The Fermi bubbles: update on multi-wavelength observations, numerical simulations, and implications to the past activities in the Galactic center

Meng Su

Pappalardo/Einstein fellow
MIT

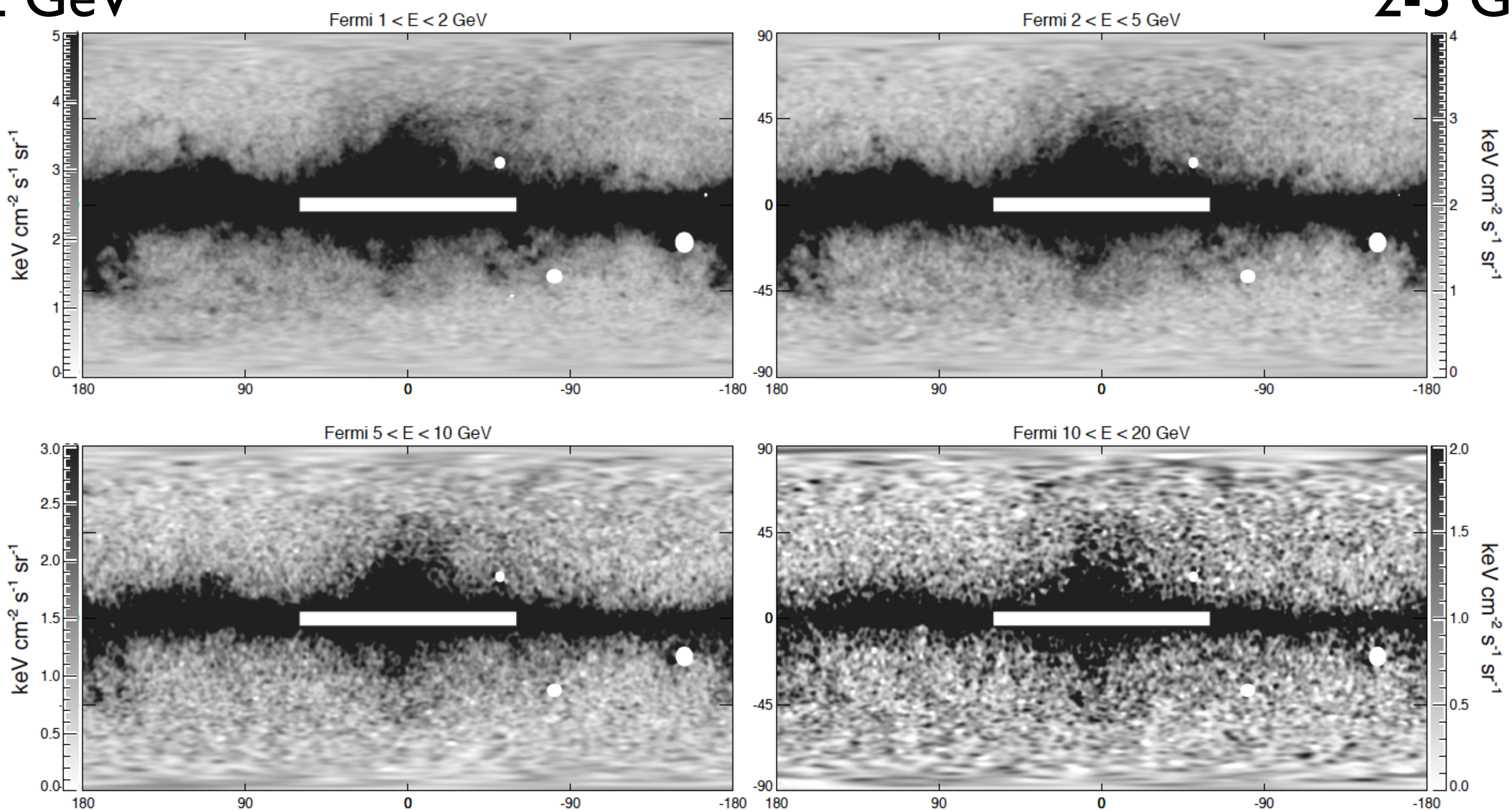
6th Fermi Symposium

Nov. 12th, 2015

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

1-2 GeV

2-5 GeV

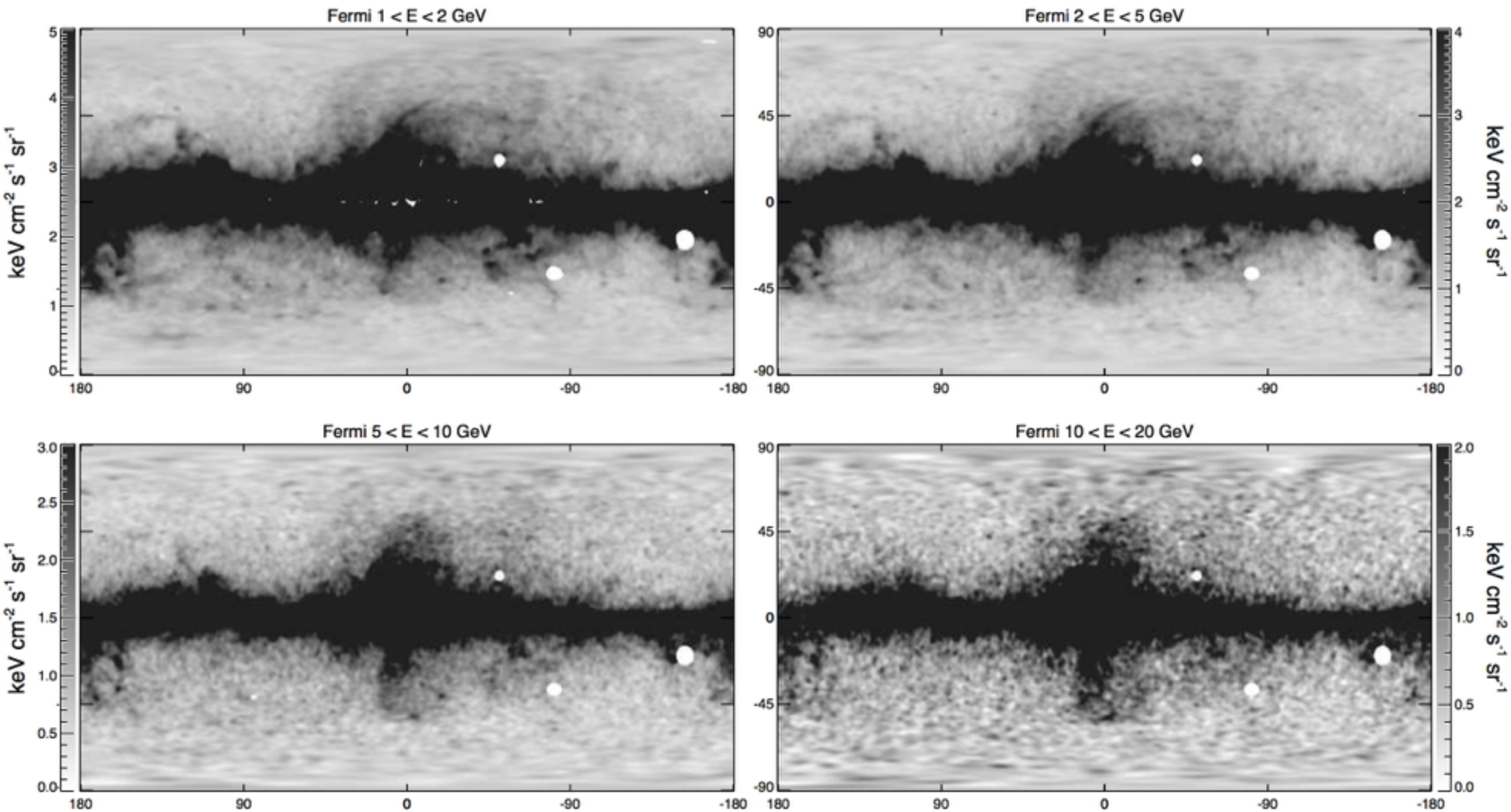


5-10 GeV

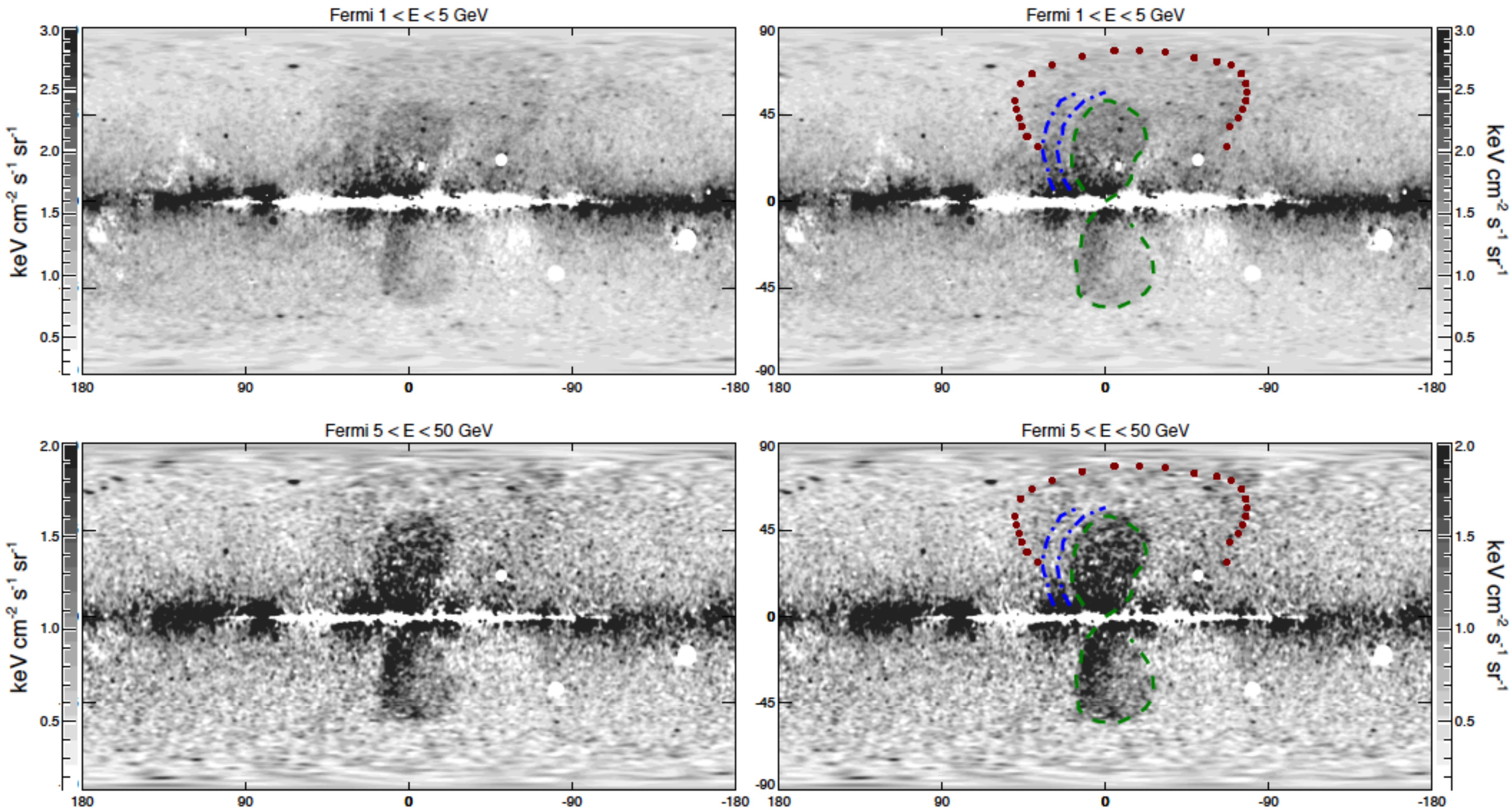
10-20 GeV

MS, Slatyer, Finkbeiner (2010)

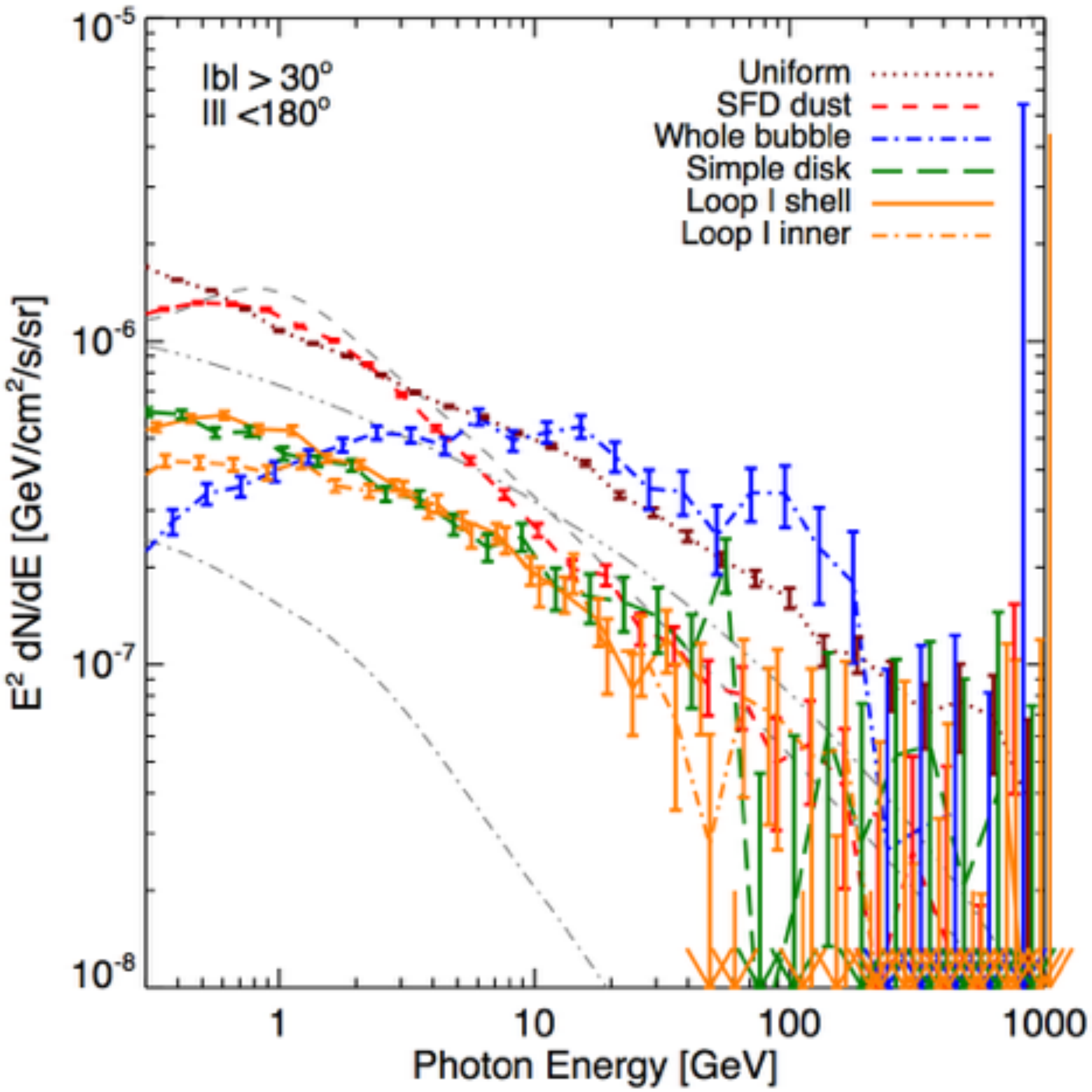
FB from six years LAT data

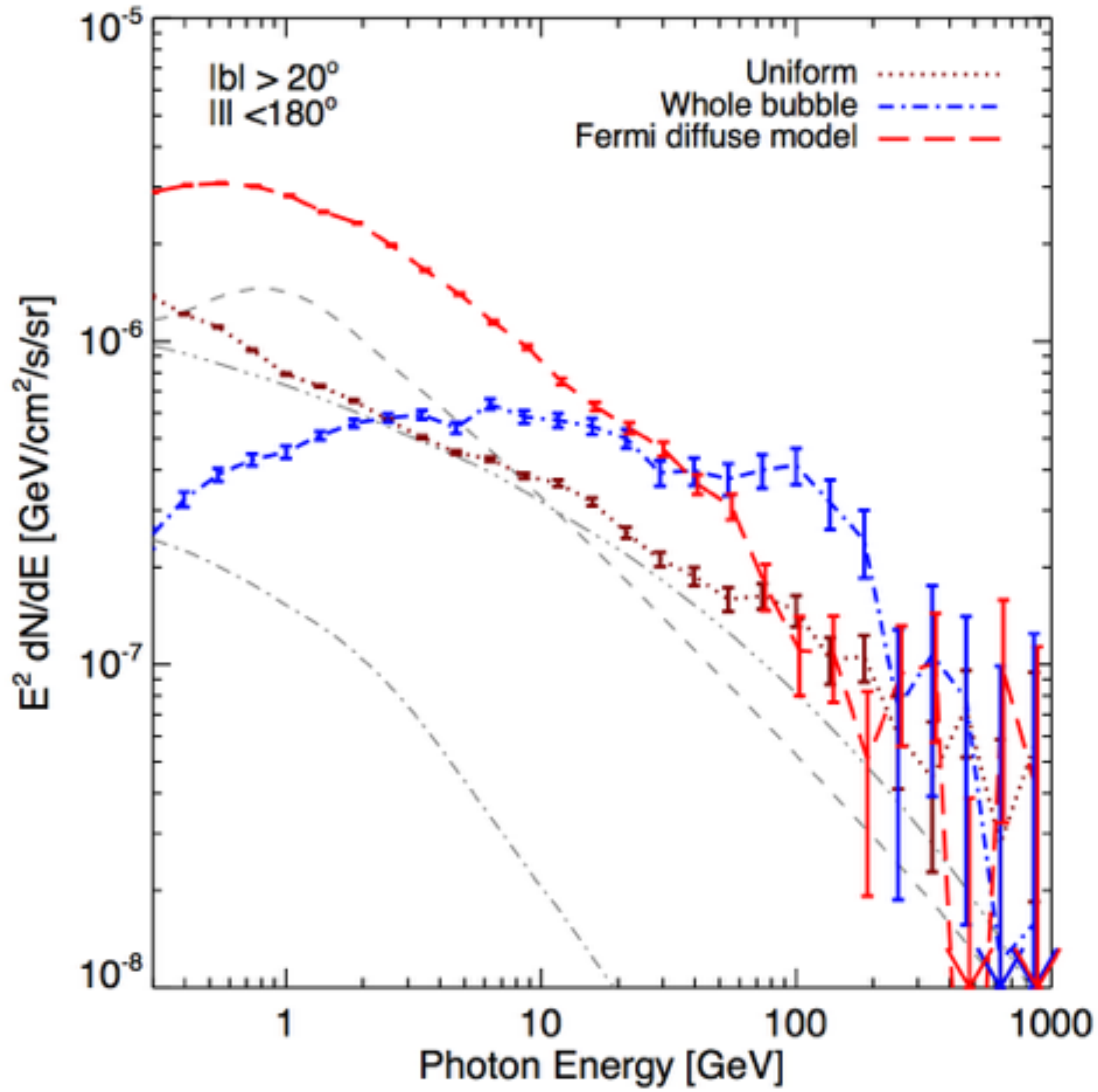


FB from six years LAT data

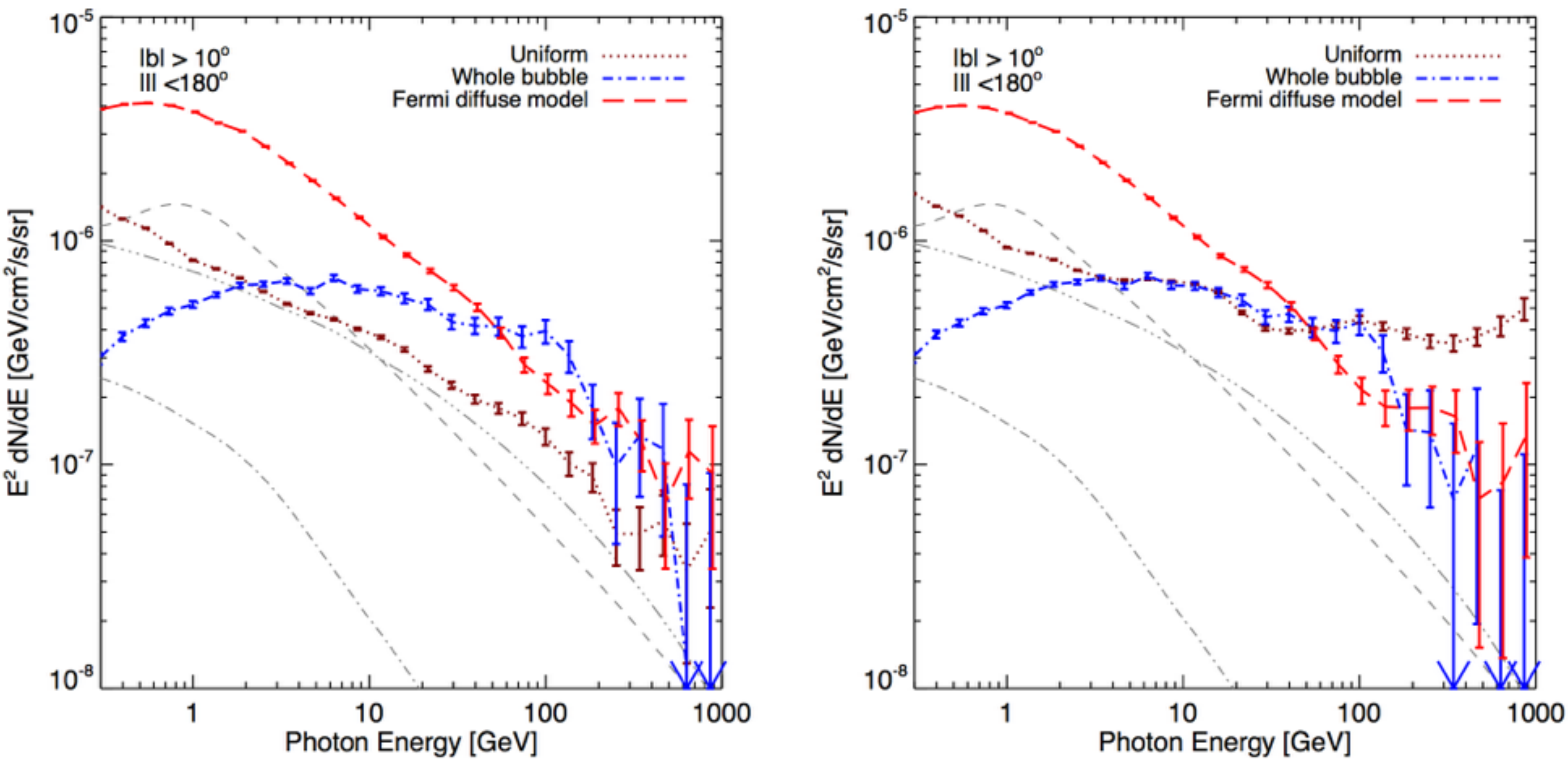


FB has a hard spectrum *with high energy cut-off*

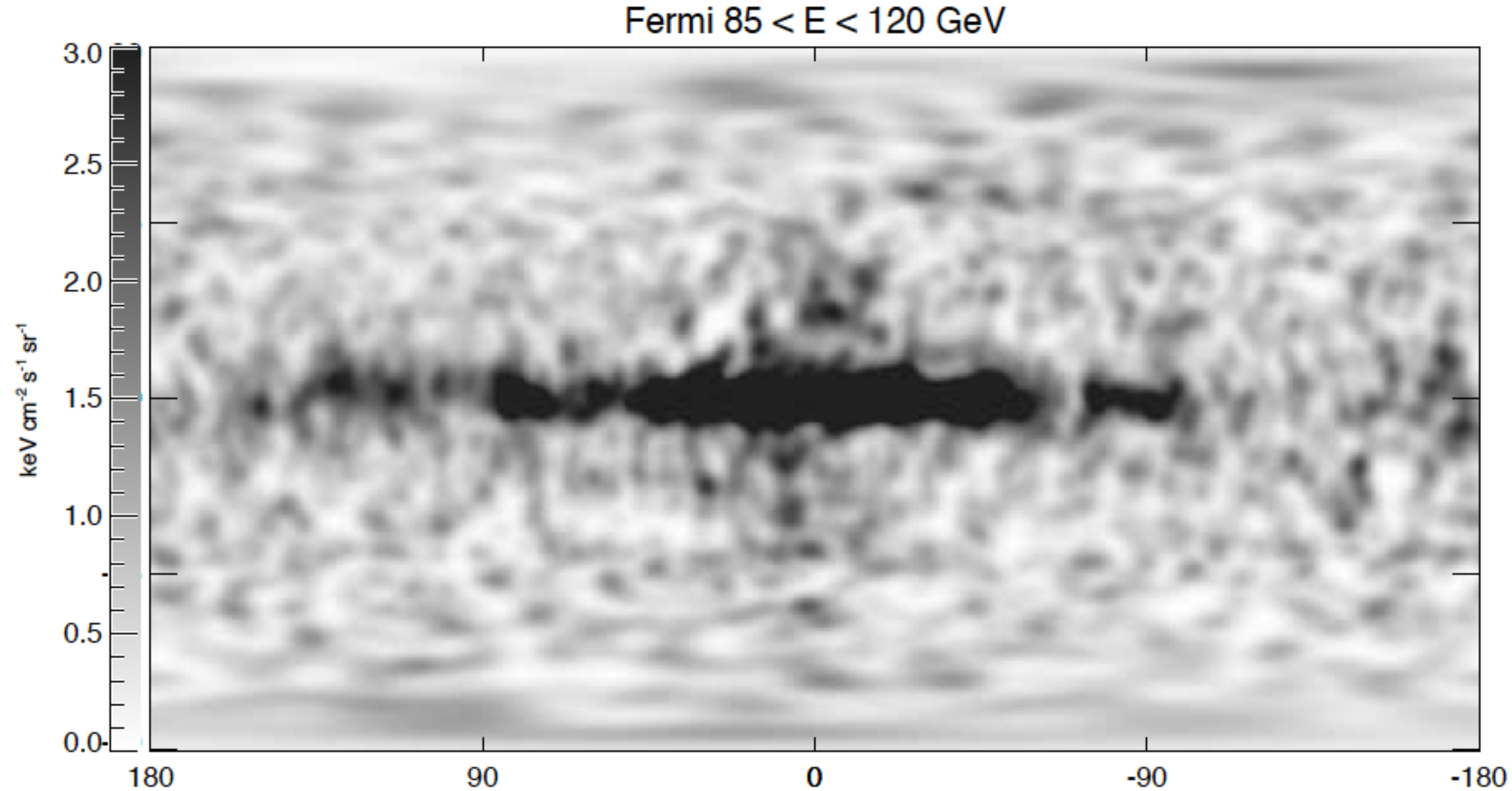




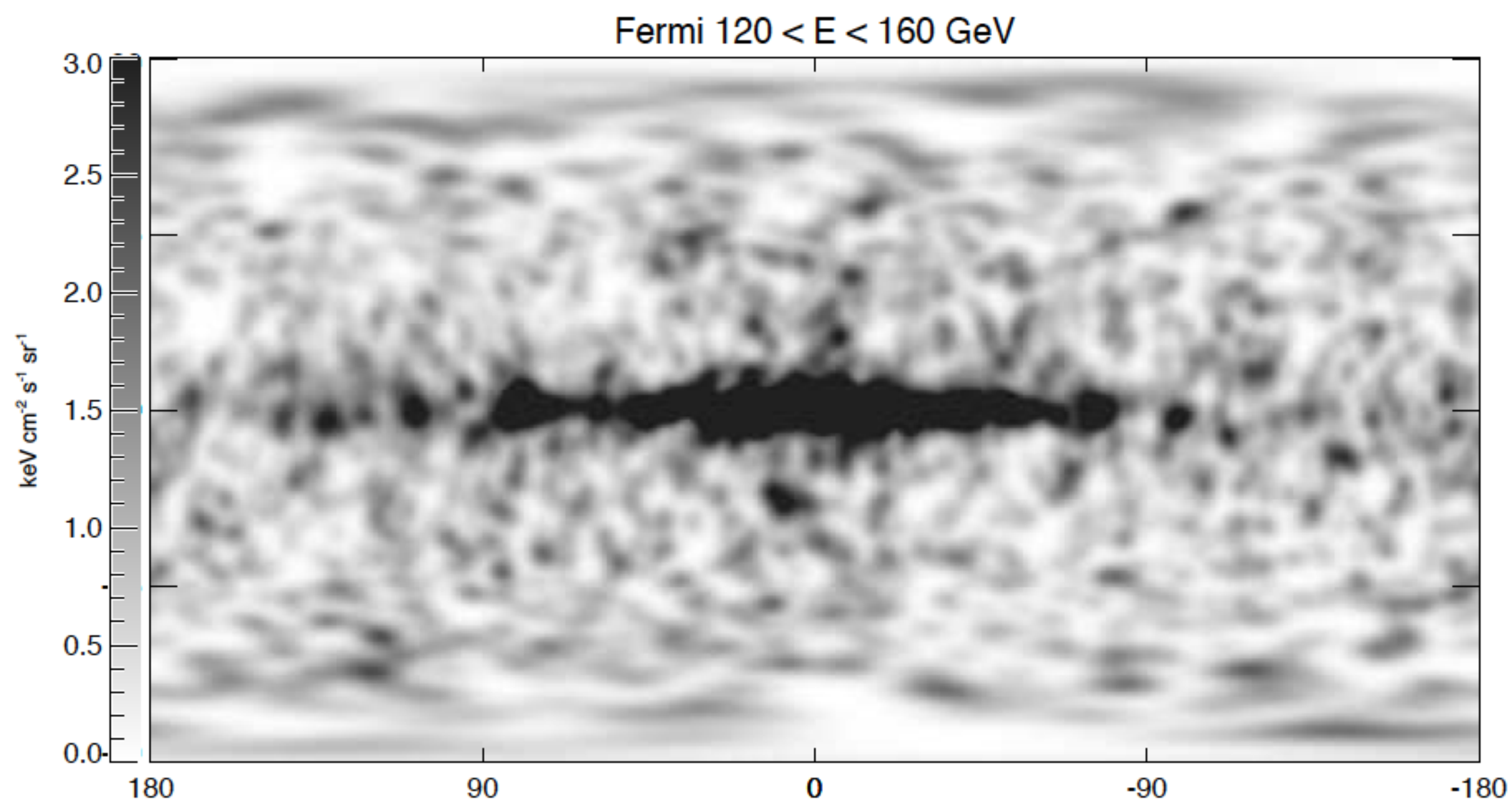
FB has a hard spectrum *with high energy cut-off*



