PONT Avignon 2014, April 15th 2014

Dark Matter Interpretations of Extended Gamma Ray Emission towards the Galactic Center

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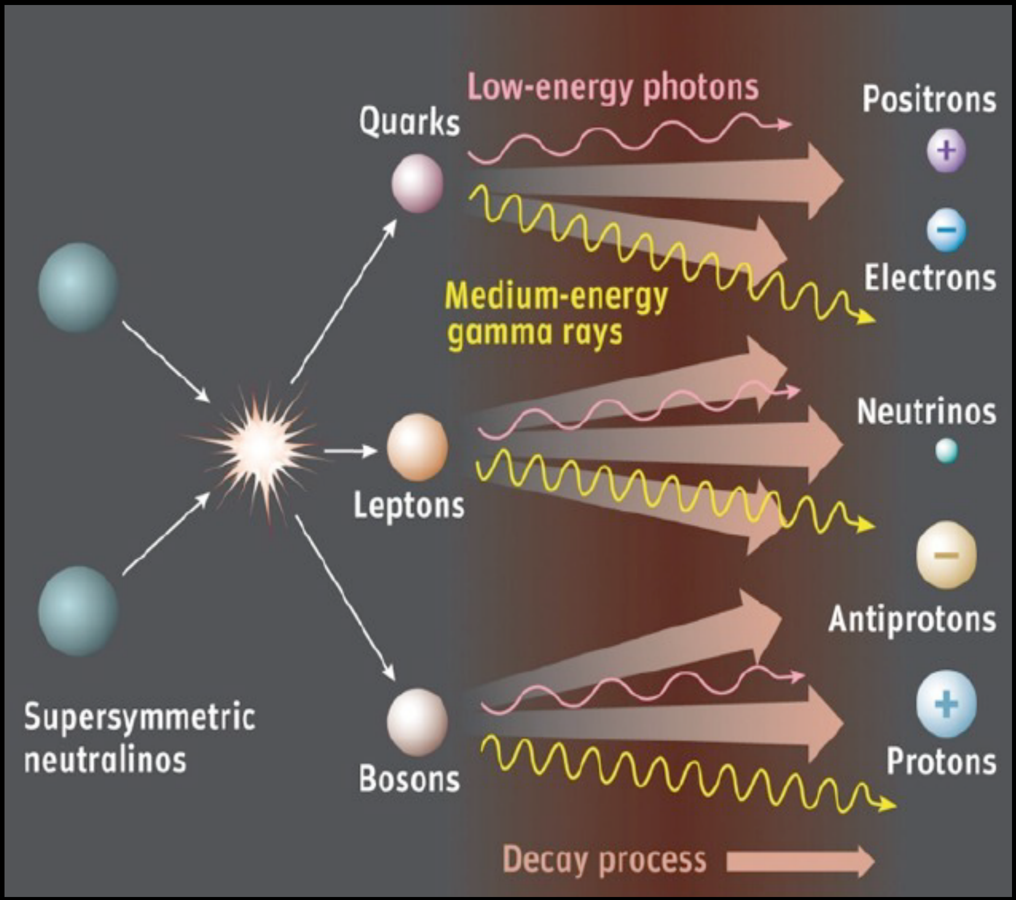
Based on ref. *arXiv:1402.4090, submitted to PRD*

With Kevork Abazajian, Nick Canac, and Manoj Kaplinghat (UC Irvine)

Outline

- Background
  - The Galactic Center GeV Excess (GCE)
  - Multi-wavelength view of the Galactic Center
- Analysis
  - Fit Procedure
  - GCE spectrum and spatial morphology
- Interpretation
  - As dark matter annihilation
  - As millisecond pulsars (MSPs)
- Conclusions

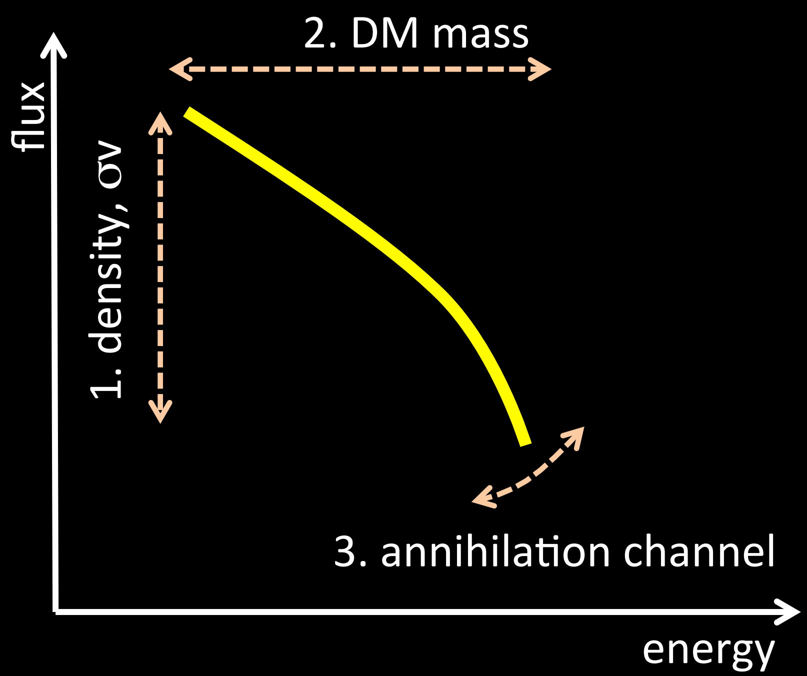
Dark matter annihilation signal



Tomorrow morning's talk by Jan Conrad

The observables reveal:

1. Density and σ
2. Dark matter mass
3. Coupling to SM particles



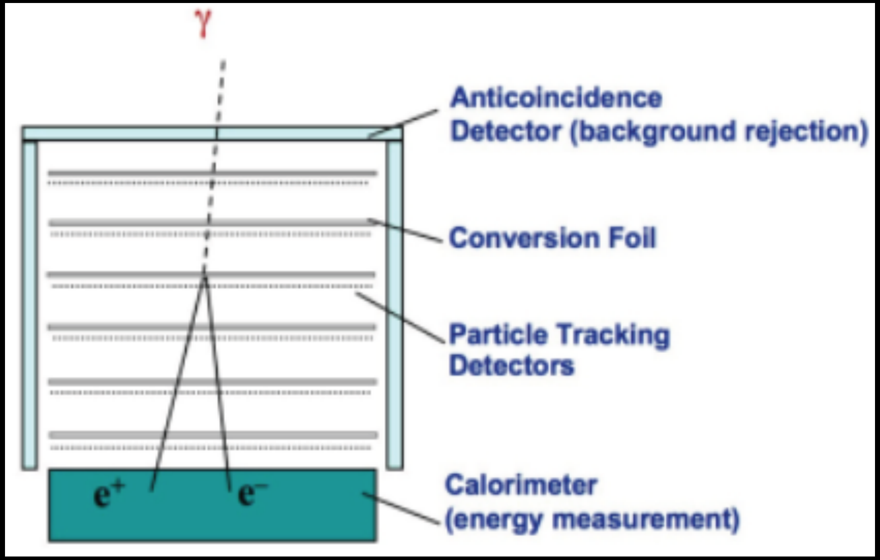
Fermi satellite

Launched in June 2008

Large area telescope (LAT)

- Primary instrument of Fermi, consists of:
  - Anticoincidence
  - Pair conversion detector
  - Calorimeter
- 20 MeV – 300 GeV
- Field of view 2.4 sr at 1 GeV
- PSF < 1 deg above 1 GeV

Data and analysis tools are public:
http://fermi.gsfc.nasa.gov/ssc/data/

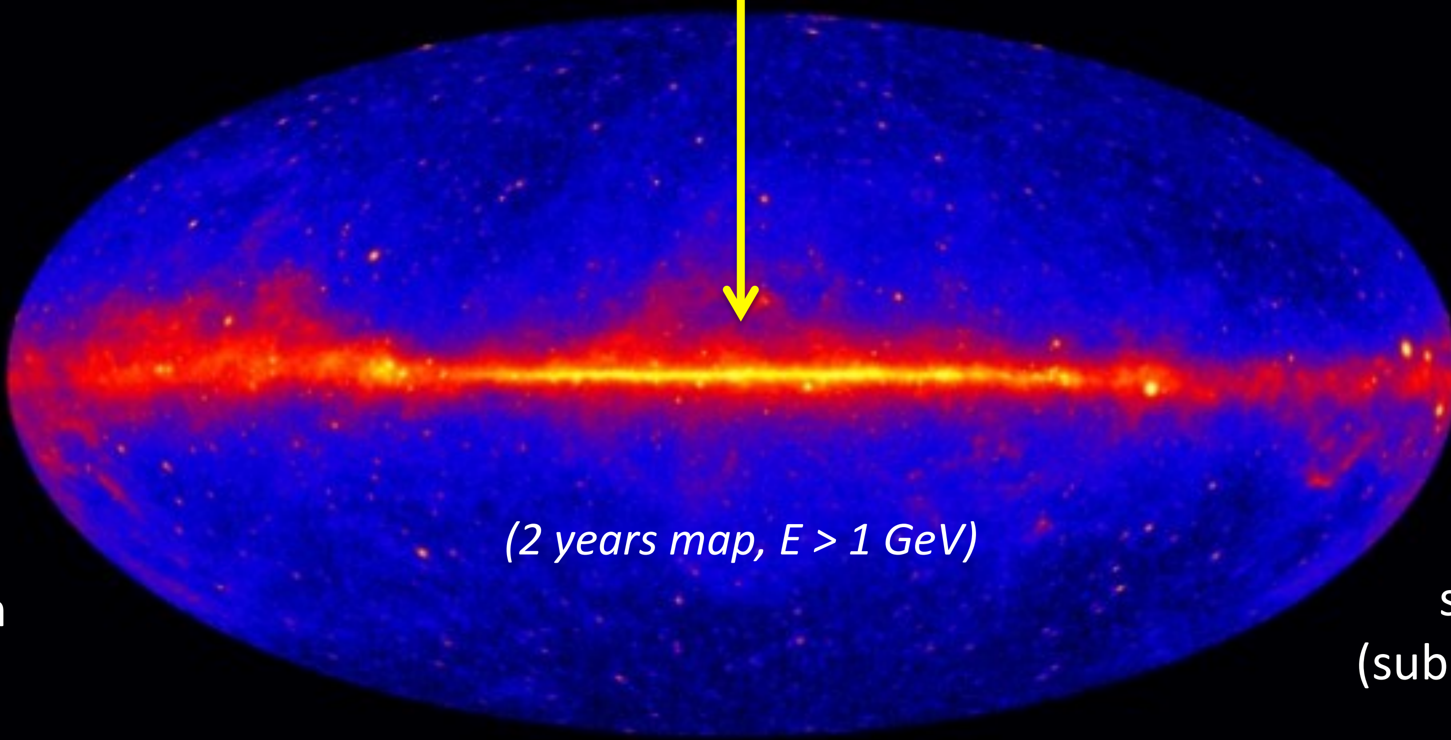


Where to look

Galactic Center

Inner galaxy

Galactic halo



The sun

un-ID
sources
(subhalos?)

