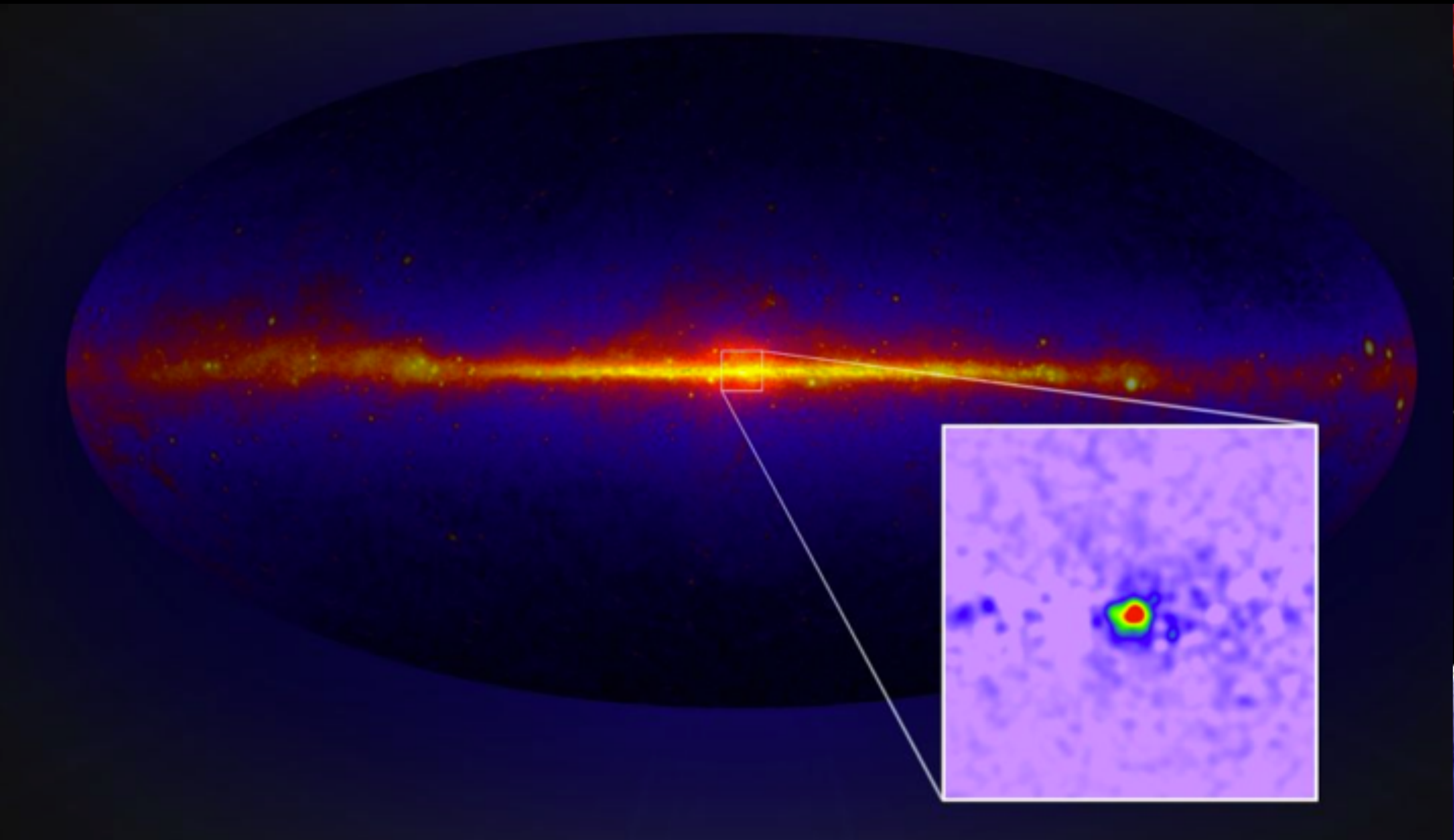


What is the Source of the Galactic Center Gamma-Ray Excess?

Tim Linden

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

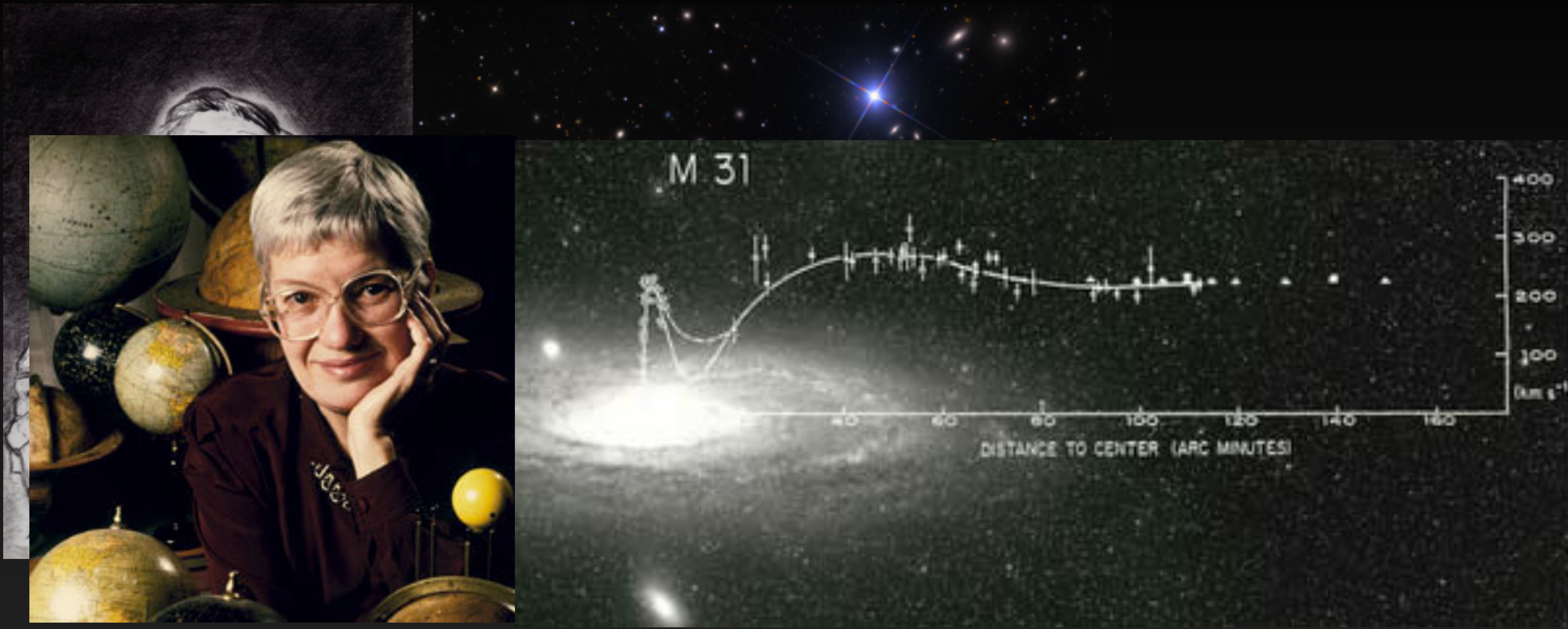
Heidelberg ABHM Workshop

15/12/15

Gravitational Dark Matter

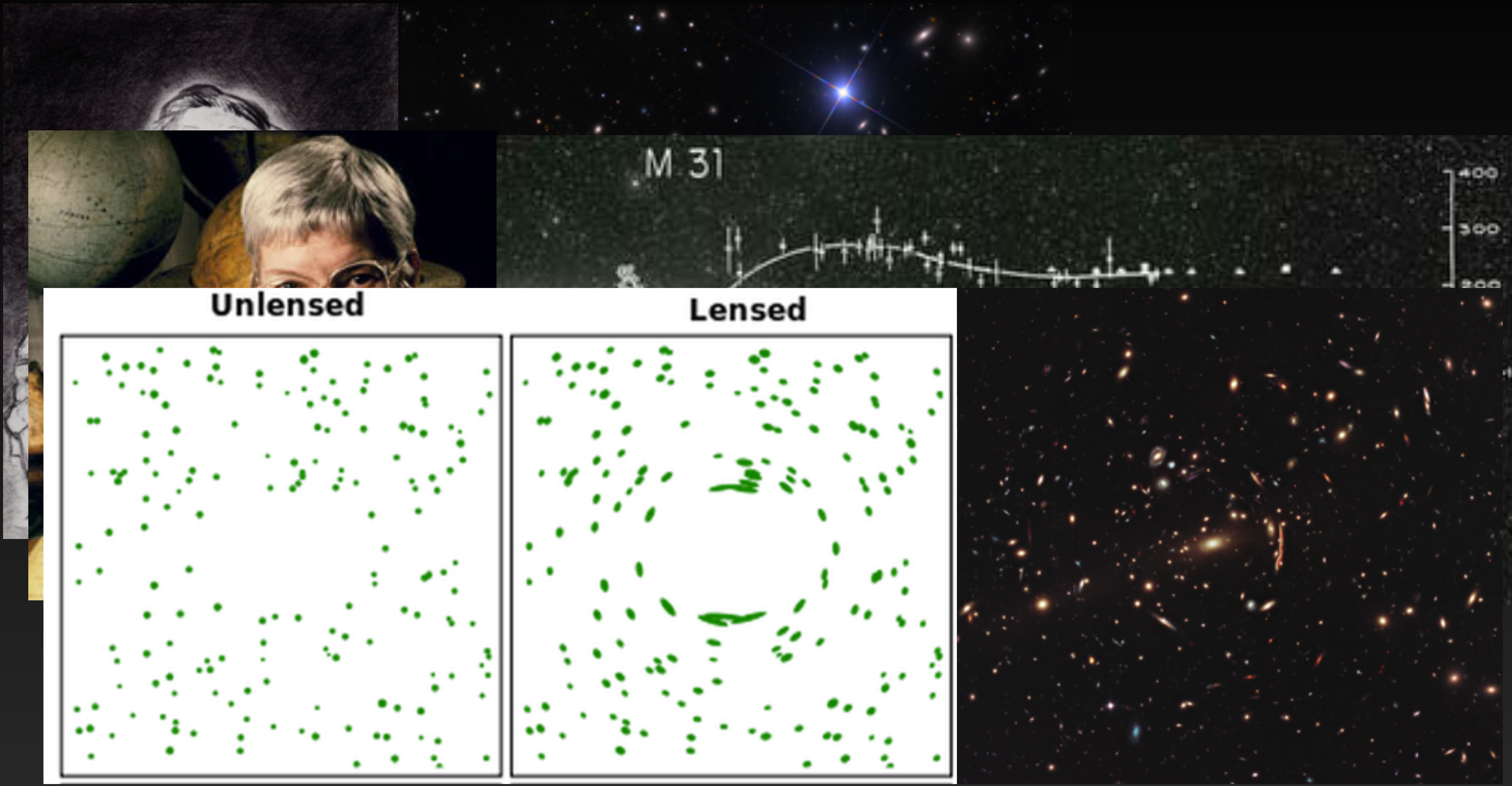
1933: Zwicky observers dark matter in Coma Cluster

Gravitational Dark Matter



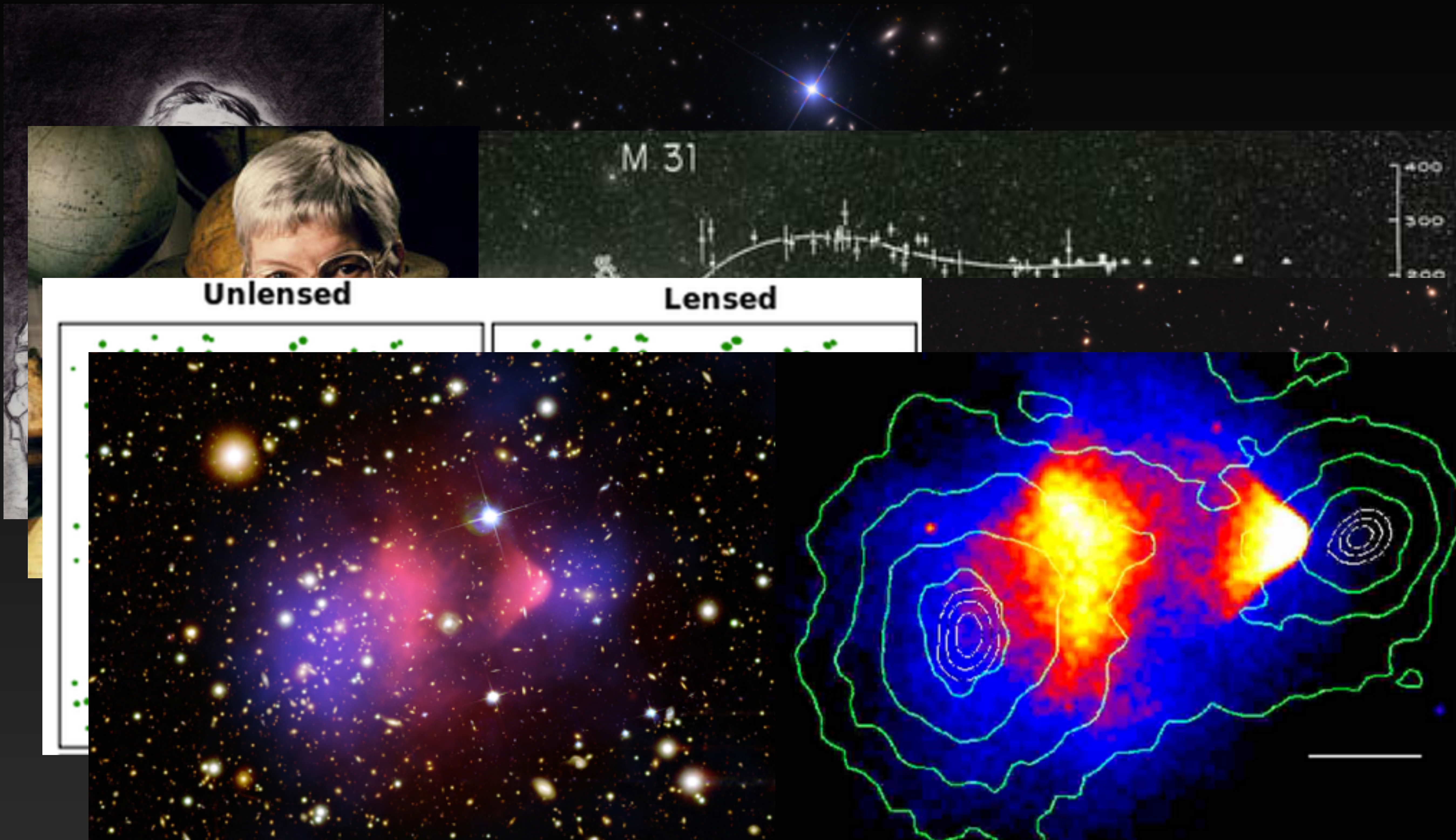
1970s: Vera Rubin observes anomalous rotation velocities in M31

Gravitational Dark Matter



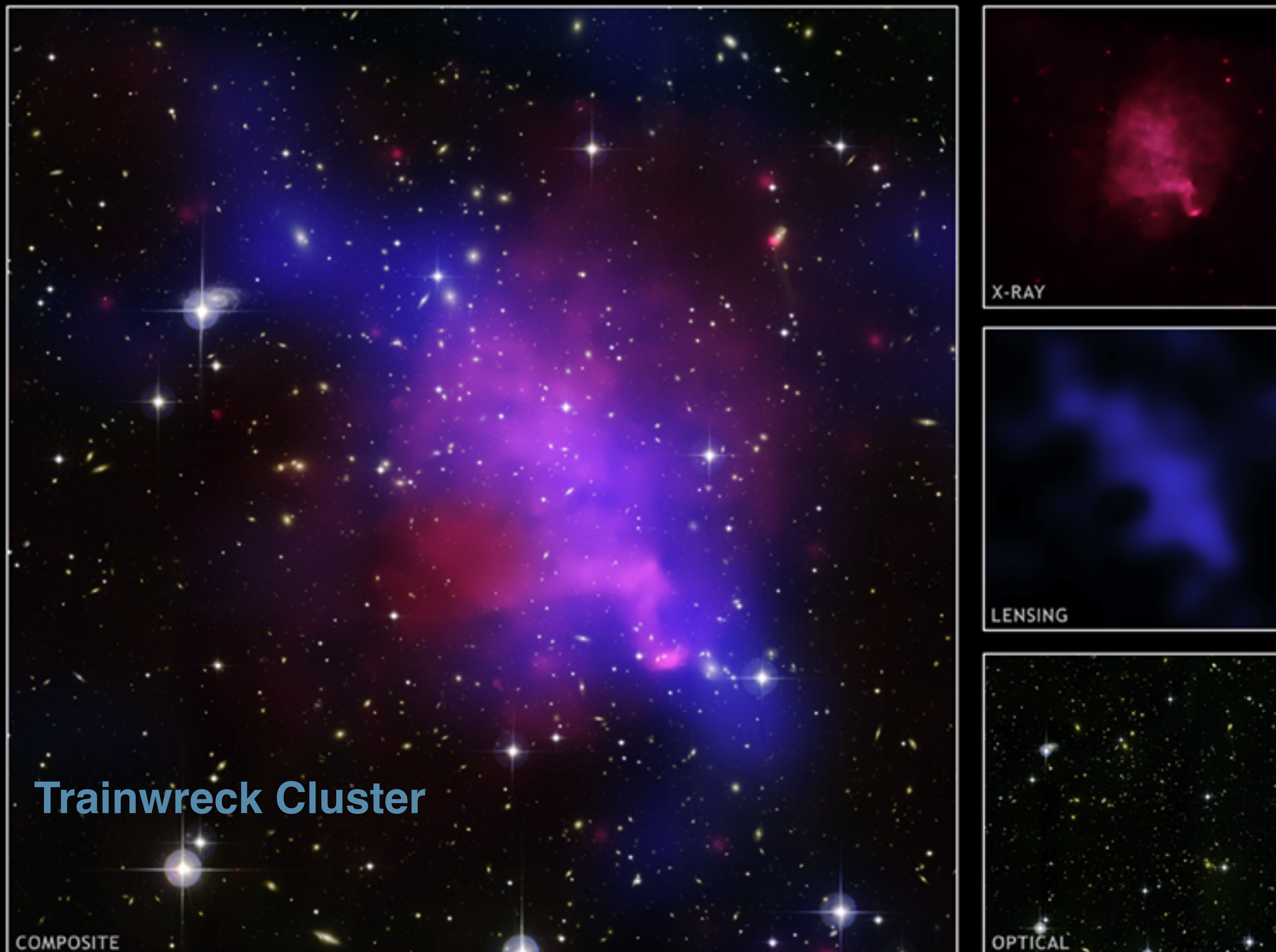
1996: Weak Gravitational Lensing Observed from Dark Matter Halos

Gravitational Dark Matter



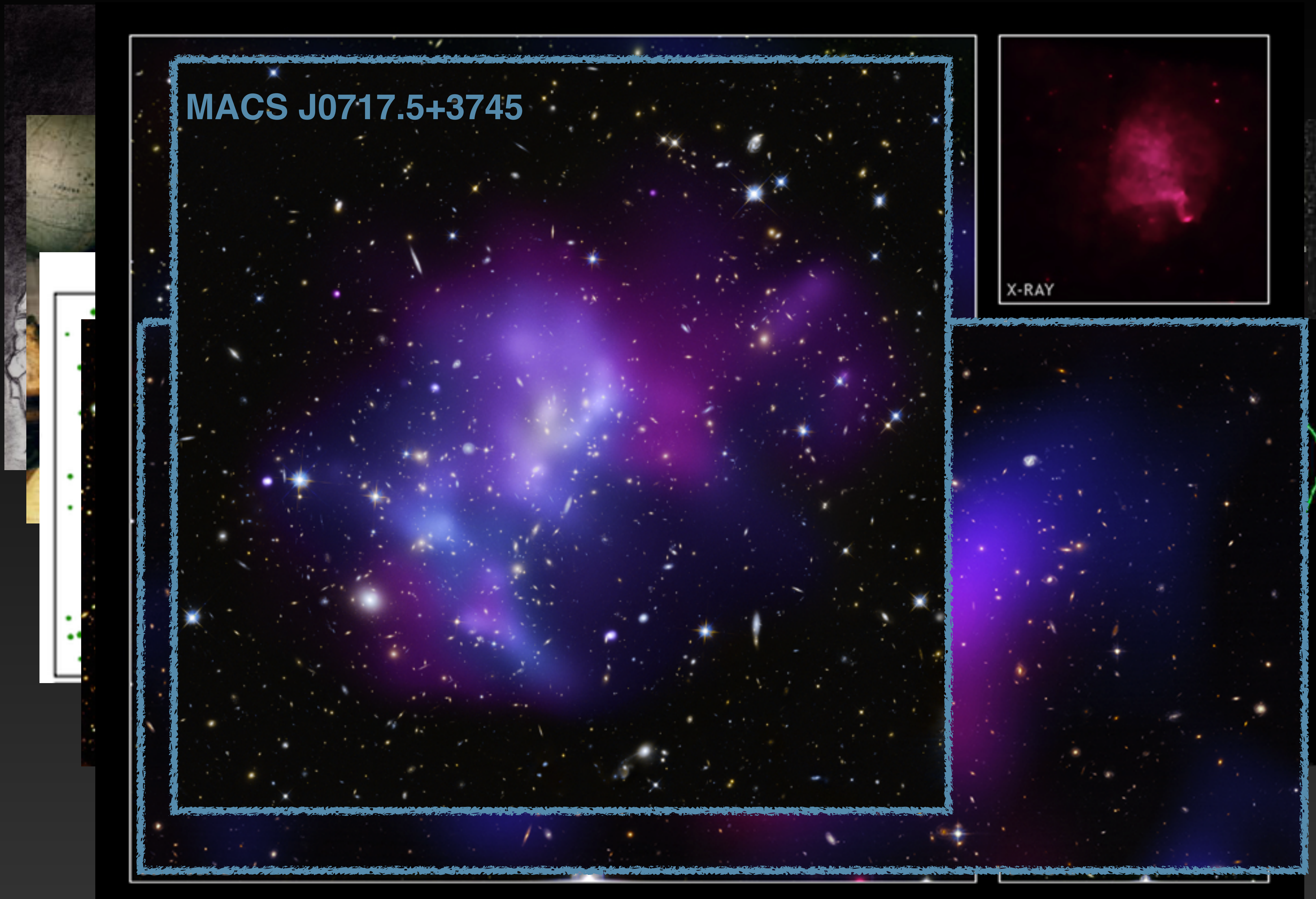
2006: Bullet Cluster Observations Show Offset Between Mass and Hot Gas

Gravitational Dark Matter

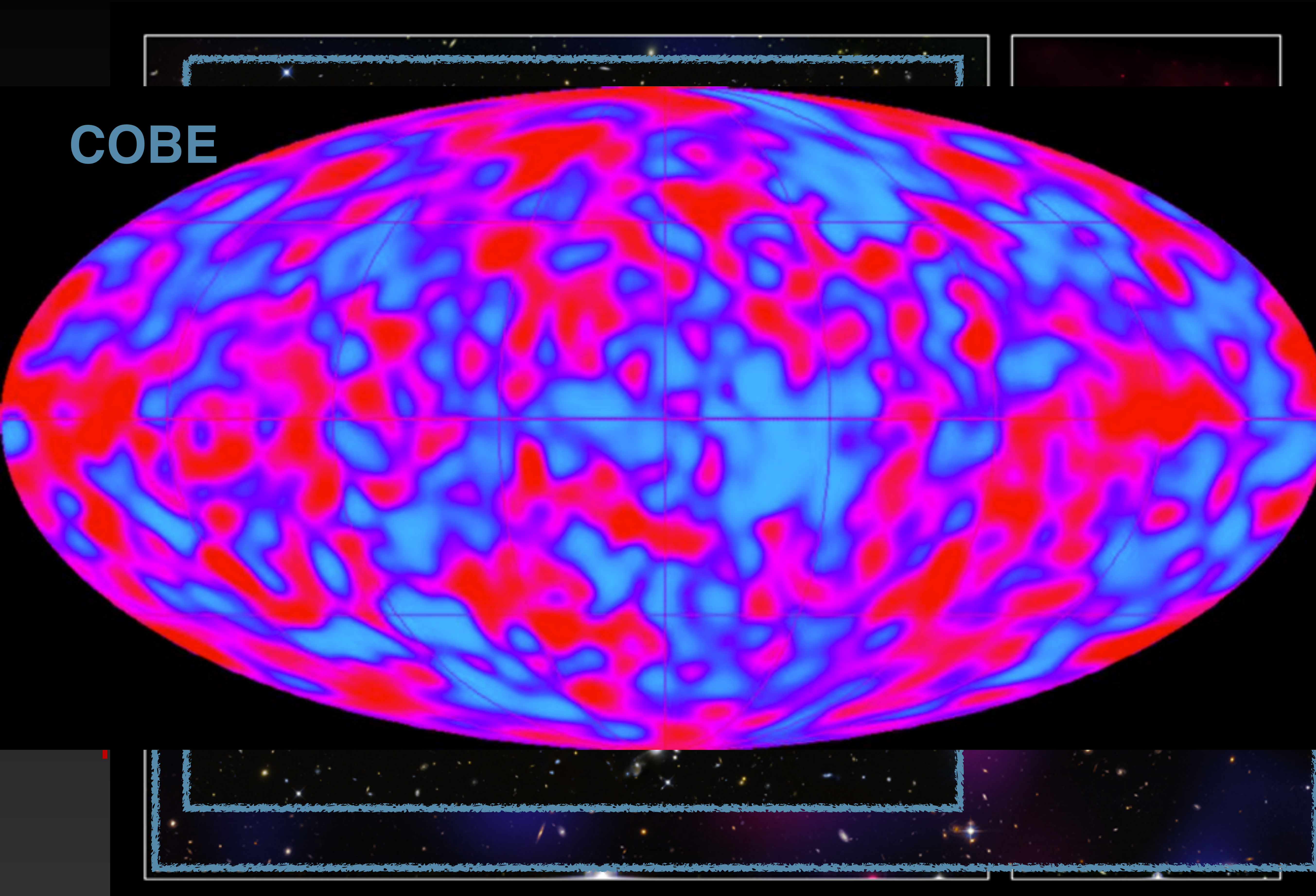


Gravitational Dark Matter

Gravitational Dark Matter



Gravitational Dark Matter



Gravitational Dark Matter

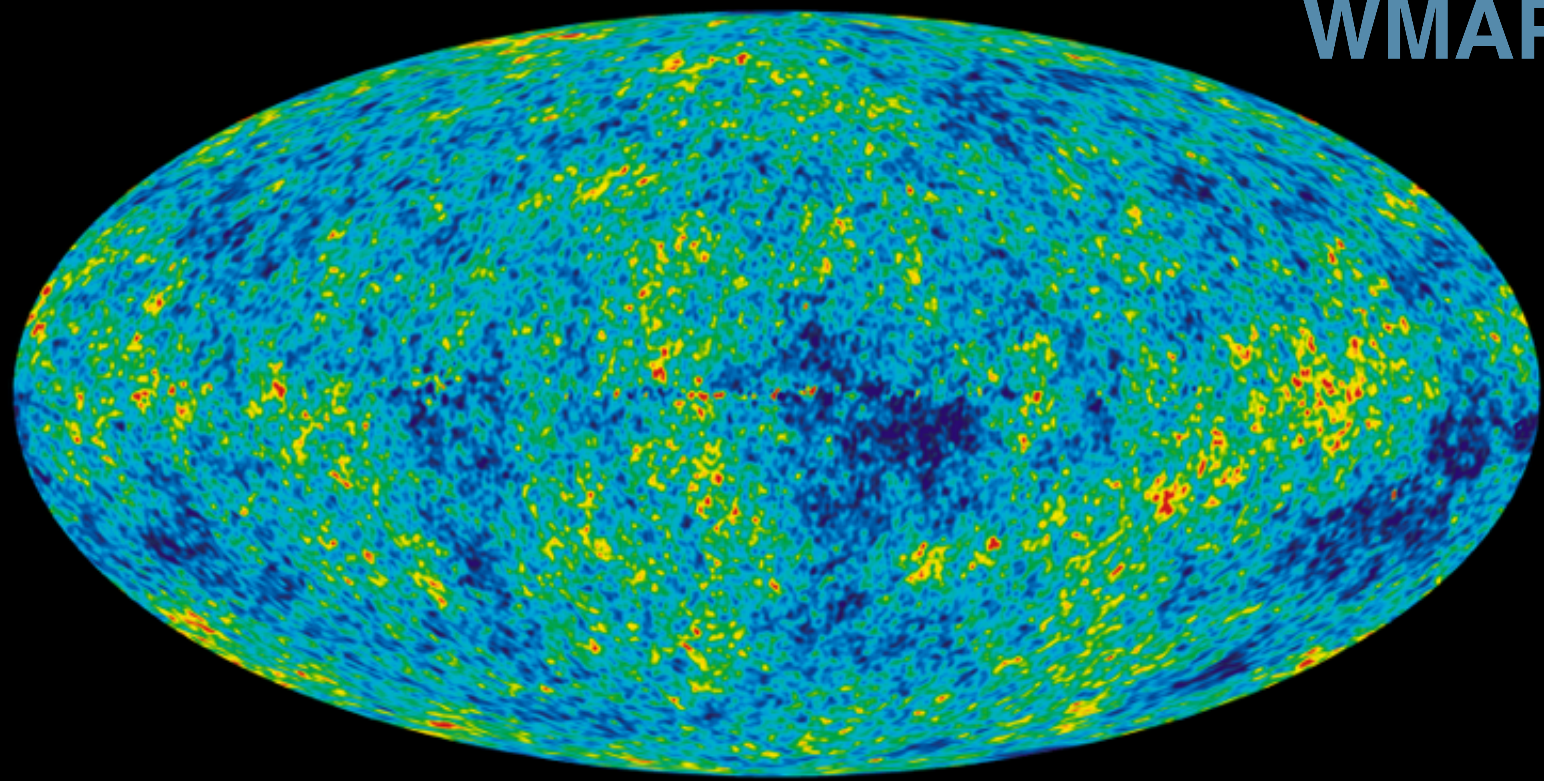
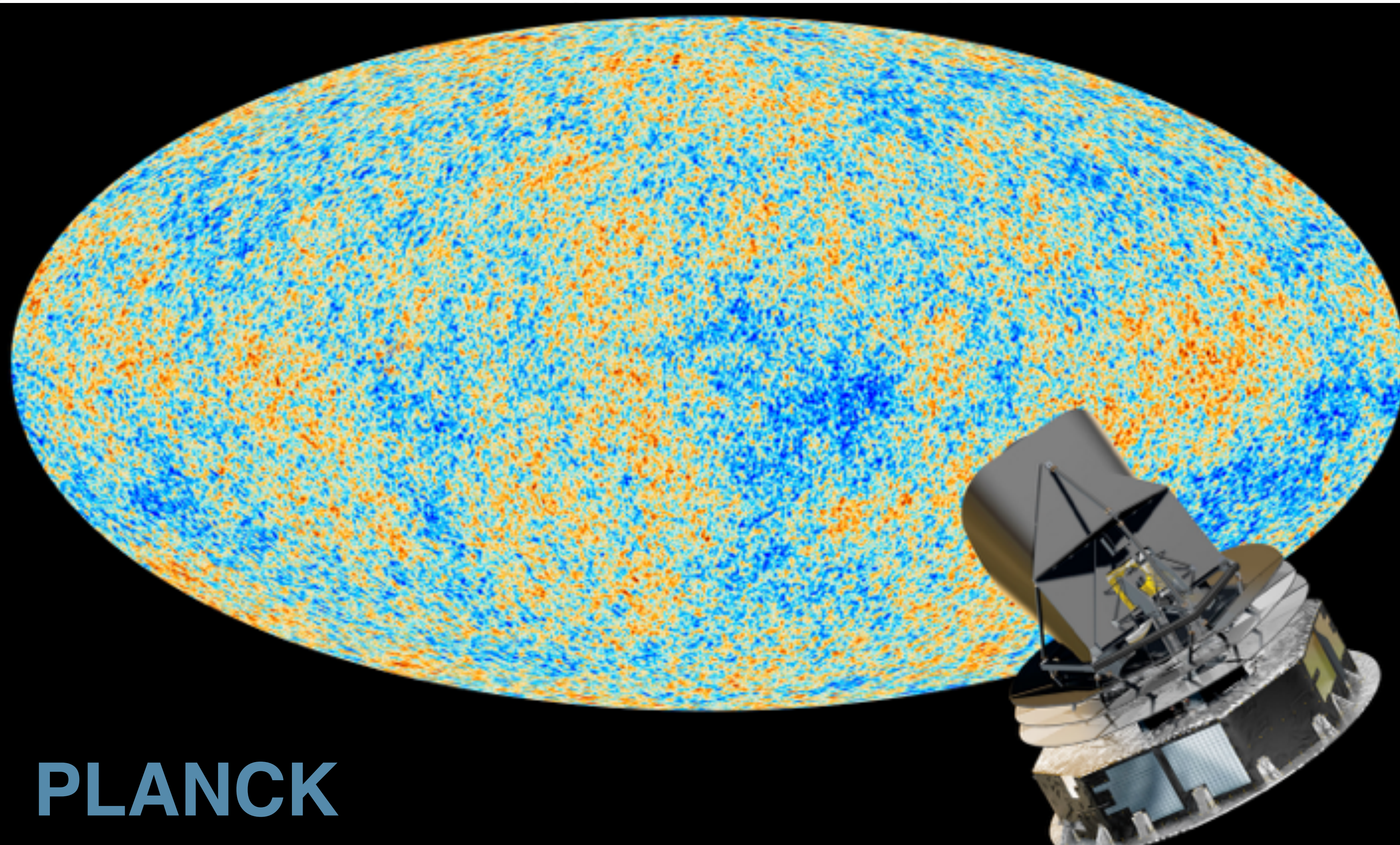


Table 6. Cosmological Parameter Summary

Description	Symbol	WMAP-only
Parameters for Standard ΛCDM 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

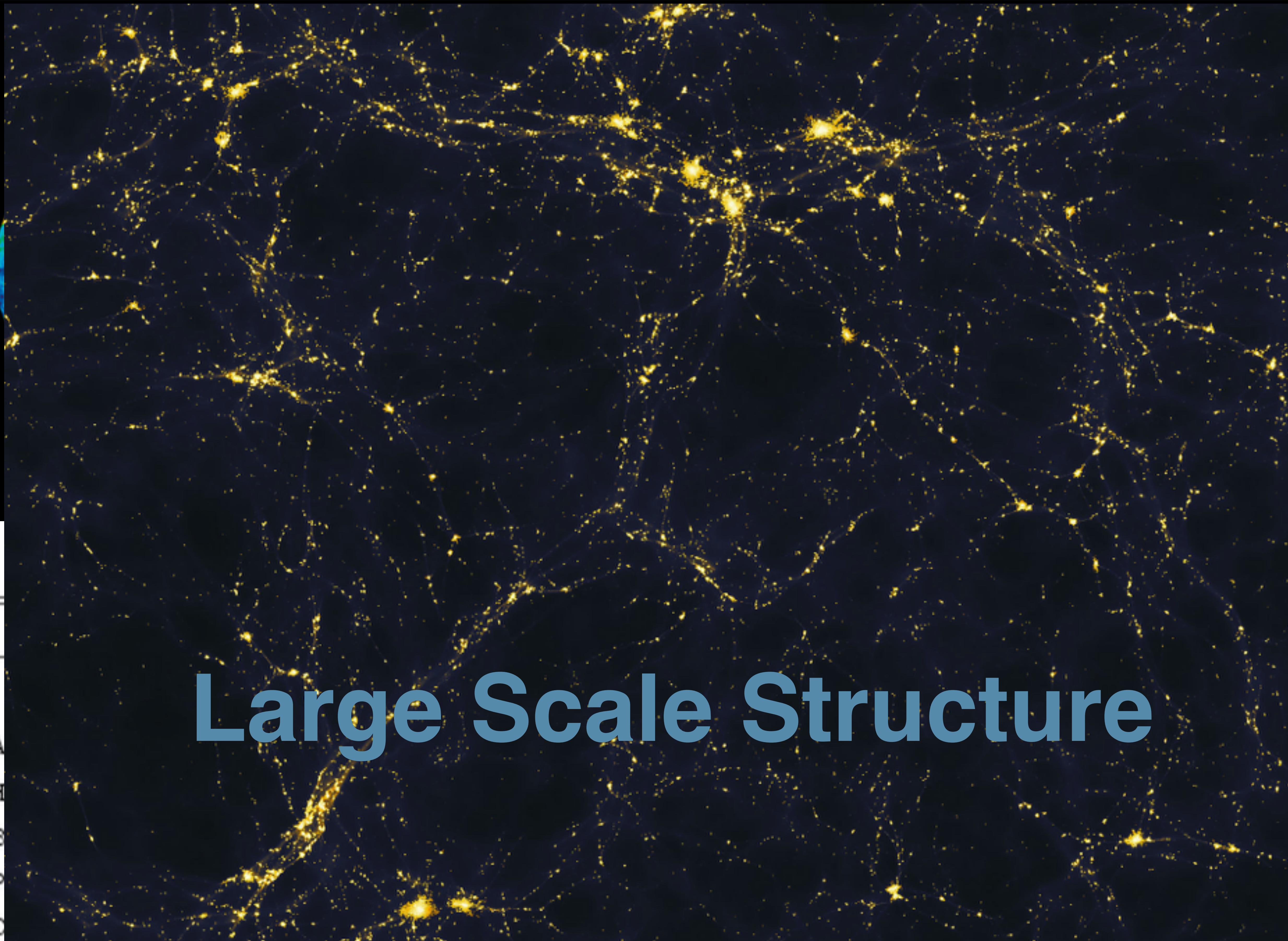
Gravitational Dark Matter

Parameter	*Planck* Best fit	*Planck* 68% limits	*Planck*+lensing Best fit	*Planck*+lensing 68% limits	*Planck*+WP Best fit	*Planck*+WP 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