- 85-120 GeV:

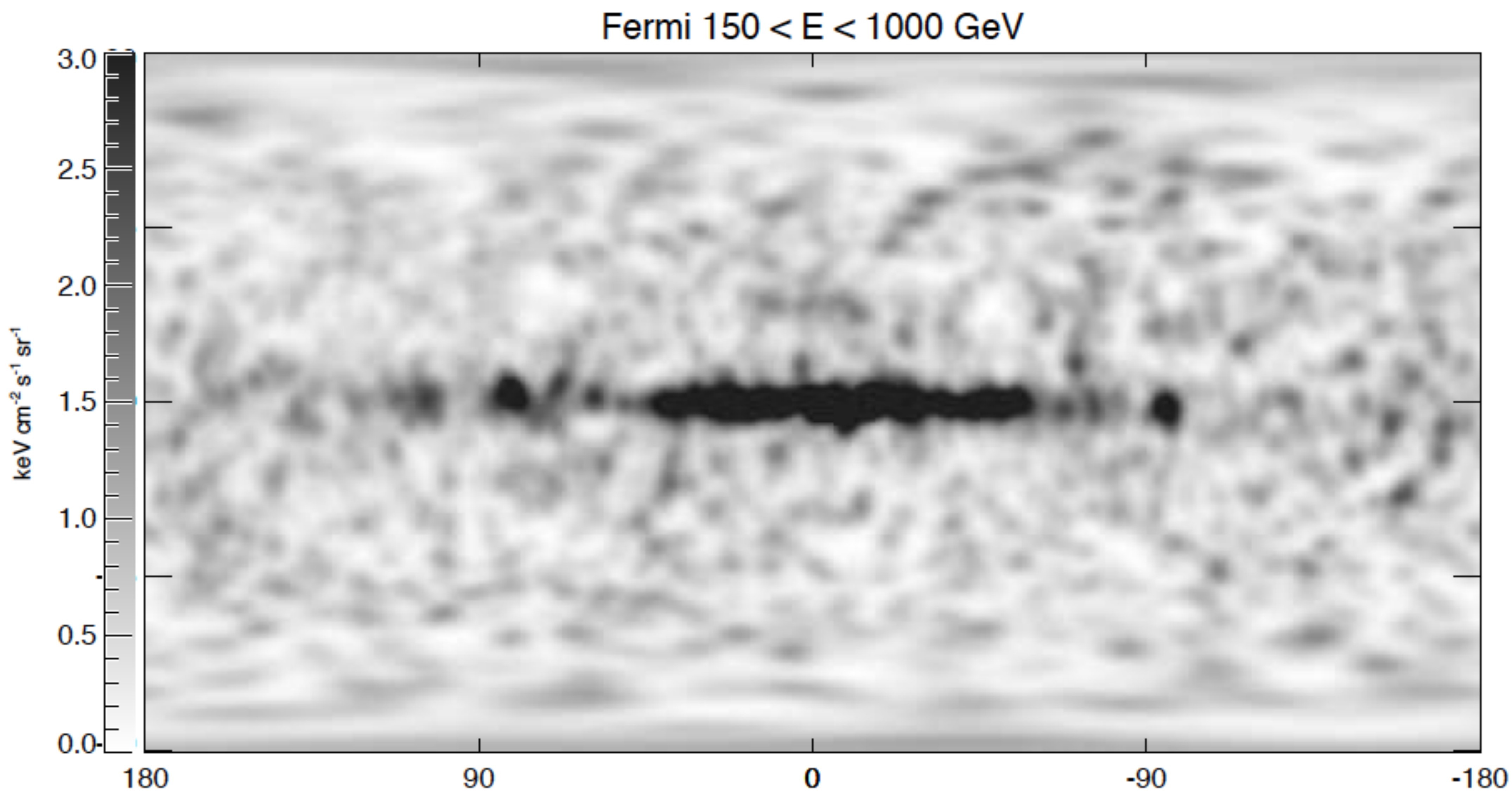


- 120-160 GeV



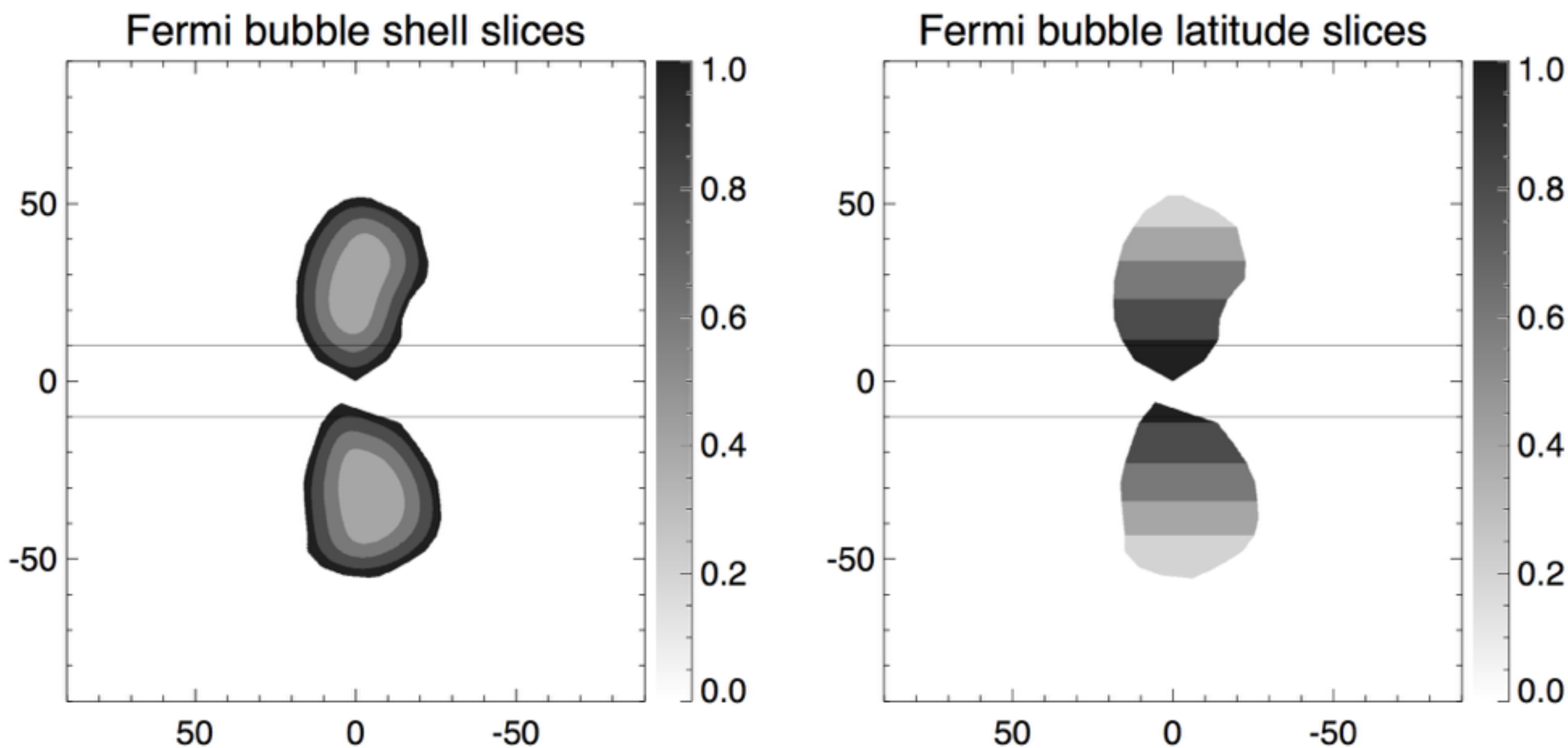
MS & Finkbeiner (2014)

FB disappears at >150 GeV

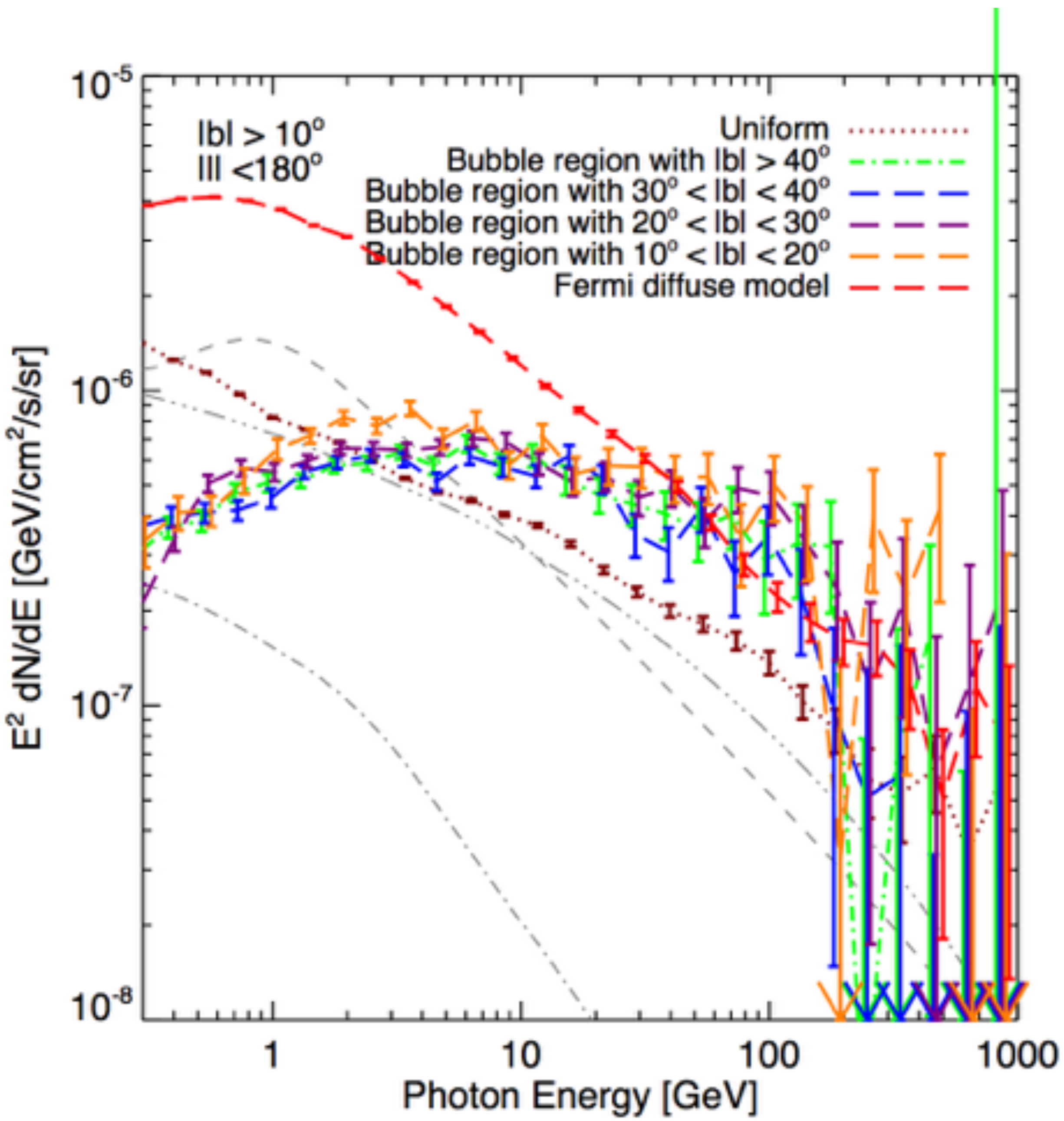


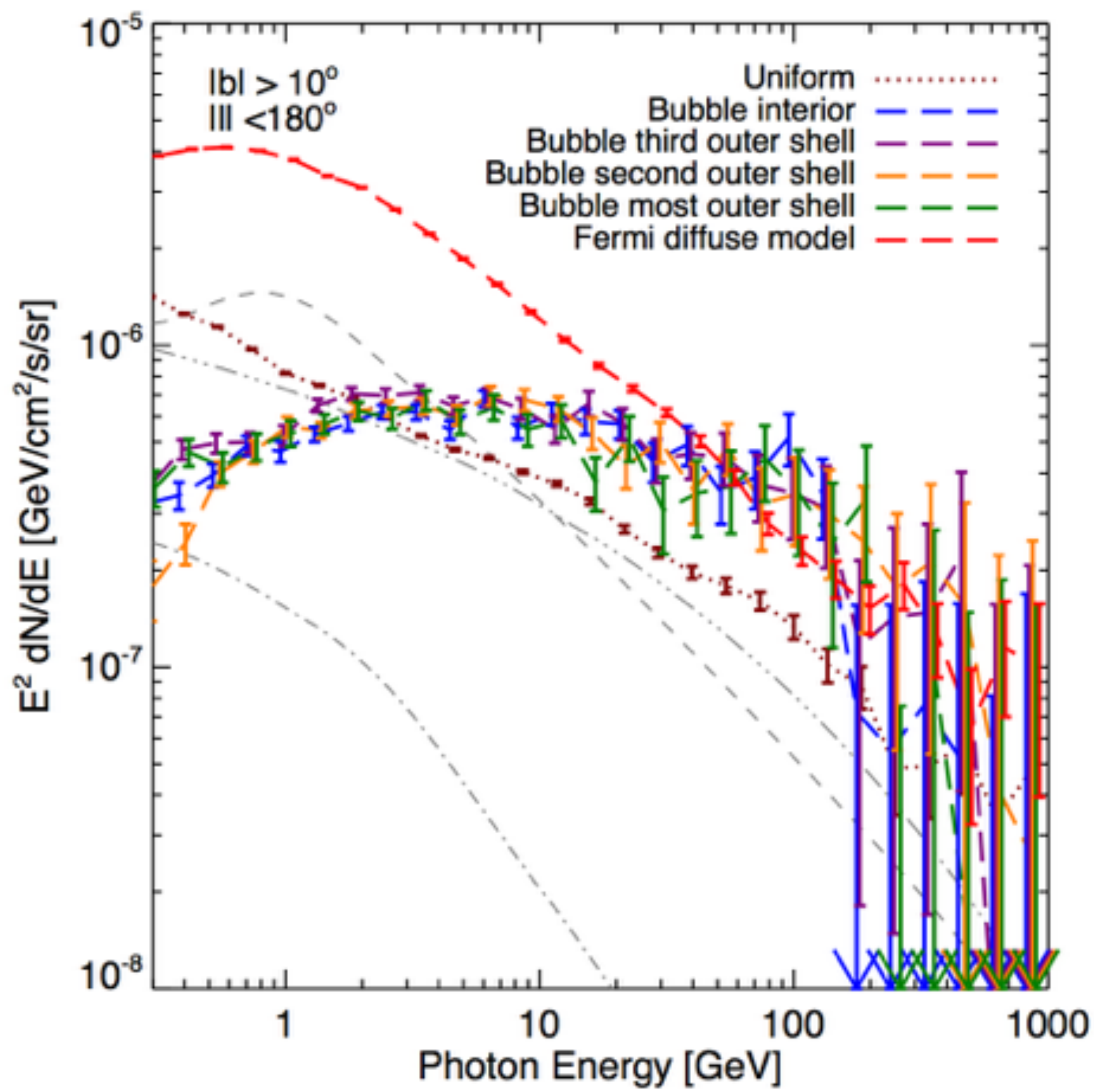
MS & Finkbeiner (2014)

Divide the bubble into pieces…



Divide the bubble into pieces…

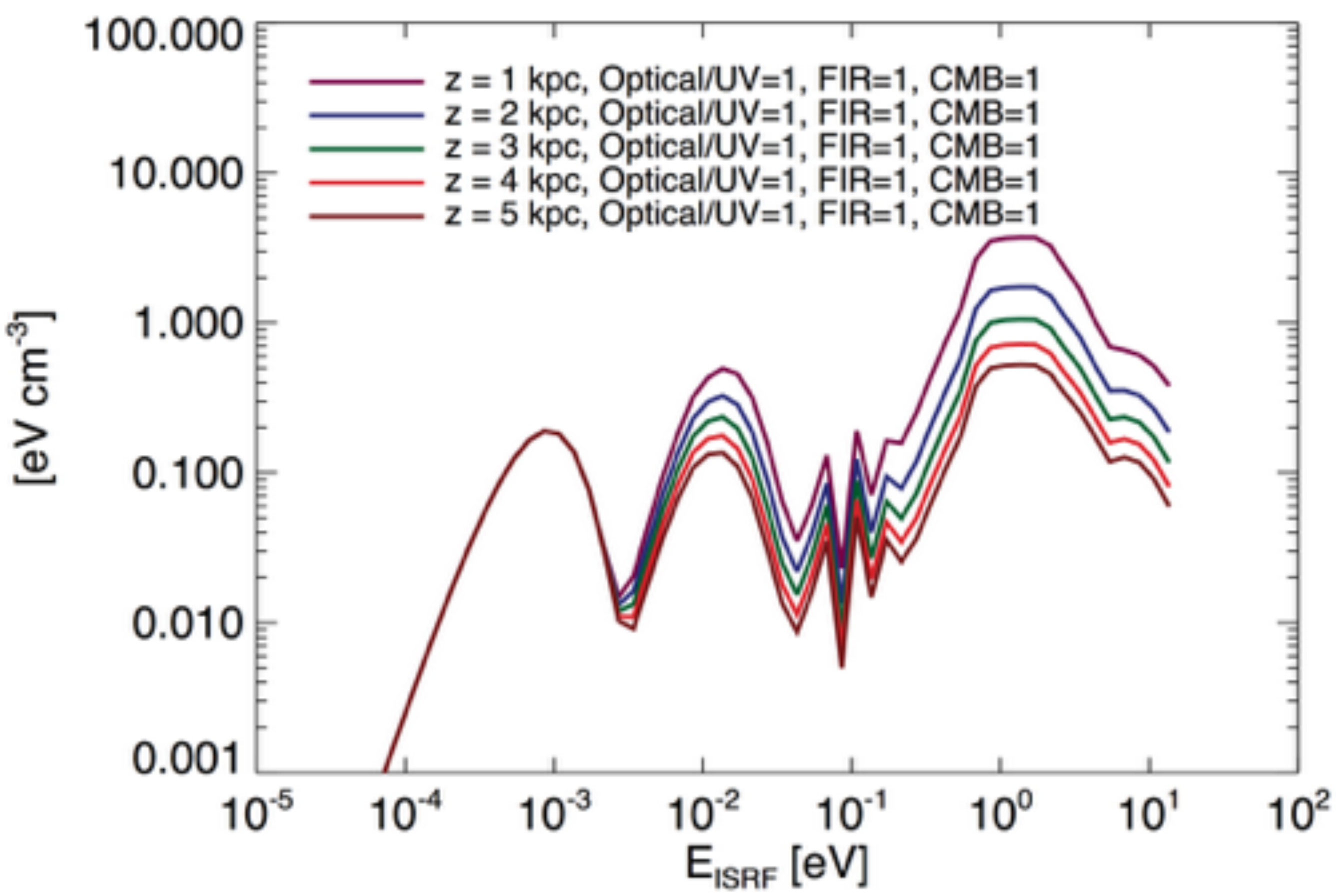




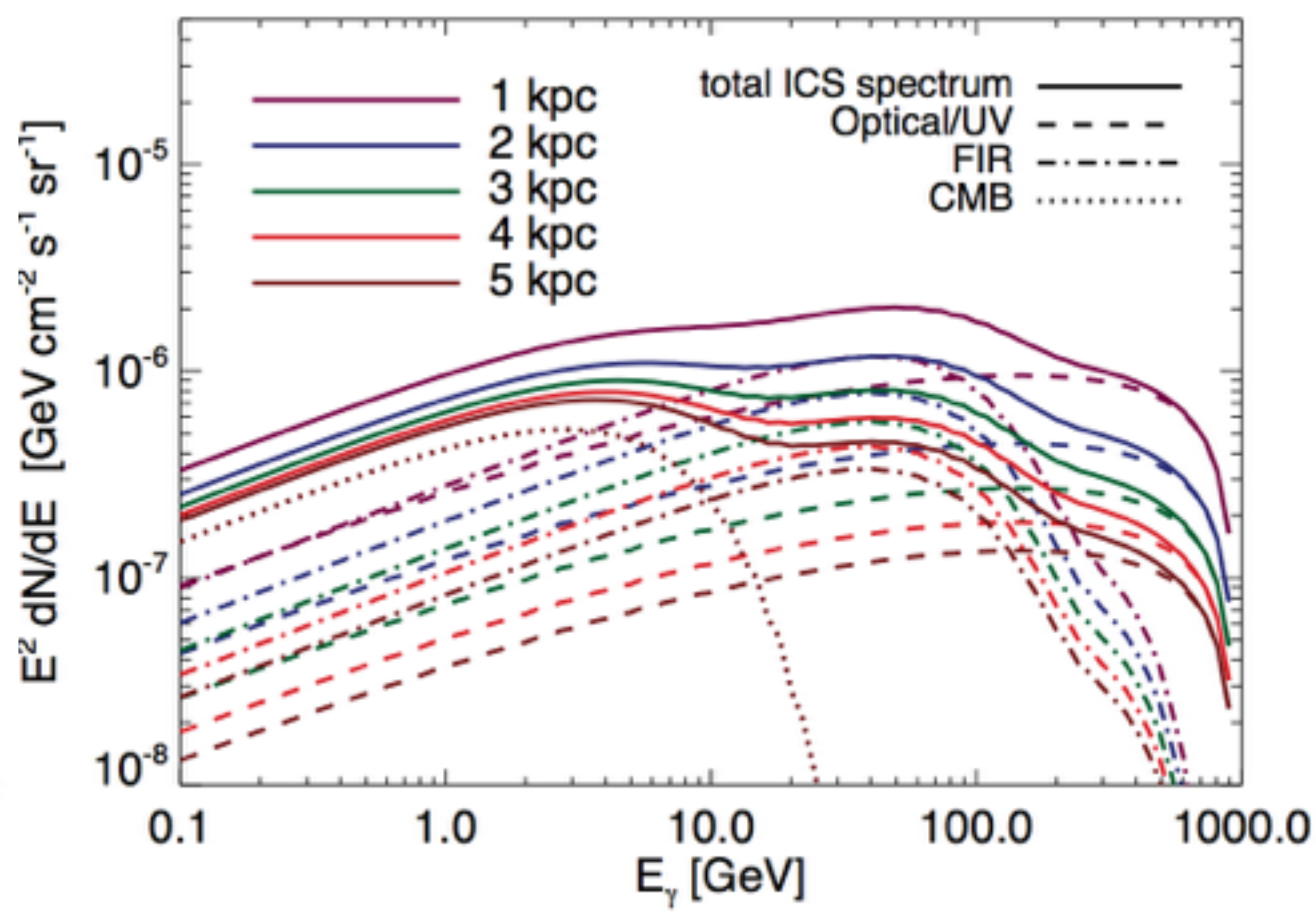
No evidence for spectral variation across Bubbles at mid-high latitude

However, it’s a puzzle!

