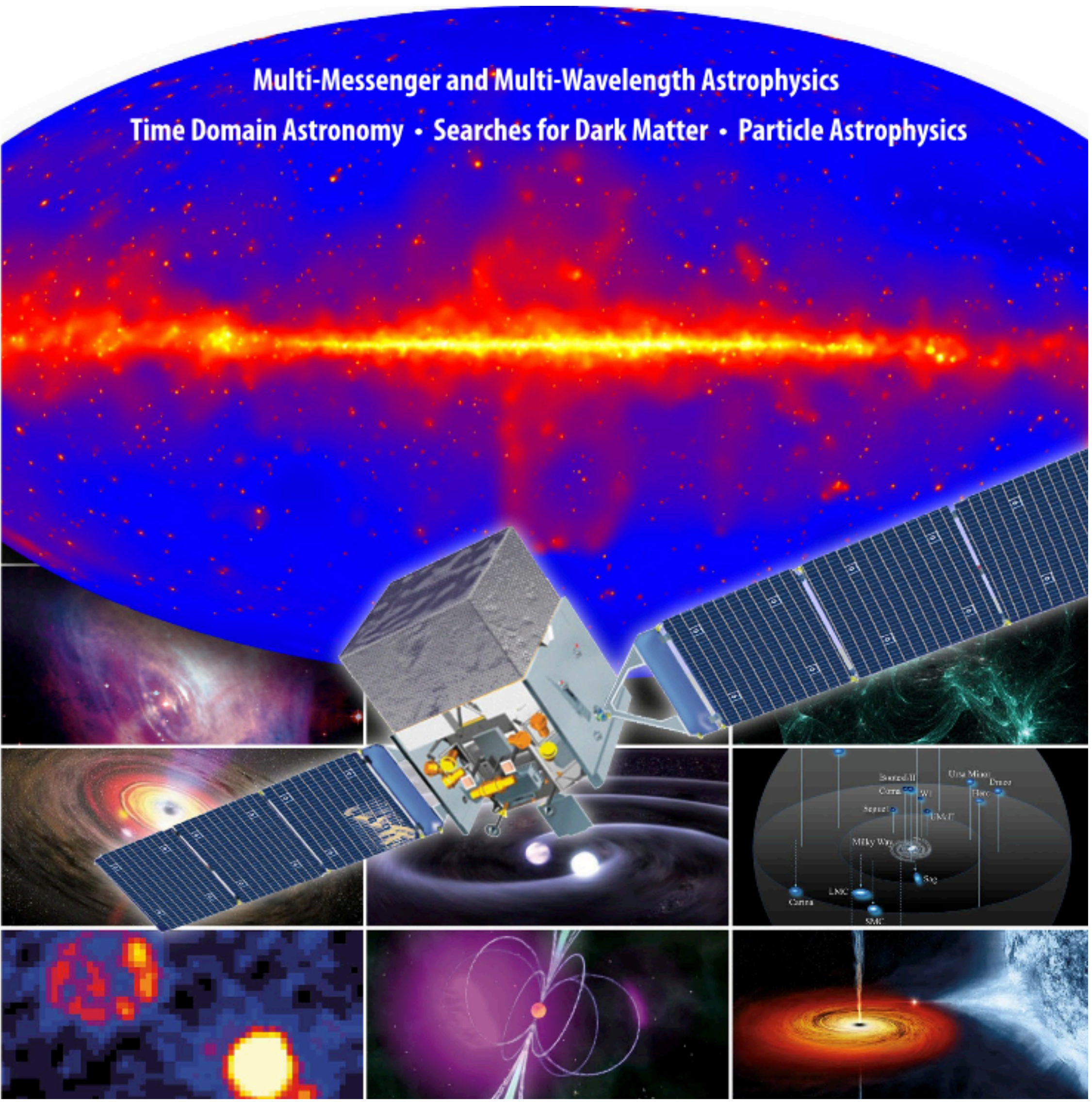
Observations and Models of Gamma-ray Emission Toward the Galactic Center the case of the *Fermi* GeV Excess



Elliott Bloom

KIPAC-SLAC, Stanford University

Andrea Albert,

Eric Charles,

Anna Franckowiak,

Dmitry Malyshev,

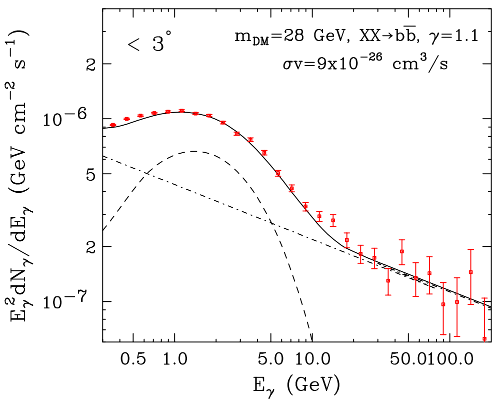
Luigi Tibaldo

On behalf of the Fermi LAT collaboration

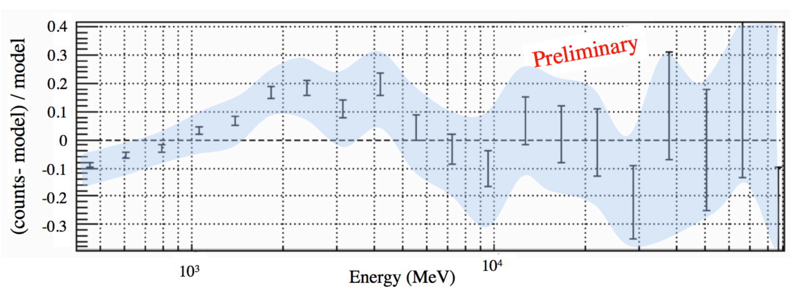
TeVPA, CERN, 9/15/16

Study of Galactic Center (GC) Excess Emission

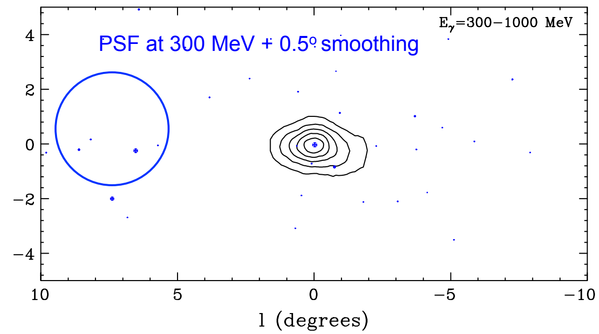
- First hints of an excess in Fermi-LAT data:



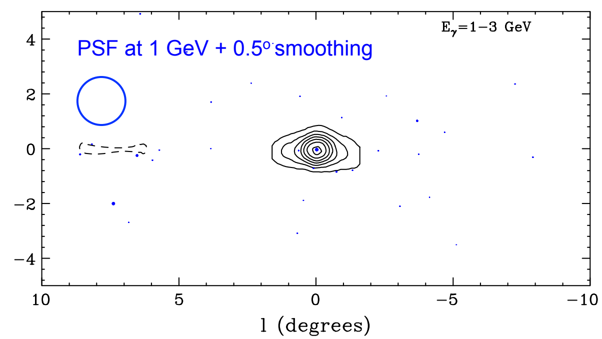
Goodenough & Hooper
arxiv:0910.2998, Oct 2009



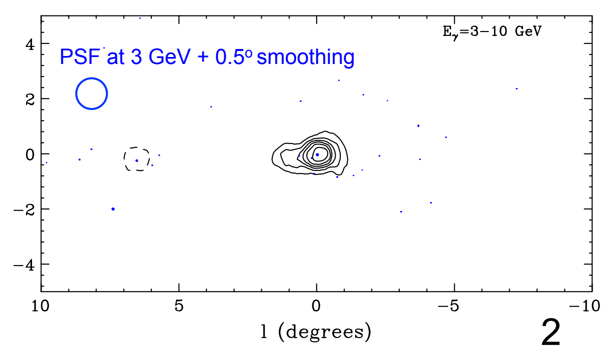
Vitale & Morselli, Proceedings of the 2009 Fermi Symposium, arxiv:0912.3828, Dec 2009



300 MeV – 1 GeV



1 GeV – 3 GeV

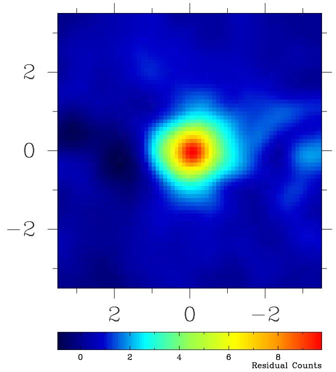


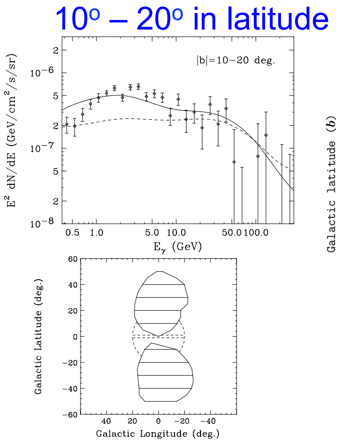
3 GeV – 10 GeV

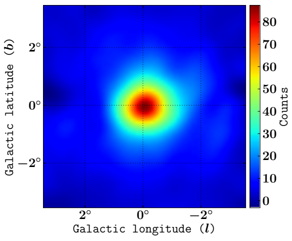
Hooper & Linden
PRD, 84 (2011)

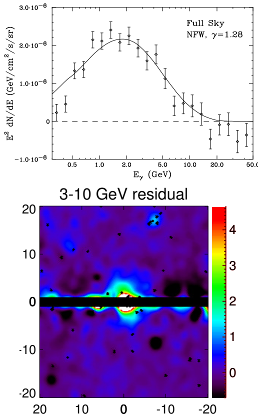
GC "Excess Emission"

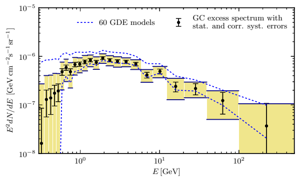
More recent Fermi – LAT analyses

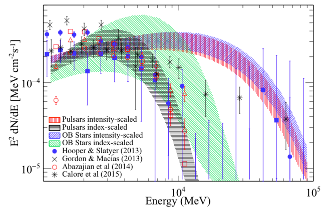












Abazajian & Kaplinghat PRD 87 (2012)

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)

