Fermi Gamma-ray Space Telescope

Galactic center excess analysis with Pass 8 data

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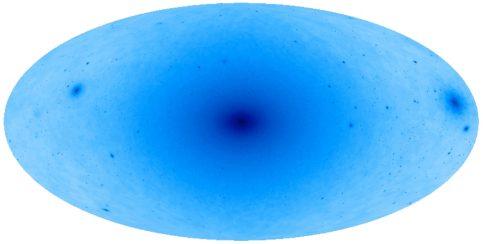
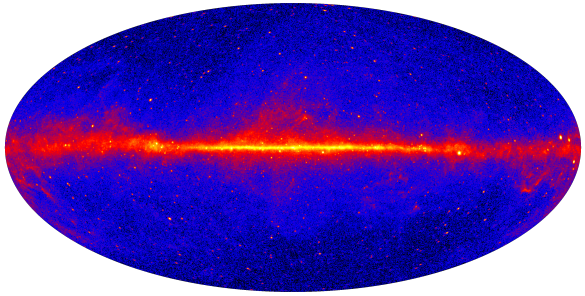
Dark matter annihilation in the Galactic center?

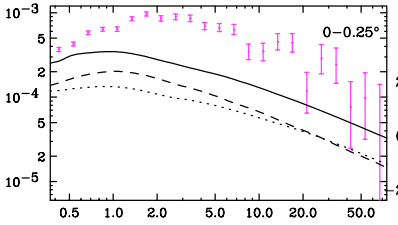


Via Lactea II, Kuhlen et al, arxiv:0907.0005

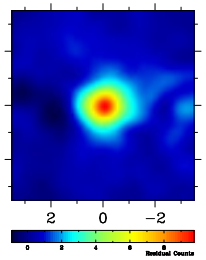


Fermi LAT, 6 years, Pass 8 data

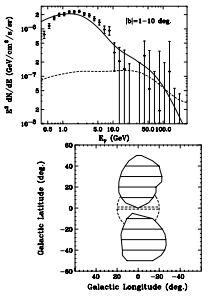
Excess emission



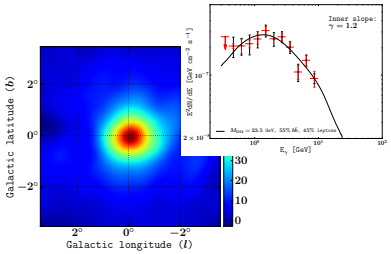
Goodenough & Hooper arxiv:1010.2752



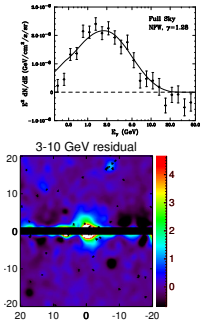
Abazajian & Kaplinghat arxiv:1207.6047



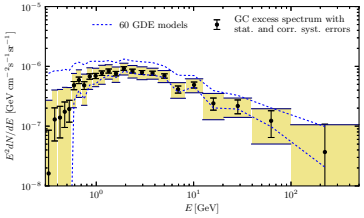
Hooper & Slatyer arxiv:1302.6589



Gordon & Macias arxiv:1306.5725



Daylan et al. arxiv:1402.6703



Calore et al. arxiv:1409.0042

and counting

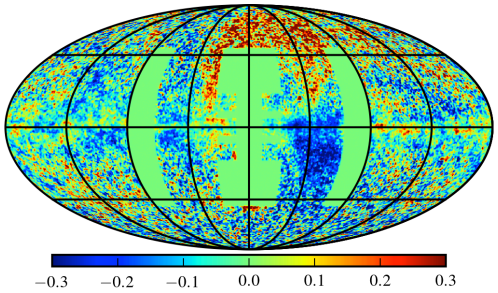
Dark matter annihilation, unresolved sources, CR electrons?