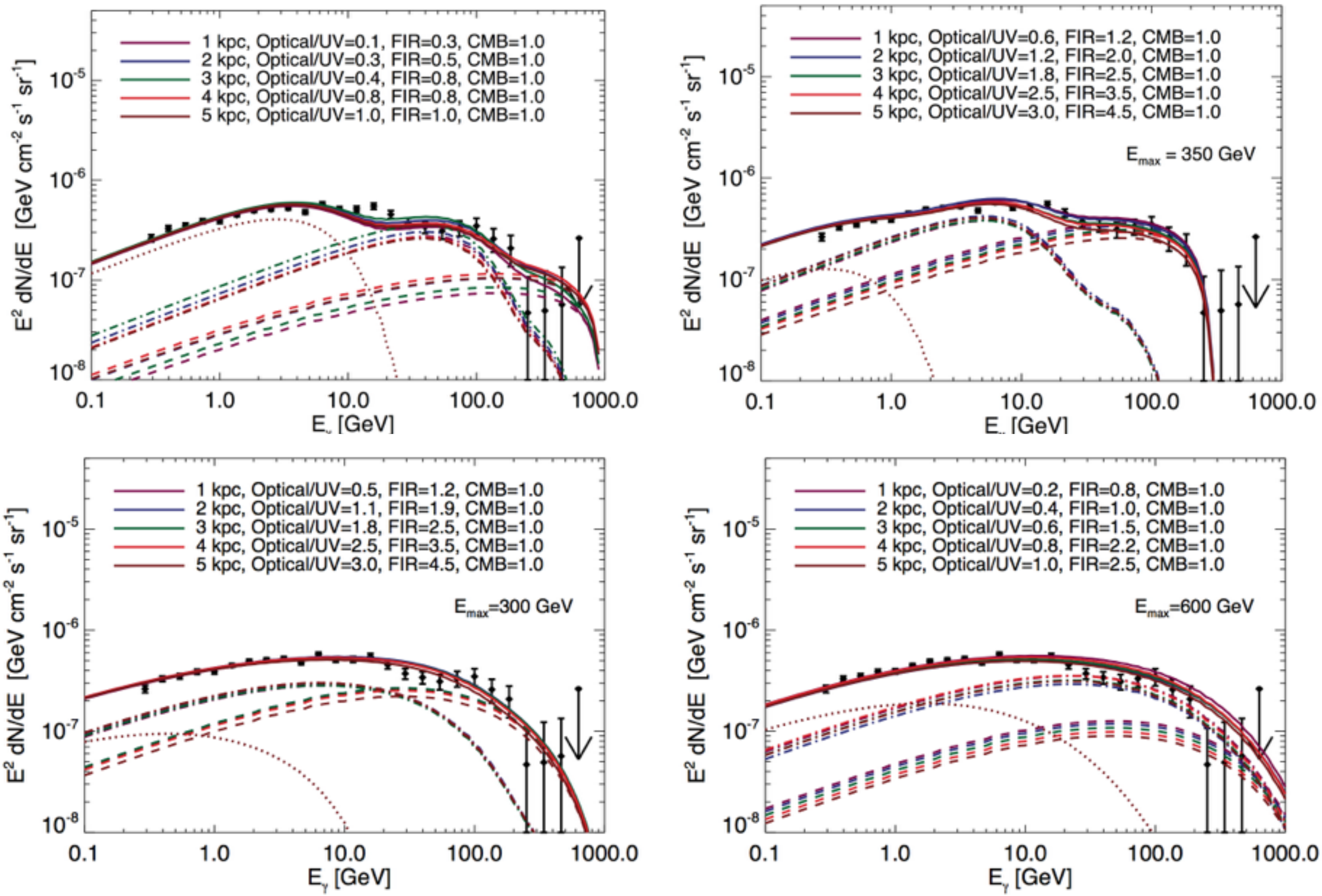
Interstellar radiation field



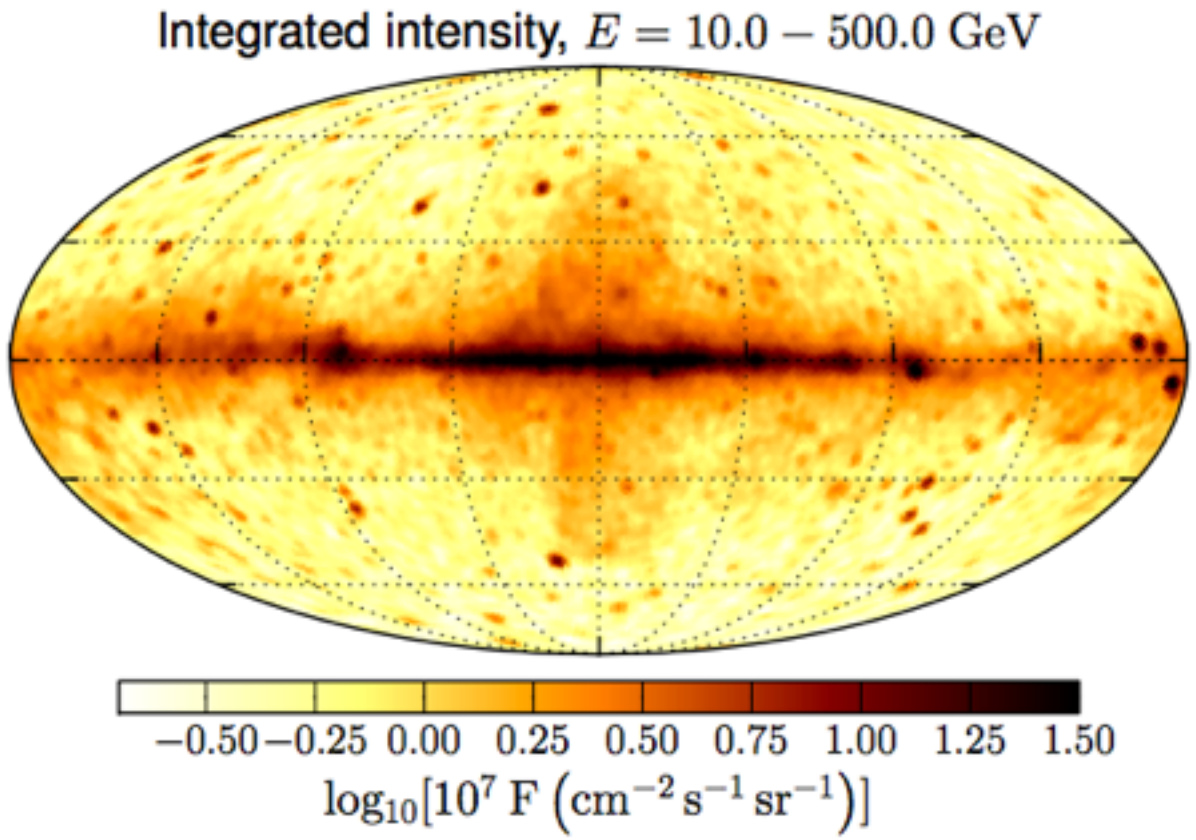
Predicted bubble spectrum

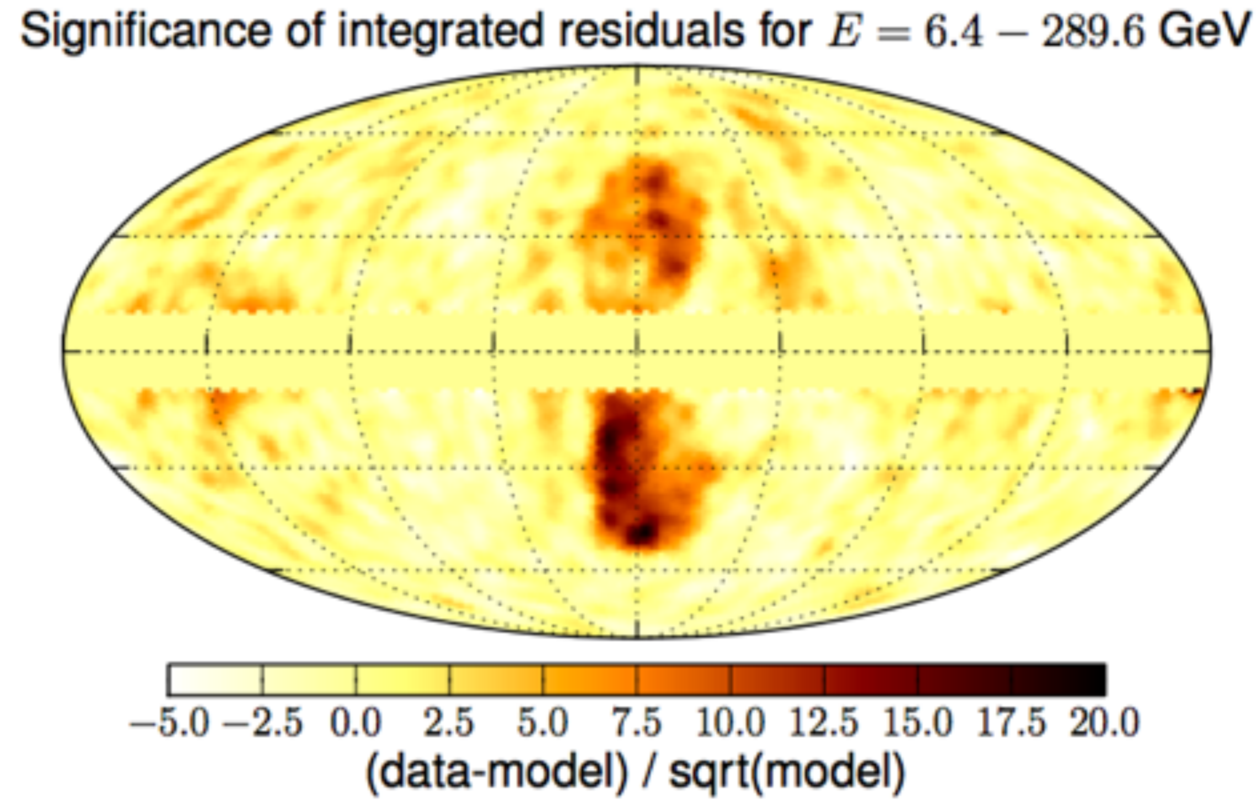


MS & Finkbeiner (2014)

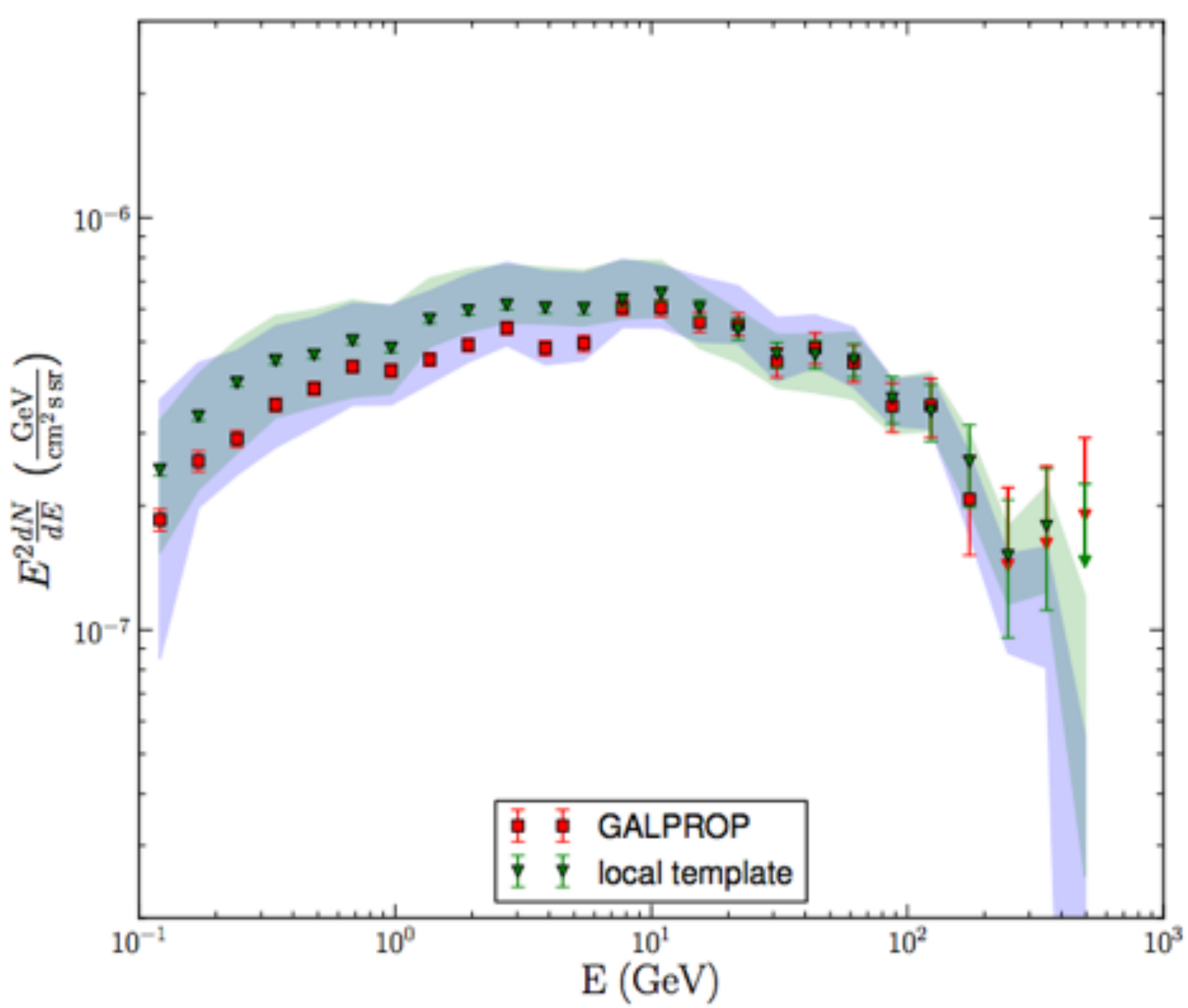


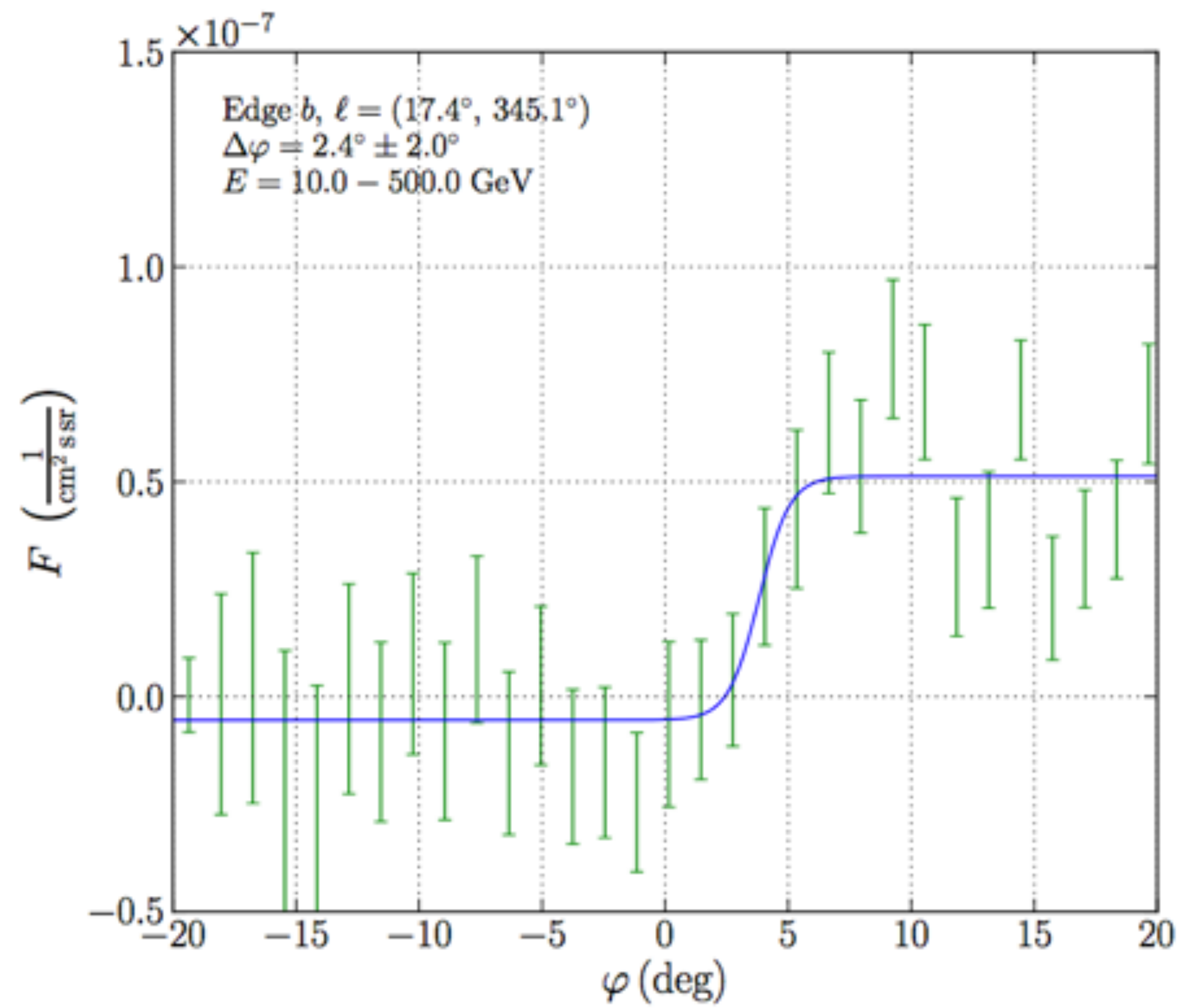
MS & Finkbeiner (2014)





Analysis by Fermi Collaboration on 50 months data, Ackermann et al ‘14

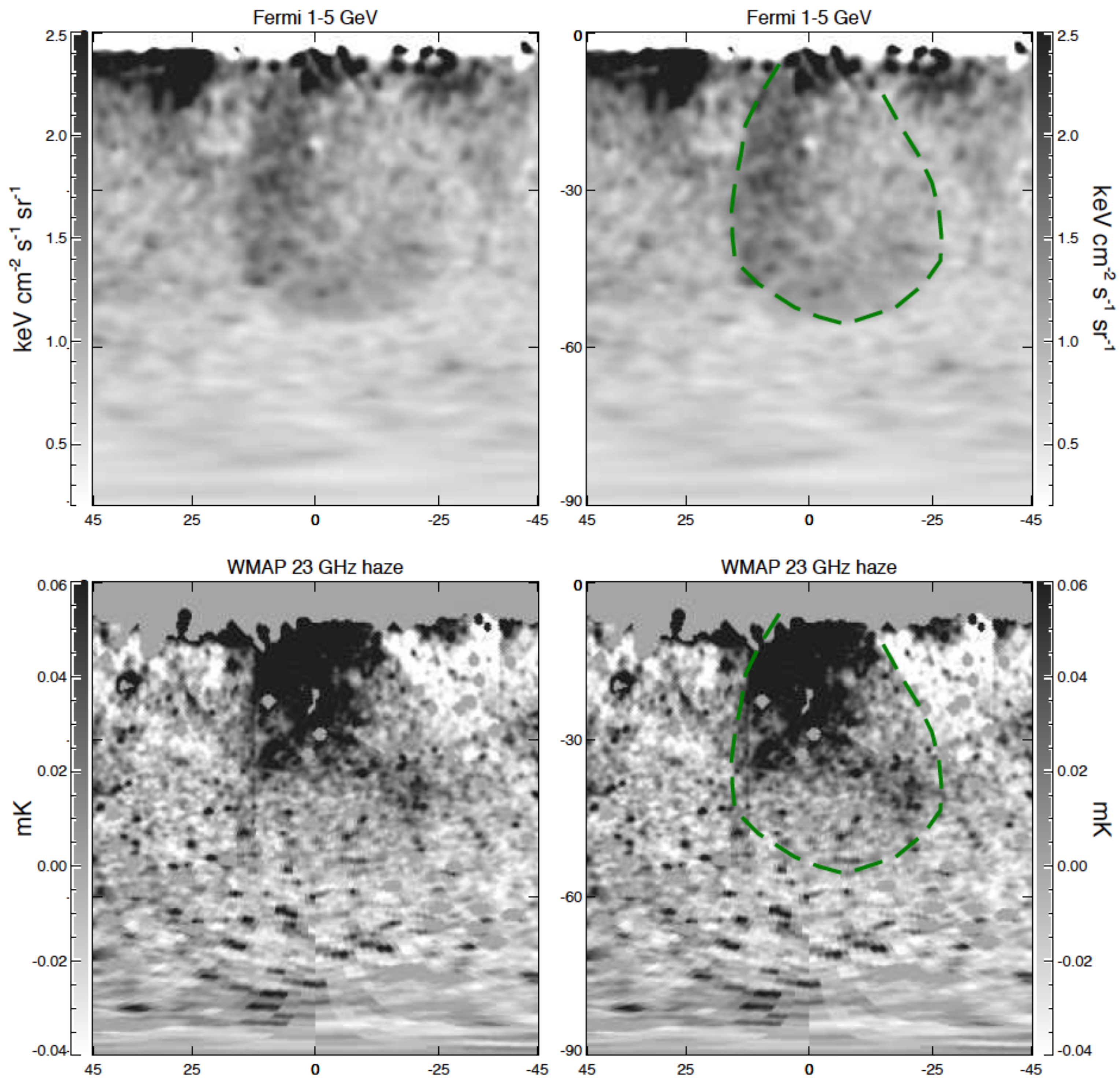




Microwave counterpart of FB

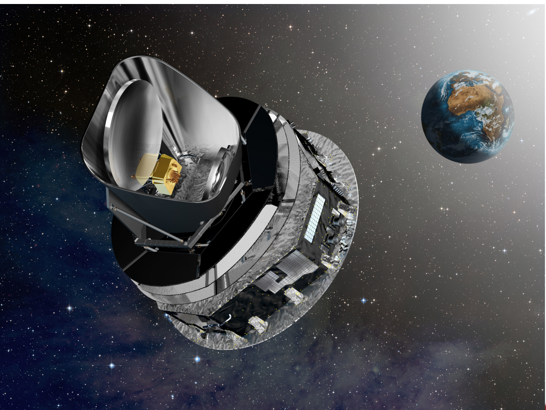
Fermi 1-5 GeV:

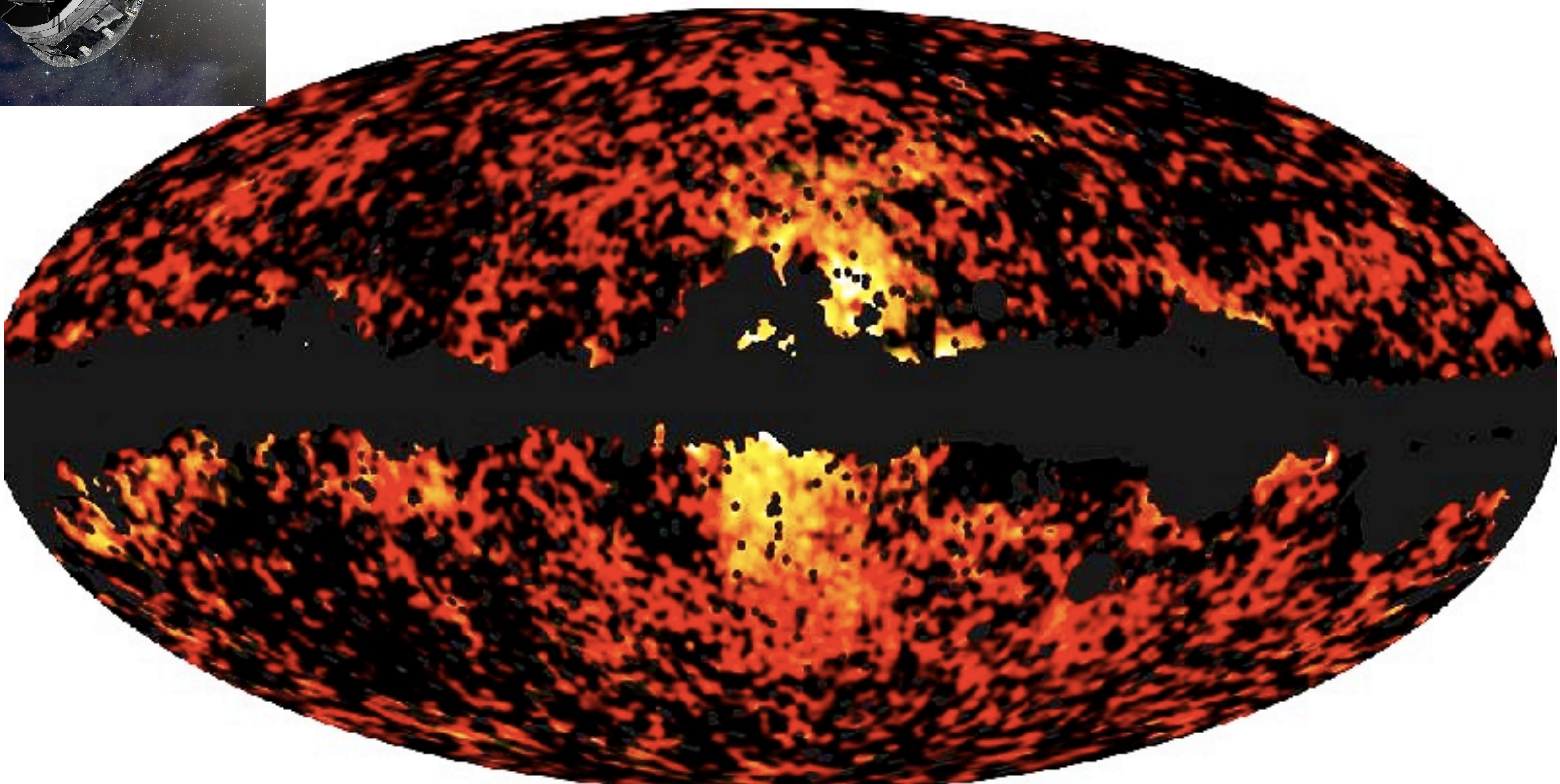
WMAP 23 GHz:



Su, Slatyer & Finkbeiner 2010

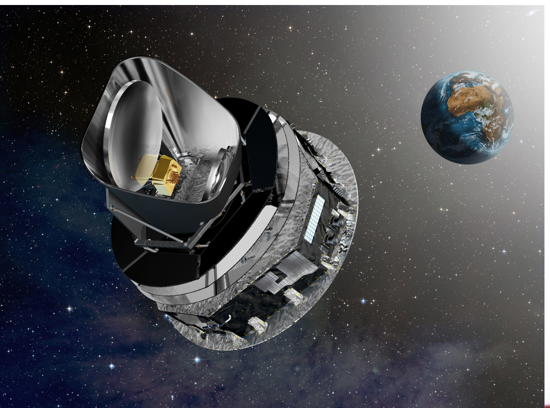
Planck 30 and 44 GHz haze map

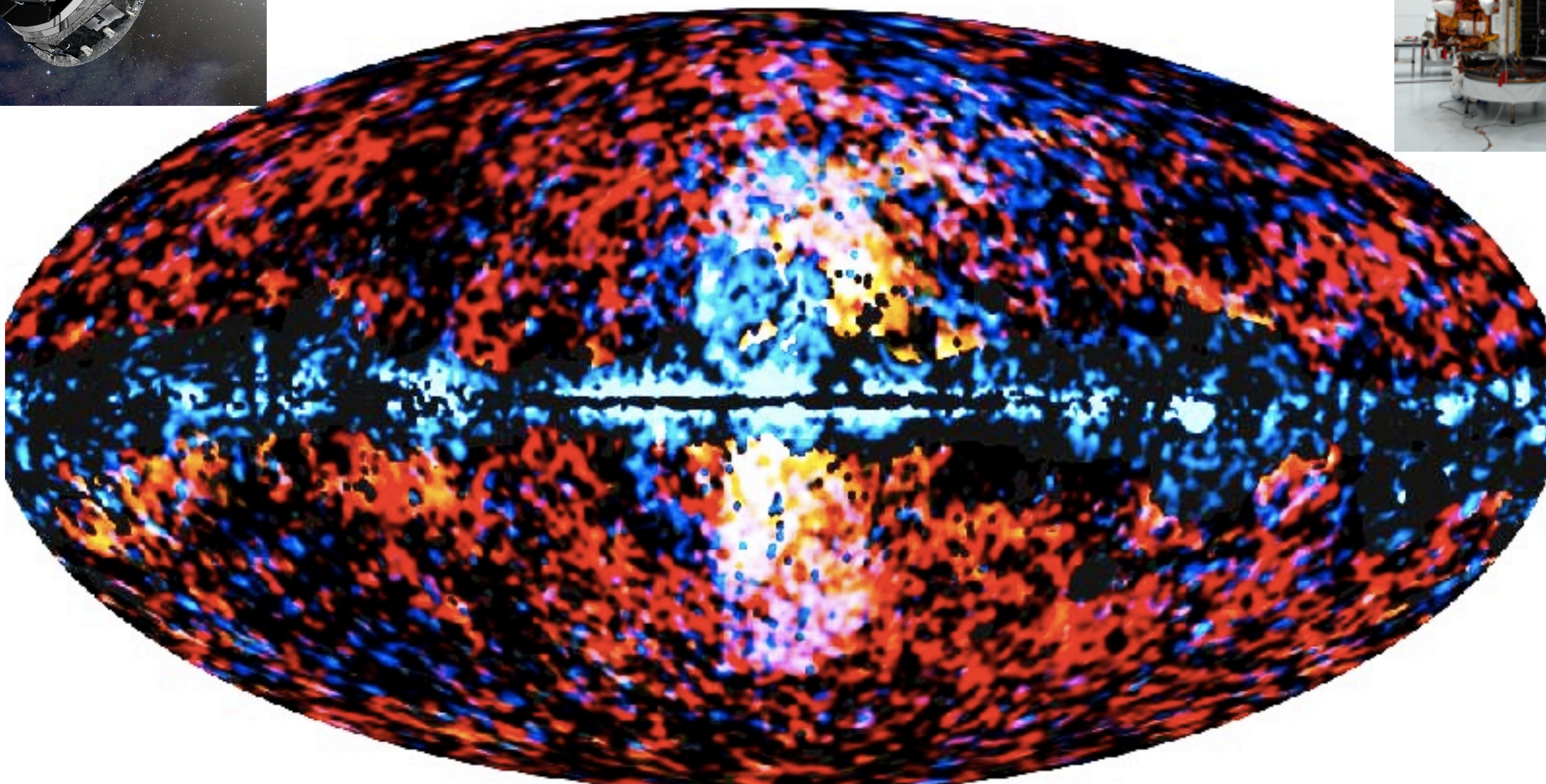




Credits: ESA/Planck Collaboration.

