Fermi
Gamma-ray Space Telescope

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

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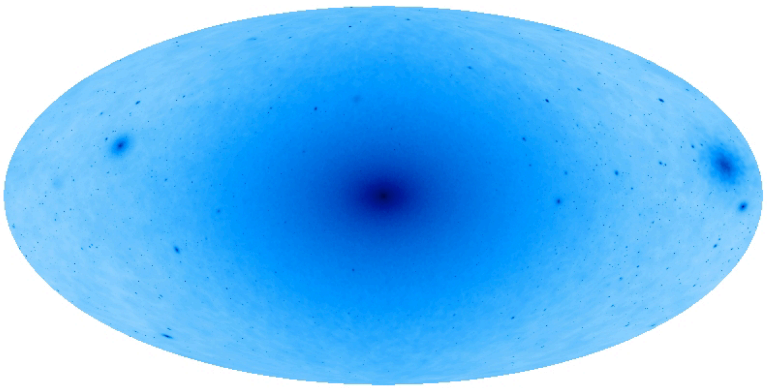
on behalf of the Fermi LAT collaboration

HEA 2016, Moscow
December 22, 2016

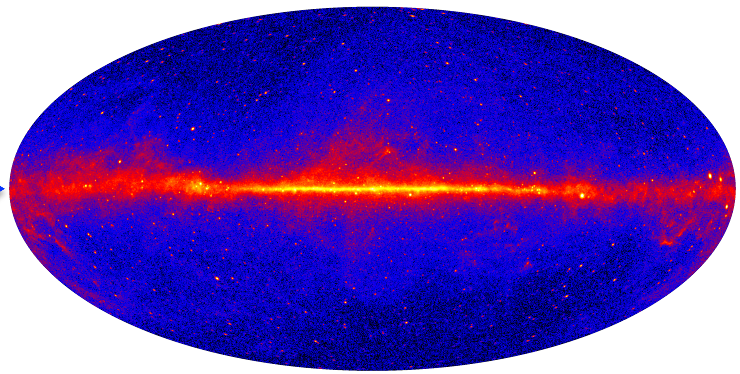
Dark matter annihilation

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



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

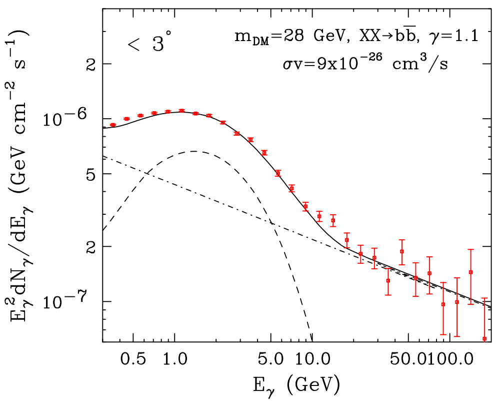
?



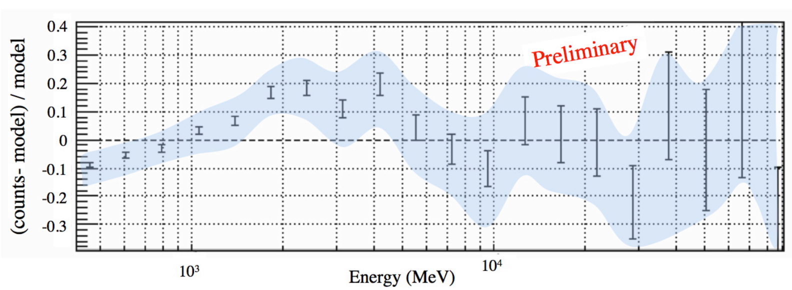
Fermi Large Area Telescope (LAT),
6 years, Pass 8 data

GC excess emission

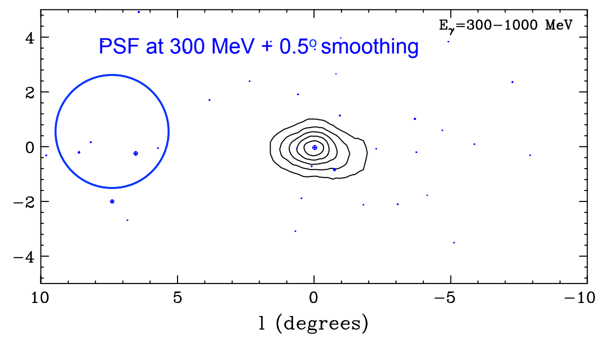
- **First hints of an excess**



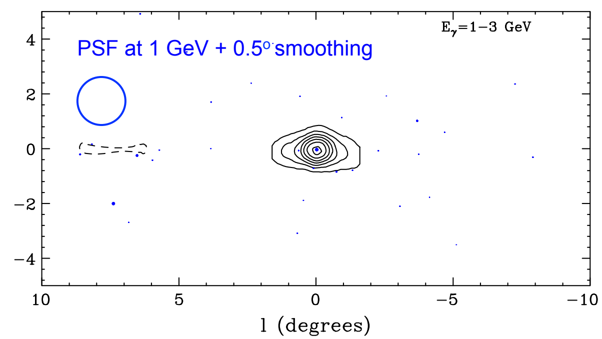
Goodenough & Hooper
arxiv:0910.2998



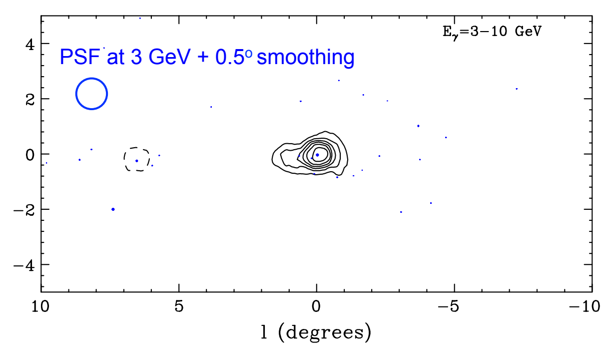
Vitale & Morselli
arxiv:0912.3828



300 MeV – 1 GeV



1 GeV – 3 GeV

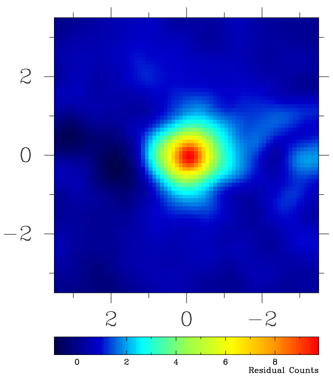


3 GeV – 10 GeV

Hooper & Linden
PRD, 84 (2011)

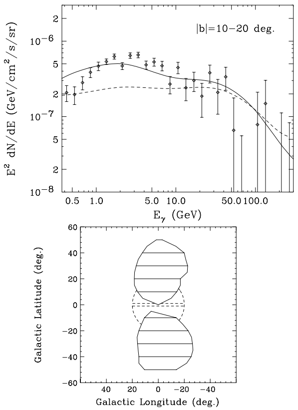
GC excess emission

- **More recent analysis**

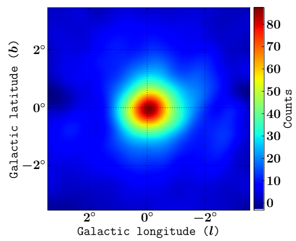


Abazajian & Kaplinghat
PRD 87 (2012)

