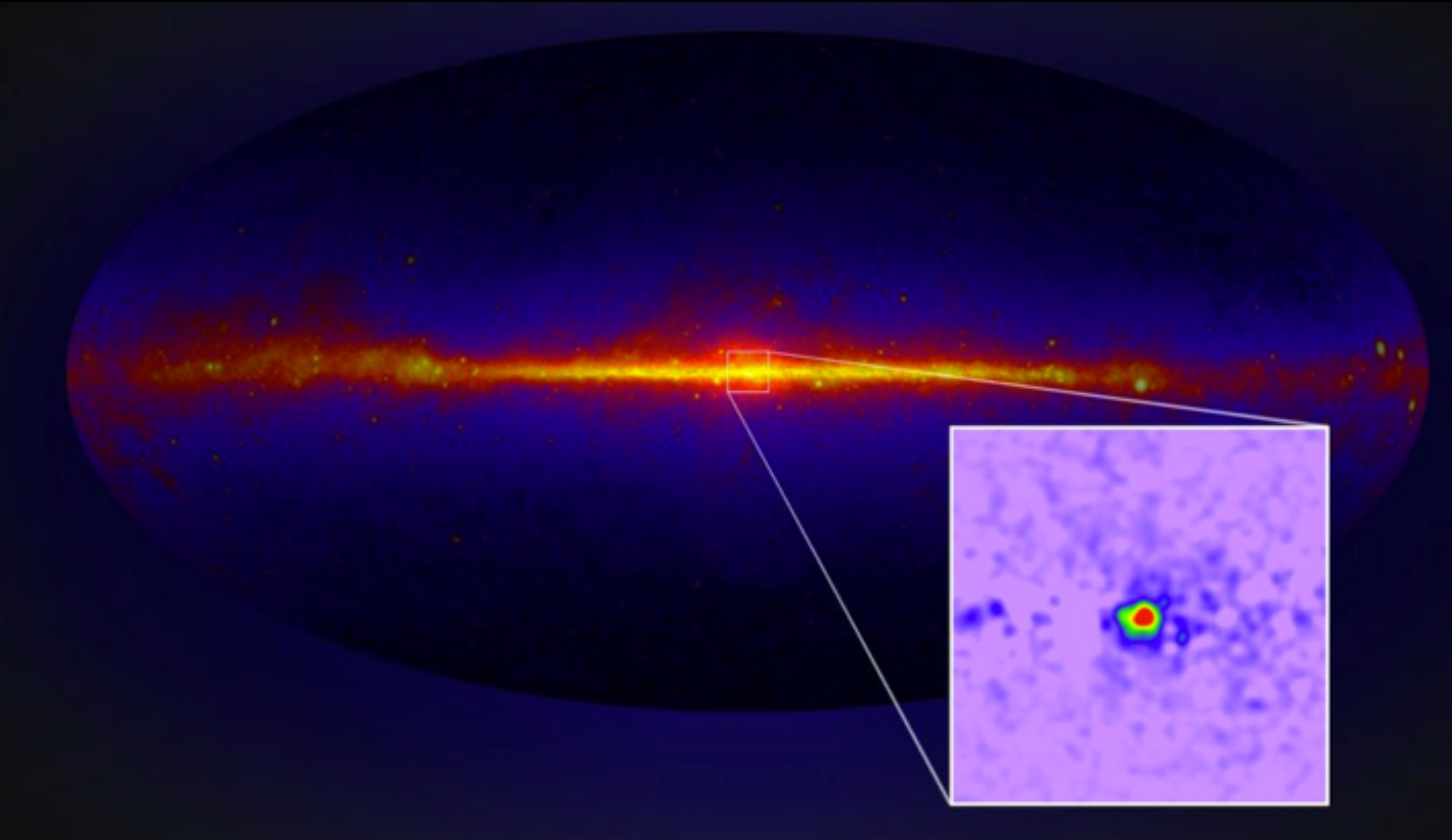


What is the Source of the Galactic Center Gamma-Ray Excess?

Tim Linden

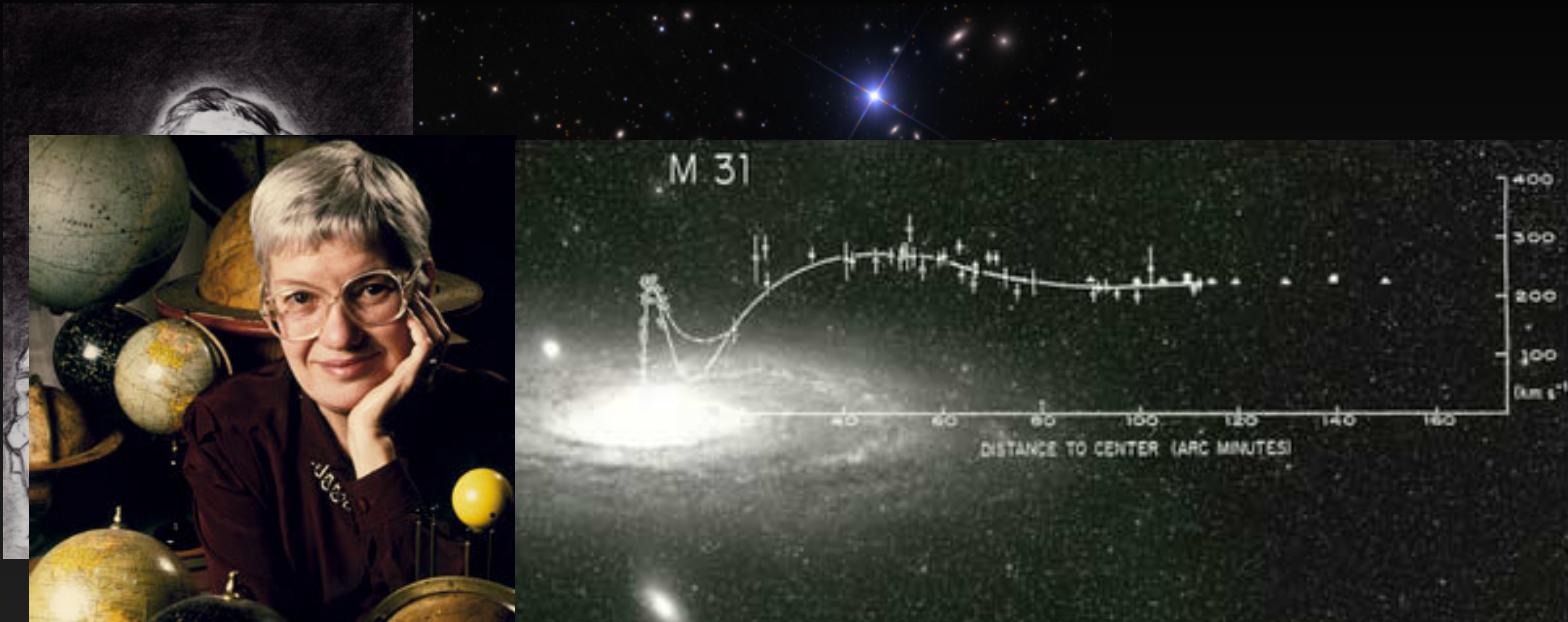
Einstein Postdoctoral Fellow
Center for Cosmology and Astro-Particle Physics
The Ohio State University

SMU Physics Seminar November 16, 2015

Gravitational Dark Matter

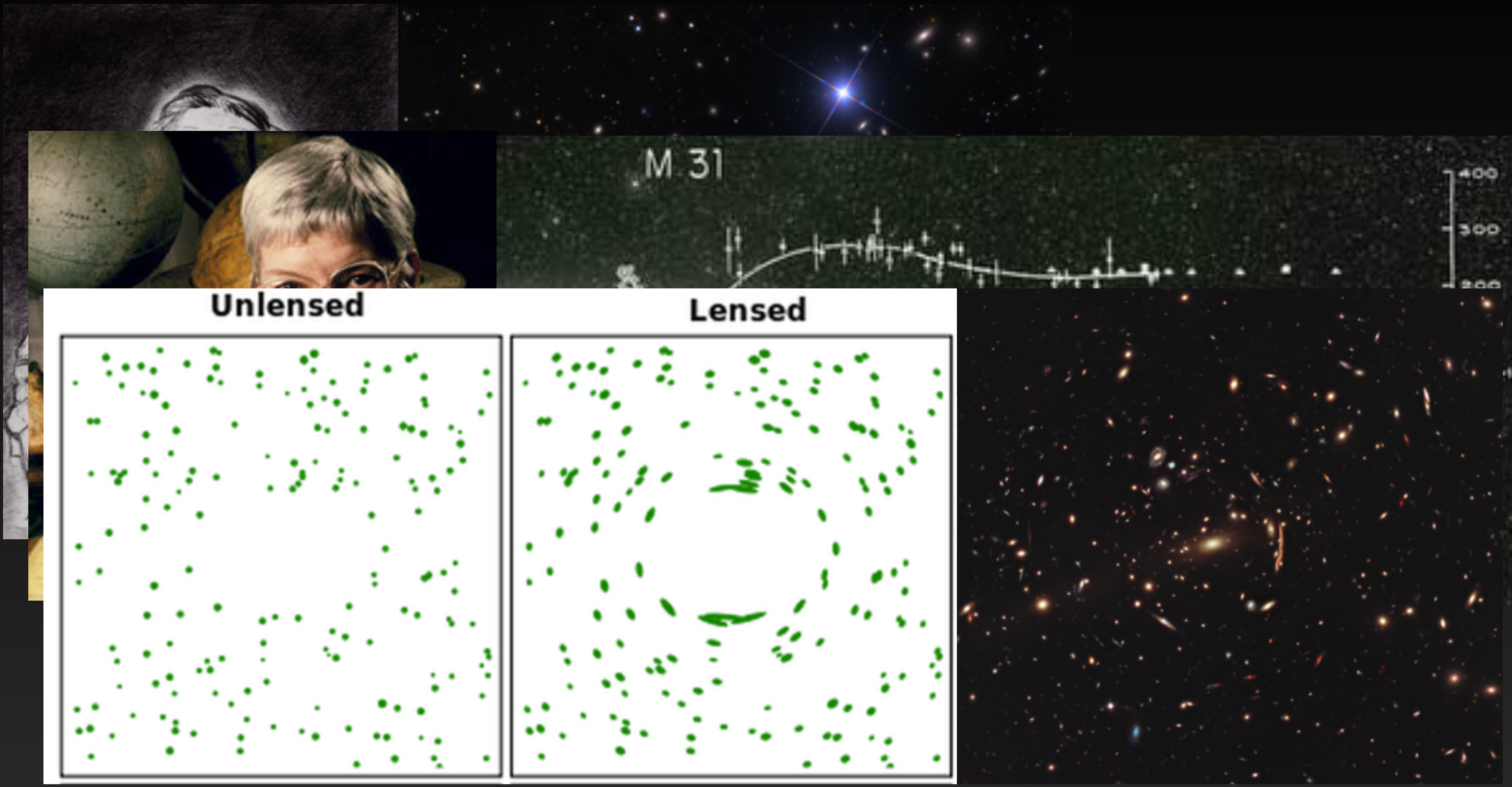

1933: Zwicky observers dark matter in Coma Cluster

Gravitational Dark Matter



1970s: Vera Rubin observes anomalous rotation velocities in M31

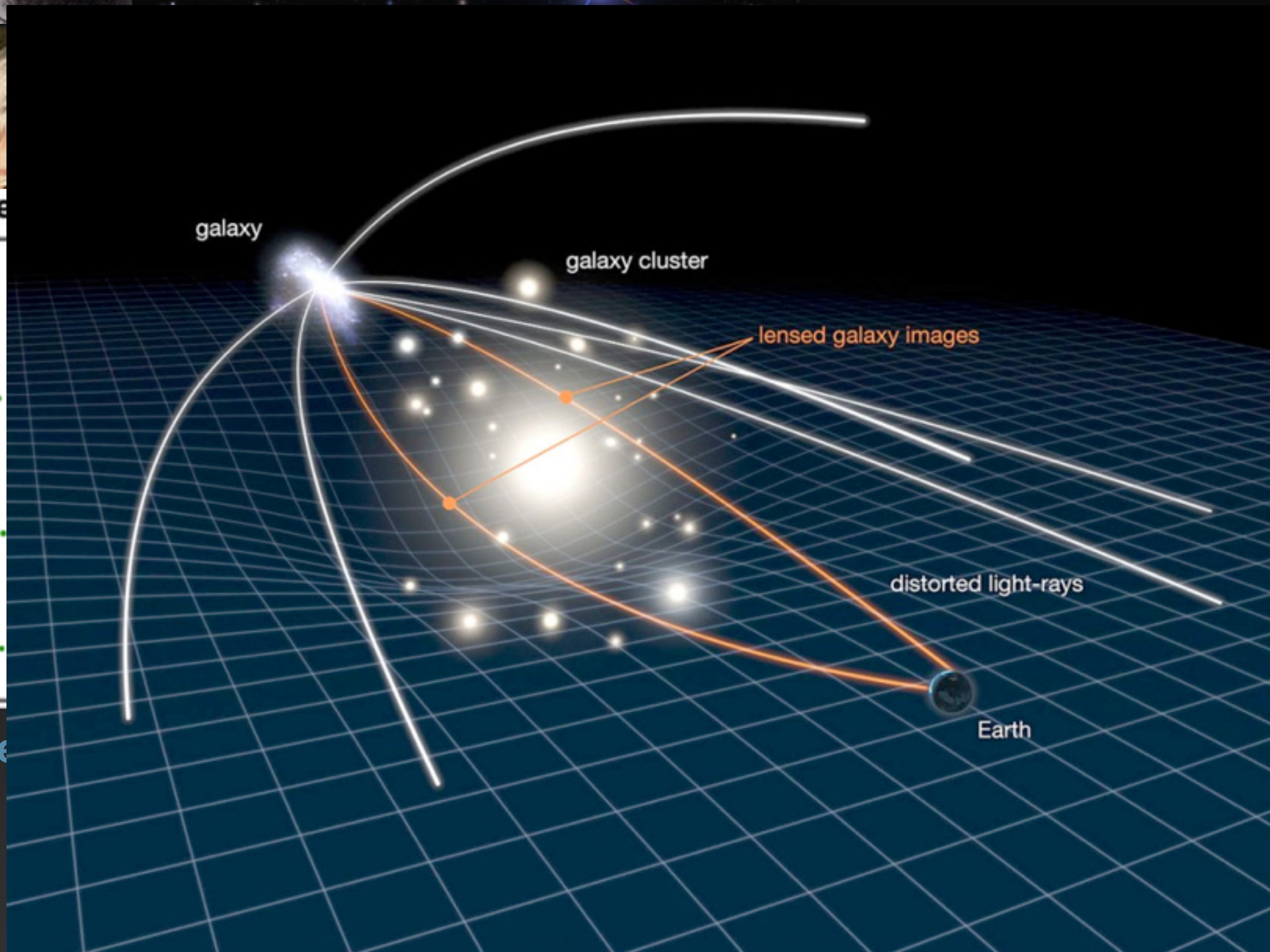
Gravitational Dark Matter



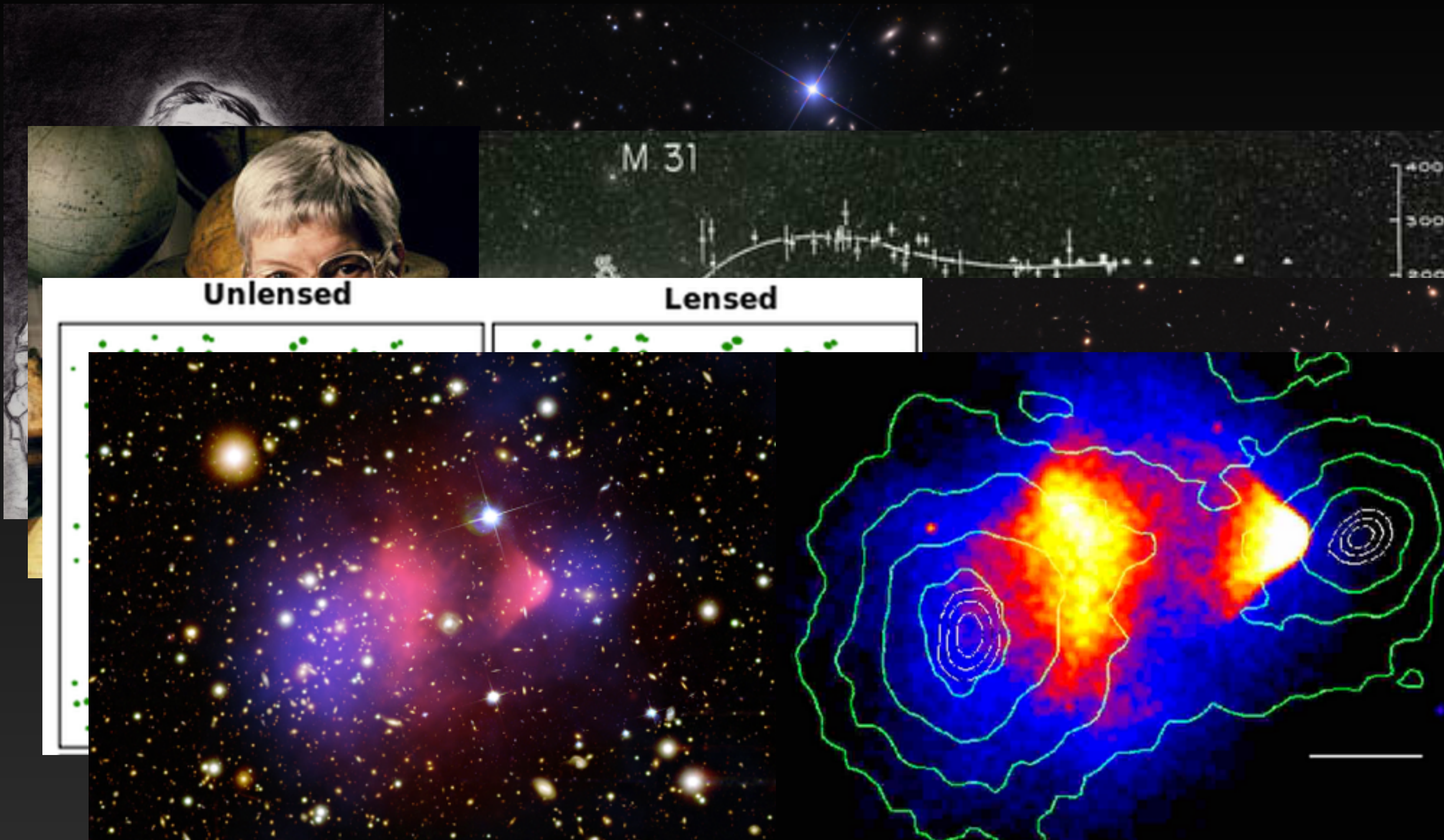
1996: Weak Gravitational Lensing Observed from Dark Matter Halos

Gravitational Dark Matter

1996: We

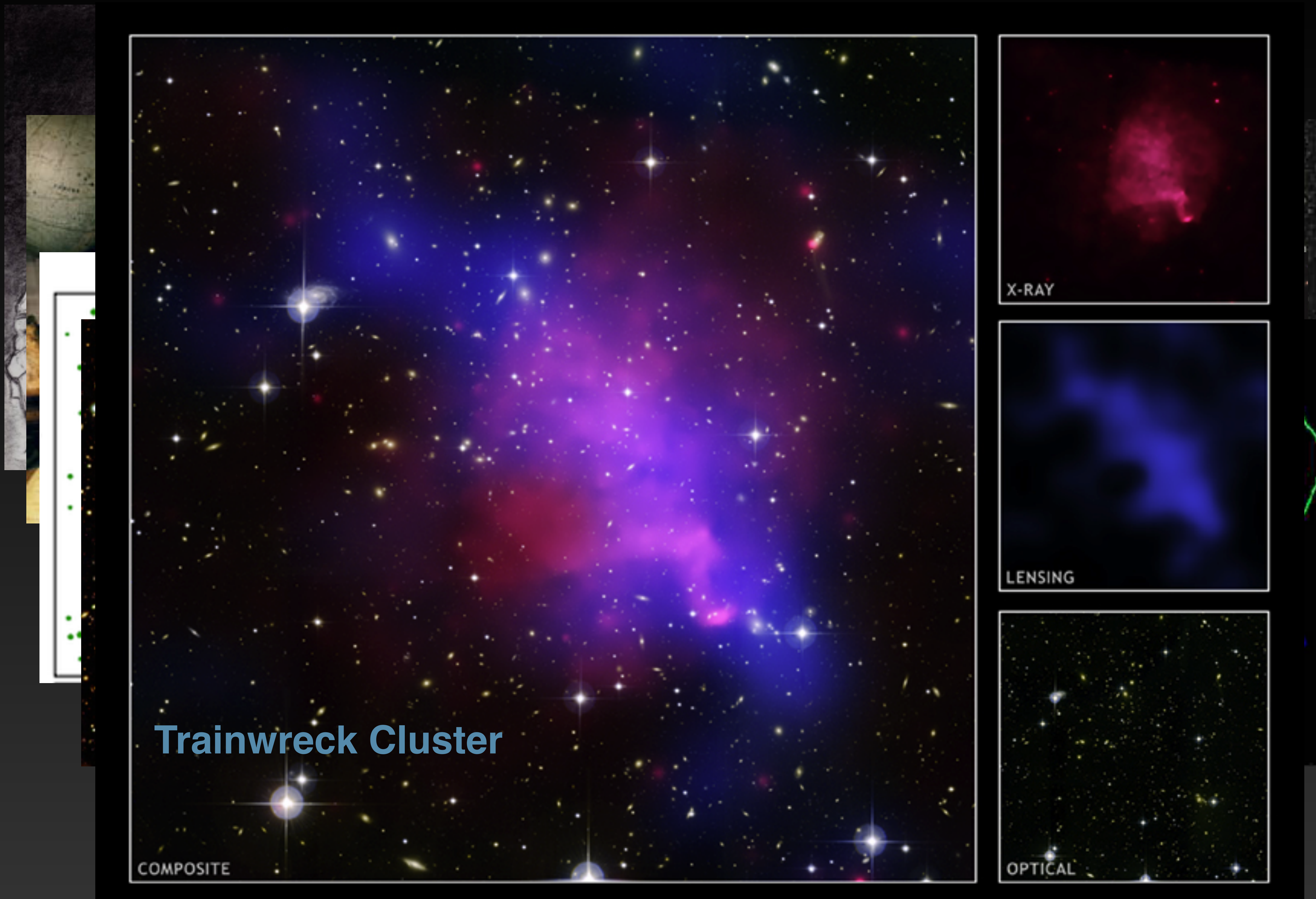


Gravitational Dark Matter



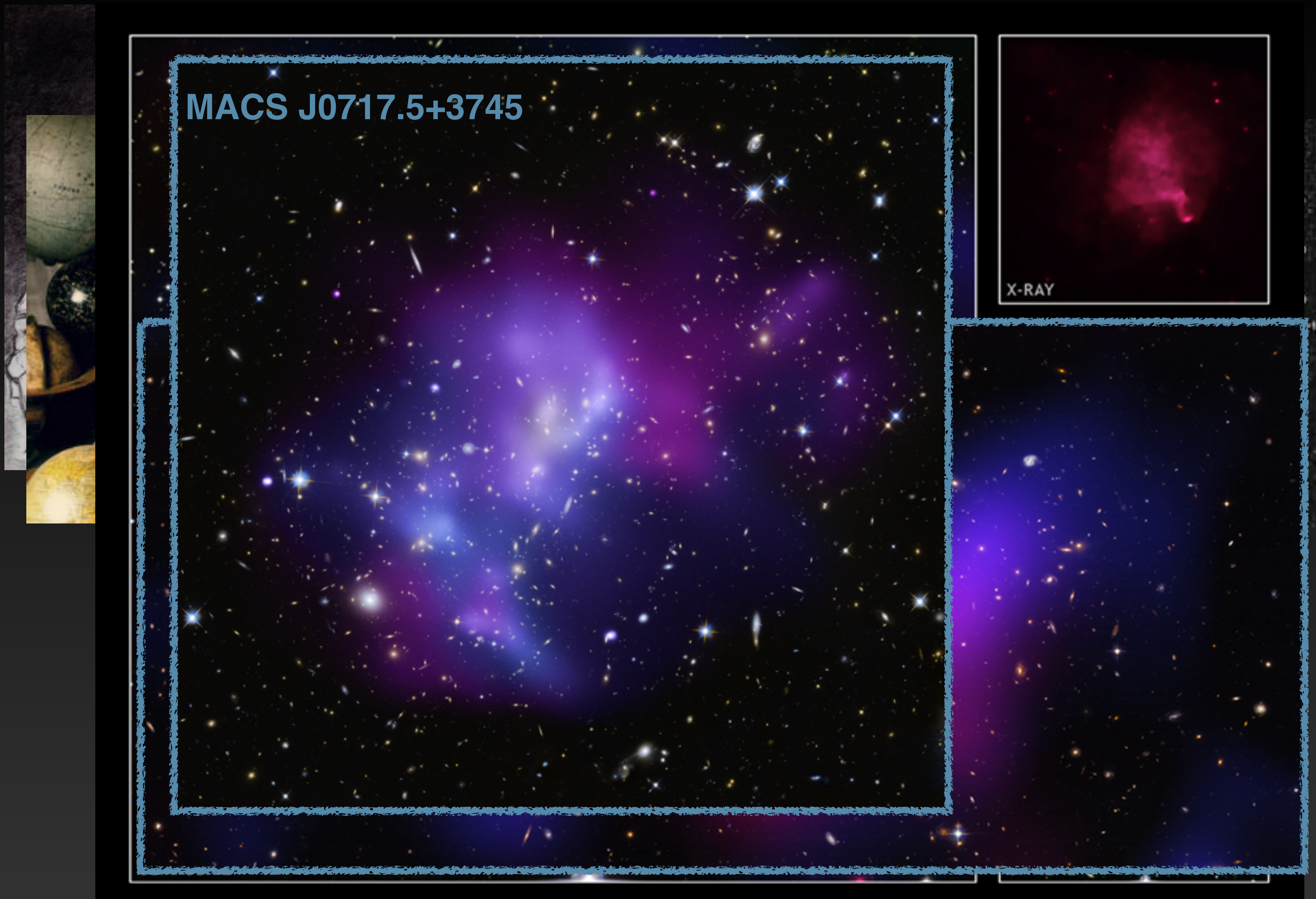
2006: Bullet Cluster Observations Show Offset Between Mass and Hot Gas

Gravitational Dark Matter



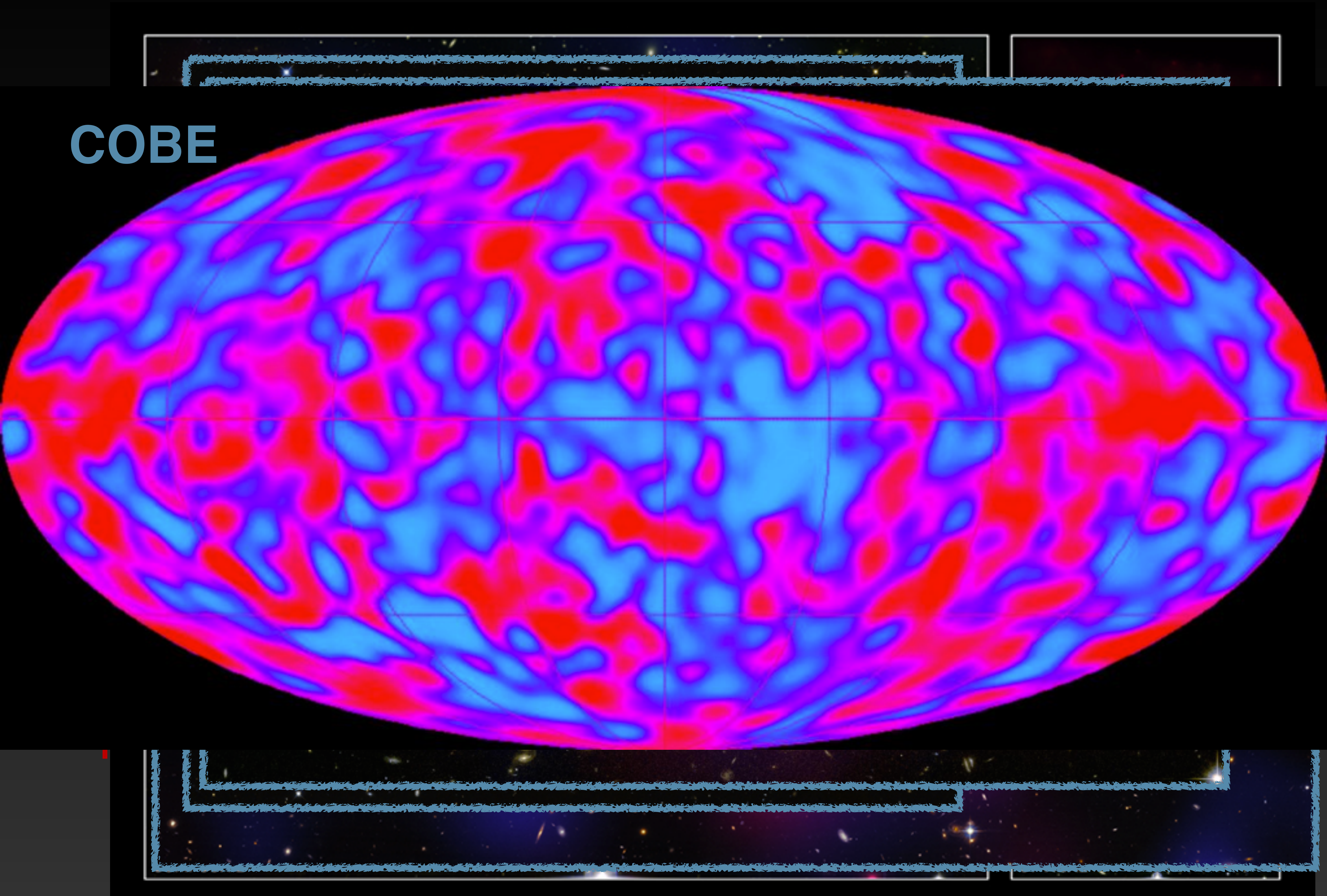
Gravitational Dark Matter

Gravitational Dark Matter



Gravitational Dark Matter

Gravitational Dark Matter



Gravitational Dark Matter

WMAP

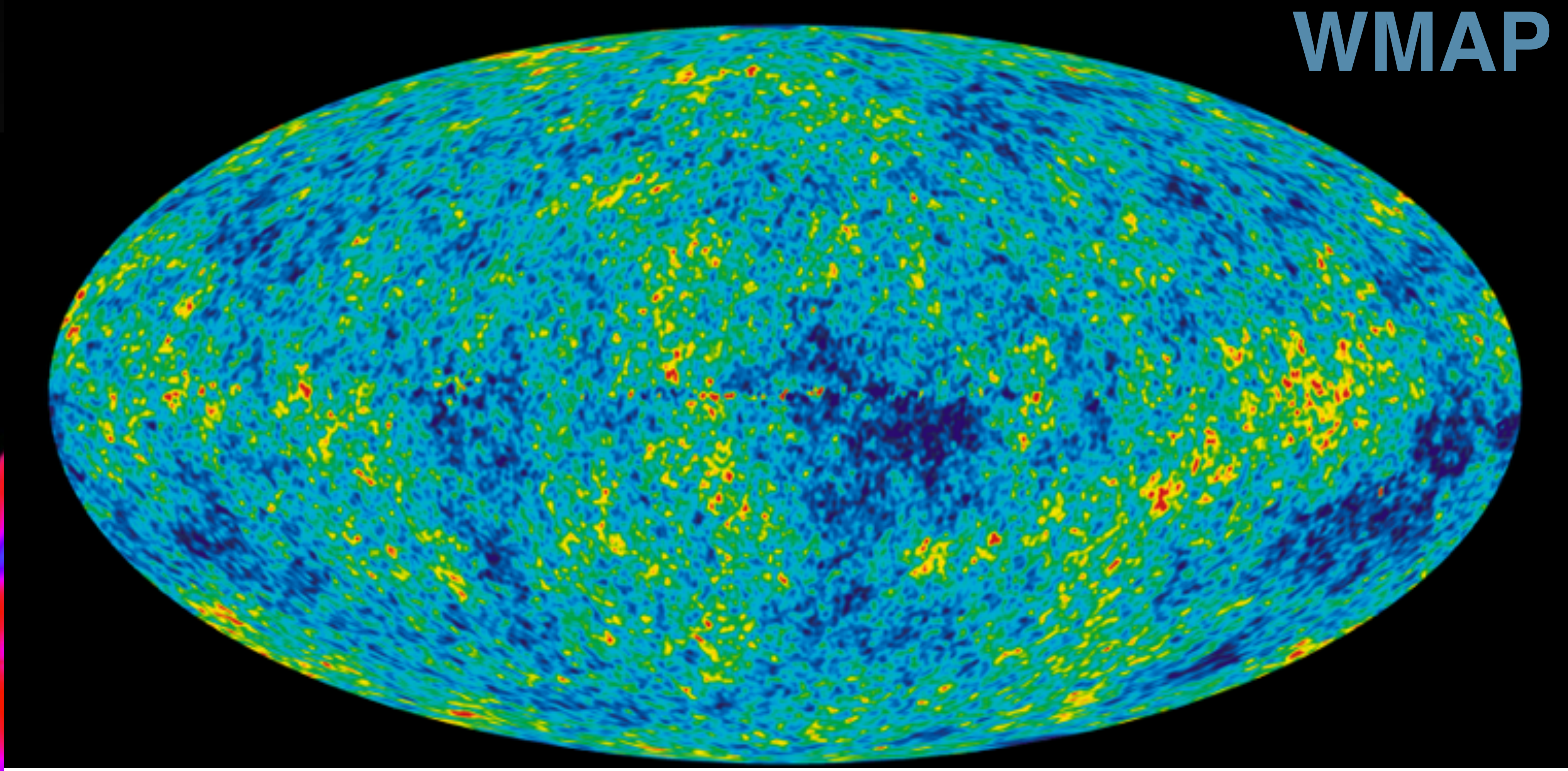
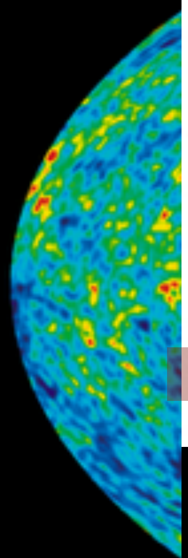


Table 6. Cosmological Parameter Summary

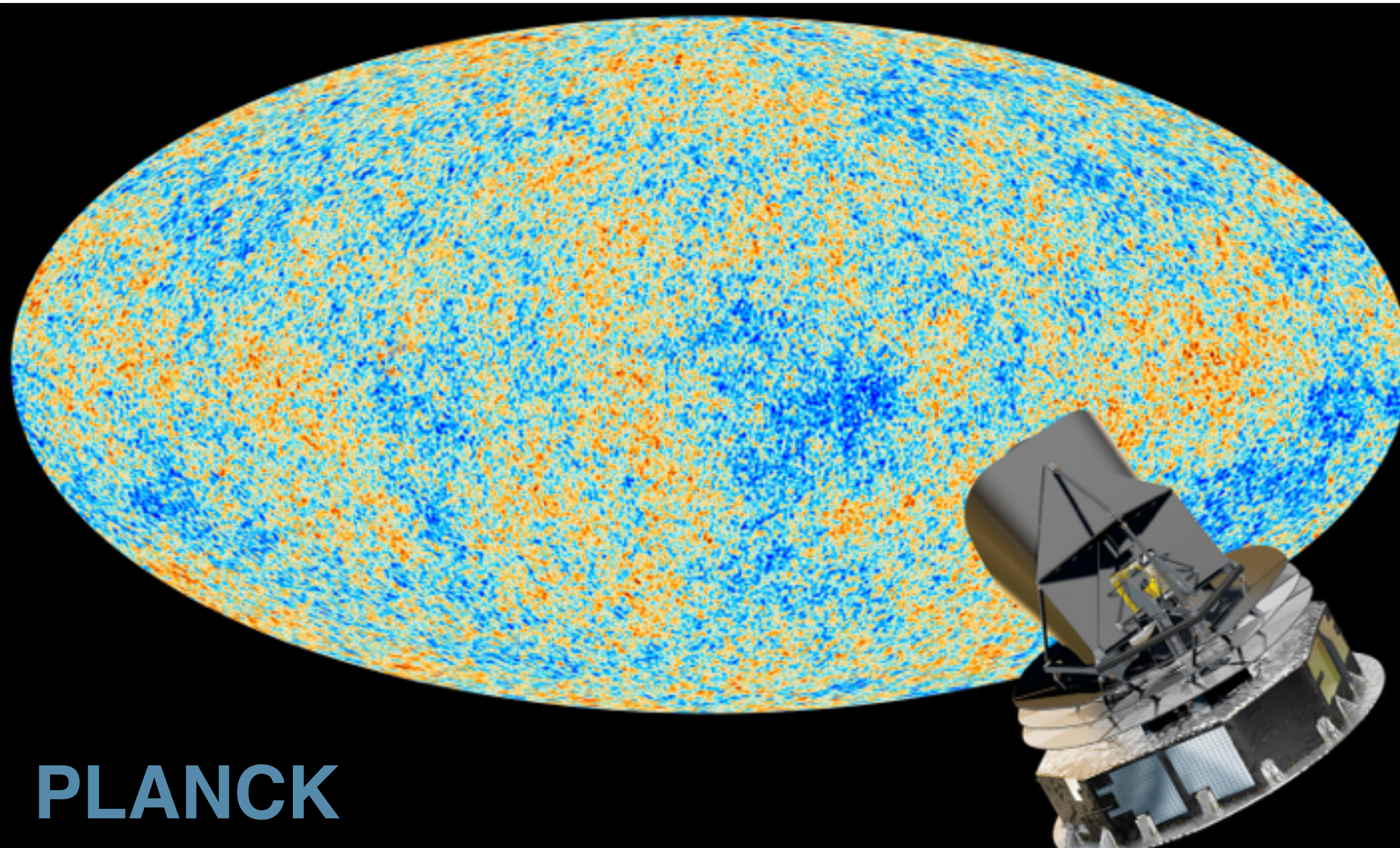
Description	Symbol	WMAP-only
Parameters for Standard ΛCDM Model [a]		
Age of universe	t_0	13.69 ± 0.13 Gyr
Hubble constant	H_0	$71.9^{+2.6}_{-2.7}$ km/s/Mpc
Baryon density	Ω_b	0.0441 ± 0.0030
Physical baryon density	$\Omega_b h^2$	0.02273 ± 0.00062
Dark matter density	Ω_c	0.214 ± 0.027

