Galactic center excess analysis with Pass 8 data and dark matter limits

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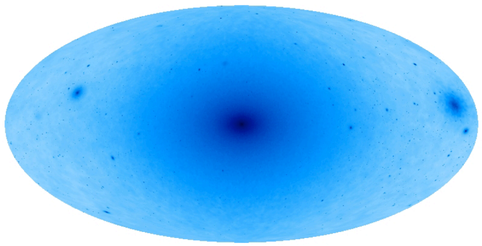
on behalf of the Fermi LAT collaboration

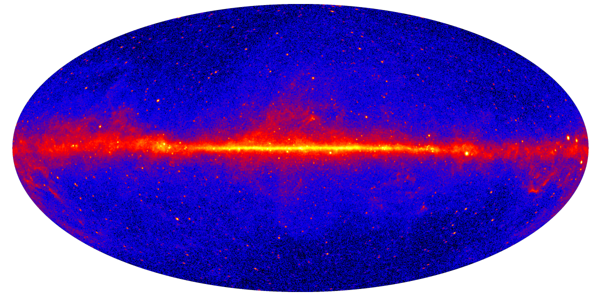
Gamma Rays & Dark Matter

Obergurgl, Dec 7 - 11, 2015

Dark matter annihilation in the Galactic center?

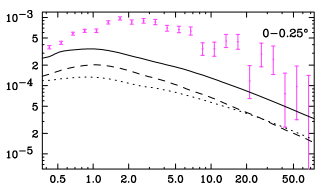


Via Lactea II, Kuhlen et al, arxiv:0907.0005

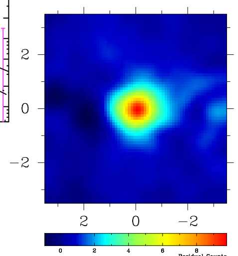


Fermi LAT, 6 years, Pass 8 data

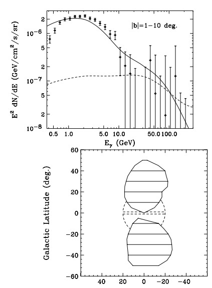
Excess emission



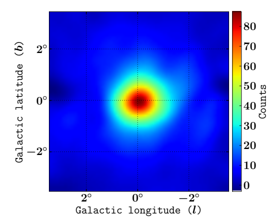
Goodenough & Hooper arxiv:1010.2752



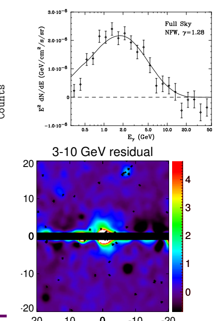
Abazajian & Kaplinghat arxiv:1207.6047



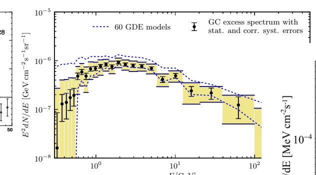
Hooper & Slatyer arxiv:1302.6589



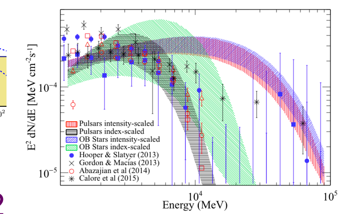
Gordon & Macias arxiv:1306.5725



Daylan et al. arxiv:1402.6703



Calore et al. arxiv:1409.0042



Ajello et al. arxiv:1511.02938 Simona's talk on Friday

Dark matter annihilation, unresolved sources, CR electrons?

– **Mirabal (arxiv:1309.3428), Petrovic et al. (arxiv:1411.2980), Cholis et al. (arxiv:1506.05119), Lee et al. (arxiv:1506.05124), Bartels et al. (arxiv:1506.05104), Brandt & Kocsis (arxiv:1507.05616), Carlson et al. (arXiv:1510.04698) etc.**

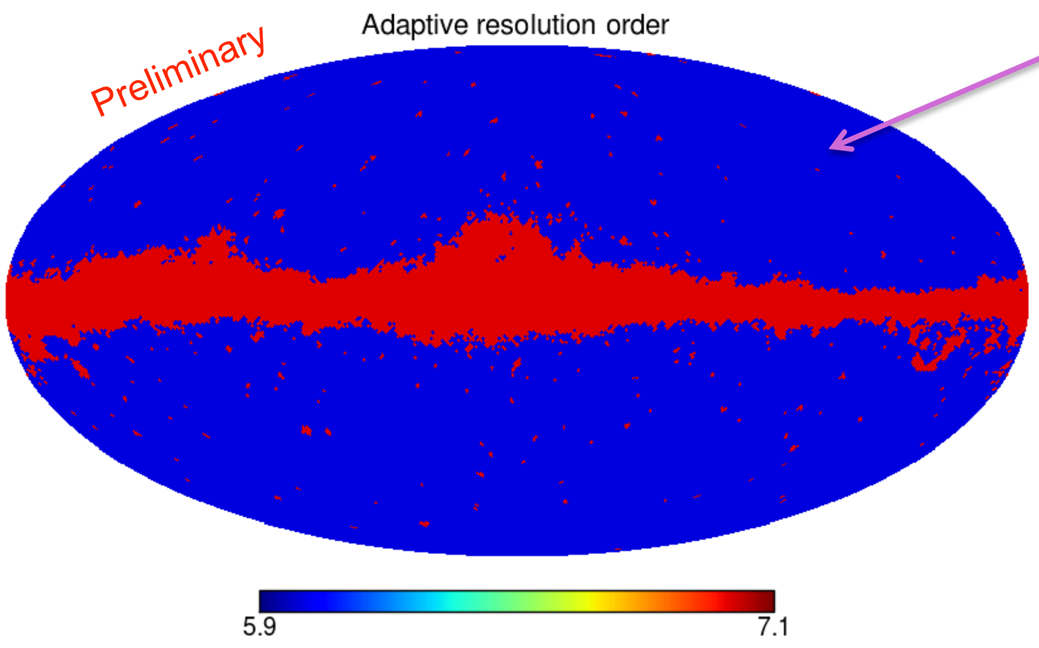
Outline of the talk

Main goal of this analysis: estimate the uncertainty of the excess energy spectrum due to diffuse emission modeling

- Data used for this analysis
  - Pass 8
- Diffuse models analysis
  - Variations of GALPROP parameters
  - Alternative distribution of gas along the line of sight
  - Additional source of CR electrons near the GC
  - Derivation of the Fermi bubbles at low latitudes
- Limits on dark matter annihilation
  - Scan of the cusp template along the Galactic plane to estimate uncertainty on diffuse emission modeling
- Summary

Data Set

- 6.5 years of Pass 8 data (Aug 8, 2008 – Jan 31, 2015)
- Pass 8, Ultracleanveto Class, zenith angle less than 90°
- 27 energy bins from 100 MeV – 1 TeV
- Binned into HEALPix maps of order 6 / 7 (resolution 1° / 0.5°)