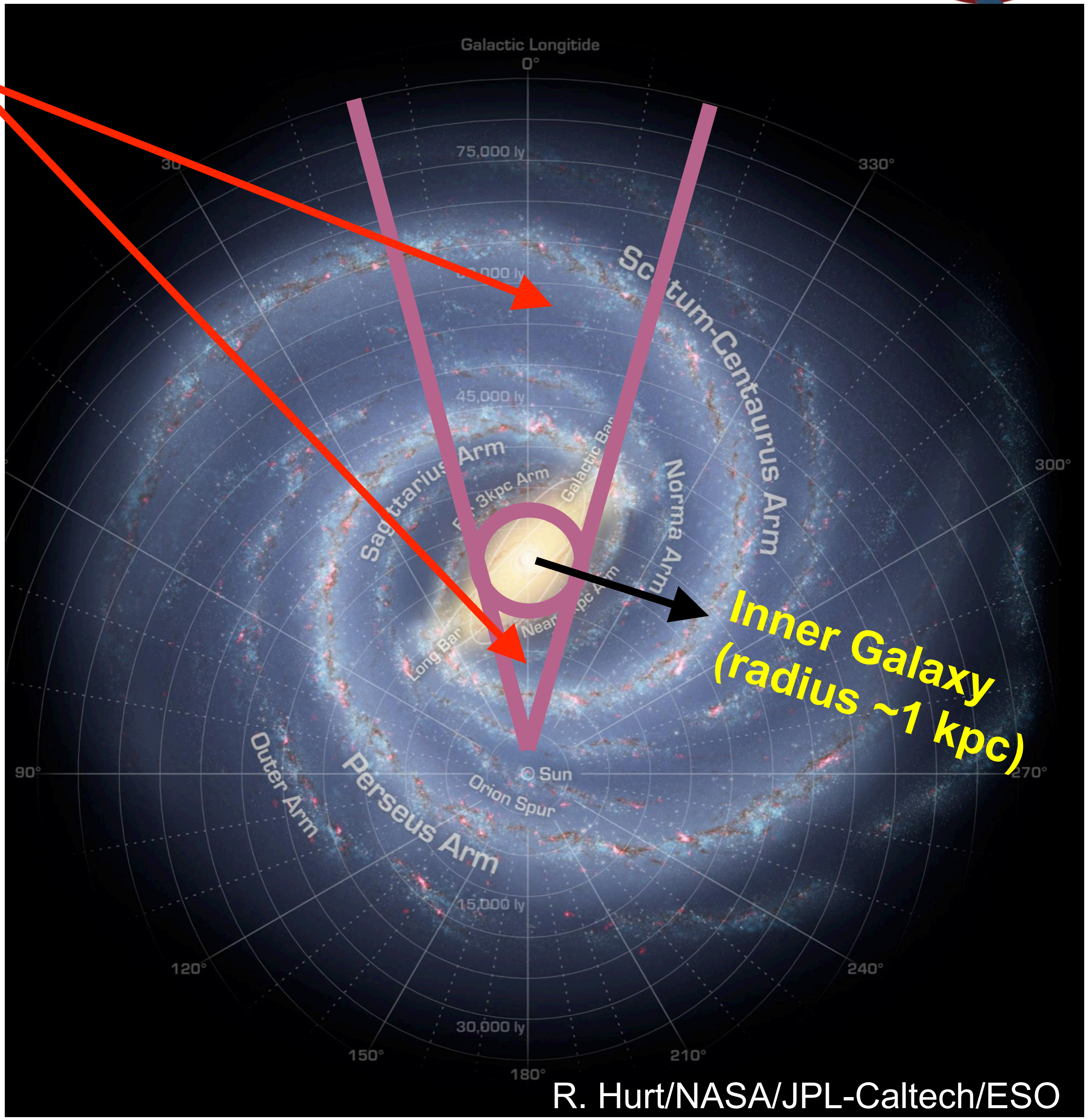
Ajello et al. ApJ 819 (2016)

Dark matter annihilation, unresolved sources, CR electrons?

– **Mirabal** (MNRAS 436 (2013) 2461), **Petrovic et al.** (JCAP 1502 (2015) 02,023), **Cholis et al.** (JCAP 1512 (2015) 12, 005), **Lee et al.** (arXiv:1506.05124), **Bartels et al.** (arXiv:1506.05104), **Brandt & Kocsis** (ApJ 812 (2015) 1, 15), **Carlson et al.** (arXiv:1510.04698) **etc.**

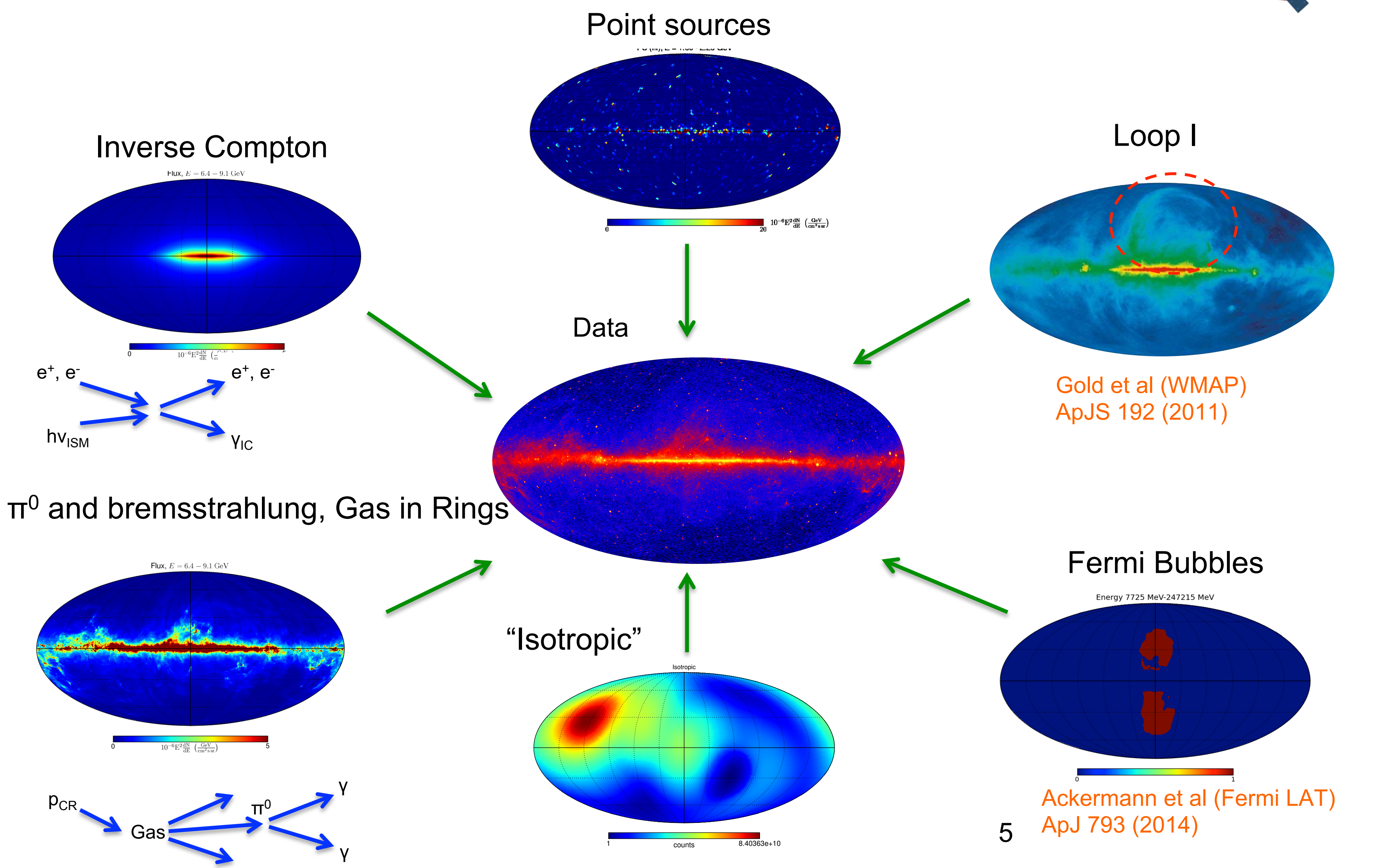
Fermi-LAT Analysis of Diffuse Emission Toward the Inner Galaxy

- Fore/background modeling is critical to studying IG
  - ~80% of the emission (1-100 GeV) in the line of sight is from fore/background interstellar emission
- Goal: study the effects of varying diffuse emission modeling on the GeV excess
- 6.5 years of Pass 8 data Ultracleanveto Class zenith angle < 90°
- 100 MeV – 1 TeV
  - 27 bins in log energy
- Binned into HEALPix maps of order 6 / 7 (1° / 0.5°)



R. Hurt/NASA/JPL-Caltech/ESO

Gamma-ray emission component templates used in Fermi-LAT analysis



Gamma-ray emission component templates (continued)

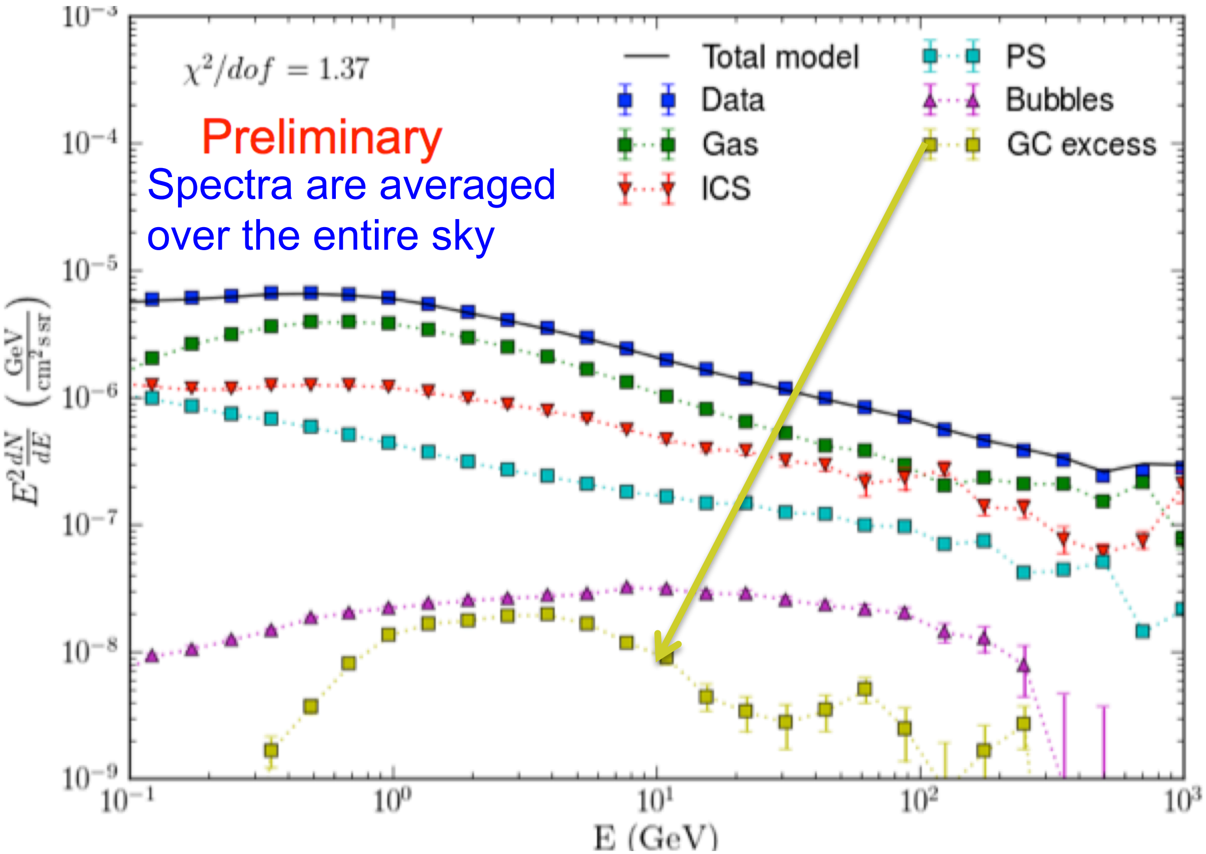
- **Baseline templates:**
  - **Gas correlated (π^0 decay, bremsstrahlung) GALPROP in 5 rings**
    - **Separate H I and CO templates (trace atomic and molecular hydrogen)**
  - **Inverse Compton (starlight, IR, CMB) GALPROP**
  - **Loop I** **(Wolleben, ApJ 664 (2007))**
  - **Isotropic**
  - **Fermi Bubbles** **(The Fermi-LAT Collaboration, Ackermann et al. ApJ 793 (2014))**
  - **Point Sources (preliminary 4FGL list)**
    - **Derived with 6 years of Pass 8 data**
    - **The cores of 300 brightest PS are masked**
  - **Sun / Moon (Fermi-LAT Science Tool gtsuntemp etc.)**

