Fermi bubbles

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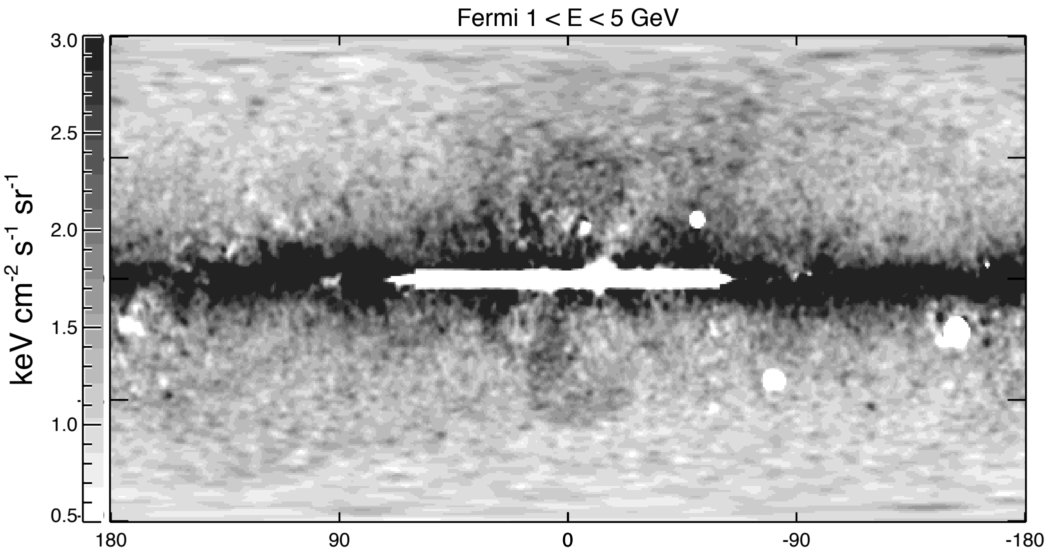
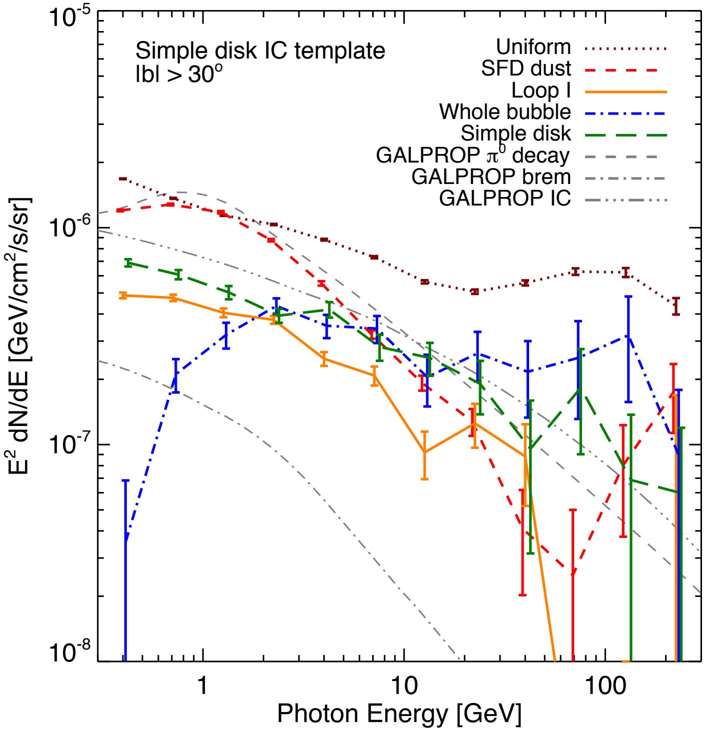
Discovery of the Fermi bubbles

- **Su, Slatyer, Finkbeiner, May 2010**
  - **E^{-2} spectrum up to 100 GeV**
  - **have narrow edges**
  - **stretch up to 55° above and below the Galactic center**





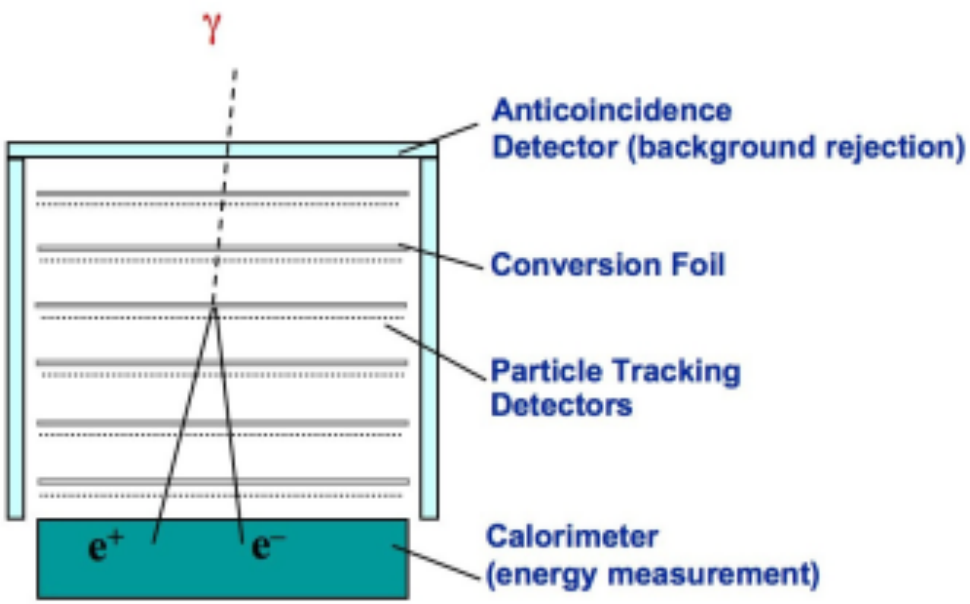
Su, Slatyer, Finkbeiner, ApJ 724 (2010)

