Analysis of Fermi LAT gamma-ray data near the Galactic center

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on behalf of the Fermi LAT collaboration

La Thuile
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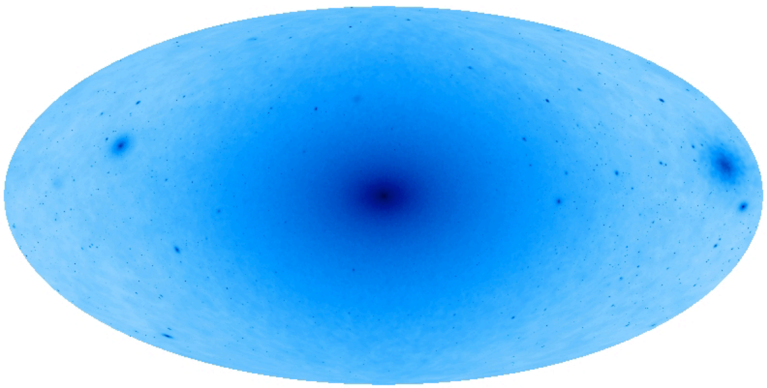
Plan

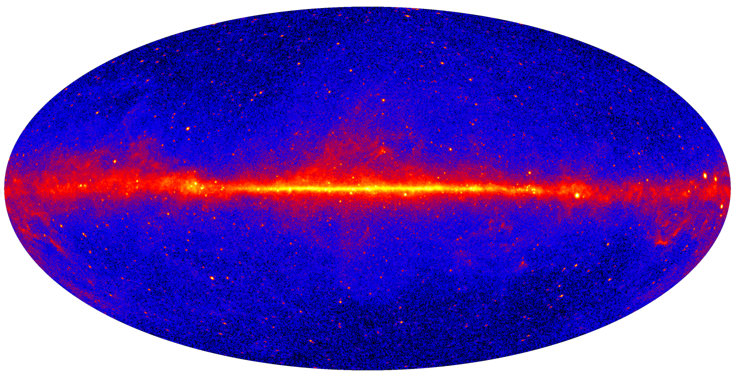
- Motivation
  - Dark matter (DM) annihilation and Galactic center (GC) 3 GeV gamma-ray excess
- Fermi-LAT gamma-ray data analysis
  - Estimation of modeling and systematic uncertainties of the GC excess properties
    - Distribution of cosmic-ray sources
    - Distribution of gas towards the GC
    - Fermi bubbles near the GC
- Interpretations of the GC excess
  - DM annihilation
  - Millisecond pulsars (MSPs)
- Future prospects

Dark matter annihilation

- **Is the DM annihilation signal present in the gamma-ray data?**



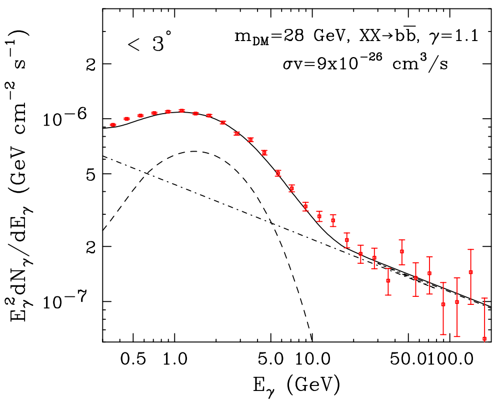
Via Lactea II, Kuhlen et al, Science, 325 (2009)



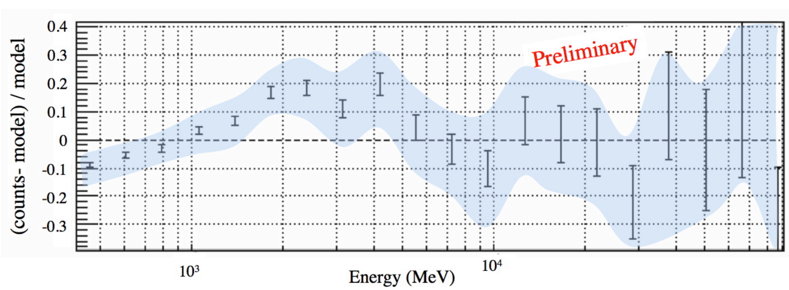
Fermi Large Area Telescope (LAT), 6 years, Pass 8 data

GC excess emission

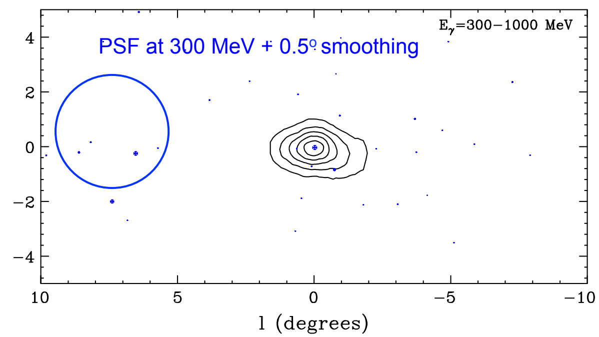
- **First hints of an excess**



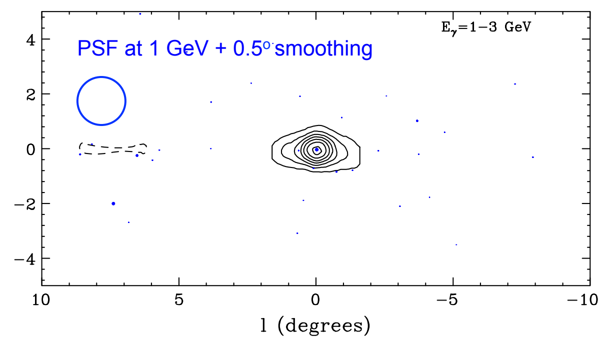
Goodenough & Hooper
arxiv:0910.2998



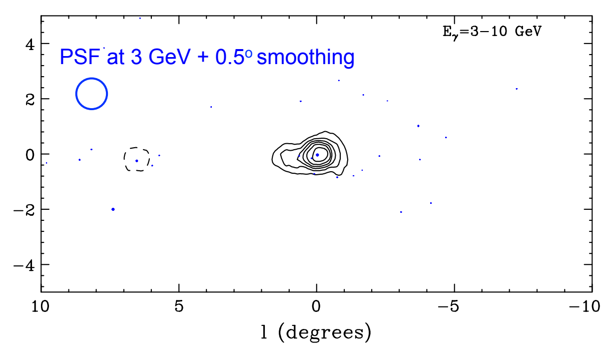
Vitale & Morselli
arxiv:0912.3828



300 MeV – 1 GeV



1 GeV – 3 GeV



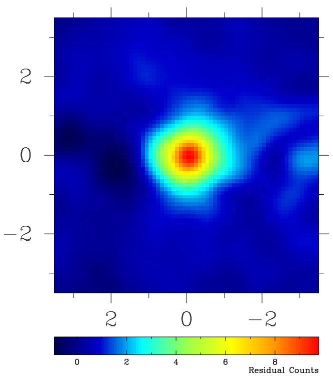
3 GeV – 10 GeV

Hooper & Linden
PRD, 84 (2011)

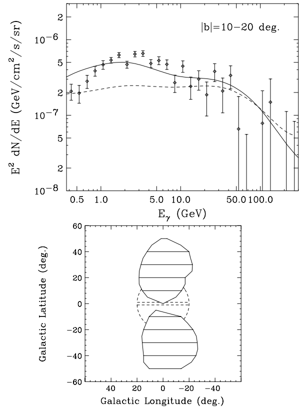
GC excess emission

- **More recent analysis**

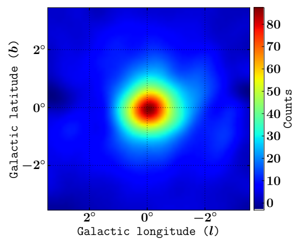
10° – 20° in latitude



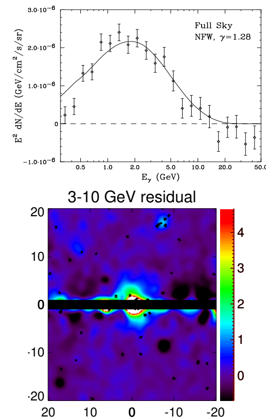
Abazajian & Kaplinghat PRD 87 (2012)



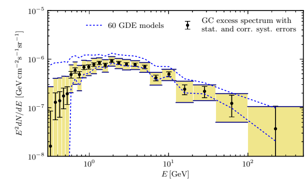
Hooper & Slatyer Phys.Dark Univ. 2 (2013)



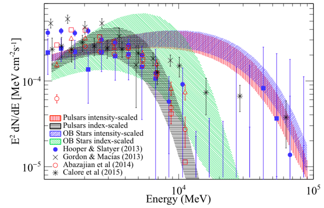
Gordon & Macias PRD 88 (2013)



Daylan et al. Phys.Dark Univ. 12 (2016)



Calore et al. JCAP 1503 (2015)

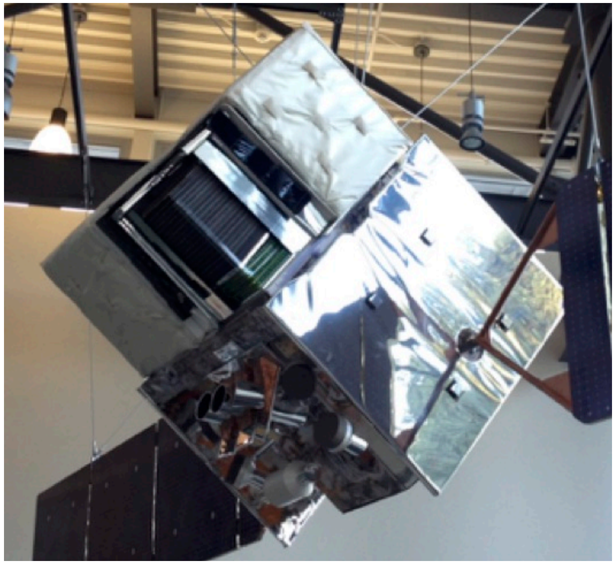


Ajello et al. ApJ 819 (2016)

