# Hot gas outflows in the Milky Way Galaxy

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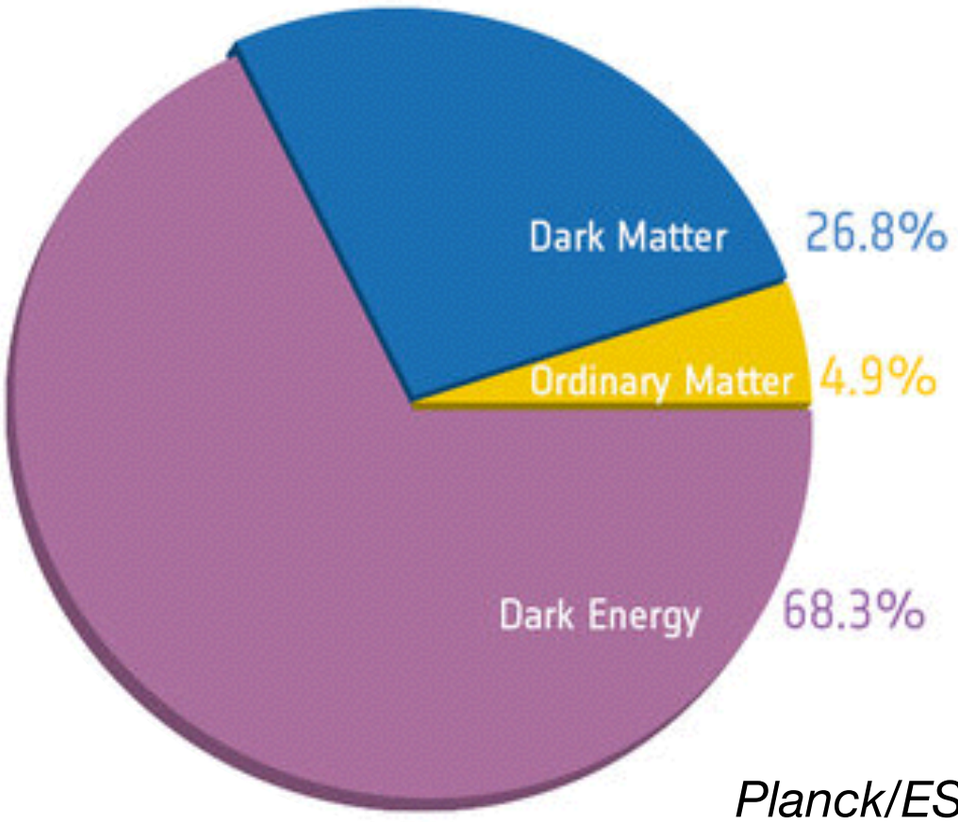
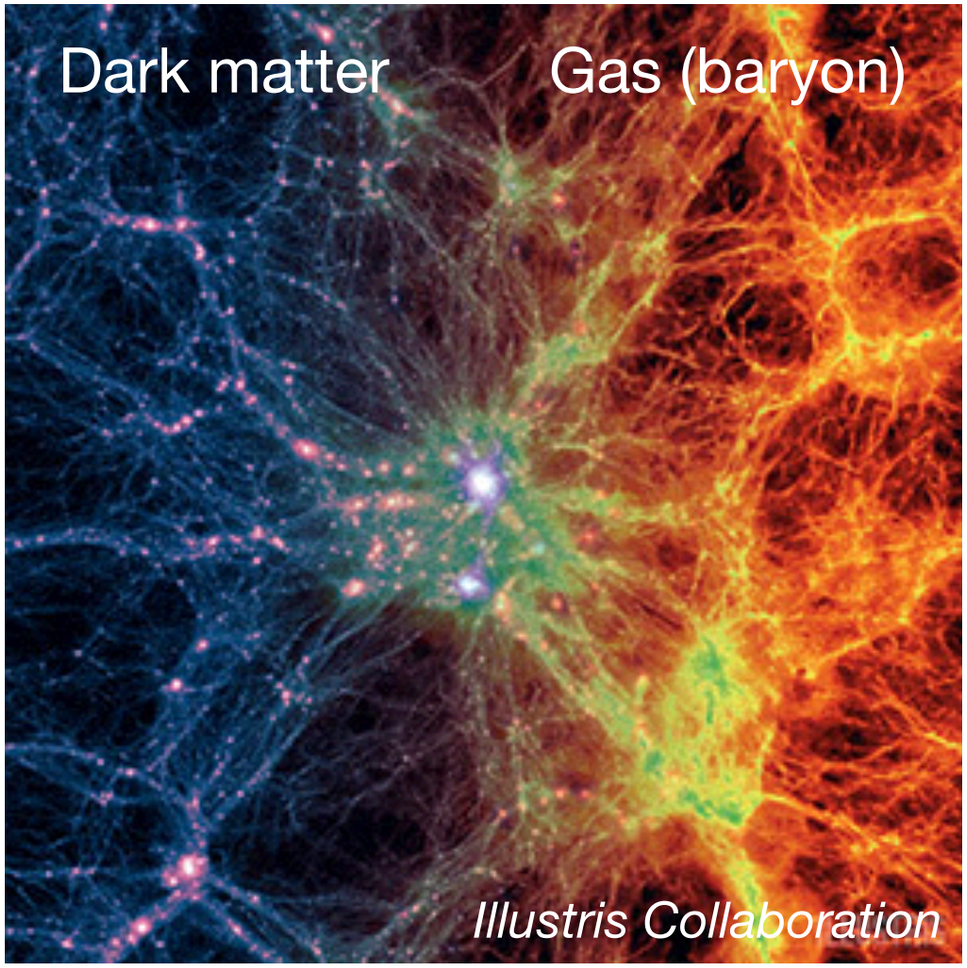
# Outline

- Introduction
- 100 pc scale outflow in the Galactic Center
- 10 kpc scale outflow (North Polar Spur, Fermi bubbles)
- Galactic hot gaseous halo
- Future prospects

# Current standard cosmological model



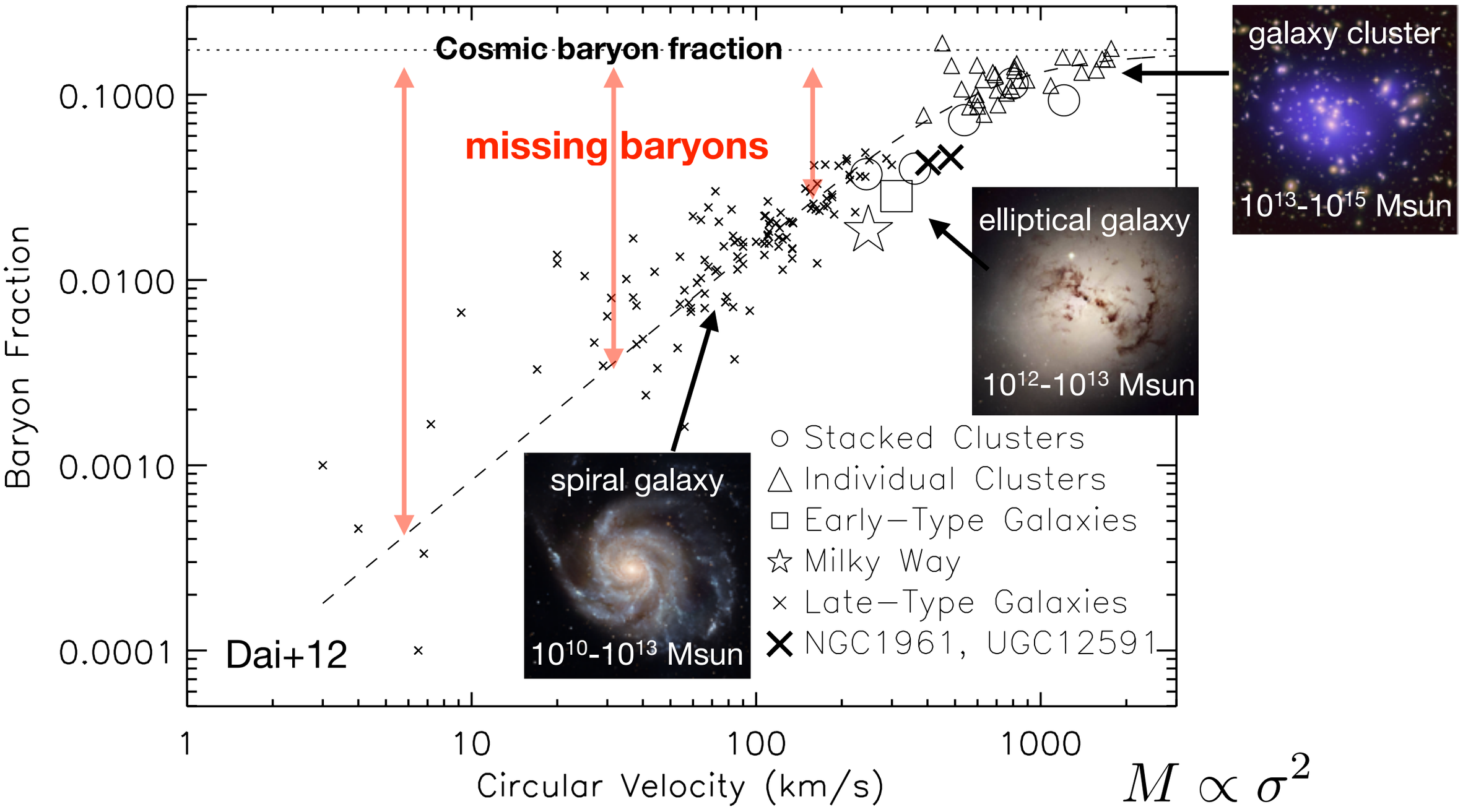

*Planck/ESA*




*Illustris Collaboration*

- CMB measurements determines cosmological parameters (WMAP, Planck).
- Cosmological simulations successfully reproduce the large-scale cosmic web:
  - Virialized halos: overdensity (local density/cosmic mean density) > 200
  - Filaments: overdensity 30—200
- Baryons simply follow dark matter distribution?

# Baryon behavior is not so simple



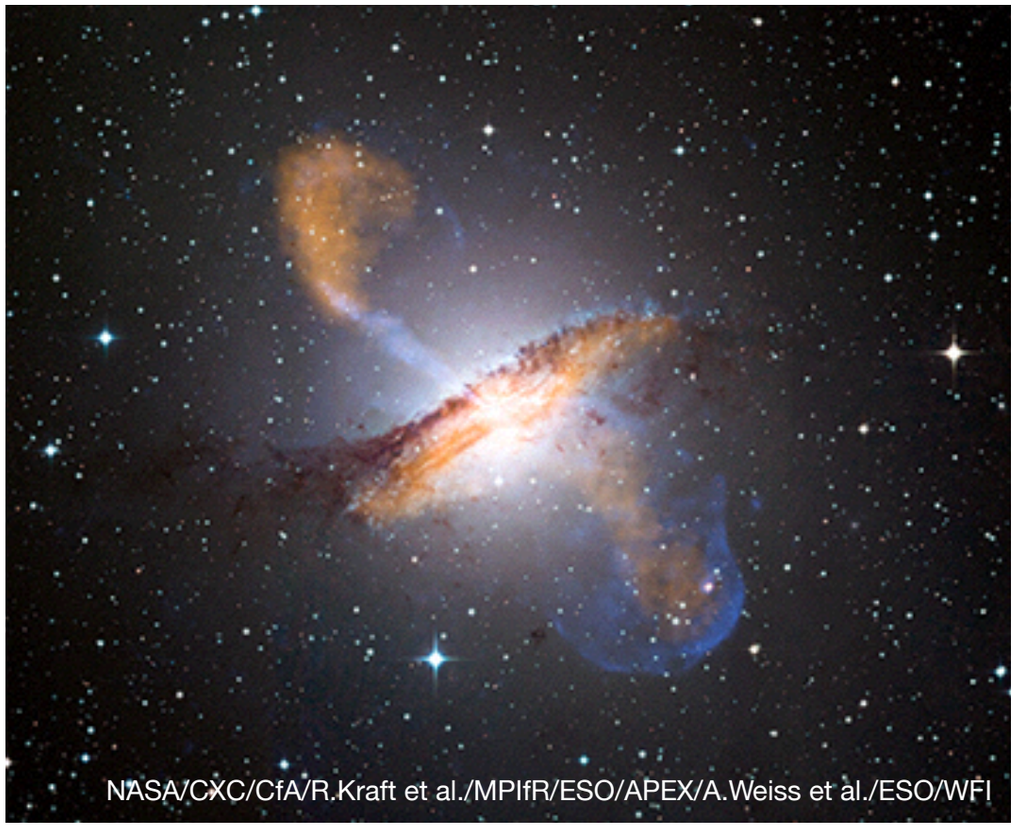

$M \propto \sigma^2$

- Massive galaxy clusters have nearly all their baryons.
- However, field galaxies missing 70-95% of baryons -> baryons escape from halos?
- If so, how to strip baryons from galaxies?

# Supernova/AGN feedback?

M82: starburst wind

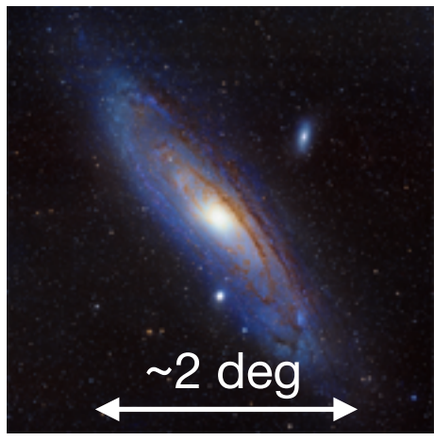

Cen A: AGN jets & lobes

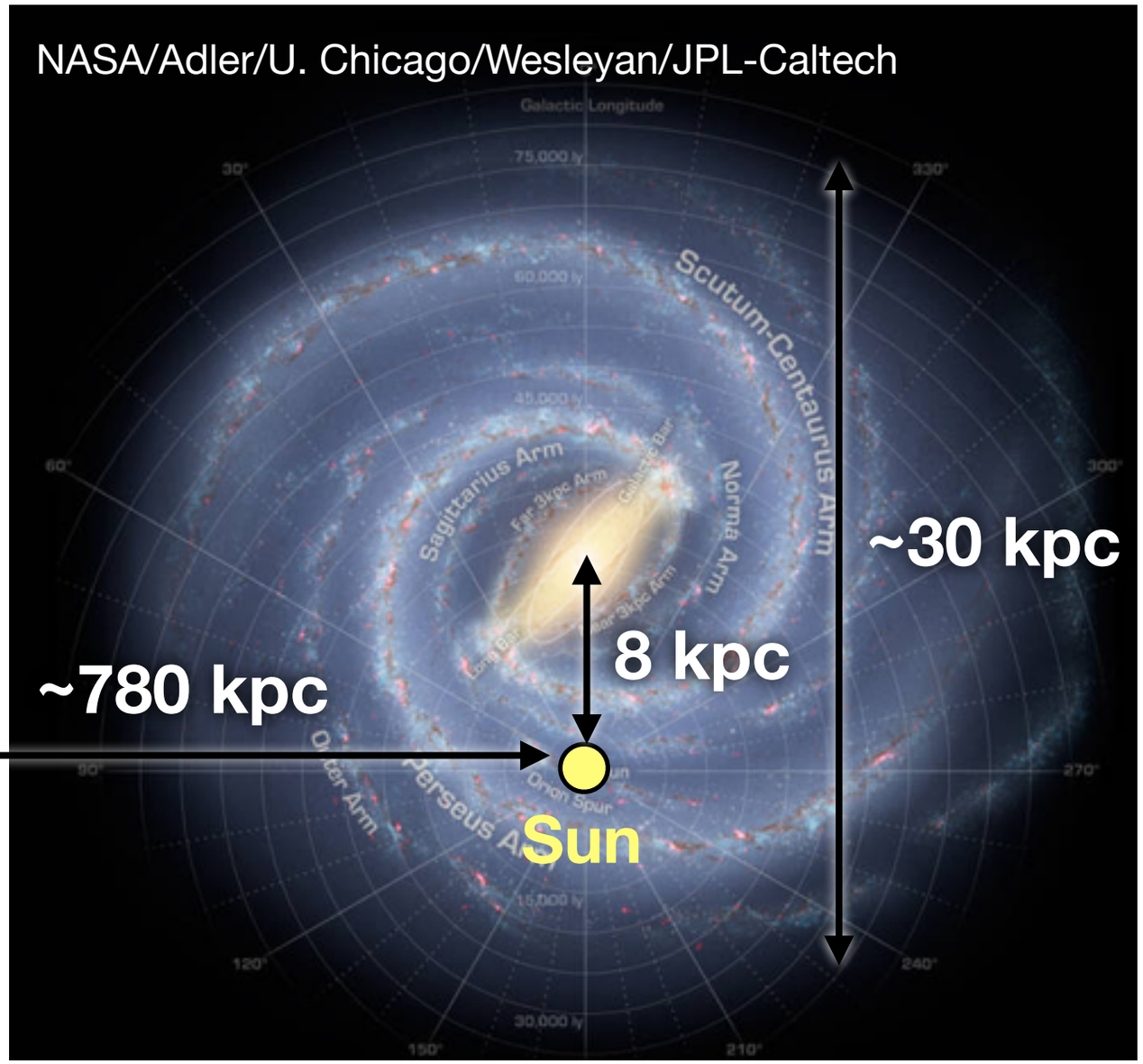



- Supernovae and AGN release large energies.
- They probably heat surrounding ISM and drive outflow from galaxies.
- X-rays from outflowing hot gas are a direct tracer, and some extreme cases are actually observed (starburst galaxies, nearby AGNs).
- How about in “normal” galaxies? Observational test is still on the way.