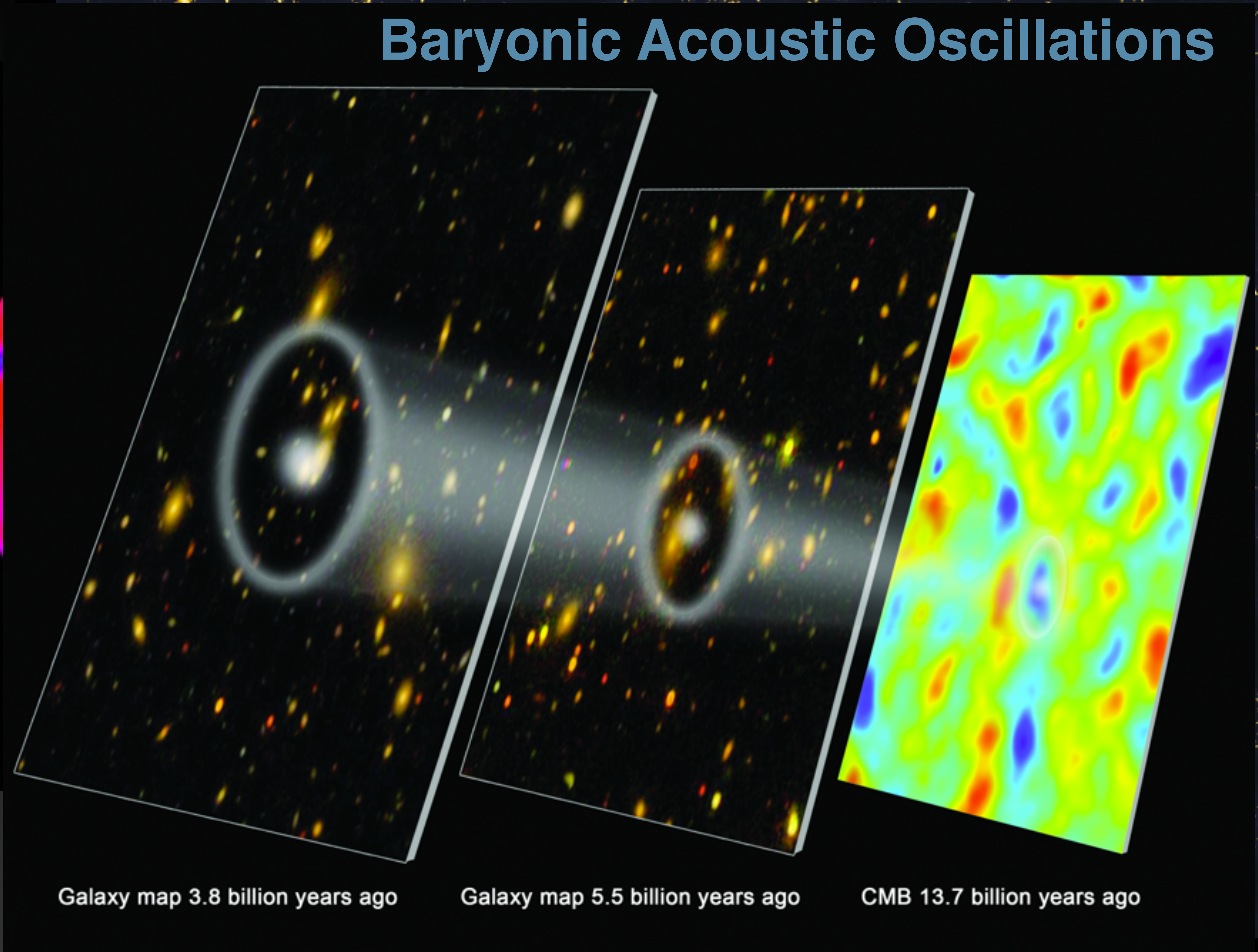


PLANCK

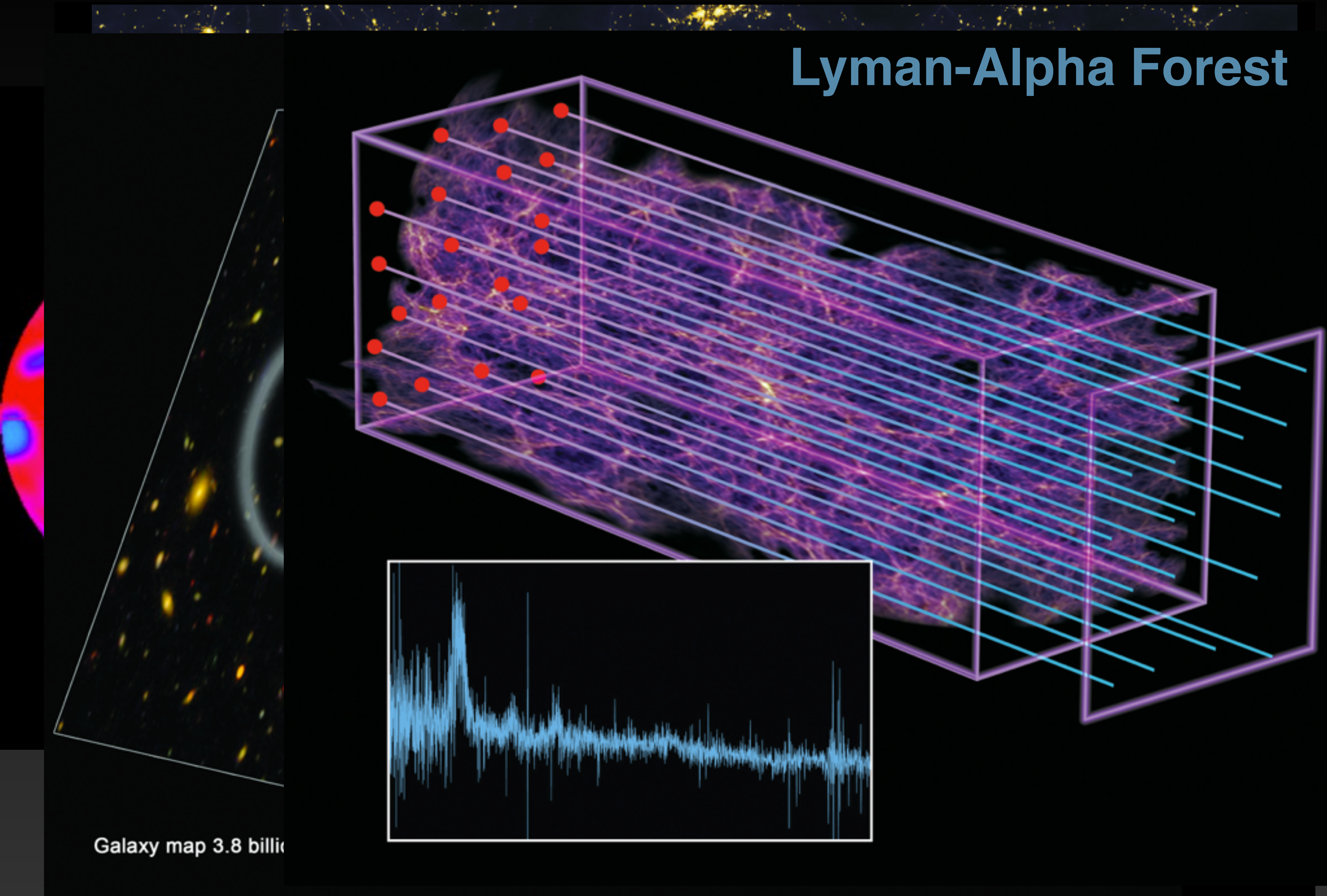
Gravitational Dark Matter



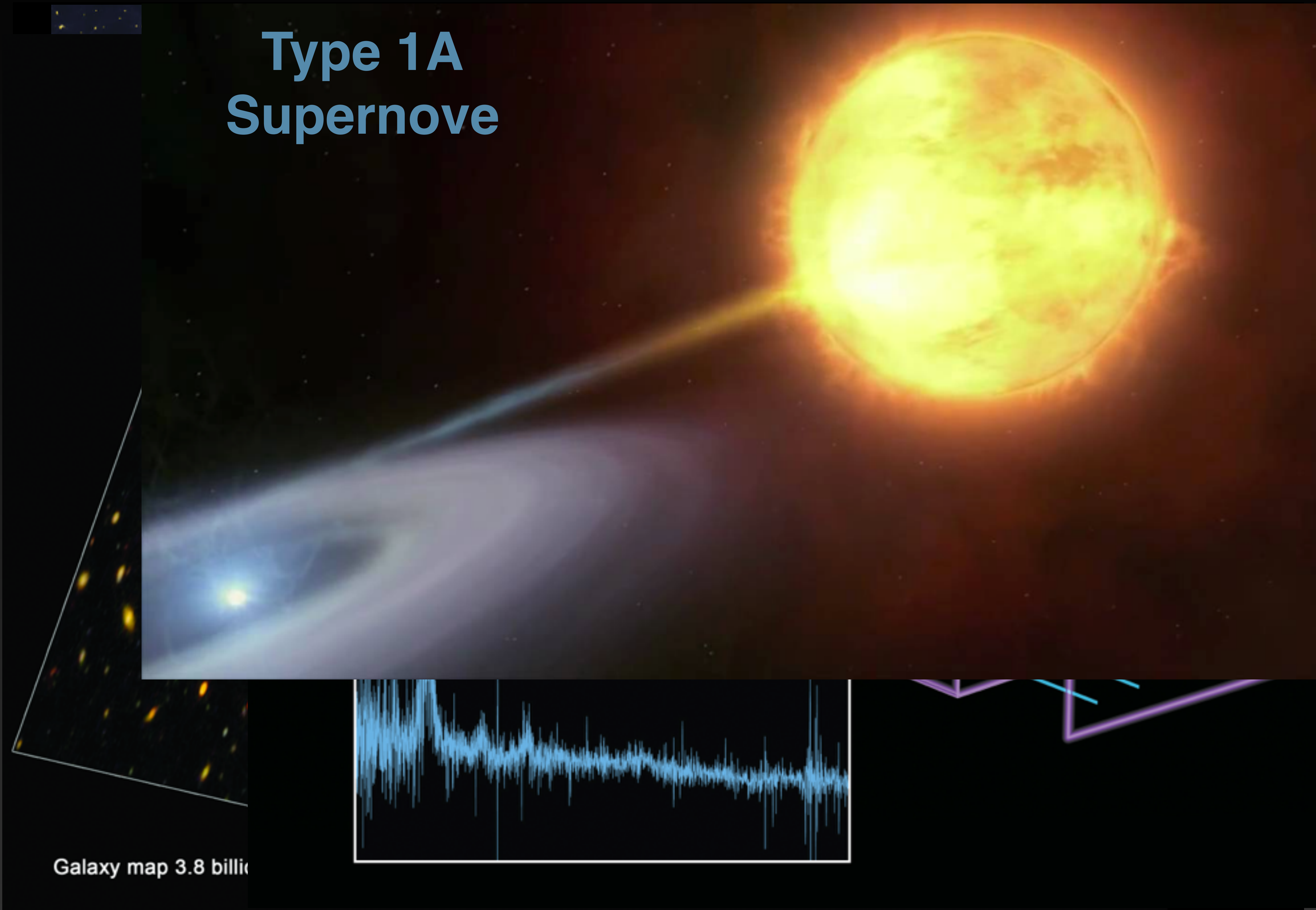
Gravitational Dark Matter



Gravitational Dark Matter



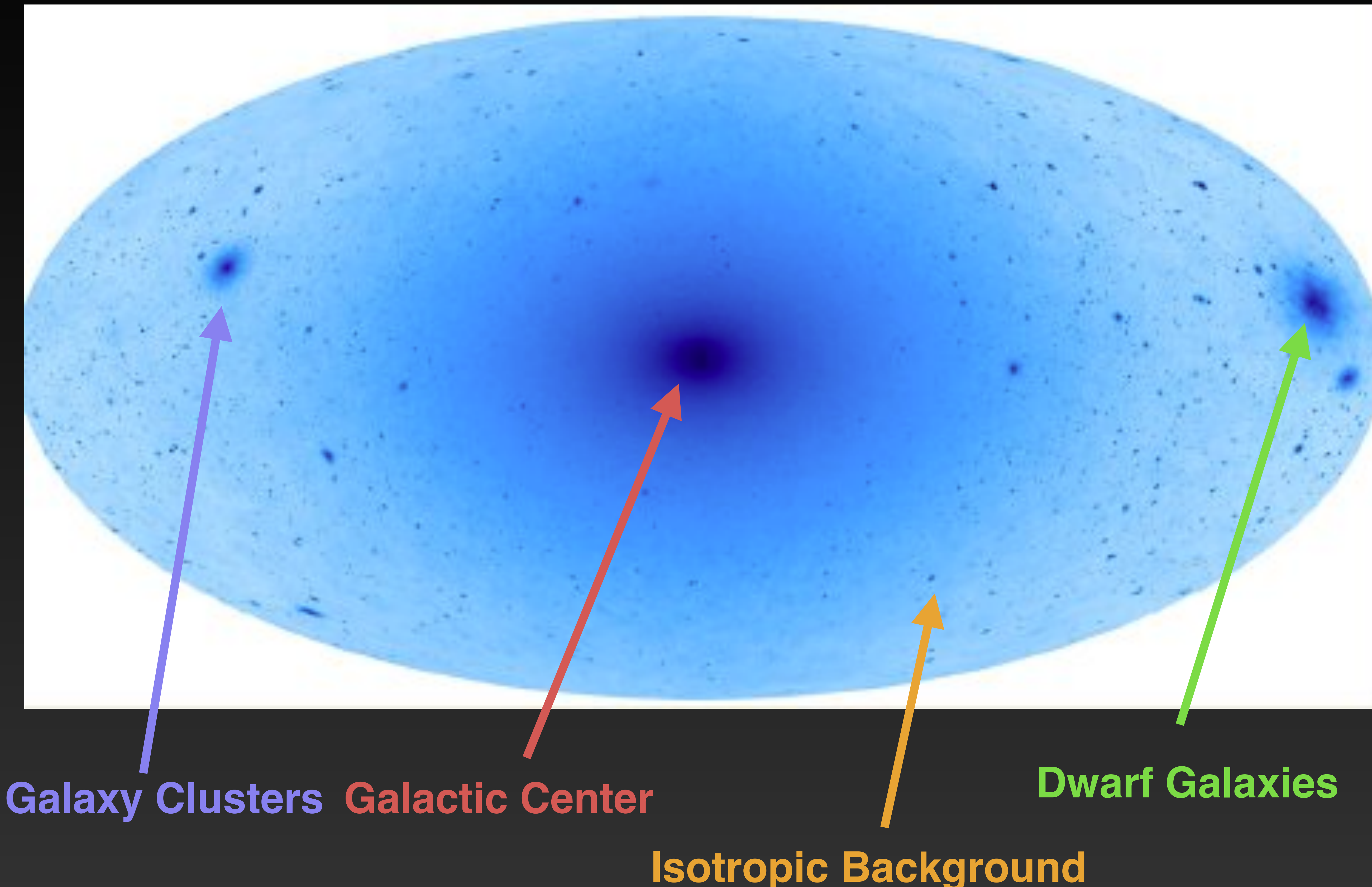
Gravitational Dark Matter



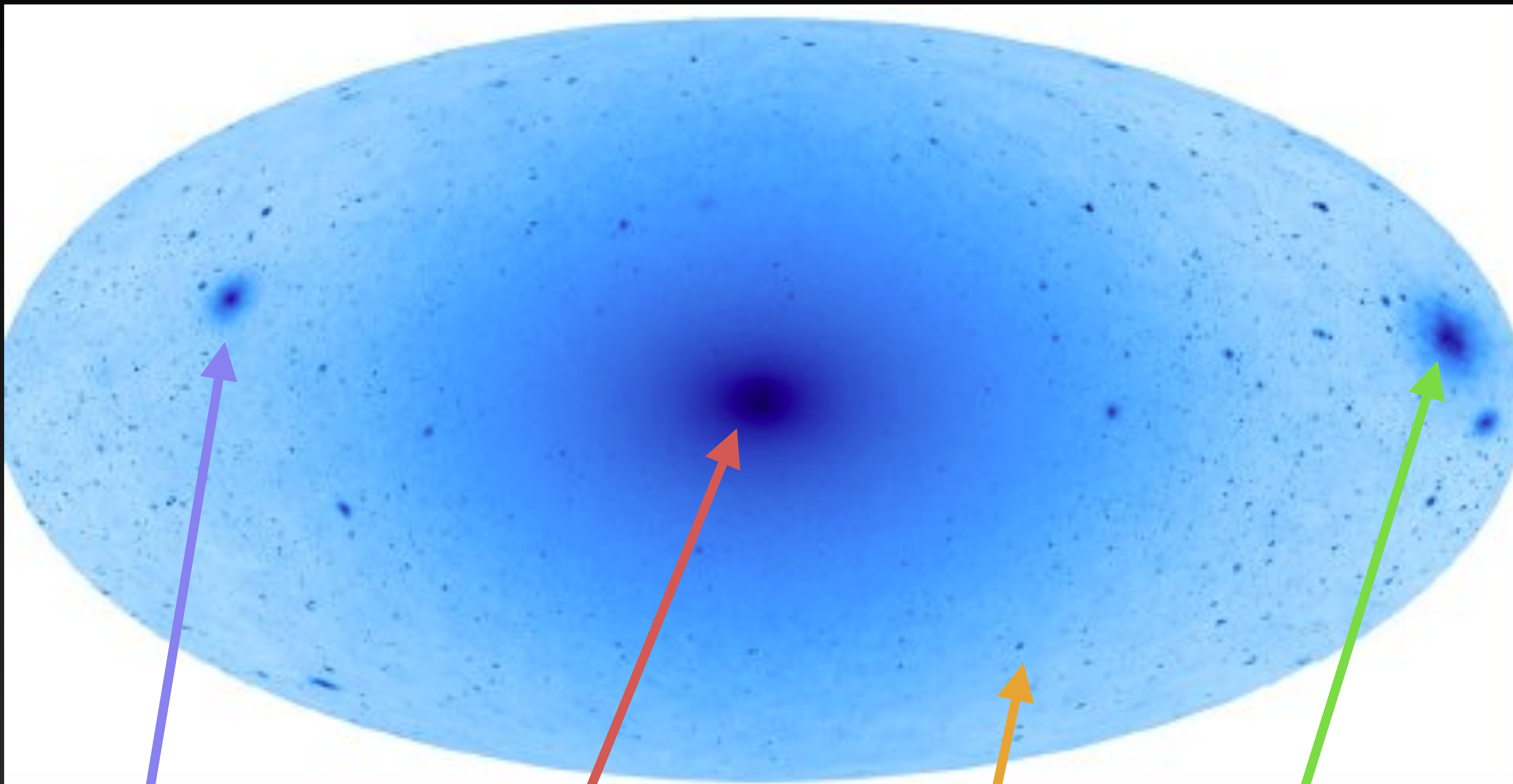
Astrophysical Dark Matter

Astrophysics not only tells us that dark matter exists — but also where to look.

Where to Observe Dark Matter



Where to Observe Dark Matter



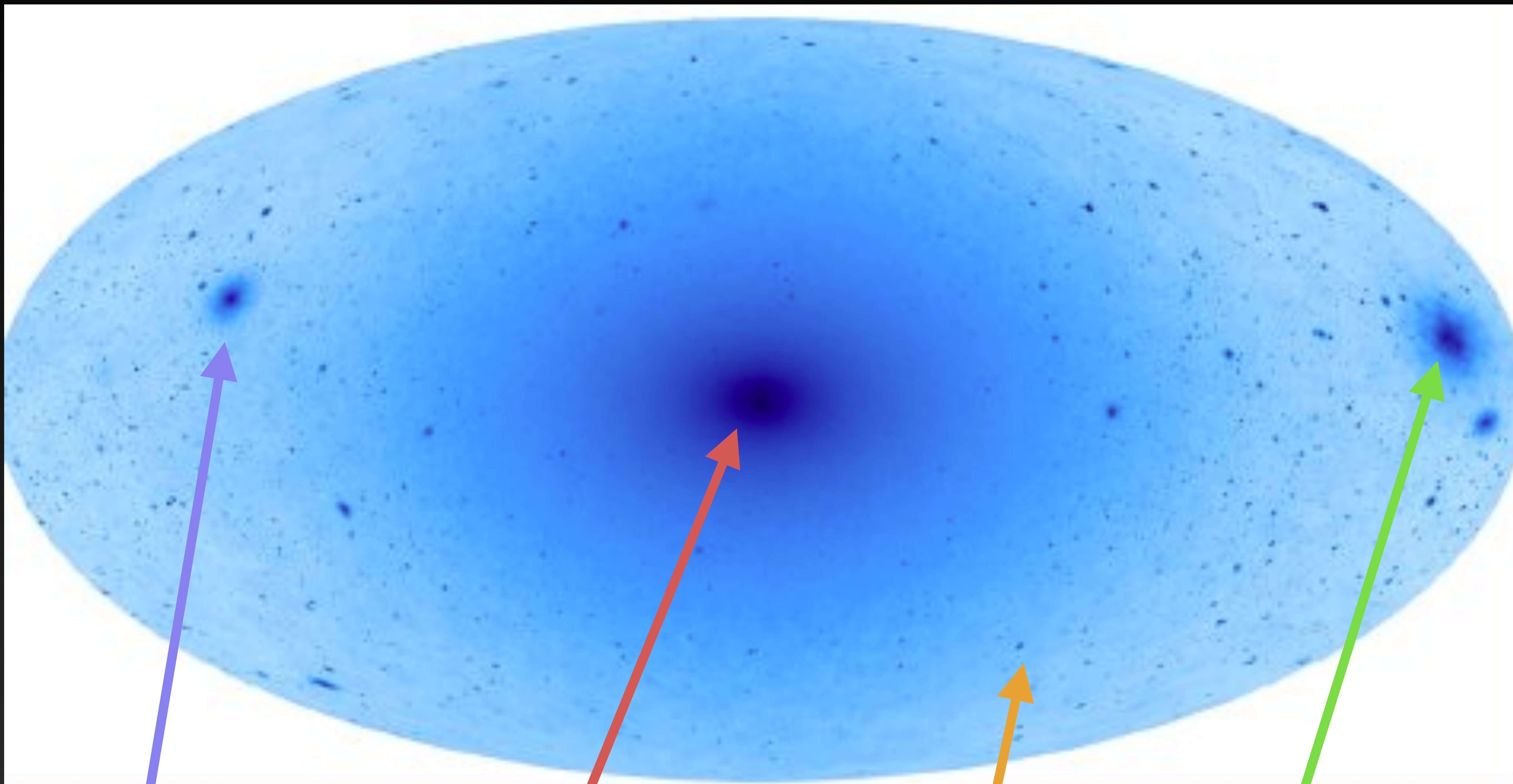
Backgrounds Unknown
Smaller signal

High Signal
High Background

Large Signal
Background depends on halo formation history

Low background
Low signal

Where to Observe Dark Matter



Exposure

Astrophysical emission models

Halo Formation History
Models of Astrophysical Anisotropy

Exposure

Where: Galactic Center

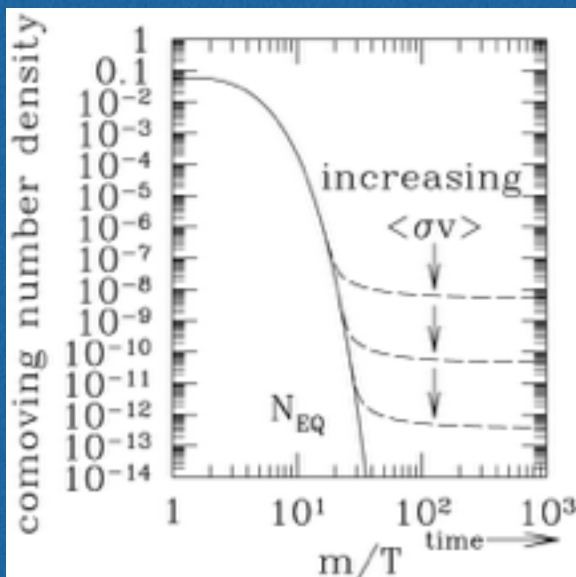
$$\rho_{NFW} = \left(\frac{r}{r_s}\right)^{-\gamma}\left(1+\frac{r}{r_s}\right)^{-3+\gamma}$$

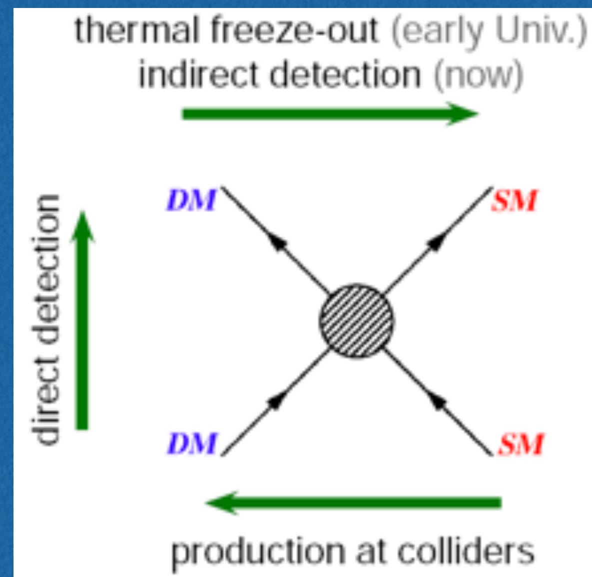
For the remainder of this talk, we employ a simple analytical model, known as the “generalized NFW Profile” which provides a reasonable fit to the observed dark matter density distribution of dark matter halos.

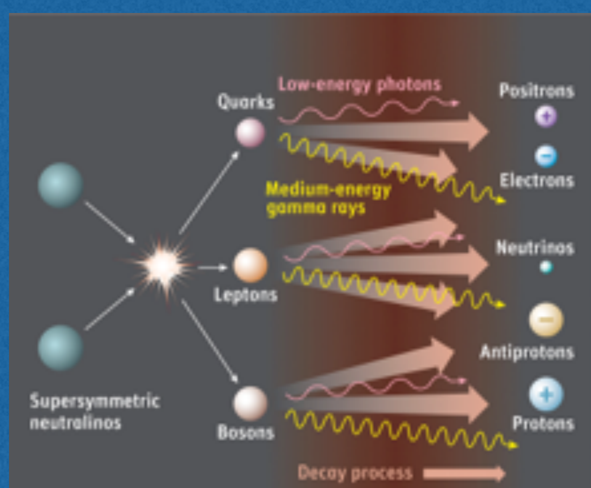
In the standard NFW scenario, $\gamma = 1$

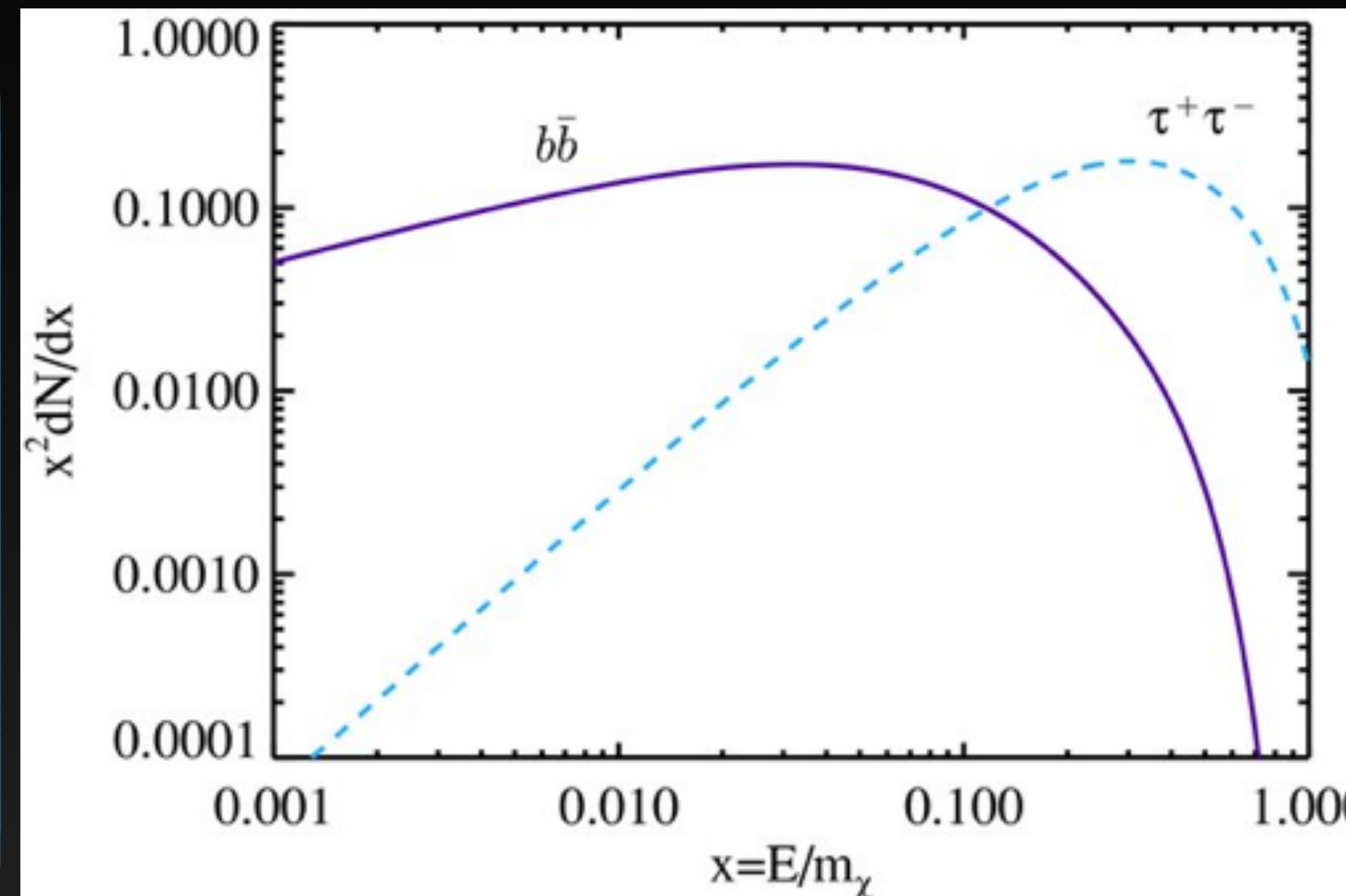
Navarro, Frenk, White (1996)
Springel et al. (2008, 0809.0898)

What: Gamma-Rays









WIMP models are well motivated.

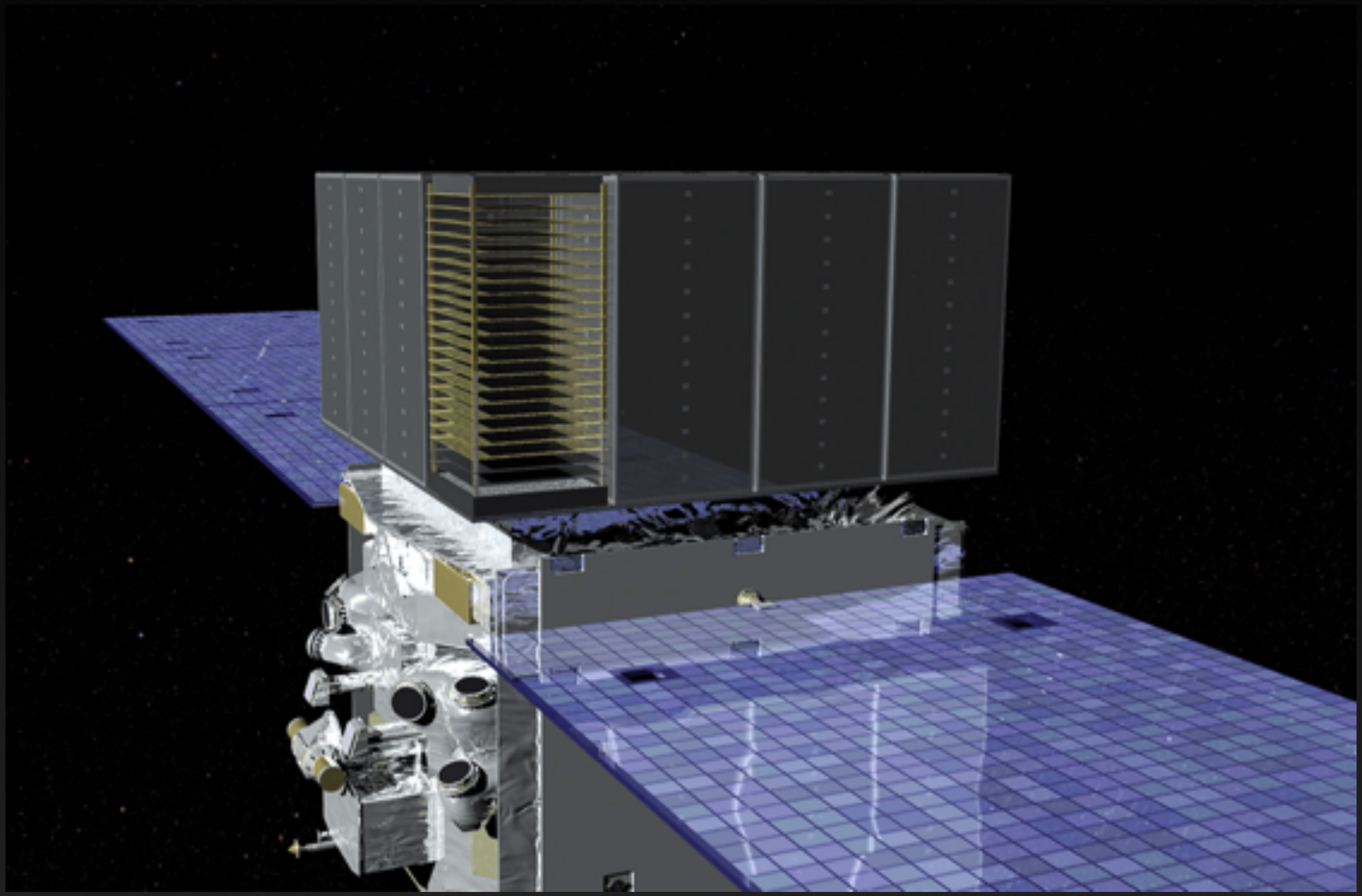
For standard WIMP scenarios, the majority of the annihilation energy is deposited at gamma-ray energies.

How: The Fermi-LAT Instrument

Launched: June 2008

Observes Gamma-Rays with Energies 30 MeV - 1 TeV

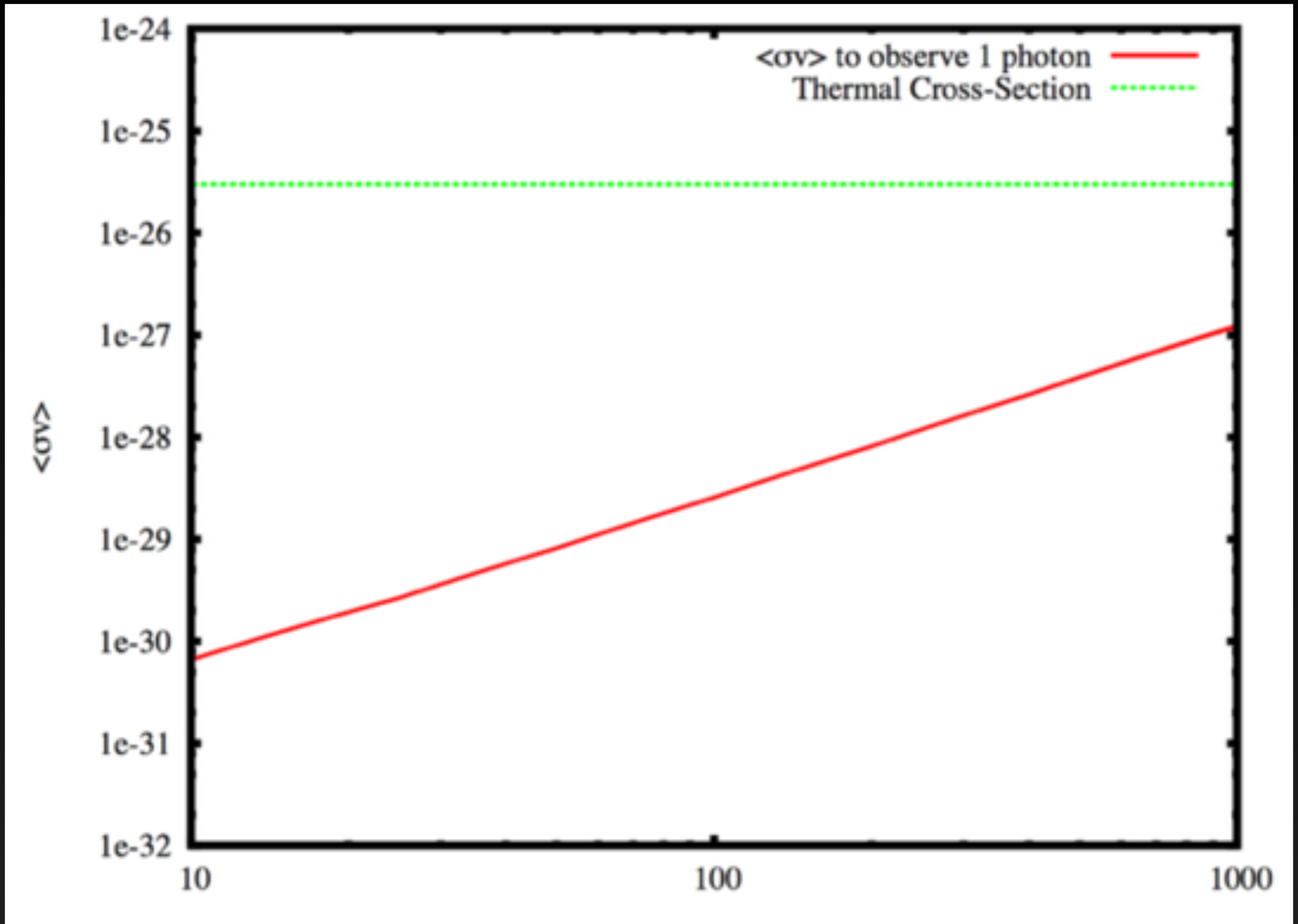
Collaboration of five countries and dozens of institutions.



Operational Characteristics:

- Effective Area ~ 1 m^2
- Field of View ~ 2 sr
- Energy Resolution ~ 10%

Why: Do We Care?



If we were in a background free experiment, or could separate dark matter gamma-rays from other signals, then we would set limits far below the thermal annihilation cross-section.

Alternatively, if dark matter annihilates at the thermal cross-section, it produces many gamma-rays observed by the Fermi-LAT.

Why: Astrophysics Has Been (Relatively) Cooperative

The observed gamma-ray intensity from the inner 1o surrounding the Galactic center, in an energy range between 1-3 GeV is:

$$1 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$$

The prediction from a 100 GeV neutralino annihilating to bb at a thermal cross section is:

$$2 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$$

There is no particular reason this needs to be true - the astrophysical gamma-ray flux could easily be a million times brighter.

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?).