– **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.**

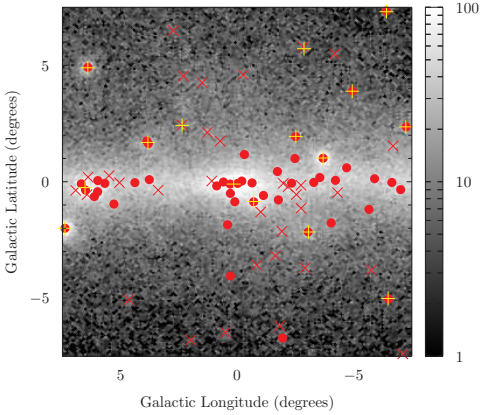
Fermi LAT collaboration Pass 7 analysis

- **Construct interstellar emission model (IEM) with a combination of templates from GALPROP**
  - **Test different CR distributions (pulsars, OB stars)**
  - **Refit intensity of components**
  - **Refit both index and intensity**
- **Find and characterize the point sources near the GC for each IEM**
- **There is a residual near the GC with a spectrum peaking at a few GeV (NFW template) – strong dependence on IEM**

PRELIMINARY

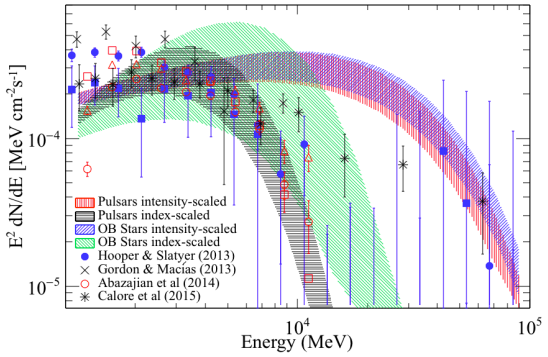


PRELIMINARY

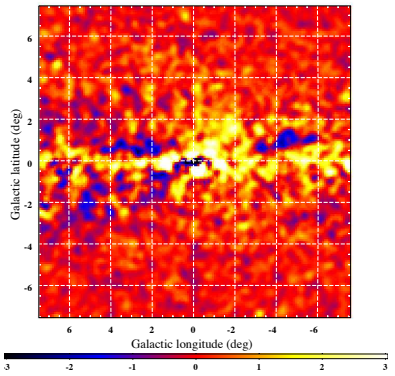


Ajello et al., arxiv:1511.02938

PRELIMINARY



PRELIMINARY

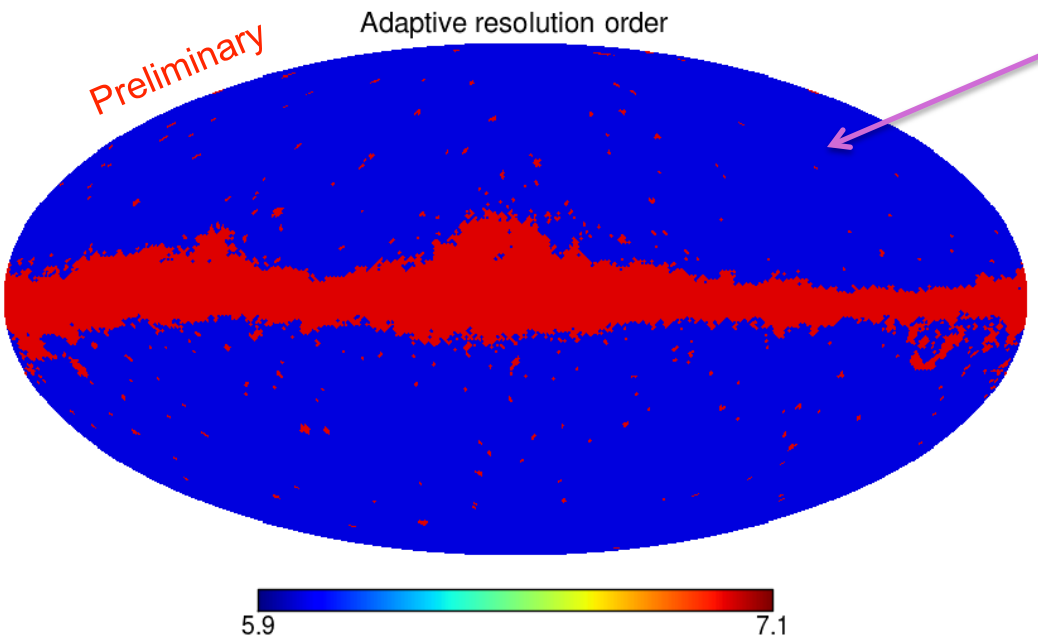


Outline of the talk

- Data used for this analysis
  - Pass 8
- Analysis method
  - Template fitting
- Variations of GALPROP parameters
- Alternative distribution of gas along the line of sight
  - Derived with starlight extinction data
- Additional source of CR electrons near the GC
- Derivation of the Fermi bubbles at low latitudes
  - Use the spectral information to derive a template for the bubbles
- Summary
  - the band of the GC excess flux