Fermi bubbles – an elephant in gamma-ray sky

- **Fermi bubbles' solid angle is about 1 sr**
  - **This is comparable to an elephant at 3 m**

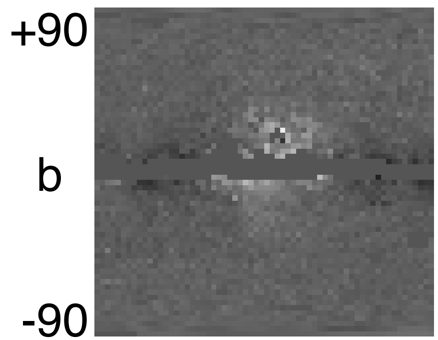
Fermi-LAT

- **Fermi Large Area Telescope – gamma ray space telescope**
- **Launched on June 11, 2008**
  - **20 MeV to more than 1 TeV**
  - **2.4 sr field of view**
  - **Better than 1° resolution above 1 GeV**
  - **Covers the sky in two orbits (3 hours)**

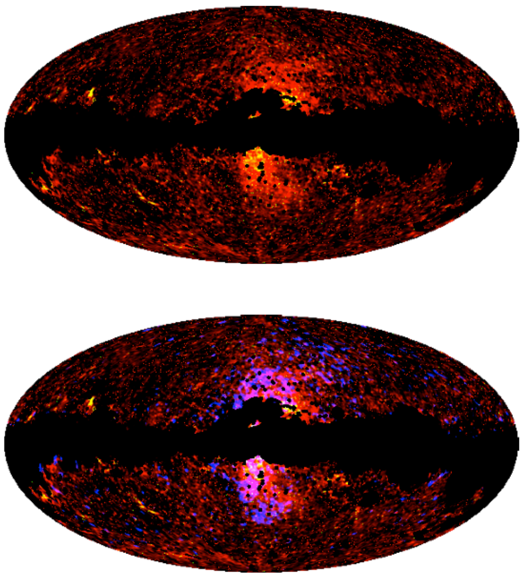


Haze

- **Microwave haze**

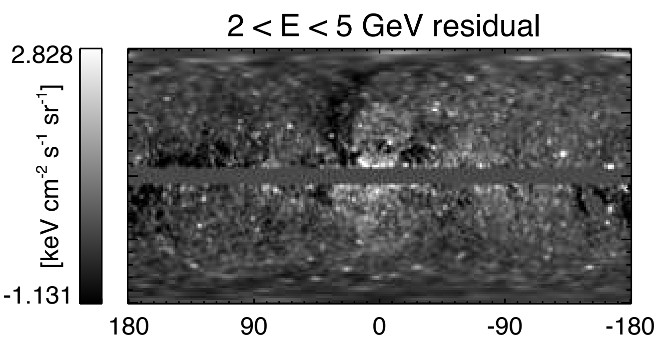


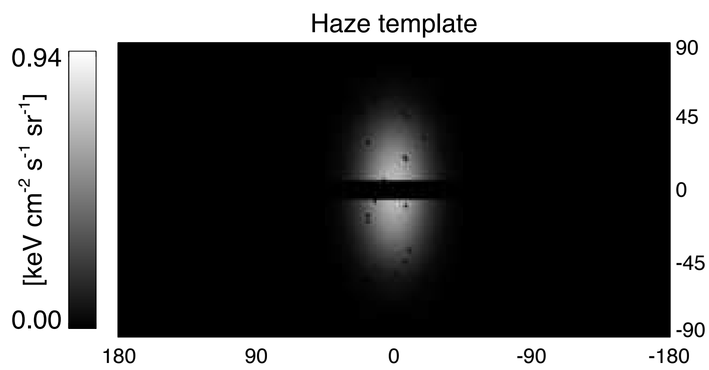
Finkbeiner, ApJ 614 (2004)



Planck Collaboration A&A 554 (2013)

- **Gamma-ray haze**

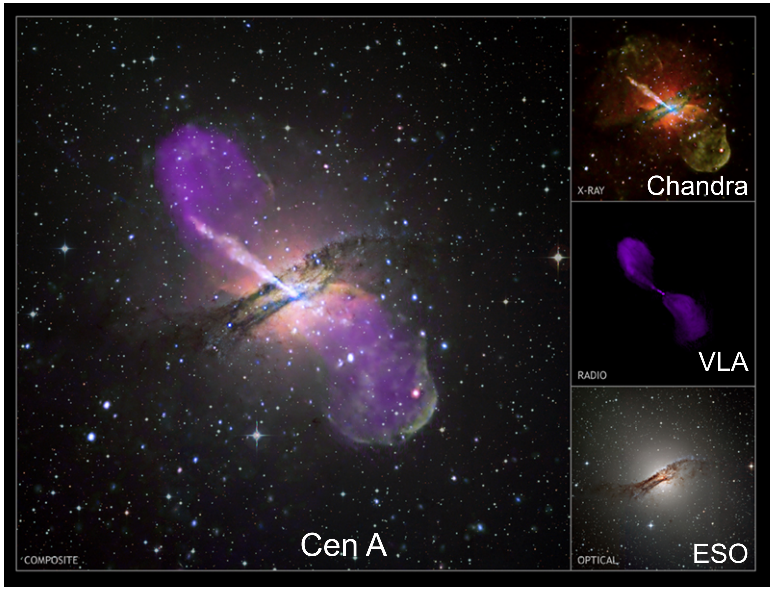




Dobler et al, ApJ 717 (2010)