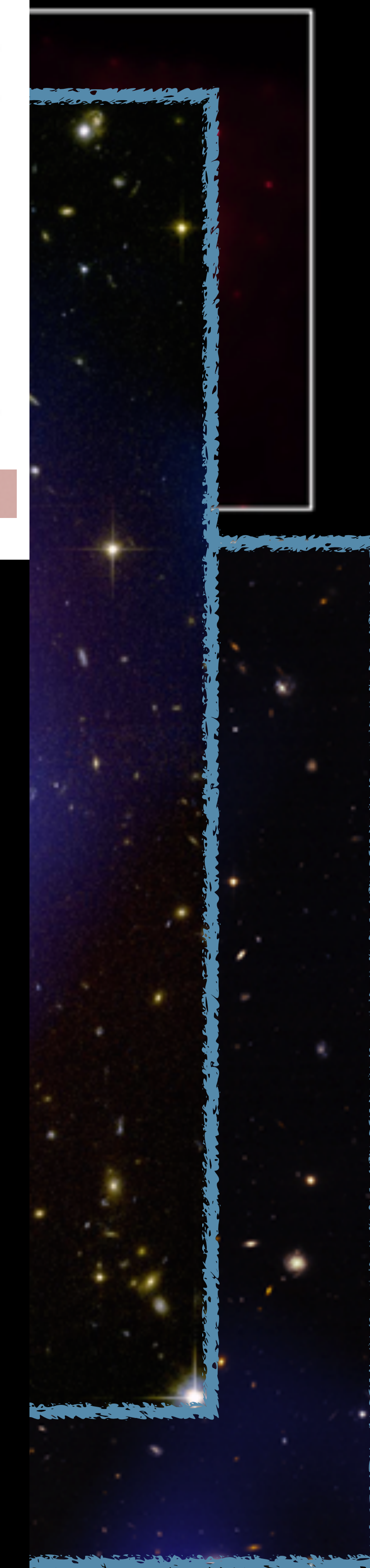
Gravitational Dark Matter

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



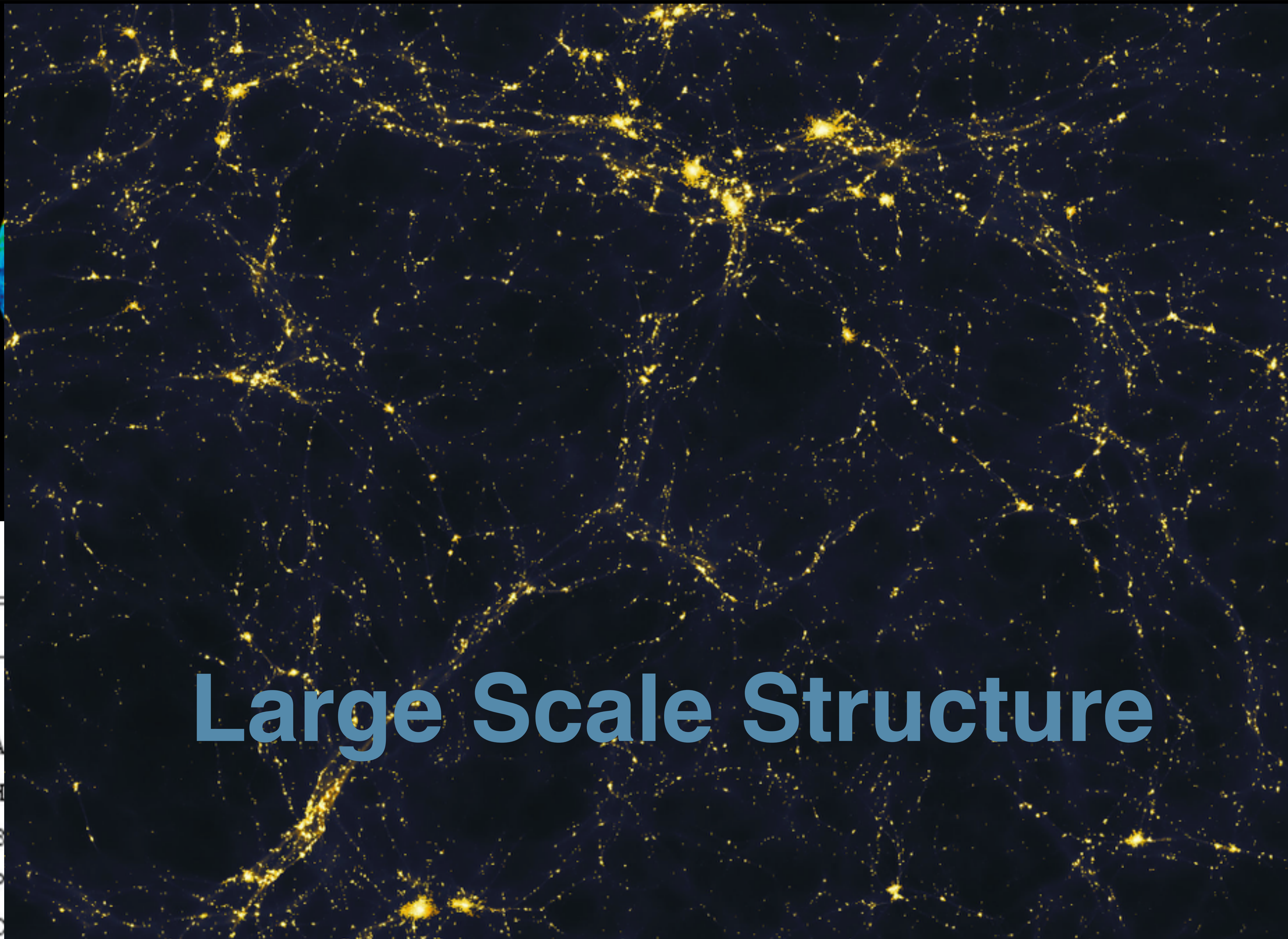
Age of u
Hubble
Baryon
Physical
Dark ma





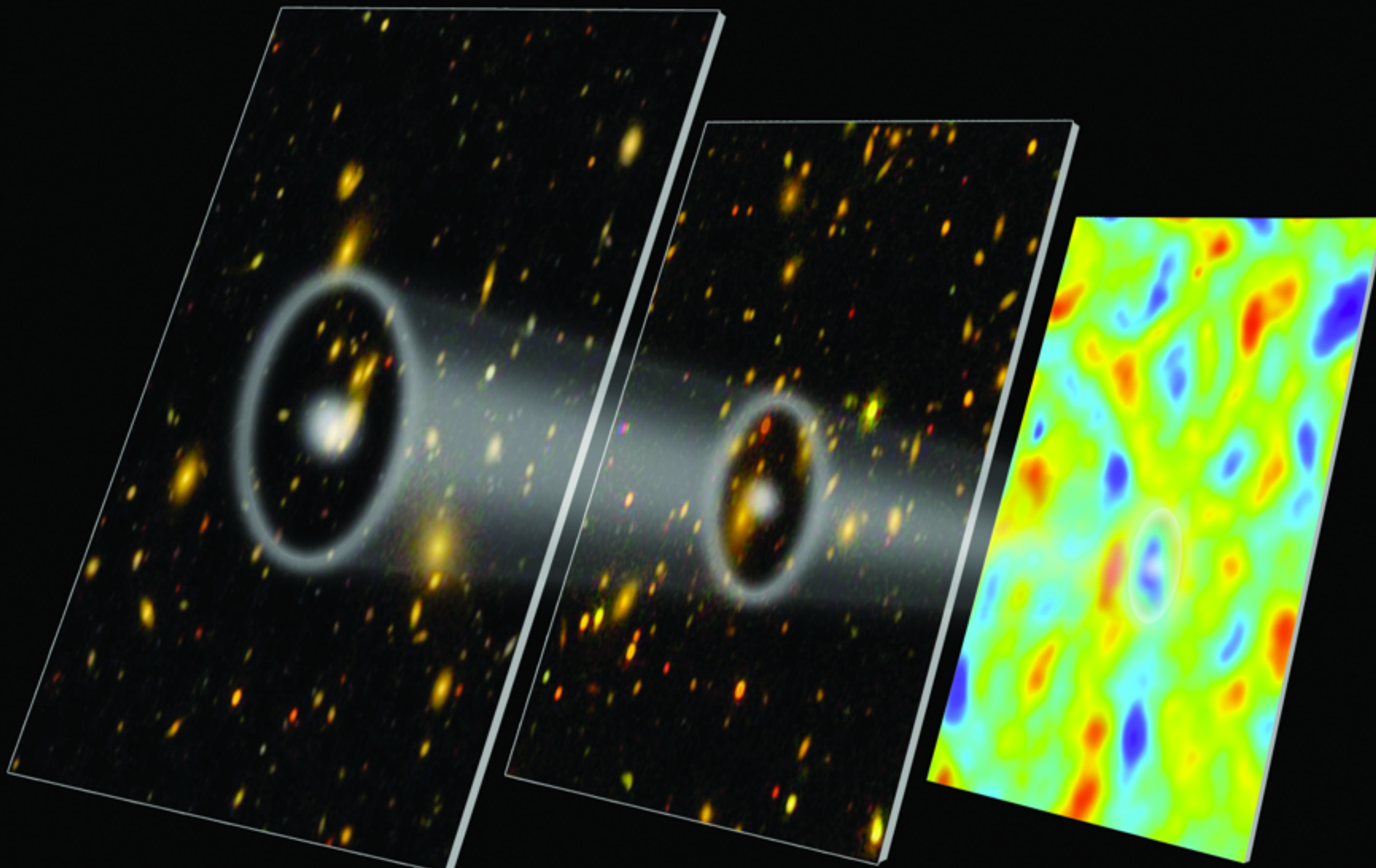
PLANCK

Gravitational Dark Matter



Gravitational Dark Matter

Baryonic Acoustic Oscillations

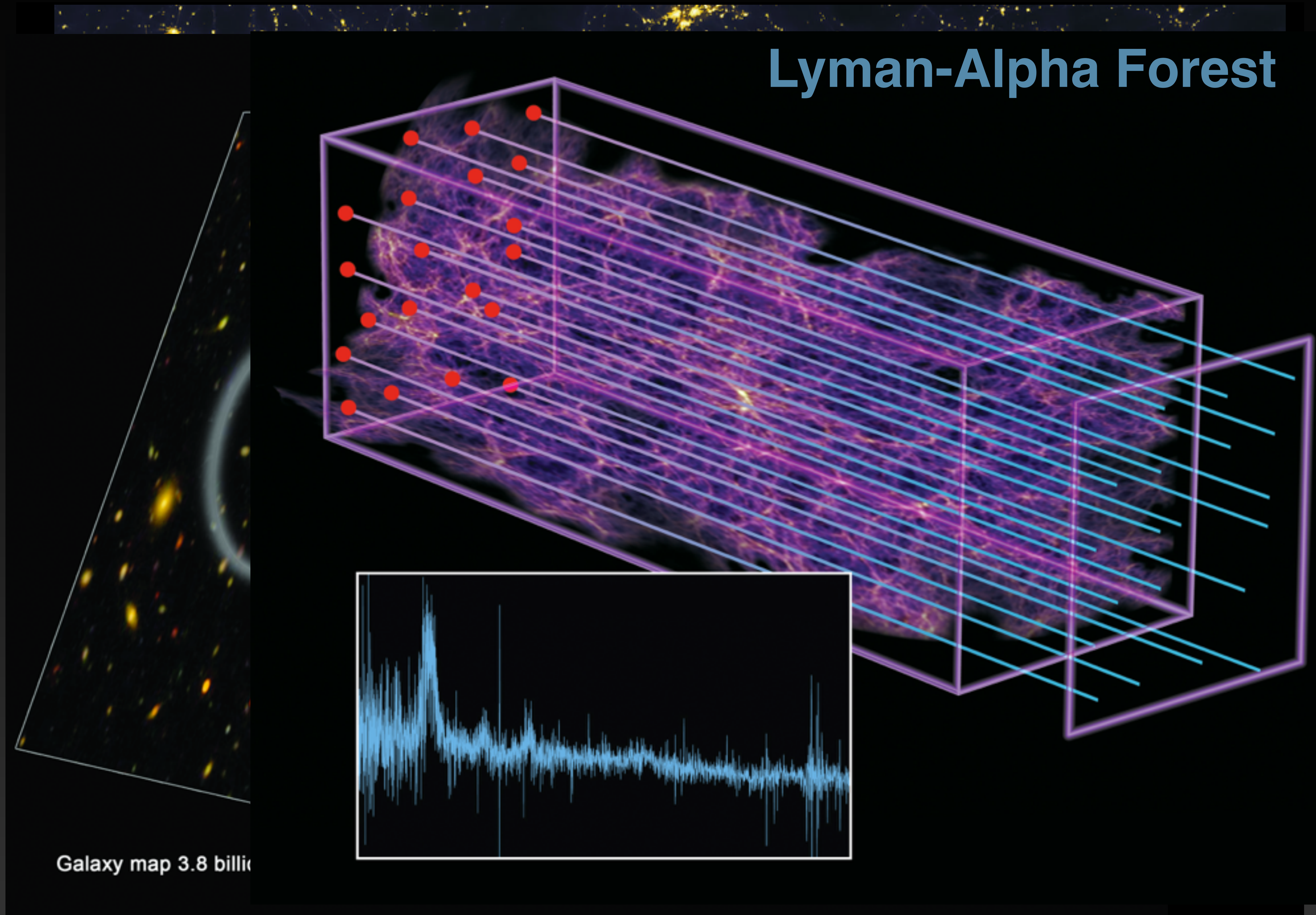


Galaxy map 3.8 billion years ago

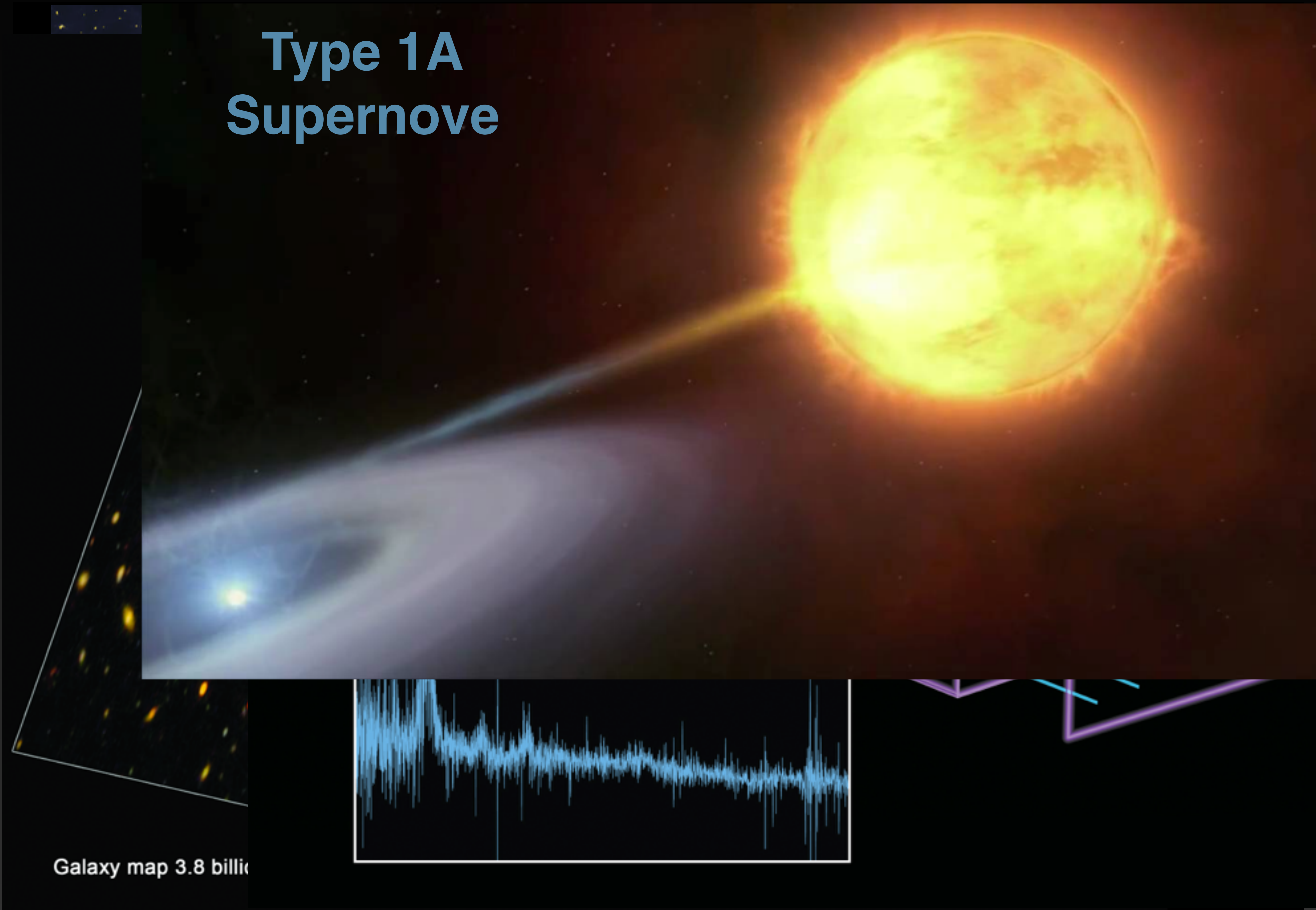
Galaxy map 5.5 billion years ago

CMB 13.7 billion years ago

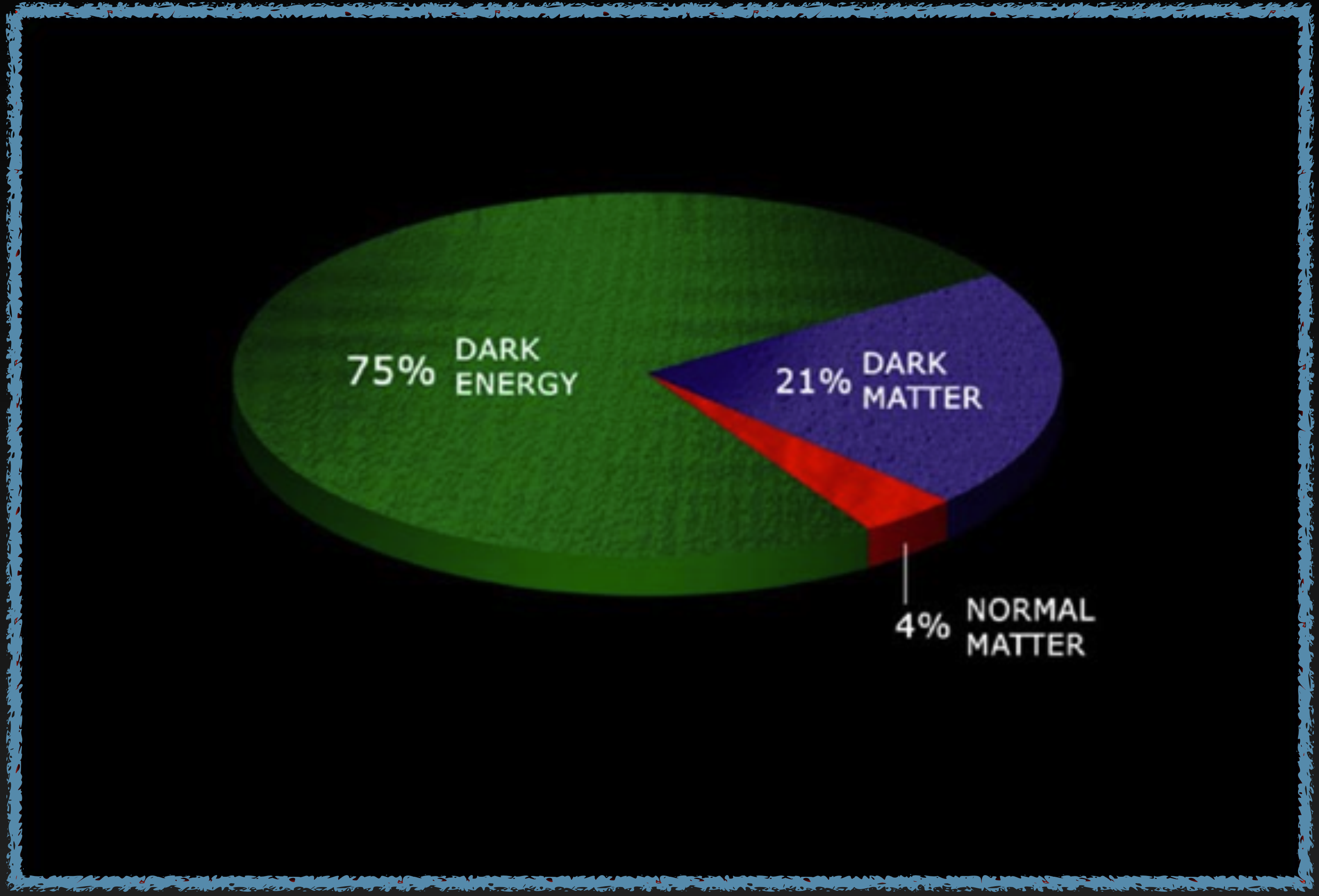
Gravitational Dark Matter



Gravitational Dark Matter



Dark Matter Cosmology

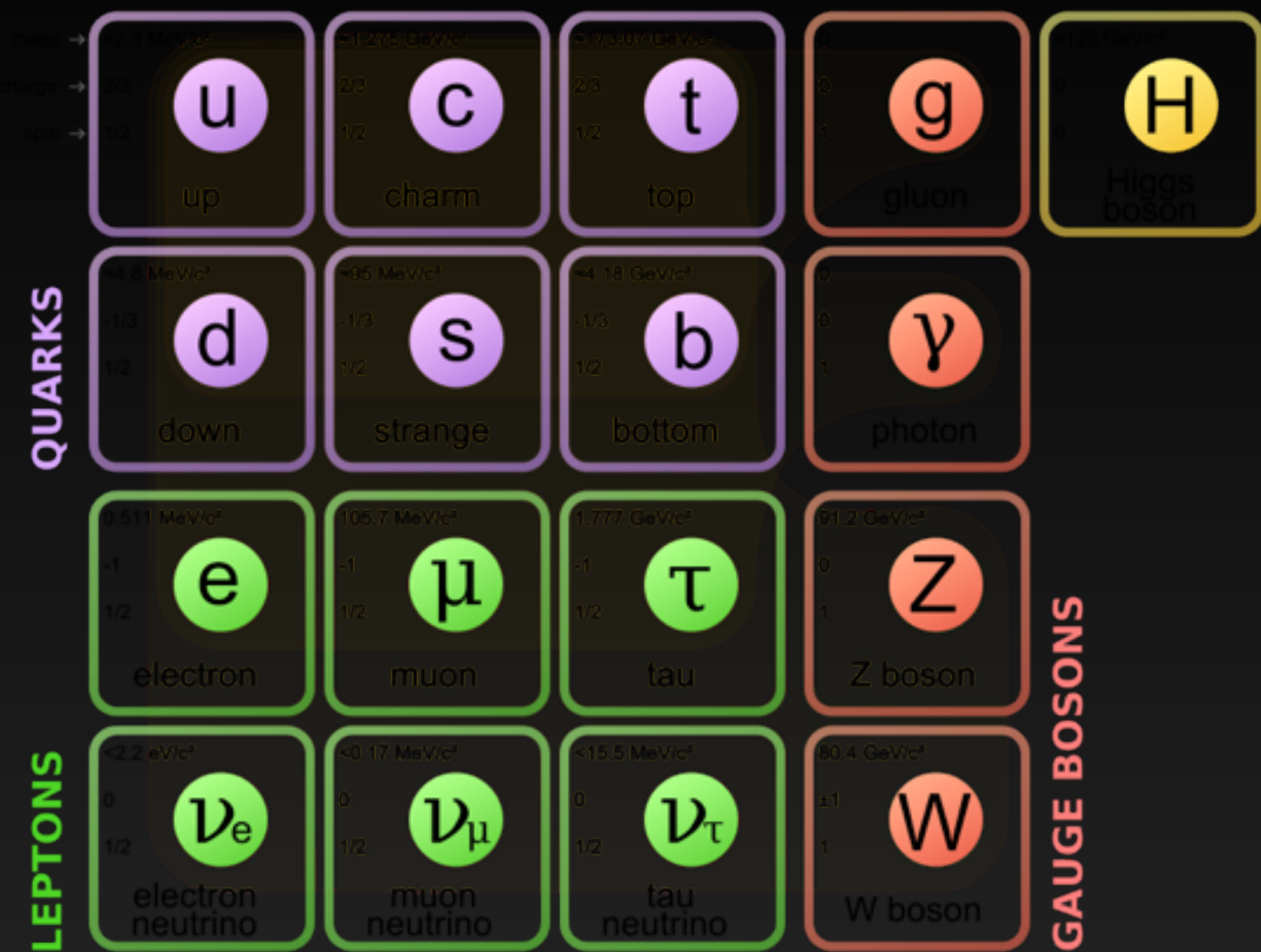


Dark Matter Is:

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

These are trivial statements.

Dark Matter Cosmology

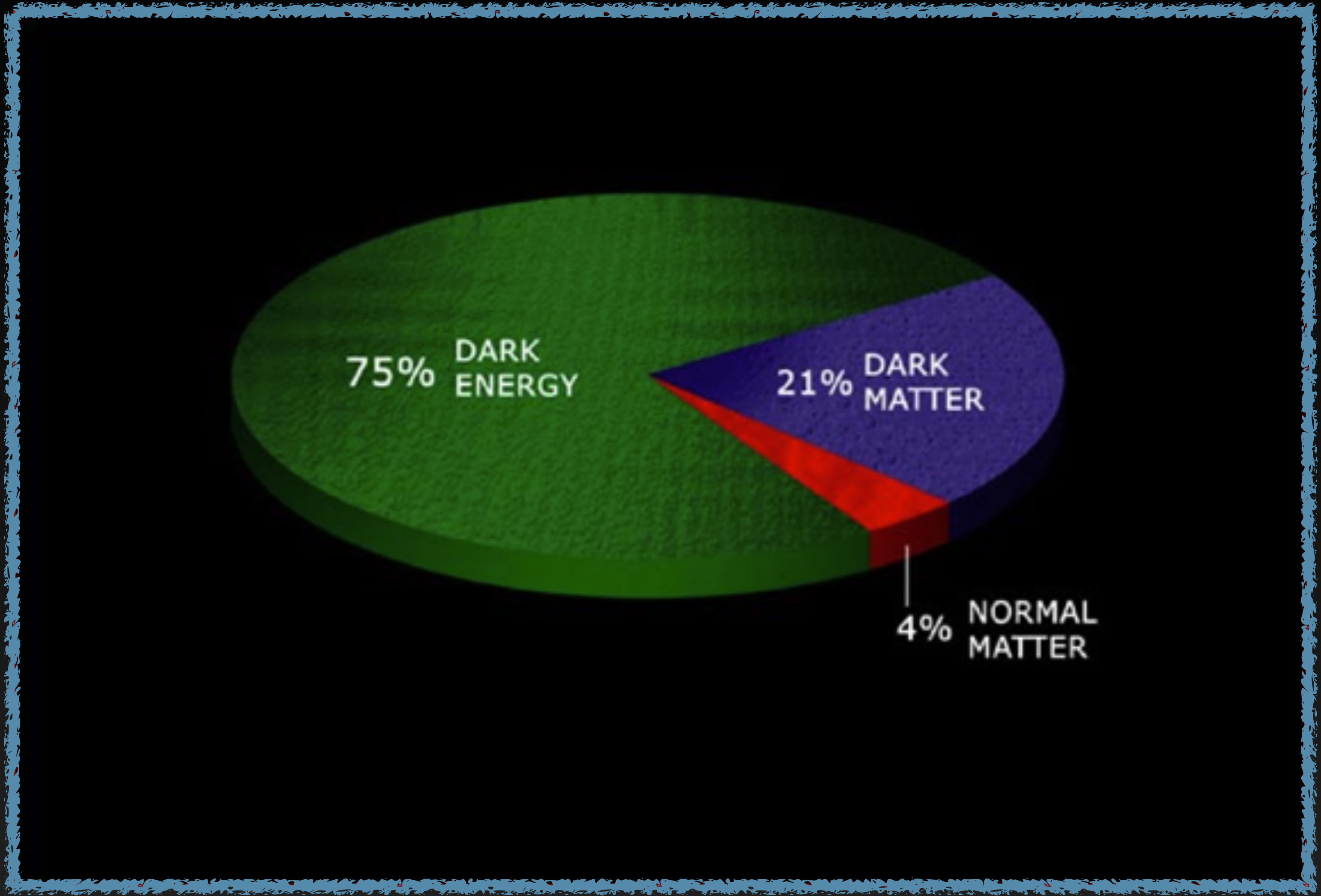


Dark Matter Is:

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

These are profound statements.

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

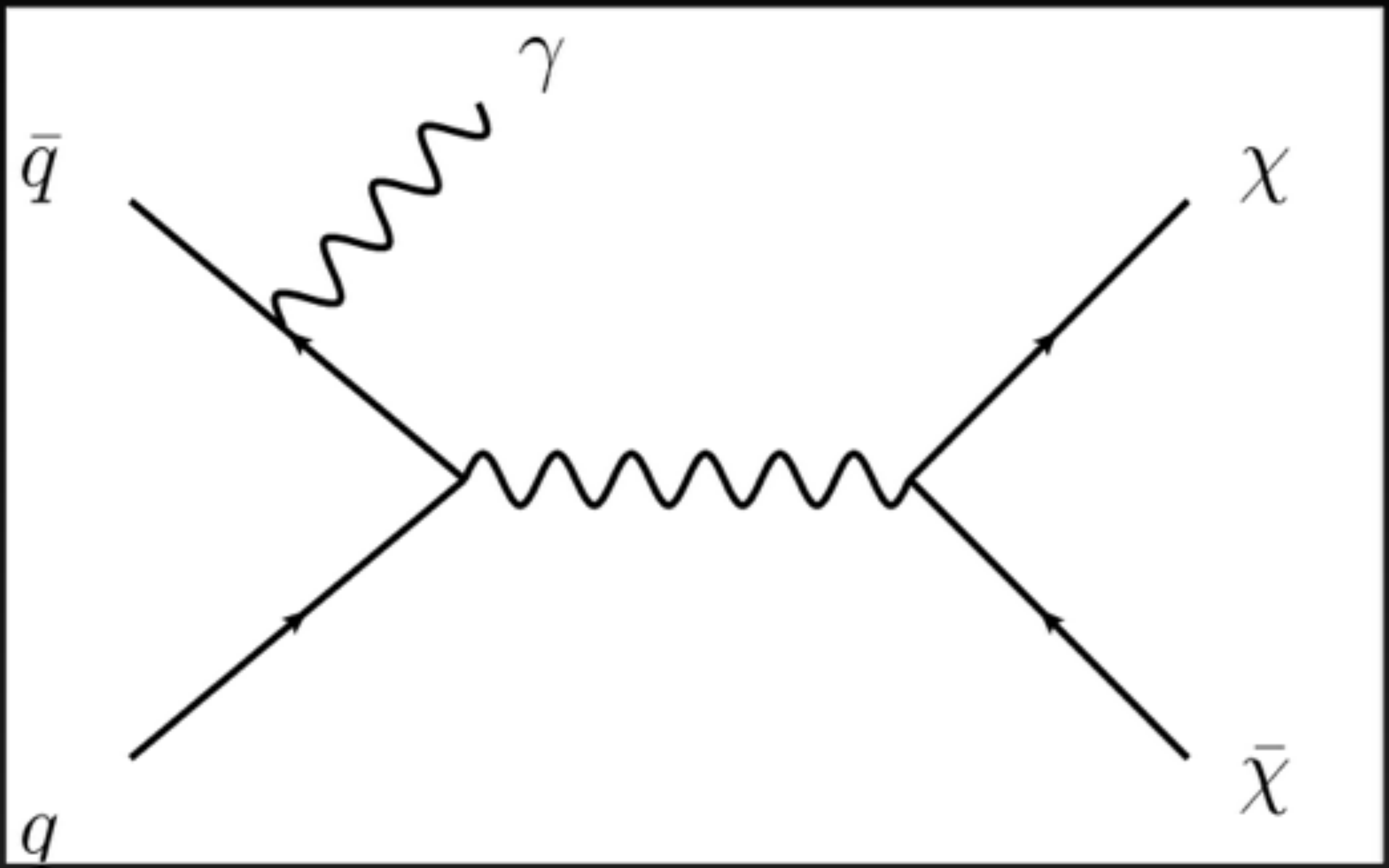
Gravity is Weak!

- 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?

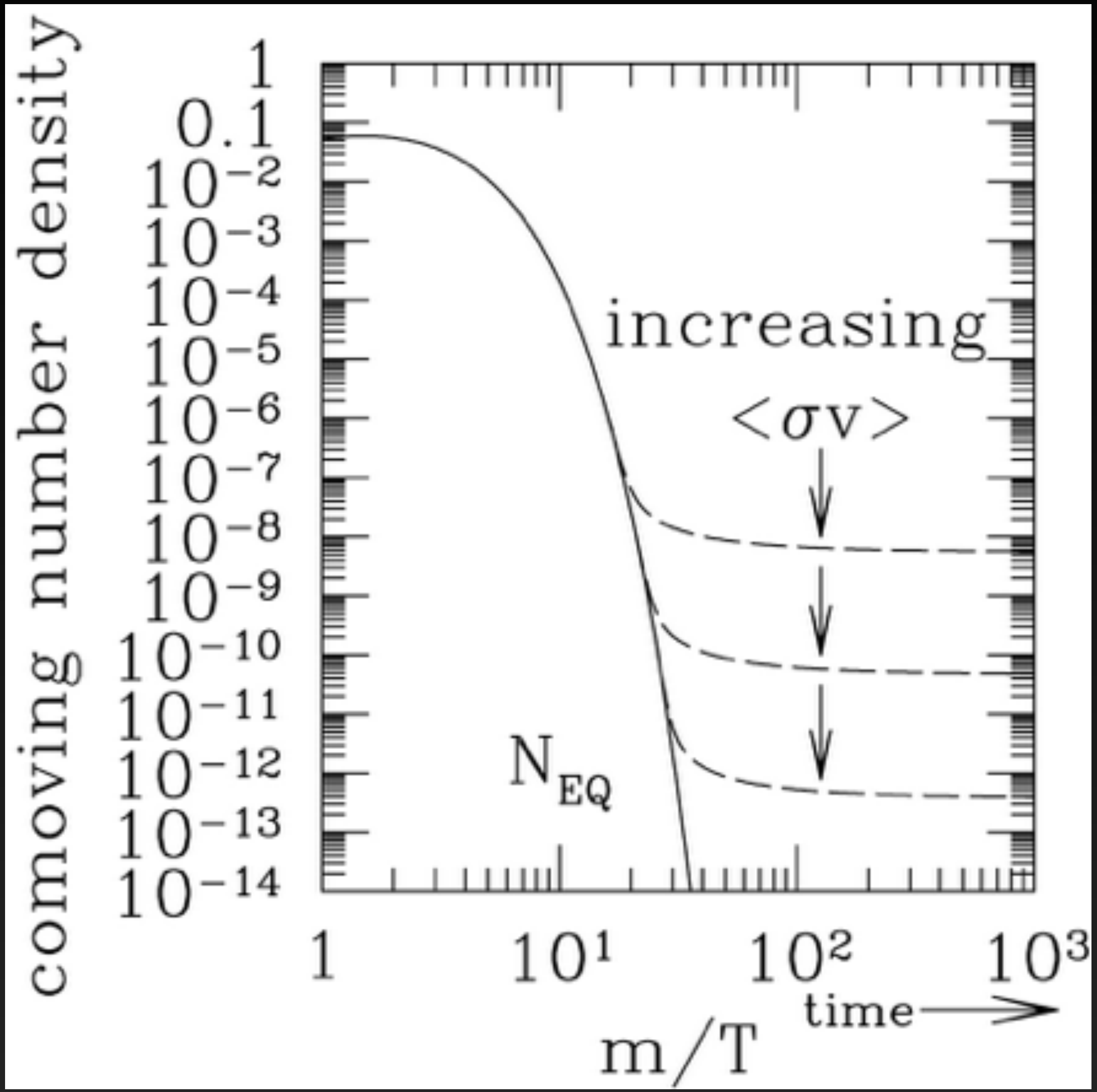
Dark Matter in Thermal Equilibrium



In the early universe, the temperature is far above the mass of both dark matter and baryonic particles, and they can be exchanged freely.

At the end of this period, the number density of dark matter and baryonic matter should be similar.

Dark Matter in Thermal Equilibrium



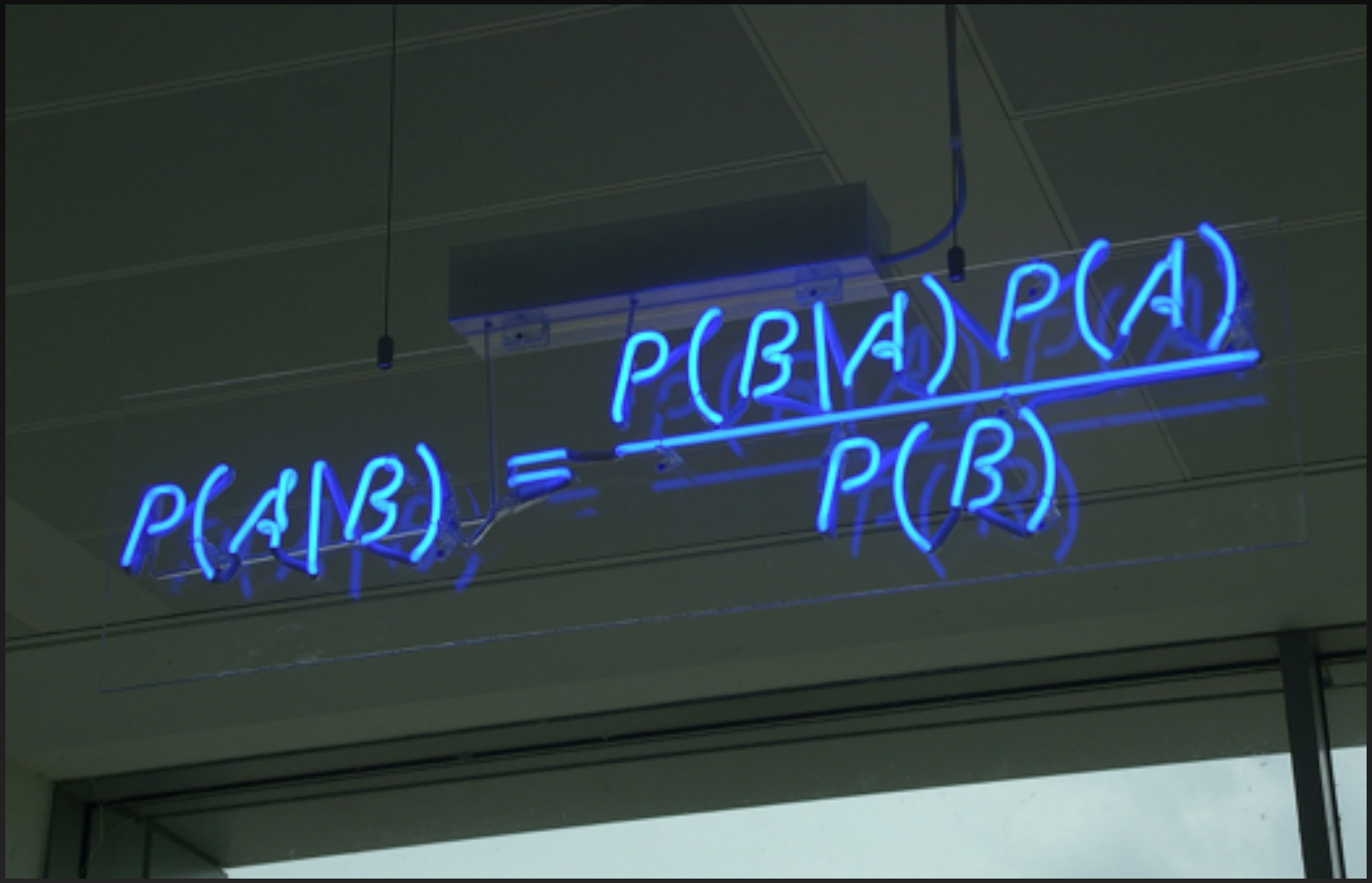
A particle with a weak interaction cross-section and a mass on the weak scale is expected to naturally obtain the correct relic abundance through thermal freeze-out in the Early Universe.

