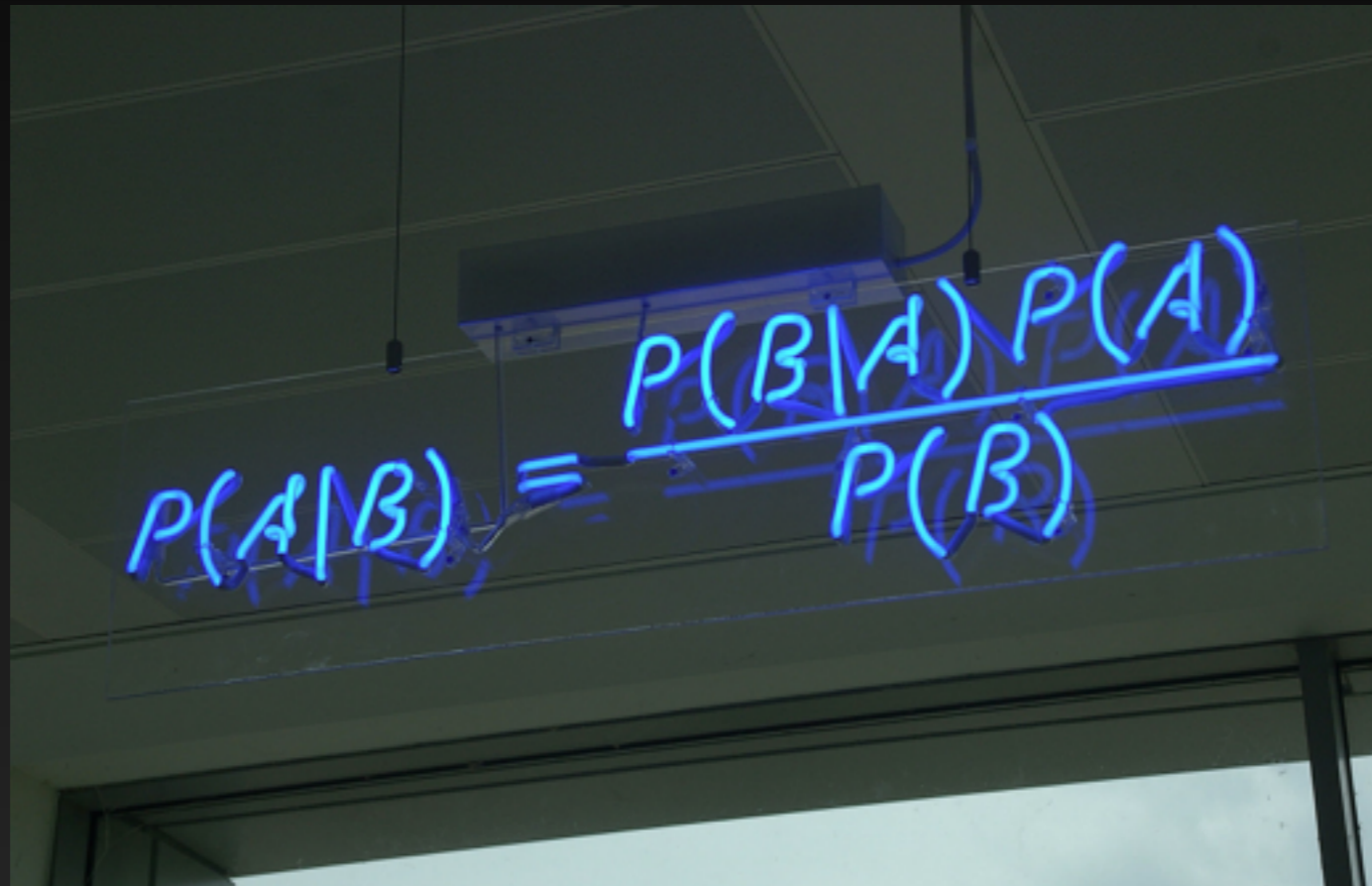
A particle with a weak interaction cross-section and a mass on the weak scale is expected to naturally obtain the correct relic abundance through thermal freeze-out in the Early Universe.

$$\left(\frac{\Omega_\chi}{0.2} \right) \simeq \frac{x_{\text{f.o.}}}{20} \left(\frac{10^{-8} \text{ GeV}^{-2}}{\sigma} \right)$$

$$\langle \sigma v \rangle \sim 10^{-8} \text{ GeV}^{-2} (3 \times 10^{-28} \text{ GeV}^2 \text{ cm}^2) 10^{10} \frac{\text{cm}}{\text{s}} = 3 \times 10^{-26} \frac{\text{cm}^3}{\text{s}}$$

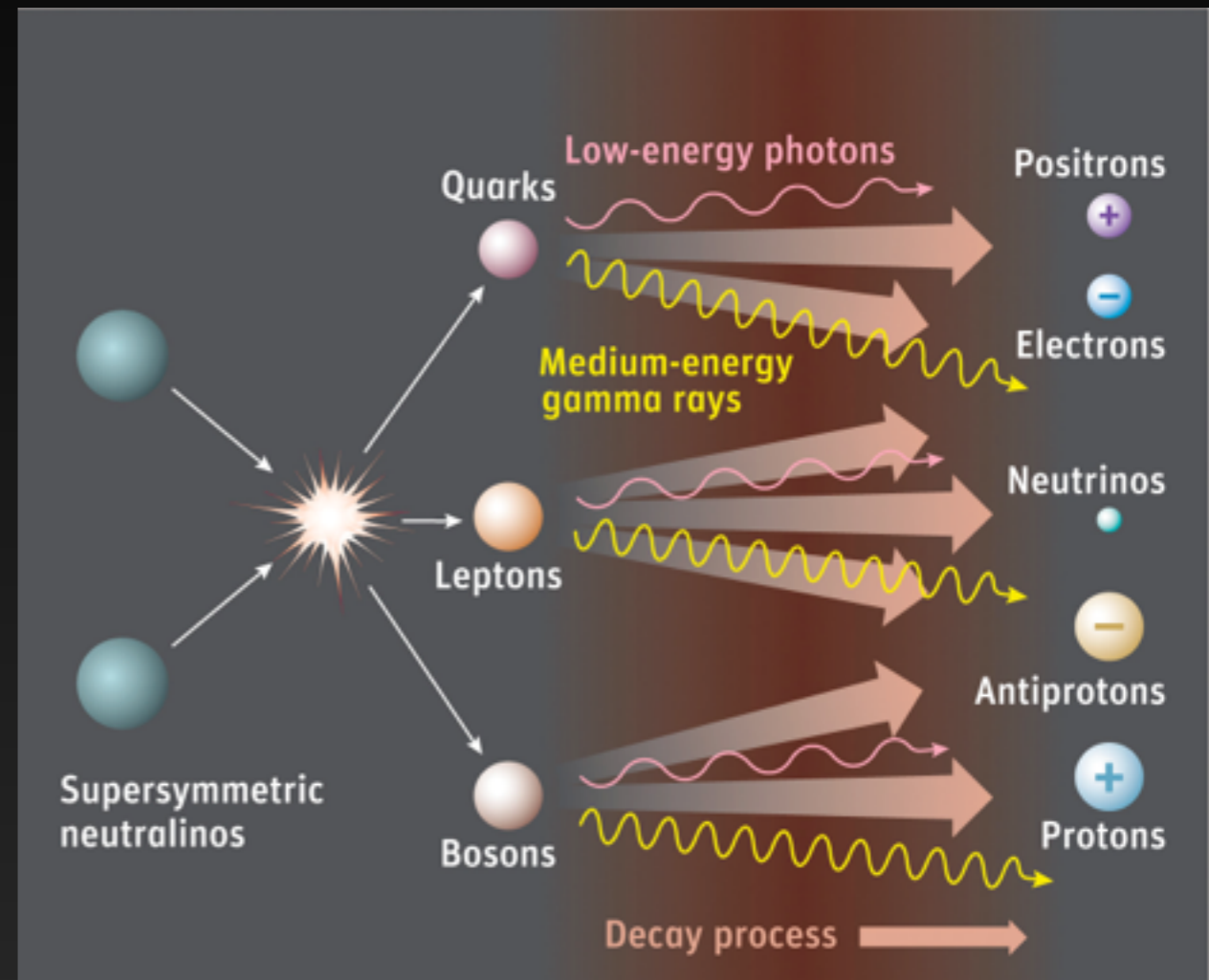
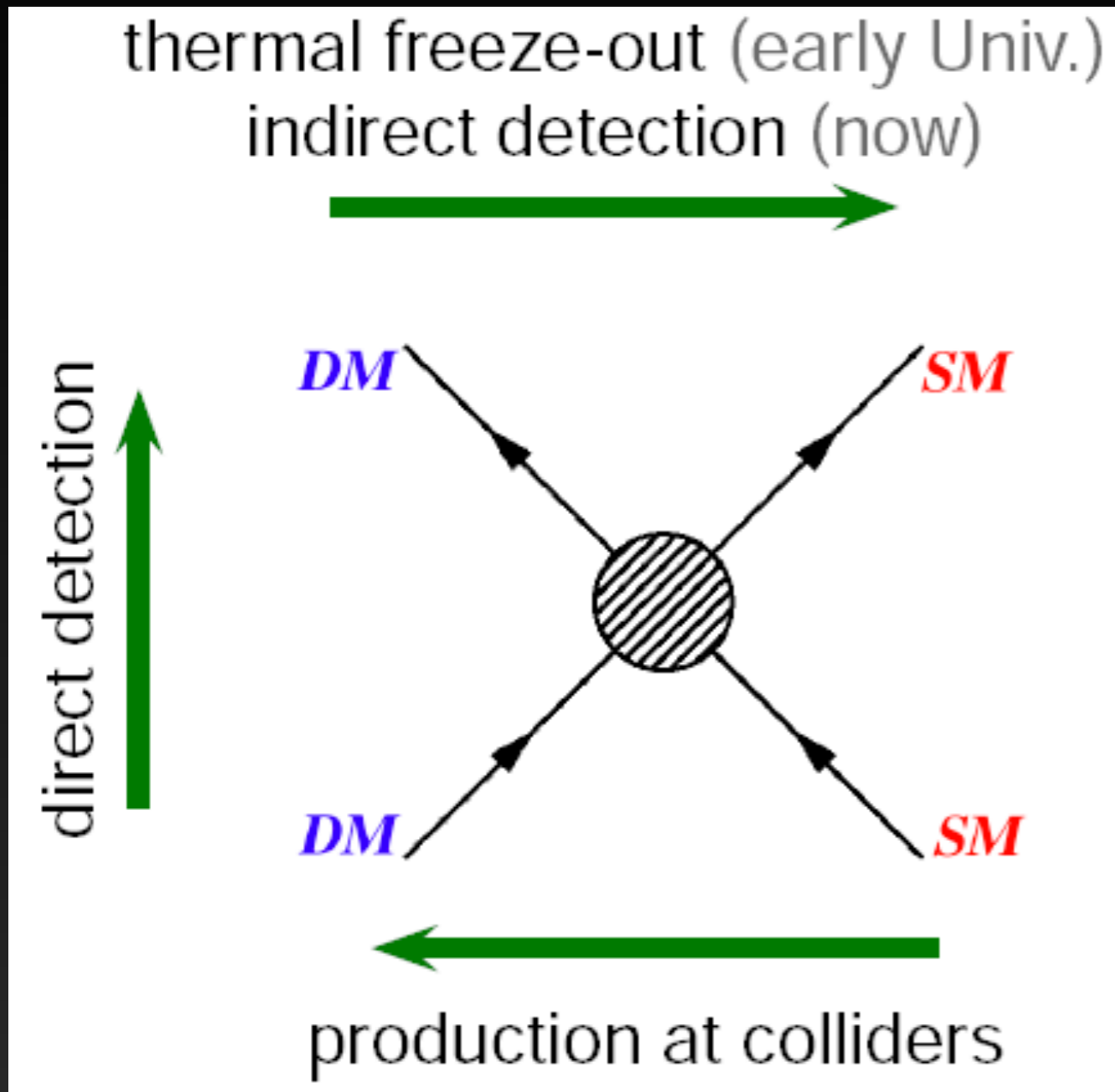
Observing a Dark Matter Particle

Myriad Evidence Suggests Dark Matter exists, and should have non-gravitational interactions:

A photograph of a whiteboard with a probability formula written in blue marker. The formula is $P(A|B) = \frac{P(B|A)P(A)}{P(B)}$. The whiteboard is mounted on a wall, and the lighting is somewhat dim, with the blue marker providing the primary source of color in the image.
$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

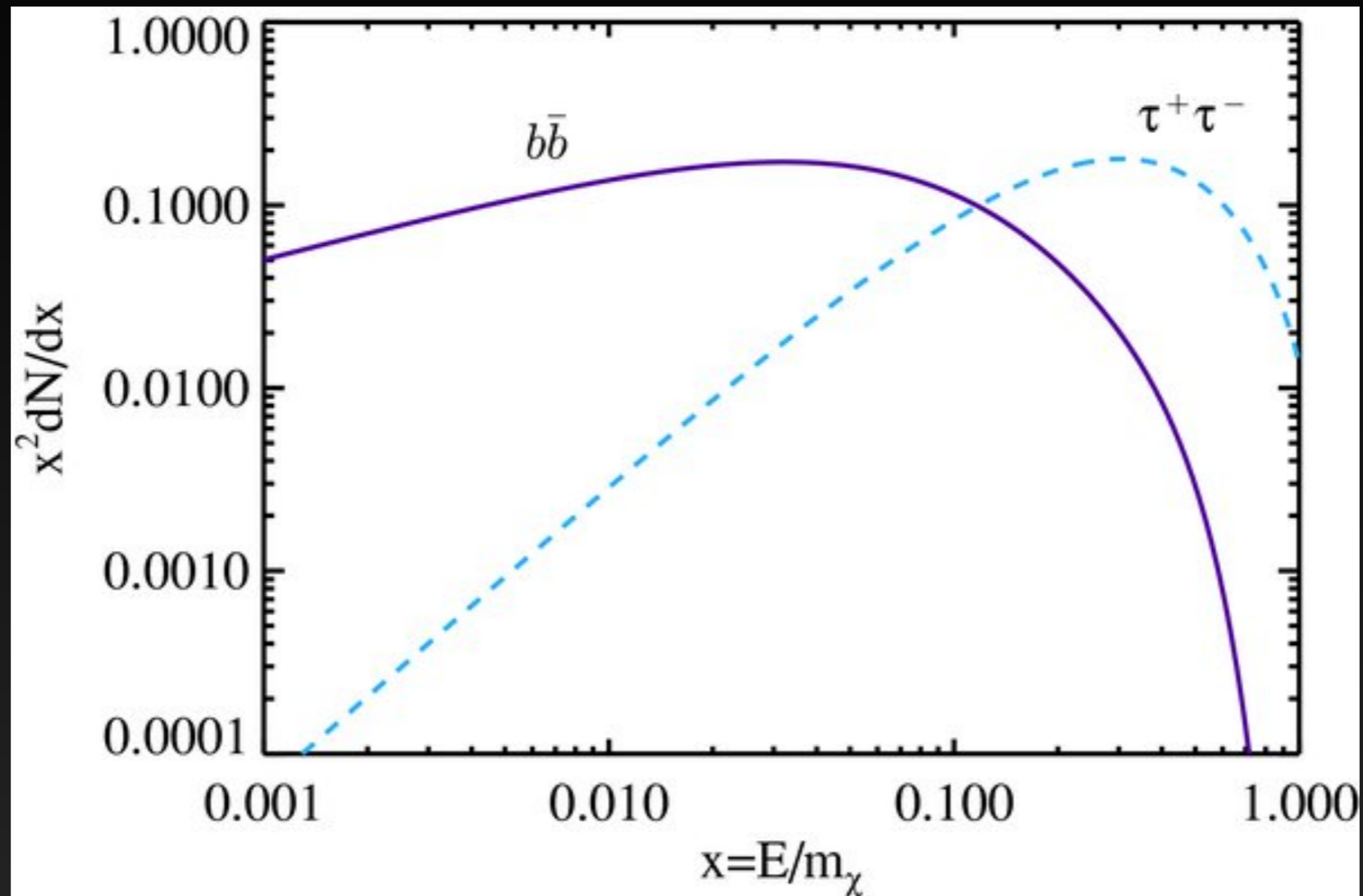
We shouldn't think of dark matter searches as a "needle in a haystack". Our theoretical priors should lead us to bet that particle dark matter can be feasibly observed.

Gamma-Rays from WIMPs



If dark matter had a thermal cross-section in the early universe, it should still have an observable cross-section today.

Gamma-Rays from WIMPs

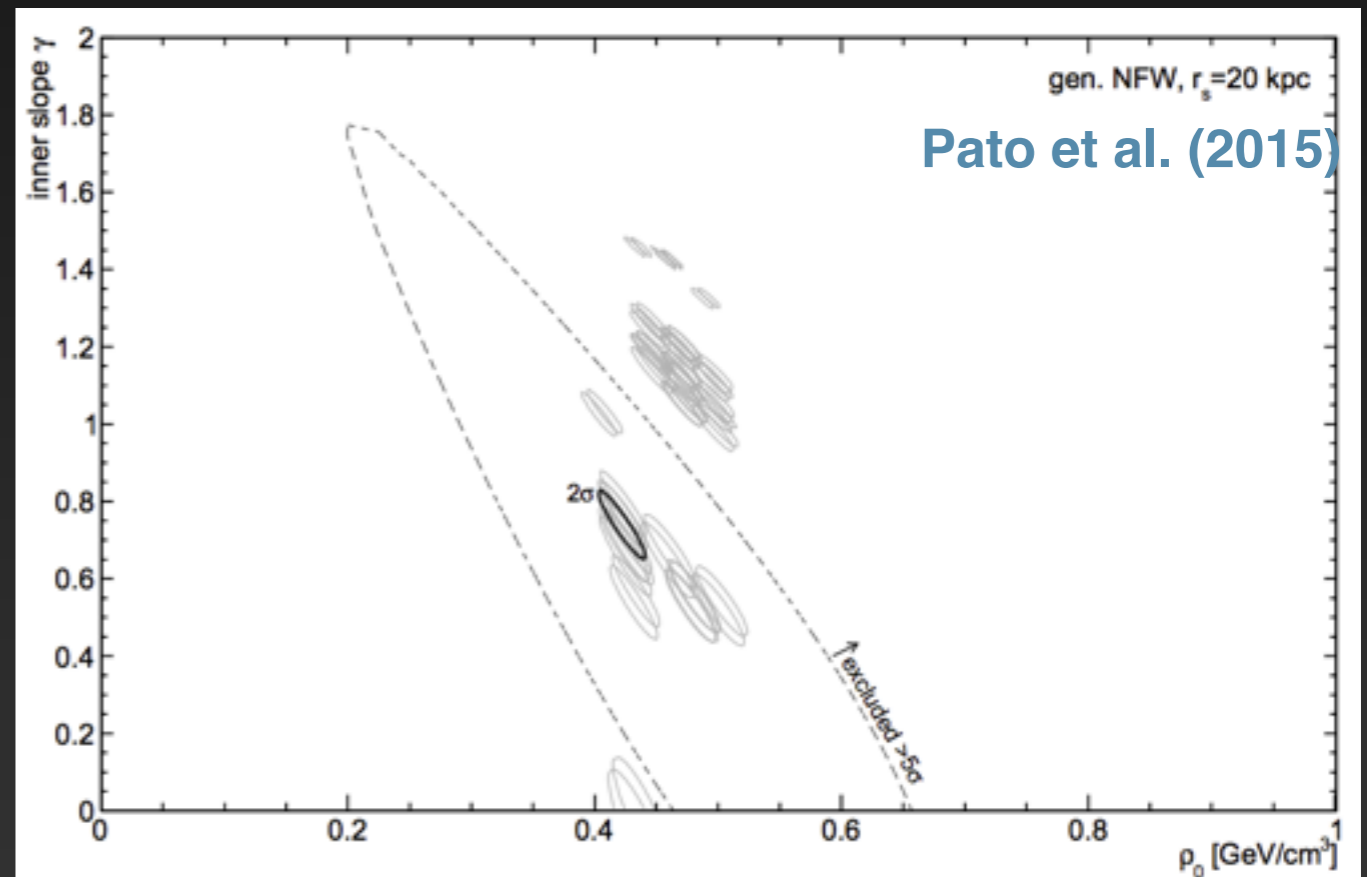
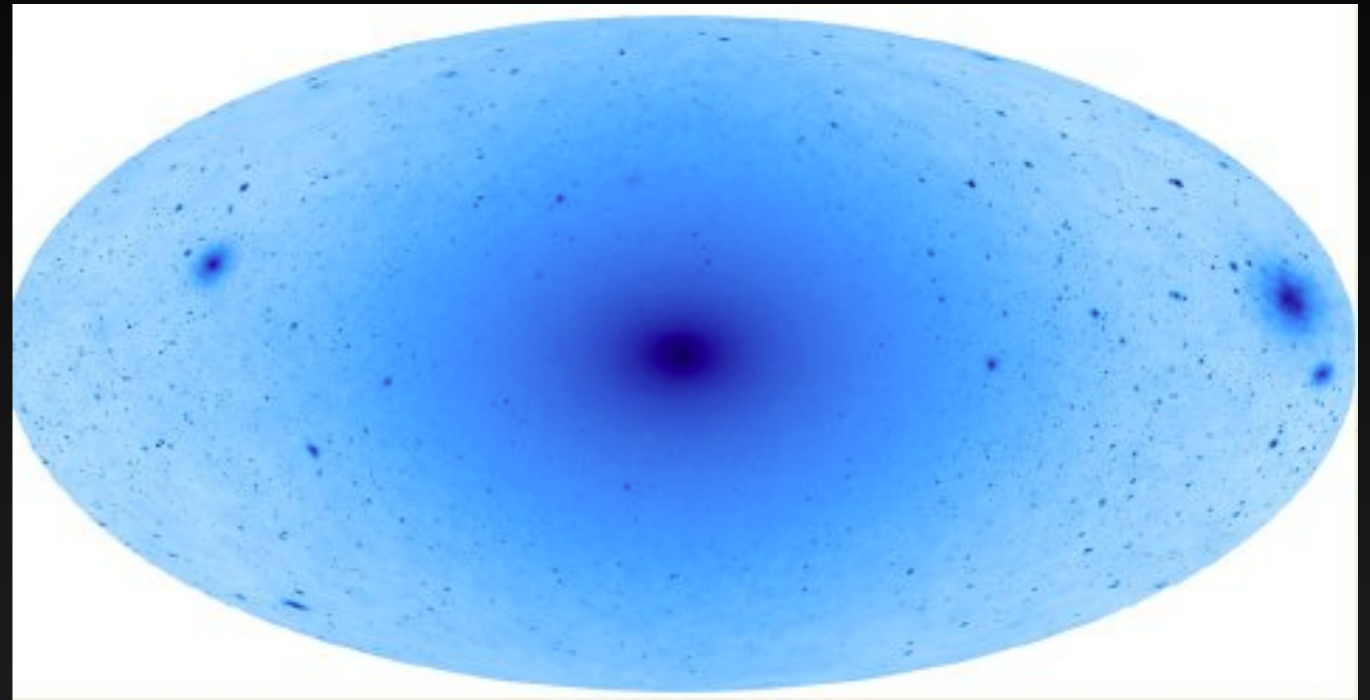


Once a standard model final state is selected, the resulting photon spectrum can be calculated from known physics.

For WIMP scale dark matter, photon energy peaks in the GeV range.

Dark Matter in the Galactic Center

Both observational data and simulations indicate that the Galactic Center should produce the highest flux of dark matter annihilation products of any location in the sky.



Recent work has provided the first direct evidence for dark matter within the Milky Way solar circle.

Dark Matter in the Galactic Center

$$\rho_{\text{NFW}} = \left(\frac{r}{r_s} \right)^{-\gamma} \left(1 + \frac{r}{r_s} \right)^{-3+\gamma}$$

For the remainder of this talk, we employ a simple analytical model, known as the “generalized NFW Profile” which provides a reasonable fit to the observed dark matter density distribution of dark matter halos.

In the standard NFW scenario, $\gamma = 1$

Navarro, Frenk, White (1996)

Springel et al. (2008, 0809.0898)

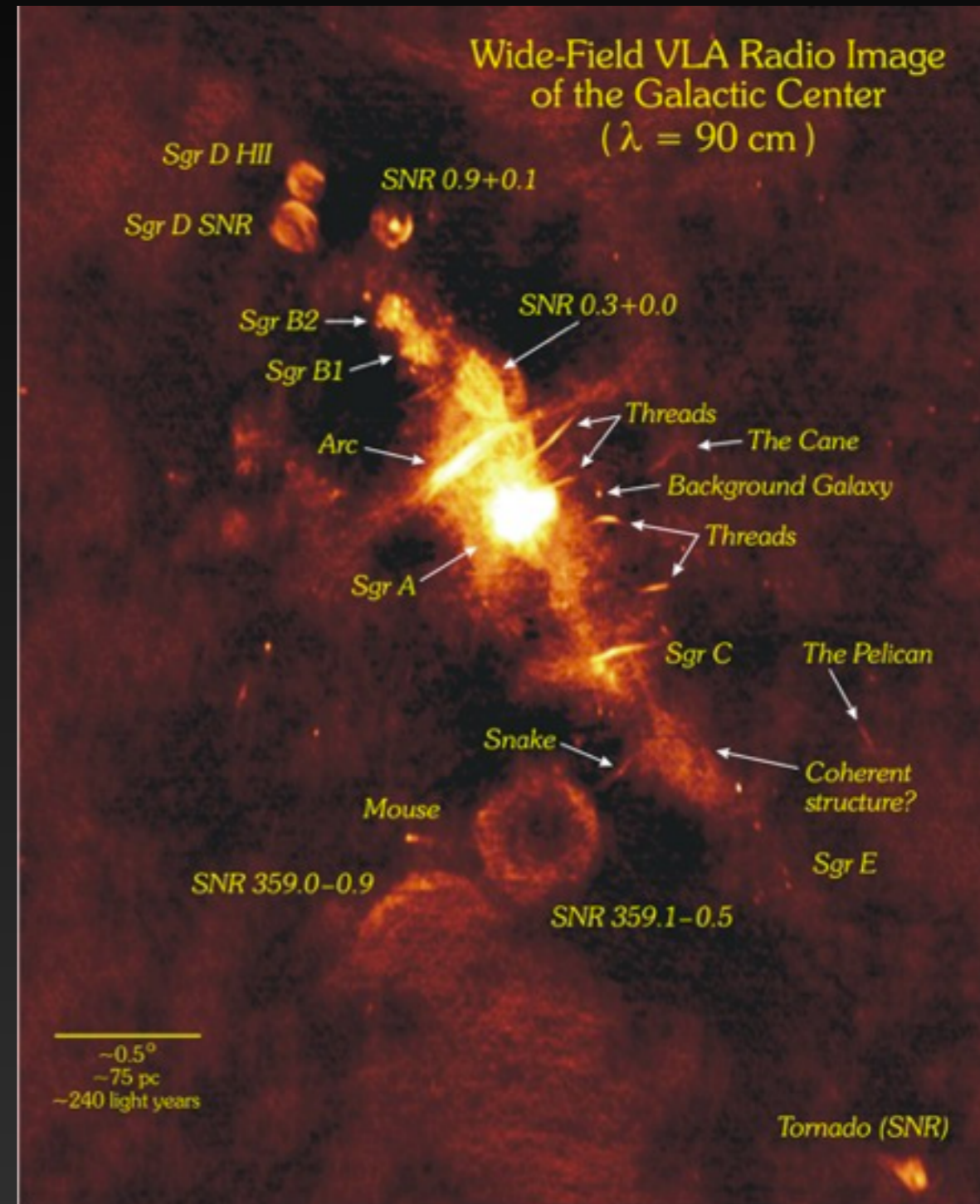
The Galactic Center in Gamma-Rays



Multi-wavelength observations indicate the complexity of the galactic center region.

Chandra observes ~9000 point sources in inner degree.

VLA finds bright non-thermal emission structures.