Dwarf galaxies

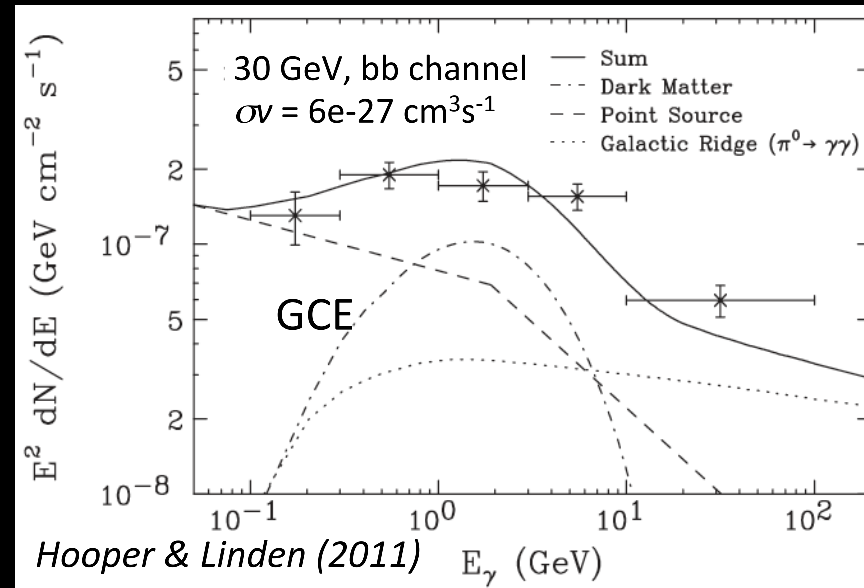
Galaxy clusters

Isotropic gamma-ray background

The Galactic Center GeV Excess (GCE)

Claimed detections of an extended excess towards the Galactic Center region, first by Goodenough & Hooper (2009) and independently by multiple groups, with the following main features:

- Spectrum peaks at several GeV
- Morphology follows $\sim r^{-2.4}$
- Peak flux of a few x 10^{-7} GeV cm^{-2} s^{-1}

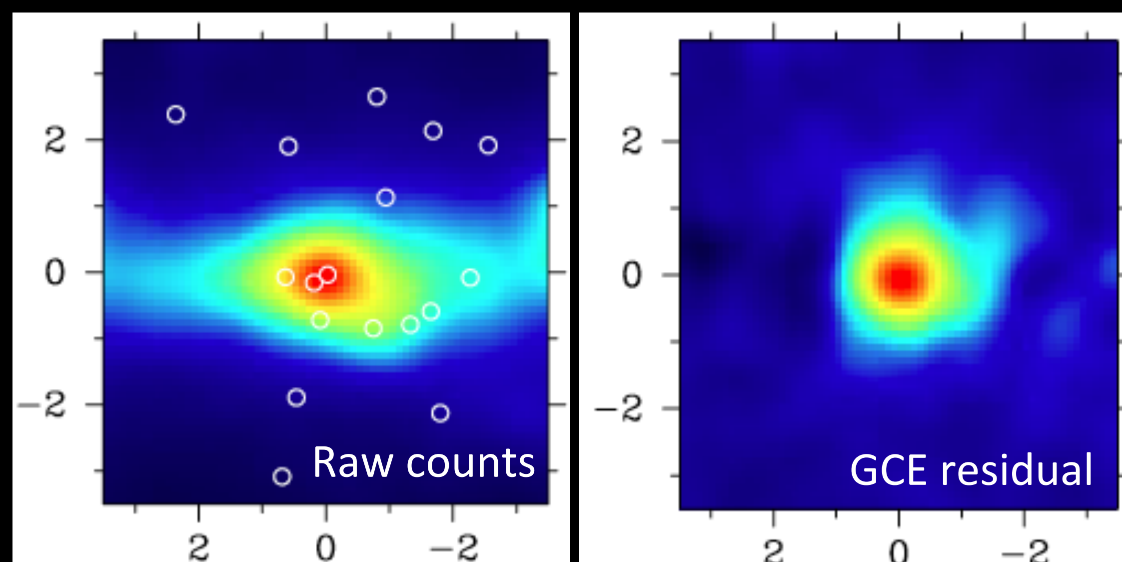


Hooper & Linden (2011)

- *Fermilab/U Chicago: Hooper, Linden*
- *Hardard/MIT: Finkebeiner, Slatyer, Daylan*
- *Leiden/Lausanne: Boyarsky, Rochaysky*
- *Christchurch: Gordon Macias*
- *UC Irvine: Abazajian, Canac, Horiuchi, Kaplinghat*

If interpreted as dark matter, these imply:

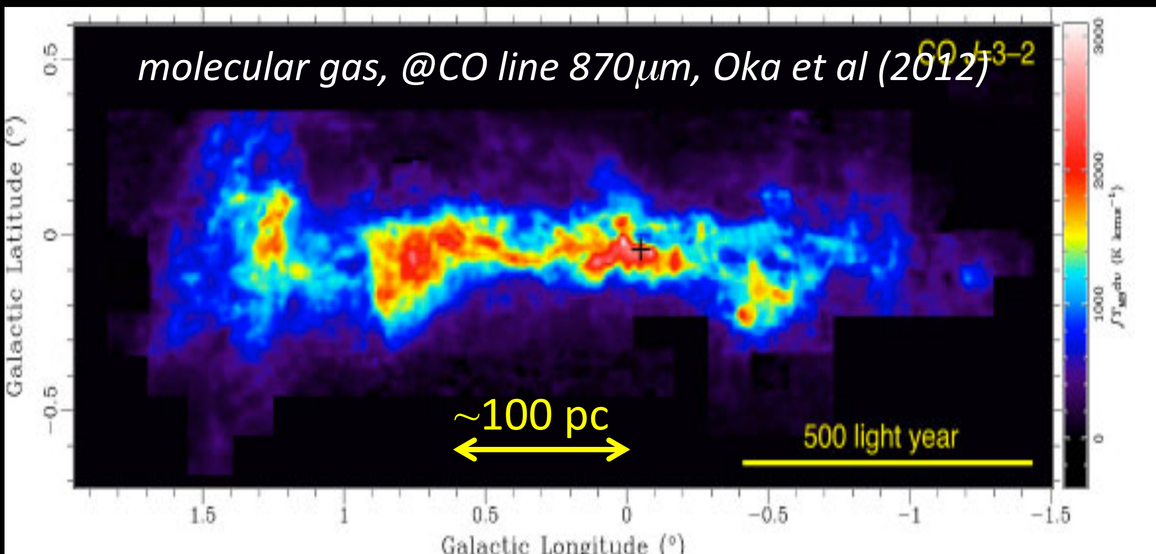
- 10 – 100 GeV mass
- Density scales as $r^{-1.2}$
- Close to thermal σv

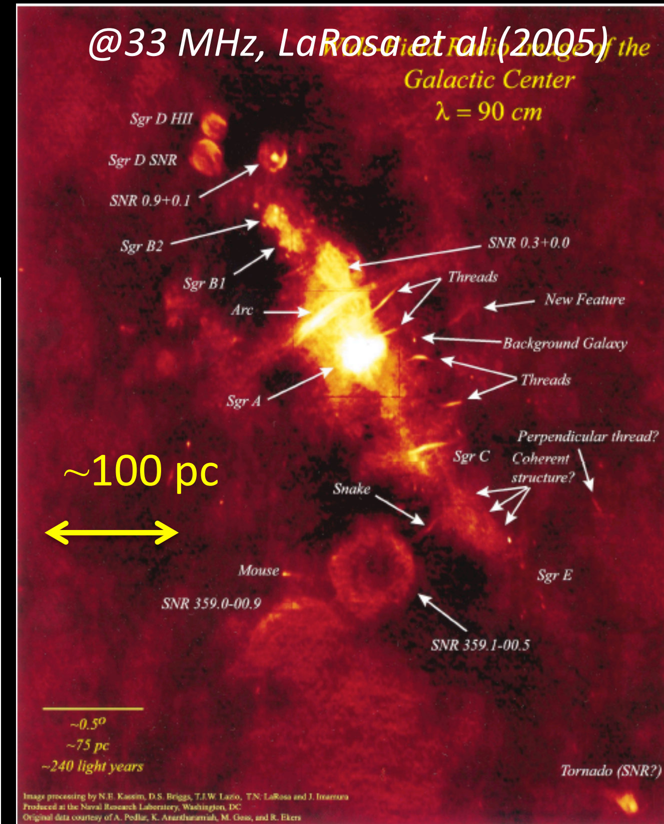


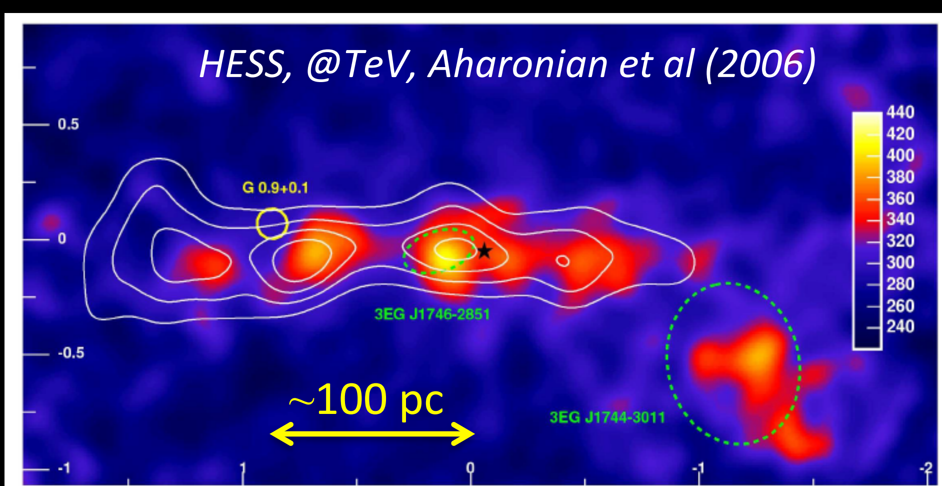
Abazajian & Kaplinghat, PRD 2012

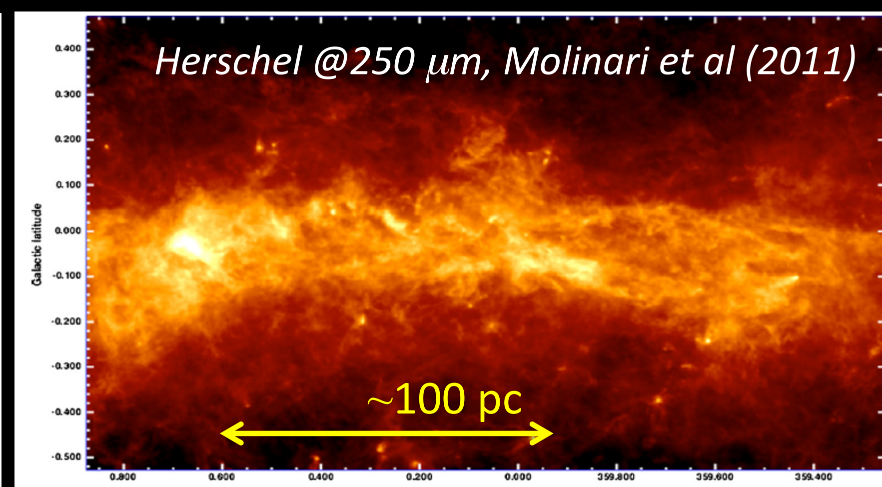
The Galactic Center

We have a wide spectral window view of the Galactic Center showing rich phenomenology