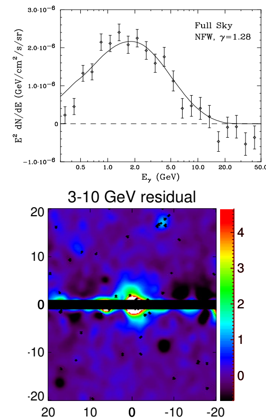
10° – 20° in latitude



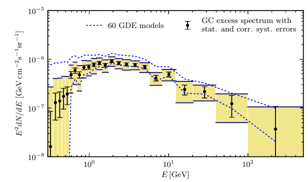
Hooper & Slatyer
Phys.Dark Univ. 2 (2013)



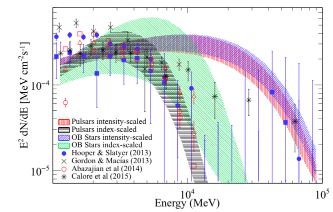
Gordon & Macias
PRD 88 (2013)



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



Calore et al.
JCAP 1503 (2015)



Ajello et al.
ApJ 819 (2016)

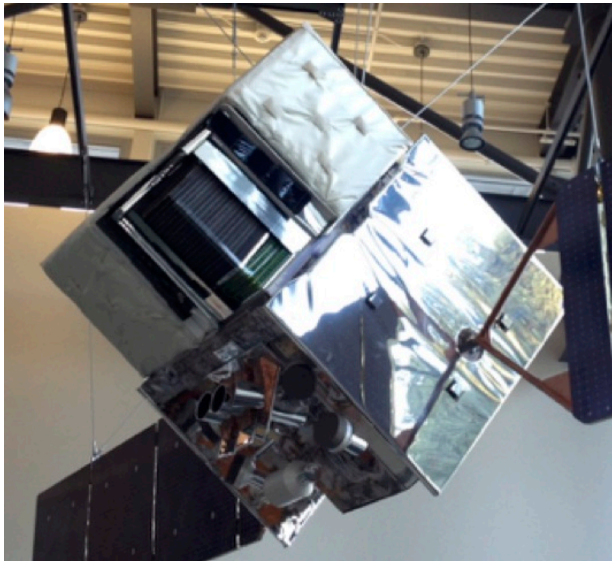
- **Possible interpretations:**
  - **DM annihilation, millisecond pulsars (e.g., Brand&Kocsis 2015), cosmic ray sources near the GC (e.g., Carlson et al 2016), Fermi bubbles (Yang & Aharonian 2016)**

Our work

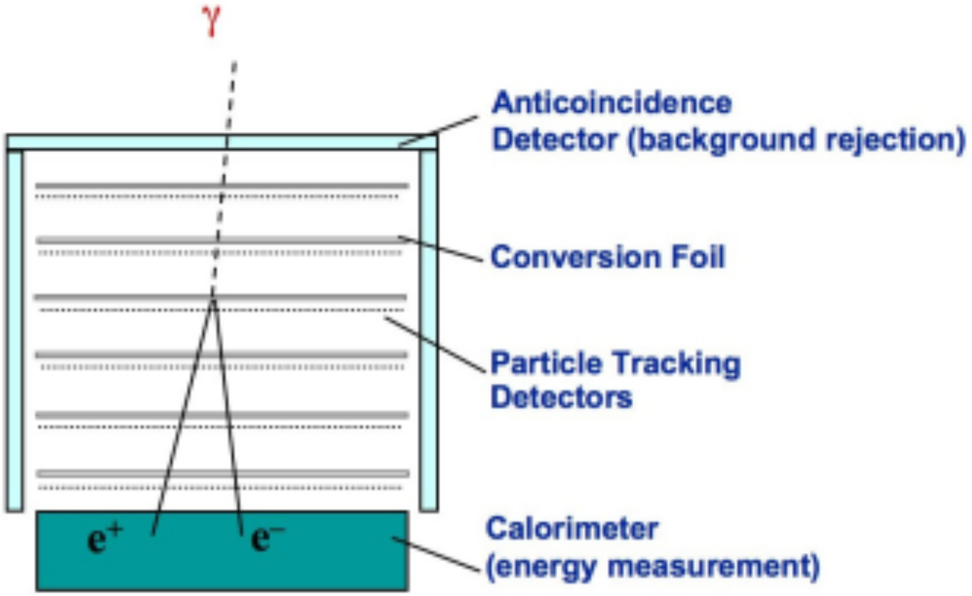
- Estimation of modeling and systematic uncertainties of the GC excess spectrum and morphology
- Distribution of cosmic rays
  - Distribution of CR sources in the Galaxy
  - Additional CR sources near the GC
  - Propagation parameters
- Distribution of targets in the Galaxy
  - Gas
  - Interstellar radiation fields
- Fermi bubbles near the GC
- Reevaluation of point sources near the GC
- Derivation of limits on DM annihilation towards the GC