Haze superimposed over the FB





Credits: ESA/Planck Collaboration.

Leptonic

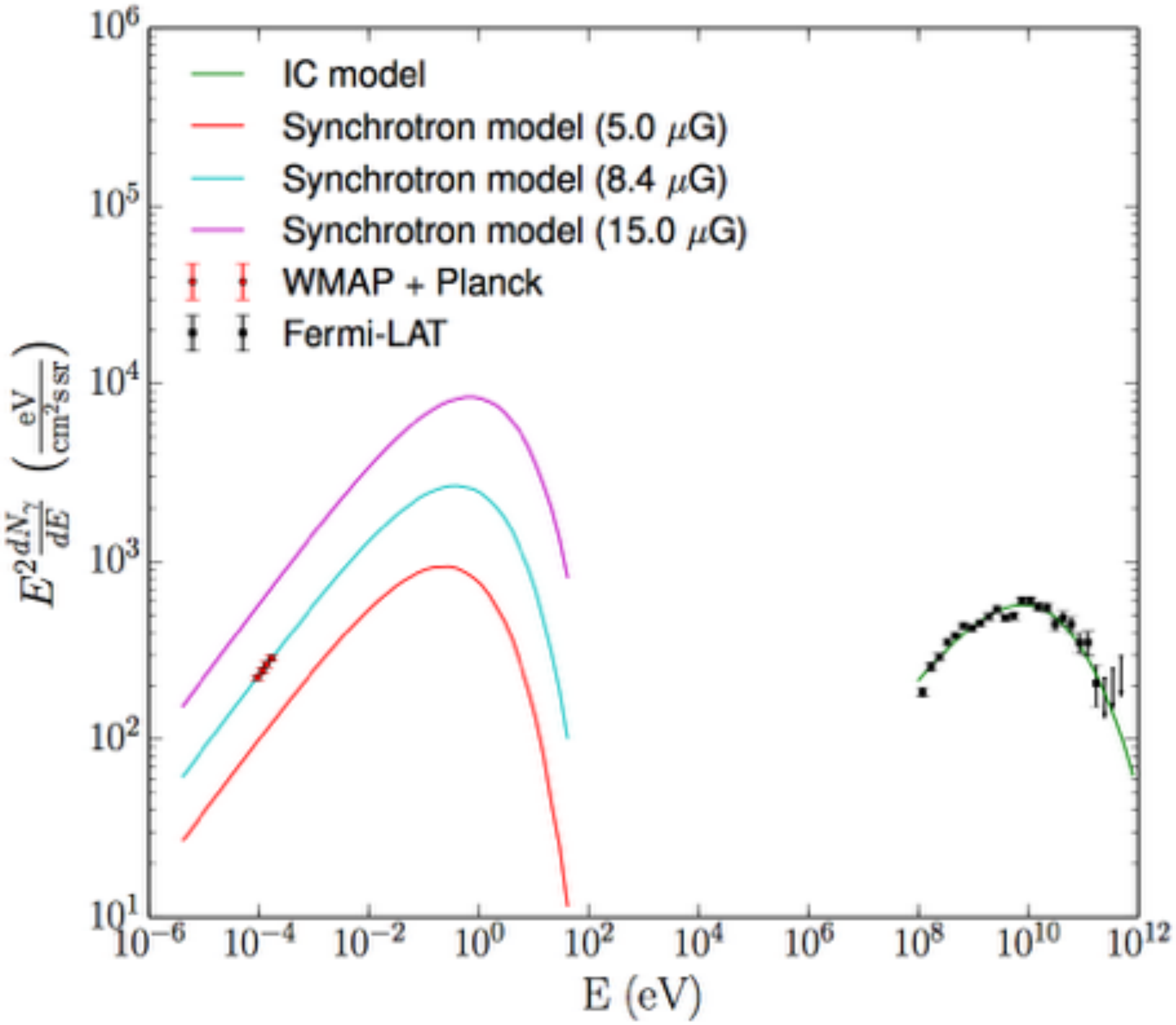
(electrons scattering on interstellar radiation)

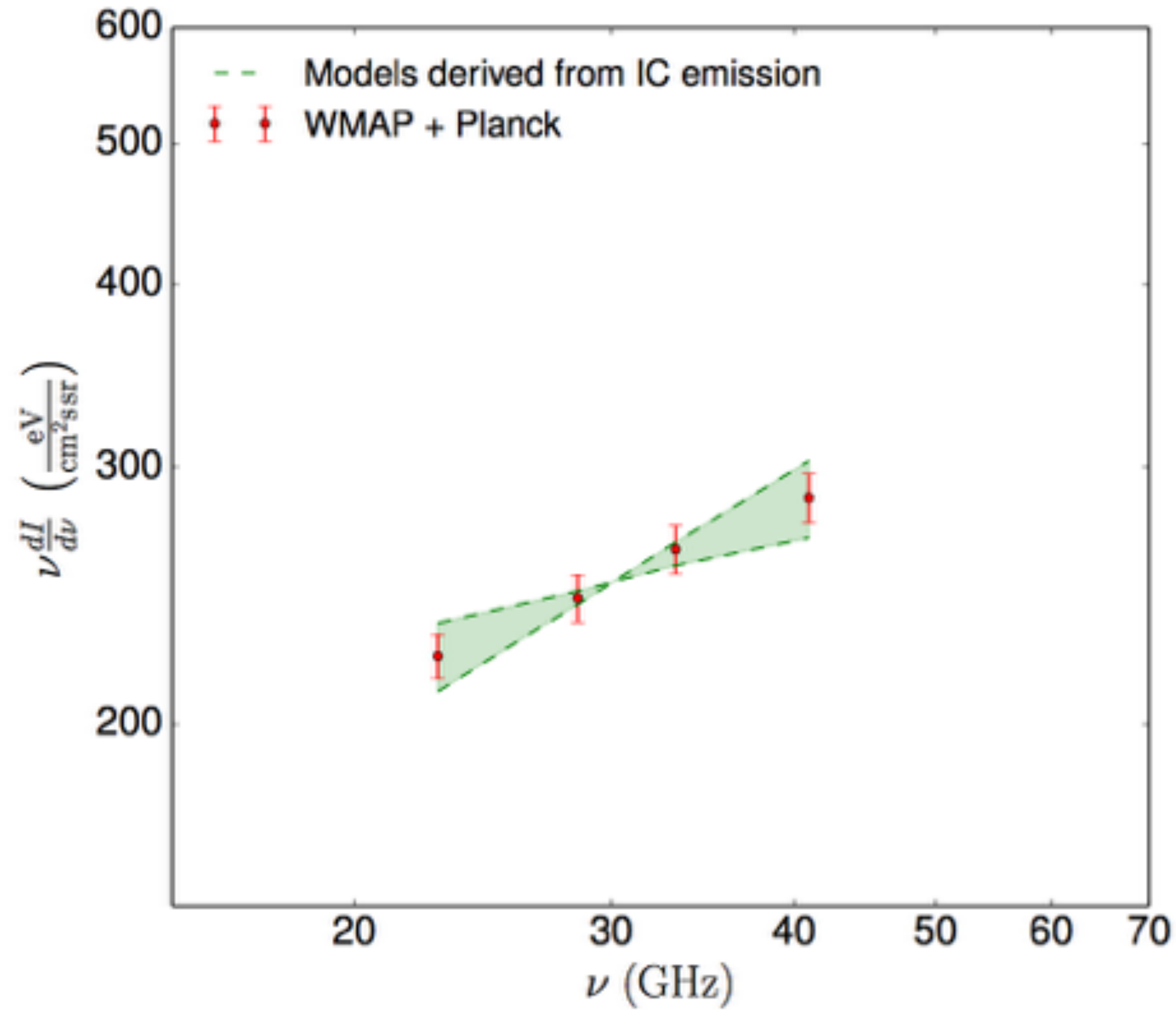
or

hadronic?

(protons scattering on gas)

Leptonic model

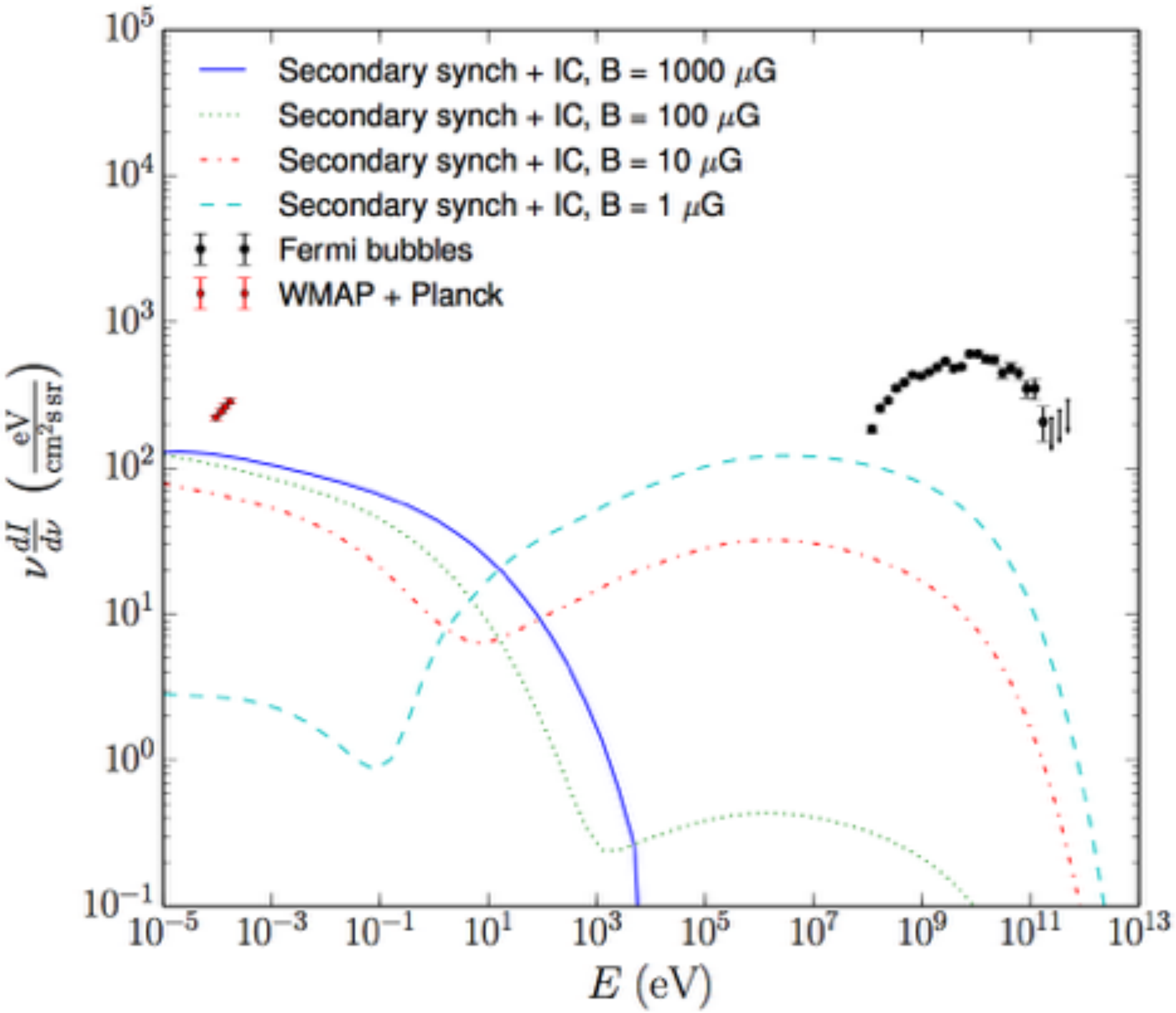


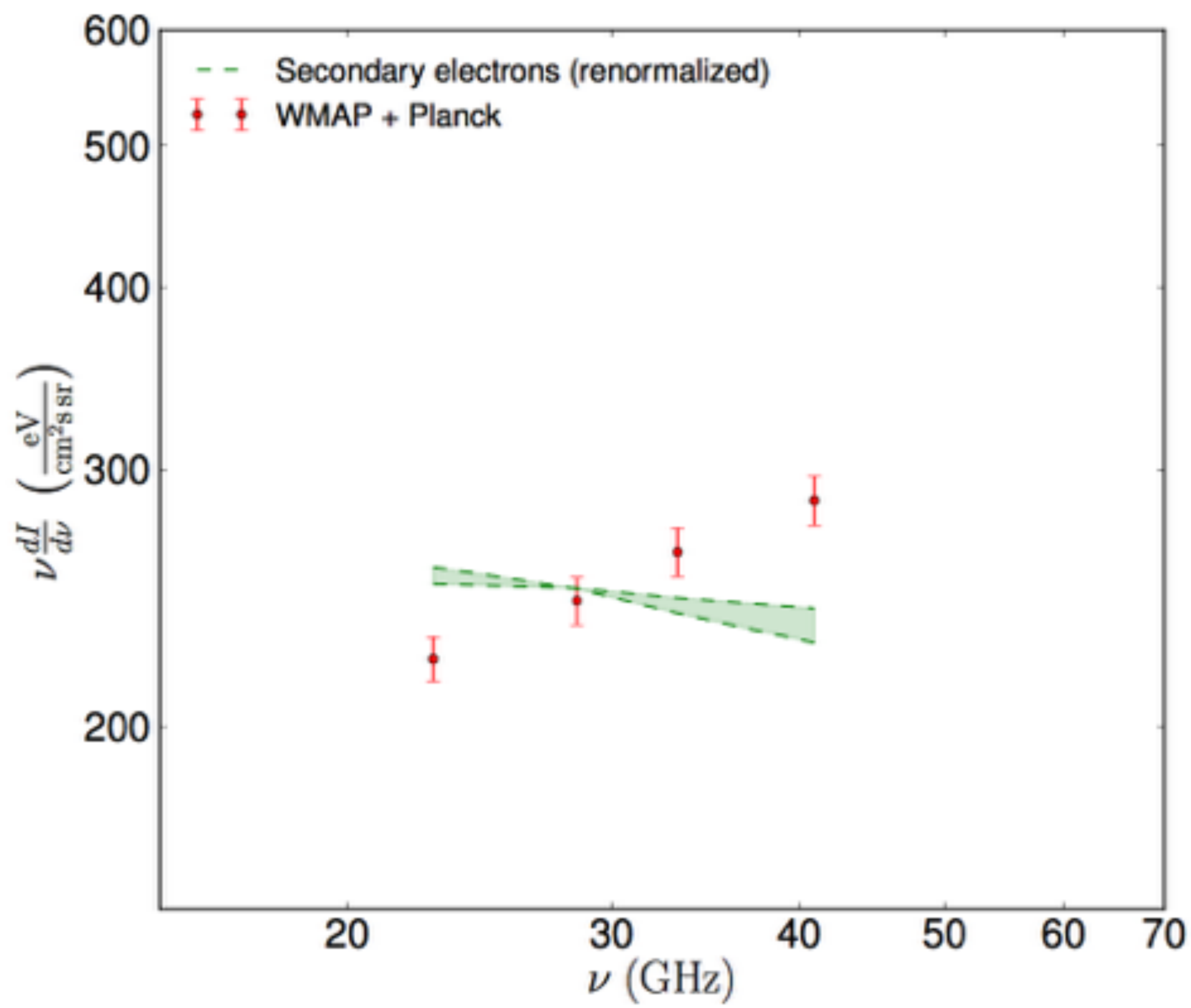


Good match to microwave data - but spatial invariance of spectrum is surprising

Fermi-LAT collaboration (2014)

Hadronic model





In hadronic scenario, if proton spectrum extends to high (PeV) energies, Bubbles could contribute high-energy neutrinos detectable by IceCube

Fermi-LAT collaboration (2014)

Properties of the gamma-ray Bubbles

- ~Flat spectrum in E^2dN/dE from ~1-150 GeV, apparent cutoff above 150 GeV.
- Total gamma-ray luminosity ~5 x 10^{37} ergs/second.
- Spectrum appears close-to-uniform across the Bubbles, above 10 degrees in Galactic latitude.
- Sharp edges, ~few degrees in width.
- What about other wavelengths? Microwave, X-ray, radio?

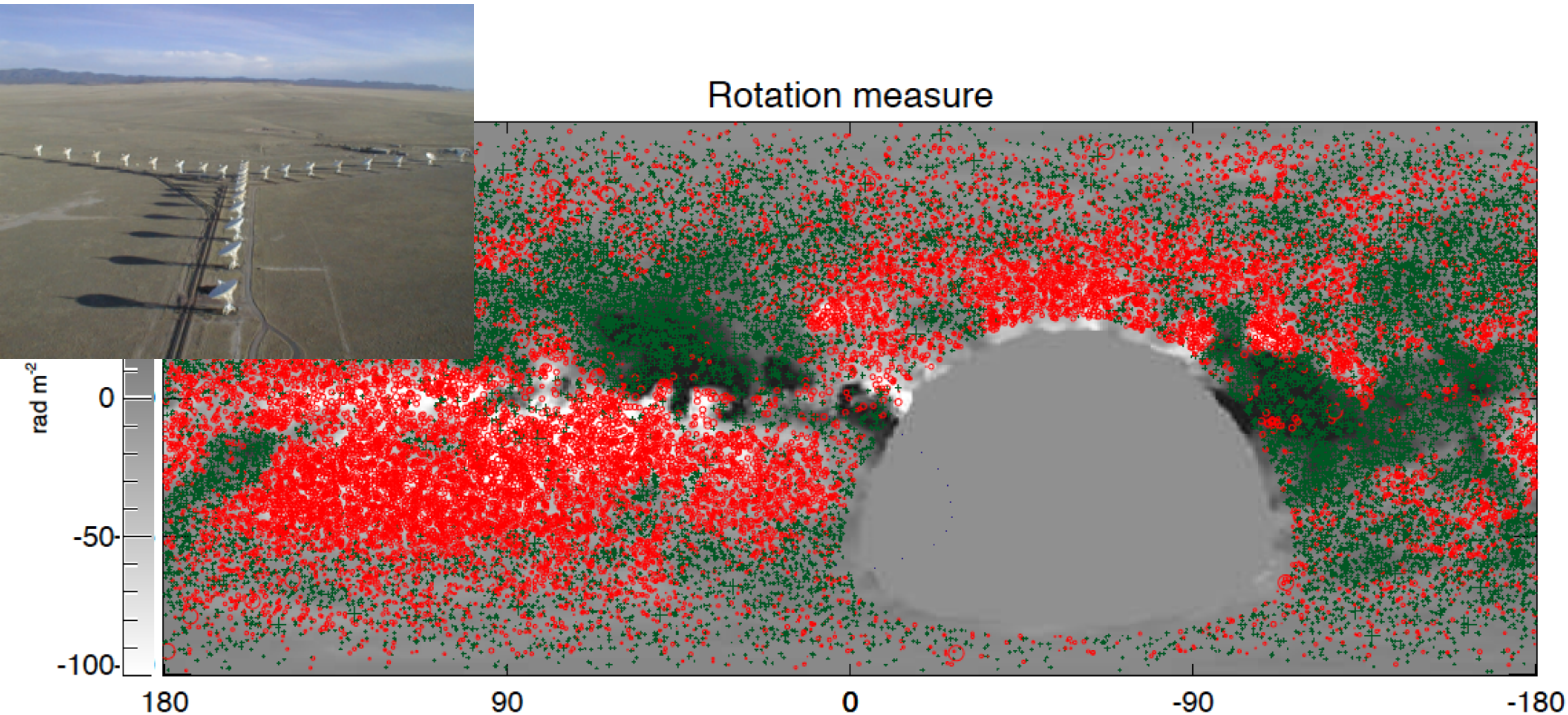
Magnetic field structure of the FB

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

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

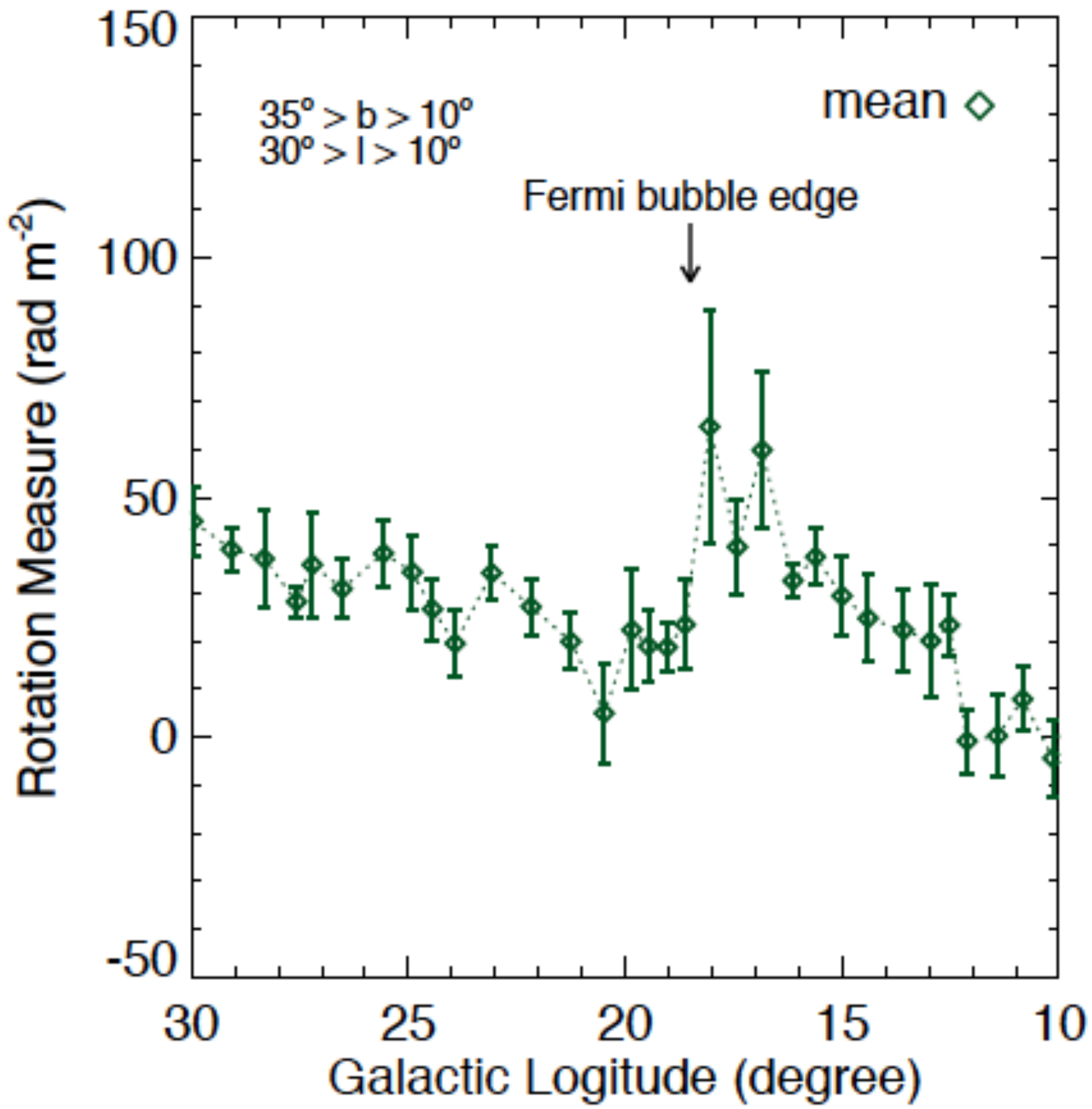
- Radio polarization (magnetic field perpendicular to the line of slight)

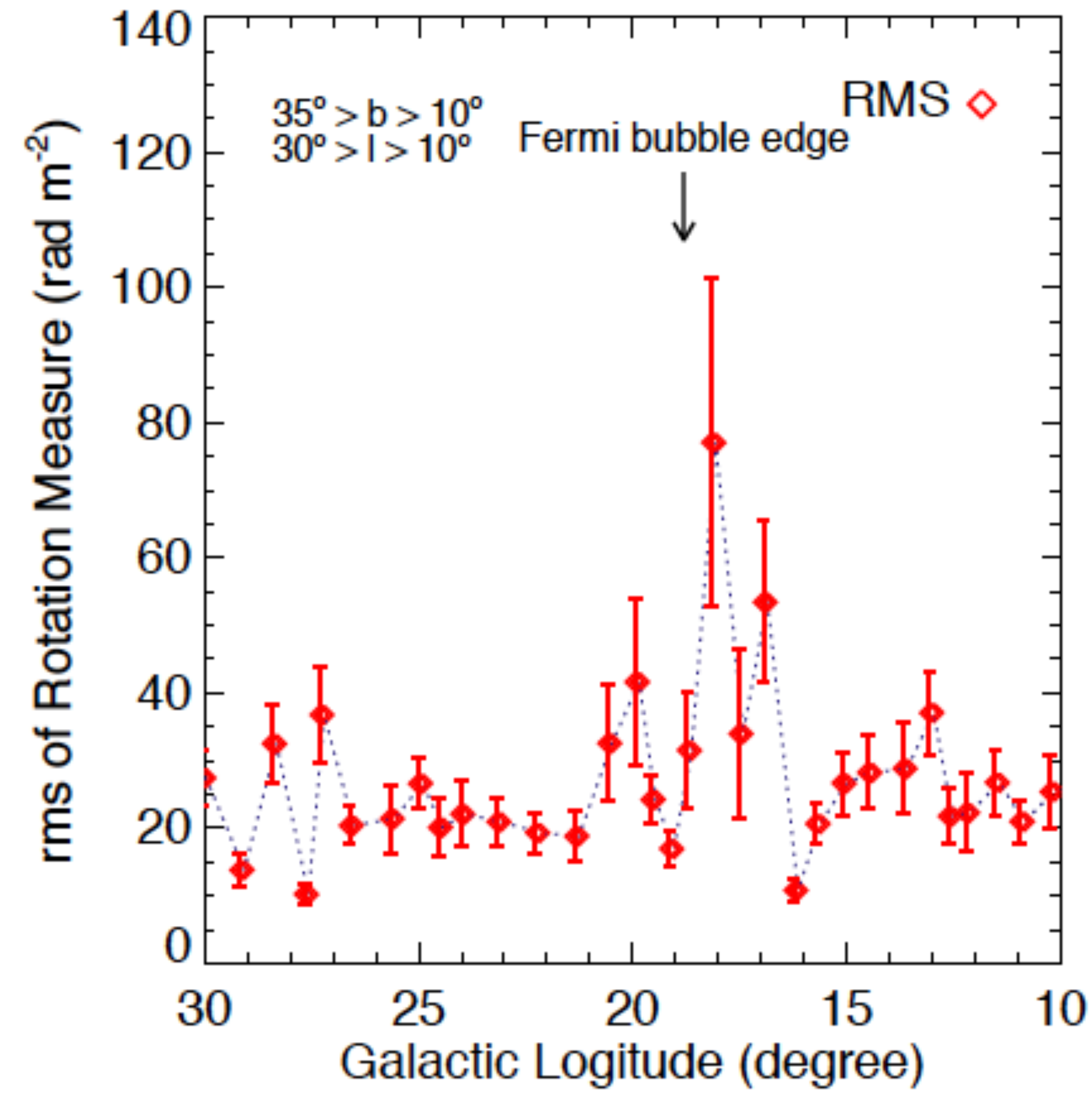
Rotation measure sky map from Very Large Array



