

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

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UC, Berkeley D4 Seminar

11/23/15

Gravitational Dark Matter



1933: Zwicky observes dark matter in Coma Cluster

Gravitational Dark Matter



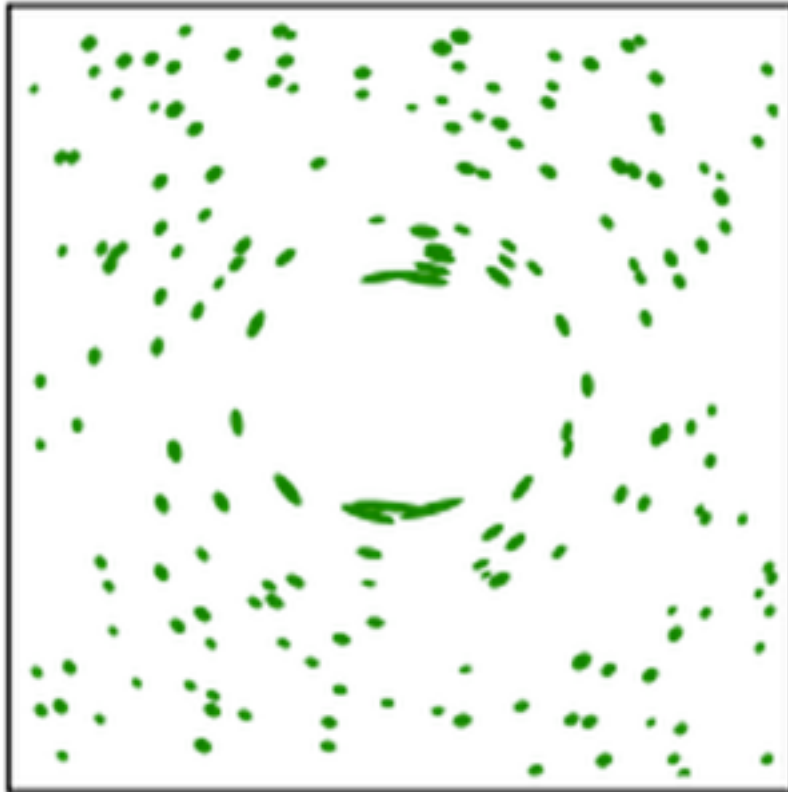
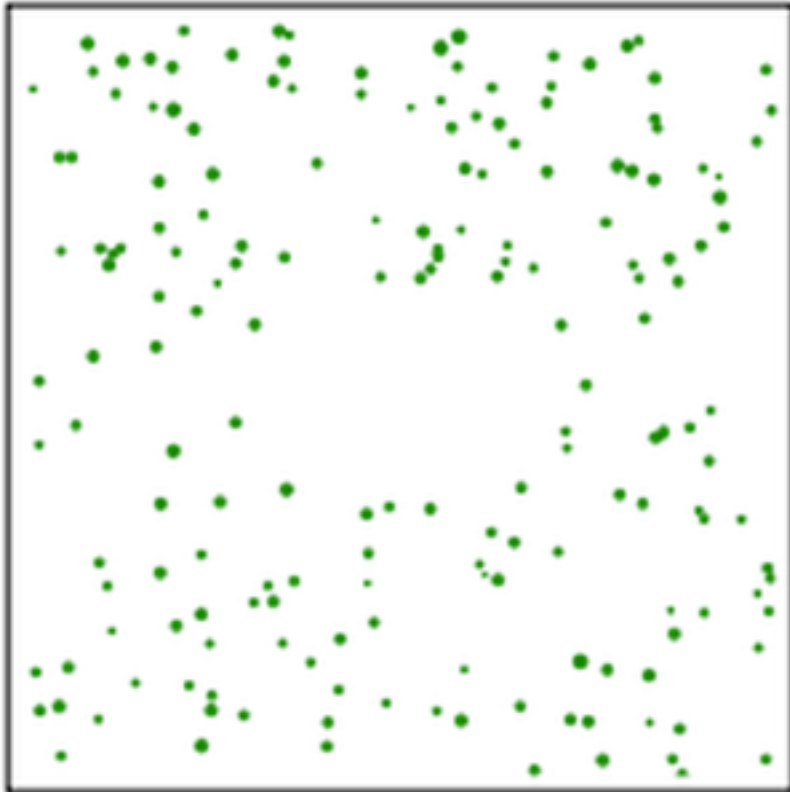
1970s: Vera Rubin observes anomalous rotation velocities in M31

Gravitational Dark Matter



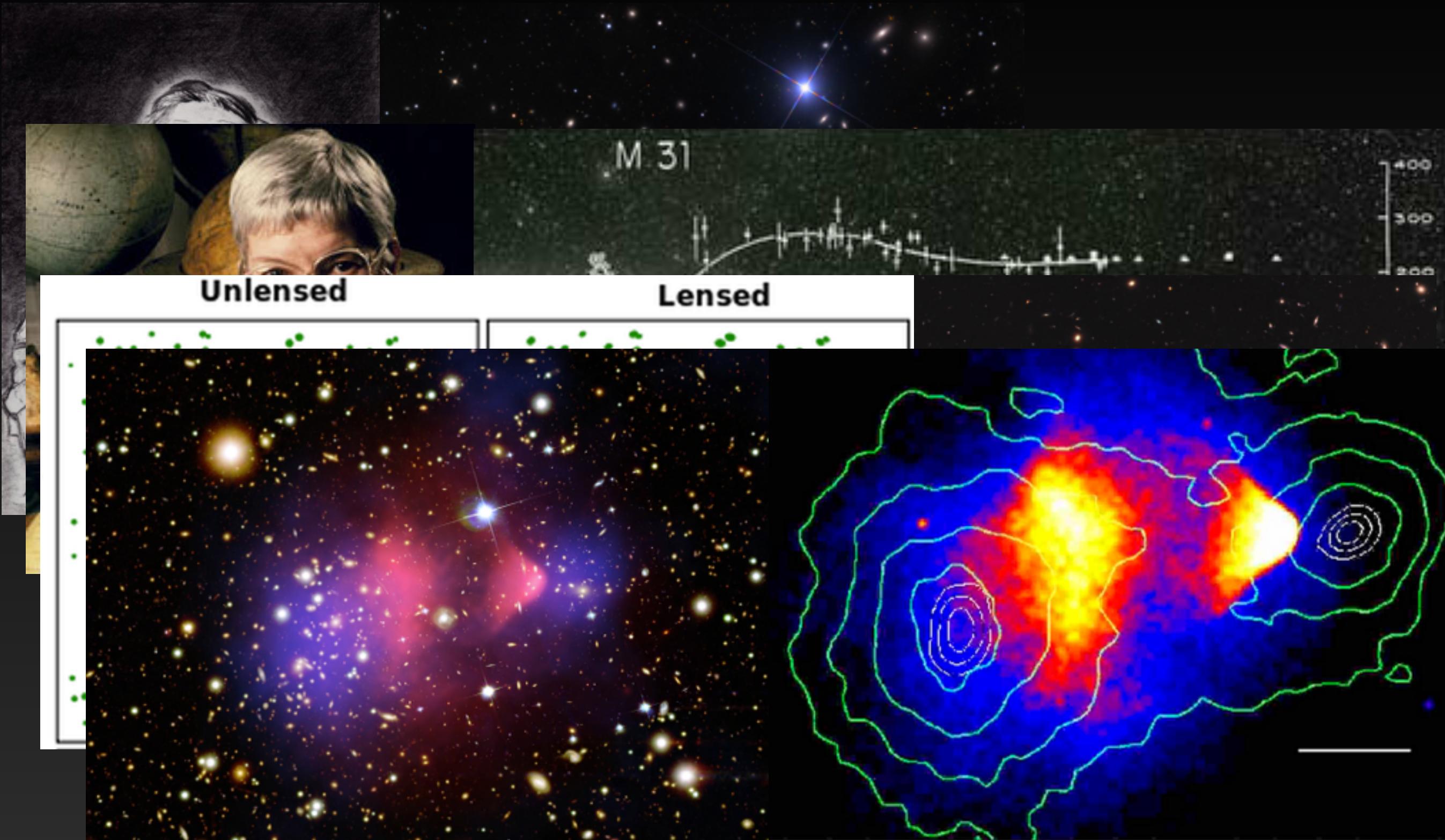
Unlensed

Lensed



1996: Weak Gravitational Lensing Observed from Dark Matter Halos

Gravitational Dark Matter

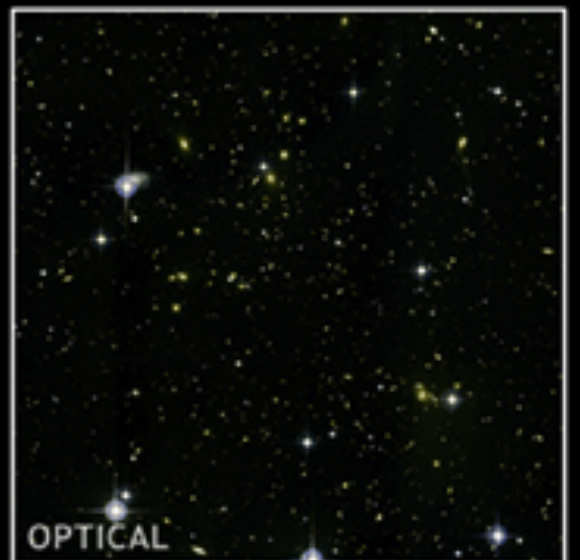
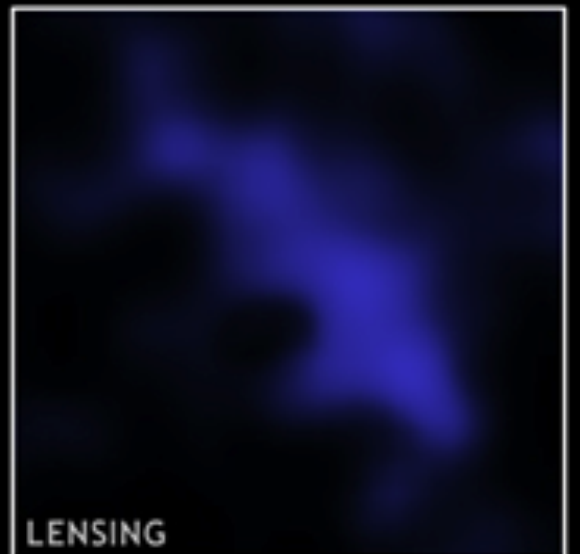
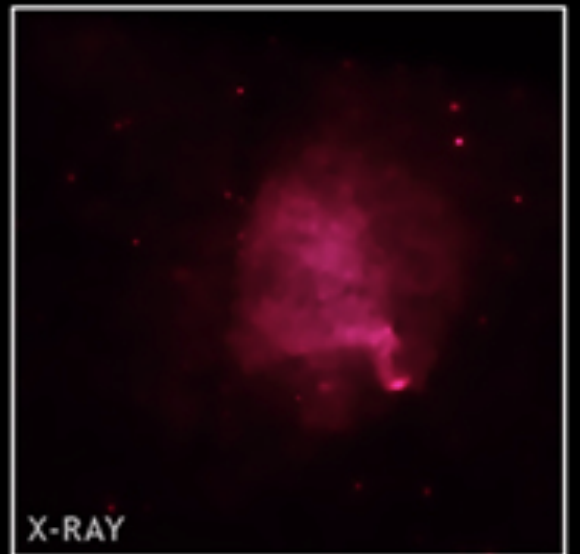


2006: Bullet Cluster Observations Show Offset Between Mass and Hot Gas

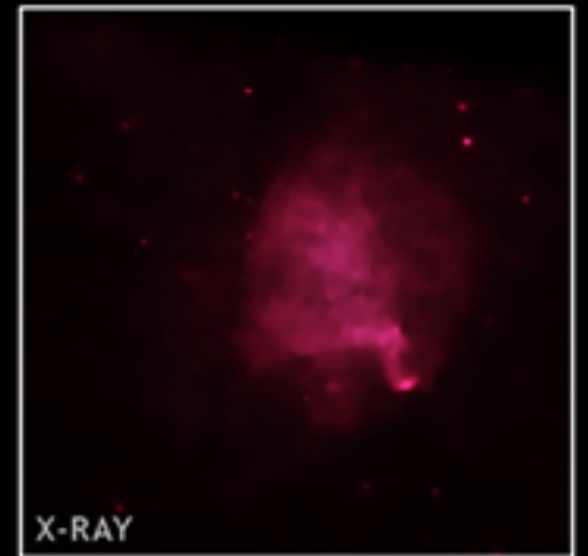
Gravitational Dark Matter



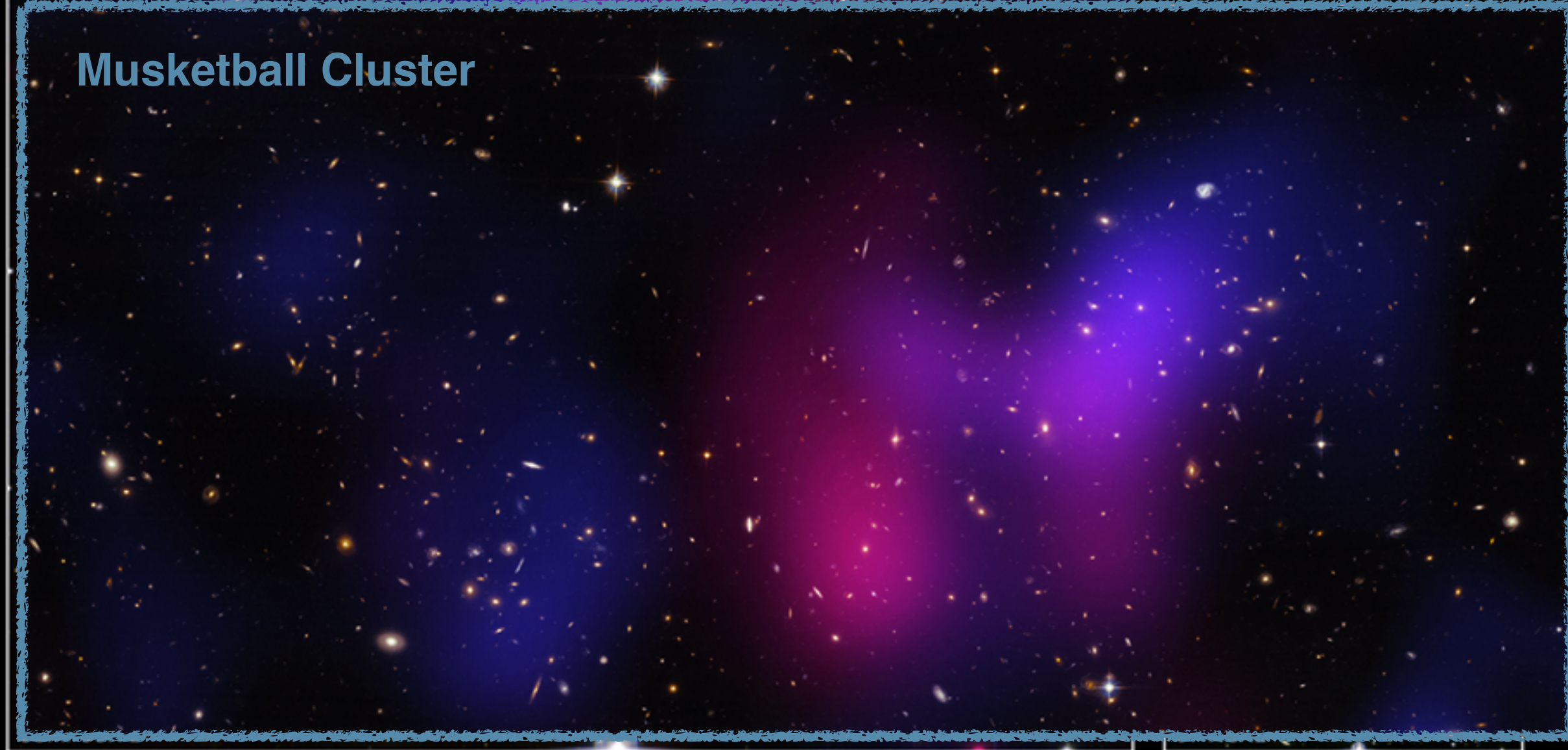
Trainwreck Cluster



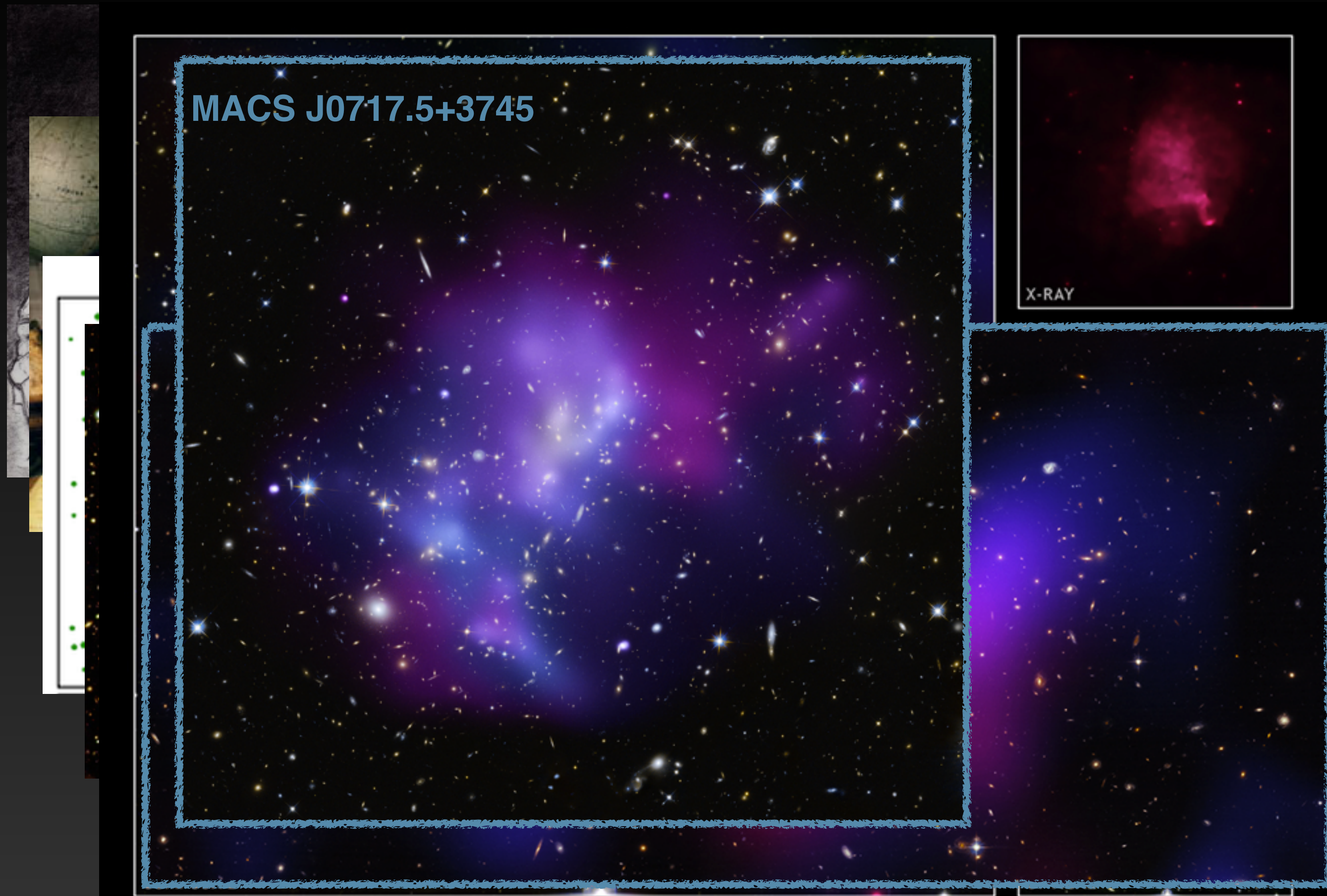
Gravitational Dark Matter



Musketball Cluster

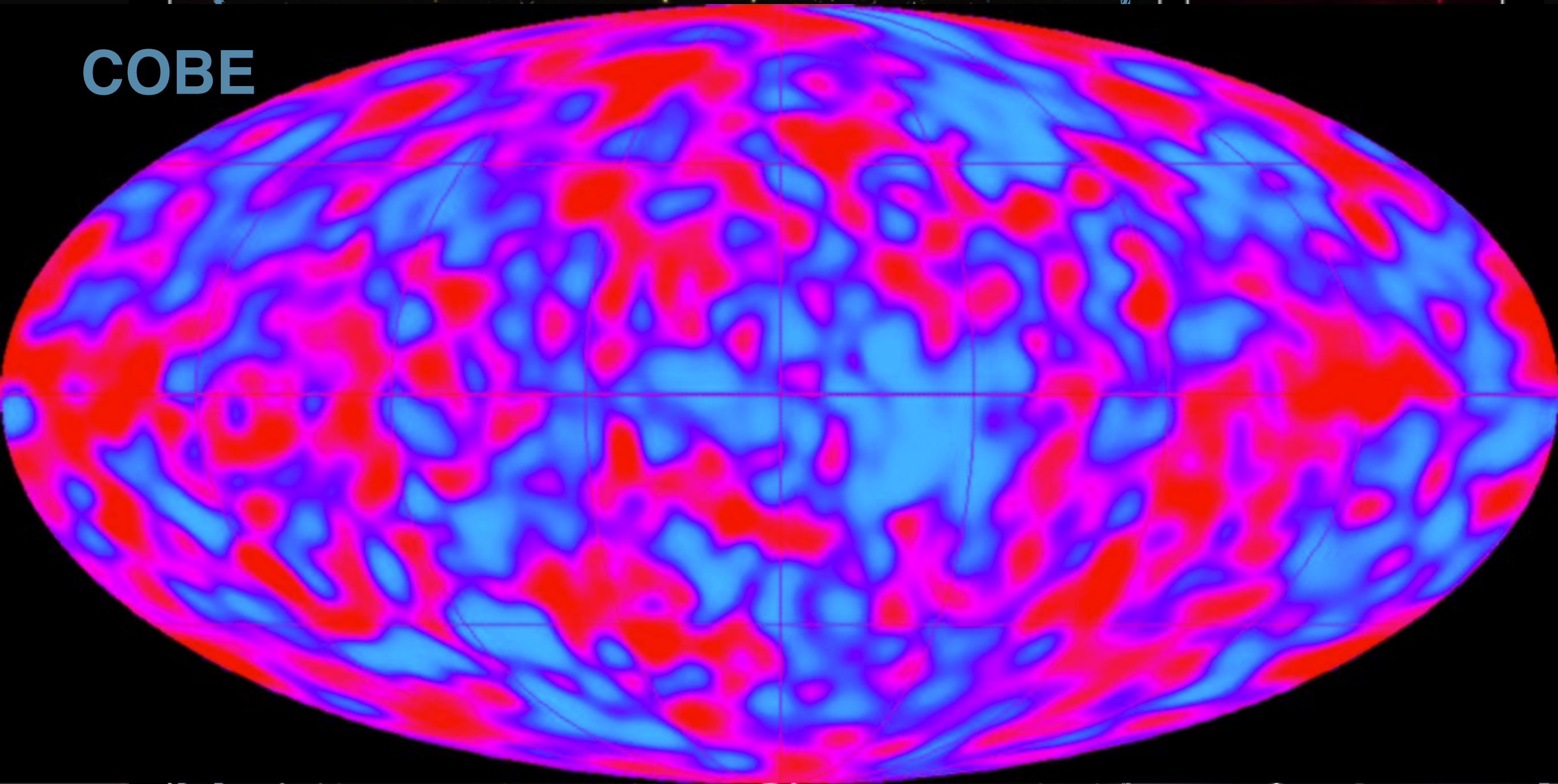


Gravitational Dark Matter



Gravitational Dark Matter

COBE



Gravitational Dark Matter

WMAP

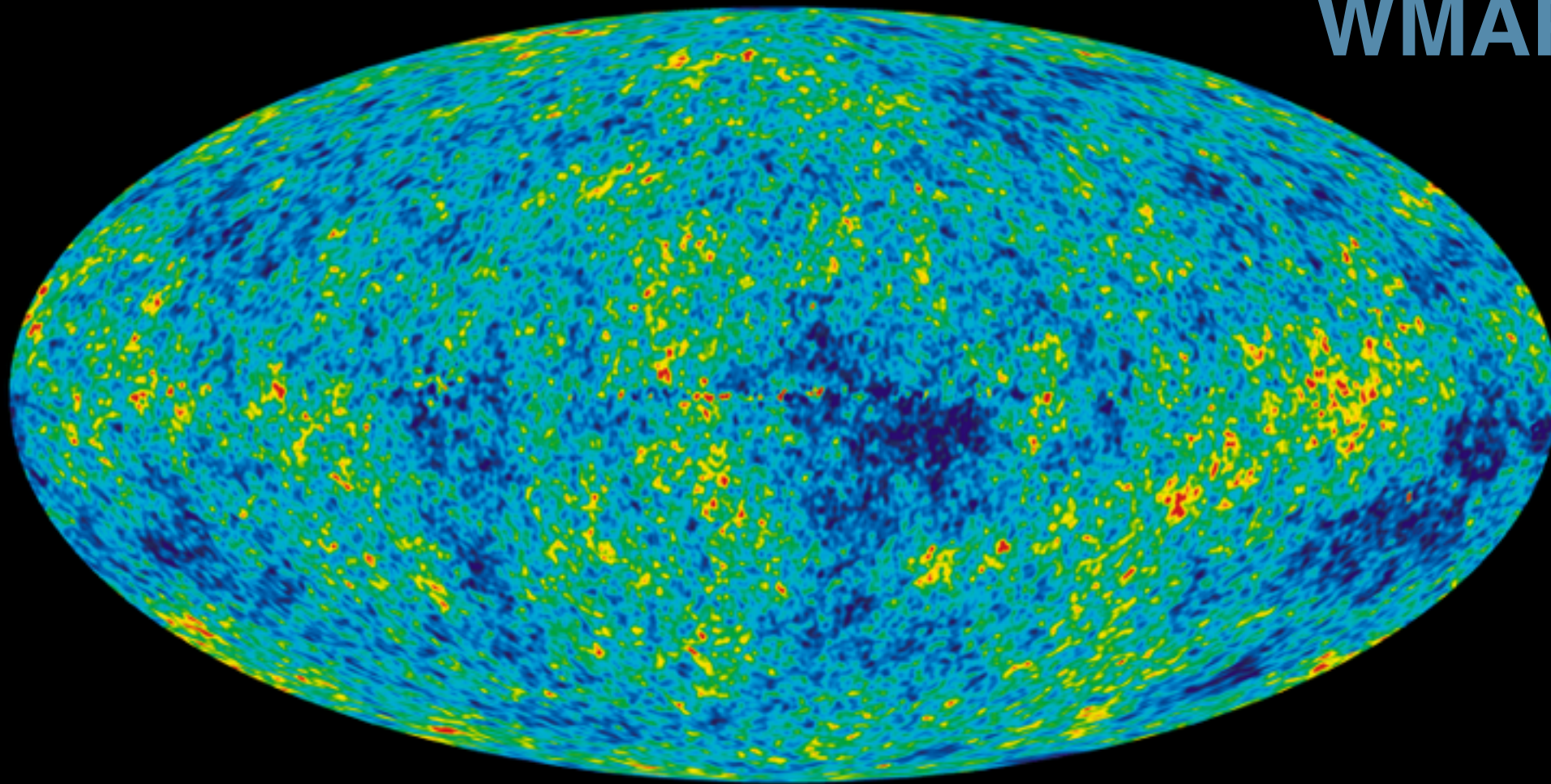
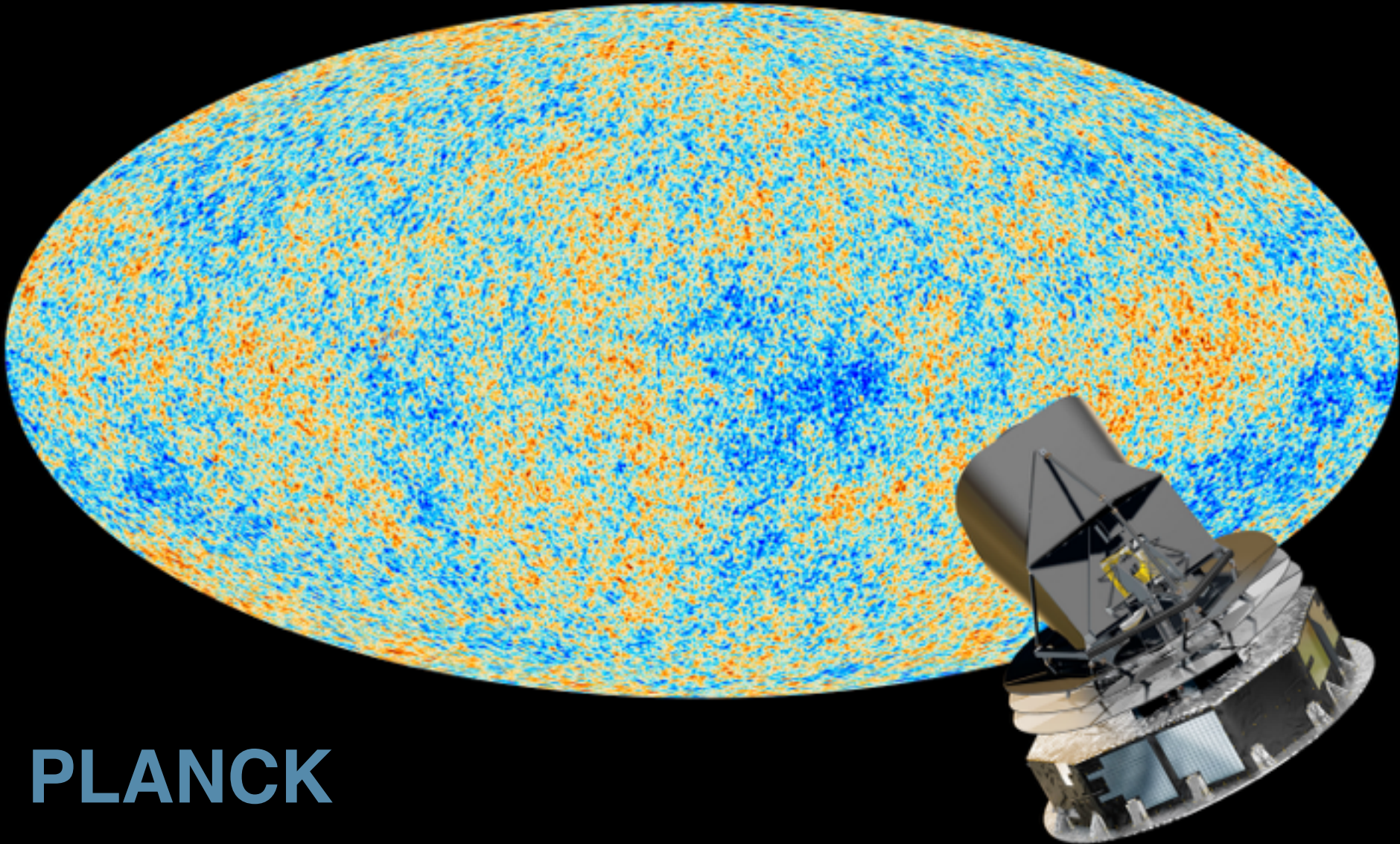


Table 6. Cosmological Parameter Summary

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



Age of u
Hubble c
Baryon c
Physical
Dark ma

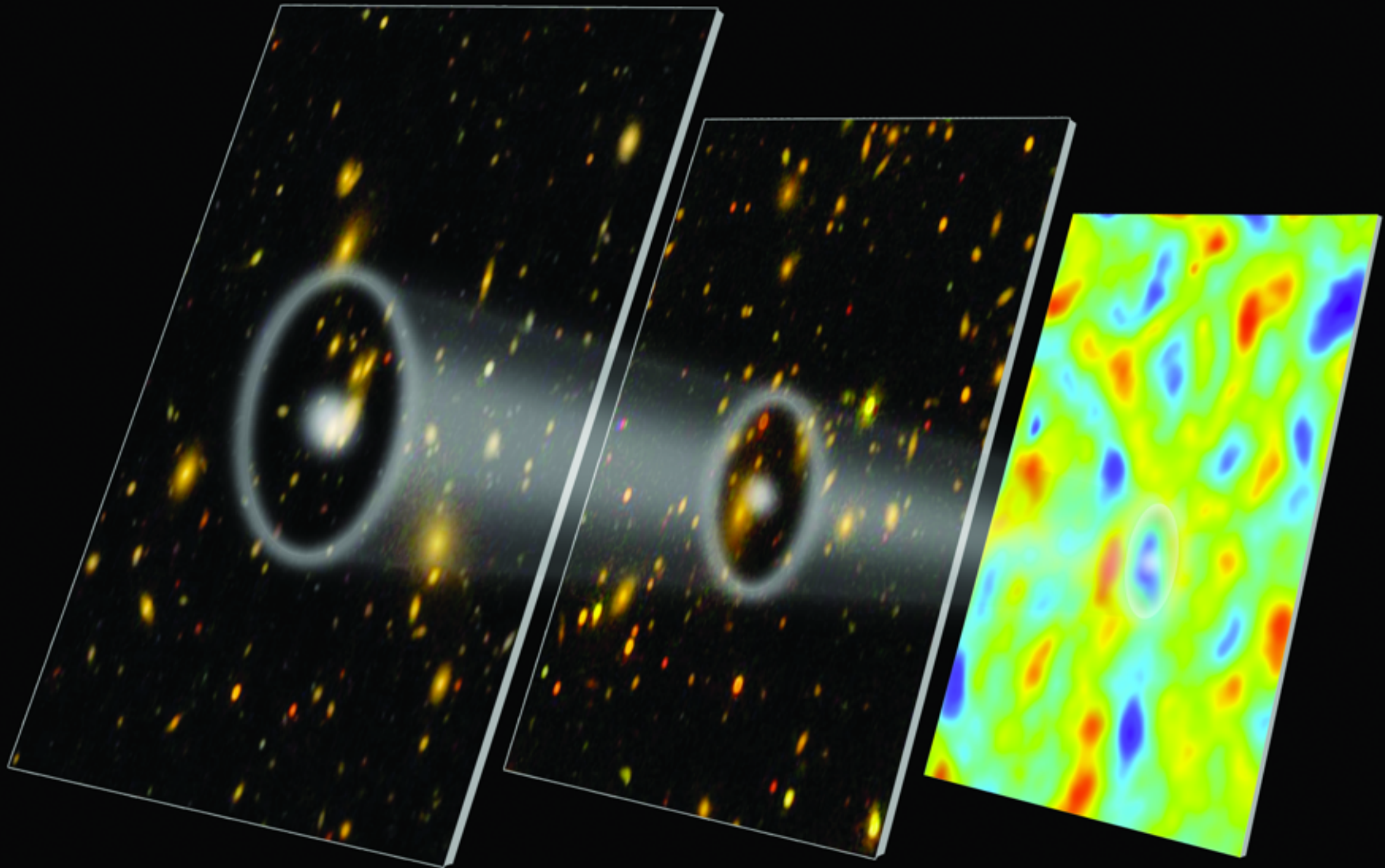
Gravitational Dark Matter

A visualization of the cosmic web, showing a vast network of dark matter filaments and galaxy clusters. The filaments are represented by thin, glowing yellow lines against a dark blue background, forming a complex, interconnected web. The clusters are represented by denser, brighter yellow regions. The overall structure is highly irregular and fractal-like, illustrating the large-scale distribution of matter in the universe.