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°)

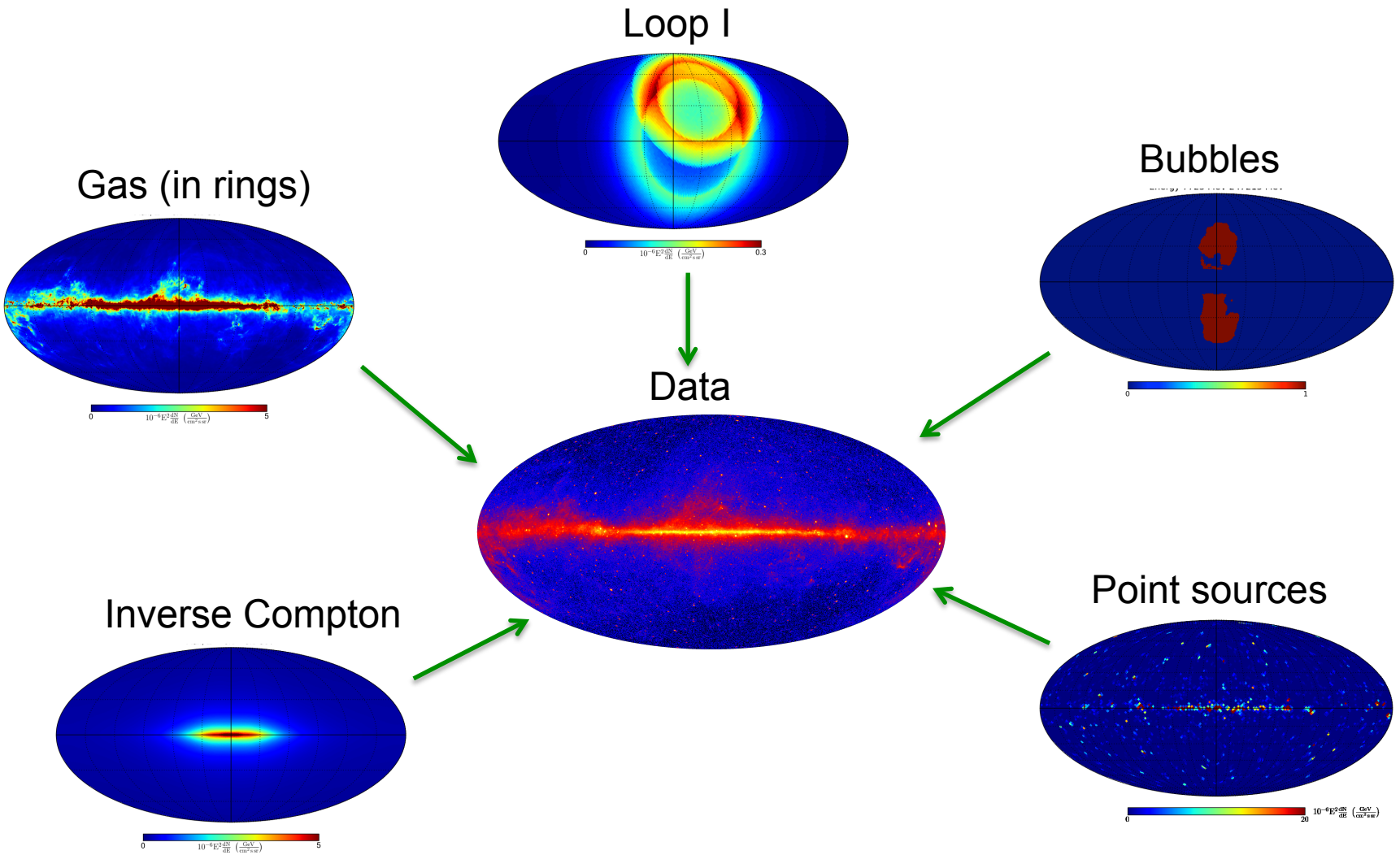


Order 6 resolution for small flux areas

Order 7 resolution for large flux areas

Template fitting

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



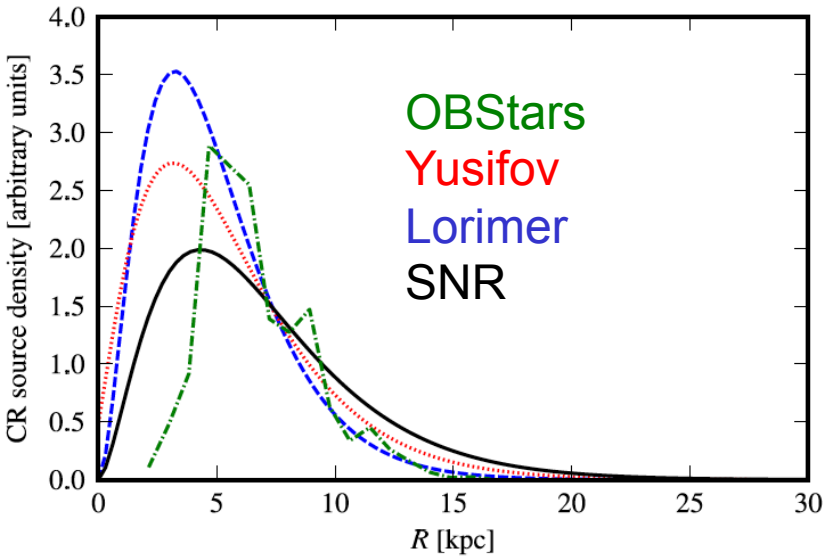
Reference model templates

- **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)
  - Point Sources (T. Burnett presentation on Wednesday)
    - Derived with Pass 8 data
    - The cores of 300 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

GALPROP parameters and alternative gas distribution