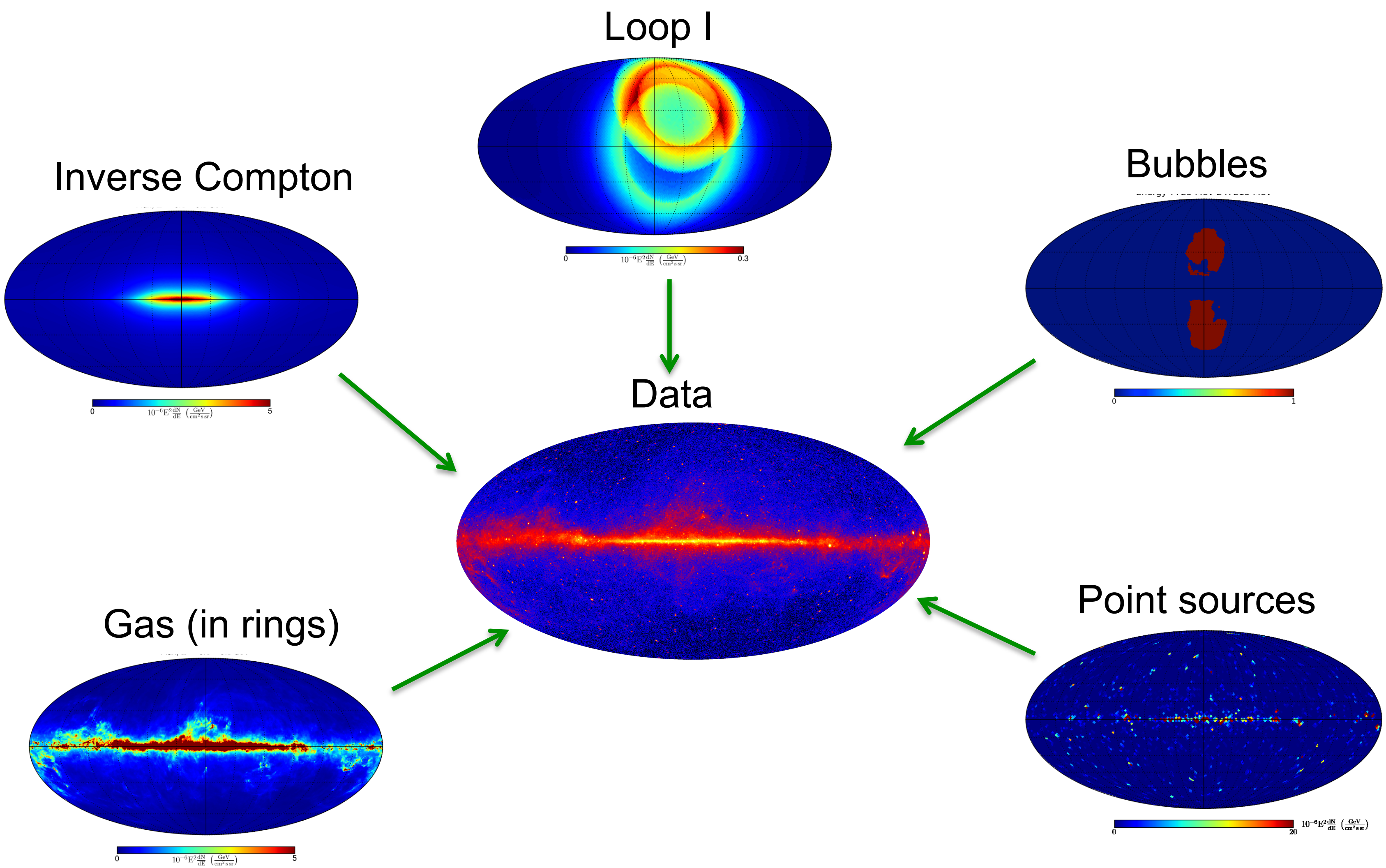


Order 6 resolution for small flux areas

Order 7 resolution for large flux areas

Template fitting

- **Fit templates to the data in energy bins (bin by bin fitting)**



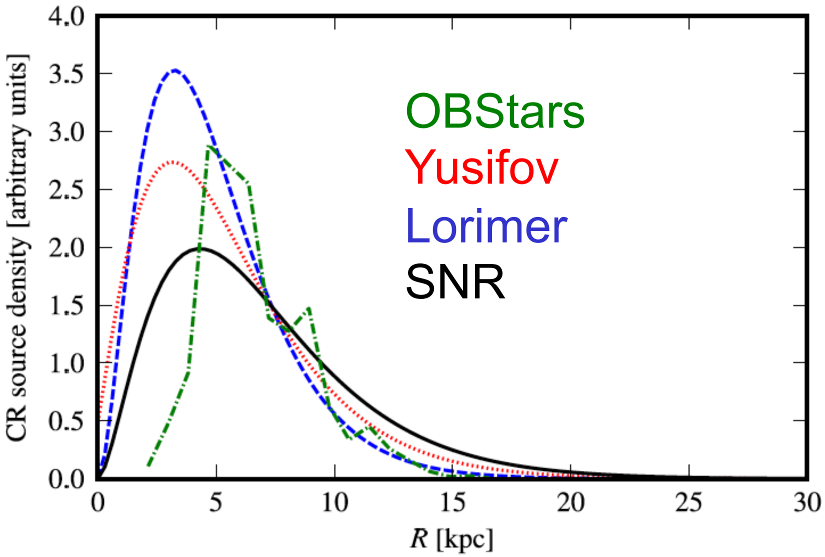
Reference model templates

- **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, arxiv:0704.0276)
  - Isotropic
  - Fermi Bubbles (Fermi collaboration, arxiv:1407.7905), See the talk by Anna Franckowiak on Thursday
  - Point Sources
    - Derived with Pass 8 data
    - The cores of 300 bright PS are masked
  - Sun / Moon (Fermi science tools)
- **Excess template:**
  - DM annihilation, contracted NFW profile (NFWc), index 1.25