# Target: the Milky Way Galaxy

Andromeda galaxy



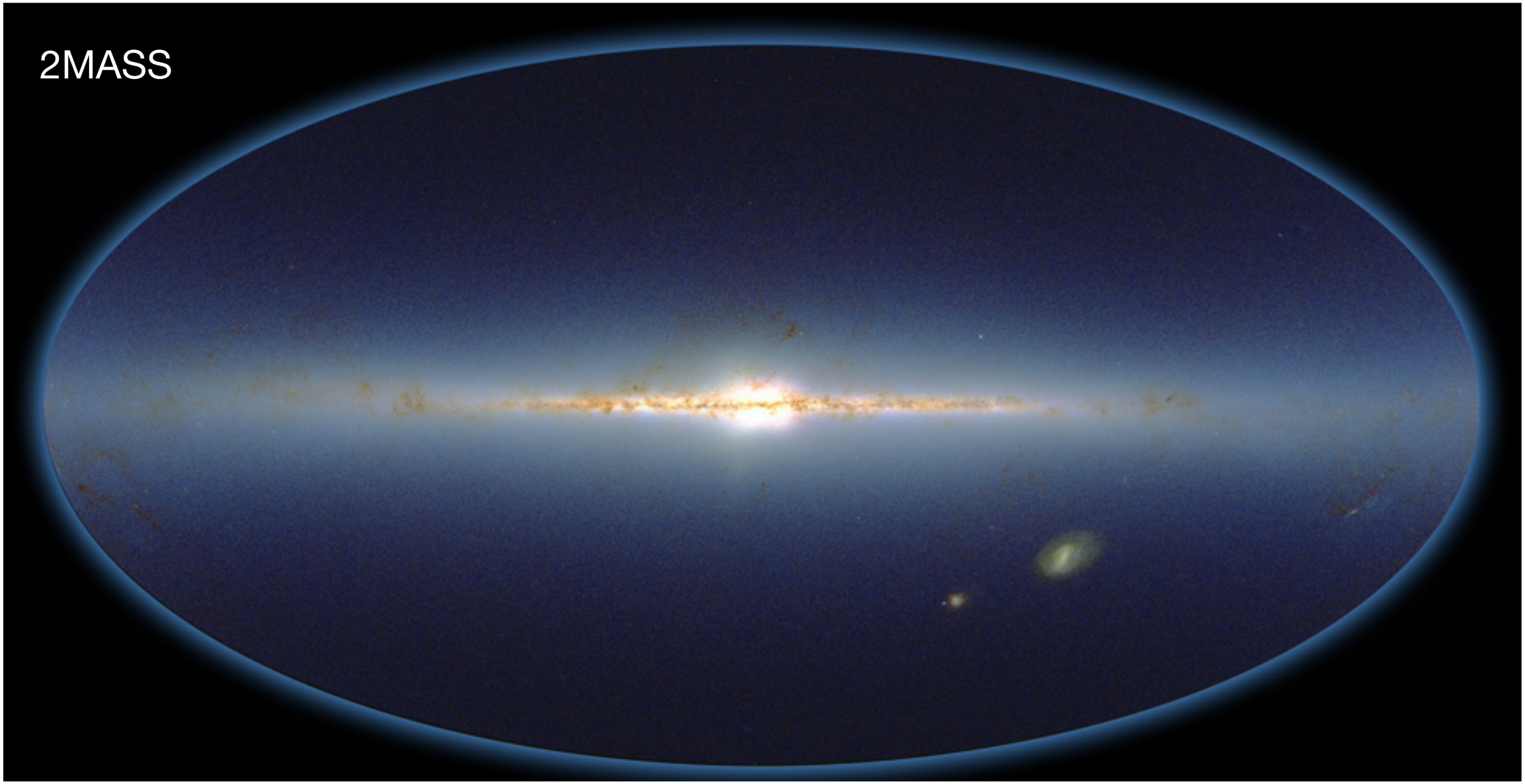

**Pros:**

- Proximity: resolve detailed structures & good photon statistics.
- Normal spiral galaxy:  moderate SFR & no AGN

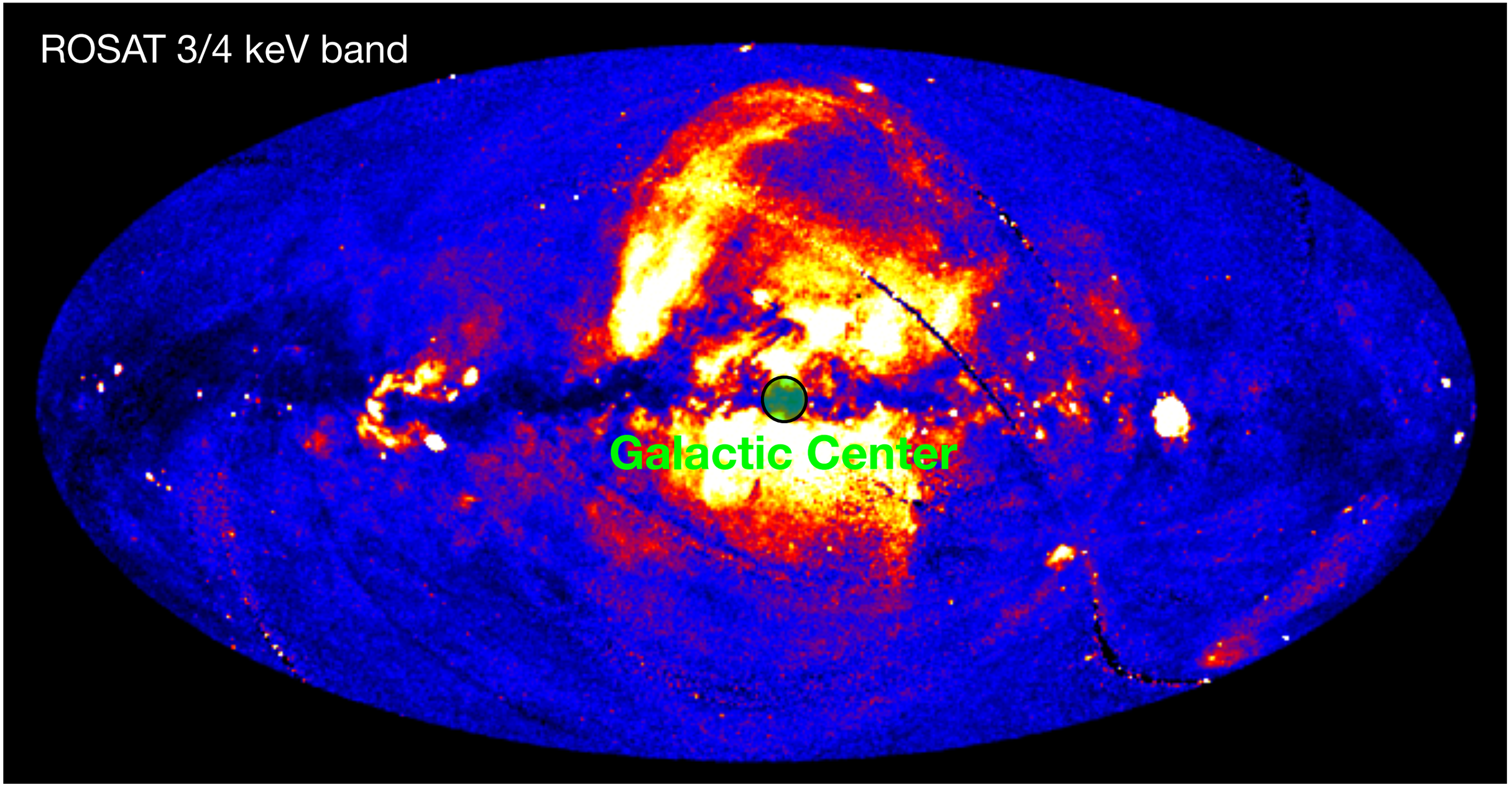
**Cons:**

- We are in the MW: difficult to identify 3D structure.
  -> but observed X-ray absorption columns give a hint.