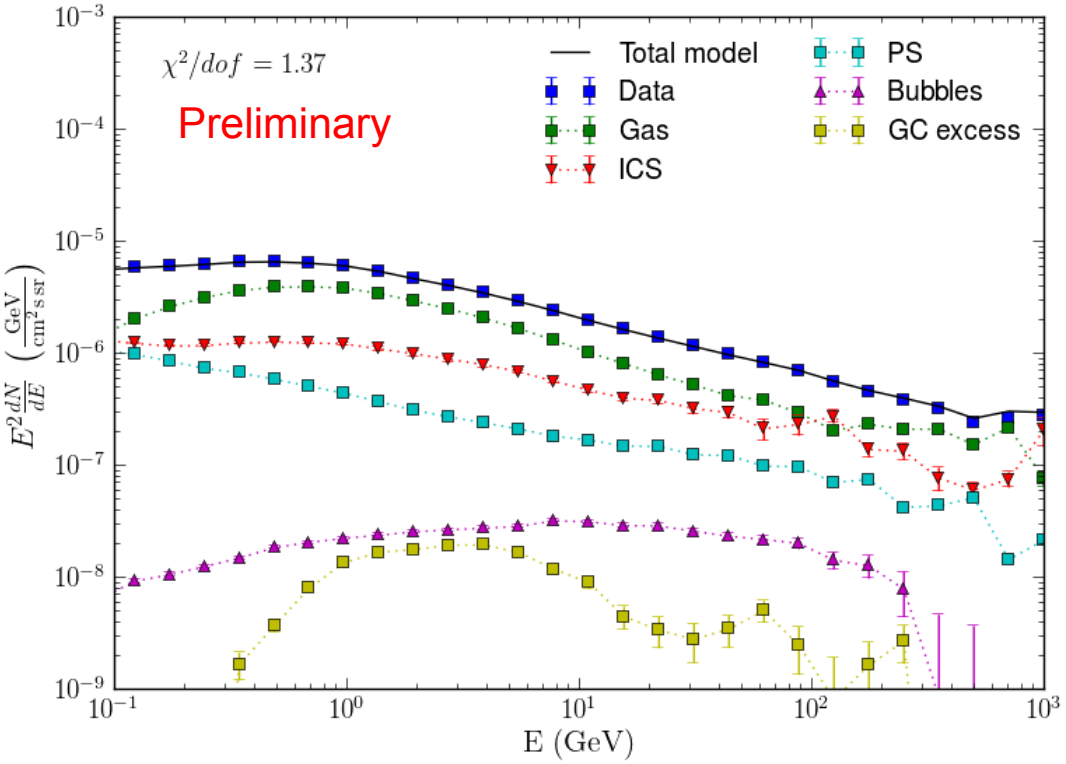
- Use models from Fermi LAT diffuse analysis (arxiv:1202.4039)
- Cosmic-ray source distribution:
  - Pulsars (Lorimer et al., astro-ph/0607640)
  - SNR (Case & Bhattacharya, astro-ph/9807162)
  - Pulsars (Yusifov & Kucuk, astro-ph/0405559)
  - OBStars (Bronfman et al., astro-ph/0006104)
- CR propagation volume
  - Radius: 20/30 kpc
  - Height: 4/10 kpc
- Spin Temperature
  - 150K/optically thin
- We derive an alternative distribution of gas along the line of sight to the GC using starlight extinction (Schultheis et al, arxiv: 1405.0503)