The Galactic Center in Gamma-Rays



Supernovae Source Cosmic-Ray Protons:

10^{51} erg (~10% in relativistic protons)

(~2% in relativistic electrons)

The Galactic Center in Gamma-Rays

Supernovae Source Cosmic-Ray Protons:

10^{51} erg (~10% in relativistic protons)

(~2% in relativistic electrons)



cosmic rays propagate

$$\frac{\partial \psi}{\partial t} = q(\vec{r}, p) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[p \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

Solved Numerically:

e.g. Galprop

The Galactic Center in Gamma-Rays

Supernovae Source Cosmic-Ray Protons:

10^{51} erg (~10% in relativistic protons)

(~2% in relativistic electrons)



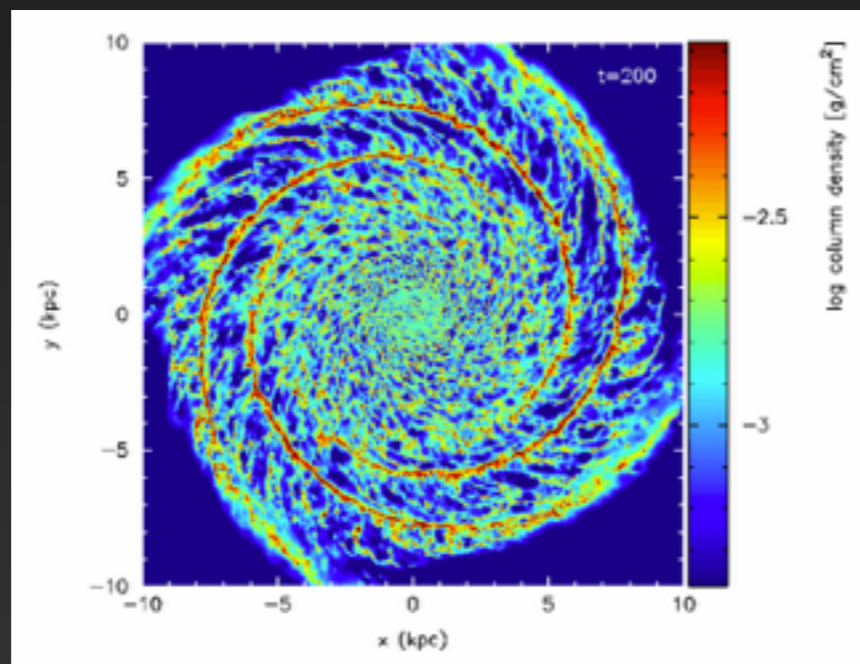
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Gas/ISRF



The Galactic Center in Gamma-Rays

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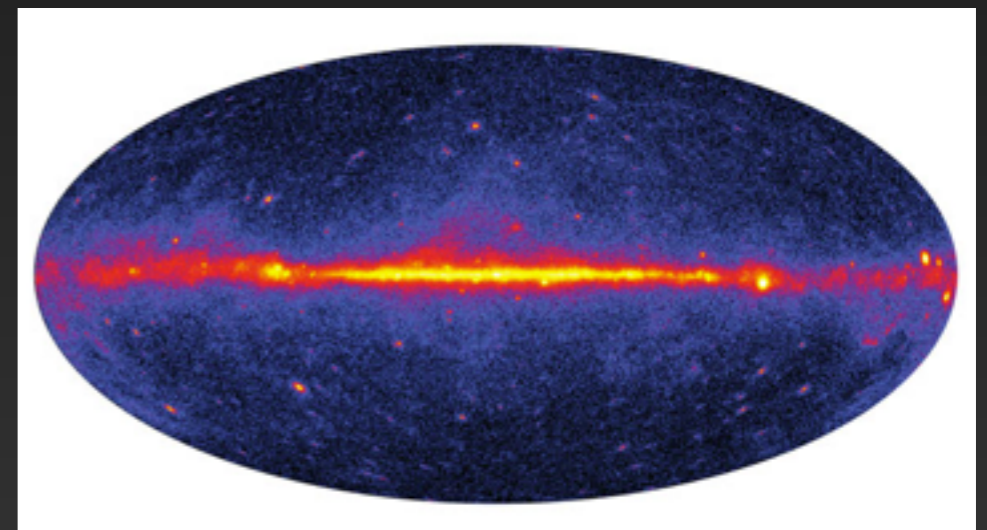
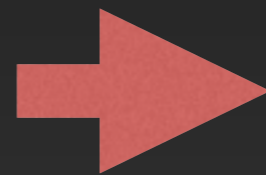
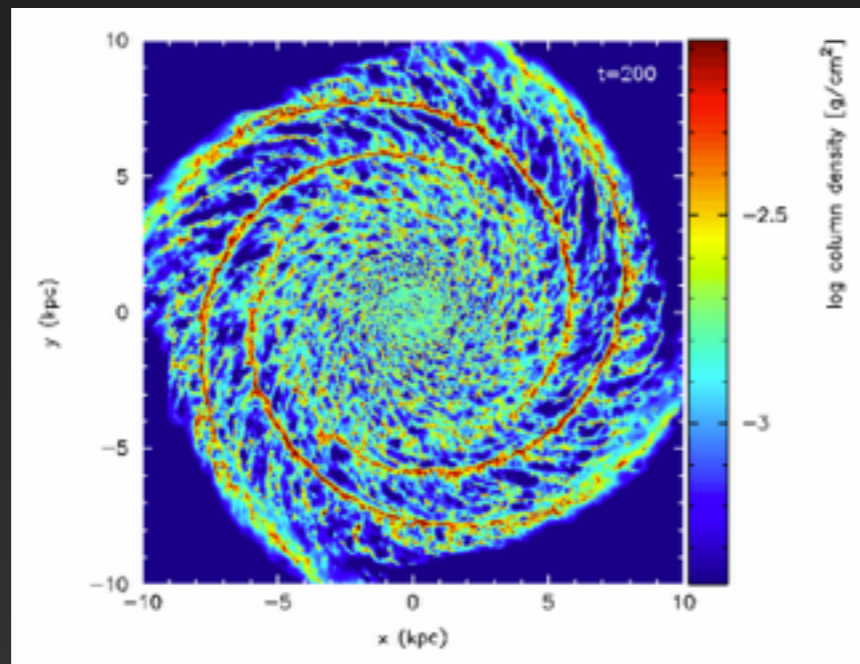
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Solved Numerically:

e.g. Galprop

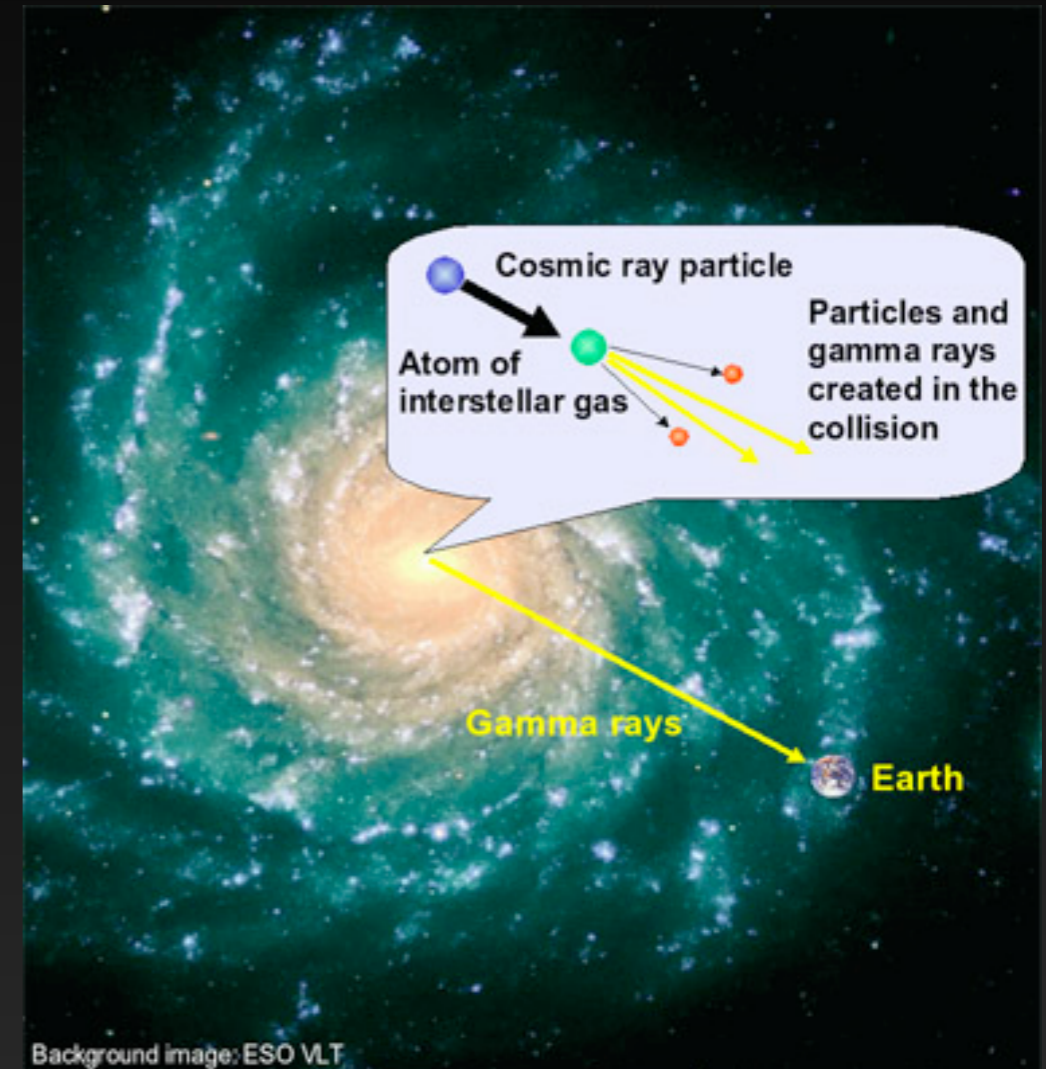
Gas/ISRF



The Galactic Center in Gamma-Rays

What Are These Backgrounds?

- * Point Sources (SNR, pulsars, etc.)
- * Hadronic Interactions ($pp \rightarrow \pi^0 \rightarrow \gamma\gamma$)
- * Bremsstrahlung
- * Inverse Compton Scattering

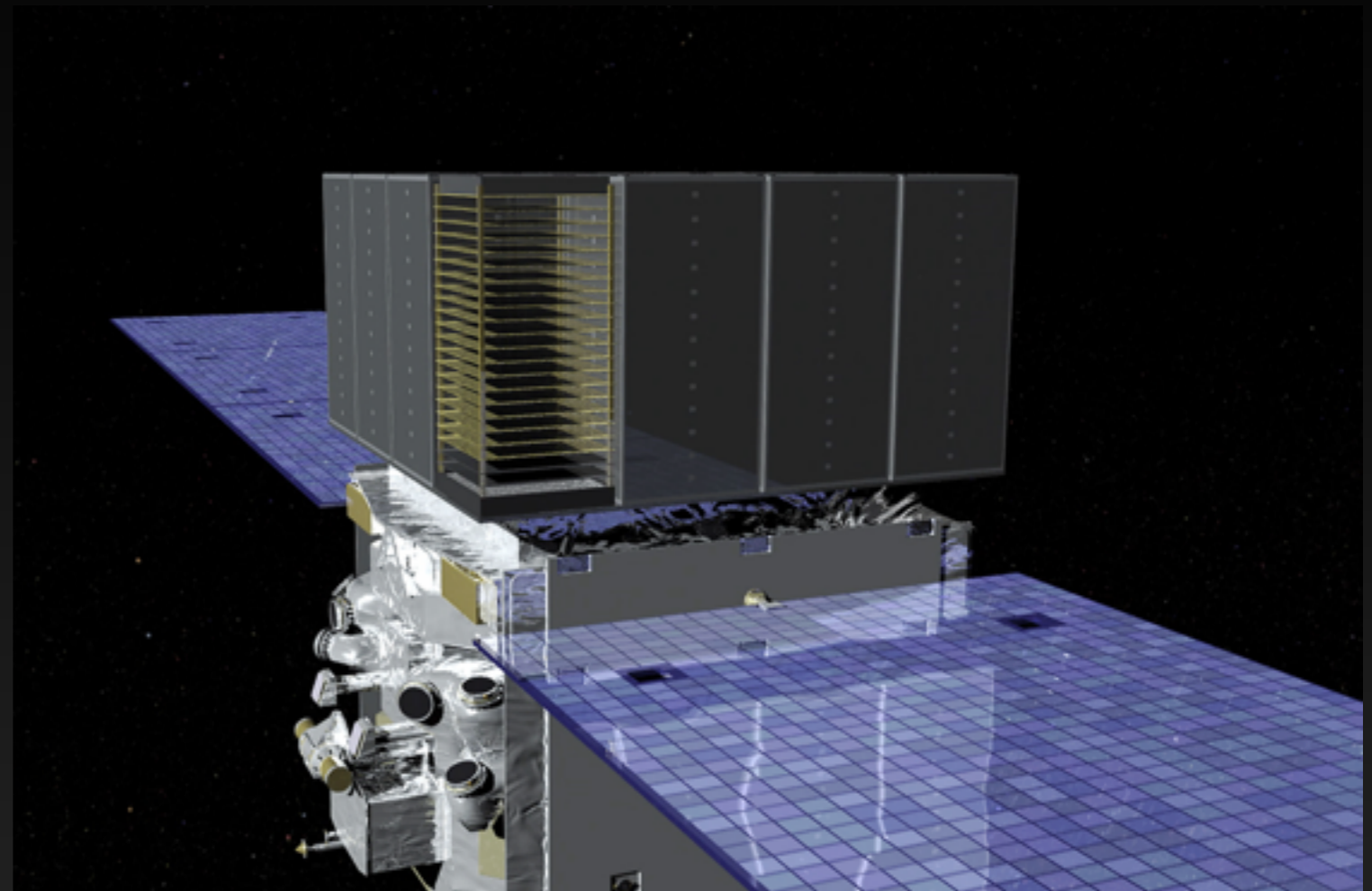


The Fermi Large Area Telescope

Launched: June 2008

**Observes Gamma-Rays with
Energies 30 MeV - 1 TeV**

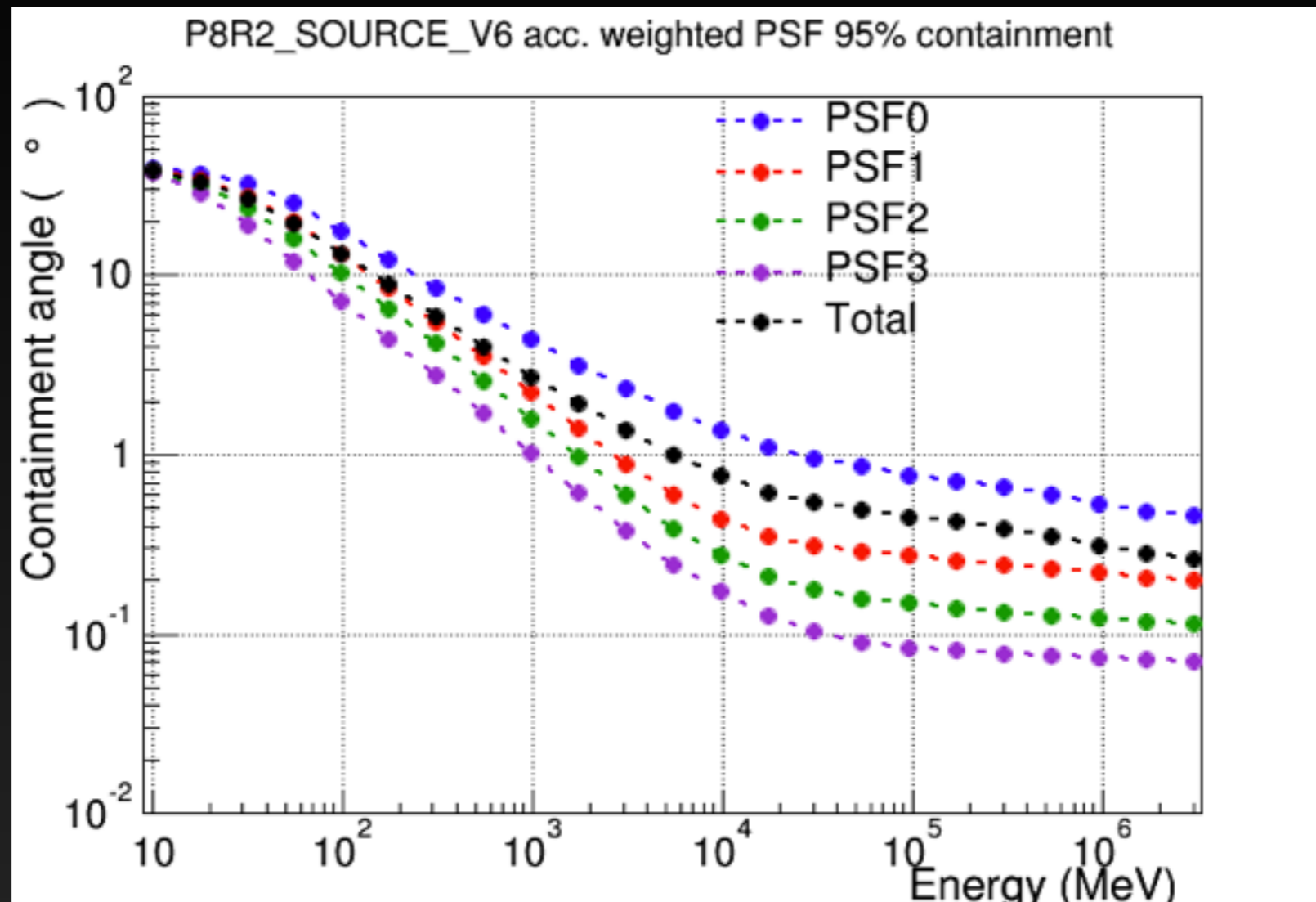
**Collaboration of five
countries and dozens of
institutions.**



Operational Characteristics:

- **Effective Area ~ 1 m²**
- **Field of View ~ 2 sr**
- **Energy Resolution ~ 10%**

Fermi-LAT Sensitivity to Dark Matter



Angular Resolution is:

- 1.) poor (compared to all other wavelengths).**
- 2.) highly energy dependent.**
- 3.) highly photon selection dependent.**

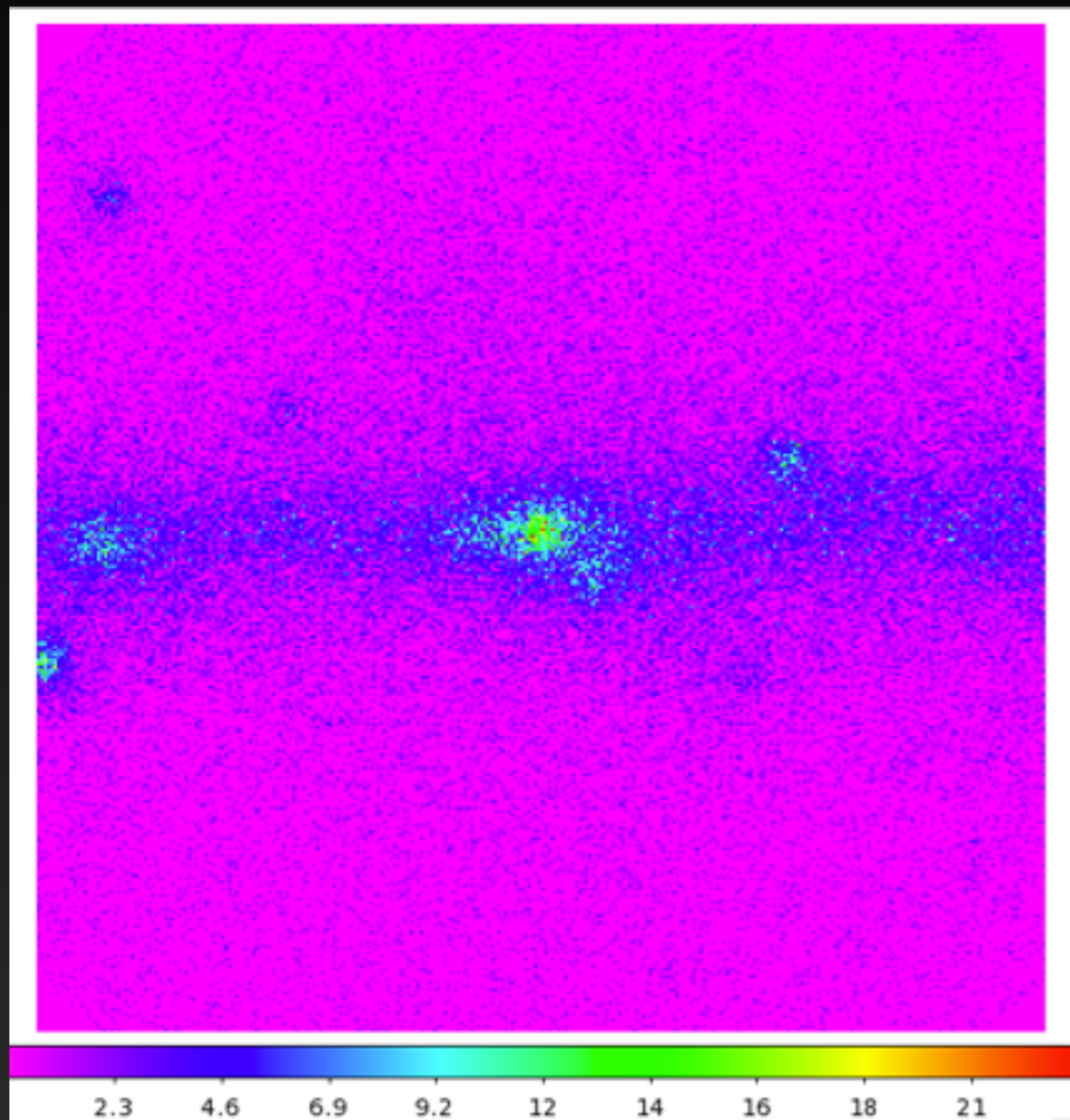
Why We're Doing What We're Doing....

- 1.) Dark Matter is a key component of the universe, and we know nothing about it.**
- 2.) WIMPs are a well-motivated model for a dark matter particle.**
- 3.) Observations of gamma rays from WIMP annihilations offers the opportunity to understand the dark matter particle.**
- 4.) The Milky Way Galactic Center is among the most promising targets for WIMP searches.**
- 5.) The Fermi-LAT instrument makes such an observation feasible (expected?).**

Many Studies

Goodenough & Hooper (2009)	0910.2998
Hooper & Goodenough (2011, PLB 697 412)	1010.2752
Hooper & TL (2011, PRD 84 12)	1110.0006
Abazajian & Kaplinghat (2012, PRD 86 8)	1207.6047
Hooper & Slatyer (2013, PDU 2 18)	1302.6589
Gordon & Macias (2013, PRD 8 8)	1306.5725
Macias & Gordon (2013, PRD 89 6)	1312.6671
Abazajian et al. (2014, PRD 90 2)	1402.4090
Daylan et al. (2014)	1402.6703
Calore et al. (2014)	1409.0042
Bartels et al. (2015)	1506.05104
Lee et al. (2015)	1506.05124
TL (2015)	1509.02928

How Does This Analysis Work?



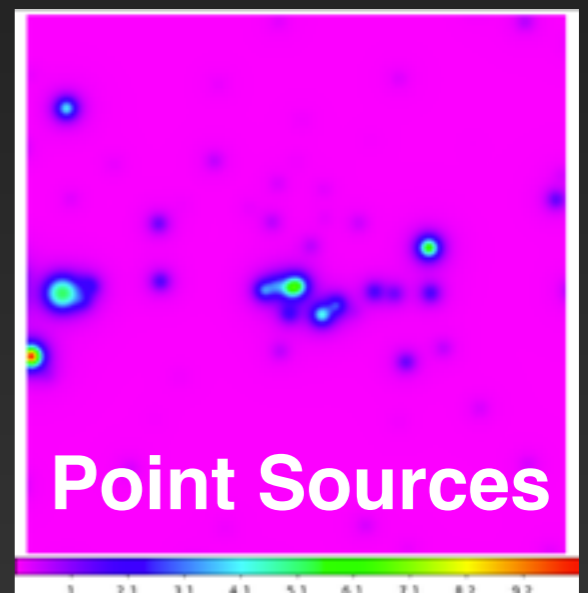
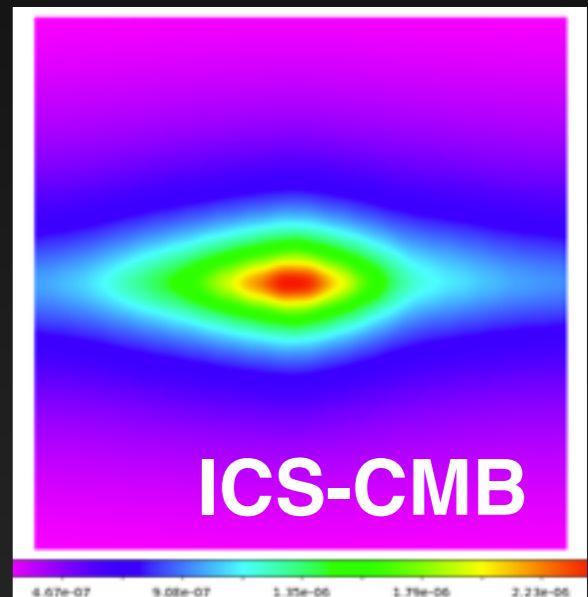
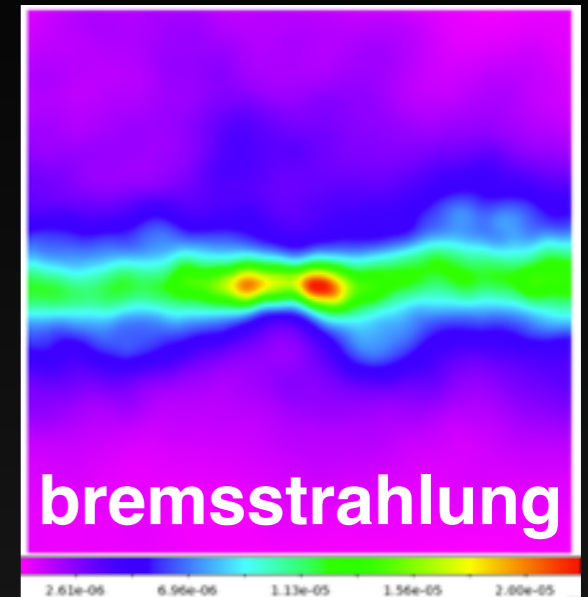
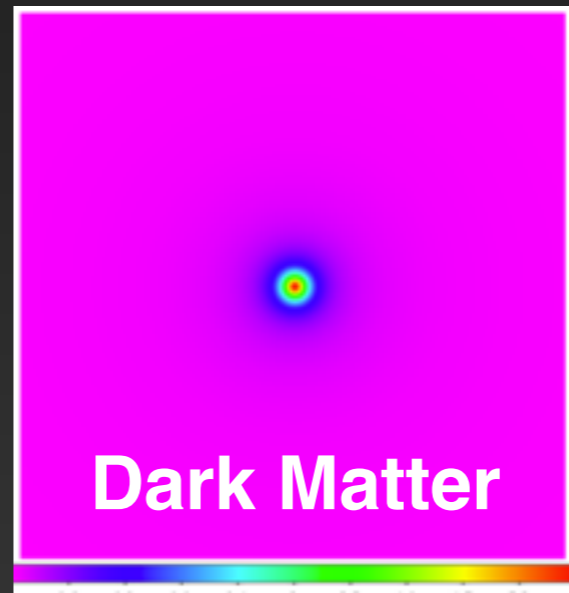
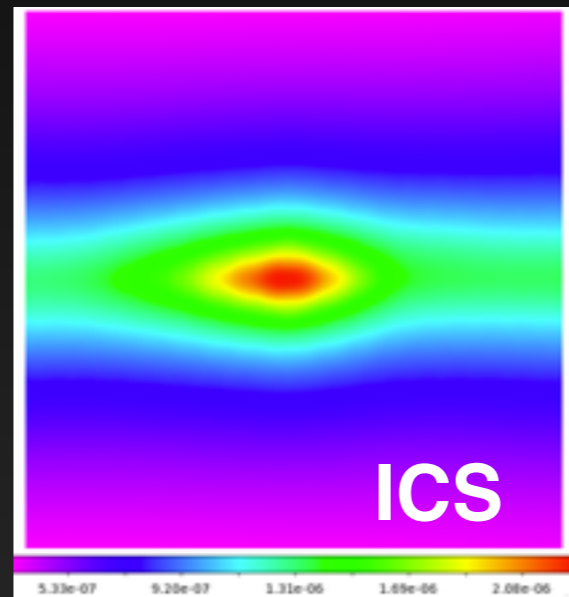
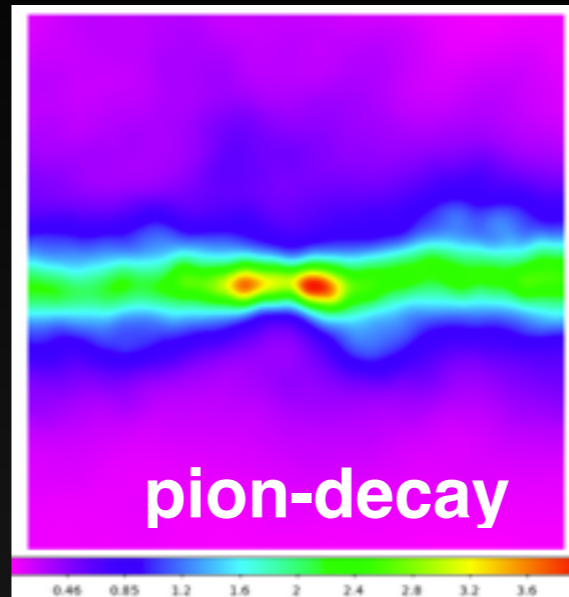
Data

750 — 950 MeV

Best Angular Resolution Cut

100 x 100 ROI

=



+

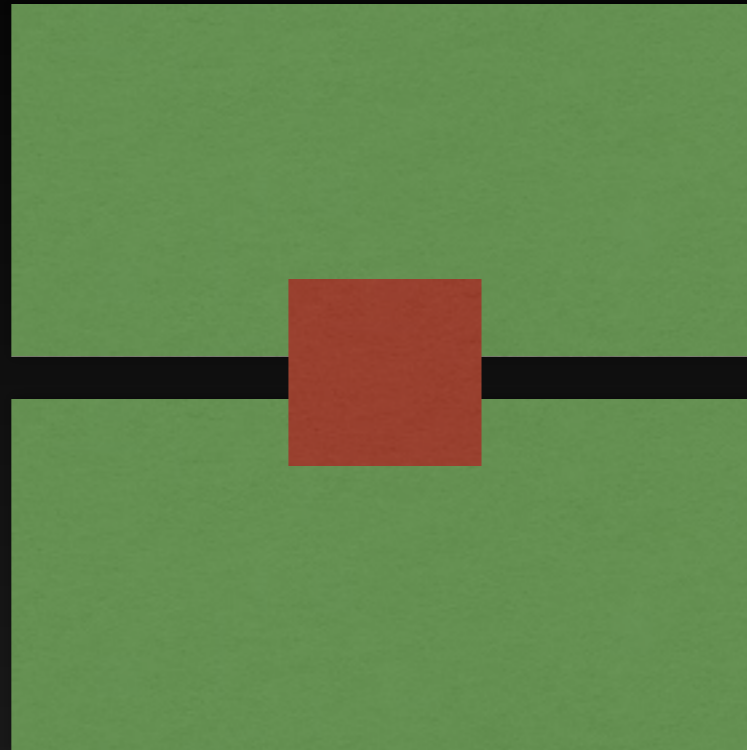
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How Does This Analysis Work?



Daylan et al. (2014)

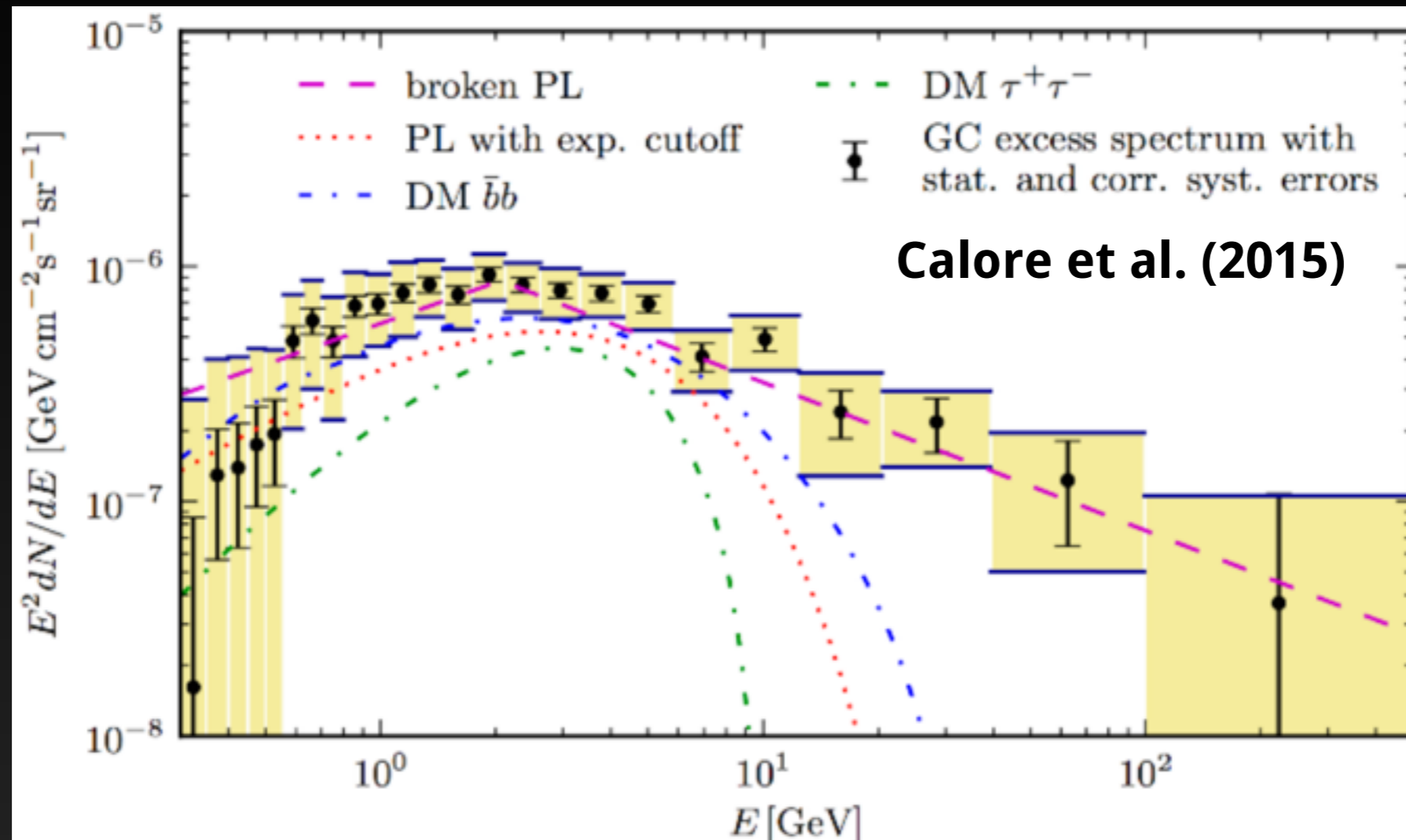
INNER GALAXY

- 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

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

Observational Results



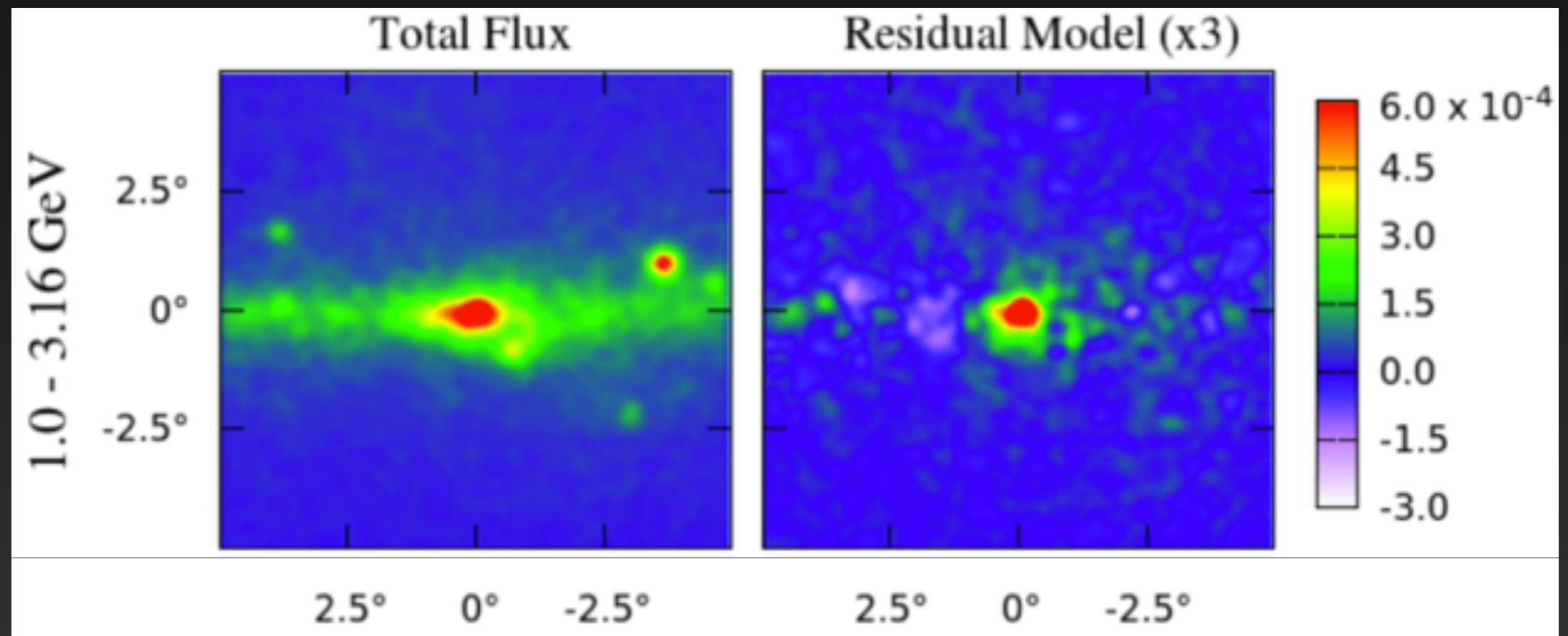
Spectral Model highly resilient to changing systematic background models ~300 models considered here.

