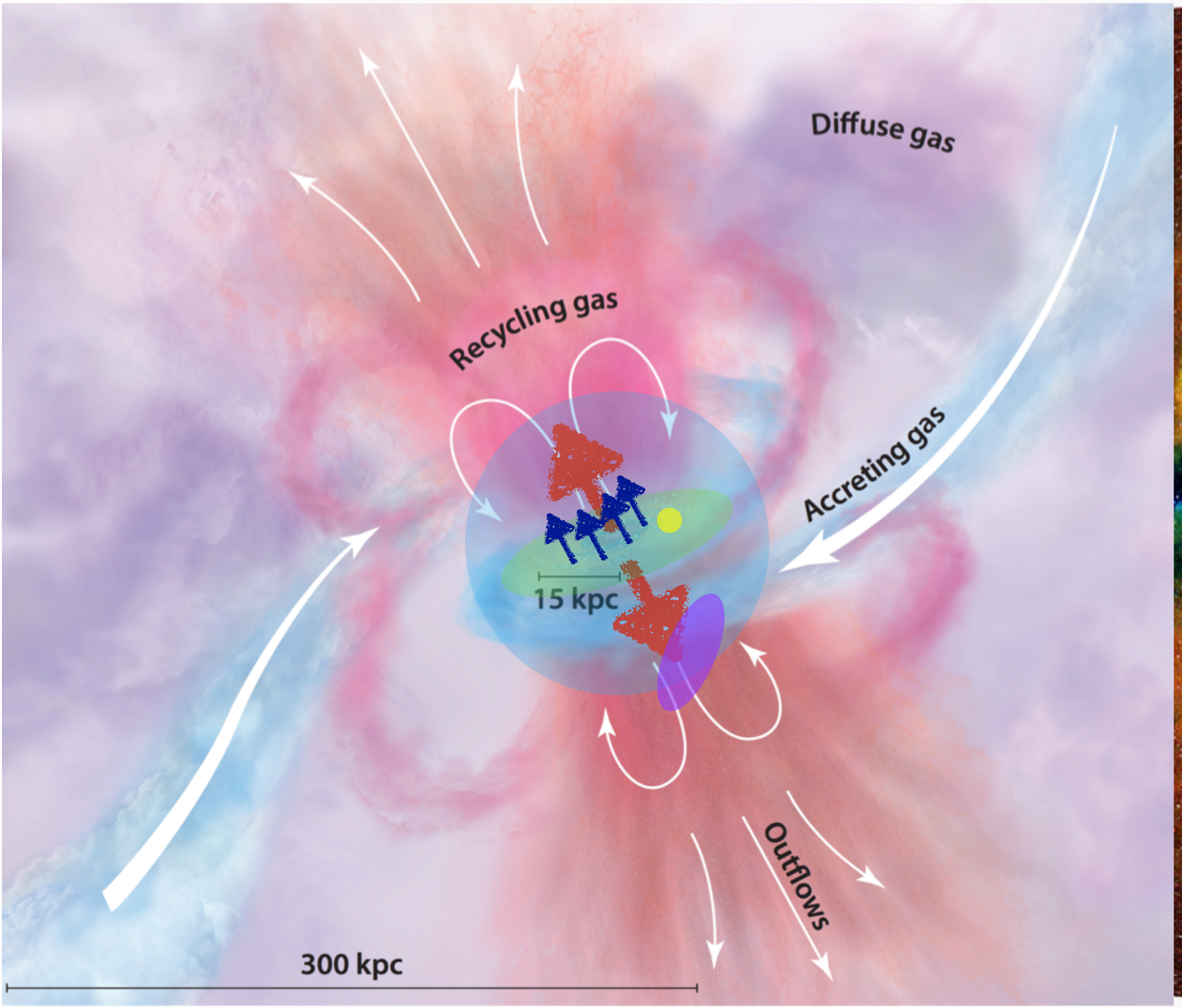
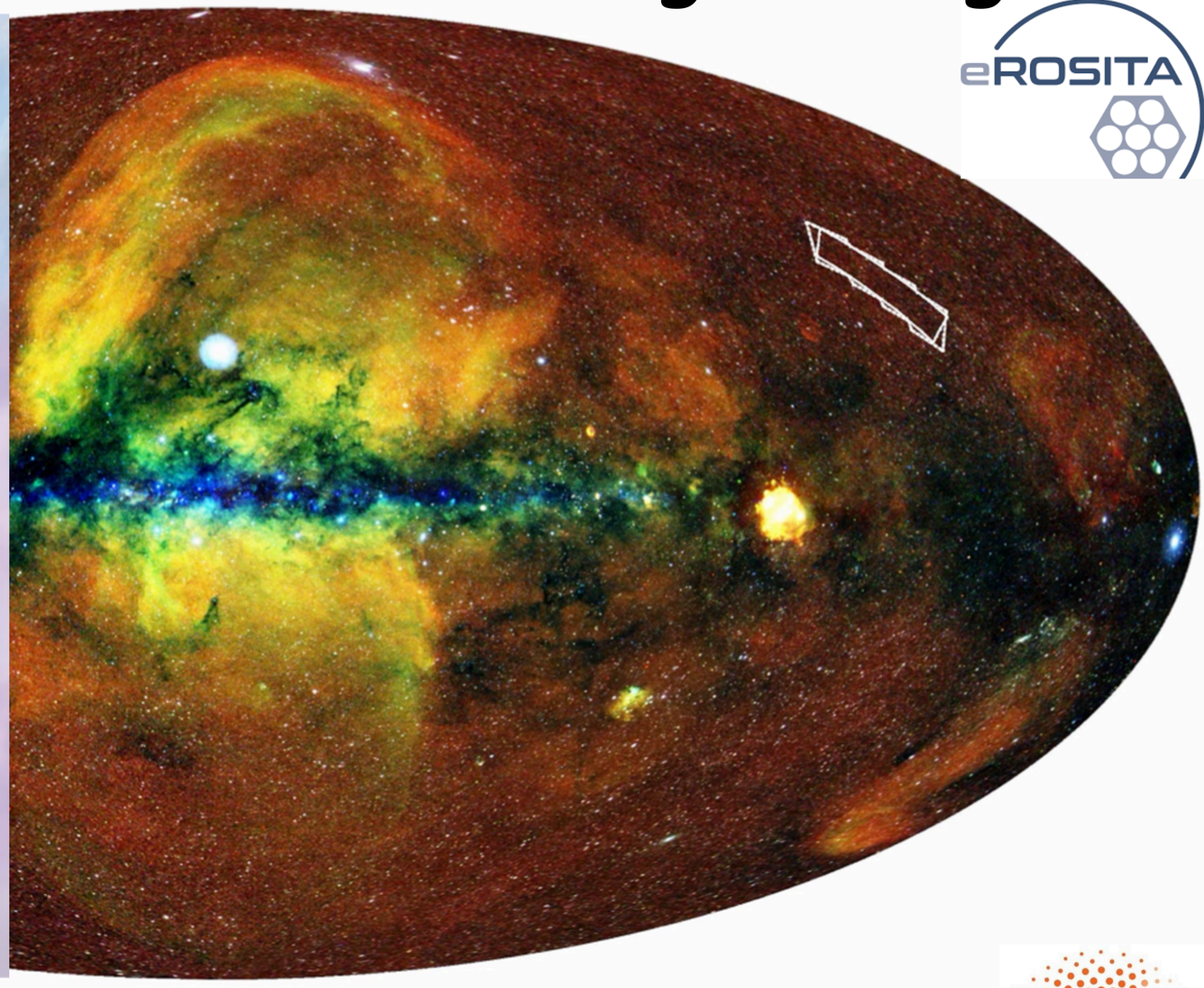
The hot phase of the Milky Way





Gabriele Ponti (INAF-OA Brera, MPE) **and the Hot Milk team:**

N. Locatelli, X. Zheng, Y. Zhang, H. Zhang, M. Yeung, M. Mayer, J. Knies, S. Sheeram, J. Comparat, J. Sanders, K. Dennerl, A. Merloni, M. Sasaki, G. Stel, T. Liu, A. Strong, M. Freyberg et al.

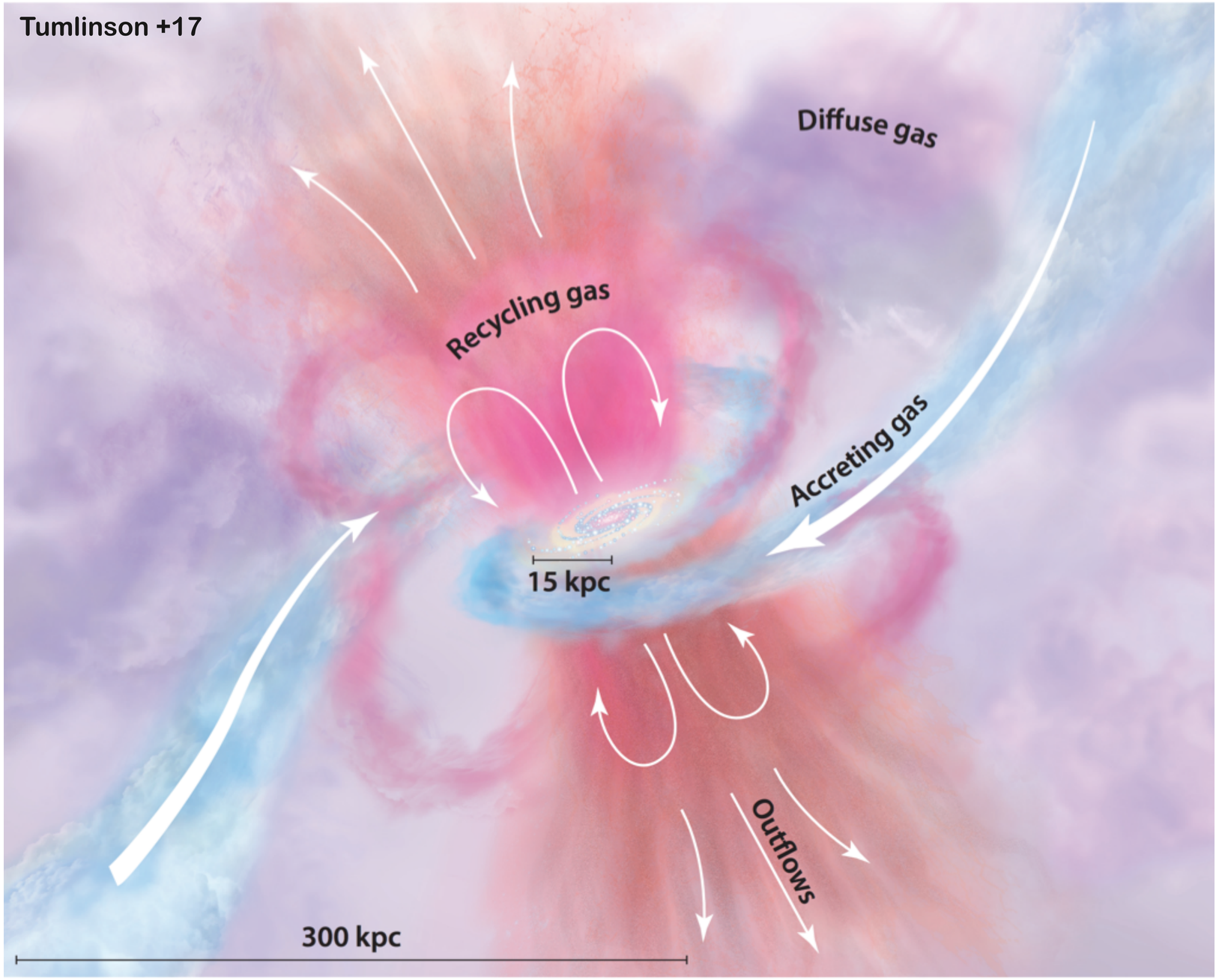
erc

Why should we care?

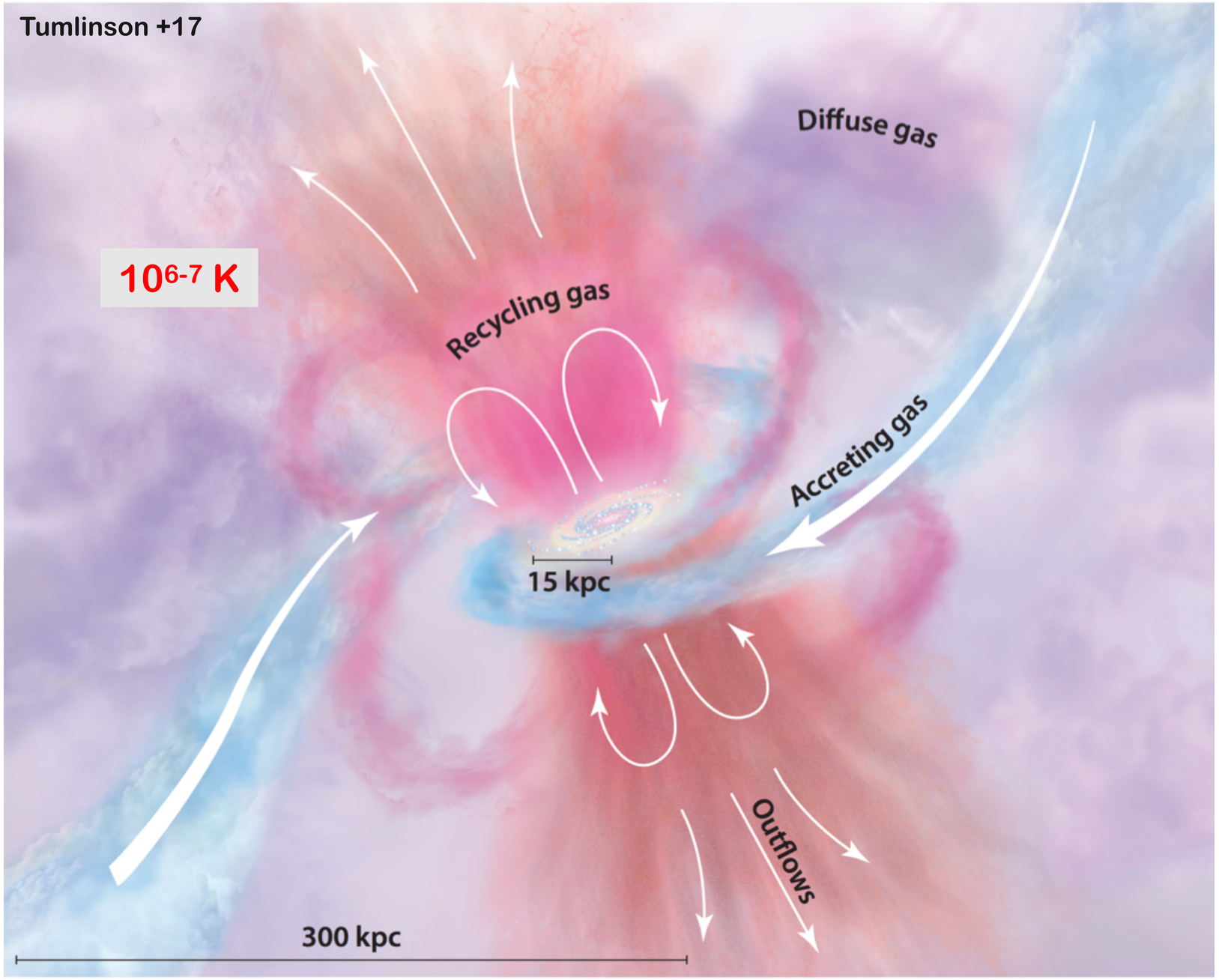
How do galaxies evolve?

NGC 7331 Hubble

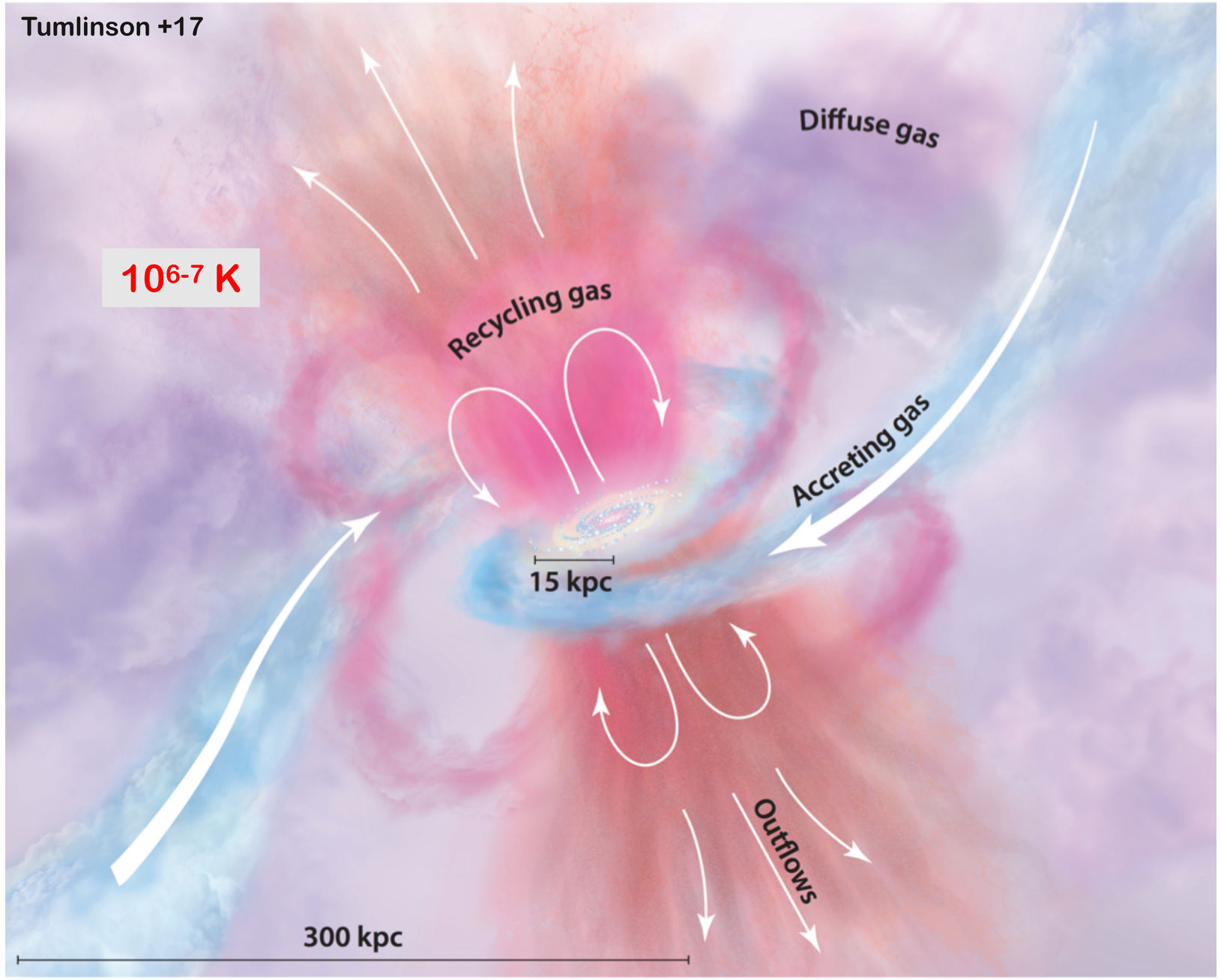
The Baryon cycle



The Baryon cycle



The Baryon cycle



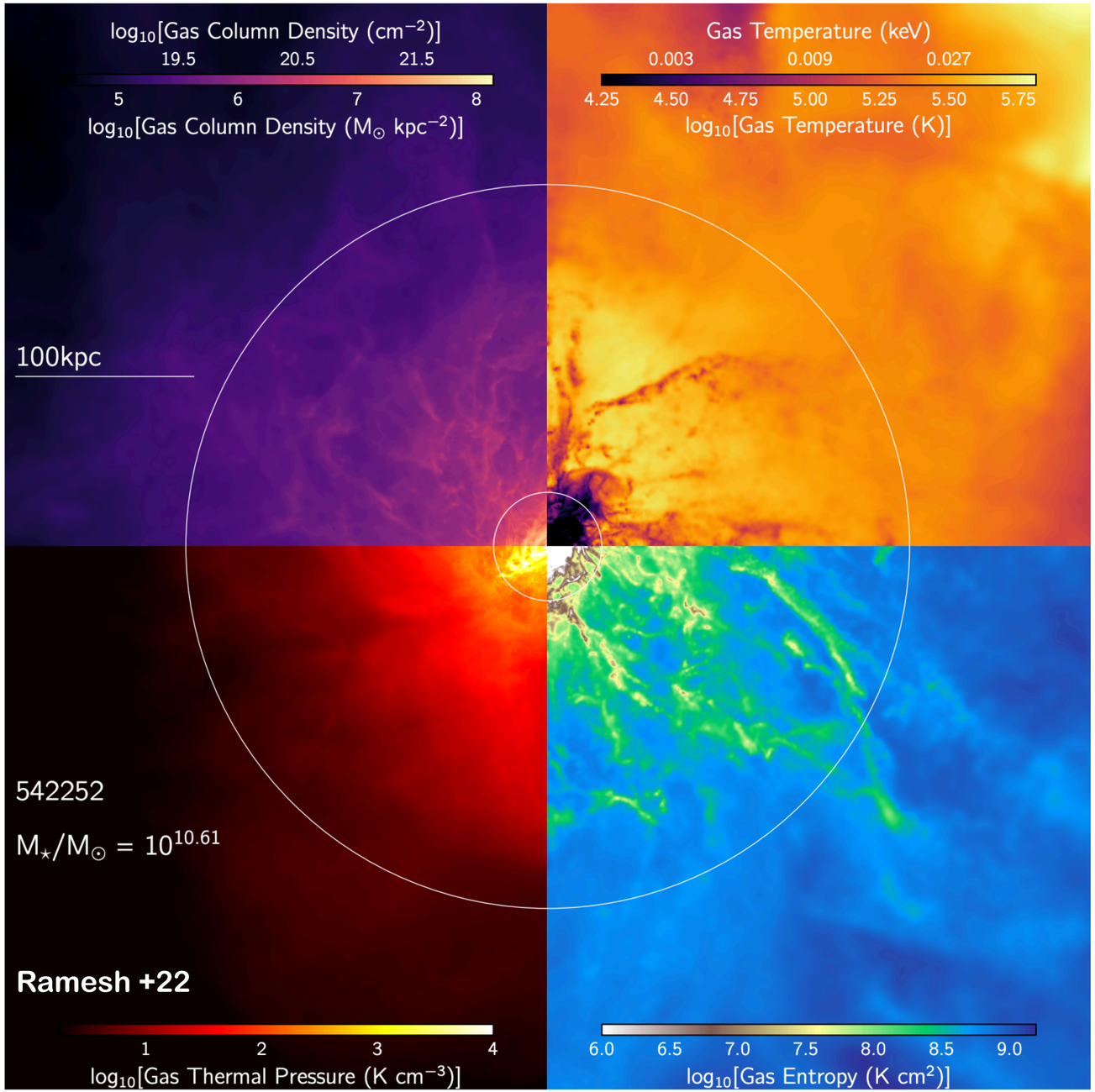
Hot Baryons:

Bulk of Baryons

Re-condensation

Driver outflows

The CGM is hot and multi-phase



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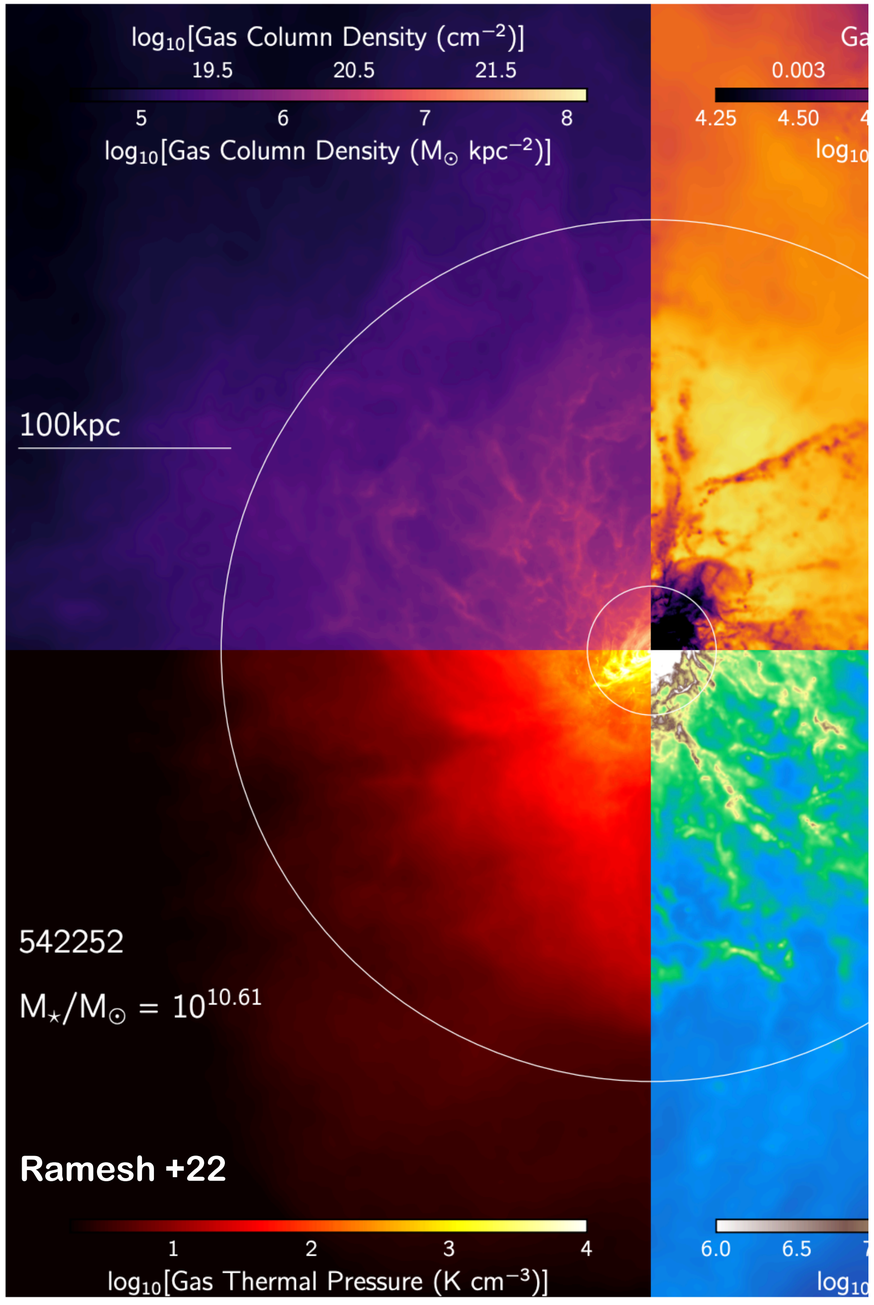

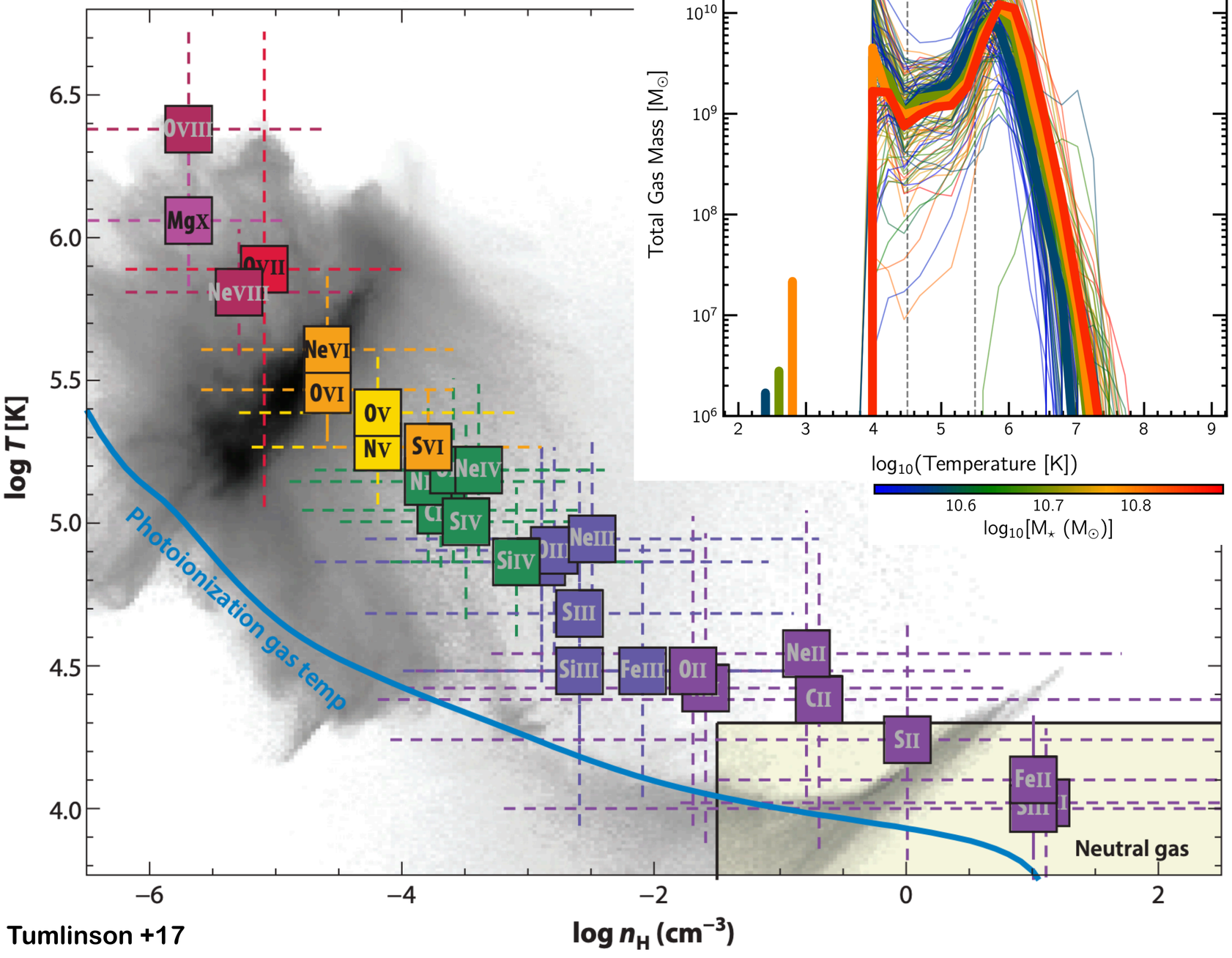

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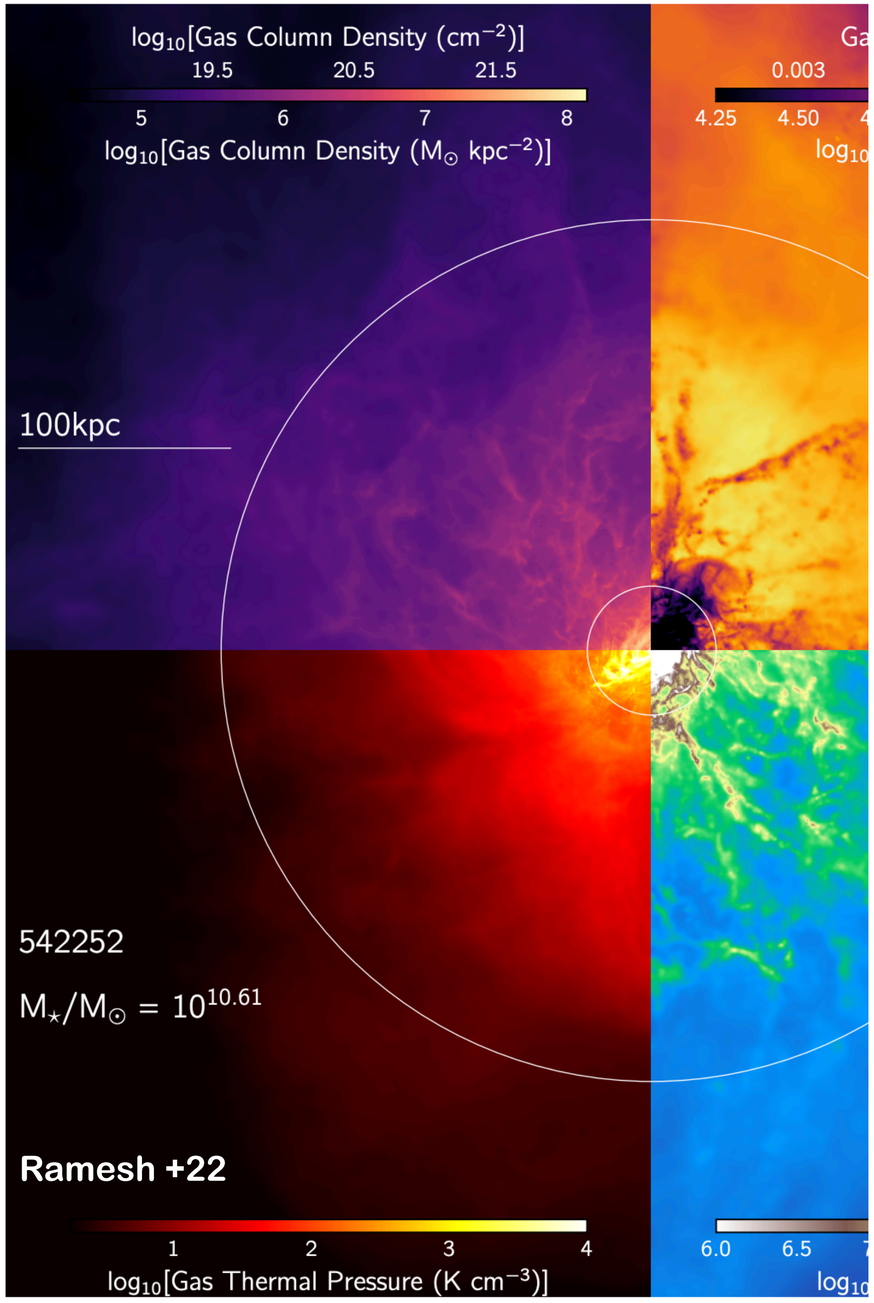
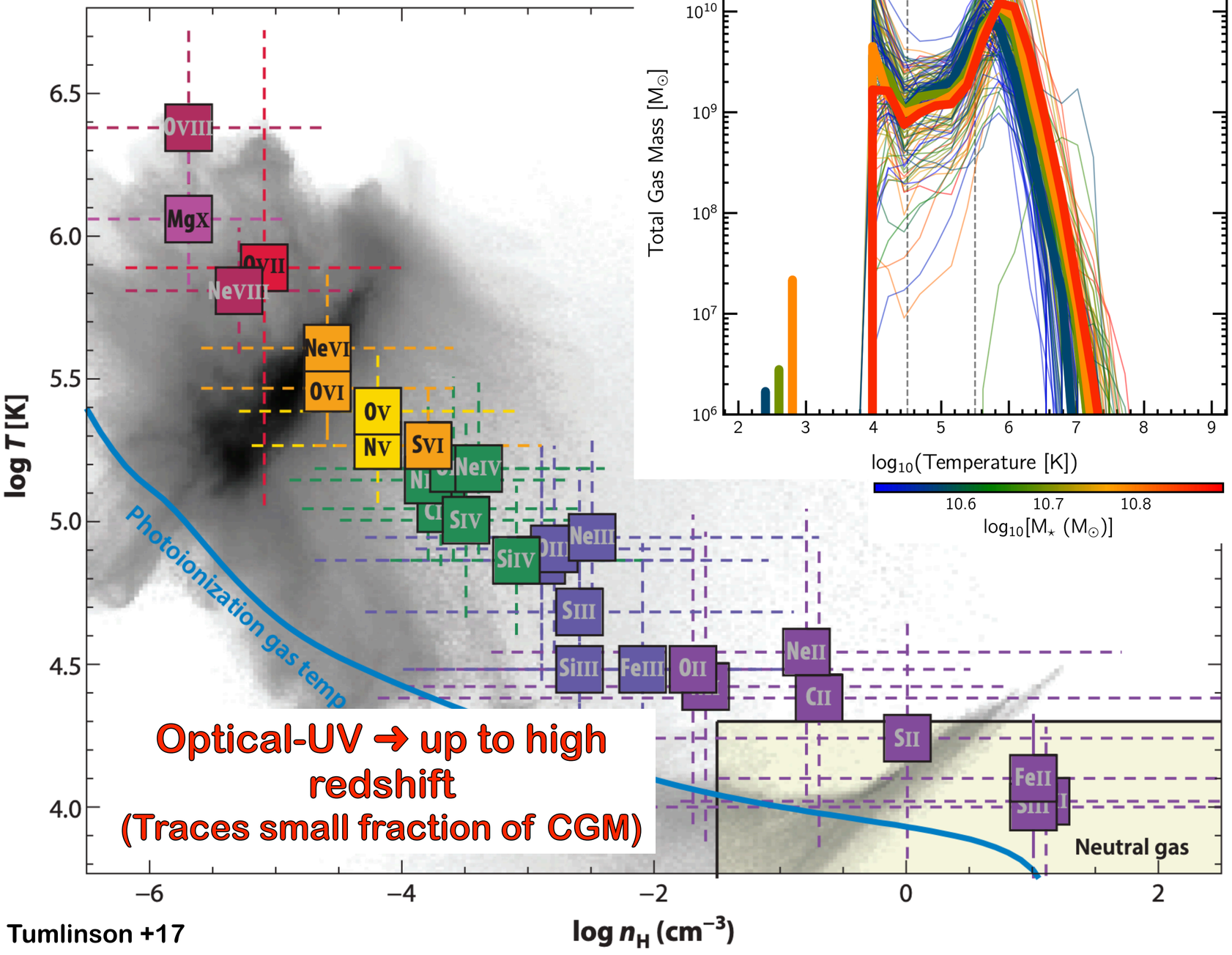
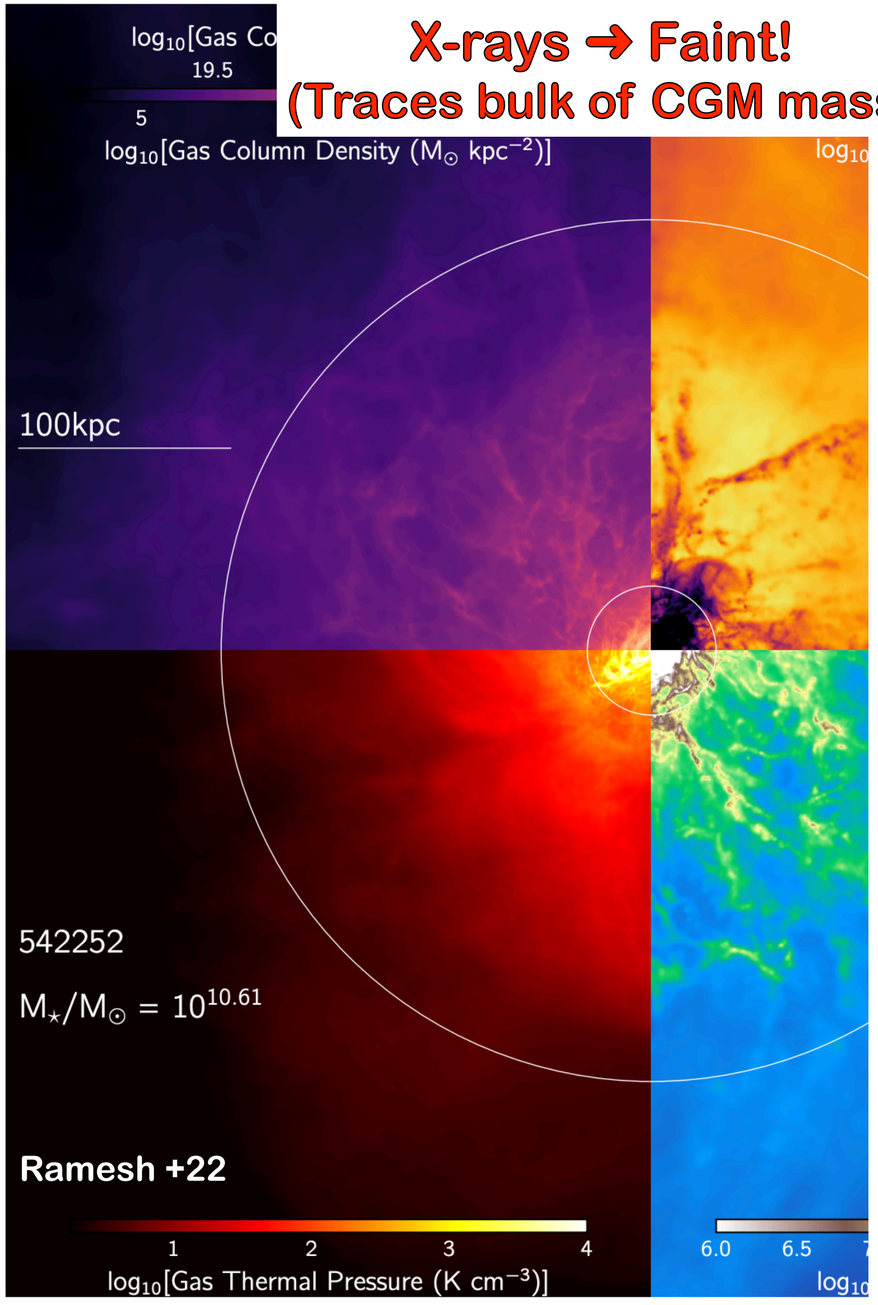
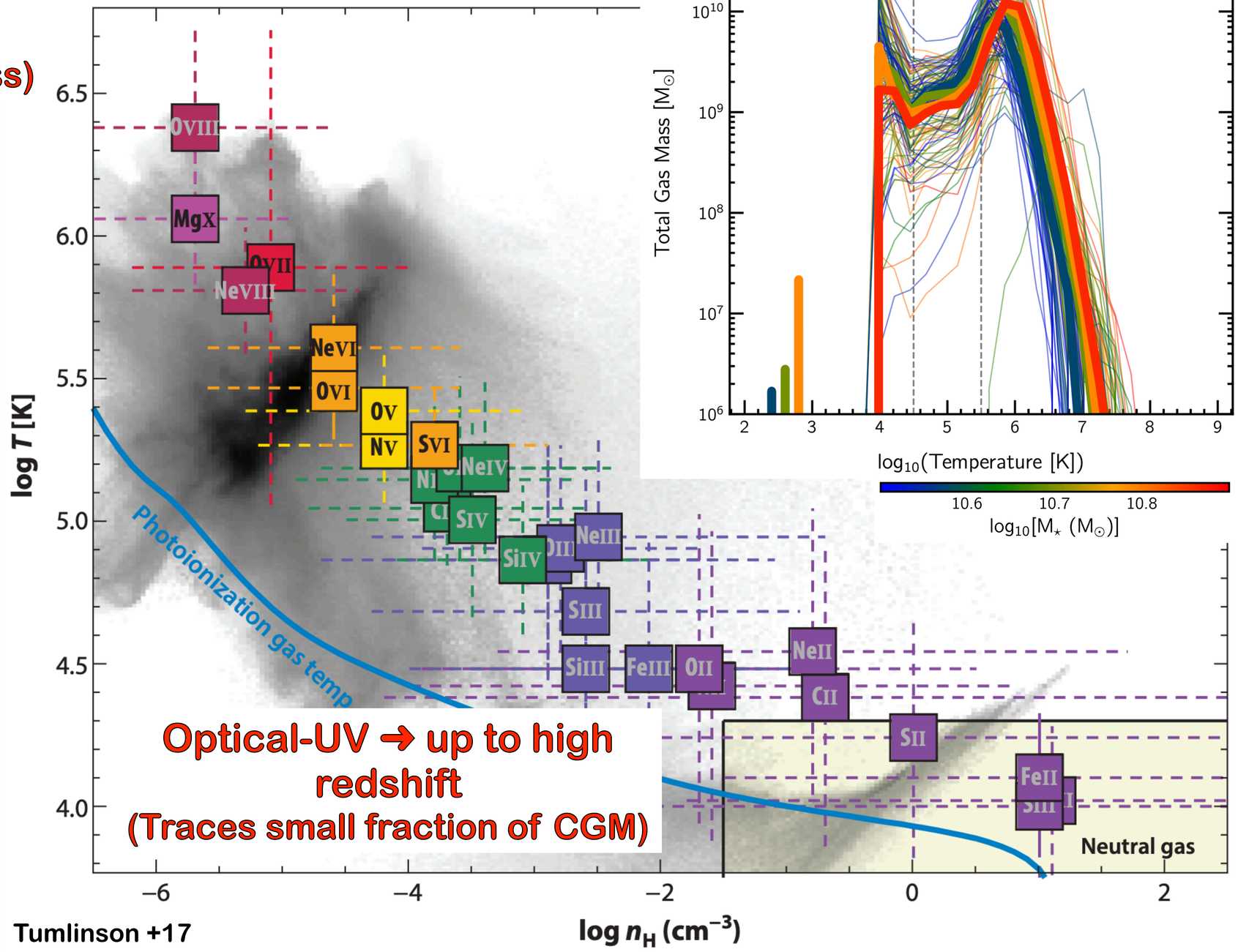




The CGM is hot and multi-phase

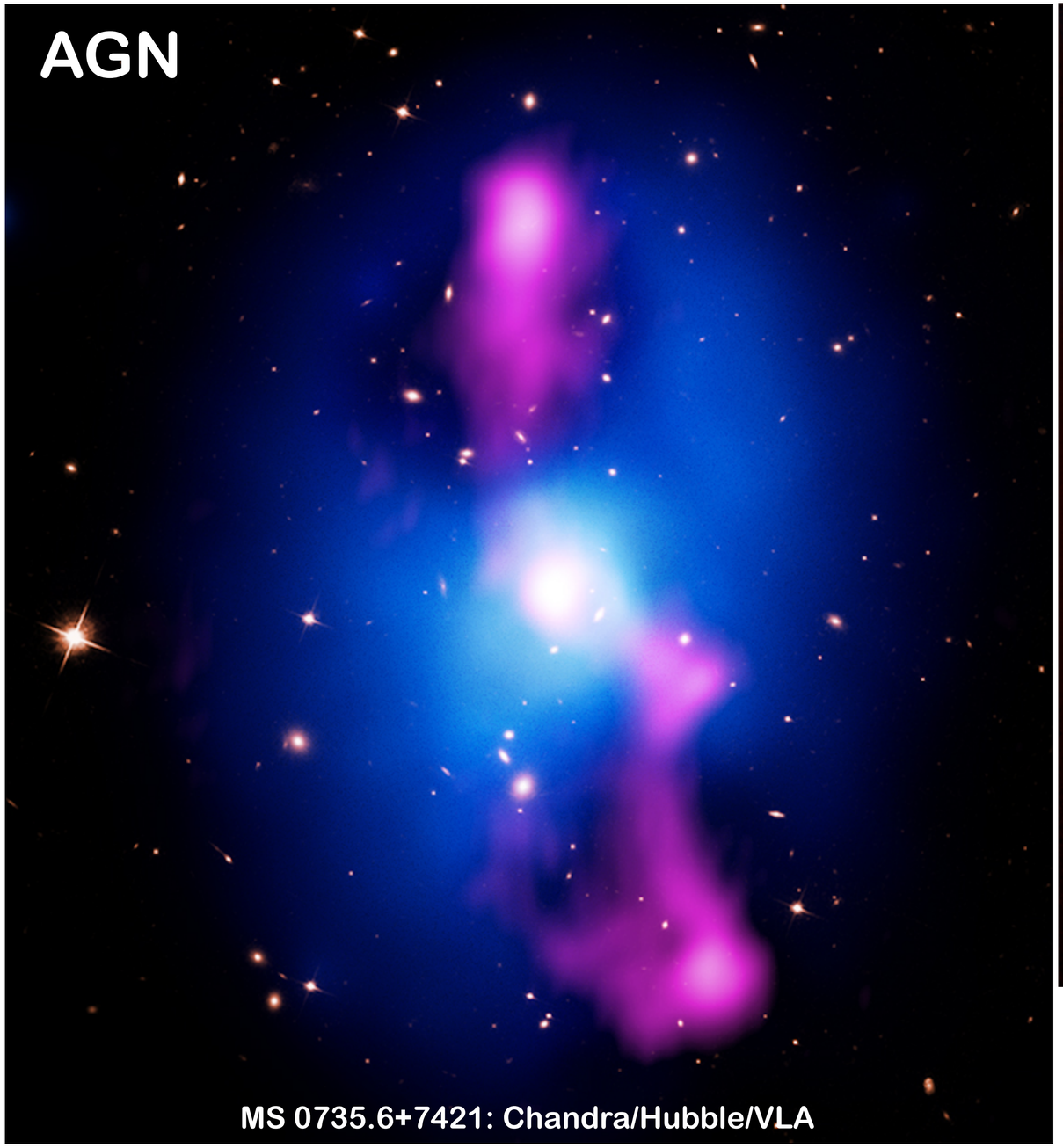
X-rays ➜ Faint!
(Traces bulk of CGM mass)

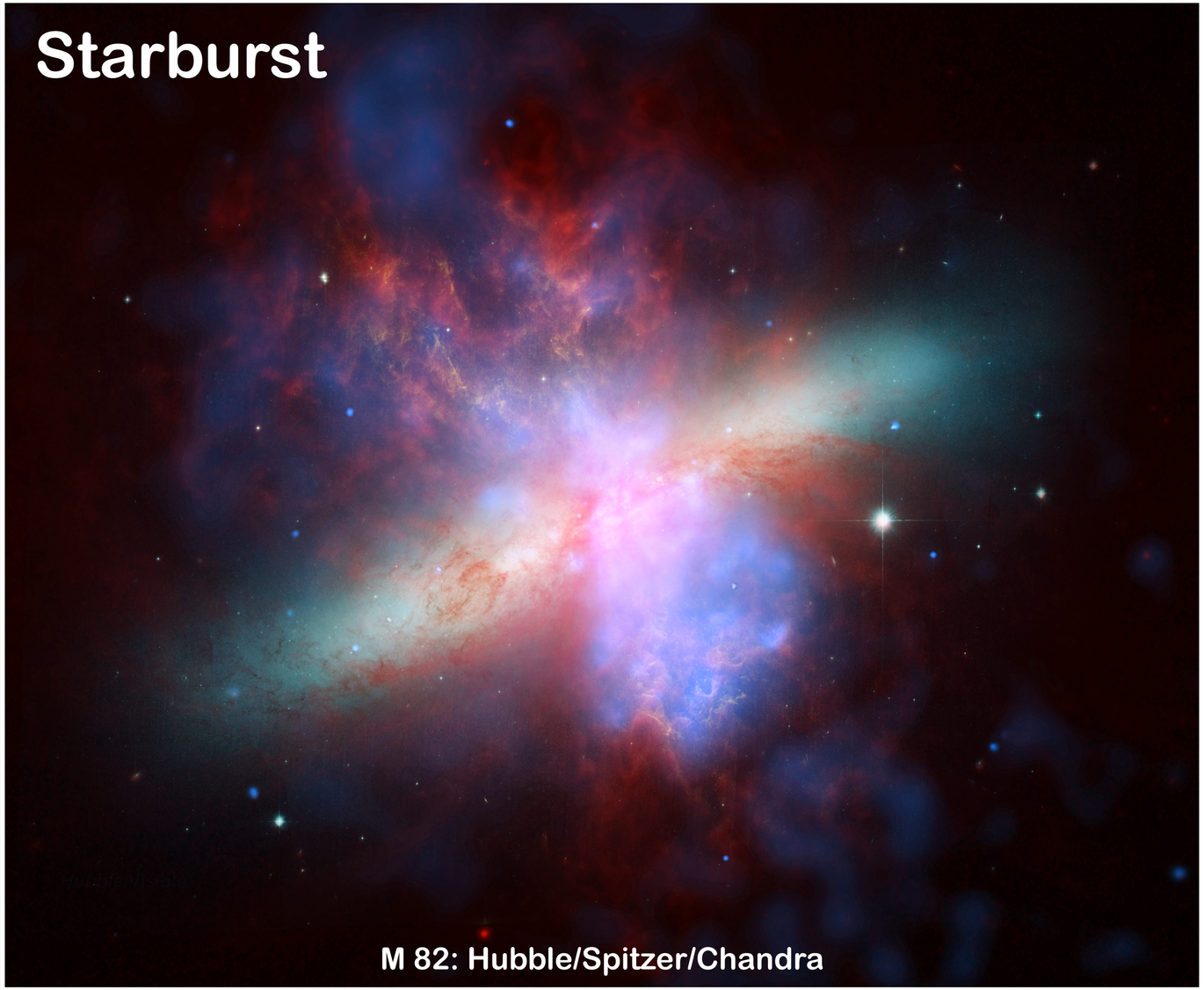




Optical-UV ➜ up to high redshift
(Traces small fraction of CGM)