Fermi LAT

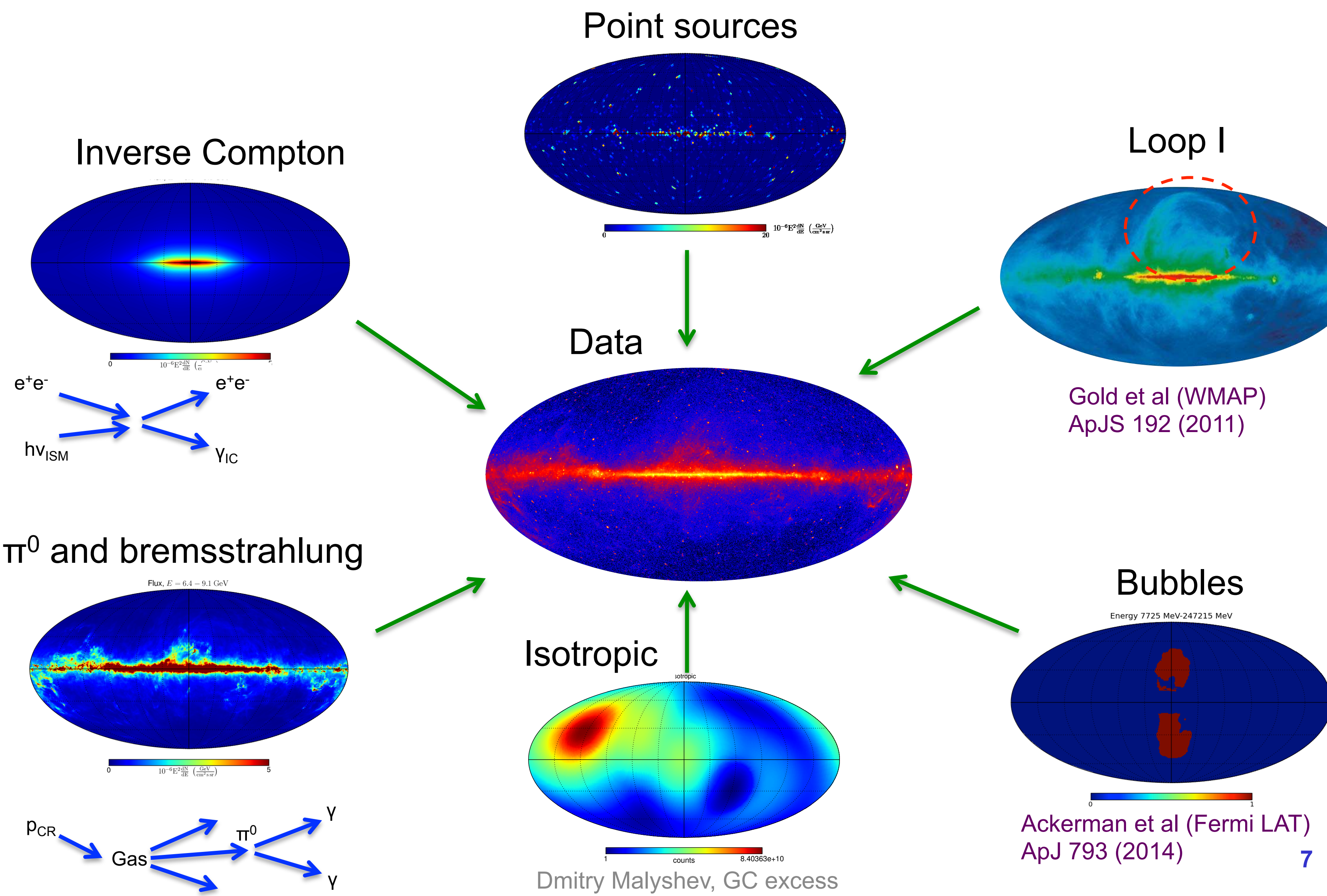
- Fermi Large Area Telescope – gamma ray space telescope
- Launched on June 11, 2008
  - 2.8 tons, 650 watts
  - 20 MeV to more than 300 GeV
  - 2.4 sr field of view
  - Less than 1° resolution above 1 GeV



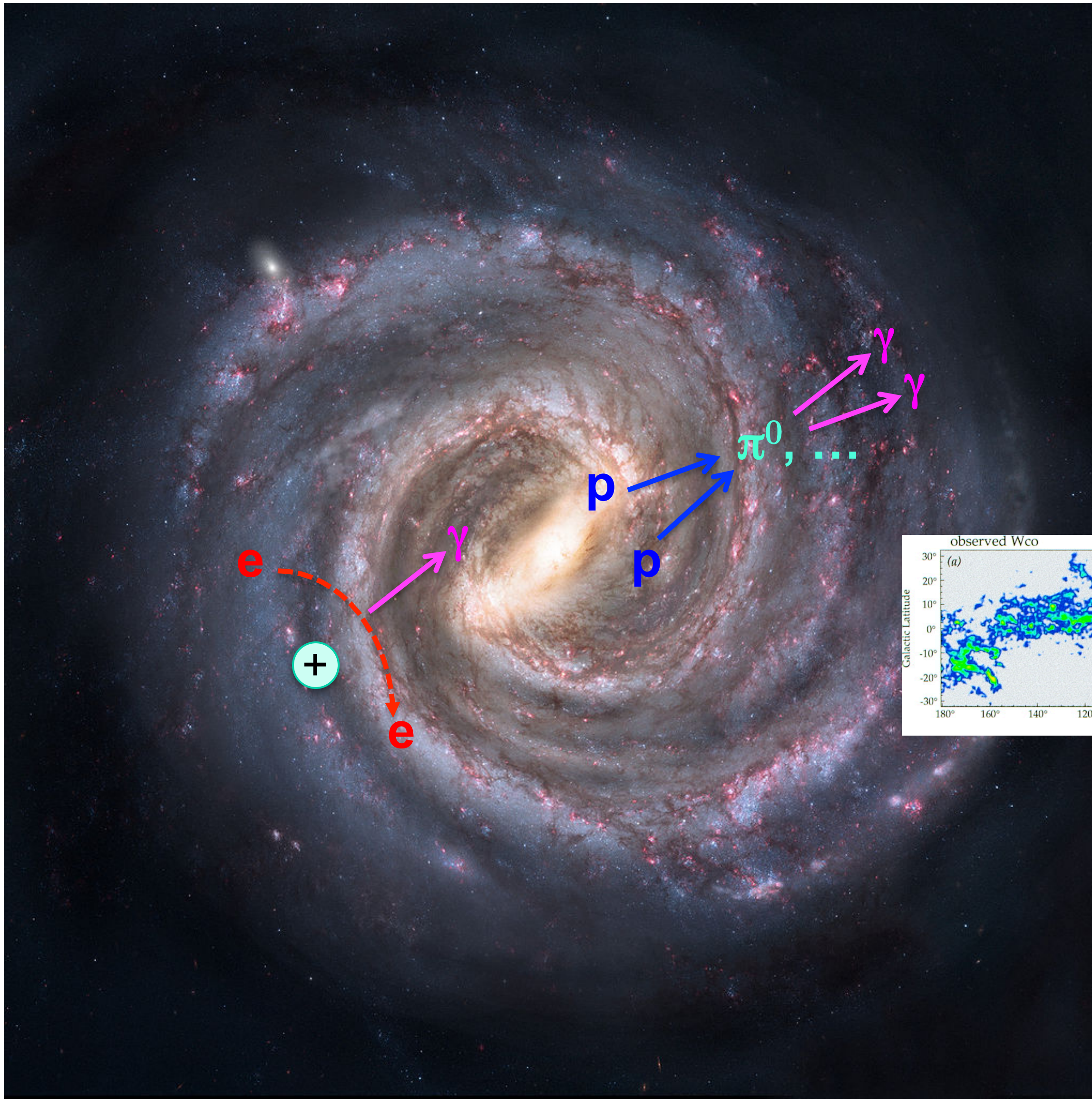
Model (half scale) of the Fermi satellite at SLAC

