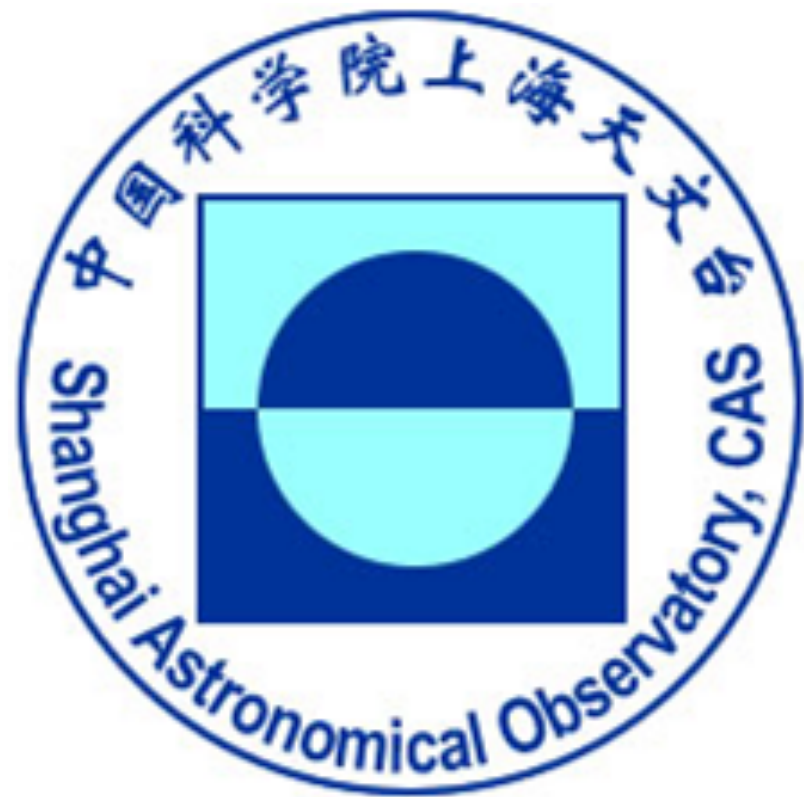


# Blowing the eROSITA and Fermi Bubbles in the Milky Way with Hydrodynamic Simulations

Fulai Guo (郭福来)

Shanghai Astronomical Observatory

Chinese Academy of Sciences

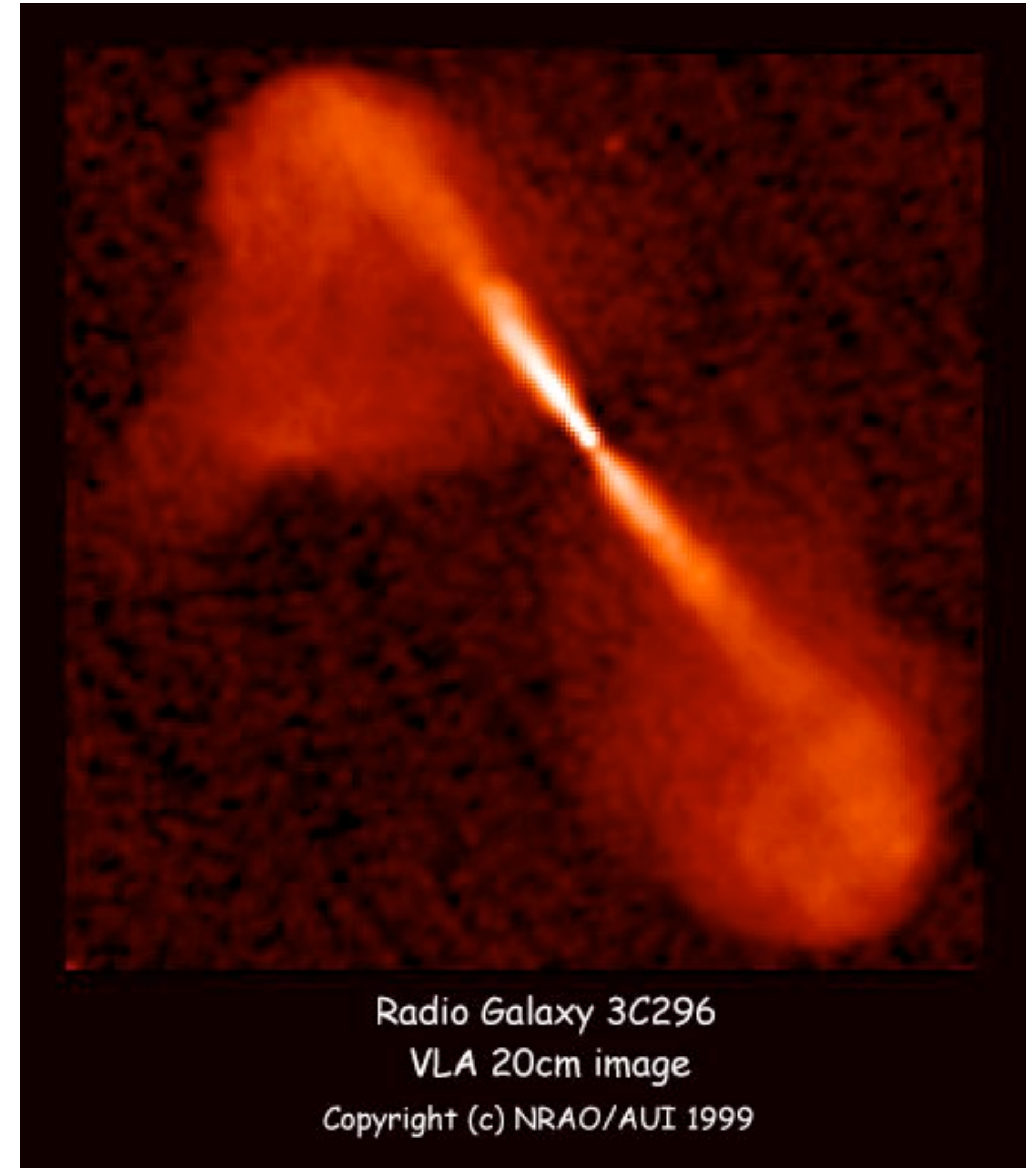


The 10th East Asian Numerical Astrophysics Meeting, Sep. 15-19, 2025

# Galactic Nucleus Feedback: a key ingredient in galaxy formation



Supernova Feedback; M82



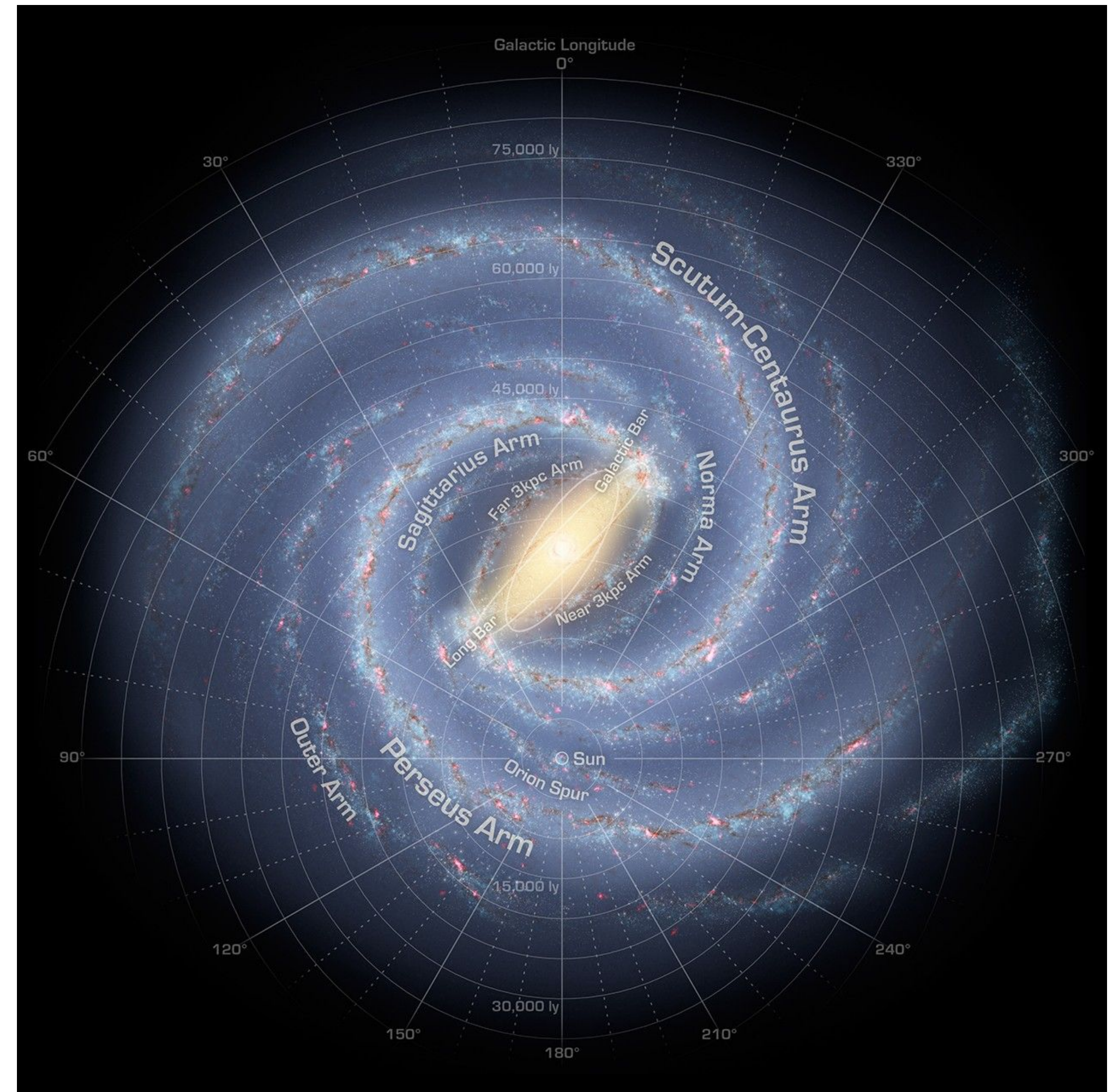
Radio Galaxy 3C296  
VLA 20cm image  
Copyright (c) NRAO/AUI 1999

AGN Feedback; Radio Galaxy

# What about Galactic Nucleus Feedback in Star-Forming Galaxies?



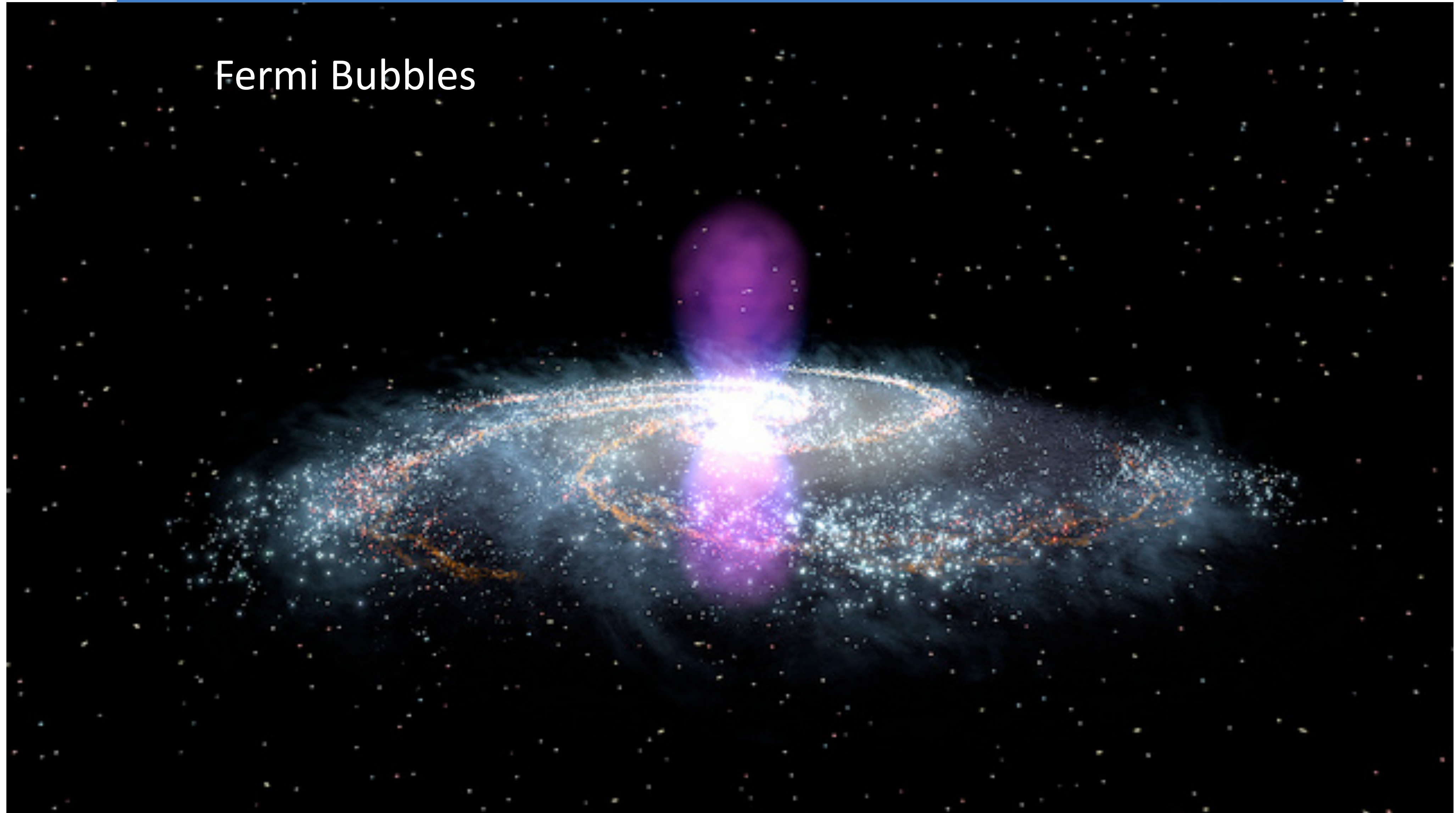
NGC 2718



Milky Way Galaxy

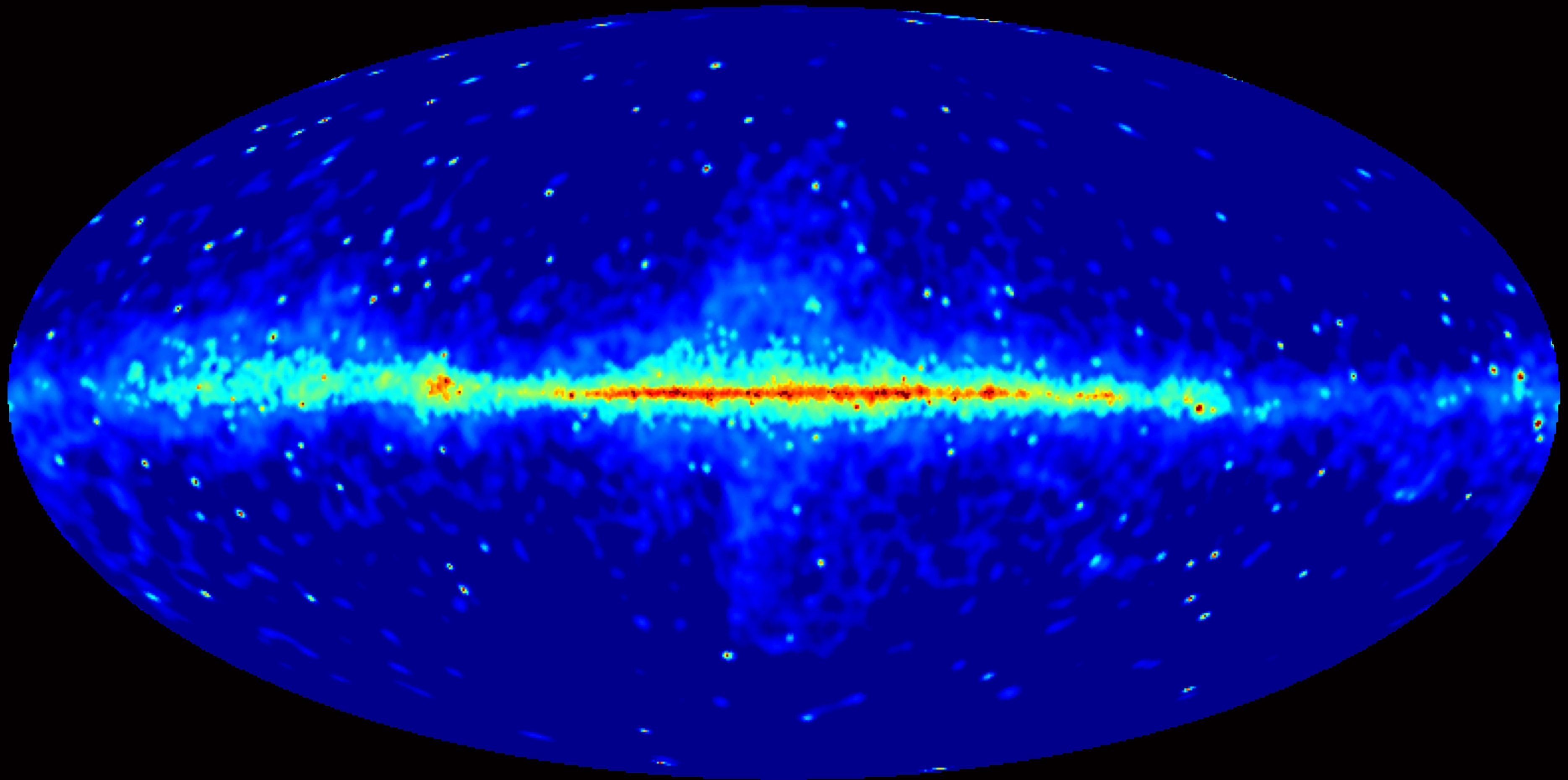
# Fermi Bubbles in the Gamma-ray Band

Fermi Bubbles



# Fermi Bubbles in the Gamma-ray Band

The All-sky Fermi View at  $E > 10$  GeV



Su et al 2010

# eROSITA Bubbles in the Soft X-ray Band

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Article | [Published: 09 December 2020](#)

## Detection of large-scale X-ray bubbles in the Milky Way halo



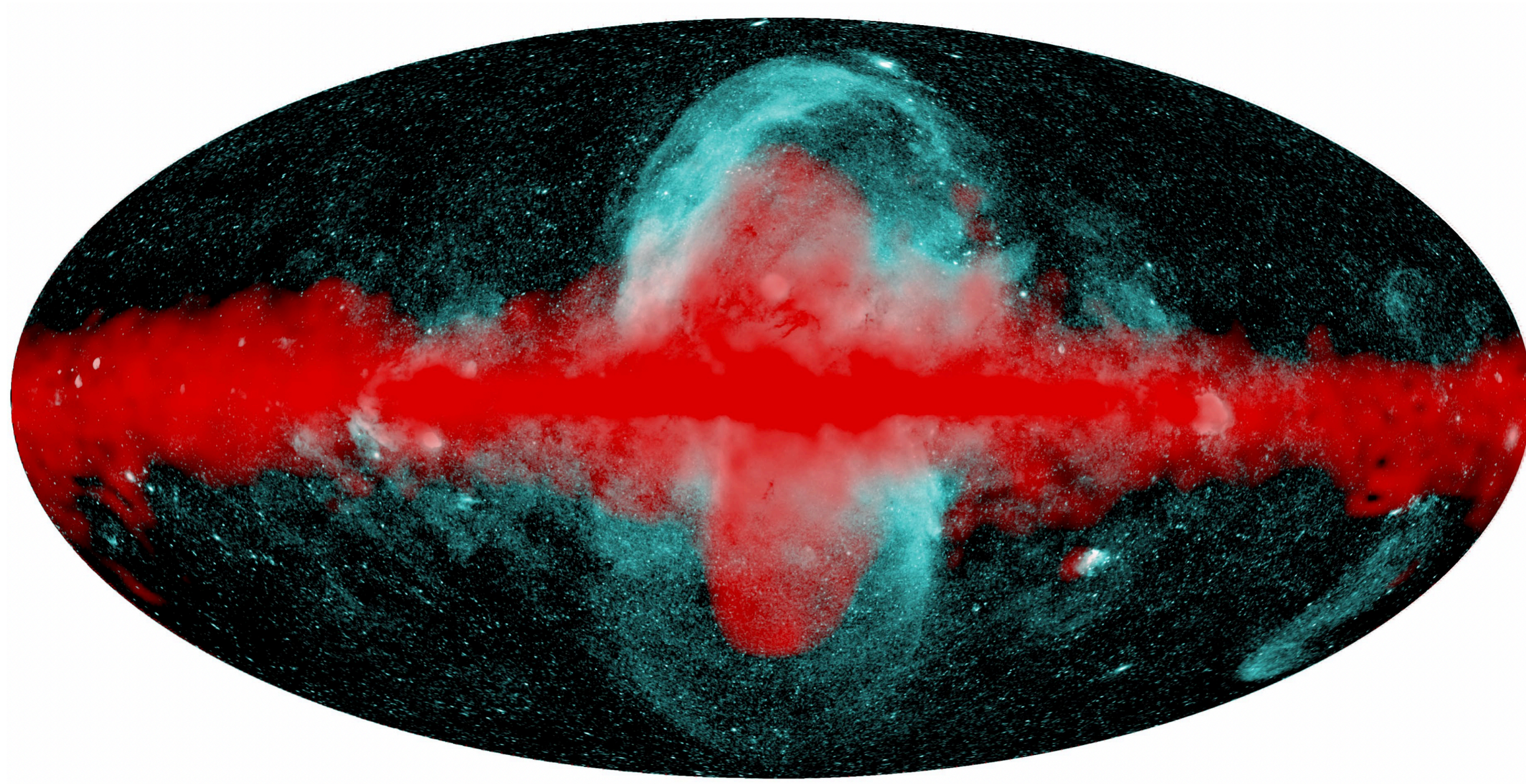
*Publ. Astron. Soc. Japan* (2020) 72 (2), 17 (1–14)  
doi: 10.1093/pasj/psz139  
Advance Access Publication Date: 2020 January 31



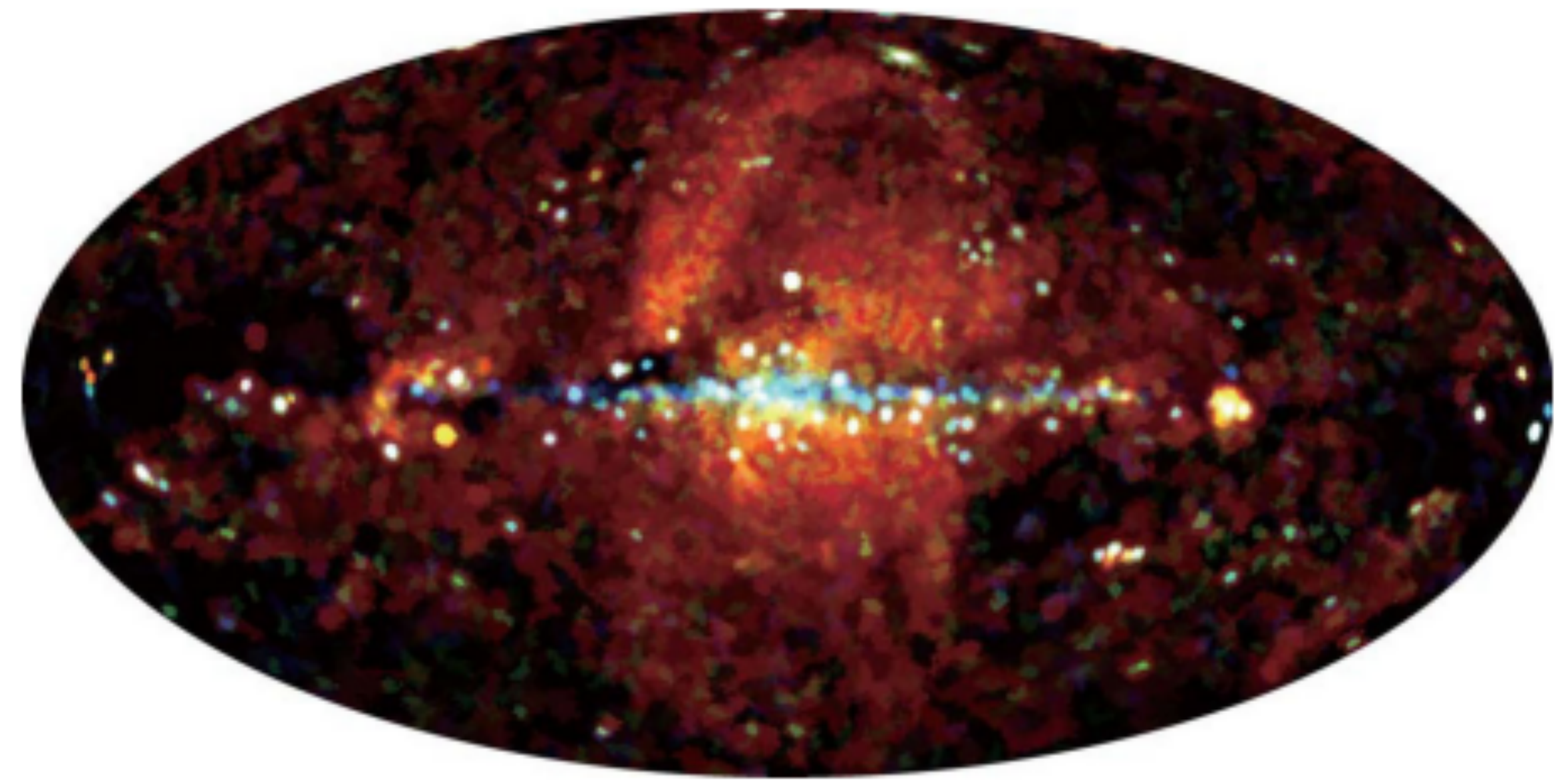
17-1

## MAXI/SSC all-sky maps from 0.7 keV to 4 keV

Satoshi NAKAHIRA,<sup>1,2,\*</sup> Hiroshi TSUNEMI,<sup>3</sup> Hiroshi TOMIDA,<sup>1</sup>  
Shinya NAKASHIMA,<sup>2</sup> Ryuho KATAOKA,<sup>4,5</sup> and Kazuo MAKISHIMA<sup>6</sup>



0.6-1 keV eROSITA bubbles (Predehl + 2020)  
red — Fermi map

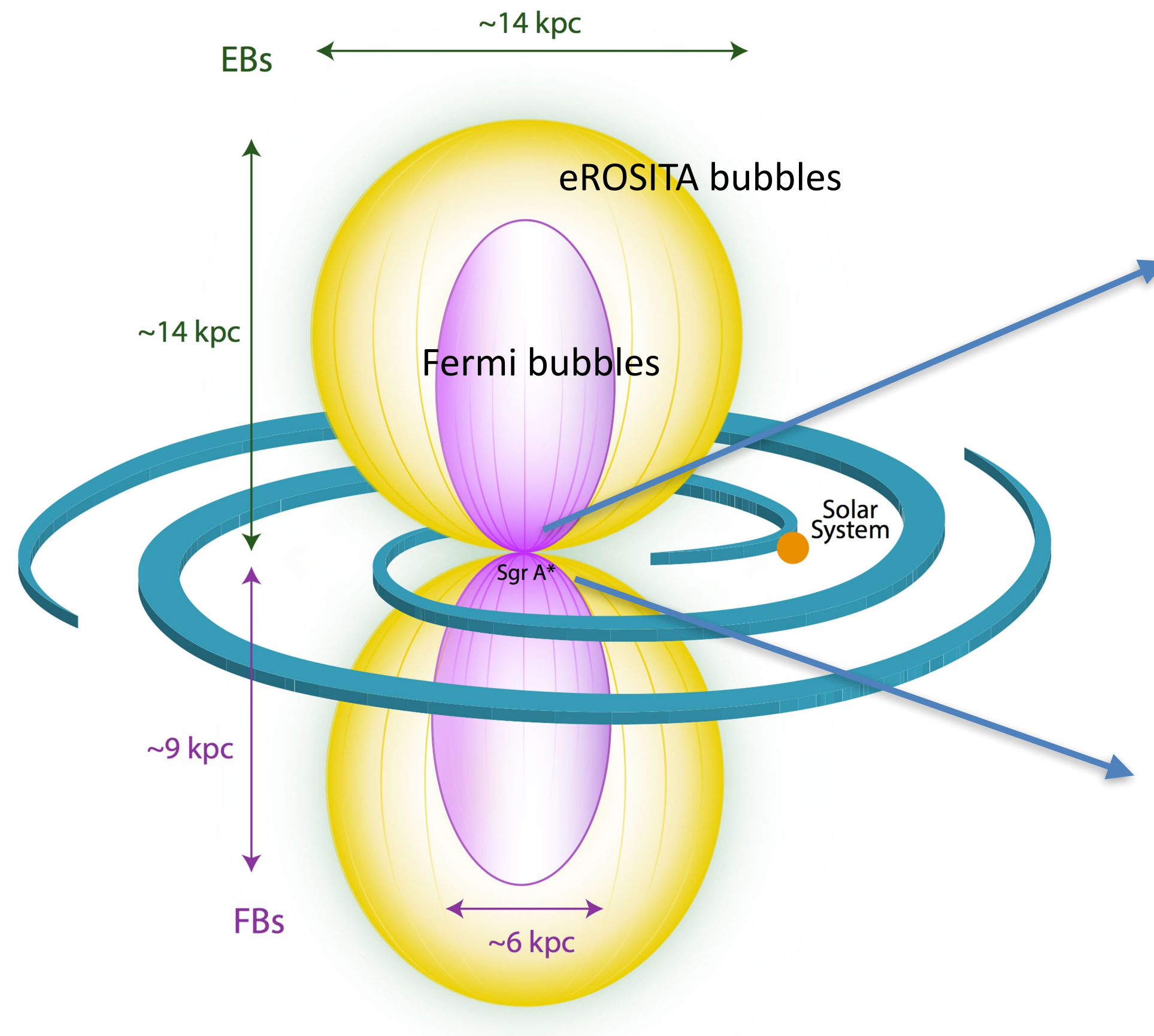


MAXI (0.7-1 keV; red), Nakahira + 2020

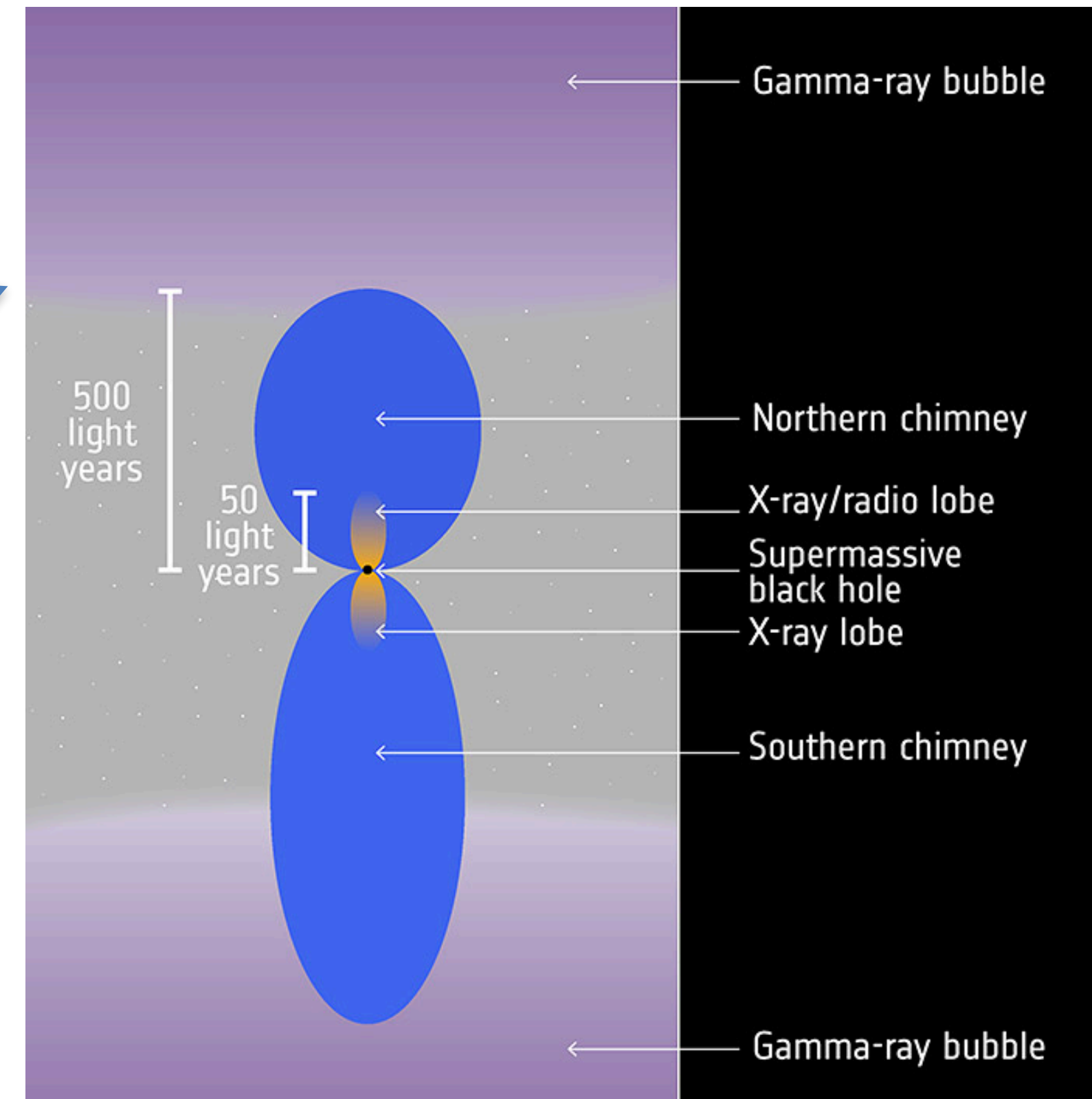
# Energetic Outbursts from the Galactic Center

How did these structures form?