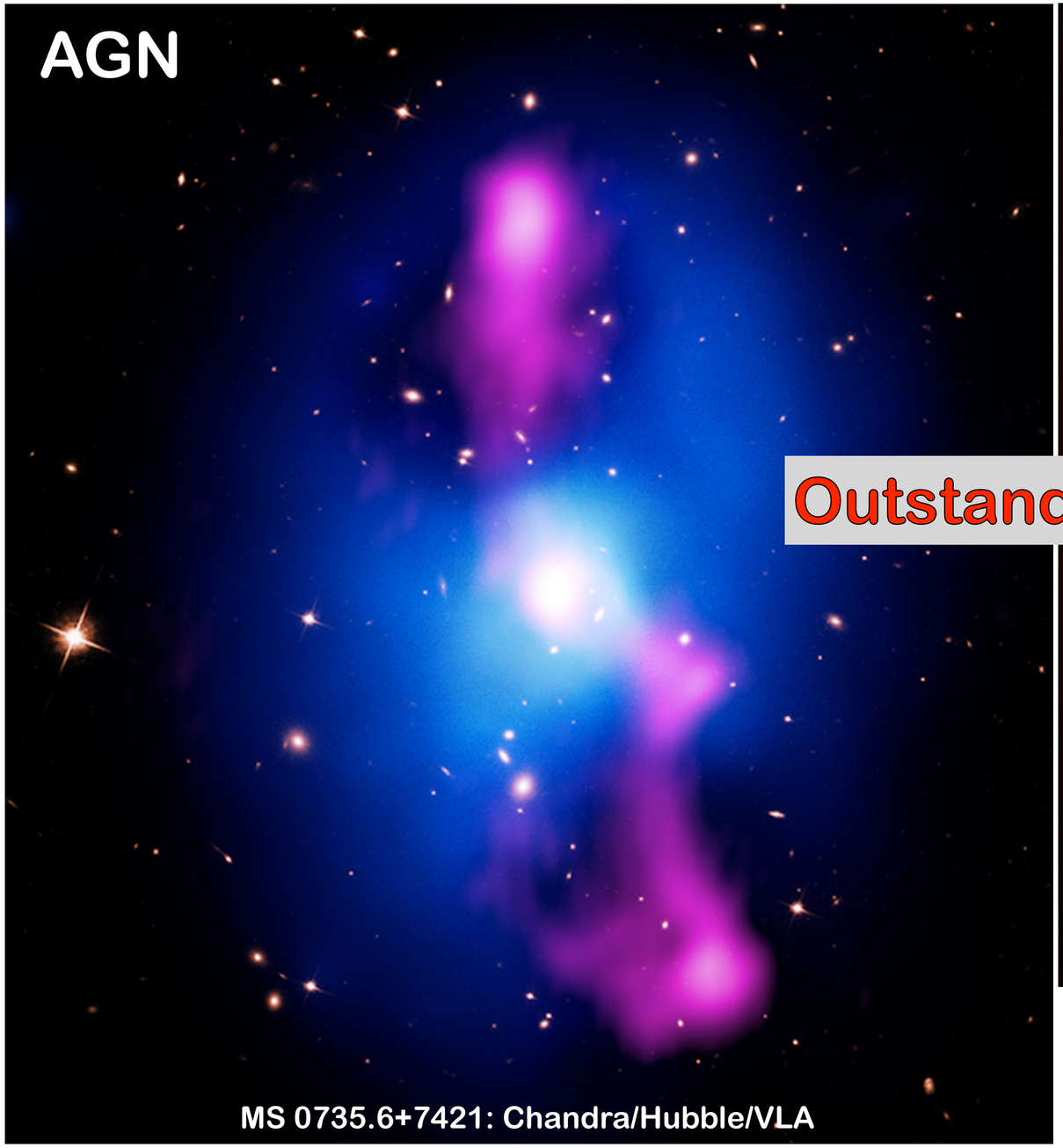
AGN and Starbursts influence CGM

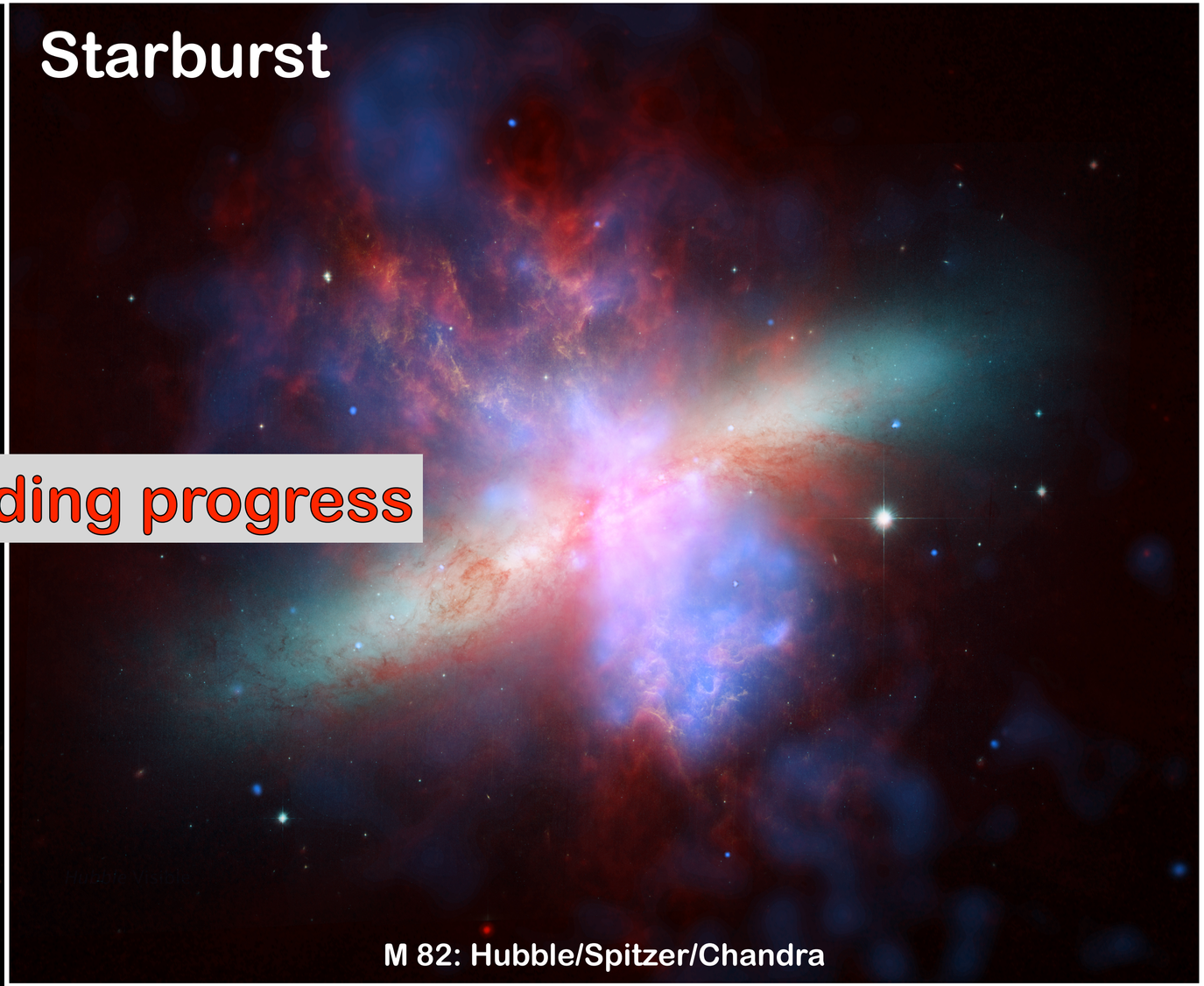




➜ Understand feedback between nucleus and CGM

AGN and Starbursts influence CGM

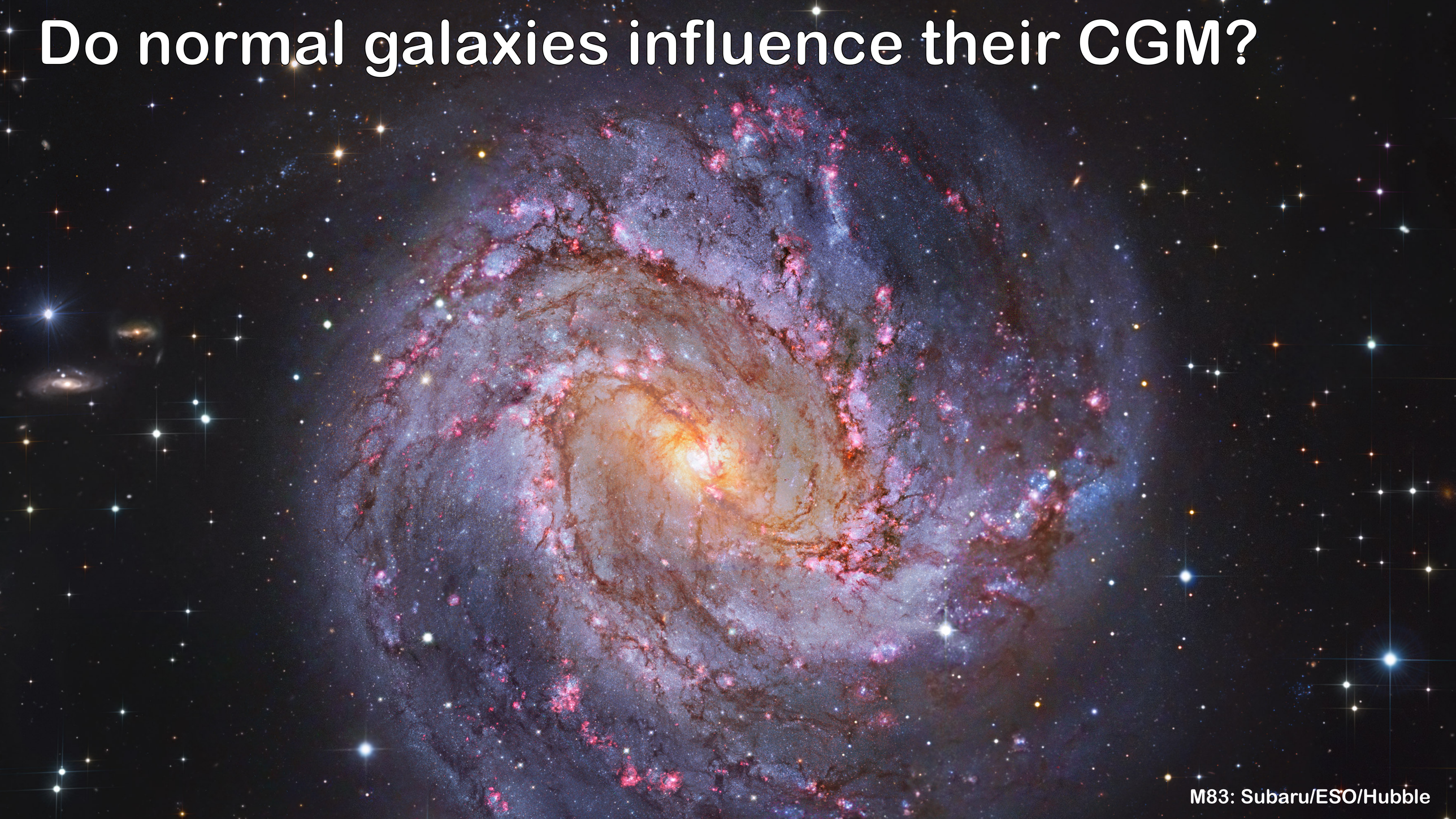




Outstanding progress

➜ Understand feedback between nucleus and CGM

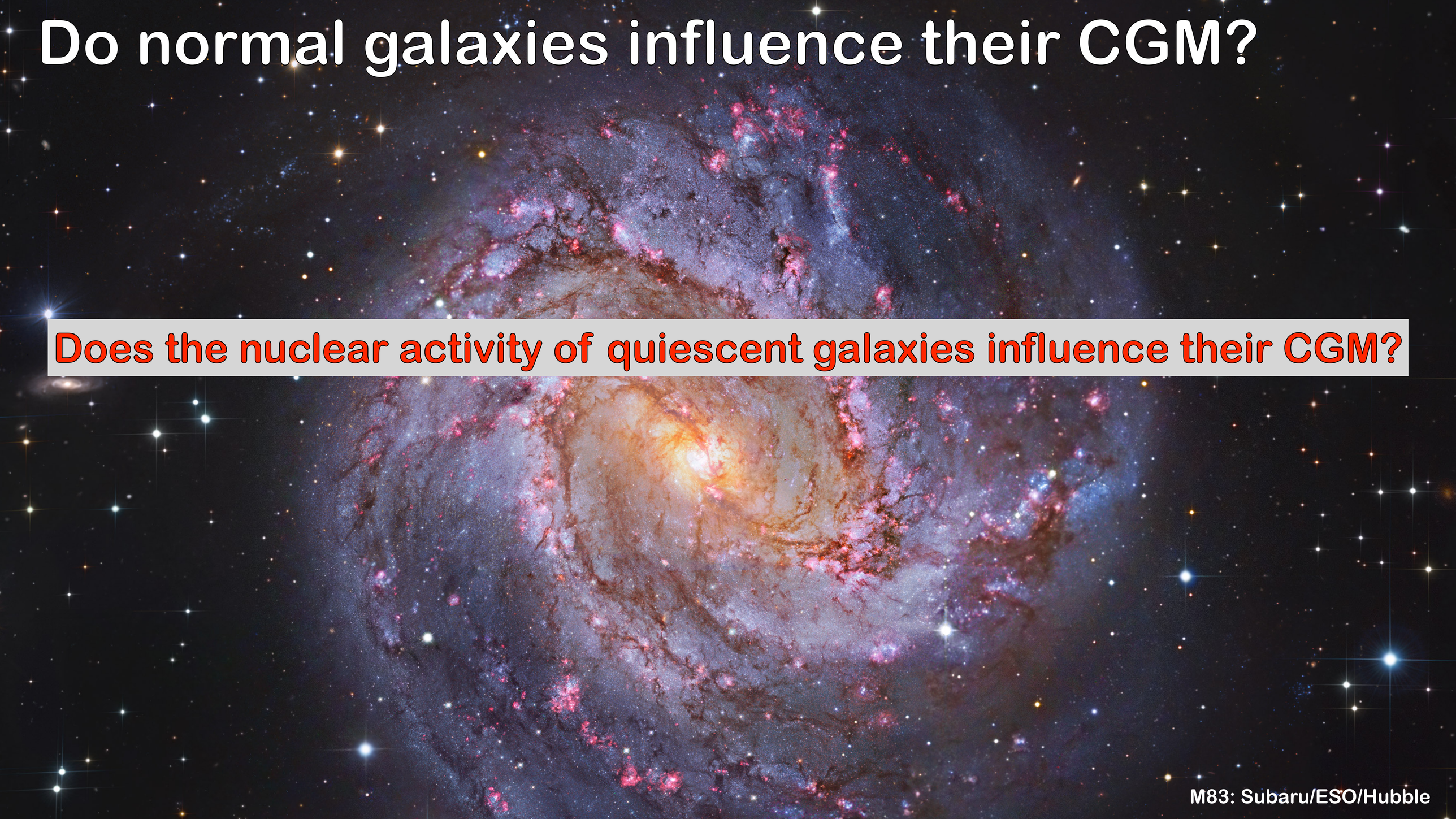
Do normal galaxies influence their CGM?



M83: Subaru/ESO/Hubble

Do normal galaxies influence their CGM?

Does the nuclear activity of quiescent galaxies influence their CGM?

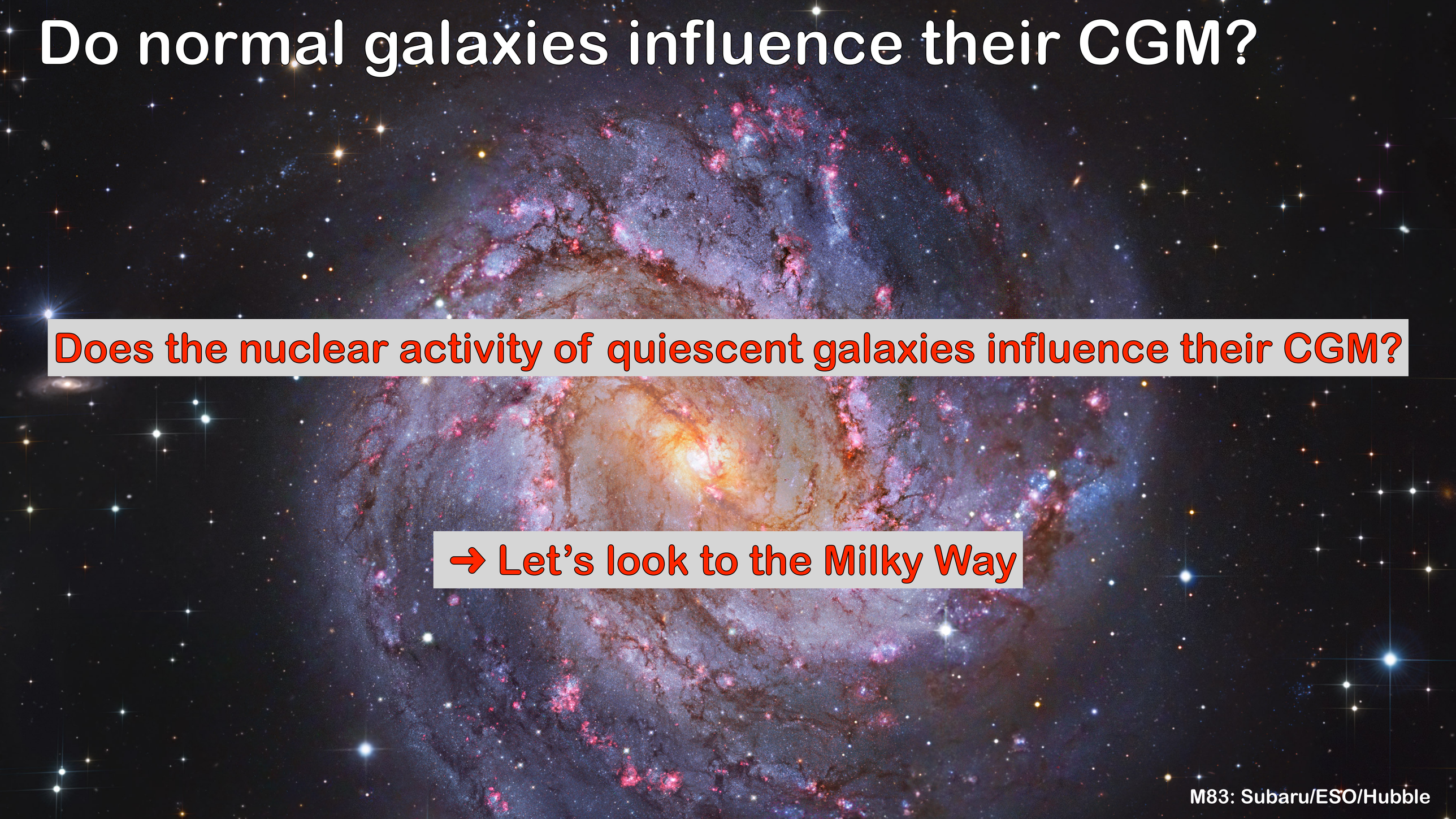


M83: Subaru/ESO/Hubble

Do normal galaxies influence their CGM?

Does the nuclear activity of quiescent galaxies influence their CGM?

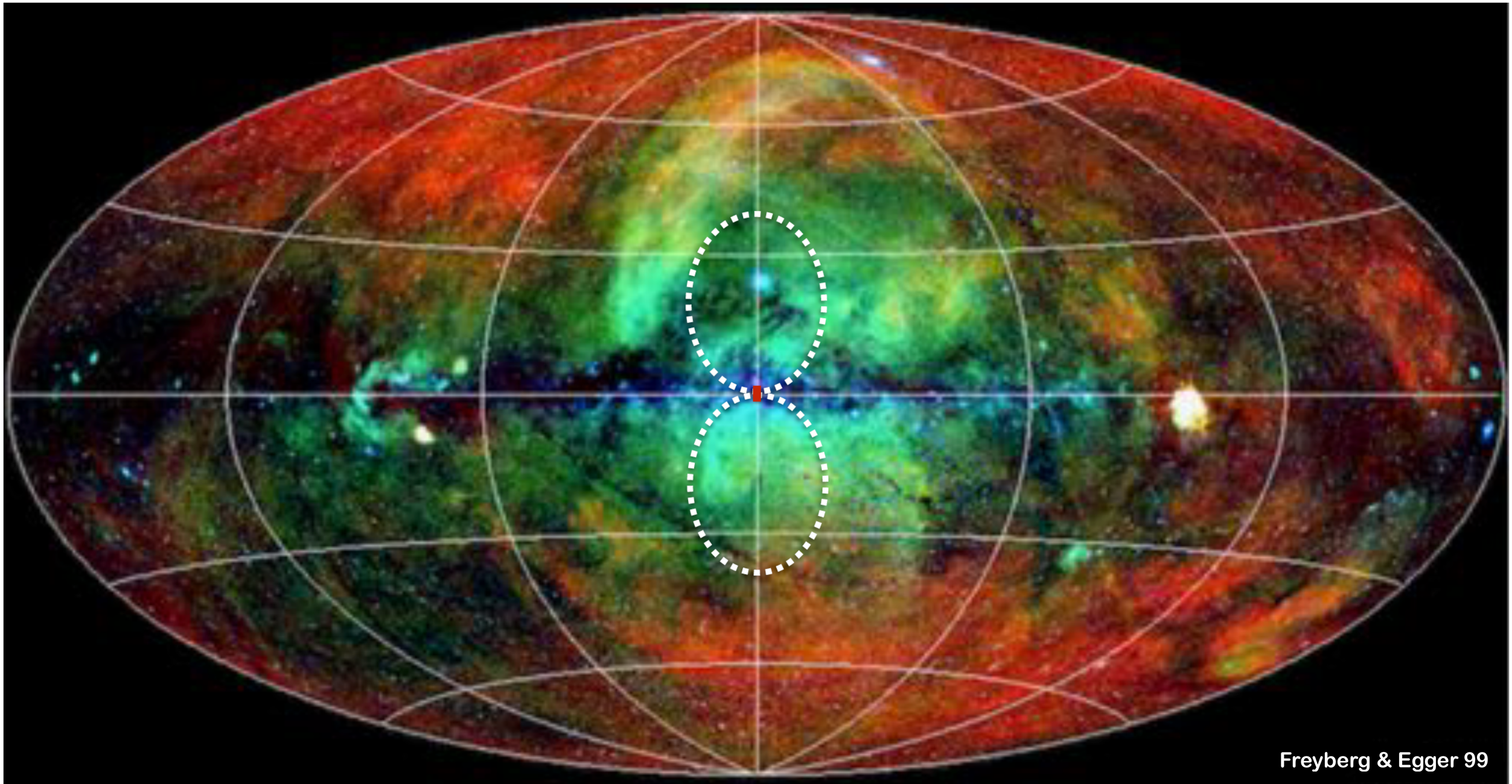
➜ Let's look to the Milky Way



M83: Subaru/ESO/Hubble

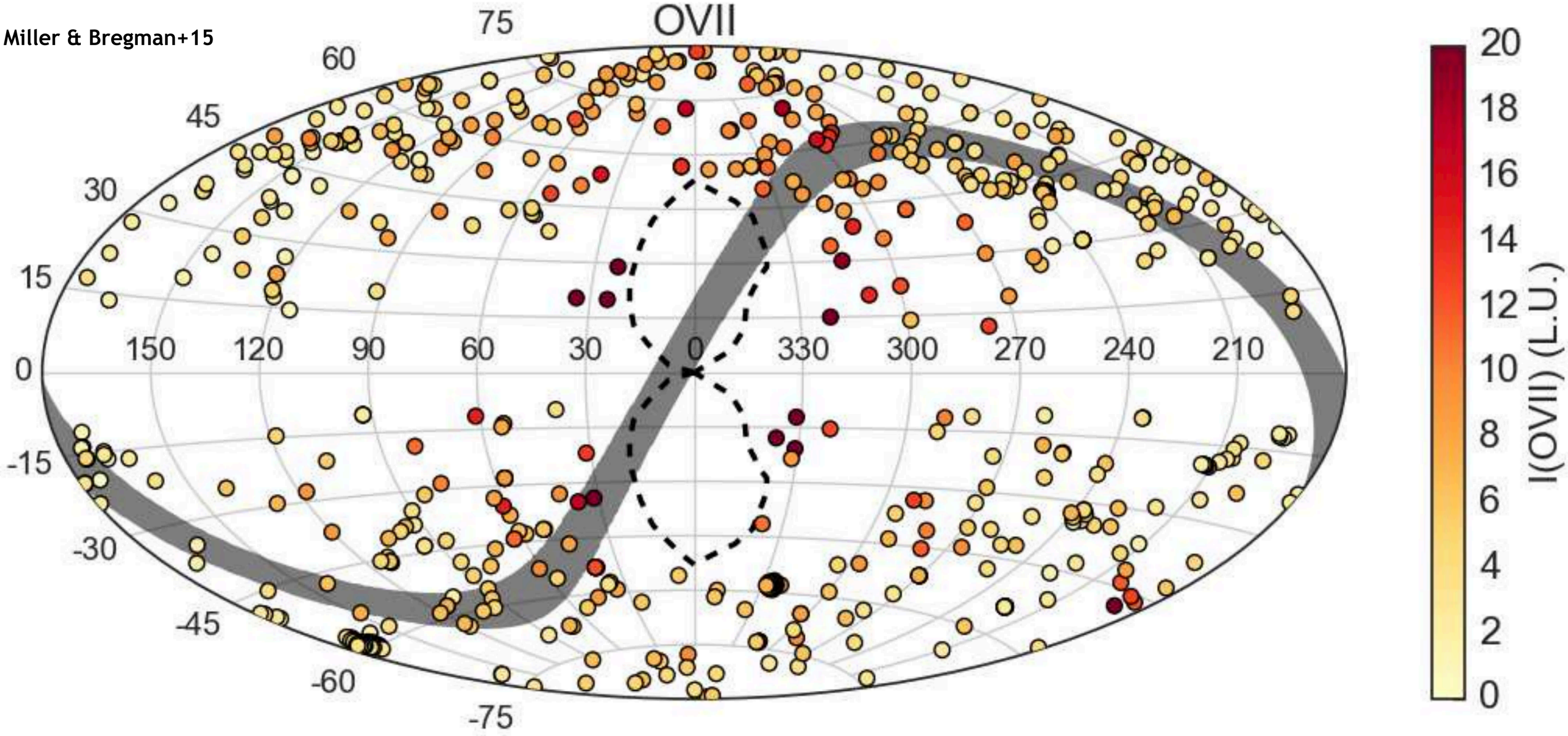
View on hot CGM of Milky Way-like galaxies before eROSITA

The previous soft X-ray all sky survey - 1990



All XMM archive to study the Milky Way CGM

Miller & Bregman+15



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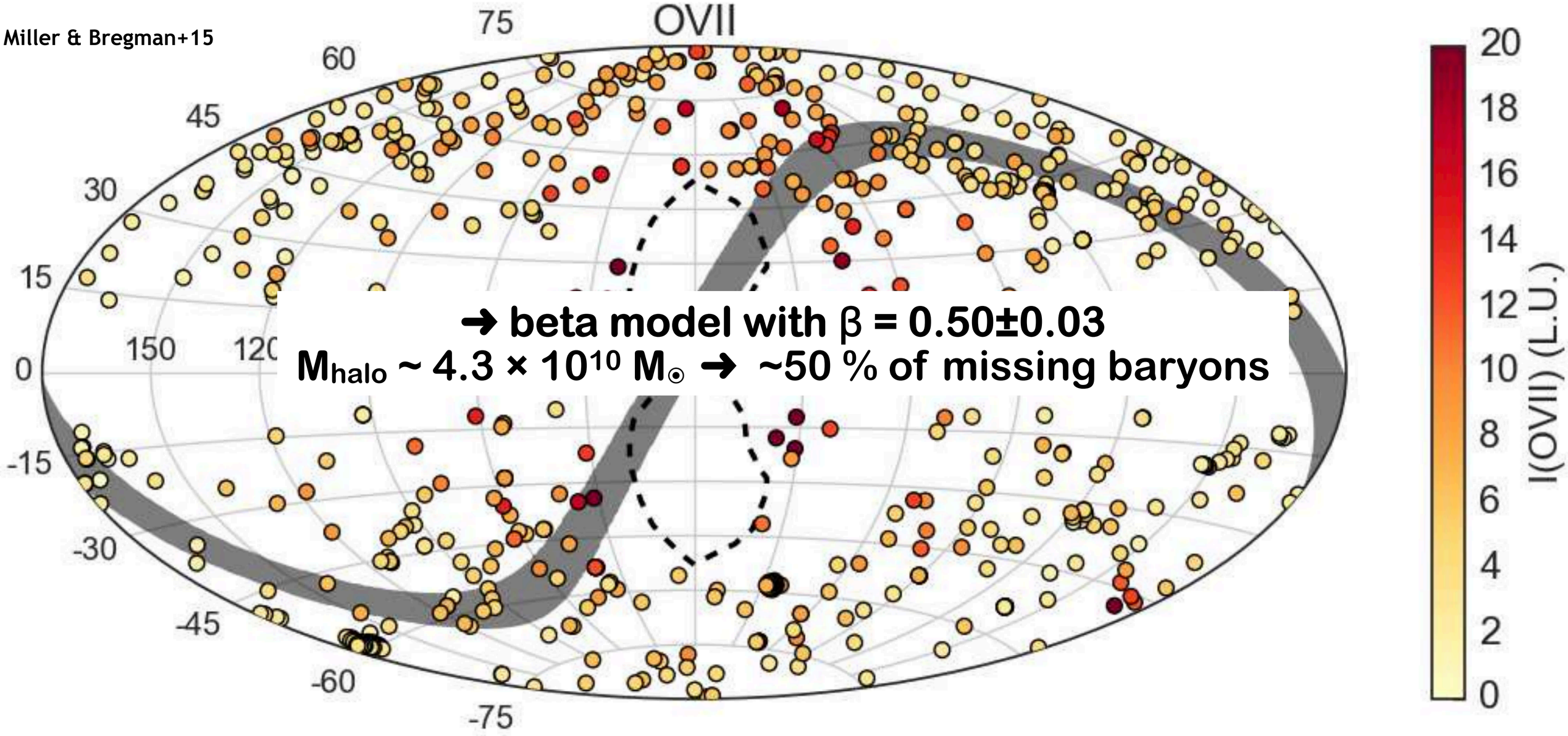

➜ beta model with $\beta = 0.50 \pm 0.03$

$M_{halo} \sim 4.3 \times 10^{10}\ M_{\odot}$ ➜ ~50 % of missing baryons

Miller & Bregman+15

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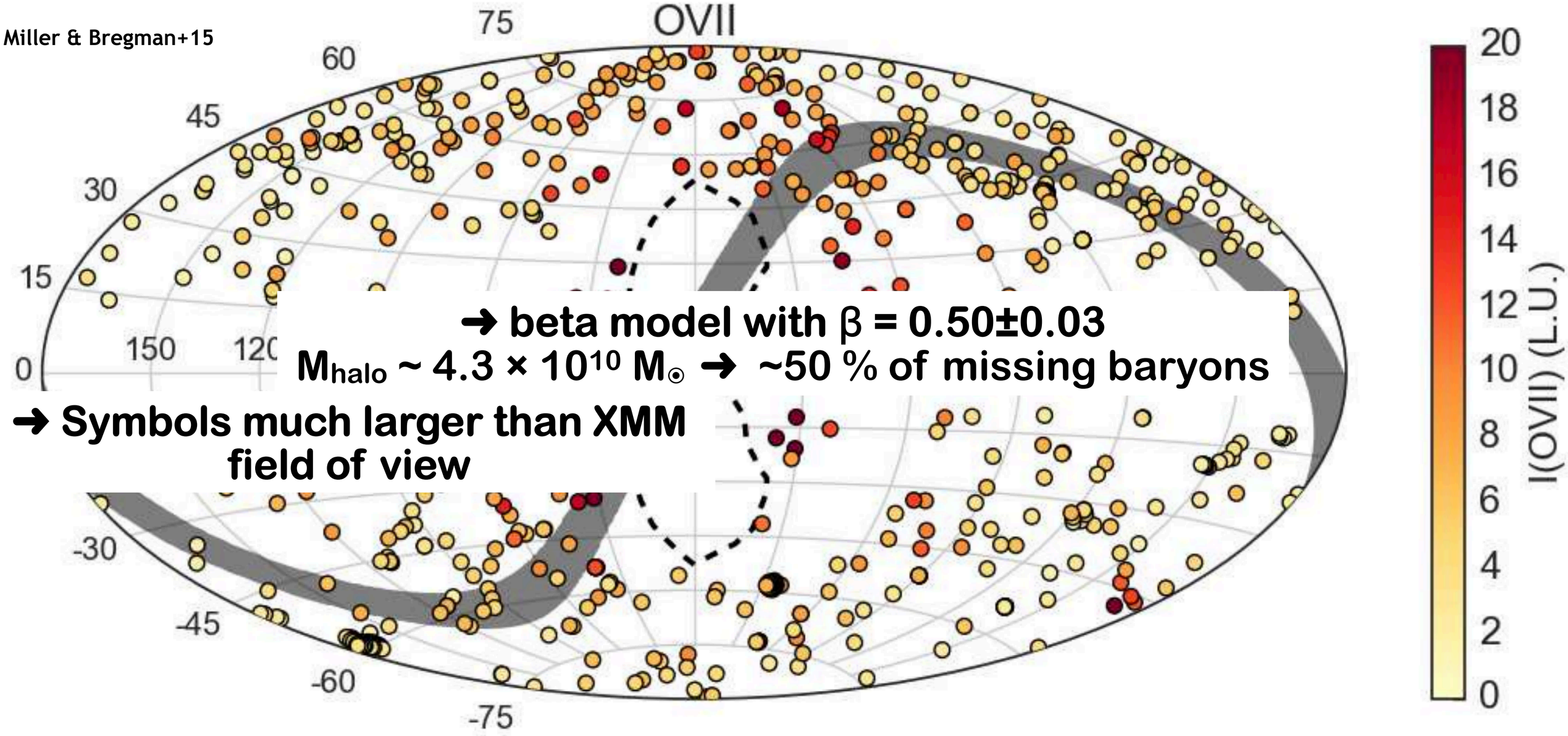

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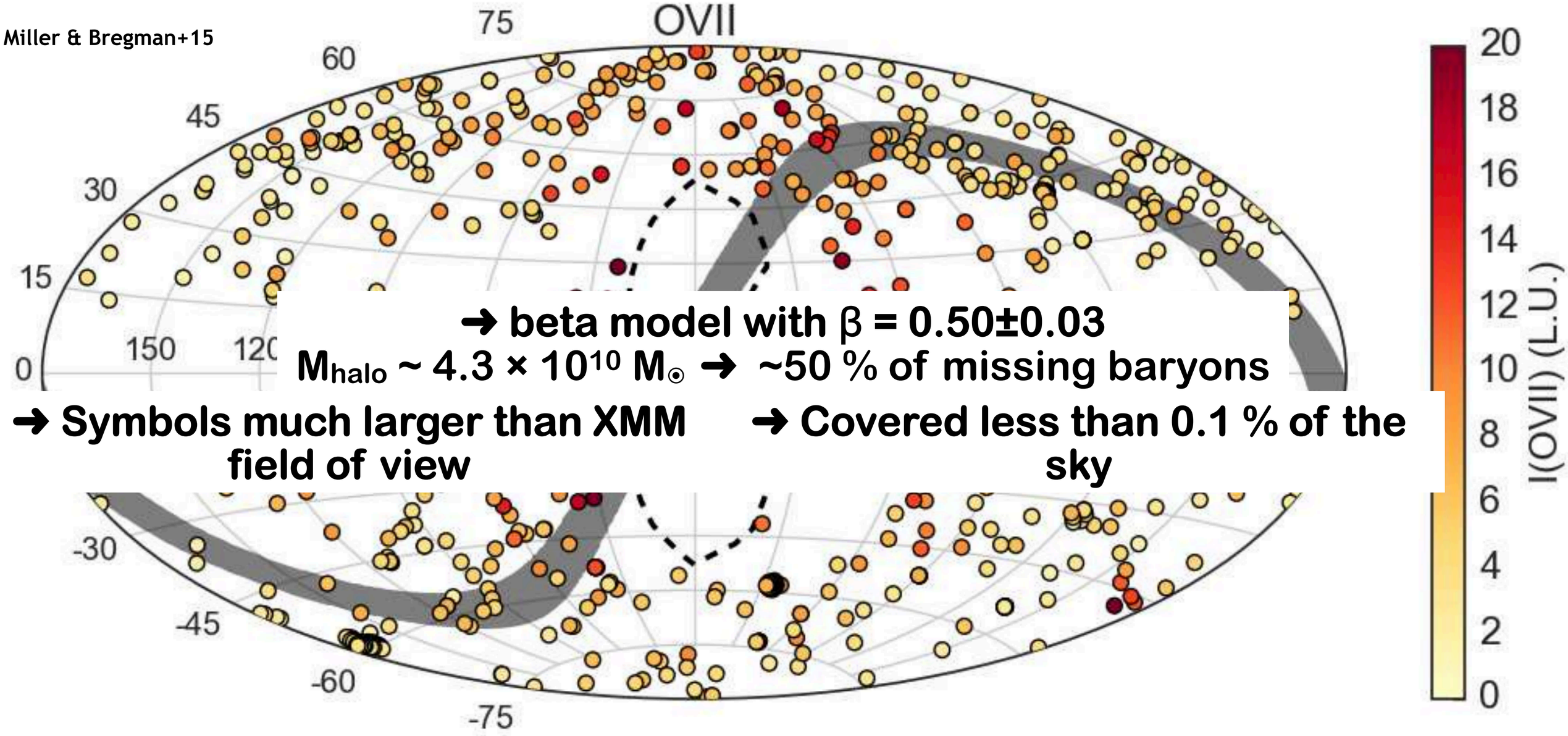

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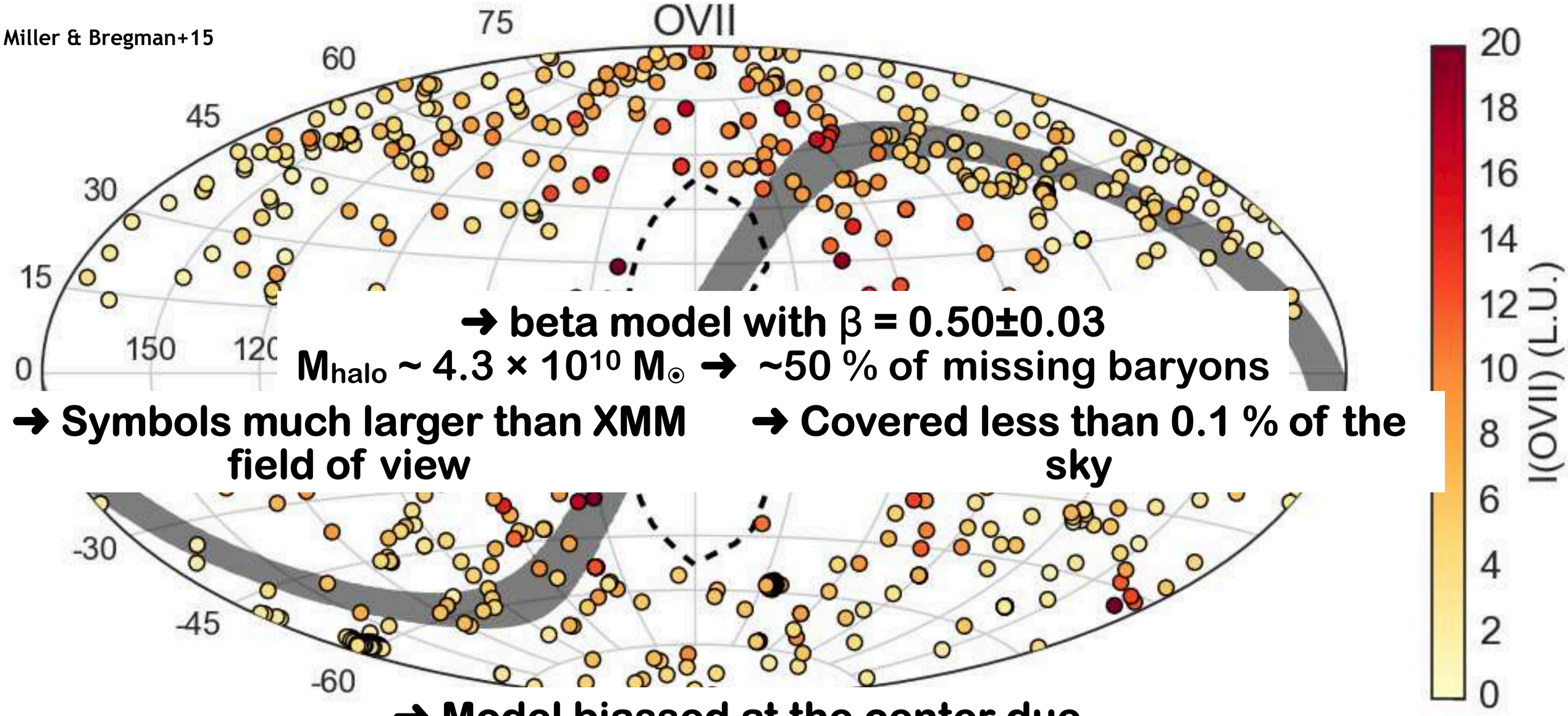

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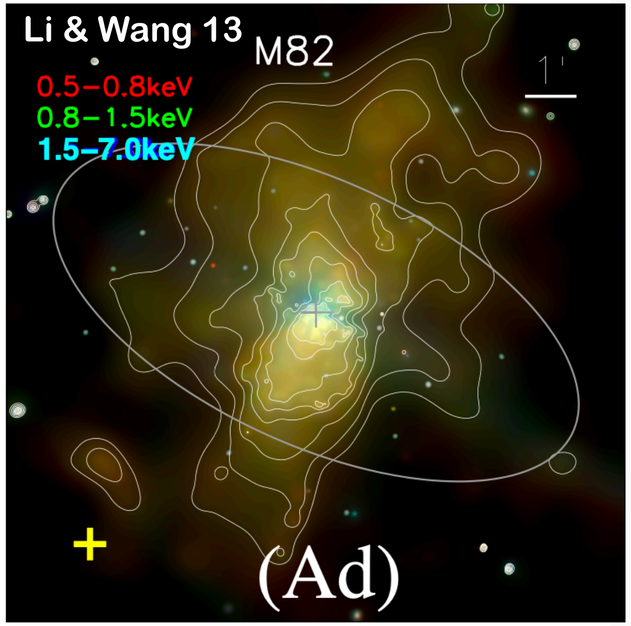
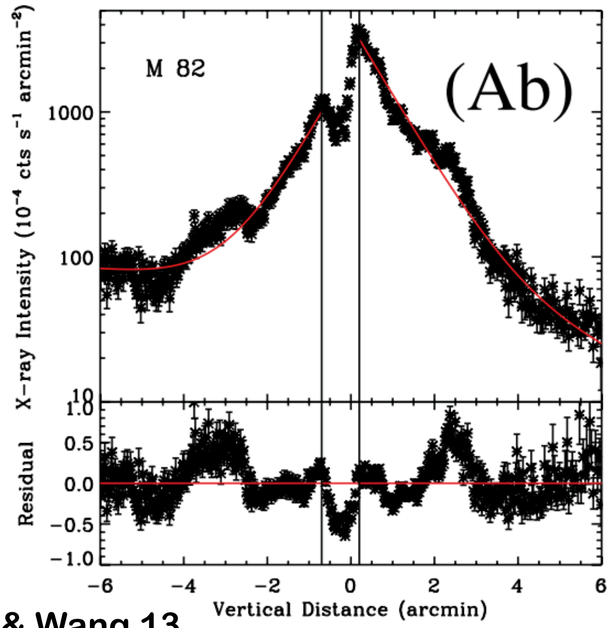
➜ Model biassed at the center due to the eROSITA bubbles

Miller & Bregman+15

Chandra survey of edge-on spiral galaxies





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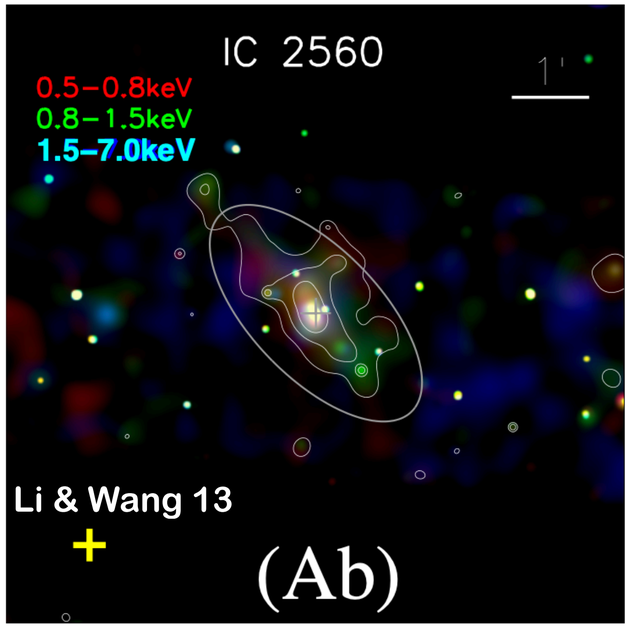
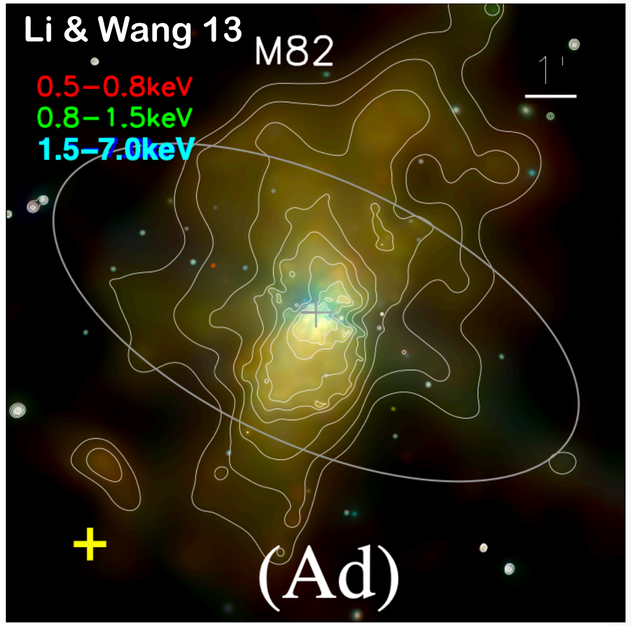
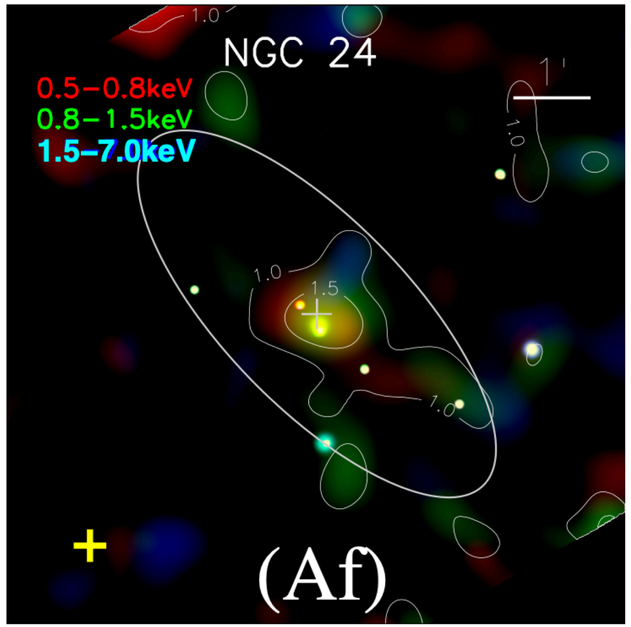
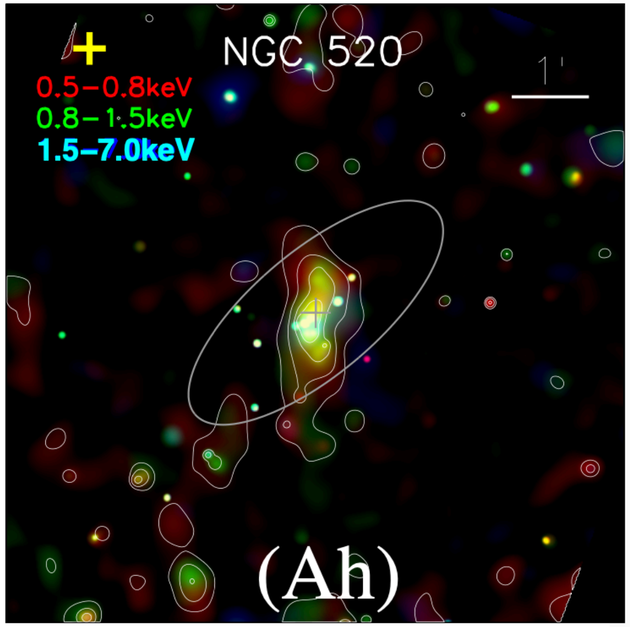
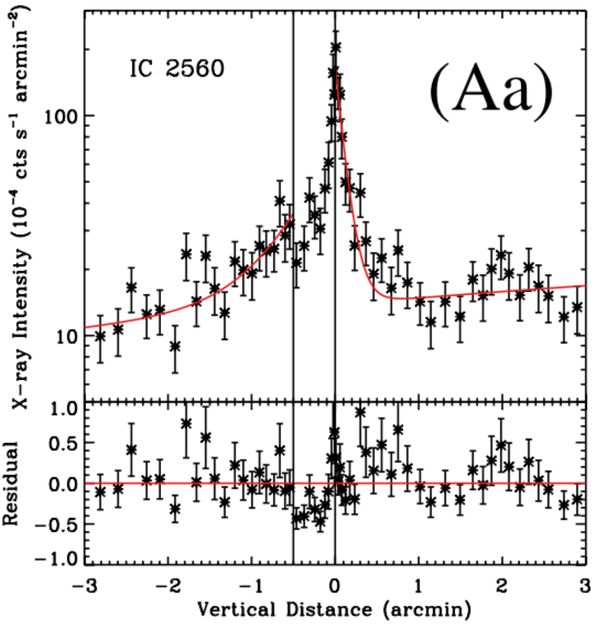
Chandra survey of edge-on spiral galaxies

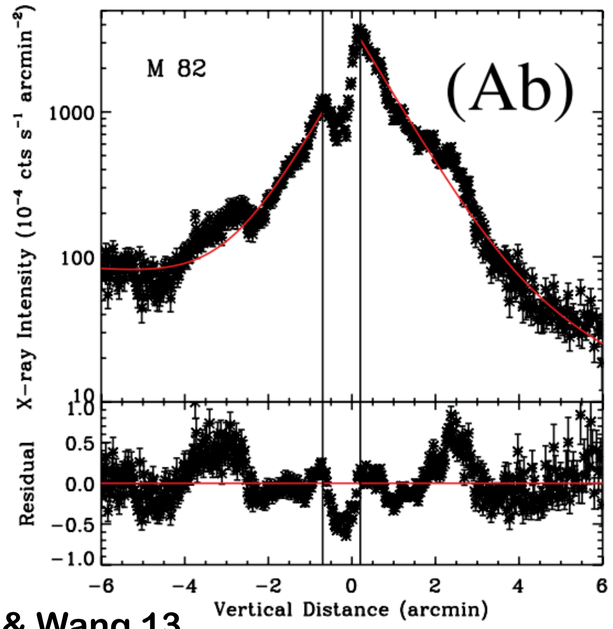


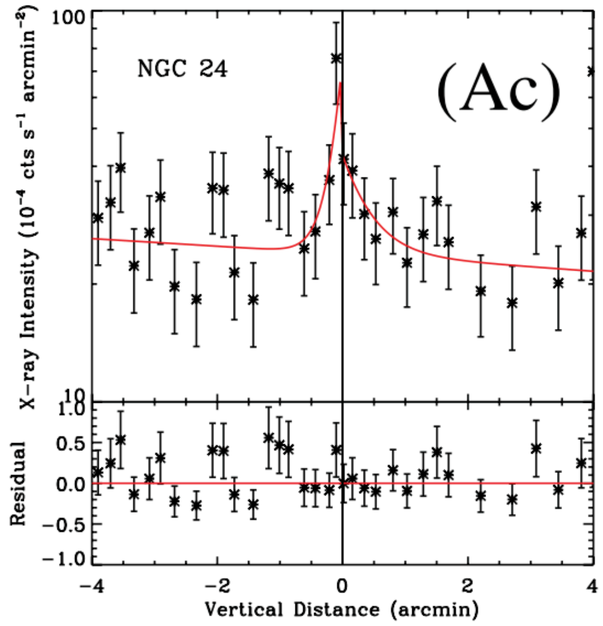


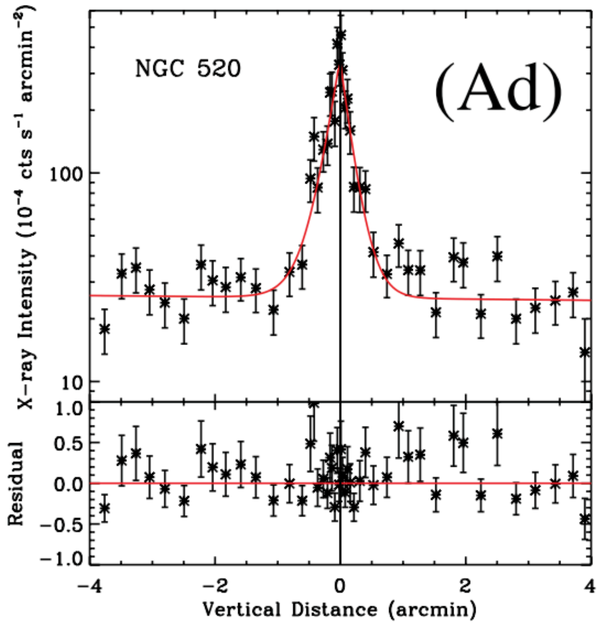












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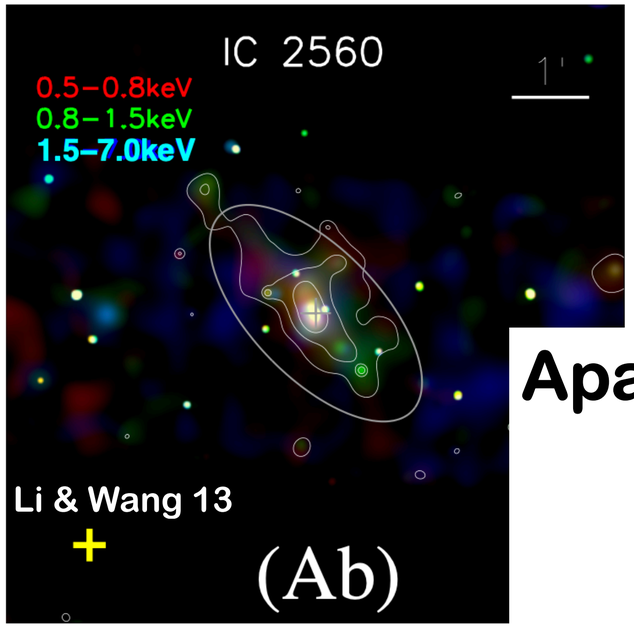
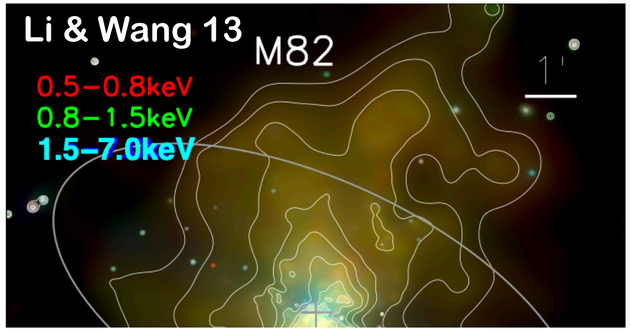
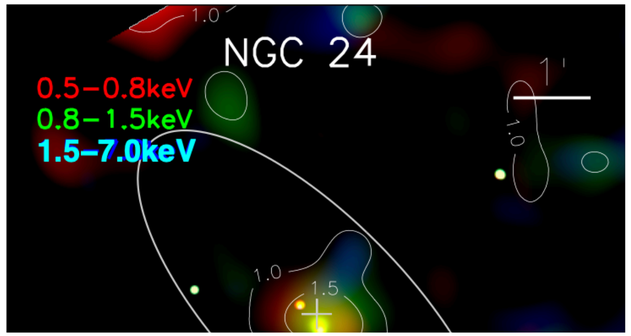
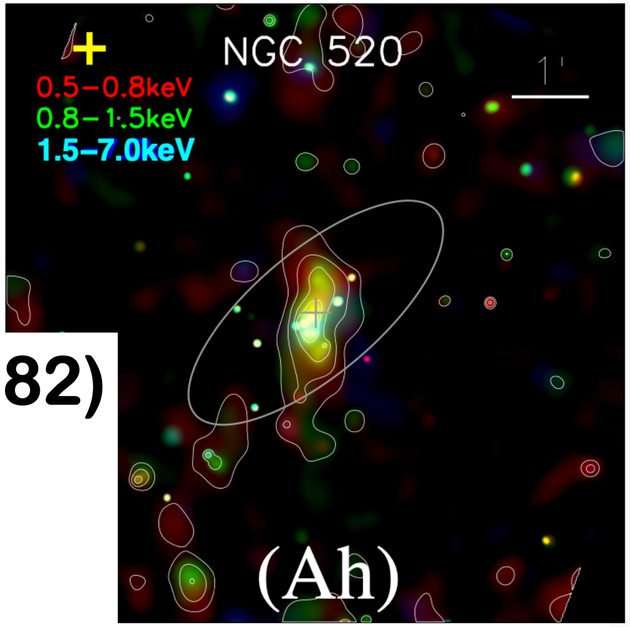
Chandra survey of edge-on spiral galaxies







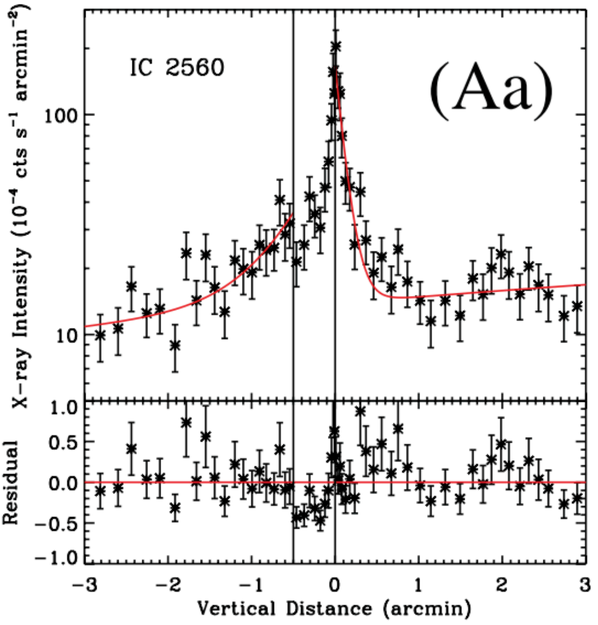


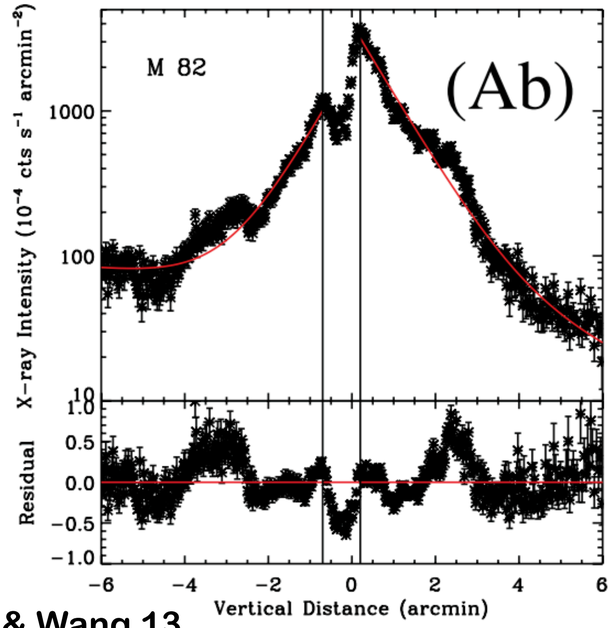
Apart from outflows in special cases (e.g. M82)

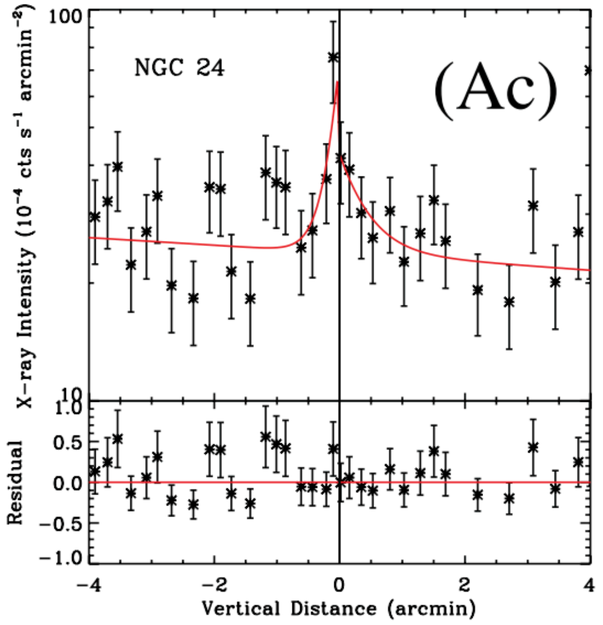
➜ Little evidence for an extended halo

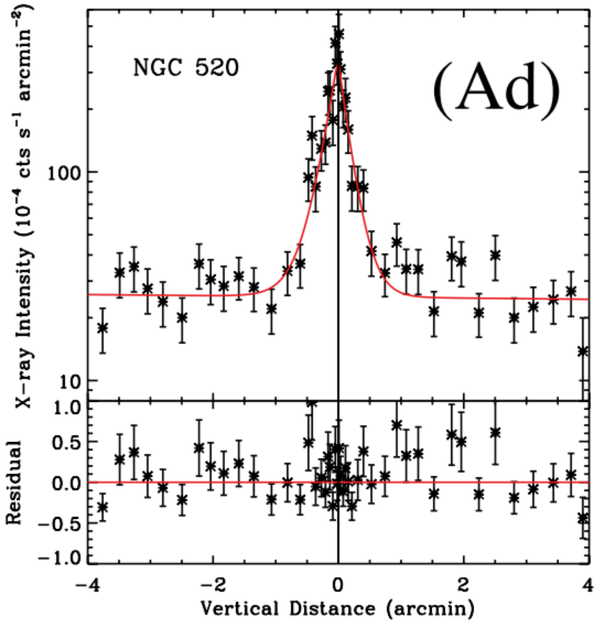
Emission from disc-halo interface

(charge exchange? galactic atmosphere?)









