X-ray Observations of the Fermi Bubbles

Kataoka et al. 2013, 2015; Tahara et al. 2015; Inoue et al. 2015; Sofue et al. 2016;
Nakashima et al. 2017 in prep. Akita et al. 2017 in prep.

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Three elephants in the gamma-ray sky @ Garmisch-Partenkirchen, Germany, 2017-10-22

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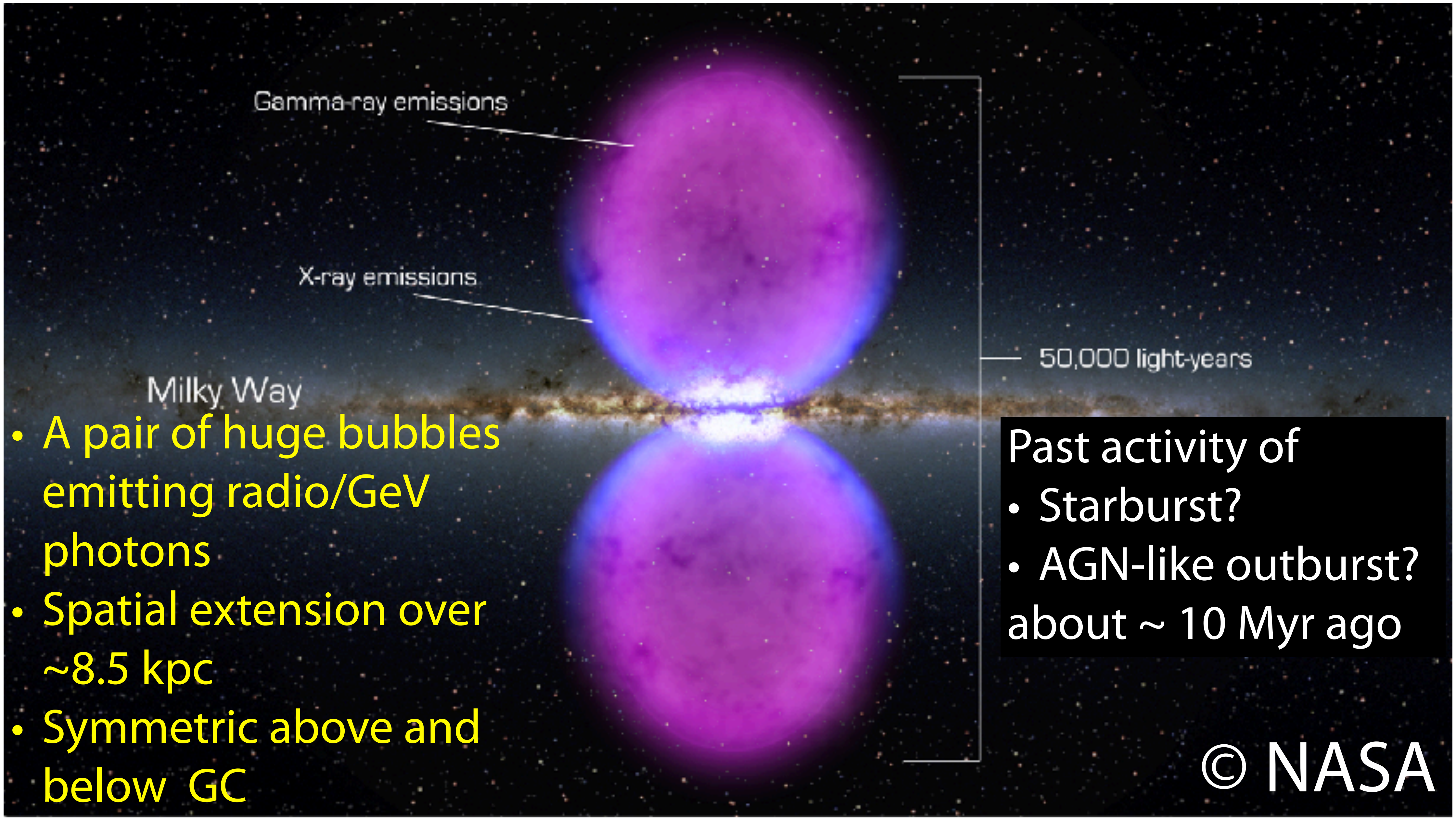
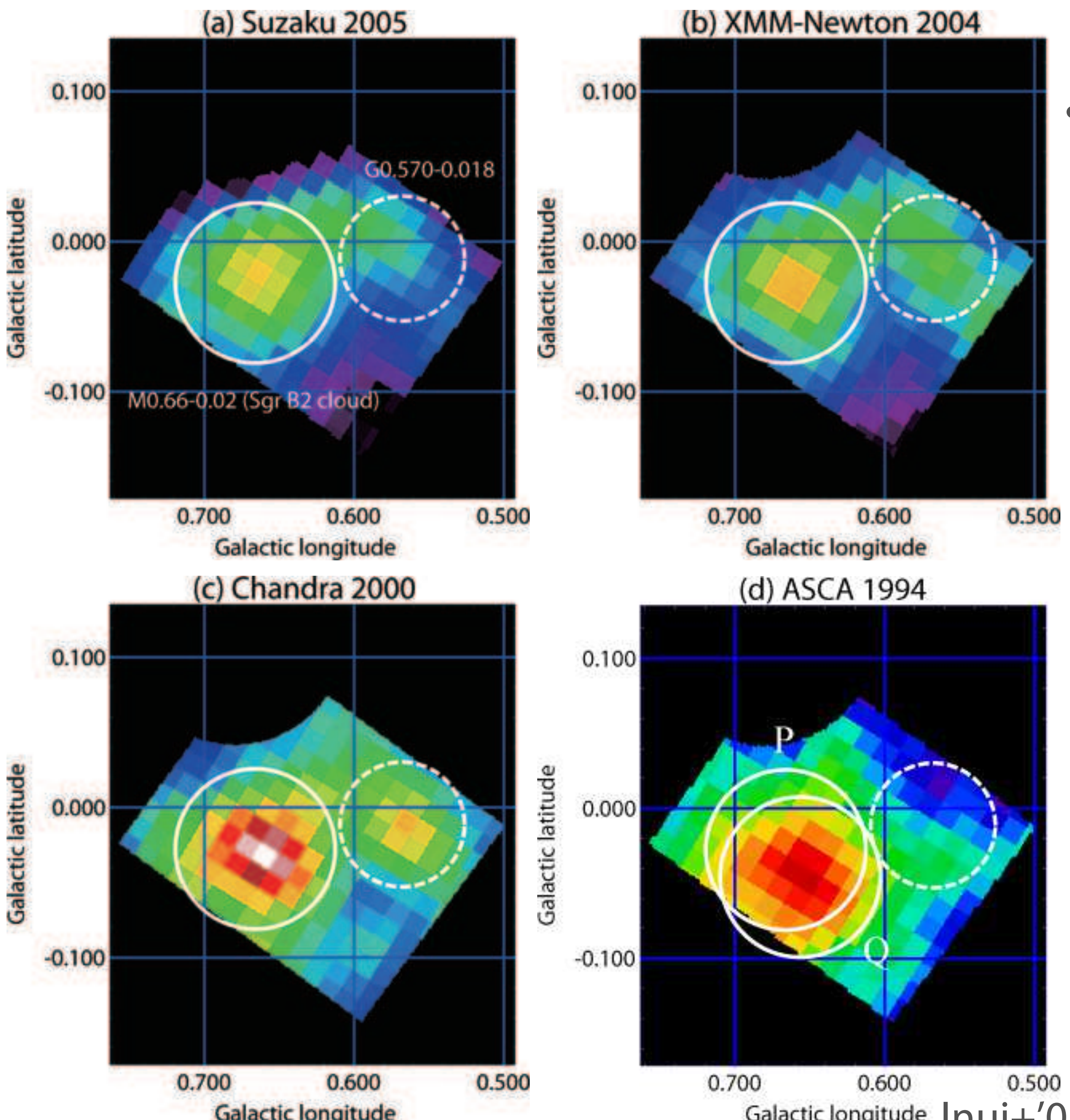
Fermi Bubbles - Past GC activity?



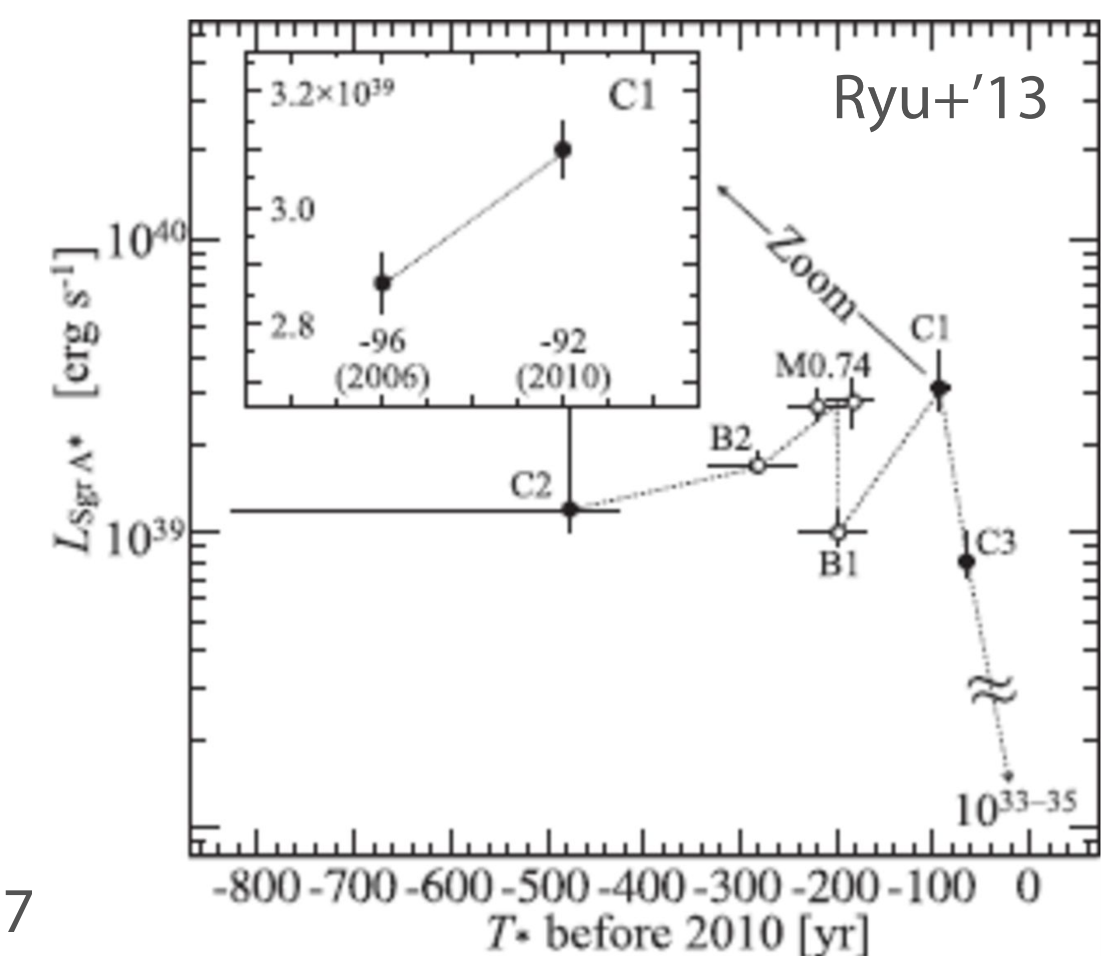
- GC has experienced multiple explosive activities
  - e.g., X-ray reflection nebulae (e.g., Koyama+'96;Inui+'07;Nobukawa+'11, Ryu+'13;Nakashima+'13)

Past Sgr A activity?*



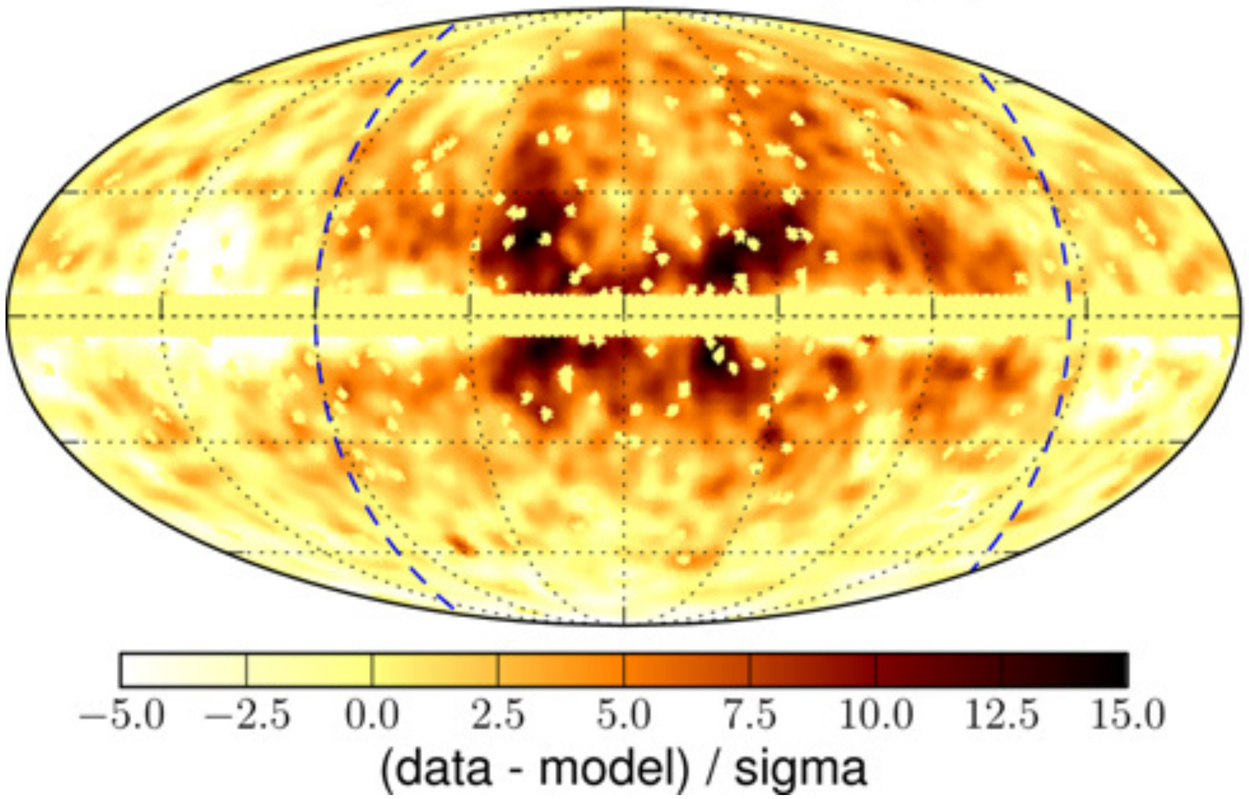
Inui+'07

- X-ray reflection nebulae: higher activity @ ~100~1000 yrs ago
(e.g., Koyama+'96; Inui+'07; Nobukawa+'11, Ryu+'13;Nakashima+'13)