**Low energy spectrum hard to constrain due to systematics
High energy spectrum difficult due to statistics**

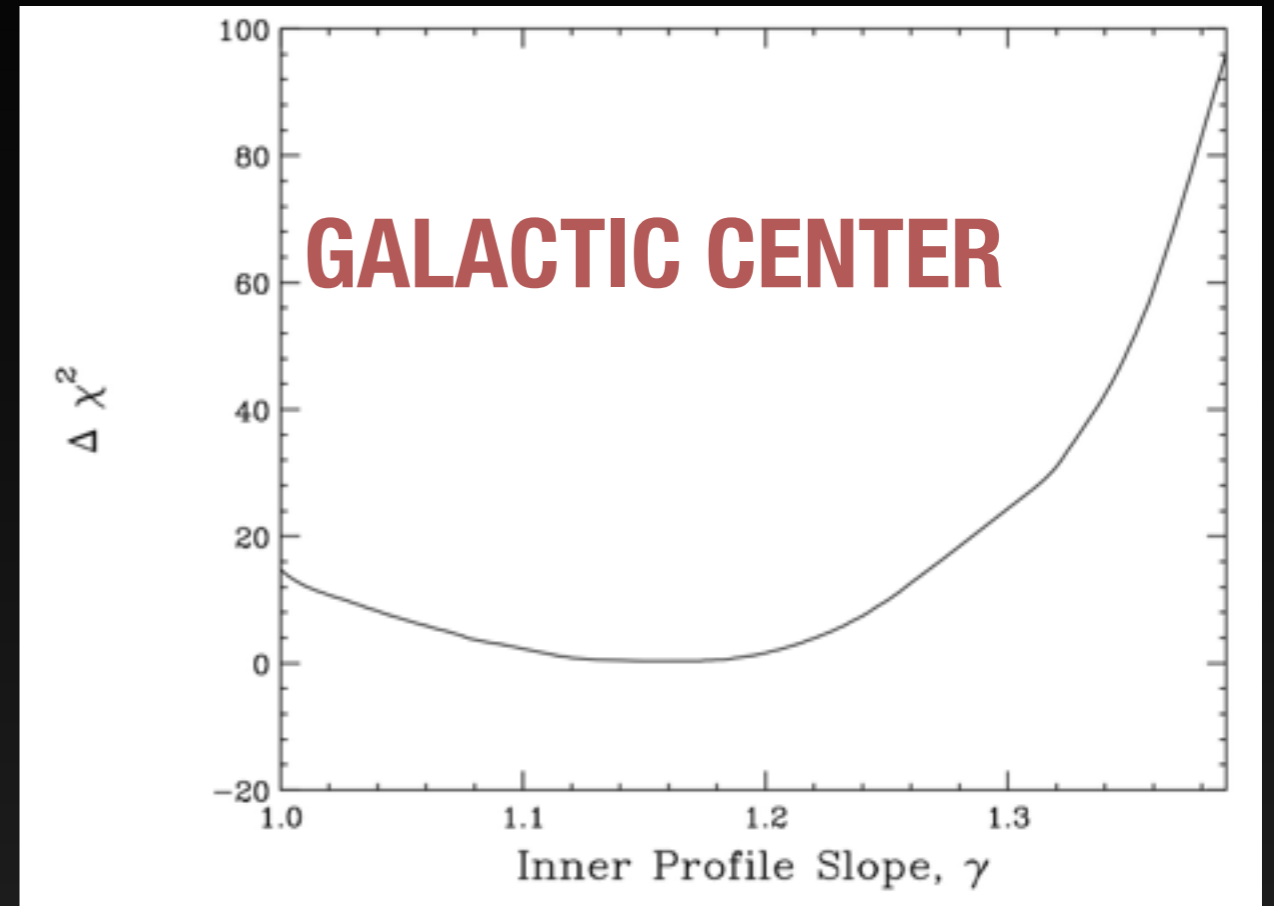
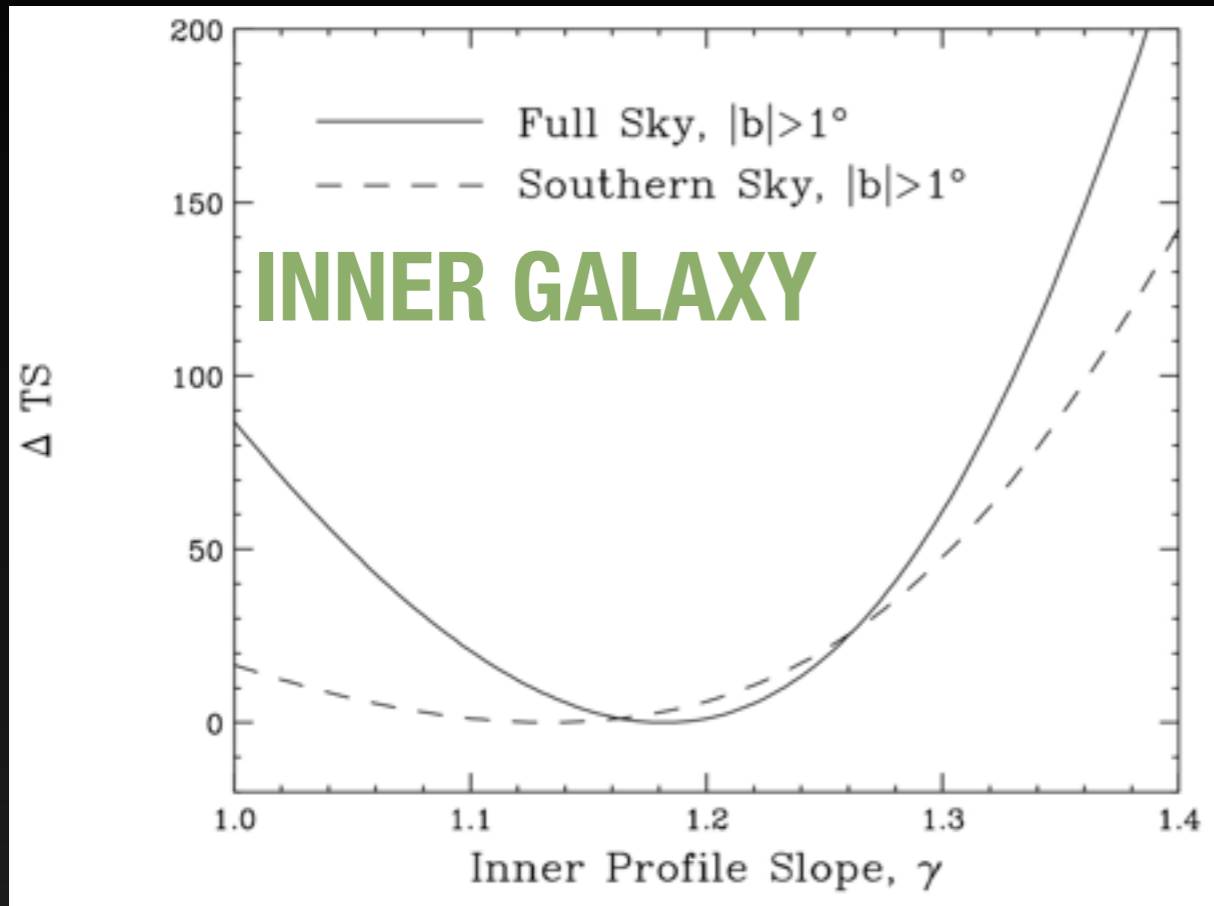
Observational Results

Utilizing our template fitting algorithm, we can determine the gamma-ray flux which is best fit by an NFW profile.

Subtracting off other astrophysical emission leaves a bright excess near the GC.



Observational Results

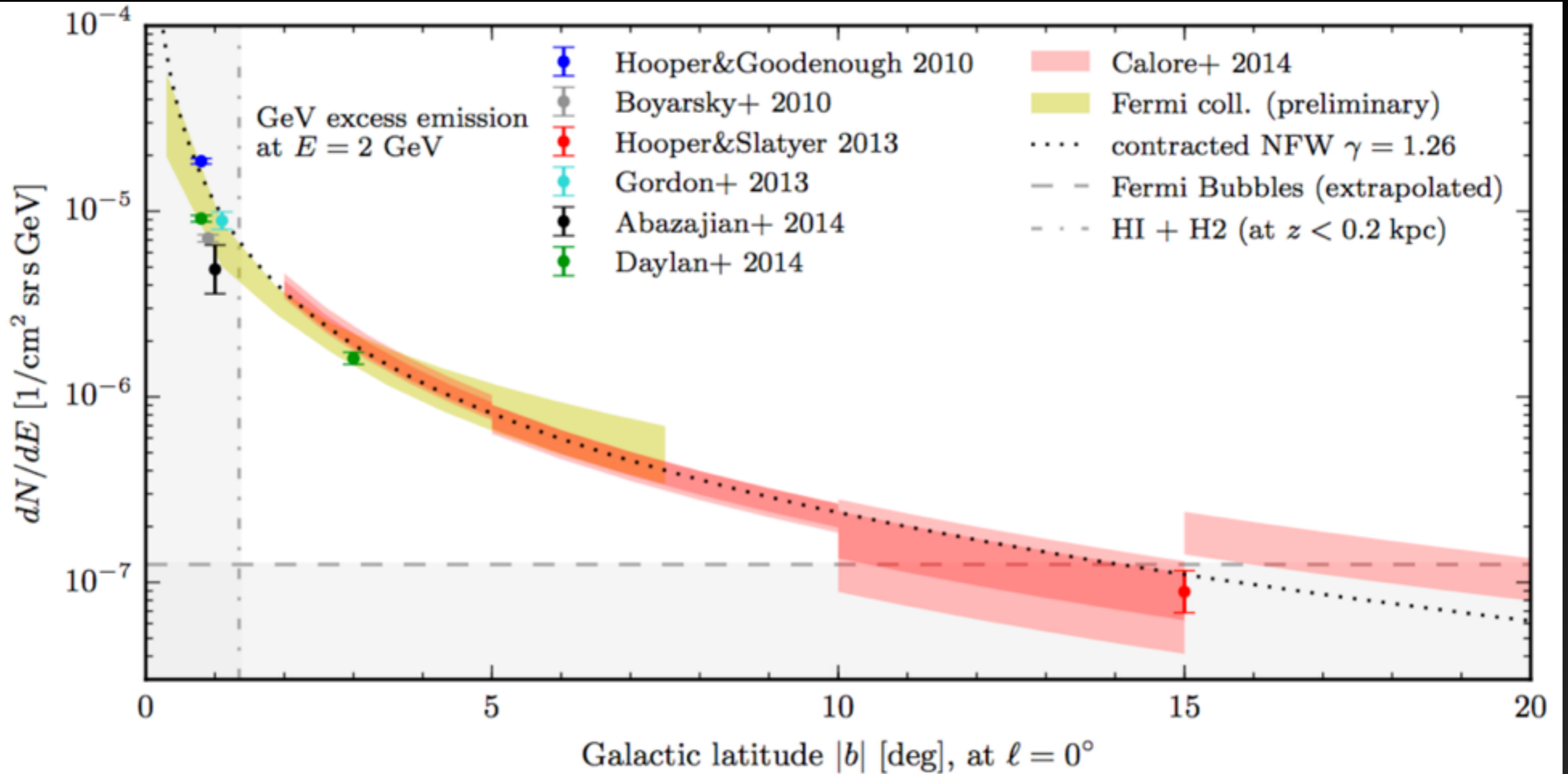


Inner galaxy prefers density profile $\gamma = 1.18$

Galactic Center prefers $\gamma = 1.17$

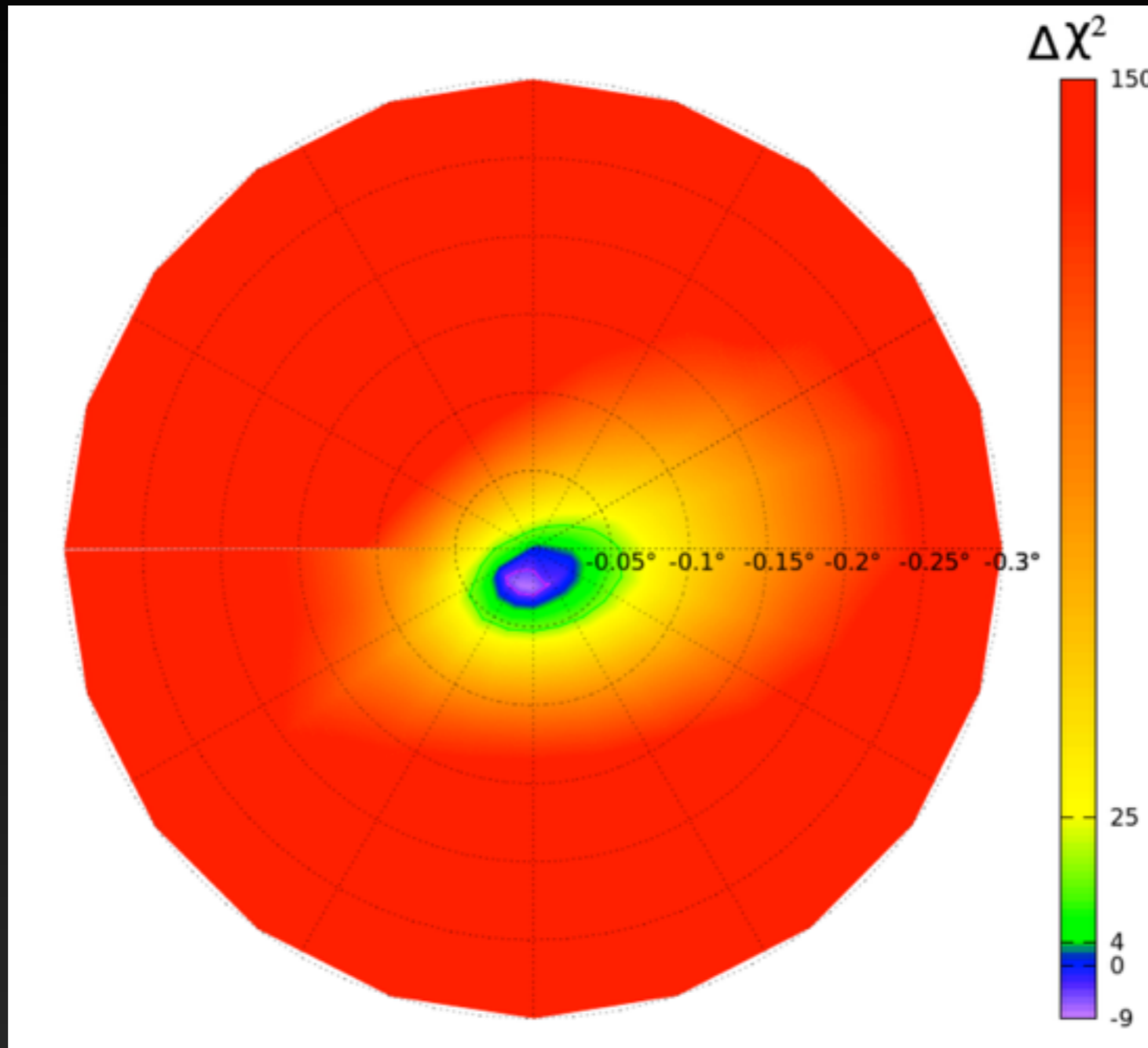
$$\rho_{\text{NFW}} = \left(\frac{r}{r_s} \right)^{-\gamma} \left(1 + \frac{r}{r_s} \right)^{-3+\gamma}$$

Observational Results



The GeV excess is statistically significant from 0.1° — 10° from the Galactic Center

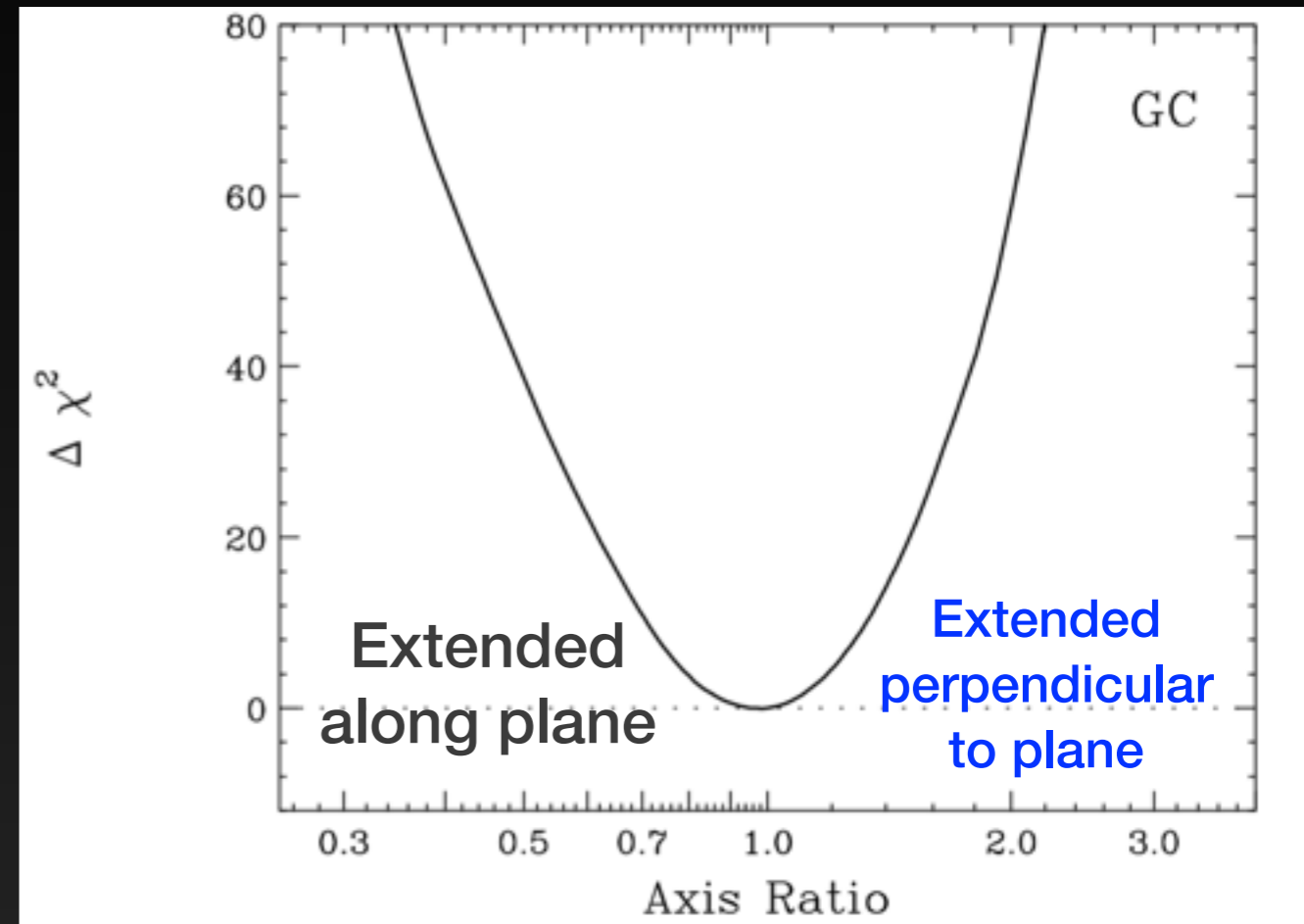
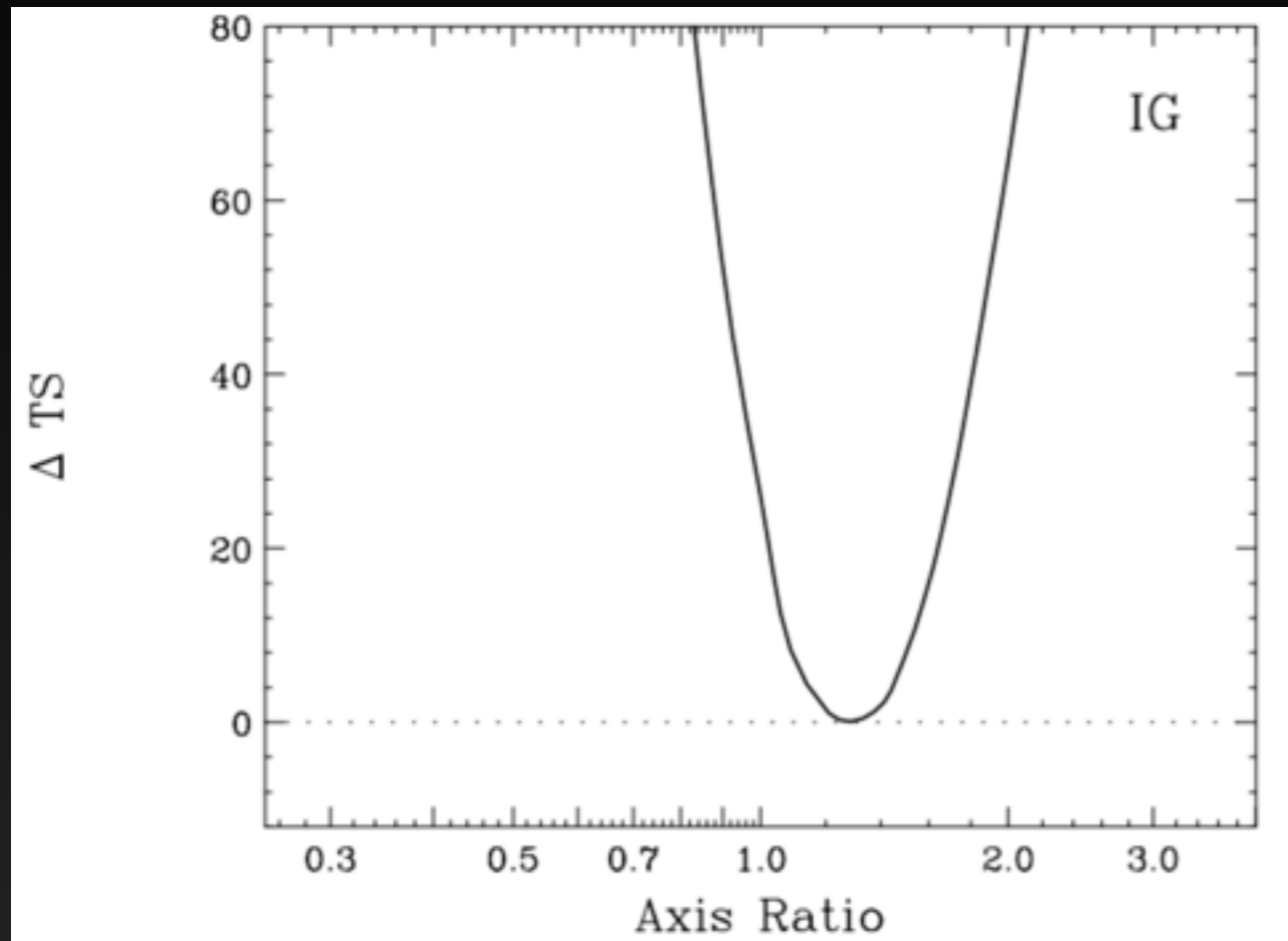
Observational Results



The peak of the new emission source lies within 0.05° of the GC.

Strong argument that this feature is dynamically centered on the GC in 3D space.

