Gamma-ray Excitement from the Galactic Center: Gigantic Bubbles, Jets, Dark Matter, or Statistical Fluke

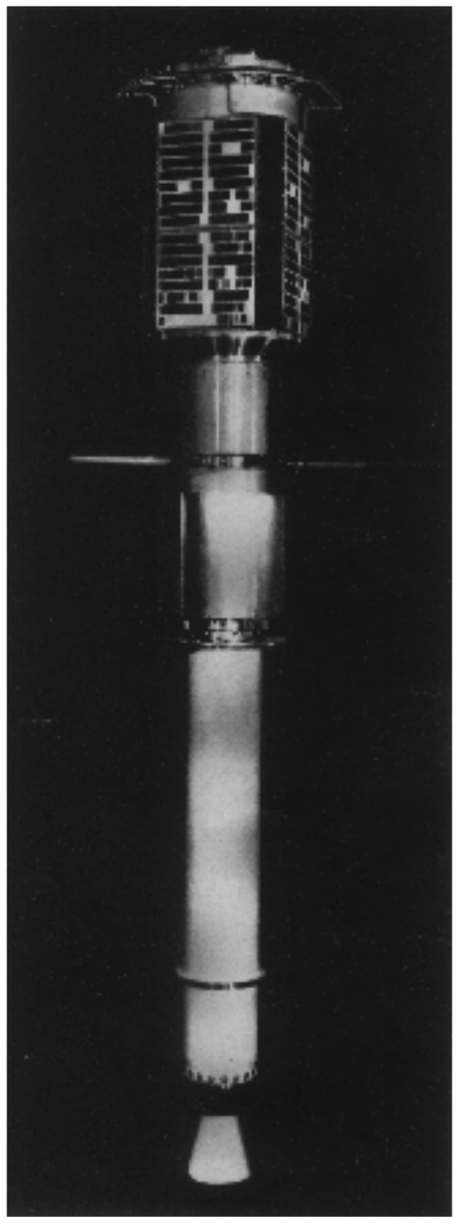
Meng Su

Pappalardo/Einstein fellow
MIT/Harvard

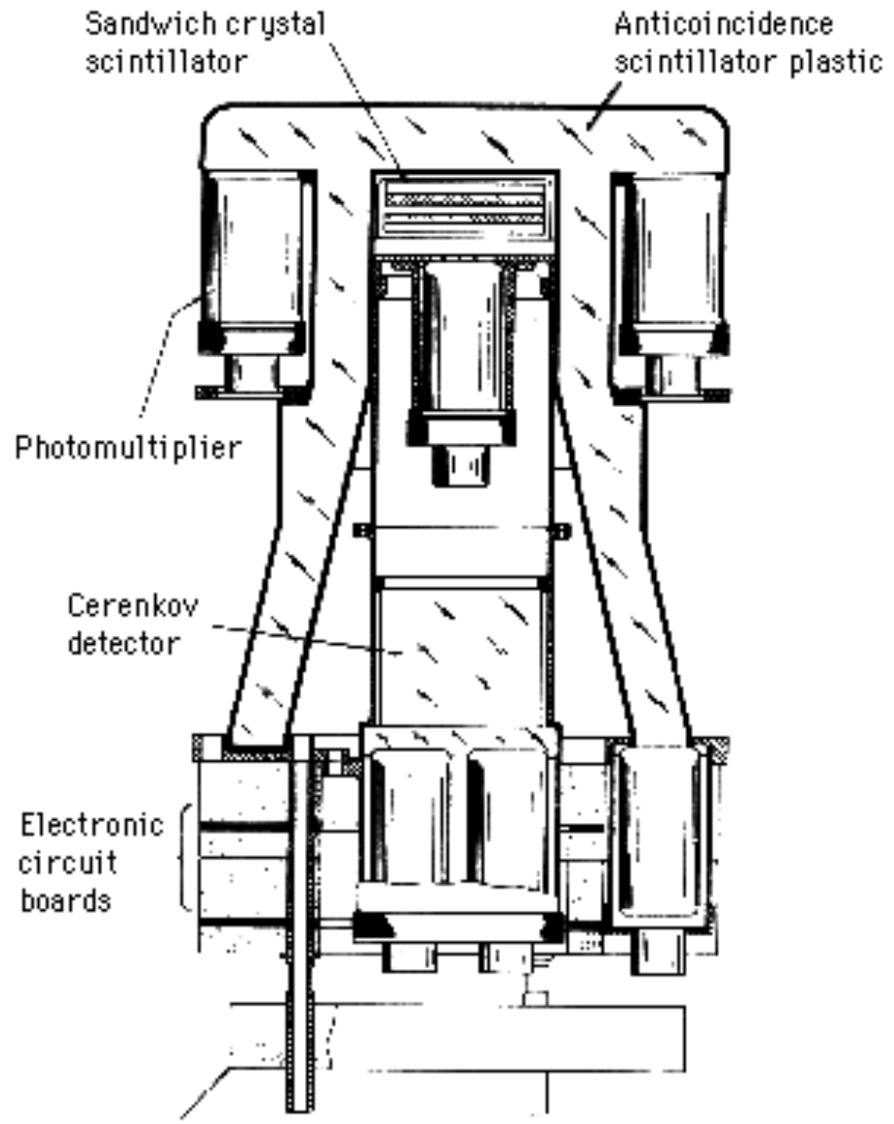
Second HERD Workshop, IHEP, Beijing
Dec. 2nd 2013

Explorer 11: the first gamma-ray detection satellite

(Launched: April 1961)



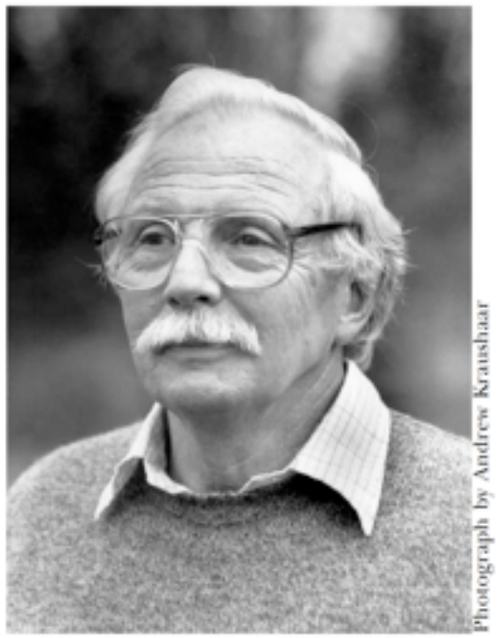
Credit:NASA



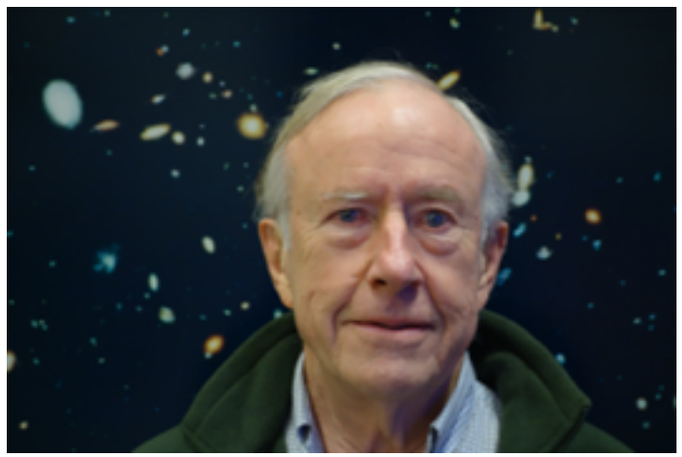
Credit:NASA

31 gamma-ray events in its 7 month operation!

Space gamma-ray astronomy was born at MIT



William L. Kraushaar (1920–2008)



George W. Clark

"... It is doubtful whether such a small number of particles have ever before been analyzed so intensively in an effort to extract information about the universe. The analysis is still continuing in our laboratory at the Massachusetts Institute of Technology, ..."

—William L. Kraushaar and George W. Clark", Scientific American, May 1962

"William Kraushaar and George W. Clark place an aluminum cover over the lead shielded, cosmic gamma ray equipment."

Credit unknown, from MIT Museum Collections

HIGH-ENERGY COSMIC GAMMA-RAY OBSERVATIONS FROM THE OSO-3 SATELLITE*

W. L. KRAUSHAAR,† G. W. CLARK, G. P. GARMIRE,‡ R. BORKEN, P. HIGBIE,§ C. LEONG, AND T. THORSOS

Laboratory for Nuclear Science,
Department of Physics and Center for Space Research,
Massachusetts Institute of Technology

Received 1972 March 27

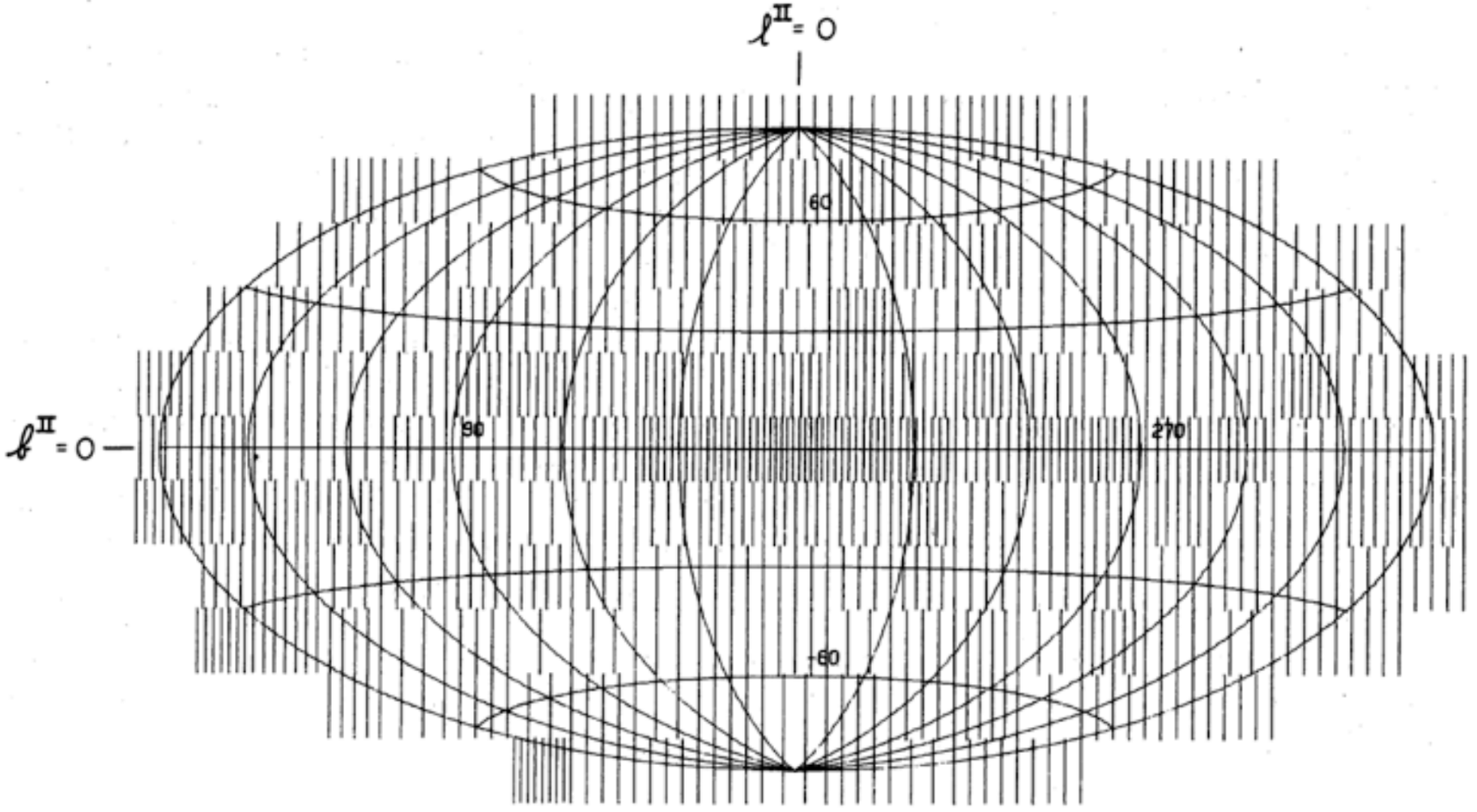
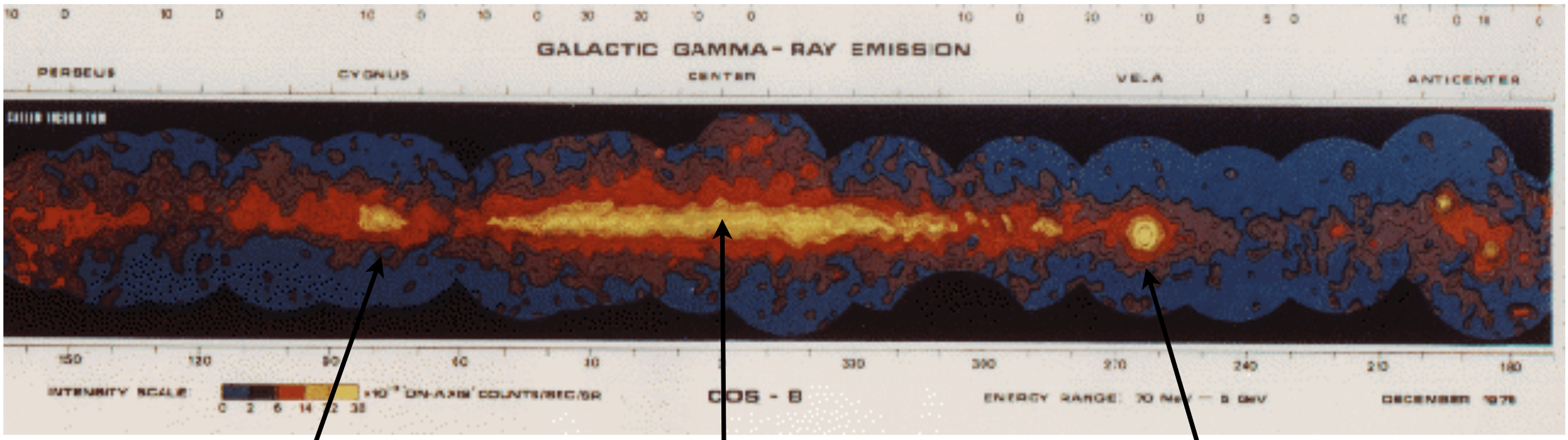


FIG. 8.—Sky map of the γ-ray intensity in galactic coordinates. The element of area on the map to which the formula given in the text applies is approximately 245 square degrees.

First gamma-ray sky map with 621 events >50 MeV

Galactic Plane from COS-B

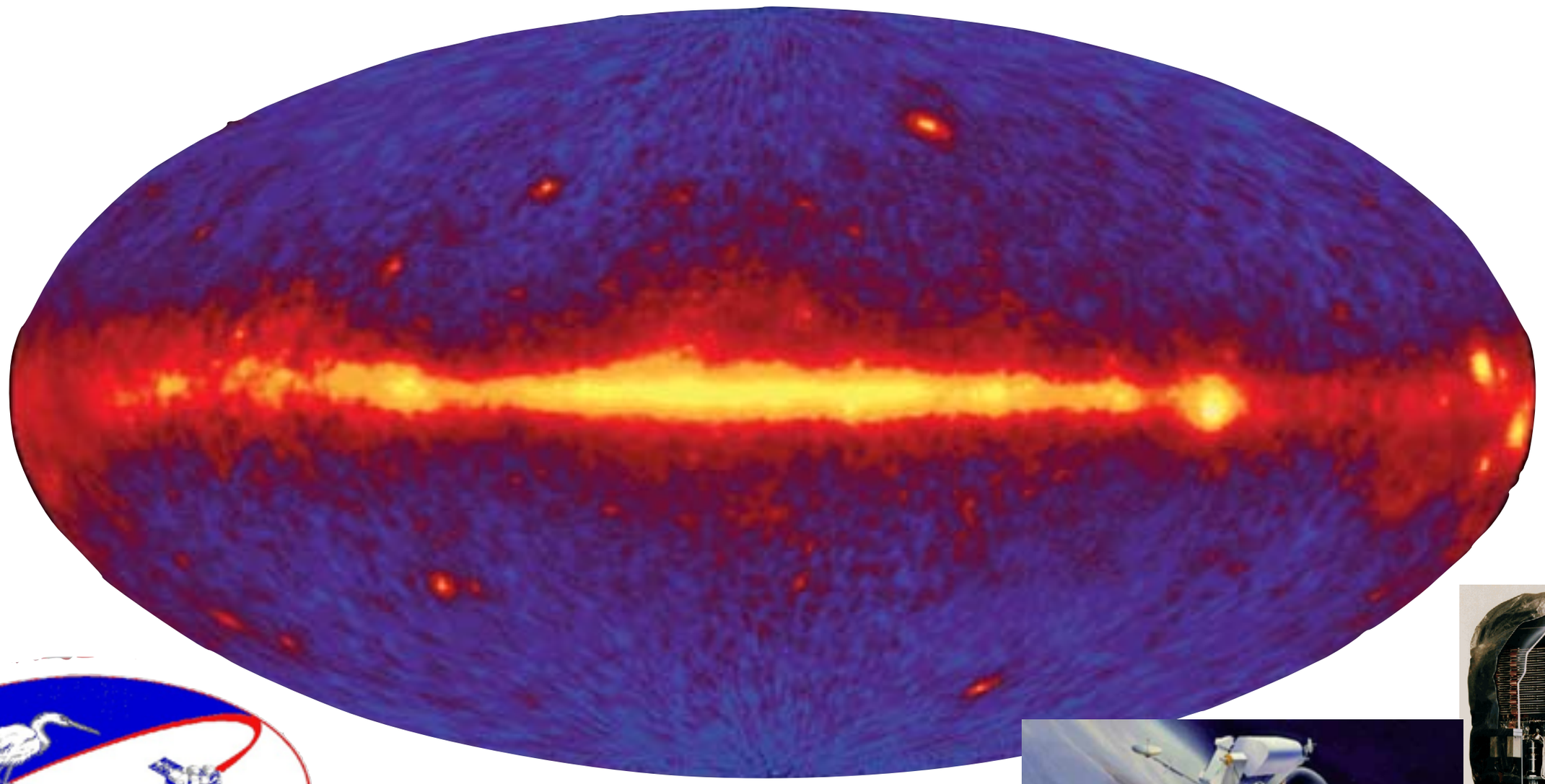


Cygnus region

Galactic center

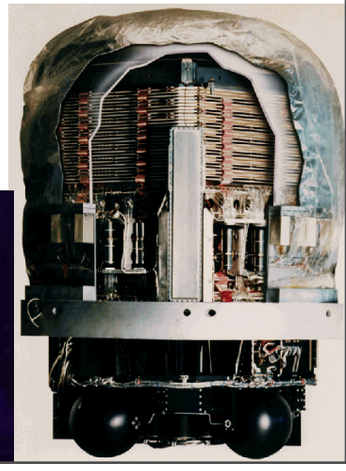
Vela pulsar

EGRET (1991-1996) full sky map (>100 MeV)

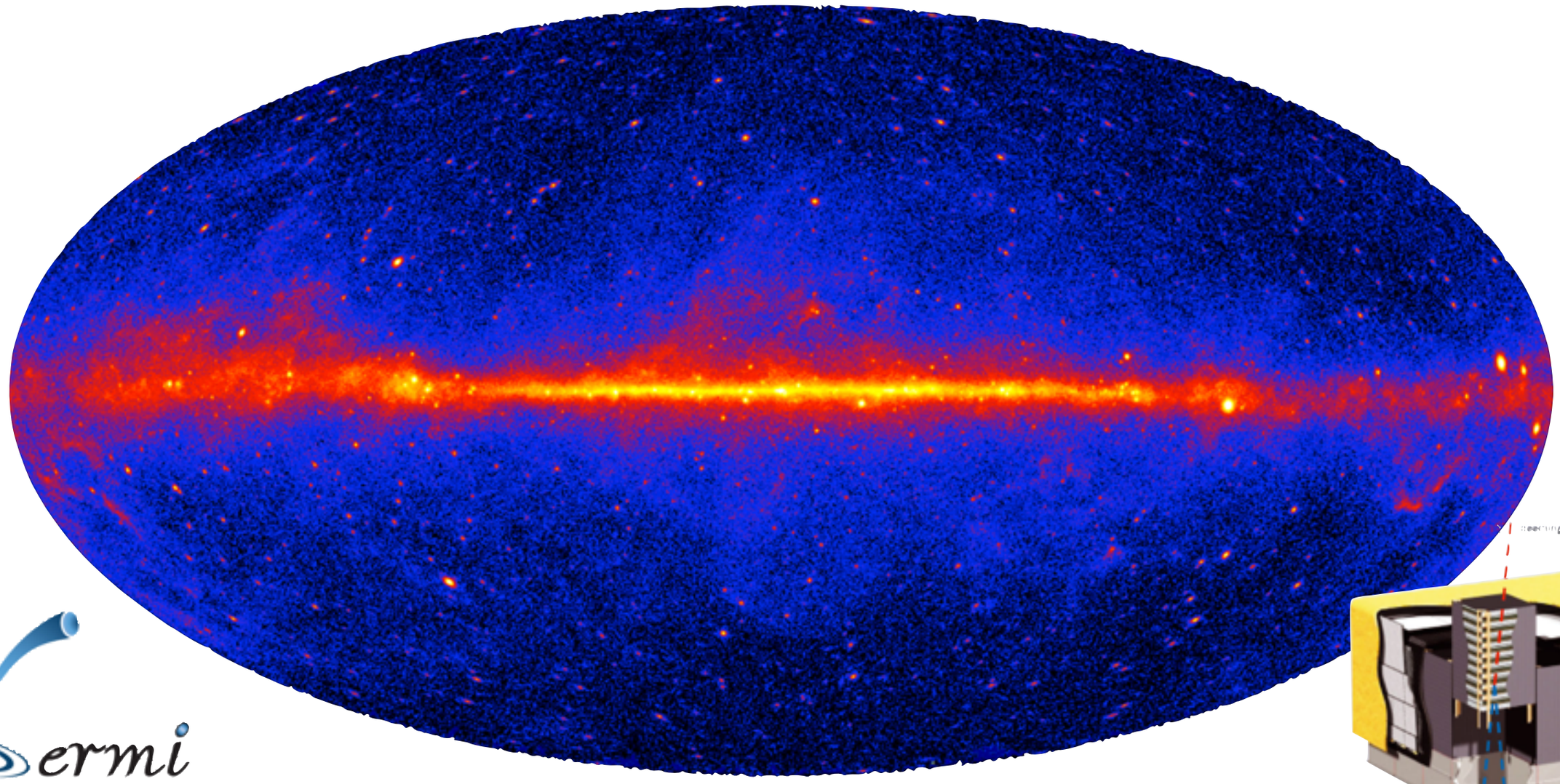


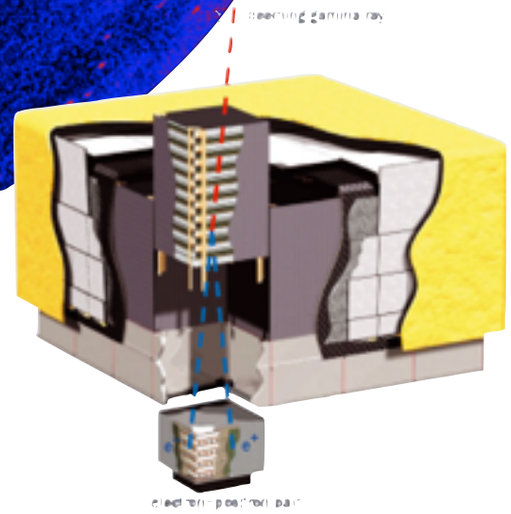
Egret
GAMMA RAY OBSERVATORY

Compton Gamma Ray Observatory



Fermi-LAT (2008 -) full sky map (>1GeV)





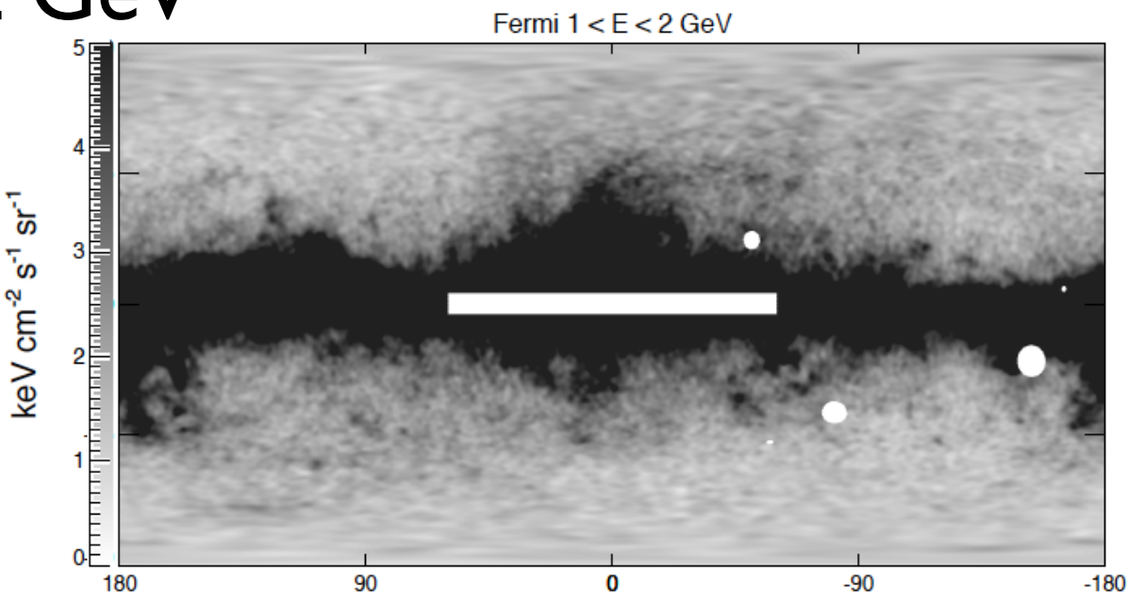
Gamma-ray Space Telescope


National Aeronautics and Space Administration
NASA
Fermi
Gamma-ray Space Telescope
www.nasa.gov/fermi

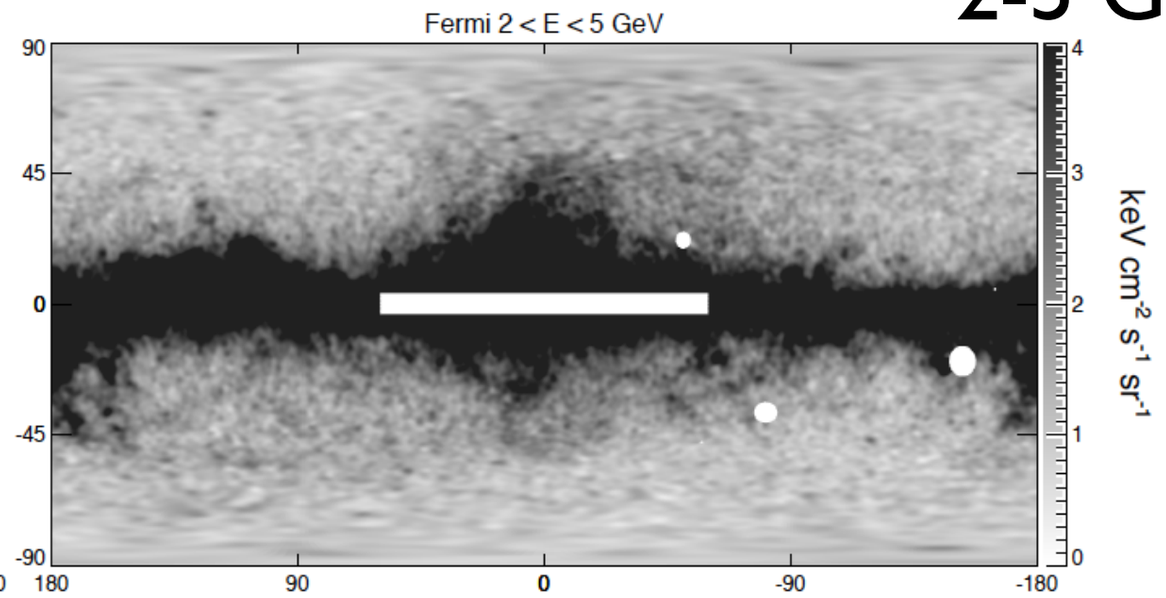

Credit:NASA

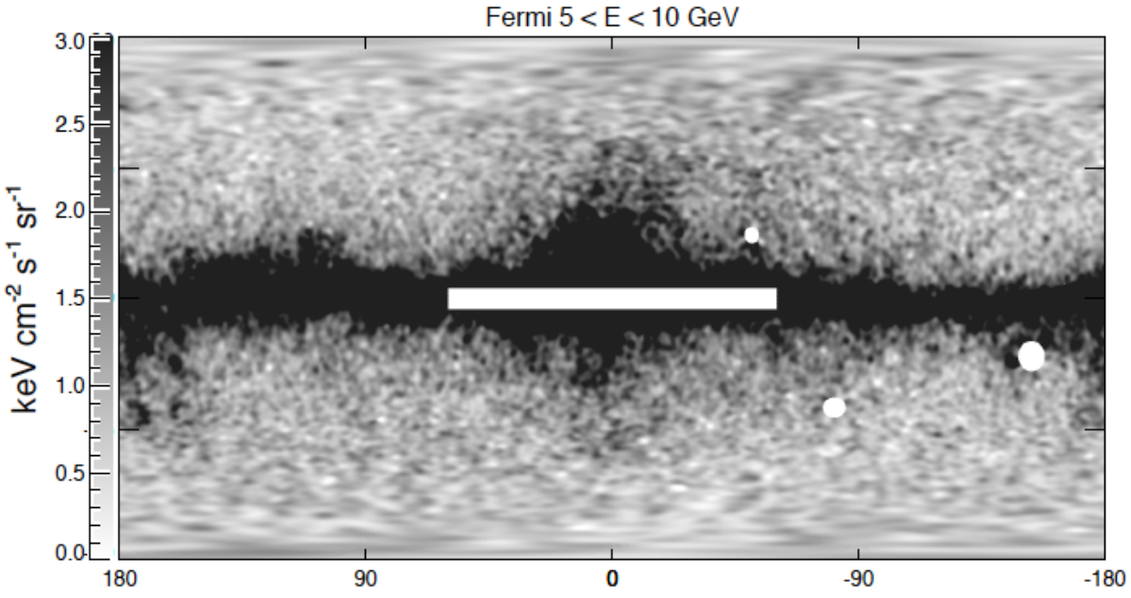
Fermi 1.6 year all-sky gamma-ray maps at different energy