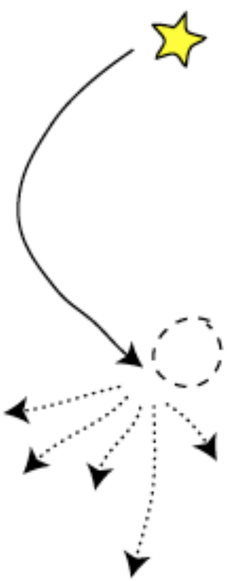
Fermi bubbles origin

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

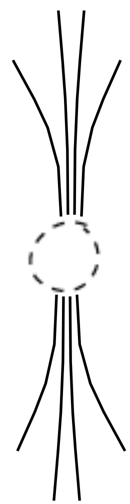


Leptonic Model

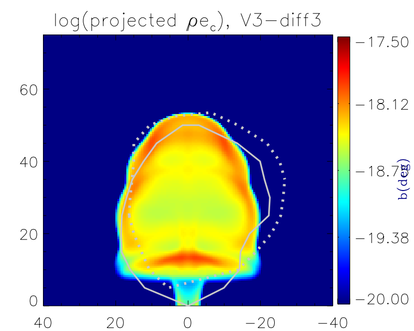
- **Electrons accelerated in the jet**
- **Gamma rays by inverse Compton scattering on radiation fields**
- **Microwave haze by synchrotron of same population of electrons**



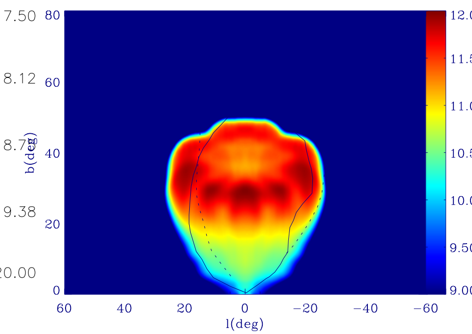
disruption of stars or
molecular clouds
by central black hole



AGN-like jet transports
particles to high latitudes



Guo & Mathews
ApJ 756 (2012)



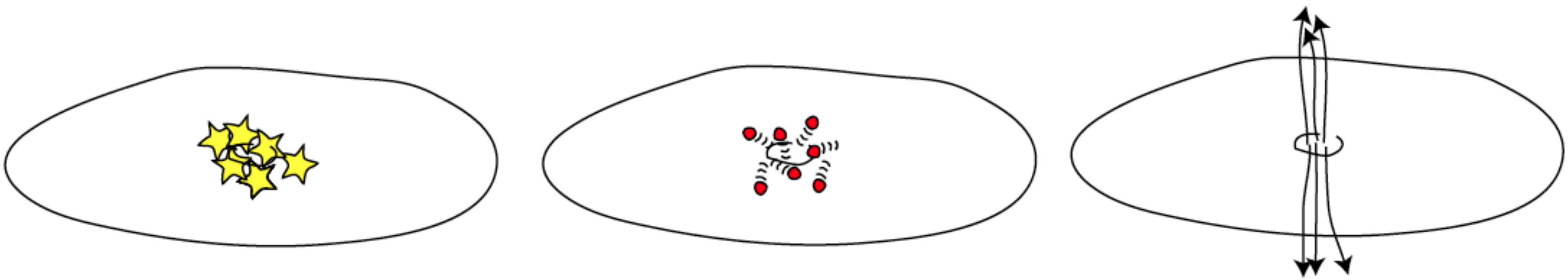
Yang et al.
ApJ 761 (2012)

Jets interact with
interstellar medium
to form bubbles

Illustrations by P. Mertsch

Hadronic Model

- **Cosmic rays accelerated by Supernovae shells**
- **Gamma rays by π^0 on thermal gas (density ~ 0.01 cm^{-3})**
- **Secondary e^+e^- produce synchrotron radiation**