Large Scale Structure

Gravitational Dark Matter

Baryonic Acoustic Oscillations



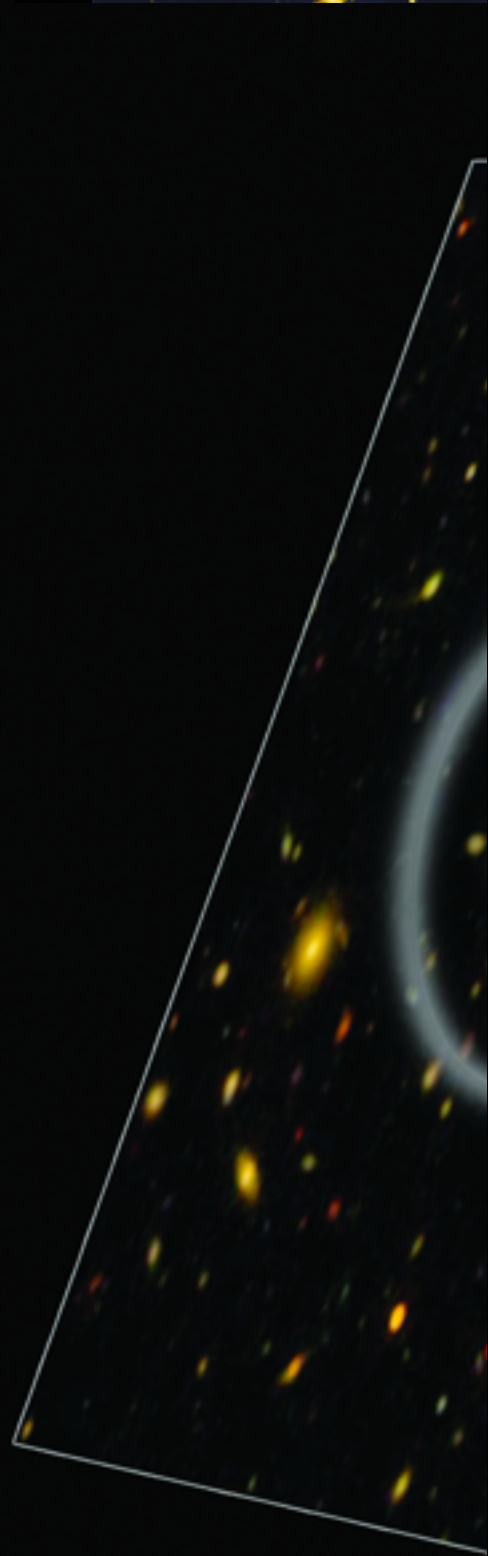
Galaxy map 3.8 billion years ago

Galaxy map 5.5 billion years ago

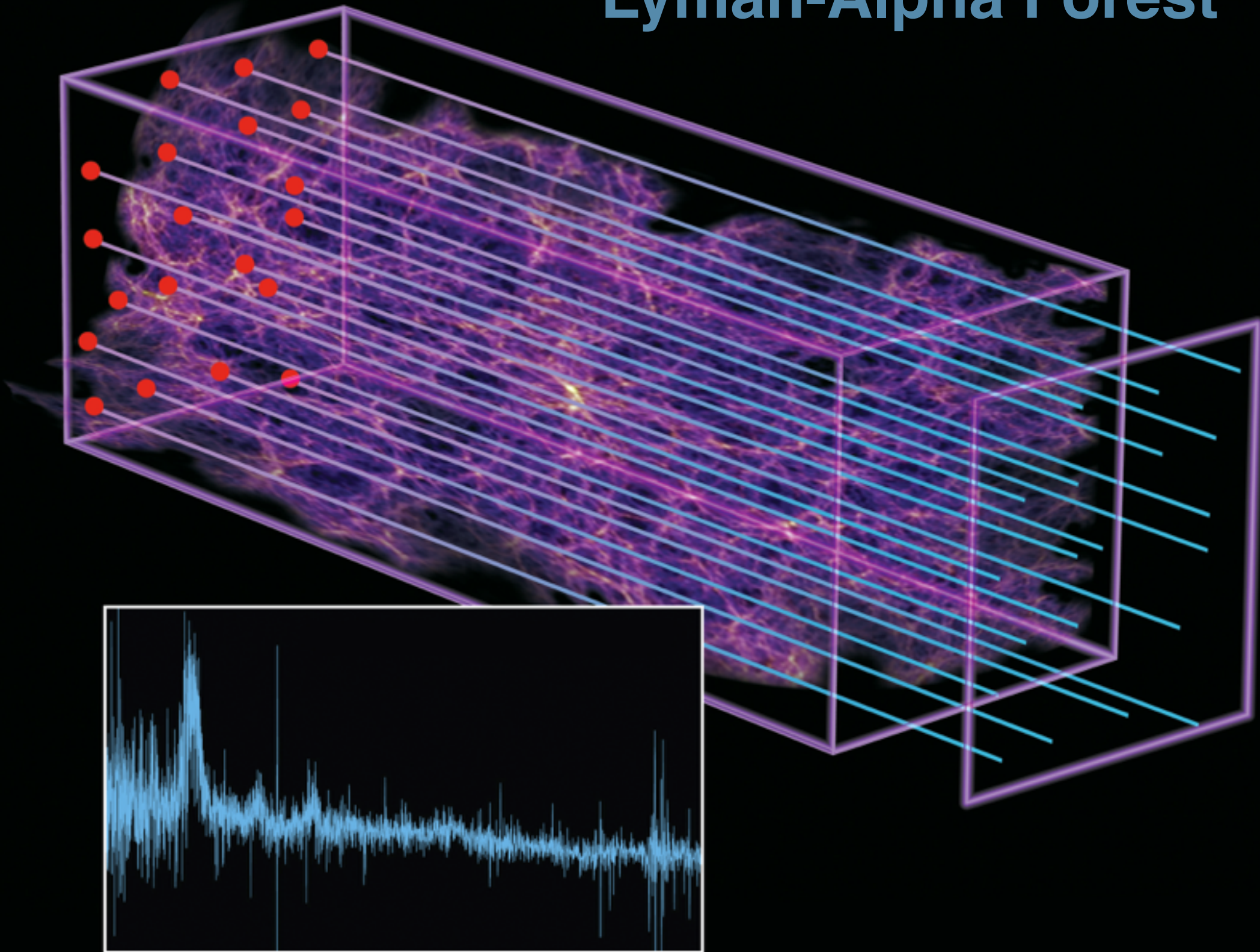
CMB 13.7 billion years ago

Gravitational Dark Matter

Lyman-Alpha Forest



Galaxy map 3.8 billion



Gravitational Dark Matter

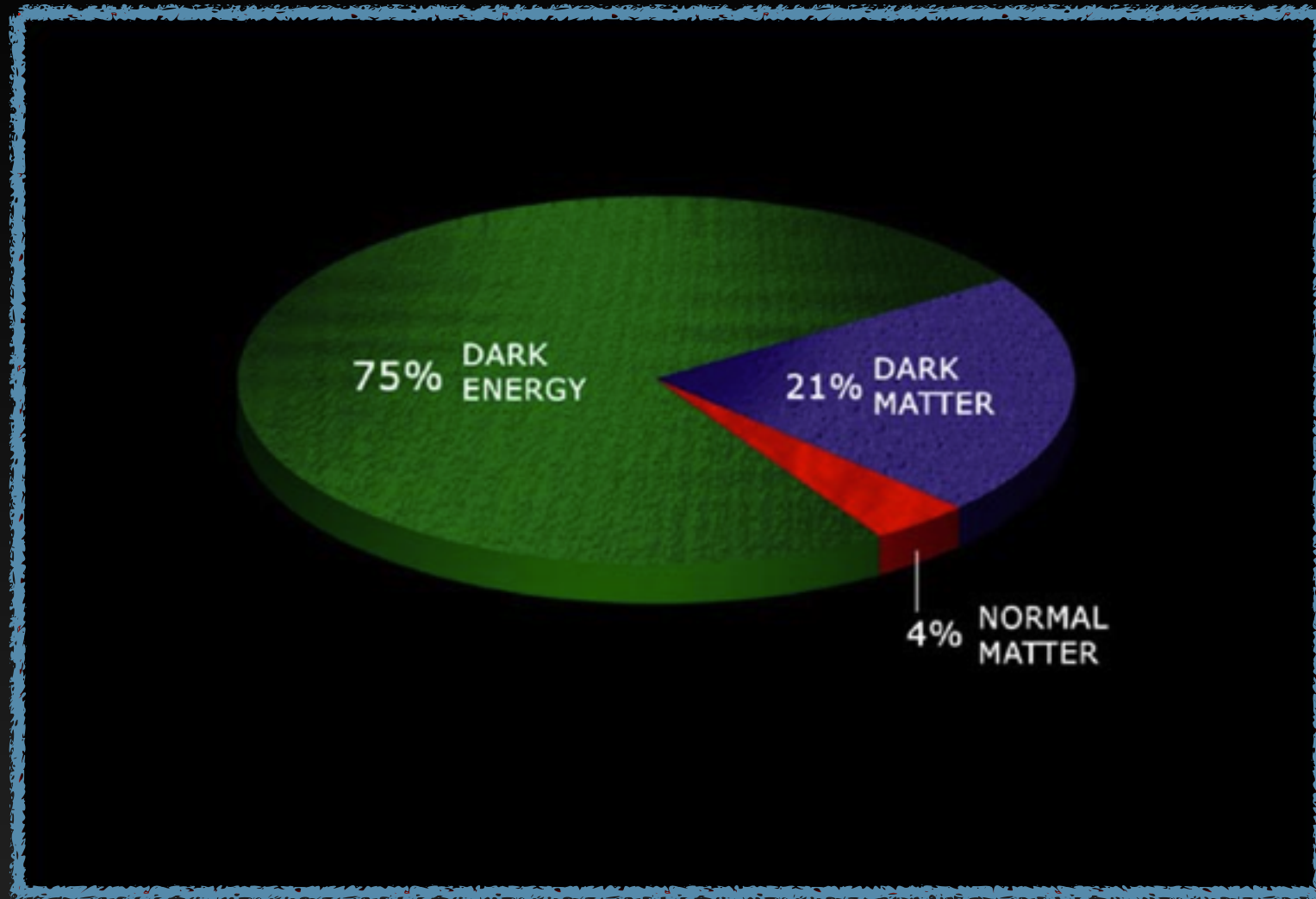
Type 1A Supernove



Galaxy map 3.8 billion



Dark Matter Cosmology

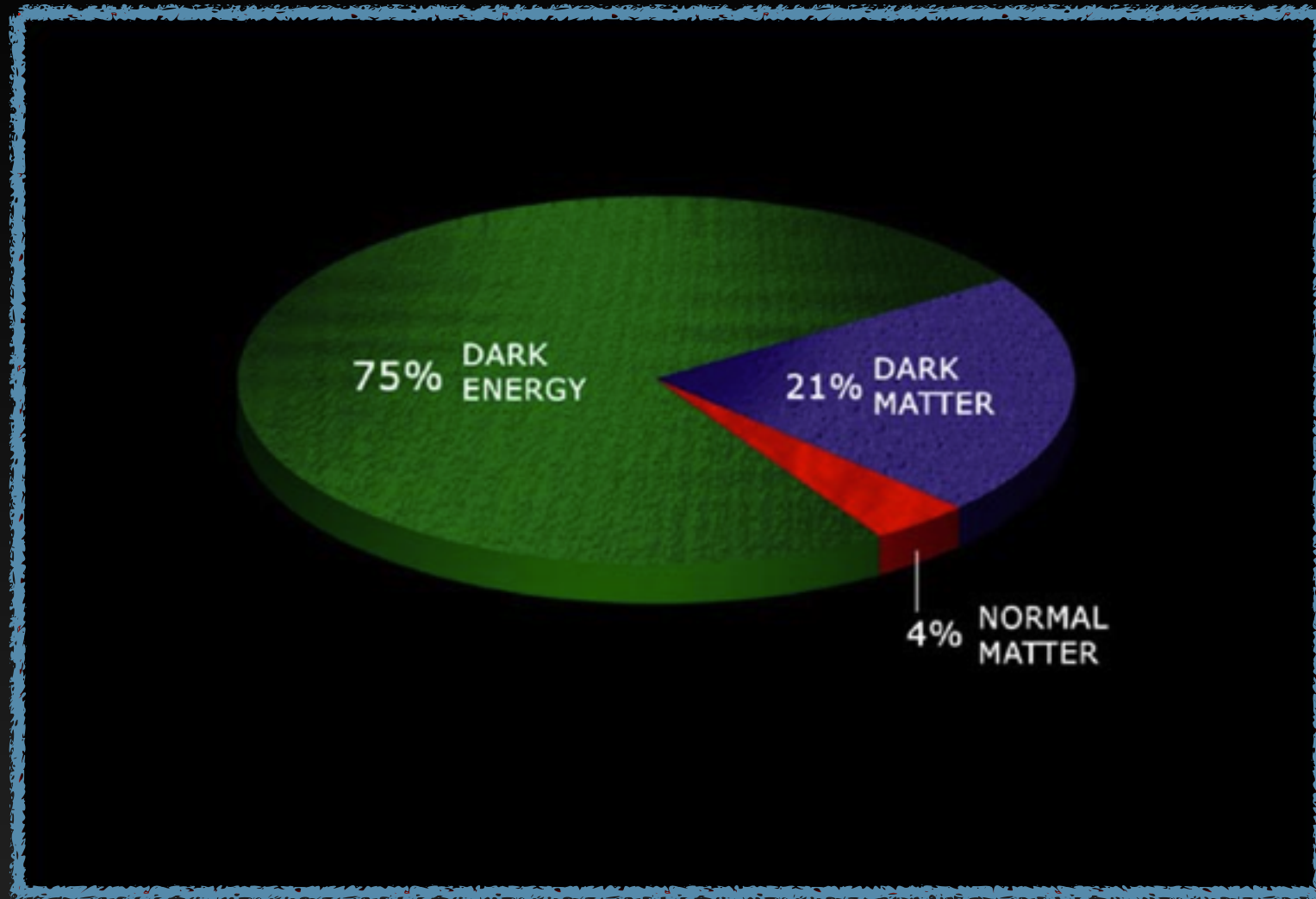


Dark Matter Is:

- 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

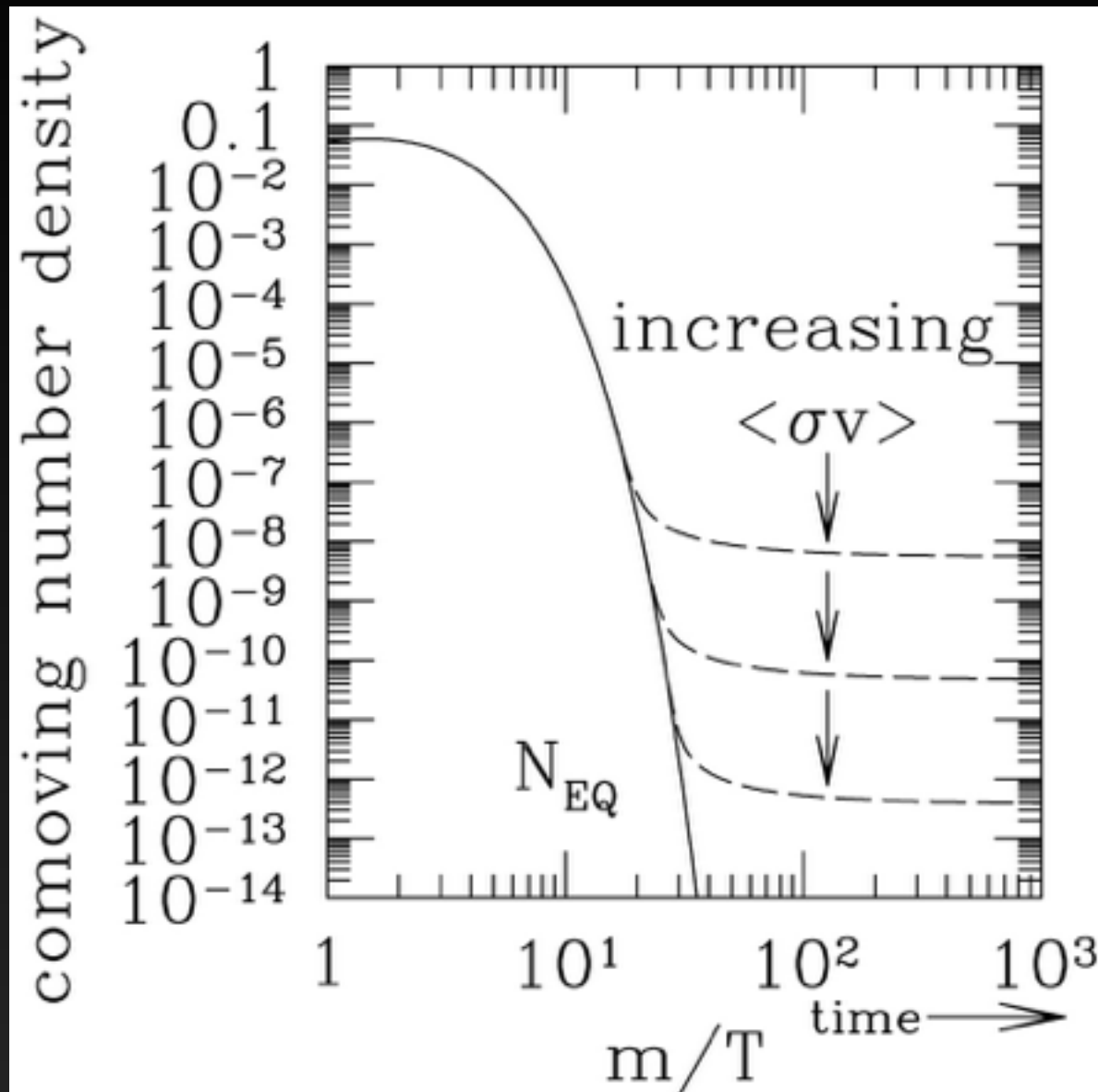
Gravity is Weak!

- 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



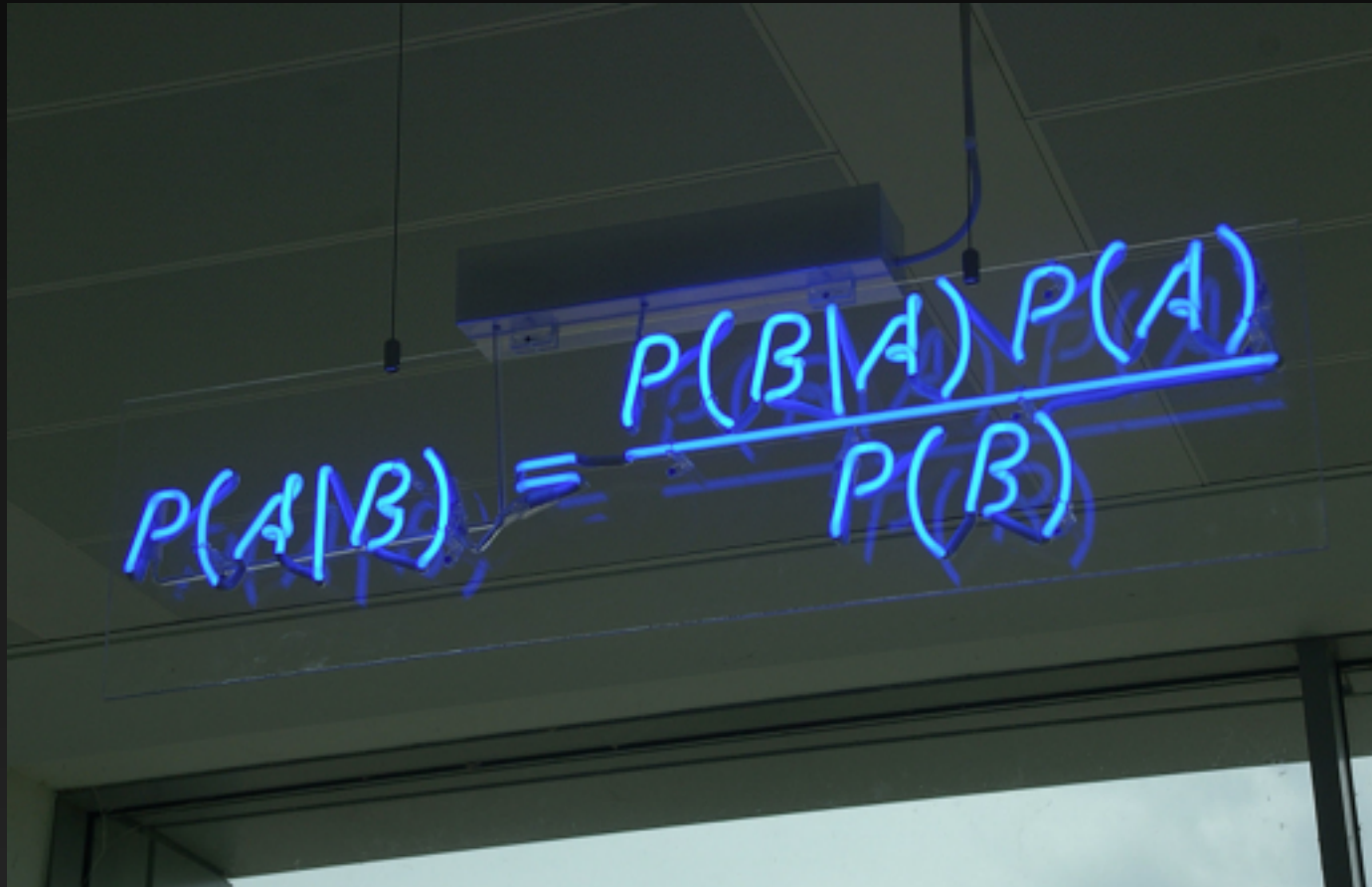
A particle with a weak interaction cross-section and a mass on the weak scale is expected to naturally obtain the correct relic abundance through thermal freeze-out in the Early Universe.

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

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

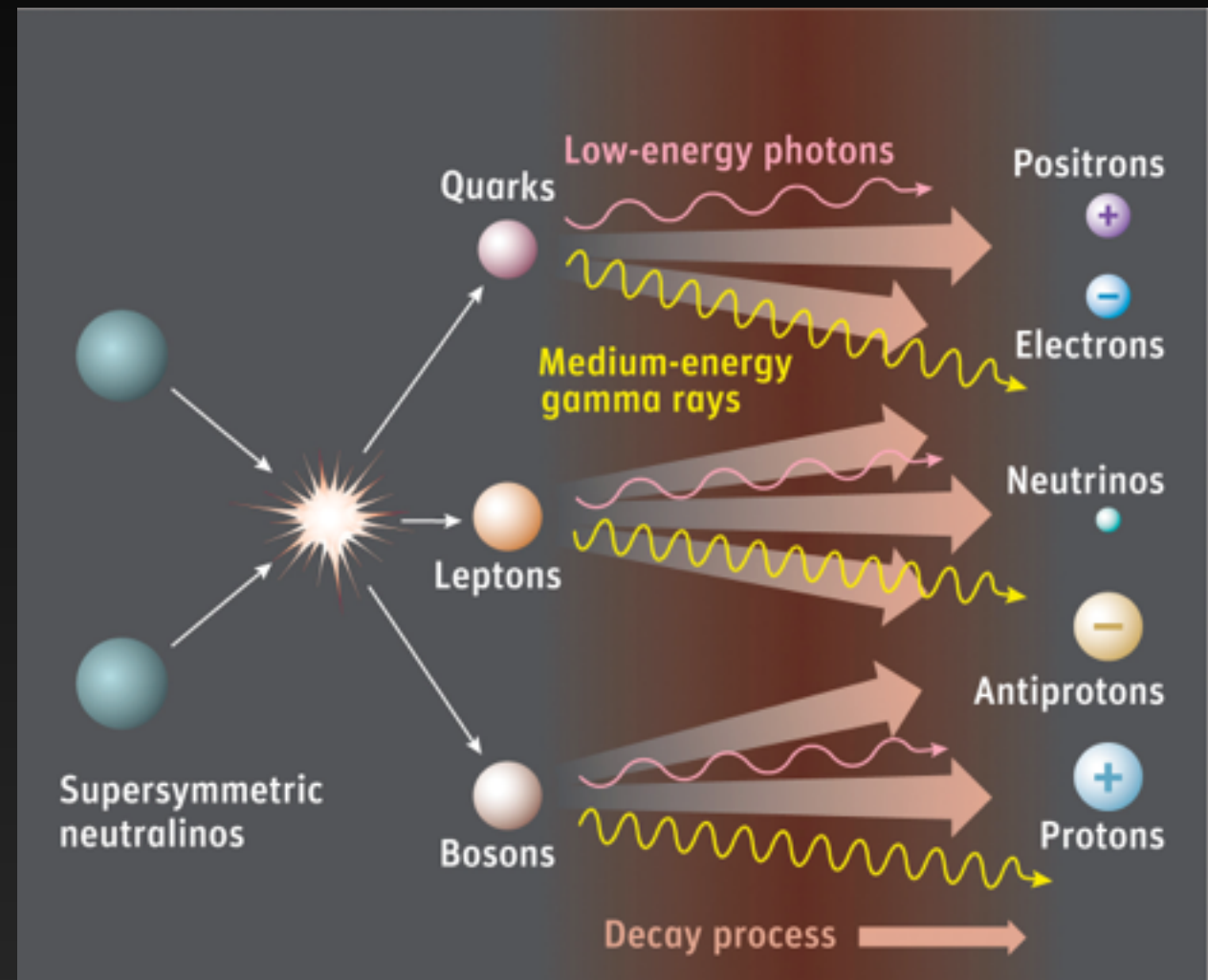
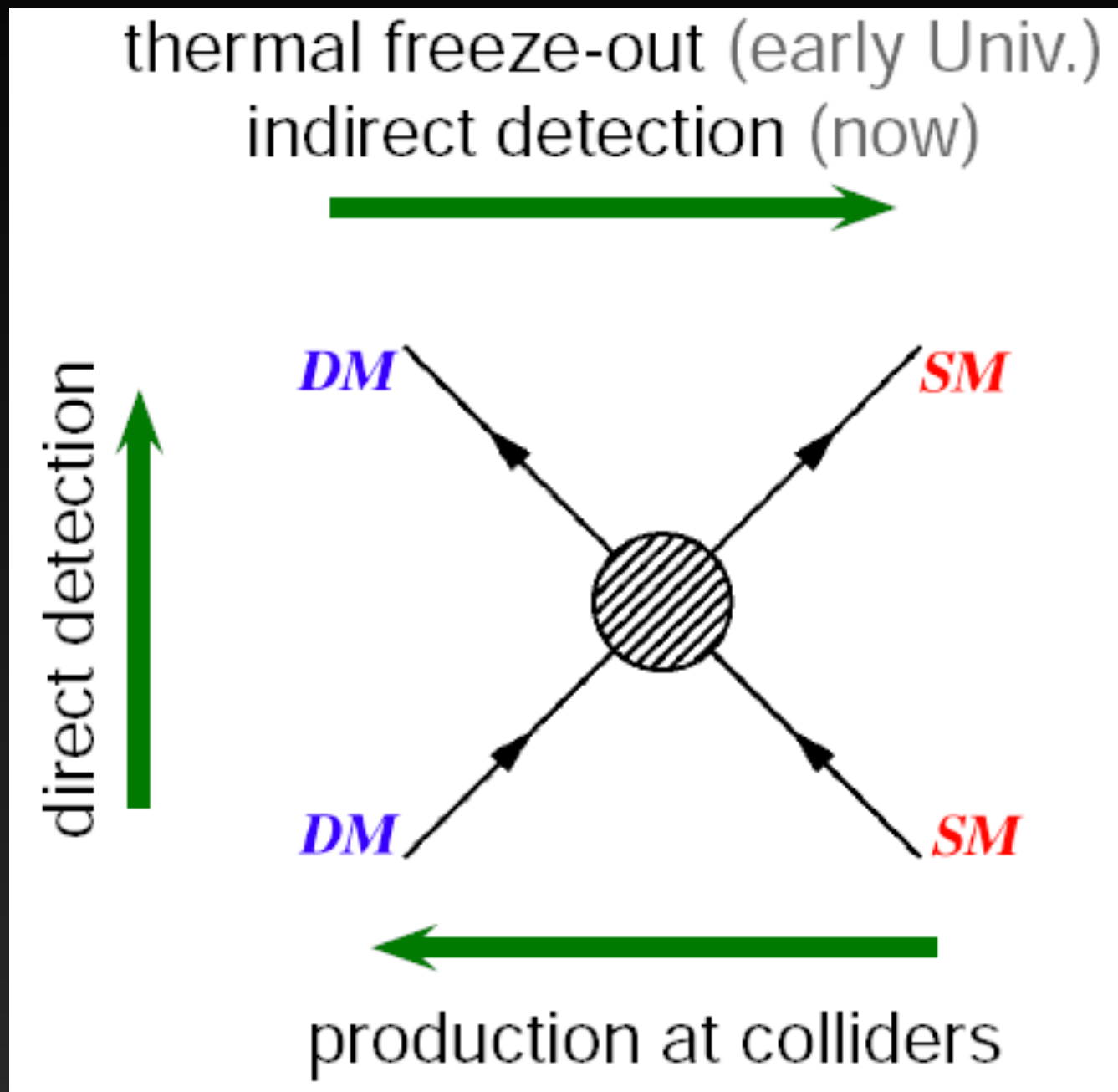
Observing a Dark Matter Particle

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

A photograph of a blue neon sign mounted on a wall. The sign displays the formula for conditional probability: $P(A|B) = \frac{P(B|A)P(A)}{P(B)}$. The sign is made of several blue neon tubes that form the letters and mathematical symbols. The background is a plain, light-colored wall.
$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

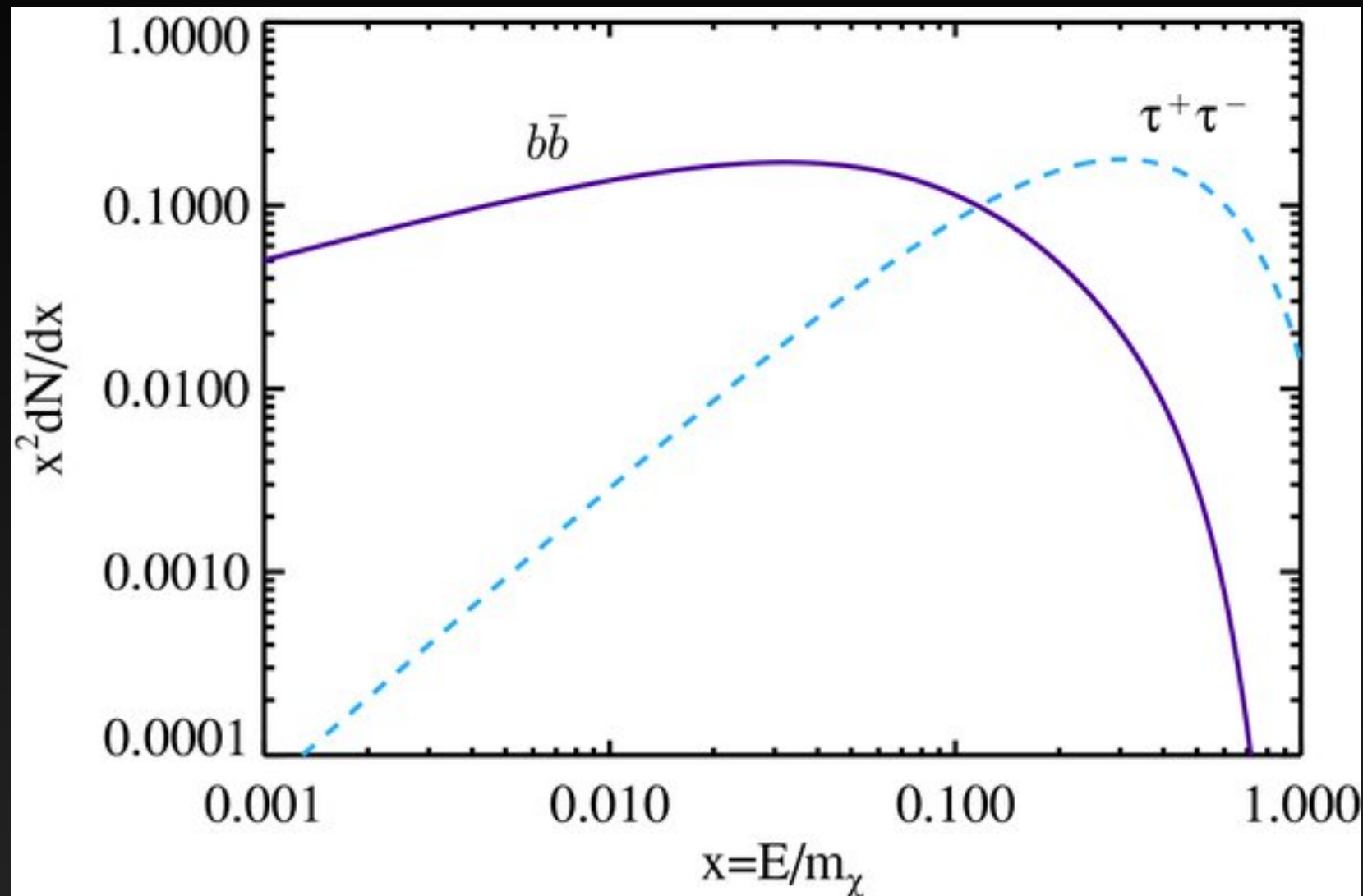
We shouldn't think of dark matter searches as a "needle in a haystack". Our theoretical priors should lead us to bet that particle dark matter can be feasibly observed.

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

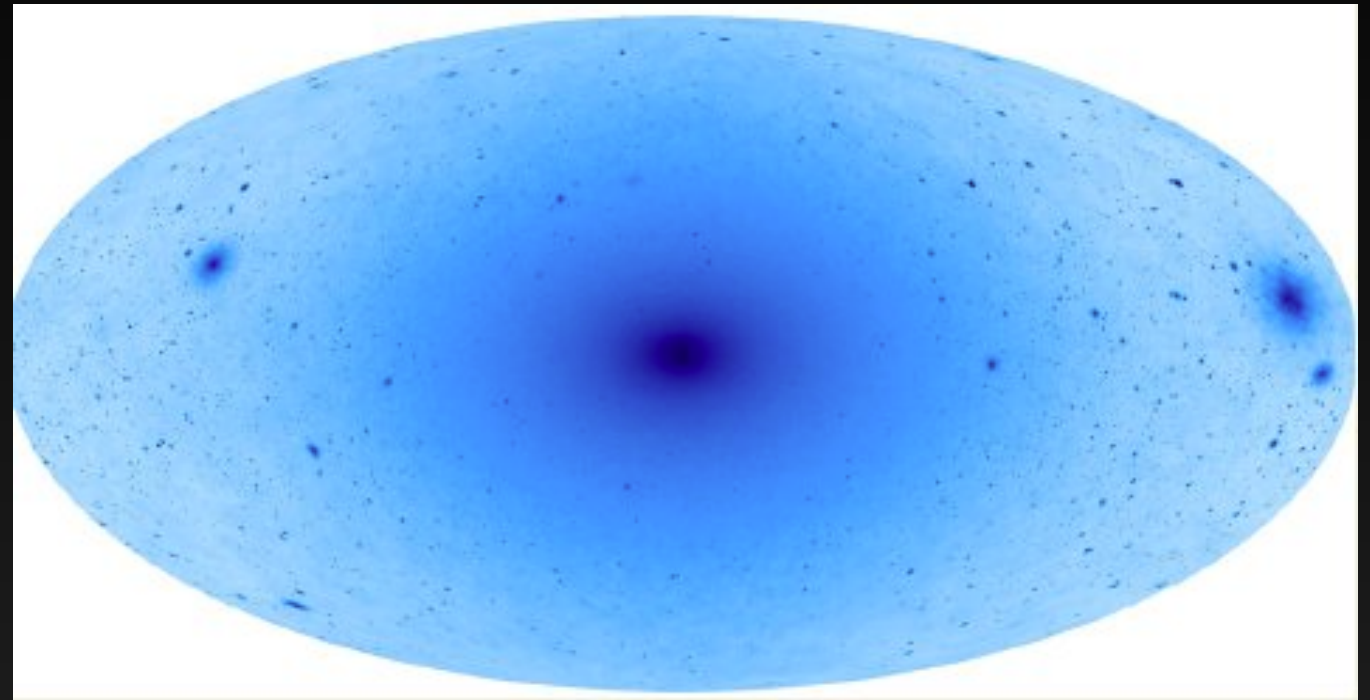


Once a standard model final state is selected, the resulting photon spectrum can be calculated from known physics.

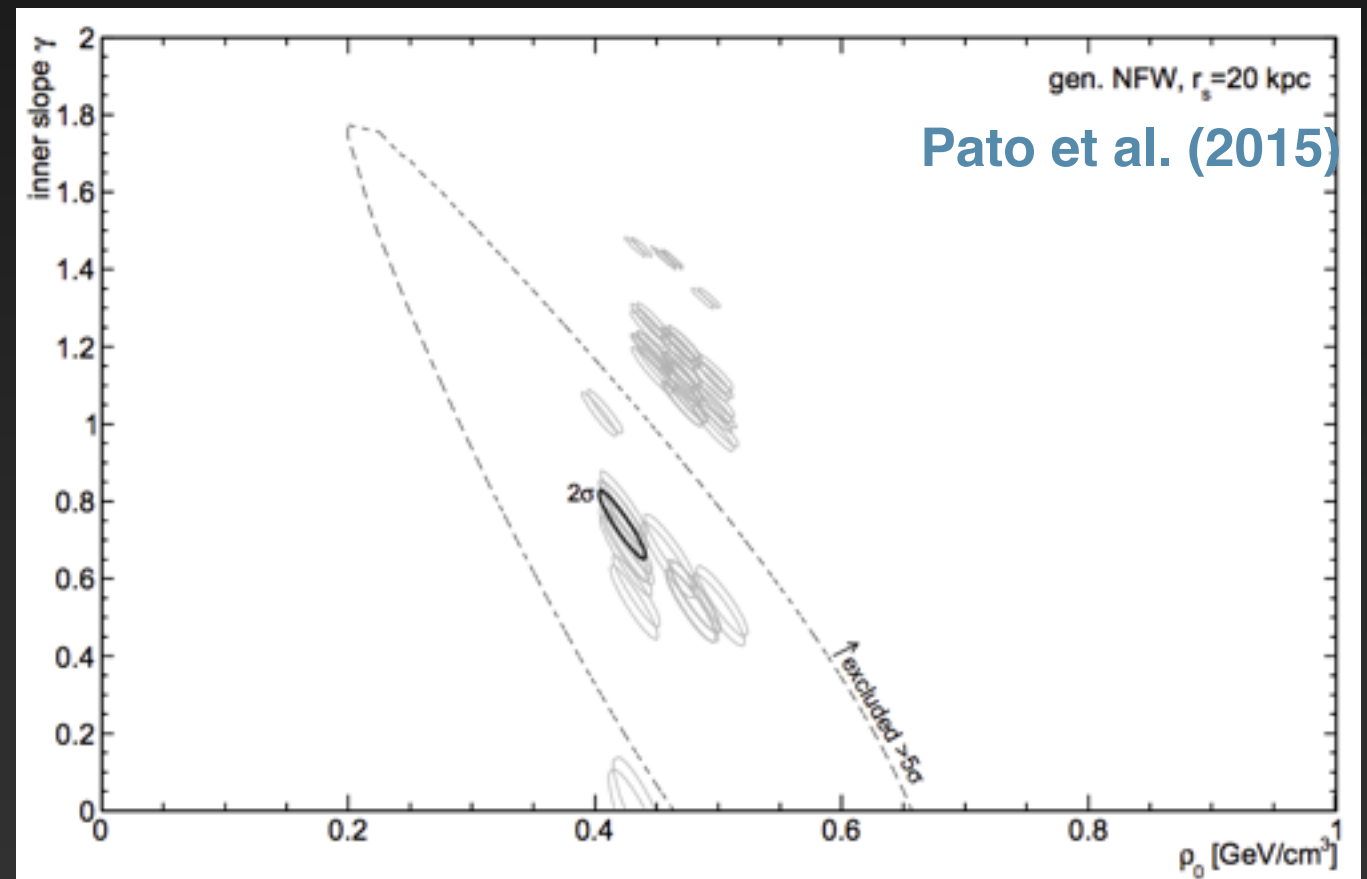
For WIMP scale dark matter, photon energy peaks in the GeV range.

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.