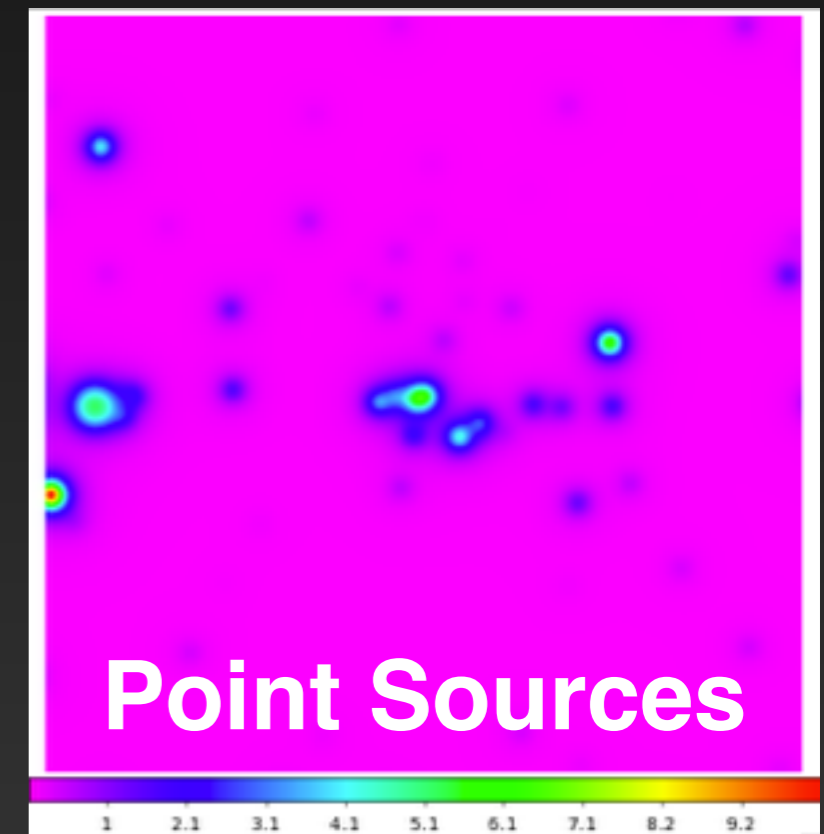
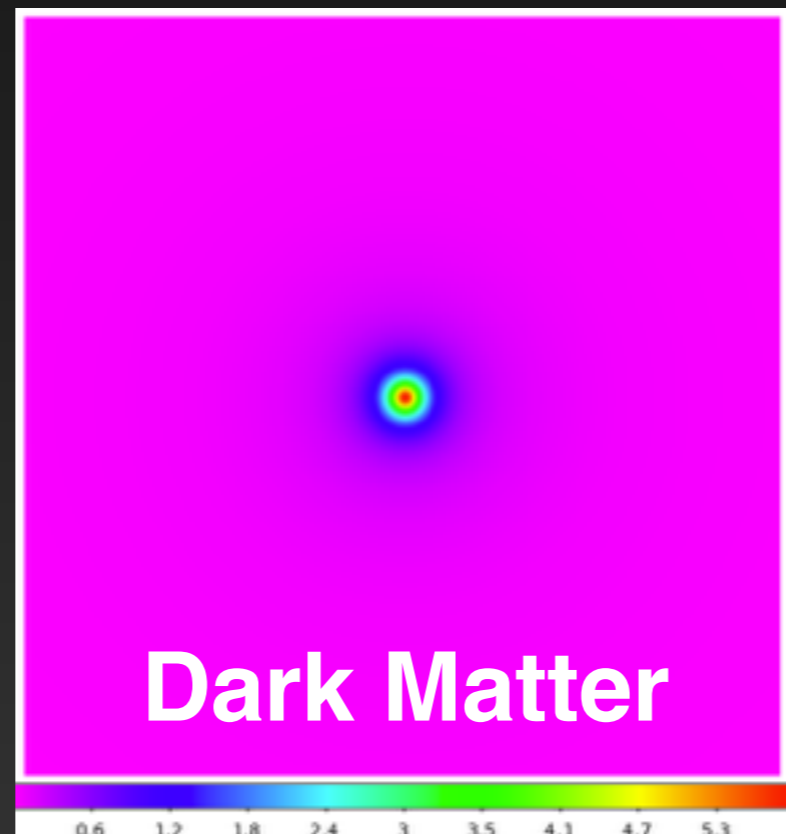
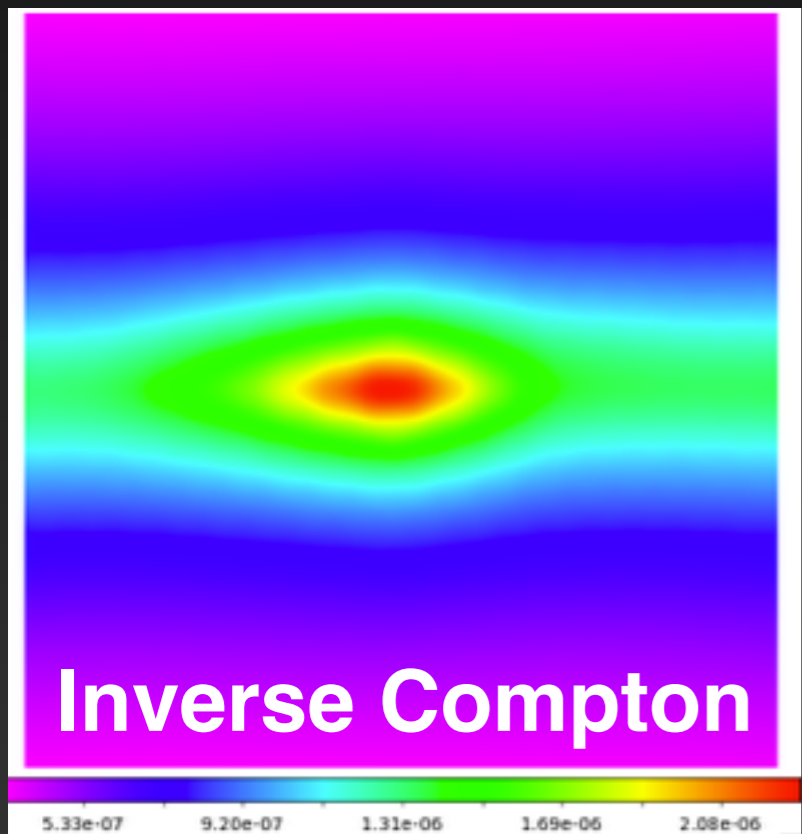
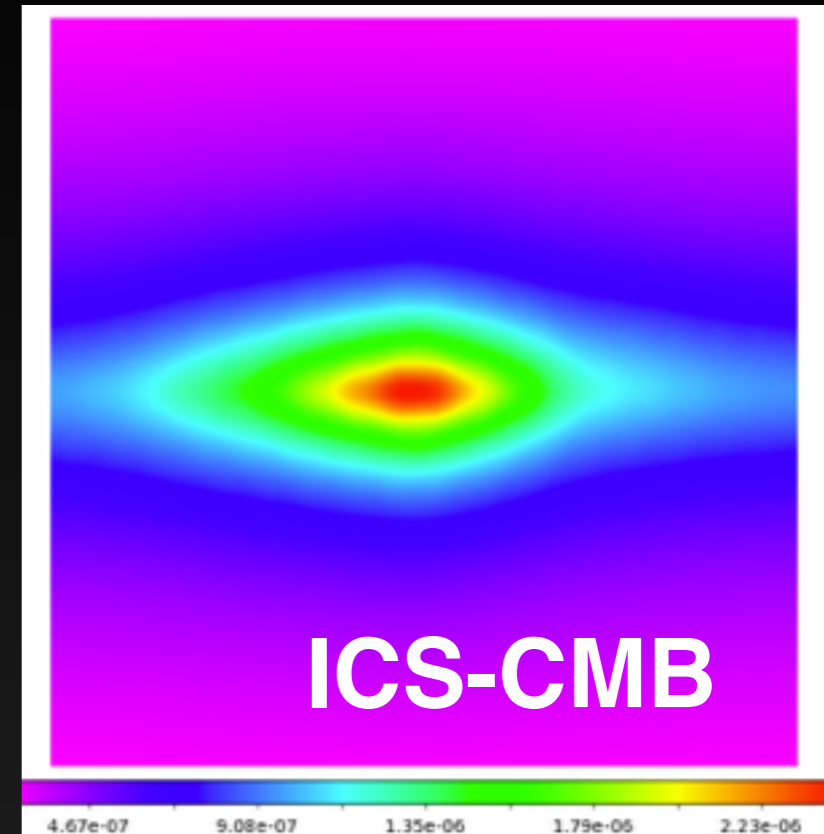
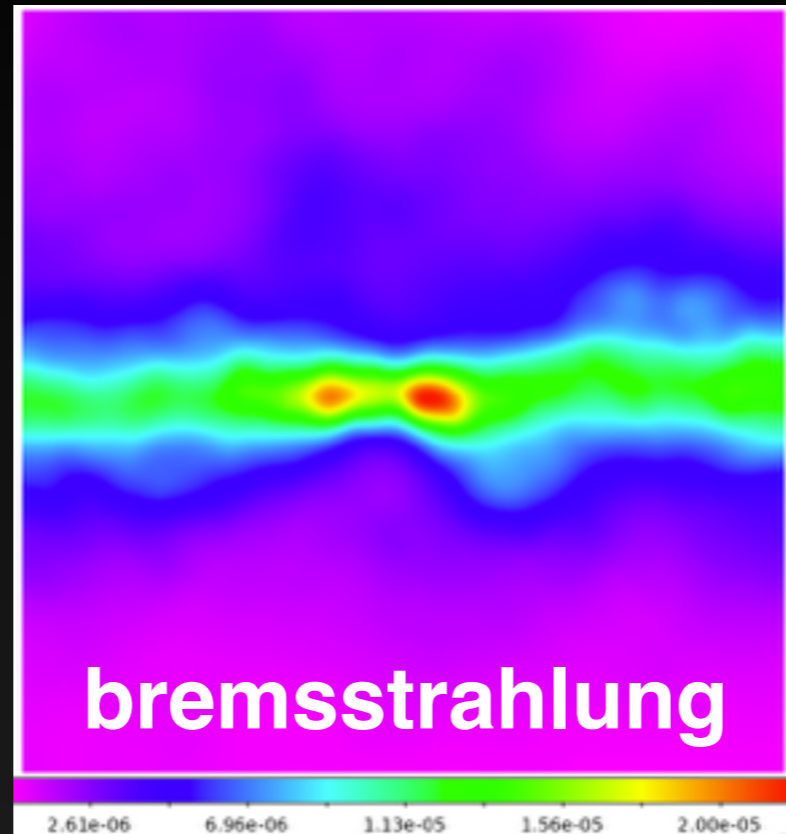
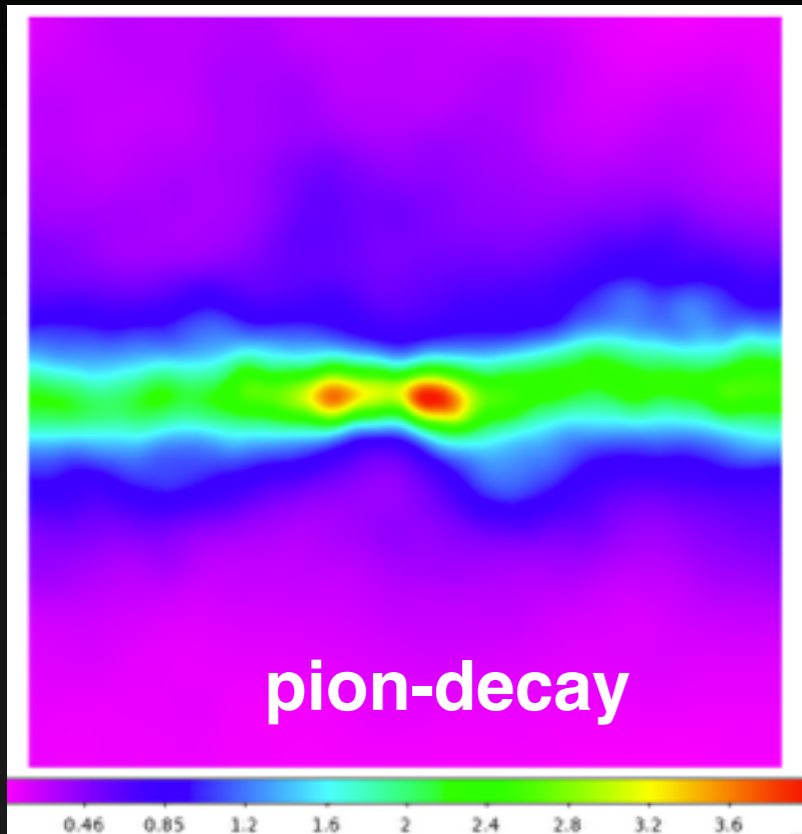
Observational Results



The Galactic Center analysis finds the excess to be spherically symmetric, to within approximately 20%.

The inner galaxy finds a weak preference for some extension perpendicular to the galactic plane.

Spherical Symmetry and the GCE

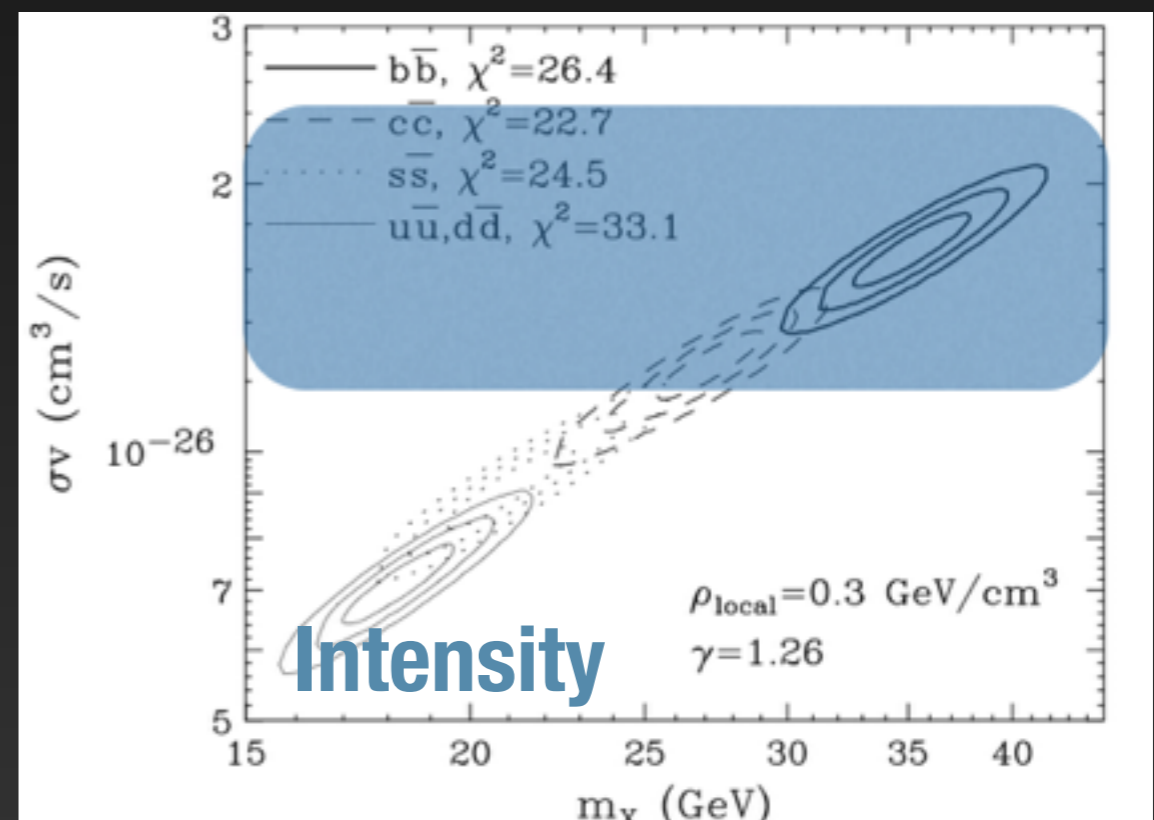
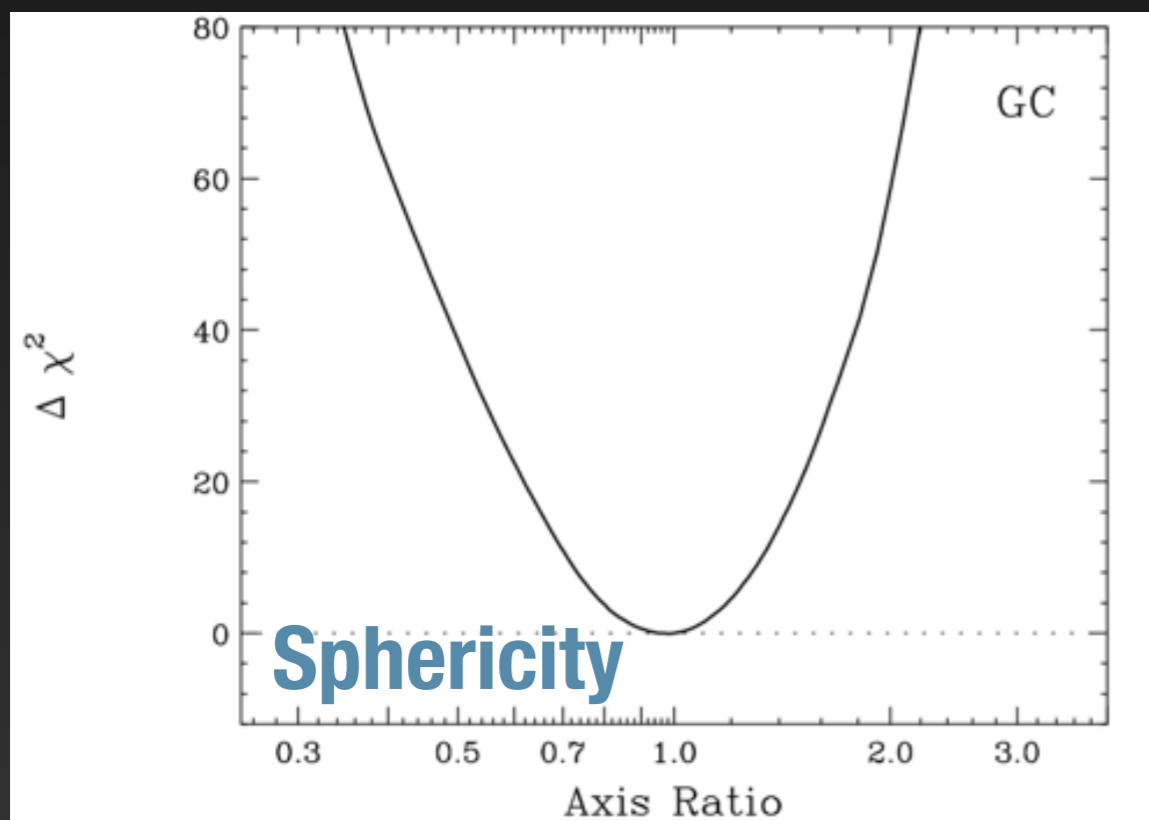
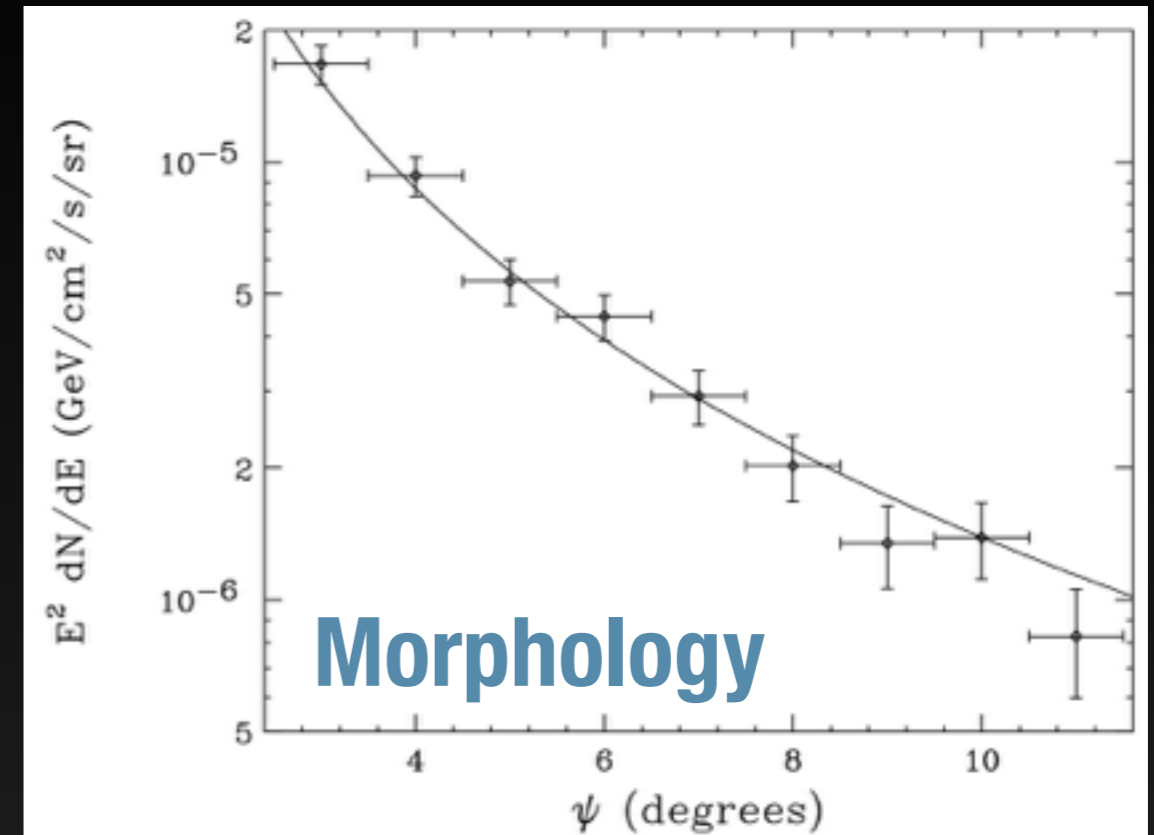
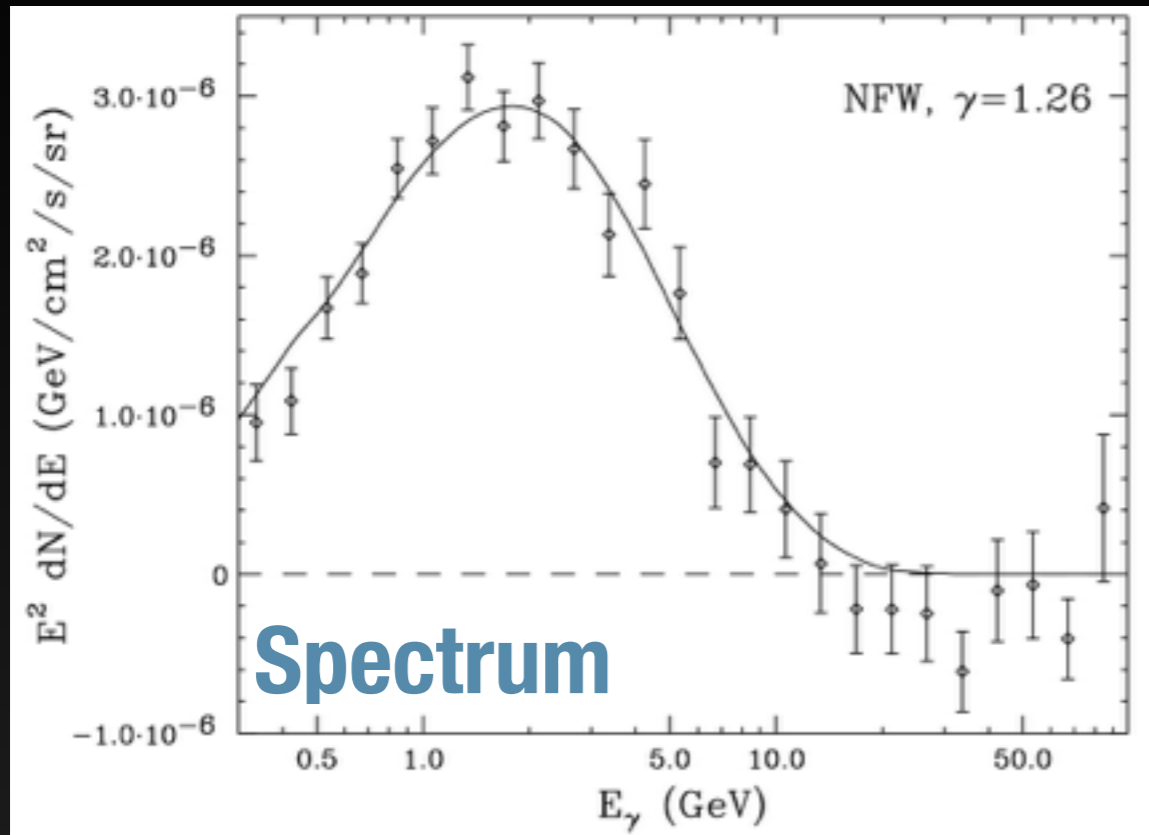


Summary of Data Analysis

All currently published observational studies of the Galactic Center excess agree:

- **Current best fit models of astrophysical gamma-ray emission have uncovered a gamma-ray excess - with a fractional intensity of ~15%**
- **The spectrum of the excess is peaked at an energy of ~2 GeV, and falls off at low energies with a spectrum that is harder than expected for astrophysical pion emission**
- **The excess extends to at least 10° away from the galactic center, following a 3D profile which falls in intensity as $r^{-2.2}$ to -2.8**

Comparison to Dark Matter Models



Comparison to Dark Matter Models

Freese et al. (1509.05076)
Bhattacharya et al. (1509.03665)
Algeri et al. (1509.01010)
Fox & Tucker-Smith (1509.00499)
Dutta et al. (1509.05989)
Liu et al. (1508.05716)
Berlin et al. (1508.05390)
Fan et al. (1507.06993)
Hektor et al. (1507.05096)
Achterbeg et al. (1507.04644)
Biswas et al. (1507.04543)
Butter et al. (1507.02288)
Mondal et al. (1507.01793)
Cao et al. (1506.06471)
Banik et al. (1506.05665)
Ipek (1505.07826)
Buchmueller et al. (1505.07826)
Balazs et al. (1505.06758)
Medina (1505.05565)
Kim et al. (1505.04620)
Ko et al. (1504.06944)
Ko & Tang (1504.03908)
Ghorbani & Ghorbani (1504.03610)
Fortes et al. (1503.08220)
Cline et al. (1503.08213)
Rajaraman et al. (1503.05919)
Bi et al. (1503.03749)
Kopp et al. (1503.02669)
Elor et al. (1503.01773)
Gherghetta et al. (1502.07173)
Berlin et al. (1502.06000)

Achterberg et al. (1502.05703)
Modak et al. (1502.05682)
Guo et al. (1502.00508)
Chen & Nomura (1501.07413)
Kozaczuk & Martin (1501.07275)
Berlin et al. (1501.03496)
Kaplinghat et al. (1501.03507)
Alves et al. (1501.03490)
Biswas et al. (1501.02666)
Ghorbani & Ghorbani (1501.00206)
Cerdeno et al. (1501.01296)
Liu et al. (1412.1485)
Hooper (1411.4079)
Arcadi et al. (1411.2985)
Cheung et al. (1411.2619)
Agrawal et al. (1411.2592)
Kile et al. (1411.1407)
Buckley et al. (1410.6497)
Heikinheimo & Spethmann (1410.4842)
Freytsis et al. (1410.3818)
Yu et al. (1410.3347)
Cao et al. (1410.3239)
Guo et al. (1409.7864)
Yu (1409.3227)
Cahill-Rowley et al. (1409.1573)
Banik & Majumdar (1408.5795)
Bell et al. (1408.5142)
Ghorbani (1408.4929)
Okada & Seto (1408.2583)
Frank & Mondal (1408.2223)
Baek et al. (1407.6588)

Tang (1407.5492)
Balazs & Li (1407.0174)
Huang et al. (1407.0038)
McDermott (1406.6408)
Cheung et al. (1406.6372)
Arina et al. (1406.5542)
Chang & Ng (1406.4601)
Wang & Han (1406.3598)
Cline et al. (1405.7691)
Berlin et al. (1405.5204)
Mondal & Basak (1405.4877)
Martin et al. (1405.0272)
Ghosh et al. (1405.0206)
Abdullah et al. (1404.5503)
Park & Tang (1404.5257)
Cerdeno et al. (1404.2572)
Izaguirre et al. (1404.2018)
Agrawal et al. (1404.1373)
Berlin et al. (1404.0022)
Alves et al. (1403.5027)
Finkbeiner & Weiner (1402.6671)

Trying to Kill the Beast

Astrophysical mechanisms might also explain the excess!

1.) What if there is a new population of point sources near the galactic center?

2.) What if our best models for diffuse astrophysical emission are wrong?

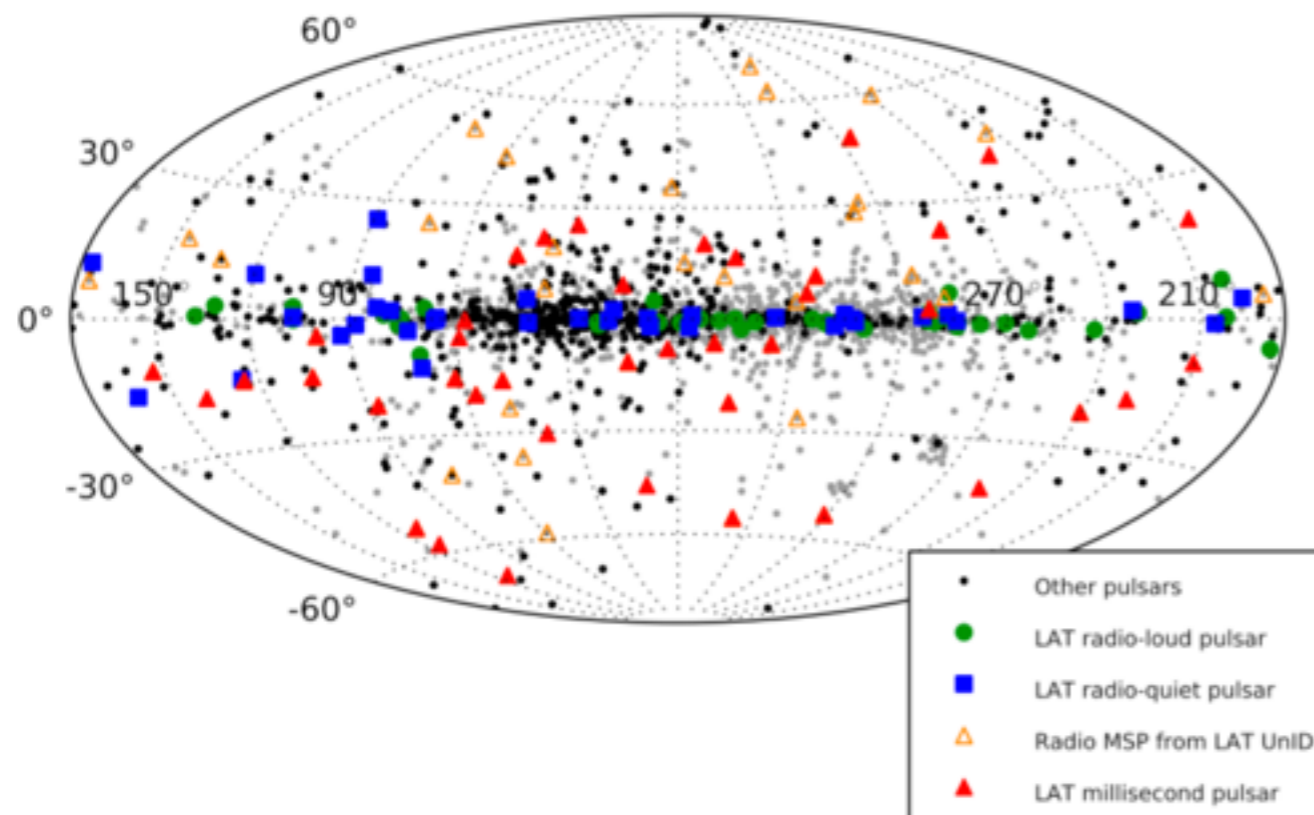
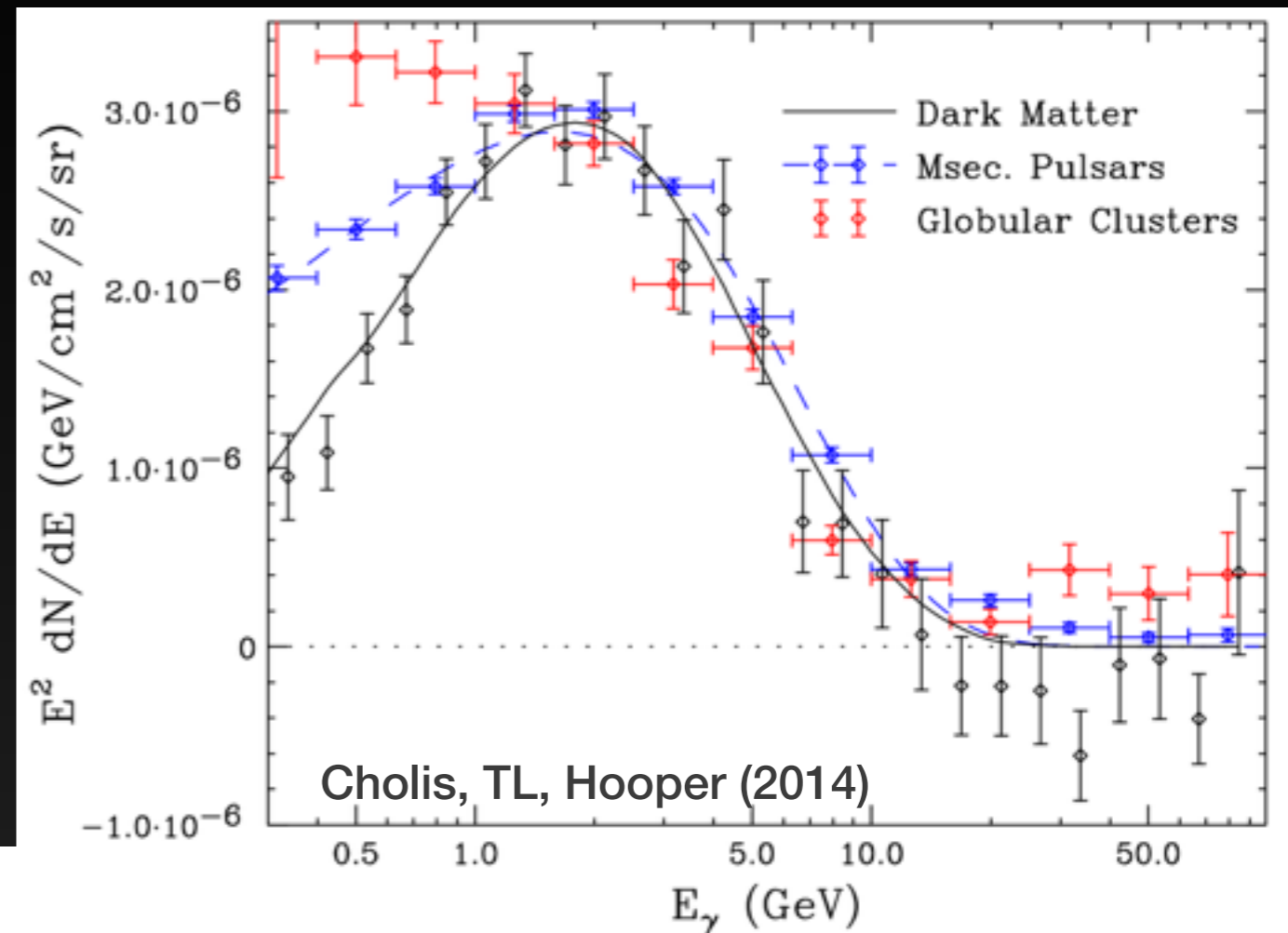
3.) What if the galactic center has a complex/active past?

To some extent, all three of these are certainly true. So a better question is:

Can uncertainties in our astrophysical modeling plausibly explain the Galactic Center observations?

