An overview of diffuse gamma-ray emission measured by Fermi LAT and H.E.S.S.

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

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Plan

- Introduction
  - Emission components in the gamma-ray sky
- Gamma-ray diffuse emission
  - Distribution of CR protons and nuclei in the Galaxy
  - PeVatron at the Galactic center
  - Fermi bubbles
  - Galactic center excess around 3 GeV
- Searches for new physics
  - Search for dark matter annihilation
  - Evaporation of primordial black holes

Gamma-ray emission components

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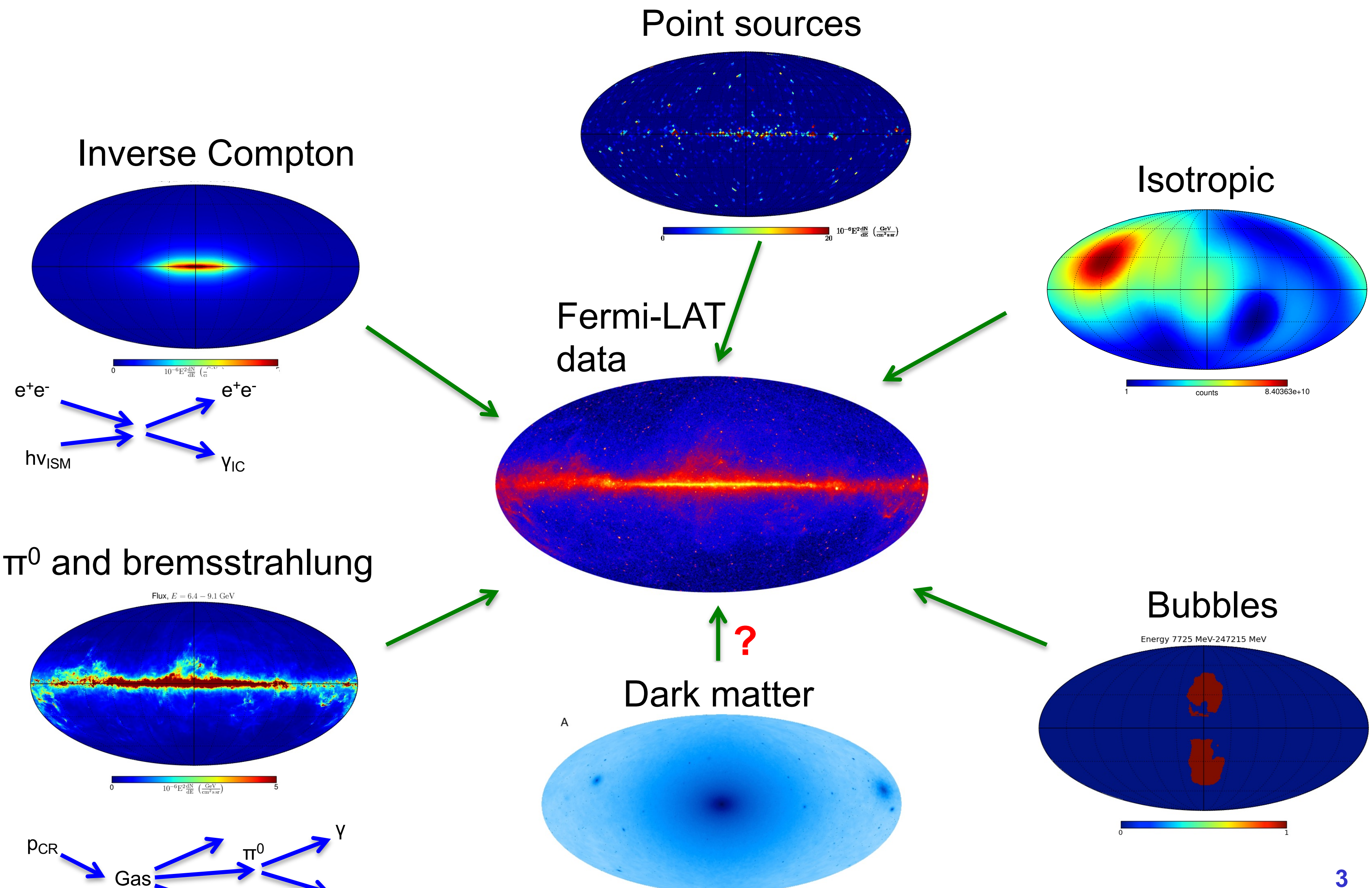


Kuhlen et al., Science 325 (2009)

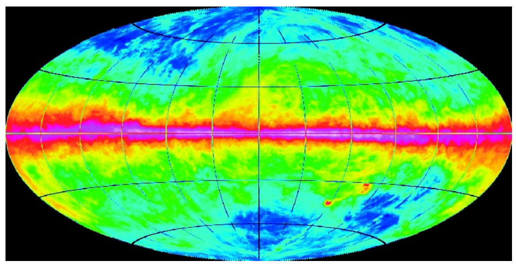
Distribution of CR protons in the Galaxy

Distribution of CR protons in the Galaxy

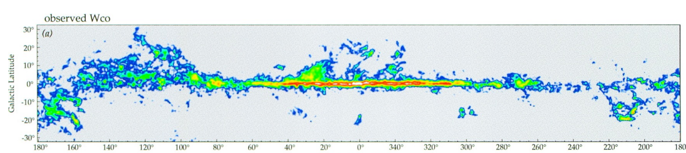
- Gamma-ray produced by interactions of CR protons with gas are proportional to the density of CRp times the density of gas

$$n_{\mathrm{CRp}} \times n_{\mathrm{gas}} \propto J_{\gamma}$$

$n_{\mathrm{CRp}} \times$

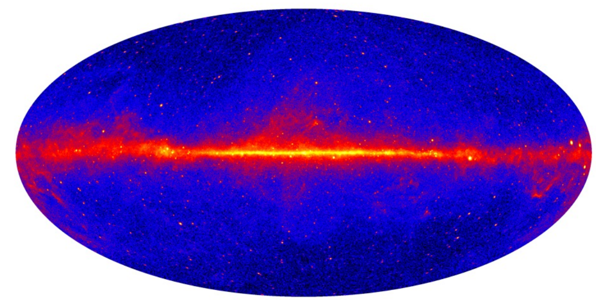


LAB Galactic 21cm H I survey,
Kalberla et al. A&A 440 (2005)



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

$\propto$

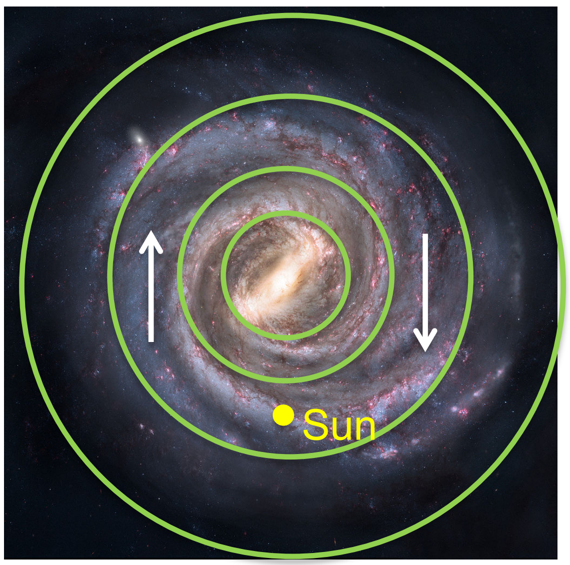


- If we know the distribution of gas and gamma rays, we can recover the density of CR protons