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

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

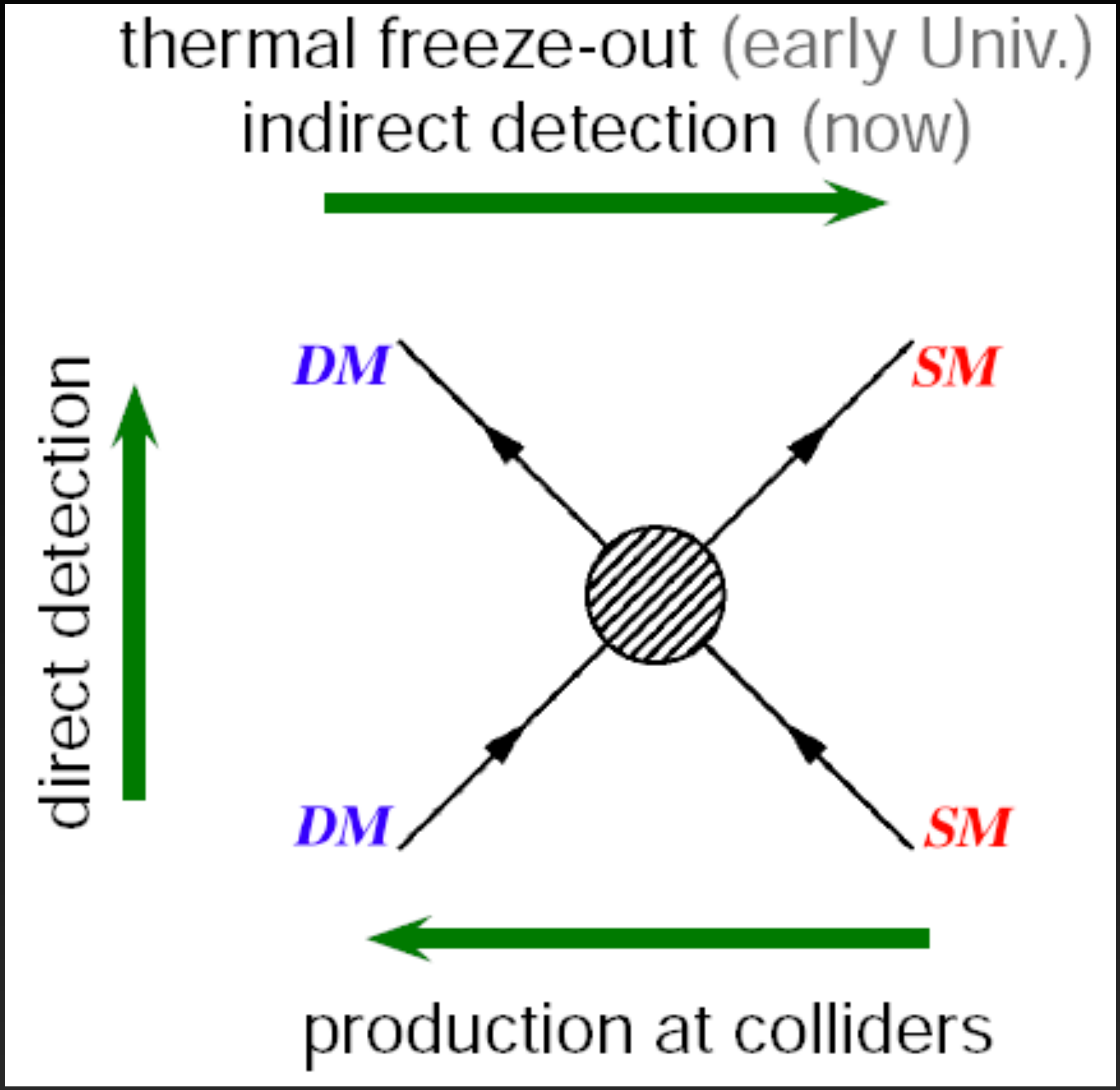
Observing a Dark Matter Particle

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



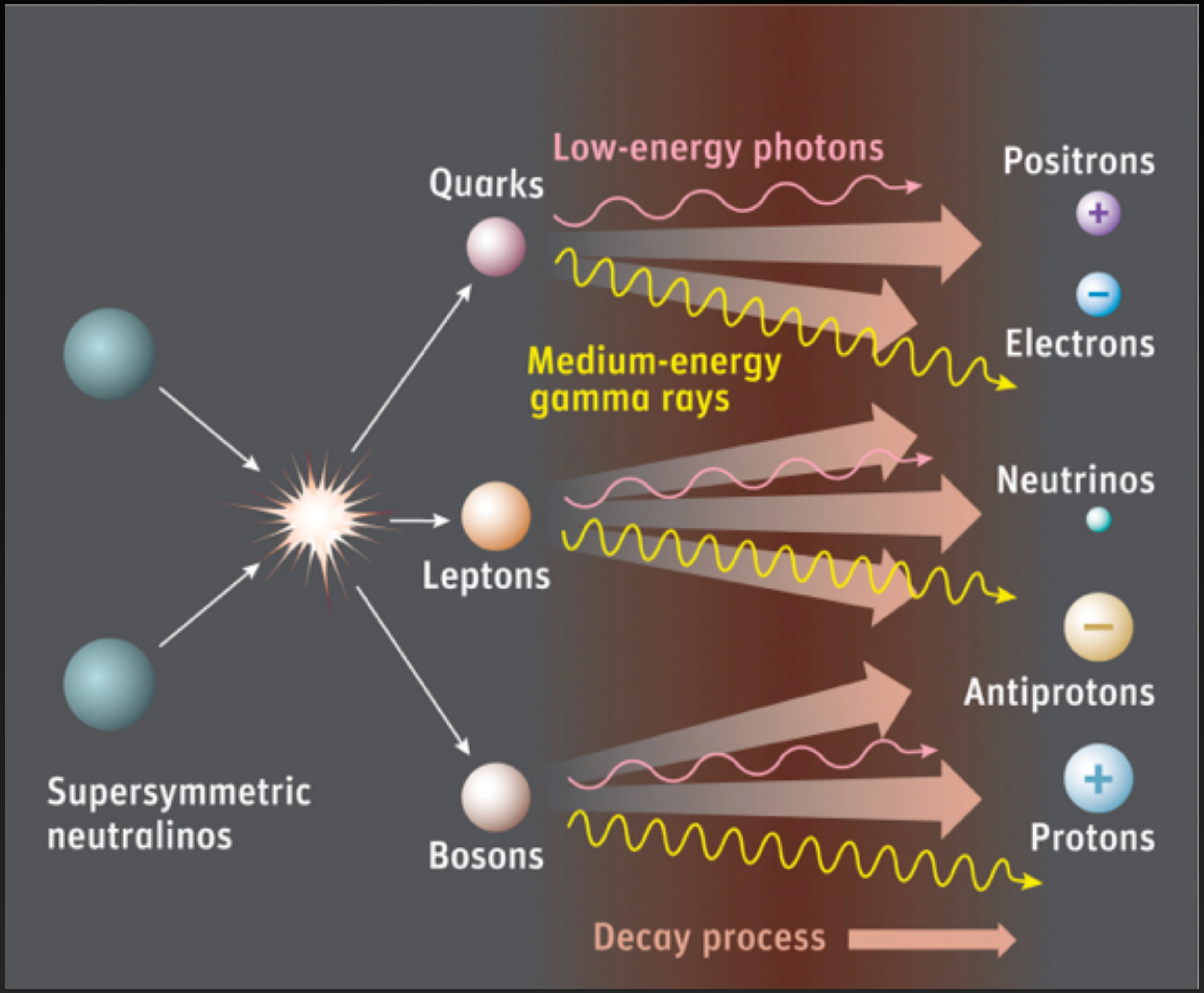
We shouldn't think of dark matter searches as a "needle in a haystack". Our theoretical priors should lead us to bet that particle dark matter can be feasibly observed.

How Do we Look For Dark Matter?



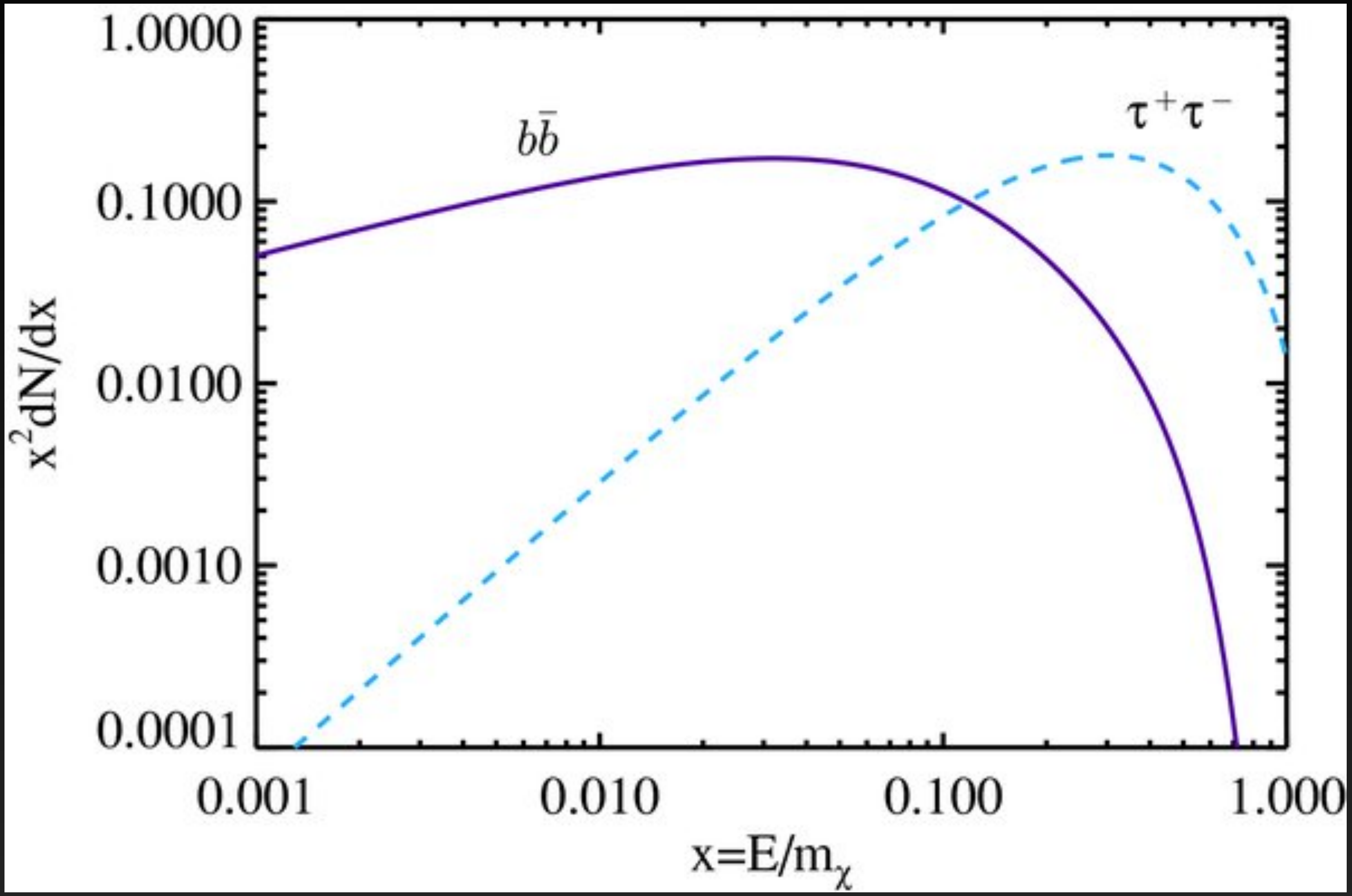
If dark matter had a thermal cross-section in the early universe, it should still have an observable cross-section today.

Gamma-Rays from WIMPs



Can think of dark matter interactions like a collision in the LHC. Jets are produced which eventually decay down to standard model particles.

Gamma-Rays from WIMPs

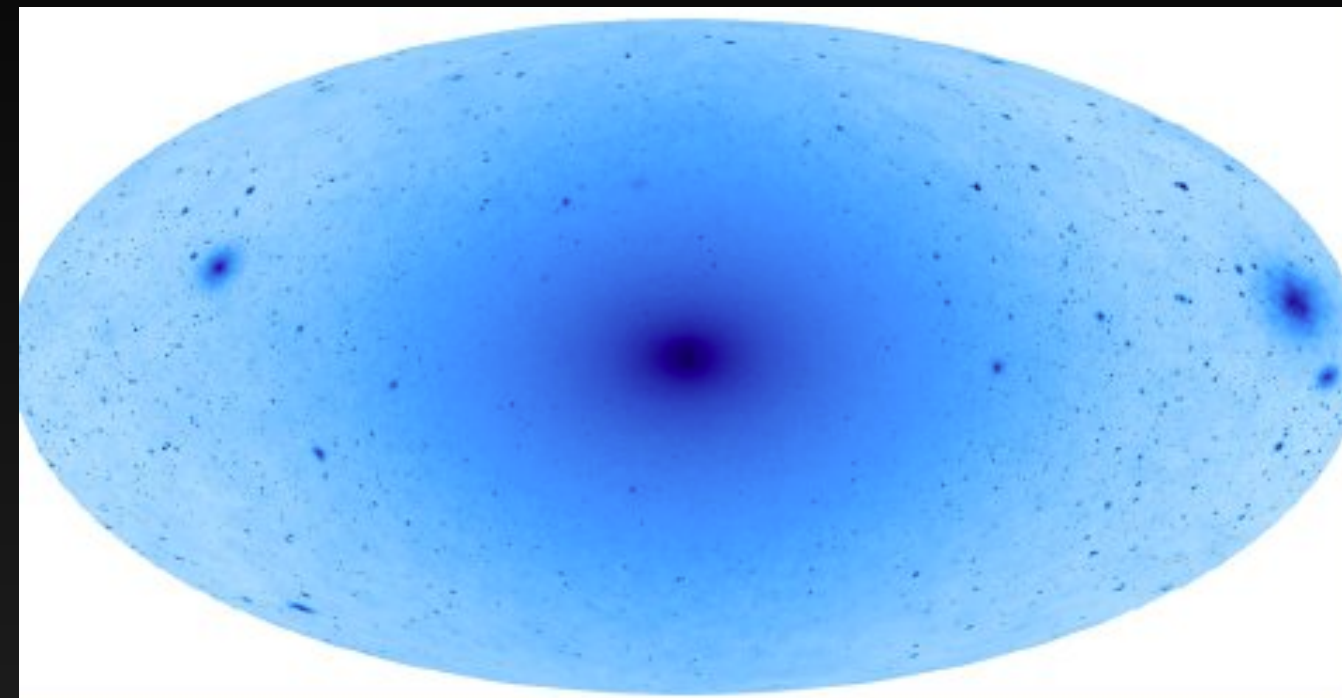


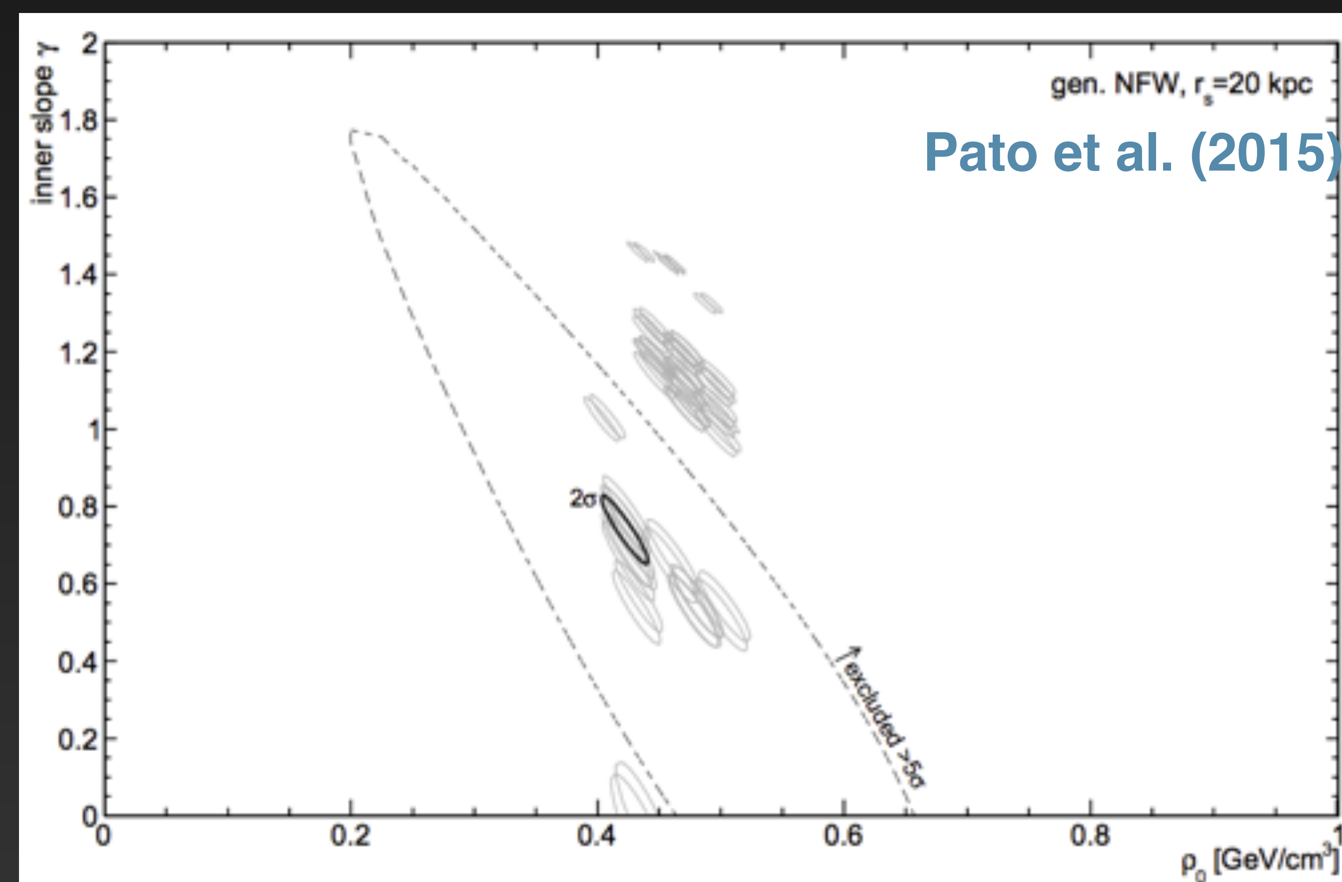
Once a standard model final state is selected, the resulting photon spectrum can be calculated from known physics.

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

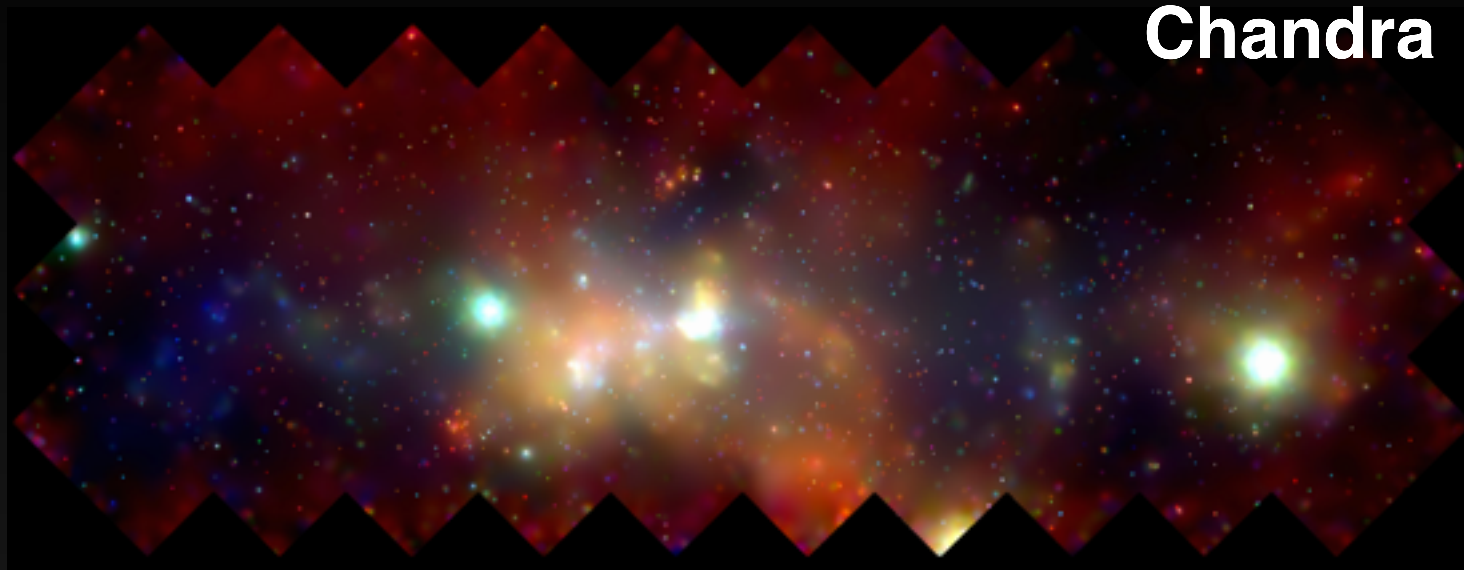
$$\rho_{NFW} = \left(\frac{r}{r_s}\right)^{-\gamma} \left(1 + \frac{r}{r_s}\right)^{-3+\gamma}$$

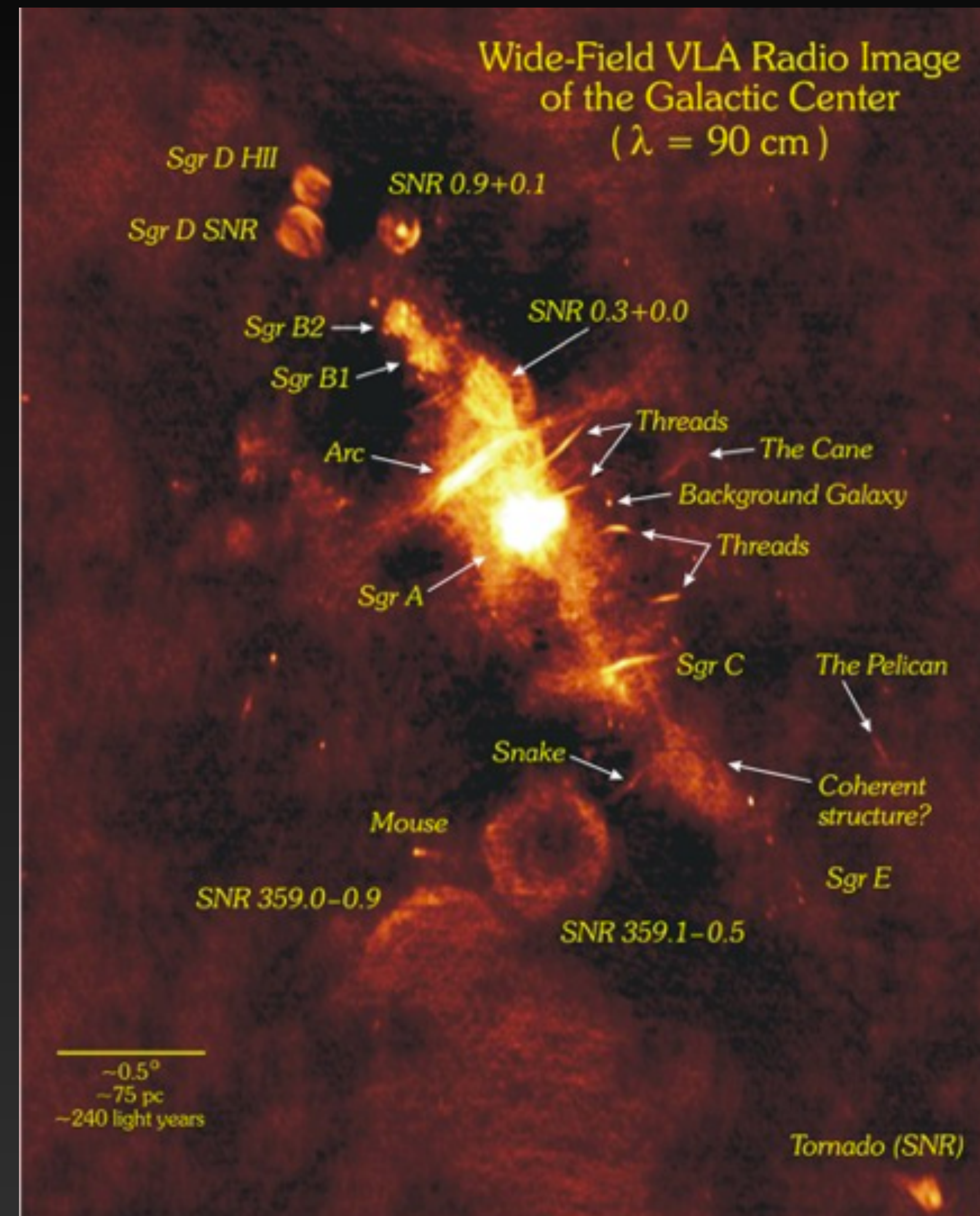
For the remainder of this talk, we employ a simple analytical model, known as the "generalized NFW Profile" which provides a reasonable fit to the observed dark matter density distribution of dark matter halos.

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

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

The Galactic Center in Gamma-Rays





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

Chandra observes ~9000 point sources in inner degree.

VLA finds bright non-thermal emission structures.

The Galactic Center in Gamma-Rays

Supernovae Source Cosmic-Ray Protons:

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

(~2% in relativistic electrons)

The Galactic Center in Gamma-Rays

Supernovae Source Cosmic-Ray Protons:

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

(~2% in relativistic electrons)

cosmic rays propagate

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

Solved Numerically:
e.g. Galprop

The Galactic Center in Gamma-Rays

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(~2% in relativistic electrons)

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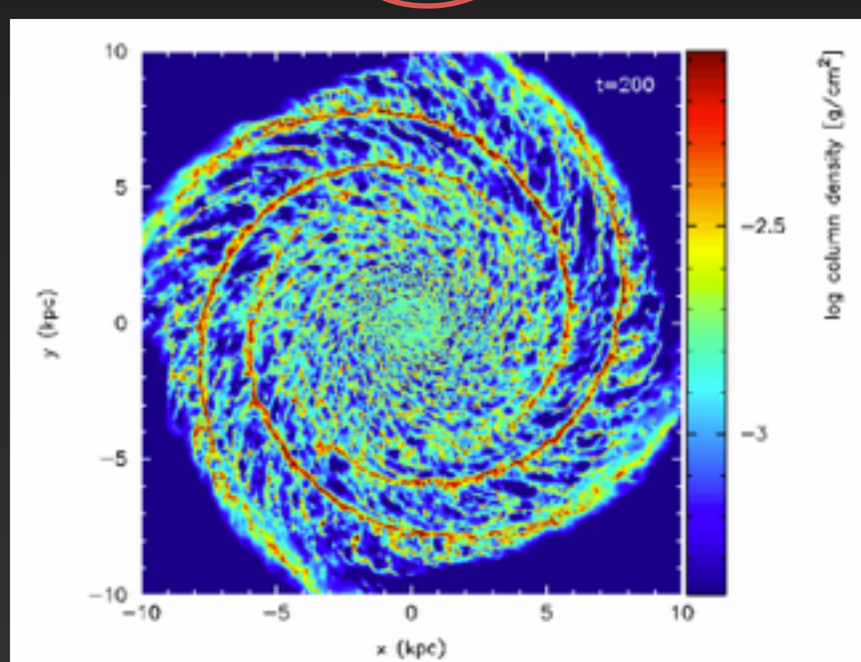
Solved Numerically:
e.g. Galprop

Gas/ISRF



The Galactic Center in Gamma-Rays

Supernovae Source Cosmic-Ray Protons:

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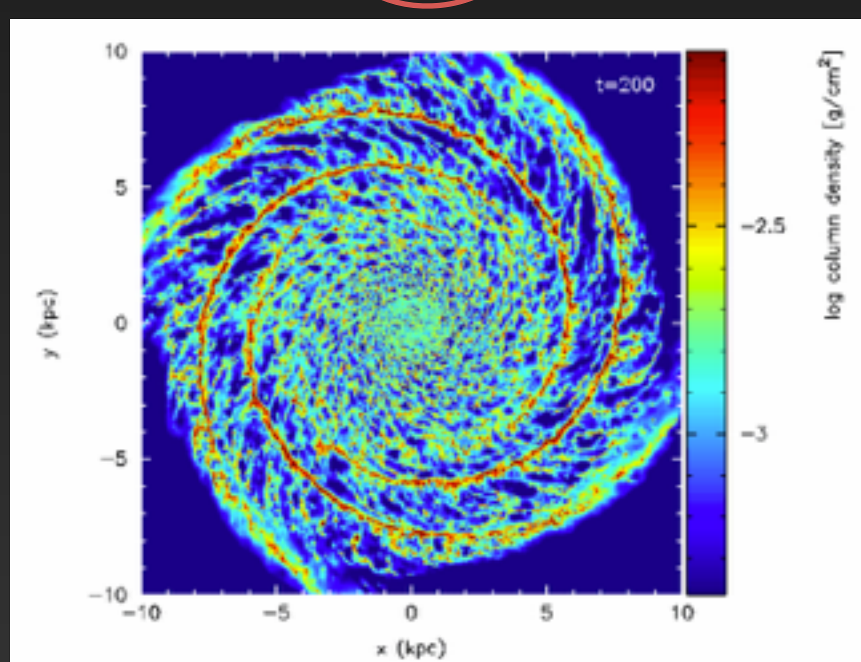
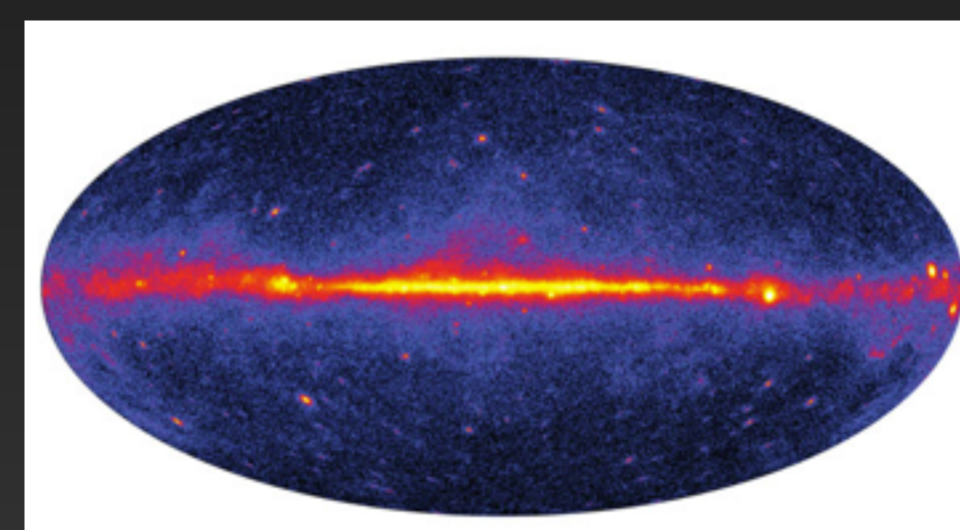
Solved Numerically:
e.g. Galprop

Gas/ISRF





The Galactic Center in Gamma-Rays

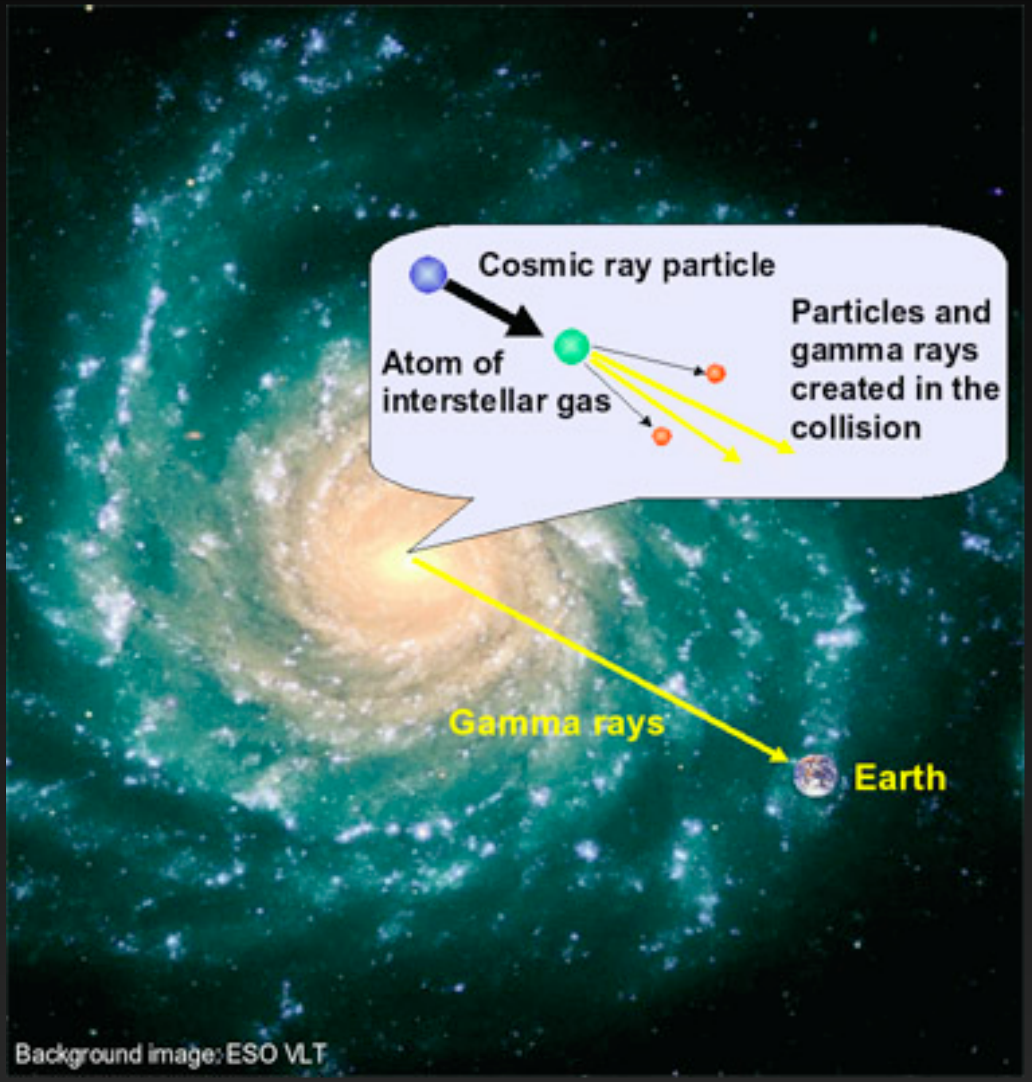
What Are These Backgrounds?

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

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

*** Bremsstrahlung**

*** Inverse Compton Scattering**

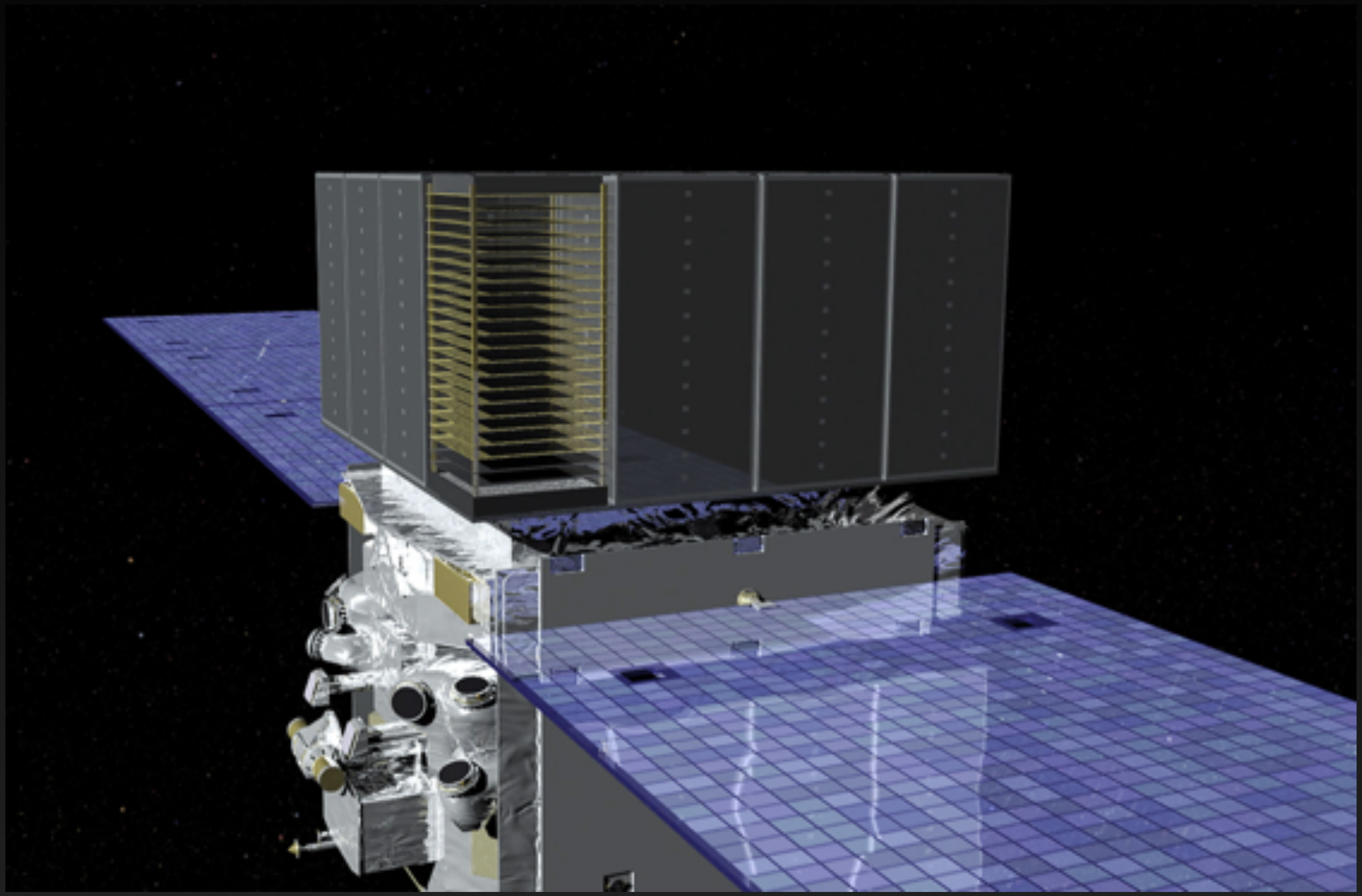


The Fermi Large Area Telescope

Launched: June 2008

Observes Gamma-Rays with Energies 30 MeV - 1 TeV

Collaboration of five countries and dozens of institutions.