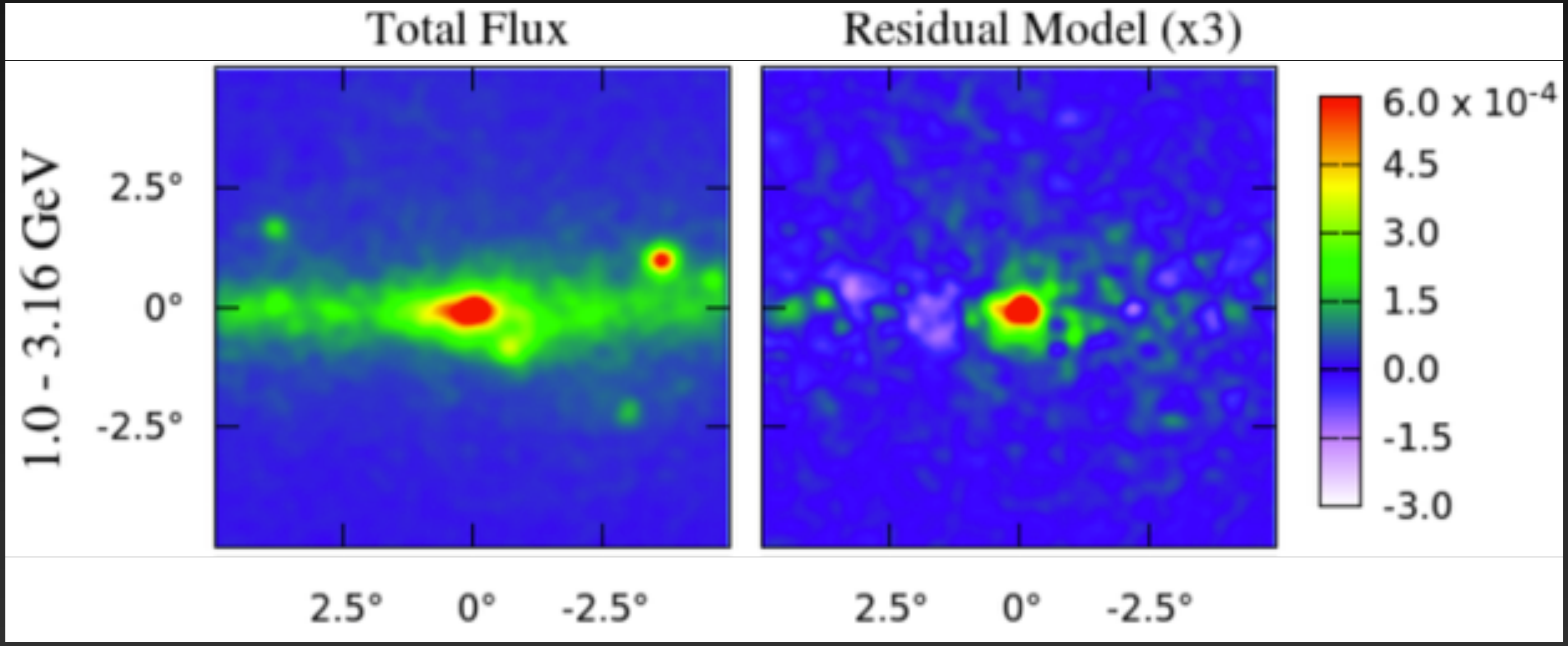
Many Studies

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

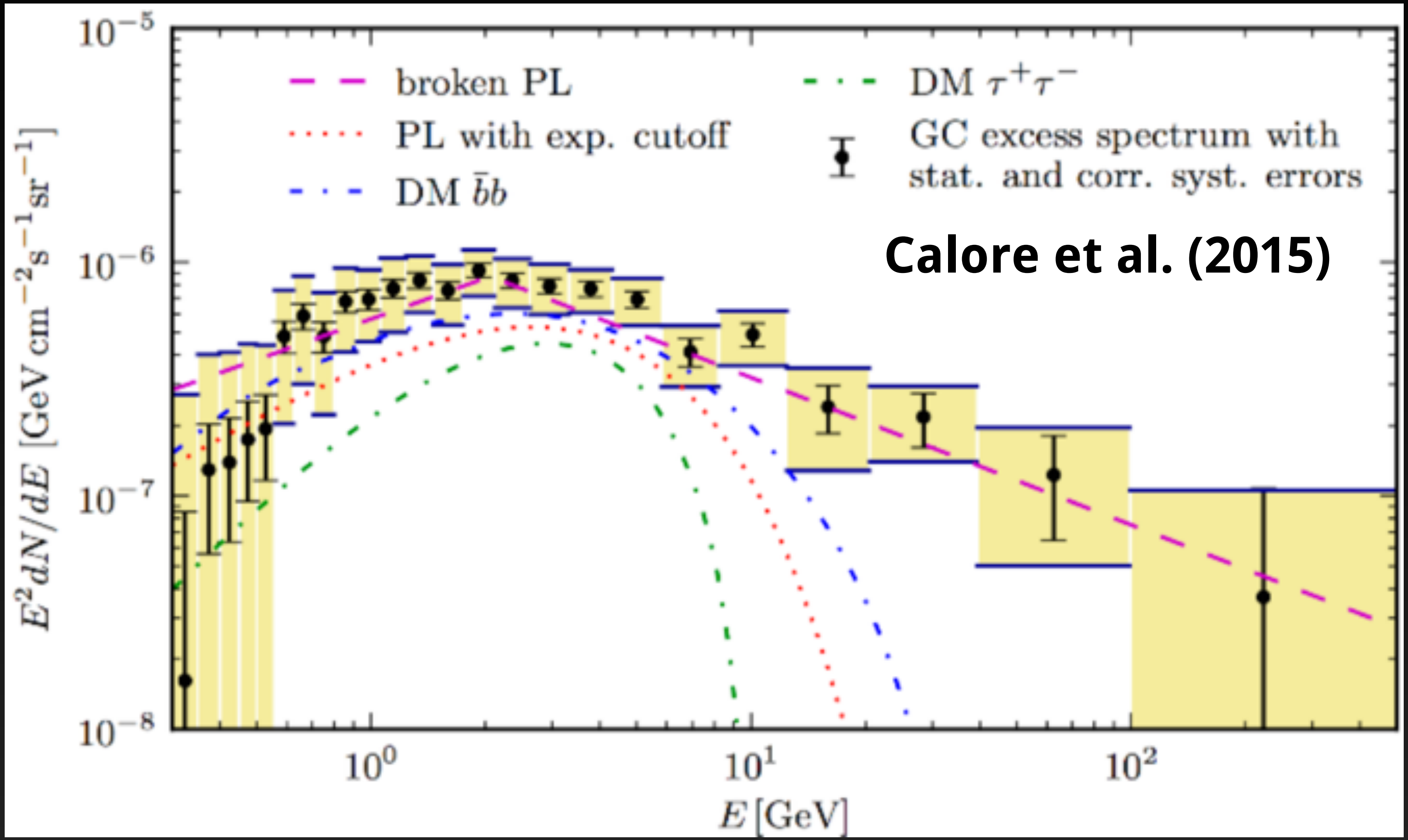
Observational Results

Utilizing a fitting algorithm, we can subtract astrophysical foregrounds and determine the the underlying signal that is morphologically consistent with an NFW profile.

This leaves a bright excess near the Galactic center.



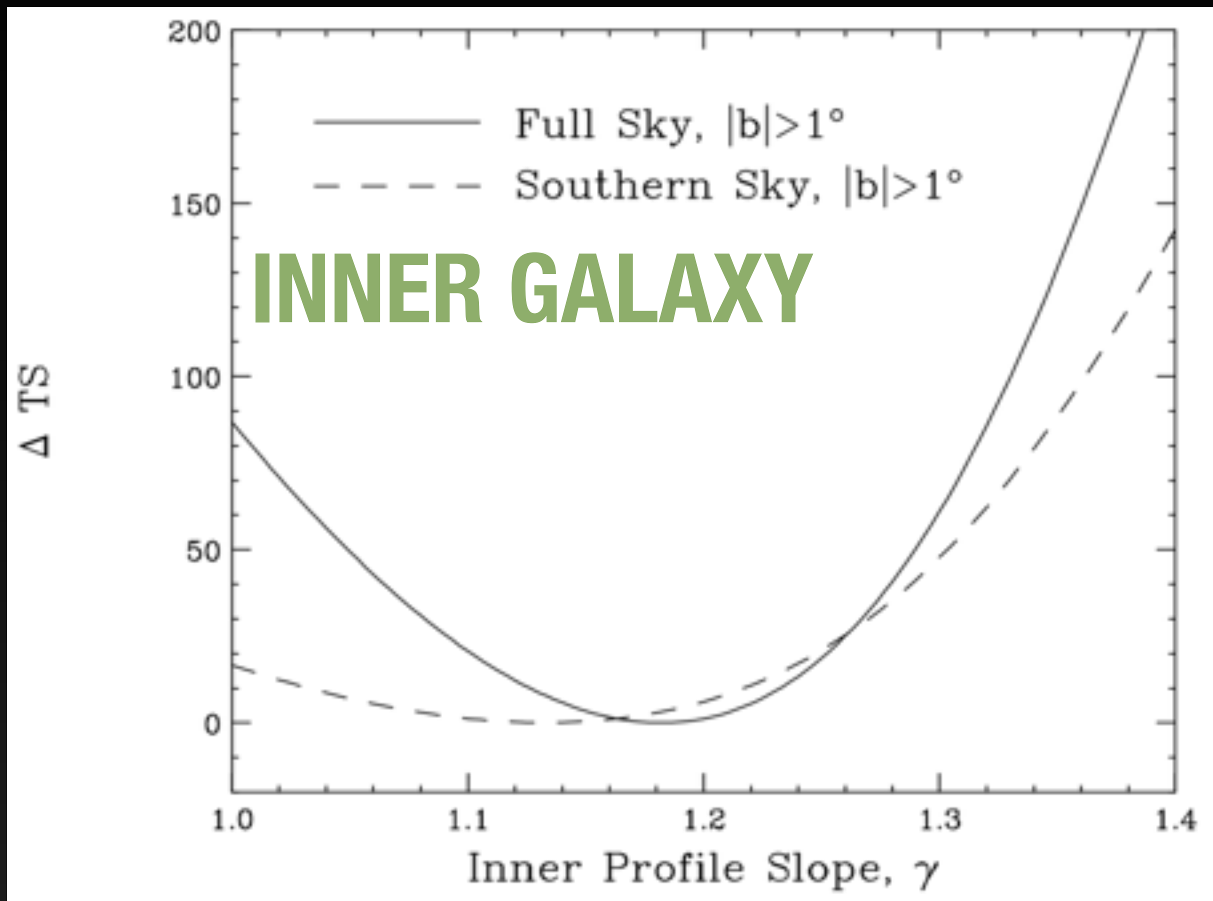
Observational Results

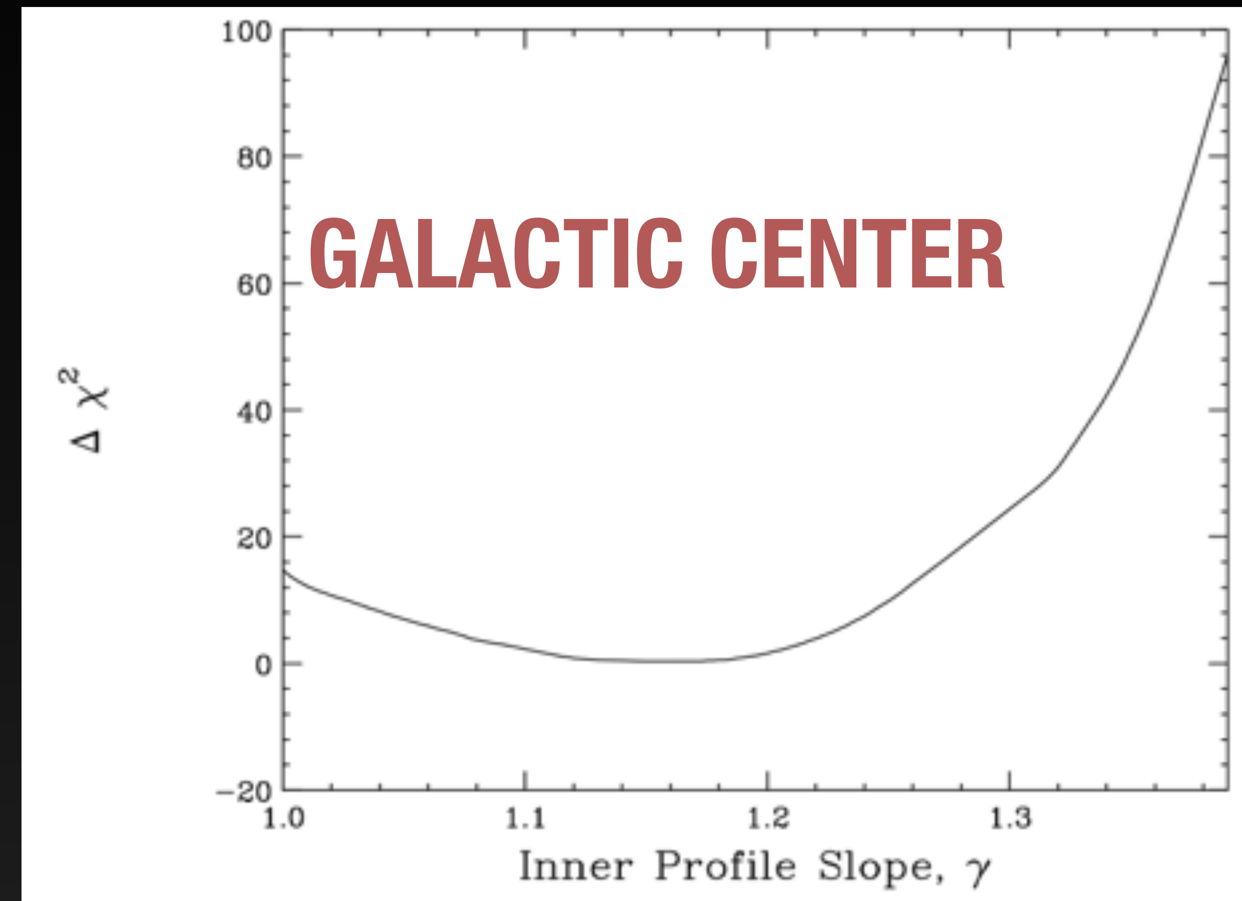


Spectral Model highly resilient to changing systematic background models ~300 models considered here.

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

Observational Results



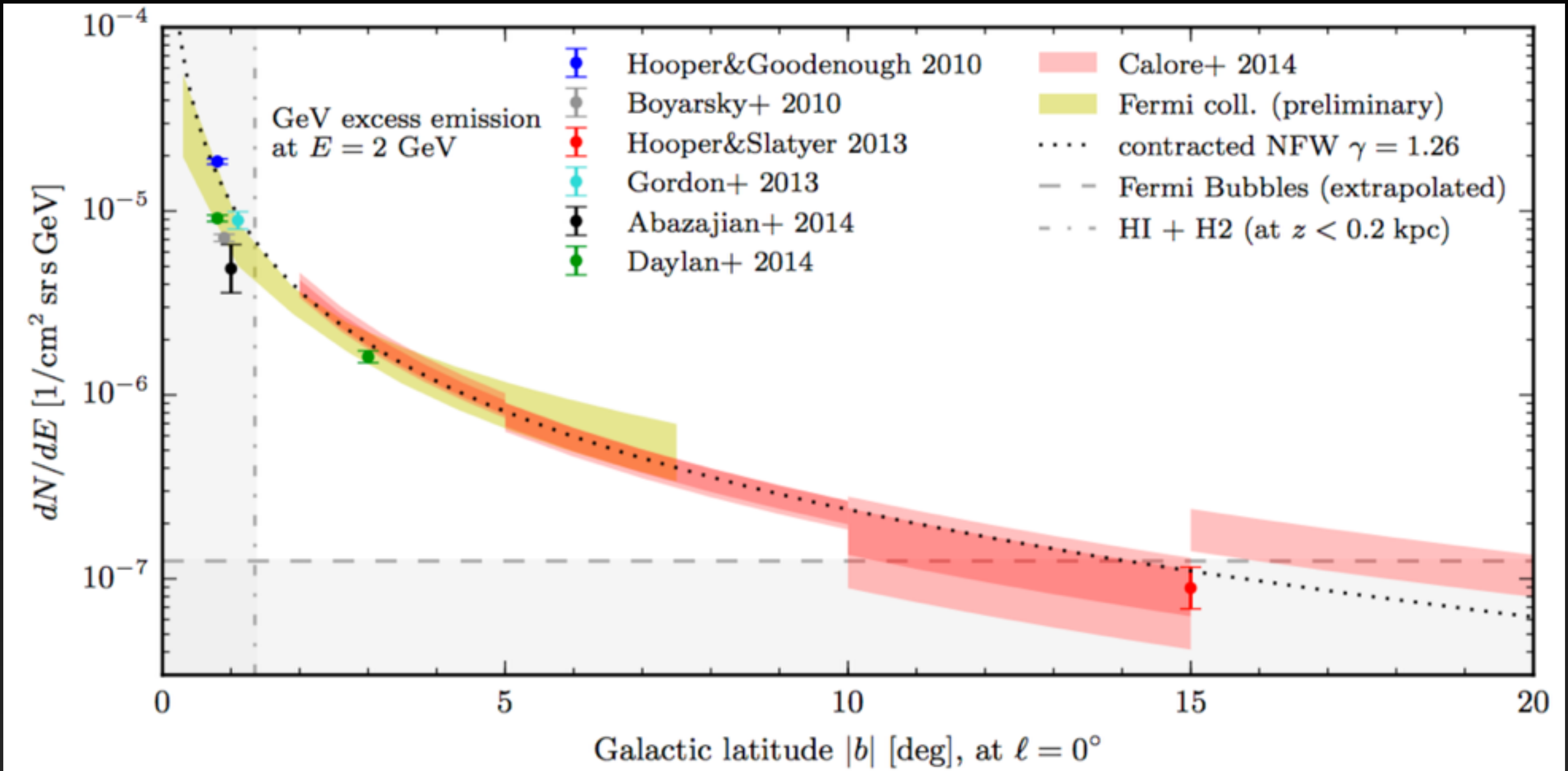


Inner galaxy prefers density profile γ = 1.18

Galactic Center prefers γ = 1.17

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

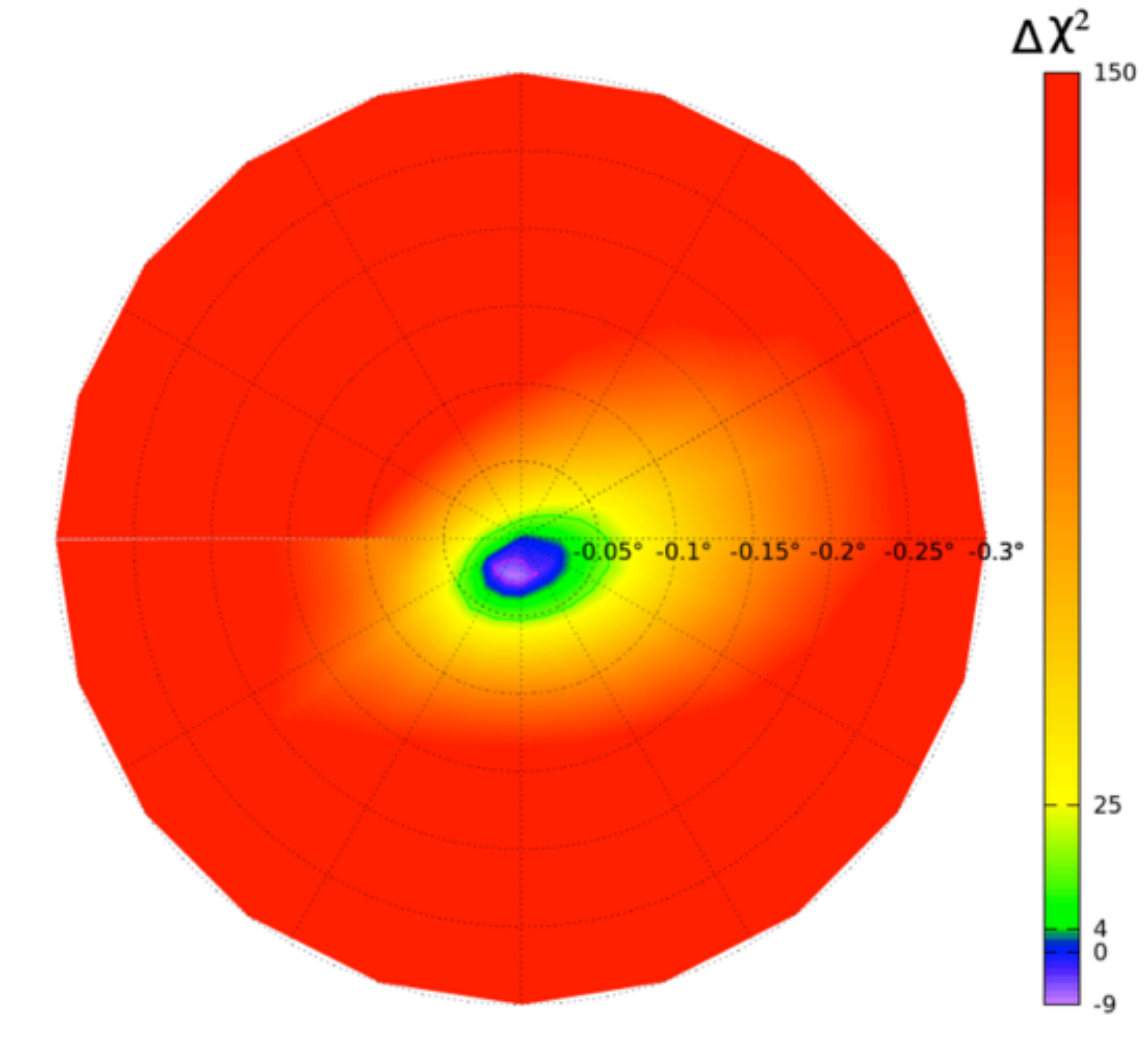
Observational Results



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

Calore et al. (2014b)

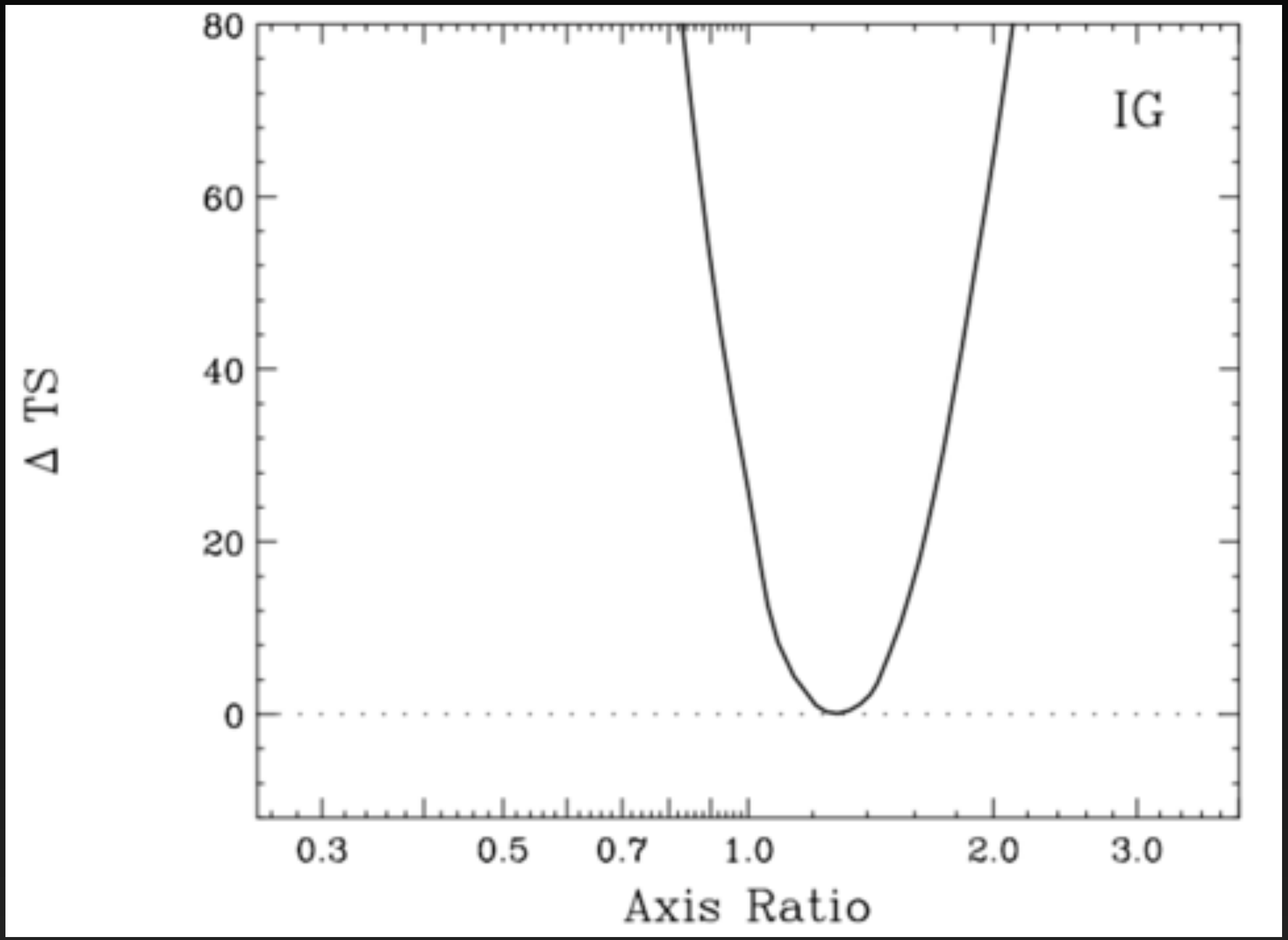
Observational Results

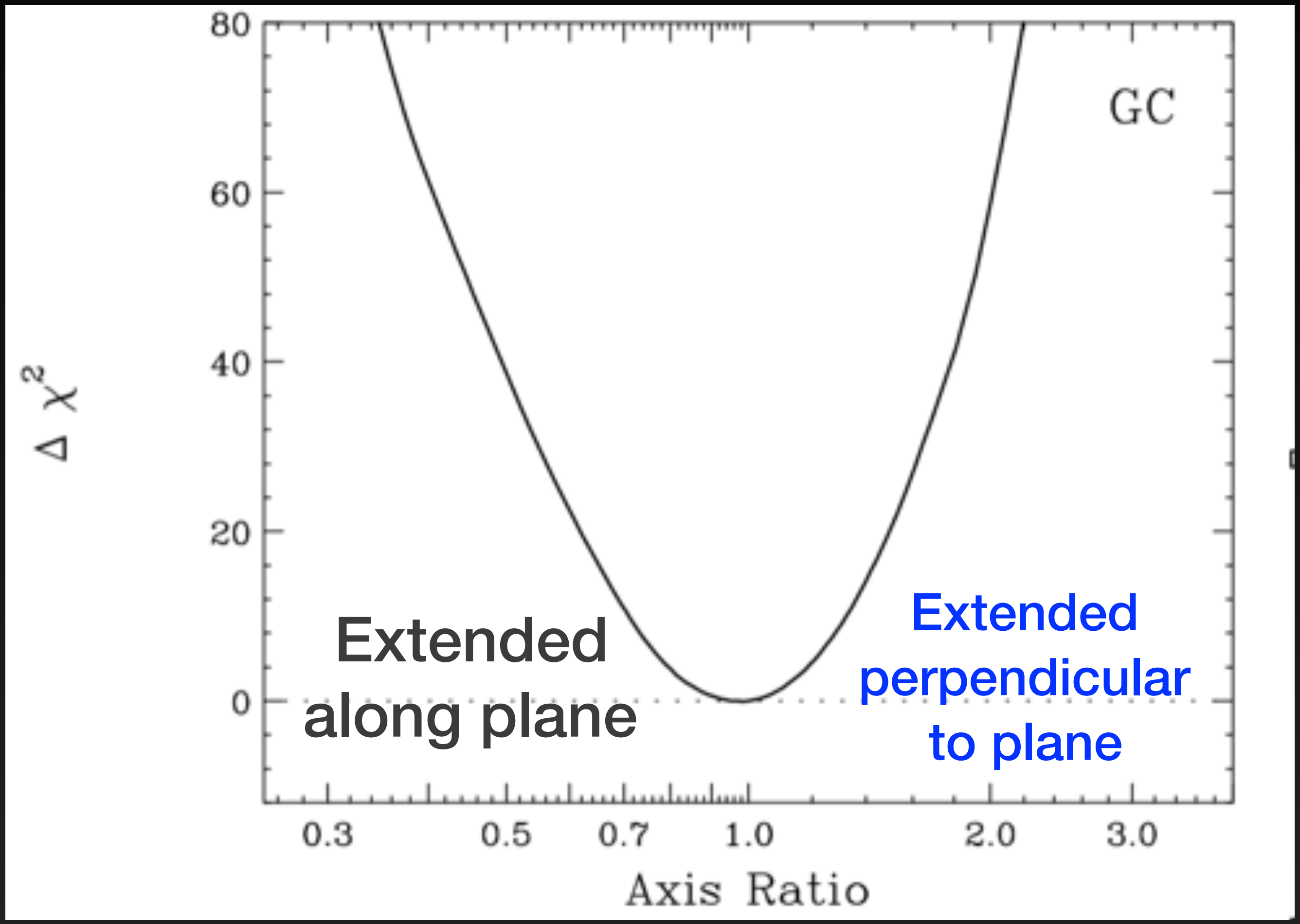


The peak of the new emission source lies within 0.05º of the GC.

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

Observational Results

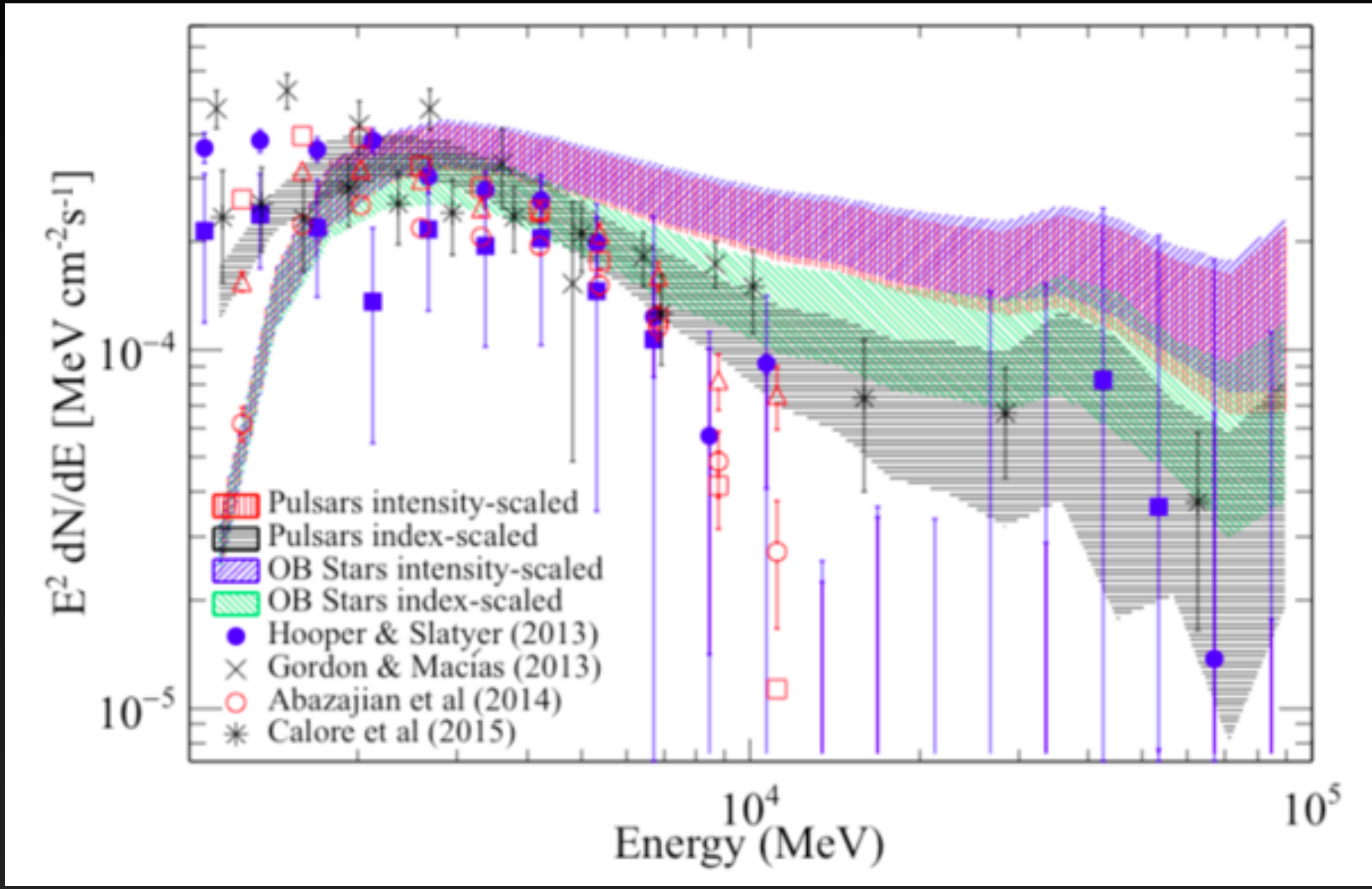




The Galactic Center analysis finds the excess to be spherically symmetric, to within approximately 20%.

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

Observational Results



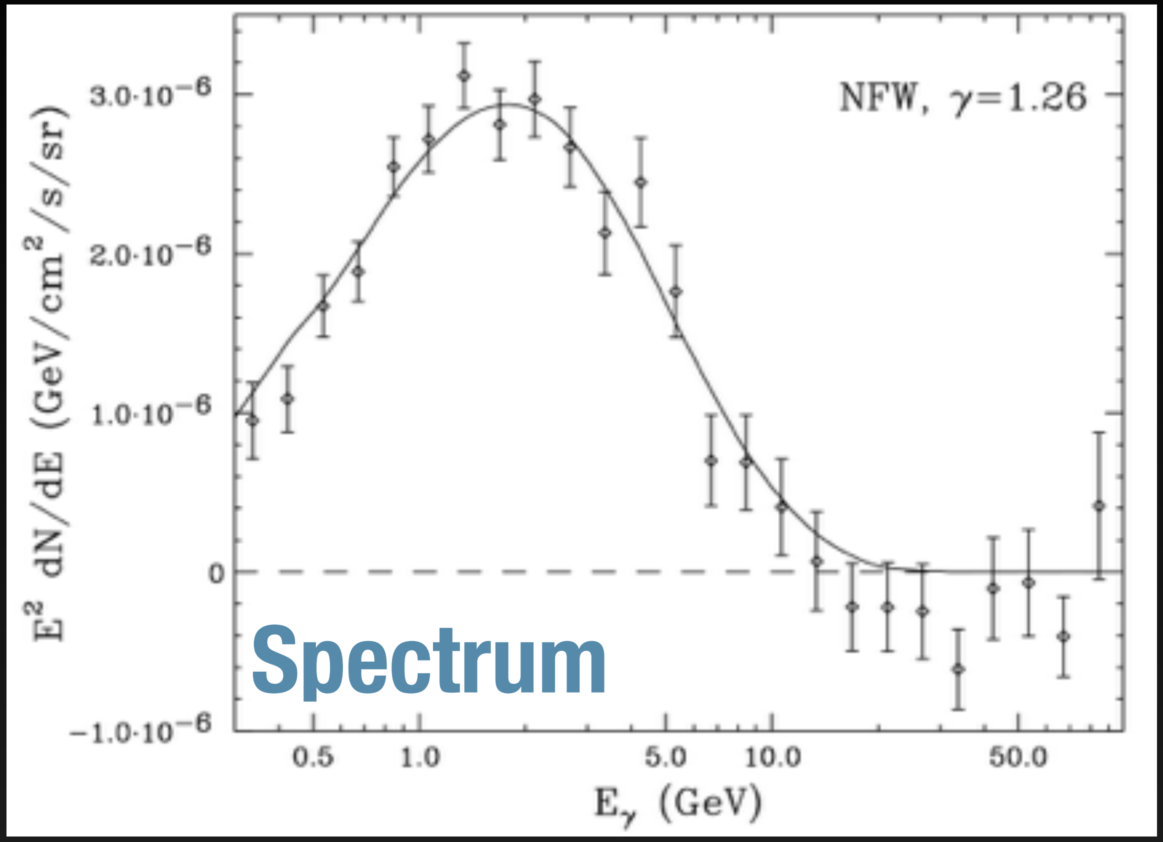
The Fermi-LAT Collaboration now officially agrees with these findings.

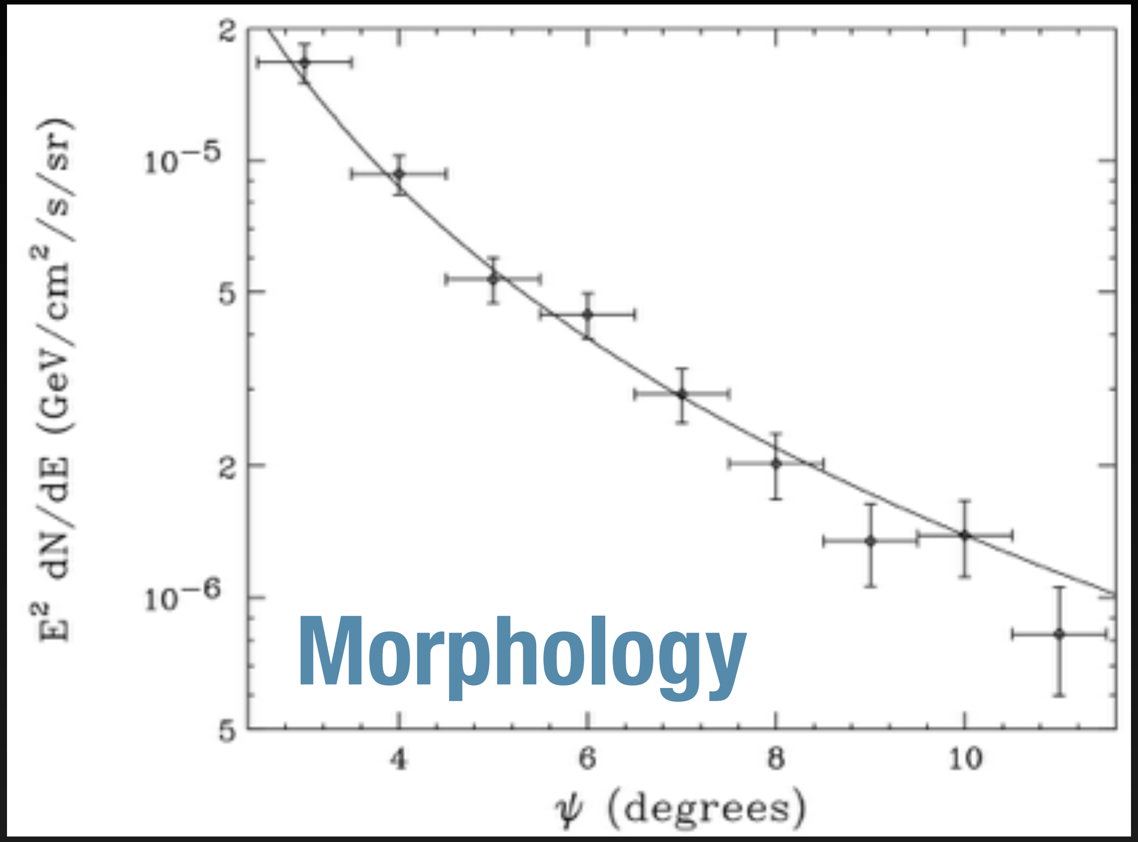
Summary of Data Analysis

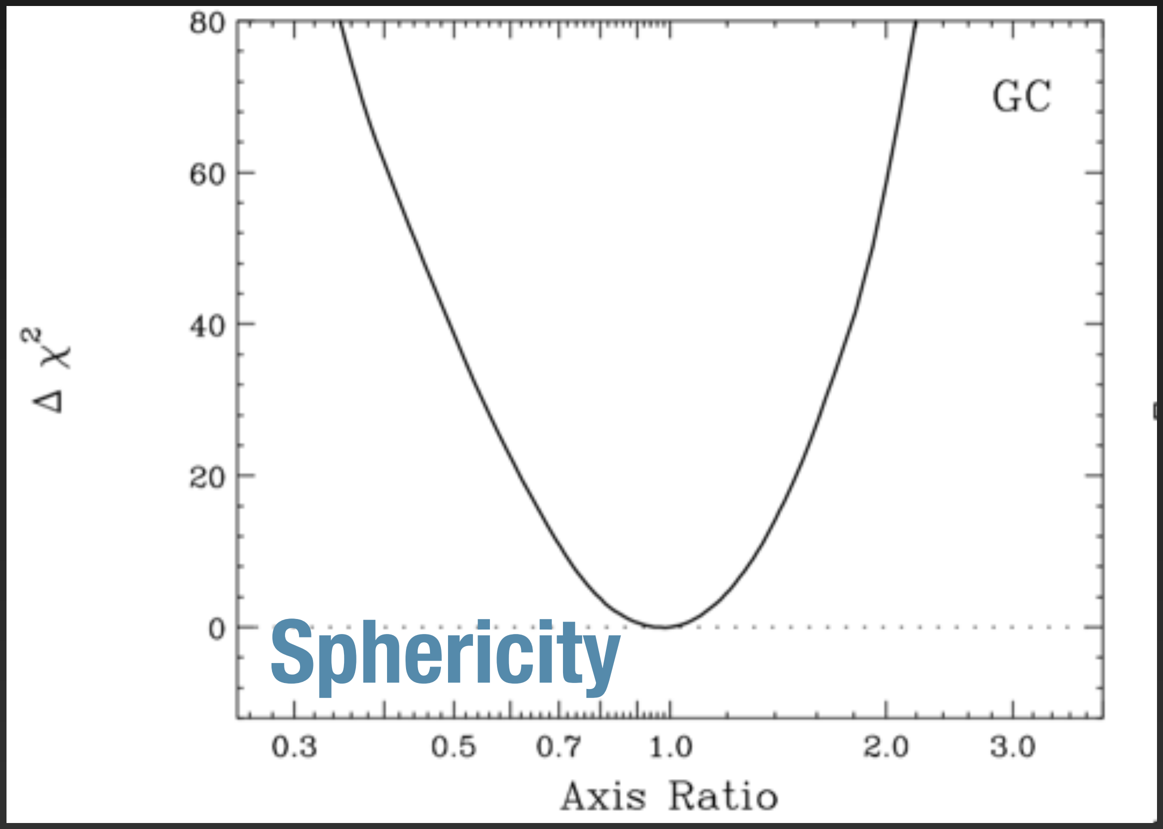
All currently published observational studies of the Galactic Center excess agree:

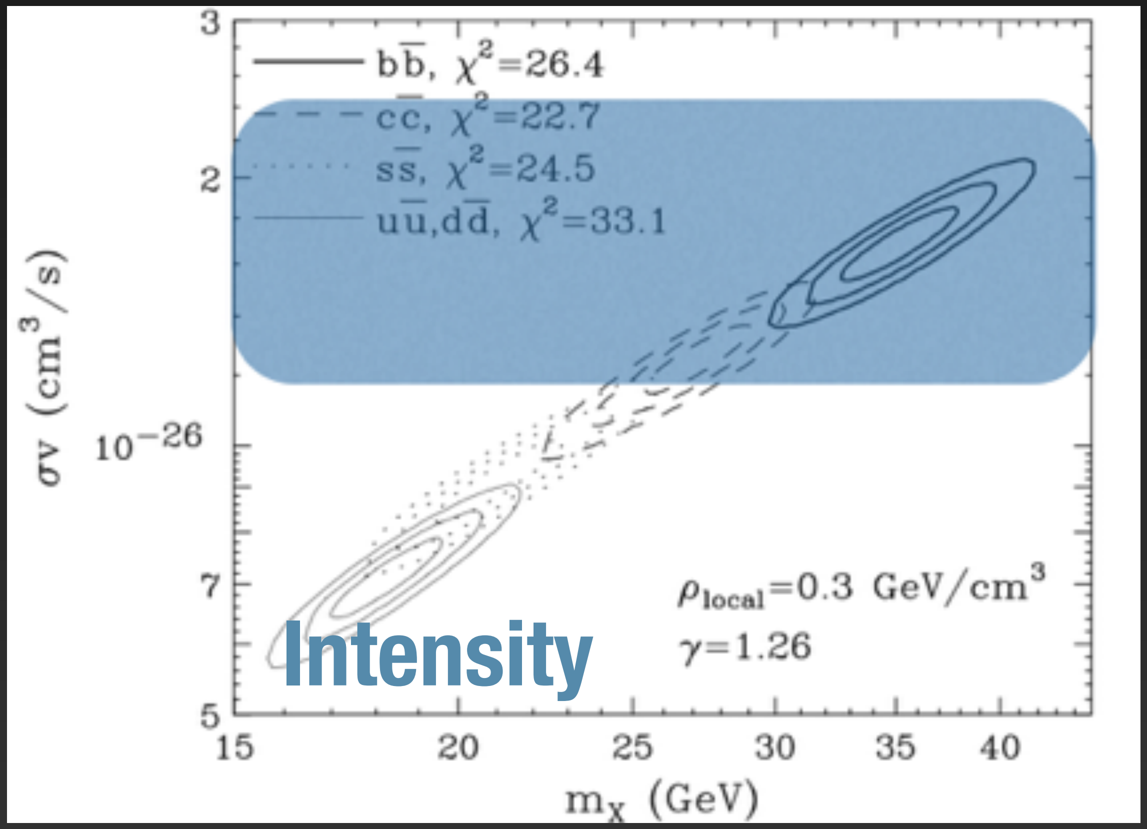
- Current best fit models of astrophysical gamma-ray emission have uncovered a gamma-ray excess - with a fractional intensity of ~15%
- The spectrum of the excess is peaked at an energy of ~2 GeV, and falls off at low energies with a spectrum that is harder than expected for astrophysical pion emission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

Naive Dark Matter Expectations









Observational Results

So we’re done right?