Distribution of CR protons in the Galaxy

- Split the gas distributions in rings
- Fit to gamma-ray data together with other components

$$n_{\mathrm{CRp}} \times n_{\mathrm{gas}} \propto J_\gamma$$

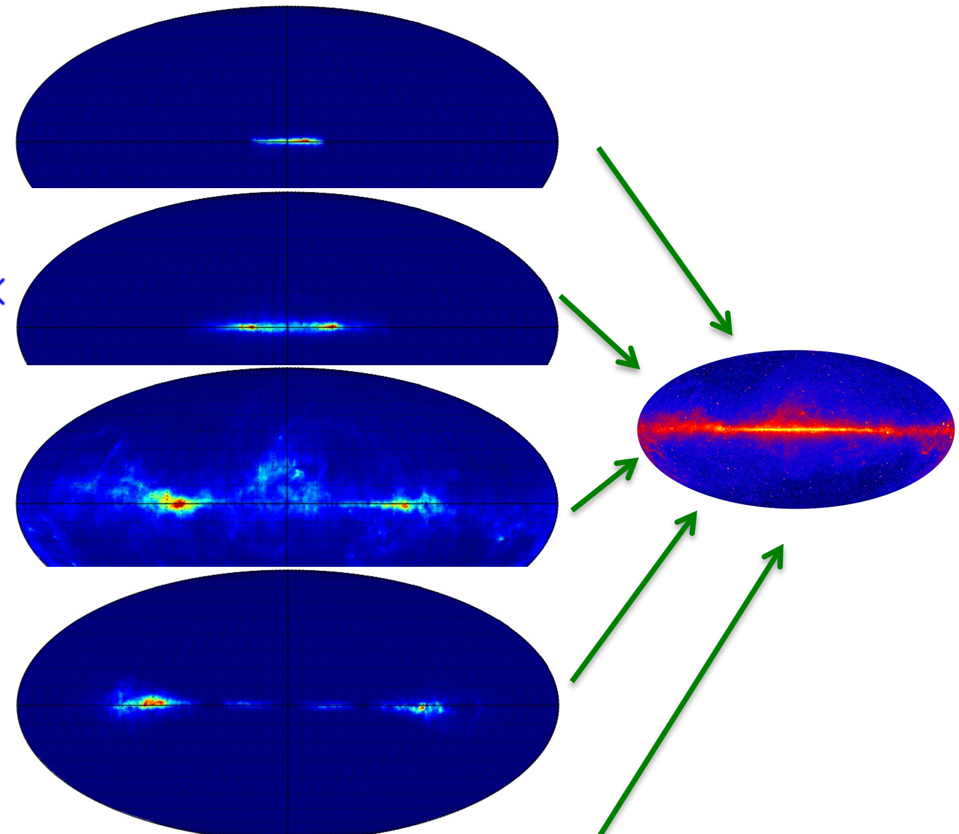


$n_p(R_1)\times$

$n_p(R_2)\times$

$n_p(R_3)\times$

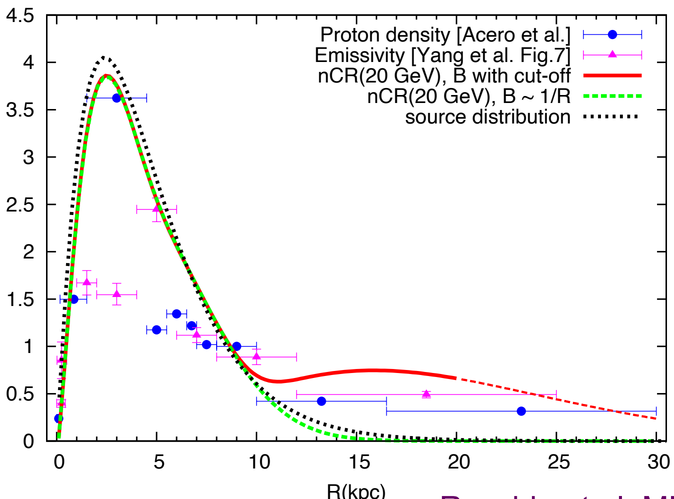
$n_p(R_4)\times$

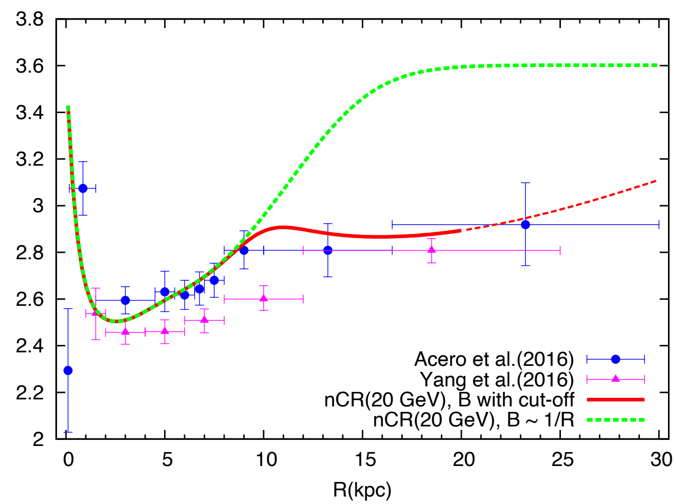


+ other components

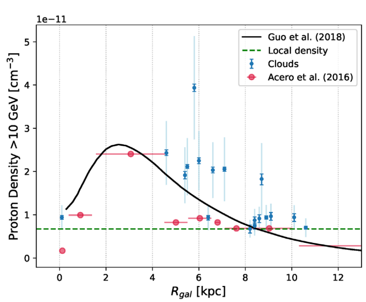
Distribution of CRp in the Galaxy

- Normalization coefficients in front of gas-in-rings maps are proportional to CR protons density
- This way we derive the CRp density as a function of Galactic radius and energy:





Recchia et al, MNRAS 462 (2016) 1, L88-L92



Molecular clouds

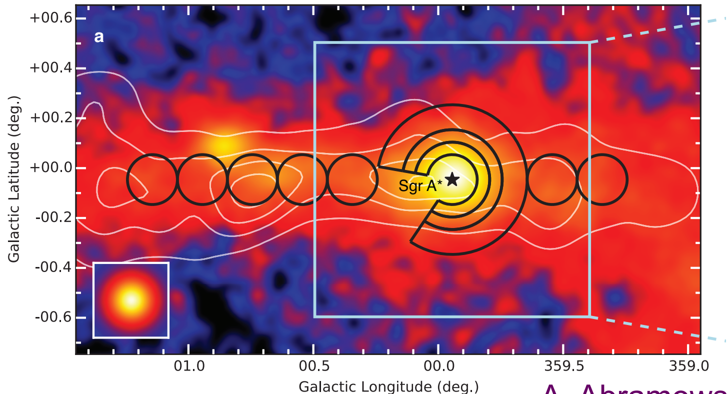
Aharonian et al, PRD 101 (2020)

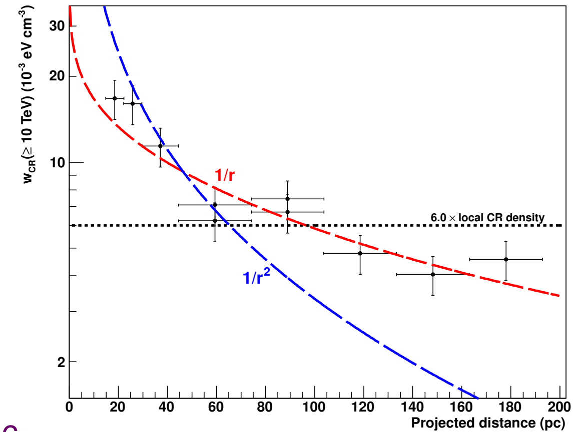
$$n_{\mathrm{CRp}}(E) \propto \frac{J_{\mathrm{CRp}}(E)}{D(E)}$$