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How can we form galaxies without a hot halo?

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With cold clouds ➜ $t_{cooling}$ is short ➜ no more hot CGM

Marinacci+11; Voit+17; McCourt+18

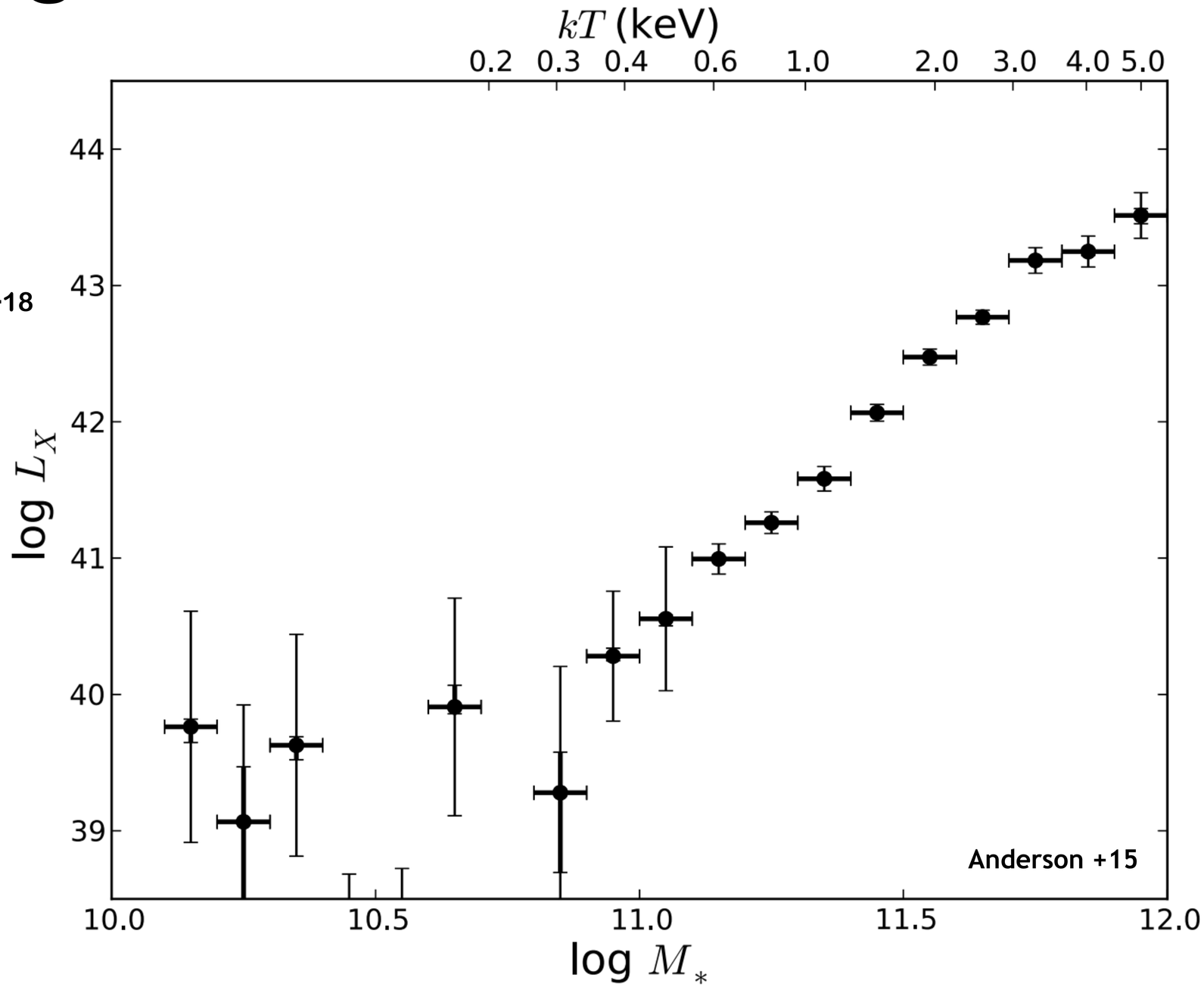
How can we form galaxies without a hot halo?

With cold clouds ➜ $t_{cooling}$ is short ➜ no more hot CGM

Marinacci+11; Voit+17; McCourt+18

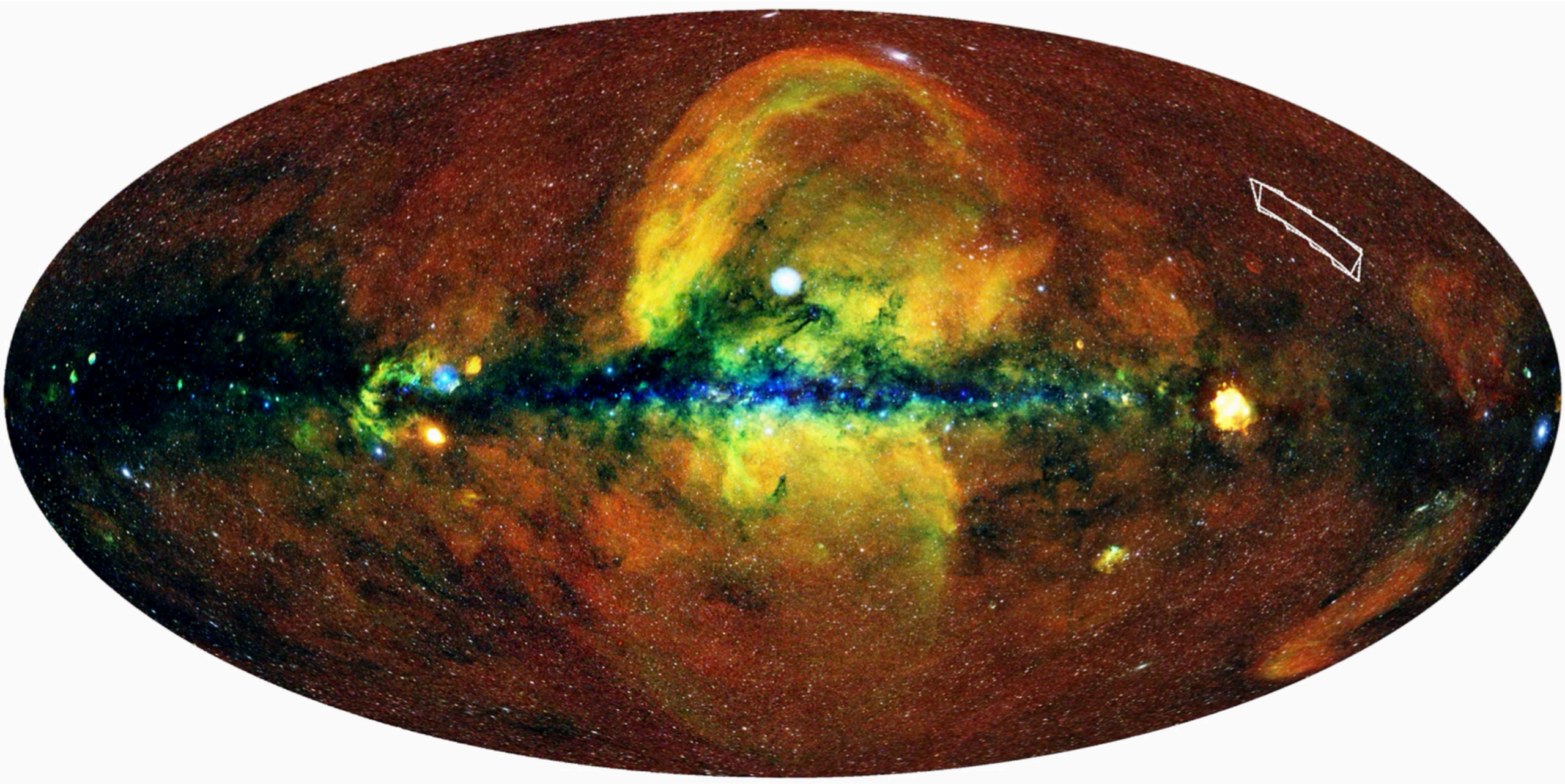
ROSAT stacks of brightest central galaxies

➜ An extended hot halo is present around massive galaxies



Then eROSITA arrives….

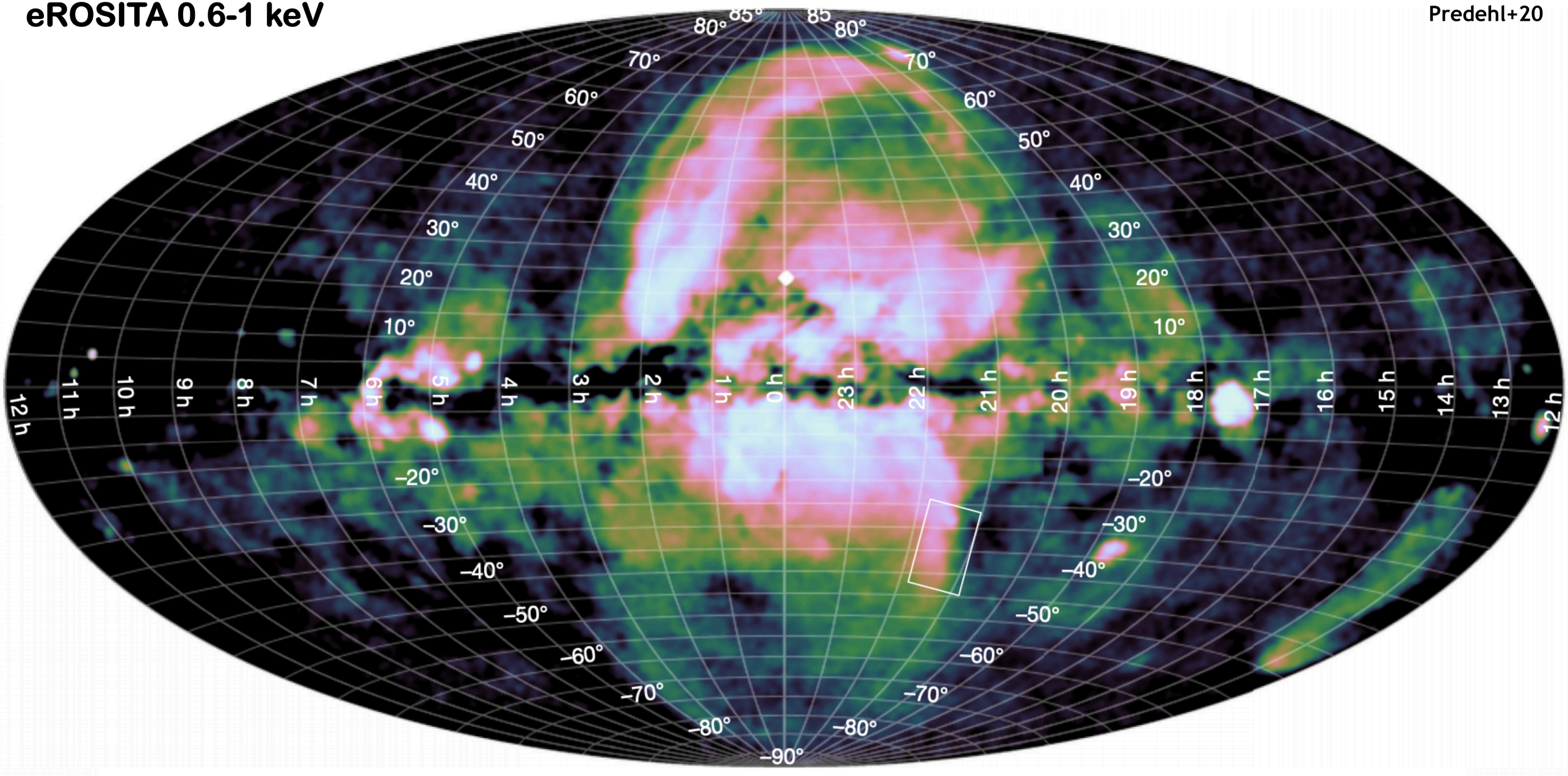
The soft X-ray Universe: eROSITA images…



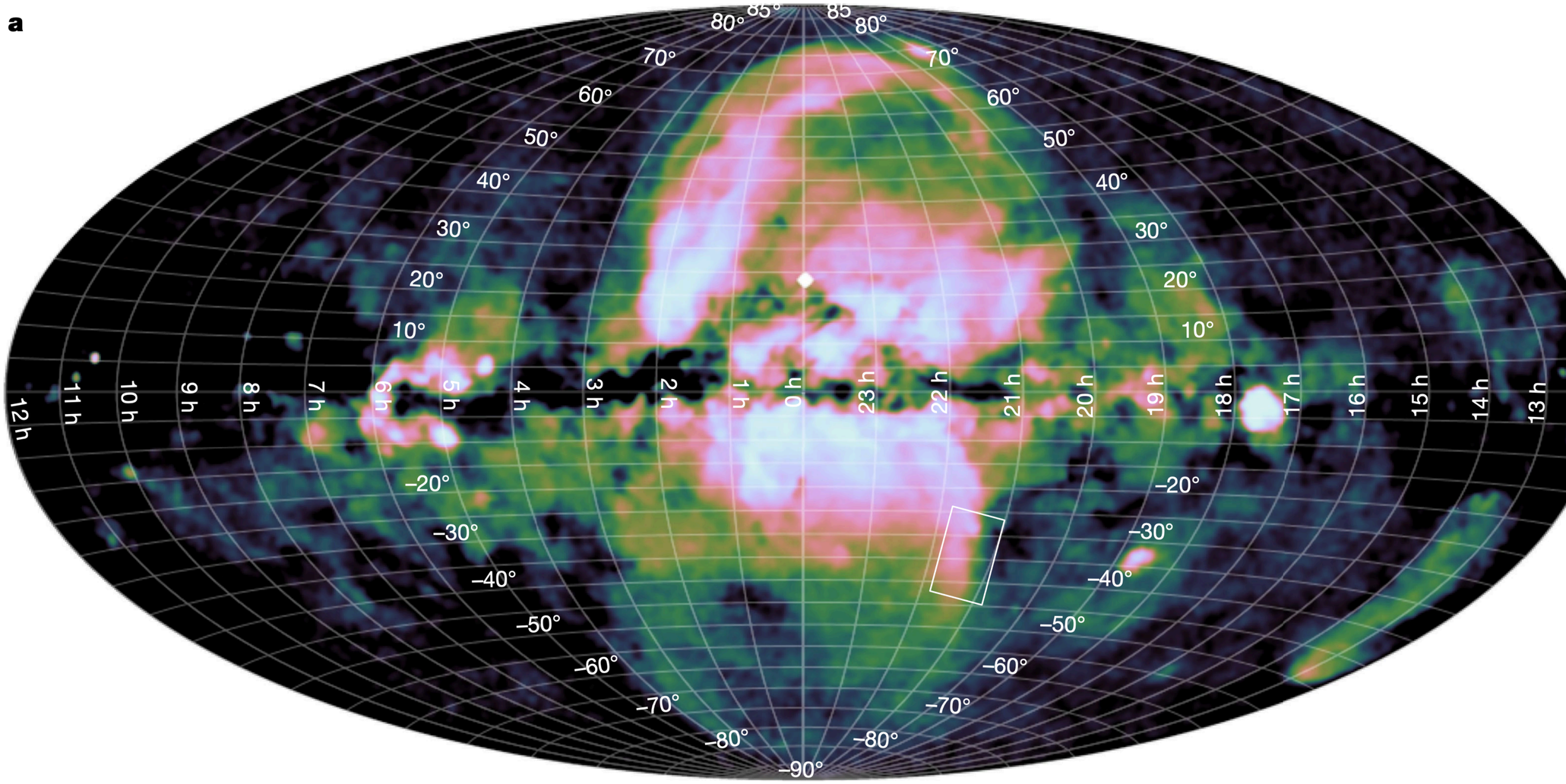
Discovery of the eROSITA bubbles!

eROSITA 0.6-1 keV

Predehl+20



Galactic outflow ➜ impact on CGM



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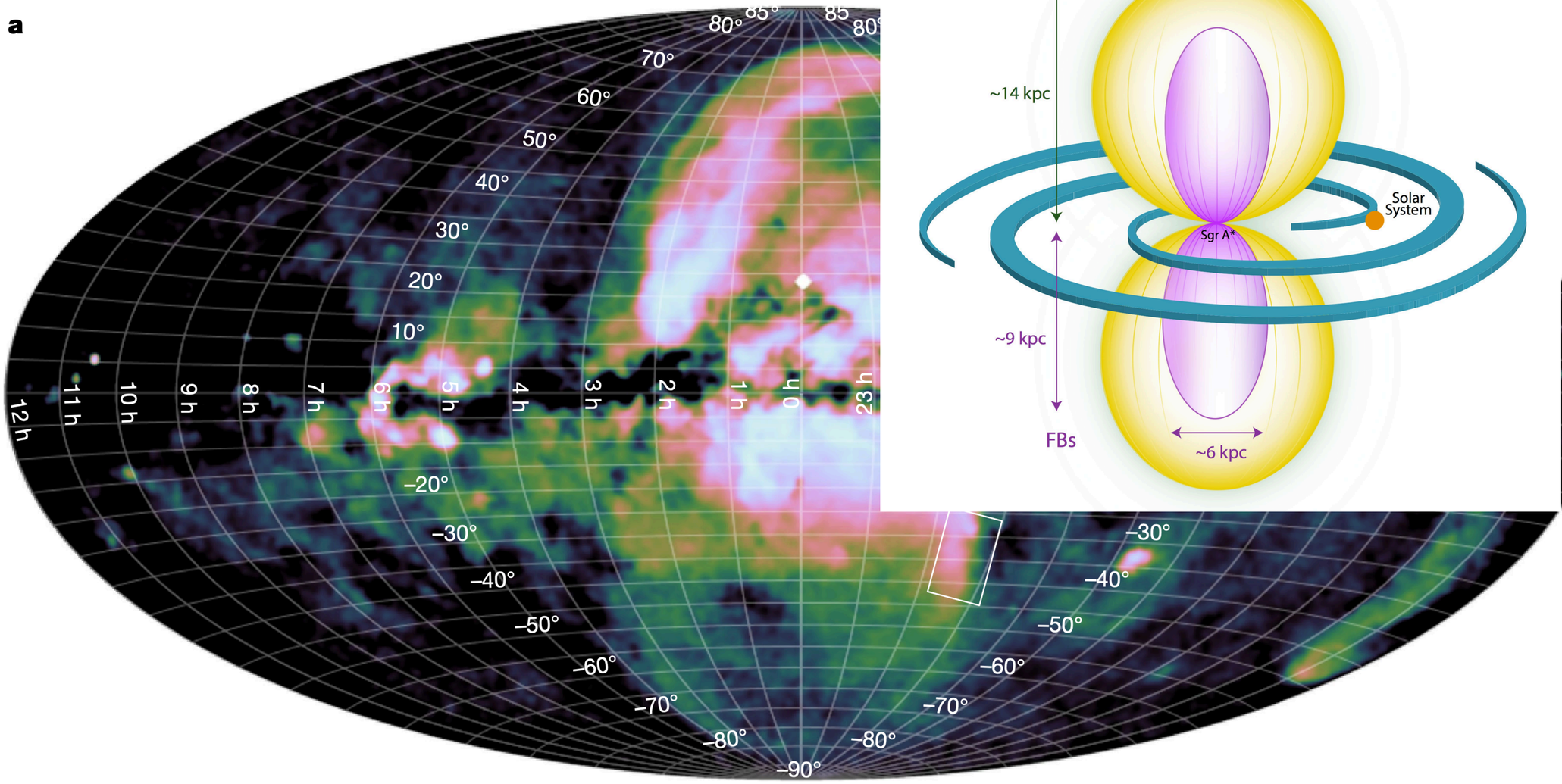

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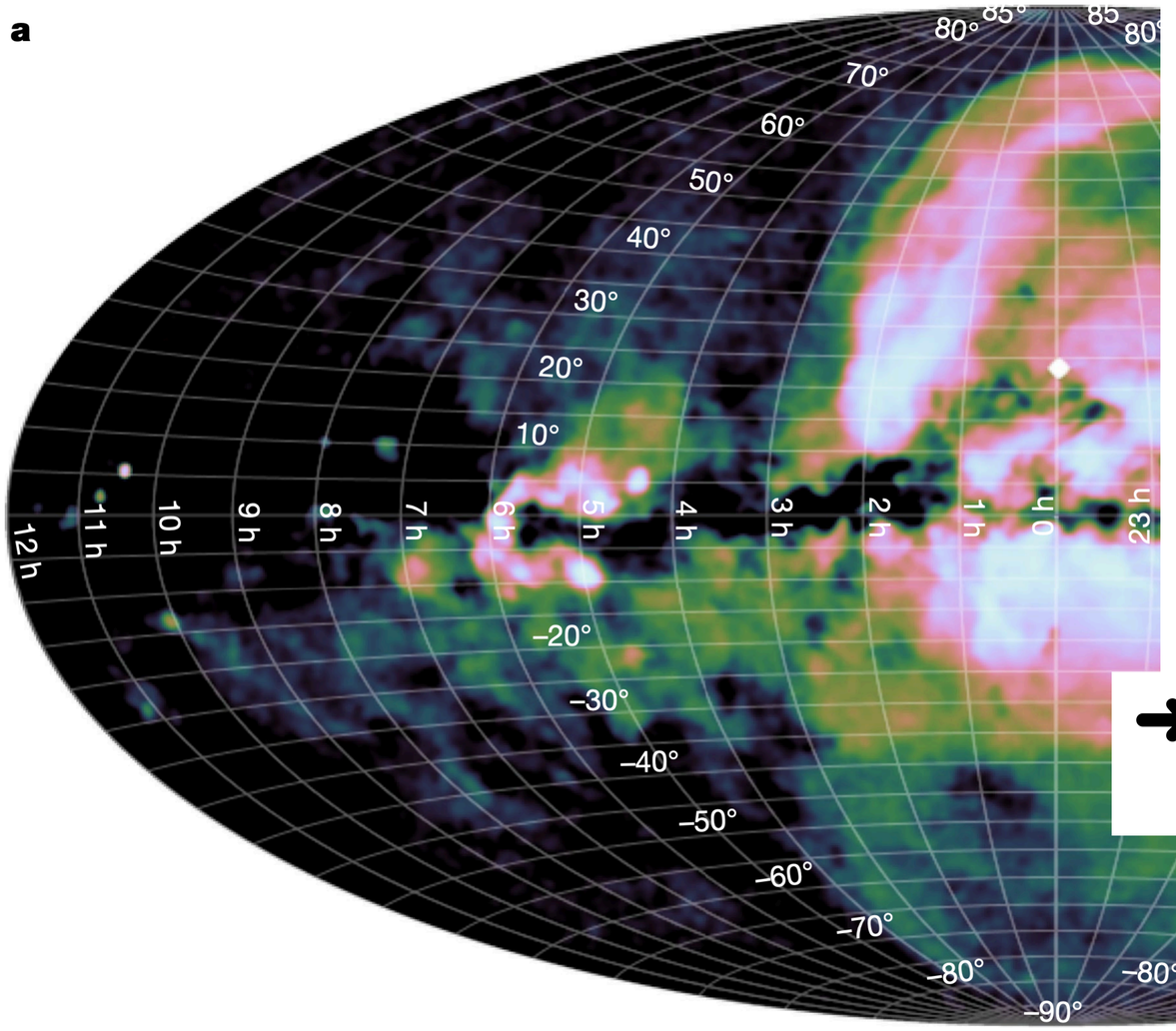
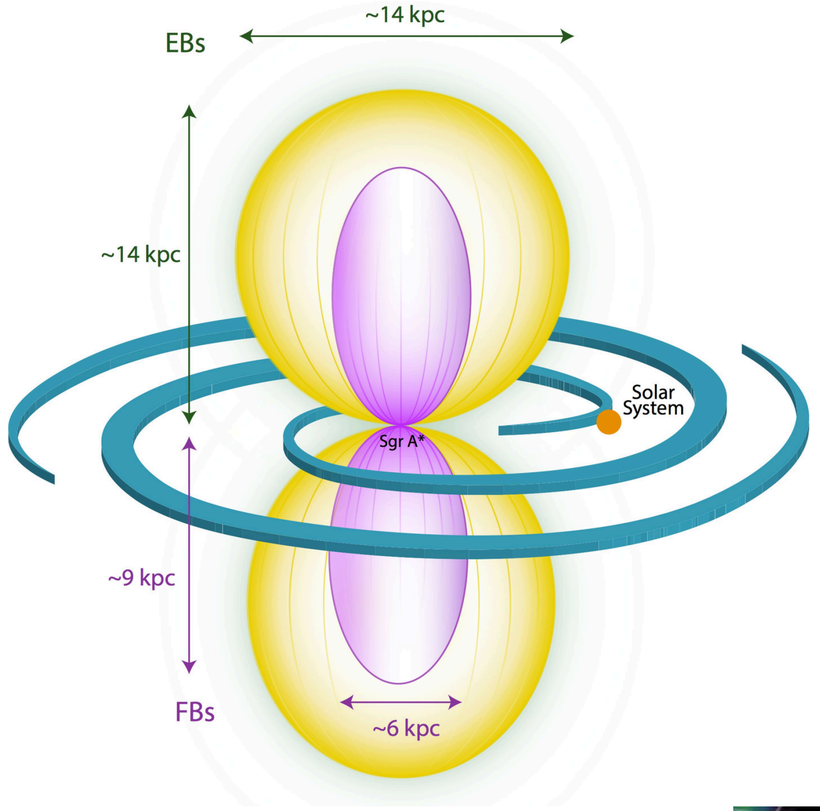
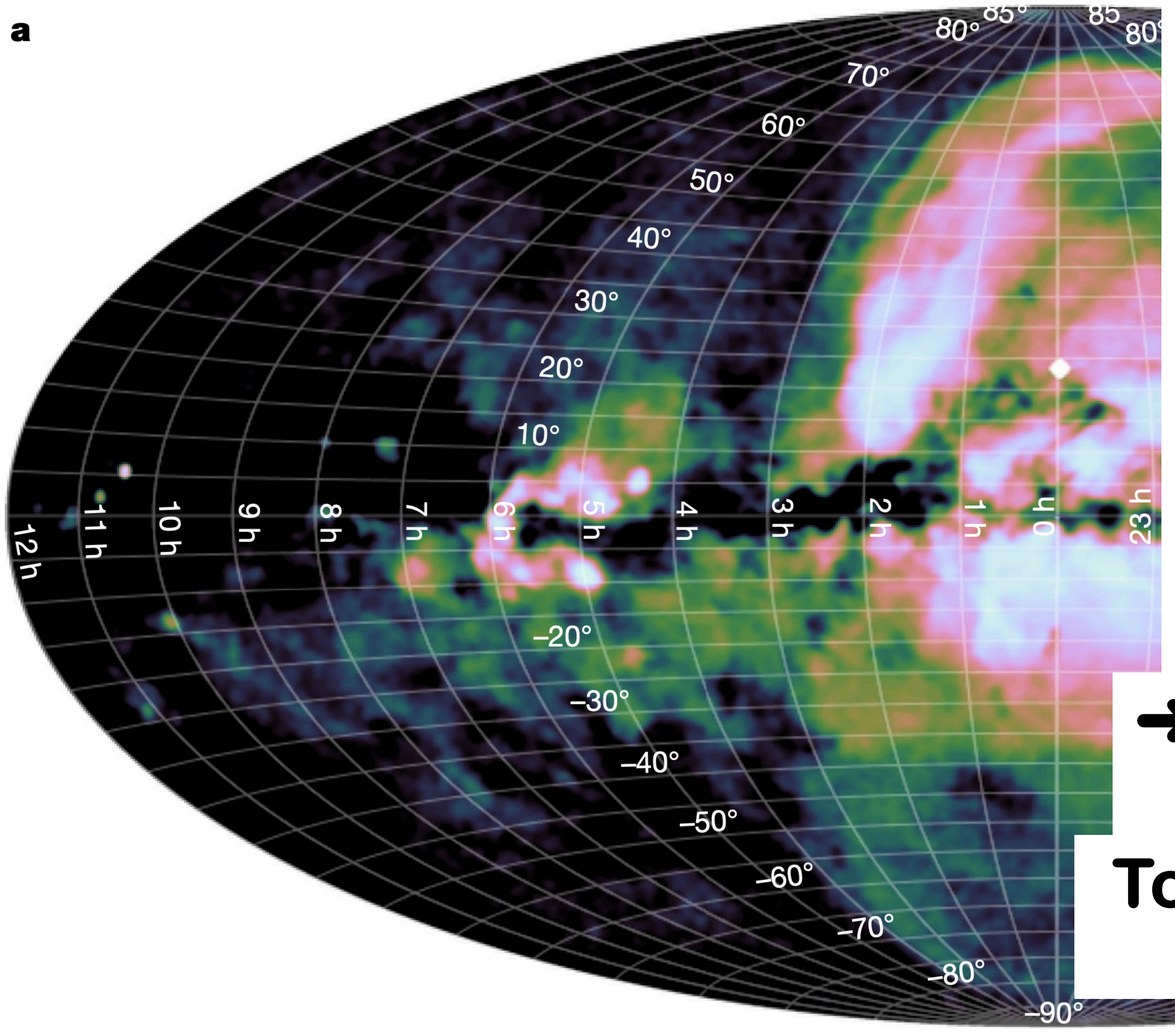
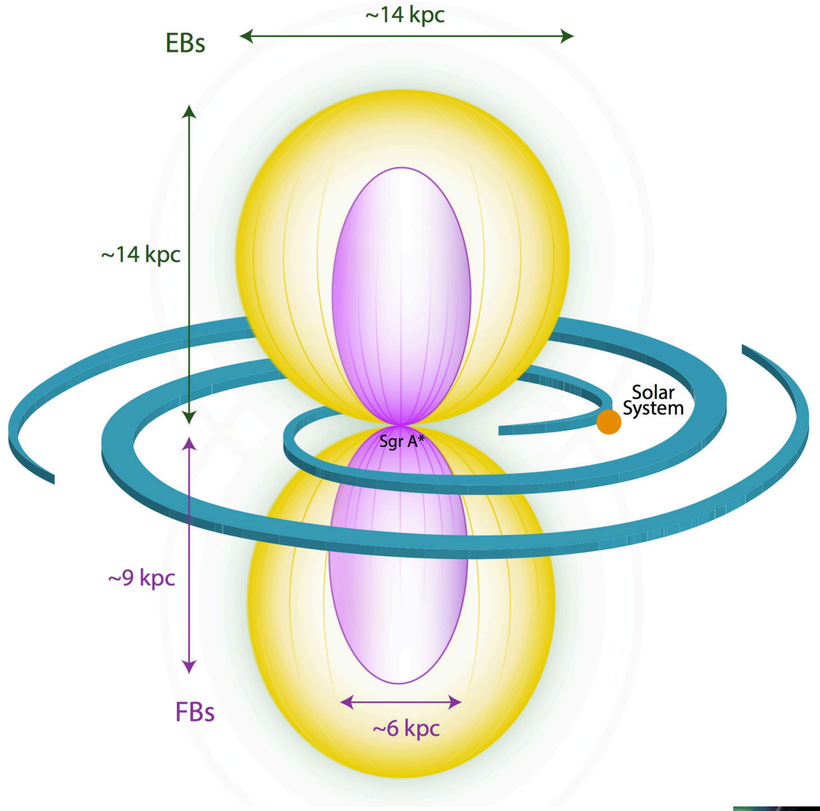




➜ 10 times more energy than Fermi bubbles

Galactic outflow ➜ impact on CGM

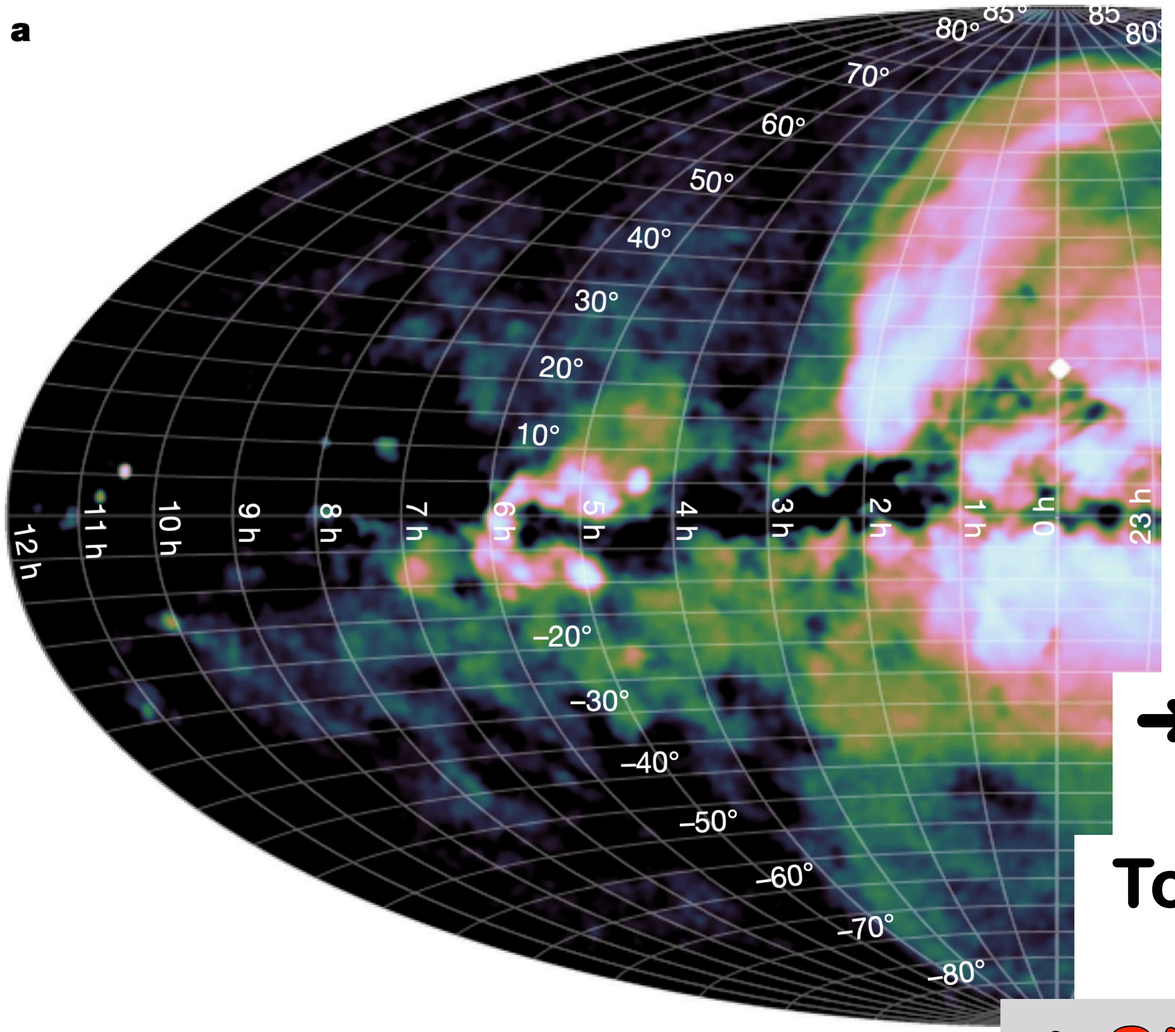


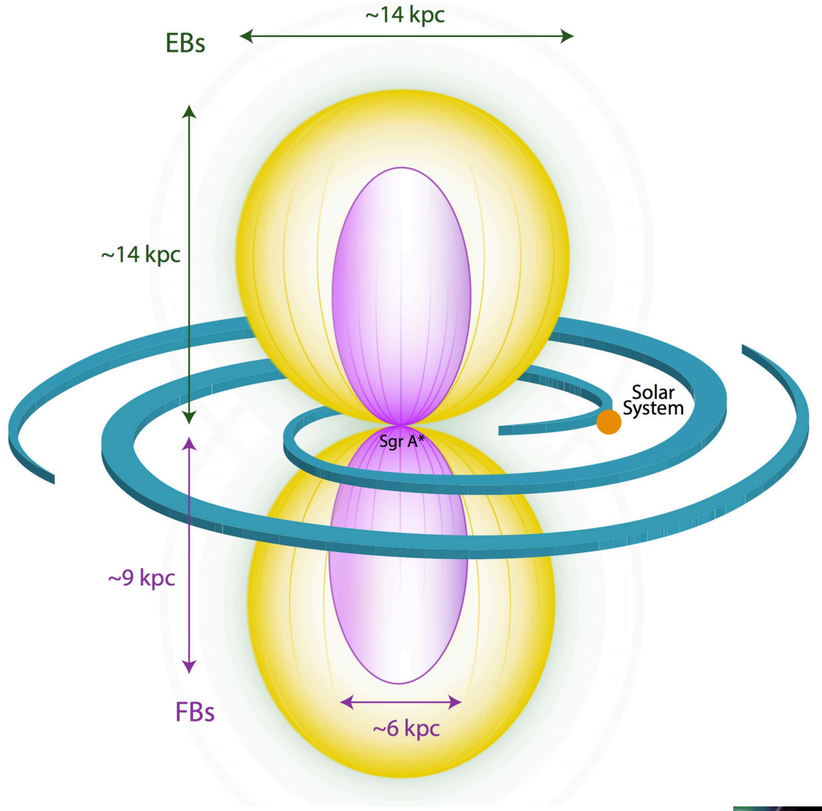


➜ 10 times more energy than Fermi bubbles

To inflate ➜ $L \sim 10^{41}$ erg s^{-1} for few 10^7 yr

Galactic outflow ➜ impact on CGM



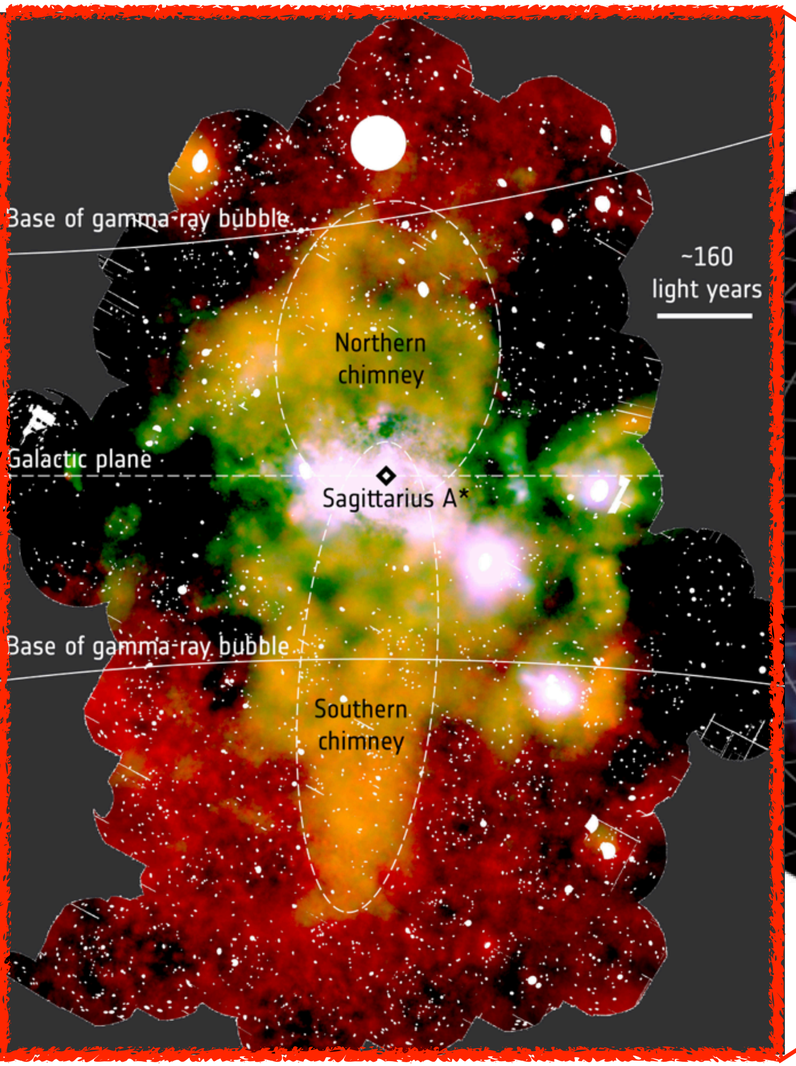


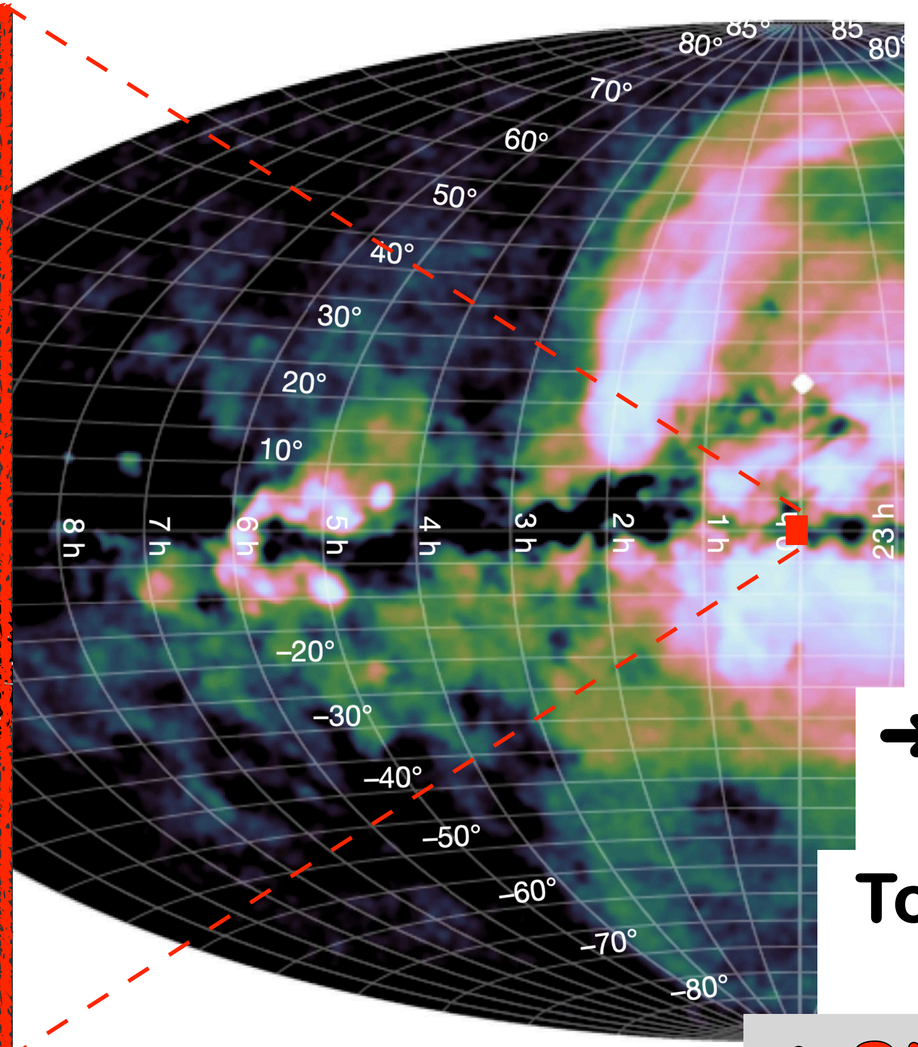
➜ 10 times more energy than Fermi bubbles

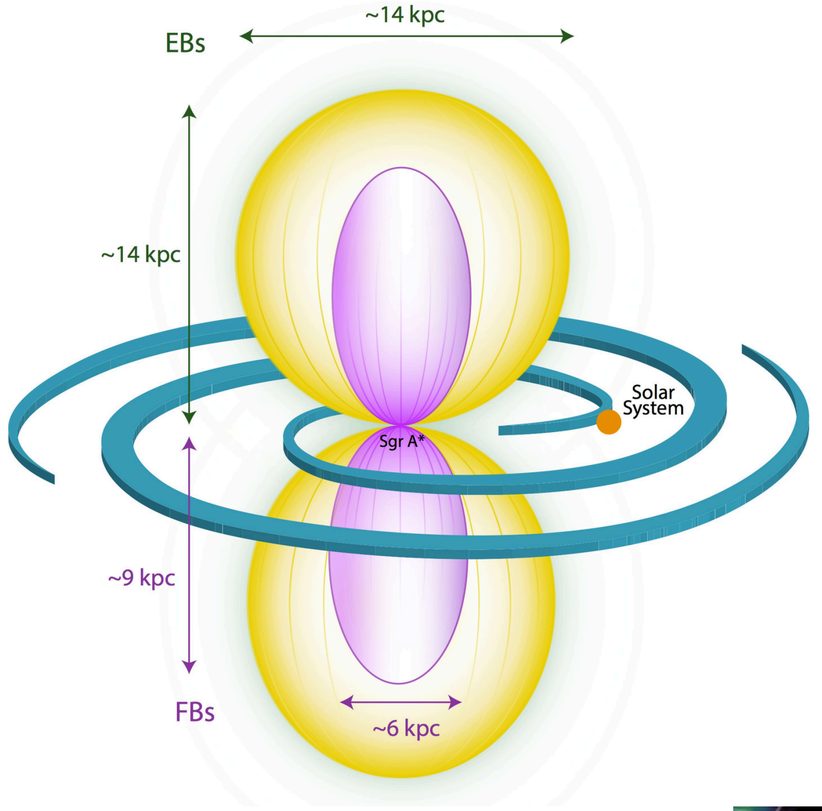
To inflate ➜ $L \sim 10^{41}$ erg s^{-1} for few 10^7 yr

➜ Strong impact on CGM!