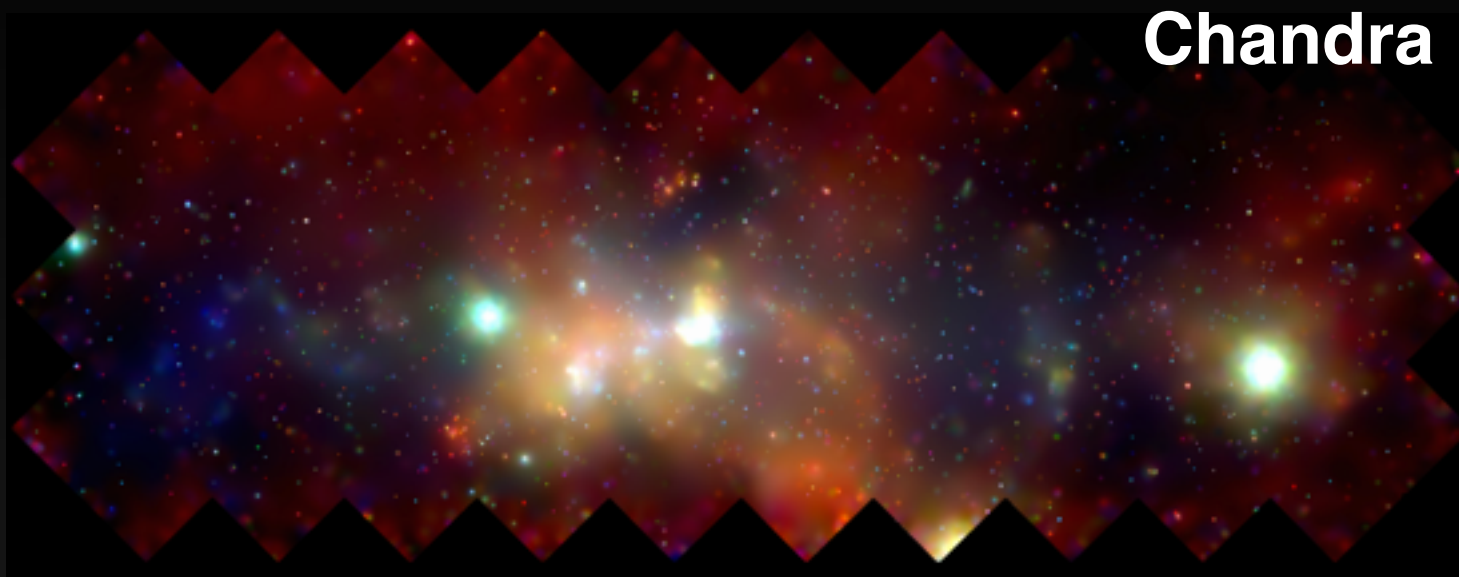
Dark Matter in the Galactic Center

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

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, $\gamma = 1$

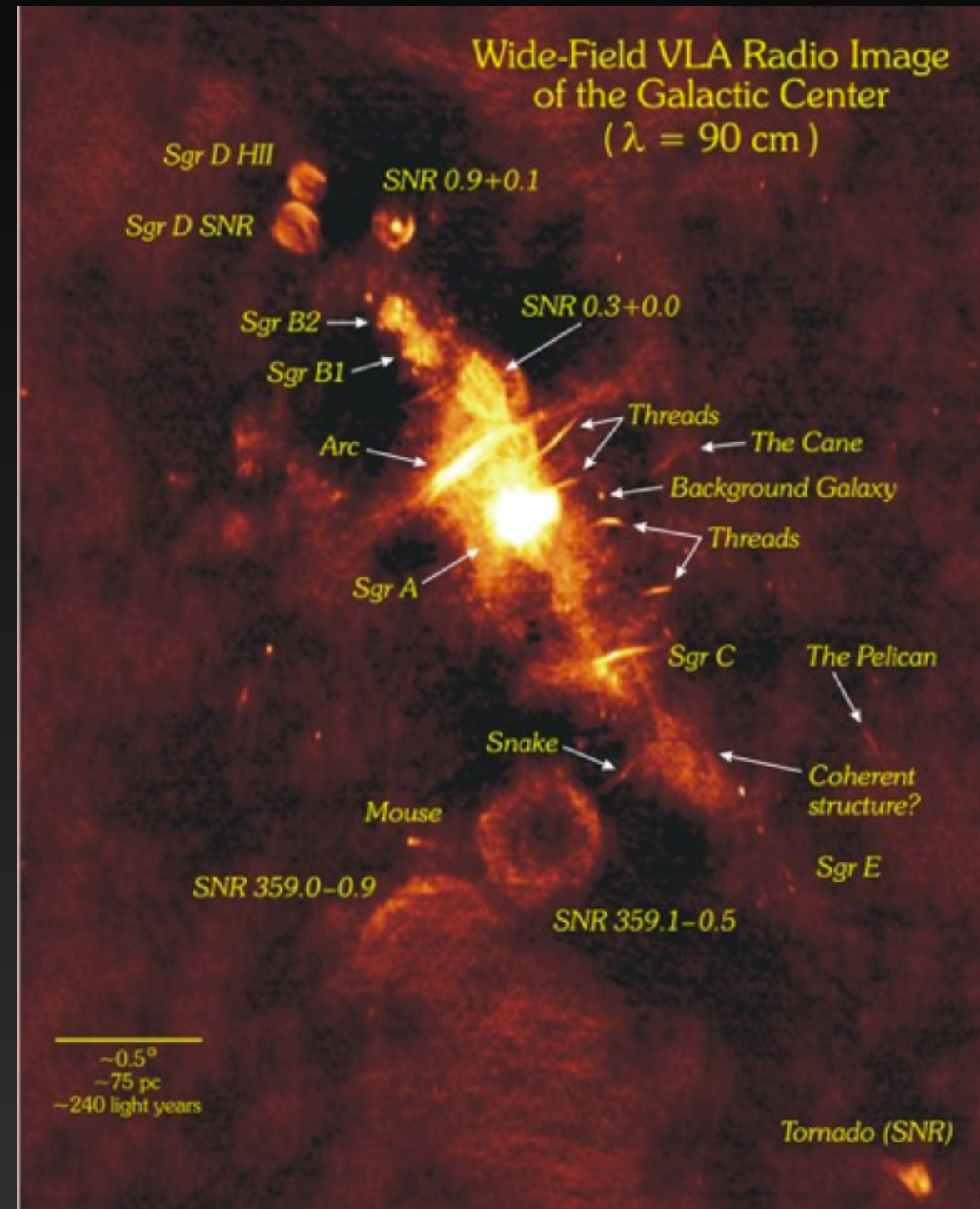
The Galactic Center in Gamma-Rays



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

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

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)



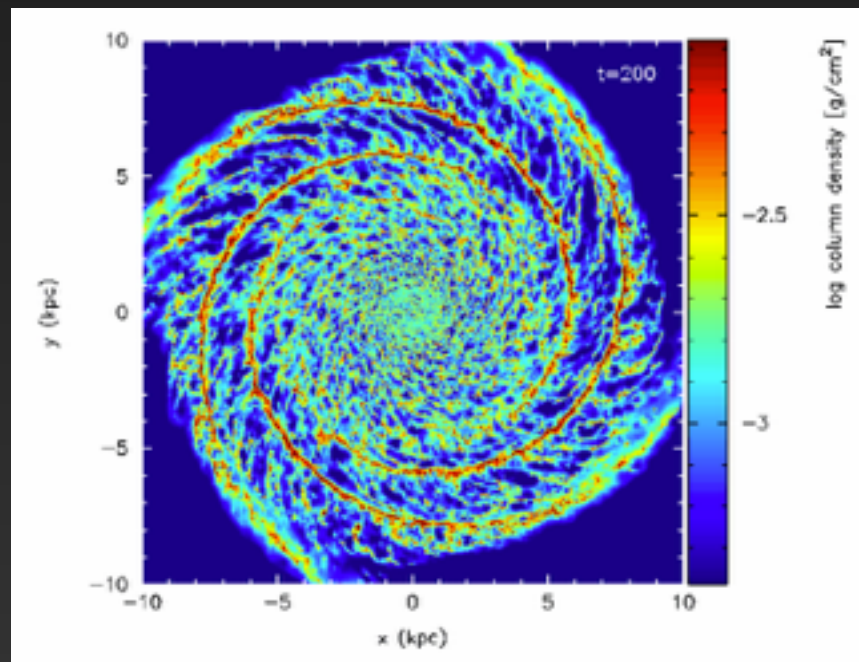
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Gas/ISRF



The Galactic Center in Gamma-Rays

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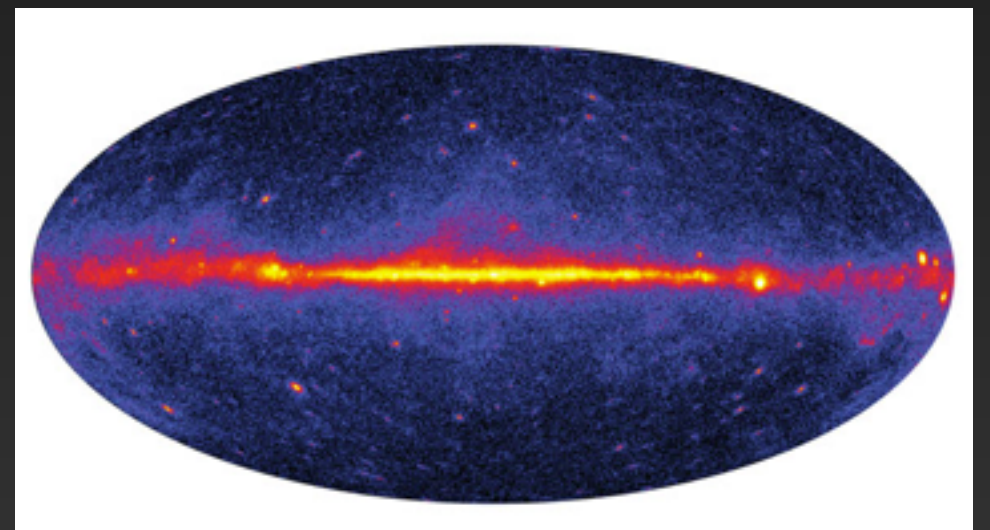
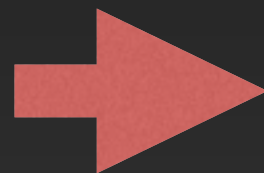
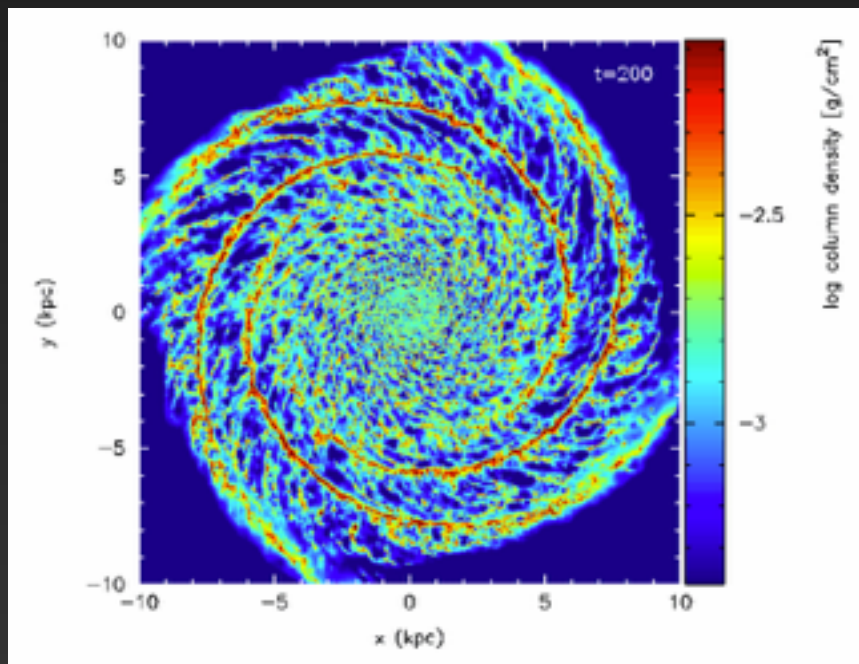
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Solved Numerically:

e.g. Galprop

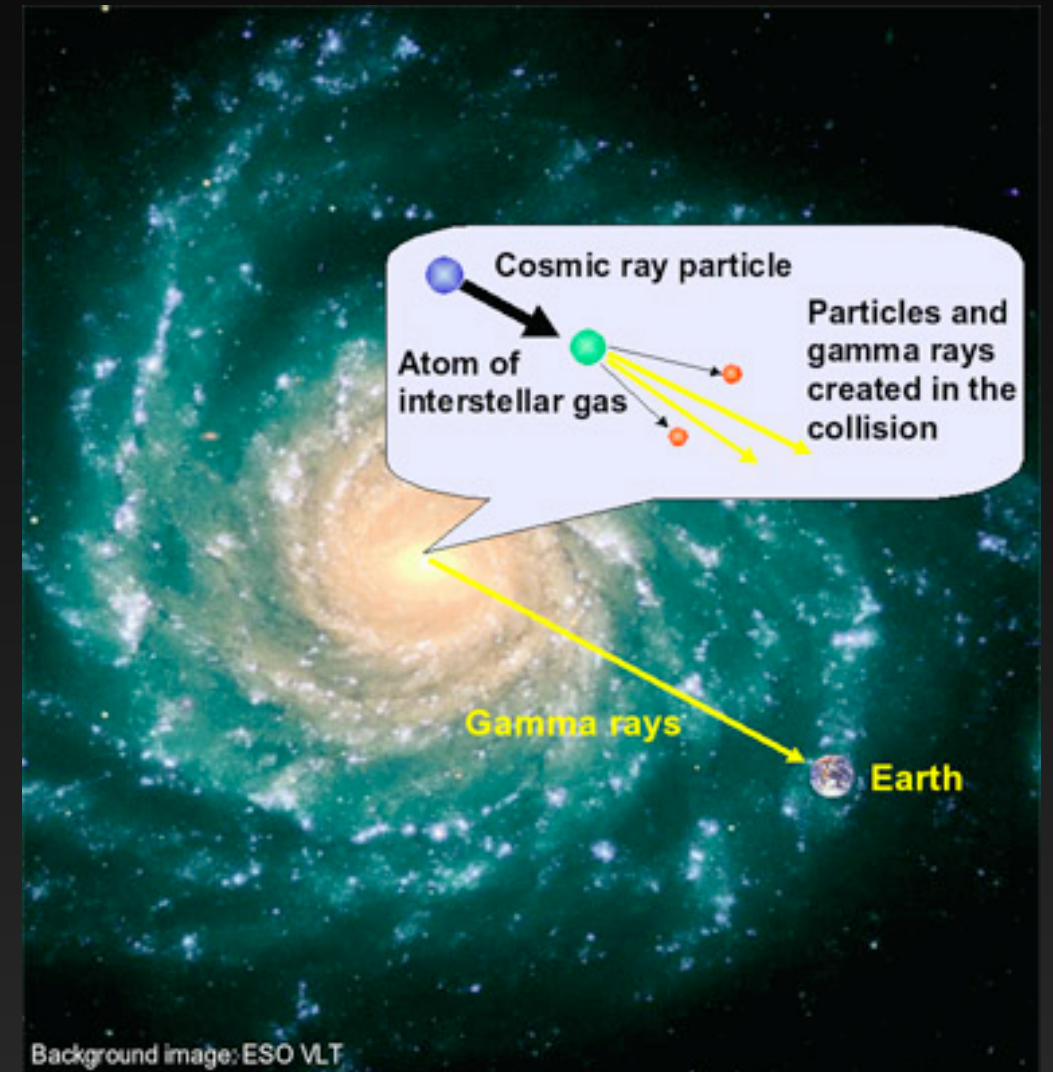
Gas/ISRF



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

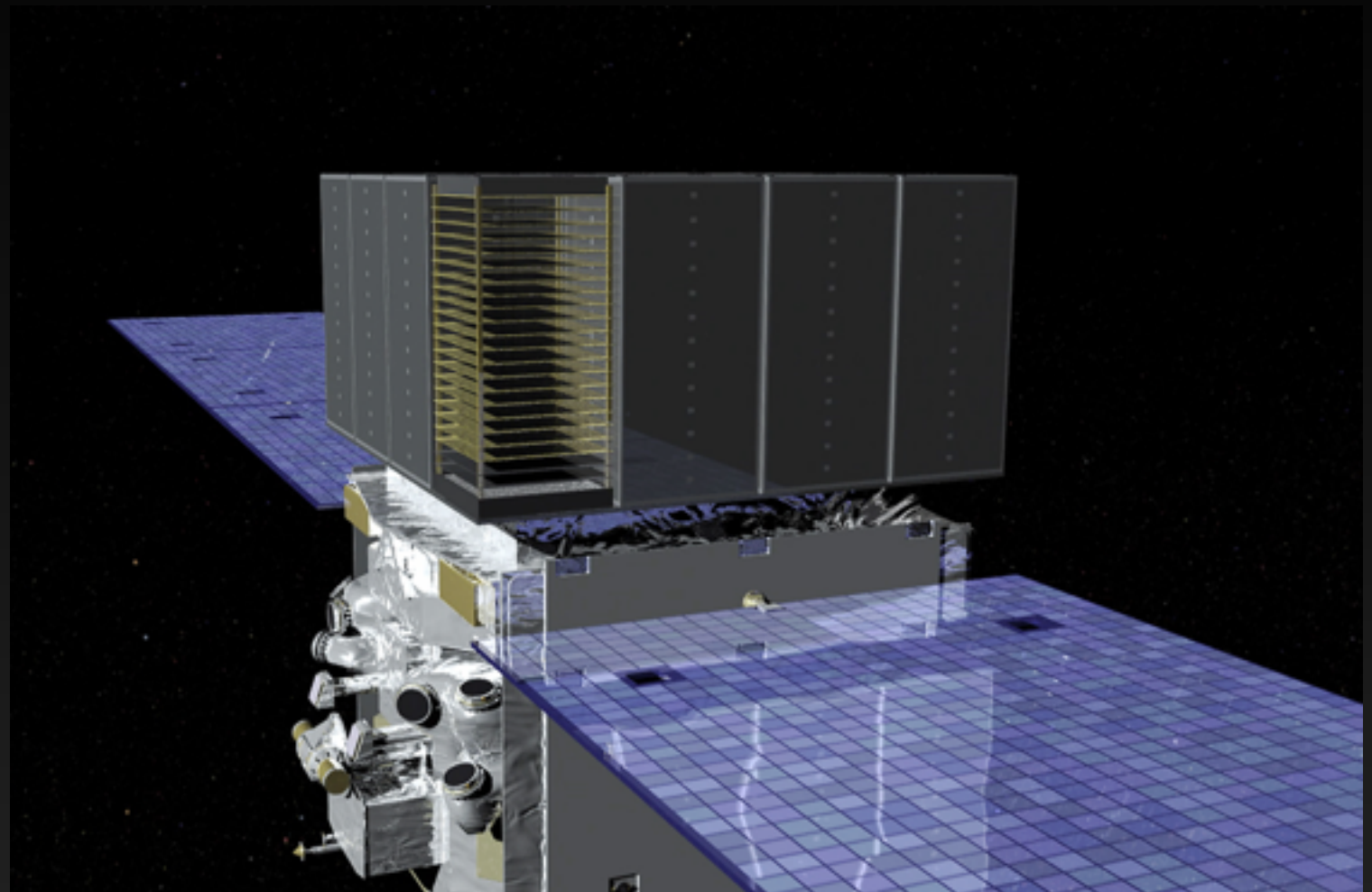


The Fermi Large Area Telescope

Launched: June 2008

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

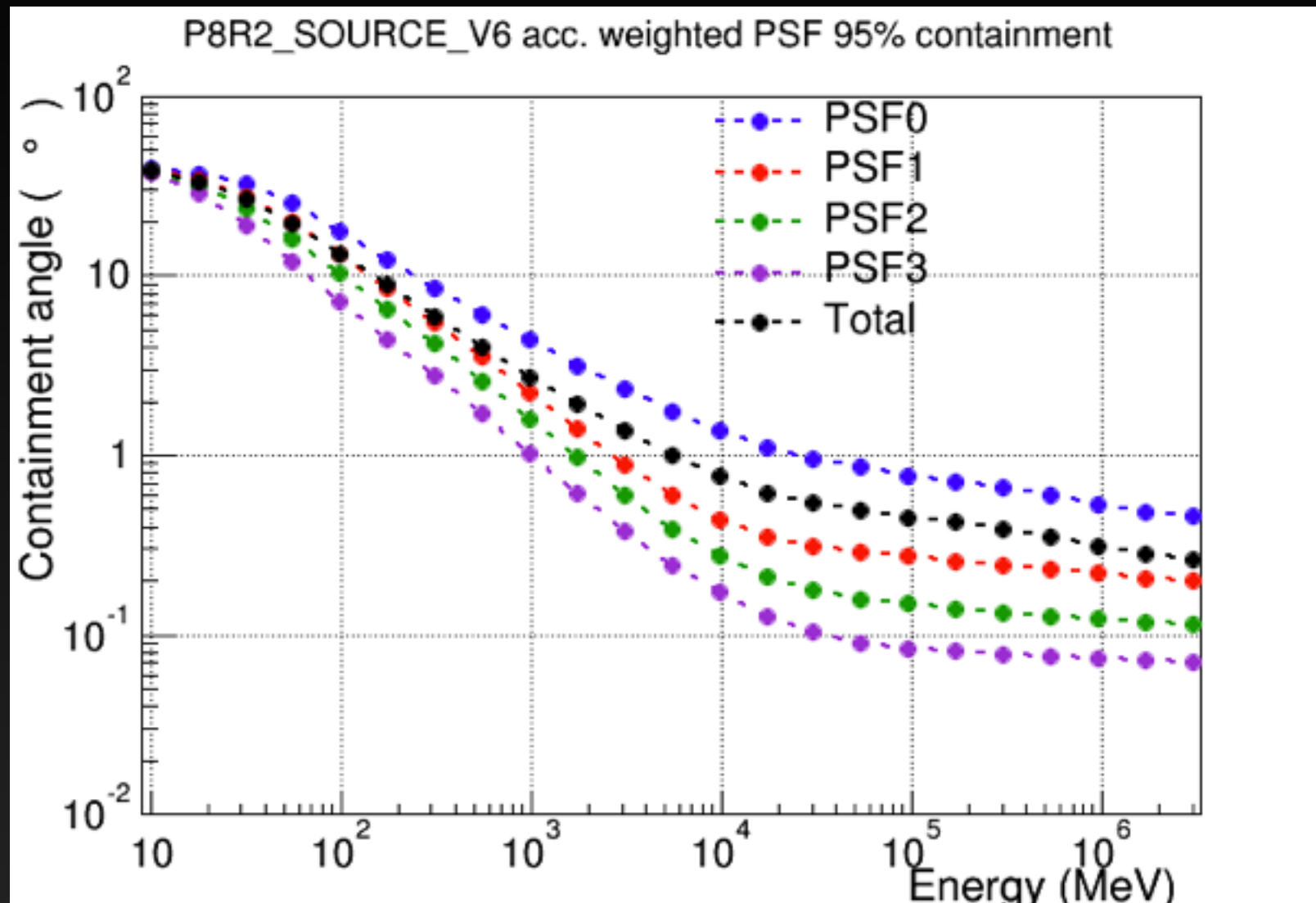
**Collaboration of five
countries and dozens of
institutions.**



Operational Characteristics:

- **Effective Area $\sim 1 \text{ m}^2$**
- **Field of View $\sim 2 \text{ sr}$**
- **Energy Resolution $\sim 10\%$**

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.

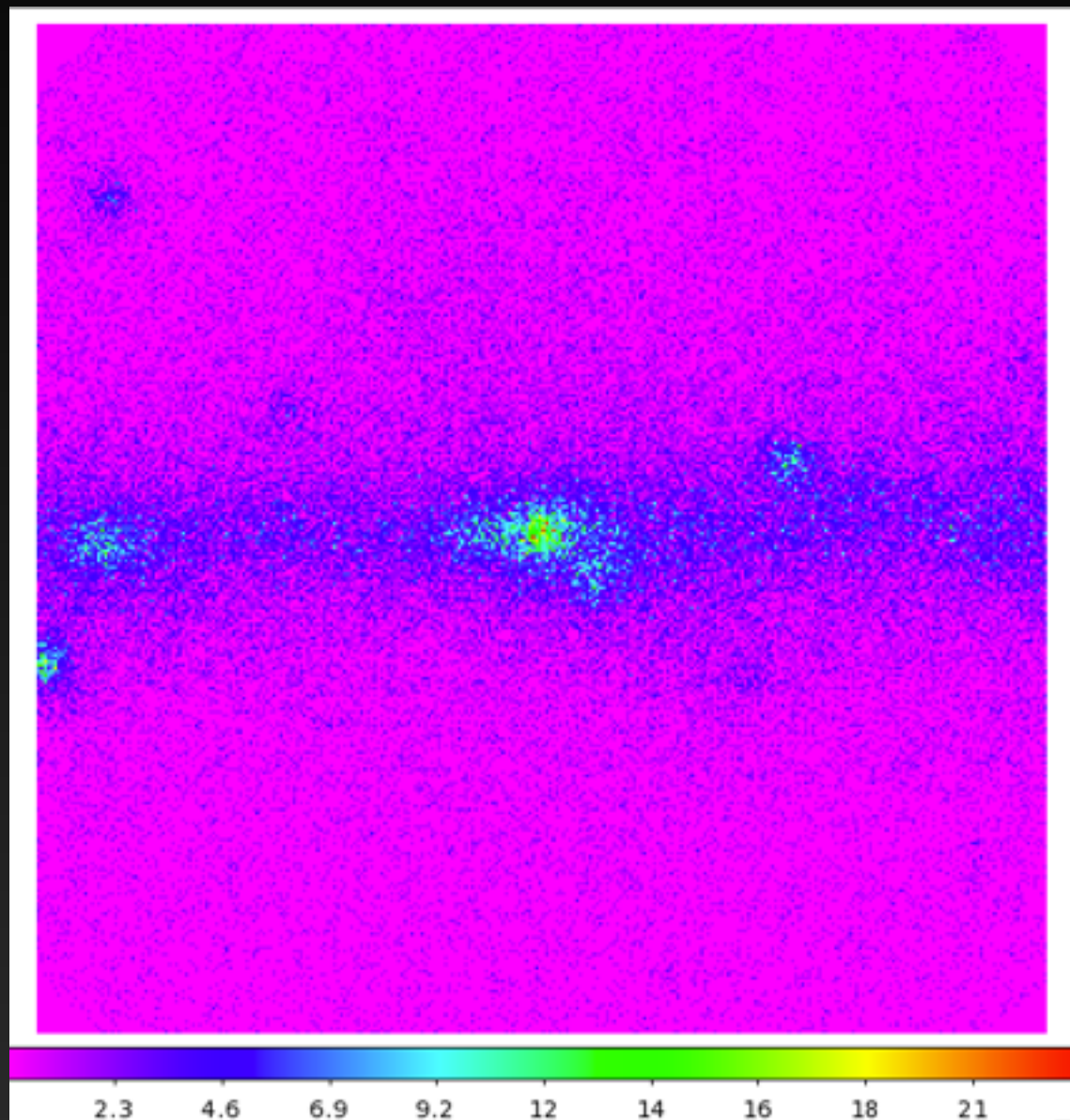
Why We're Doing What We're Doing....

- 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
Ajello et al. (2015)	1510.02938

How Does This Analysis Work?



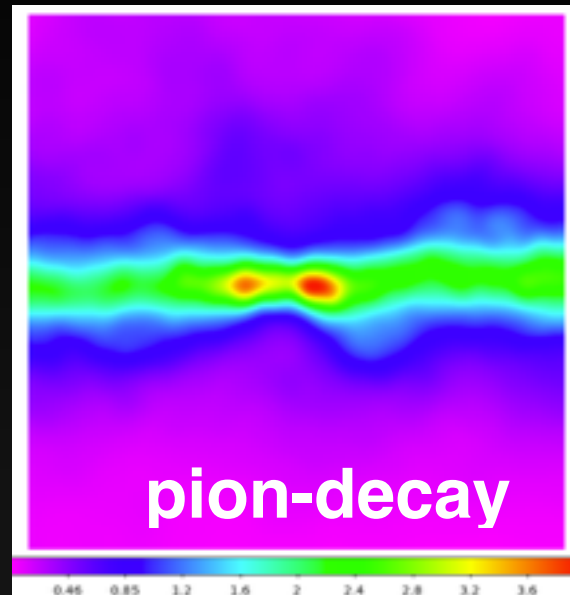
Data

750 — 950 MeV

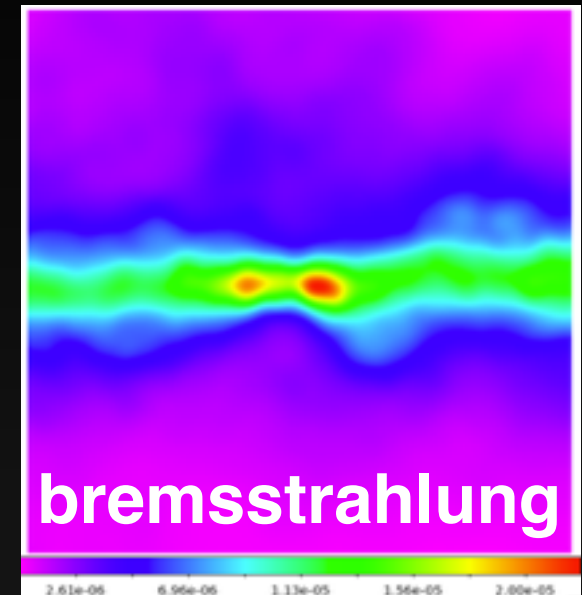
Best Angular Resolution Cut

100 x 100 ROI

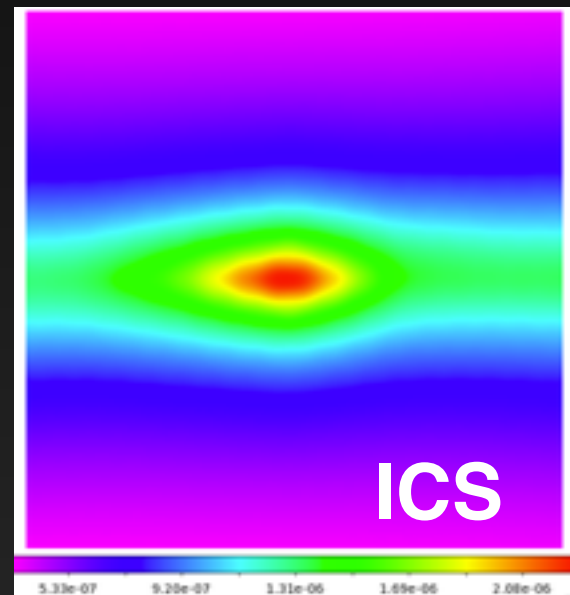
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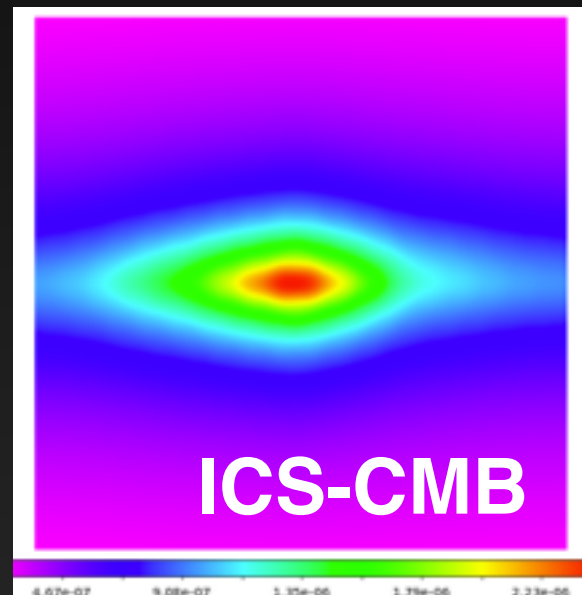
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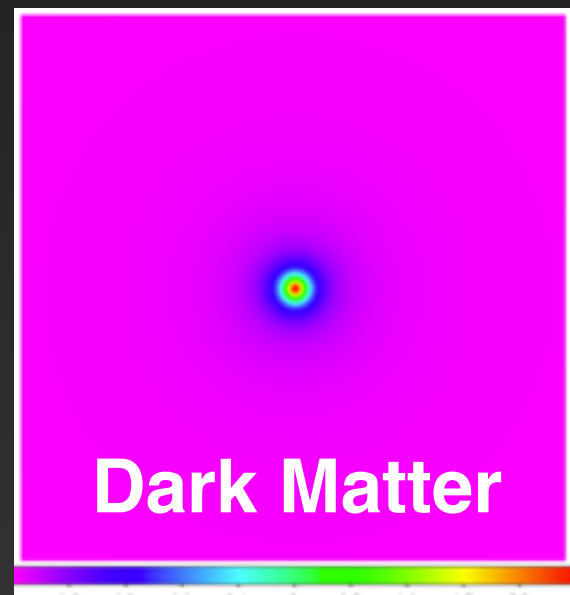
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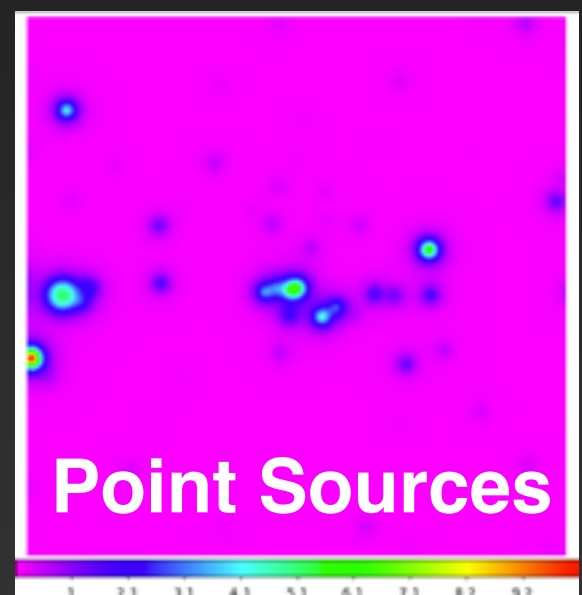
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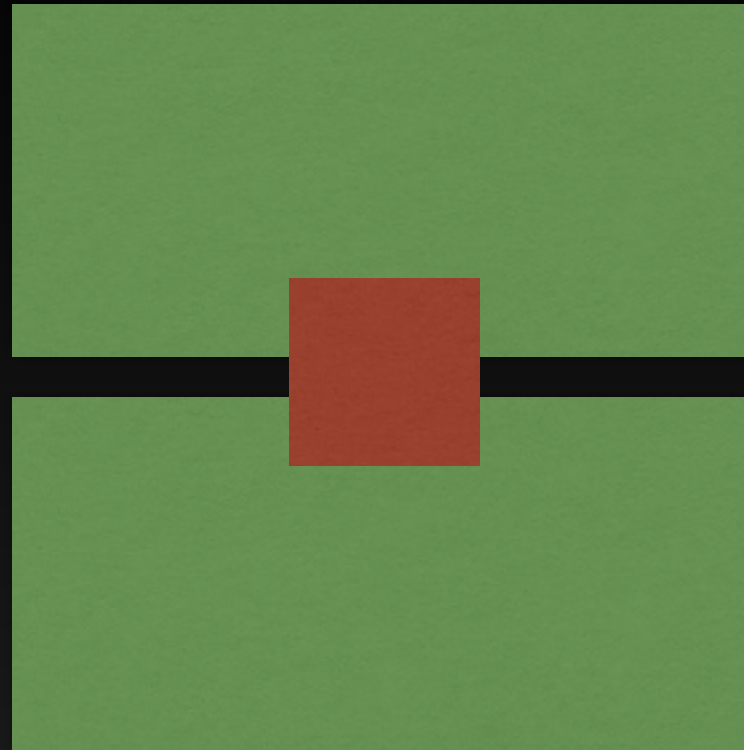
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How Does This Analysis Work?