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

GALPROP parameters

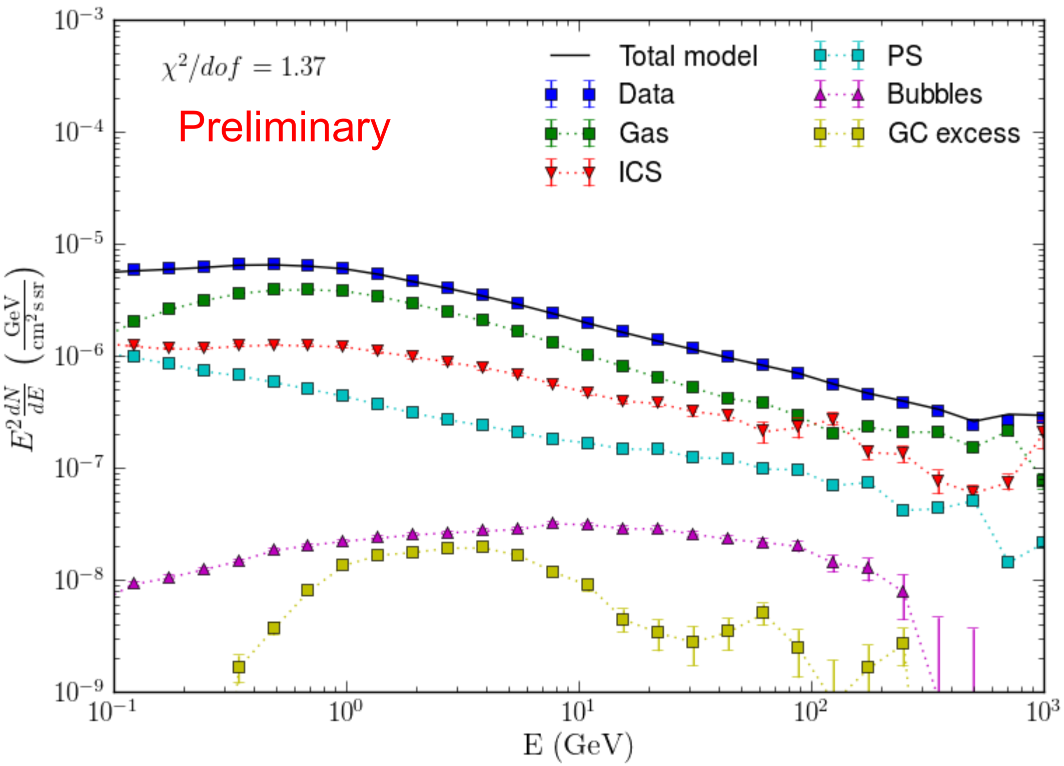
- Use models from Fermi LAT diffuse analysis (arxiv:1202.4039)
- Cosmic-ray source distribution:
  - Pulsars (Lorimer et al., astro-ph/0607640)
  - SNR (Case & Bhattacharya, astro-ph/9807162)
  - Pulsars (Yusifov & Kucuk, astro-ph/0405559)
  - OBStars (Bronfman et al., astro-ph/0006104)
- CR propagation volume
  - Radius: 20/30 kpc
  - Height: 4/10 kpc
- Spin Temperature
  - 150K/optically thin



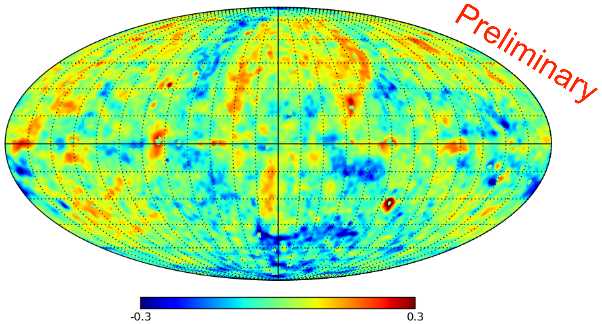
Reference model parameters shown in blue

Reference Model Spectra

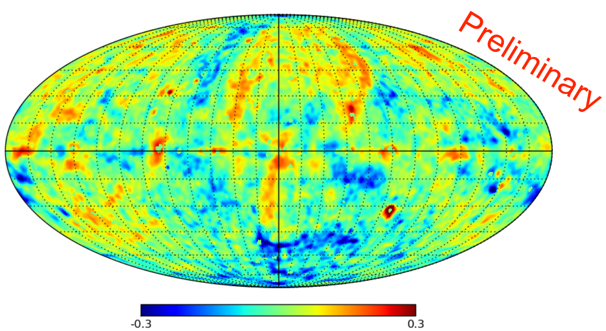
- **Contracted NFW, n = 1.25**
  - **All sky-fit**
  - **Fit normalization in each energy bin for each template**