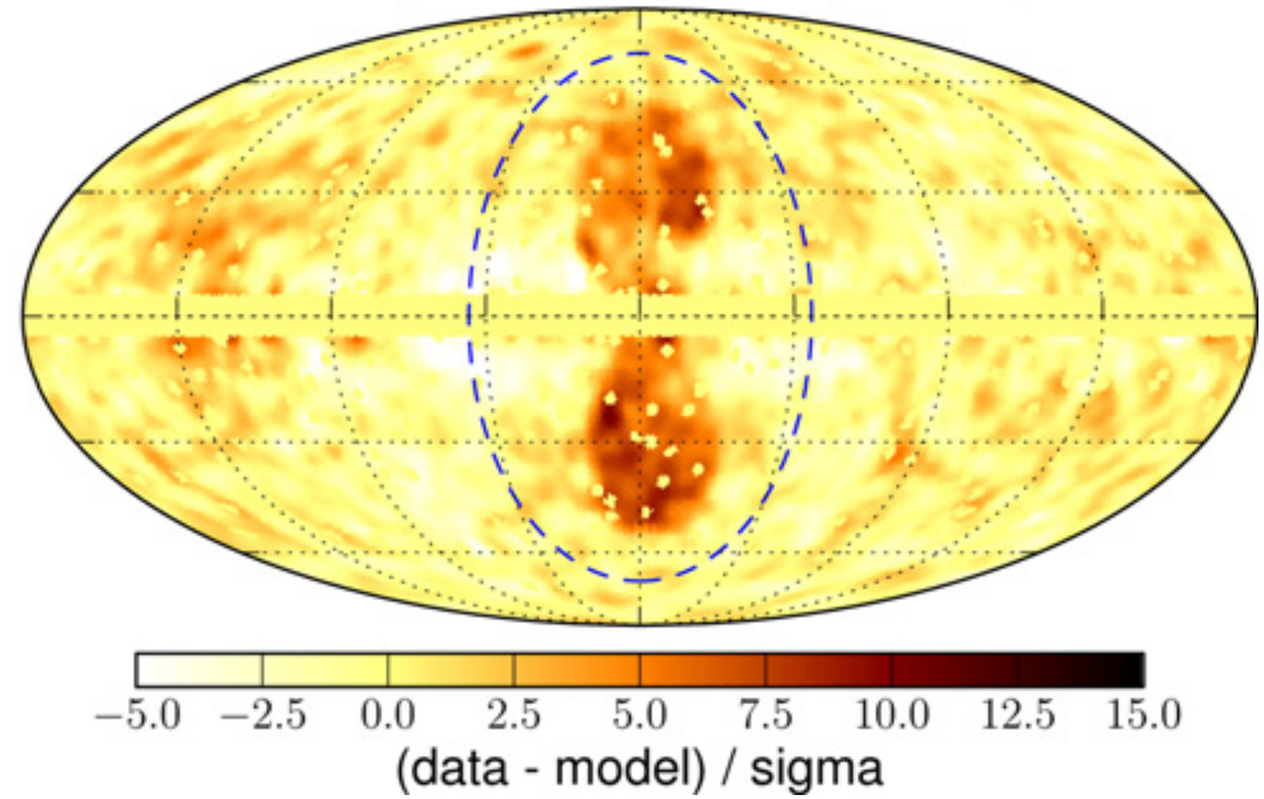


Gamma-ray view - image

Soft residual = Loop-I



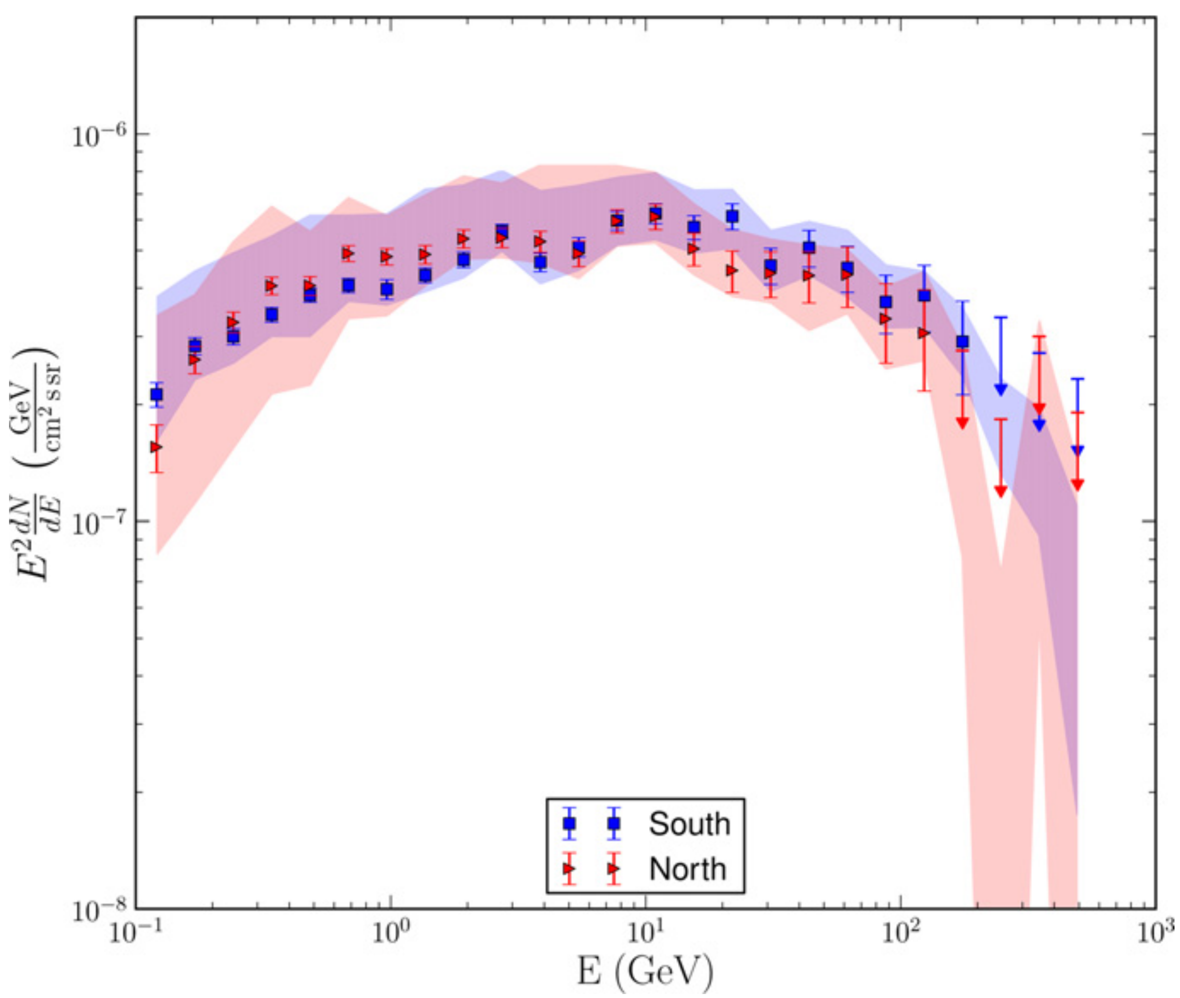
Hard residual = Fermi Bubbles

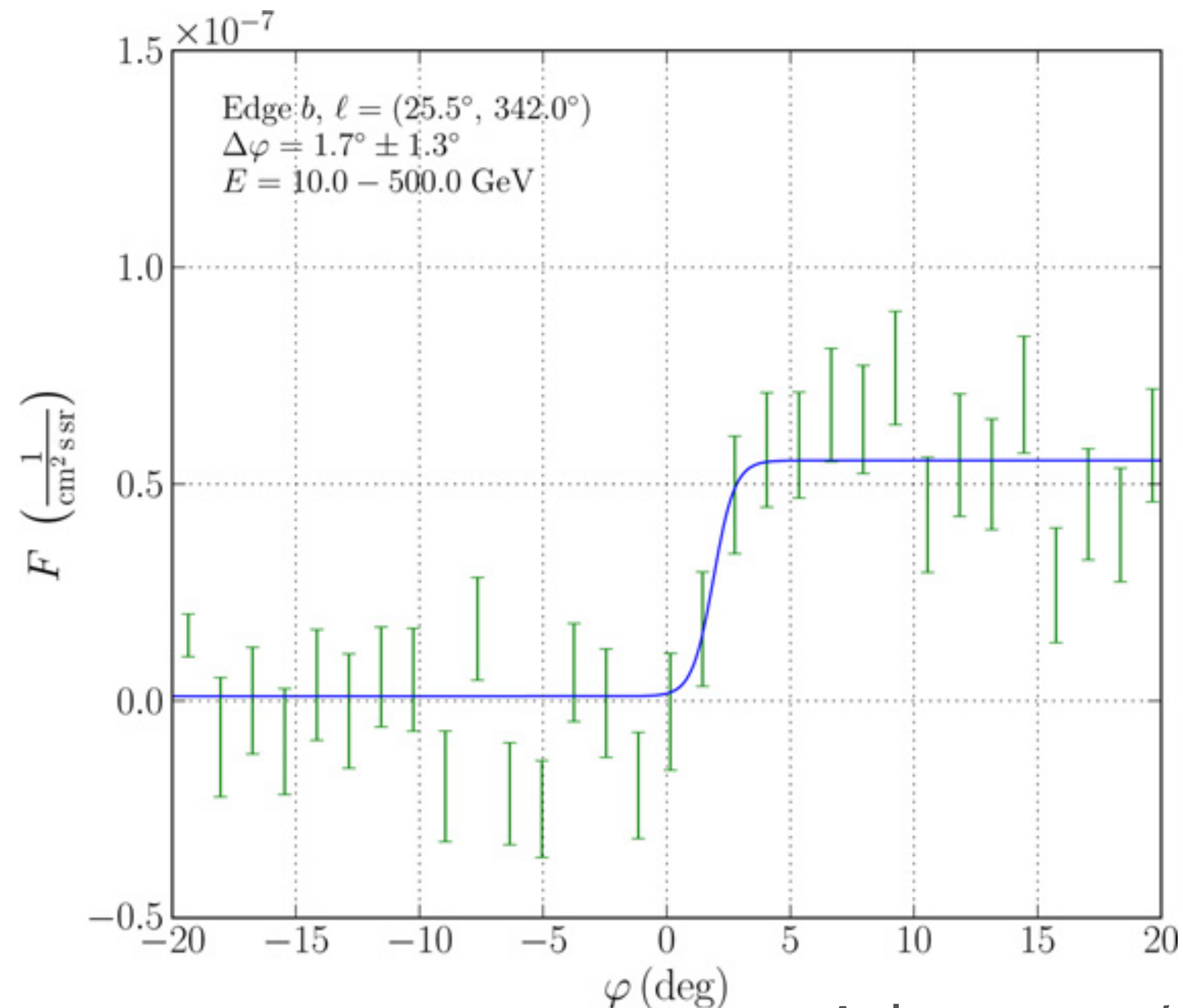


Ackermann+'14

- Fermi bubbles (Su+'10; Dobler+'10; Ackermann+'14)
- Fermi bubbles dominate the residual emission at >1GeV, while Loop I is clearly seen at <1GeV (e.g., Casandijian & Greiner '09).

Gamma-ray view - spectrum & edge

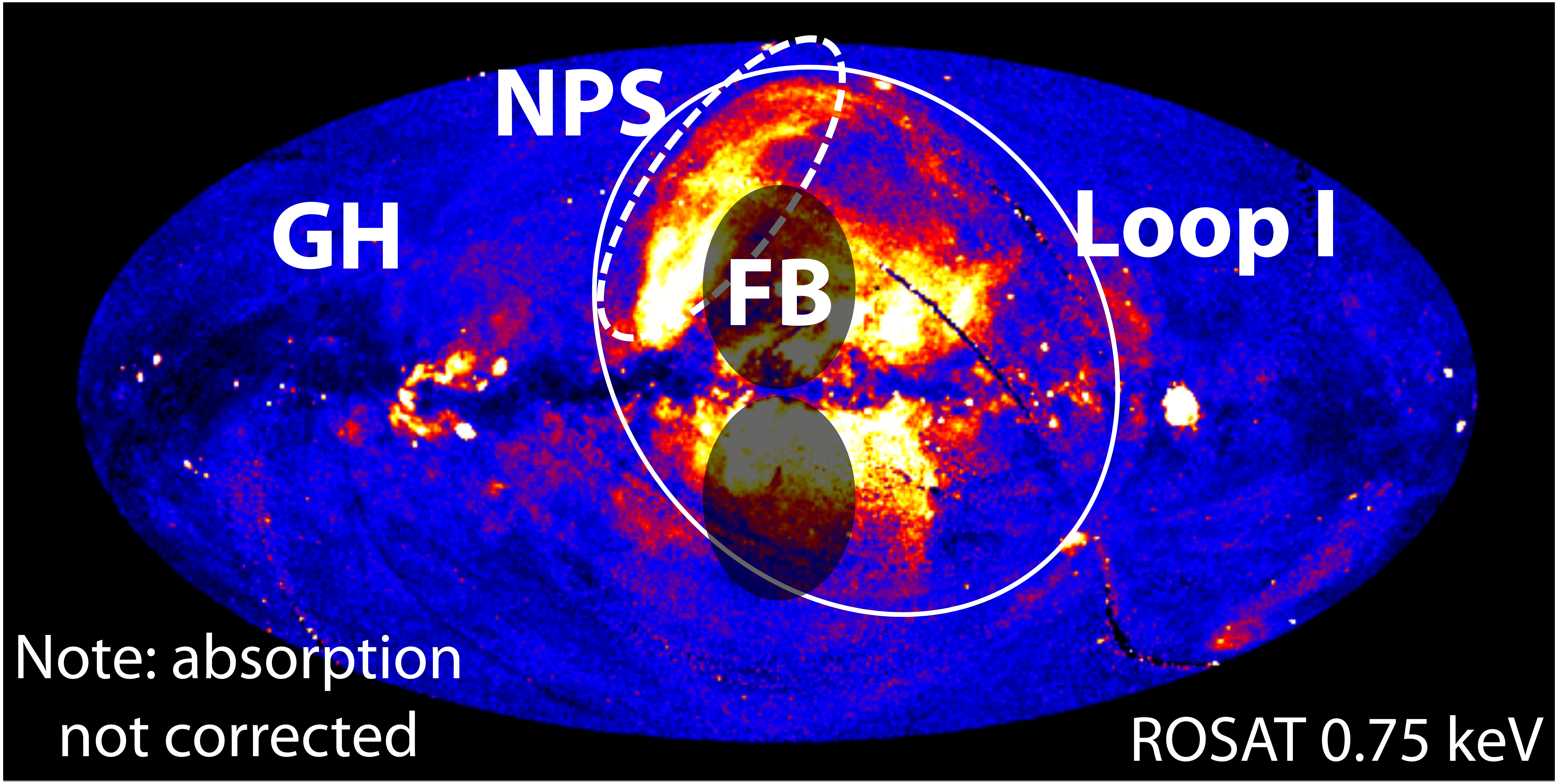




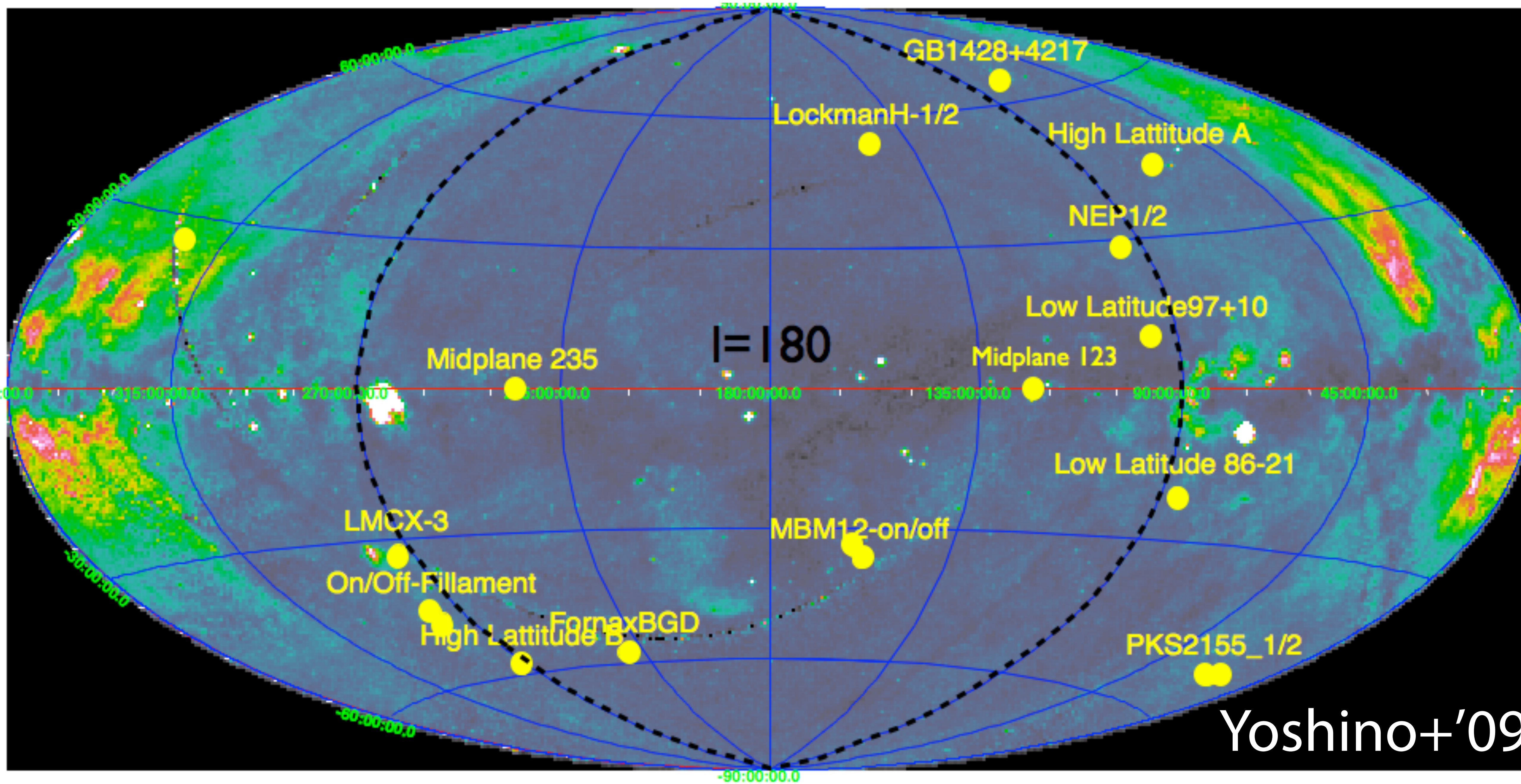
Ackermann+'14

- Hard spectrum (E^{-2}) with a low-E cutoff at ~1 GeV
- Sharp edge - no limb brightening. no central brightening
- Various follow-ups in radio, UV, & ***X-ray***
  - We can ***study the nature of thermal plasmas with X-ray observations.***

X-ray Components in the sky

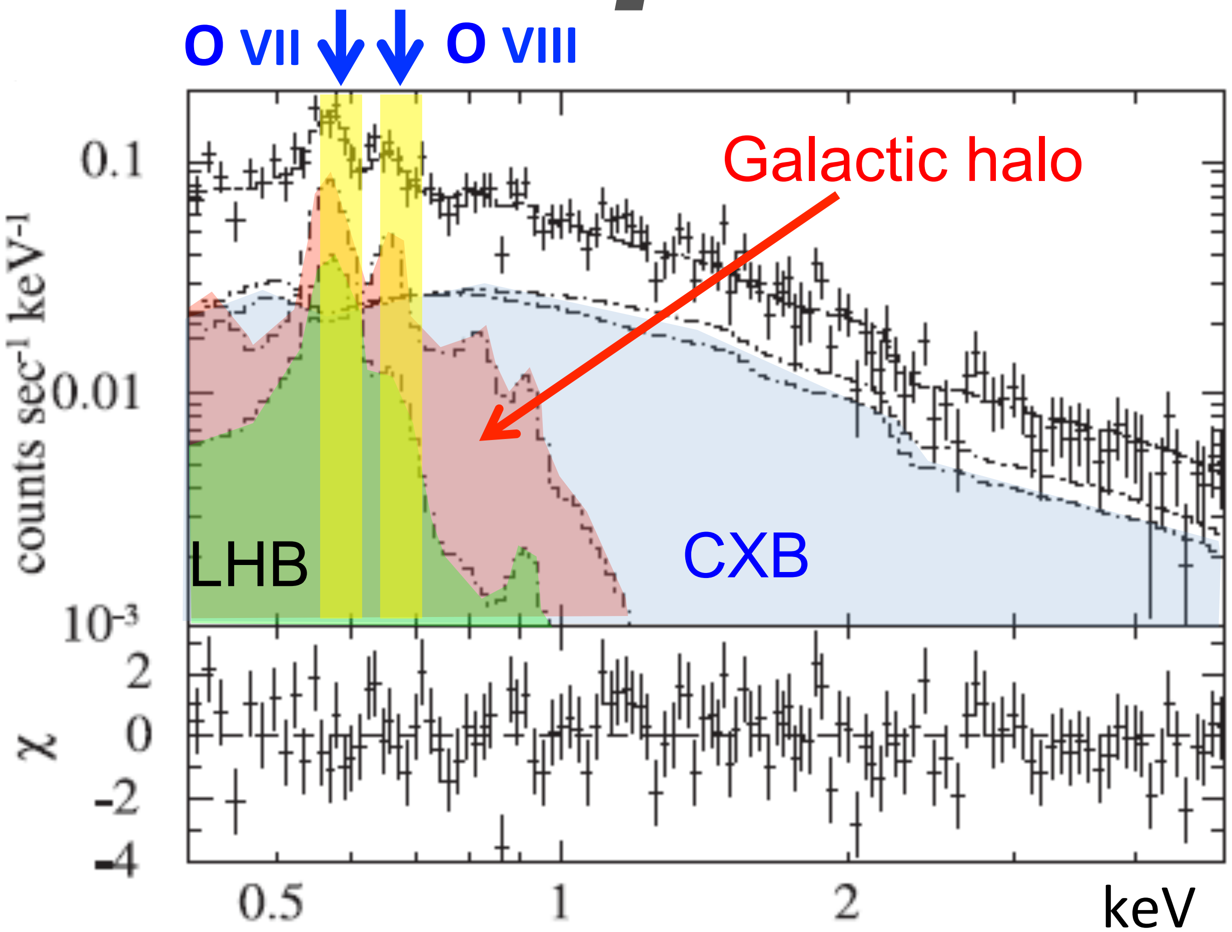


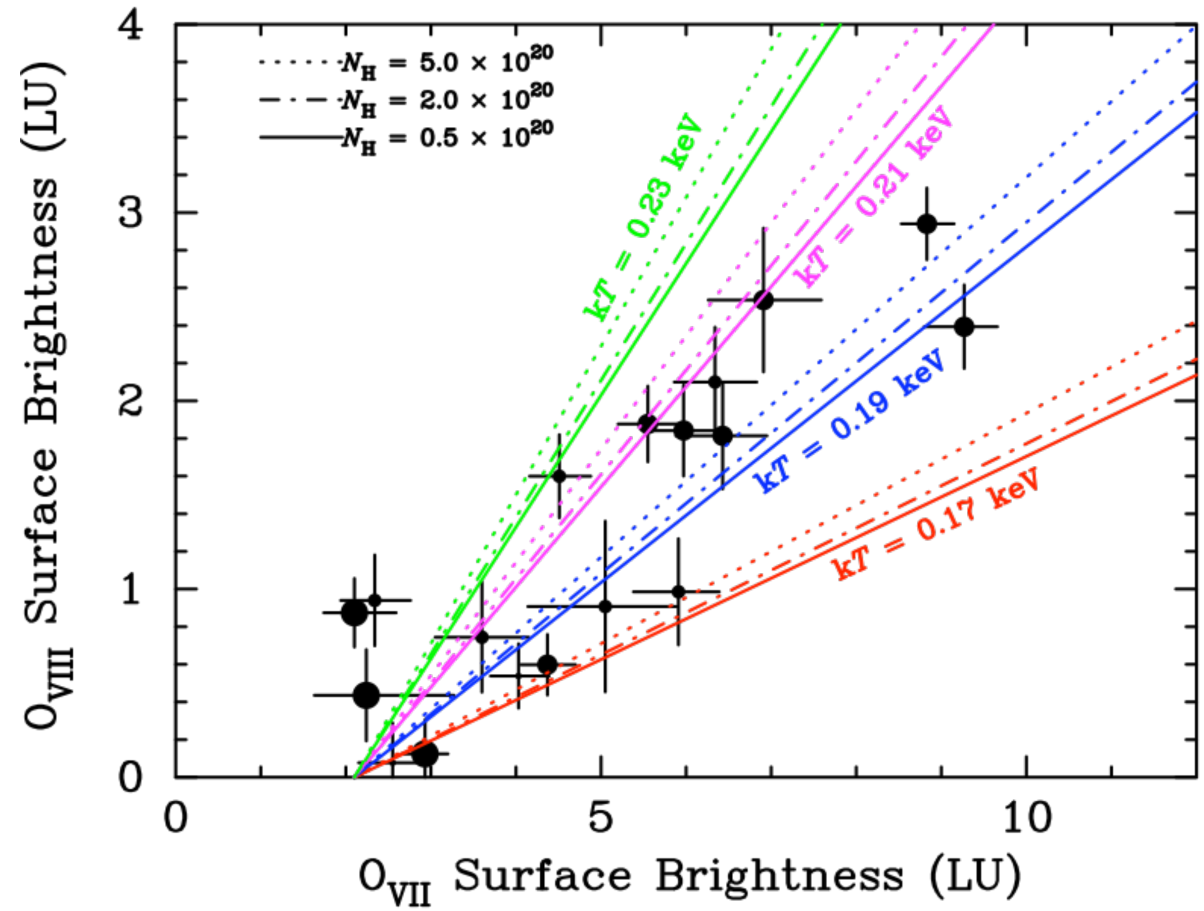
Galactic Halo Gas



- Uniform analysis of the soft diffuse X-ray emission of 12+2 fields observed w/ Suzaku at 65° < l < 295°

GH Temperature: Suzaku views

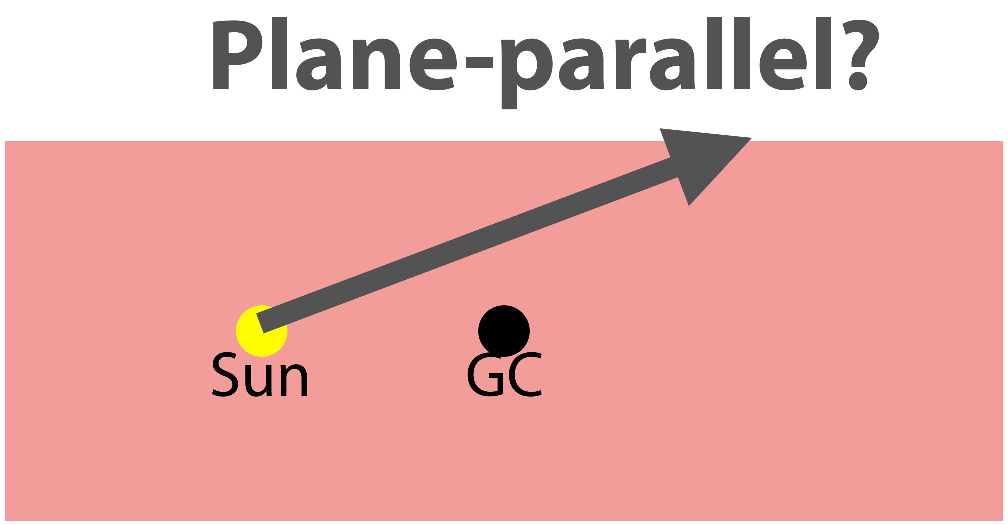


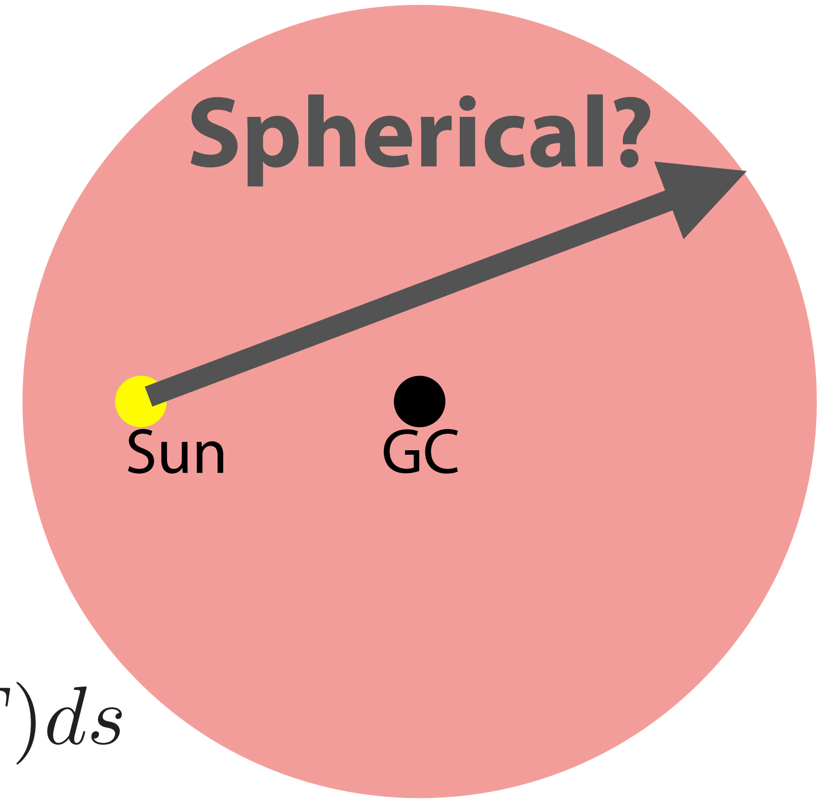


Yoshino+'09

- Spectra of all the fields are well represented by
  - ~0.1 keV w/o Galactic absorption: Local hot bubbles & Solar wind charge exchange
  - **~0.2 keV** w/ Galactic absorption: **Galactic Halo**
  - Power law Γ=1.4 : CXB
- Universal ~0.2 keV component is also confirmed by ~1000 XMM observations (Henley+'13; Miller & Bregman '16)