Are they important, in any respect?



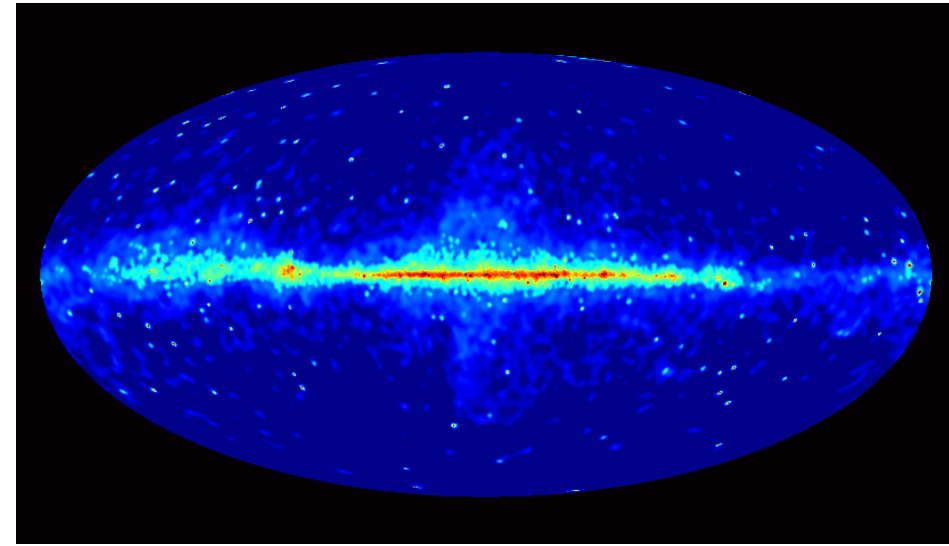
eROSITA and Fermi bubbles



Galactic Center Chimneys (blue) and the central Sgr A lobes (yellow)

# The Origin of the Fermi Bubbles

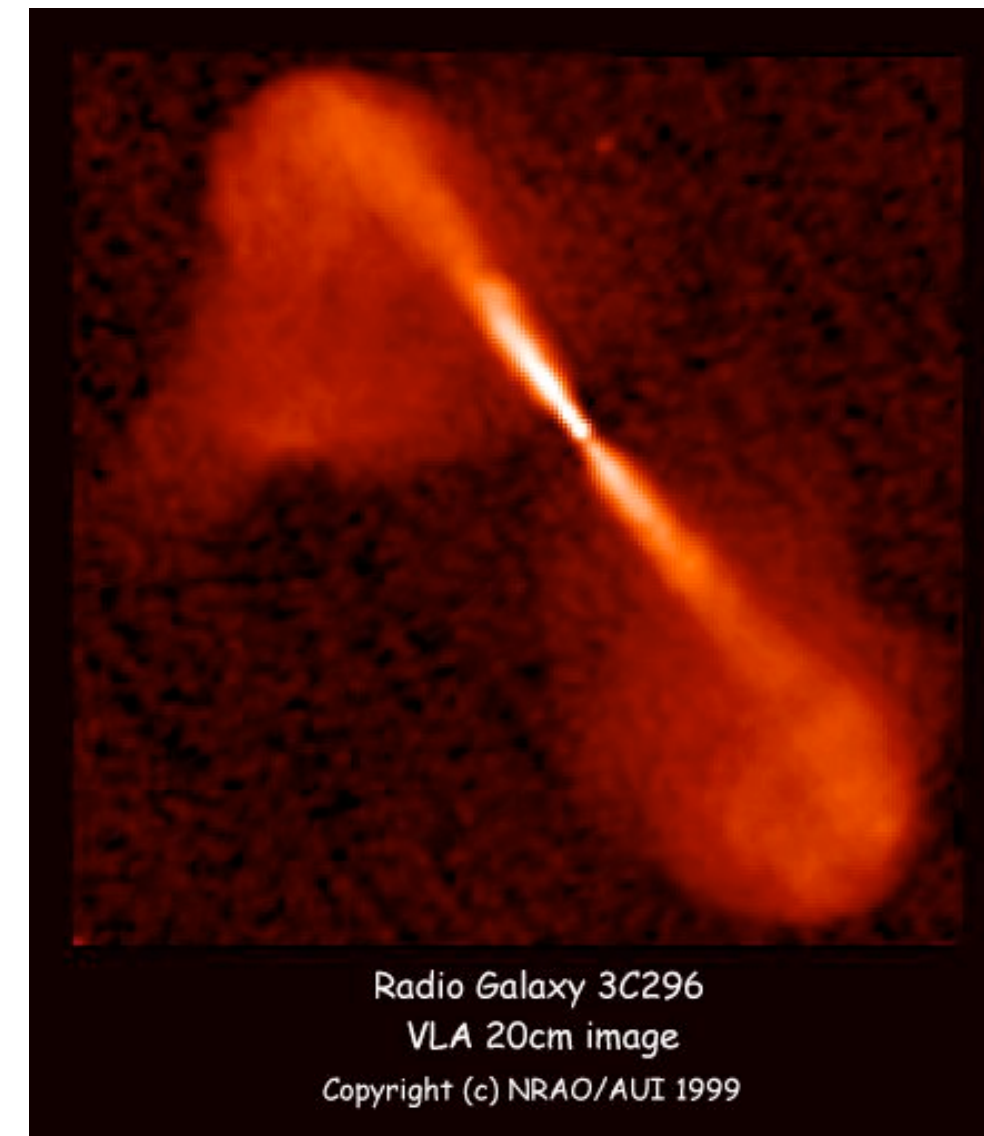
## Galactic Nucleus Feedback



Fermi bubbles, Milky Way Feedback?



Stellar Feedback; M82



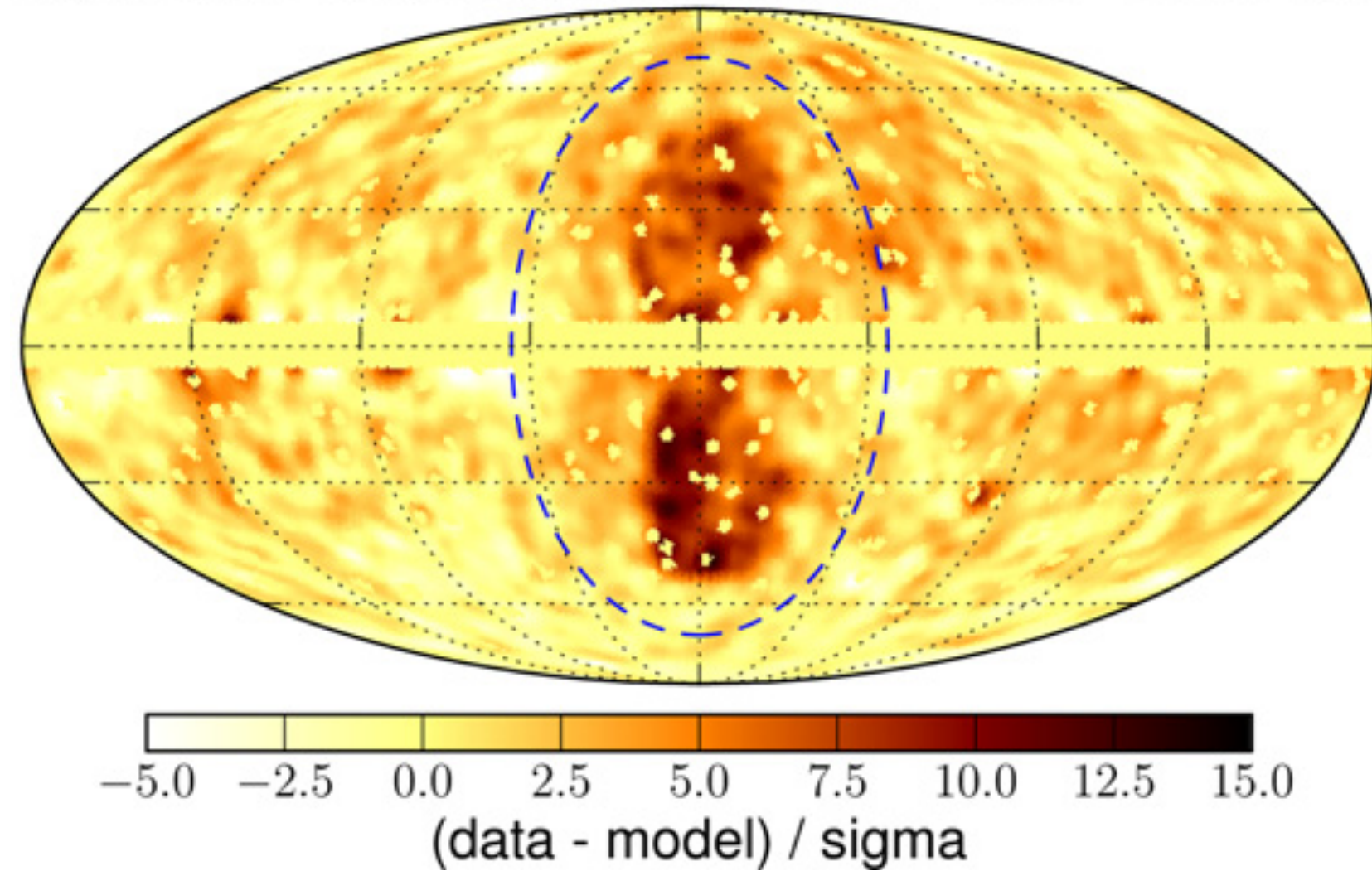
Radio Galaxy 3C296  
VLA 20cm image  
Copyright (c) NRAO/AUI 1999

AGN Feedback; Radio Galaxy

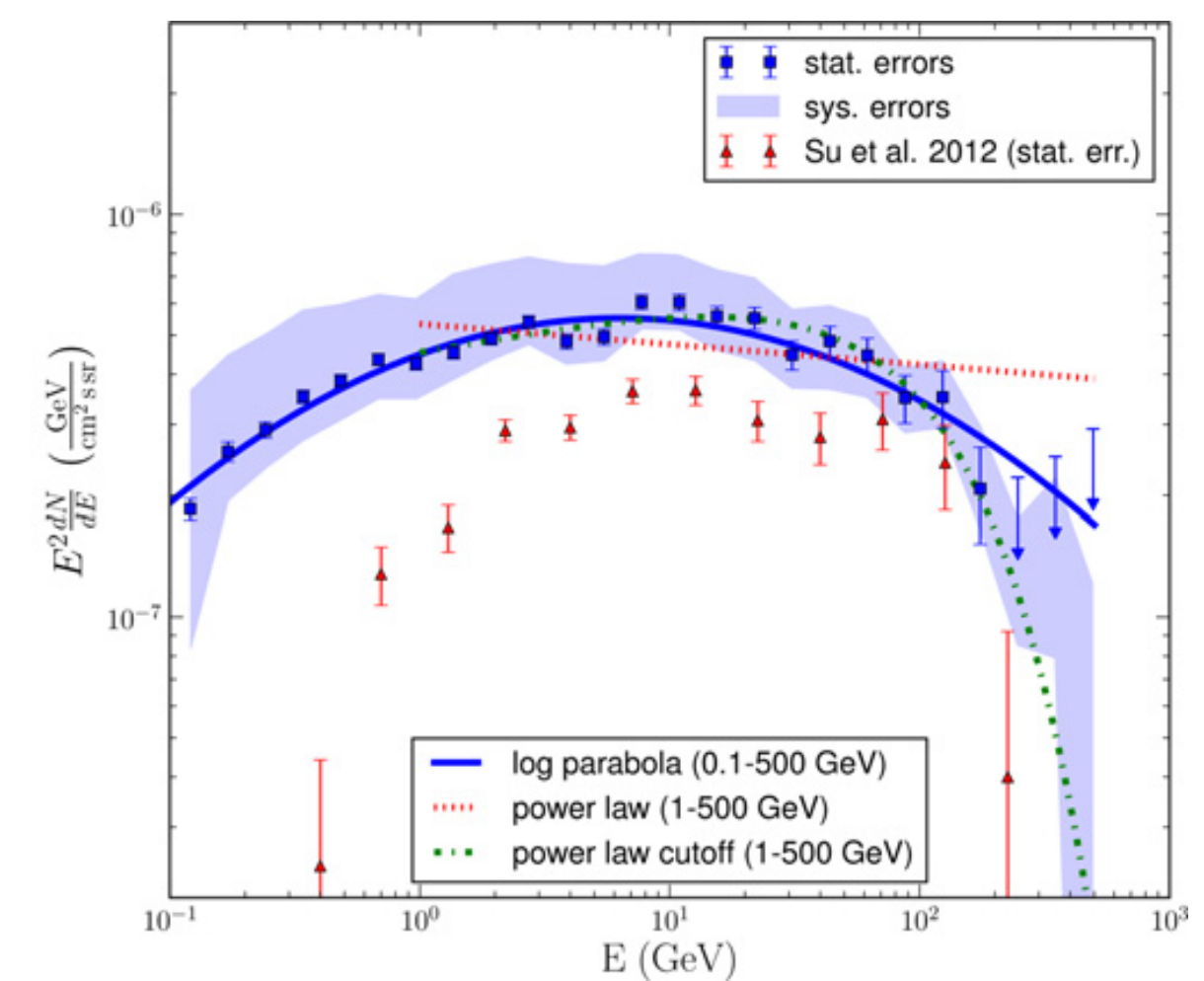
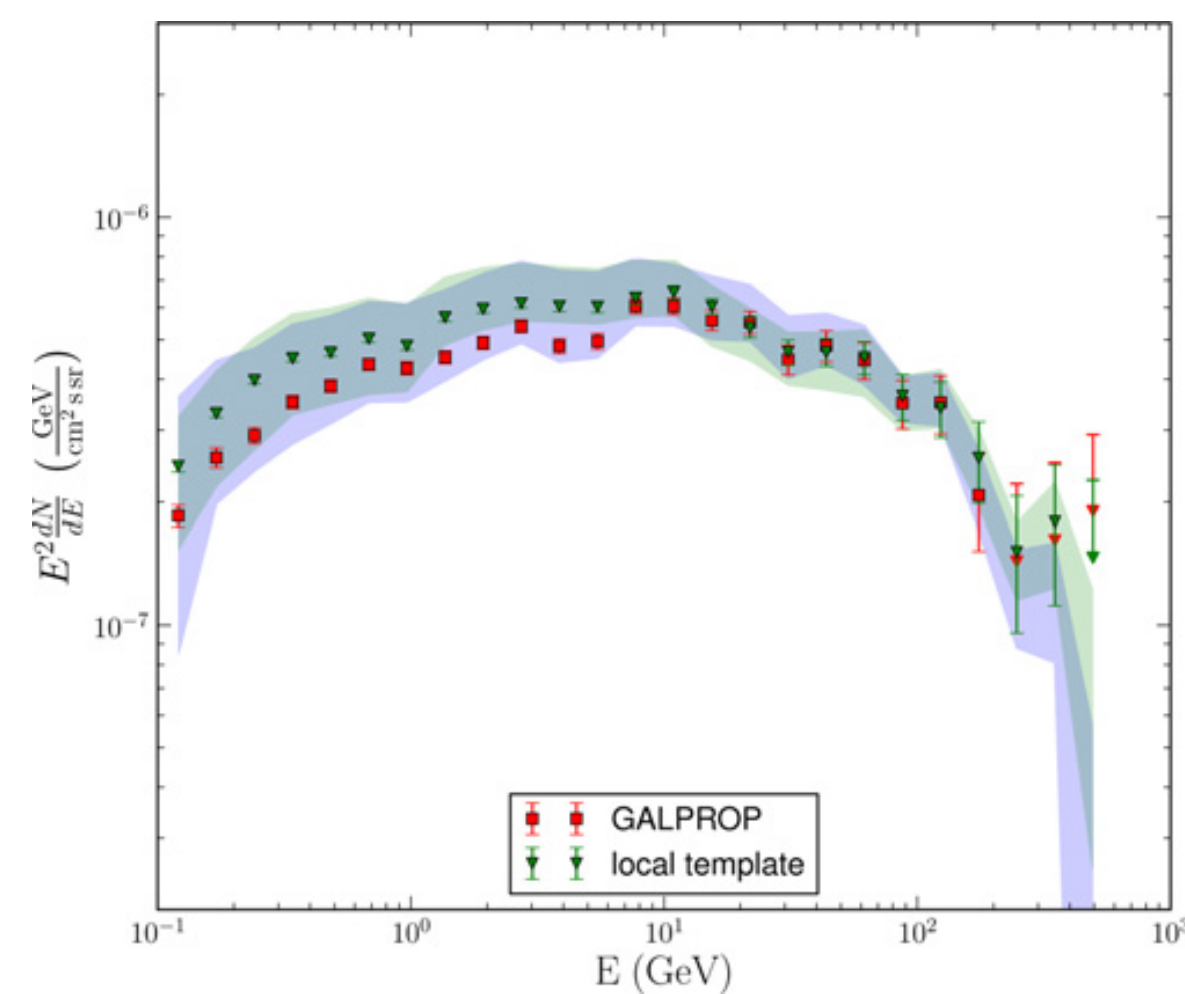
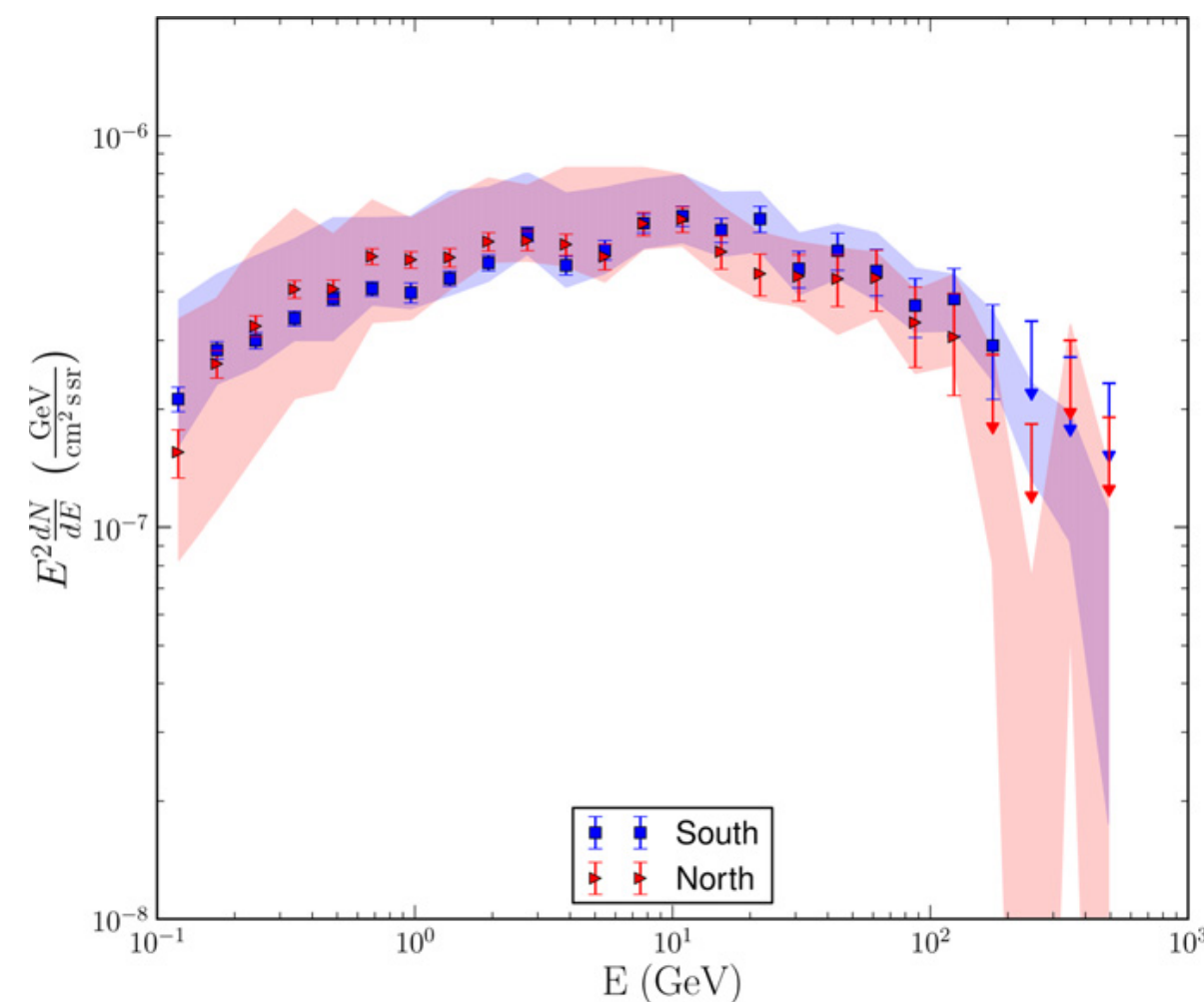
# Morphology and Spectrum of the Fermi Bubbles

Ackermann et al 2014; Dobler et al 2010; Su et al 2010

Significance of integrated residual,  $E = 10.0 - 500.0$  GeV



- sharp edges
- symmetric around the Galactic center
- 0.1-500 GeV luminosity  $\sim 4 \times 10^{37}$  erg/s
- hard spectrum  $\sim E^{-2}$

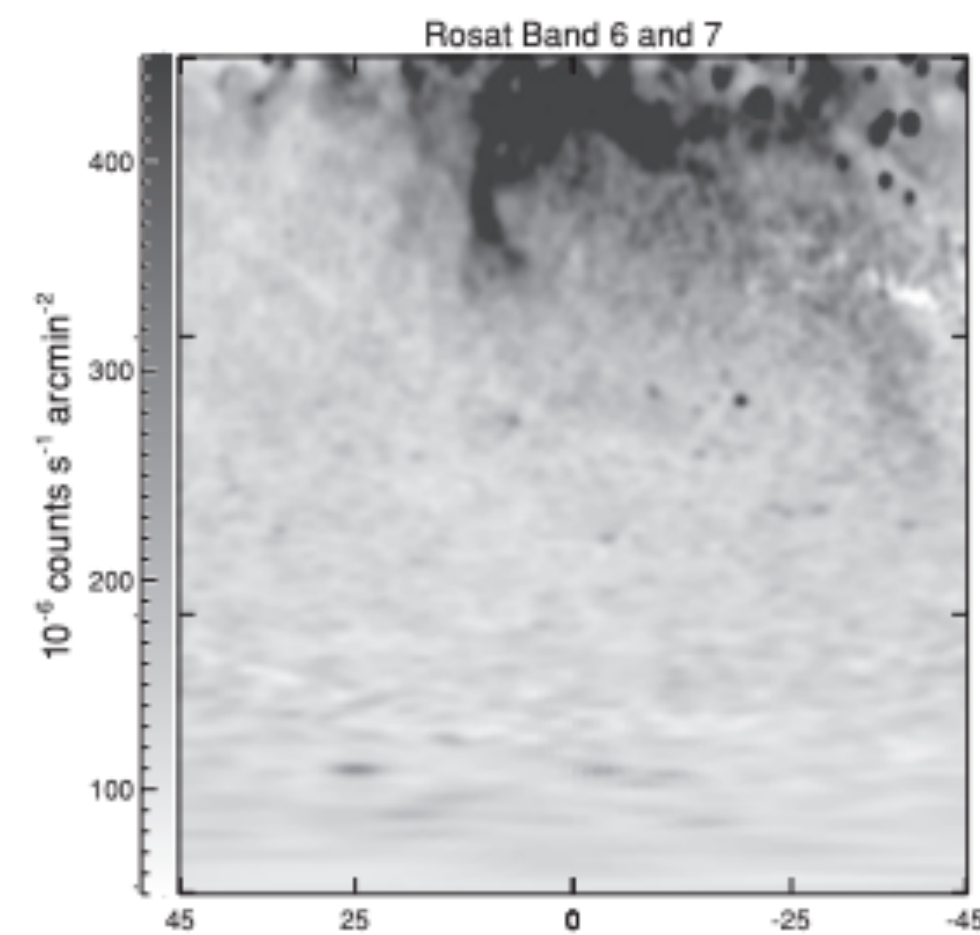
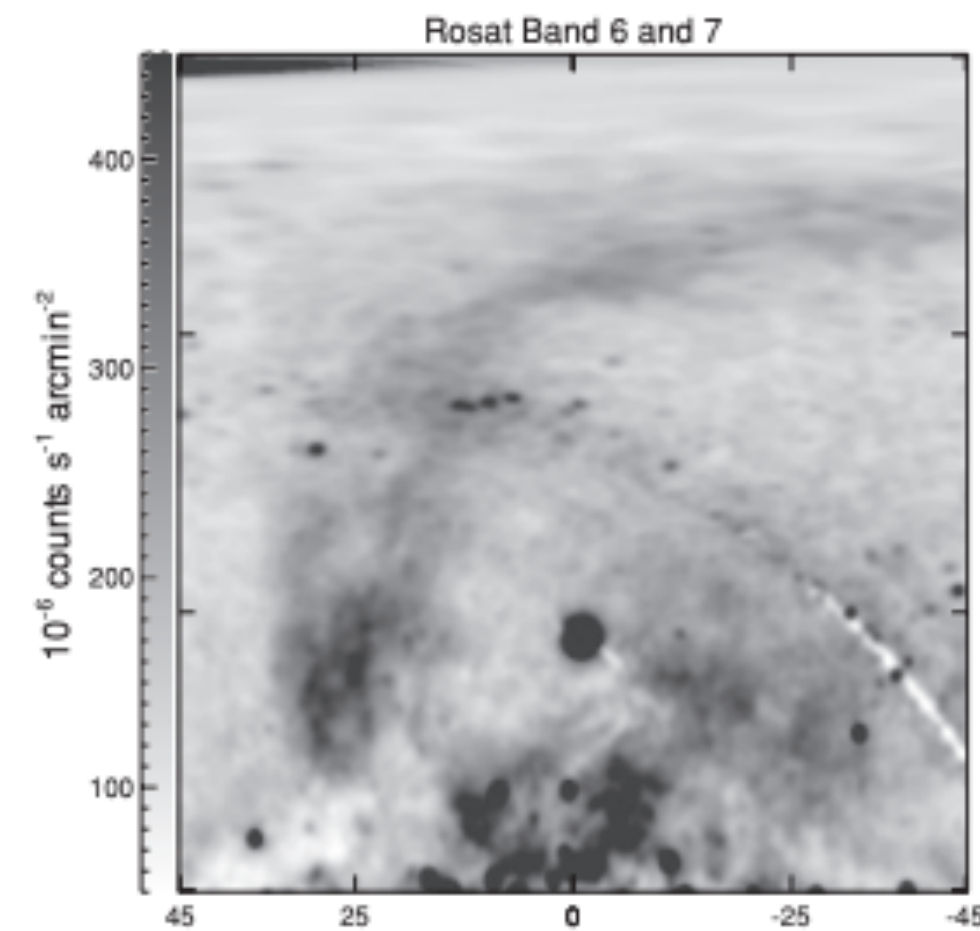