Galactic outflow ➜ impact on CGM







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Ponti+19

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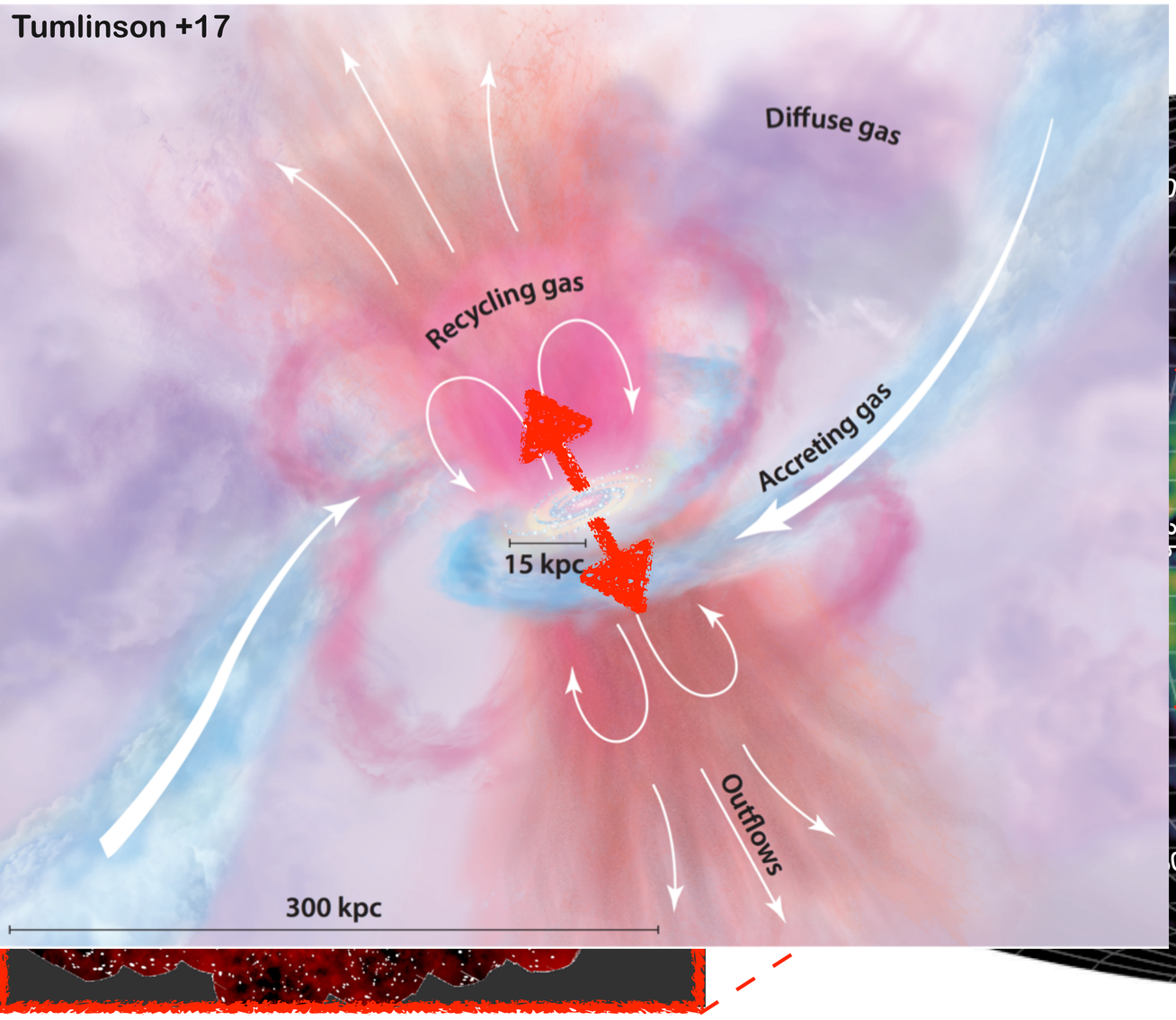
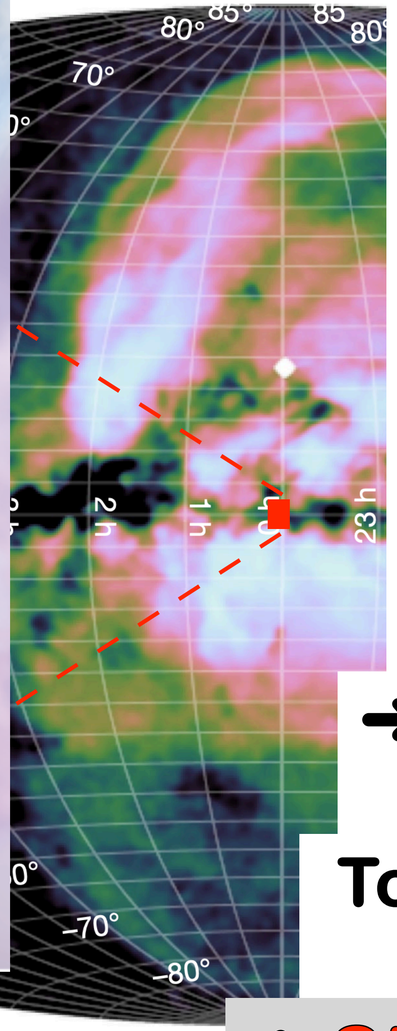
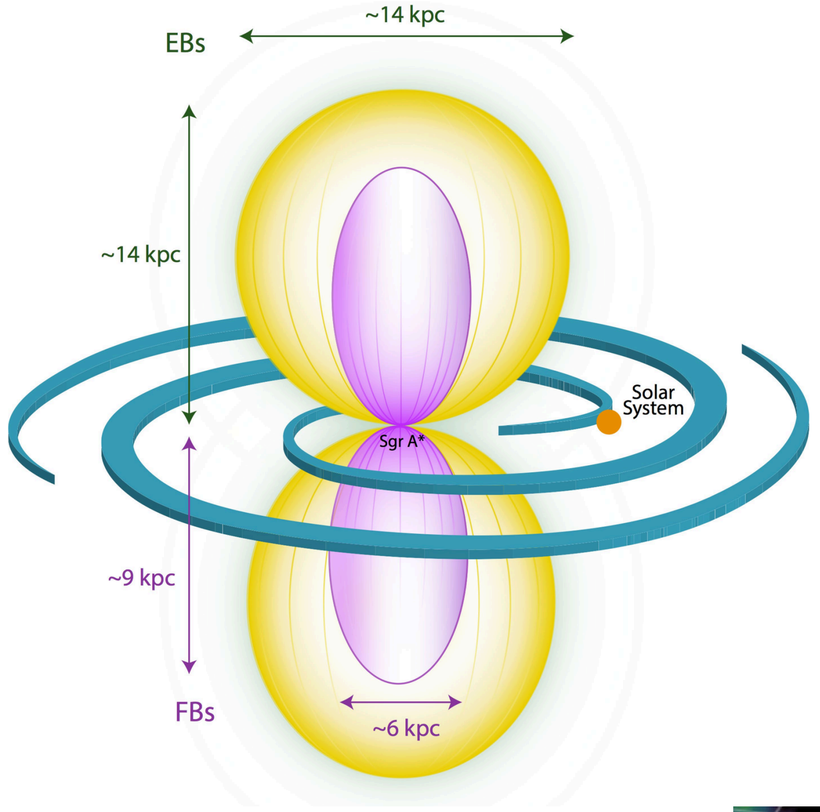


Ponti+19





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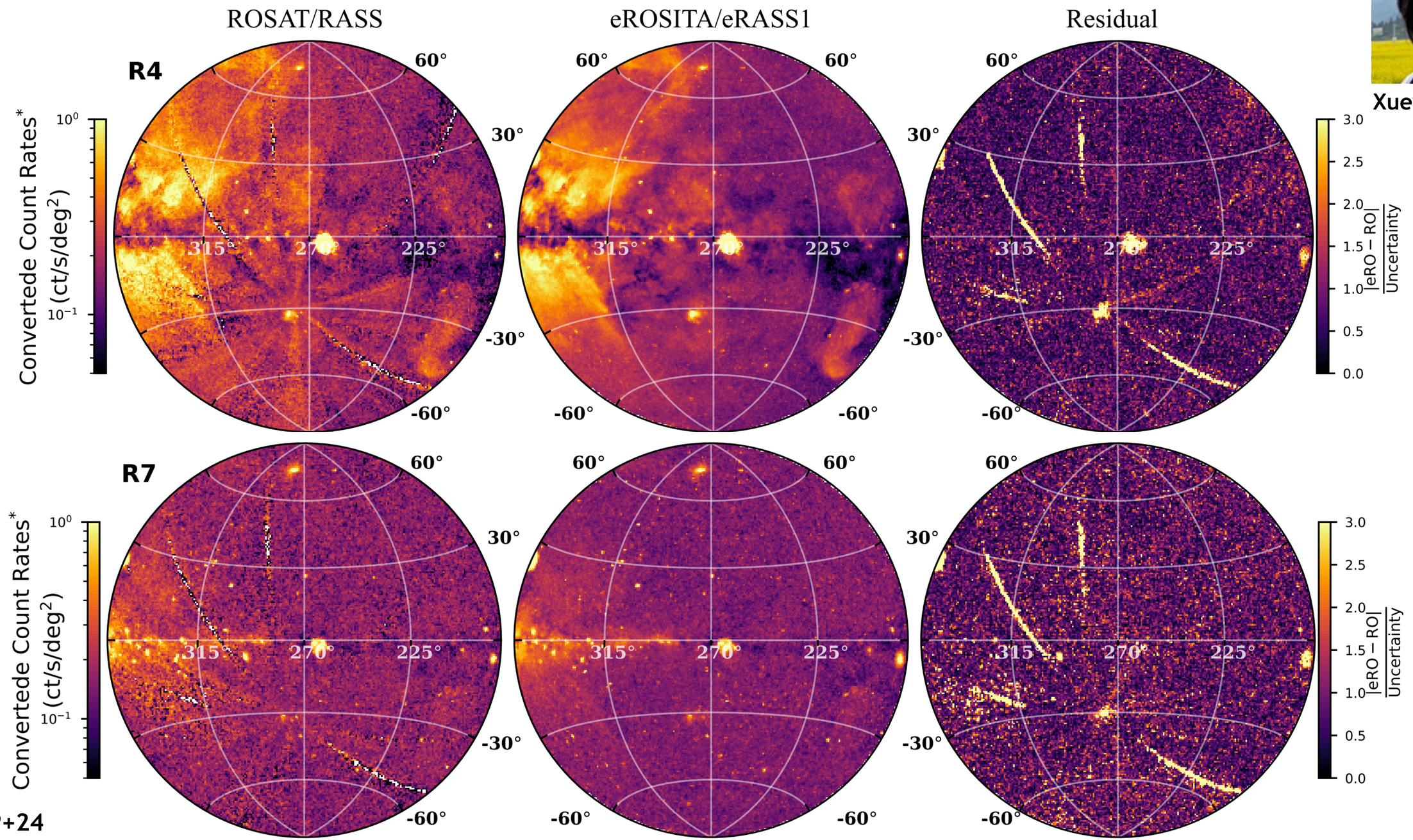
➜ Strong impact on CGM!

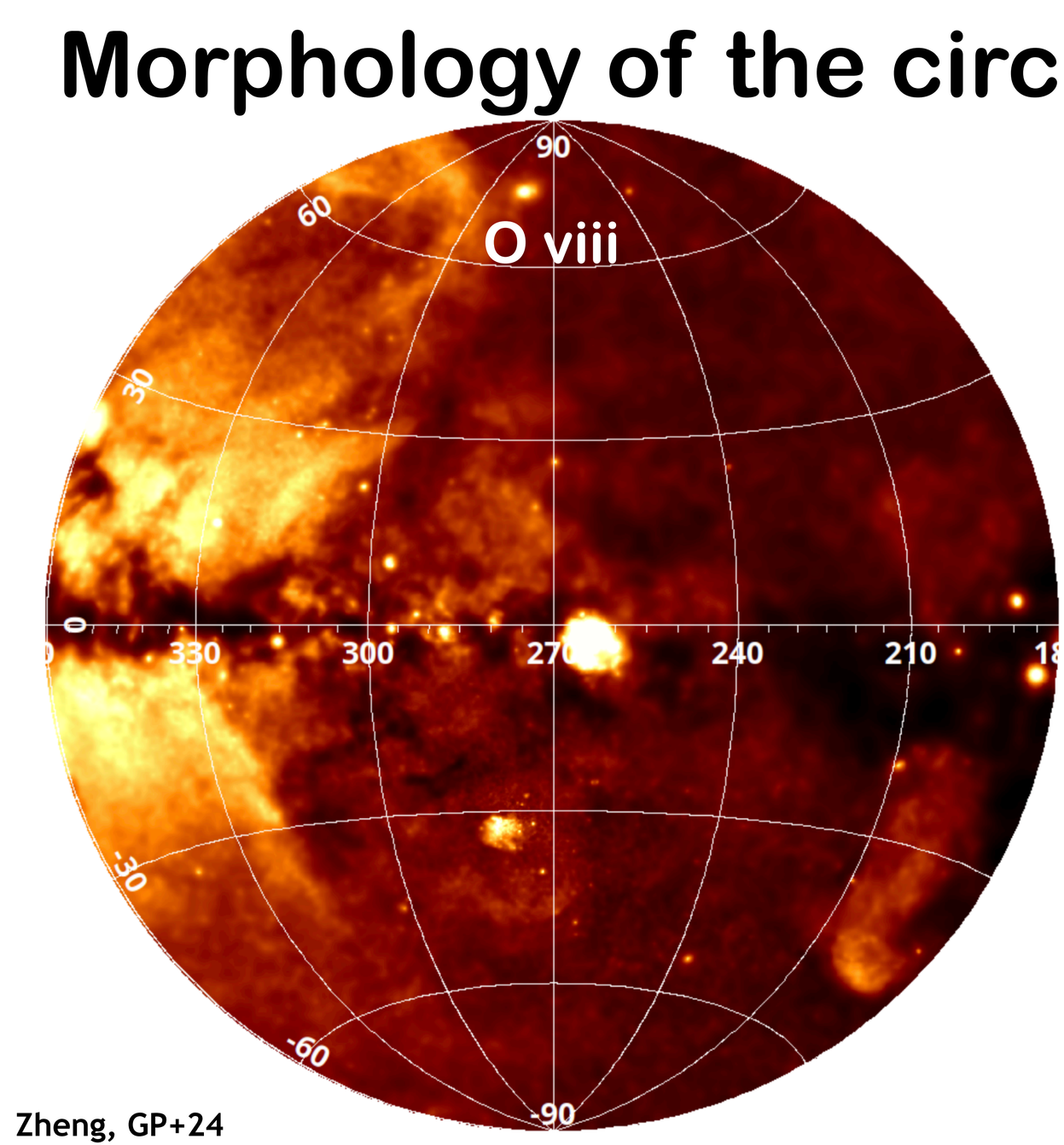
The half sky images of eROSITA

Xueying Zheng

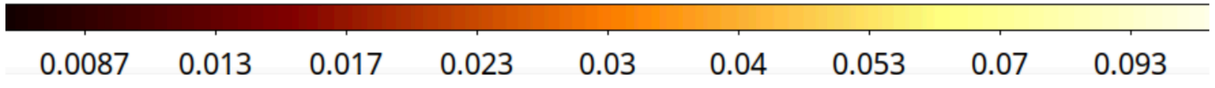


Zheng, GP+24

Morphology of the circumgalactic medium



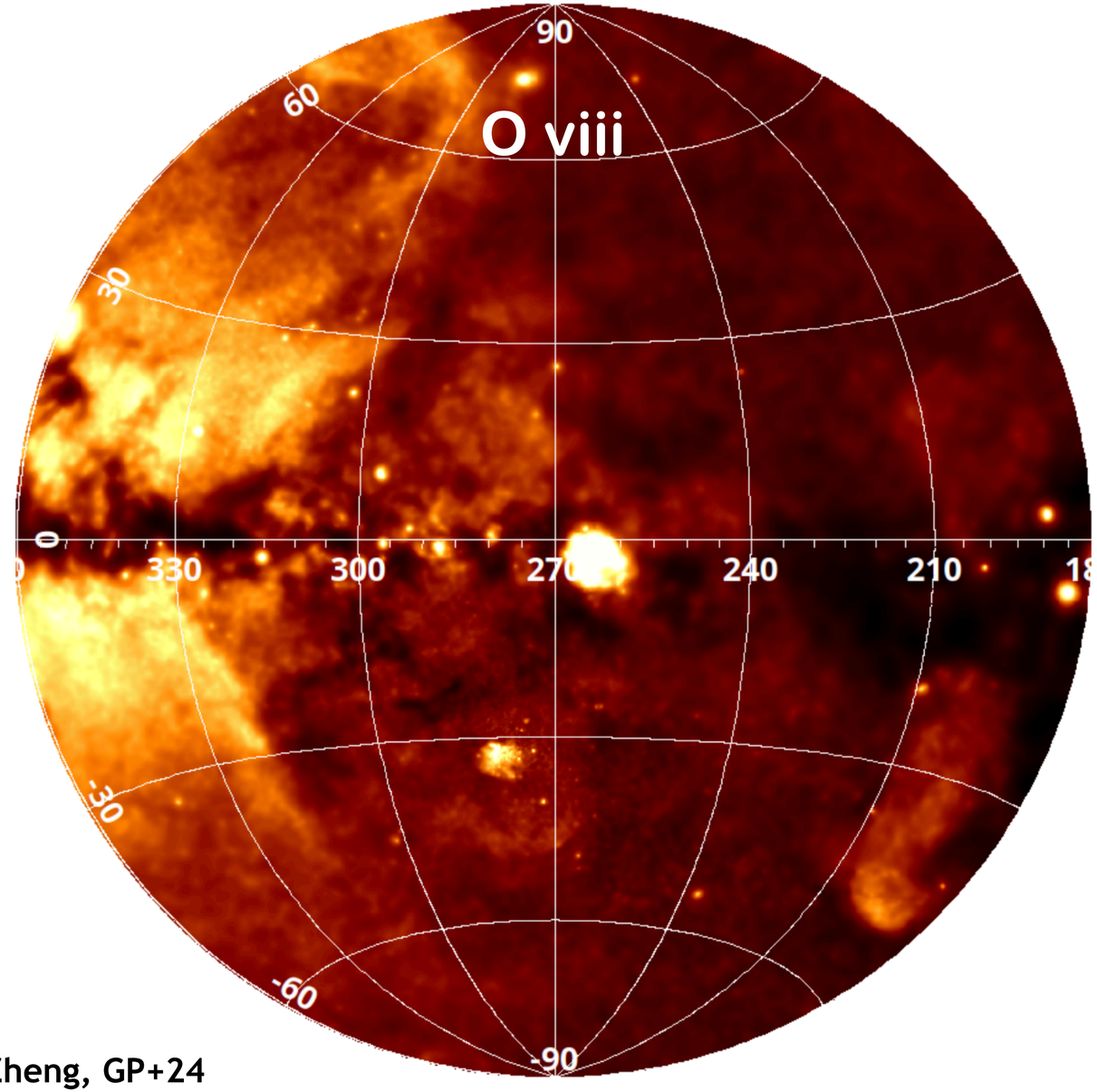
Zheng, GP+24



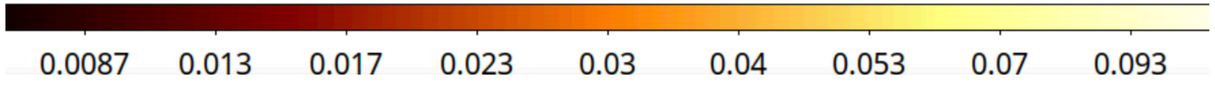
Nicola Locatelli

Morphology of the circumgalactic medium

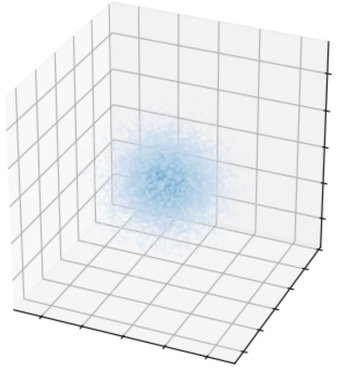
Nicola Locatelli



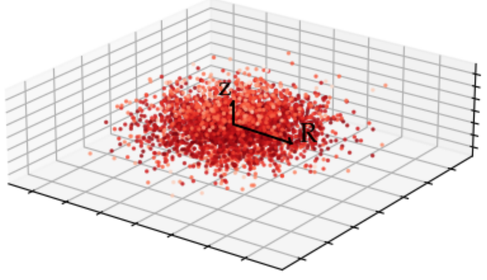
Zheng, GP+24



Spherical halo?
(beta model?)



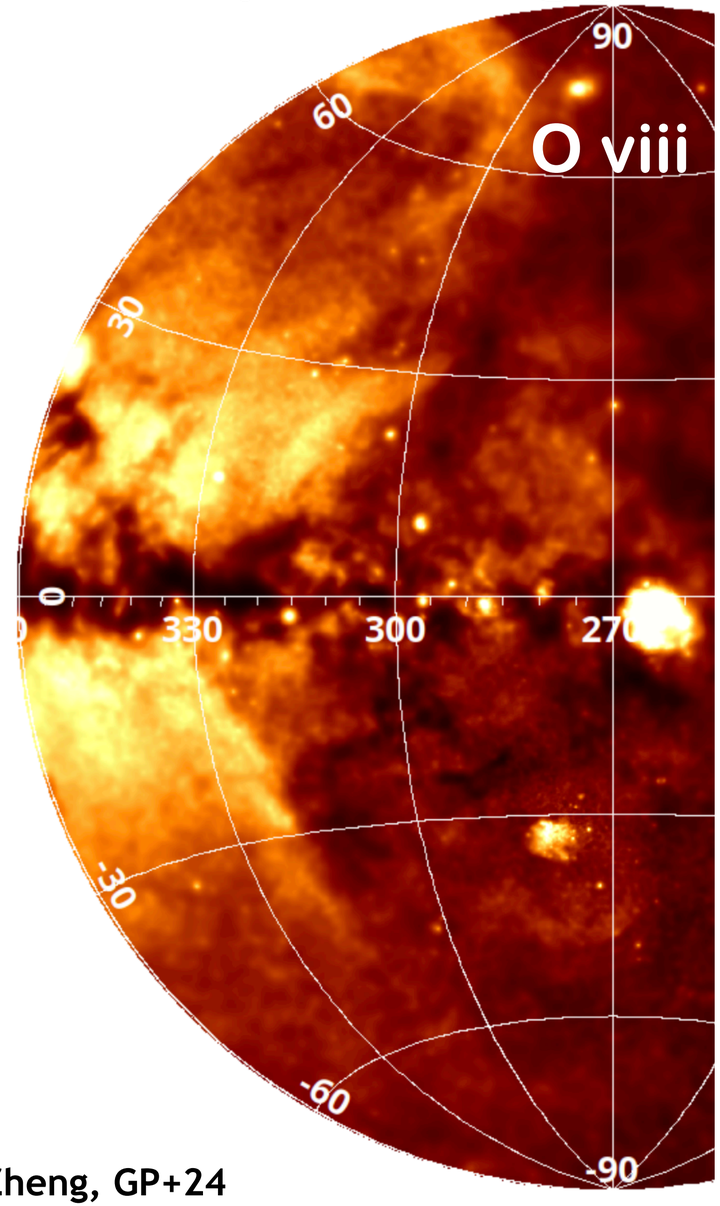
Or Exponential disc?
(corona? stars?)



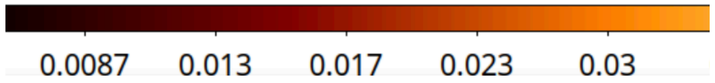
Locatelli, GP+24a; see also Bluem+22

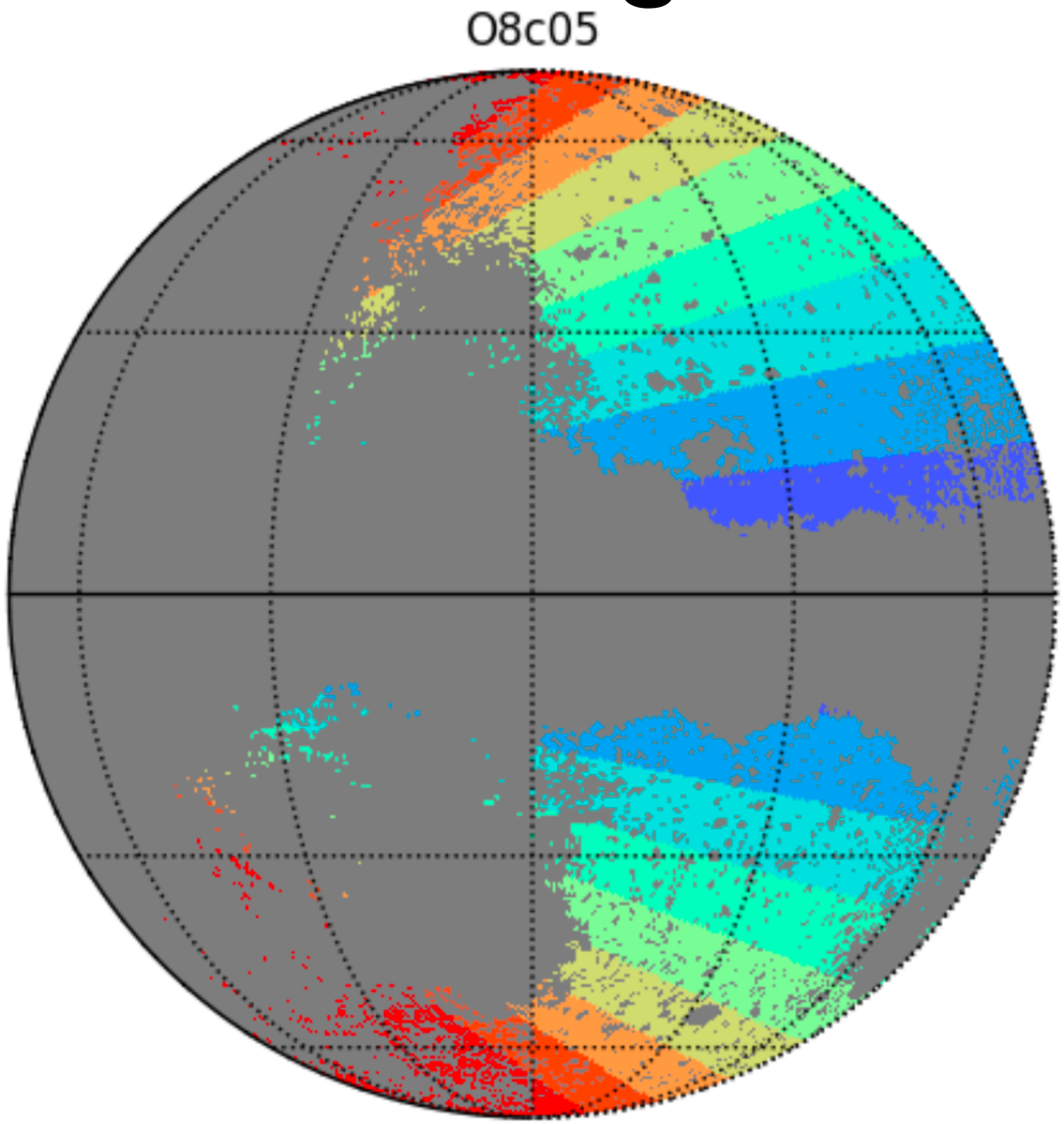
Morphology of the circumgalactic medium

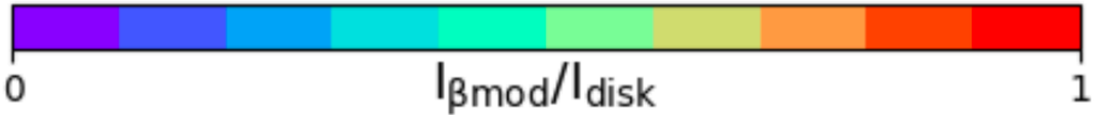
Nicola Locatelli



Zheng, GP+24







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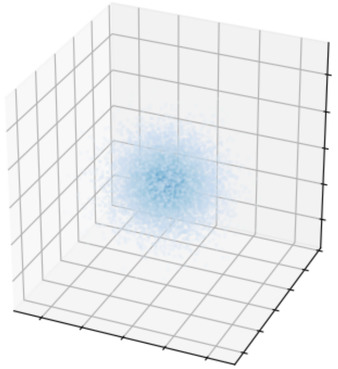

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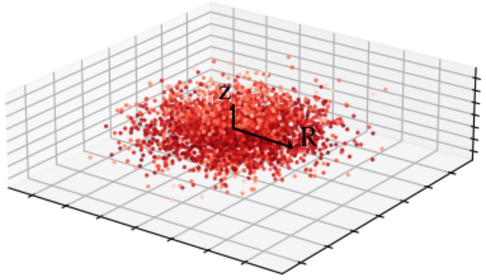

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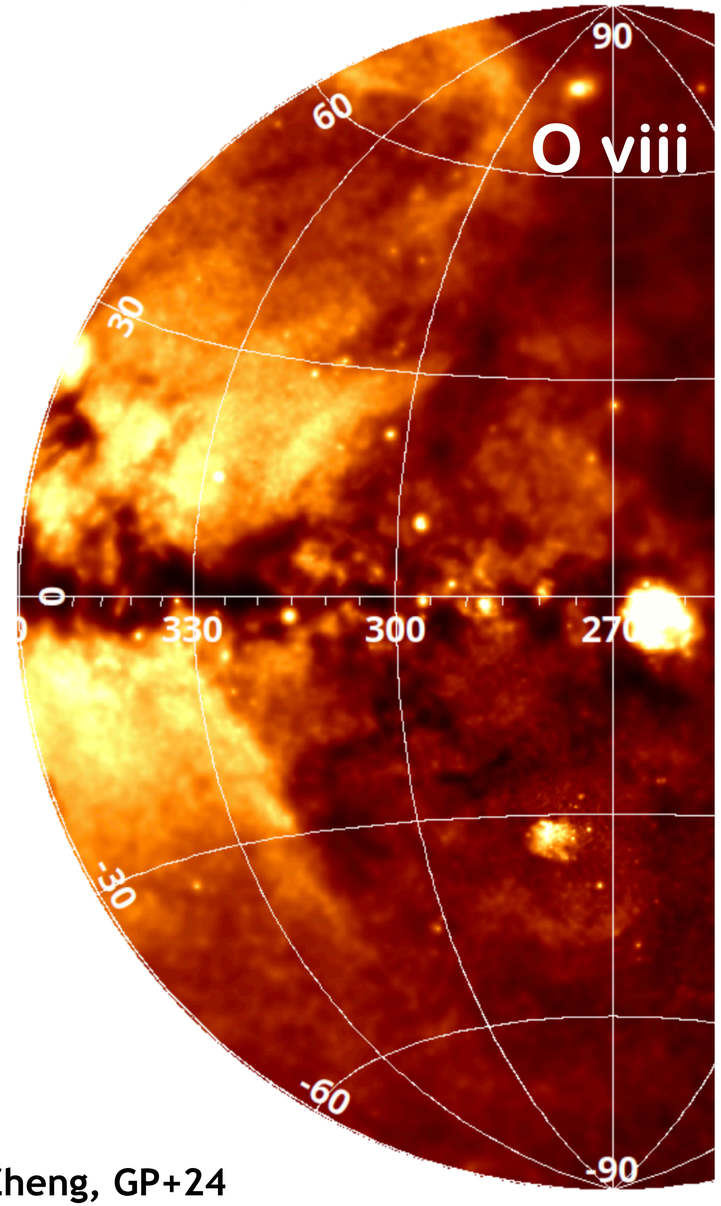
Morphology of the circumgalactic medium

Nicola Locatelli



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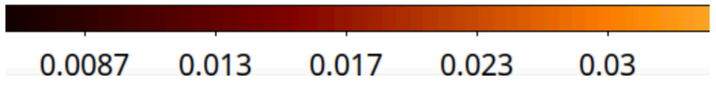

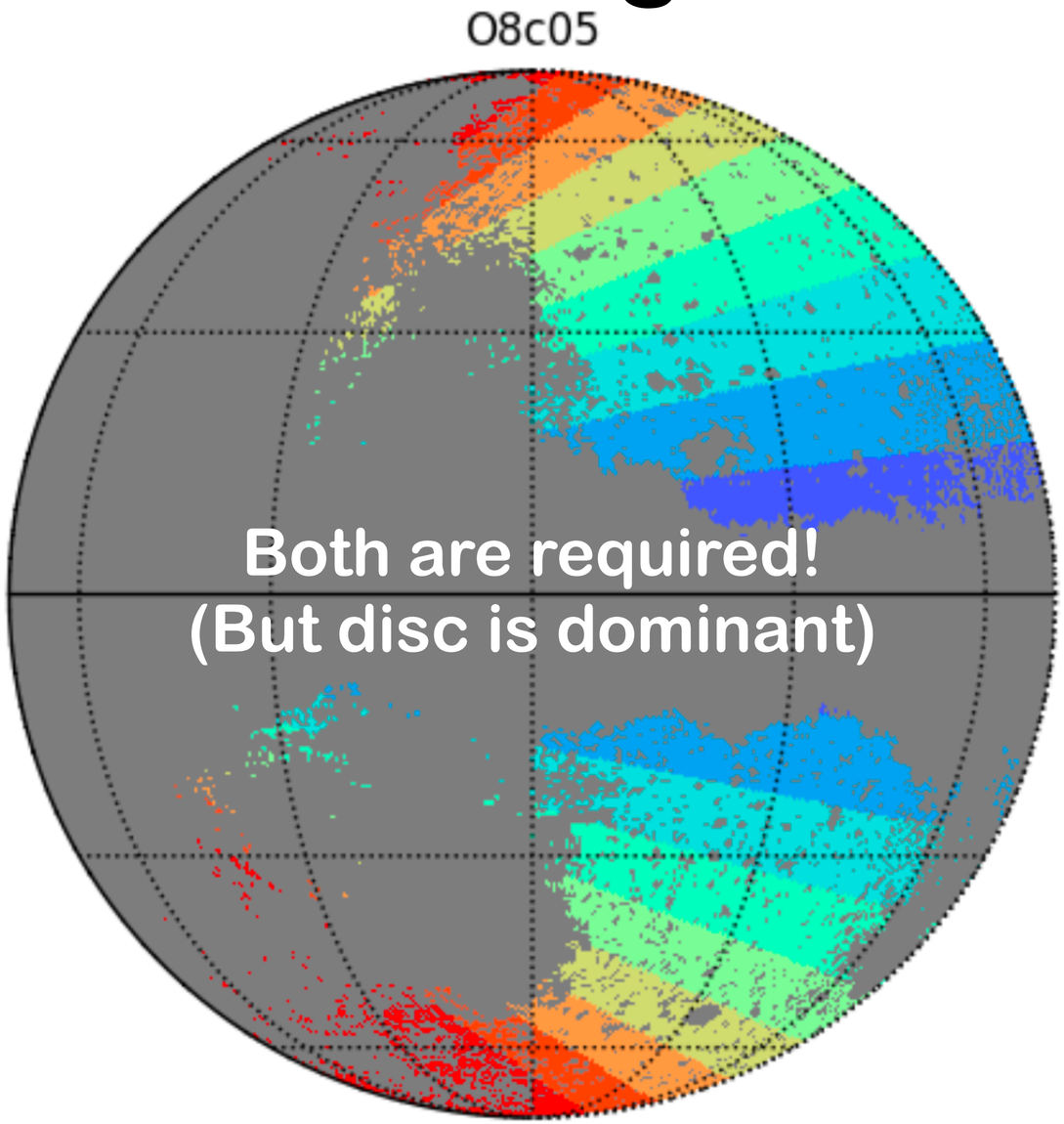

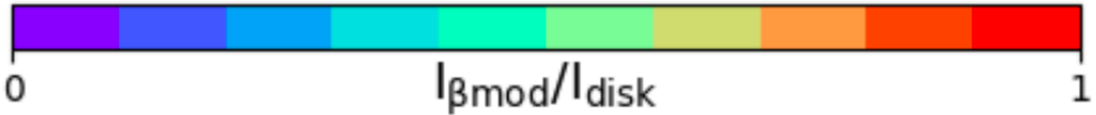

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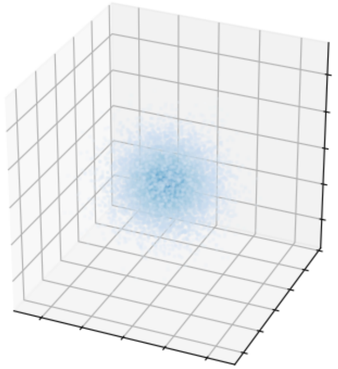

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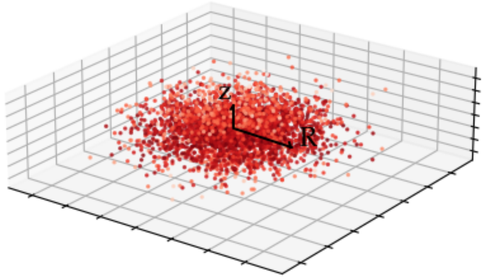

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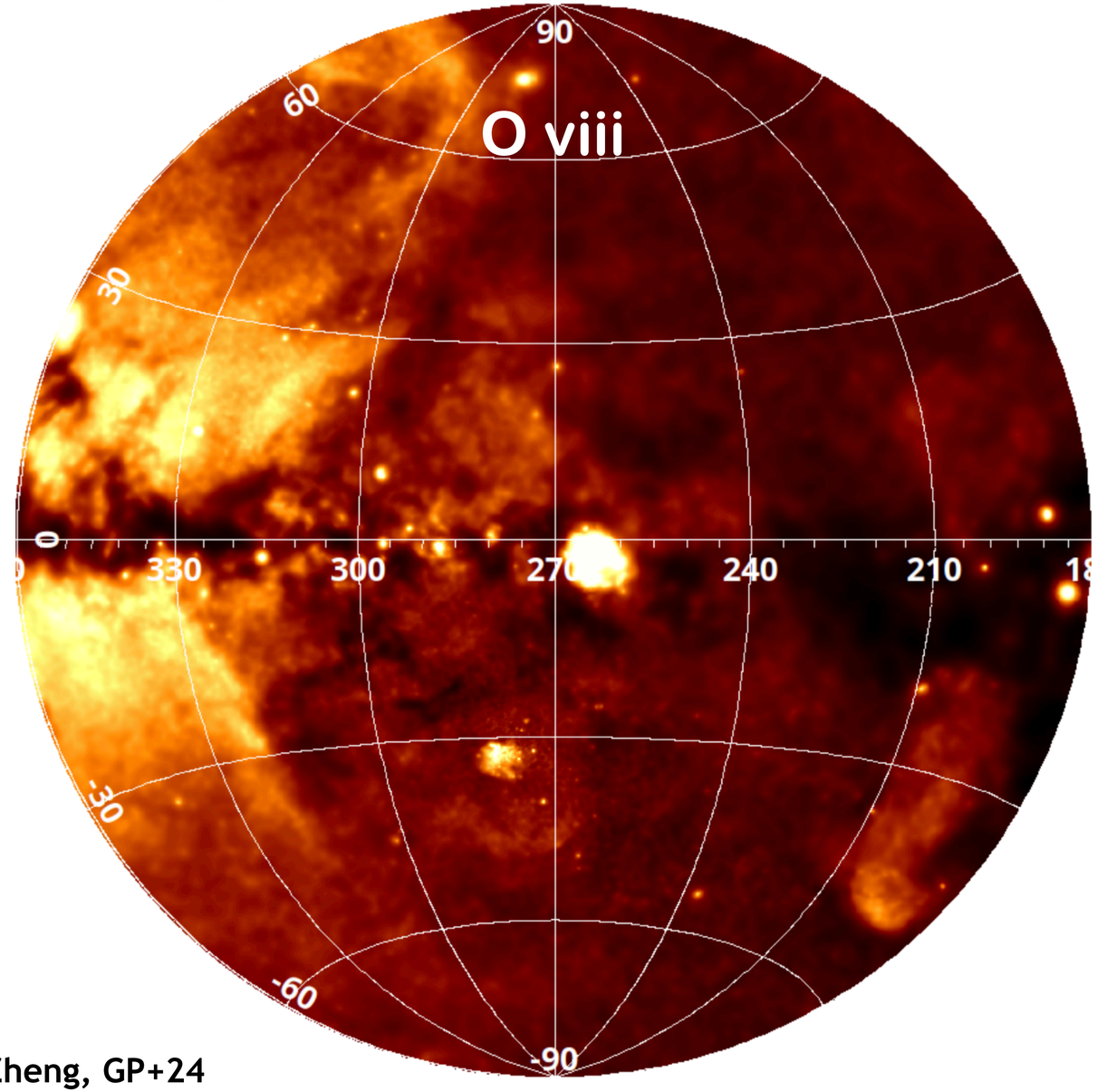

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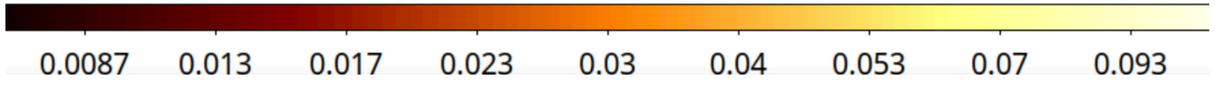

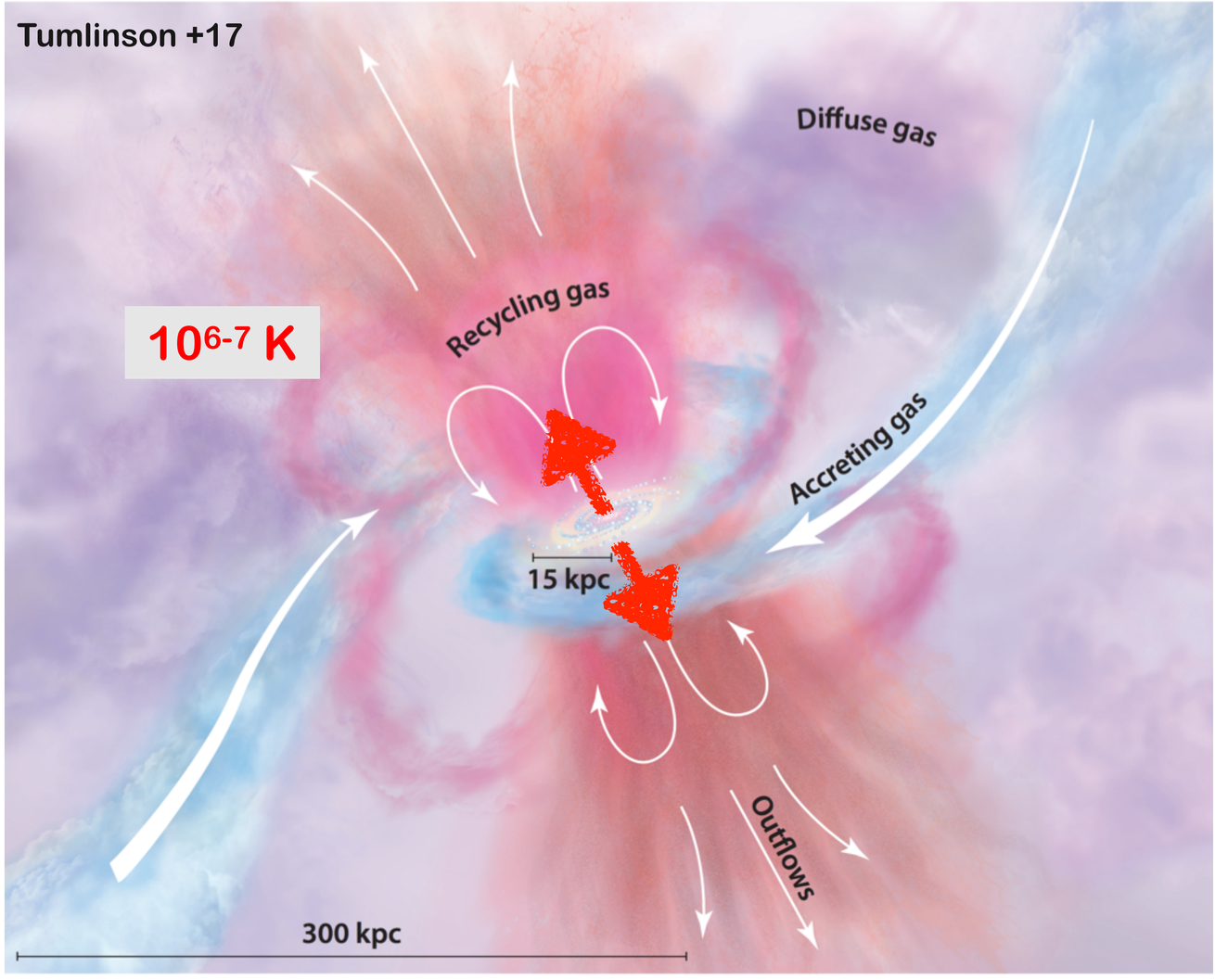

Morphology of the circumgalactic medium

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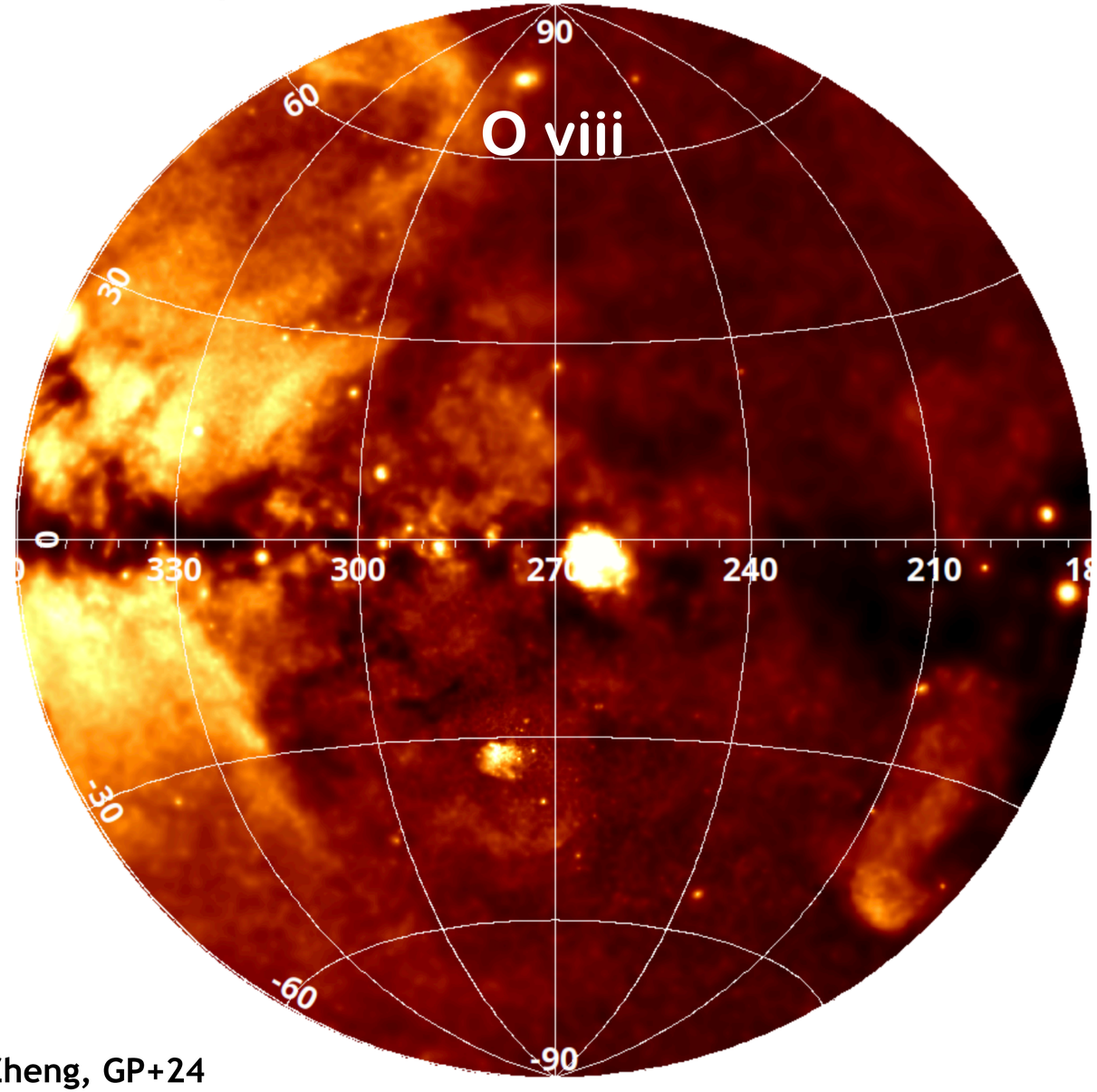

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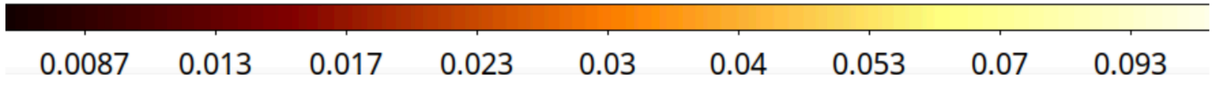

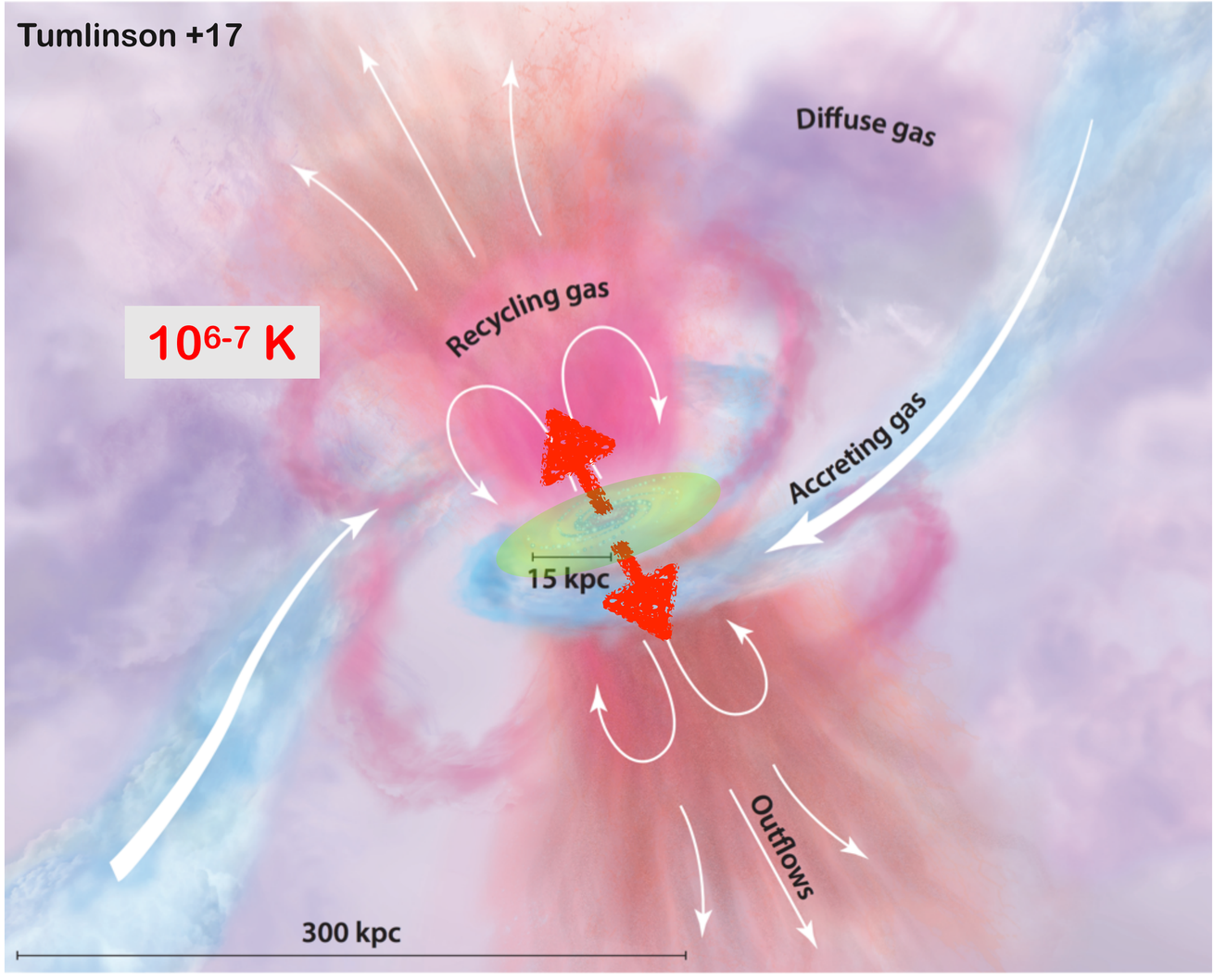

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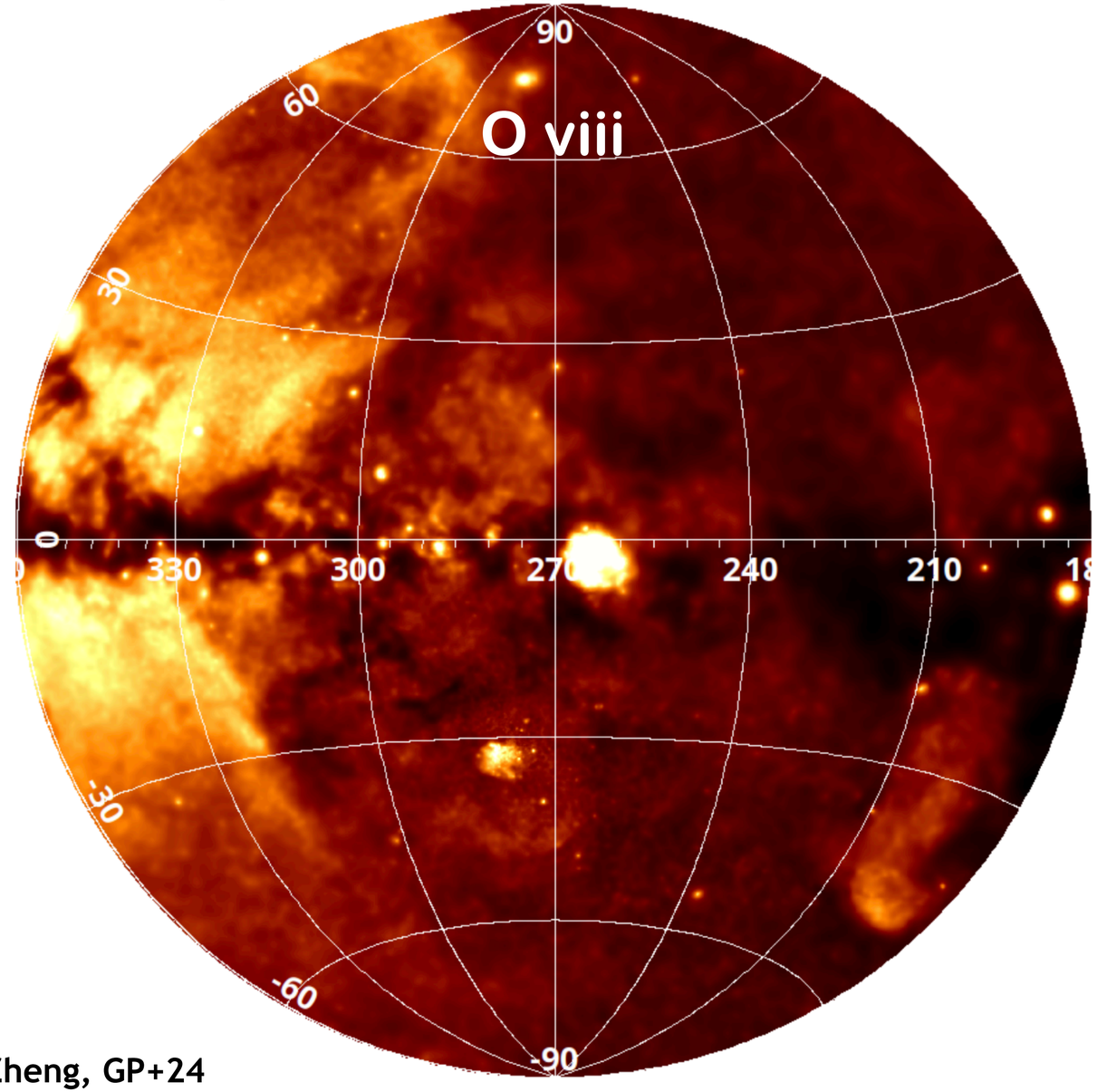