increased star formation rate close to GC

acceleration of CR protons and nuclei in SNRs

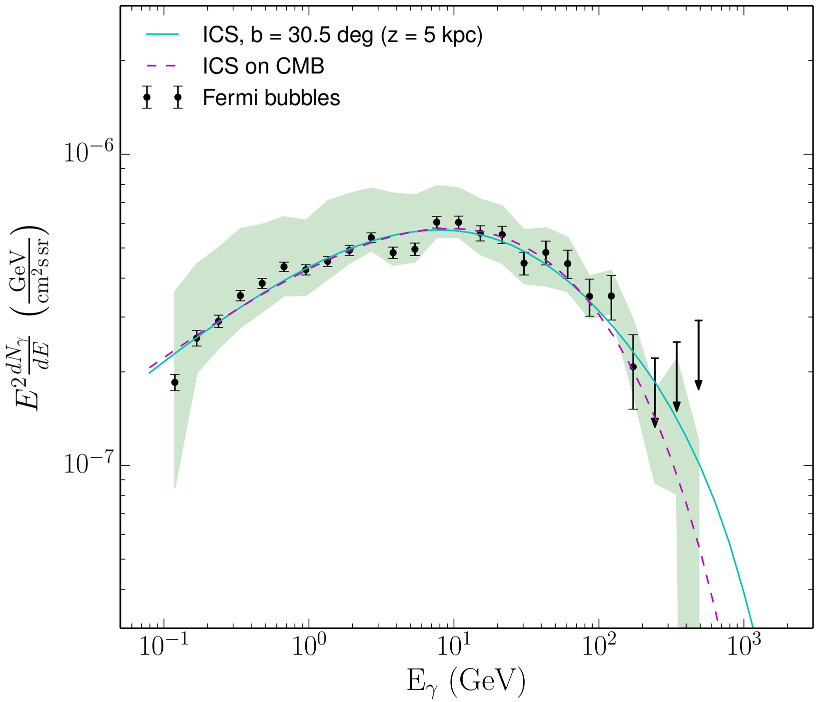
wind convects CRs away from disk

Aharonian & Crocker, PRL, 106 (2011)

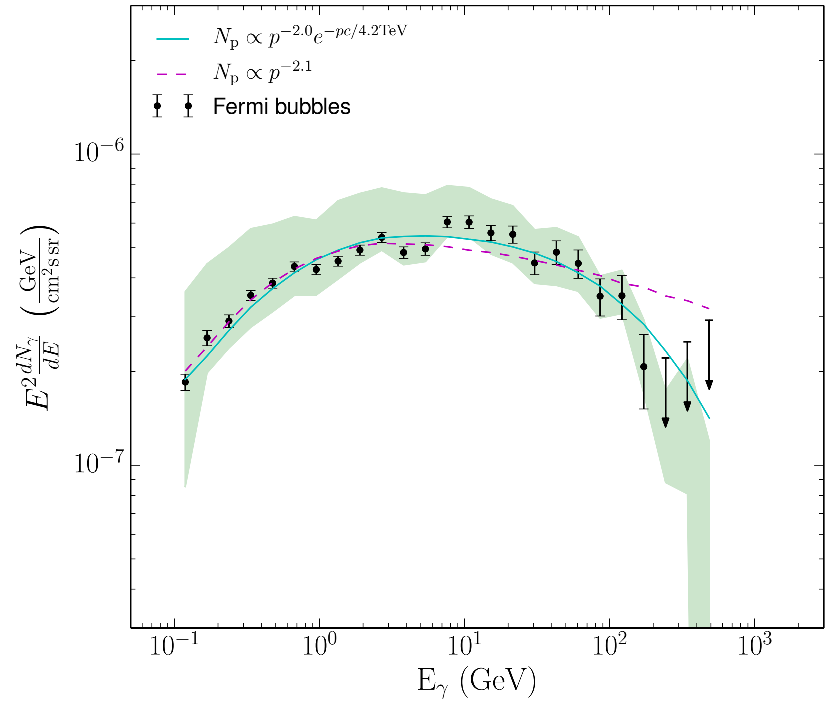
Illustrations by P. Mertsch

Gamma-ray spectrum

Leptonic model



Hadronic model + secondary IC



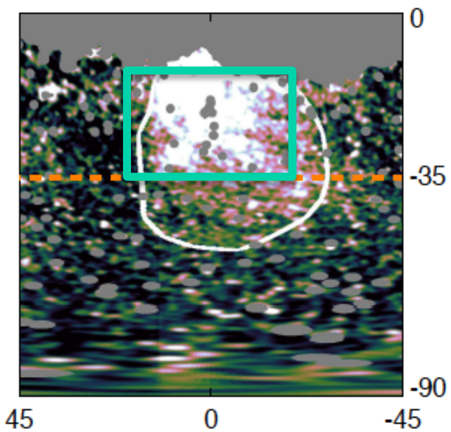
Ackermann et al (Fermi LAT), ApJ 793 (2014)