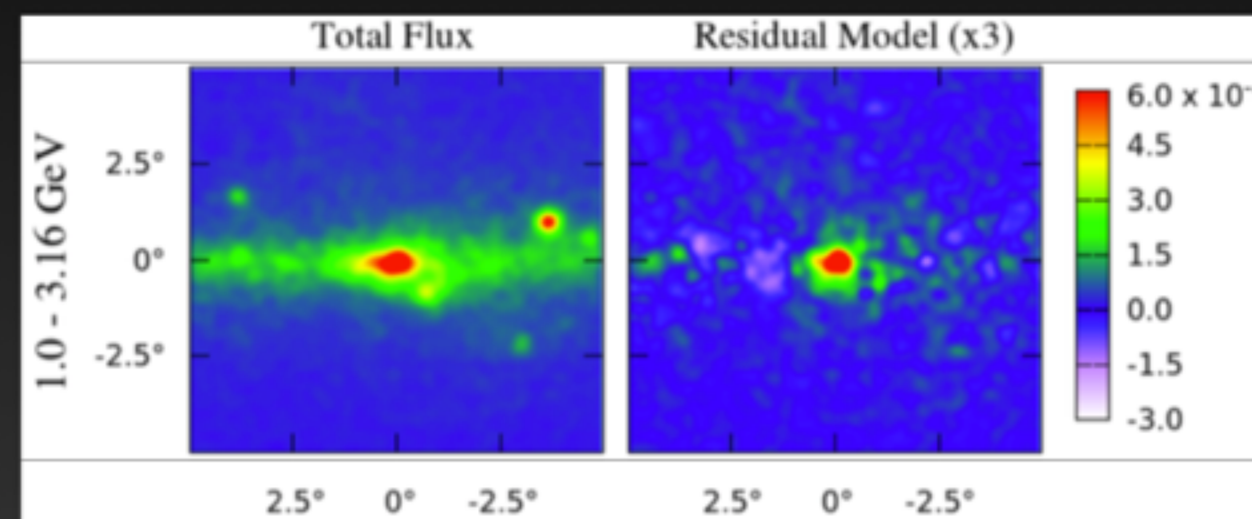
Observational Results

Like a good magician, you always make the hardest part seem easy and the easiest part seem hard.

Observational Results

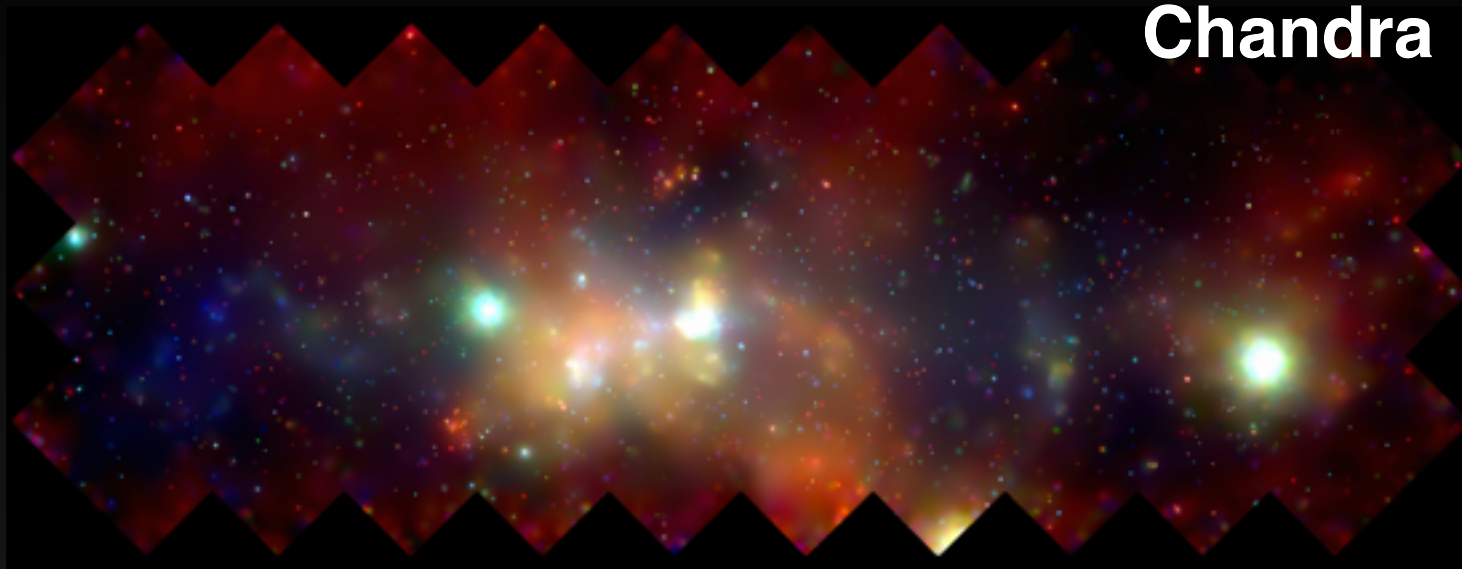
Utilizing a fitting algorithm, we can subtract astrophysical foregrounds and determine the the underlying signal that is morphologically consistent with an NFW profile.

This leaves a bright excess near the Galactic center.



How do we know what the diffuse astrophysical emission is? And how do we subtract it off?

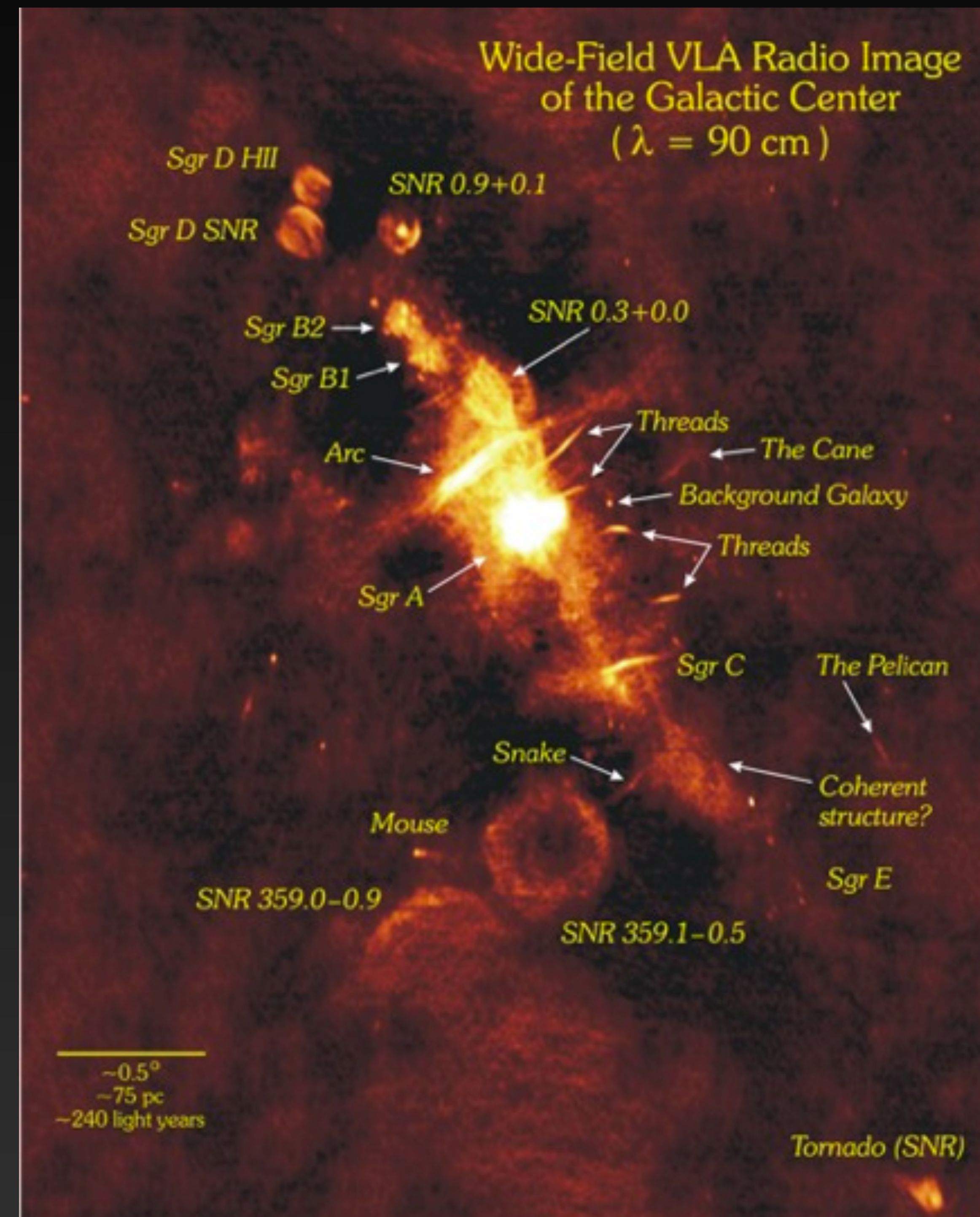
The Galactic Center in Gamma-Rays



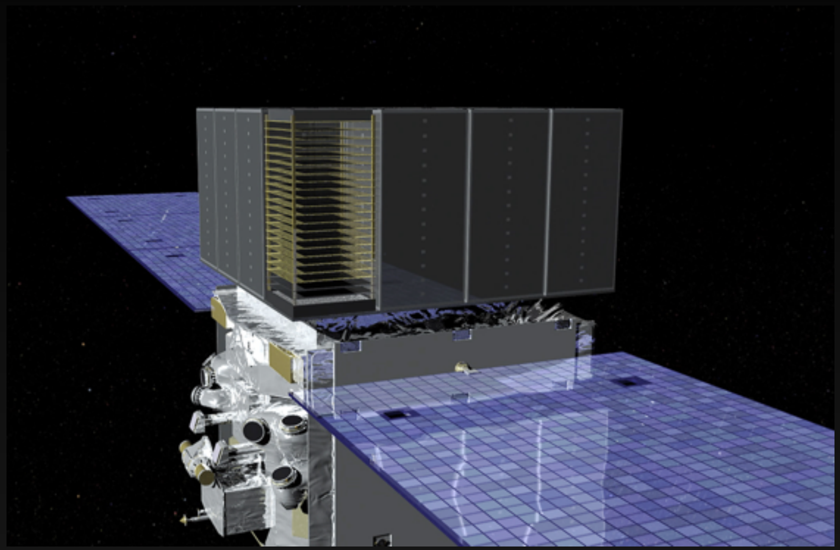
Multi-wavelength observations indicate the complexity of the galactic center region.

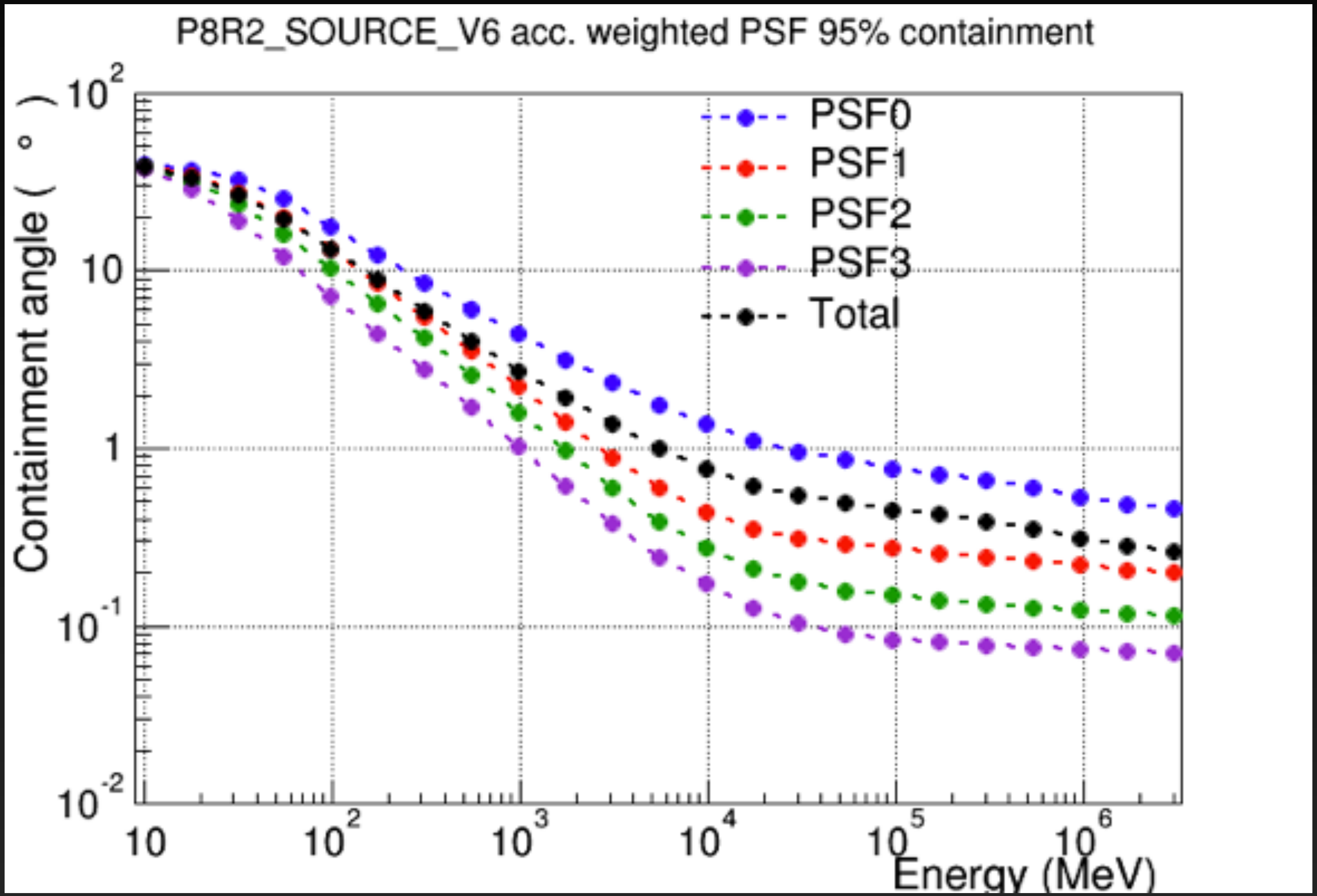
Chandra observes ~9000 point sources in inner degree.

VLA finds bright non-thermal emission structures.



Angular Resolution





The relatively poor angular resolution of the Fermi-LAT smears these signals into each other.

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

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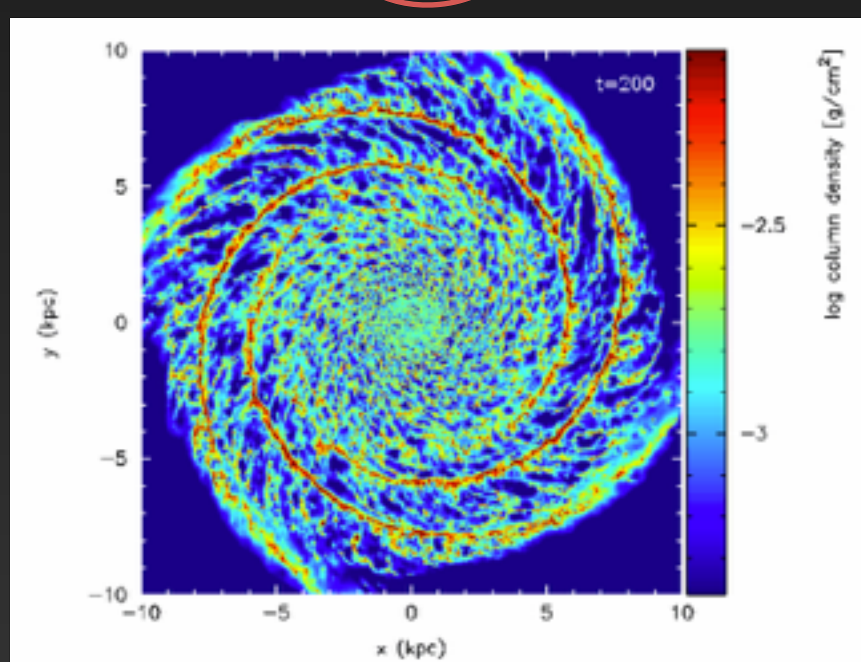
Solved Numerically:
e.g. Galprop

Gas/ISRF



The Galactic Center in Gamma-Rays

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

(~2% in relativistic electrons)

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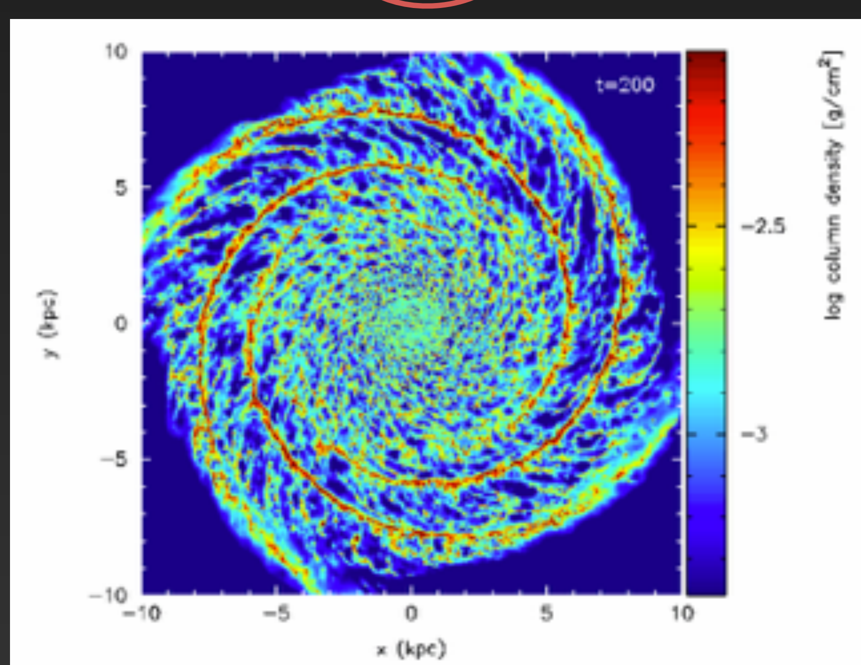
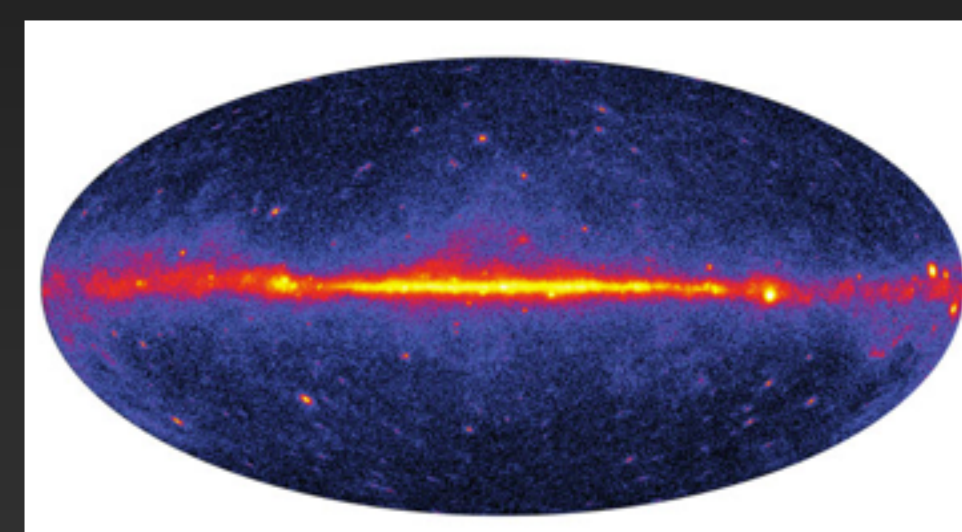
$$\frac{\partial \psi}{\partial t} = q(\vec{r},p) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi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

Solved Numerically:
e.g. Galprop

Gas/ISRF





The Galactic Center in Gamma-Rays

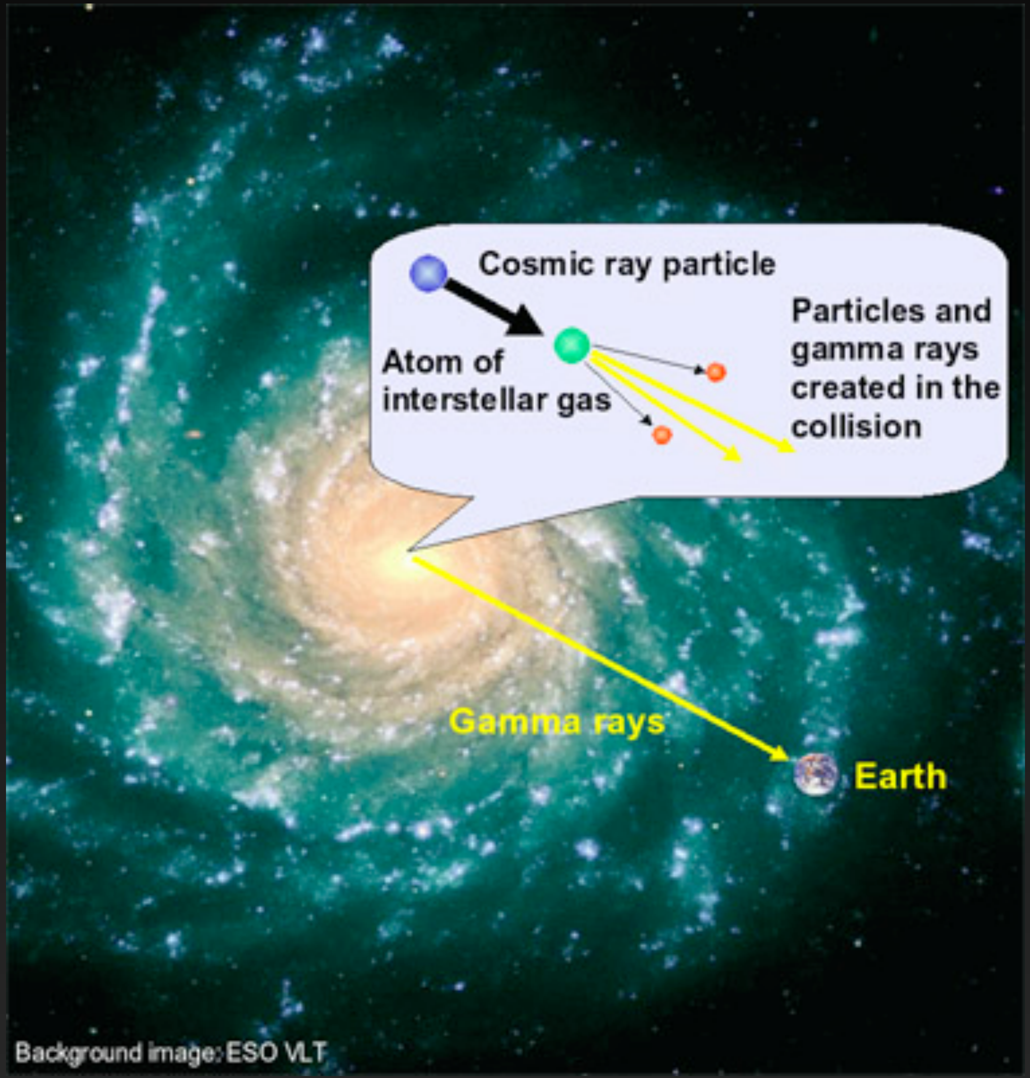
What Are These Backgrounds?

*** Point Sources (SNR, pulsars, etc.)**

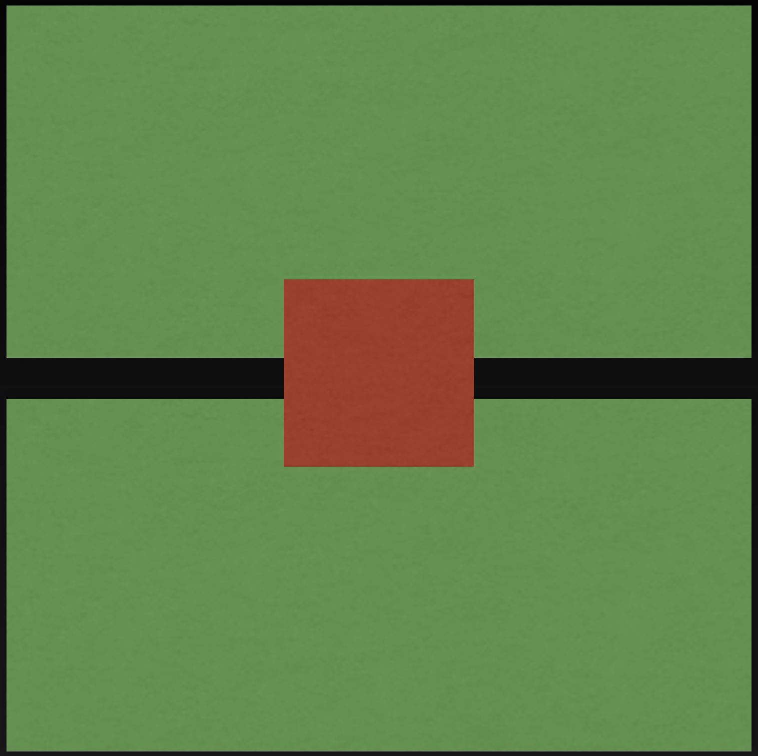
*** Hadronic Interactions (pp -> π^0 -> $\gamma\gamma$)**

*** Bremsstrahlung**

*** Inverse Compton Scattering**



How Does This Analysis Work?



Daylan et al. (2014)

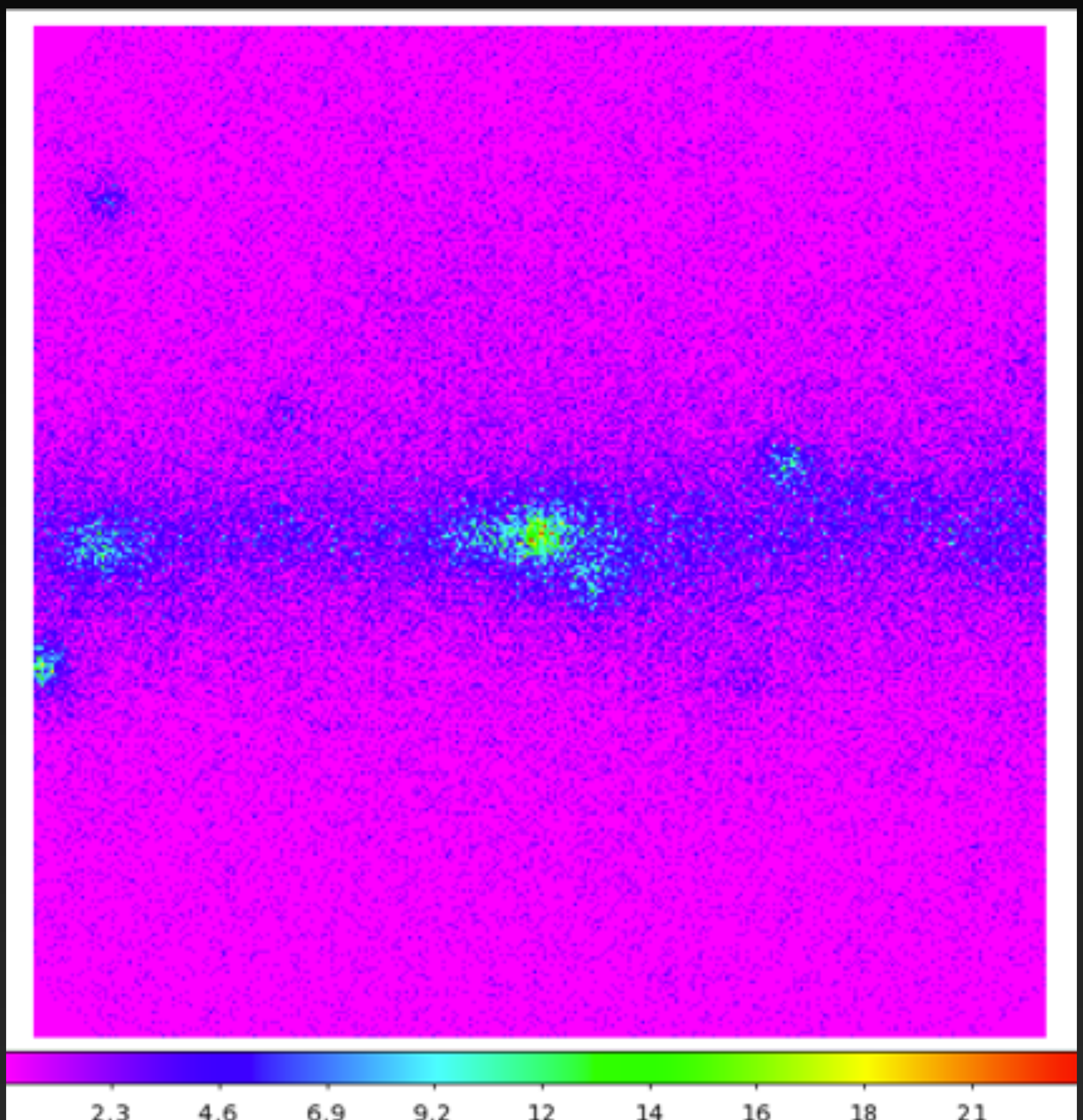
INNER GALAXY

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

GALACTIC CENTER

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

Finding an NFW Template

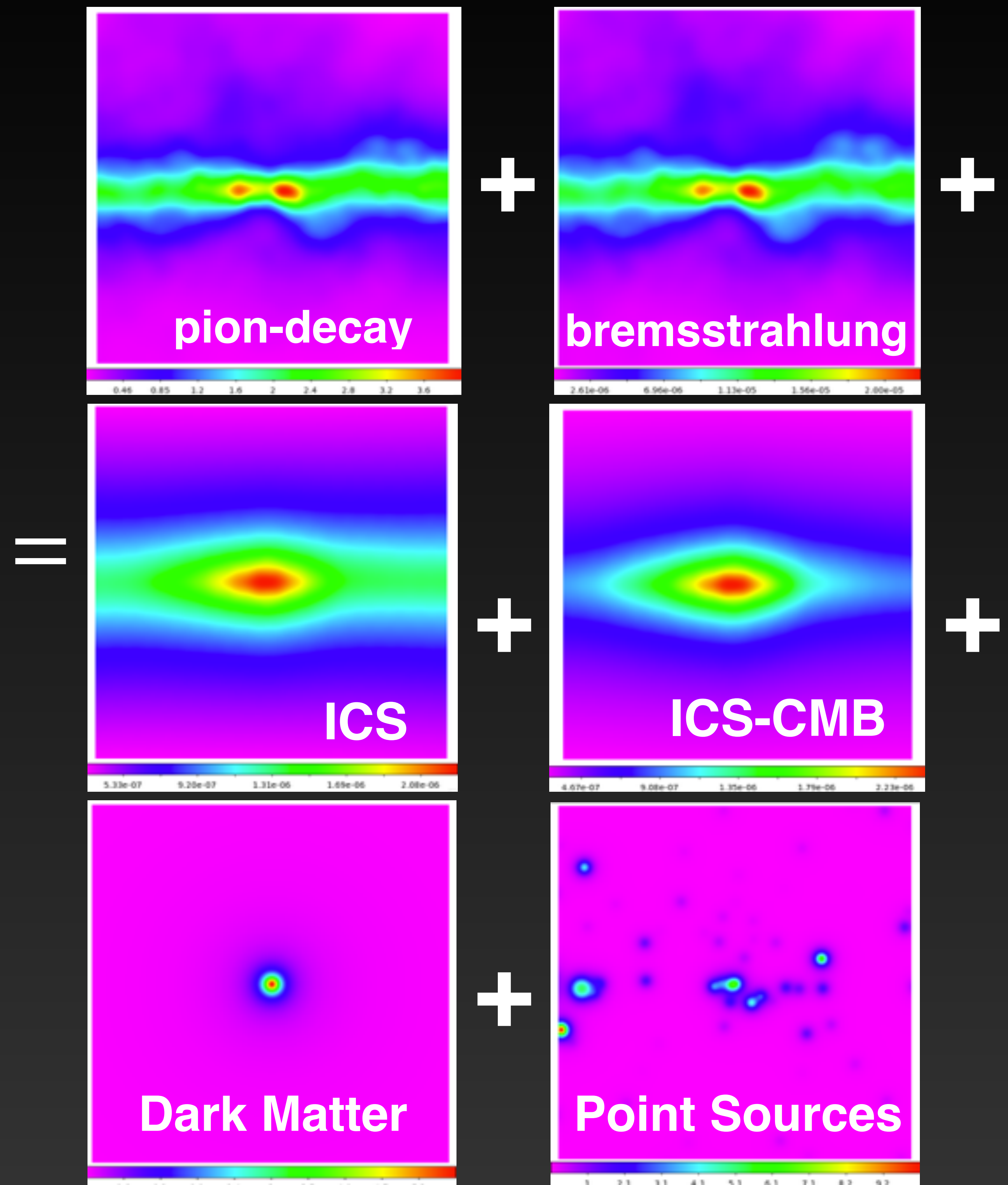


Data

750 — 950 MeV

Best Angular Resolution Cut

10o x 10o ROI



Trying to Kill the Beast

What if our astrophysical models are wrong?

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?

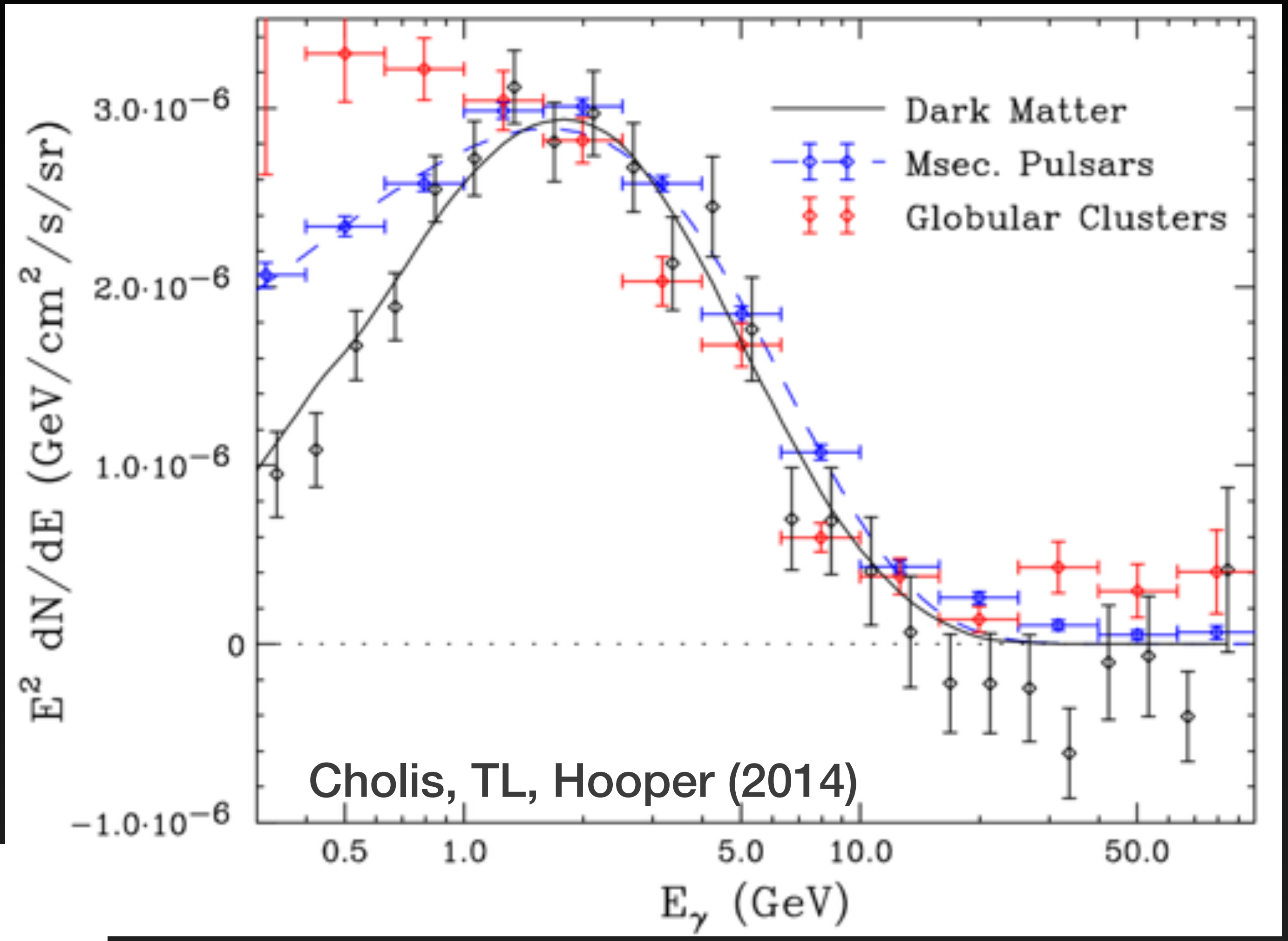
3.) What if the galactic center has a complex/active past?