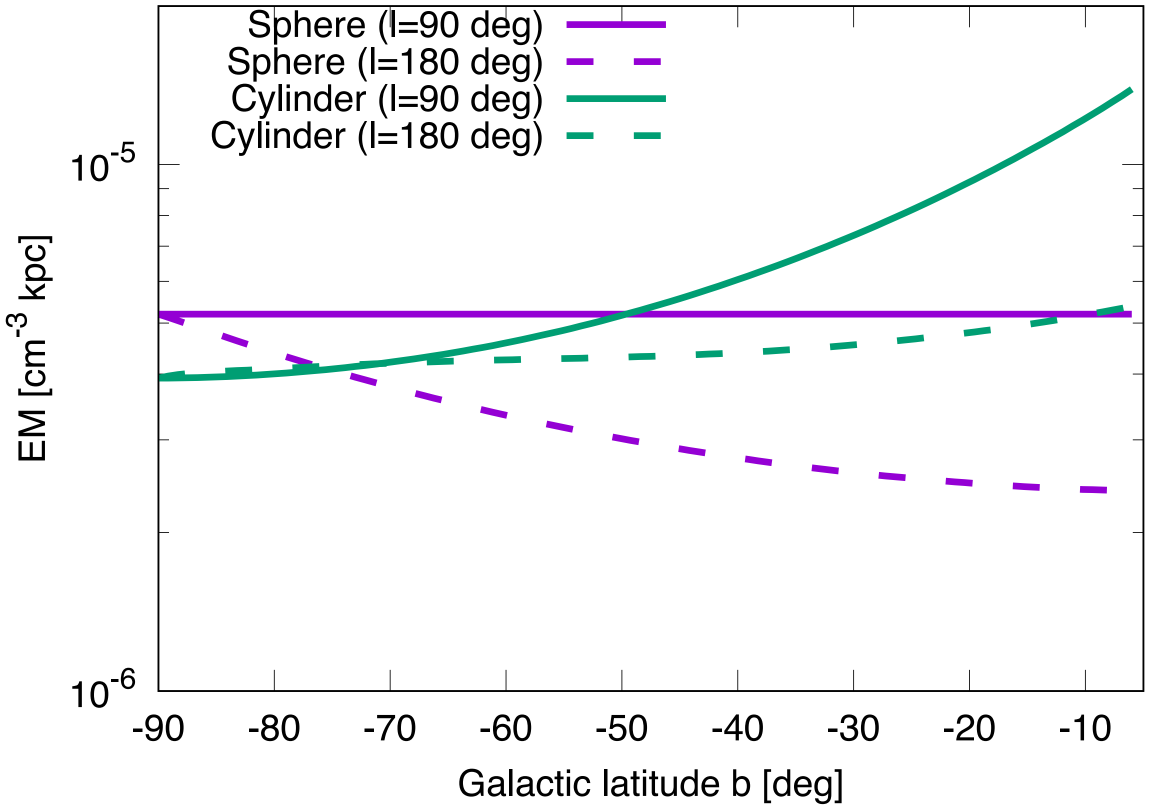
GH Spatial Distribution?





- Surface brightness $\propto \int n_e n_{\rm ion} \Lambda(T) ds$
- Absorption depth $\propto \int n_{\rm ion} \sigma ds$
  - n_{ion} ds = n_H Z ds : Size & Metallicity are degenerated.
- Spherical: ~100 kpc & 0.2 Z_{sun} (e.g. Miller & Bregman '16) ?
- Plane-parallel: ~10 kpc & Z_{sun} (e.g. Yao+'09; Sakai+'14) ?

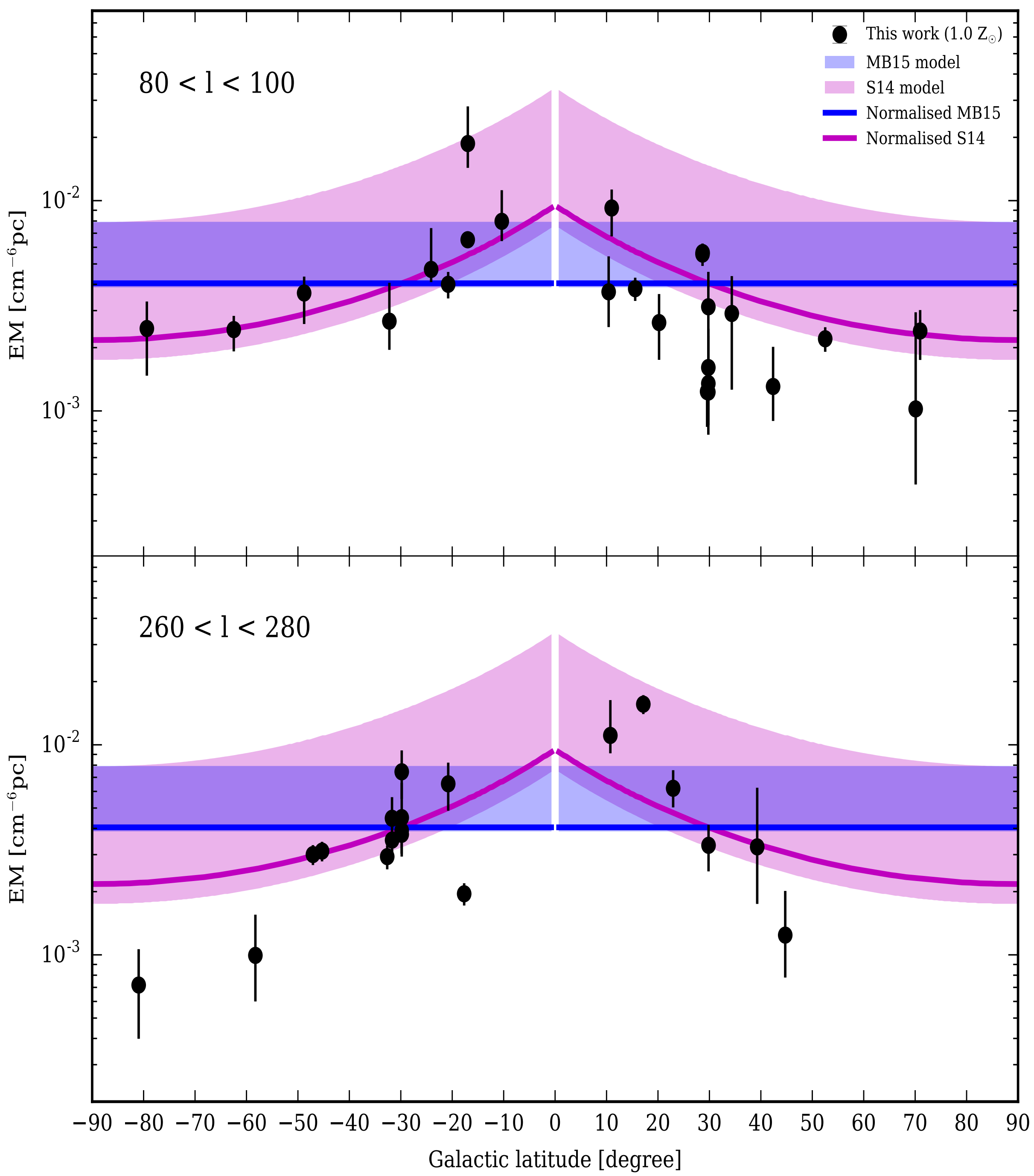
Emission Measure Distribution



- EM spatial distribution depends on the GH gas morphology.

Nakashima, YI, + in prep.

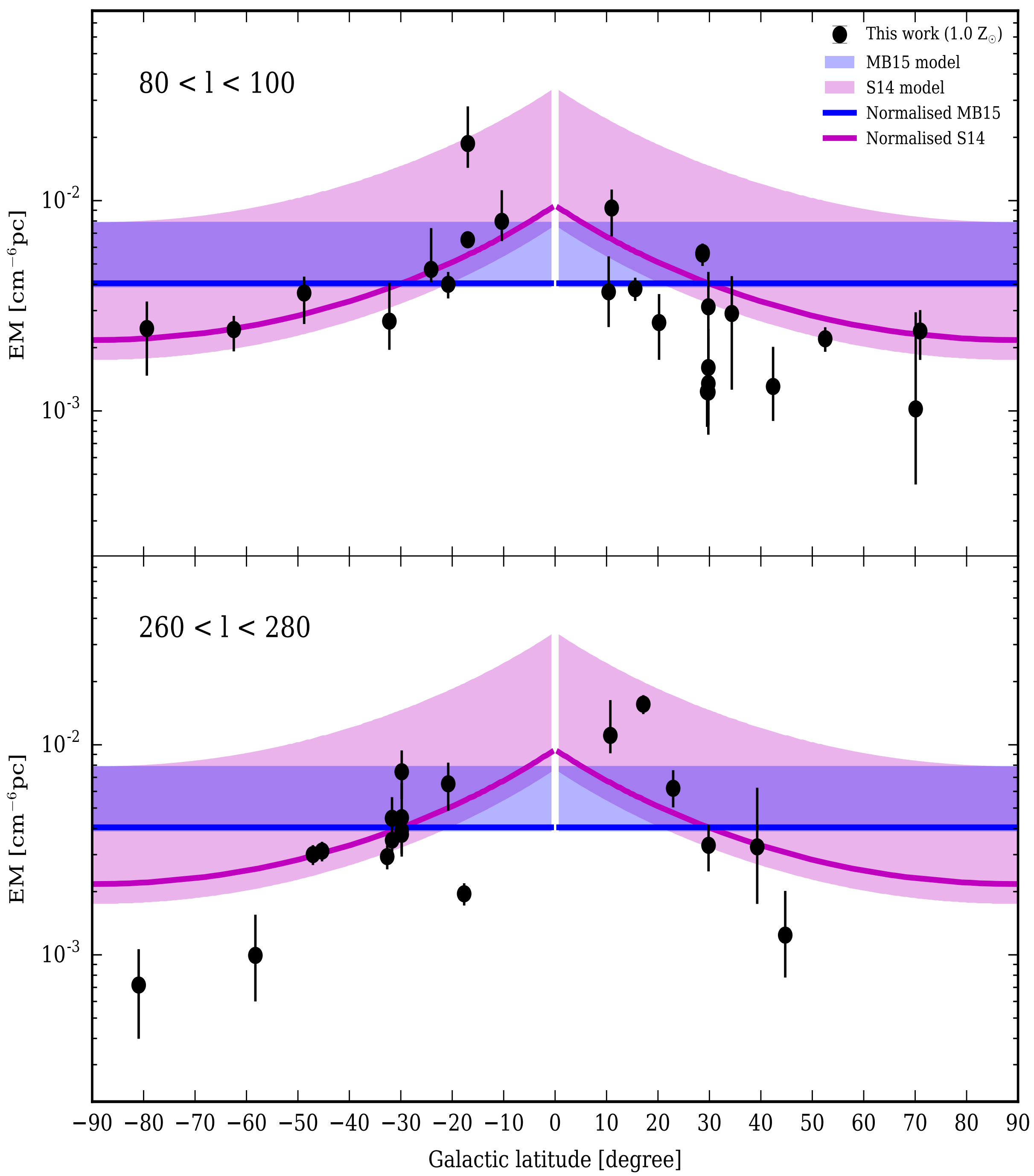
Emission Measure Distribution



Nakashima, YI, + in prep.

- EM spatial distribution depends on the GH gas morphology.

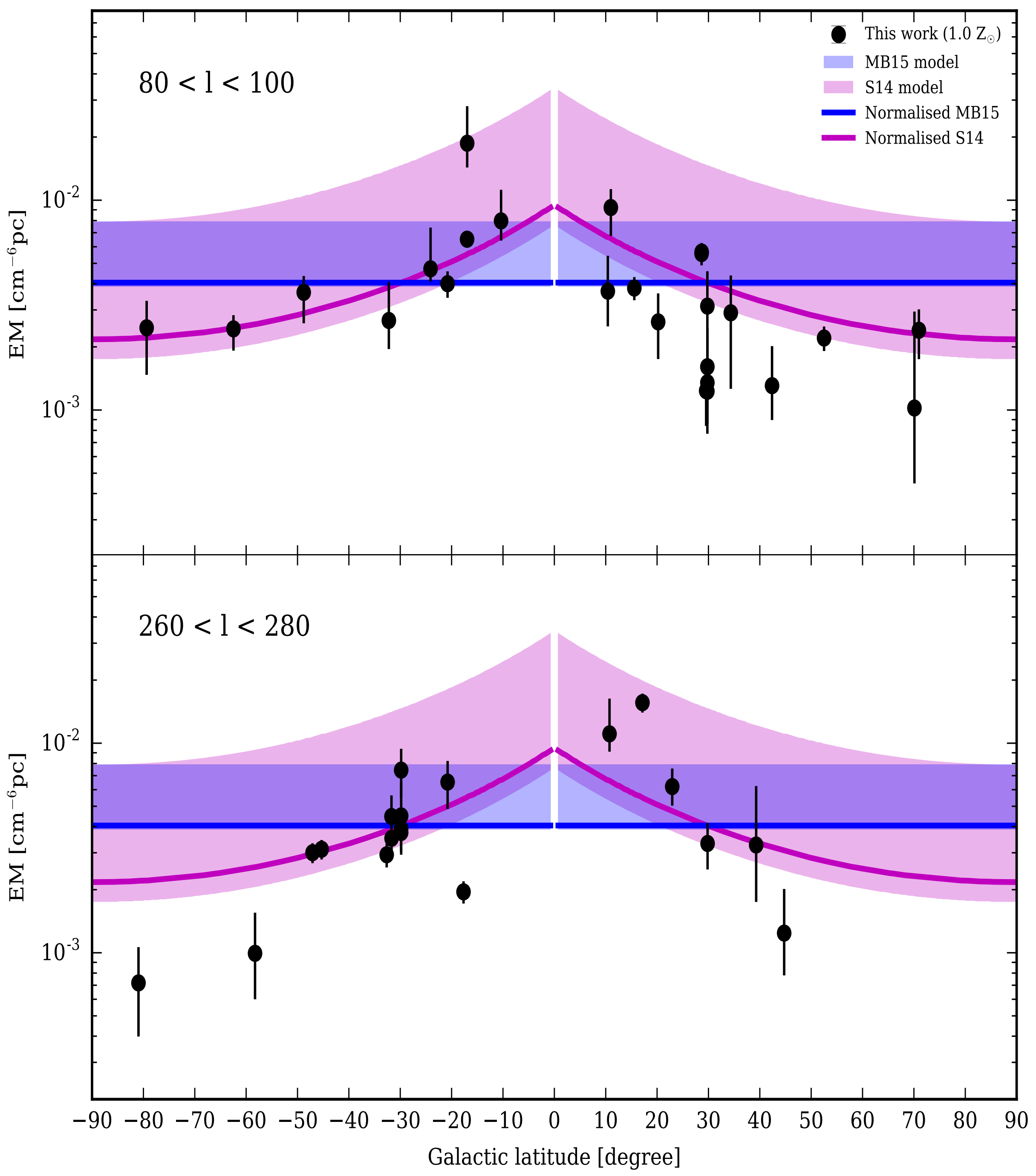
Emission Measure Distribution



Nakashima, YI, + in prep.

- EM spatial distribution depends on the GH gas morphology.
- EMs decreases with Galactic latitudes.

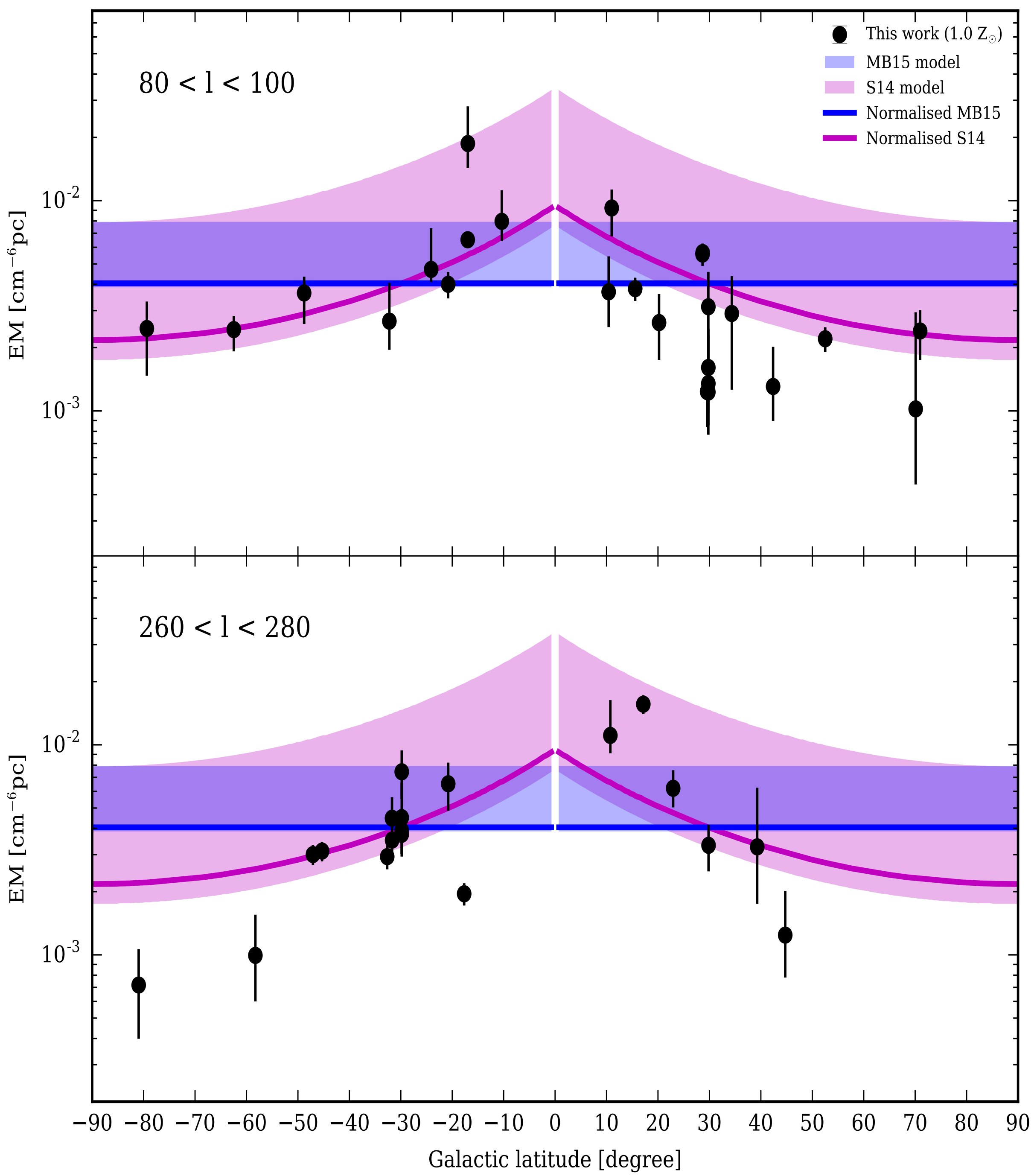
Emission Measure Distribution



Nakashima, YI, + in prep.

- EM spatial distribution depends on the GH gas morphology.
- EMs decreases with Galactic latitudes.
    - Disk-like morphology is preferred.