1-2 GeV

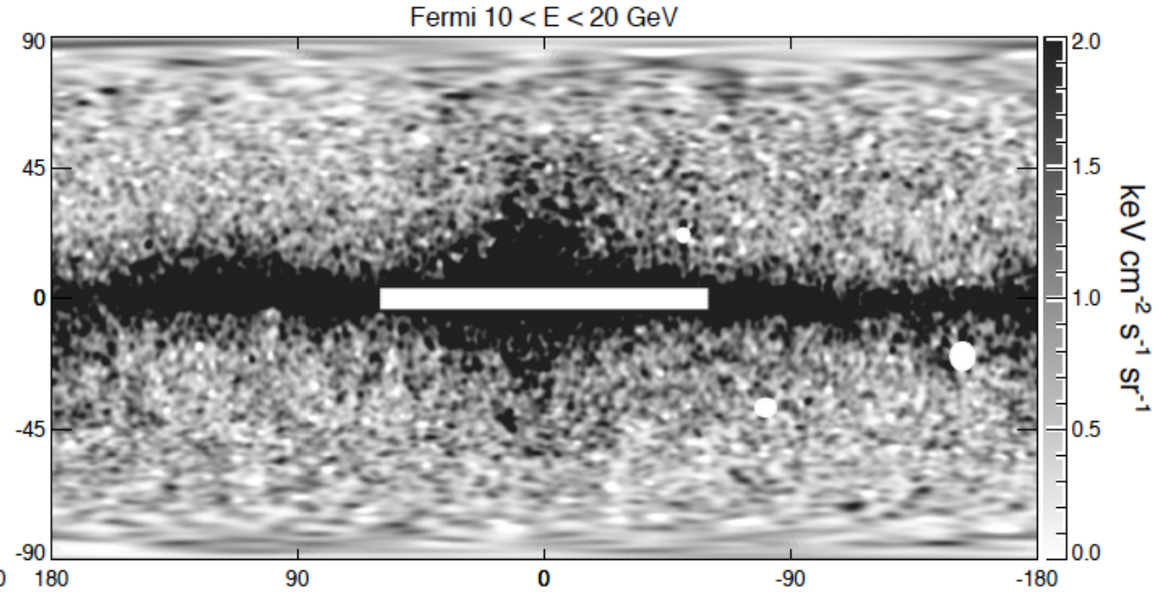


2-5 GeV





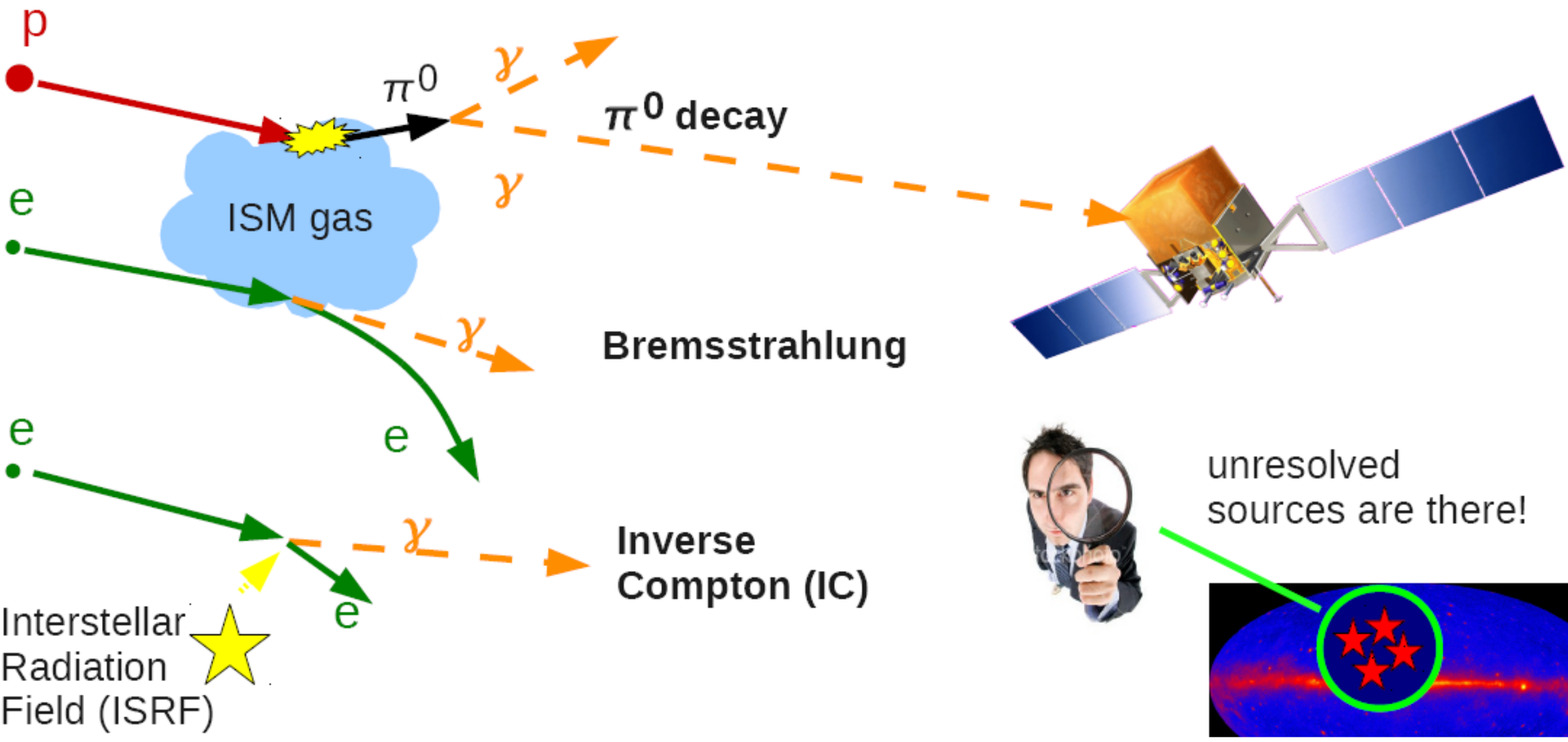
5-10 GeV



10-20 GeV

MS, Slatyer, Finkbeiner (2010), with 200+ citations

Galactic Diffuse Gamma-ray Emission

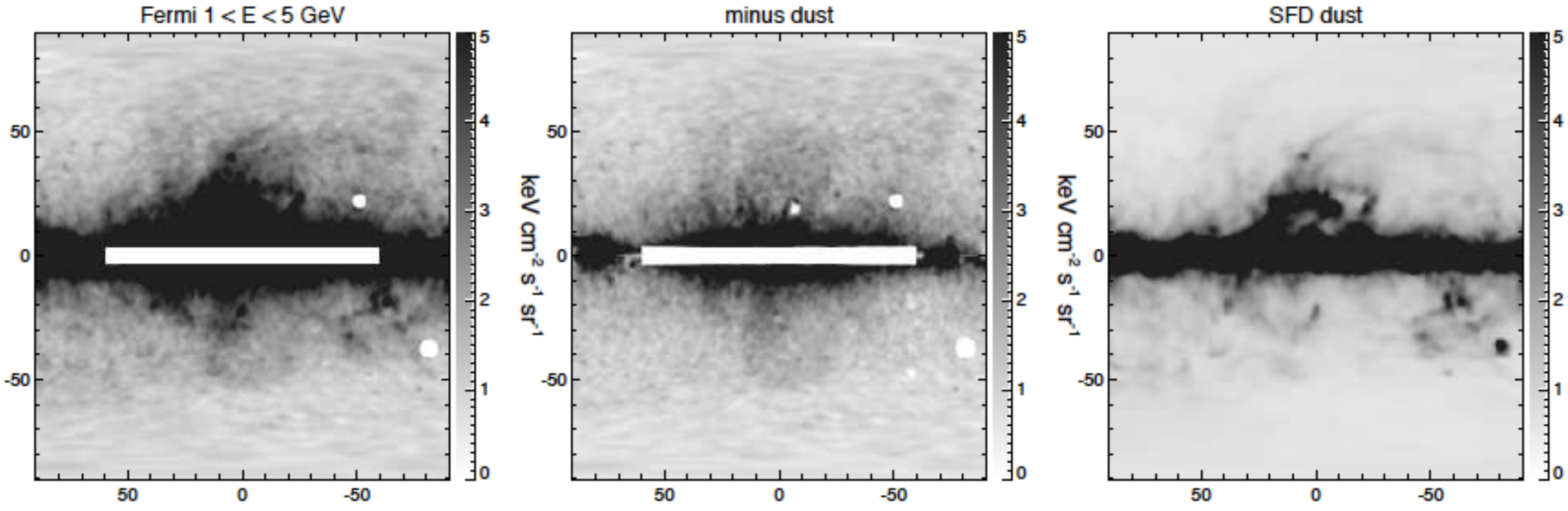


Galactic gas map as a tracer of diffuse π^0 gamma-rays

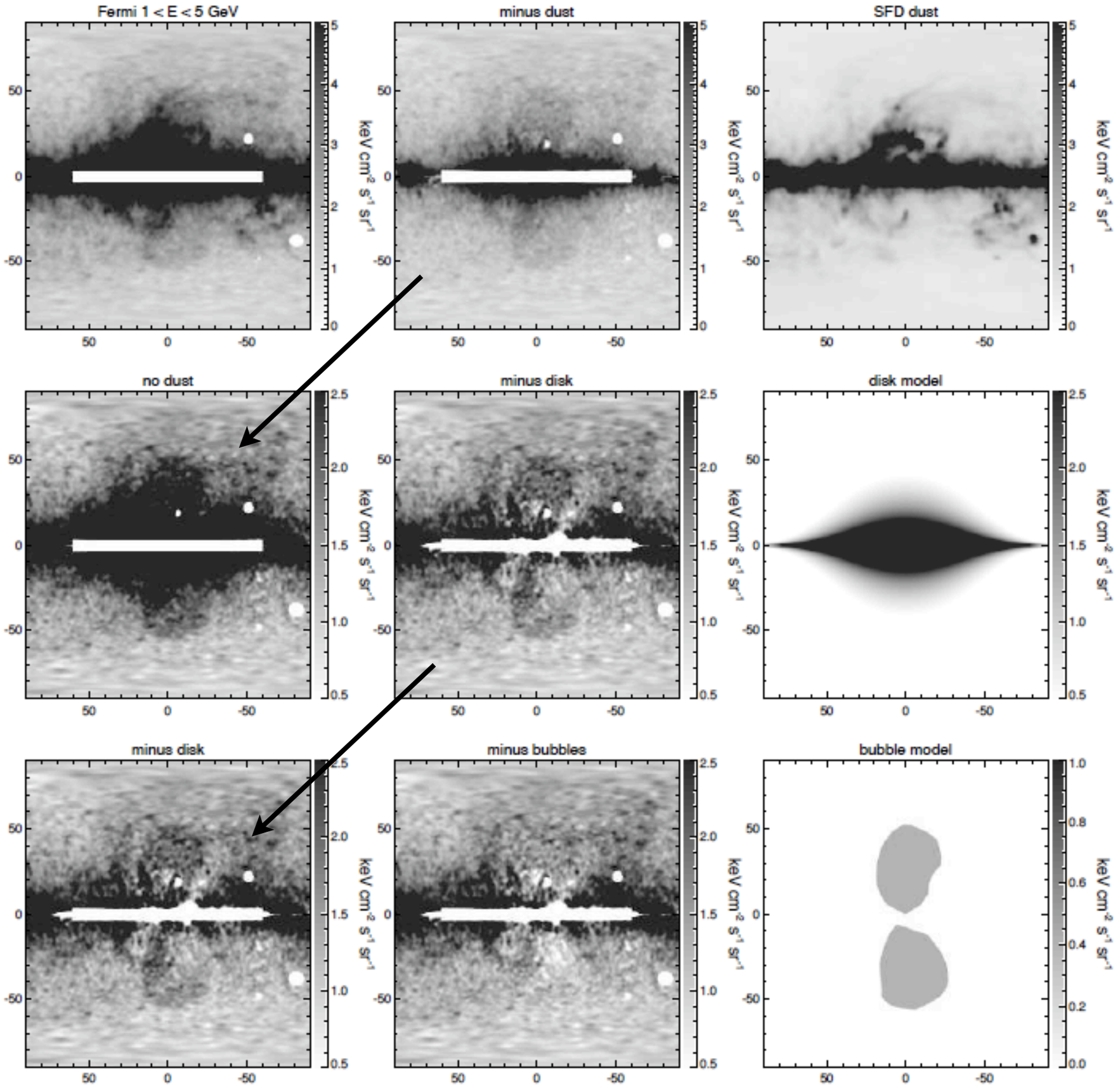
Gamma-ray

Residual

Gas map

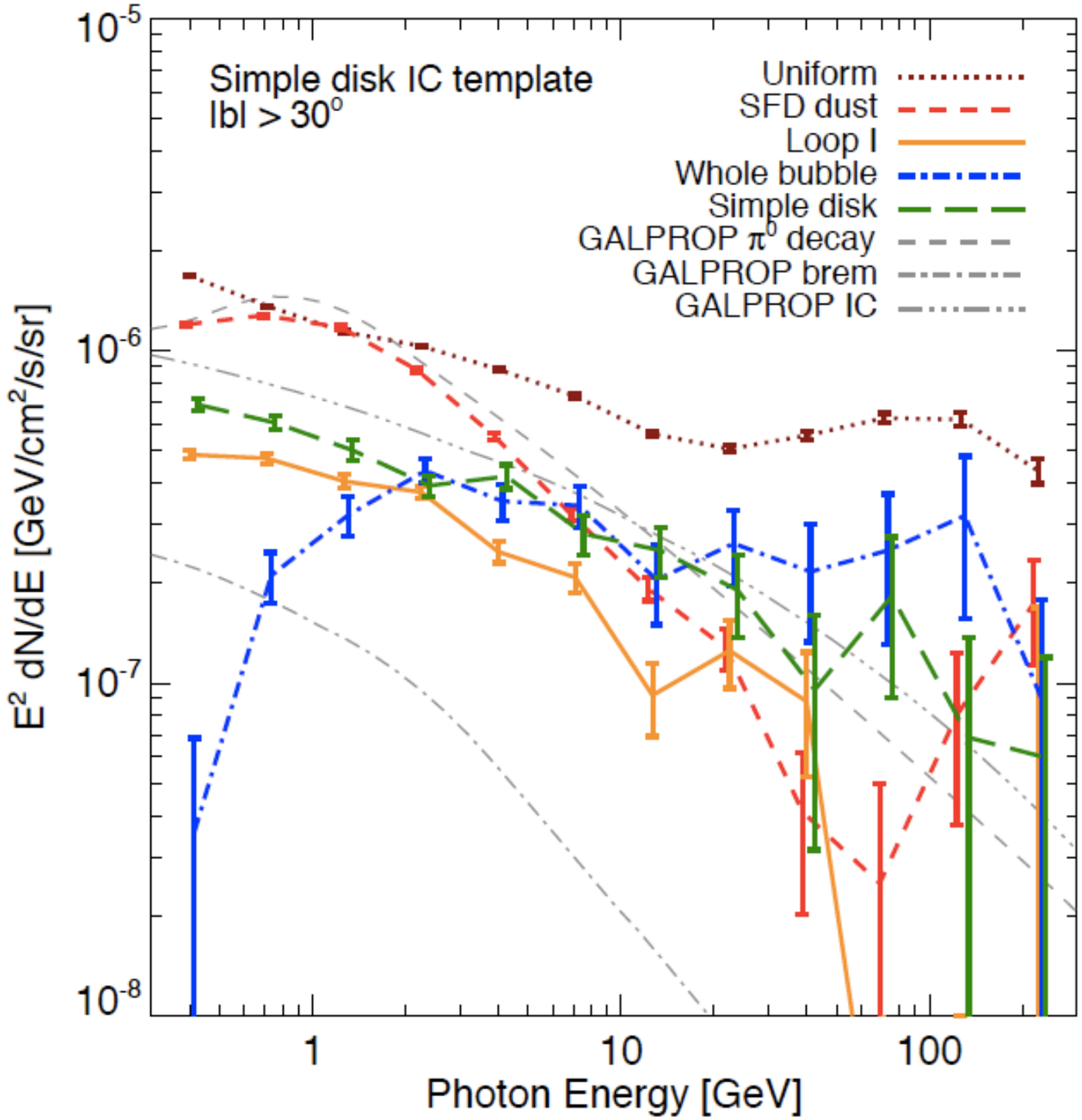


MS, Slatyer, Finkbeiner (2010)



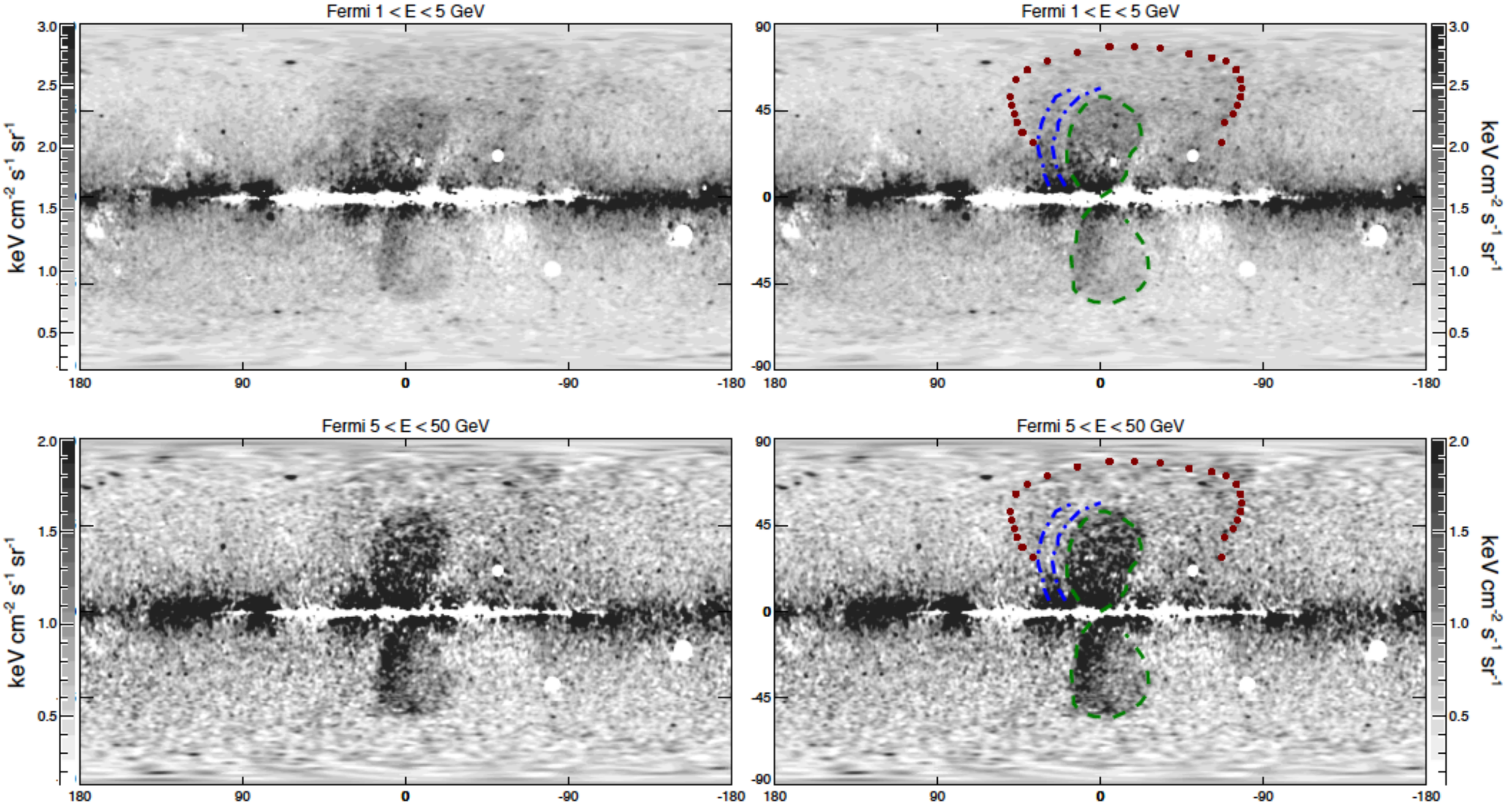
MS, Slatyer, Finkbeiner (2010)

Energy spectrum of FB



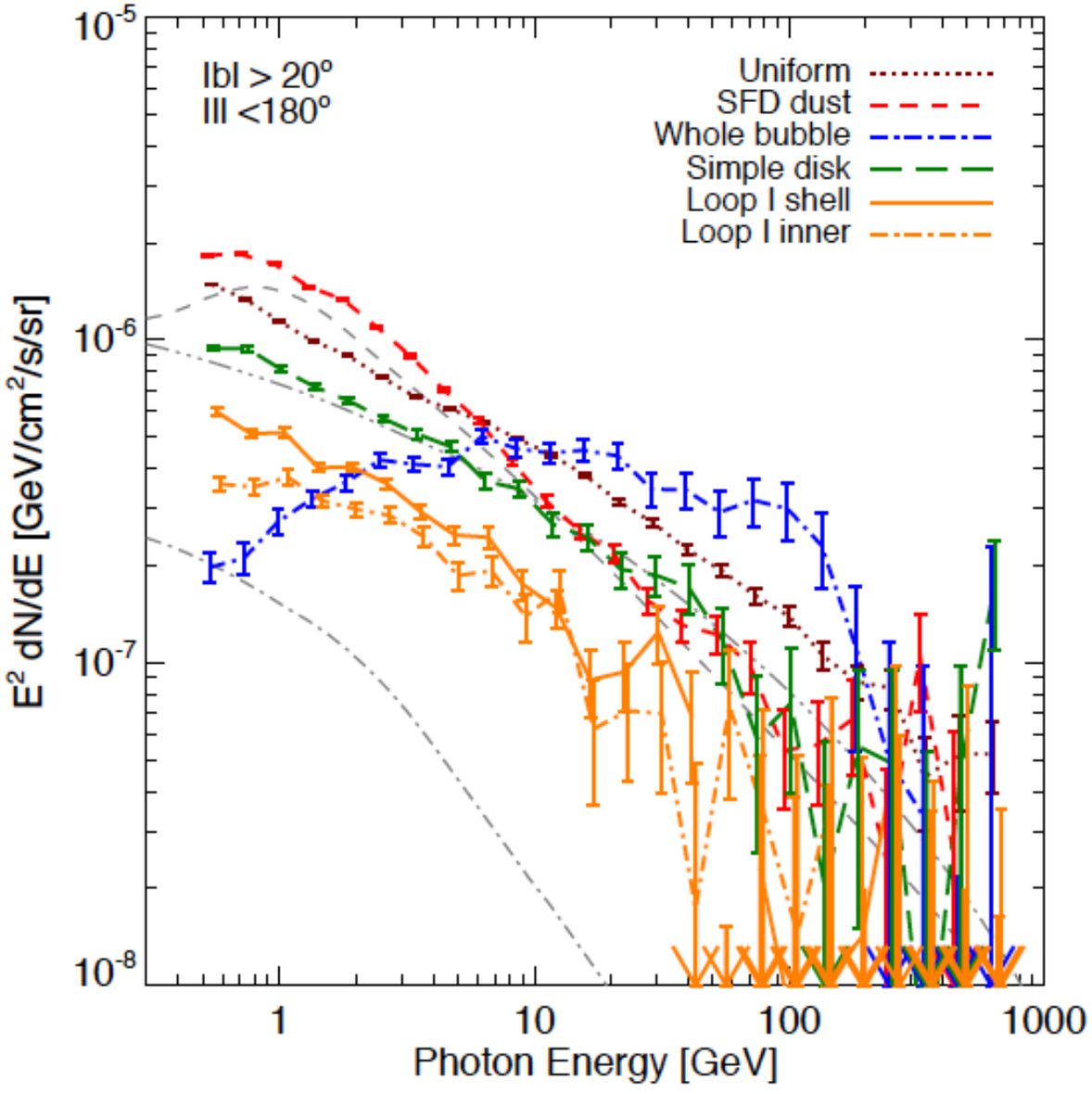
MS, Slatyer, Finkbeiner (2010)

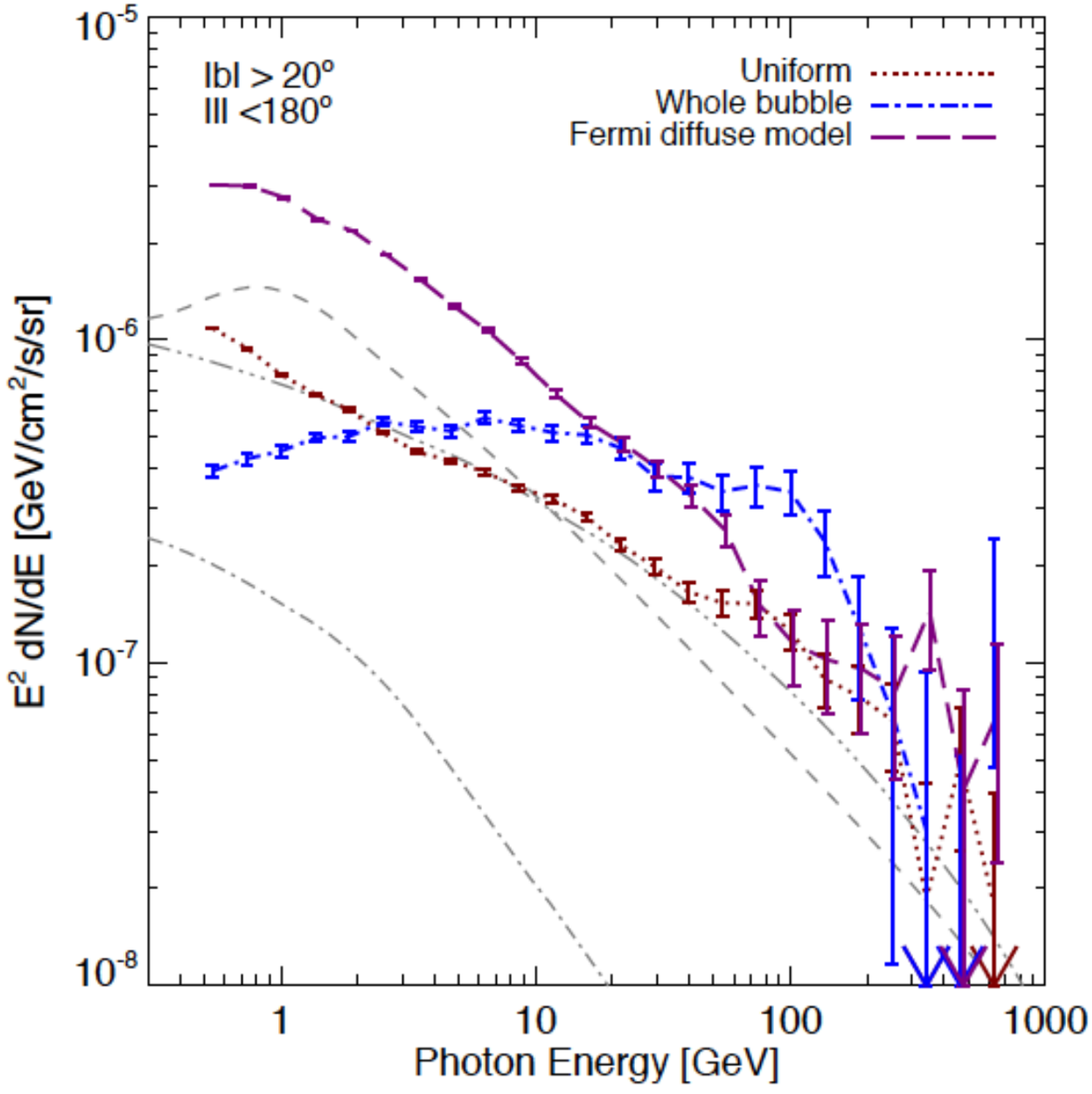
FB from five years Fermi data



MS & Finkbeiner (2013)

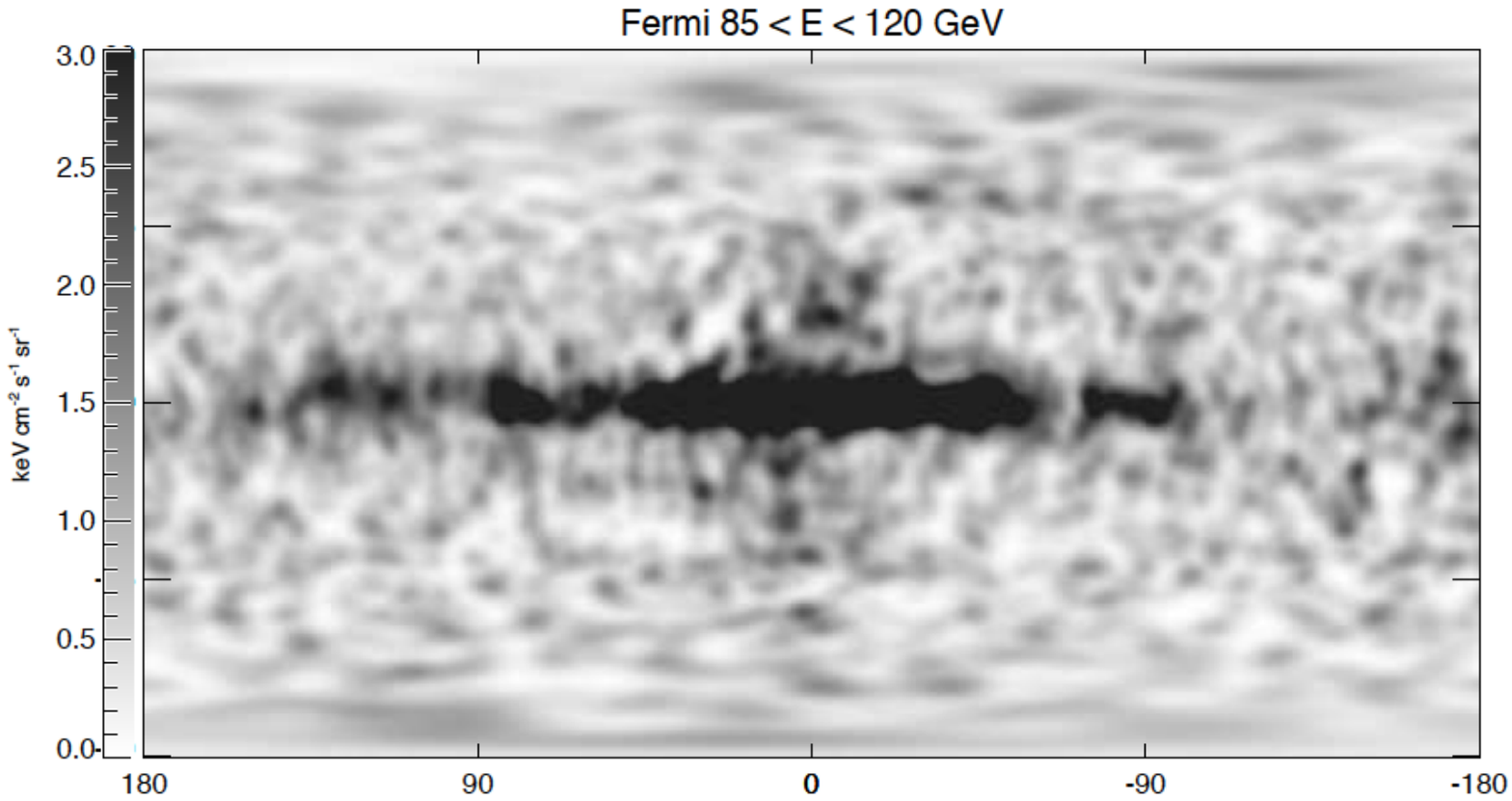
FB has a hard spectrum with high energy cut-off



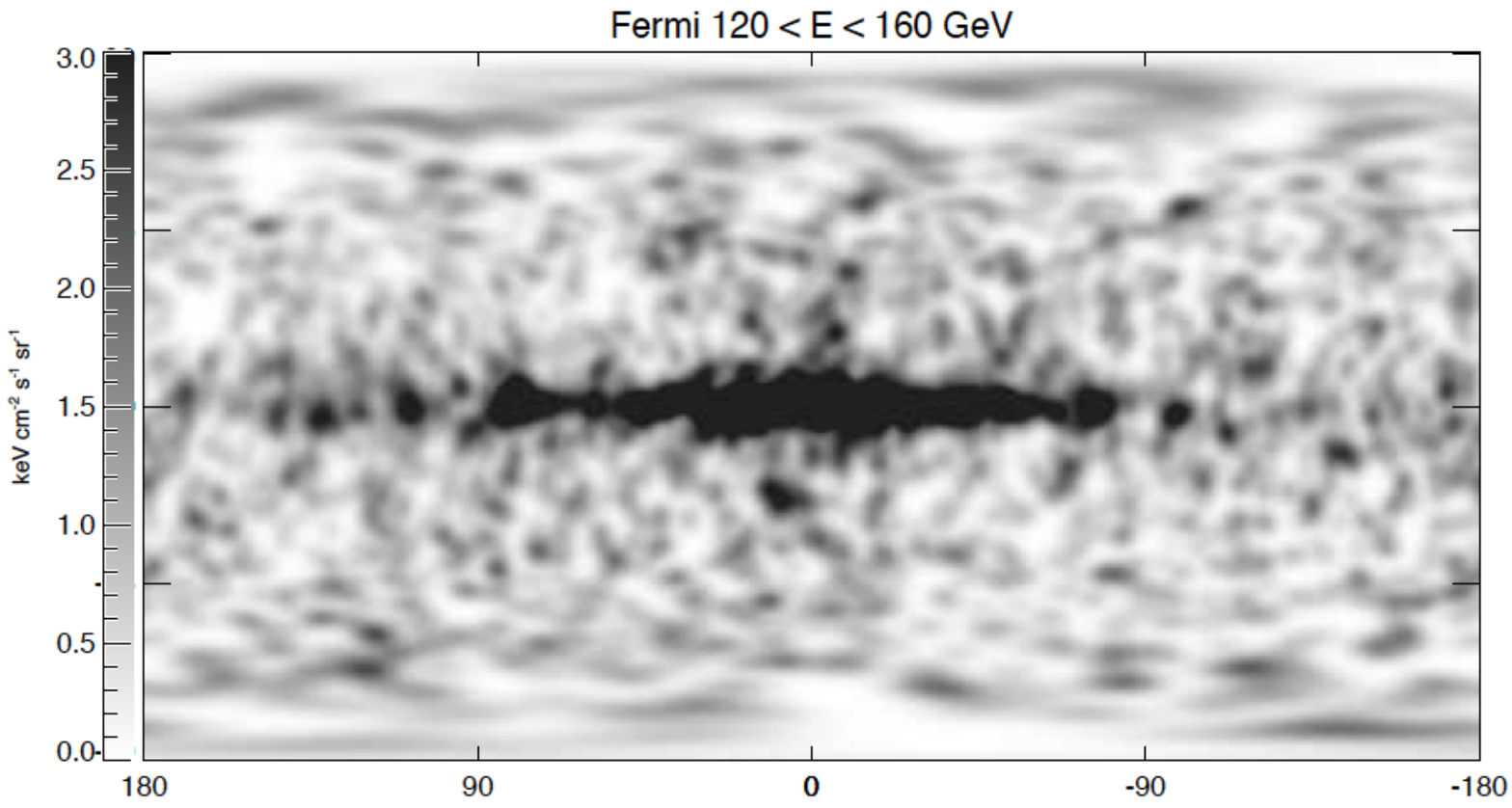


MS & Finkbeiner (2013)

- 85-120 GeV:

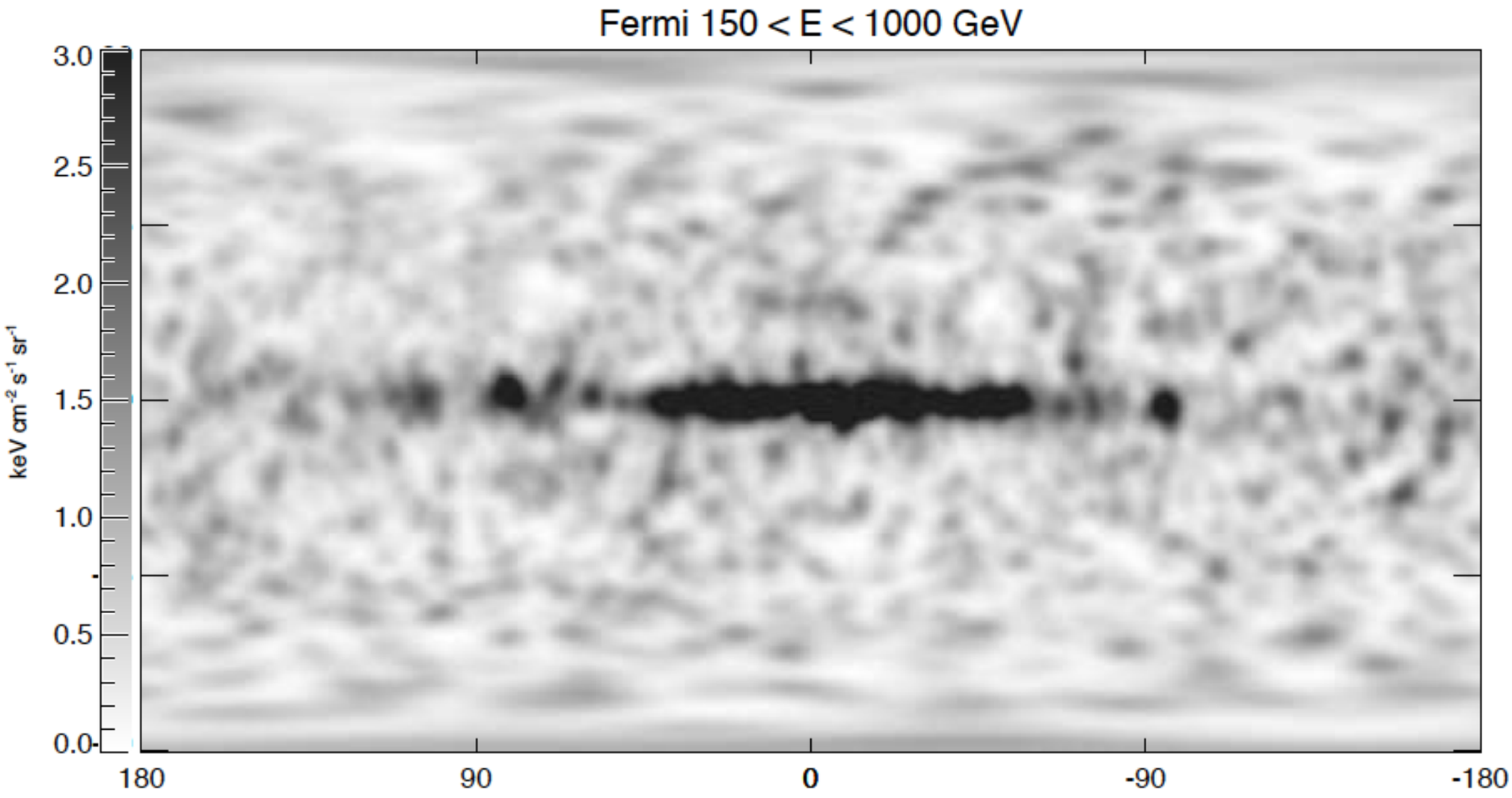


- 120-160 GeV



MS & Finkbeiner (2013)

FB disappears at >150 GeV



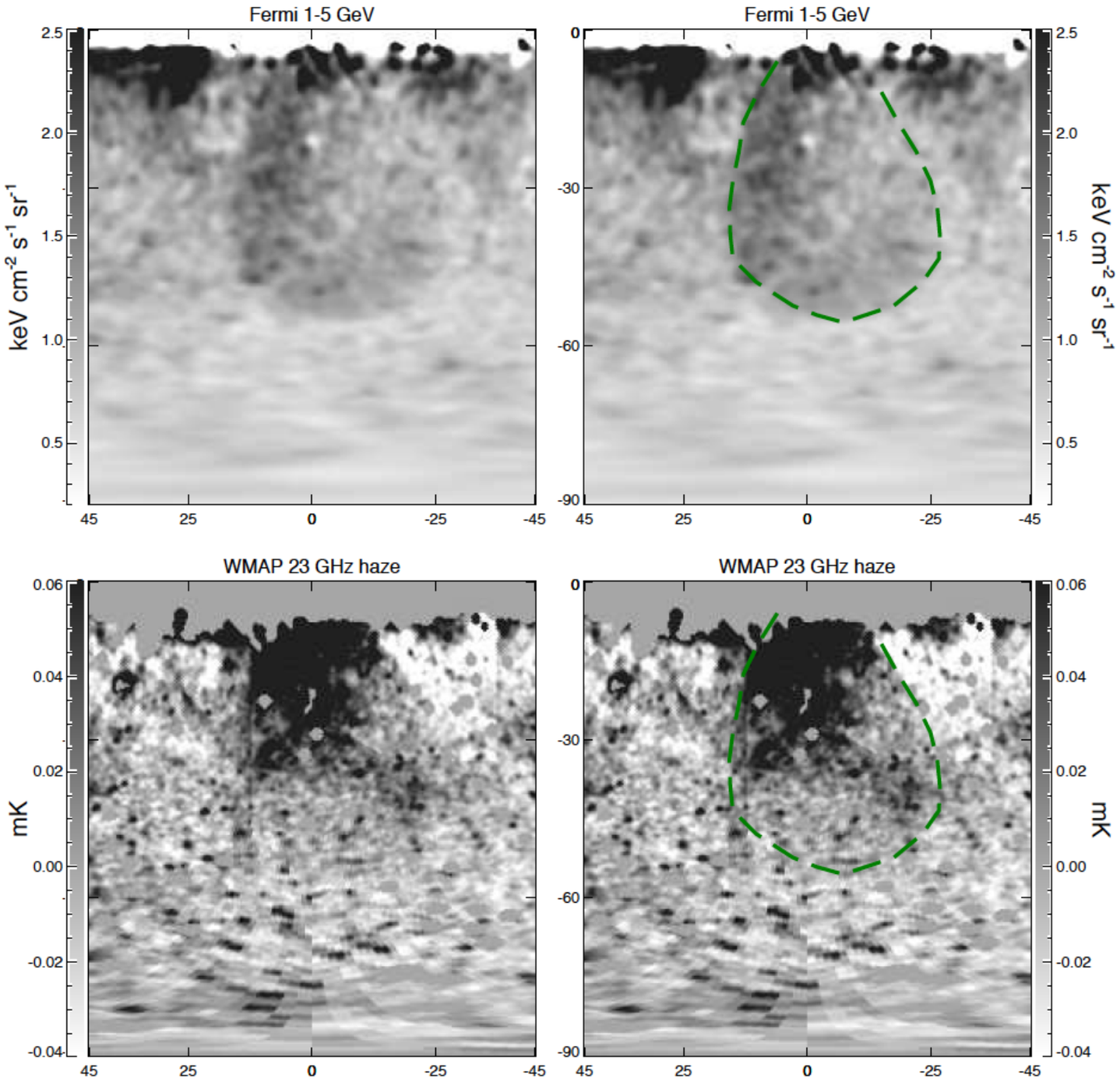
MS & Finkbeiner (2013)

How about other wavelength?