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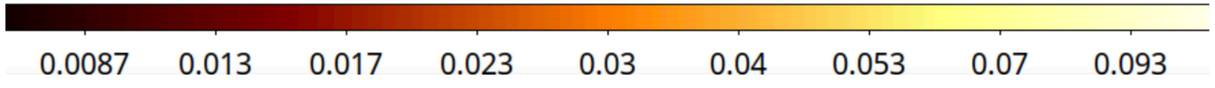
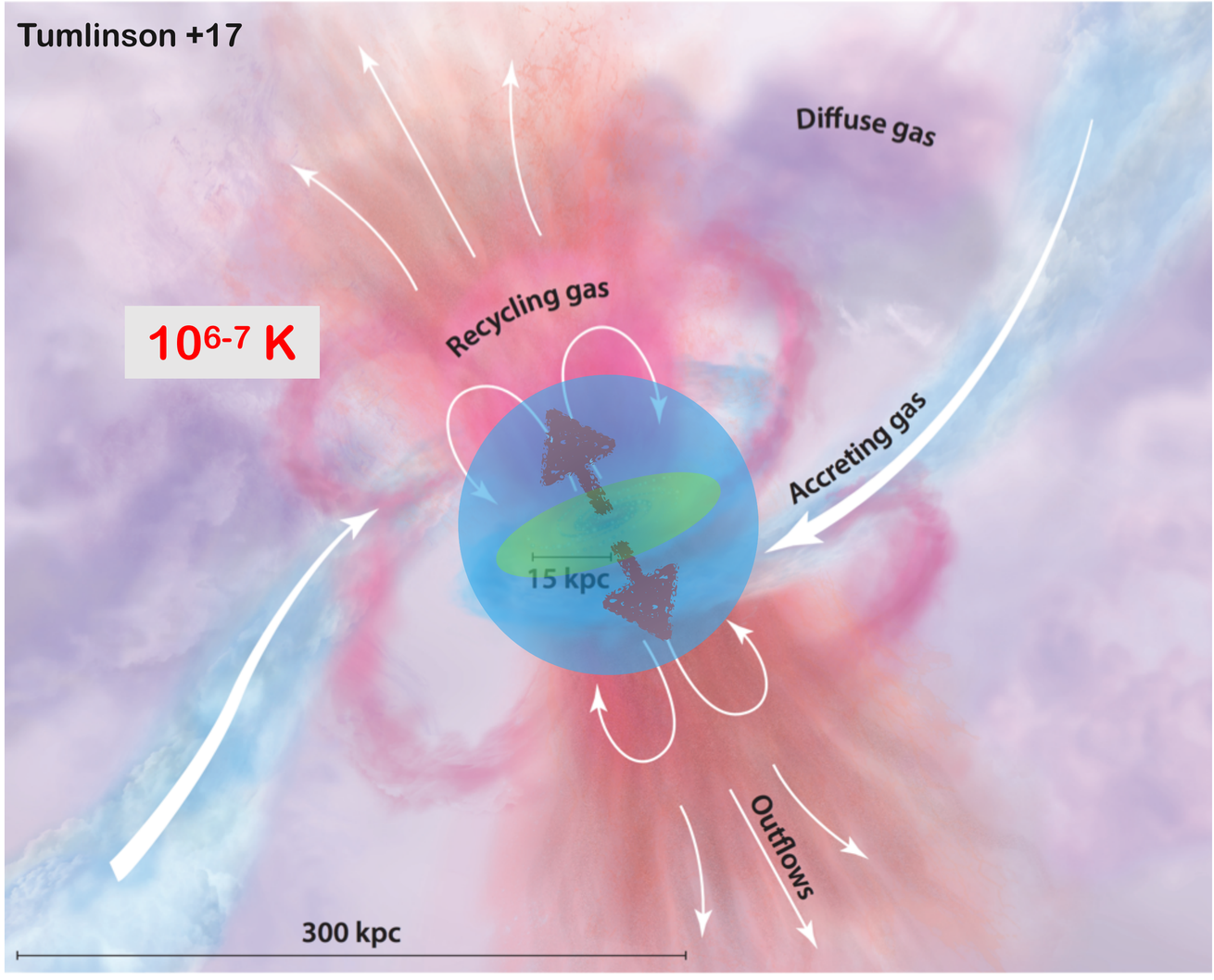
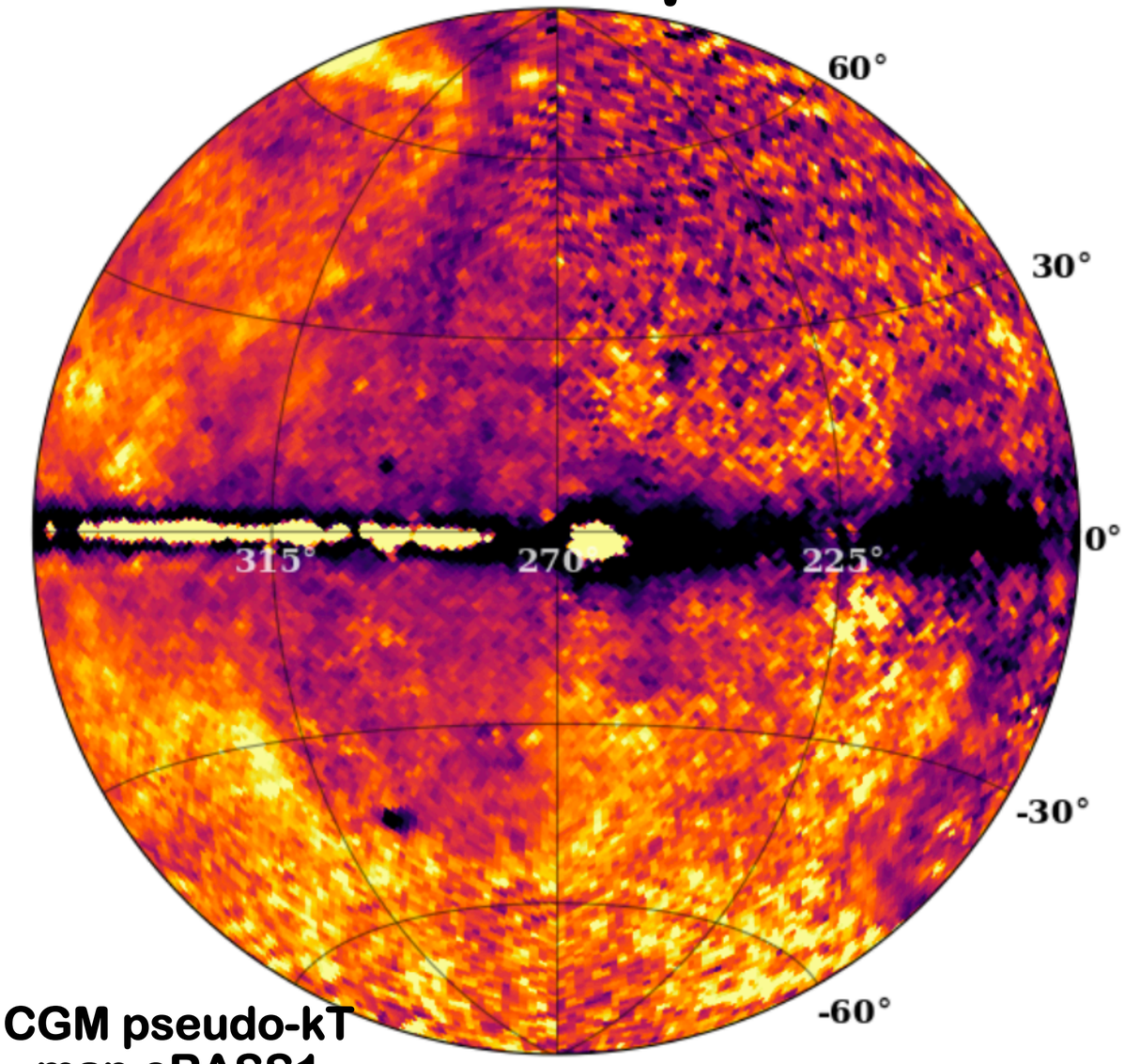


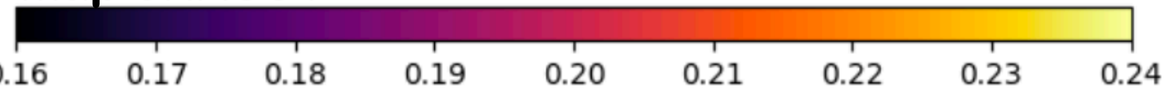


Pseudo-temperature map from Oviii/Ovii

Xueying Zheng



CGM pseudo-kT map eRASS1

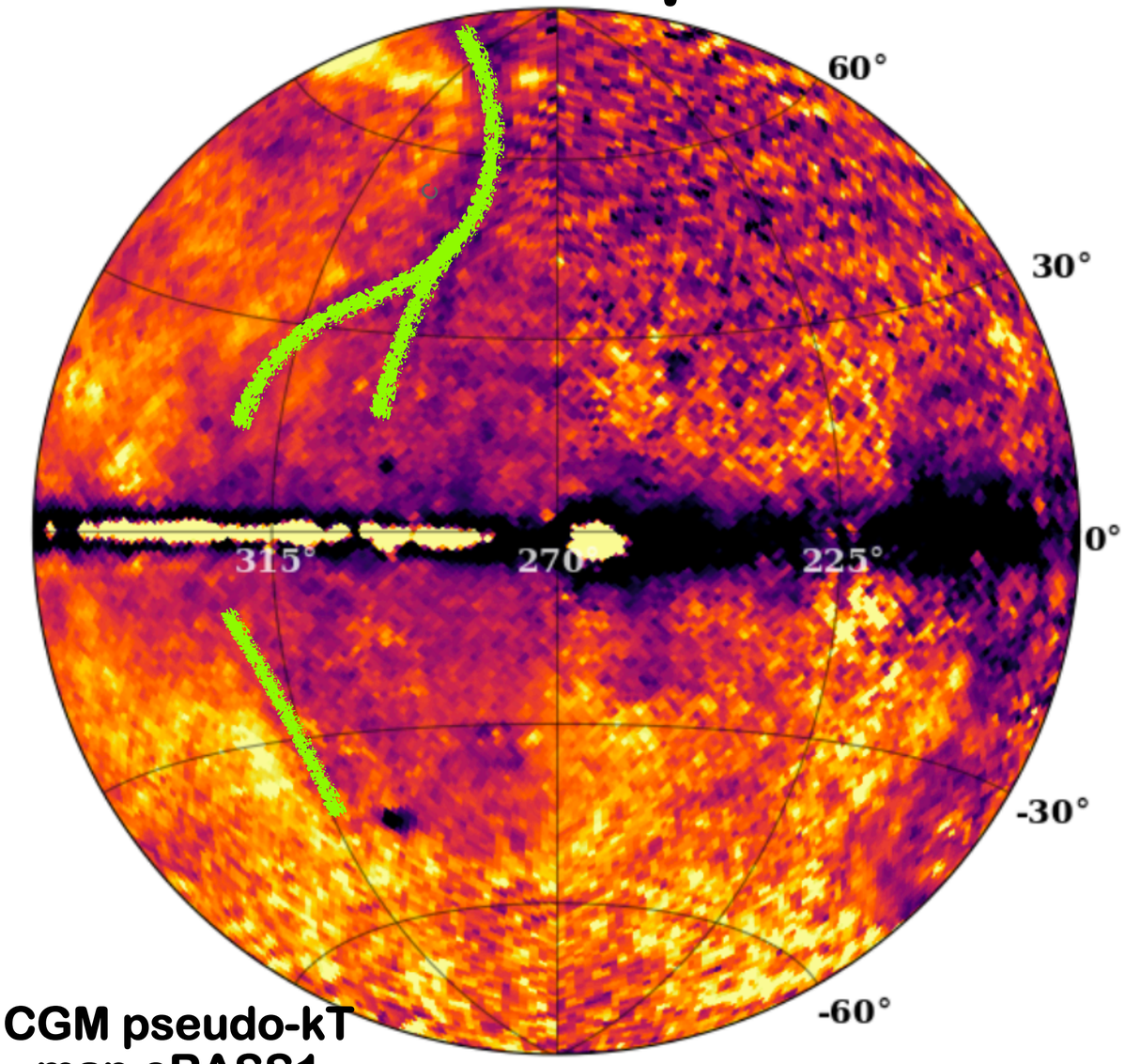


Zheng, GP+24

$\mathcal{T}$(OVIII, OVII) [keV]

Pseudo-temperature map from Oviii/Ovii

Xueying Zheng



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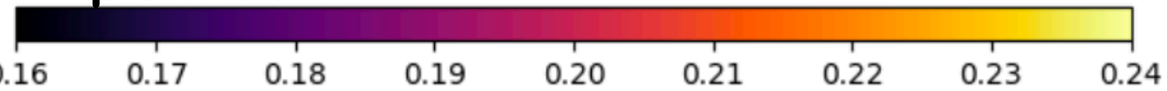

Zheng, GP+24

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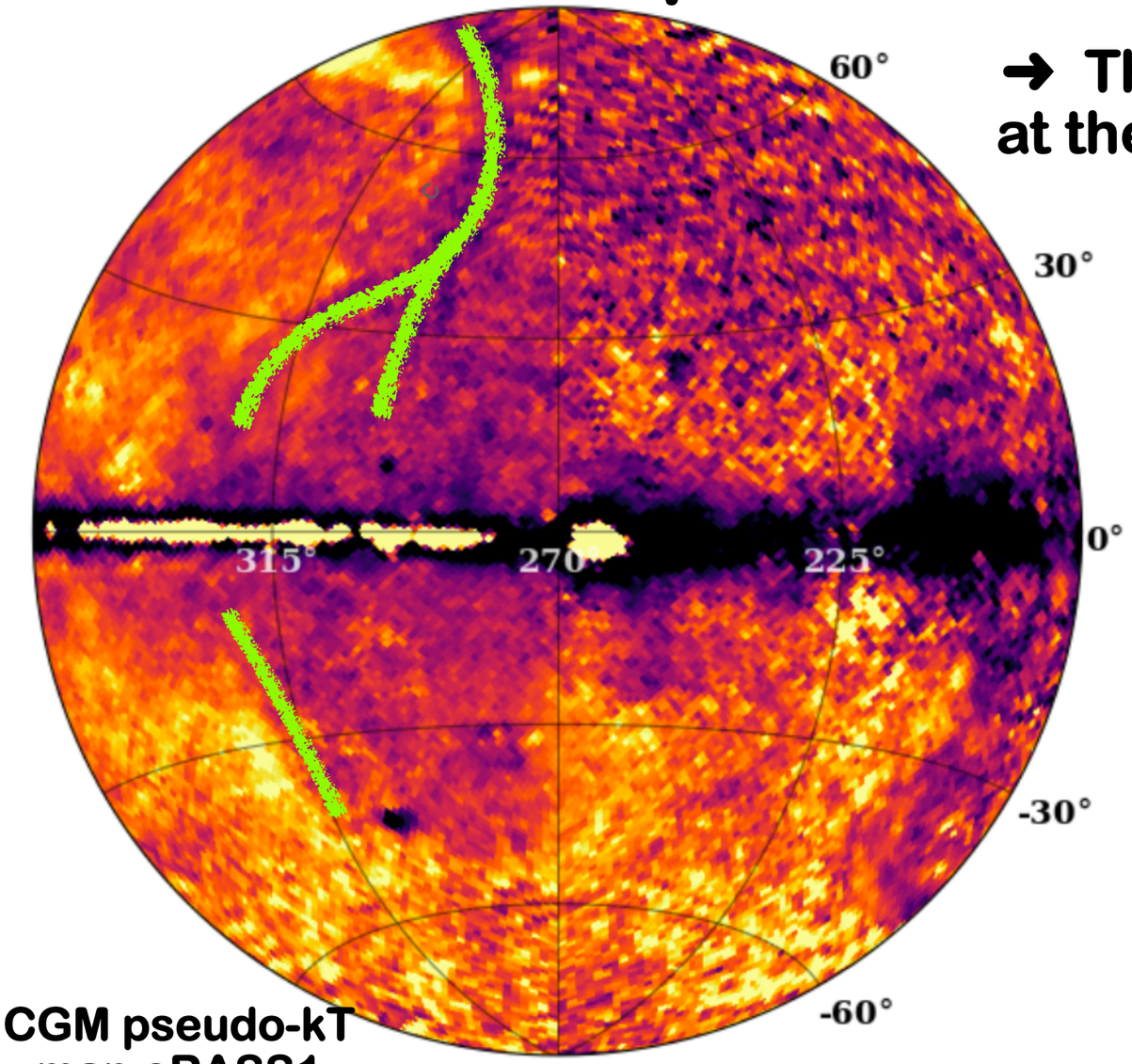

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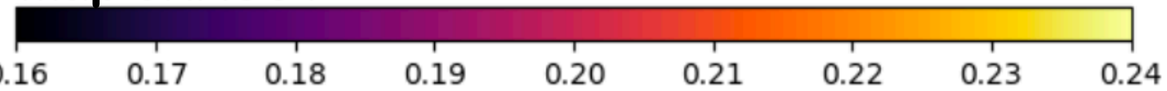


Zheng, GP+24

$\mathcal{T}$(OVIII, OVII) [keV]

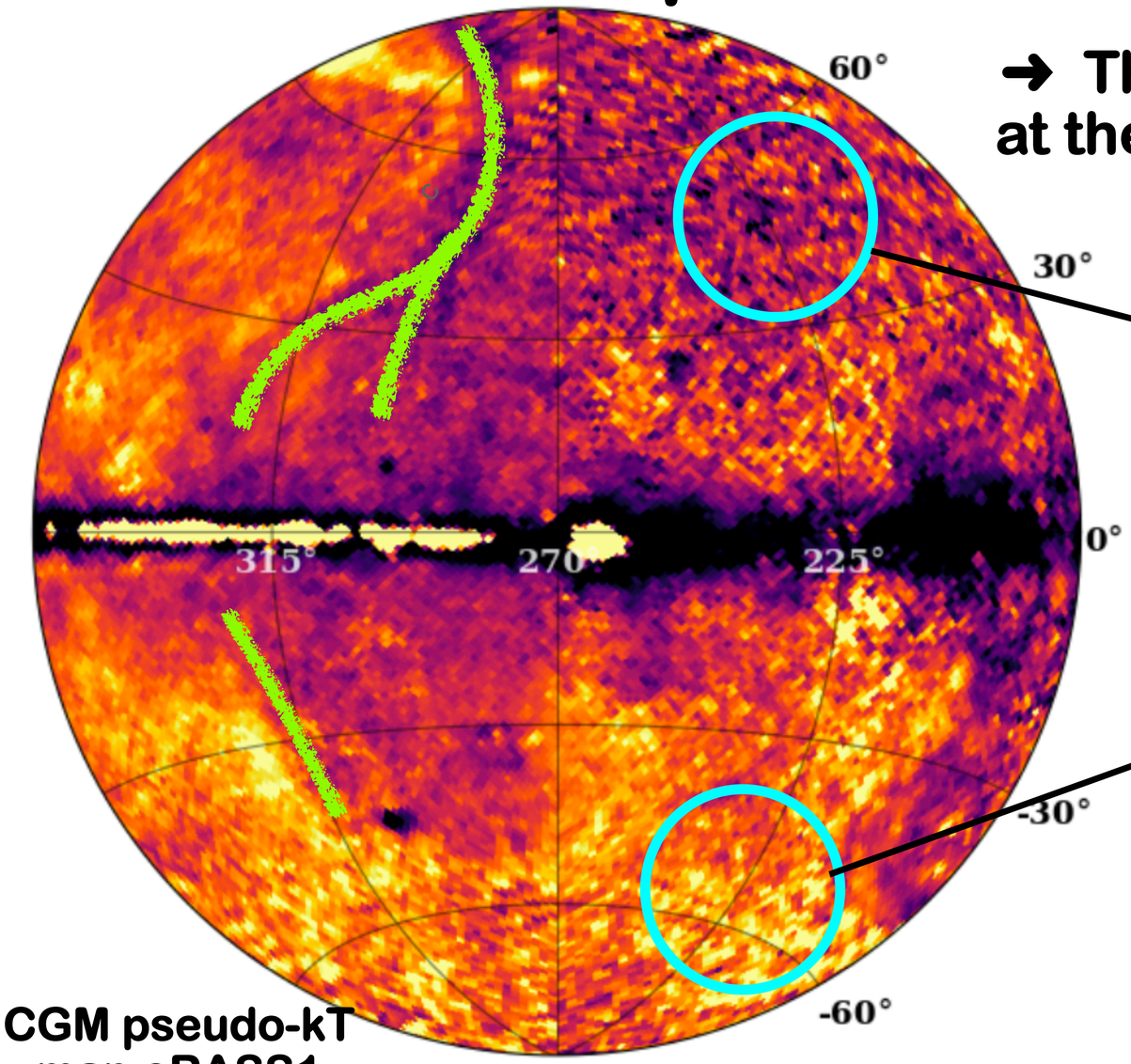
➜ Thick (~10º) shell of (colder?) plasma at the interface with the Galactic outflow

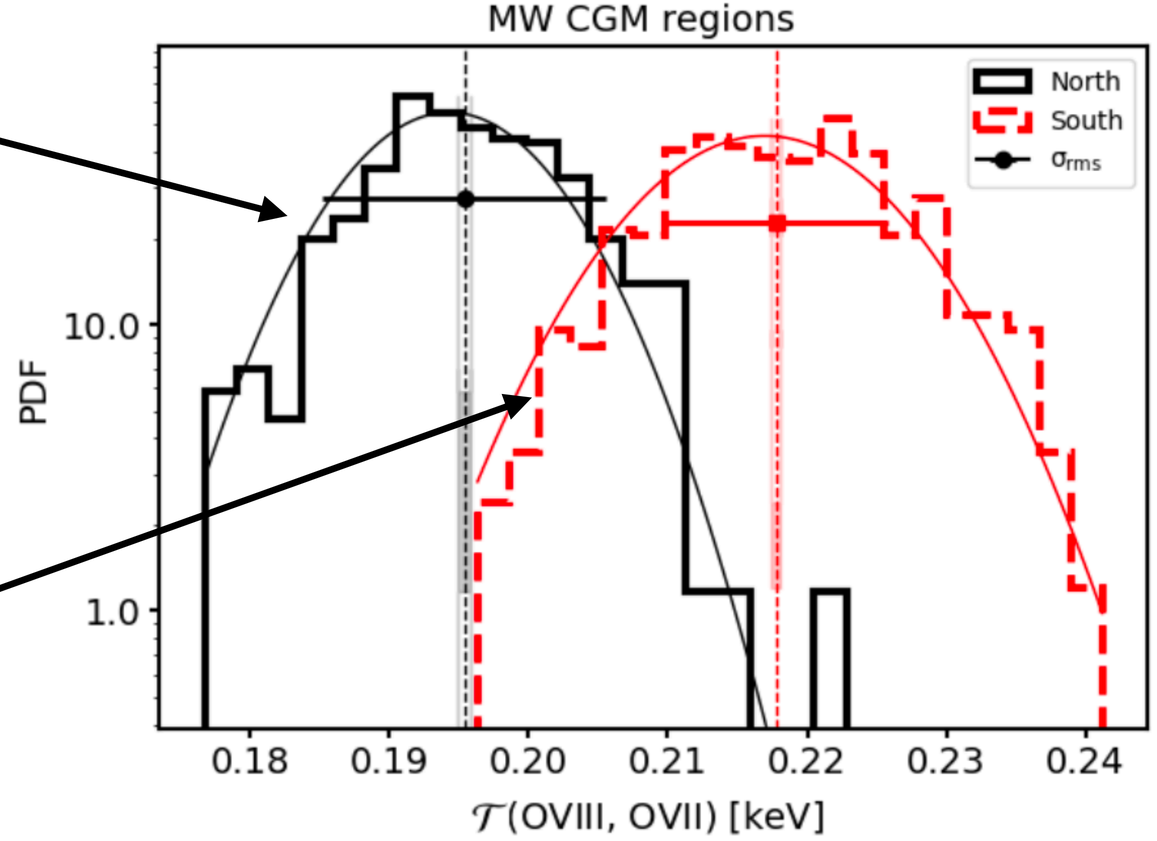
Xueying Zheng

Pseudo-temperature map from Oviii/Ovii

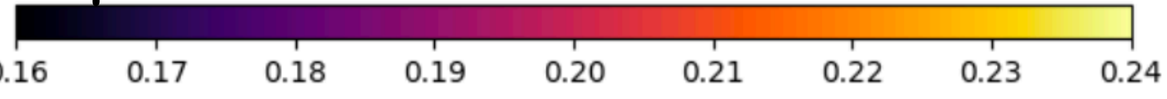
Xueying Zheng

➜ Thick (~10º) shell of (colder?) plasma at the interface with the Galactic outflow





CGM pseudo-kT map eRASS1



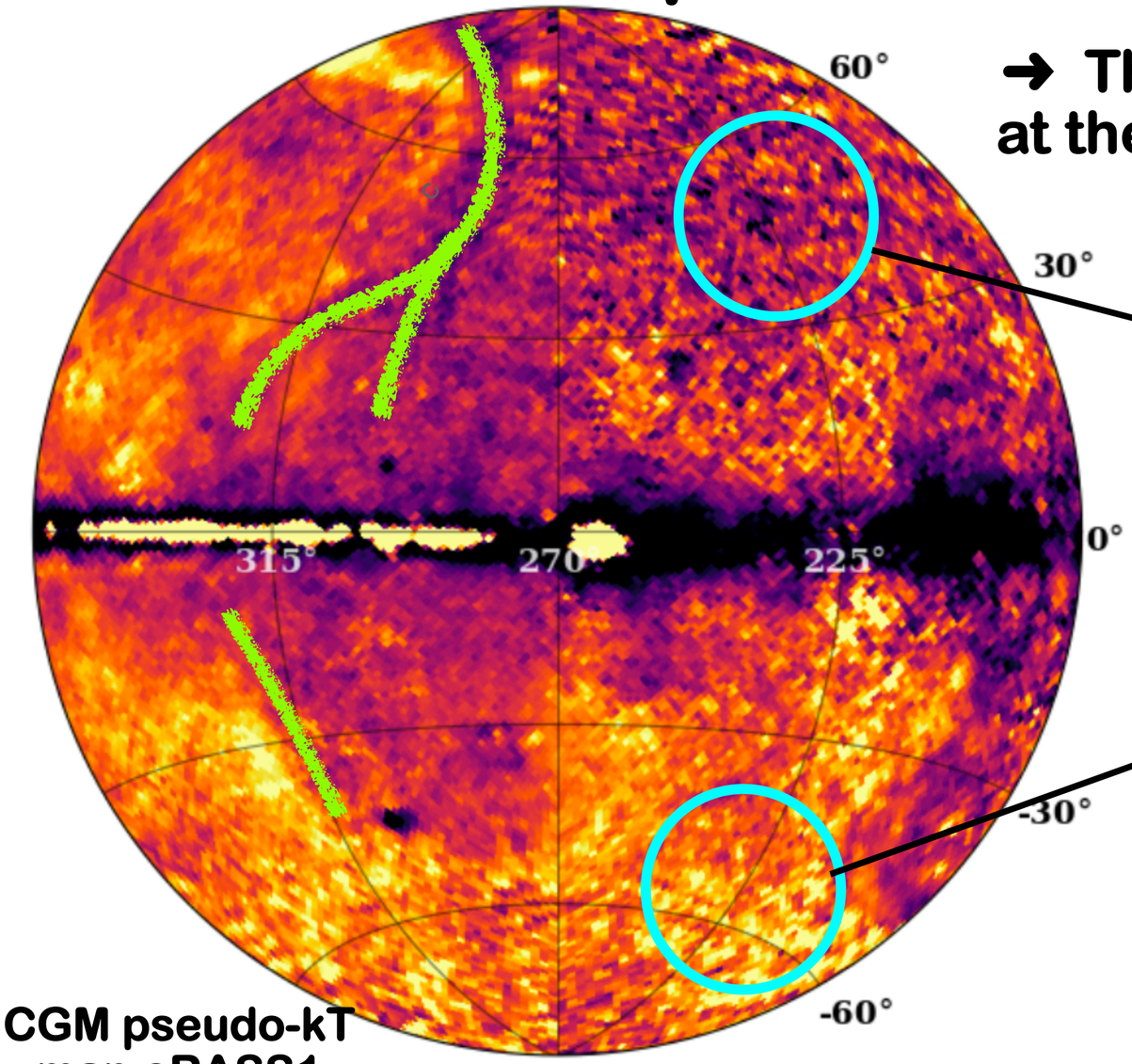
Zheng, GP+24

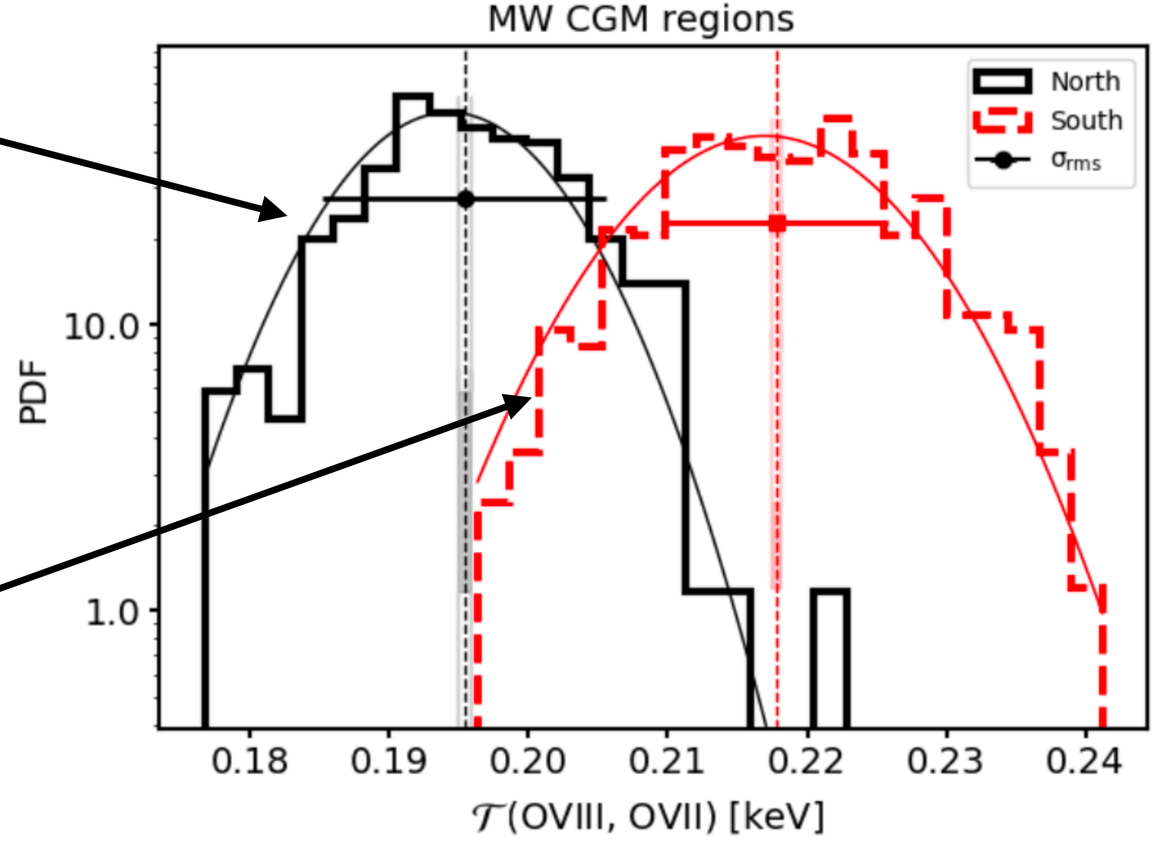
➜ ΔkT_{CGM} ~ 12% between north and south

Pseudo-temperature map from Oviii/Ovii

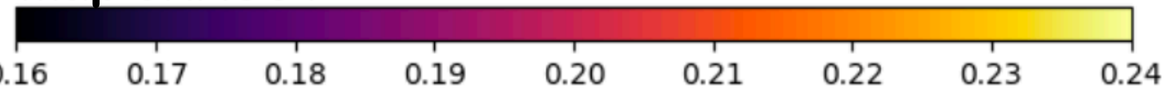
Xueying Zheng

➜ Thick (~10º) shell of (colder?) plasma at the interface with the Galactic outflow





CGM pseudo-kT map eRASS1



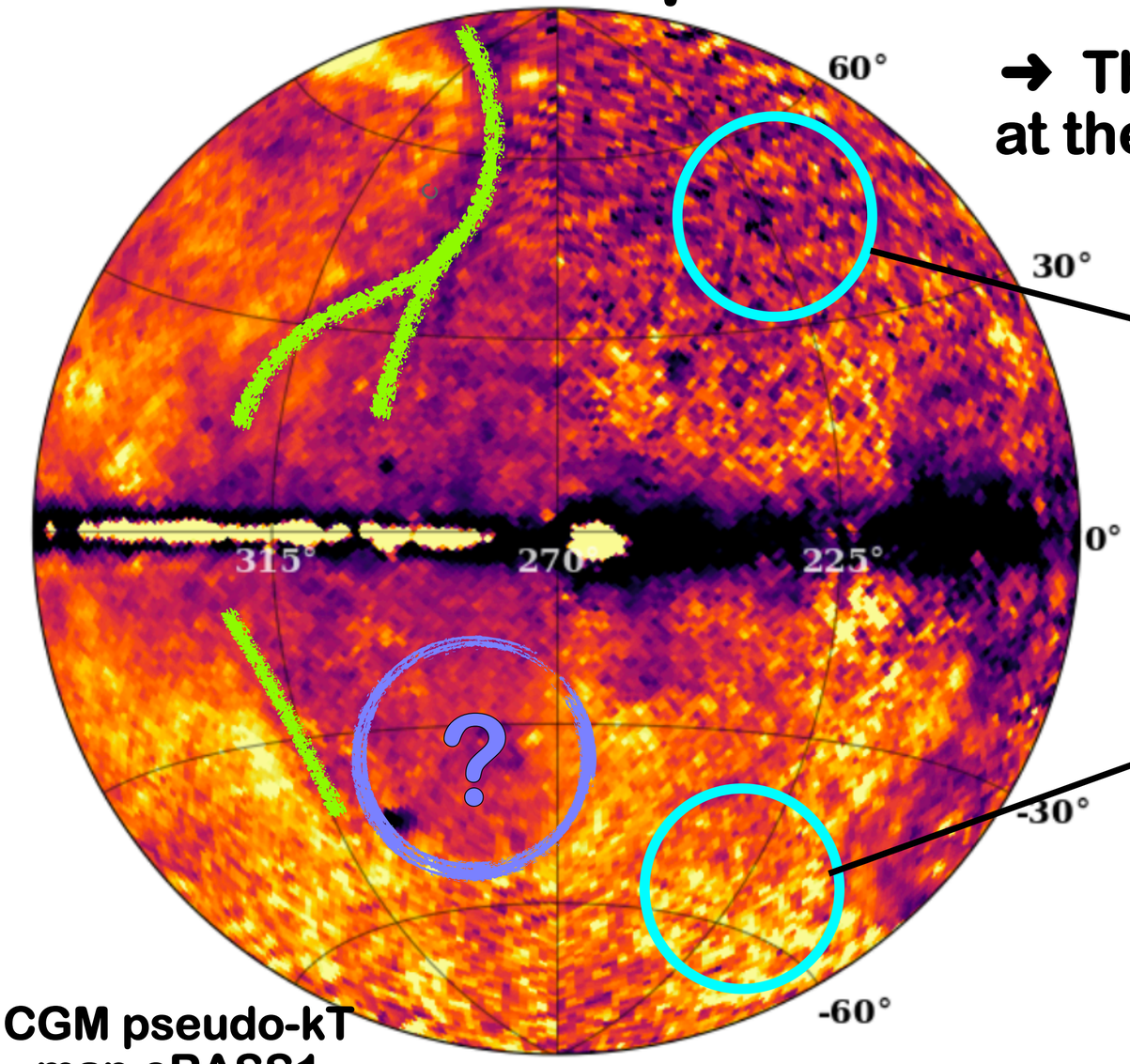
➜ ΔkT_{CGM} ~ 12% between north and south

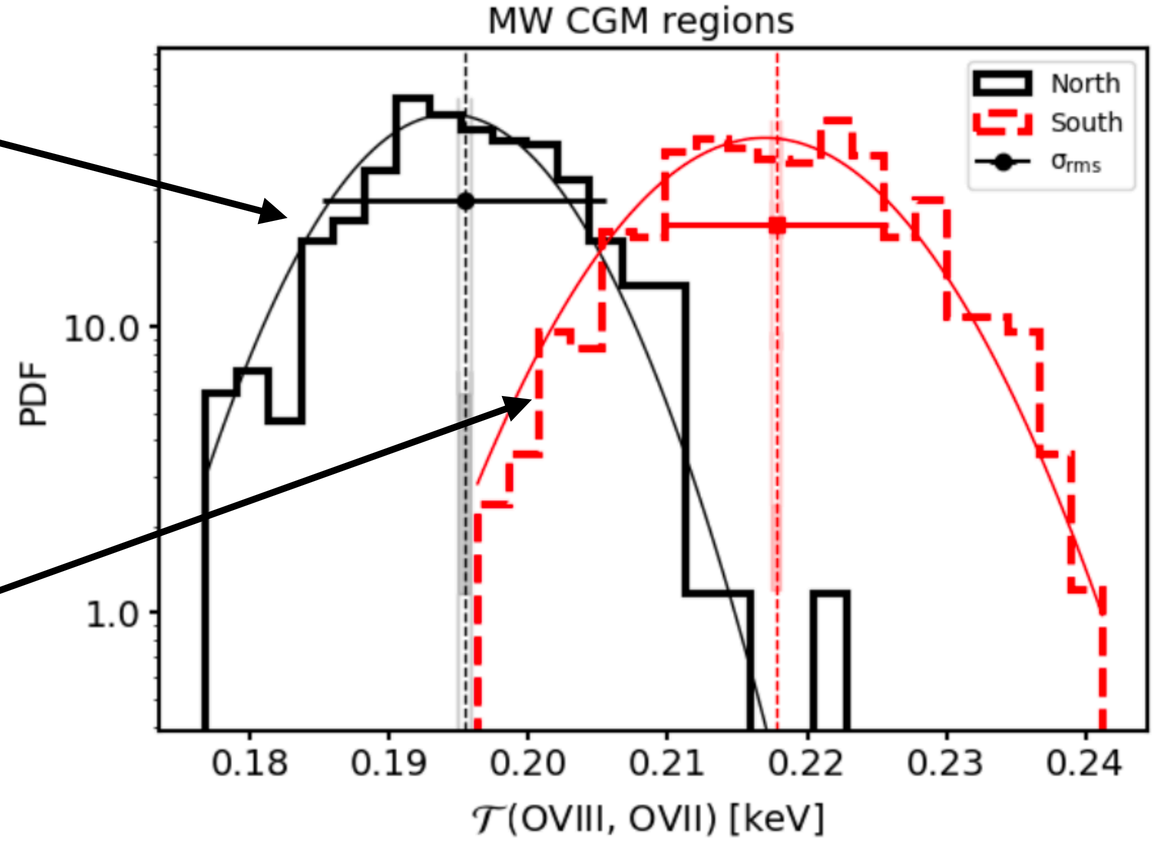
➜ ΔkT_{CGM} ~ 2.7% on small (2º-20º) scales

Pseudo-temperature map from Oviii/Ovii

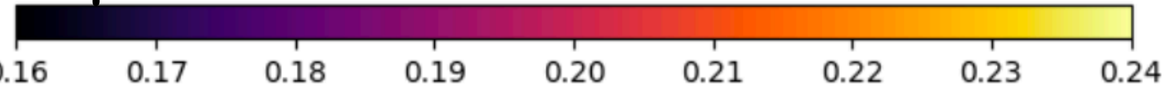
Xueying Zheng

➜ Thick (~10º) shell of (colder?) plasma at the interface with the Galactic outflow





CGM pseudo-kT map eRASS1



Zheng, GP+24

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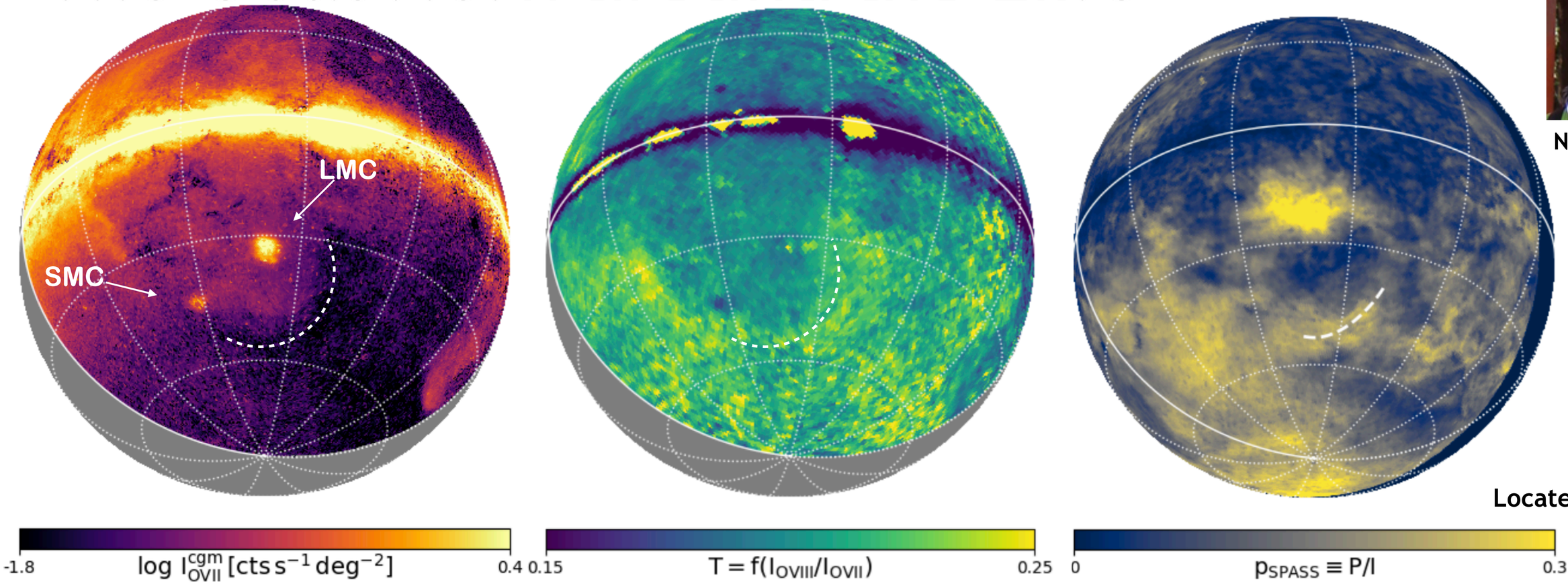
➜ ΔkT_{CGM} ~ 2.7% on small (2º-20º) scales