Operational Characteristics:

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

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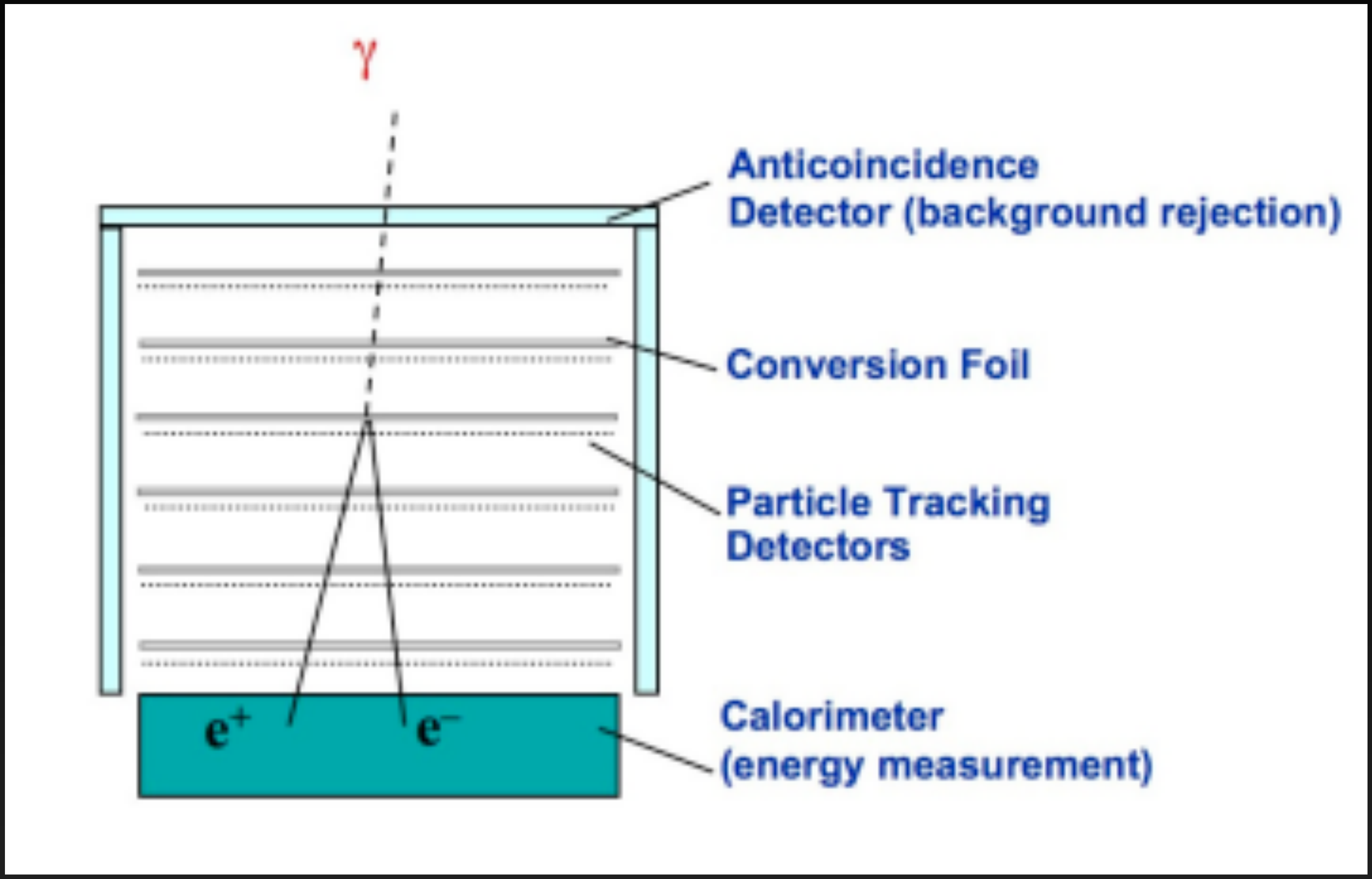
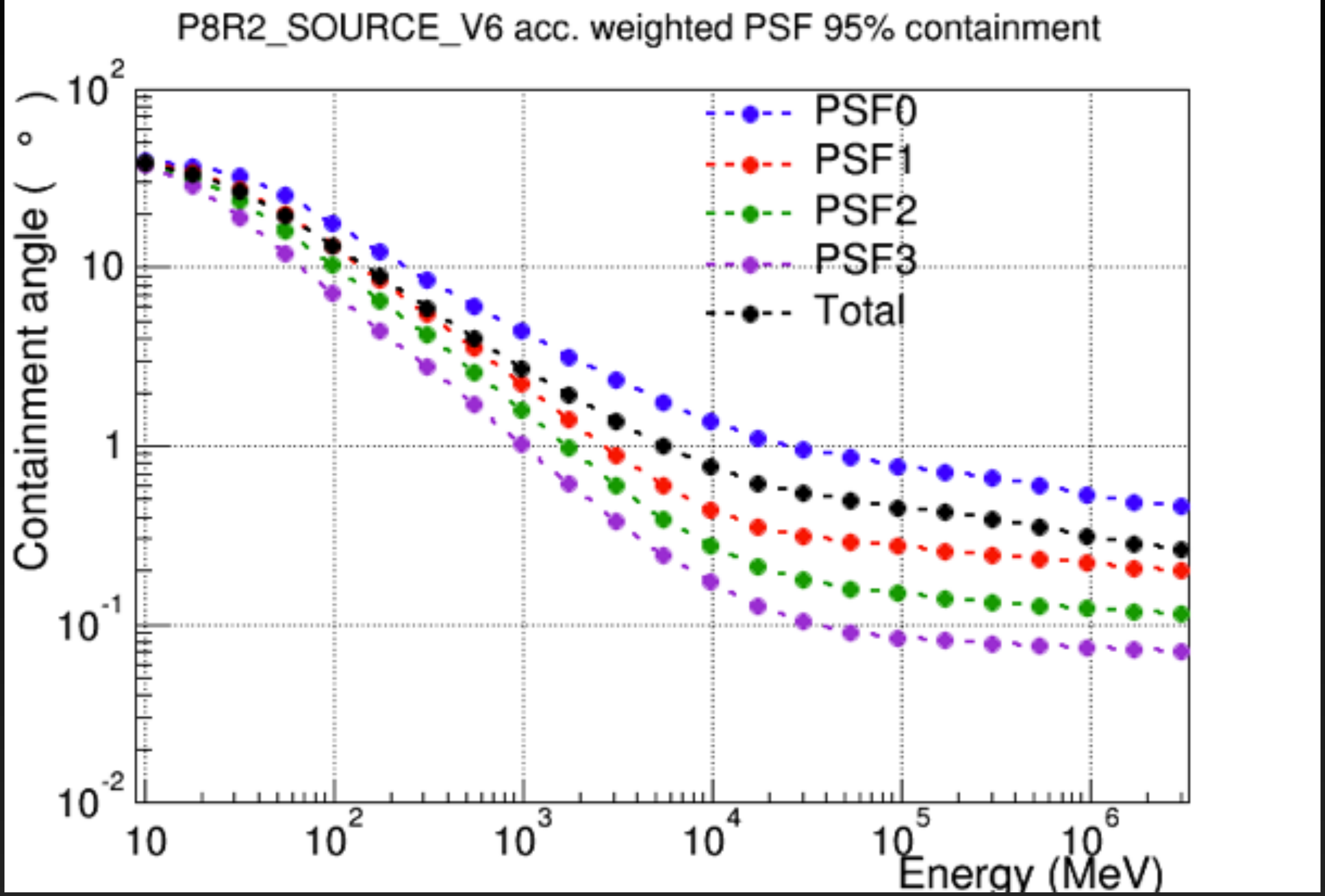


Operational Characteristics:

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

Fermi-LAT Sensitivity to Dark Matter



Angular Resolution is:

1.) poor (compared to all other wavelengths).

2.) highly energy dependent.

3.) highly photon selection dependent.

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

1.) Dark Matter is a key component of the universe, and we know nothing about it.

2.) WIMPs are a well-motivated model for a dark matter particle.

3.) Observations of gamma rays from WIMP annihilations offers the opportunity to understand the dark matter particle.

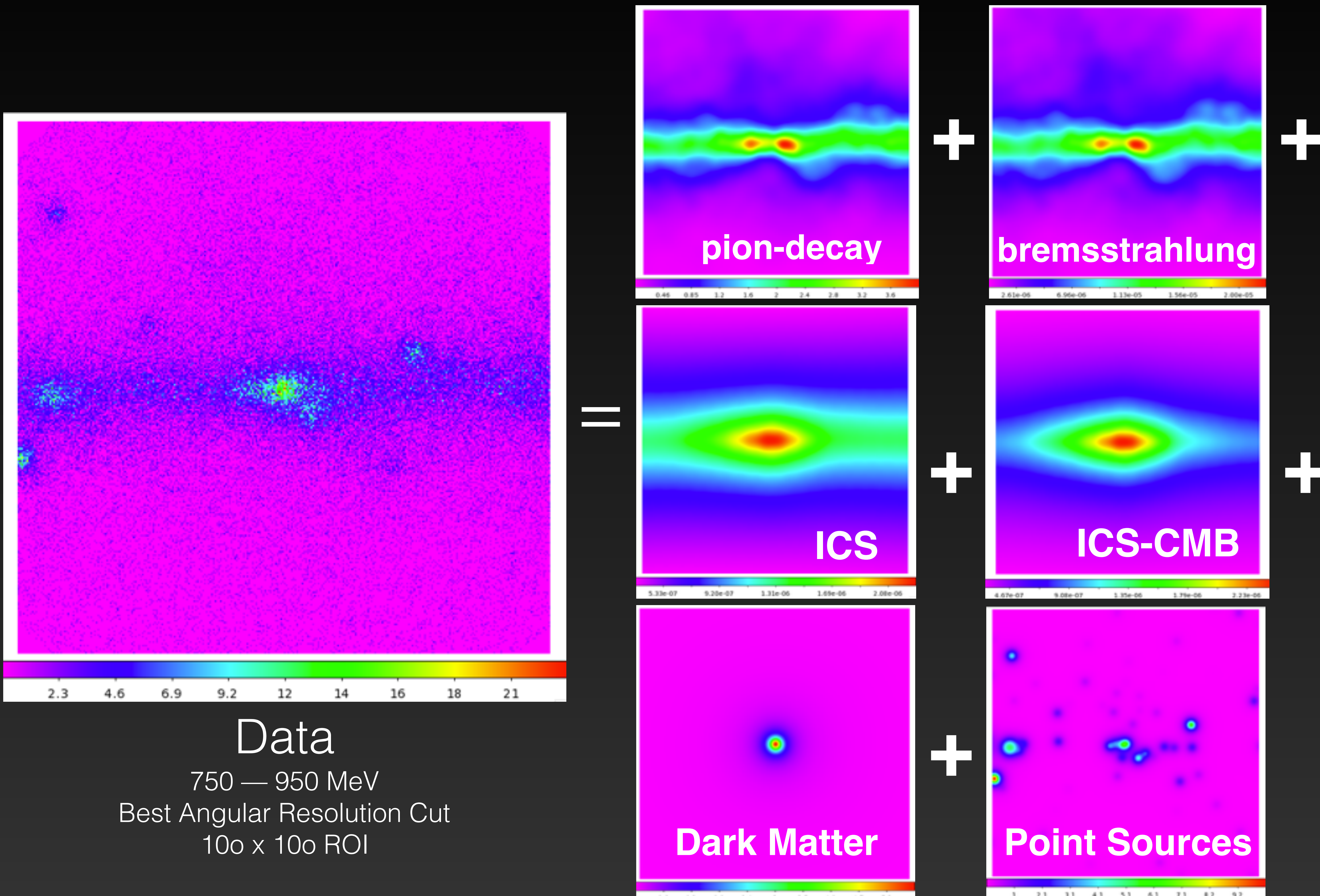
4.) The Milky Way Galactic Center is among the most promising targets for WIMP searches.

5.) The Fermi-LAT instrument makes such an observation feasible (expected?).

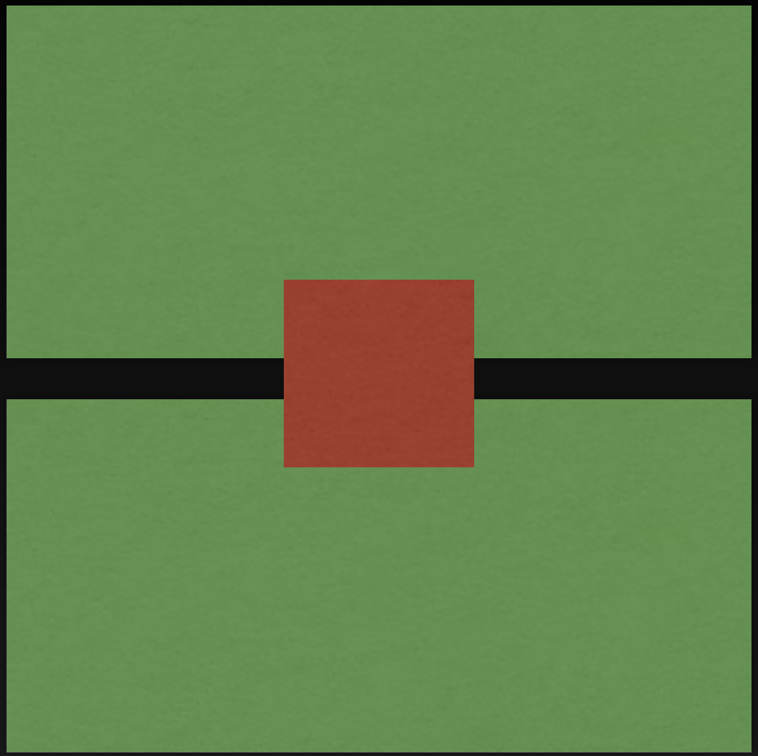
Many Studies

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

How Does This Analysis Work?



How Does This Analysis Work?



Daylan et al. (2014)

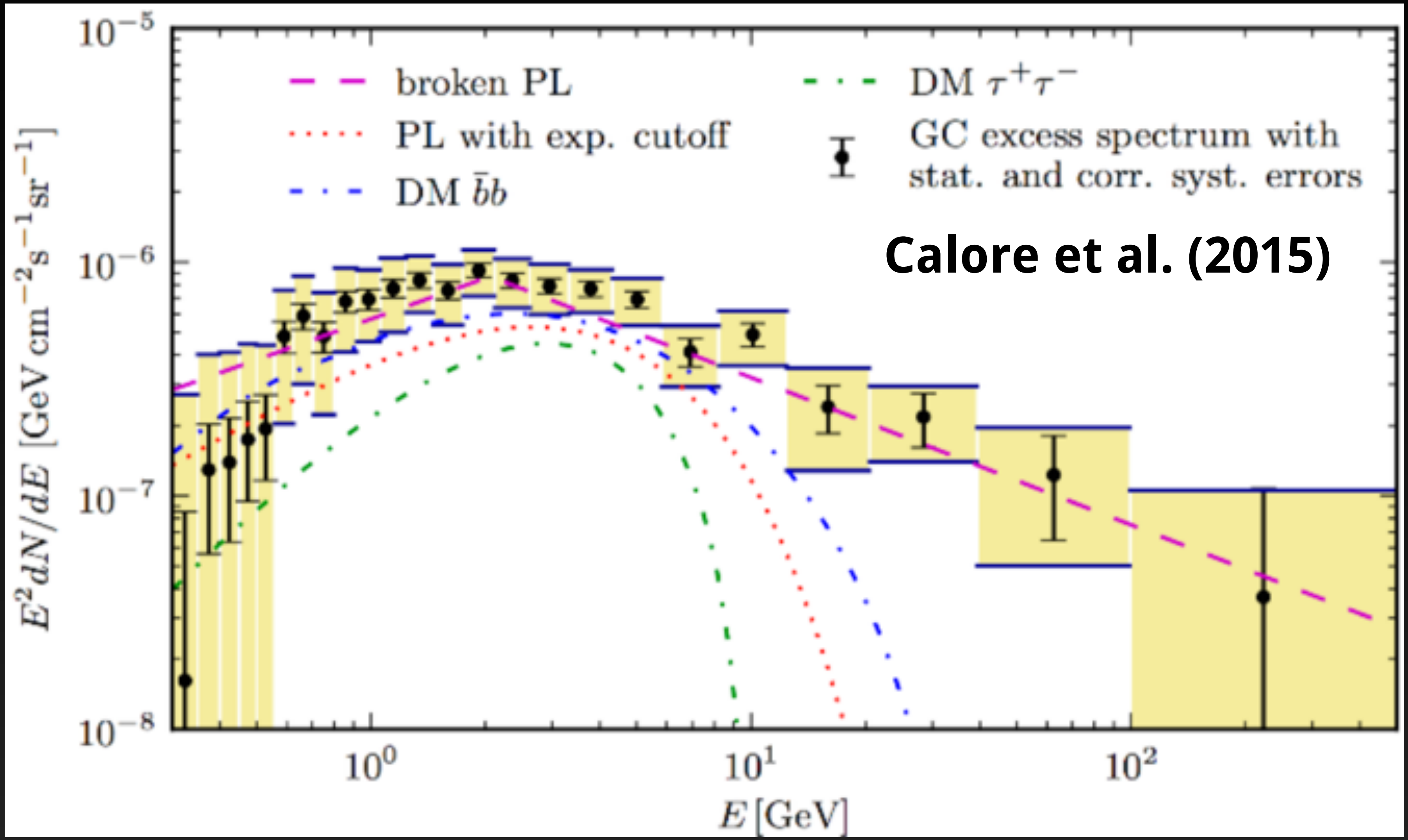
INNER GALAXY

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

GALACTIC CENTER

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

Observational Results



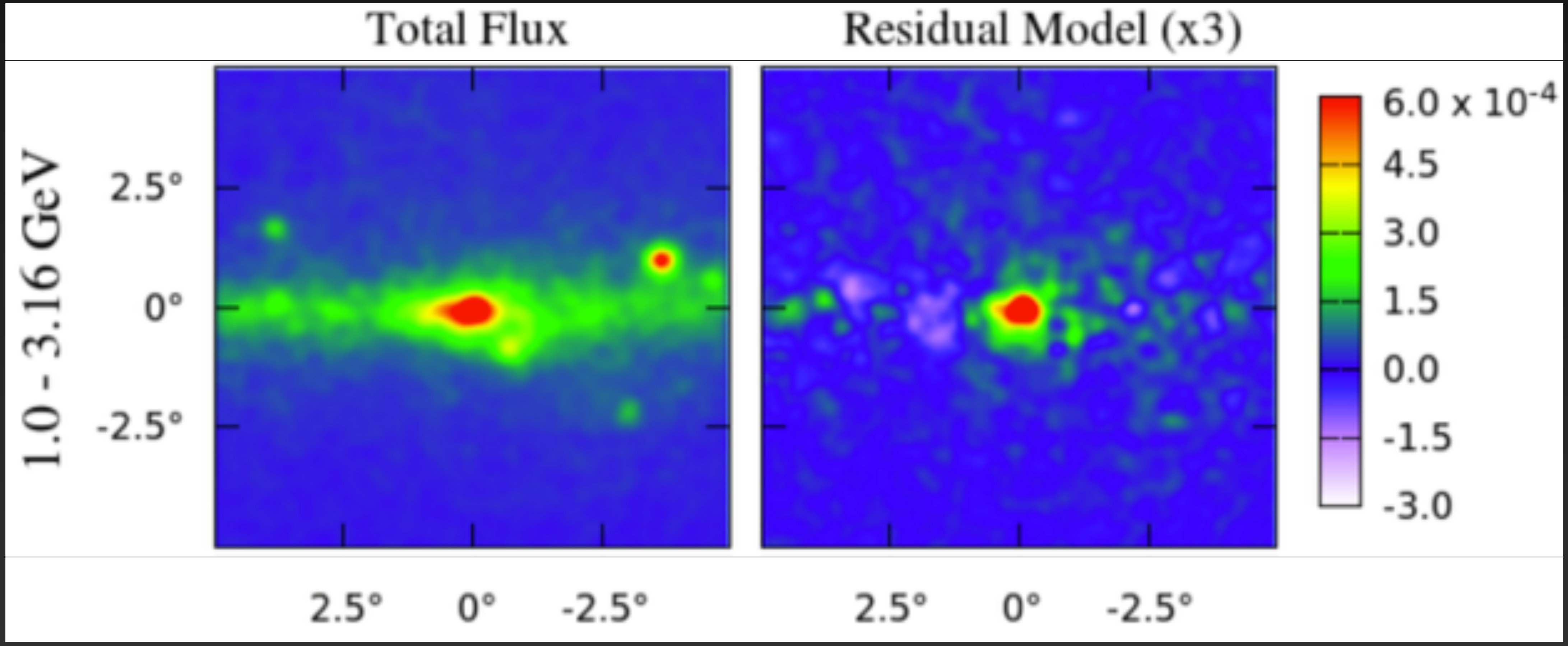
Spectral Model highly resilient to changing systematic background models ~300 models considered here.

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

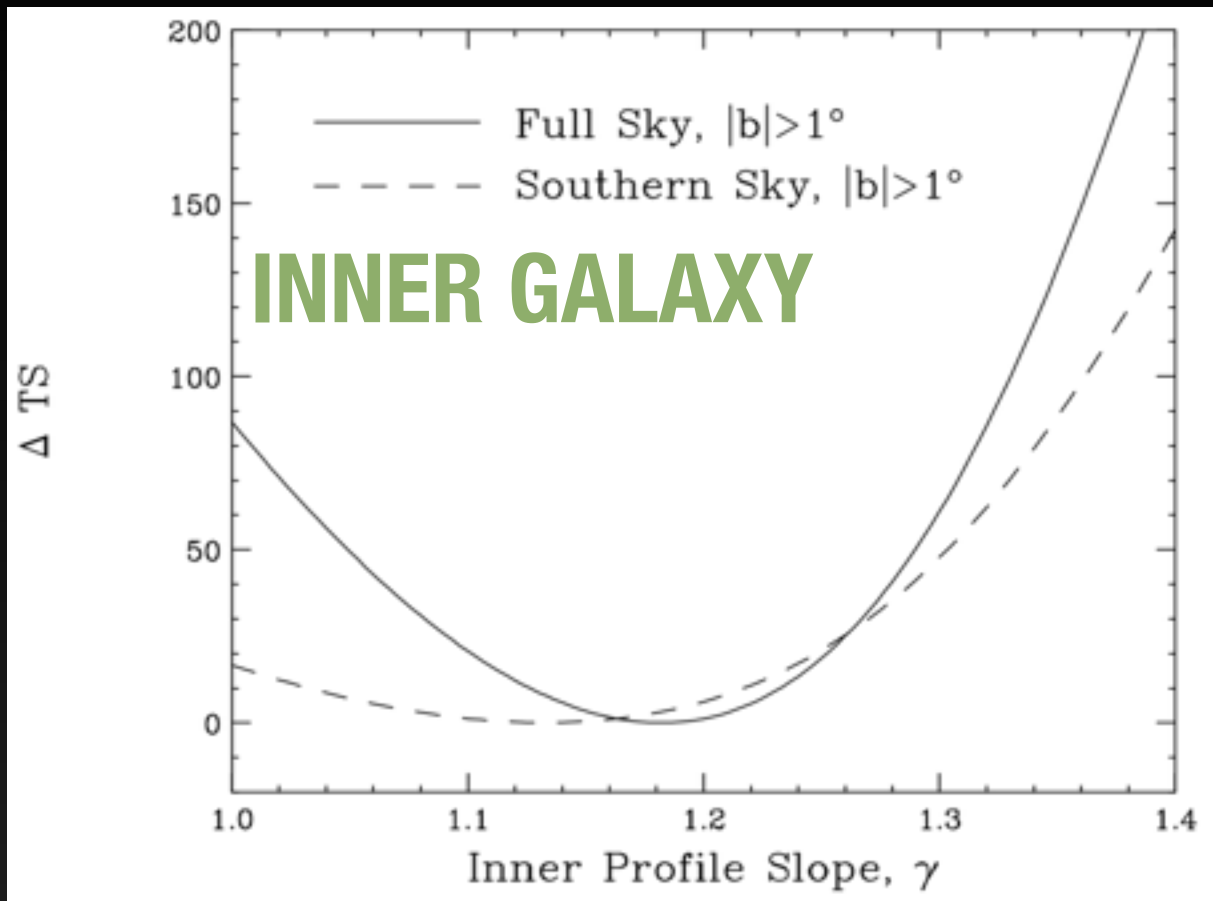
Observational Results

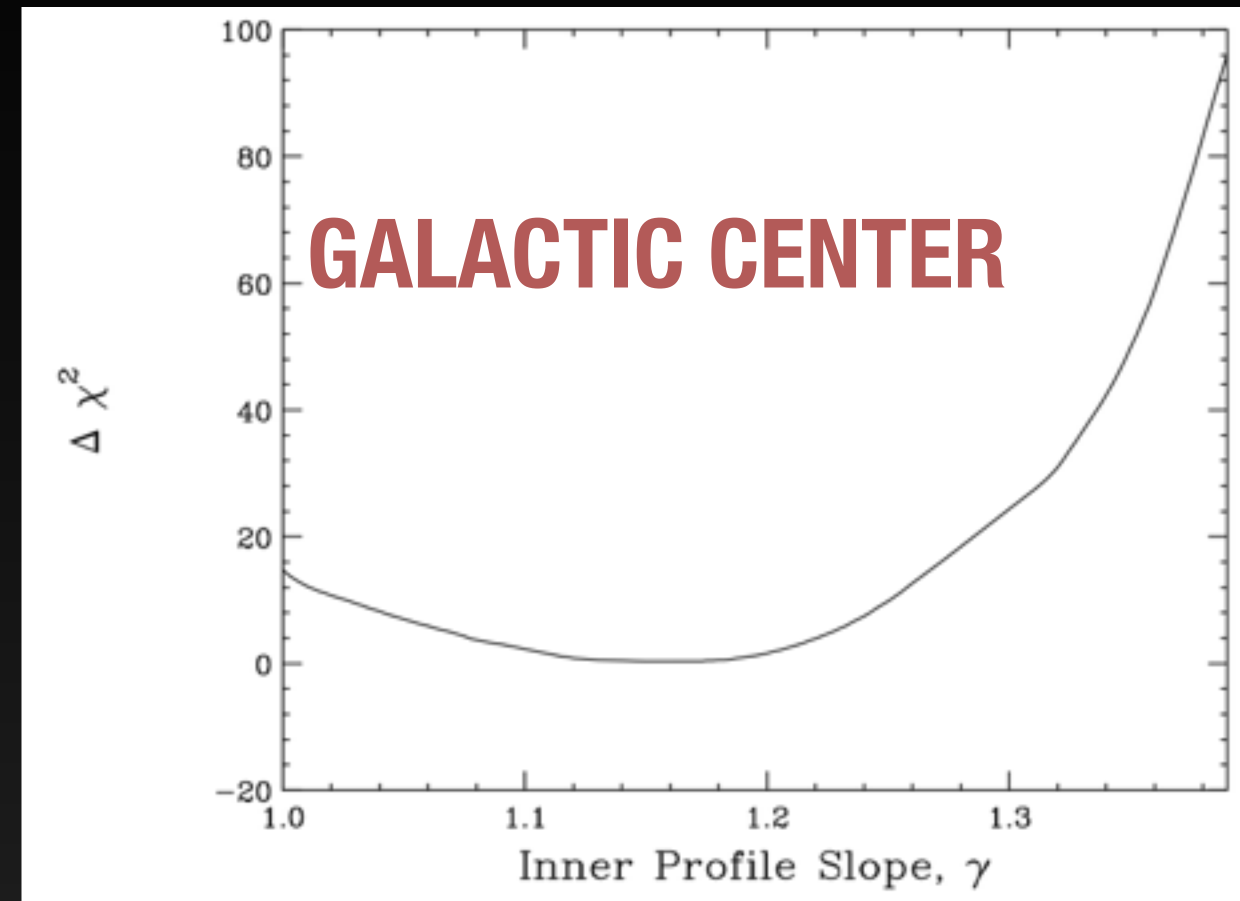
Utilizing our template fitting algorithm, we can determine the gamma-ray flux which is best fit by an NFW profile.

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



Observational Results



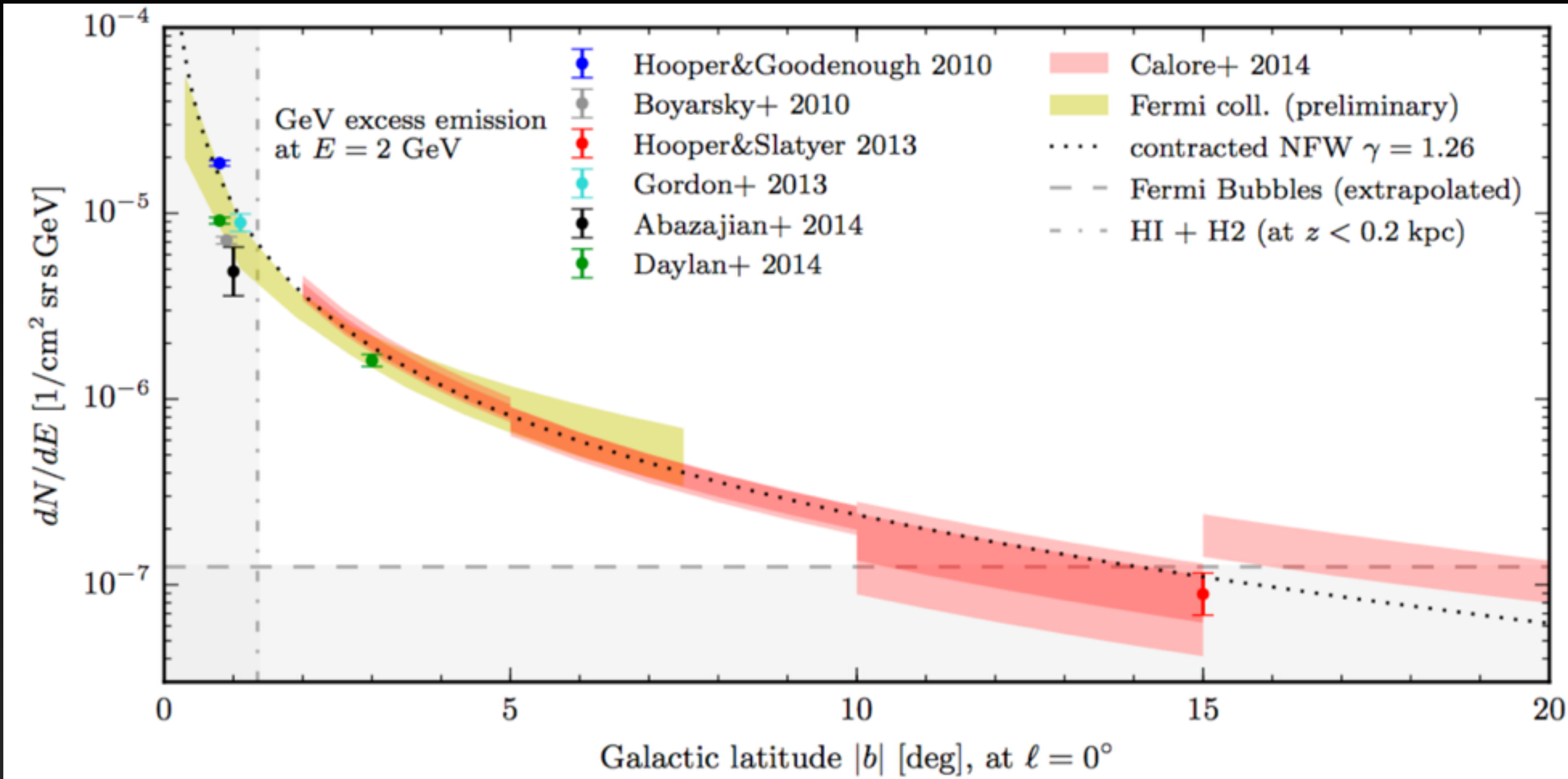


Inner galaxy prefers density profile γ = 1.18

Galactic Center prefers γ = 1.17

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

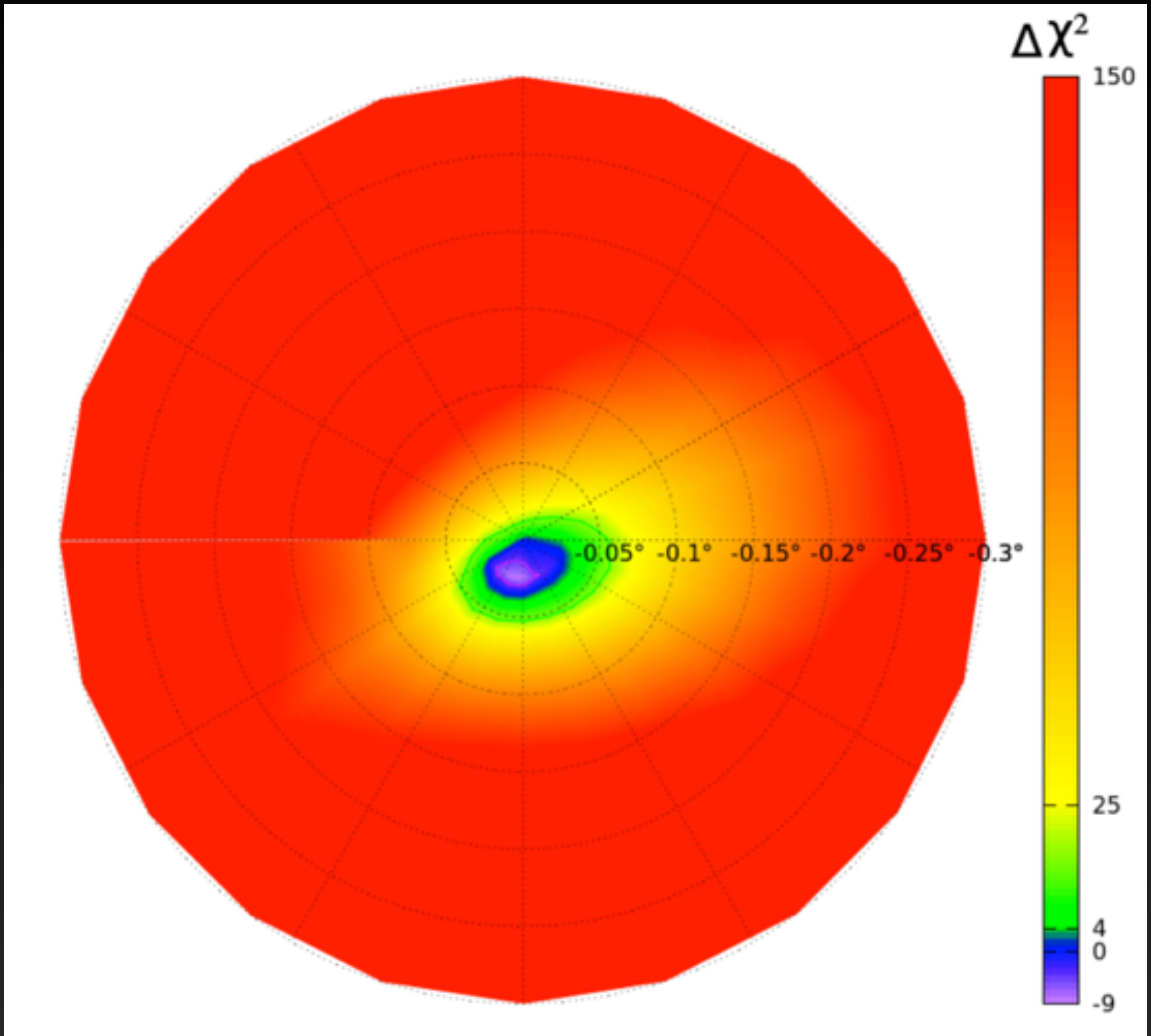
Observational Results



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

Calore et al. (2014b)

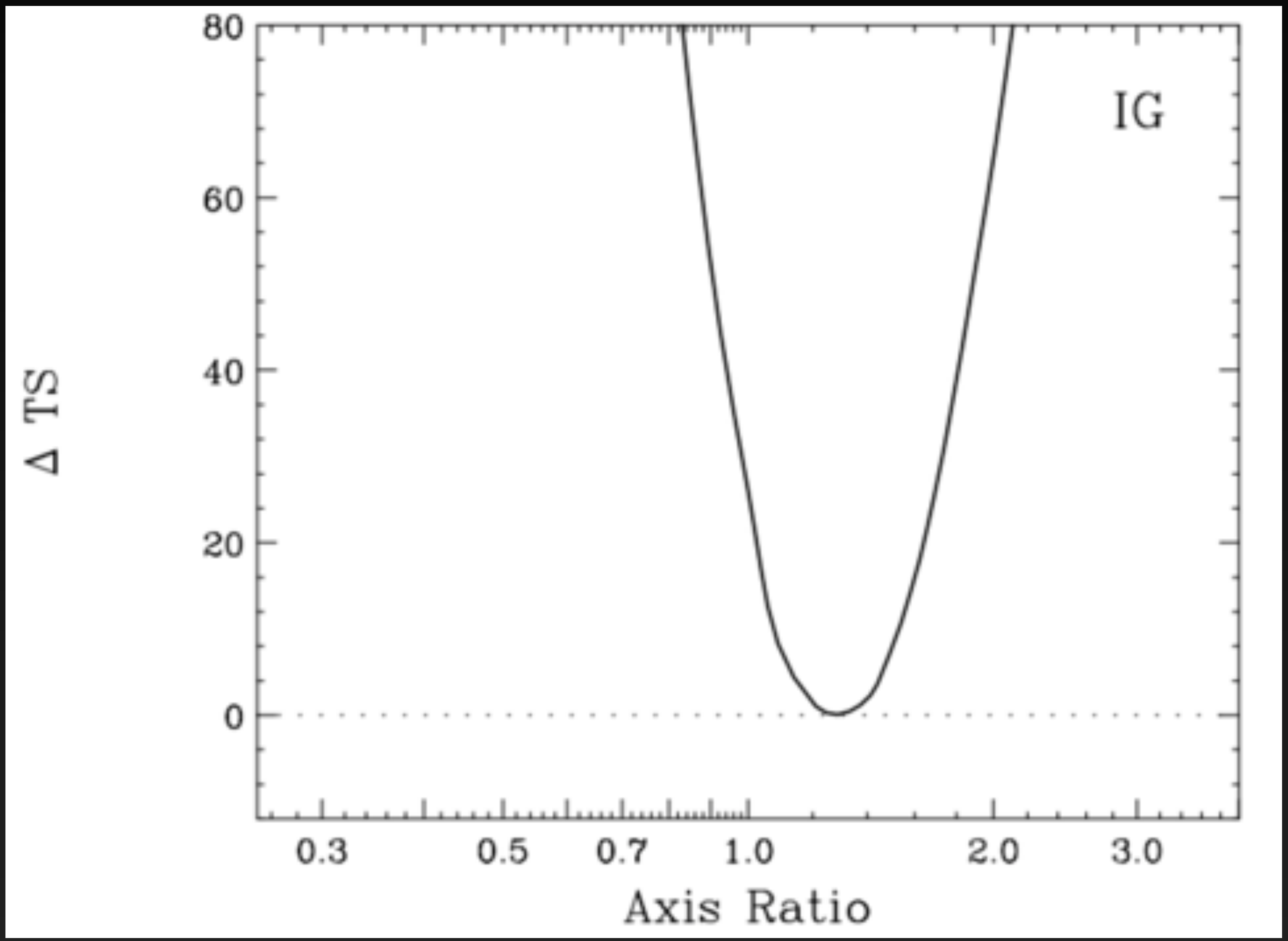
Observational Results

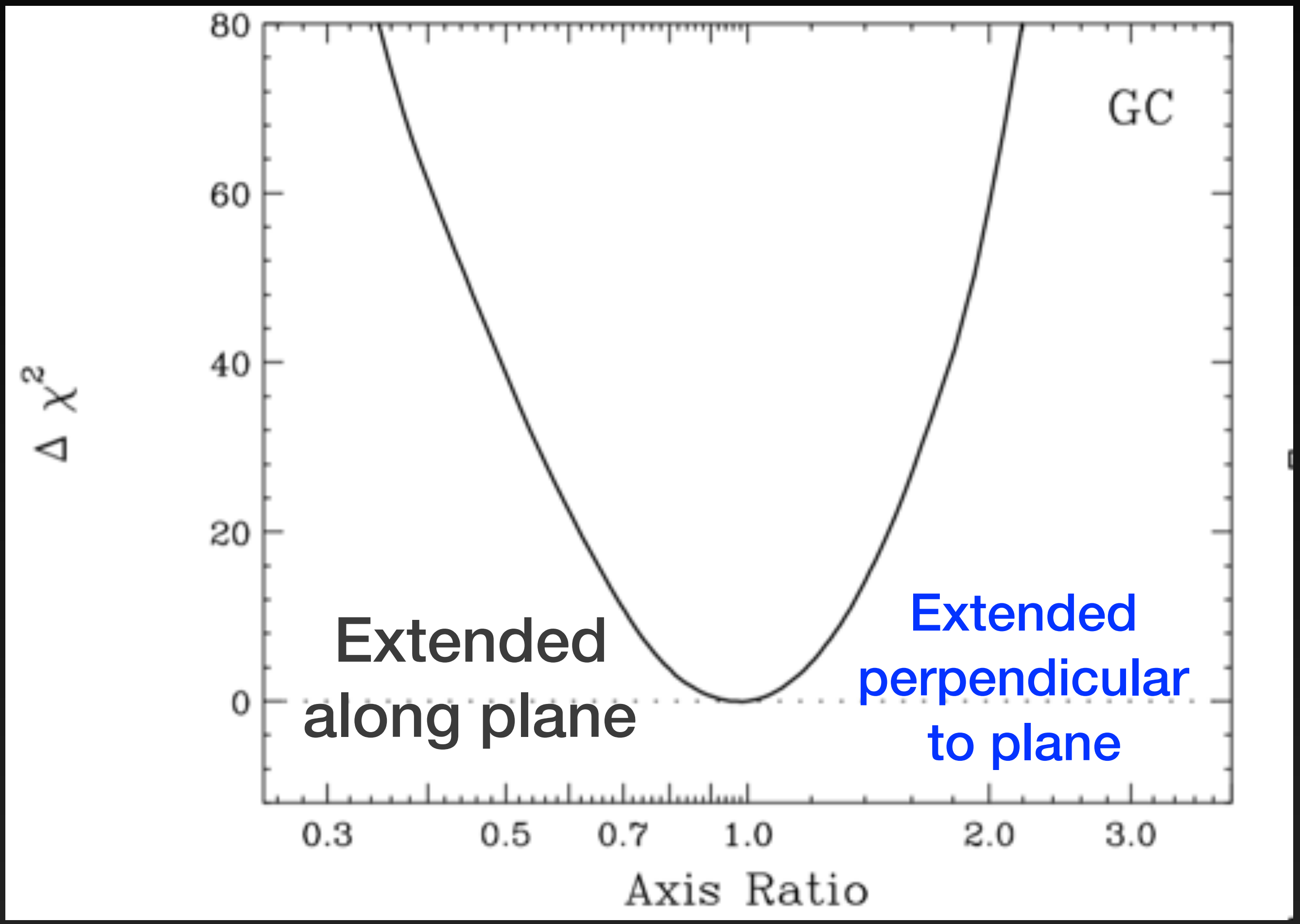


The peak of the new emission source lies within 0.05º of the GC.