Daylan et al. (2014)

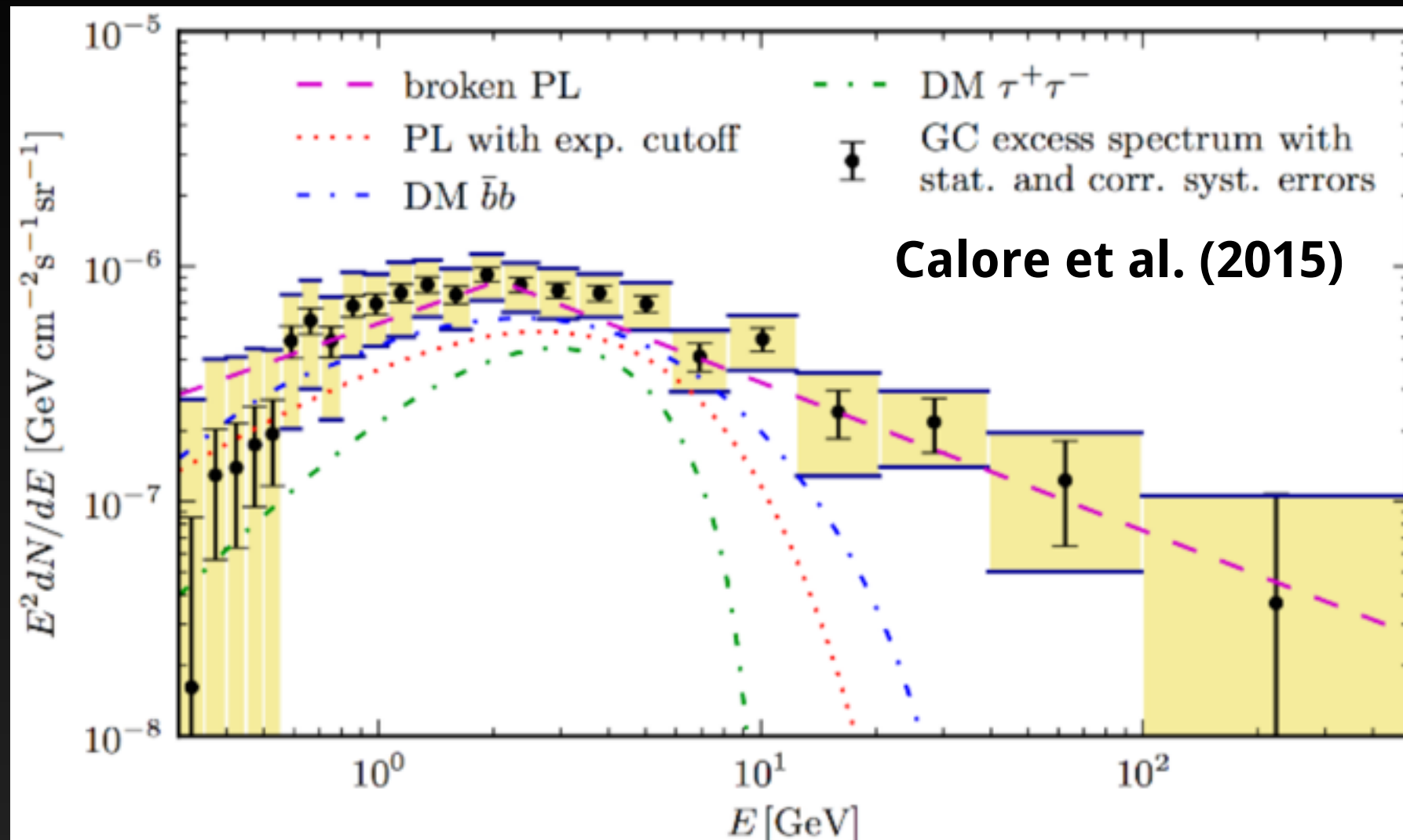
INNER GALAXY

- 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



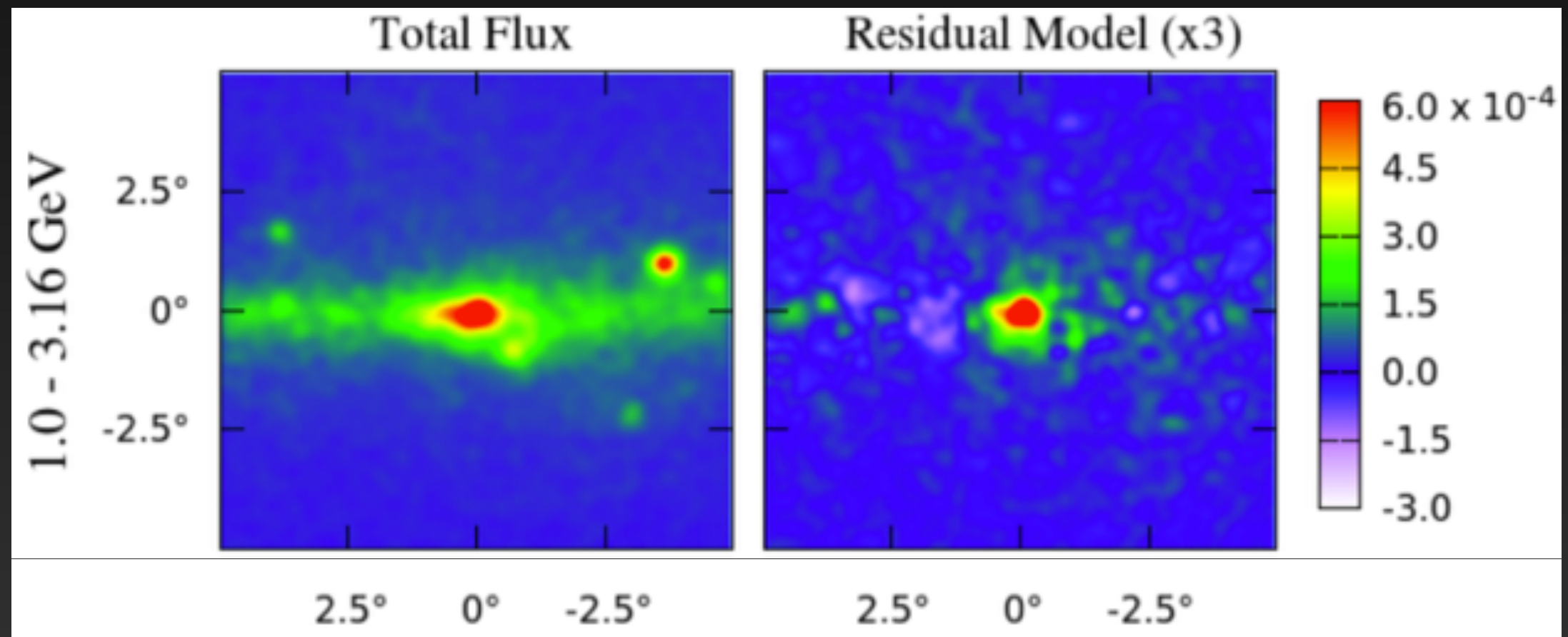
Spectral Model highly resilient to changing systematic background models ~300 models considered here.

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

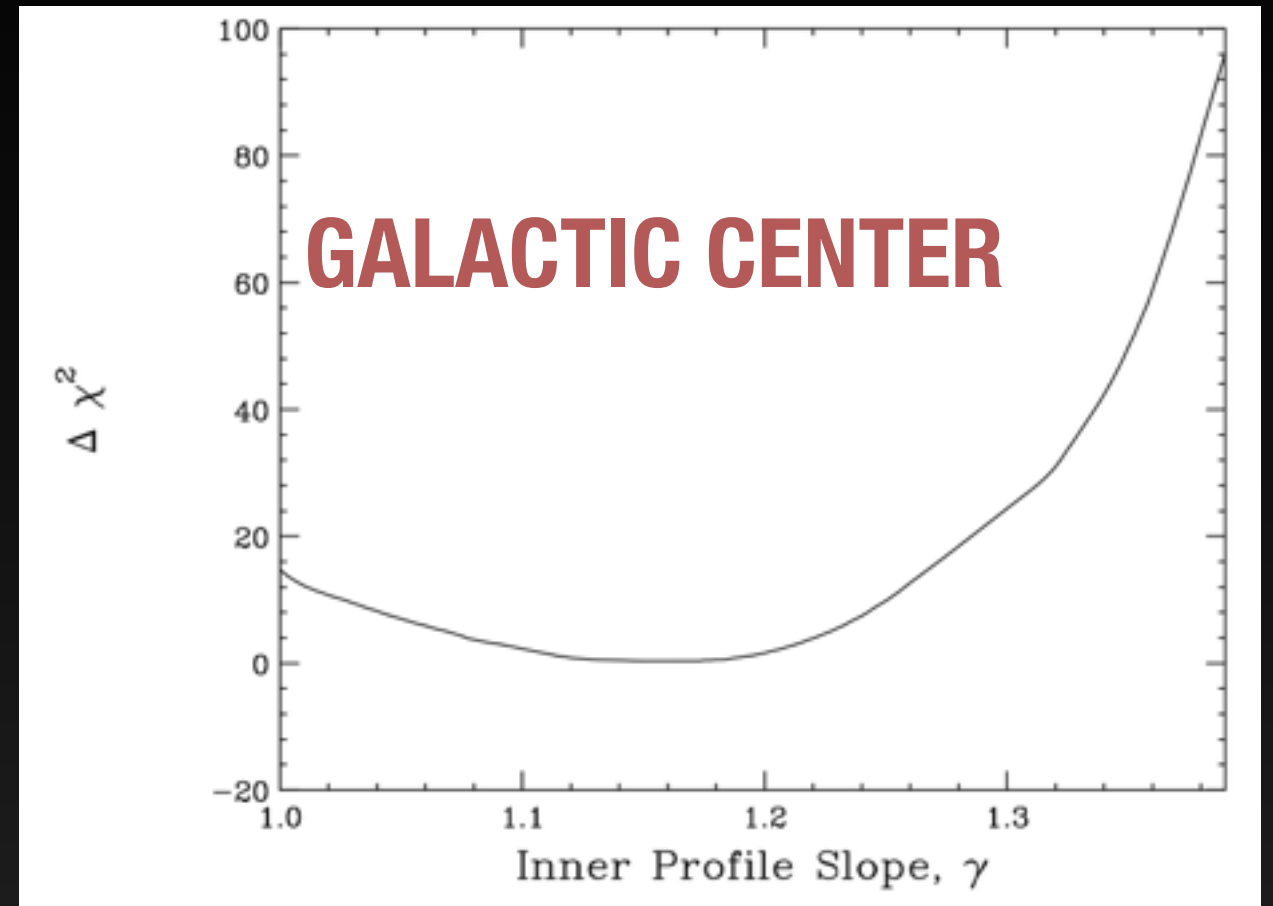
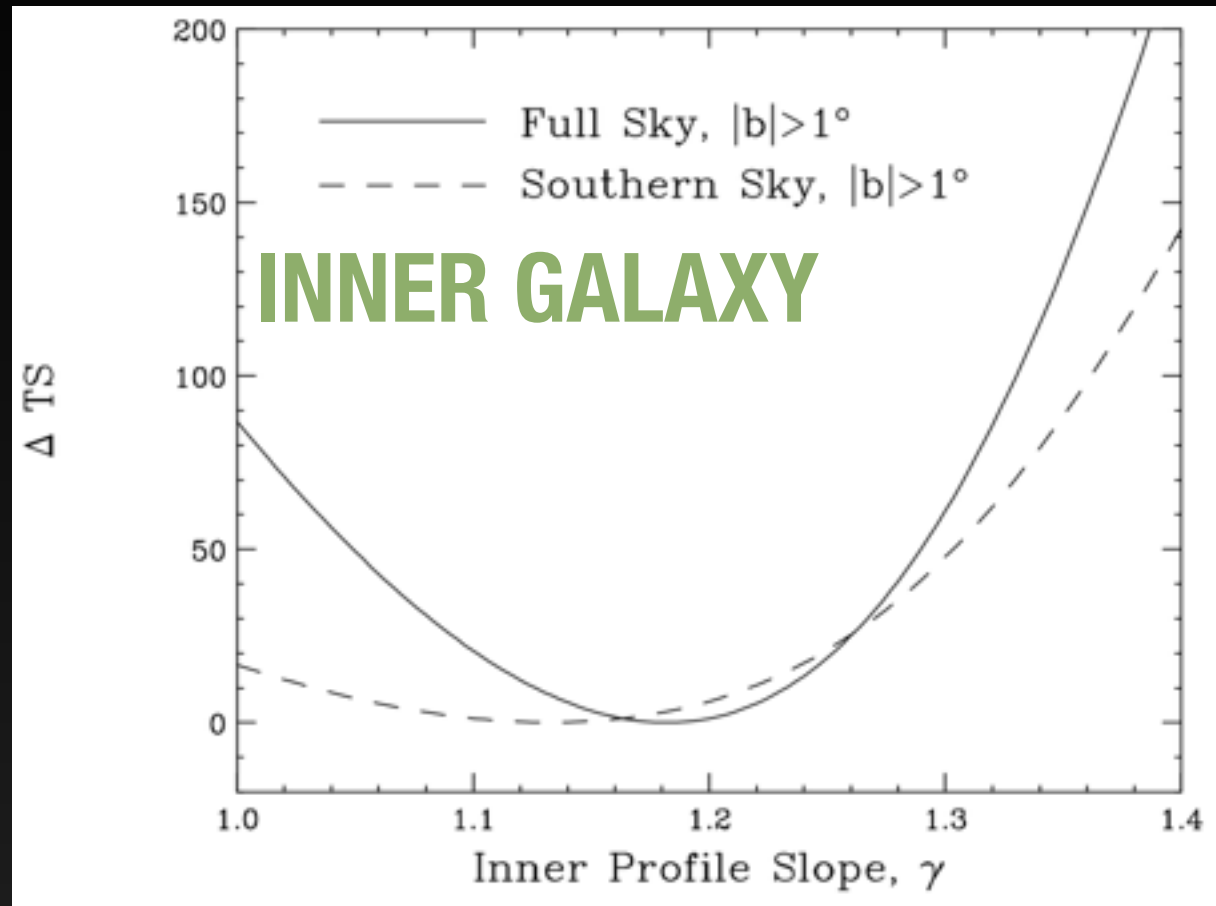
Observational Results

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

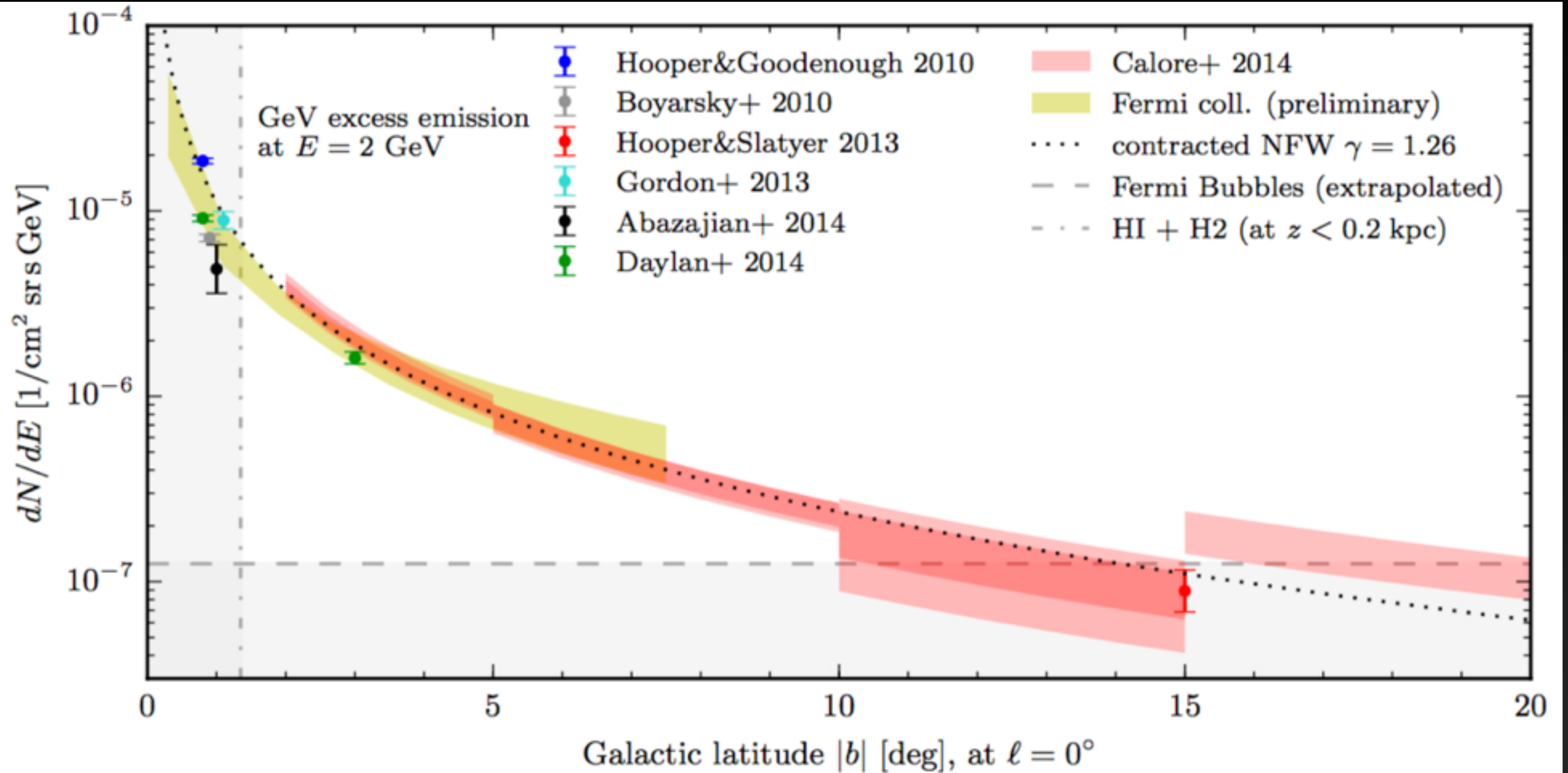


Inner galaxy prefers density profile $\gamma = 1.18$

Galactic Center prefers $\gamma = 1.17$

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

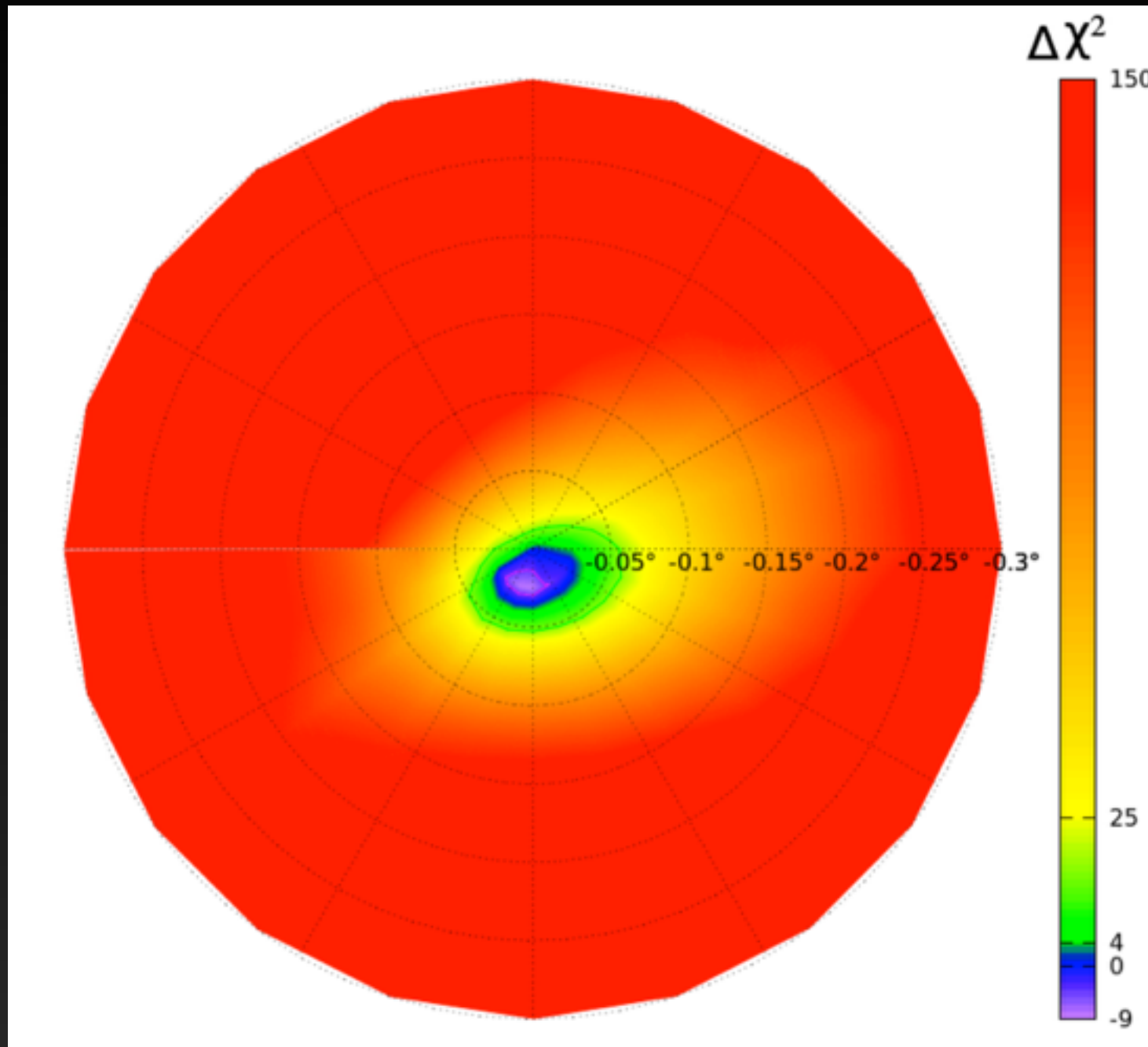
Observational Results



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

Calore et al. (2014b)

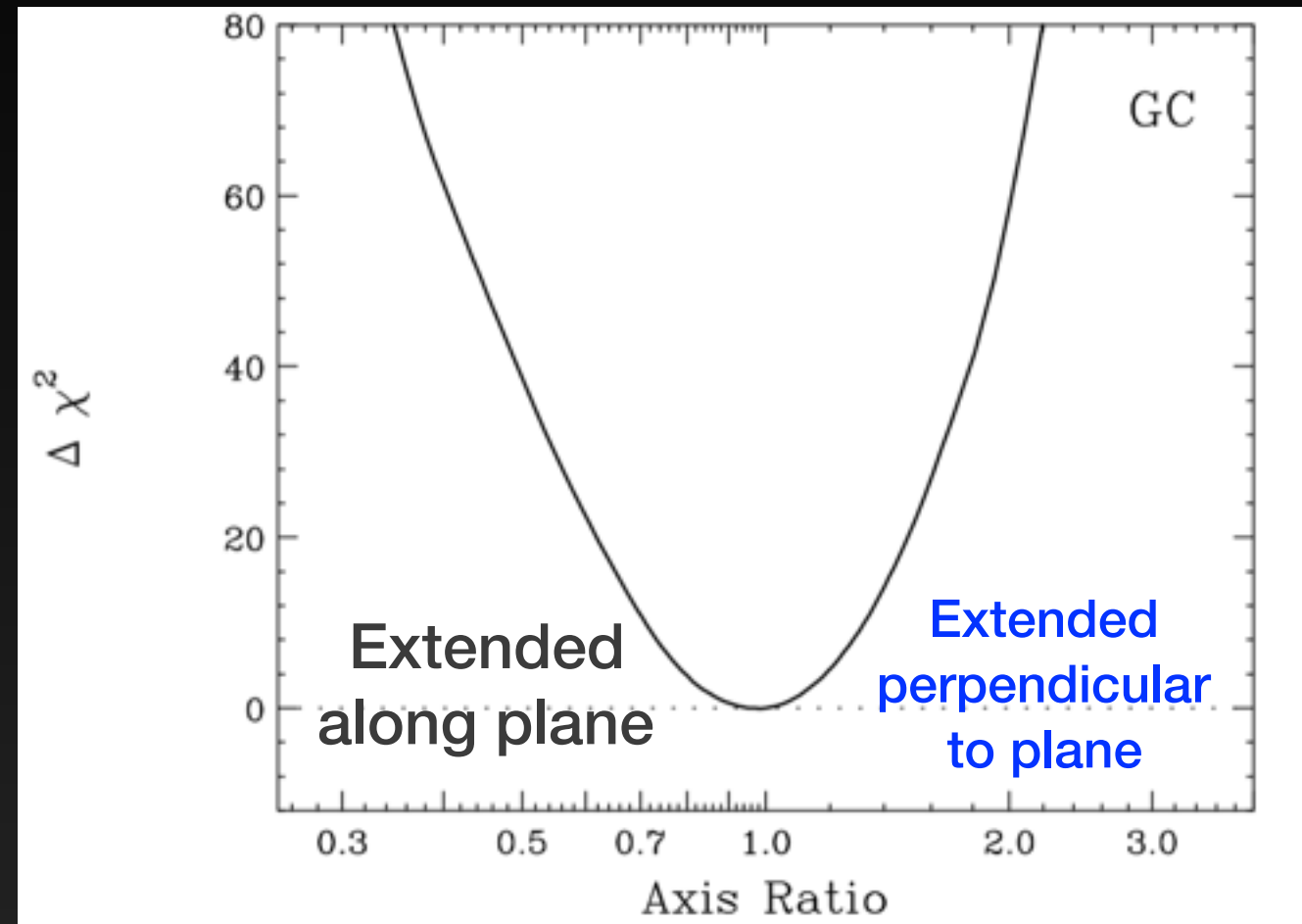
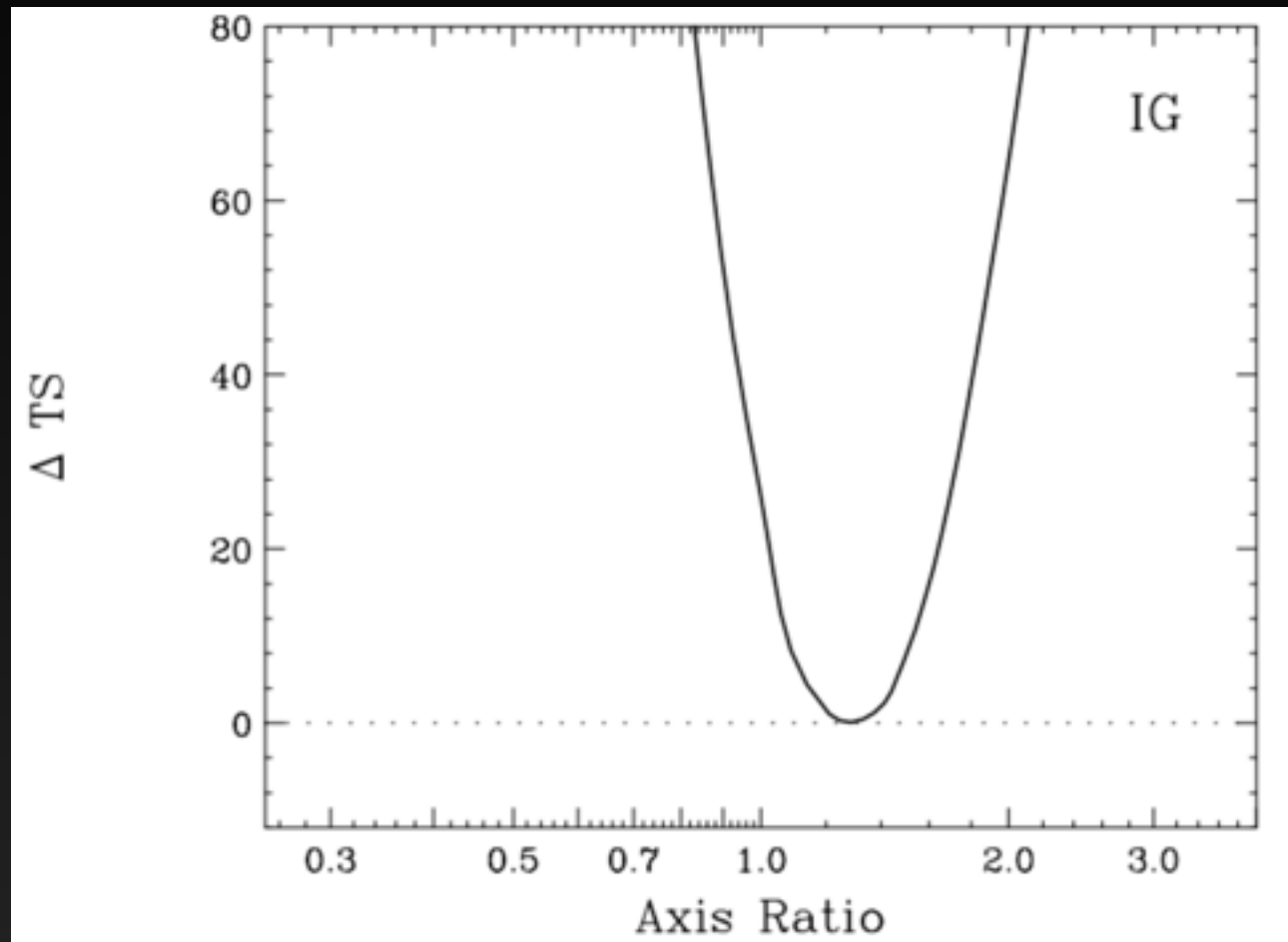
Observational Results



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.

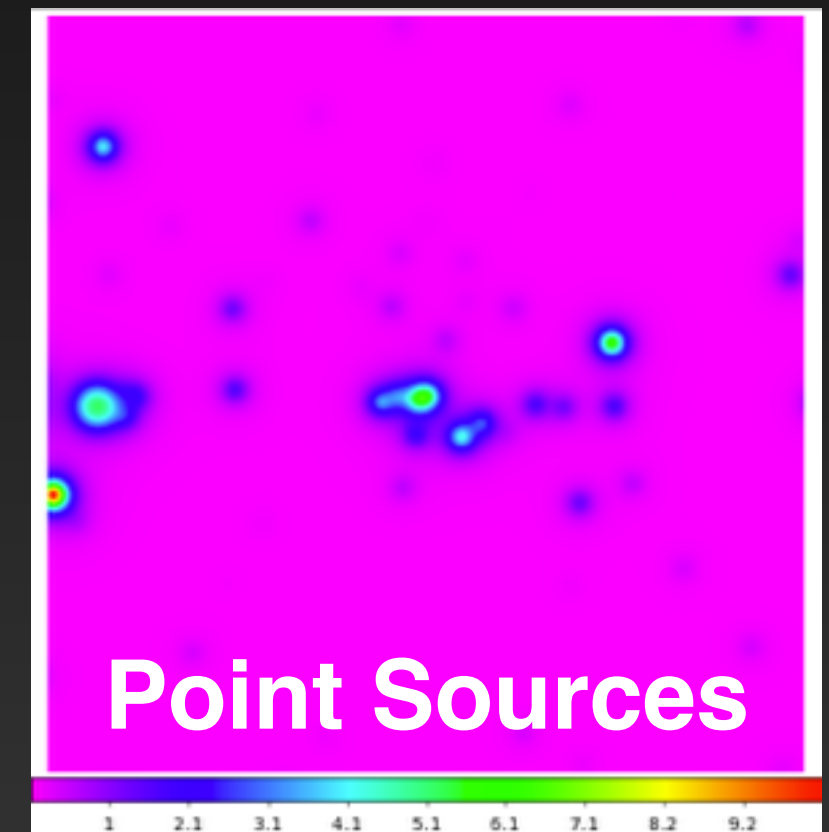
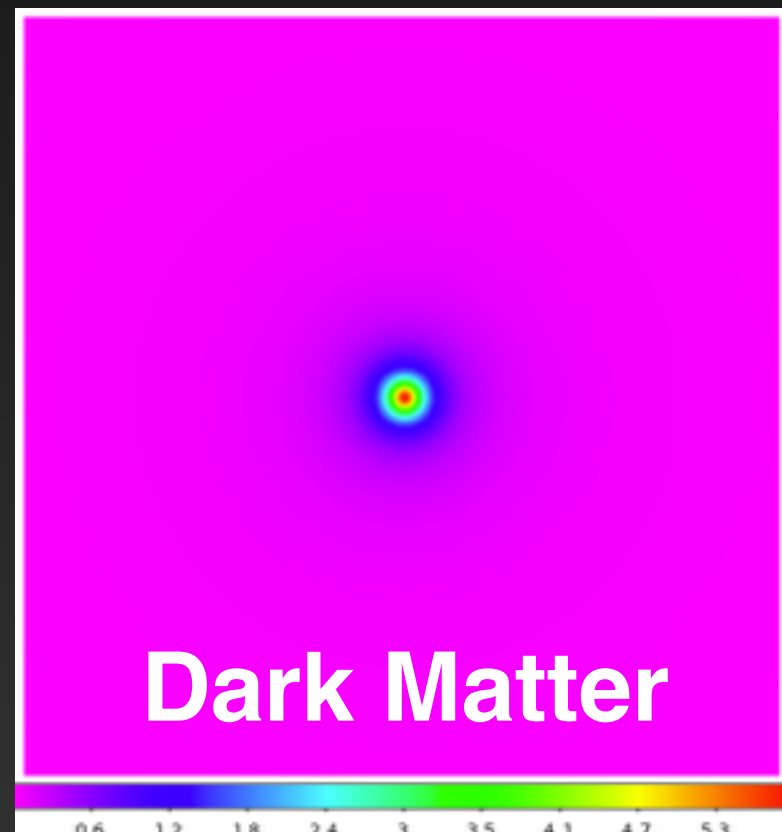
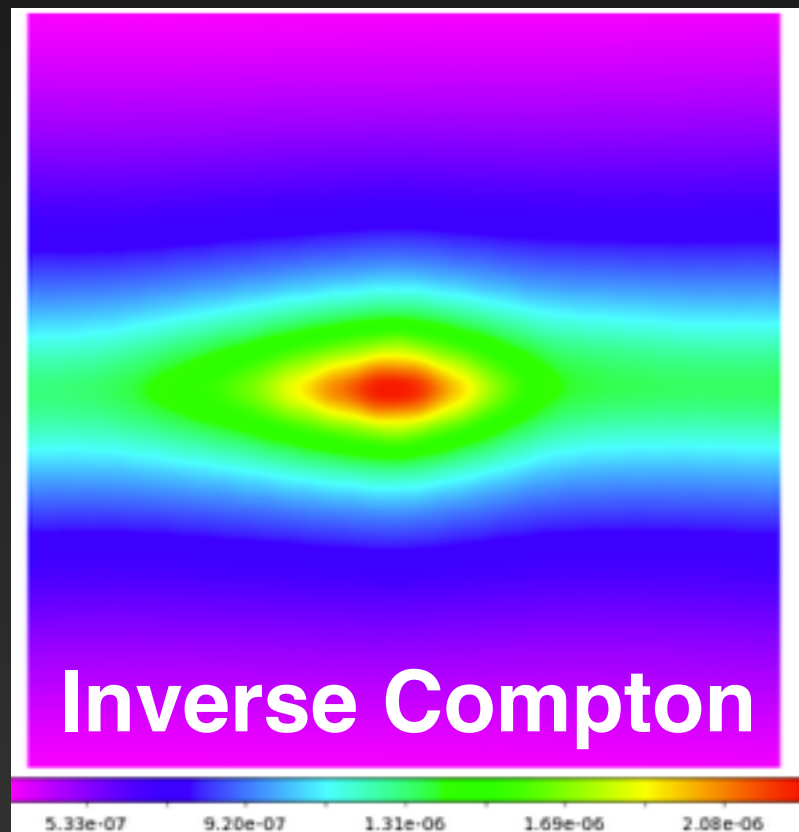
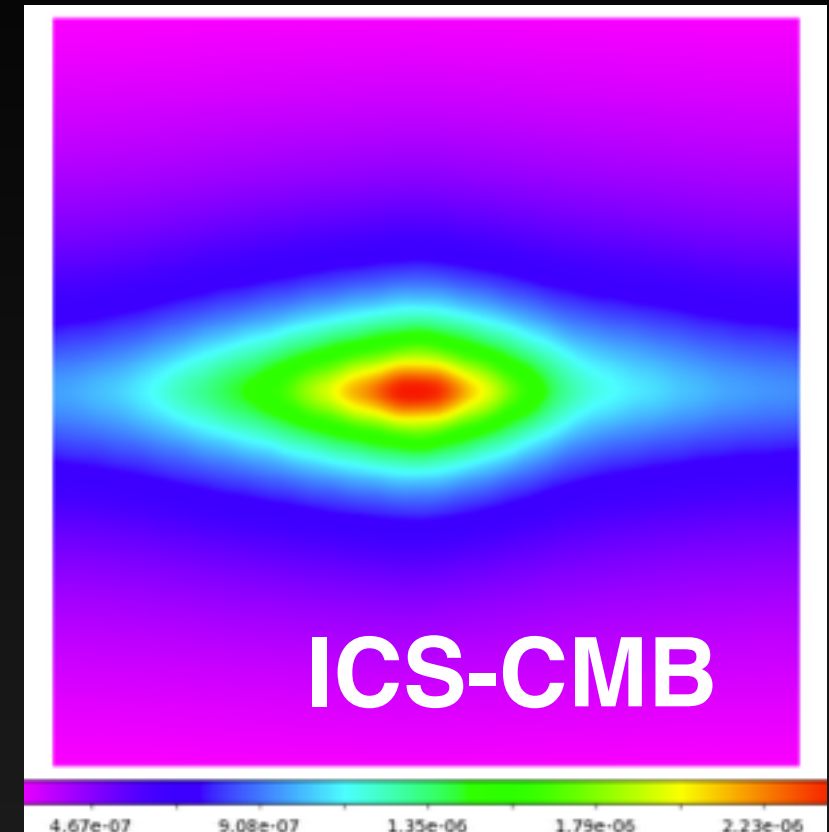
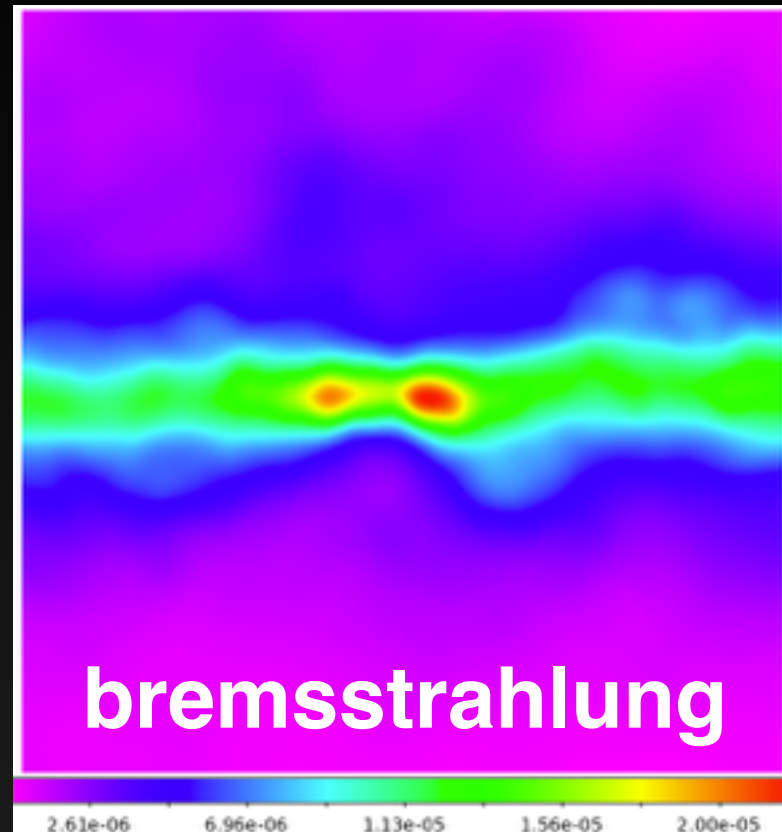
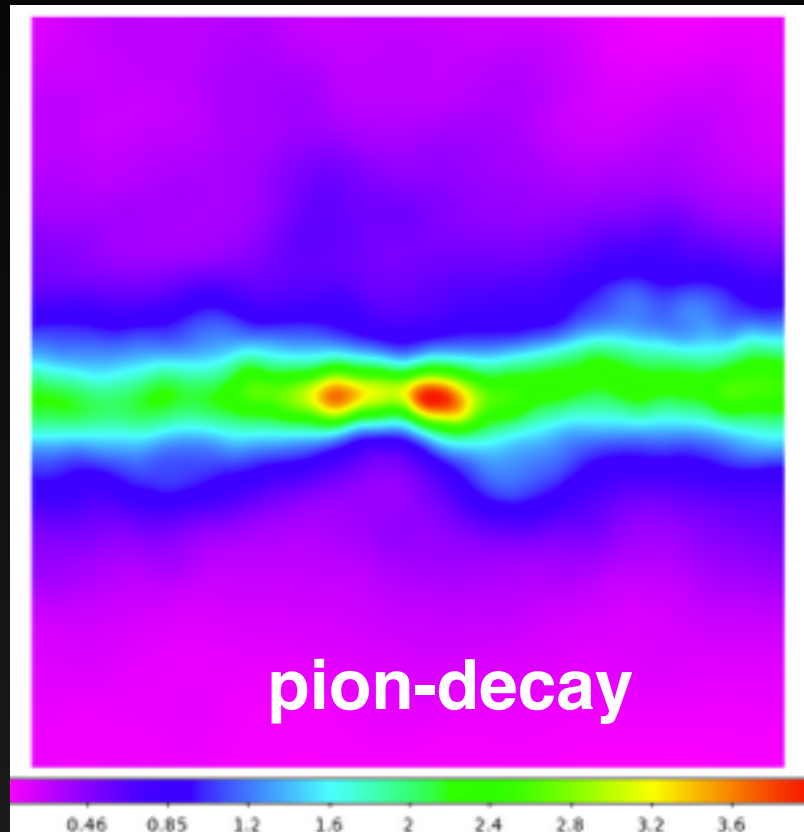
Observational Results