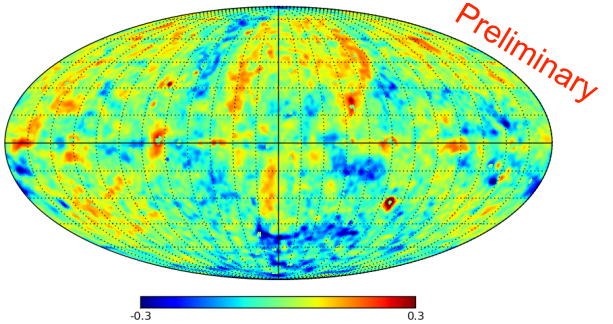
Reference model parameters shown in blue

Reference Model Spectra

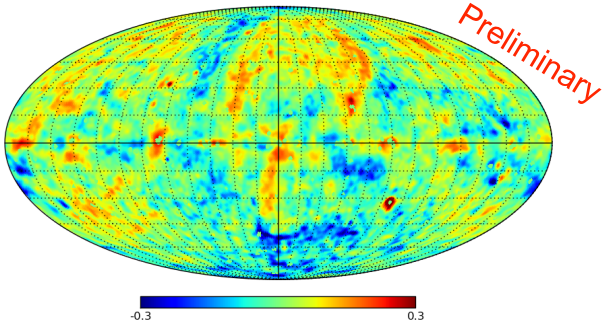
- **Contracted NFW, n = 1.25**
  - **All sky-fit**
  - **Fit normalization in each energy bin for each template**