# The origin of the Fermi bubbles

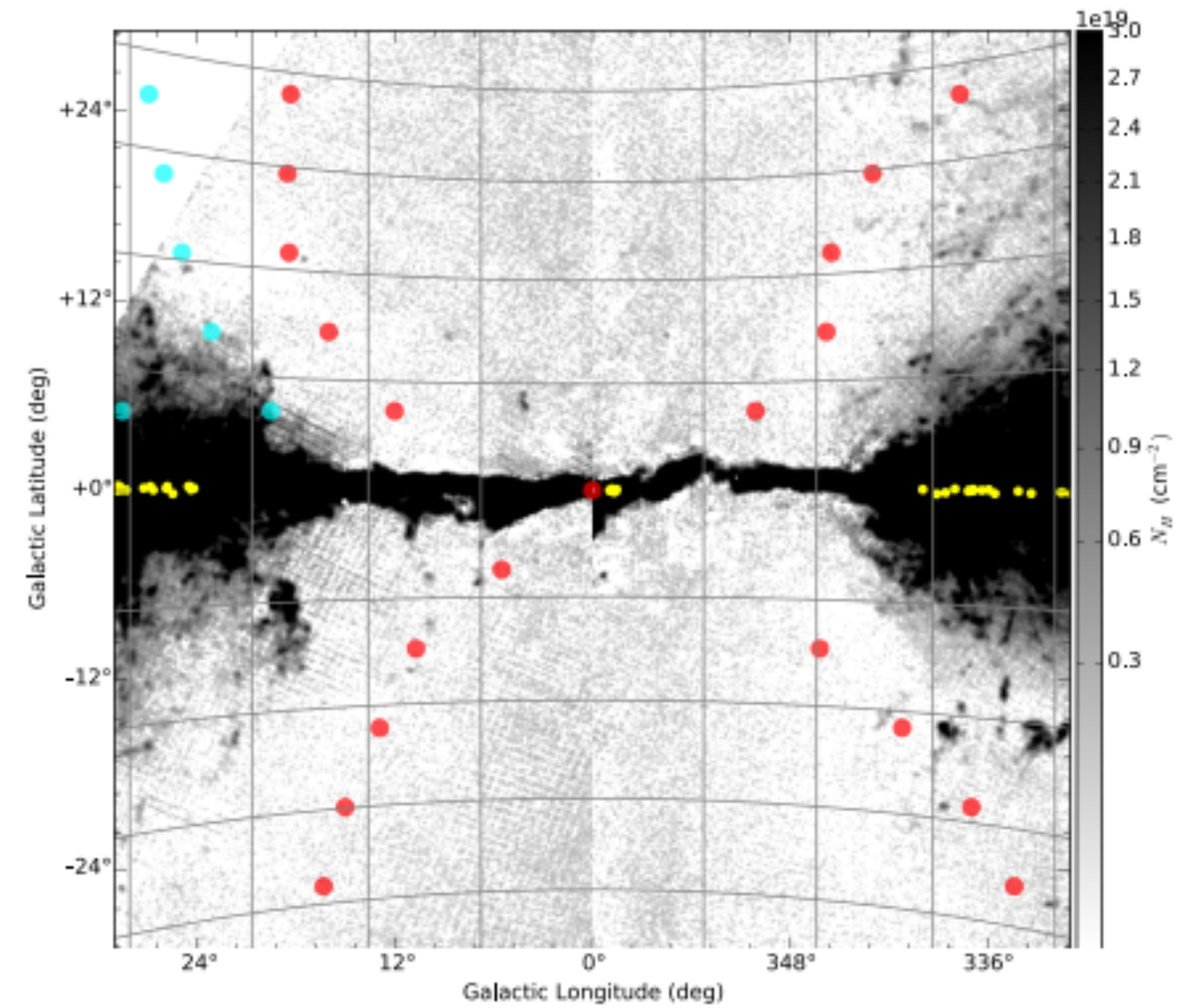
- Galactic winds from the Galactic Center? (Crocker & Aharonian 2011; Sarkar et al 2015; Sarkar 2024)



M82 wind due to Type II SNe



ROSAT X-ray map

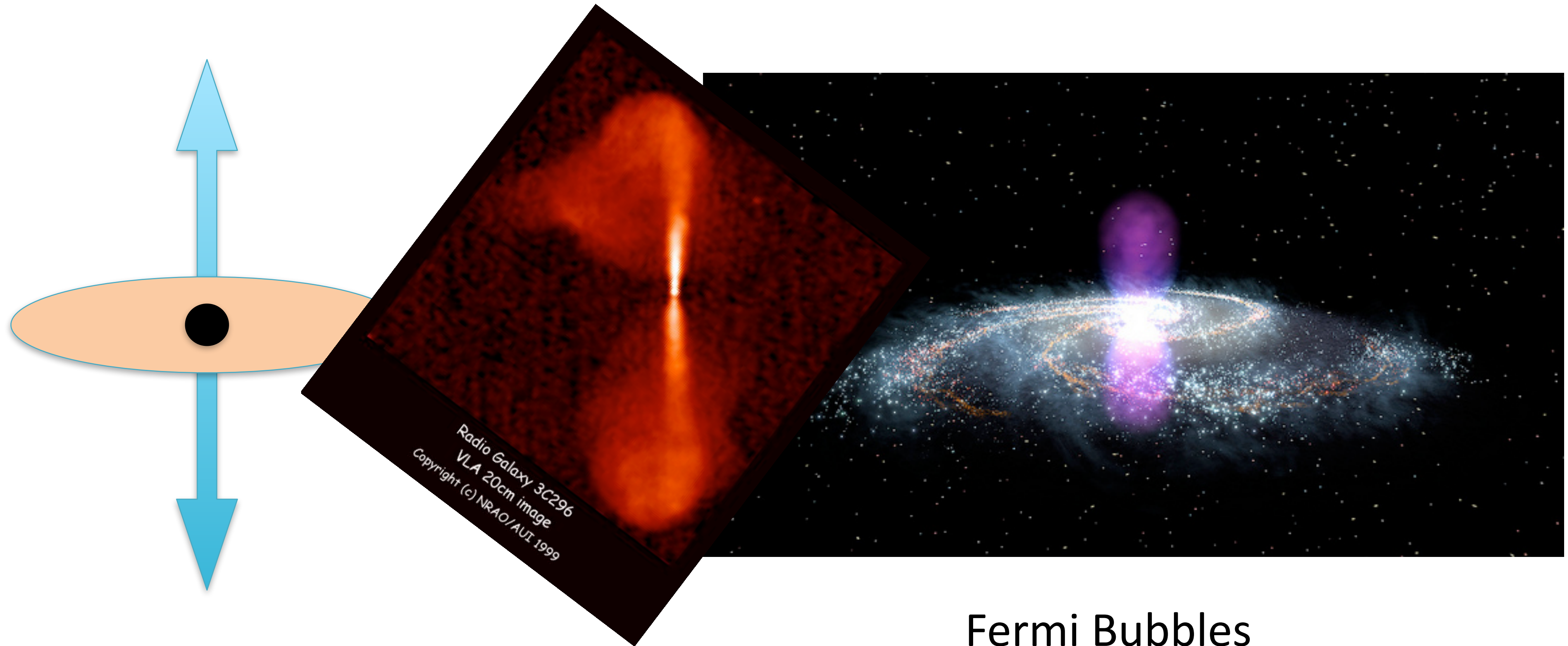


Lockman, McClure-Griffiths (2016)

# The AGN Jet Model of the Fermi Bubbles

## Active Galactic Nucleus (AGN)

Bipolar Jets



Fermi Bubbles

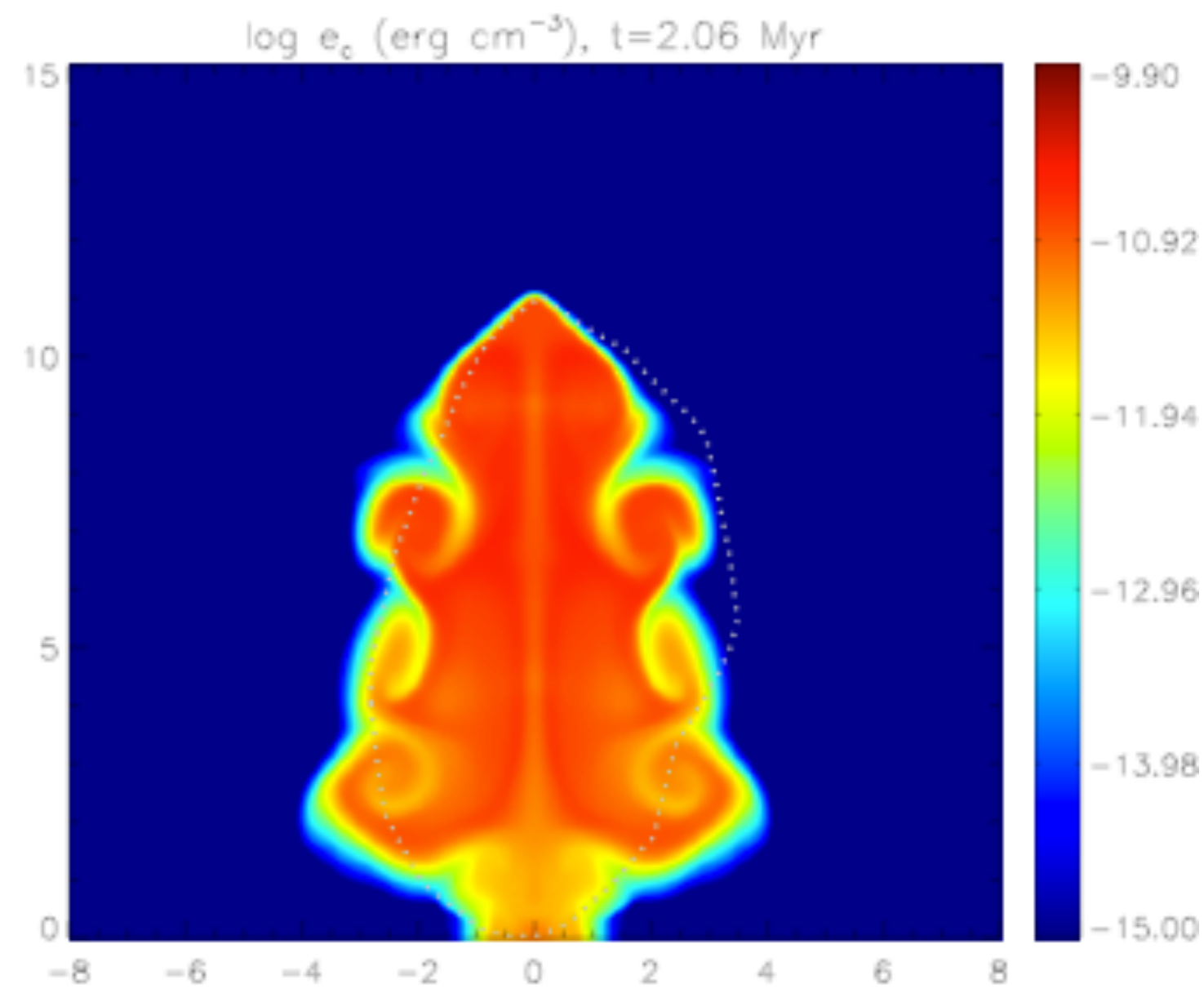
- Guo & Mathews 2012; Guo + 2012, ApJ; Guo 2017

other AGN models: Quasar outflow model, hot accretion flow - outflow model

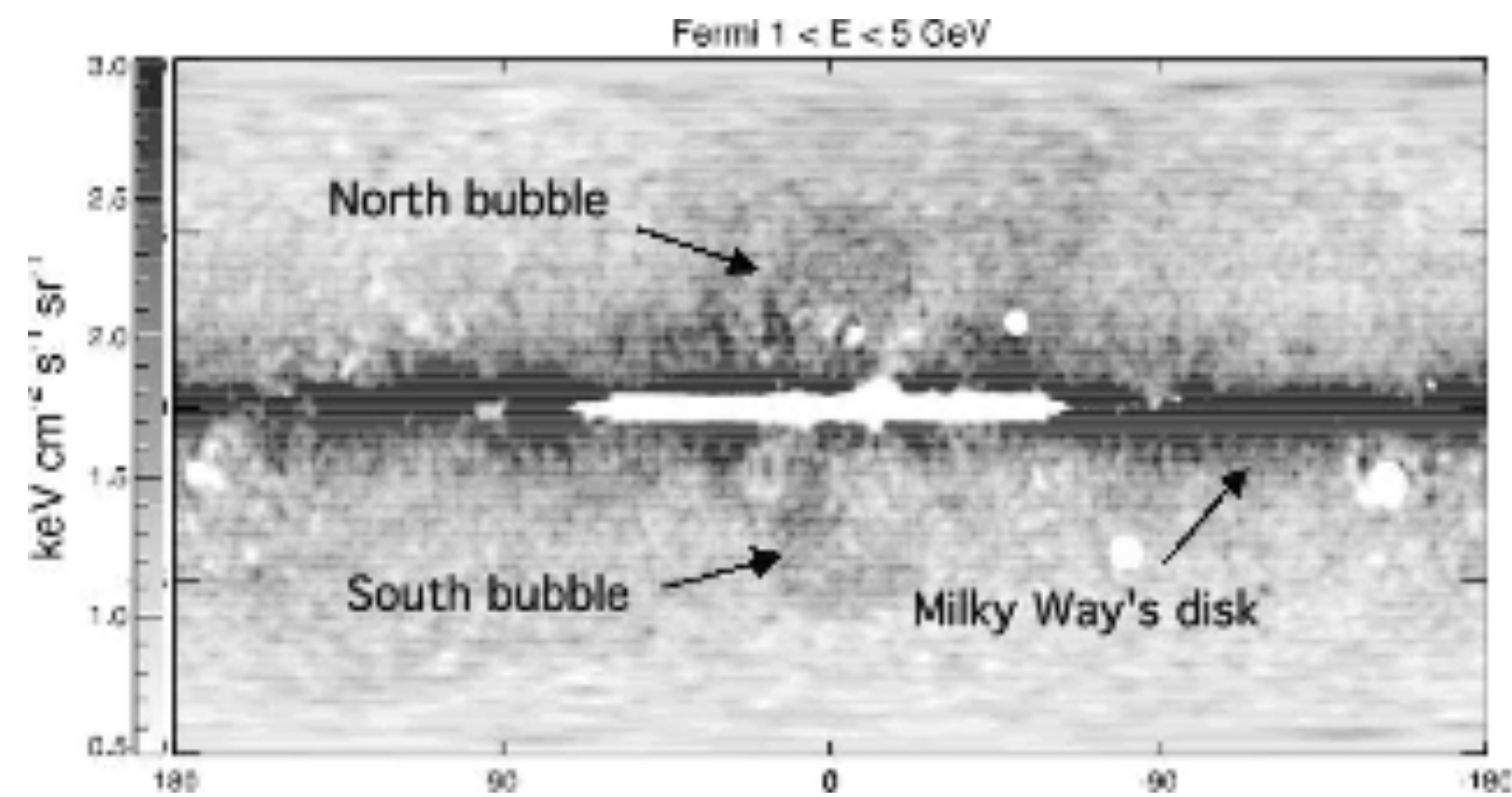
# A recent jet event reproduces many bubble features

location, size, shape, sharp edges

CR particle distribution



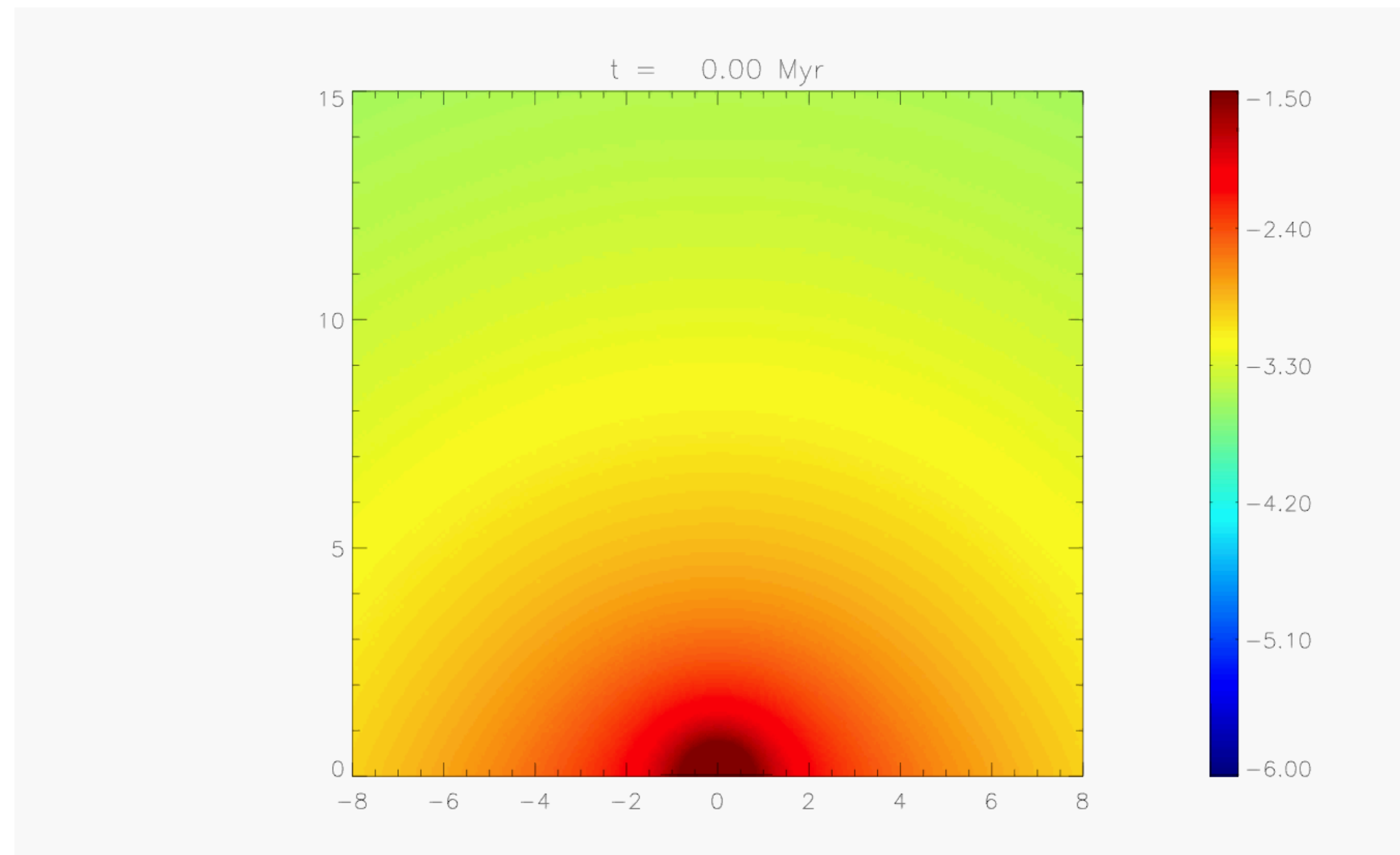
Guo & Mathews 2012  
Guo et al 2012



Su, Slatyer, and Finkbeiner, 2010

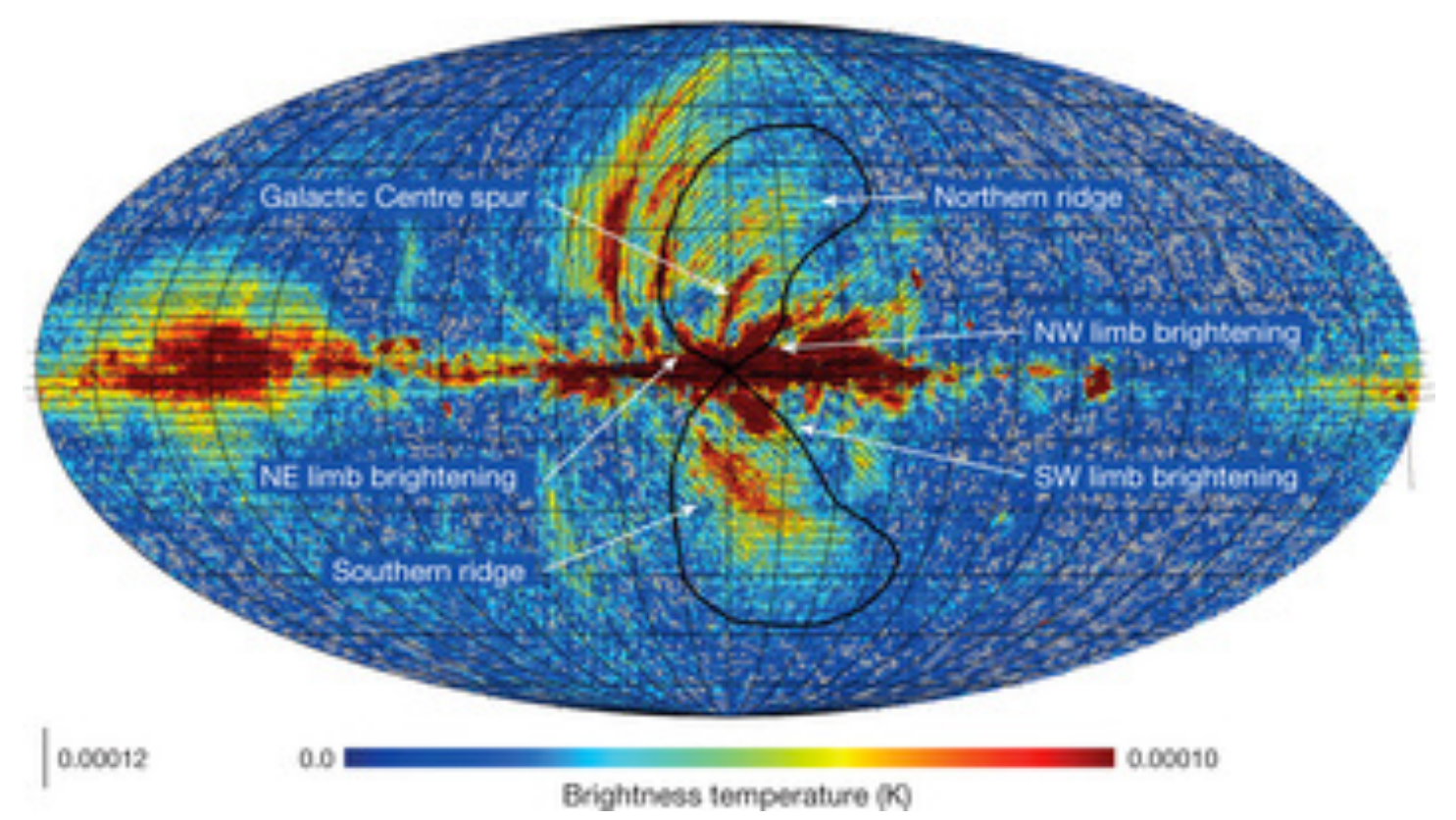
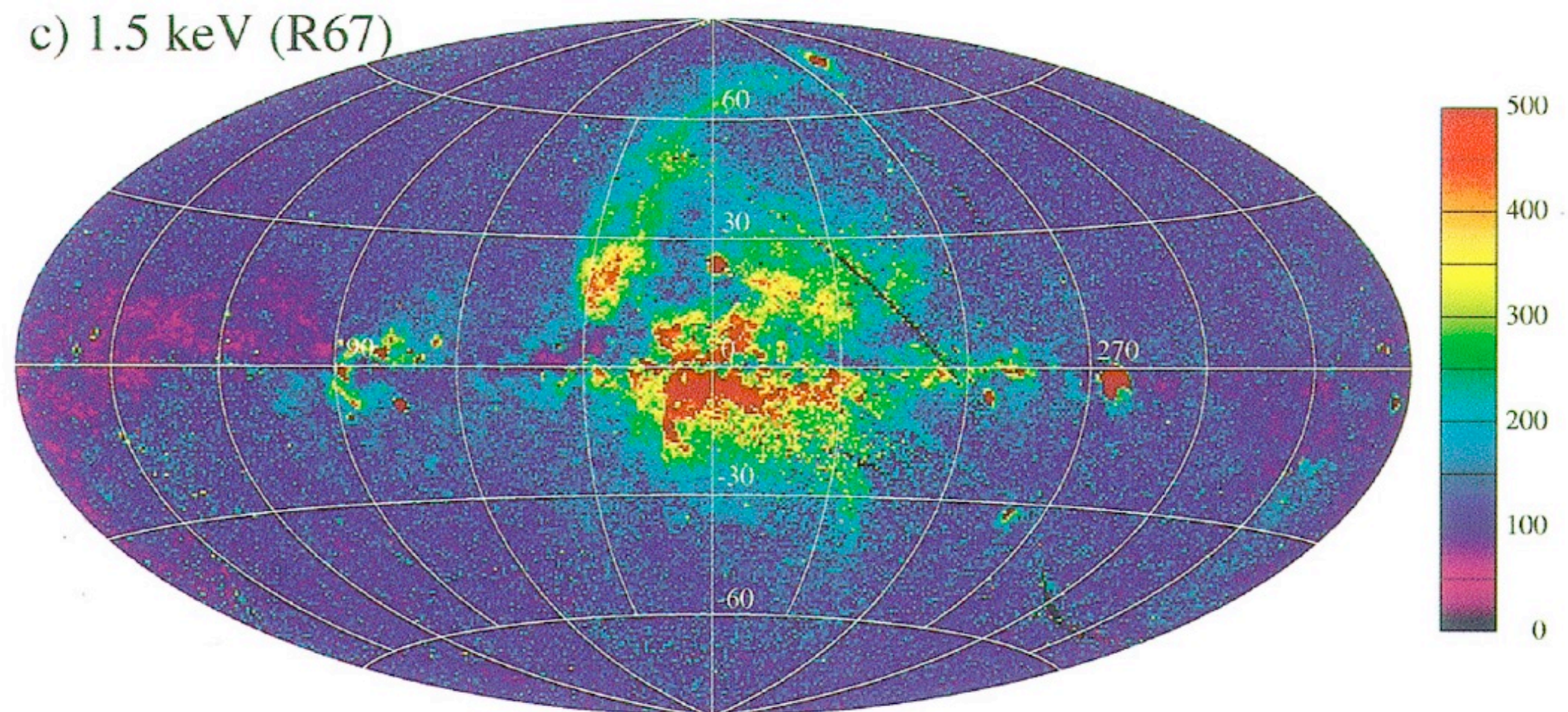
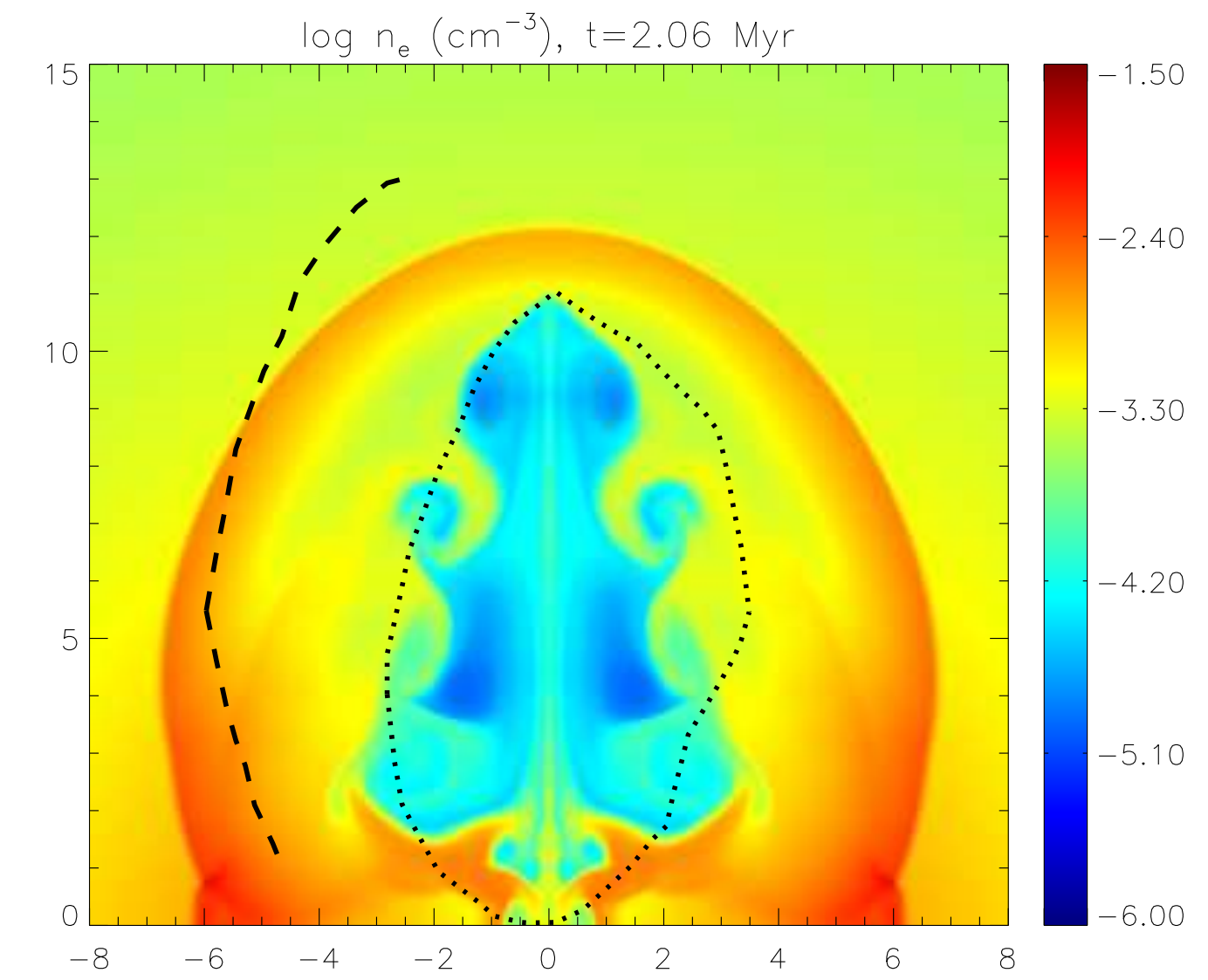
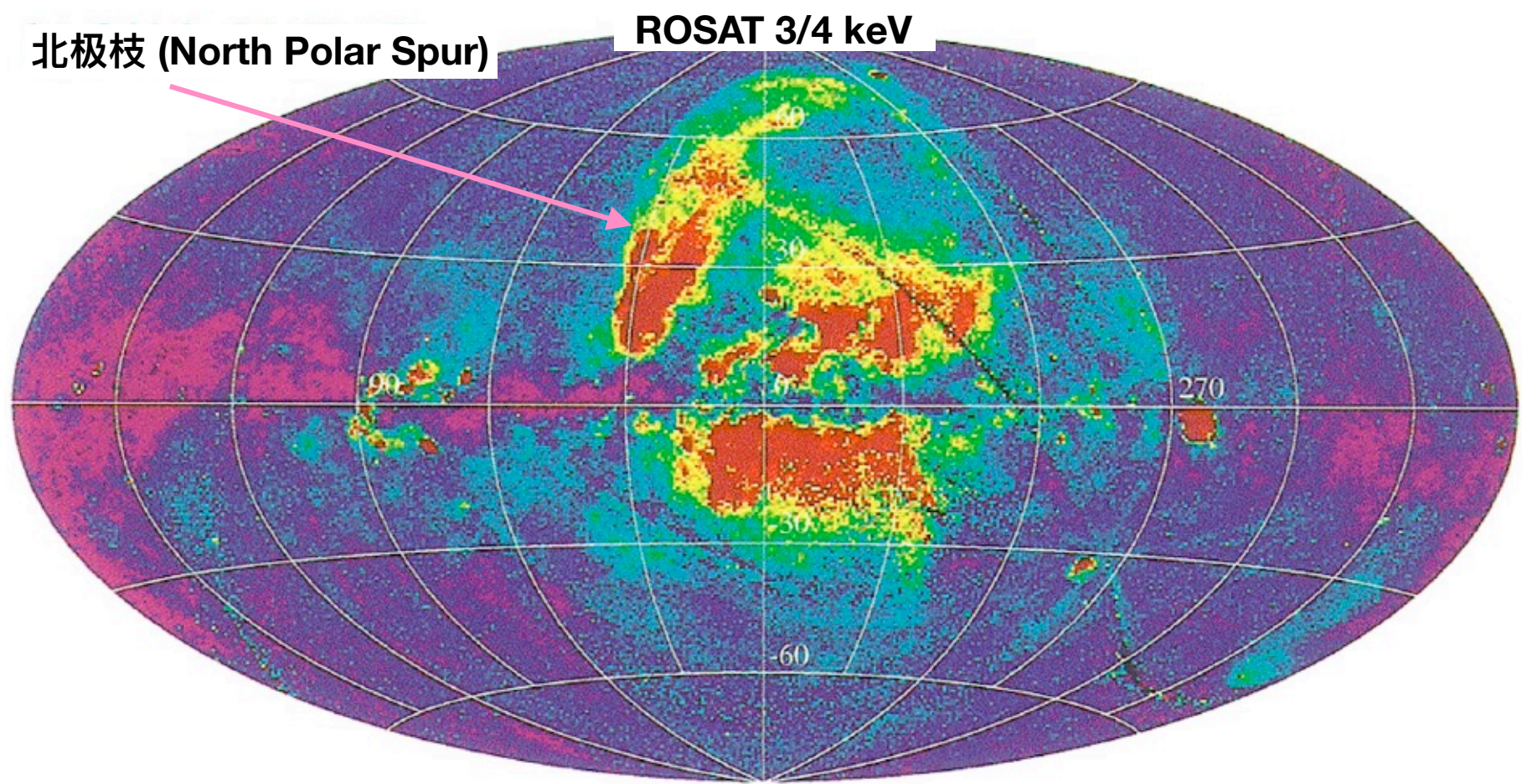
# Prediction: forward shock in the Galactic halo