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

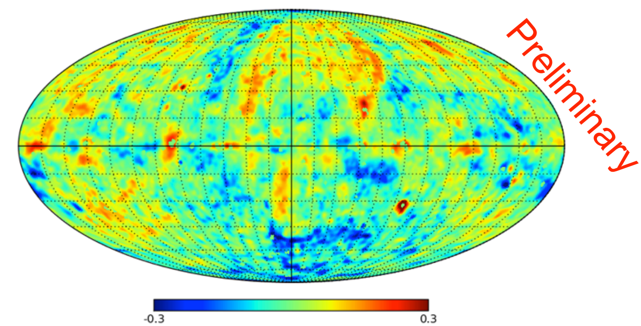
- **Template for the GeV Excess:**
  - **Model as for DM annihilation, generalized NFW profile (gNFW), $\gamma = 1.25$**

Reference template model all-sky fit

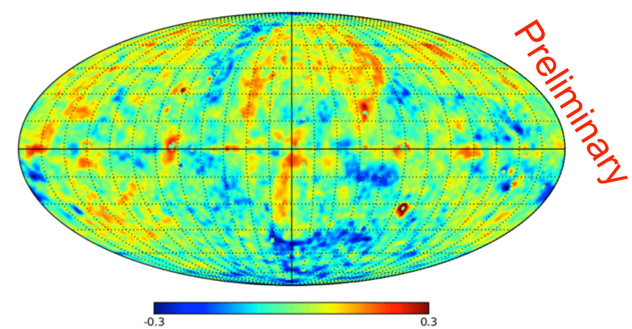
- **Baseline templates:** **All-sky fit is made separately in each energy bin.**



Fractional residual, 1.1 – 6.5 GeV



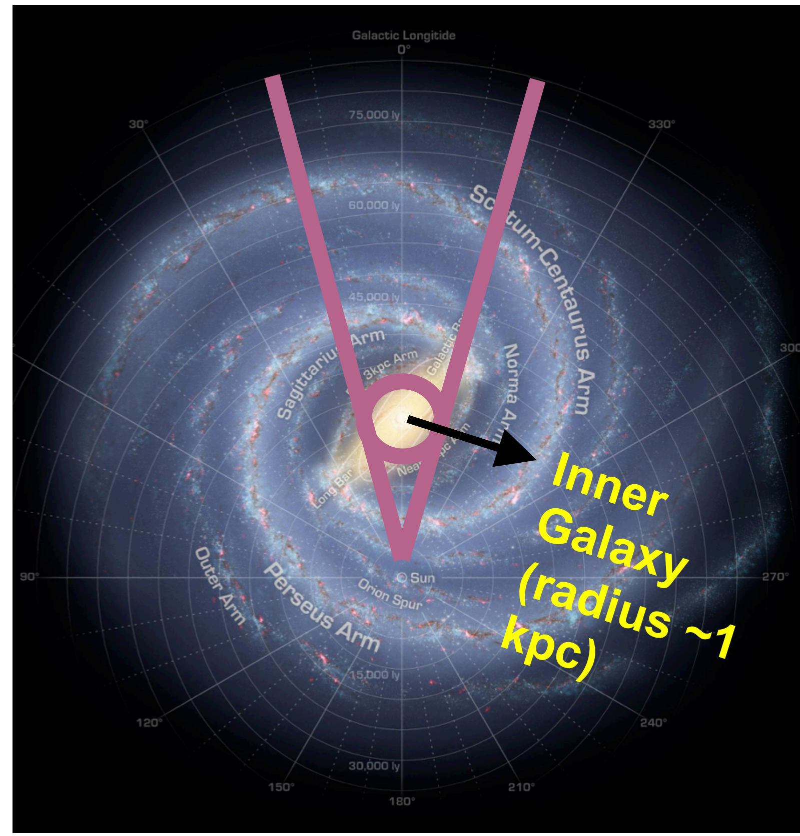
Fit without gNFW template



- **GC excess template:**
  - **Model for DM annihilation, generalized NFW profile (gNFW), γ = 1.25**

Some Modeling uncertainties

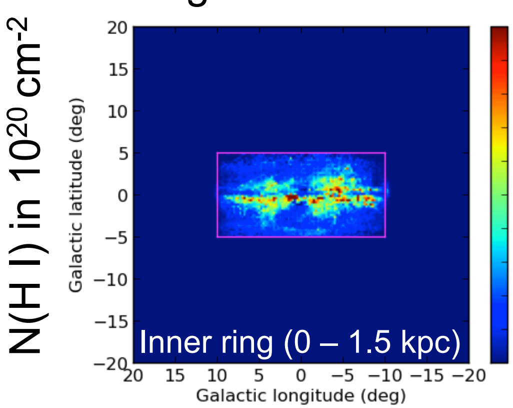
- Cosmic ray distribution in the Galaxy
  - Sources of Cosmic rays
    - CR sources near the GC
  - Propagation parameters
- Distribution of targets in the Galaxy
  - Gas
  - Interstellar radiation fields
- Fermi bubbles near the GC



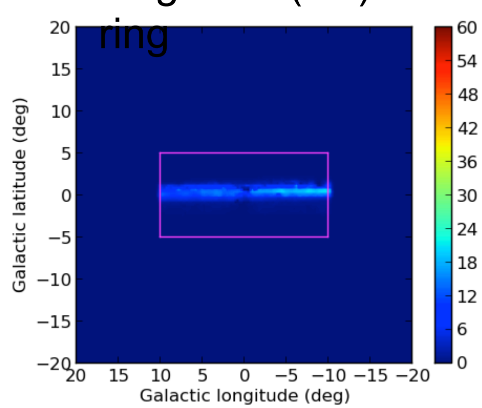
Alternative Gas Maps

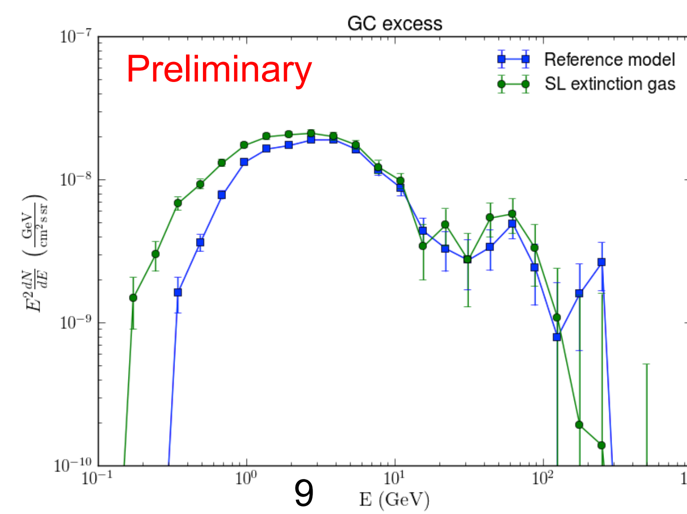
- Hard to model distribution of gas towards the GC due to **lack of Doppler shift** information
  - In our usual decomposition of the gas distribution into rings the Gas distribution is interpolated from |Lon| > 10°, the total column densities are then adjusted to match the data.
- **Use starlight (SL) extinction** (Schultheis et al., A&A 556 (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
- Not meant to be a substitute for the current gas maps
  - useful for estimation of modeling uncertainties

Using SL extinction



Original N(H I) ring

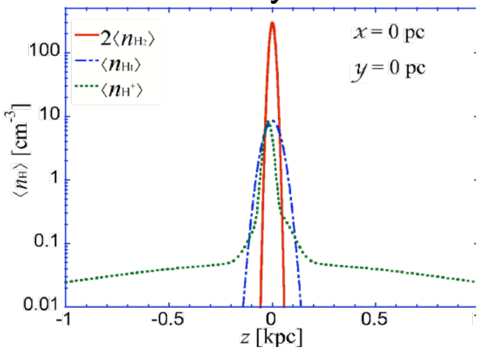




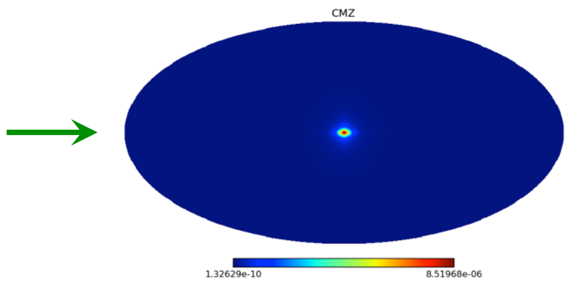
Potential sources of additional CR electrons near the GC

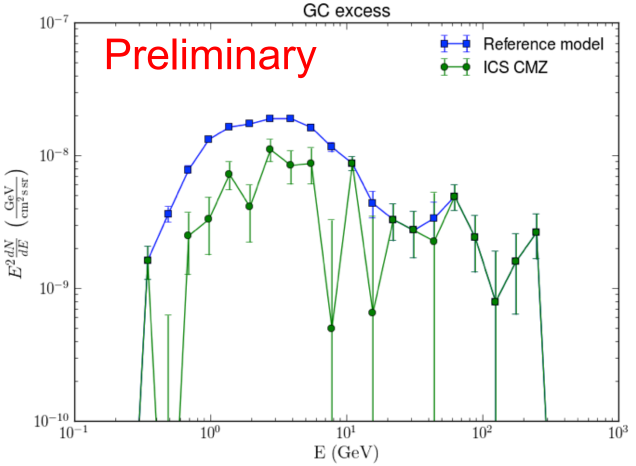
- **CR electron sources in the bulge** (Petrovic et al. JCAP 1502 (2015) 02)
  - Electrons are produced by MSPs in the bulge
- **Starbursts in molecular clouds near the GC**
  - Burst-like emission from the GC nucleus
    (Cholis et al. JCAP 1512 (2015) 12)
  - Steady-state CR production traced by molecular clouds
    (Carlson et al. arXiv:1510.04698)
- **Similar to Carlson et al. (2015), we find that a source of CR electrons in the central molecular zone (CMZ) region can reduce the flux associated with gNFW template below ~ 20 GeV:**