Taylor et al. (2009)
MS in preparation

Rotation measure changes at the FB edge

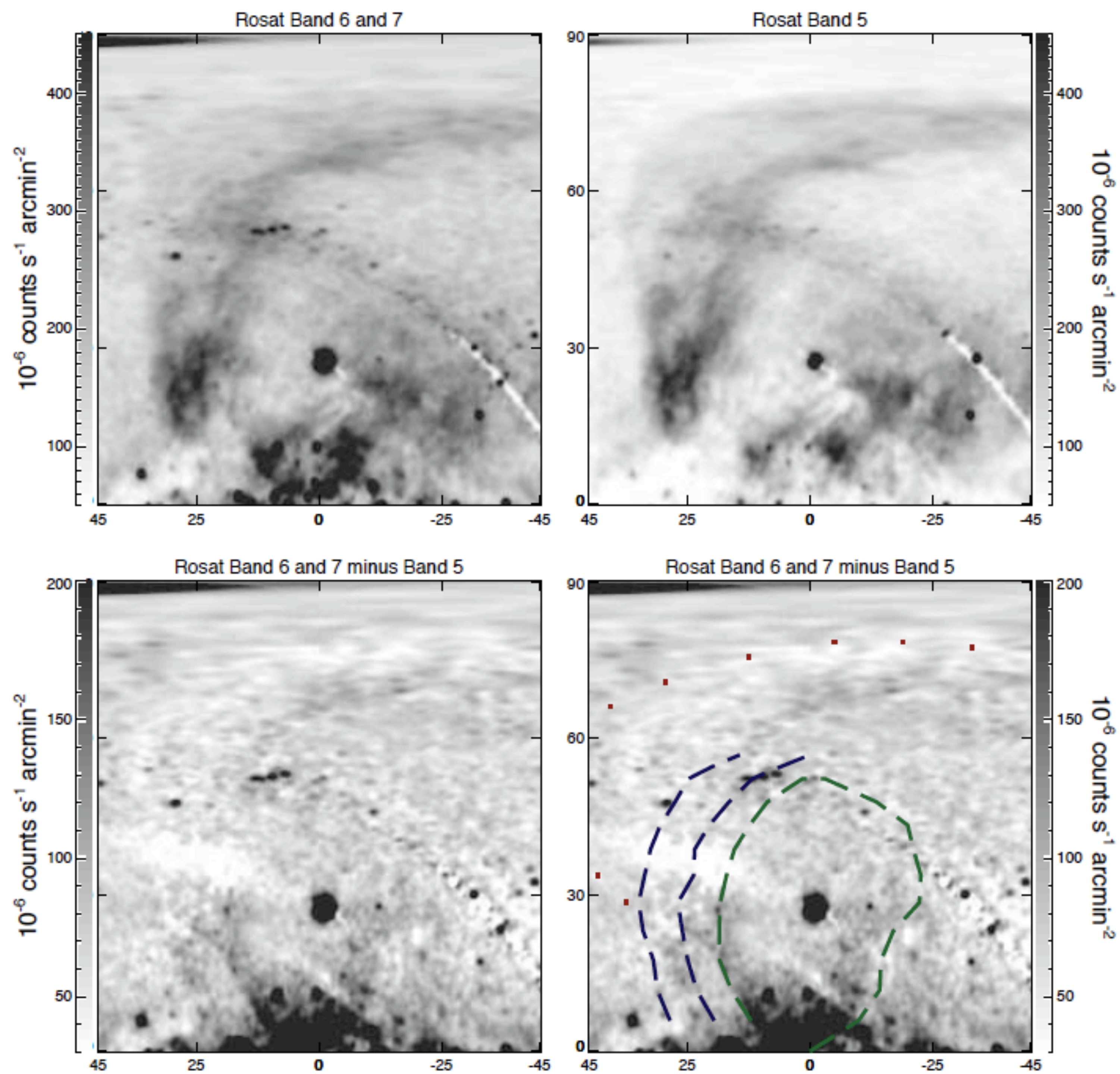




- New data from Jansky Very Large Array

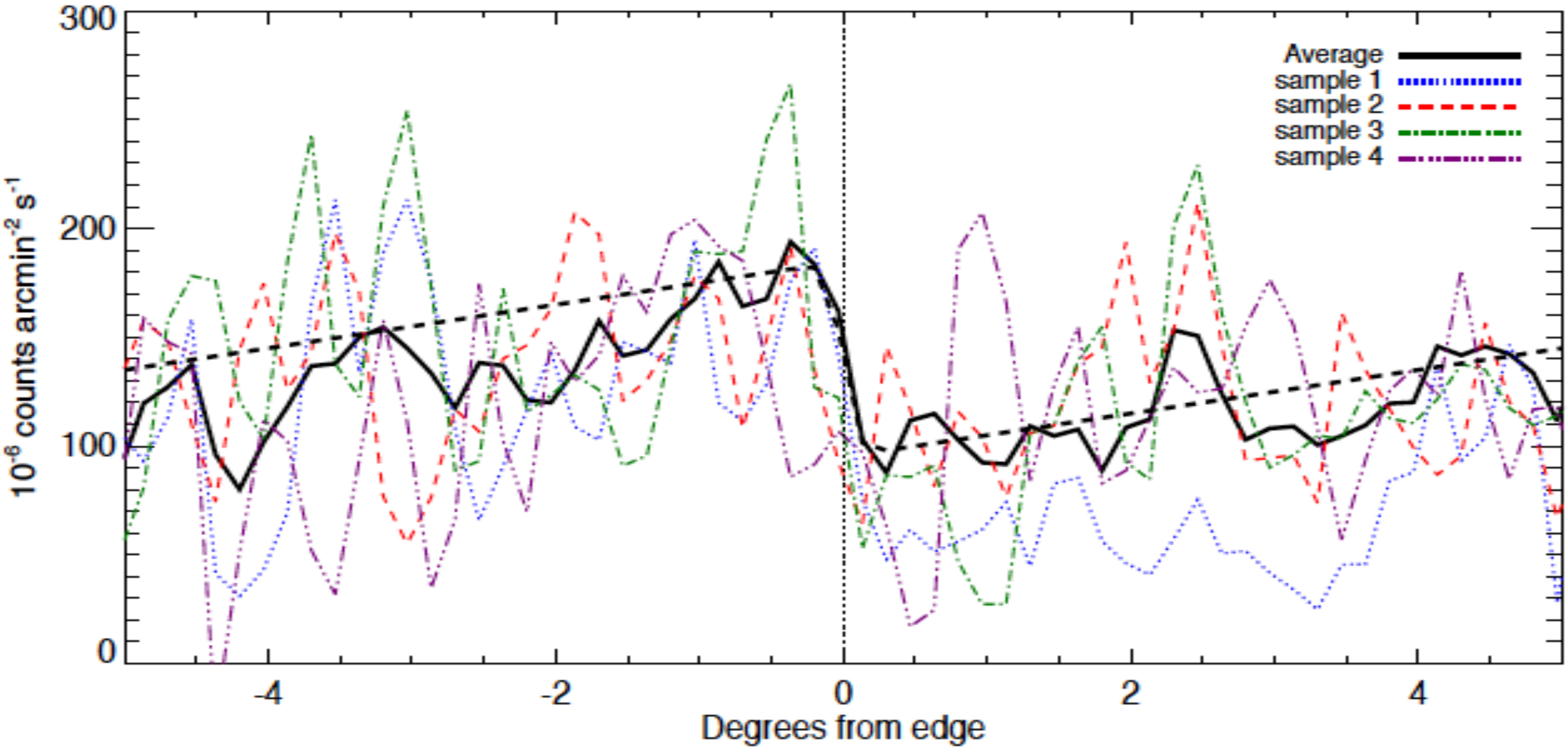
MS et al. in preparation

ROSAT reveals the bubble edge in X-ray

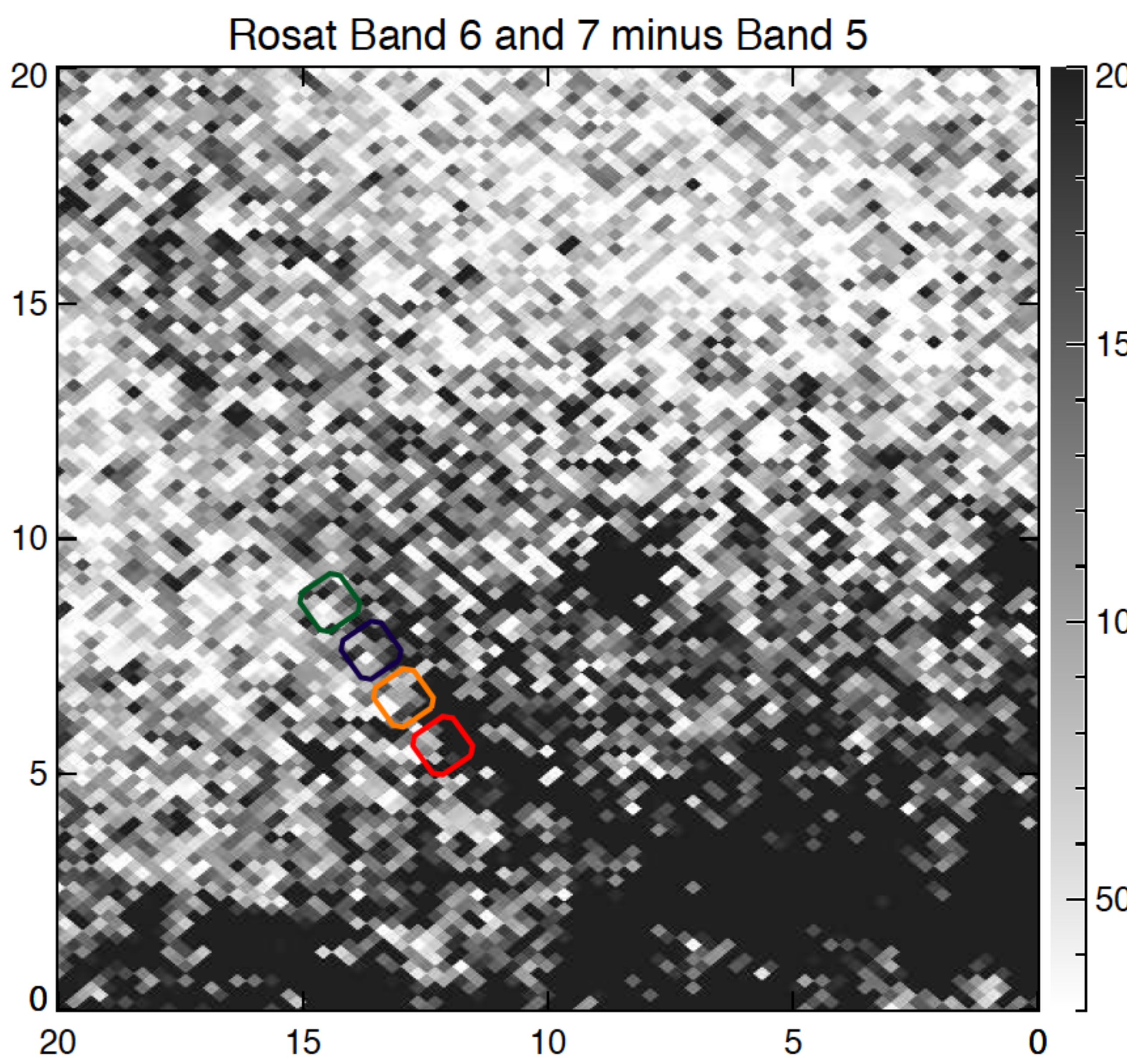


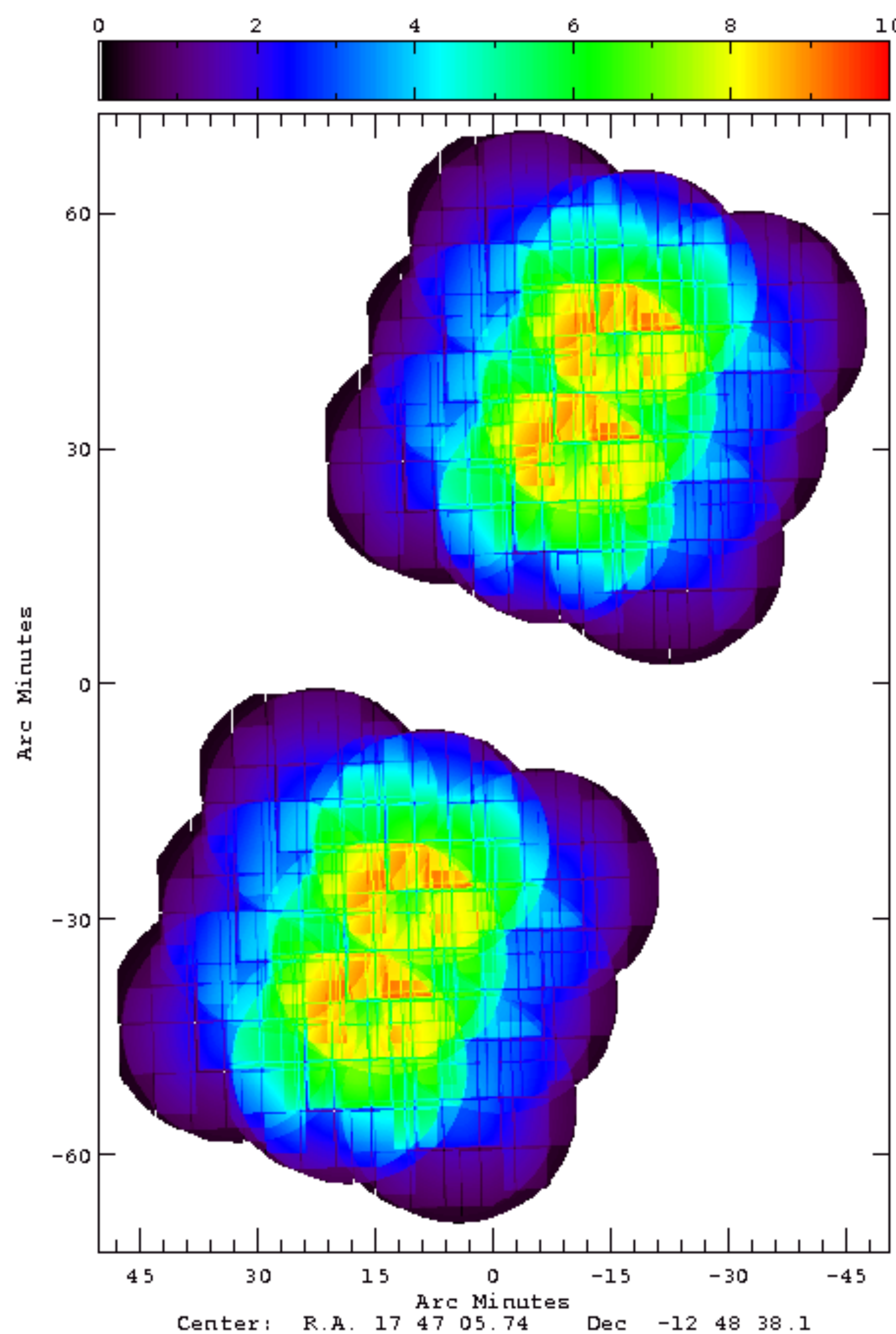
Su, Slatyer, Finkbeiner (2010)

FB has a sharp edge in X-ray



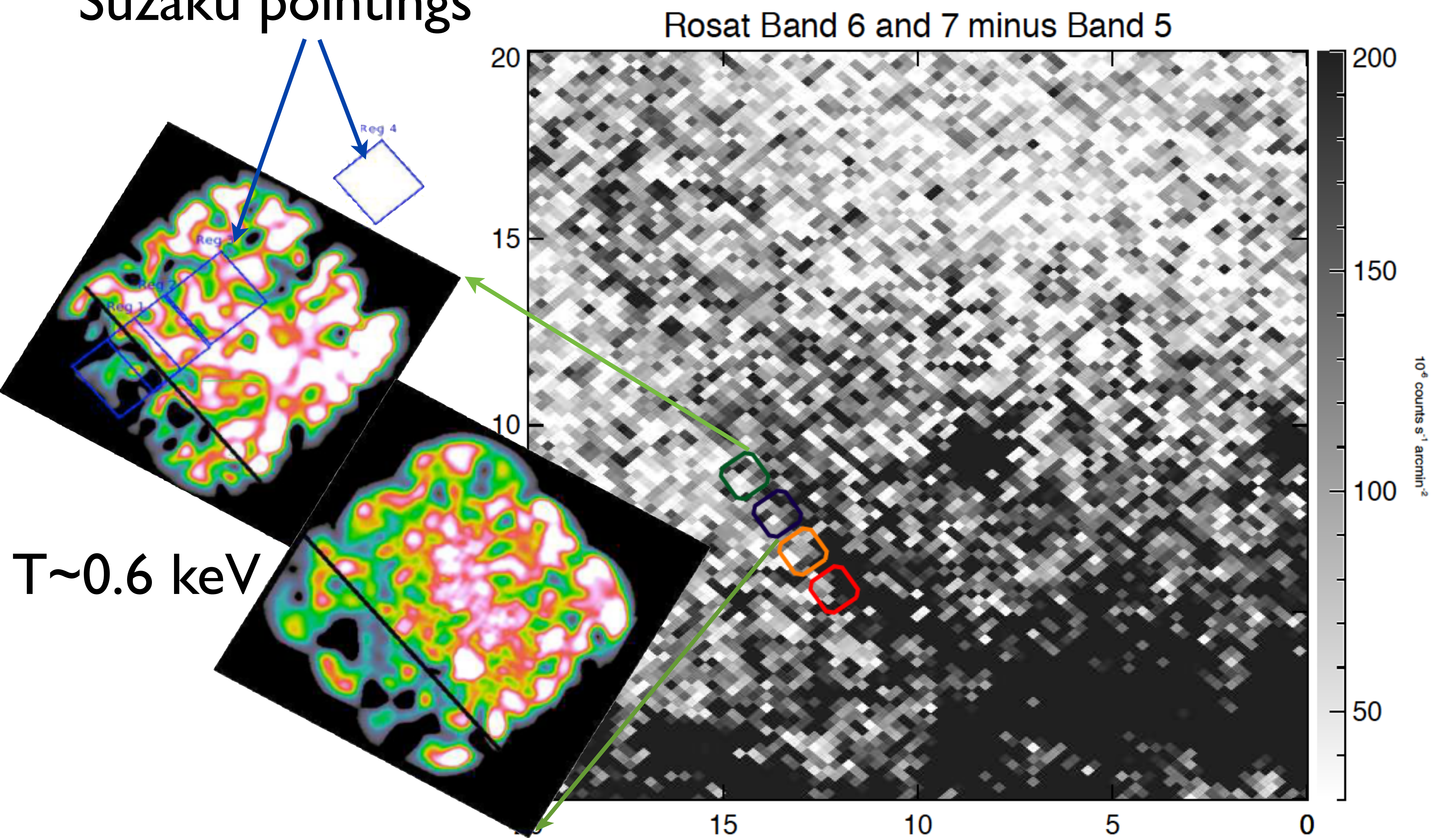
Mosaic XMM-Newton Observations on the FB edge





MS et al. in preparation

Suzaku pointings



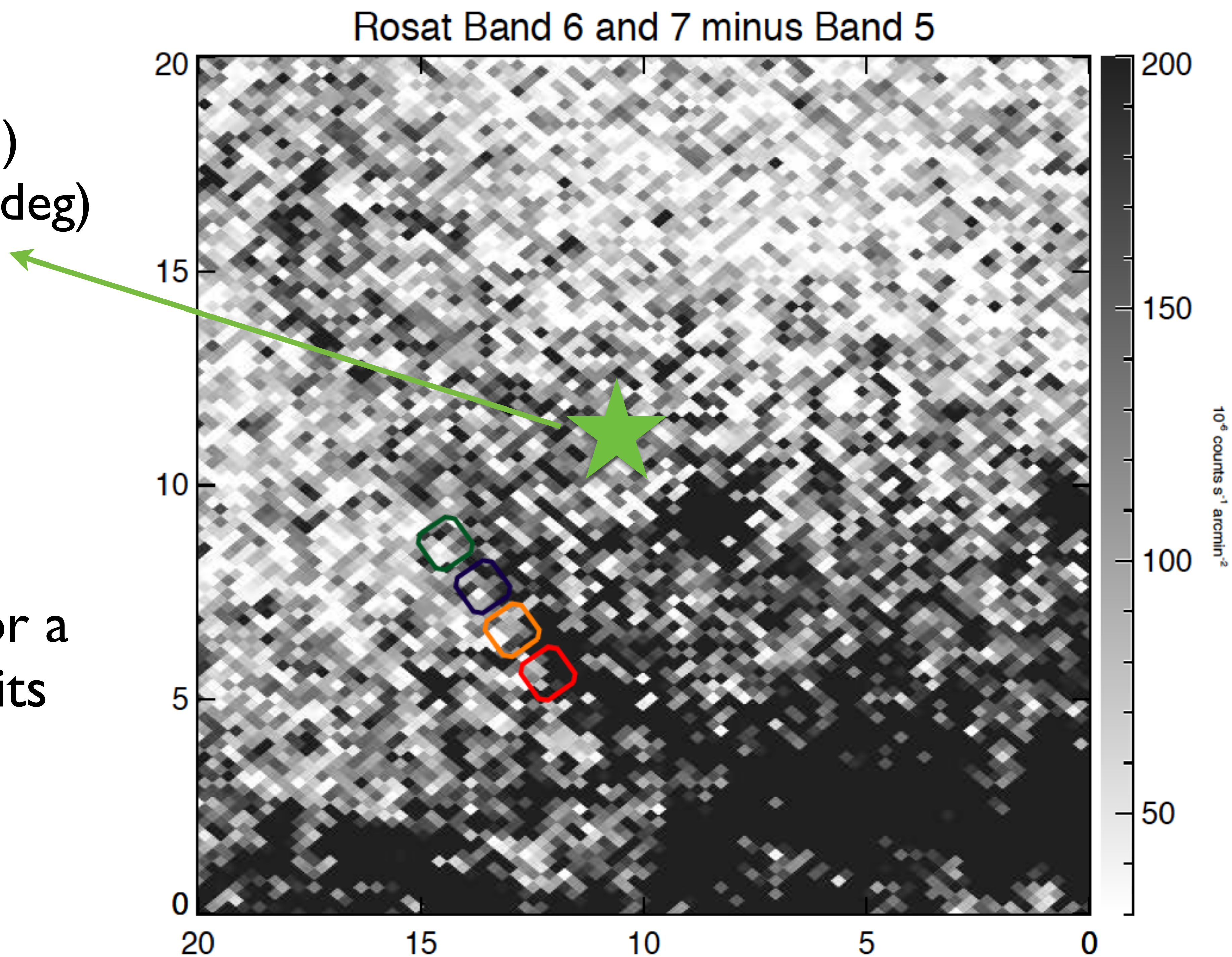
T~0.6 keV

MS et al. in preparation

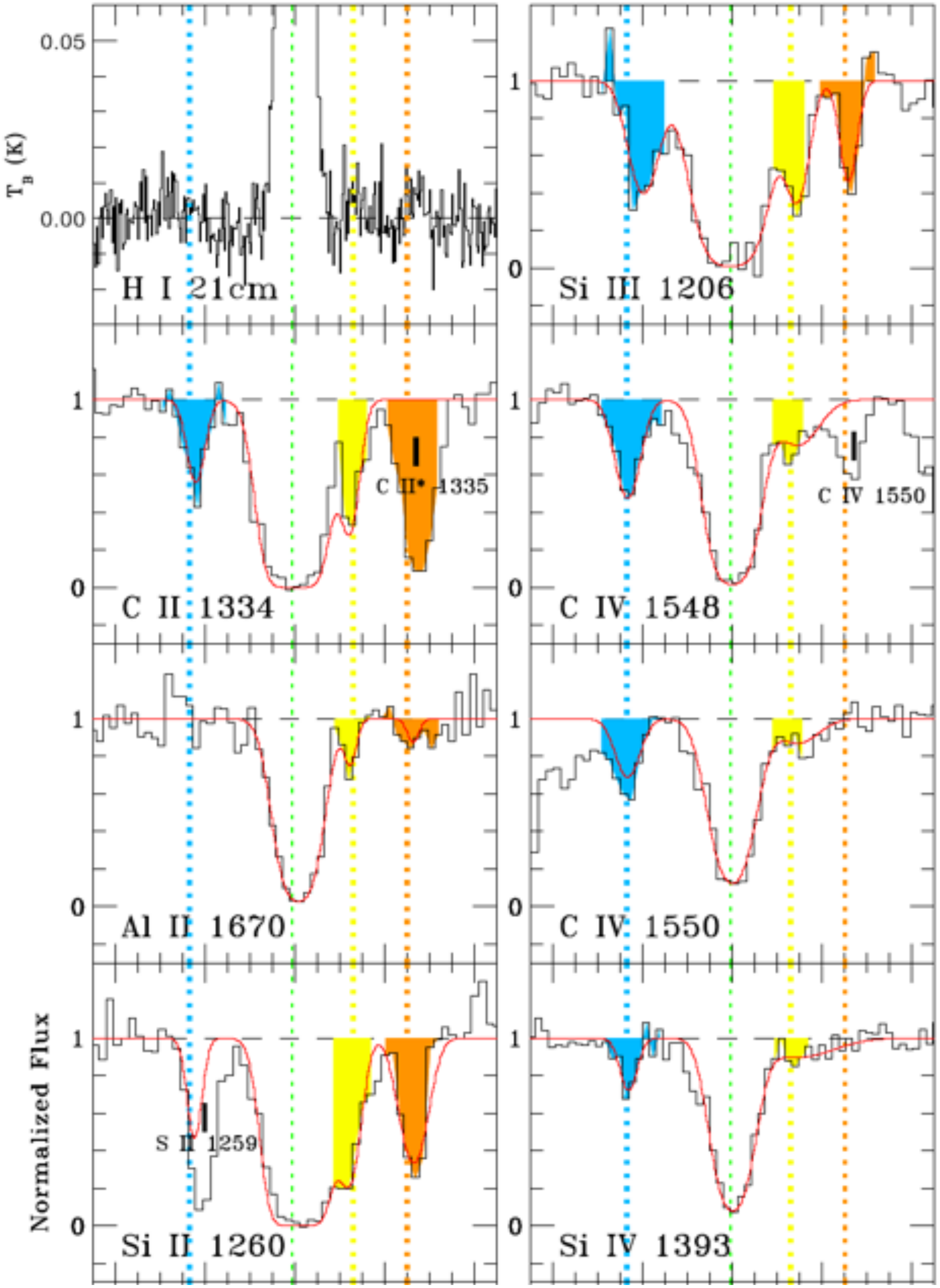
Expanding bubbles with an age ~Myr?
(UV absorption lines with Hubble)