- **Both leptonic and hadrnoic models fit the spectrum**

Microwave haze

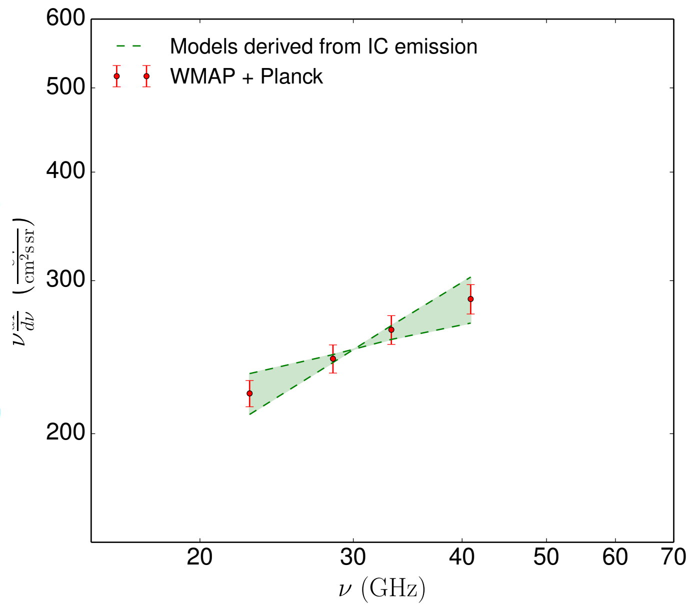
Leptonic

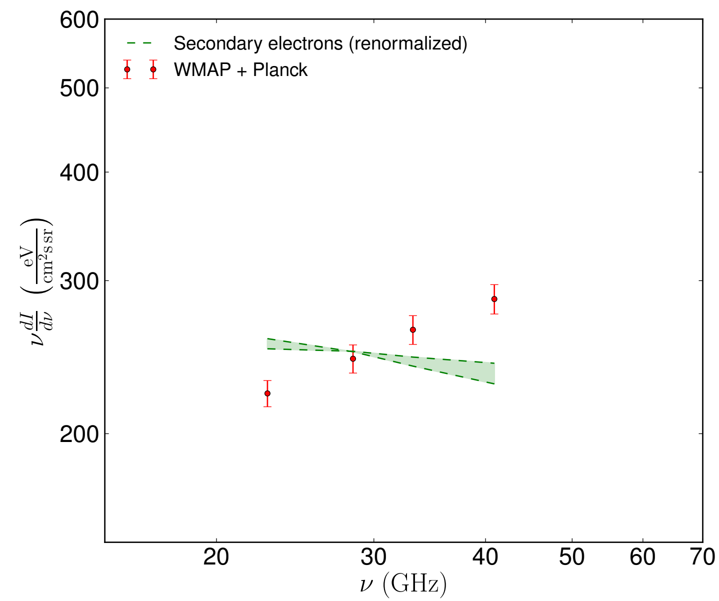
Hadronic (secondary leptons)



|l| < 25° and
-35° < b < -10°

Planck Collaboration
A&A 554 (2013)



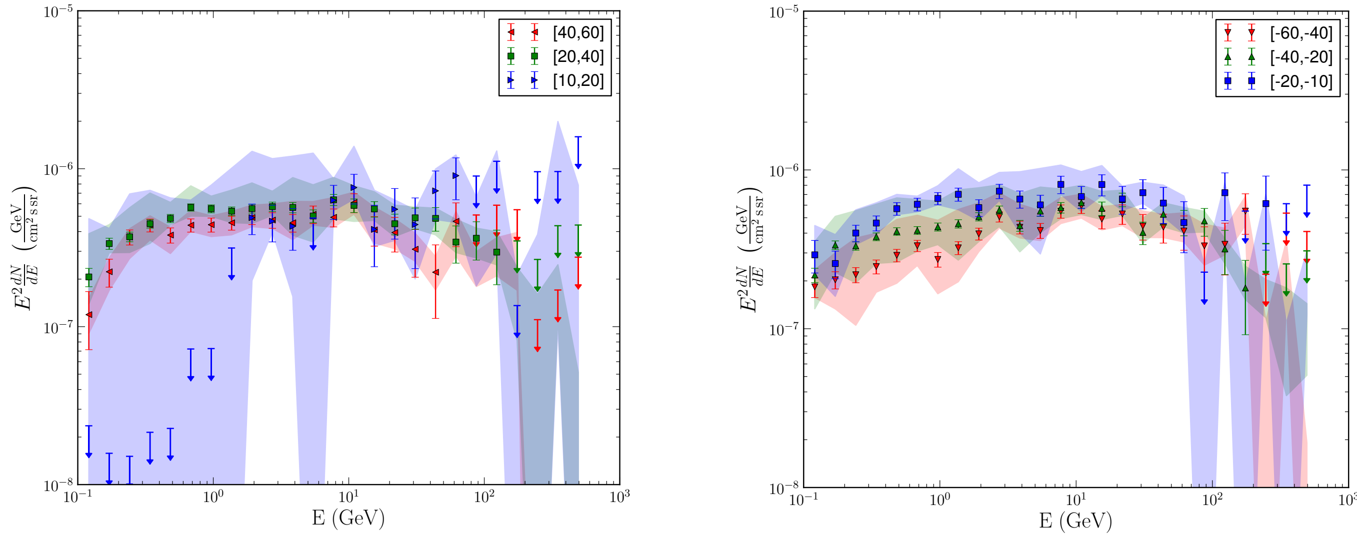


Ackermann et al (Fermi LAT), ApJ 793 (2014)

- **Synchrotron emission from secondary leptons in hadronic models cannot explain the microwave haze**

Spectrum in stripes

- At latitudes |b| > 10°, the spectrum is uniform



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

- Natural in hadronic models
- In leptonic models the velocity should be > 10000 km/s to avoid e^+e^- cooling before they reach z ~ 10 kpc distance
  - stochastic reacceleration: **Mertsch & Sarkar PRL 107 (2011)**

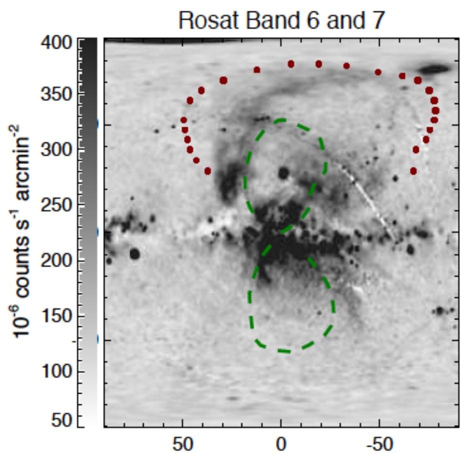
Bubbles boundary

- Narrow boundary
  - Natural in AGN models – result of expansion
  - In star-formation models, one needs a mechanism that keeps CR from escaping, e.g., magnetic draping
- Absence of a shock
  - Natural in star-formation / hadronic models
  - In leptonic models one needs to (re)accelerate electrons