Fractional residual, 1.1 – 6.5 GeV

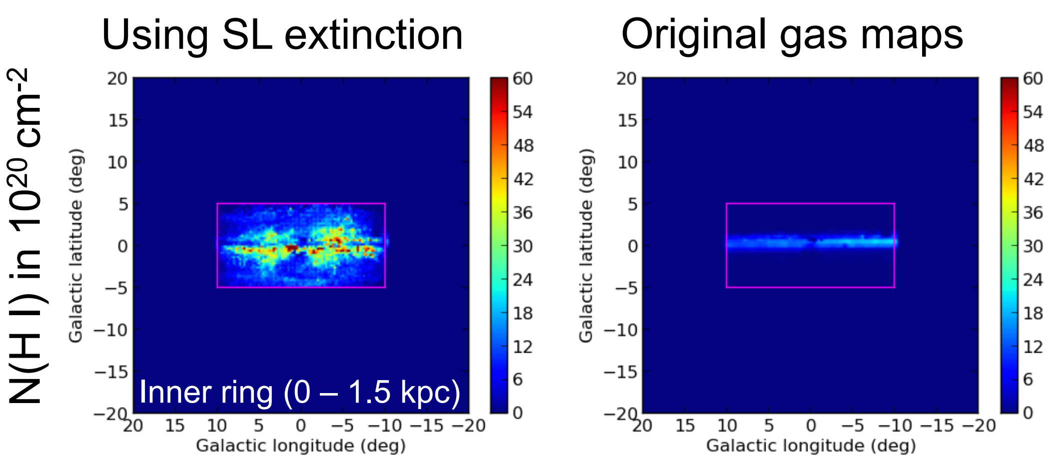


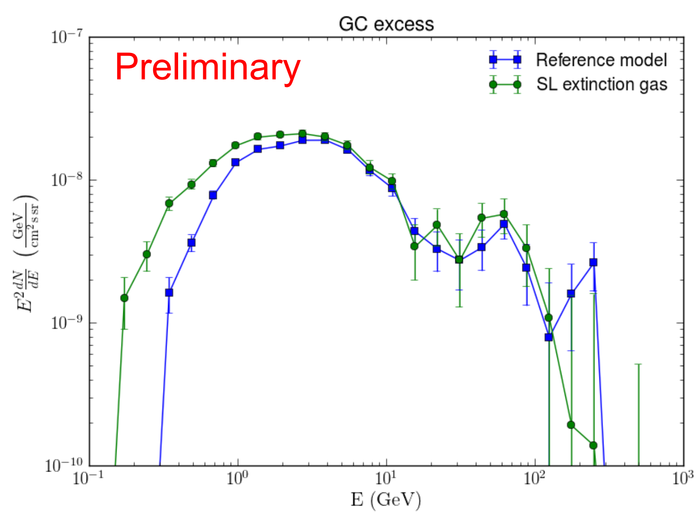
Add back the GC excess signal



Alternative Gas Maps

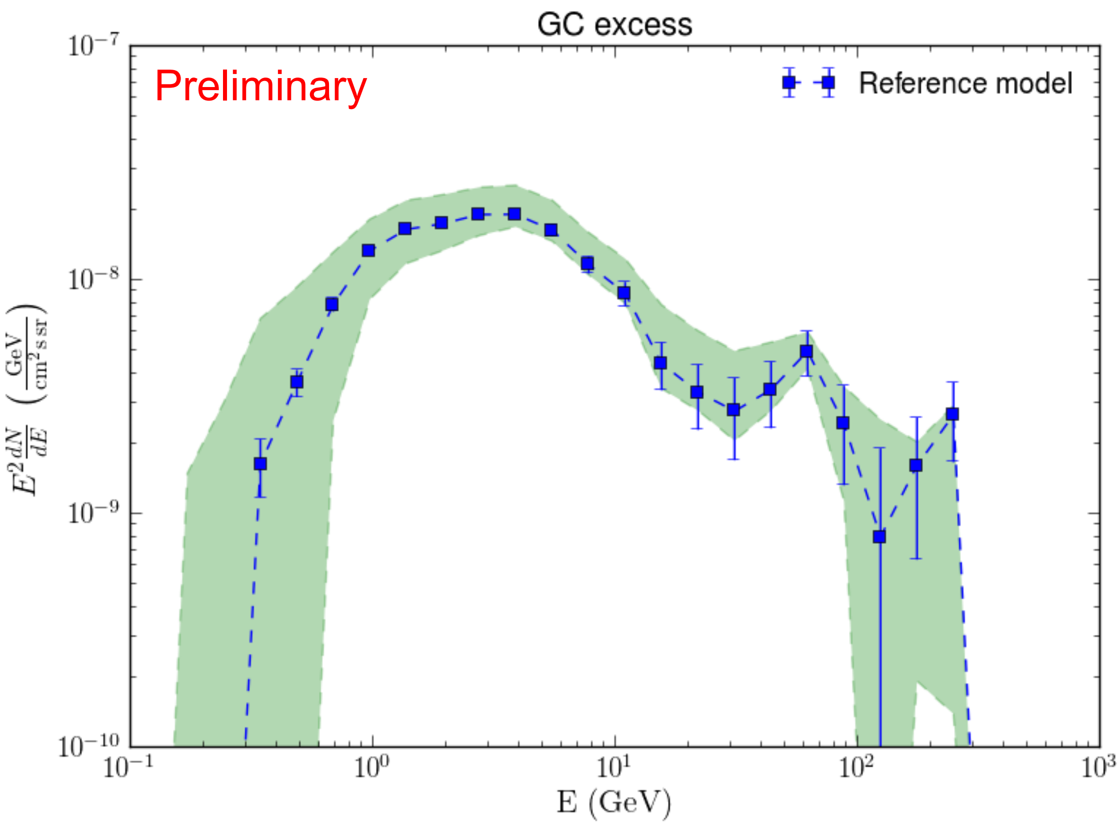
- Hard to model distribution of gas towards the GC due to **lack of Doppler shift** information
  - Gas distribution is interpolated from |Lon| > 10°
- **Use starlight (SL) extinction** (Schultheis et al, arxiv:1405.0503) to find the distribution of dust along the LOS towards the GC
  - Derive the distribution of gas assuming homogeneous mixing of dust and gas
- Not meant to be a substitution for the current gas maps
  - useful for estimation of modeling uncertainties





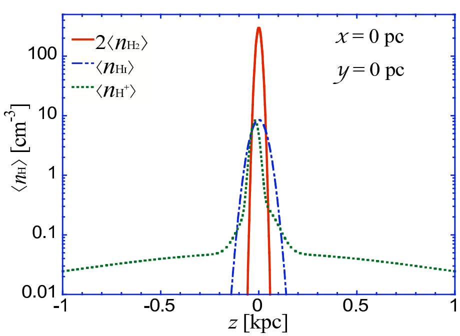
GALPROP parameters and alternative gas distribution

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

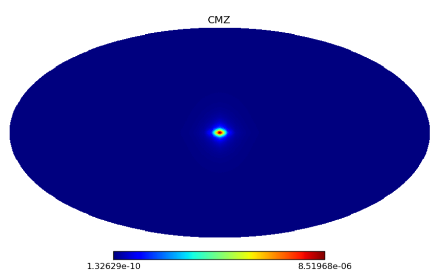


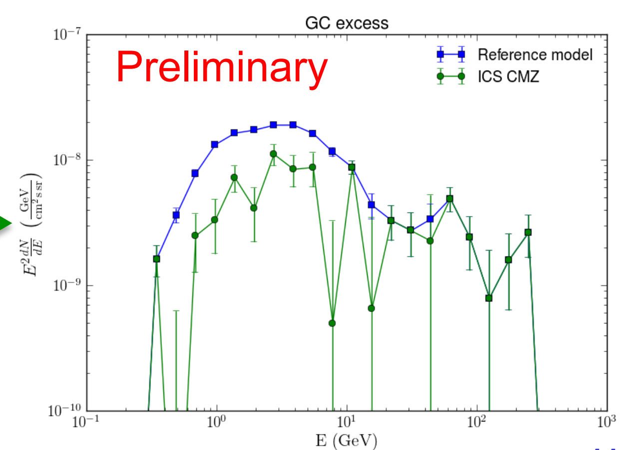
Sources of CR electrons near the GC

- CR electron sources in the bulge (Petrovic et al. arxiv:1411.2980)
  - Electrons are produced by MSPs in the bulge
- Star formation in molecular clouds near the GC
  - Burst-like emission from the GC nucleus (Cholis et al. arxiv: 1506.05119)
  - Stationary CR production by molecular clouds (Carlson et al. arXiv:1510.04698)
- Similar to Carlson et al (2015), we find that a source of CRe electrons in the central molecular zone (CMZ) region can reduce the flux associated with NFWc template:



Ferriere et al., astro-ph:0702532

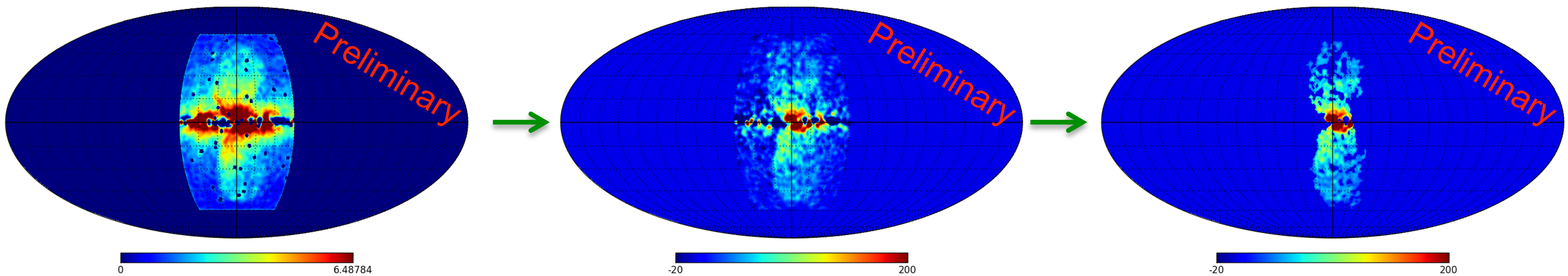




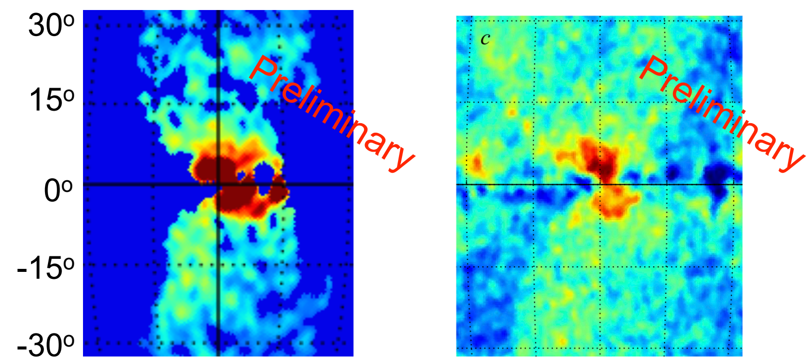
Bubbles template

- **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 bubbles template**

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



- **Fermi bubbles template in the inner Galaxy looks similar to the template found in Casandjian (2015)**
- **But beware of modeling uncertainties**

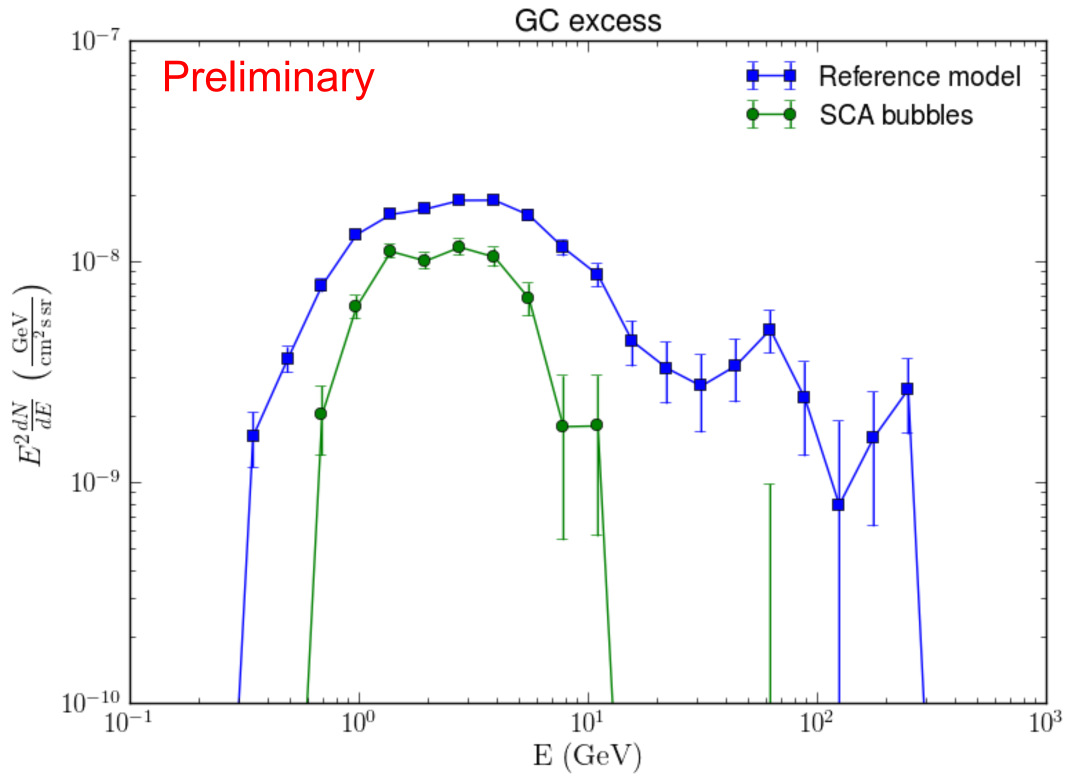


This work

J.-M. Casandjian for the Fermi LAT collaboration, arxiv:1502.07210

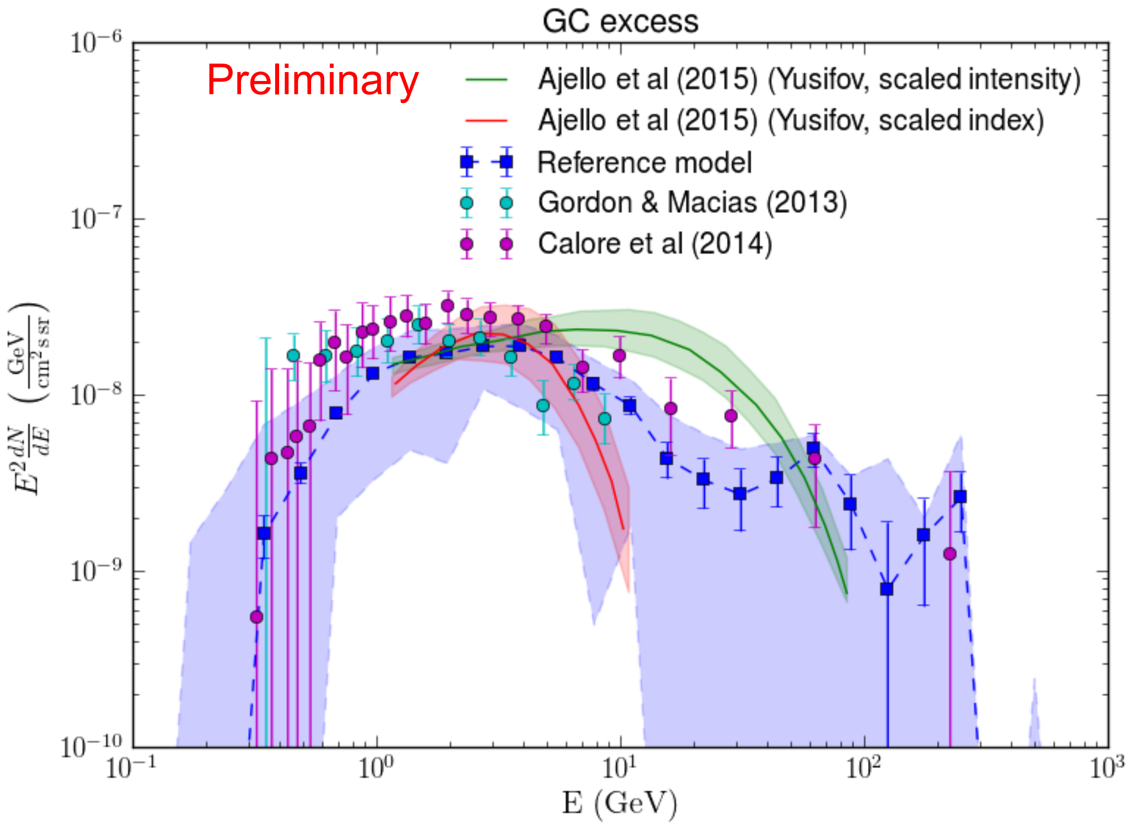
GC excess and all-sky bubbles

- **Fit the NFWc profile together with the all-sky bubbles determined with spectral components analysis (SCA)**
  - **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



Spectra are normalized to 4π sr

Interpretation of excess

- The presence of excess is confirmed by many groups
  - but what is it?
- Known astrophysical sources?
  - MSPs
  - CR leptons
  - Bubbles
- Or is it dark matter annihilation?