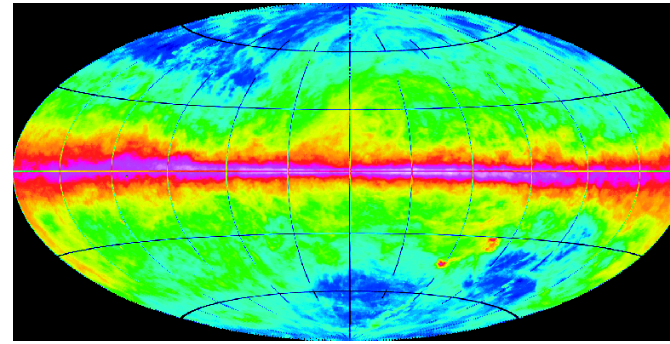


Gamma-ray emission components

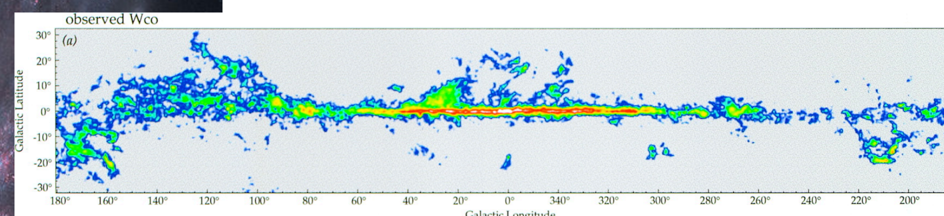


Gas-correlated emission





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

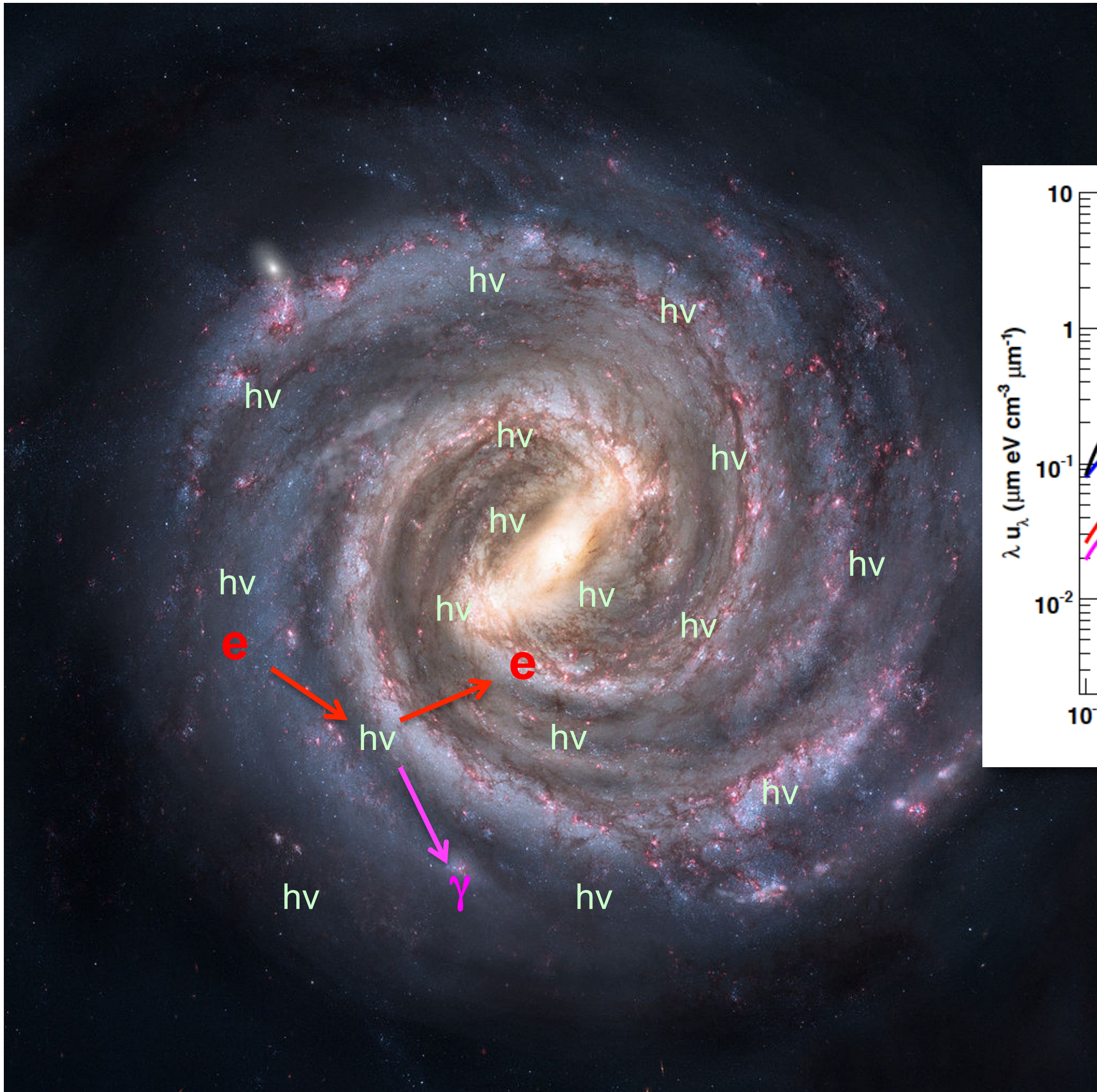


CO surveys to trace molecular hydrogen
(Dame et al. ApJ 547, 2001)

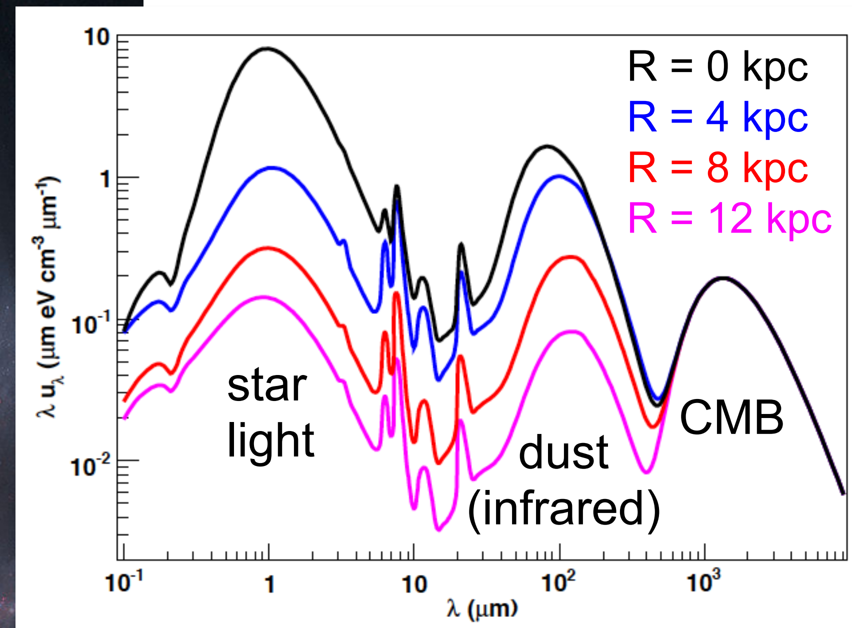
We use GALPROP
(Moskalenko&Strong ApJ 493, 1998)
for propagation and interactions of CRs

Image credit: Nick Risinger. Graphics: Anna Franckowiak

Inverse Compton emission



Milky Way interstellar radiation field model



Porter et al.,
ApJ, 682 (2008)

Image credit: Nick Risinger.