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

Observational Results

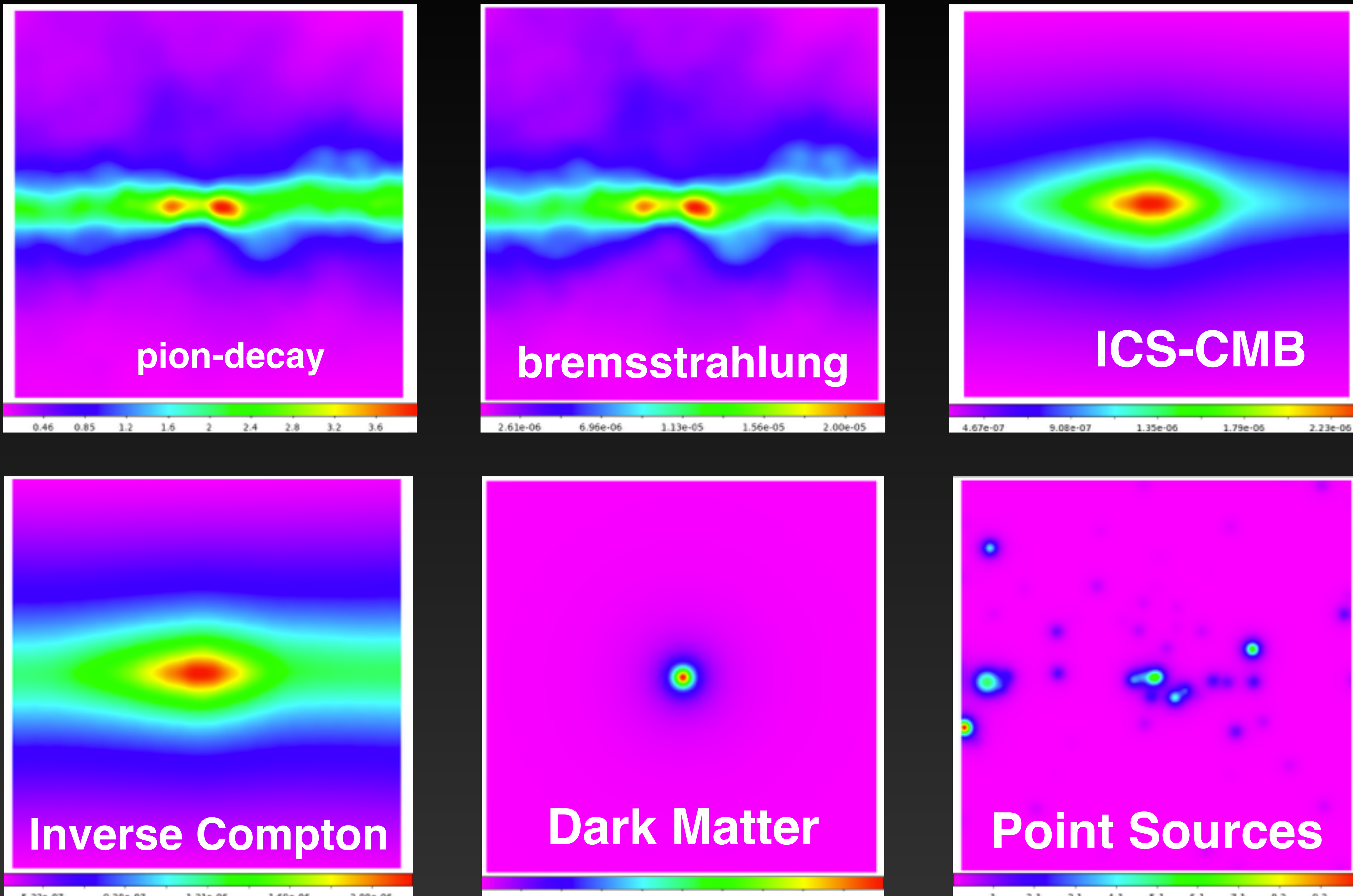




The Galactic Center analysis finds the excess to be spherically symmetric, to within approximately 20%.

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

Spherical Symmetry and the GCE



Summary of Data Analysis

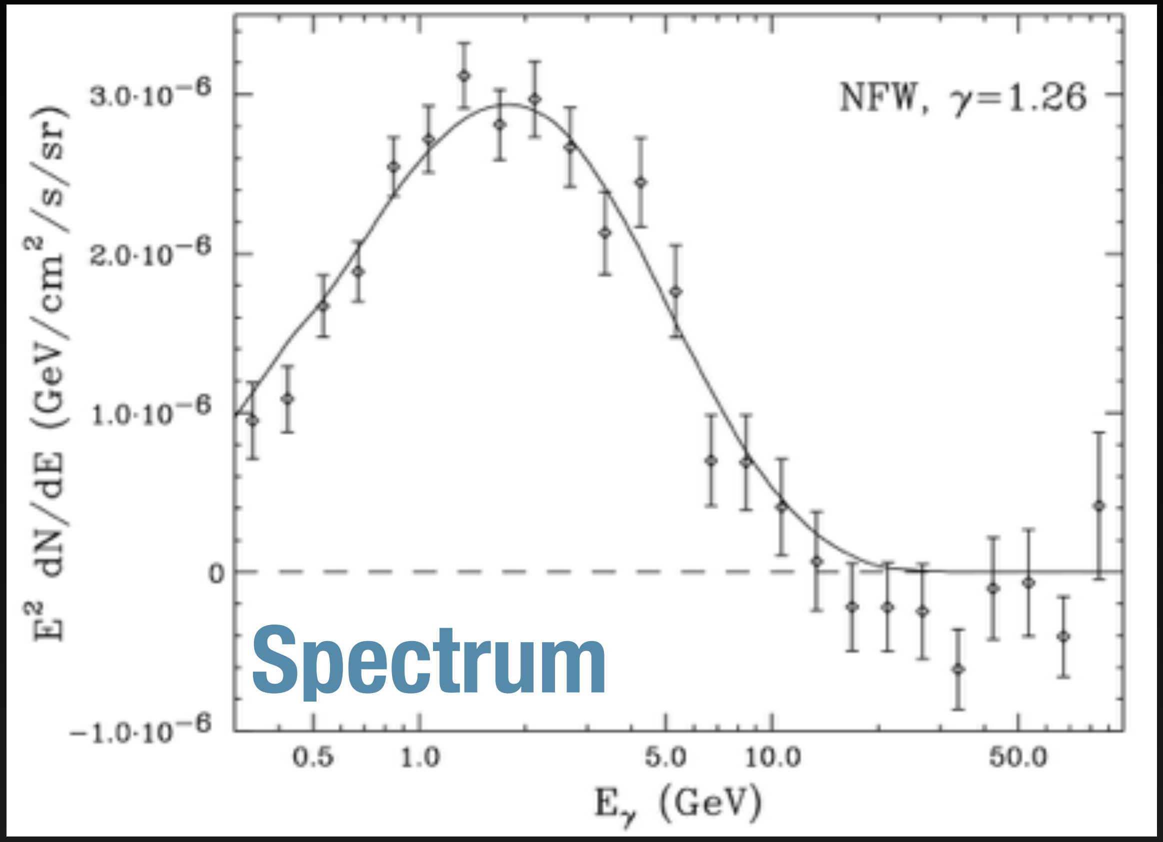
<u>All</u> currently published observational studies of the Galactic Center excess agree:

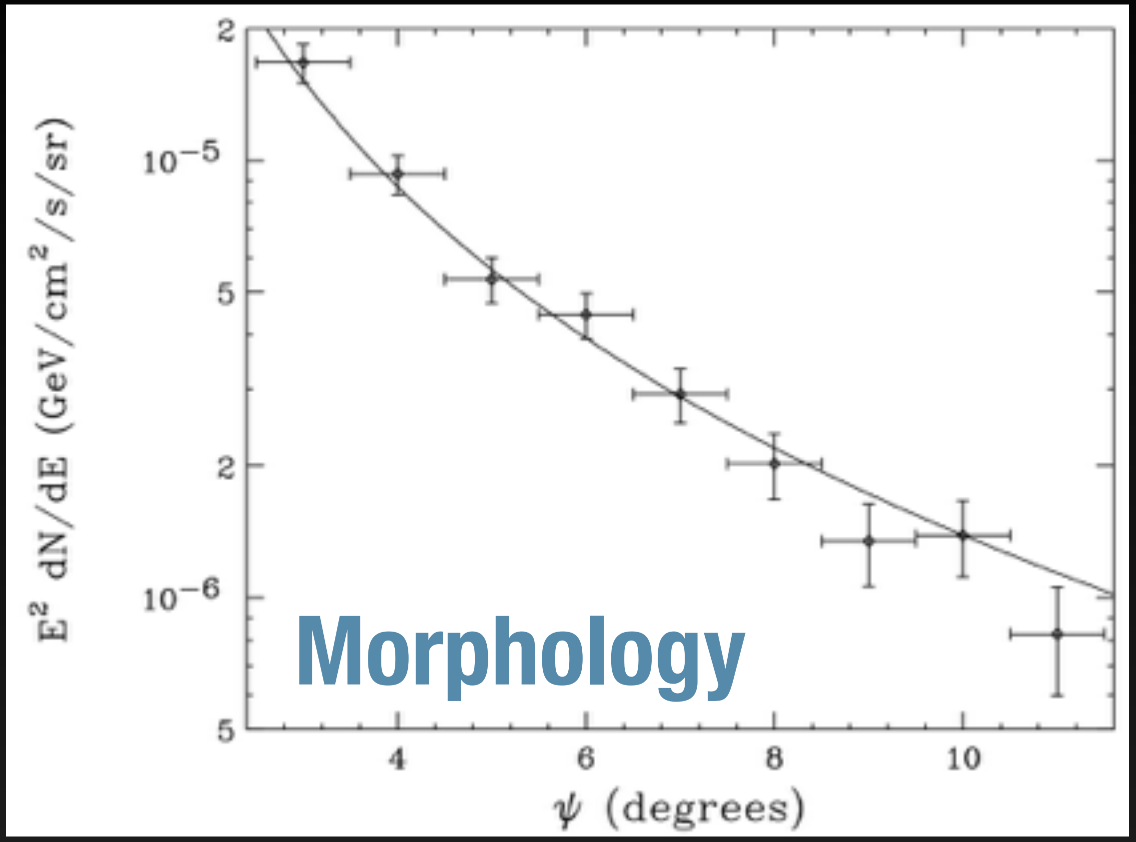
- **Current best fit models of astrophysical gamma-ray emission have uncovered a gamma-ray excess - with a fractional intensity of ~15%**

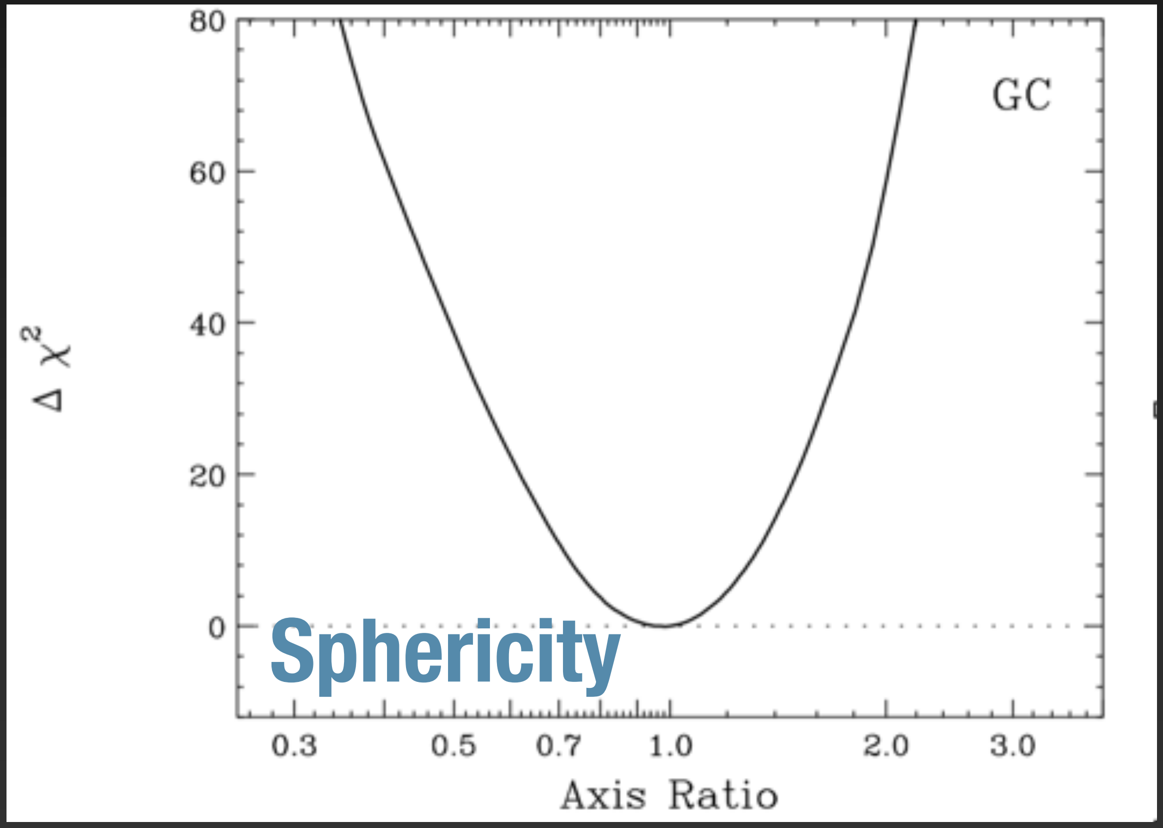
- **The spectrum of the excess is peaked at an energy of ~2 GeV, and falls off at low energies with a spectrum that is harder than expected for astrophysical pion emission**

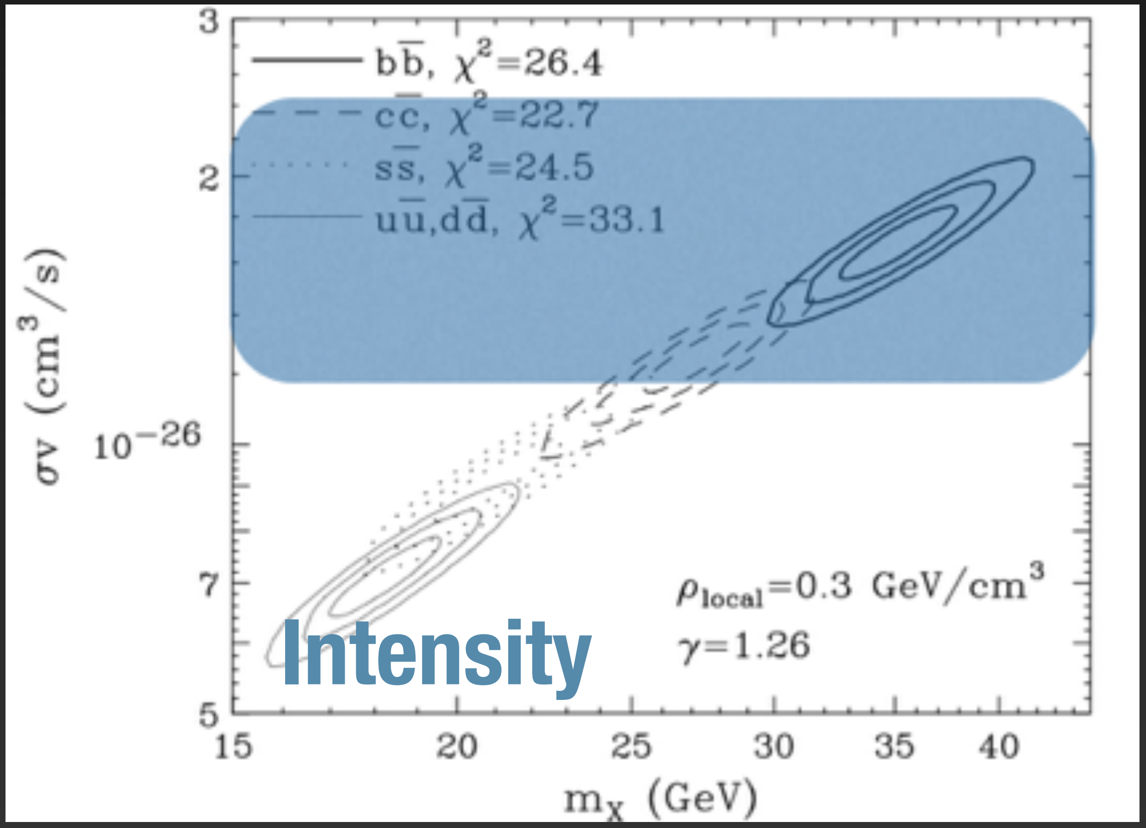
- **The excess extends to at least 10º away from the galactic center, following a 3D profile which falls in intensity as $r^{-2.2 \text{ to } -2.8}$**

Comparison to Dark Matter Models









Comparison to Dark Matter Models

Freese et al. (1509.05076)
Bhattacharya et al. (1509.03665)
Algeri et al. (1509.01010)
Fox & Tucker-Smith (1509.00499)
Dutta et al. (1509.05989)
Liu et al. (1508.05716)
Berlin et al. (1508.05390)
Fan et al. (1507.06993)
Hektor et al. (1507.05096)
Achterbeg et al. (1507.04644)
Biswas et al. (1507.04543)
Butter et al. (1507.02288)
Mondal et al. (1507.01793)
Cao et al. (1506.06471)
Banik et al. (1506.05665)
Ipek (1505.07826)
Buchmueller et al. (1505.07826)
Balazs et al. (1505.06758)
Medina (1505.05565)
Kim et al. (1505.04620)
Ko et al. (1504.06944)
Ko & Tang (1504.03908)
Ghorbani & Ghorbani (1504.03610)
Fortes et al. (1503.08220)
Cline et al. (1503.08213)
Rajaraman et al. (1503.05919)
Bi et al. (1503.03749)
Kopp et al. (1503.02669)
Elor et al. (1503.01773)
Gherghetta et al. (1502.07173)
Berlin et al. (1502.06000)
Achterberg et al. (1502.05703)
Modak et al. (1502.05682)
Guo et al. (1502.00508)
Chen & Nomura (1501.07413)
Kozaczuk & Martin (1501.07275)
Berlin et al. (1501.03496)
Kaplinghat et al. (1501.03507)
Alves et al. (1501.03490)
Biswas et al. (1501.02666)
Ghorbani & Ghorbani (1501.00206)
Cerdeno et al. (1501.01296)
Liu et al. (1412.1485)
Hooper (1411.4079)
Arcadi et al. (1411.2985)
Cheung et al. (1411.2619)
Agrawal et al. (1411.2592)
Kile et al. (1411.1407)
Buckley et al. (1410.6497)
Heikinheimo & Spethmann (1410.4842)
Freytsis et al. (1410.3818)
Yu et al. (1410.3347)
Cao et al. (1410.3239)
Guo et al. (1409.7864)
Yu (1409.3227)
Cahill-Rowley et al. (1409.1573)
Banik & Majumdar (1408.5795)
Bell et al. (1408.5142)
Ghorbani (1408.4929)
Okada & Seto (1408.2583)
Frank & Mondal (1408.2223)
Baek et al. (1407.6588)
Tang (1407.5492)
Balazs & Li (1407.0174)
Huang et al. (1407.0038)
McDermott (1406.6408)
Cheung et al. (1406.6372)
Arina et al. (1406.5542)
Chang & Ng (1406.4601)
Wang & Han (1406.3598)
Cline et al. (1405.7691)
Berlin et al. (1405.5204)
Mondal & Basak (1405.4877)
Martin et al. (1405.0272)
Ghosh et al. (1405.0206)
Abdullah et al. (1404.5503)
Park & Tang (1404.5257)
Cerdeno et al. (1404.2572)
Izaguirre et al. (1404.2018)
Agrawal et al. (1404.1373)
Berlin et al. (1404.0022)
Alves et al. (1403.5027)
Finkbeiner & Weiner (1402.6671)

Trying to Kill the Beast

Astrophysical mechanisms might also explain the excess!

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

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

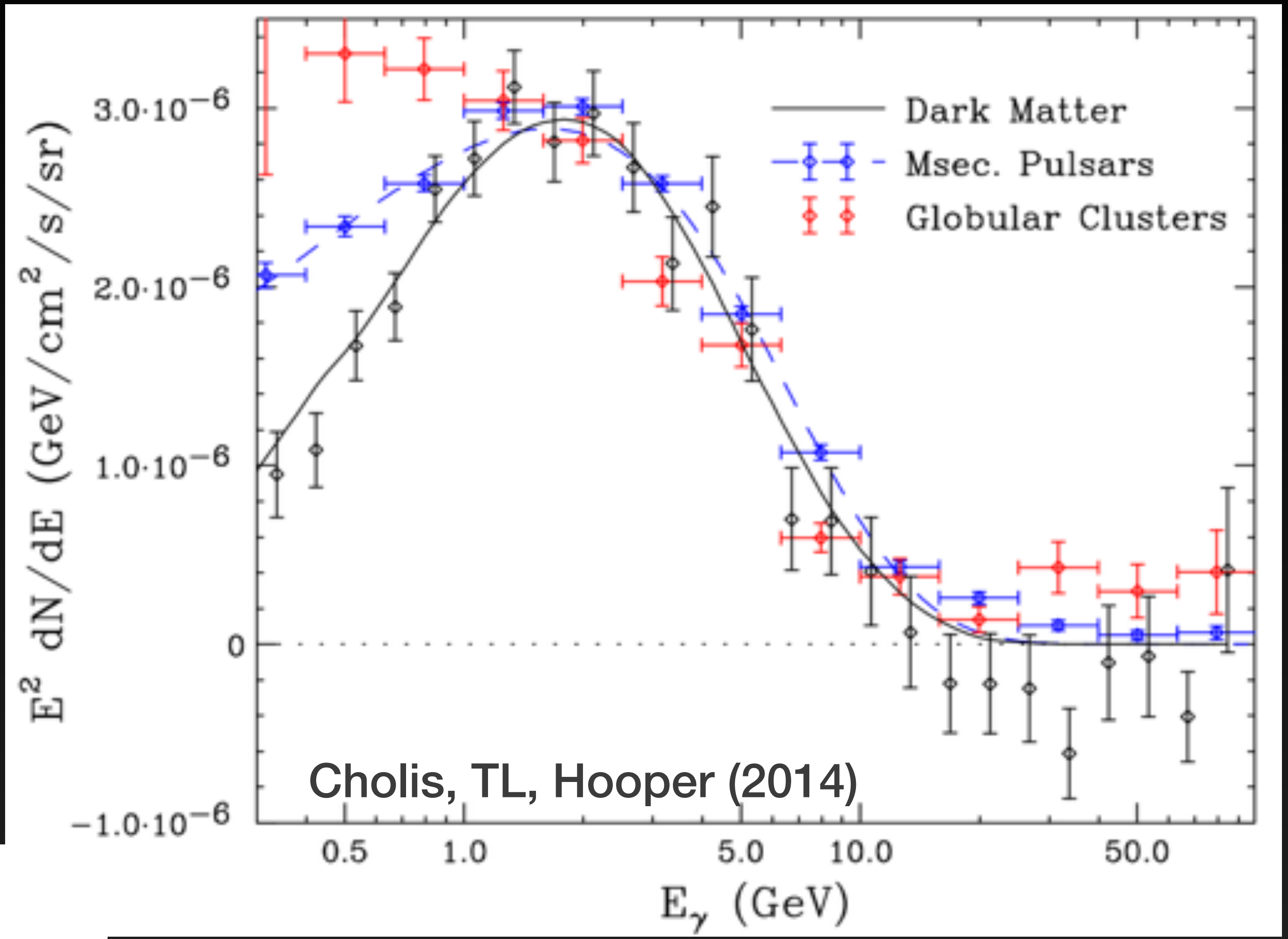
3.) What if the galactic center has a complex/active past?

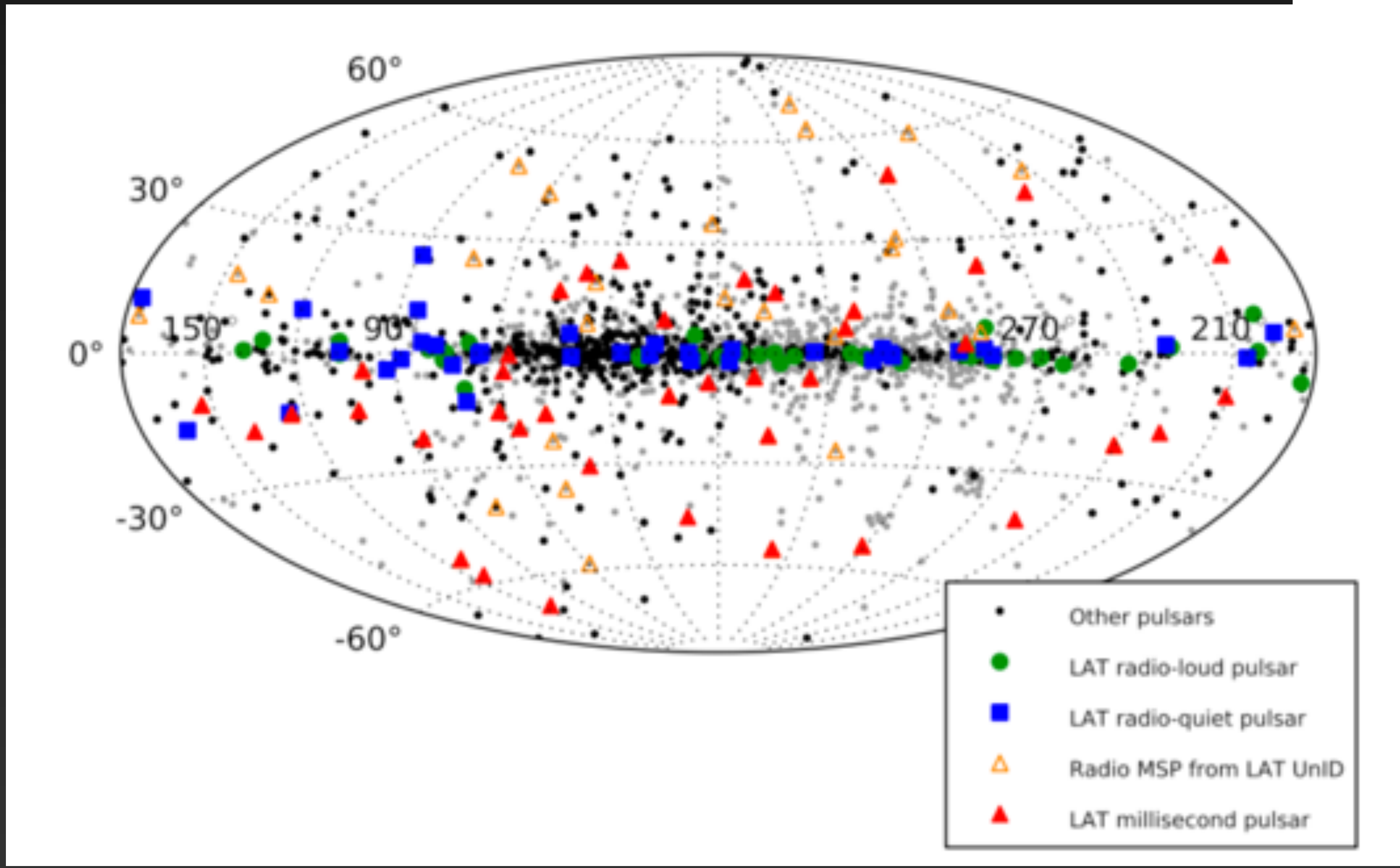
To some extent, all three of these are certainly true. So a better question is:

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

Pulsars in the Galactic Center

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

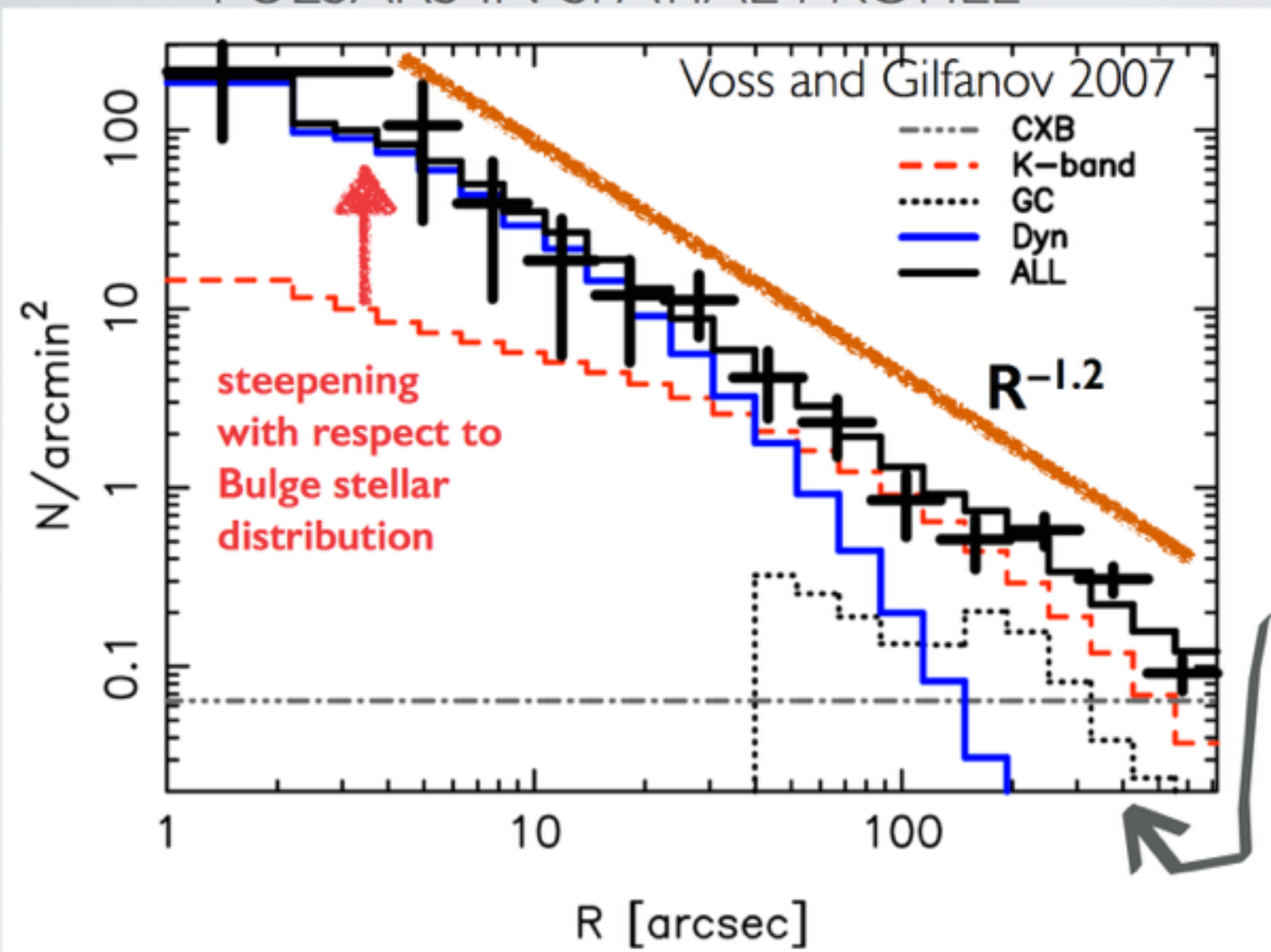




- MSPs are thought to be overabundant in dense star-forming regions like the Galactic Center

Pulsars in the Galactic Center

DEGENERACY WITH MILLI-SECOND PULSARS IN SPATIAL PROFILE



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

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

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

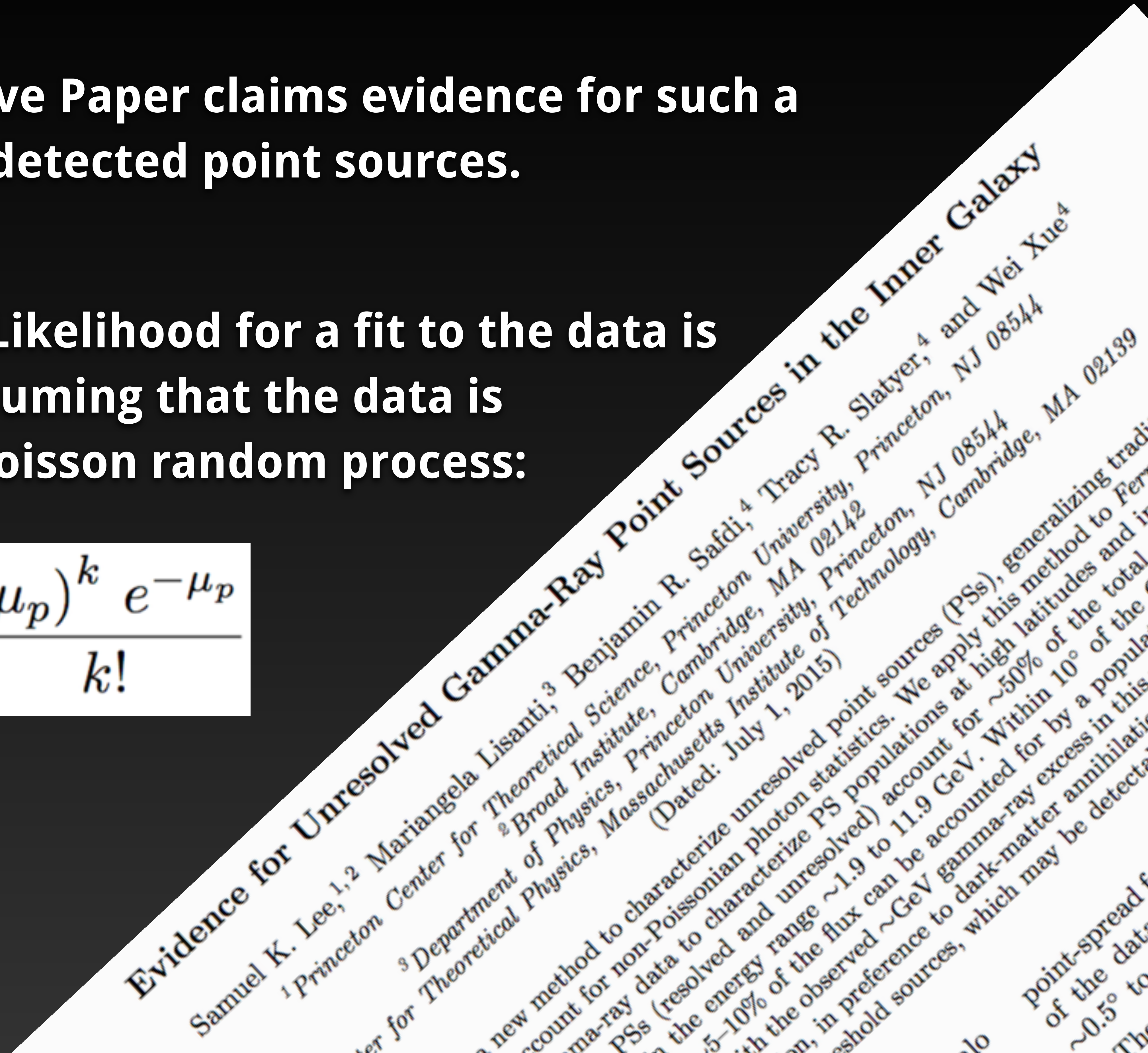
Slide from Manoj Kaplinghat

Pulsars in the Galactic Center

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

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

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


Evidence for Unresolved Gamma-Ray Point Sources in the Inner Galaxy

Samuel K. Lee,[1,2] Mariangela Lisanti,[3] Benjamin R. Safdi,[4] Tracy R. Slatyer,[4] and Wei Xue[4]
[1]Princeton Center for Theoretical Science, Princeton University, Princeton, NJ 08544
[2]Broad Institute, Cambridge, MA 02142
[3]Department of Physics, Princeton University, Princeton, NJ 08544
ter for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139

(Dated: July 1, 2015)

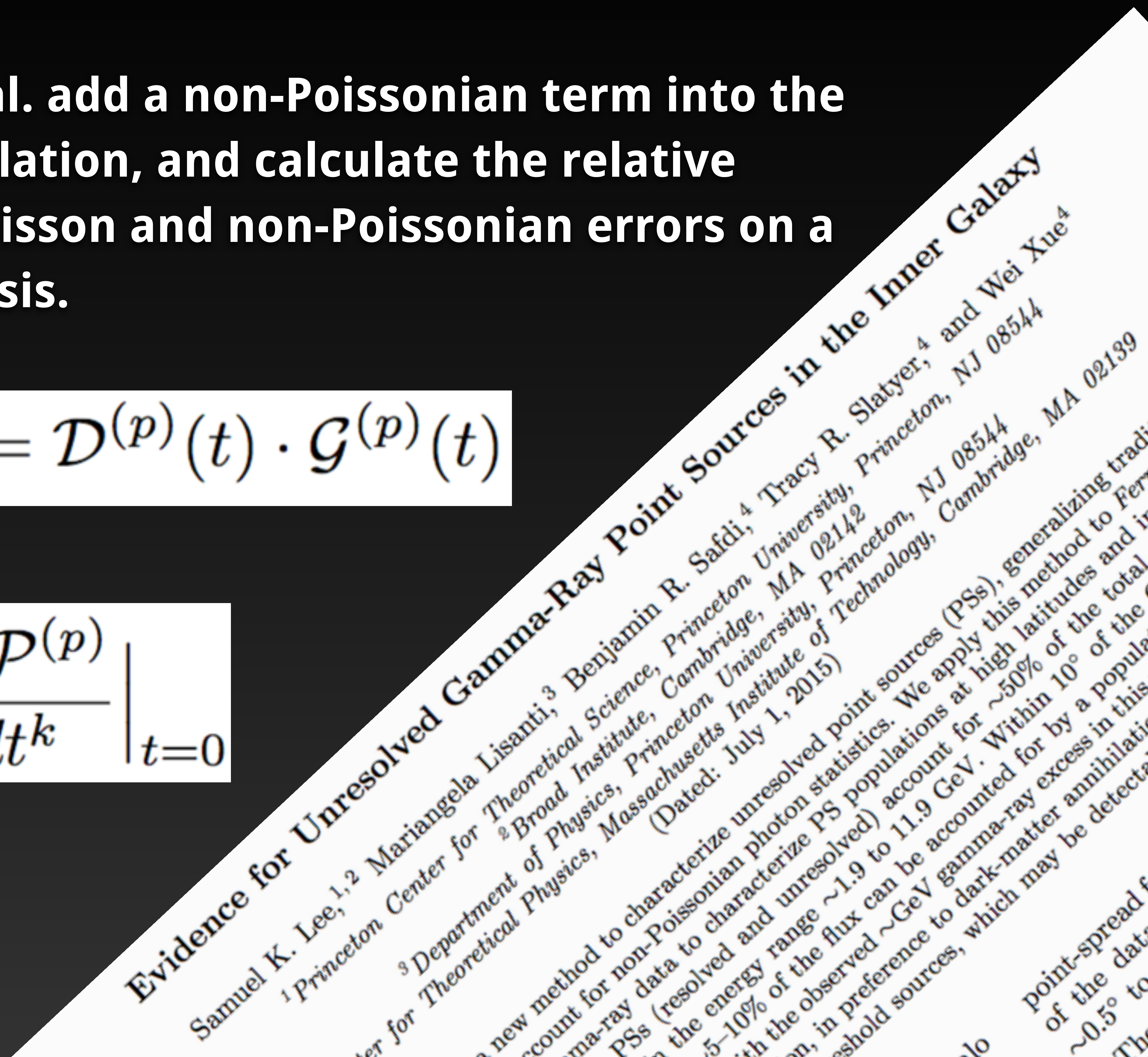
new method to characterize unresolved point sources (PSs), generalizing tradi
ccount for non-Poissonian photon statistics. We apply this method to Fer
ma-ray data to characterize PS populations at high latitudes and i
PSs (resolved and unresolved) account for ~50% of the total
n the energy range ~1.9 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

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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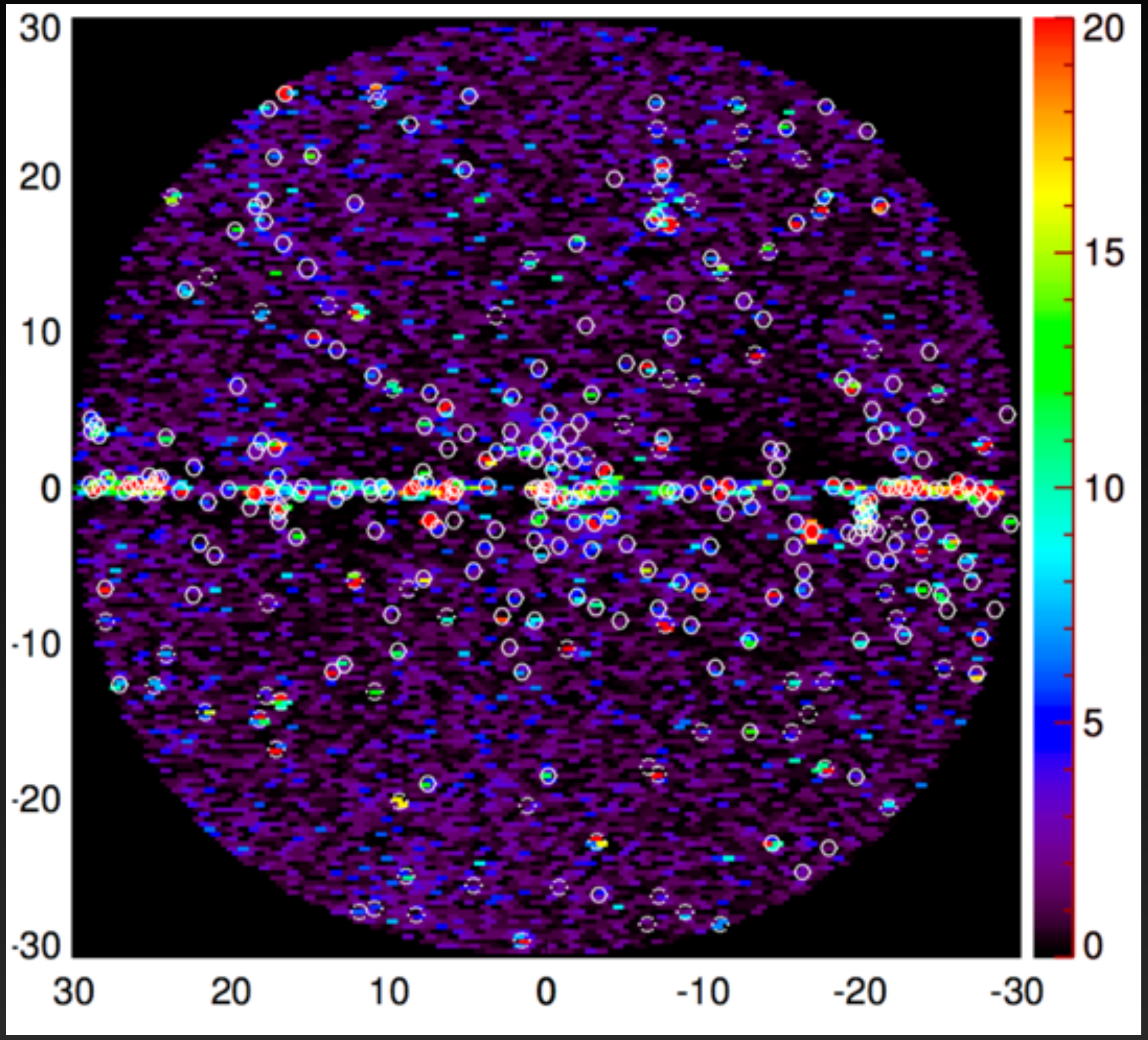
...th the observed ~GeV gamma-ray excess in this...
...n, in preference to dark-matter annihilati...
...eshold sources, which may be detecta...