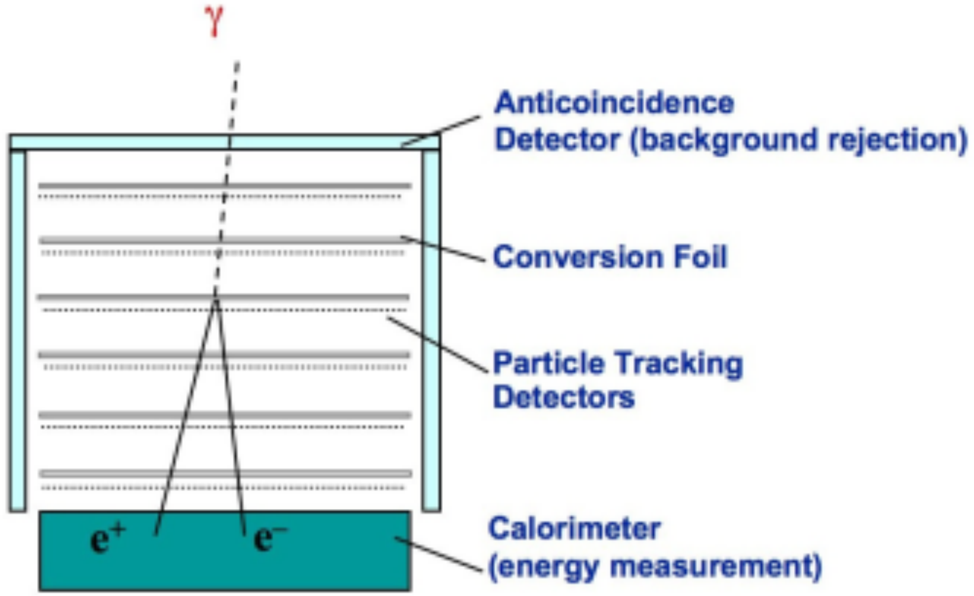
- **Possible interpretations:**
  - **DM annihilation, millisecond pulsars (e.g., Brand&Kocsis 2015), cosmic-ray sources near the GC (e.g., Carlson et al 2016), Fermi bubbles (Yang & Aharonian 2016)**

Fermi LAT

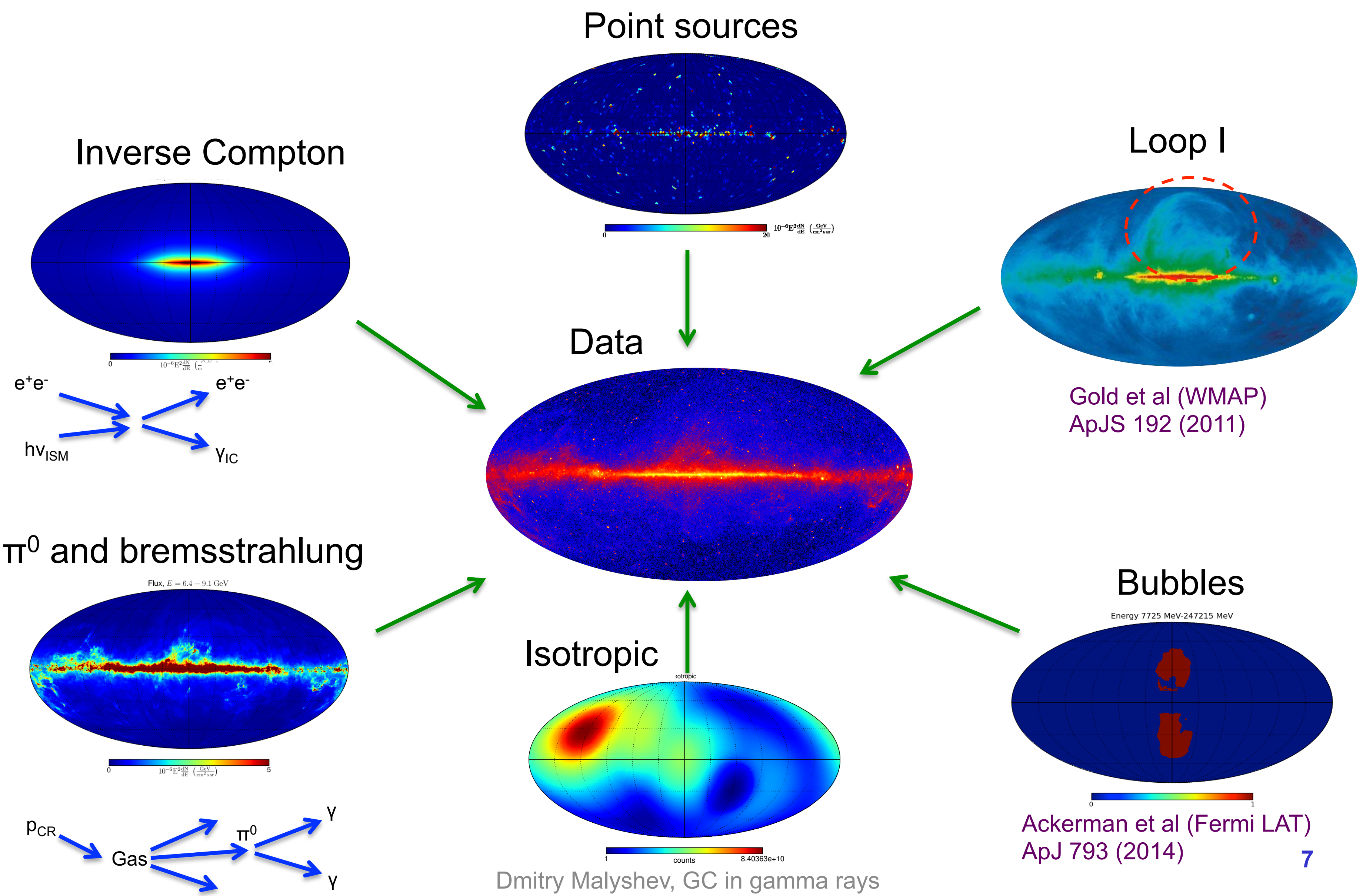
- Fermi Large Area Telescope – gamma-ray space telescope
- Launched on June 11, 2008
  - 2.8 tons, 650 watts
  - 20 MeV to more than 300 GeV
  - 2.4 sr field of view
  - Better than 1° resolution above 1 GeV



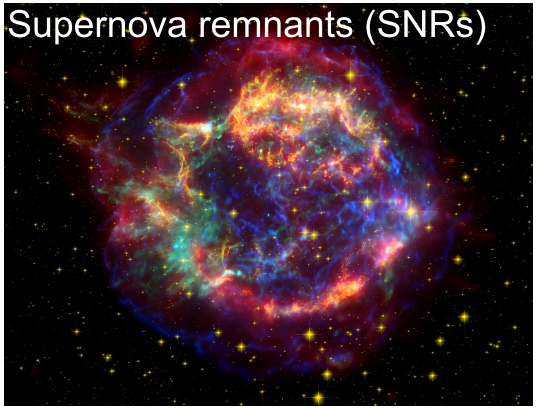
Model (half scale) of the Fermi satellite at SLAC