PeVatron at the Galactic center

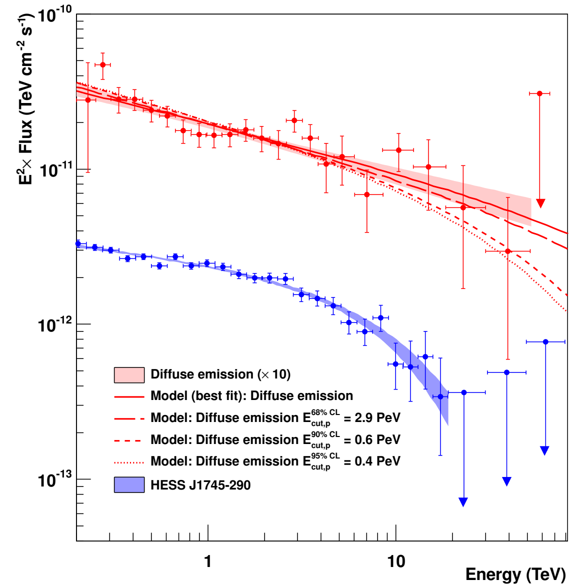
PeVatron in the GC

- H.E.S.S. measurement of diffuse gamma-ray emission near the GC





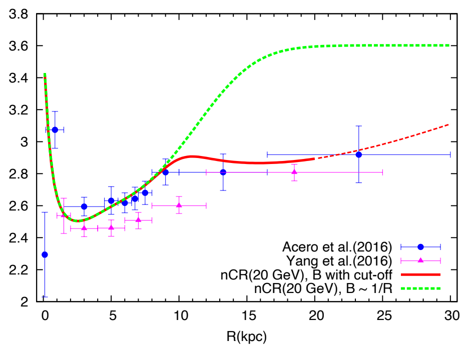
A. Abramowski et al.
Nature 531 (2016) 476



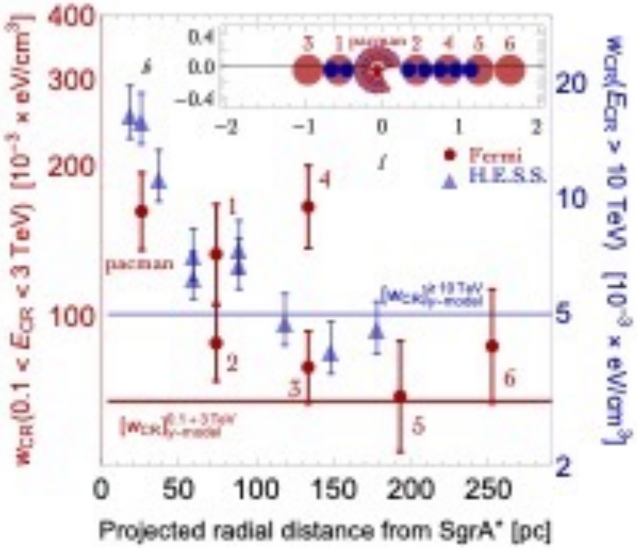
- Emission is correlated with the distribution of molecular clouds (white contours)
- Radial profile ~ 1/r – characteristic of diffusion
- Spectrum is consistent with a power law up to several tens of TeV, which means that the CR spectrum extends up to ~ PeV

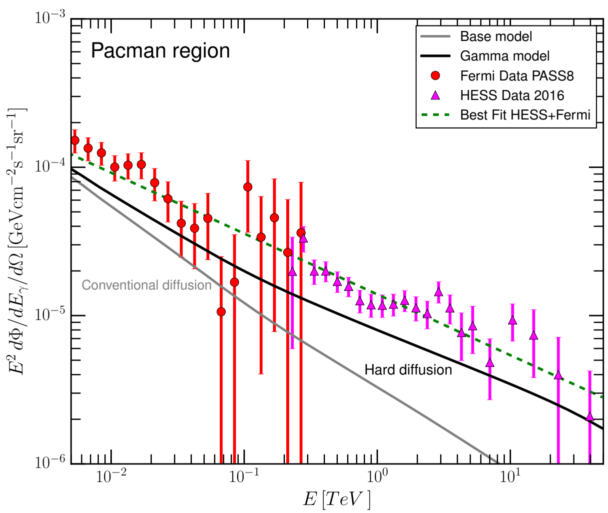
Diffusion near the GC

- Gaggero et al. (2017) have found similar distribution of CRp near the GC from the Fermi data
- However, they propose a different interpretation that the 1 / R dependence can be explained by radially-dependent diffusion, which can at the same time explain the change in CRp index at larger distances:



Recchia et al, MNRAS 462 (2016) 1, L88-L92





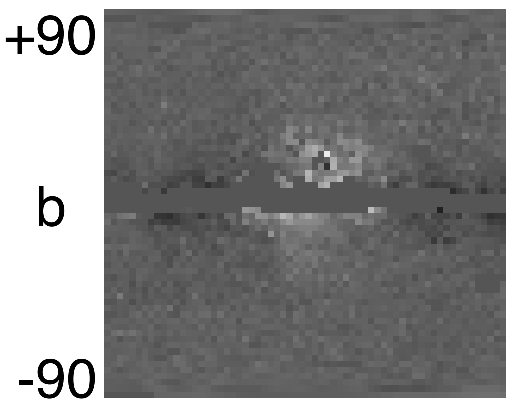
Gaggero et al. PRL 119, 031101 (2017)

Fermi bubbles

GC activity

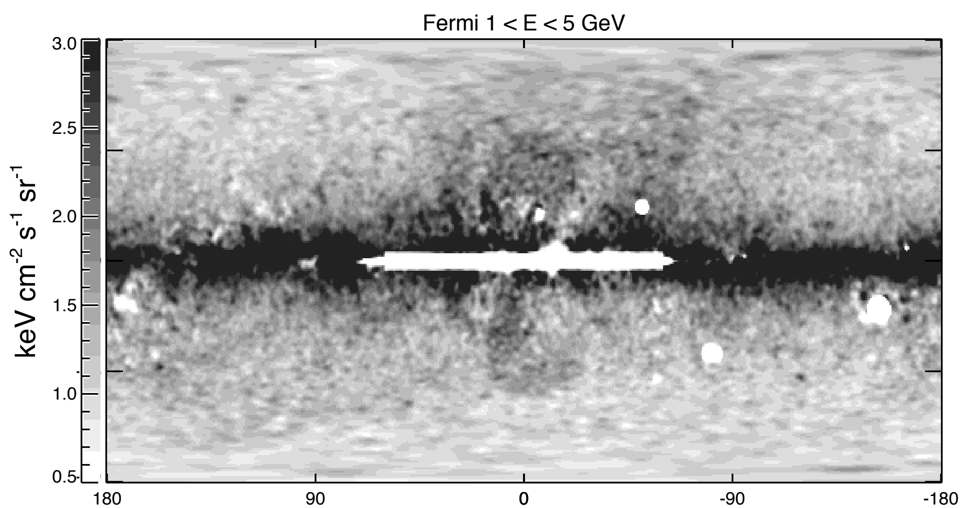
- Another manifestation of an activity at or near the GC is a “surprise” discovery of the Fermi bubbles
- Although there was a residual “haze” emission near the GC discovered in the WMAP data, the shape of the bubbles in the Fermi LAT data turned out to be rather different

WMAP haze



Finkbeiner, ApJ 614 (2004)