Reference model

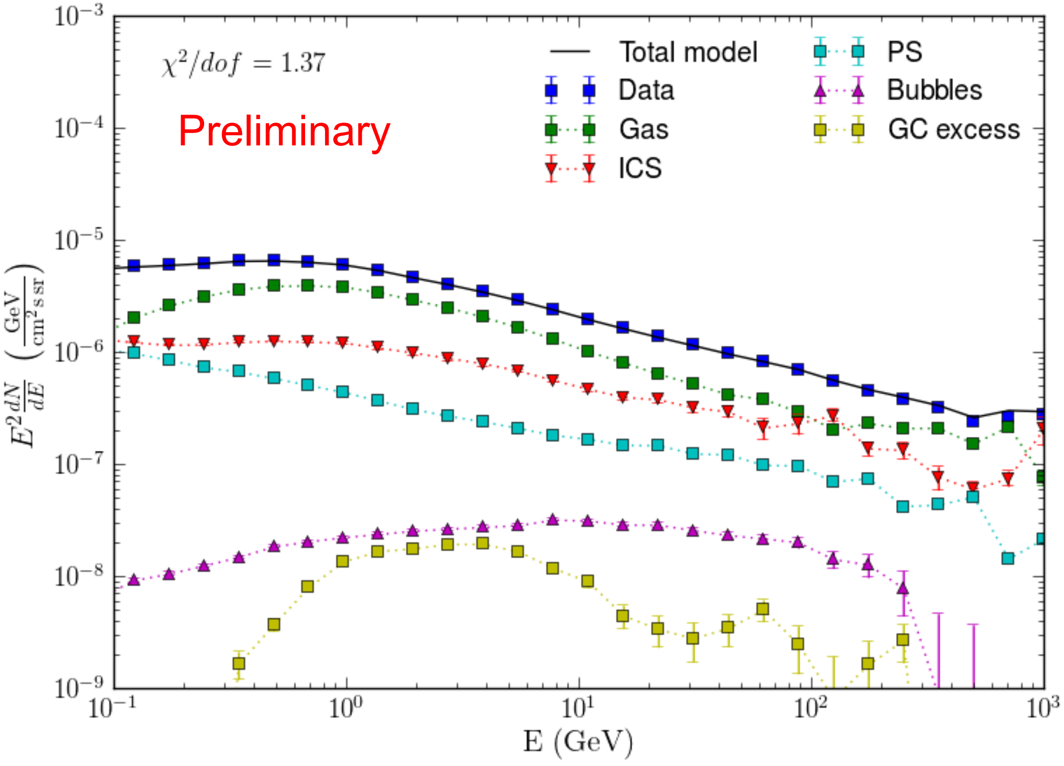
- Data: 6.5 years of Pass 8 UltraCleanVeto
  - 100 MeV to 1 TeV
- Gas correlated (π^0 decay, bremsstrahlung) – GALPROP in 5 rings
  - Separate H I and CO templates (trace atomic and molecular hydrogen)
- Inverse Compton – GALPROP
  - Separate starlight, IR, CMB components
- Loop I (Wolleben, ApJ 664 (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:
  - Contracted NFW DM annihilation (index 1.25)

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

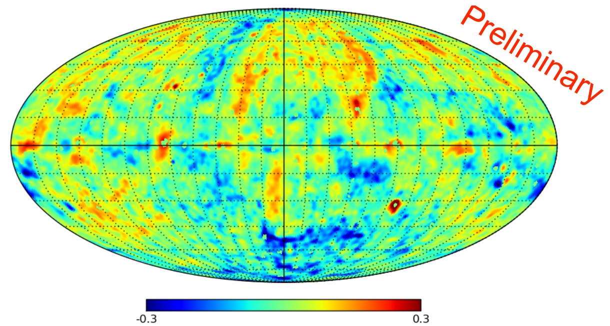
$$\rho(r) \propto \frac{1}{\left(\frac{r}{r_s}\right)^{\gamma}\left(1+\frac{r}{r_s}\right)^{3-\gamma}}$$

Reference model spectra

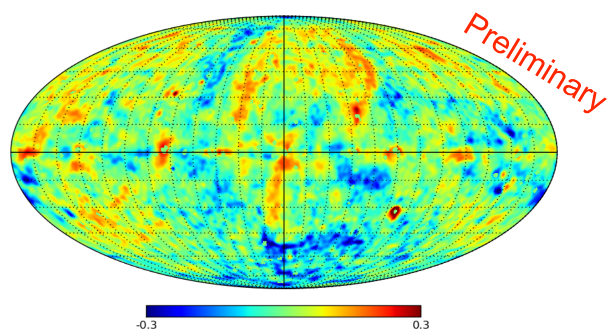
- **All sky-fit**
- **Fit normalization in each energy bin for each template**



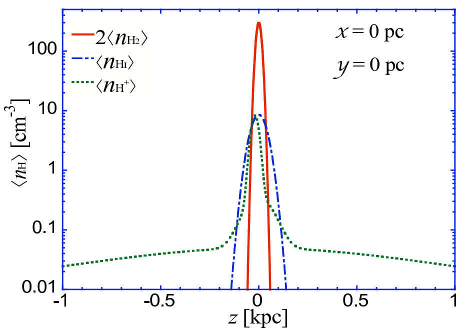
Fractional residual, 1.1 – 6.5 GeV



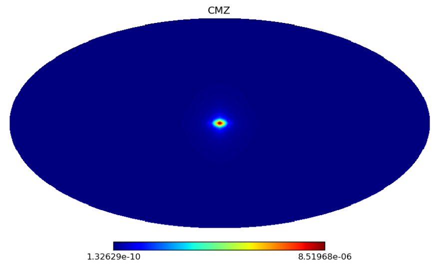
GC excess added back

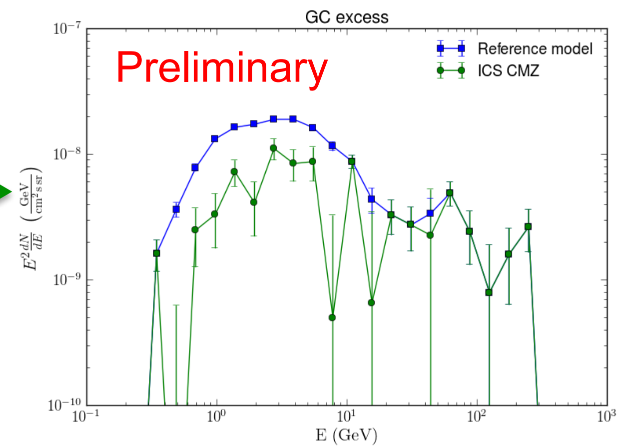


Sources of CR electrons near the GC

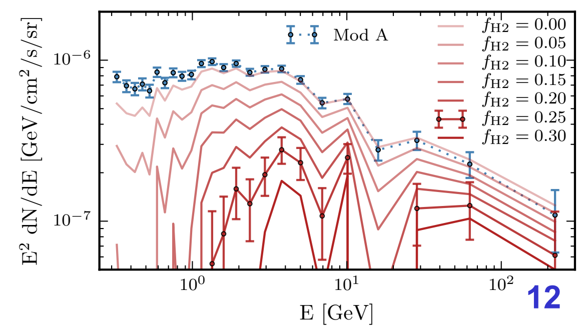


Ferriere et al.,
A&A, 467 (2007)