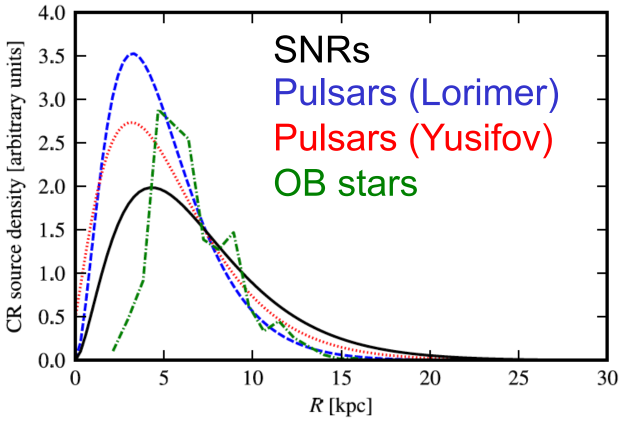
Gamma-ray emission components



Modeling of Galactic Diffuse Emission
CR Sources



Cas A SNR
Spitzer, Hubble, Chandra



Assumption: azimuthal symmetry

Image credit: Nick Risinger. Stars: Anna Franckowiak

Gas-correlated emission

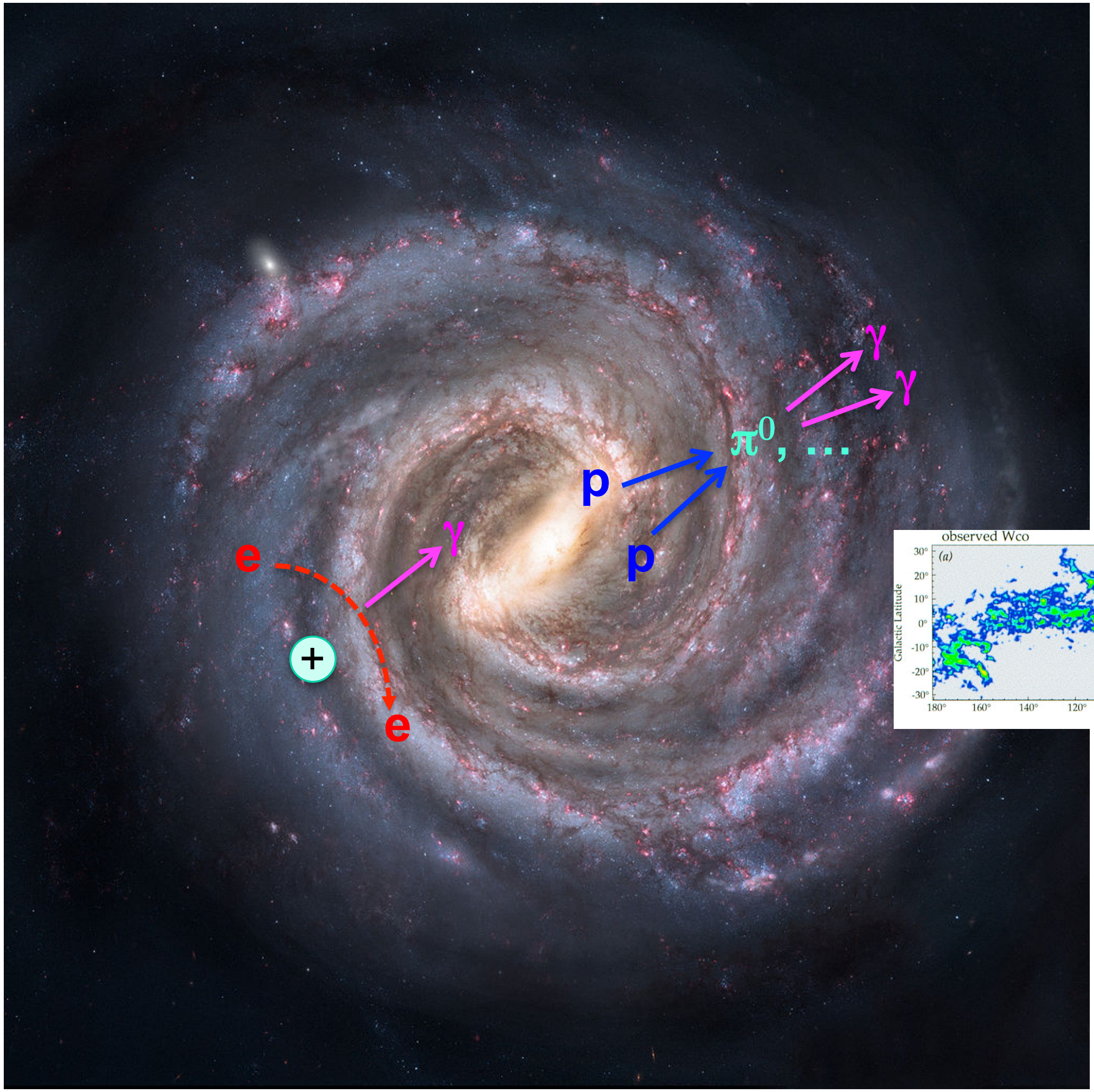
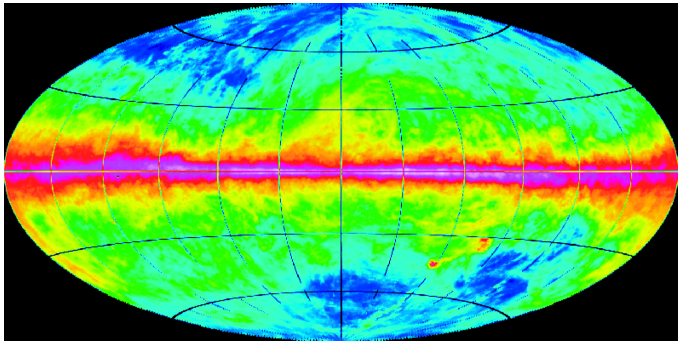
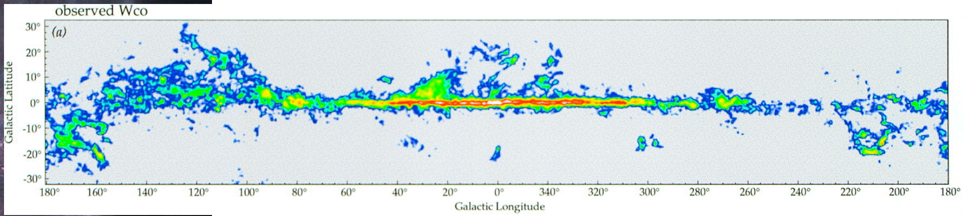


Image credit: Nick Risinger. Graphics: Anna Franckowiak



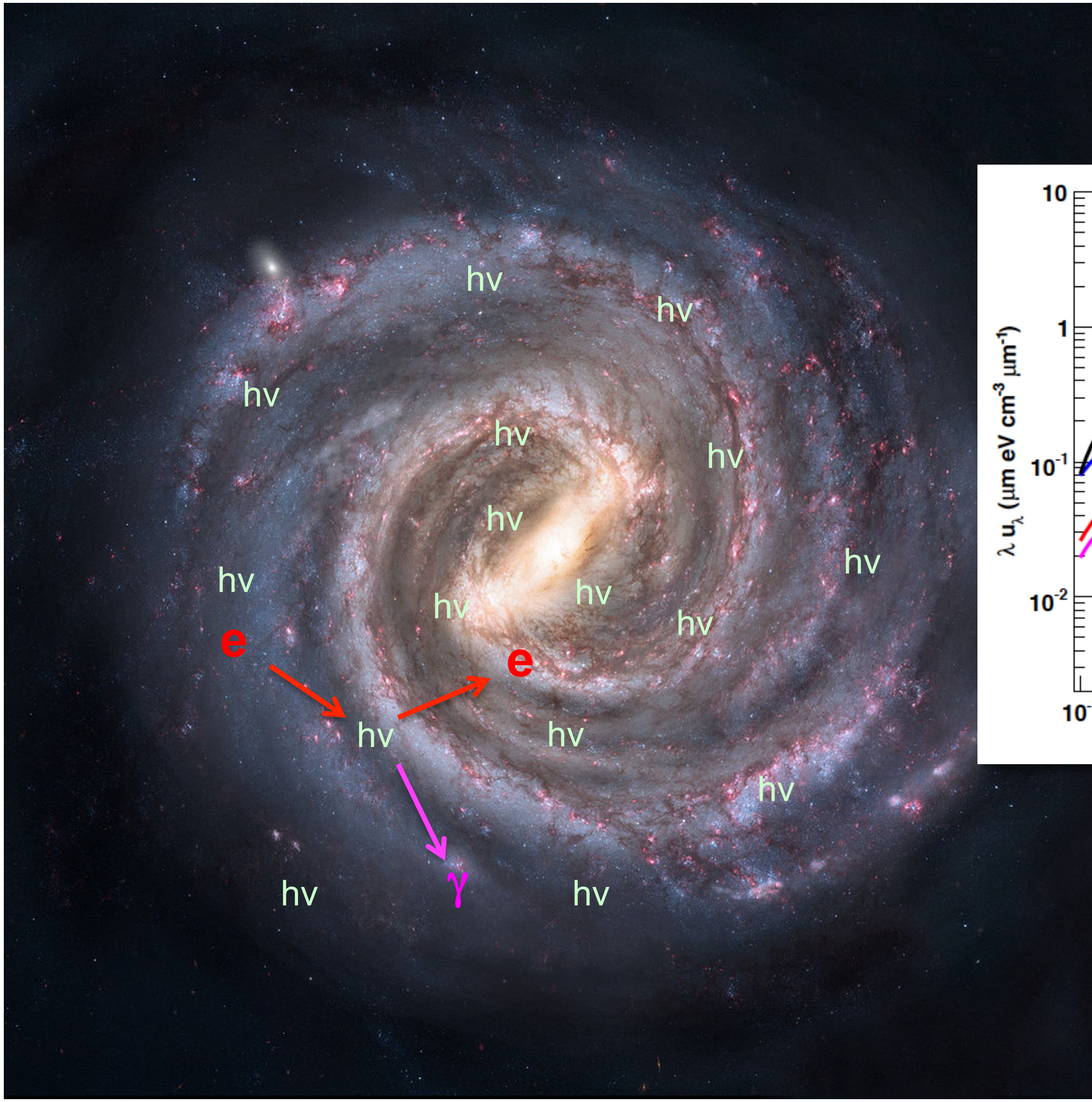
Leiden/Argentine/Bonn Galactic 21cm atomic hydrogen survey
(Kalberla et al. A&A 440, 2005)



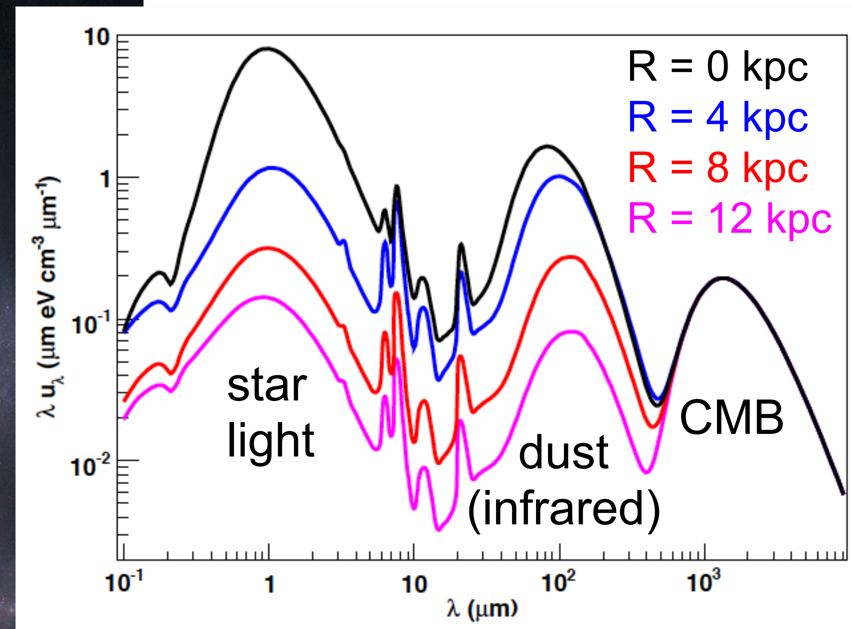
CO surveys to trace molecular hydrogen
(Dame et al. ApJ 547, 2001)

We use GALPROP
(Moskalenko&Strong ApJ 493, 1998)
for propagation and interactions of CRs

Inverse Compton emission



Milky Way interstellar radiation field model



Porter et al., ApJ, 682 (2008)

Image credit: Nick Risinger.