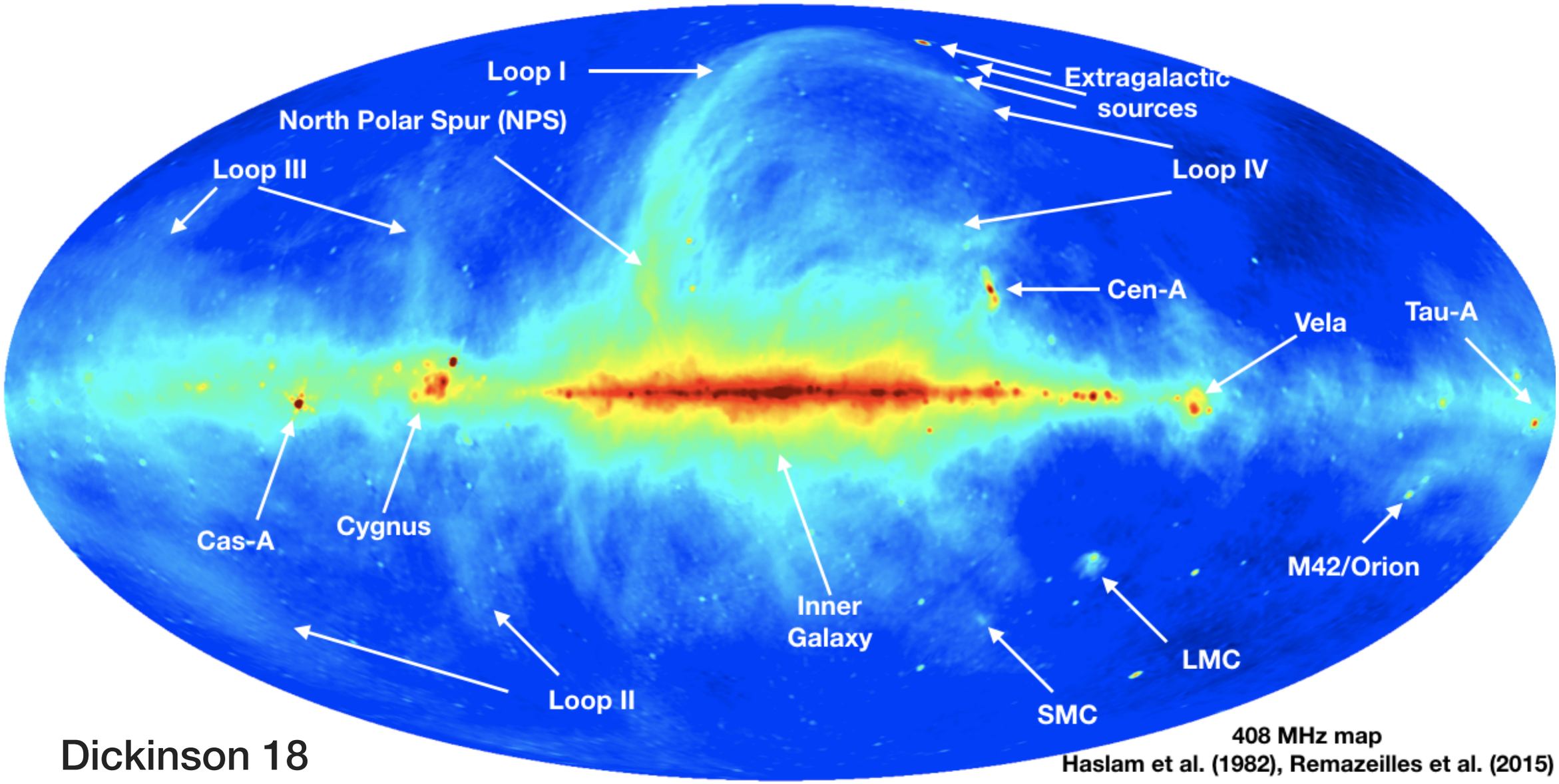
# All-sky view in near-infrared



# All-sky view in X-ray



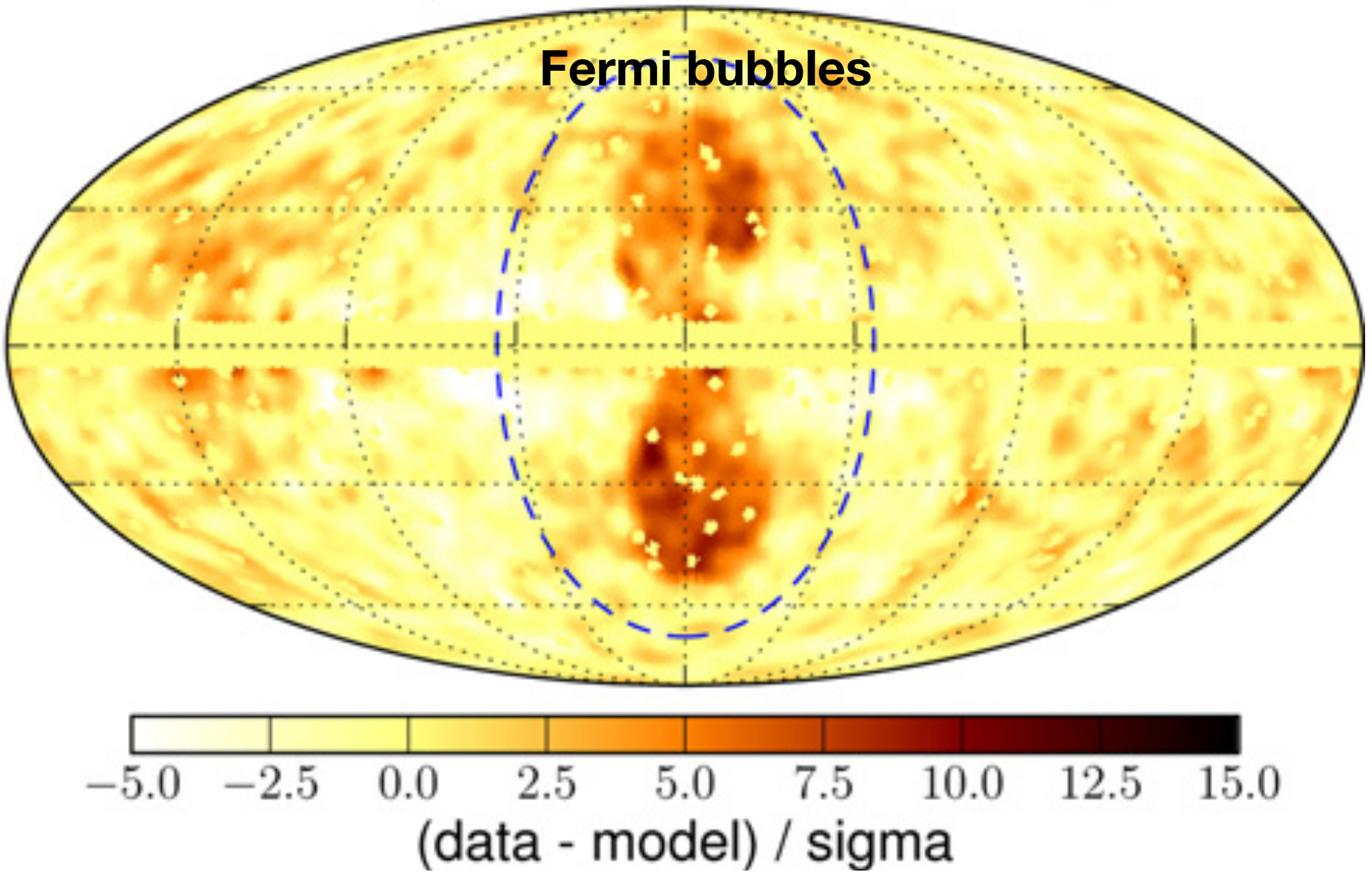
# All-sky view in radio continuum




Dickinson 18

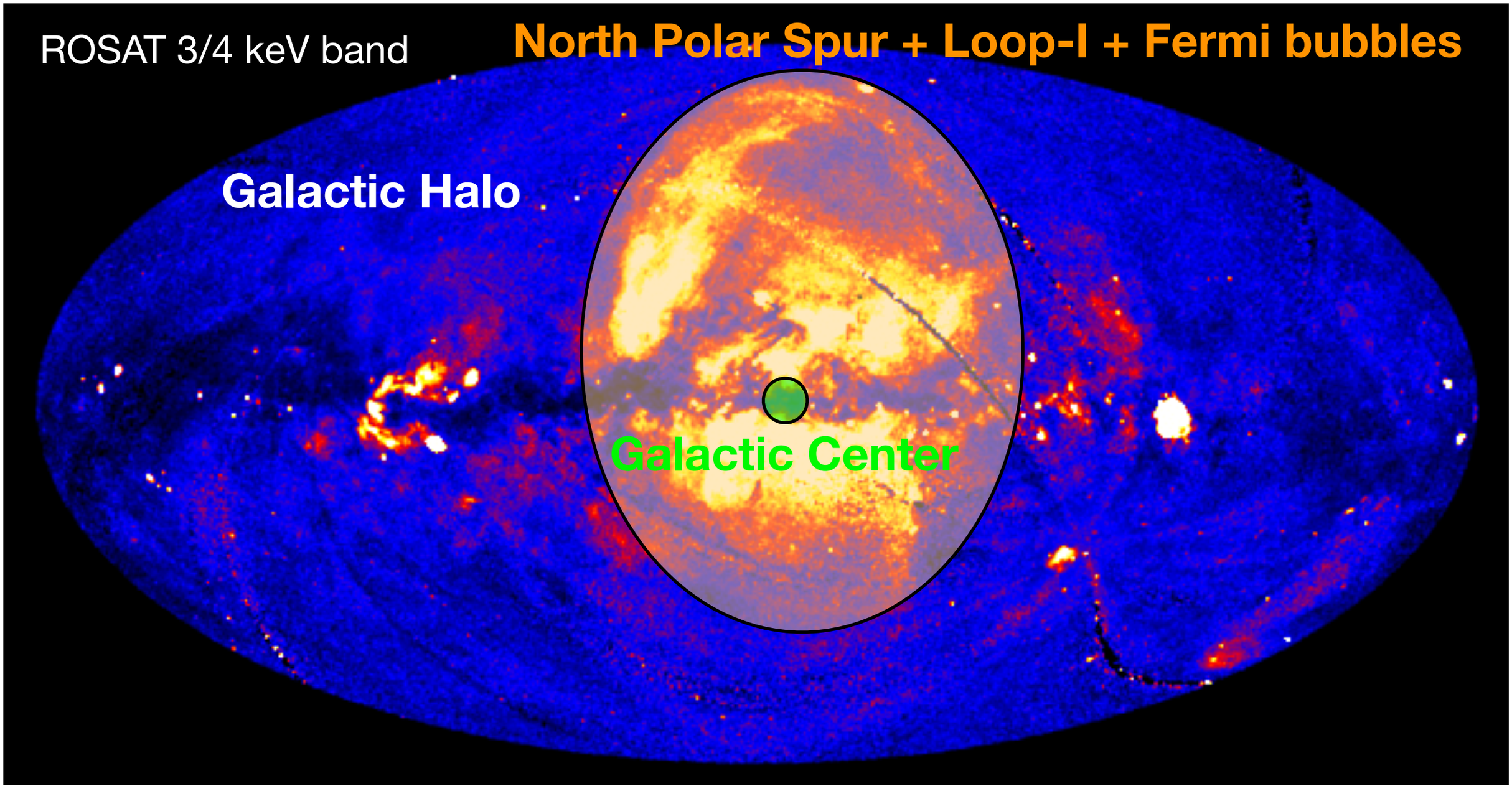
408 MHz map
Haslam et al. (1982), Remazeilles et al. (2015)

# Fermi bubbles: Gamma-ray counterpart?




- Fermi satellite found GeV gamma-ray bubbles above/below the Galactic center

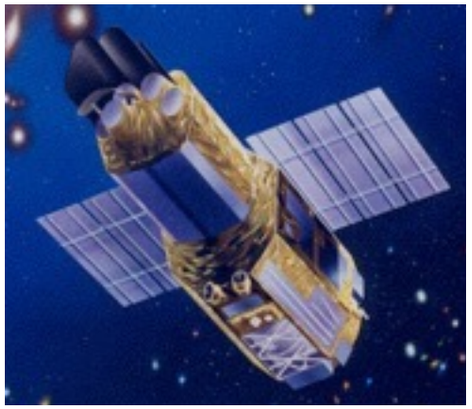
# All-sky view in X-ray



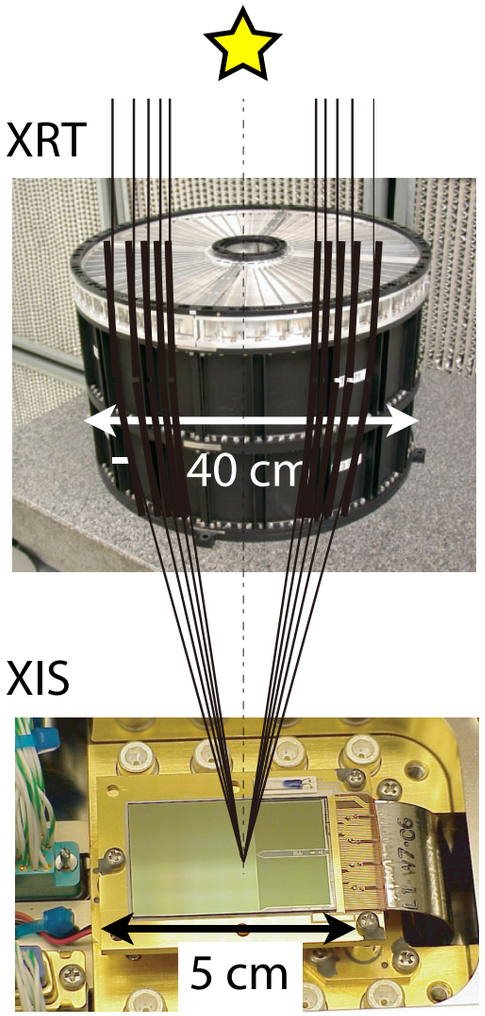

Energy band & resolution are limited in ROSAT (promotional counter)

-> High quality imaging spectrometer (CCD) is necessary to derive physical parameters.

# Suzaku X-ray observatory



- Japanese 5th X-ray astronomy satellite launched in 2005
- X-ray telescope + X-ray CCD (& non-imaging hard X-ray detector )
- Good spectroscopic performance, large effective area, and very low instrumental background

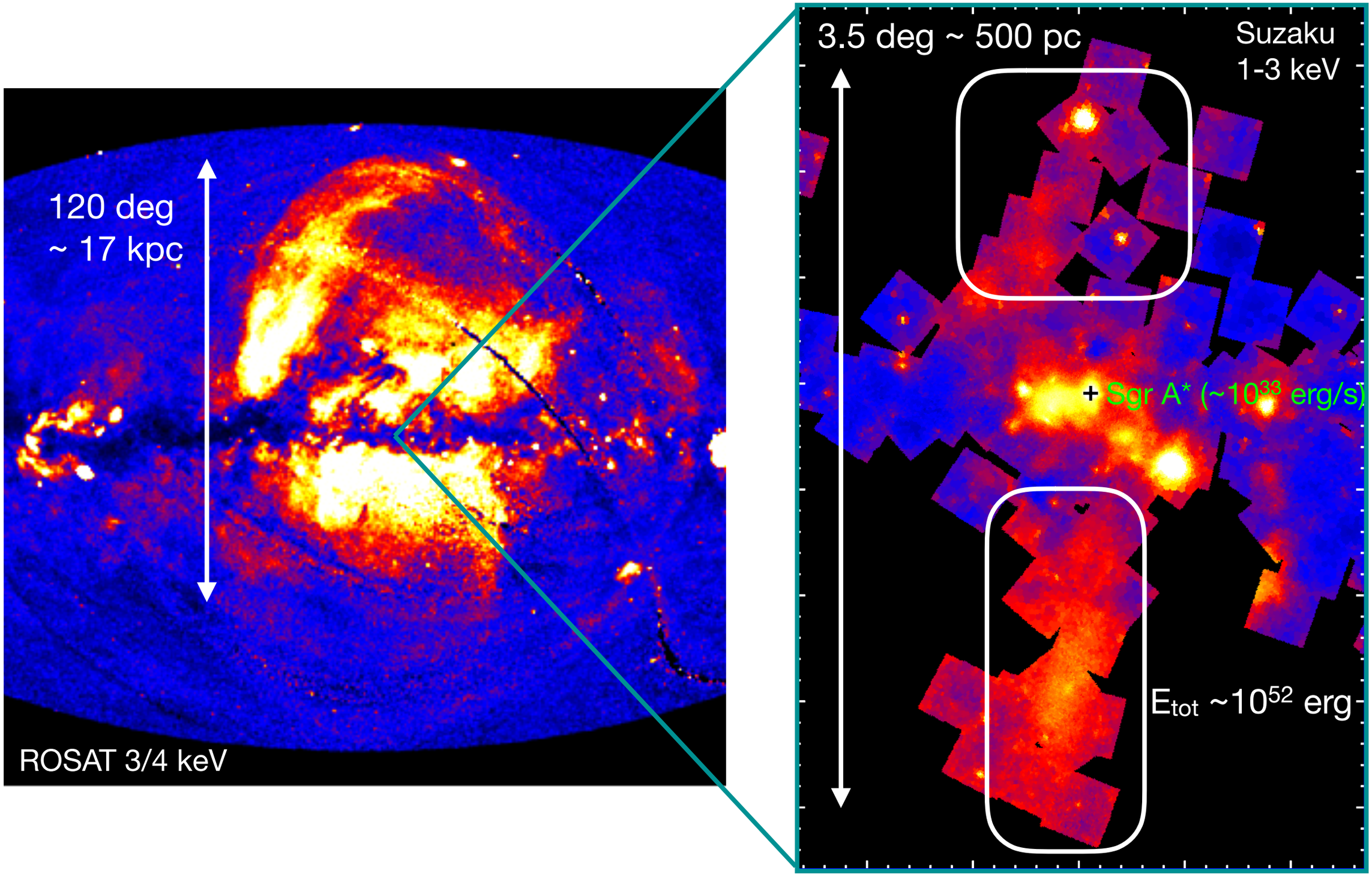



Comparison between CCDs in different X-ray satellites

| Name | FoV | Spatial resolution | Energy resolution | Effective area @1.5 keV | Relative background level |
|---|---|---|---|---|---|
| **Suzaku** | 18’ | 120” | 130 eV | 1000 $cm^2$ | 1 |
| **Chandra** | 1’ | 0.5” | 200 eV | 600 $cm^2$ | 2-5 |
| **XMM-Newton** | 30’ | 15” | 130 eV | 1200 $cm^2$ | 2-5 on flare >10 |
| **Swift** | 24’ | 18” | 140 eV | 110 $cm^2$ | 1 |

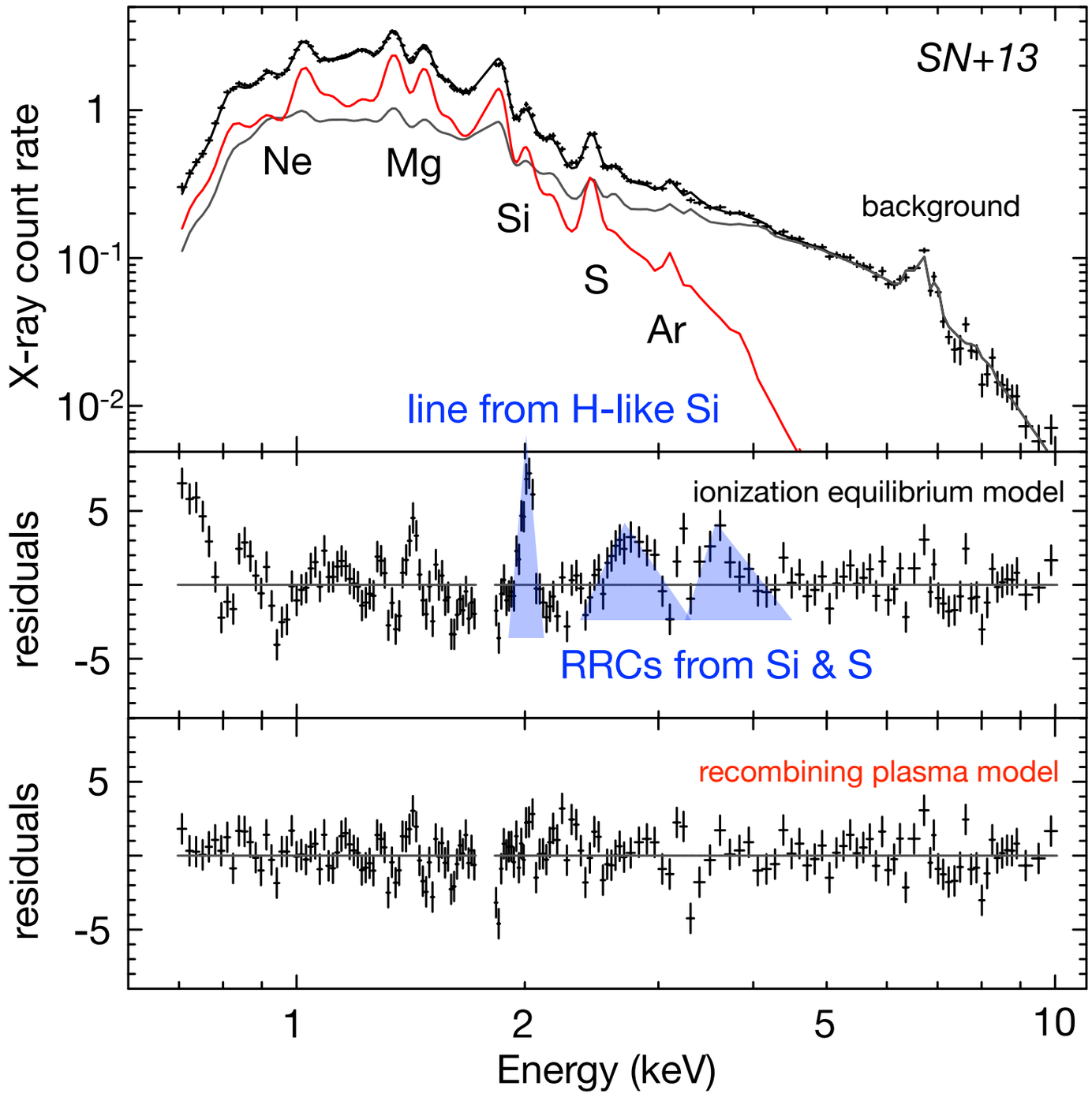
**The highest sensitivity and spectroscopic performance for diffuse source**

