Dark Matter at the Galactic Center

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CCAPP

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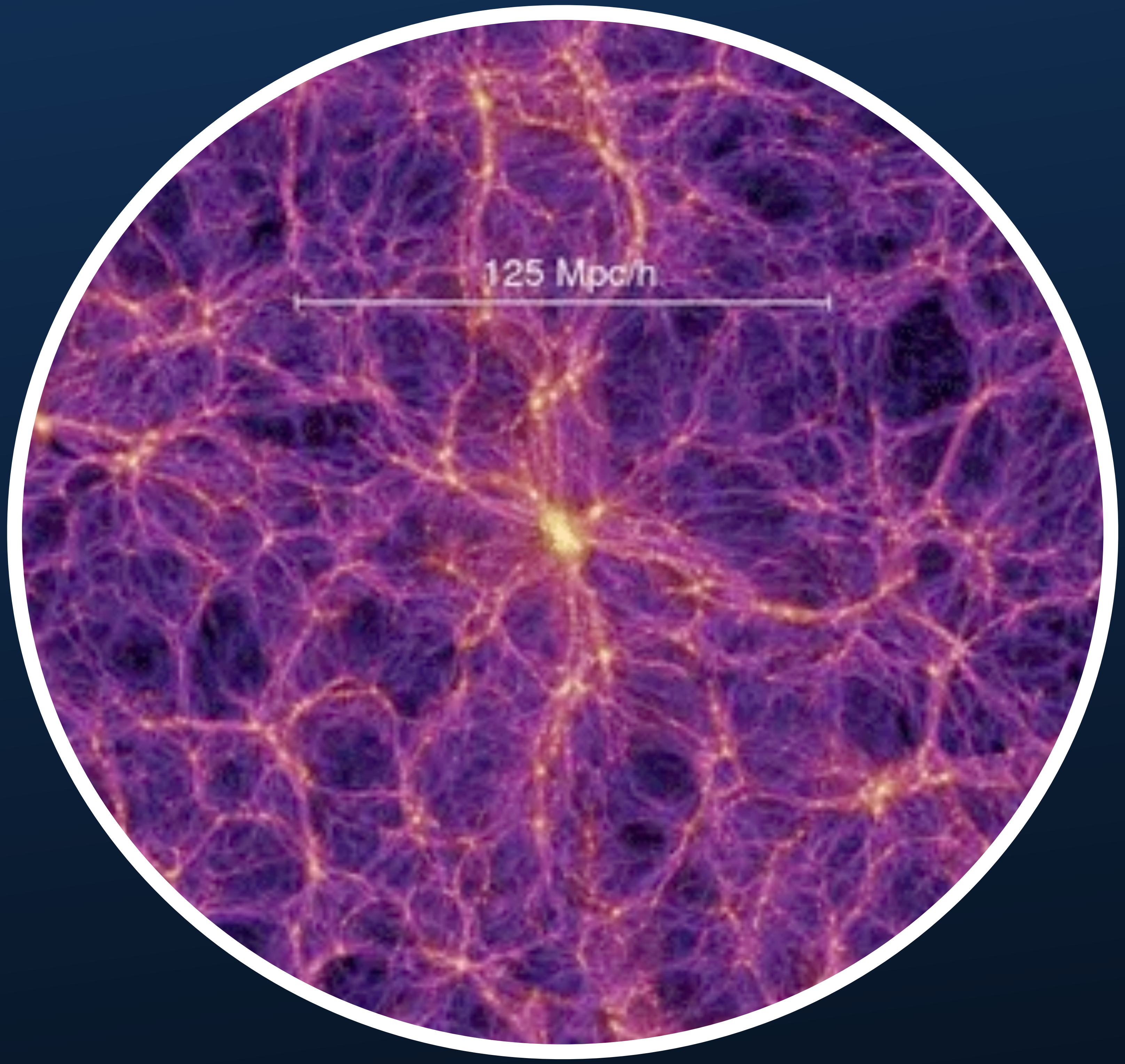
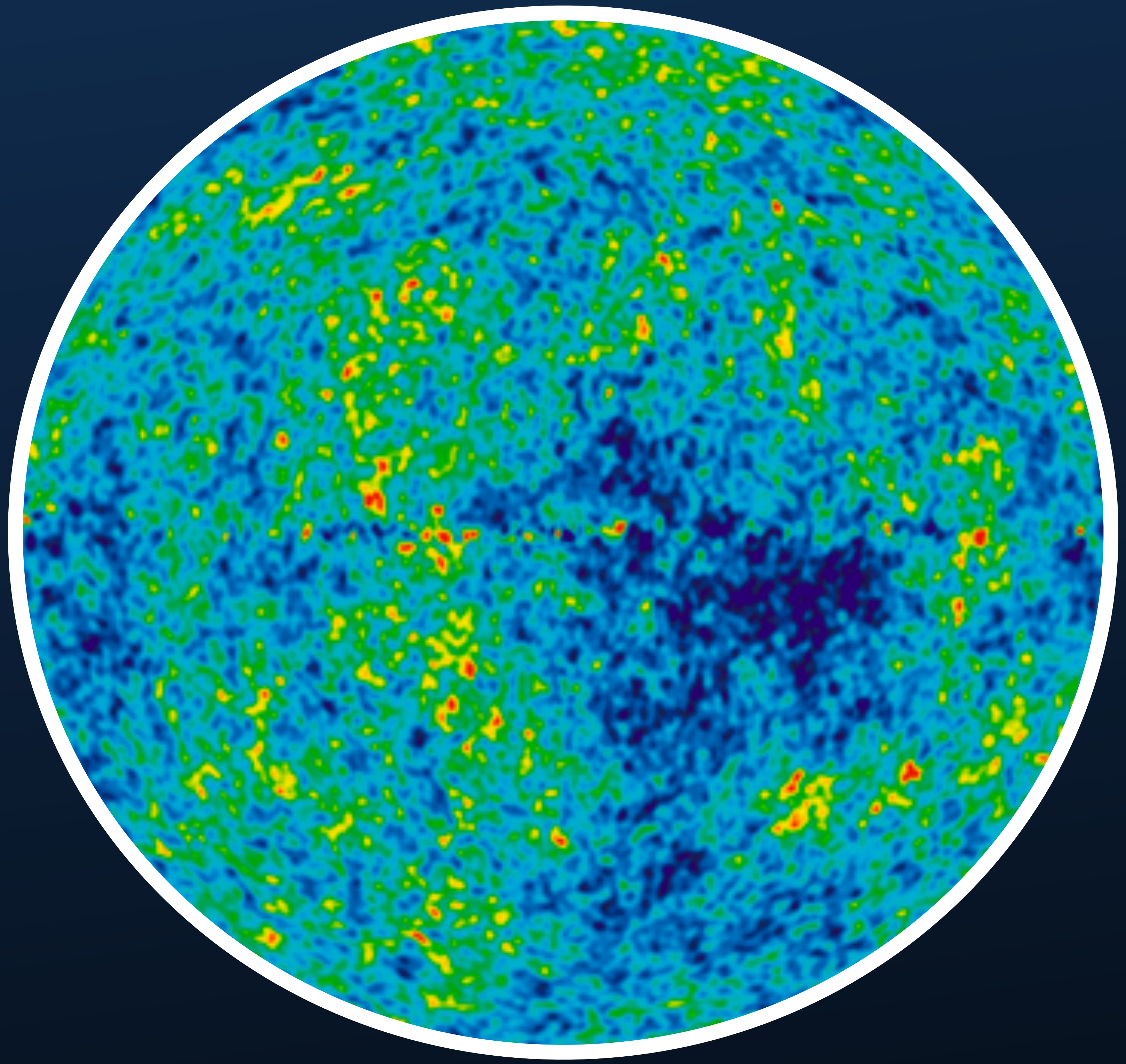
Gravitational Dark Matter





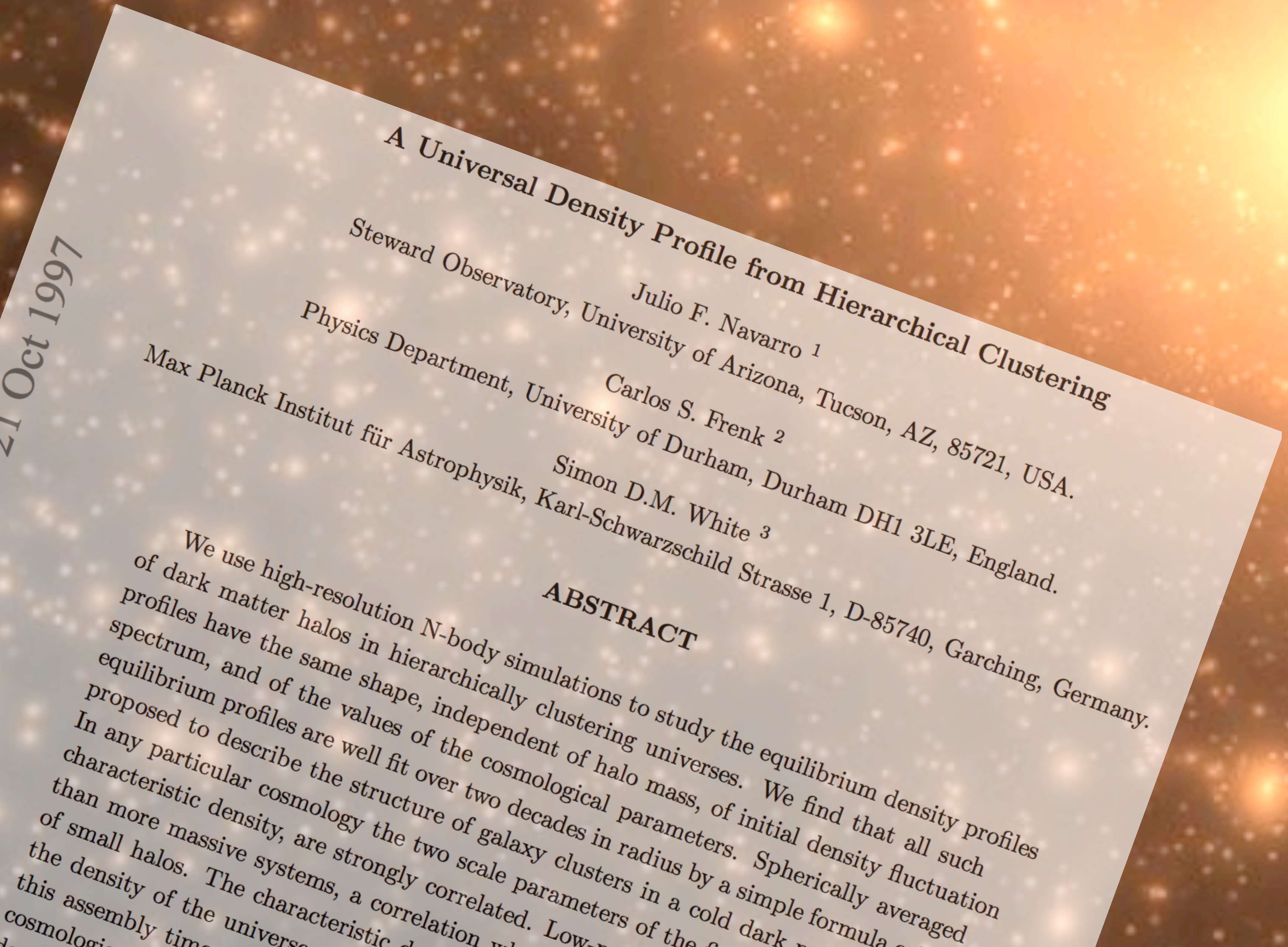
Dark Matter is:

Cold

Collisionless

How Much Dark Matter is in the Galactic Center?

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$


21 Oct 1997

A Universal Density Profile from Hierarchical Clustering

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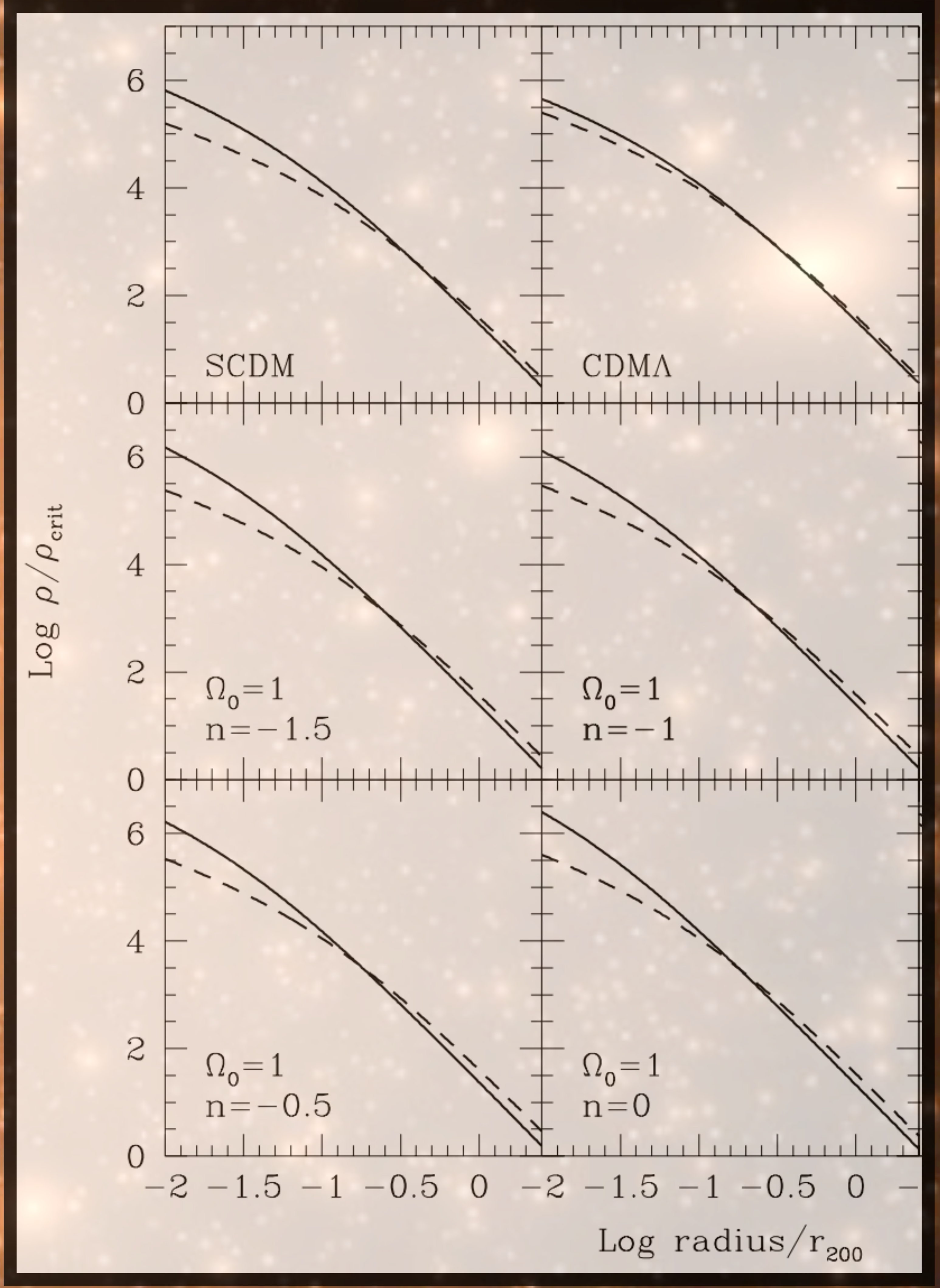
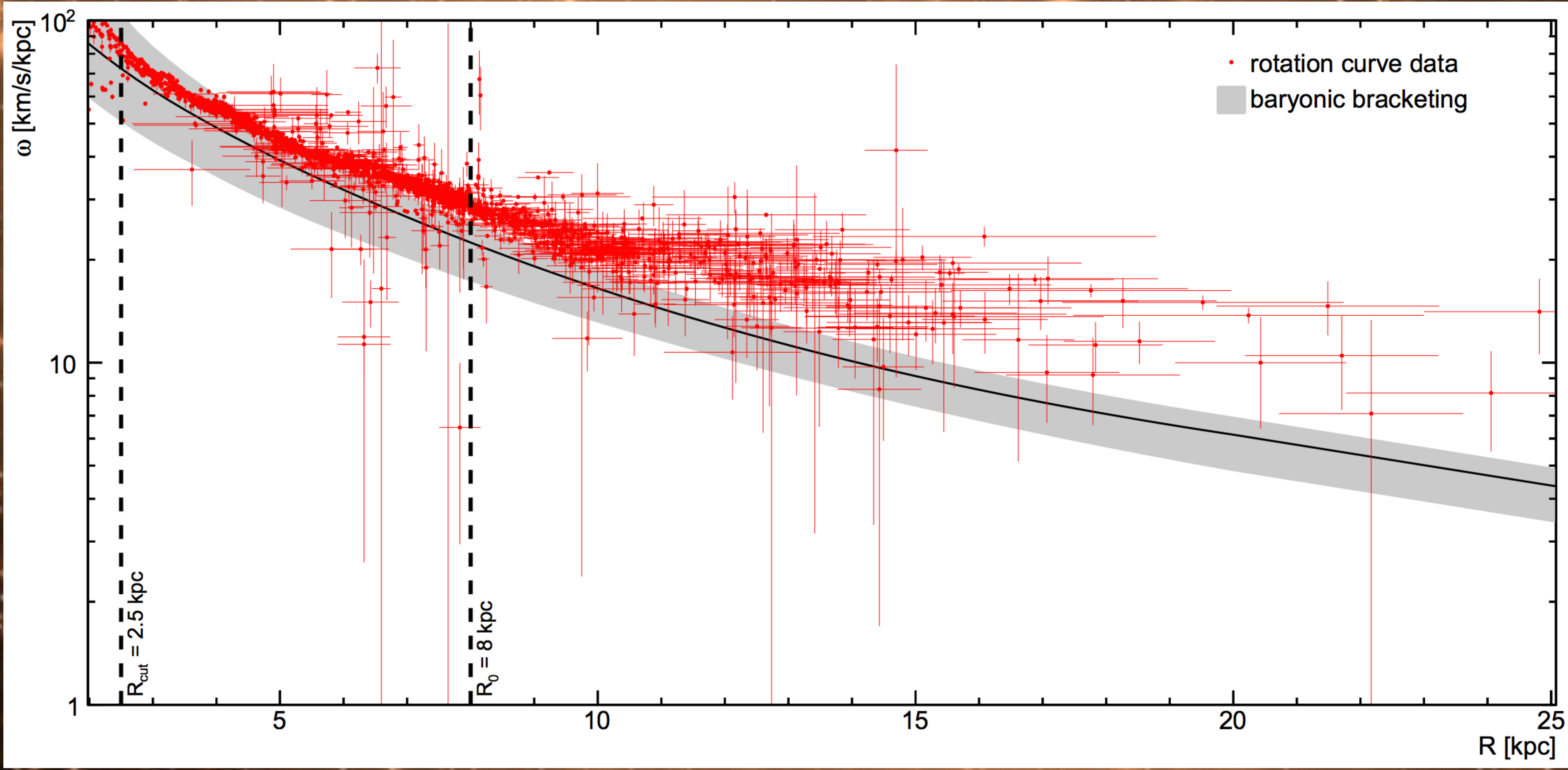
ABSTRACT

We use high-resolution N-body simulations to study the equilibrium density profiles of dark matter halos in hierarchically clustering universes. We find that all such profiles have the same shape, independent of halo mass, of initial density fluctuation spectrum, and of the values of the cosmological parameters. Spherically averaged equilibrium profiles are well fit over two decades in radius by a simple formula proposed to describe the structure of galaxy clusters in a cold dark In any particular cosmology the two scale parameters of the characteristic density, are strongly correlated. Low- than more massive systems, a correlation wh of small halos. The characteristic the density of the univers this assembly tim cosmologi



How Much Dark Matter is in the Galactic Center?

Pato et al. (1504.06324)



How Much Dark Matter is in the Galactic Center?

Dark Matter density within 1 pc of GC is 10,000x higher than near Earth

Still the total dark matter mass is small:

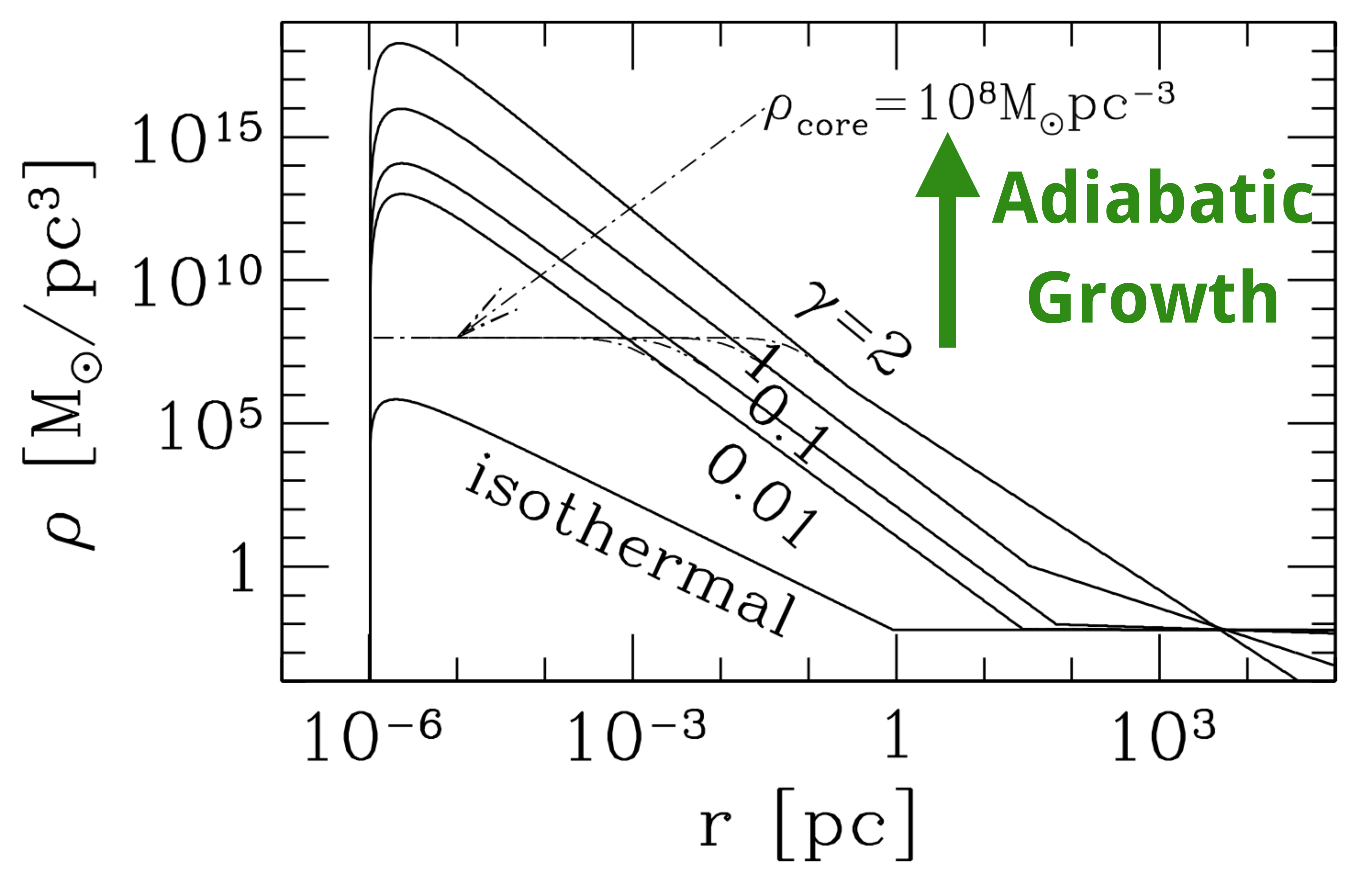
~300 $M_\odot$ within 1 pc

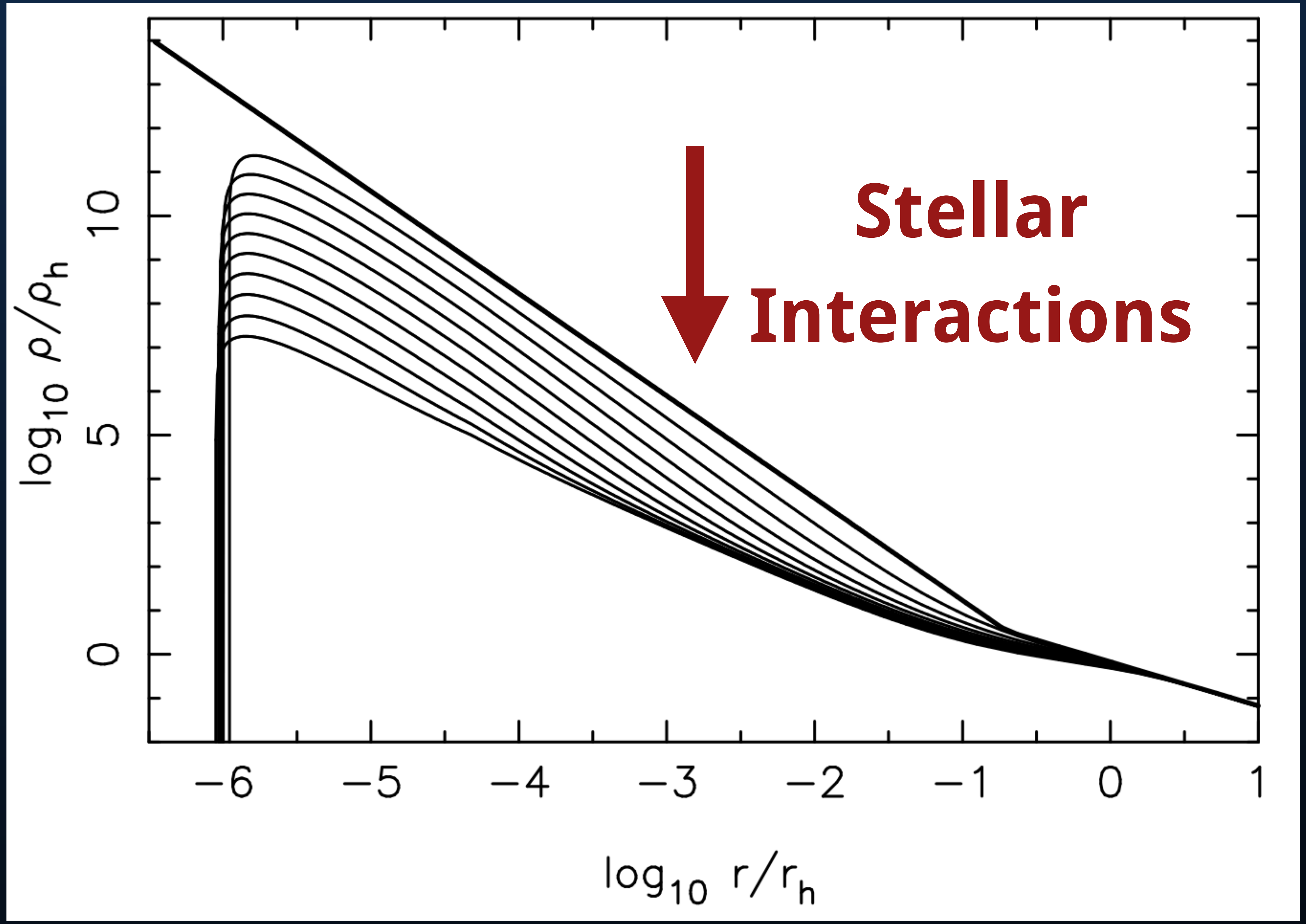
Dark Matter is not dynamically important near the Galactic center.

Dark Matter Density Spike

Gondolo & Silk (astro-ph/9906391)

Merritt (astro-ph/0311594)

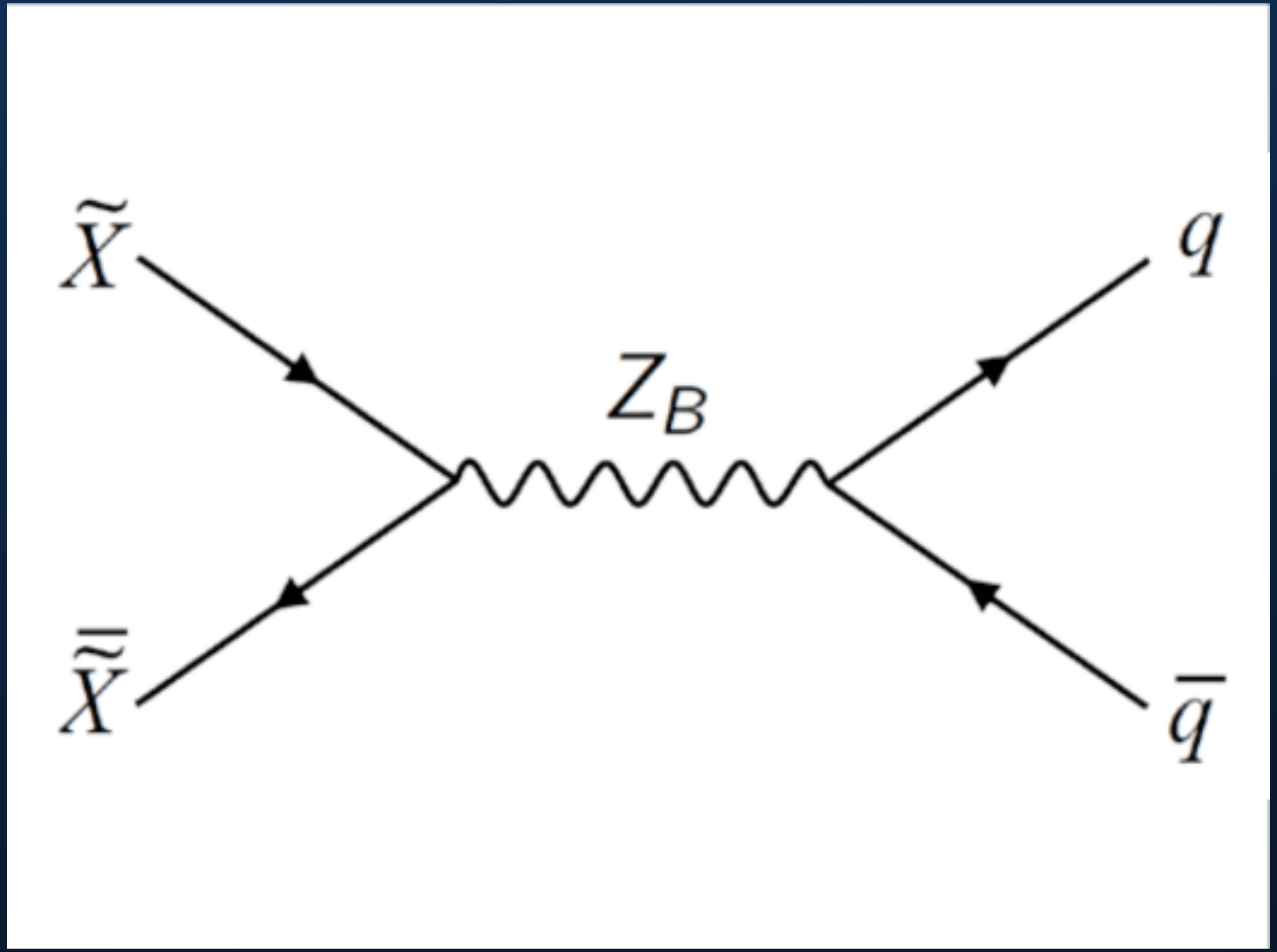


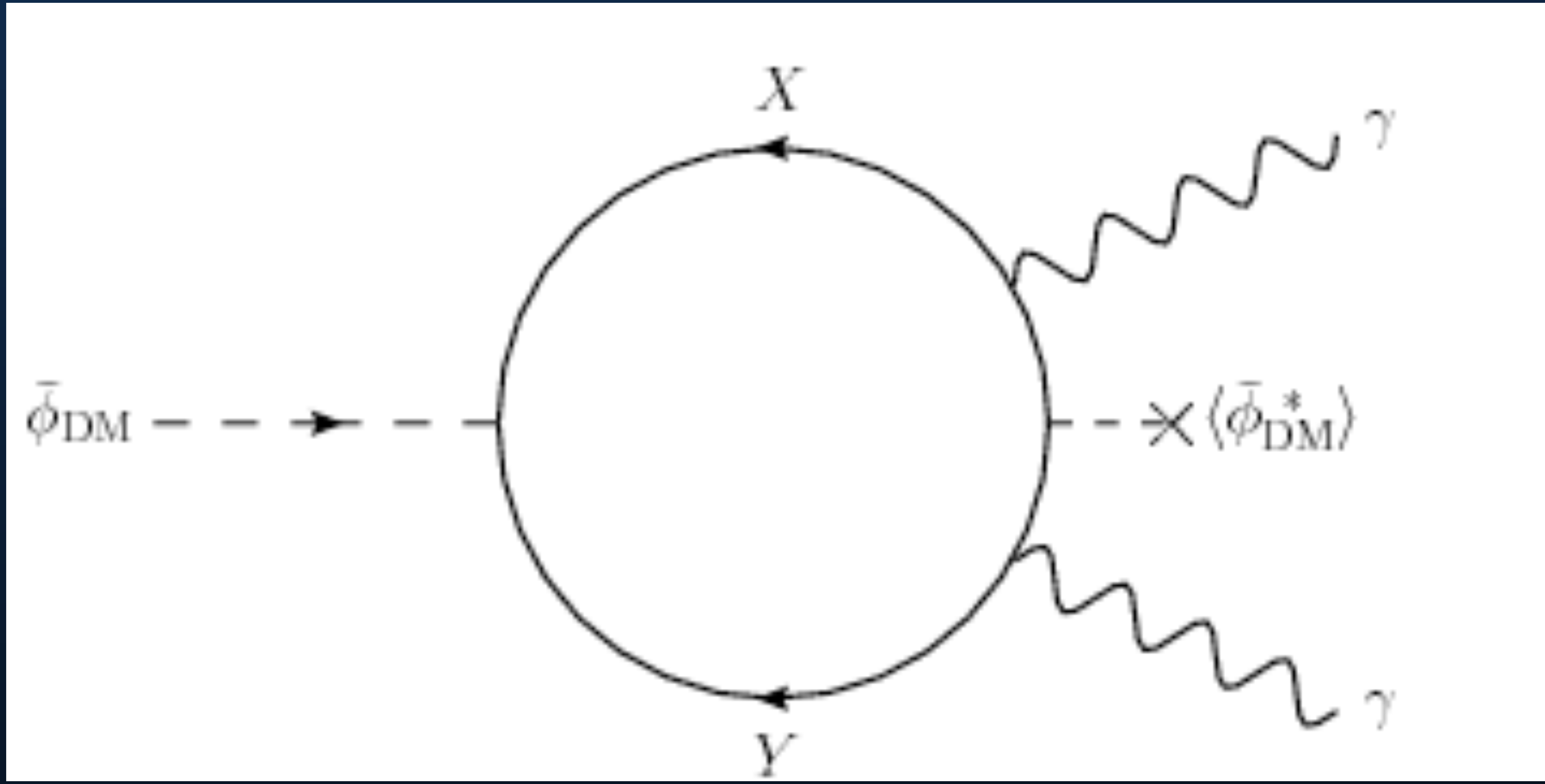


<u>Caveat</u> - Adiabatic growth of the central black hole can produce a spike in the dark matter density.