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.



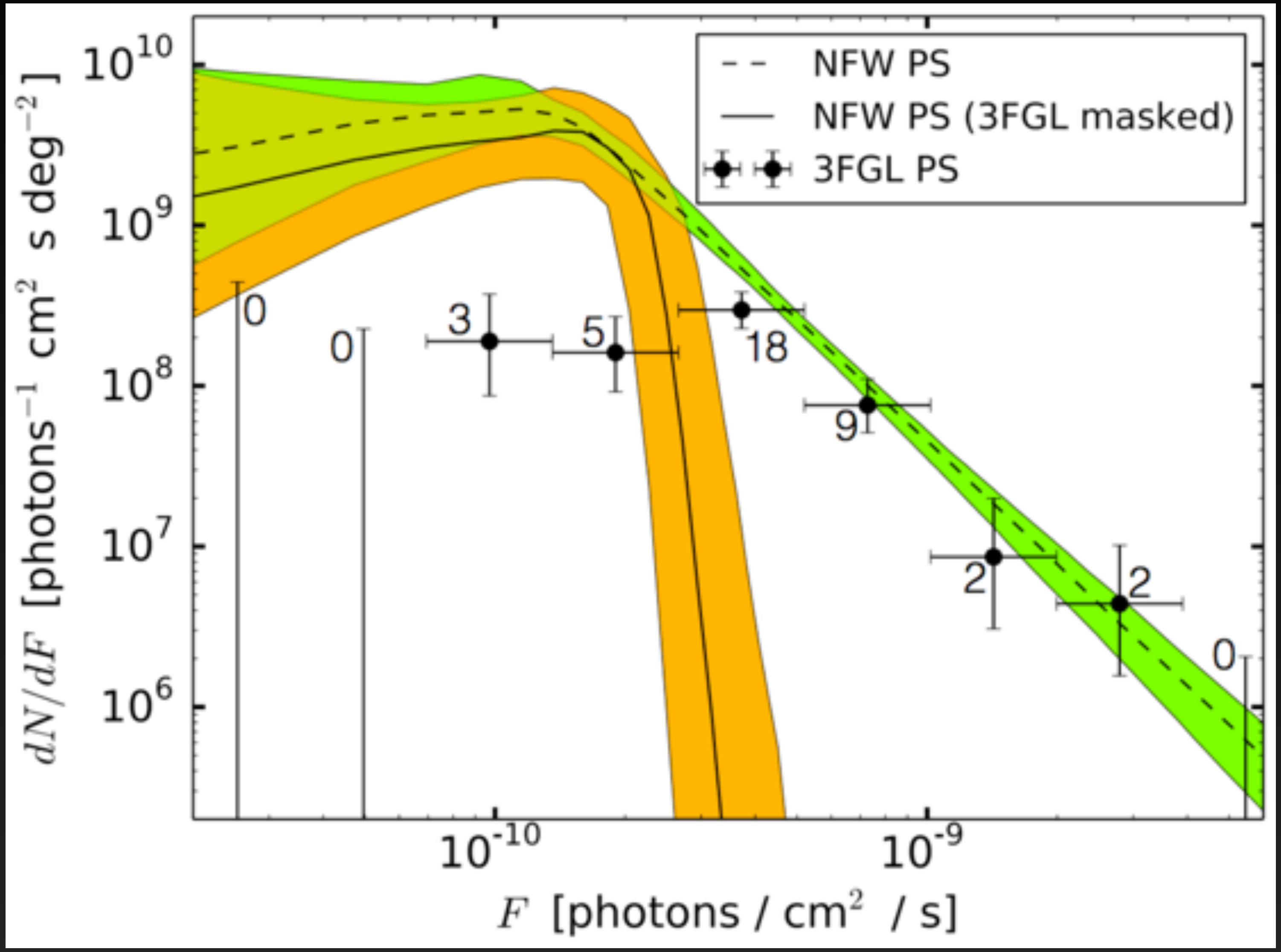
Lee et al. (2015)

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.

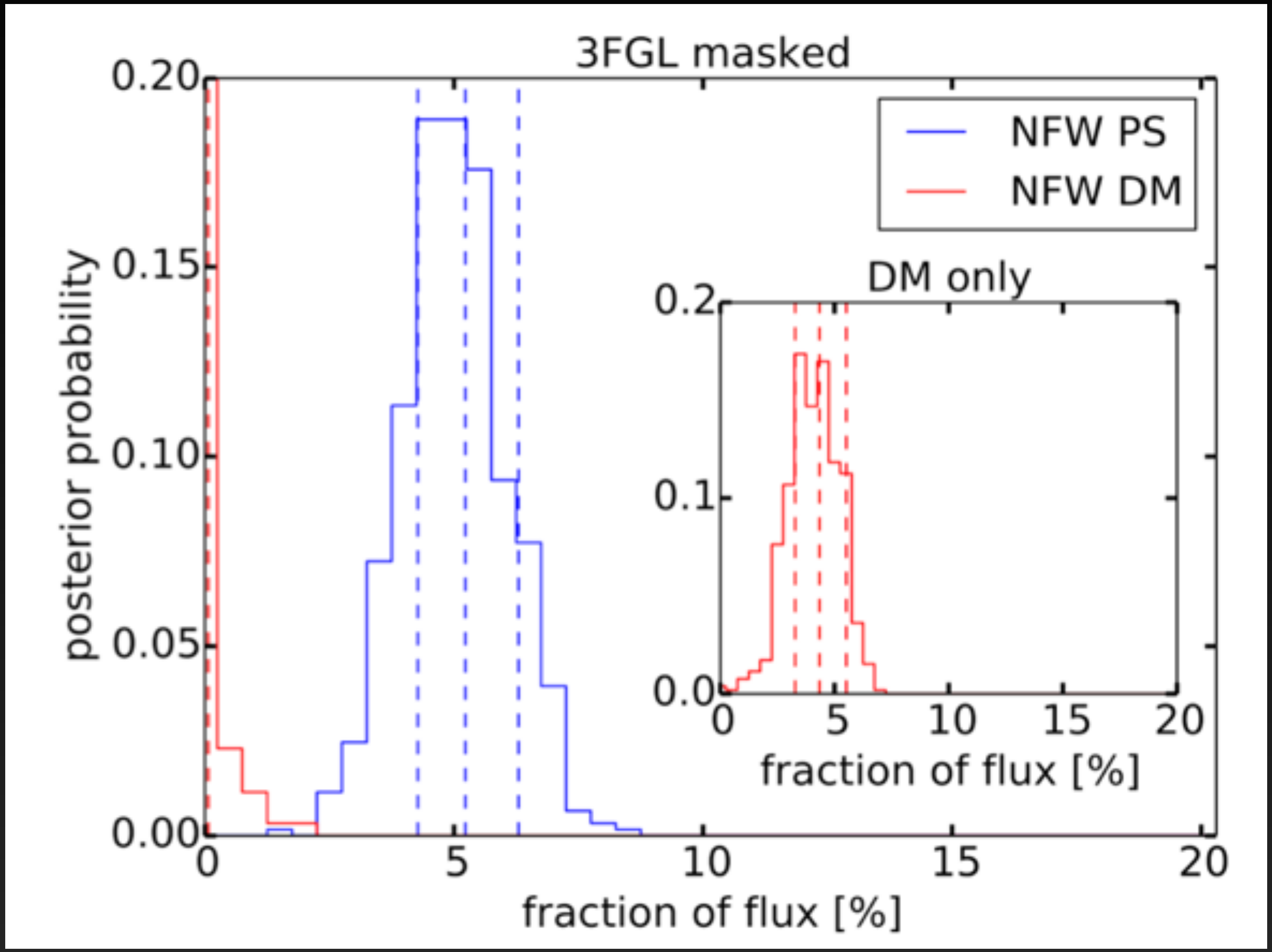


Lee et al. (2015)

2.) Fit data to the GC excess.

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

Pulsars in the Galactic Center

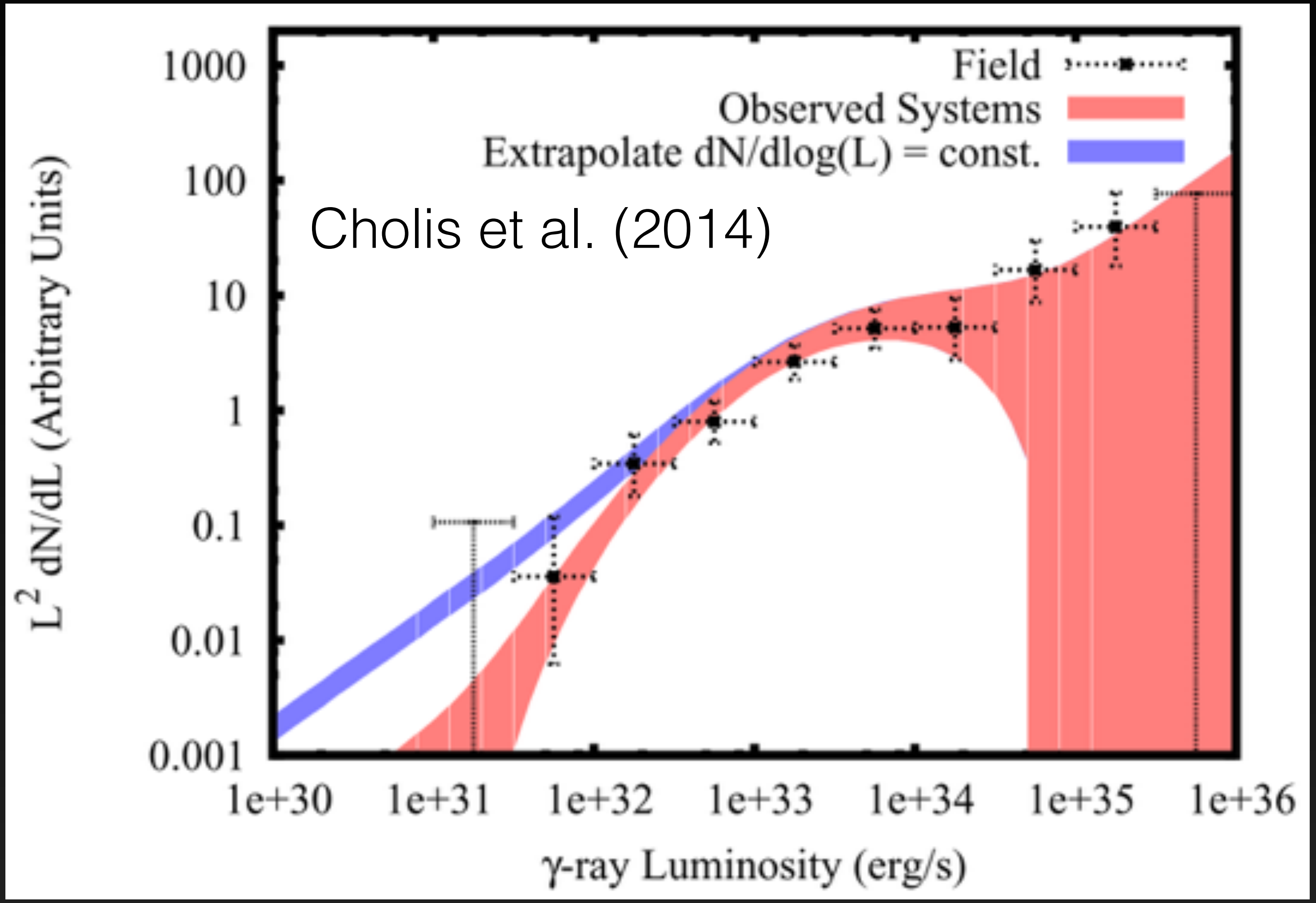


When both a traditional NFW template and the non-Poissonian NFW template are allowed to float arbitrarily, the non-Poissonian template absorbs the gamma-ray excess.

Lee et al. (2015)

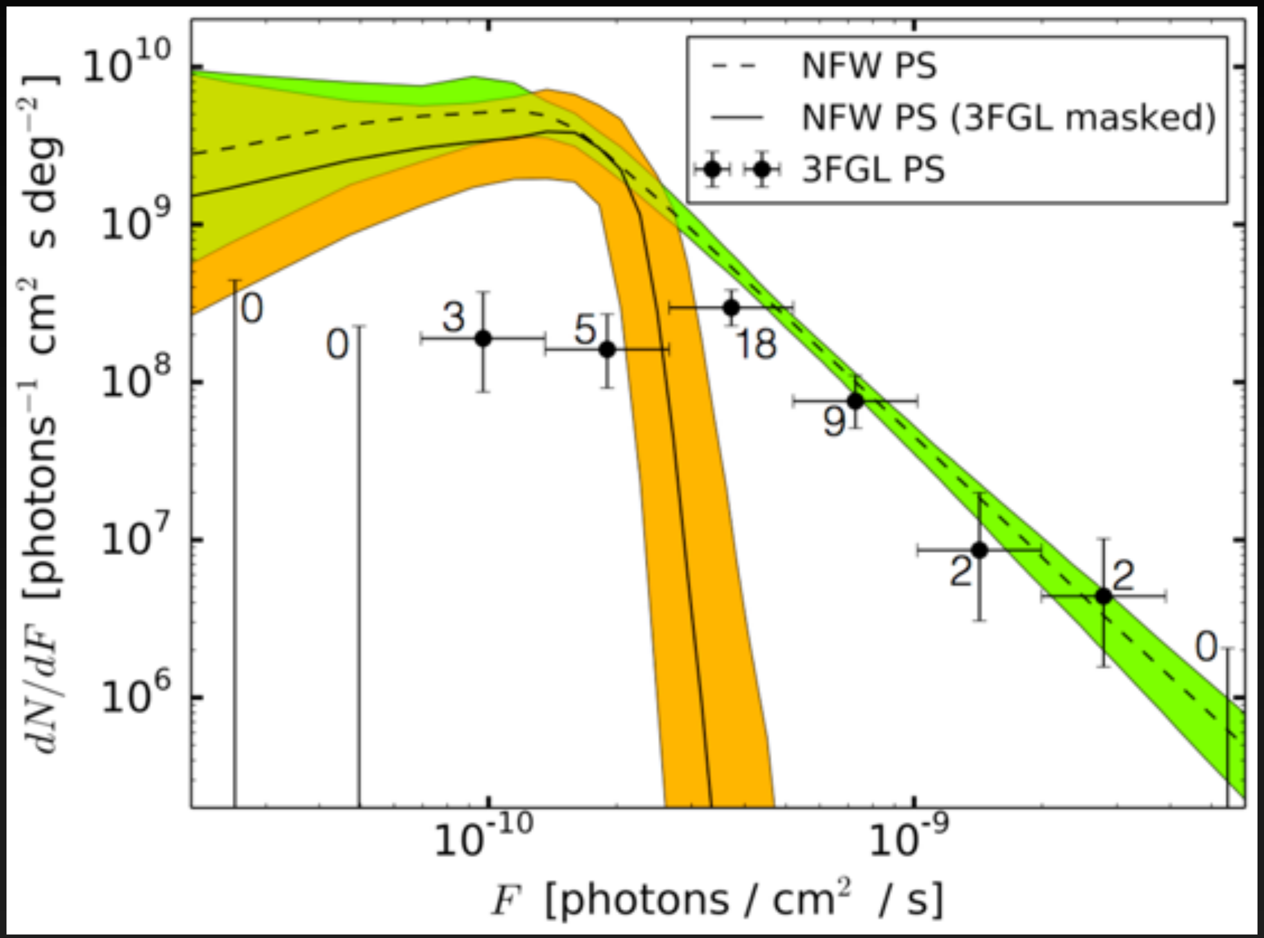
Why Not Pulsars?

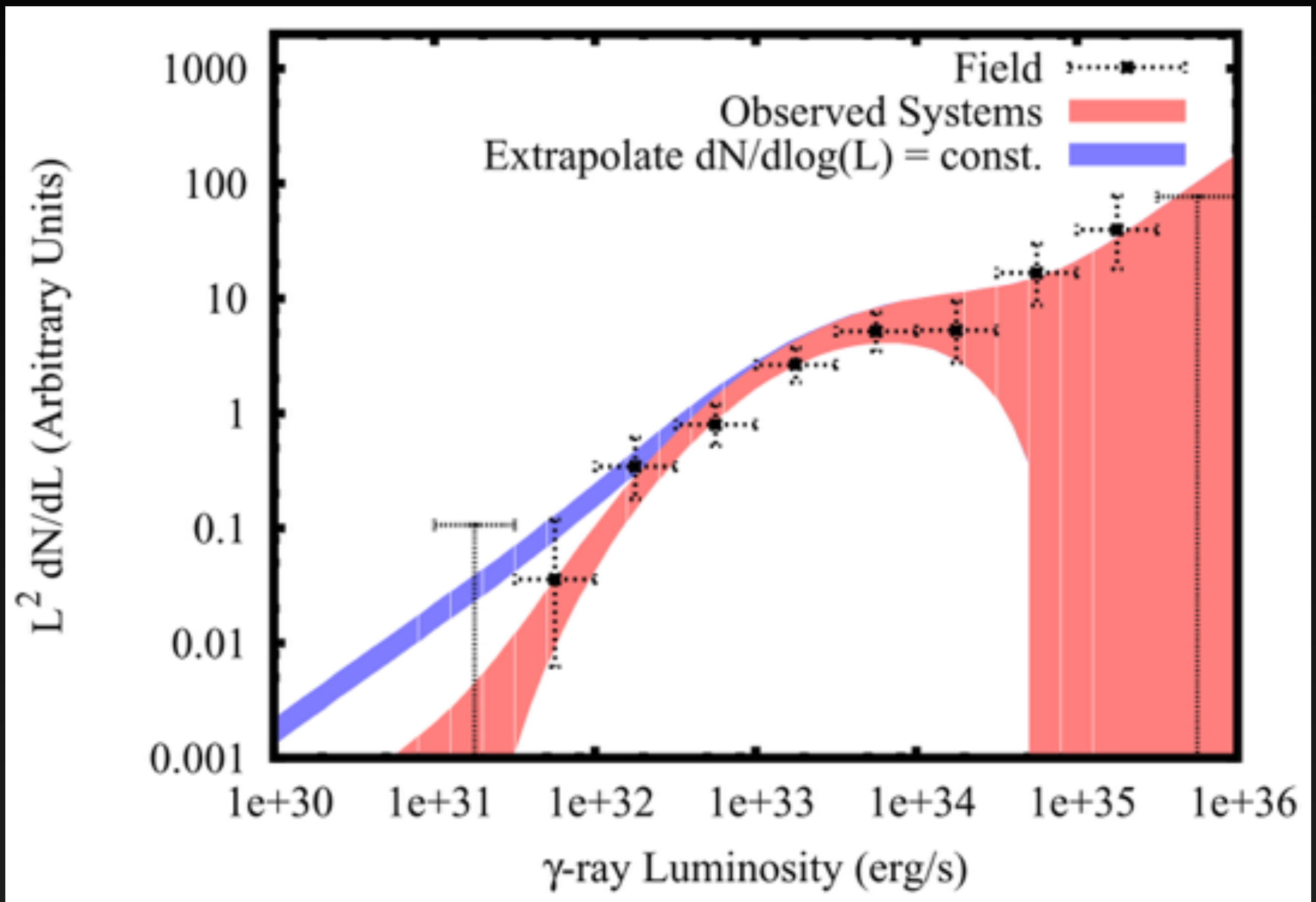
- **Can measure the fluxes of known MSPs and calculate the expected fluxes of MSPs in the Galactic Center.**



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

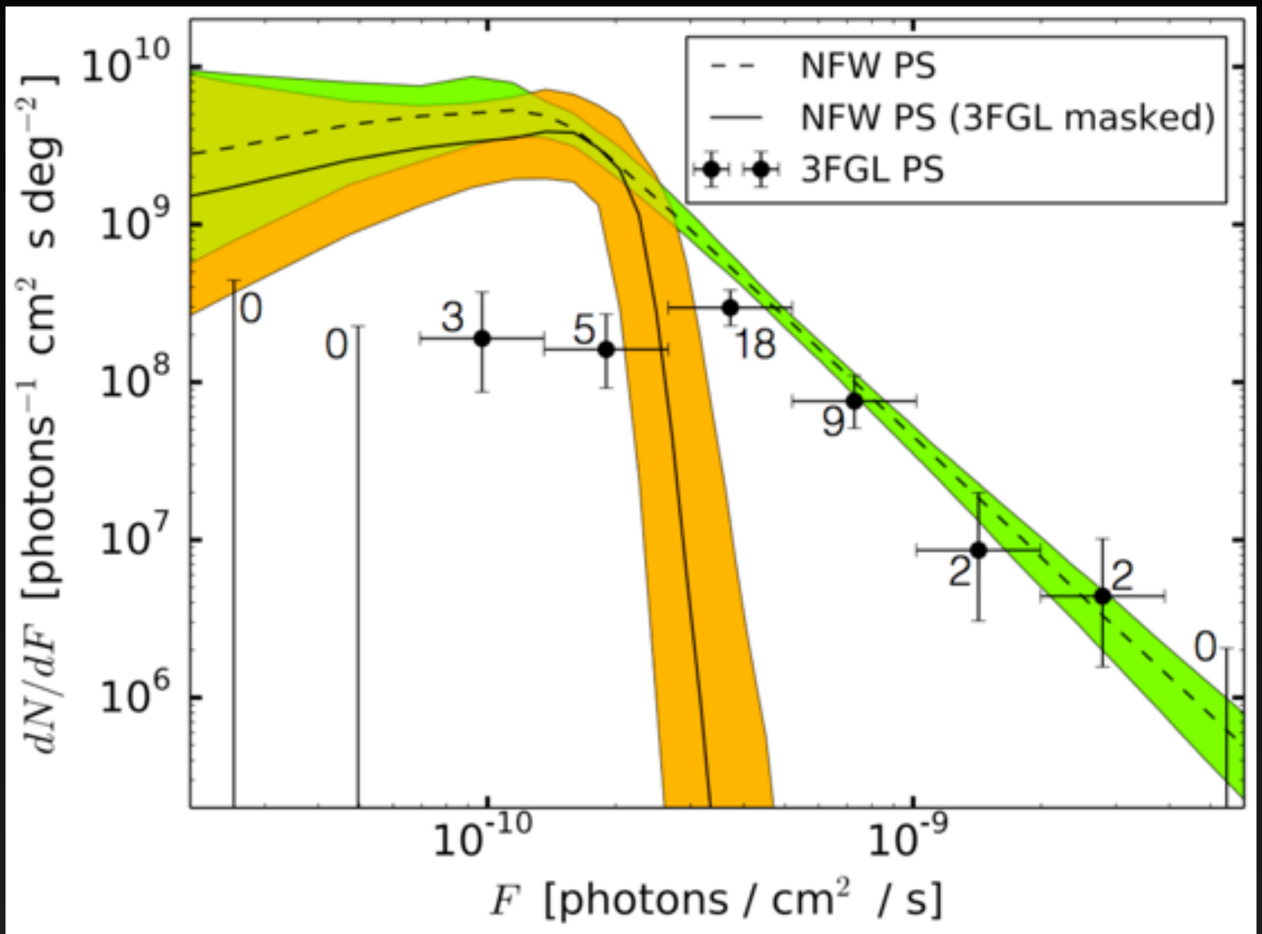
Why Not Pulsars?

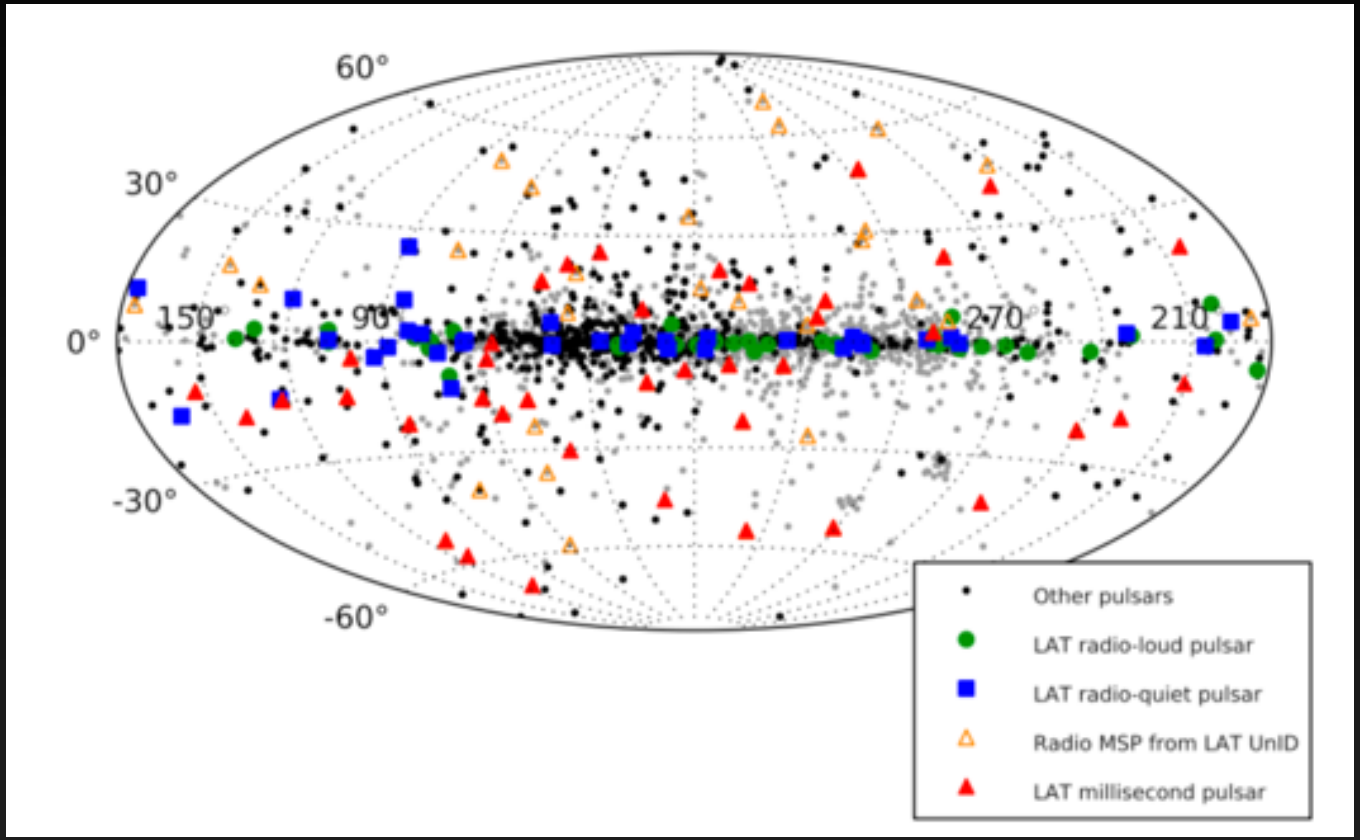




- A luminosity of 10^{35} erg s^{-1} at the galactic center is equivalent to a gamma-ray flux of 8.0 x 10^{-9} photons cm^{-2} s^{-1}. These systems have not been observed in the Galactic Center.

Why Not Pulsars?

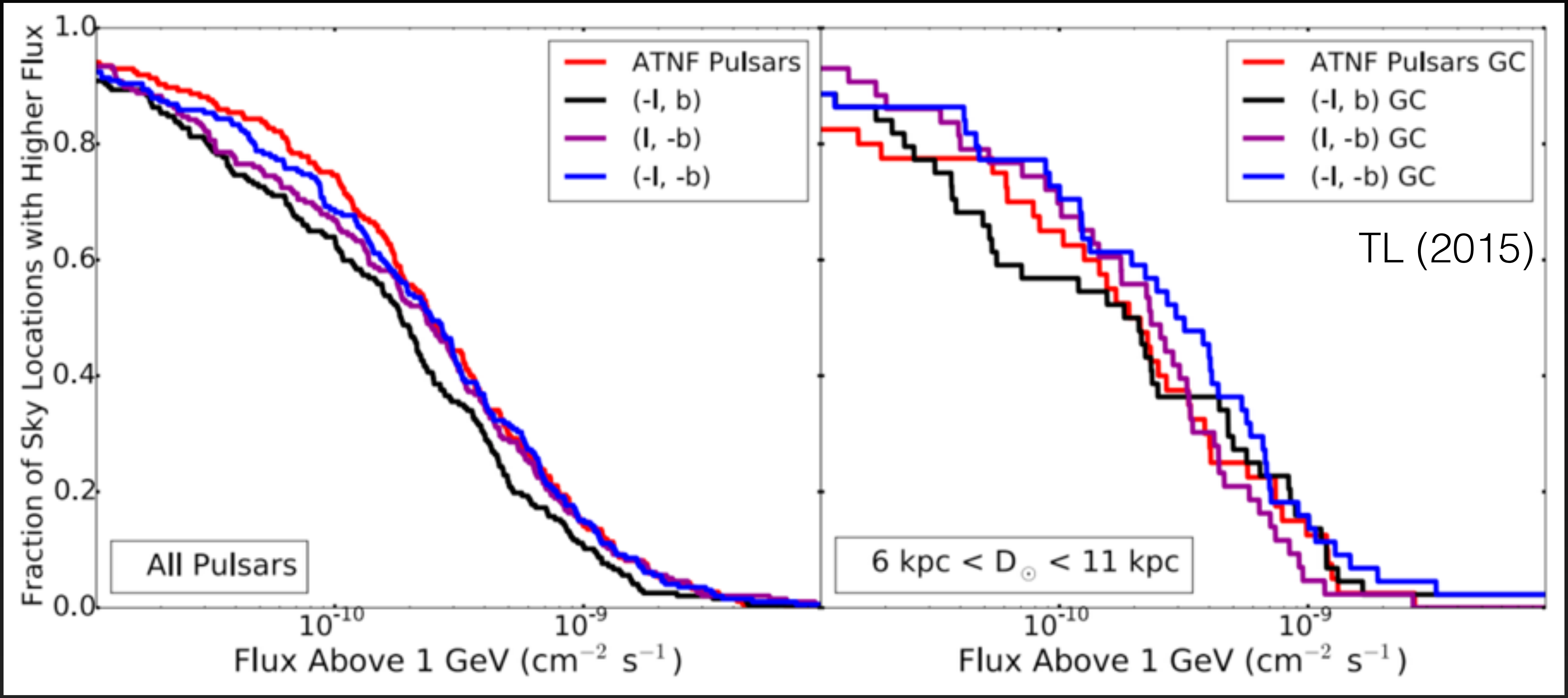




- Note that the population of new point sources have fluxes barely below the Fermi-LAT point source detection threshold.

- Can see if these hotspots cross-correlate with known radio pulsars.

Why Not Pulsars?



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

How Do We Test the Pulsar Hypothesis?

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

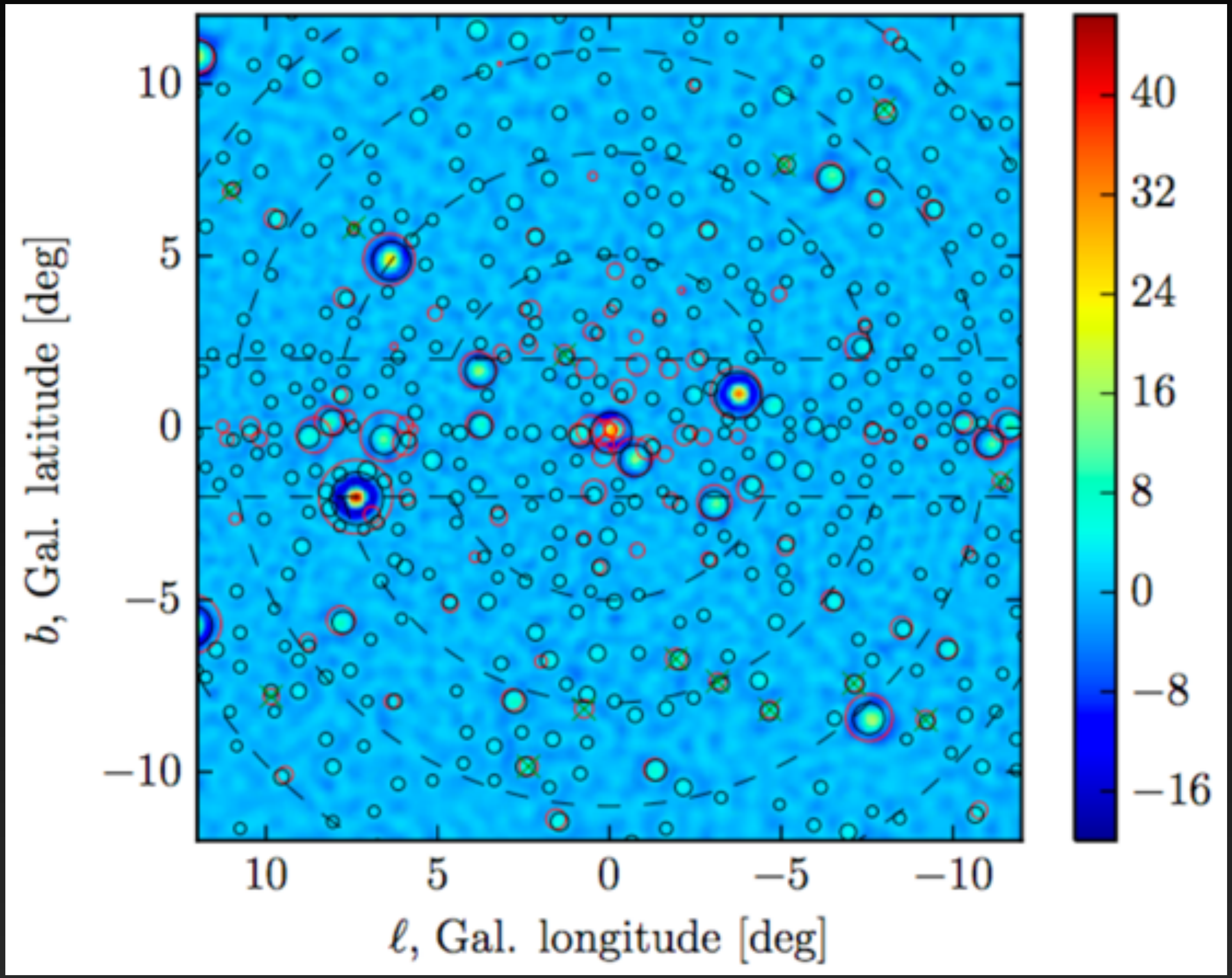
- **The observation of radio pulsars coincident with gamma-ray hotspots would serve as smoking gun evidence for a pulsar interpretation.**

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.



Other Explanations Also Exist

1.) **Outbursts of hadronic (Carlson & Profumo, 2014), or leptonic (Petrovic et al. 2014, Cholis et al. 2015) origin.**

2.) **New gas models for the galactic center region (Gaggero et al. 2015, Carlson et al. 2015)**

Note that all of these models expect some multi-wavelength signature! Either we should see the gas clouds, or we should see synchrotron radiation from the outbursts, etc.