# Suzaku view of the Galactic Center




Extended X-ray features were discovered by Suzaku

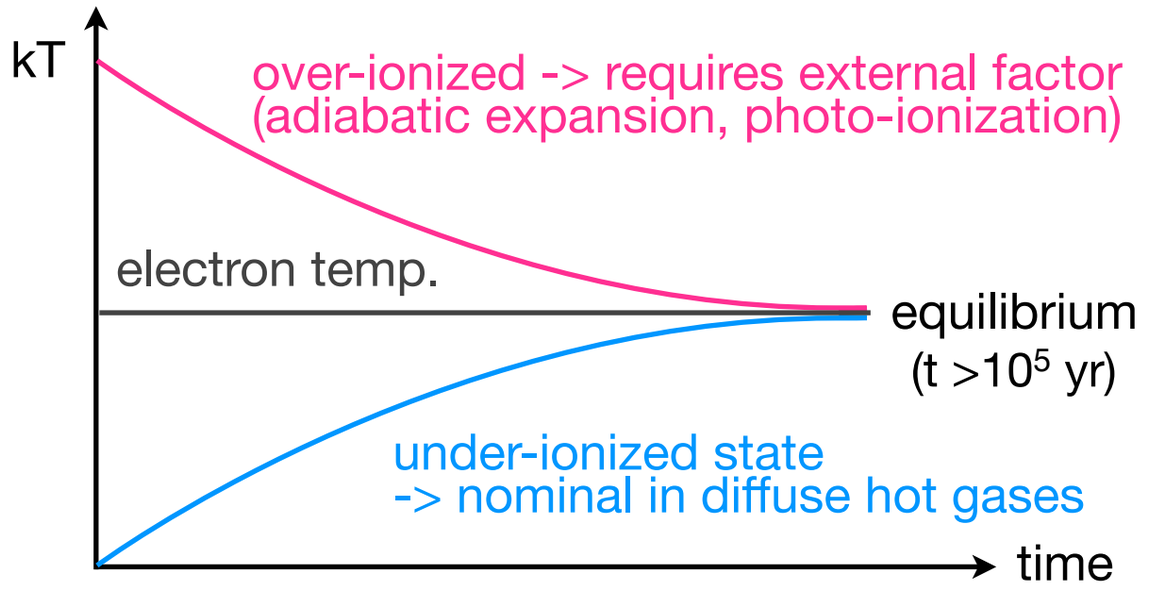
# X-ray spectroscopy of the diffuse hot gas




- Detect emission lines from highly ionized elements -> thin thermal plasma
- Fit with a collisional ionization plasma model

**free-free (bremsstrahlung)** -> electron temp.
**free-bound (RRC)** -> ionization degrees
**bound-bound (line)** -> metallicity
**absorption due to ISM** -> distance

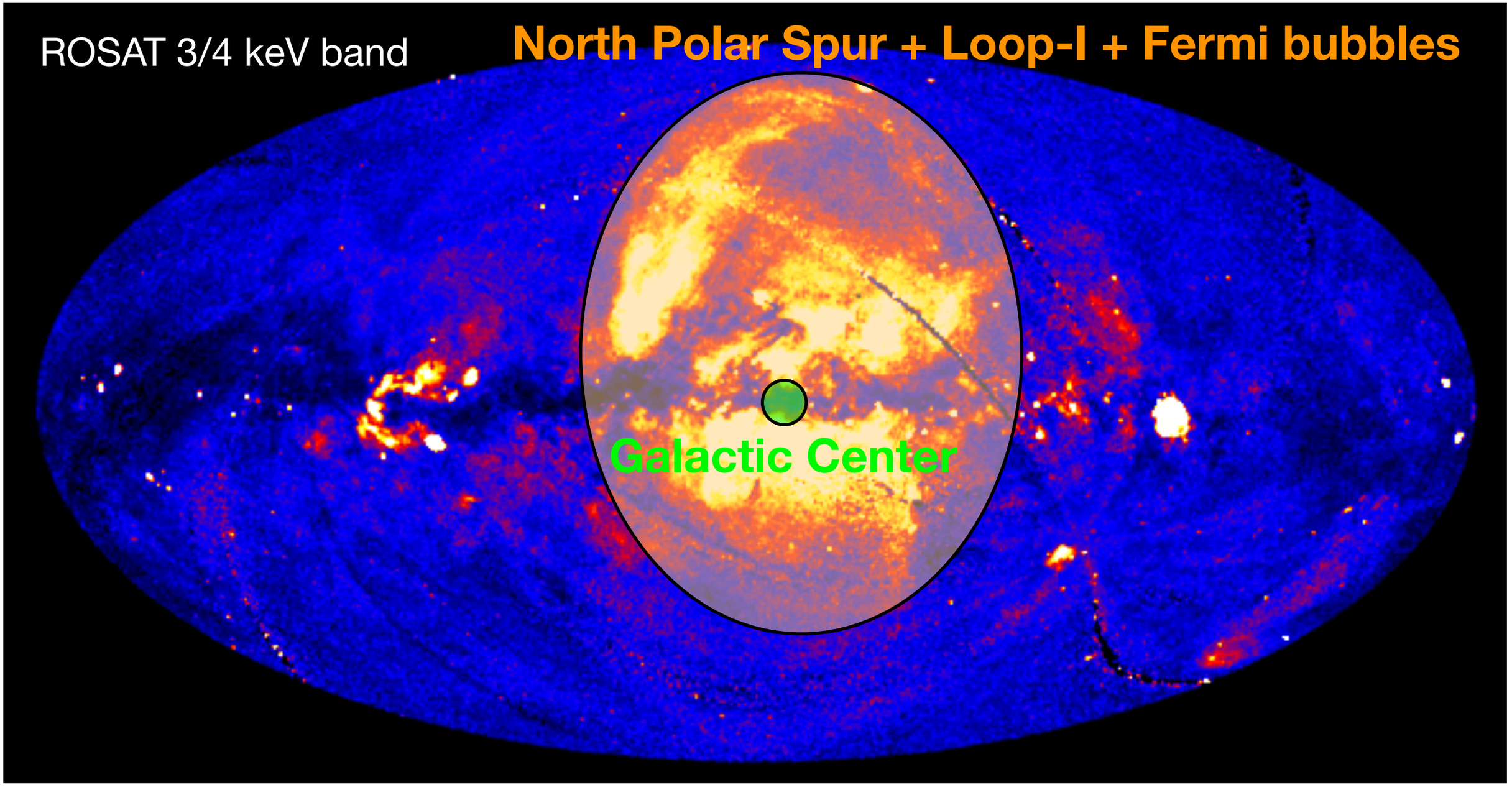
- RRCs are enhanced -> recombination process is dominant in the plasma (non-equilibrium, recombining plasma)



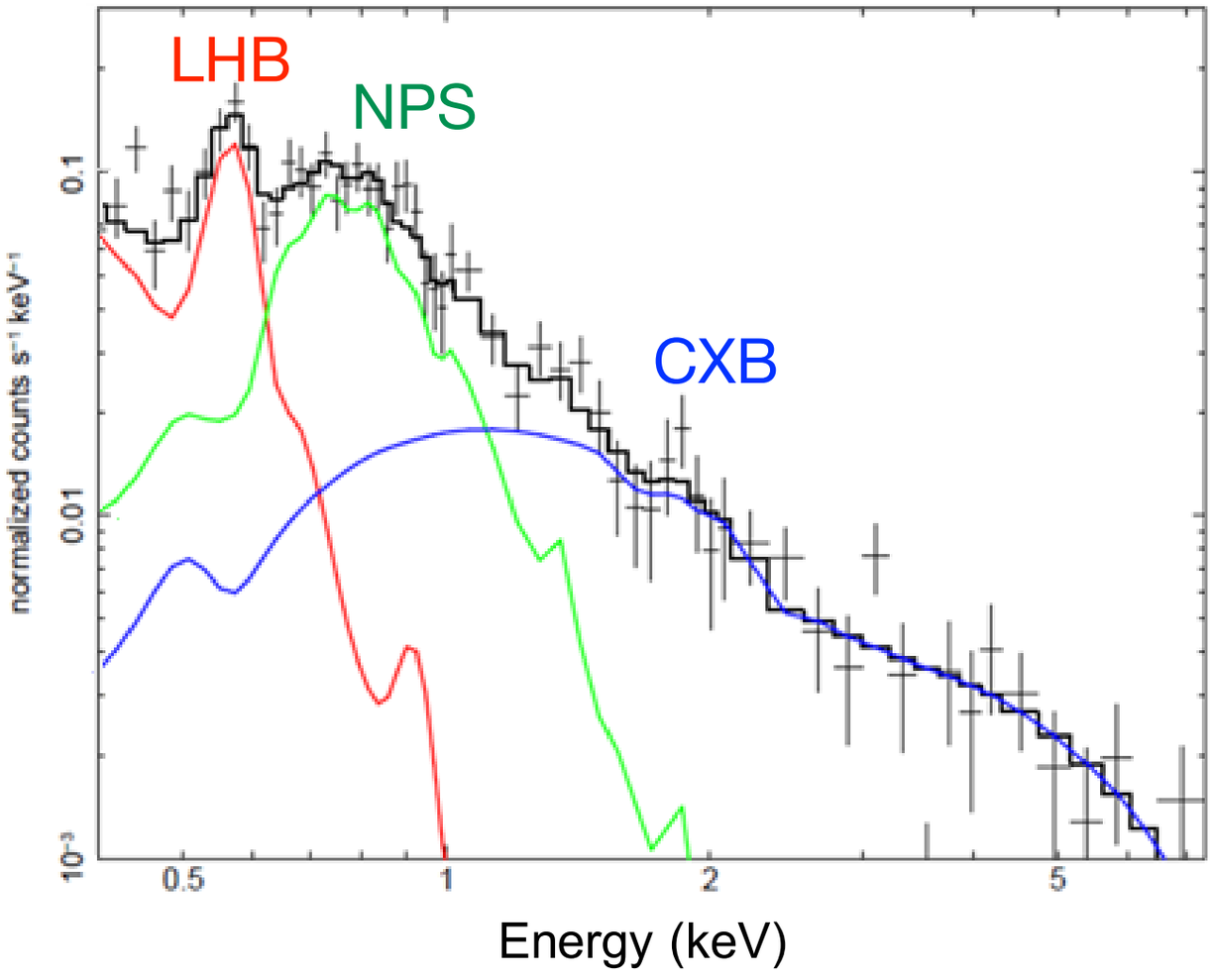

Required energy input is >$10^{39}$ erg/s
-> Past (0.1 My ago) explosion event is necessary.
Starburst or Sgr A* flare ?

$N_H$ ~ 7 x $10^{21}$ $cm^{-2}$ -> **GC distance**
kTe ~ 0.5 keV, Z ~ 0.8 Zsun,
nt ~ 5 x $10^{11}$ s $cm^{-3}$ (n ~ 0.1 $cm^{-3}$, **t ~ 0.1 Myr**)