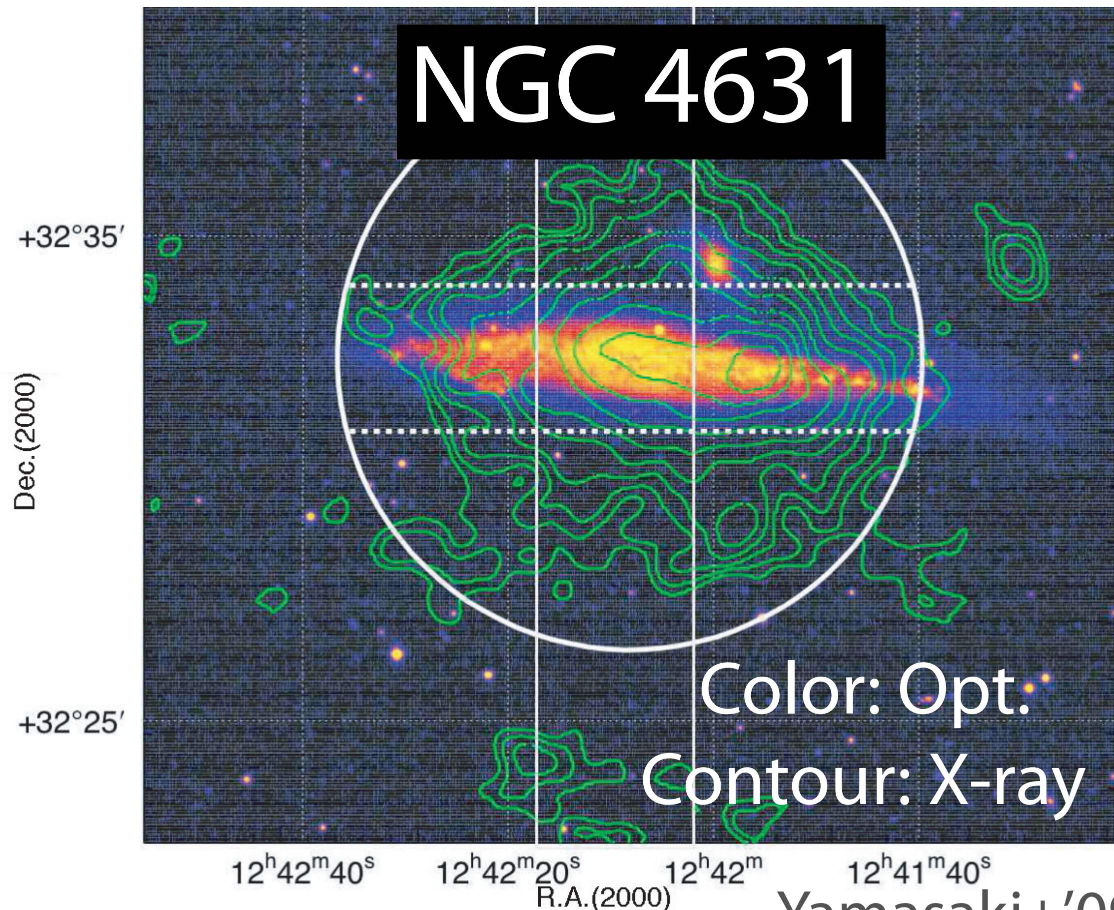
Emission Measure Distribution



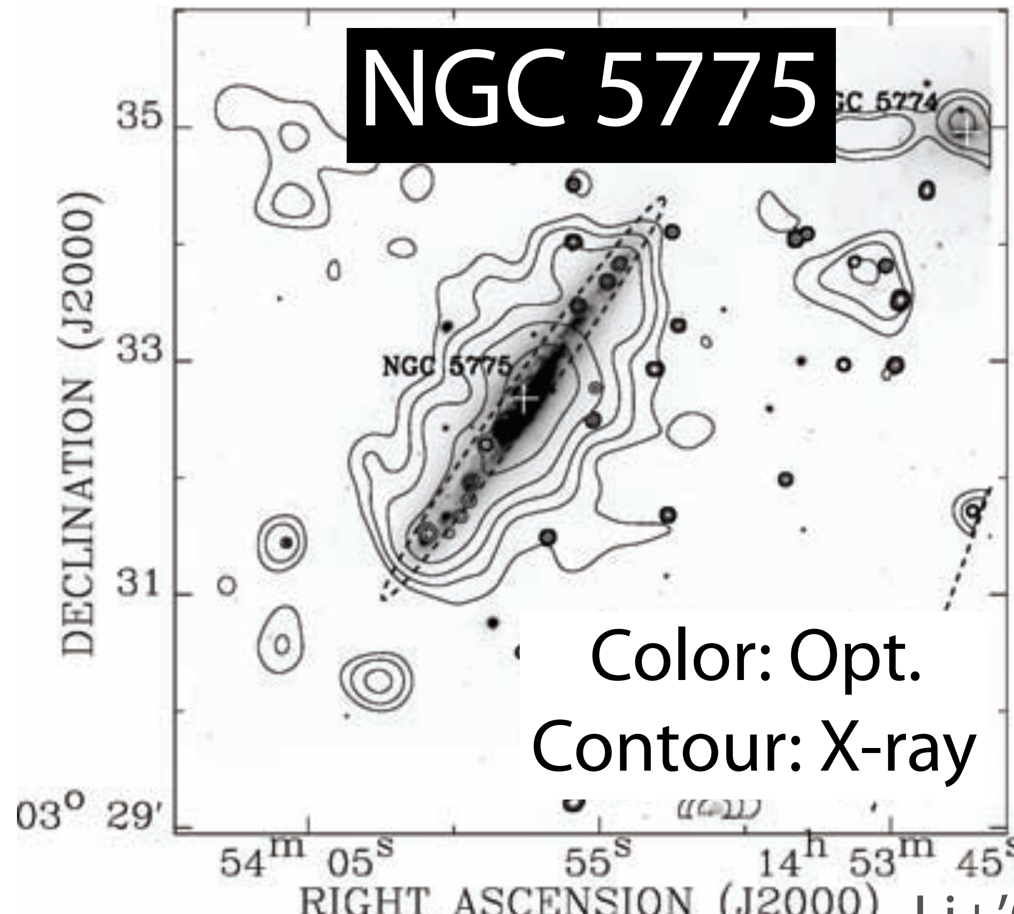
Nakashima, YI, + in prep.

- EM spatial distribution depends on the GH gas morphology.
- EMs decreases with Galactic latitudes.
  - Disk-like morphology is preferred.
    - formed by a fountain of hot ISM gas by SNe in disk?

External Spiral Galaxies



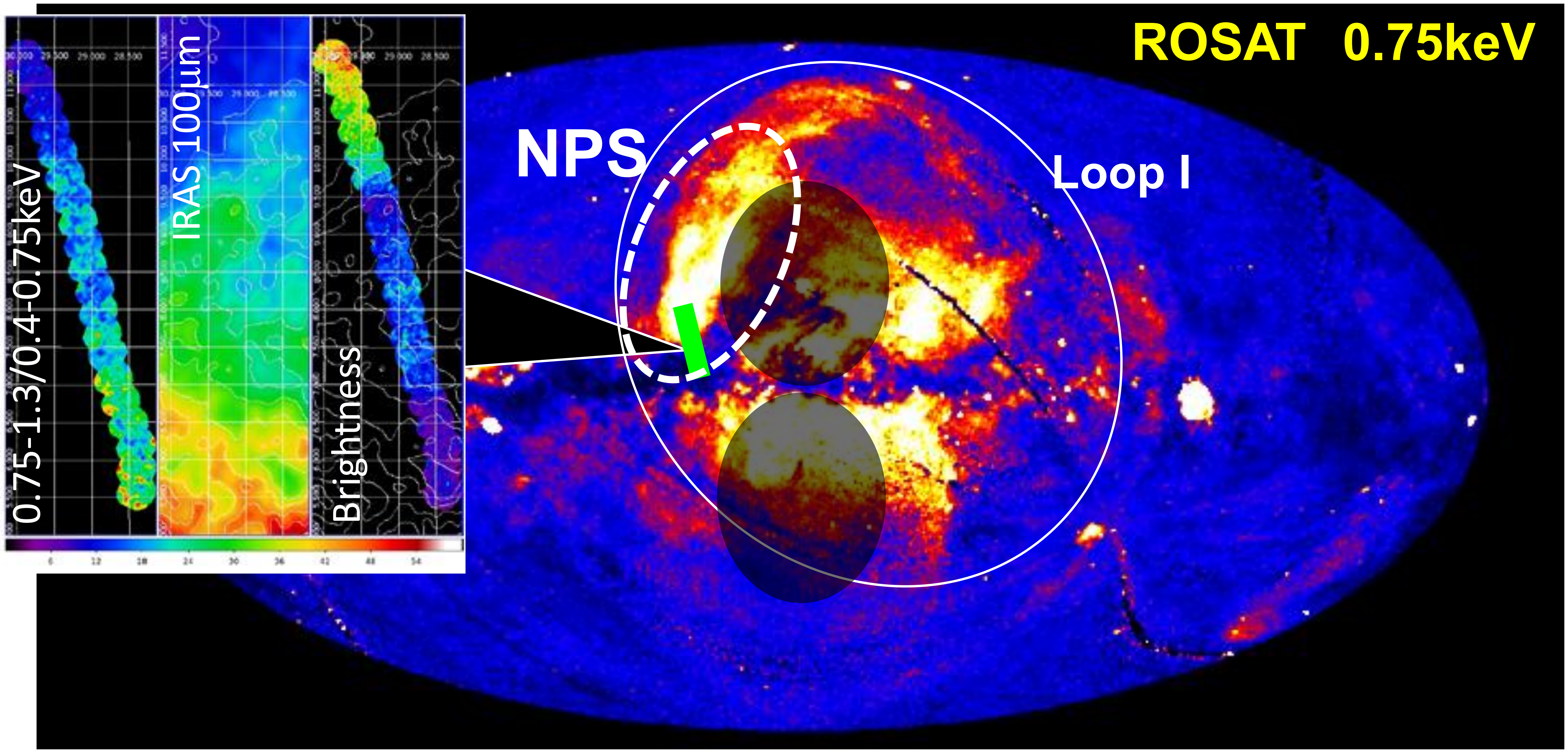
Yamasaki+'09



Li+'08

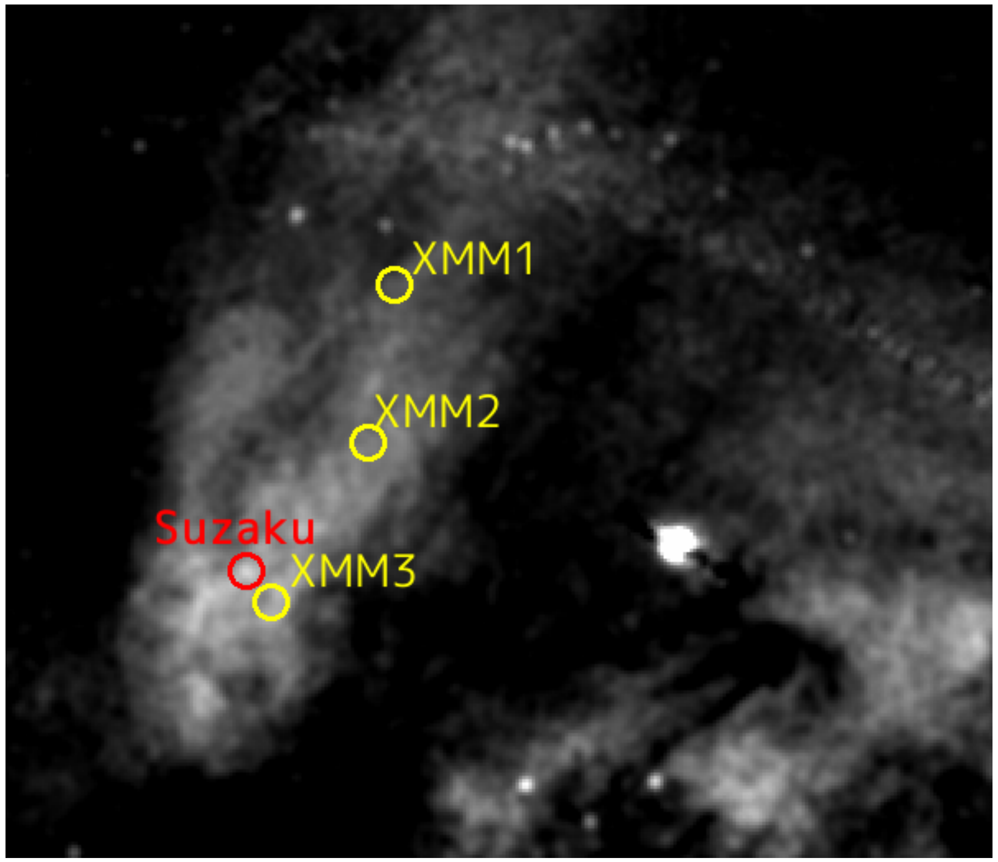
- plane-parallel X-ray halo
- up to ~10 kpc
  - Temperature: ~ 0.1-0.6 keV (e.g. Li+'08; Yamasaki+'09)

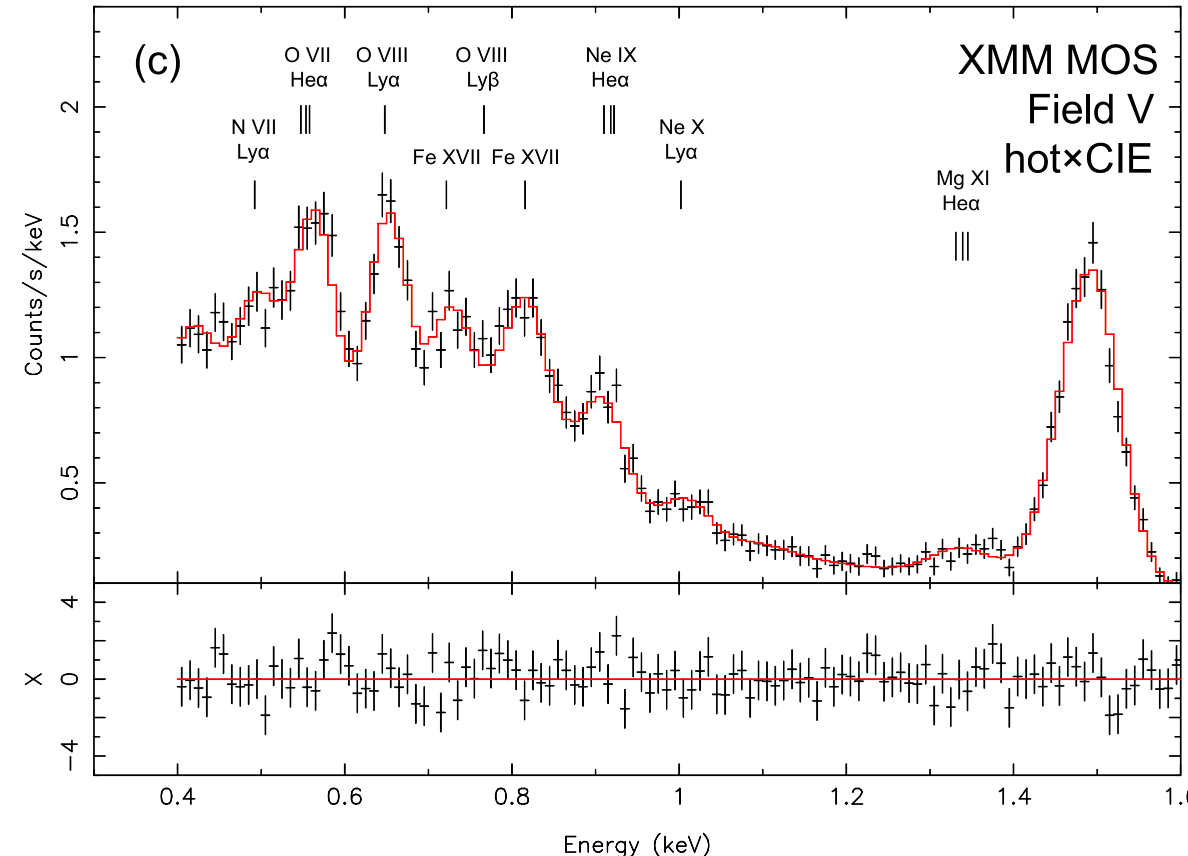
NPS: near? far?



- Study of X-ray absorbing column towards the NPS suggests the lower limit to the distance from 0.4 to 4 kpc (Sofue '15; Lallement+'17)
  - rule out local origin (i.e. Sco-Cen association)
- Shadow X-ray observations toward MBM36 also supports this (Ursino+'16)

NPS in X-ray

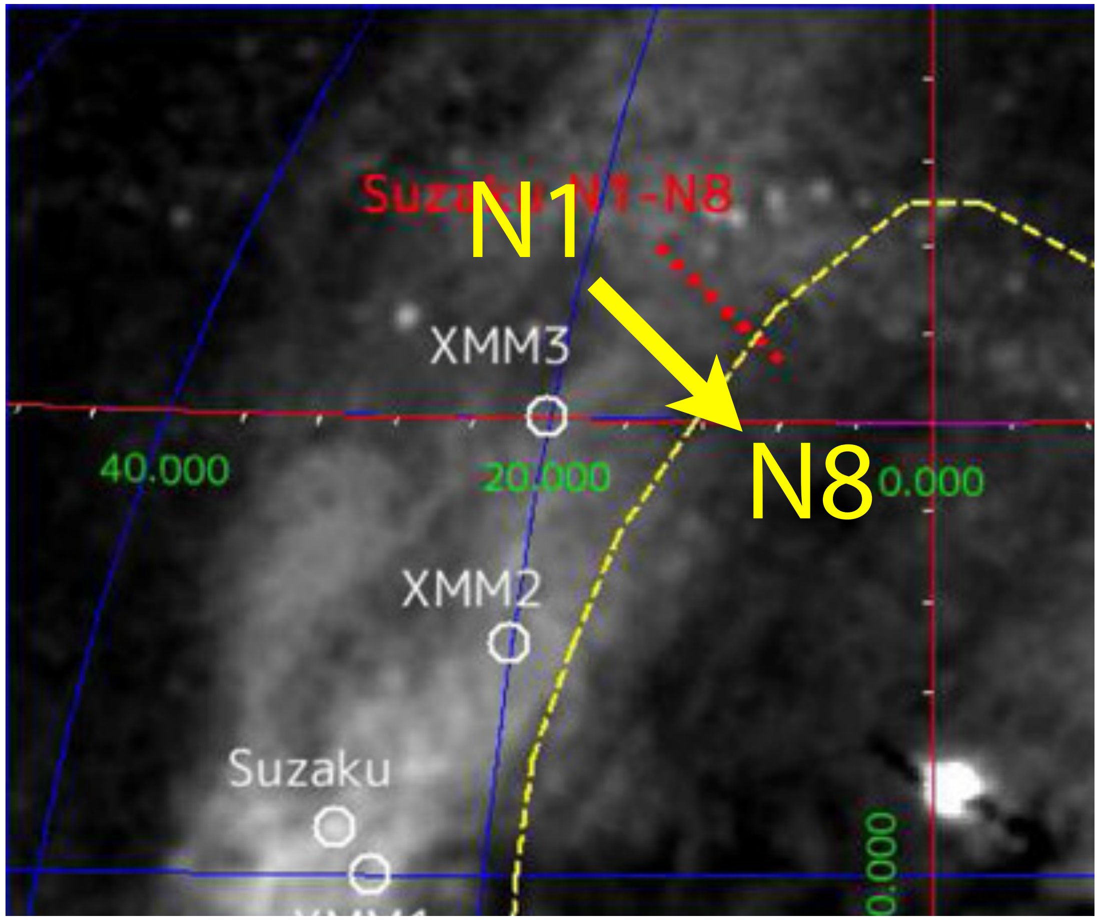


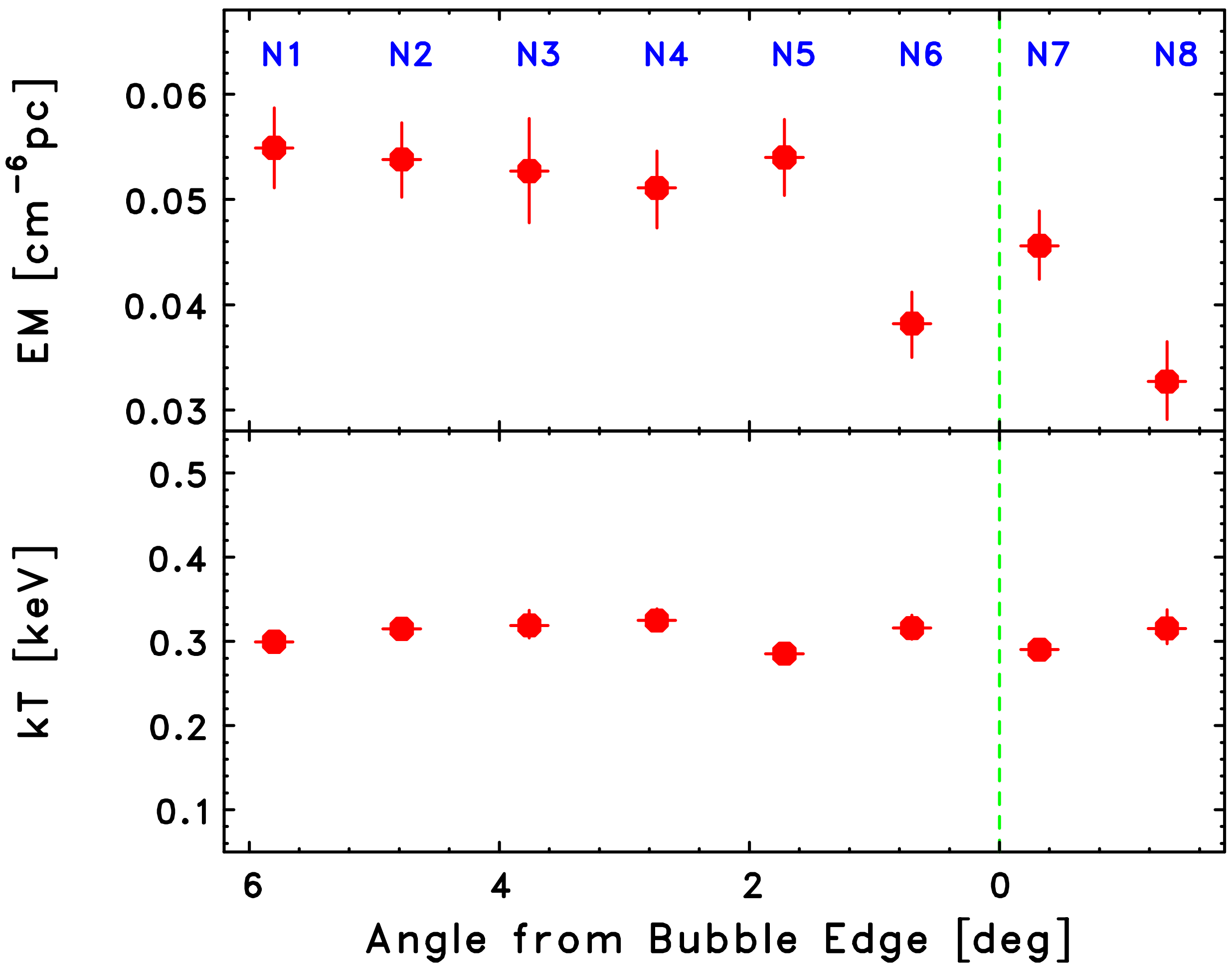


Gu+'16

- X-ray spectra pointed at NPS are represented by the same model as the GH gas
    - but, kT ~ 0.25 -0.30 keV
- Substantial amount of absorber: 3-5 x 10^{19} cm^{-2}
    - Suggesting NPS is a structure in the Galactic Halo