Sample Model

- Data: 6.5 years of Pass 8 UltraCleanVeto
  - 100 MeV to 1 TeV in 27 logarithmic bins
- Gas correlated (π^0 decay, bremsstrahlung) – GALPROP in 5 rings
  - Separate H I and CO templates (trace atomic and molecular hydrogen)
- Inverse Compton – GALPROP
  - Separate starlight, IR, CMB components
- Loop I (Wolleben, ApJ 664 (2007))
- Isotropic
- Fermi Bubbles (Fermi collaboration, ApJ 793 (2014))
- Point Sources – 3FGL
  - The cores of 200 bright PS are masked
- Sun / Moon (Fermi Science Tools)
- Excess template:
  - Generalized NFW DM annihilation: $\gamma = 1.25$

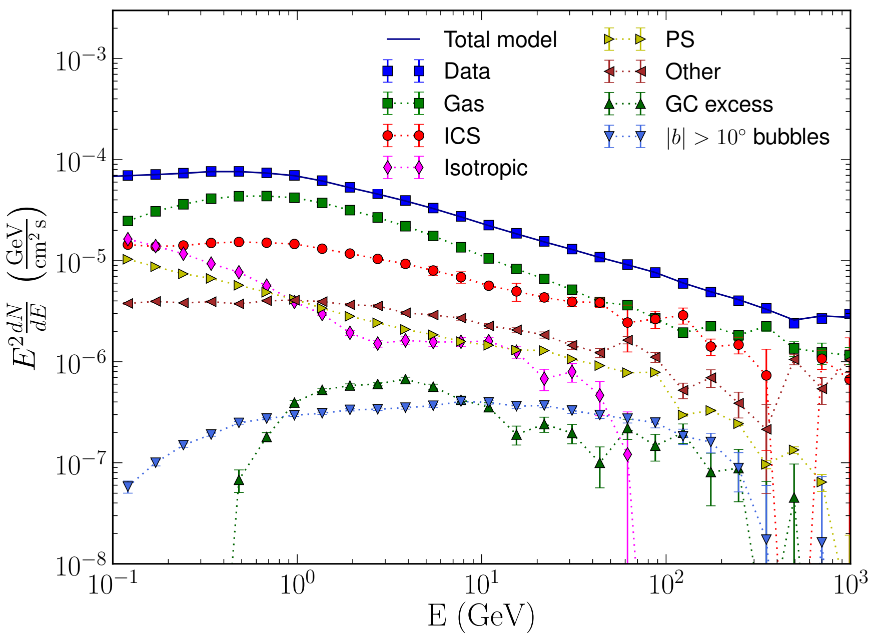
	R [kpc]
Inner	0 – 1.5
Inner	1.5 – 3.5
Inner	3.5 – 8
Local	8 – 10
Outer	10 – 50

$$\rho(r) \propto \frac{1}{\left(\frac{r}{r_s}\right)^{\gamma}\left(1+\frac{r}{r_s}\right)^{3-\gamma}}$$

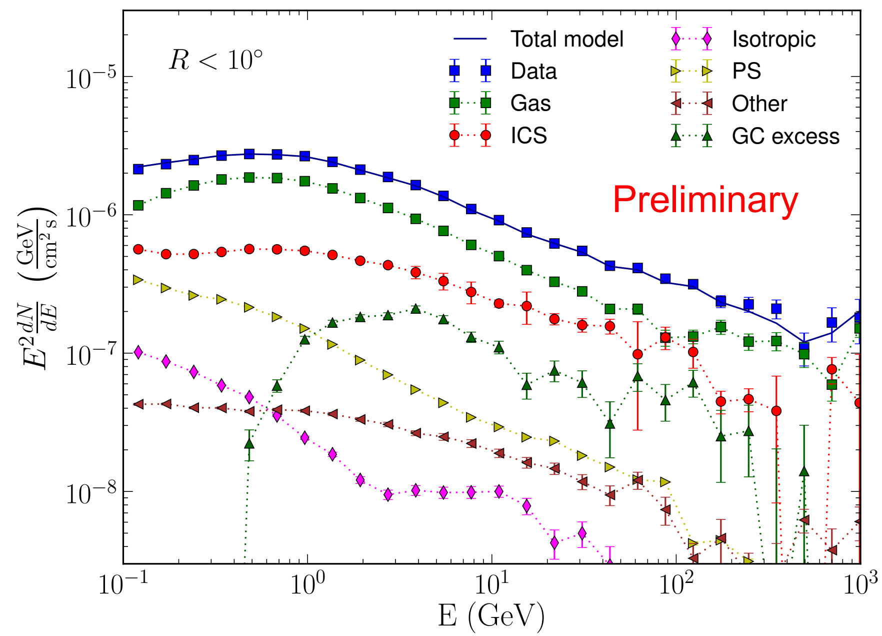
Sample Model Spectra

- **All sky-fit**
- **Fit normalization in each energy bin for each template**

Flux integrated over the whole sky



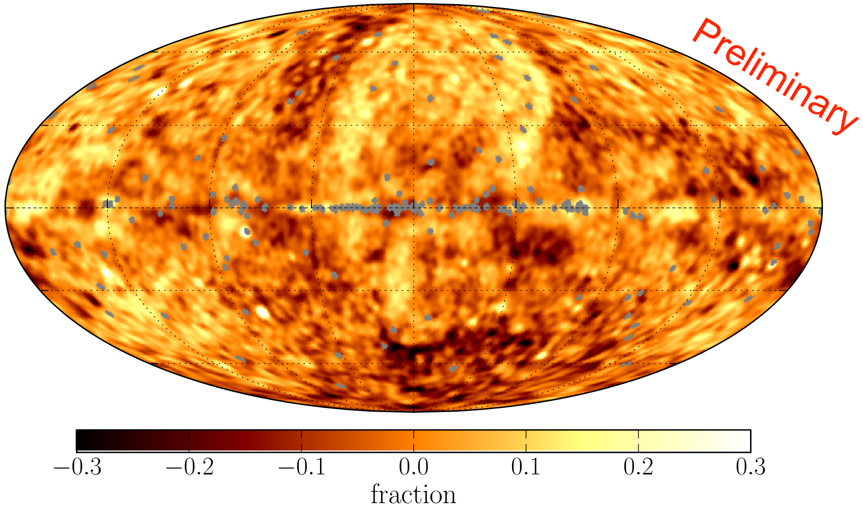
Flux integrated over R < 10°



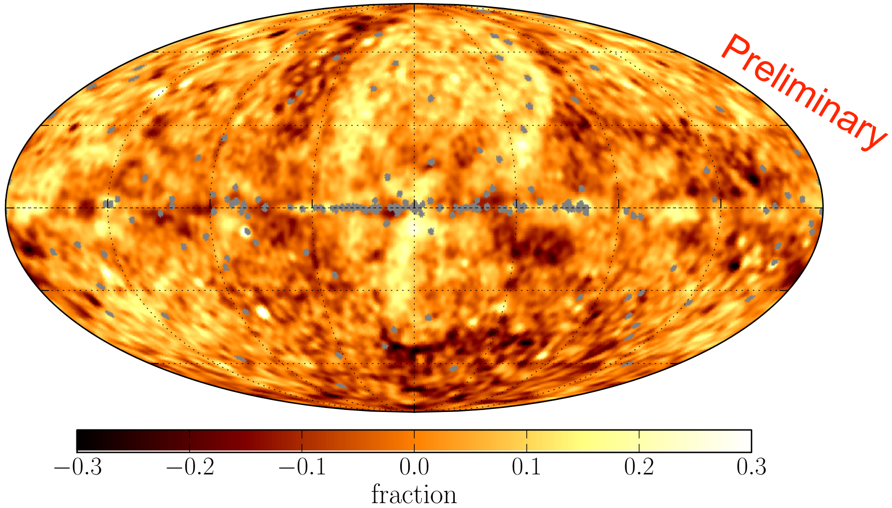
Residuals

- The residual near the GC is clearly visible
- Hard to say whether the morphology is spherical
- Similar fractional size as other residuals

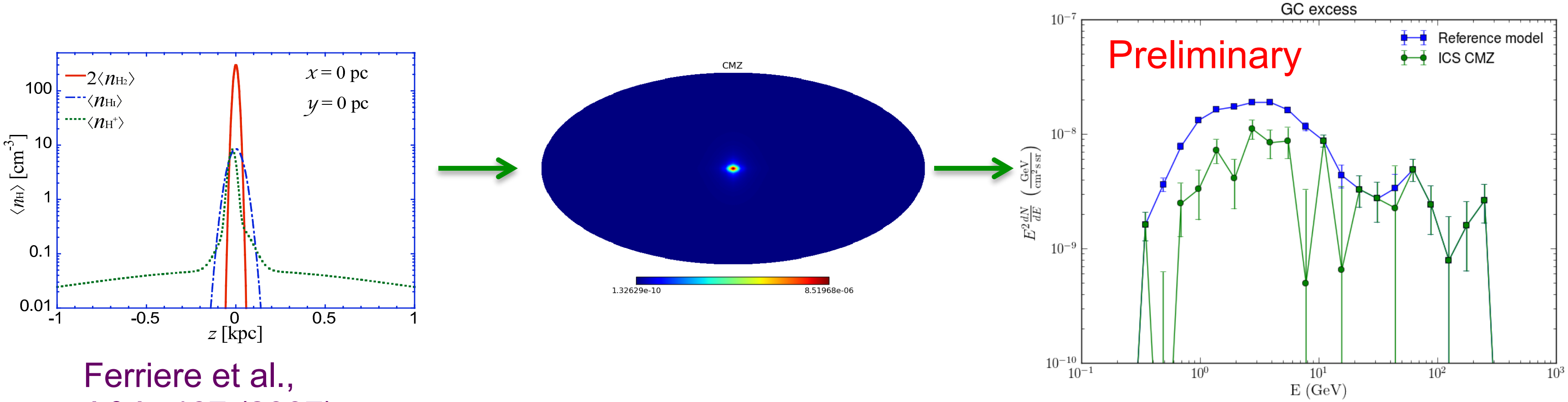
Fractional residual, 1.1 – 6.5 GeV



Add back the gNFW template



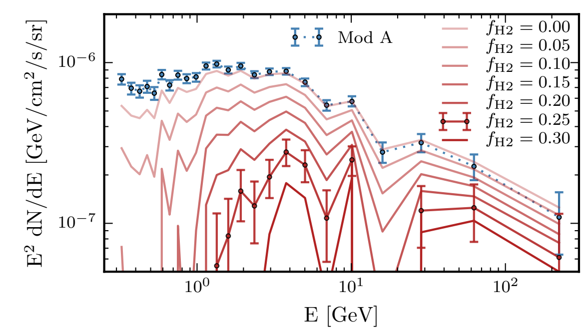
Possible sources of CR electrons near the GC