thermal gas density distribution



produce a forward shock and expansion of the inner gaseous halo

# North Polar Spur in the ROSAT X-ray map



# The newly-discovered eROSITA Bubbles

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Article | [Published: 09 December 2020](#)

## Detection of large-scale X-ray bubbles in the Milky Way halo



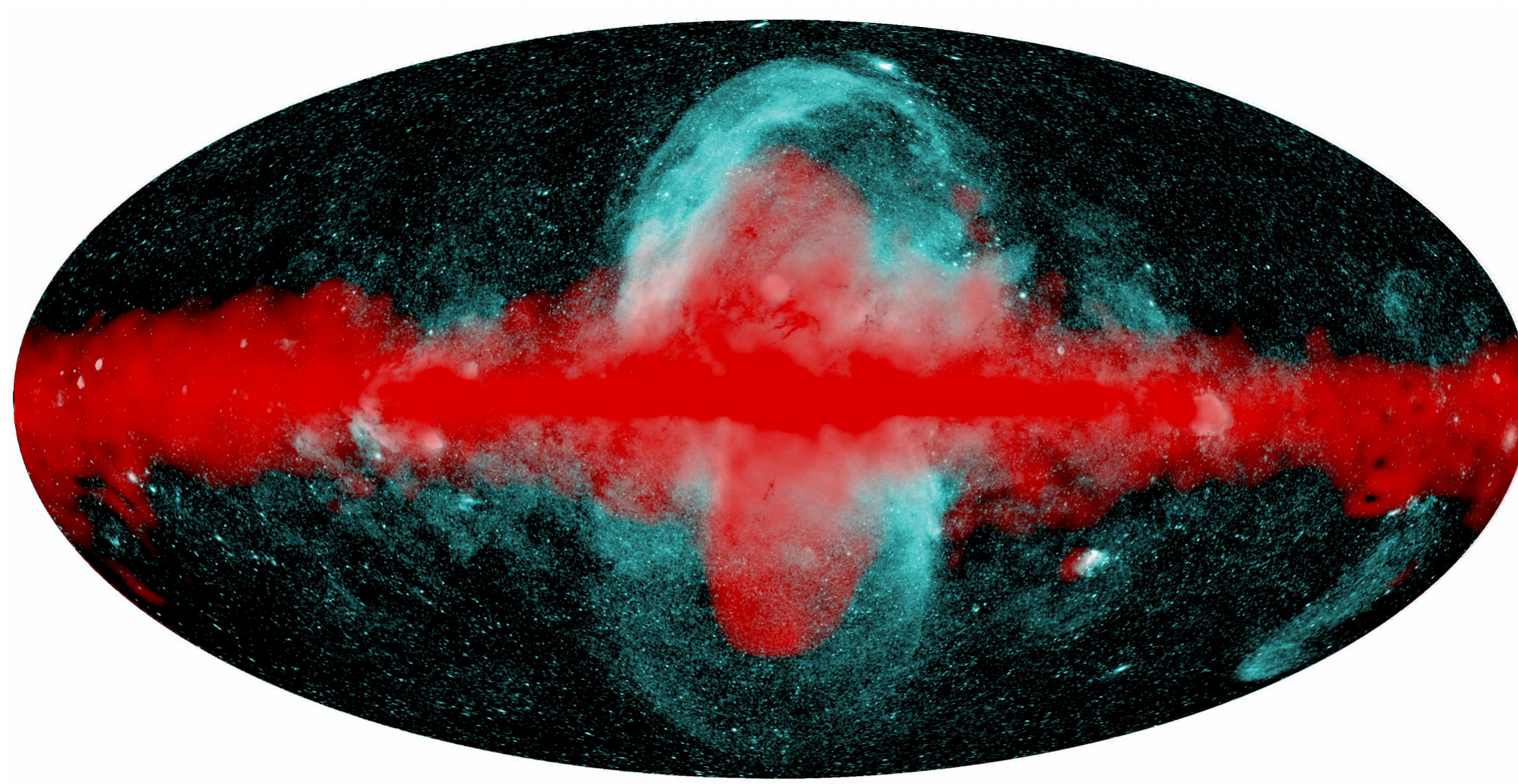
*Publ. Astron. Soc. Japan* (2020) 72 (2), 17 (1–14)  
doi: 10.1093/pasj/psz139  
Advance Access Publication Date: 2020 January 31



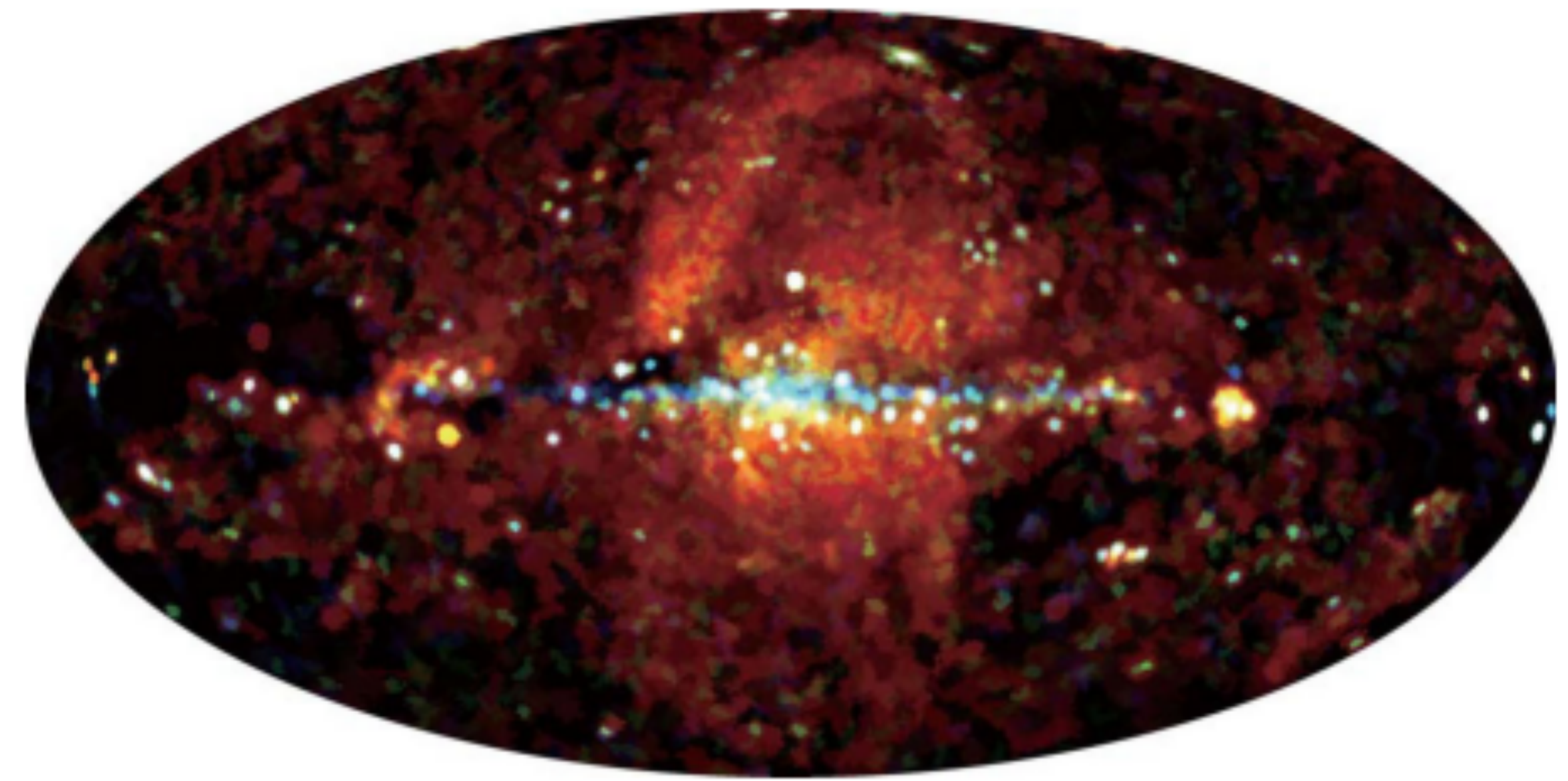
17-1

## MAXI/SSC all-sky maps from 0.7 keV to 4 keV

Satoshi NAKAHIRA,<sup>1,2,\*</sup> Hiroshi TSUNEMI,<sup>3</sup> Hiroshi TOMIDA,<sup>1</sup>  
Shinya NAKASHIMA,<sup>2</sup> Ryuho KATAOKA,<sup>4,5</sup> and Kazuo MAKISHIMA<sup>6</sup>

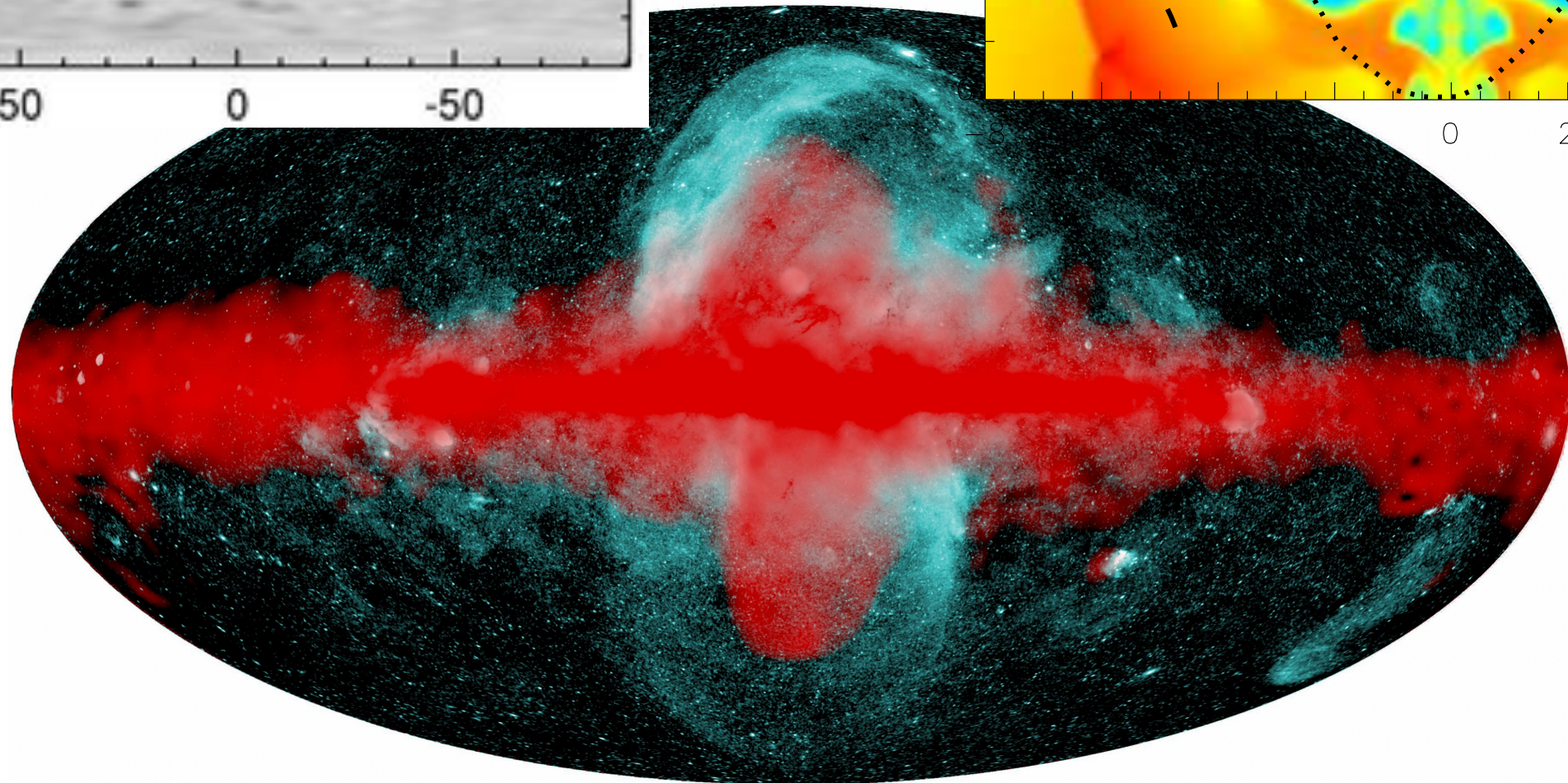
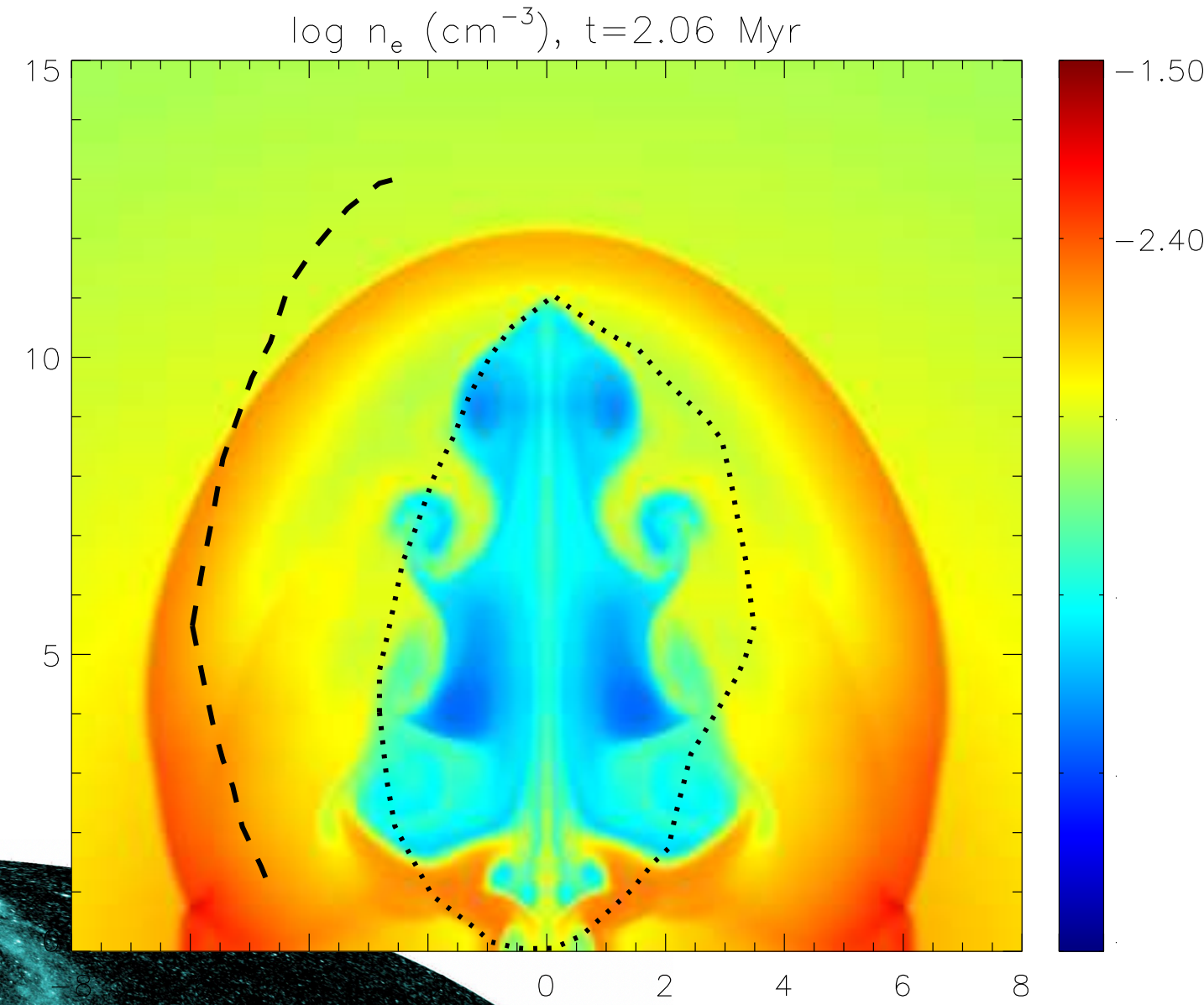
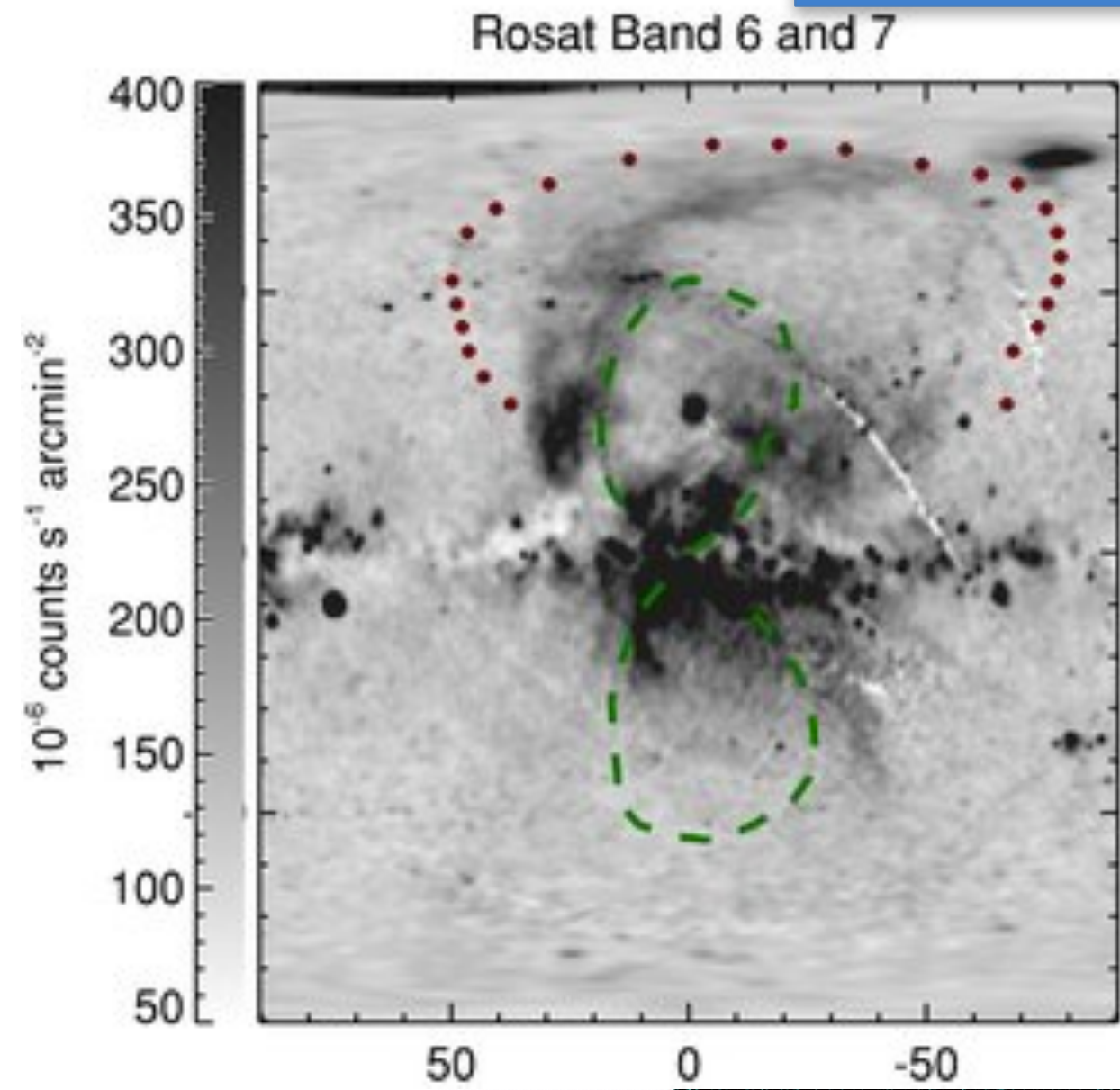


0.6-1 keV eROSITA bubbles (Predehl + 2020)  
red — Fermi map

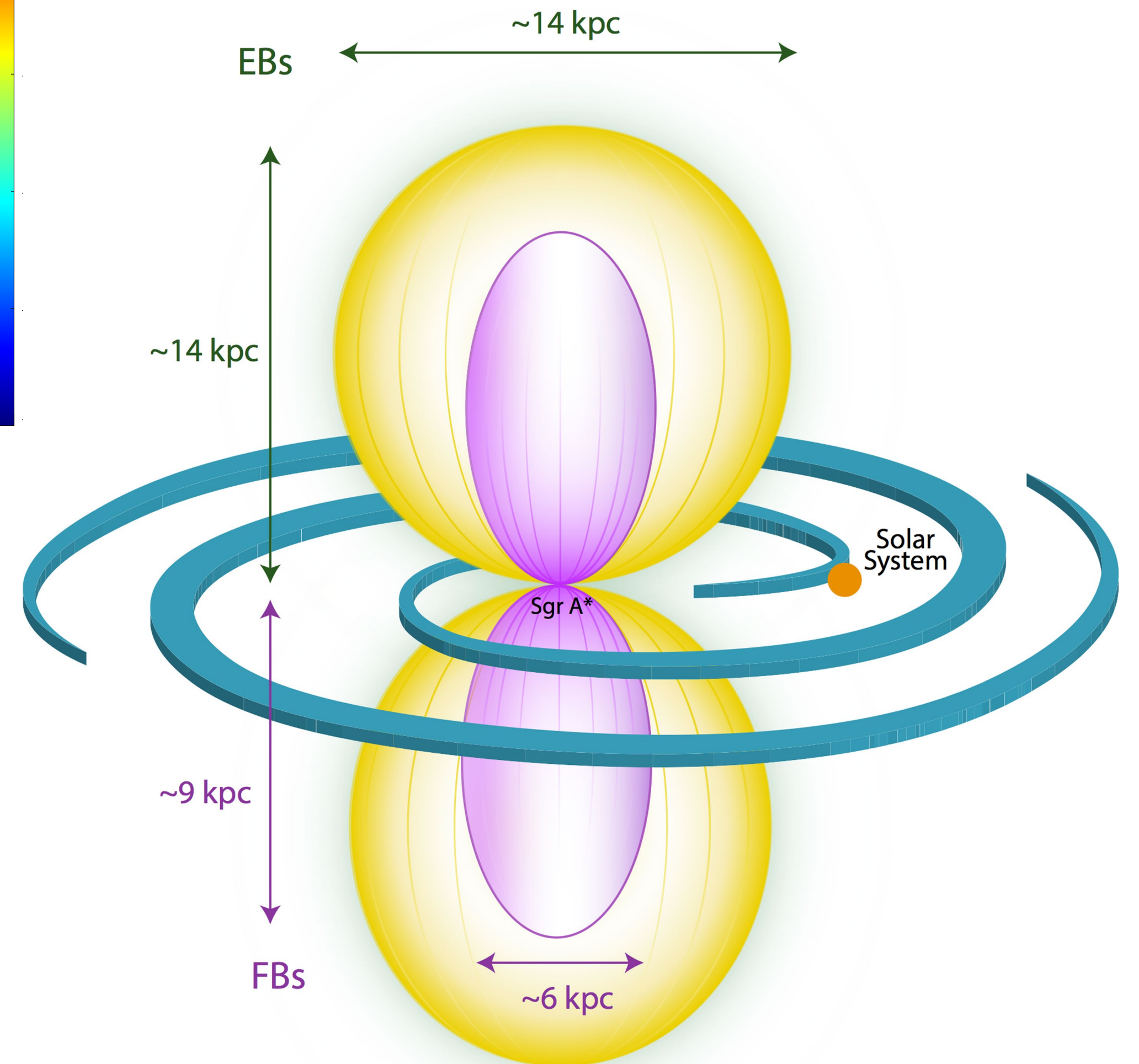


MAXI (0.7-1 keV; red), Nakahira + 2020

Fermi Bubbles : gamma-ray emission of Ejecta Lobes in the Milky Way?  
 eROSITA bubbles: shocked CGM bubbles of the Fermi bubble event?