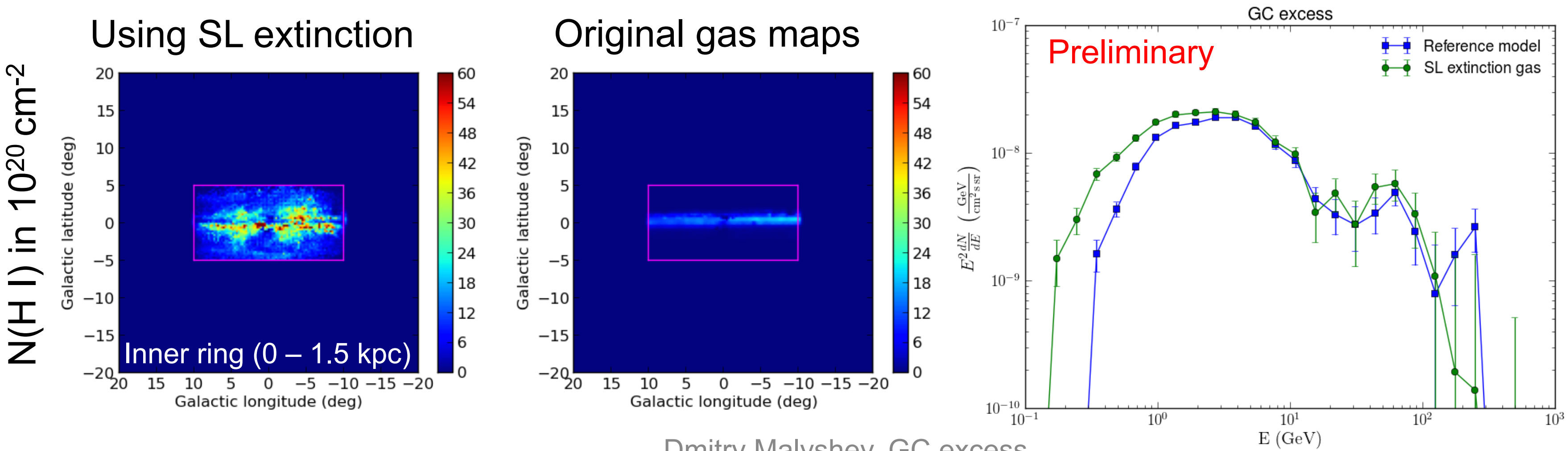


- **A source of CR electrons in the central molecular zone (CMZ) region can reduce the flux associated with gNFW template**
  - **Burst-like emission from the GC nucleus (Cholis et al. JCAP 1512, 2015)**
  - **CR production correlated with molecular clouds in CMZ (Carlson et al. PRL 117, 2016)**



Alternative gas maps

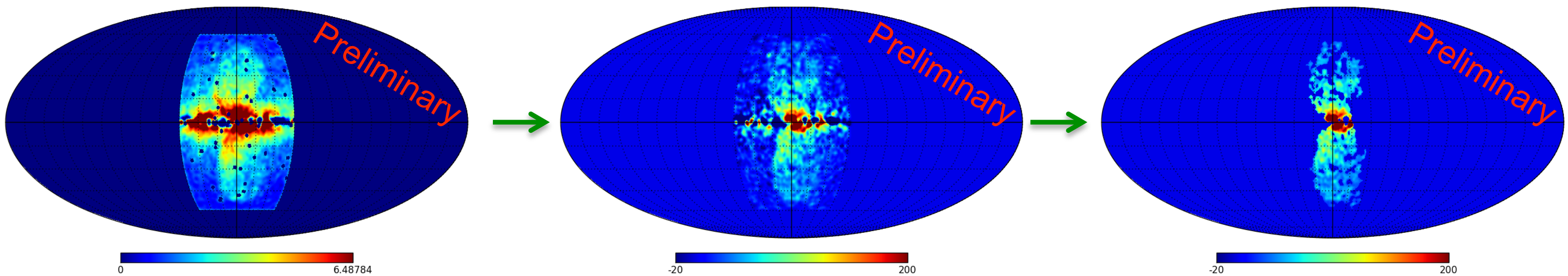
- Hard to model distribution of gas towards the GC due to lack of Doppler shift information
  - Gas distribution is interpolated from |Lon| > 10°
- Use starlight (SL) extinction (Schultheis et al, A&A 566 (2014)) to find the distribution of dust along the LOS towards the GC
  - Derive the distribution of gas assuming homogeneous mixing of dust and gas



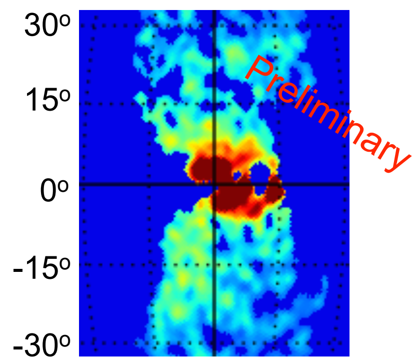
Bubbles template from Spectral components analysis (SCA)

- **Assume that the bubbles have the same spectrum near the GC as at high latitudes $\sim E^{-2.0}$ between 1 and 10 GeV**
- **Cut on significance to obtain the bubbles template**

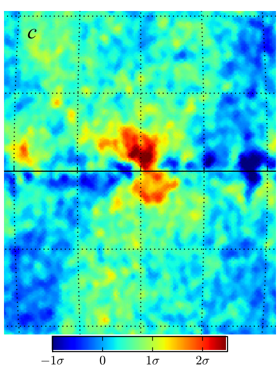
Data – gas – PS | $\sim E^{-2.0}$ component | Bubbles template