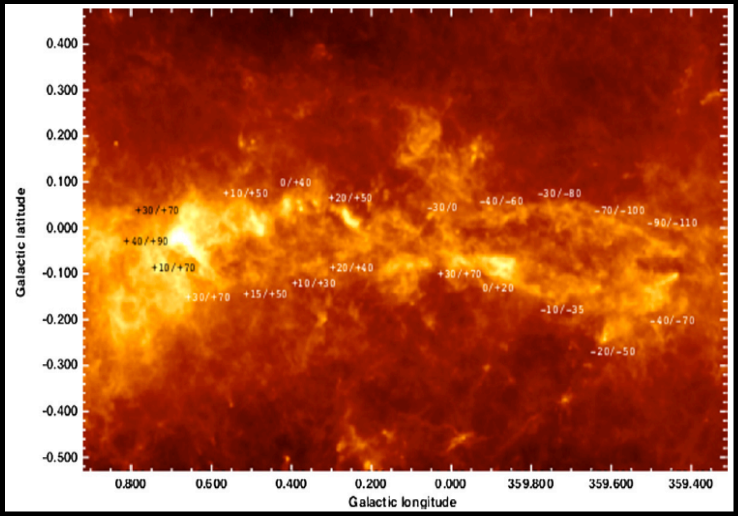




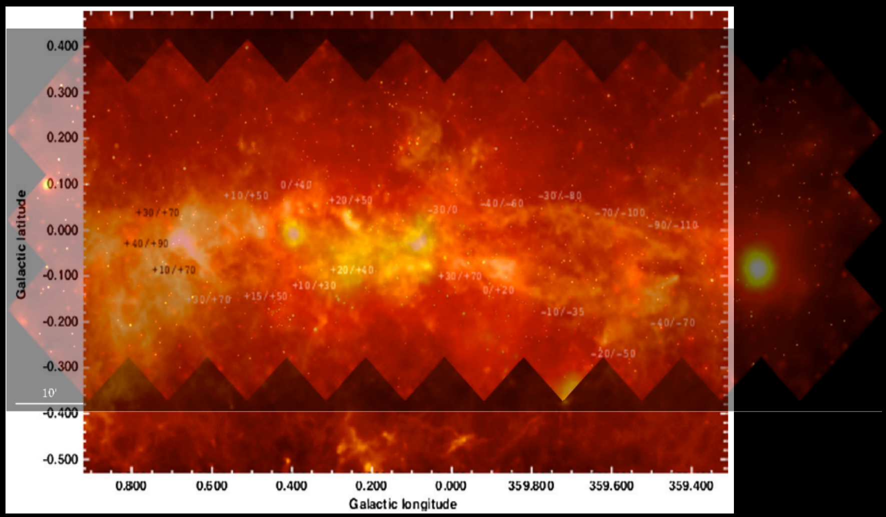




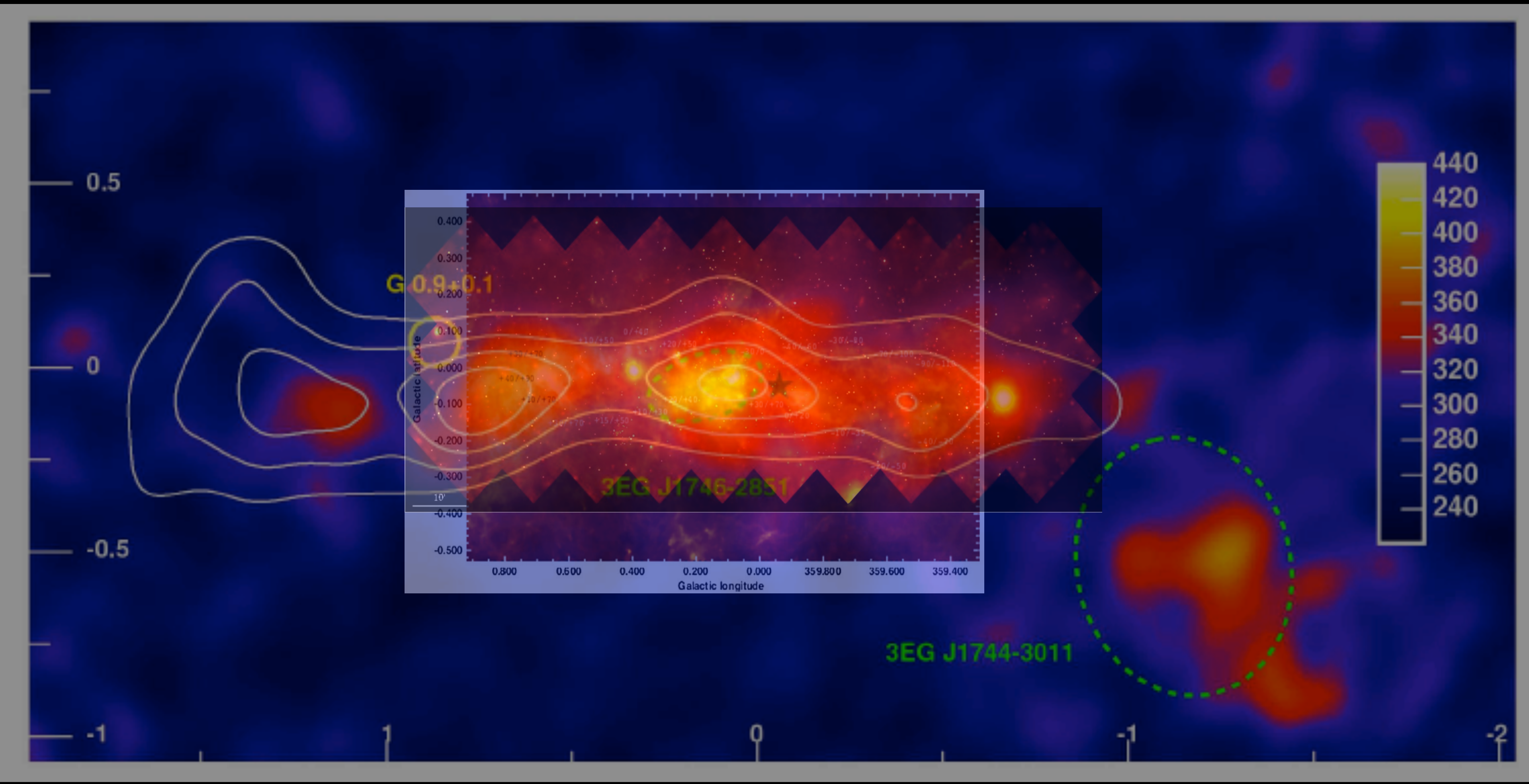
The Galactic Center



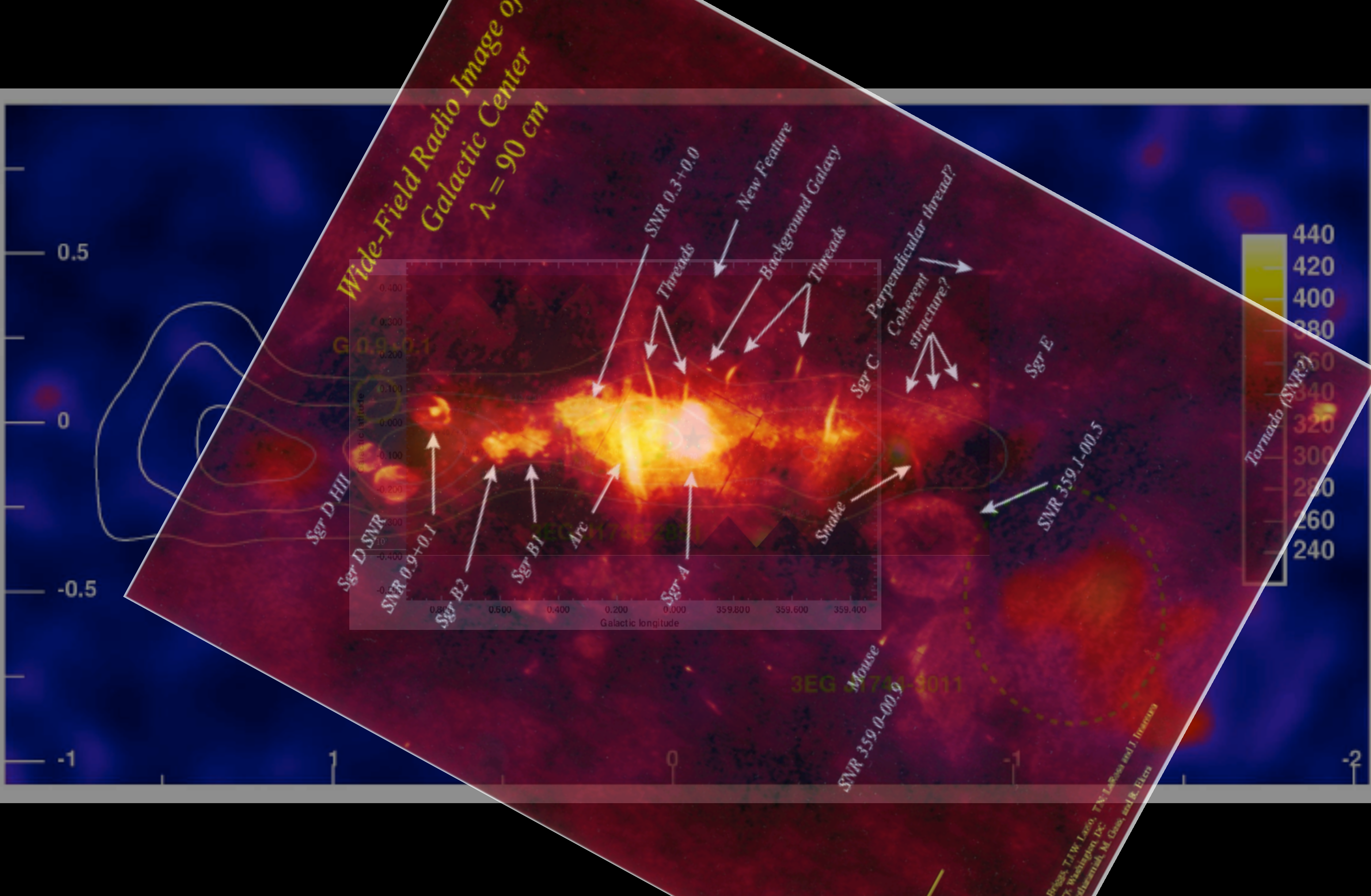
The Galactic Center



The Galactic Center



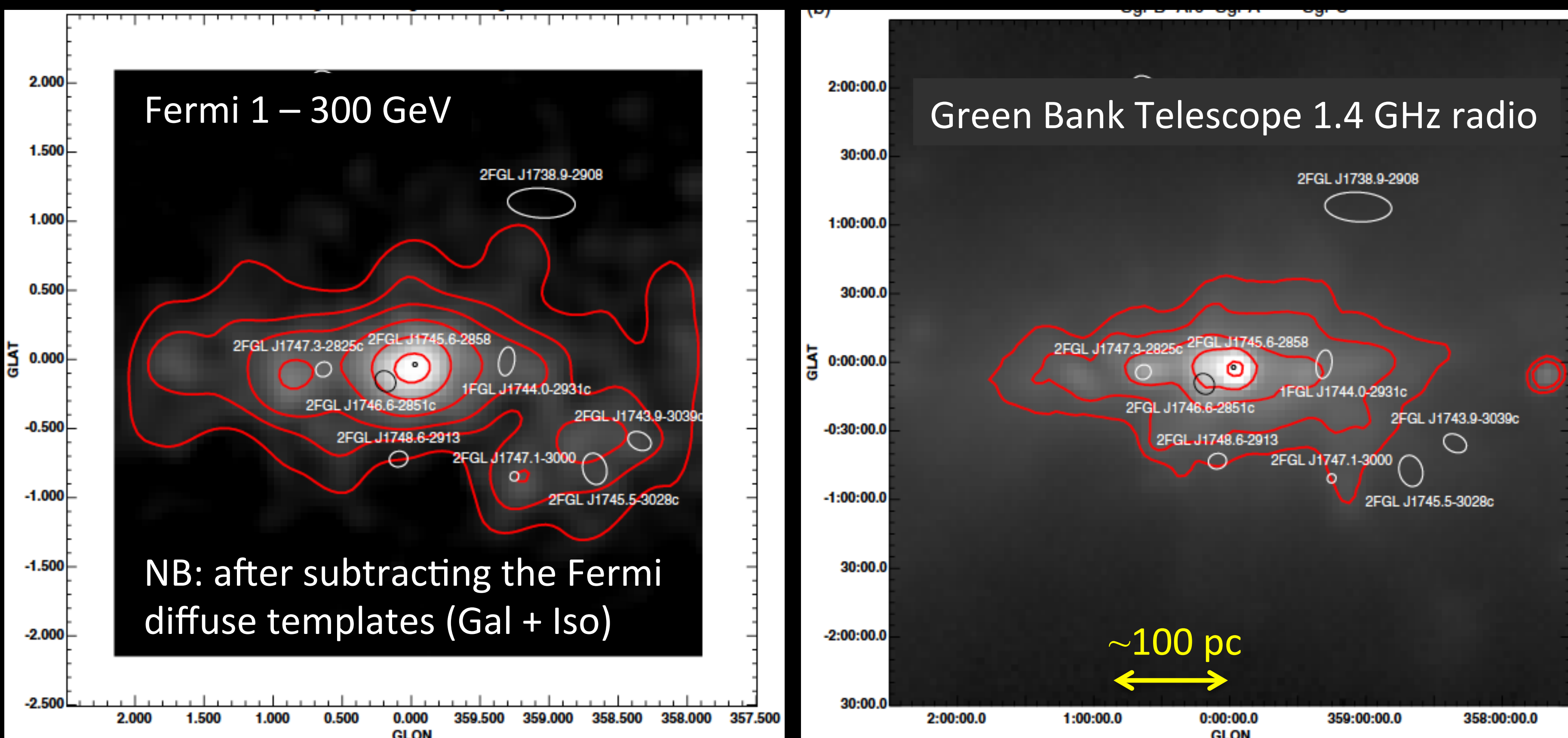
The Galactic Center



Cosmic-ray electrons

- Non-thermal e^- can be probed by @1.4 GHz map
- As argued in Yusef-Zadeh et al (2012), the same e^- will bremsstrahlung on molecular gas nuclei leading to gamma rays
- The similarity of the radio and Fermi maps support a link.
- The scenario also consistently explains X-ray line observations

Yusef-Zadeh et al, ApJ (2012)



Fit procedure

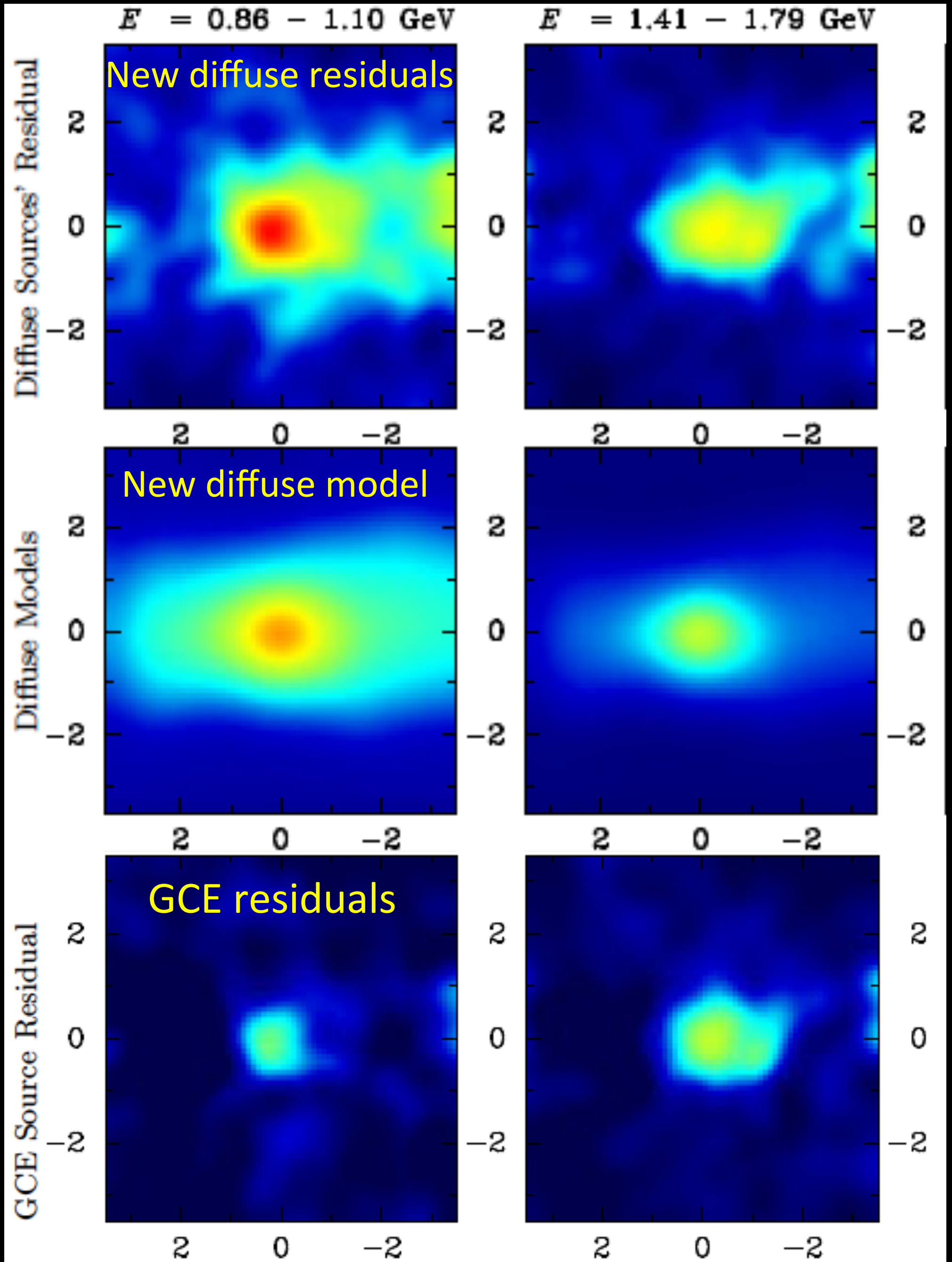
- Use 57 months of public Pass7 data (do not use Pass7REP since they are not recommended for diffuse searches larger than ~2 deg)
  - Unless otherwise stated, use 0.2 – 300 GeV source class photons
- Use the standard Fermi science tools
- Modeled point sources include:
  1. All 2FGL catalogued point sources (17) in the ROI (7x7 deg^2)
  2. Two point sources not in 2FGL detected with high significance ($\Delta \ln L > 25$)
- Modeled diffuse sources include:
  3. The galactic diffuse-emission model provided by the Fermi Collaboration