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

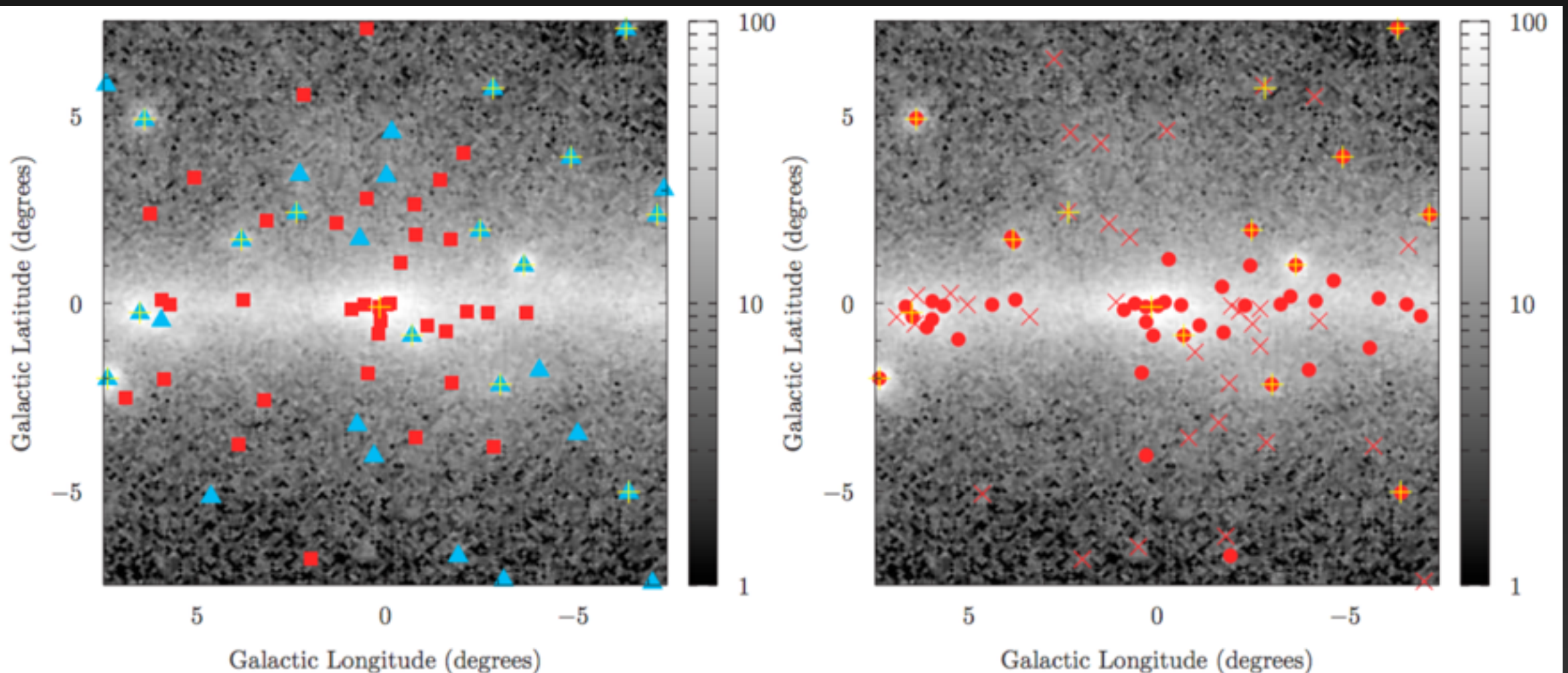
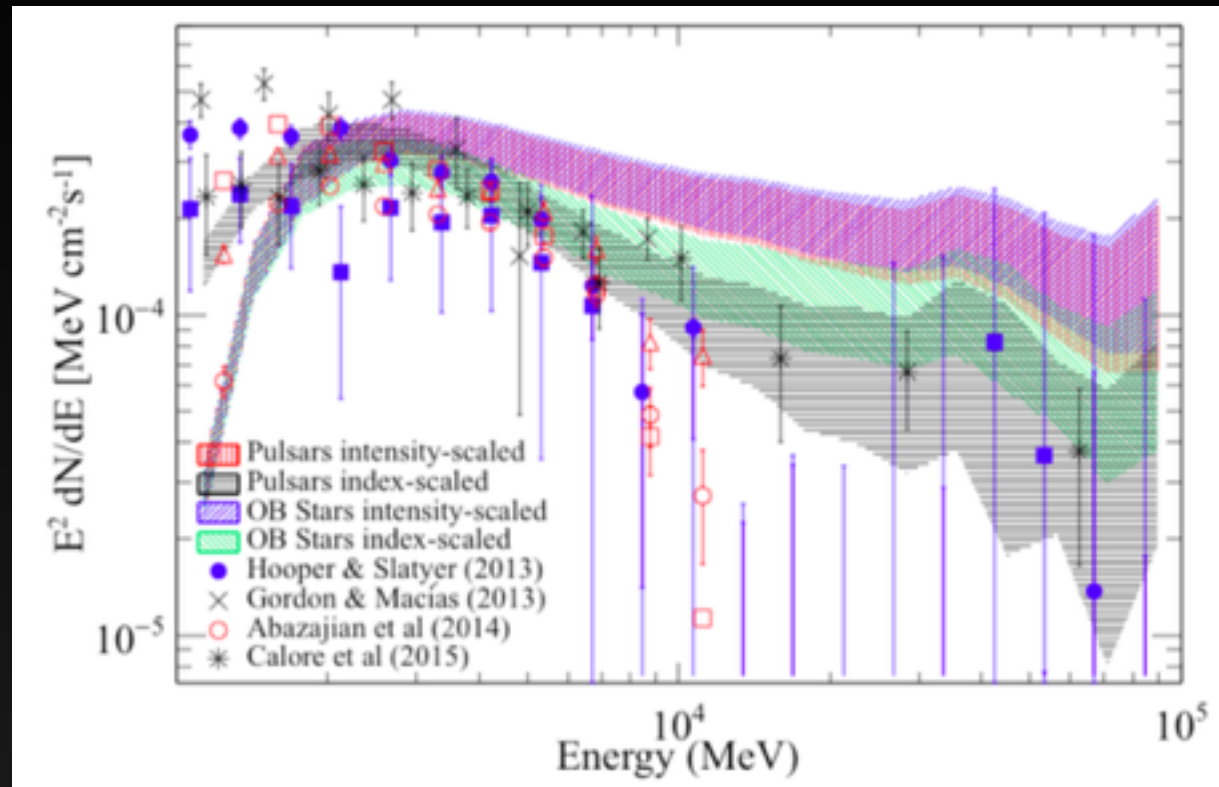
The inner galaxy finds a weak preference for some extension perpendicular to the galactic plane.

Spherical Symmetry and the GCE



Observational Results

**The Fermi-LAT
Collaboration now
officially agrees
with these findings.**

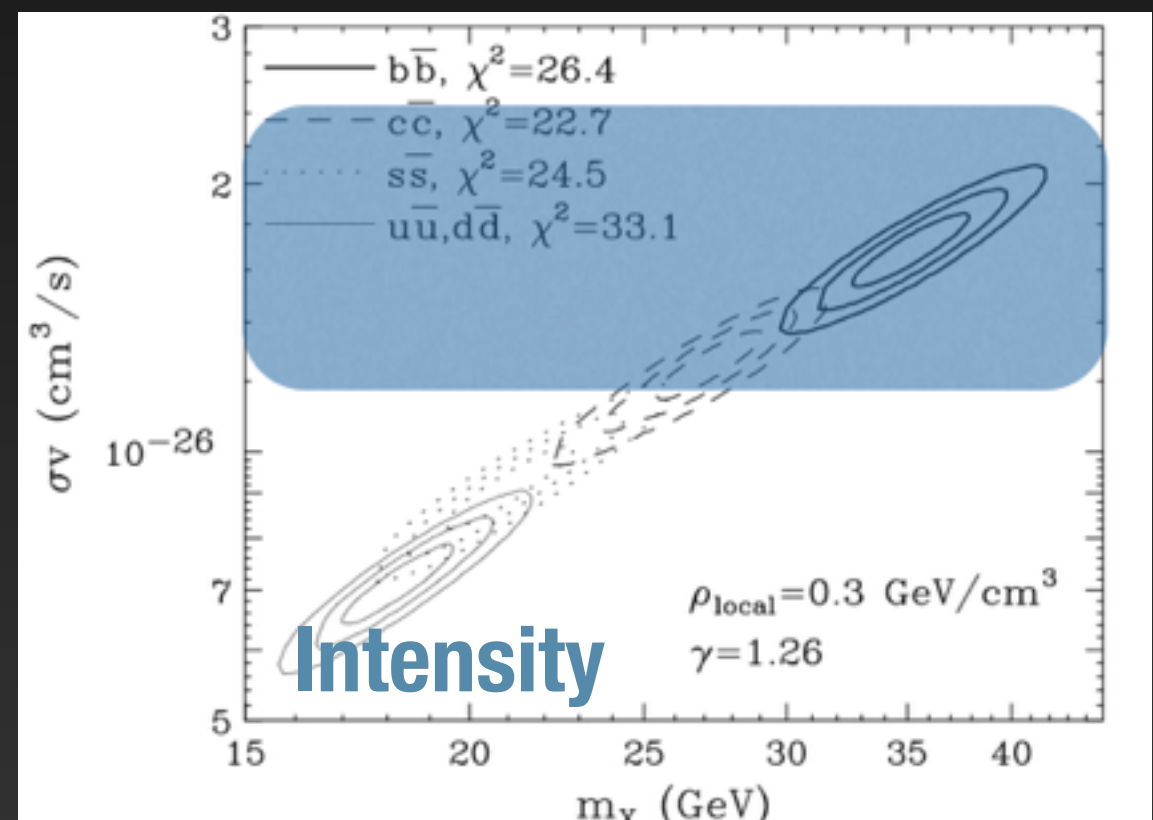
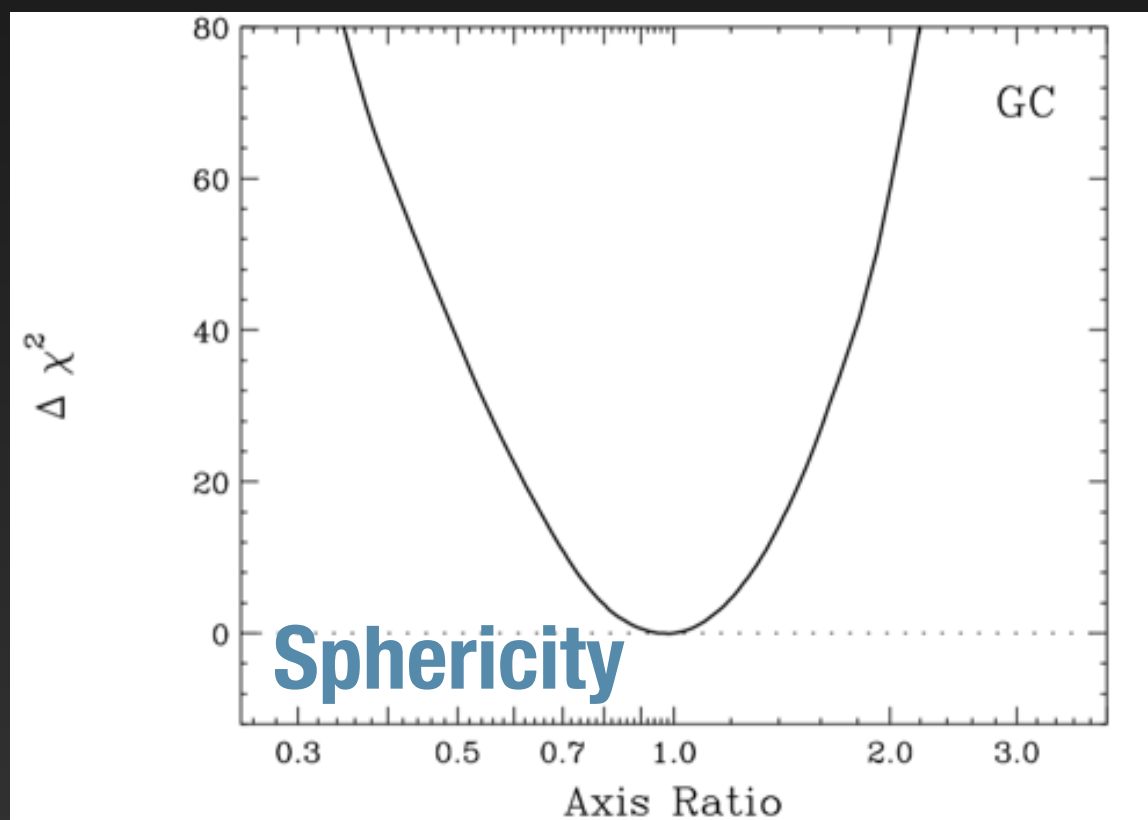
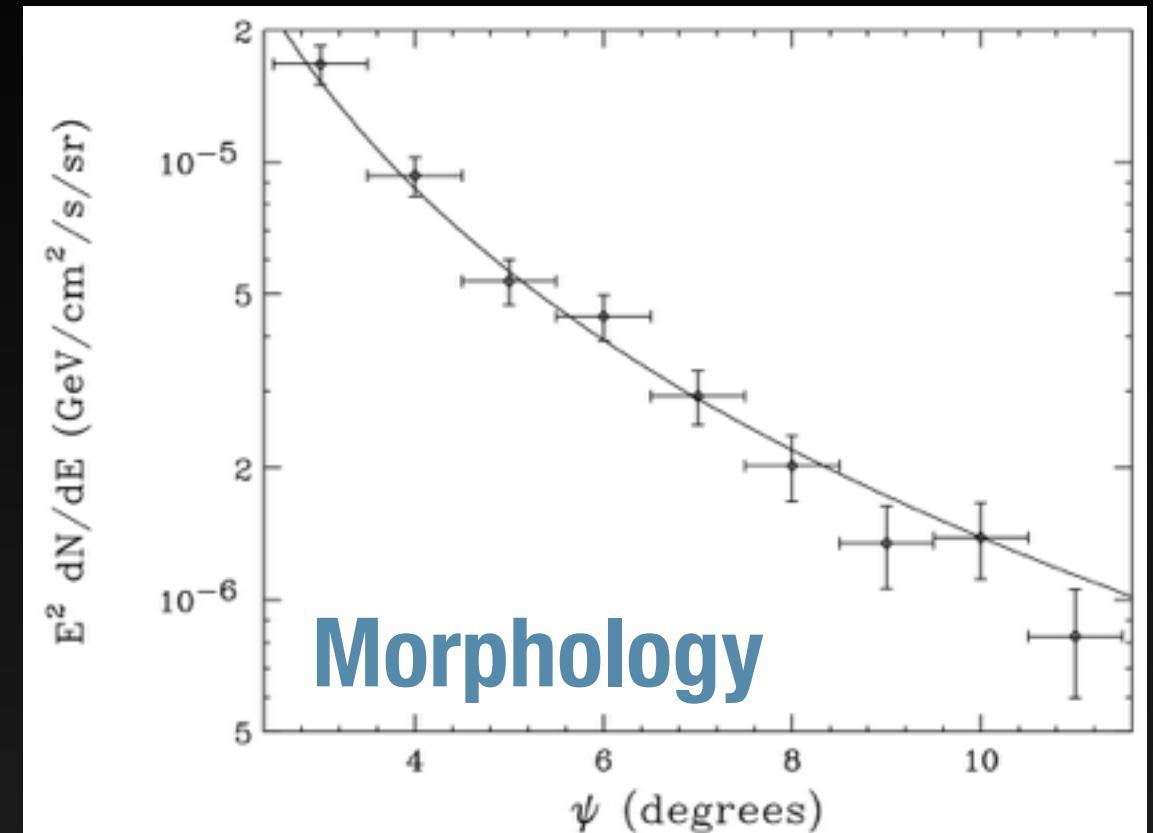
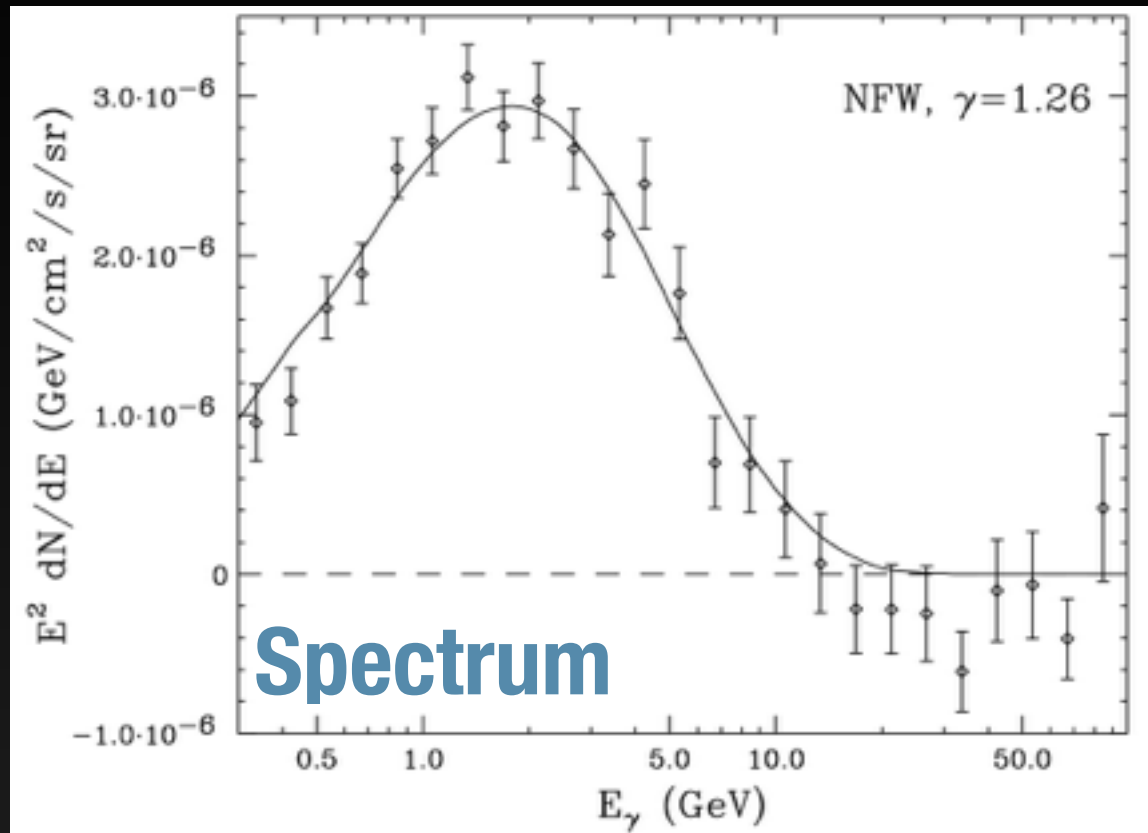


Summary of Data Analysis

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)	Achterberg et al. (1502.05703)	Tang (1407.5492)
Bhattacharya et al. (1509.03665)	Modak et al. (1502.05682)	Balazs & Li (1407.0174)
Algeri et al. (1509.01010)	Guo et al. (1502.00508)	Huang et al. (1407.0038)
Fox & Tucker-Smith (1509.00499)	Chen & Nomura (1501.07413)	McDermott (1406.6408)
Dutta et al. (1509.05989)	Kozaczuk & Martin (1501.07275)	Cheung et al. (1406.6372)
Liu et al. (1508.05716)	Berlin et al. (1501.03496)	Arina et al. (1406.5542)
Berlin et al. (1508.05390)	Kaplinghat et al. (1501.03507)	Chang & Ng (1406.4601)
Fan et al. (1507.06993)	Alves et al. (1501.03490)	Wang & Han (1406.3598)
Hektor et al. (1507.05096)	Biswas et al. (1501.02666)	Cline et al. (1405.7691)
Achterbeg et al. (1507.04644)	Ghorbani & Ghorbani (1501.00206)	Berlin et al. (1405.5204)
Biswas et al. (1507.04543)	Cerdeno et al. (1501.01296)	Mondal & Basak (1405.4877)
Butter et al. (1507.02288)	Liu et al. (1412.1485)	Martin et al. (1405.0272)
Mondal et al. (1507.01793)	Hooper (1411.4079)	Ghosh et al. (1405.0206)
Cao et al. (1506.06471)	Arcadi et al. (1411.2985)	Abdullah et al. (1404.5503)
Banik et al. (1506.05665)	Cheung et al. (1411.2619)	Park & Tang (1404.5257)
Ipek (1505.07826)	Agrawal et al. (1411.2592)	Cerdeno et al. (1404.2572)
Buchmueller et al. (1505.07826)	Kile et al. (1411.1407)	Izaguirre et al. (1404.2018)
Balazs et al. (1505.06758)	Buckley et al. (1410.6497)	Agrawal et al. (1404.1373)
Medina (1505.05565)	Heikinheimo & Spethmann (1410.4842)	Berlin et al. (1404.0022)
Kim et al. (1505.04620)	Freytsis et al. (1410.3818)	Alves et al. (1403.5027)
Ko et al. (1504.06944)	Yu et al. (1410.3347)	Finkbeiner & Weiner (1402.6671)
Ko & Tang (1504.03908)	Cao et al. (1410.3239)	
Ghorbani & Ghorbani (1504.03610)	Guo et al. (1409.7864)	
Fortes et al. (1503.08220)	Yu (1409.3227)	
Cline et al. (1503.08213)	Cahill-Rowley et al. (1409.1573)	
Rajaraman et al. (1503.05919)	Banik & Majumdar (1408.5795)	
Bi et al. (1503.03749)	Bell et al. (1408.5142)	
Kopp et al. (1503.02669)	Ghorbani (1408.4929)	
Elor et al. (1503.01773)	Okada & Seto (1408.2583)	
Gherghetta et al. (1502.07173)	Frank & Mondal (1408.2223)	
Berlin et al. (1502.06000)	Baek et al. (1407.6588)	

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?

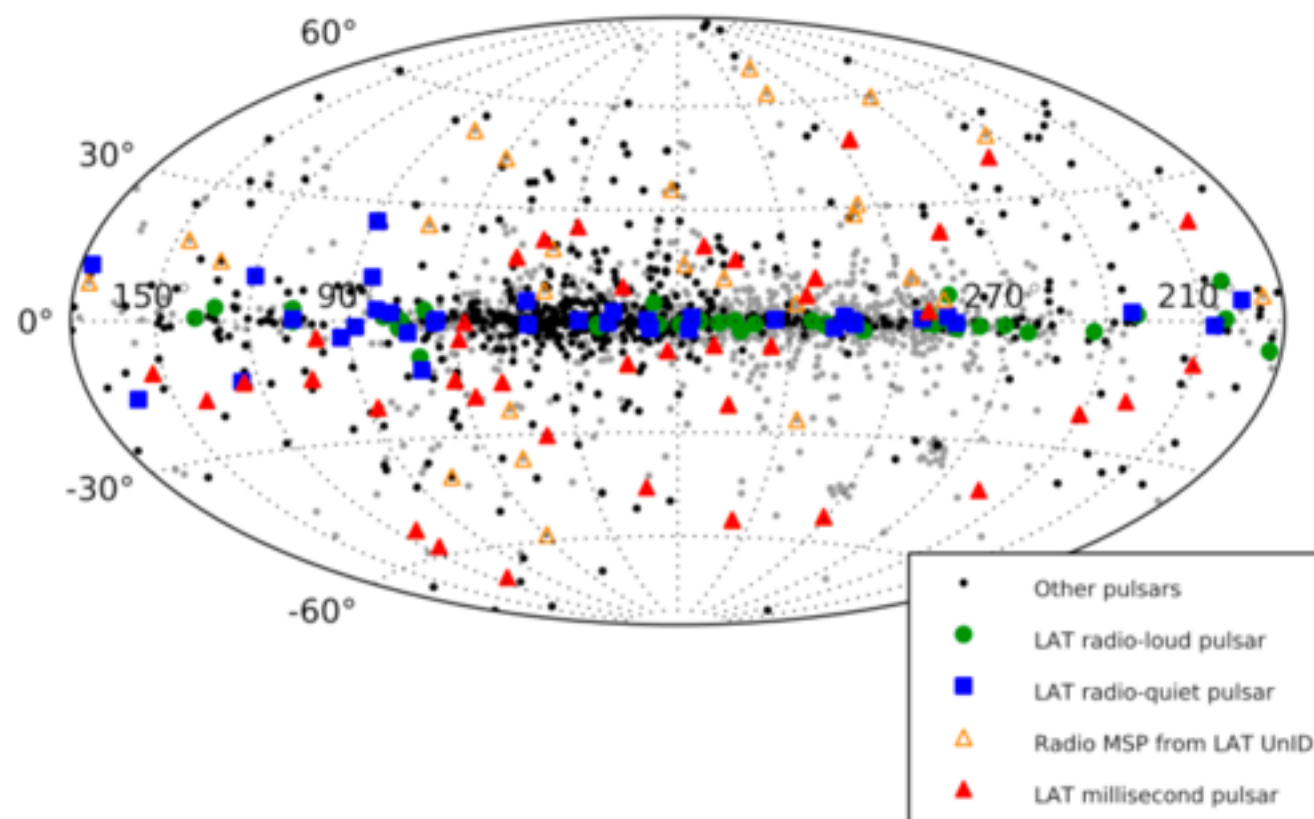
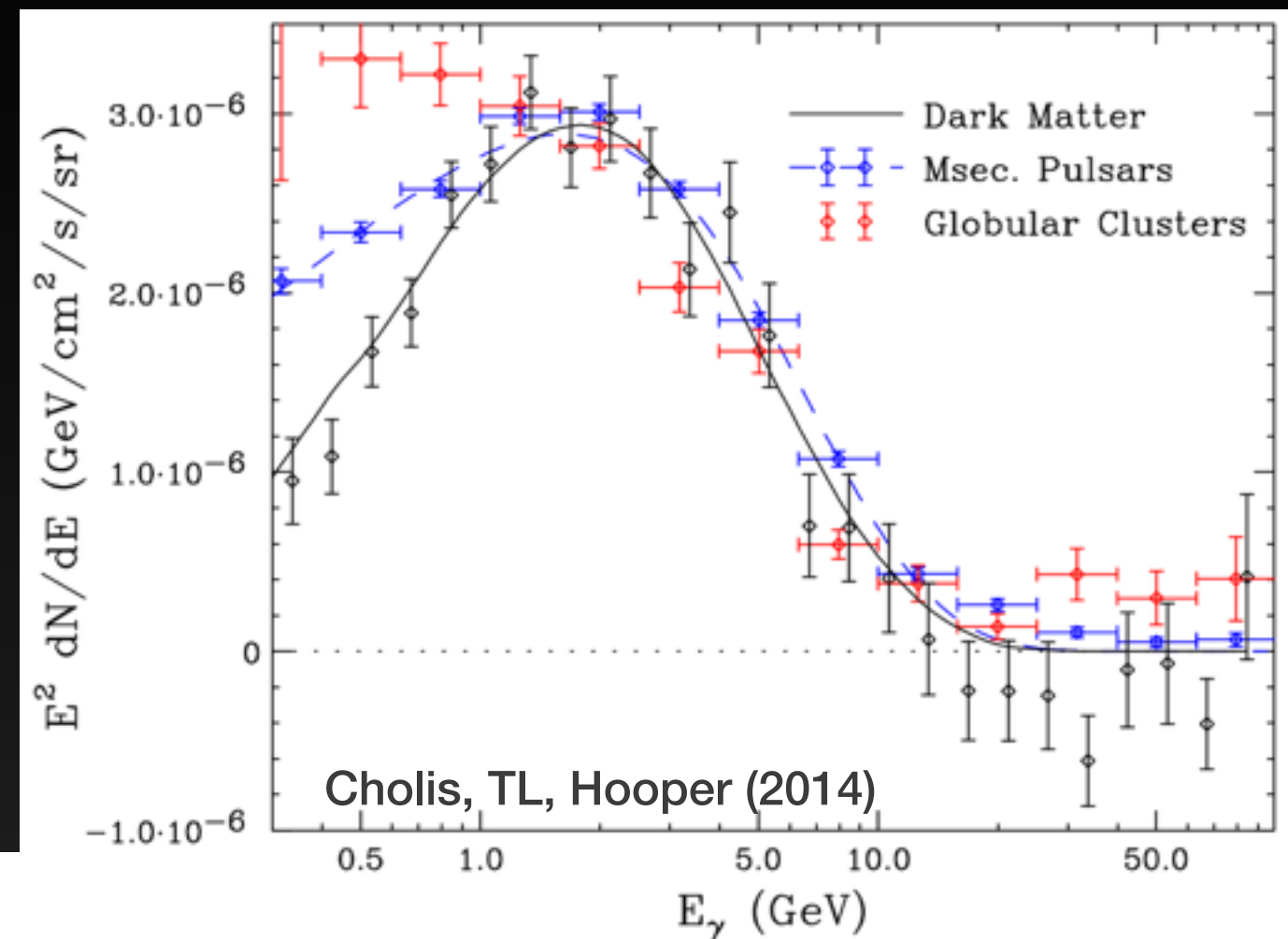
3.) What if the galactic center has a complex/active past?

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

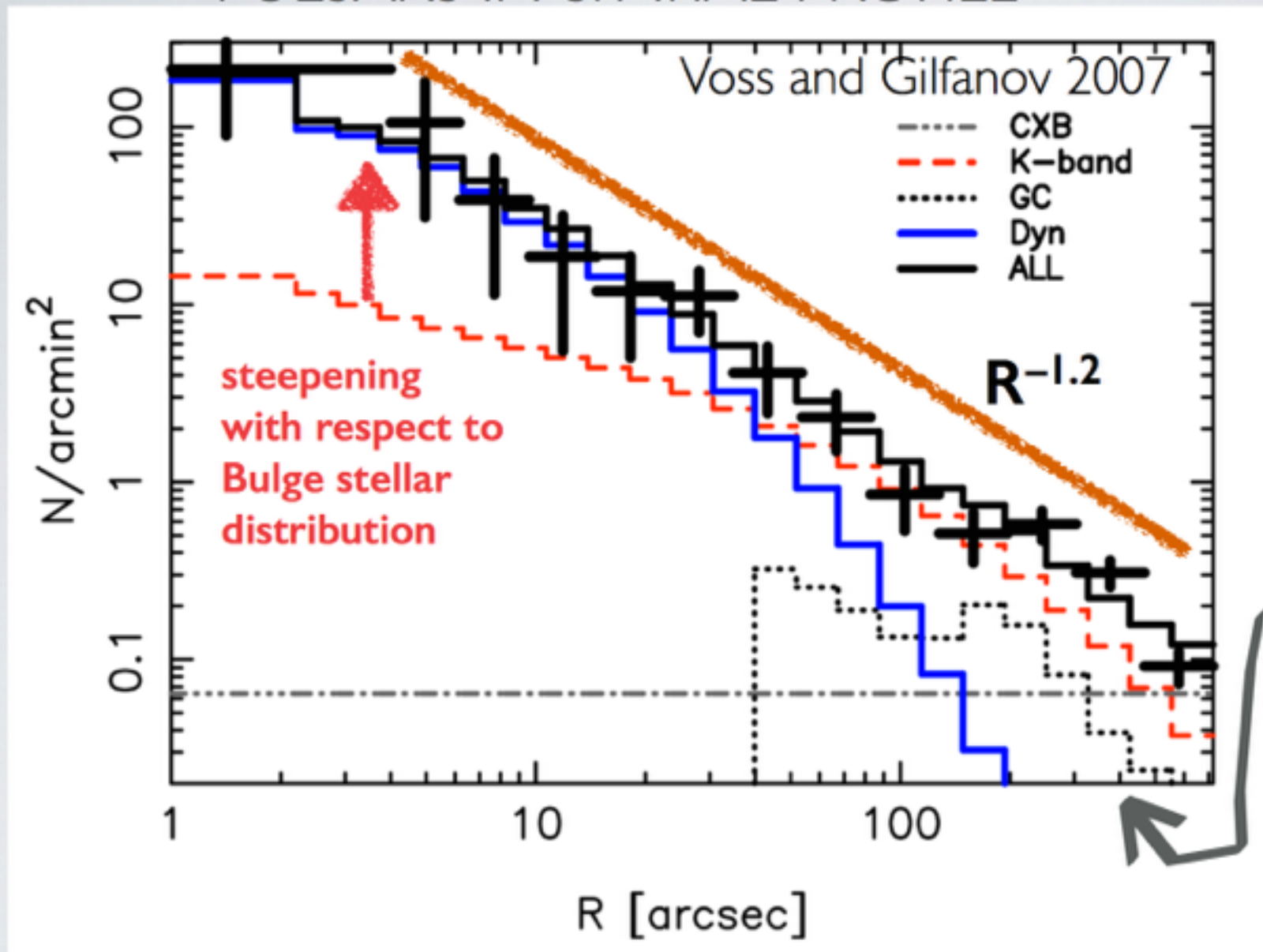
- The peak of the MSP energy spectrum matches the peak of the GeV excess



- 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)!

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)

We present a new method to characterize unresolved point sources (PSs), generalizing traditional Fermi point-spread functions to high latitudes and in the energy range ~ 1.9 to 11.9 GeV. We apply this method to Fermi 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, in preference to dark-matter annihilation threshold sources, which may be detected in the $\sim 0.5^\circ$ to 1° point-spread function of 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.

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

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

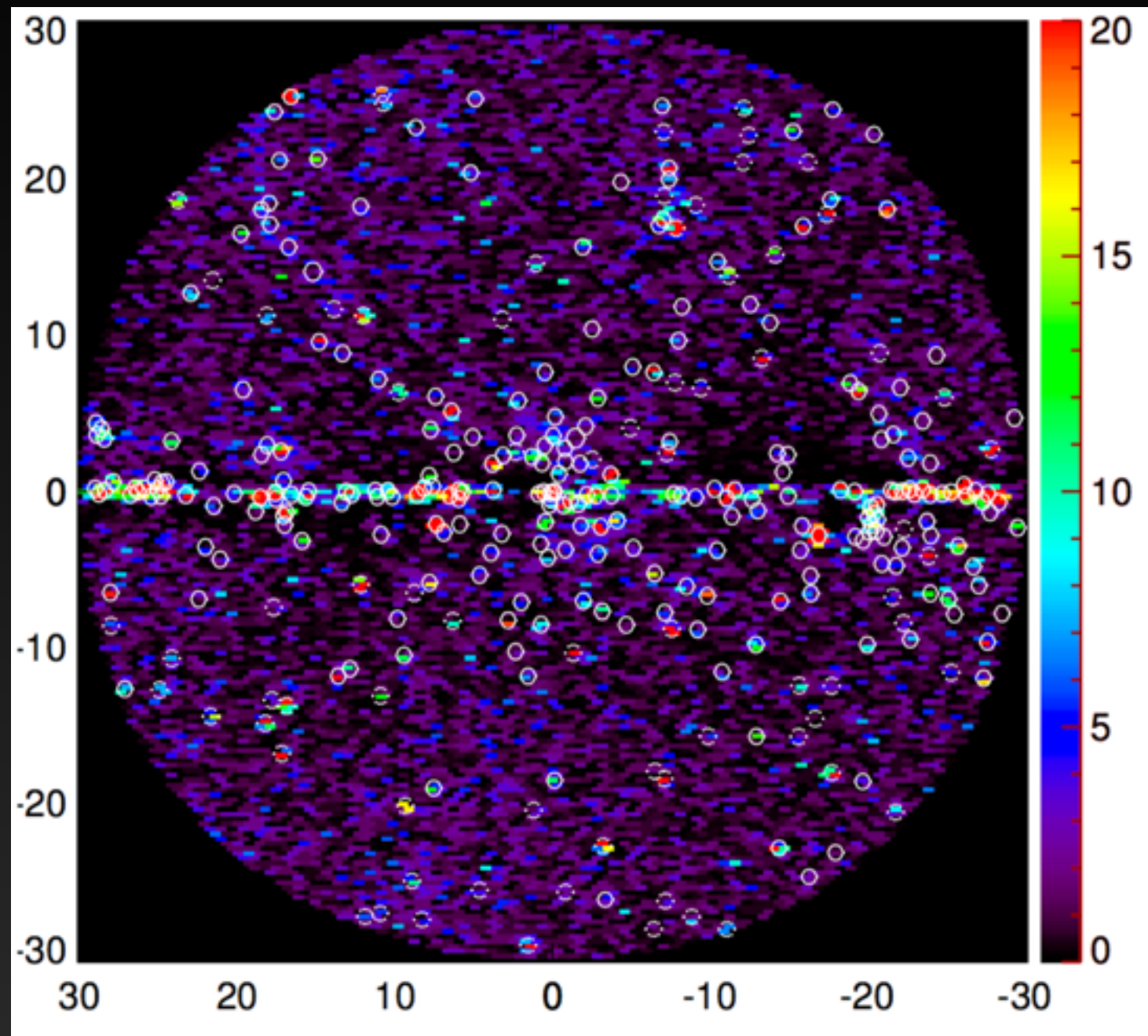
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Pulsars in the Galactic Center

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.