CMZ density distribution



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

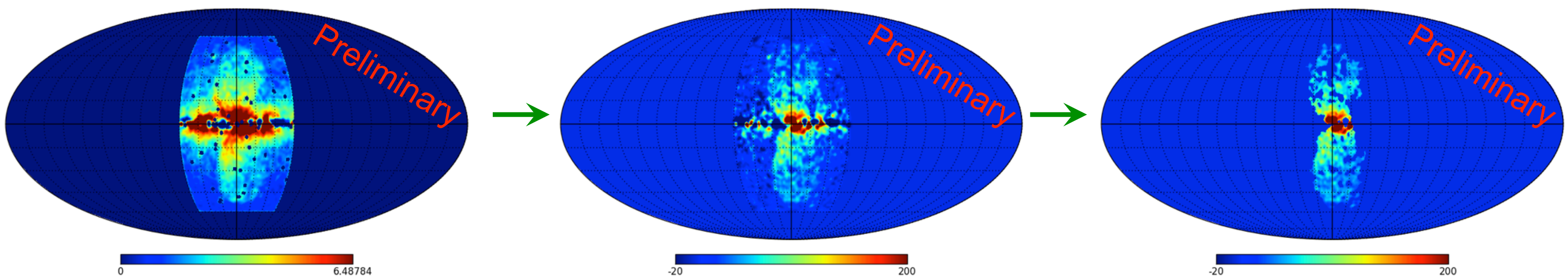




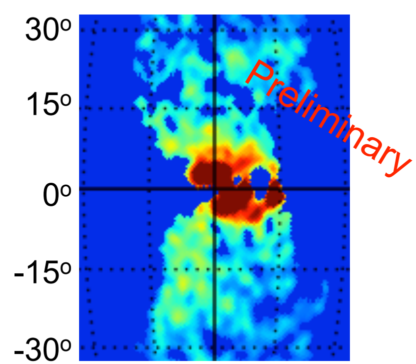
Bubbles template

- Assume that the bubbles have the same spectrum near the GC as at high latitudes ~E^{-2} between 1 and 10 GeV
- Cut on significance to obtain the full bubbles template including b=0

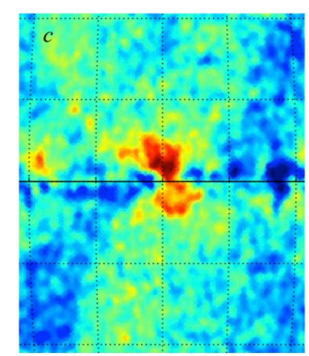
Data – gas – PS | ~E^{-2} component | Bubbles template



- The Fermi bubbles template in the inner Galaxy looks similar to the residual found in Casandjian, et al (2016)
- But beware of modeling uncertainties



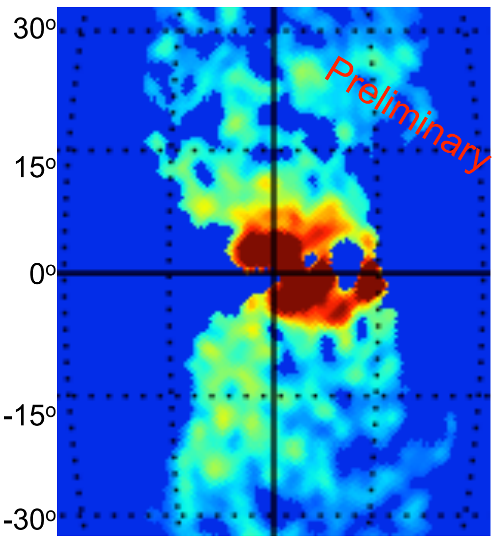
This work

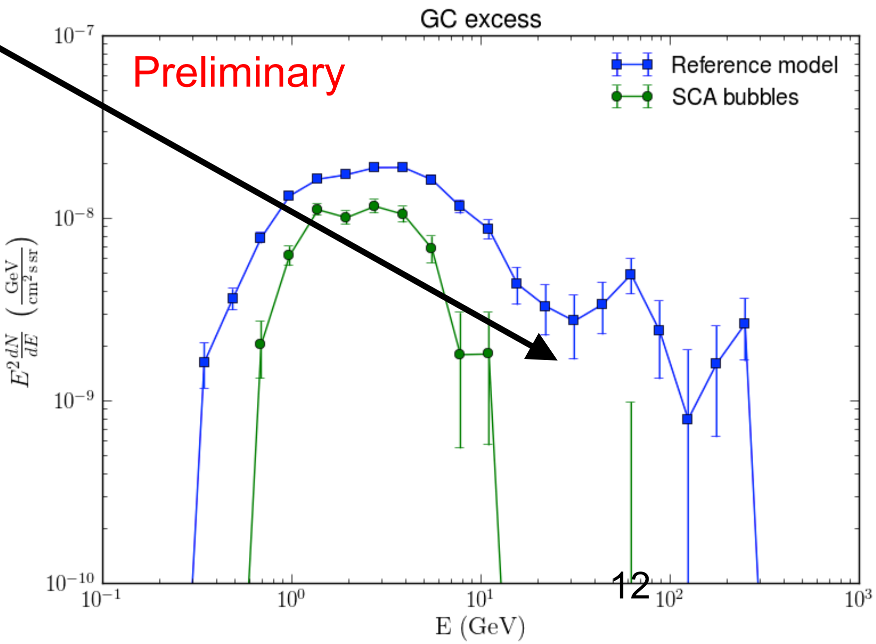


F. Acero,… Casandjian... et al, Astrophysical Journal Supplement Series, Volume 223, 2 (2016)

Additional & Alternative Templates

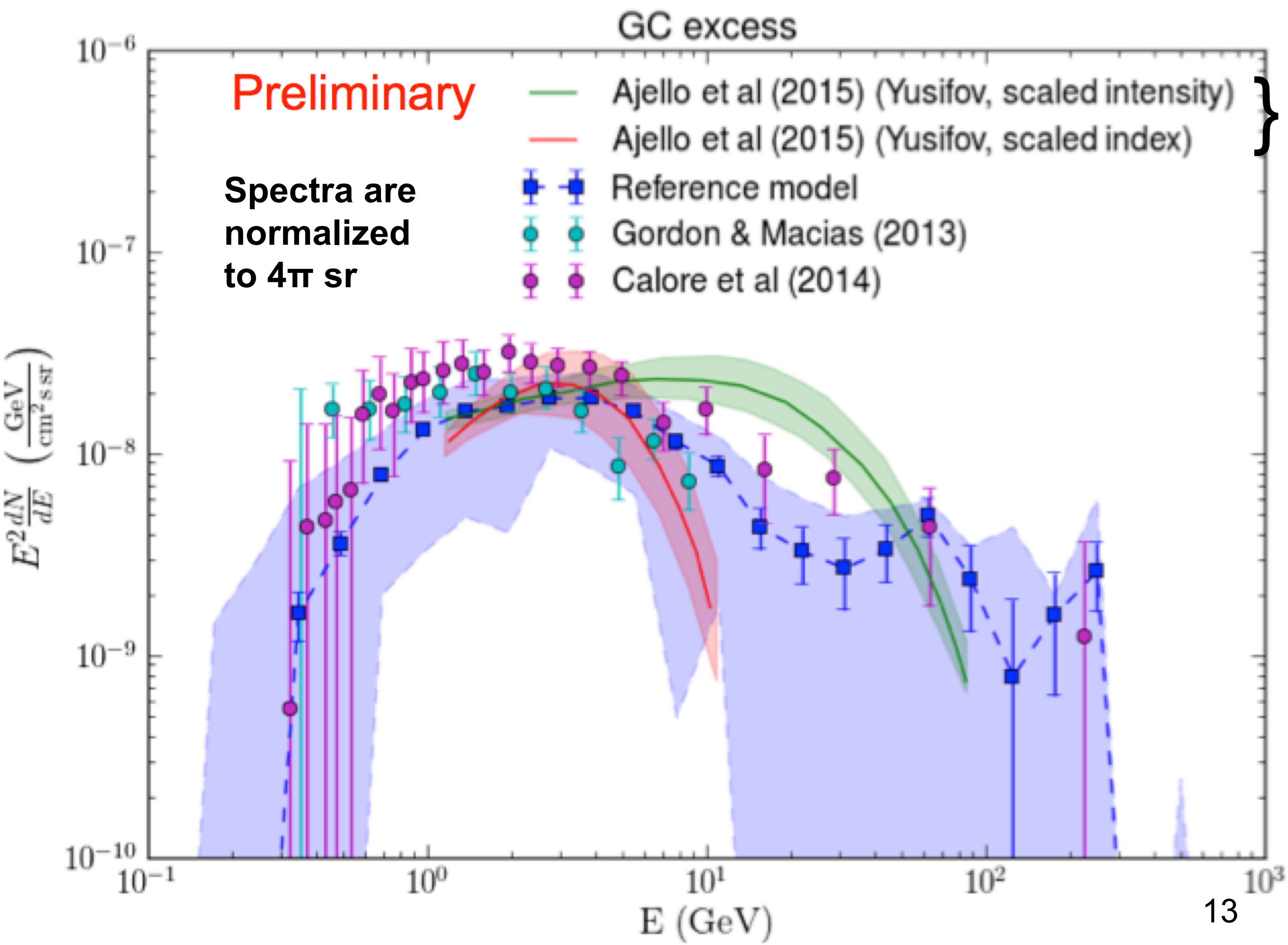
- Variation of GALPROP model parameters
  - Small effect on spectrum of the GeV excess
- Alternative gas maps based on 3D dust extinction model
  - Softer excess spectrum at low energies (< 1 GeV)
- Include additional sources of cosmic-ray electrons in the GC
  - Excess is reduced
- Add data-driven template for low-latitude Fermi Bubbles
  - Excess above 10 GeV is gone, excess below 10 GeV is reduced