- **Fermi bubbles template in the inner Galaxy:**



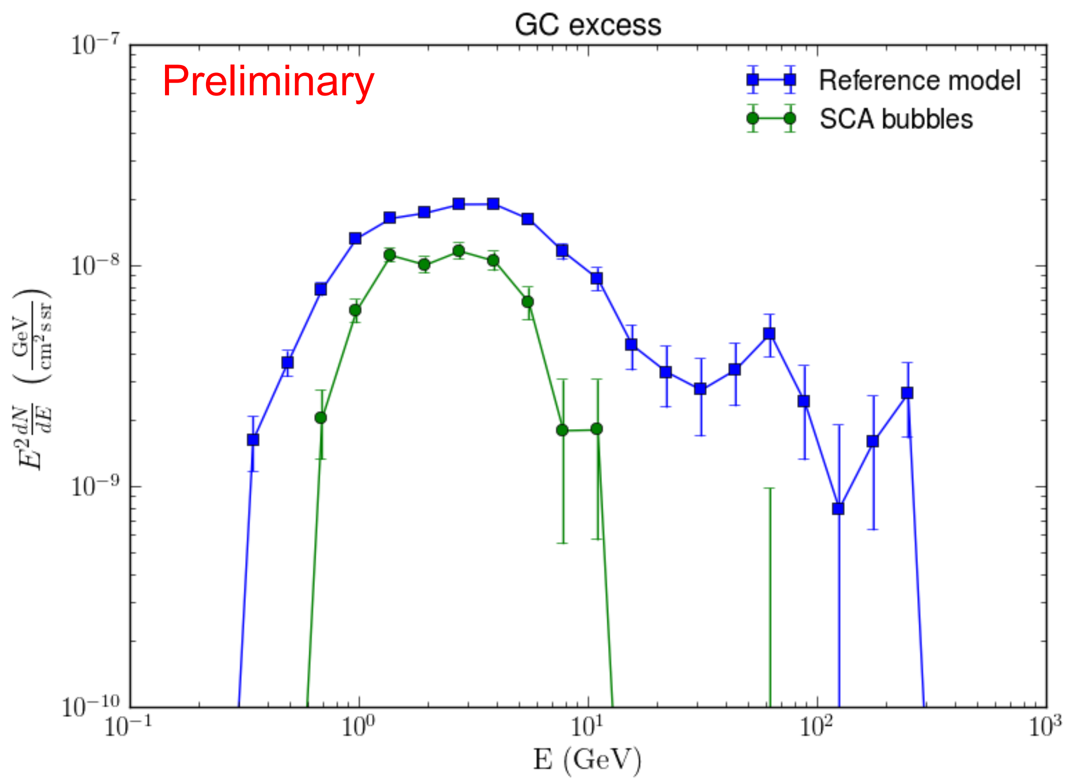
This work



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

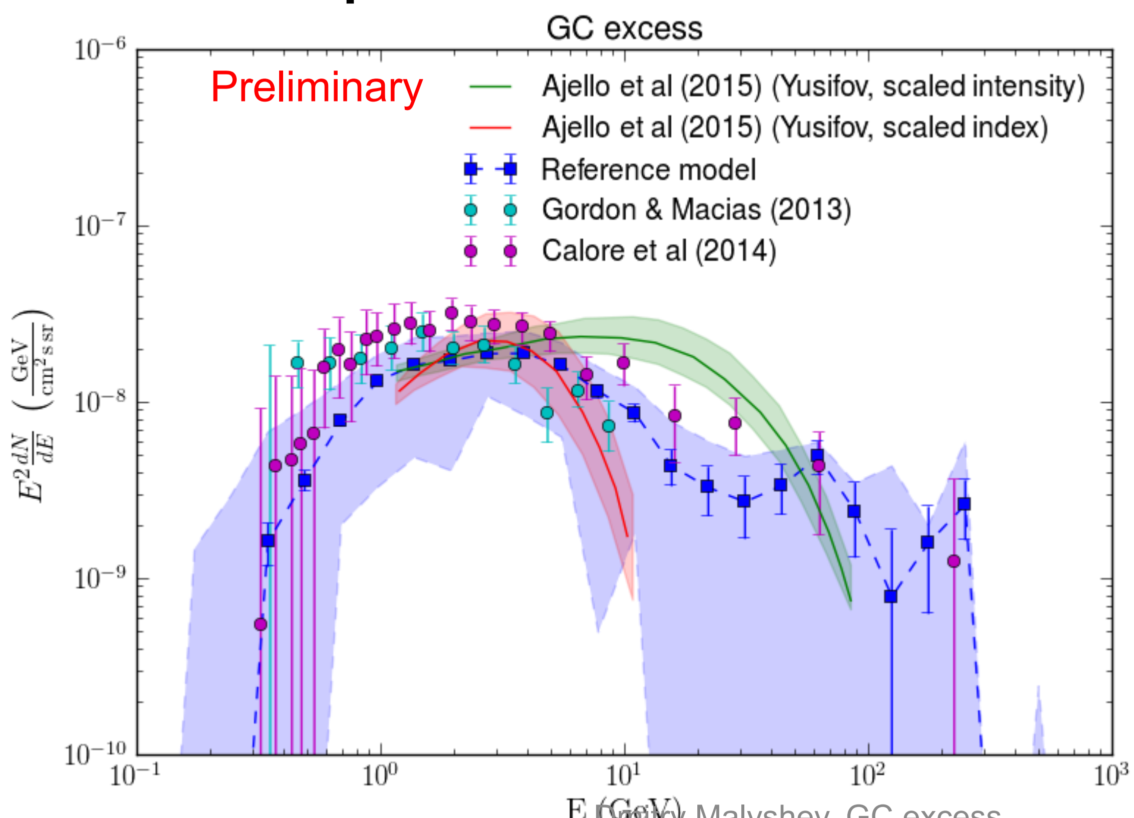
GC excess and all-sky bubbles

- 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

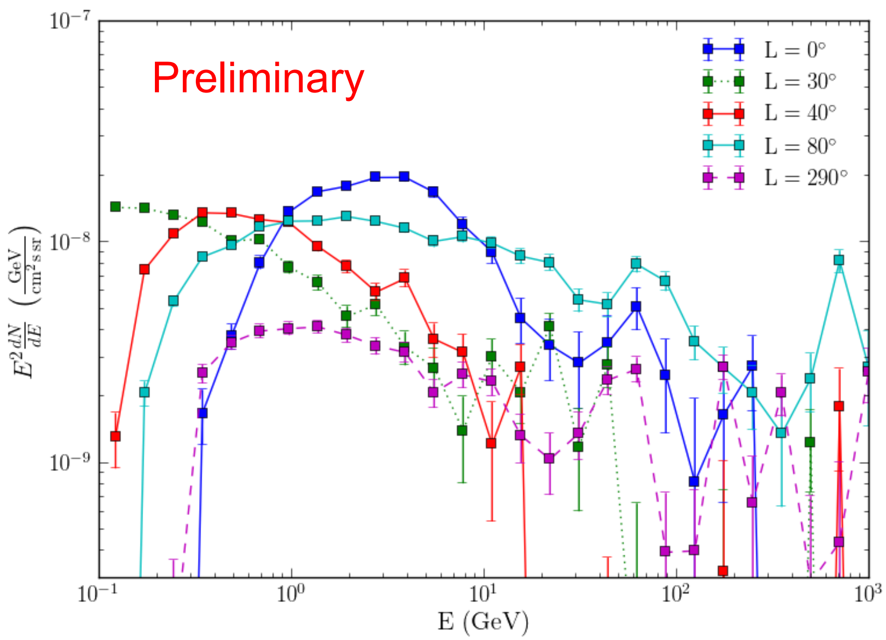
- **The spectrum uncertainty band comes from**
  - **Variations of GALPROP models and gas distribution**
  - **CMZ source of CR electrons**
  - **Fermi bubbles at low latitudes**
- **The excess persists in all models that we have tested**



Spectra are normalized to 4π sr

Scan along the plane

- We expect DM annihilation in the GC but not along the Galactic plane
- We use a scan of the cusp profile along the Galactic plane to determine the level of modeling uncertainty "σ_{model}" which we can use to put the limit on DM at the level
  - "signal + n σ_{model}"