The Goat Horn around the LMC

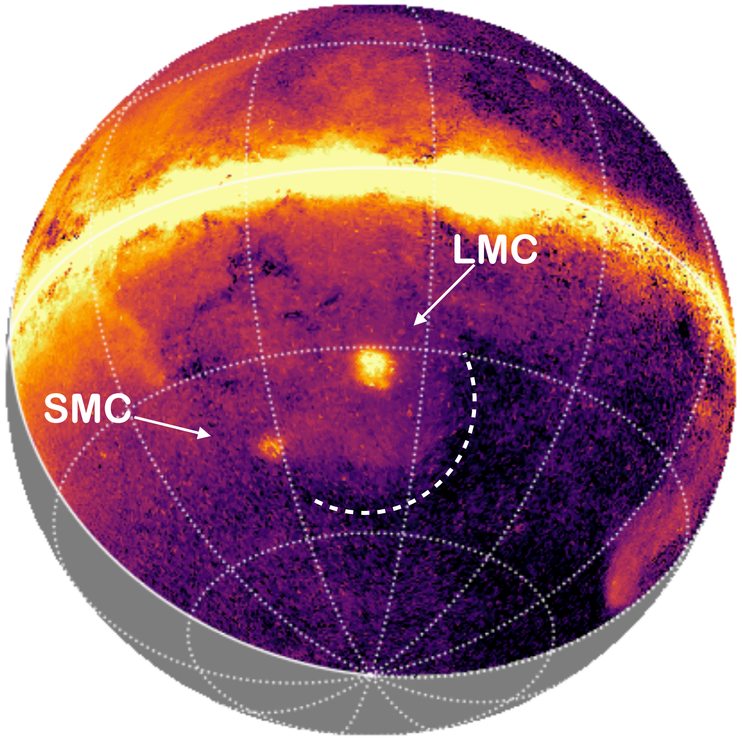


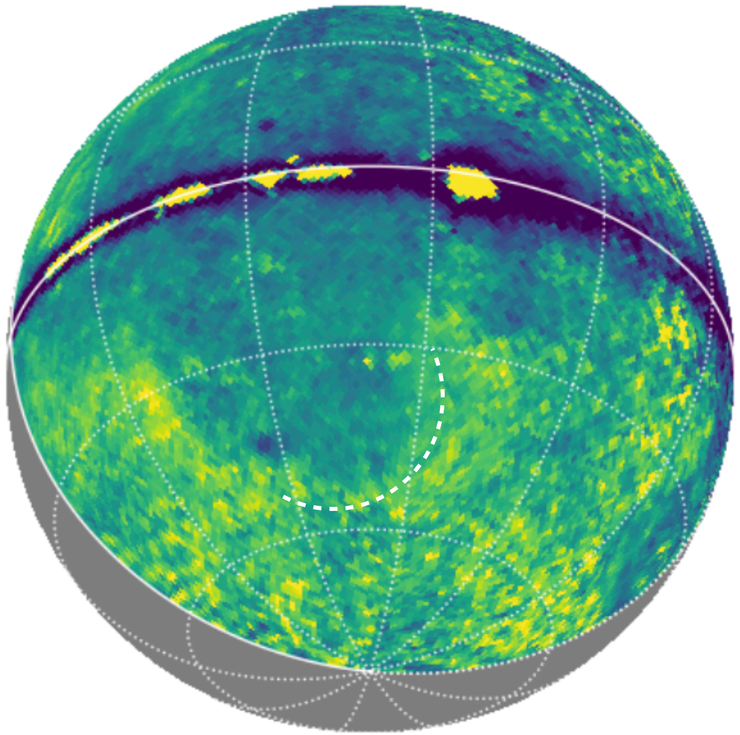
Nicola Locatelli

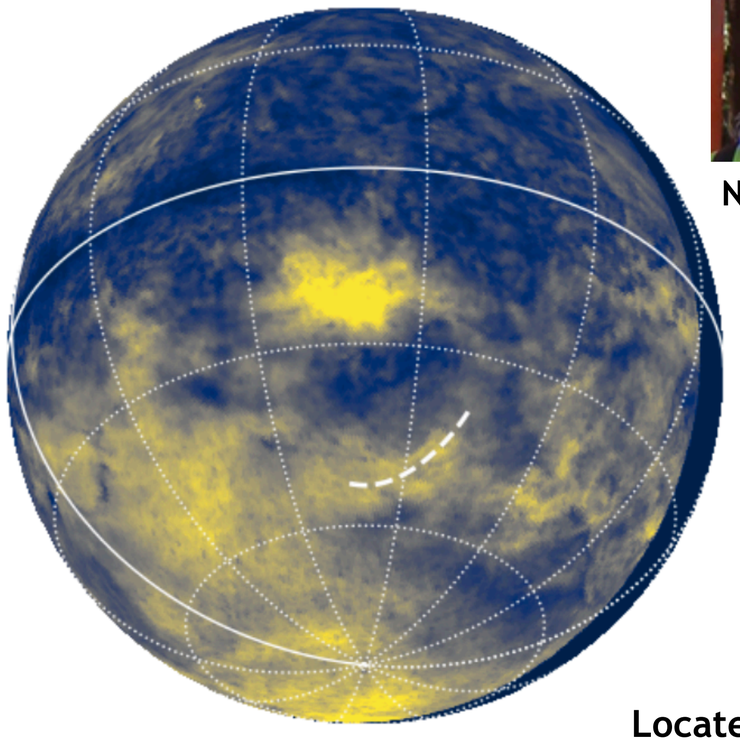
Locatelli, GP+24b

The Goat Horn around the LMC

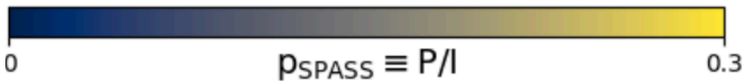
Nicola Locatelli

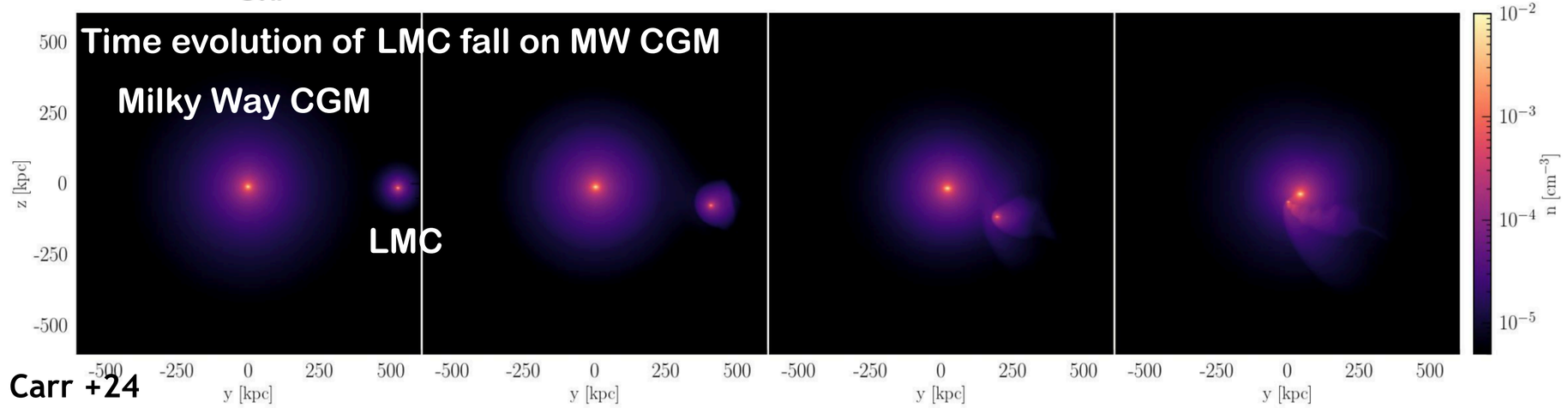






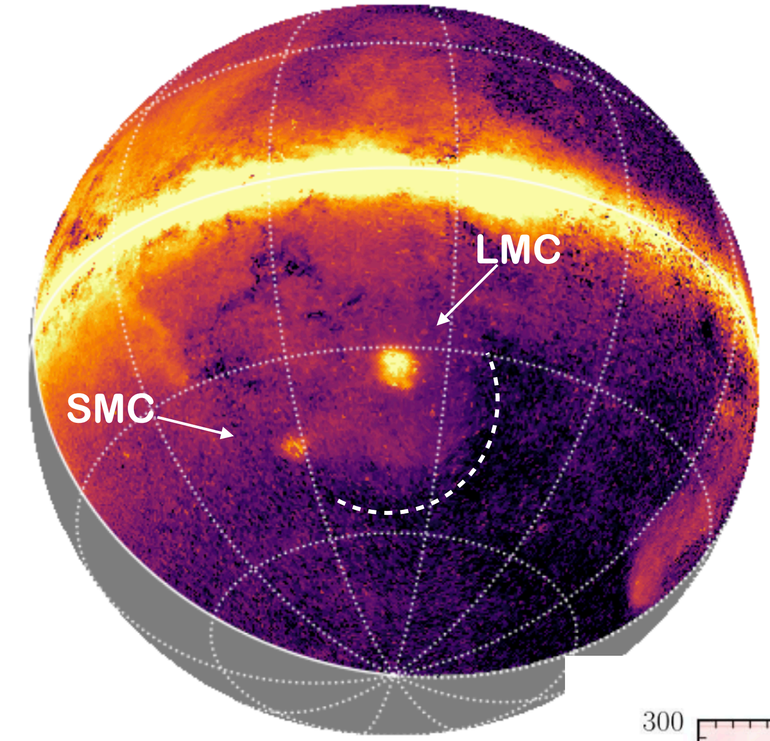
Locatelli, GP+24b

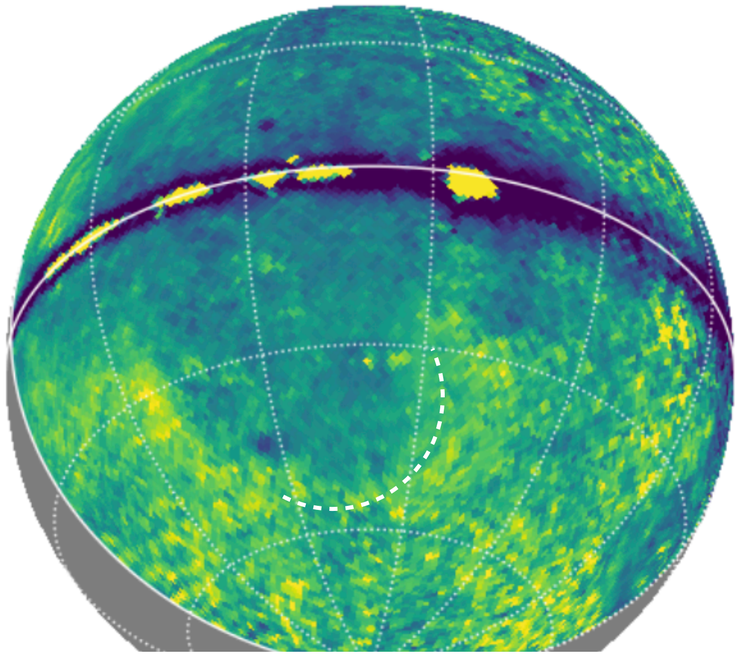


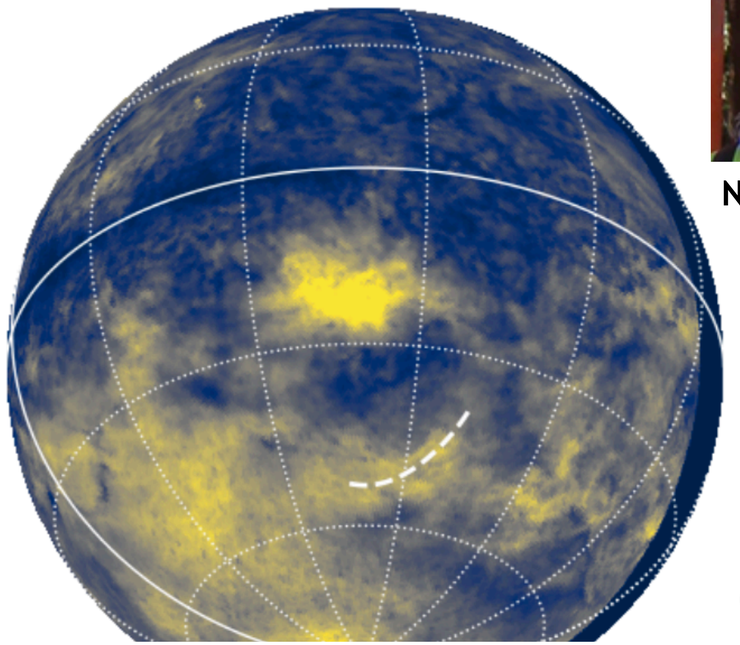


Carr +24

The Goat Horn around the LMC

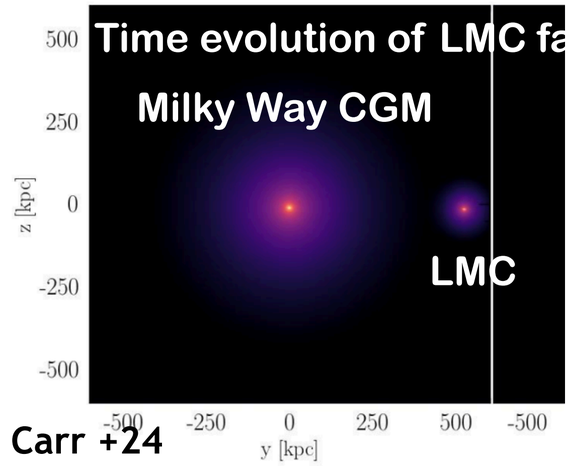




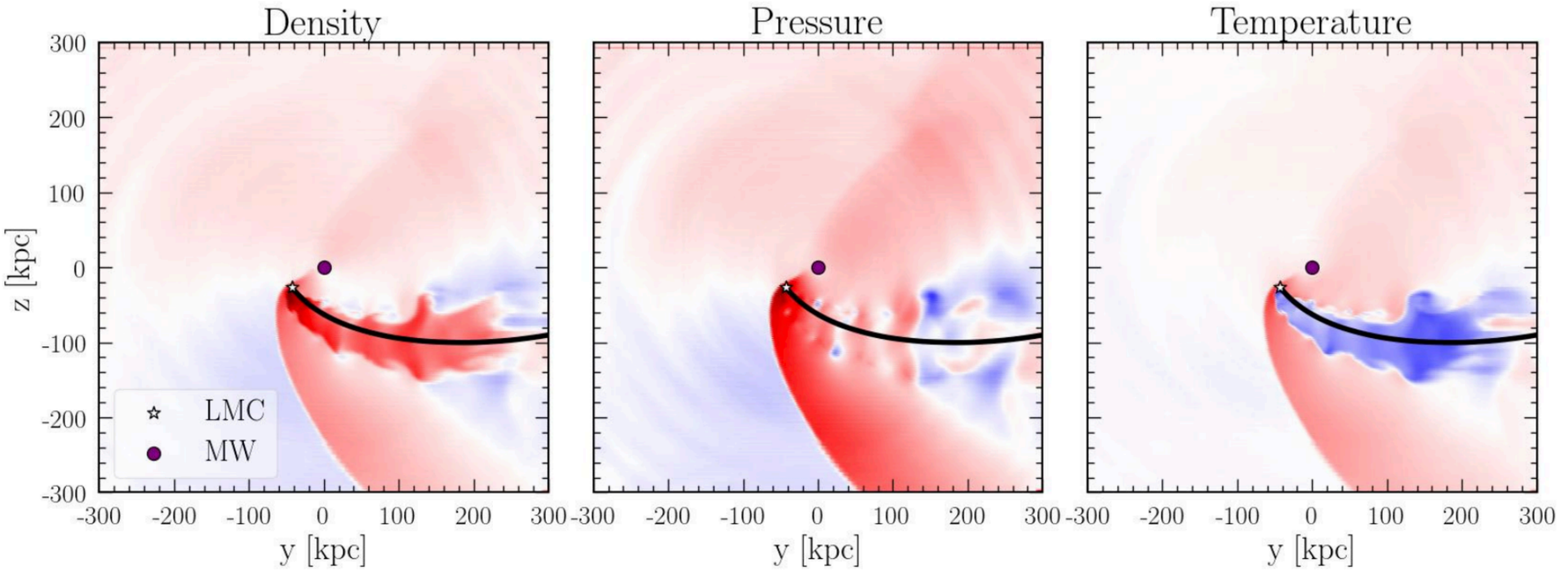


Nicola Locatelli

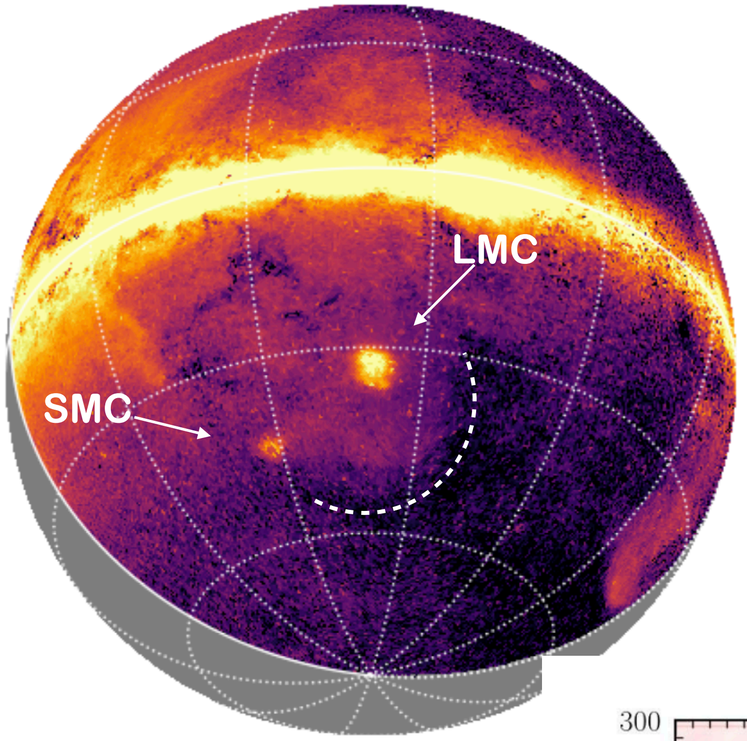
Carr +24

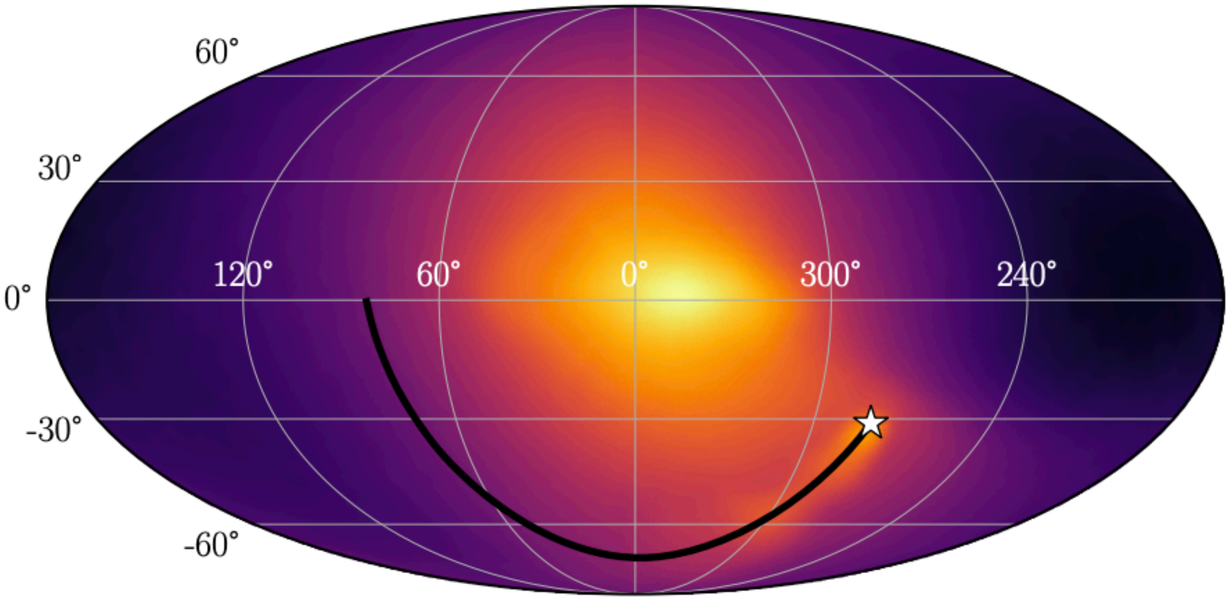


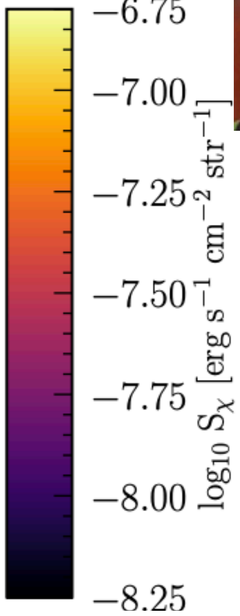
Carr +24



The Goat Horn around the LMC

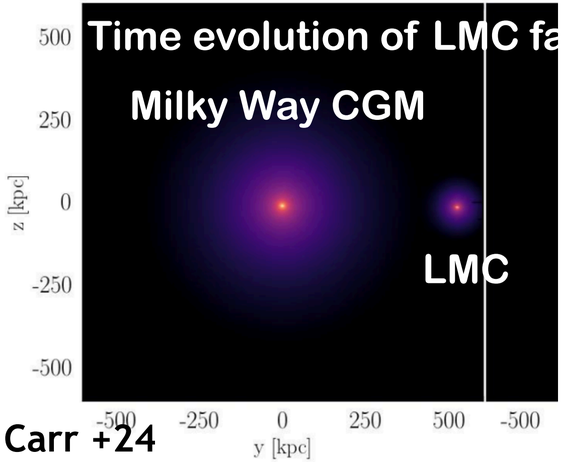




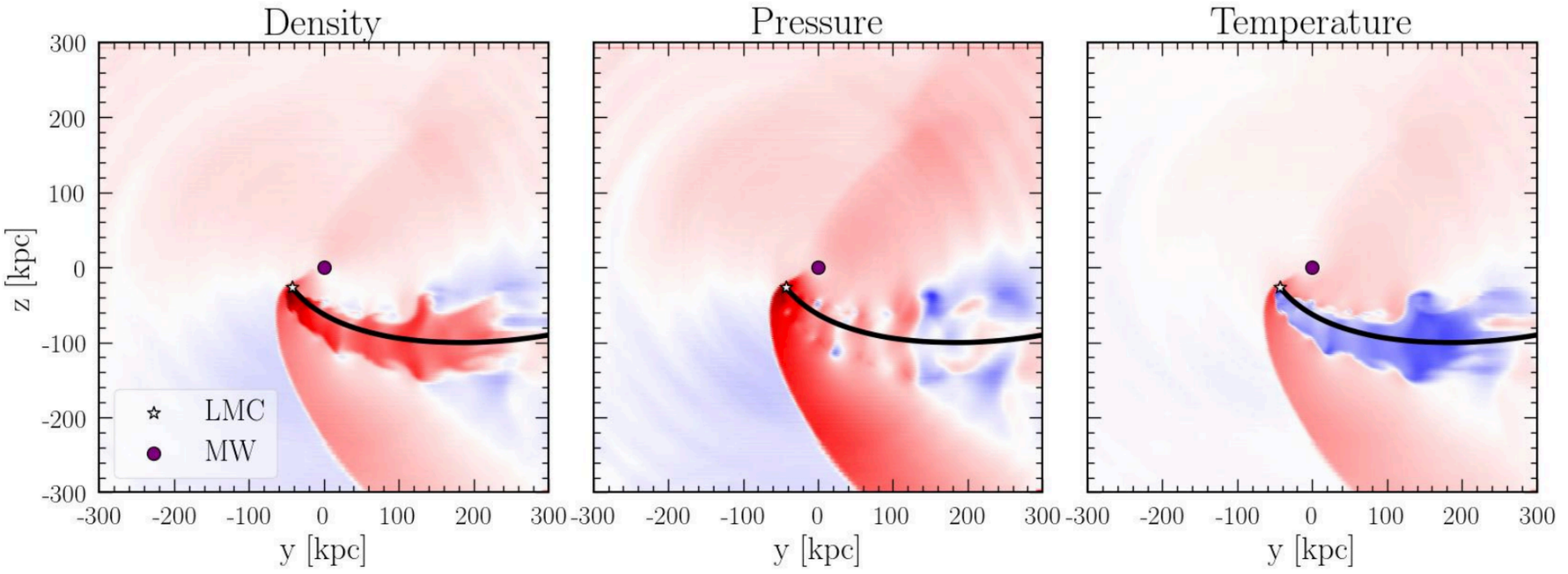


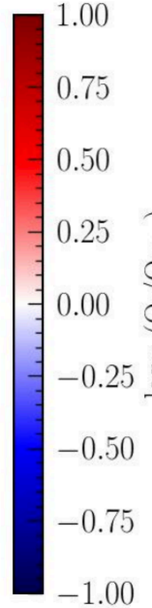
Nicola Locatelli

Carr +24

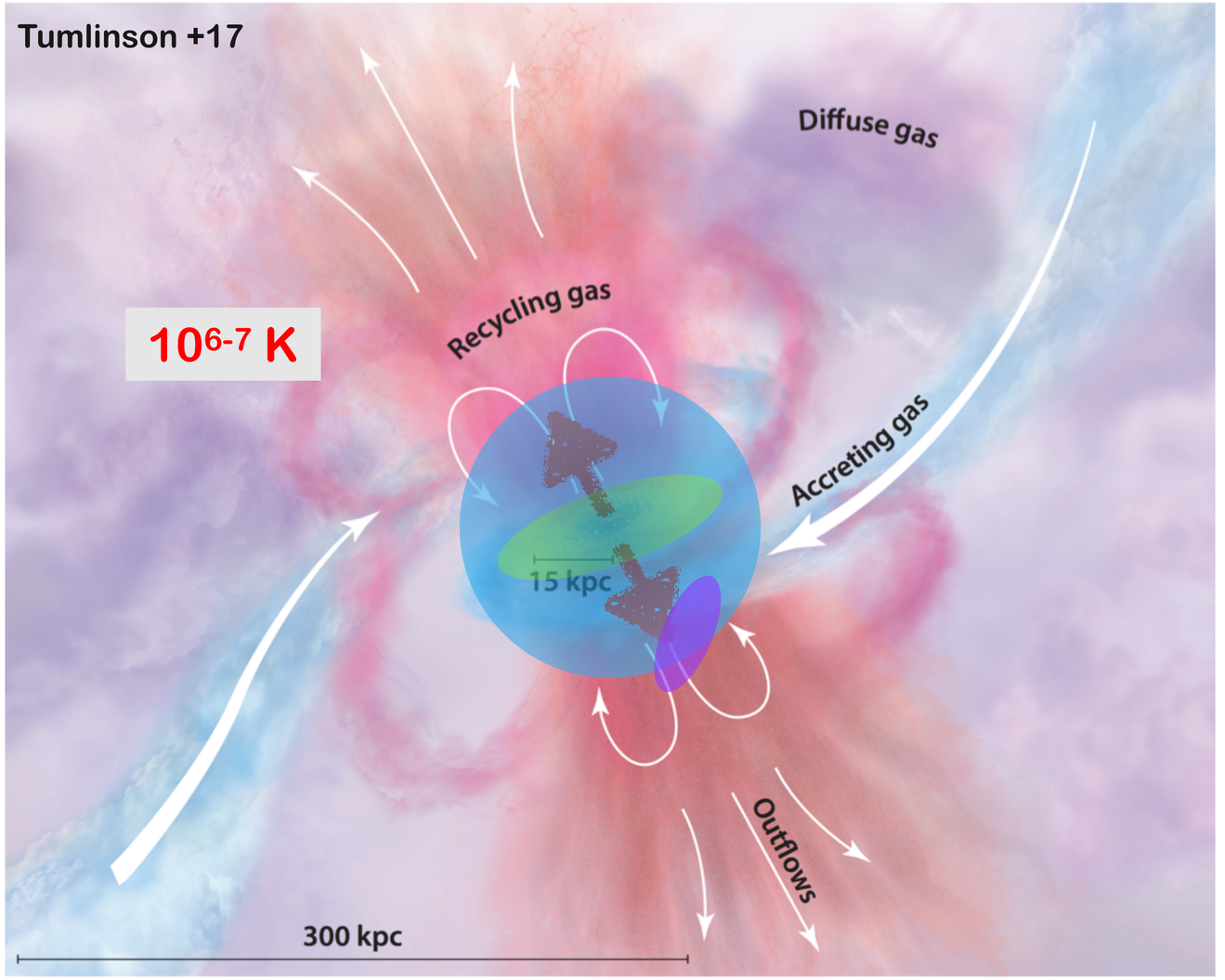


Carr +24



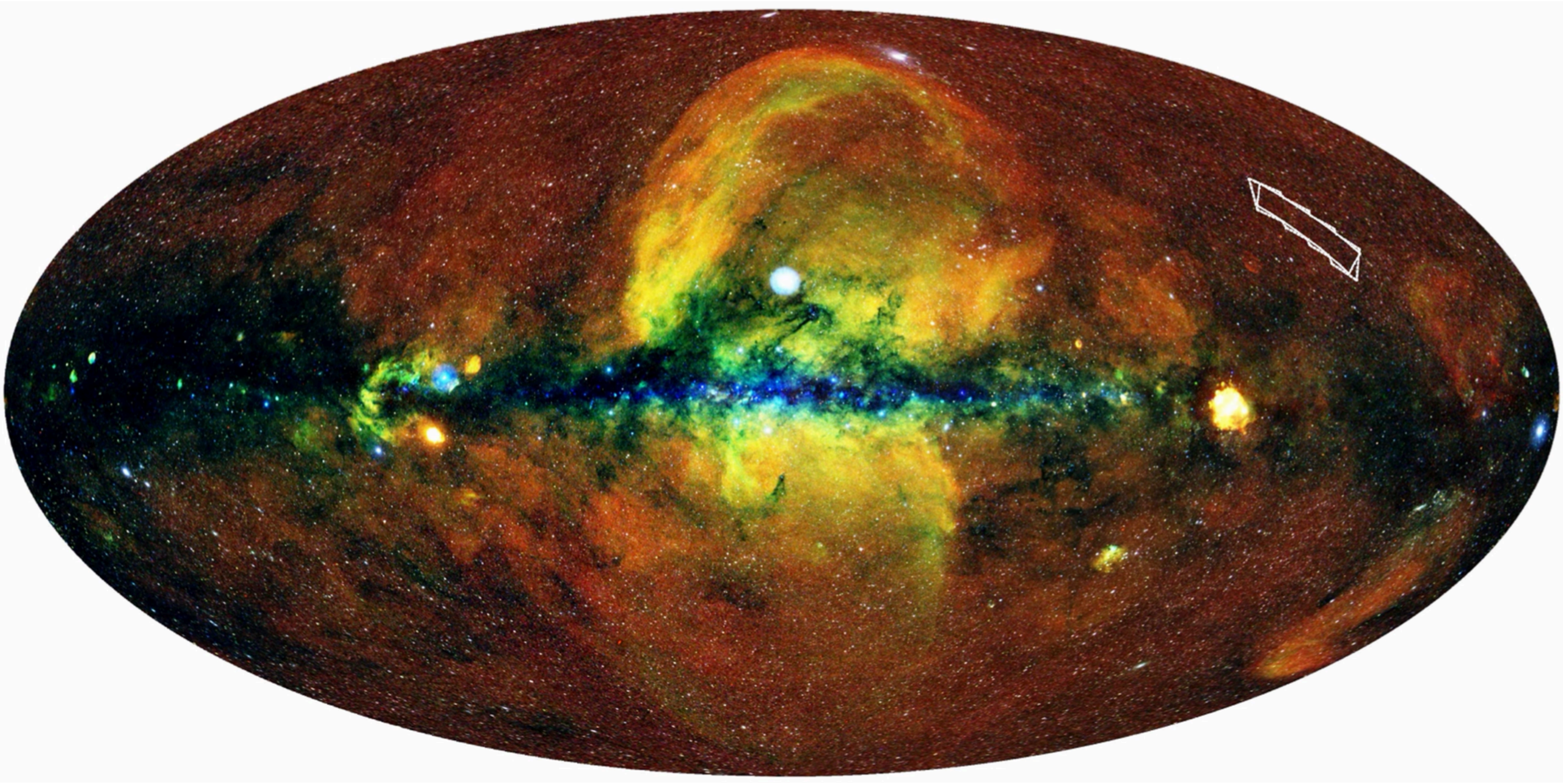


The merging of the LMC's CGM with ours

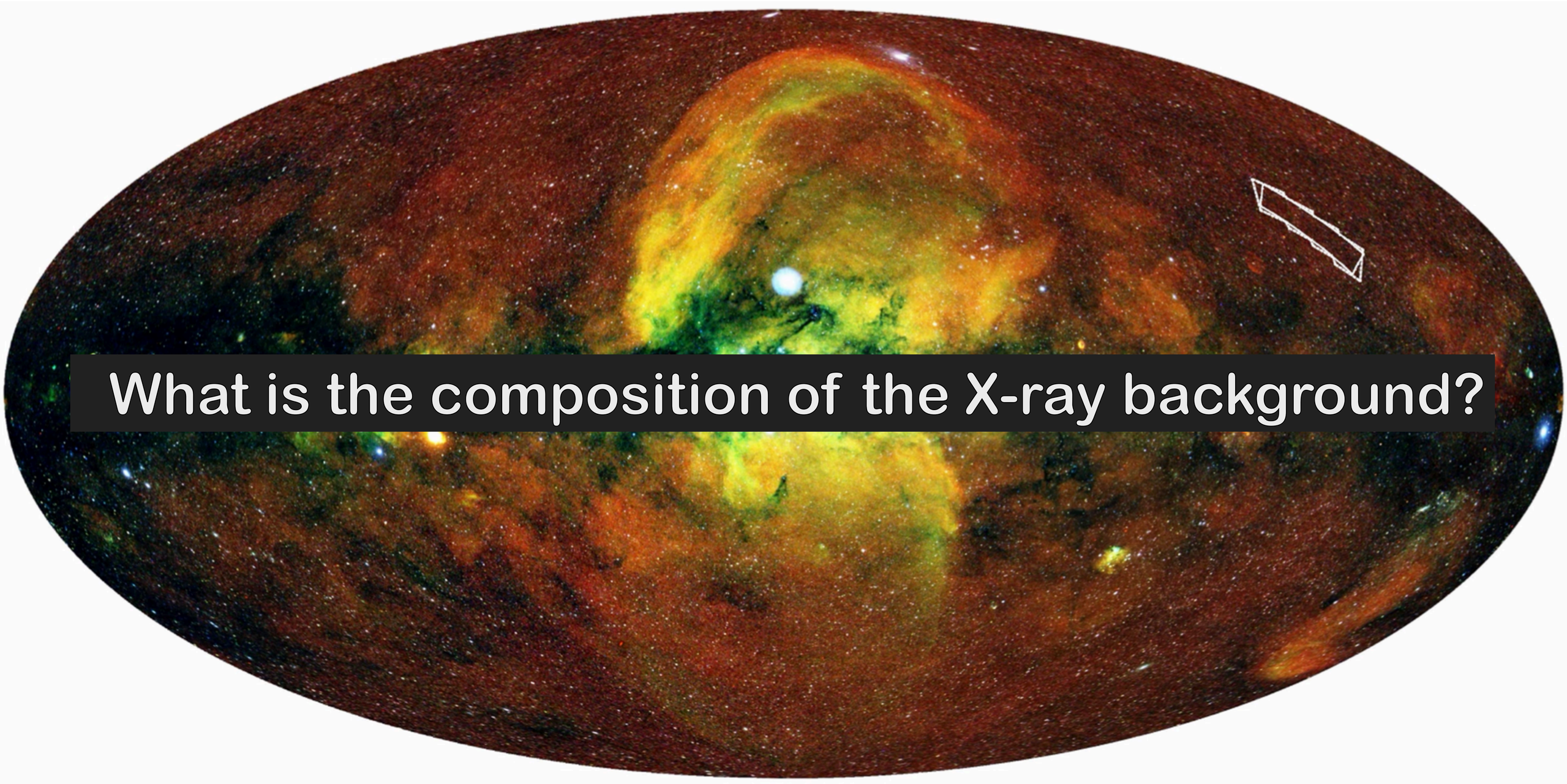


The power of eROSITA's spectra

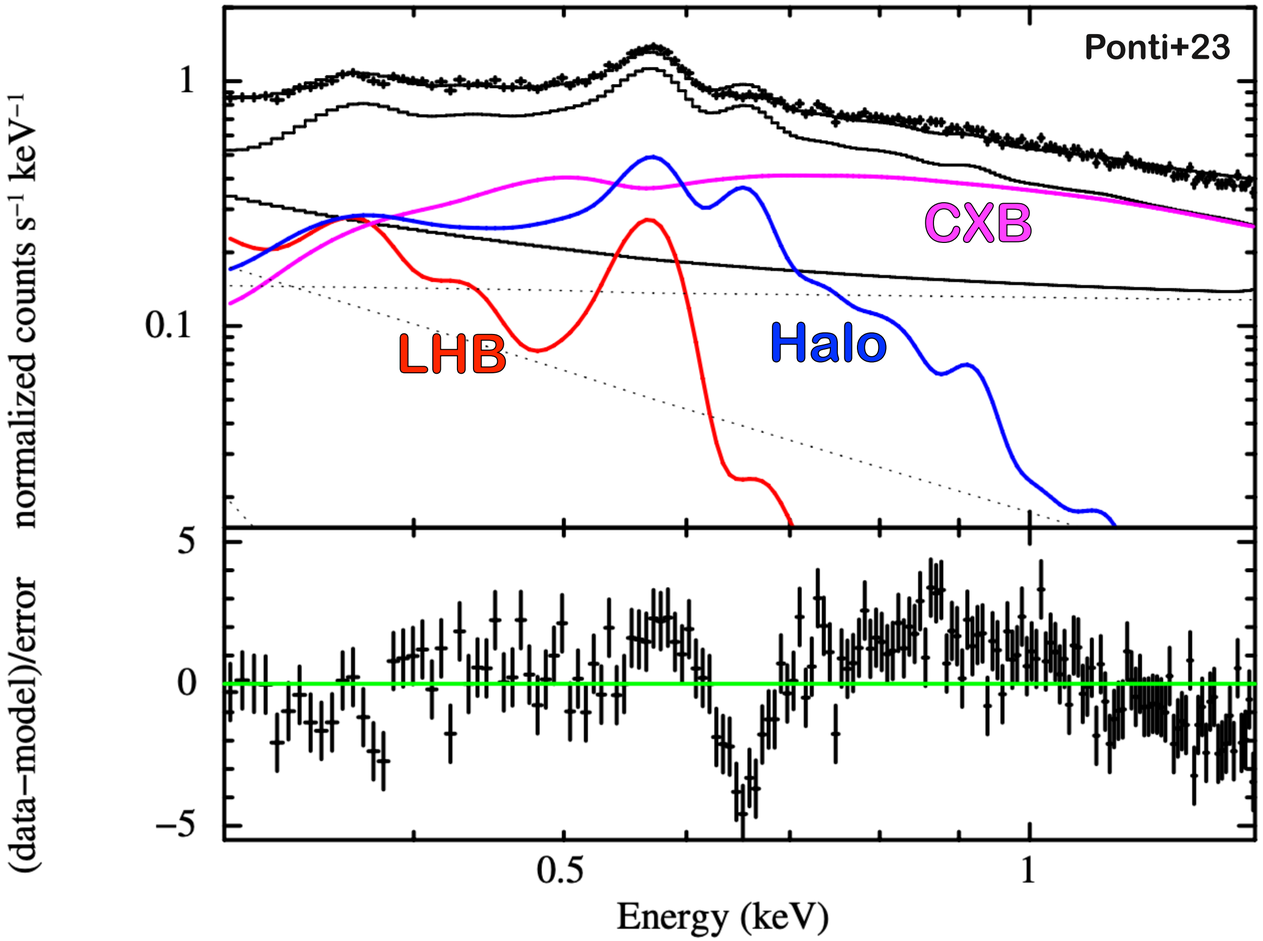
Decomposing the soft X-ray background



Decomposing the soft X-ray background



The warm-hot CGM in the eFEDS field

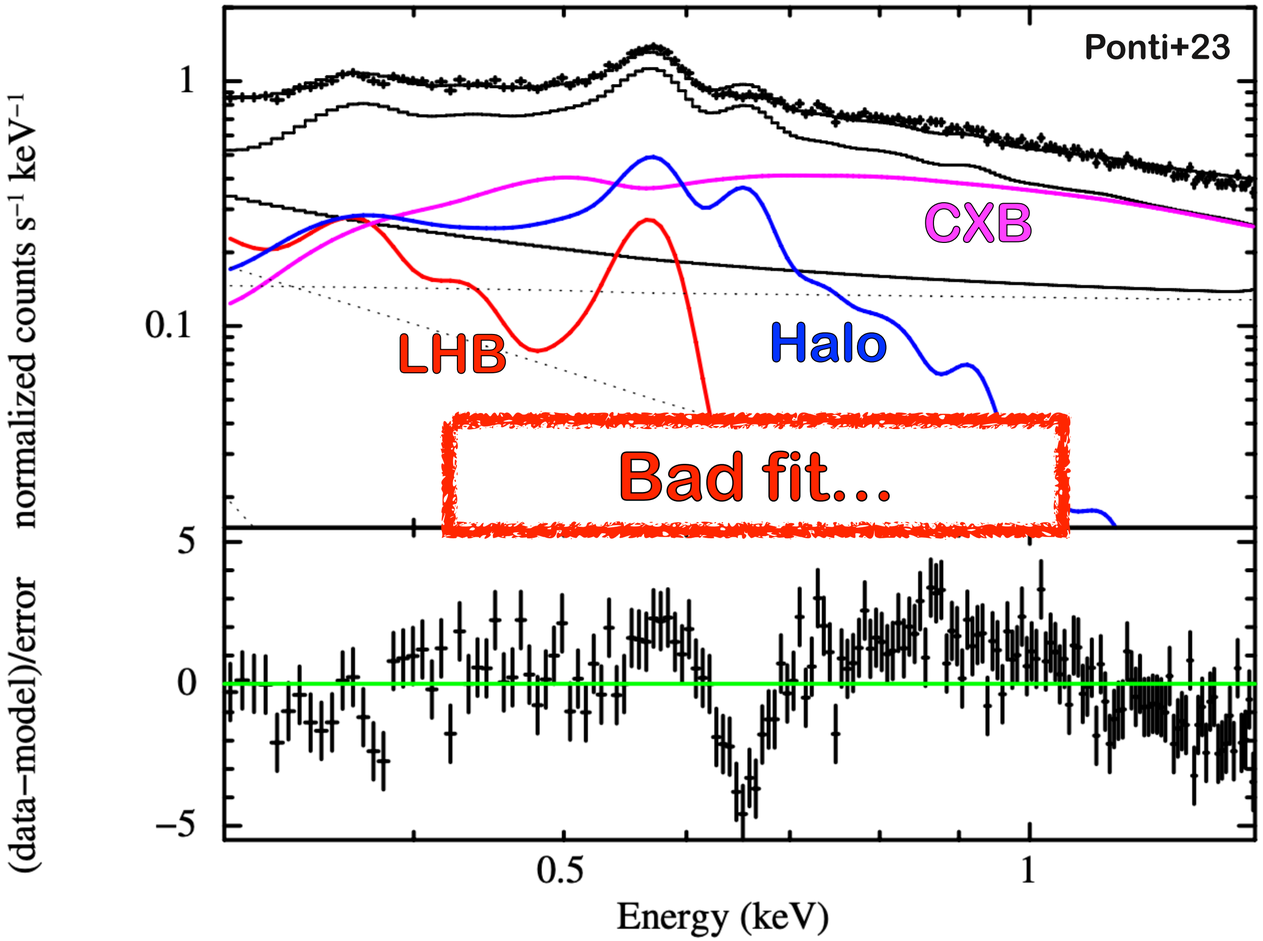


LHB: Local hot bubble

Halo: Circum Galactic medium

CXB: Cosmic X-ray background

The warm-hot CGM in the eFEDS field



LHB: Local hot bubble

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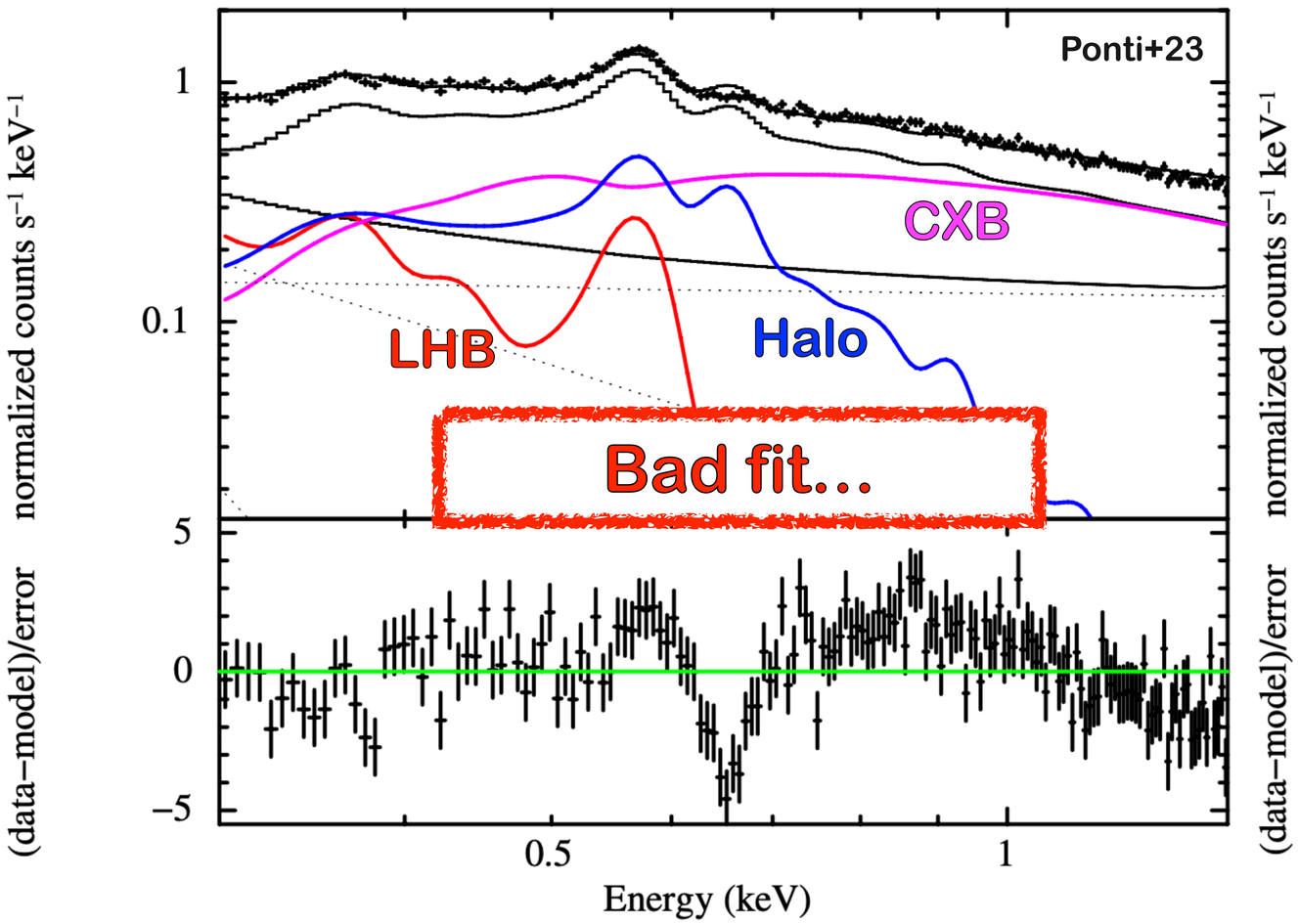
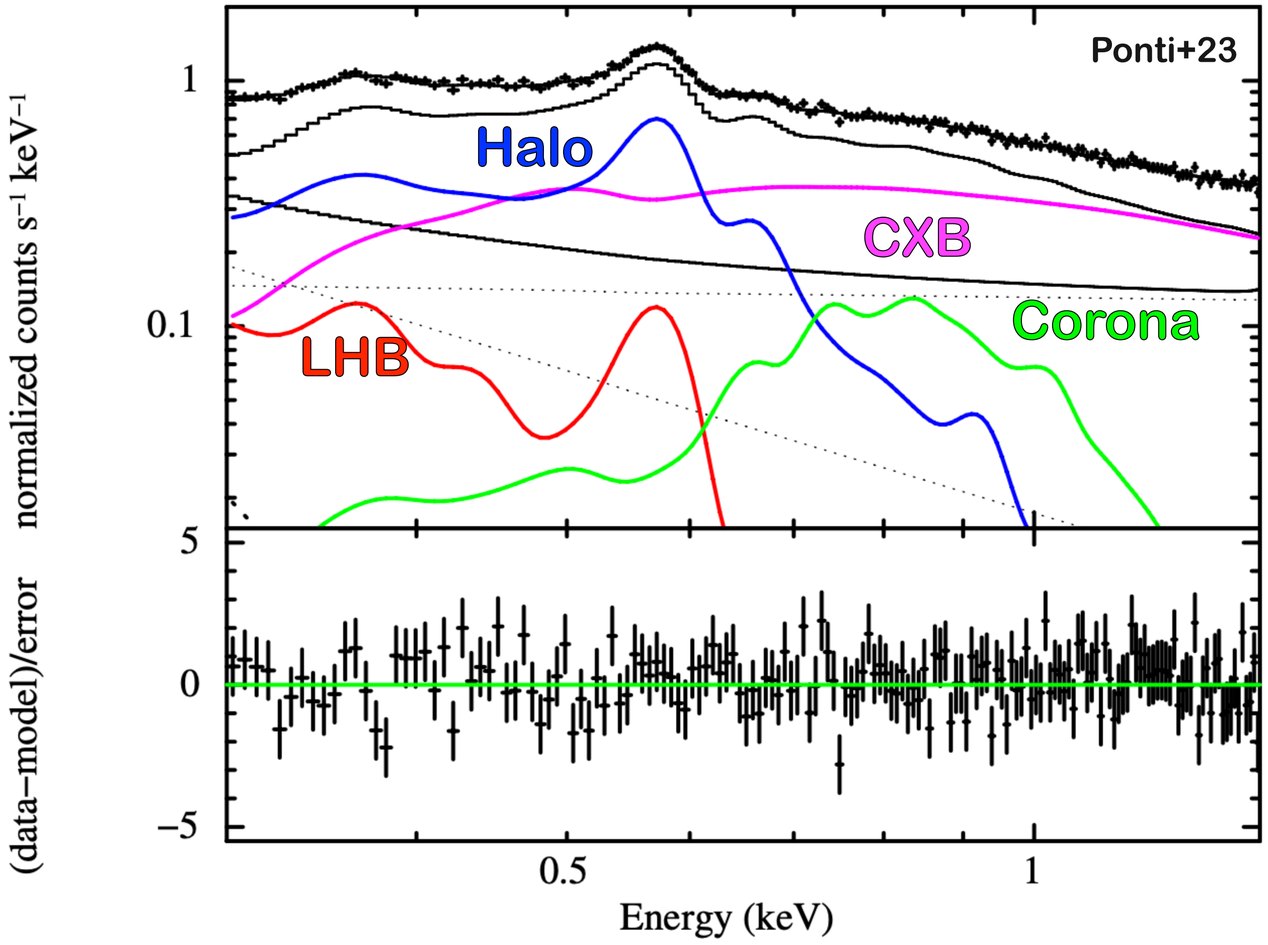
The warm-hot CGM in the eFEDS field





LHB: Local hot bubble

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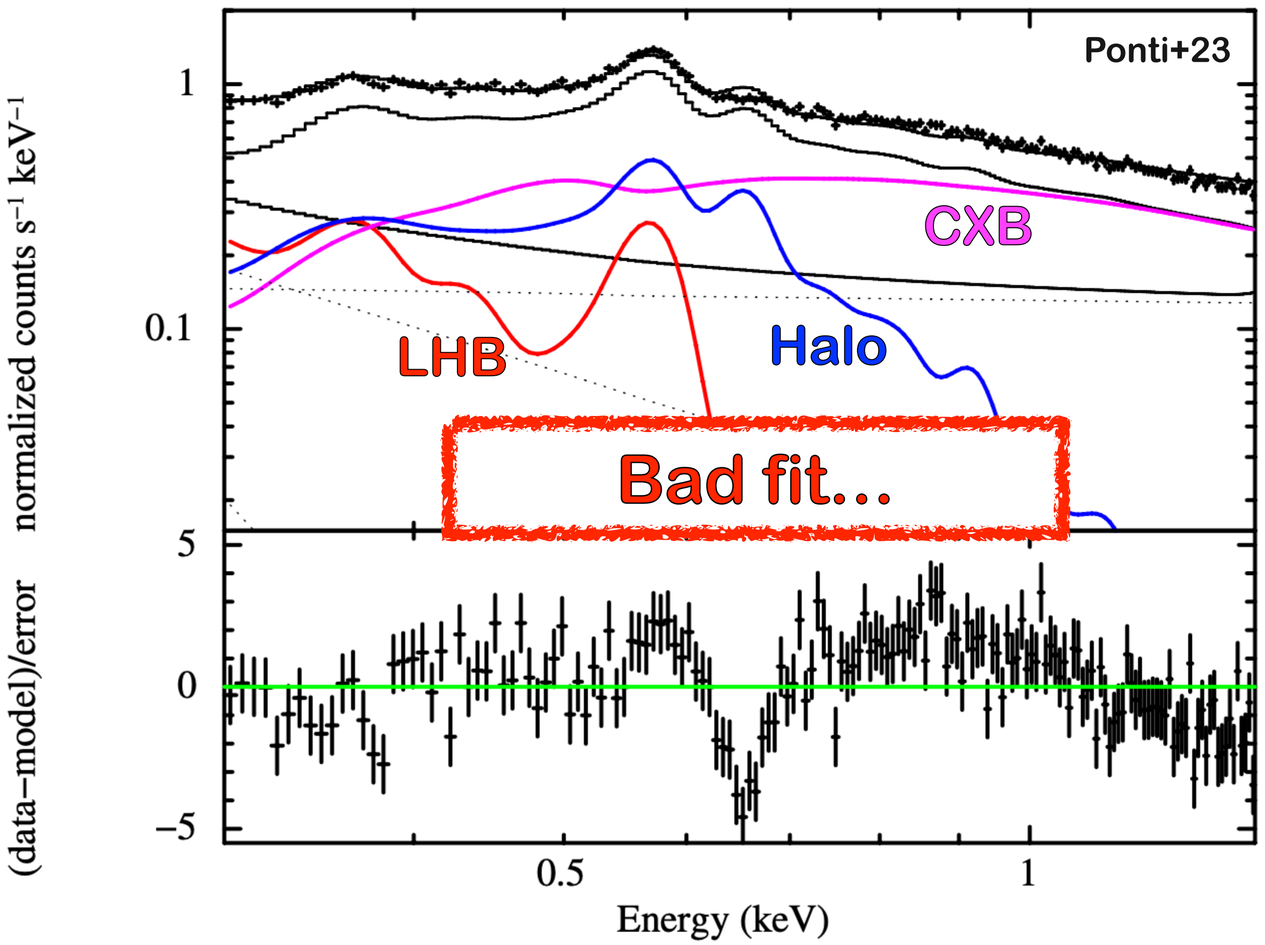
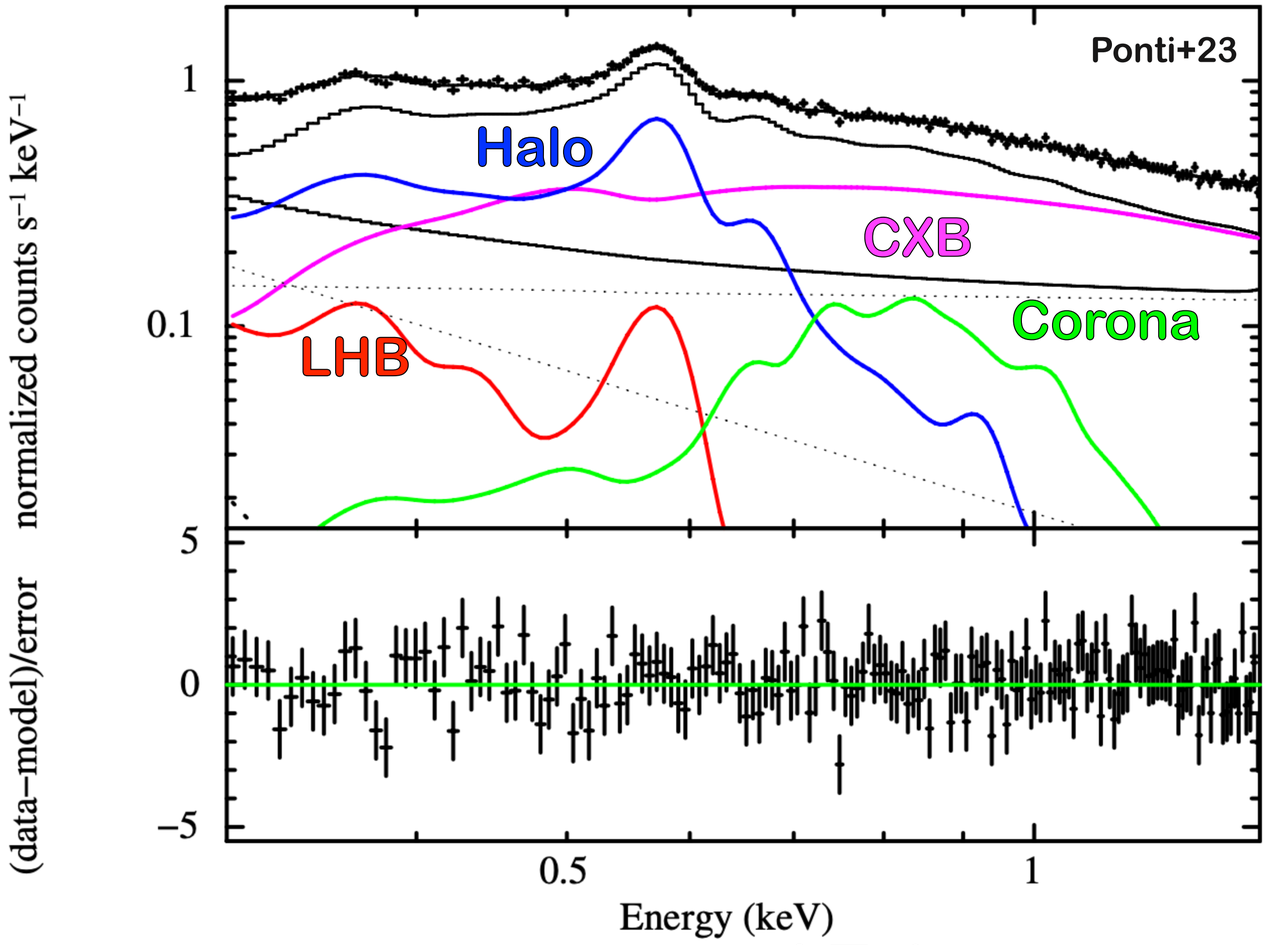
The warm-hot CGM in the eFEDS field





LHB: Local hot bubble

Halo: Circum Galactic medium

CXB: Cosmic X-ray background

Corona → Required!