Only significantly contributes to mass in the most extreme scenarios.

Cold and Collisionless is Not Enough





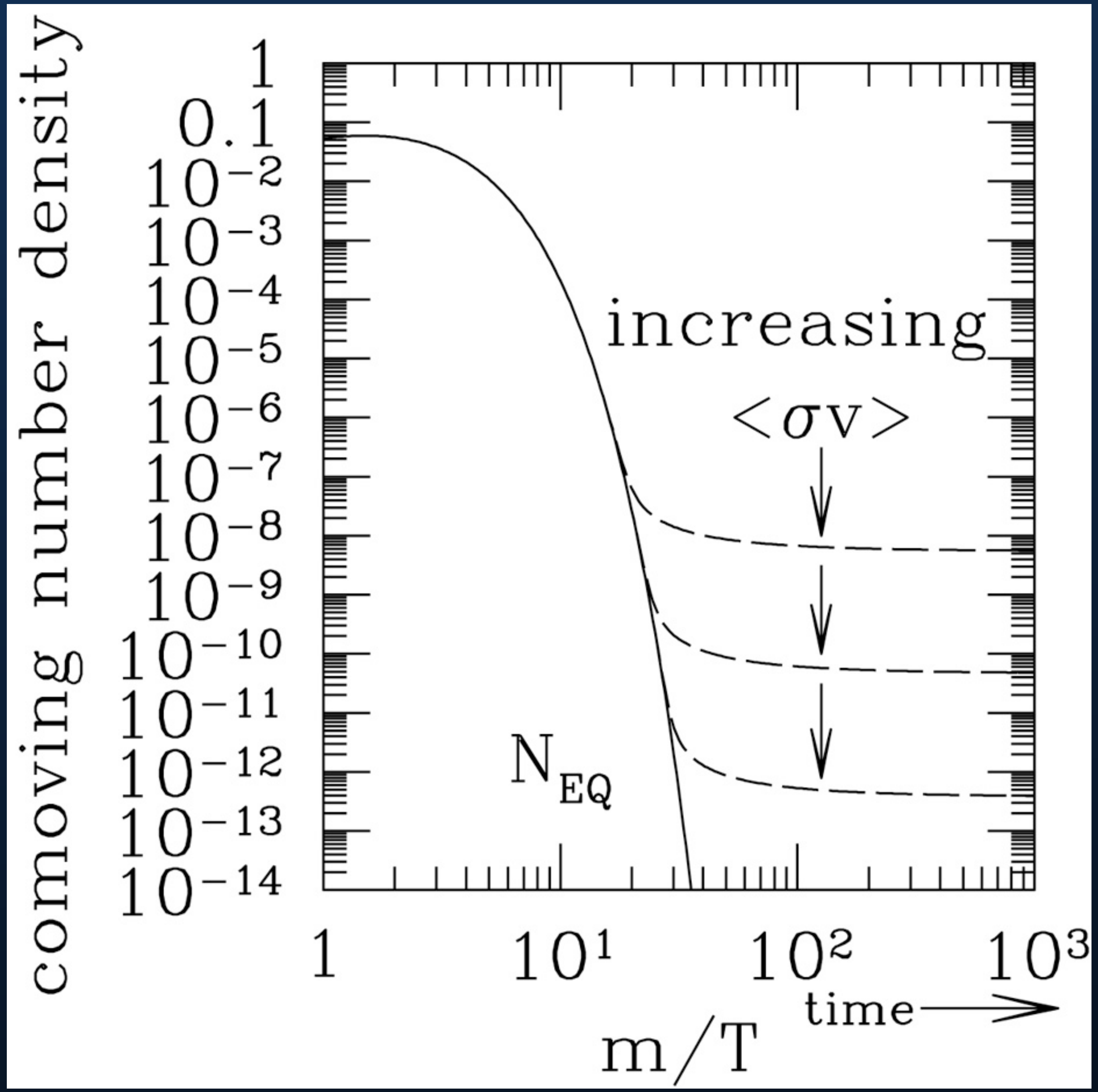
Annihilation

$$\Phi \propto \rho^2_{NFW} = \rho_0 \left(\frac{R_s}{r}\right)^2 \left(1 + \frac{r}{R_s}\right)^{-4}$$

Decay

$$\Phi \propto \rho^2_{NFW} = \rho_0 \left(\frac{R_s}{r}\right) \left(1 + \frac{r}{R_s}\right)^{-2}$$

WIMP-y Dark Matter At the Galactic Center



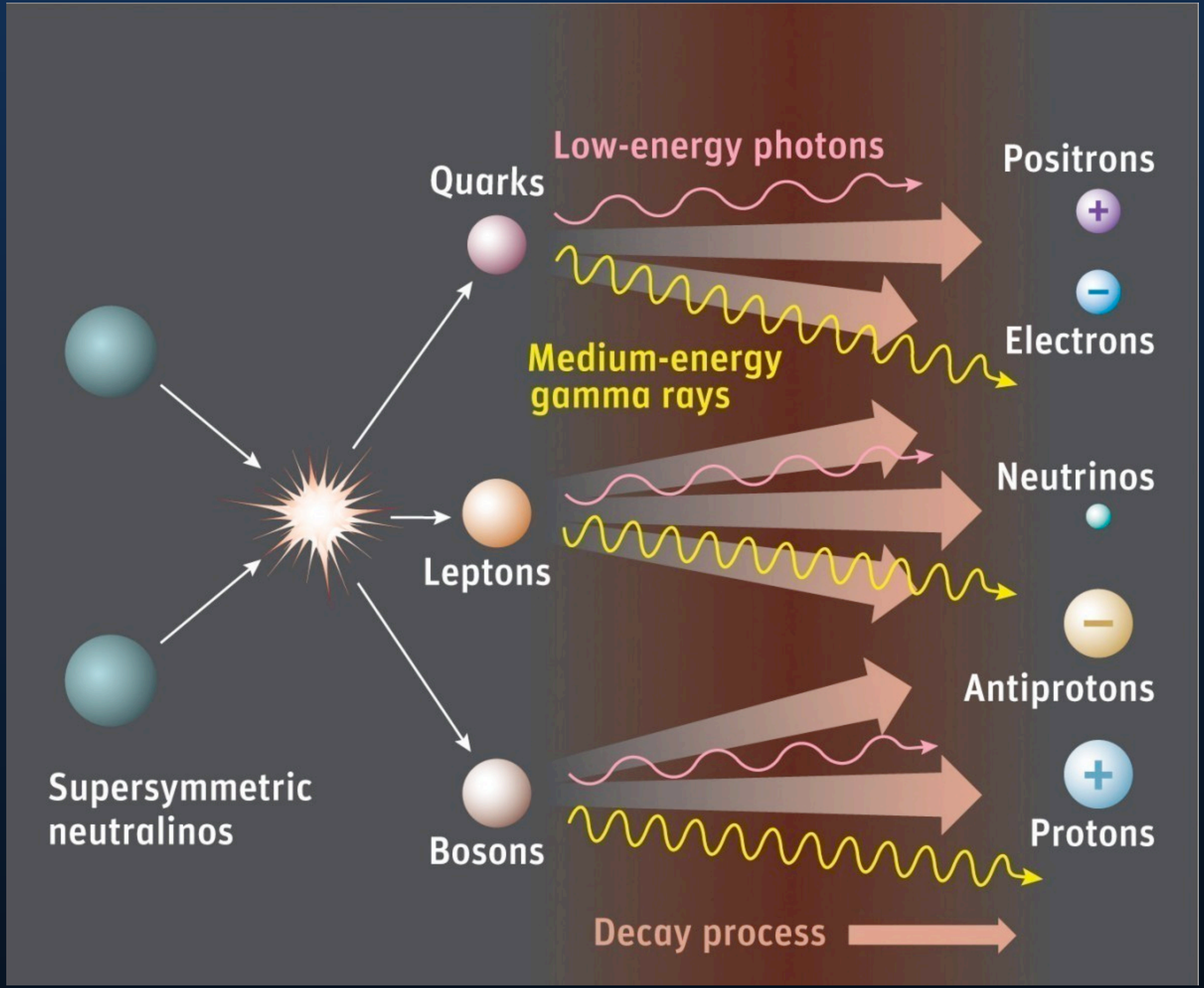
Motivated by the WIMP miracle:

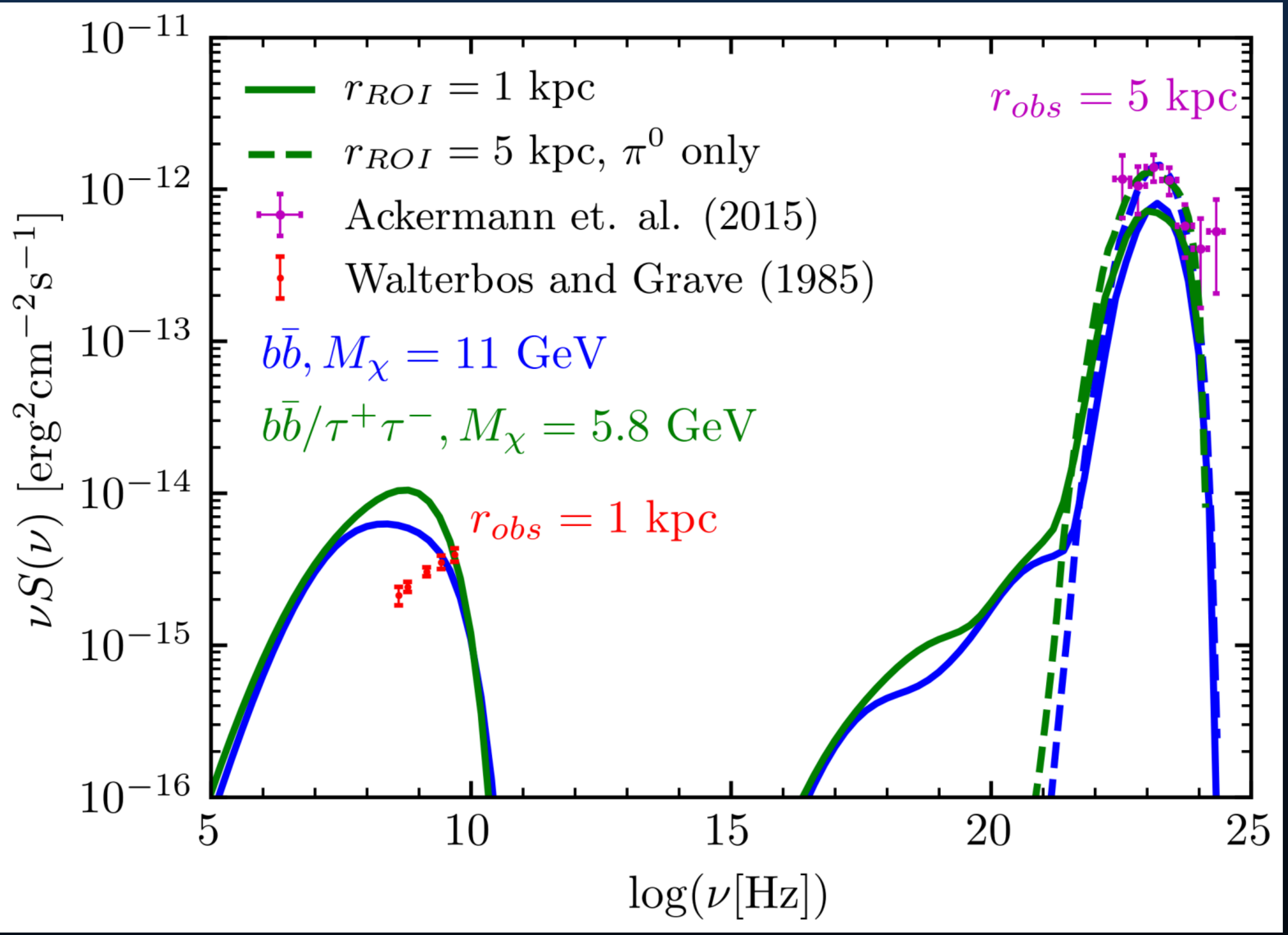
- **Mass Between MeV — PeV**
- **Annihilates into Standard Model Particles**
- **Annihilation sets observed abundance**

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

What Does Dark Matter Do in the Galactic Center?

McDaniel et al. (1802.05258)

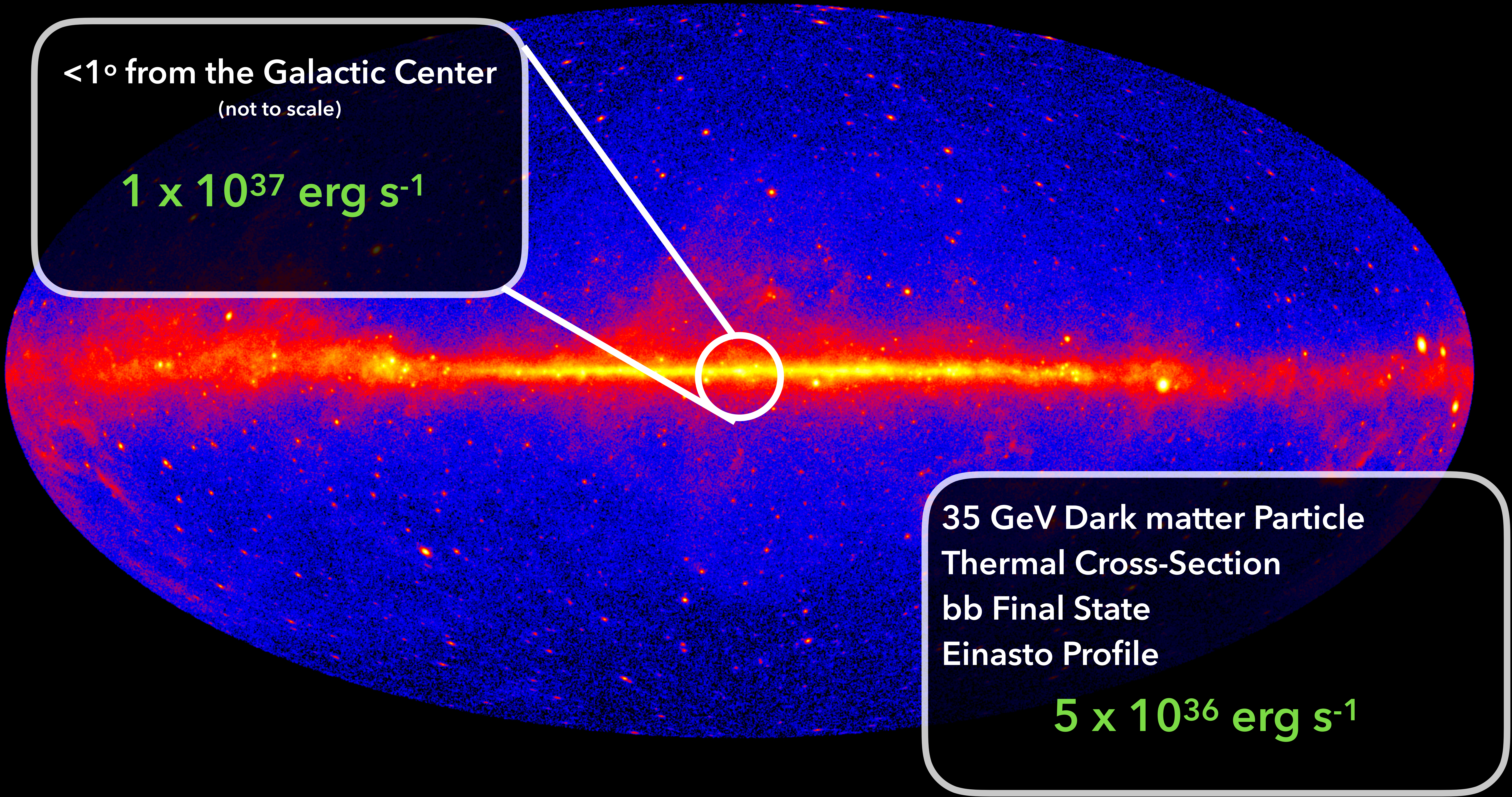




Dark Matter annihilation produces relativistic (~GeV) particles.

- **Gamma-Rays** (prompt + inverse Compton scattering + bremsstrahlung)
- **Radio** (synchrotron)

Energy Injection Compared to Observations

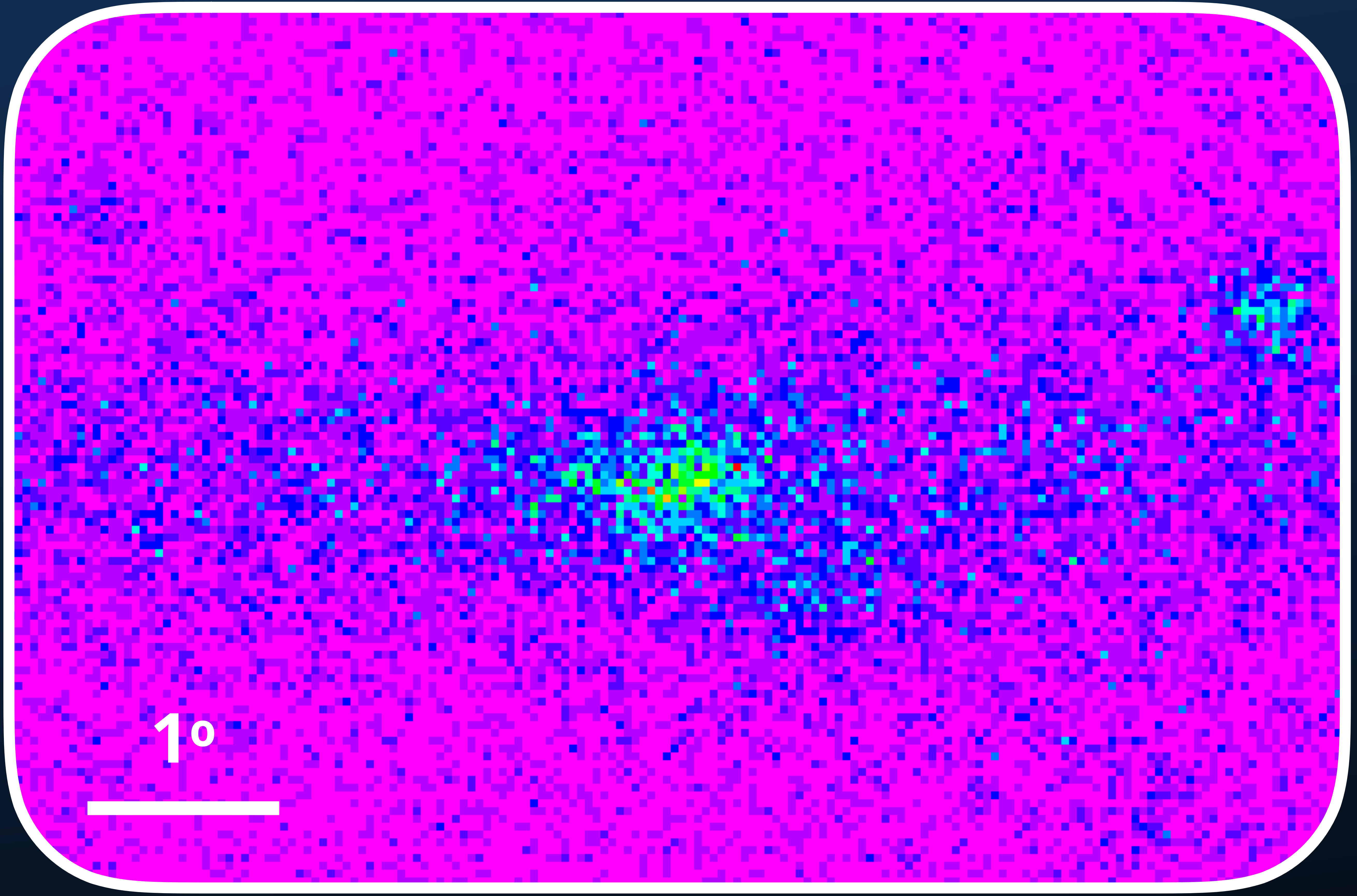


Energy Injection Compared to Observations

Gamma-Ray Observations of the GC

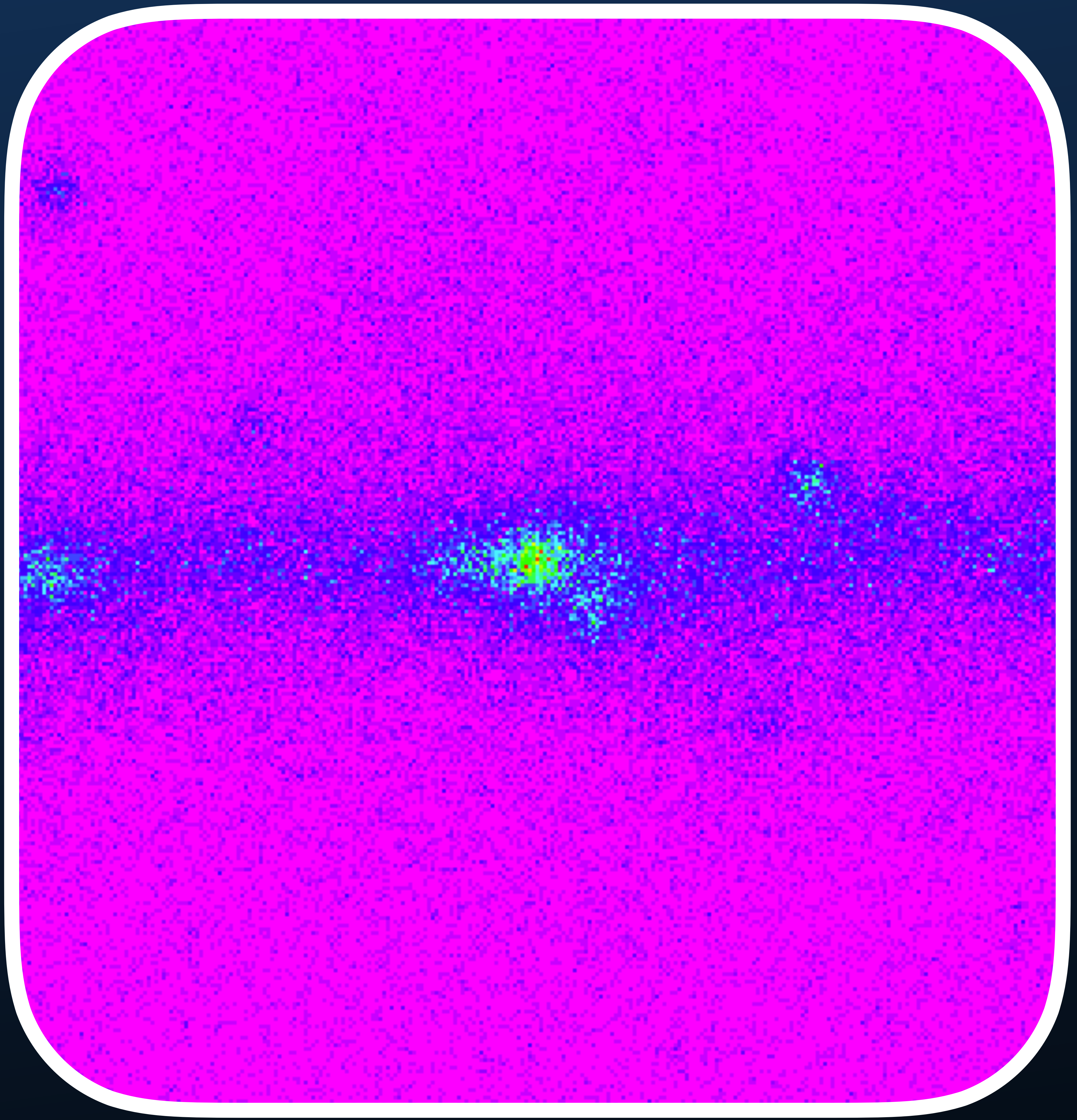
Sensitive probe of non-thermal emission

Gamma-Ray Observations of the GC



Angular resolution is .... not ideal.