  4. The isotropic emission model provided by the Fermi Collaboration
  5. The Greenbank Telescope 1.4 GHz map [NEW]
  6. A power-law $\theta^{-\Gamma}$ morphology source [NEW]
  7. An isotropic uniform offset [in which case #4 is kept constant]
  8. The GCE source with $r^{-\gamma}$ morphology

Detections

Use the standard Fermi analysis tools to model the instrument response, and perform studies including the new diffuse template:

- The new diffuse source is detected with high significance ($\Delta \ln L$ improvement of ~503)
- The Galactic Center Excess continue to be detected at high significance ($\Delta \ln L$ improvement of ~85)

NB: Fermi collaboration criteria for point source detection is $\Delta \ln L = 25$



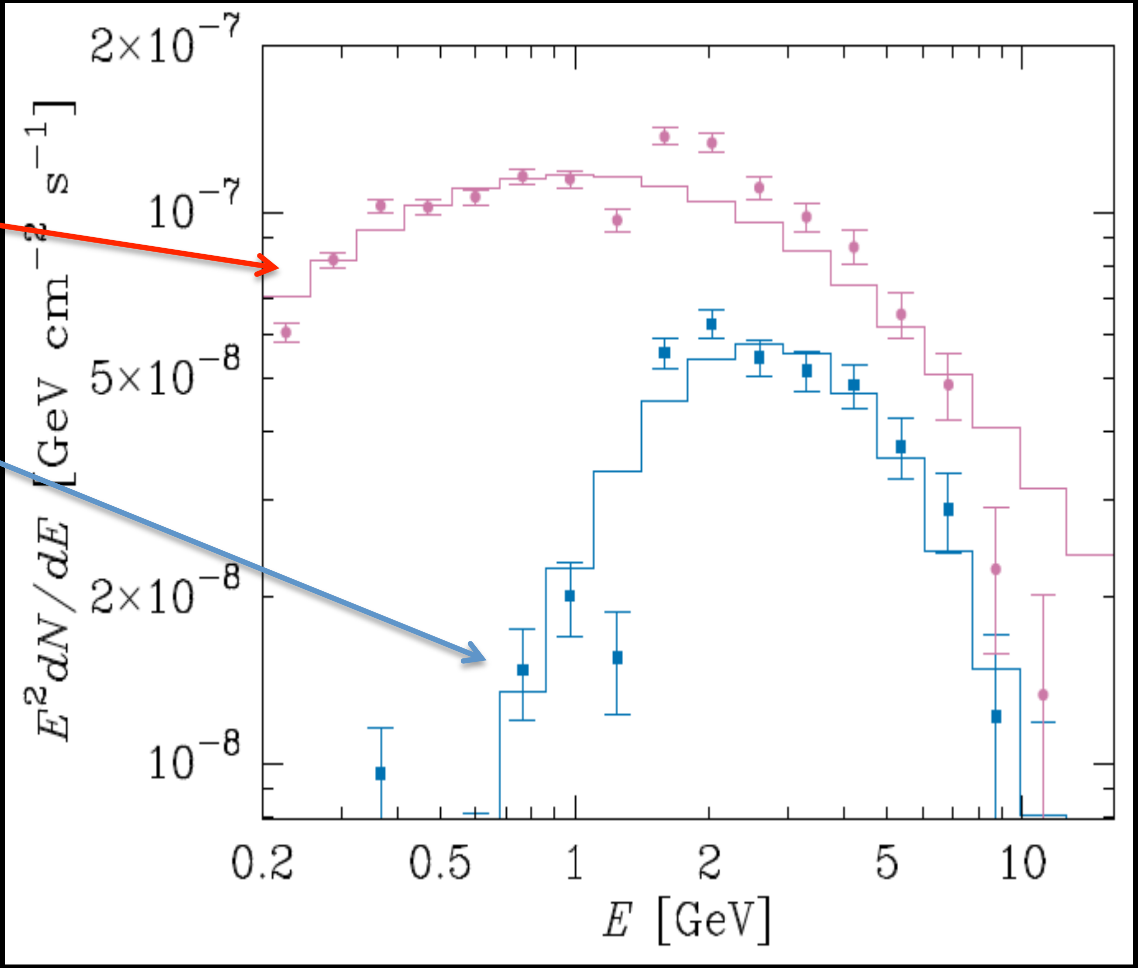
GCE spectrum

When the new diffuse sources (isotropic + 1.4 GHz + power-law) are included, the best-fit GCE spectrum changes dramatically more than the statistical uncertainties

Diffuse sources similar to previous studies

With the new diffuse sources (isotropic + 1.4GHz + power-law source)

The change is especially striking at low energies, which impact both the dark matter and pulsar interpretations of the GCE