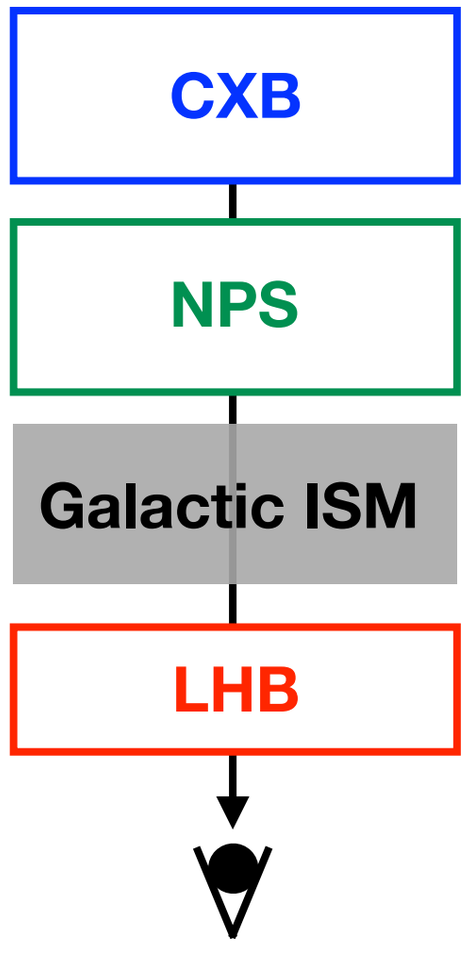
# NPS + Loop-I + Fermi bubbles



# X-ray spectrum of NPS




Spectra are represented by 3 components



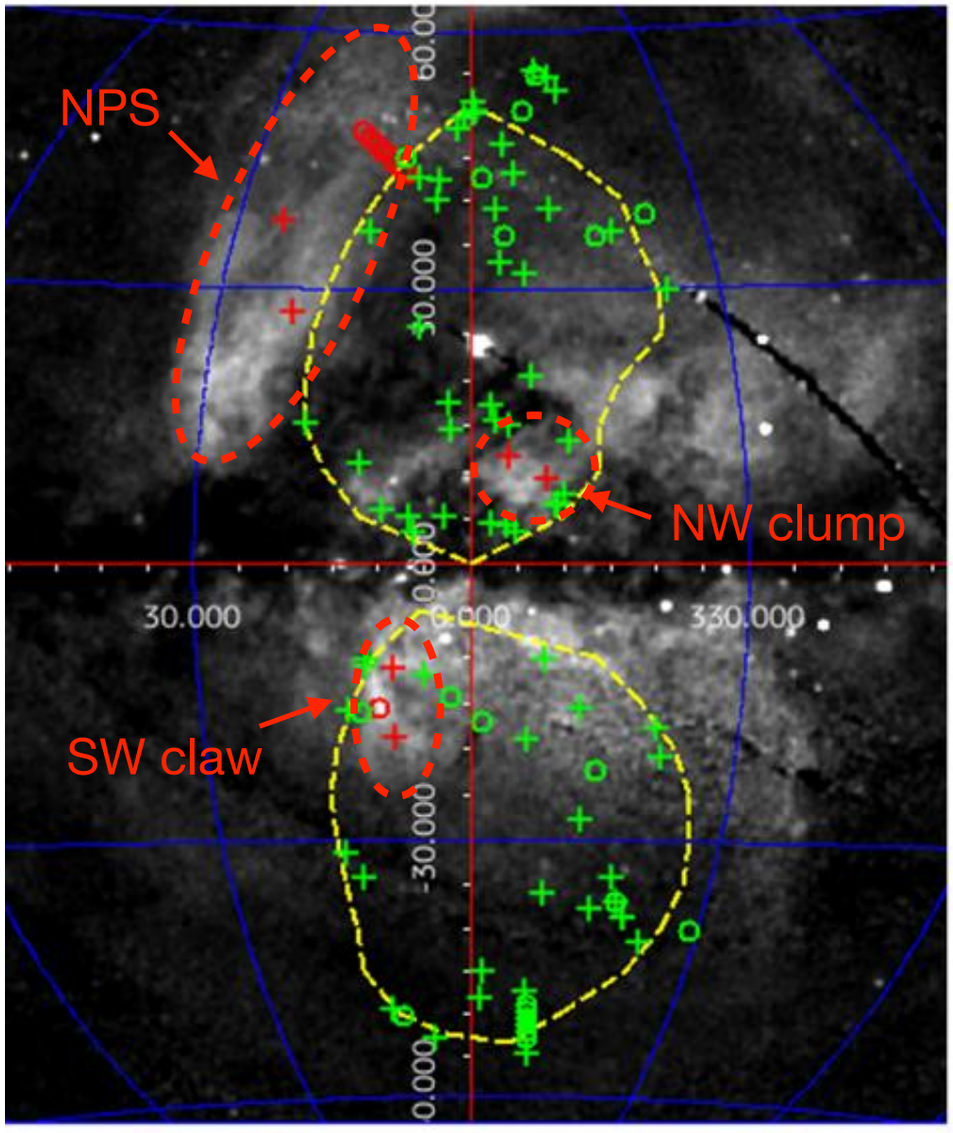

Γ = 1.45
w/ absorption

kT ~ 0.3 keV
w/ absorption

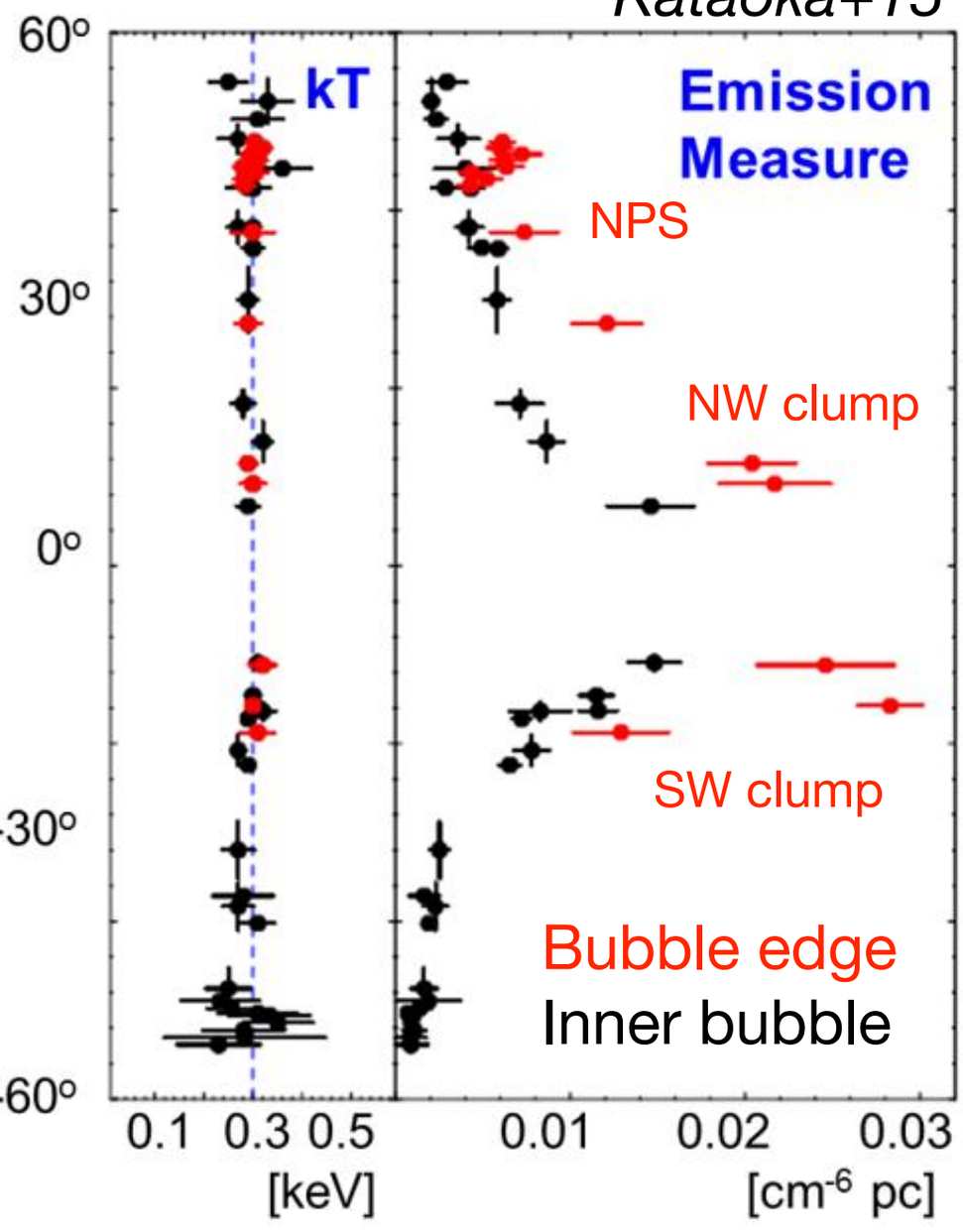
$N_H$ from HI obs.

kT = 0.1 keV
w/o absorption

# X-ray survey across Fermi bubbles



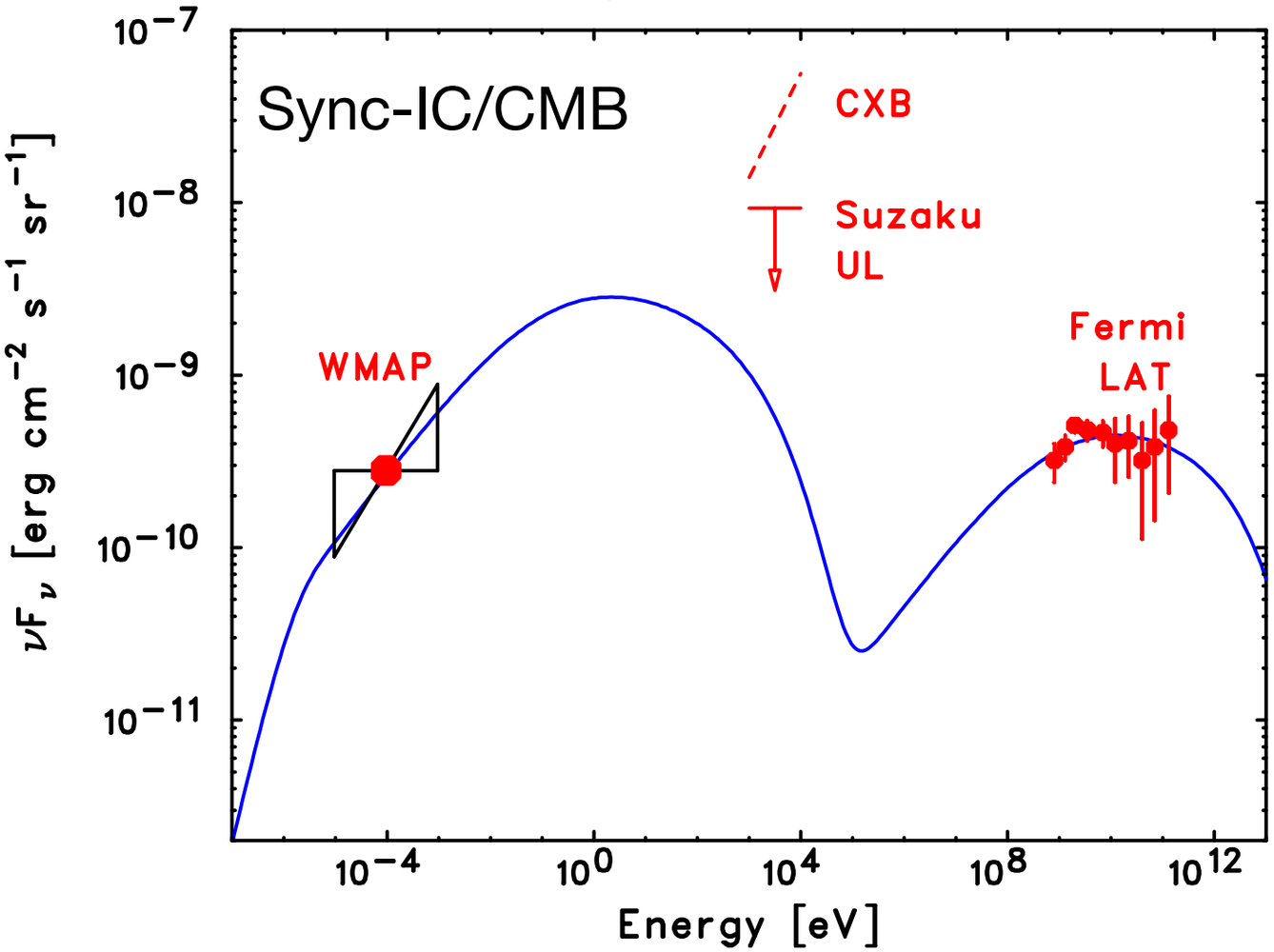

*Kataoka+15*




- Ubiquitous kT ~ 0.3 keV plasma with $N_H$ ~ $N_{Gal}$ as same as NPS.
- Significant enhancement of EM near the bubbles' edge. -> compression of GH?
- Assuming shock compression of ~0.2 keV GH, expansion velocity is ~300 km/s.

# Pressure balance between FB and NPS

*Kataoka+13, see also Ackerman+14*




**FB Non-thermal (leptonic SED model)**

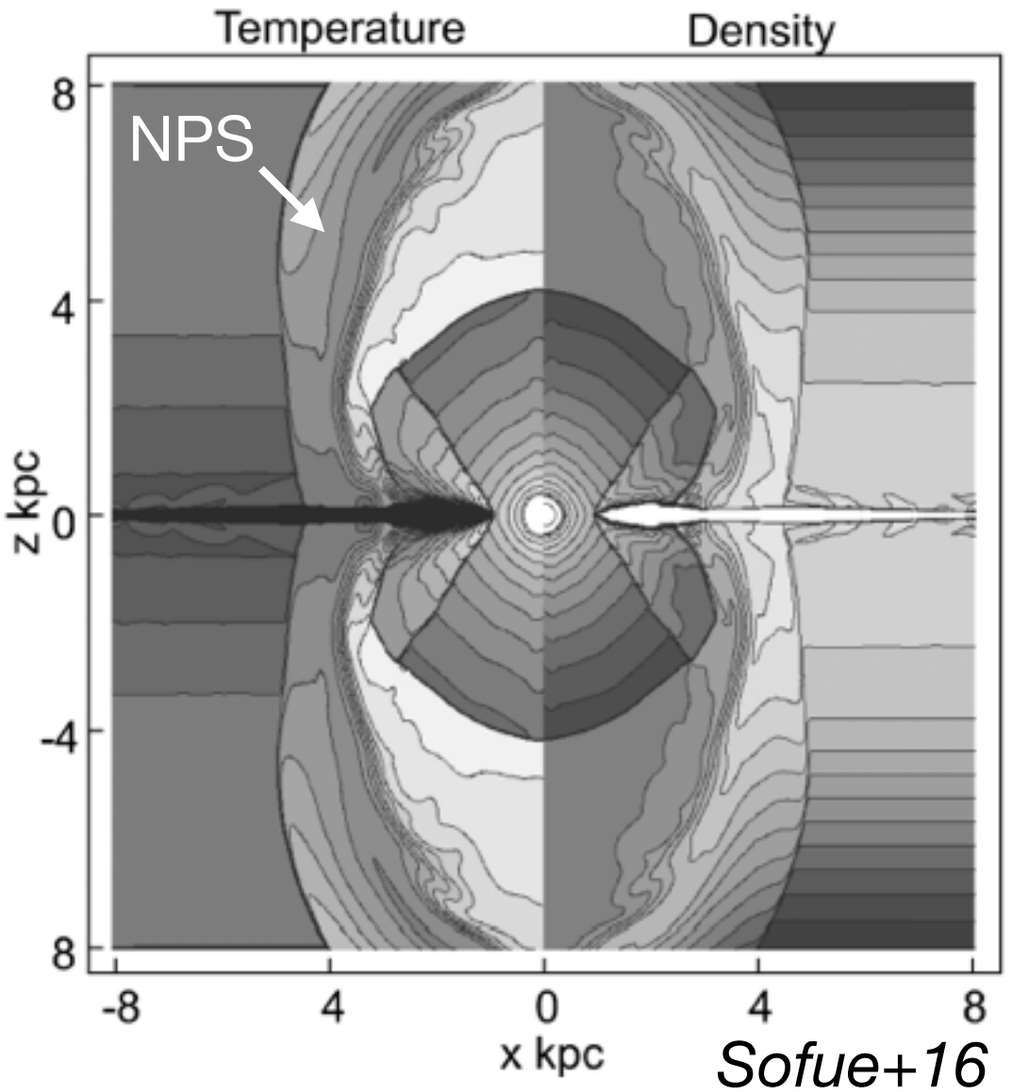
- B = 12 μG
  ($U_B = 5.7\times10^{-12}$ erg/cm$^3$)
- $U_{e,non\text{-}th} = 1.4\times10^{-12}$ erg/cm$^3$
- $P_{non\text{-}th} \sim 2\times10^{-12}$ erg/cm$^3$
- Spherical radius ~ 4 kpc
- $E_{non\text{-}th} \sim 10^{56}$ erg

**Approximately Equipartition**

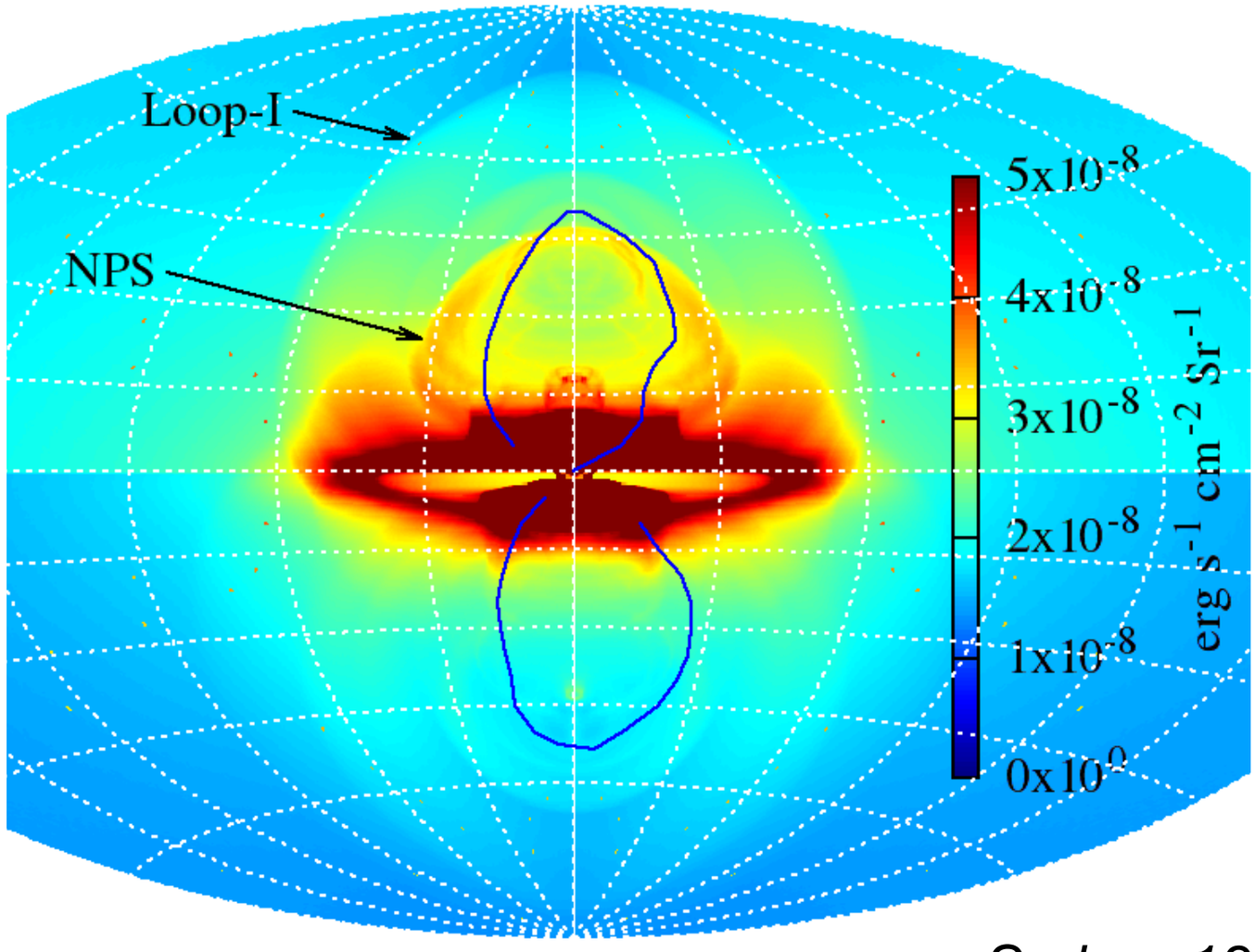
**NPS Thermal (X-ray hot gas)**

- $P_{th} \sim n_e\, kT \sim 3\times10^{-12}$ erg/cm$^3$
  we assume n ~ $5\times10^{-3}$ 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