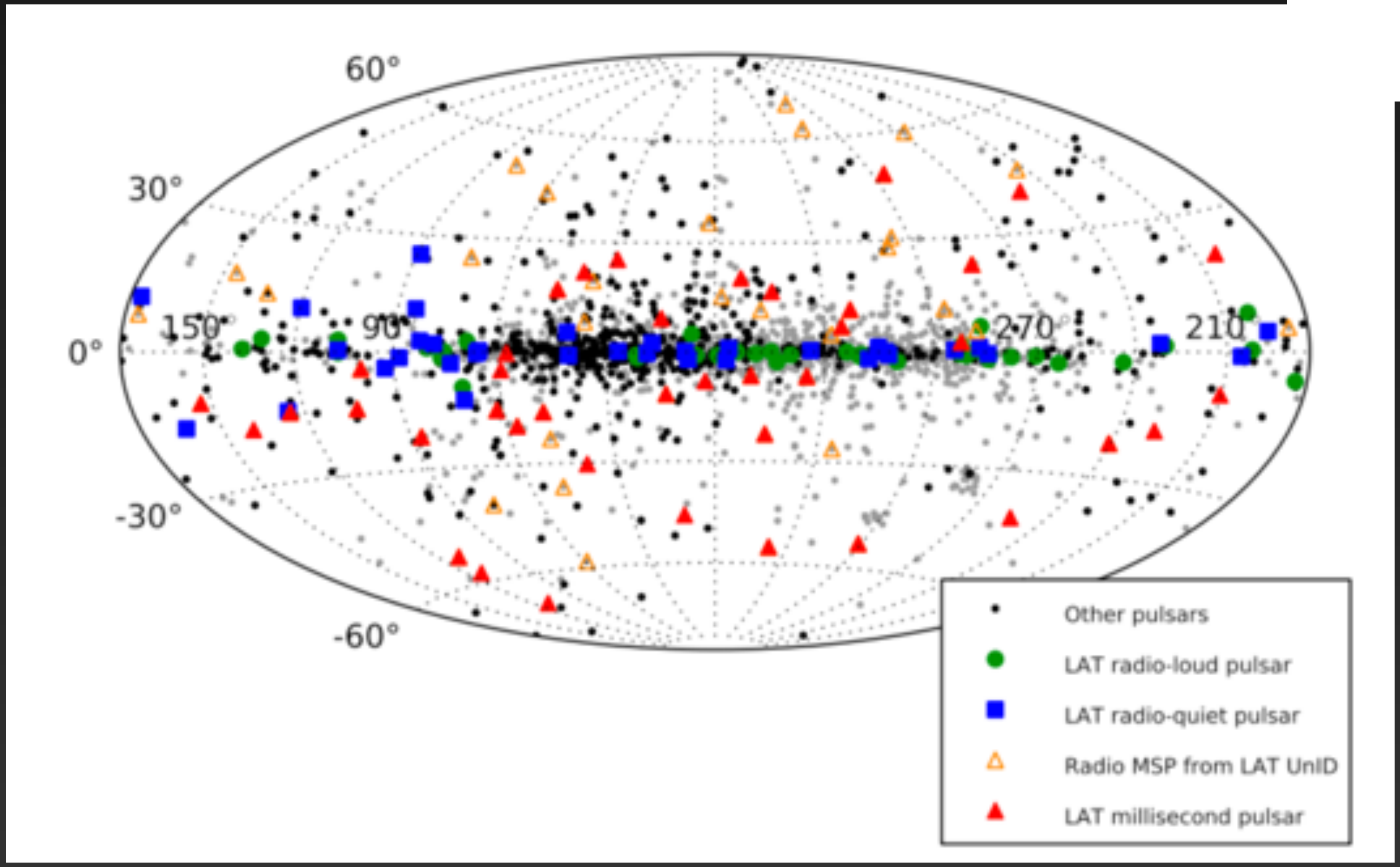
To some extent, all three of these are certainly true. So a better question is:

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

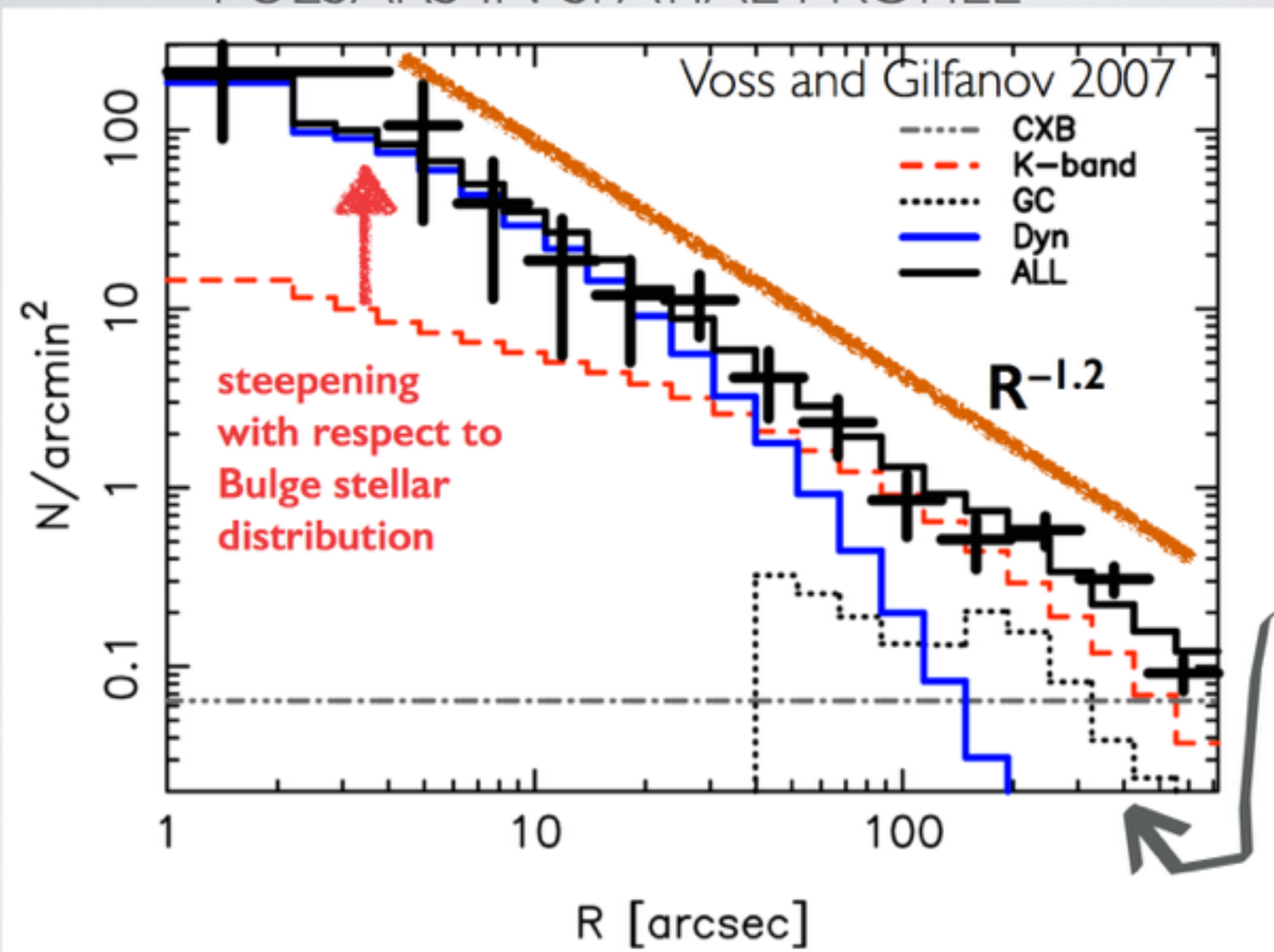




- MSPs are thought to be overabundant in dense star-forming regions like the Galactic Center

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

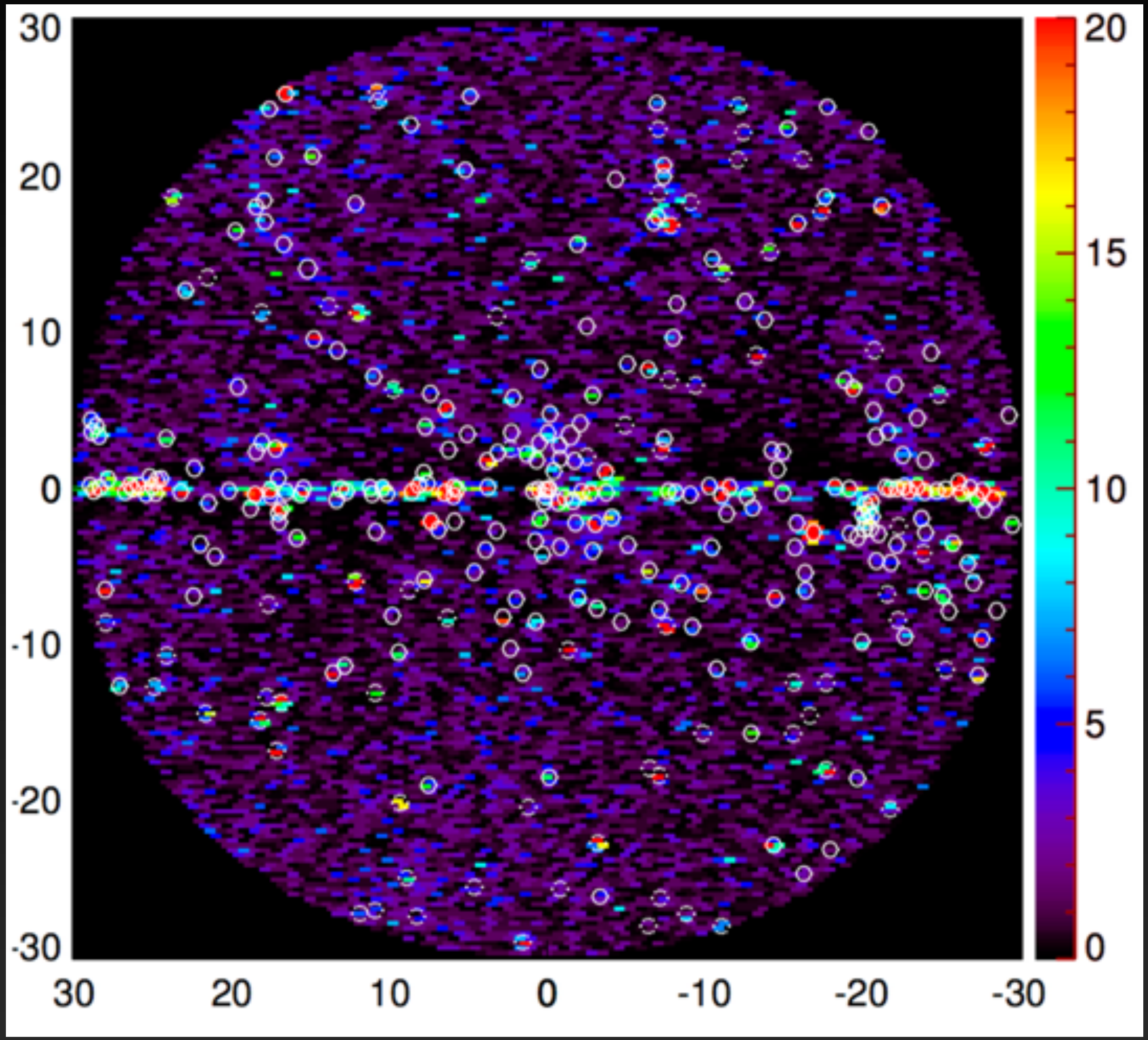
Orange line is same as best-fit excess template ($R^{-1.2}$ in projection implies $r^{-2.2}$ de-projected)!

Slide from Manoj Kaplinghat

Pulsars in the Galactic Center

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.



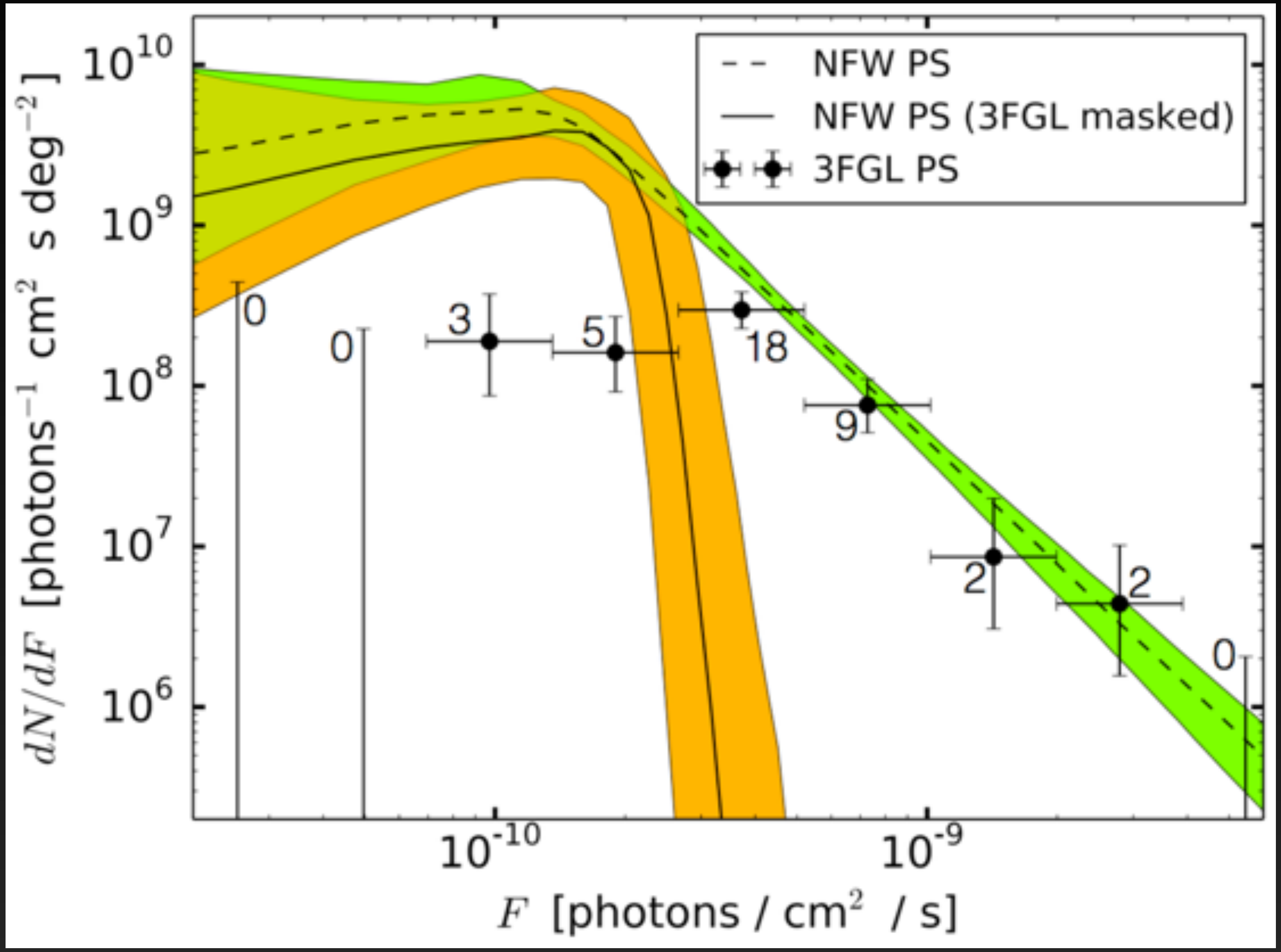
Lee et al. (2015)

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

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

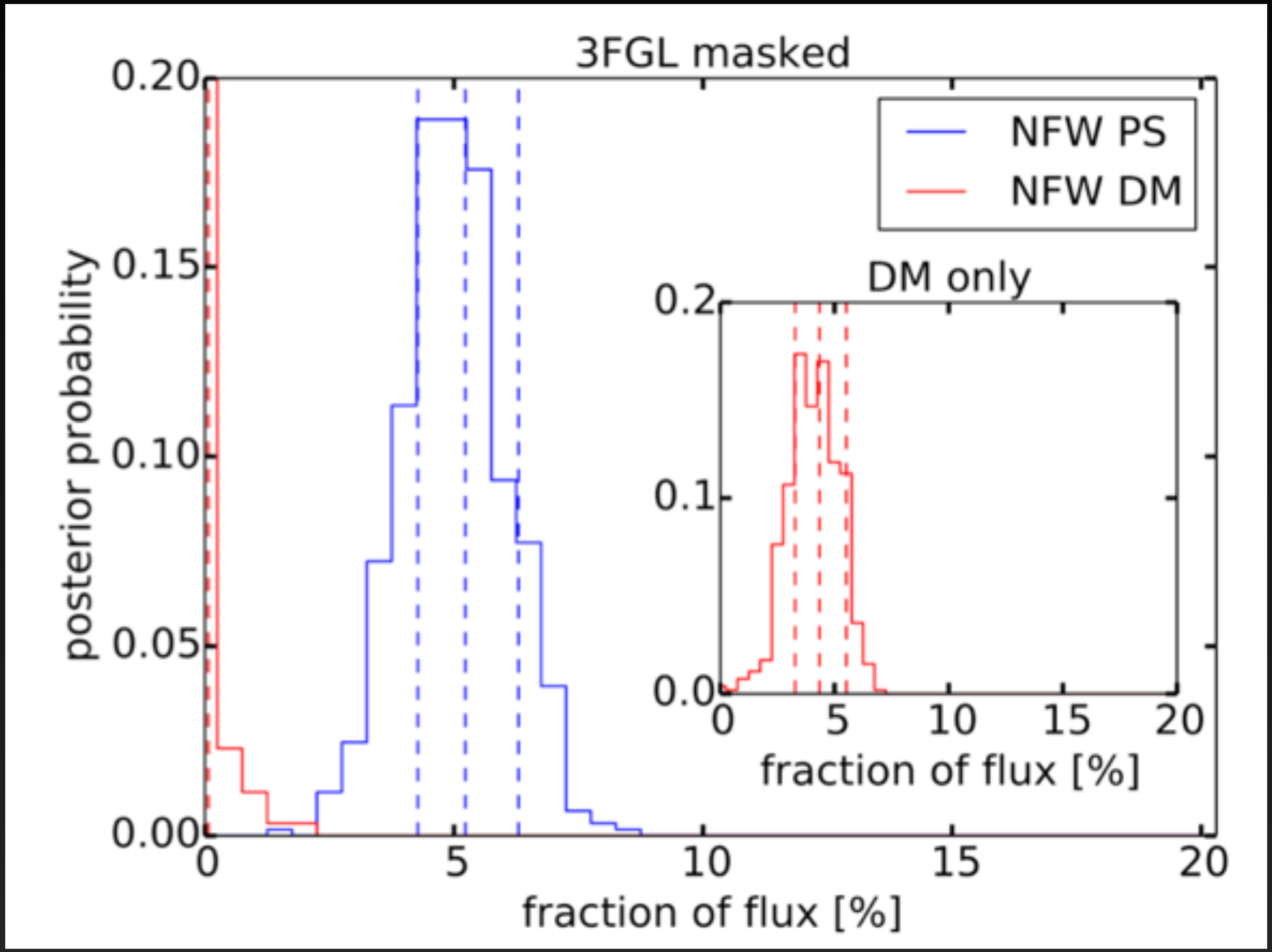
The circled areas correspond to known Fermi-LAT point sources.



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

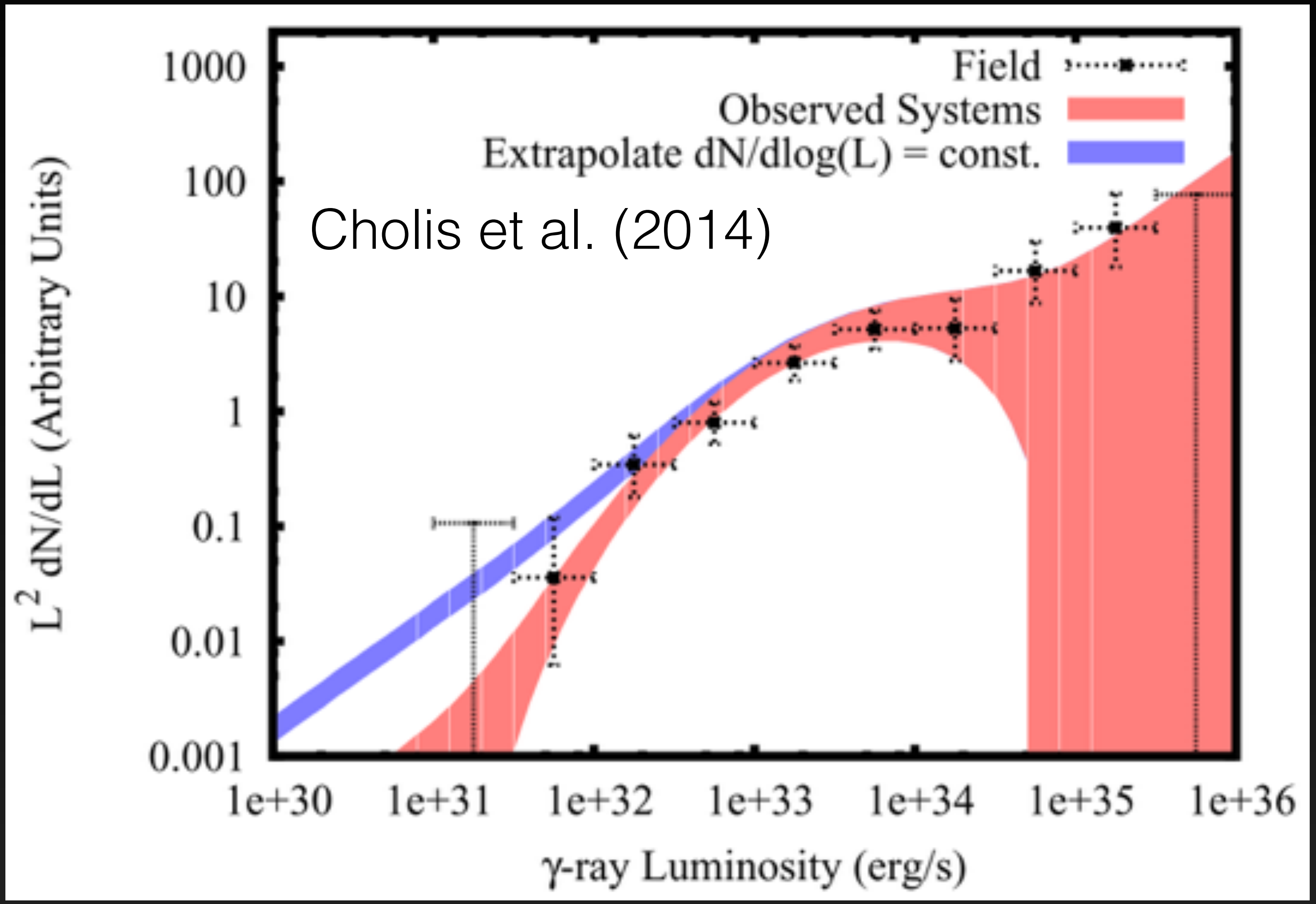


When both a traditional NFW template and the non-Poissonian NFW template are allowed to float arbitrarily, the non-Poissonian template absorbs the gamma-ray excess.

Lee et al. (2015)

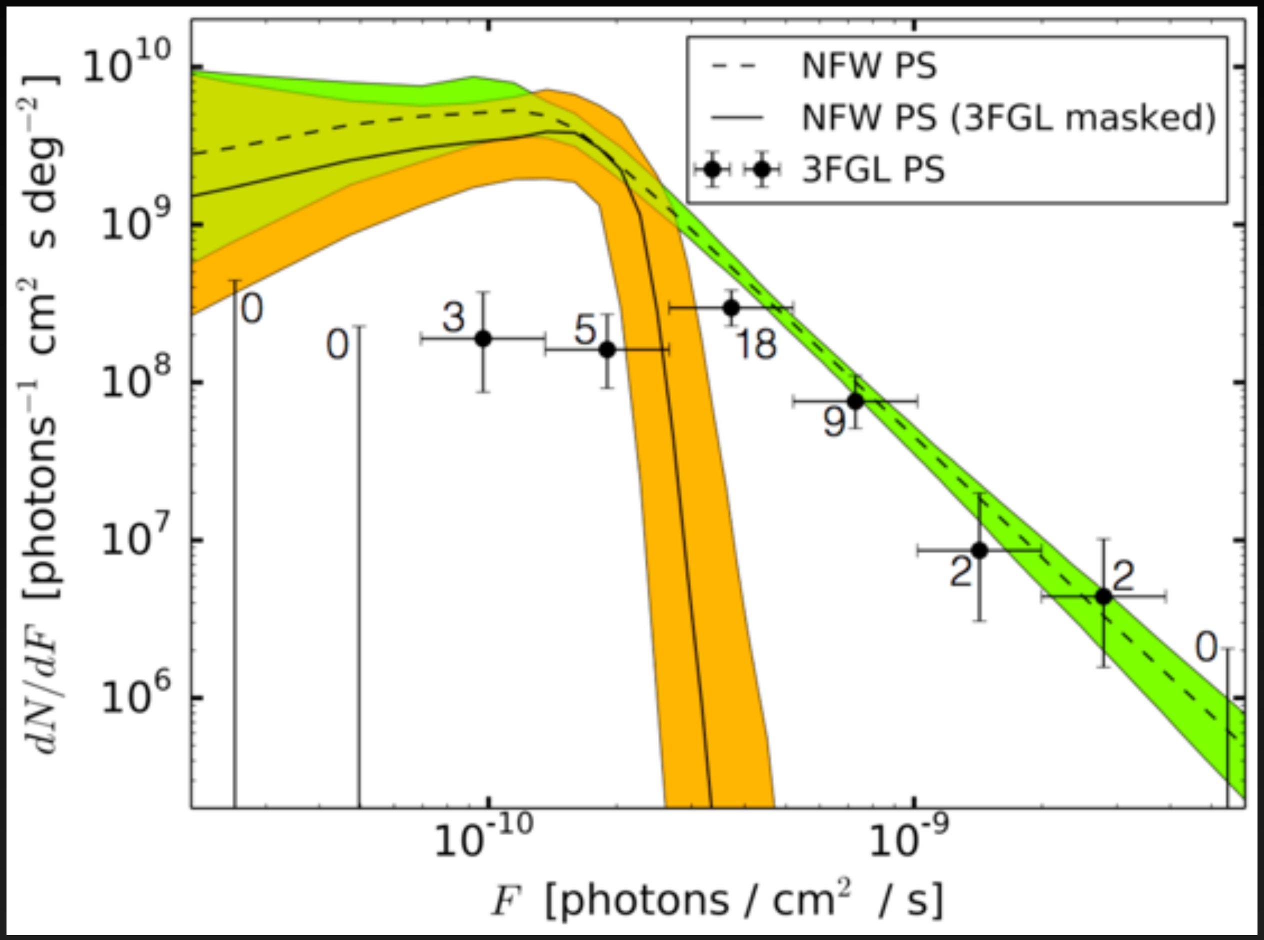
Why Not Pulsars?

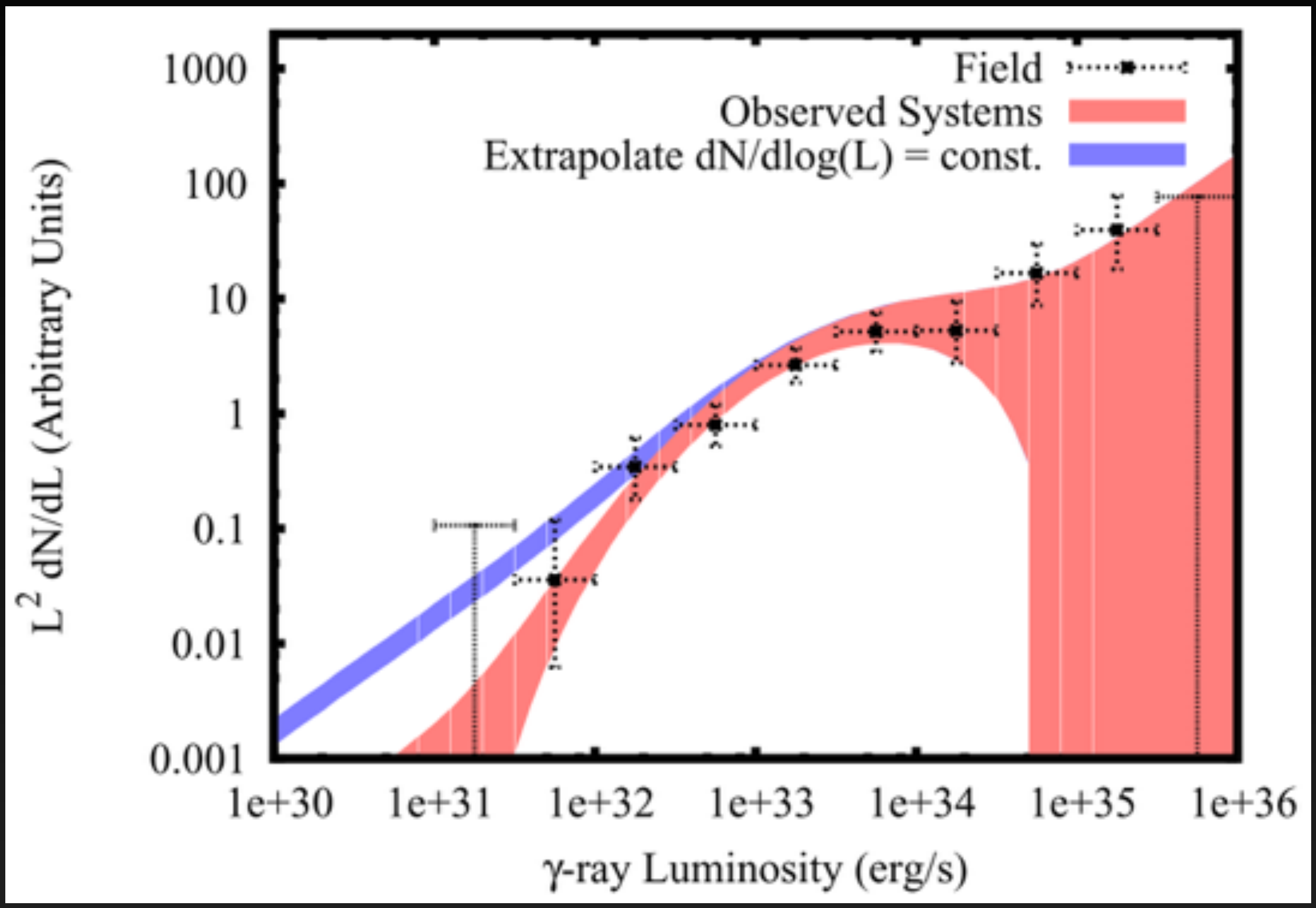
- **Can measure the fluxes of known MSPs and extrapolate to a posited galactic center population.**



- **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}.**

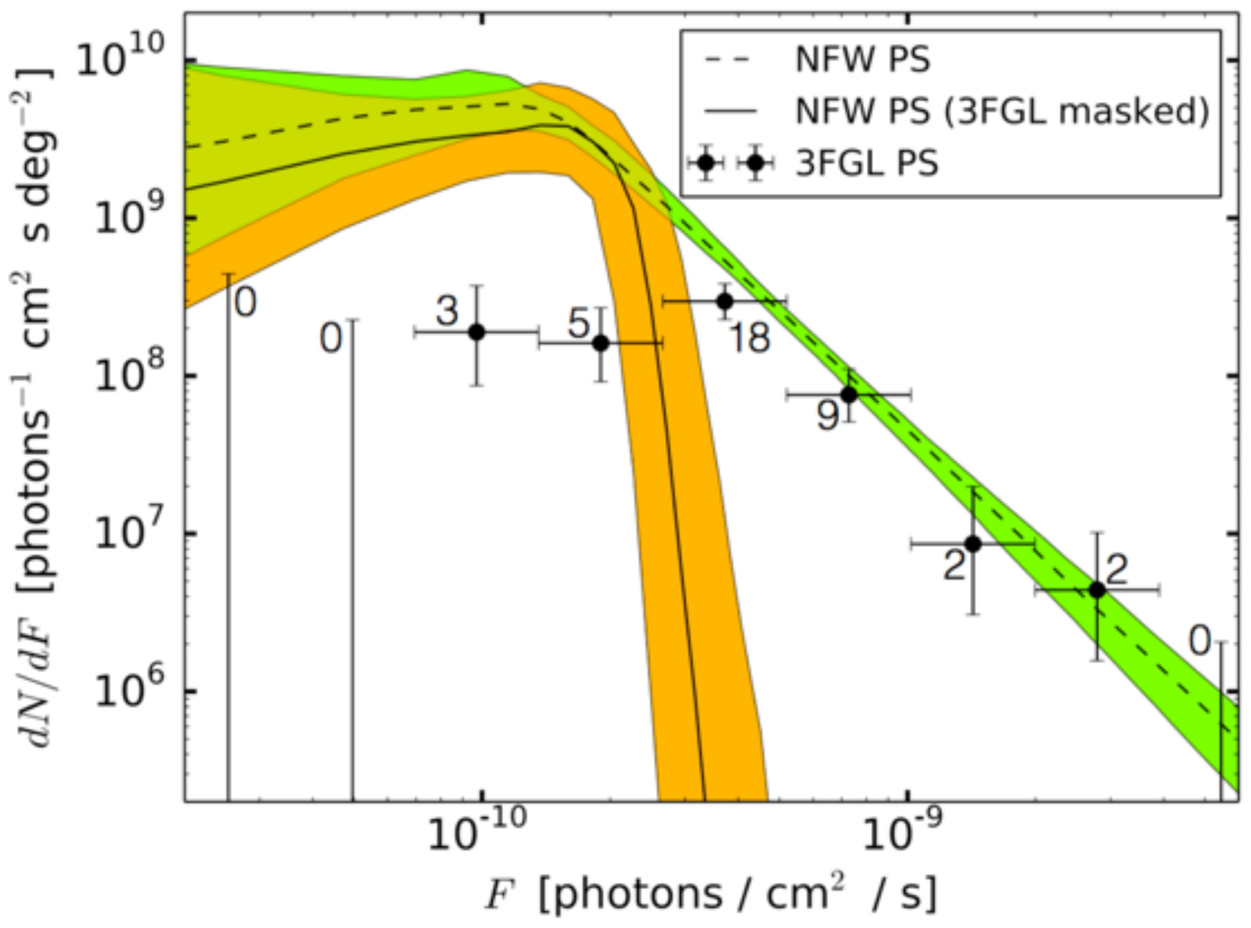
Why Not Pulsars?

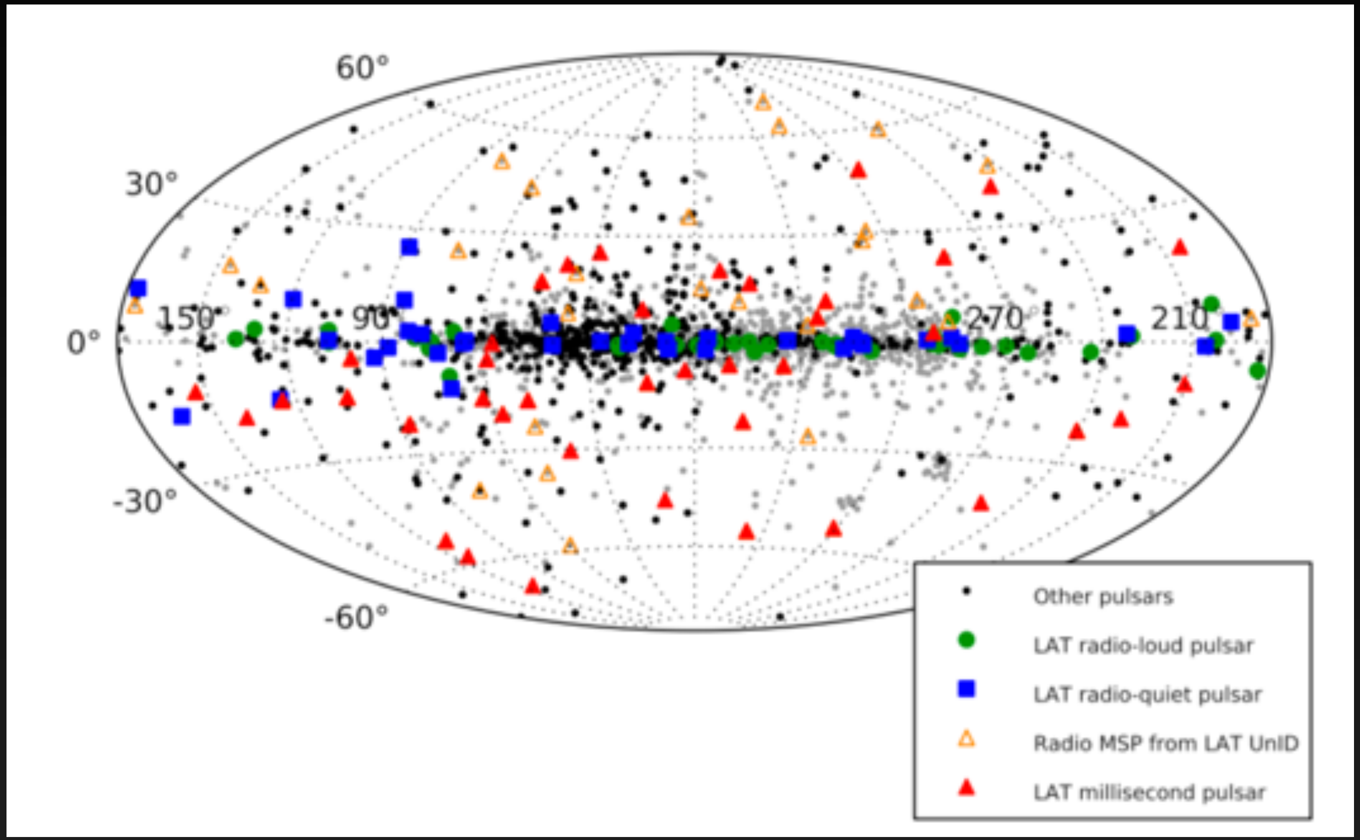




- A luminosity of 10^{35} erg s^{-1} at the galactic center is equivalent to a gamma-ray flux of 8.0×10^{-9} photons cm^{-2} s^{-1}. These systems have not been observed in the Galactic Center.