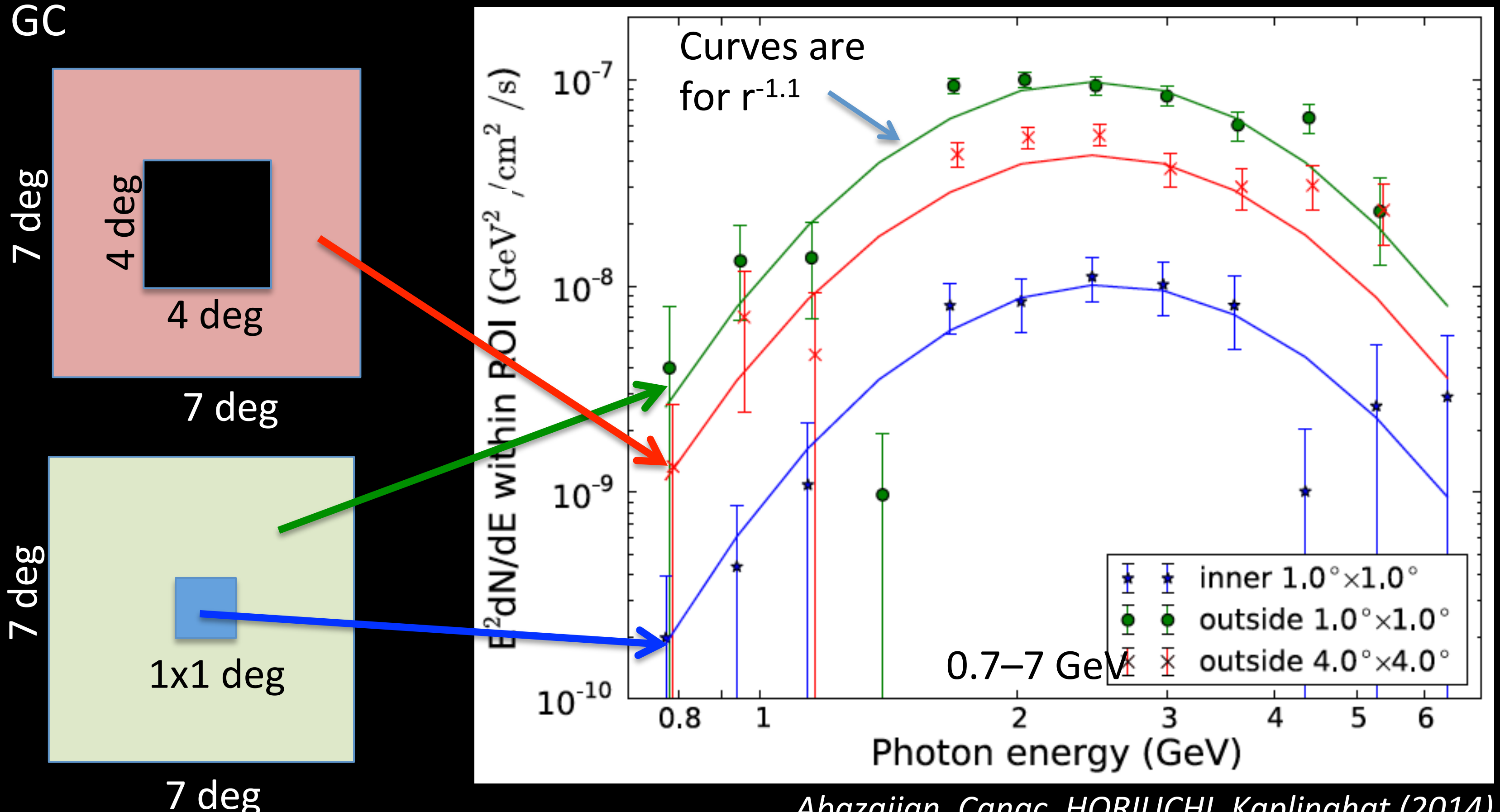


Abazajian, Canac, HORIUCHI, Kaplinghat (2014)

GCE spatial morphology

With the inclusion of the new diffuse sources (isotropic + 1.4 GHz + power-law source), the best-fit GCE morphology follows $r^{2\gamma}$ with $\gamma = -1.12 \pm 0.05$ (1σ).

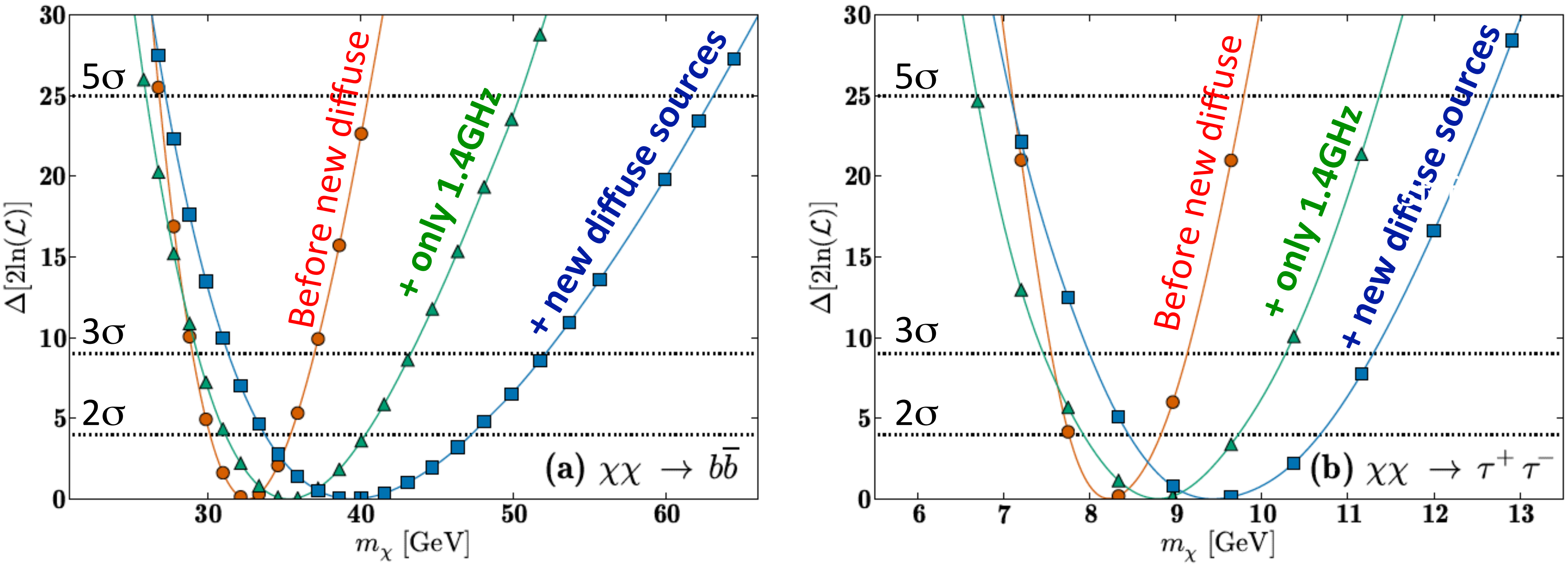
The morphological fit is robust: it is supported by data at various distances from the GC



Abazajian, Canac, HORIUCHI, Kaplinghat (2014)

Impact on dark matter interpretation

The best-fit uncertainty is dominated by systematics:



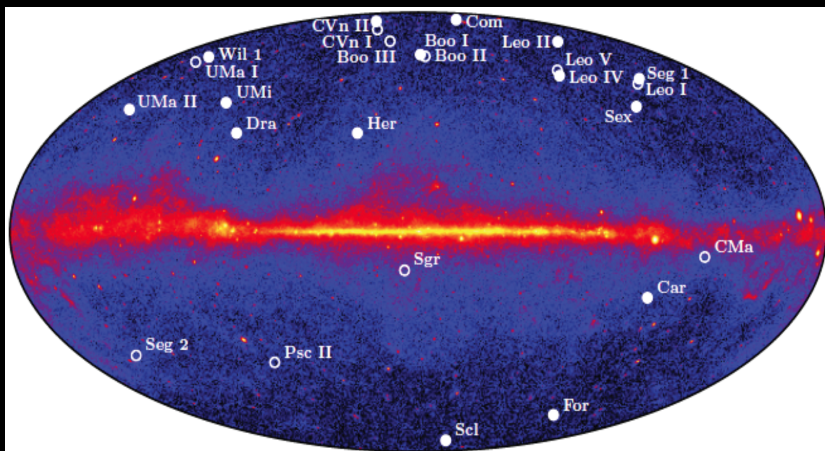
Abazajian, Canac, HORIUCHI, Kaplinghat (2014)

- Both channels are equally good fits.
- The mass is well determined to within ~10 – 20%.
- Bremsstrahlung softens the spectrum (*Cirelli et al 2013*), giving higher mass
  bb: ~40.9 GeV ττ: ~10.2 GeV

bb:
$$m_\chi = 39.4\left(^{+3.7}_{-2.9}\text{ stat.}\right)(\pm 7.9\text{ sys.})\ \text{GeV}$$
$$\langle\sigma v\rangle_{b\bar{b}} = (5.1 \pm 2.4)\times 10^{-26}\ \text{cm}^3\ \text{s}^{-1},$$

ττ:
$$m_\chi = 9.43\left(^{+0.63}_{-0.52}\text{ stat.}\right)(\pm 1.2\text{ sys.})\ \text{GeV}$$
$$\langle\sigma v\rangle_{\tau^+\tau^-} = (0.51 \pm 0.24)\times 10^{-26}\ \text{cm}^3\ \text{s}^{-1},$$

Consistency with other limits

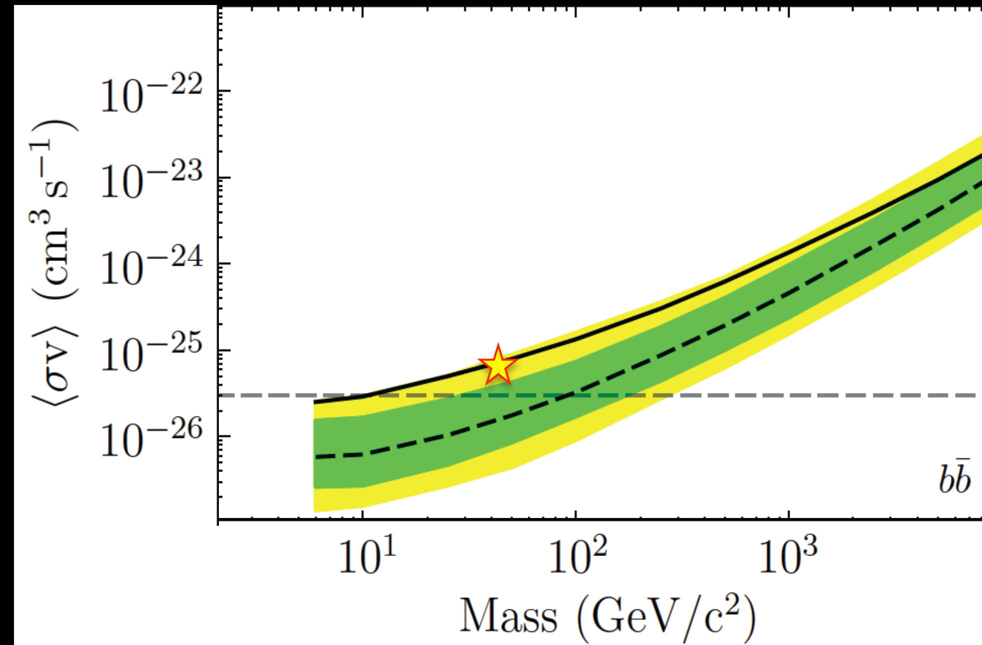


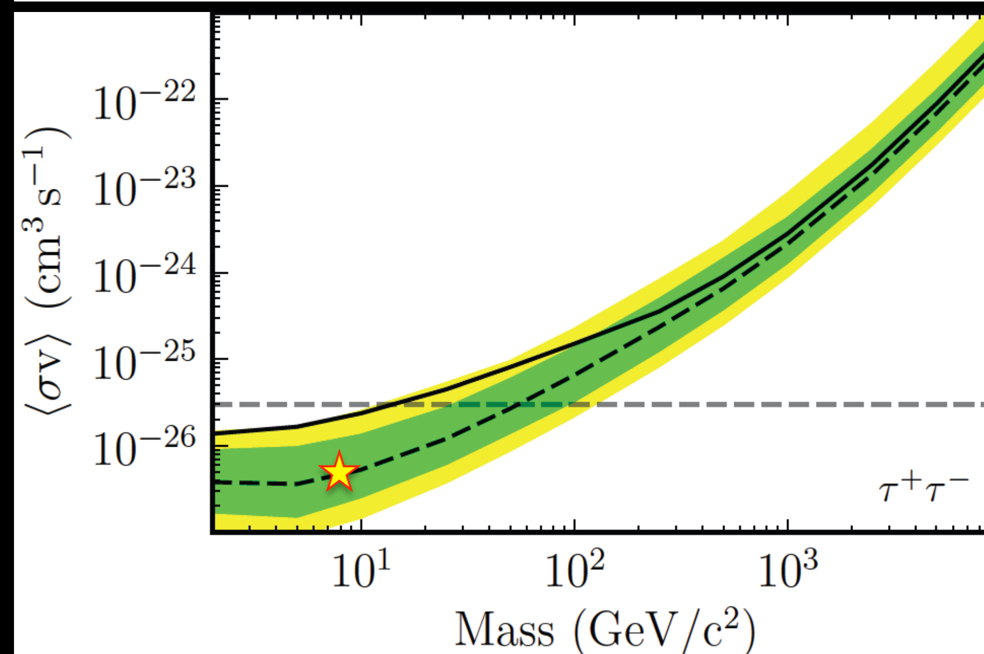
- Dwarf limits: strong limits set on annihilation; the GCE is currently consistent with these

Ackerman et al (2013)

- Direct detection: strong spin-independent scattering cross section (e.g., LUX); can also evade these

e.g., Boehm et al (2014)





Can the GCE be due to pulsars?