Possible Indications of Dark Matter Annihilation



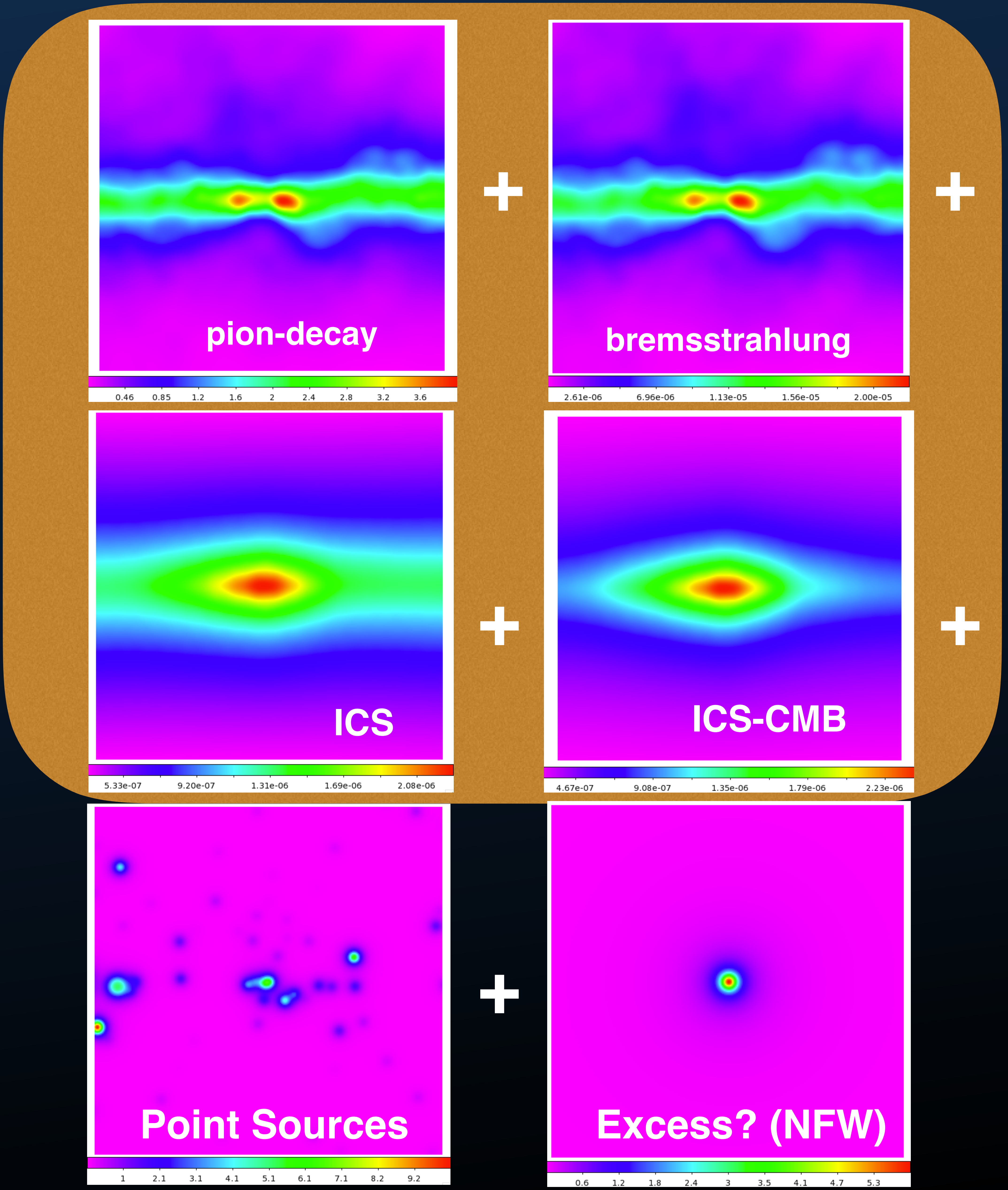
Data

750 — 950 MeV

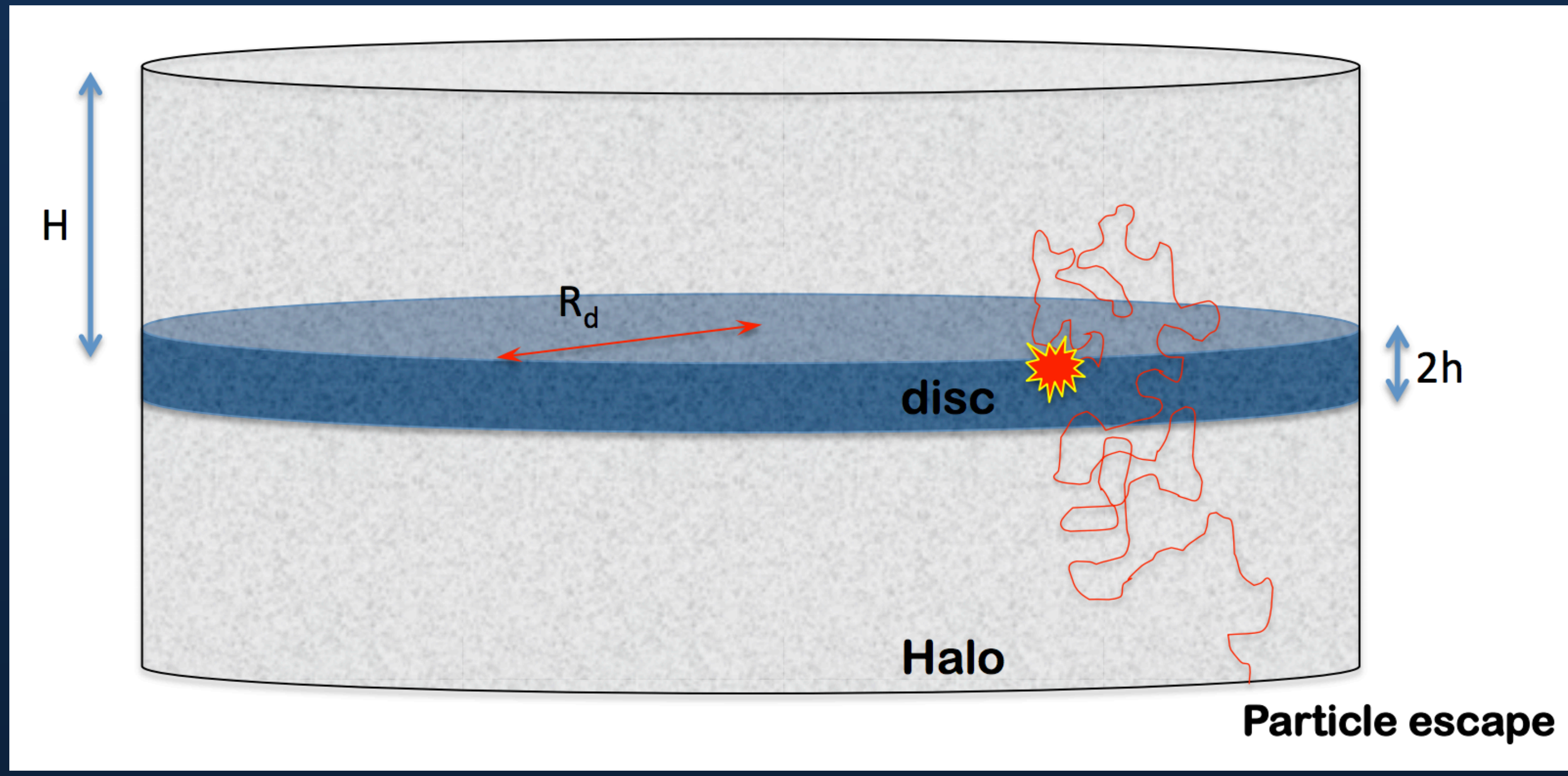
Best Angular Resolution Cut

10° x 10° ROI

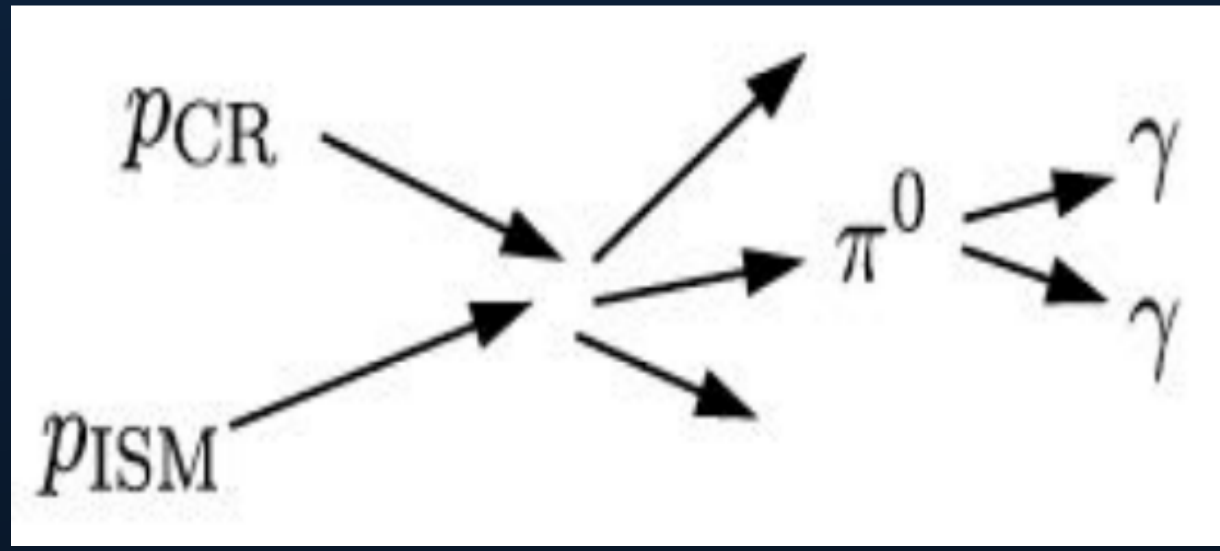
=

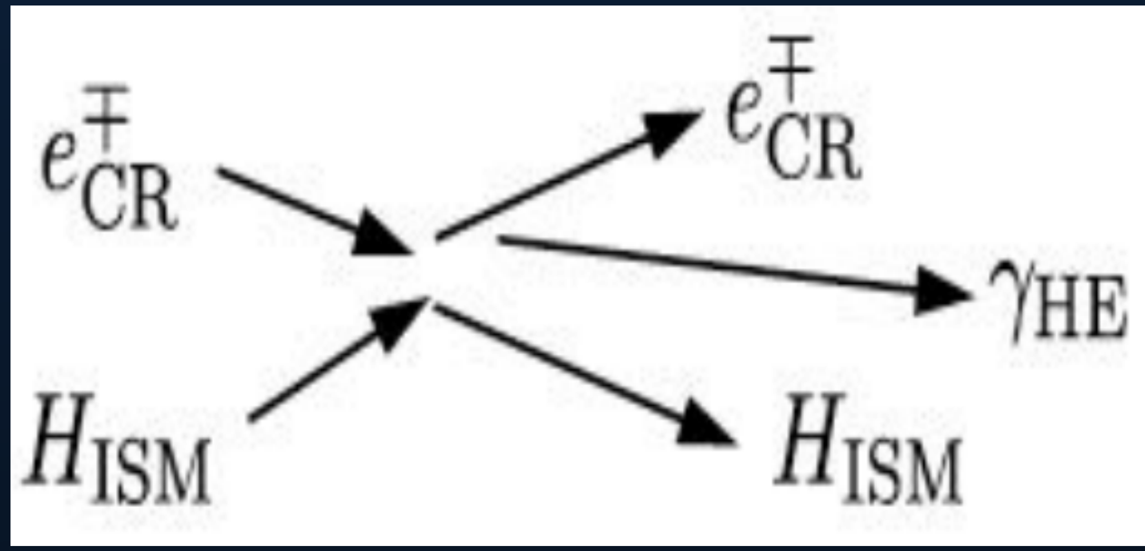


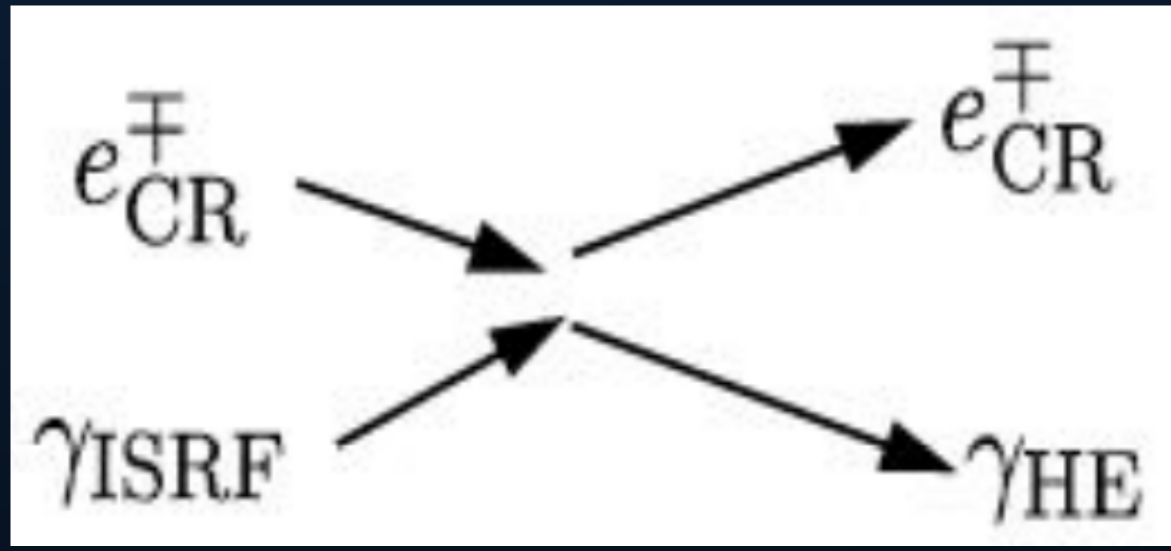
Cosmic-Ray Propagation Models



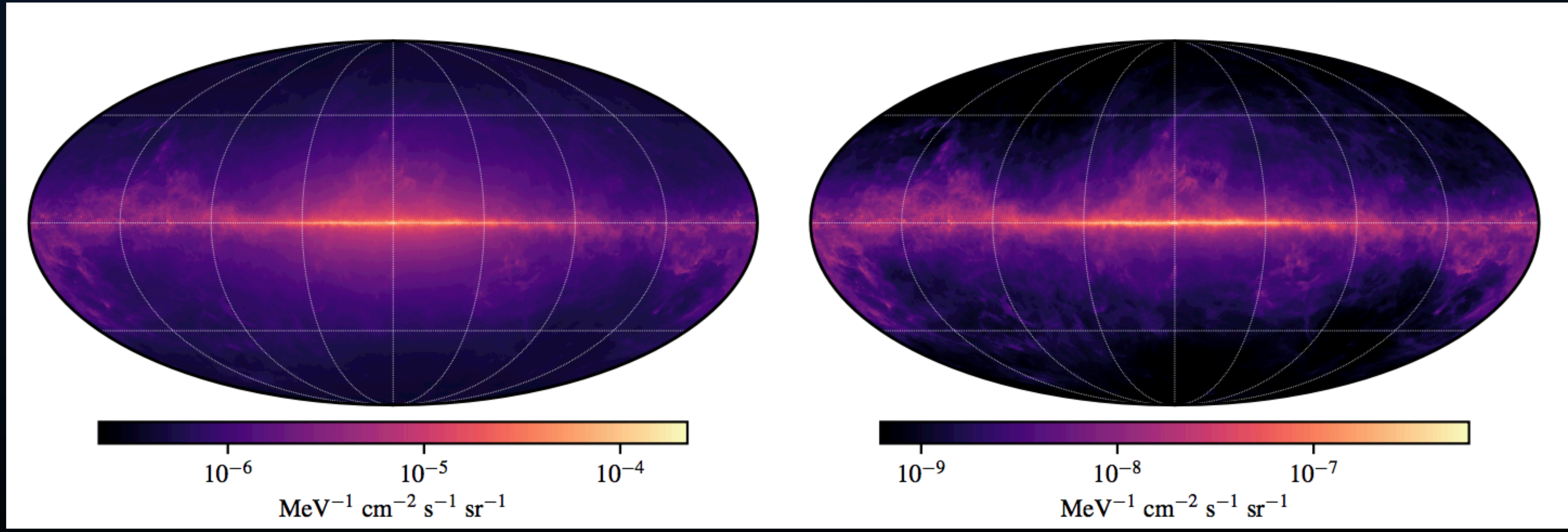
Calculate the diffusion of cosmic-rays from central sources.







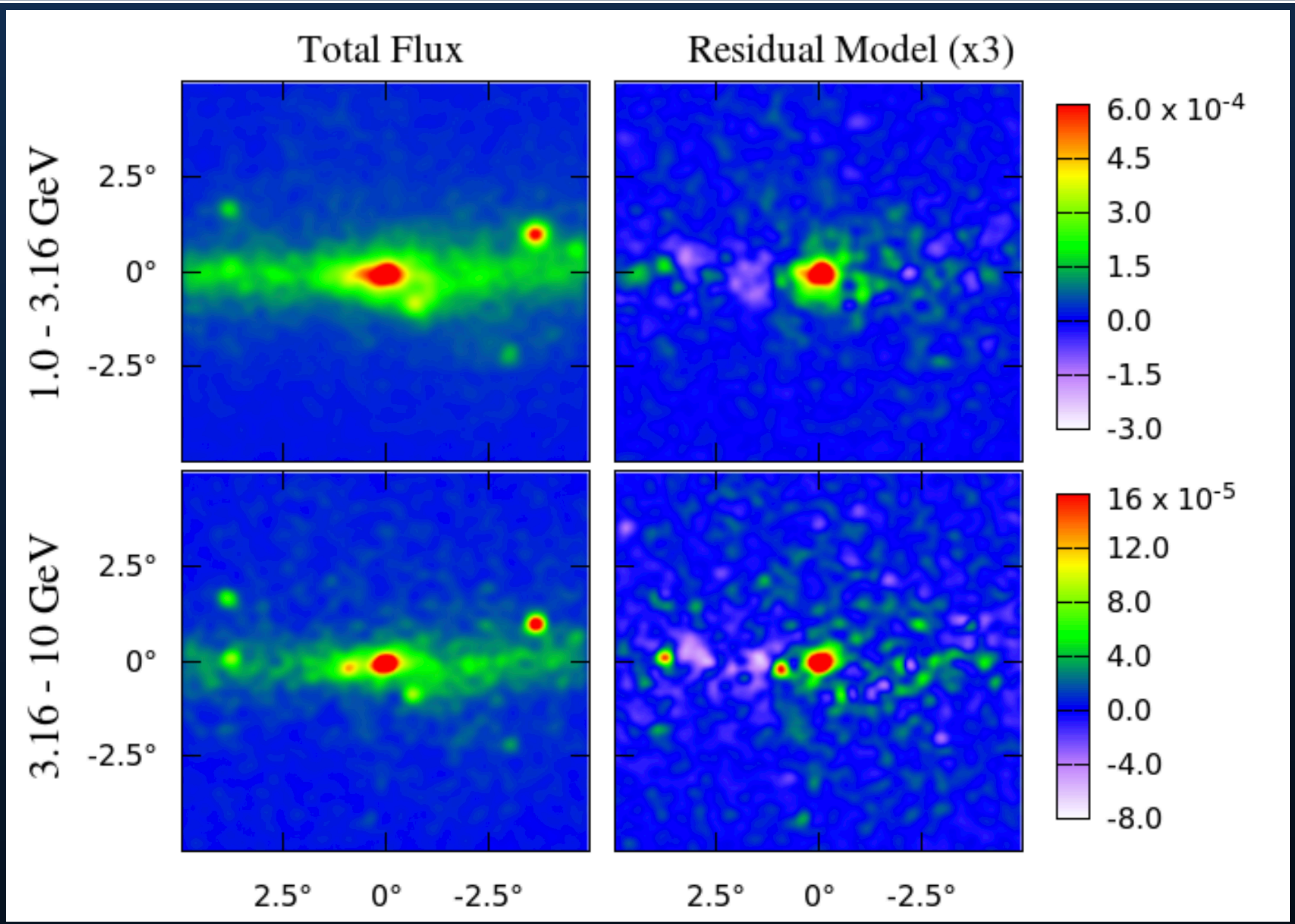
Cosmic rays interact with the interstellar medium and produce gamma-ray emission.



The Galactic Center Excess

The Galactic Center Excess

Daylan et al. (incl. TL) (1402.6703)

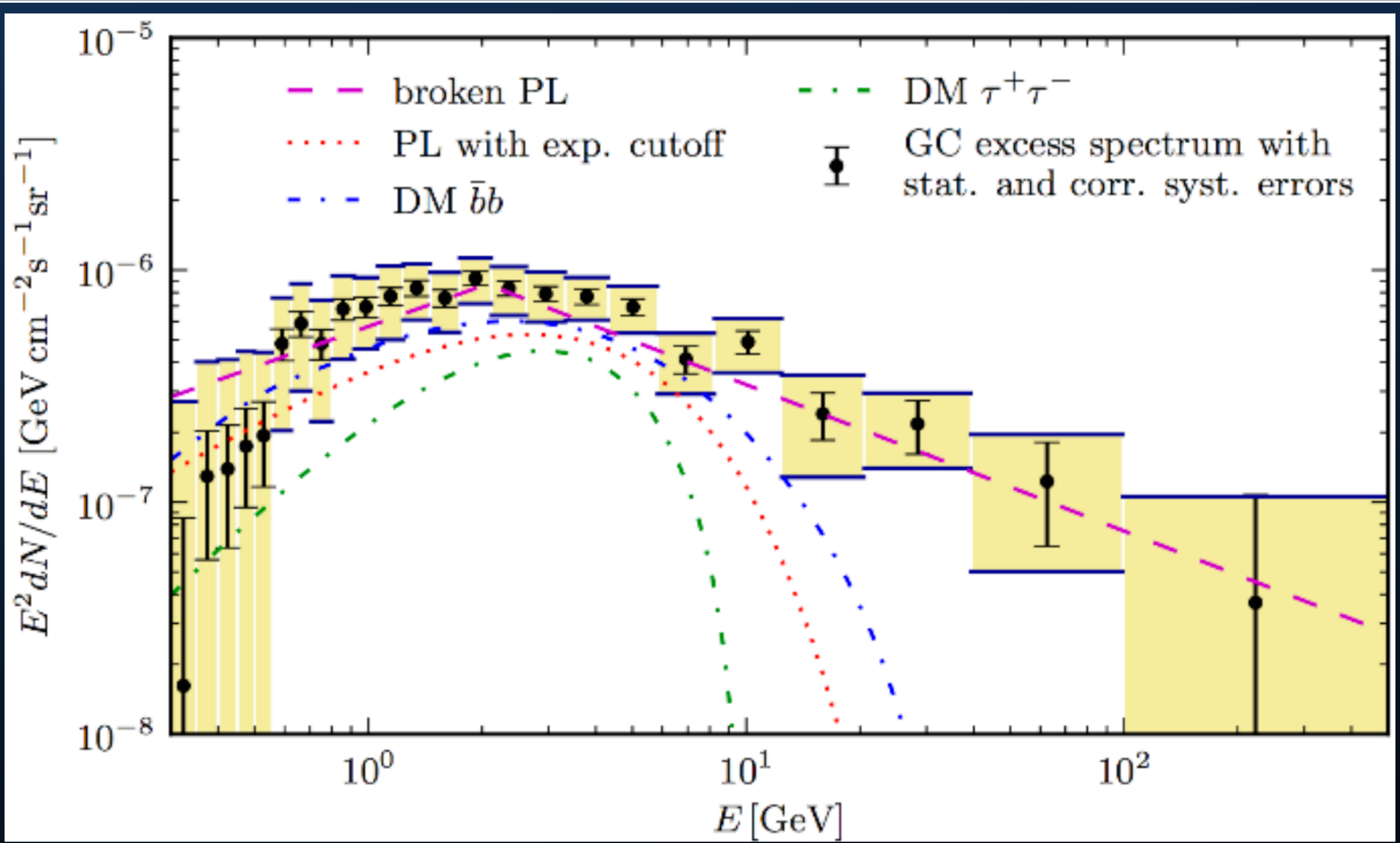


There are four resilient features of the GeV Excess:

1.) High Luminosity of ~2×10^{37} erg s^{-1}

The Galactic Center Excess

Calore et al. (1409.0042)

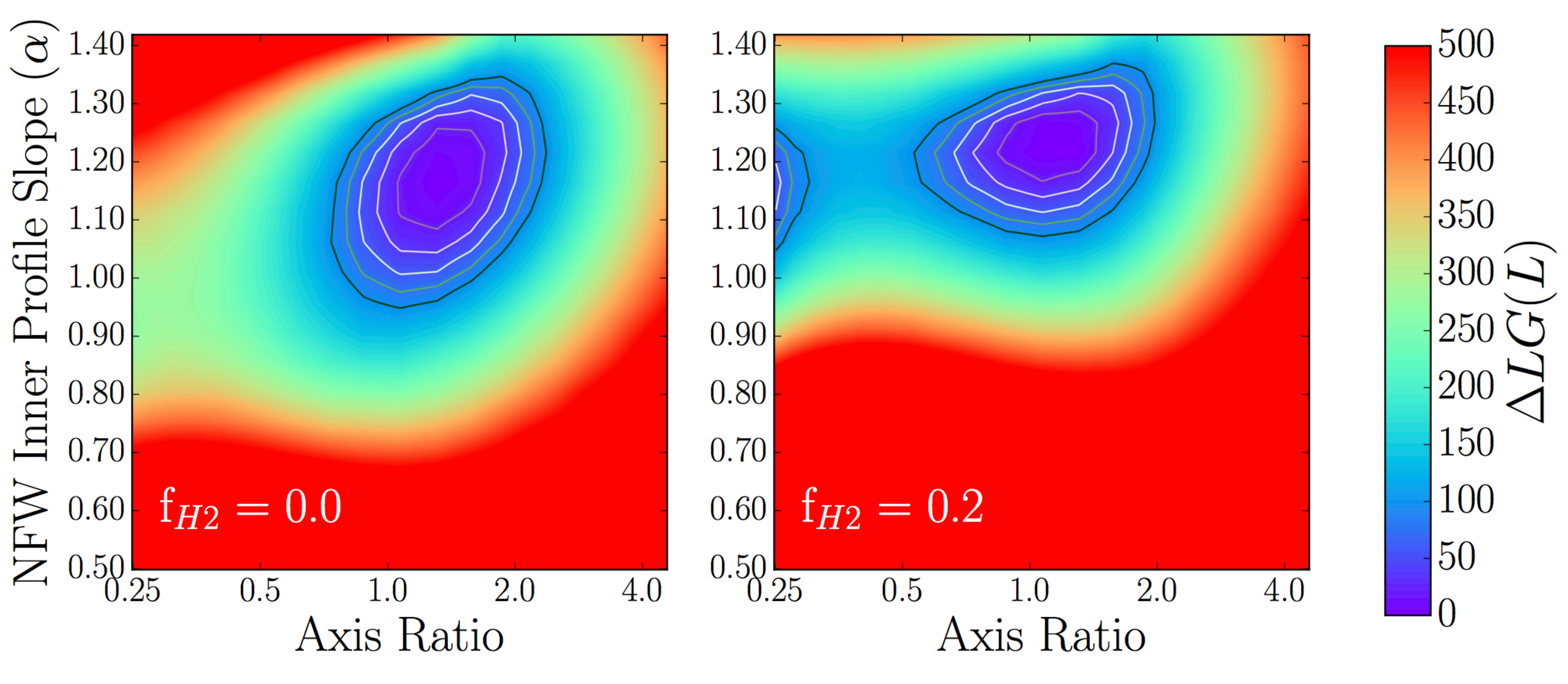


There are four resilient features of the GeV Excess:

2.) Hard Gamma-Ray Spectrum peaking at ~2 GeV

The Galactic Center Excess

Carlson, TL, Profumo (1603.06584)

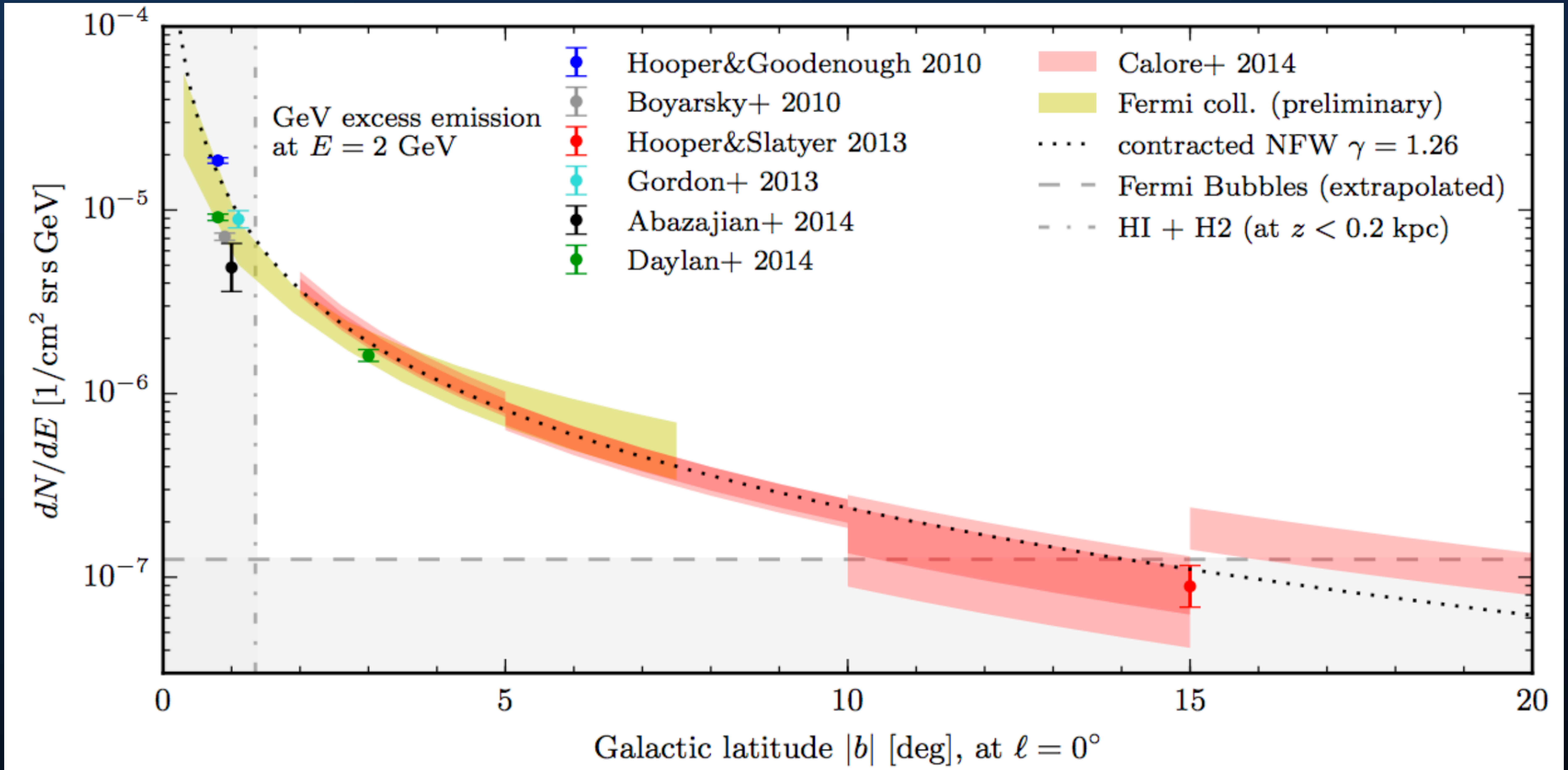


There are four resilient features of the GeV Excess:

3.) Spherically Symmetric Emission Morphology

The Galactic Center Excess

Calore et al. (1411.4647)

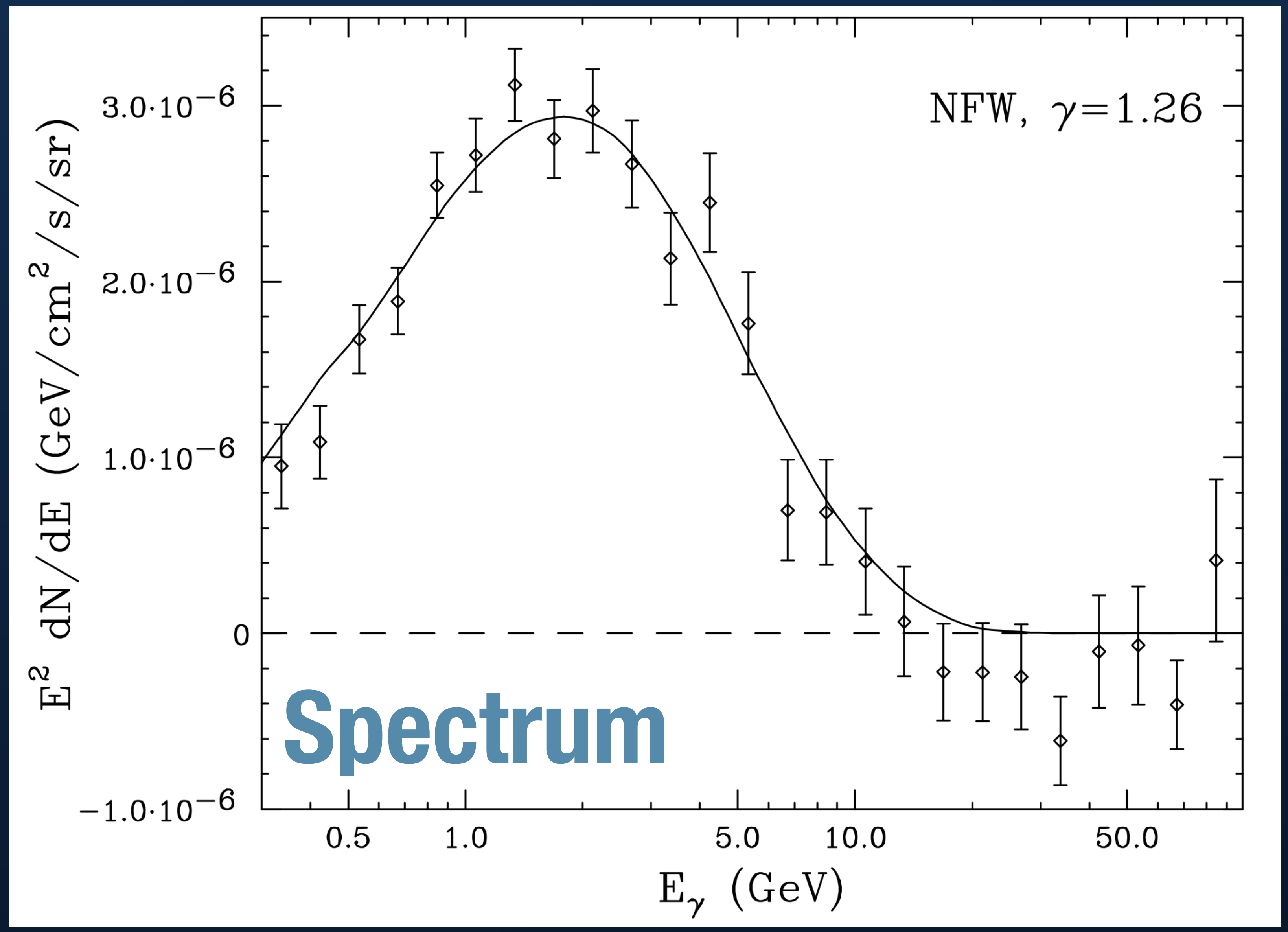


<u>**There are four resilient features of the GeV Excess:**</u>

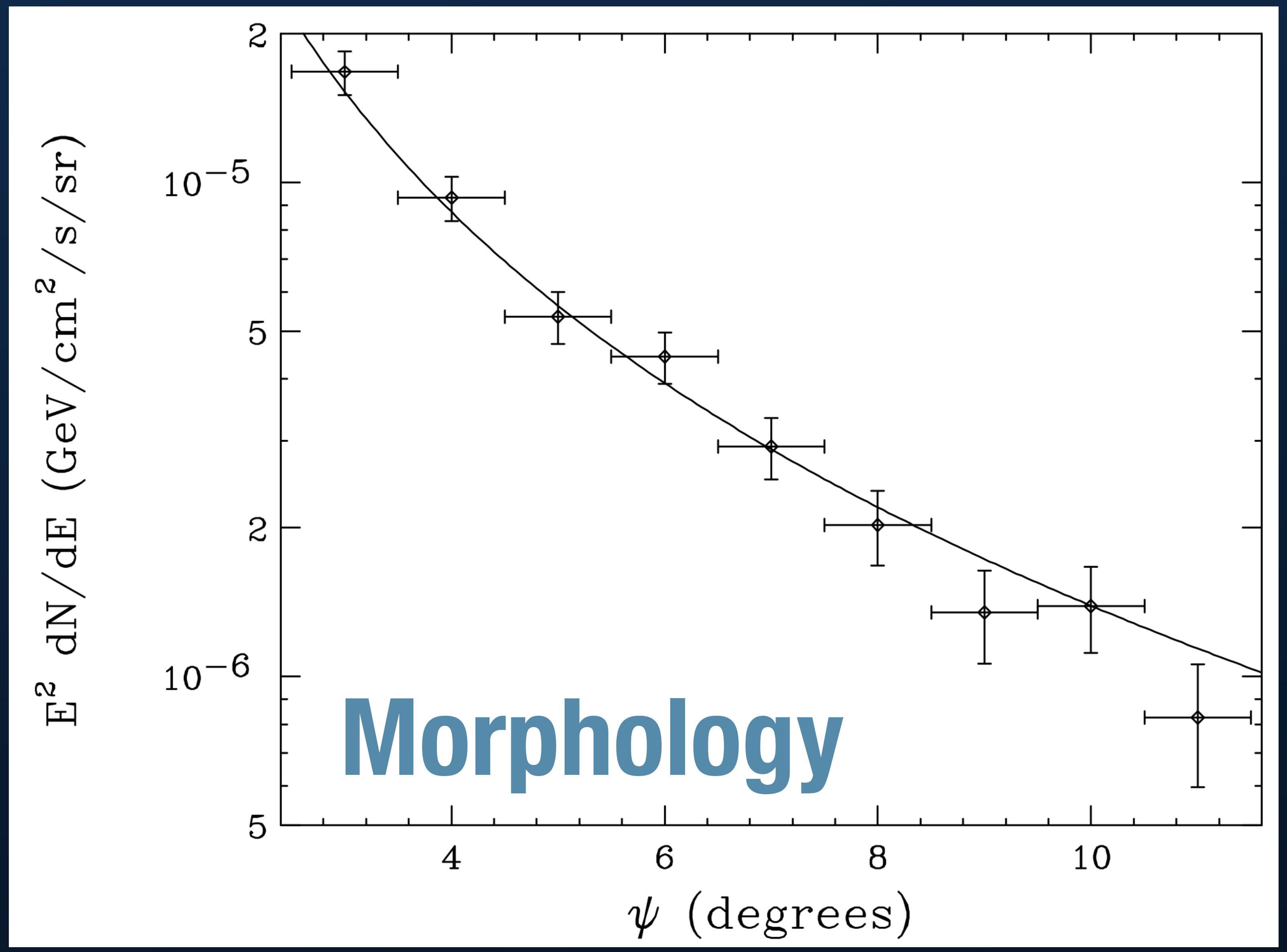
4.) Extension from 0.1° to 10° from the GC.