Also see Yang+2021, Nature Astronomy



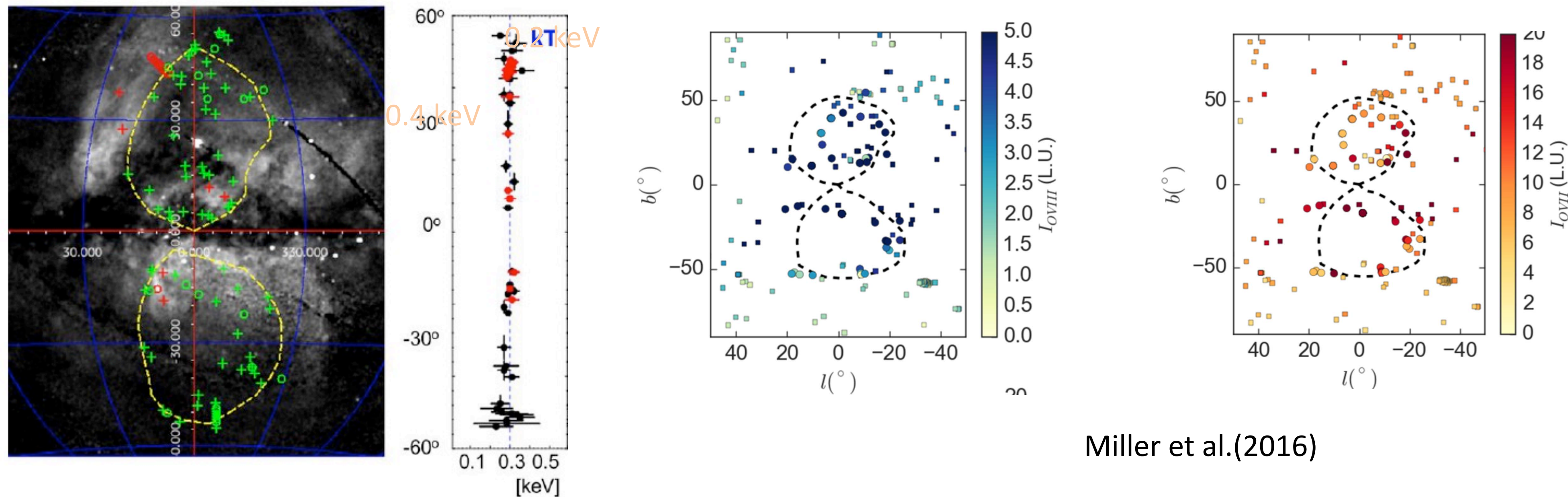
North Polar Spur and eROSITA Bubbles

# Potential Problems with this Model

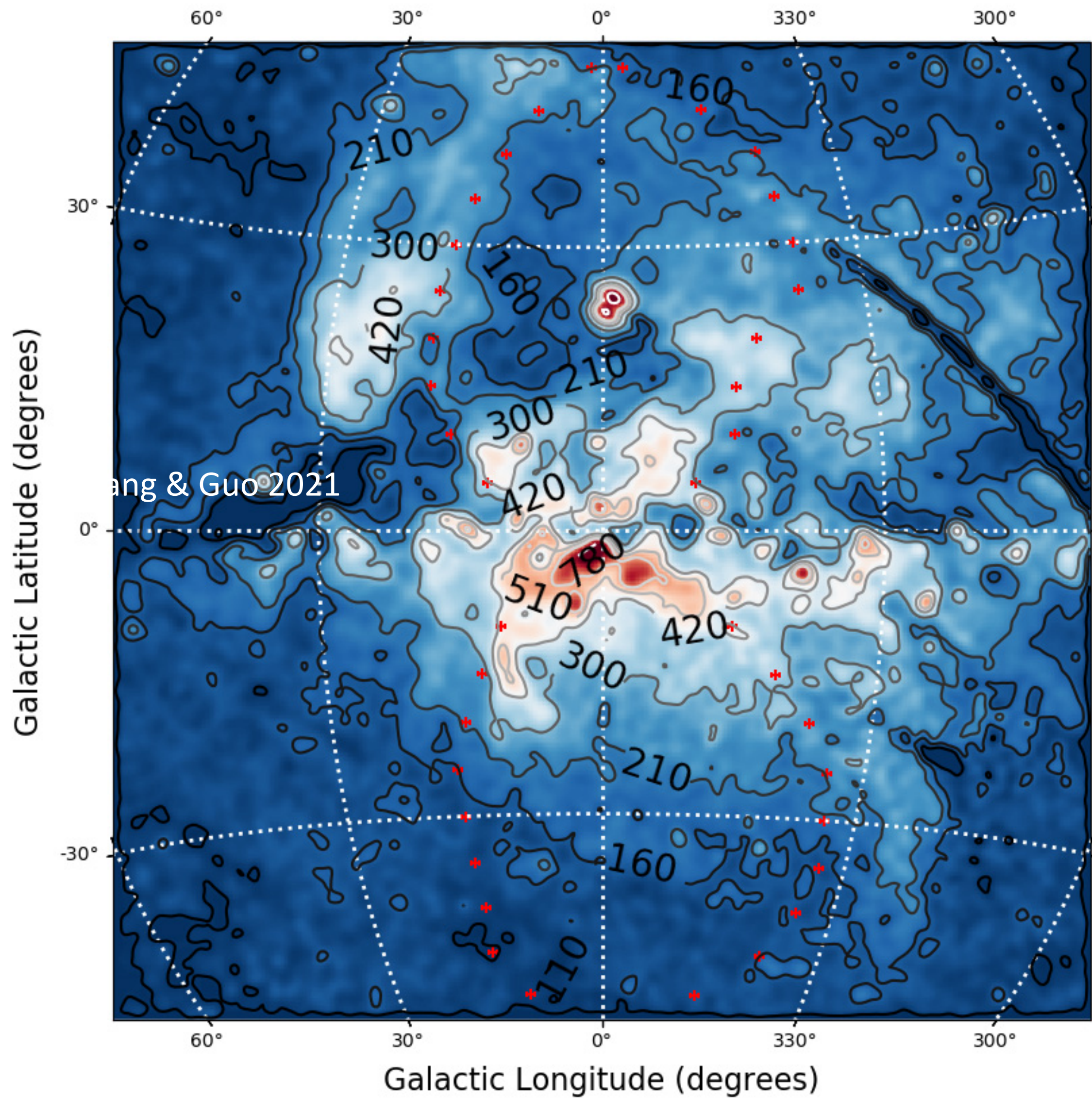
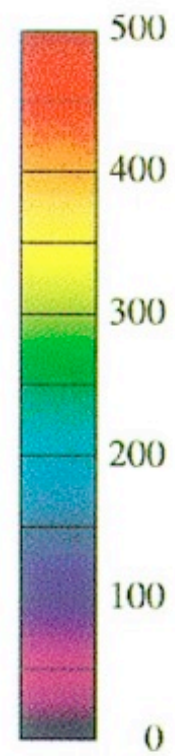
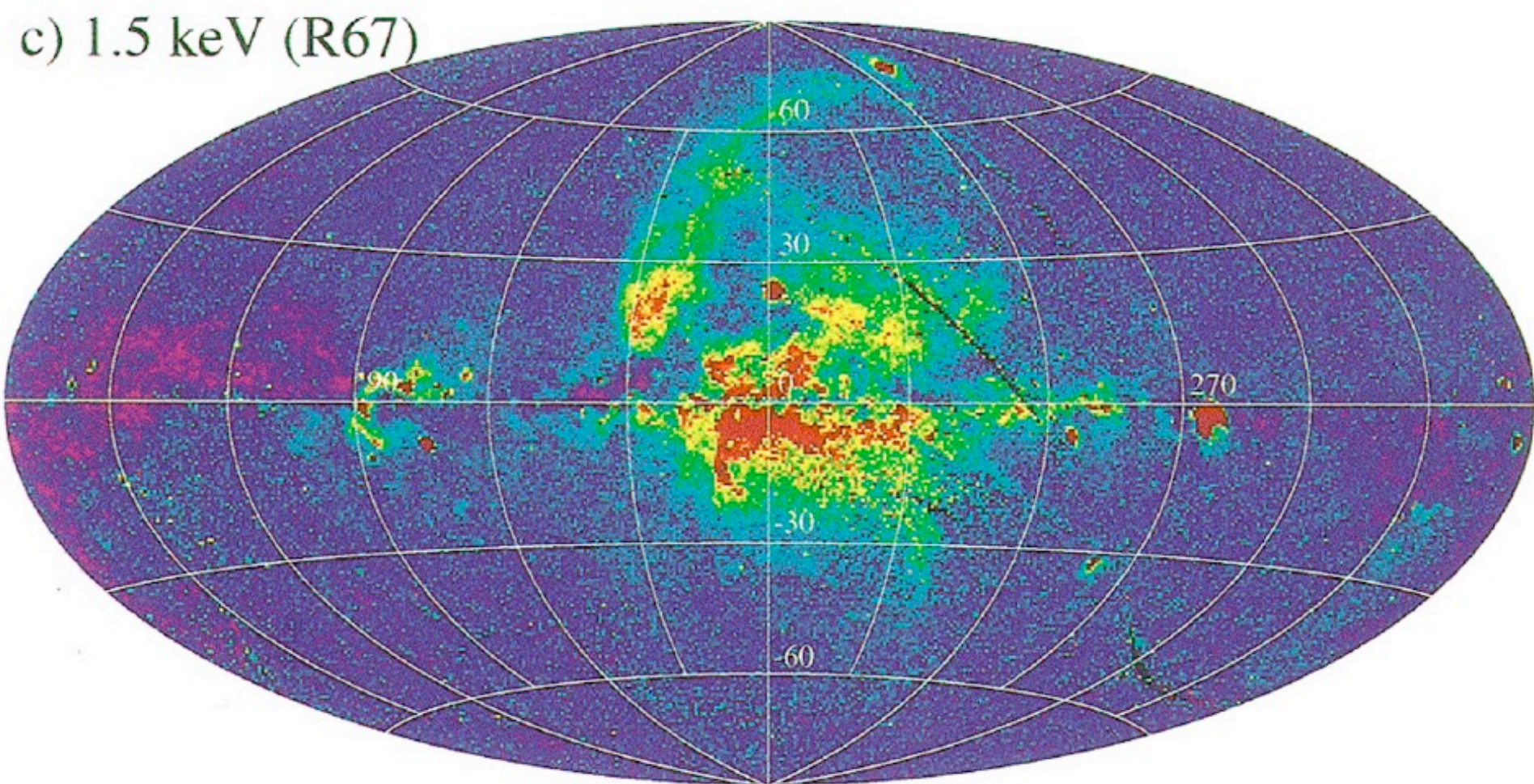
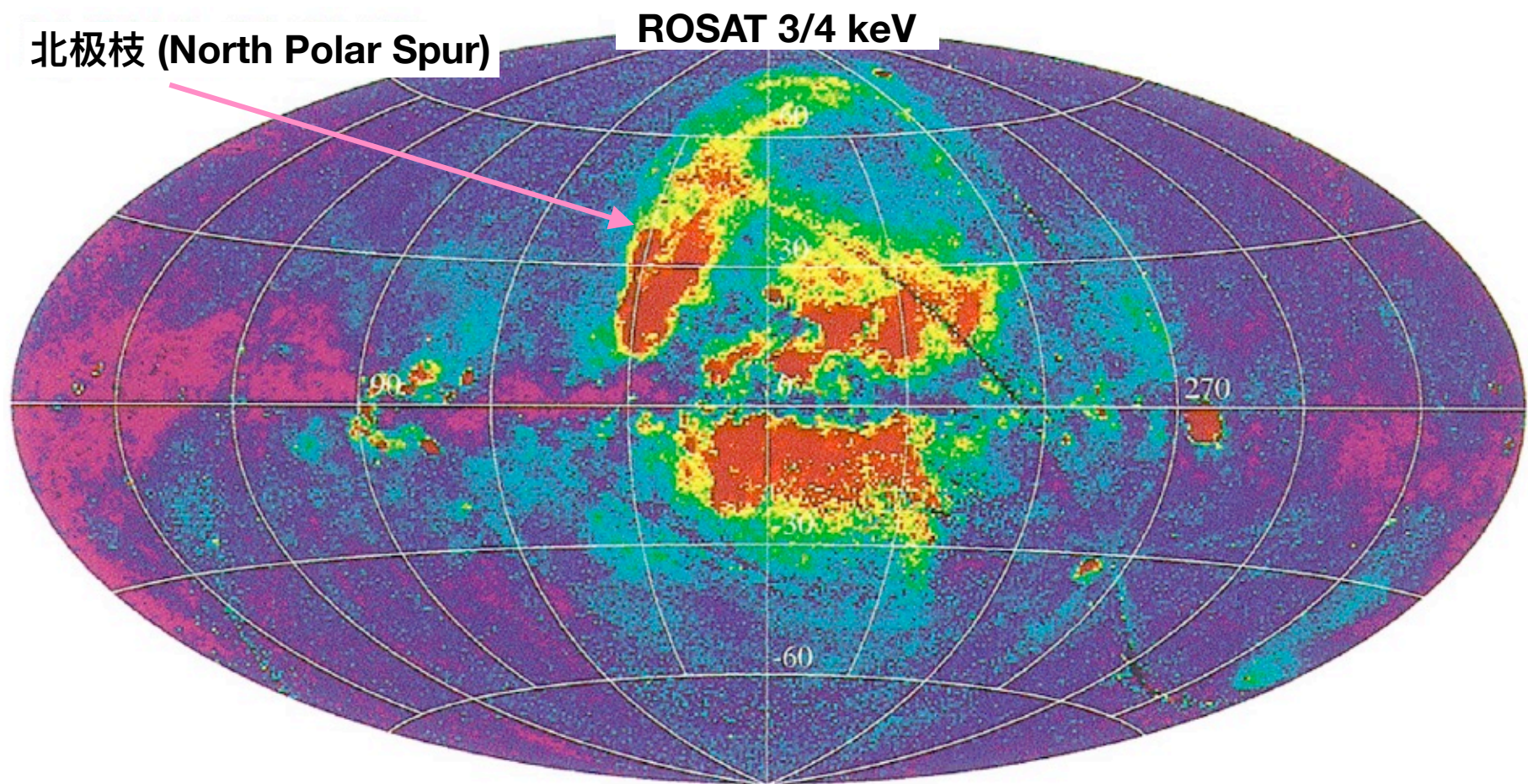
Miller et al.(2016) found the bubble temperature is  $kT \sim 0.40$  keV, gas density  $\sim 0.001$  cm<sup>-3</sup>

Bordoloi et al.(2017) found the bubble age is 5-9 Myr from UV absorption line studies of HVCs towards the bubbles.

Sgr A\* is orbited by over a hundred massive stars with ages  $\sim 6 \pm 2$  Myr

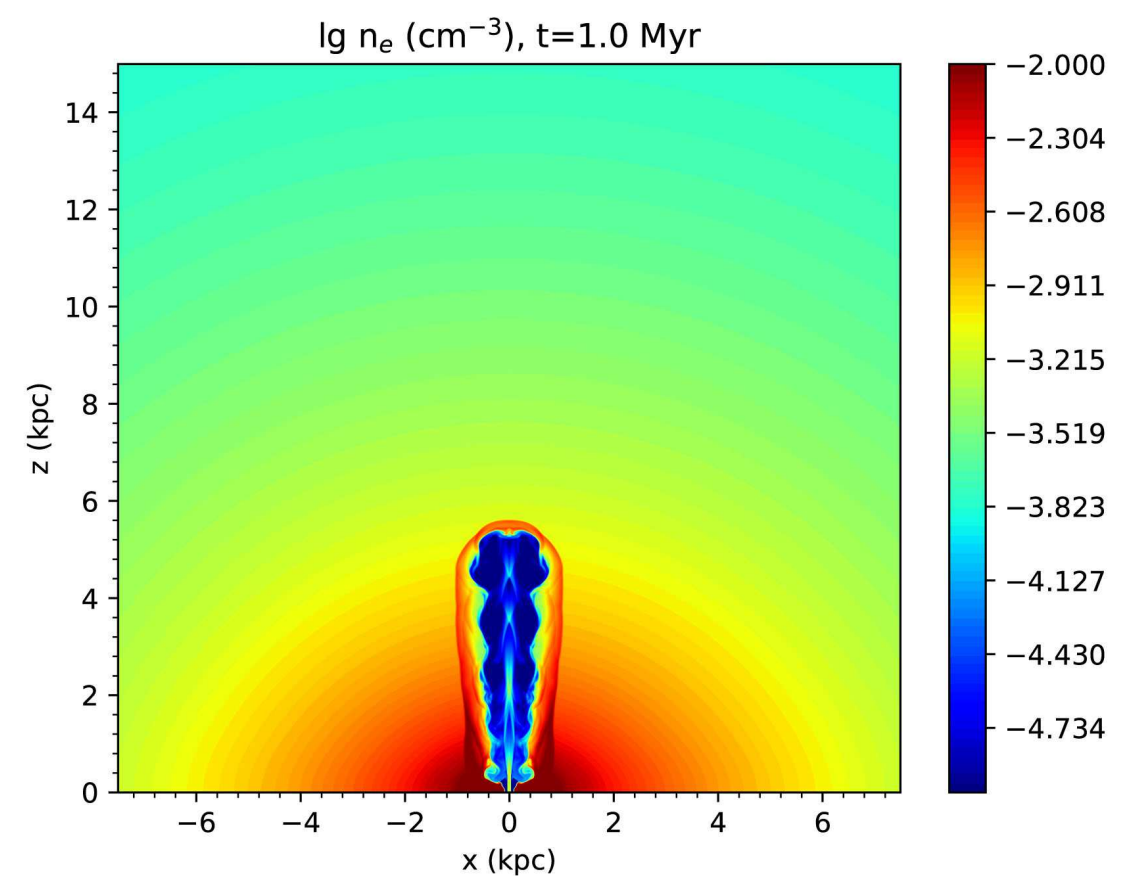


# Where is the forward shock?

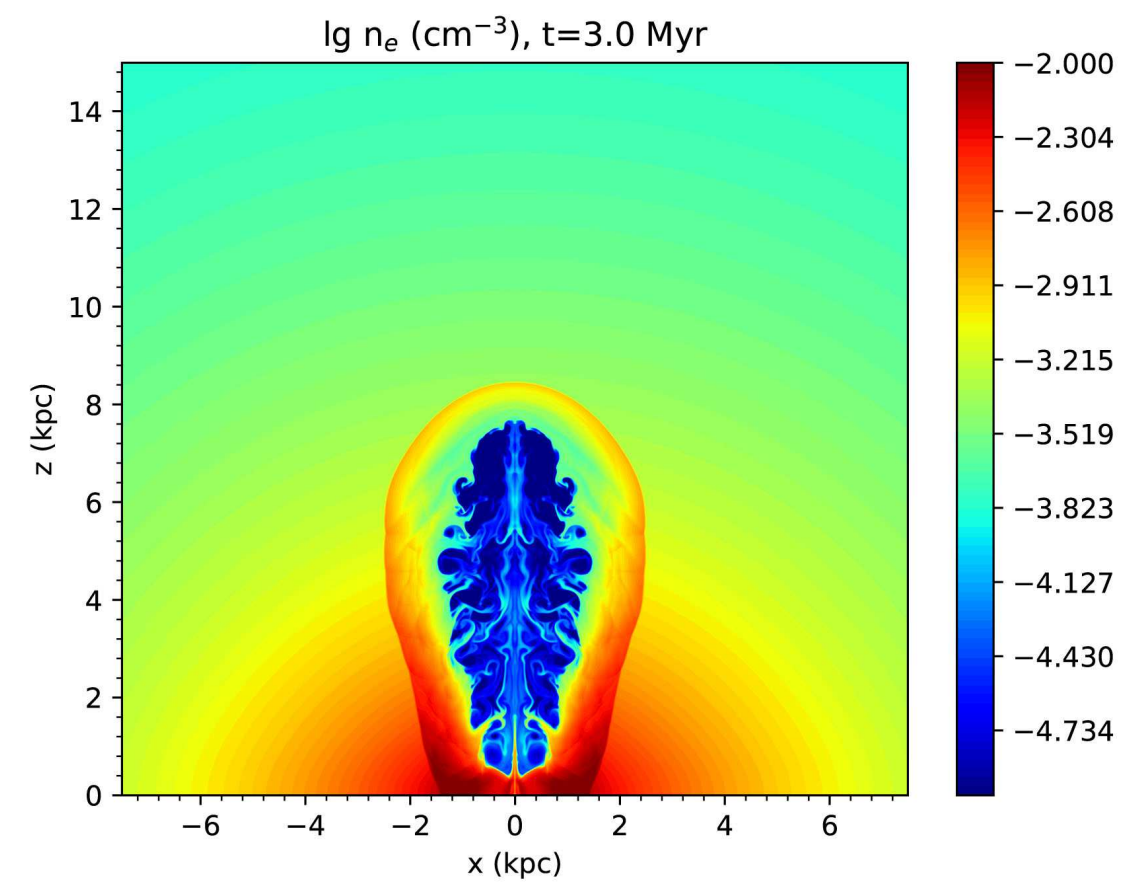


# The Evolution of Fermi bubbles

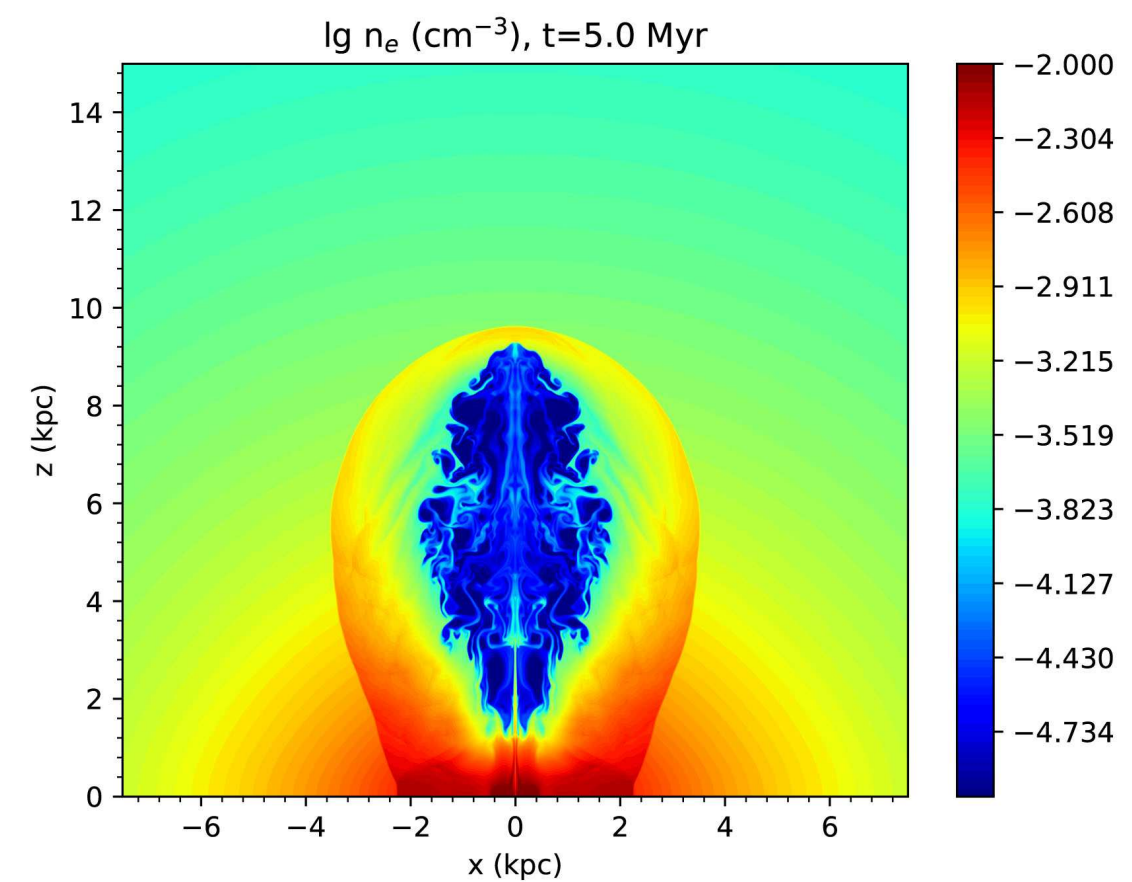
The energetics and age of the bubbles are constrained very well by the bubble morphology and the gas temperature within the bubbles!



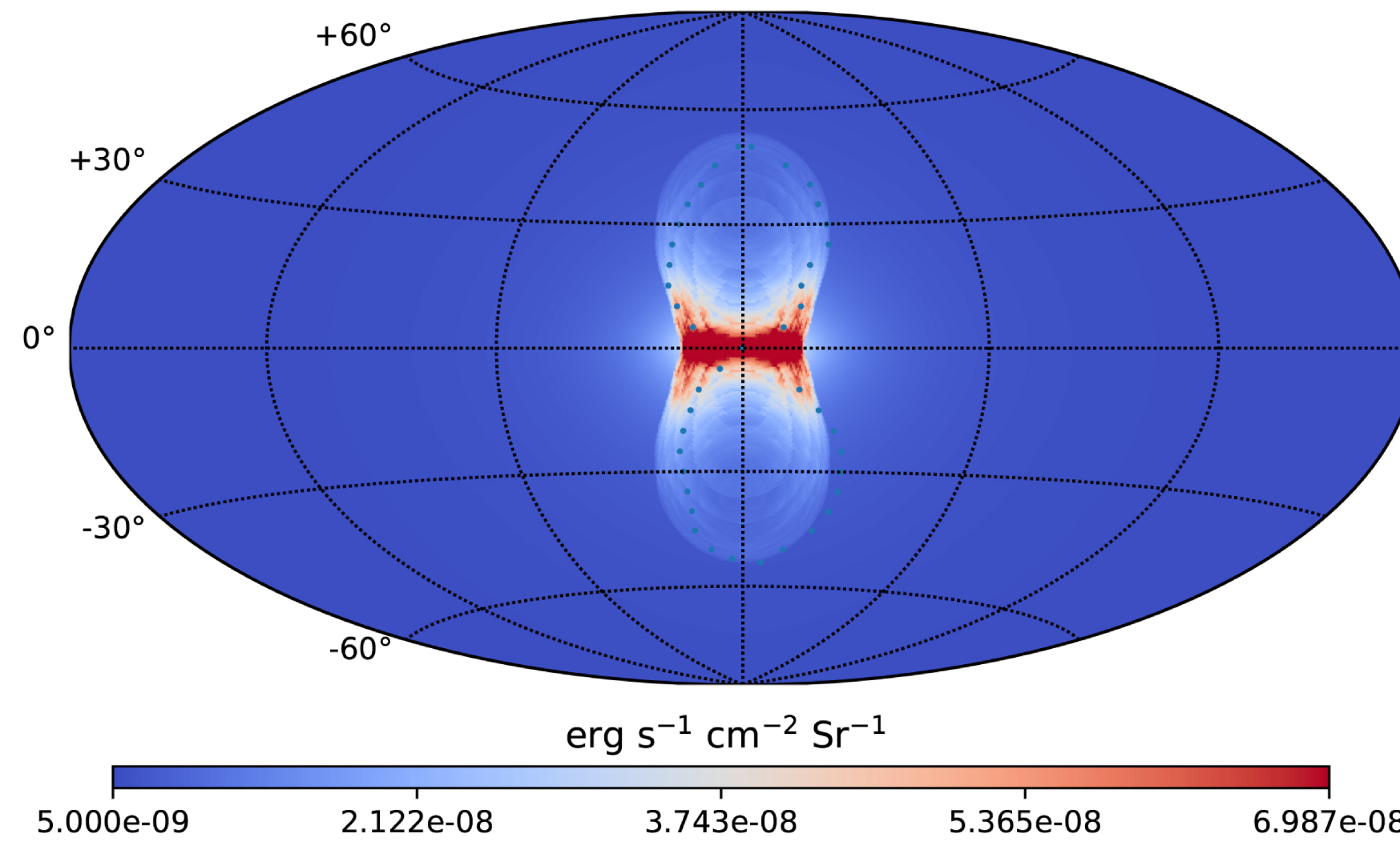
(a)



(b)



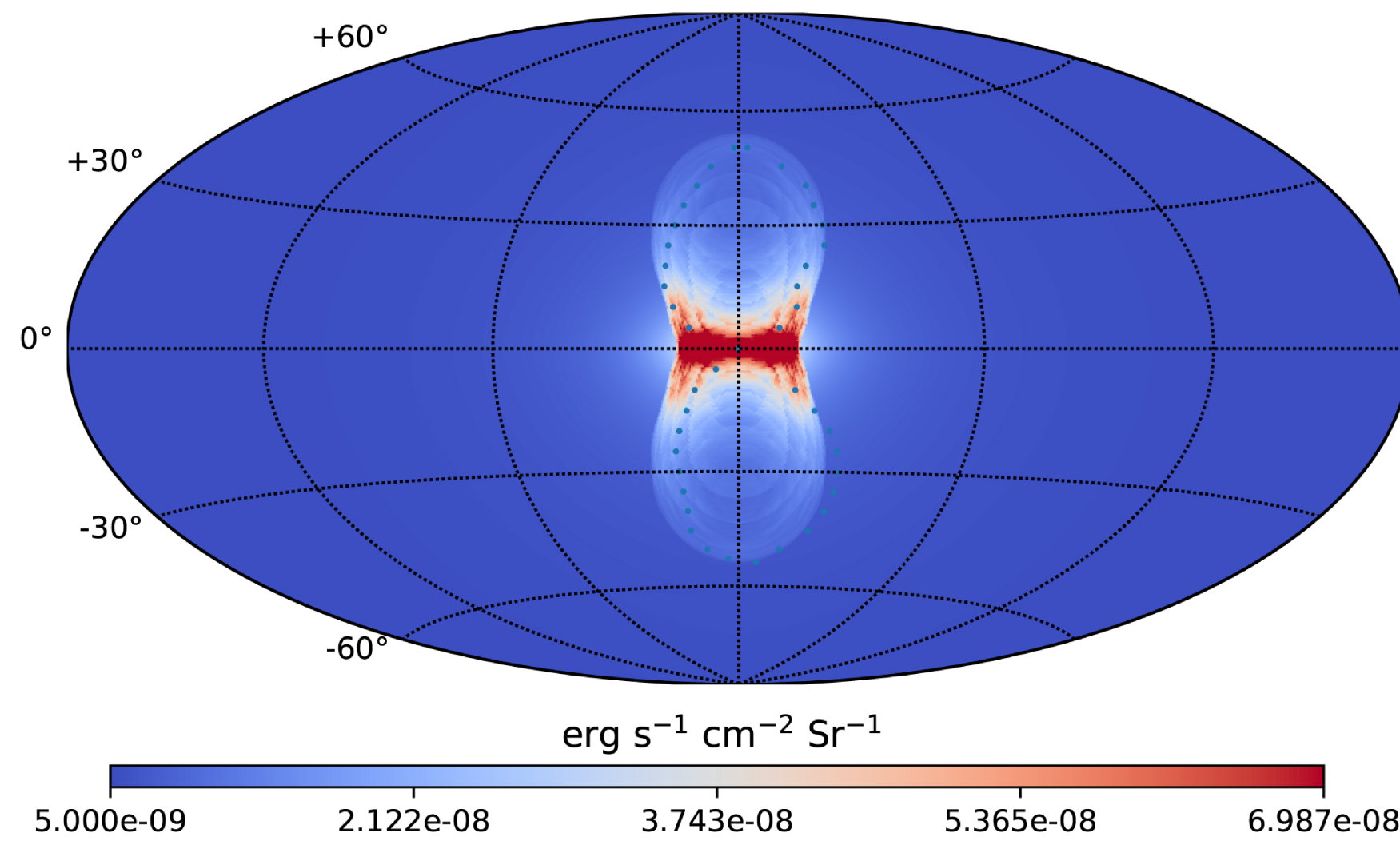
(c)



**Figure 9.** Synthetic X-ray (0.7–2 keV) surface brightness map in Galactic coordinates with a Hammer-Aitoff projection for run A at  $t = 5$  Myr. The dots represent the edge of the observed Fermi bubbles.