EM and kT across the bubble edge

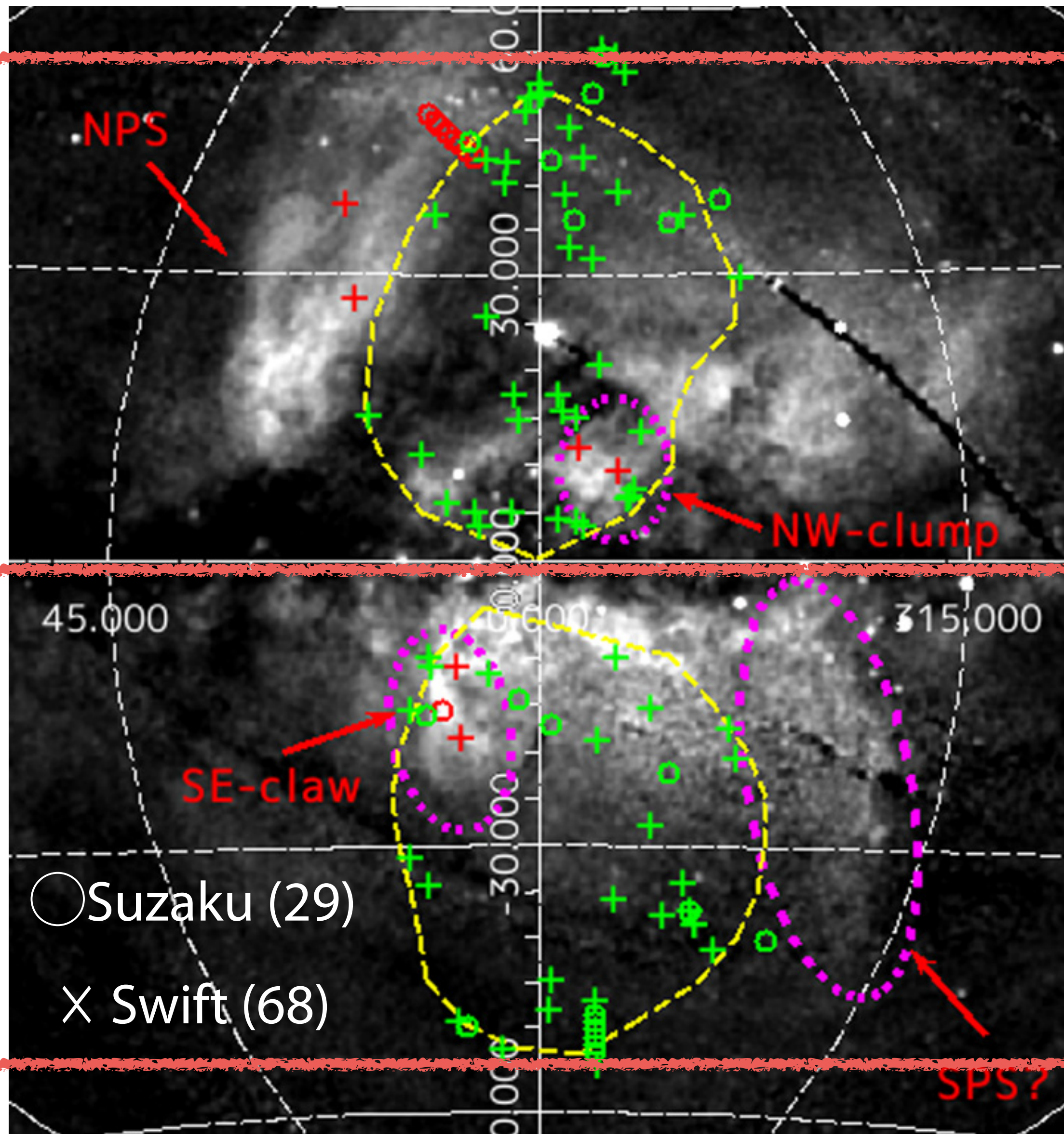


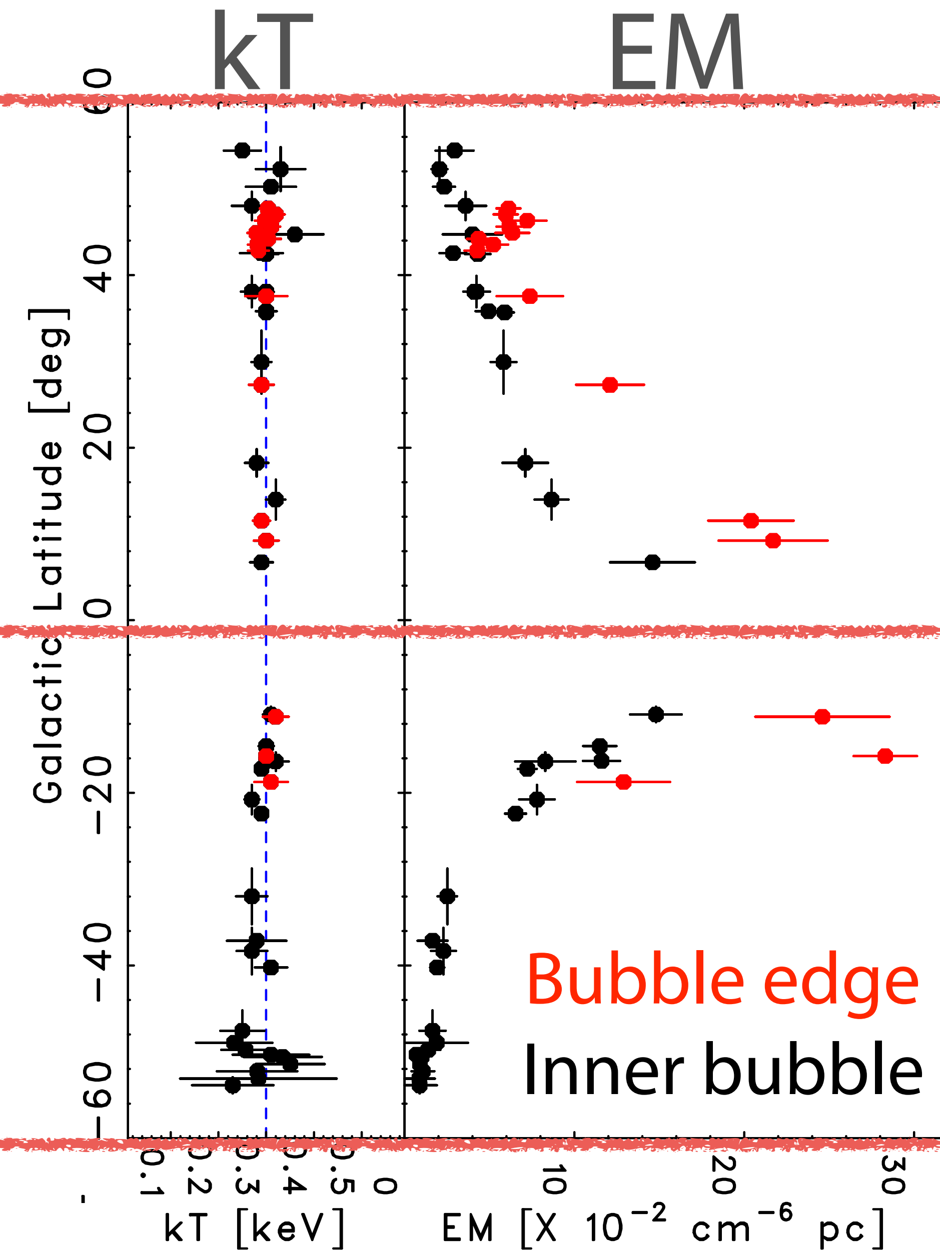


Kataoka,YI+'13

- EM drops ~50% across the bubble edge
  - But, constant kT of 0.3 keV (GH has 0.2 keV)
  - implying expansion velocity of ~300 km/s.
- All the spectra were consistent with the brightest part of the NPS, with absorption $N_H \sim N_{Gal}$

Suzaku & Swift Survey

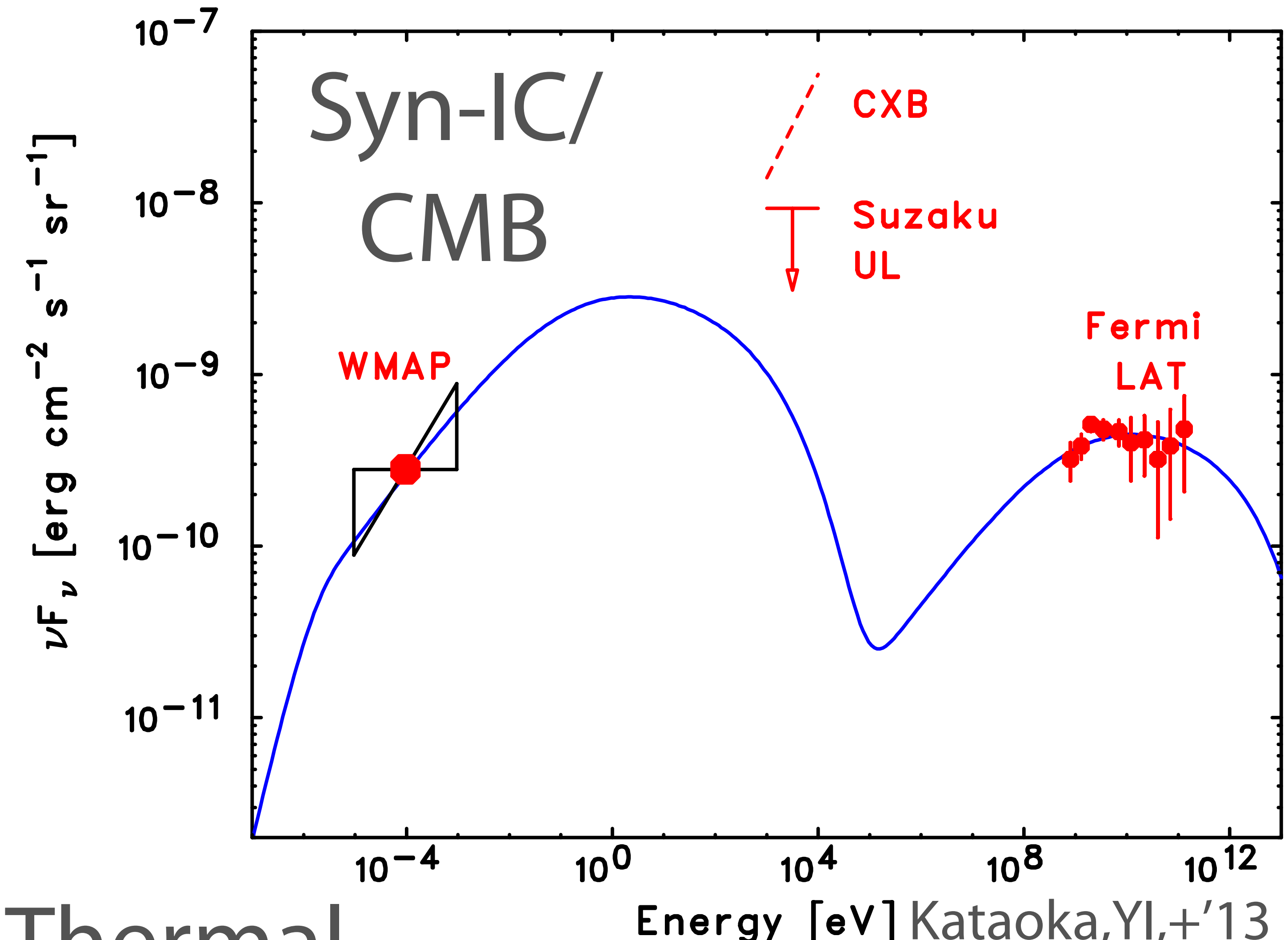




Kataoka,YI+'15

- ubiquitous ~0.3 keV plasma
- significant enhancement of EM near the bubbles' edge

Energy Balance



Kataoka,YI,+'13

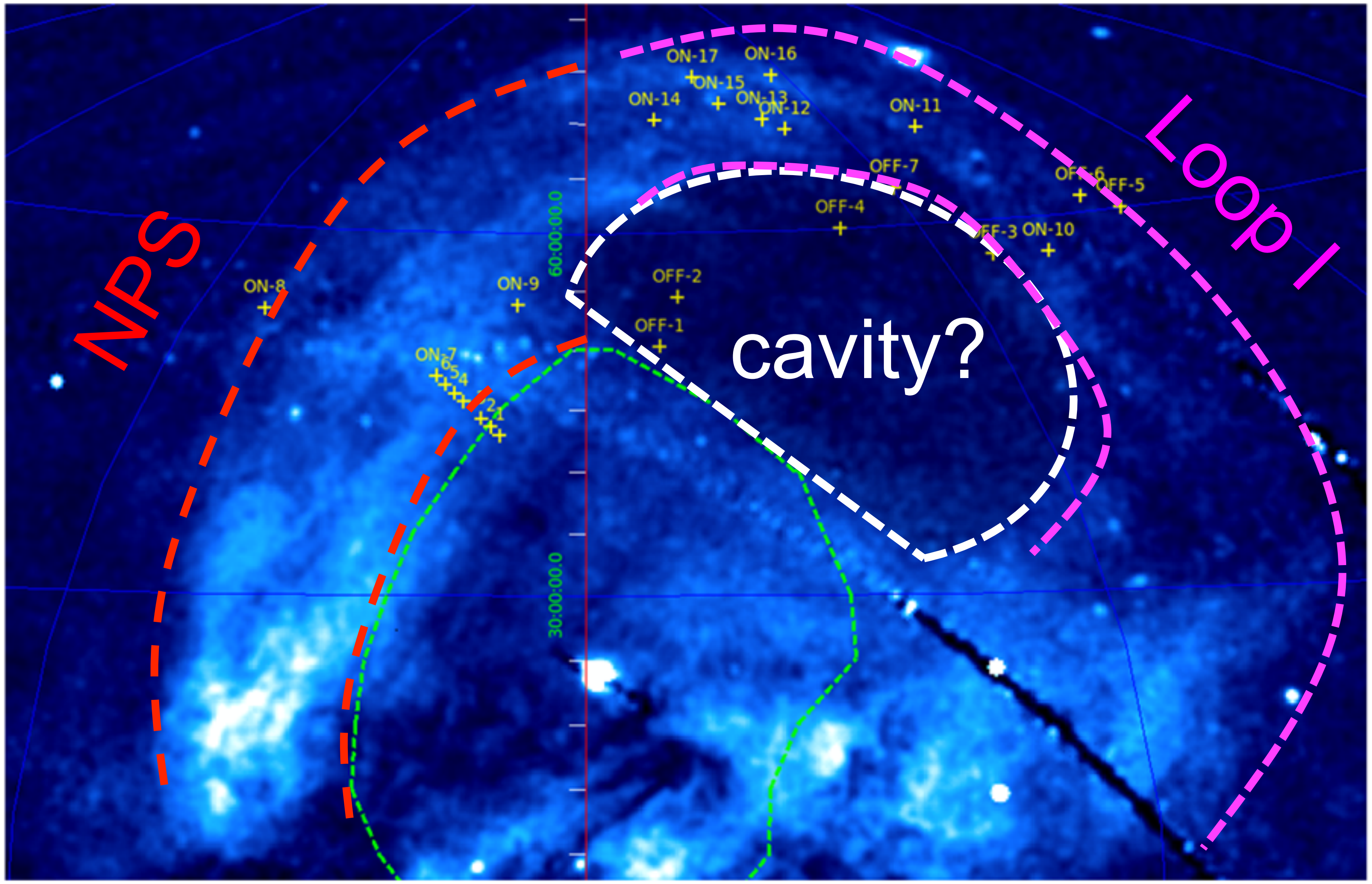
Non-thermal

- $B = 12\ \mu G$
  $U_B = 5.7\times10^{-12}$ erg/cm^3
- $U_{e,non\text{-}th} = 1.4\times10^{-12}$ erg/cm^3
- spherical radius r~4 kpc
- $P_{non\text{-}th} \sim 2\times10^{-12}$ erg/cm^3
- $E_{non\text{-}th} \sim 10^{56}$ erg

Thermal

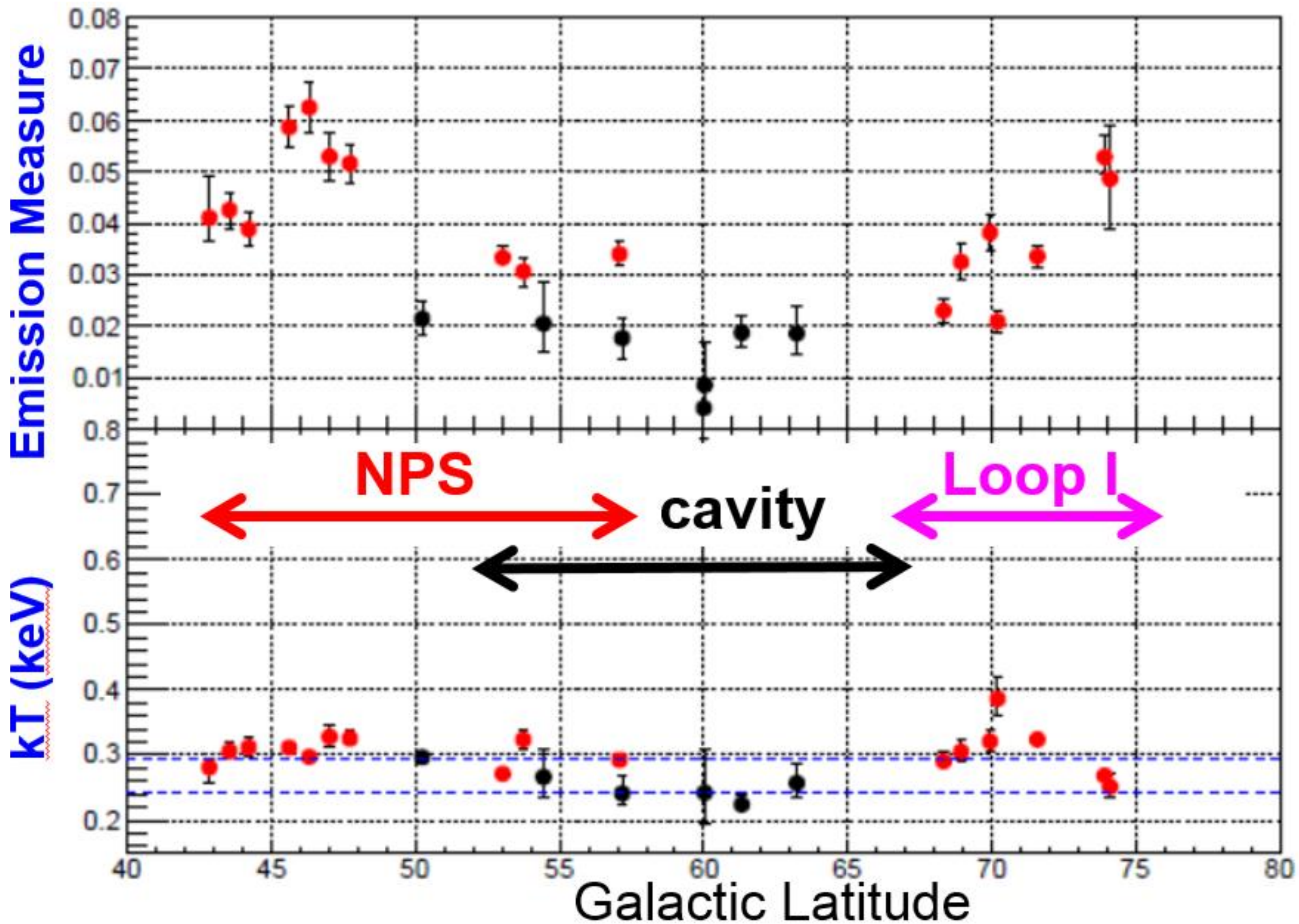
- $P_{th} \sim n_e\, kT \sim 3\times10^{-12}$ erg/cm^3
  we assume $n_e \sim 5\times10^{-3}$ cm^{-3}, kT~0.3 keV
- $E_{th} \sim P_{th}\, V \sim 10^{56}$ erg
  we assume thickness of envelop is ~1/2 of bubble radius ~2 kpc