Ferriere et al.,
A&A, 467 (2007)

- **A source of CR electrons in the central molecular zone (CMZ) region can reduce the flux associated with gNFW template**
  - **Burst-like emission from the GC nucleus (Cholis et al. JCAP 12, 2015)**
  - **CR production correlated with molecular clouds in CMZ**

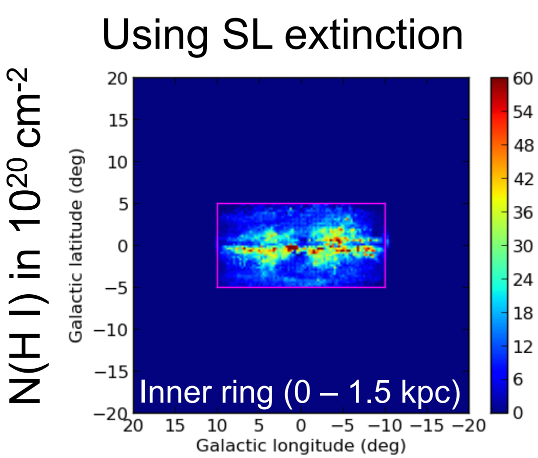
Gaggero et al JCAP 12, 2015
Carlson et al PRL 117, 2016

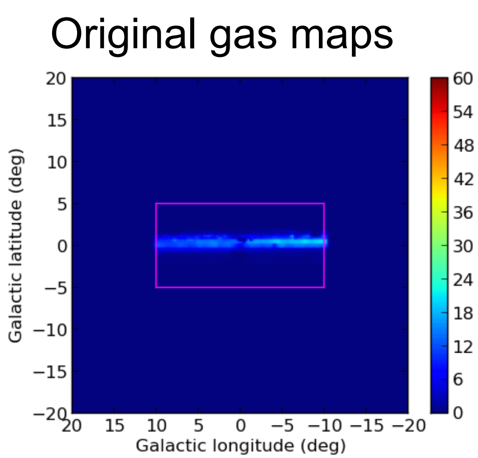


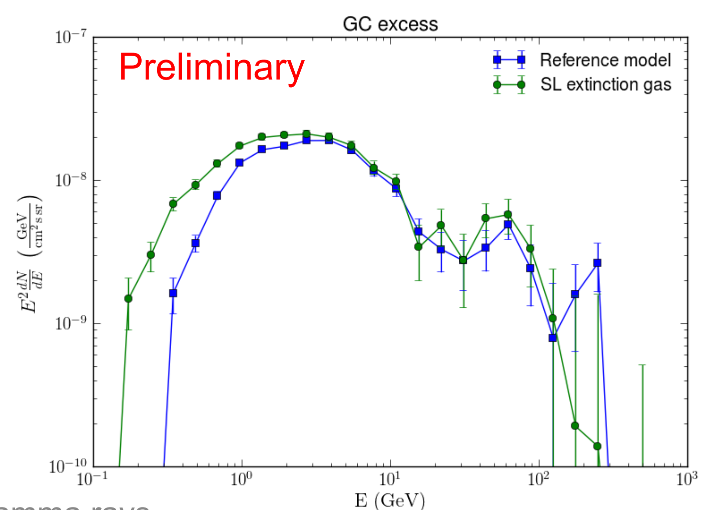
Carlson et al PRL 117, 2016

Alternative gas maps

- Hard to model distribution of gas towards the GC due to **lack of Doppler shift** information
  - Gas distribution is interpolated from |Lon| > 10°
- **Use starlight (SL) extinction** (Schultheis et al, A&A 566 (2014)) to find the distribution of dust along the line of sight towards the GC
  - Derive the distribution of gas assuming homogeneous mixing of dust and gas (not necessarily more accurate but can be used as an alternative)



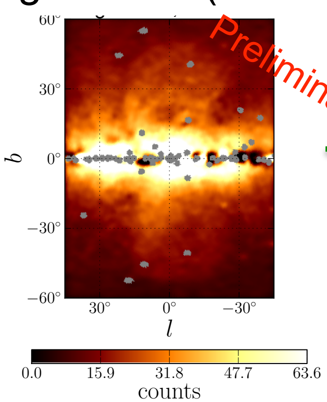




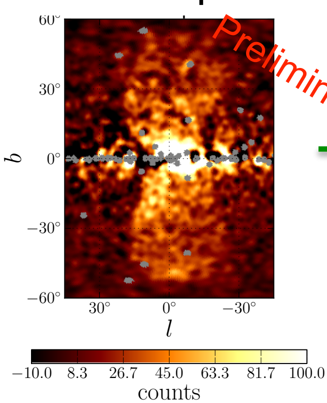
Bubbles template from spectral components analysis (SCA)

- **Assume that the bubbles have the same spectrum near the GC as at high latitudes** **~E$^{-1.9}$ between 1 and 10 GeV**
- **Cut on significance to obtain the bubbles template**

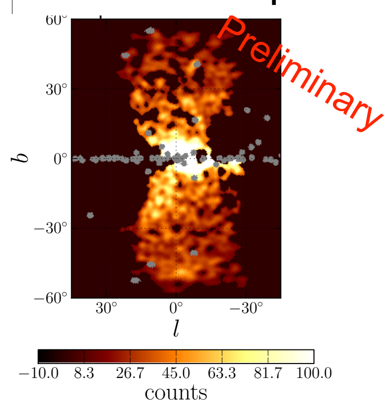
Data – gas – PS (1.1 – 6.5 GeV)



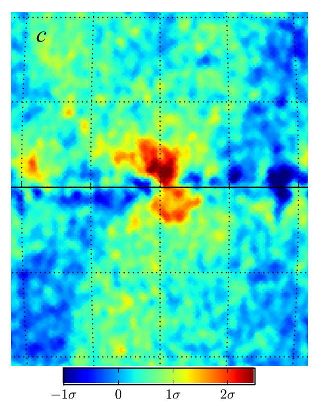
~E$^{-1.9}$ component



Bubbles template



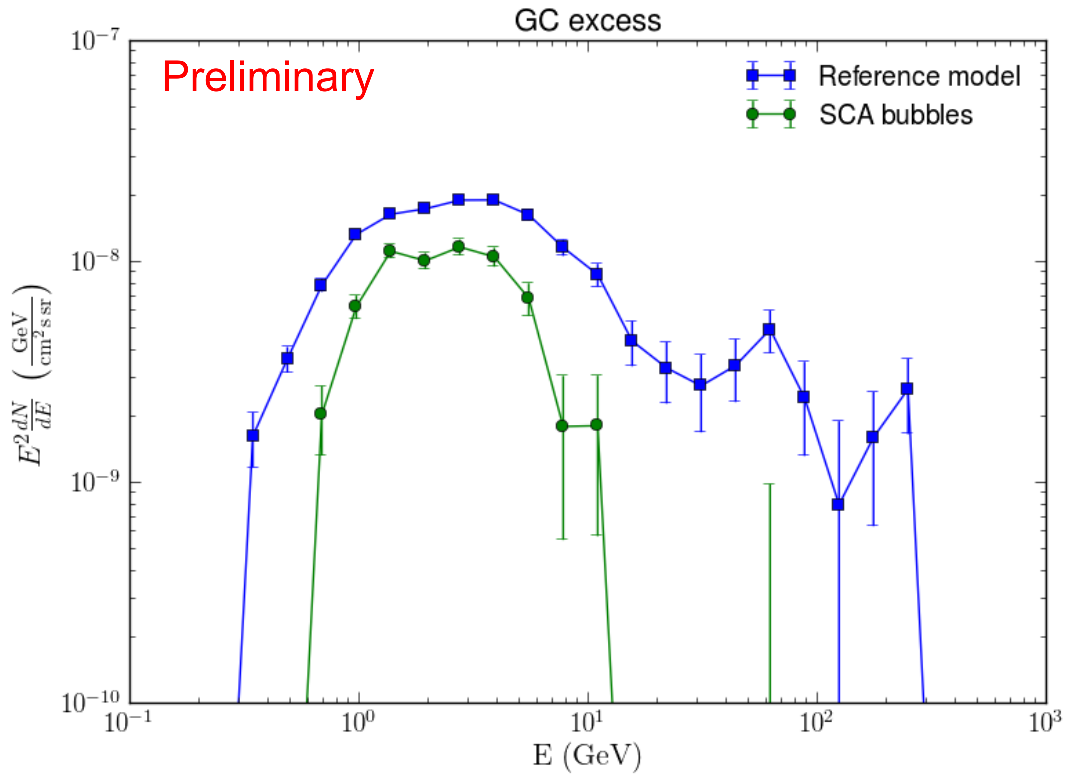
- **Comparison with the Fermi diffuse model paper:**



Acero et al (Fermi LAT), ApJS 223 (2016)