Coming to a Conclusion

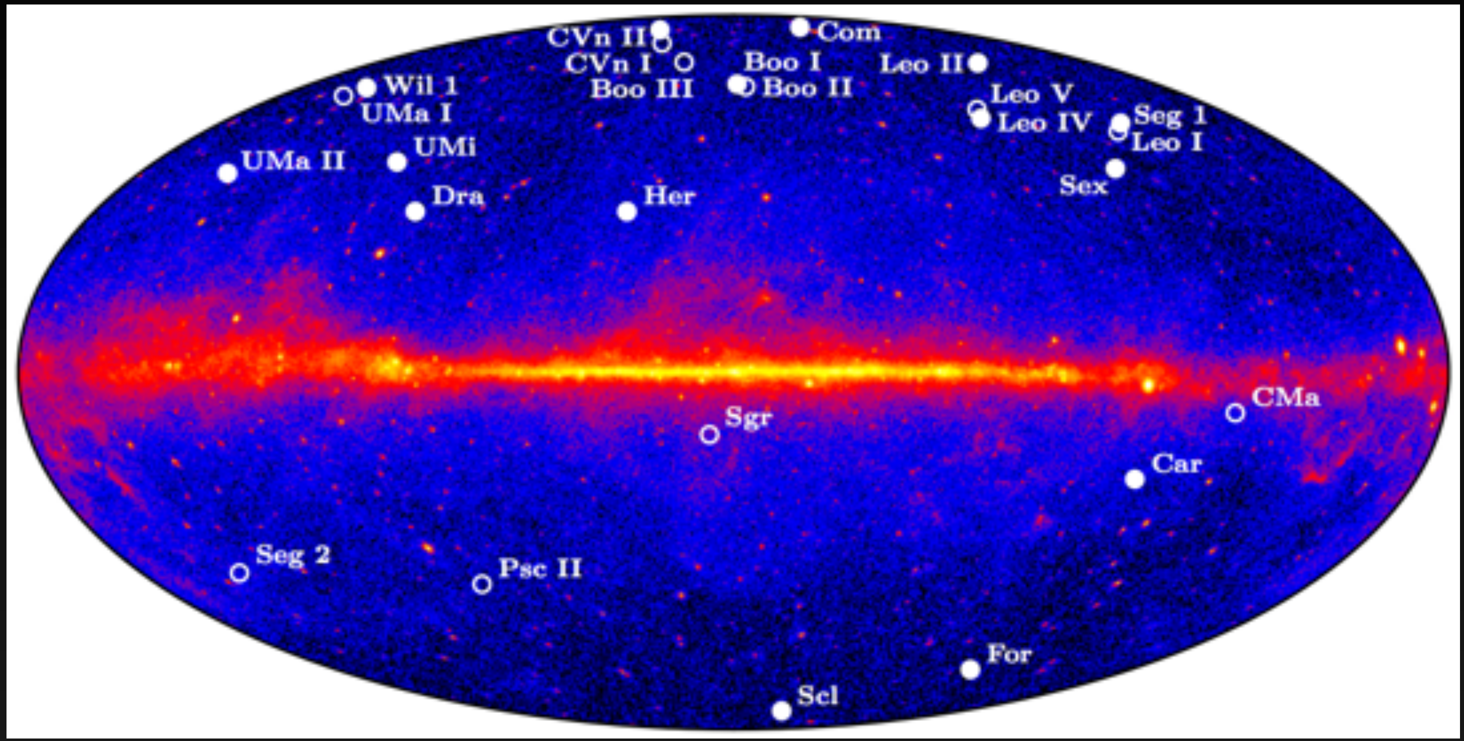
1.) Over the last two years - the existence of a significant gamma-ray excess (compared to current astrophysical models) has been confirmed.

2.) The gamma-ray excess has features compatible with a dark matter signal — a dark matter motivated NFW profile remains the best fitting template to the gamma-ray data.

3.) Several well motivated astrophysical models have been produced, and new techniques are being developed to differentiate between these models.

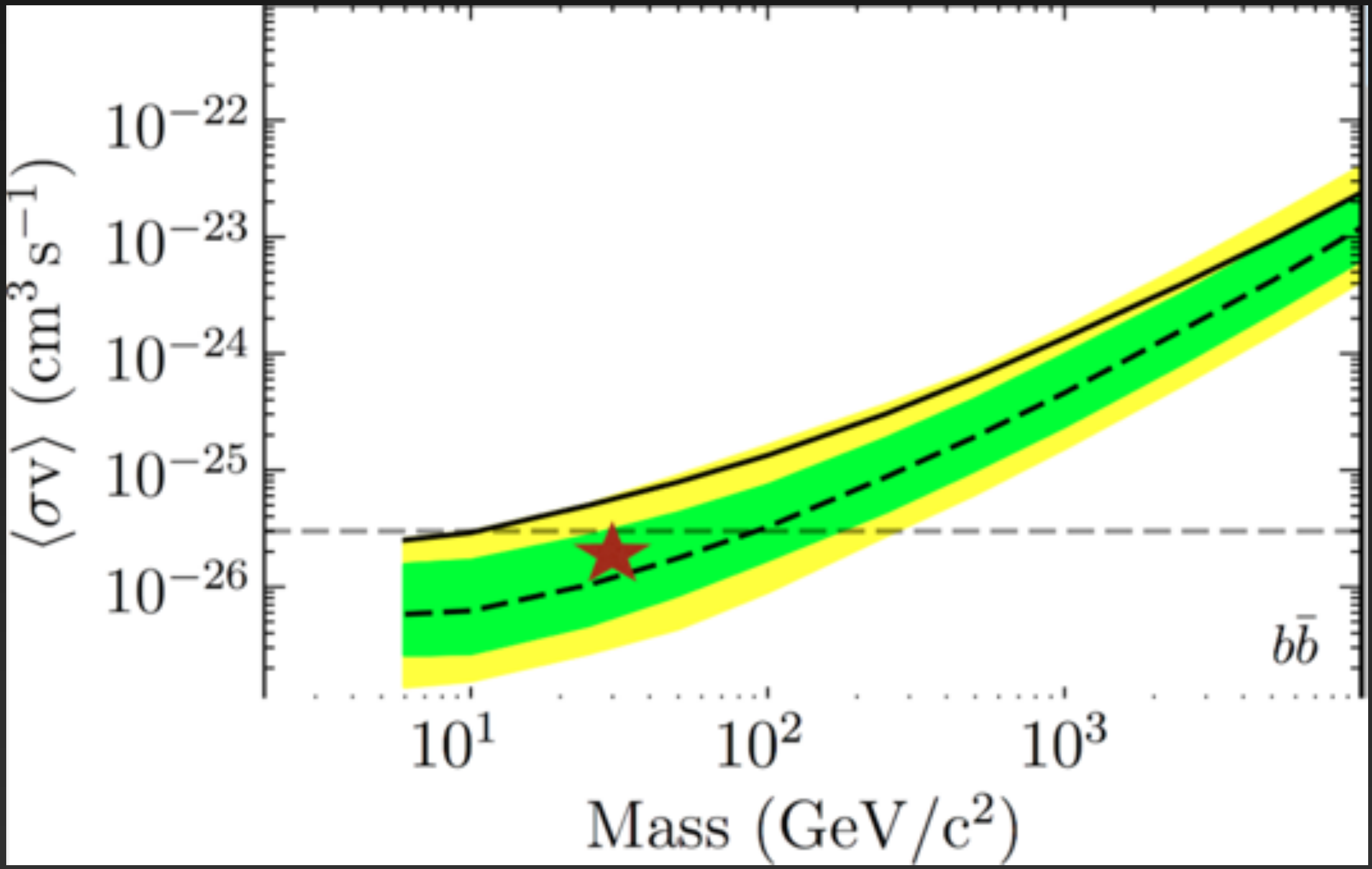
4.) New multi wavelength models and studies are needed.

Alternative Targets

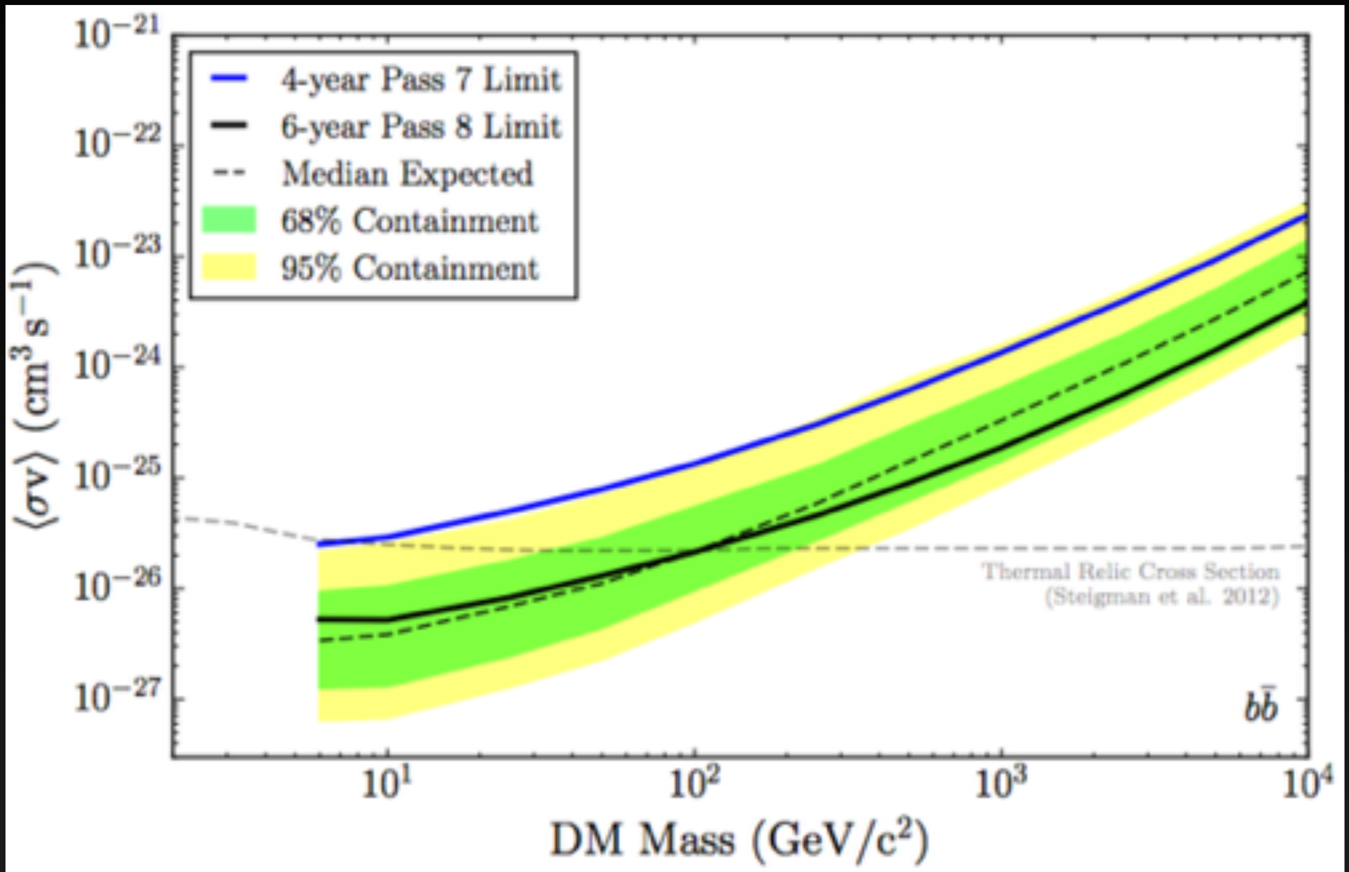


Dwarf Galaxies can also produce a significant γ-ray signal from dark matter annihilation.

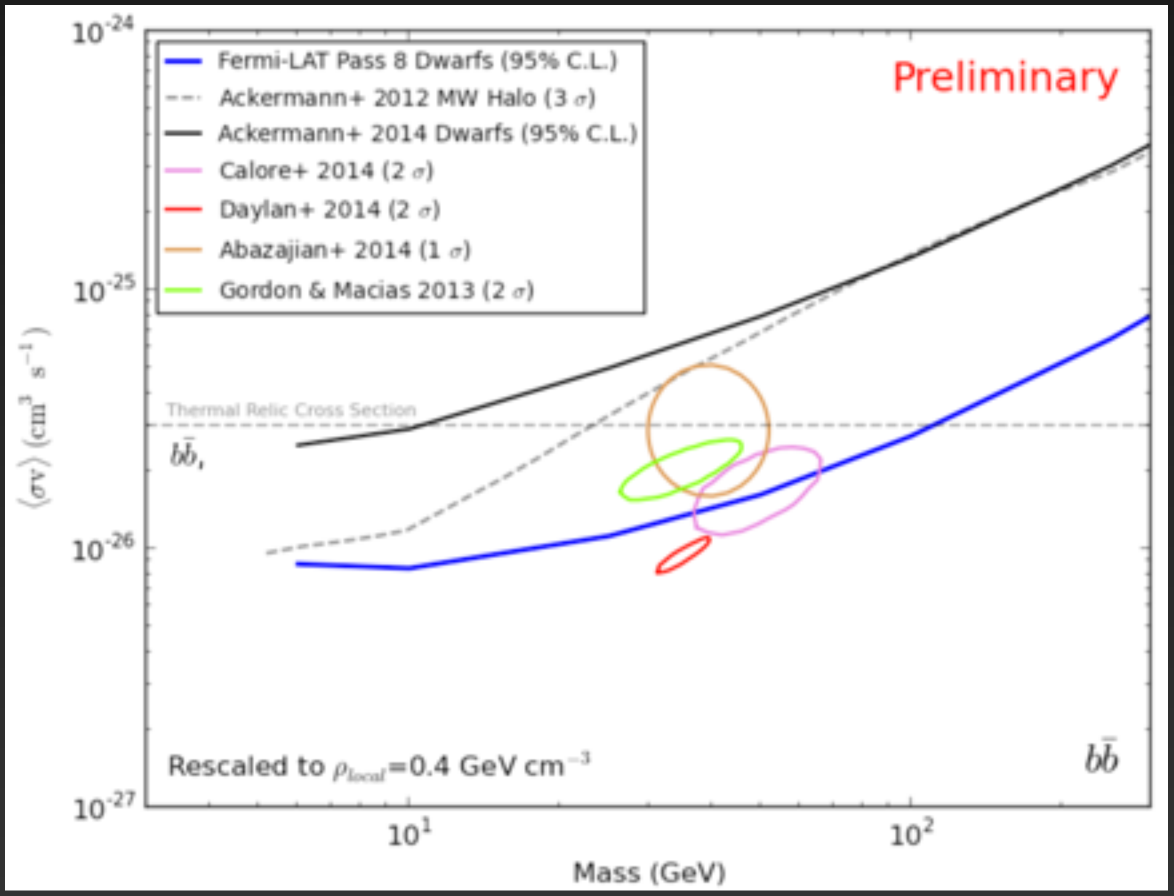
Latest published results showed a TS = 8.7 local excess at the mass of the GC signal.



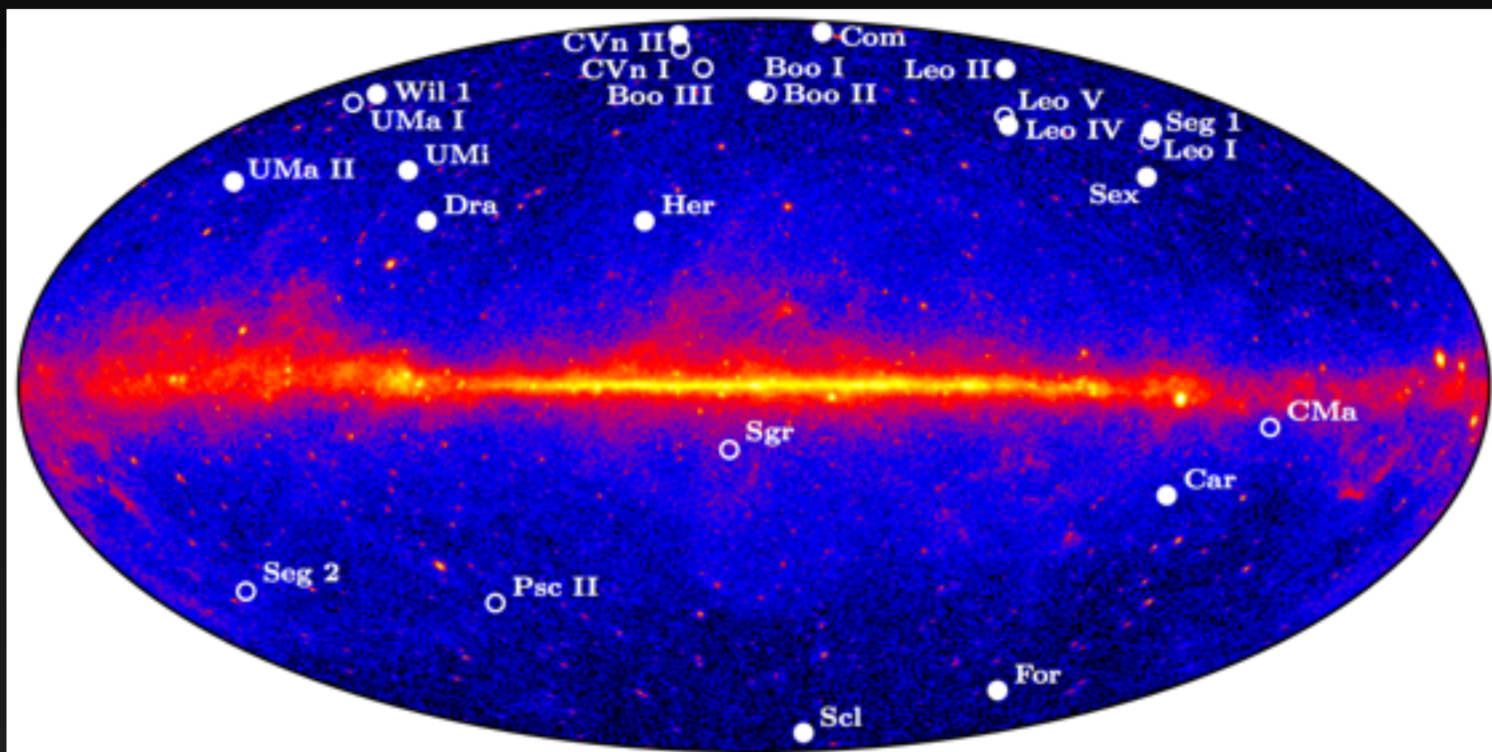
Alternative Targets



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



Alternative Targets



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

Alternative Targets

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

Alternative Targets

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

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]	$\log_{10}(J(\alpha_{\rm int}))$ $[J/{\rm GeV}^2\,{\rm cm}^{-5}]^{\rm a}$
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.

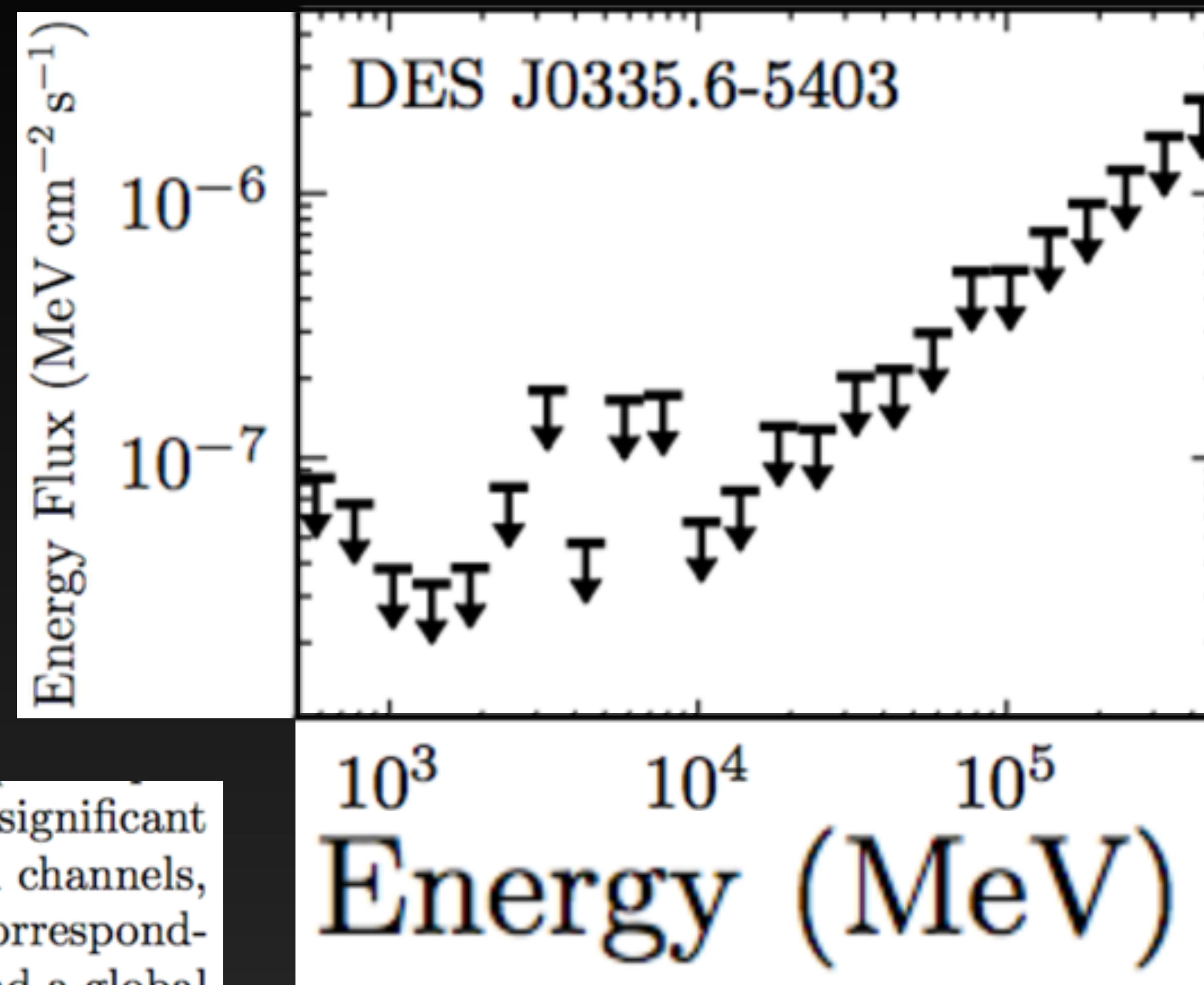
Yeoman's work by several optical spectroscopers has given us two estimations of the J-factors for Reticulum 2

Alternative Targets

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

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

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



Reticulum 2 also has an excess!

Alternative Targets

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

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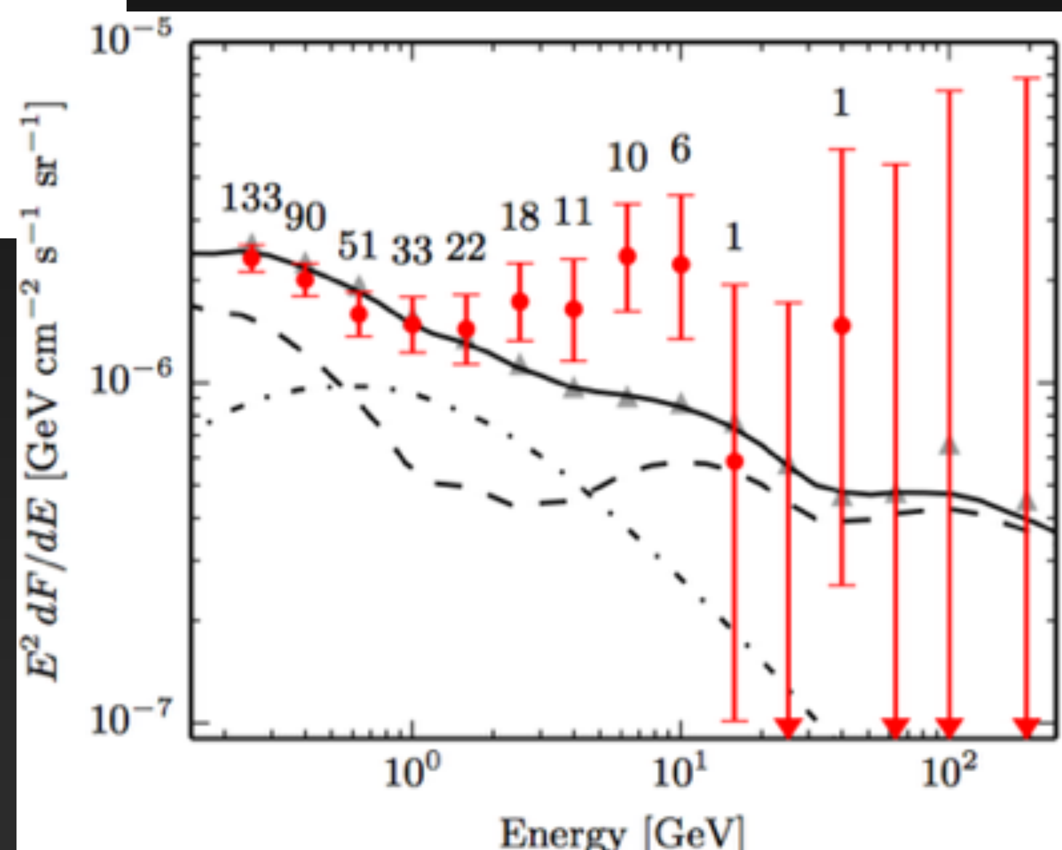
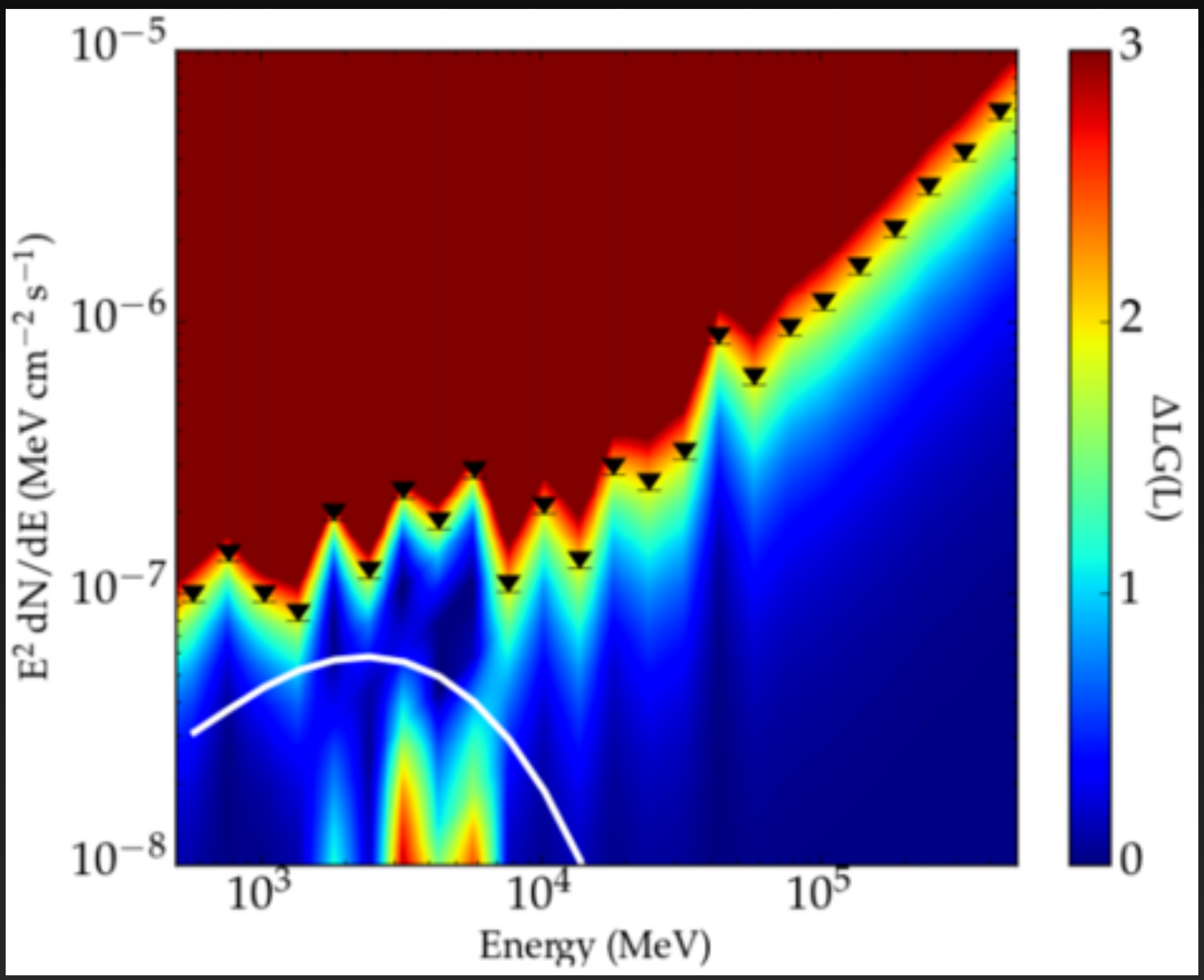
(Dated: March 10, 2015)

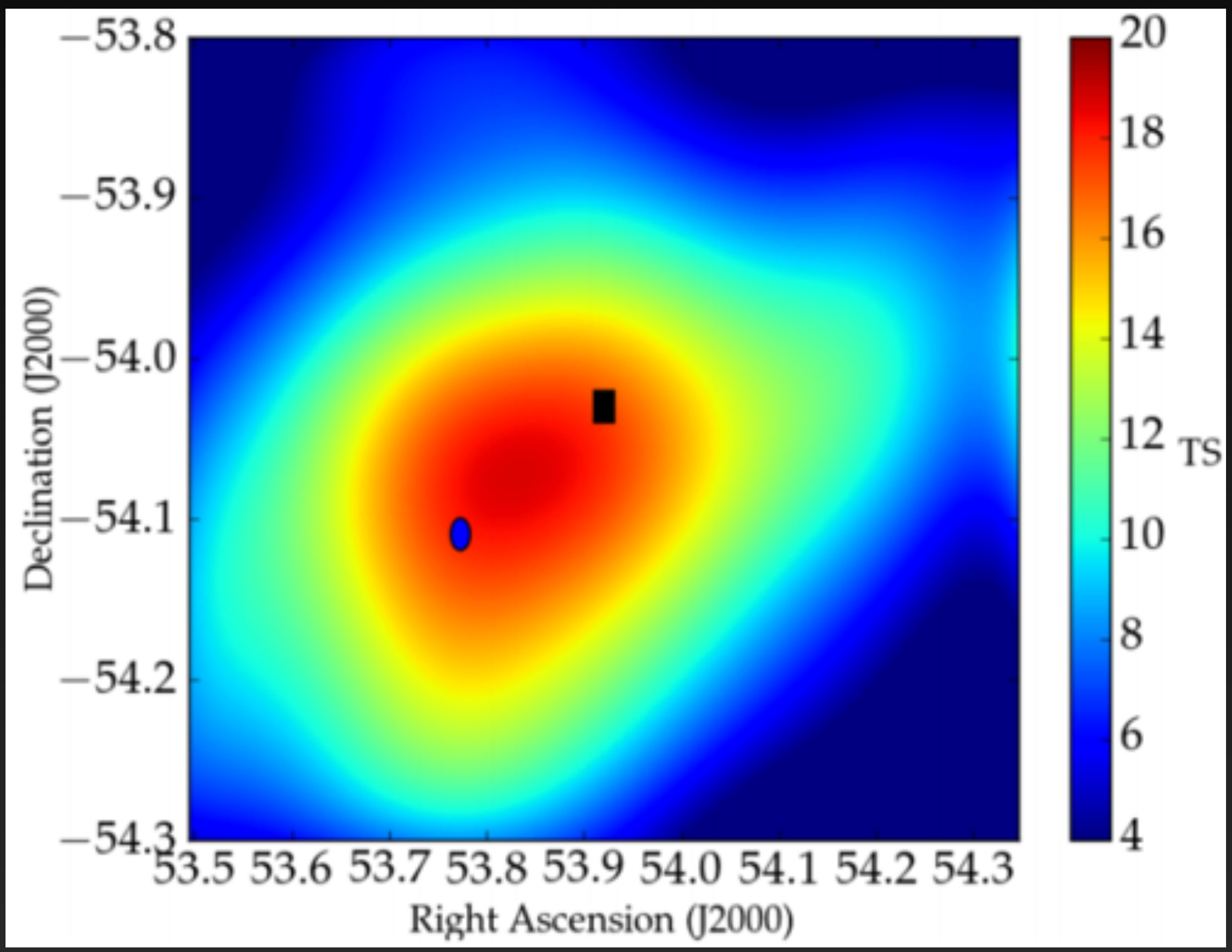
We present a search for γ-ray emission from the direction of the newly discovered dwarf galaxy Reticulum 2. Using Fermi-LAT data, we detect a signal that exceeds expected backgrounds between $\sim 2 - 10$ GeV and is consistent with annihilation of dark matter for particle masses less than a few $\times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



Reticulum 2 also has an excess!

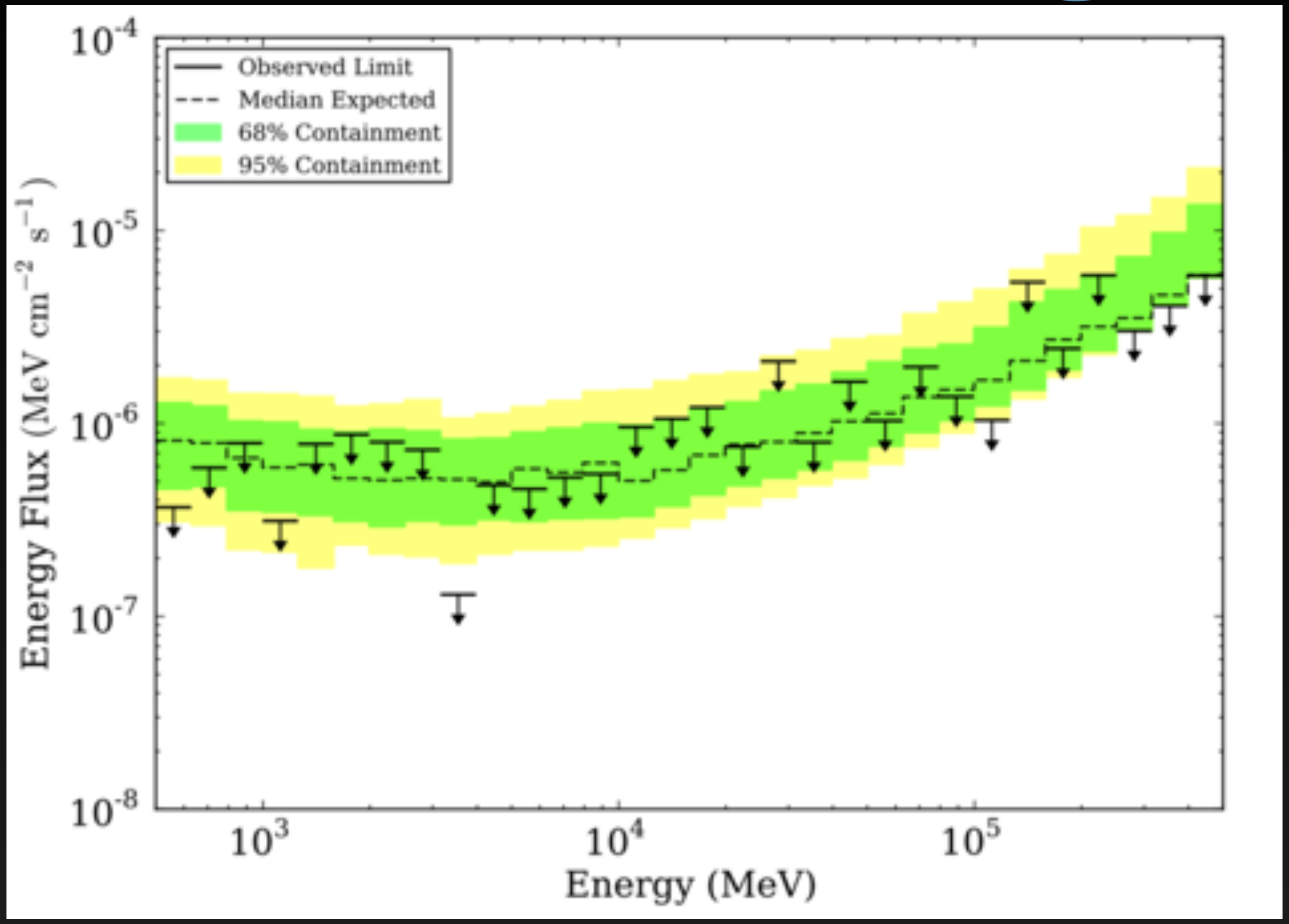
Alternative Targets

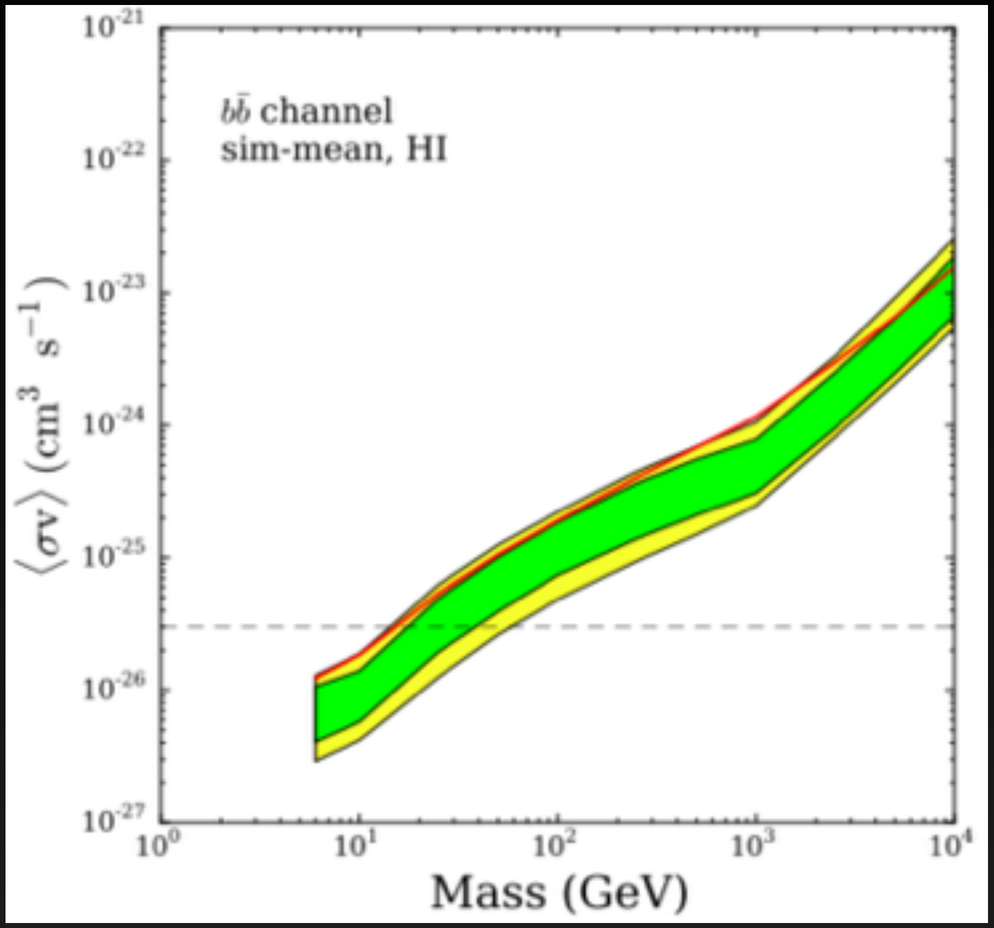




Reticulum 2 also has an excess!

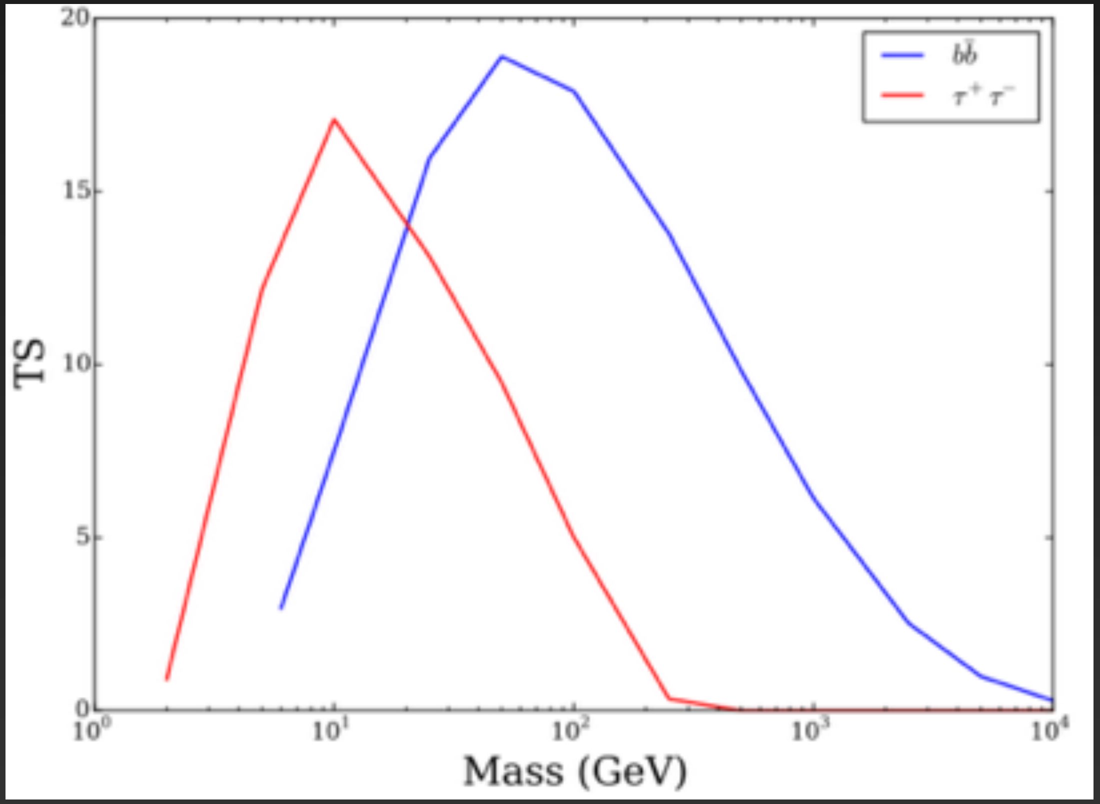
Alternative Targets





The LMC also shows hints of a dark matter excess

However, there are considerable backgrounds here as well.