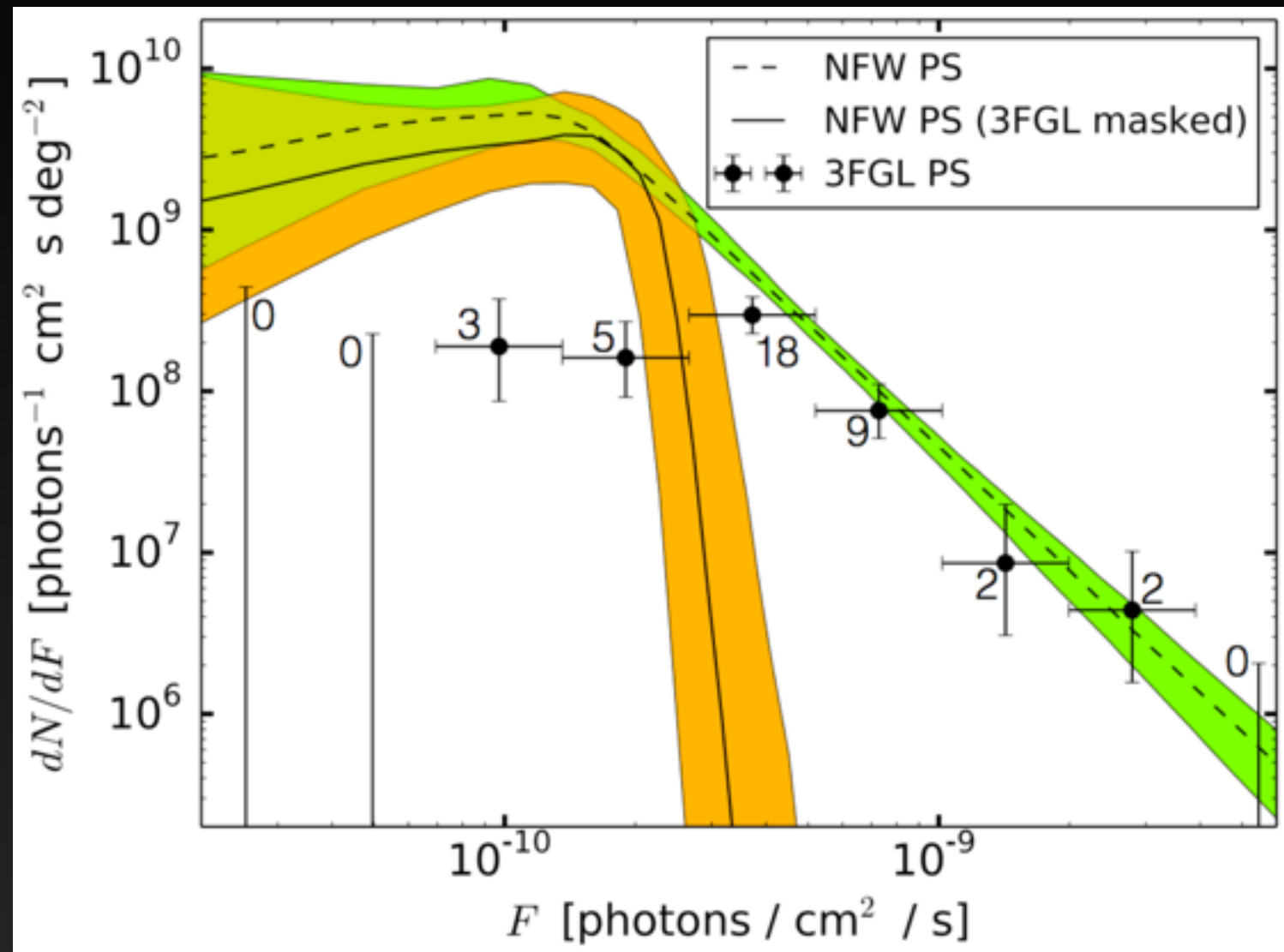
Pulsars in the Galactic Center

Method:

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

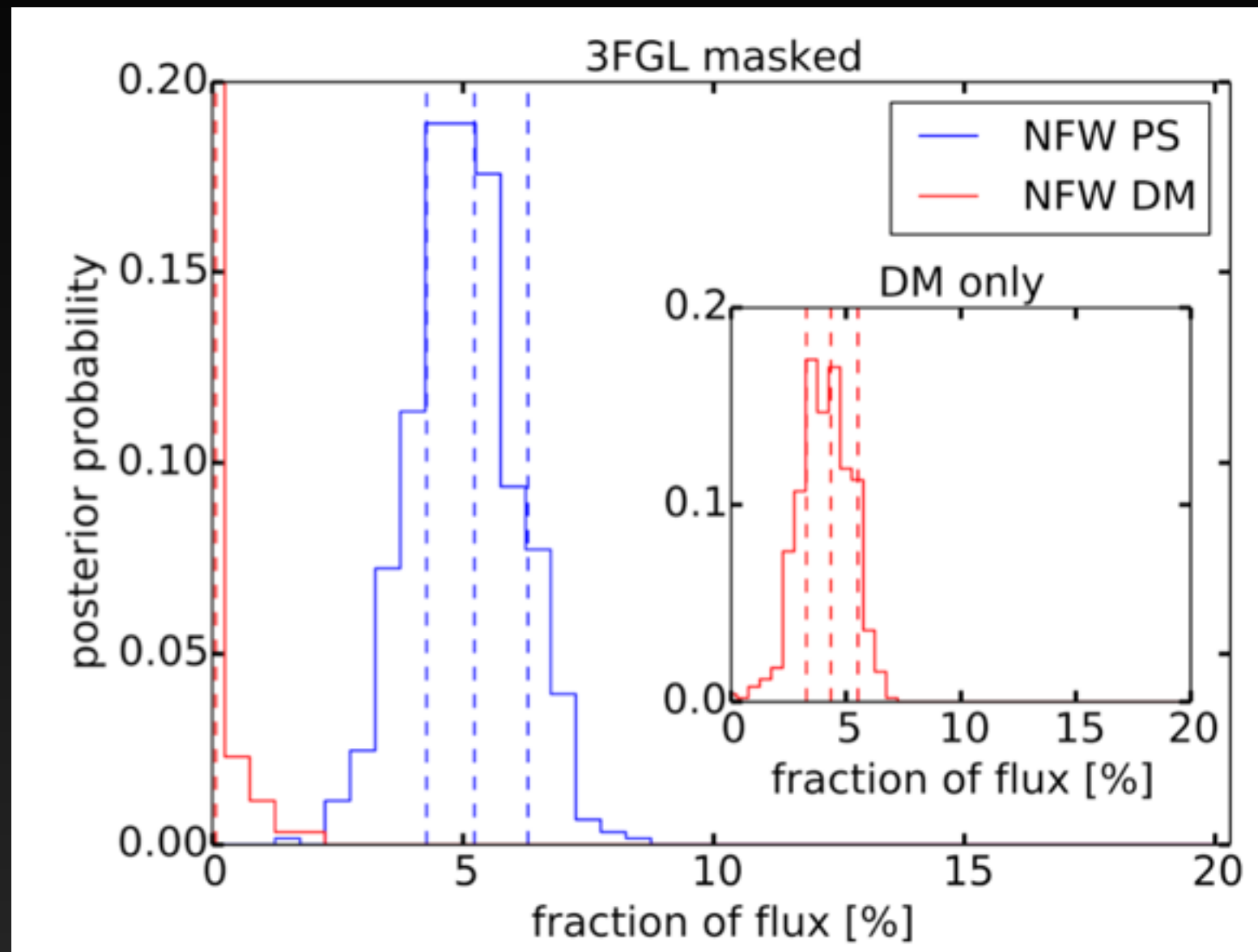
2.) Fit data to the GC excess.

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



Lee et al. (2015)

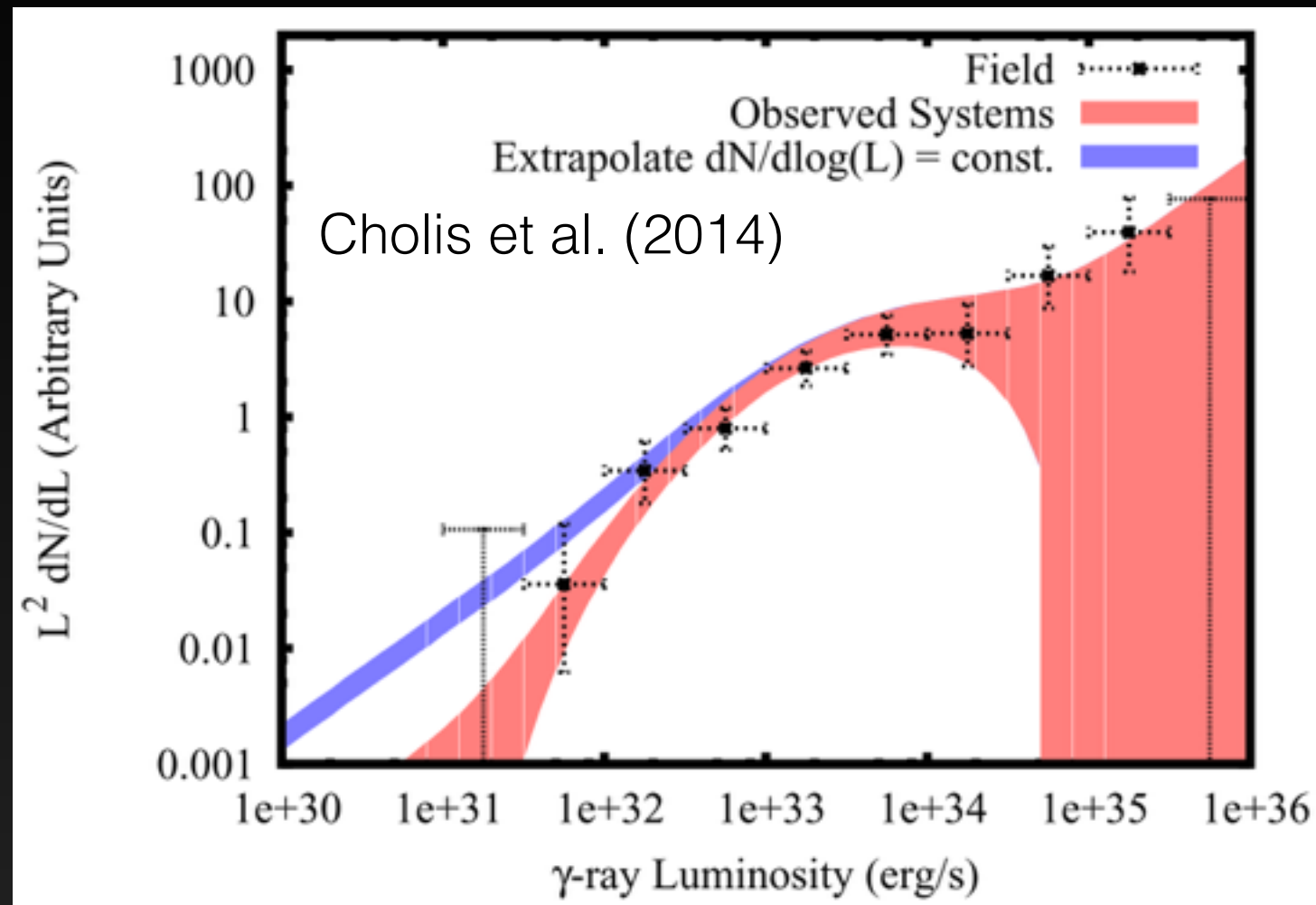
Pulsars in the Galactic Center



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.

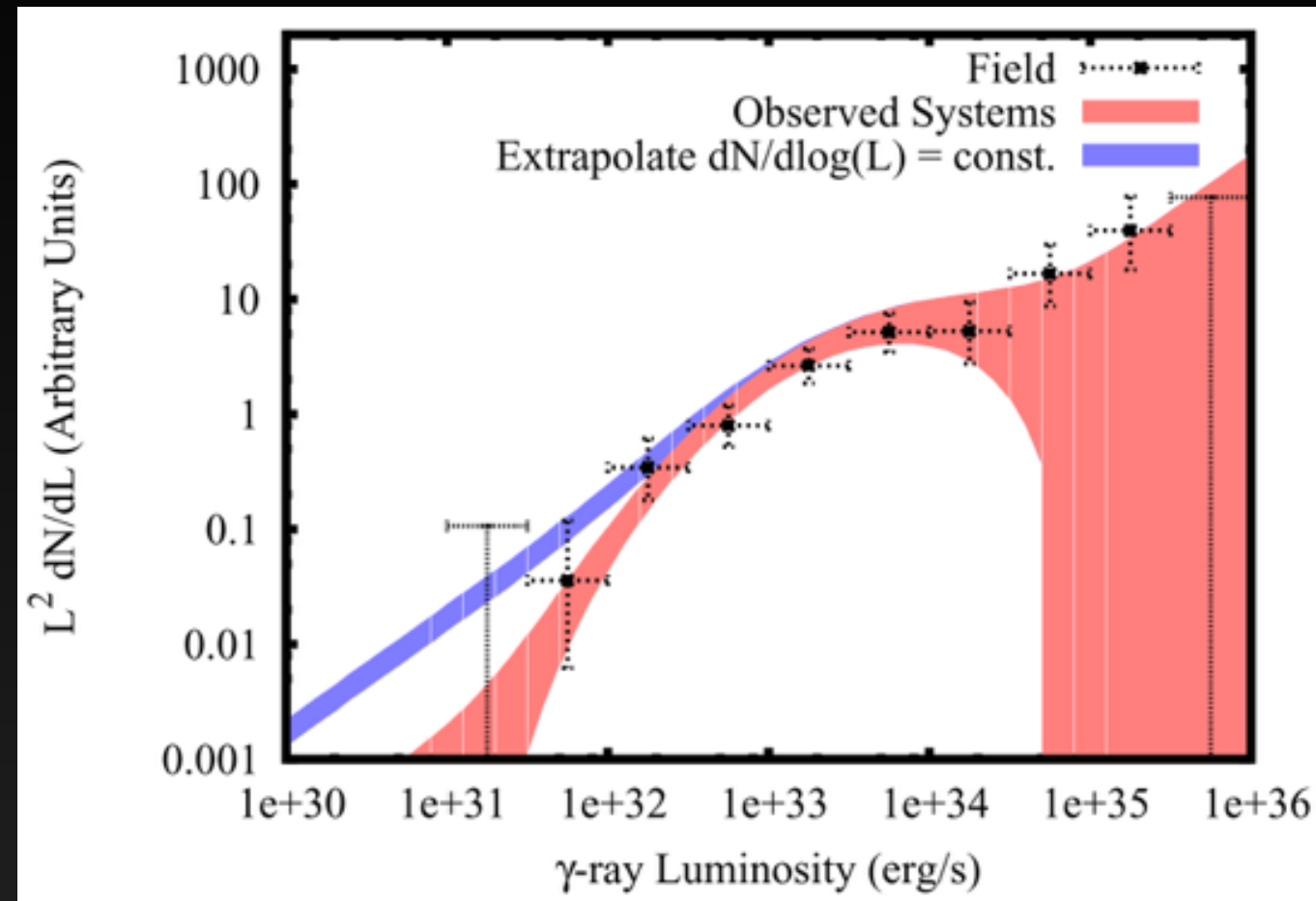
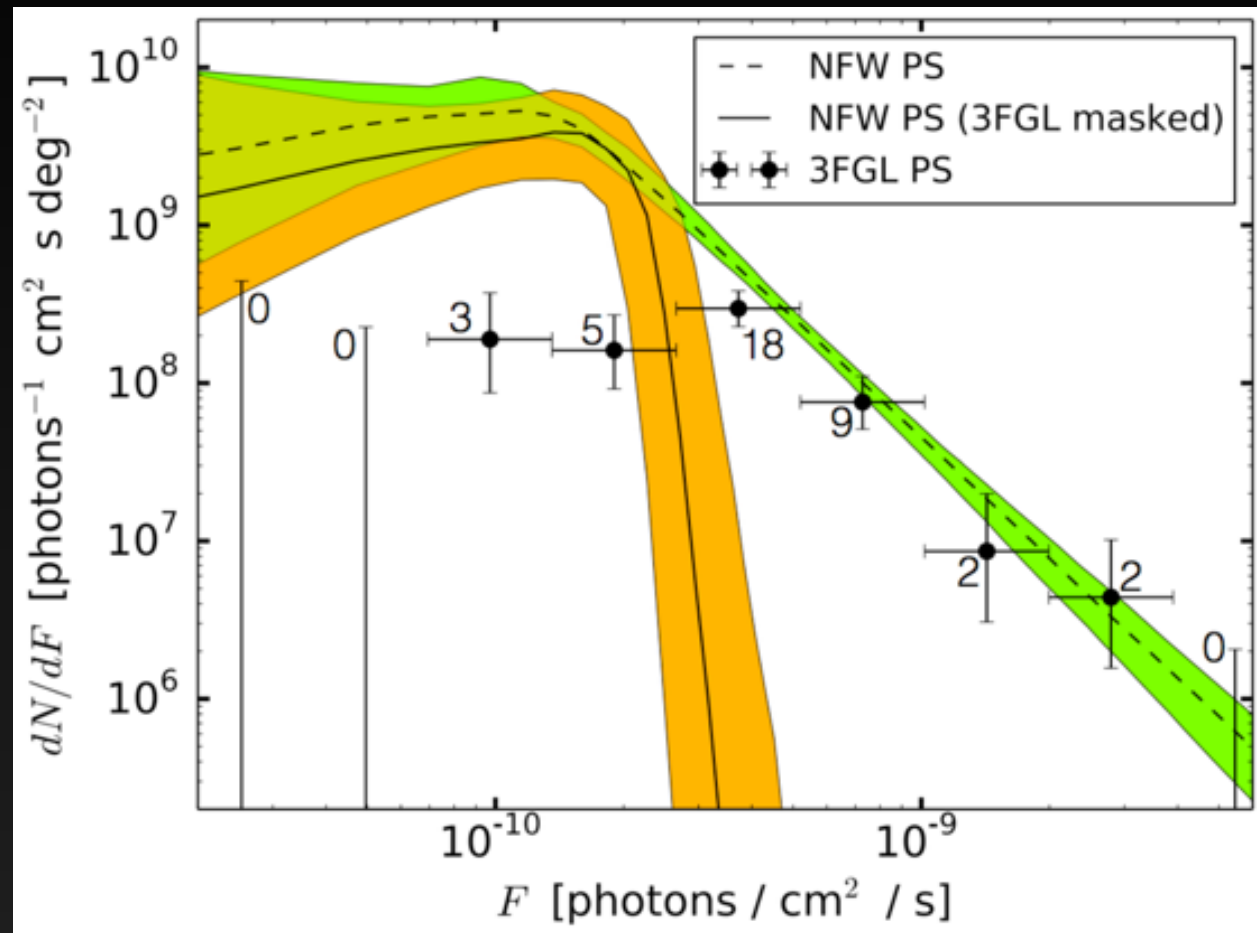
Why Not Pulsars?

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



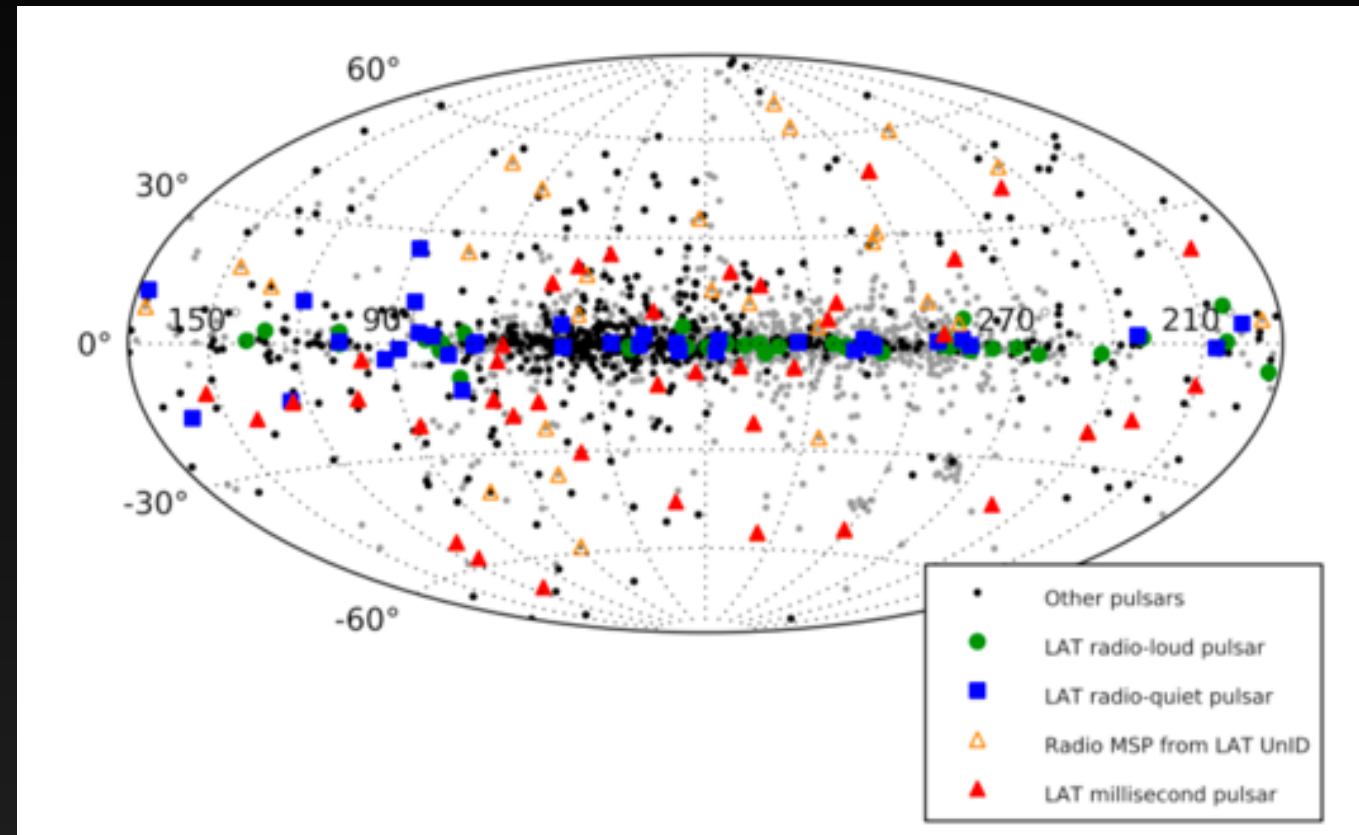
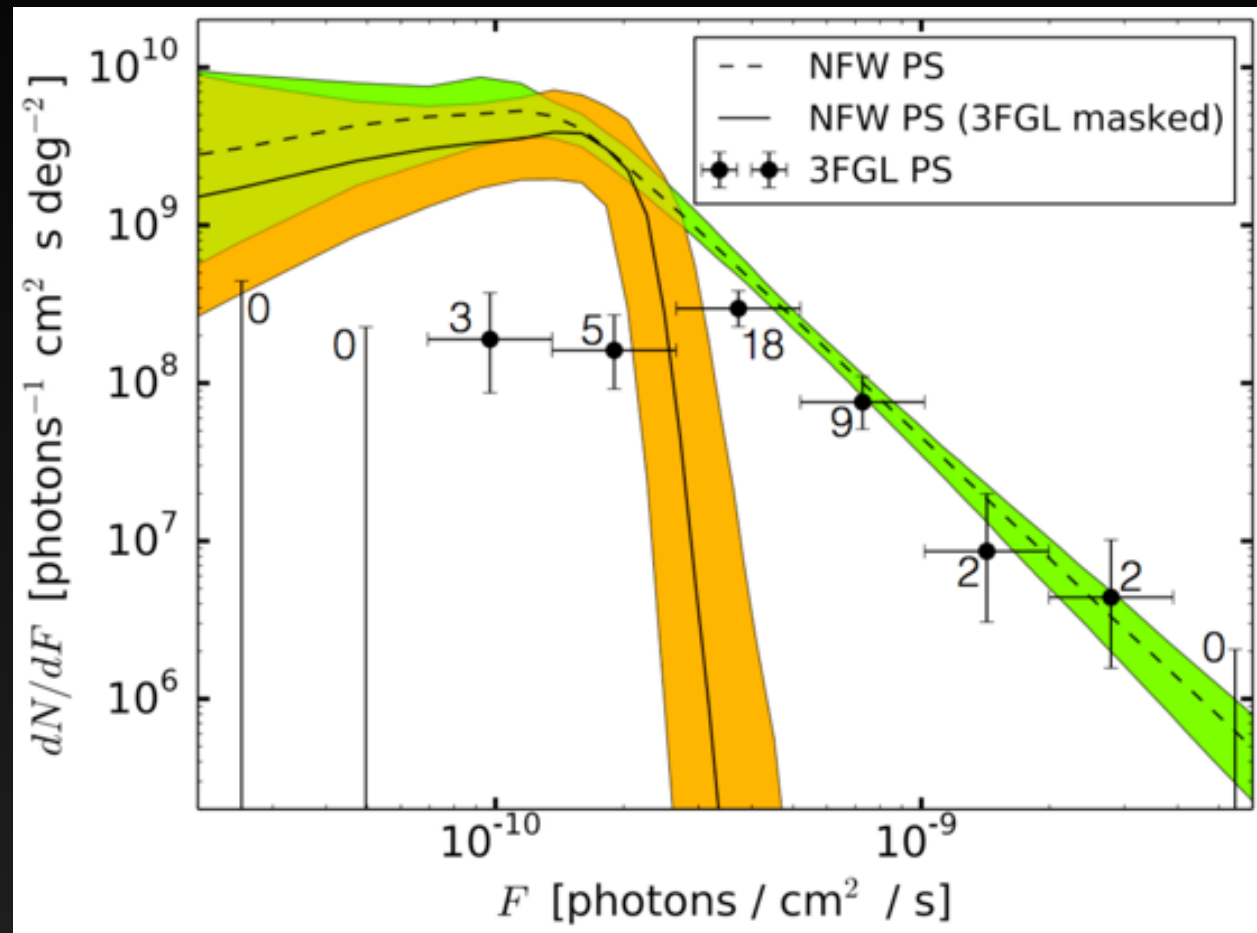
- There would need to be 226 (+91/-67) MSPs with luminosity $> 10^{34}$ erg s $^{-1}$ in the circular region, and 61.9 (+60/-33.7) with luminosity $> 10^{35}$ erg s $^{-1}$.

Why Not Pulsars?



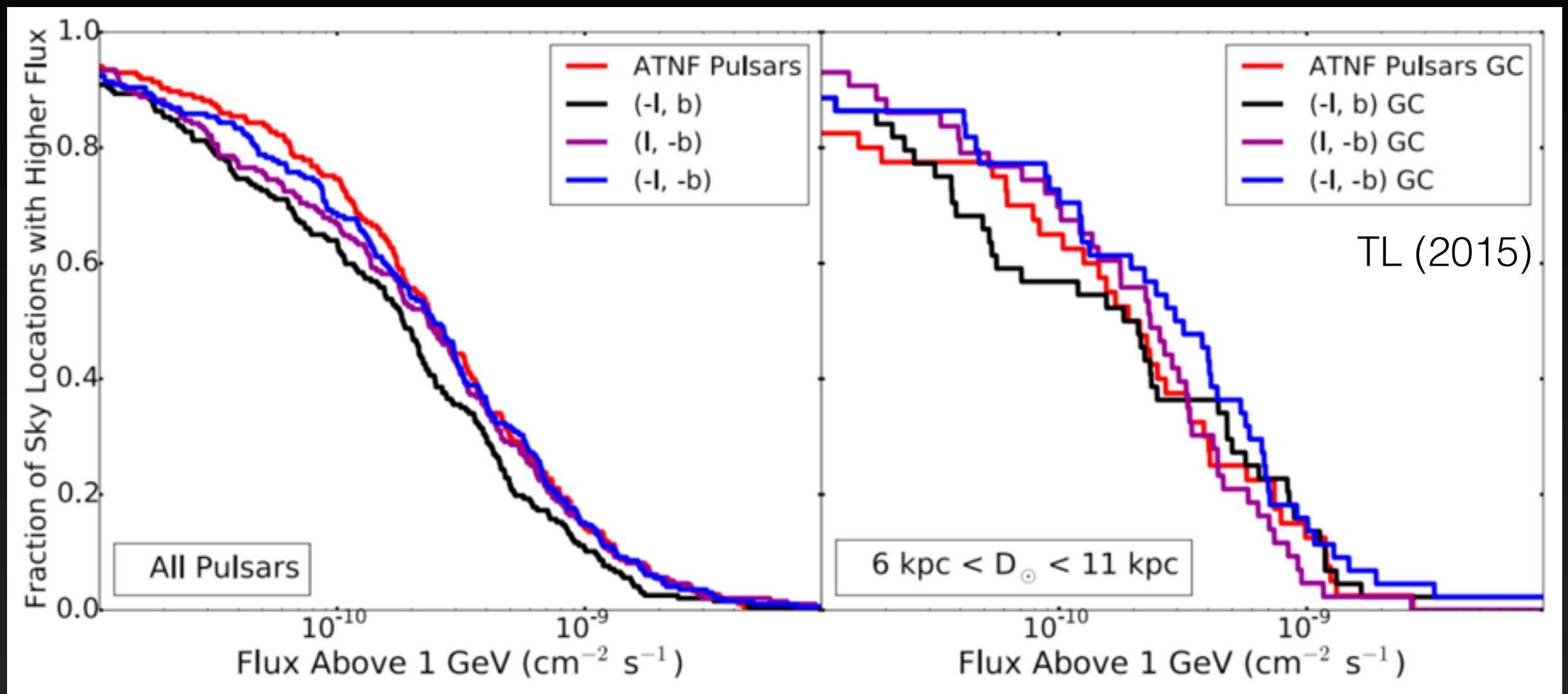
- A luminosity of $10^{35} \text{ erg s}^{-1}$ at the galactic center is equivalent to a gamma-ray flux of $8.0 \times 10^{-9} \text{ photons cm}^{-2} \text{ s}^{-1}$. These systems have not been observed in the Galactic Center.

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.

How Do We Test the Pulsar Hypothesis?

- **Future Gamma-Ray Observations by the Fermi-LAT are unlikely to resolve this degeneracy**

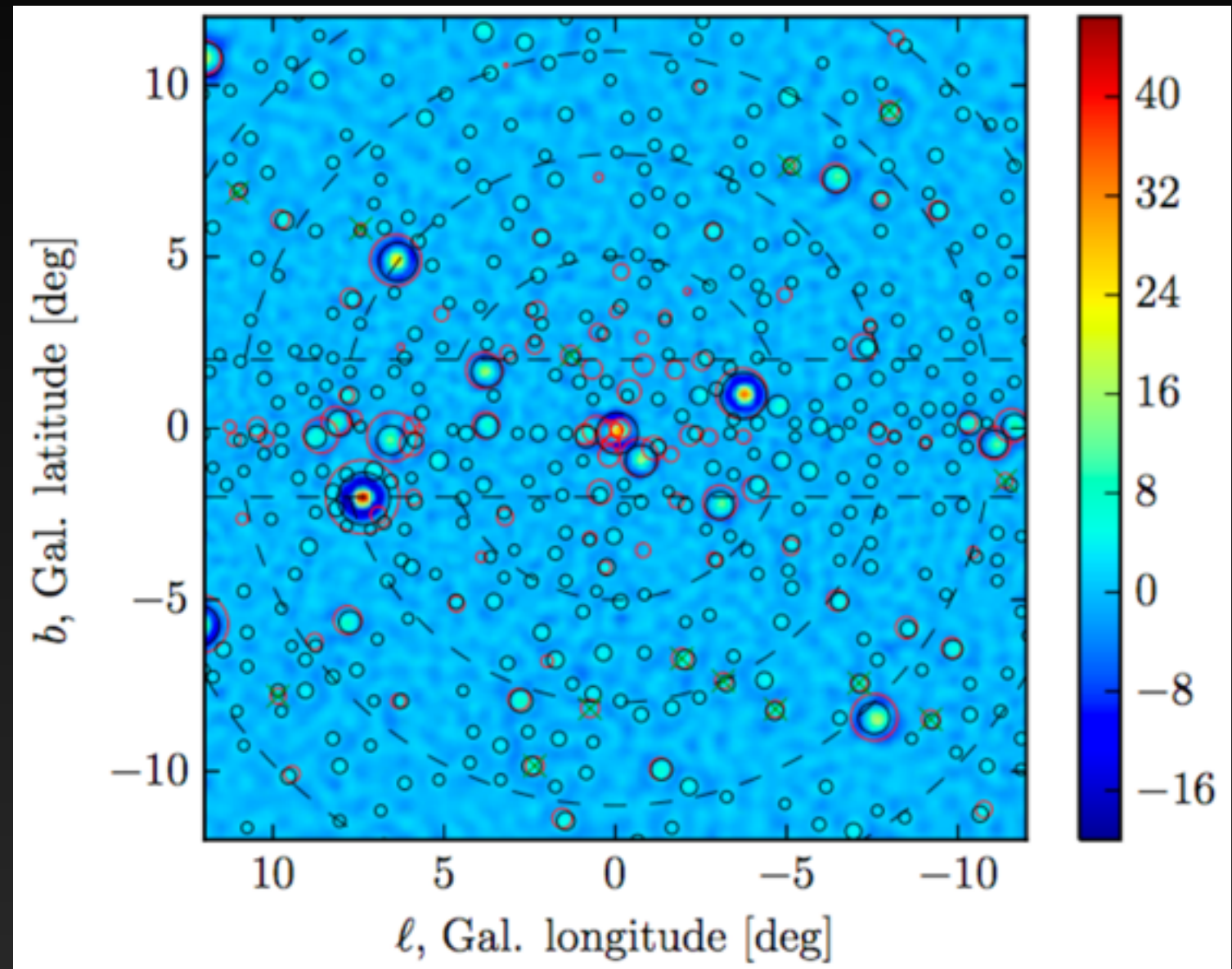


- **The observation of radio pulsars coincident with gamma-ray hotspots would serve as smoking gun evidence for a pulsar interpretation.**



How Do We Test the Pulsar Hypothesis?

- 1.) Utilize gamma-ray hotspots to seed radio pulsar searches
- 2.) Detect, or constrain, the population of millisecond pulsars at these hotspots.
- 3.) Use observations to prove, or constrain, MSP explanations for the galactic center excess.



Diffuse Gamma-Ray Models



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

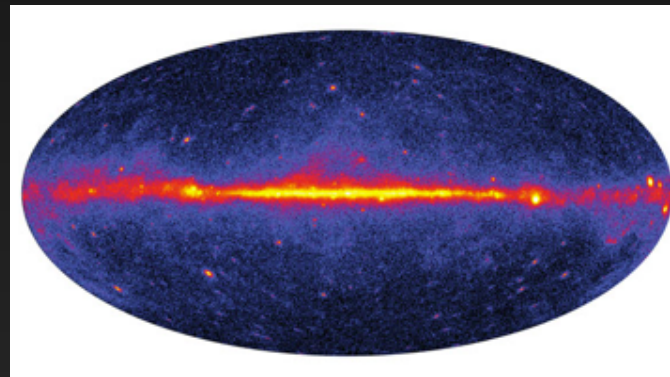
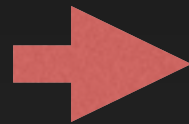
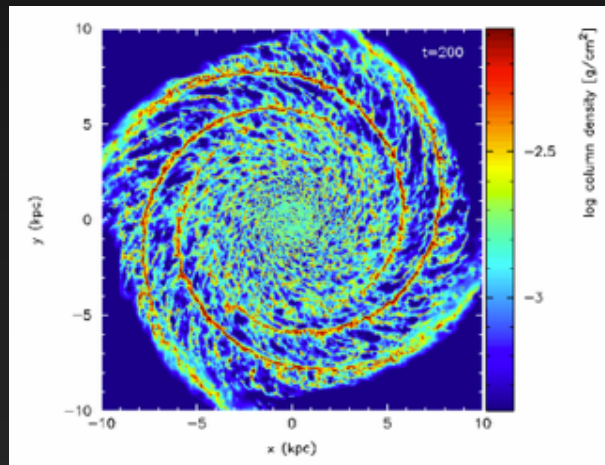
cosmic rays propagate

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

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
Ajello et al. (2015)	1511.02938

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.

Putting Cosmic Rays Back Where They Belong: Tracing Injection with Molecular Hydrogen

Eric Carlson* and Stefano Profumo†
Department of Physics and Santa Cruz Institute for Particle Physics,
University of California, Santa Cruz, CA 95064, USA

Tim Linden‡
Kavli Institute for Cosmological Physics, University of Chicago, IL 60637, USA and
Department of Physics, The Ohio State University Columbus, OH, 43210

present, all physical models of diffuse Galactic γ -ray emission have assumed that the injection morphology of cosmic rays traces the observed populations of either OB stars, pulsars, or supernova remnants. To accomplish this task, we employ state-of-the-art 3D particle diffusion and gas density of the residual γ -ray emission from the Galactic center (GC) to trace the H₂ gas should also provide a physically motivated, high resolution tracer. To accomplish this task, we employ state-of-the-art 3D particle diffusion and gas density of the residual γ -ray emission from the Galactic center (GC) to trace the H₂ gas should also provide a physically motivated, high resolution tracer. To accomplish this task, we employ state-of-the-art 3D particle diffusion and gas density of the residual γ -ray emission from the Galactic center (GC) to trace the H₂ gas should also provide a physically motivated, high resolution tracer.