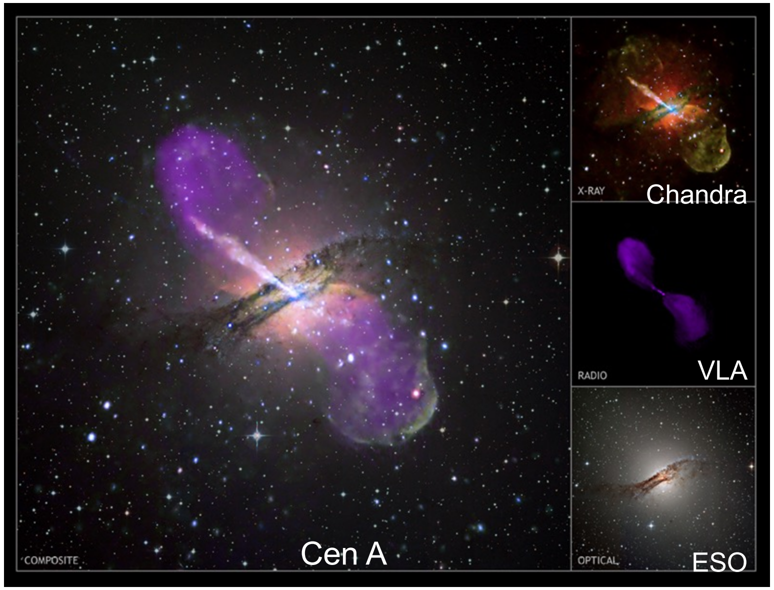
Fermi bubbles



Su, Slatyer, Finkbeiner, ApJ 724 (2010)

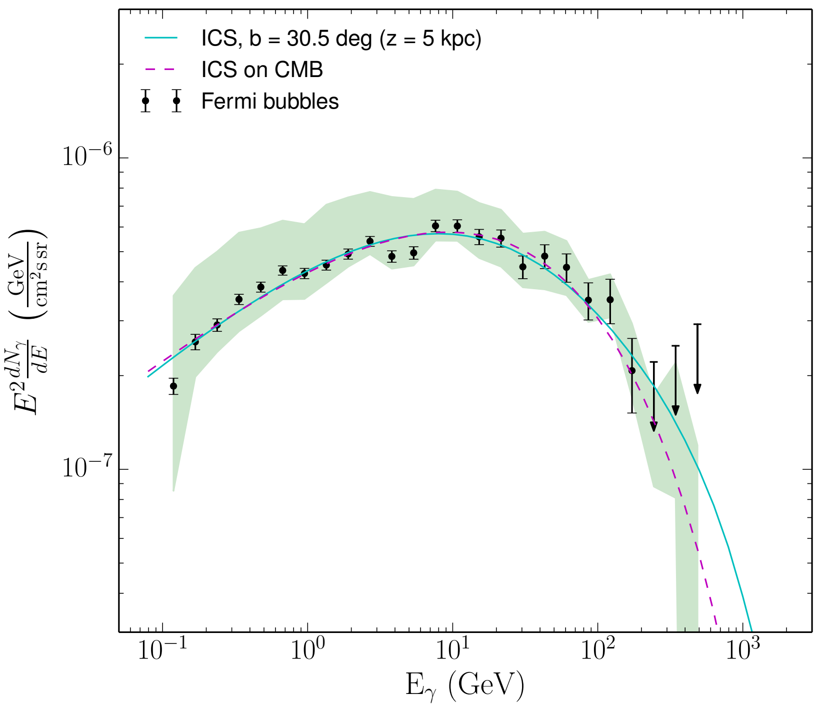
Fermi bubbles origin

- Emission mechanisms
  - Leptonic (inverse Compton)
  - Hadronic
- Origin
  - AGN-like activity
  - Star formation or star-burst

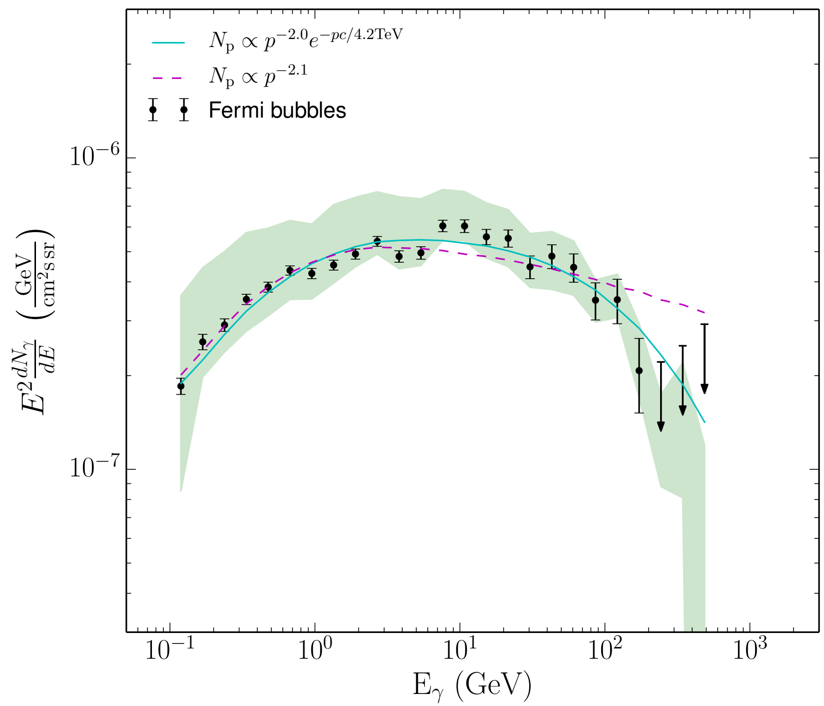


Gamma-ray spectrum at high latitudes

Leptonic model



Hadronic model + secondary IC

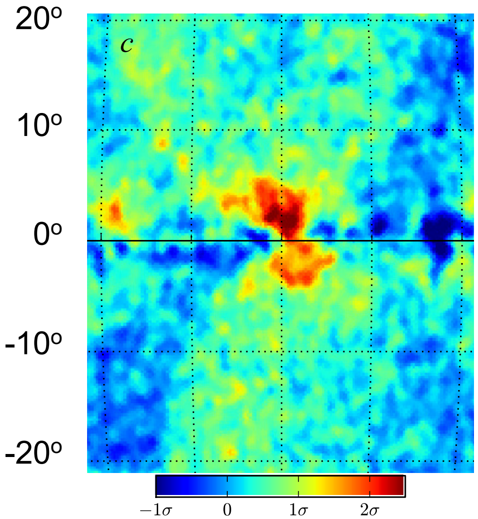


Ackermann et al (Fermi LAT), ApJ 793 (2014)

- Cutoff or softening above ~ 100 GeV
- Both leptonic and hadrnoic models fit the spectrum

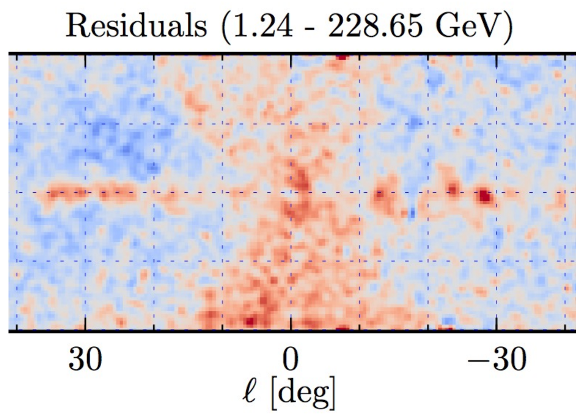
Fermi bubbles near the GC

Fermi bubbles in Fermi LAT Pass 7 diffuse model



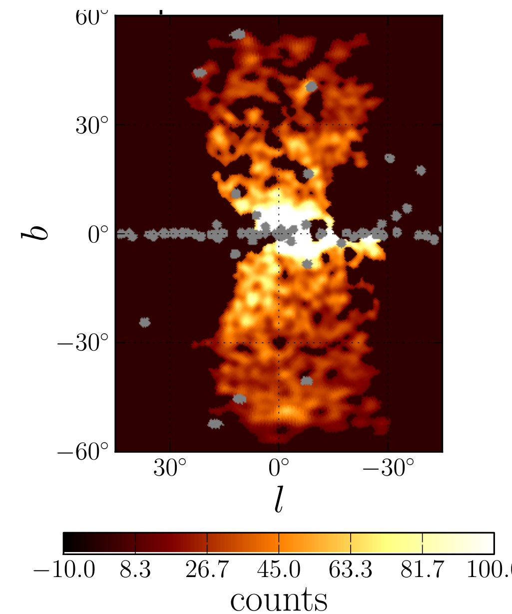
Acero et al (Fermi LAT)
ApJS 223 (2016)