More puzzles

- **X-rays**

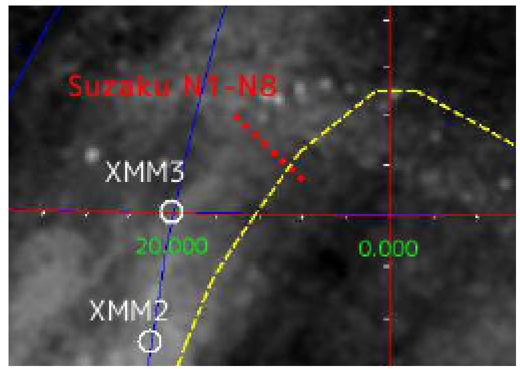
ROSAT



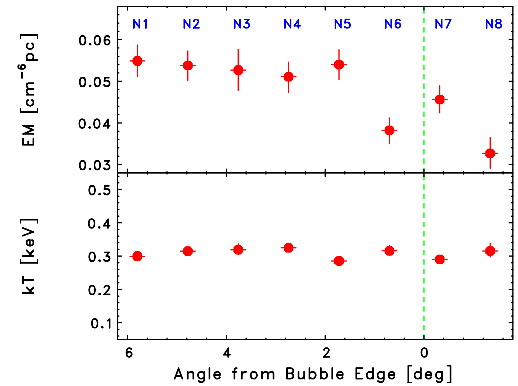
Su, Slatyer, Finkbeiner
ApJ 724 (2010)

Suzaku

Pointings



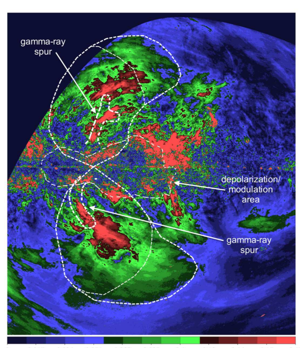
Emission measure



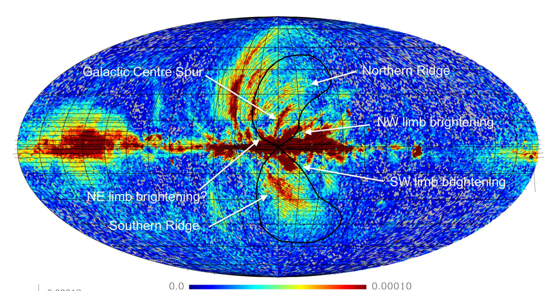
Kataoka et al, ApJ 779 (2013)

- **Polarization**

S-PASS, 2.3 GHz

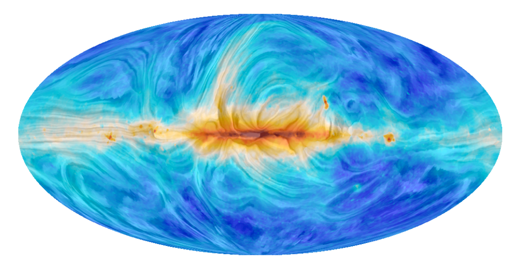


WMAP, 23 GHz polarization



Carretti et al, Nature 493 (2013)

Planck, 30 GHz polarization



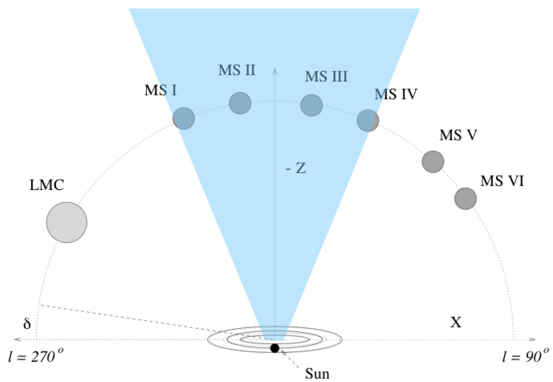
Adam et al (Planck), arXiv:1502.01582

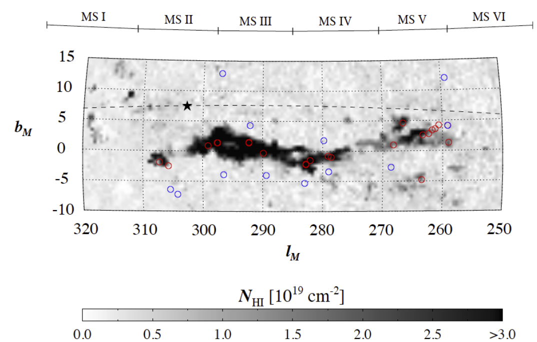
Scoreboard

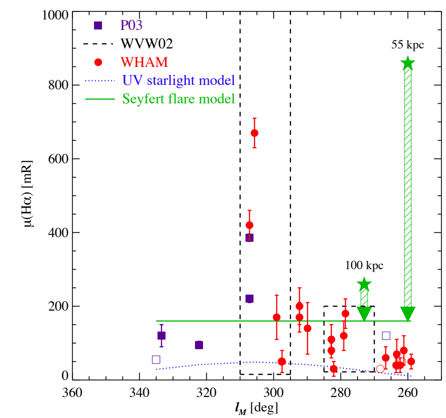
	Leptonic	Hadronic
Energy spectrum	✔	with secondary IC
WMAP / Planck haze	✔	extra component
Isotropic emission	reacceleration	✔
Narrow boundary	✔	magnetic draping
No visible shock	?	✔