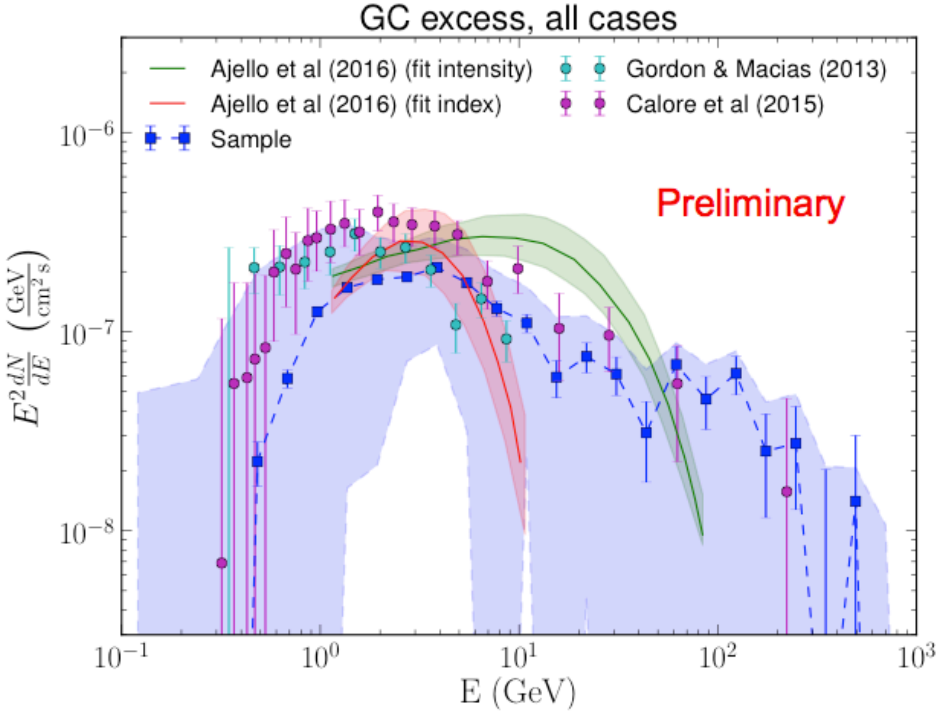
GC excess and all-sky bubbles

- **Fit the gNFW profile together with the all-sky bubbles determined with spectral components analysis**
  - **The high-energy tail of the GC excess is gone**
  - **Overall normalization is reduced**



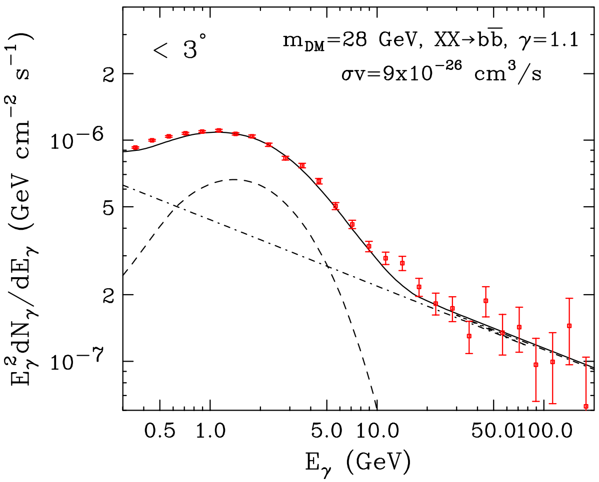
Band of GC excess fluxes

- **The spectrum uncertainty band comes from**
  - **Variations of GALPROP models and gas distribution**
  - **CMZ source of CR electrons**
  - **Fermi bubbles at low latitudes**
  - **Properties of point sources near the GC**

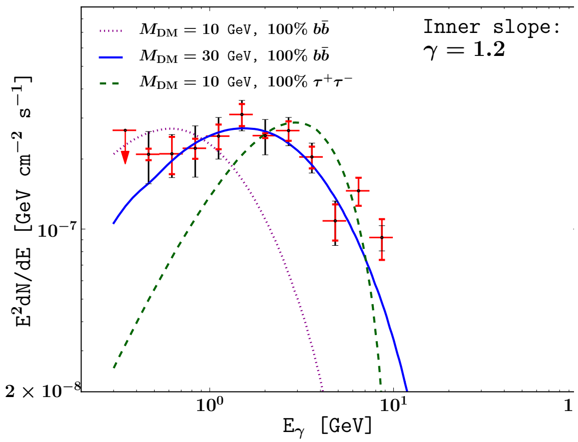


Dark Matter

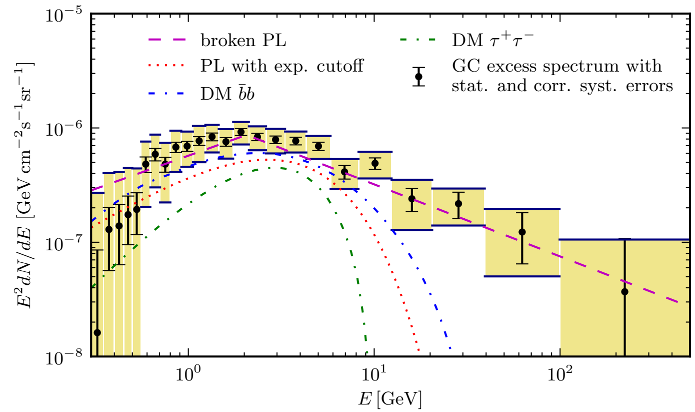
- **Dark matter models fit the excess spectrum reasonably well**



Goodenough & Hooper
arxiv:0910.2998

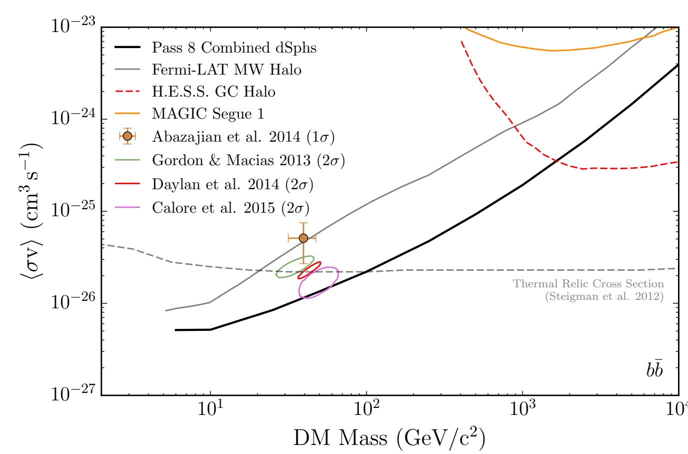


Gordon & Macias
PRD 88 (2013)



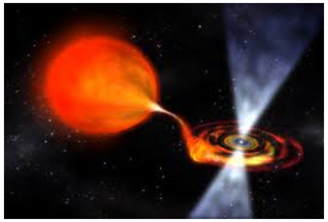
Calore et al.
JCAP 3 (2015)

- **Comparison with dwarfs:**
  - **There is a slight tension with DM limits from observation of dwarf galaxies**

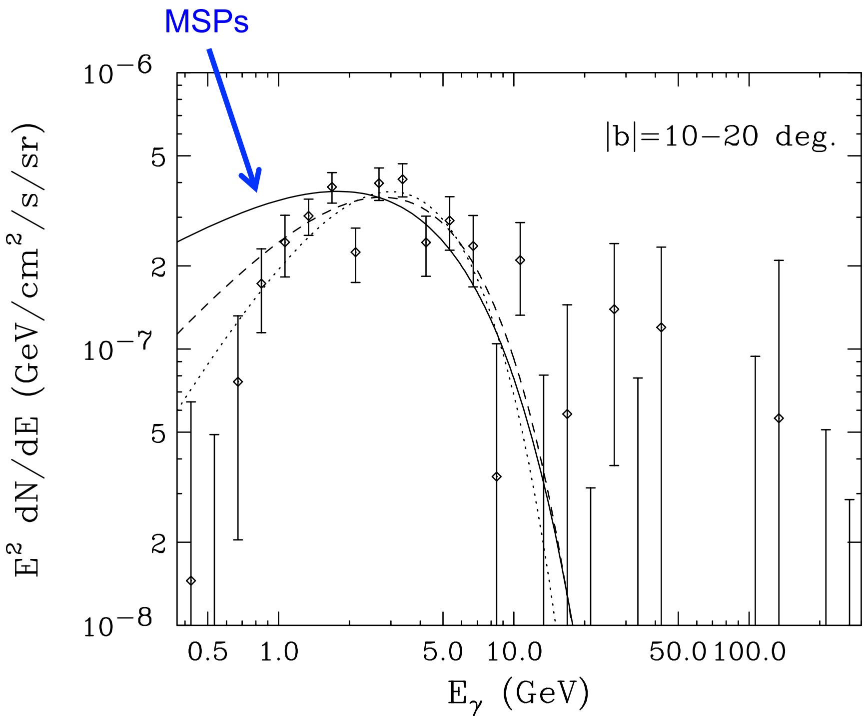


Ackerman et al. (Fermi LAT) PRL 115 (2015)

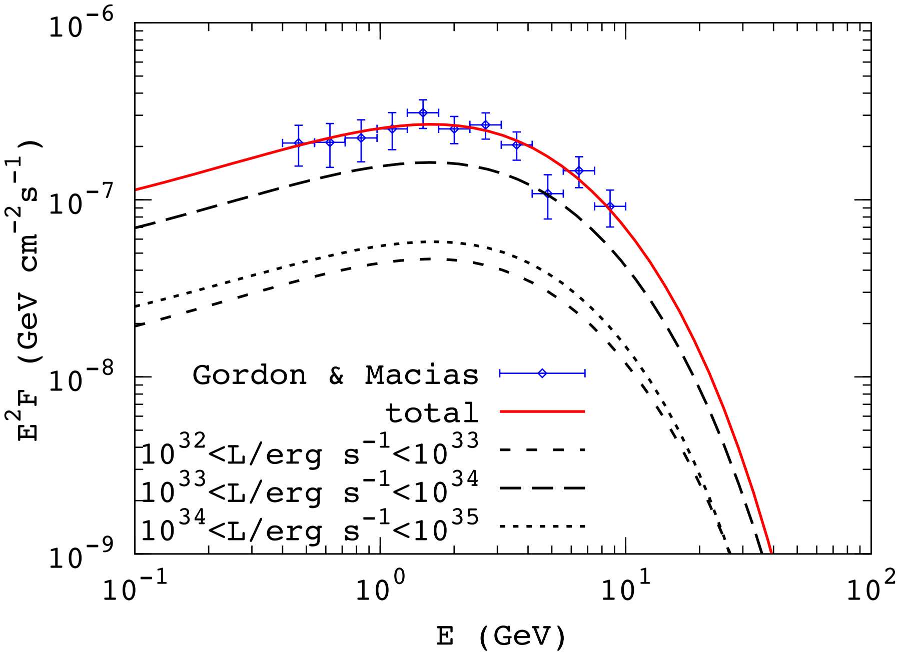
Millisecond pulsars (MSPs)