Fractional residual, 1.1 – 6.5 GeV

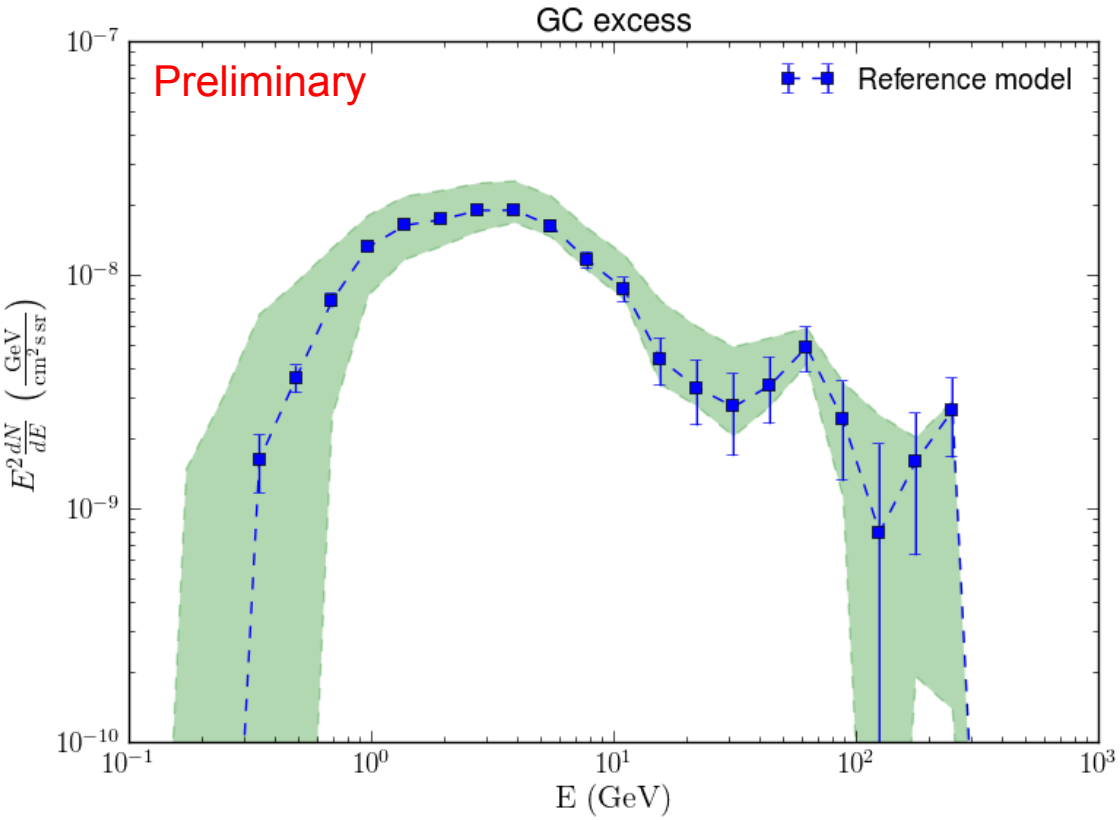


Add back the GC excess signal



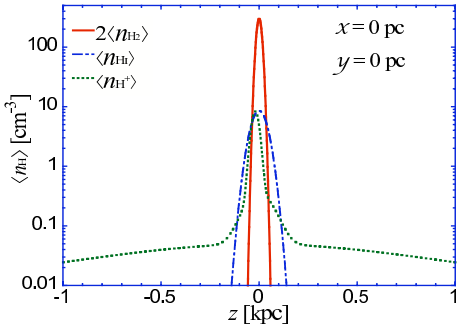
GALPROP parameters and alternative gas distribution

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

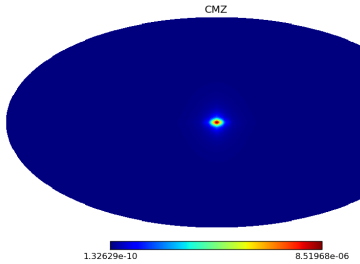


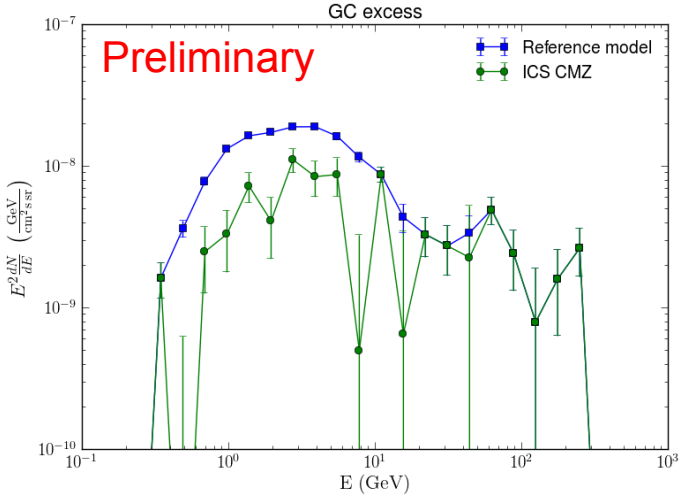
Sources of CR electrons near the GC

- **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 CMZ region can reduce the flux associated with NFWc template:**



Ferriere et al., astro-ph:0702532

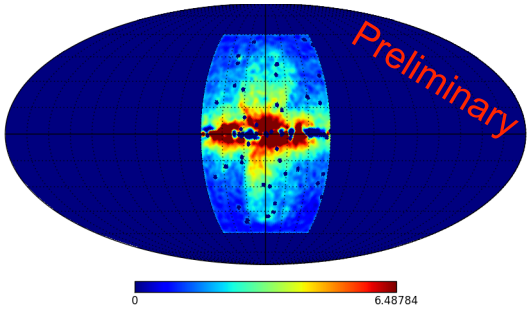




Bubbles template

- **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



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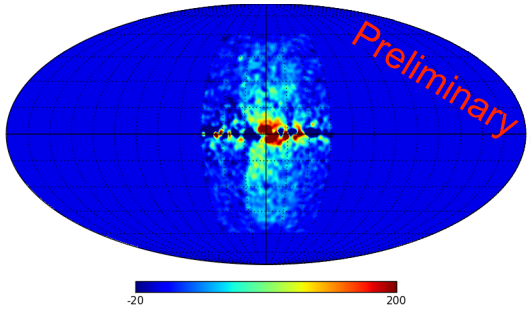
~E^{-2} component