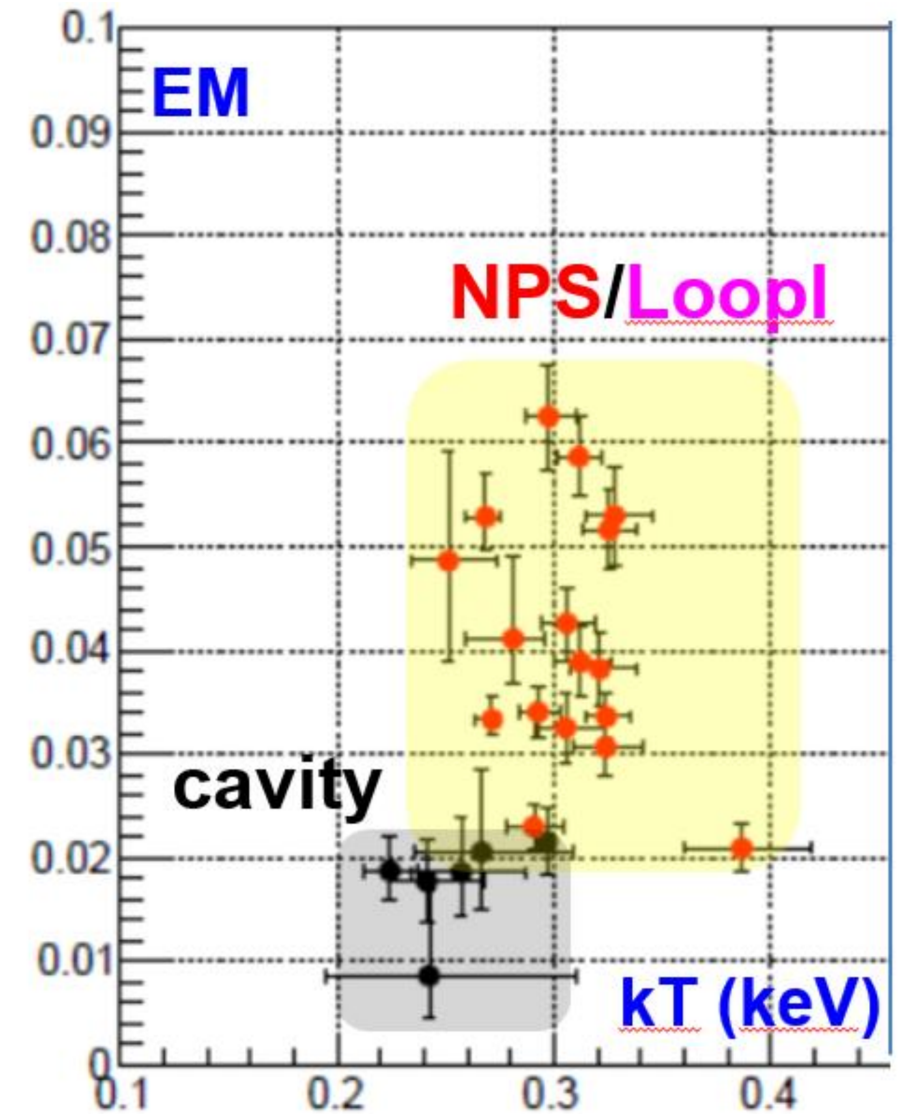
X-ray emission from Loop-I



- NPS is the brightest edge of Loop-I
- Is Loop I also a giant structure in the Galactic halo?
- There exists a cavity between the bubbles' edge and Loop-I

EM and kT from Loop-I

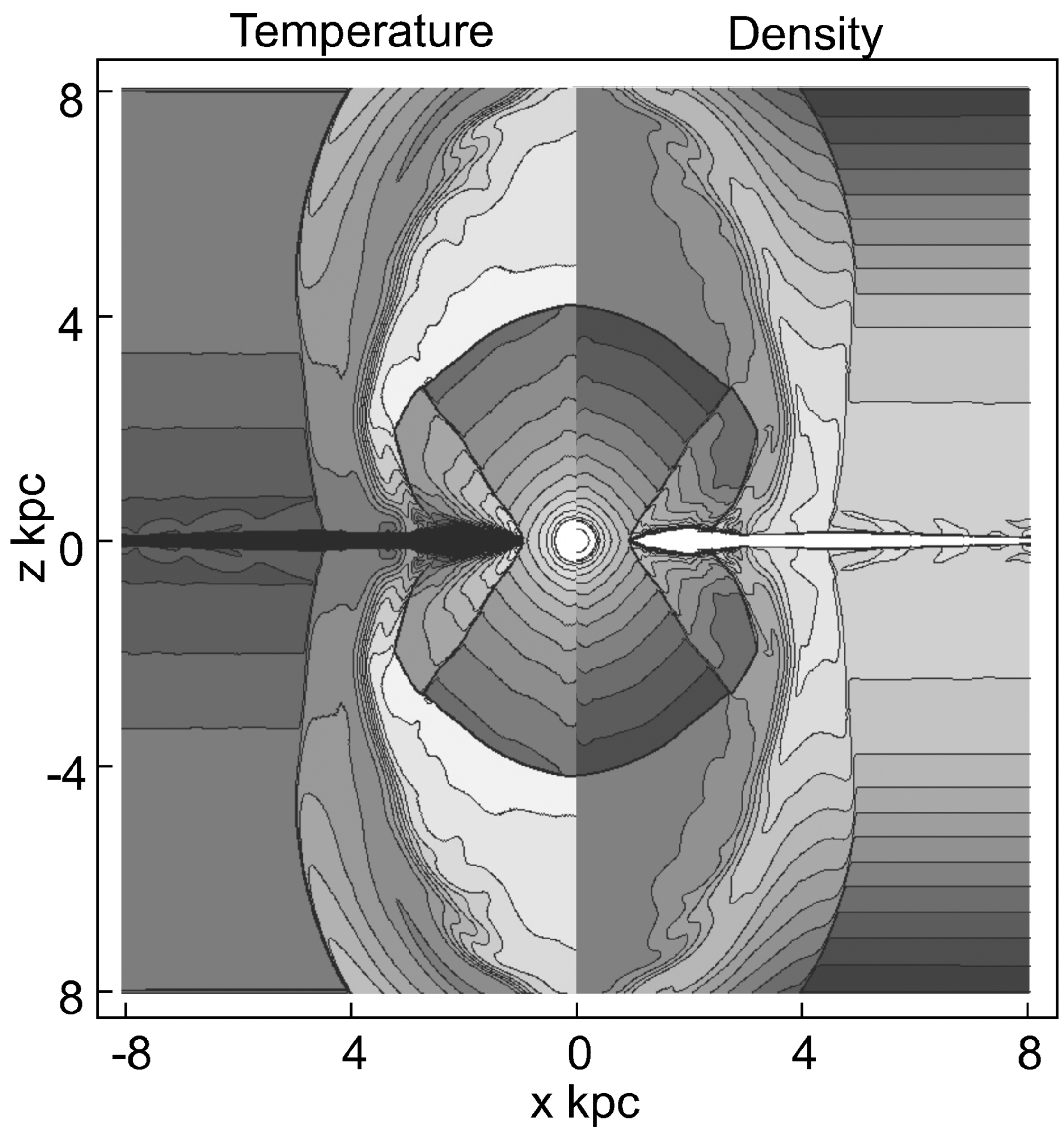




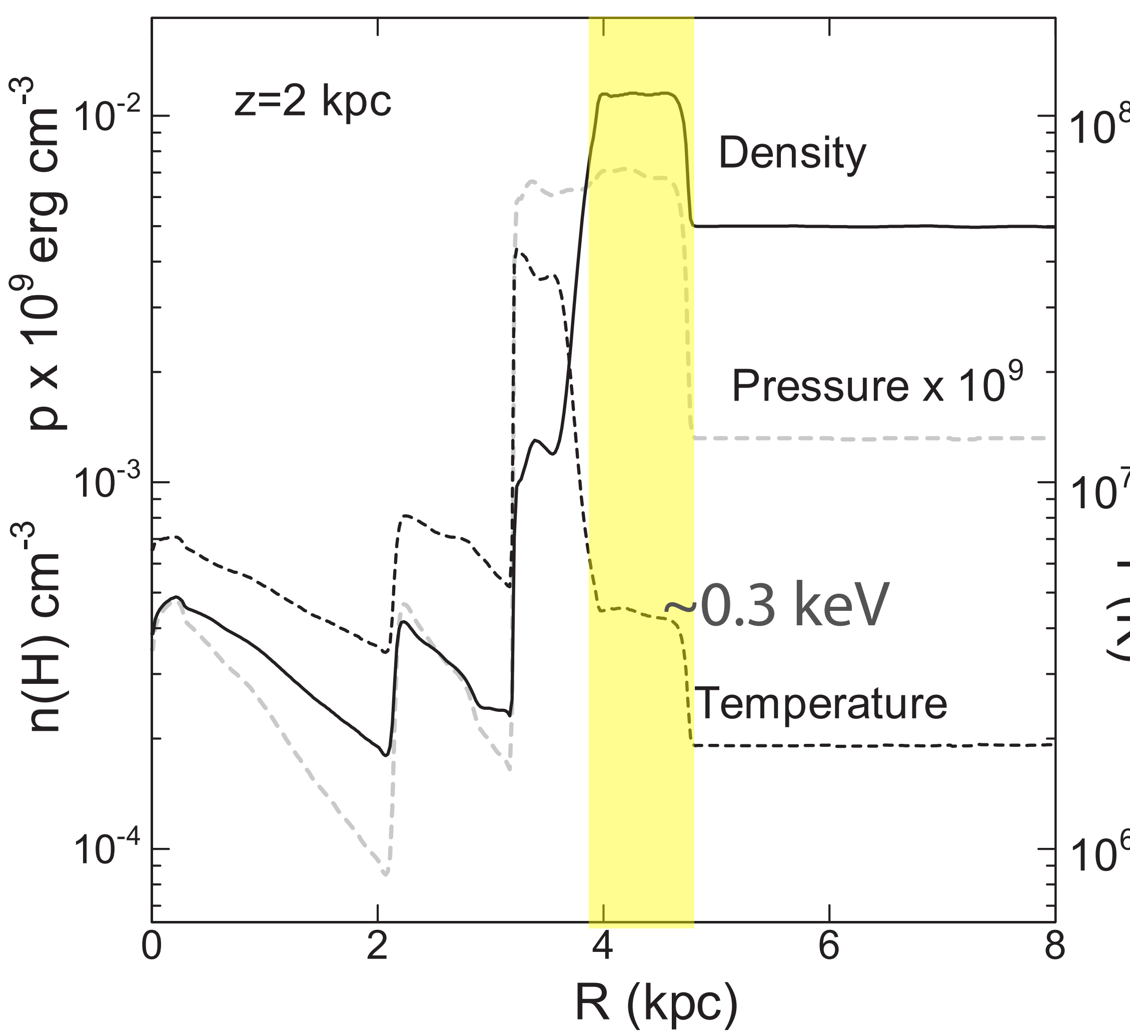
Akita+in prep.

- Ubiquitous 0.3 keV plasma w/ N_H~N_{Gal}
- NPS & Loop-I have slightly higher kT and EM than cavity.

2D HD simulations *(Sofue, YI+'16; Sarkar+'17)*



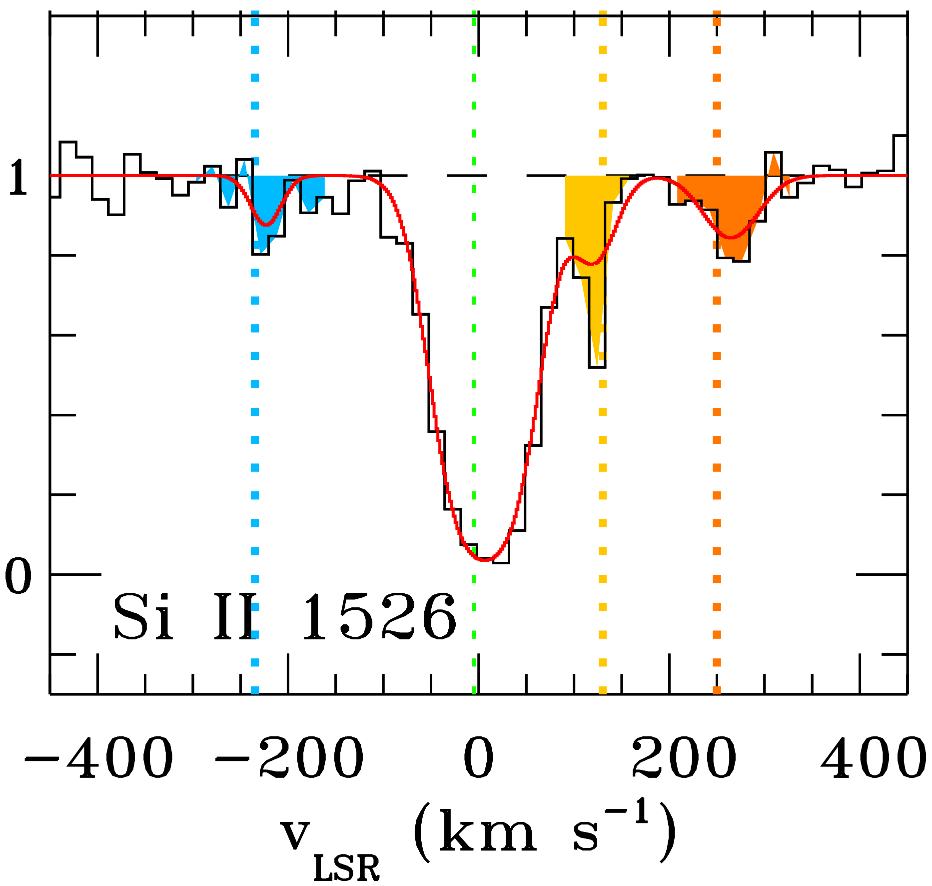
NPS

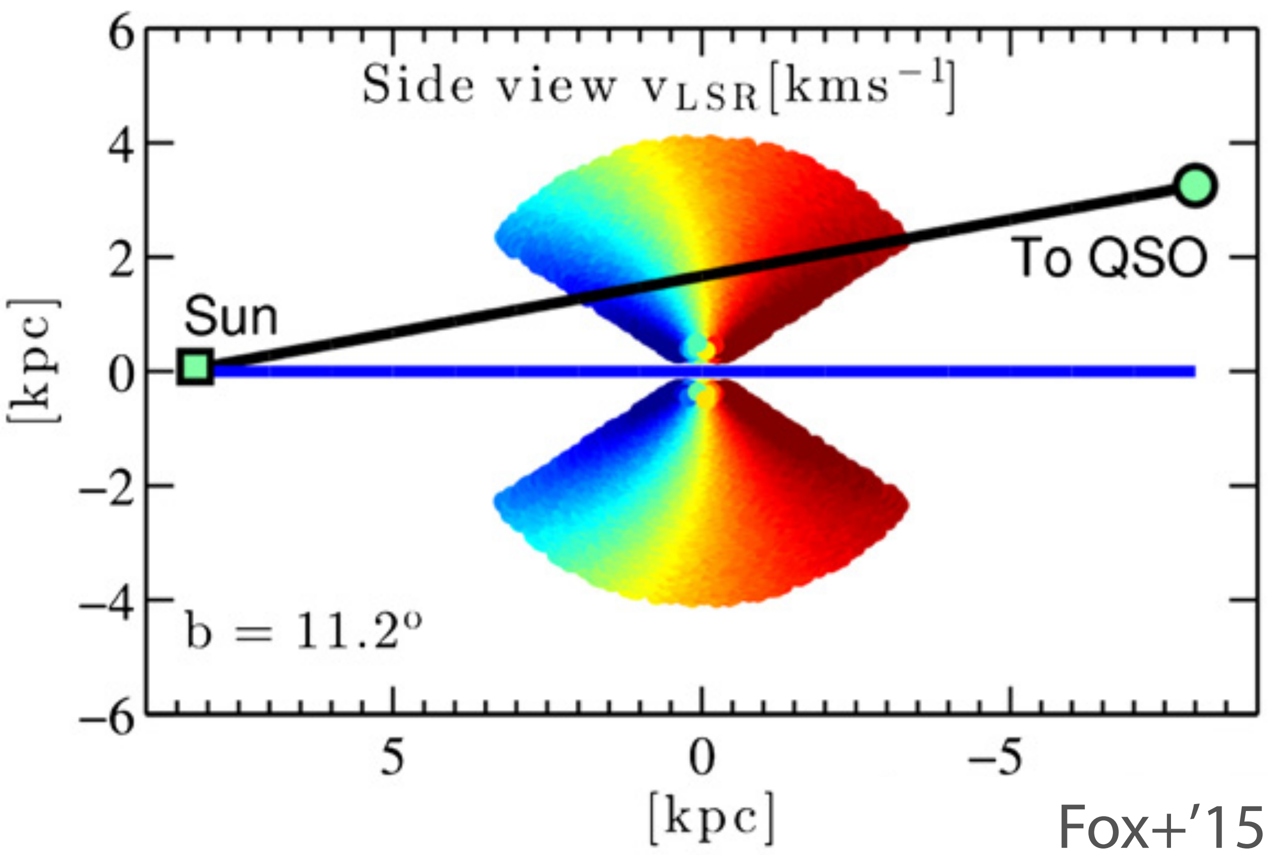


Sofue, YI+'16

- Almost consistent w/ X-ray observations, if energy injection at the GC ~10 Myr ago with total energy of $4x10^{56}$ erg
  - Dense shell (NPS) is ~0.3 keV.

Comparison with UV observations

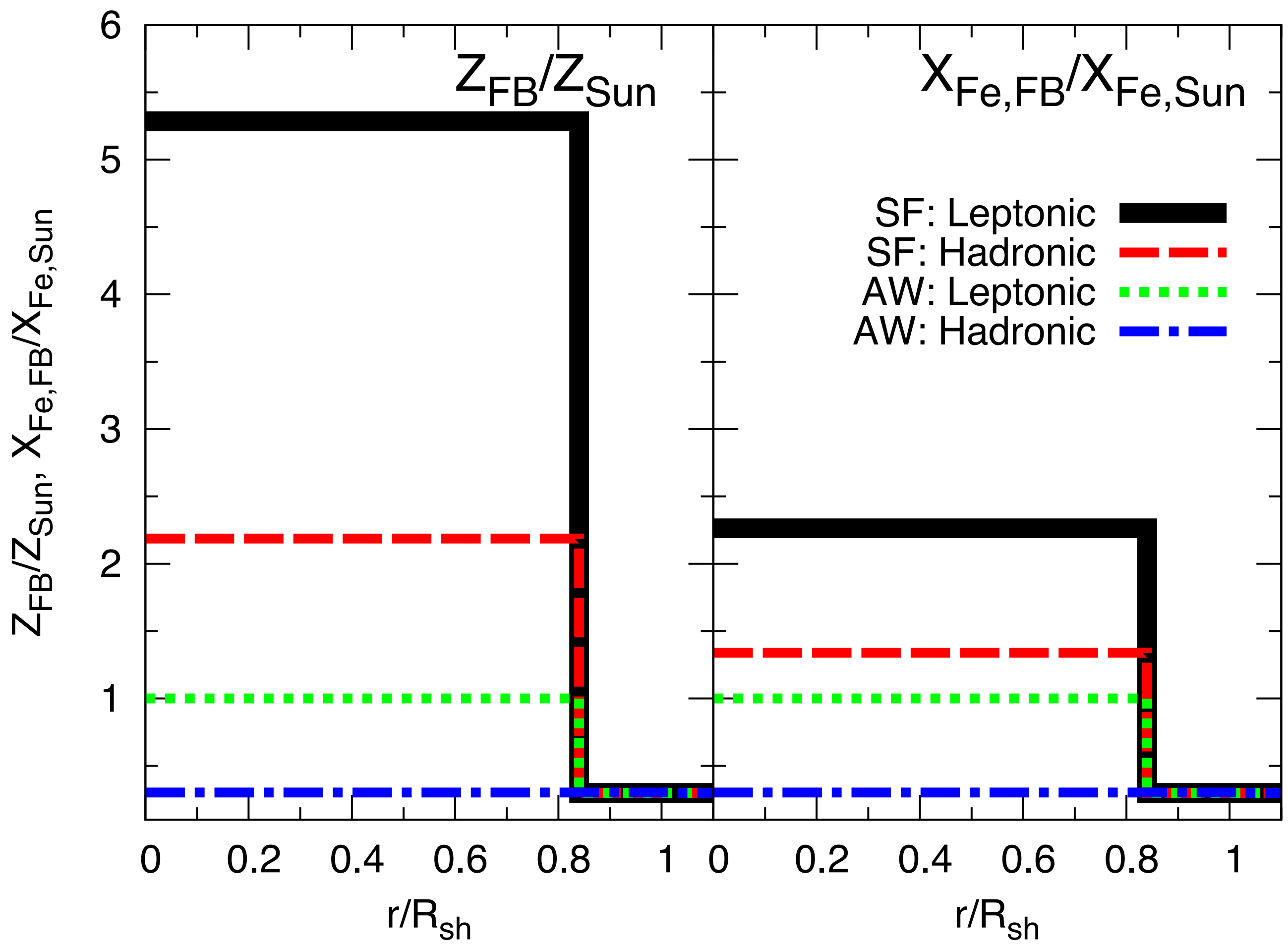




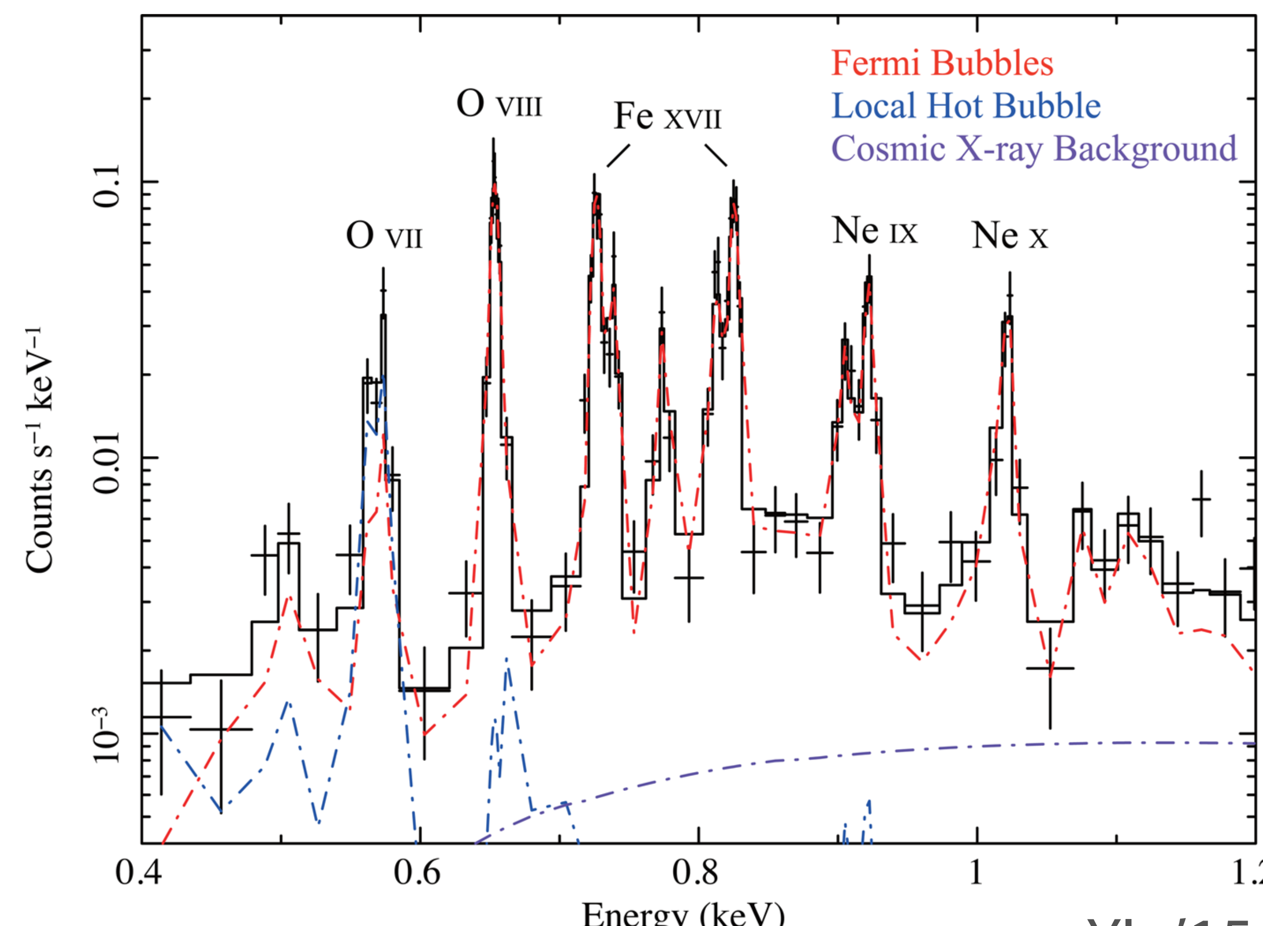
Fox+'15

- UV absorption line spectra from HST observations of PDS456 suggests metal absorption components at v_{abs}~±250 km/s (Fox+'15)
- Systematic survey of 47 background QSO indicates outflow velocity of v_{out}~1000~1300 km/s (Bordoloi+'17)
- Depend on model geometry
- also outflow velocity does not necessarily coincide with v_{exp} (see jet & lobes of AGNs)

Abundance Measurements?