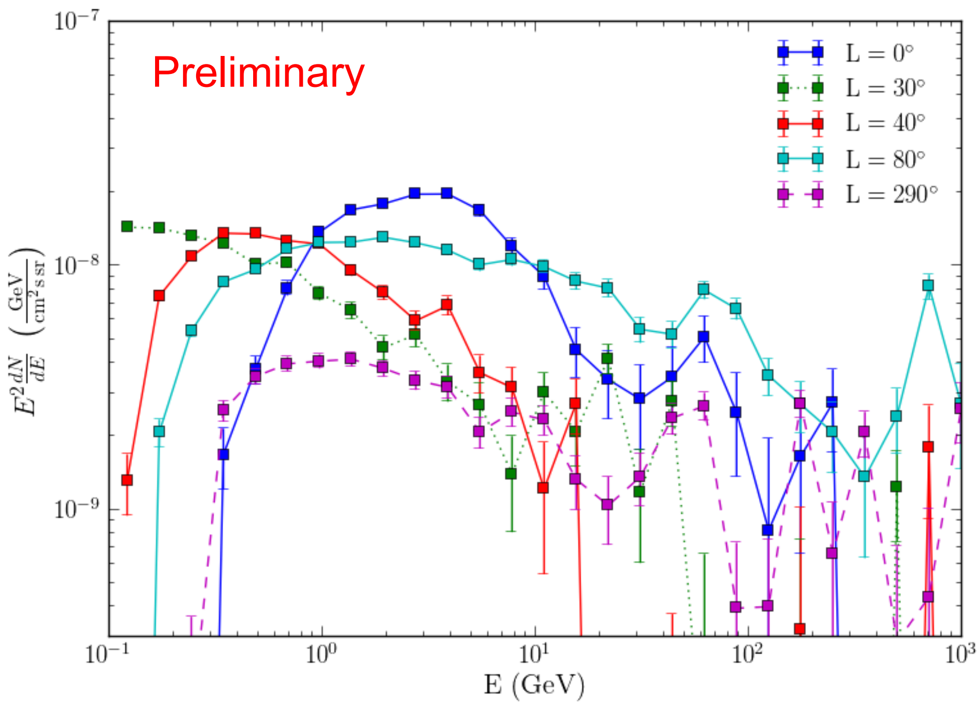
- Although the nature of excess is not known, we can still constrain, e.g., dark matter annihilation.
- The question is:
  - How do we constrain a signal in the presence of a signal of unknown origin?

Strategy on DM limits

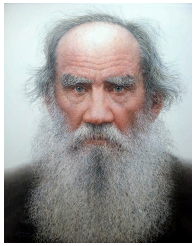
- Analogy with limits from dwarf spheroidal galaxies
  - Look for signal
  - If the signal is consistent with stat. noise, then put limits at the level "signal + n σ_{stat}"
- In our case an analog of the stat. uncertainty is the modeling uncertainty of astrophysical foregrounds
- Motivations:
  - Astrophysical emission has "random" components:
    - Supernovae happen at random locations
    - There are bursts of star formation
    - There are jets / bubbles from centers of galaxies
  - On top of that, there are imperfections of the model
- We parameterize the level of modeling uncertainty as a fraction of the background, which we determine by looking at control regions

Scan along the plane

- **Goal: 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}"**
- **Scan the cusp profile along the Galactic plane**



Five positions with largest flux at 3 GeV

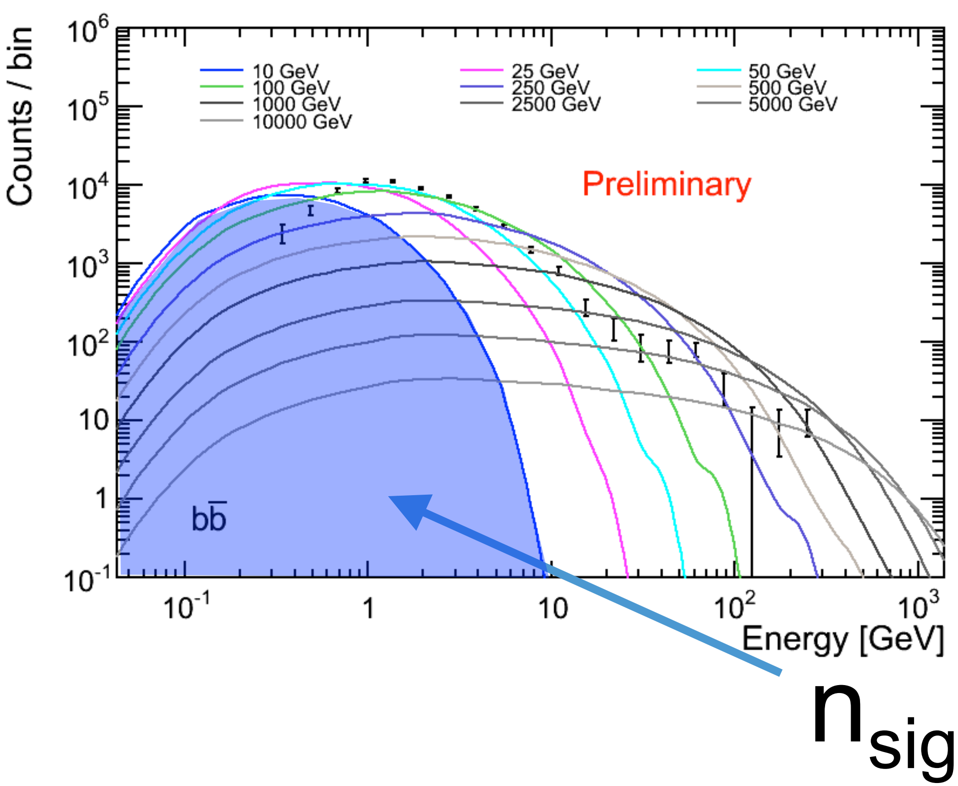


What would Leo Tolstoy say?

All good residuals look alike, each bad residual is bad in its own way.