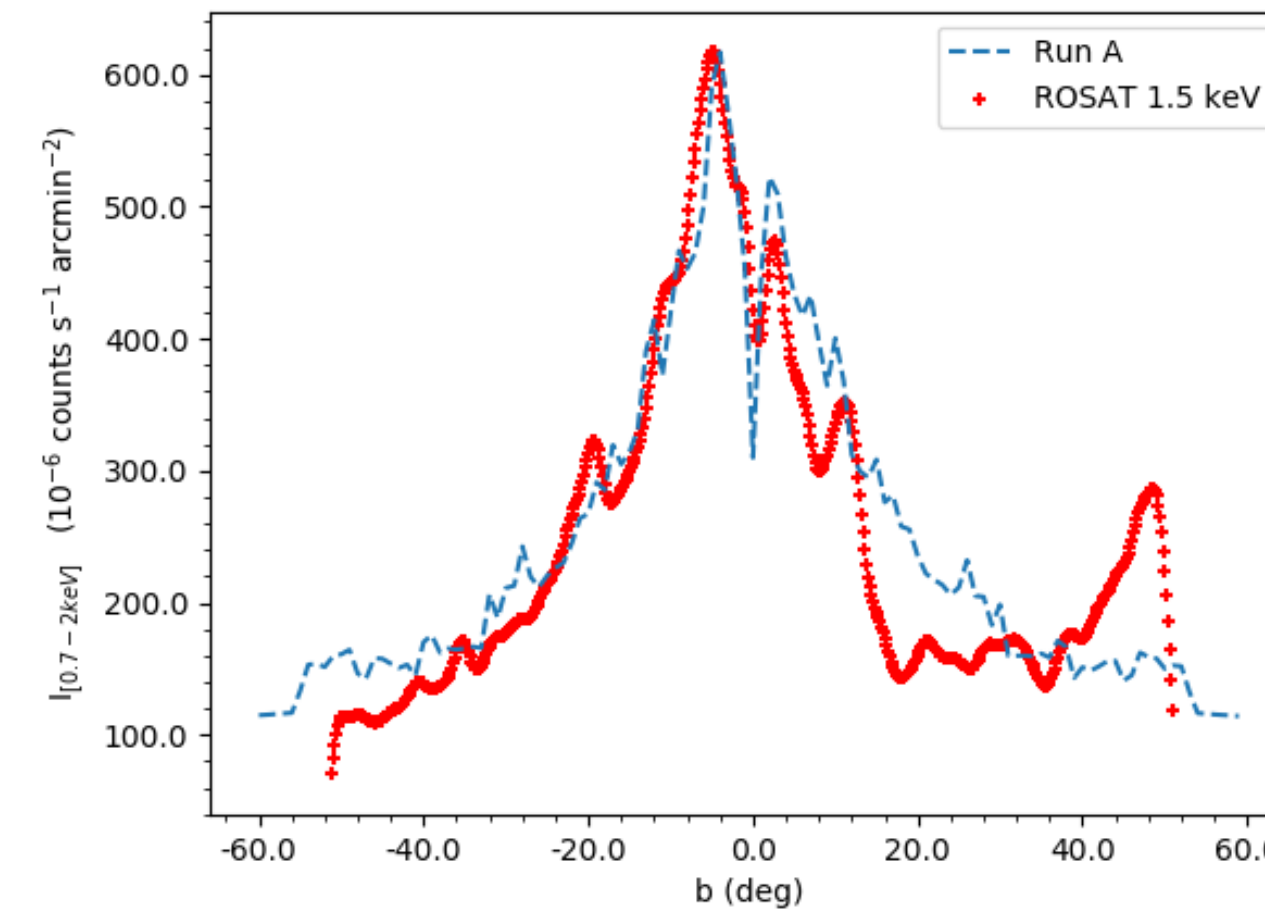
Zhang & Guo, 2020

# 1.5 keV X-ray Surface Brightness Map



**Figure 9.** Synthetic X-ray (0.7–2 keV) surface brightness map in Galactic coordinates with a Hammer-Aitoff projection for run A at  $t = 5$  Myr. The dots represent the edge of the observed Fermi bubbles.

Zhang & Guo, 2020



**Figure 5.** The X-ray surface brightness, cuts across the Galactic plane at  $l = 5^\circ$ . The dots represent the observation data in ROSAT 1.5 keV band at the same latitude. The dashed line represent the results synthetic from Run A (normalized by the maximum value around the Galaxy center), and a uniform background emission of  $10^{-4} \text{ counts s}^{-1} \text{ arcmin}^{-2}$  is added in the synthetic data.

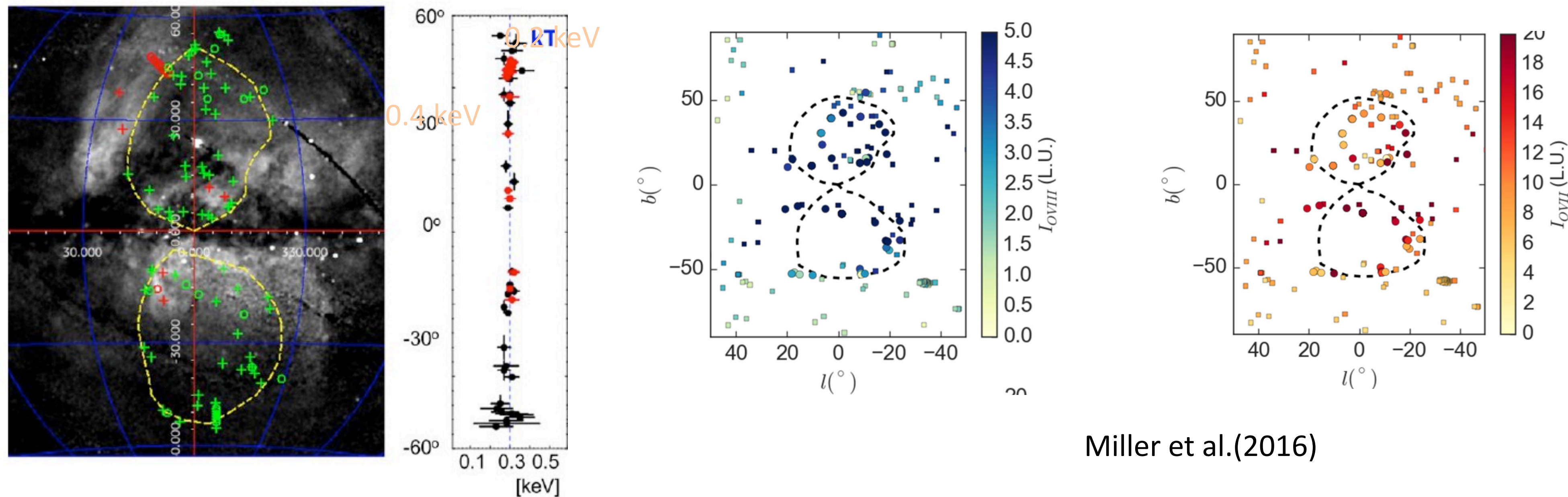
Zhang & Guo, 2021

# Consistent with Other Observations

Miller et al.(2016) found the bubble temperature is  $kT \sim 0.40$  keV, gas density  $\sim 0.001$  cm<sup>-3</sup>

Bordoloi et al.(2017) found the bubble age is 5-9 Myr from UV absorption line studies of HVCs towards the bubbles.

Sgr A\* is orbited by over a hundred massive stars with ages  $\sim 6 \pm 2$  Myr



## Properties of the Fermi bubbles in Our Model

single-jet Power:  $3.42 \times 10^{41} \text{ erg s}^{-1}$

Jet duration: 1 Myr

**Current Fermi bubble age: 5 Myr**

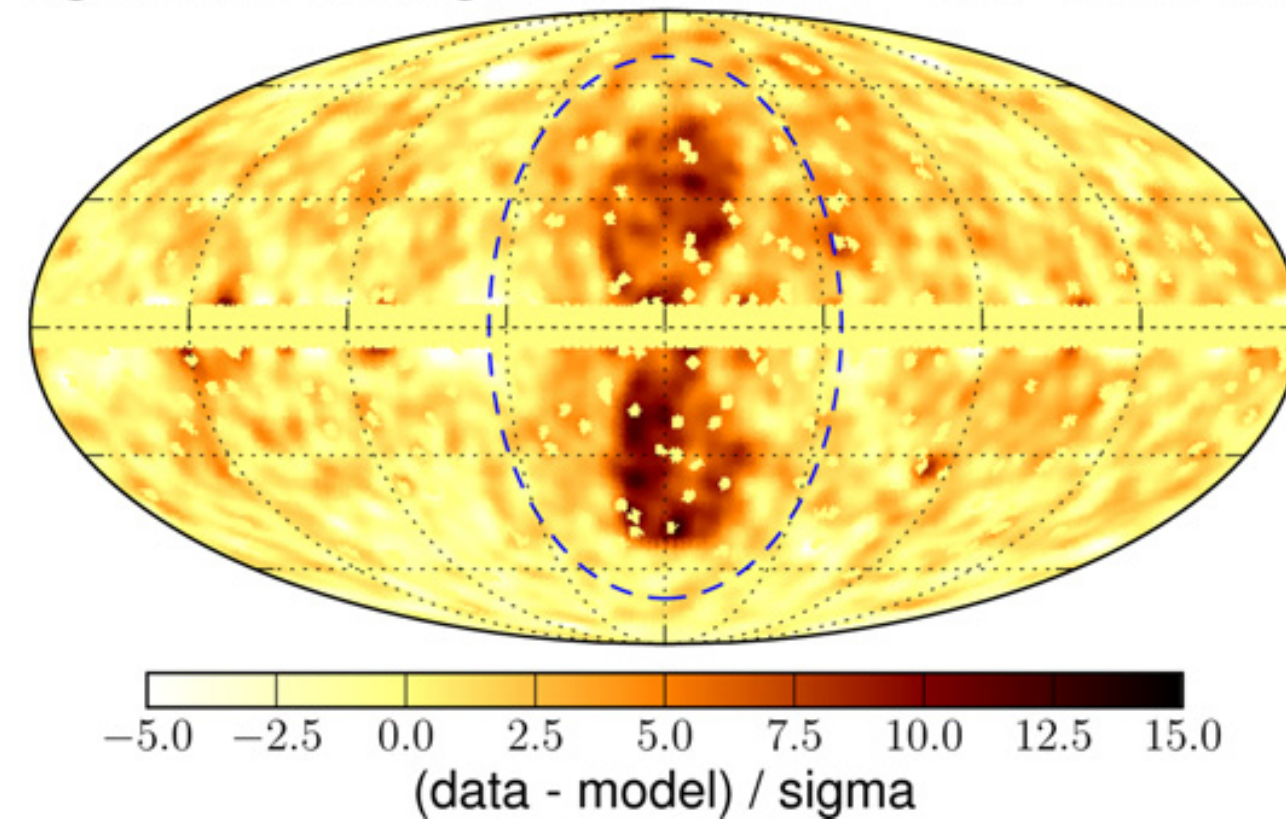
Total injected energy  $\sim 2 \times 10^{55} \text{ erg}$

**Eddington ratio:  $\sim 0.001$ , hot accretion mode**

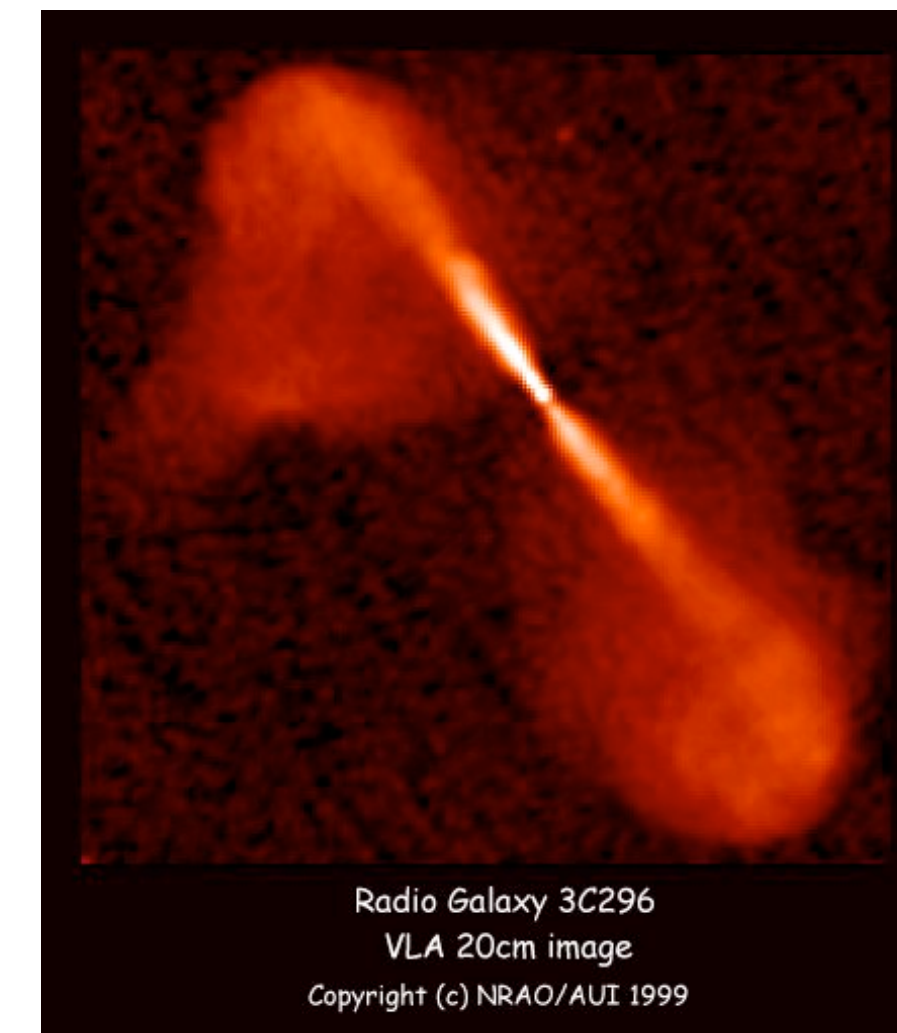
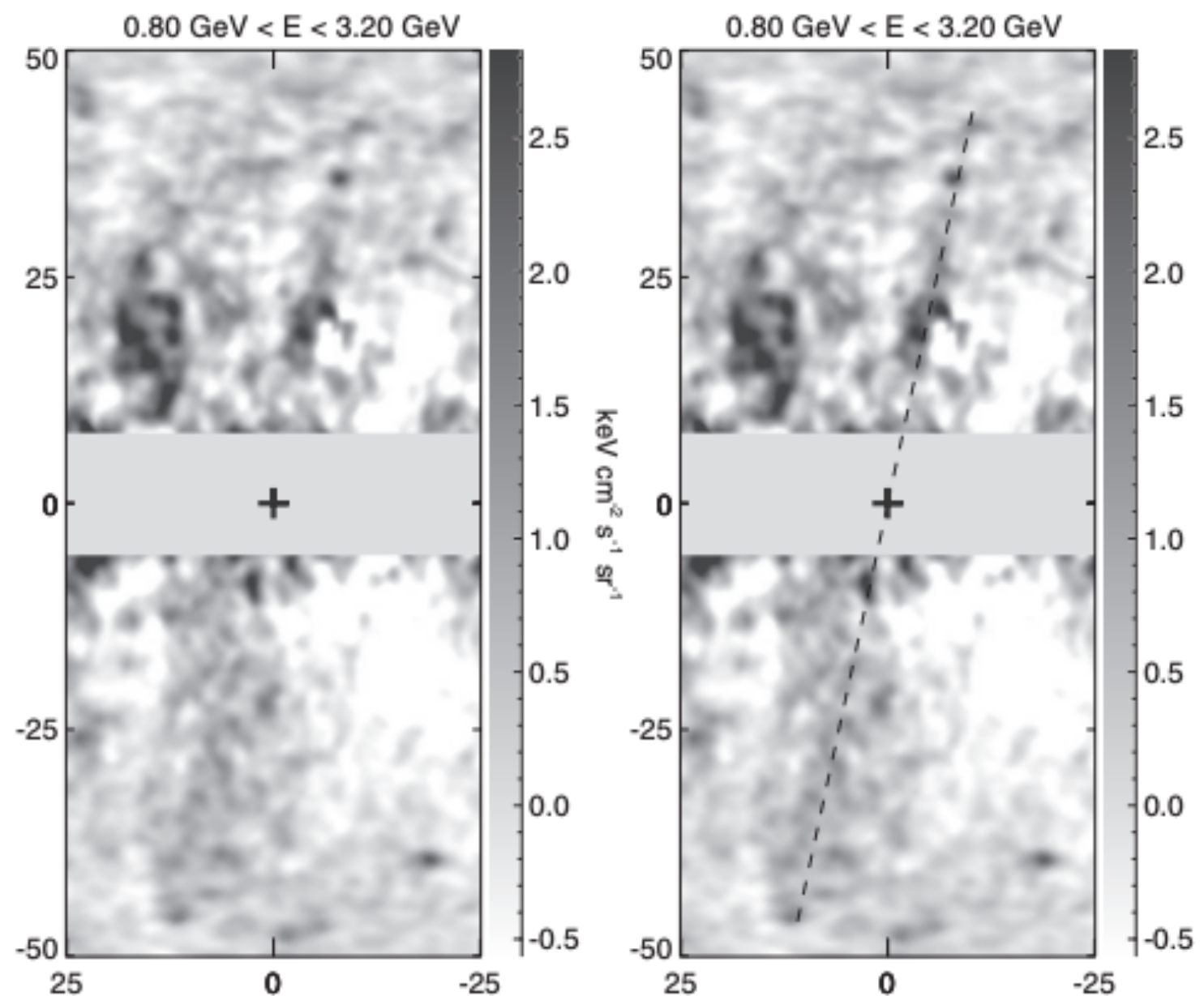
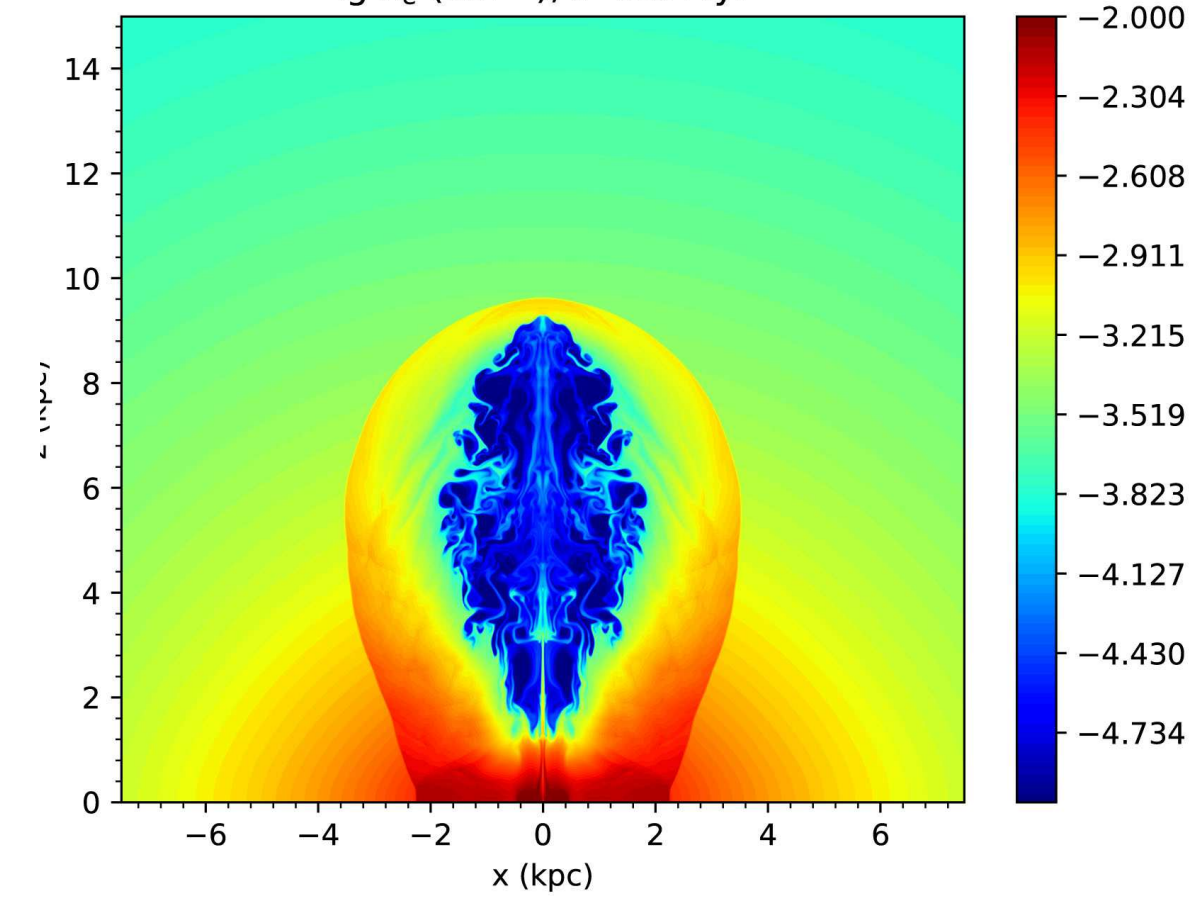
Sgr A\* accretion rate  $\sim 0.0001 \text{ solar mass/yr}$

# Fermi Bubbles : Forward shock + (unseen) inner lobes

Significance of integrated residual,  $E = 10.0 - 500.0$  GeV



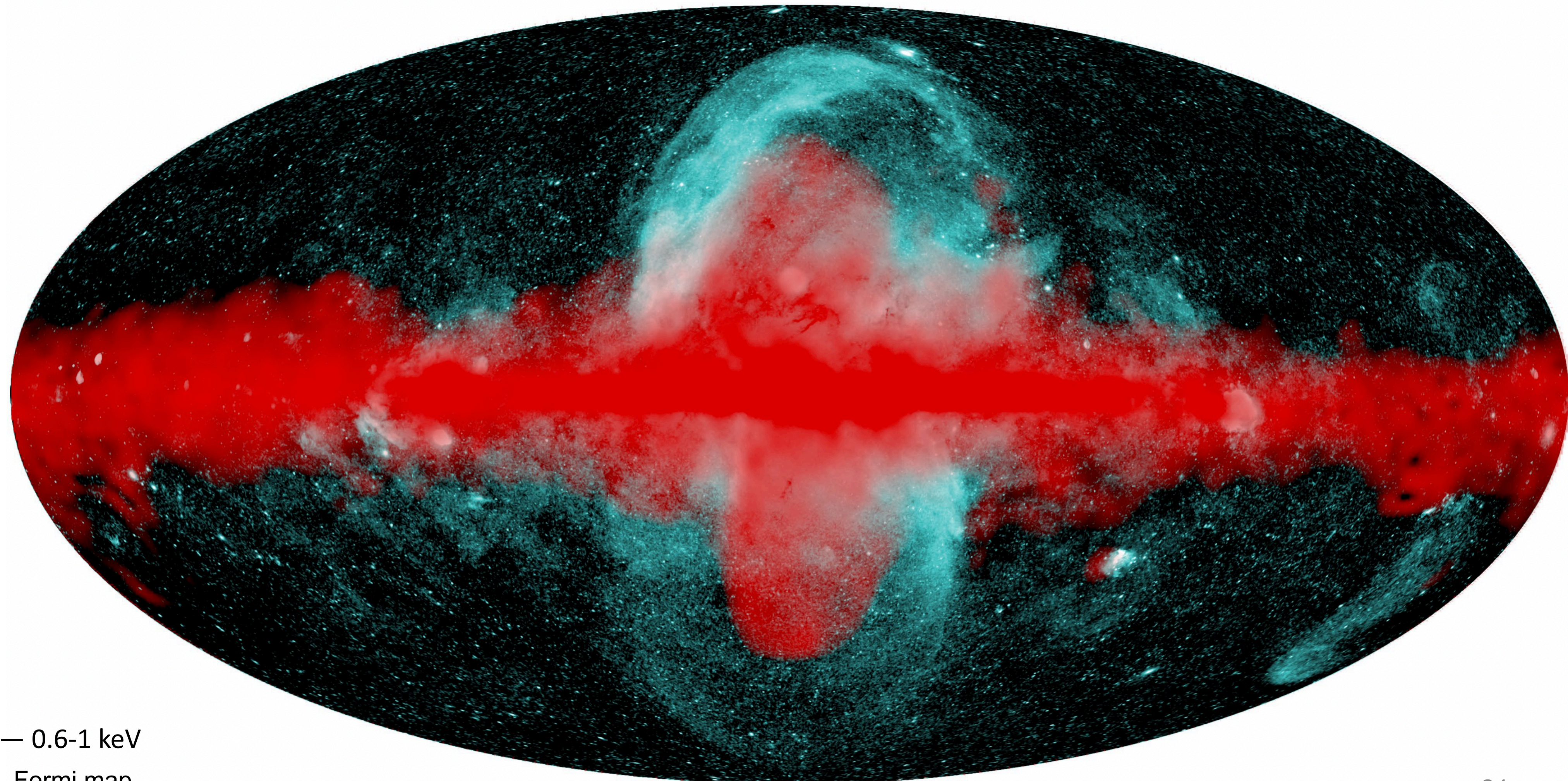
$\lg n_e$  ( $\text{cm}^{-3}$ ),  $t=5.0$  Myr