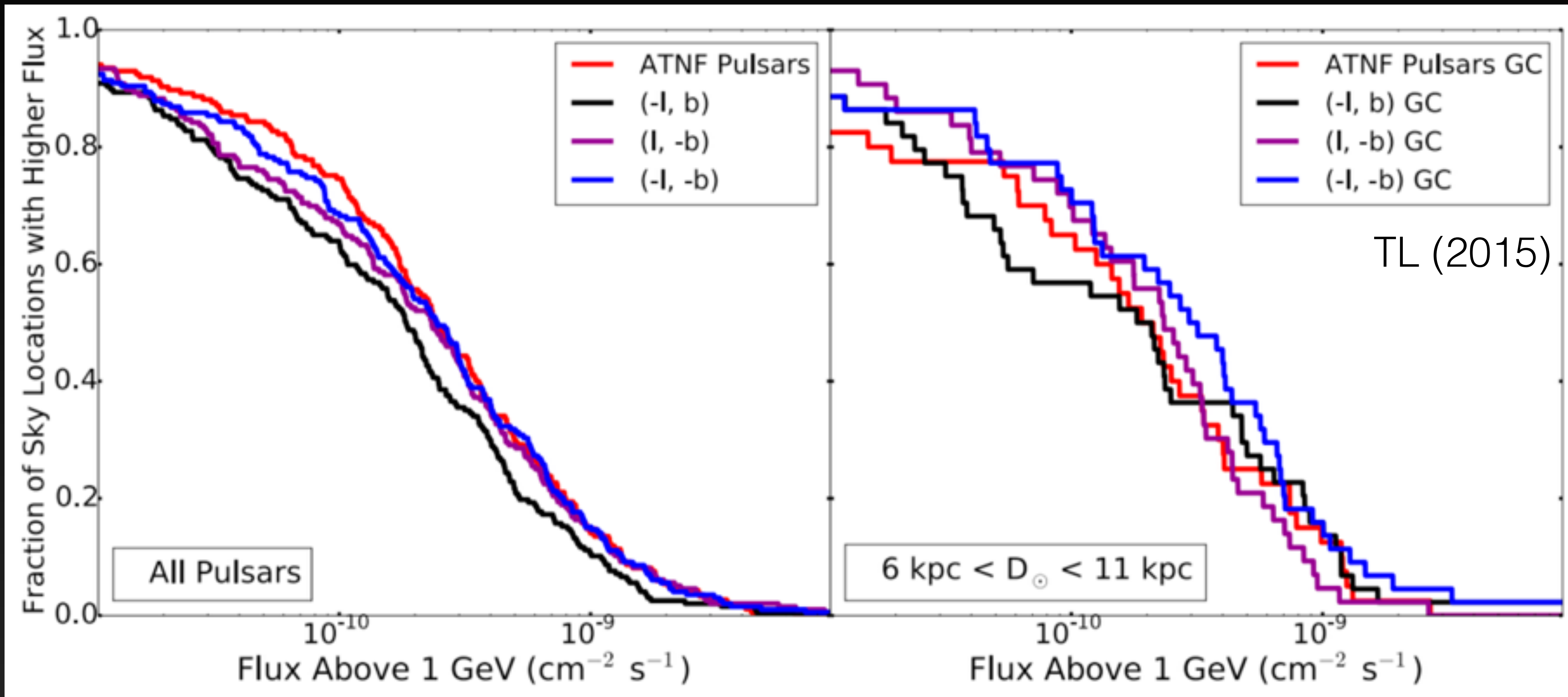
Why Not Pulsars?





- Even if the previous models are a little off, these should be relatively bright sources.
- We can cross-correlate these hotspots 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**

- **see Christoph Weniger's talk tomorrow**

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

Diffuse Gamma-Ray Models

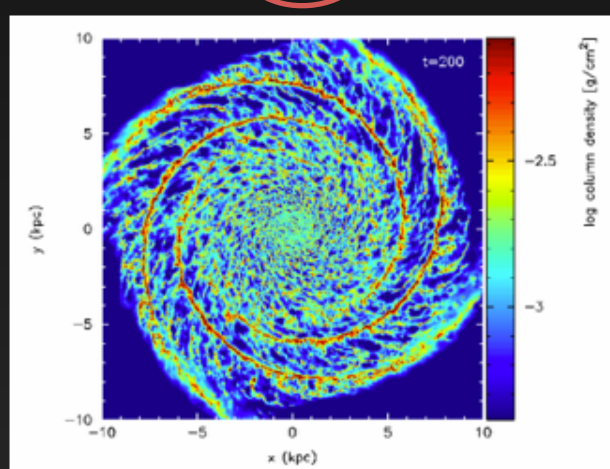
Supernovae Source Cosmic-Ray Protons:
10^{51} erg (~10% in relativistic protons)
(~2% in relativistic electrons)

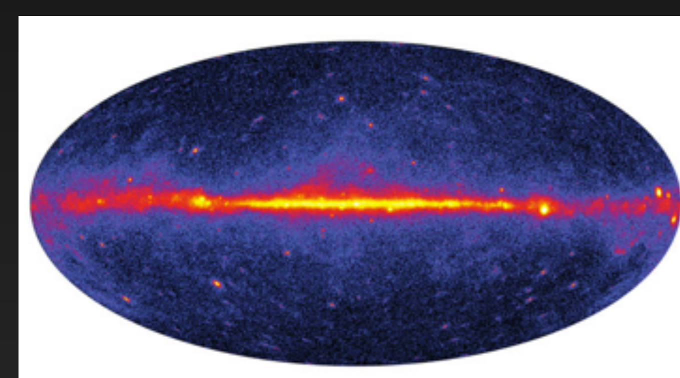
cosmic rays propagate

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

Solved Numerically:
e.g. Galprop

Gas/ISRF





Uncertainties in every step of cosmic-ray diffusion

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

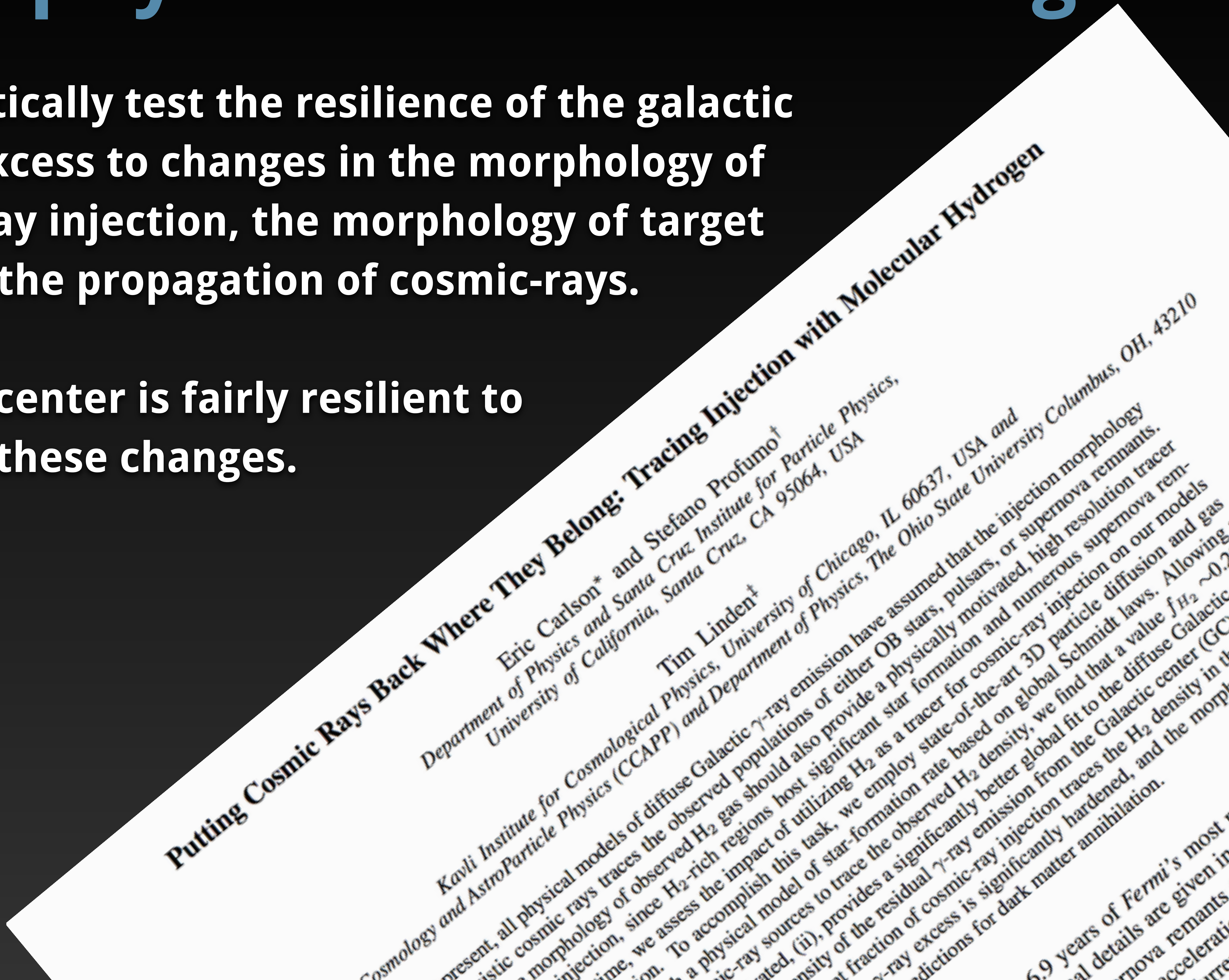
Goodenough & Hooper (2009)	0910.2998
Hooper & Goodenough (2011, PLB 697 412)	1010.2752
Hooper & TL (2011, PRD 84 12)	1110.0006
Abazajian & Kaplinghat (2012, PRD 86 8)	1207.6047
Hooper & Slatyer (2013, PDU 2 18)	1302.6589
Gordon & Macias (2013, PRD 8 8)	1306.5725
Macias & Gordon (2013, PRD 89 6)	1312.6671
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
Cosmology and AstroParticle Physics (CCAPP) 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
istic cosmic rays traces the observed populations of either OB stars, pulsars, or supernova remnants.
morphology of observed H_2 gas should also provide a physically motivated, high resolution tracer
injection, since H_2-rich regions host significant star formation and numerous supernova rem-
time, we assess the impact of utilizing H_2 as a tracer for cosmic-ray injection on our models
To accomplish this task, we employ state-of-the-art 3D particle diffusion and gas
a physical model of star-formation rate based on global Schmidt laws. Allowing
ic-ray sources to trace the observed H_2 density, we find that a value f_{H_2} ~0.2
ated, (ii), provides a significantly better global fit to the diffuse Galactic
nsity of the residual γ-ray emission from the Galactic center (GC
t fraction of cosmic-ray injection traces the H_2 density in th
-ray excess is significantly hardened, and the morph
dictions for dark matter annihilation.

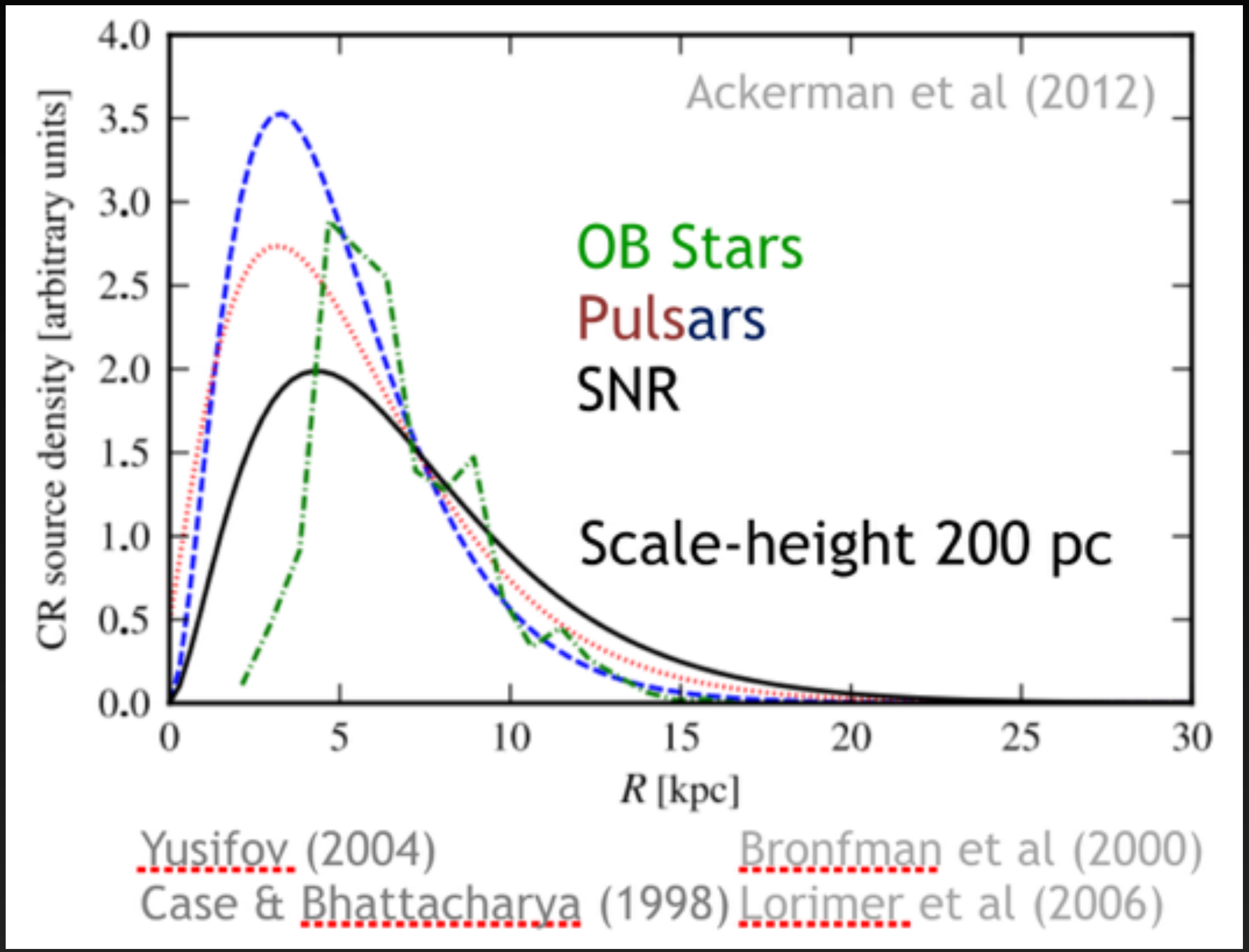
6.9 years of *Fermi*'s most
al details are given in
rnova remnants
accelera

Cosmic-Ray Injection Sources

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

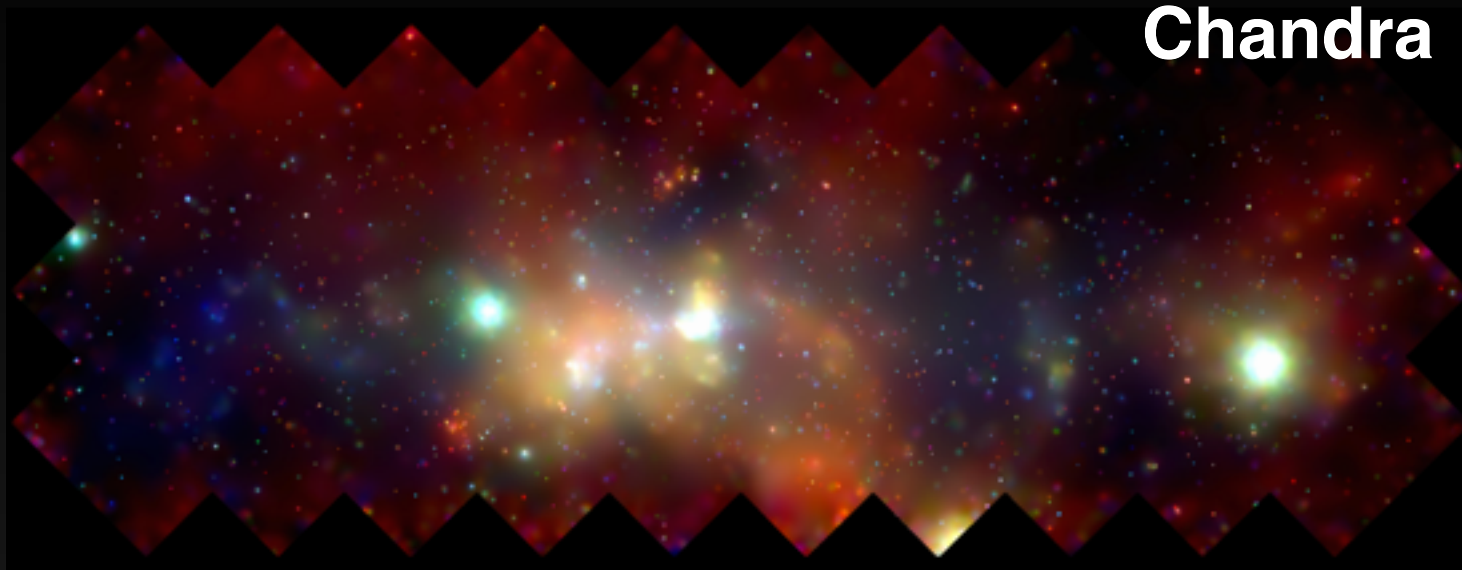
Need tracers of current and past supernovae rate:

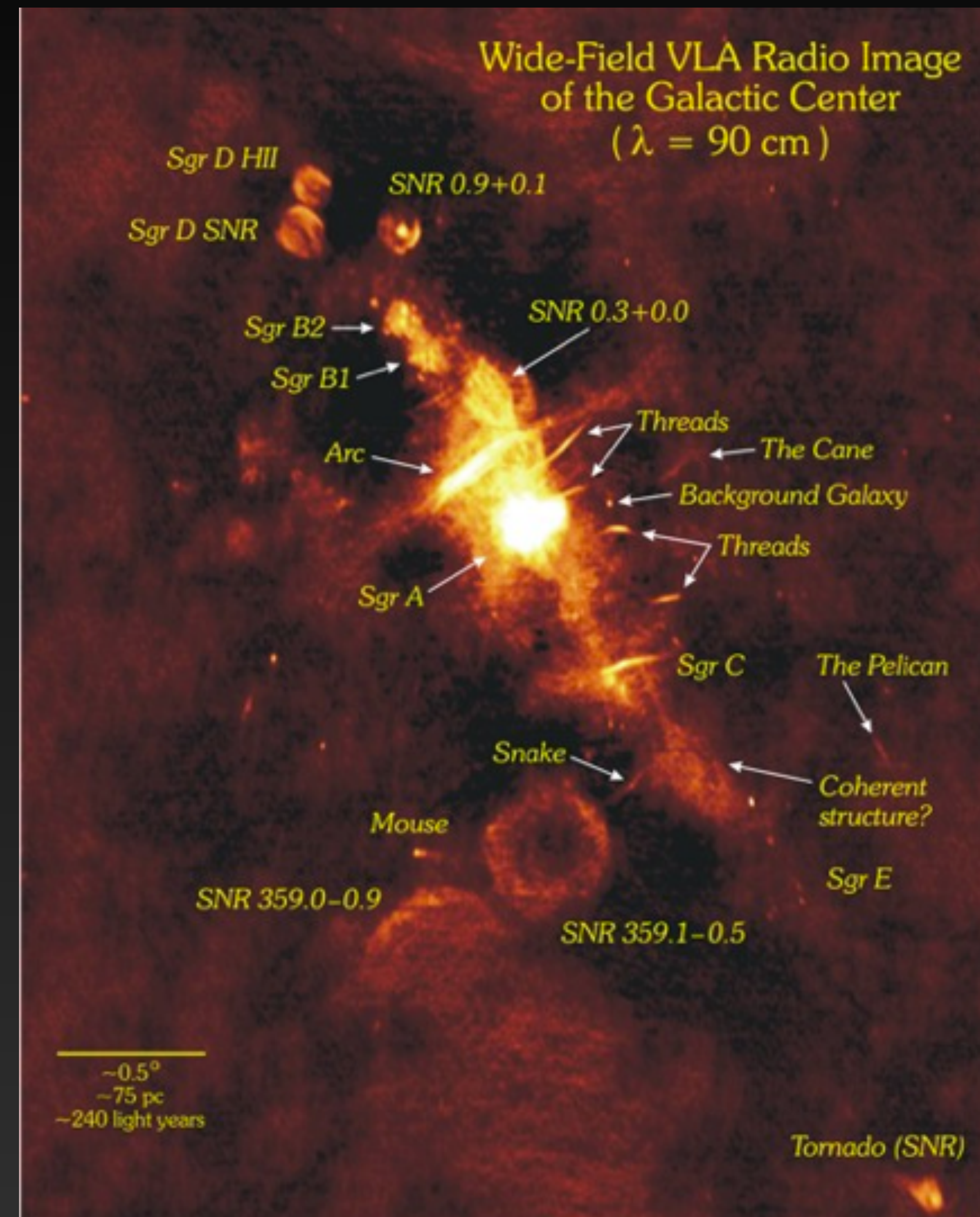
- **Observed SNR**
- **Pulsars**
- **OB Stars**



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

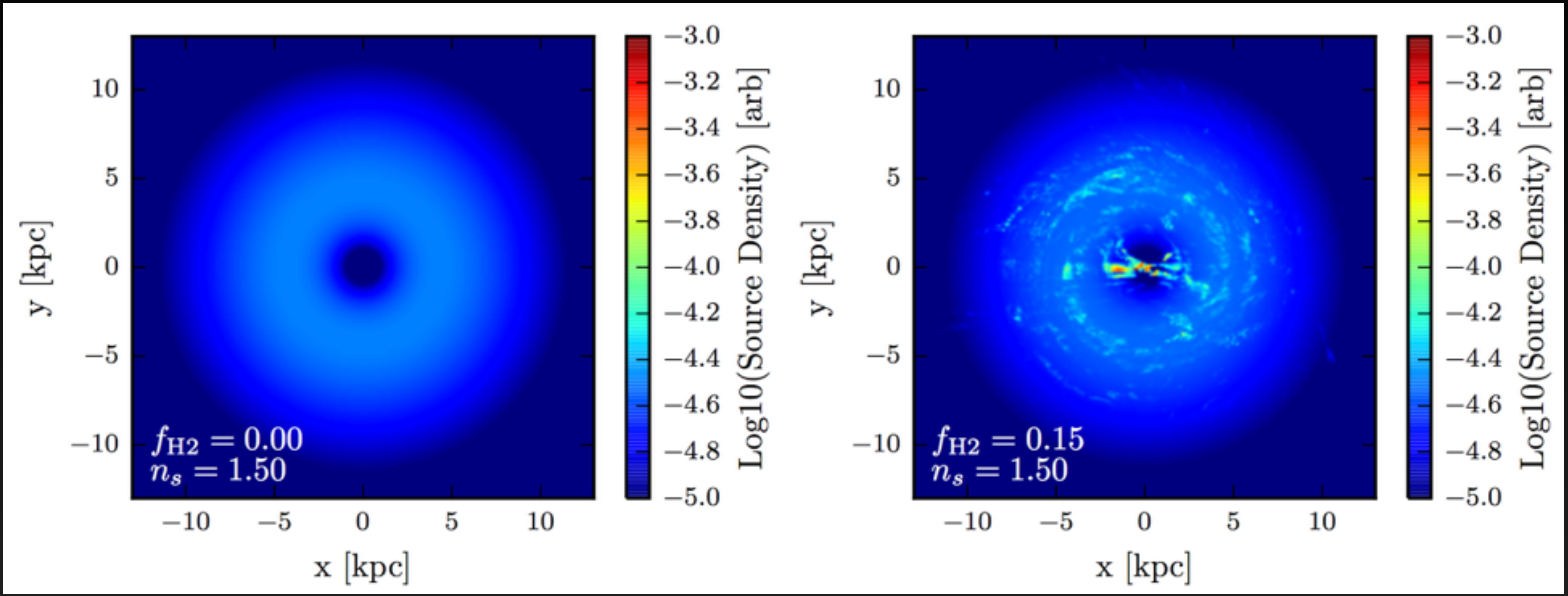
The Galactic Center in Gamma-Rays





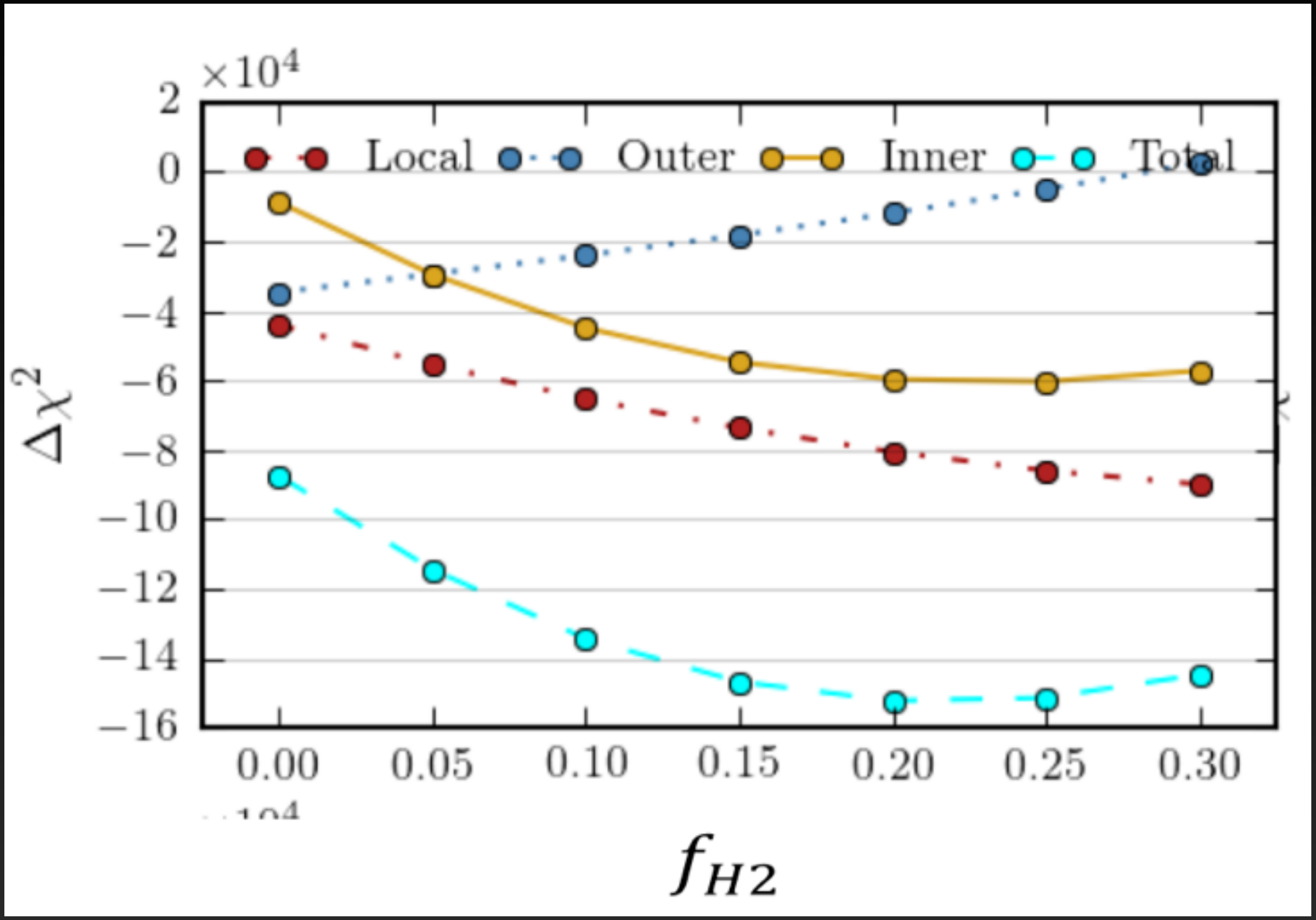
But we know that the Galactic Center contains significant cosmic-ray injection.

Adding a Molecular Gas Component



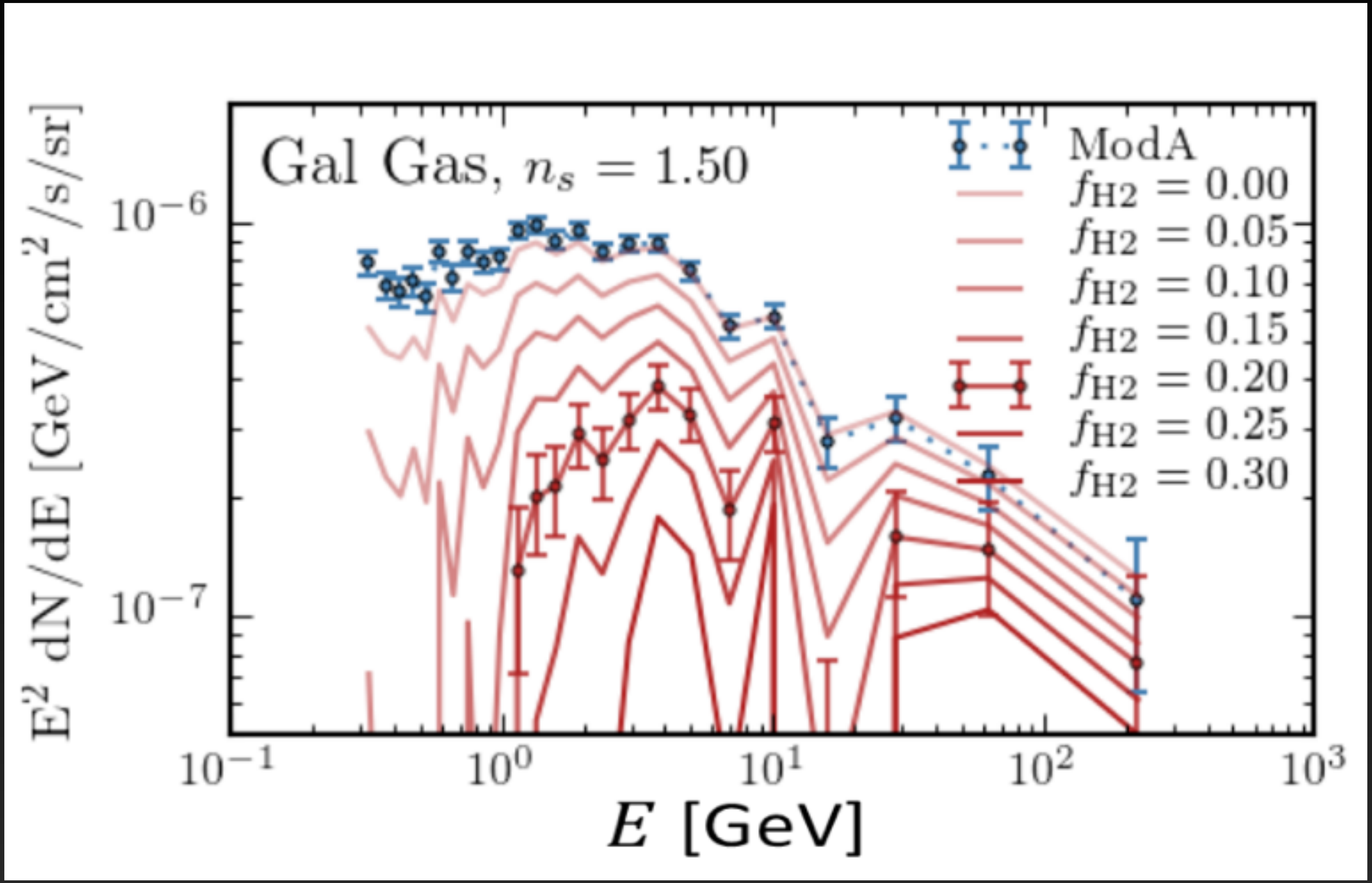
Adds significant cosmic-ray injection to the inner galaxy, and additionally a large bar structure.

Adding a Molecular Gas Component



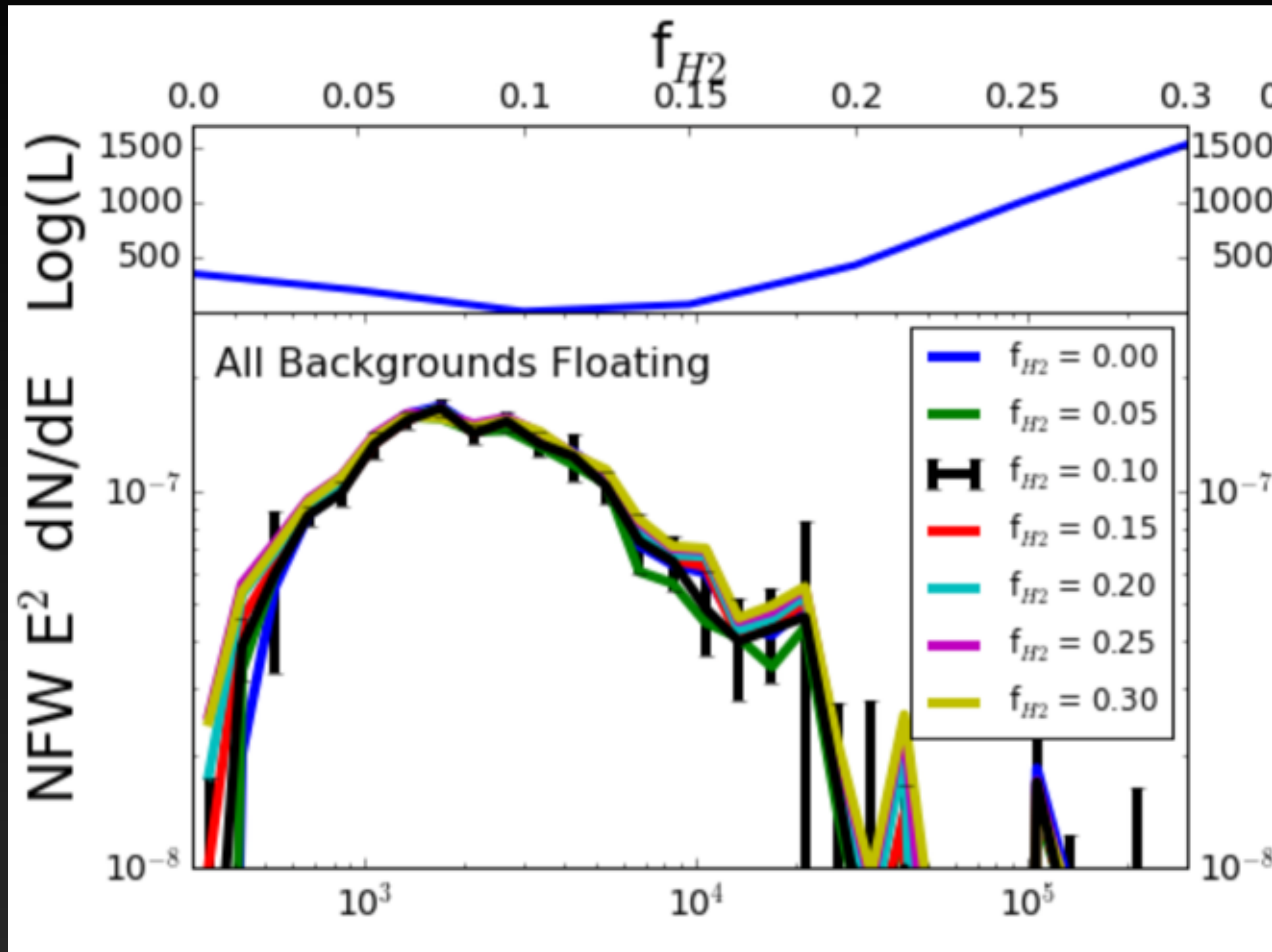
This tracer improves the fit to the gamma-ray data over the full sky.

This Reduces the Gamma-Ray Excess!



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

Why Not Astrophysical Modeling?



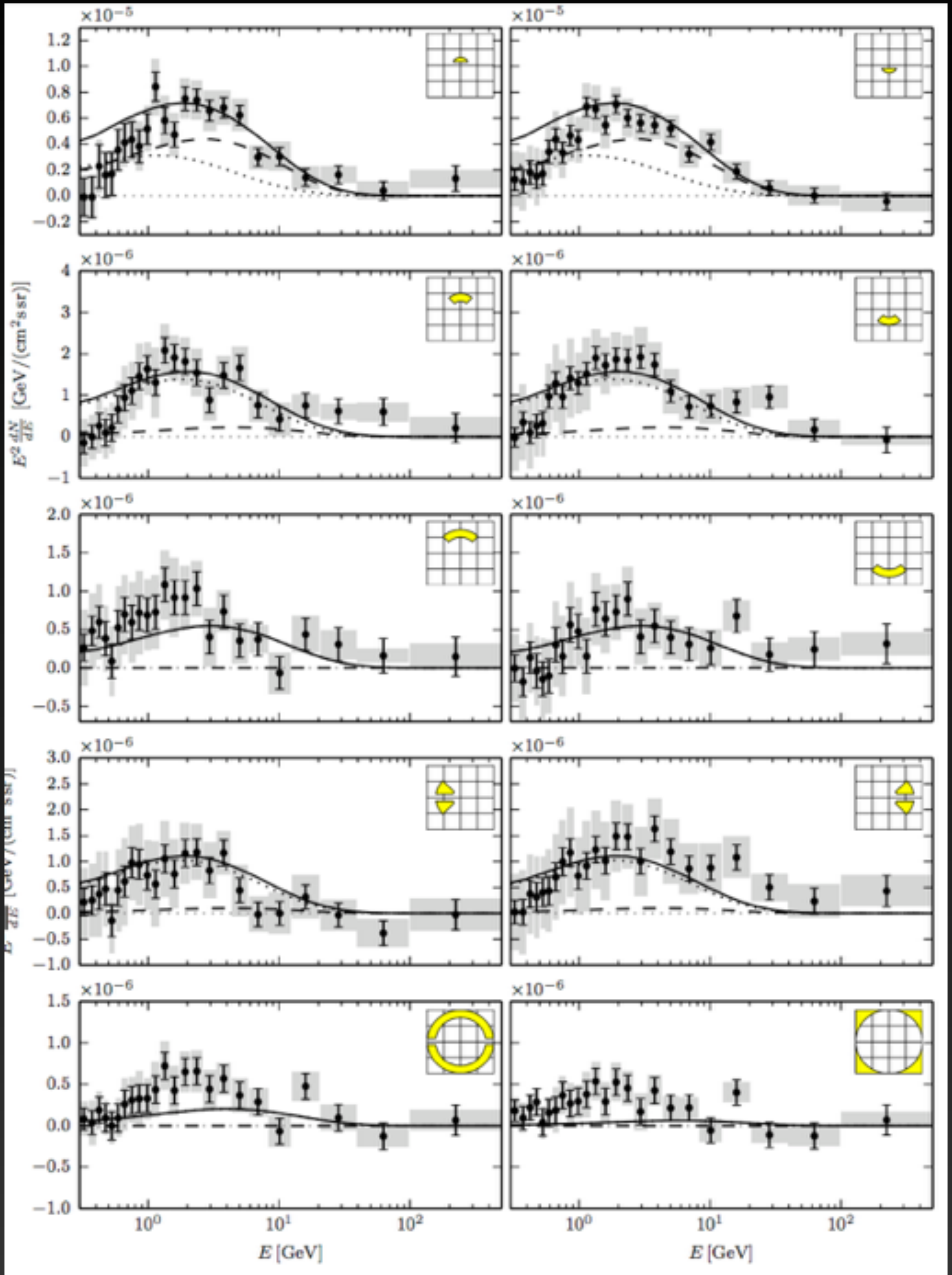
Moreover, when we focus on the very center of the galaxy (<2º), these alterations to the gamma-ray model do not appear to decrease the intensity of the gamma-ray excess.

Leptonic Outbursts

Cholis et al. (2015)

Outbursts of high energy electrons from the Galactic center can produce gamma-rays through inverse Compton scattering of the starlight.

Starlight is relatively spherically symmetric, so this can reproduce the spherical symmetry of the excess.



Why not Leptonic Outbursts?