# HD simulations




*Sofue+16*




*Sarker+18*

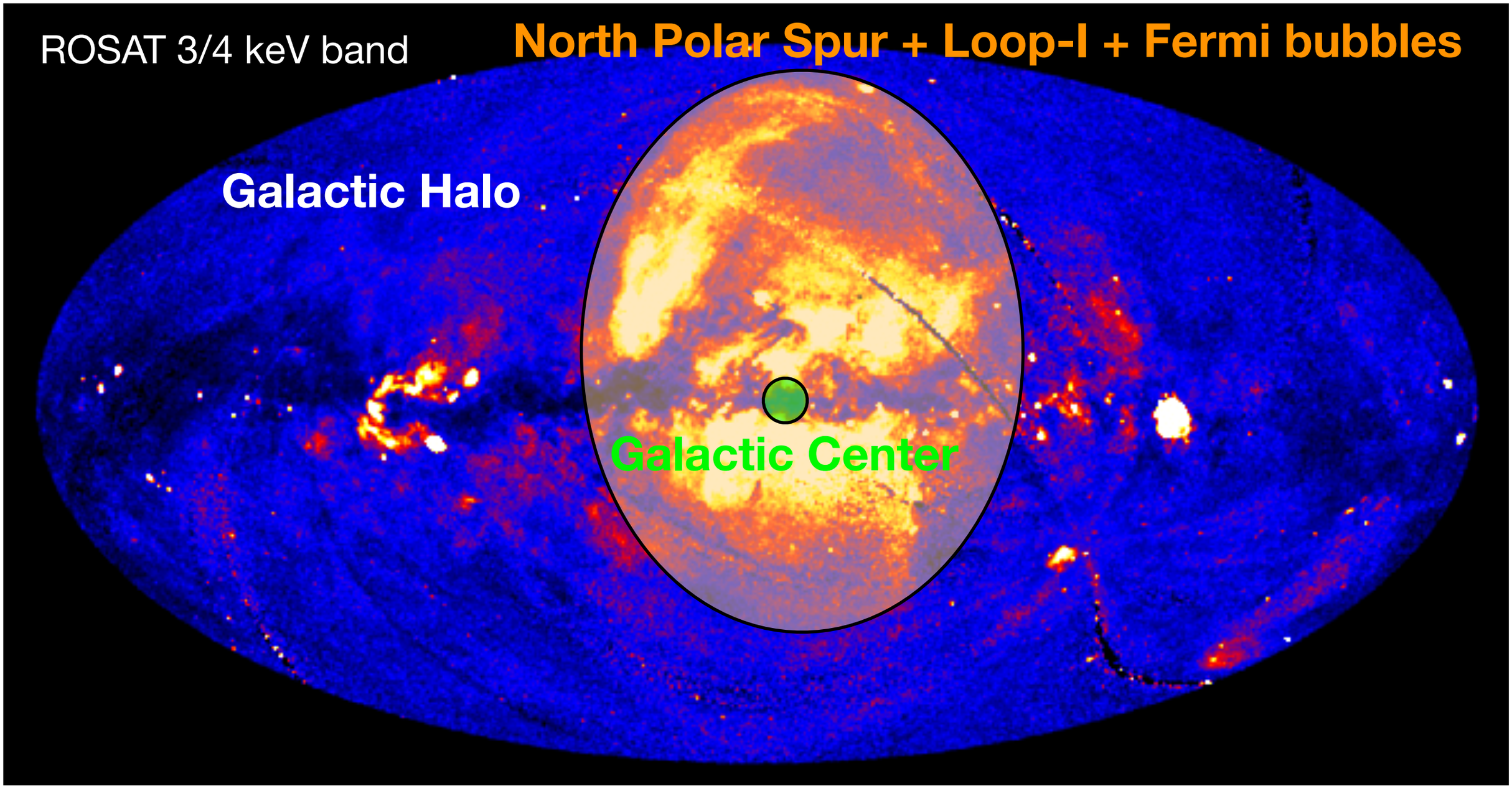
- Sofue+16: Hyper-shell model with E ~ $4\times10^{56}$ erg and t ~ 10 Myr.

  -> Reproduces kT ~ 0.3 keV shell that agrees with the X-ray observations.
- Sarker+18: Different halo gas density between north and south (by ~20%)

  -> Reproduces X-ray asymmetry between north and south.

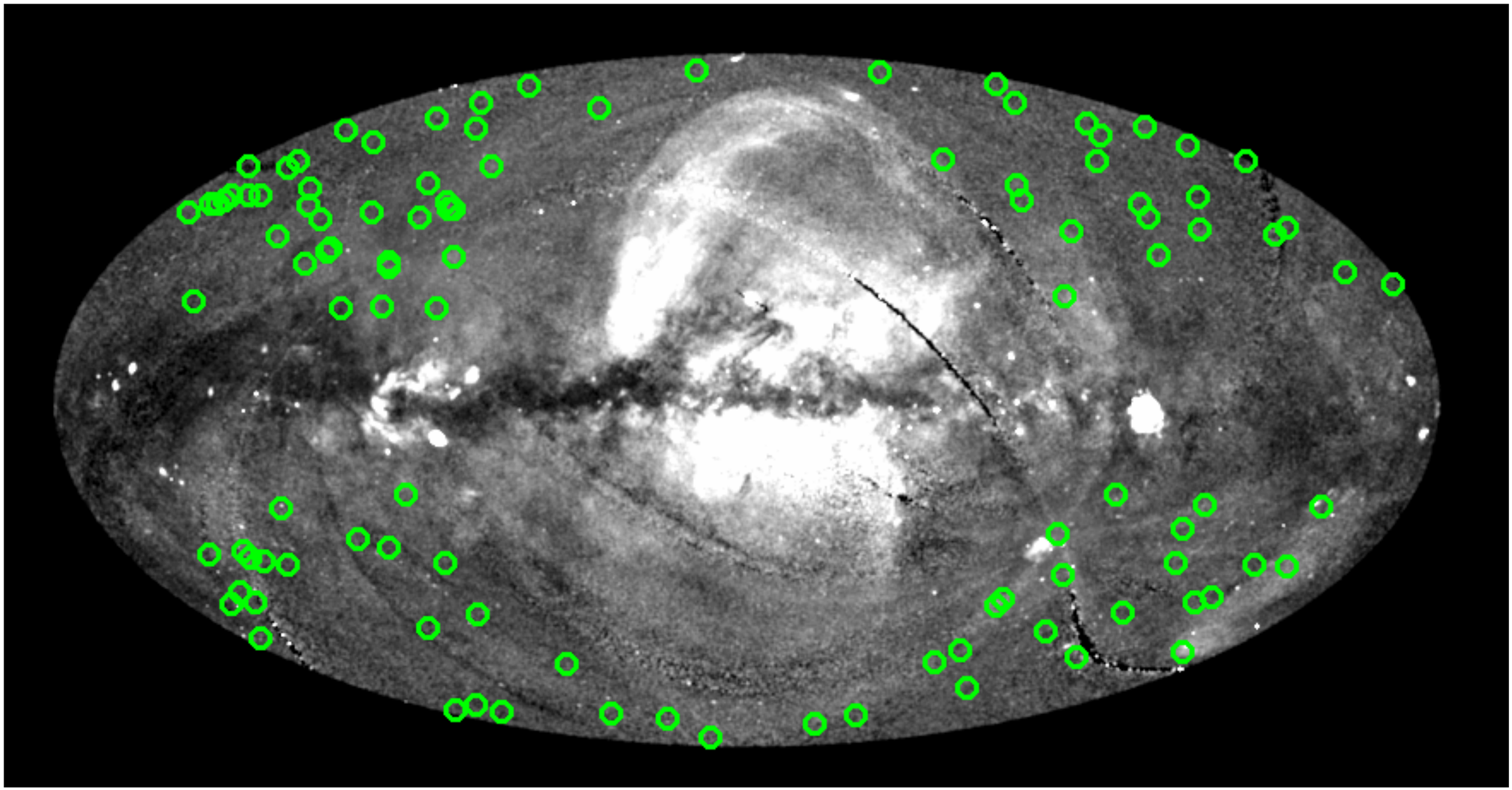
Explosion (starburst of Sgr A* flare ) in the GC is origin of X-ray features (and Fermi bubbles)

# Galactic hot gaseous halo



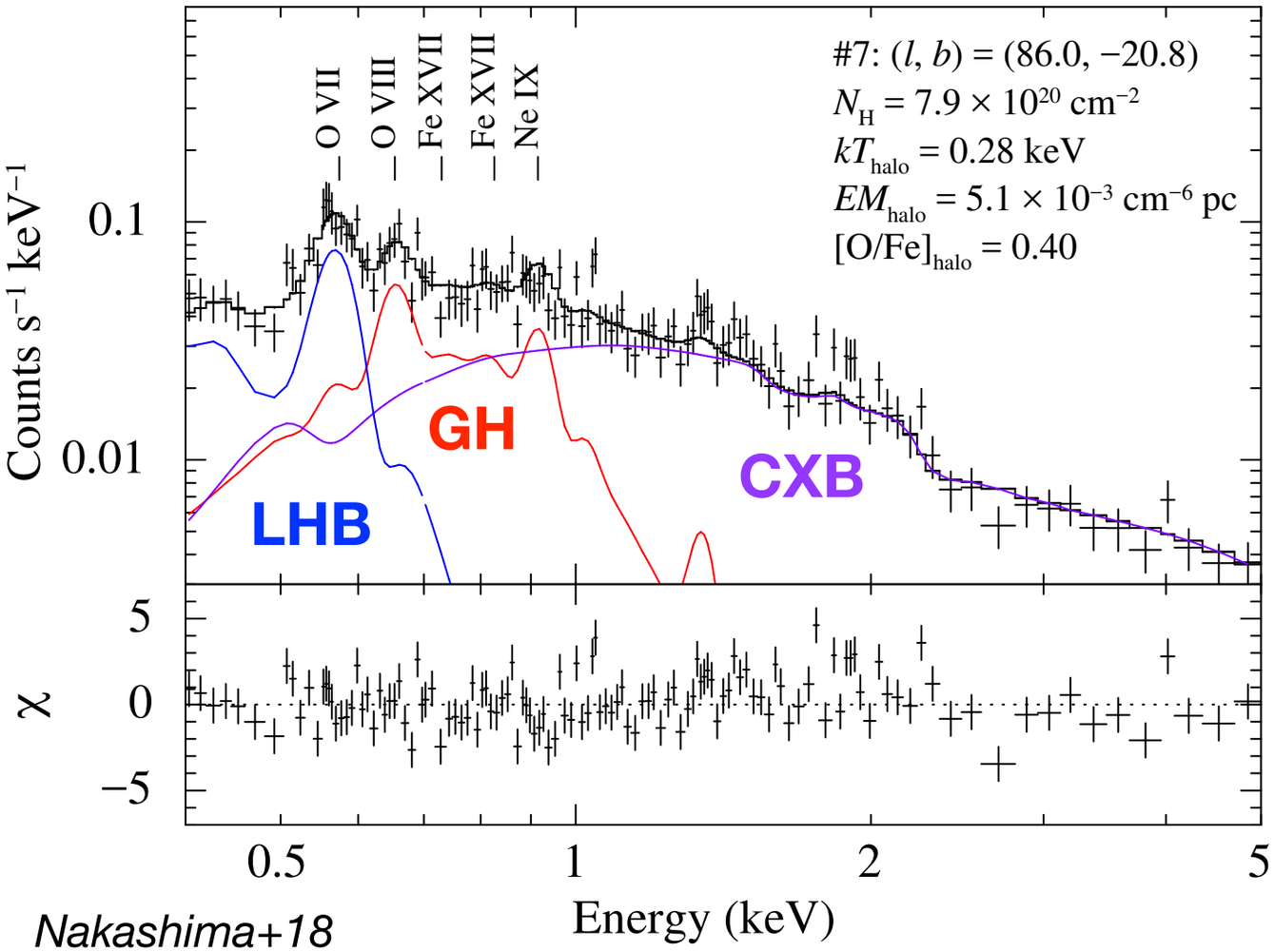

Cosmic X-ray background (superposition of AGNs) explains only 50% of the observed flux

# Observations of Galactic Halo



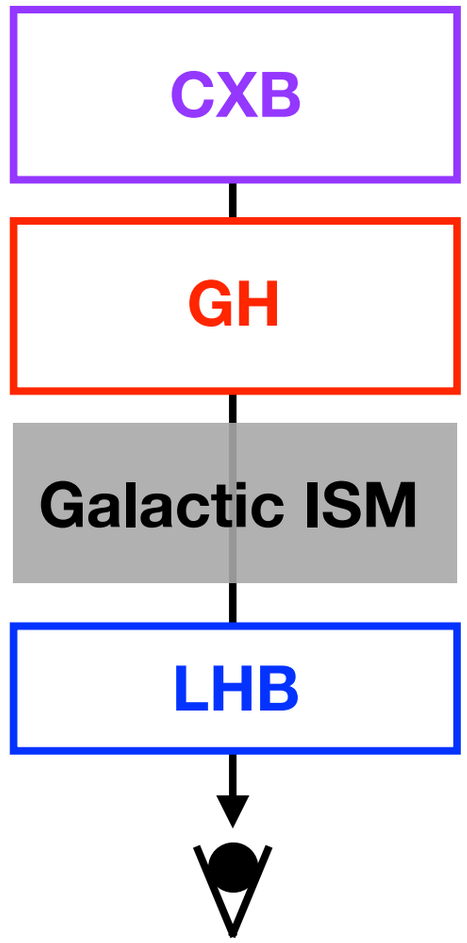
- Uniform analysis of the soft diffuse X-ray emission of 107 fields observed with Suzaku at 75° < l < 285°

# X-ray spectrum of GH




*Nakashima+18*

Spectra are represented by 3 components




Γ = 1.45
w/ absorption

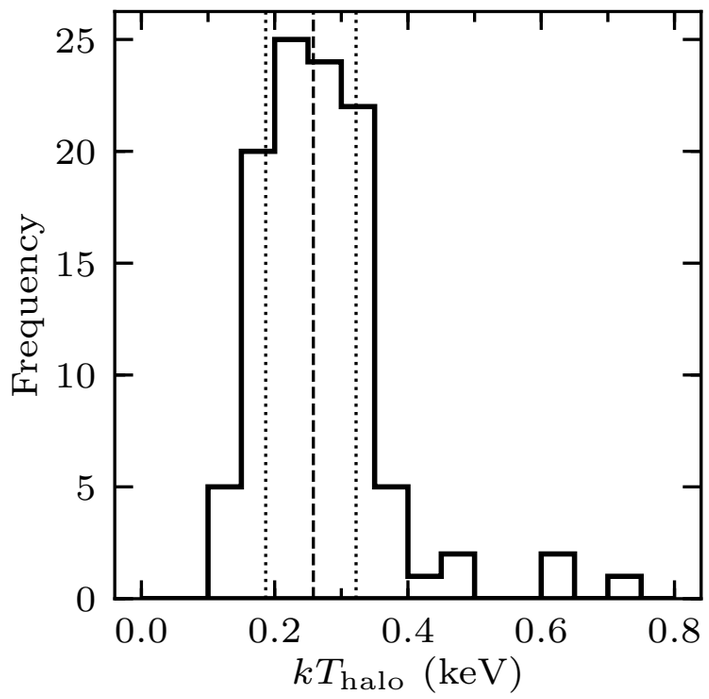
kT ~ 0.2-0.3 keV
w/ absorption

$N_H$ from HI obs.