Quasar PDS 456
(IRAS17254-1413)
(l, b=10.4 deg, +11.2 deg)

Observed with Cosmic Origins Spectrograph onboard HST for a total of five orbits



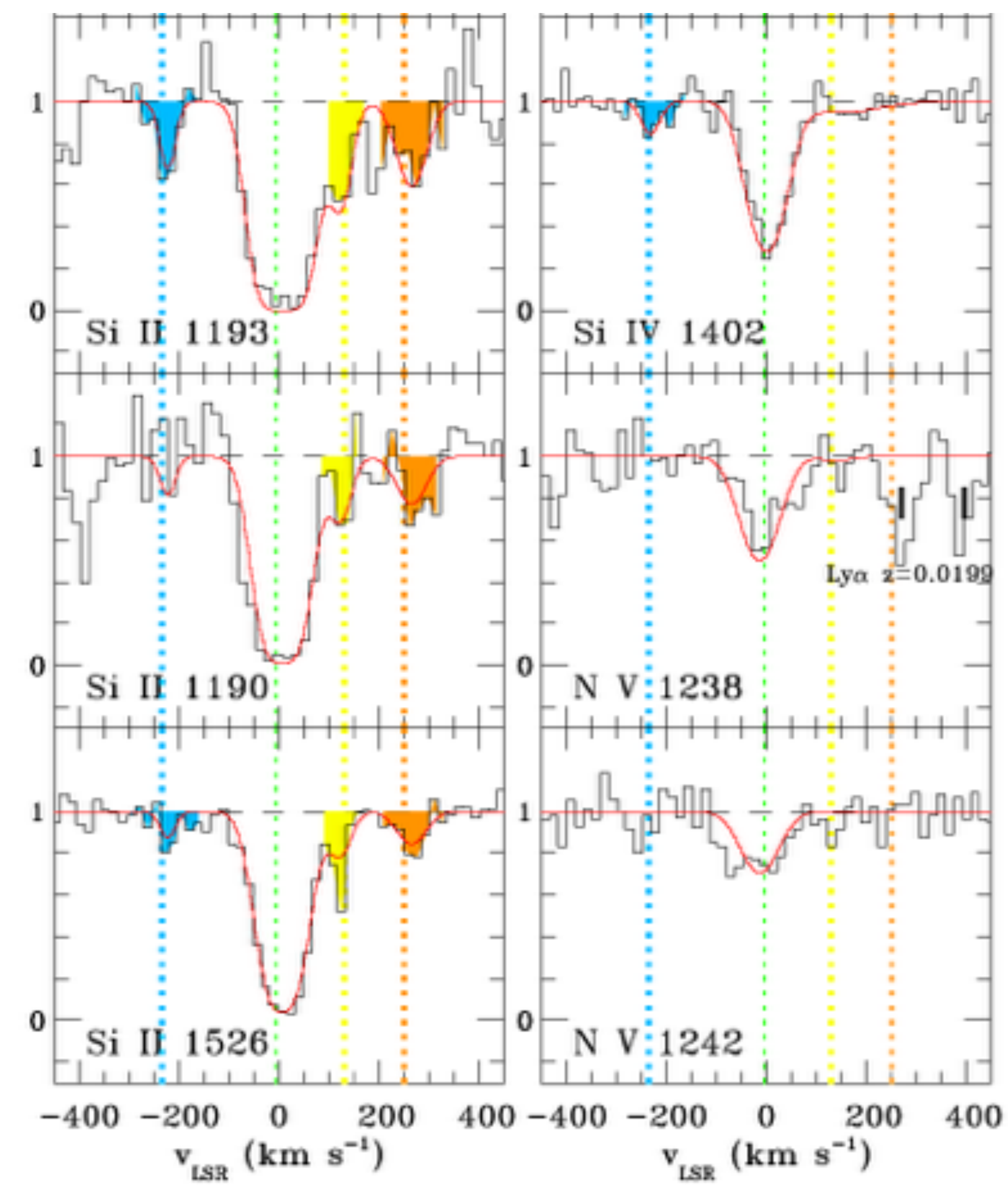
Fox et al. (2014)



Two high-velocity metal absorption components, at v_LSR=−235 and +250 km/s, suggest an origin on the front and back side of an expanding biconical outflow emanating from the Galactic Center over the last ≈2.5-4.0 Myr

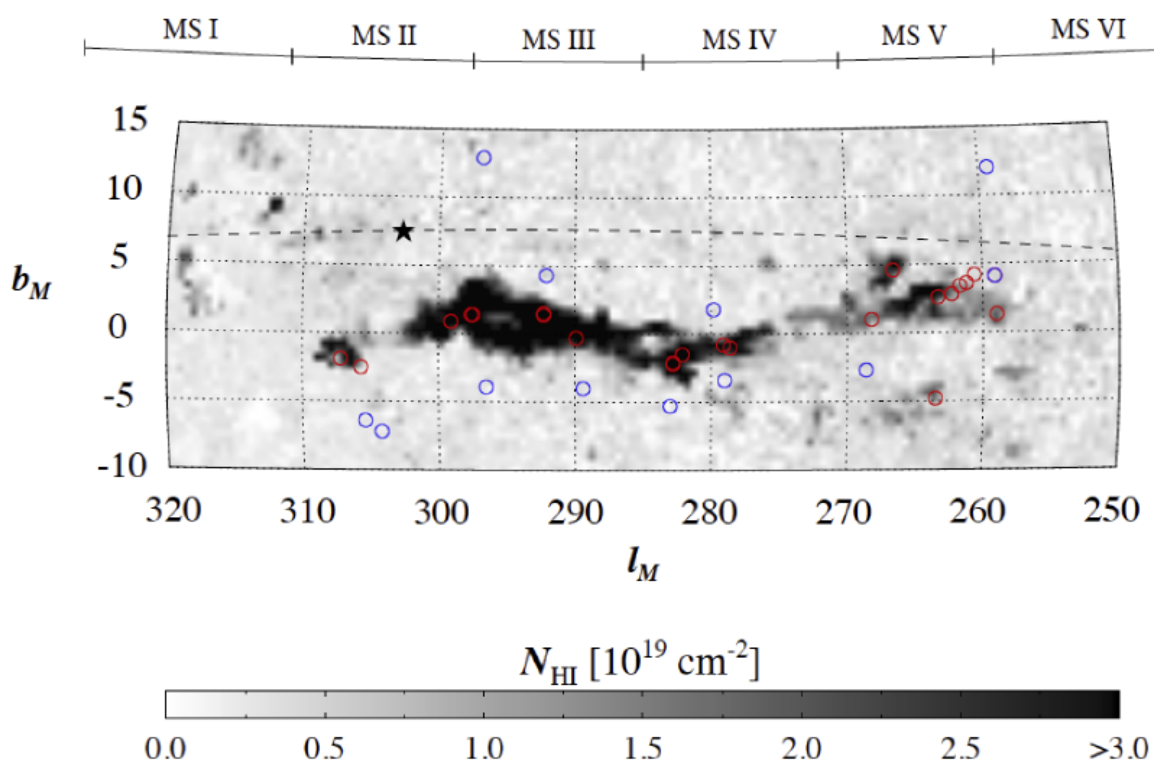
).

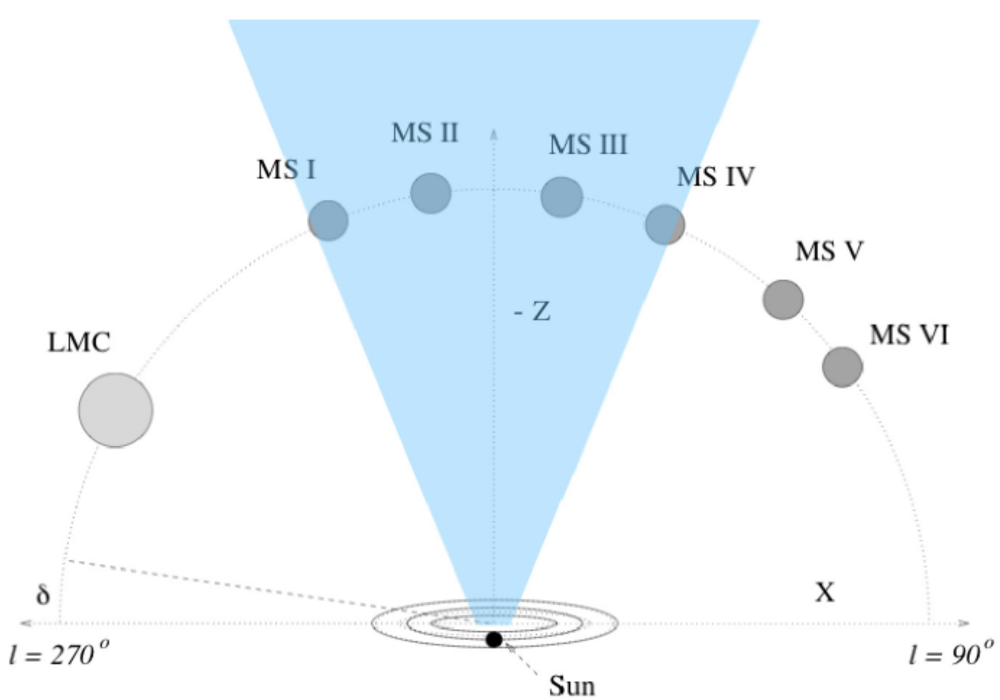
.

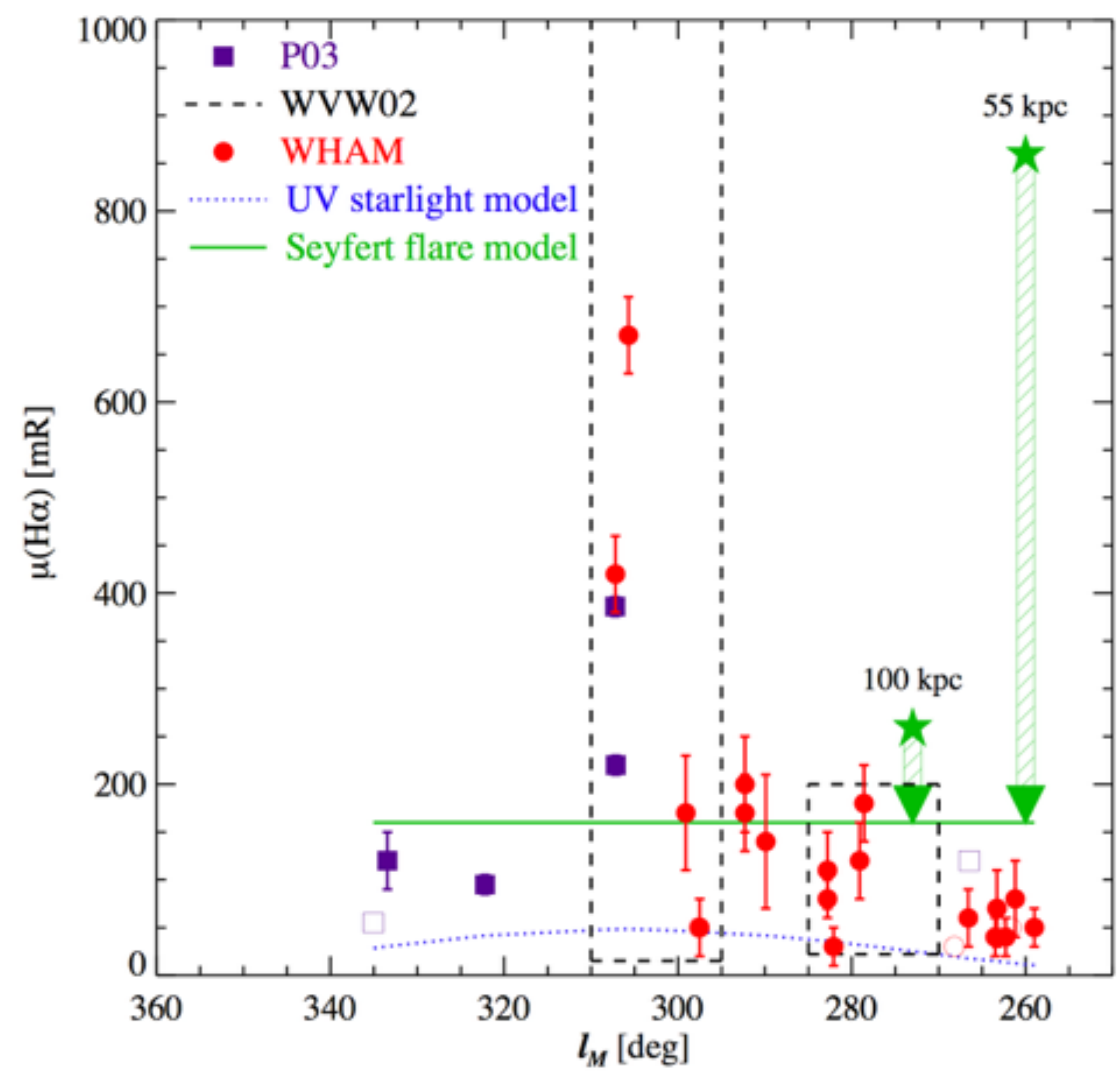


Fox et al. (2014)

Fossil imprint on the Magellanic Stream: a 'Seyfert flare' from the GC ~1-3 Myr ago?







Bland-Hawthorn et al., (2013)

What produced the FB?

- Energetic transients

  (~10^6 years, episodic)

- Moderate energy input

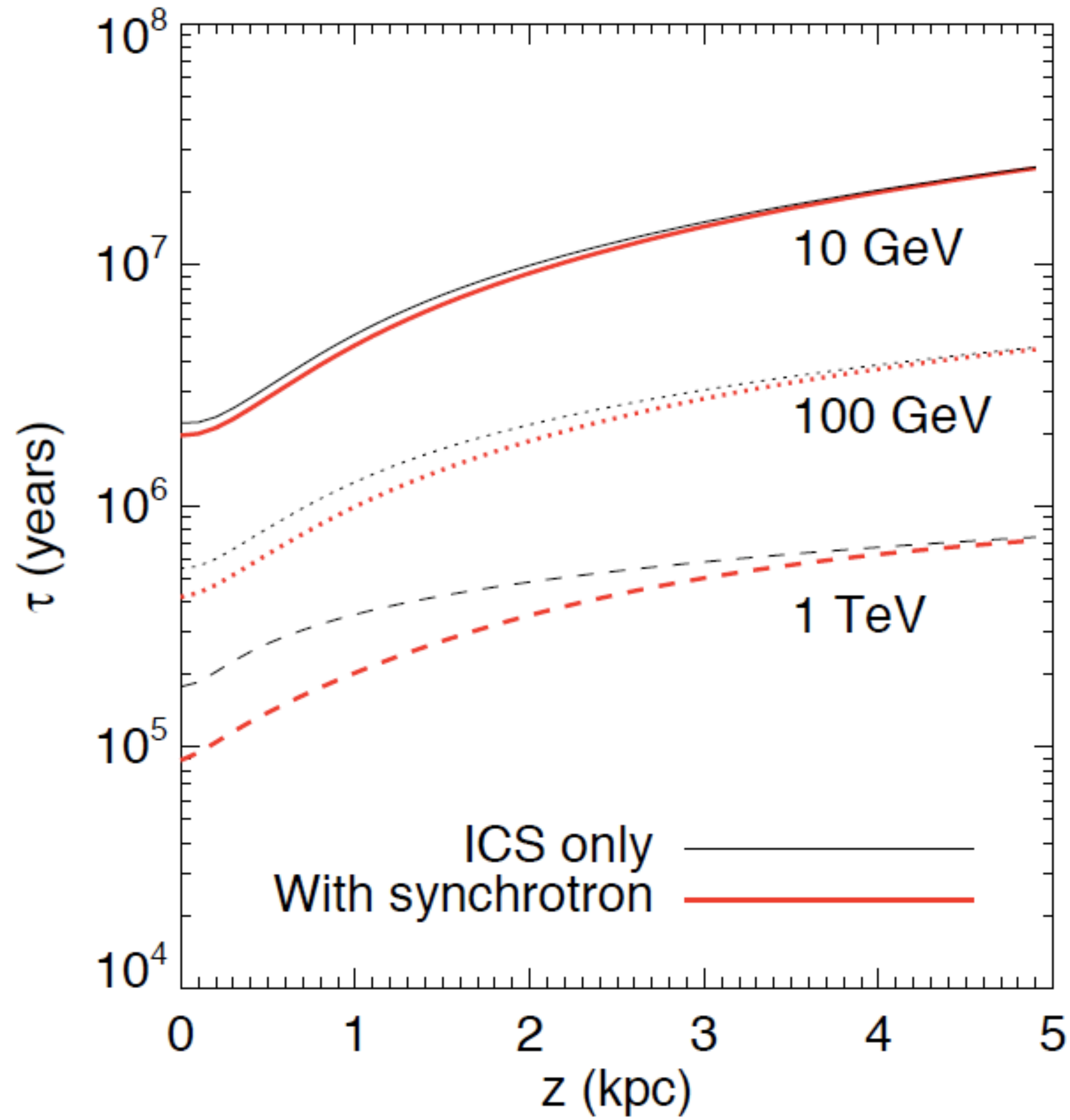
  (~10^9 years, persistent)

  (Crocker & Aharonian 2011)

- Black hole "burp" (jet)
- Accretion disk outflow
- Starburst wind bubble
- Dark matter

- FB : remnant of past activity from the Galactic center ~10^6 years ago, by accretion of the central black hole Sgr A*

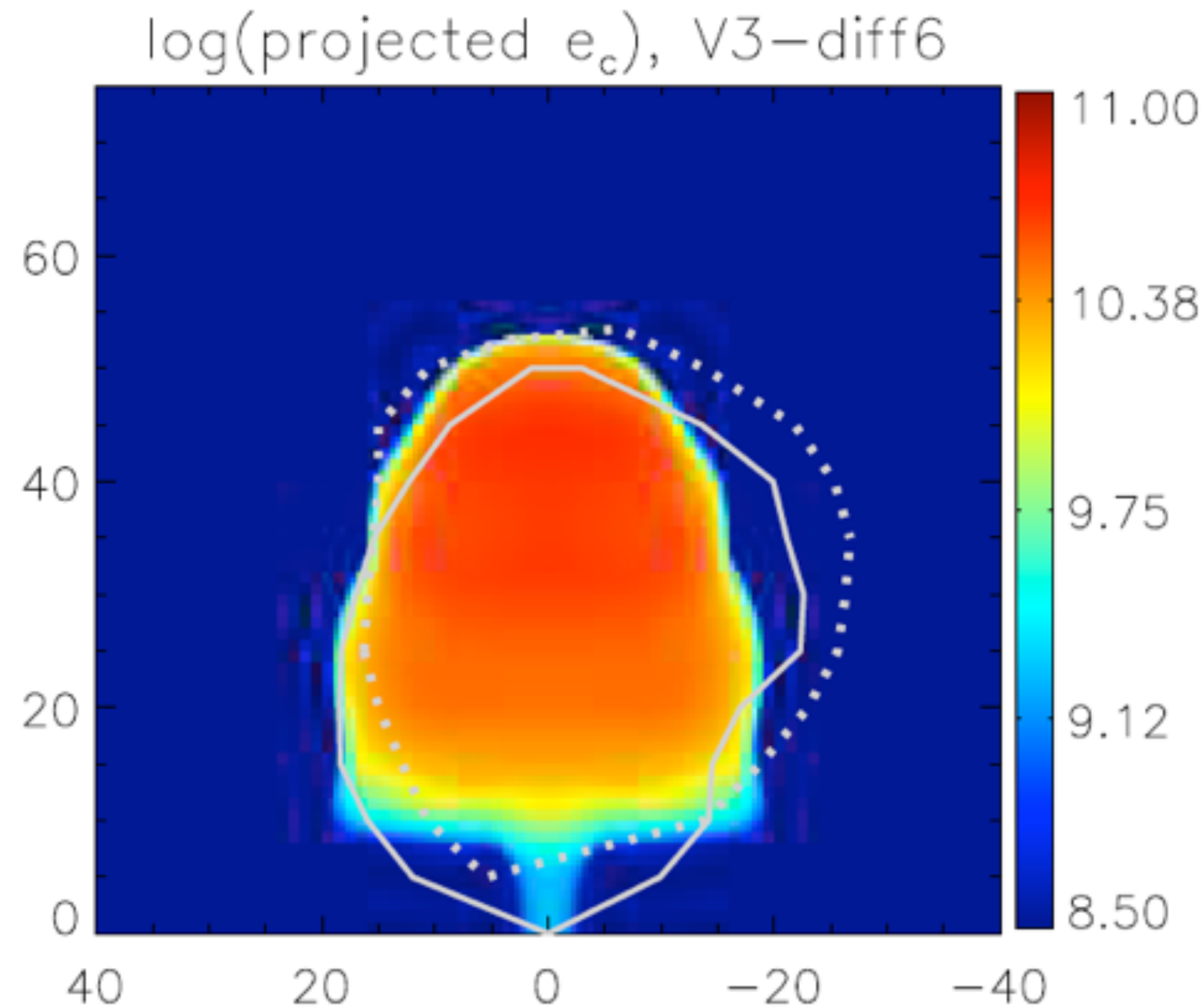
Key question: where/how to accelerate/propagate ~TeV cosmic ray electrons within the bubbles



Su, Slatyer, Finkbeiner (2010)

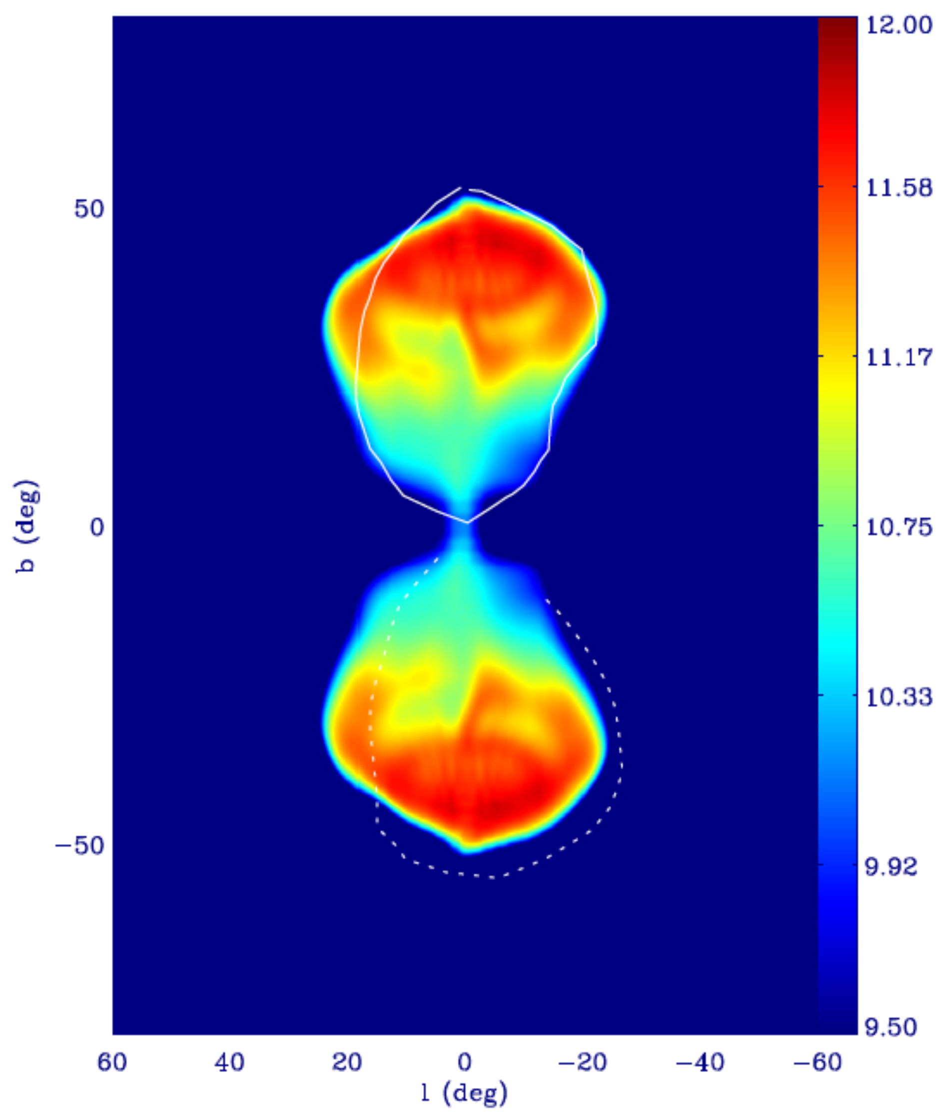
Transient energetic jet (or quasar outflow) from the central BH can produce the bubbles

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



Guo et al. (2012)

(See also Zubovas et al. 2012)



Yang et al. (2012)

Problems

- Cosmic rays carried by the jet diffuse to today's morphology (B-field confinement)
- Jet direction to be perpendicular to the plane of the Galaxy
- Velocity required in the jet model is as low as ~0.1c
- Typically requires super-Eddington
- X-ray shows no strong shocks as predicted