- Microwave
- X-ray
- Radio (magnetic field of FB)

FB has its microwave counterpart

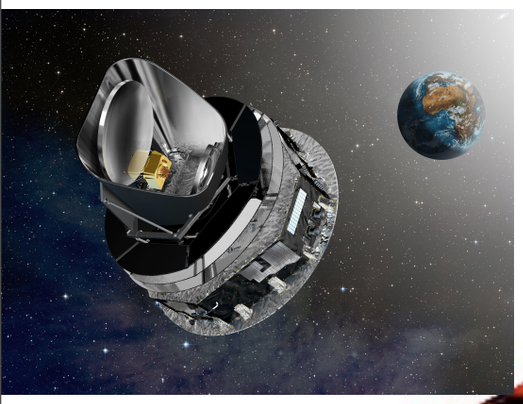
FB 1-5 GeV:

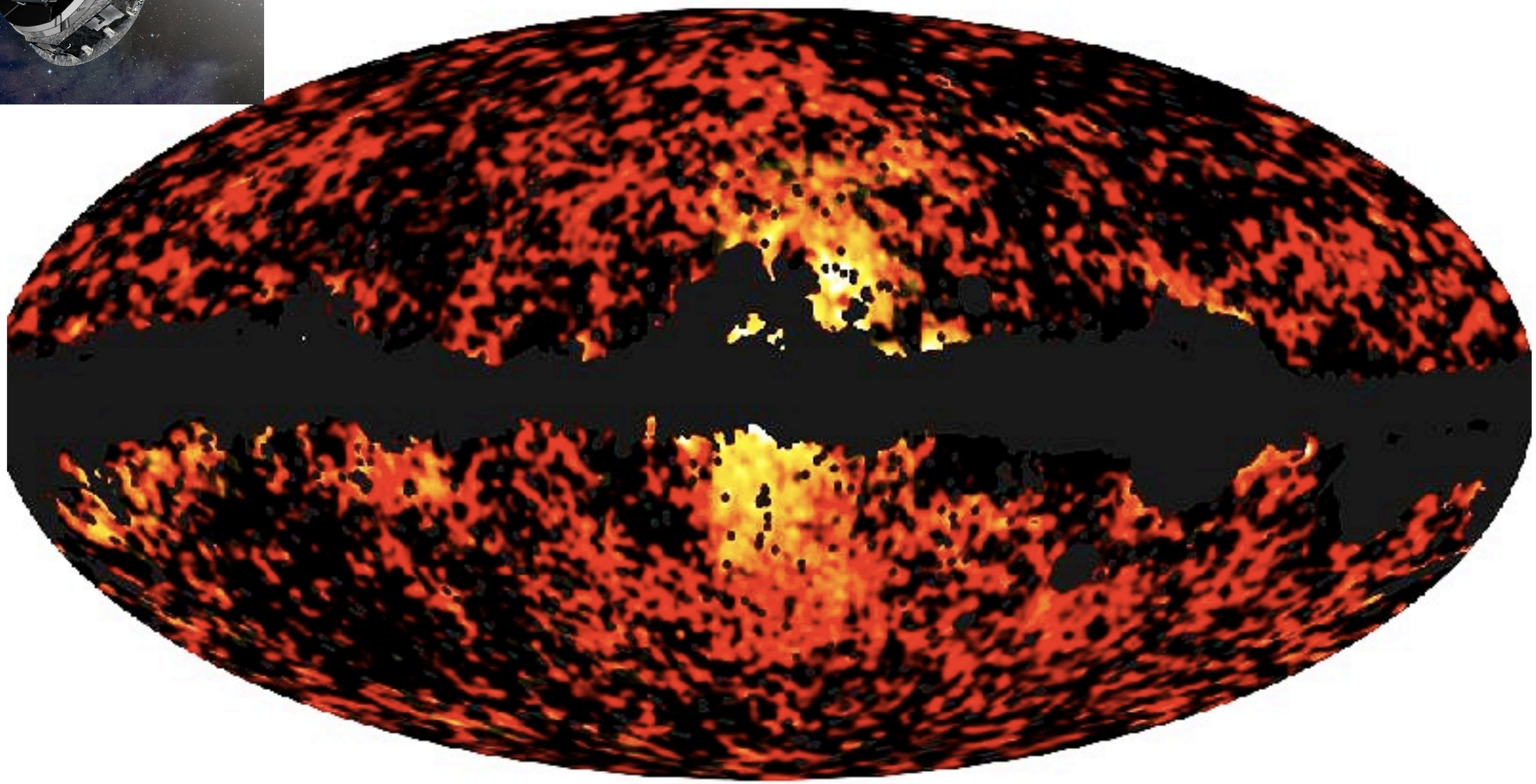


WMAP 23 GHz:

(discovered in 2003 by D.Finkbeiner)

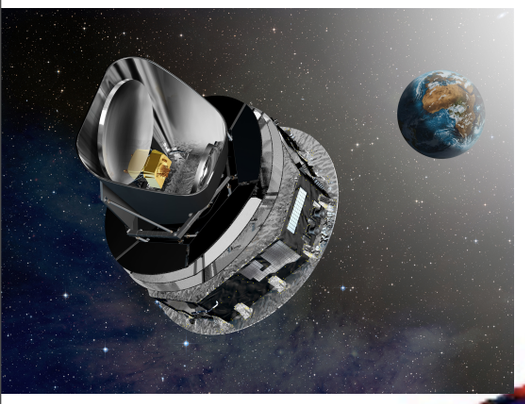
Planck 30 and 44 GHz haze map

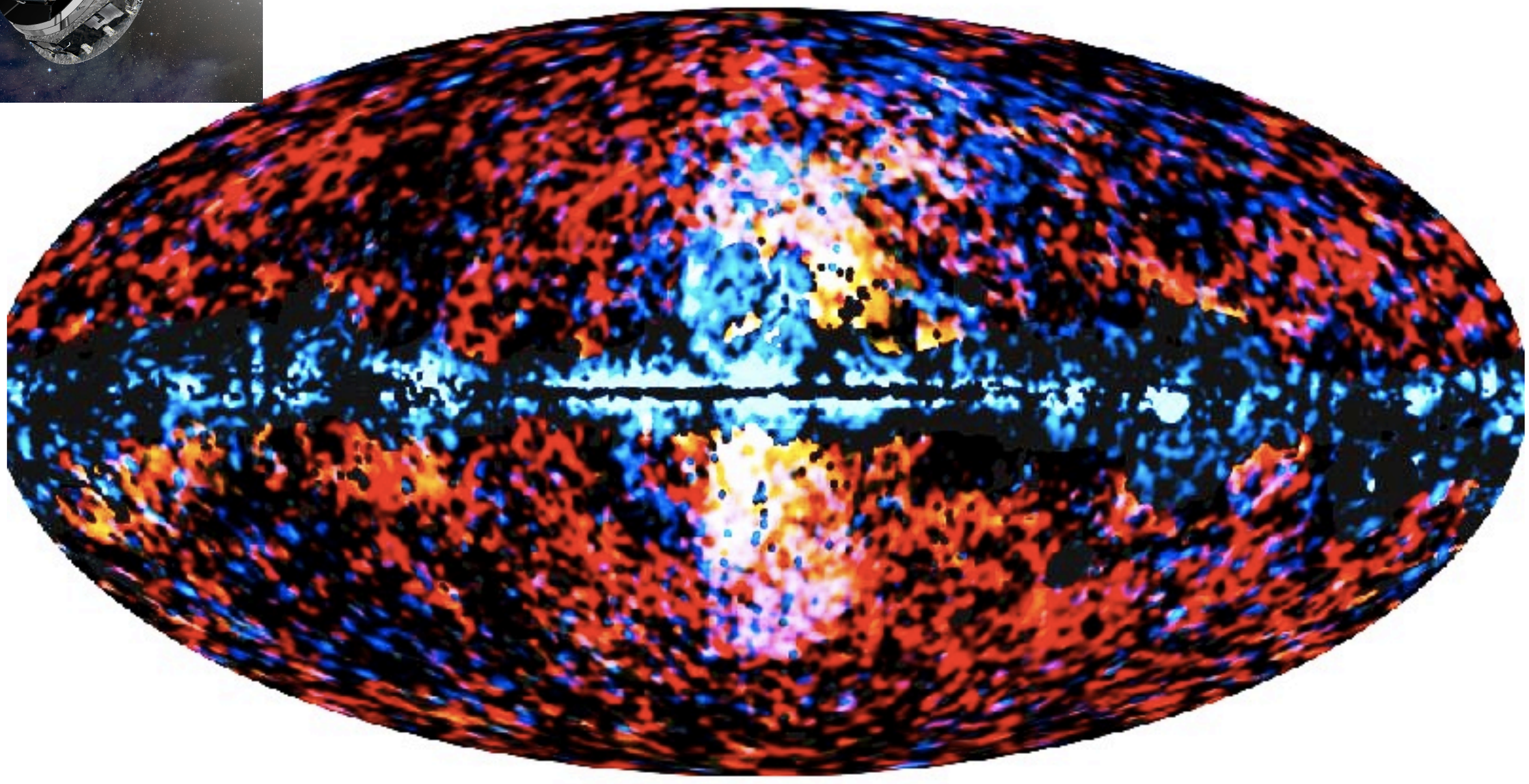




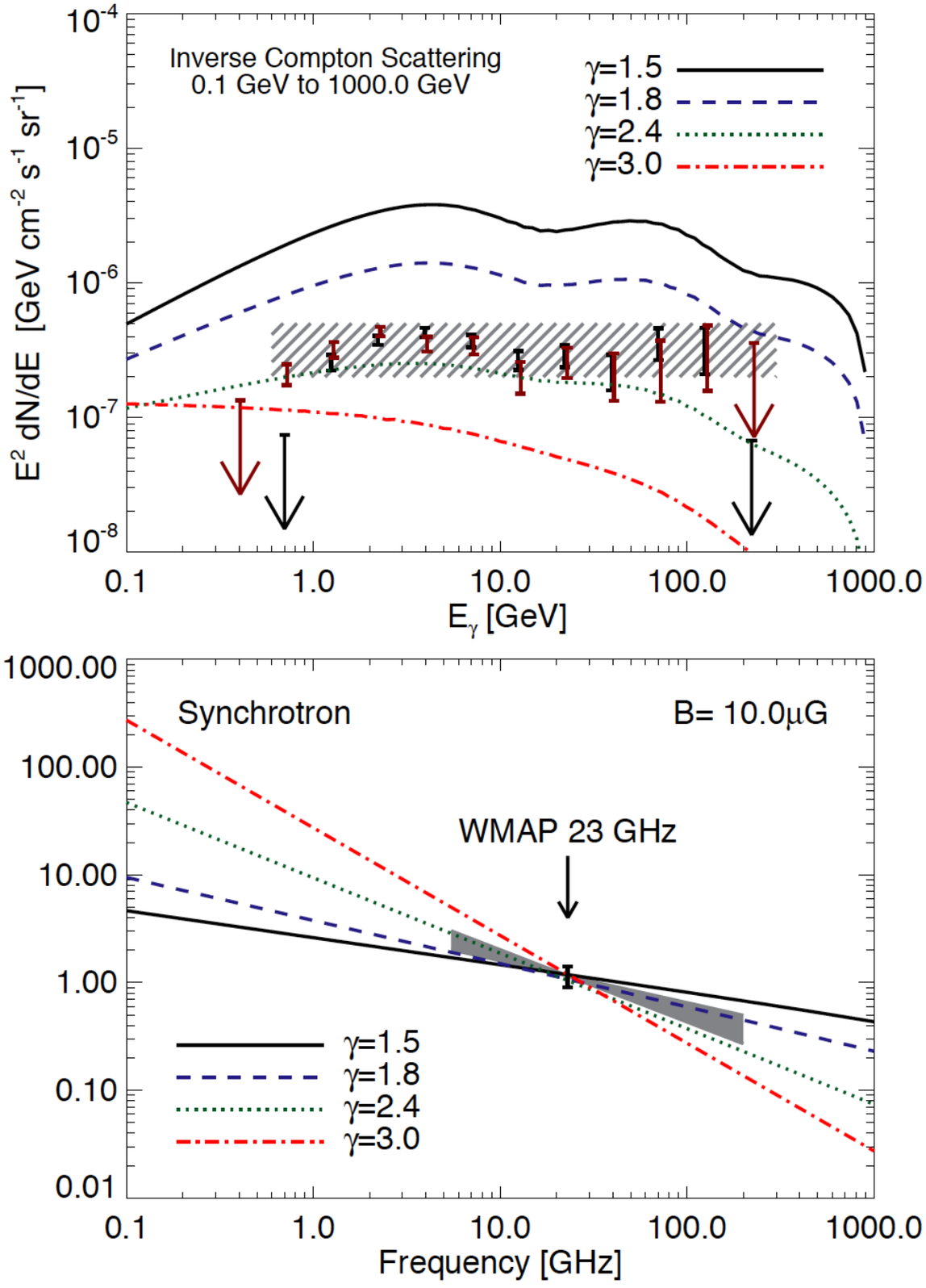
Credits: ESA/Planck Collaboration.

Haze superimposed over the FB





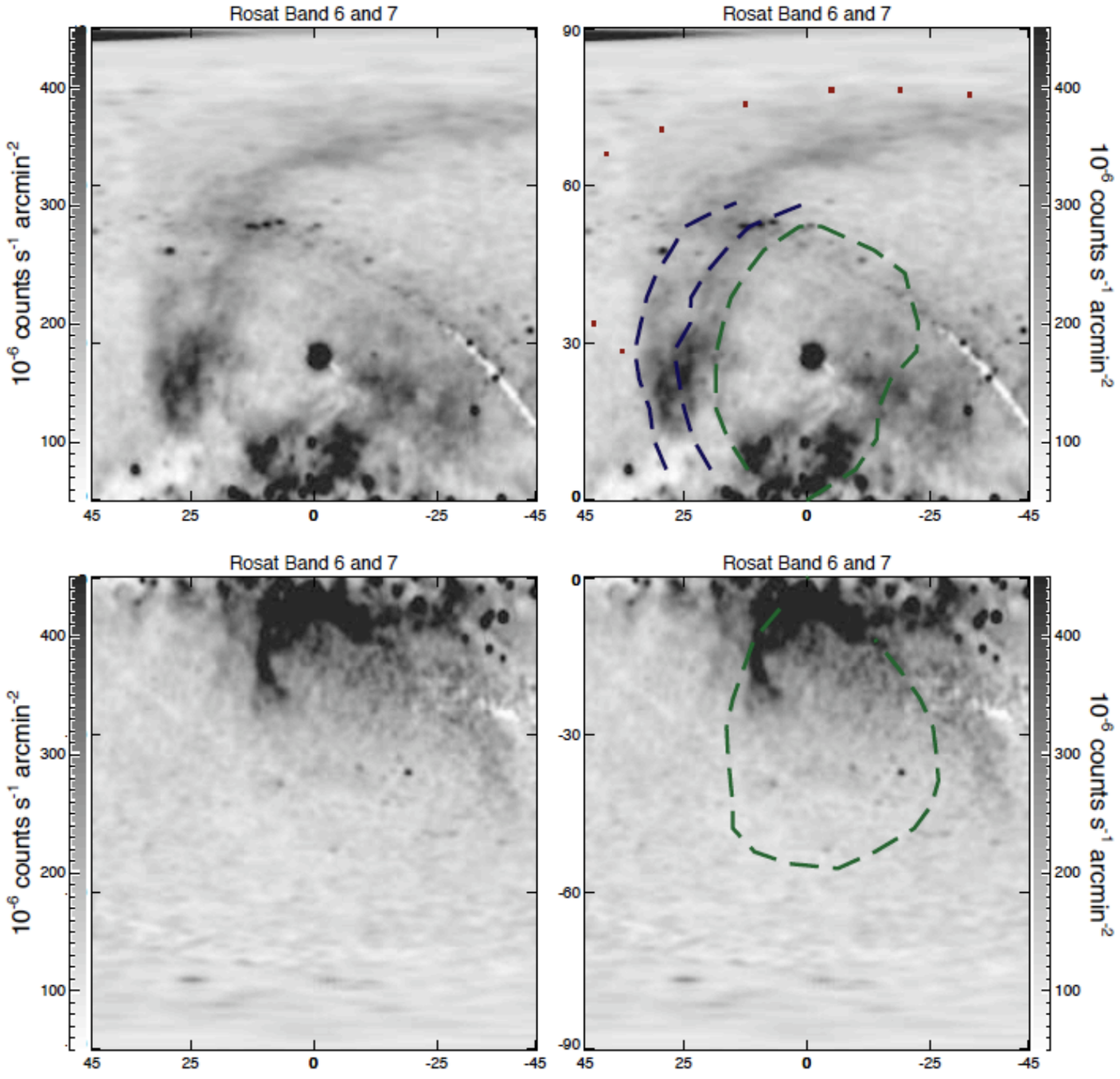
Credits: ESA/Planck Collaboration.



Not only the morphology, the spectrum of both "gamma-ray bubble" and "microwave haze" can be explained by a single power-law CR electrons

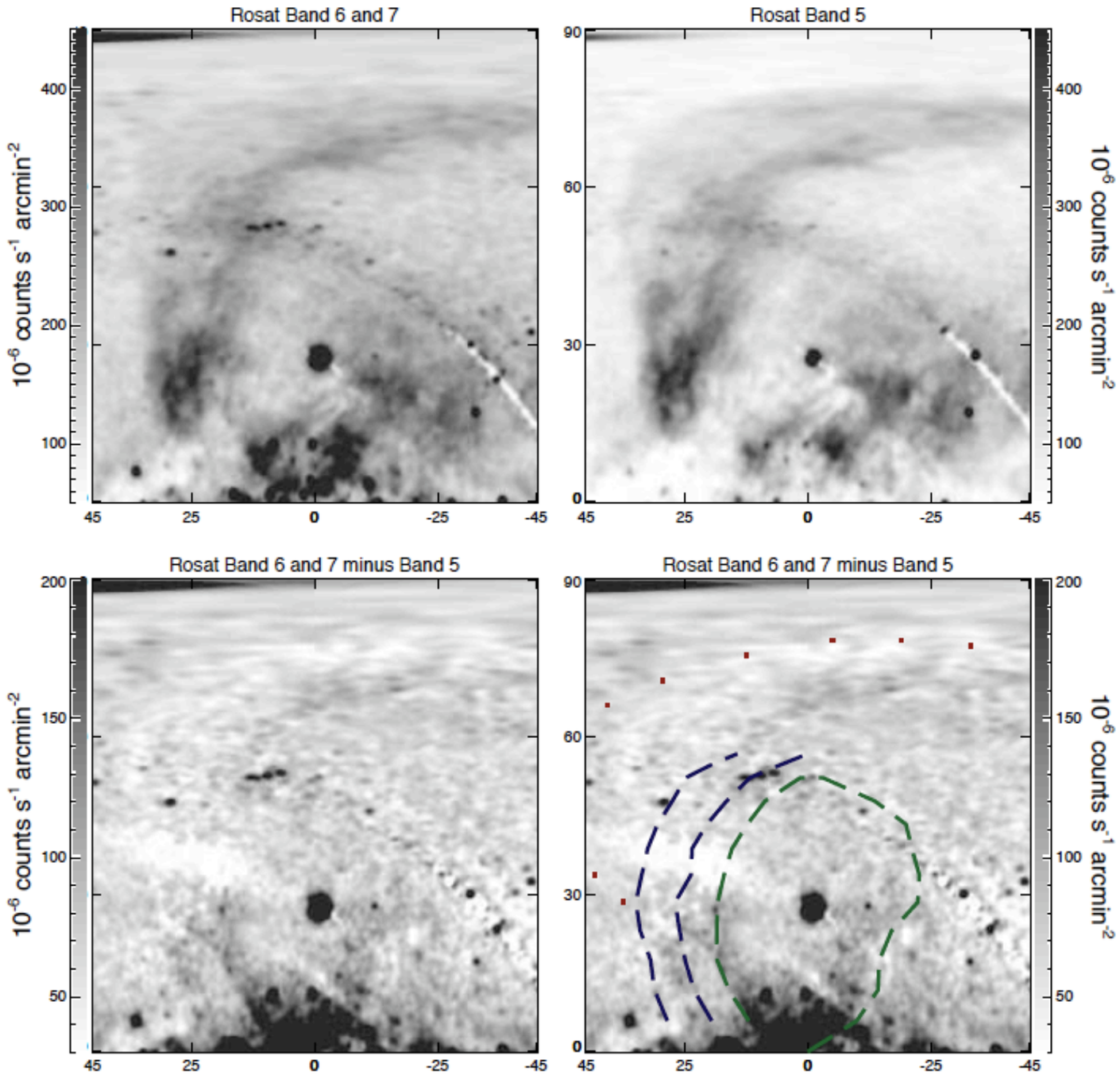
MS, Slatyer, Finkbeiner (2010)

ROSAT X-ray at 1.5 KeV



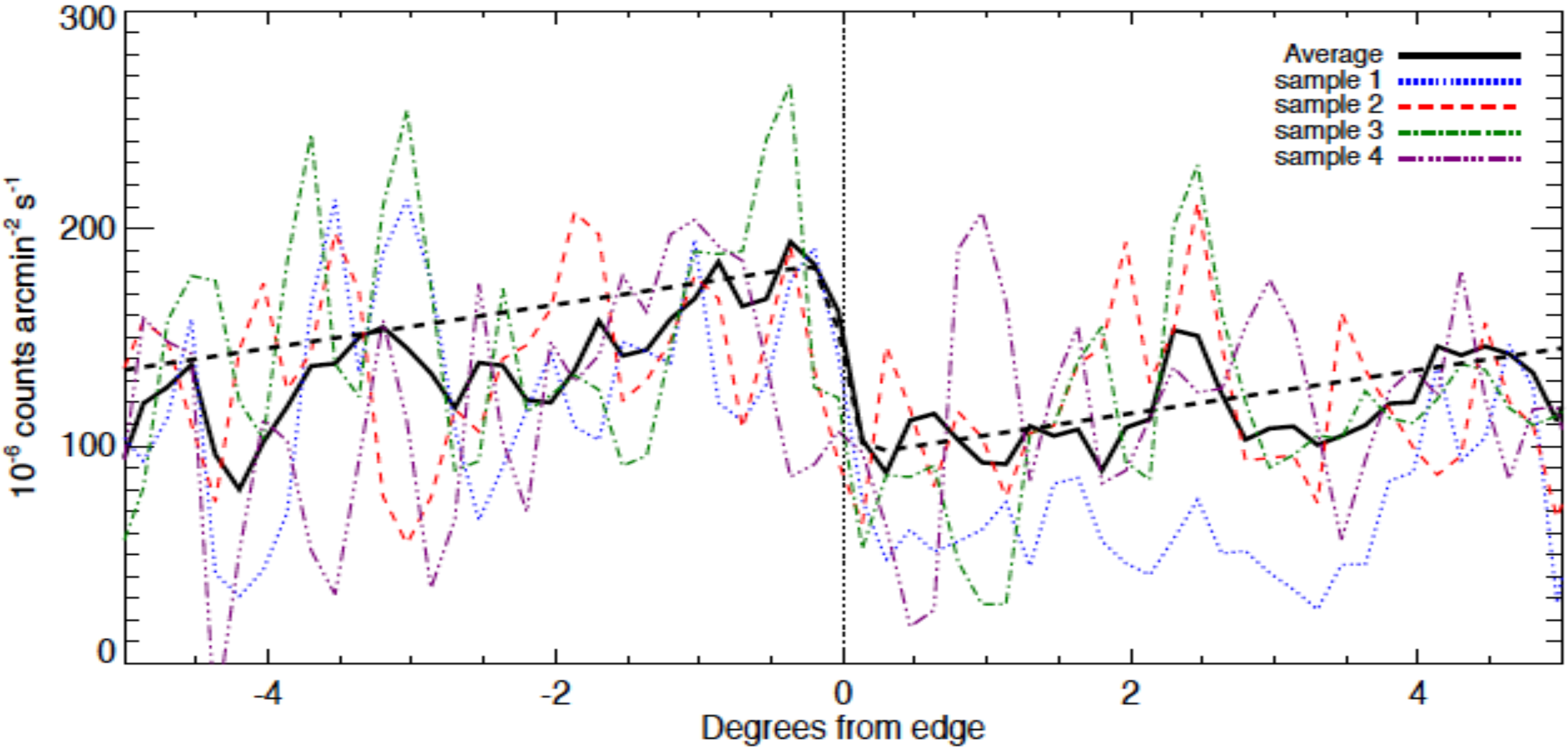
MS, Slatyer, Finkbeiner (2010)

Removing soft X-ray <1 keV

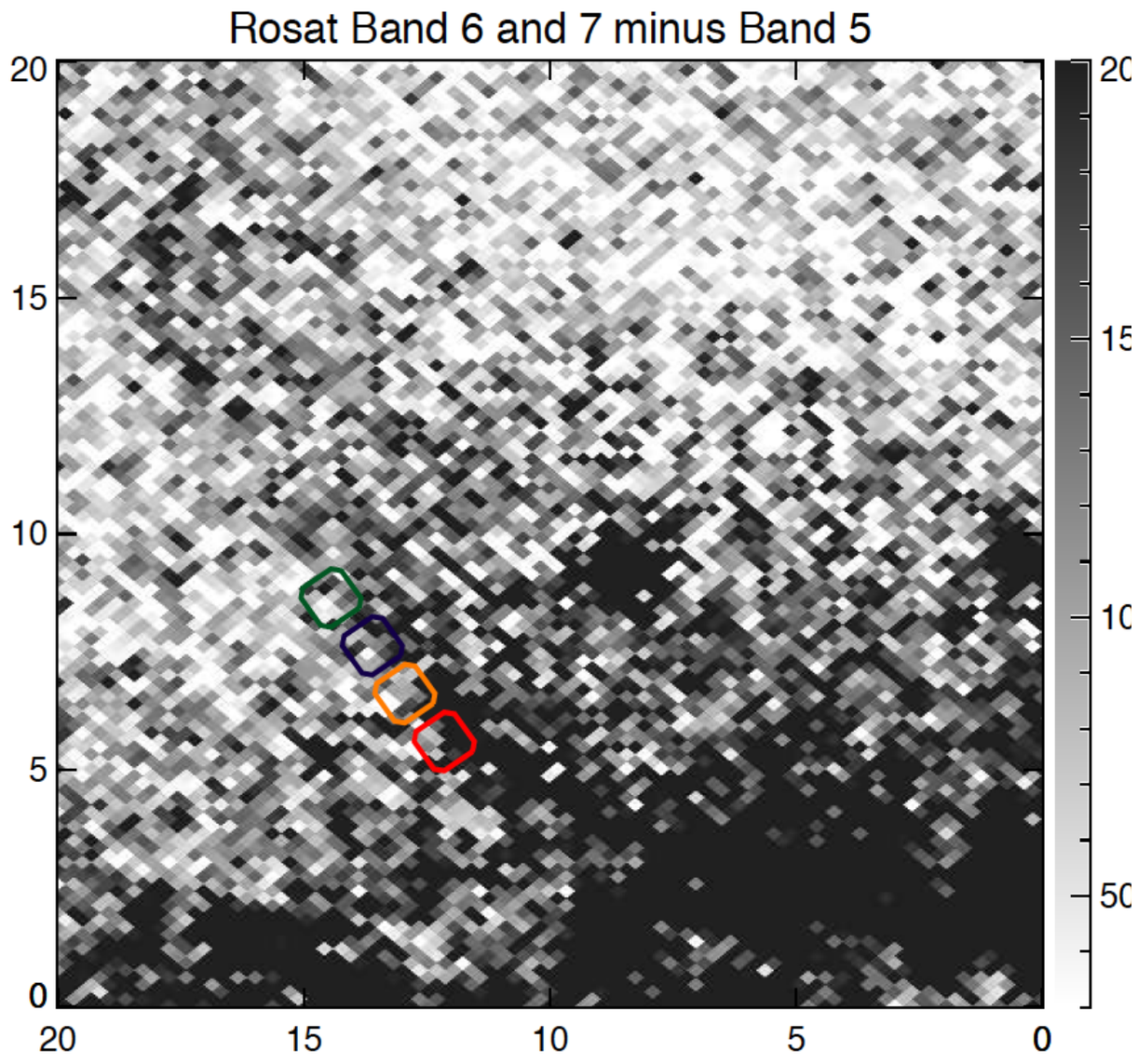


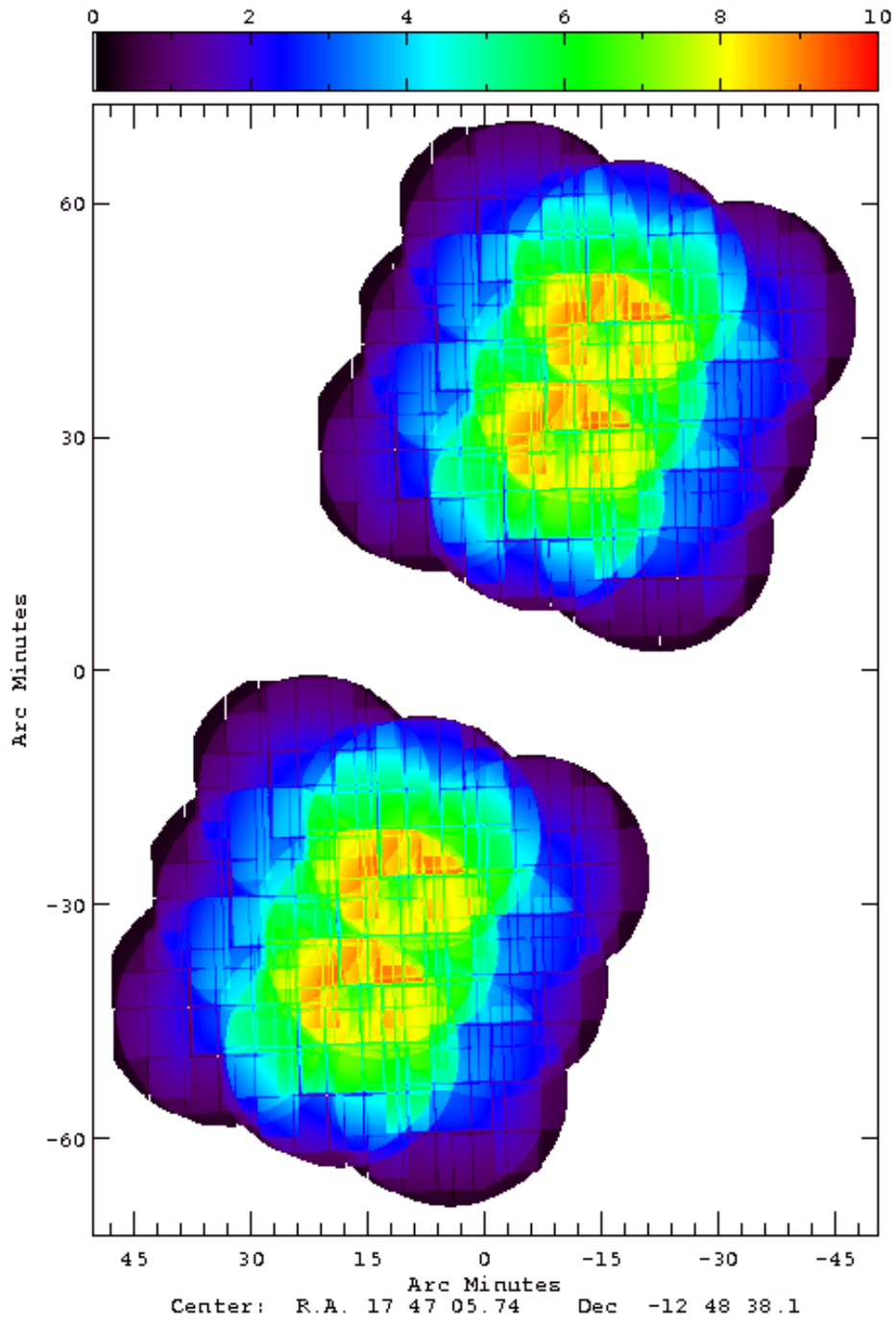
MS, Slatyer, Finkbeiner (2010)

FB has a sharp edge in X-ray



Mosaic XMM-Newton Observations on FB edge





MS et al. in preparation

More data, more data, more data...

- Suzaku (in collaboration with Eric Miller at MKI)
- New XMM-Newton observations
- eROSITA (external collaborator)
- Micro-X? (with Enectali Figueroa-Feliciano)

Magnetic field structure of the FB

- Faraday rotation measure: a birefringence effect when linearly polarized light travels through a magnetized media.