Dark Matter Interpretations of the Galactic Center Excess

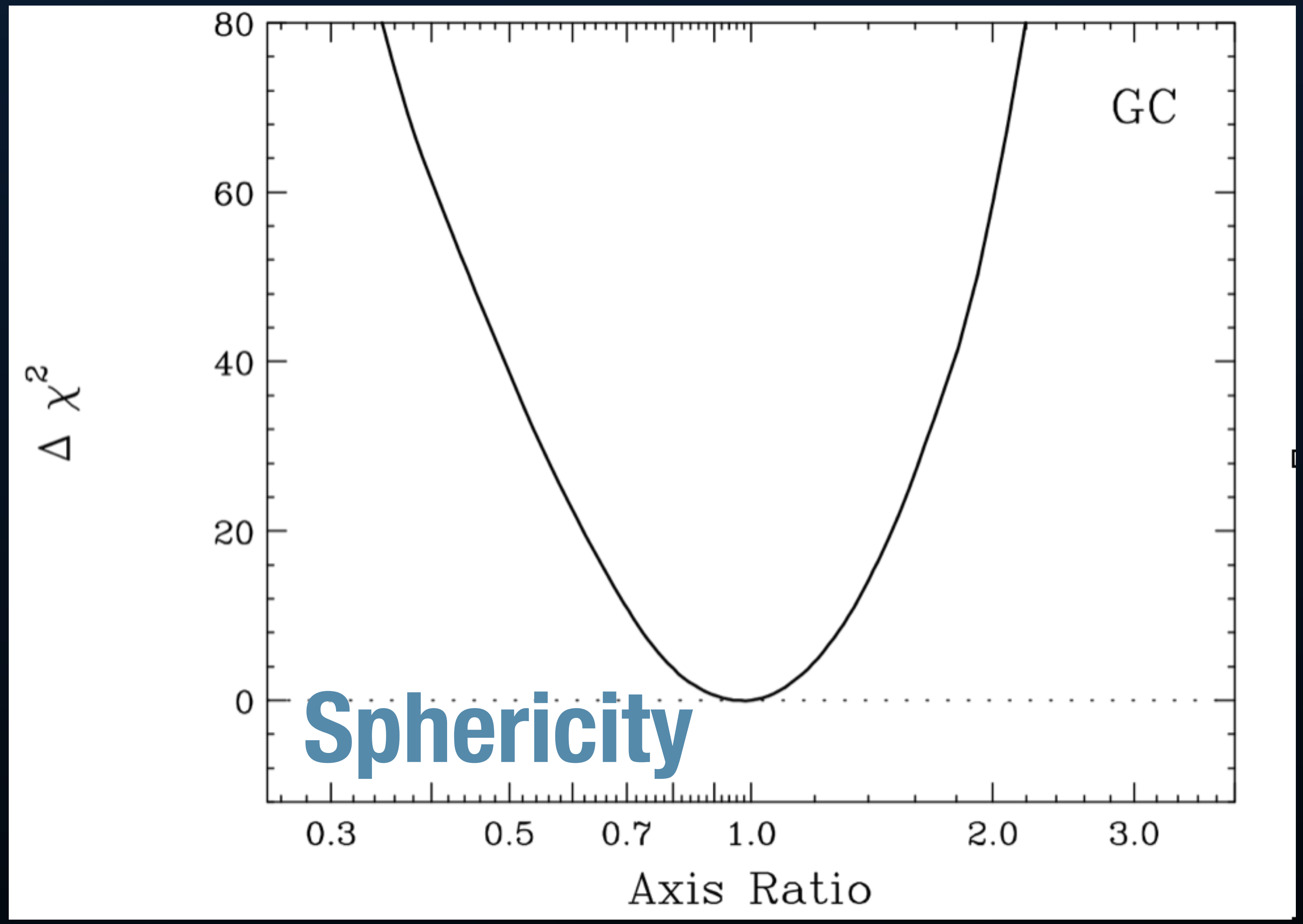
Significant Freedom

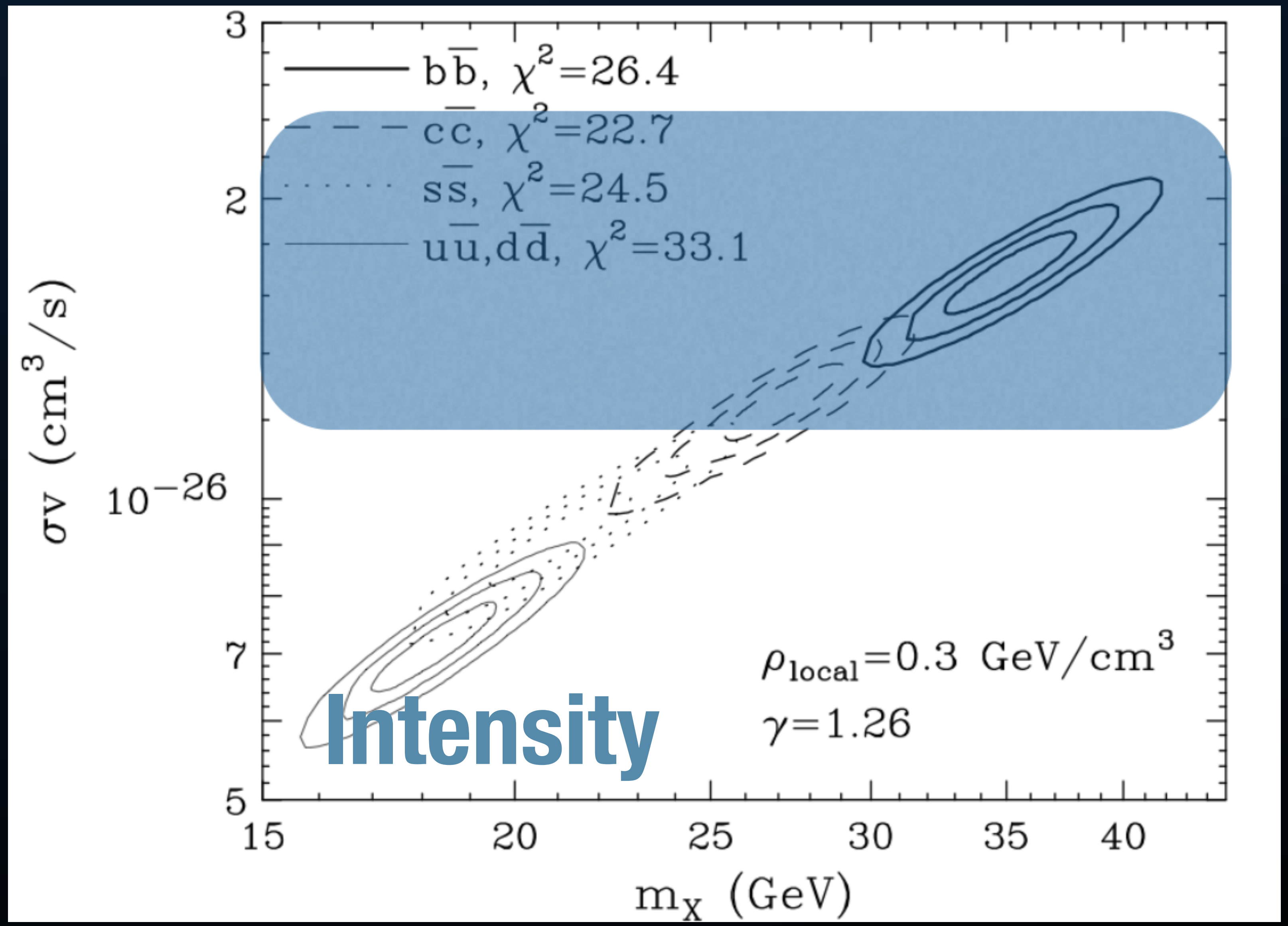


Constrained



Constrained

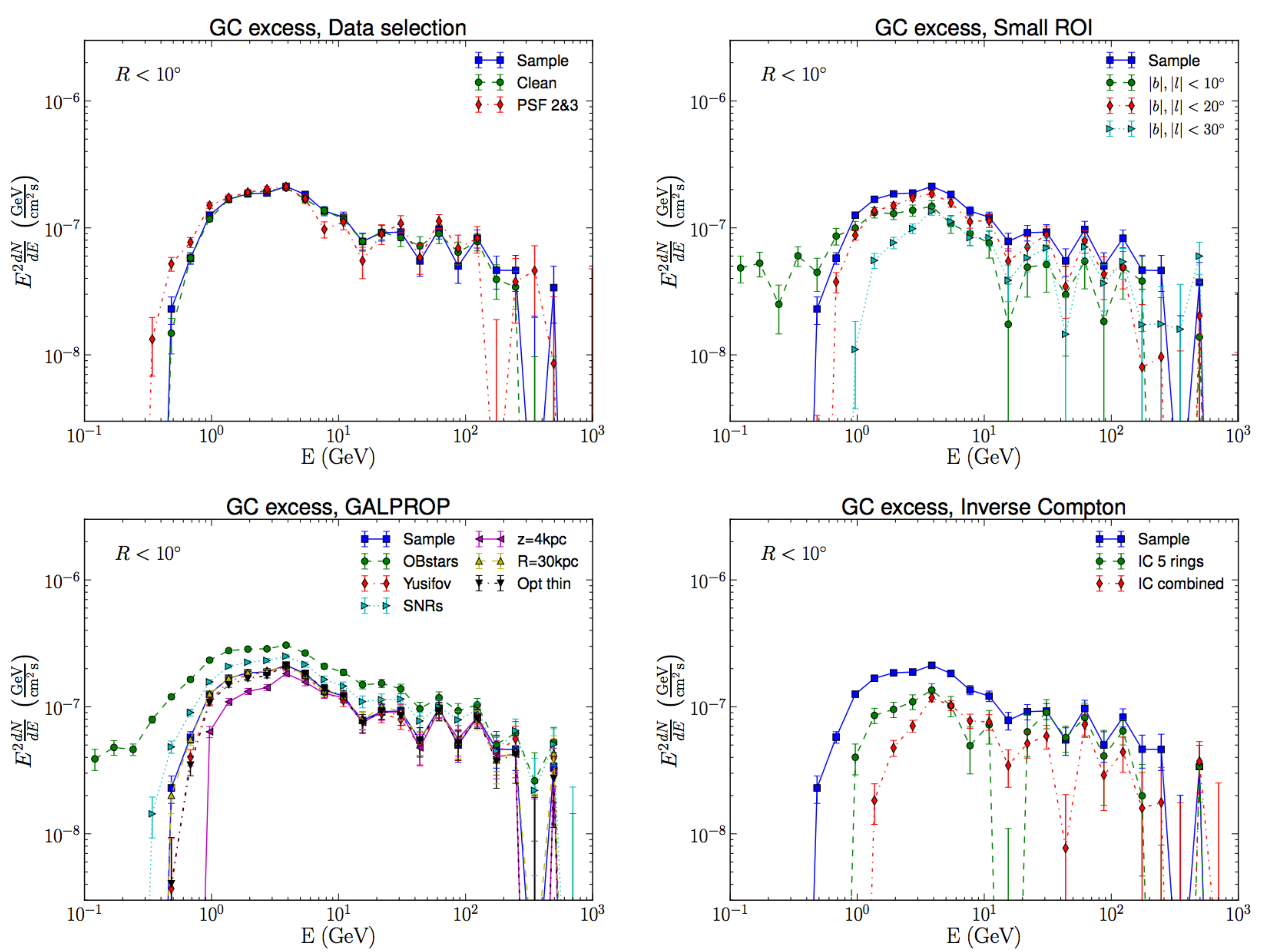




Constrained

Effect of Diffuse Emission Models

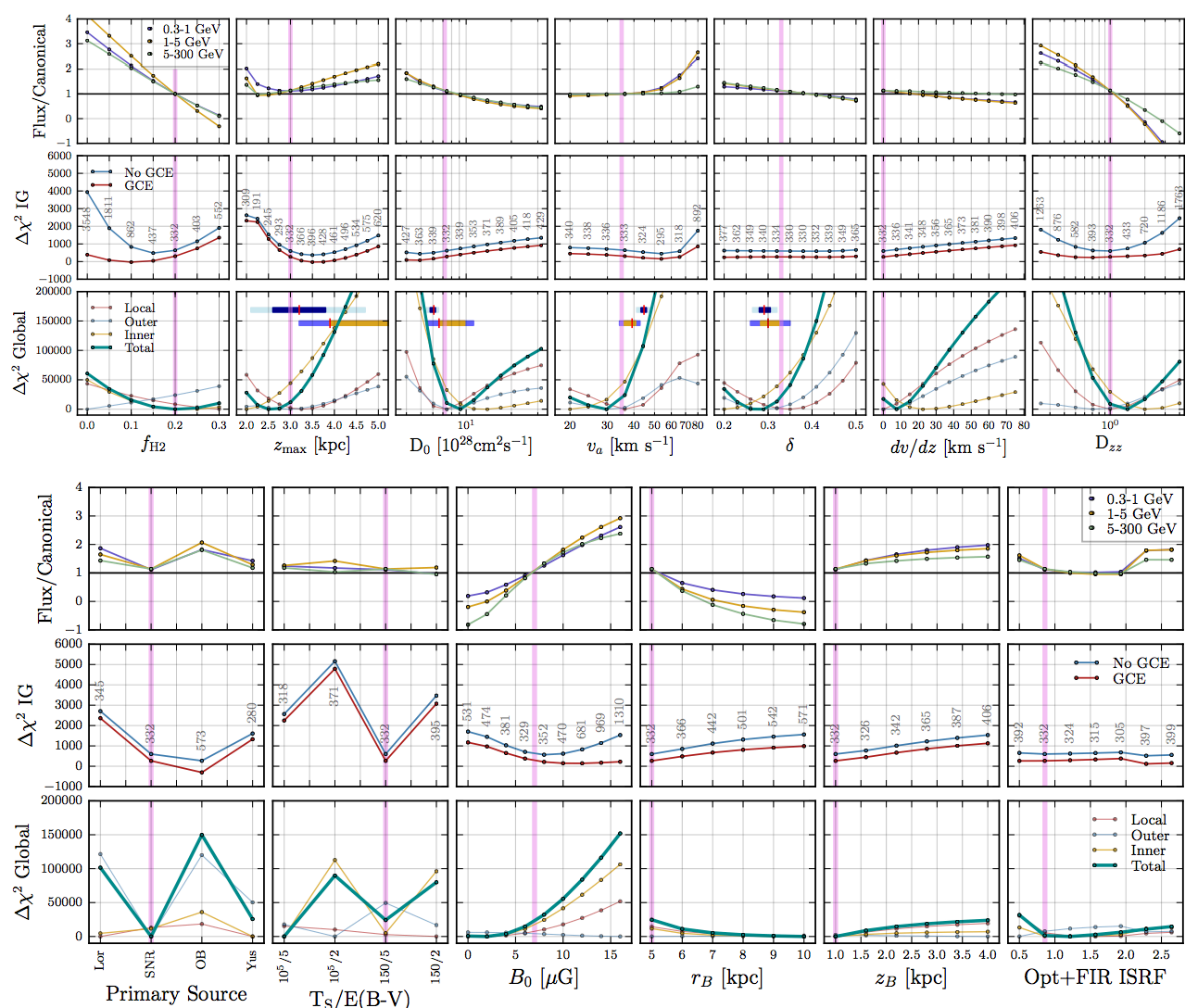
Fermi-LAT Collaboration (1704.03910)



Normalization and some other features can depend sensitively on diffuse emission modeling.

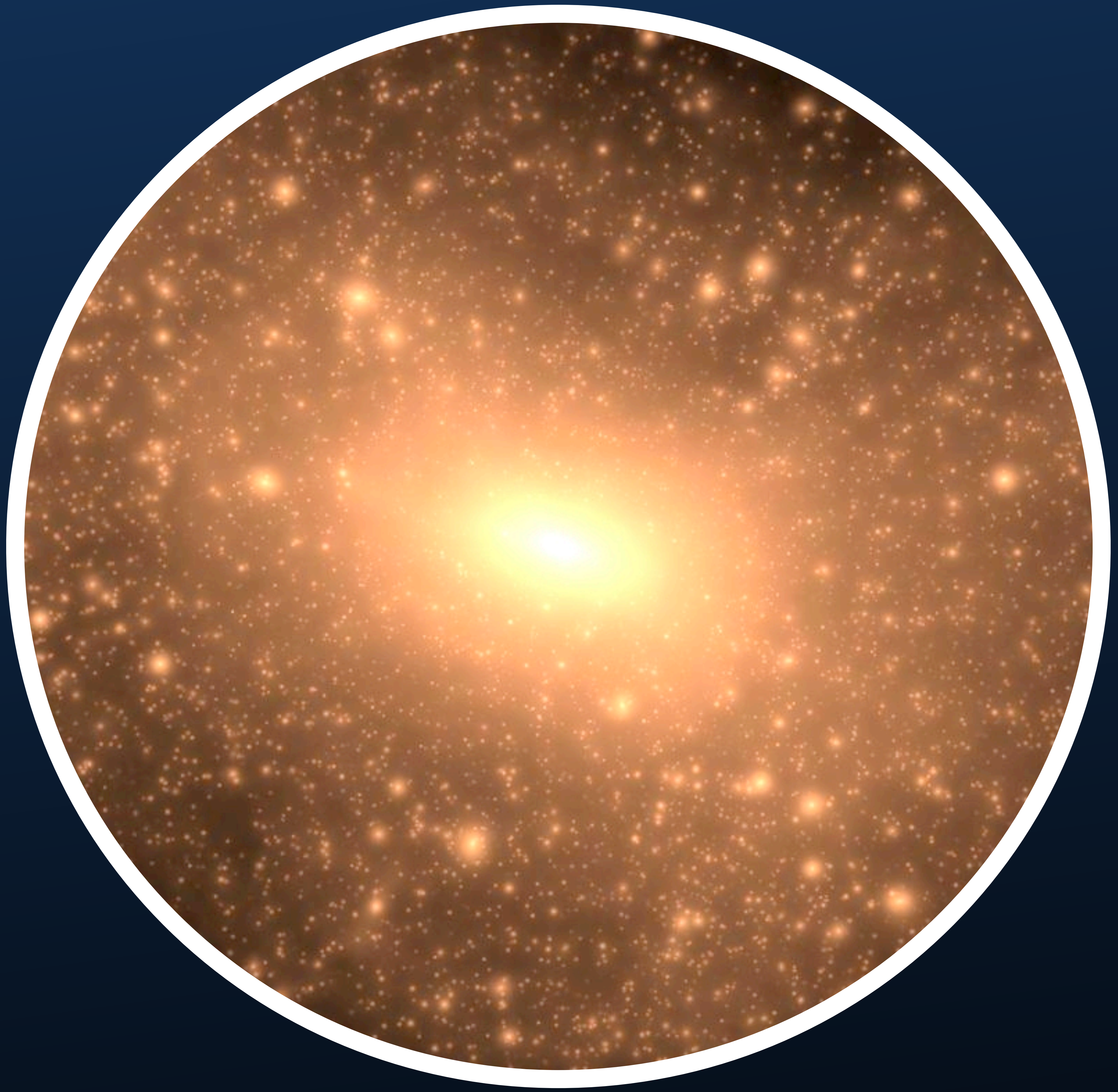
Effect of Diffuse Emission Models

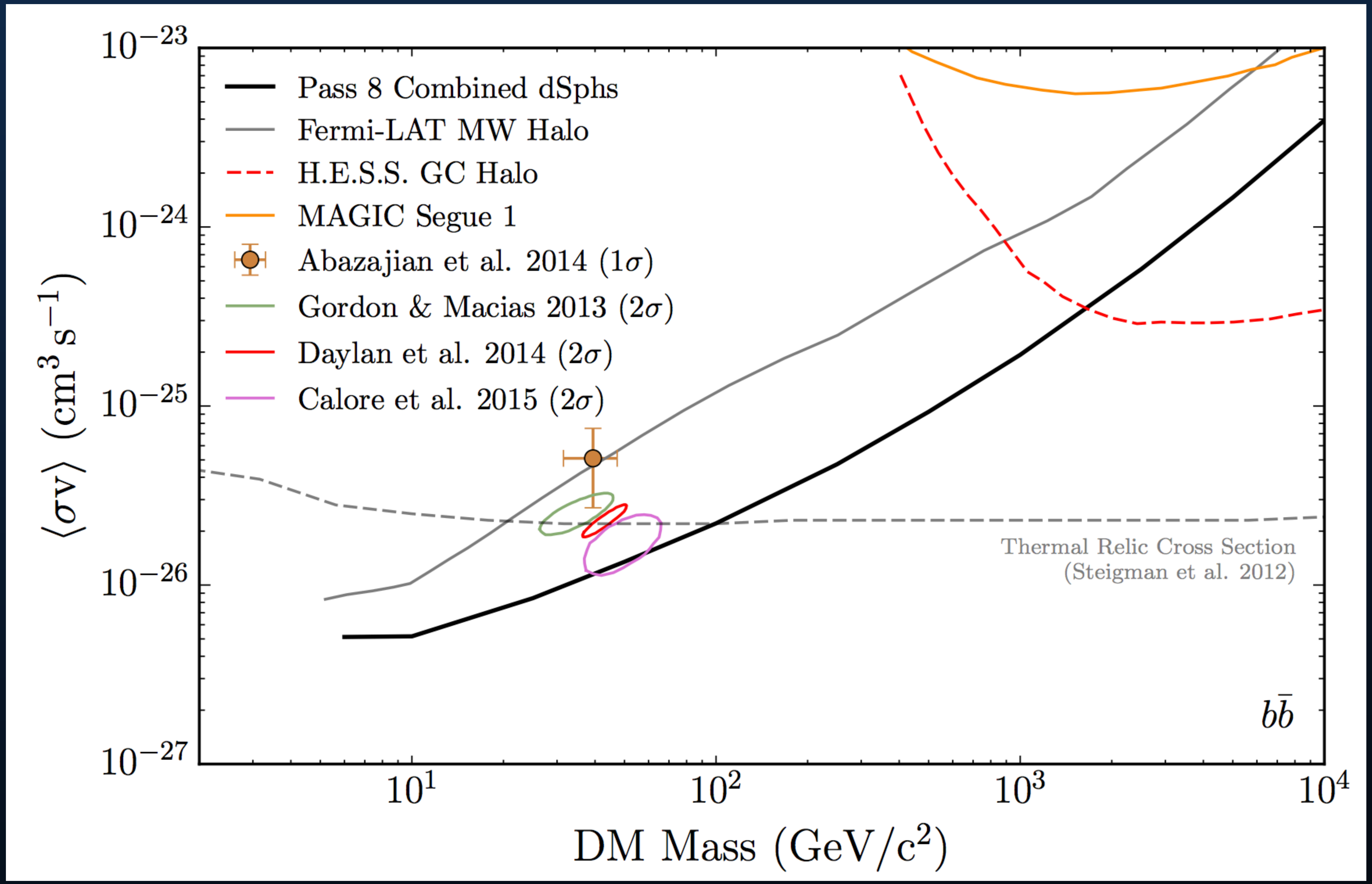
Carlson, TL & Profumo (1603.06584)



Galactic Center is the Brightest Source!

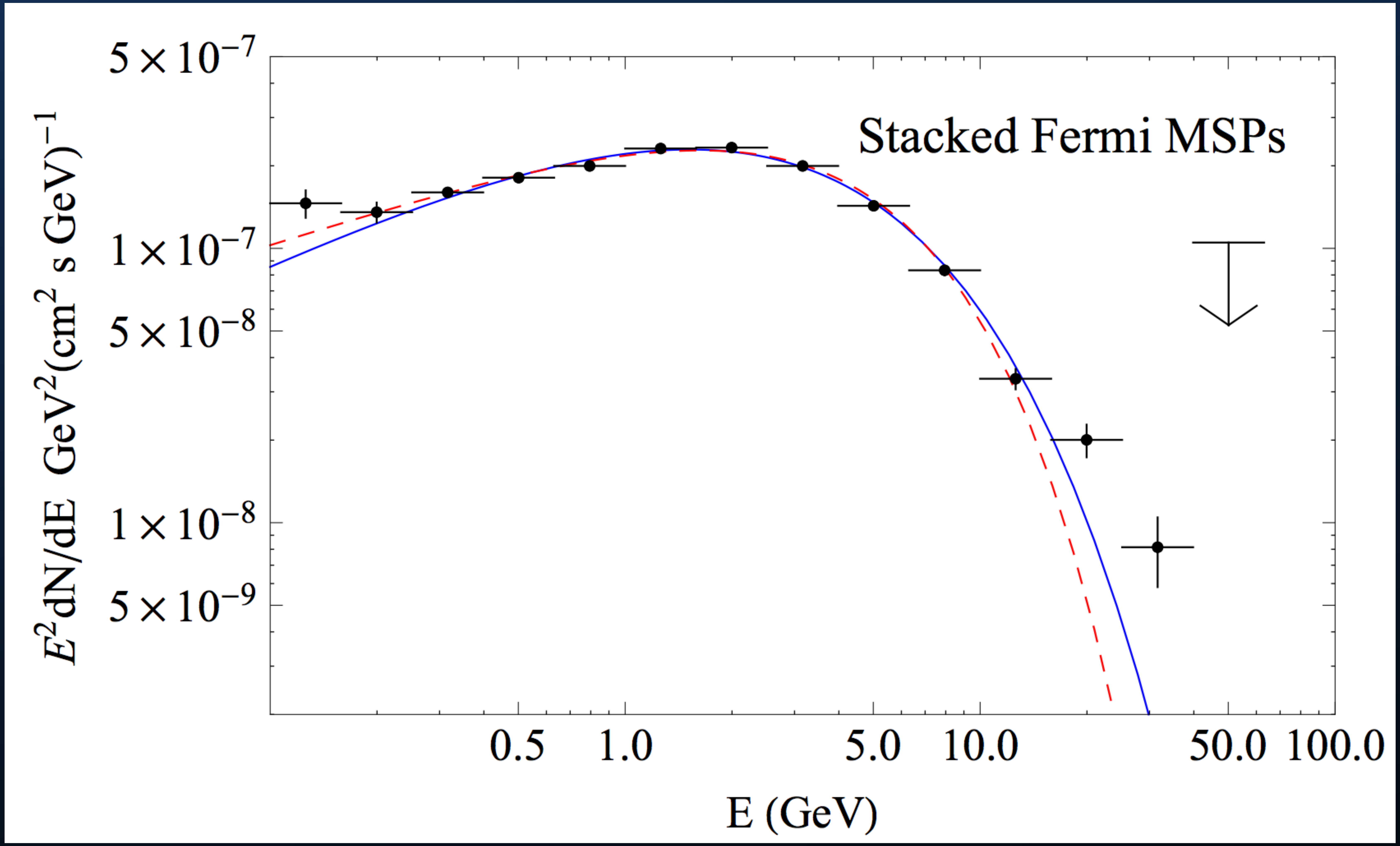
Ackermann et al. (1503.02641)





Bright signal at the galactic center still (reasonably) consistent with null observations in other targets.

Millisecond Pulsars and the Galactic Center Excess



The gamma-ray spectrum of MSPs also looks like the excess.

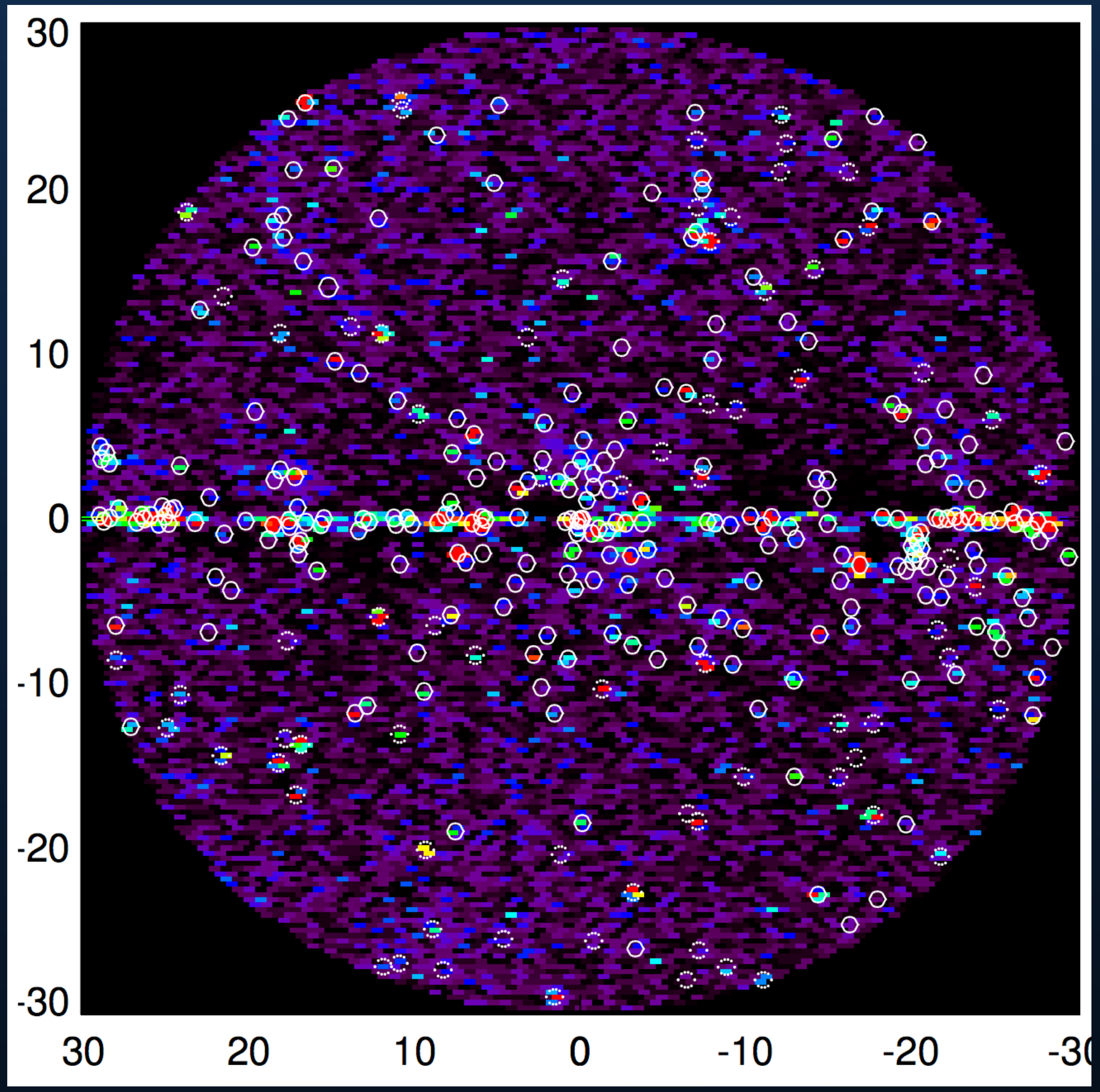
Millisecond Pulsars and the Galactic Center Excess

Bartels et al. (1711.04778)

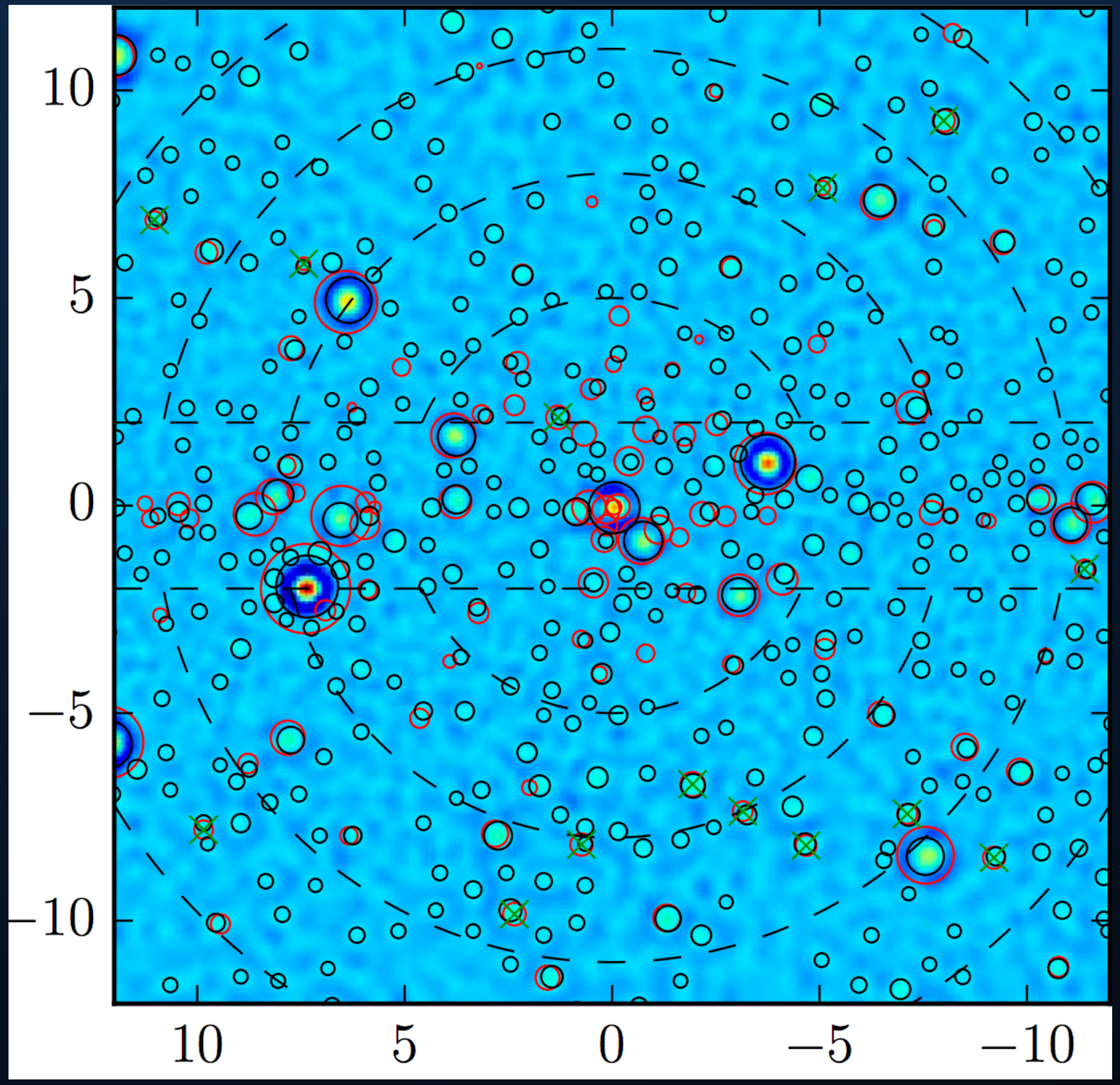
The excess may be better fit by a "bulge" component that traces the nuclear bulge and the morphology of Red Clump Giants.