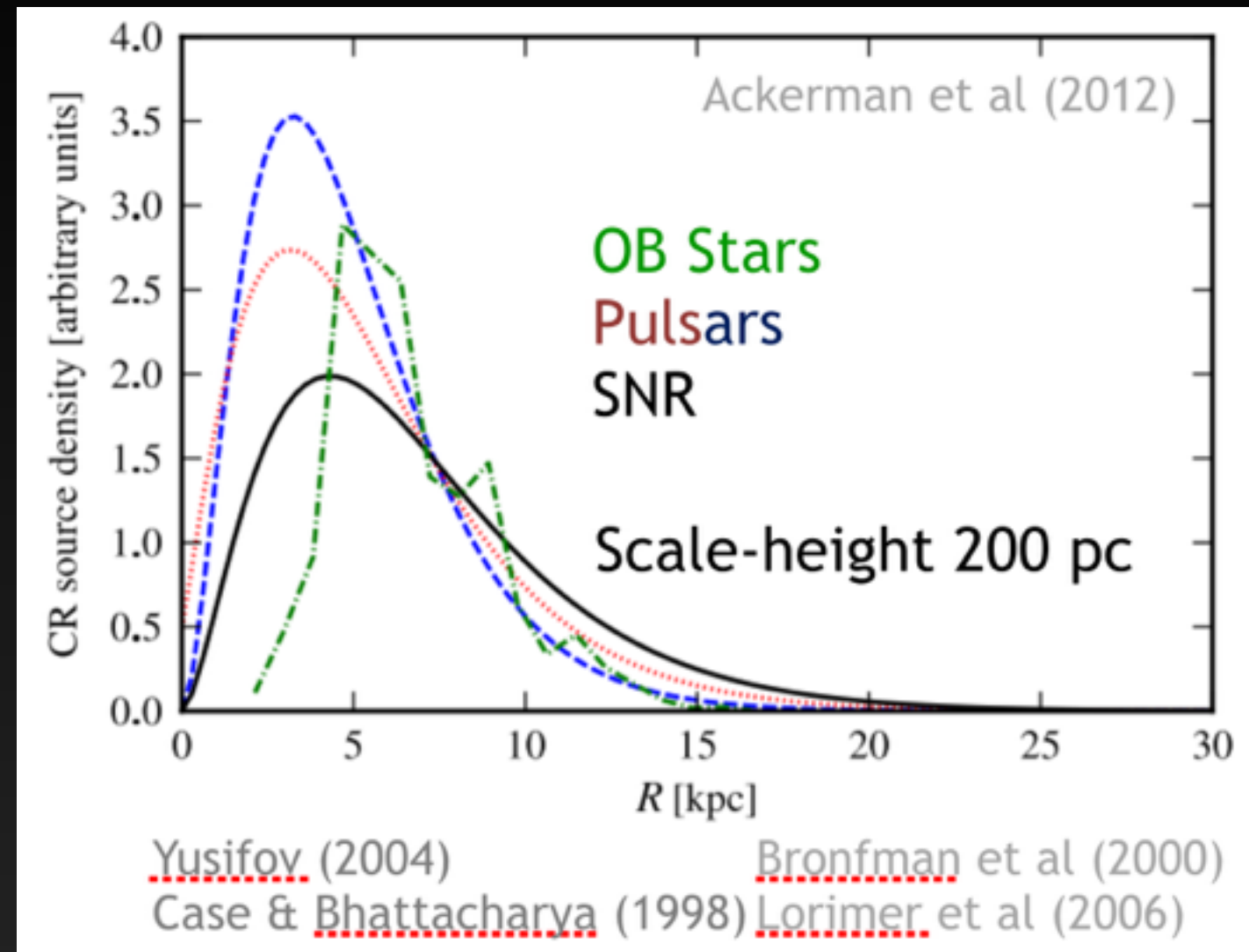
6.9 years of Fermi's most
al details are given in
nova remnants
accelerati

Cosmic-Ray Injection Sources

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

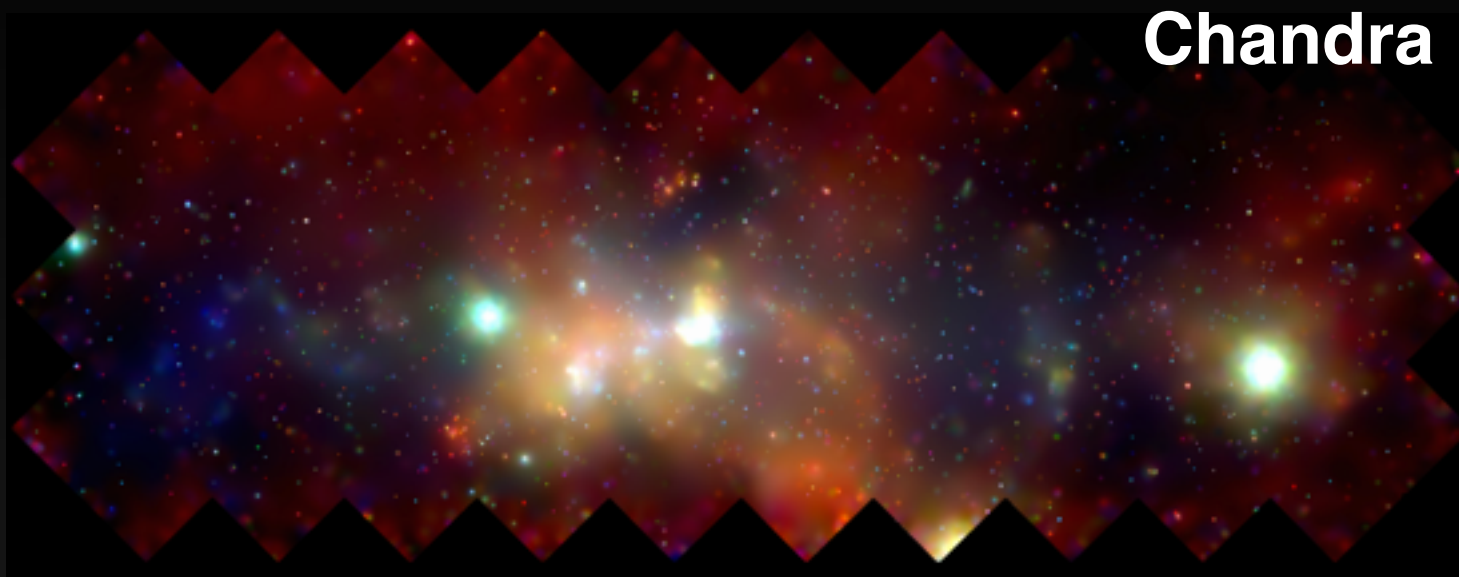
Need tracers of current and past supernovae rate:

- + Observed SNR
- + Pulsars
- + OB Stars

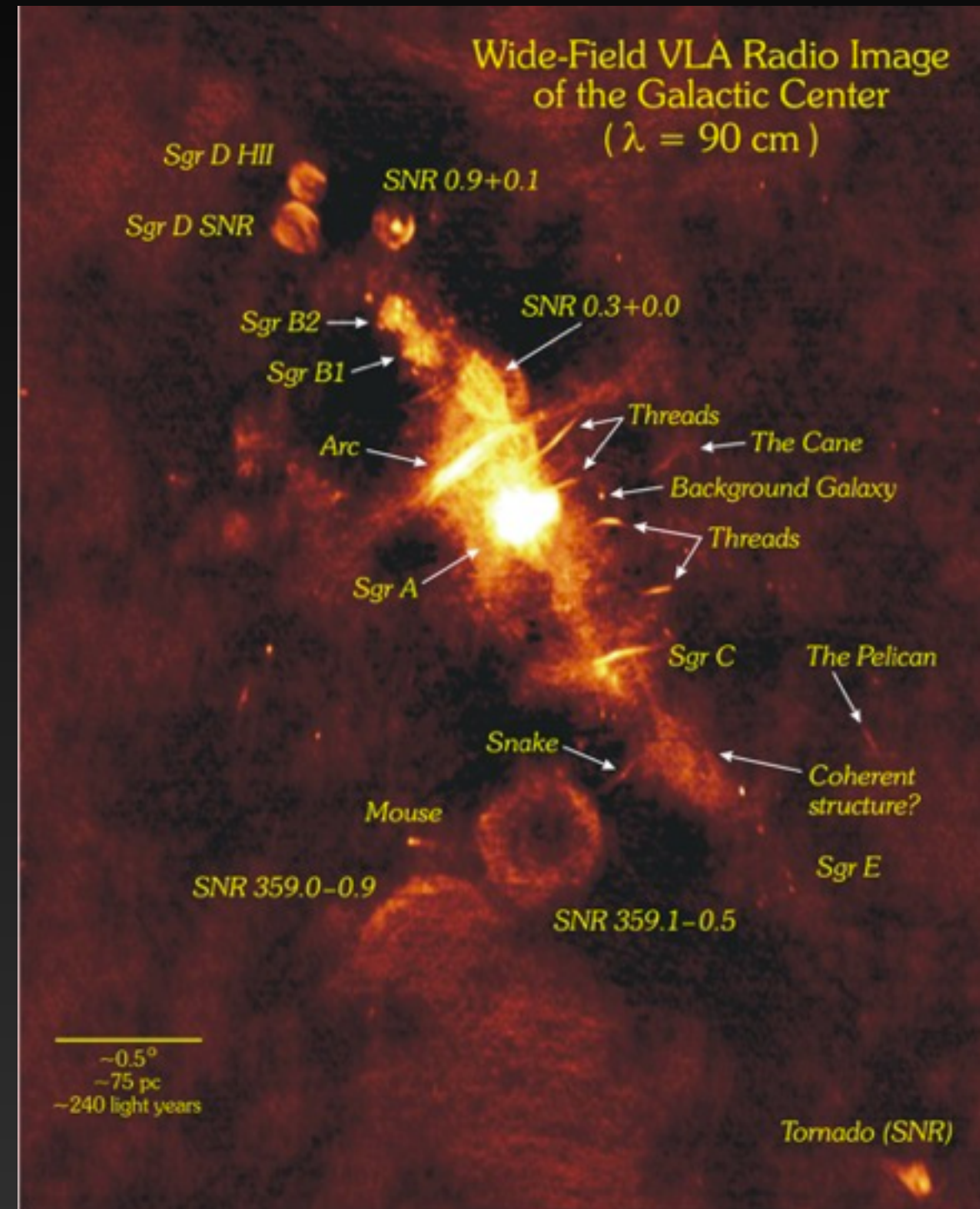


Interestingly the models used for these analyses have extremely small injection rates near the GC (in several cases identically 0).

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.

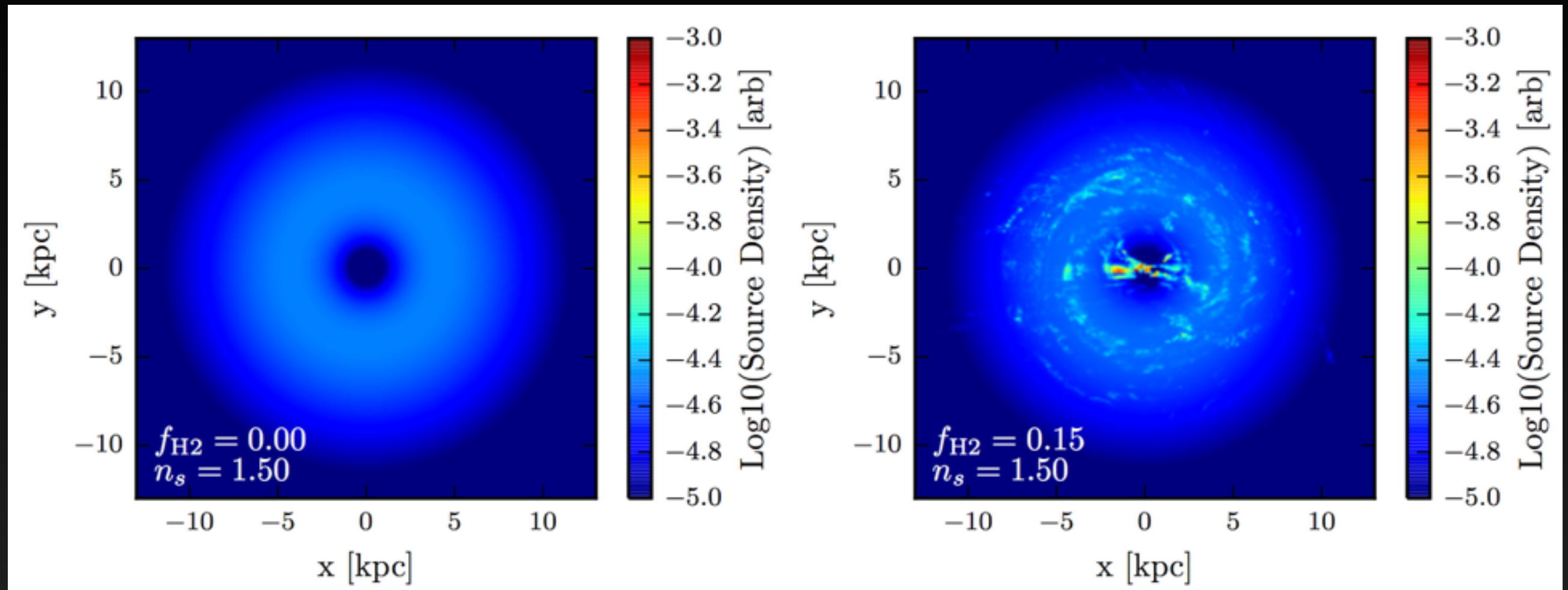
Theoretically Motivated: Molecular Gas is the seed of star formation, the Kennicutt-Shmidt Law gives

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

Specifically we adopt:

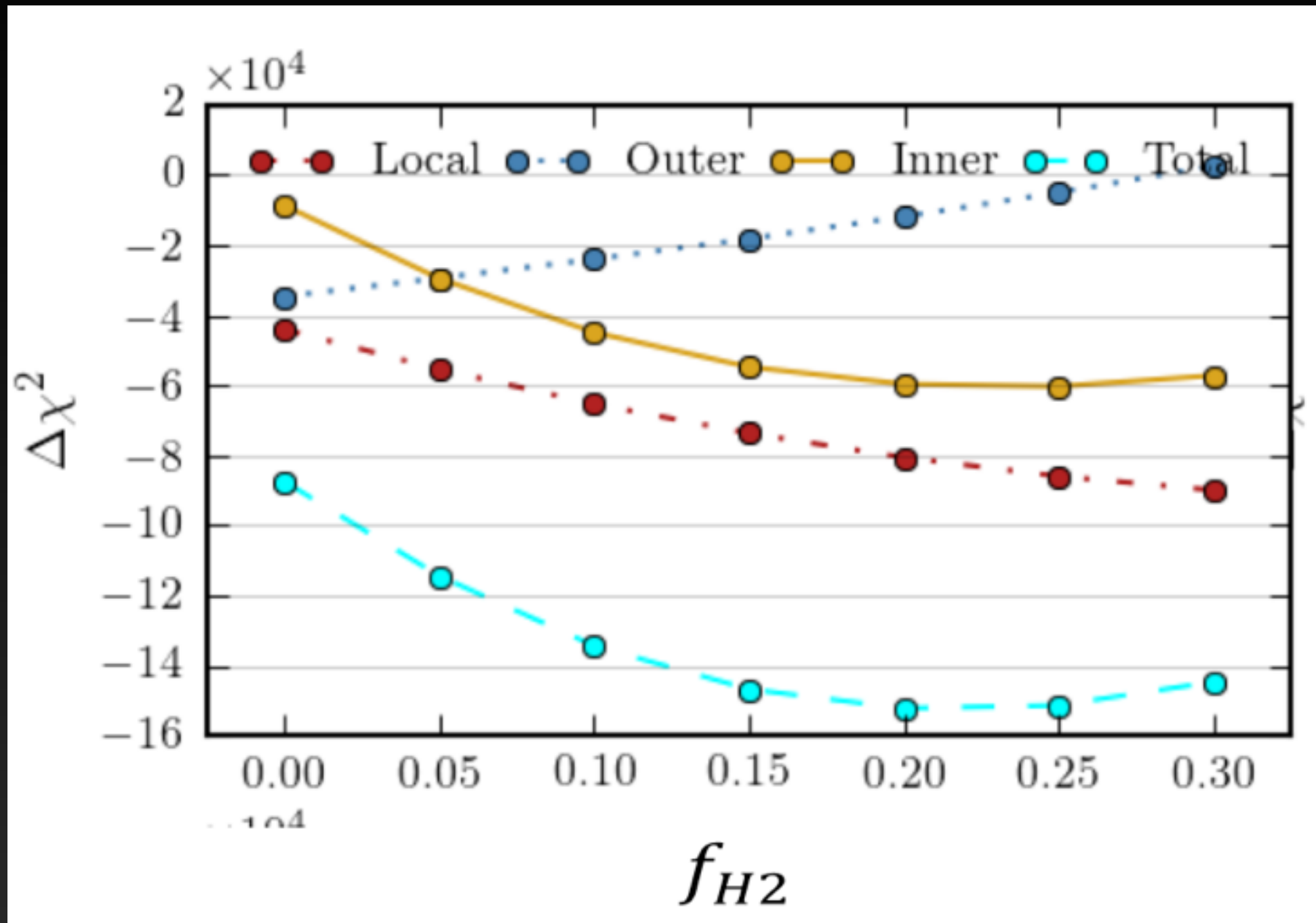
$$Q_{\text{CR}}(\vec{r}) \propto \begin{cases} 0 & \rho_{\text{H2}} \leq \rho_s \\ \rho_{\text{H2}}^{n_s} & \rho_{\text{H2}} > \rho_s \end{cases}$$

Adding a Molecular Gas Component



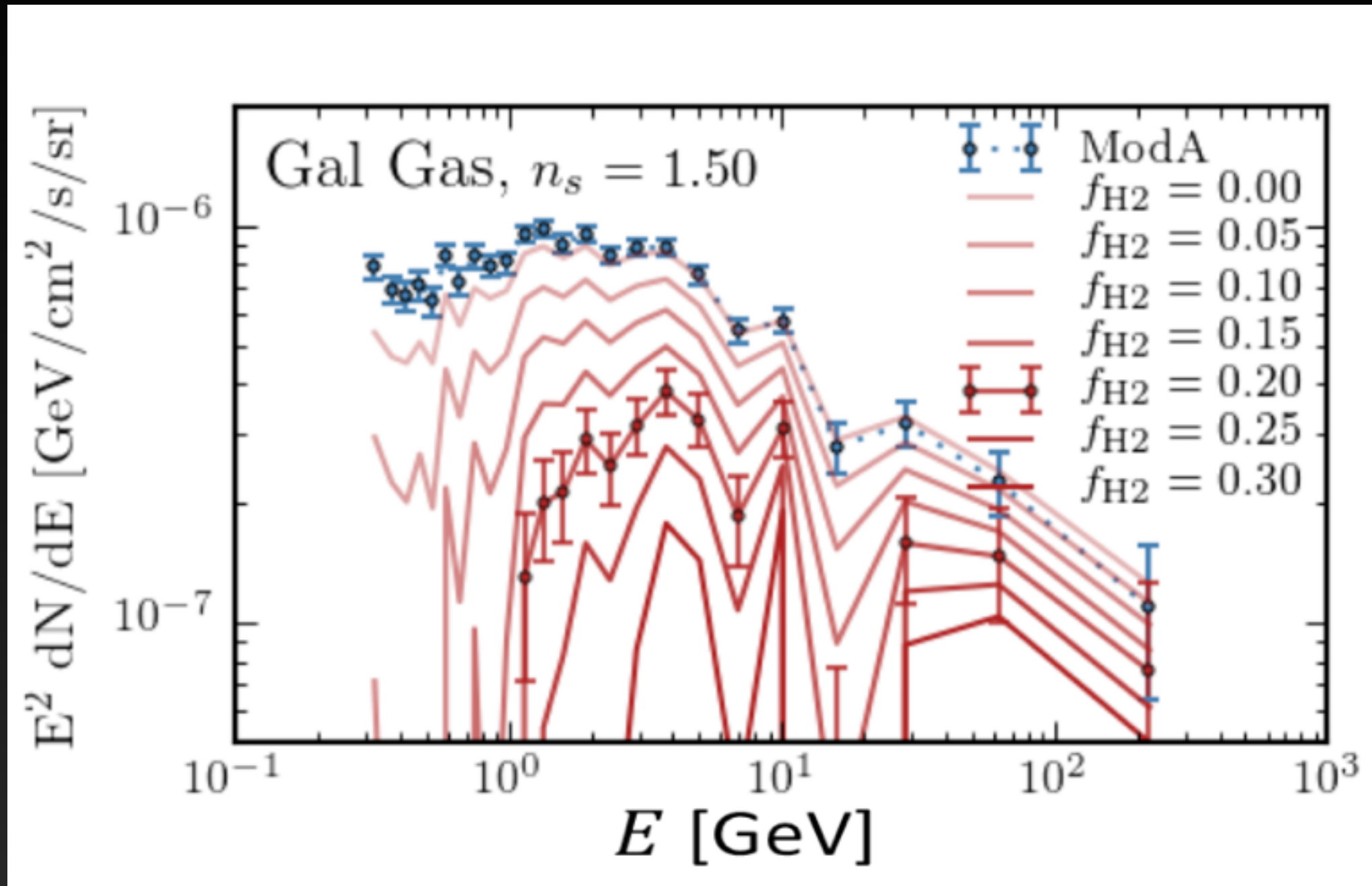
Adds significant cosmic-ray injection to the inner galaxy, and additionally a large bar structure.

Adding a Molecular Gas Component



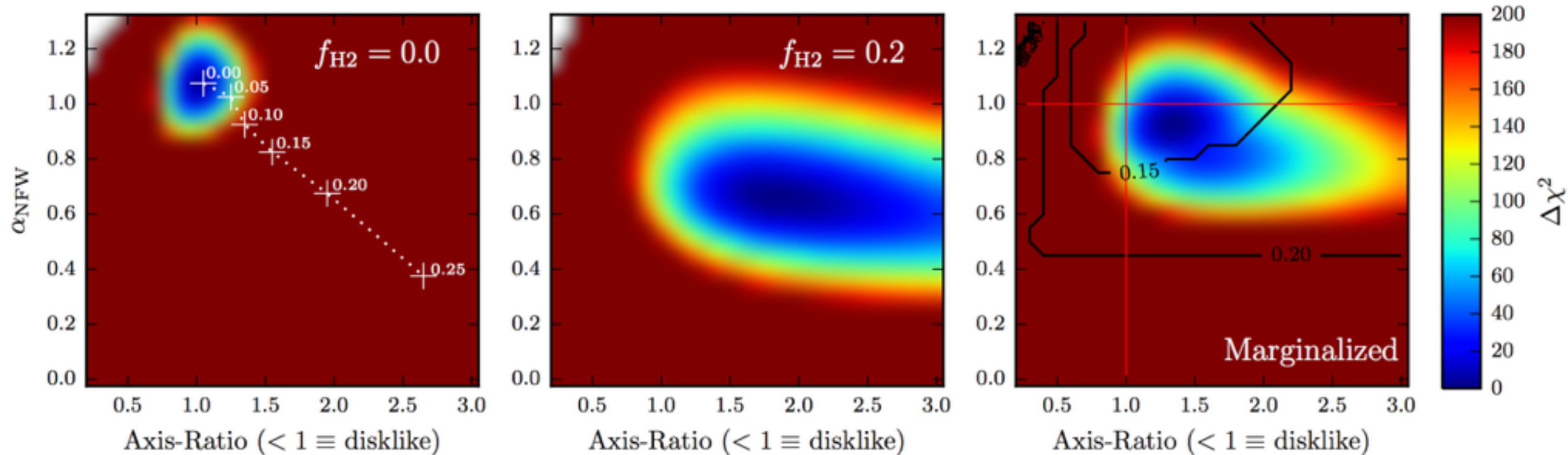
This tracer improves the fit to the gamma-ray data over the full sky.

This Reduces the Gamma-Ray Excess!



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

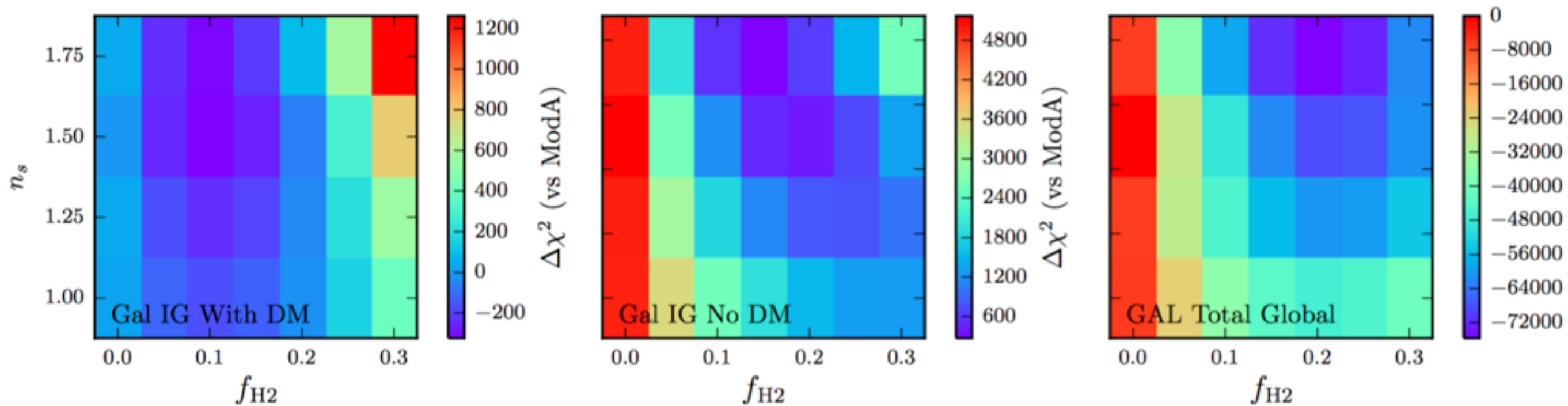
This alters the gamma-ray excess



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.

Why Not Astrophysical Modeling?

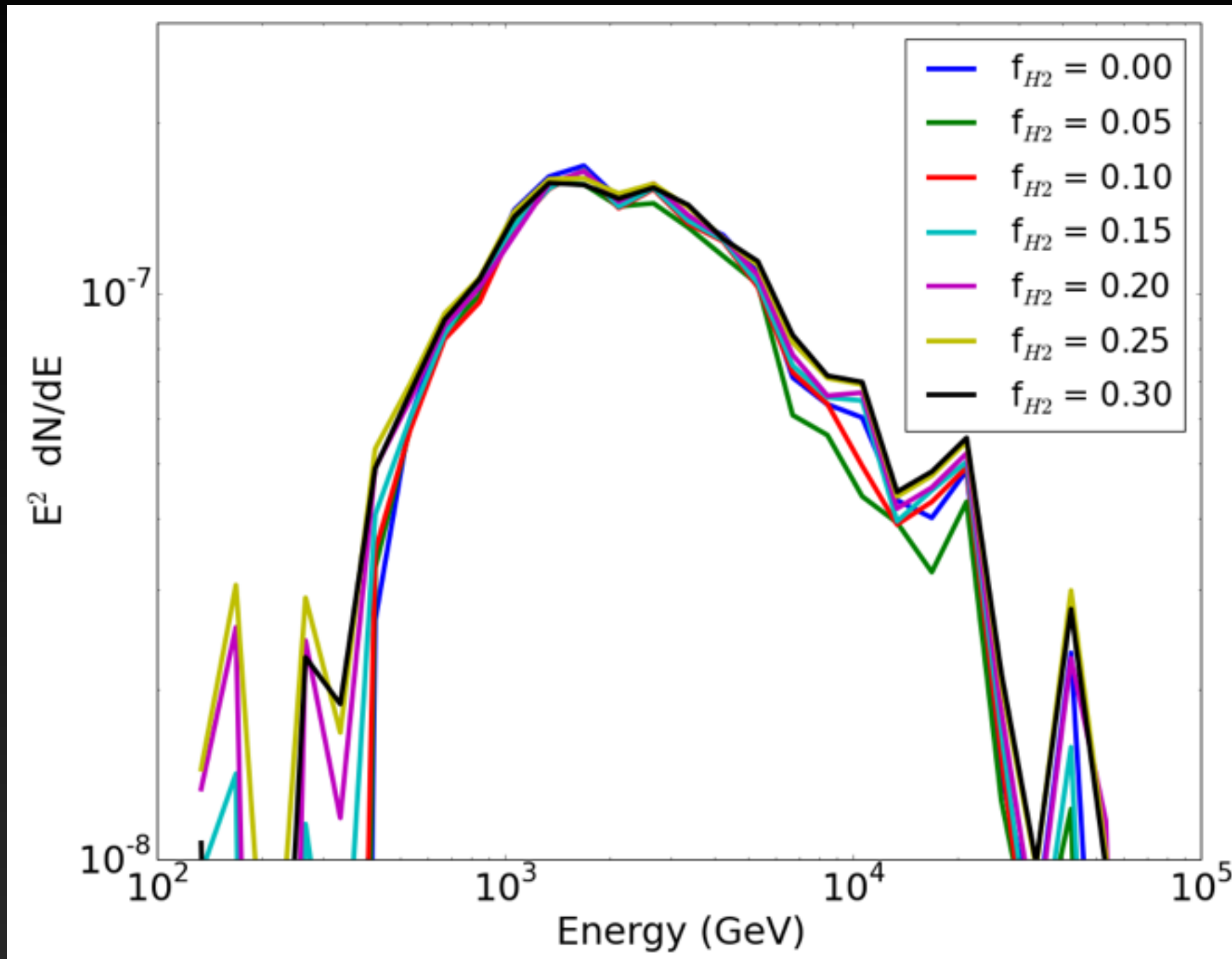


However, these fits were performed in models without an NFW template.

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?



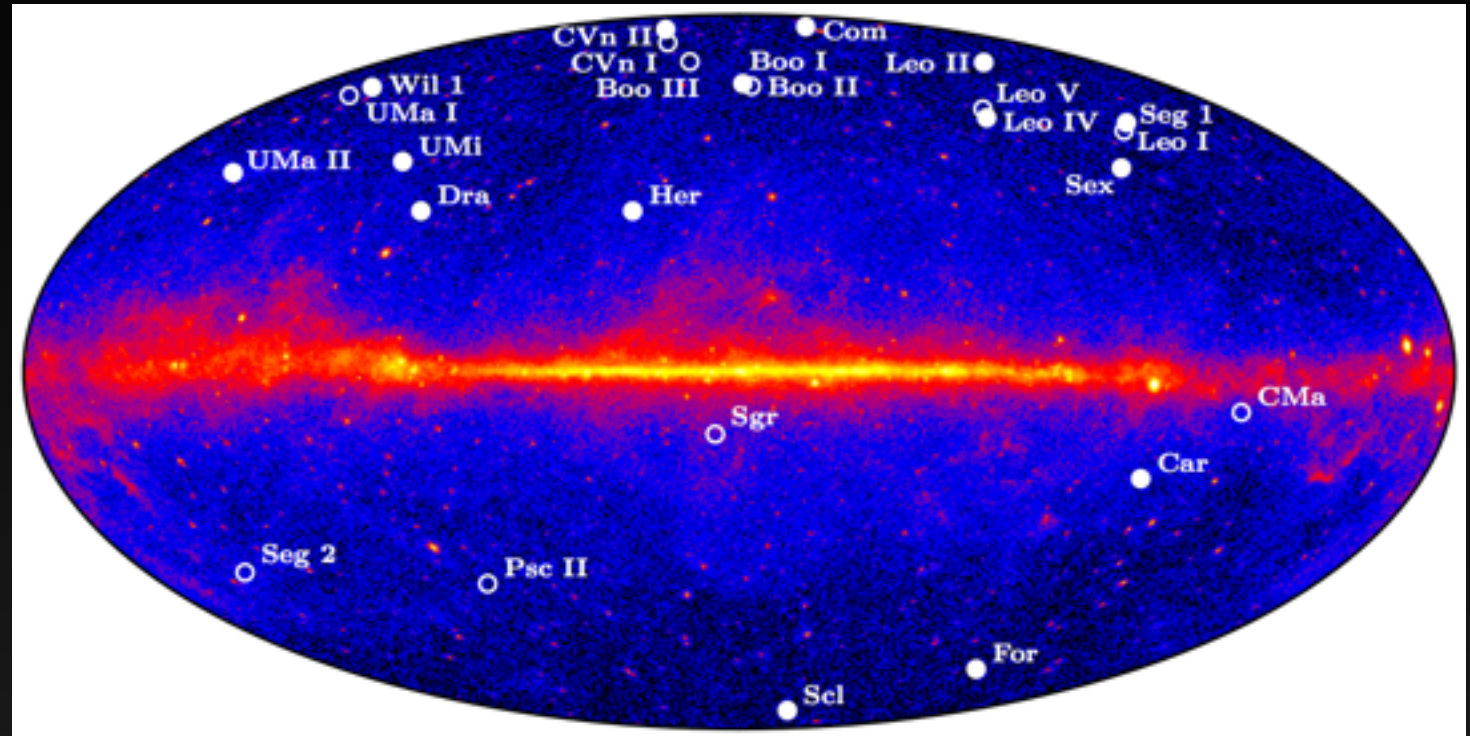
Moreover, when we focus on the very center of the galaxy ($<2^\circ$), these alterations to the gamma-ray model do not appear to decrease the intensity of the gamma-ray excess.

Coming to a Conclusion

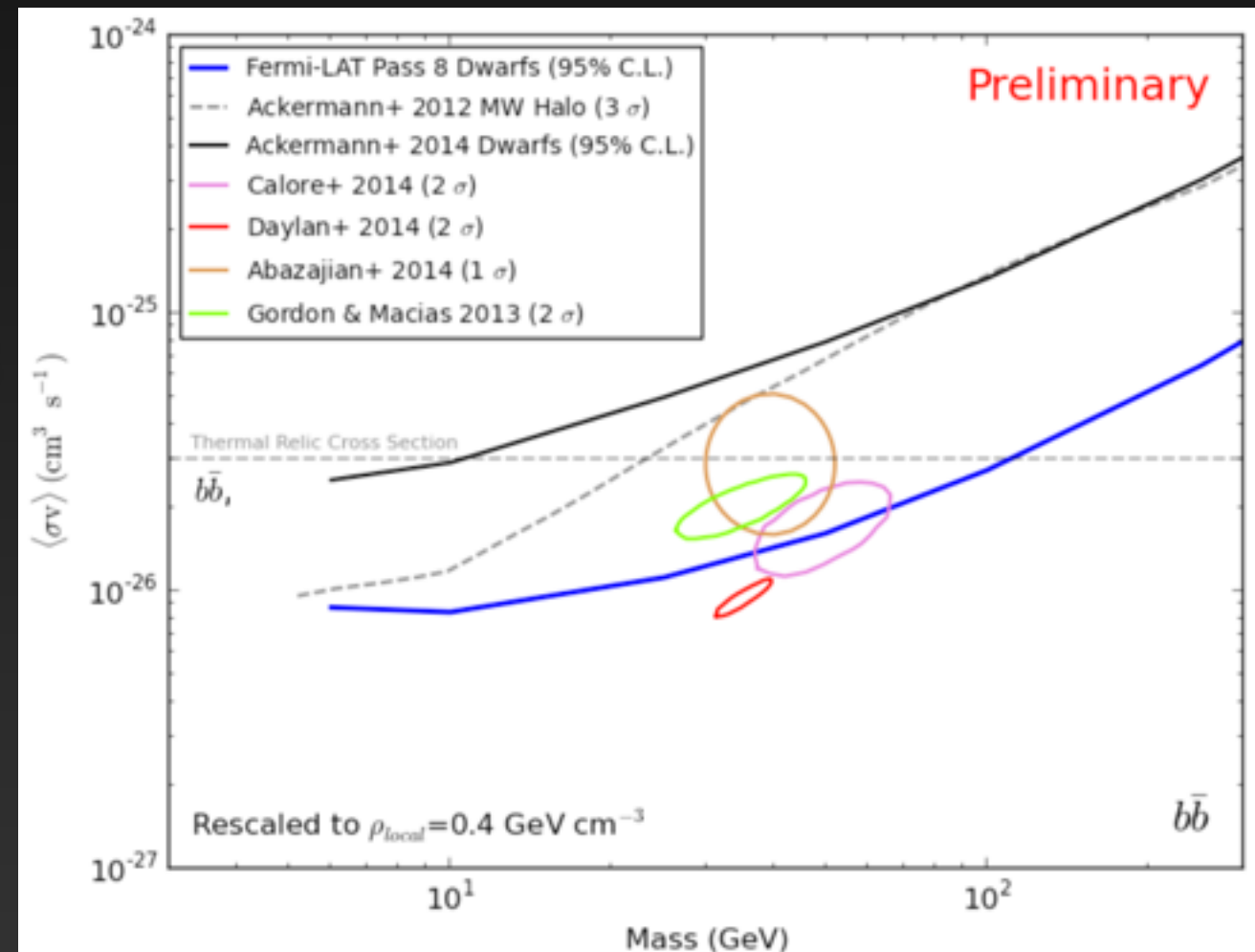
- 1.) Over the last two years - the existence of a significant gamma-ray excess (compared to current astrophysical models) has been confirmed.**
- 2.) The gamma-ray excess has features compatible with a dark matter signal — a dark matter motivated NFW profile remains the best fitting template to the 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

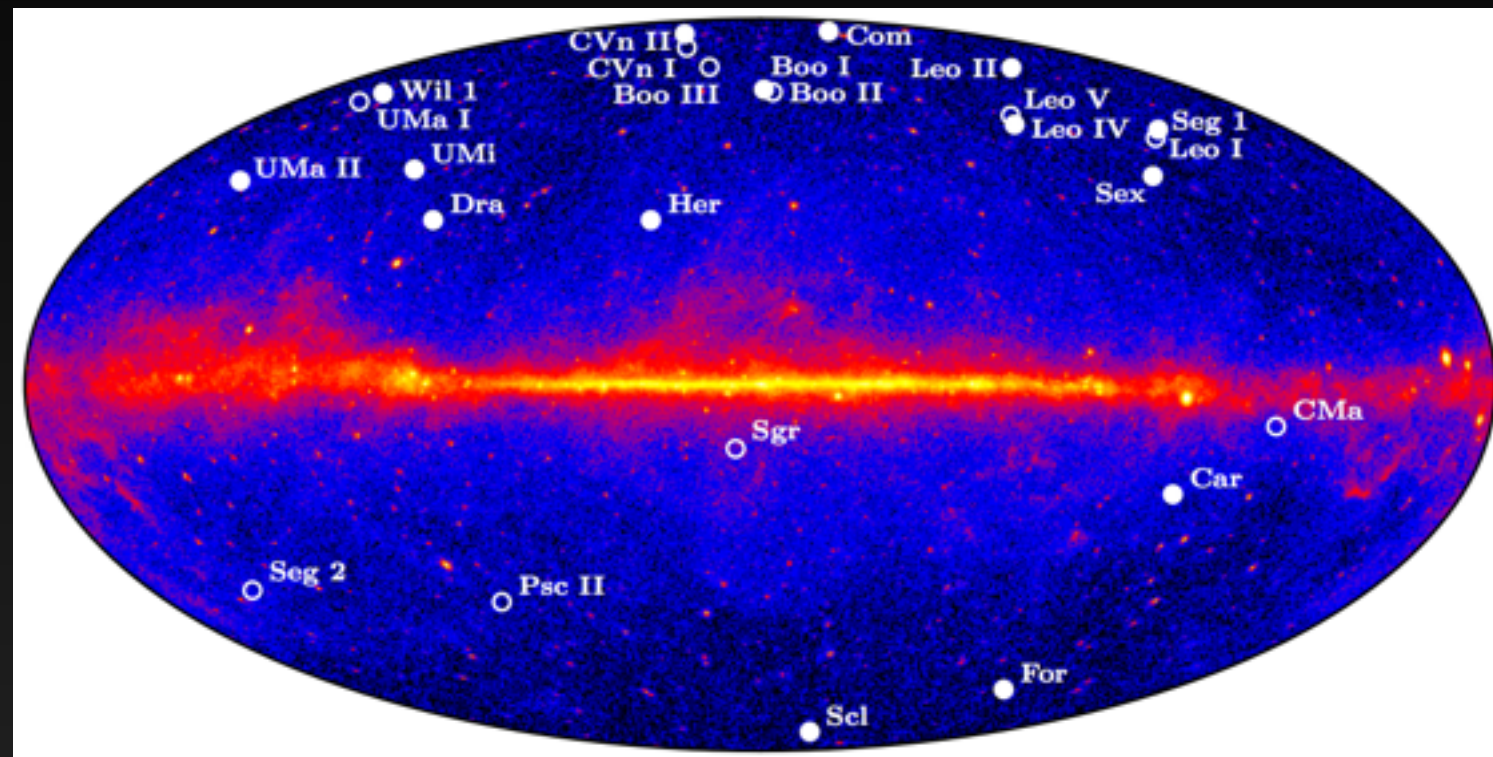
Dwarf Galaxies can also produce a significant γ -ray signal from dark matter annihilation.