Pulsars in the Galactic Center

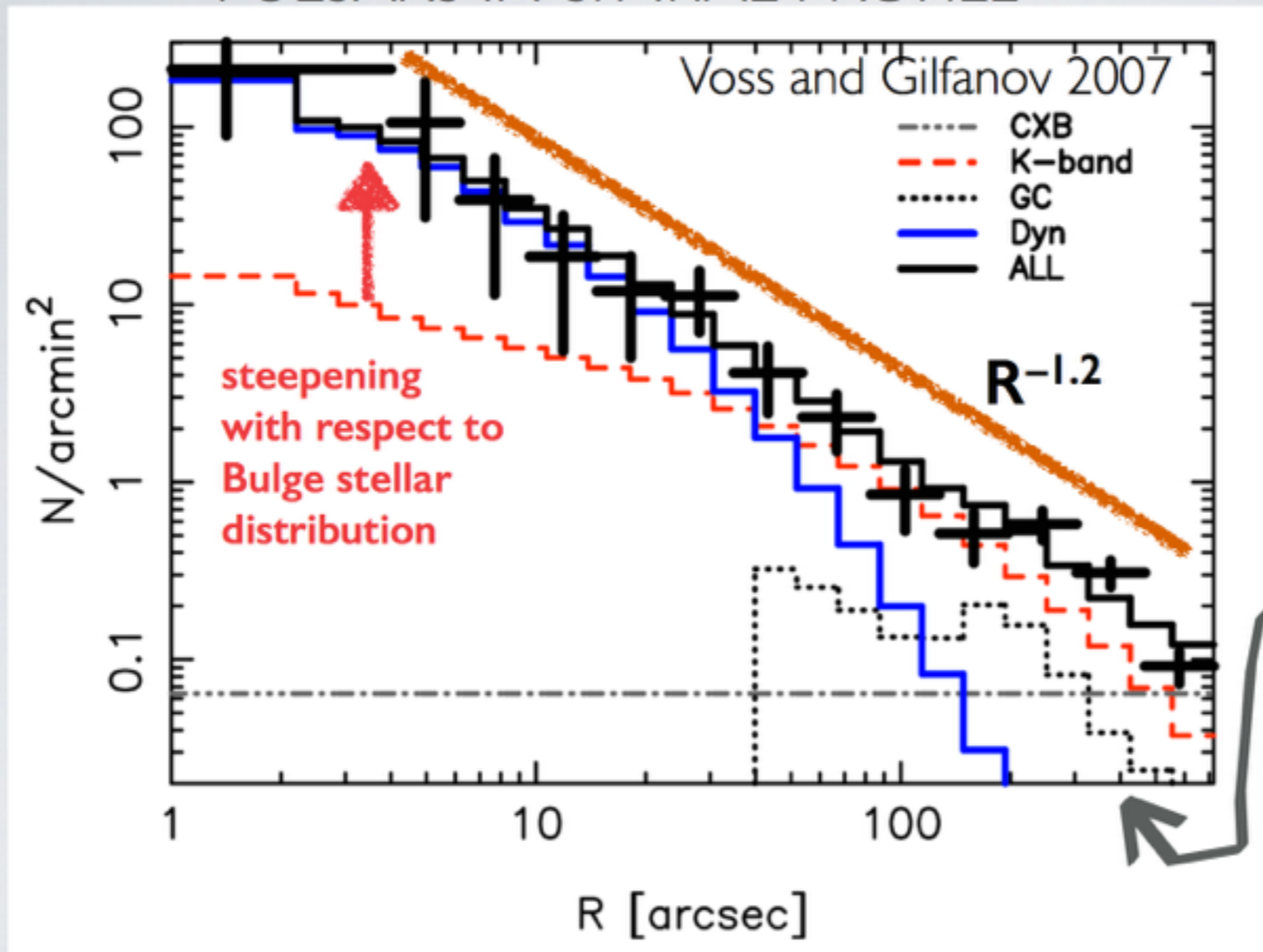
- The peak of the MSP energy spectrum matches the peak of the GeV excess



- MSPs are thought to be overabundant in dense star-forming regions like the Galactic Center

Pulsars in the Galactic Center

DEGENERACY WITH MILLI-SECOND PULSARS IN SPATIAL PROFILE



We make the reasonable assumption that Low-Mass X-ray Binaries have the same spatial distribution as MSPs

400'' towards M31 center =
1.5 kpc distance from center =
10 degrees towards MW center

Orange line is same as best-fit excess template ($R^{-1.2}$ in projection implies $r^{-2.2}$ de-projected)!

Slide from Manoj Kaplinghat

Pulsars in the Galactic Center

Recent Provocative Paper claims evidence for such a population of undetected point sources.

Normally, a Log-Likelihood for a fit to the data is calculated by assuming that the data is generated by a Poisson random process:

$$p_k^{(p)} = \frac{(\mu_p)^k e^{-\mu_p}}{k!}$$

Evidence for Unresolved Gamma-Ray Point Sources in the Inner Galaxy
Samuel K. Lee,^{1,2} Mariangela Lisanti,³ Benjamin R. Safdi,⁴ Tracy R. Slatyer,⁴ and Wei Xue⁴
¹Princeton Center for Theoretical Science, Princeton University, Princeton, NJ 08544
²Broad Institute, Cambridge, MA 02142
³Department of Physics, Princeton University, Princeton, NJ 08544
⁴Massachusetts Institute of Technology, Cambridge, MA 02139
(Dated: July 1, 2015)

A new method to characterize unresolved point sources (PSs), generalizing traditional methods for non-Poissonian photon statistics. We apply this method to Fermi-LAT gamma-ray data to characterize PS populations at high latitudes and in the energy range ~ 1.9 to 11.9 GeV. Within 10° of the total PSs (resolved and unresolved) account for $\sim 50\%$ of the total flux. $5-10\%$ of the flux can be accounted for by a population of $\sim 10^4$ PSs, in preference to dark-matter annihilation. This population of threshold sources, which may be detected by a population of $\sim 0.5^\circ$ to 1° point-spread functions, is consistent with the data.

Pulsars in the Galactic Center

Instead, Lee et al. add a non-Poissonian term into the Likelihood calculation, and calculate the relative weight of the Poisson and non-Poissonian errors on a pixel by pixel basis.

$$\mathcal{P}^{(p)}(t) = \mathcal{D}^{(p)}(t) \cdot \mathcal{G}^{(p)}(t)$$

$$p_k^{(p)} = \frac{1}{k!} \left. \frac{d^k \mathcal{P}^{(p)}}{dt^k} \right|_{t=0}$$

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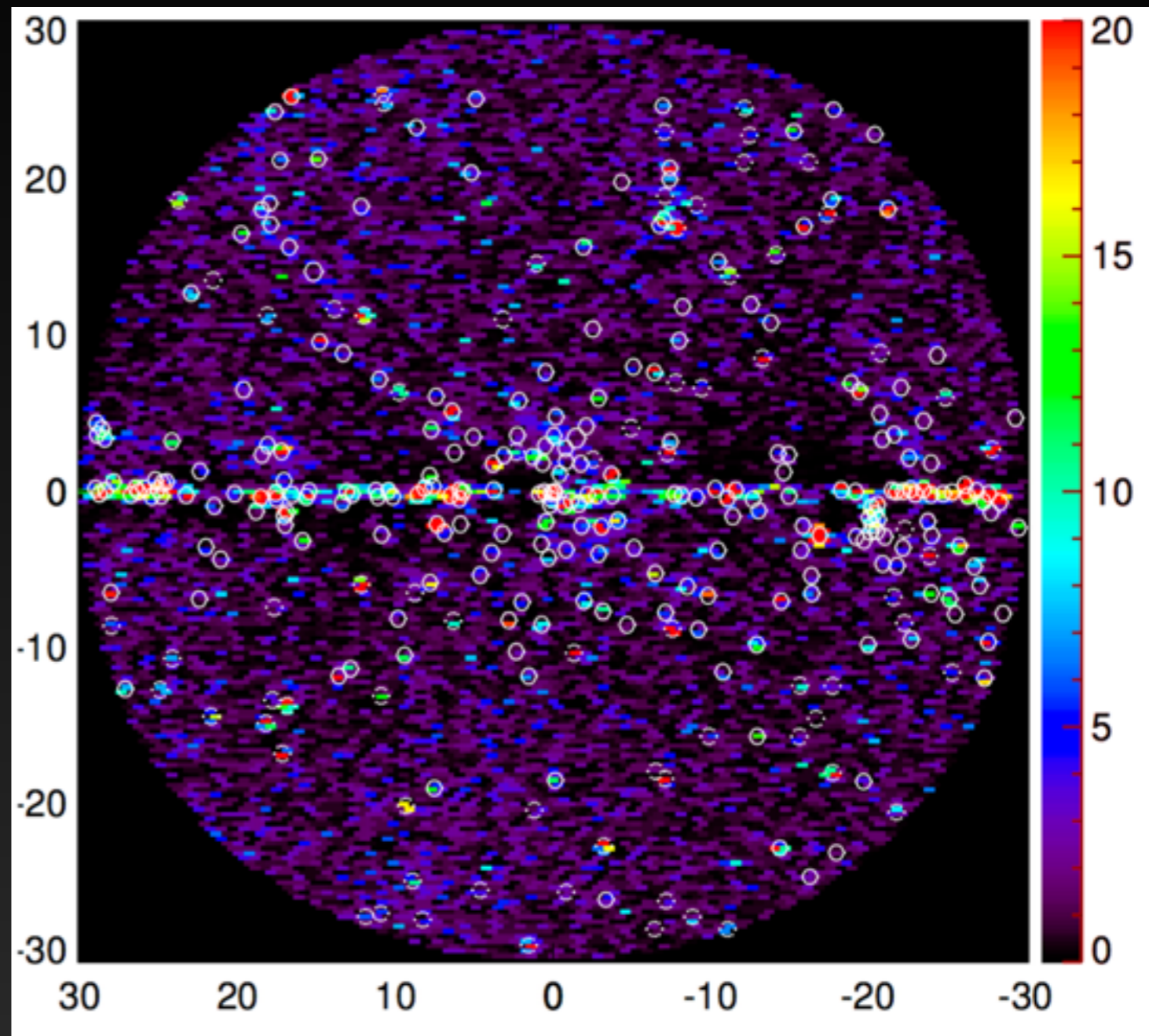
(Dated: July 1, 2015)

A new method to characterize unresolved point sources (PSs), generalizing traditional gamma-ray data to characterize PS populations at high latitudes and in PSs (resolved and unresolved) account for ~50% of the total flux in the energy range ~1.9 to 11.9 GeV. We apply this method to Fermi-LAT data to characterize PS populations at high latitudes and in PSs (resolved and unresolved) account for ~50% of the total flux in the energy range ~1.9 to 11.9 GeV. Within 10° of the Galactic Center, in preference to dark-matter annihilation, the observed ~GeV gamma-ray excess can be accounted for by a population of threshold sources, which may be detected by a population of point-spread functions of the data.

Pulsars in the Galactic Center

In each pixel, you can calculate the probability that the data is explained by Poisson variations, or whether a non-Poissonian variation is required.

The circled areas correspond to known Fermi-LAT point sources.



Lee et al. (2015)

Can produce skymaps and flux distributions of non-Poissonian emission, and see how this absorbs the point-to-point variations.

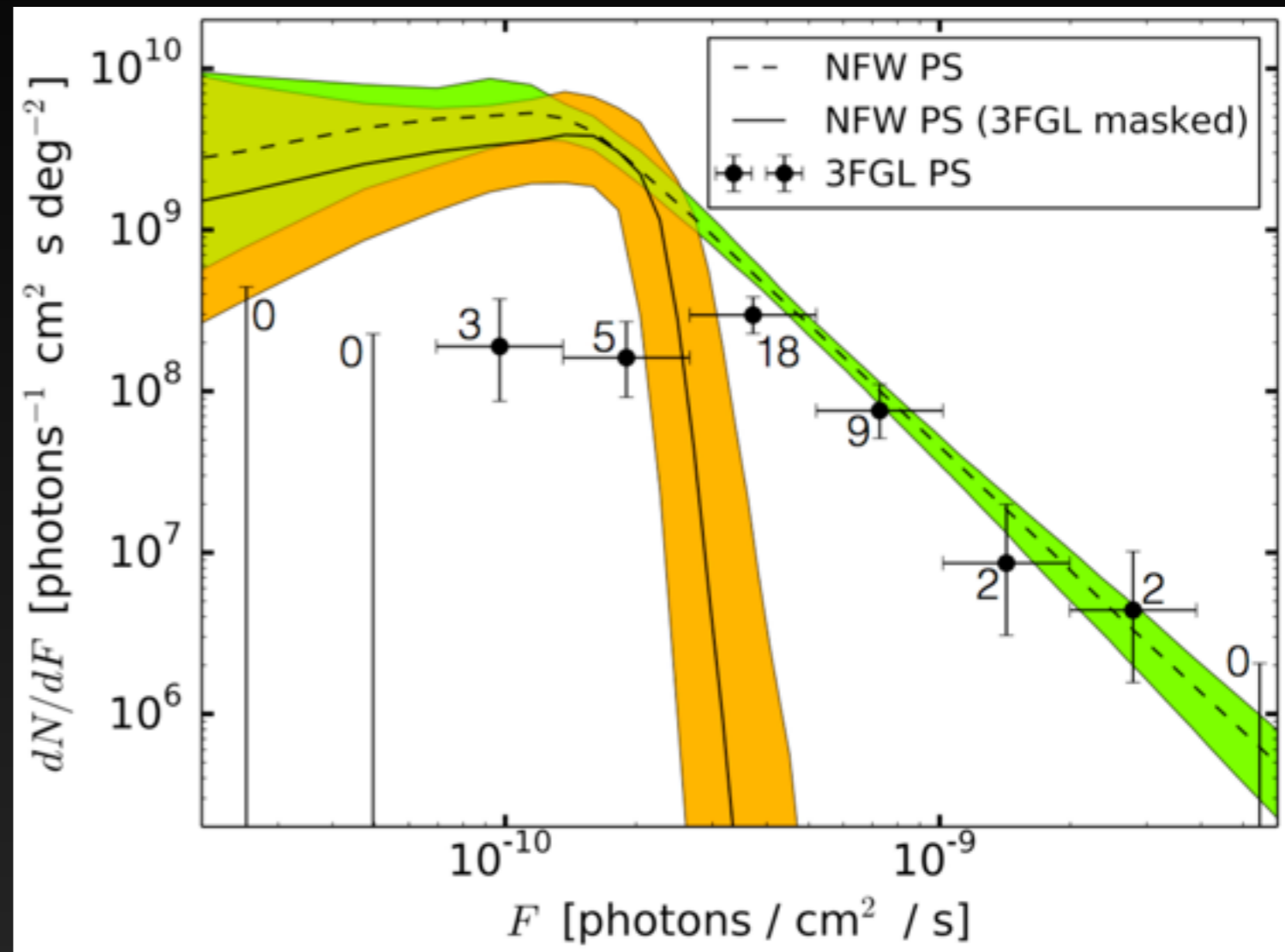
Pulsars in the Galactic Center

Method:

1.) Add in a new template that has the global morphology of the NFW template, but contributes with non-Poissonian statistics.

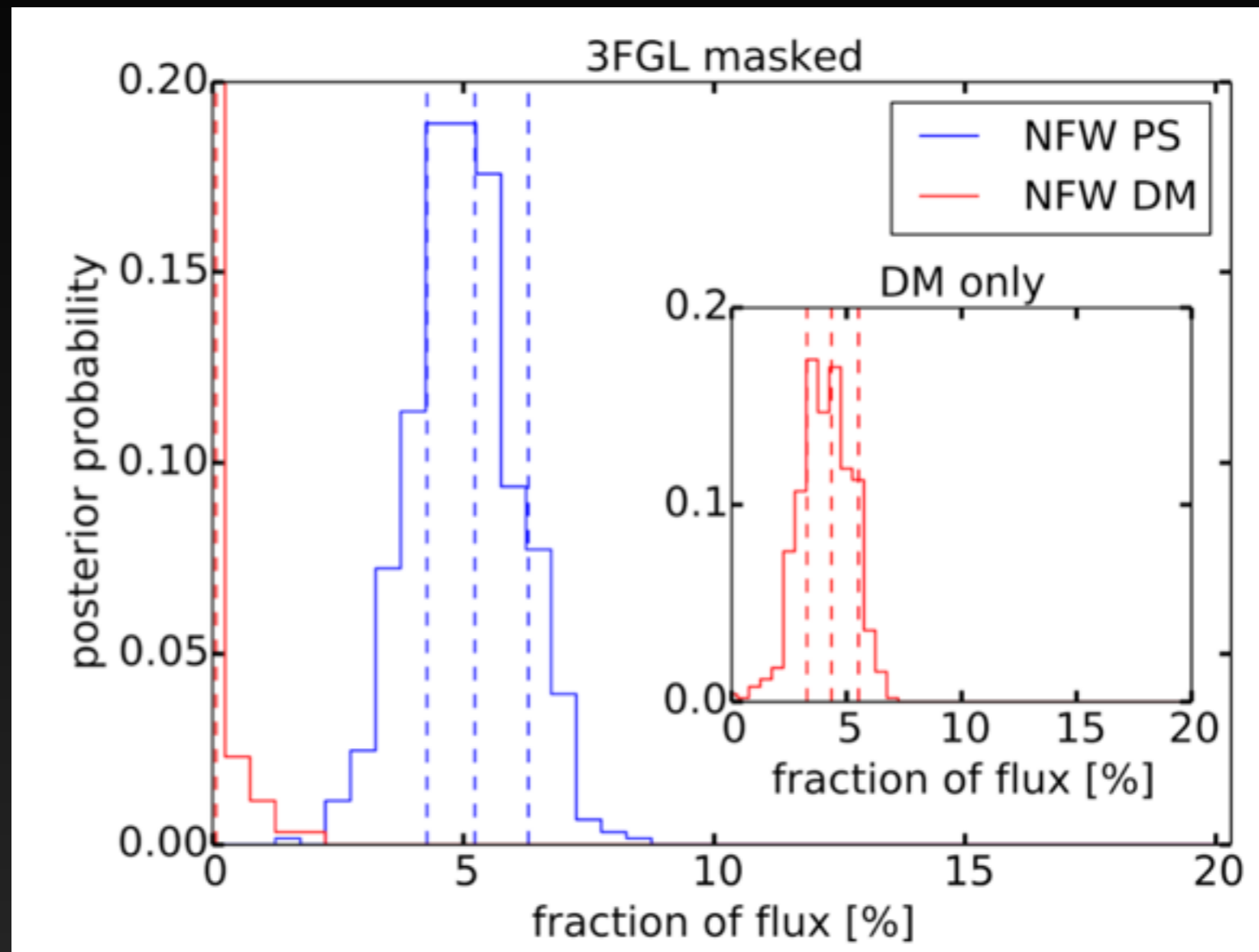
2.) Fit data to the GC excess.

3.) Find the flux distribution of non-Poissonian datapoint near the Galactic Center



Lee et al. (2015)

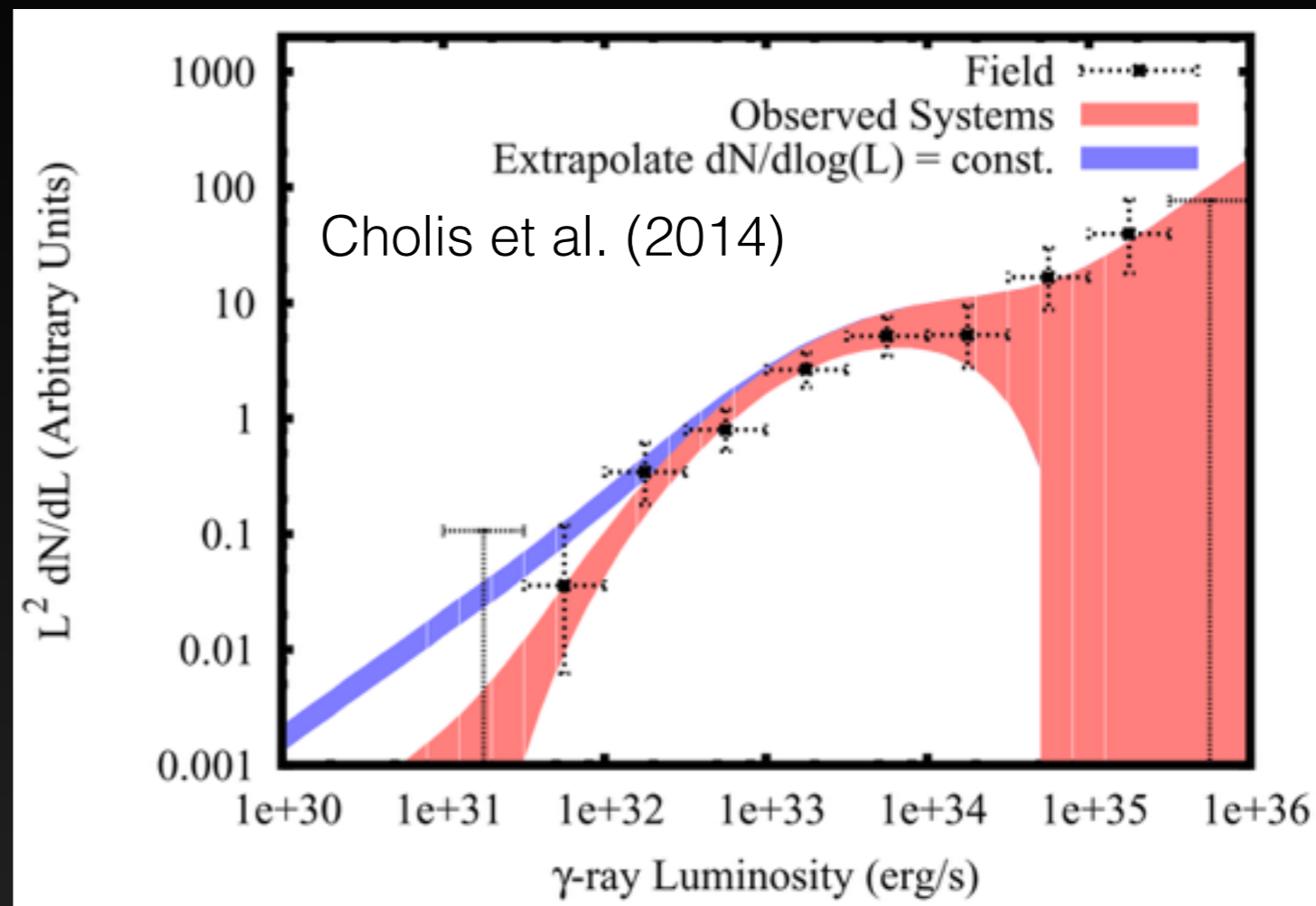
Pulsars in the Galactic Center



When both a traditional NFW template and the non-Poissonian NFW template are allowed to float arbitrarily, the non-Poissonian template absorbs the gamma-ray excess.

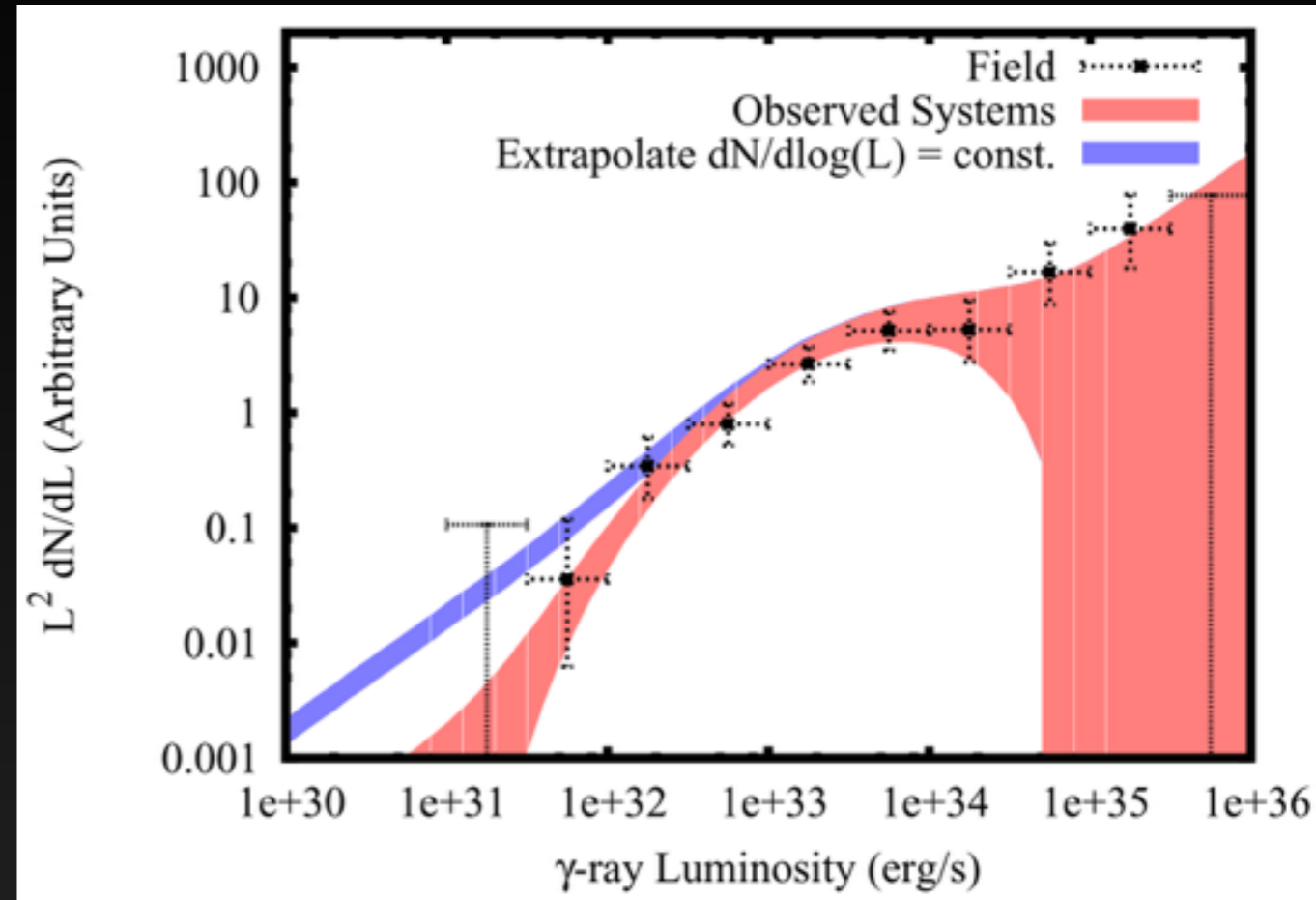
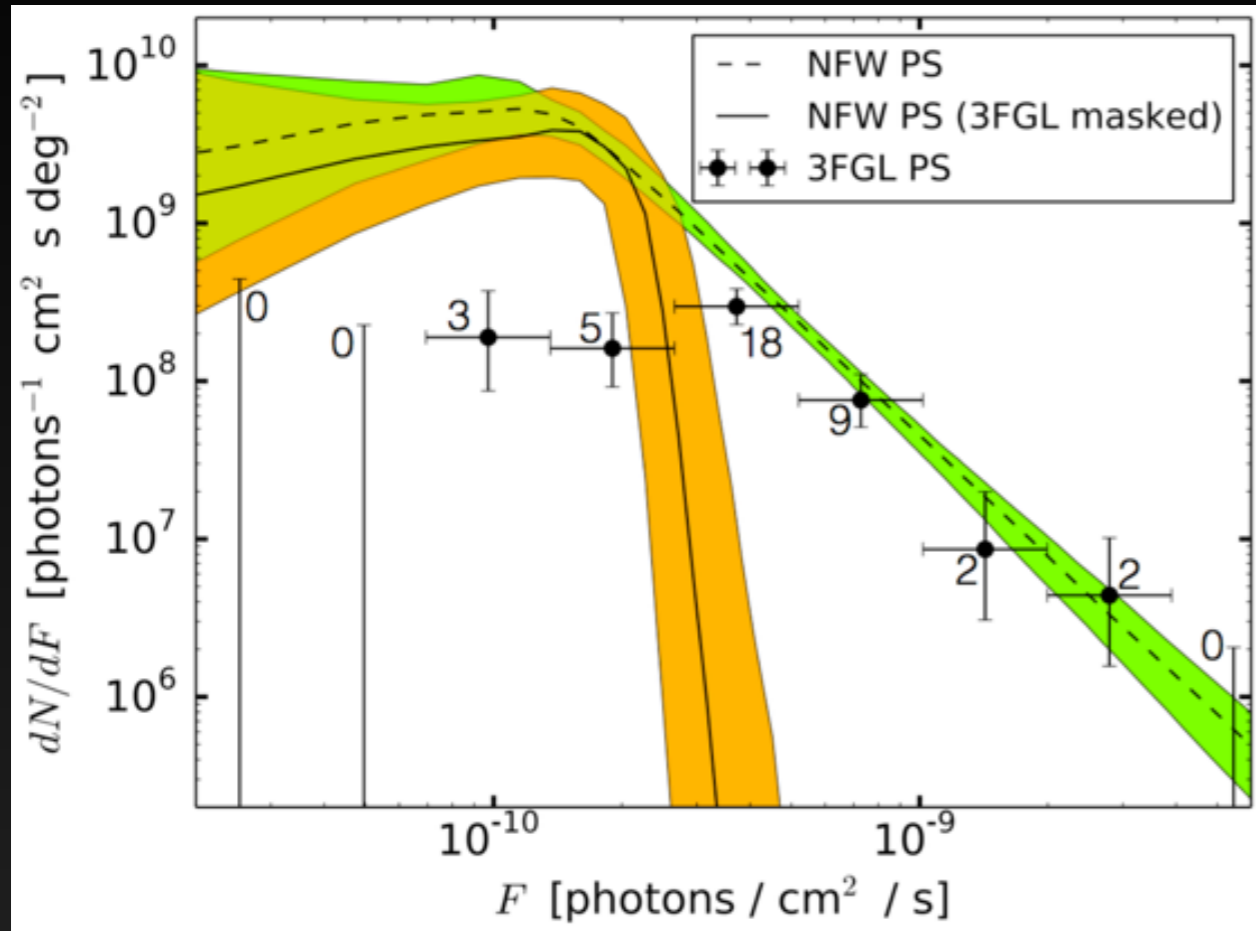
Why Not Pulsars?

- Can measure the fluxes of known MSPs and calculate the expected fluxes of MSPs in the Galactic Center.