Evidence for Point Source Contributions to the Excess

Bartels et al (2015; 1506.05104)



Lee et al (2015; 1506.05124)



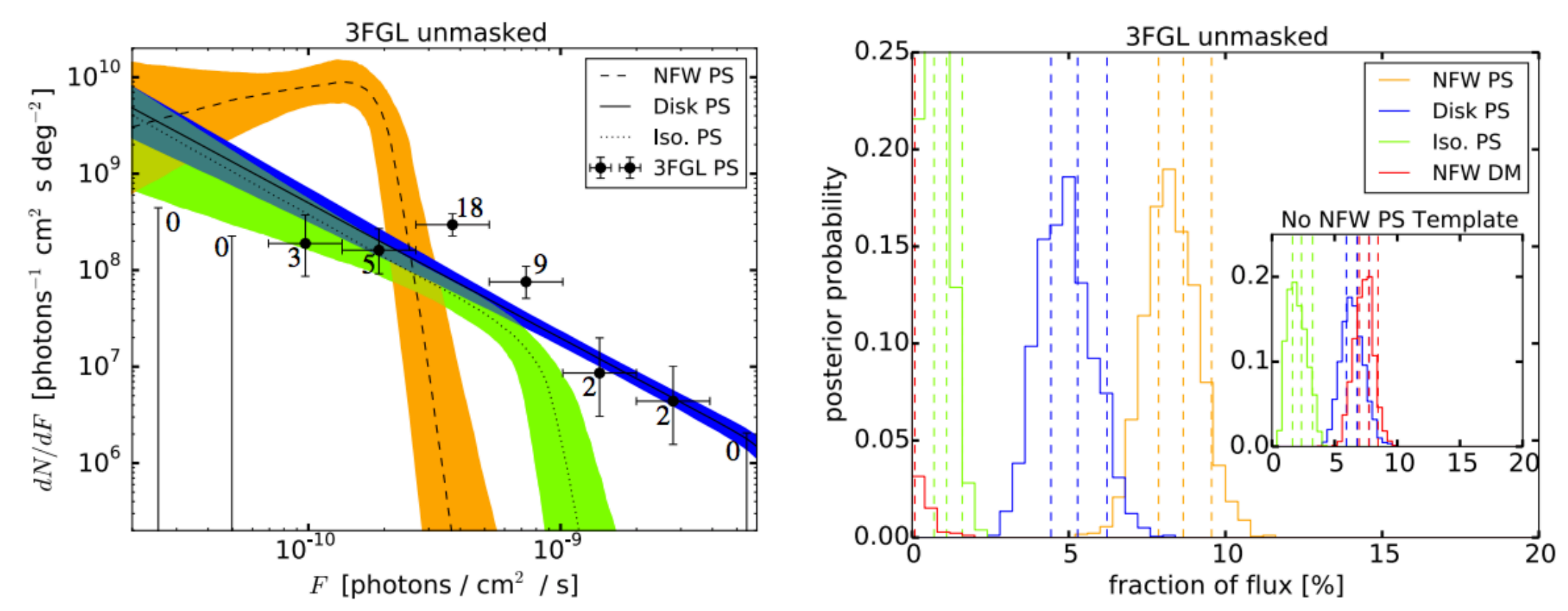
Two Analyses Found fluctuations exceeding Poisson noise in the Fermi data:

Non-Poissonian Template Fitting (Lee et al.)

Wavelet Analyses (Bartels et al.)

Millisecond Pulsar Explanations for the Galactic Center Excess

Lee et al (2015; 1506.05124)

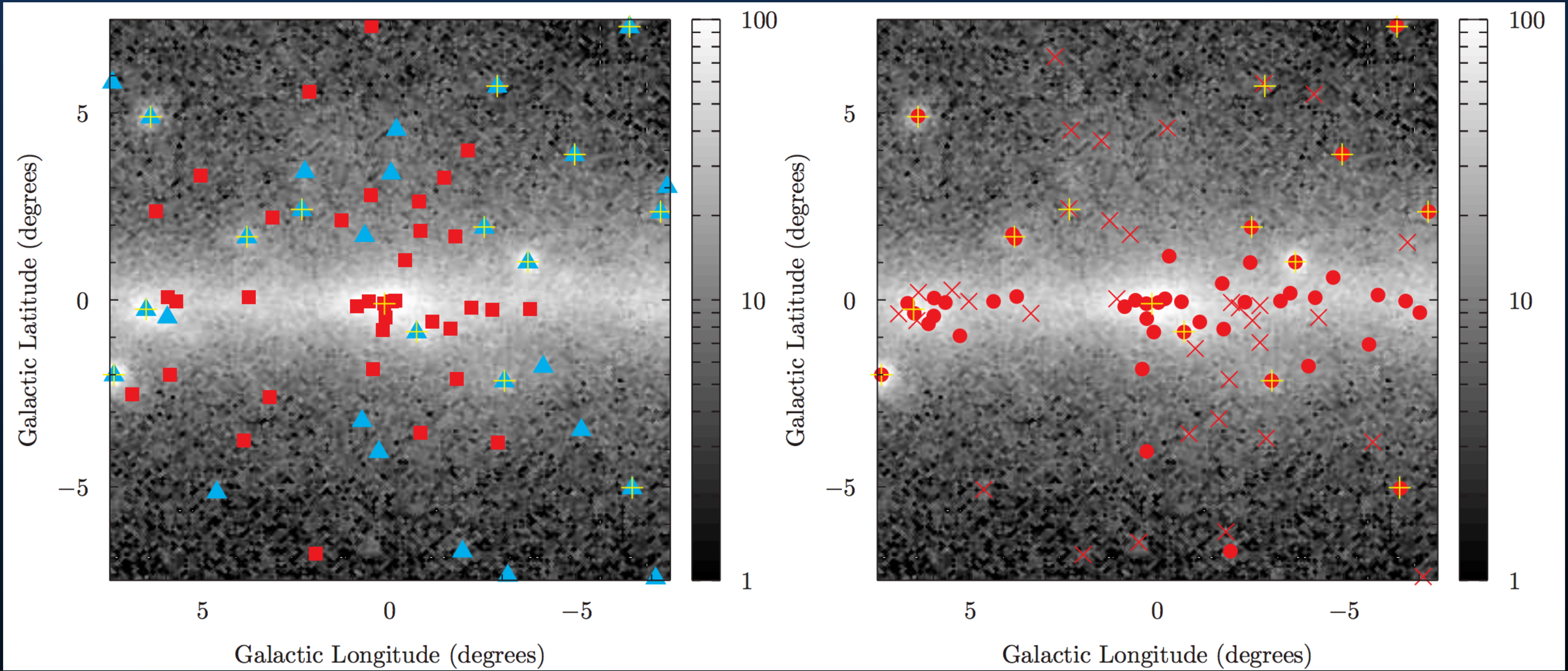


Number of sources peaks just below the Fermi-LAT detection threshold.

Sub-threshold point sources absorb the majority of the Galactic Center flux.

Are Point Source Models Reliable?

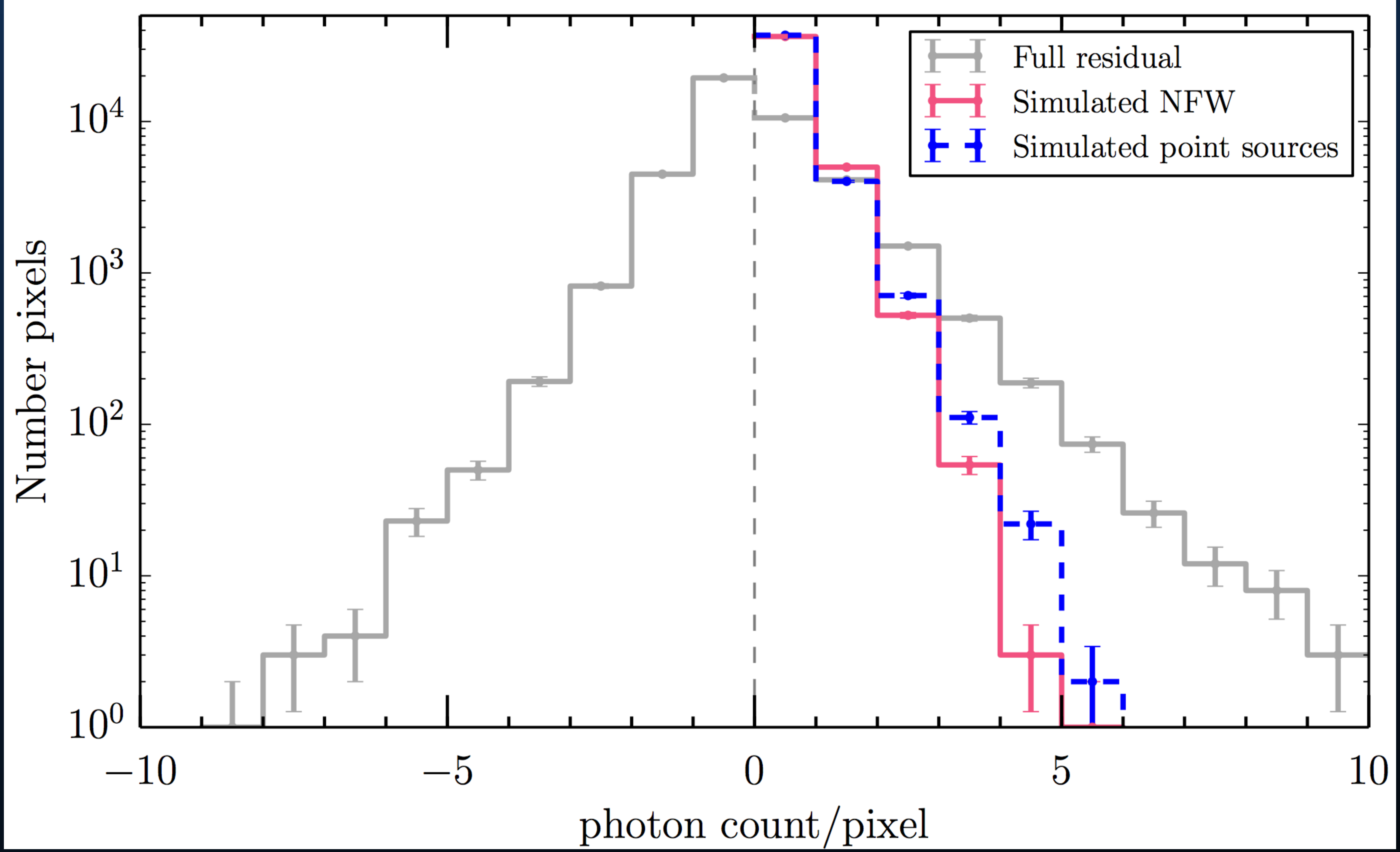
Ajello et al. (1511.02938)



Point Source determinations depend heavily on diffuse modeling.

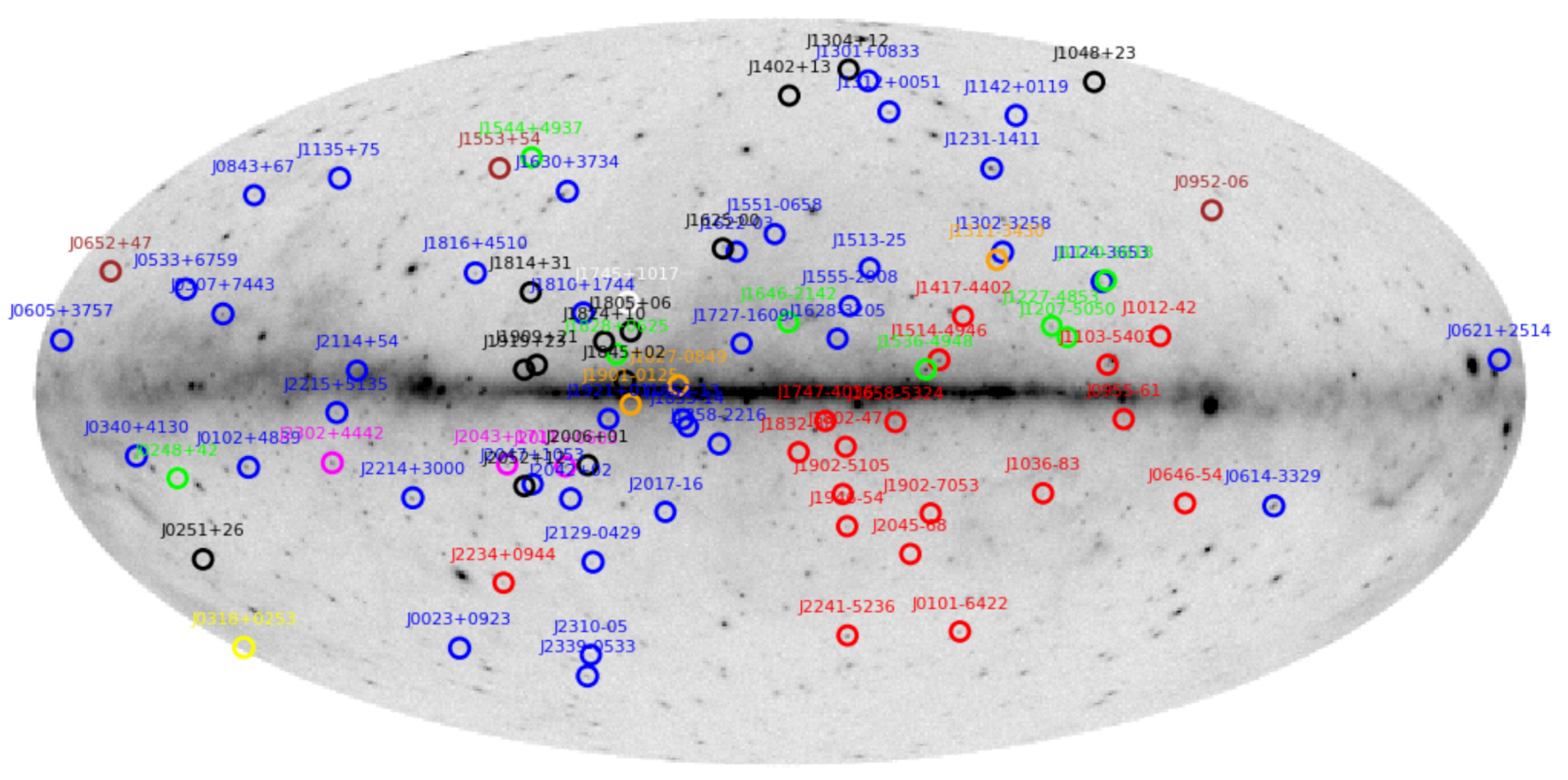
Are Point Source Models Reliable?

Horiuchi et al. (1604.01402)



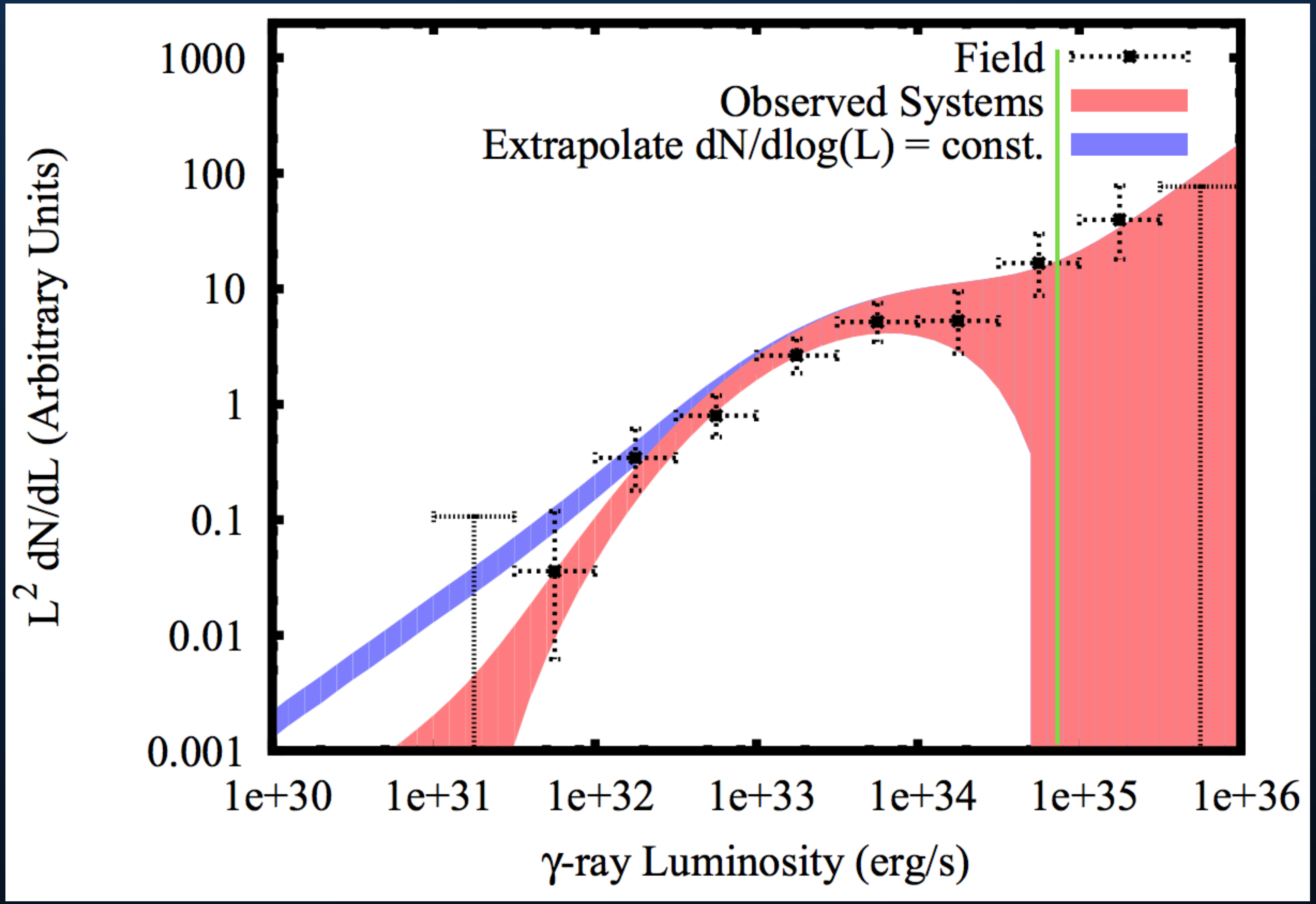
Point Source determinations depend heavily on diffuse modeling.

Why Haven't We Found the Pulsars?

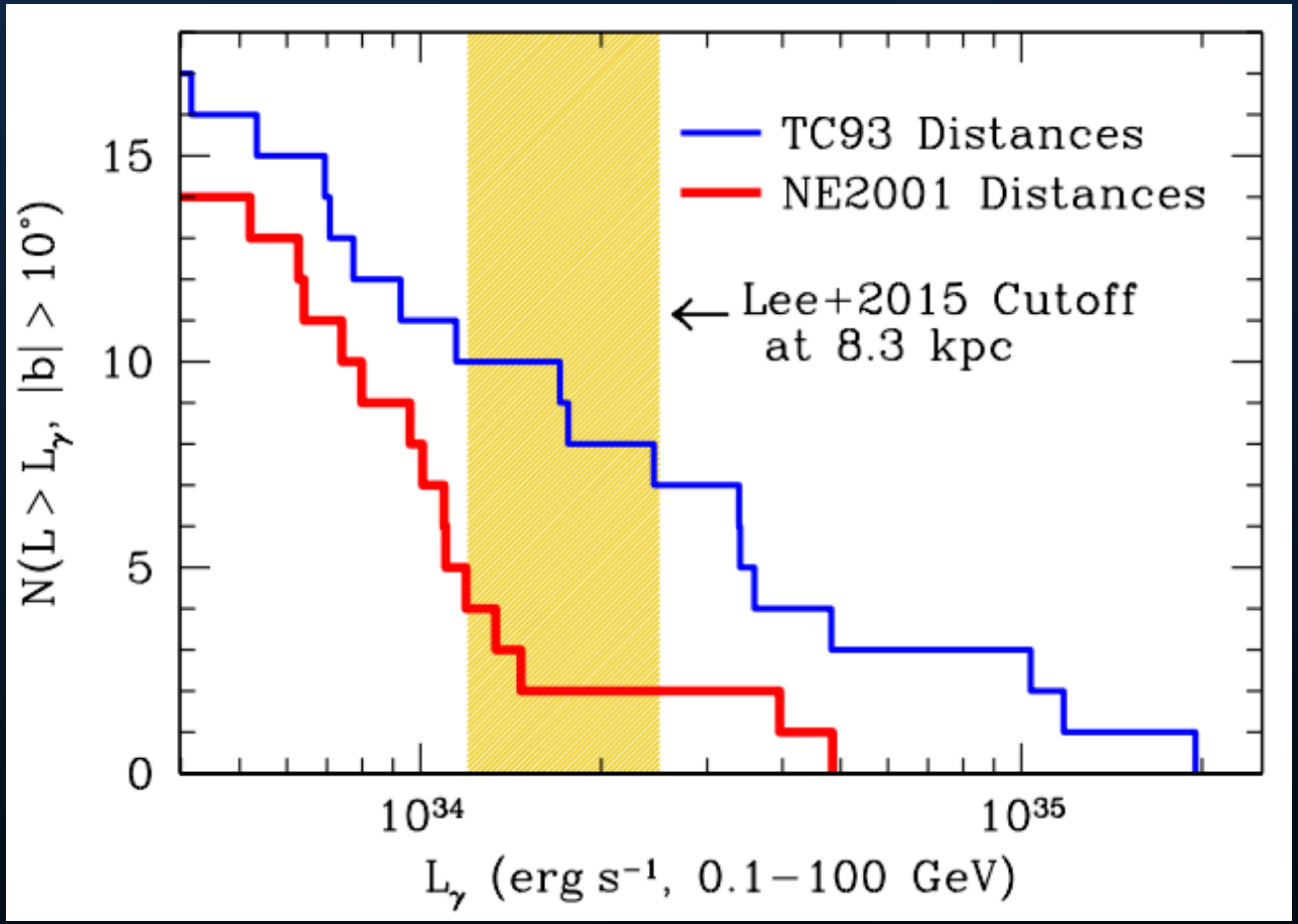


Why Haven't We Found the Pulsars?

Hooper Cholis, TL (1407.5583)



Brandt & Kocsis (1507.05616)



Hard Luminosity Spectrum:

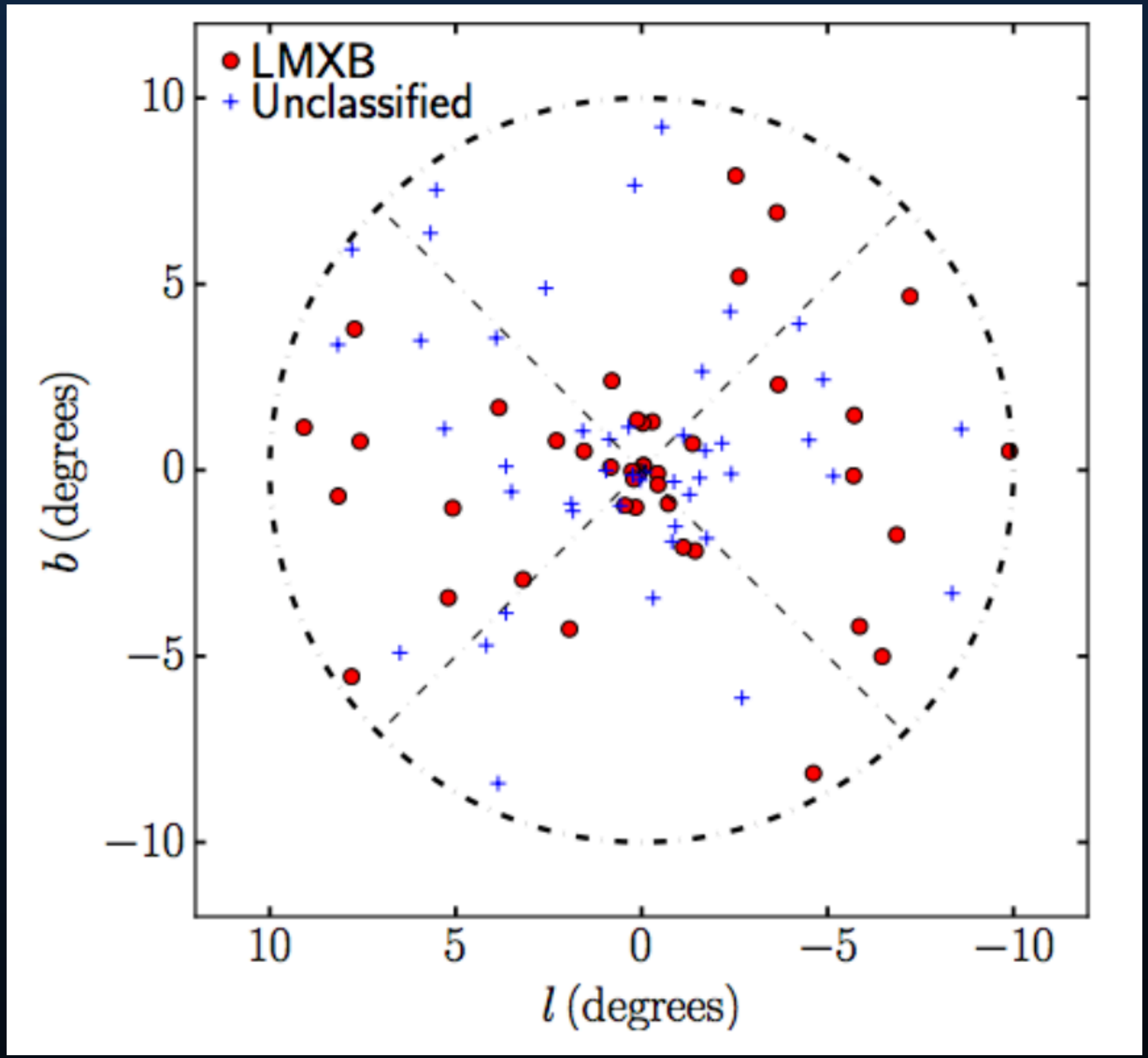
Should already see ~50 pulsars

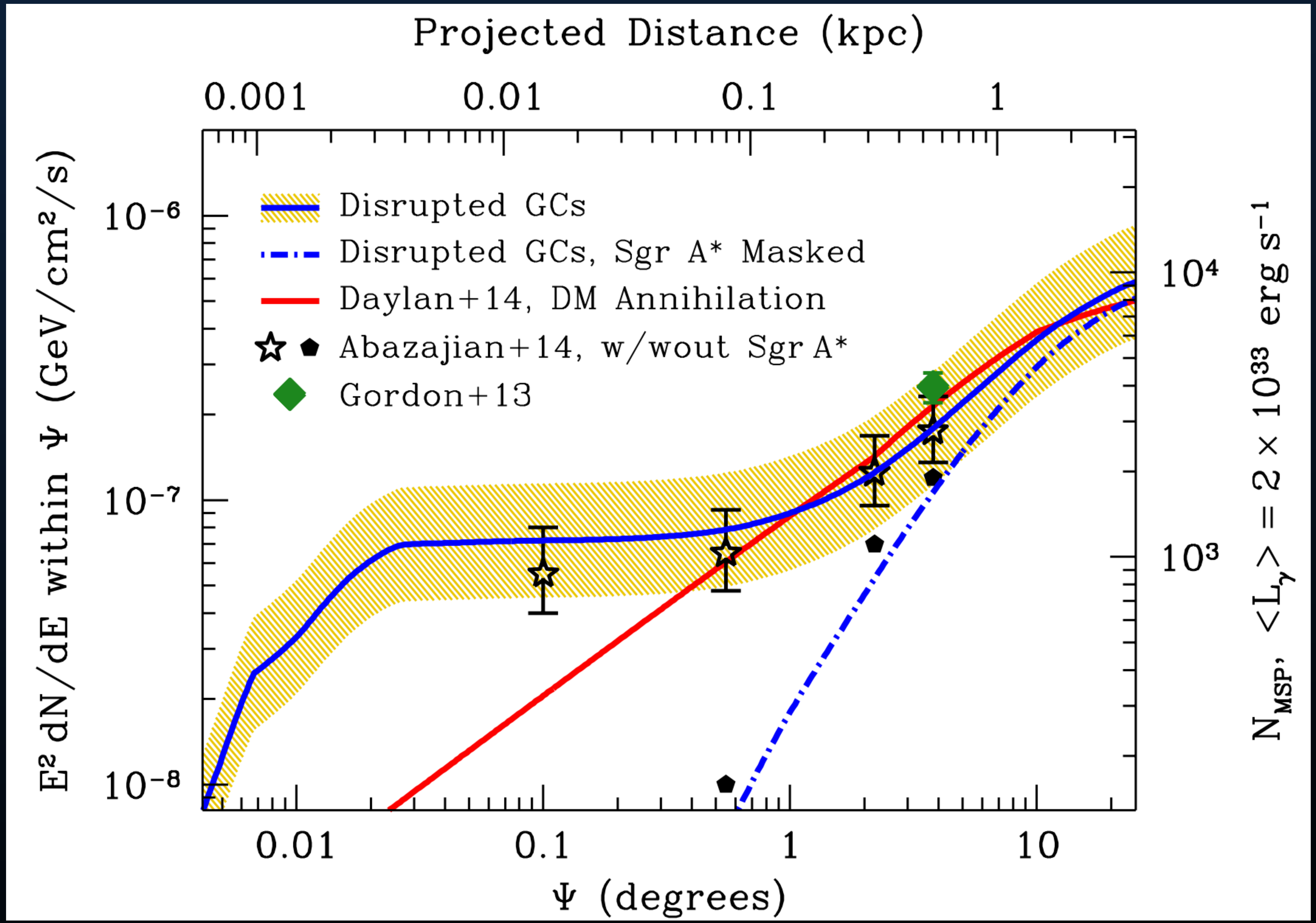
Soft Luminosity Spectrum

Should not see many pulsars

Why Haven't We Found the LMXBs?

$$L_\gamma^{\rm IG} = L_\gamma^{\rm clusters} \times \left(\frac{N_{\rm LMXB}^{\rm IG}}{N_{\rm LMXB}} \right)$$

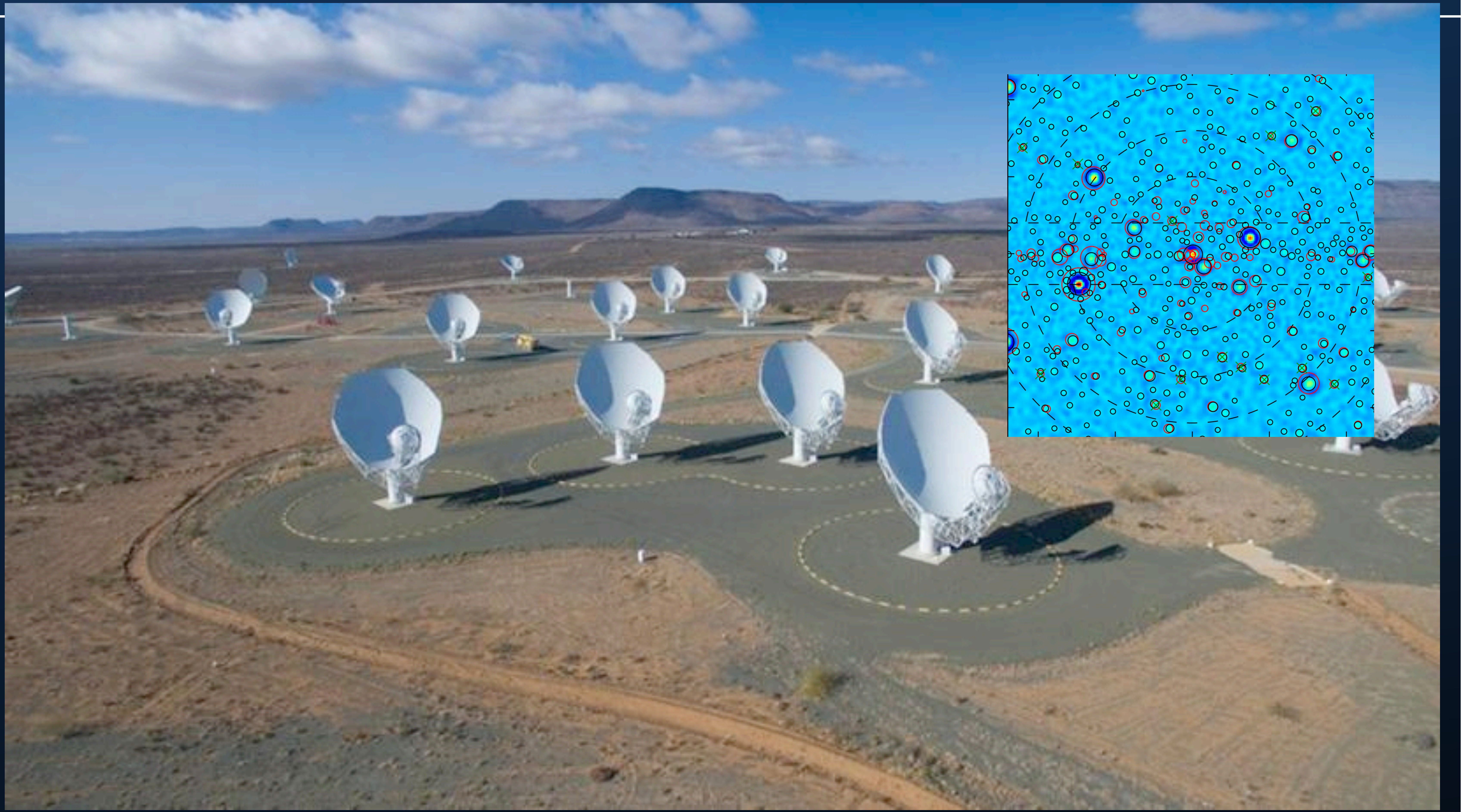




Haggard et al. (incl TL, 1701.02726)
Hooper & TL (1606.09250)