While results utilizing the Pass 7 dataset found a small excess consistent with the GC, this excess has gone away in more recent studies, which are now in mild tension with models for the GC excess.



Alternative Targets

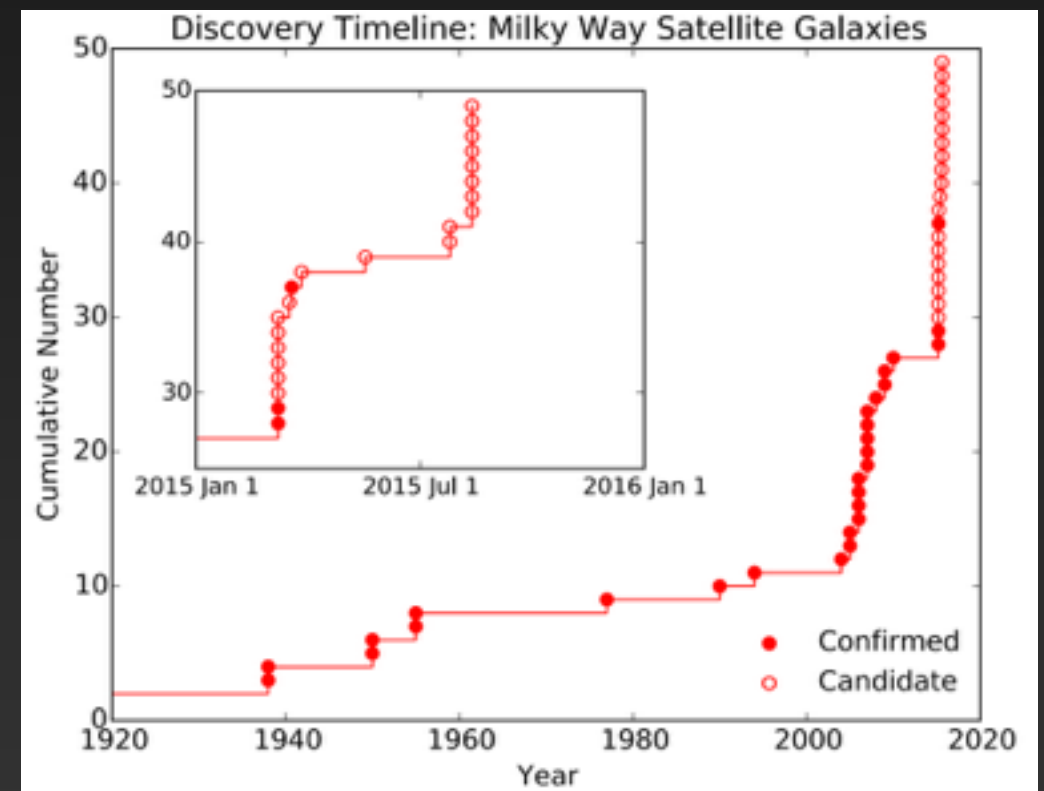


The Dark Energy Survey is likely to greatly improve the detection of dwarf spheroidal galaxies in the Southern Hemisphere. Future limits may improve drastically if nearby dwarfs are discovered.

Alternative Targets



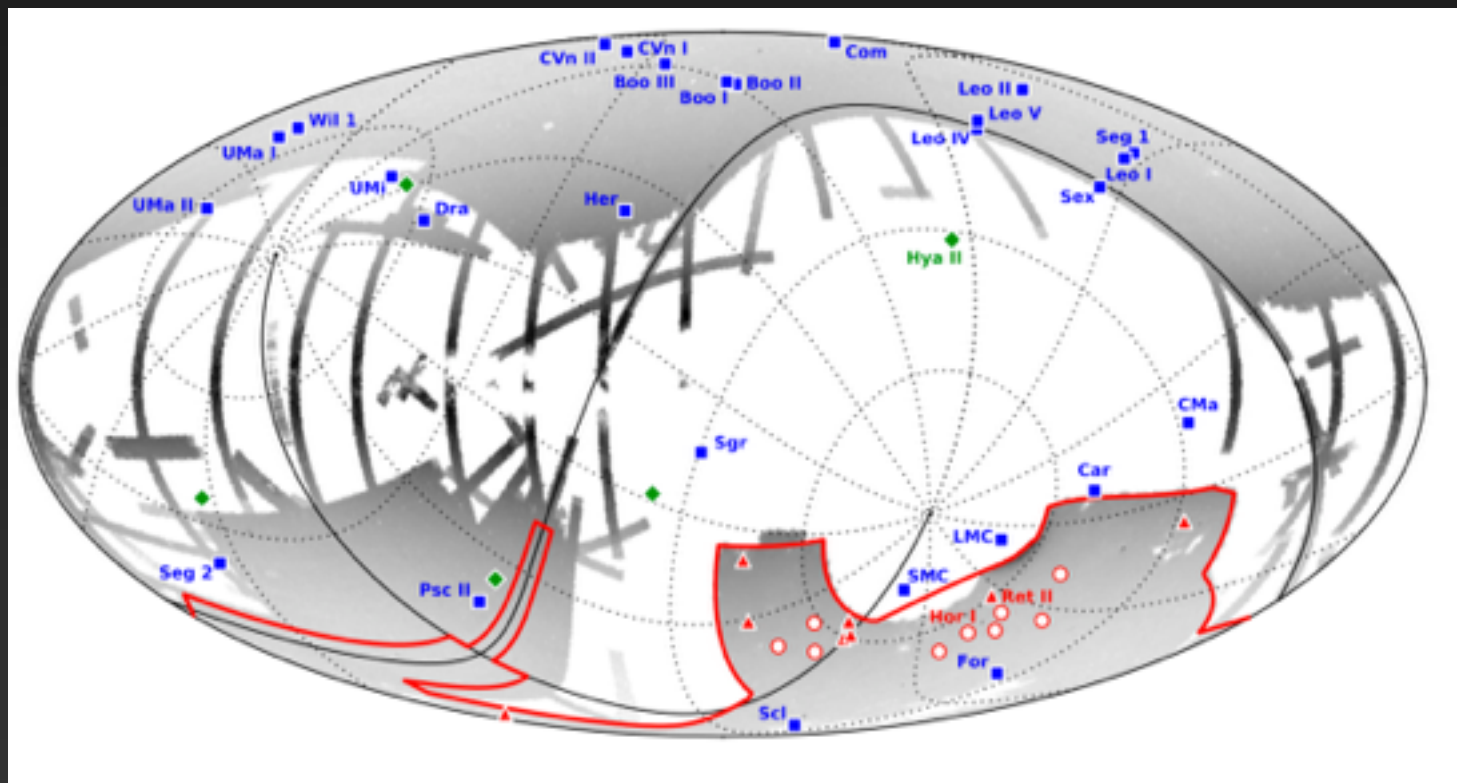
Analyses of the DES, and Pan-Starrs Data have recently observed 19 (and counting) new dwarf candidates in the Southern Hemisphere.



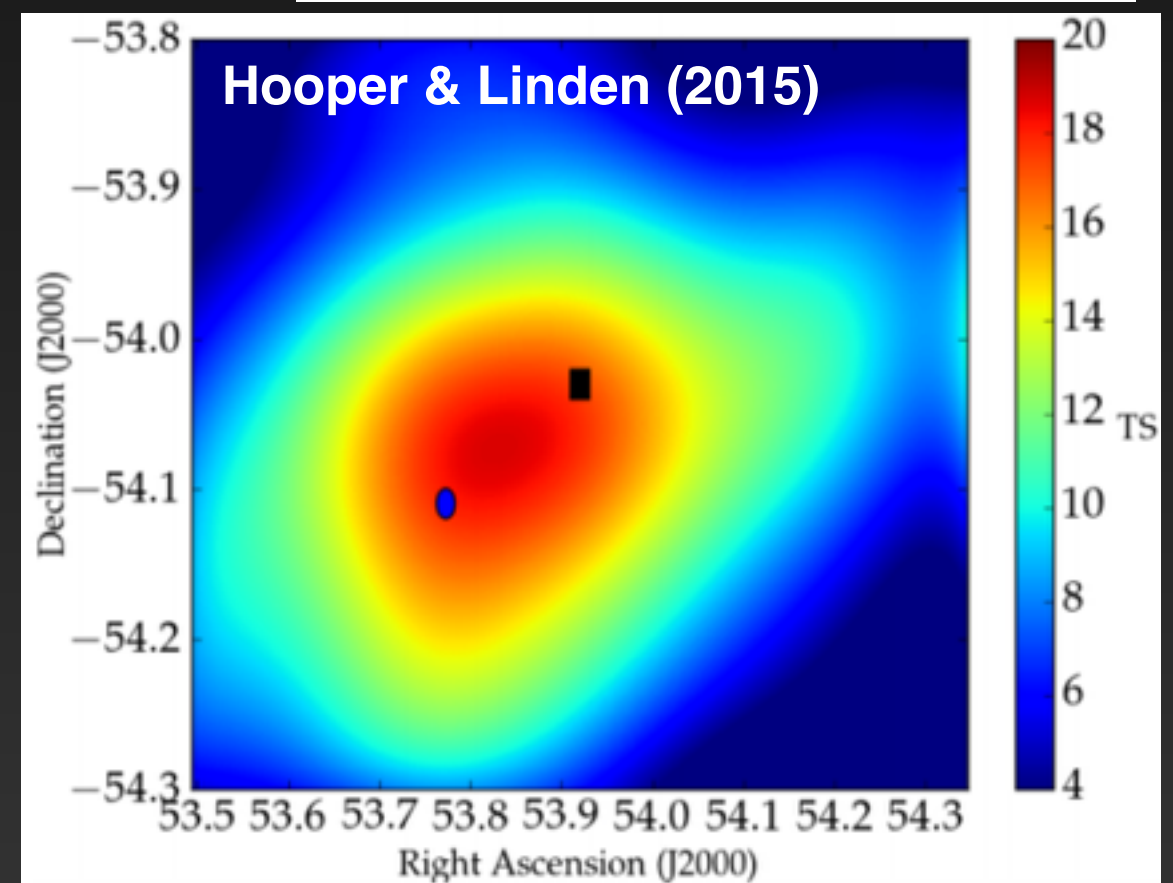
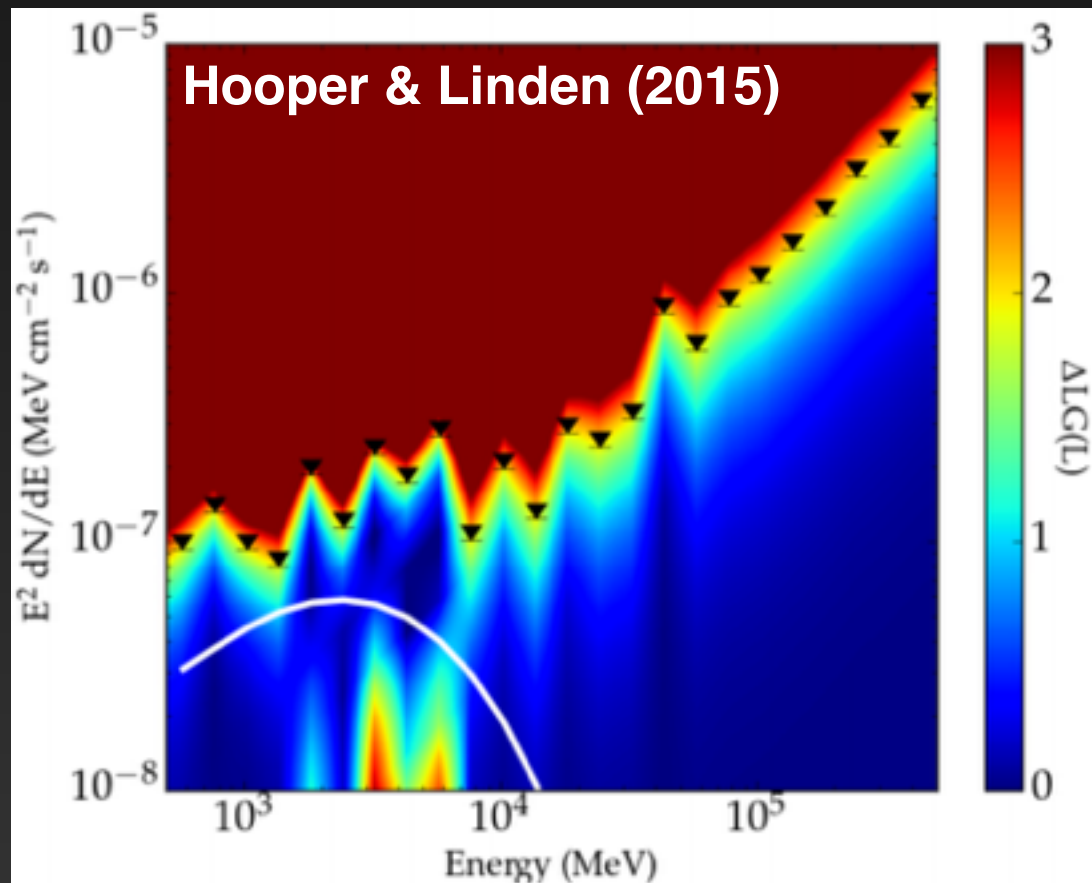
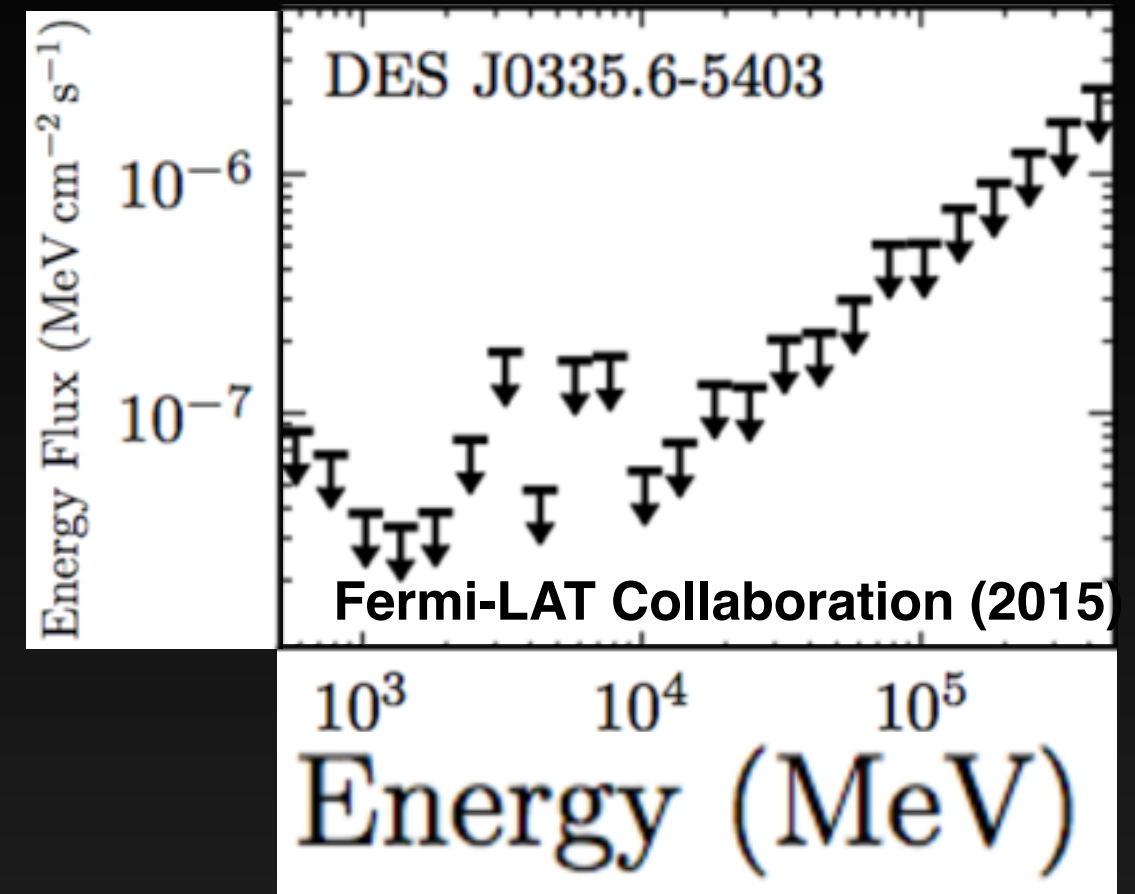
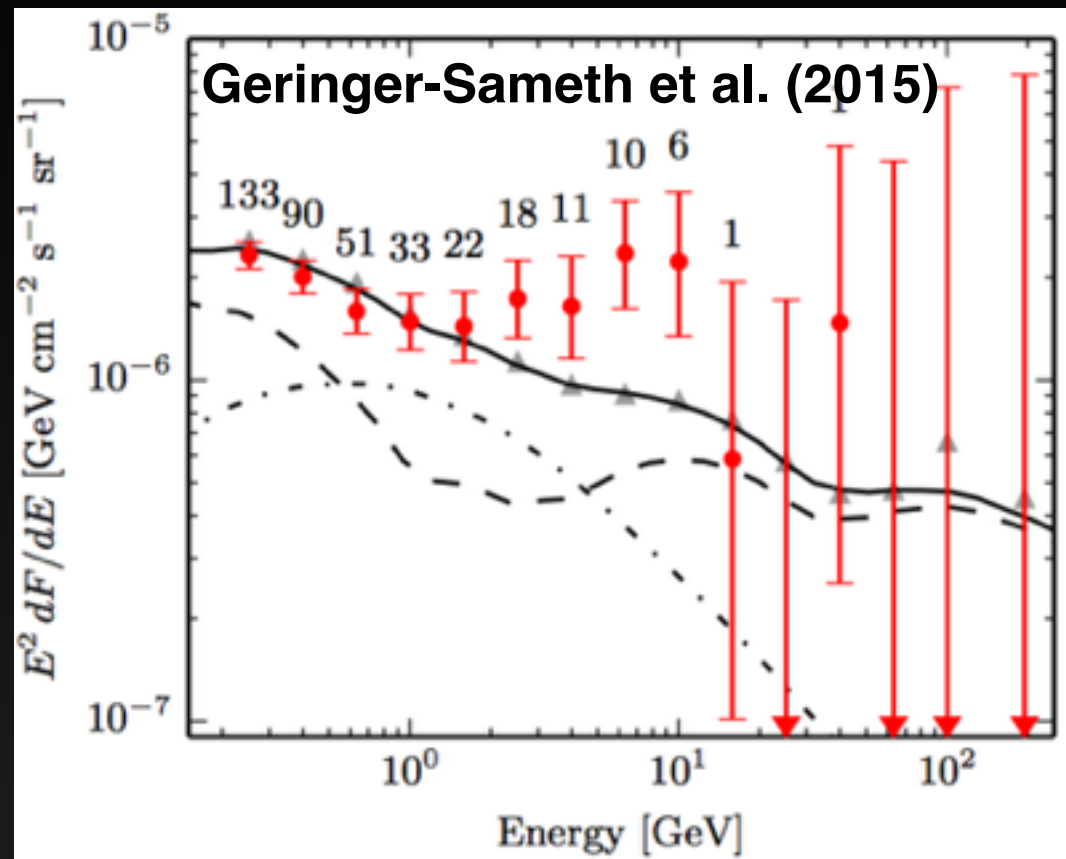
Alternative Targets



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



Reticulum 2 has an excess!



Reticulum 2 has an excess!

Other potentially bright (and recently discovered) dwarf candidates, such as Triangulum 2, do not show any sign of an excess.

Dark Matter models require that the calculated flux scales linearly with the J-factor of the target dwarf galaxy.

TRIANGULUM II: POSSIBLY A VERY DENSE ULTRA-FAINT DWARF GALAXY
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Accepted to ApJL on 2015 November 3

ABSTRACT

We recently discovered Triangulum II, a satellite of the Milky Way. Its Galactocentric distance is only $450 L_{\odot}$. Using Keck/DEIMOS, we measured the radial velocities of six member stars of Triangulum II, and we found a velocity dispersion of $\sigma_v = 5.1^{+4.0}_{-1.4} \text{ km s}^{-1}$. We also observed three stars and found a range of 0.8 dex in $[\text{Fe}/\text{H}]$. The velocity and metallicity of Triangulum II as a dark matter-dominated galaxy. The galaxy is moving very quickly toward the Galactic center, rules out an association with the Triangulum–Andromeda stream. The ellipticity is low, and there is strong evidence for disruption in our data set. The process of being tidally disrupted is possible. The density within the 3-D half-light radius of $3600^{+3500}_{-2100} M_{\odot} L_{\odot}^{-1}$, the highest of any non-disrupted dwarf galaxy in the Local Group — galaxies: abundances. Triangulum II is an excellent candidate for the

years has
globular
Kopos
2015

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.**

Alternative Targets

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

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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

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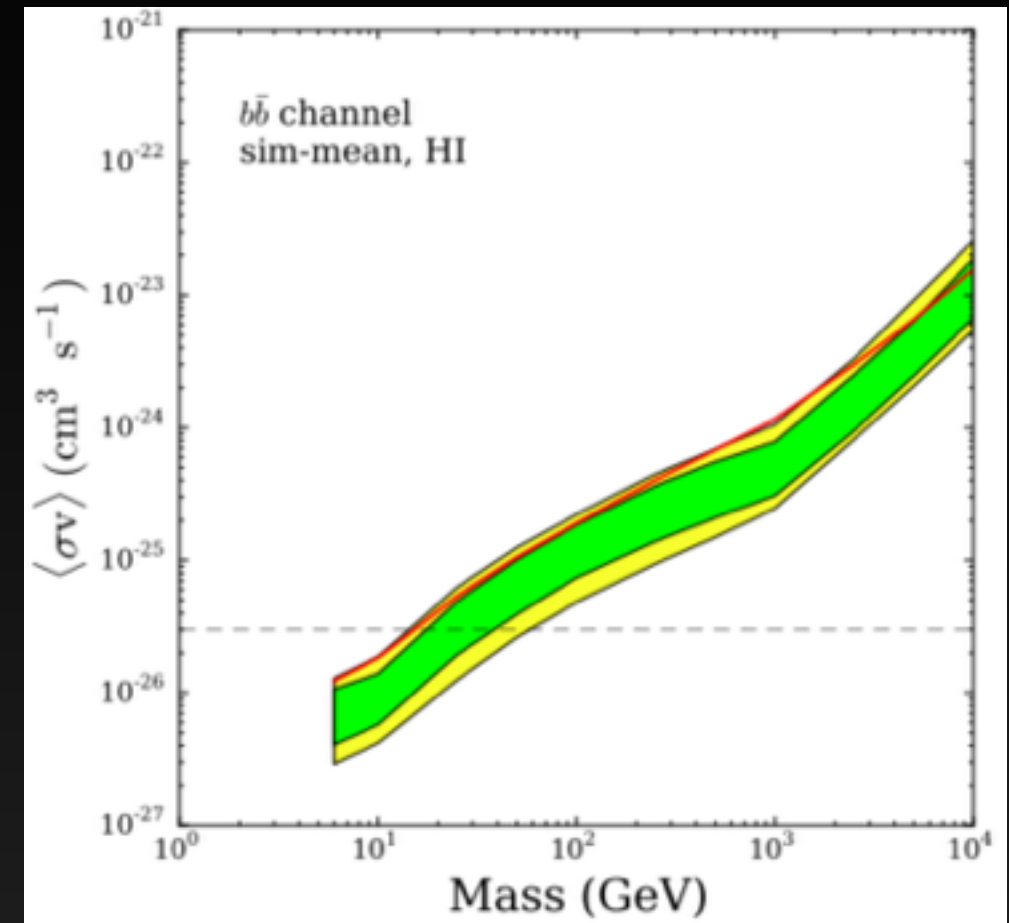
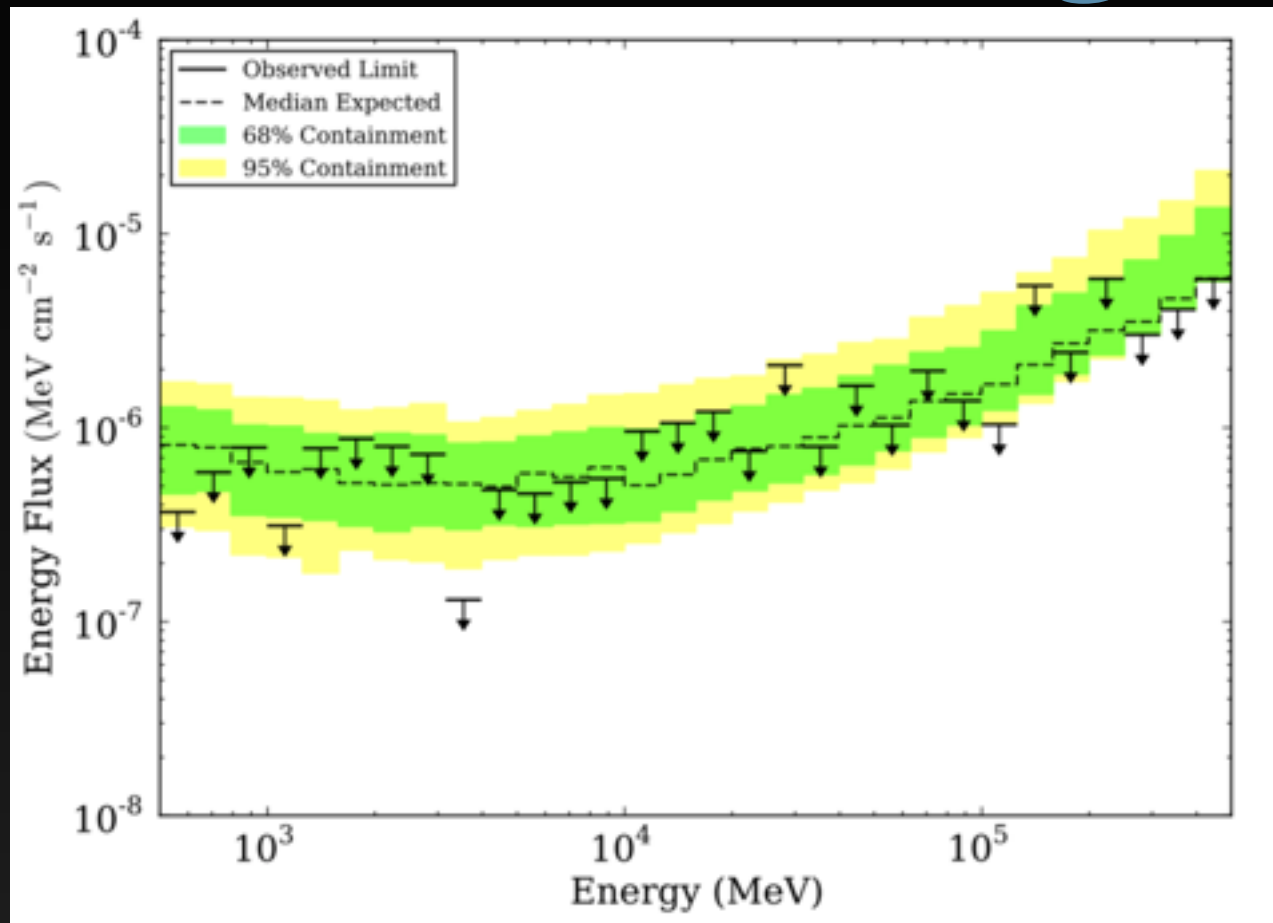
Draft version April 14, 2015

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 spectroscopiers has given us two estimations of the J-factors for Reticulum 2

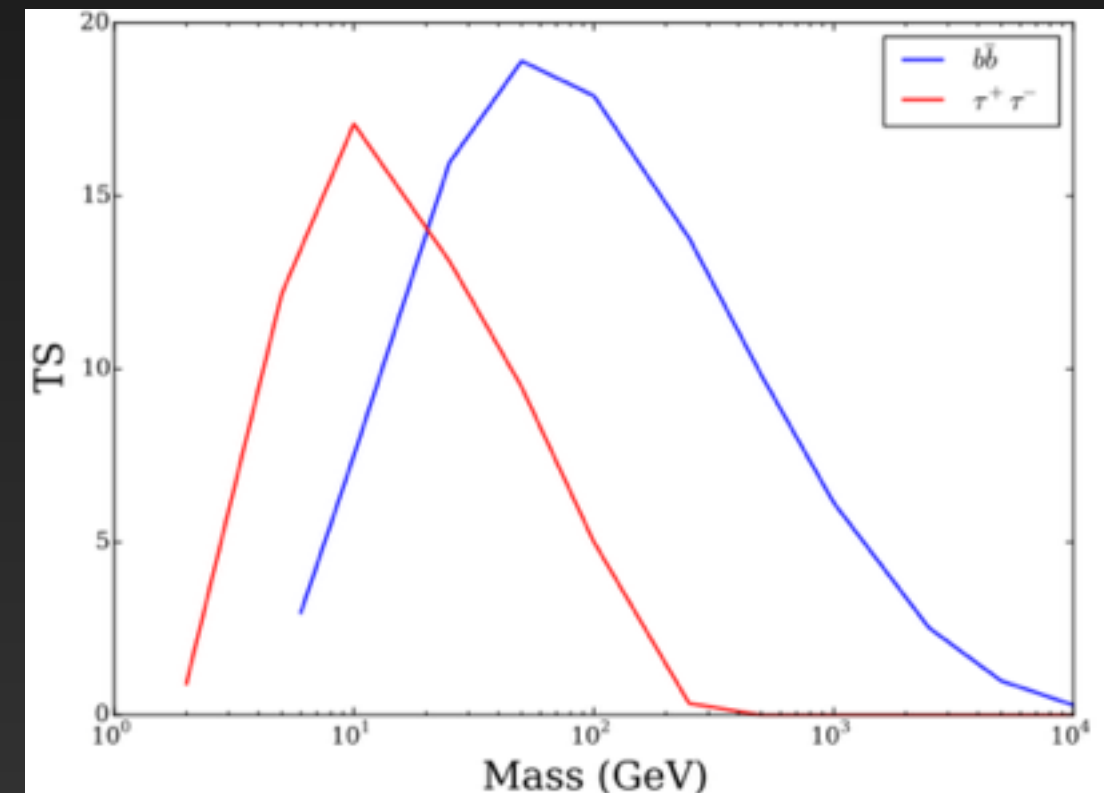
Alternative Targets



The LMC also shows hints of a dark matter excess

However, there are considerable backgrounds here as well.

Buckley et al. (2015)



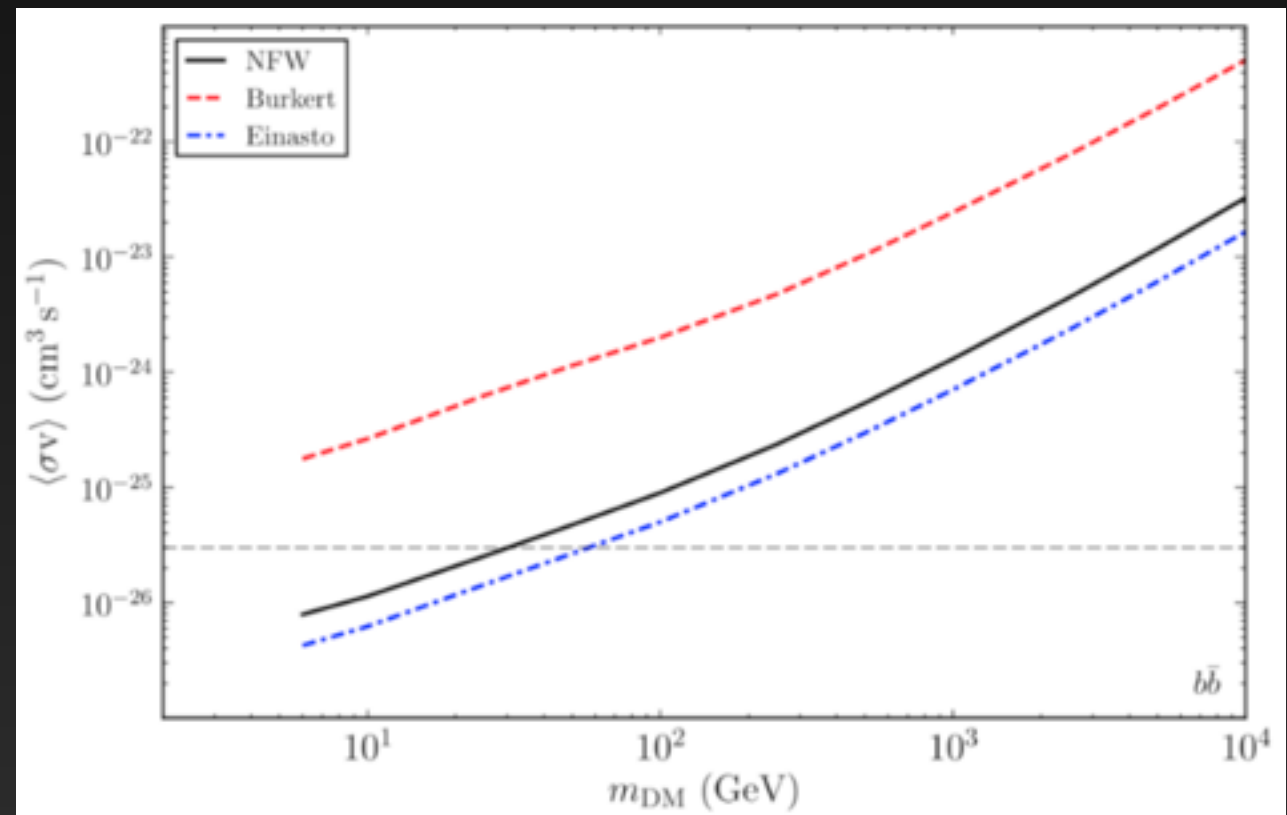
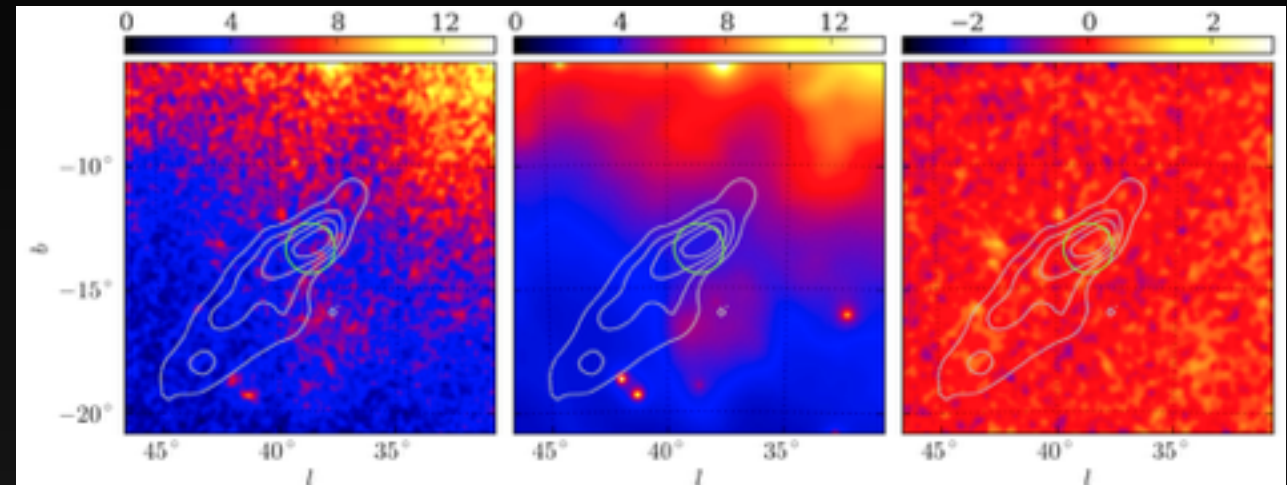
Alternative Targets

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)