Signal

- Choose annihilation channel
- Choose a set of DM masses
- Find the normalization that best fits the residual
- Integrate over energy to get the number of signal counts



Effective background

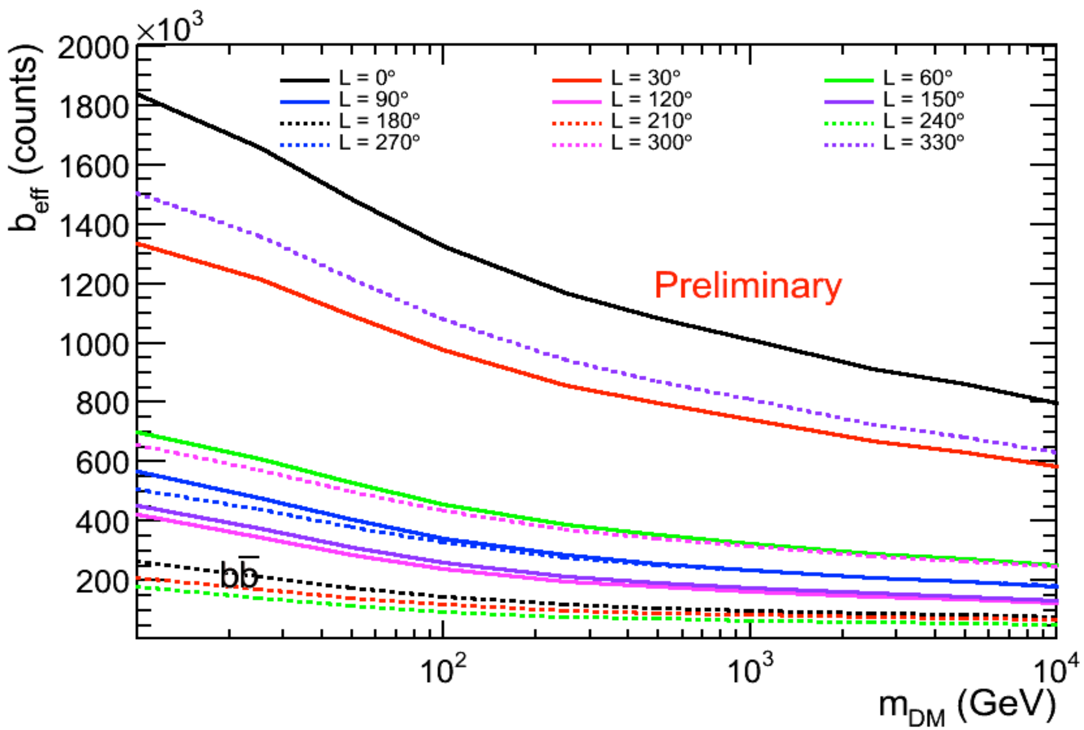
- Plot the excess as a fraction of “effective background” – background under the signal region (in space and energy)
- Intuitive picture:
  - Use only background in the signal ROI
  - Weigh the background more where the signal is larger
- Formal derivation:
  - $b_{eff} = \sigma^2_{signal}$, where σ^2_{signal} is the variance of the signal in the two-model case “signal + background”
  - For small signal:

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

  - Look at the fraction along the Galactic plane: $f = \frac{n_{sig}}{b_{eff}}$

Effective background along the plane

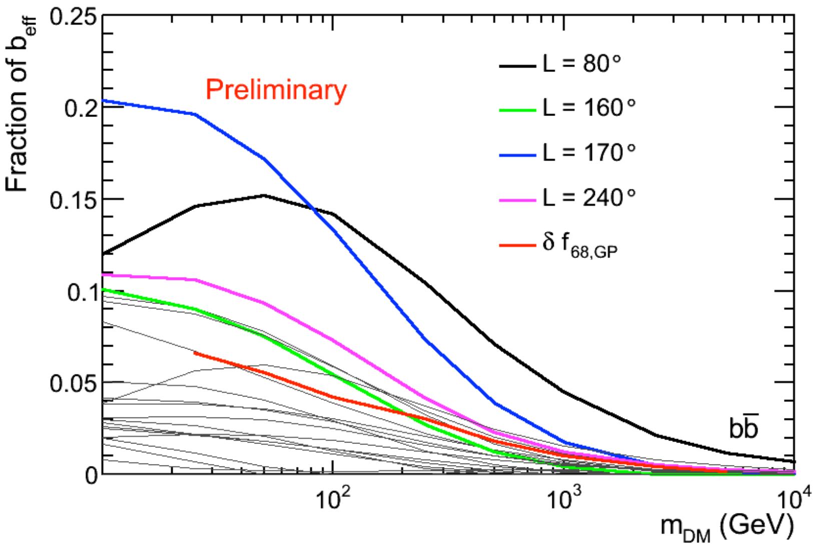
- **For each point along the plane (10 deg steps) away from the GC**
  - **Use the DM annihilation spectrum and the cusp NFWc profile to find the value of effective background as a function of DM mass**

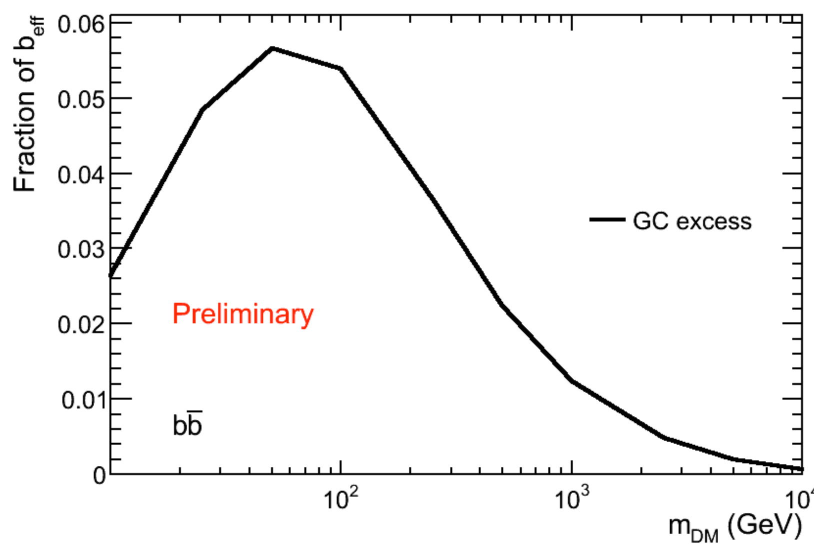


$$b_{\text{eff}} = \frac{N}{\left(\sum_k \frac{P^2_{\text{sig},k}(\mu)}{P_{\text{bkg},k}(\theta)}\right) - 1}$$