SkyFACT residual significance



Storm et al
JCAP 08 (2017) 022

Fermi bubbles template

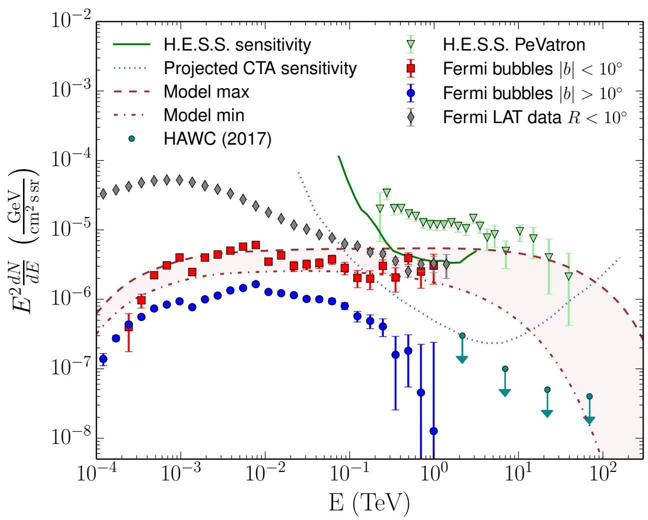


Ackermann et al ApJ 840 (2017)

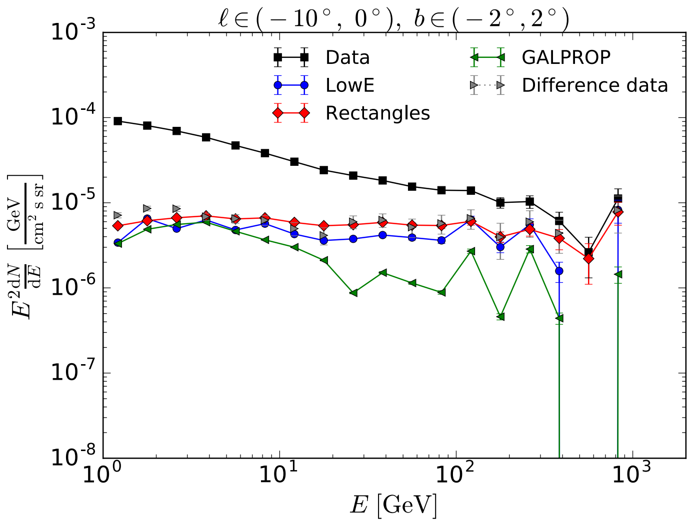
- Intensity is higher near the Galactic plane
- Fermi bubbles at the Galactic plane are shifted to the right from the GC

Spectrum of the FB at low latitudes

- The intensity of the Fermi bubbles emission at low latitudes is larger than at high latitudes
- There seems to be no cutoff up to ~ 1 TeV



Adapted from Ackermann et al ApJ 840 (2017)



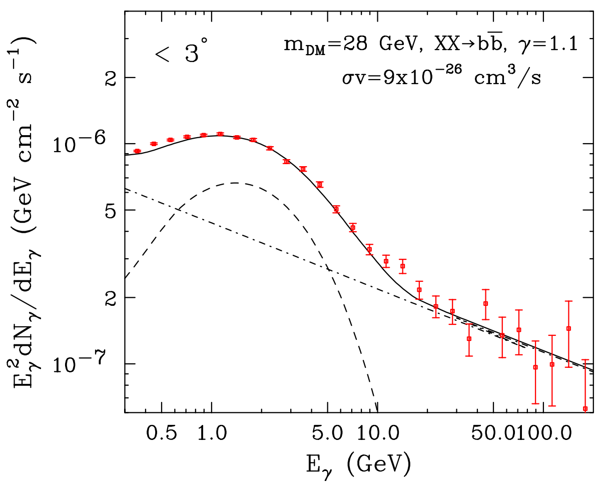
Herold & DM, A&A 625 (2019)

- CTA and SWGO should be sensitive to the FB emission at low latitudes
  - May be possible to detect at a few sigma level with H.E.S.S.

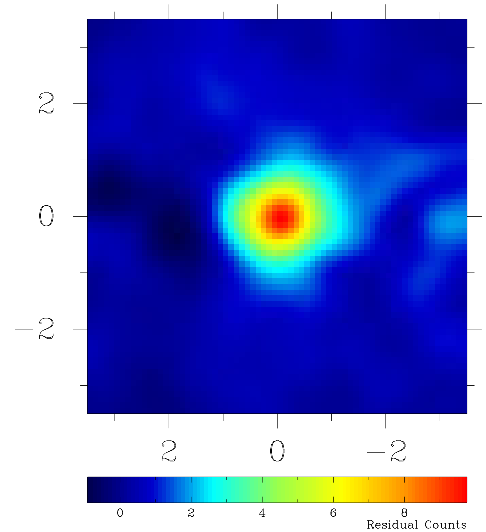
Galactic center excess around 3 GeV

GC excess around 3 GeV

- There is an excess emission near the Galactic center with
  - a peak in the spectral distribution around 3 GeV
  - approximately spherical morphology, consistent with DM annihilation
- Possible interpretations:
  - Dark matter annihilation?
  - Millisecond pulsars?
  - Additional source of CR near the GC?



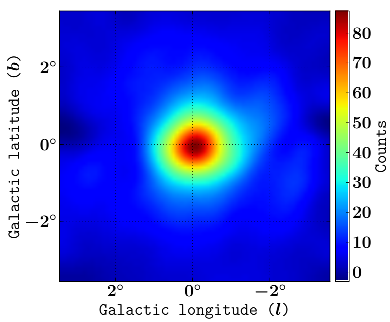
Goodenough & Hooper
arxiv:0910.2998



Abazajian & Kaplinghat
PRD 87 (2012)

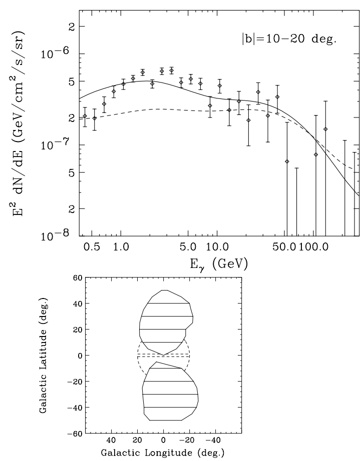
GC excess emission

A lot of groups have studied the excess with similar conclusion about the spectrum and morphology

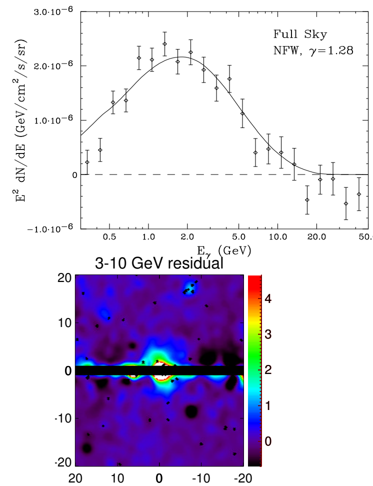


Gordon & Macias PRD 88 (2013)

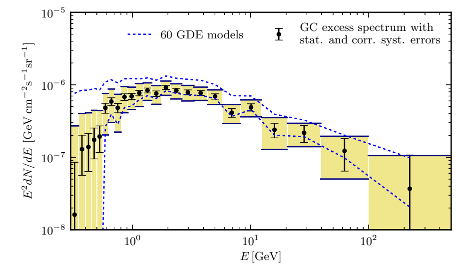
10° – 20° in latitude



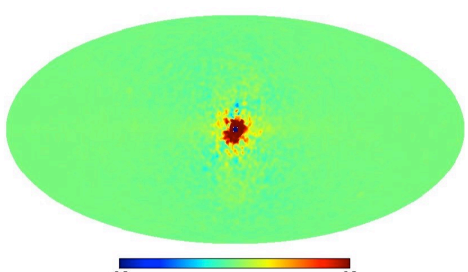
Hooper & Slatyer Phys.Dark Univ. 2 (2013)