Su & Finkbeiner 2012

# What about the eROSITA Bubbles?

An older event from the Galactic Center

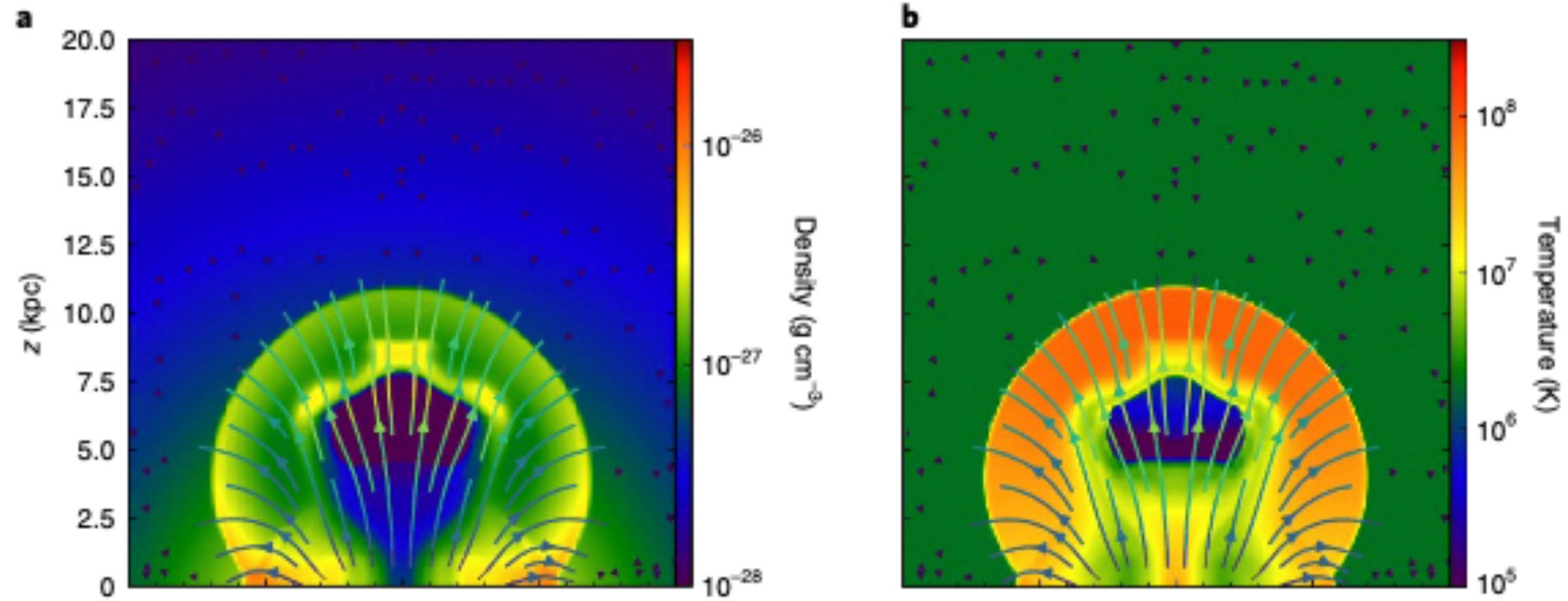


Cyan — 0.6-1 keV

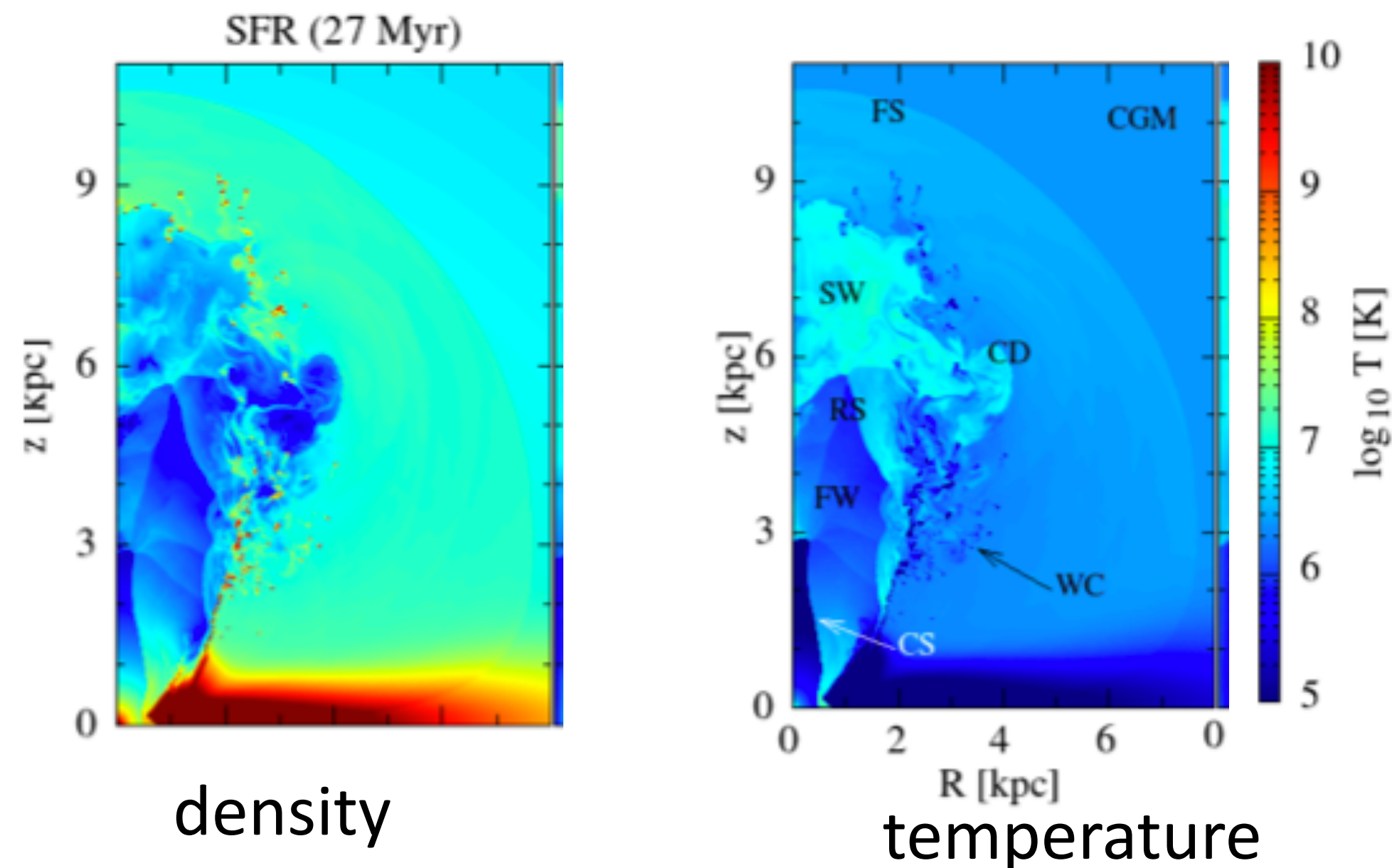
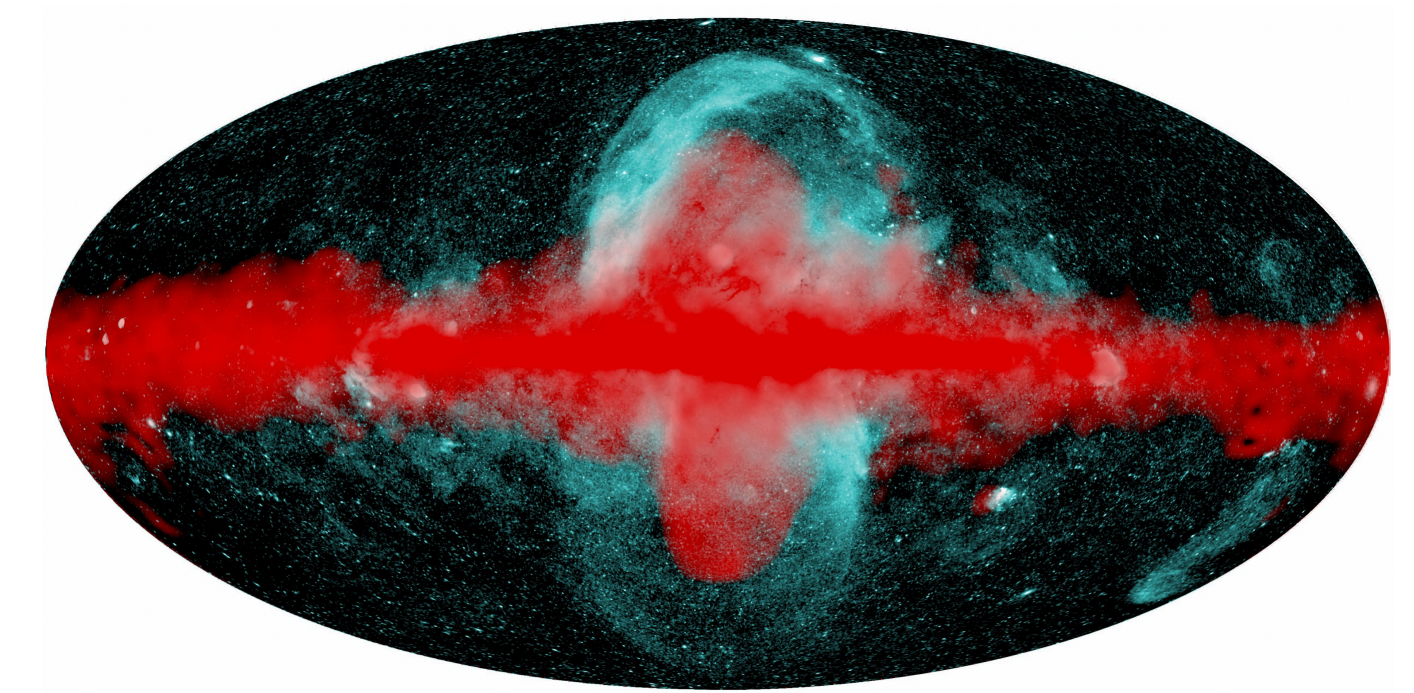
red — Fermi map

eROSITA bubbles (Predehl + 2020)

# Models of the eROSITA Bubbles

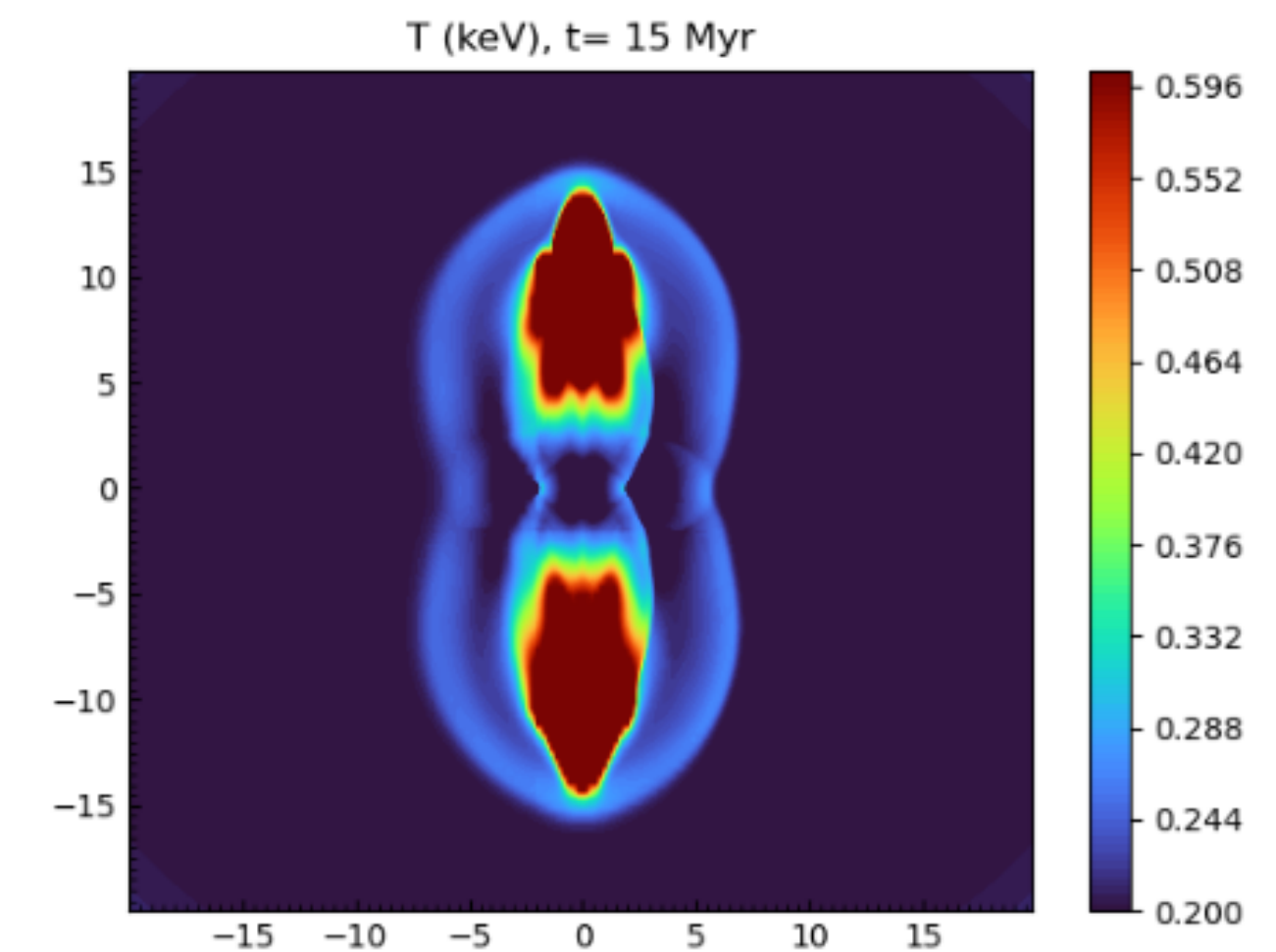
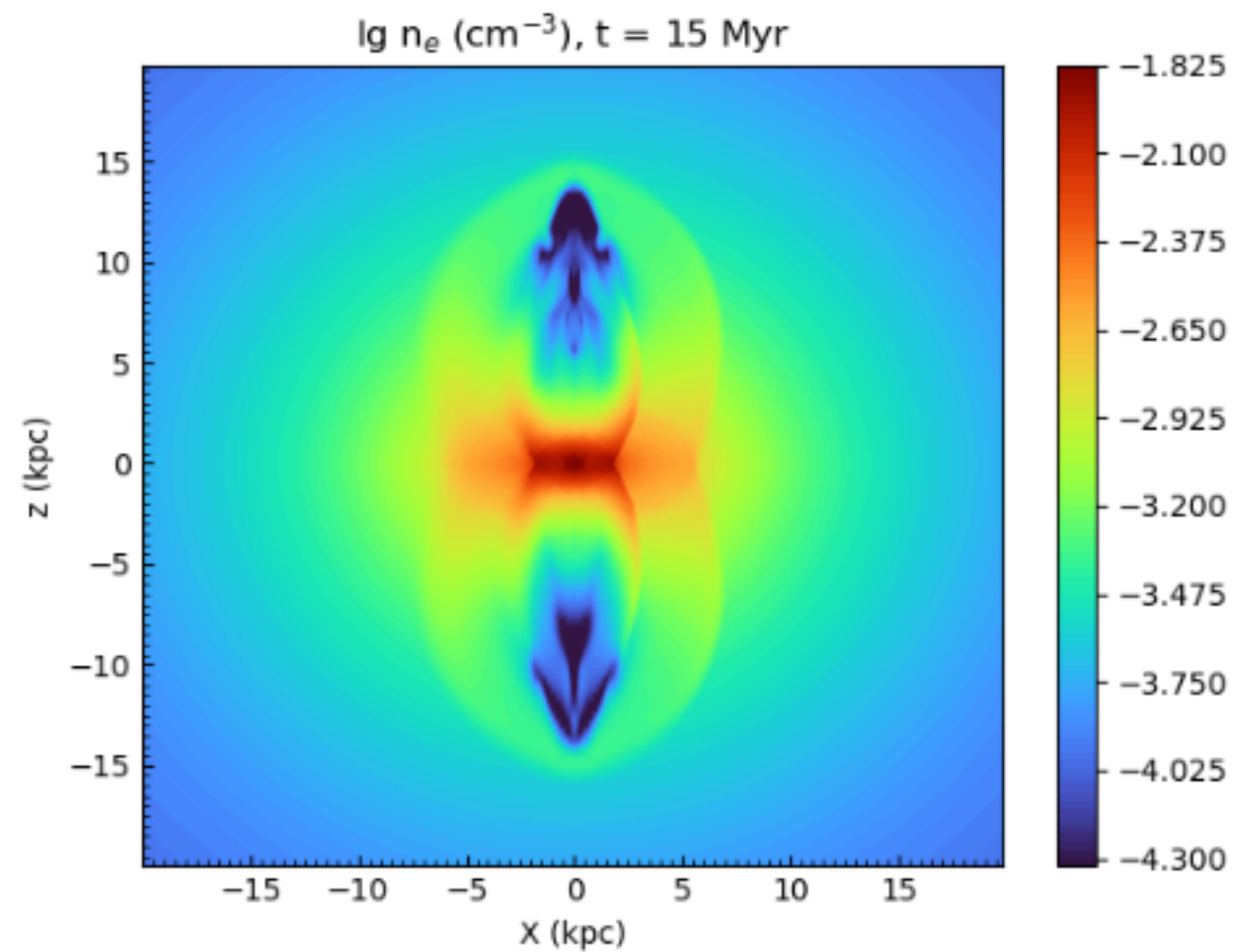


One AGN jet activity 2.6 Myr ago produces both; Yang+21



One starburst activity about 20-30 Myr ago produces both; Sarkar 2024

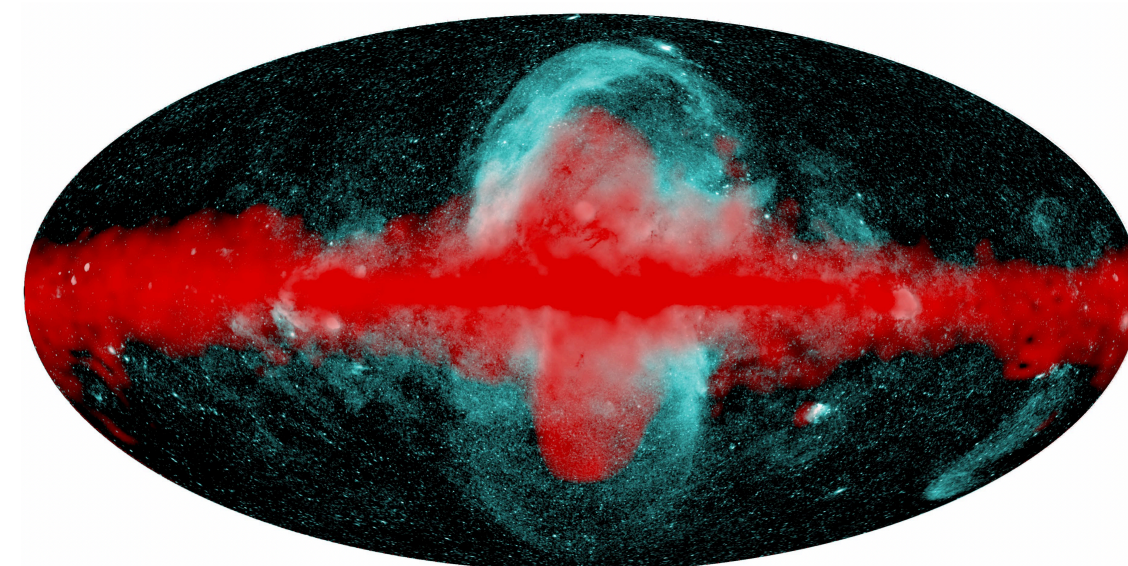
# The Double-episode Jet Model of the eROSITA and Fermi Bubbles



The first AGN jet activity occurred about 15 Myr ago, lasting for 1 Myr and produced the eROSITA bubbles seen today

The second AGN jet activity occurred about 5 Myr ago, lasting for 0.5 Myr and produced the Fermi bubbles seen today

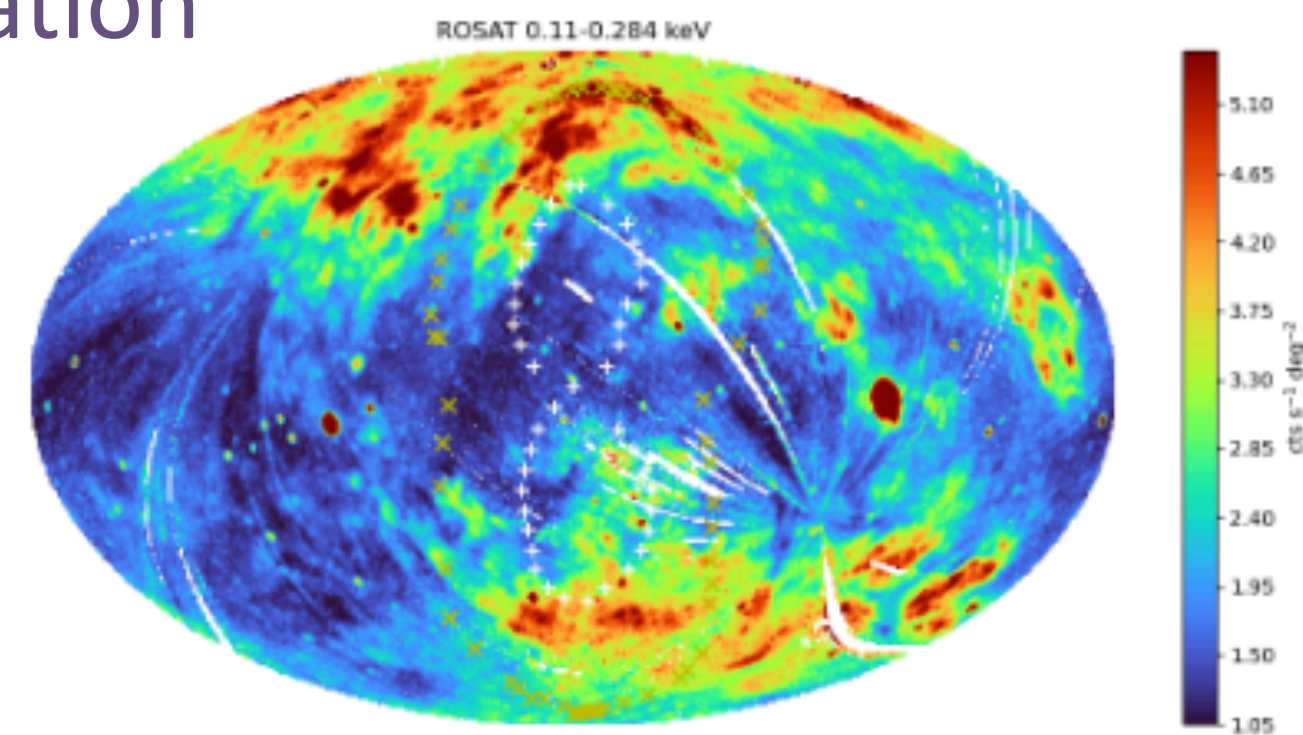
These two bubble pairs are delineated by the forward shocks



- Zhang, Guo, et al 2025, under review

# The Double-episode Jet Model of the eROSITA and Fermi Bubbles

observation

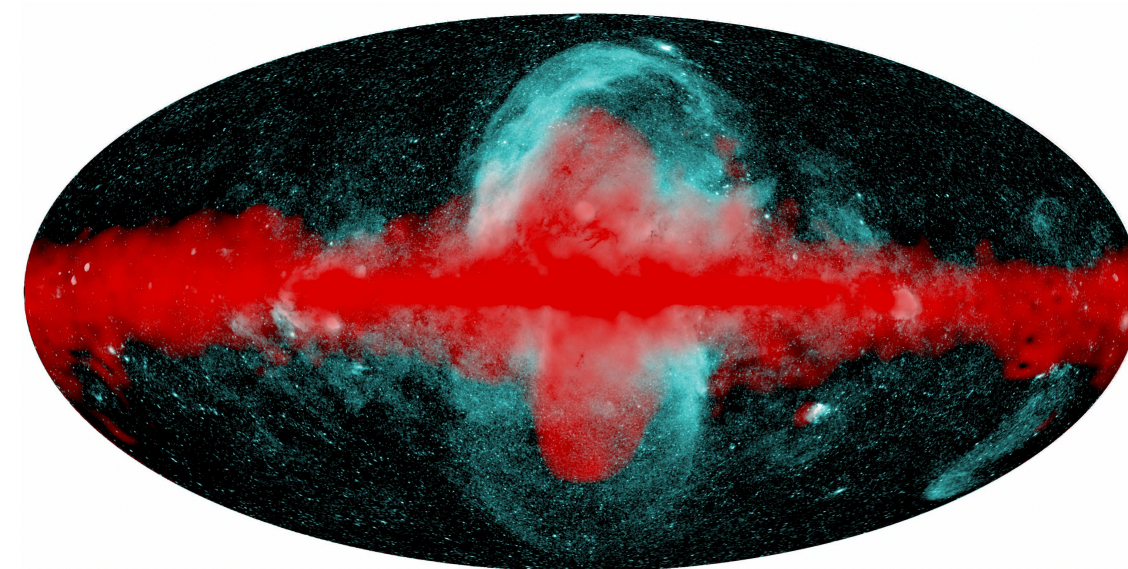
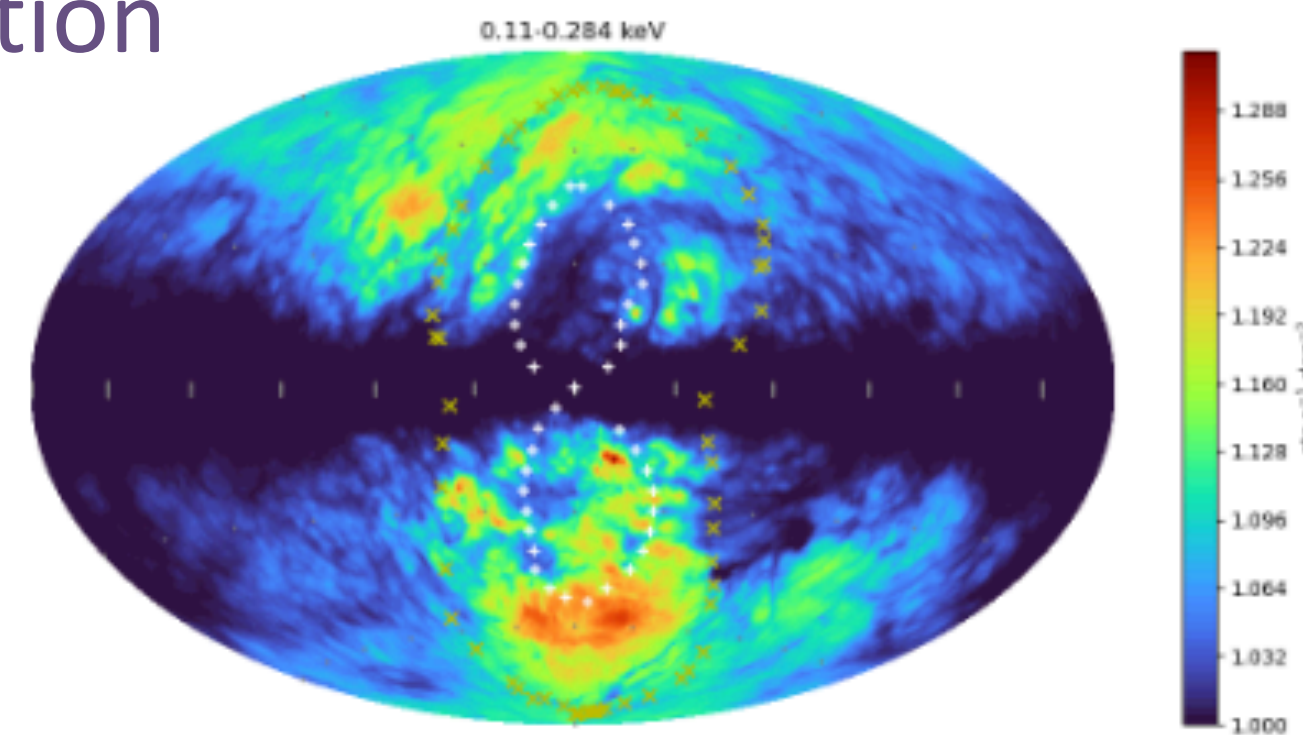


(a)

The left top panel shows the ROSAT map in the 0.11-0.284 keV band only the top regions of the eROSITA bubbles are seen as the lower-latitude part is obscured by HI absorption

The left lower panel shows our simulated X-ray map in the same soft X-ray band, agreeing with observations quite well

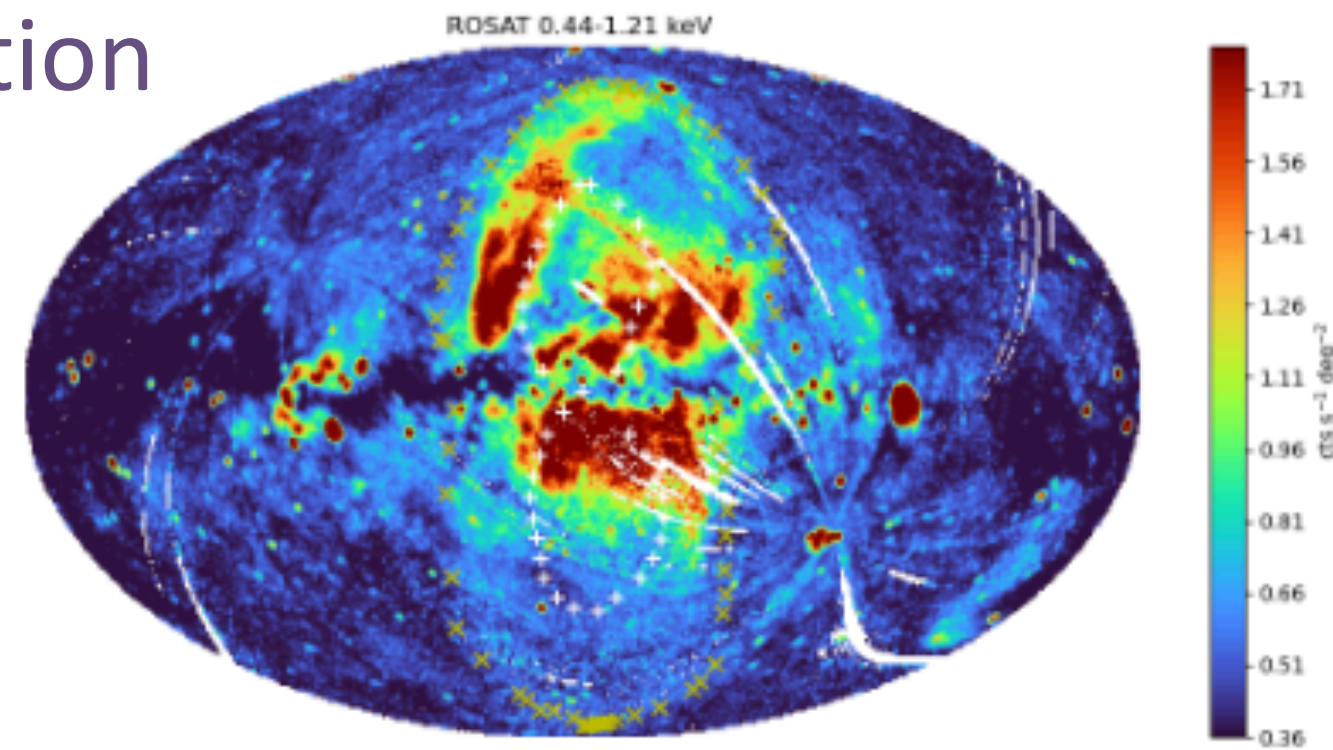
simulation



- Zhang, Guo, et al 2025

# The Double-episode Jet Model of the eROSITA and Fermi Bubbles

observation

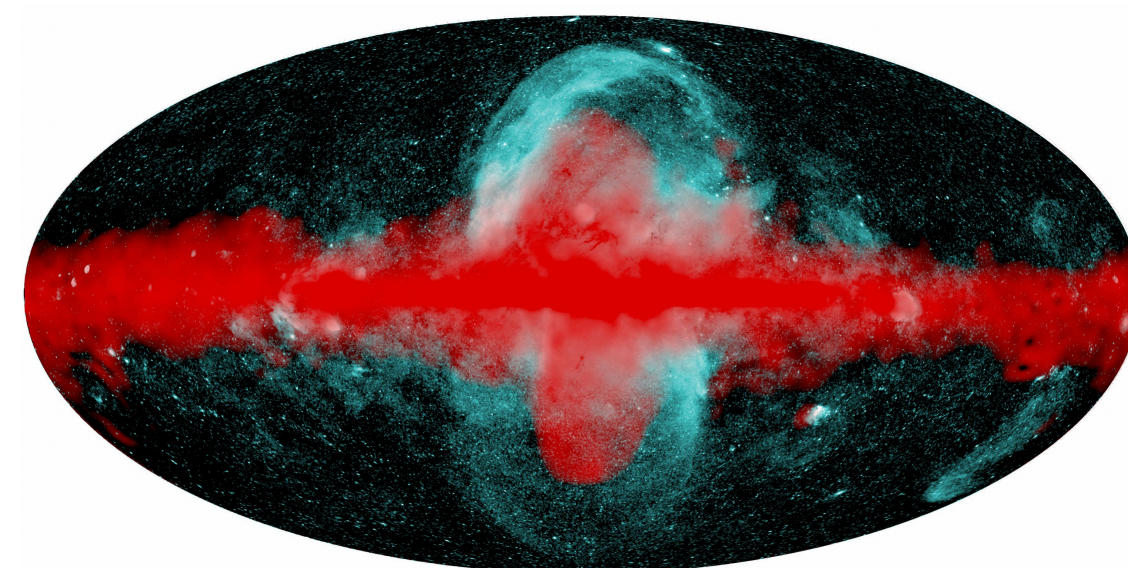
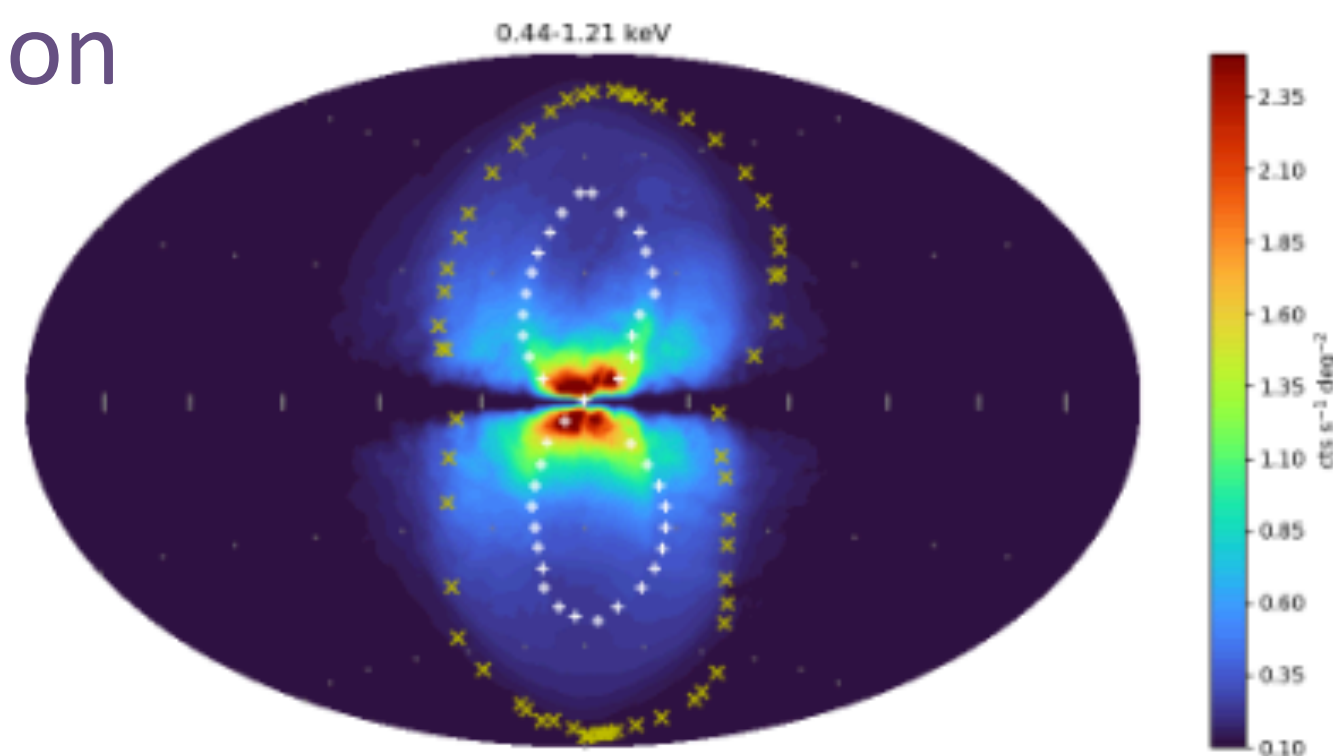