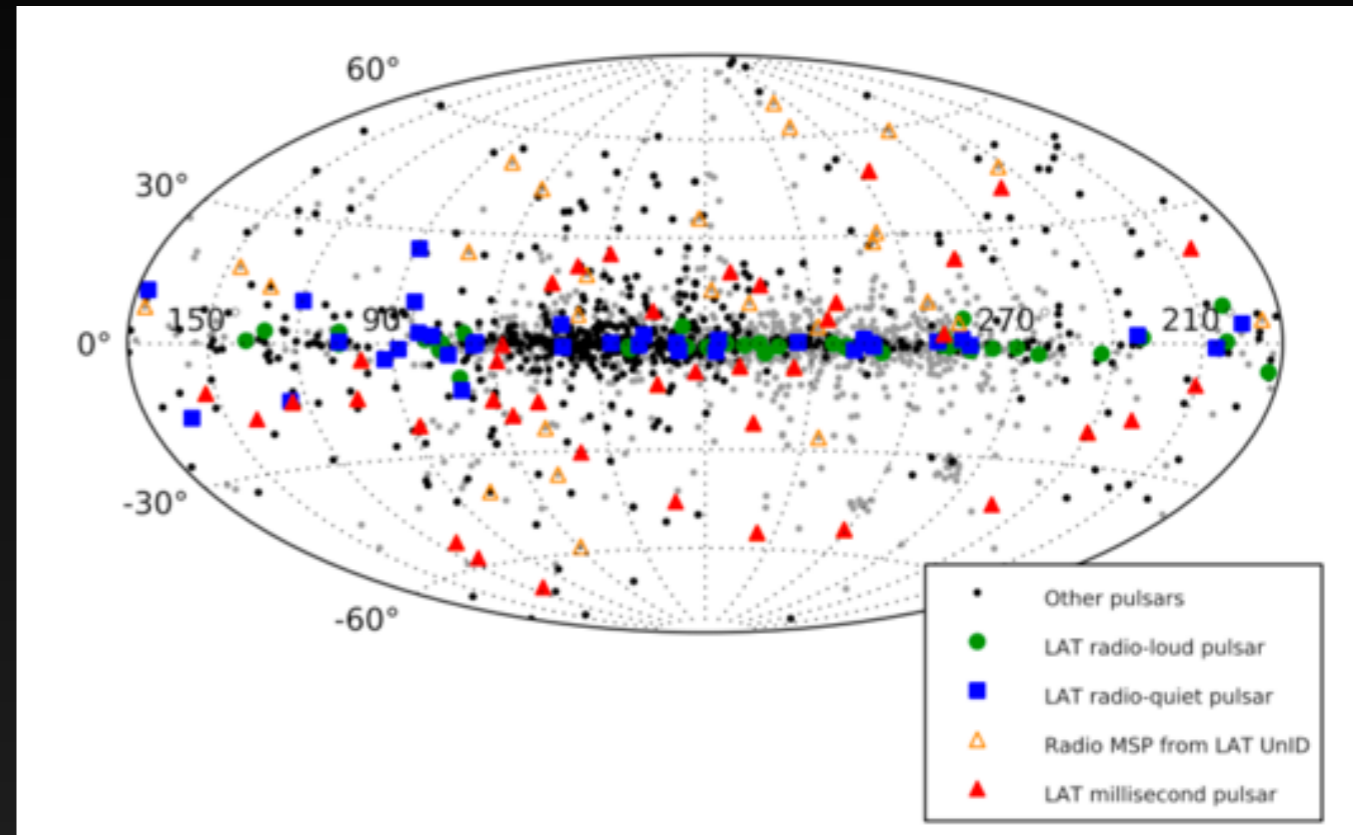
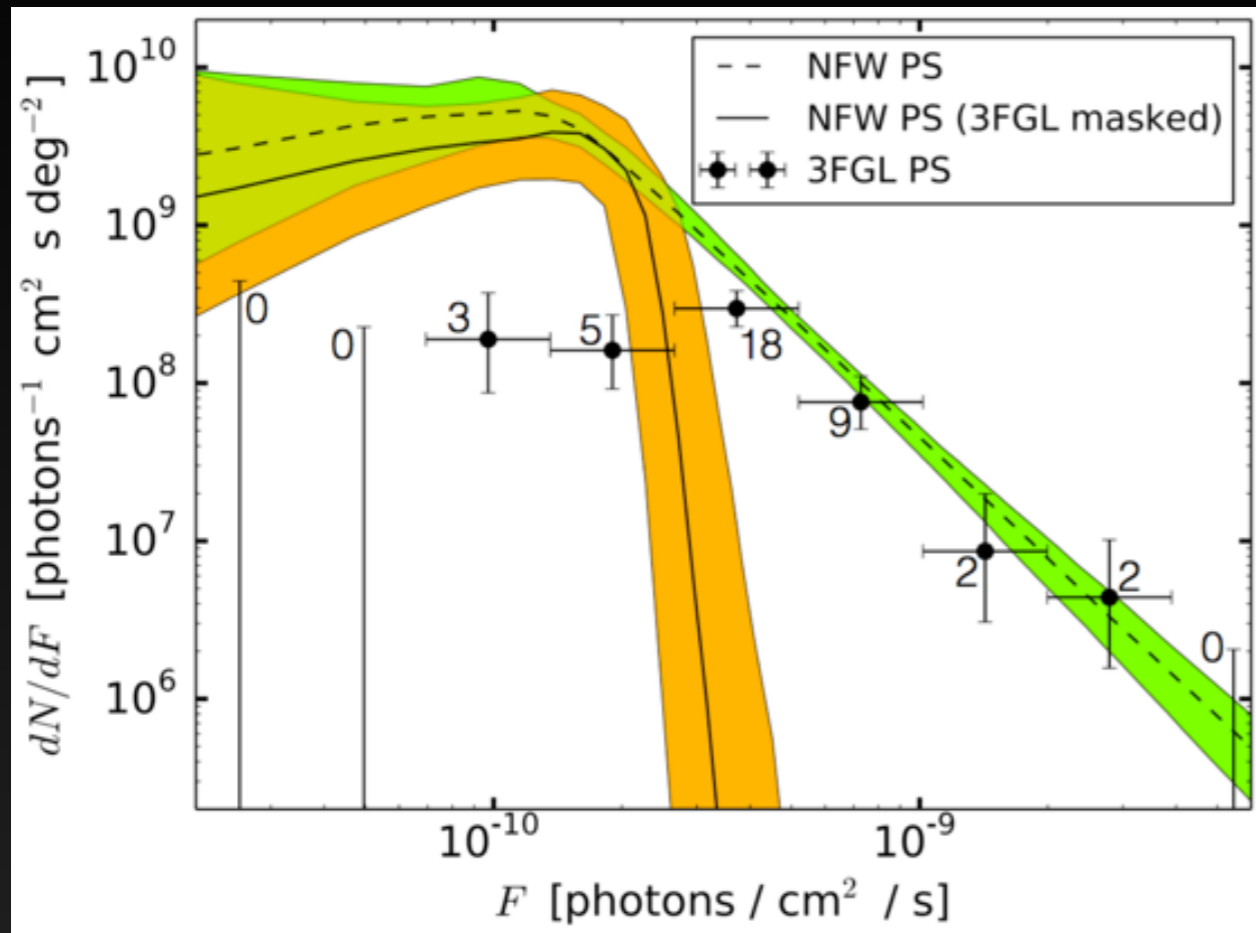
- There would need to be 226 (+91/-67) MSPs with luminosity $> 10^{34}$ erg s $^{-1}$ in the circular region, and 61.9 (+60/-33.7) with luminosity $> 10^{35}$ erg s $^{-1}$.

Why Not Pulsars?



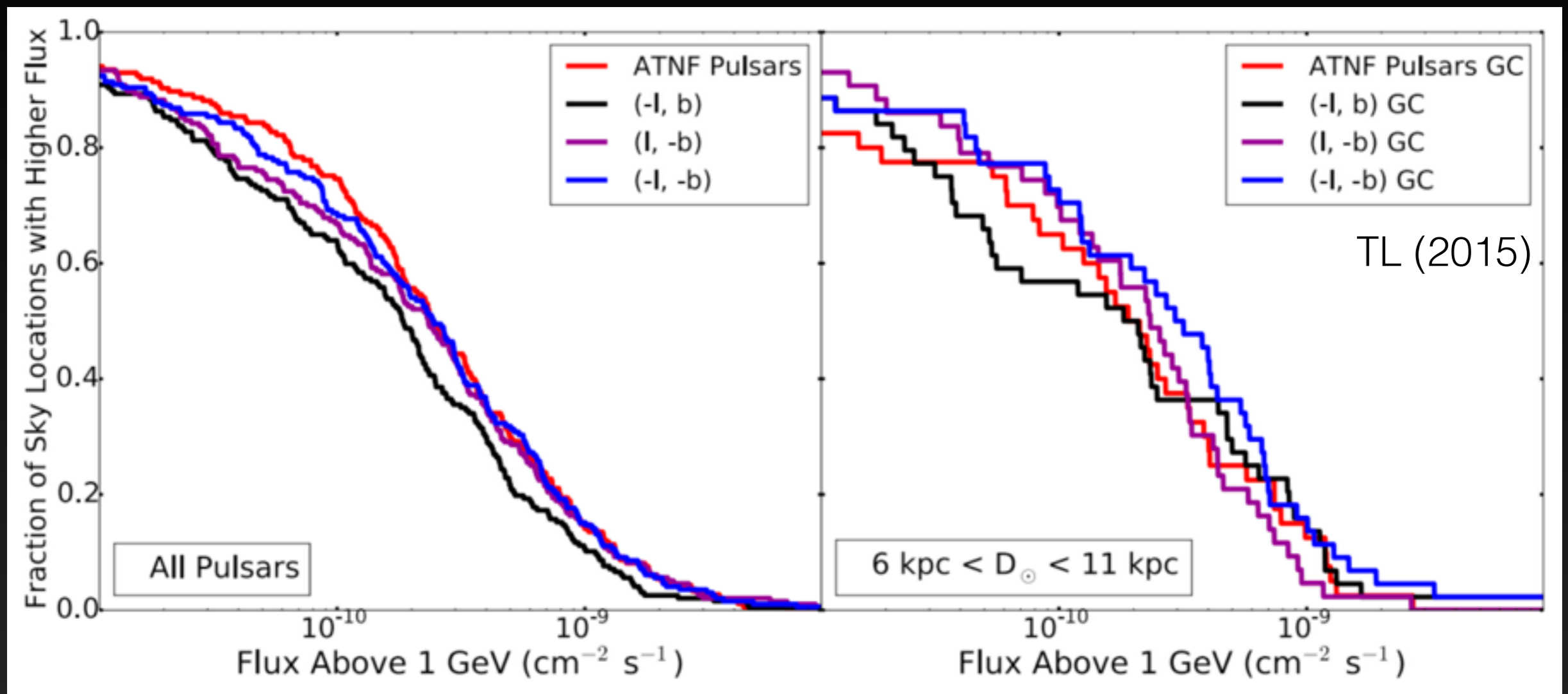
- A luminosity of 10^{35} erg s⁻¹ at the galactic center is equivalent to a gamma-ray flux of 8.0×10^{-9} photons cm⁻² s⁻¹. These systems have not been observed in the Galactic Center.

Why Not Pulsars?



- Note that the population of new point sources have fluxes barely below the Fermi-LAT point source detection threshold.
- Can see if these hotspots cross-correlate with known radio pulsars.

Why Not Pulsars?



- After building a technique to evaluate blank sky locations, we find that the positions of ATNF pulsars do not correlate with gamma-ray hotspots.

Diffuse Gamma-Ray Models



Supernovae Source Cosmic-Ray Protons:
 10^{51} erg (~10% in relativistic protons)
(~2% in relativistic electrons)

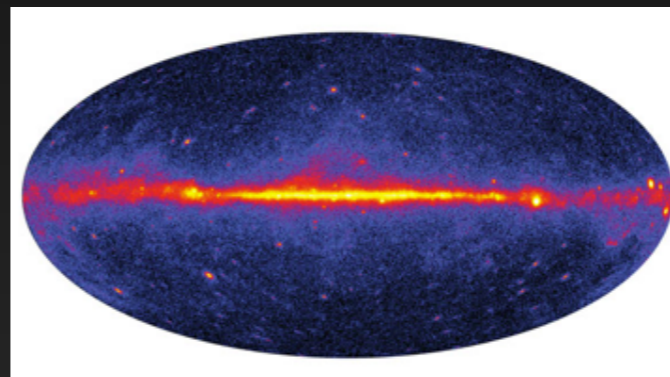
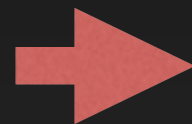
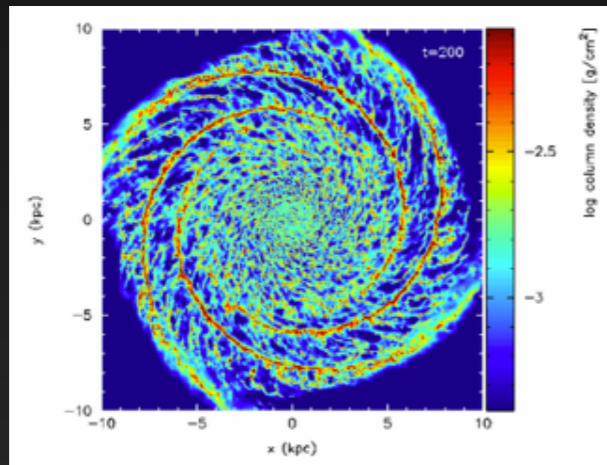
cosmic rays propagate

$$\frac{\partial \psi}{\partial t} = q(\vec{r}, p) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[p \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

Solved Numerically:
e.g. Galprop

Uncertainties in
every step of
cosmic-ray diffusion

Gas/ISRF



Only ways to constrain models:

- 1.) Compare with gamma-rays outside the GC ROI
- 2.) Local measurements of cosmic-ray primary/secondary ratios.

Many Studies

Goodenough & Hooper (2009)	0910.2998
Hooper & Goodenough (2011, PLB 697 412)	1010.2752
Hooper & TL (2011, PRD 84 12)	1110.0006
Abazajian & Kaplinghat (2012, PRD 86 8)	1207.6047
Hooper & Slatyer (2013, PDU 2 18)	1302.6589
Gordon & Macias (2013, PRD 8 8)	1306.5725
Macias & Gordon (2013, PRD 89 6)	1312.6671
Abazajian et al. (2014, PRD 90 2)	1402.4090
Daylan et al. (2014)	1402.6703
Calore et al. (2014)	1409.0042
Bartels et al. (2015)	1506.05104
Lee et al. (2015)	1506.05124
TL (2015)	1509.02928

But all models have used very similar diffuse backgrounds!

Astrophysical Diffuse Modeling

Systematically test the resilience of the galactic center excess to changes in the morphology of cosmic-ray injection, the morphology of target gas, and the propagation of cosmic-rays.

Galactic center is fairly resilient to many of these changes.

**Novel Diffuse Emission Models
Confront the Galactic Center Excess**

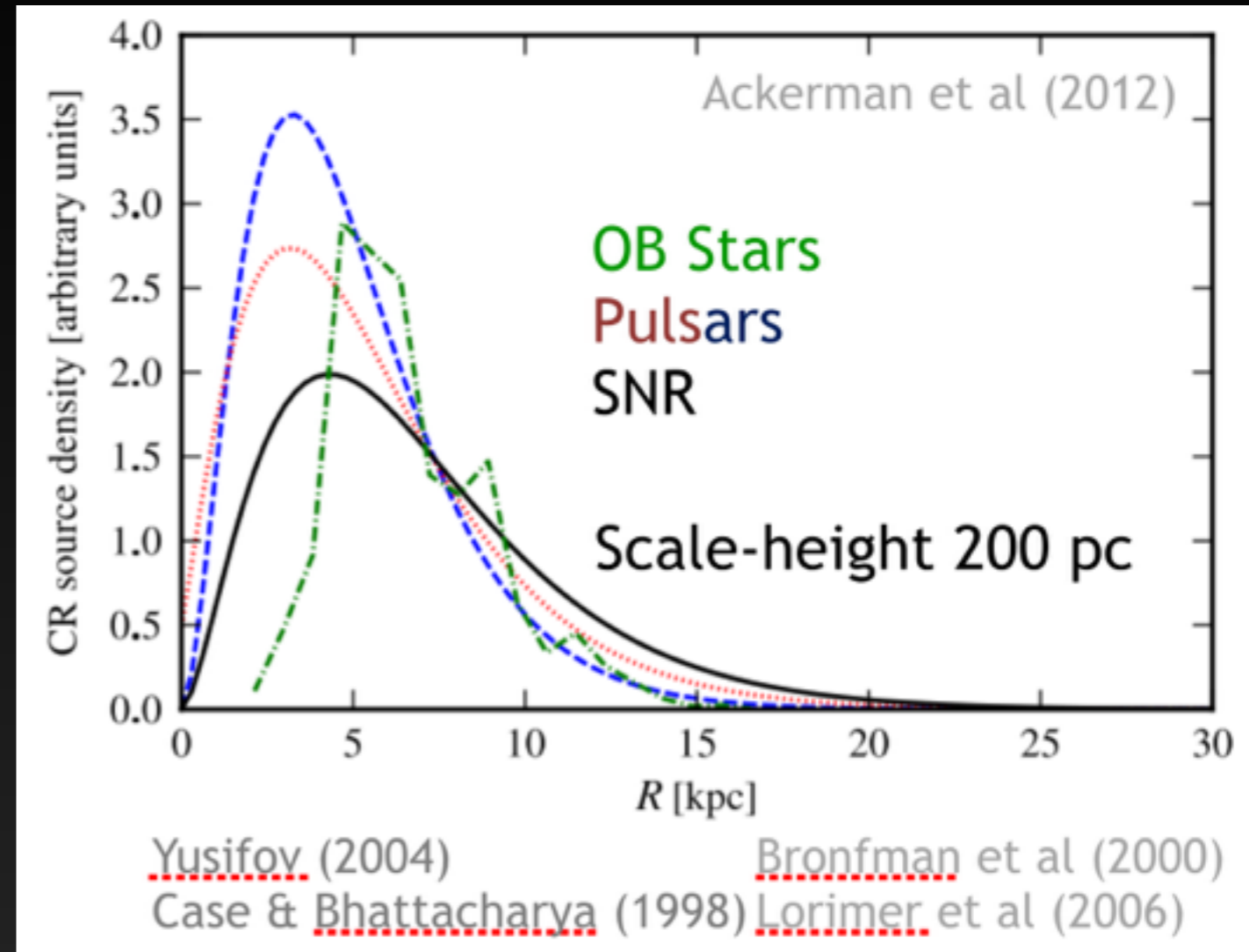
Eric Carlson^{a,b} **Tim Linden^c** **Stefano Profumo^{a,b}**
Department of Physics, University of California, Santa Cruz
1156 High St, Santa Cruz, CA 95064
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Observations of the Milky Way
of GeV γ -rays extended
addressed to
the Galactic

Cosmic-Ray Injection Sources

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

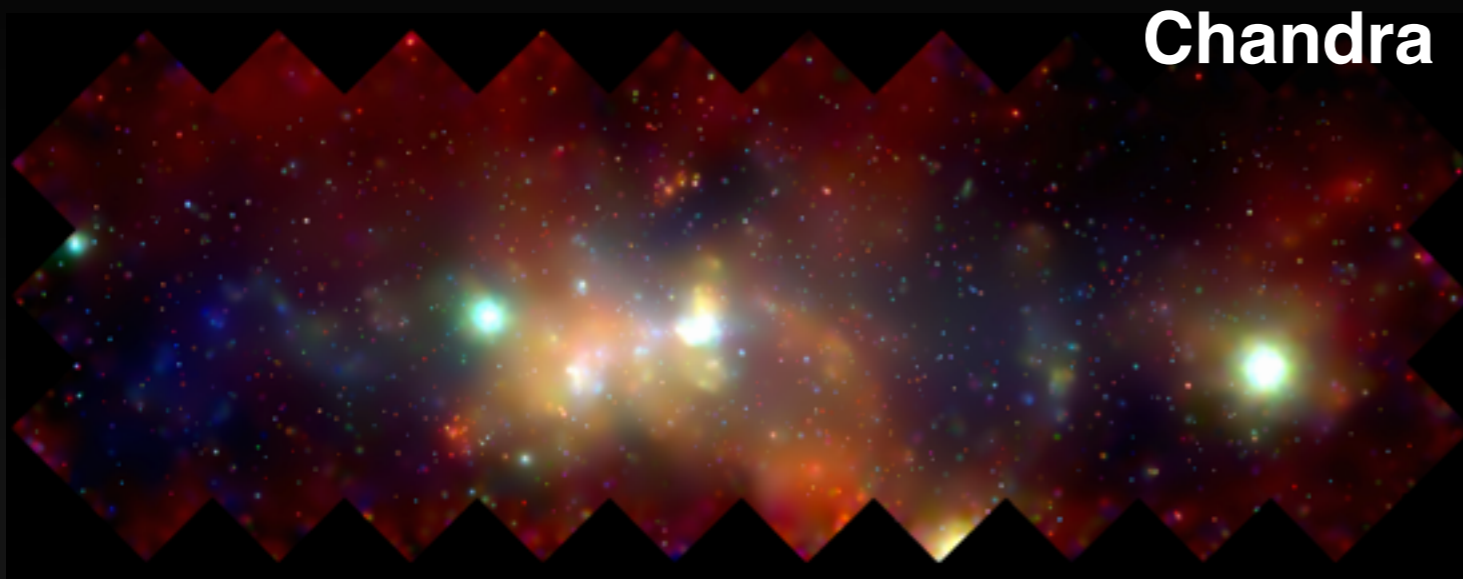
Need tracers of current and past supernovae rate:

- + Observed SNR
- + Pulsars
- + OB Stars

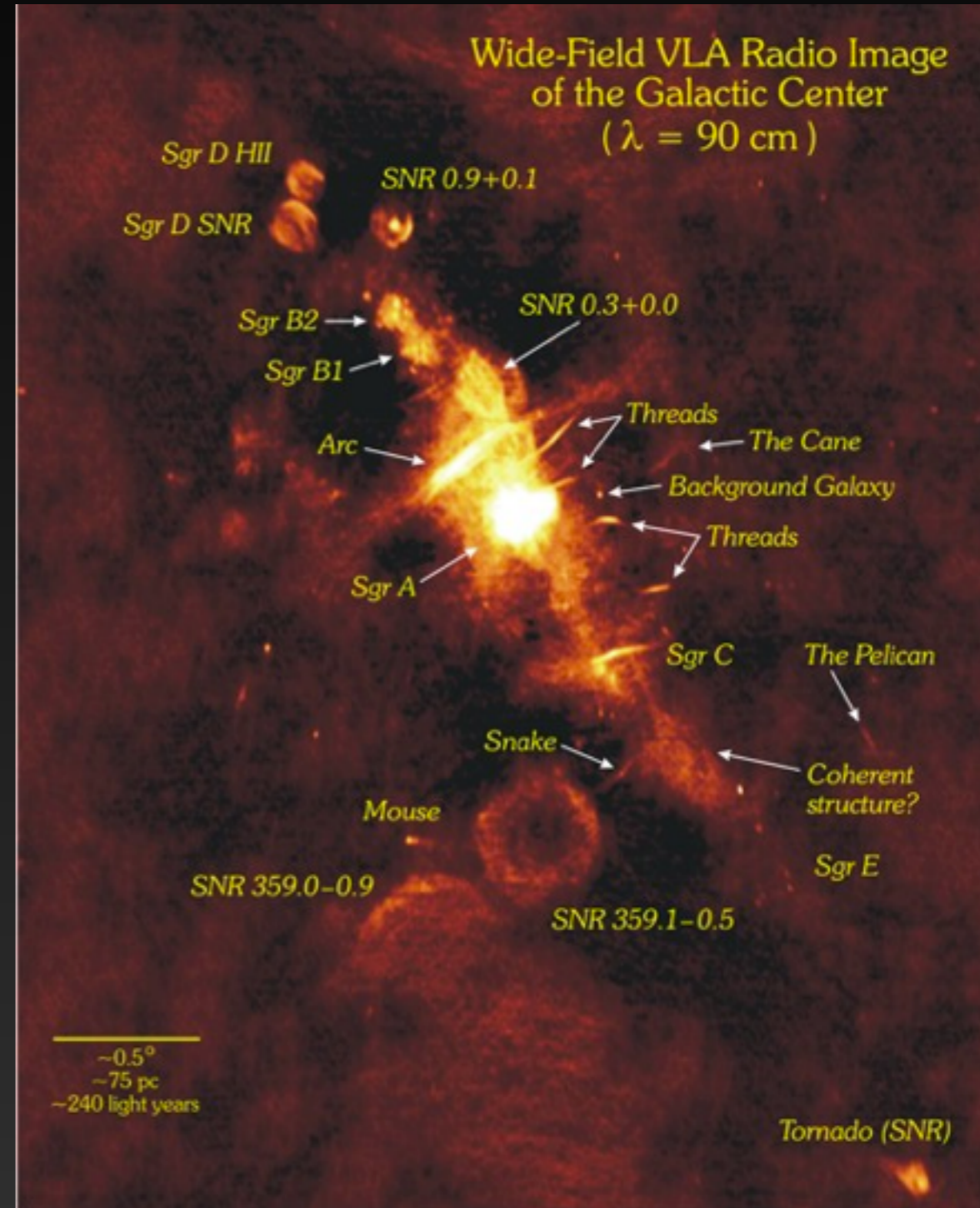


Interestingly the models used for these analyses have extremely small injection rates near the GC (in several cases identically 0).

The Galactic Center in Gamma-Rays



But we know that the Galactic Center contains significant cosmic-ray injection.



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.

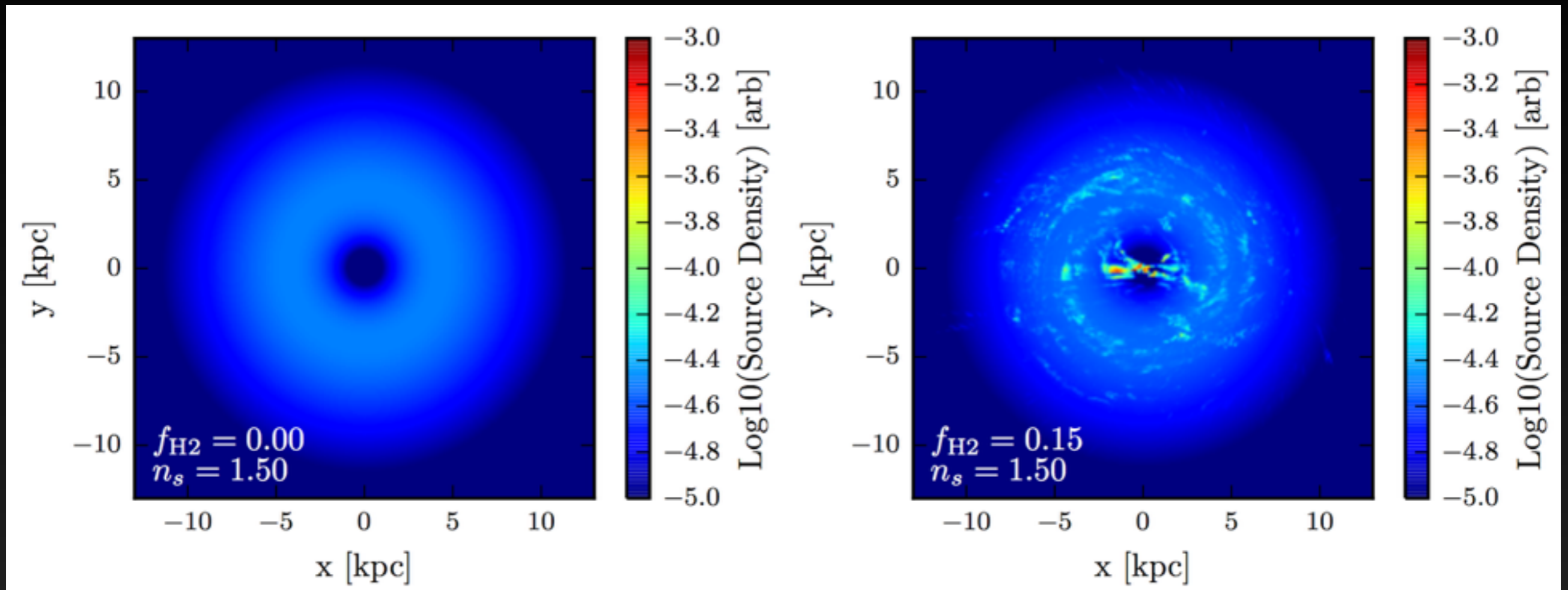
Theoretically Motivated: Molecular Gas is the seed of star formation, the Kennicutt-Schmidt Law gives

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

Specifically we adopt:

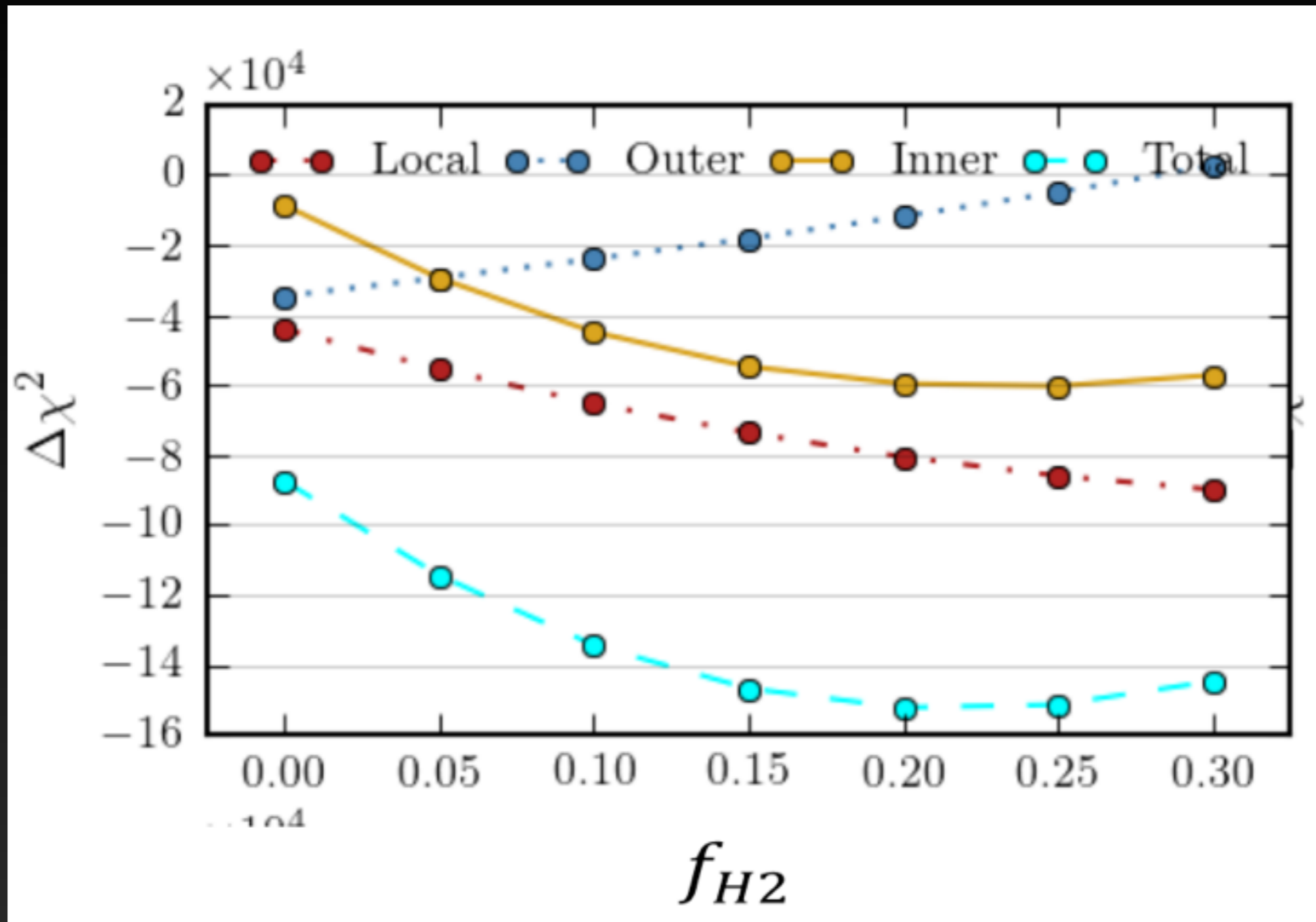
$$Q_{\text{CR}}(\vec{r}) \propto \begin{cases} 0 & \rho_{\text{H}_2} \leq \rho_s \\ \rho_{\text{H}_2}^{n_s} & \rho_{\text{H}_2} > \rho_s \end{cases}$$

Adding a Molecular Gas Component



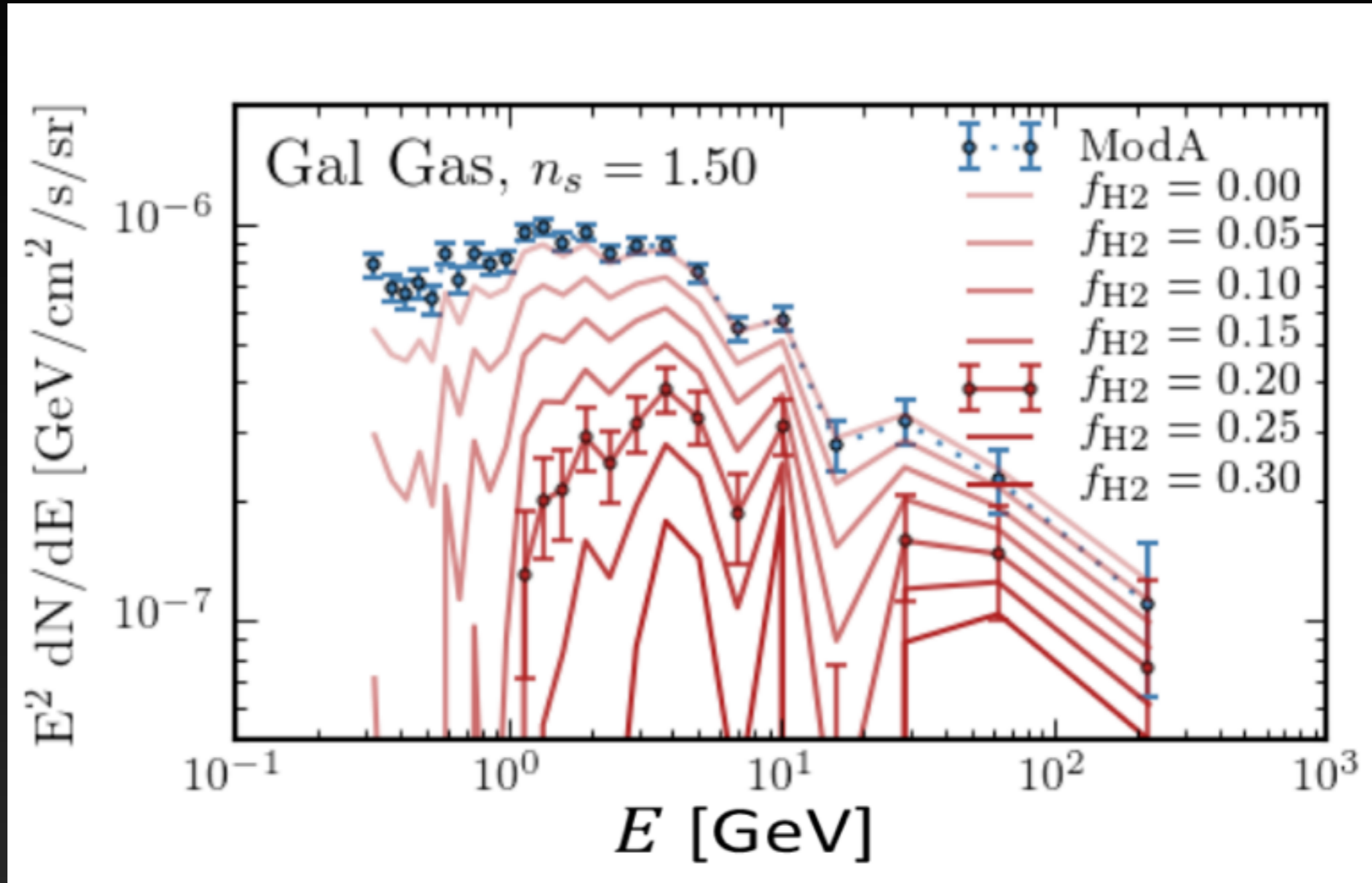
Adds significant cosmic-ray injection to the inner galaxy, and additionally a large bar structure.