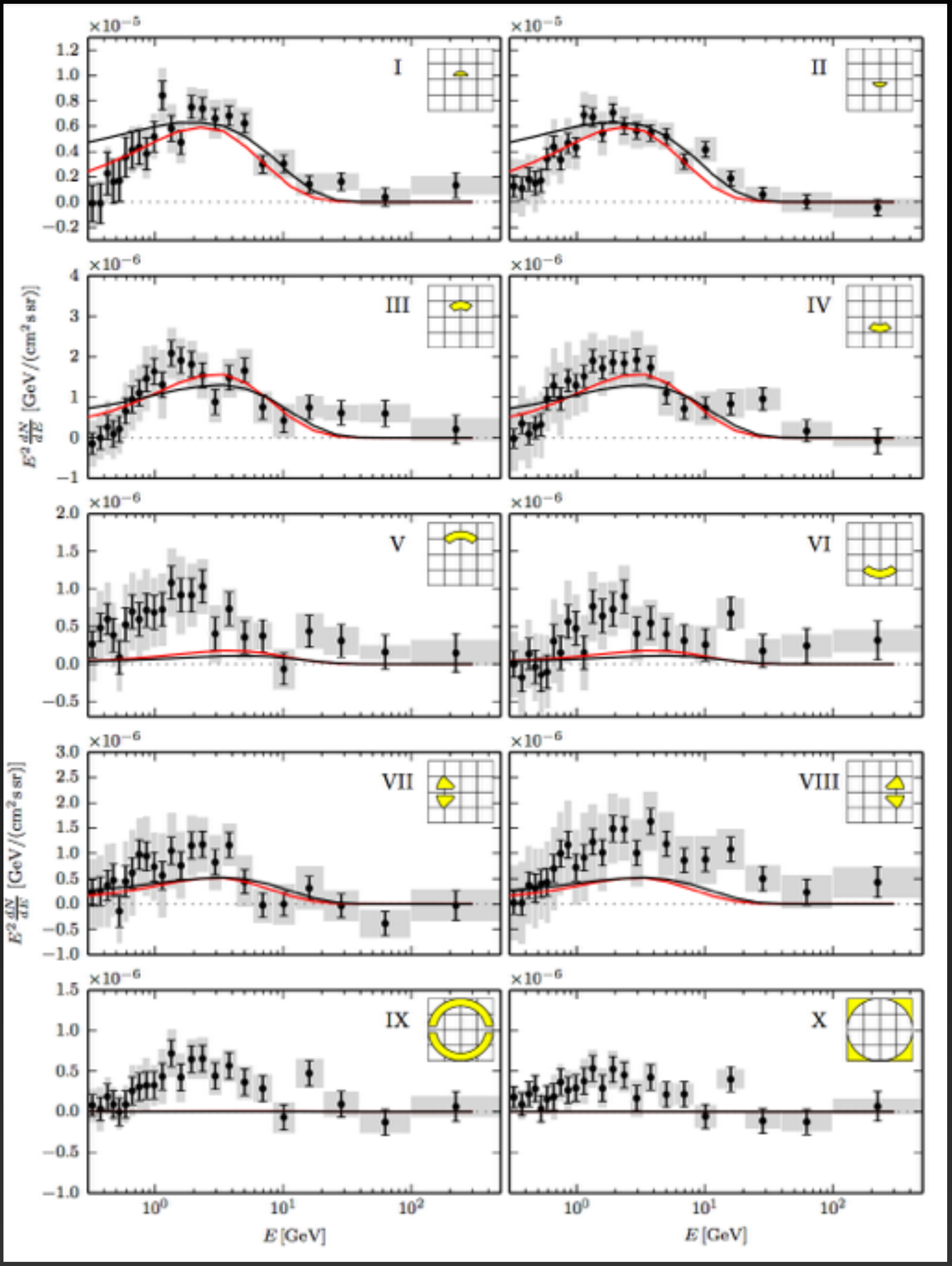
However, the previous model uses two outbursts, which must be:

Hard spectrum (compared to astrophysical diffuse emission)

Well timed (100 kyr and 1 Myr)

Carefully weighted (older outburst must be 10x brighter)

Single outbursts cannot produce the GC morphology.



The Status of the Galactic Center Excess

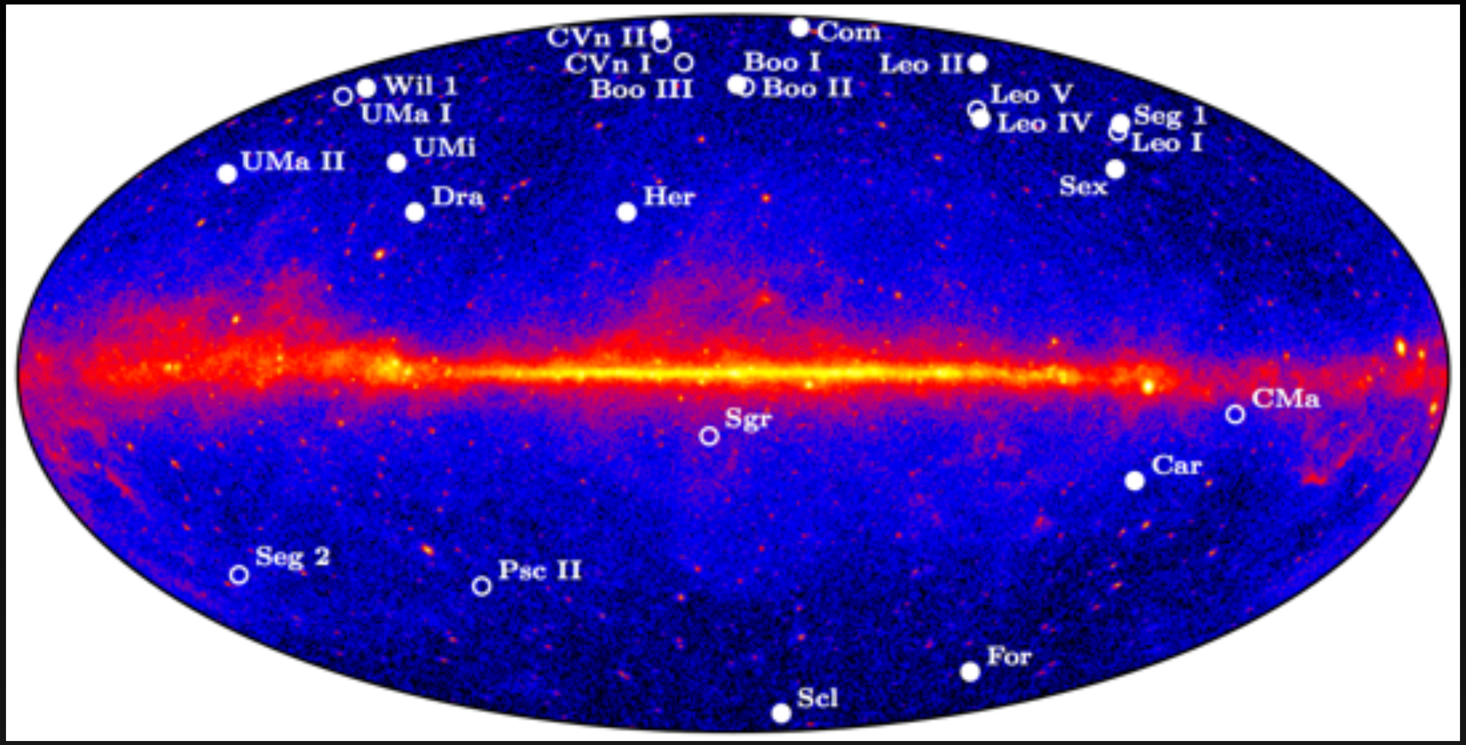
1.) Over the last two years - the existence of a significant gamma-ray excess (compared to current astrophysical models) has been confirmed.

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.

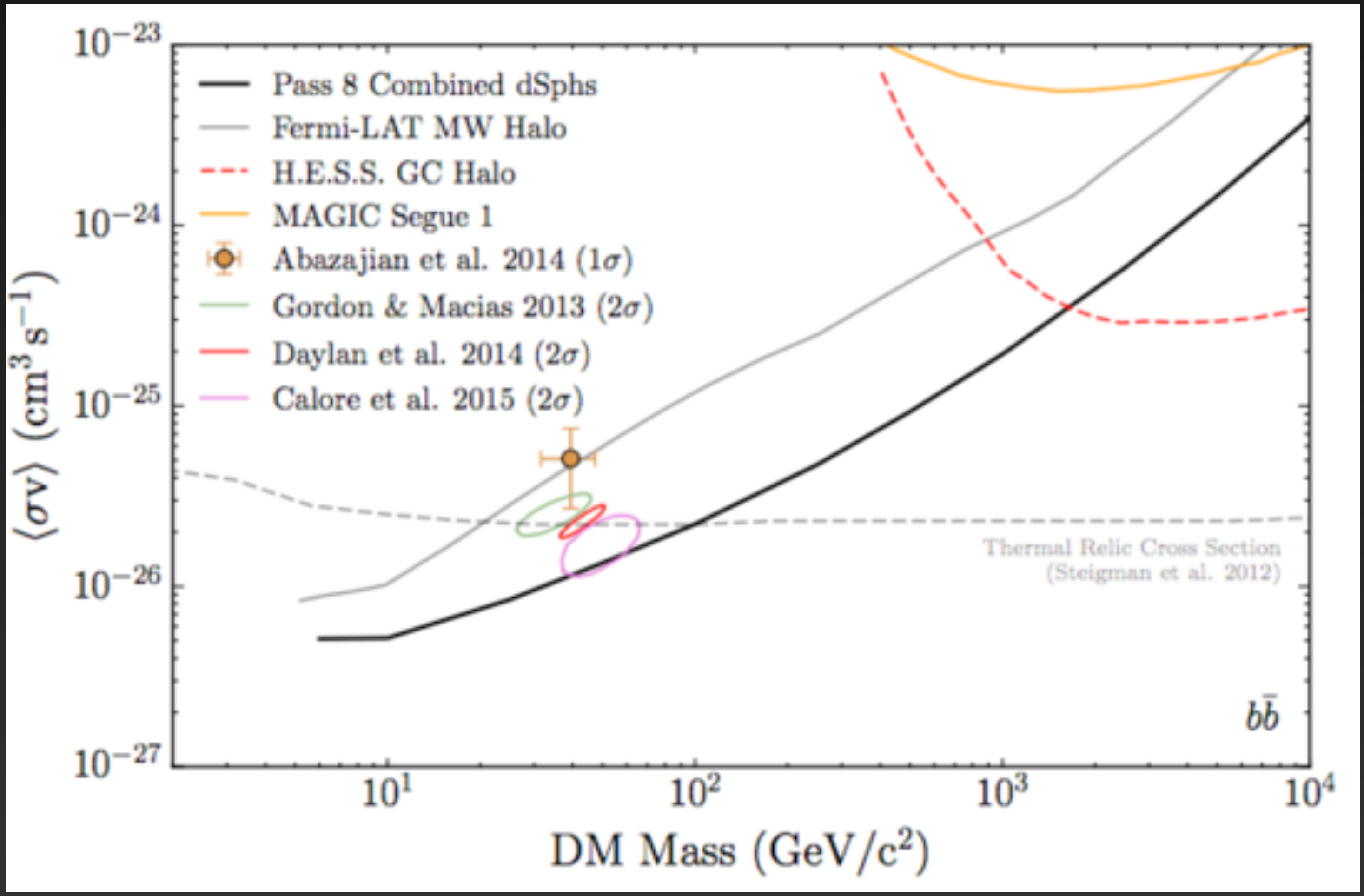
4.) New multi wavelength models and studies are needed.

Dwarf Galaxies

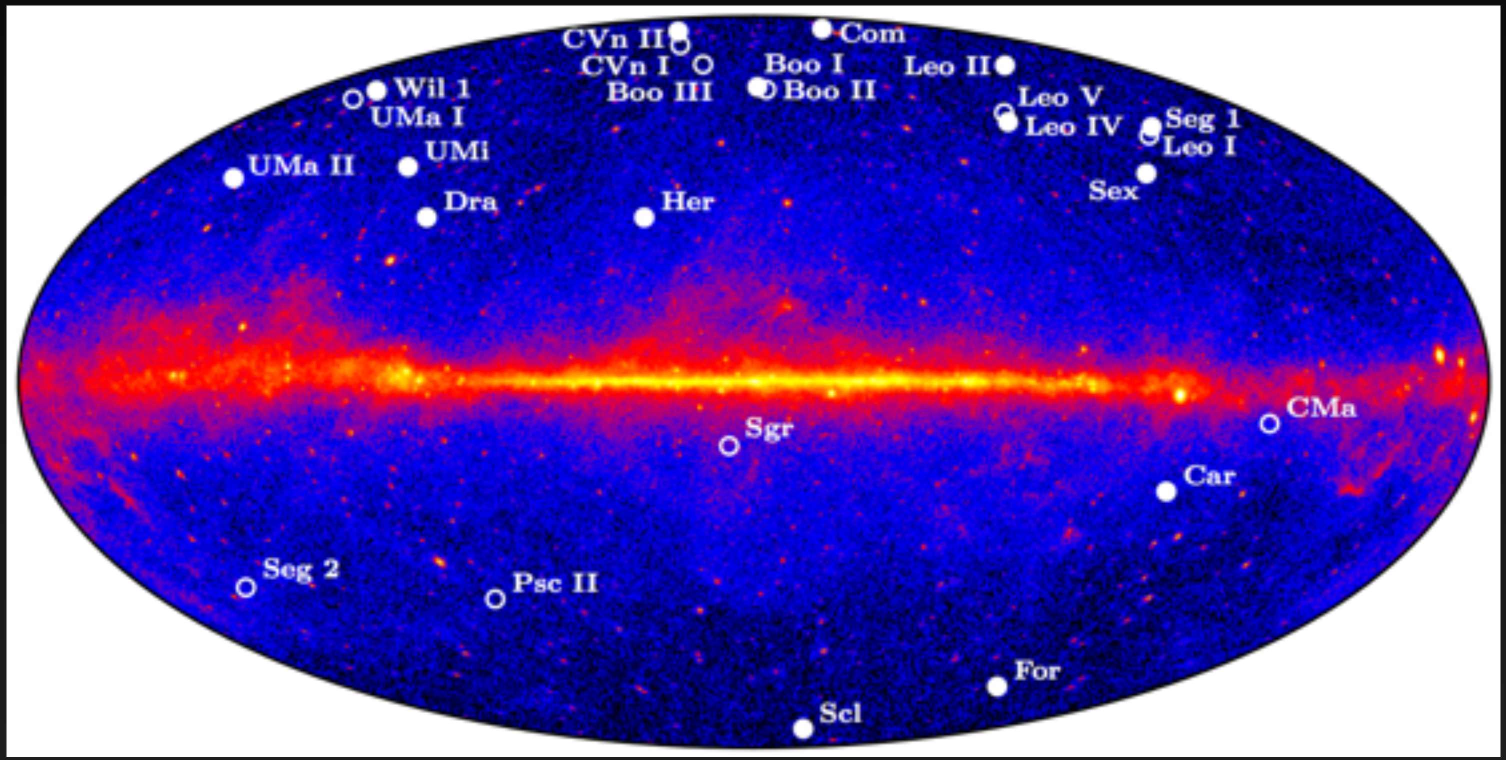


Dwarf Galaxies can also produce a significant γ-ray signal from dark matter annihilation.

Current results using 6 years of Fermi-LAT data are already in slight tension with the GC excess, though many systematic uncertainties remain.

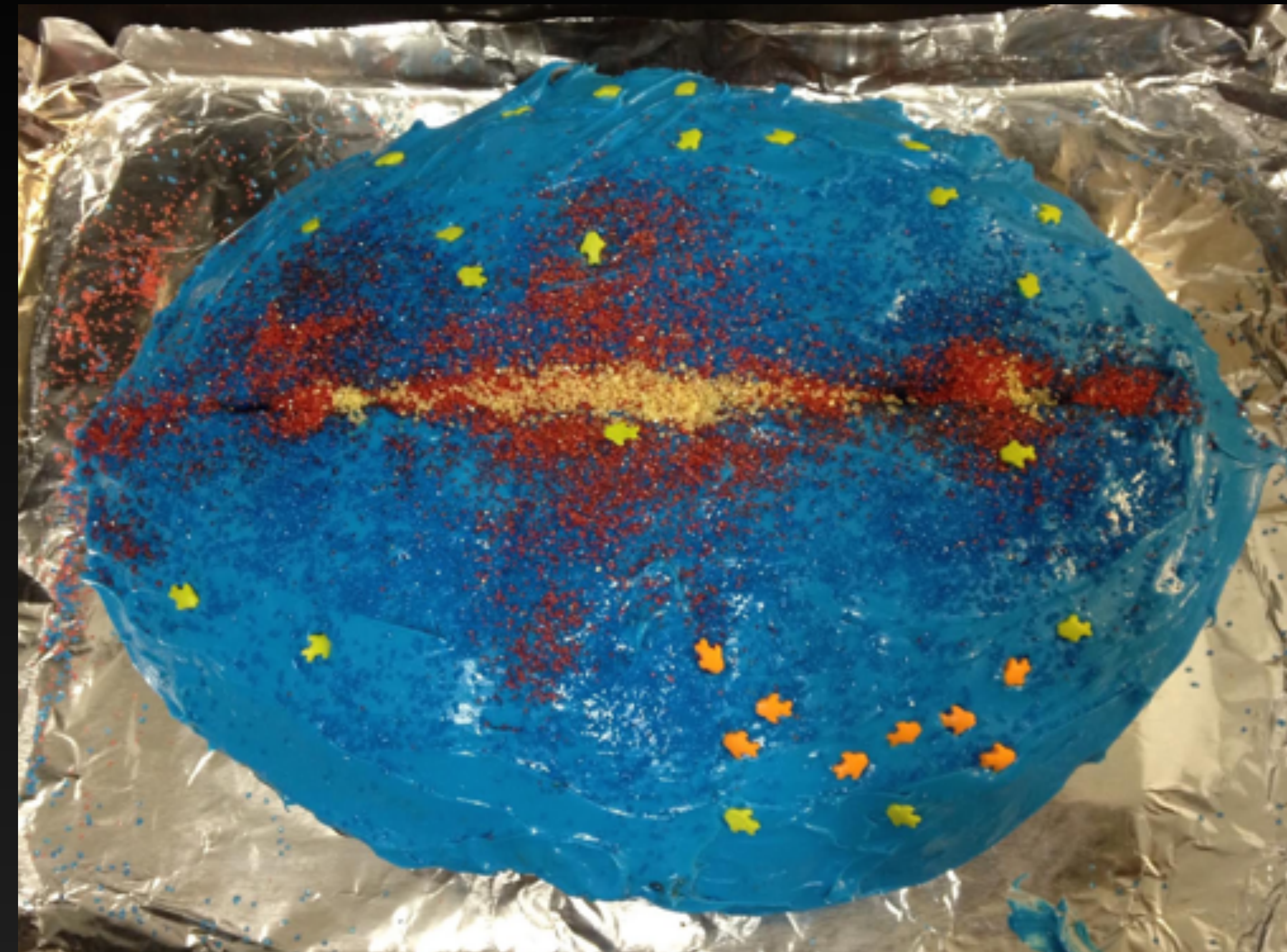


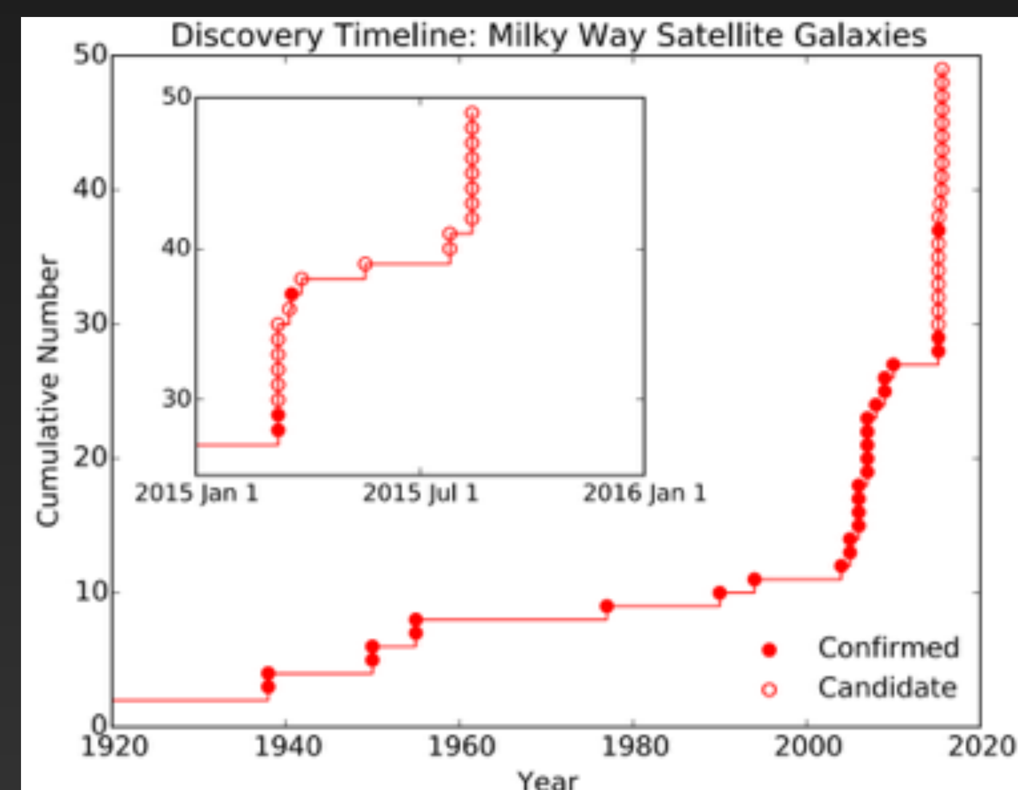
Alternative Targets



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.

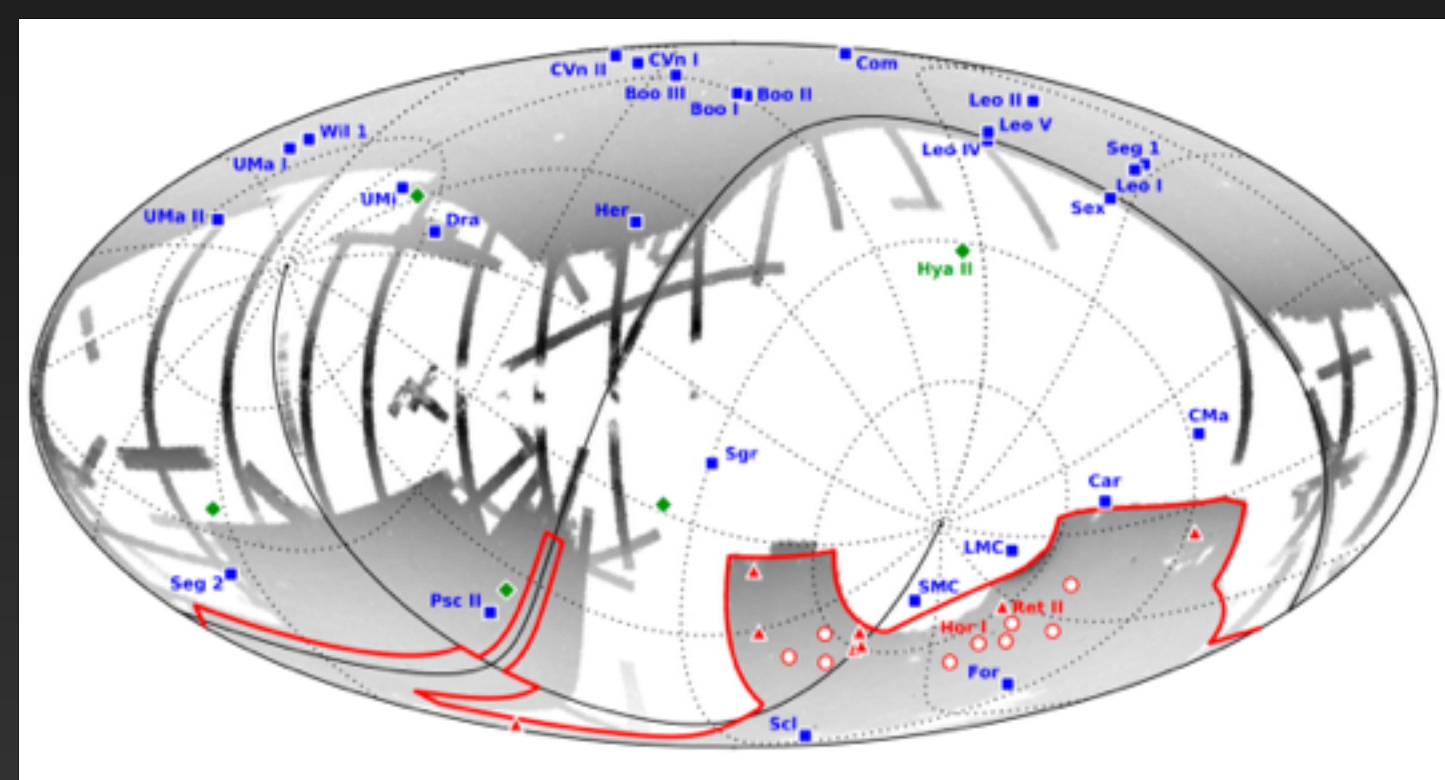
Alternative Targets





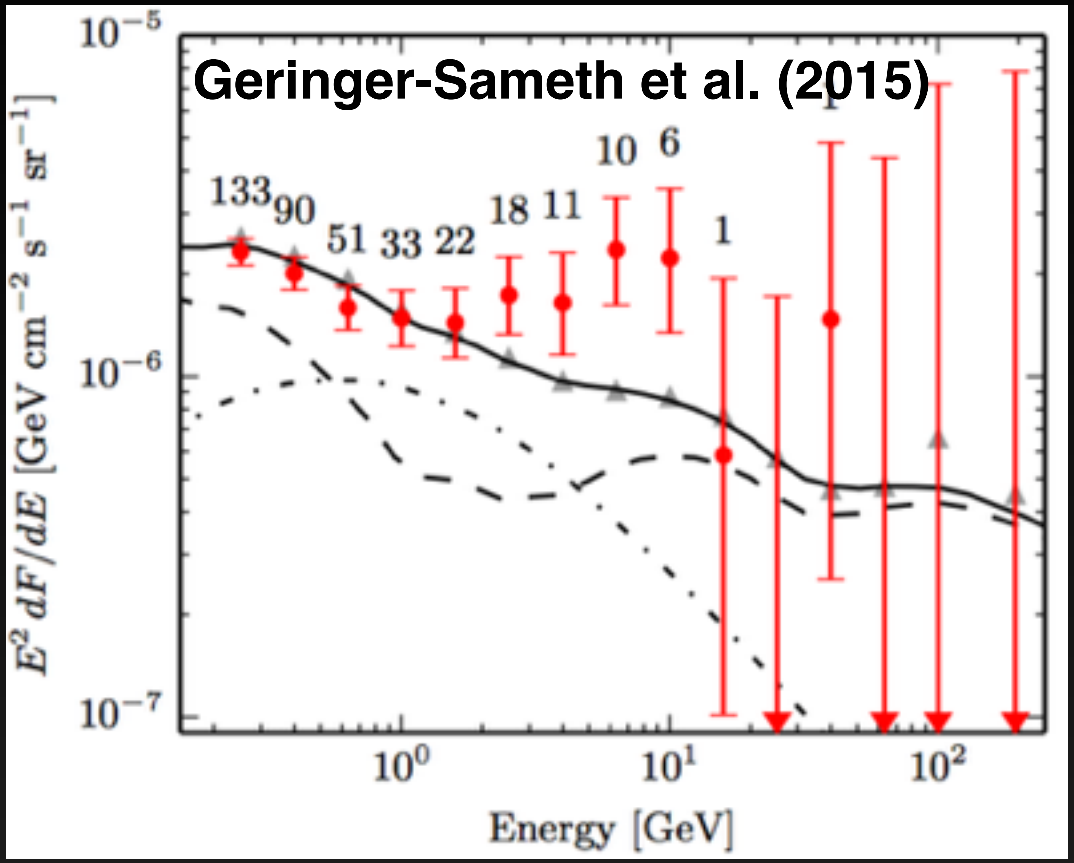
Analyses of the DES, and Pan-Starrs Data have recently observed 19 (and counting) new dwarf candidates in the Southern Hemisphere.

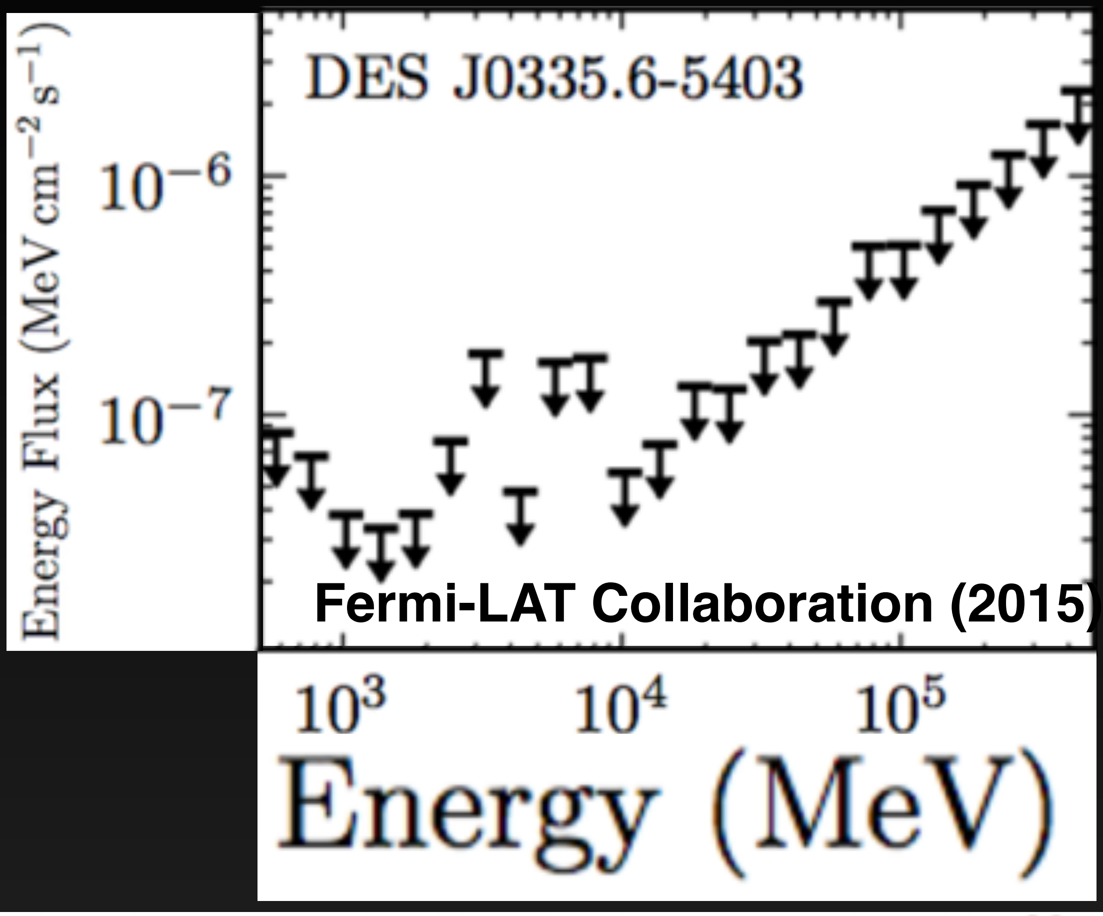
Alternative Targets

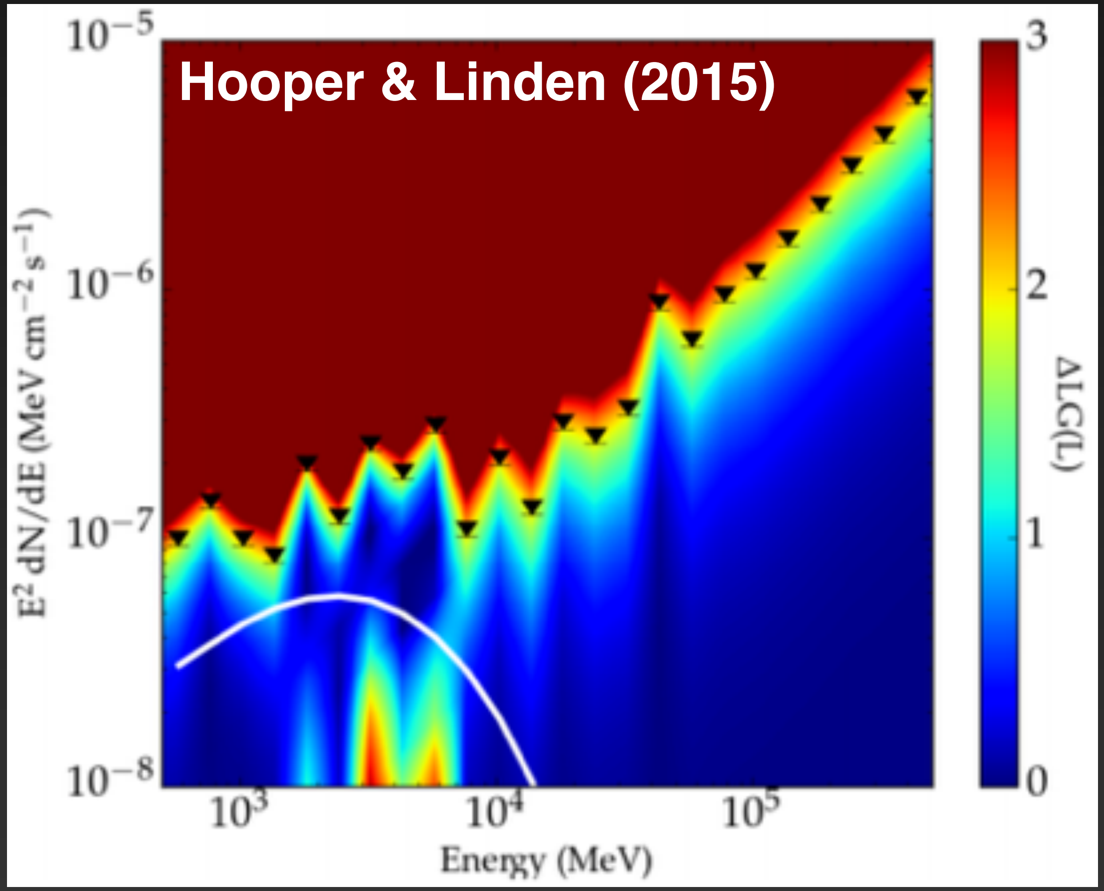


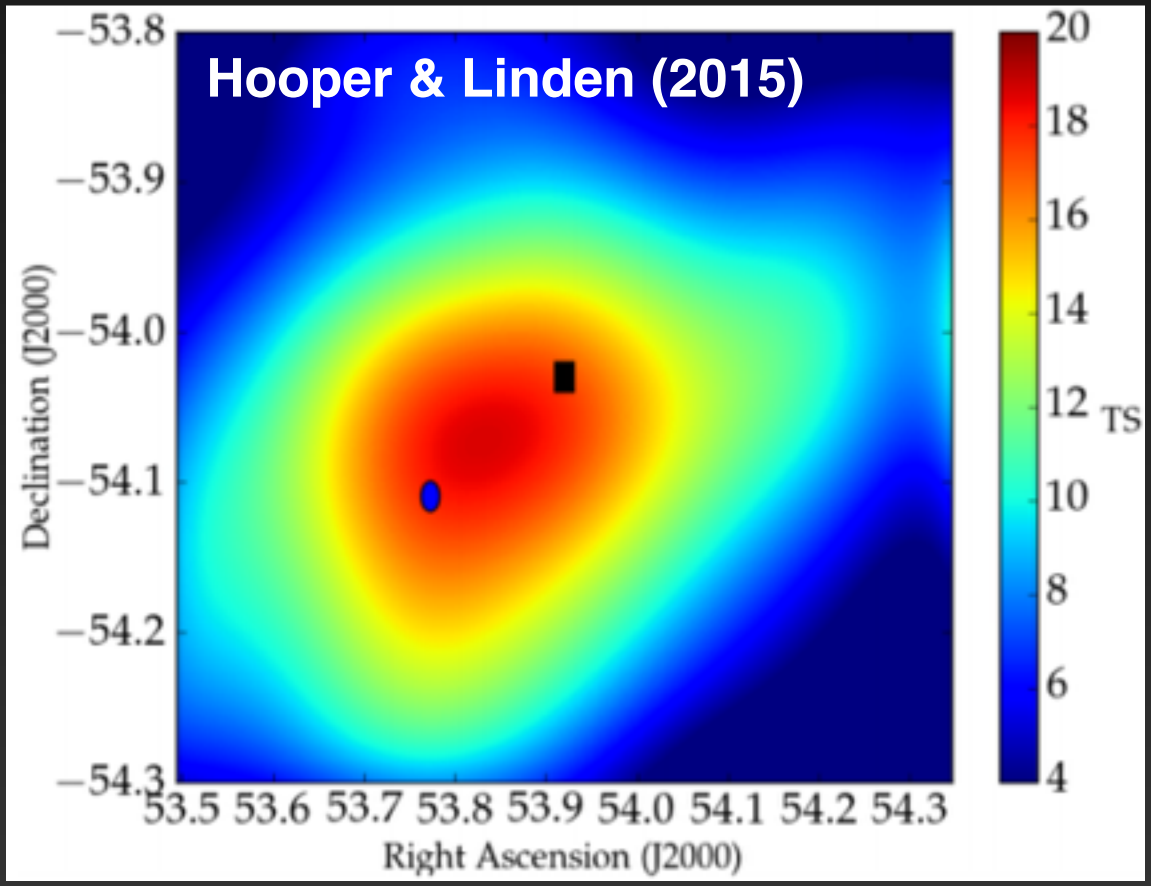
Analyses of the DES, and Pan-Starrs Data have recently observed 19 (and counting) new dwarf candidates in the Southern Hemisphere.

Reticulum 2 has an excess!









But other Dwarfs Do Not

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.

A self consistent picture requires that Reticulum II have the largest J-factor of any known dwarf galaxy.


TRIANGULUM II: POSSIBLY A VERY DENSE ULTRA-FAINT DWARF GALAXY

Evan N. Kirby[1], Judith G. Cohen[1], Joshua D. Simon[2], Puragra Guhathakurta[3]

Accepted to ApJL on 2015 November 3

ABSTRACT

...s et al. recently discovered Triangulum II, a satellite of the Milky Way. Its Galactocentric distance is ...inosity is only 450 $L_\odot$. Using Keck/DEIMOS, we measured the radial velocities of six member st... ...ter of Triangulum II, and we found a velocity dispersion of $\sigma_v = 5.1^{+4.0}_{-1.4}$ km s^{-1}. We al... ...of three stars and found a range of 0.8 dex in [Fe/H]. The velocity and metallic... ...II as a dark matter-dominated galaxy. The galaxy is moving very quickly to... ...km s^{-1}). Although it might be in the process of being tidally disrupt... ...rong evidence for disruption in our data set. The ellipticity is low, a... ...s^{-1}, rules out an association with the Triangulum–Andromeda s... ...rvey (PAndAS) stellar stream. If Triangulum II is in dyn... ...of 3600^{+3500}_{-2100} $M_\odot$ $L_\odot^{-1}$, the highest of any non-disru... ...ble). The density within the 3-D half-light rad... ...ngulum II is an excellent candidate for the...

...Local Group — galaxies: abunda...

...years has ... globular ... Kopo... 201...