(a)

The left top panel shows the ROSAT map in the 0.44-1.21 keV band the eROSITA bubbles are clearly seen, and the lower part of the Fermi bubbles are also seen

The left lower panel shows our simulated X-ray map in the same X-ray band, agreeing with observations quite well

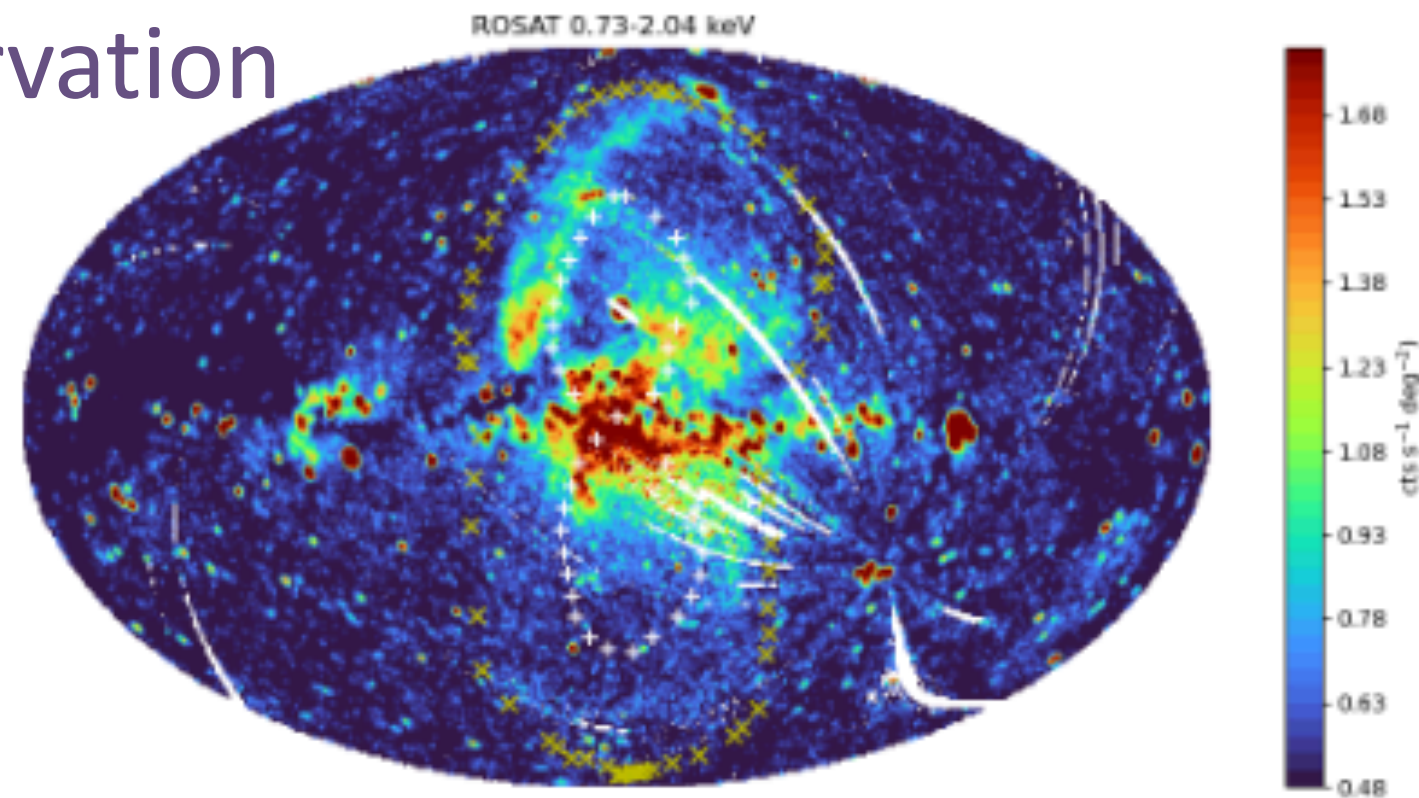
simulation



- Zhang, Guo, et al 2025

# The Double-episode Jet Model of the eROSITA and Fermi Bubbles

observation

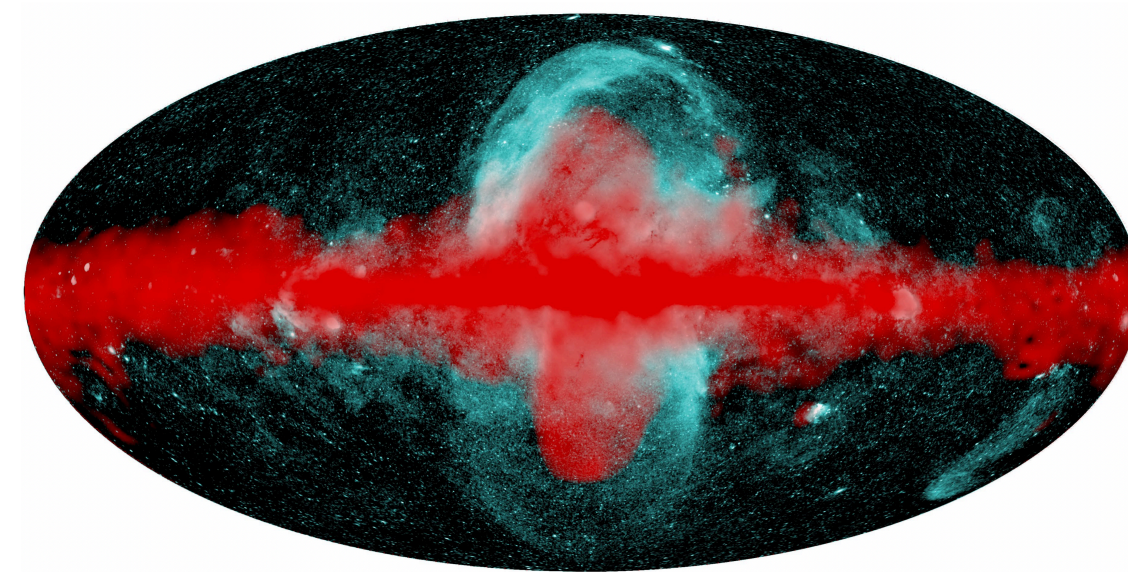
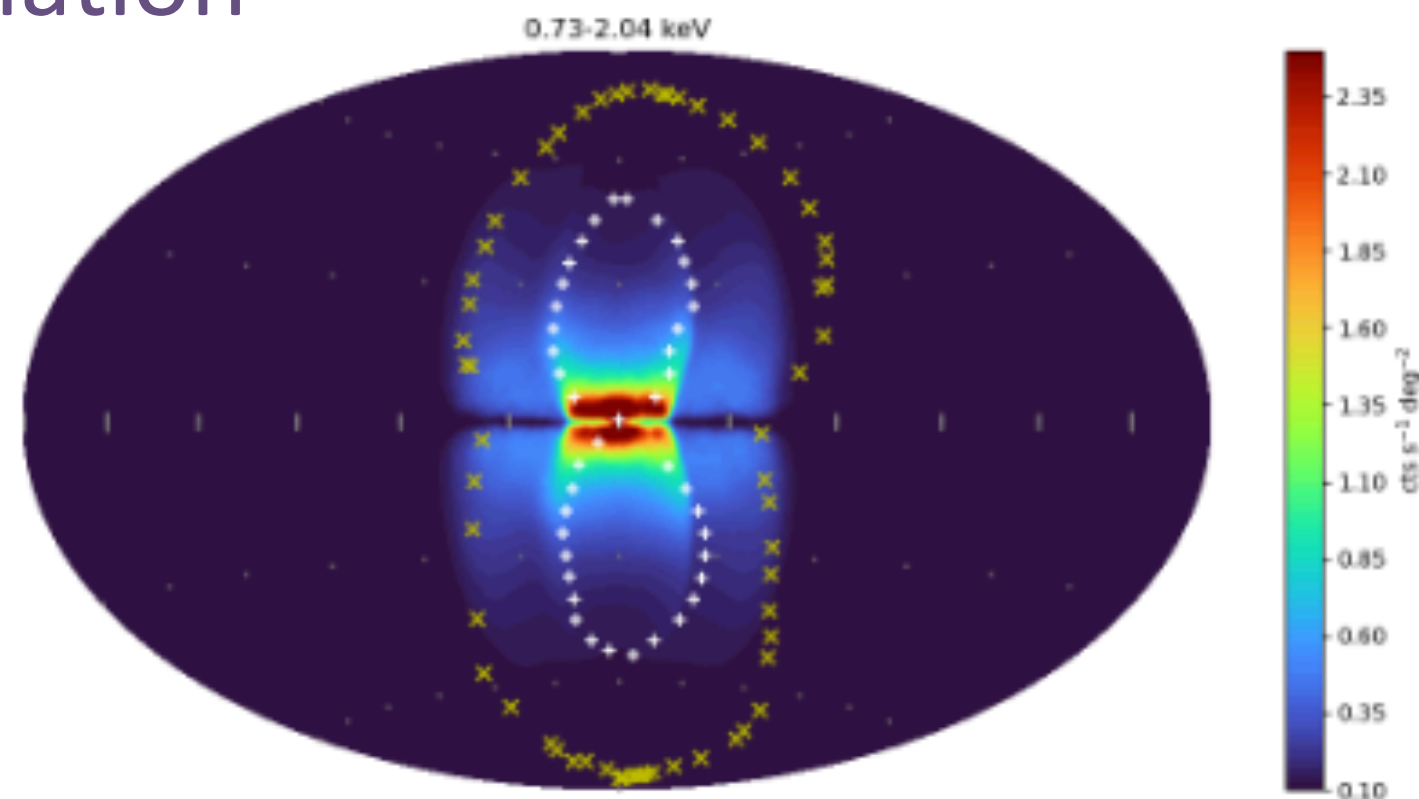


(a)

The left top panel shows the ROSAT map in the 0.73-2.04 keV band the eROSITA bubbles are quite weak due to its relatively low temperature  $\sim 0.25$  keV, and the lower part of the Fermi bubbles are very bright ( $T \sim 0.3-0.4$  keV)

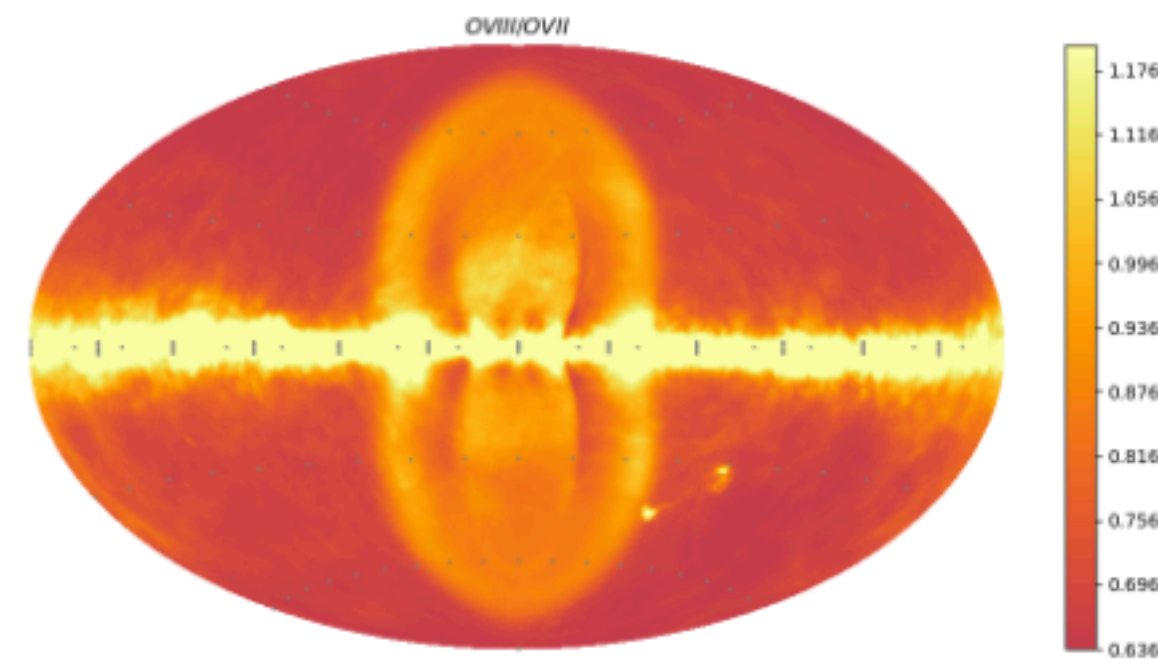
The left lower panel shows our simulated X-ray map in the same X-ray band, agreeing with observations quite well

simulation



- Zhang, Guo, et al 2025

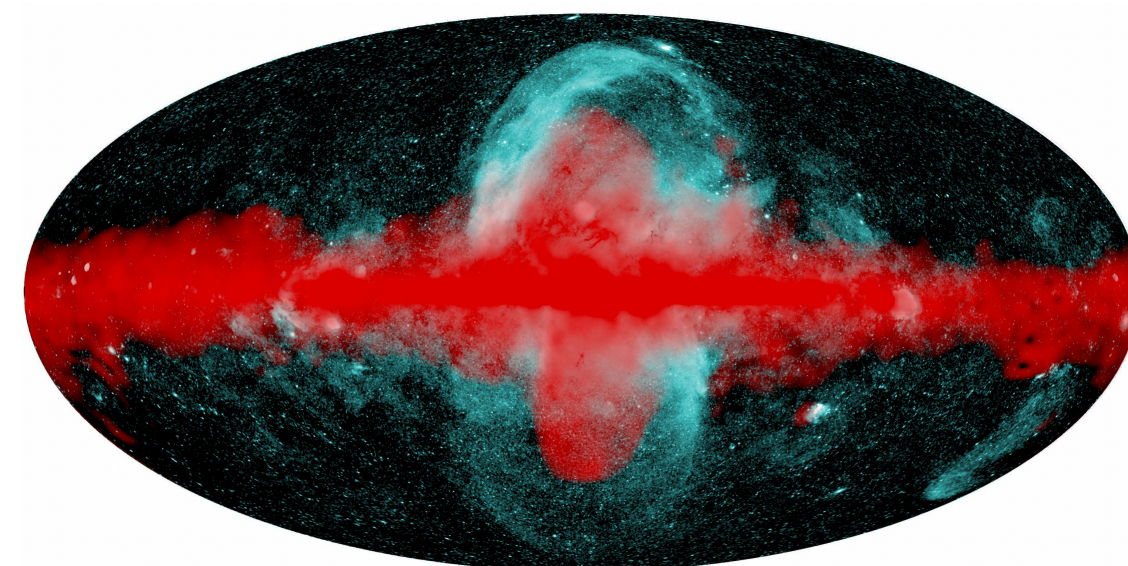
# The Double-episode Jet Model of the eROSITA and Fermi Bubbles



**Fig. 5:** Synthetic O VIII/O VII line intensity ratio map in the Hammer-Aitoff projection, showing temperature variations across the boundary of the eROSITA and Fermi bubbles.

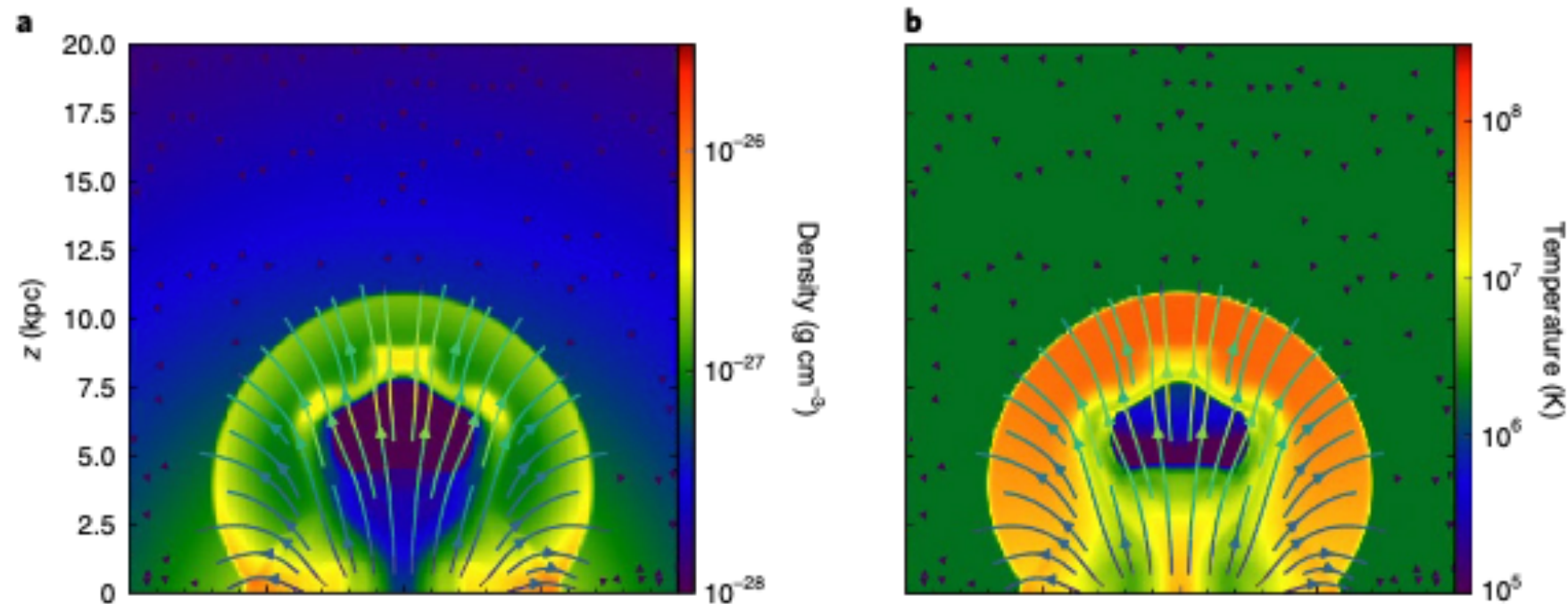
Our simulations reproduce the observed morphology, multi-band X-ray surface brightness distributions (0.11–2.04 keV), and O VIII/O VII line ratios, matching *ROSAT* and *eROSITA* observations.

Our model supports a Galactic-scale origin for these structures and suggest **episodic jet activities at the Galactic center.**

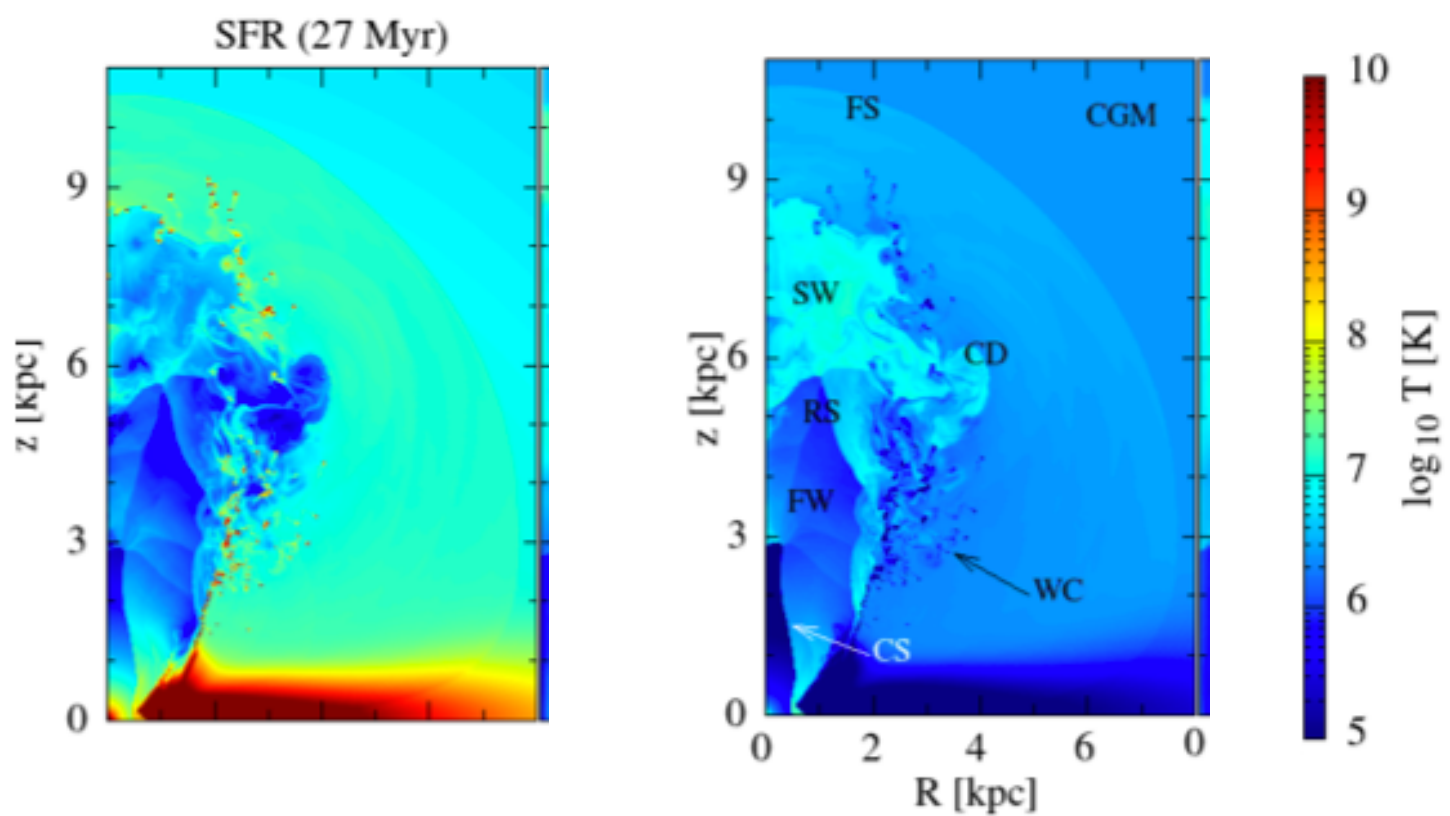


- Zhang, Guo, et al 2025

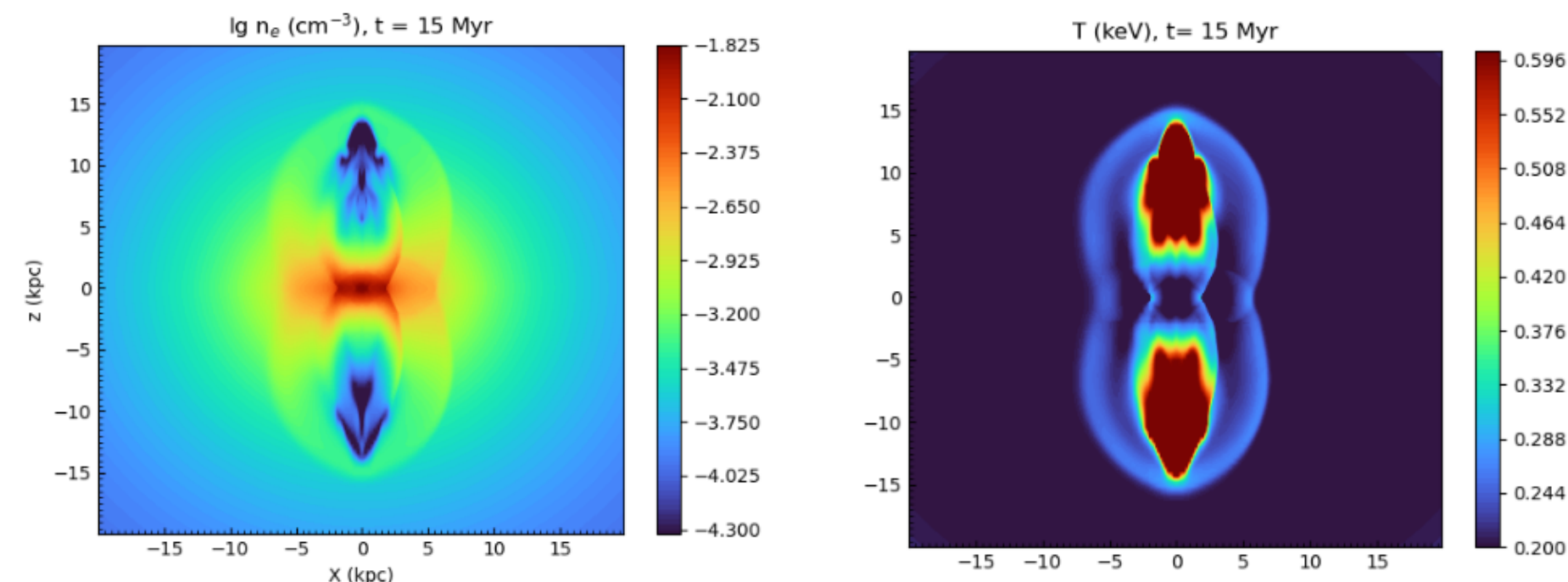
# Models of the eROSITA Bubbles



One AGN jet activity 2.6 Myr ago produces both; Yang+21  
Gas temperature in the bubbles is way too high



One starburst activity produces both; Sarkar 2024  
not easy to explain the smooth Fermi bubble edge, not able to explain the bipolar X-ray emission from the Fermi bubble base



Double-episode jet model, Zhang, Guo, et al 2025

reproduce the observed morphology, multi-band X-ray surface brightness distributions (0.11–2.04 keV), and O VIII/O VII line ratios, matching *ROSAT* and *eROSITA* observations.

# Summary & Outstanding Problems

- The AGN jet-shock model explains the common origin of Fermi bubbles and the central bipolar X-ray outflows
- The double-episode jet model explains the origins of both the eROSITA and Fermi bubbles, suggesting episodic jet activities from the Galactic center.
- How are cosmic rays accelerated in the Fermi bubbles?
- What is (was) the jet direction and the spin direction of Sgr A\*?