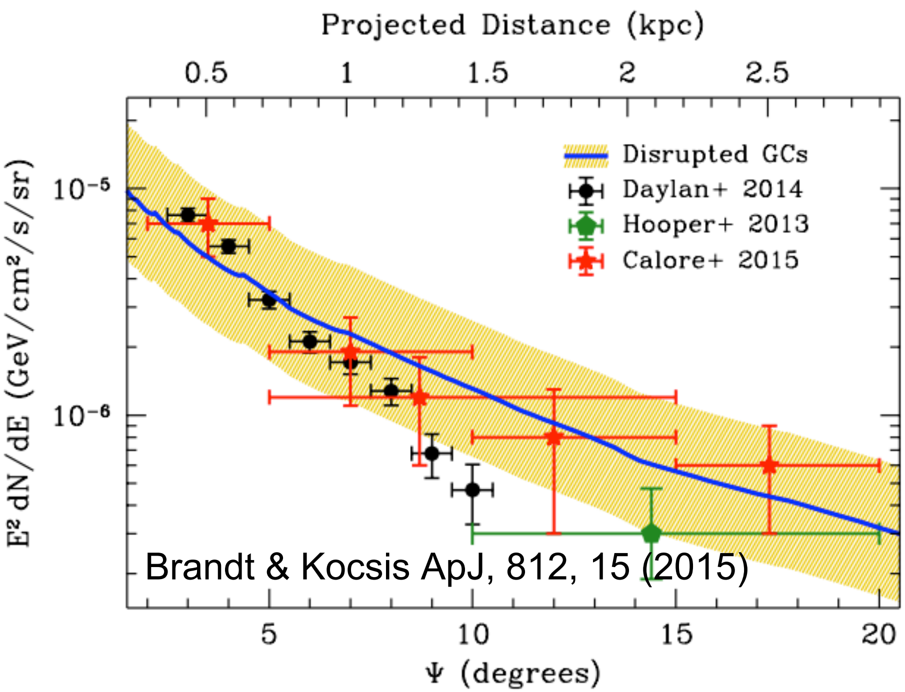
Addition/substitution of templates generates a band of GC excess fluxes

- The spectrum uncertainty band in purple comes from additions/ variations described on previous slides



Ajello et al. (The Fermi-LAT Collaboration) ApJ 819 1 44 (2016)

Exploring a potential MSP interpretation for the GeV excess



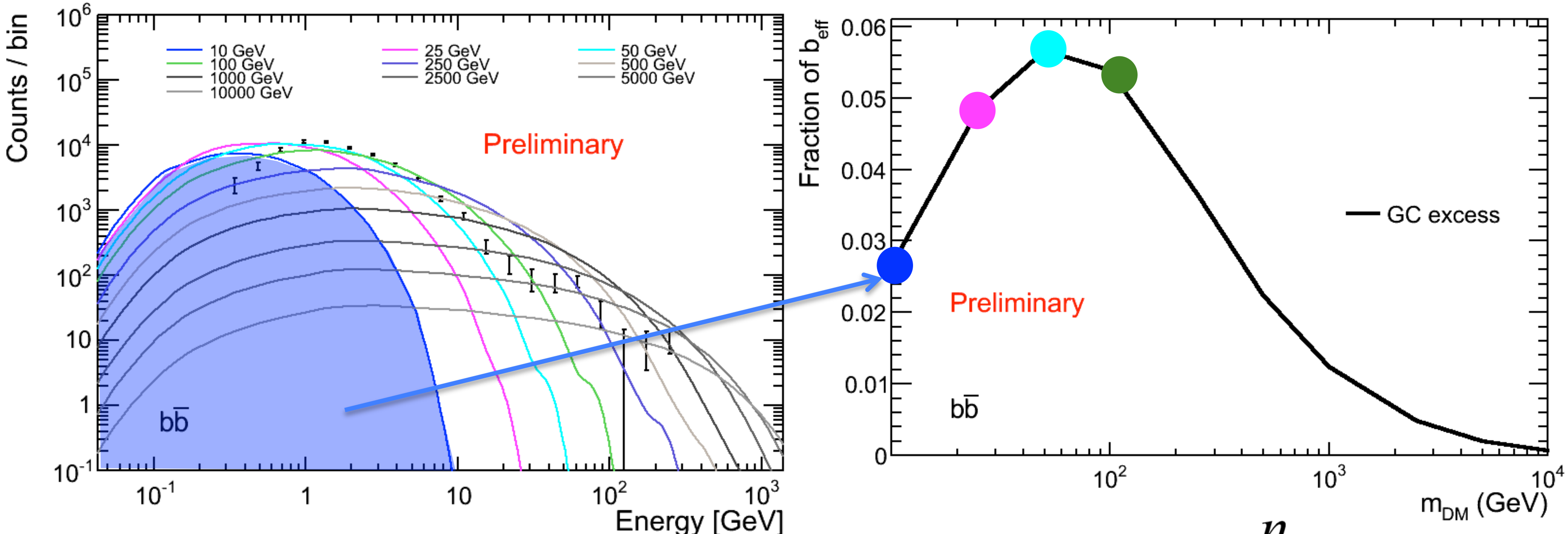
- **Challenging to predict the number and luminosity function of unresolved MSPs**
  - **need to extrapolate properties of fainter MSPs from observed MSPs**
  - **Soft MSP luminosity functions can account for GeV excess**
    - **e.g. Yuan and Zhang (2014), Petrovic et. al. (2015)**
- **Statistically derived templates from unresolved point sources can account for the excess**
  - **Bartels et al. (2015), Lee el al (2015)**

Galactic Bulge may contain MSPs from dissolved Globular Clusters

  - **Brandt and Kocsis (2015)**

- **Many papers have shown a population of unresolved MSPs can account for the excess**
  - **In this presentation we do not include a MSP template in our fits**
- **See Talk by Mattia Di Mauro, "Searches for Point Sources in the Galactic Center region" later this session.**

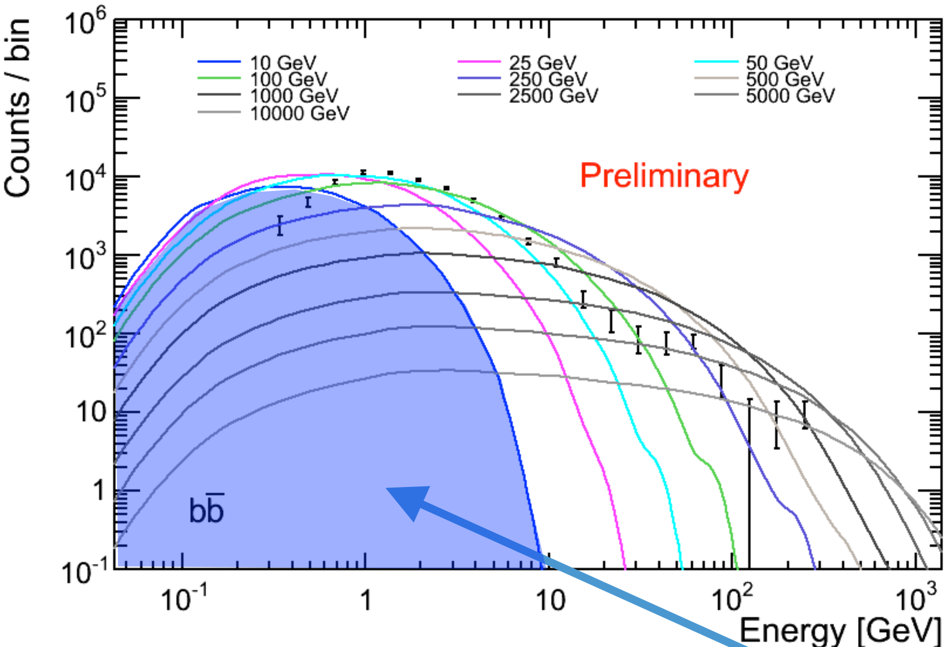
GC Excess modeled as DM -- Fractional Signal

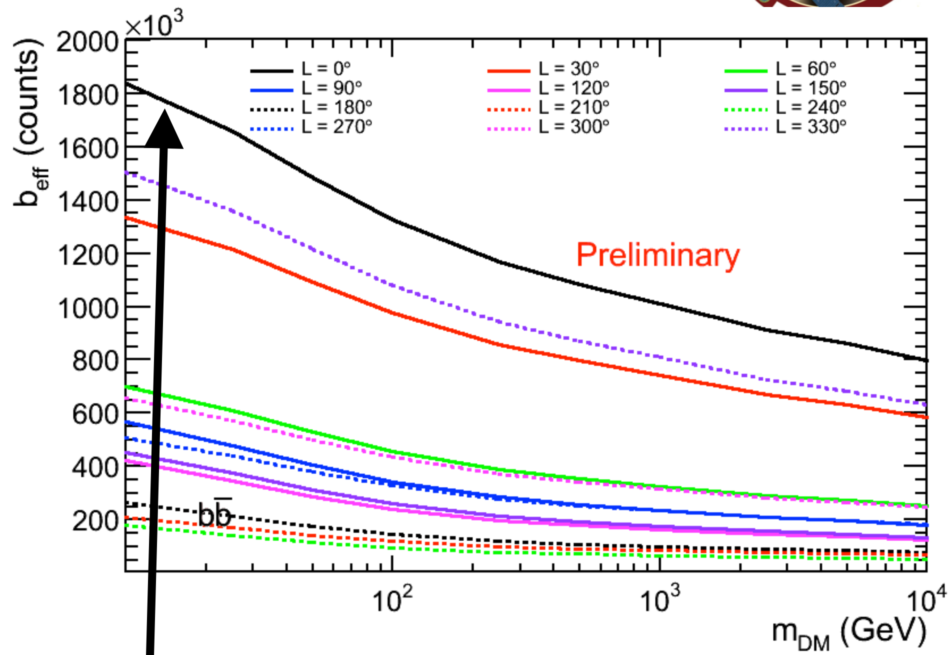


$$f = n_{sig} / b_{eff} \qquad signif \approx \frac{n_{sig}}{\sqrt{b_{eff}}}$$

- **We can quantify dark-matter-like signals as a *fraction of the effective background* (b_{eff})**
  - **b_{eff} is the "background counts under the signal"**
  - **see backup slide for details on b_{eff}**
    - **also see Buckley et al. PRD 91 10 1020001 (2015) and Ackermann et al. PRD 91 12 122002 (2015)**