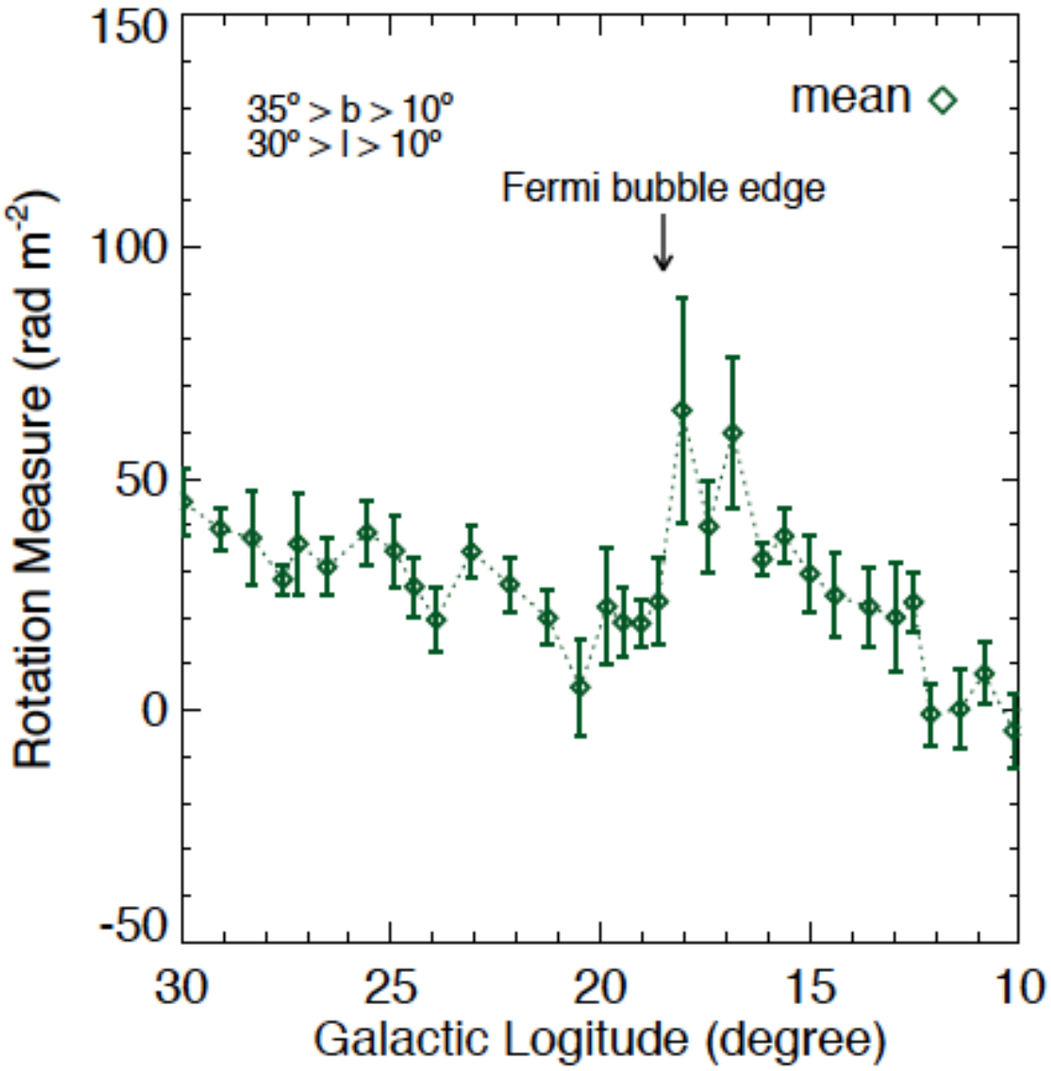
$$\Delta\psi = \mathrm{RM}\lambda^2 \quad \sim \quad \int_{source}^{observer} n_e(l) B_{||}(l) dl$$

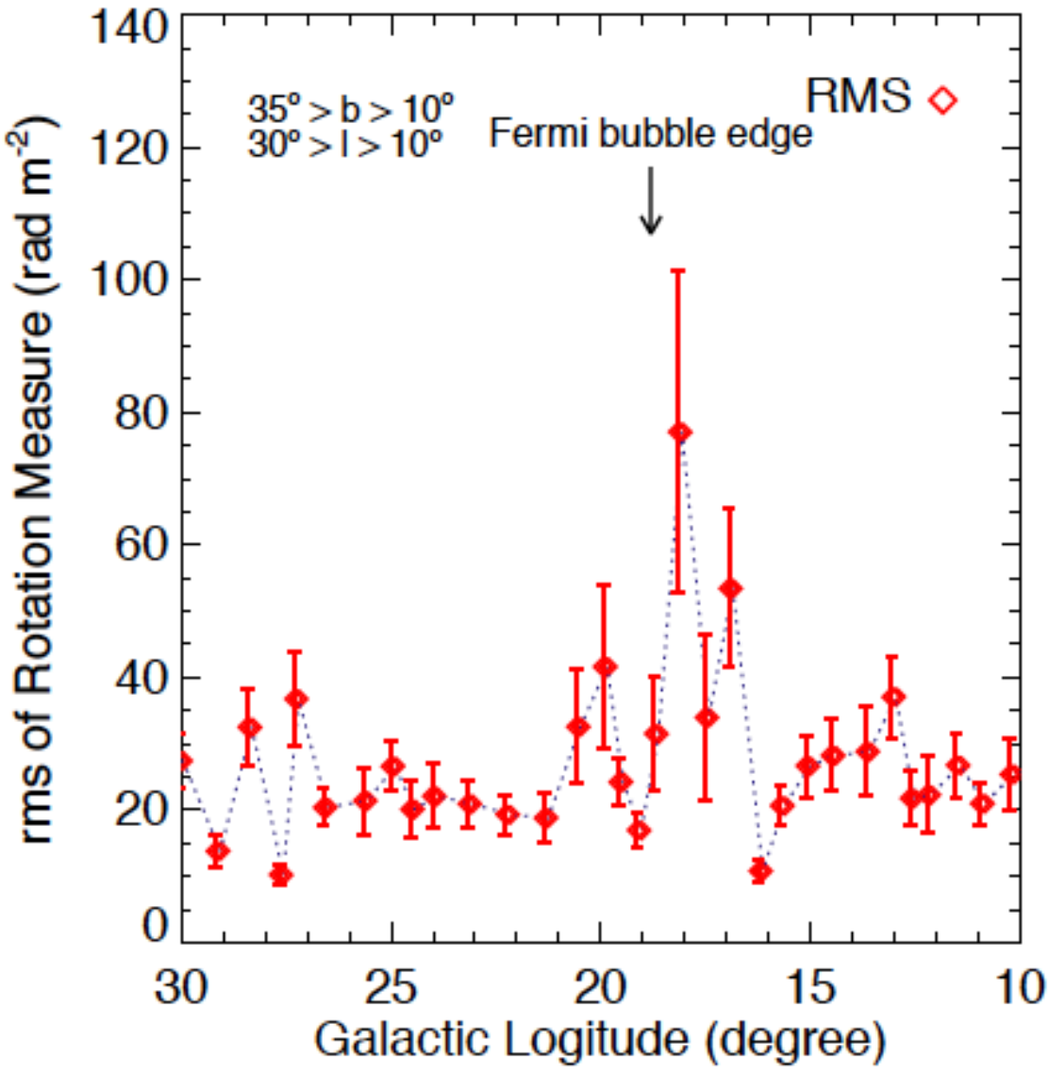
- Radio polarization (magnetic field perpendicular to the line of slight)

Rotation measure sky map from Very Large Array

MS et al. in preparation

Rotation measure changes at the FB edge

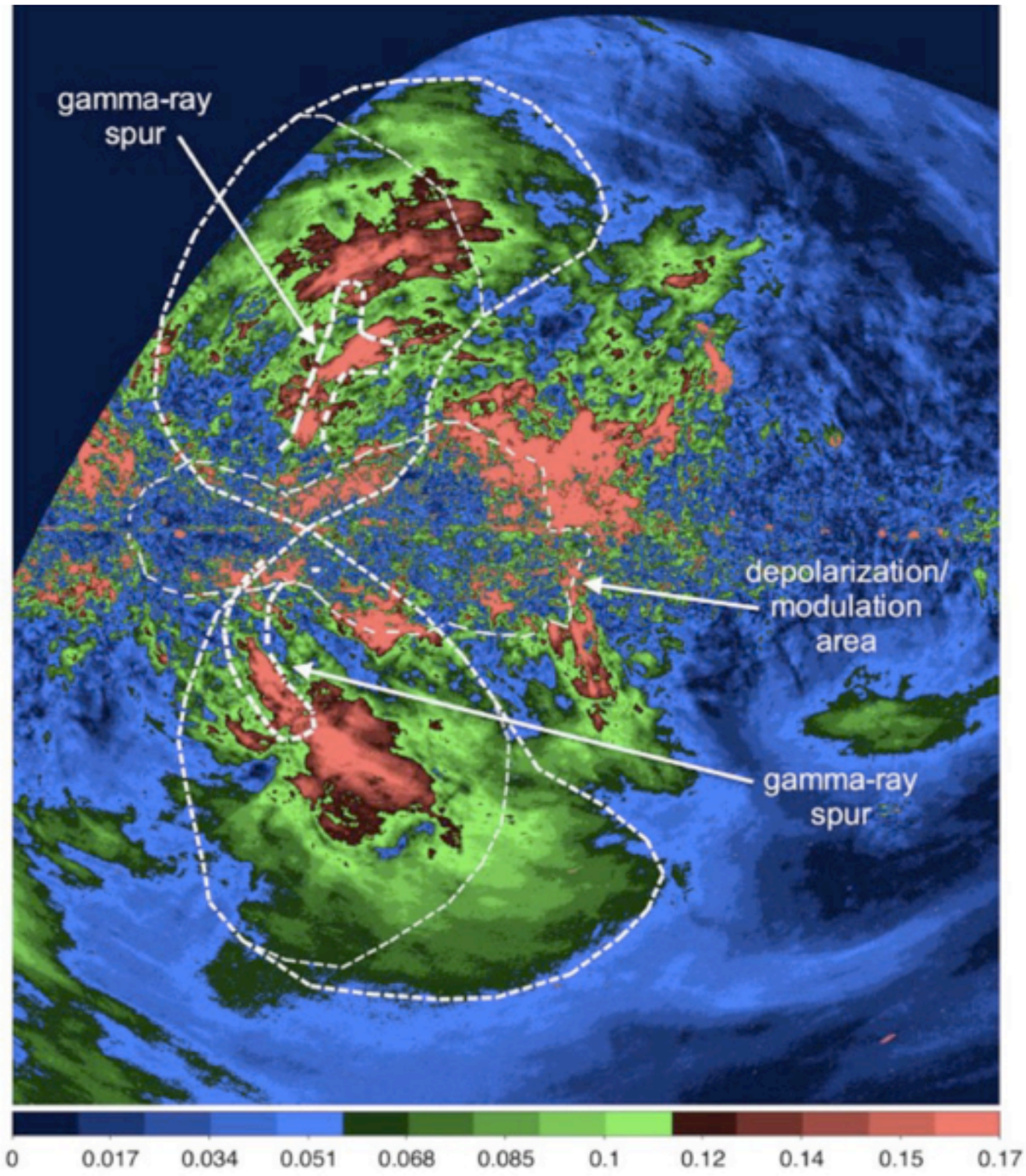




- Leading a proposal for Very Large Array sky survey

MS et al. in preparation

S-PASS 2.3 GHz map



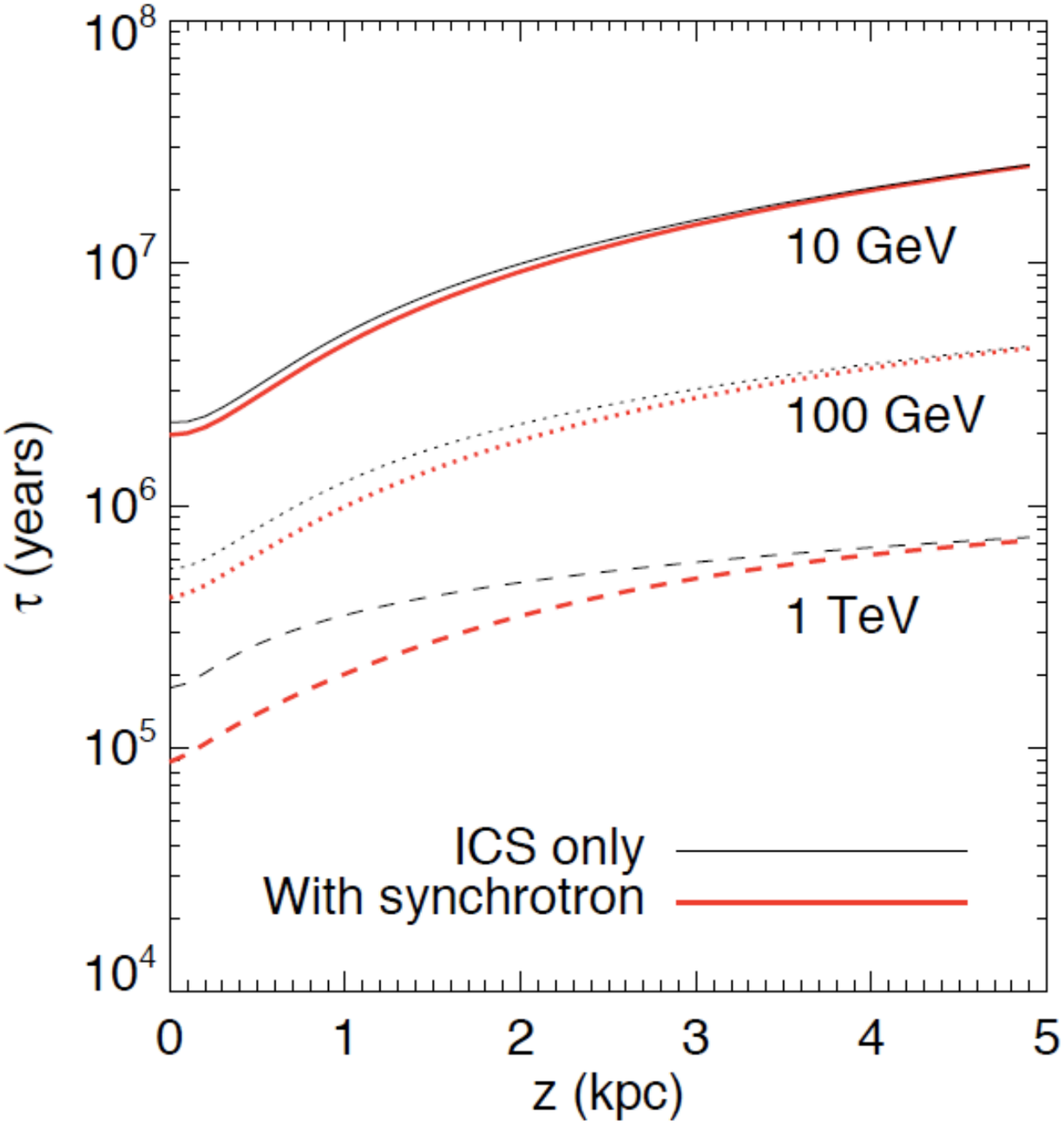
Carretti et al. (2013)

What produced the FB?

- Energetic transients
  (~10^6 years, episodic)
- Moderate energy input
  (~10^9 years, continuous)
- Black hole "burp" (jet)
- Accretion disk outflow
- Starburst wind bubble
- Dark matter

- FB : remnant of past activity from the Galactic center, possibly an active galactic nucleus (AGN) ~10^6 years ago, by accretion of the central black hole

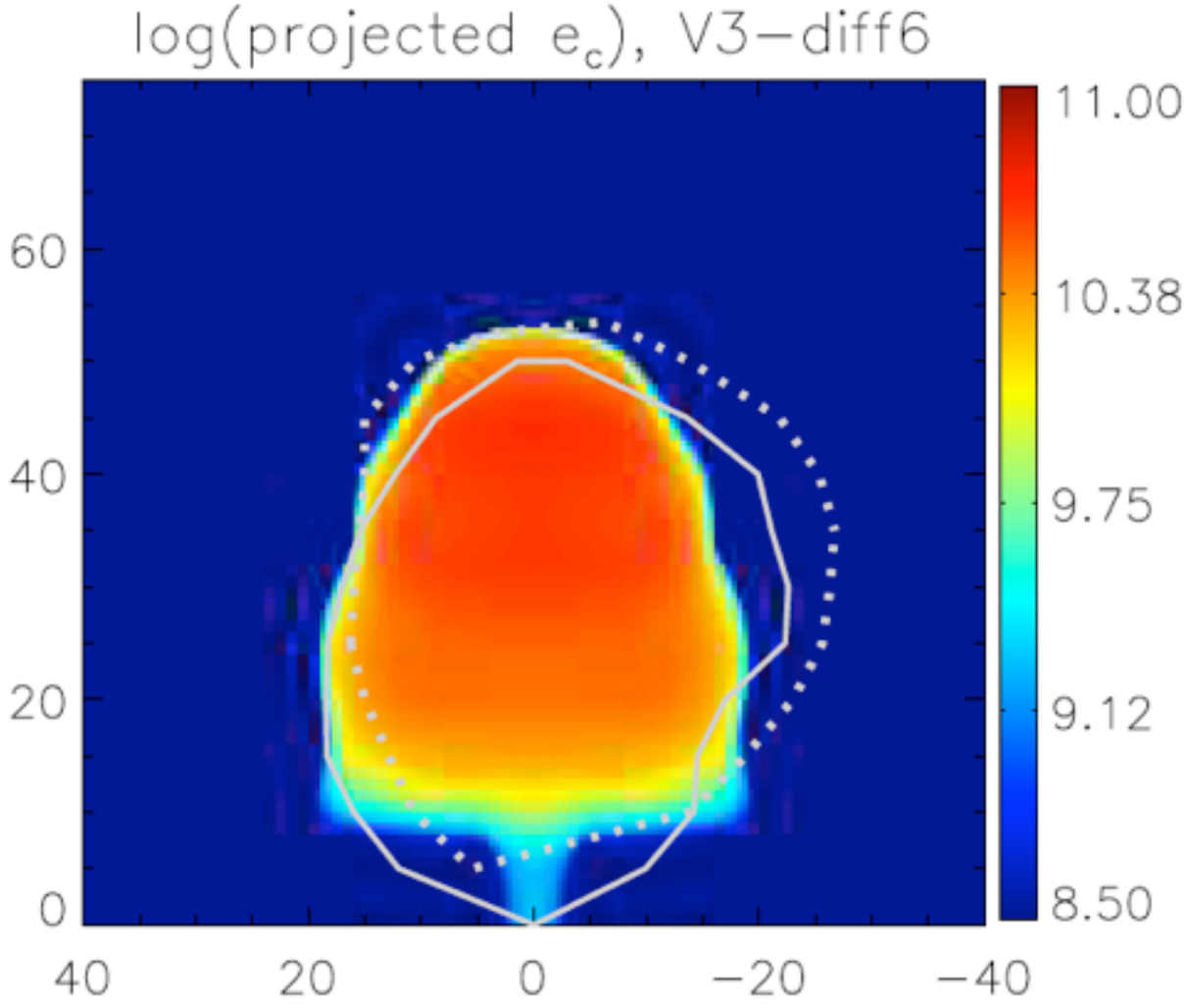
Key question: where/how to accelerate/ propagate ~TeV cosmic ray electrons



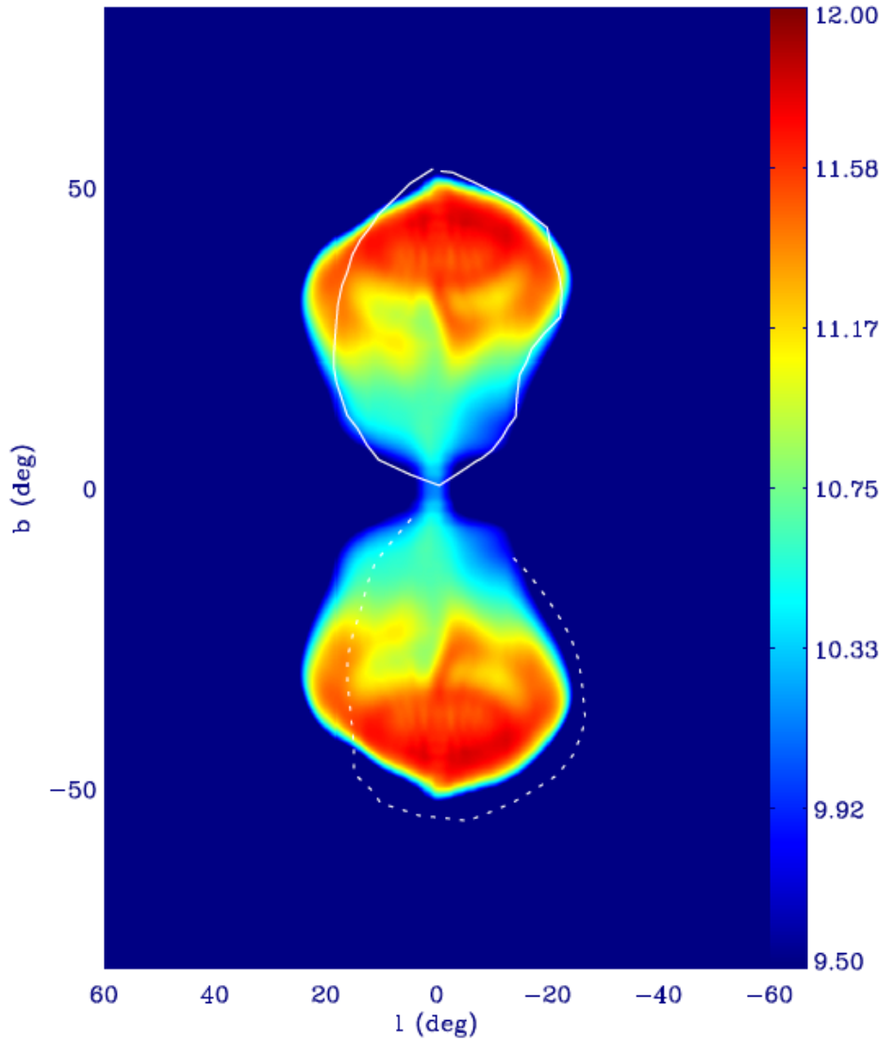
MS, Slatyer, Finkbeiner (2010)

Transient energetic jet from the central BH can produce the bubbles

E ~$10^{57\text{-}58}$ erg and requires violent accretion to the BH!



Guo et al. (2012)

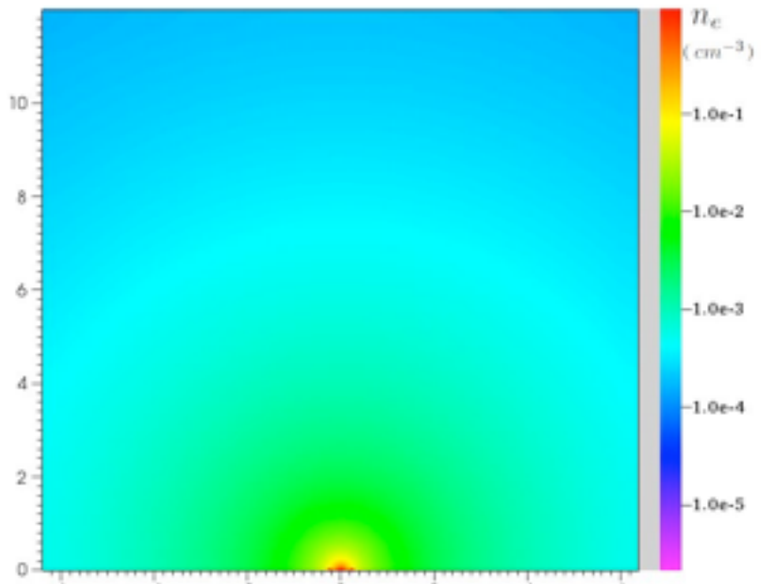


Yang et al. (2012)

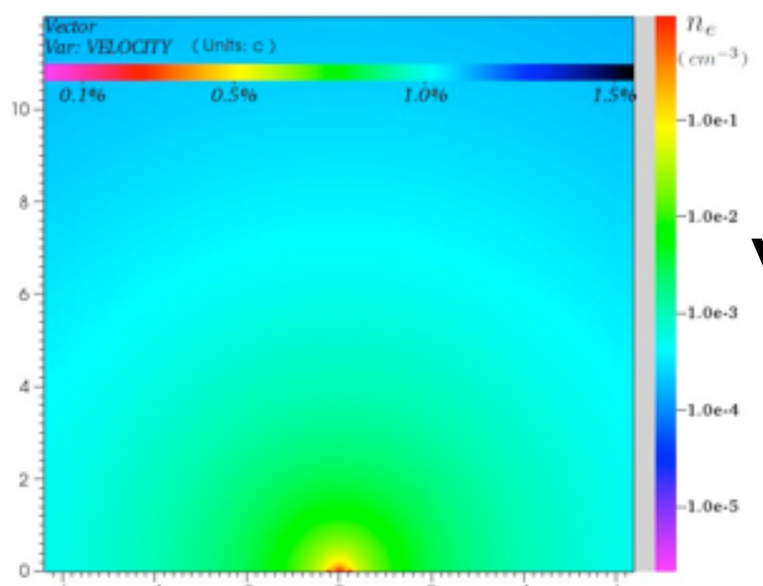
AGN outflow can produce the bubbles

E ~10^{55} erg with moderate accretion rate

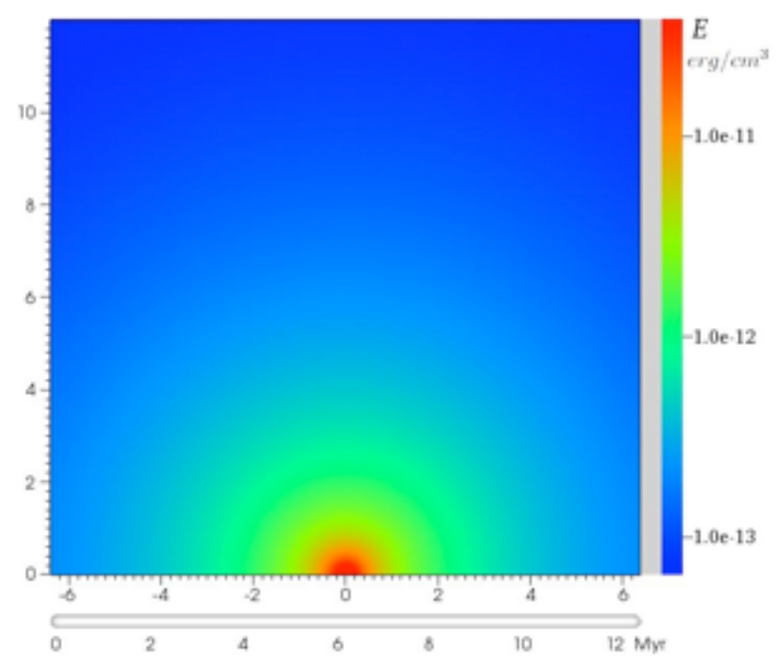
Density



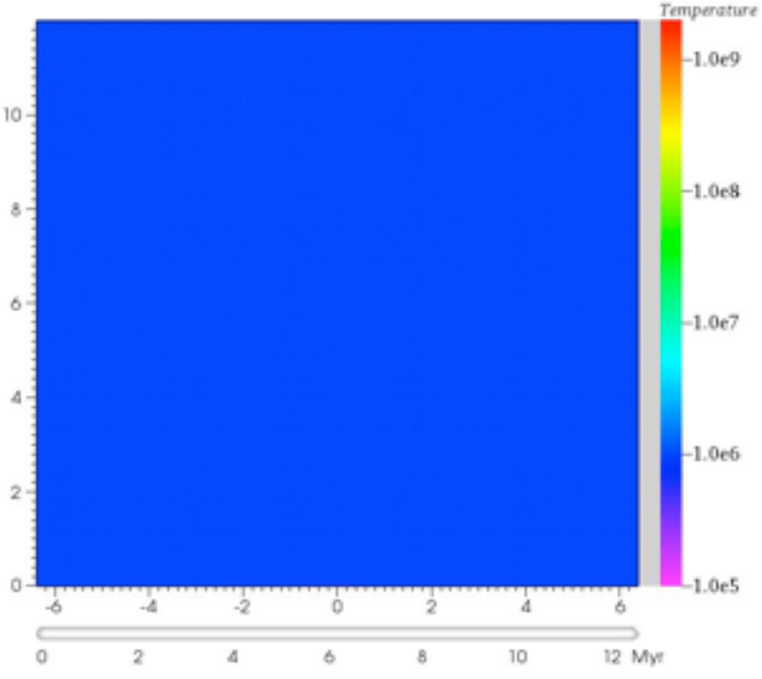
Velocity



Energy

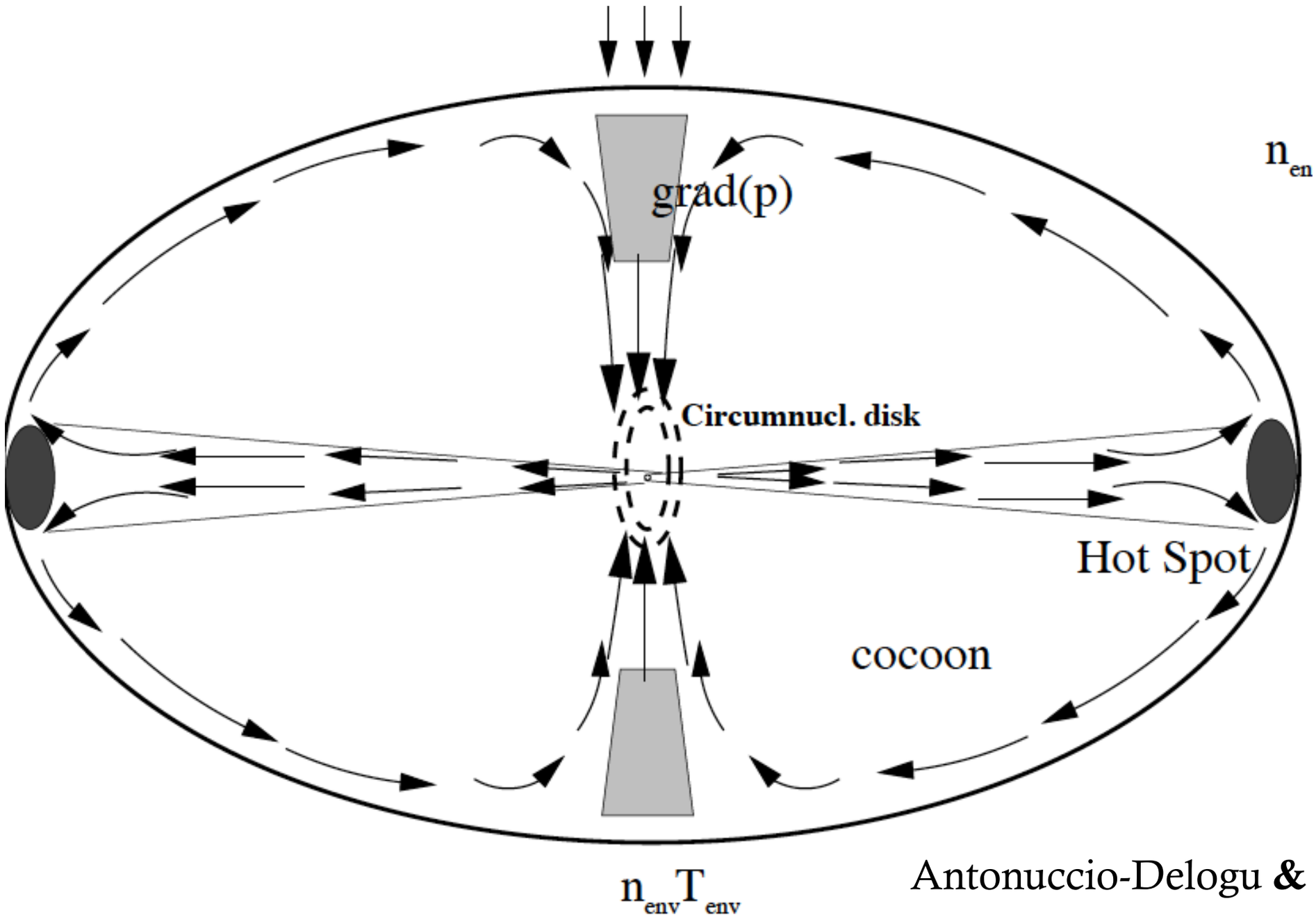


T



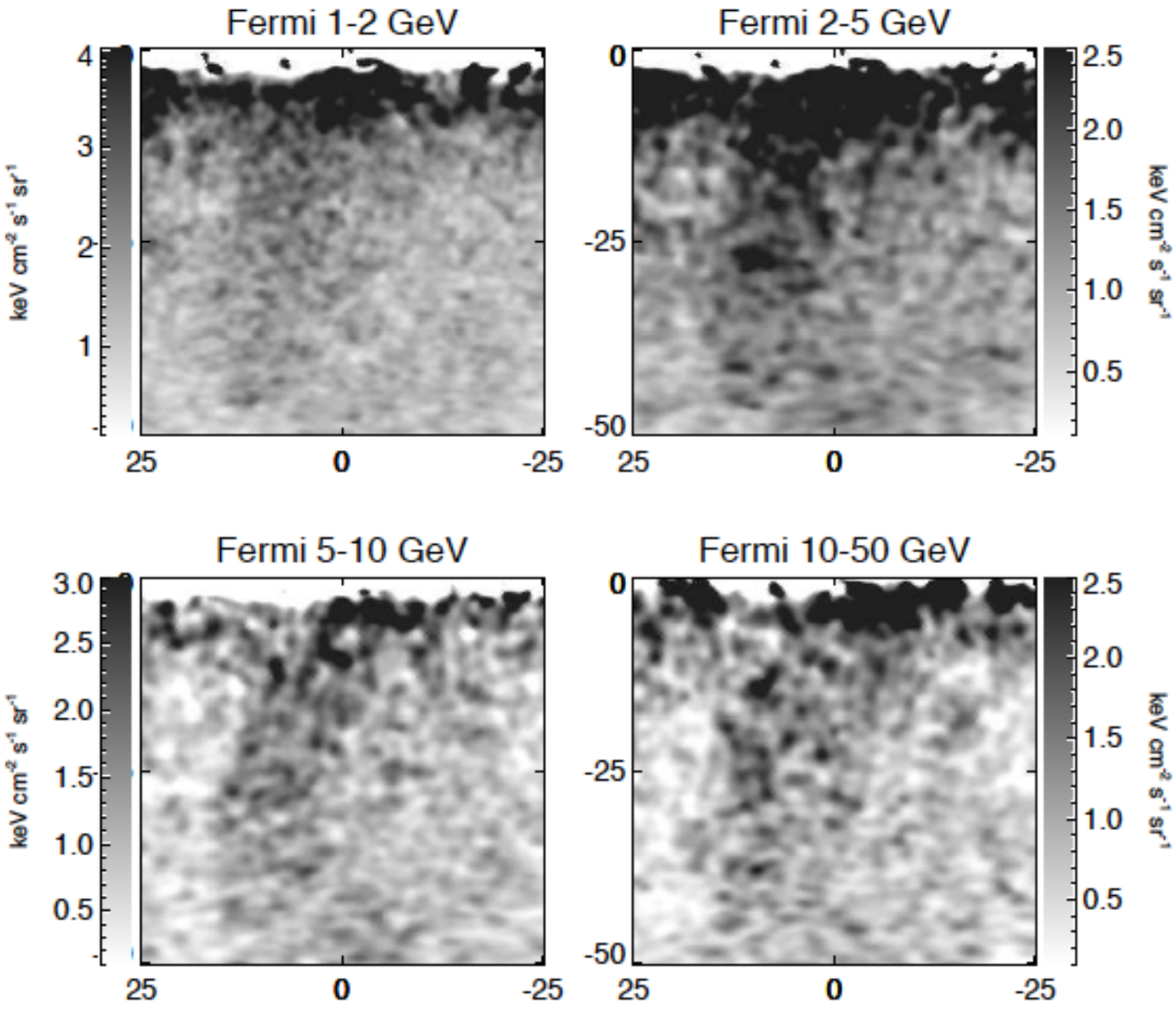
MS in collaboration with G. Mou, F. Yuan, etc.

Is there jet/cocoon within the bubbles?