Simulation for Hitomi/SXS



YI+'15

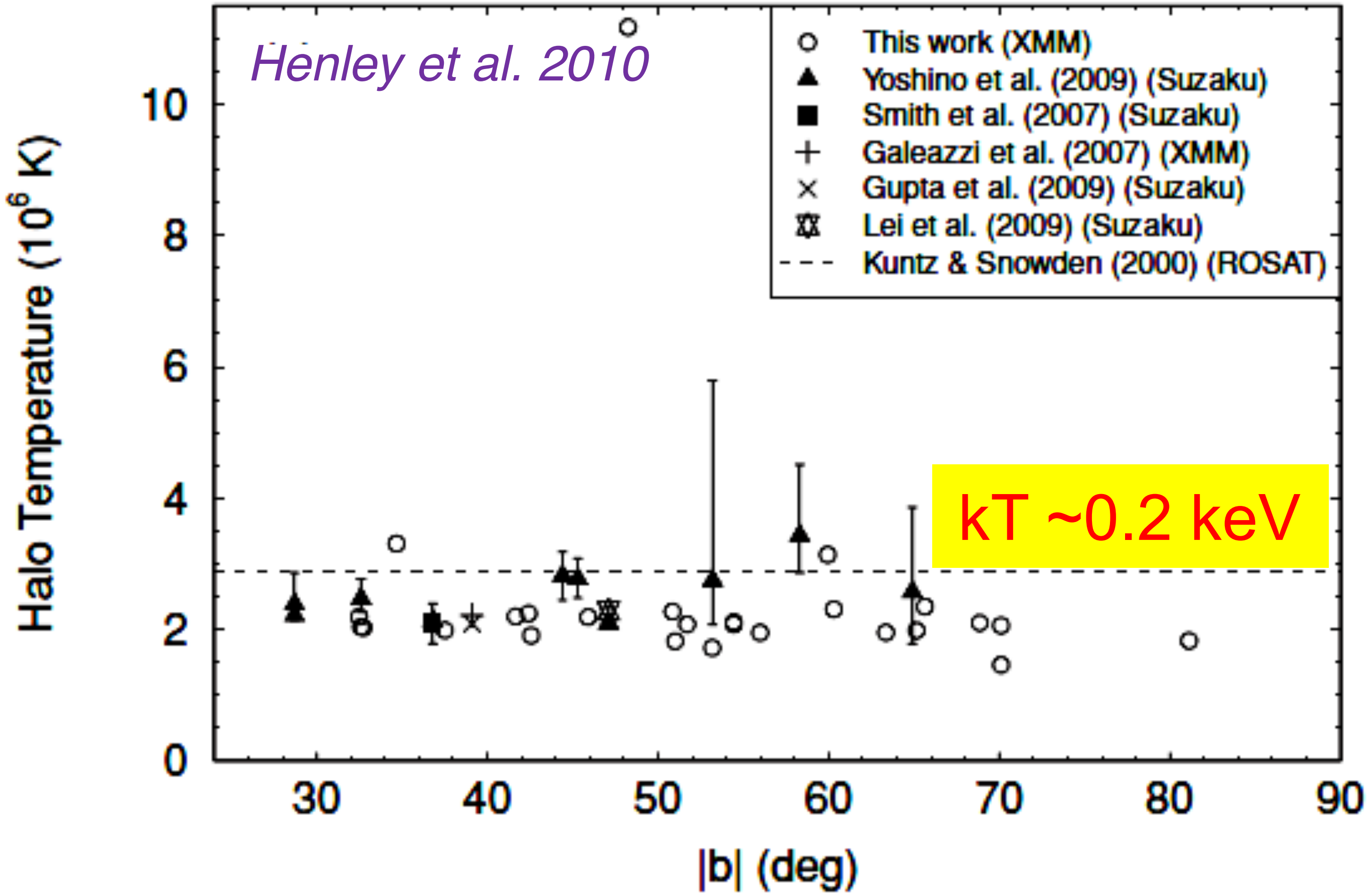
- So, what is the origin? Starburst? SMBH? What is the emissoin mechanism? Leptonic? Hadronic?
- Metal abundance will be a smoking gun.
  - Starburst scenarios will make more metals than AGNs.
- Future high resolution spectroscopy can measure the abundance.

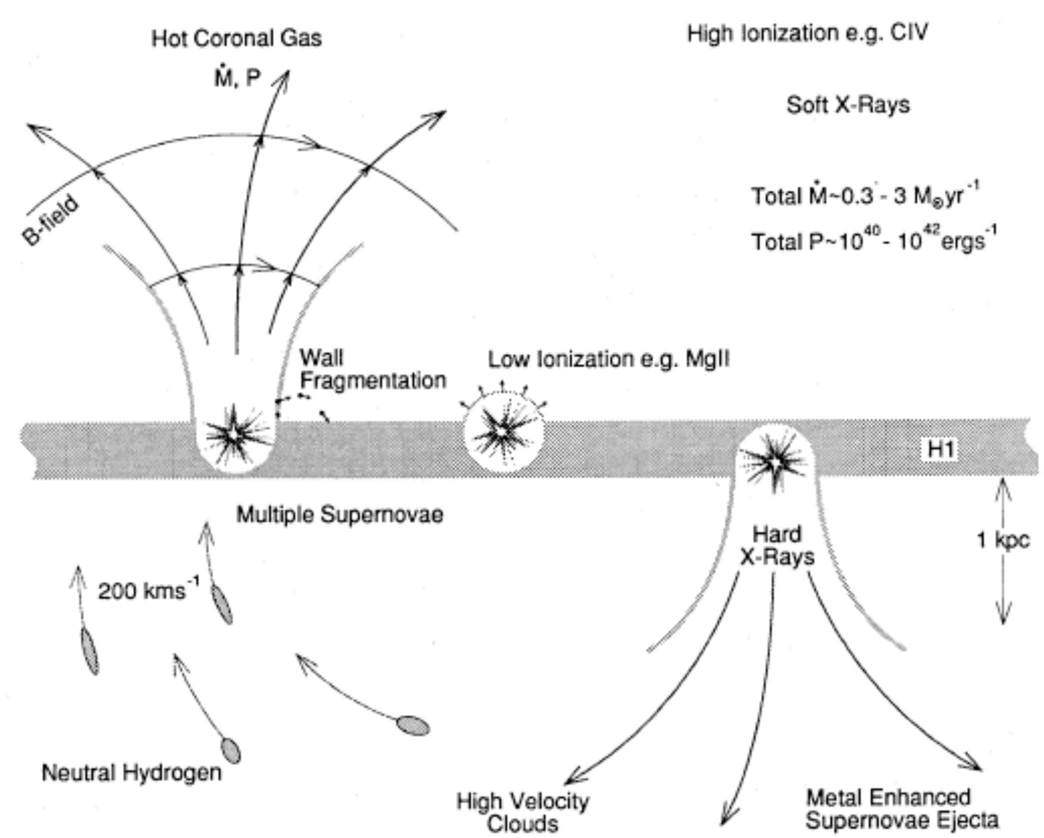
Summary

- Galactic Halo
  - ~0.2 keV plasma, plane-parallel geometry?
- NPS, bubbles, Loop-I
  - ubiquitous ~0.3 keV plasma, absorption column density $N_H \sim N_{Gal}$
  - EM decreases with latitudes, but significant enhancement near the edge, NPS, Loop-I
- A weak shock driven by the bubbles' expansion in the GH with v_{exp}~300 km/s compressed the GH gas to form the NPS feature
- Non-thermal and thermal pressure and energy in equipartition between the bubbles and NPS

Backups

Halo kT measurement by XMM

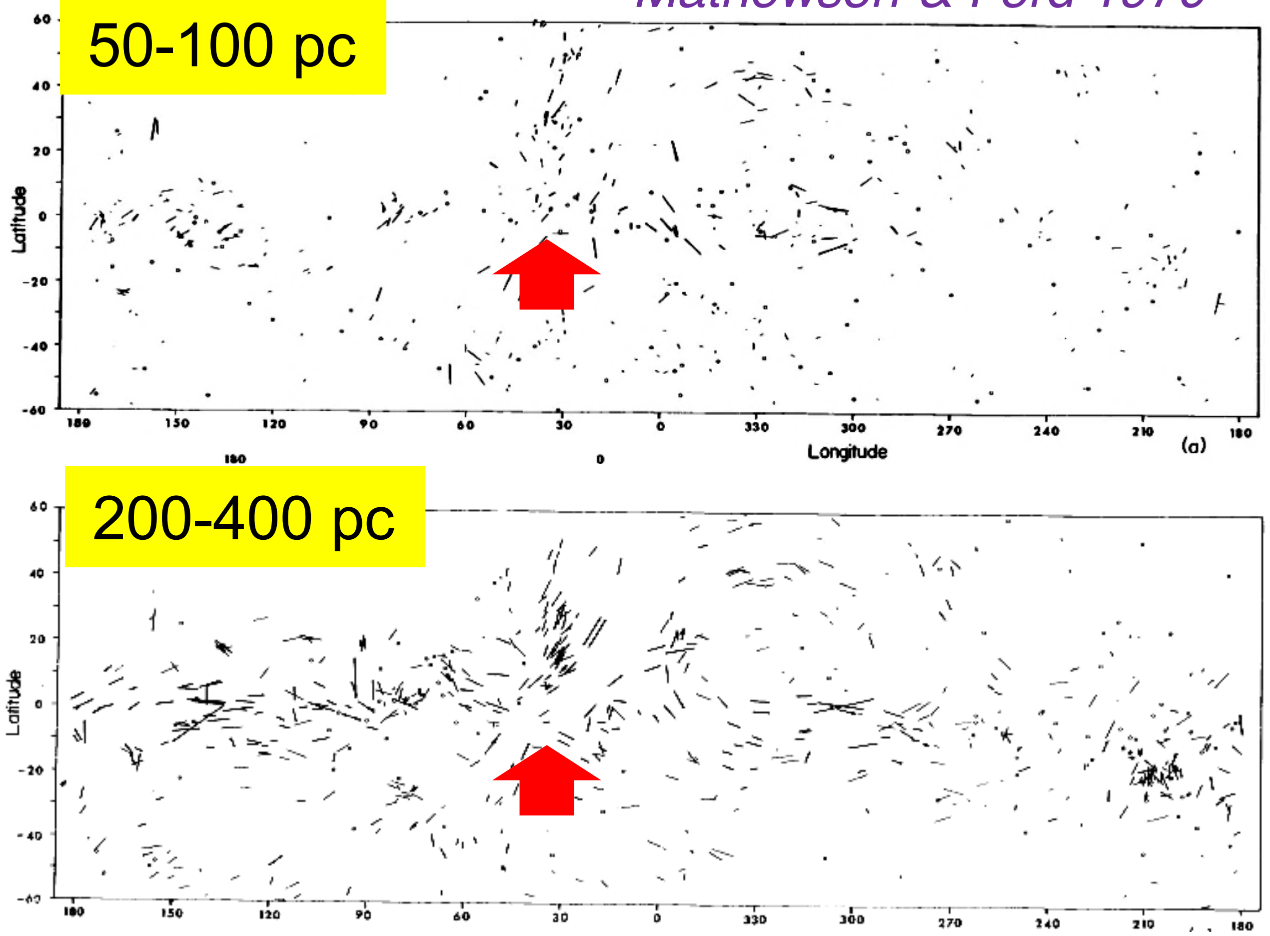




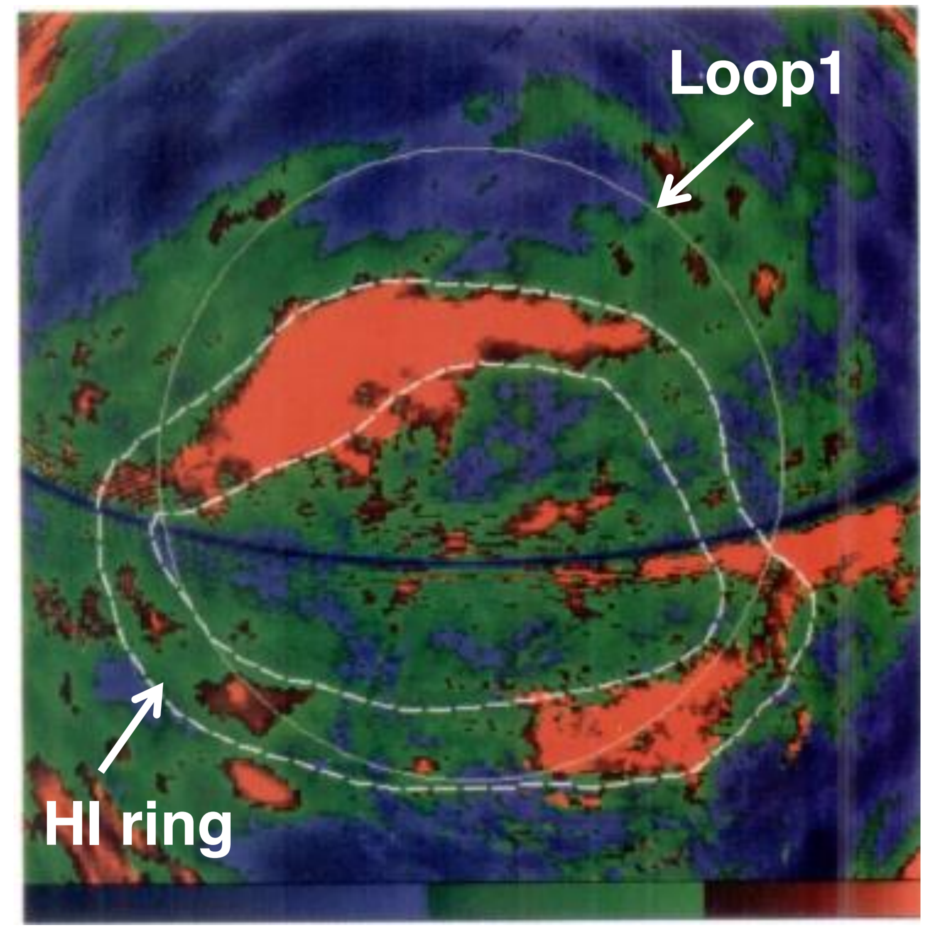
- Similar study using 26 high latitude XMM observations of the soft X-ray background between 120° < l < 240° also suggests that observed halo temperature is fairly constant across the sky, **0.16 keV < *kT* < 0.21 keV**
- They compared the observed X-ray properties of the halo with the three physical models for the origin of the hot gas: (1) a disk galaxy formation model (2) a model in which the halo is heated by extraplanar SNe, and (3) a fountain of hot ISM gas driven into the halo by disk SNe, which they argue (3) is most likely

NPS – [A] nearby SNR?

Mathewson & Ford 1970



Egger & Aschenbach 1995

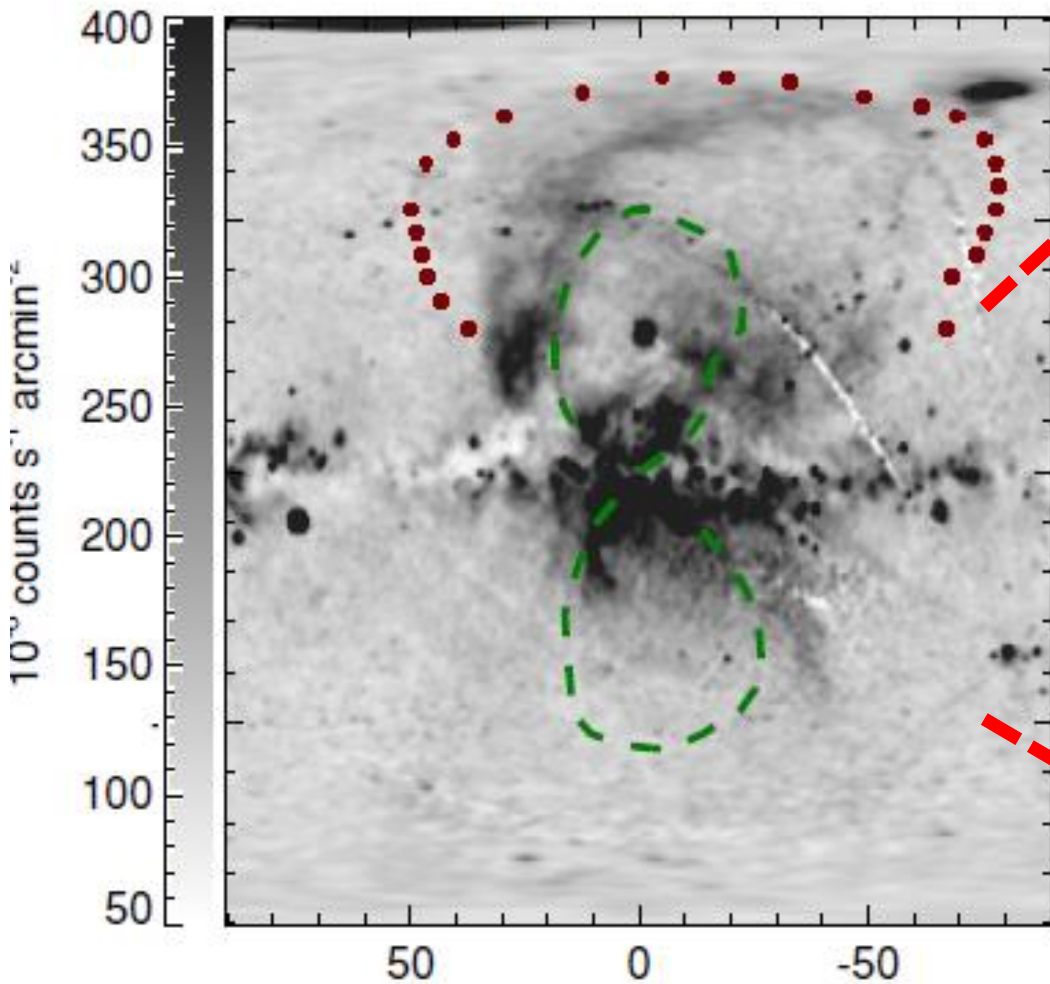


- An interstellar polarization feature at distance of ~100 pc which clearly follows much of the N- and E- parts of Loop I, including the NPS, with the expected polarization orientation *(Mathewson & Ford 1970)*
- In addition, the H I features seen nearby (~70pc) appear to be due to an interaction of Loop I with the Local Bubble, although somewhat speculative *(Egger & Aschenbach 1995).*