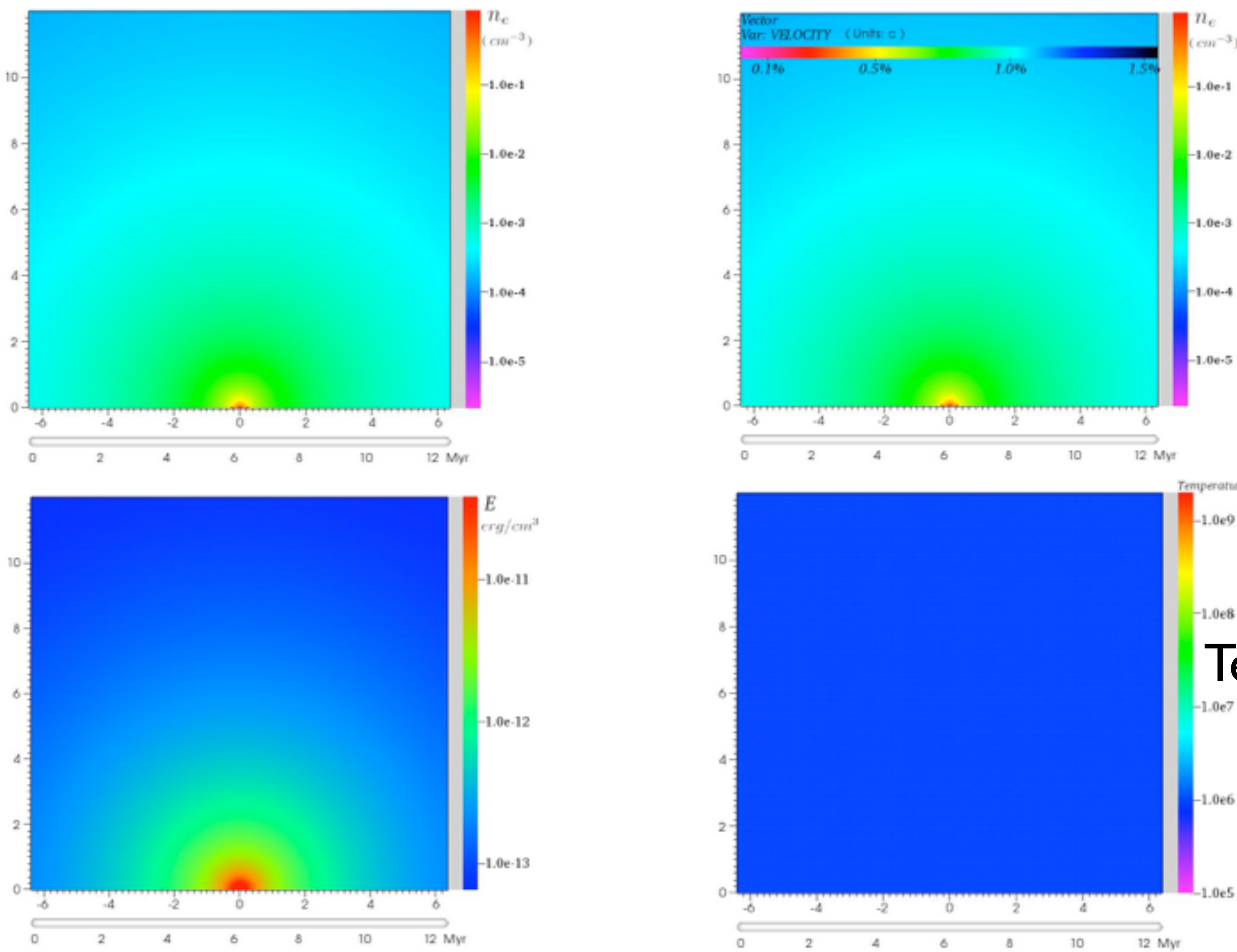
Fermi Bubbles can be inflated by the wind launched from the hot accretion flow

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

Wind power: ~10^{41} erg/s

Density

Velocity

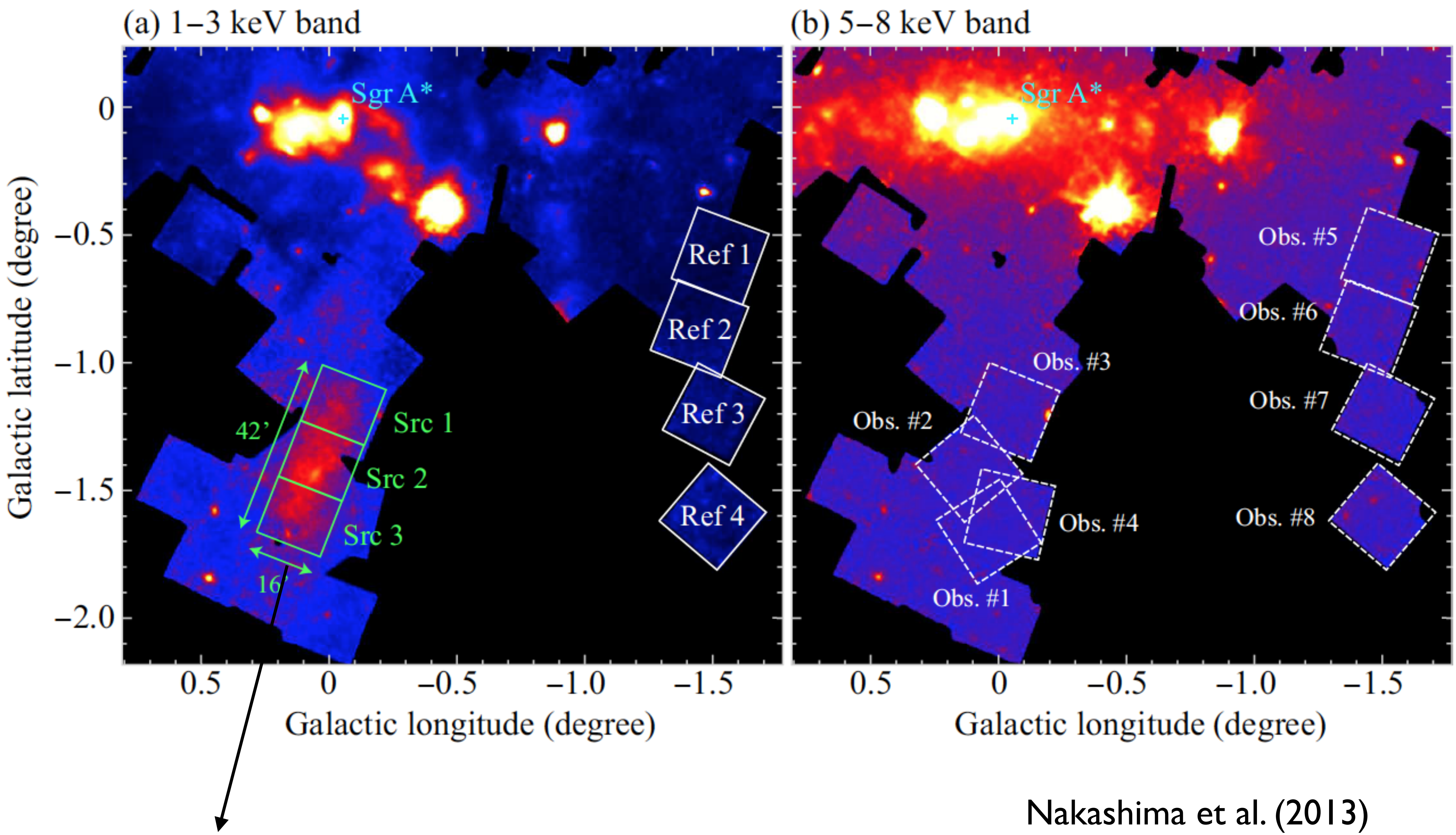


Energy

Temperature

Mou et al. (2014)

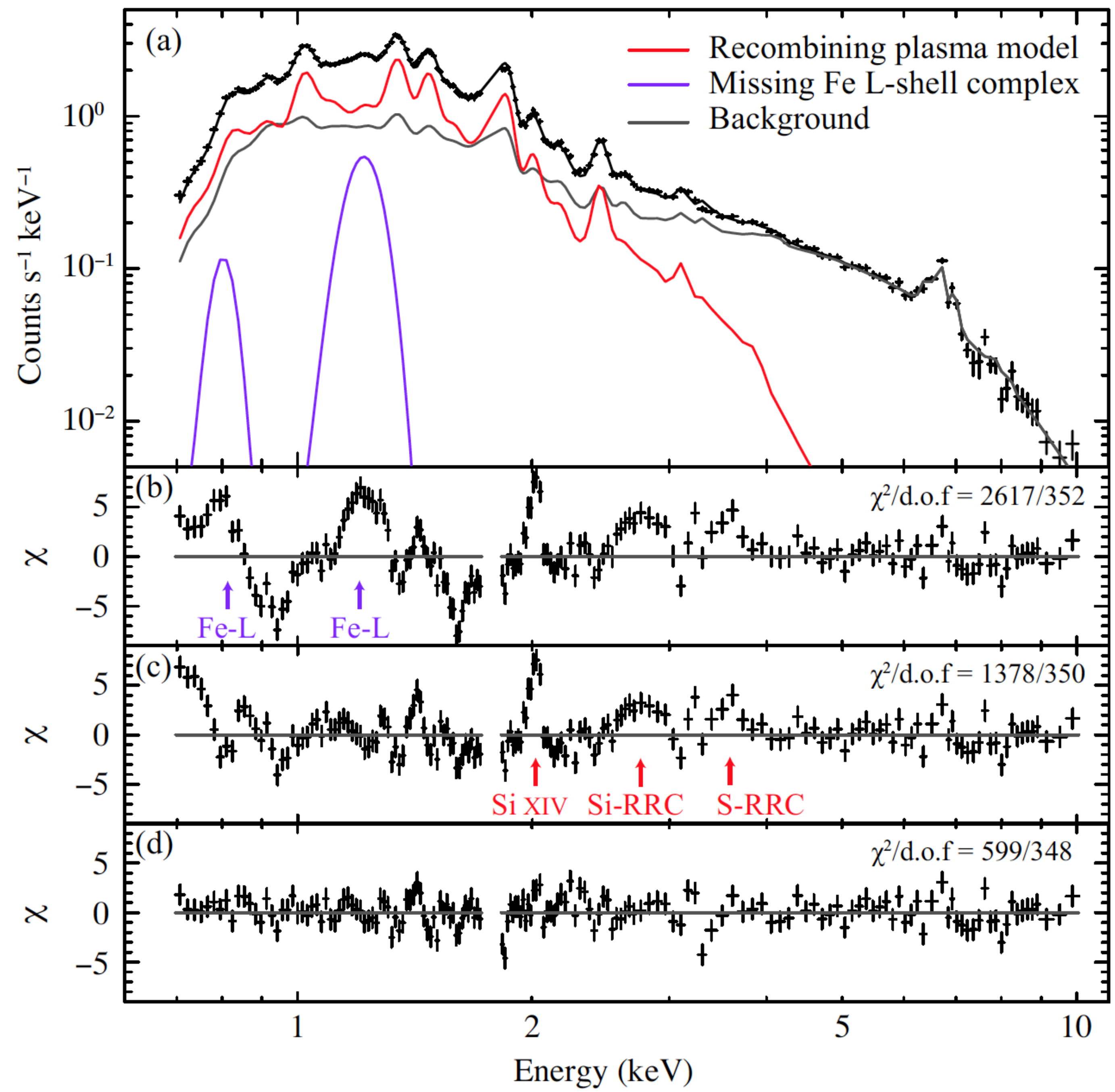
A recombination dominant plasma: a relic of a giant flare of Sgr A*



Nakashima et al. (2013)

Recombining plasma model is favored from the Suzaku spectrum

- Shock heated hot plasma? (unlikely)
- Rapid adiabatic expansion (electron temperature)?
- Photoionization by collimated radiation injection?
- Suggest a past Sgr A* activity ~10^5 years



Nakashima et al. (2013)

How to better measure the gamma-ray spectrum of the Fermi bubbles?

Future high energy gamma-ray instruments

NEWS & ANALYSIS

Science, 20 May 2011

SPACE SCIENCE

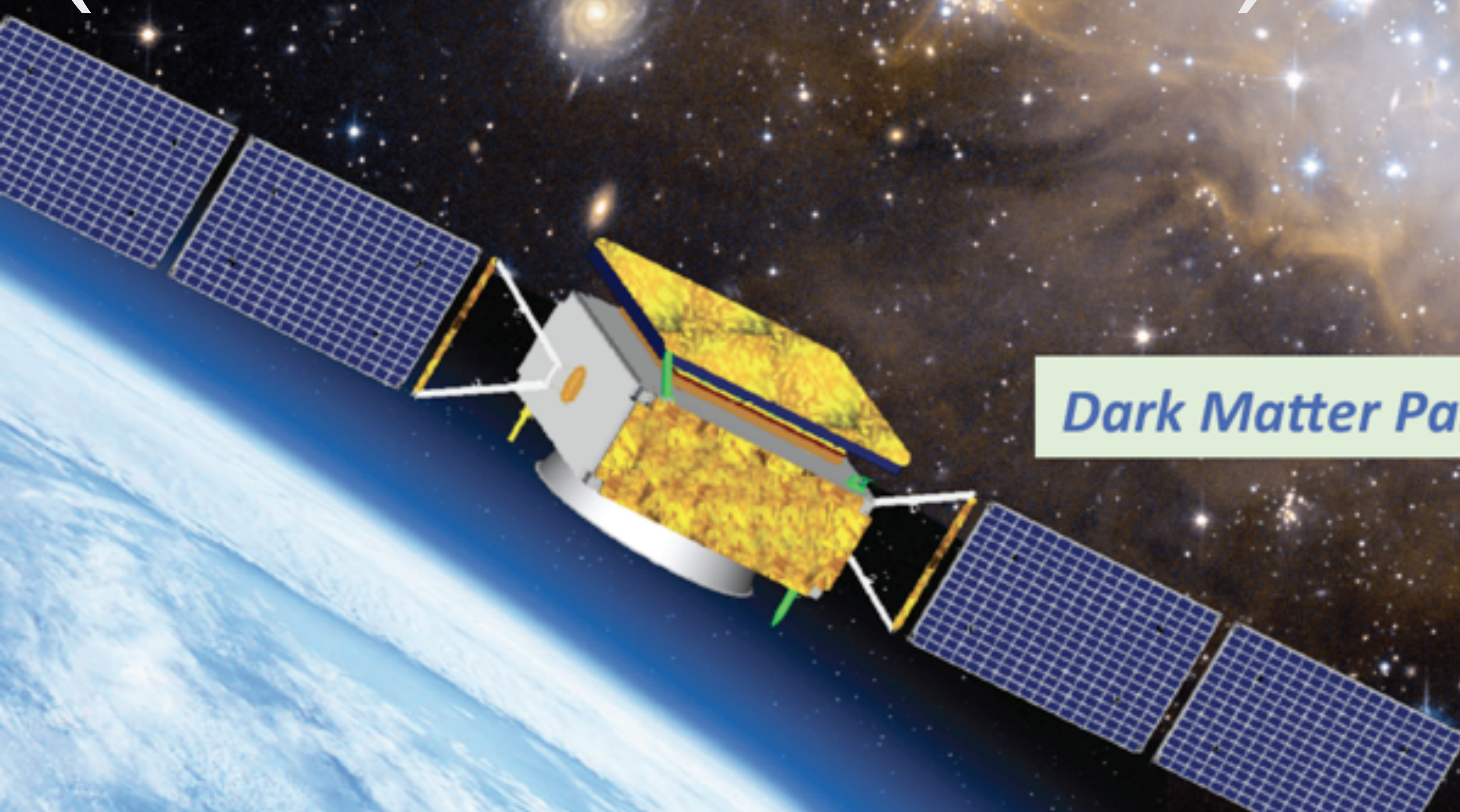
Chinese Academy Takes Space Under Its Wing

LOFTY AMBITIONS

Mission	Chief scientist	Goals	Estimated launch
HXMT	Li Tipei, CAS Institute of High Energy Physics and Tsinghua University	Survey of x-ray sources; detailed observations of known objects	2014
Shijian-10	Hu Wenrui, CAS Institute of Mechanics	Study physical and biological systems in microgravity and strong radiation environment	Early 2015
KuaFu Project	William Liu, Canadian Space Agency and CAS Center for Space Science and Applied Research	Study solar influence on space weather	Mid-2015
Dark Matter Satellite	Chang Jin, CAS Purple Mountain Observatory	Search for dark matter; study cosmic ray acceleration	Late 2015
Quantum Science Satellite	Pan Jianwei, University of Science and Technology of China	Quantum key distribution for secure communication; long-distance quantum entanglement	2016

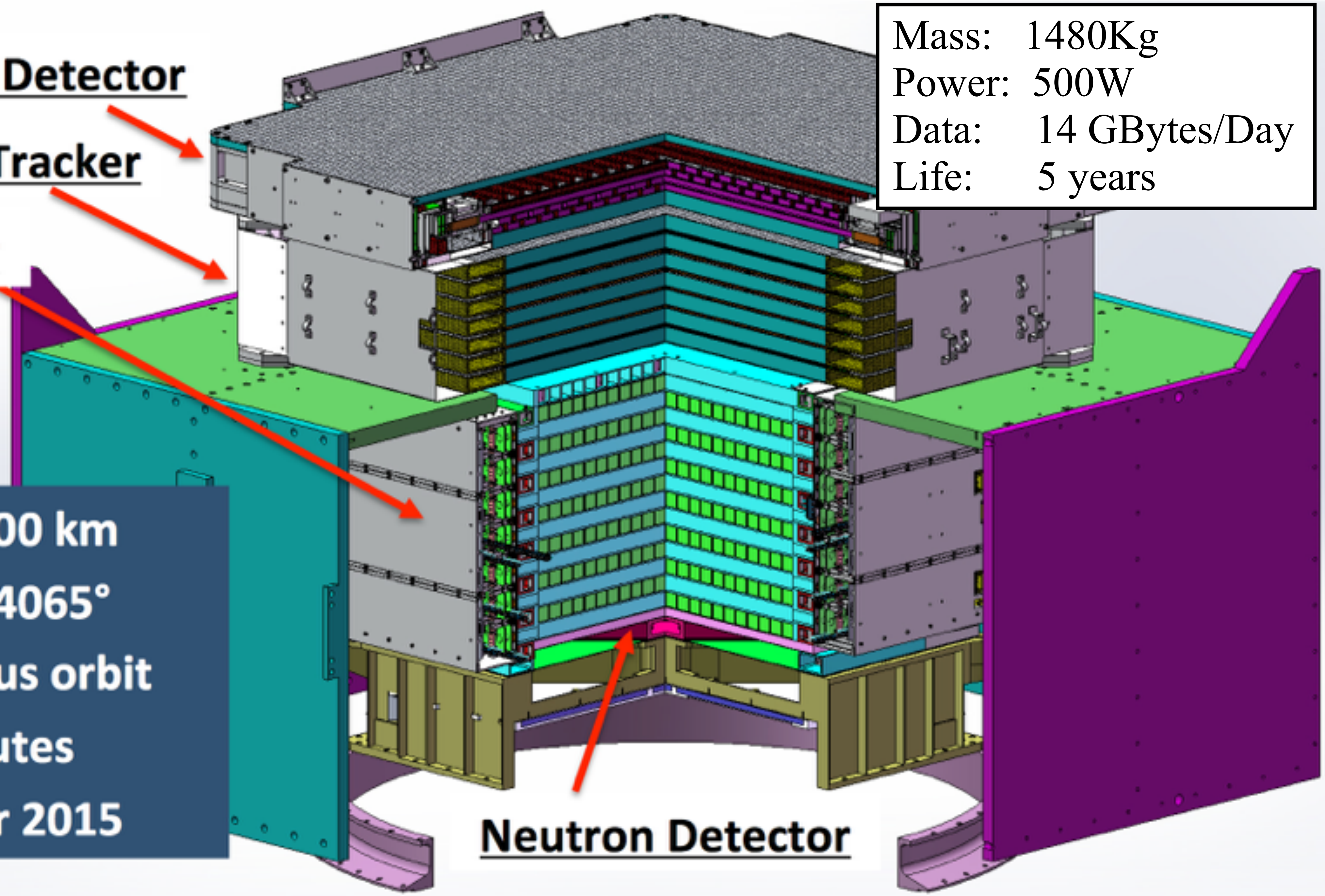
Strategic Priority Research Program in Space Science

DAMPE (launch Dec. 17th)



Dark Matter Particle Explorer Satellite

The DAMPE Detector



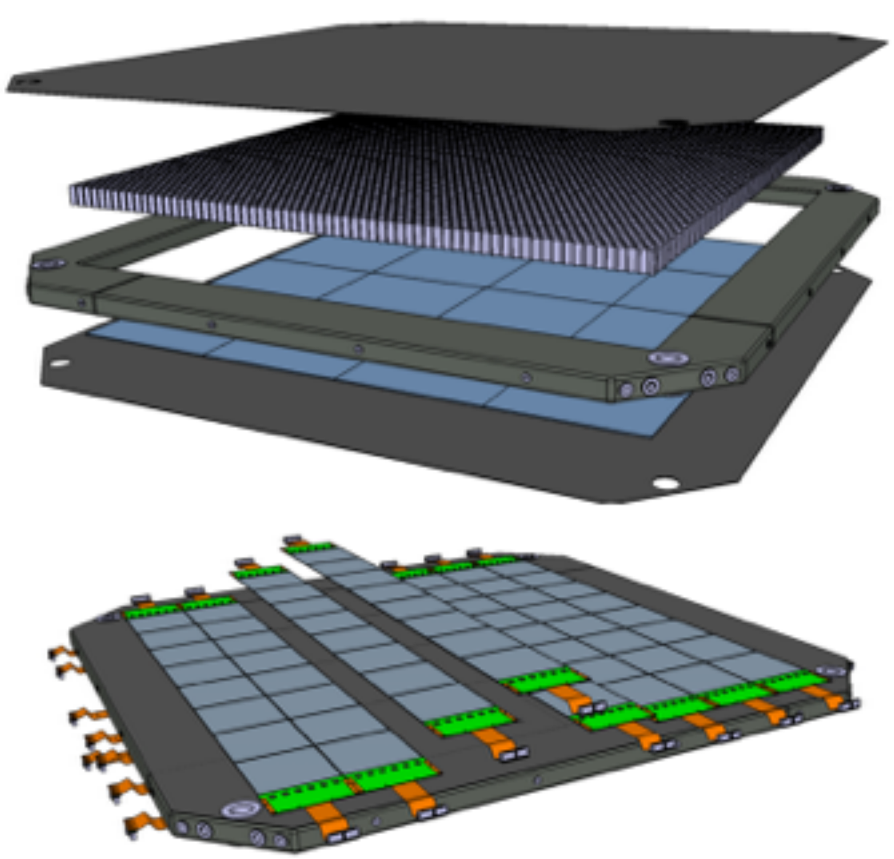
Mass: 1480Kg
Power: 500W
Data: 14 GBytes/Day
Life: 5 years

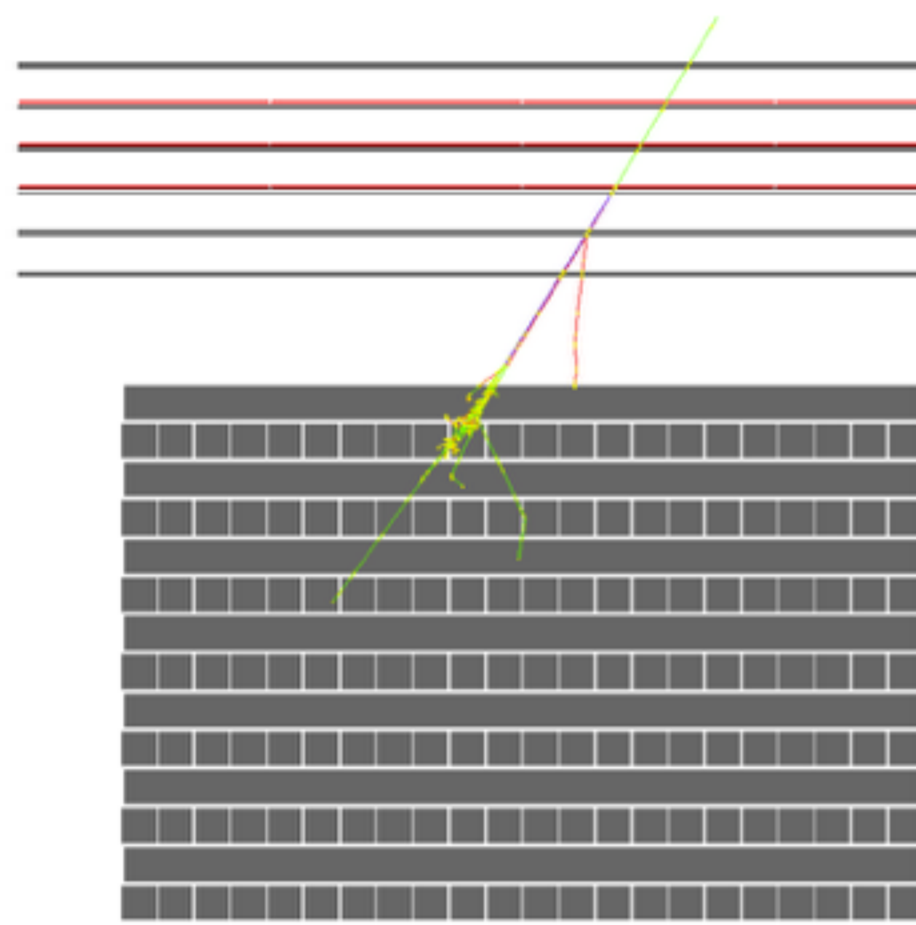
- Altitude: LEO 500 km
- Inclination: 87.4065°
- Sun-synchronous orbit
- Period: 95 minutes
- Launch October 2015

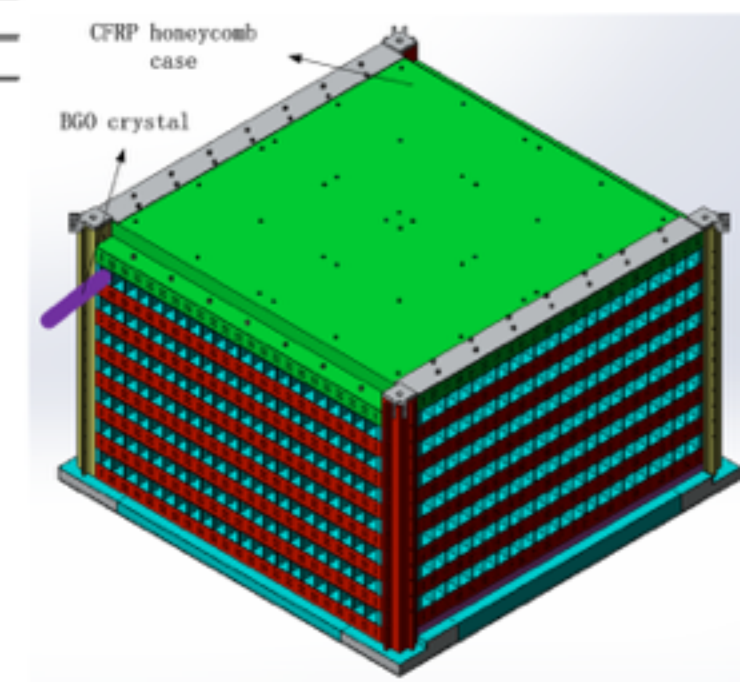
W converter + thick calorimeter (total 32 X_0) + precise tracking + charge measurement ➡ high energy γ-ray, electron and CR telescope