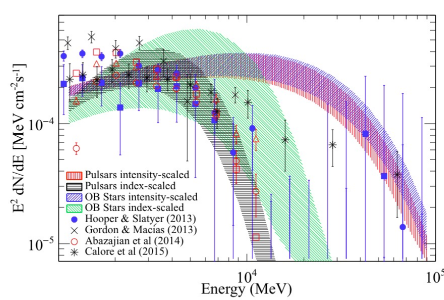
Daylan et al Phys.Dark Univ. 12 (2016)



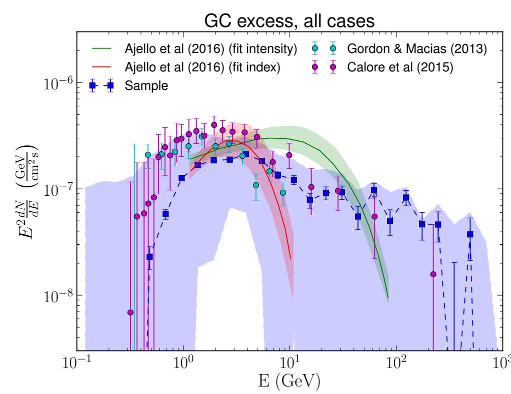
Calore et al JCAP 1503 (2015)



Huang et al, JCAP 4 (2016)



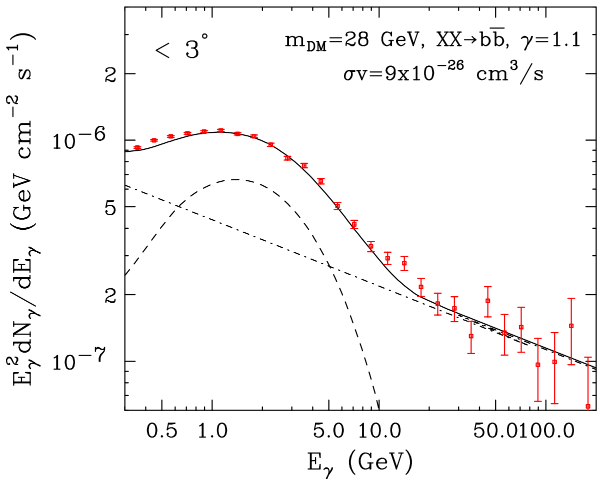
Ajello et al ApJ 819 (2016)



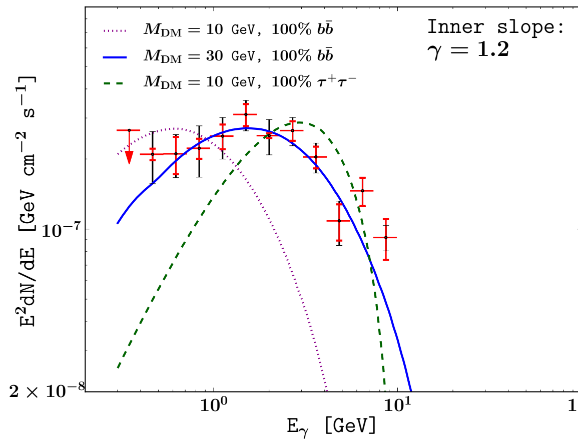
Ackermann et al ApJ 840 (2017)

Dark Matter

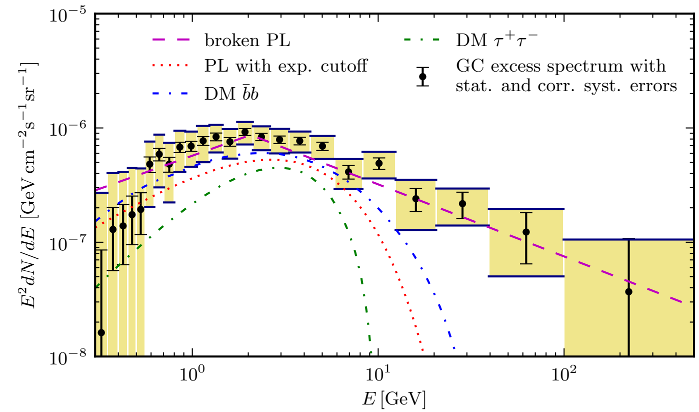
- Dark matter models fit the excess spectrum reasonably good



Goodenough & Hooper
arxiv:0910.2998

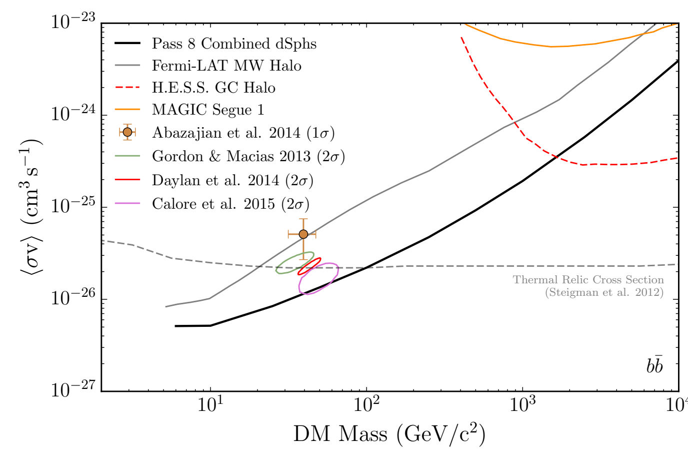


Gordon & Macias
PRD 88 (2013)



Calore et al.
JCAP 3 (2015)

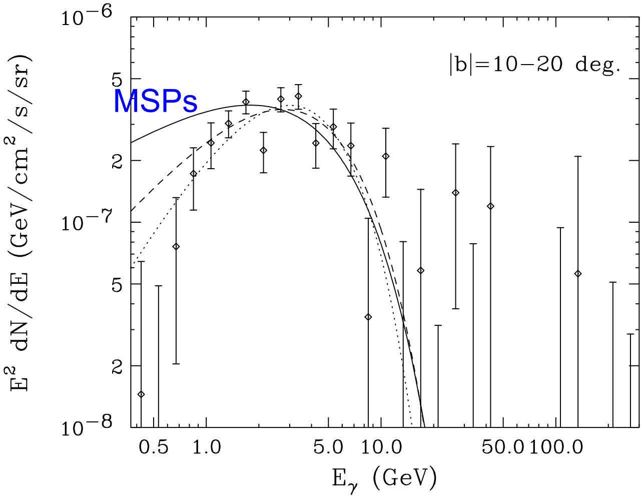
- Comparison with dwarfs:
  - There is a slight tension with DM limits from observation of dwarf galaxies



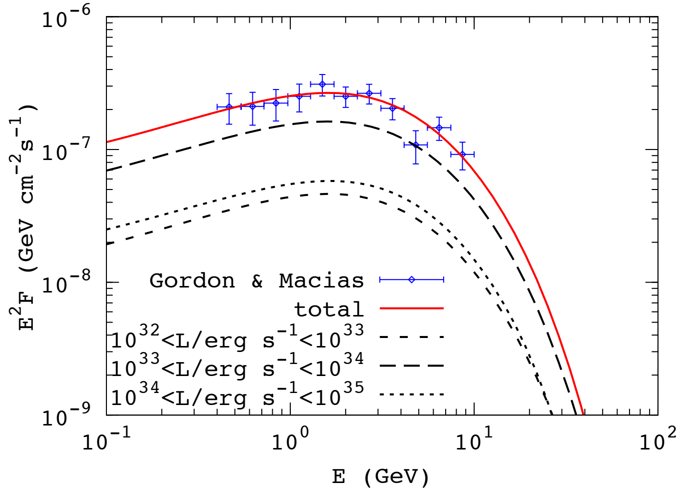
Ackerman et al. (Fermi LAT) PRL 115 (2015)