GC Excess modeled as DM -- Fractional Signal

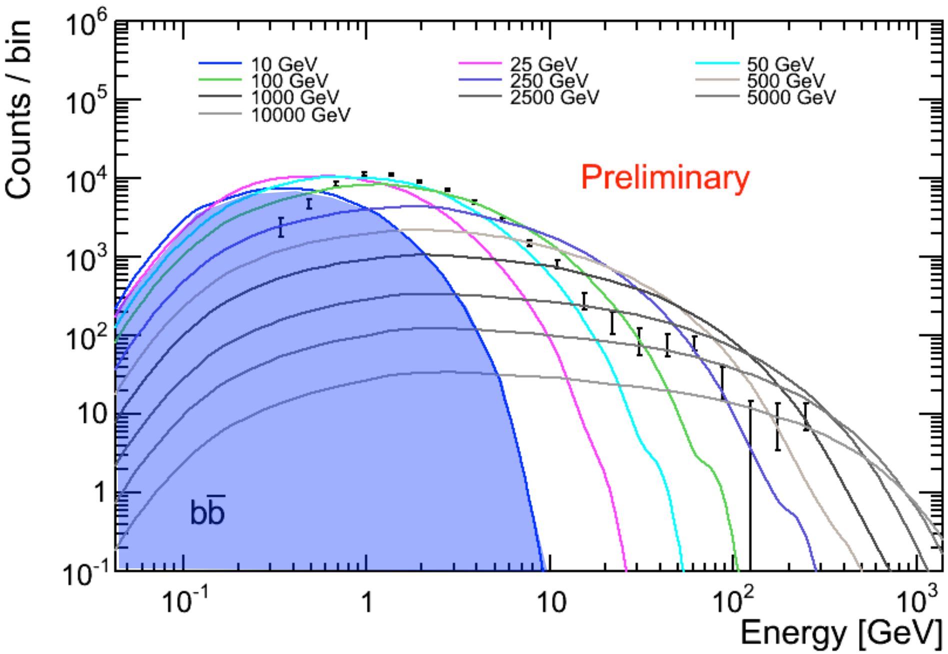


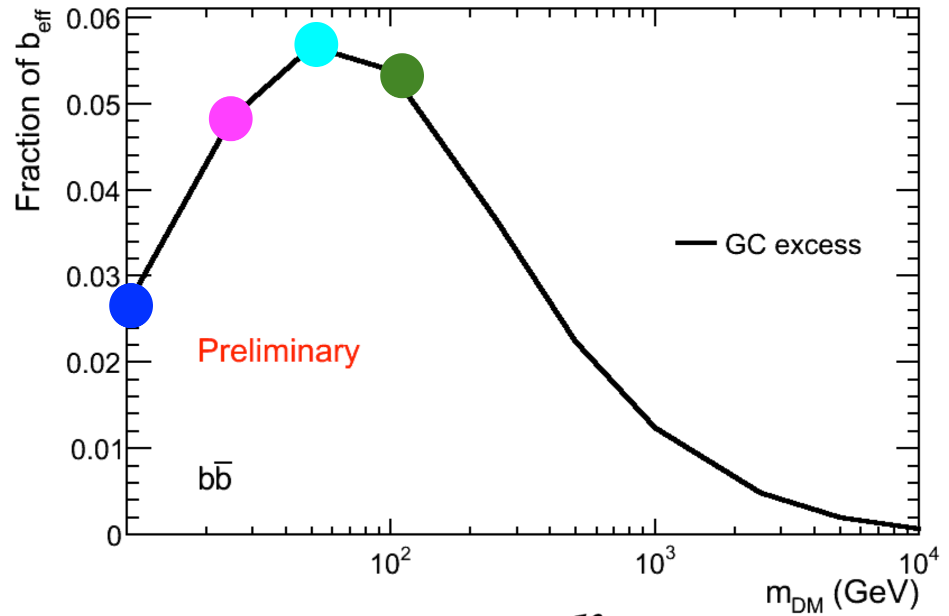


$$f = n_{sig} / b_{eff}$$

- **Fit gNFW template in each energy bin independently**
  - **DM models do not provide a good fit to entire excess**
- **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}**

GC Excess modeled as DM -- Fractional Signal

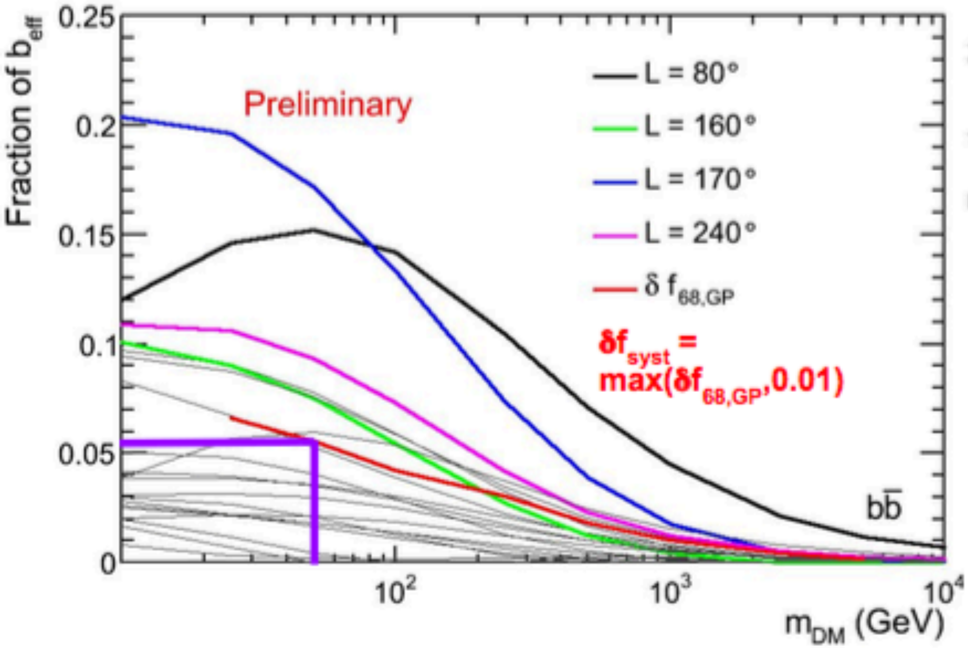


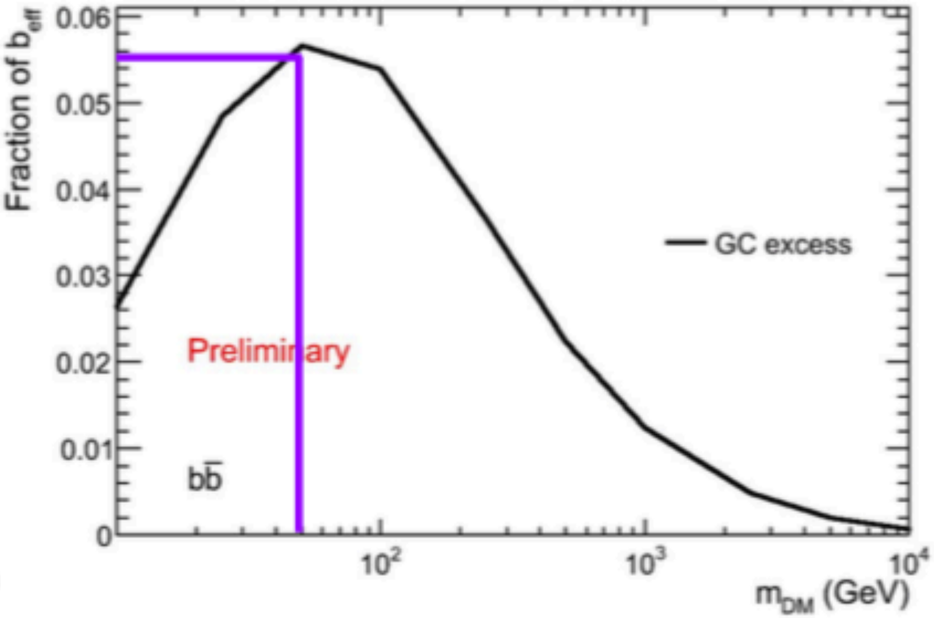


$$f = n_{sig} / b_{eff} \qquad signif \approx \frac{n_{sig}}{\sqrt{b_{eff}}}$$

- **Fit gNFW template in each energy bin independently**
  - **DM models do not provide a good fit to entire excess**
- **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}**
- **Galactic Center excess is only a small fraction of b_{eff}**

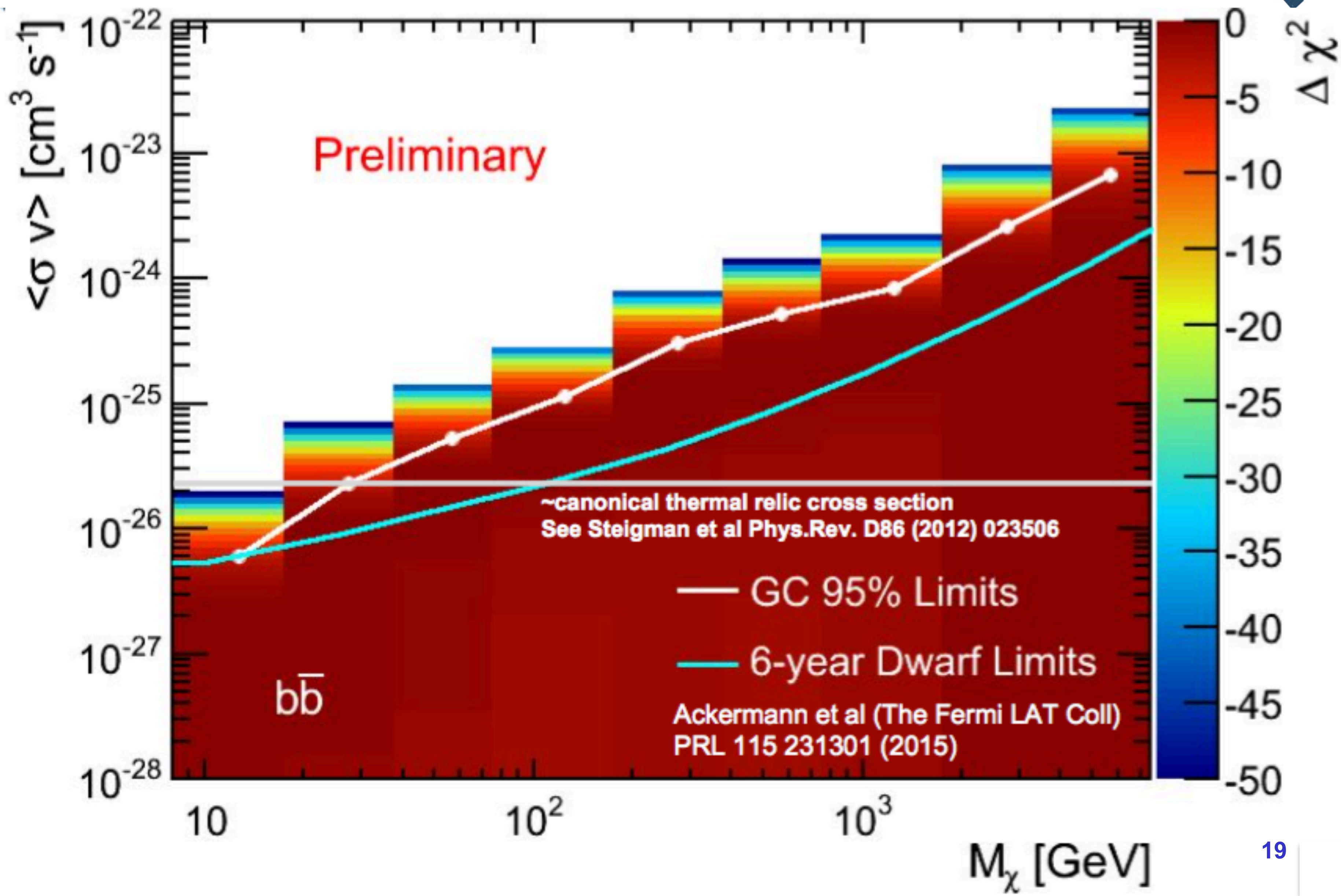
Galactic Plane Scan for DM like signals





- **Perform same fitting with the gNFW template centered along the Galactic Plane, but excluding the center**
  - **Off-center GP is a control region where very little dark matter is expected**
  - **Use 68% containment from GP scan as an estimate of the level of dark-matter-like residuals, δf_{syst}**
- **Size of dark-matter-like residuals at other longitudes is comparable to the fractional signal in the Galactic Center**