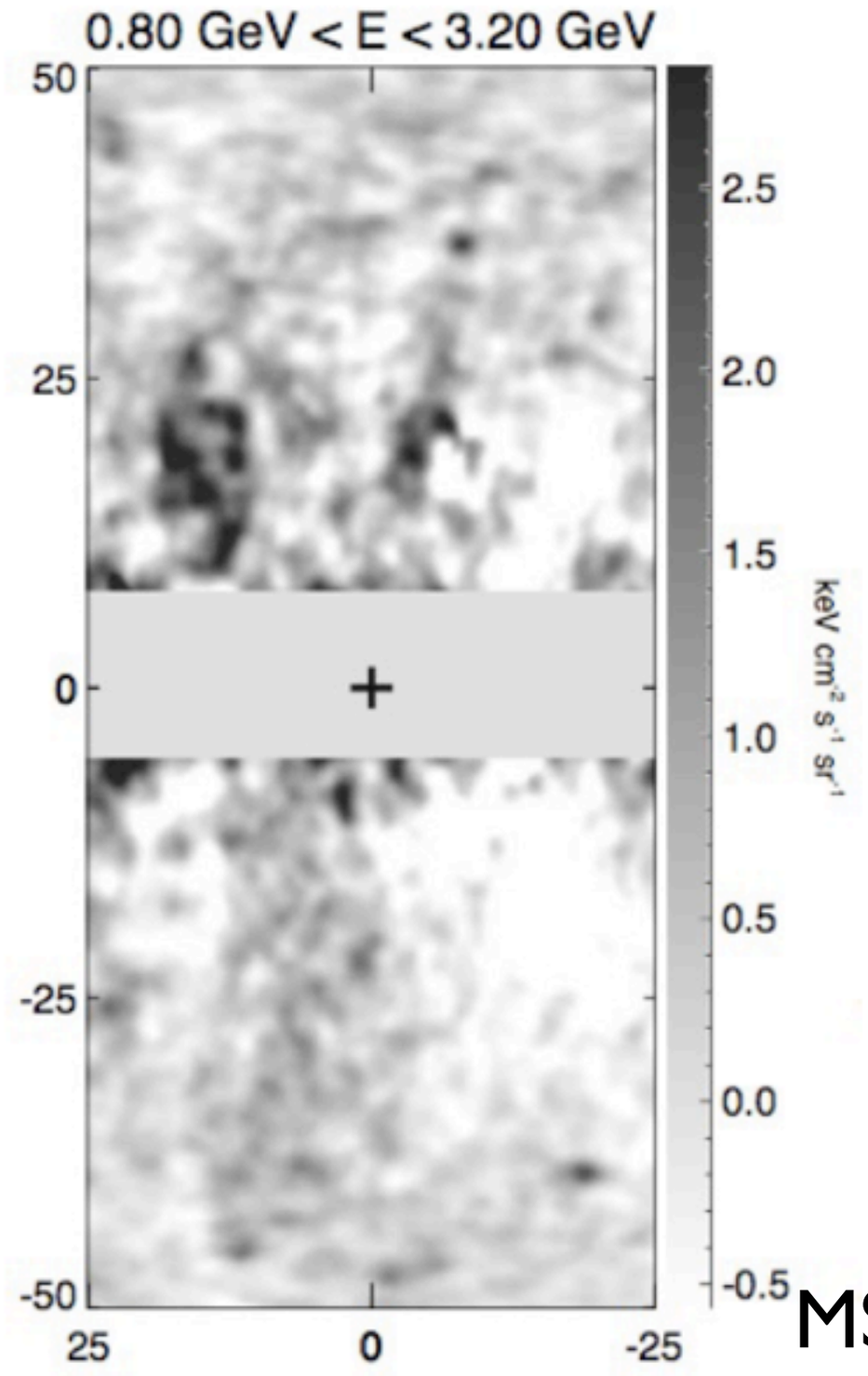
Antonuccio-Delogu **&** Silk (2010)

Searching for jet/cocoon in Fermi data



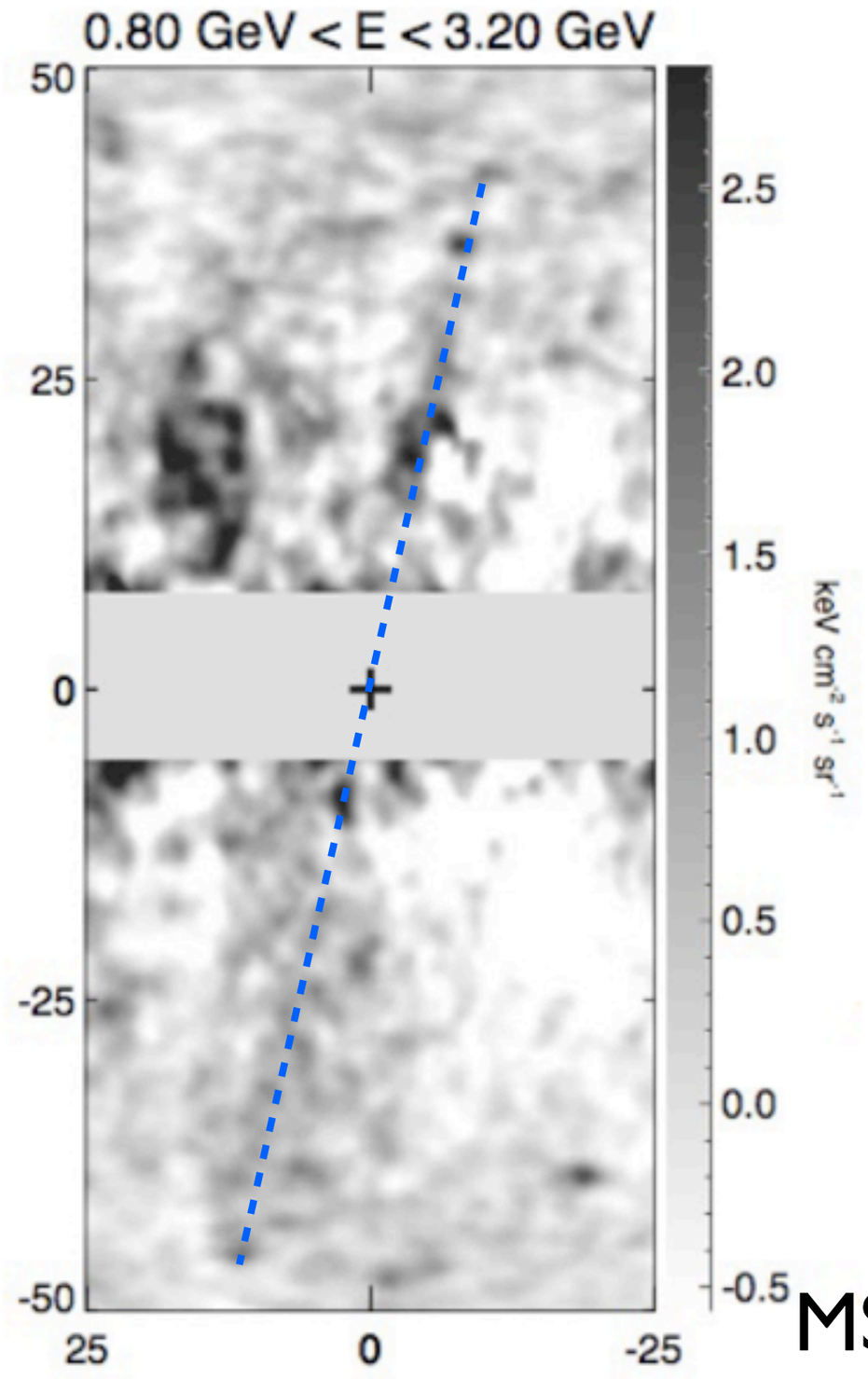
MS & Finkbeiner (2012)

Cocoon + collimated jet?



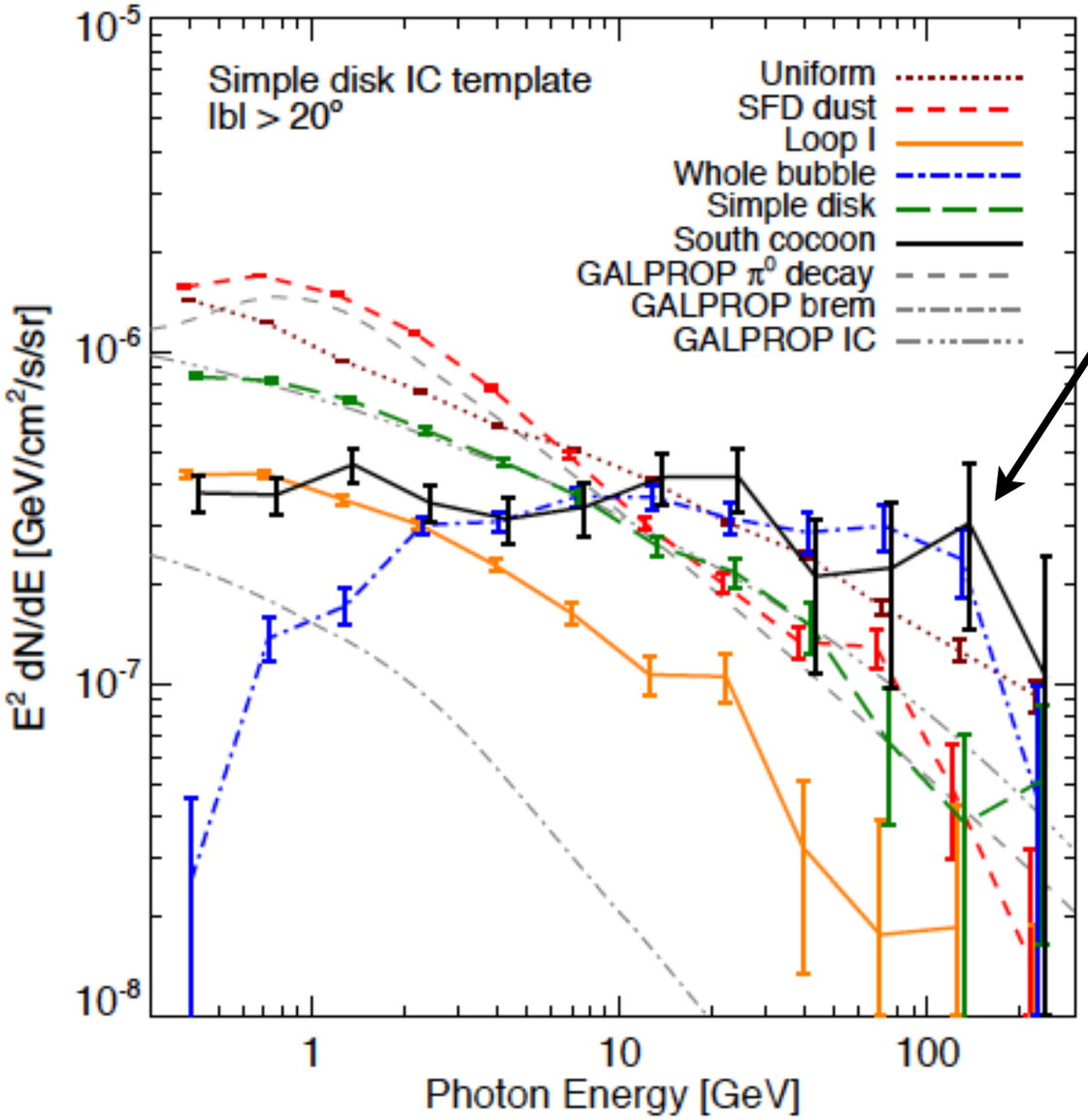
MS & Finkbeiner (2012)

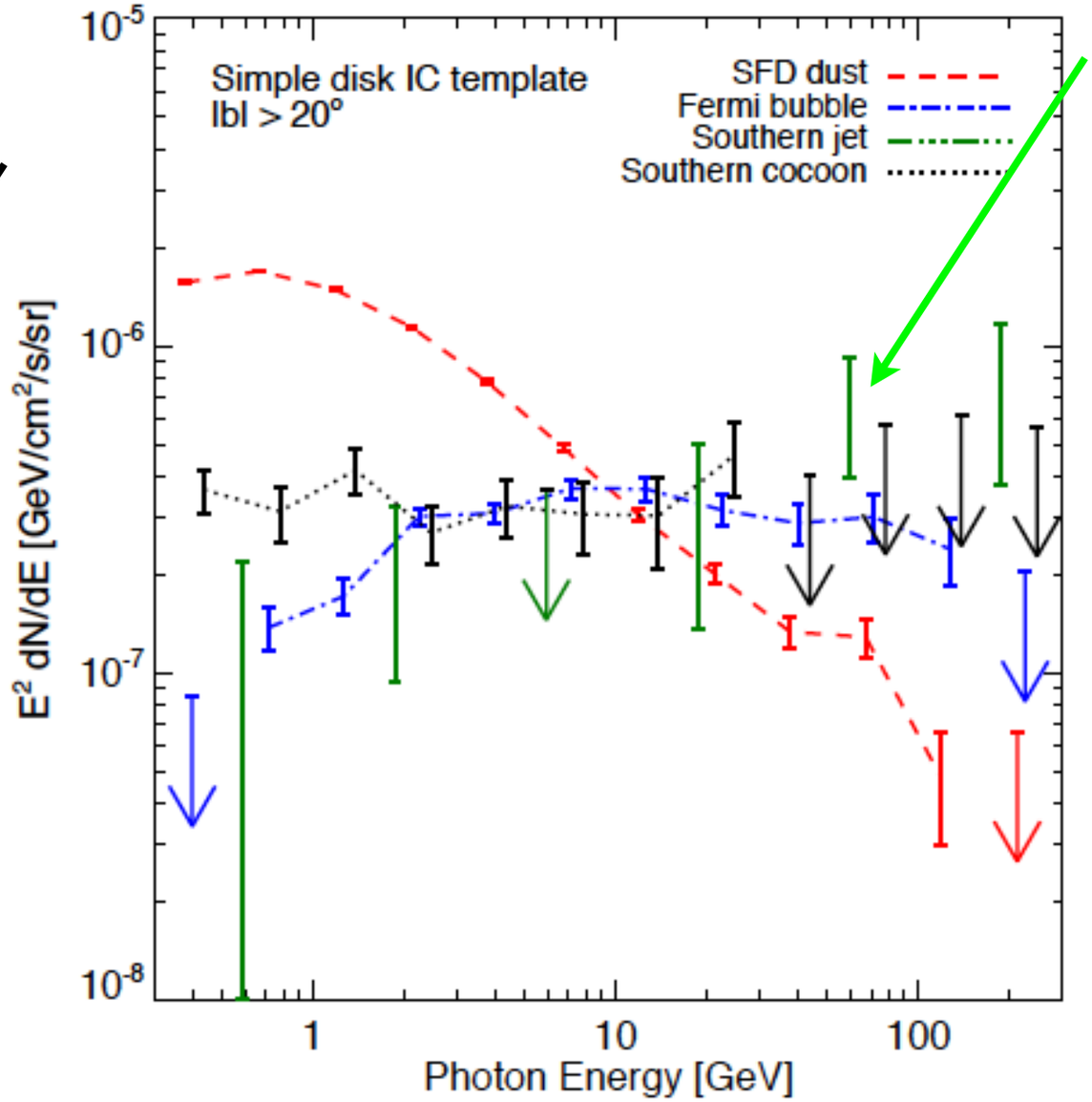
Cocoon + collimated jet?



MS & Finkbeiner (2012)

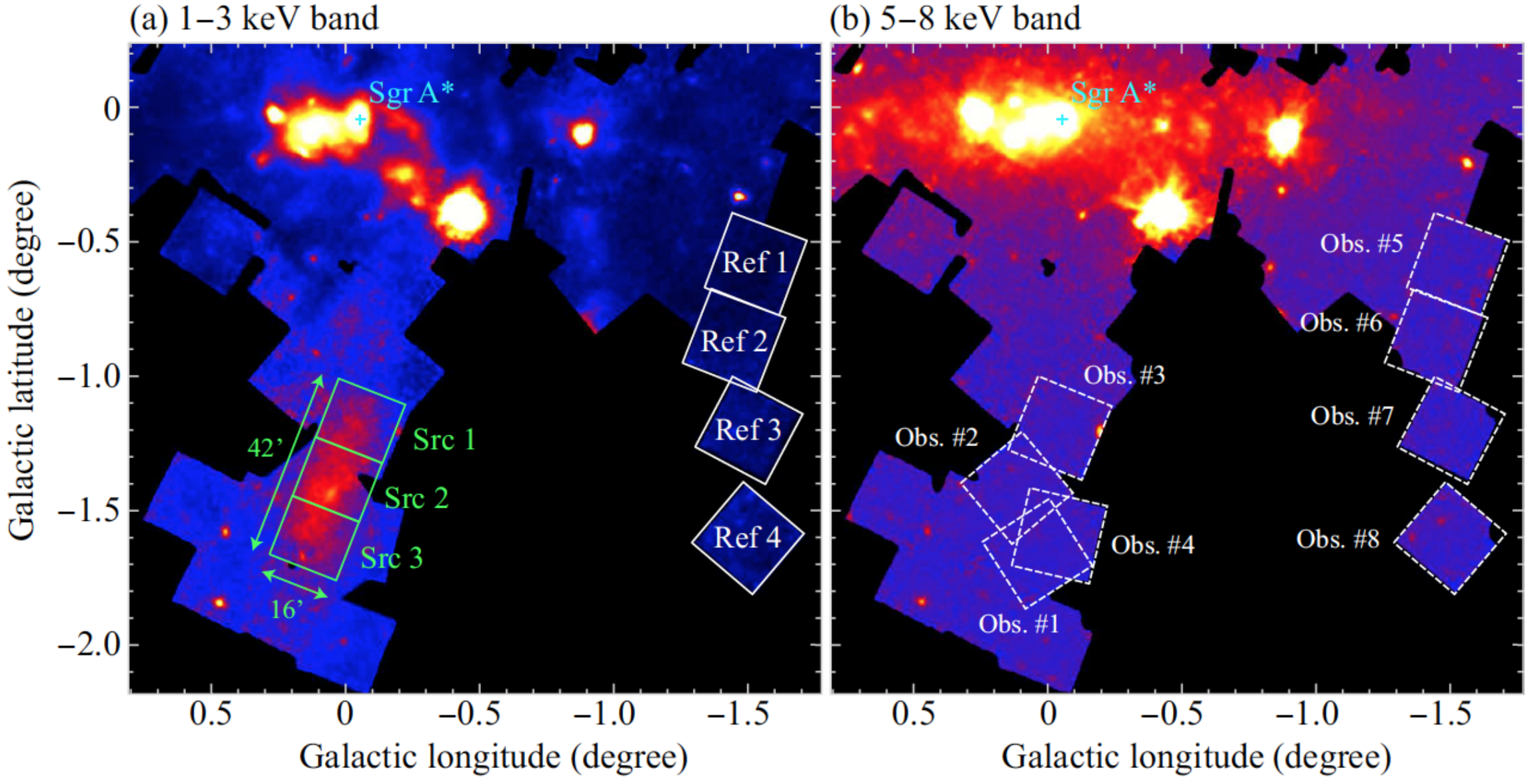
Both the cocoon and "jet" have hard spectrum





MS & Finkbeiner (2012)

Recombining plasma in the south of the Galactic center

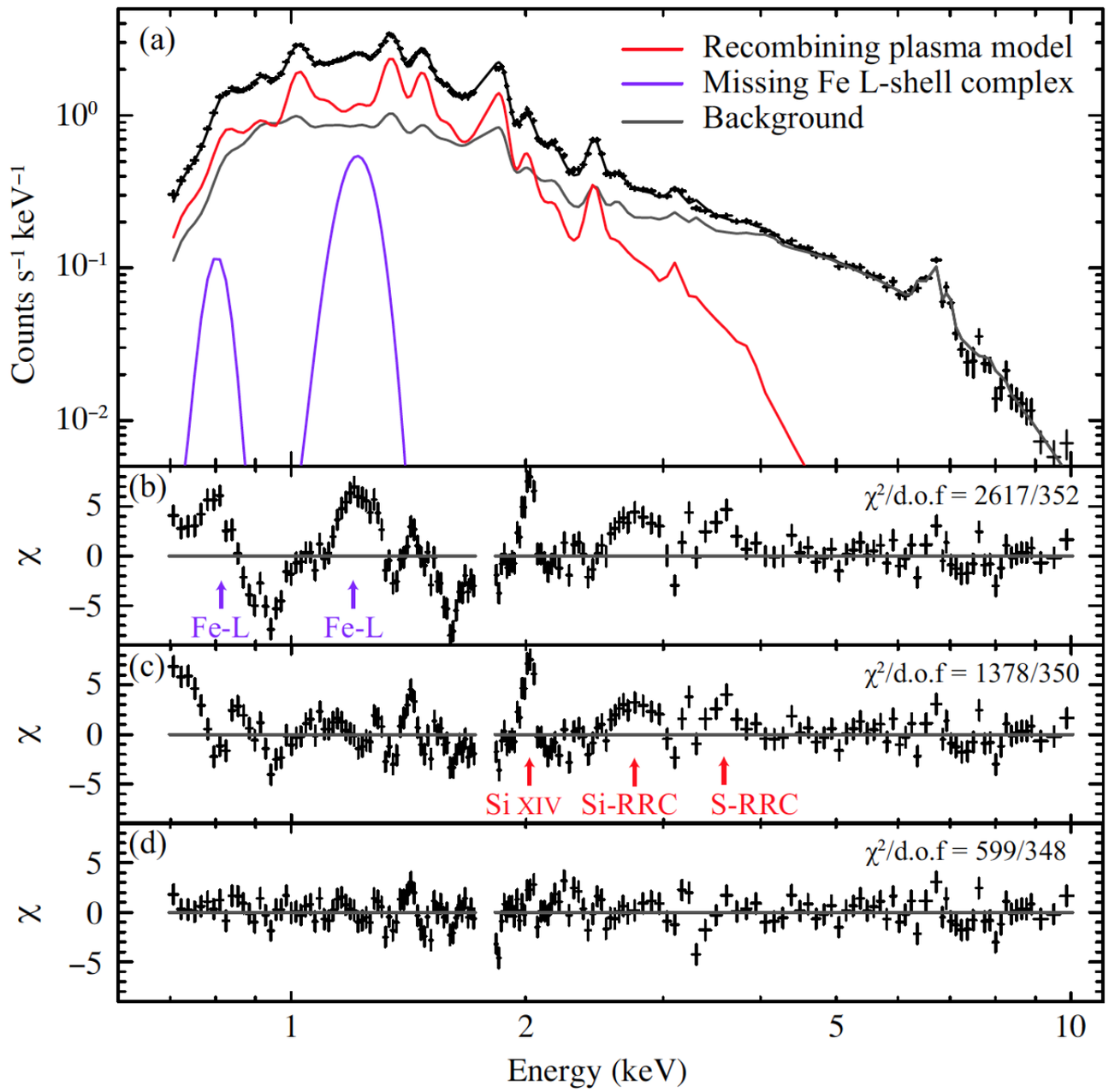


Nakashima et al. (2013)

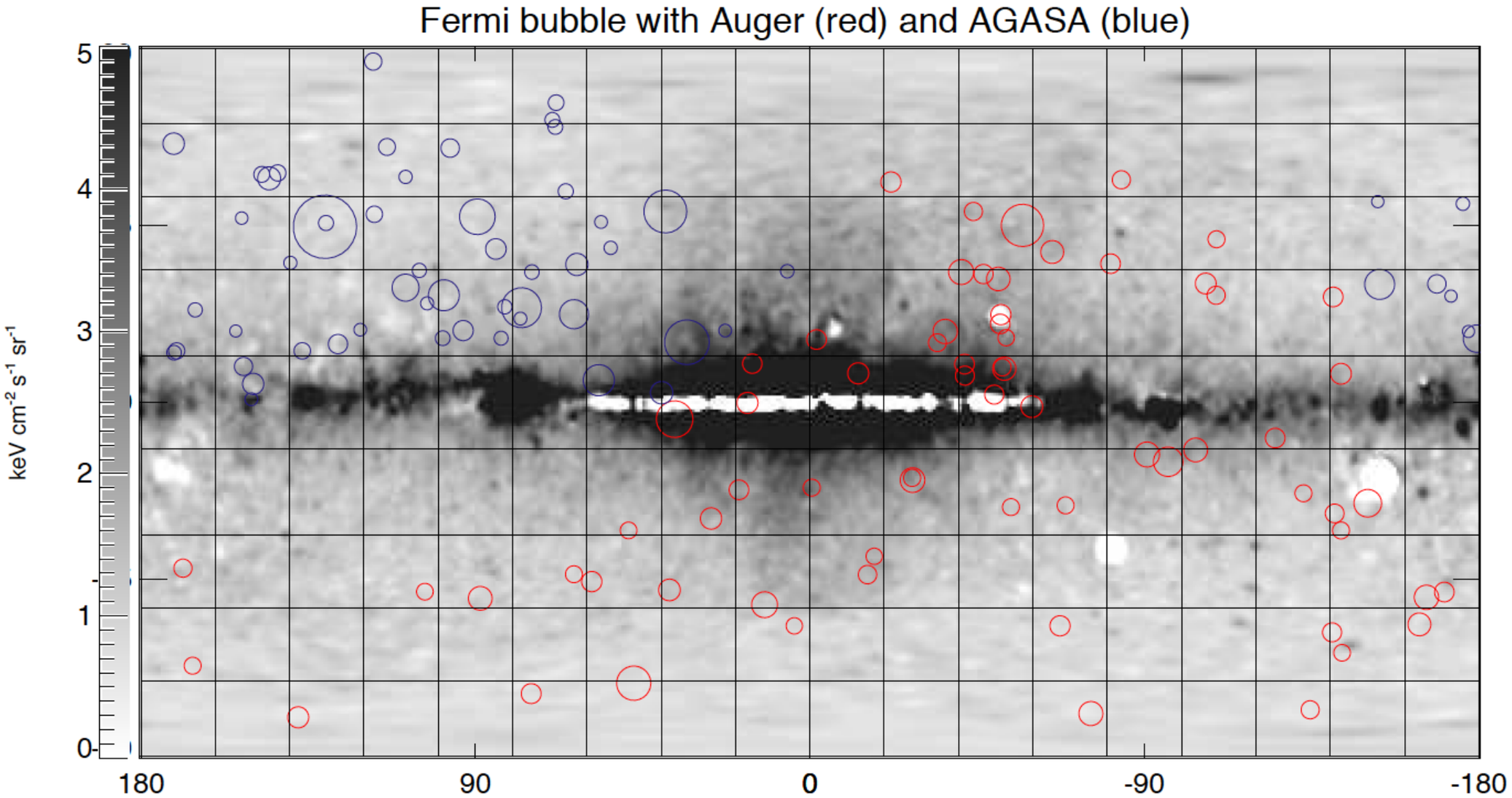
Recombining plasma model is favored

- Shock heated hot plasma?
- Adiabatic expansion?
- Photoionization?
- Suggest a past AGN with collimated radiation injection

Nakashima et al. (2013)

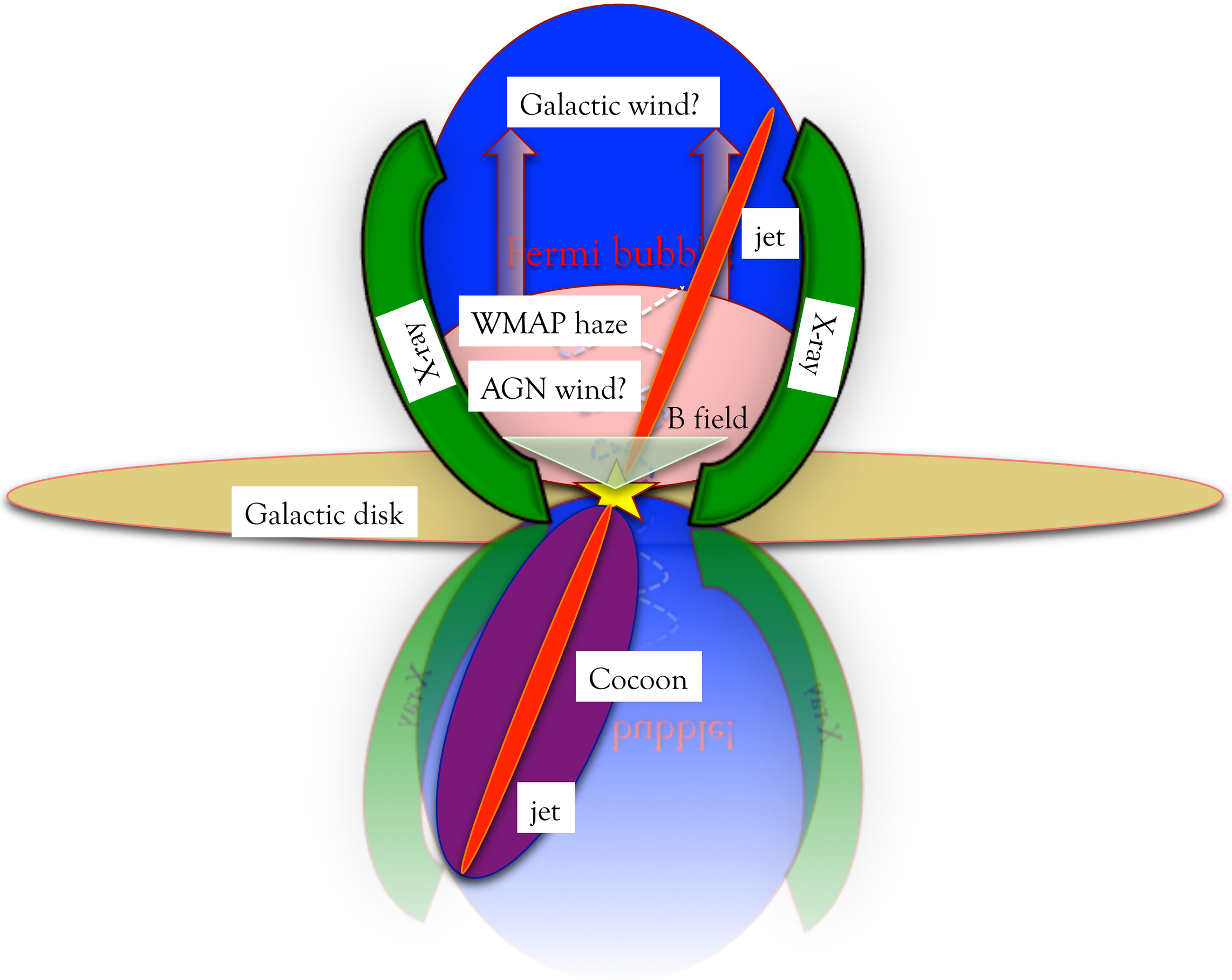


What's the highest energy that FB can accelerate particles up to?

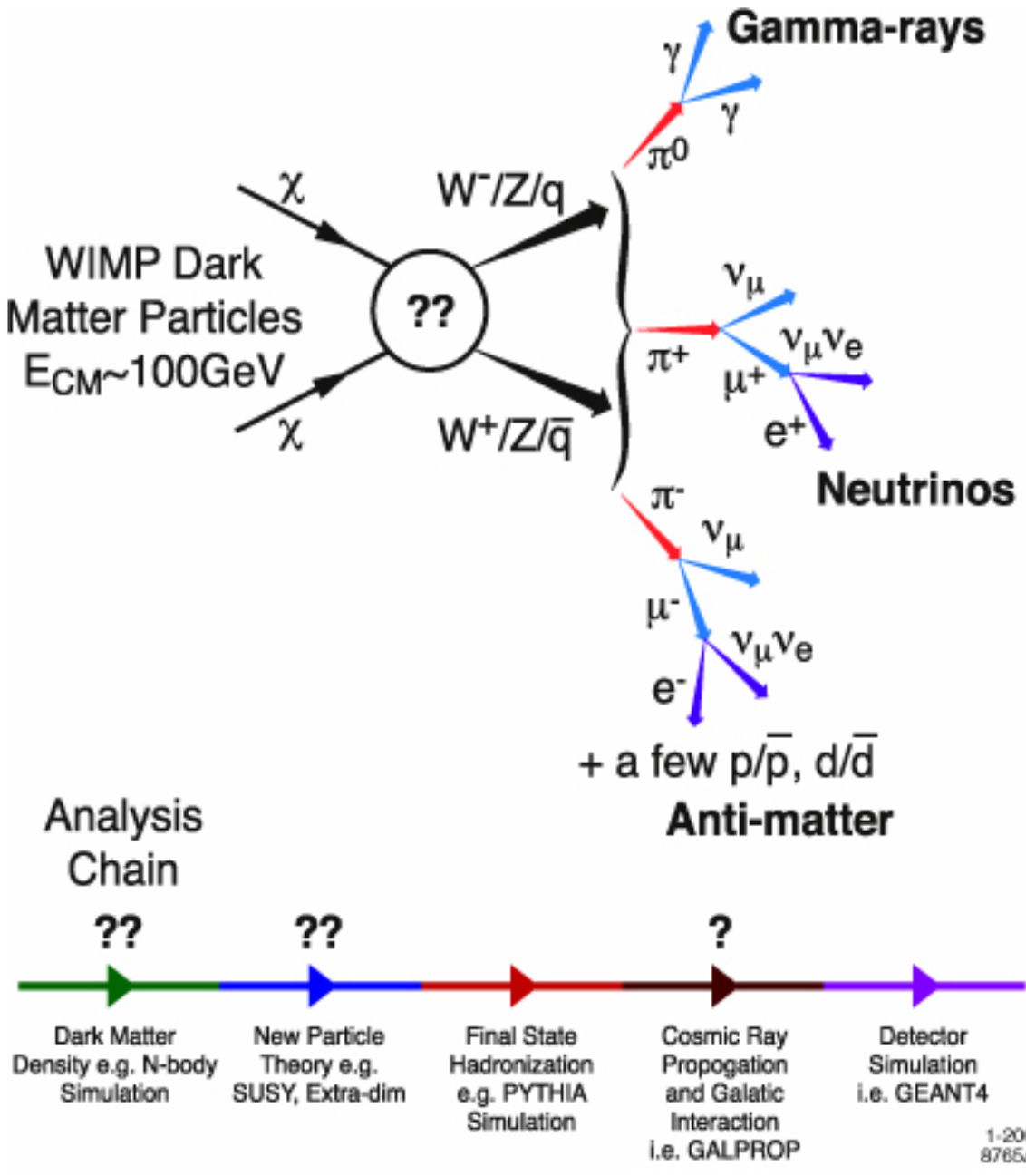


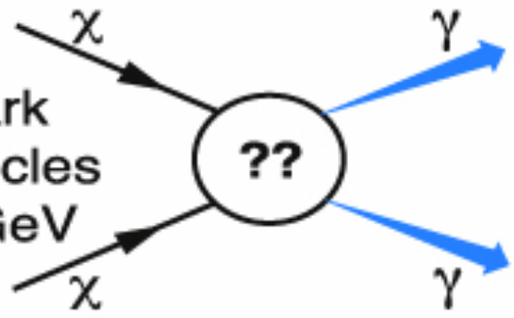
$$E_{max} = 10^2 \beta \, \mathrm{Ze(B/10\,\mu G)(R/10\,kpc)\ EeV}$$

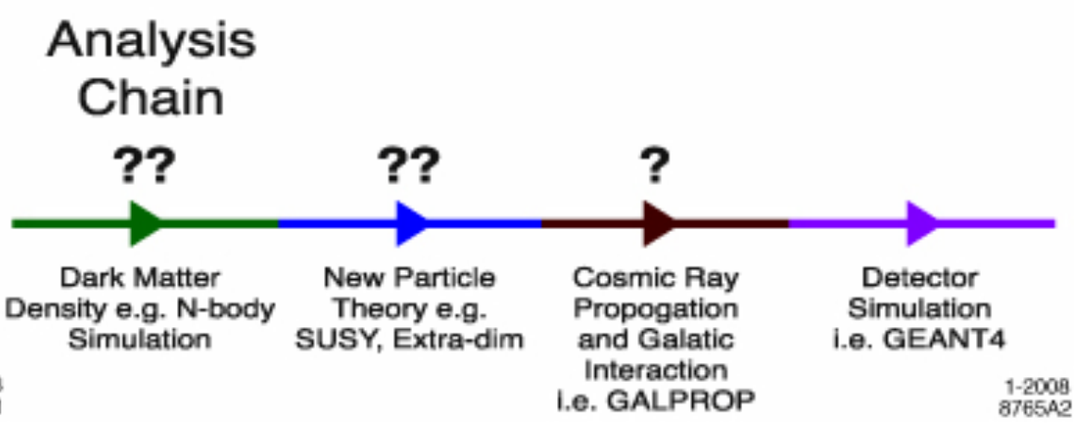
MS (2013)


Galactic wind?
Fermi bubble
jet
WMAP haze
X-ray
X-ray
AGN wind?
B field
Galactic disk
Cocoon
jet