Signal to effective background fraction

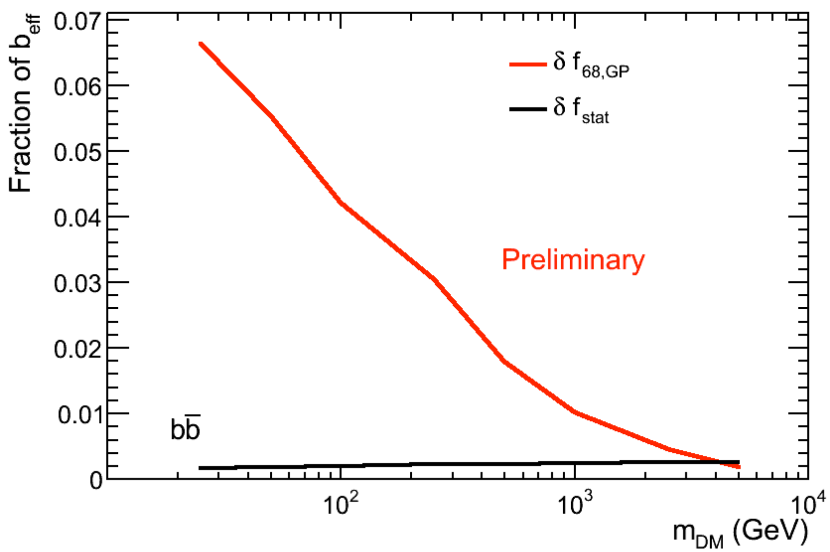
- Scan the cusp profile with a DM annihilation spectrum along the plane
- Divide signal counts by effective background counts
- Use the 68% median as an estimate of the modeling uncertainty

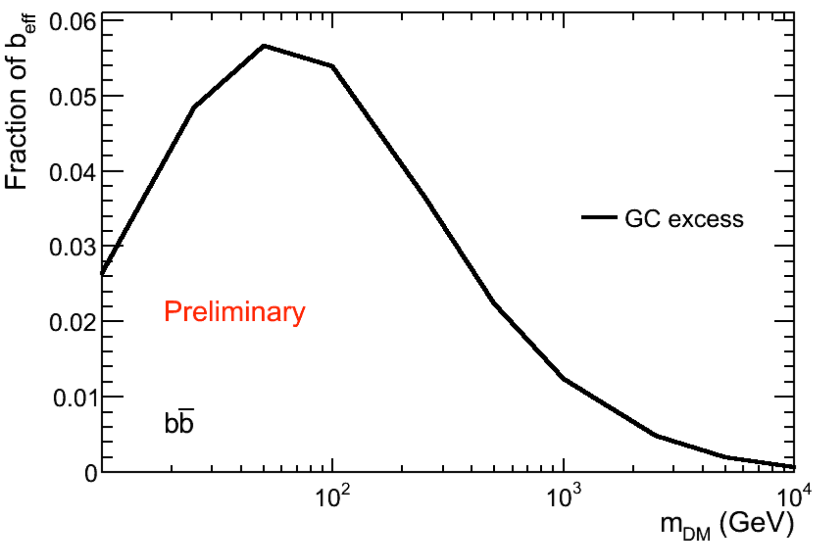




Comparison with GC excess

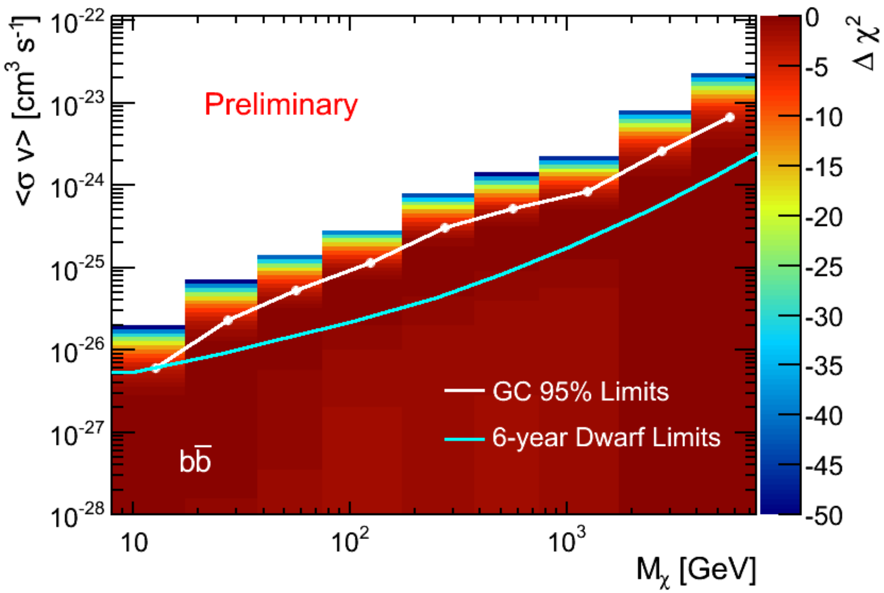
- **The fractional signal is similar to the uncertainty derived from the Galactic plane scan:**

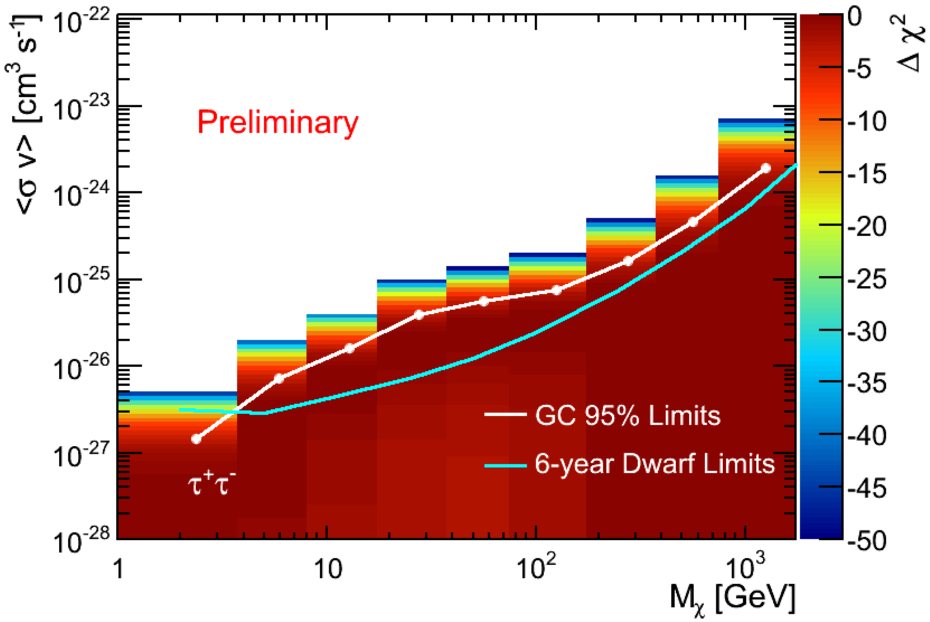




Limits on DM annihilation

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





Conclusions

- Some model-related uncertainties on the GC excess were investigated using Pass 8 data
- The following uncertainties have relatively small effect on the excess spectrum:
  - Variation of GALPROP models
  - Distribution of gas along the line of sight
- Most significant sources of uncertainty are
  - Fermi bubbles morphology
  - Sources of CR electrons near the GC
- Since the astrophysical explanations of the excess, e.g., MSPs cannot be excluded at the moment, we put limits on DM annihilation
  - Use a scan of NFWc profile along the plane to estimate diffuse emission modeling uncertainty
  - The limits are a factor of a few less constraining than the limits from dSph (up to uncertainties in DM profile)