WIMP Limits for b-bbar from GC Excess

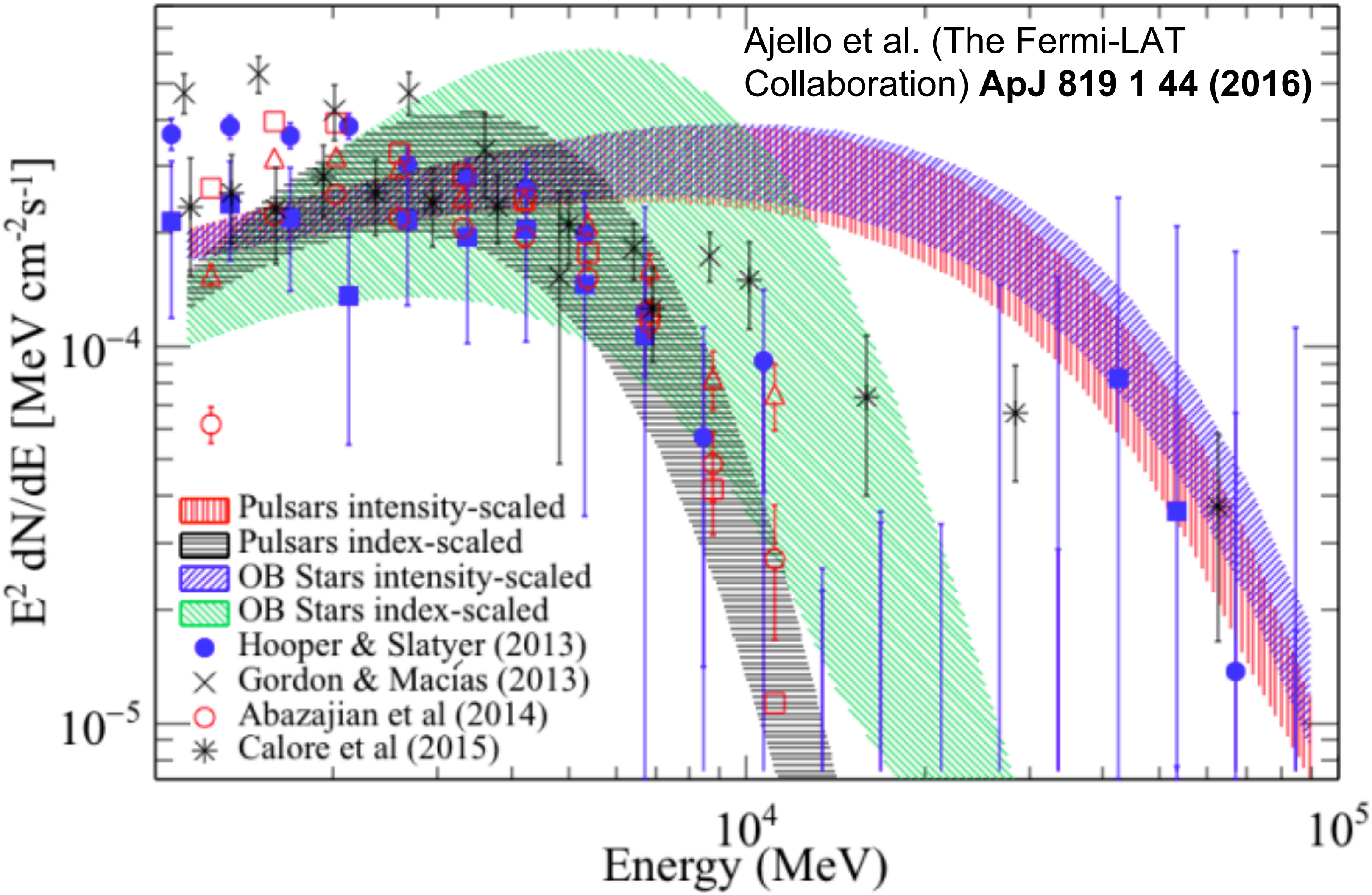


Conclusions

- We investigated the robustness of the GC excess against many modeling uncertainties
- A Galactic Center excess in γ-rays exists
- The origin of this excess is not yet clear
- Possible contributions to the excess include:
  - A population of weak point sources, e.g., MSPs
  - CR injection near the GC
  - The Fermi Bubbles
  - Dark matter
  - …
- Statistical methods prefer a new population of point sources, but there are modeling uncertainties – References on slide 14
- The dark matter limits from this GC study are a factor of a few greater [except at ~15 GeV mass] than the current limits from dwarf galaxies
  - The fractional size of the GC excess is similar to that of other excesses along the GP where no DM signal is expected.

Backup Slides

LAT Inner Galaxy Results

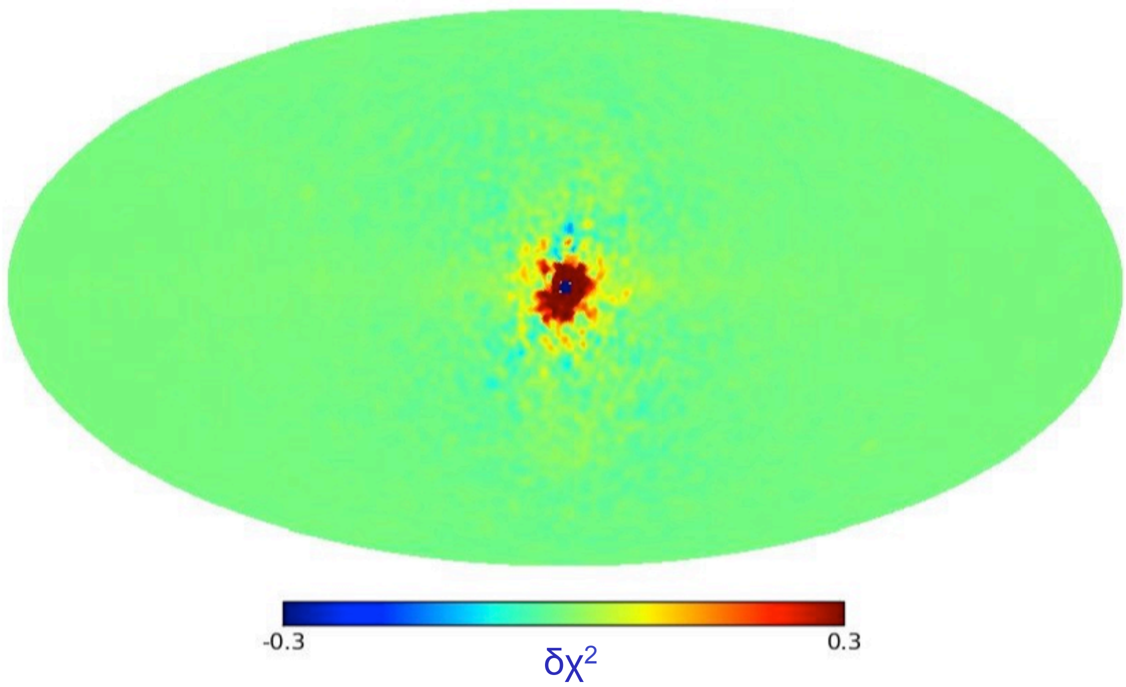


Results from a complementary LAT-team work exploring the Galactic Center Excess template used was standard NFW, excess spectrum modeled with exponential cut-off power-law

Fermi-LAT GC Excess from D3PO Algorithm

"Denoising, deconvolving, and decomposing photon observations"

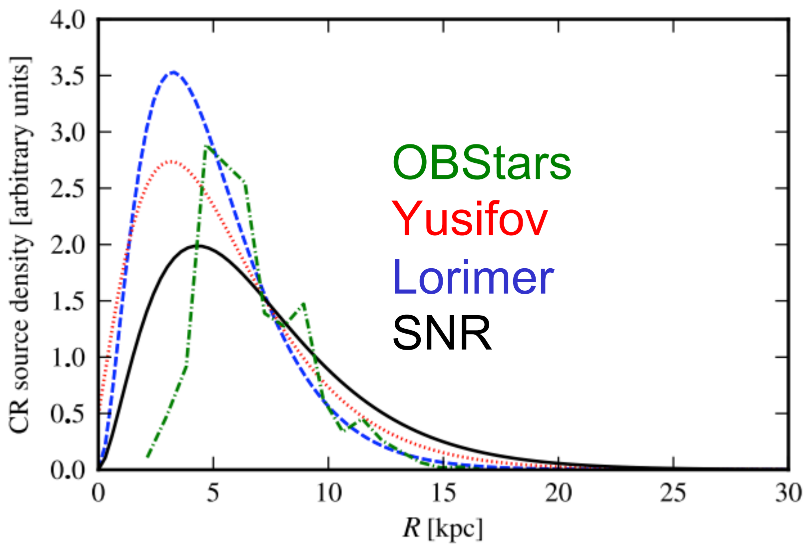
- Spectral model of the Galactic diffuse emission + NFW DM
  - Improvement of the fit with the DM component:



Huang et al, JCAP 4 (2016)