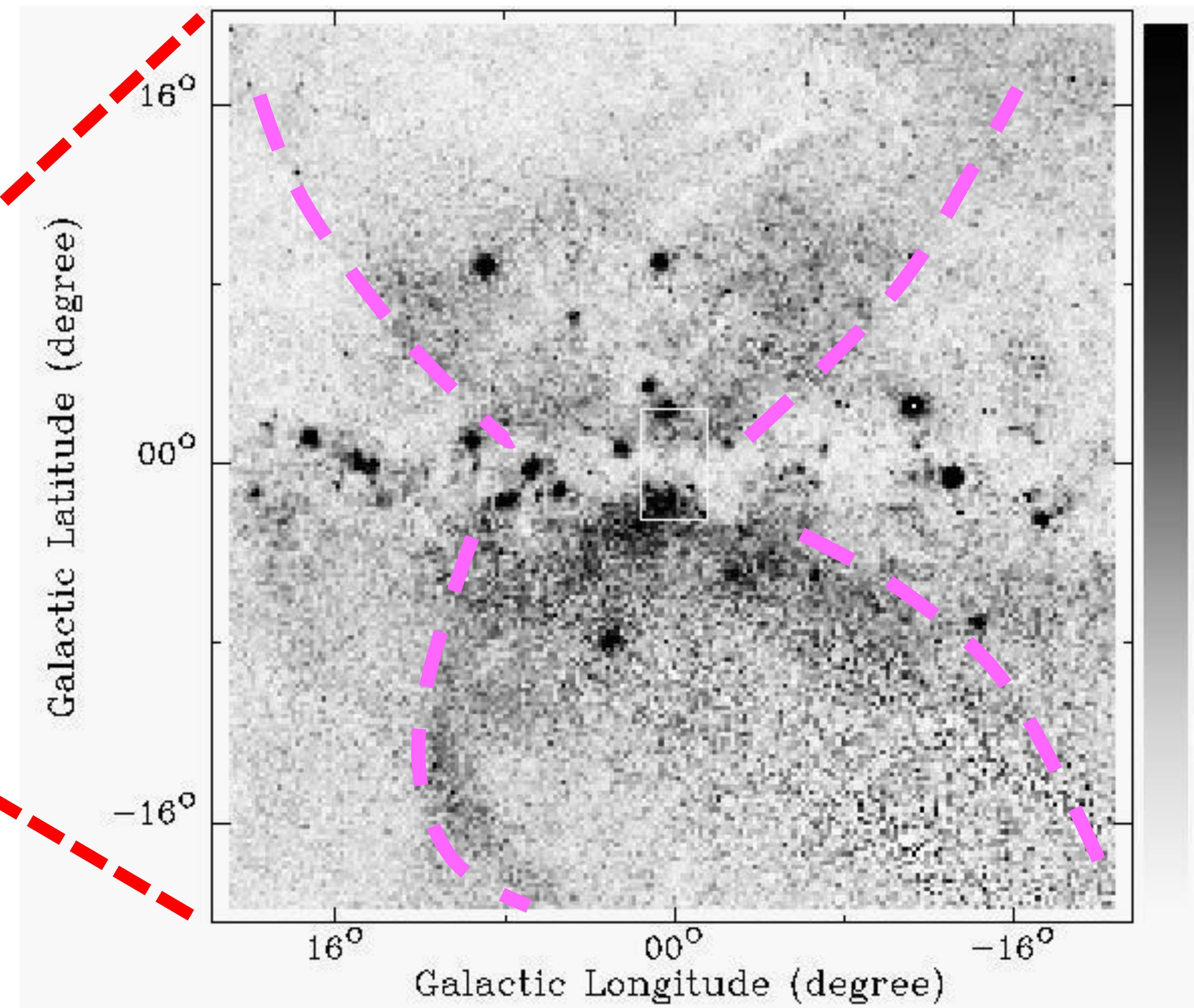
These results favor the local NPS scenario

NPS – [B] GC origin?

Su et al. 2010



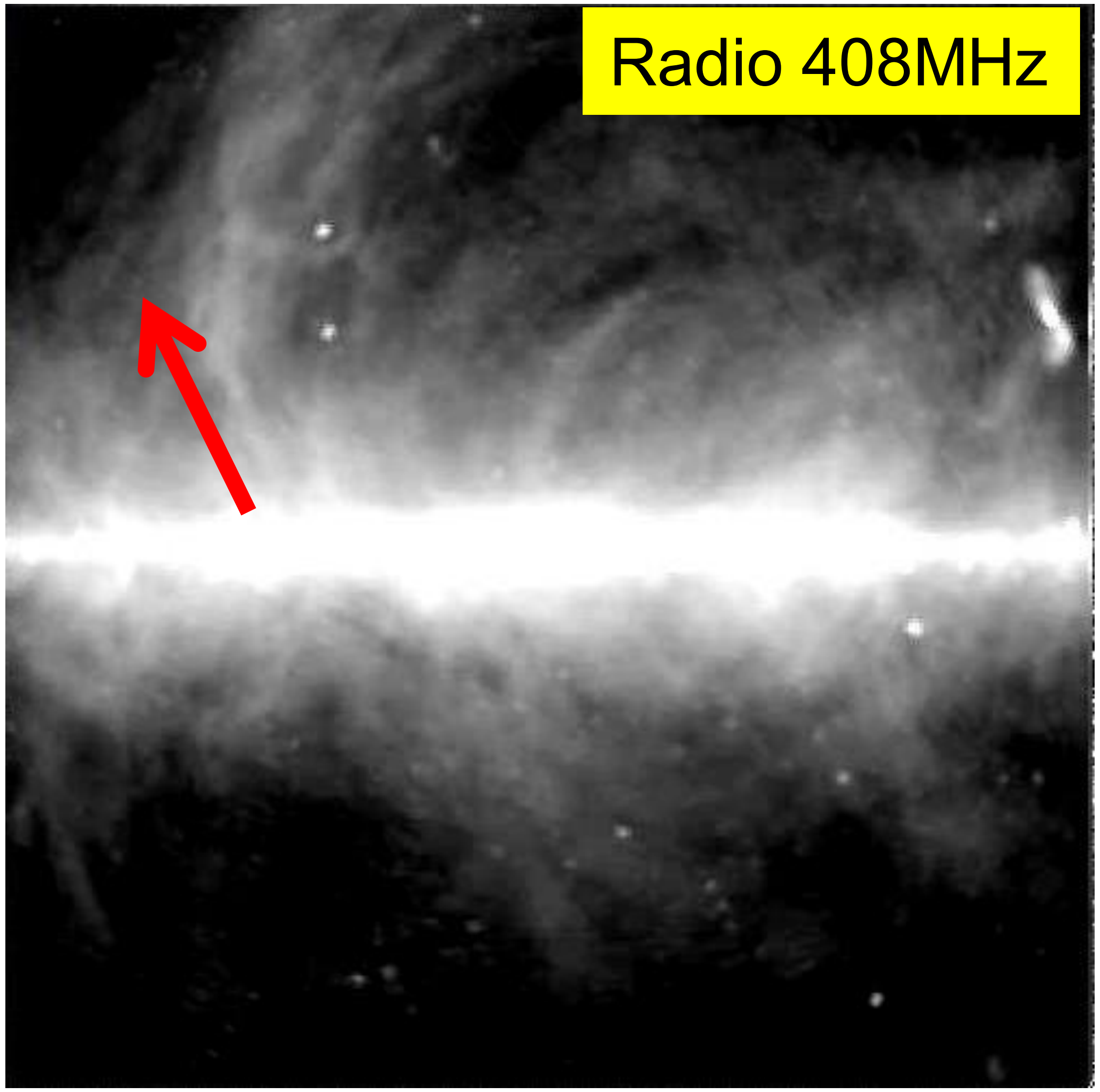
Wang et al. 2002

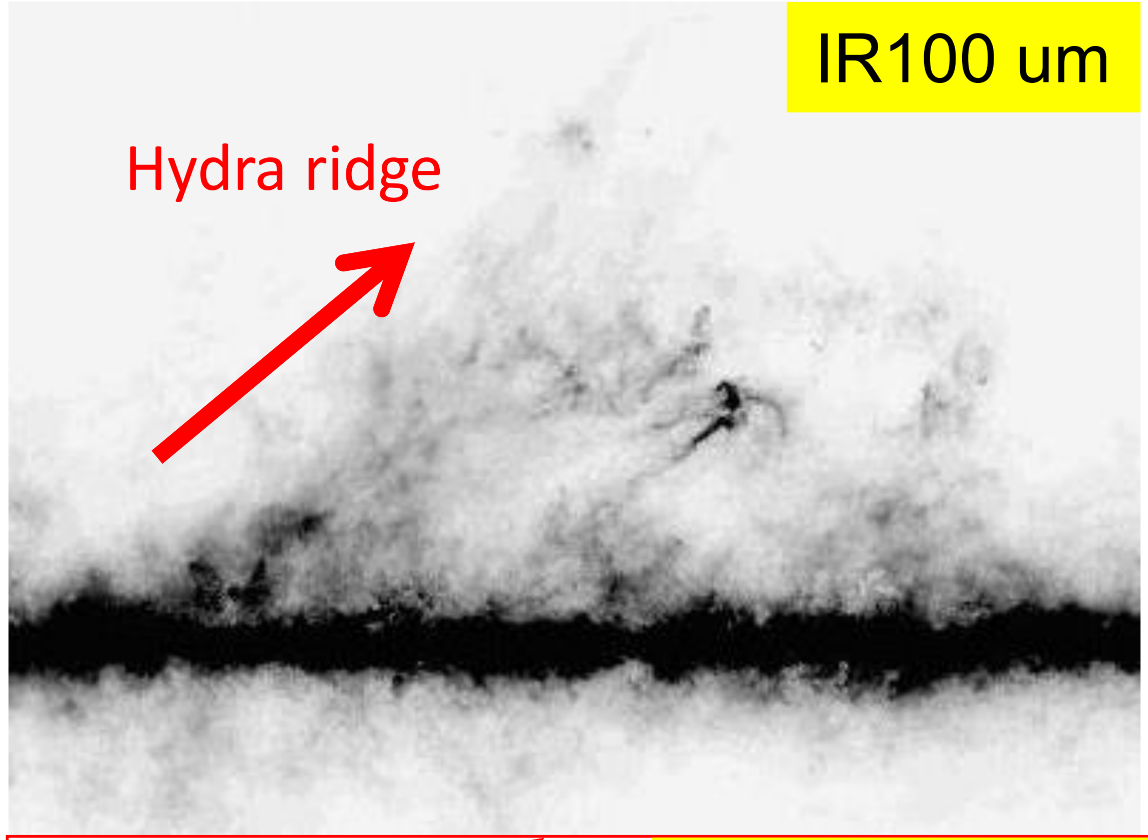


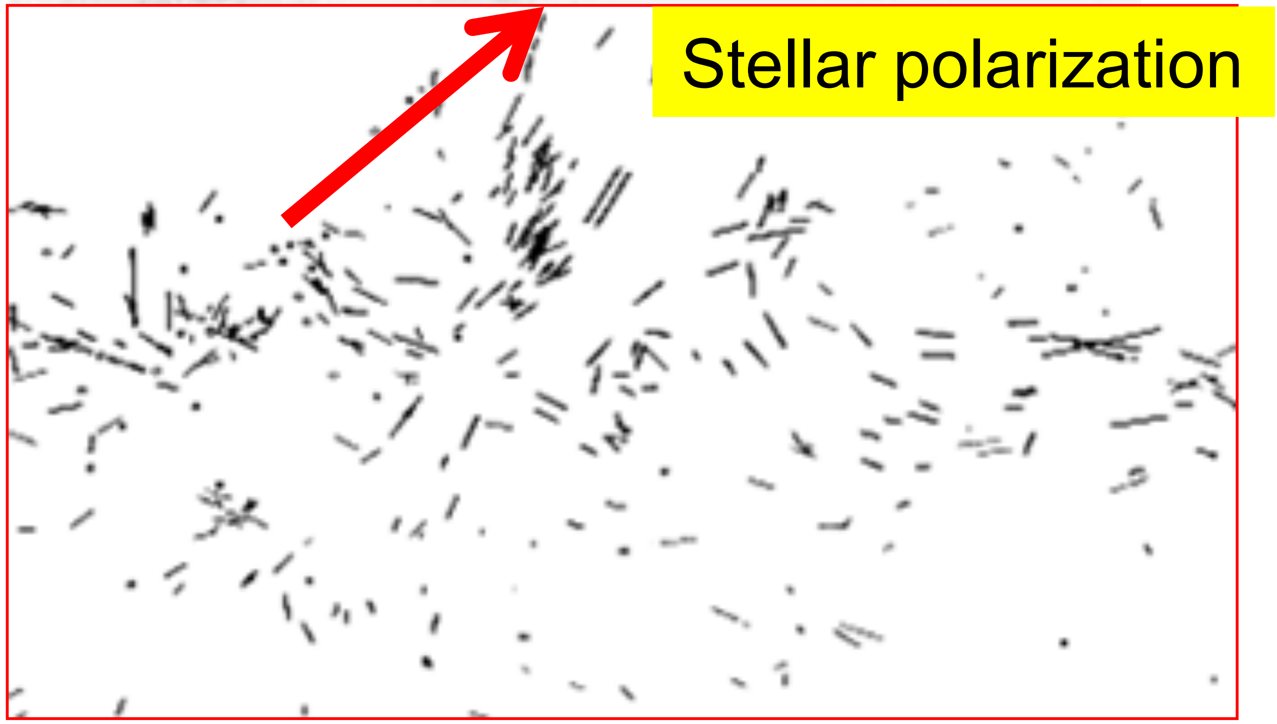
- Under the “GC model”, the NPS is the remnant of a starburst or explosion near the GC ~15 Myr ago and is at a distance of several kpc. But this scenario is based largely on morphological arguments
- However, the *ROSAT* 1.5 keV image presented by Wang (2002) clearly shows the hourglass geometry characteristic of a bipolar flow, even in the South of GC with angular scale of more than ~20^{o} !

NPS – [B] GC origin? (2)

Y.Sofue, private comm.



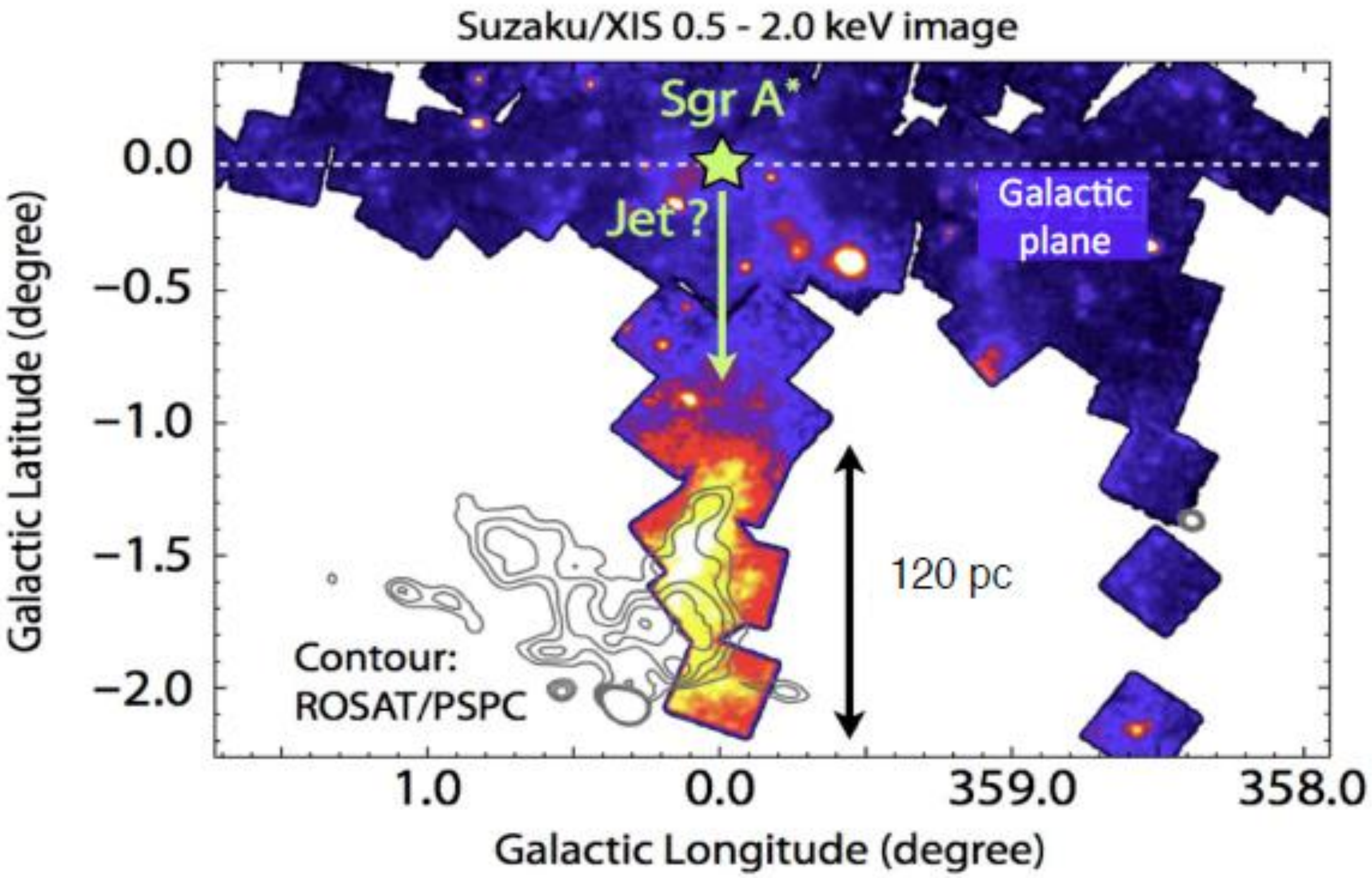


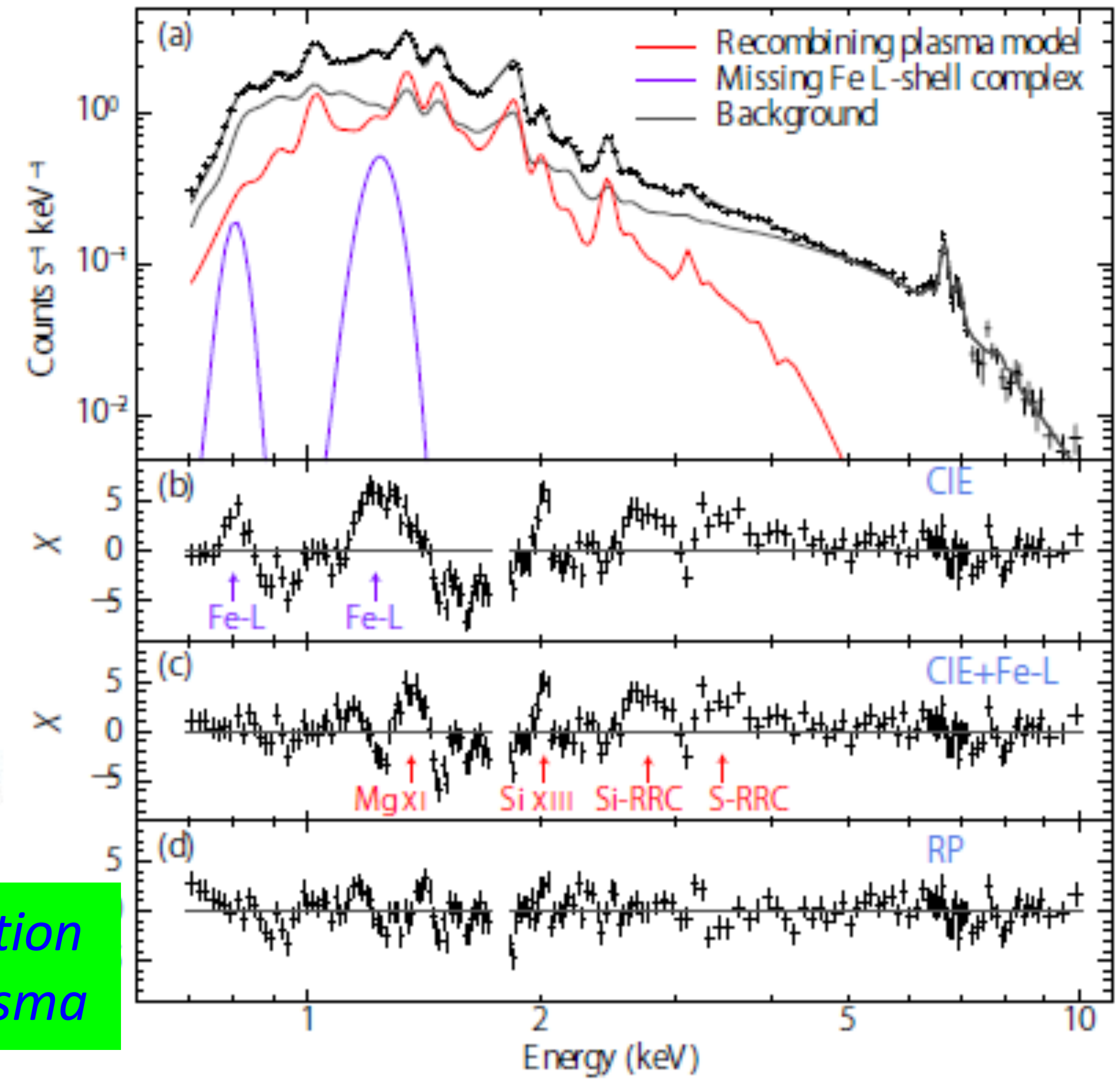


- Direction of starlight polarization is perpendicular to the NPS, but almost parallel to the HI filament of Hydra ridge!

Another Relic of GC Activity

Nakashima et al. 2013





CIE: collisional ionization
RP: recombining plasma

- Suzaku found an island of thermal emission of about 0.5 keV temperature at around *(l, b)= (0◦, −1◦.5)*
- Remarkable features of this plasma is that it has a jet-like structure ejected from Sgr A∗ and the plasma is in recombining process
- Almost fully ionized plasma was made by jet-like activity (flare) of Sgr A∗ about 2×10^5 years ago, and then now is still in recombining phase