- **MSPs – pulsars spun up by accretion from a companion**
  - **Have a spectrum similar to the GC excess**
  - **Long lifetime (billions of years) – there may be a population of MSPs in the Galactic bulge**



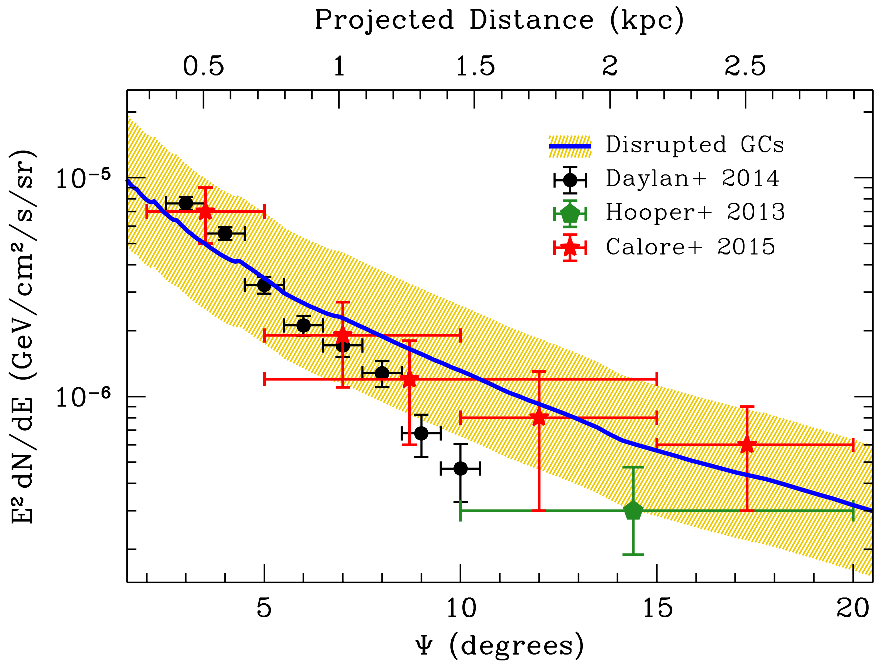
Hooper et al, PRD 88 (2013)



Yuan & Zhang, JHEAp 3 (2014)

MSPs from disrupted globular clusters

- **Population of MSPs**
  - **Should be enough MSPs in the Galactic bulge if the bulge is formed by disruption of globular clusters**

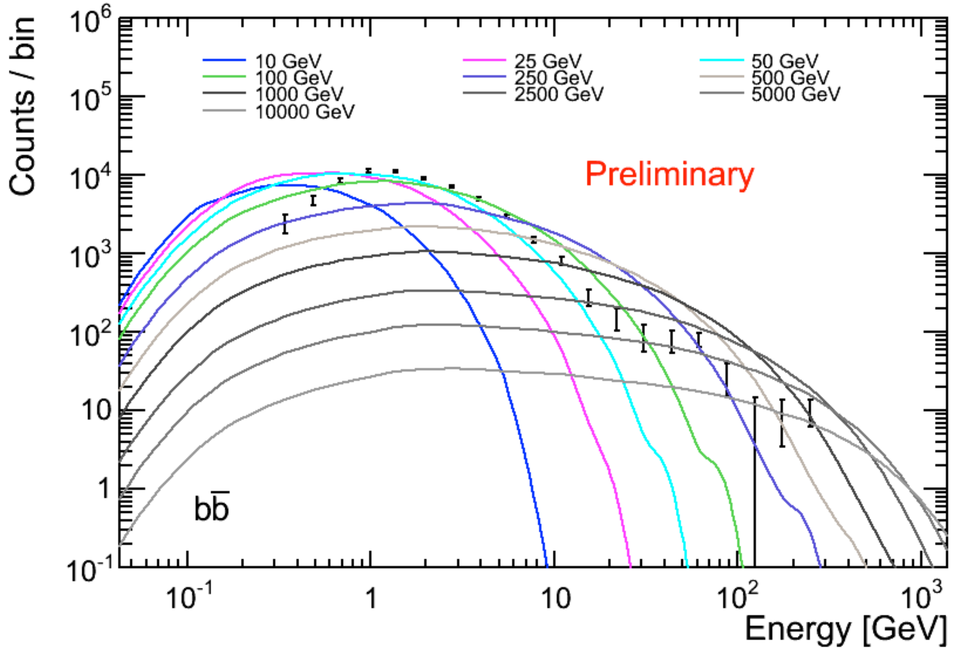


Brandt & Kocsis, ApJ 812 (2015)

GC excess – DM or not?

- We cannot exclude neither DM nor astrophysical interpretation of the GC excess
- Is the GC excess signal significant relative to modeling uncertainties?
  - Independent estimate of uncertainties by scanning gNFW profile along the Galactic plane where we do not expect to see the DM annihilation signal
  - Compare the "DM-like" signals along the plane (relative to background) to the excess at the GC
- Even if the GC excess is not robust relative to modeling uncertainties, we can still put limits on DM annihilation from the observations of the Galactic center

GC Excess as a Fractional Signal



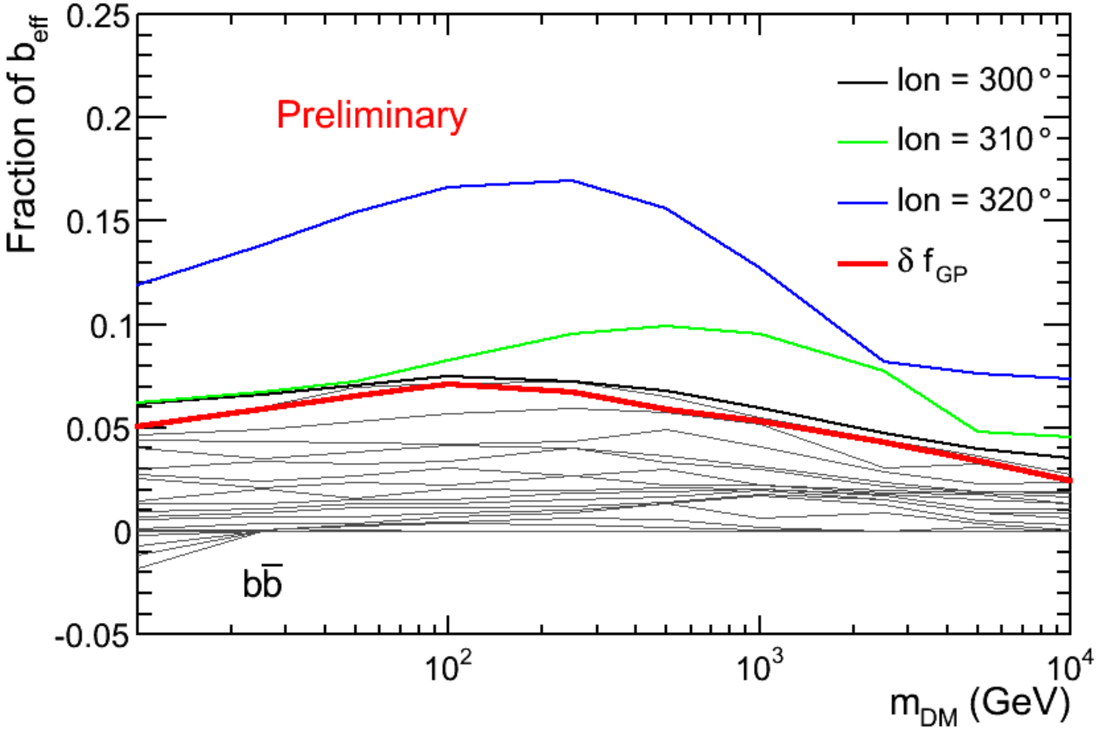
To estimate the modeling significance of the GC excess we compare the fractional excess at the GC to excesses along the Galactic plane away from the GC:

$$f = n_{sig} / b_{eff}$$

- **Signal counts (n_{sig}):**
  - **We fit gNFW template in each energy bin independently**
  - **For a specific annihilation channel (e.g. $\chi\chi \rightarrow b\bar{b}$) and DM mass, we find the best fit to the gNFW template spectrum**
  - **Integrate over energy to get total n_{sig}**
- **Effective background (b_{eff}): background counts weighted with gNFW spatial profile and DM annihilation spectrum**

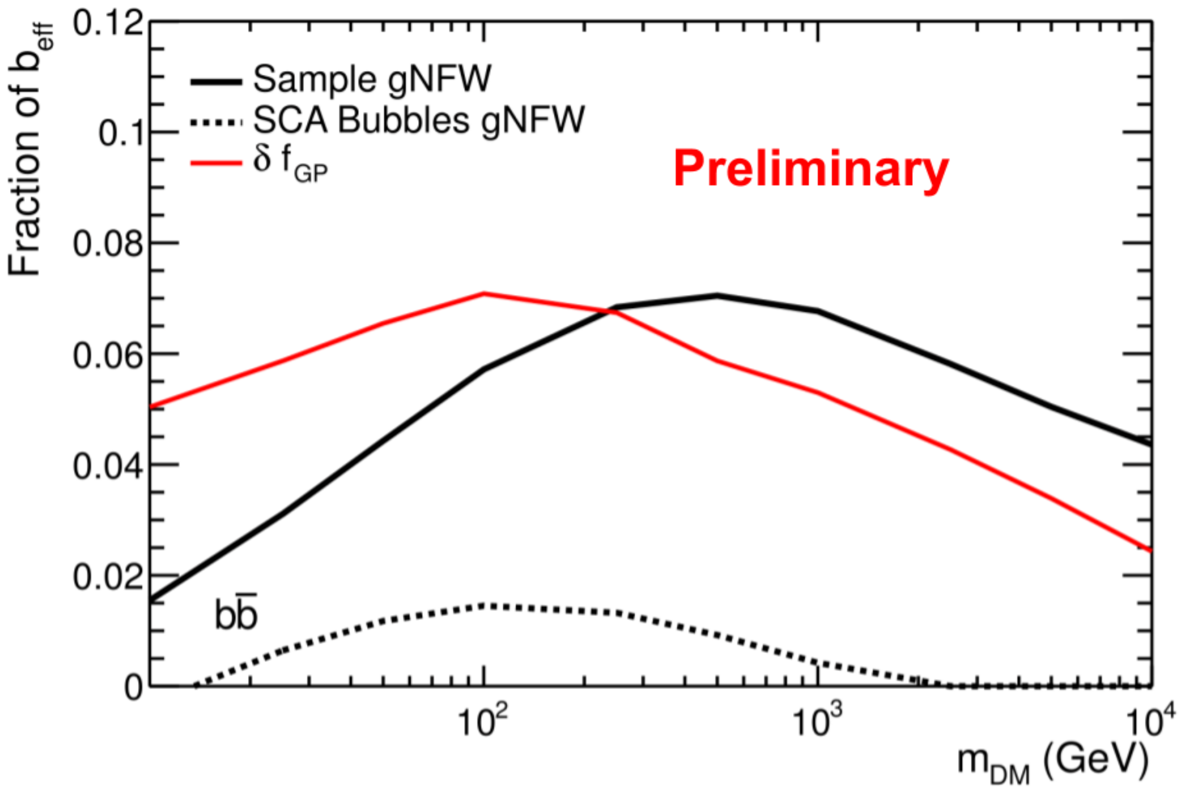
Modeling uncertainty

- We calculate the ratio of DM-like signal to effective background for locations along the Galactic plane away from the GC
- We use 84% (one-sided "1 sigma" exclusion) as an estimate of modeling uncertainty