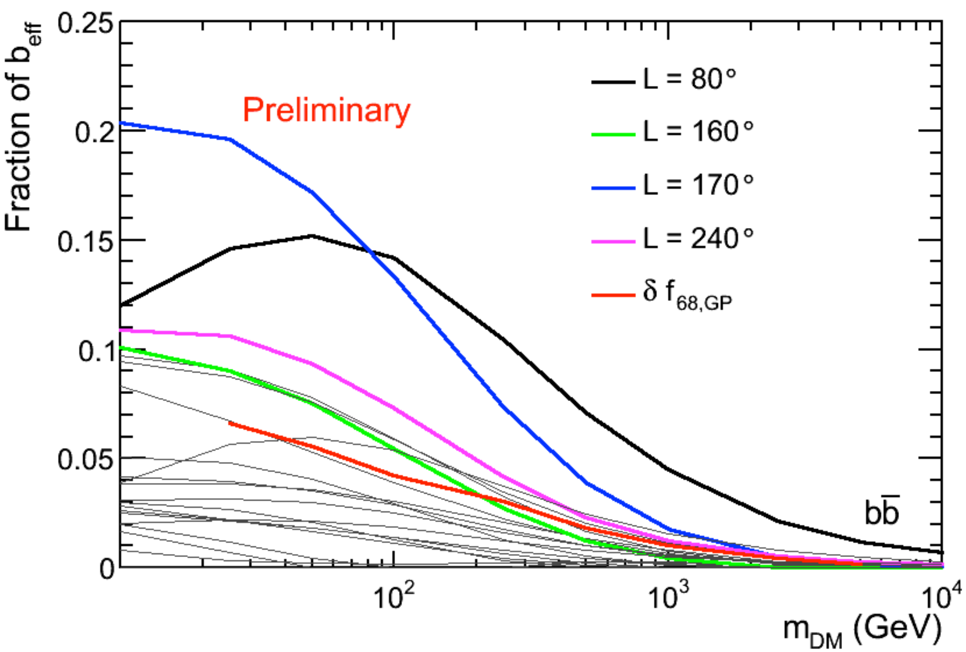


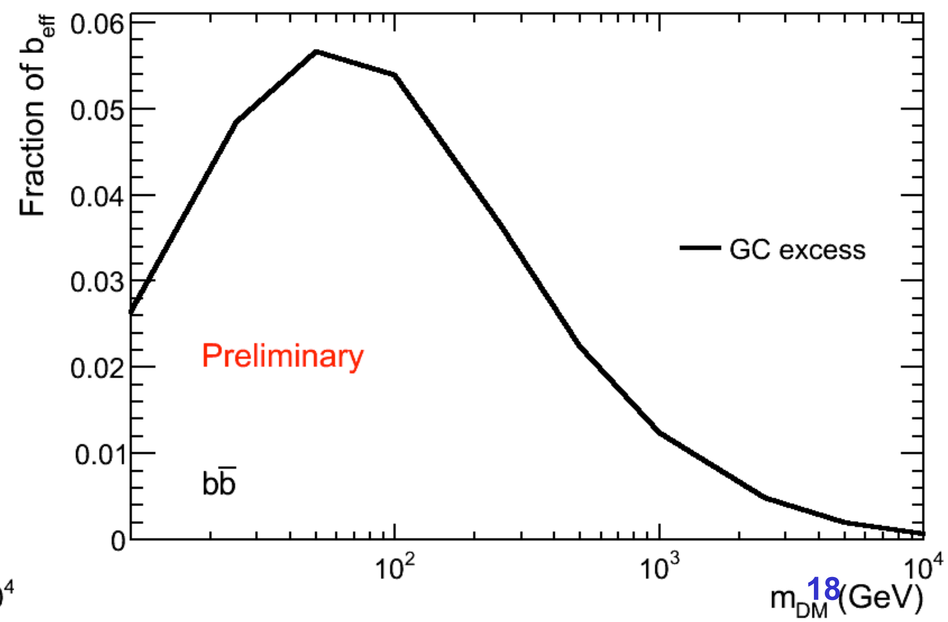
Five positions with largest flux at 3 GeV

Signal to effective background fraction

- Scan the cusp profile with a DM annihilation spectrum along the plane
- Divide signal counts by effective background counts
- Use the 68% median as an estimate of the modeling uncertainty
- **Fractional signal in the GC is comparable to the fractional excesses along the Galactic plane**

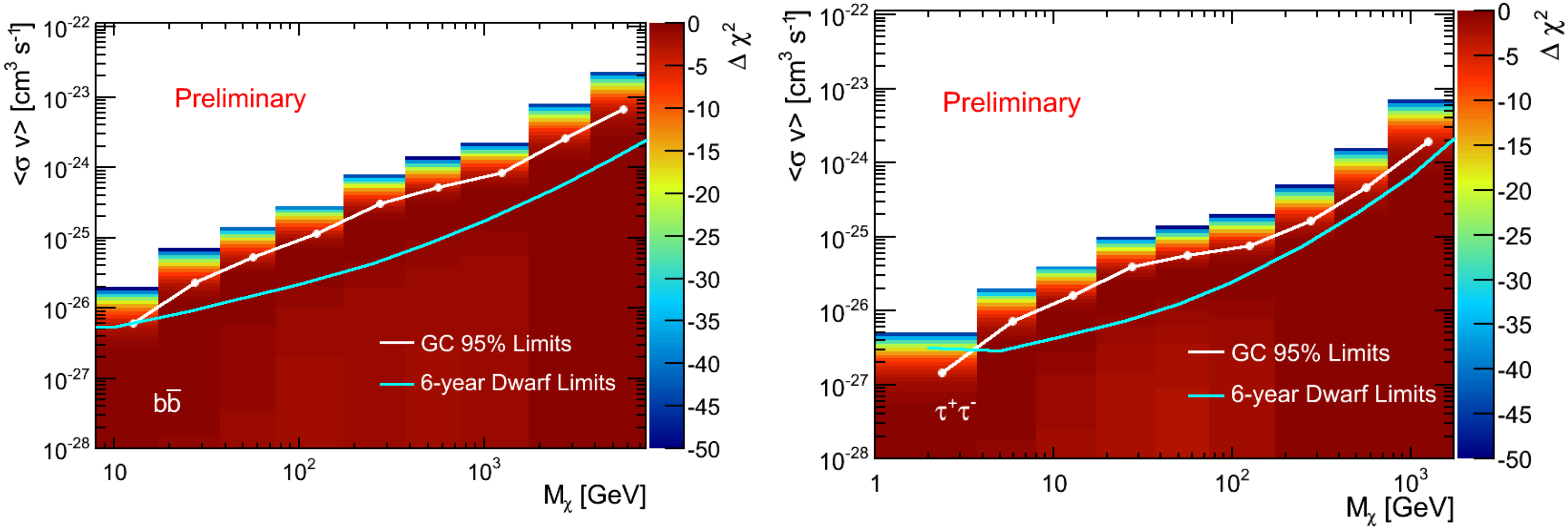
$$f = \frac{n_{sig}}{b_{eff}}$$





Limits on DM annihilation

- $b\bar{b}$ and $\tau^+\tau^-$ channels, gNFW (n=1.25) profile
  - NB: the limits are sensitive to the choice of the profile



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 but a bit less constraining than the limits from dwarf galaxies

Future

- eROSITA
  - Modeling of the Fermi bubbles
  - Look for correlated features near the Galactic center
- HESS, MAGIC, CTA
  - Fermi bubbles near the GC are much brighter
  - Possible to see with Cherenkov telescopes?
- Radio observations, MeerKAT, SKA
  - Search for individual pulsars in the halo around the GC
- Radio surveys, Planck
  - Look for correlated synchrotron emission near the GC
- More Fermi LAT analysis
  - Diffuse emission modeling
  - Analysis of point sources near the GC