kT_{Halo} = 0.153 - 0.178 keV ~ kTvir

Uncertainty on CXB

Abun = 0.05 - 0.10 $Z_\odot$

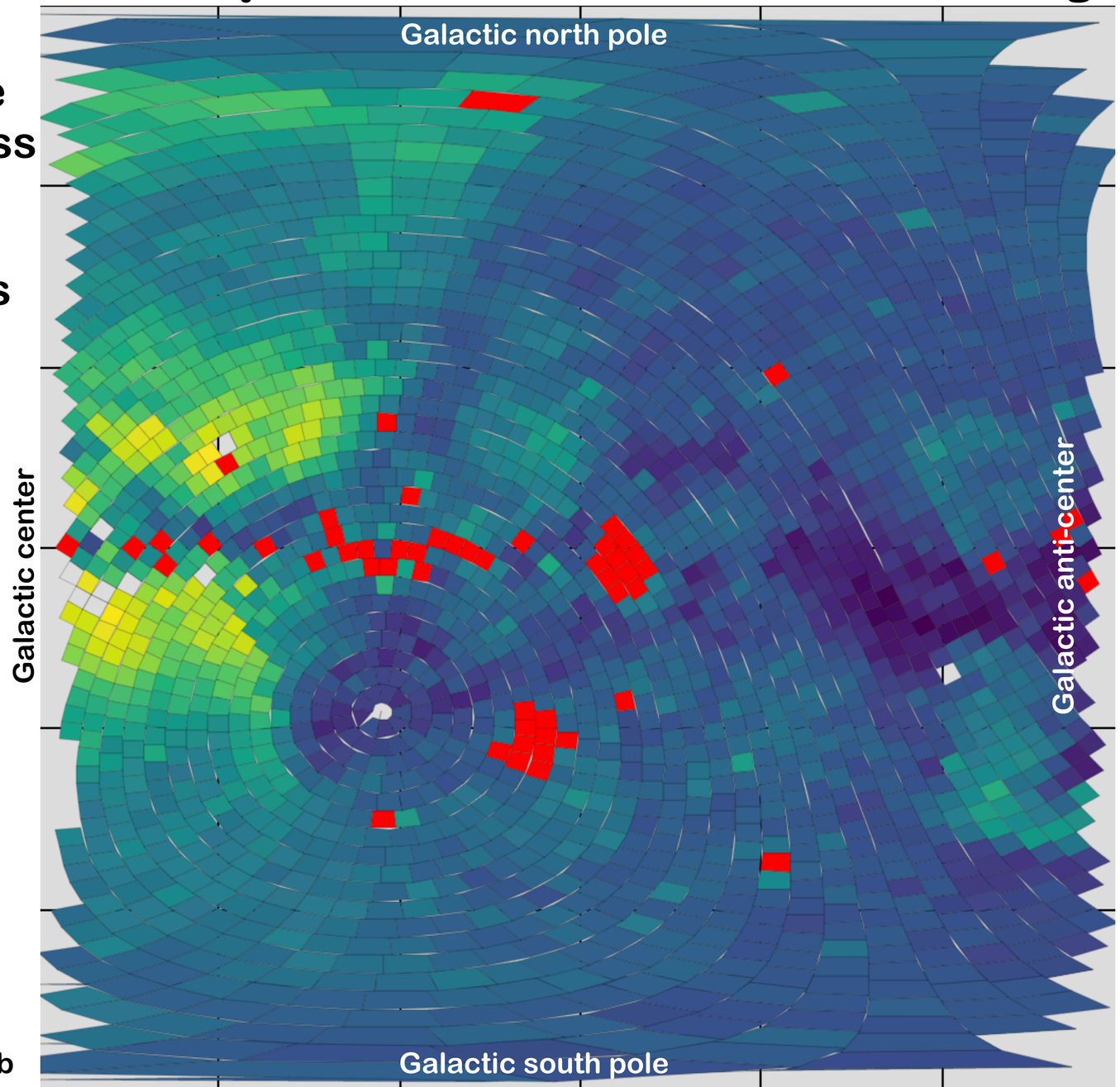
kT_{Coro} = 0.4 - 0.7 keV

The power of eROSITA's spectra over the half sky

The composition of the X-ray background

Surface brightness

Sky Tiles 3×3°

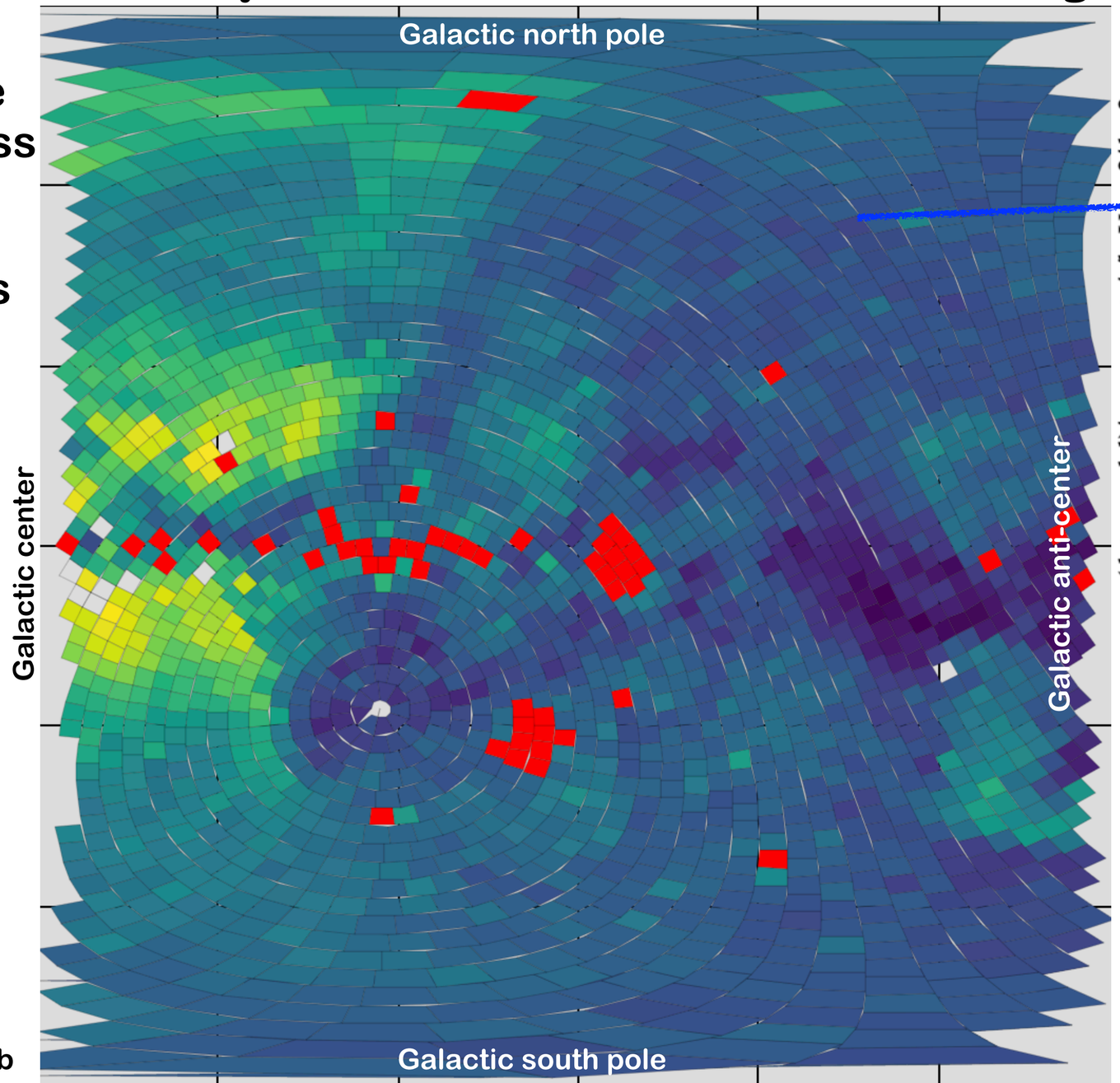


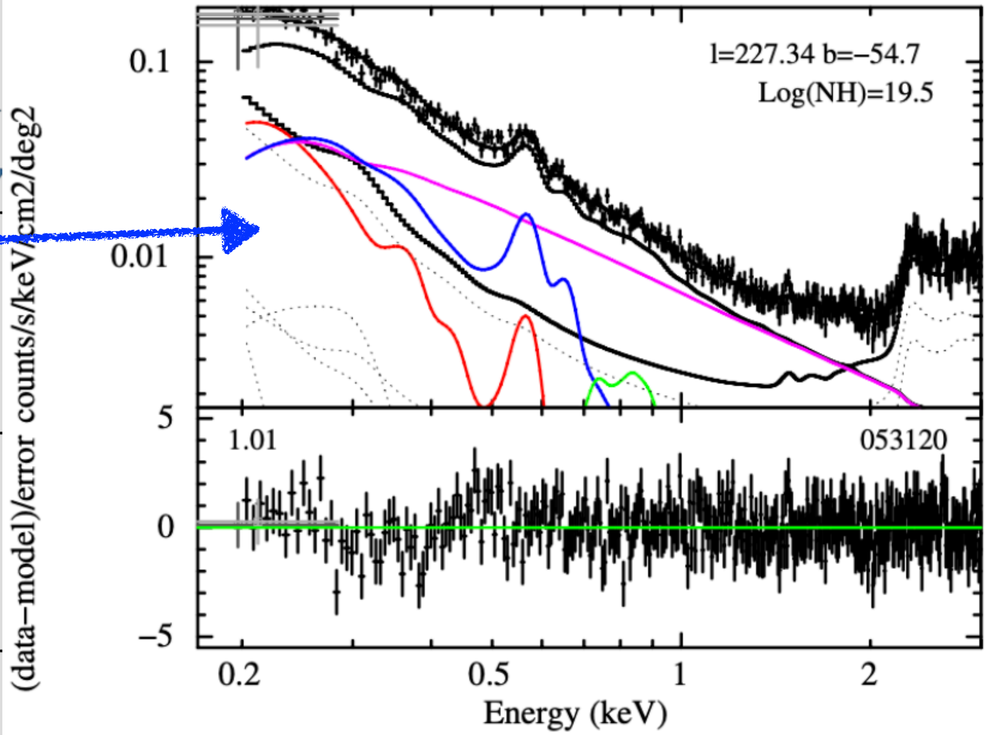
Ponti+sub

The composition of the X-ray background

Surface brightness

Sky Tiles 3×3°



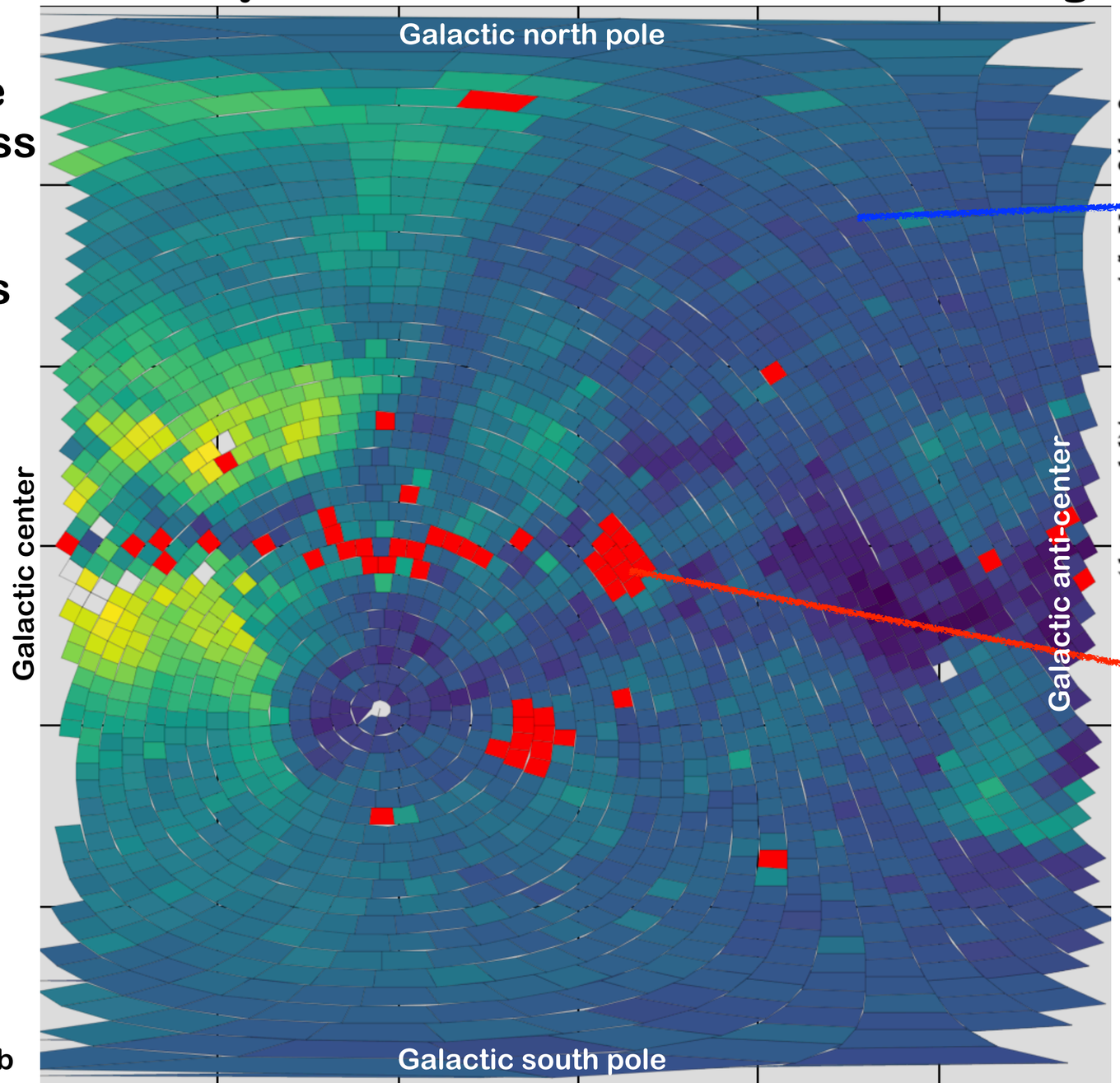


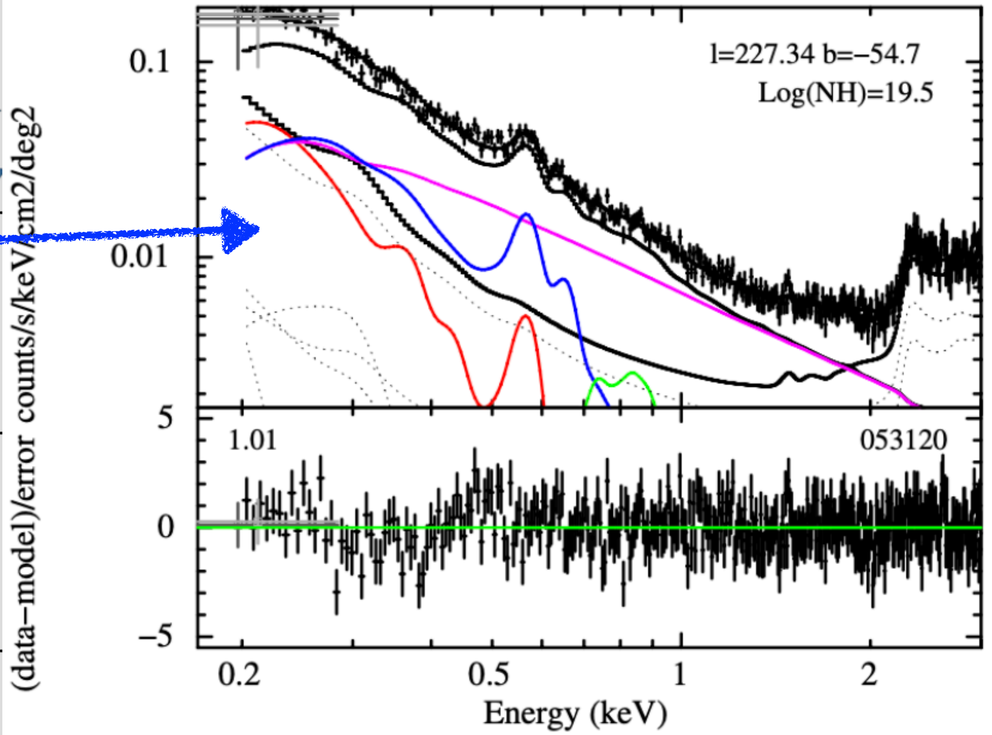
Ponti+sub

The composition of the X-ray background

Surface brightness

Sky Tiles 3×3°





$\chi^2_{red} > 1.5$

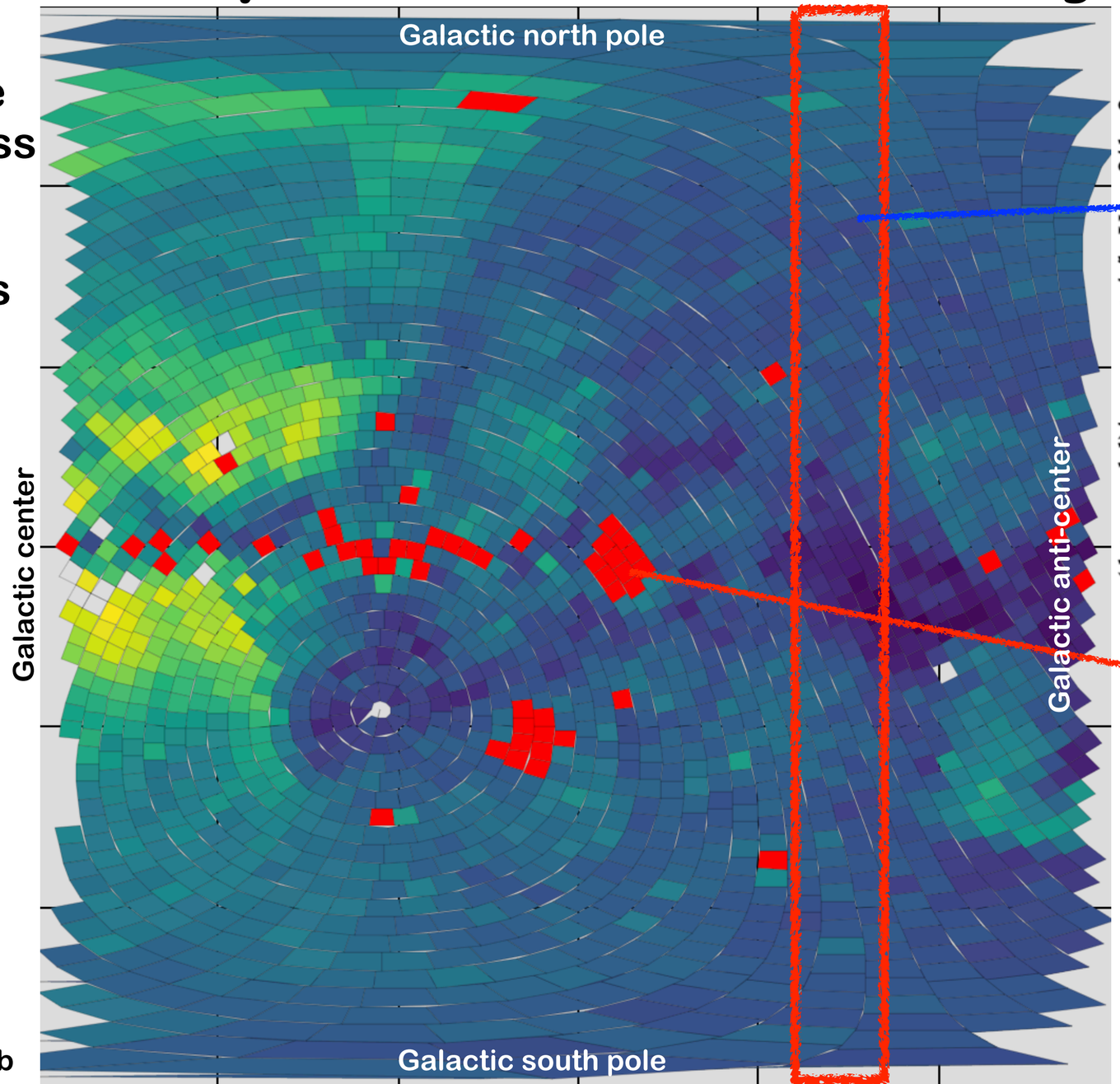
Good fit over most of the sky even with oversimplified model

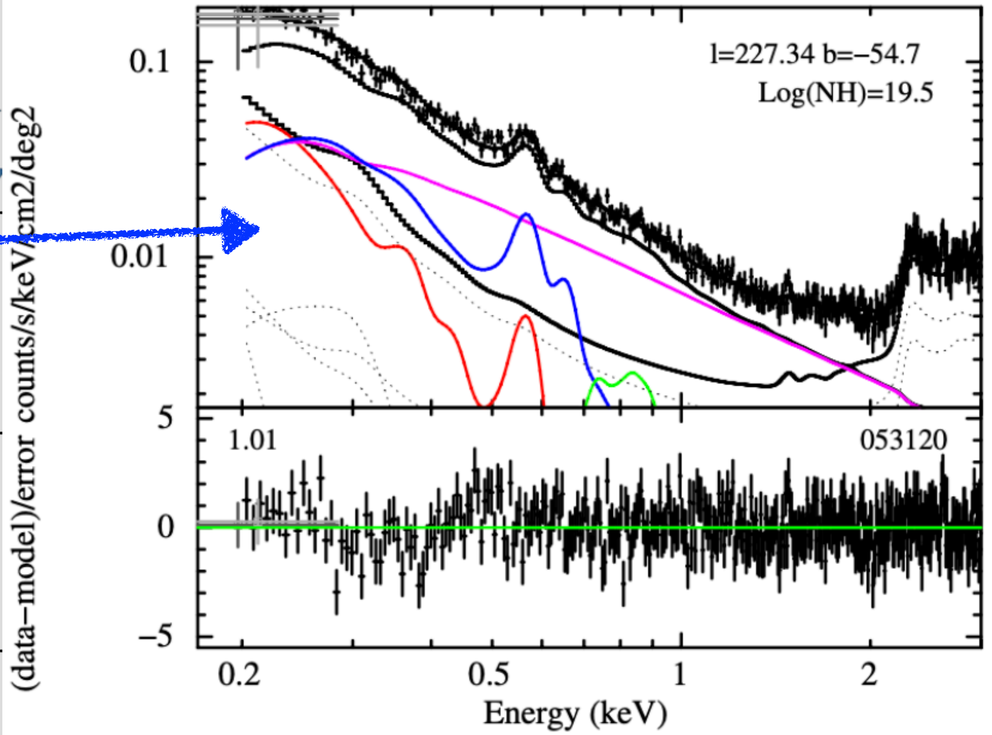
Ponti+sub

The composition of the X-ray background

Surface brightness

Sky Tiles 3×3°



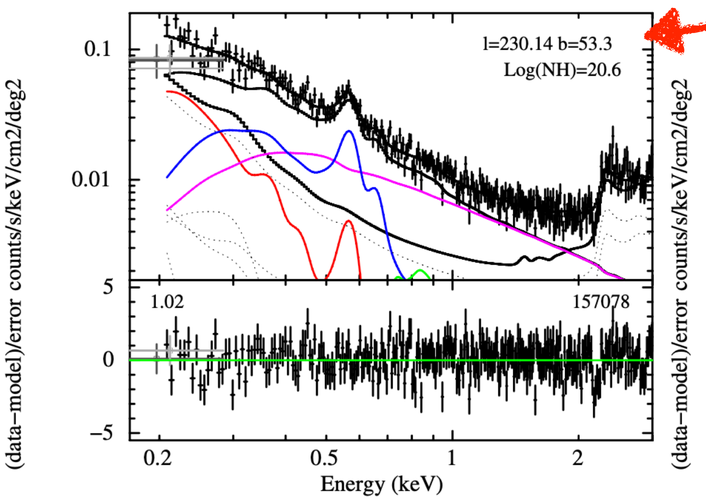


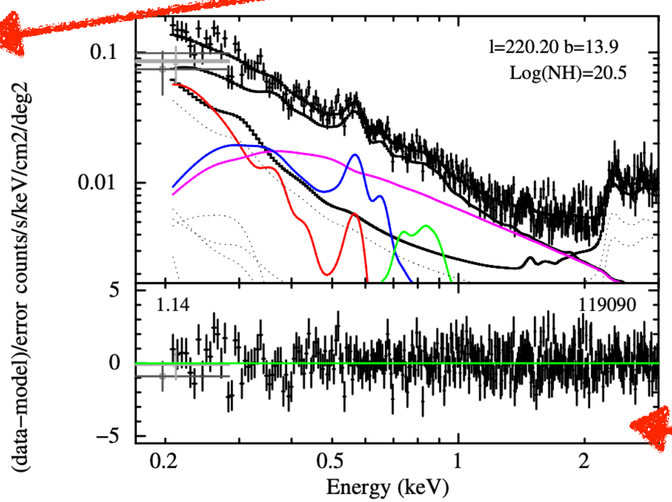
$\chi^2_{red} > 1.5$

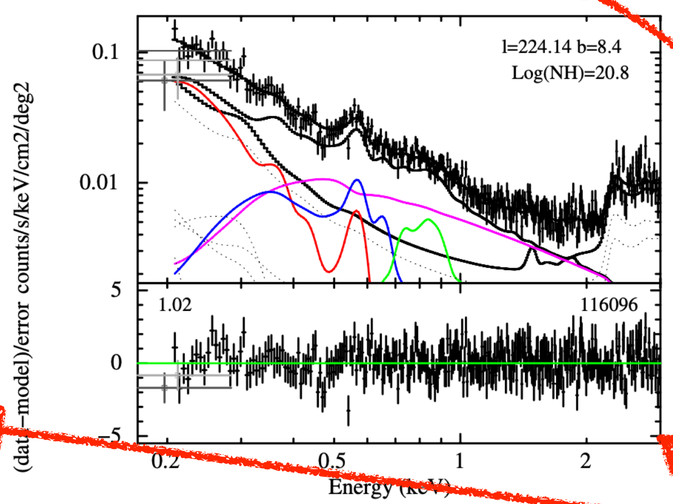
Good fit over most of the sky even with oversimplified model

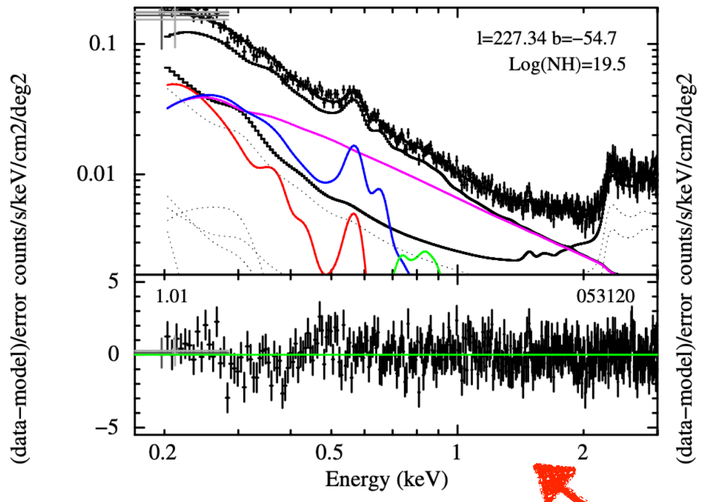
Ponti+sub

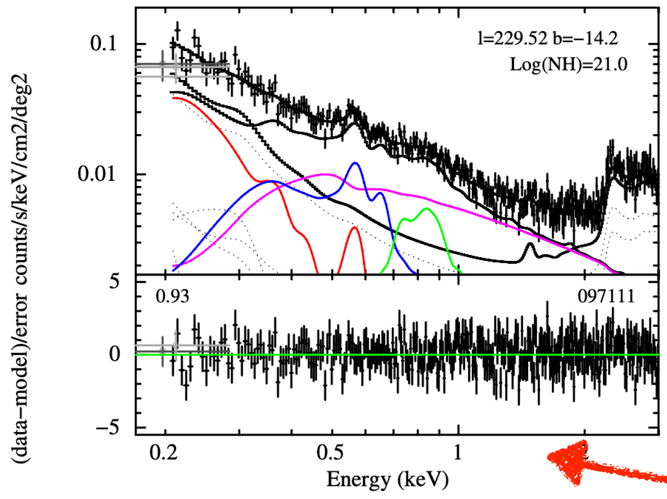
Spectral variations over the half-sky

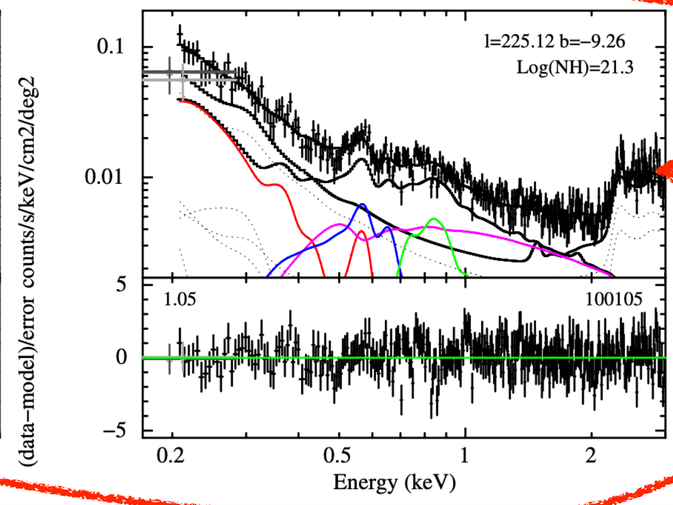


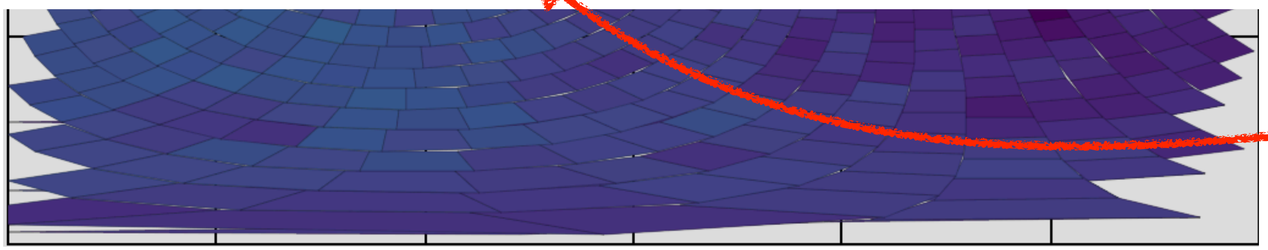


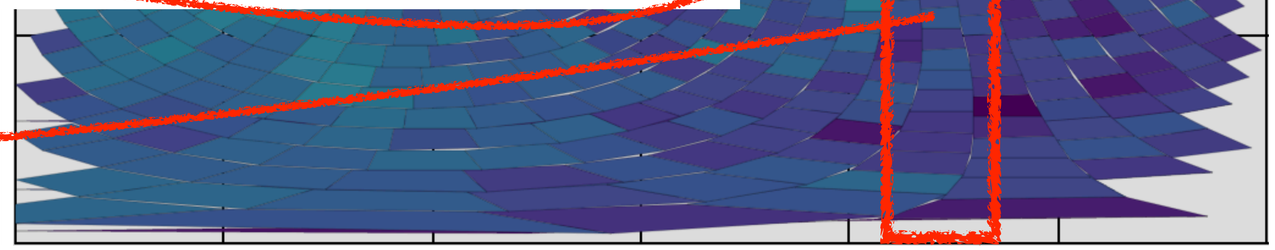








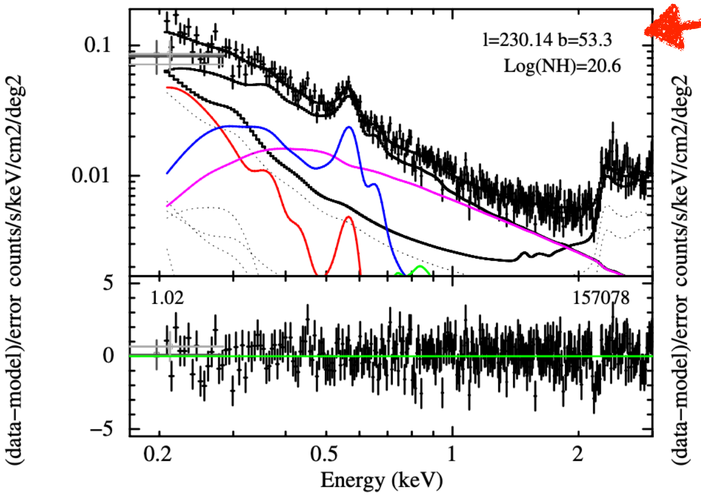


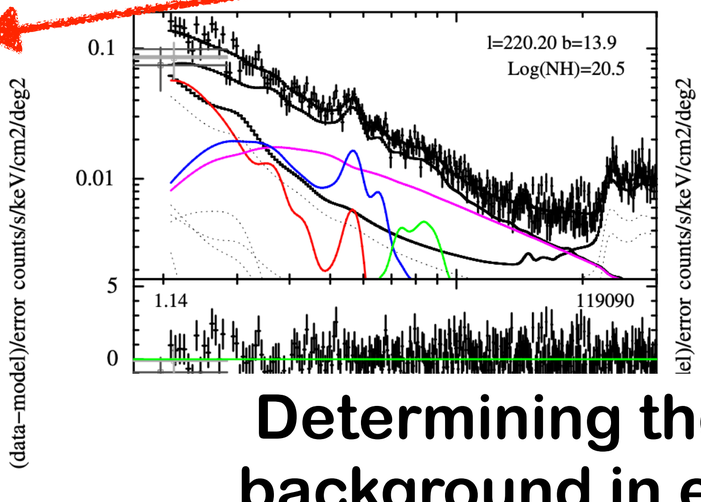


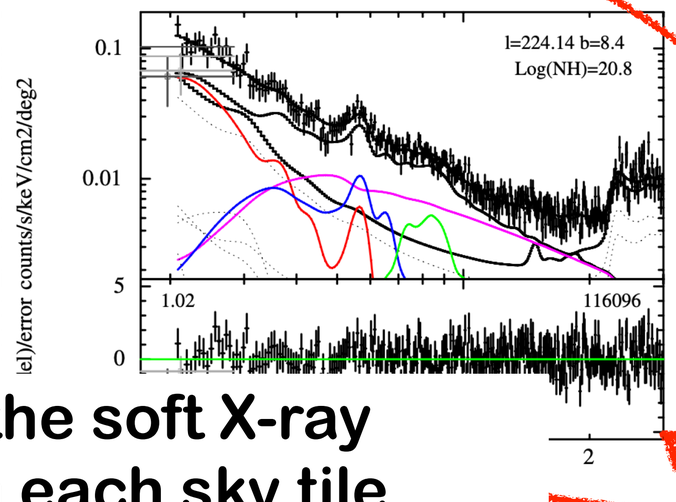
Ponti+sub

Ponti+sub

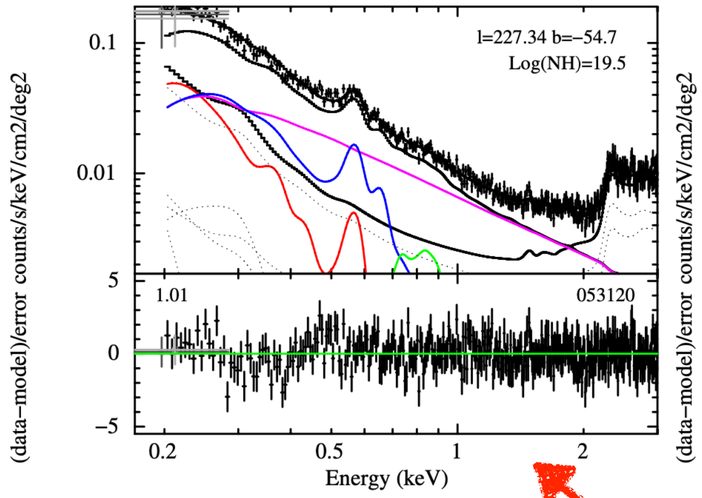
Spectral variations over the half-sky

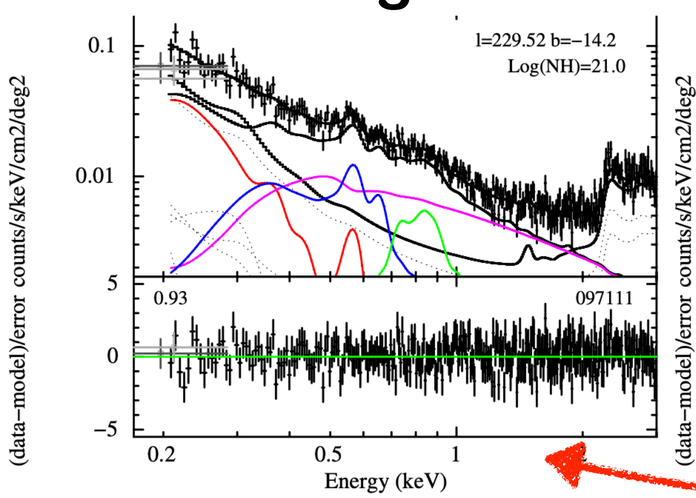


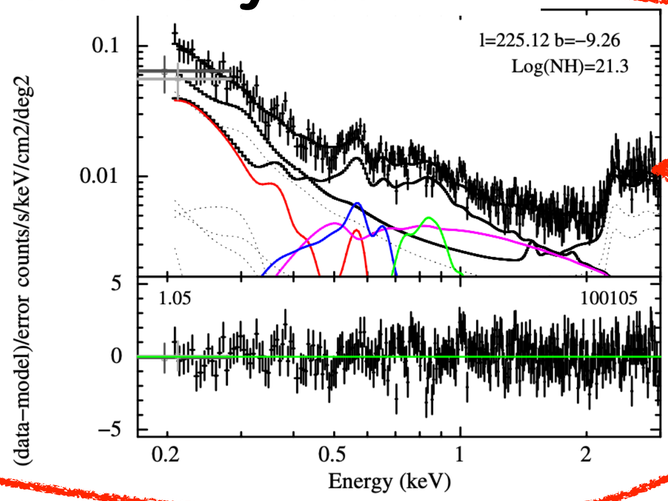


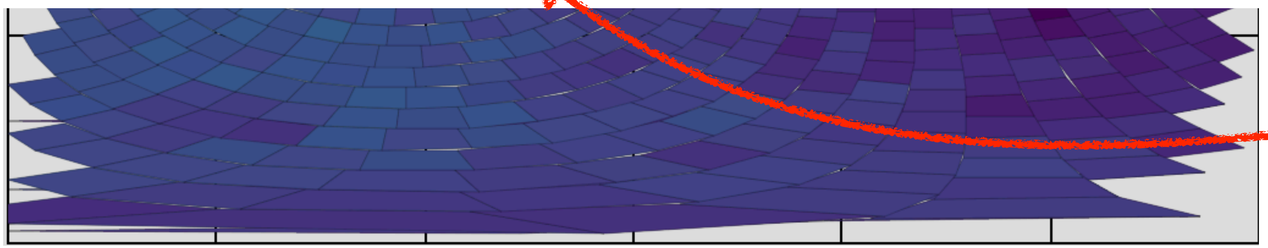


Determining the soft X-ray background in each sky tile

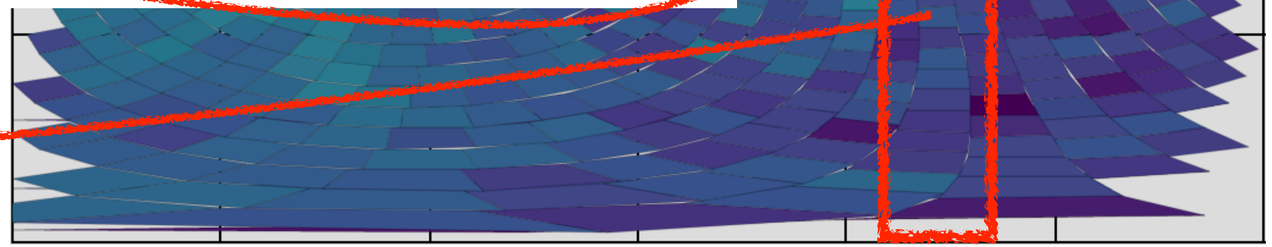






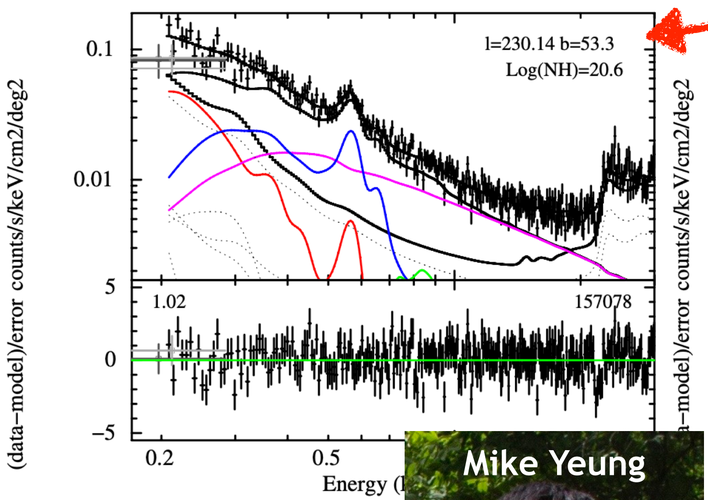


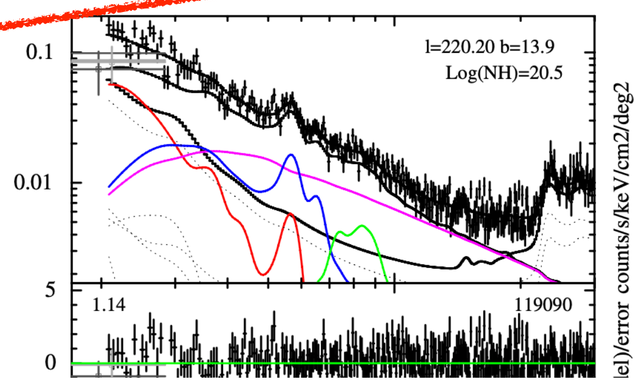
Ponti+sub

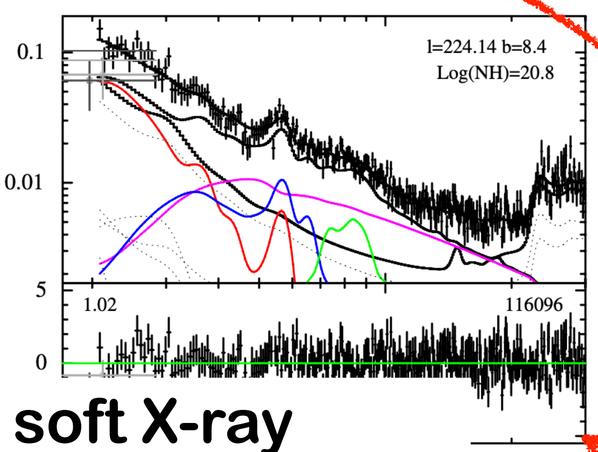


Ponti+sub

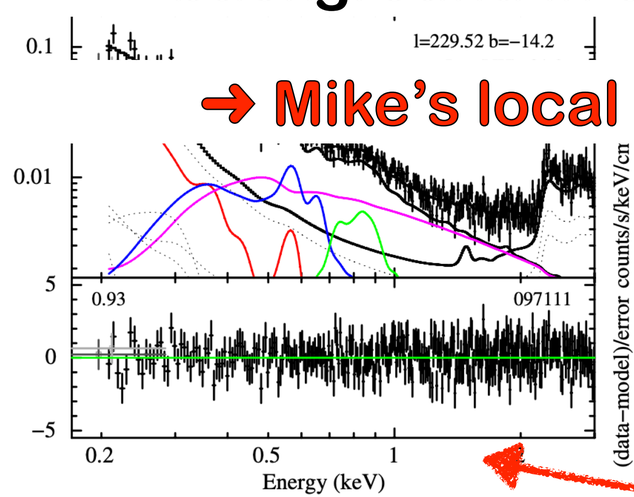
Spectral variations over the half-sky

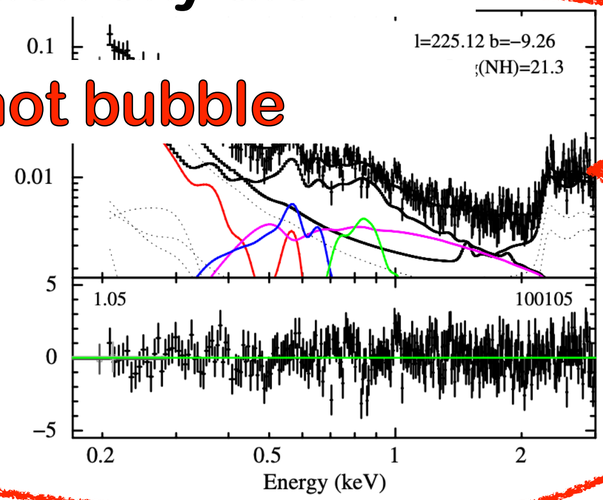




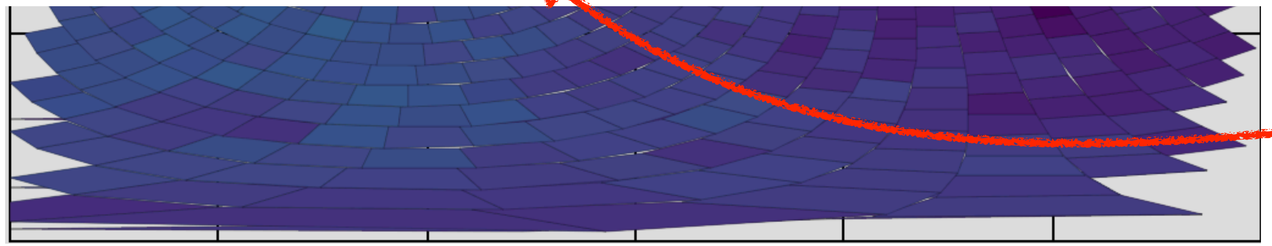


Determining the soft X-ray background in each sky tile

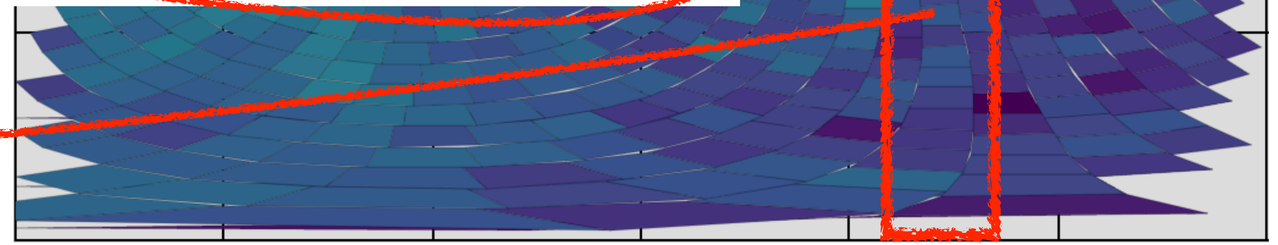




➜ Mike's local hot bubble

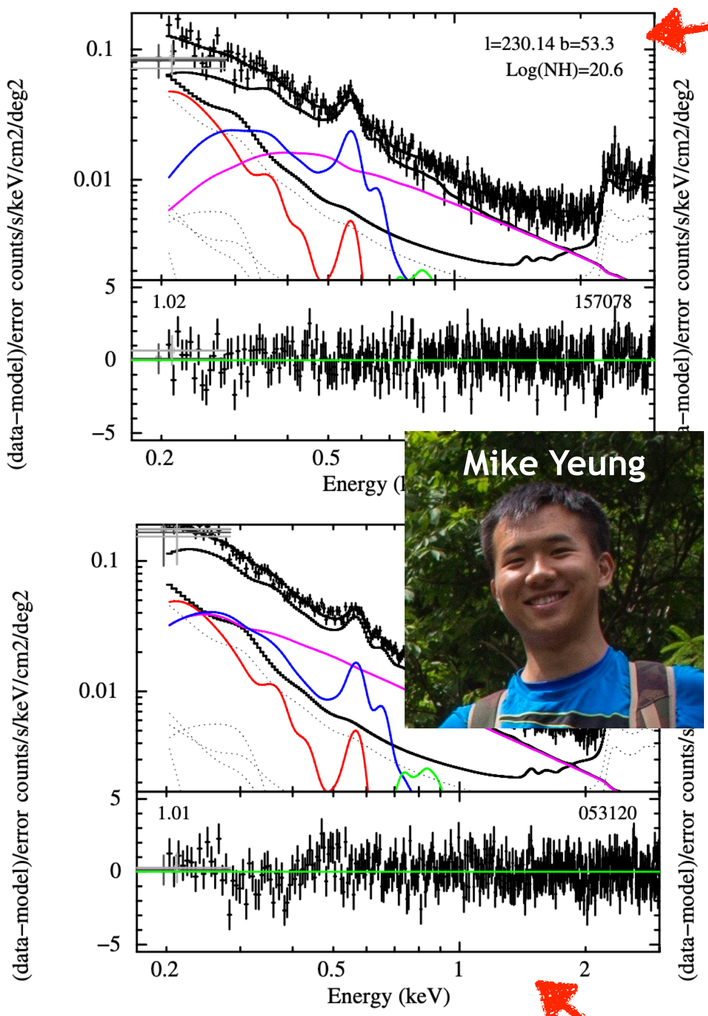


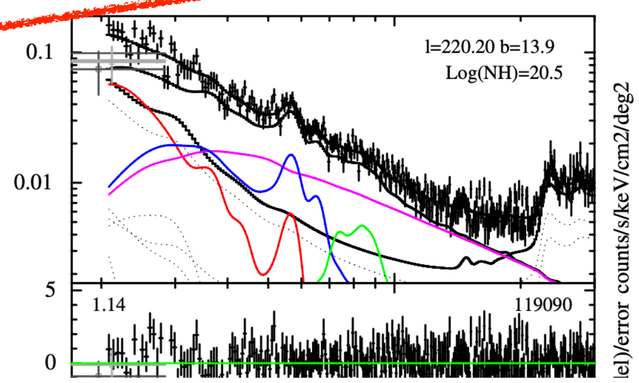
Ponti+sub

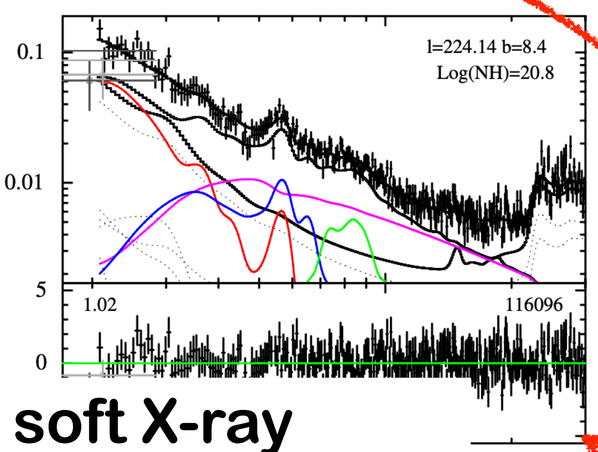


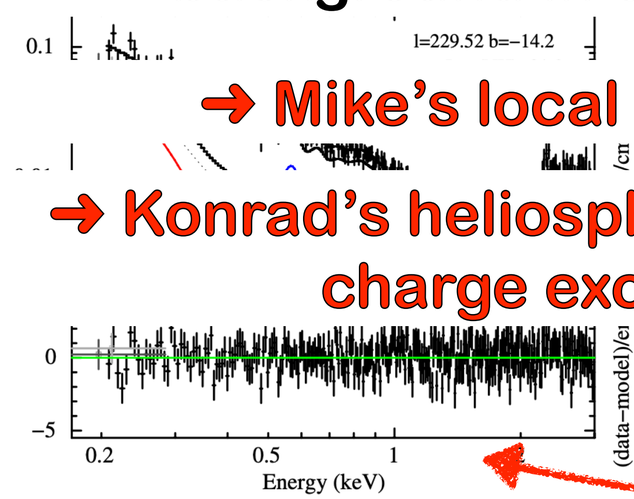
Ponti+sub

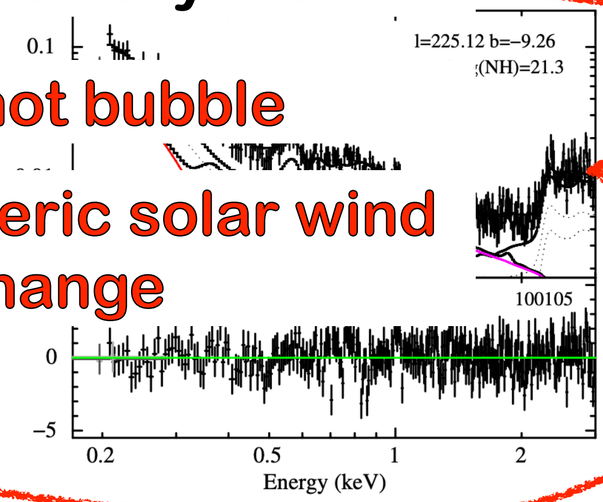
Spectral variations over the half-sky











Determining the soft X-ray background in each sky tile

➔ Mike's local hot bubble

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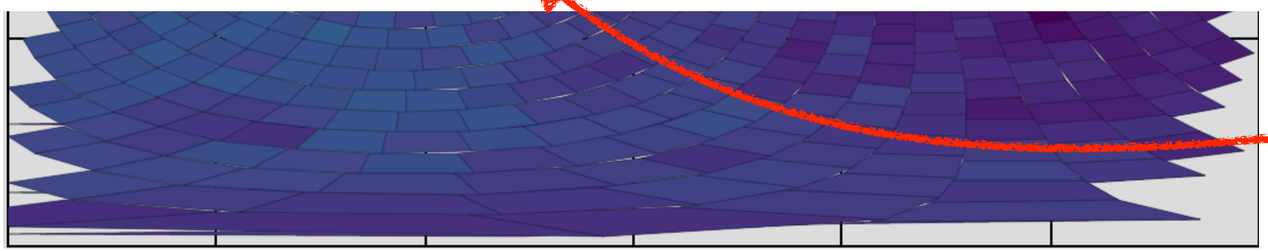

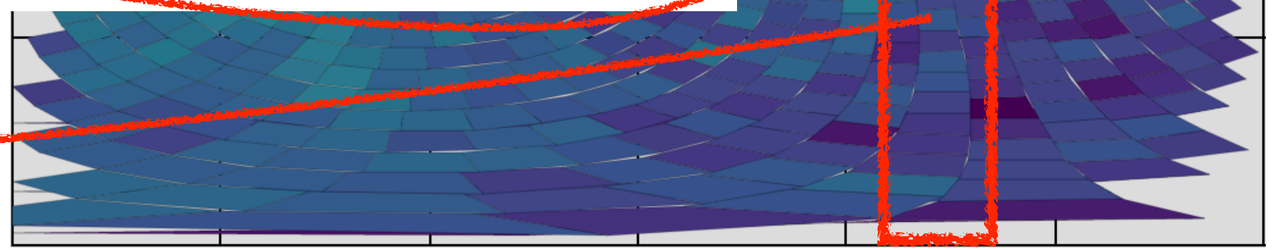

Ponti+sub

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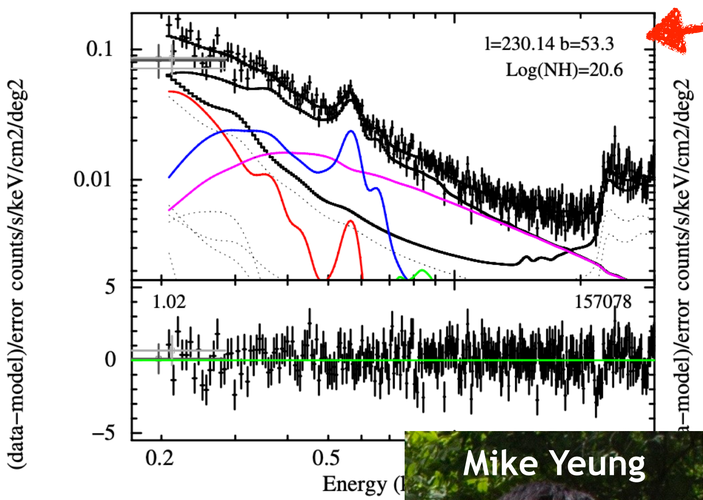
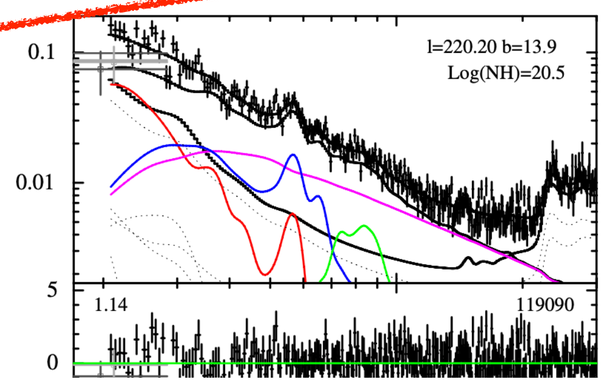
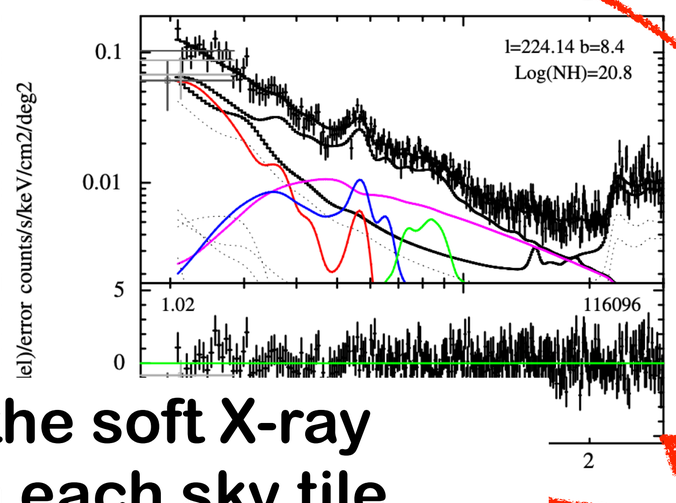
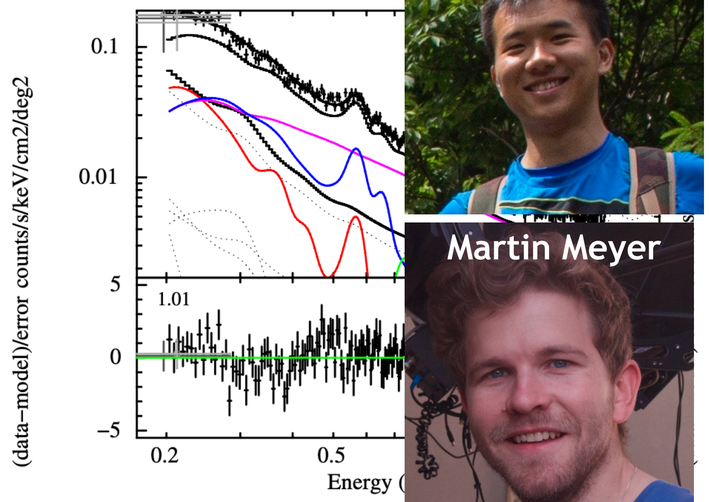
Spectral variations over the half-sky









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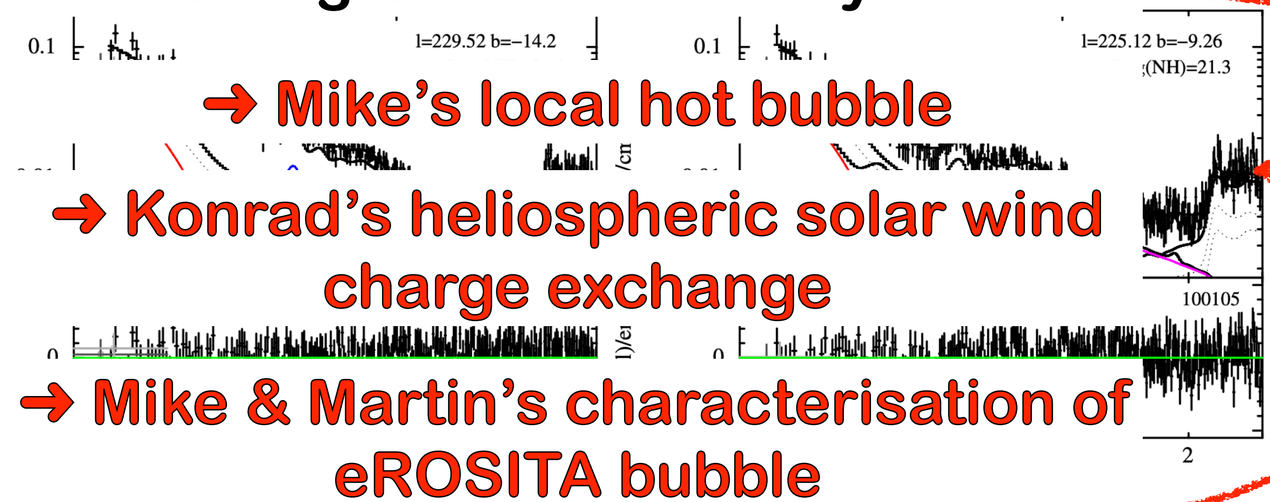

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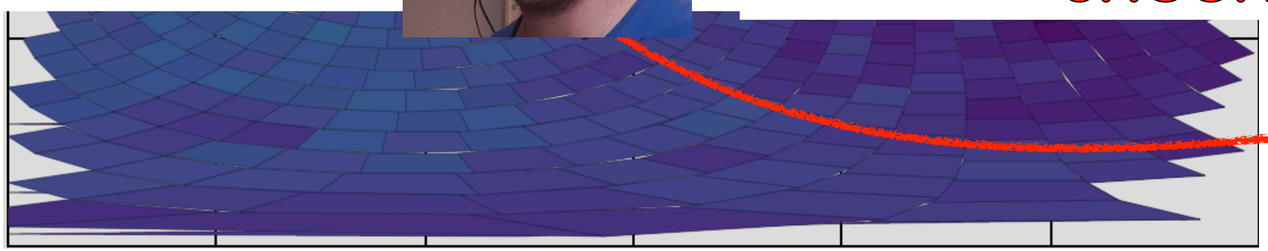

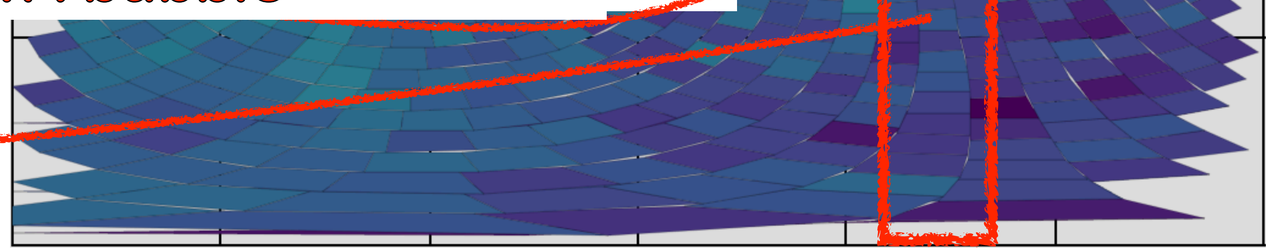

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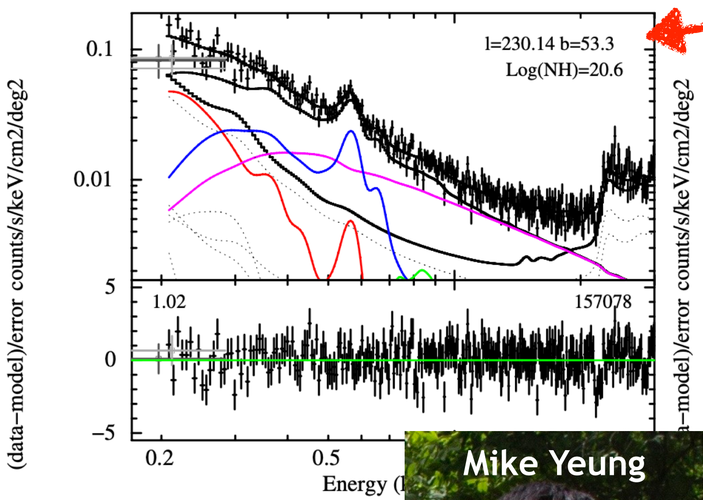