Adding a Molecular Gas Component



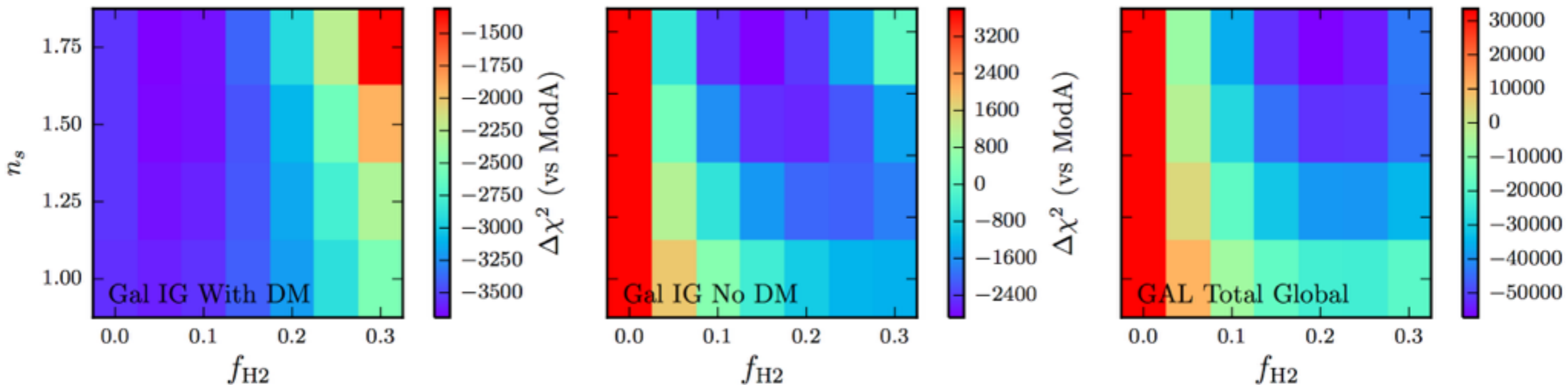
This tracer improves the fit to the gamma-ray data over the full sky.

This Reduces the Gamma-Ray Excess!



And it greatly reduces the intensity of the gamma-ray excess!

Why Not Astrophysical Modeling?

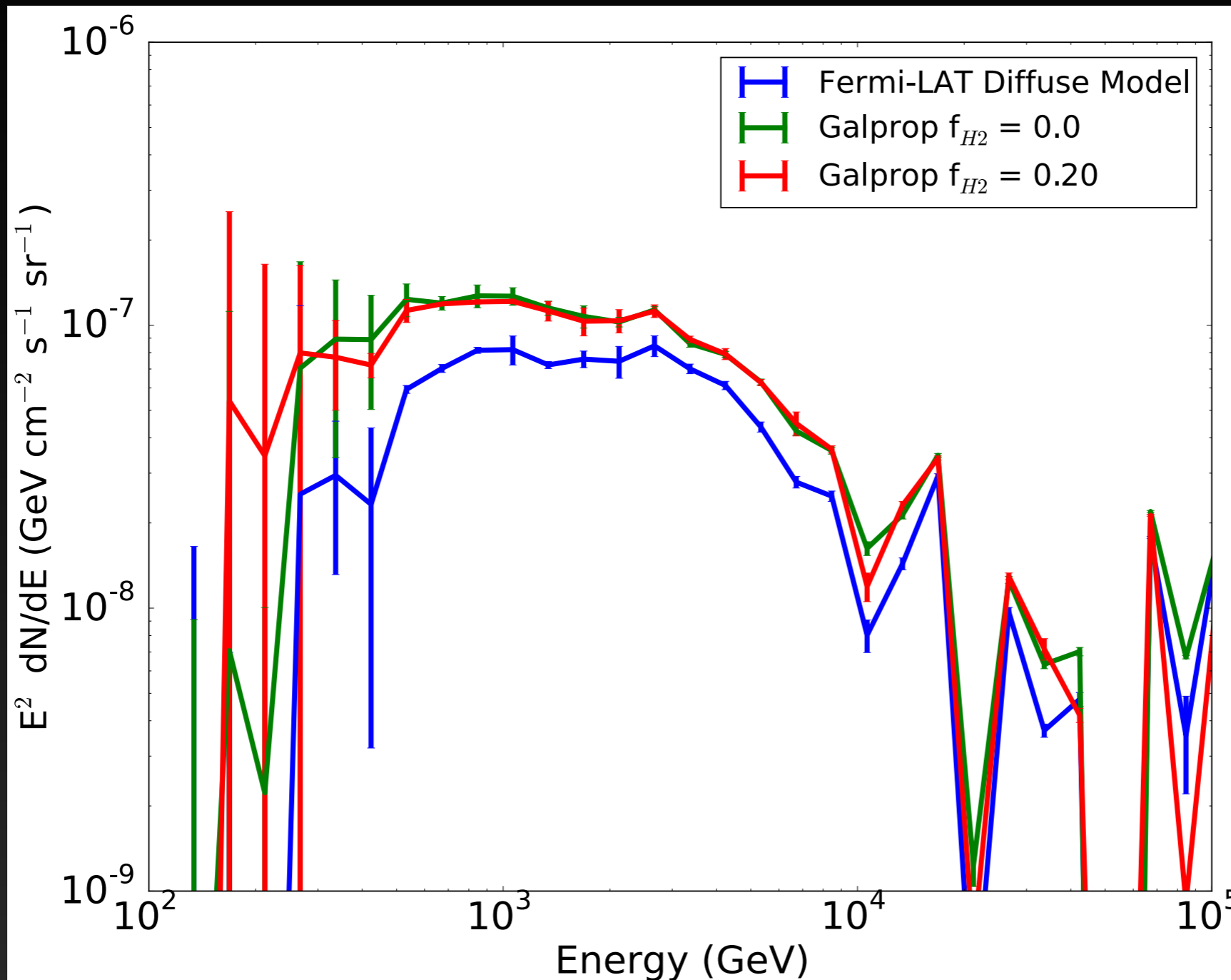


However, these fits were performed in models without an NFW template.

Adding an NFW template into the fit eliminates the need for $f_{H2} > 0$ in the inner galaxy, and still provides a slightly better fit to the data.

However, the overall fit to the gamma-ray sky prefers $f_{H2} \sim 0.2$

Why Not Astrophysical Modeling?



Moreover, when we focus on the very center of the galaxy ($<5^\circ$), these alterations to the gamma-ray model do not appear to decrease the intensity of the gamma-ray excess.

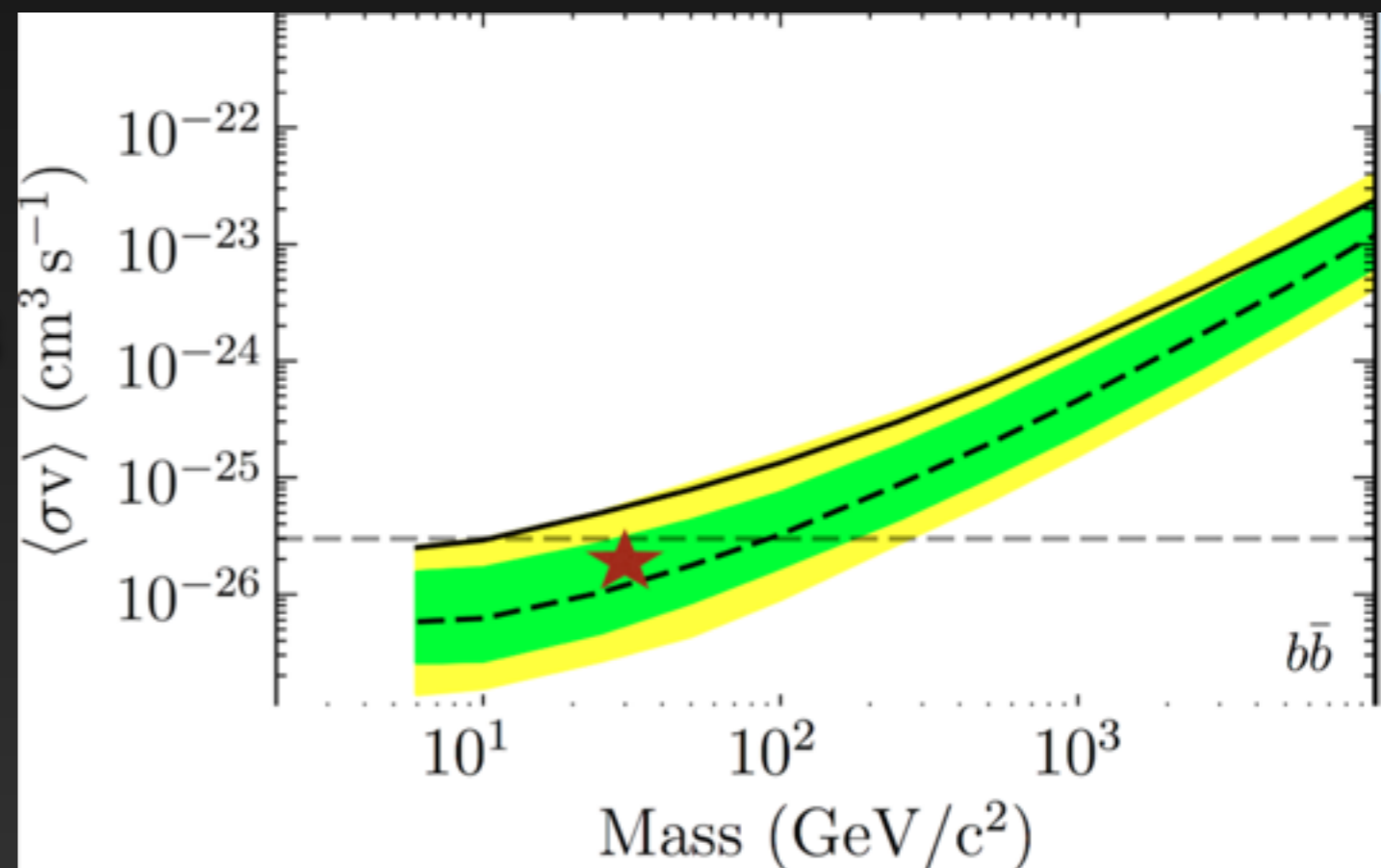
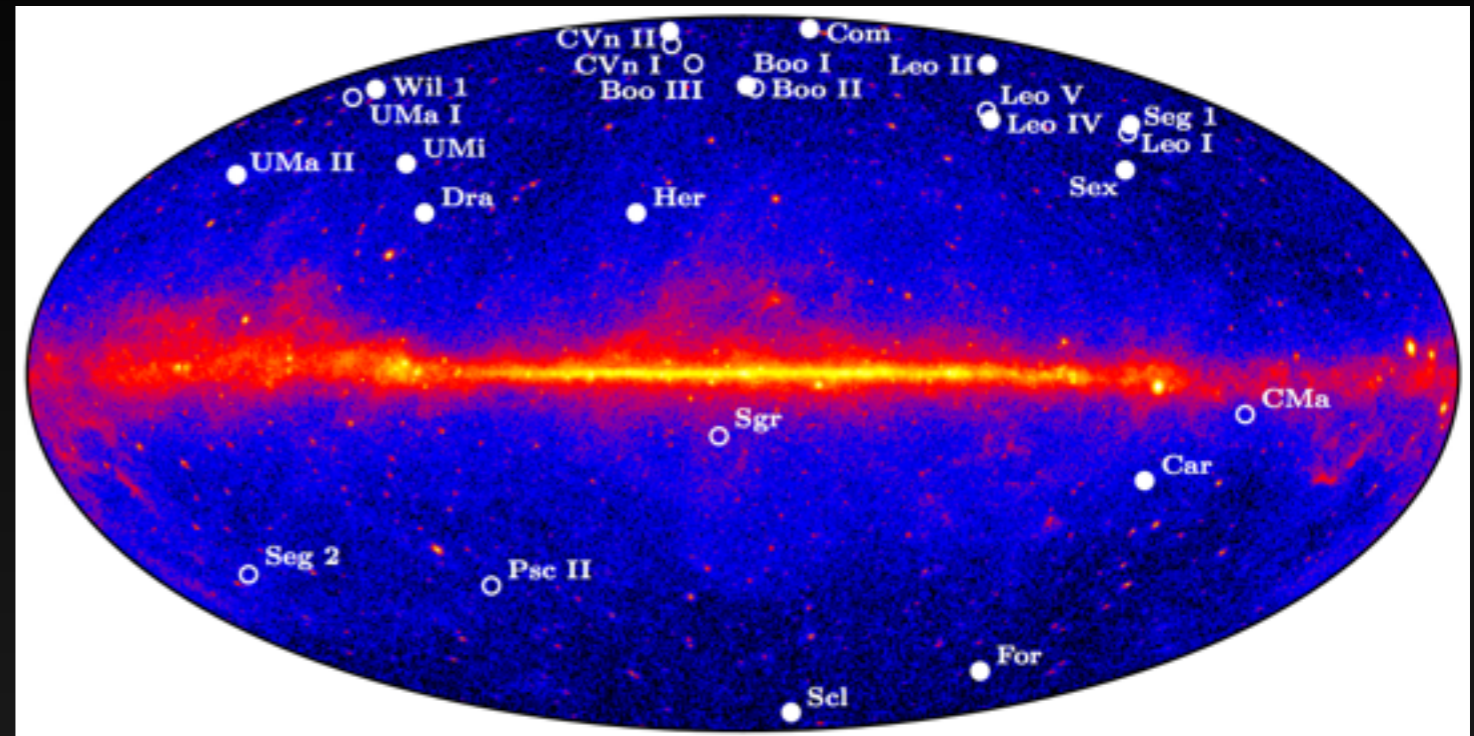
Coming to a Conclusion

- 1.) Over the last two years - the existence of a significant gamma-ray excess (compared to current astrophysical models) has been confirmed.**
- 2.) The gamma-ray excess has features compatible with a dark matter signal — a dark matter motivated NFW profile remains the best fitting template to the gamma-ray data.**
- 3.) Several well motivated astrophysical models have been produced, and new techniques are being developed to differentiate between these models.**
- 4.) New multi wavelength models and studies are needed.**

Alternative Targets

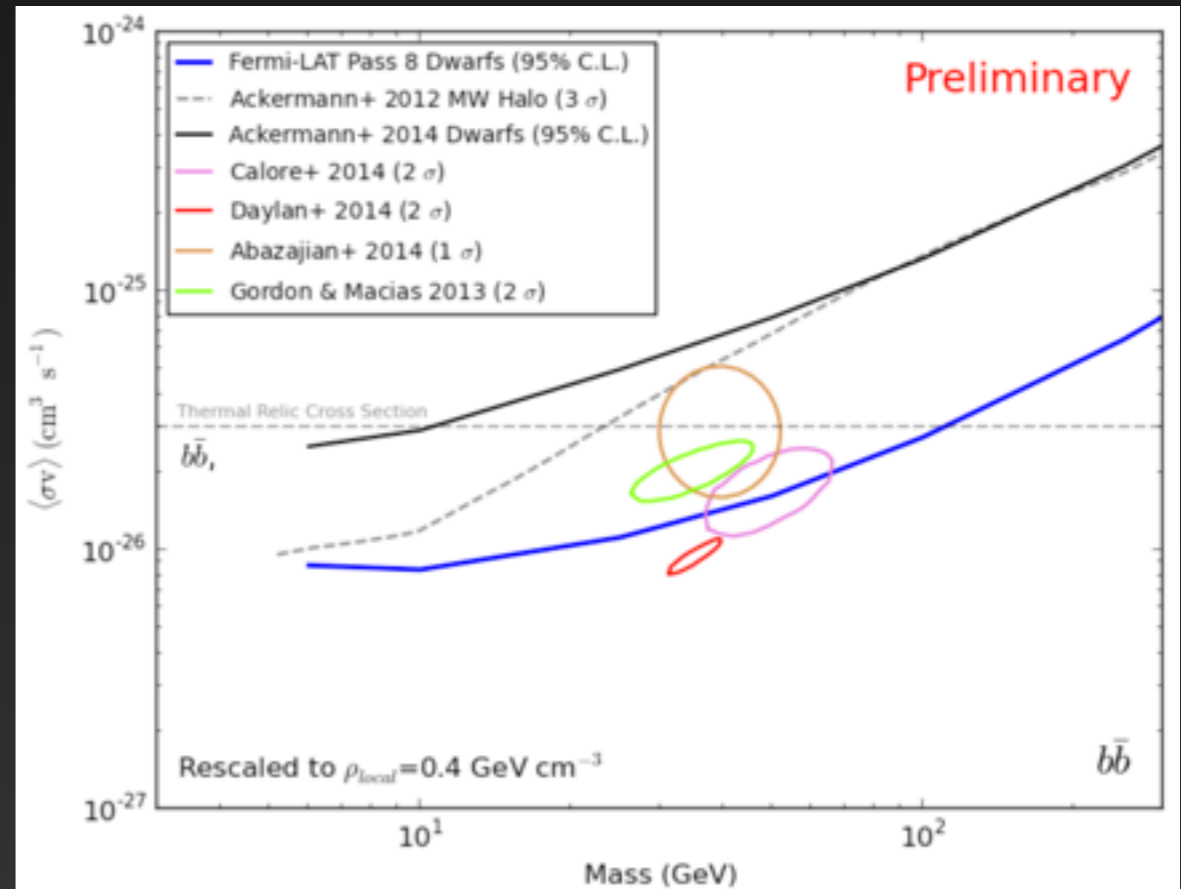
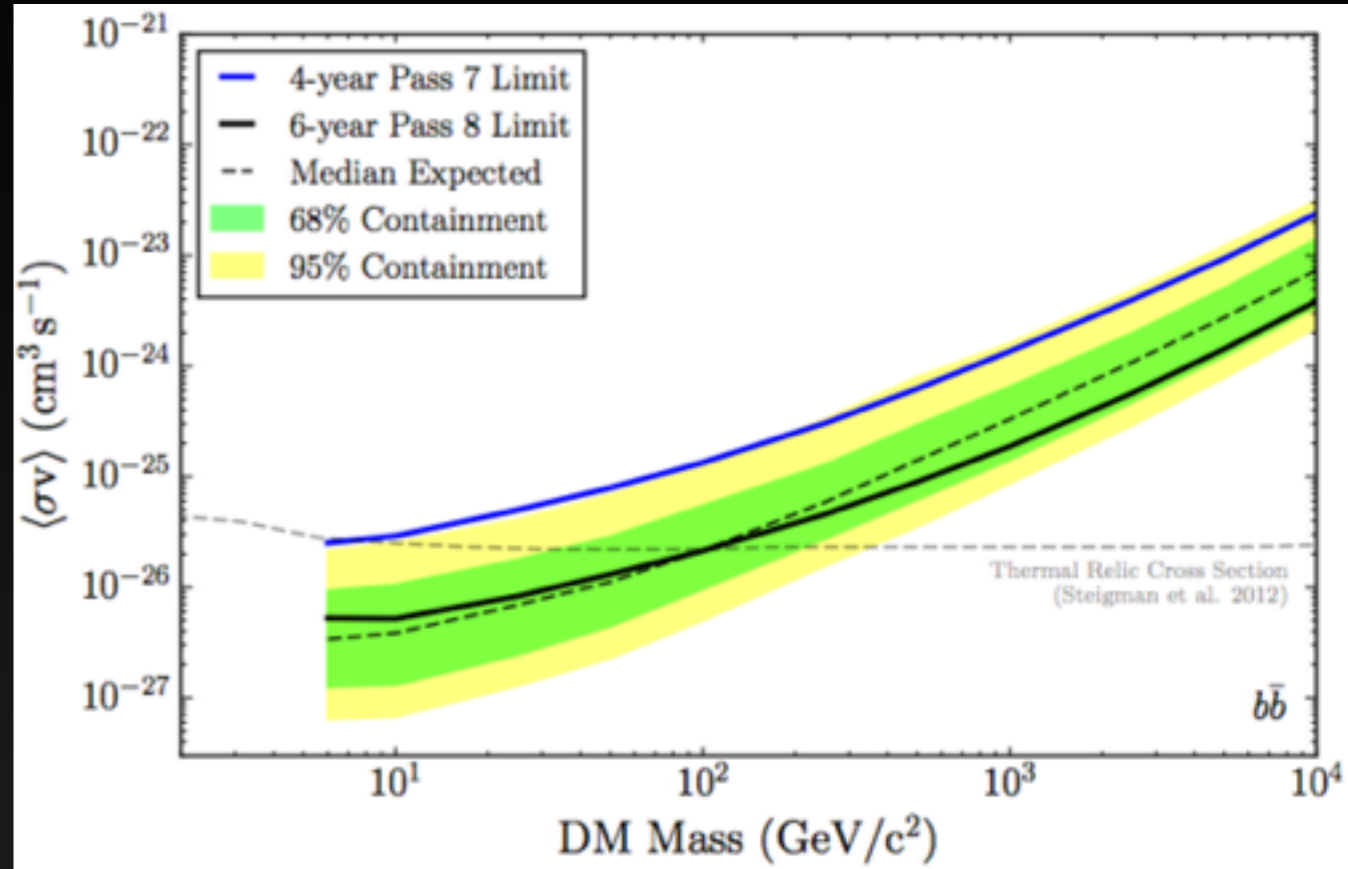
Dwarf Galaxies can also produce a significant γ -ray signal from dark matter annihilation.

Latest published results showed a $TS = 8.7$ local excess at the mass of the GC signal.

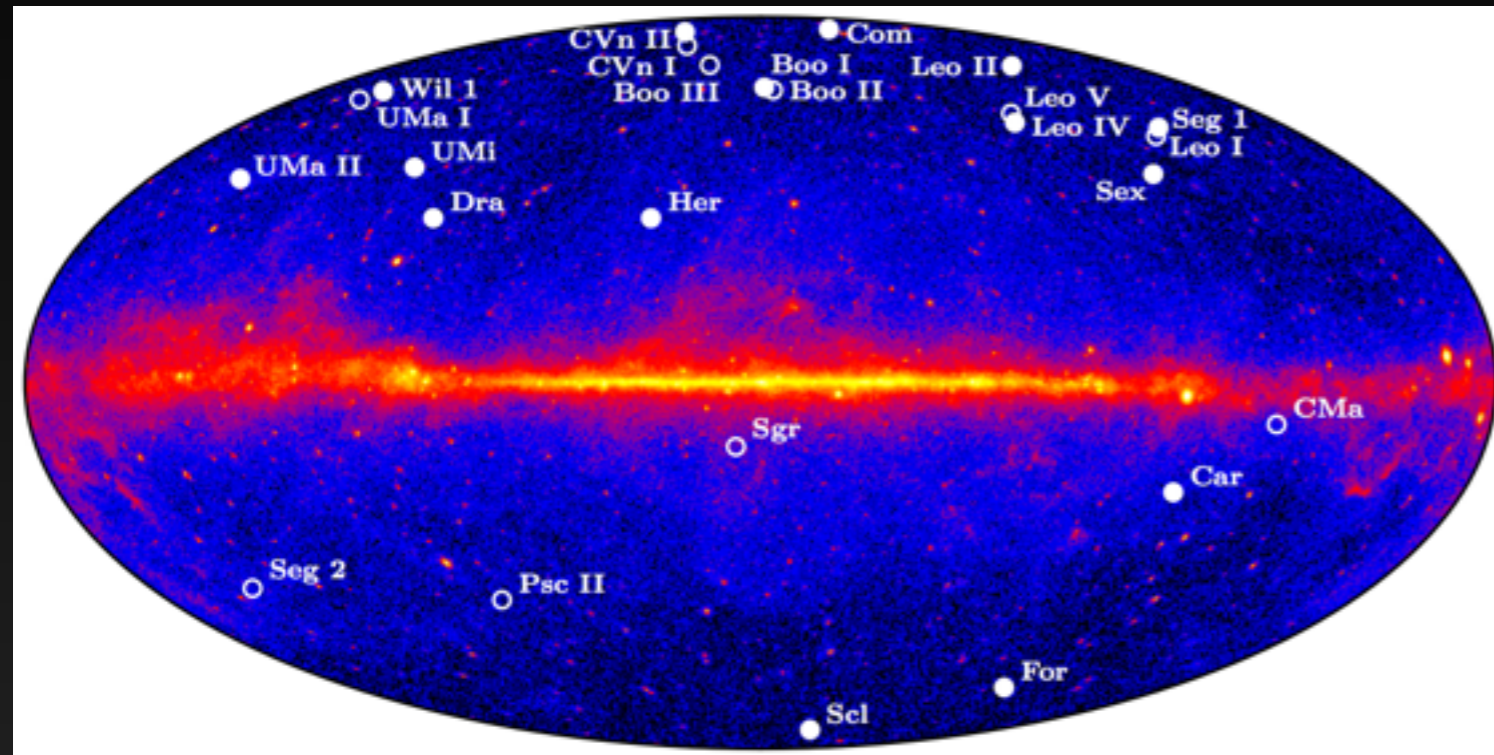


Alternative Targets

The observed excess has disappeared, and the new limit is now in mild tension with some models of the GC excess



Alternative Targets



The Dark Energy Survey is likely to greatly improve the detection of dwarf spheroidal galaxies in the Southern Hemisphere. Future limits may improve drastically if nearby dwarfs are discovered.

Alternative Targets



Analyses of the DES, and Pan-Starrs Data have recently observed 19 (and counting) new dwarf candidates in the Southern Hemisphere.

Alternative Targets

STELLAR KINEMATICS AND METALLICITIES IN THE ULTRA-FAINT DWARF GALAXY RETICULUM II

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D. A. FINLEY,² B. FLAUGHER,² J. FRIEMAN,^{2,5} E. GAZTANAGA,¹³ D. GERDES,²³ D. GRUEN,^{25,26} R. A. GRUENDL,^{20,21}
K. HONSCHIED,^{27,28} D. JAMES,¹² K. KUEHN,²⁹ N. KUROPATKIN,² O. LAHAV,¹⁷ M. A. G. MAIA,^{7,19} M. MARCH,¹⁴
P. MARTINI,^{27,30} C. J. MILLER,^{31,23} R. MIQUEL,²⁴ R. OGANDO,^{7,19} A. K. ROMER,³² A. ROODMAN,^{10,11} E. S. RYKOFF,^{10,11}
M. SAKO,¹⁴ E. SANCHEZ,³³ M. SCHUBNELL,²³ I. SEVILLA,^{33,20} R. C. SMITH,¹² M. SOARES-SANTOS,² F. SOBREIRA,^{2,7}
E. SUCHYTA,^{27,28} M. E. C. SWANSON,²¹ G. TARLE,²³ J. THALER,³⁴ D. TUCKER,² V. VIKRAM,³⁵ A. R. WALKER,¹² AND
W. WESTER²

(THE DES COLLABORATION)

galaxy known. Although Ret II is the third-closest dwarf galaxy to the Milky Way, the line-of-sight integral of the dark matter density squared is $\log_{10}(J) = 18.8 \pm 0.6 \text{ GeV}^2 \text{ cm}^{-5}$ within 0.2° , indicating that the predicted gamma-ray flux from dark matter annihilation in Ret II is lower than that of several other dwarf galaxies.

Yeoman's work by several optical spectroscopists has given us two estimations of the J-factors for Reticulum 2

Alternative Targets

DARK MATTER ANNIHILATION AND DECAY PROFILES FOR THE RETICULUM II DWARF SPHEROIDAL GALAXY

VINCENT BONNIVARD¹, CÉLINE COMBET¹, DAVID MAURIN¹, ALEX GERINGER-SAMETH², SAVVAS M. KOUSHIAPPAS³,
MATTHEW G. WALKER², MARIO MATEO⁴, EDWARD W. OLSZEWSKI⁵, AND JOHN I. BAILEY III⁴

Draft version April 14, 2015

α_{int} [deg]	$\log_{10}(J(\alpha_{\text{int}}))$ [$J/\text{GeV}^2 \text{ cm}^{-5}$] ^a
0.01	$16.9^{+0.5(+1.1)}_{-0.4(-0.8)}$
0.05	$18.2^{+0.5(+1.0)}_{-0.4(-0.7)}$
0.1	$18.6^{+0.6(+1.1)}_{-0.4(-0.8)}$
0.5	$19.5^{+1.0(+1.6)}_{-0.6(-1.3)}$
1	$19.7^{+1.2(+2.0)}_{-0.9(-1.5)}$

against several of its ingredients. We find that Ret II presents one of the largest annihilation J -factors among the Milky Way's dSphs, possibly making it one of the best targets to constrain the DM particle properties. However, it is important to obtain follow-up photometric and spectroscopic data in order to test the assumptions of dynamical equilibrium as well as a negligible fraction of binary stars in the kinematic sample. Nevertheless, the proximity of Ret II and its potential large dark matter content make it the most interesting object from the newly discovered dwarf galaxies.