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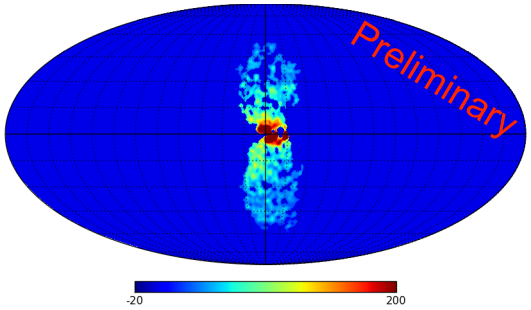
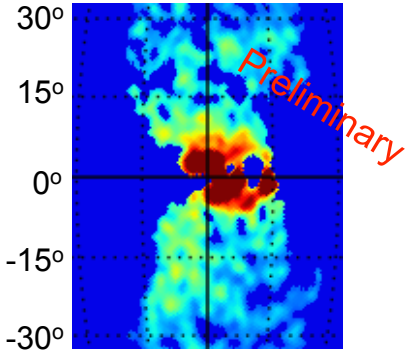
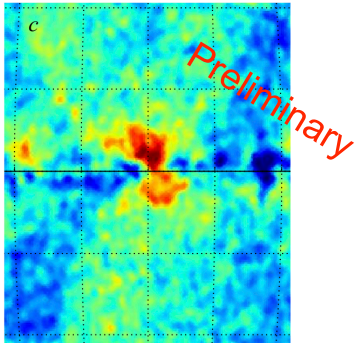
Bubbles template



- **Fermi bubbles template in the inner Galaxy looks similar to the template found in Casandjian (2014)**
- **But beware of modeling uncertainties**