Differences between the GCE and MSP spectra in the low-energy region, but this region is dominated by systematic uncertainties due to the diffuse modeling.

Above E ~ 2 GeV, the best-fit GCE match well, and the spectra are in agreement with MSPs.

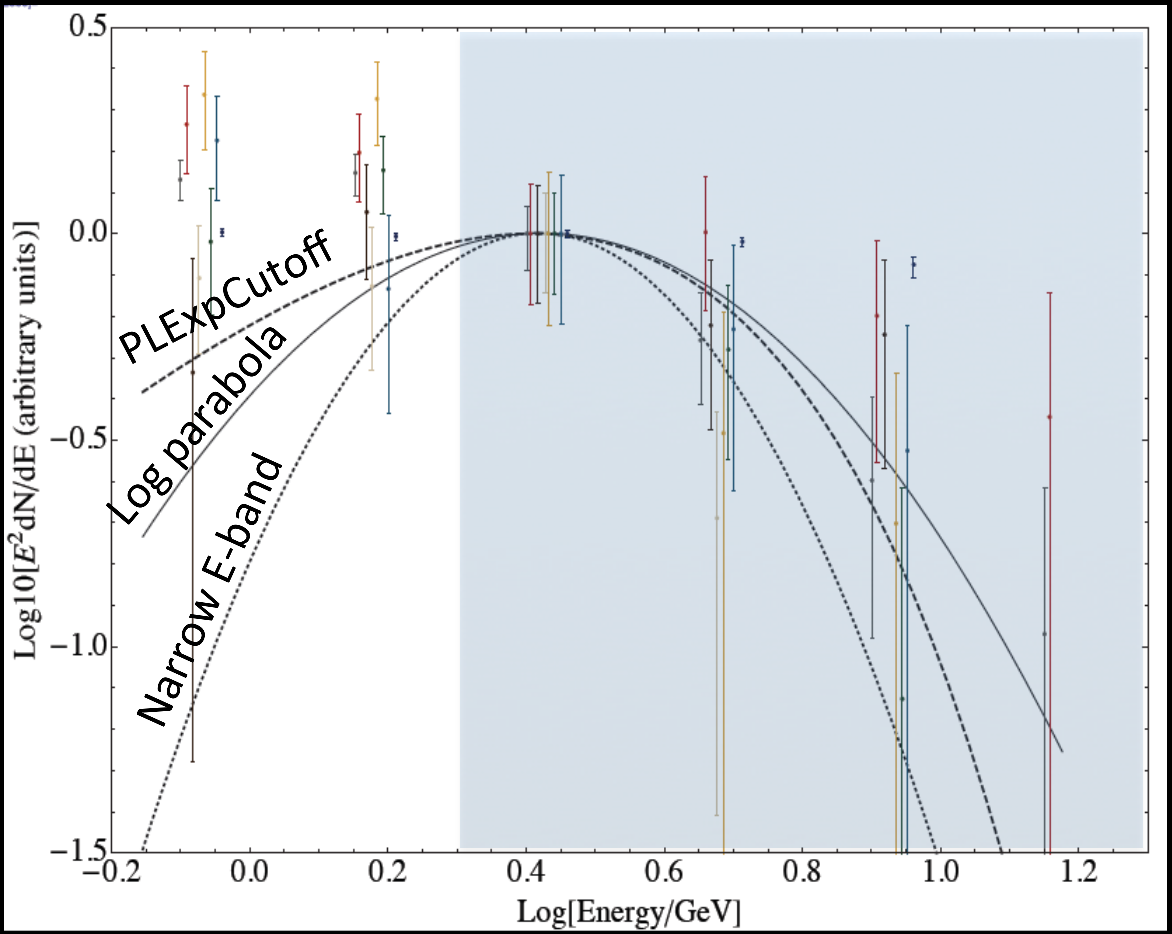
The number of MSPs required can be estimated from energetics, e.g.:

$$N_{\rm MSP}^{\rm 47Tuc} \frac{E_{\rm GCE}^{>2{\rm GeV}}}{E_{\rm MSP,47Tuc}^{>2{\rm GeV}}}$$

➔ Needs 3700 – 4800 MSPs.

cf stellar mass ~10^9 Msun

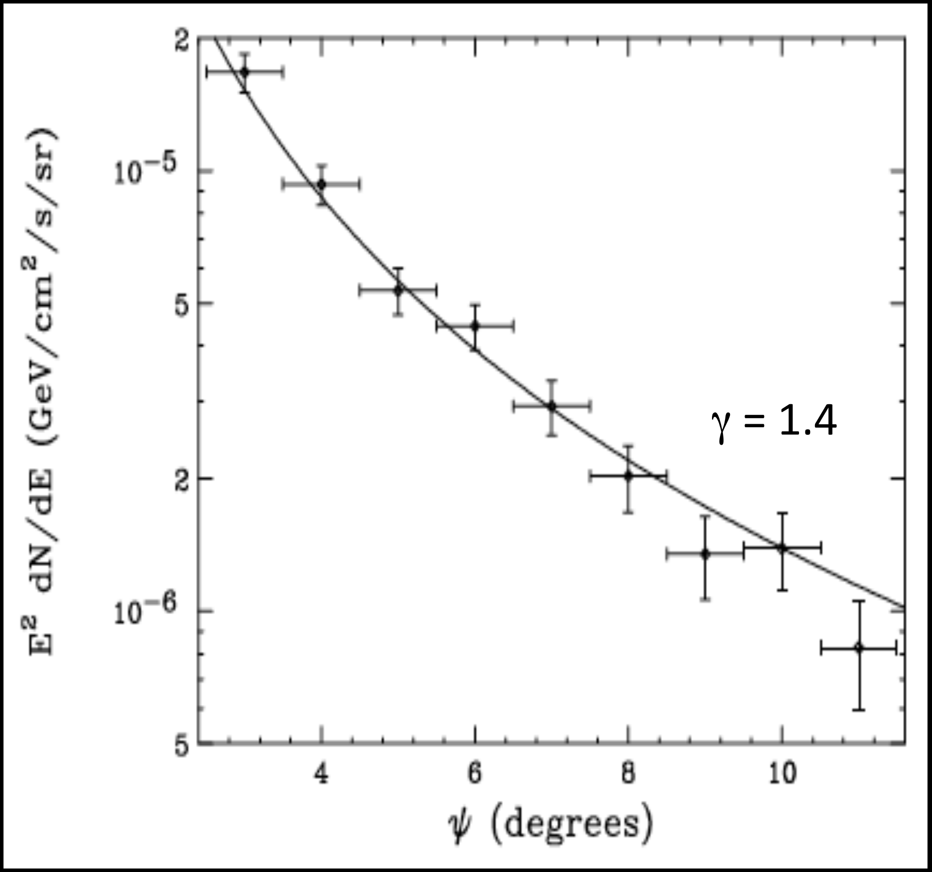
e.g., Abazajian (2011)



Abazajian, Canac, HORIUCHI, Kaplinghat (2014)

GCE signal in the inner galaxy?

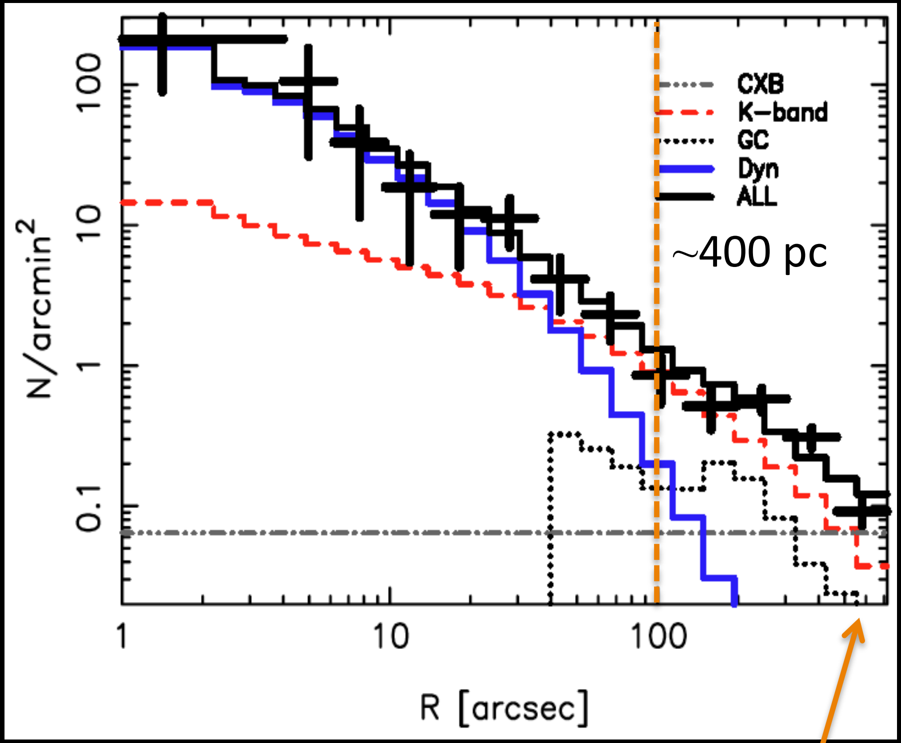
GCE-like signal may reach ~10 degree



Daylan et al (2014), also Hooper & Slatyer (2012)

Millisecond pulsar?

Using M31 X-ray binaries as a template, distribution ~consistent with GCE



Voss & Gilfanov, A&A (2007)

~15 deg equiv

Not inconsistent with MSP when luminosity function is relaxed

Yuan & Zhang (2014)

Conclusions

- Galactic Center GeV Excess (GCE): triple coincidence with ~vanilla dark matter predictions gathering interest

- However, the Galactic Center is a complex region
  → motivates constant improvement of background modeling
  → We specifically explored emission with spatial morphology of the 1.4GHz radio map, probing cosmic-ray e^- interaction on molecular gas

- The GCE is detected at high significance. However, determination of GCE properties – its low-energy spectrum in particular – is systematics dominated. Currently:
    - The DM mass is determined well, at better than ~20%
    - bbar and $\tau^+\tau^-$ channels are equally favored
- MSP interpretation remains viable with some modifications to observed MSP

Thank you!