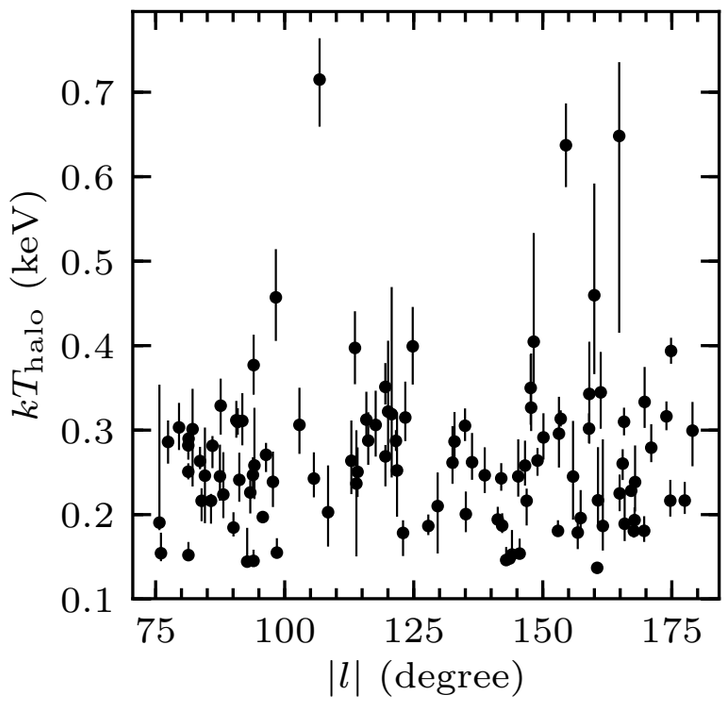
kT = 0.1 keV
w/o absorption

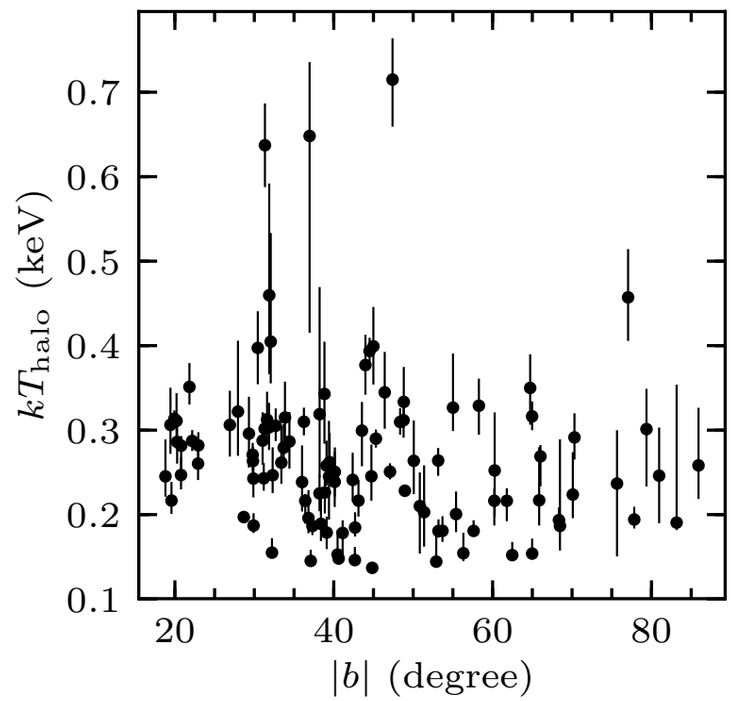
# Temperature & emission measure

kT = 0.26±0.06 keV

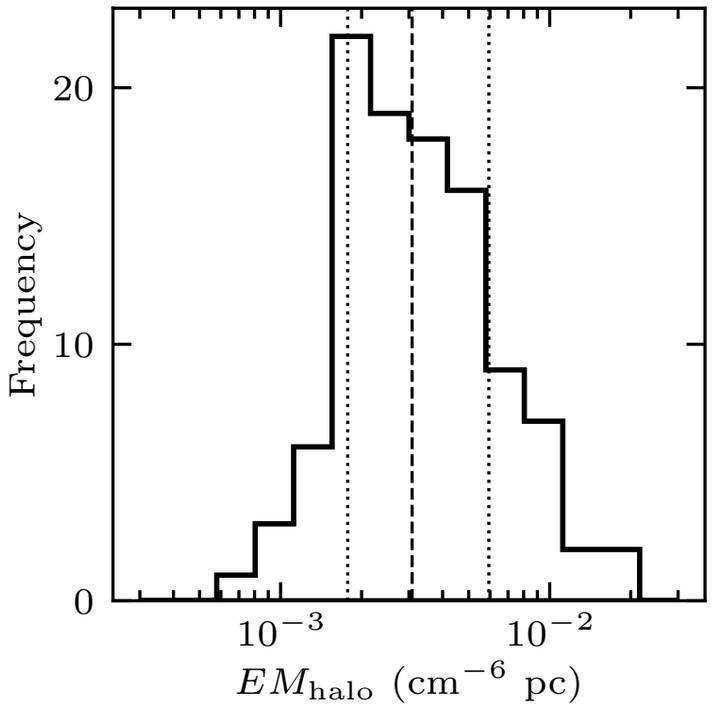



No clear correlation to the Galactic coordinates

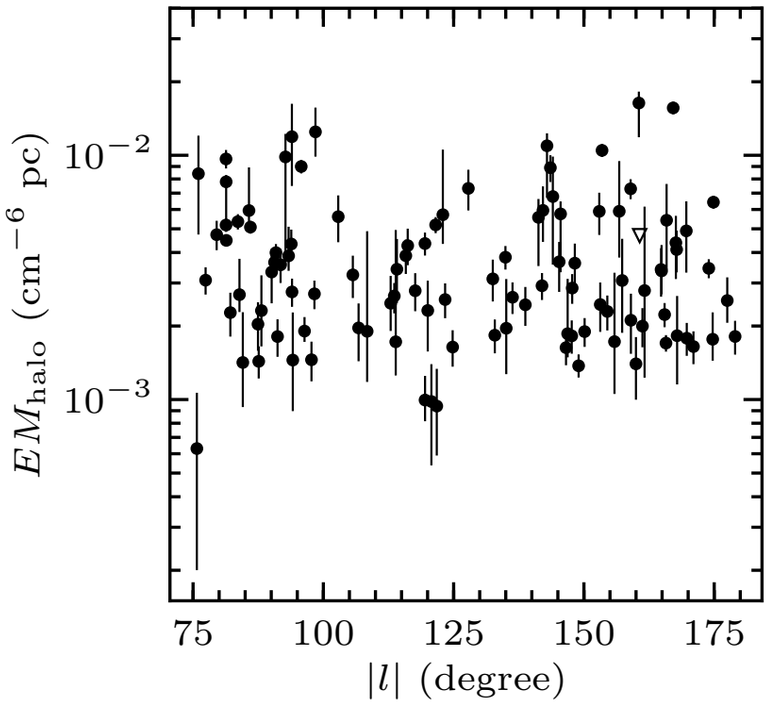


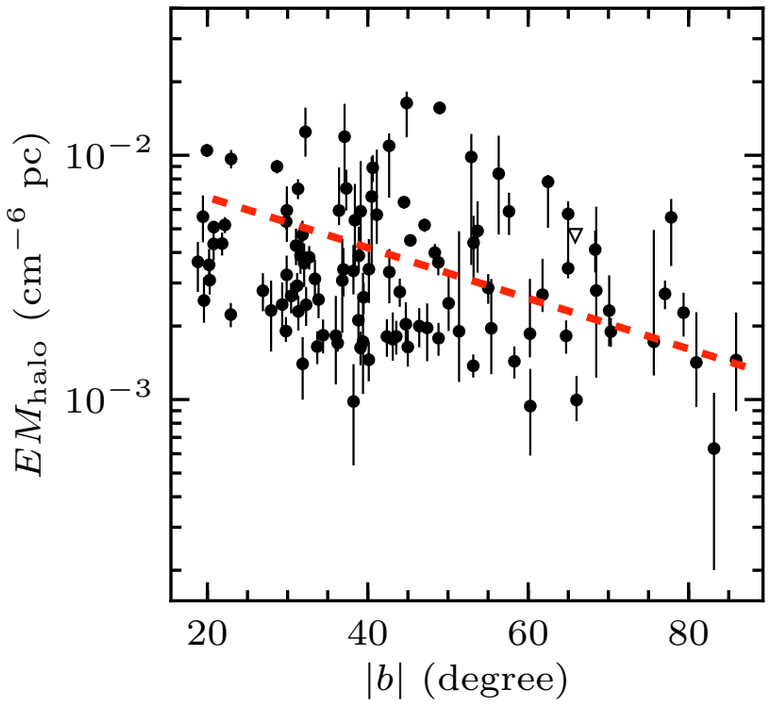




EM = $10^{-3}$-$10^{-2}$ cm$^{-6}$ pc



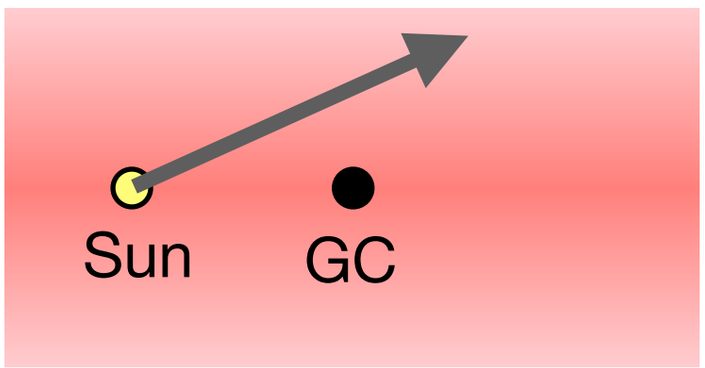

Weak correlation to the Galactic latitude



# Spatial density distribution of GH

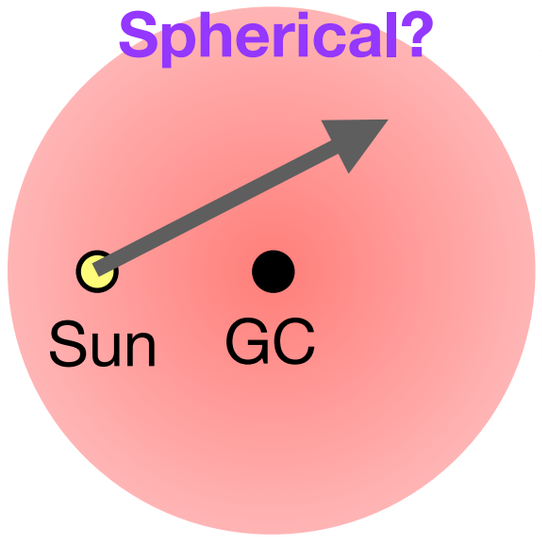
**Disk-like?** *Yao+09; Hagihara+10; Sakai+14*




$$n \propto \exp\left(\frac{R}{R_0}\right)\exp\left(\frac{z}{z_0}\right)$$

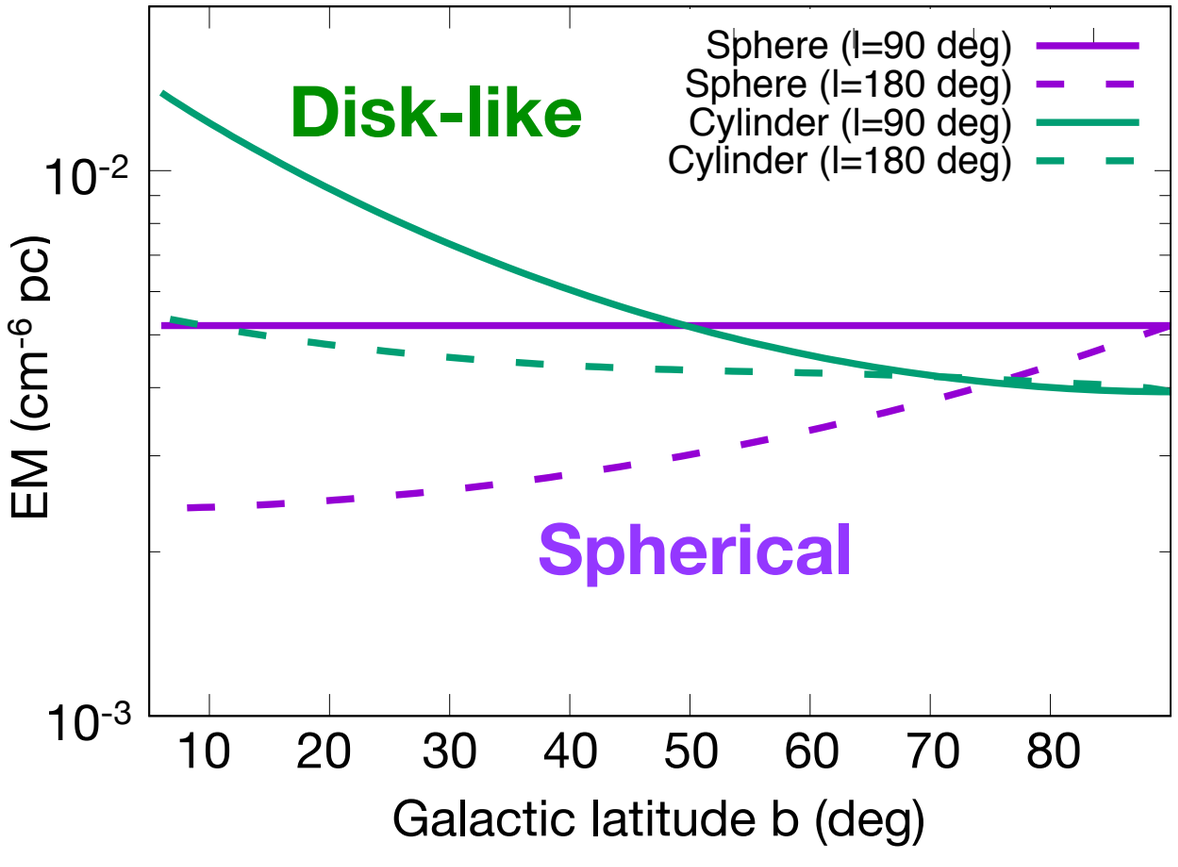
- z ~ 1-5 kpc (thick disk-like)
- outflows from the disk?

**Spherical?** *Miller+13,15; Li+17*




$$n \propto \left(1+\left(\frac{r}{r_c}\right)^2\right)^{-3\beta/2}$$

- β ~ 0.5, $r_c$ ~ 2 kpc (thin spherical)
- accretion of intergalactic medium?