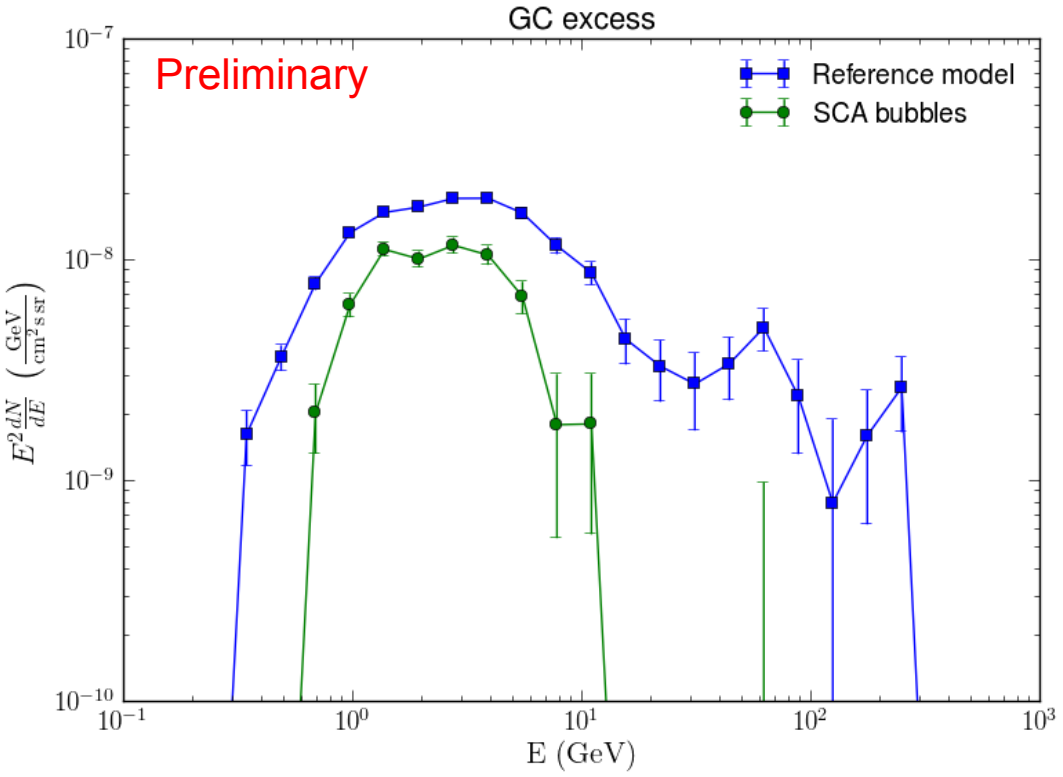
This work



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

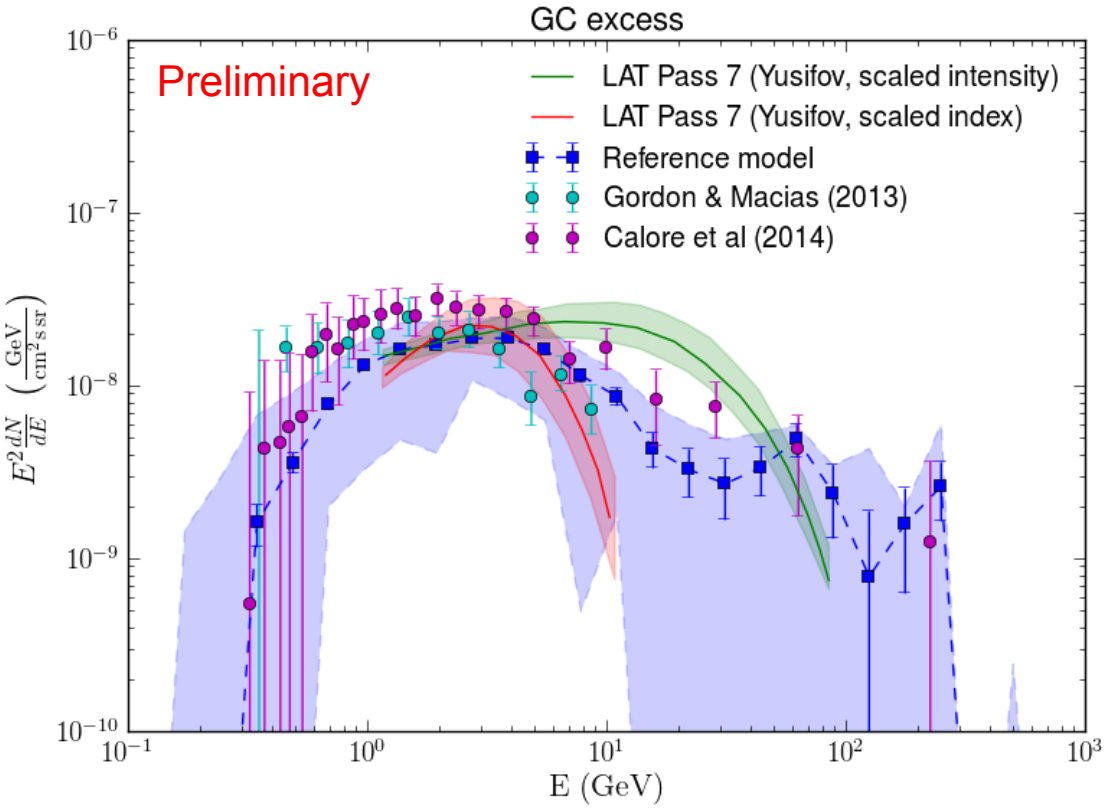
GC excess and all-sky bubbles

- **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

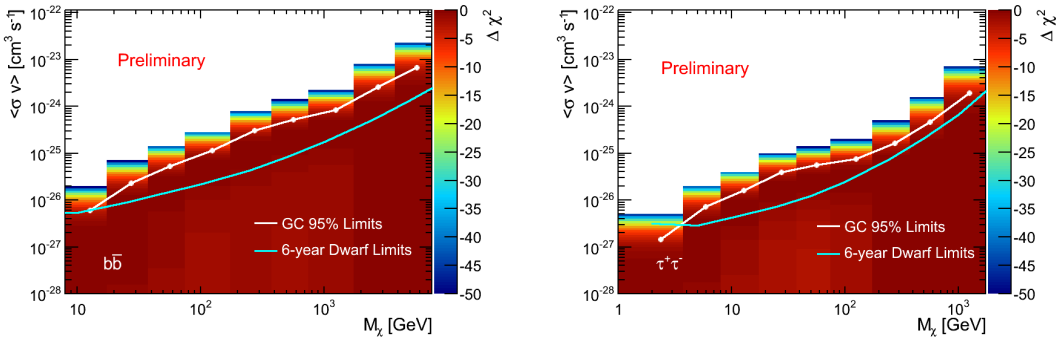
- **The spectrum uncertainty band**
  - **Variations of GALPROP models and gas distribution**
  - **CMZ source of CR electrons**
  - **Fermi bubbles at low latitudes**



Spectra are normalized to 4π sr

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 (Andrea Albert's talk on Thursday)



Backup slides

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**