Comparison with AMS-02 and Fermi

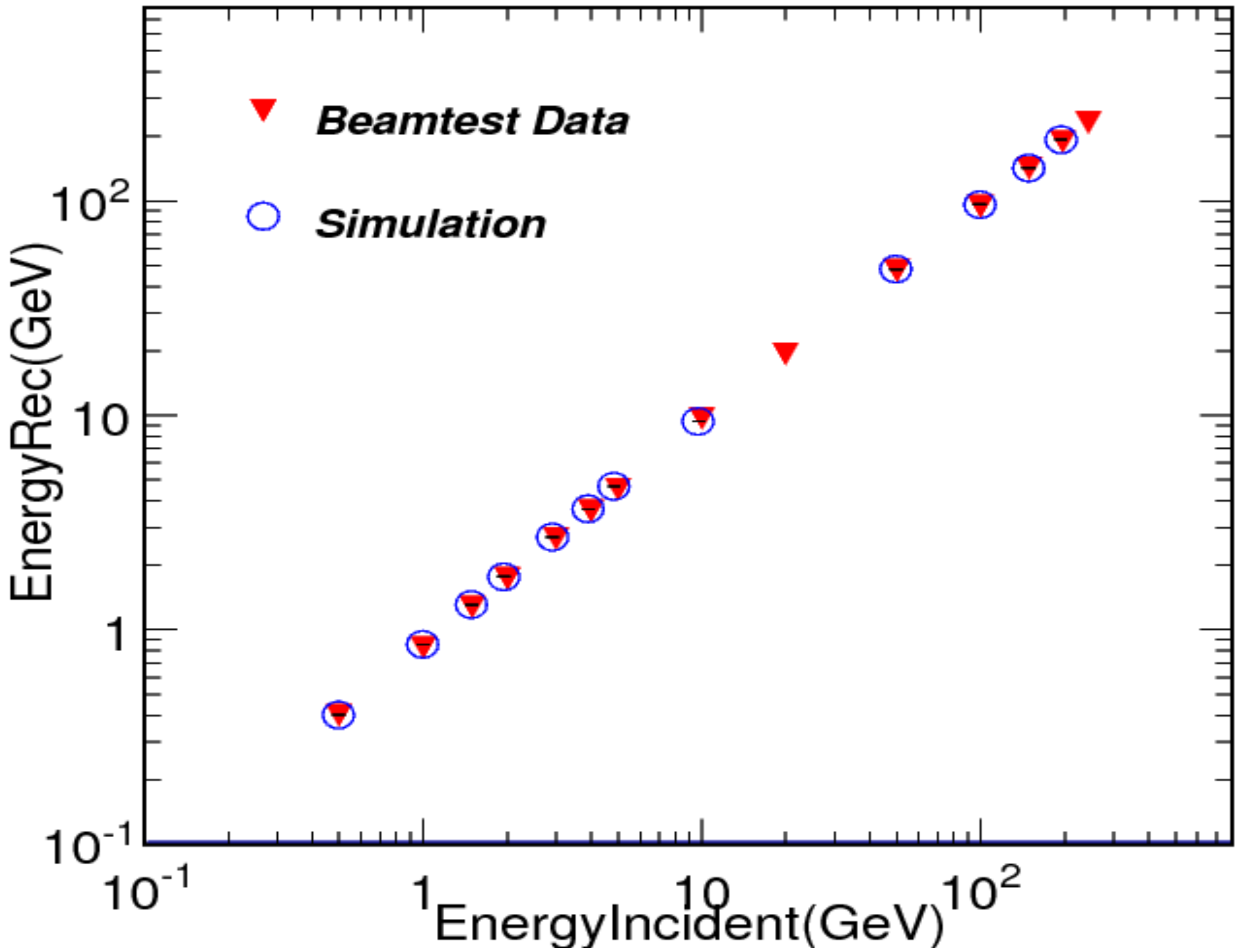
	DAMPE	AMS-02	Fermi LAT
e/γ Energy res.@100 GeV (%)	1.5	3	10
e/γ Angular res.@100 GeV (°)	0.1	0.3	0.1
e/p discrimination	10^5	10^5 - 10^6	10^3
Calorimeter thickness (X_0)	31	17	8.6
Geometrical accep. (m^2sr)	0.29	0.09	1



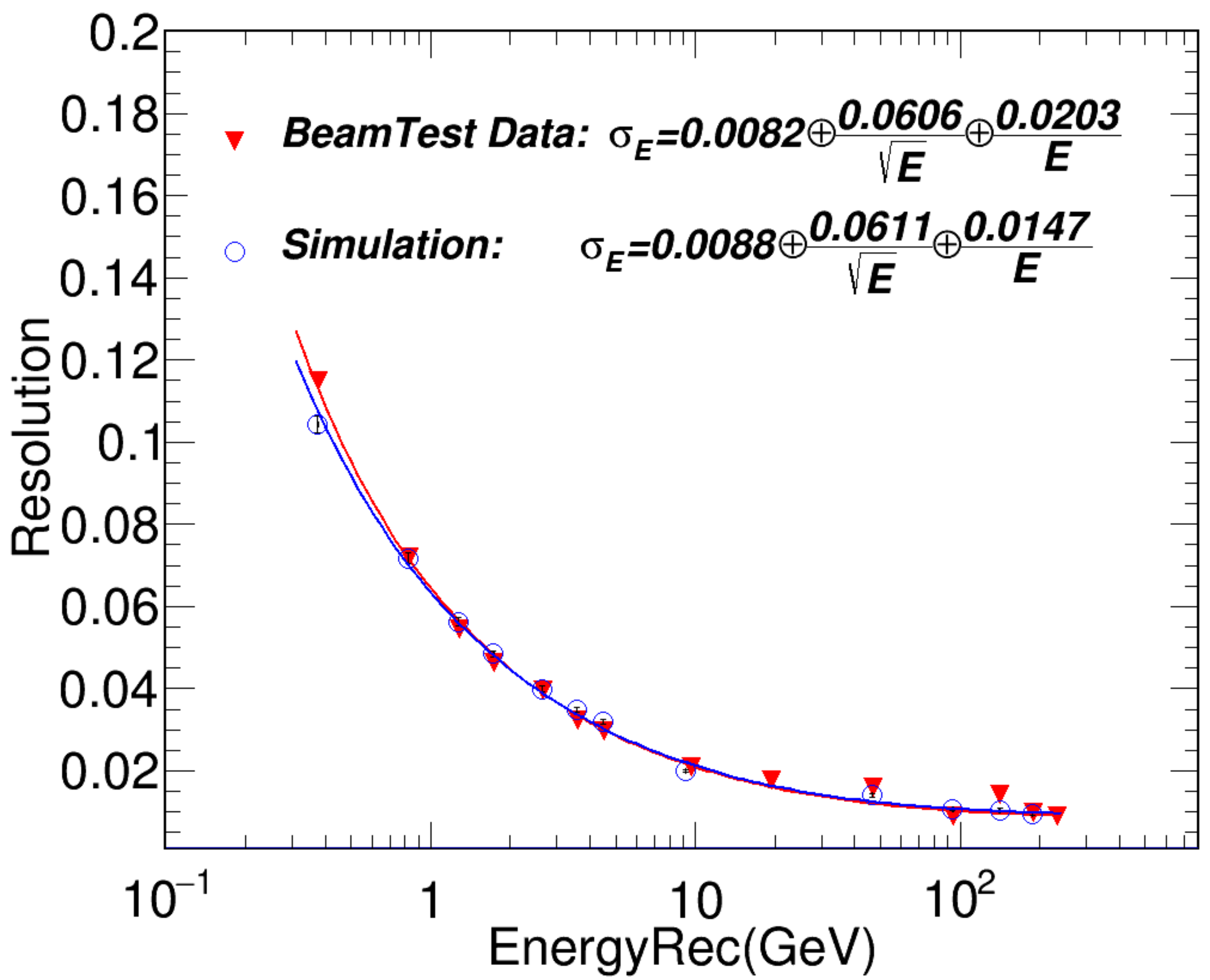




The reconstruction raw energy versus the incident electron energies

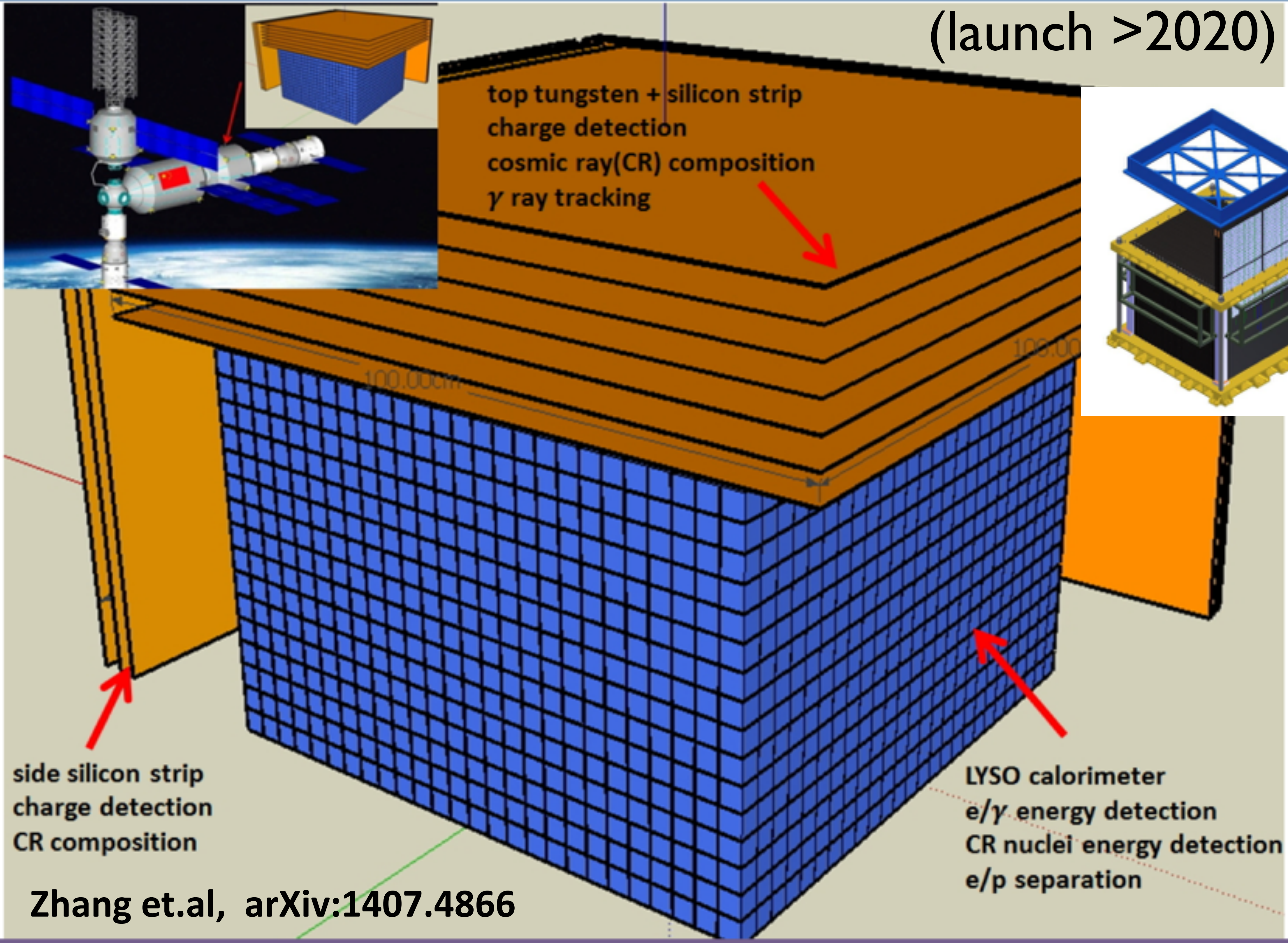


The energy resolutions change with the incident electron energies



HERD Conceptual Design

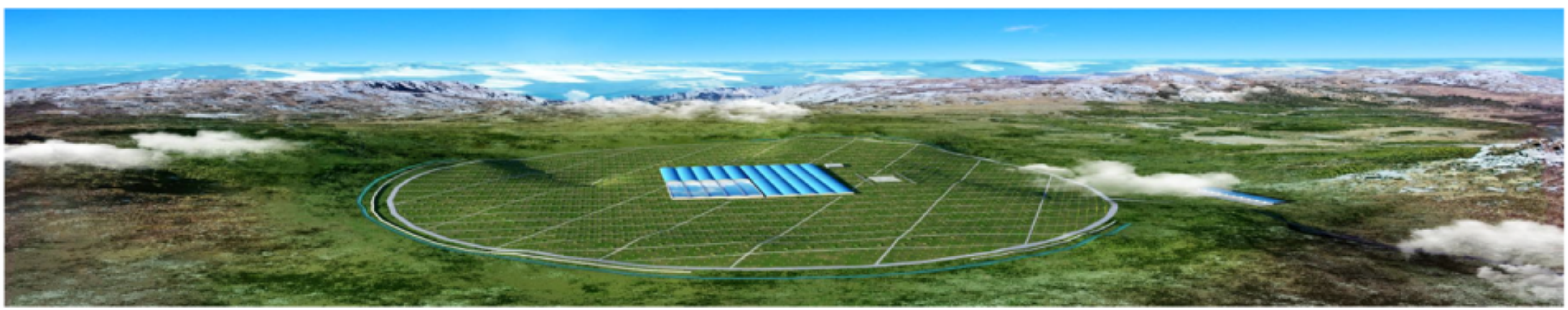
(launch >2020)



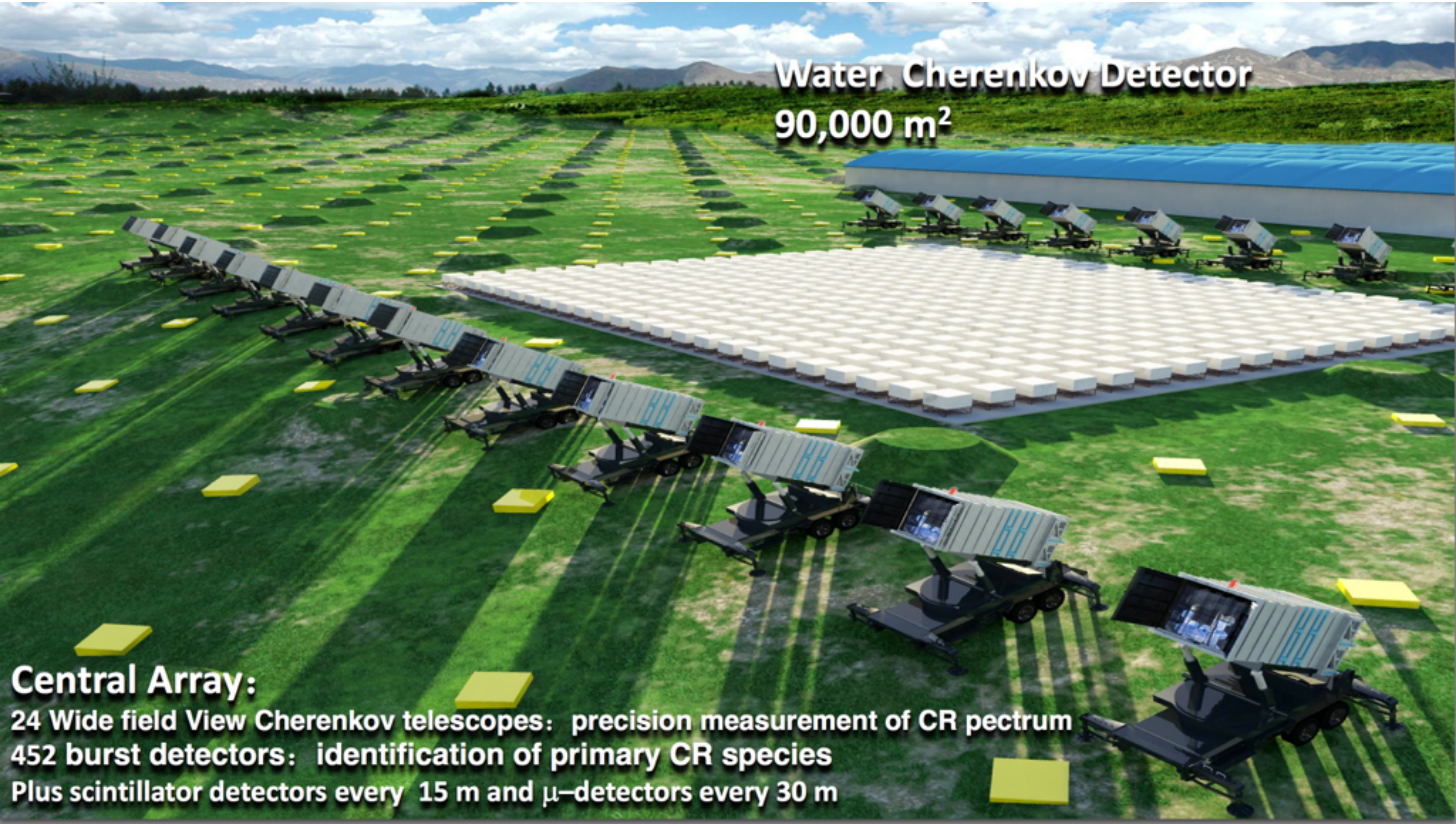
Zhang et.al, arXiv:1407.4866

Silicon-Tungsten Tracker + LYSO Calorimeter

Large High Altitude Air Shower Observatory (LHAASO)



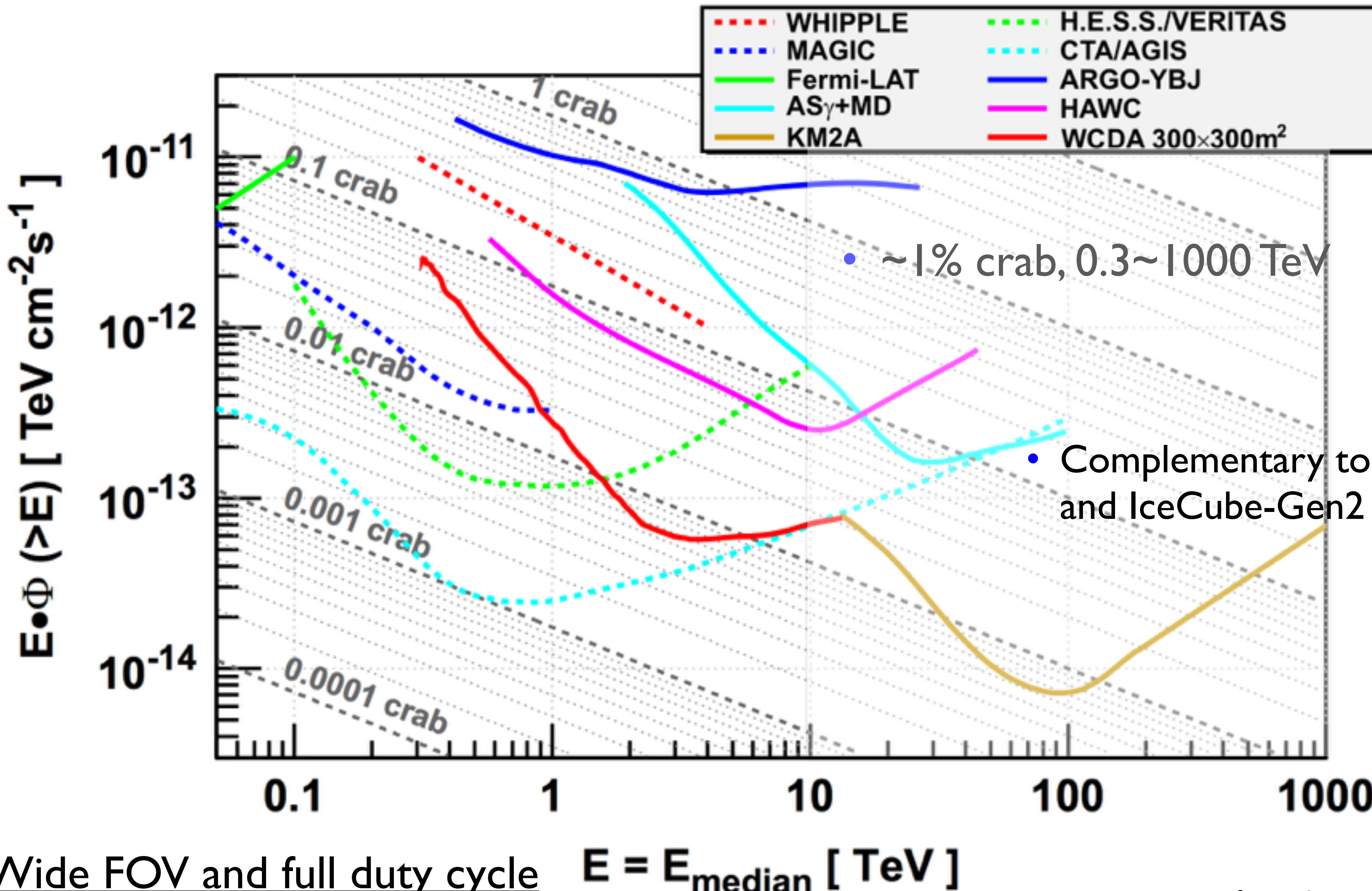
Two Gamma Ray Astronomic Devices
– A Wide FOV Survey Facility for more sources
– A Spectrometer for deep study of interesting sources: spectroscopy & morphology



- Complementary to CTA
- Unique for CR measurements at the knees

The most Sensitive detector for 10 TeV γ-sky

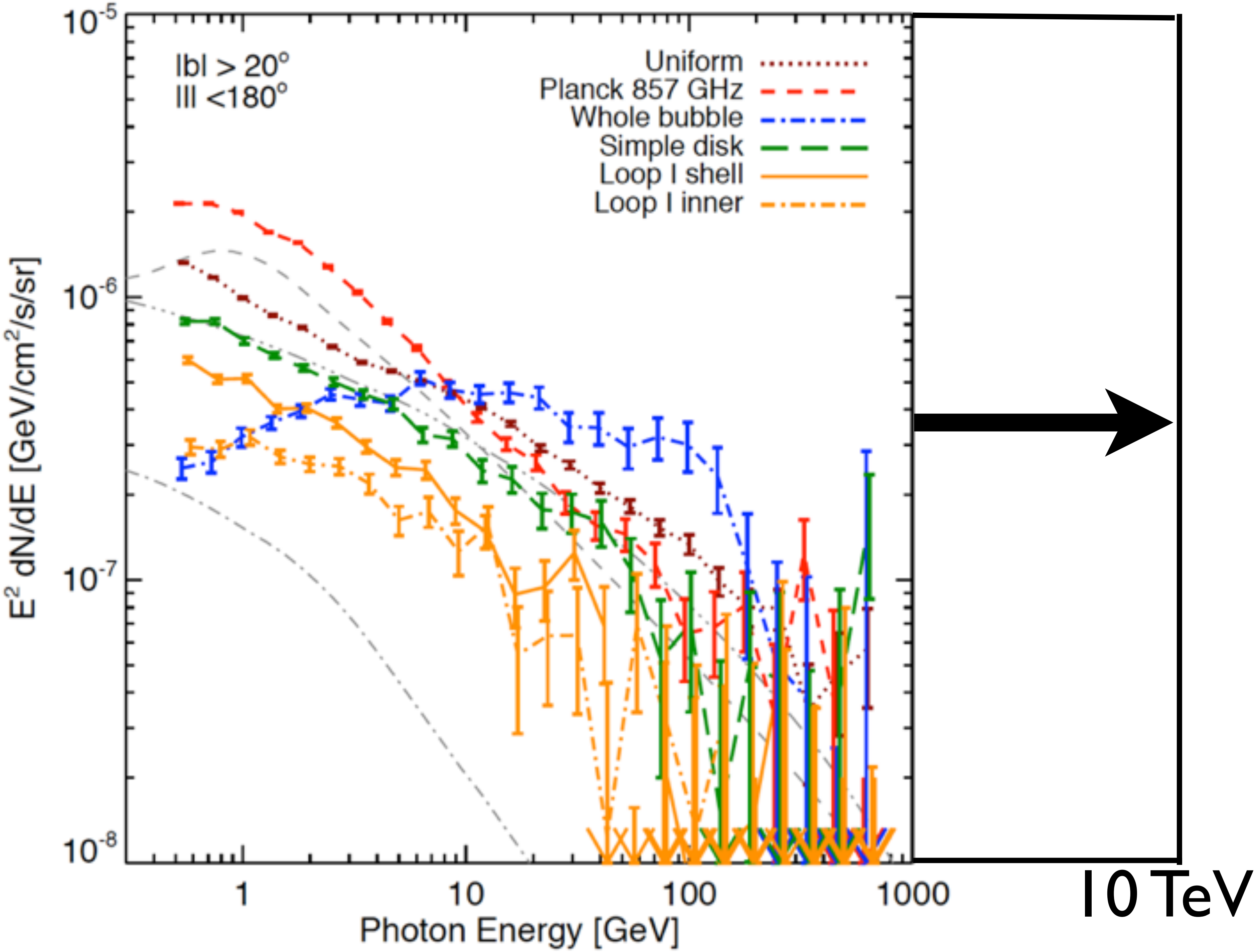
A few hundred extra-galactic sources are expected!

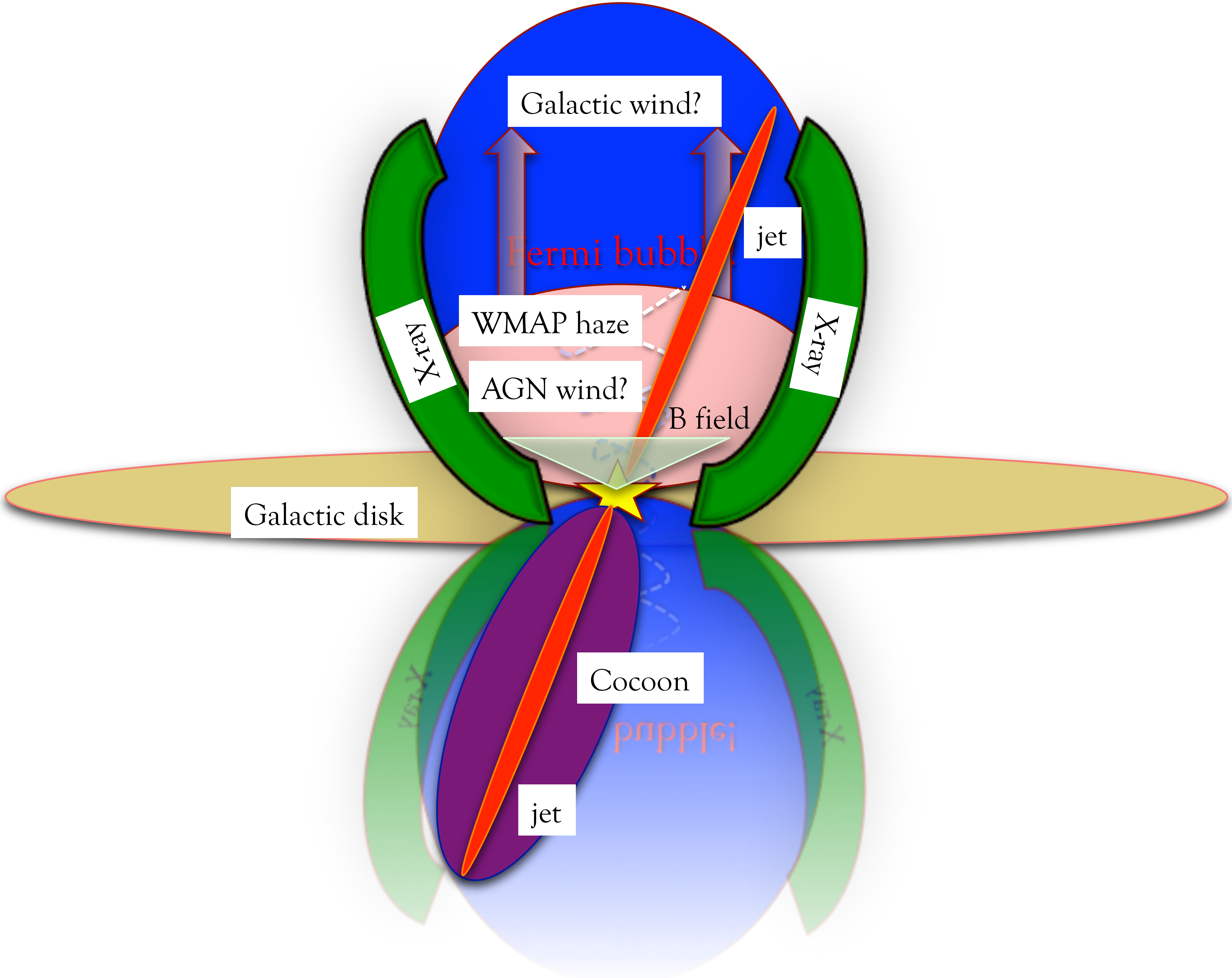


- ~1% crab, 0.3~1000 TeV
- Complementary to IceCube and IceCube-Gen2
- <u>Wide FOV and full duty cycle</u>

Cao et al. arXiv:1407.4530

DAMPE/HERD/LHAASO will extend the FB spectrum up to ~10 TeV




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


Thank you!