AGN or starburst

- **Often happen together**
- **Evidence for an AGN-like activity 0.5 – 5 Myr ago**
  - **Magellanic stream ionization**

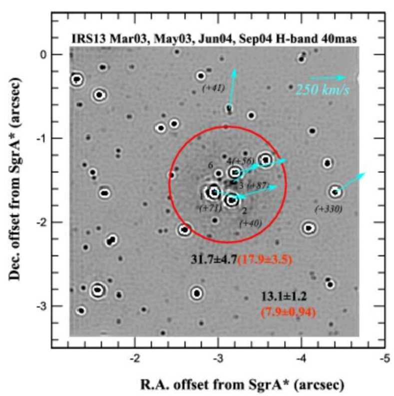


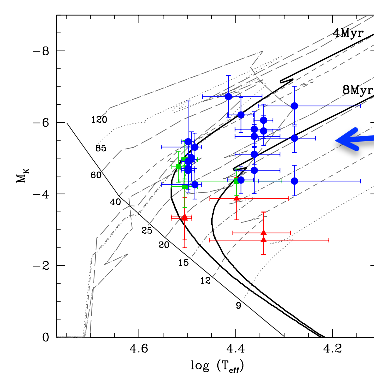




Bland-Hawthorn et al, ApJ 778 (2013)

- **Young (~ 6 Myr) stellar population near the GC (~ 10^4 M_{sun})**



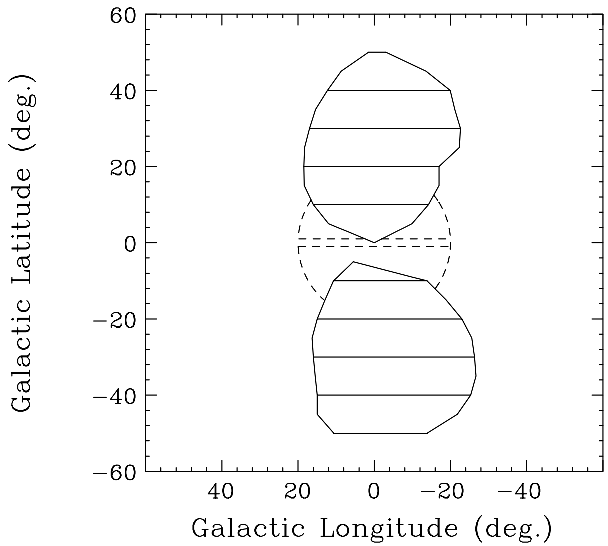


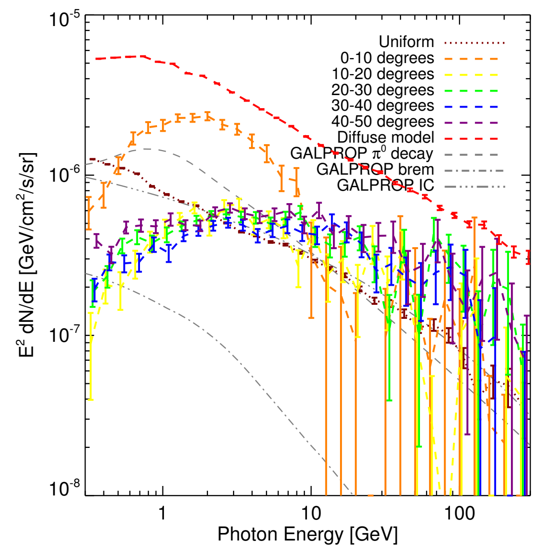
OB supergiants
(~ few Myr lifetime)

Paumard et al,
ApJ 643 (2006)

Galactic center and the Fermi bubbles

- **Fermi bubbles spectrum for |b| < 10°**



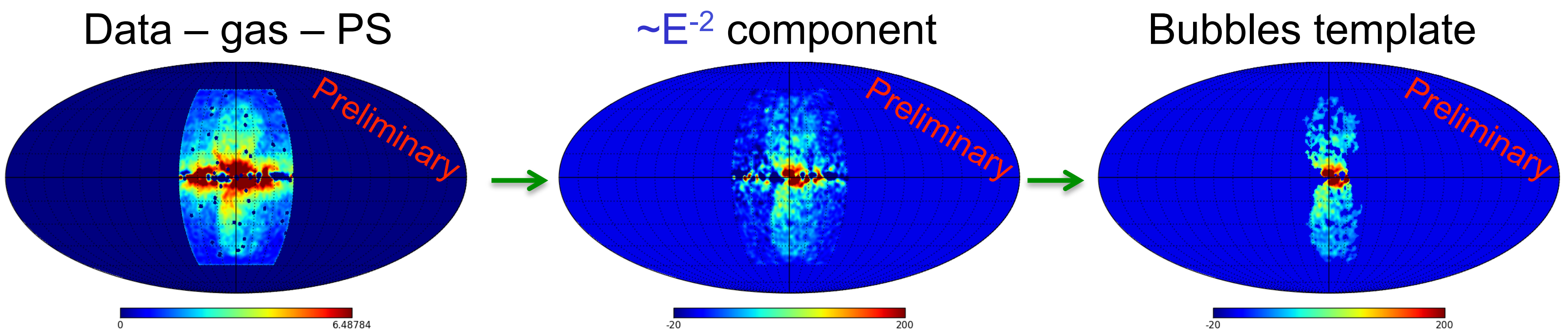


Hooper & Slatyer
Phys.Dark Univ. 2 (2013)