Millisecond pulsars (MSPs)

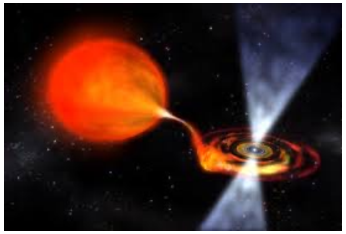
- GC excess spectrum is similar to spectrum of MSPs
  - Large uncertainties due to diffuse emission modeling



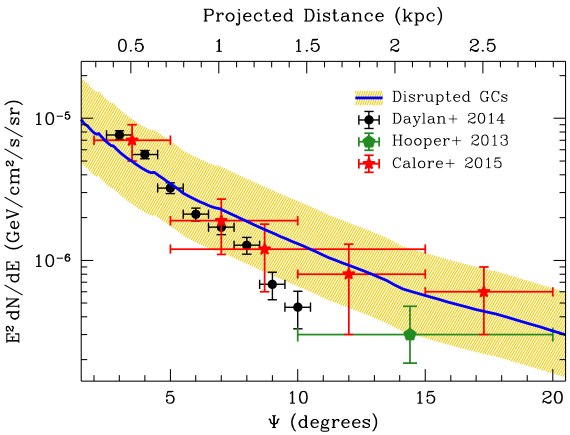
Hooper et al, PRD 88 (2013)



Yuan & Zhang, JHEAp 3 (2014)



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



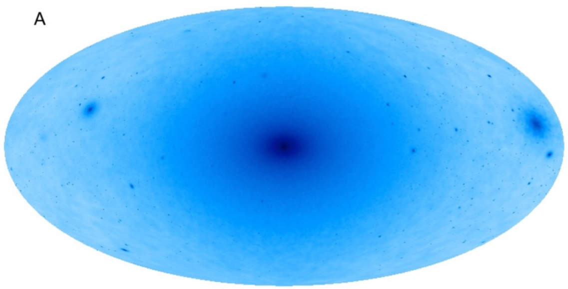
Brandt & Kocsis, ApJ 812 (2015)

Limits on dark matter annihilation

Limits on dark matter

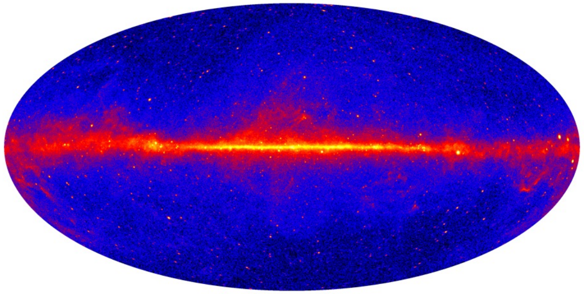
- GC is the brightest expected source of DM annihilation, but the astrophysical emission is also very large with a lot of uncertainties

Simulation of DM annihilation in a Milky Way-like galaxy



Kuhlen et al., Science 325 (2009)

Fermi-LAT gamma-ray data

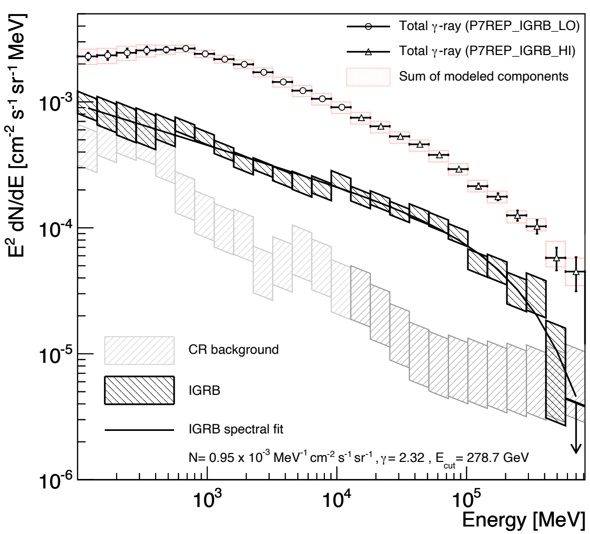


Fermi-LAT / NASA

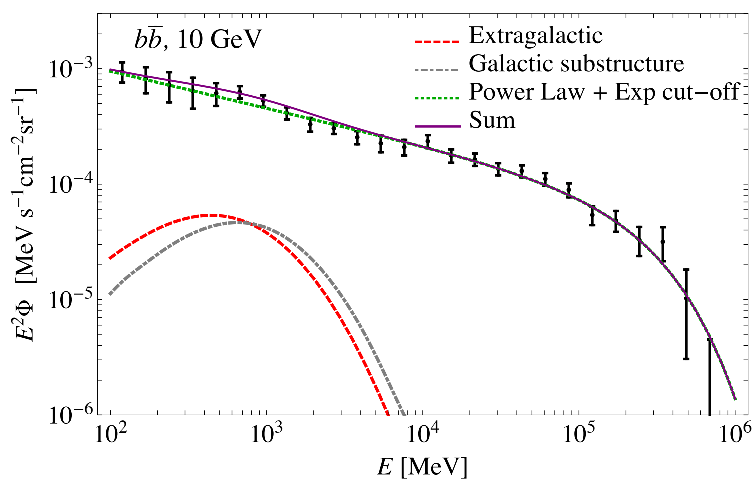
- One can also place limits on DM annihilation at high latitudes above the Galactic plane:
  - DM annihilation in other galaxies
  - DM annihilation in the halo of Milky Way

Limits on DM annihilation

- Use Isotropic gamma-ray background (IGRB)
- IGRB is derived after removing from gamma-ray data: Galactic emission, known point sources, CR contamination
- The Galactic and extragalactic DM annihilations are added until the deviation from a simple power-law model with an exponential cutoff overproduces the observed IGRB



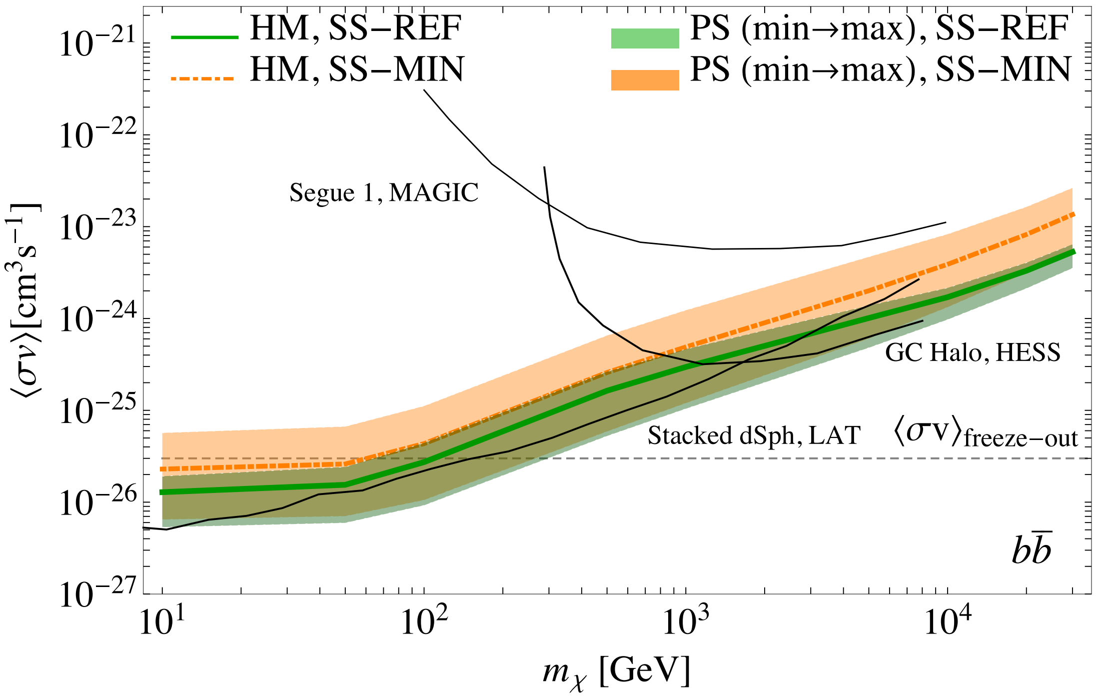
Ackermann et al. ApJ 799 (2015)