Brandt & Kocsis (1507.05616)

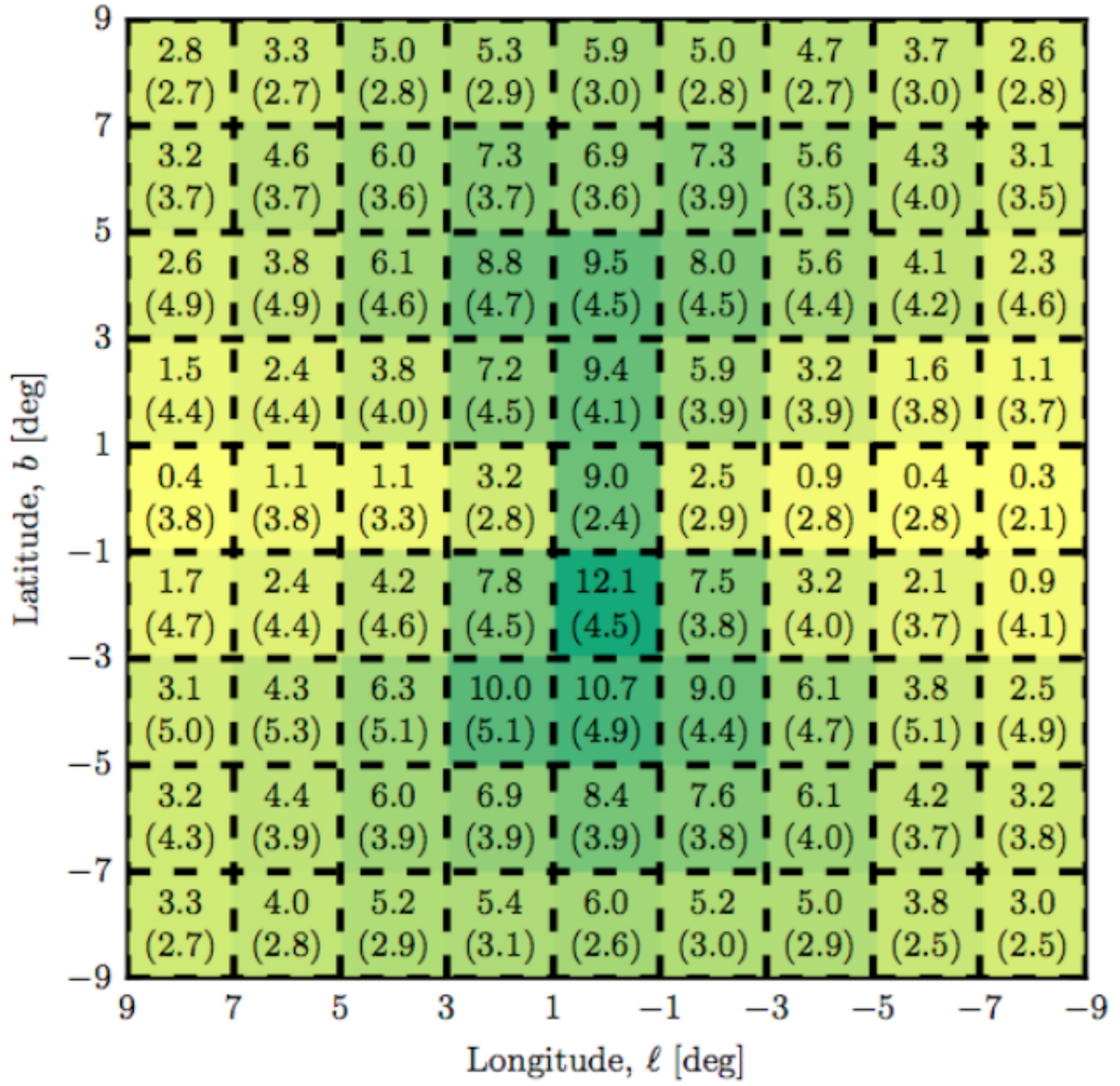
The Path Forward

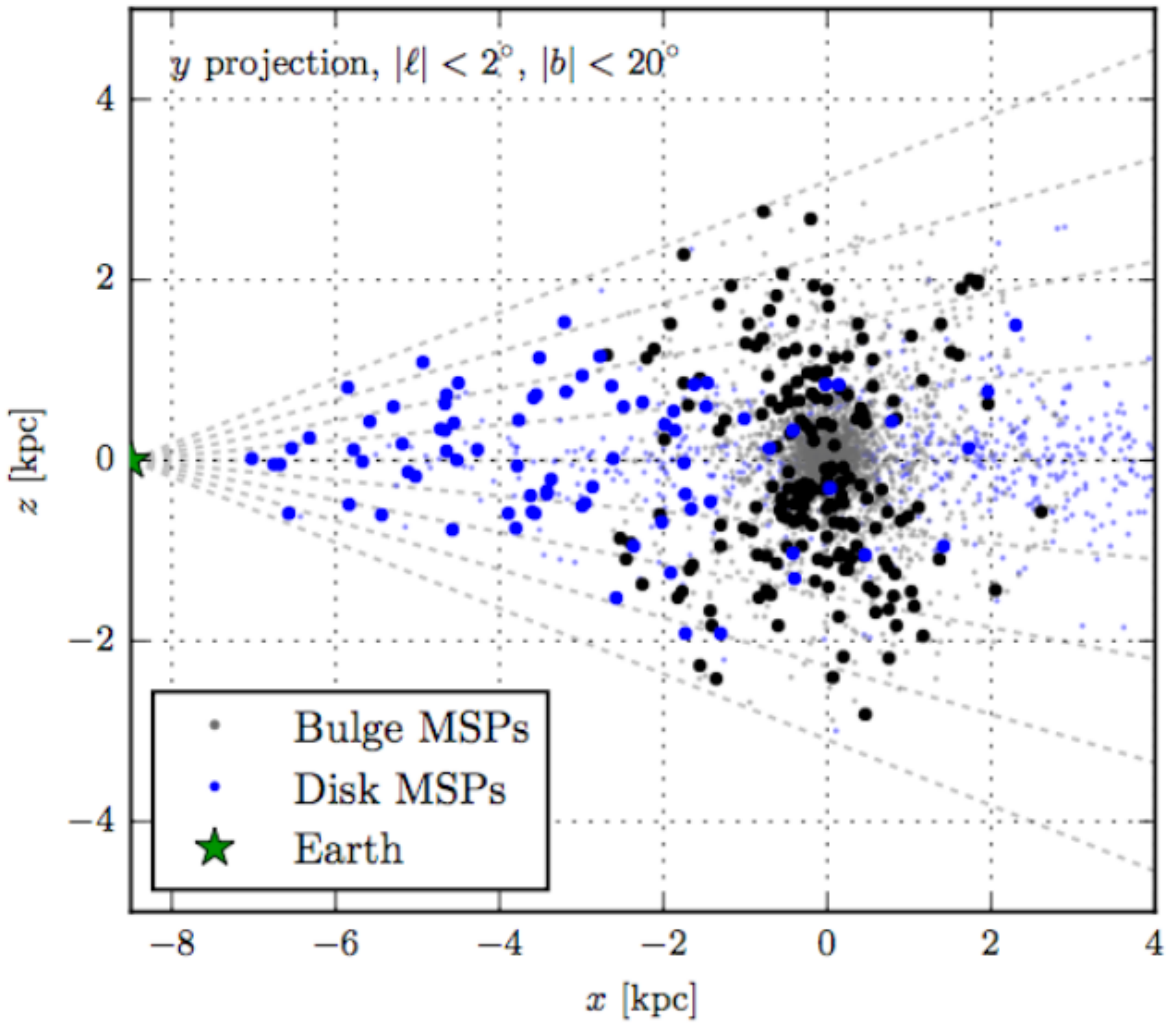


Radio surveys must find MSPs.

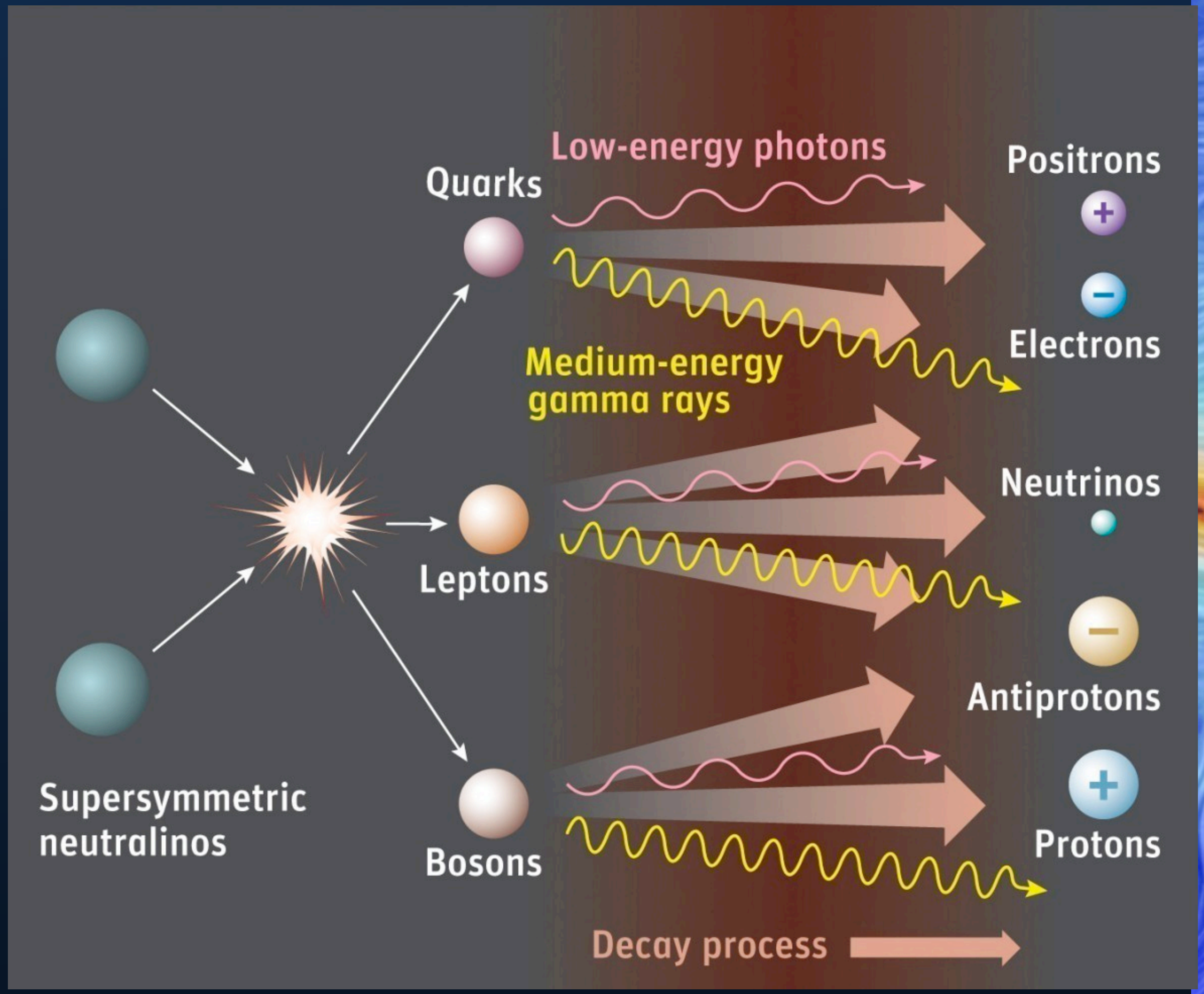
Can correlate observed MSPs with gamma-ray data.

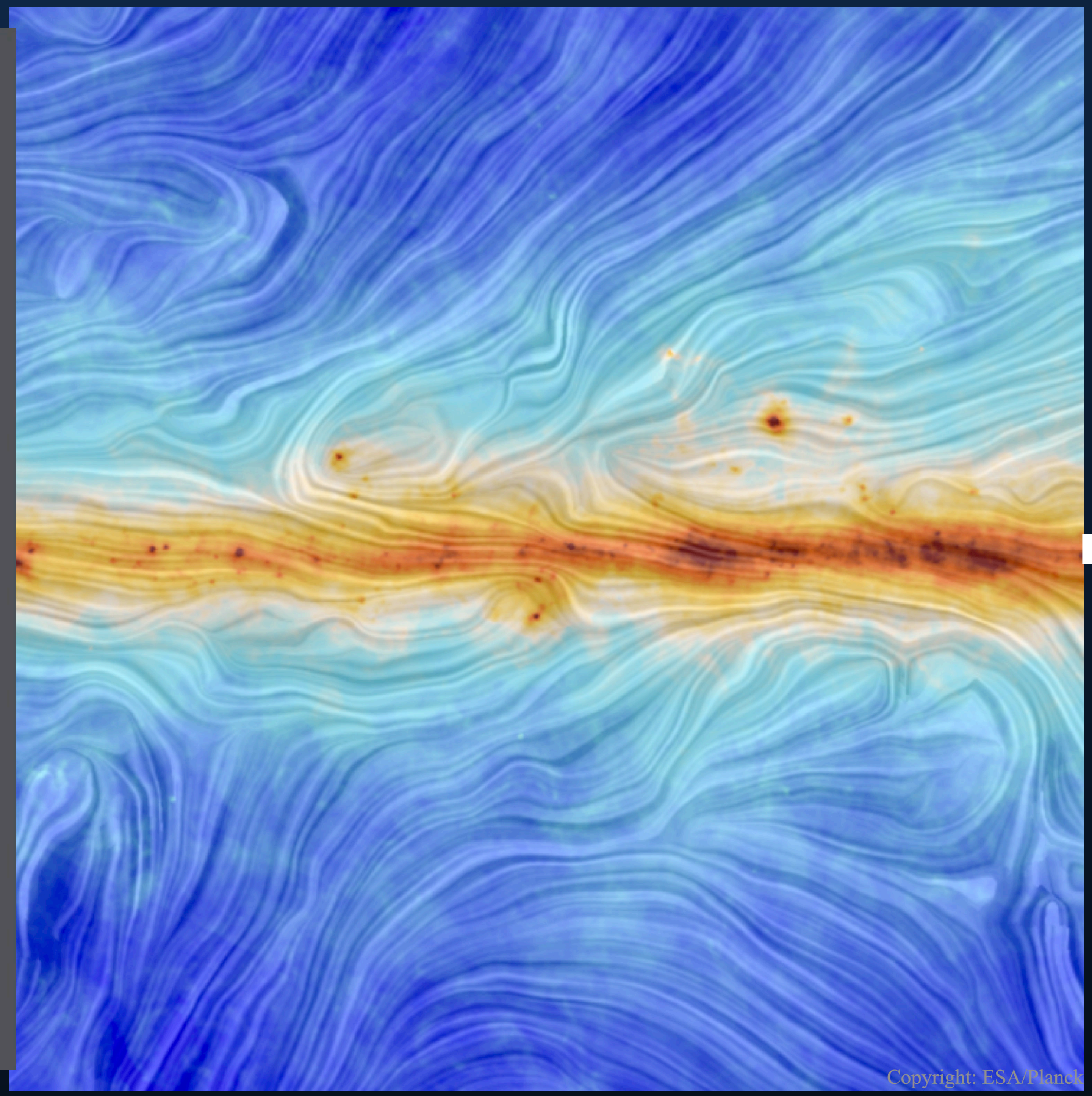
Calore et al. (2016; 1512.06825)

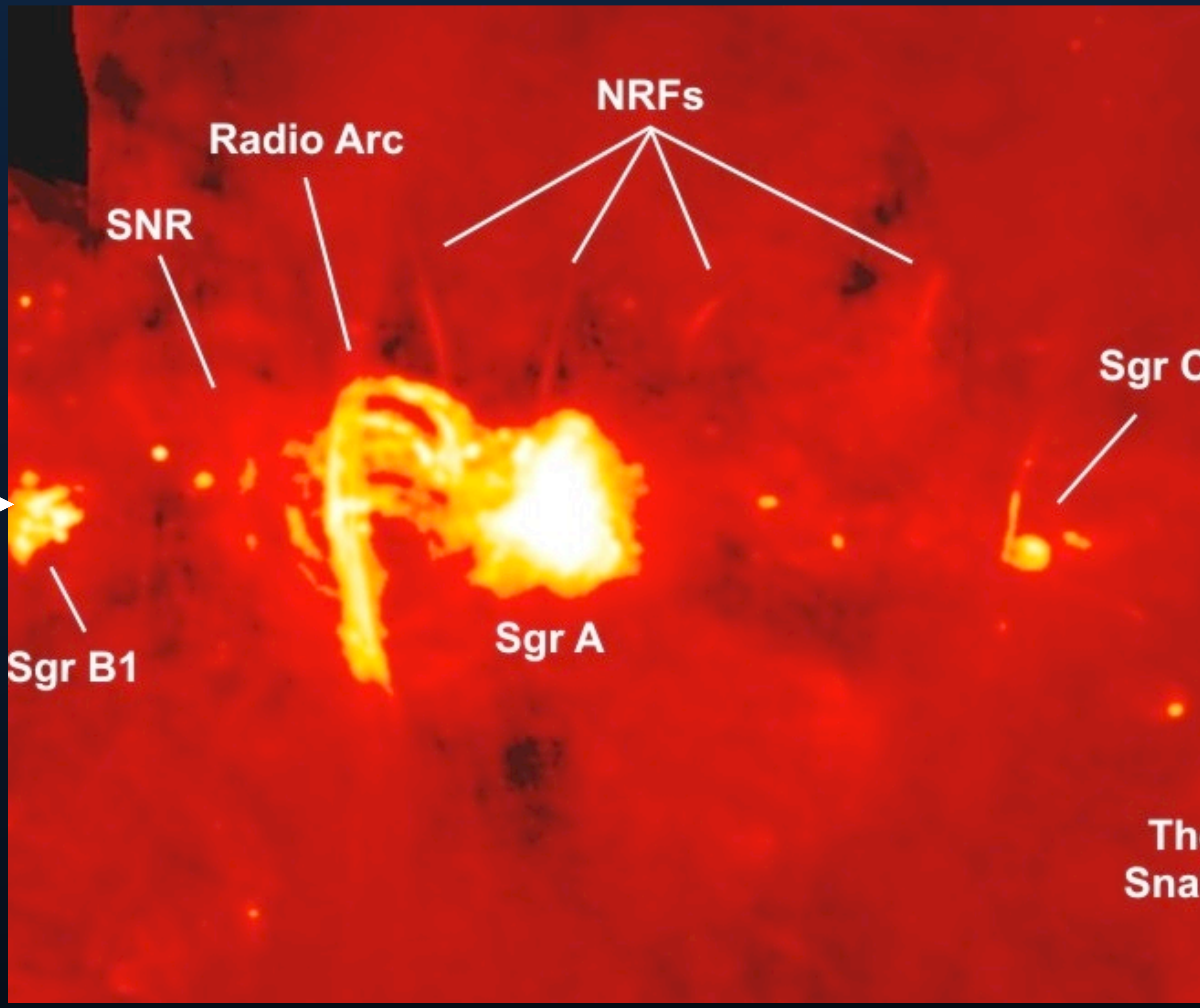




Radio Searches for Dark Matter Annihilation



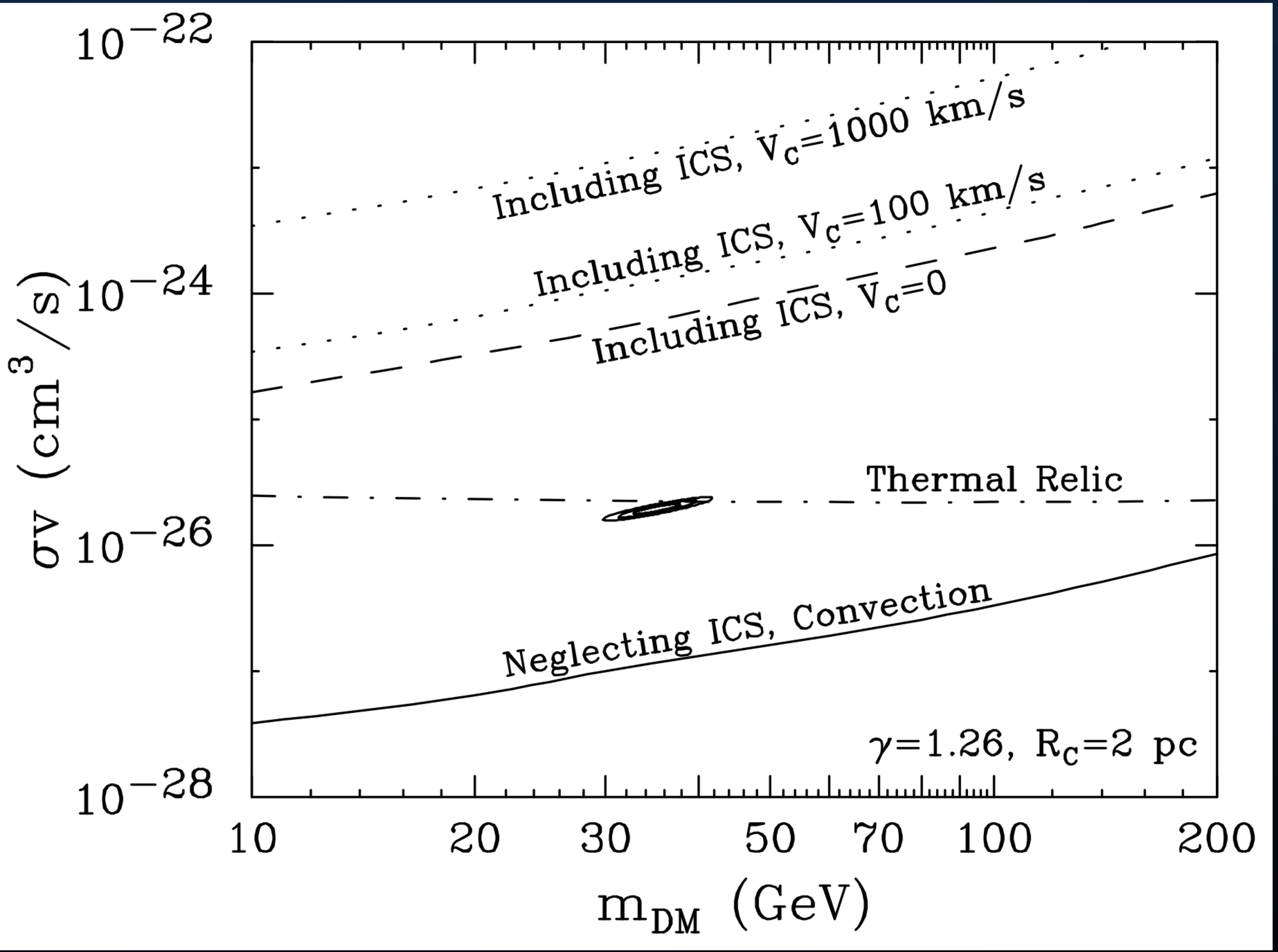




Radio Observations are Cool

Radio Searches for Dark Matter Annihilation

Cholis, Hooper, TL (1408.6224)

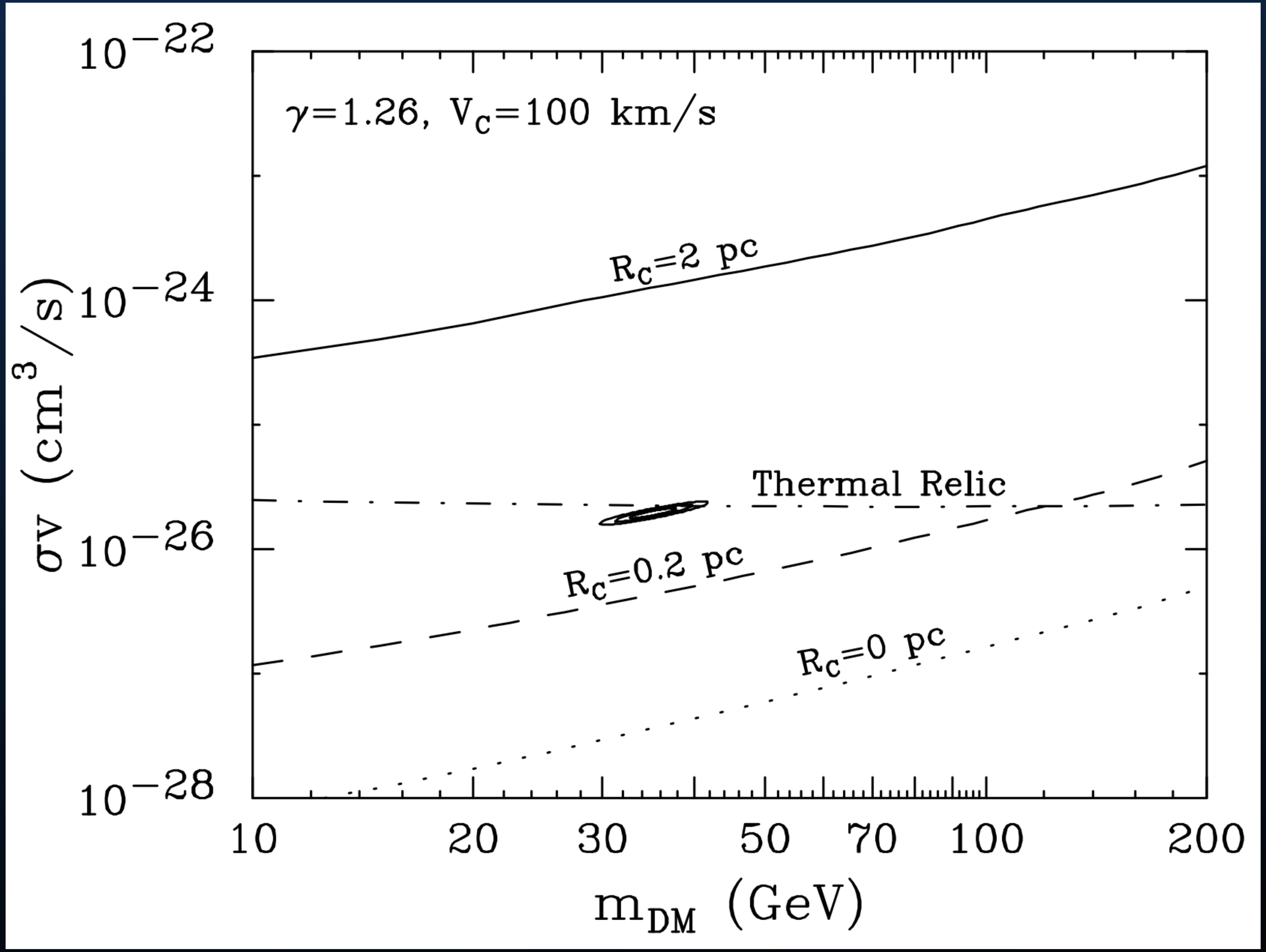


Radio Constraints Dominated by Modeling Uncertainties:

- Starlight vs. Magnetic Field
- Diffusion / Convection

Radio Searches for Dark Matter Annihilation

Cholis, Hooper, TL (1408.6224)



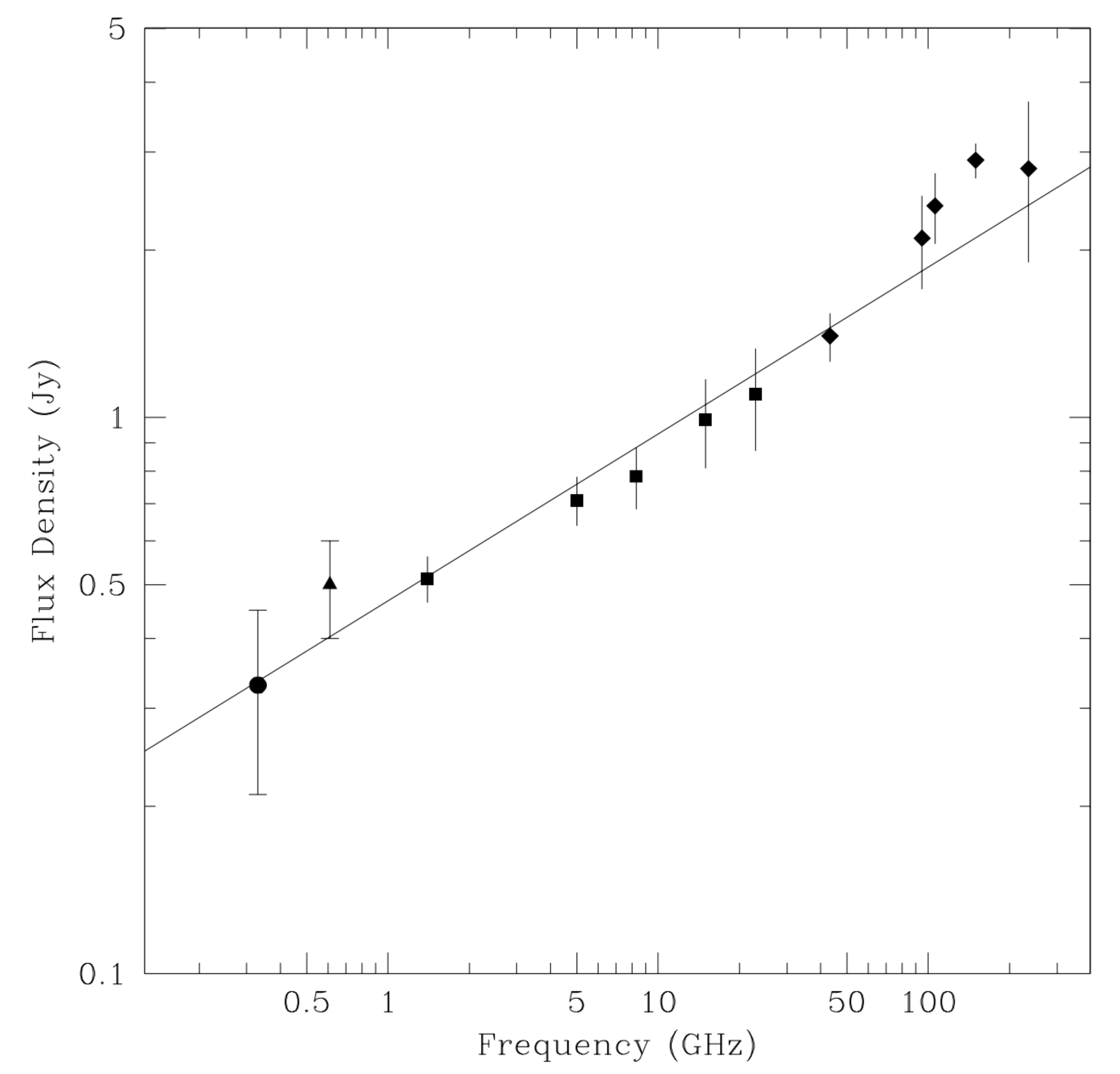
Some irreducible uncertainties:

Size of the dark matter core.