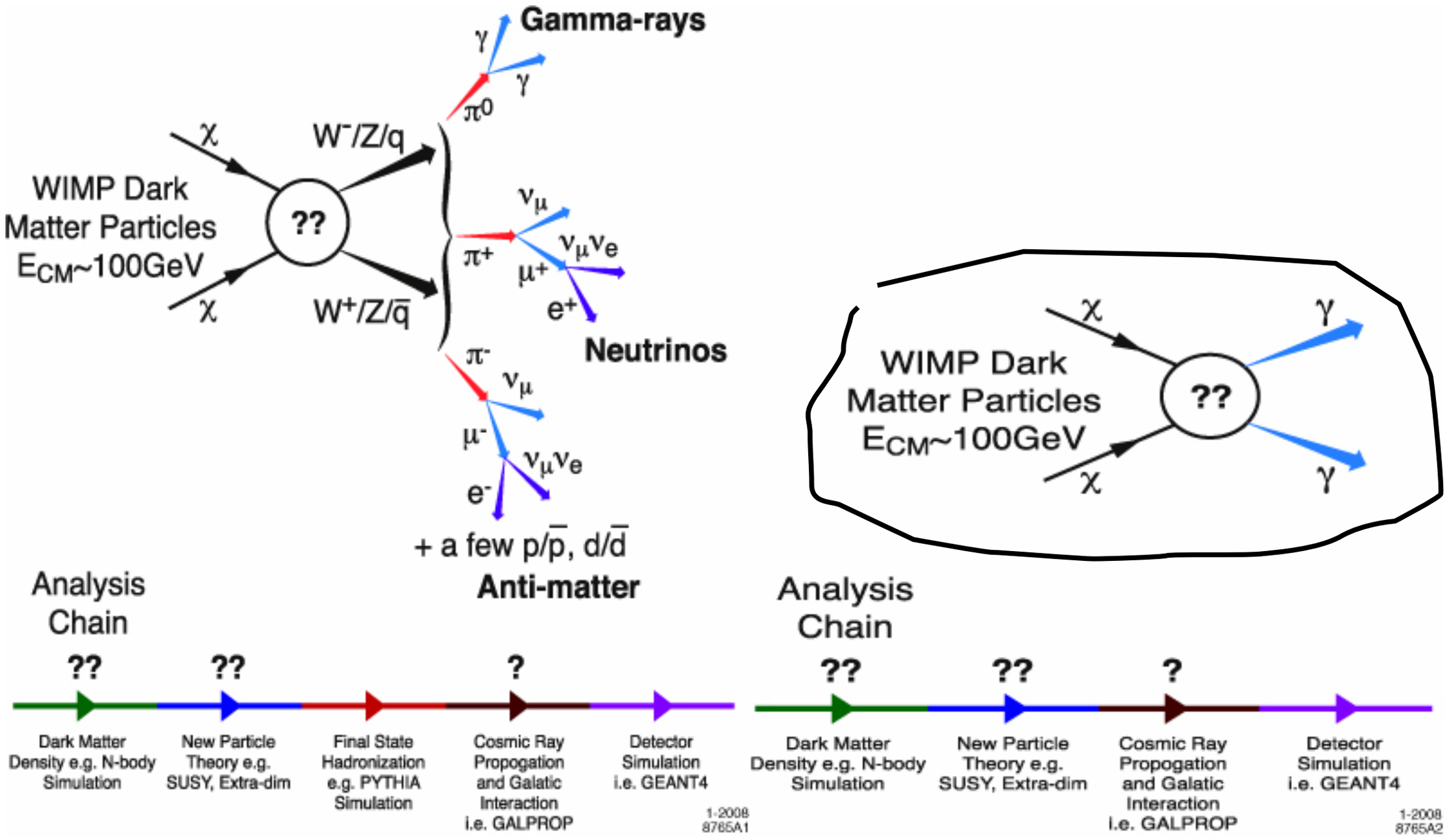
Searching for DM produced gamma-ray



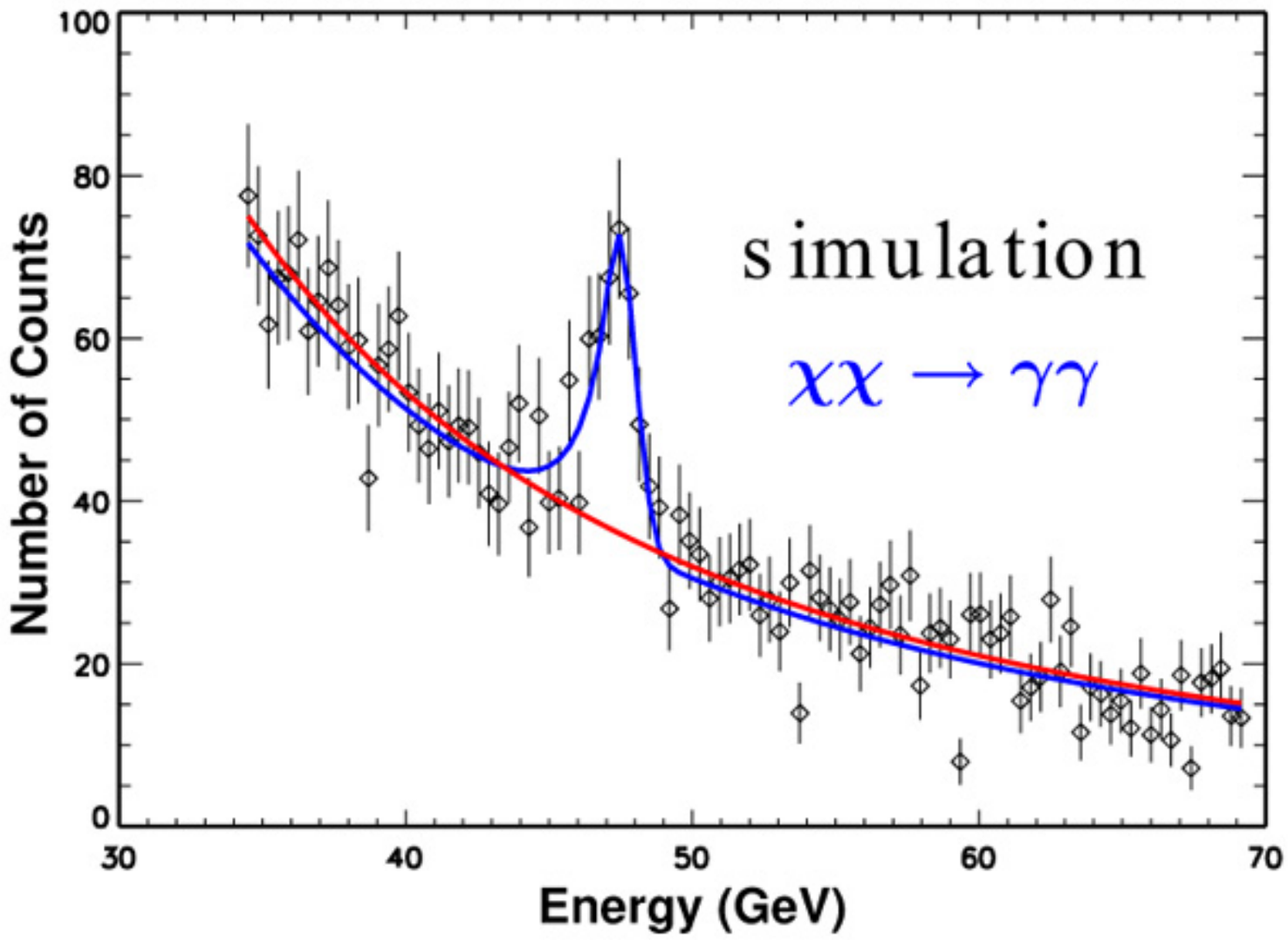




Searching for DM produced gamma-ray

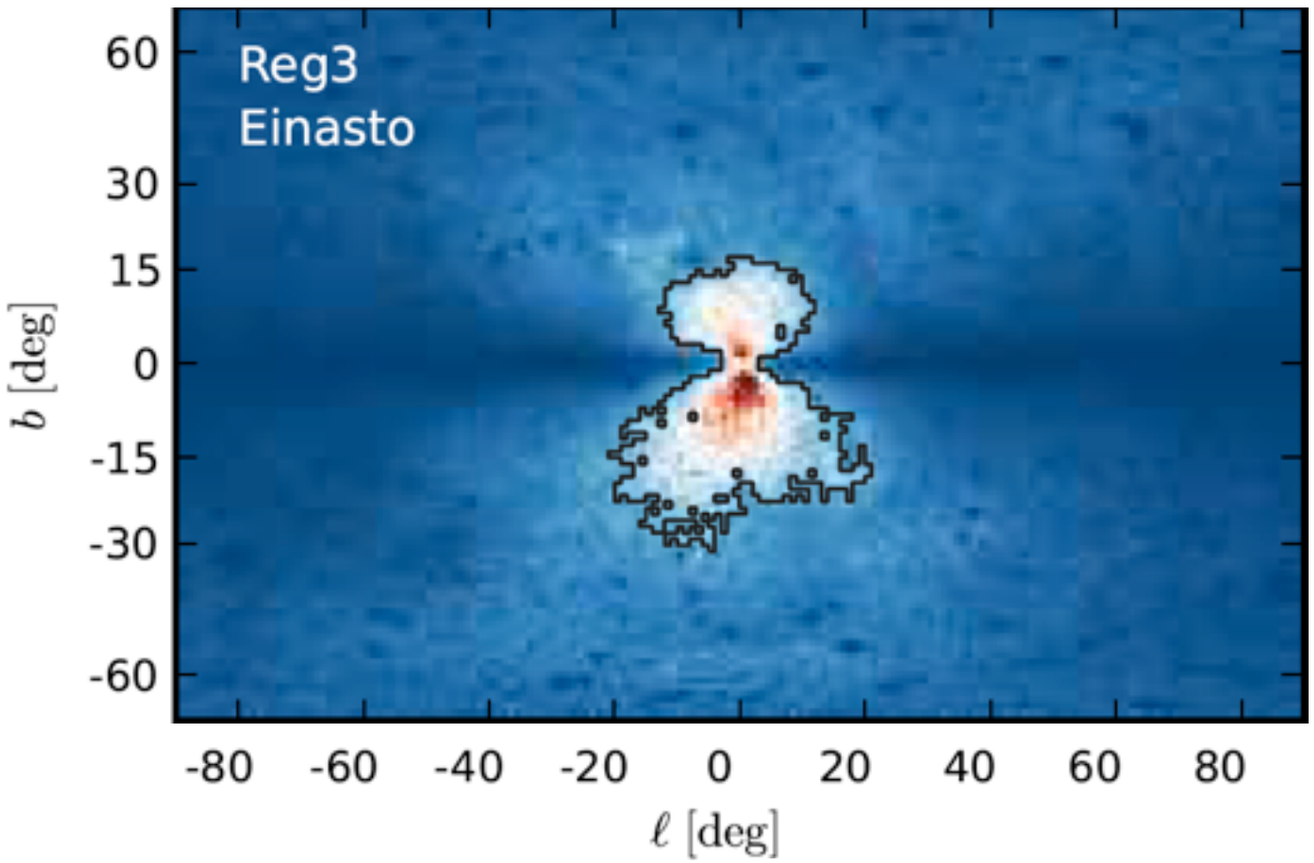


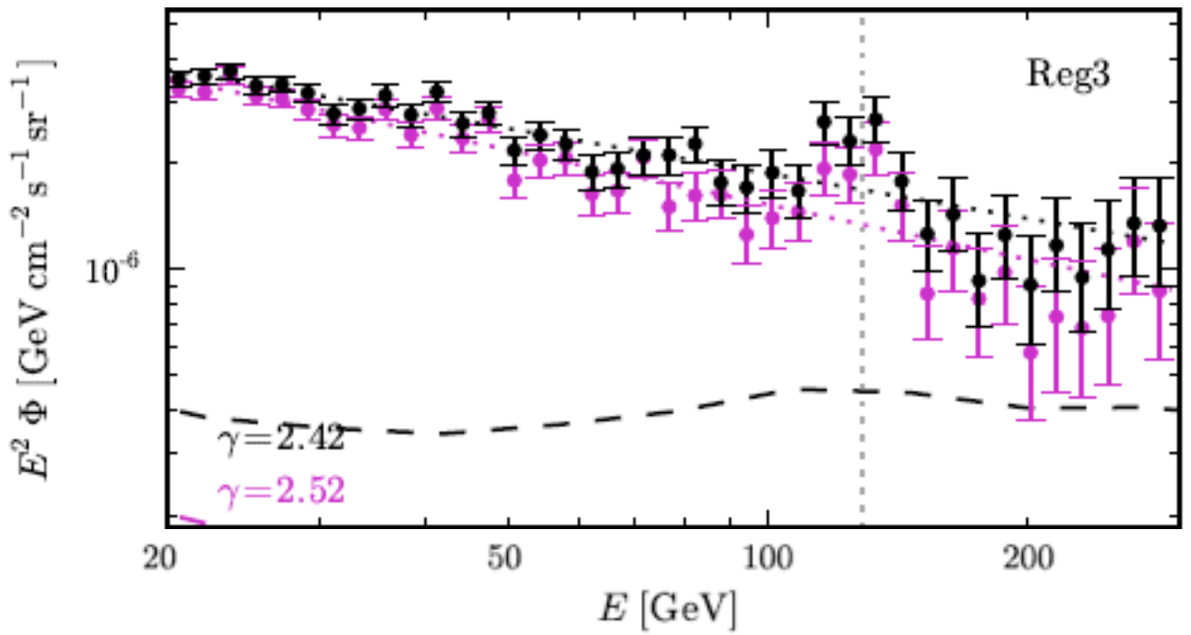
Smoking gun signature of dark matter particle



Fermi-LAT collaboration

Evidence for a gamma-ray line at ~130 GeV from Galactic center





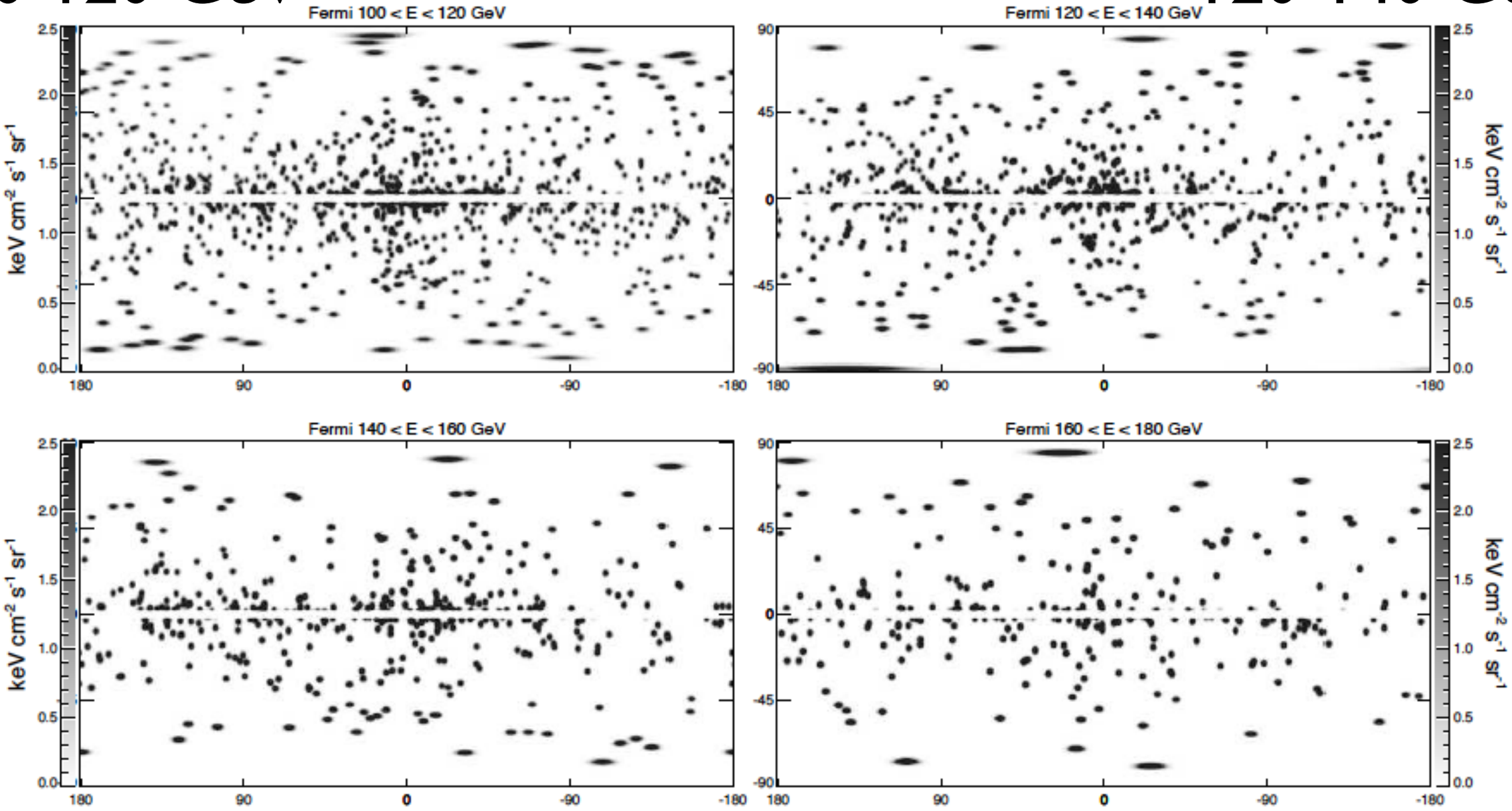
$$\frac{dJ}{dE} = S\ \delta(E - E_\gamma) + \beta \left(\frac{E}{E_\gamma}\right)^{-\gamma}$$

Weniger (2012)

Fermi-LAT maps at 100-180 GeV

100-120 GeV

120-140 GeV



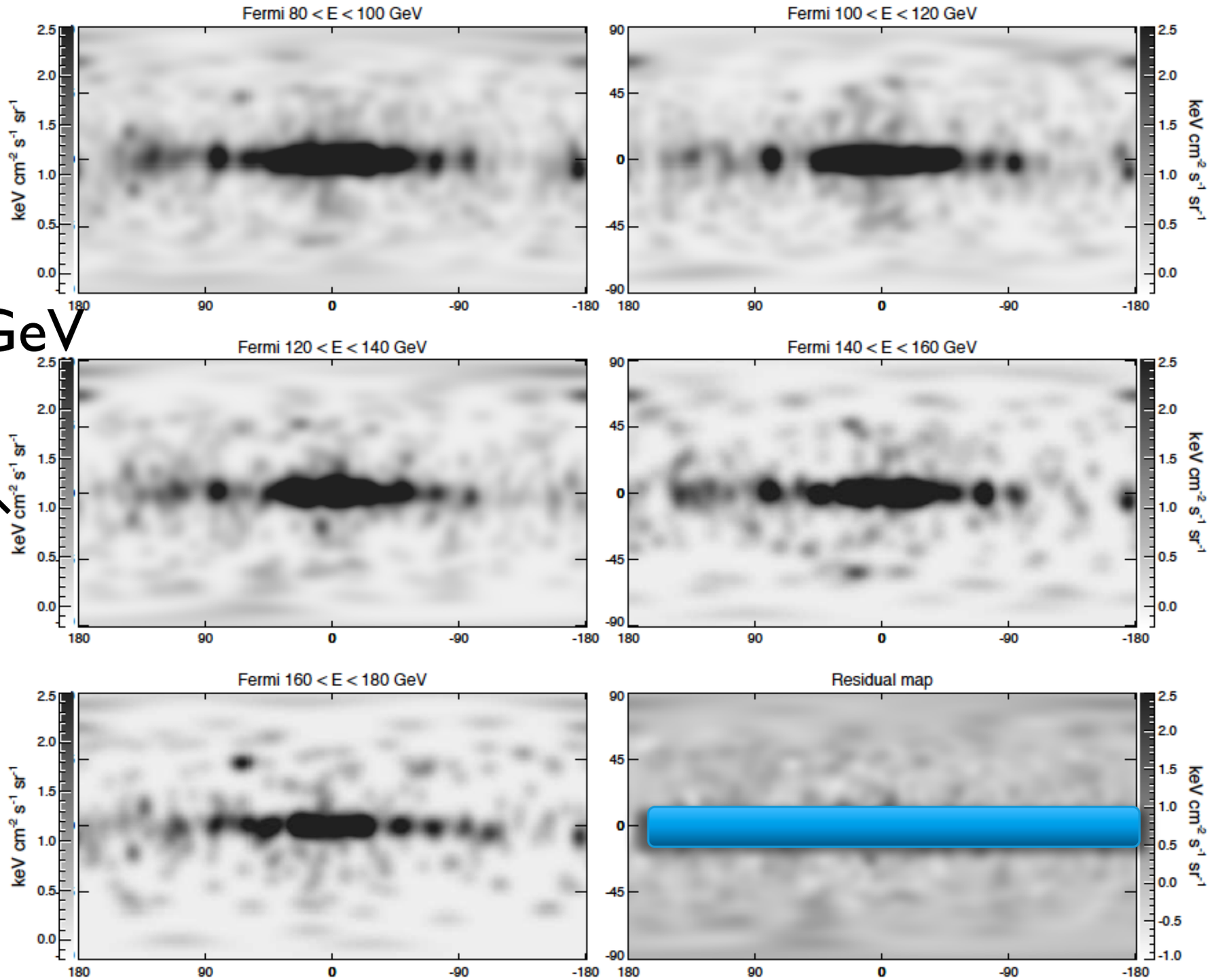
140-160 GeV

MS & Finkbeiner (2012)

160-180 GeV

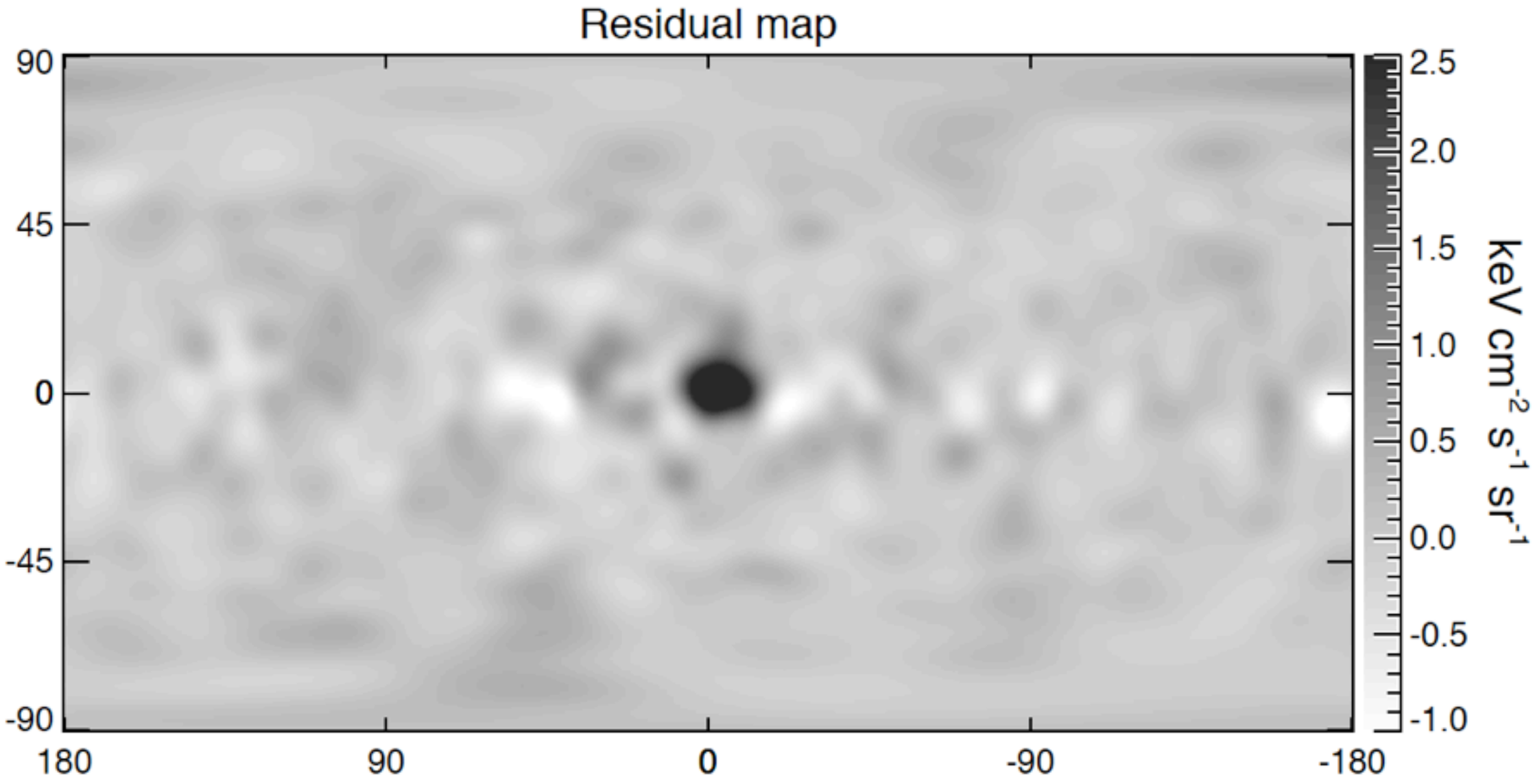
Smoothed with 10 degree Gaussian

120-140 GeV



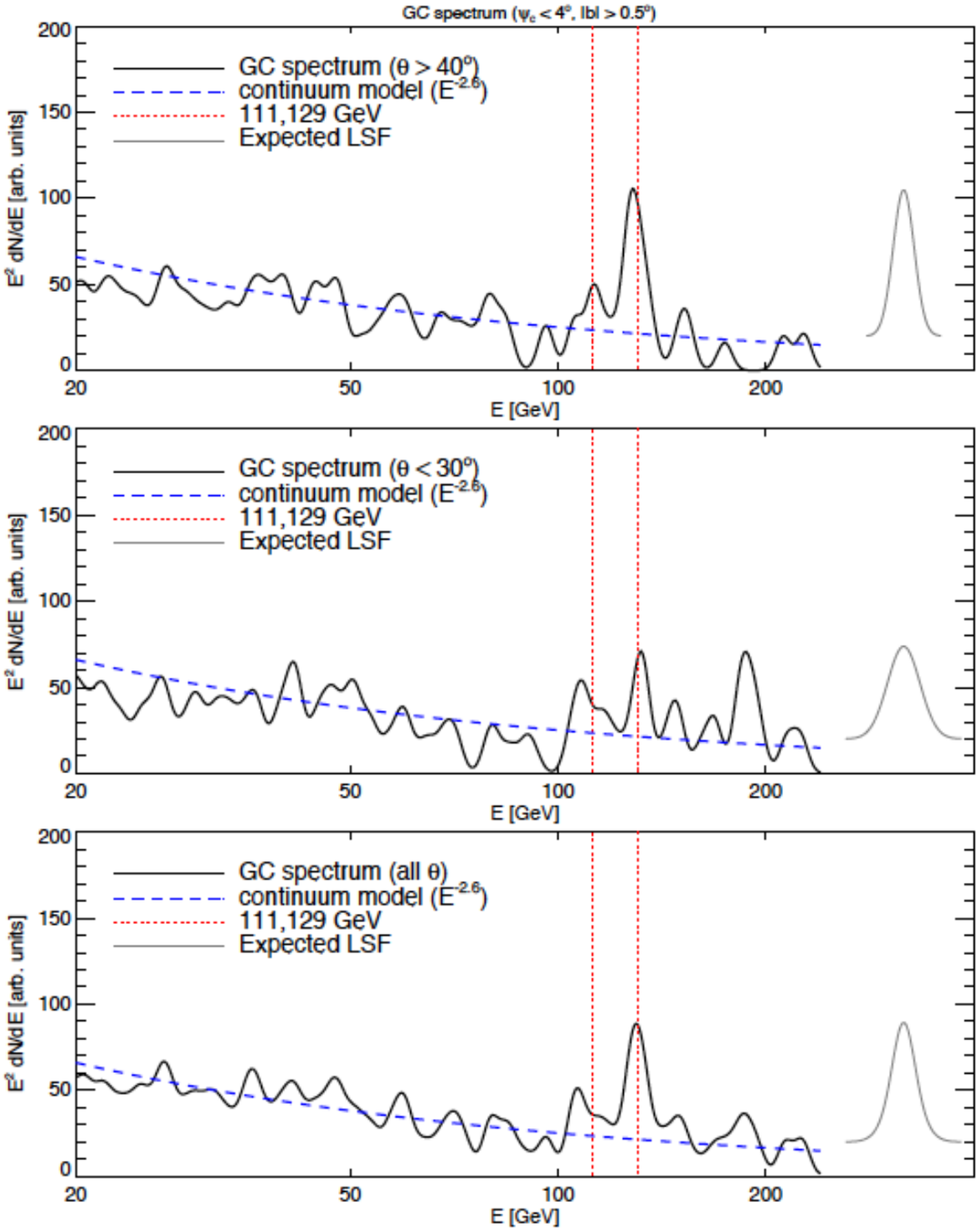
MS & Finkbeiner (2012)

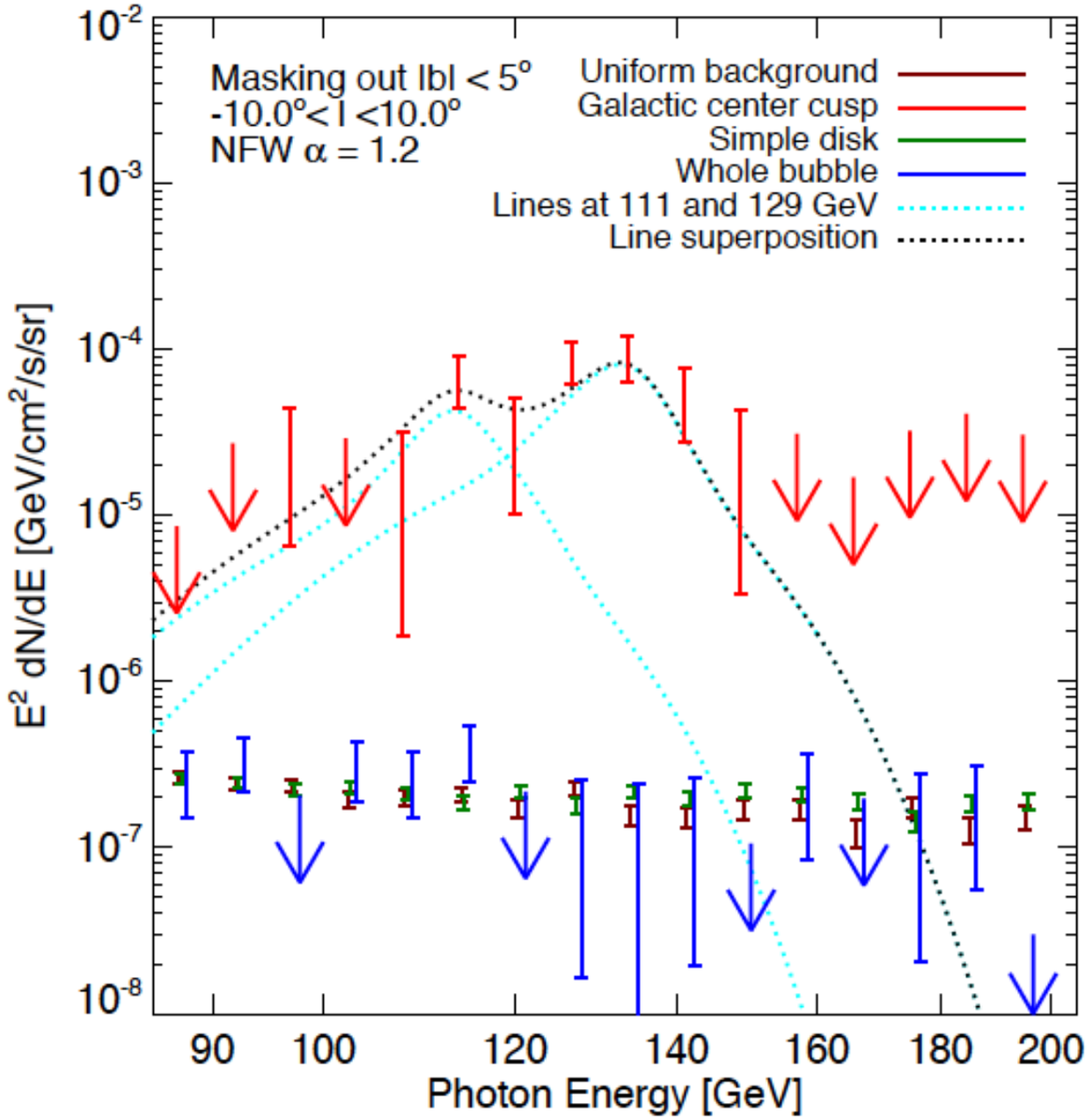
MS & Finkbeiner (2012)



MS & Finkbeiner (2012)

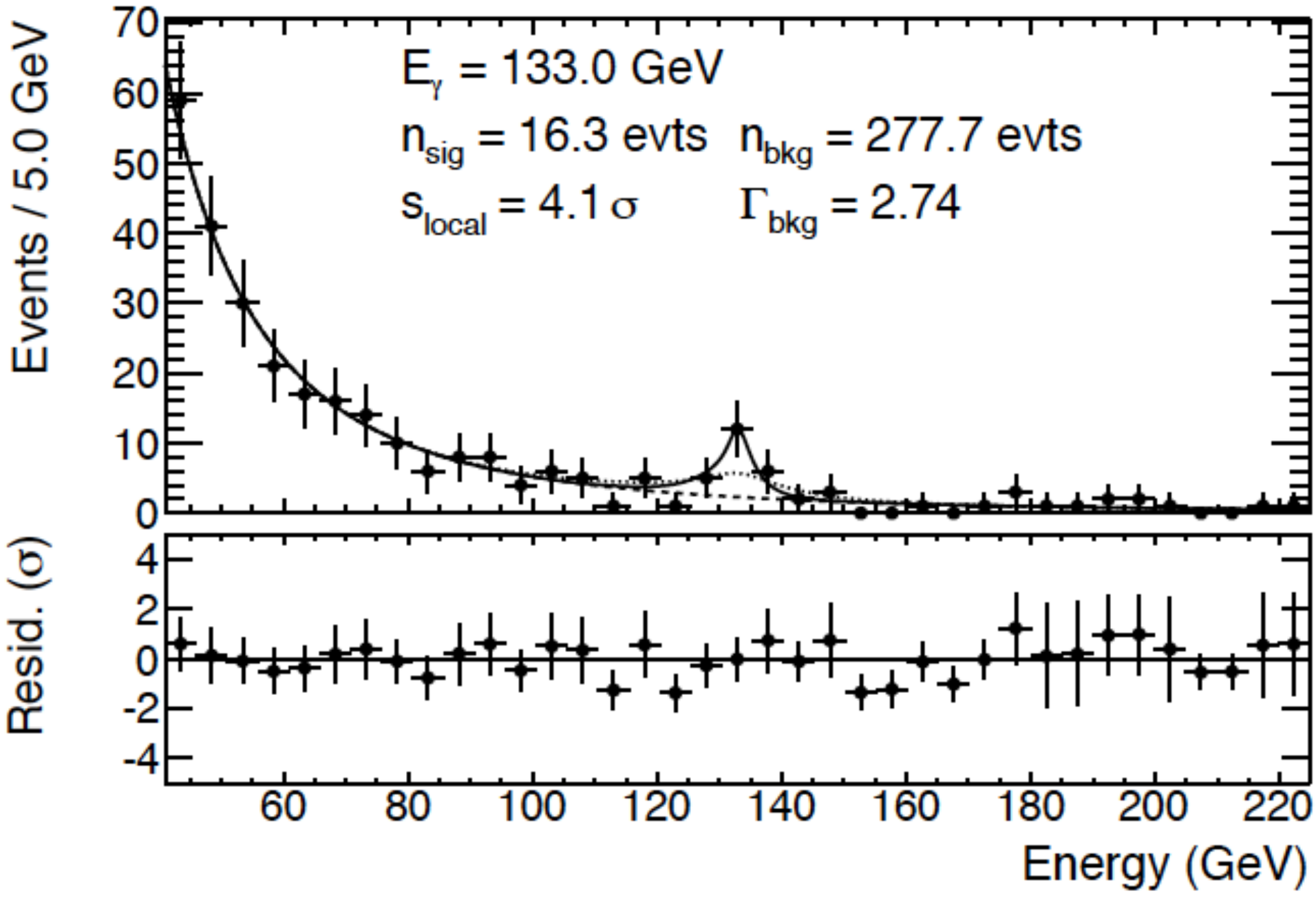
Properly fitting spectrum





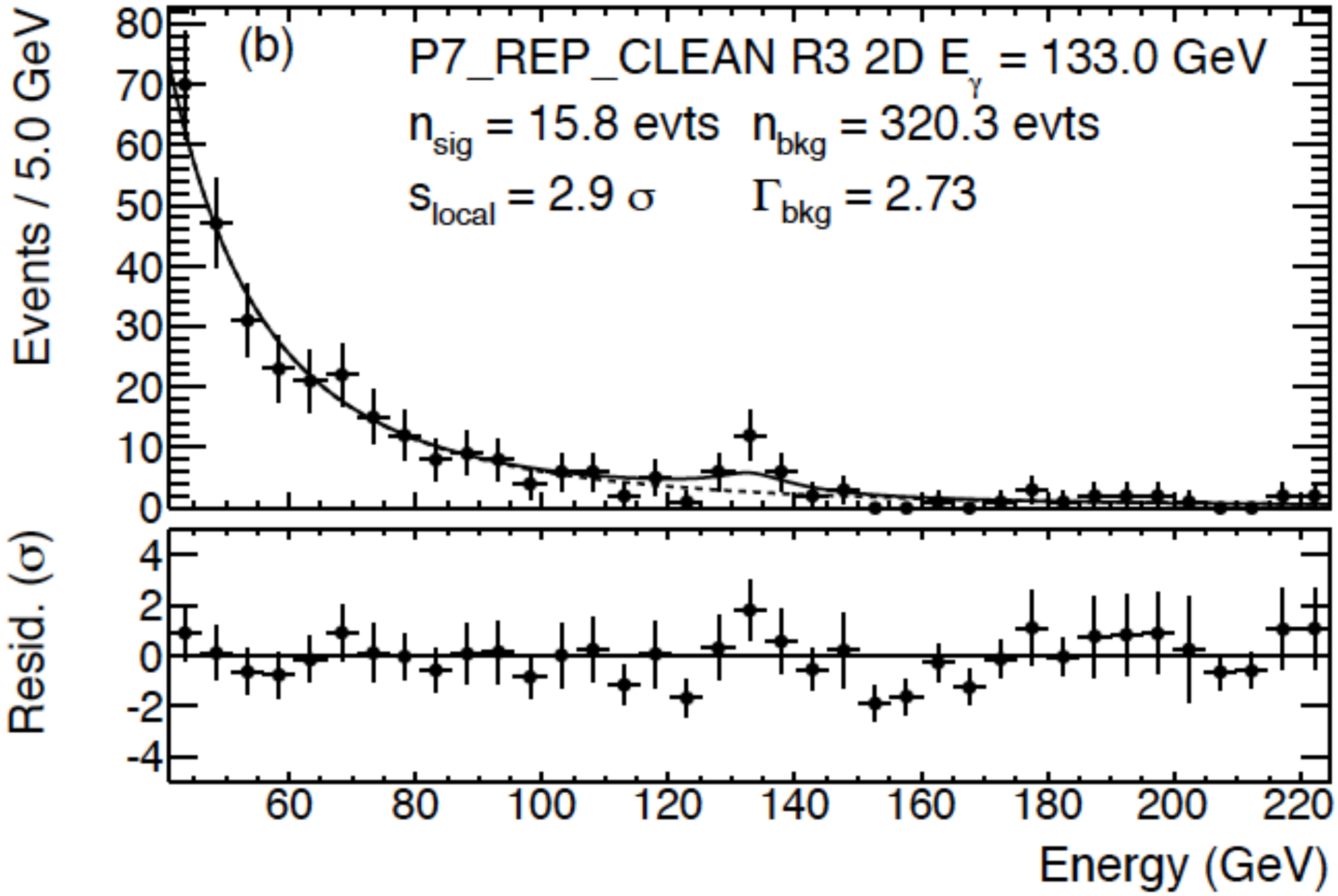
MS & Finkbeiner (2012)

Line search result from Fermi-LAT collaboration



Fermi-LAT collaboration (2013)

The 130 GeV line is too narrow



Fermi-LAT collaboration (2013)

What can go wrong?