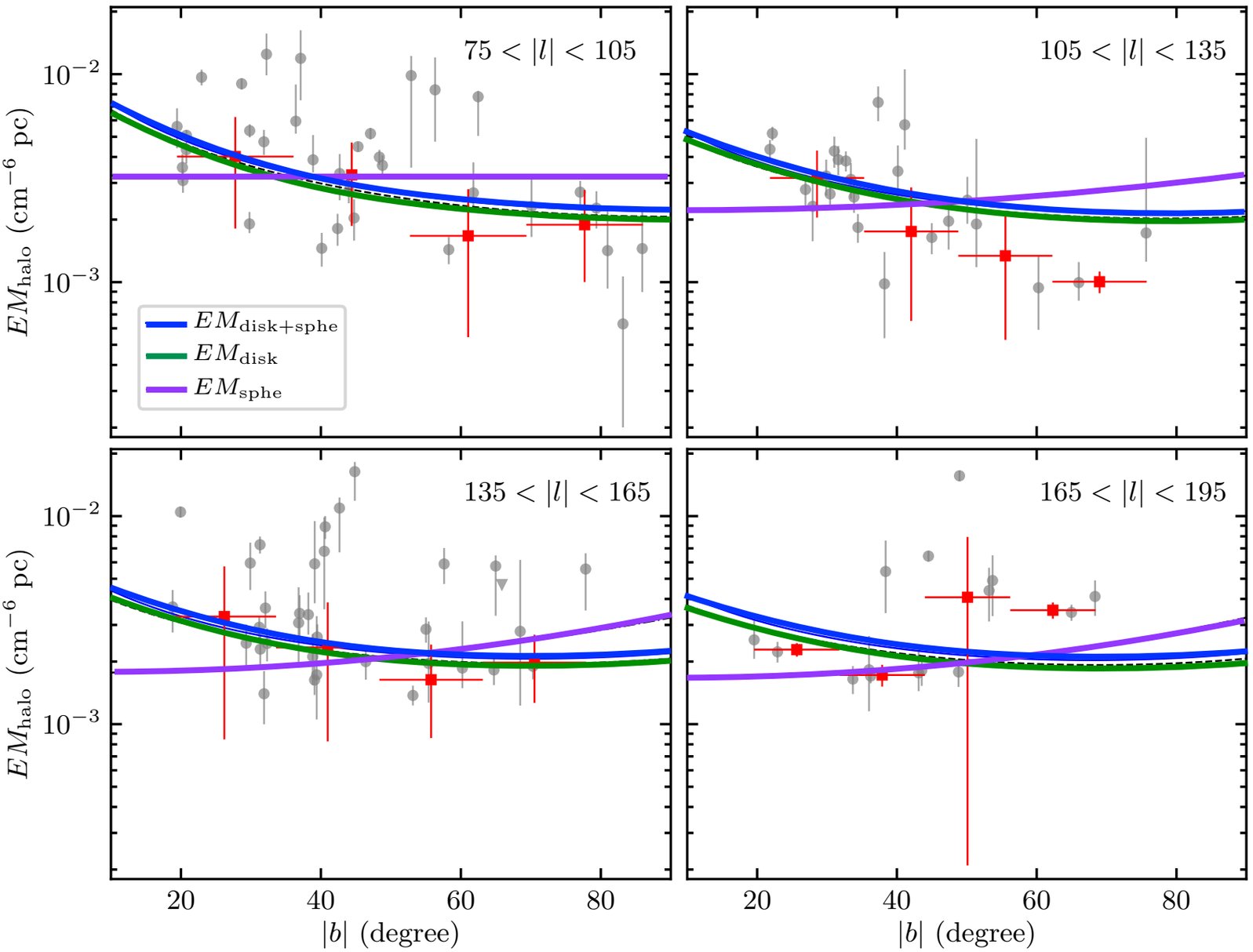



EM v.s. (l, b) depends on the models

$$EM = \int n_e n_H ds$$

-> We can test the model with our observations

# Emission measure distribution




- Scatter is large but roughly follows the disk model
- Fitting with "disk"+"spherical" model shows that "disk" is dominant component.

  disk: $n_0$ ~ 4×10$^{-3}$ cm$^{-3}$, $R_0$ ~ 7 kpc, $z_0$ ~ 2 kpc

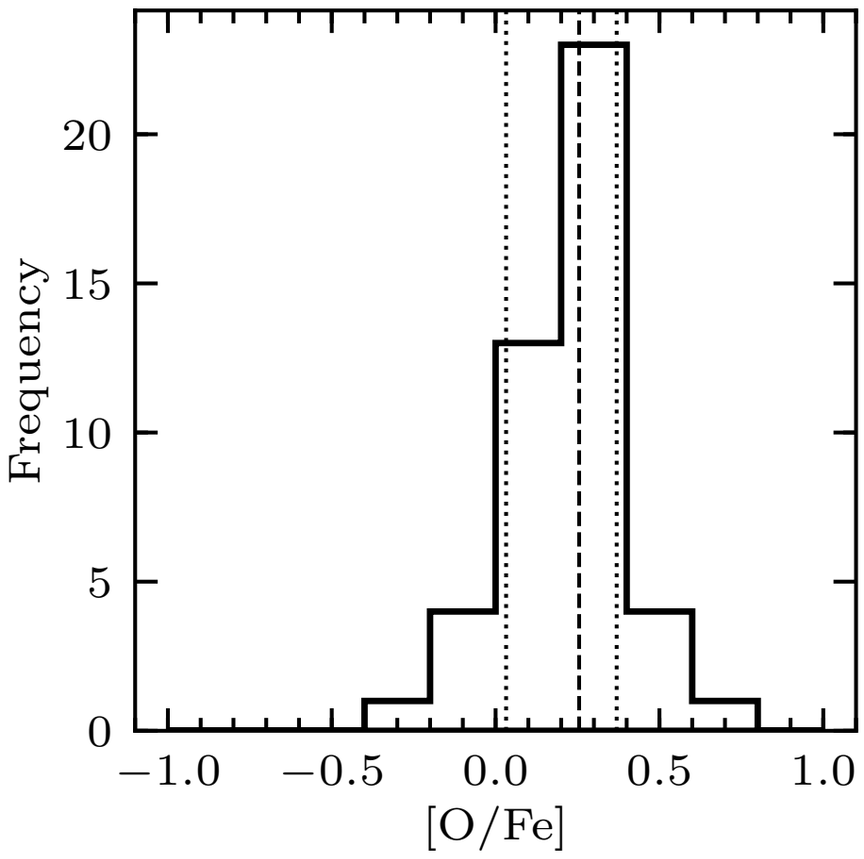
  spherical: $n_c$ ~ 1×10$^{-3}$ cm$^{-3}$, $r_c$ ~ 2.4 kpc, $\beta$ ~ 0.5

- Note: emission is biased toward high density regions. Integrated mass is dominated by spherical model.

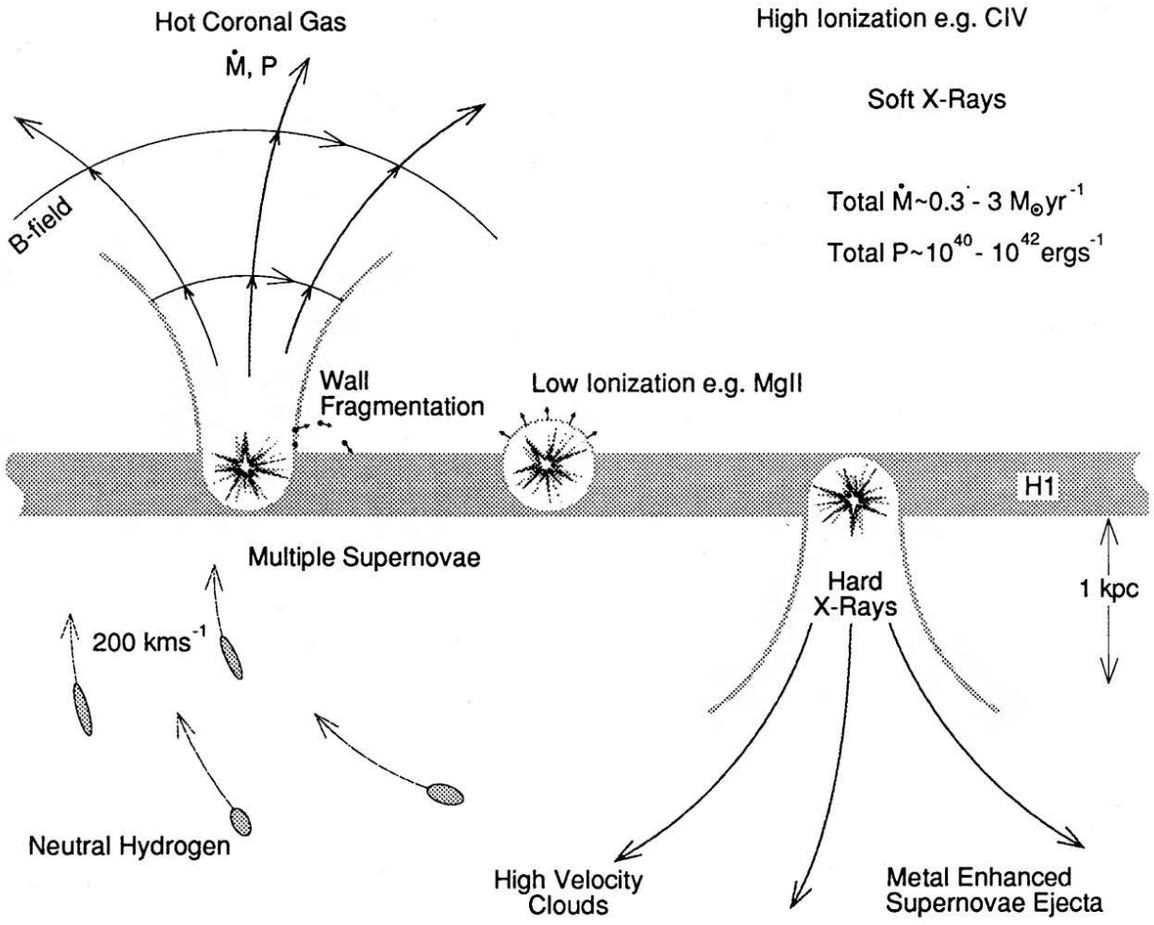
  (disk ~ 10$^7$ Msun, sphe ~ 10$^9$ Msun)

Disk component is clearly shown in X-ray emissions.
Spherical component is not excluded (might be "disk + spherical")

# Origin of the disk-like hot halo gas




0.25 +0.22/-0.12

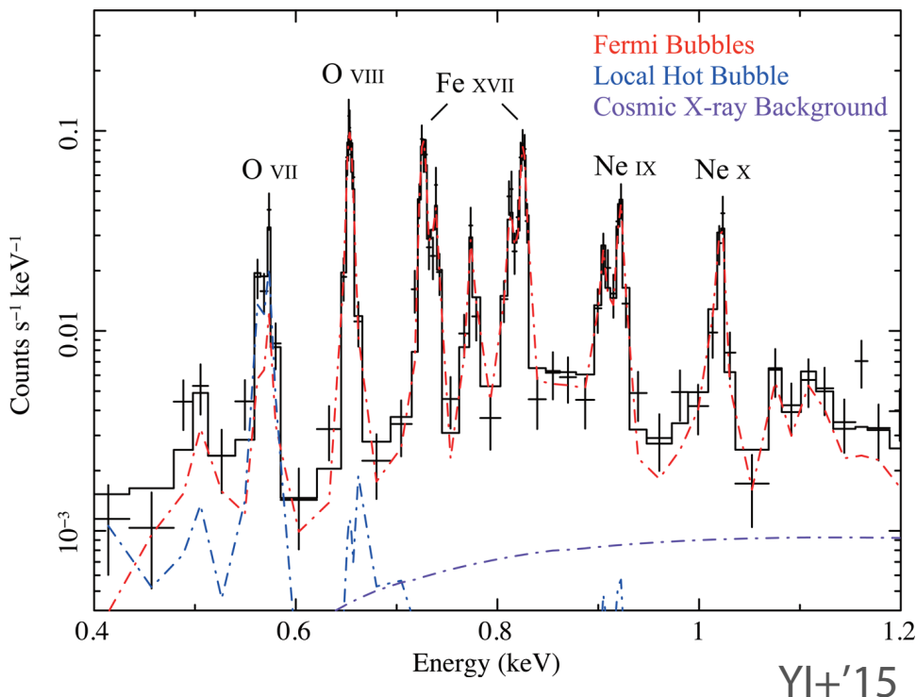



- [O/Fe] is larger than the solar value => significant contribution of the core-collapse SNe (but uncertainty is very large in the CCD spectral resolution).
- Multiple SNe at star-forming regions make a super bubble and “chimney” of hot gas outflows (Norman & Ikeuchi 89).

# Future Prospects

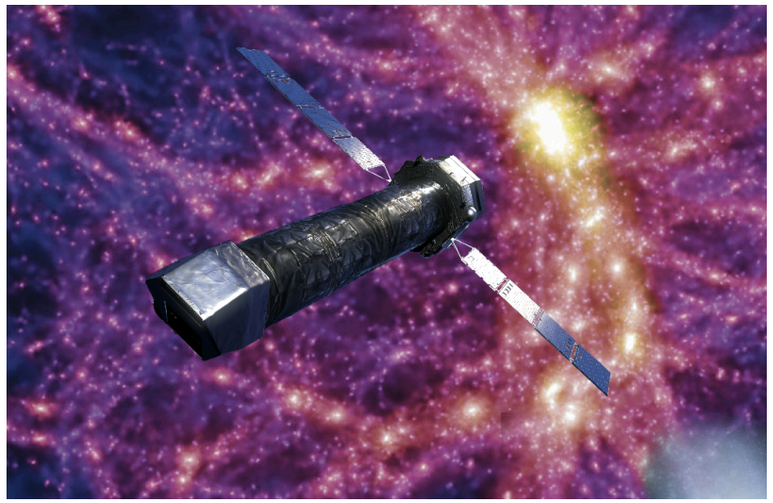
**XRISM (JAXA & NASA mission)**

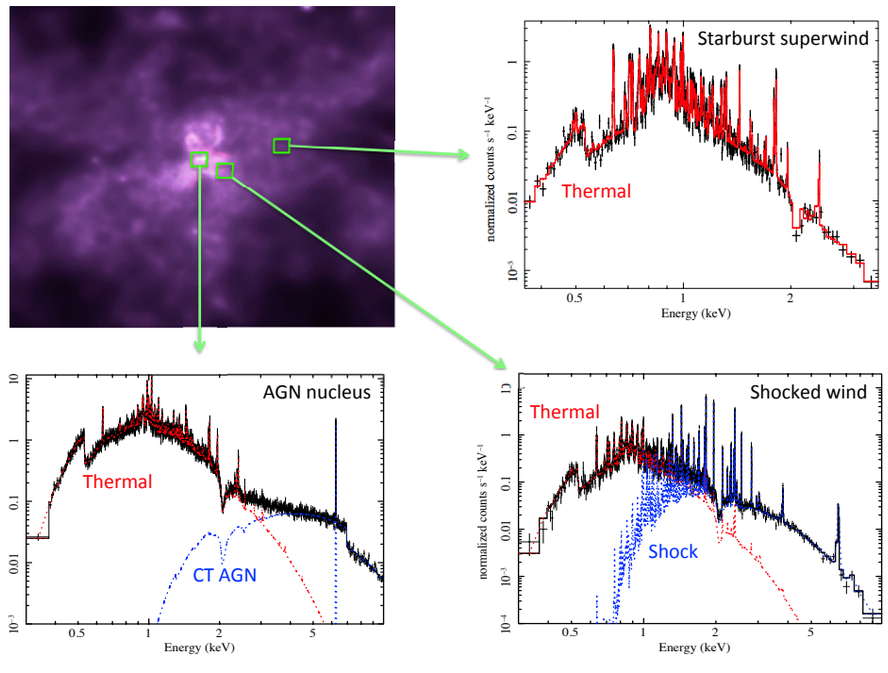
- to be launched in 2021
- x30 energy resolution of CCD (like Hitomi)
- precise measurements of metal abundance and ionization state.




**Athena (ESA mission)**

- to be launched in early 2030s
- higher spatial resolution than that of XRISM
- observation of other galaxies





# Summary

- Suzaku revealed the nature of diffuse hot gases in the MW
- Galactic Center
  - ~100 pc scale of hot gas outflow was found
  - Starburst or Sgr A* flare 0.1 Myr ago?
- NPS, Loop-I, and Fermi bubbles
  - ~10 kpc scale hot gaw with ubiquitous kT ~ 0.3 keV
  - Starburst or Sgr A* flare 10 Myar ago?
- Hot gaseous halo
  - Spatial distribution of EM shows disk-like morphology.
  - [O/Fe] shows contribution of SNcc: outflows from the disk?
- XRISM and Athena will provide more precise picture.