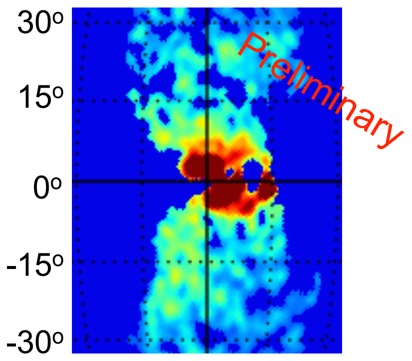
- **Is it a part of the Fermi bubbles or a separate component?**
- **Options**
  - **Only bubbles**
  - **No bubbles**
  - **Both the bubbles and a new component**

Fermi bubbles at low latitudes

- Assume that the bubbles have the same spectrum near the GC as at high latitudes ~ E^{-2} between 1 and 10 GeV
- Subtract π^0 component and PS from data and represent the residual using two components:
  - Bubble-like ~ E^{-2}
  - Other components (IC, ISO, Loop I etc.) ~ $E^{-2.4}$



- Fermi bubbles template near the GC:
  - Larger intensity
  - Displaced to the right from the GC

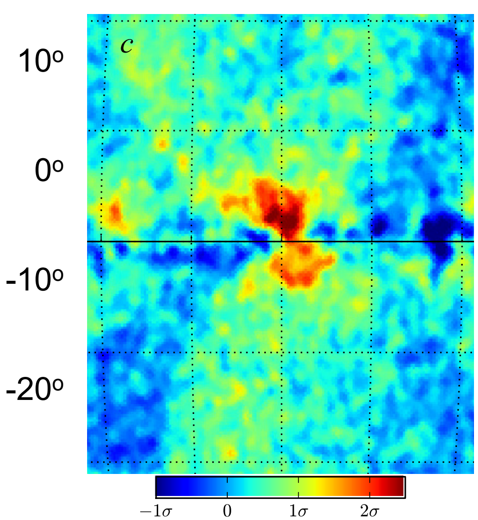


Fermi bubbles near the GC

- **Center of the Fermi bubbles intersection with the Galactic plane:**
  ~ 1º – 2º or about 100 – 300 pc to the right of the GC?

Fermi LAT Pass 7 diffuse model

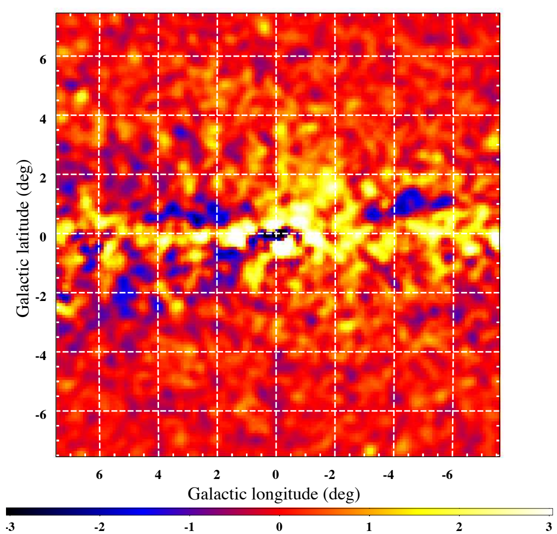
Fermi bubbles



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

Fermi LAT analysis of the GC excess?

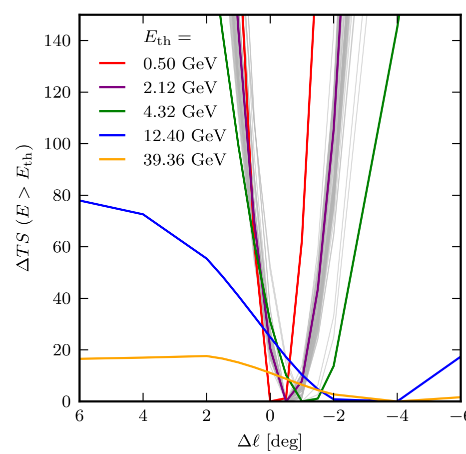
Residual 1.6 – 10 GeV



Ajello et al (Fermi LAT) ApJ 819 (2016)

Calore et al GC excess analysis?

Displacement of the GC excess:



Calore et al, JCAP 1503 (2015)

Future

- eROSITA
  - Search for cavity in hot gas plasma due to CR pressure inside the Fermi bubbles
- HESS, MAGIC, VERITAS, CTA, HAWC
  - Fermi bubbles near the GC seem to be brighter
  - Possible to see with Cherenkov telescopes?
- IceCube, KM3NeT
  - Search for neutrinos from the Fermi bubbles
- More analysis of existing data
  - Fermi LAT (Pass 8 data)
  - Planck polarization

Conclusions

- Fermi bubbles are a unique feature on gamma-ray sky
  - Relatively bright in gamma rays
  - No clear counterpart at high latitudes in X-rays or radio
- Possible origin and emission mechanisms
  - AGN-like activity of Sgr A* (IC gamma rays)
  - Enhanced star formation near the GC (π^0 gamma rays)
    - Both scenarios have advantages and disadvantages
- Tentative characterization at low latitudes:
  - Enhanced intensity near the Galactic plane
  - Displaced to the right (negative longitudes) from the GC
- Origin of the Fermi bubbles is an exciting question
  - Should learn more soon using new data from
    - eROSITA, HAWC, CTA, IceCube and KM3NeT