Is the 130 GeV Line Real? A Search for Systematics in the Fermi-LAT Data

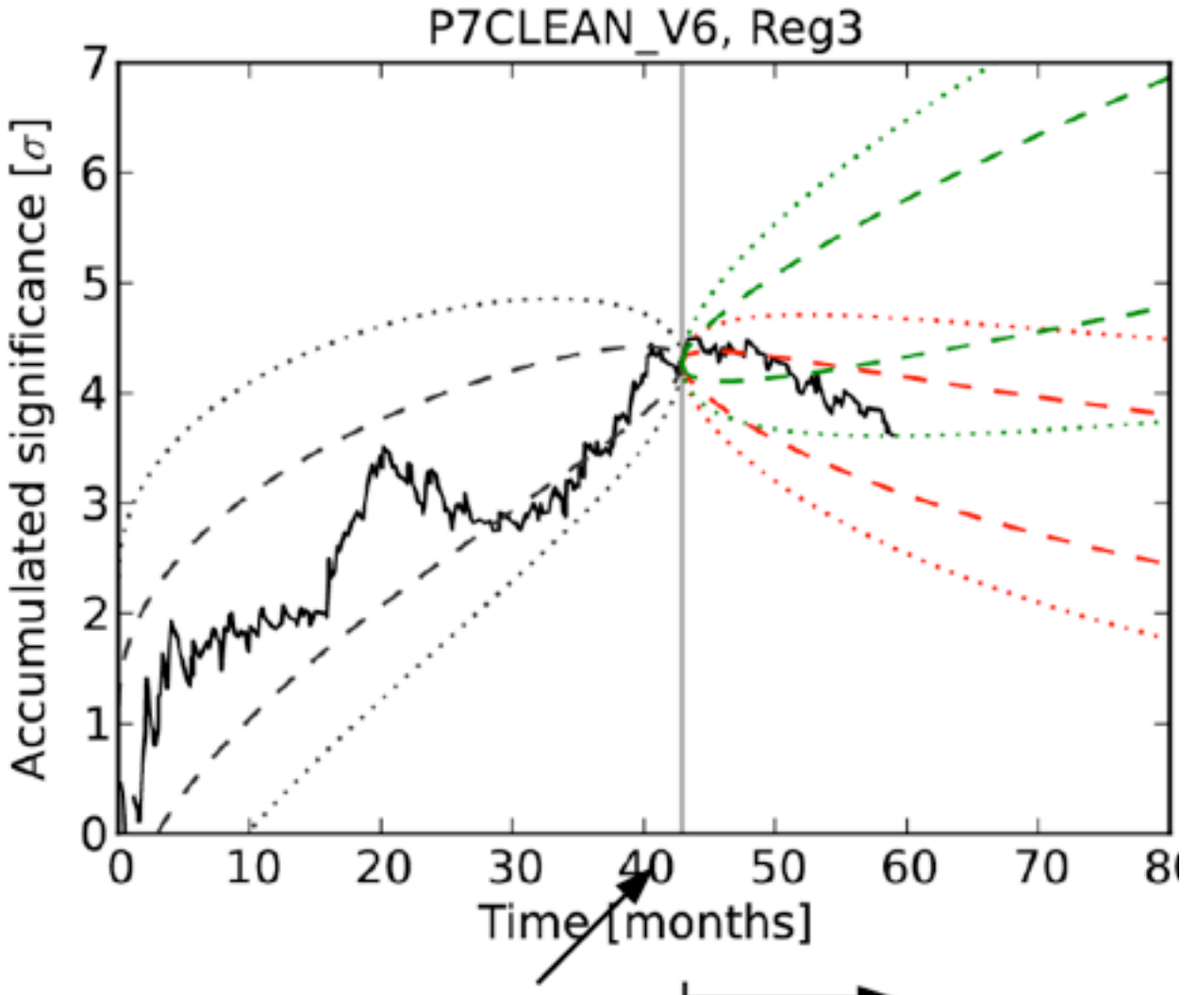
Douglas P. Finkbeiner,[1,2] Meng Su,[1,3,4] and Christoph Weniger[5]

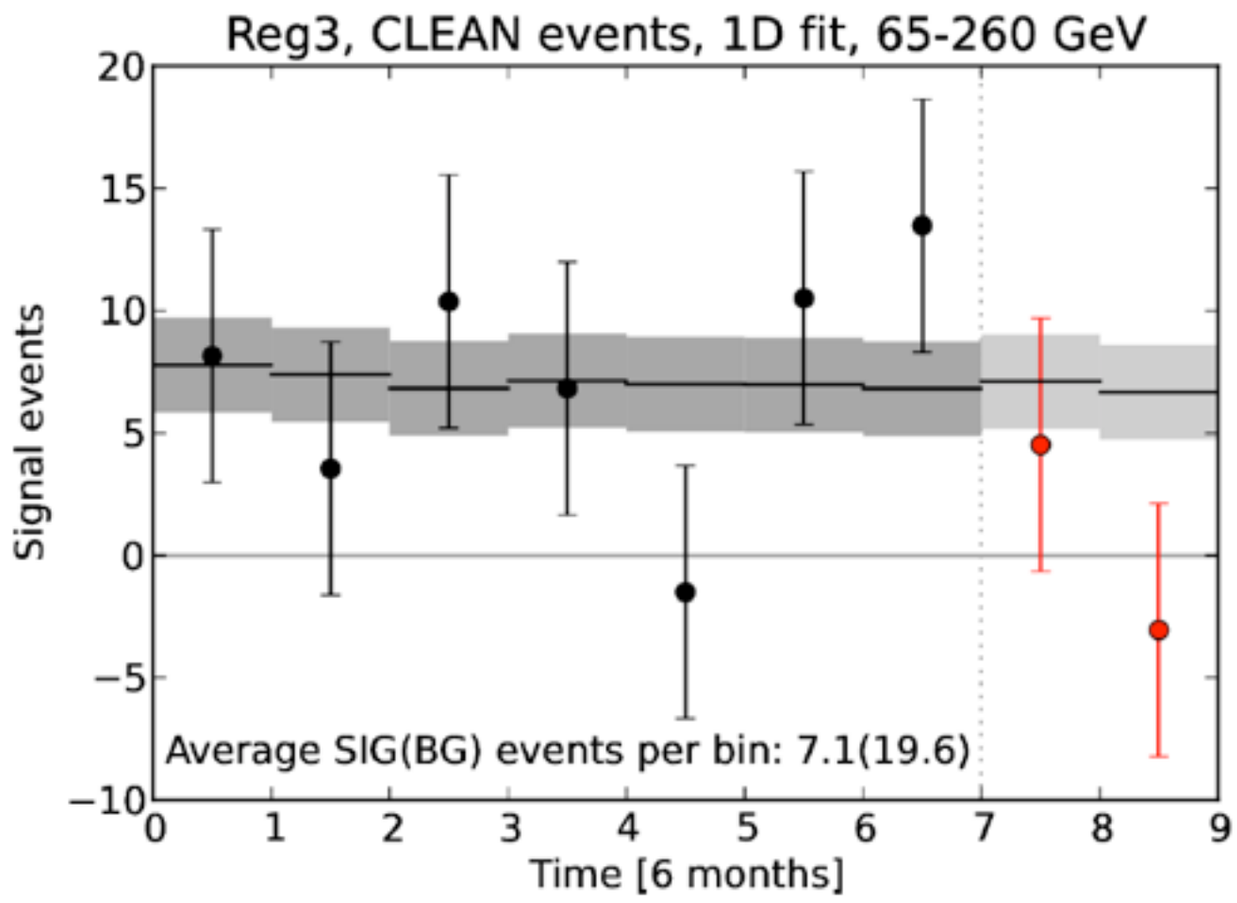
[1] *Institute for Theory and Computation, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, MS-51, Cambridge, MA 02138, USA*
[2] *Center for the Fundamental Laws of Nature, Physics Department, Harvard University, Cambridge, MA 02138 USA*
[3] *Department of Physics, and Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[4] *Einstein Fellow*
[5] *Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany*

Our recent claims of a Galactic center feature in *Fermi*-LAT data at approximately 130 GeV have prompted an avalanche of papers proposing explanations ranging from dark matter annihilation to exotic pulsar winds. Because of the importance of such interpretations for physics and astrophysics, a discovery will require not only additional data, but a thorough investigation of possible LAT systematics. While we do not have access to the details of each event reconstruction, we do have information about each event from the public event lists and spacecraft parameter files. These data allow us to search for suspicious trends that could indicate a spurious signal. We consider several hypotheses that might make an instrumental artifact more apparent at the Galactic center, and find them implausible. We also search for an instrumental signature in the Earth limb photons, which provide a smooth reference spectrum for null tests. We find no significant 130 GeV feature in the Earth limb sample. However, we do find a marginally significant 130 GeV feature in Earth limb photons with a limited range of detector incidence angles. This raises concerns about the 130 GeV Galactic center feature, even though we can think of no plausible model of instrumental behavior that connects the two. A modest amount of additional limb data would tell us if the limb feature is a statistical fluke. If the limb feature persists, it would raise doubts about the `Pass 7` processing of $E > 100$ GeV events. At present we find no instrumental systematics that could plausibly explain the excess Galactic center emission at 130 GeV.

Finkbeiner, MS, Weniger (2012)

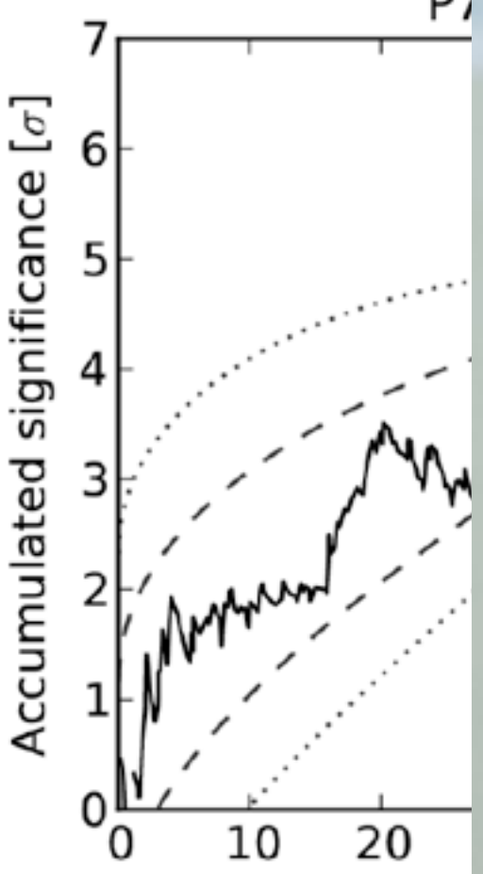
What happened after the "line claim"

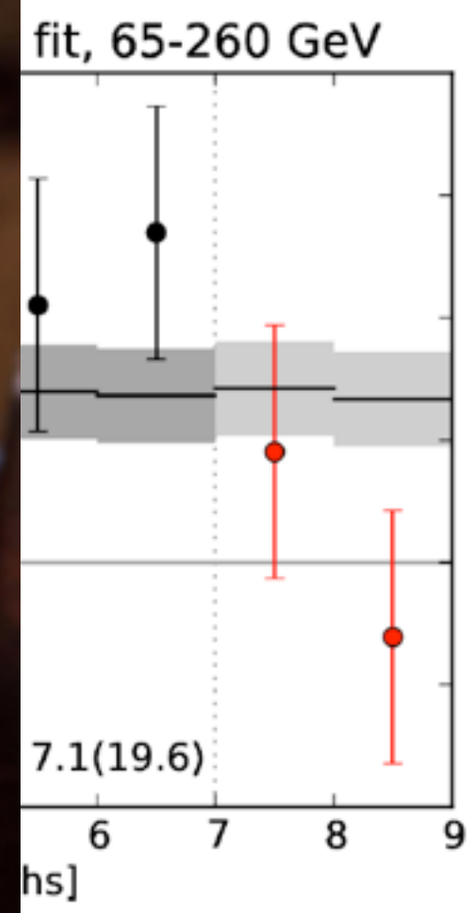




Weniger, MS, et al. (2013)

What happened after the “line claim”





Definition of signal hypothesis

Trial-free measurement

Weniger, MS, et al. (2013)

What's next

- Improved events selection/calibration
- Change Fermi's survey strategy
- Current/future gamma-ray detectors in space
- Current/future ground-based Cherenkov telescopes

Fermi white paper call: three were selected for committee review

- Fermi-LAT collaboration (19 pages, no change)
- Fermi-GBM collaboration (4 pages, doesn't matter)
- Weniger, MS, et al. (21 pages, immediate change)

Committee Recommendation:

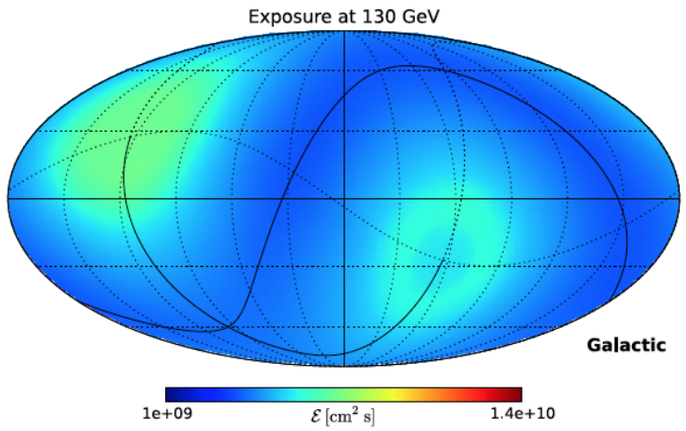
"We recommend that the Fermi mission undertake a new observing strategy that emphasizes coverage of the Galactic center region"

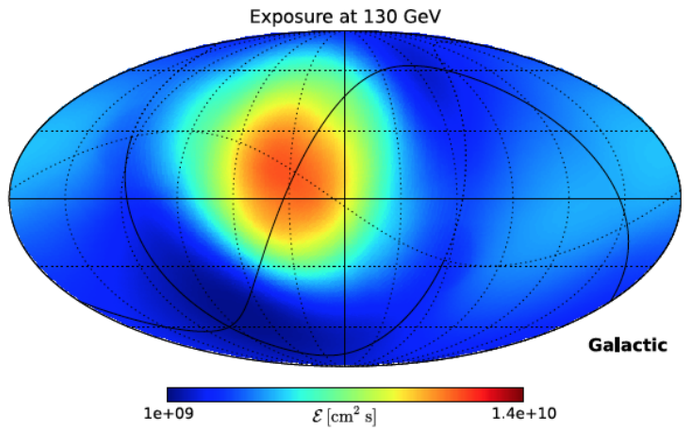
Our motivation

- The passage of the "G2 cloud" around central BH
- Young, energetic gamma-ray pulsars towards the inner Galaxy
- 130 GeV line

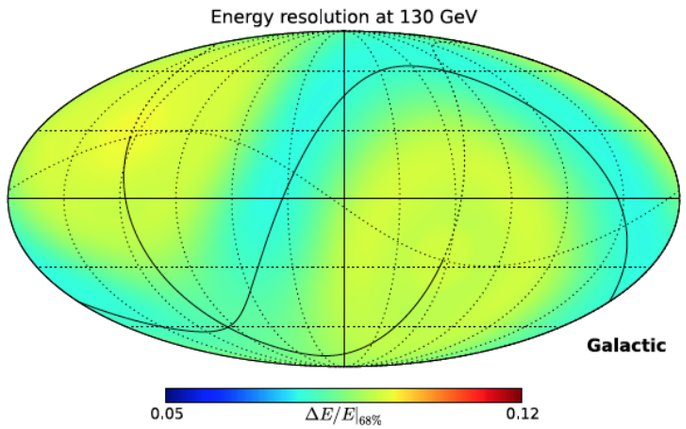
Fermi White Paper Call for Alternative Fermi Observing Strategies

Exposure map:





Energy resolution:



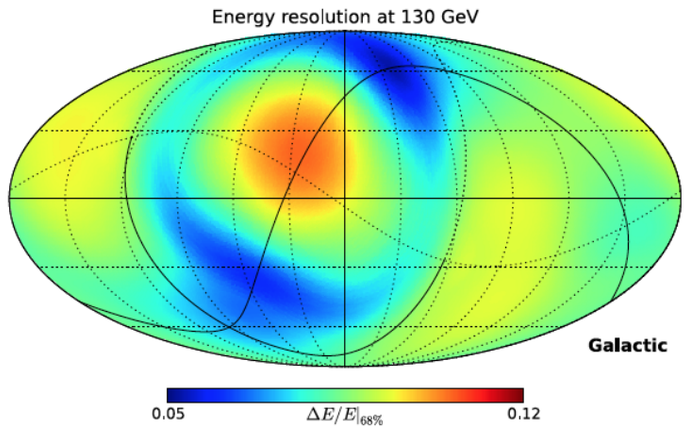
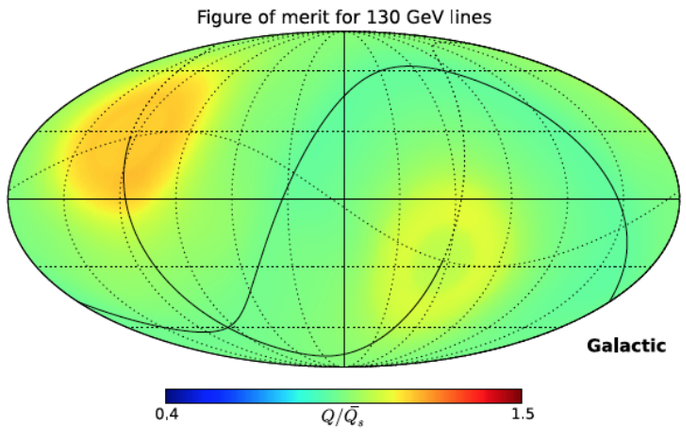
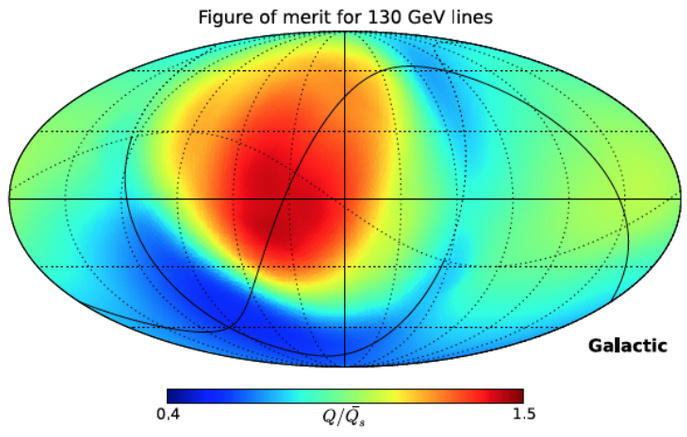


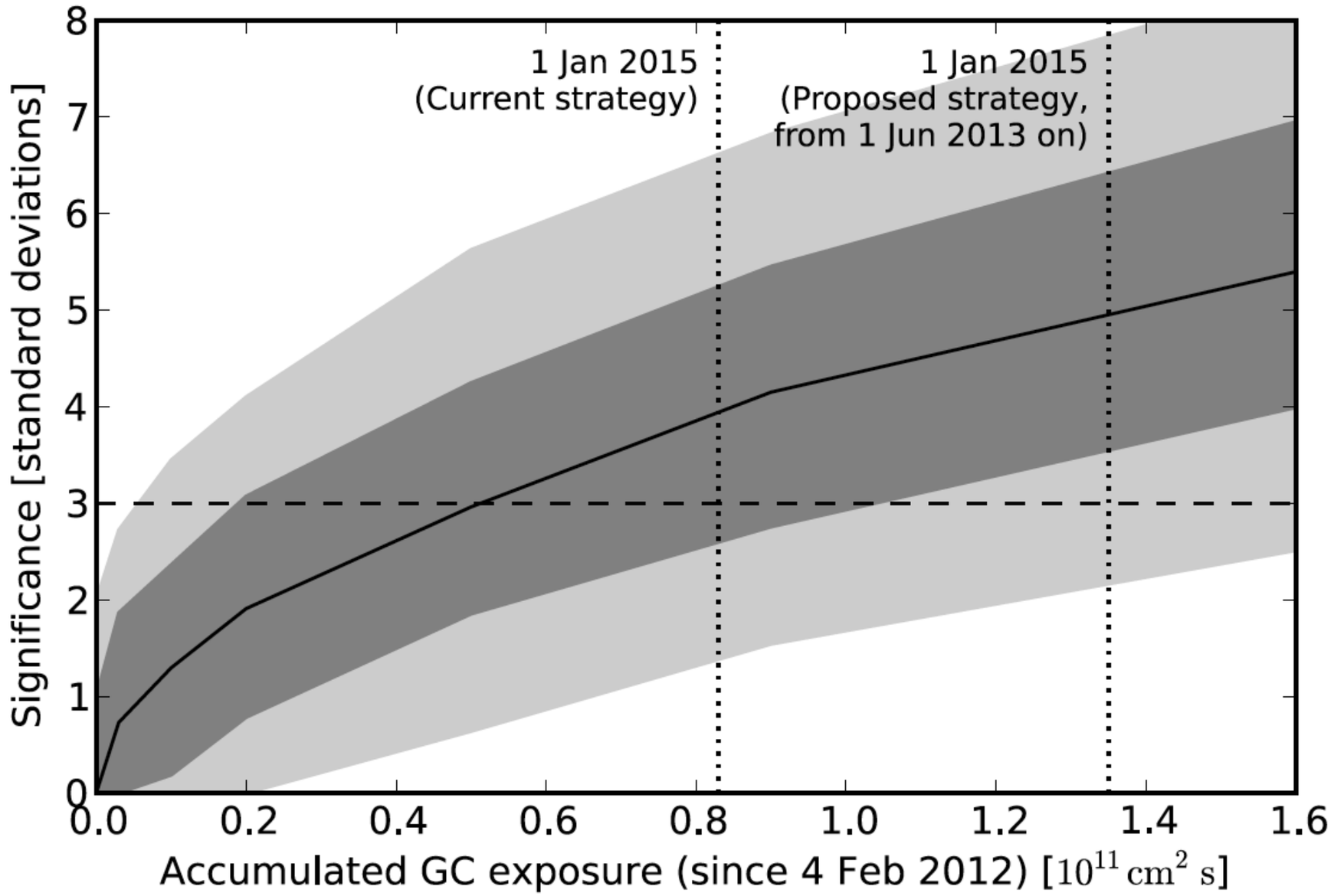
Figure of merit:





Weniger, MS, et al. (2013)

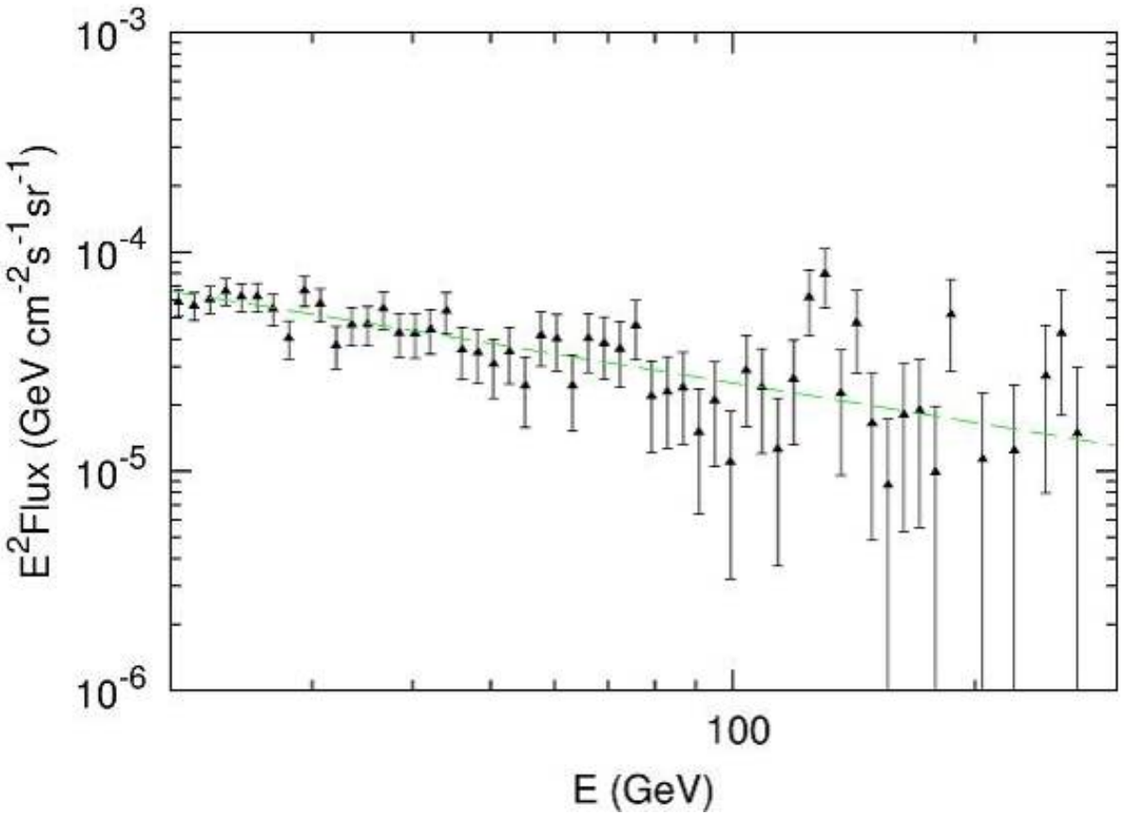
Predicted significance if it's a real signal



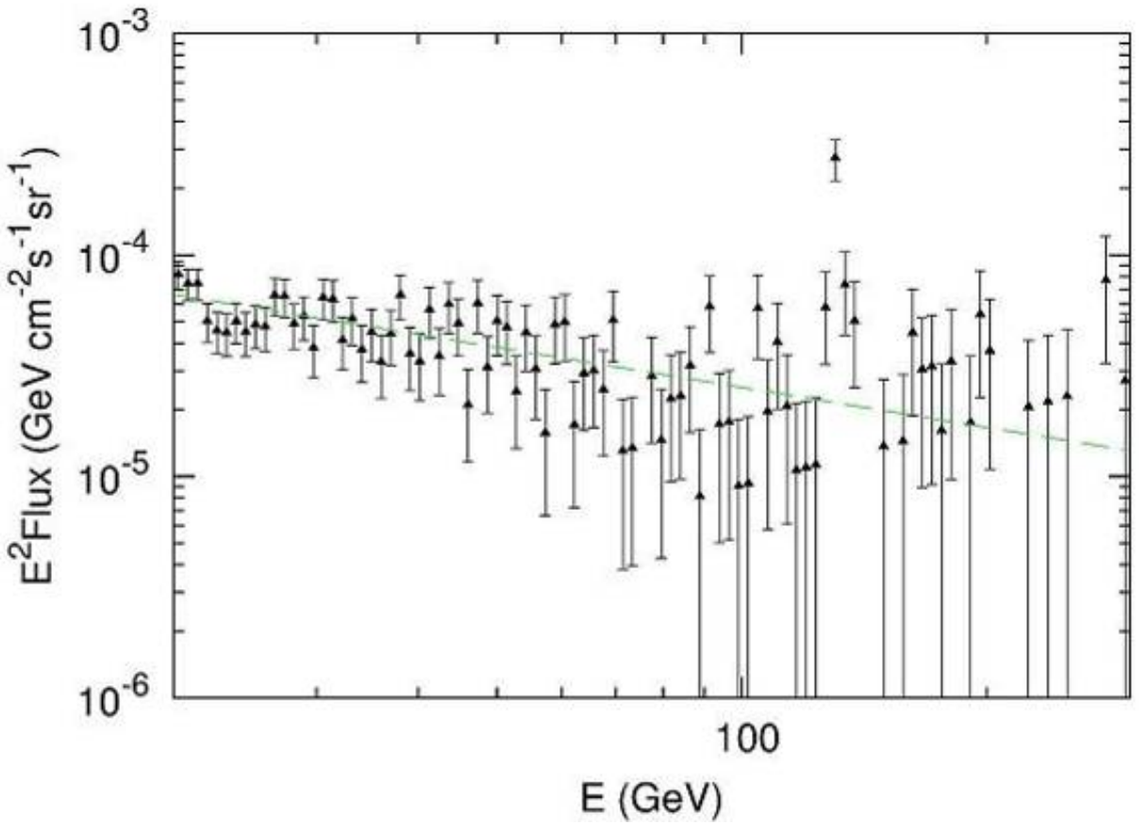
Weniger, MS, et al. (2013)

IF the 130 GeV line is real

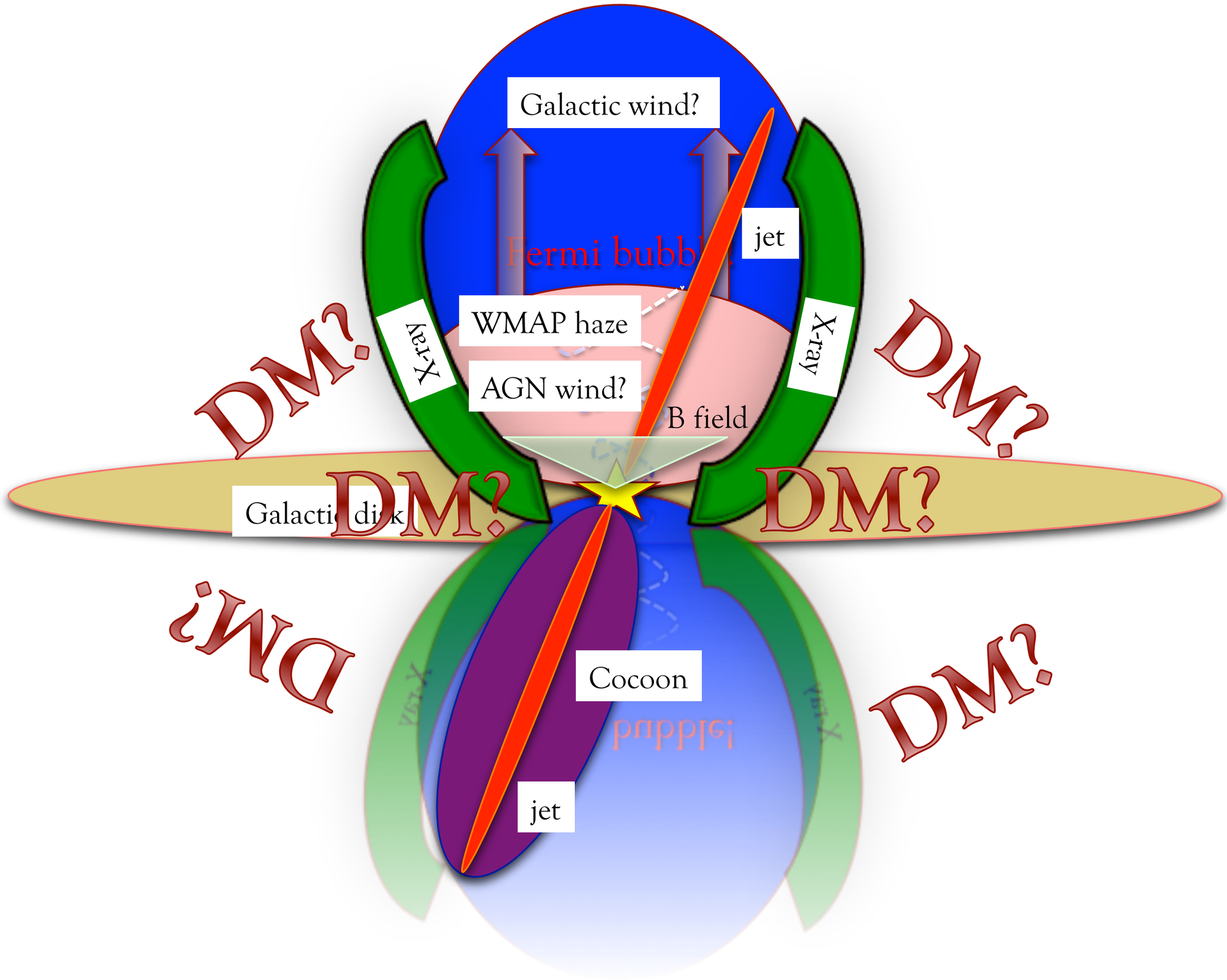
Fermi 4 years



DAMPE 3 years



8 sigma detection!

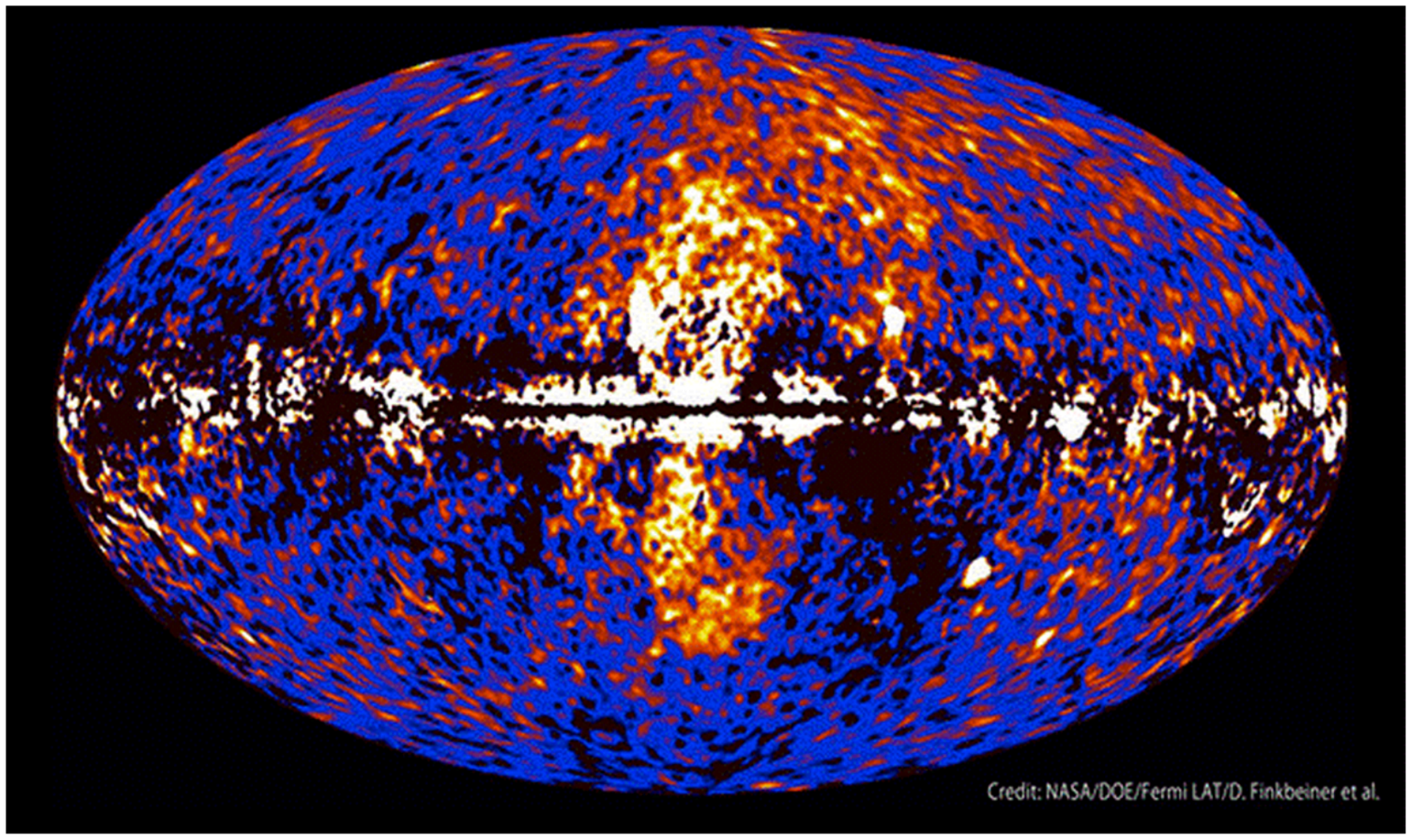

Galactic wind?
Fermi bubble
jet
WMAP haze
X-ray
X-ray
AGN wind?
B field
DM?
DM?
DM?
DM?
Galactic disk
Cocoon
jet
DM?
DM?