Significant Room for Improvement

Nord et al. (astro-ph/0312219)

$$S_{\mathrm{corr}} = S_0 e^{-(\theta_s/\theta)^2}$$

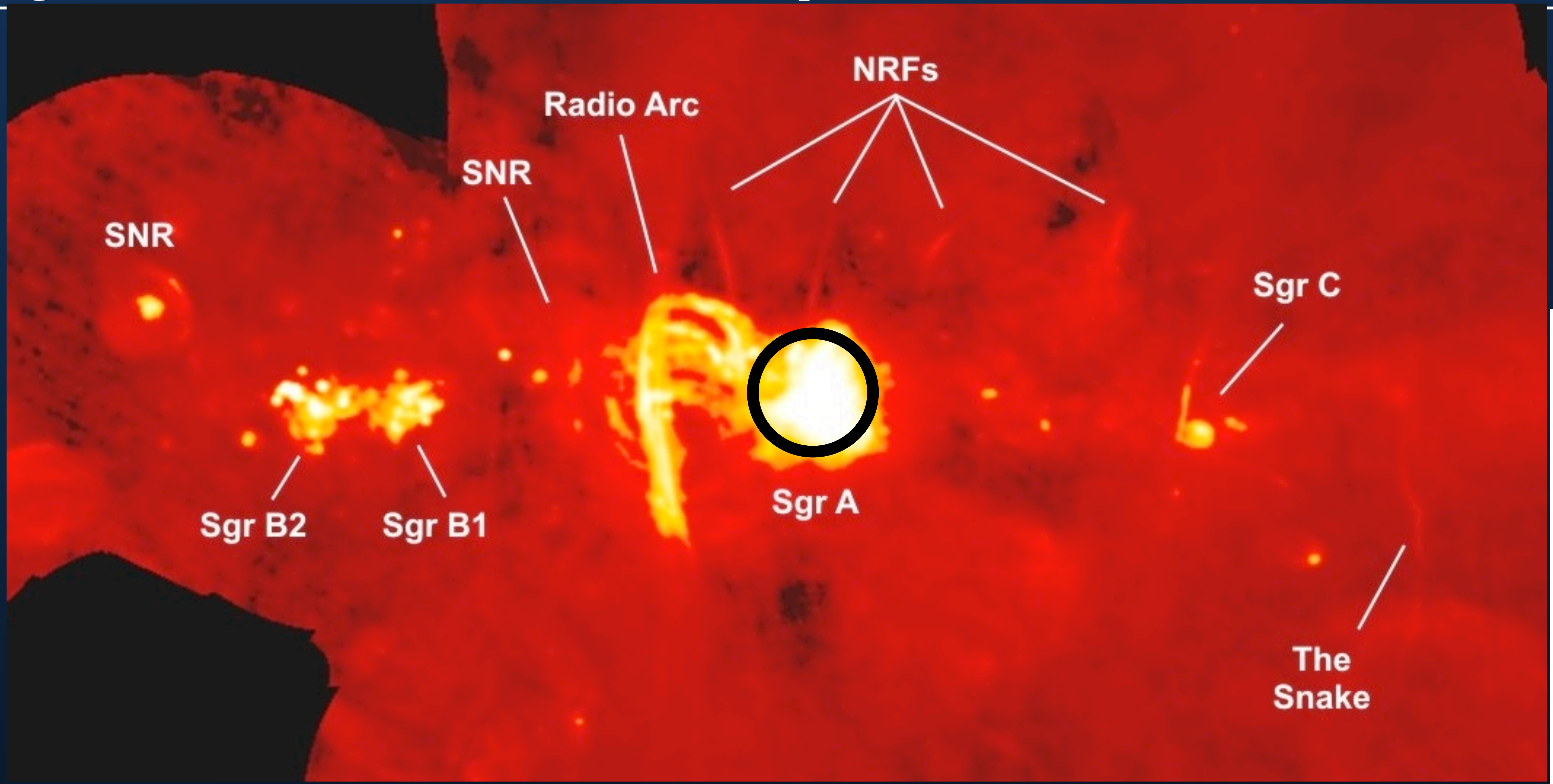


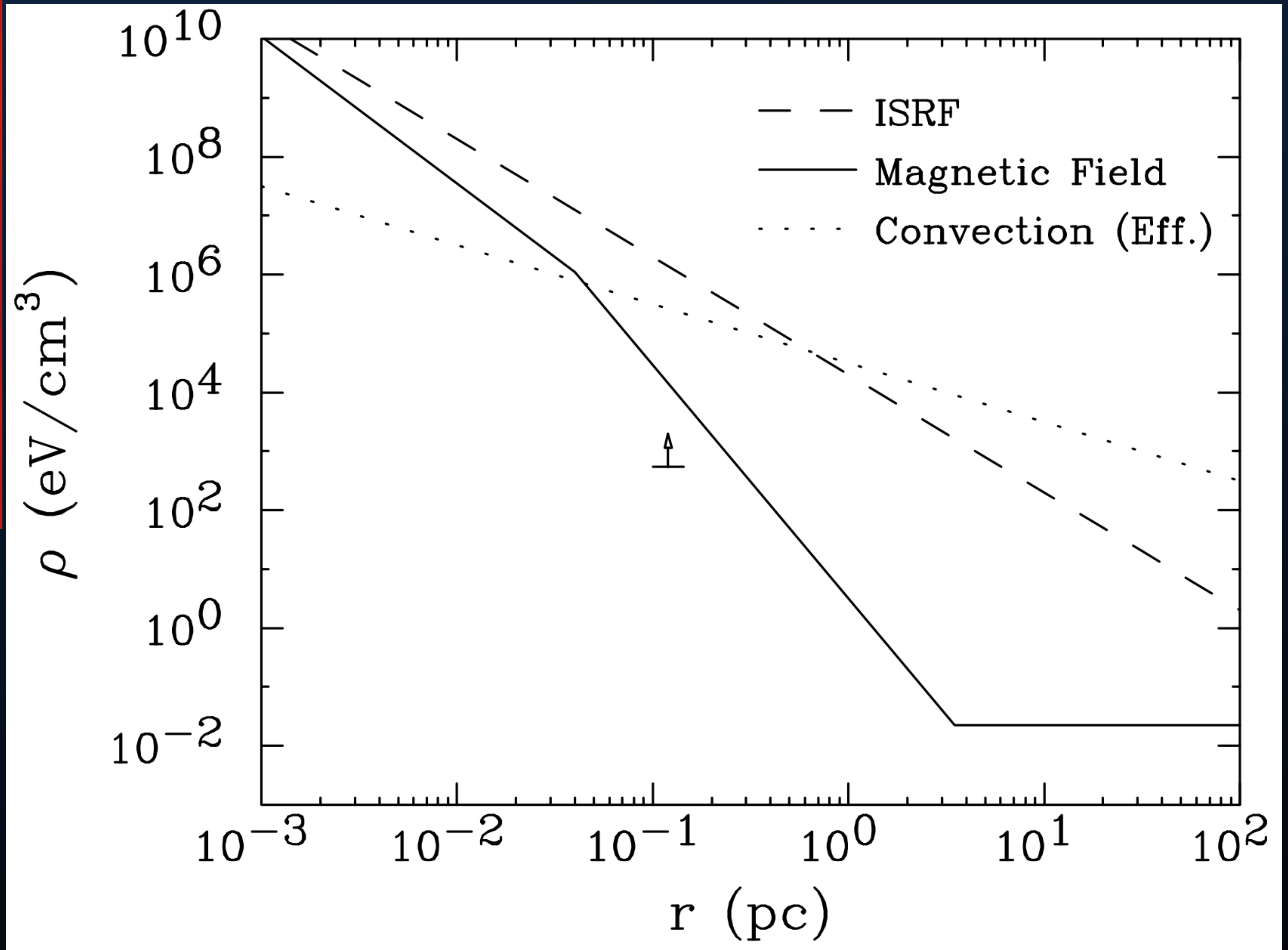
Lots of low-hanging fruit!

Better radio constraints on the diffuse synchrotron emission (point source separation).

Modeling the spectrum of synchrotron emission near the Galactic center.

Significant Room for Improvement



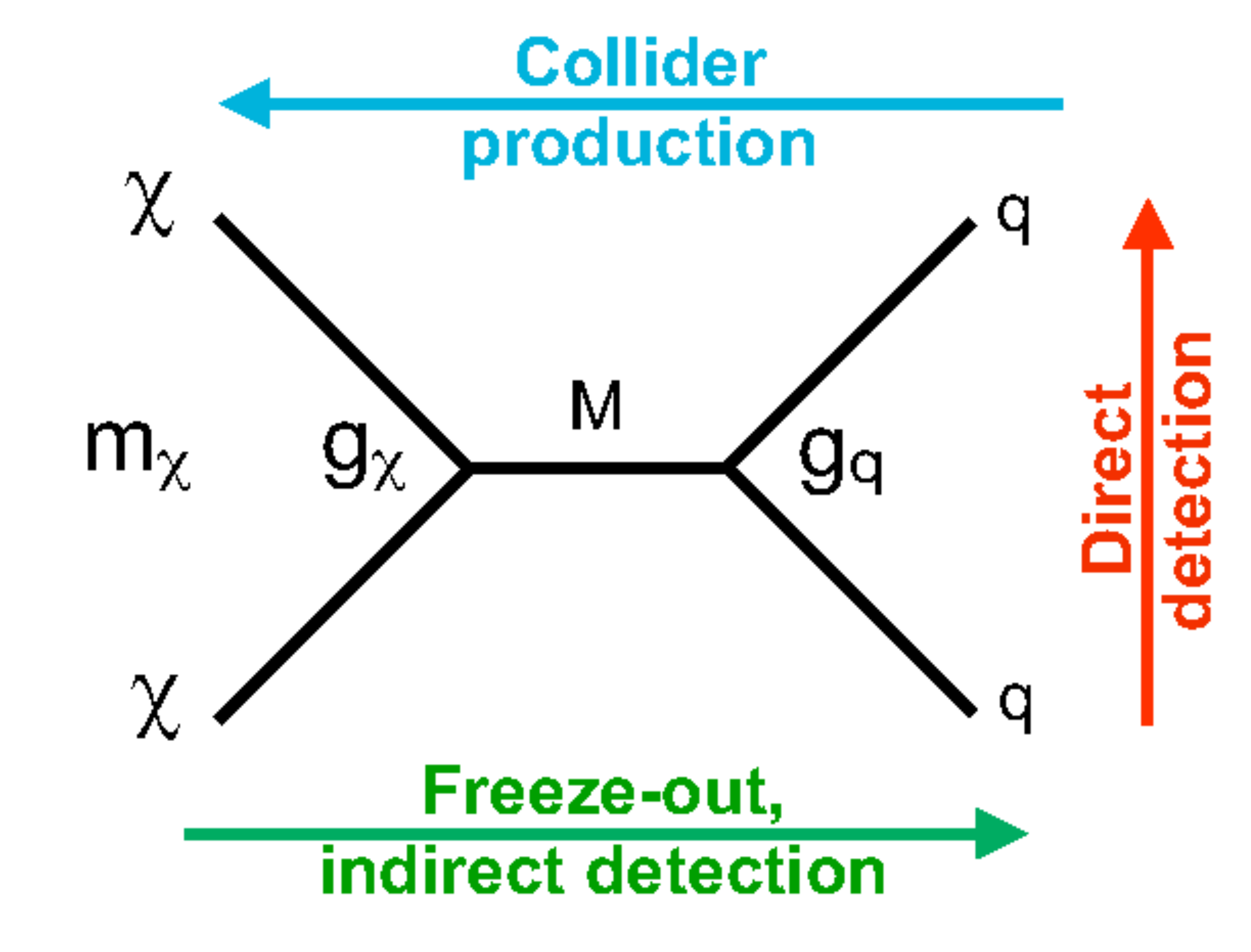


Previous radio constraints have concentrated on the Galactic center — only because of diffusion.

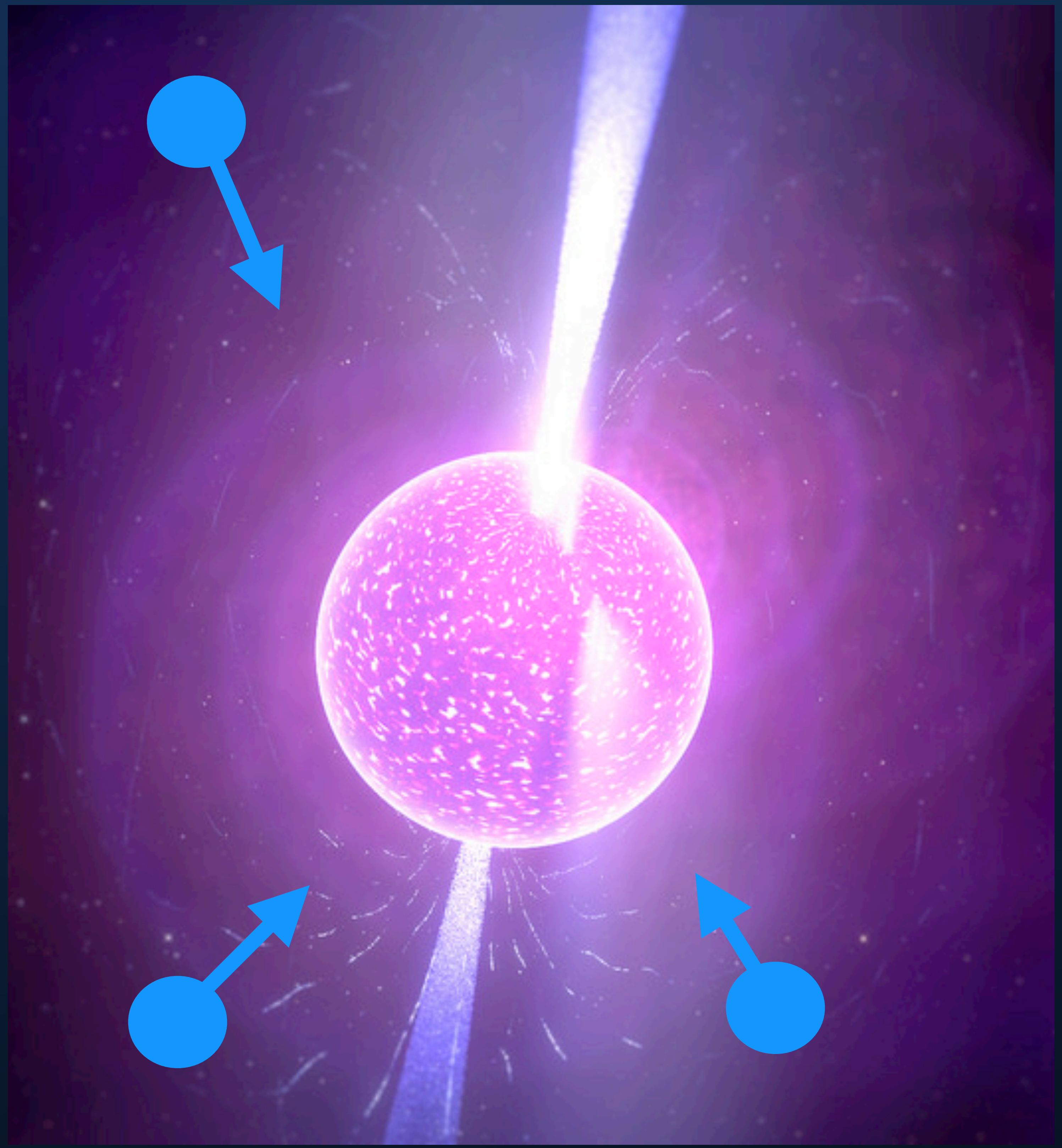
Influential paper could be written on synchrotron constraints in 1-100 pc regions!

Dark Matter Interactions with Compact Objects

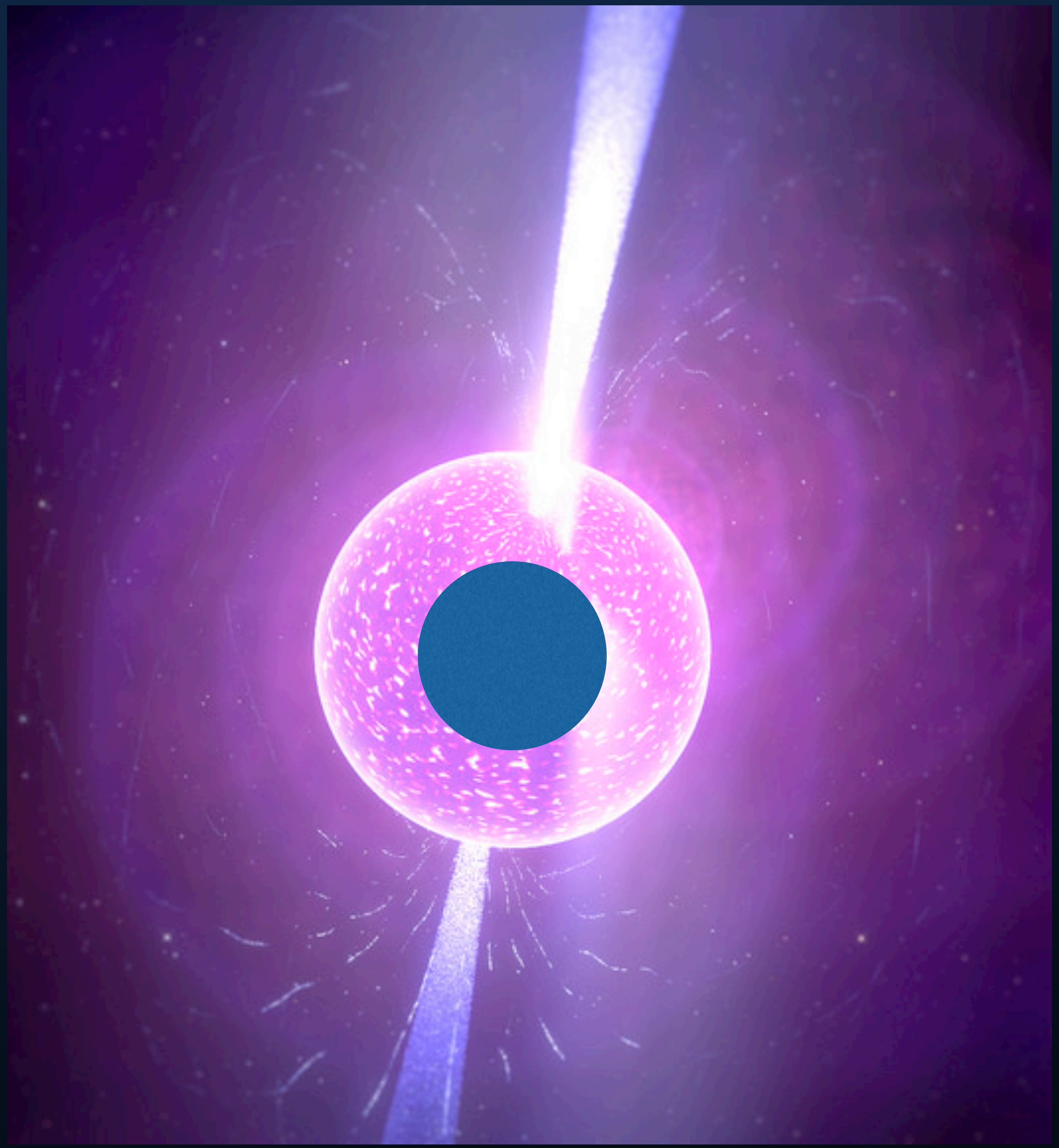
What Happens When Dark Matter Doesn't Annihilate?



Dark Matter Induced Neutron Star Collapse



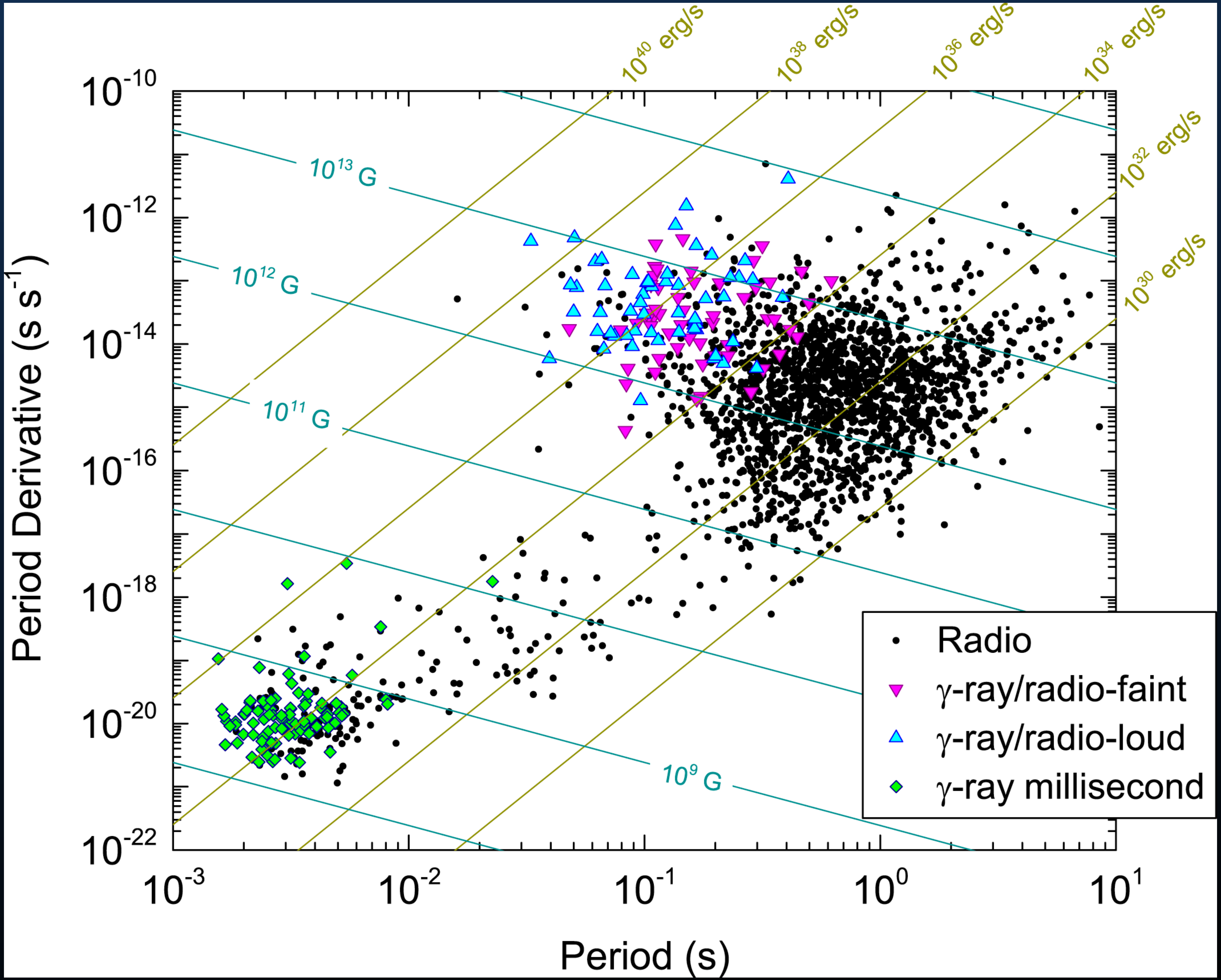
Dark Matter Accreted
by Neutron Star



Dark Matter Accumulates
and Collapses into Black Hole

Black Hole Accretes
Neutron Star

Dark Matter Induced Neutron Star Collapse



Dark Matter Induced Neutron Star Collapse

THE PECULIAR PULSAR POPULATION OF THE CENTRAL PARSEC

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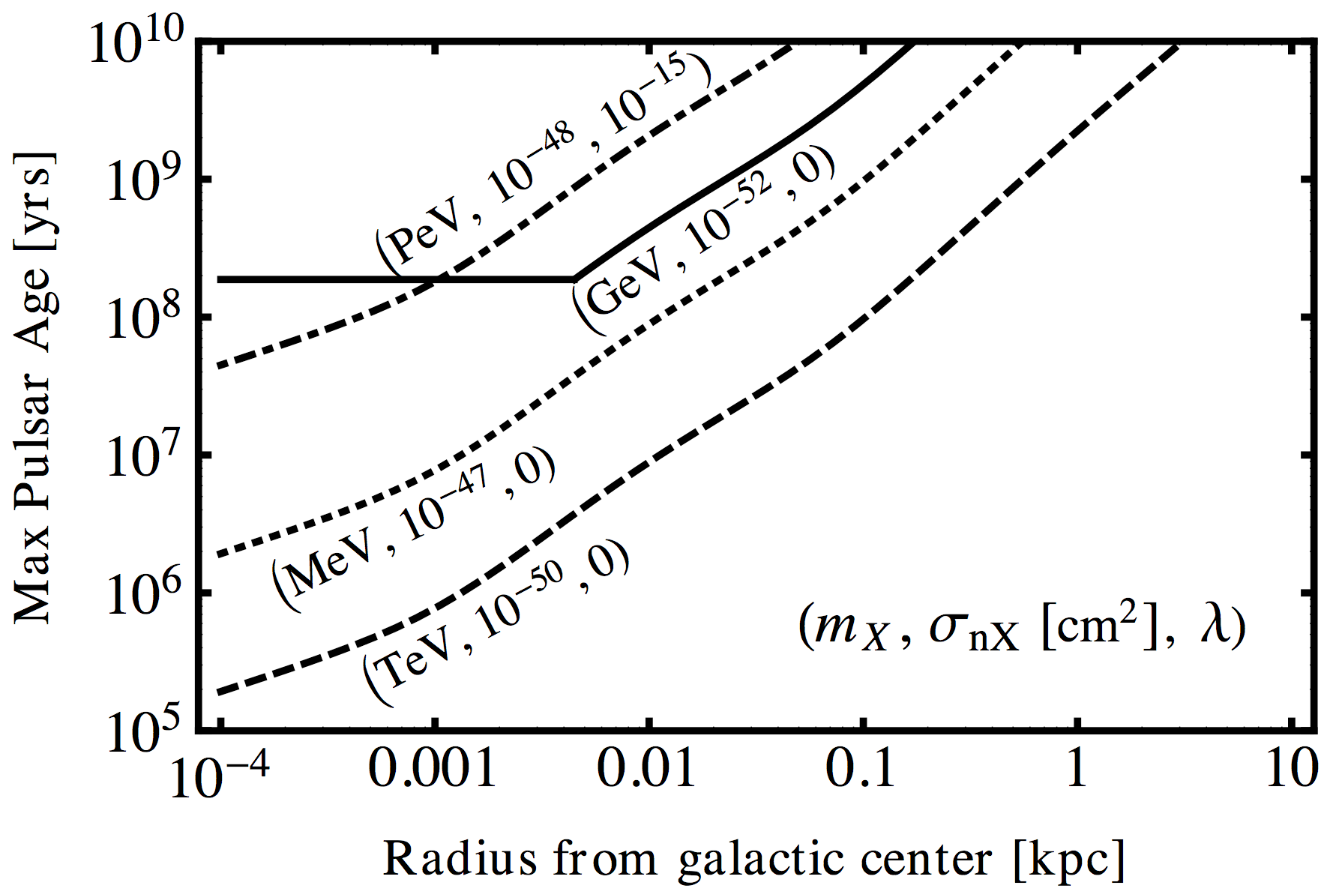
ABSTRACT

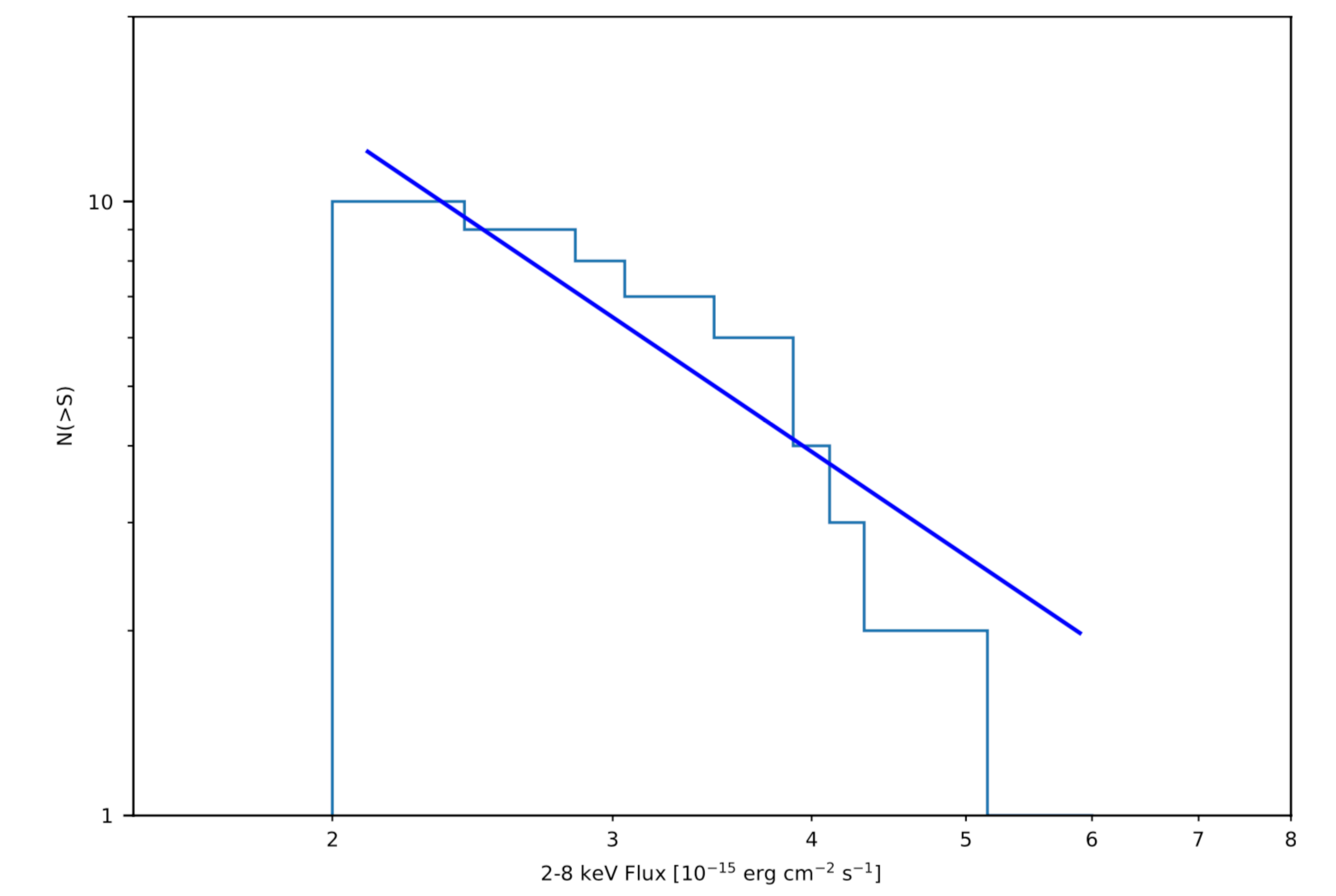
he Galactic center black hole, Sgr A*, would be potential prob
y even be used to test general relativity. Despite predic
d millisecond pulsars in the Galactic center, none
veys. One explanation has been that hypers
the recent discovery of radio pulsations
c shows that the temporal scat
ficit in the ordinary pulsar
missing pulsar problem
gnetar implies
rm magnet
Effici

Bramante & TL (1405.1031)



Dark Matter Induced Neutron Star Collapse

Hailey et al. (2018)



Dark Matter Induced Neutron Star Collapse

Conclusions

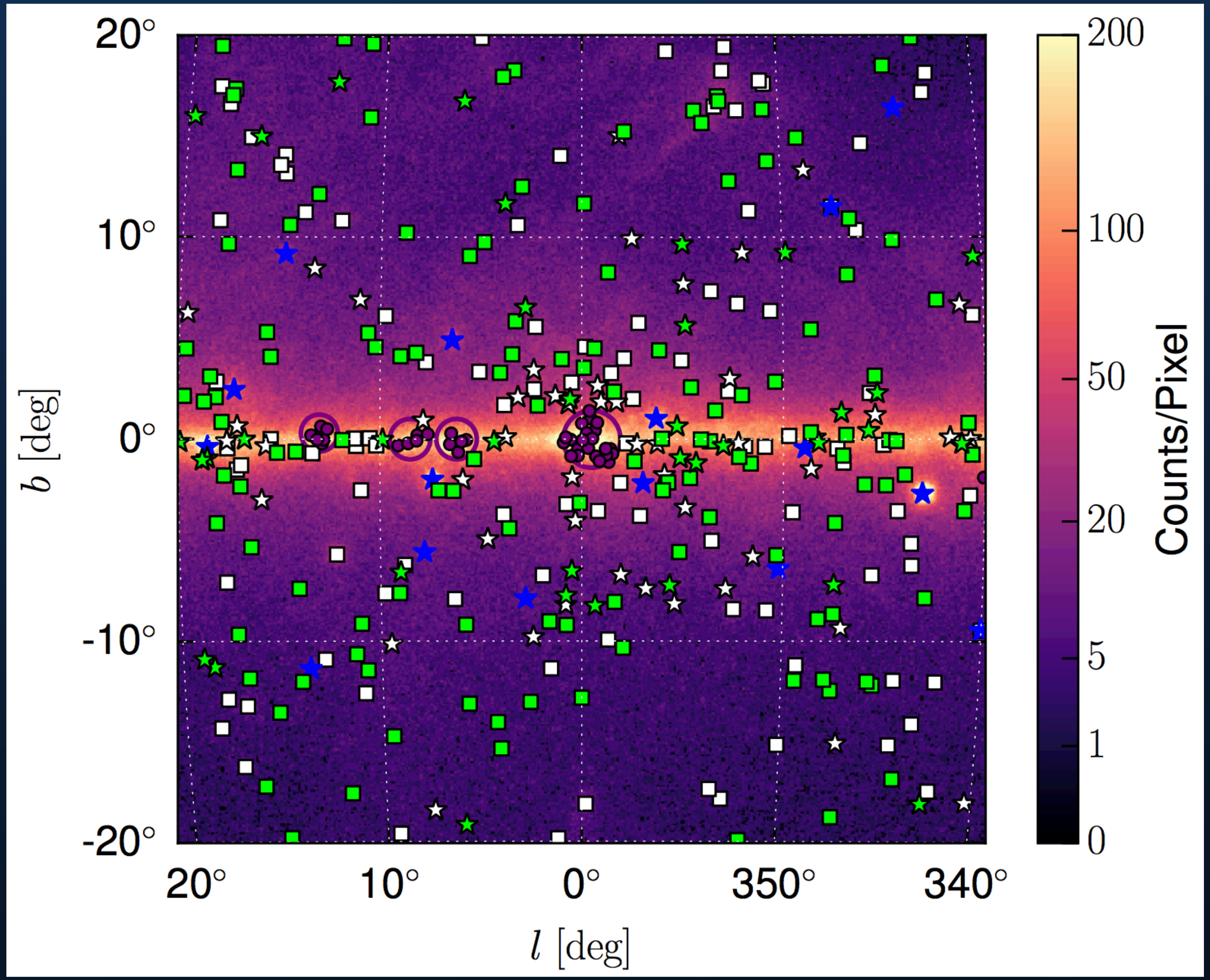
1.) Dark Matter is prevalent into the Galactic Center.