Ackermann et al. ApJ 799 (2015)

Limits on DM annihilation

- The limits on DM annihilation from IGRB are competitive to other limits derived from gamma-ray data for DM masses ~ 100 GeV – 1 TeV

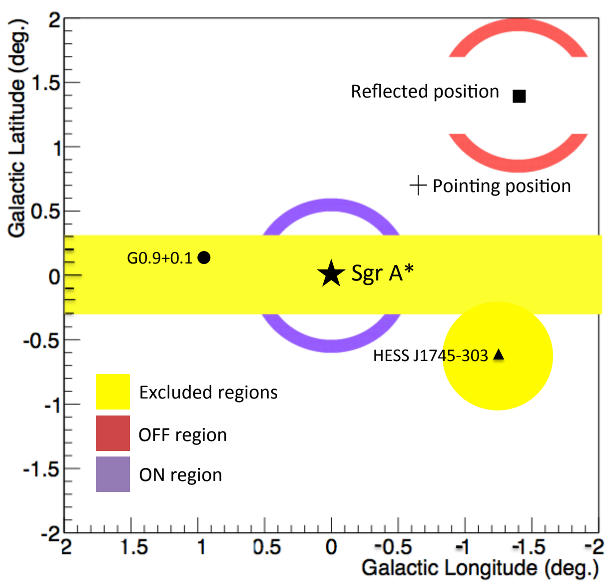


Ackermann et al. ApJ 799 (2015)

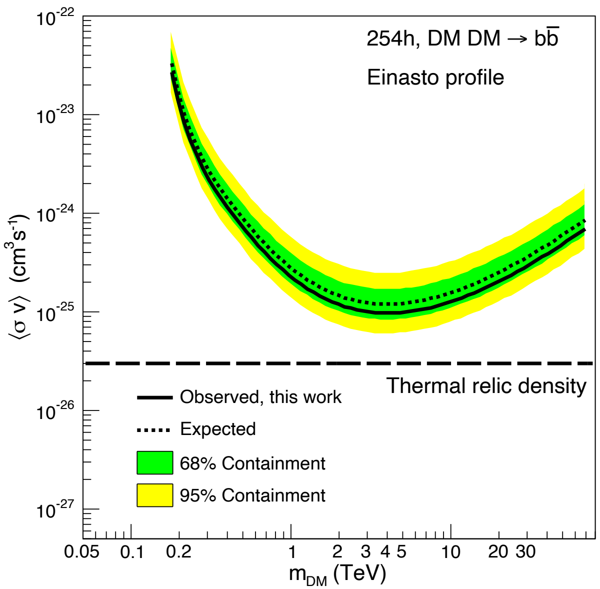
Limits on DM annihilation

- At energies above ~ 1 TeV the most constraining limits can be obtained with Cherenkov Telescopes
- For example, the limits obtained with H.E.S.S. for DM annihilation near the GC:

Reflected background



DM limits



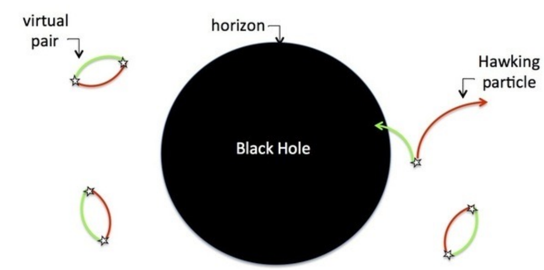
Abdallah et al. PRL 117 (2016)

Limits on primordial black holes

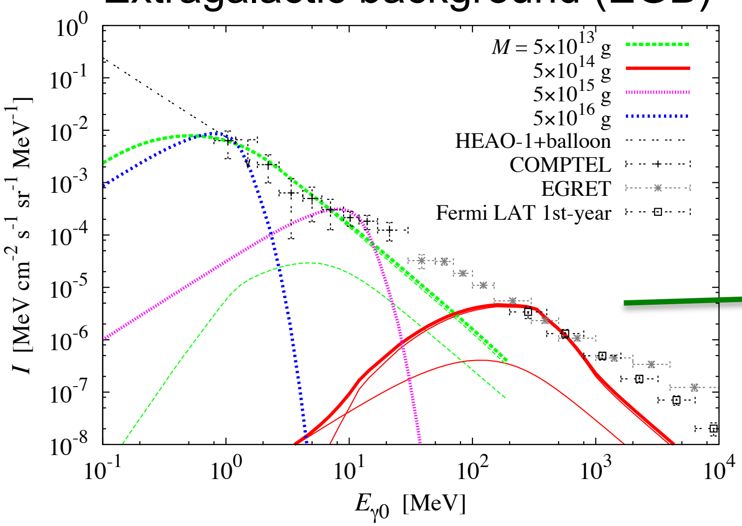
Limits on primordial black holes (PBHs)

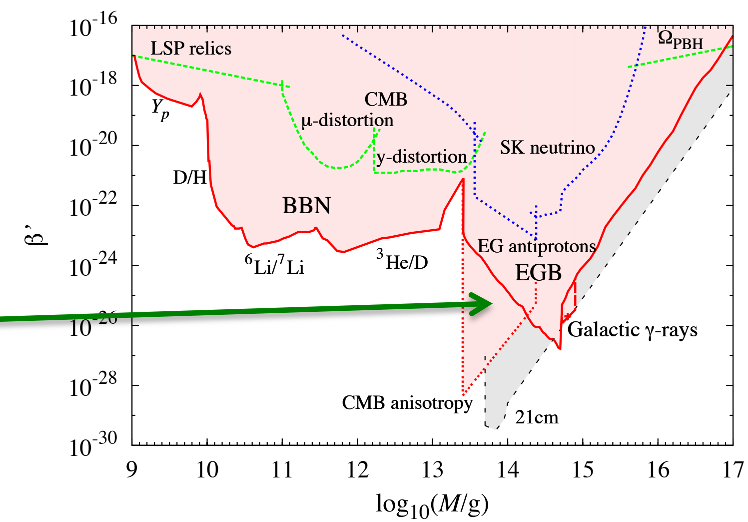
- PBHs can be created in the early Universe due to high density fluctuations with a range of masses from Planck mass to the mass of supermassive black holes
- BHs are expected to emit particles due to Hawking radiation with temperature

$$T = \frac{M_{\rm P}^2}{8\pi M}$$



Extragalactic background (EGB)





Carr et al, PRD 81 (2010), arxiv:0912.5297

Conclusions

- Diffuse gamma-rays are a unique probe of some of the most basic properties of our Galaxy and fundamental laws of nature
- Using diffuse gamma-rays we can
  - map the distribution of cosmic rays in the Galaxy and, e.g., study the diffusion in different parts of the Galaxy;
  - study Fermi bubbles – could be our only chance to study this type of objects in details (although similar structures can be detected in some nearby galaxies, such as Andromeda)
  - understand the past activity at the Galactic center – is there a source of cosmic rays up to PeV energies there?
  - search for or constrain dark matter annihilation
  - search for or constrain evaporation of primordial black holes (with initial masses around 10^{14} – 10^{17} g).