Home
Registration
Participant List
Program
Payment Information
Travel & Directions
Visa
Accommodations
Contact
KIPAC Home

The Fermi Bubbles: Theory and Observations

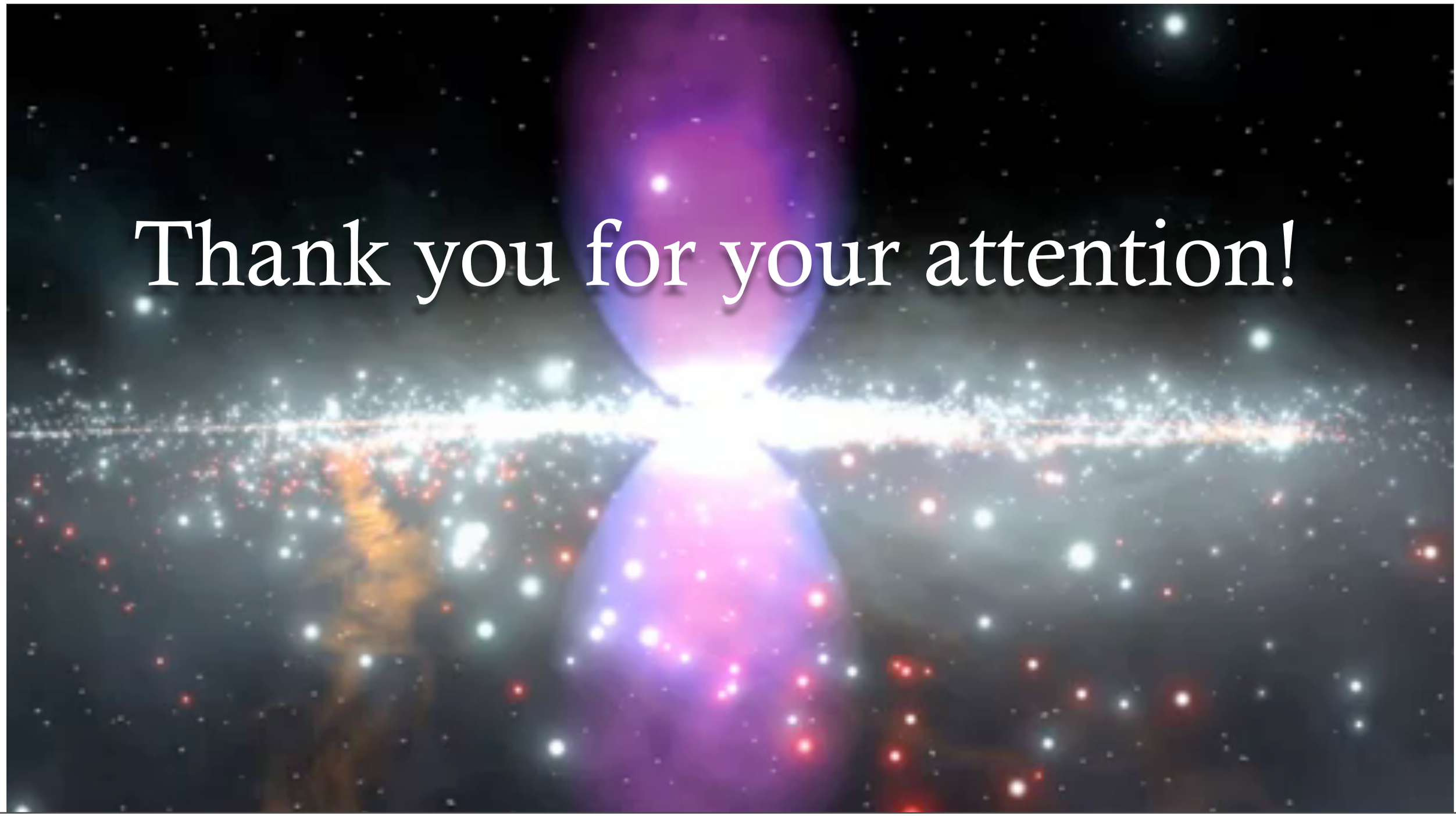
April 11 - 12, 2013

SLAC National Accelerator Laboratory, Menlo Park, California

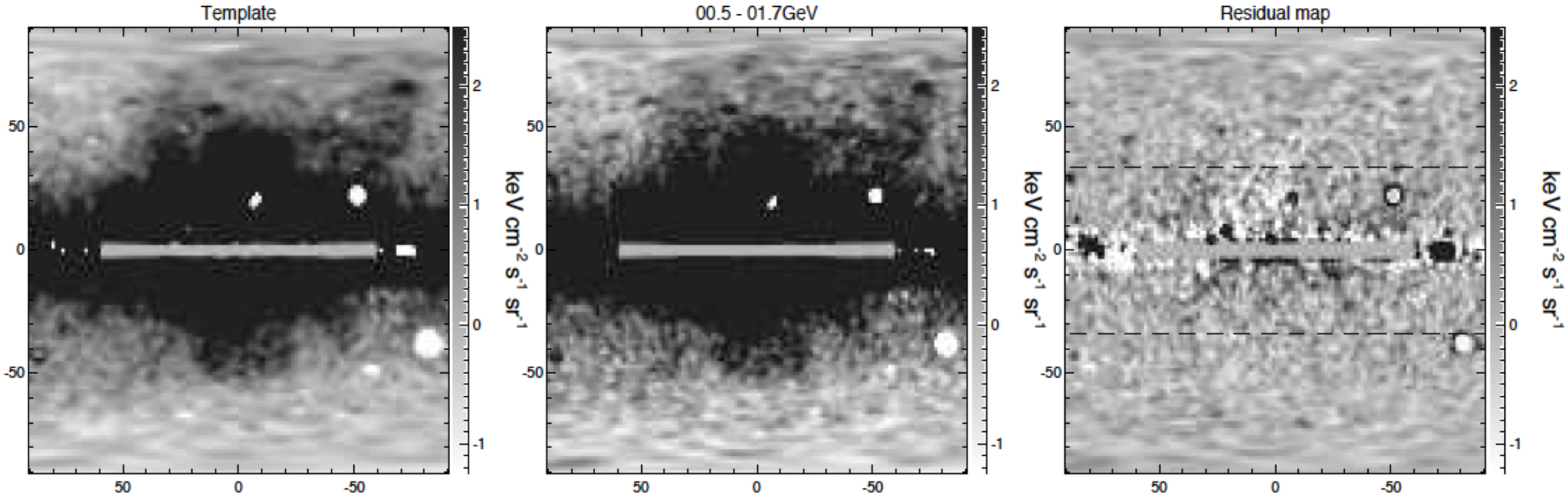


The Fermi bubbles are two large structures in gamma-rays above and below the Galactic center. They are associated with the microwave haze around the Galactic center discovered in the WMAP data and recently confirmed in the Planck data. At the moment, there are several theoretical models and simulations developed to explain the shape and the energy spectrum of the bubbles. In order to distinguish among the different models, a detailed comparison between the theory and the observations is necessary. The main purpose of the meeting is to foster a collaboration between the scientists working on the theoretical and observational sides of the problem in order to deepen our understanding of the origin and the emission mechanisms associated with the bubbles. The topics include: observational results related to the Galactic halo region, models and simulations designed to explain the bubbles, and related systems in other galaxies.

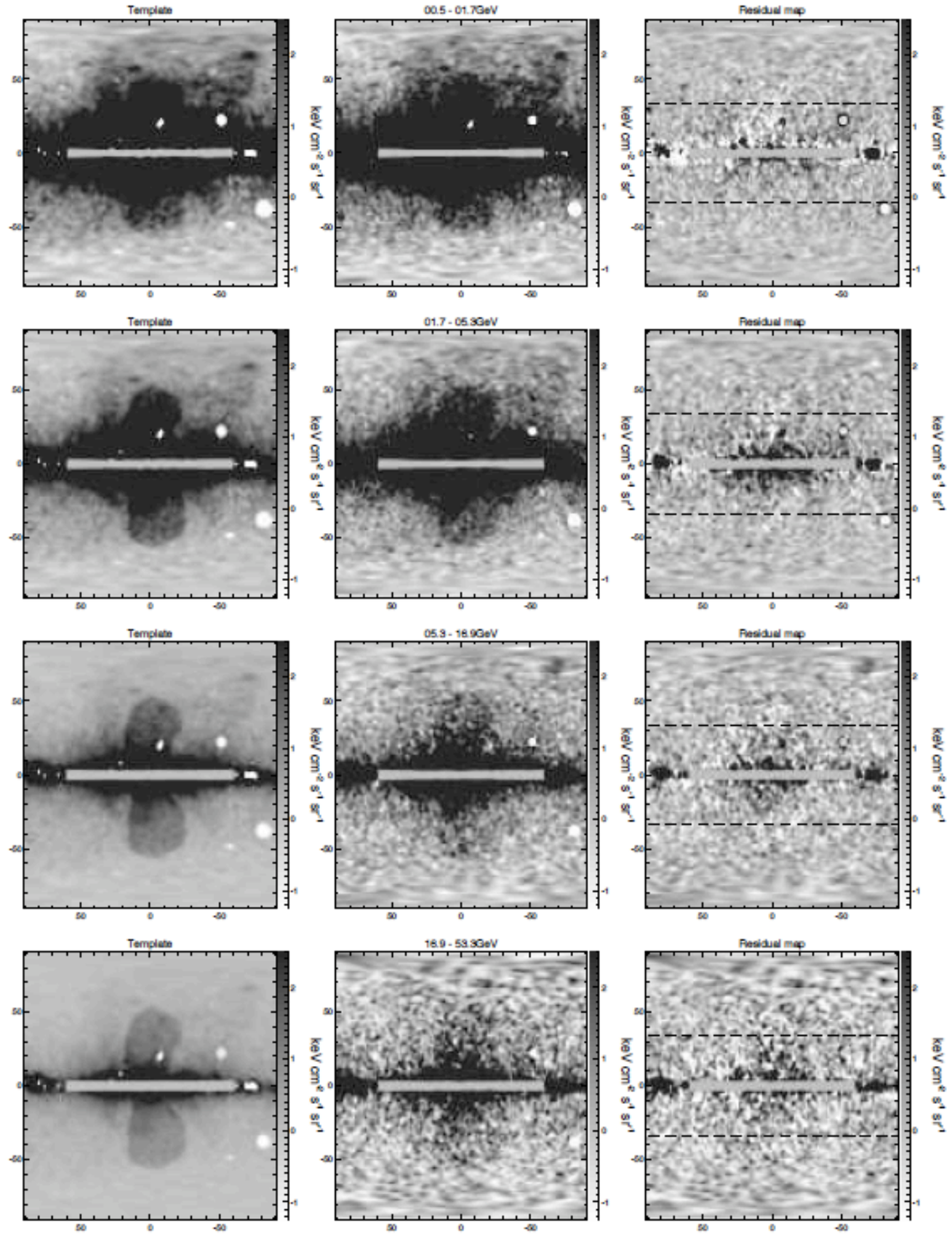
Never be surprised by the universe



Compare model with data:
Lower energy maps as templates

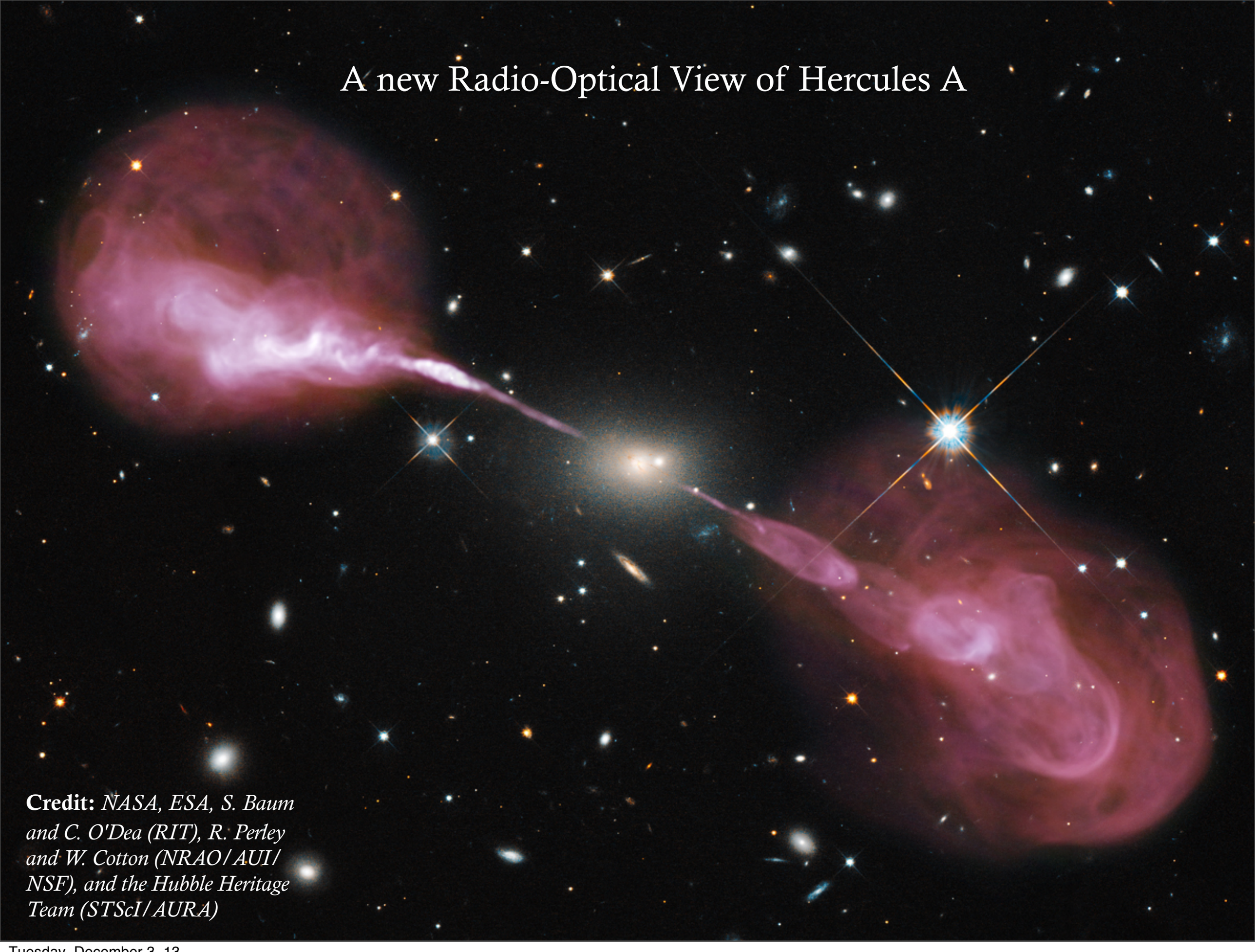


MS & Finkbeiner (2013)

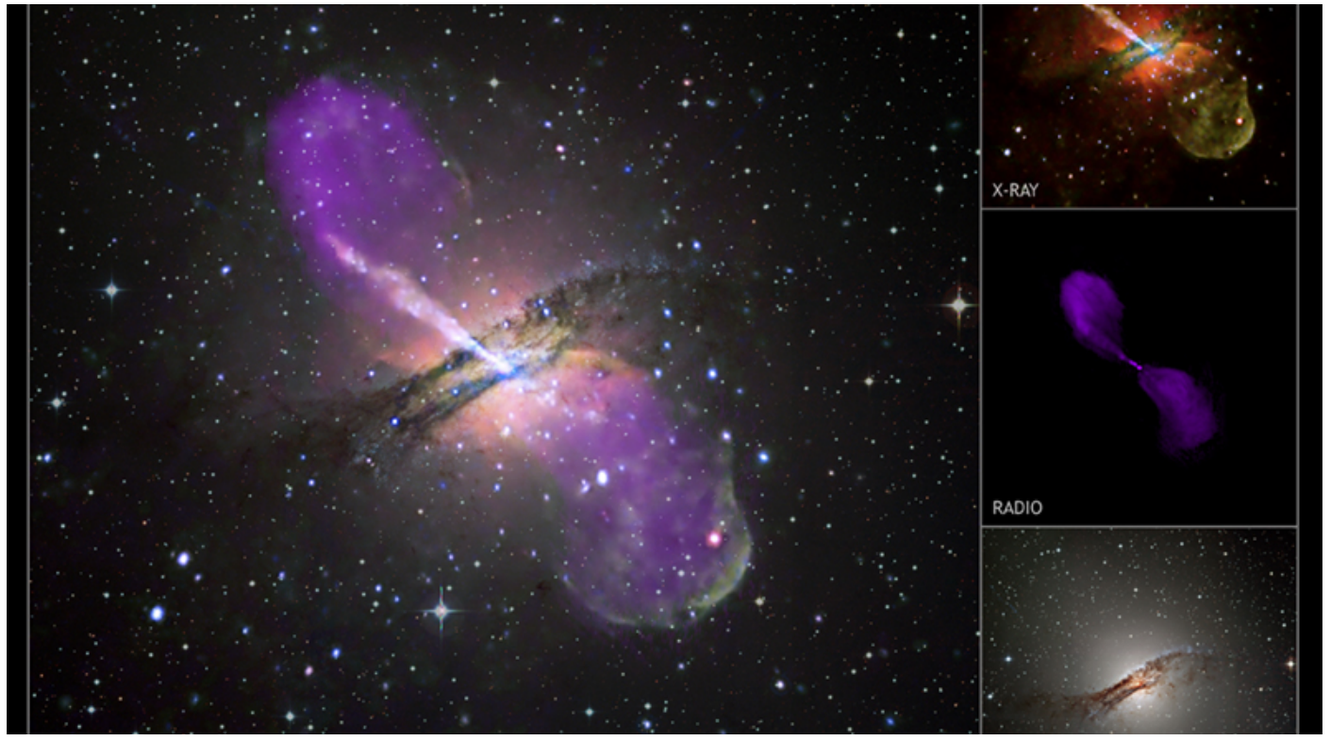


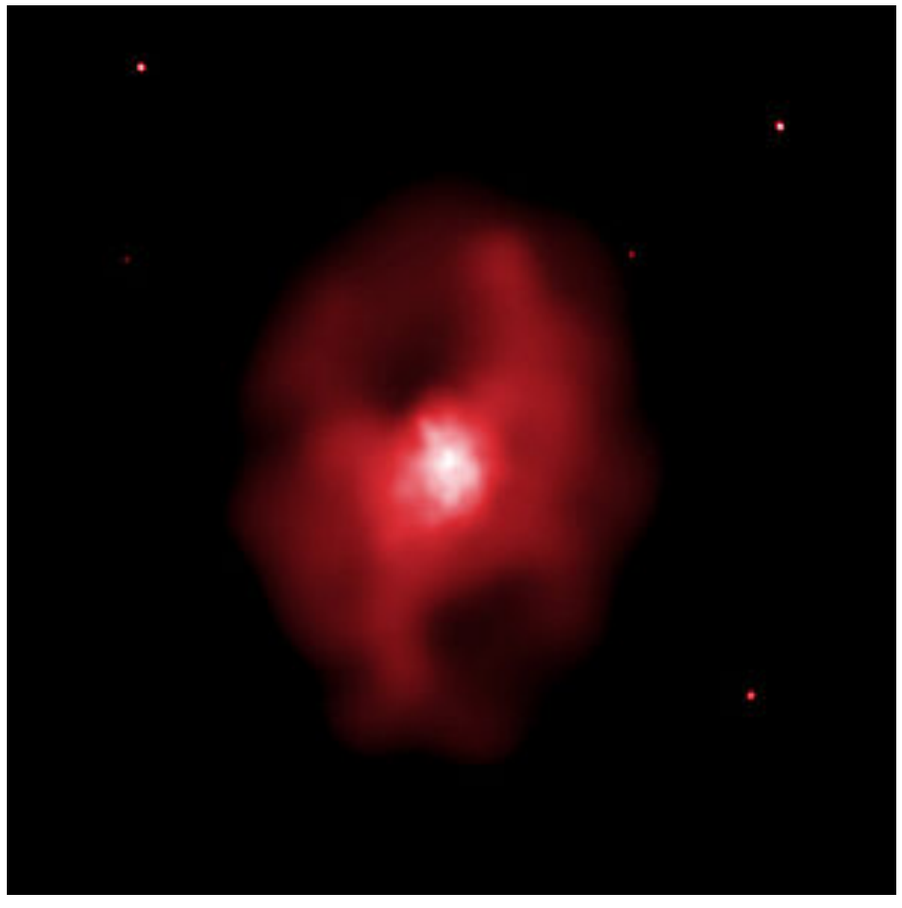
MS & Finkbeiner (2013)

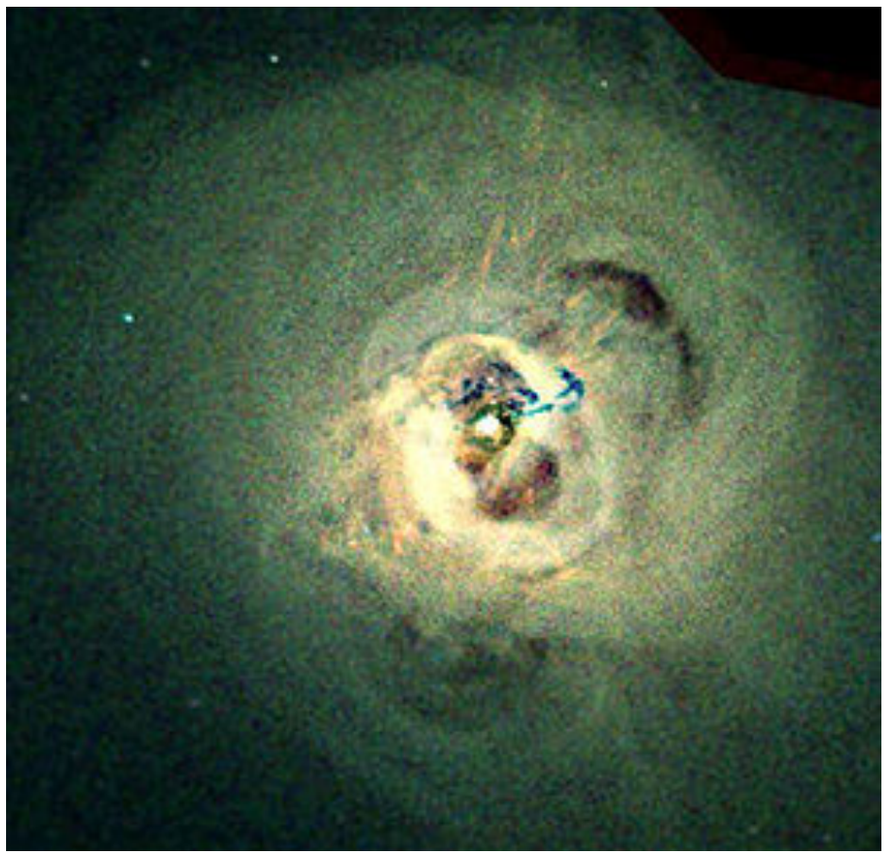
A new Radio-Optical View of Hercules A



Credit: *NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)*

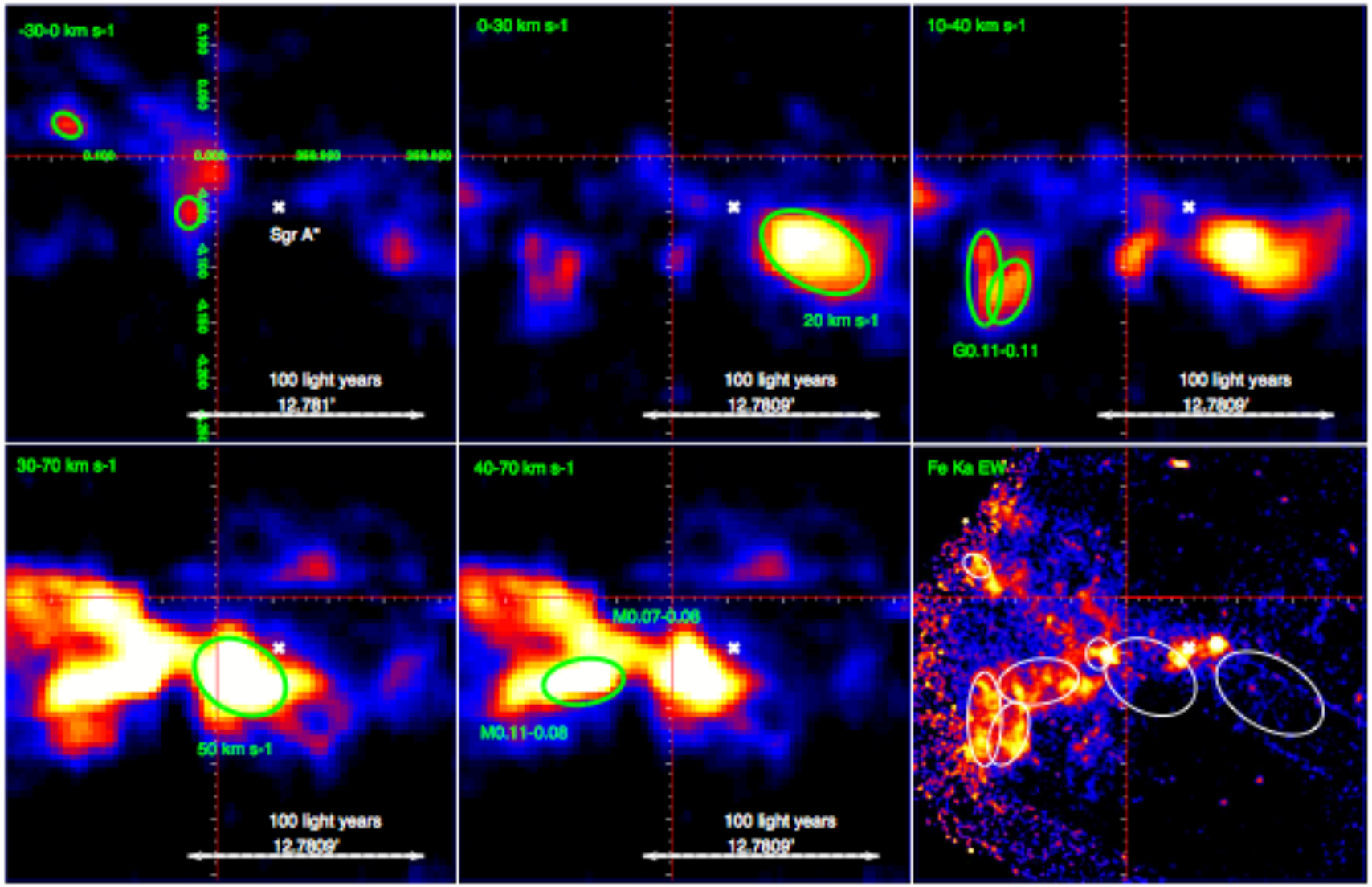

X-RAY
RADIO

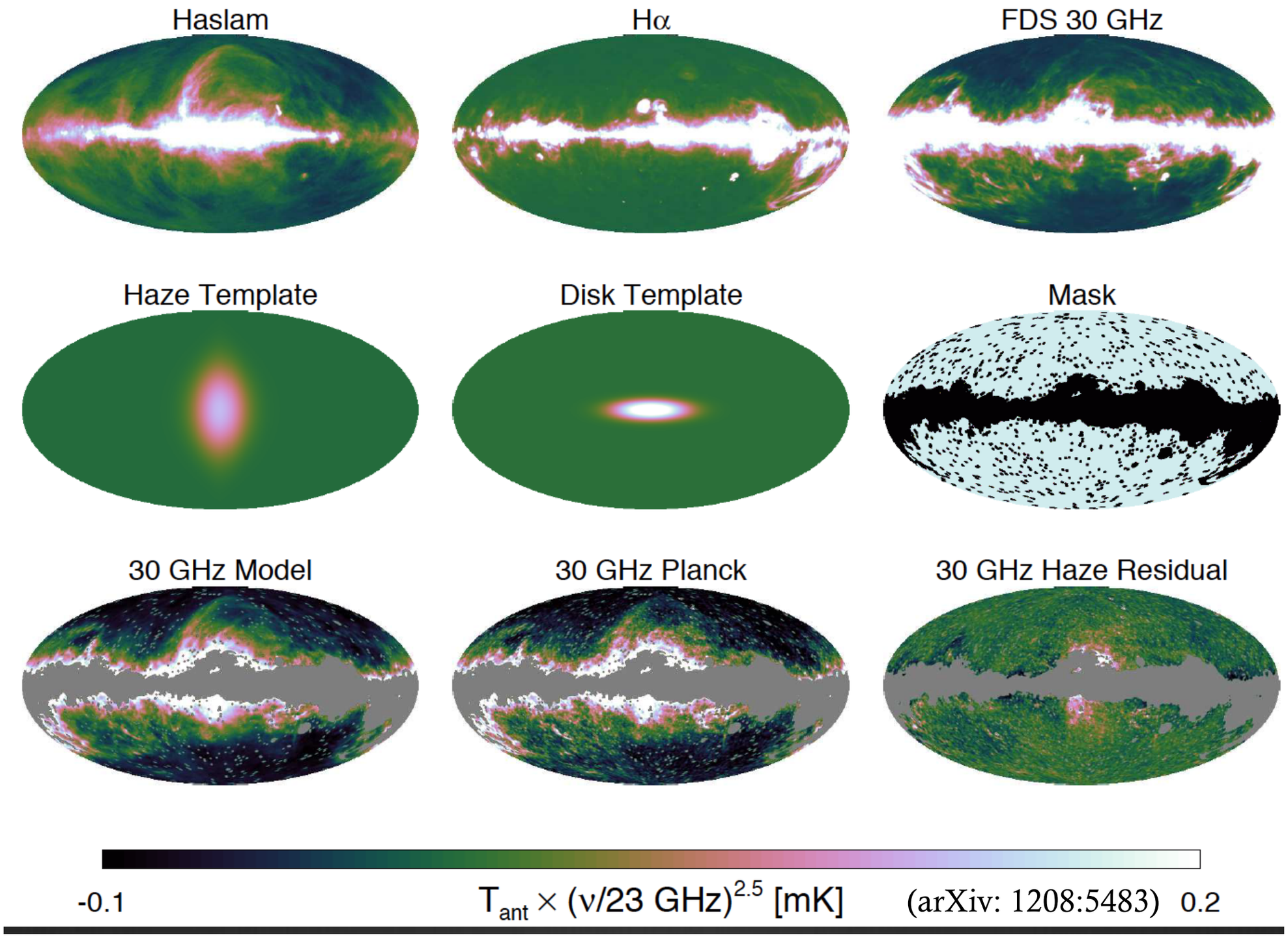


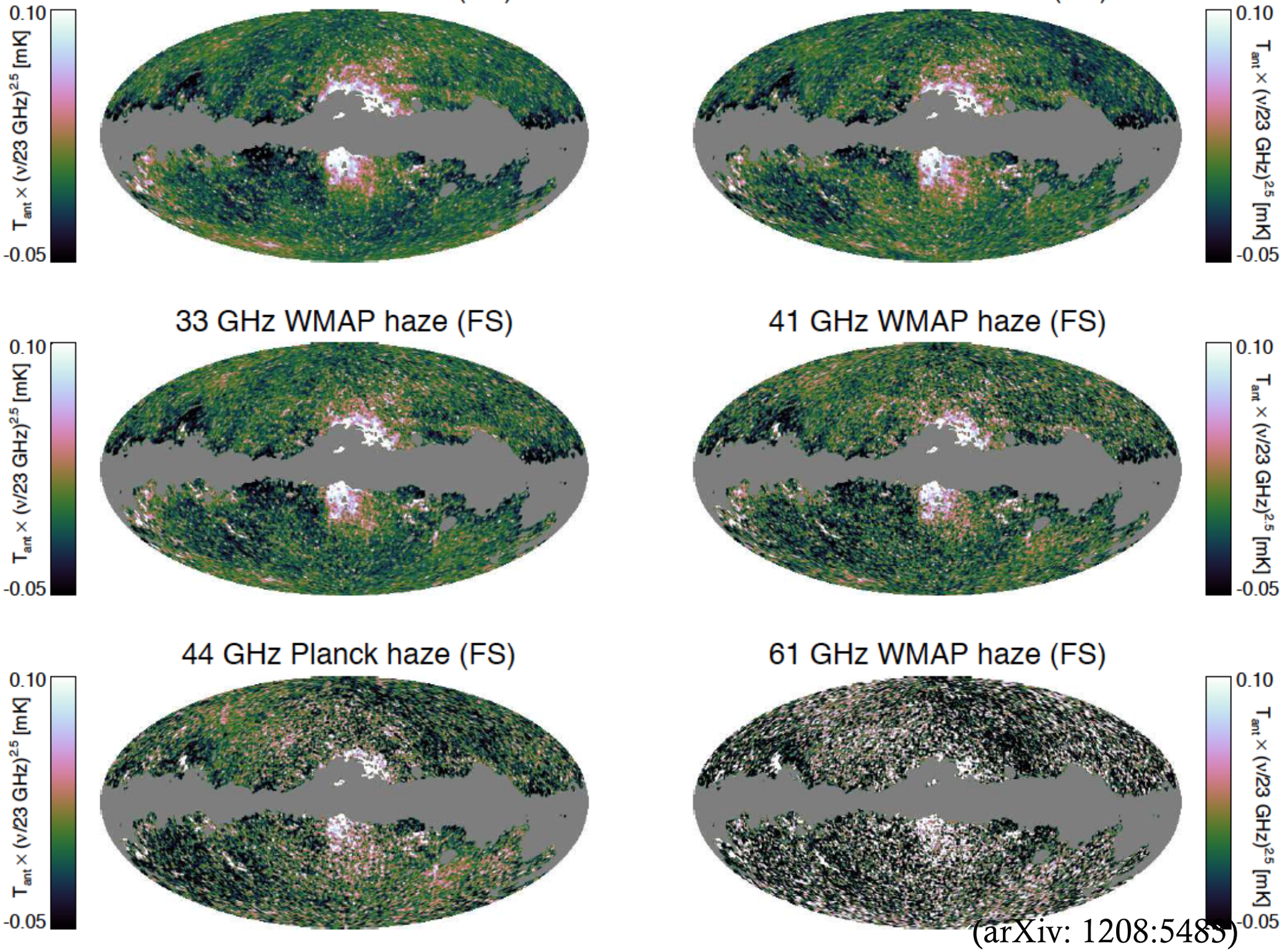


X-ray reflection nebulae in the GC

There are indications of previous GC activity from X-ray echoes and time variability of reflected X-ray lines (Sgr B1 and B2, Sgr C, and M0.11-0.11) They are likely due to reflected X-rays from previous activity of Sgr A* with high luminosity ~300 yr ago.




Haslam
Hα
FDS 30 GHz
Haze Template
Disk Template
Mask
30 GHz Model
30 GHz Planck
30 GHz Haze Residual
-0.1
$T_{ant} \times (\nu/23\ GHz)^{2.5}$ [mK]
(arXiv: 1208:5483)
0.2



(arXiv: 1208:5483)

Sub-pc jet from GC?