BACKUP

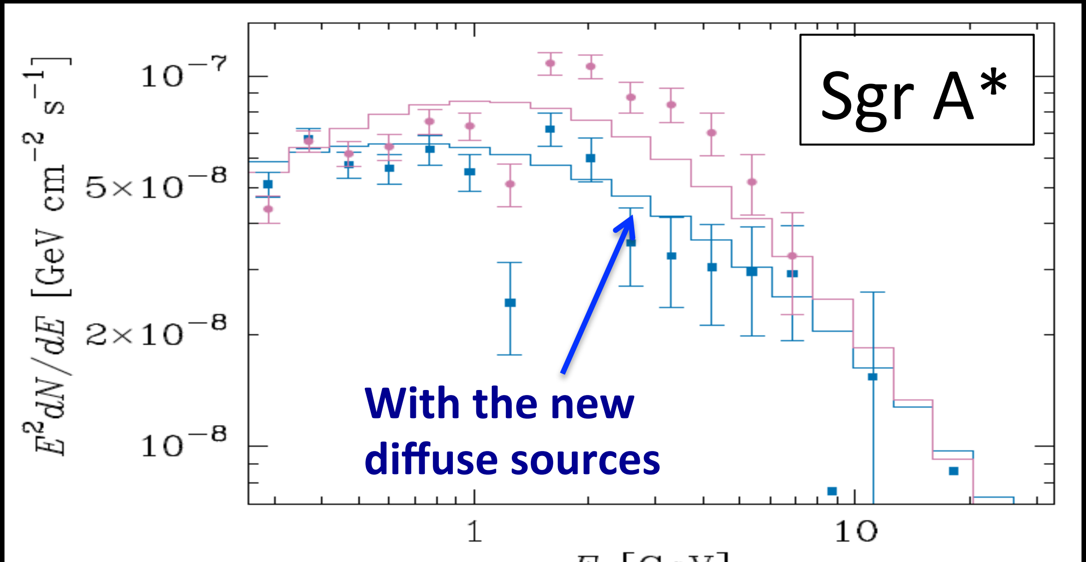
Impact on Point Sources

The new diffuse sources affect best fits of point sources in the ROI as well.

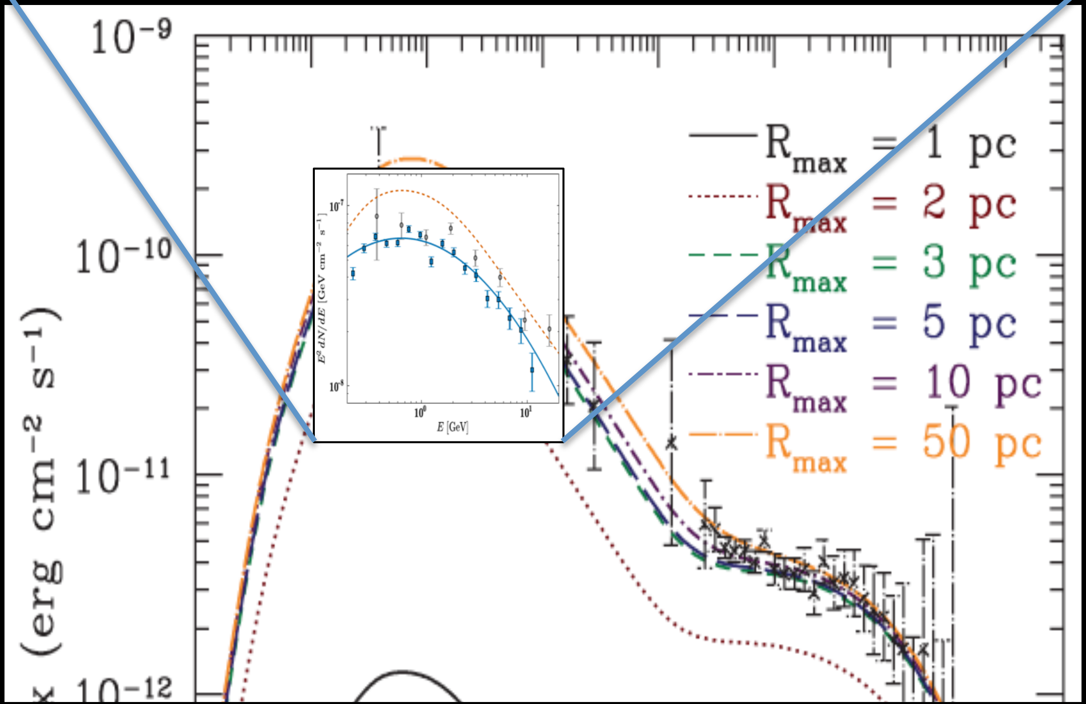
In particular, the Sgr A* spectrum becomes less curved and more power-law like with index -2.3

Under the hadronic scenario, the GeV emission comes from diffusively escaping protons → the new Sgr A* spectrum implies reduced diffusion, reduced diffusion region size, or reduced activity.

Chernyakova et al (2011)
Linden & Profumo (2012)



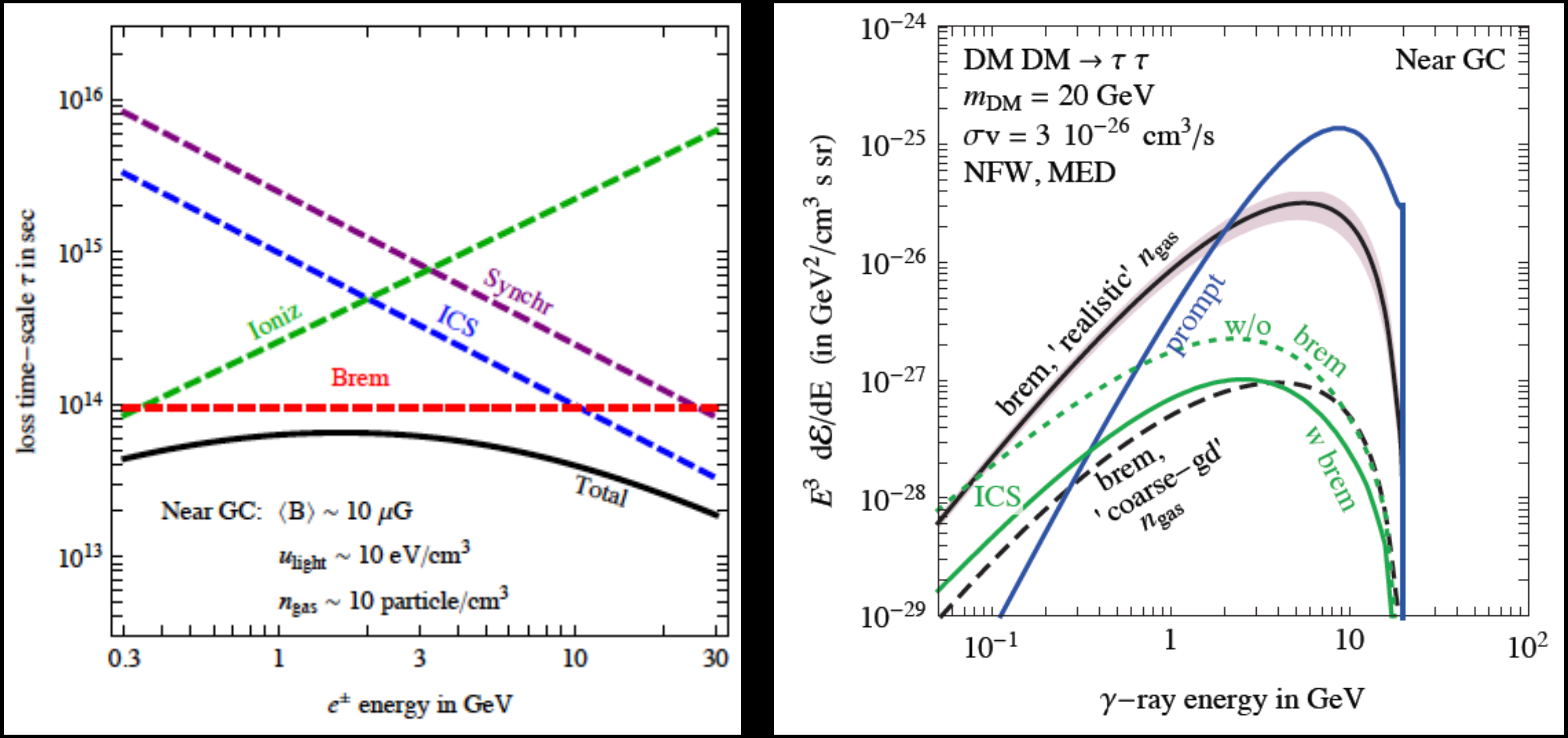
Abazajian et al (2014)



Linden & Profumo (2012)

Bremsstrahlung modification

Bremsstrahlung effects of the annihilation products tend to soften the gamma ray spectrum.
The exact effect is astro model-dependent.
The softer spectrum results in an increased best-fit DM mass:
bb: ~40.9 GeV   ττ: ~10.2 GeV

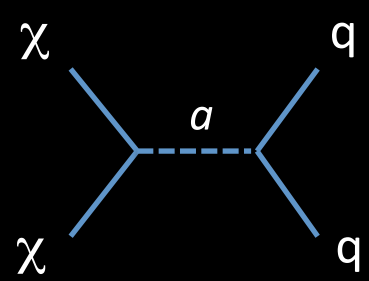


Cirelli et al (2013)

Connection to Direct Detections

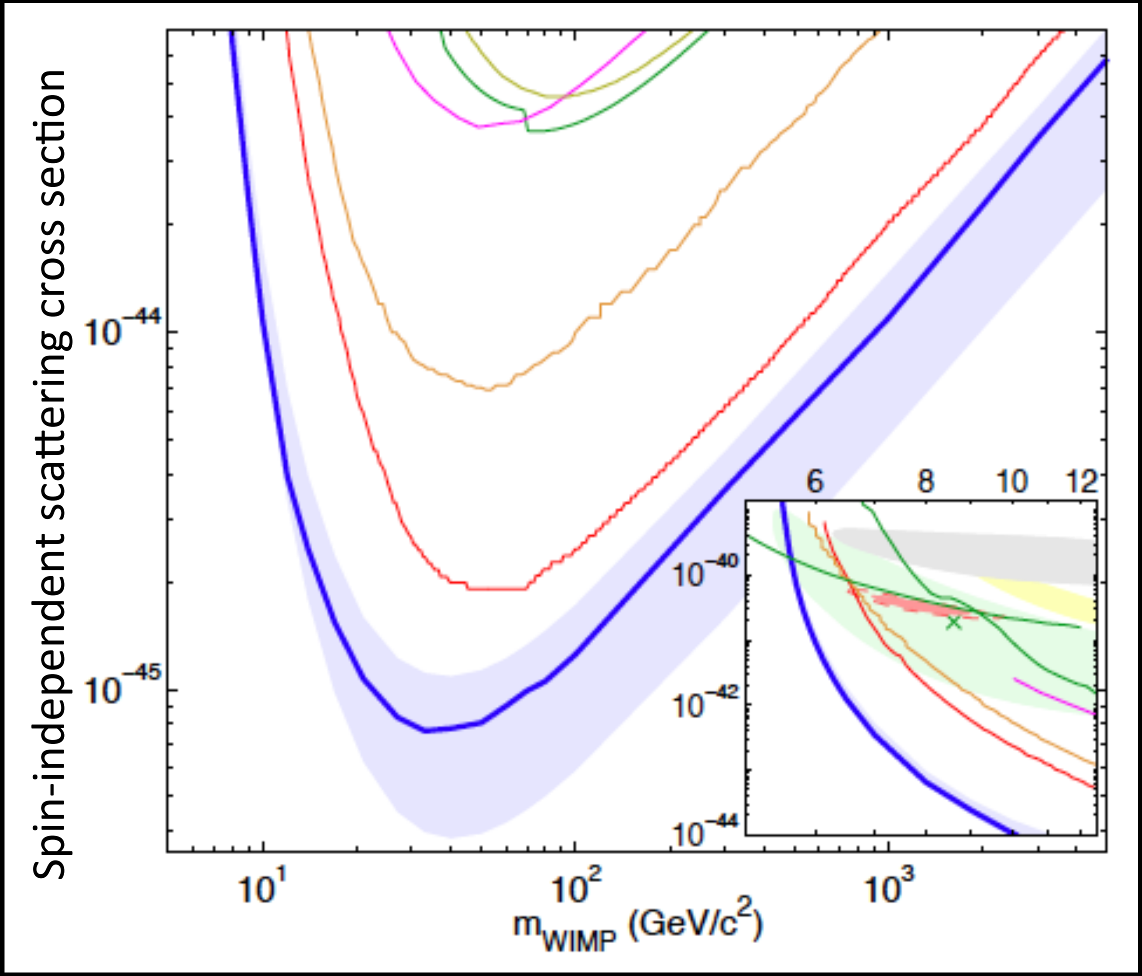
Very strong limits from e.g., LUX (Xe)