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

J. D. Simon,[1] A. Drlica-Wagner,[2] T. S. Li,[3] B. Nord,[2] M. Geha,[4] K. Bechtol,[5] E. Balbinot,[6,7] E. Buckley-Geer,[2] H. Lin,[2] J. Marshall,[3] B. Santiago,[8,7] L. Strigari,[3] M. Wang,[3] R. H. Wechsler,[9,10,11] B. Yanny,[2] T. Abbott,[12] A. H. Bauer,[13] G. M. Bernstein,[14] E. Bertin,[15,16] D. Brooks,[17] D. L. Burke,[10,11] D. Capozzi,[18] A. Carnero Rosell,[7,19] M. Carrasco Kind,[20,21] C. B. D'Andrea,[18] L. N. da Costa,[7,19] D. L. DePoy,[3] S. Desai,[22] H. T. Diehl,[2] S. Dodelson,[2,5] C. E Cunha,[10] J. Estrada,[2] A. E. Evrard,[23] A. Fausti Neto,[7] E. Fernandez,[24] 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. Honscheid,[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. Wester[2]
(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 $\log_{10}(J) = 18.8 \pm 0.6\,\mathrm{GeV}^2\,\mathrm{cm}^{-5}$ 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 spectroscopers 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 Bonnivard[1], Céline Combet[1], David Maurin[1], Alex Geringer-Sameth[2], Savvas M. Koushiappas[3], Matthew G. Walker[2], Mario Mateo[4], Edward W. Olszewski[5], and John I. Bailey III[4]

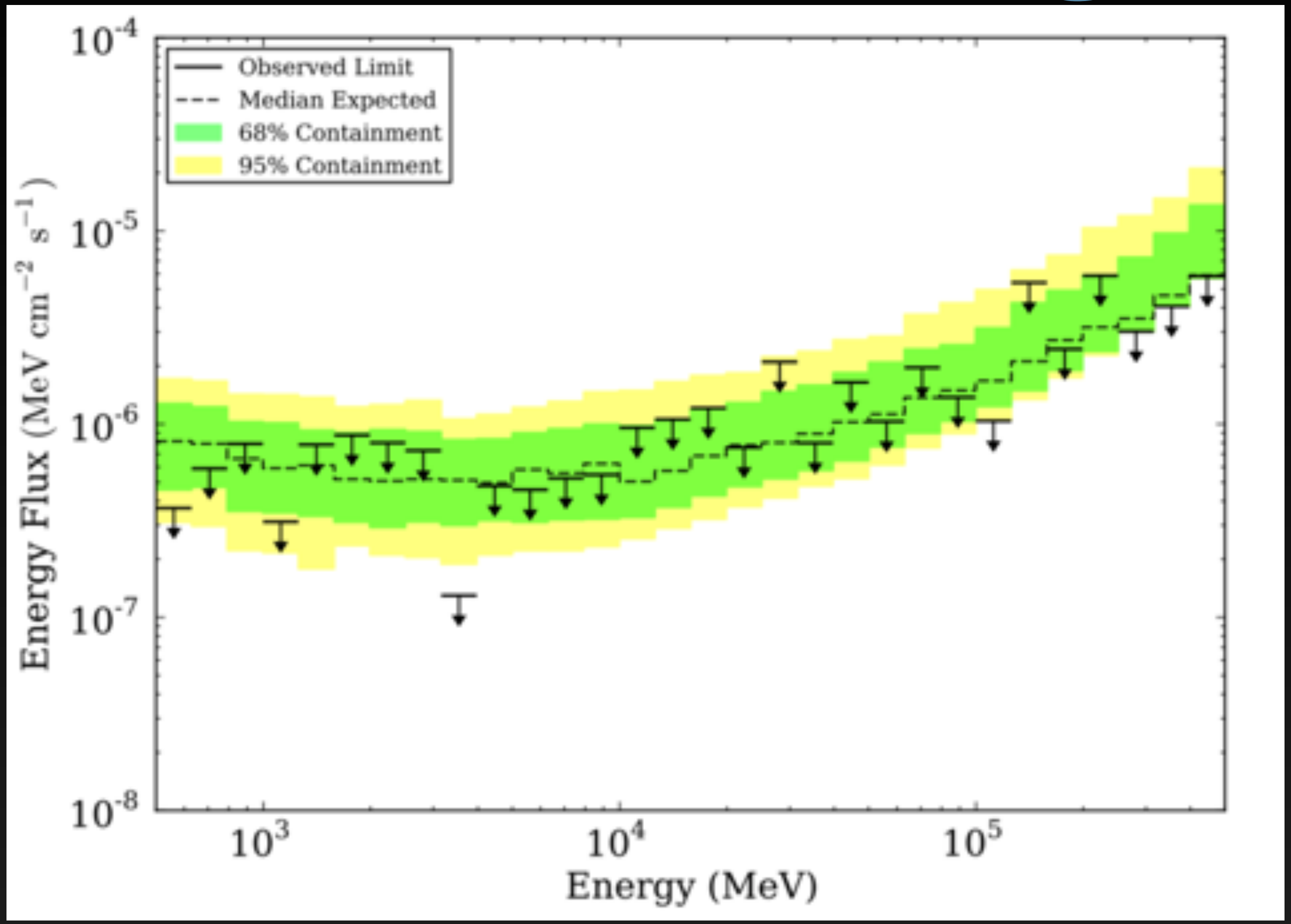
Draft version April 14, 2015

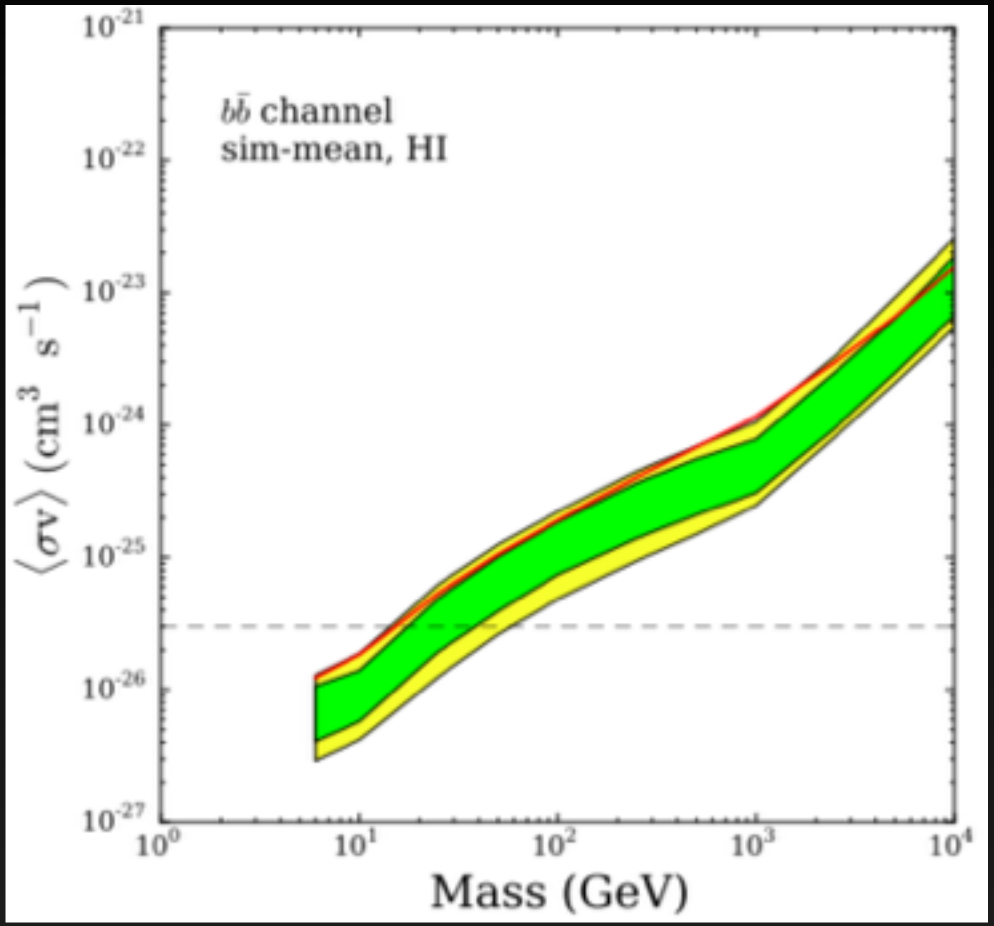
$\alpha_{\rm int}$ [deg]	$\log_{10}(J(\alpha_{\rm int}))$ $[J/{\rm GeV}^2\,{\rm cm}^{-5}]$[a]
0.01	$16.9^{+0.5(+1.1)}_{-0.4(-0.8)}$
0.05	$18.2^{+0.5(+1.0)}_{-0.4(-0.7)}$
0.1	$18.6^{+0.6(+1.1)}_{-0.4(-0.8)}$
0.5	$19.5^{+1.0(+1.6)}_{-0.6(-1.3)}$
1	$19.7^{+1.2(+2.0)}_{-0.9(-1.5)}$

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

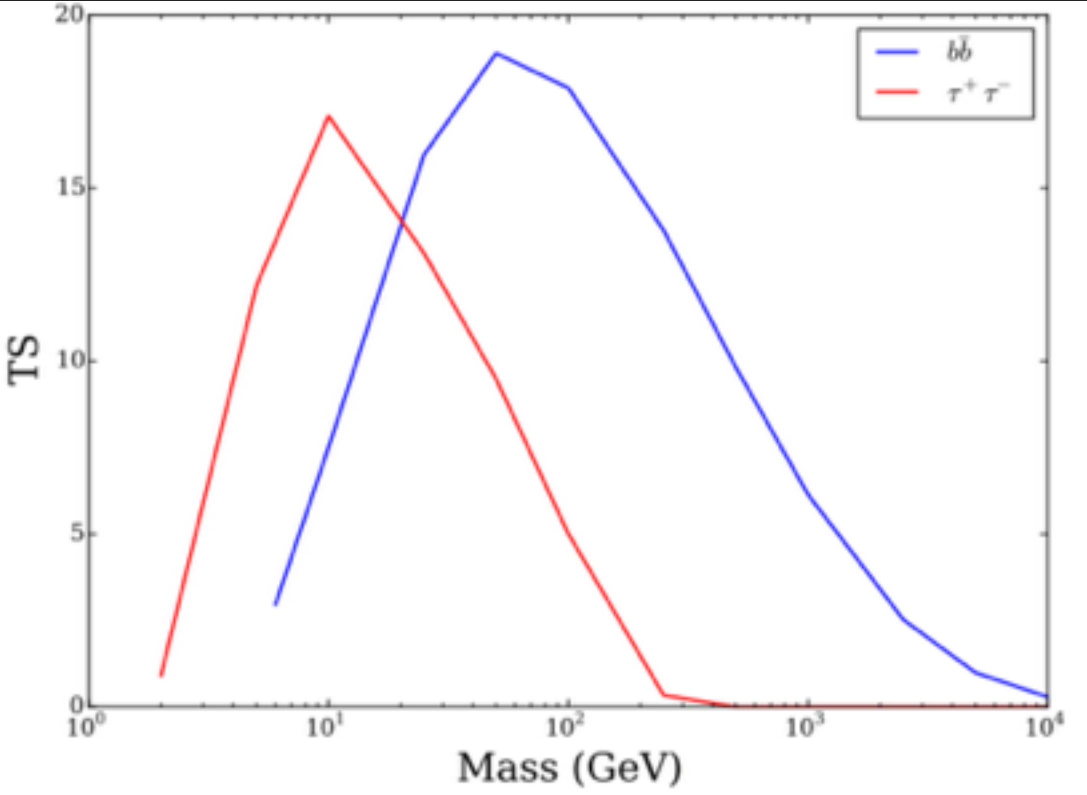
Alternative Targets





The LMC also shows hints of a dark matter excess

However, there are considerable backgrounds here as well.



Buckley et al. (2015)

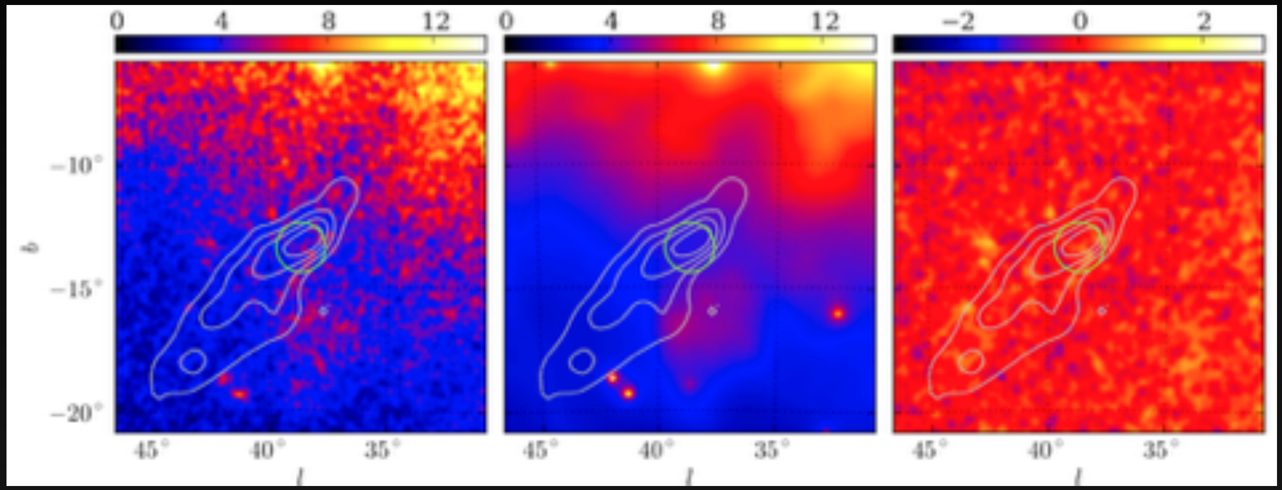
Alternative Targets

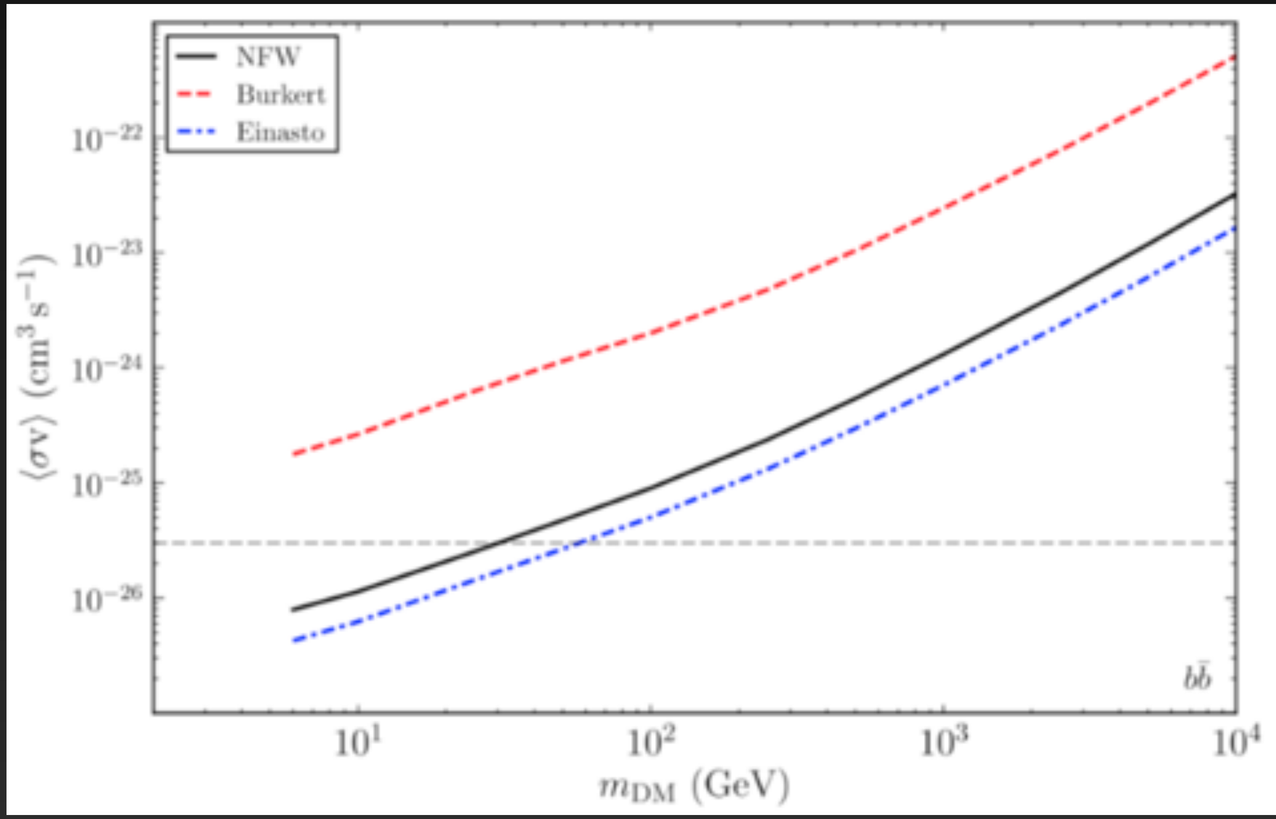
May find other bright indirect detection targets.

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)

Comparison to Dark Matter Models

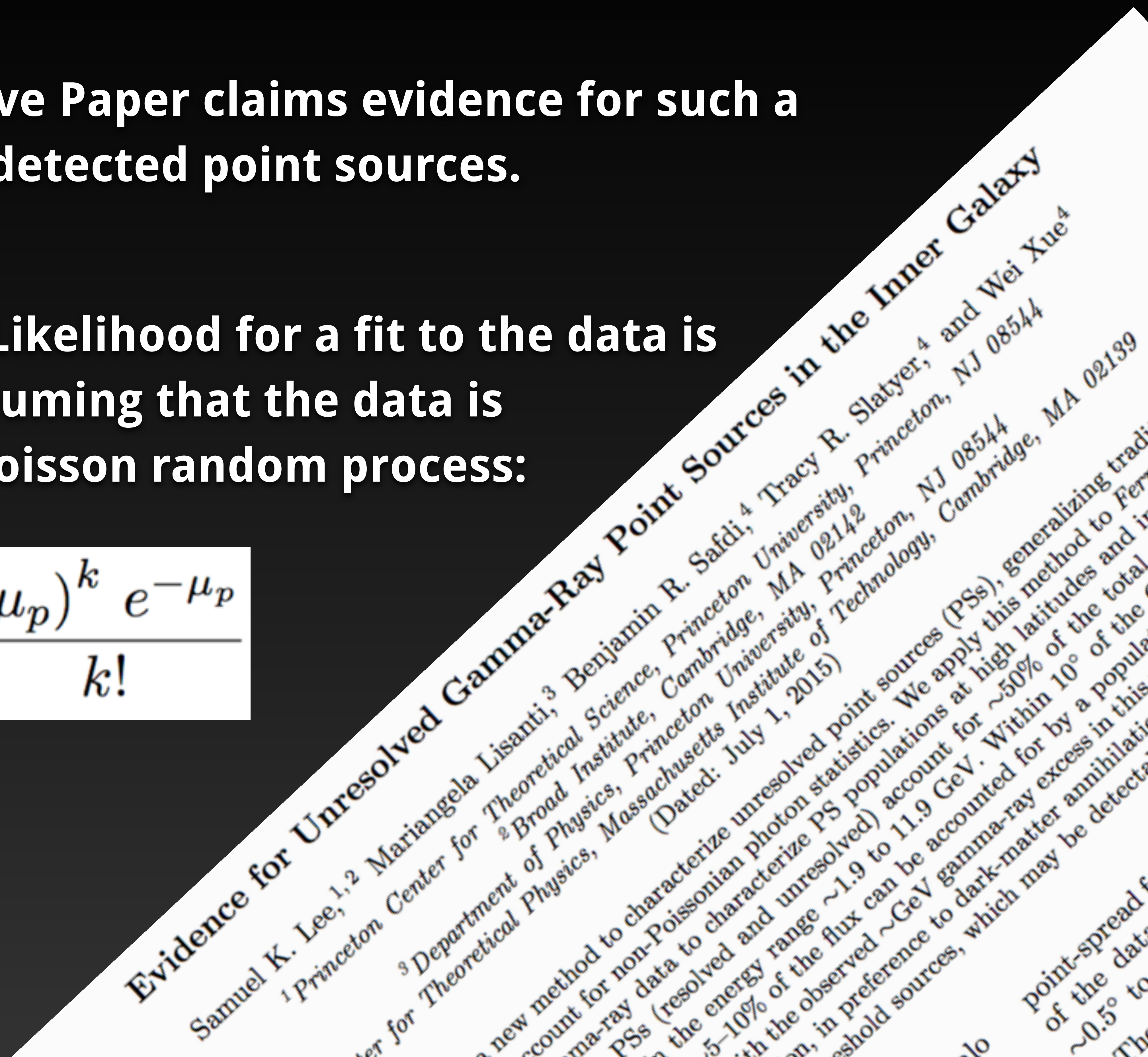
Freese et al. (1509.05076)
Bhattacharya et al. (1509.03665)
Algeri et al. (1509.01010)
Fox & Tucker-Smith (1509.00499)
Dutta et al. (1509.05989)
Liu et al. (1508.05716)
Berlin et al. (1508.05390)
Fan et al. (1507.06993)
Hektor et al. (1507.05096)
Achterbeg et al. (1507.04644)
Biswas et al. (1507.04543)
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)

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 Xue[4]

[1]Princeton Center for Theoretical Science, Princeton University, Princeton, NJ 08544
[2]Broad Institute, Cambridge, MA 02142
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ter for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139
(Dated: July 1, 2015)

new method to characterize unresolved point sources (PSs), generalizing tradi
ccount for non-Poissonian photon statistics. We apply this method to Fer
ma-ray data to characterize PS populations at high latitudes and in
PSs (resolved and unresolved) account for ~50% of the total
n the energy range ~1.9 to 11.9 GeV. Within 10° of the
5–10% of the flux can be accounted for by a popula
th the observed ~GeV gamma-ray excess in this
n, in preference to dark-matter annihilati
eshold sources, which may be detecta

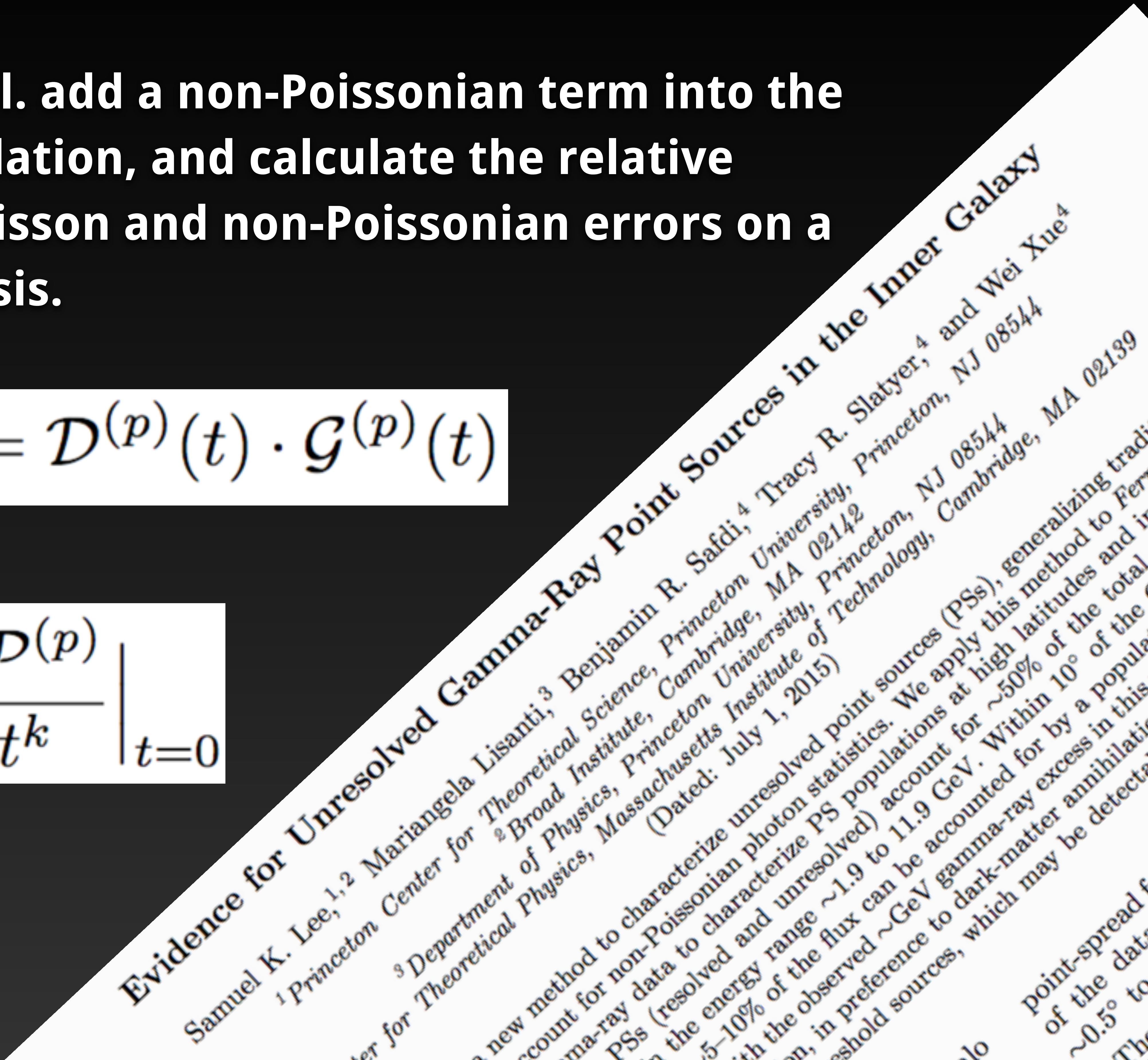
point-spread
of the dat
~0.5° t

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.

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

$$p_k^{(p)} = \frac{1}{k!} \frac{d^k \mathcal{P}^{(p)}}{dt^k}\bigg|_{t=0}$$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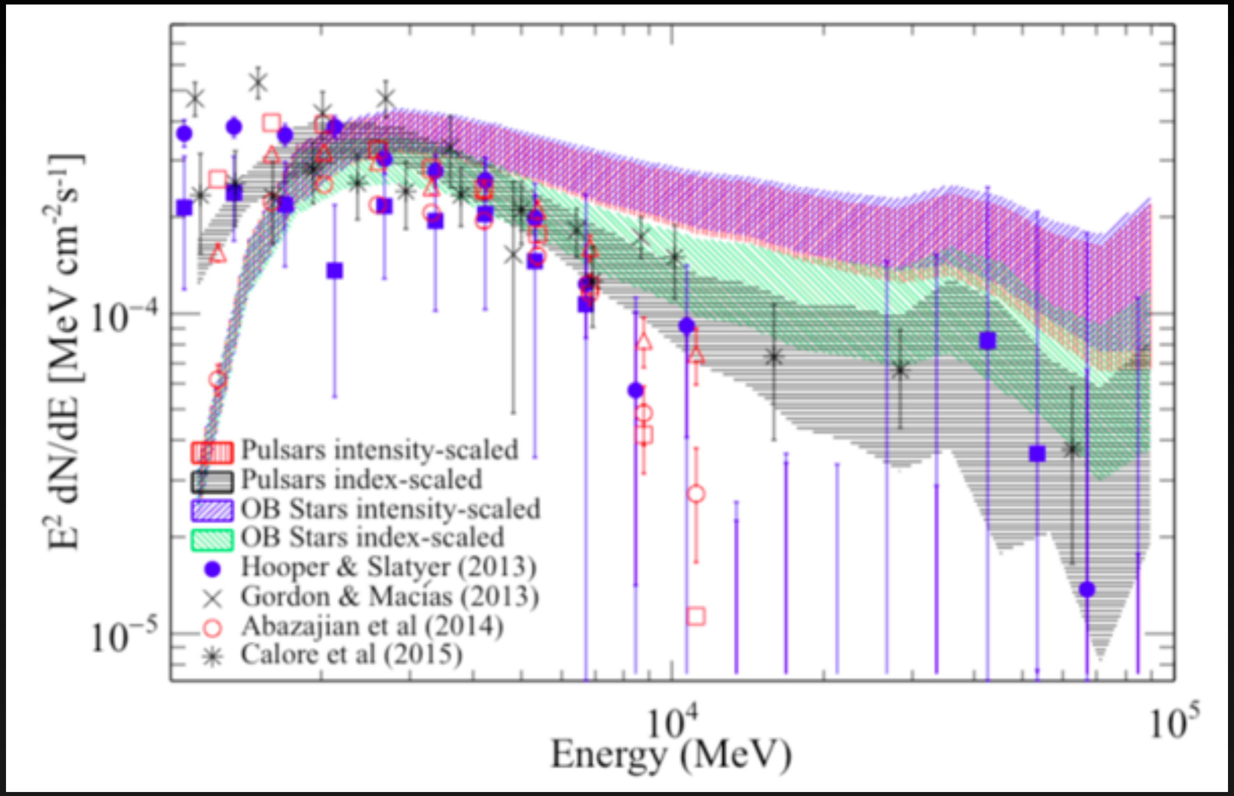
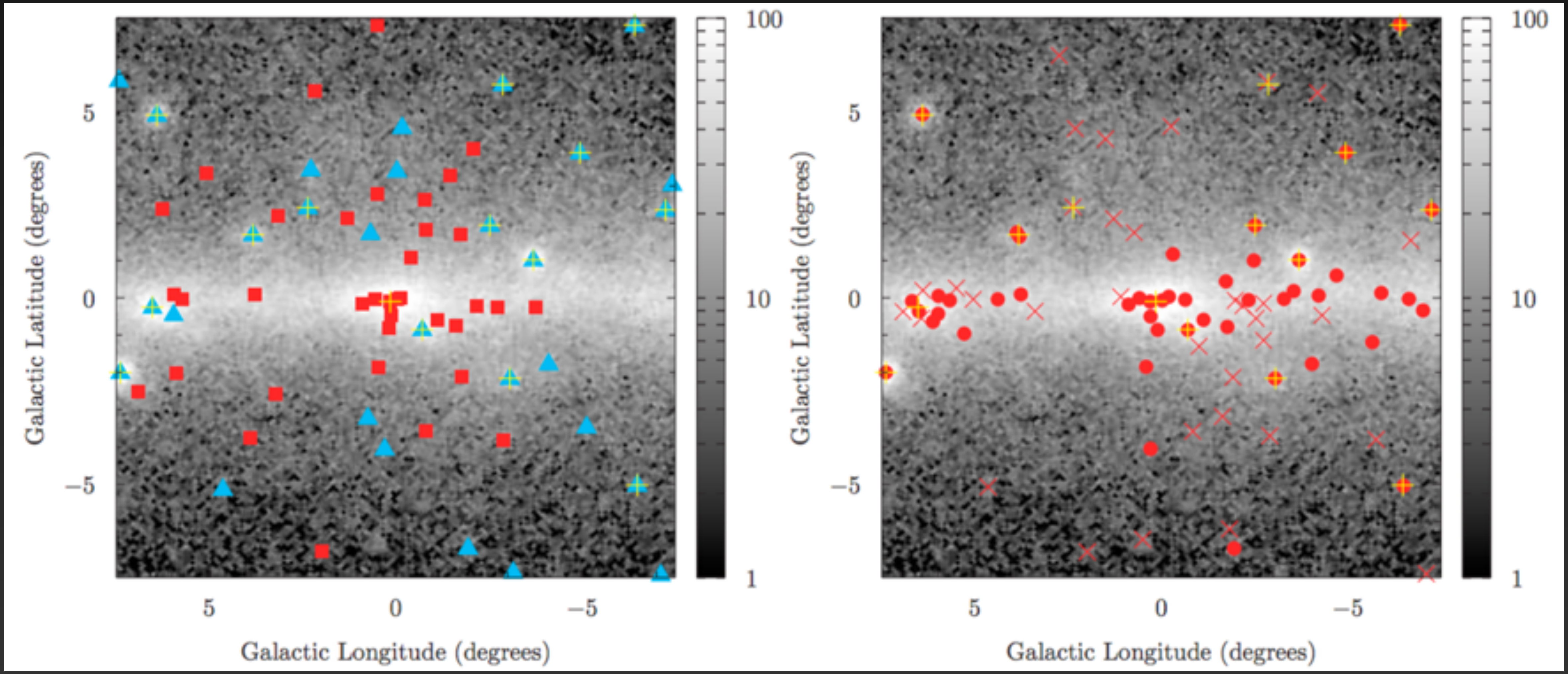
Observational Results



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



Cosmic-Ray Injection Sources

Solution: Add a new cosmic-ray injection morphology tracing the molecular gas density.

Observational Resilient: Several tracers of molecular gas are sensitive to the galactic center region.

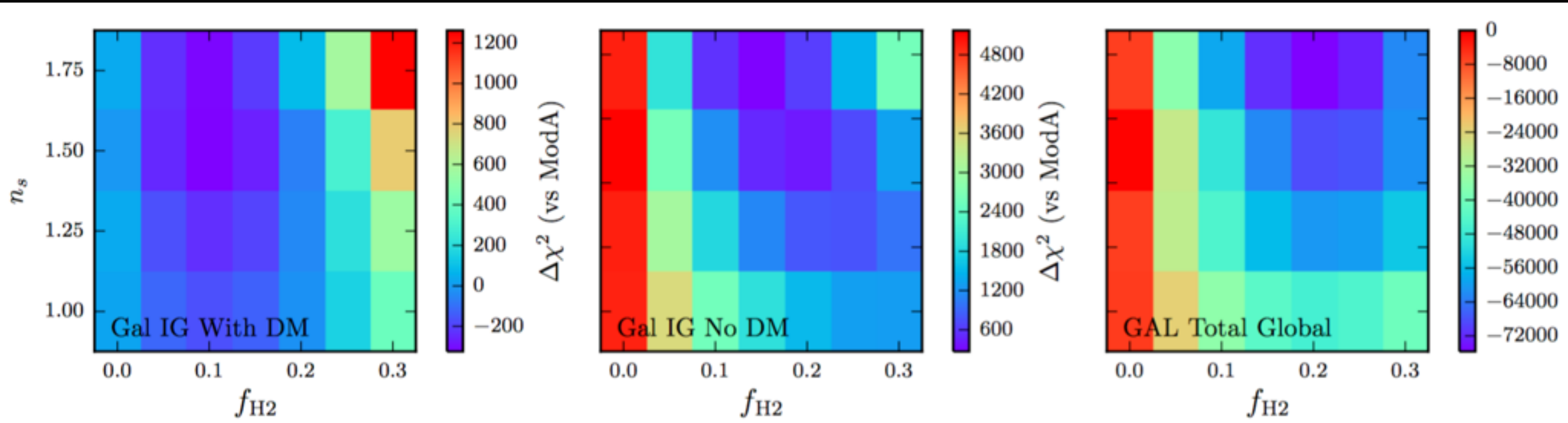
Theoretically Motivated: Molecular Gas is the seed of star formation, the Kennicutt-Shmidt Law gives

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

Specifically we adopt:

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

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.

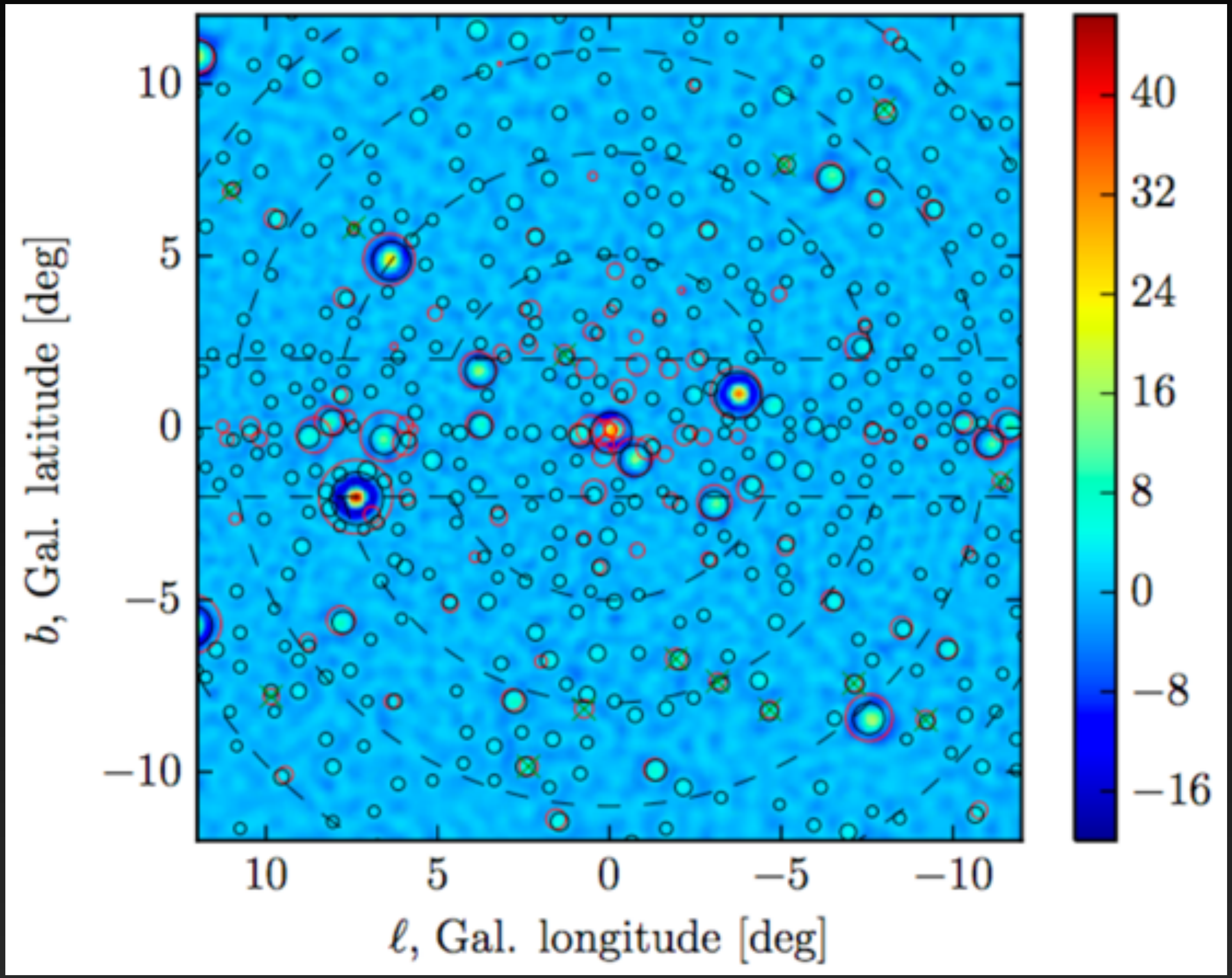
However, the overall fit to the gamma-ray sky prefers $f_{H2} \sim 0.2$

How Do We Test the Pulsar Hypothesis?

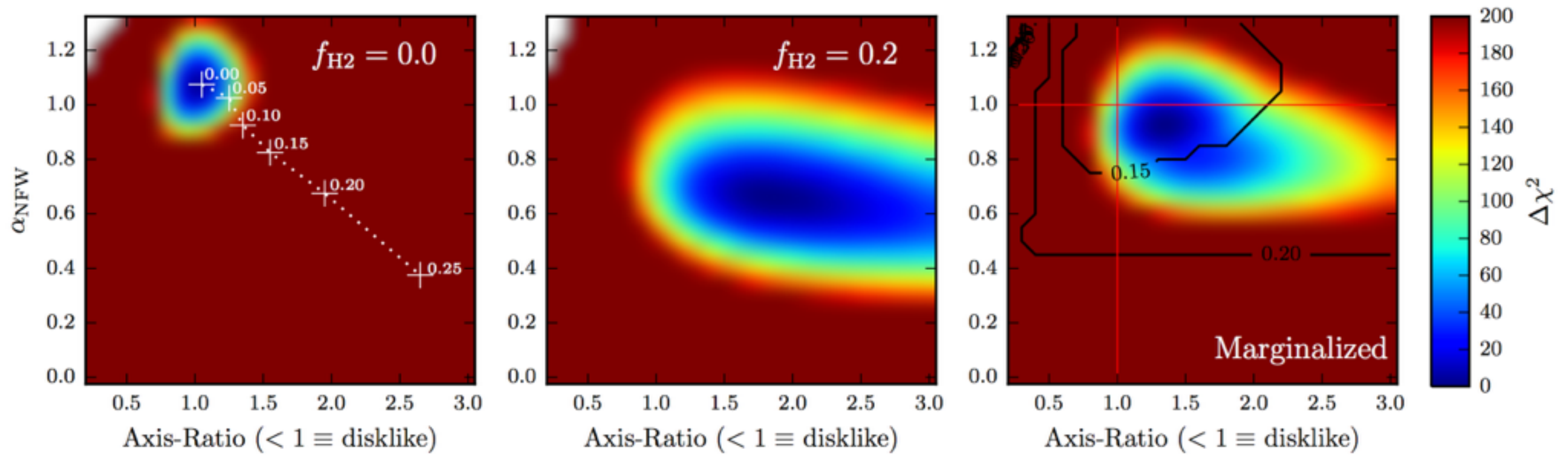
1.) Utilize gamma-ray hotspots to seed radio pulsar searches

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.



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.