GALPROP parameters

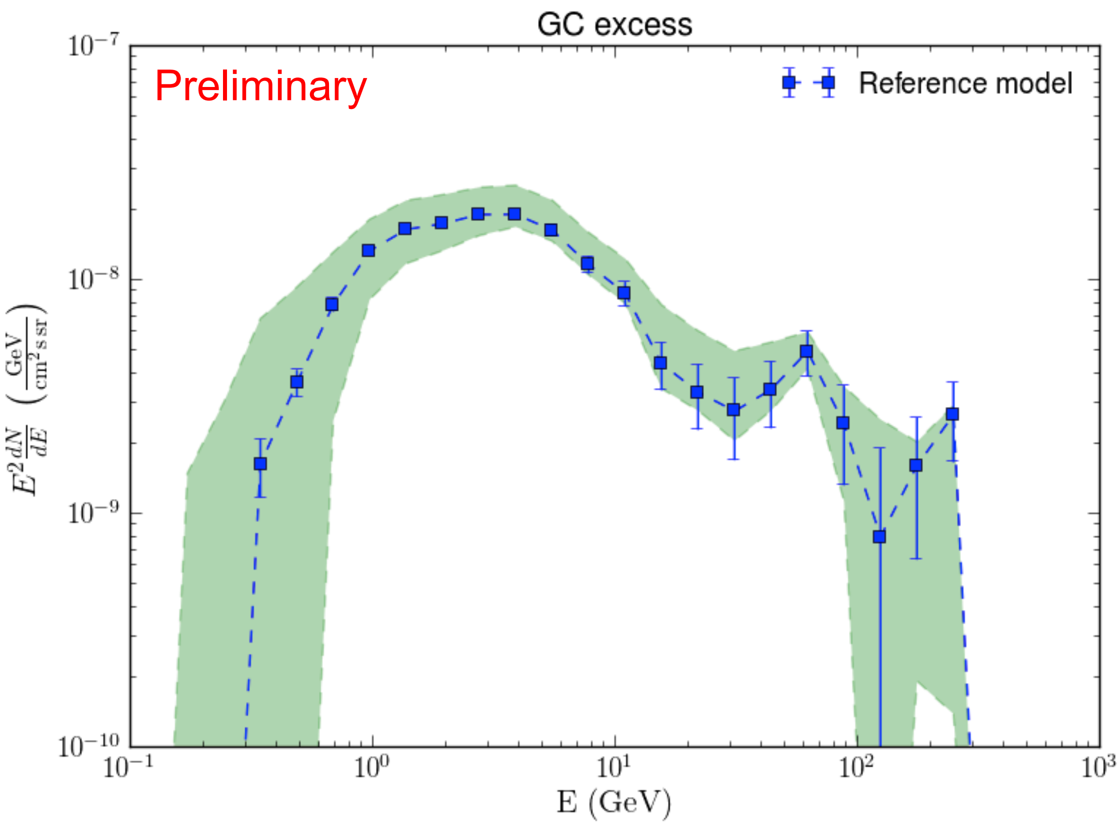
- **Use models from Fermi LAT diffuse analysis** (Ackermann et al. ApJ 793 (2014))
- **Cosmic-ray source distribution:**
  - **Pulsars** (Lorimer et al., MNRAS 372 (2006) 777-800)
  - **SNR** (Case & Bhattacharya, ApJ 504 (1998) 761)
  - **Pulsars** (Yusifov & Kucuk, A&A 422 (2004) 545-553)
  - **OBStars** (Bronfman et al., A&A 358 (2000) 521)
- **CR propagation volume**
  - **Radius: 20/30 kpc**
  - **Height: 4/10 kpc**
- **Spin Temperature**
  - **150K/optically thin**



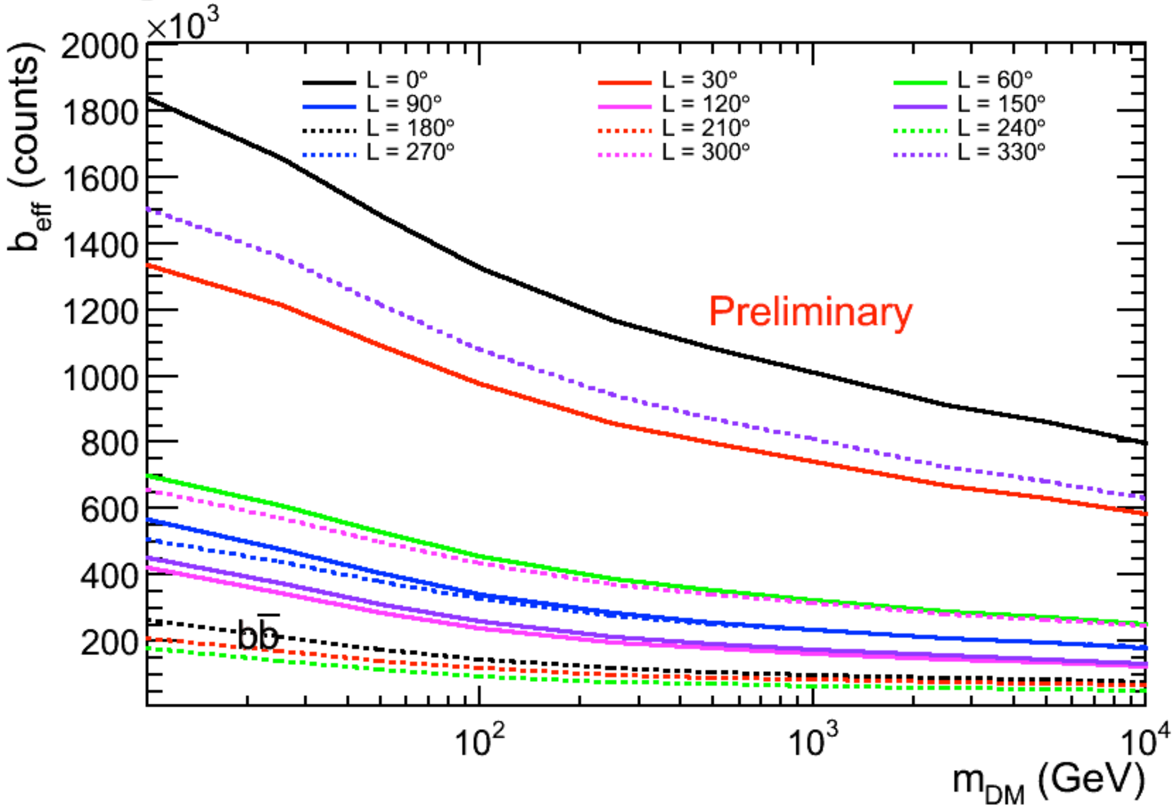
Reference model parameters shown in blue

GALPROP parameters and alternative gas distribution

- **Variation of GALPROP parameters and the distribution of gas along the line of sight systematics**



Effective Background



$$b_{\mathrm{eff}} = \frac{N}{\left(\sum_k \frac{P^2_{\mathrm{sig},k}(\mu)}{P_{\mathrm{bkg},k}(\theta)}\right) - 1}$$

sum over spatial and energy bins

N = total counts

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

$$signif \approx \frac{n_{sig}}{\sqrt{b_{eff}}}$$

- **b_{eff} is the weighted "number of background counts under the signal"**
  - **Background Model (P_{bkg}) = adopted Reference Model**
  - **Signal Model (P_{sig}) = gNFW (γ = 1.25) centered on B = 0°**
- **If signal model and background model overlap more, the effective background is higher**

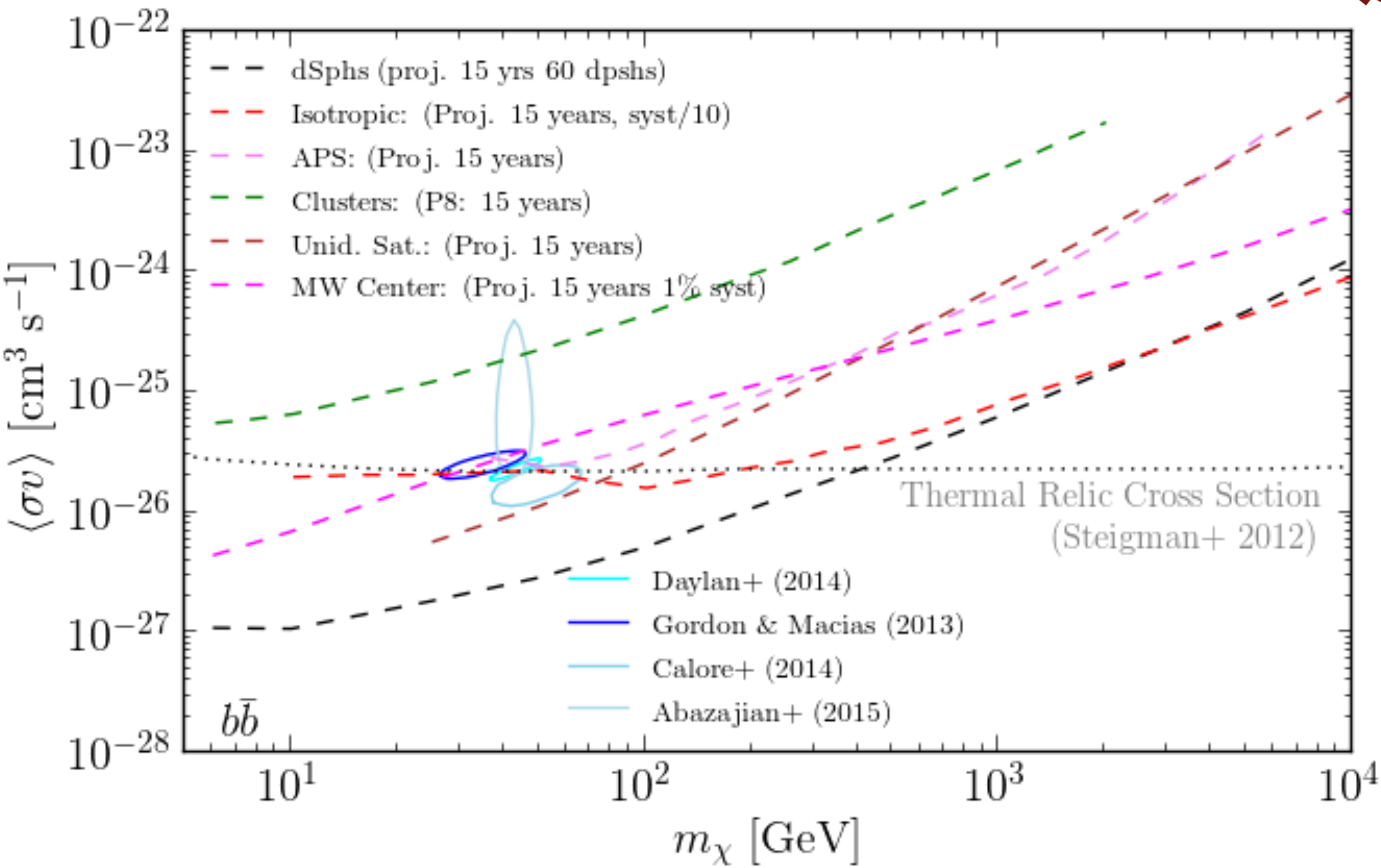
Fitting Including δf_{syst}

- It is useful to define $\delta f_{syst} = \delta n_{syst} / b_{eff}$ since b_{eff} and n_{syst} both scale with the total number of counts in the fit
  - We define $\delta f_{syst} = \max(\delta f_{68,GP}\ , 0.01)$

- Separate best fit "apparent signal" into n_{syst} and n_{sig} using a nuisance parameter
  - Constrain n_{syst} with a gaussian prior with width $\delta n_{syst} = \delta f_{syst} * b_{eff}$
  - Can only observe a signal when $n_{sig} > n_{syst}$
    - We are only sensitive to dark matter signals larger than the dark-matter-like signals seen in control regions

- Similar to technique used in LAT-Collaboration P8 Line Search and Search for Dark Matter in the LMC
  - Ackermann, M. et al. 2015, Phys. Rev. D, D91, 122002
  - Buckley, M. R. et al. 2015, Phys. Rev. D, 91, 105004

Projections of Future LAT WIMP DM Search Sensitivity-Charles et al. (2016) Physics Reports



The projected limits for the dSph DM search scale faster than the sqrt(time) due to the discovery of more dSphs..