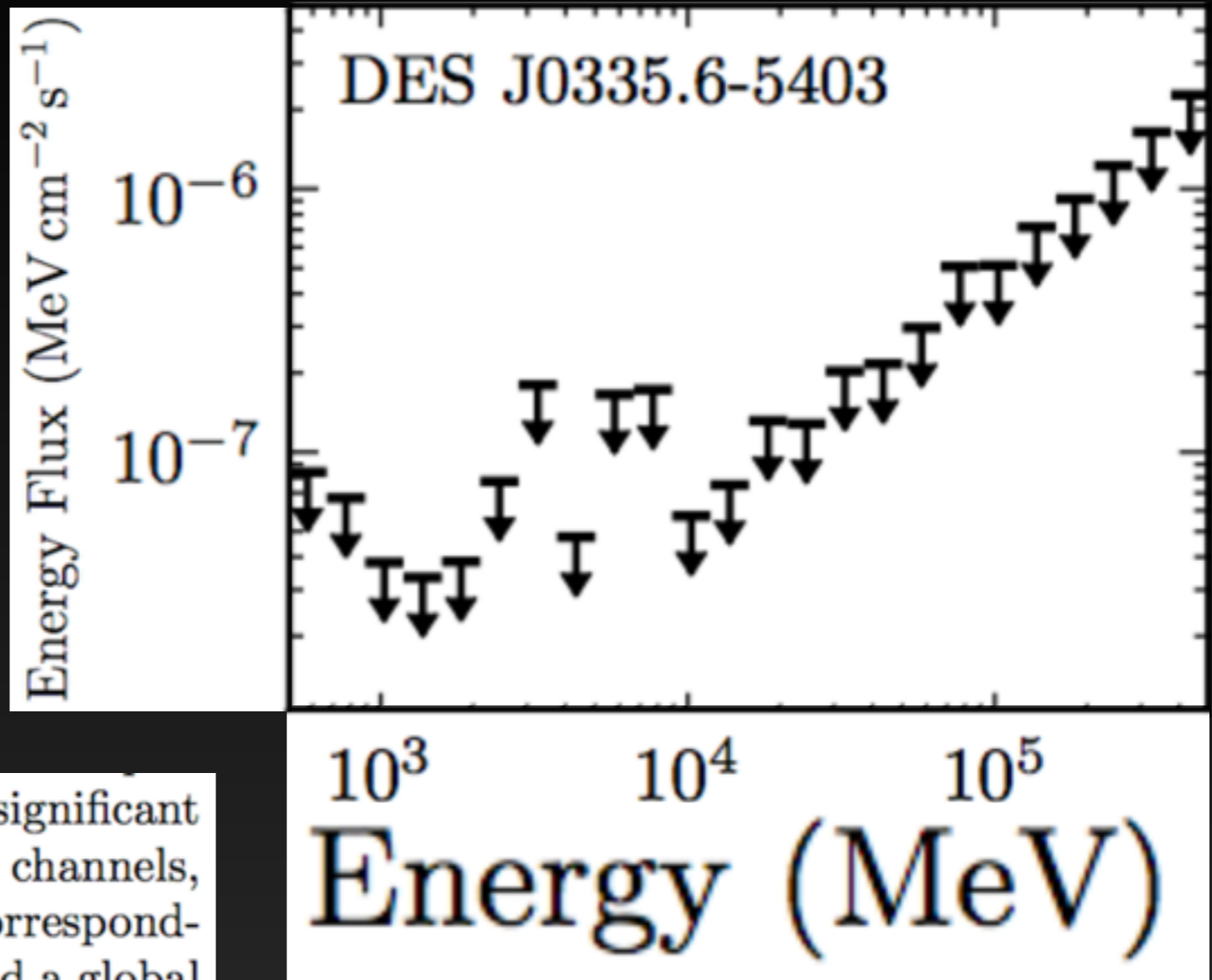
Yeoman's work by several optical spectroscopists has given us two estimations of the J -factors for Reticulum 2

Alternative Targets

Search for Gamma-Ray Emission from DES Dwarf Spheroidal Galaxy Candidates with Fermi-LAT Data

A. Drlica-Wagner,^{1,2,*} A. Albert,^{3,†} K. Bechtol,^{1,4,‡} M. Wood,^{3,5} L. Strigari,^{5,¶} M. Sánchez-Conde,^{6,7} L. Baldini,⁸ R. Essig,⁹ J. Cohen-Tanugi,¹⁰ B. Anderson,¹¹ R. Bellazzini,¹² E. D. Bloom,³ R. Caputo,¹³ C. Cecchi,^{14,15} E. Charles,³ J. Chiang,³ J. Conrad,^{7,6,11,16} A. de Angelis,¹⁷ S. Funk,³ P. Fusco,^{18,19} F. Gargano,¹⁹ N. Giglietto,^{18,19} F. Giordano,^{18,19} S. Guirio,^{20,21} M. Gustafsson,²² M. Kuss,¹² F. Loparco,^{18,19} P. Lubrano,^{14,15} N. Mirabal,^{20,21} T. Mizuno,²³ A. Morselli,²⁴ T. Ohsugi,²³ E. Orlando,³ M. Persic,^{25,26} S. Rainò,^{18,19} F. Spada,¹² D. J. Suson,²⁷ G. Zaharijas,^{28,29} and S. Zimmer^{7,6}
(The Fermi-LAT Collaboration)

tion 6 in Ackermann *et al.* [19]). The most significant excess for any of the DM masses, annihilation channels, and targets we consider here was $TS = 6.7$, corresponding to a local significance⁶ of 1.5σ ($p = 0.06$) and a global significance of 0.26σ ($p = 0.40$). This coincides with



Reticulum 2 also has an excess!

Alternative Targets

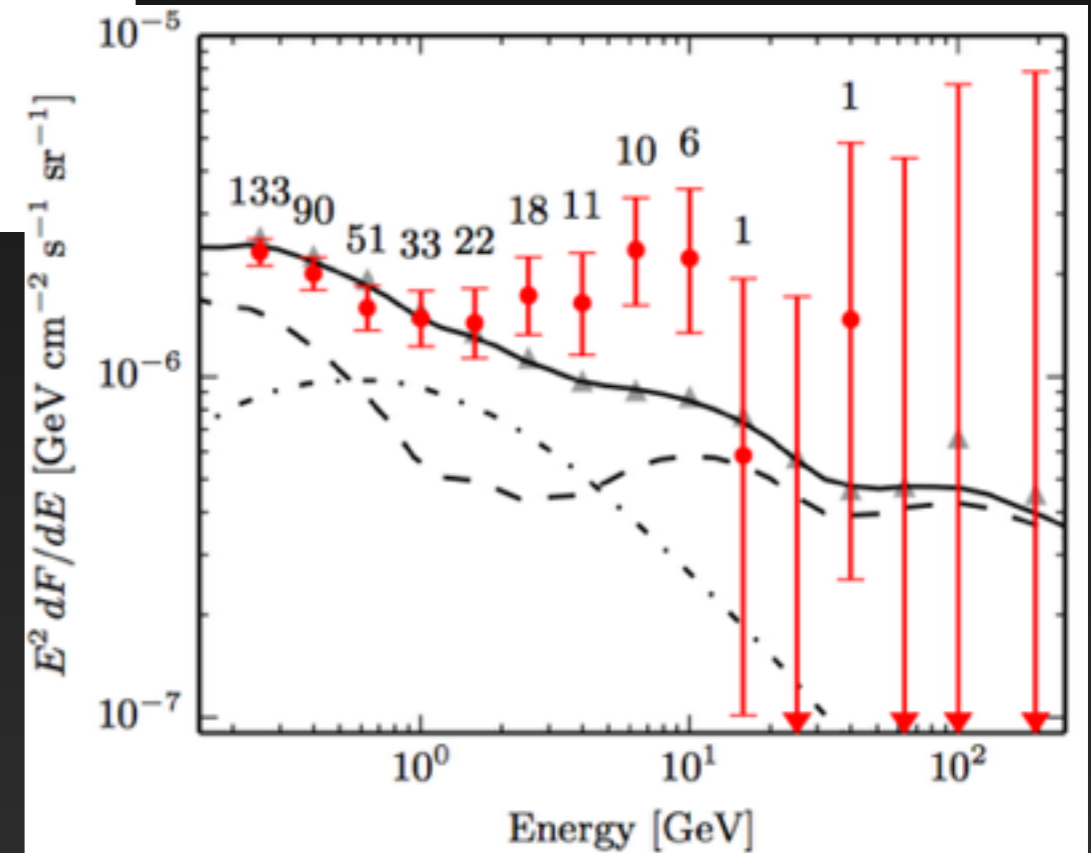
Evidence for Gamma-ray Emission from the Newly Discovered Dwarf Galaxy Reticulum 2

Alex Geringer-Sameth* and Matthew G. Walker†
*McWilliams Center for Cosmology, Department of Physics,
Carnegie Mellon University, Pittsburgh, PA 15213, USA*

Savvas M. Koushiappas‡
Department of Physics, Brown University, Providence, RI 02912, USA

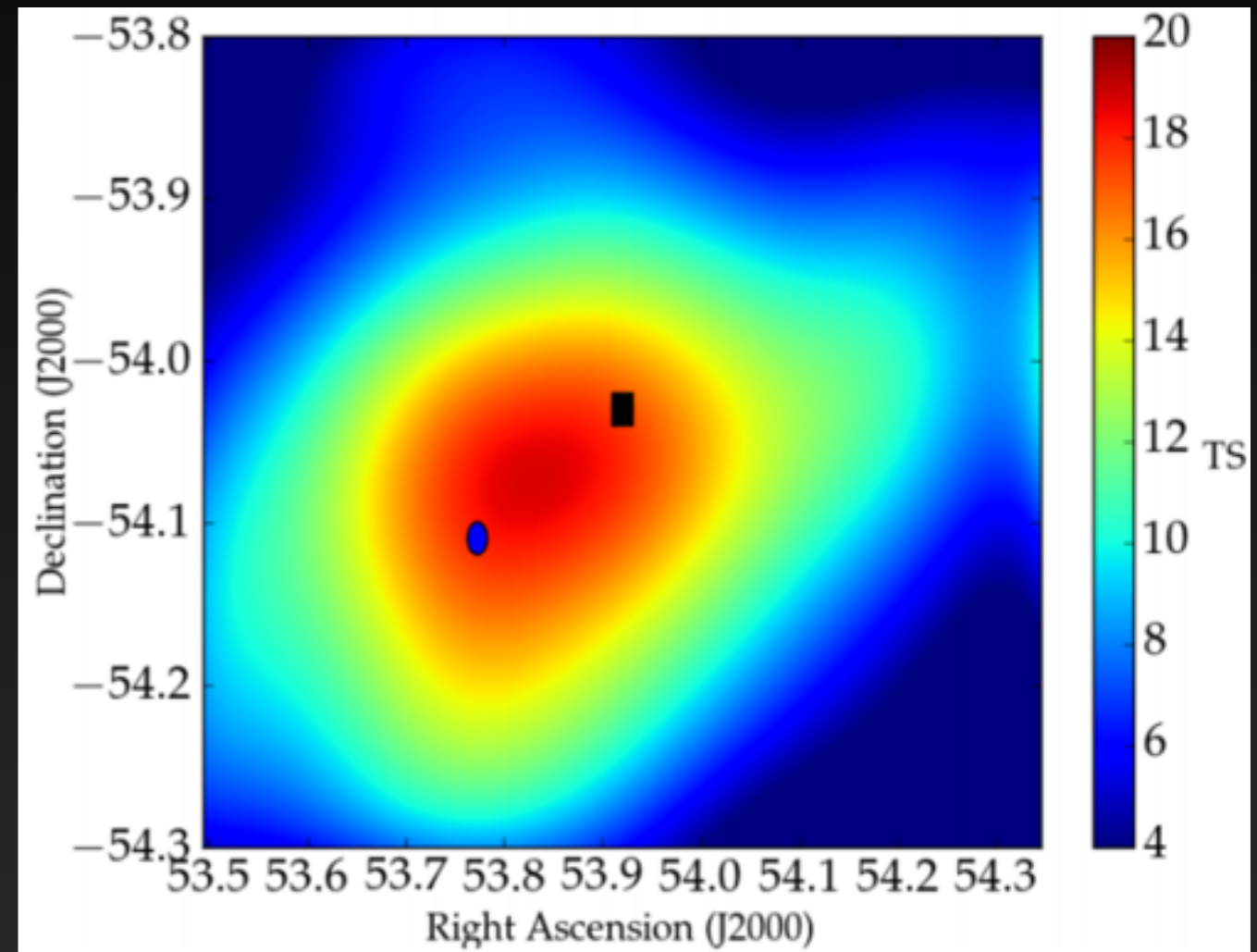
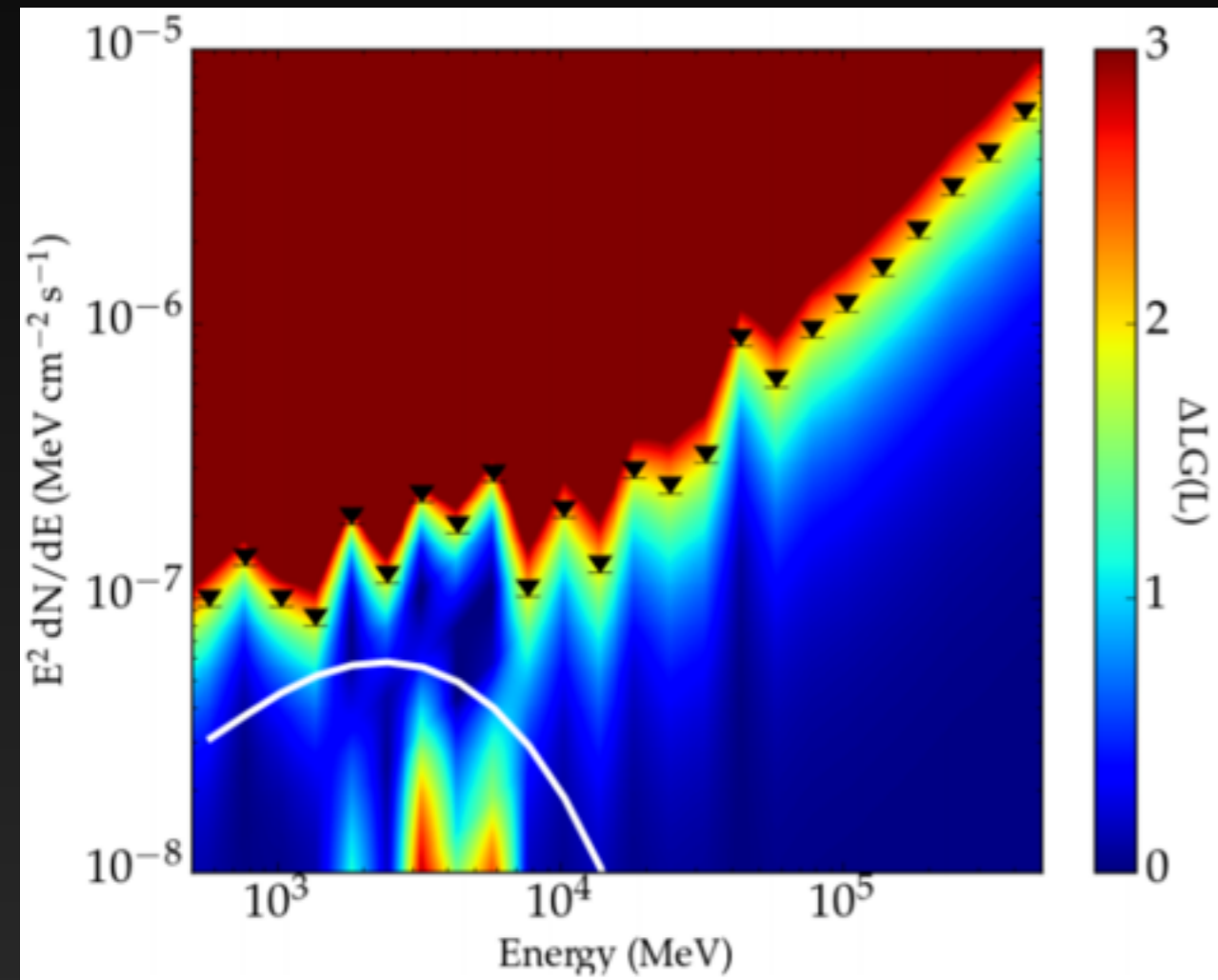
Sergey E. Koposov, Vasily Belokurov, Gabriel Torrealba, and N. Wyn Evans
Institute of Astronomy, University of Cambridge, Cambridge, CB3 0HA, UK
(Dated: March 10, 2015)

We present a search for γ -ray emission from the direction of the newly discovered dwarf galaxy Reticulum 2. Using Fermi-LAT data, we detect a signal that exceeds expected backgrounds between $\sim 2 - 10$ GeV and is consistent with annihilation of dark matter for particle masses less than a few $\times 10^2$ GeV. Modeling the background as a Poisson process based on Fermi-LAT diffuse models, and taking into account trials factors, we detect emission with p -value less than 9.8×10^{-5} ($> 3.7\sigma$). An alternative, model-independent treatment of background reduces the significance, raising the p -value to 9.7×10^{-3} (2.3σ). Even in this case, however, Reticulum 2 has the most significant γ -ray signal of any known dwarf galaxy. If Reticulum 2 has a dark matter halo that is similar to those inferred for other nearby dwarfs, the signal is consistent with the s -wave relic abundance cross section for annihilation.



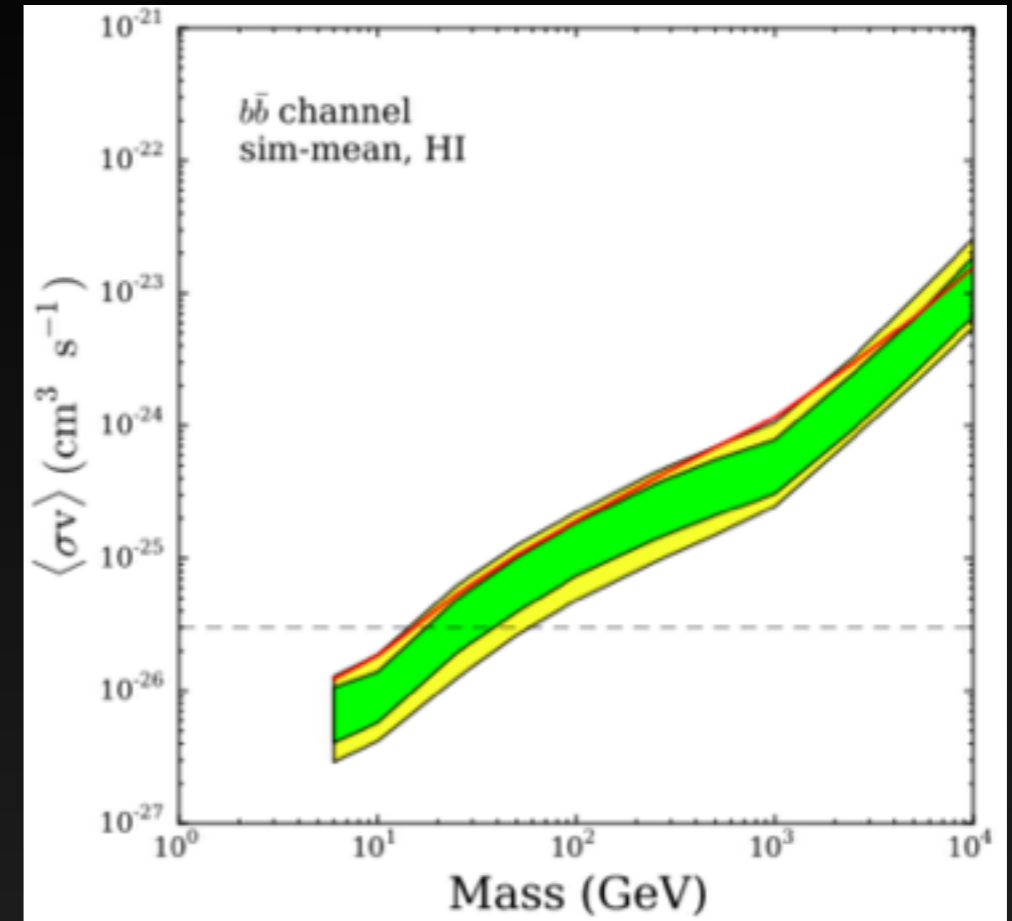
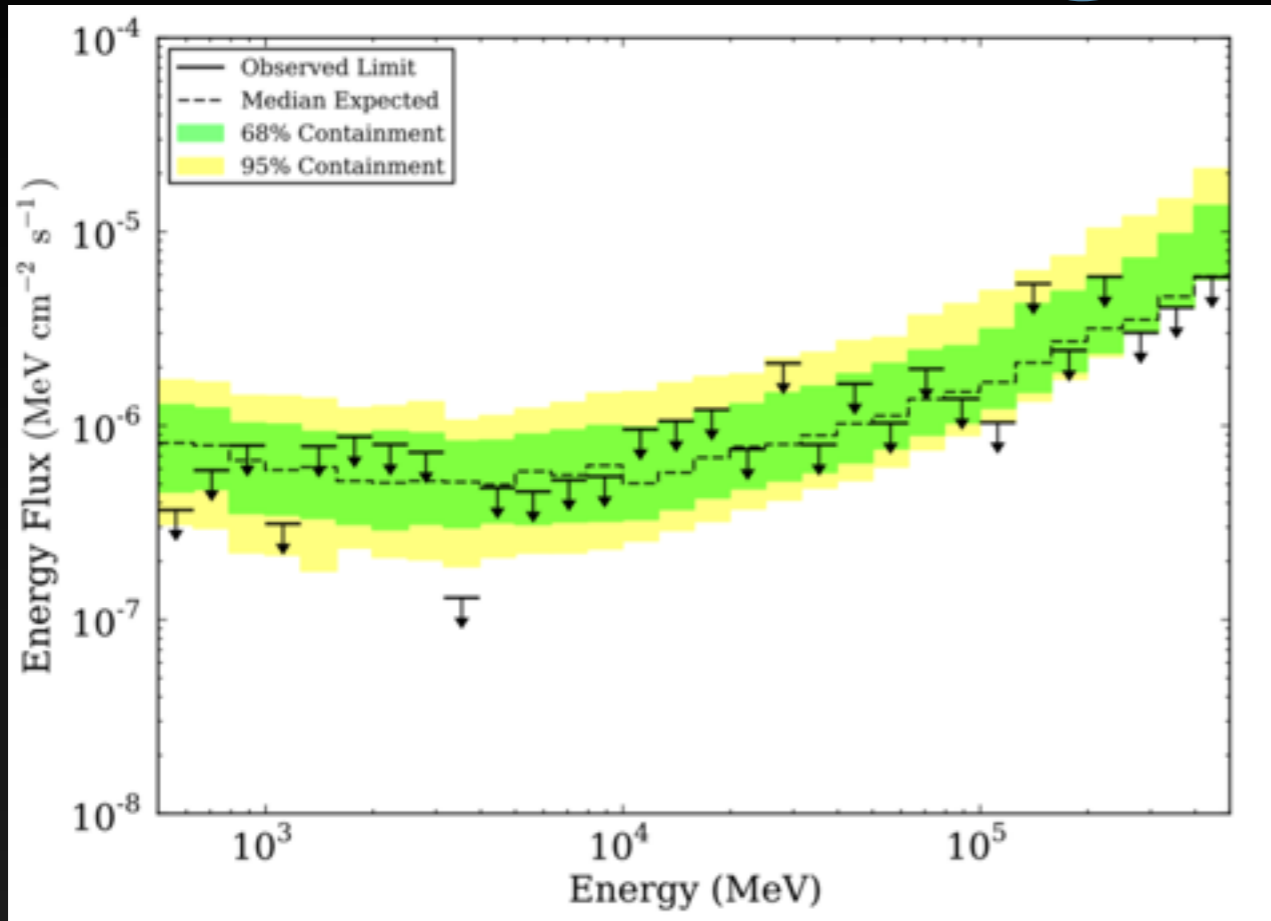
Reticulum 2 also has an excess!

Alternative Targets



Reticulum 2 also has an excess!

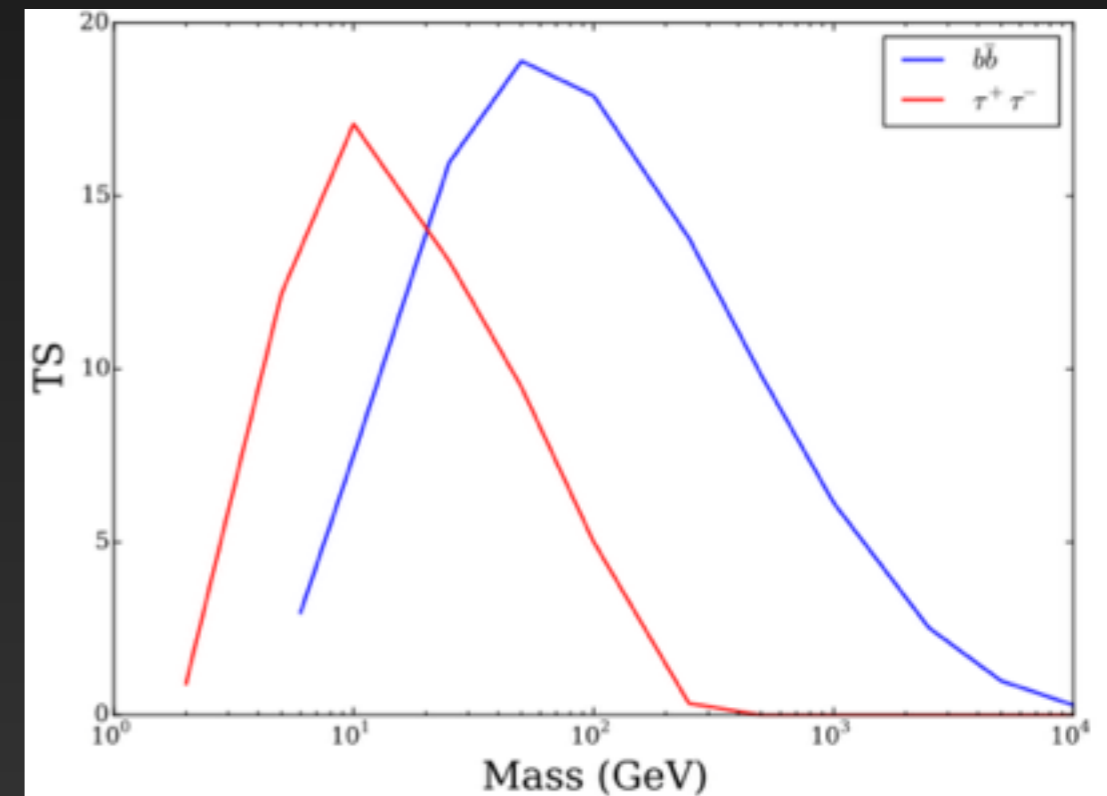
Alternative Targets



The LMC also shows hints of a dark matter excess

However, there are considerable backgrounds here as well.

Buckley et al. (2015)



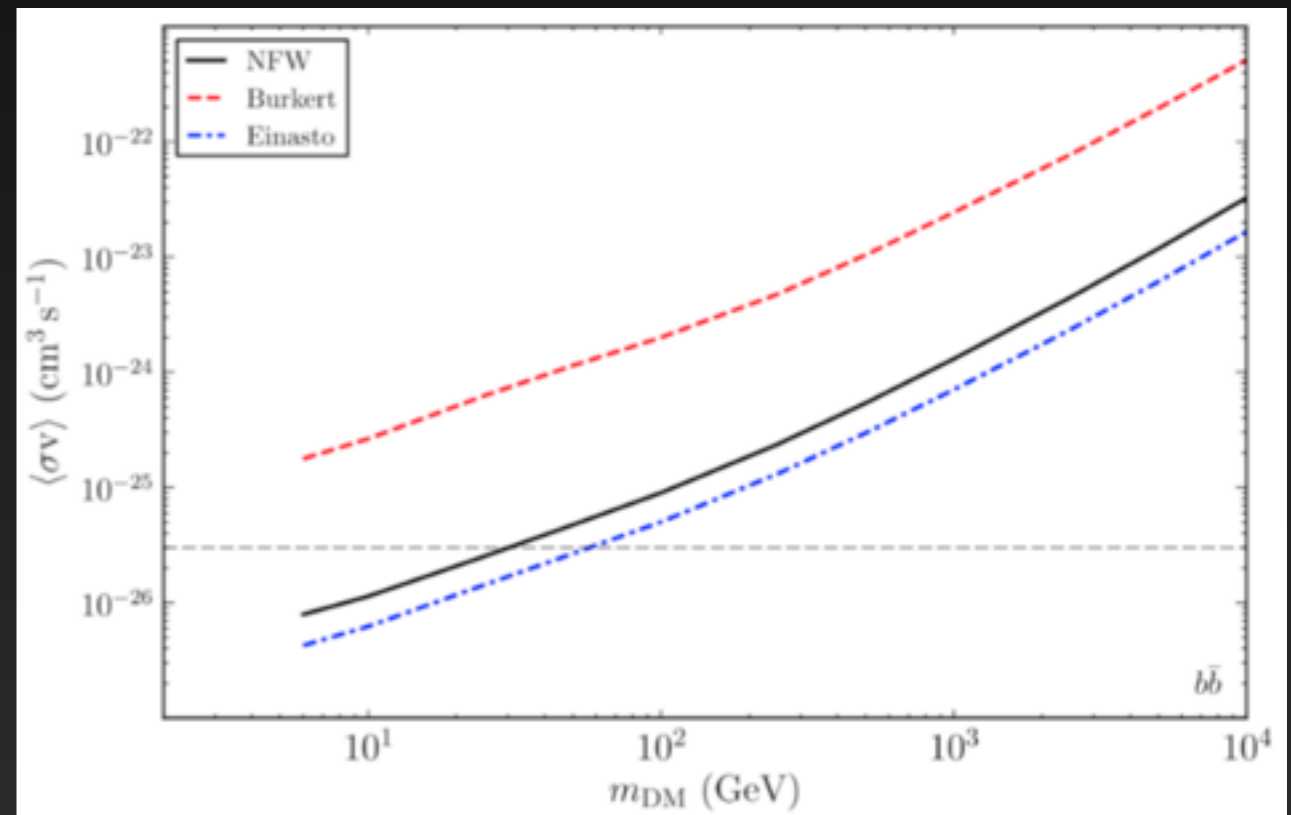
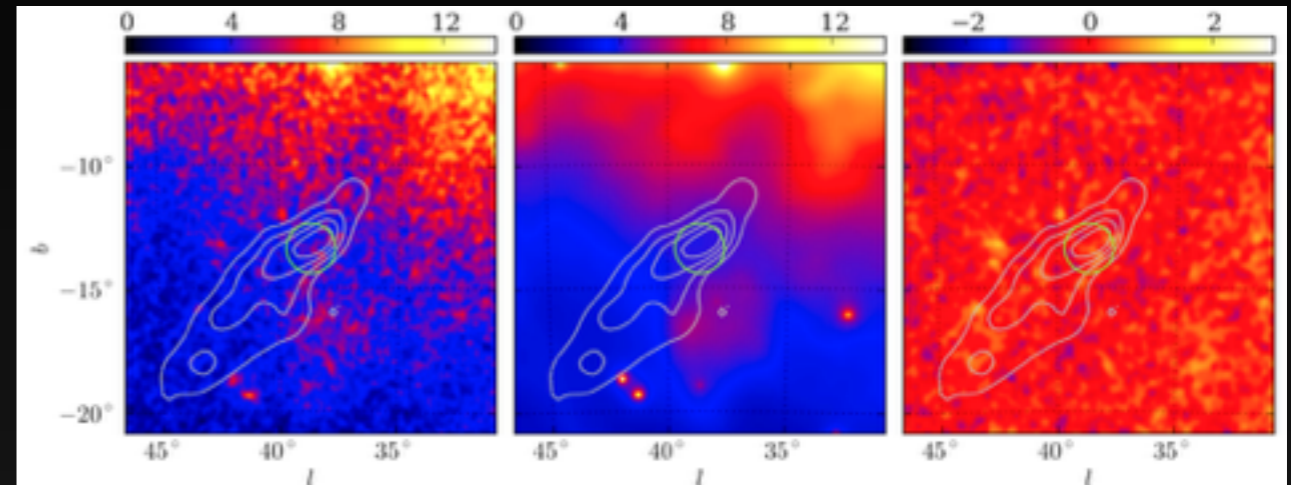
Alternative Targets

May find other bright indirect detection targets.

One possibility is the population of High Velocity Clouds orbiting the Milky Way

Some may be confined by dark matter halos

However, no γ -ray excess is observed in these systems



NICHOLS & BLAND-HAWTHORN (2009, 0911.0684)
NICHOLS ET AL. (2014, 1404.3209)
DRLICA-WAGNER ET AL. (2014, 1405.1030)

Conclusion

- **There is a comprehensive dark matter interpretation of the story:**
 - **The J-factor of the GC exceeds all dwarf spheroidal galaxies by more than 2 orders of magnitude**
 - **A relatively significant detection should appear in the LMC and SMC (study forthcoming)**
 - **The stacked analysis of the dwarfs should begin to show a statistical excess - starting with the brightest object**

Conclusion

- **For the skeptics, there are many ways this story could fall apart:**
 - **Improved J-factor measurements may indicate that Reticulum II is not the brightest dwarf**
 - **The significance of the dwarf analysis might go down with P8 data**
 - **Astrophysical explanations for excesses in the Galactic Center and the LMC may be produced**
- **The next few years promise to present significant hints (or significant constraints on) the dark matter particle models that can explain the GeV excess.**