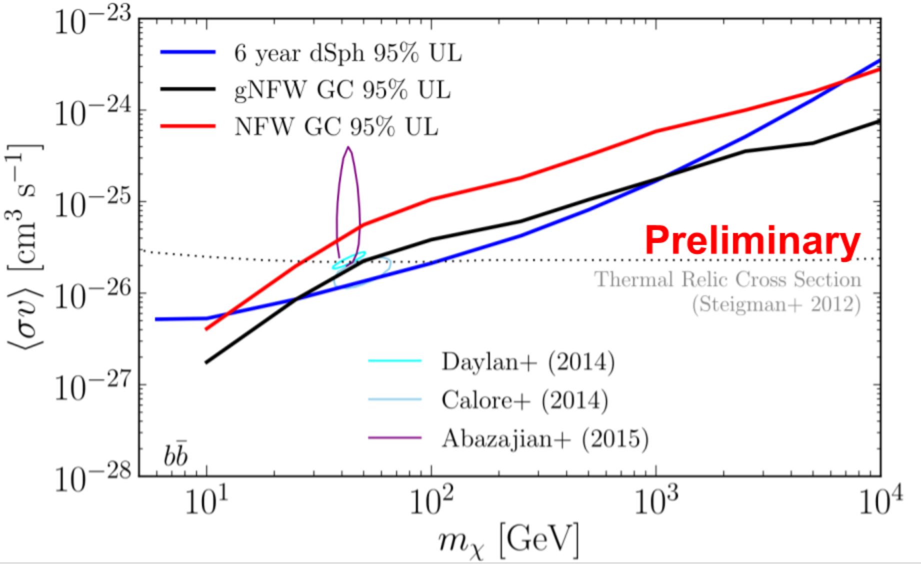
Modeling significance of GC excess

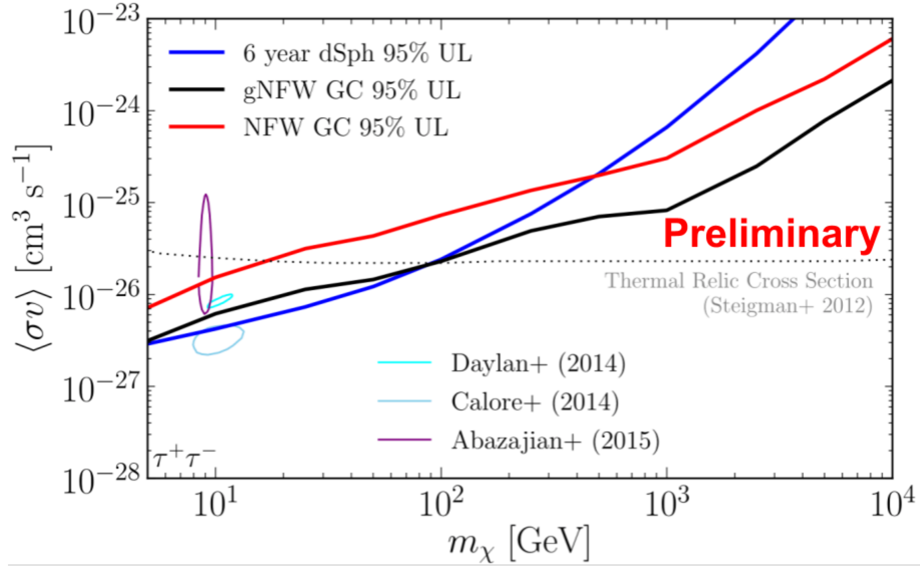
- **The observed fractional signal at the GC is at most two times larger than the modeling uncertainty**



DM limits

- Since the GC excess signal is not significant relative to the modeling uncertainties, we conservatively put limits on DM annihilation
- For the limits we require that the DM annihilation signal not exceed the upper bound of the modeling uncertainty band for the GC excess flux





Conclusions

- Galactic center excess in gamma-rays exists
- The origin of the the excess is not clear yet
- Possible sources include
  - CR injection near the GC
  - Population of weak point sources, e.g., MSPs
  - DM annihilation
- Dark matter annihilation limits are derived
  - Comparable to but a bit less constraining than the limits from dwarf galaxies

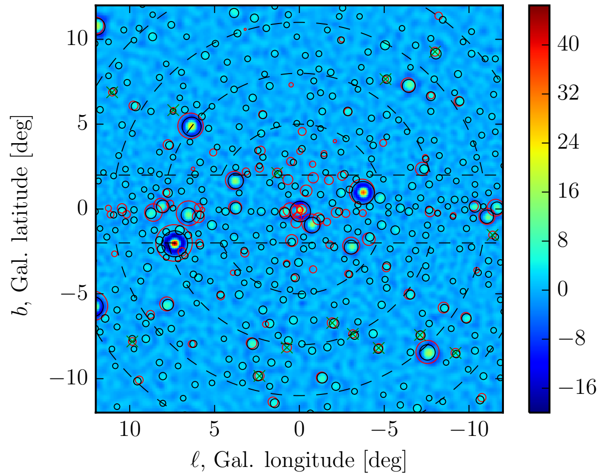
Future

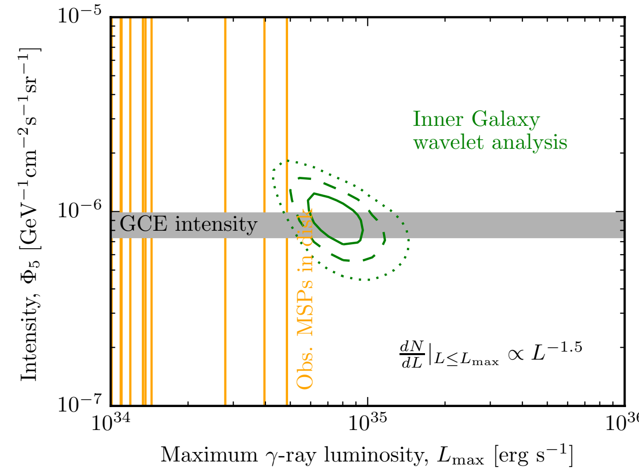
- eROSITA – new X-ray all-sky survey
  - Modeling of the Fermi bubbles
  - Look for correlated features near the Galactic center
- Cherenkov Telescope Array (CTA)
  - Fermi bubbles near the GC are much brighter
  - Possible to see with Cherenkov telescopes?
- MeerKAT, SKA – new radio telescopes
  - Search for individual pulsars in the halo around the GC
- e-ASTROGAM, AMEGO – proposed low energy gamma-ray missions
  - Low energy gamma-ray measurements

Backup slides

Statistical analysis

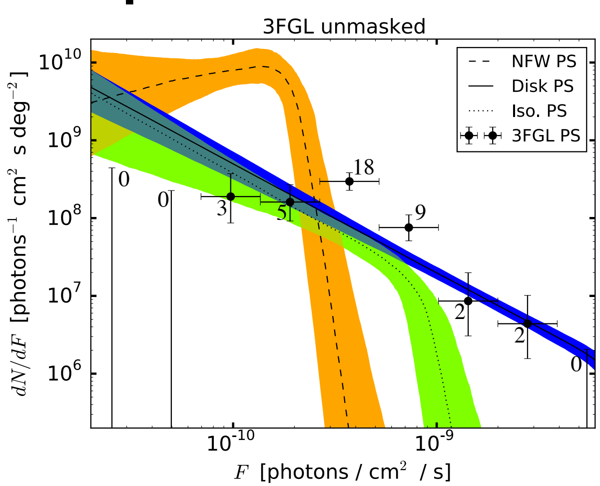
- **Wavelets**

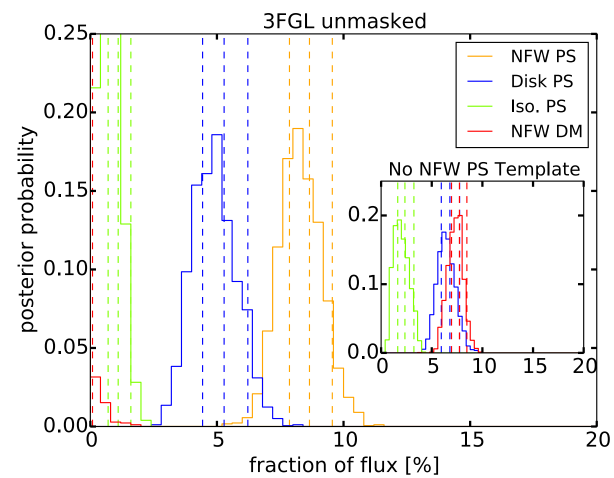




Bartels et al, PRL 116 (2016)

- **Non-Poissonian templates**





Lee et al, PRL 116 (2016)