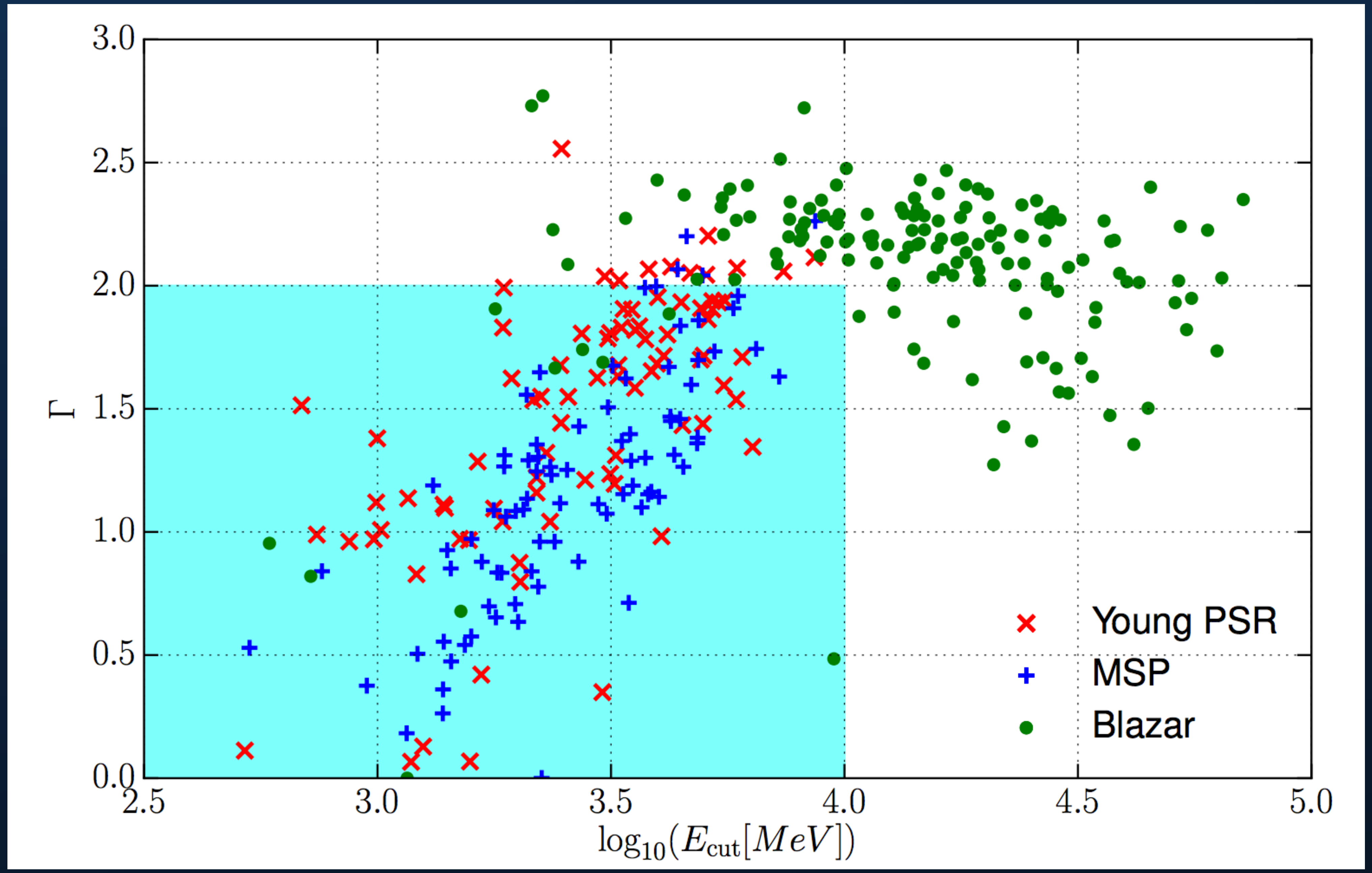
2.) May produce a significant fraction of the total gamma-ray and radio flux.

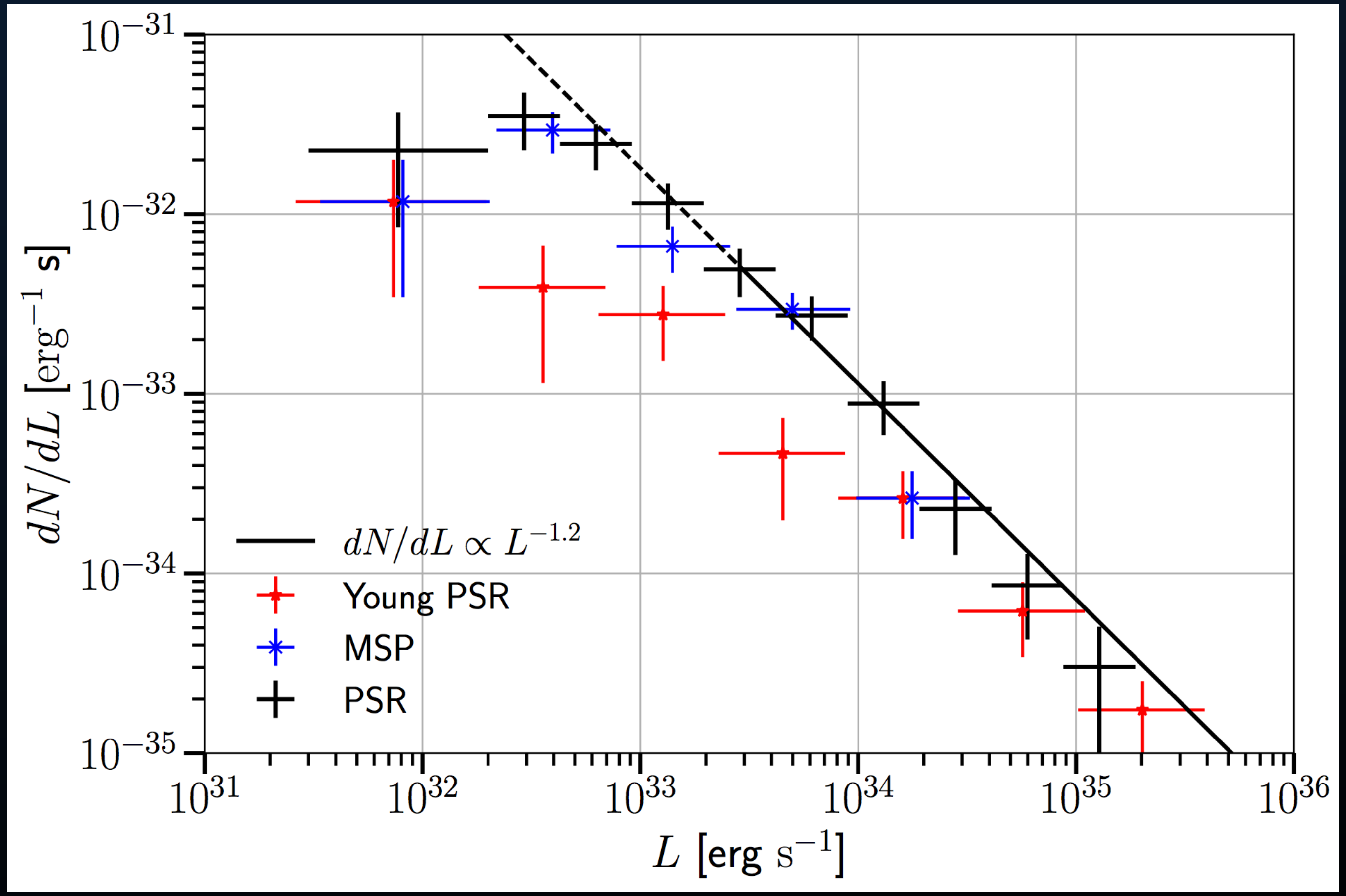
3.) Dark Matter may also noticeably affect compact objects.

4.) Future discoveries require close collaboration between astronomers and particle physicists.

2FIG Catalog







Fermi-LAT collaboration unveiled a new analysis that claimed a detection of these pulsars at >7σ.

Fermi-LAT Collaboration (2017; 1705.00009)

2FIG Catalog

We re-analyzed the Fermi-LAT data, and found very different results.

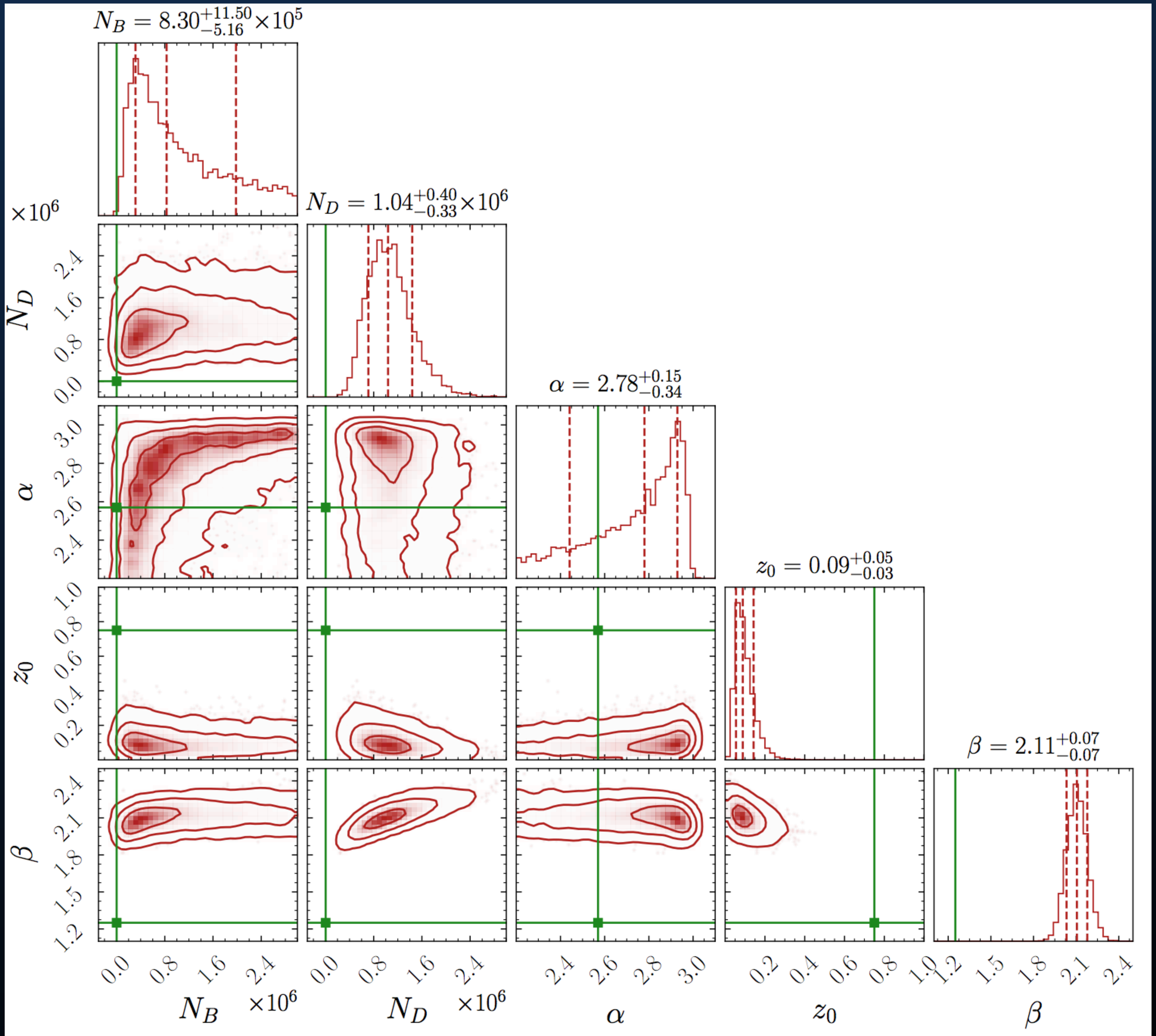
An error was subsequently found in the Fermi-LAT analysis.

$L_{\rm min} = 10^{32}$ erg/s

N_D	z_0[kpc]	β	N_B	α	TS
$(1.21^{+0.44}_{-0.35})\times10^5$	$0.19^{+0.07}_{-0.05}$	$2.08^{+0.10}_{-0.09}$	0	$\cdots$	0
$(1.07^{+0.45}_{-0.33})\times10^5$	$0.13^{+0.06}_{-0.04}$	$2.15^{+0.12}_{-0.10}$	$(5.14^{+5.50}_{-2.62})\times10^5$	2.60	8.1

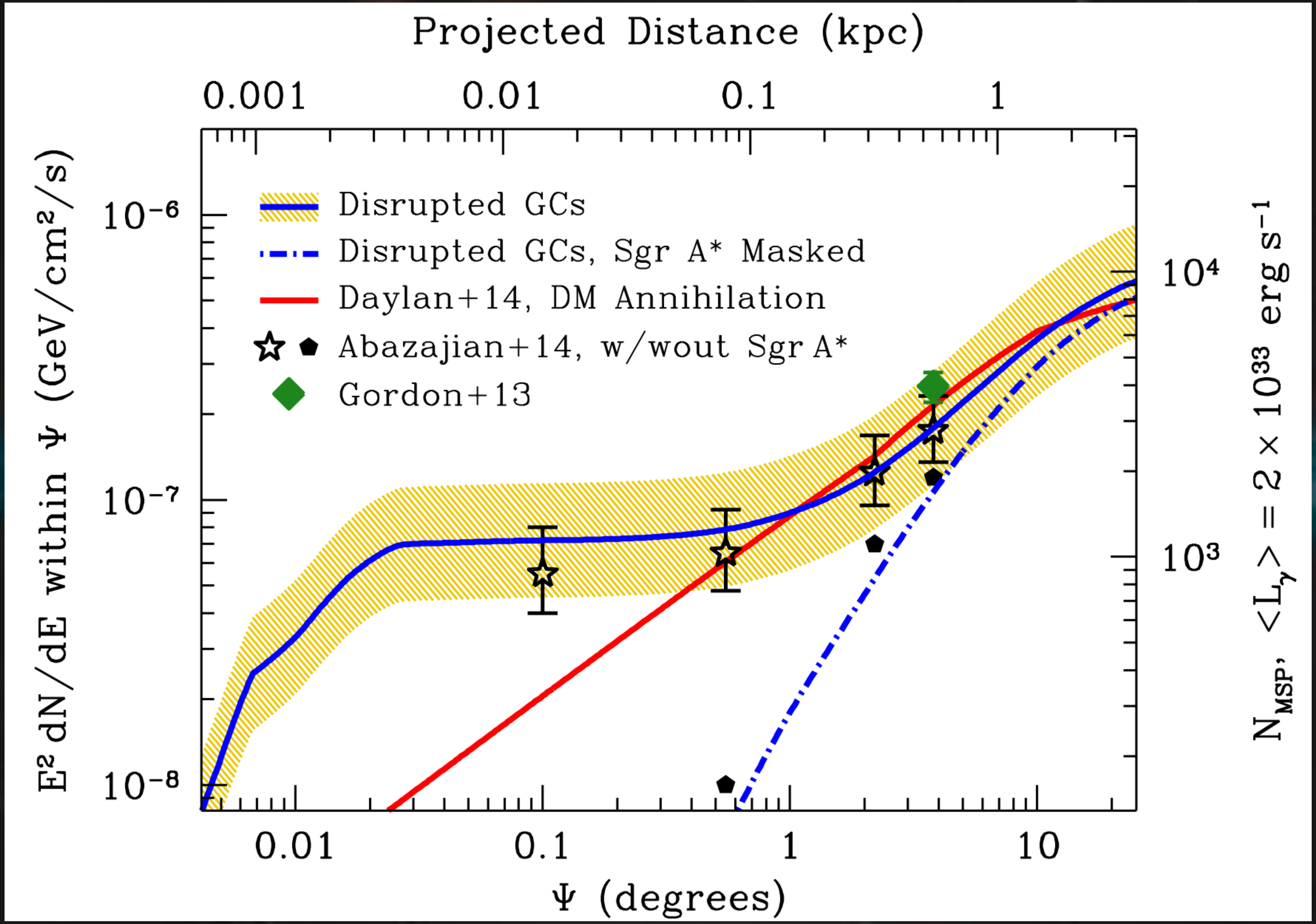
$L_{\rm min} = 10^{33}$ erg/s

N_D	z_0[kpc]	β	N_B	α	TS
$(1.24^{+0.36}_{-0.29})\times10^4$	$0.32^{+0.08}_{-0.06}$	$2.10^{+0.13}_{-0.13}$	0	$\cdots$	0
$(1.02^{+0.40}_{-0.29})\times10^4$	$0.23^{+0.09}_{-0.06}$	$2.20^{+0.17}_{-0.14}$	$(4.57^{+3.95}_{-2.07})\times10^3$	2.6	10.1



Bartels et al. (2018; 1710.10266)

Why Haven't We Found the Pulsars?



Why Haven't We Found the Pulsars?

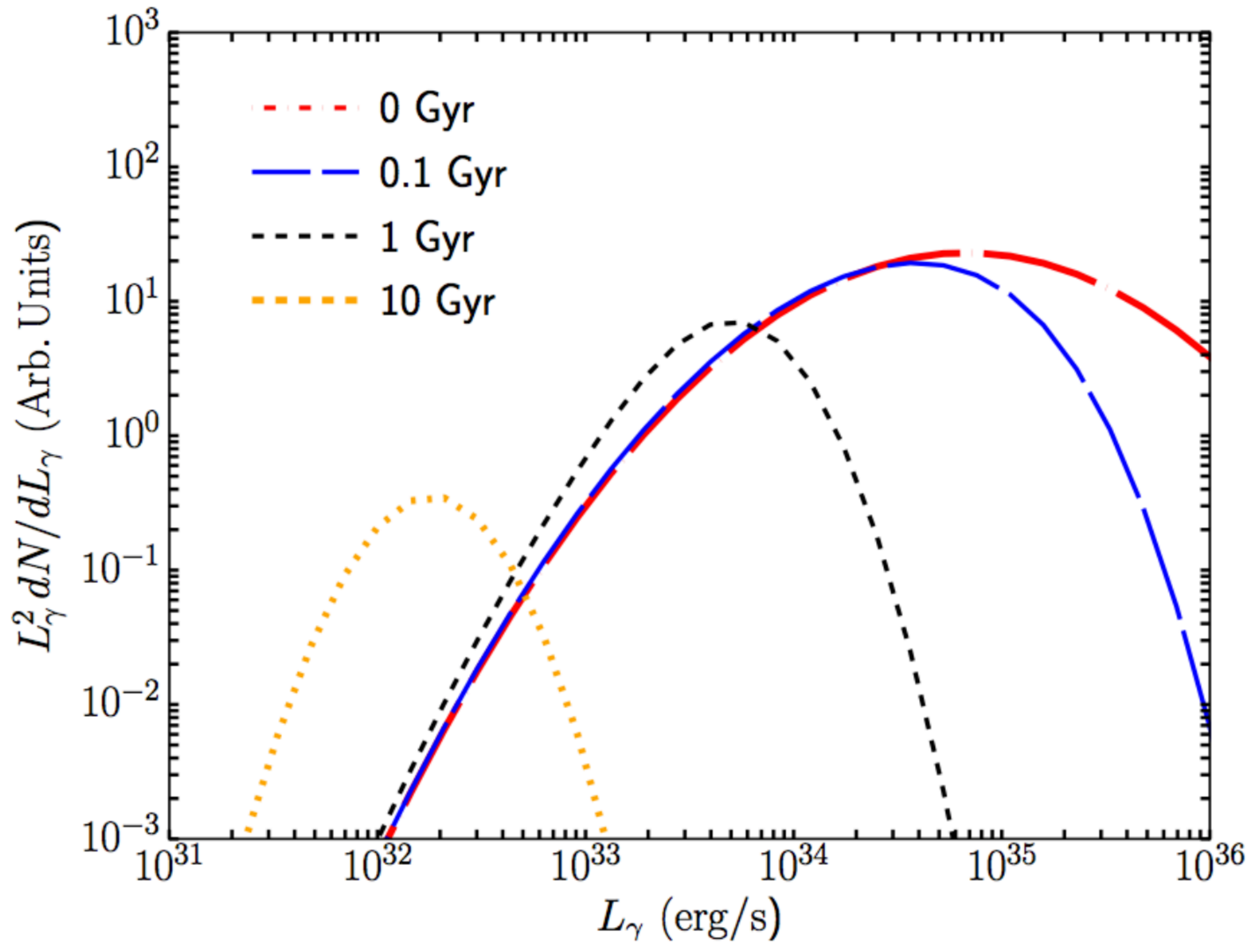
MSPs also spin-down rapidly:

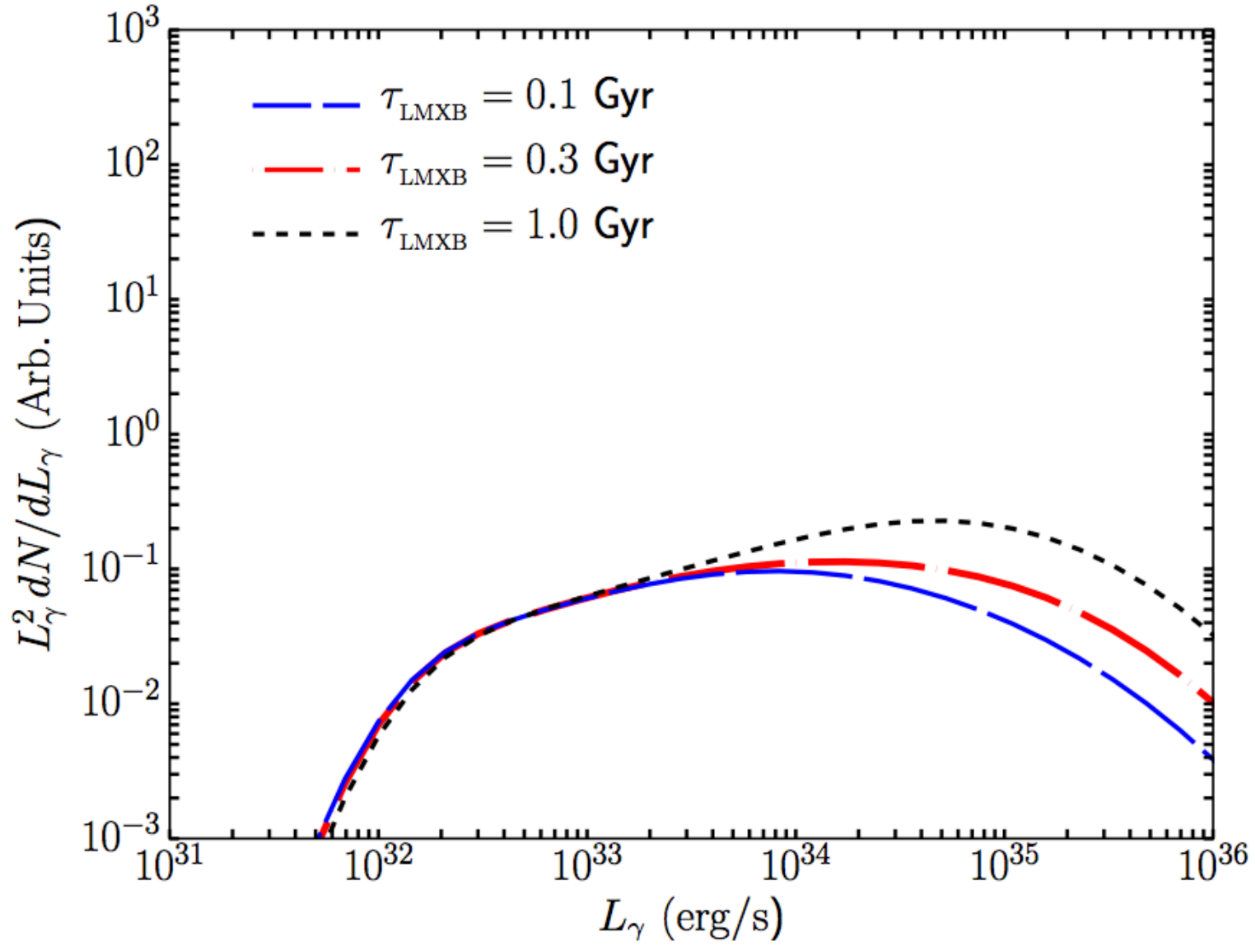
$$\tau = \frac{3c^3 I P_0^2}{4\pi^2 B_0^2 R^6}$$

For most MSPs, τ ~ 100 Myr - 1 Gyr

$$\begin{aligned} L_\gamma &= \eta_\gamma \dot{E} \\ &= \eta_\gamma \frac{4\pi^2 I \dot{P}}{P^3} \\ &\simeq 9.6 \times 10^{33}\,\mathrm{erg/s} \left(\frac{\eta_\gamma}{0.2}\right) \left(\frac{B}{10^{8.5}\,\mathrm{G}}\right)^2 \left(\frac{3\,\mathrm{ms}}{P}\right)^4 \end{aligned}$$

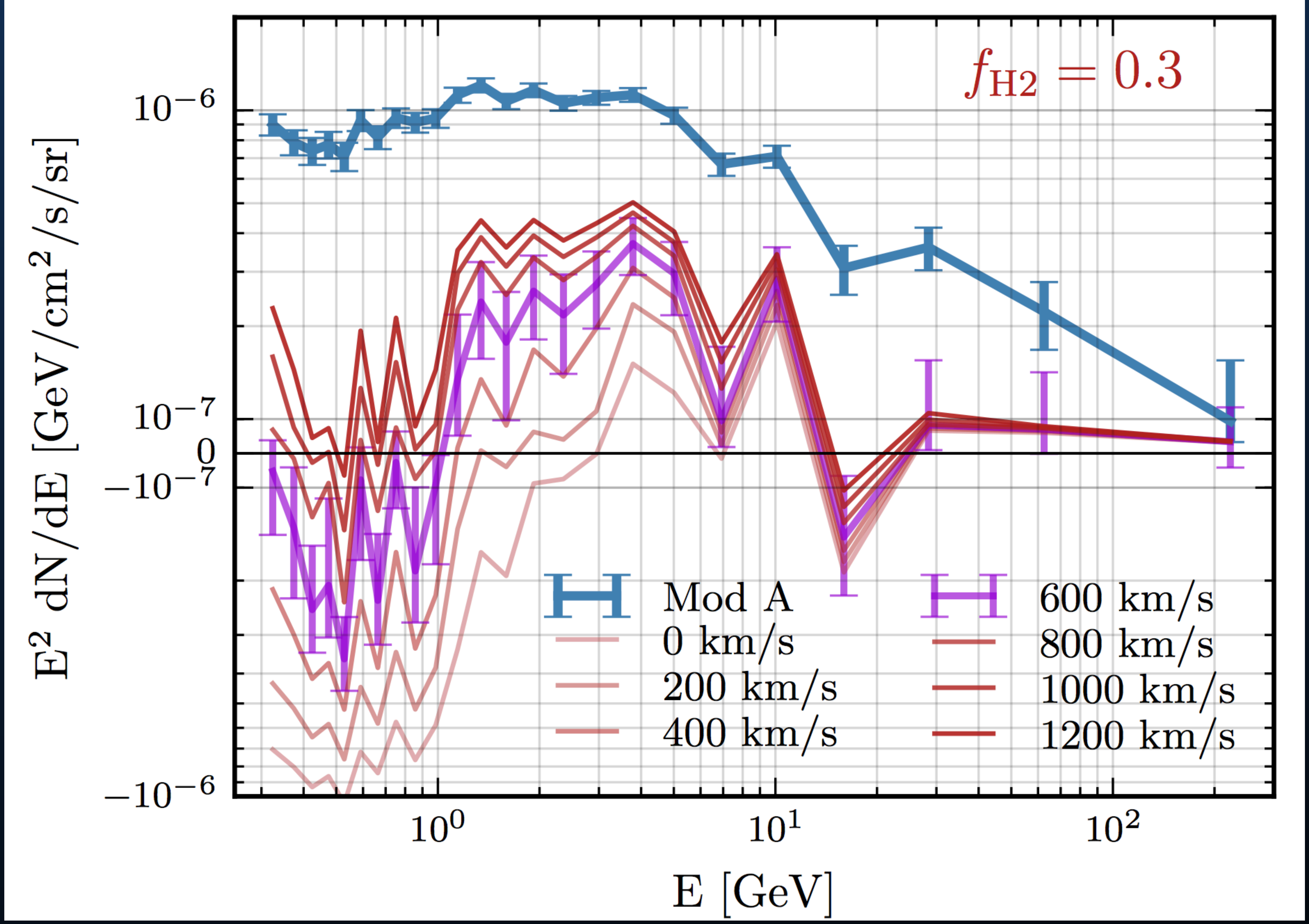
Hooper & Linden (2016; 1606.09250)





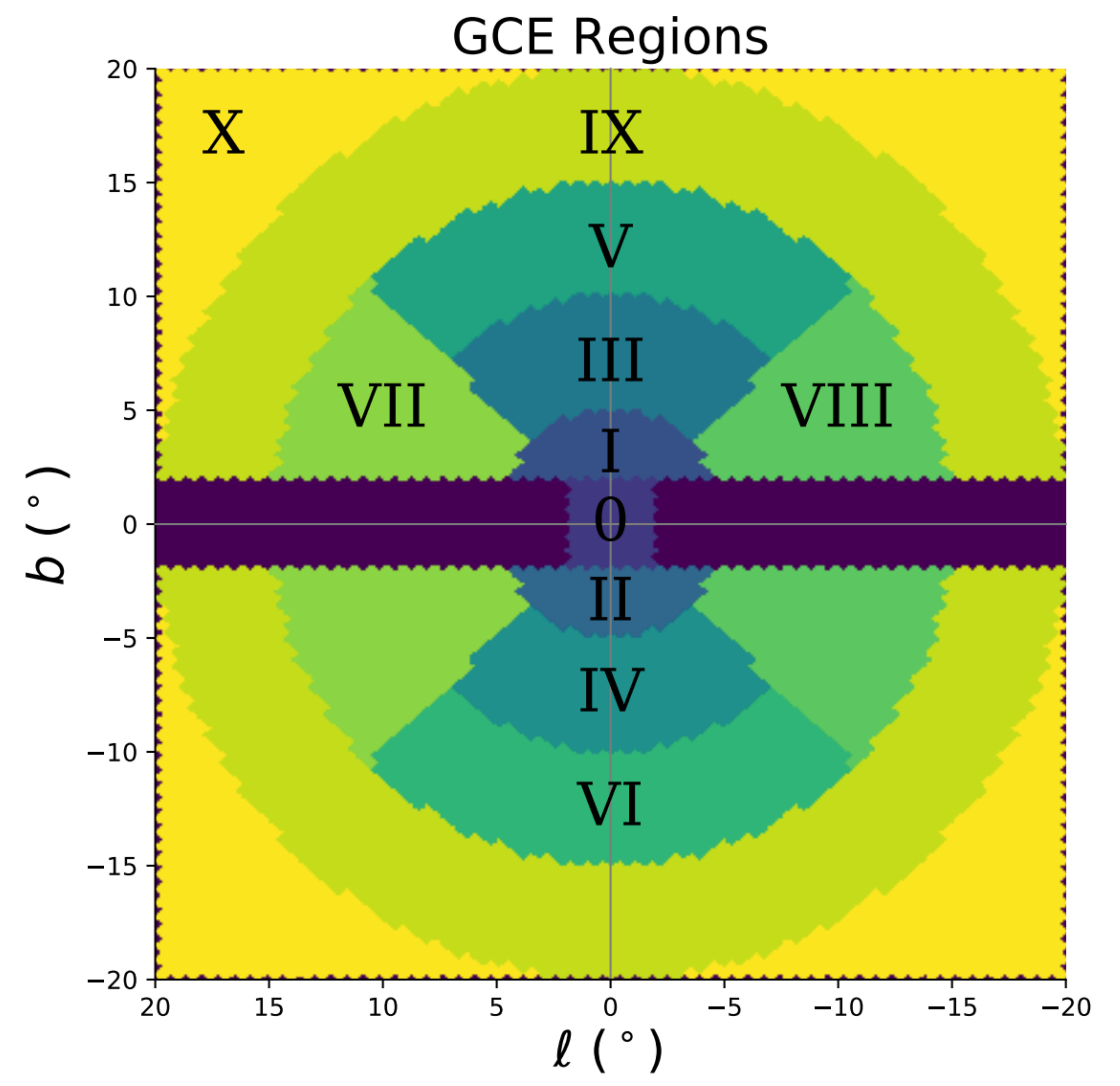
Effect of Diffuse Emission Models

Carlson, TL & Profumo (1603.06584)



Normalization and some other features can depend sensitively on diffuse emission modeling.

NPTF and Wavelet Analyses



Regions VII and VIII are the easiest to understand and compare to, since they are removed from the center, far from the Bubbles, and in these parts of the sky point sources from the Galactic disk are expected to be relatively most dominant. At 1.5 GeV and above, in these two regions we find that ∼30–50% of the total ($1 \leq j \leq 9$) emission is in the first two wavelet scales, and moreover the first two wavelet scales contribute *negatively*. There

are 1.2 3FGL point sources per deg^2 on average in these two windows. This is still higher than the average of 1.02 3FGL point sources per deg^2 along the two stripes of $2° \leq |b| \leq 5°$ extending at all longitudes: Regions VII and VIII are rich in detected point sources. Only Regions II and VI have a similar $\sim 30\%$ of their emission in the first two wavelet scales, which is also negative. The magnitude and the sign of this small scale contribution is intriguing. The negative sign in the first two wavelet levels for the regions near the Galactic center and Galactic disk means that unphysical flux has been imparted to the templates on small angular scales at intermediate angular distances from the Galactic center. This is suggestive either of mismodelled bremsstrahlung and pion emission or the inclusion of spurious point sources near the galactic center. We note that Region 0 does not suffer from a similarly large negative contribution at small angular scales. This may be an indication of the large positive contribution from the GCE, or an issue with the procedure to determine the point-source maps.

Balaji et al. (1803.01952)