Buckley et al. (2015)

Diffuse Gamma-Ray Models

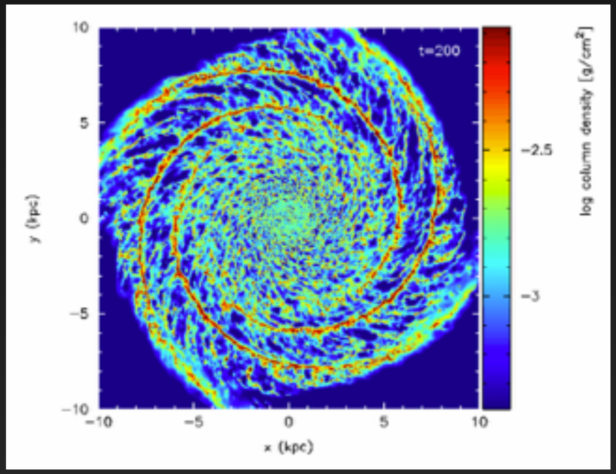
Supernovae Source Cosmic-Ray Protons:
10^{51} erg (~10% in relativistic protons)
(~2% in relativistic electrons)

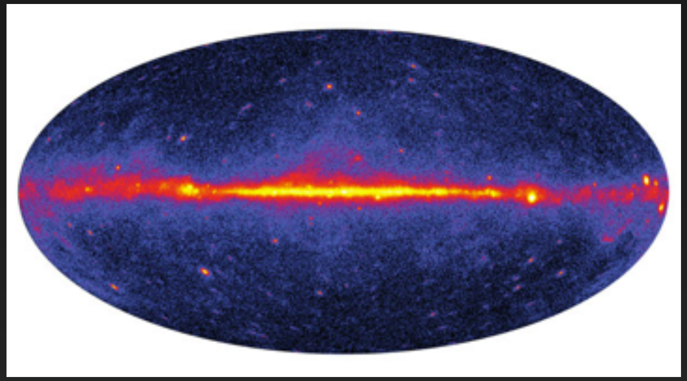
cosmic rays propagate

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

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

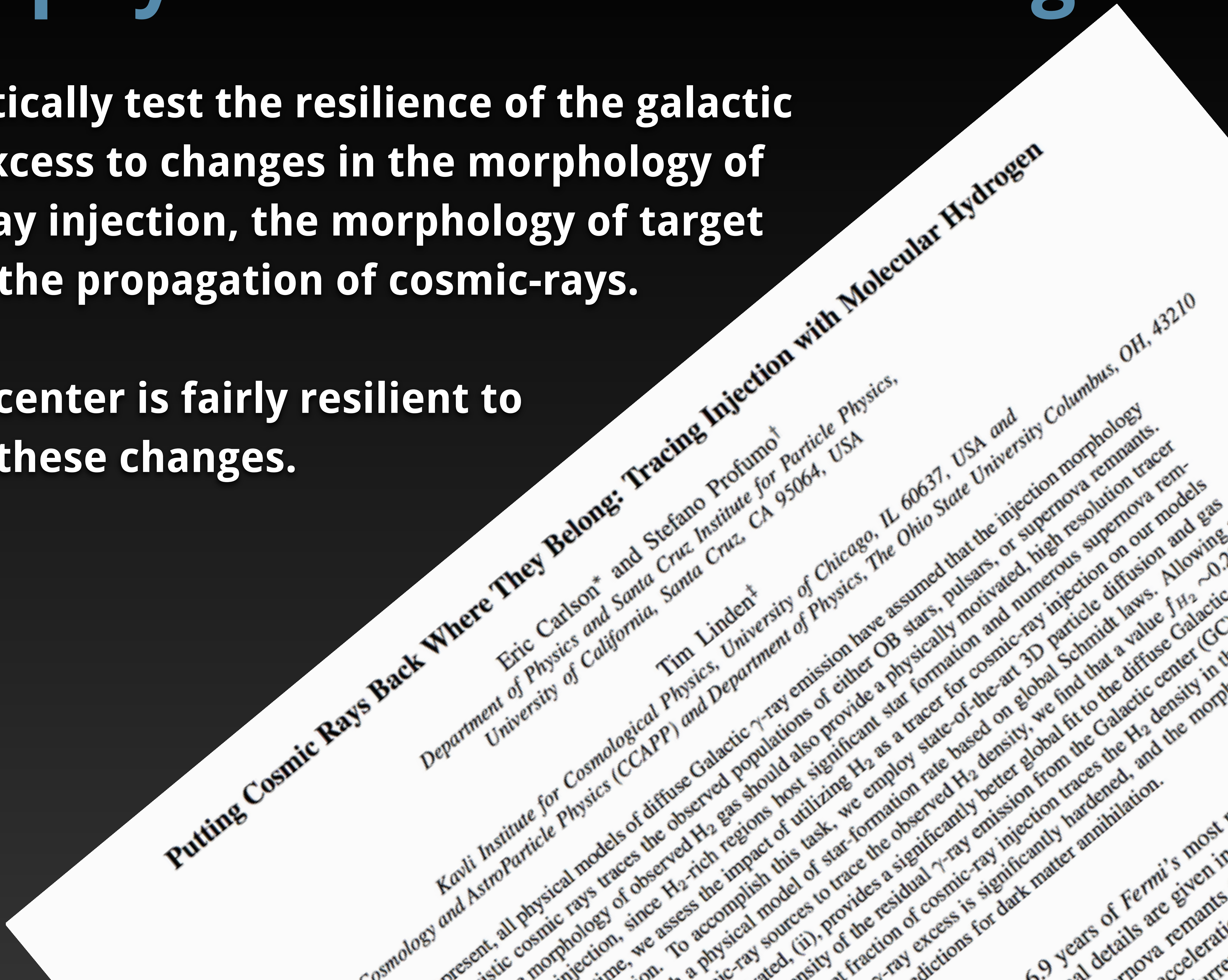
Goodenough & Hooper (2009)	0910.2998
Hooper & Goodenough (2011, PLB 697 412)	1010.2752
Hooper & TL (2011, PRD 84 12)	1110.0006
Abazajian & Kaplinghat (2012, PRD 86 8)	1207.6047
Hooper & Slatyer (2013, PDU 2 18)	1302.6589
Gordon & Macias (2013, PRD 8 8)	1306.5725
Macias & Gordon (2013, PRD 89 6)	1312.6671
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

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

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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-
... ime, we assess the impact of utilizing H_2 as a tracer for cosmic-ray injection on our models
... ion. To accomplish this task, we employ state-of-the-art 3D particle diffusion and gas
... h 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 $f_{H_2} \sim 0.2$ ...
... 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.

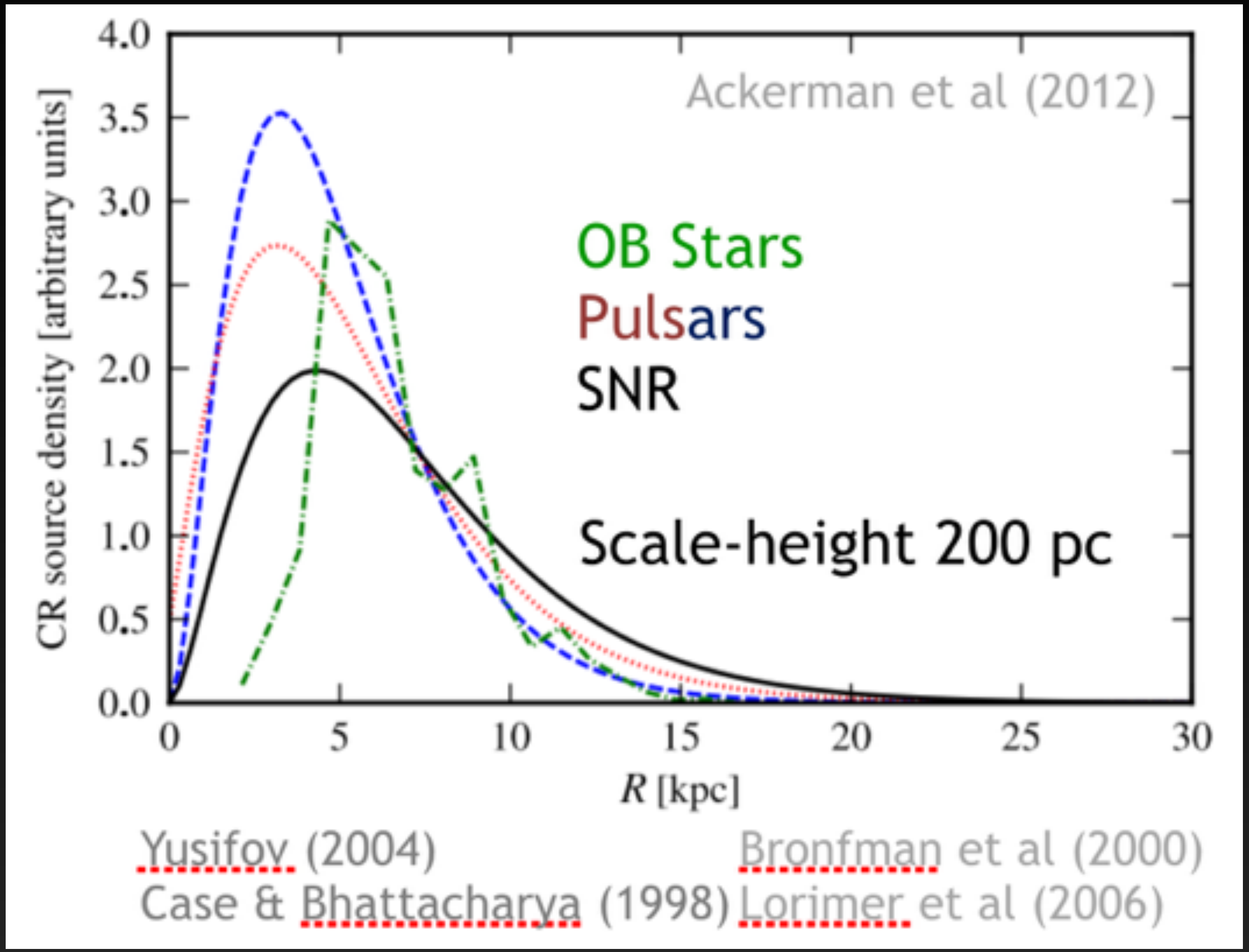
... 6.9 years of *Fermi*'s most ...
... al details are given in ...
... rnova remnants ...
... accelera ...

Cosmic-Ray Injection Sources

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

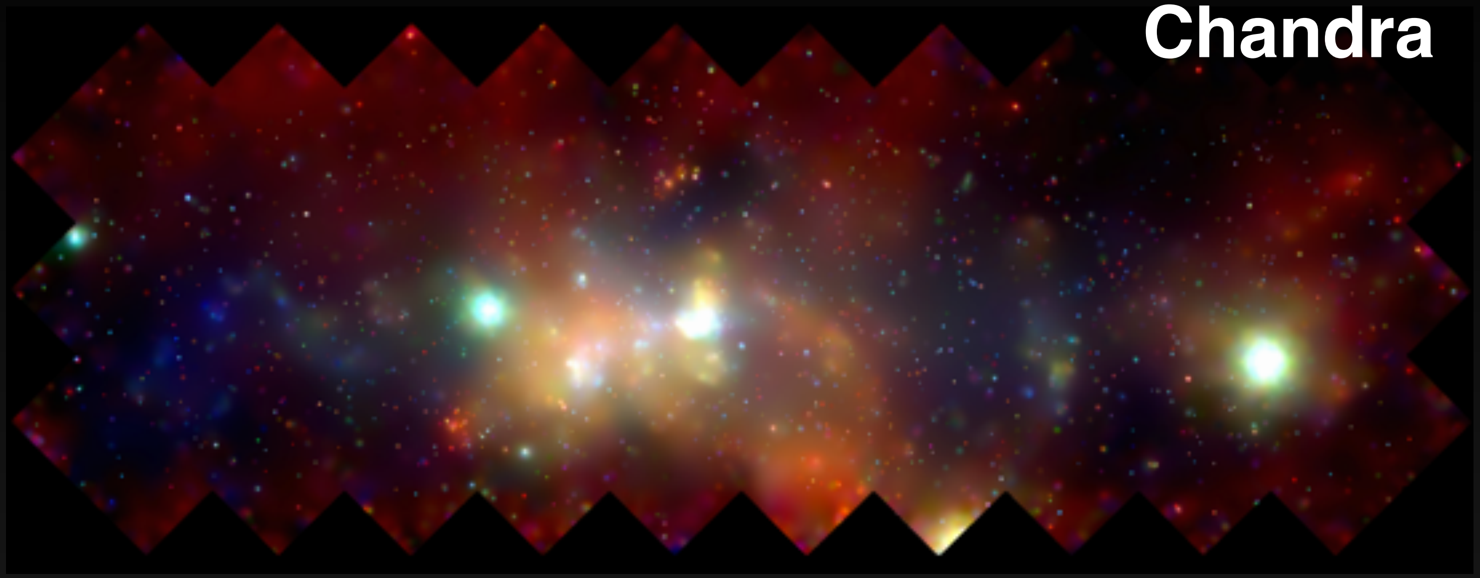
Need tracers of current and past supernovae rate:

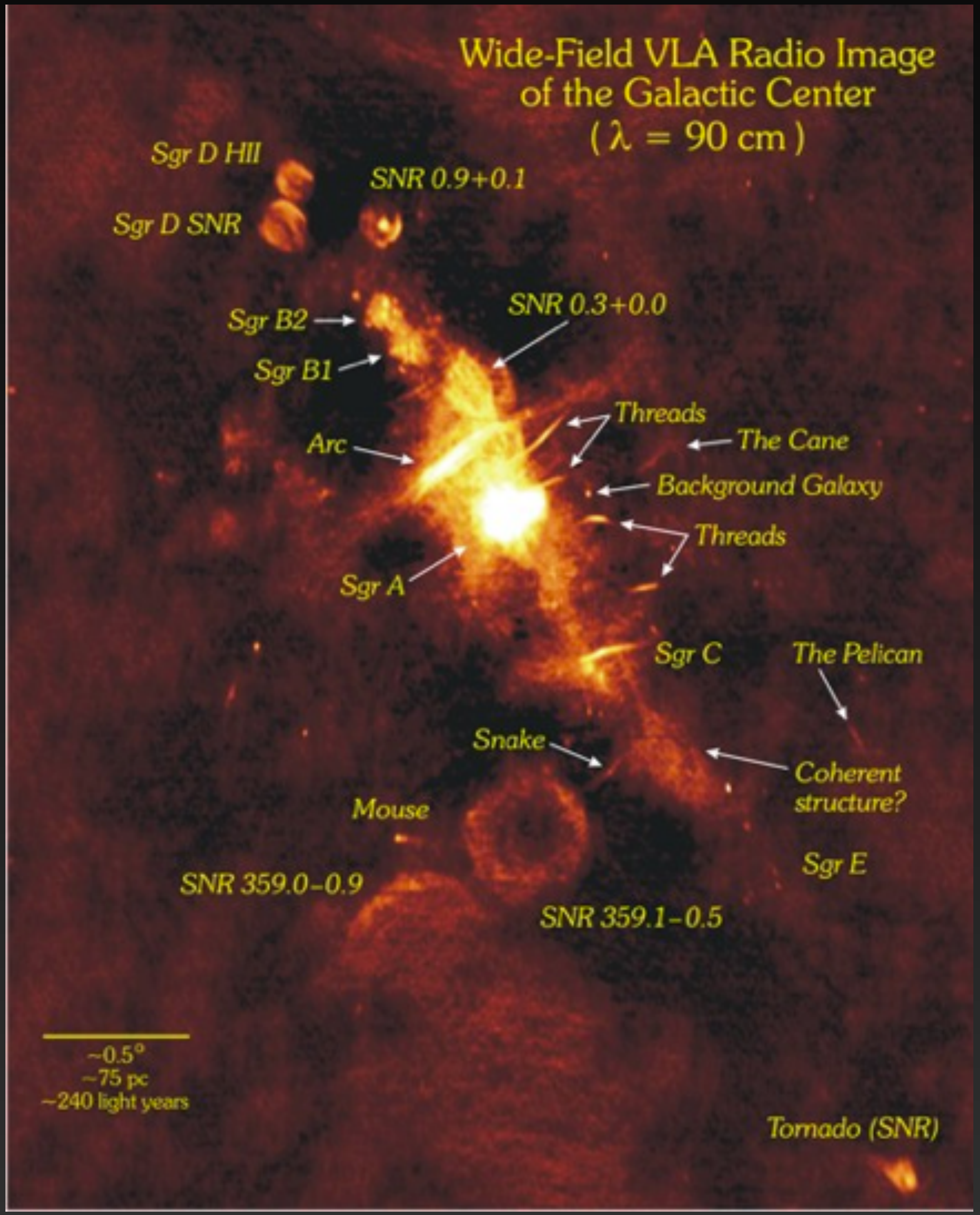
- **Observed SNR**
- **Pulsars**
- **OB Stars**



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.

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.

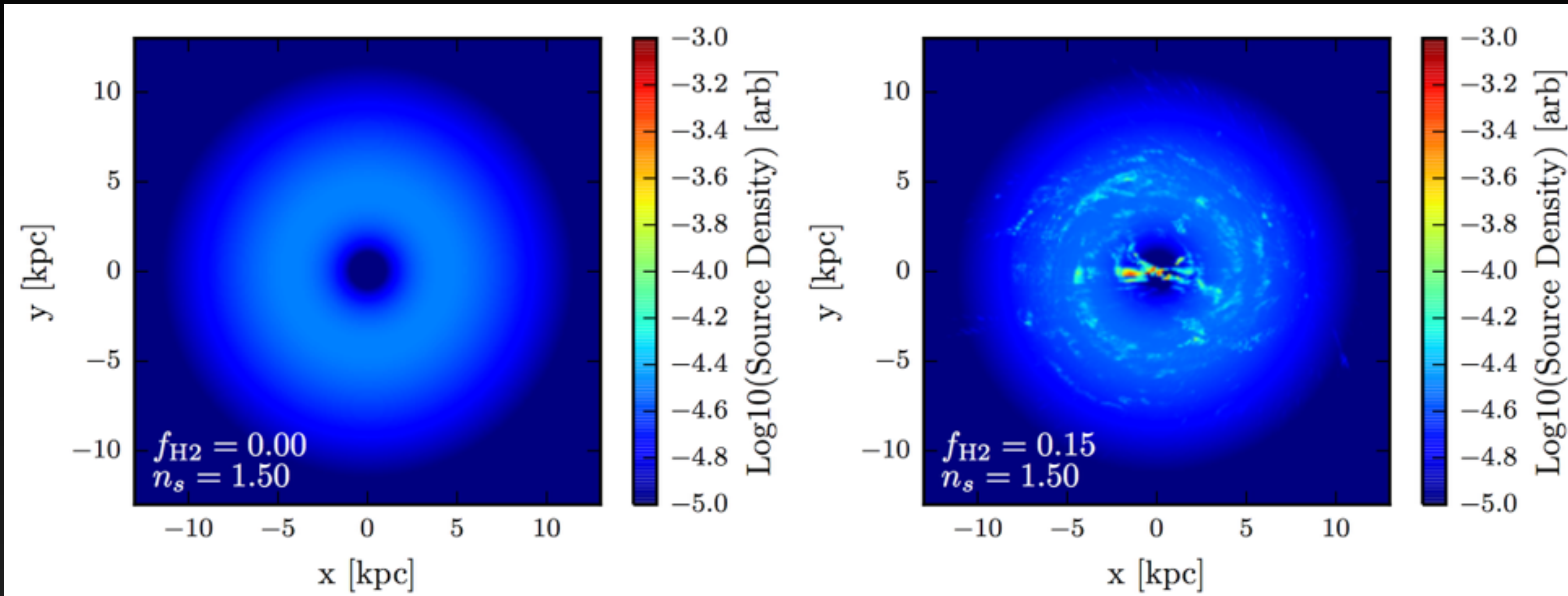
Theoretically Motivated: Molecular Gas is the seed of star formation, the Kennicutt-Shmidt Law gives

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

Specifically we adopt:

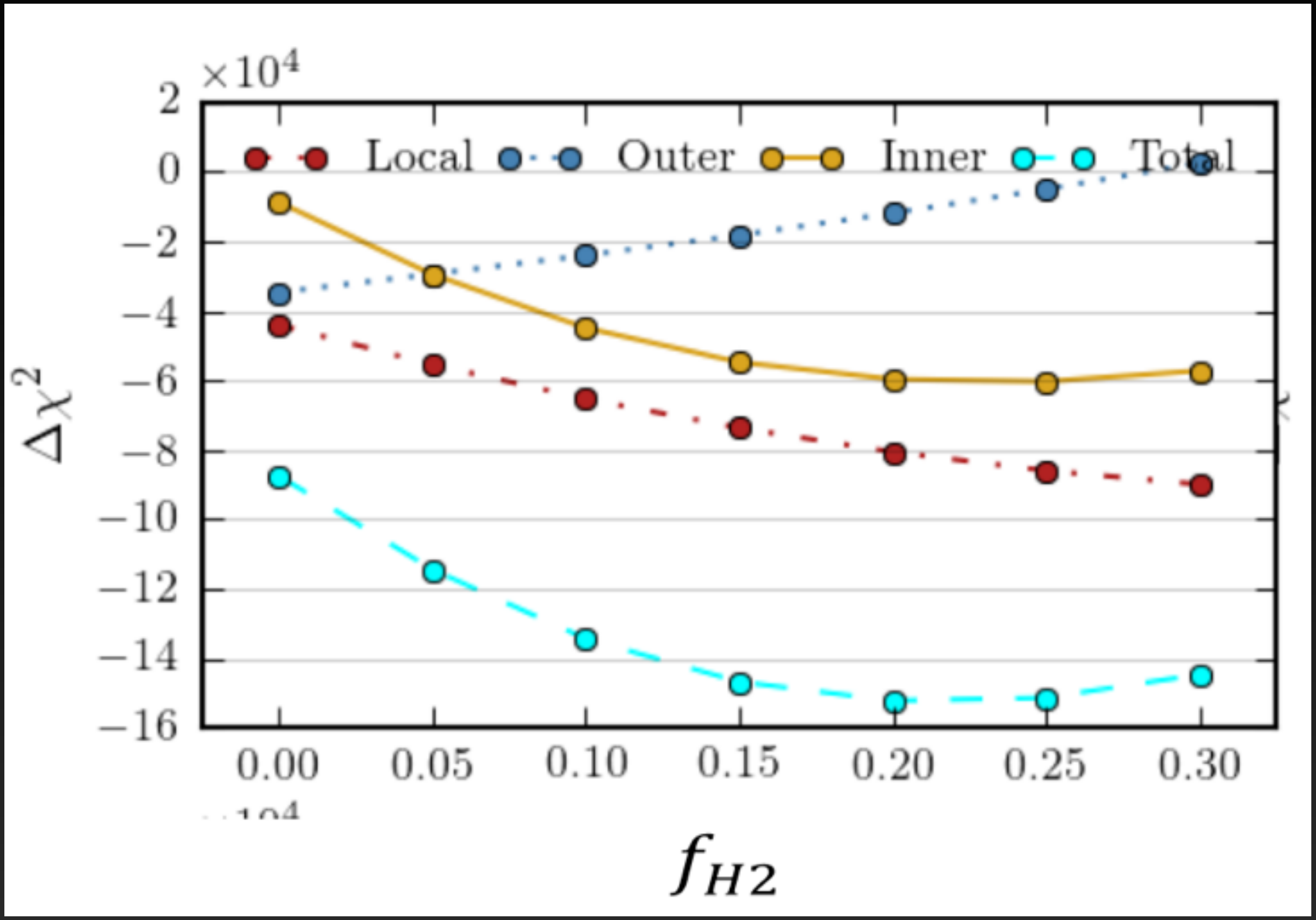
$$\mathrm{Q}_{\mathrm{CR}}(\vec{r}) \propto \begin{cases} 0 & \rho_{\mathrm{H2}} \leq \rho_s \\ \rho_{\mathrm{H2}}^{n_s} & \rho_{\mathrm{H2}} > \rho_s \end{cases}$$

Adding a Molecular Gas Component



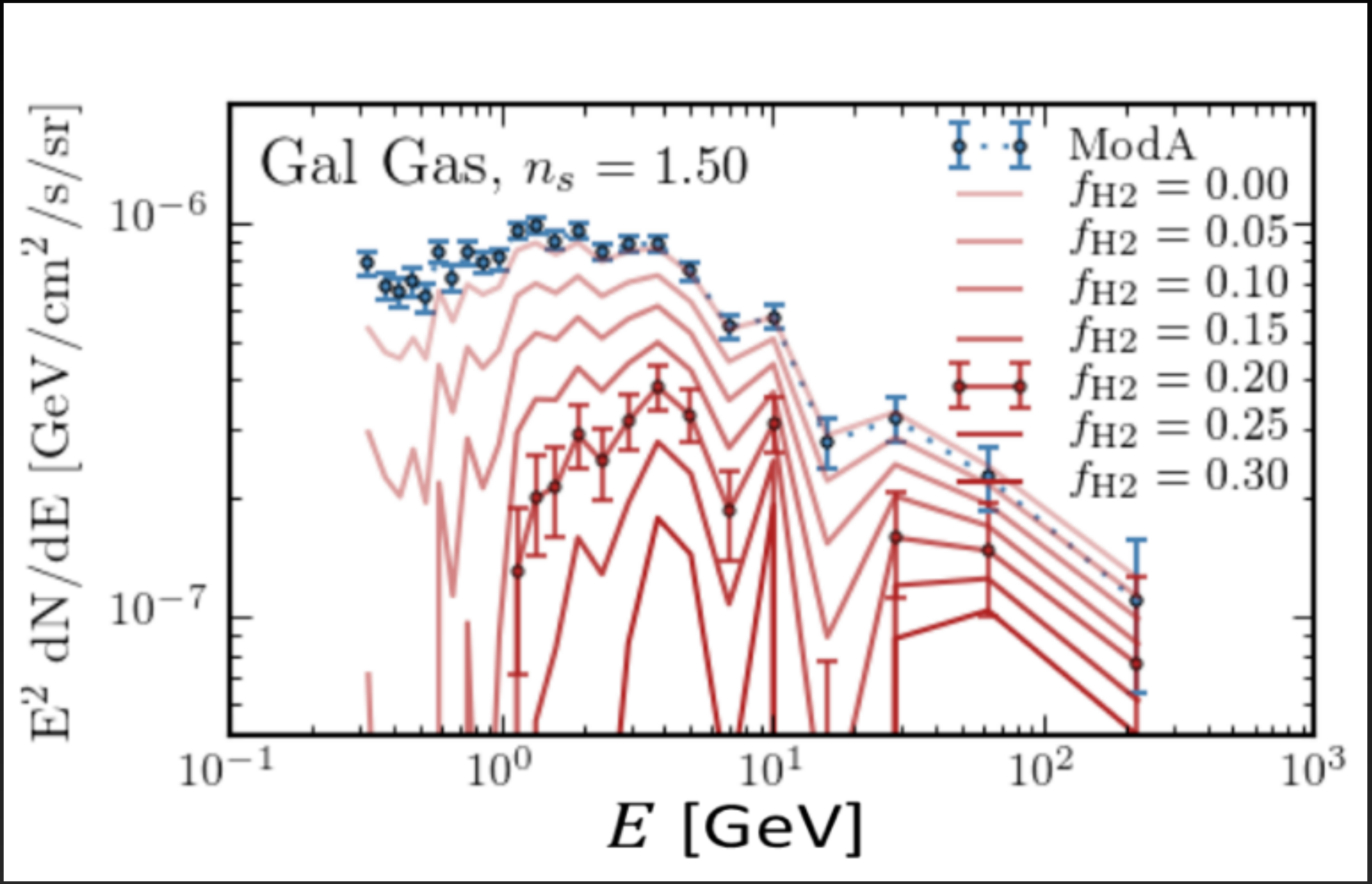
Adds significant cosmic-ray injection to the inner galaxy, and additionally a large bar structure.

Adding a Molecular Gas Component



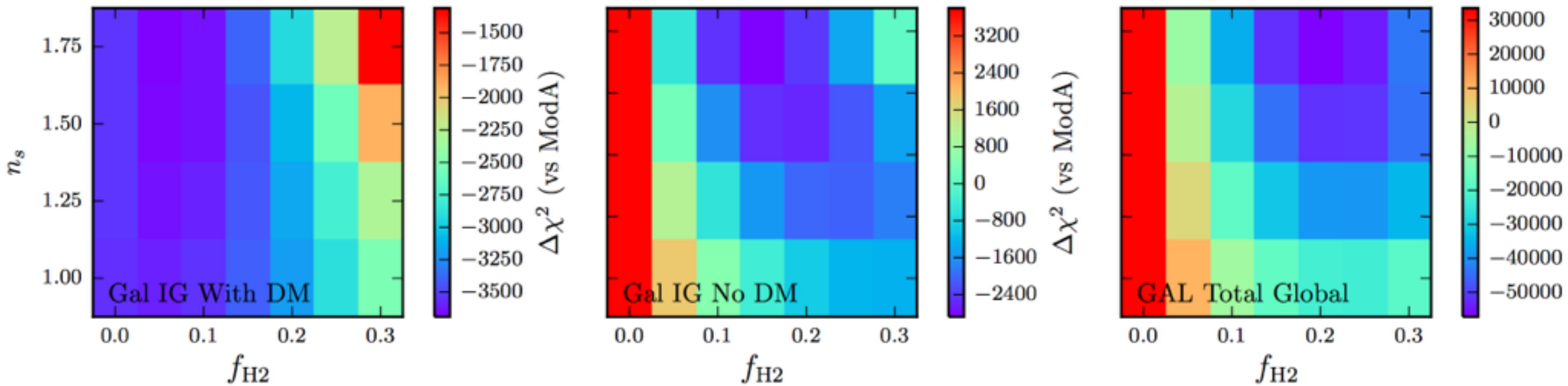
This tracer improves the fit to the gamma-ray data over the full sky.

This Reduces the Gamma-Ray Excess!



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

Why Not Astrophysical Modeling?

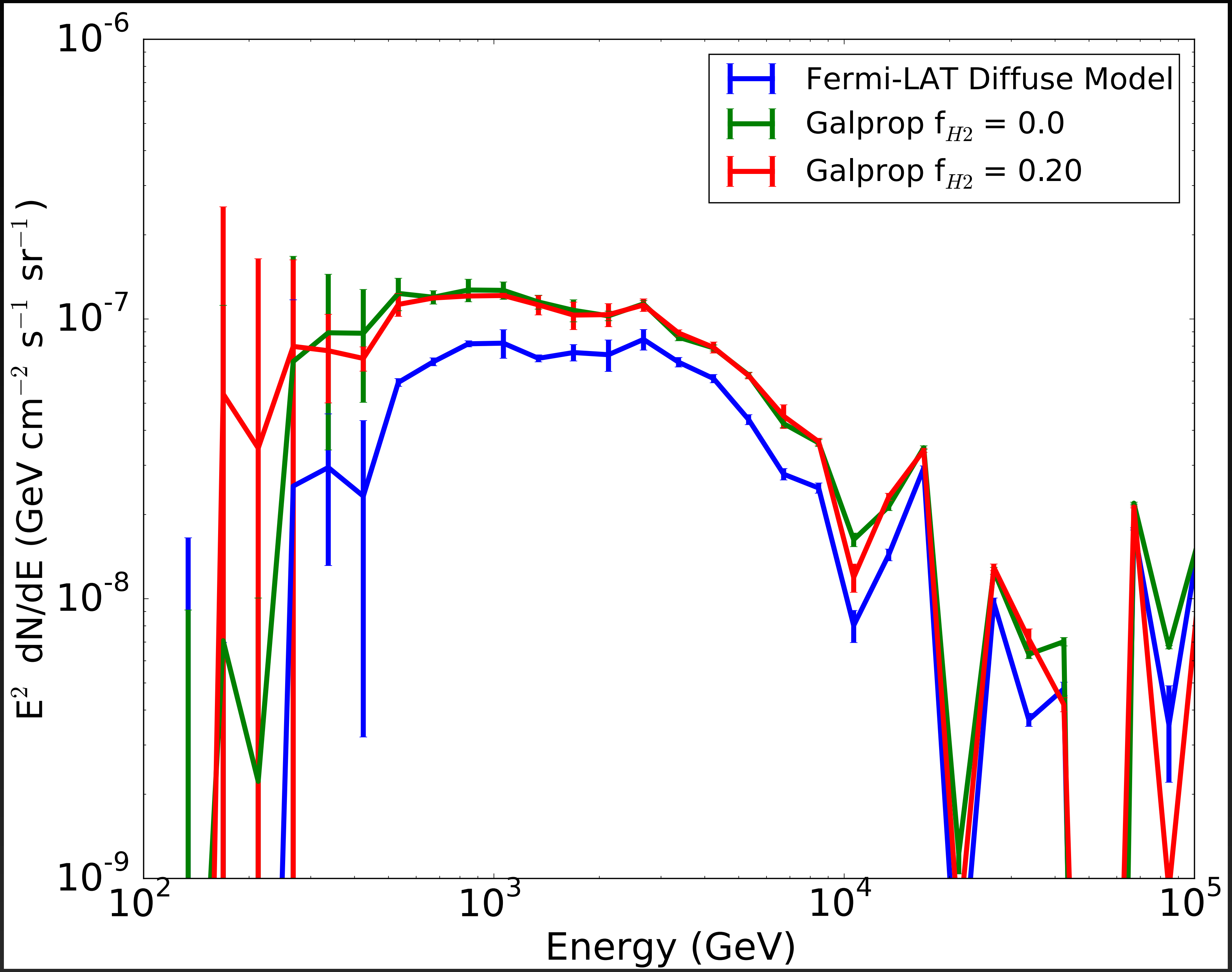


However, these fits were performed in models without an NFW template.

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

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

Why Not Astrophysical Modeling?



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

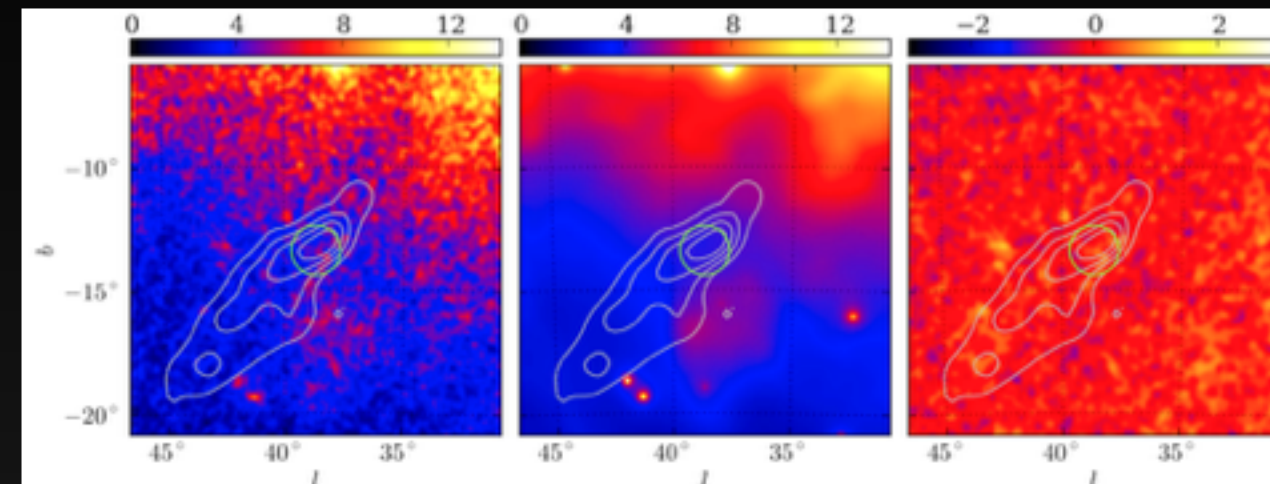
Alternative Targets

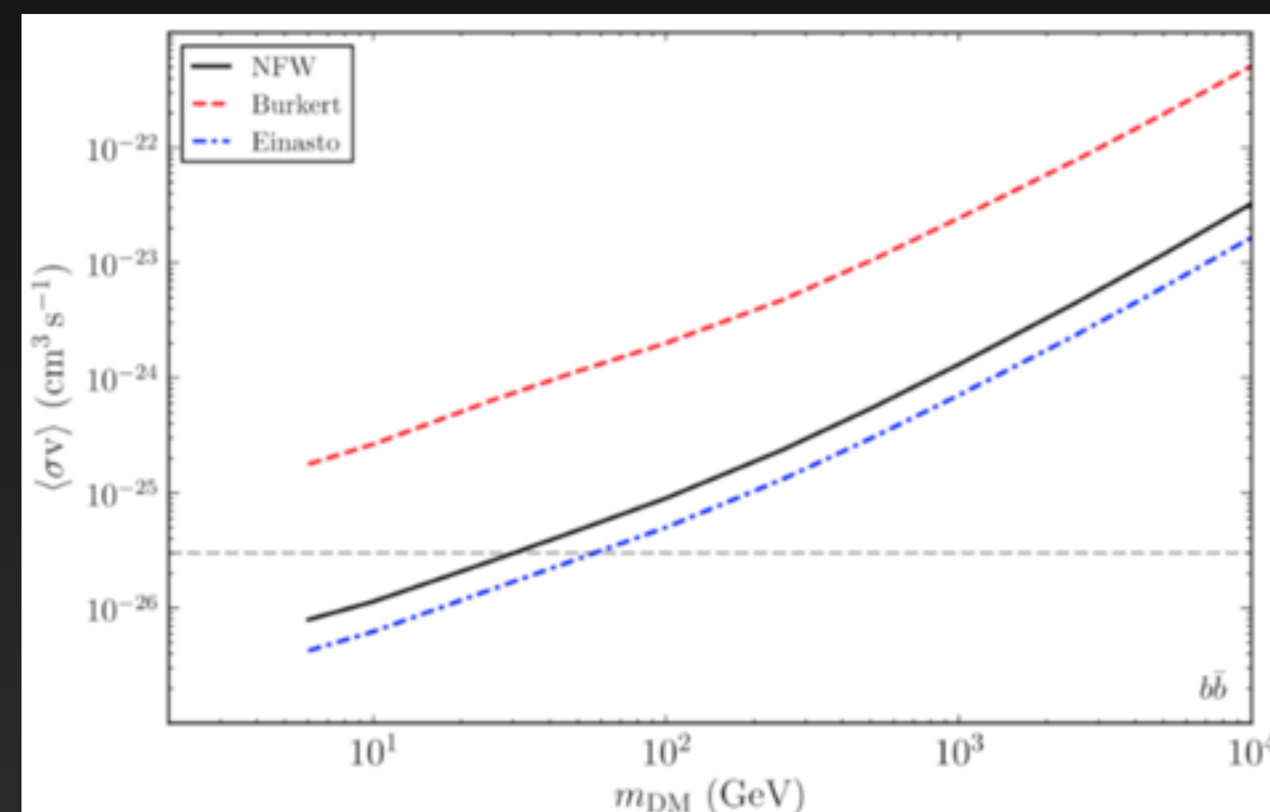
May find other bright indirect detection targets.

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

Some may be confined by dark matter halos

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





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

Conclusion

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

Conclusion

- For the skeptics, there are many ways this story could fall apart:
  - Improved J-factor measurements may indicate that Reticulum II is not the brightest dwarf
  - The significance of the dwarf analysis might go down with P8 data
  - Astrophysical explanations for excesses in the Galactic Center and the LMC may be produced

- The next few years promise to present significant hints (or significant constraints on) the dark matter particle models that can explain the GeV excess.