Limits can be evaded, e.g., if the interaction is mediated by a light (~10GeV) pseudo-scalar *a* with Yukawa couplings to the SM



The scattering cross section is spin-dependent and velocity-suppressed

e.g., Boehm et al (2014)



LUX, PRL (2014)

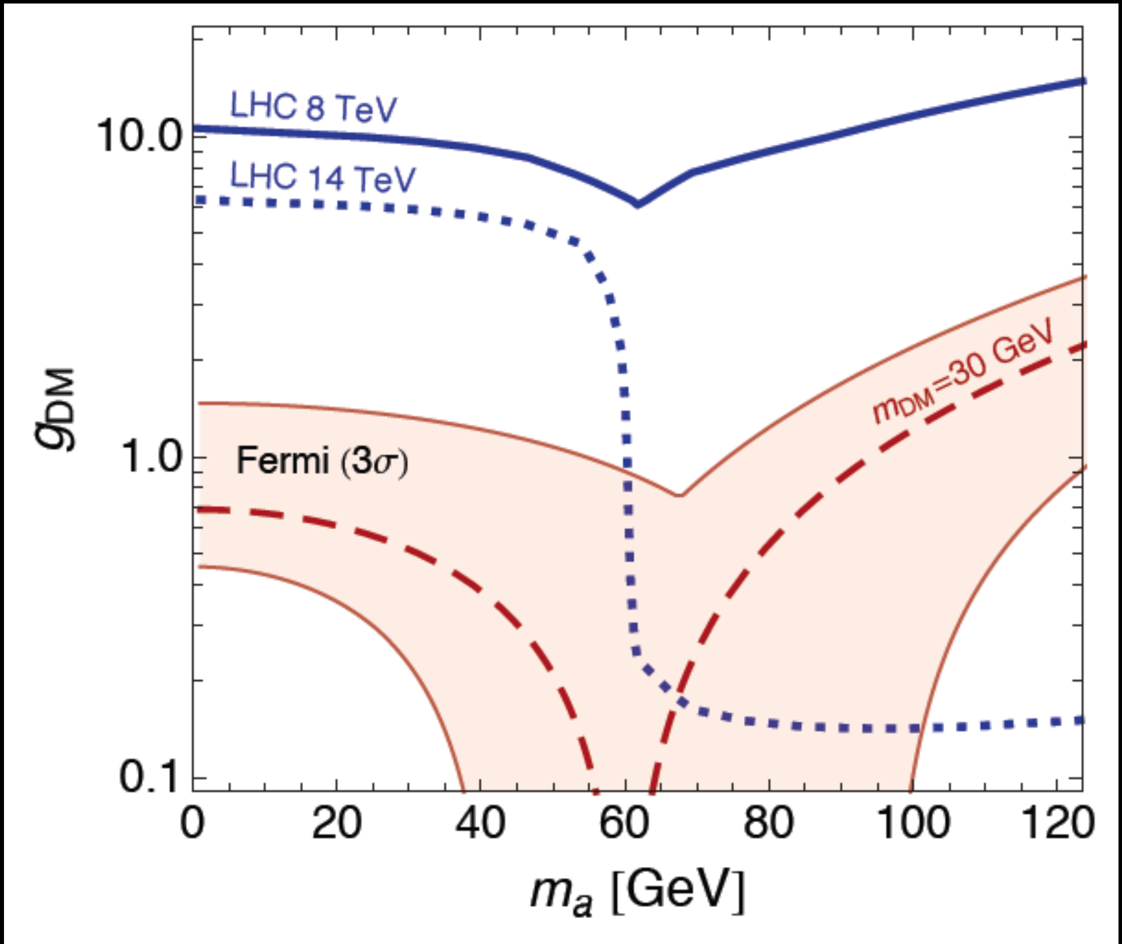
Connection to collider constraints

No constraints on the presedoscalar scenario at the moment.

Monojet search @LHC:
Limits large g_{DM}, not yet reaches values required by the GCE

Higgs → aa decay @LHC:
For $m_a < m_h / 2$

@LEP, Tevatron:
Pseudoscalar—massive vector boson coupling suppressed



Boehm et al (2014)

Other annihilation constraints

Clusters:
Gamma-ray search from Galaxy clusters; dependent on CR backgrounds, point sources, and uncertain boost factor, but can be constraining

Han et al (2012)

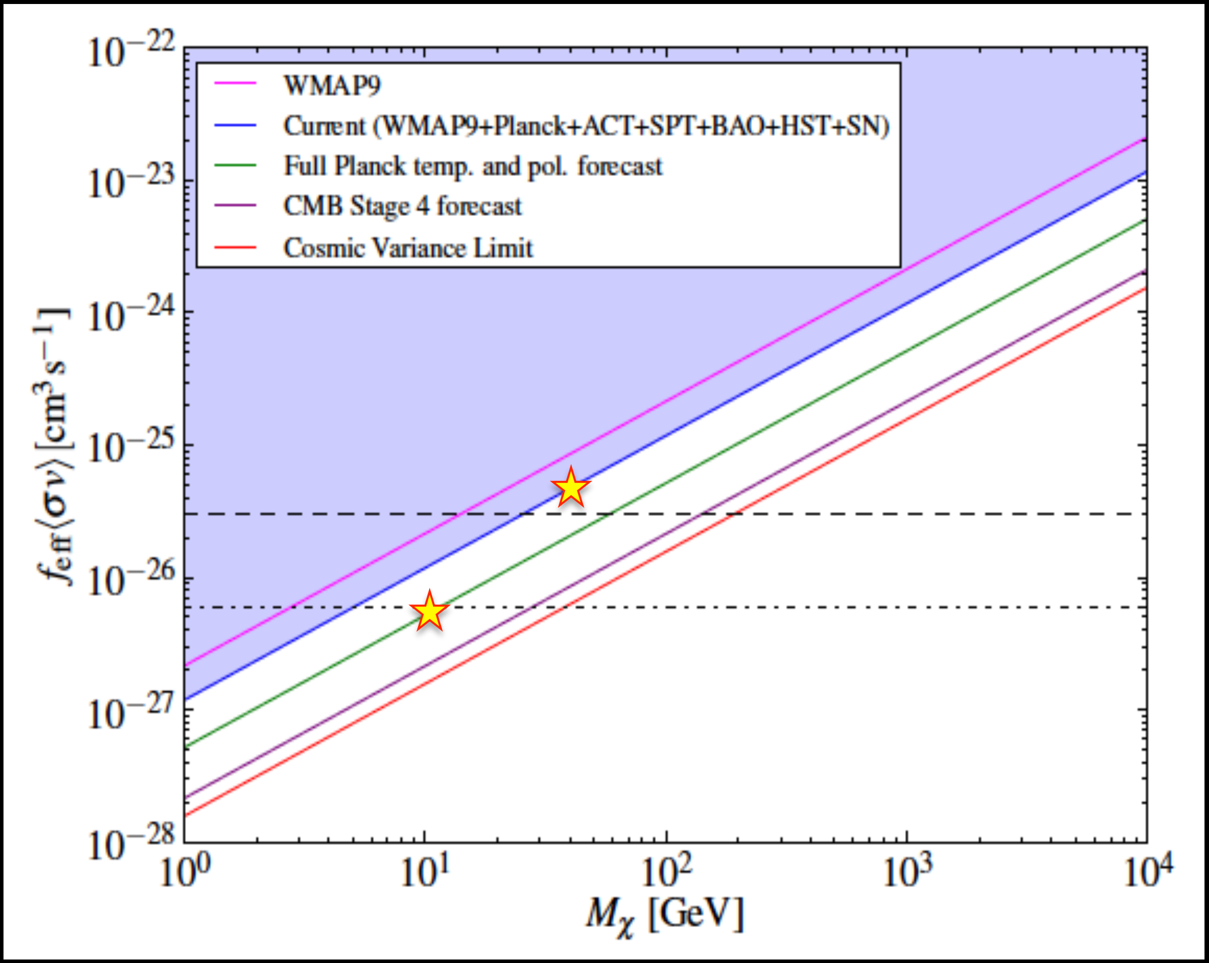
CMB:
Calorimetric measure of DM annihilation, not quite there yet

Madhavacheril et al (2013)

Anisotropy:
Gamma-ray anisotropy limits DM annihilation; not quite there yet

Ando & Komatsu (2012)

CMB limit

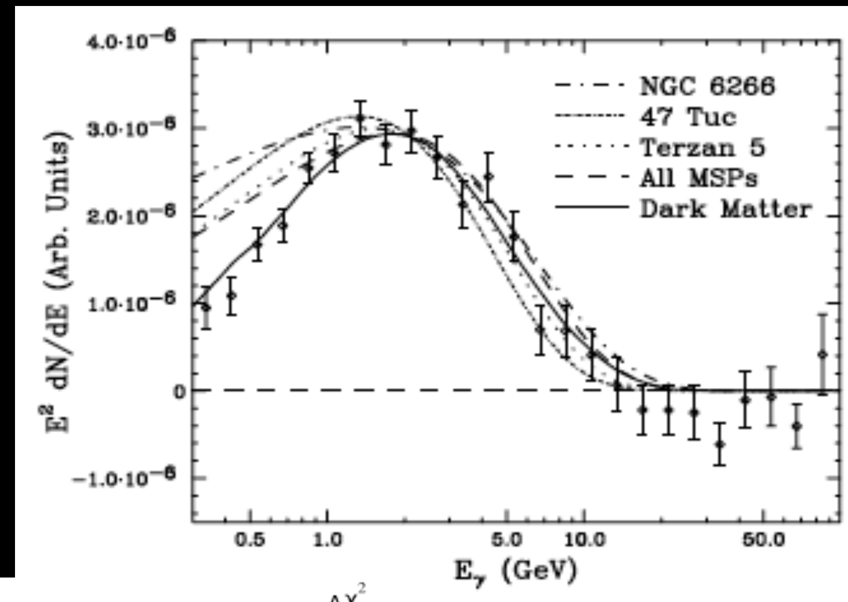


Madhavacheril et al (2013)

Can the GCE be due to pulsars?

Some arguments in the literature:

- GCE robustly detected (unlike previous hints)
- GCE requires ~vanilla WIMP (unlike previous)
- GCE doesn't have a simple astro explanation
  - GCE is spherical (to within 20%)
  - GCE is centered on Sgr A*
  - GCE spectrum different from MSP?



Daylan et al 2014