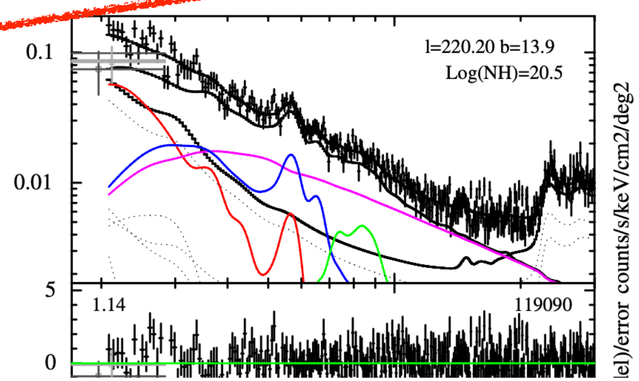

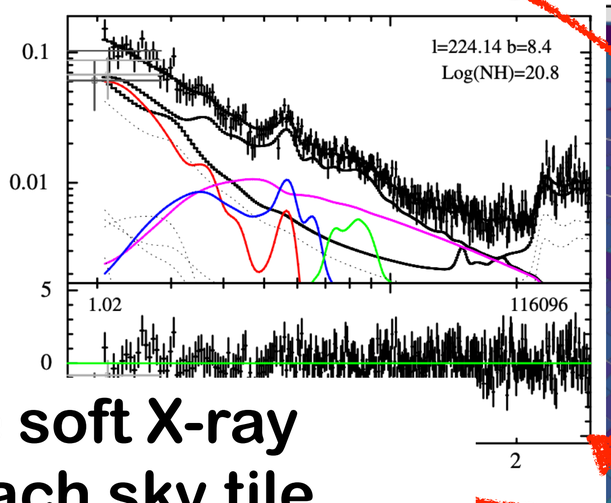

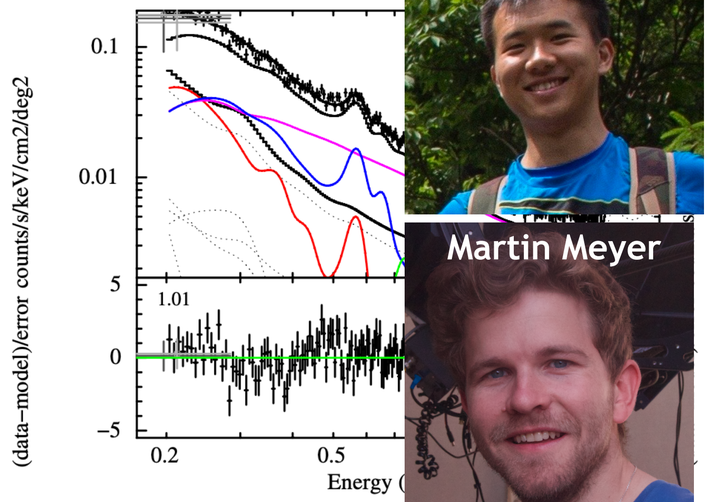

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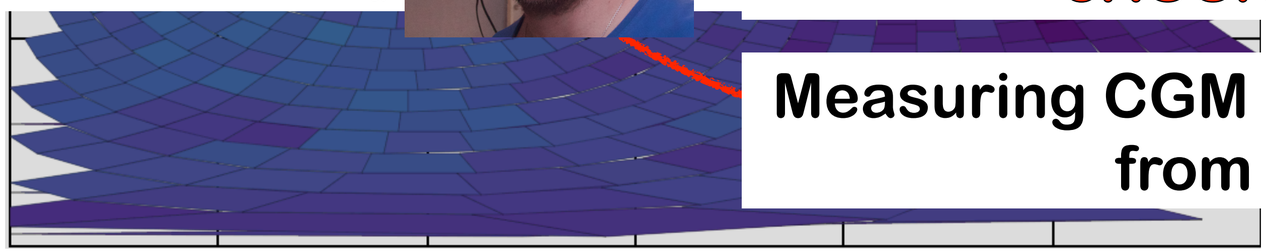
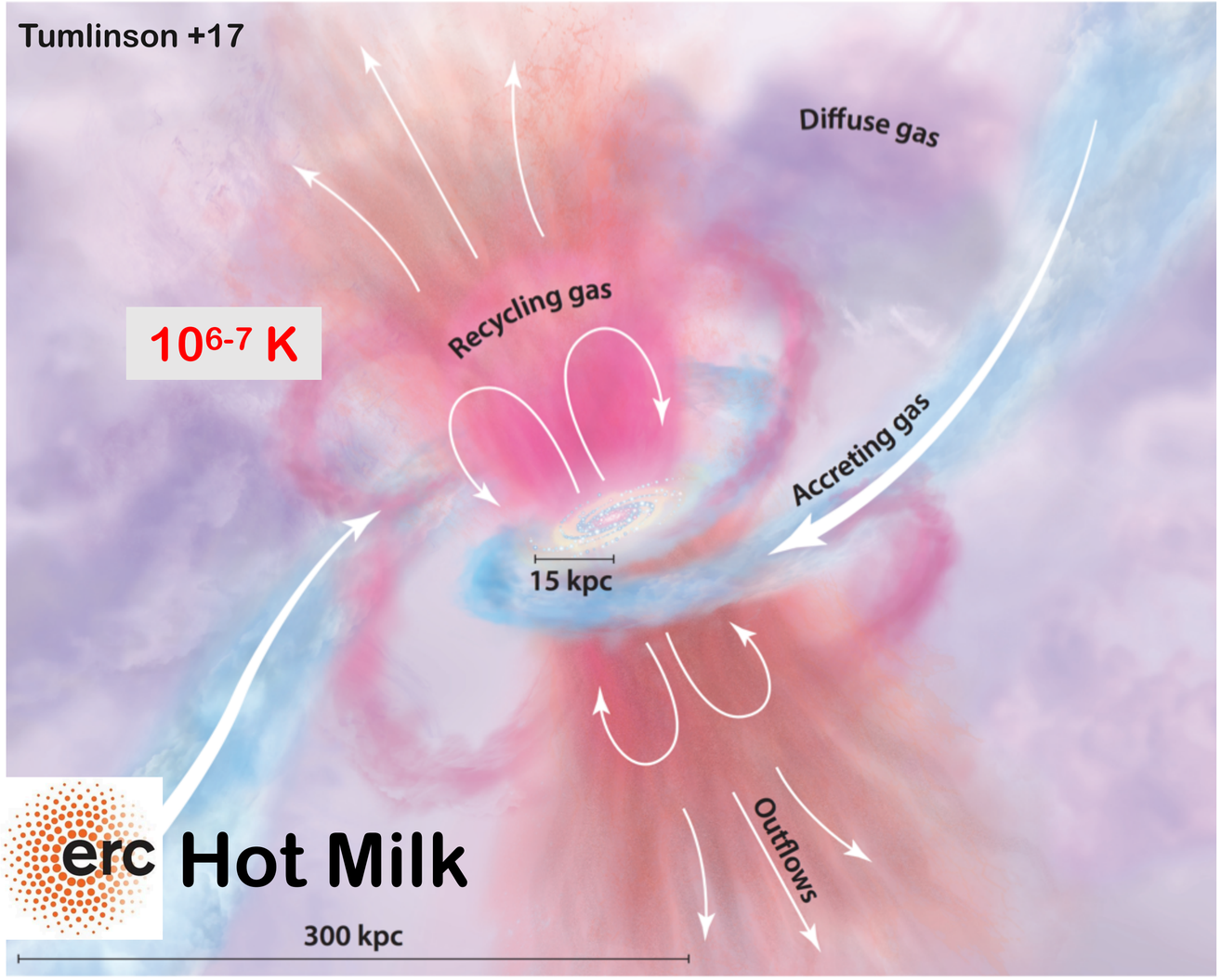


Measuring CGM physical properties from spectra

Ponti+sub

Ponti+sub

Our new view of the hot CGM



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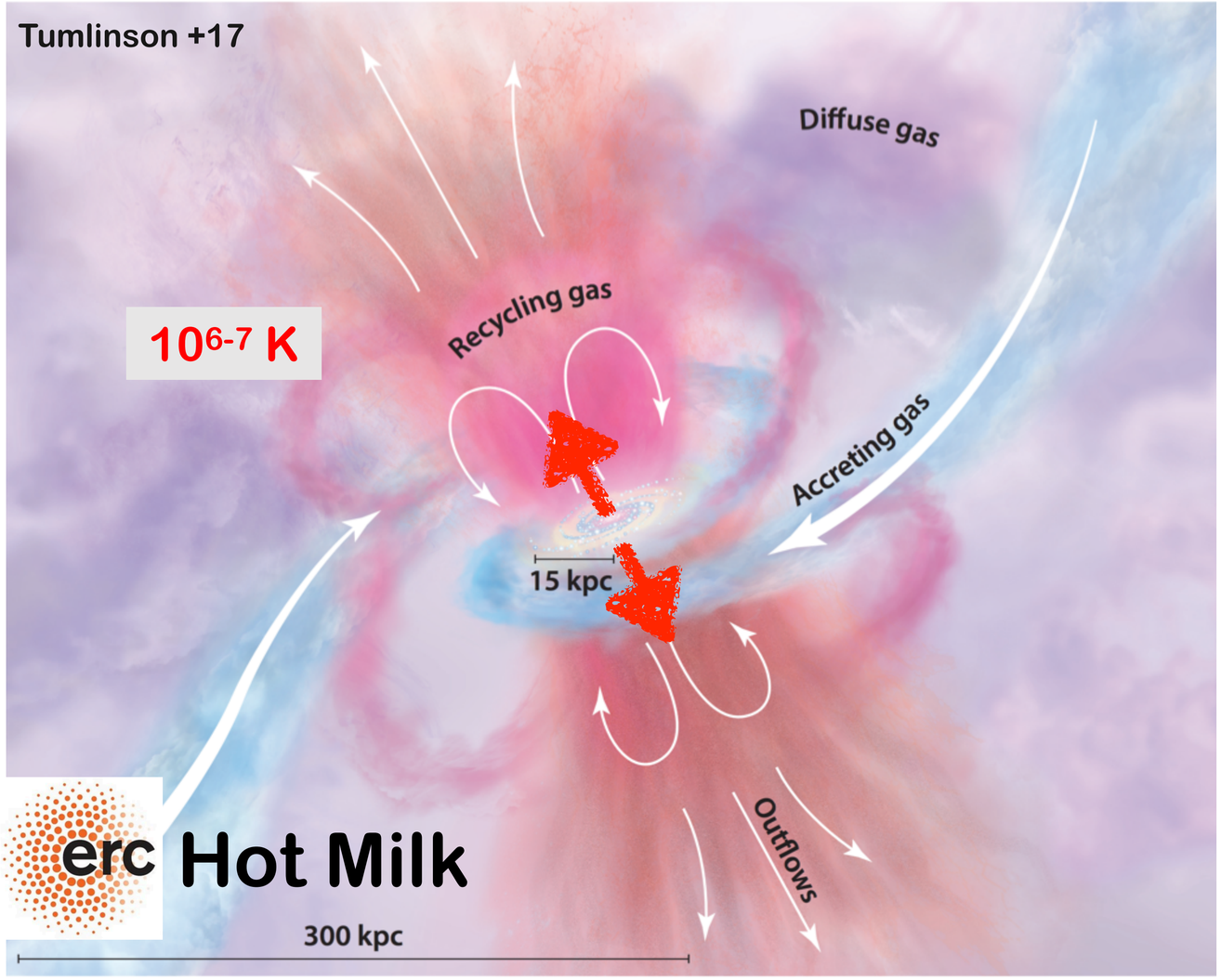

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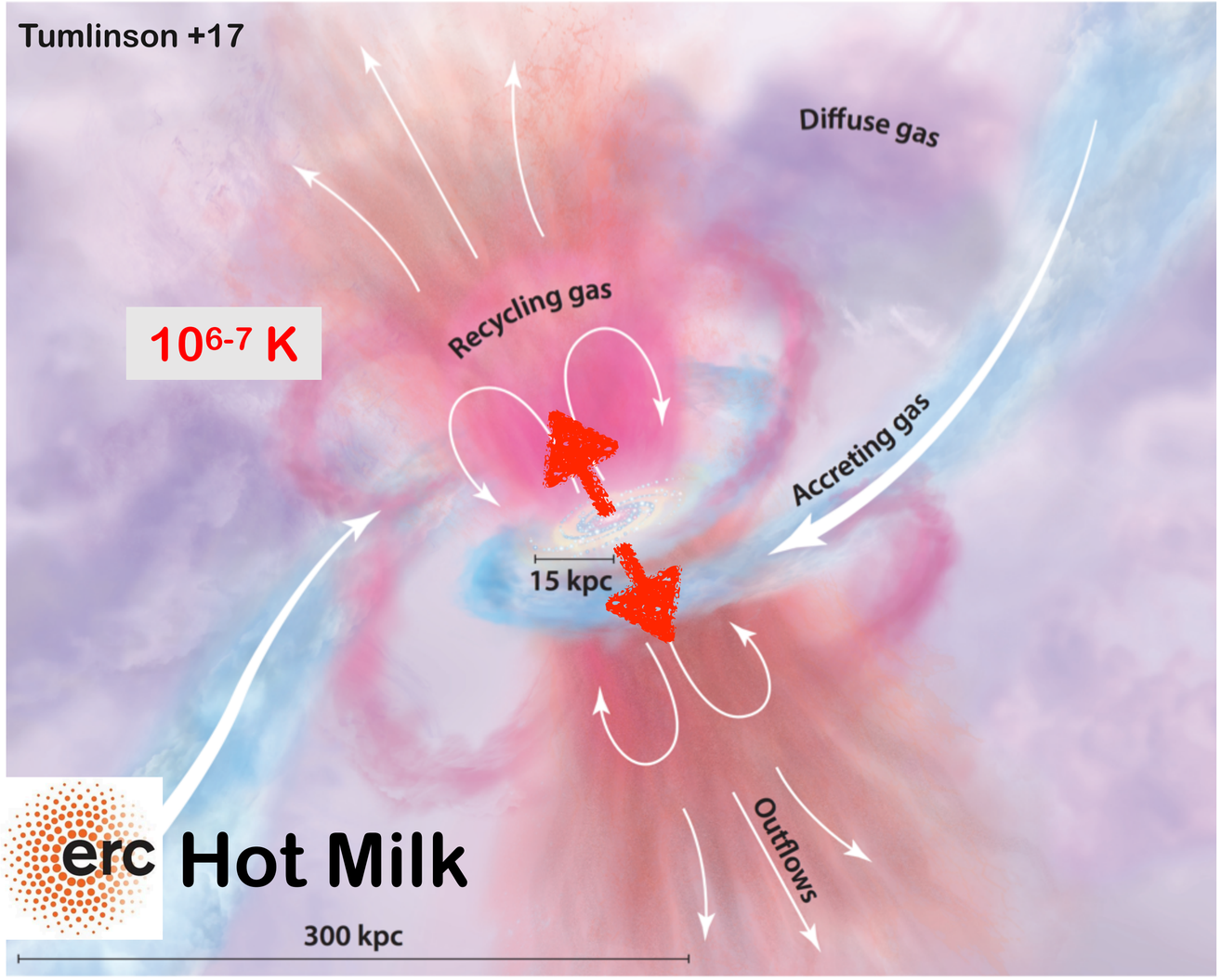

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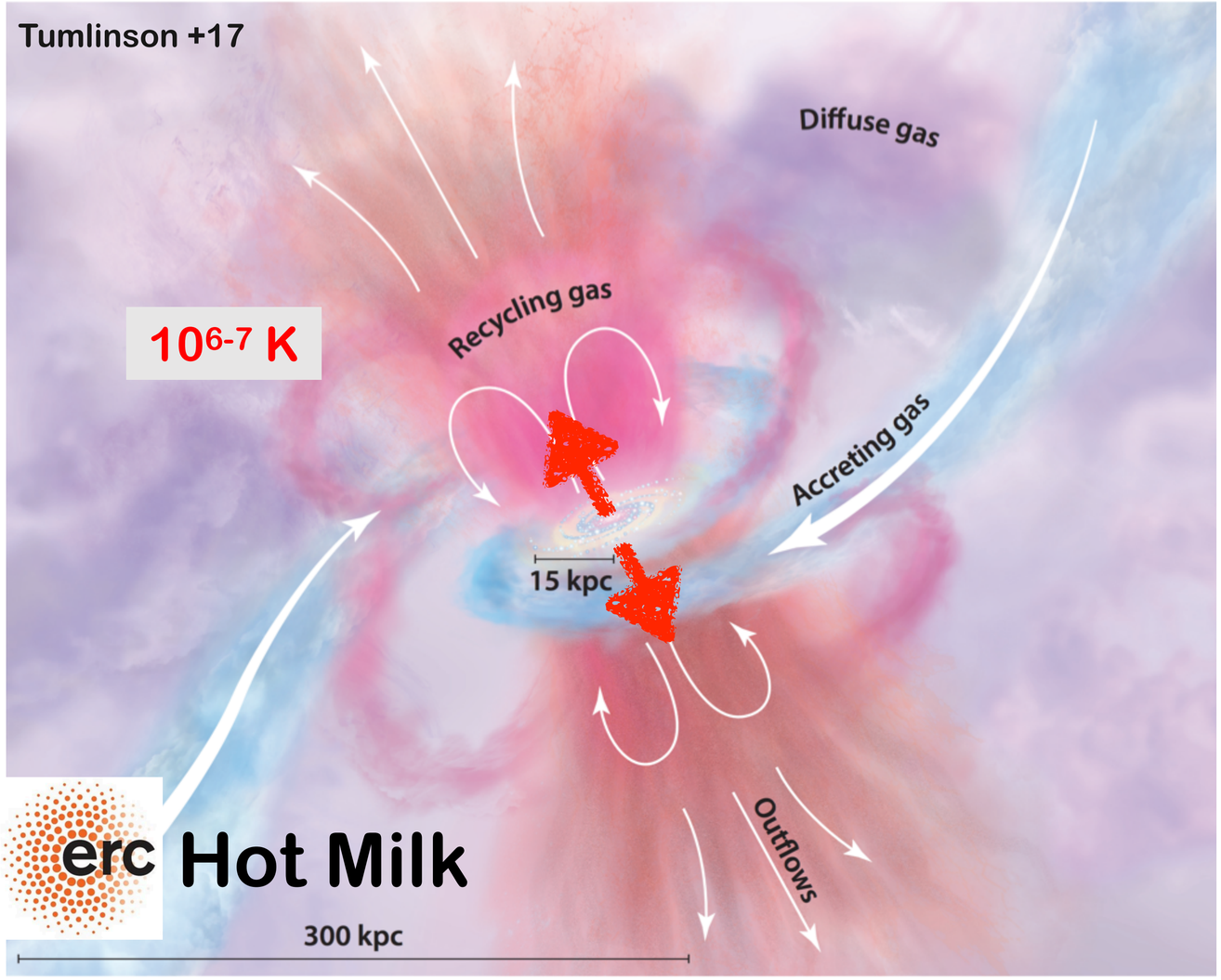

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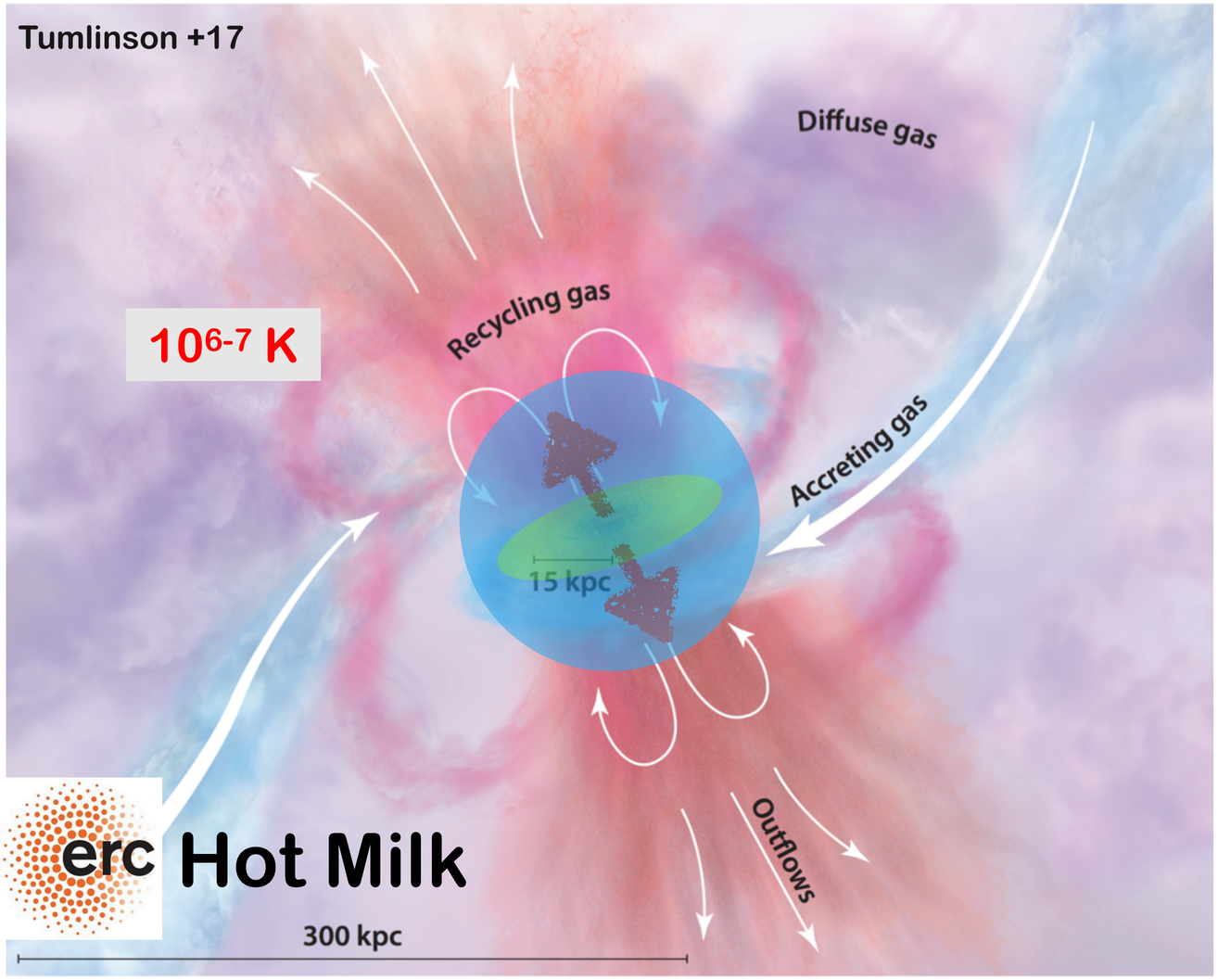

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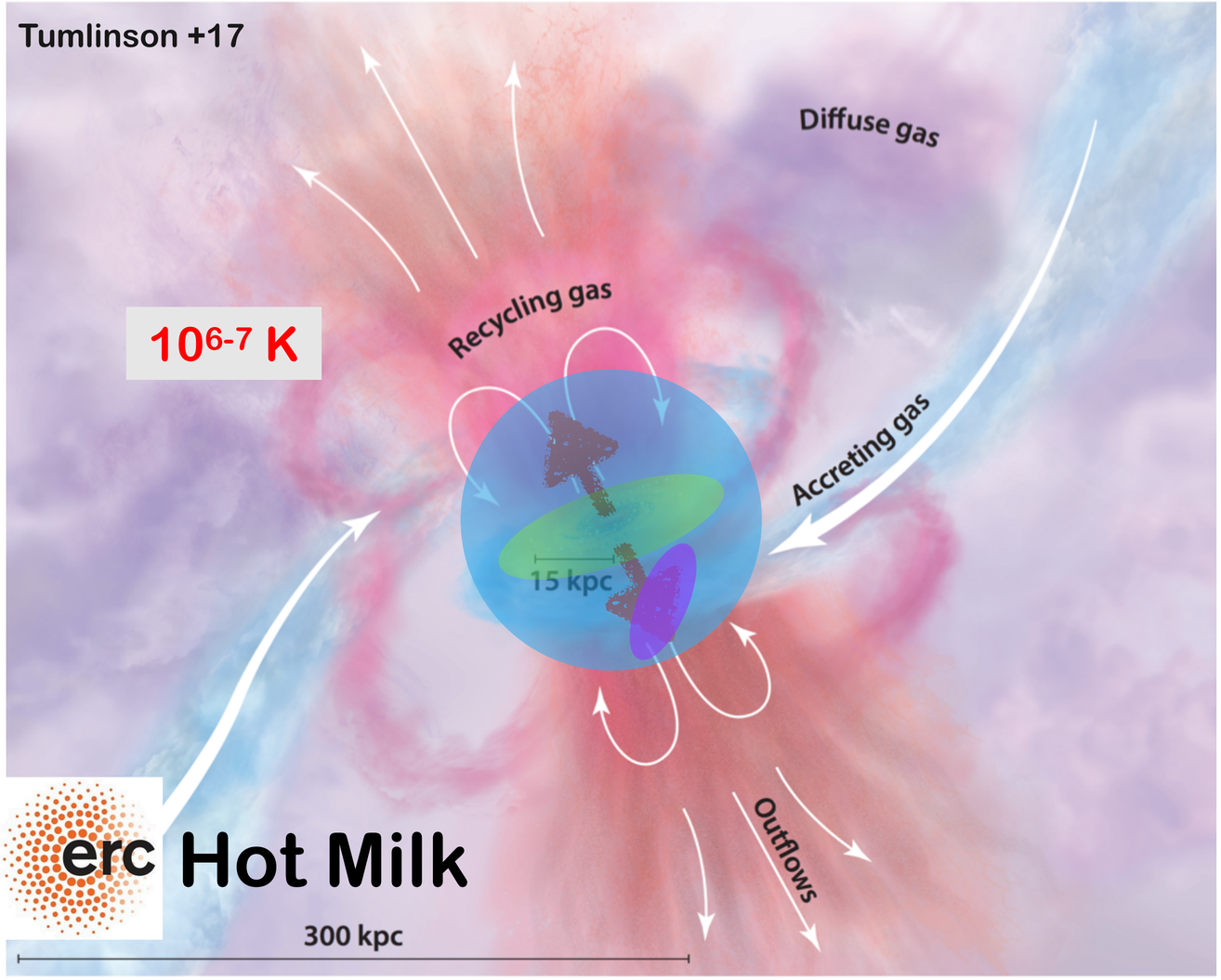

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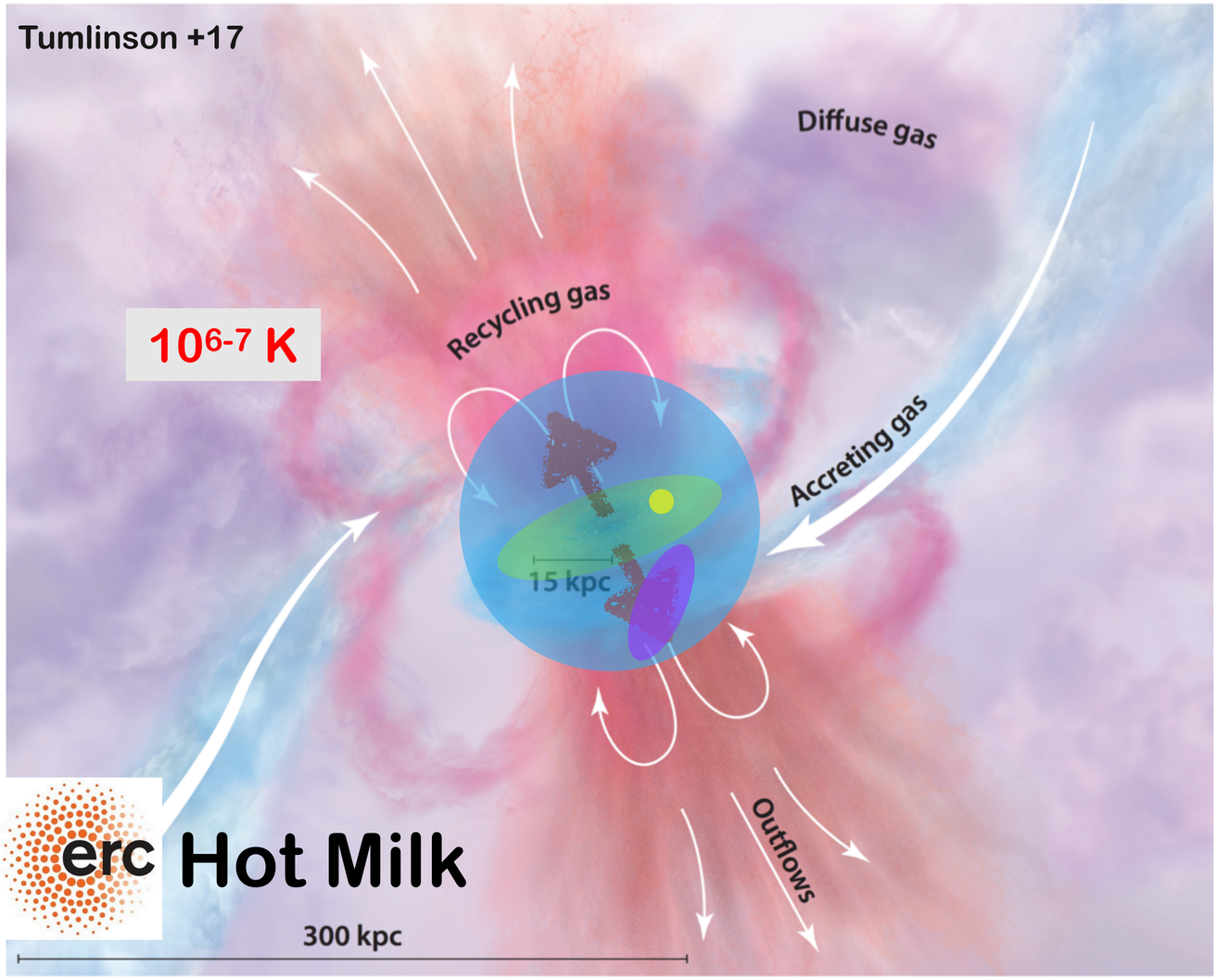

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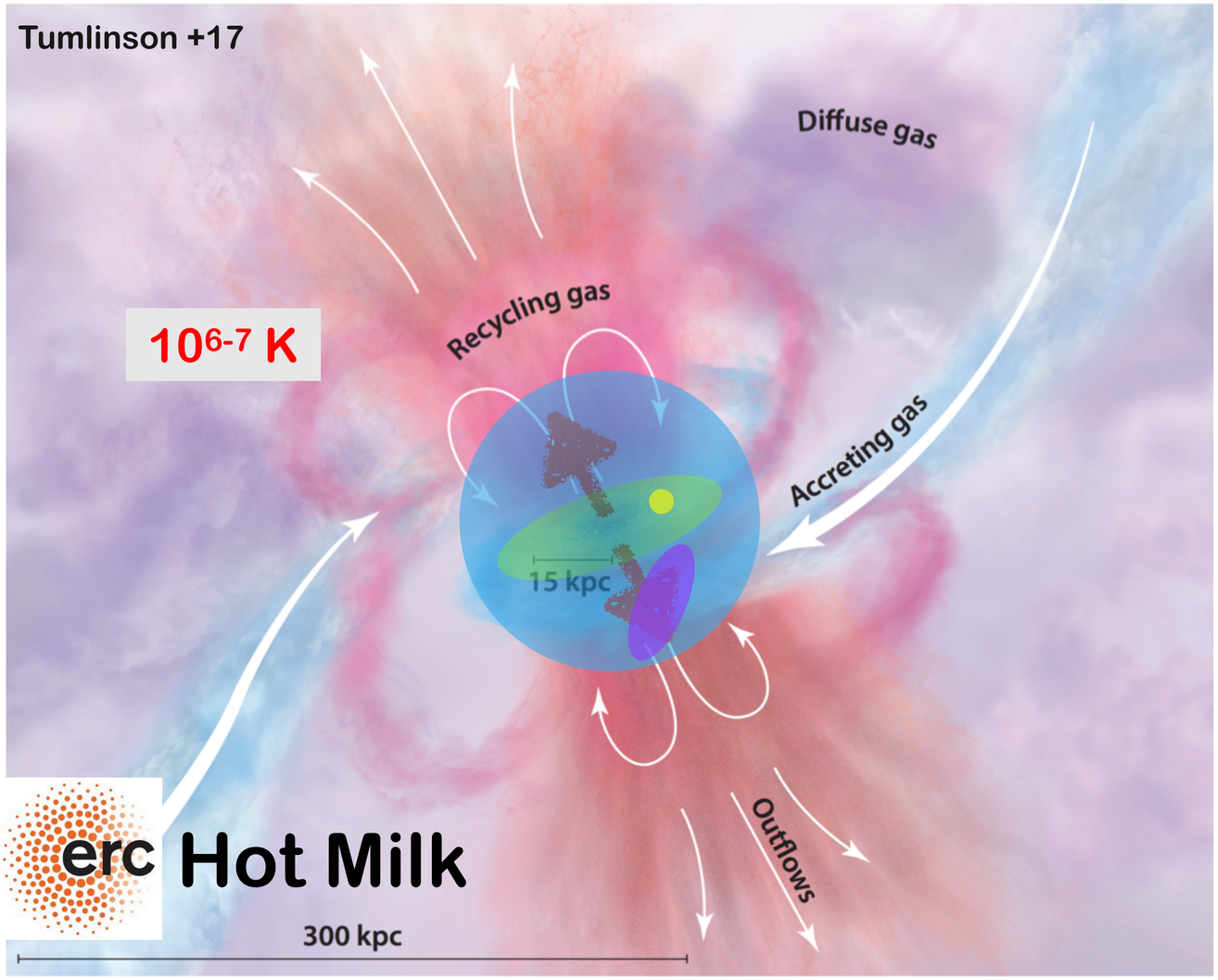

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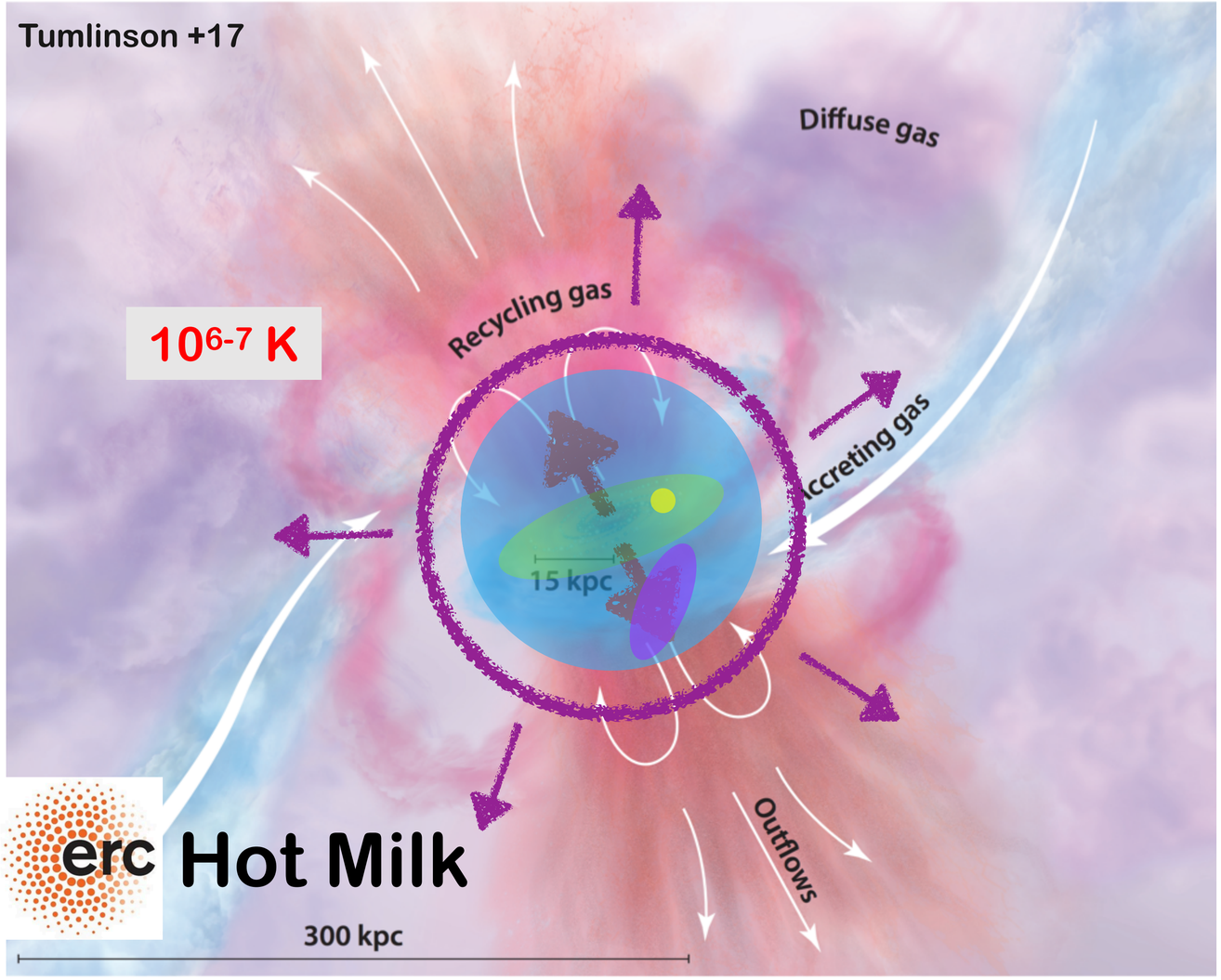

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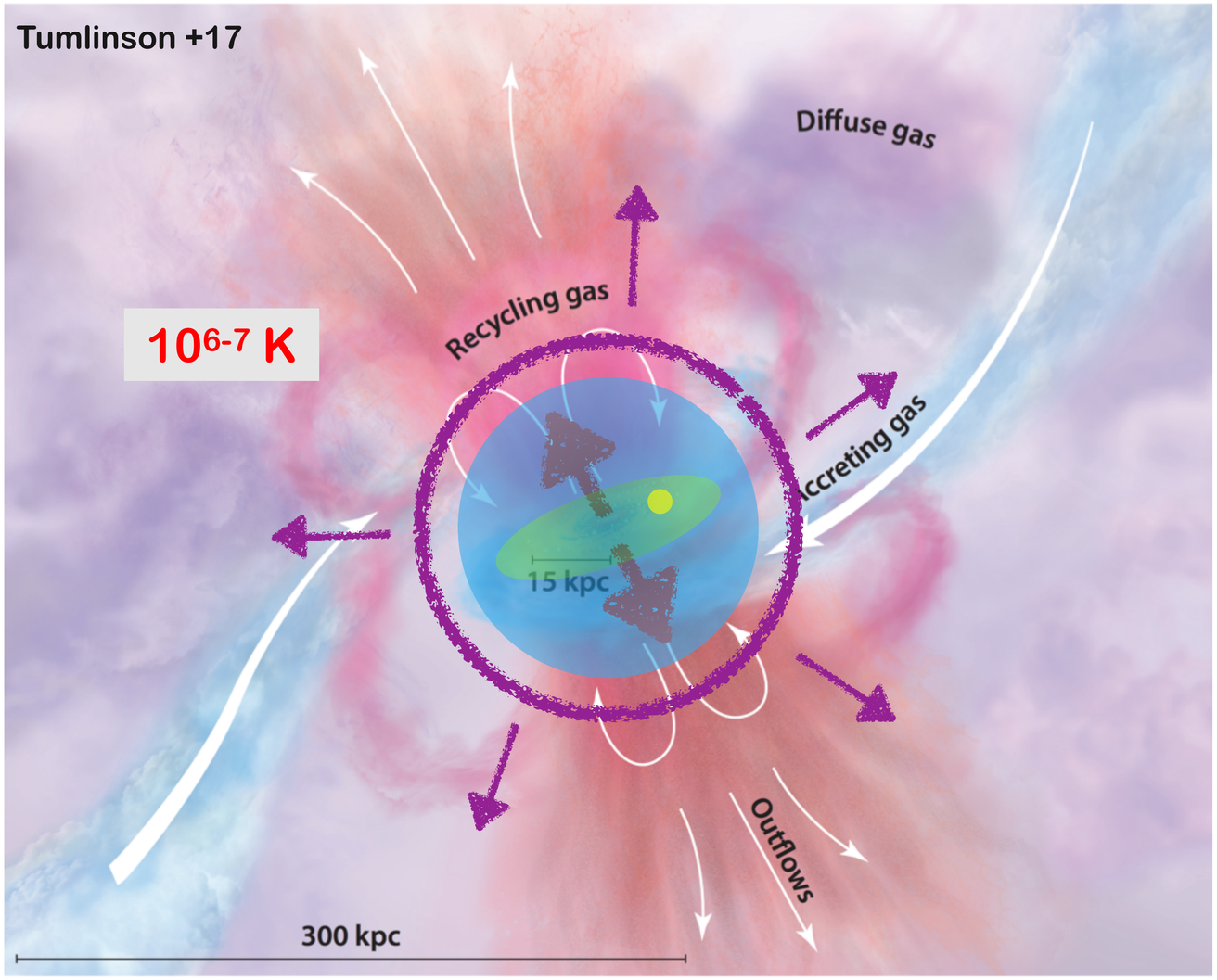
Great!

But do other galaxies have hot CGM?
Can we go beyond few tens kpc?

Our new view of the hot CGM

Yi Zhang



Yes, Milky Way-like galaxies do have hot CGM with β~0.4

Our new view of the hot CGM

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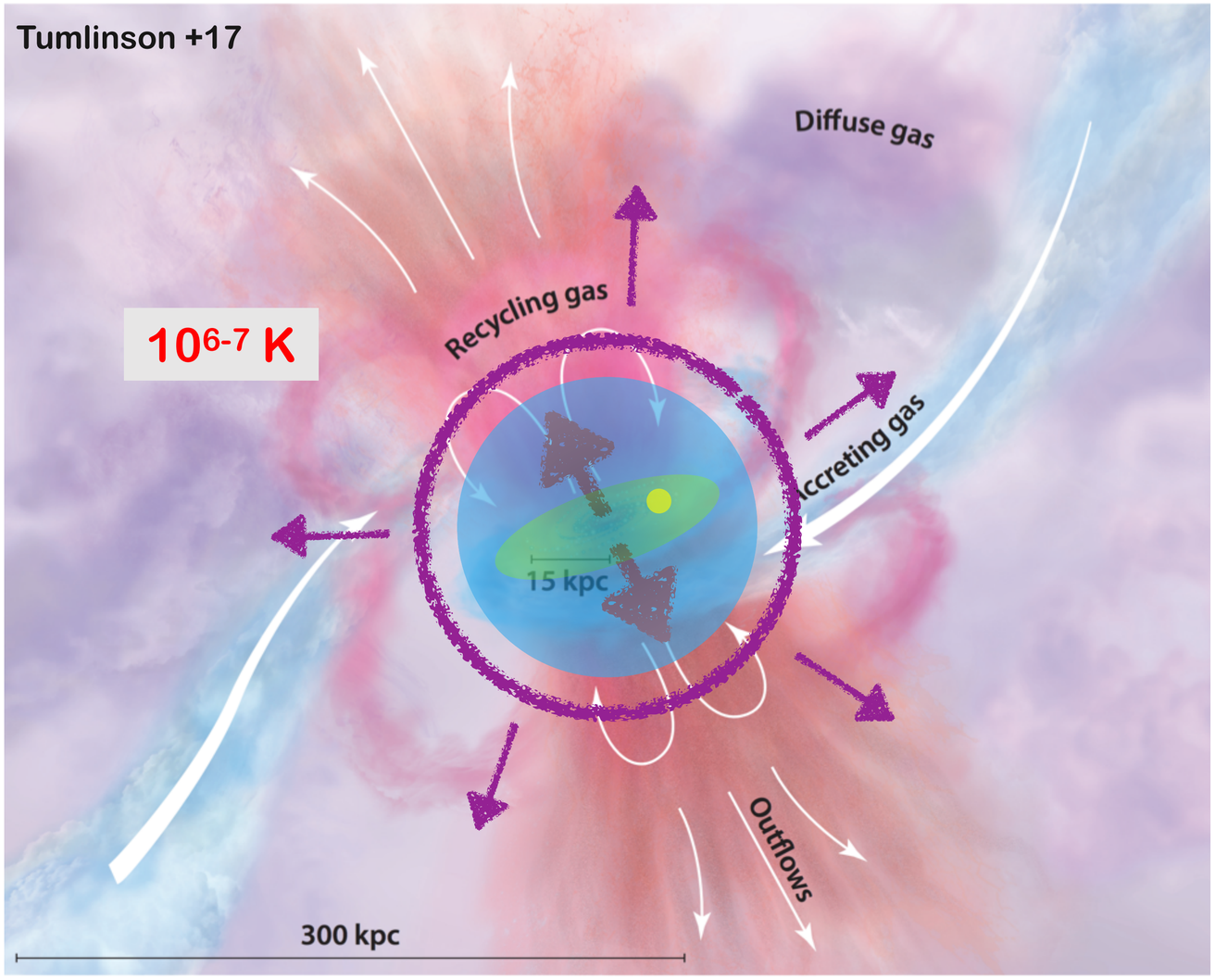

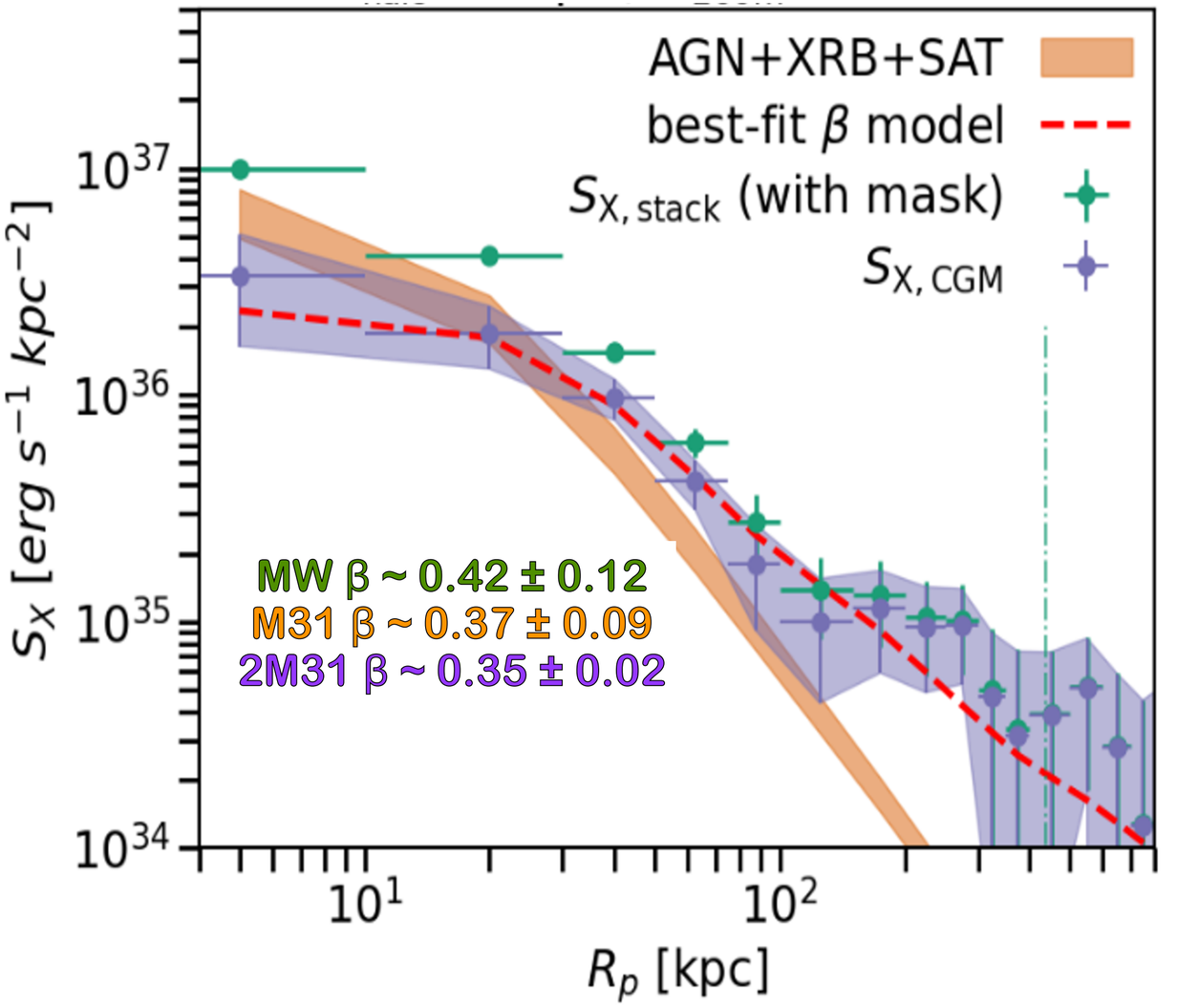

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How is the Galactic outflow plugged into the disc?

The non-thermal component of the outflow

Polarised synchrotron intensity: WMAP 22.8 GHz
X-rays: eROSITA 0.6-1 keV
Magnetic field direction

Zhang+24

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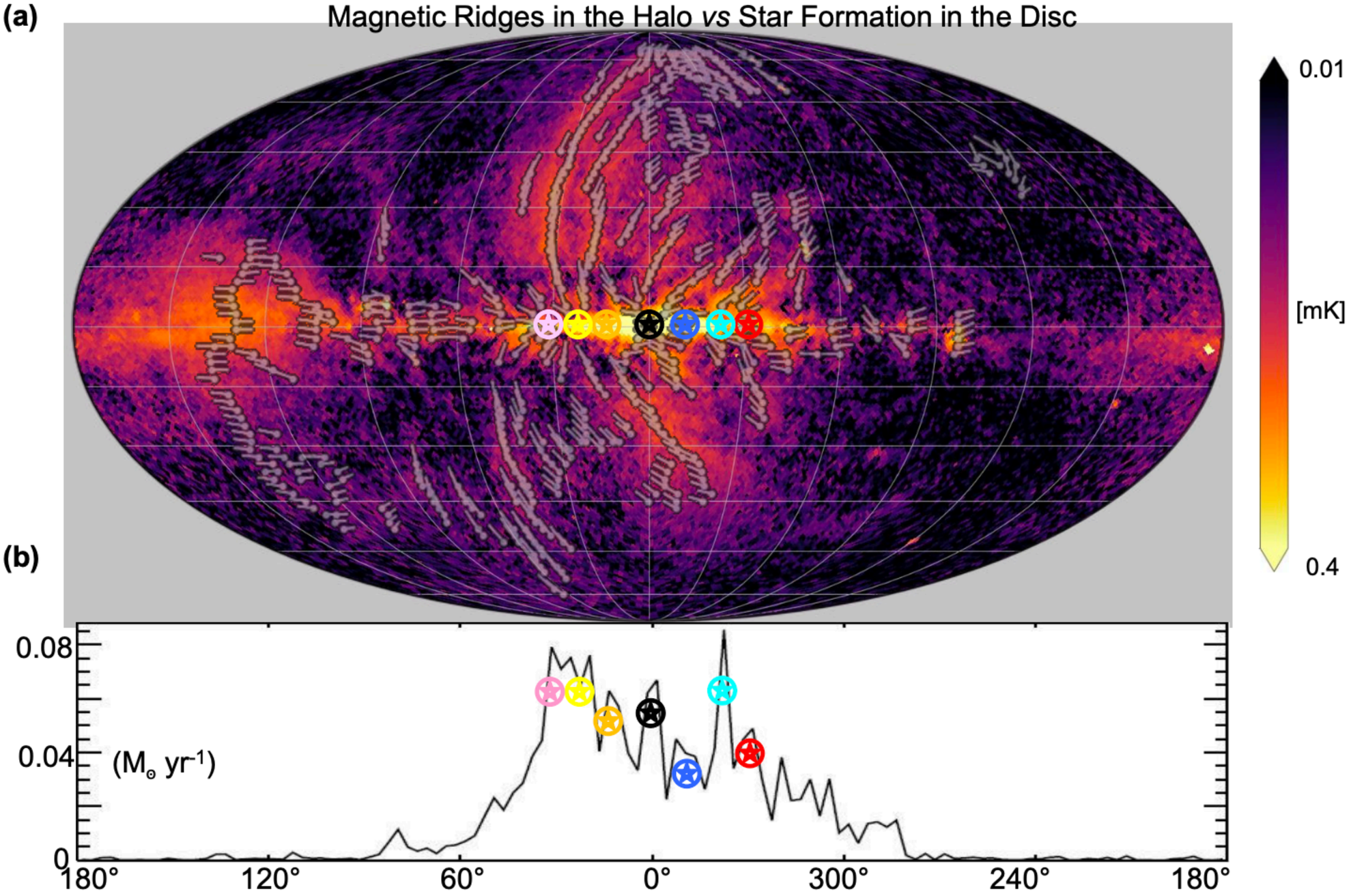
Galactic outflow ➜ shaping the magnetic halo

Outflow associated with star forming ring

Zhang+24



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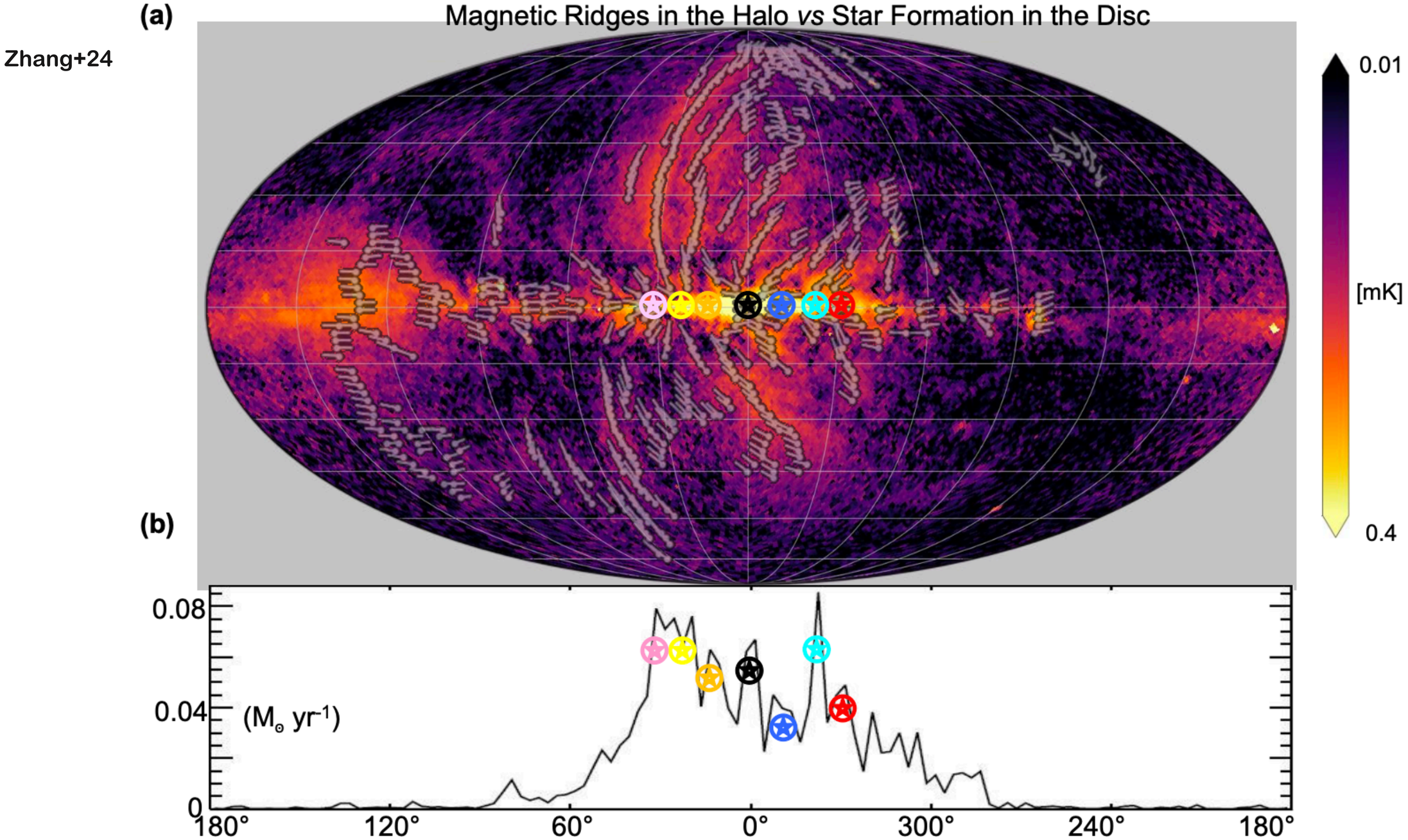
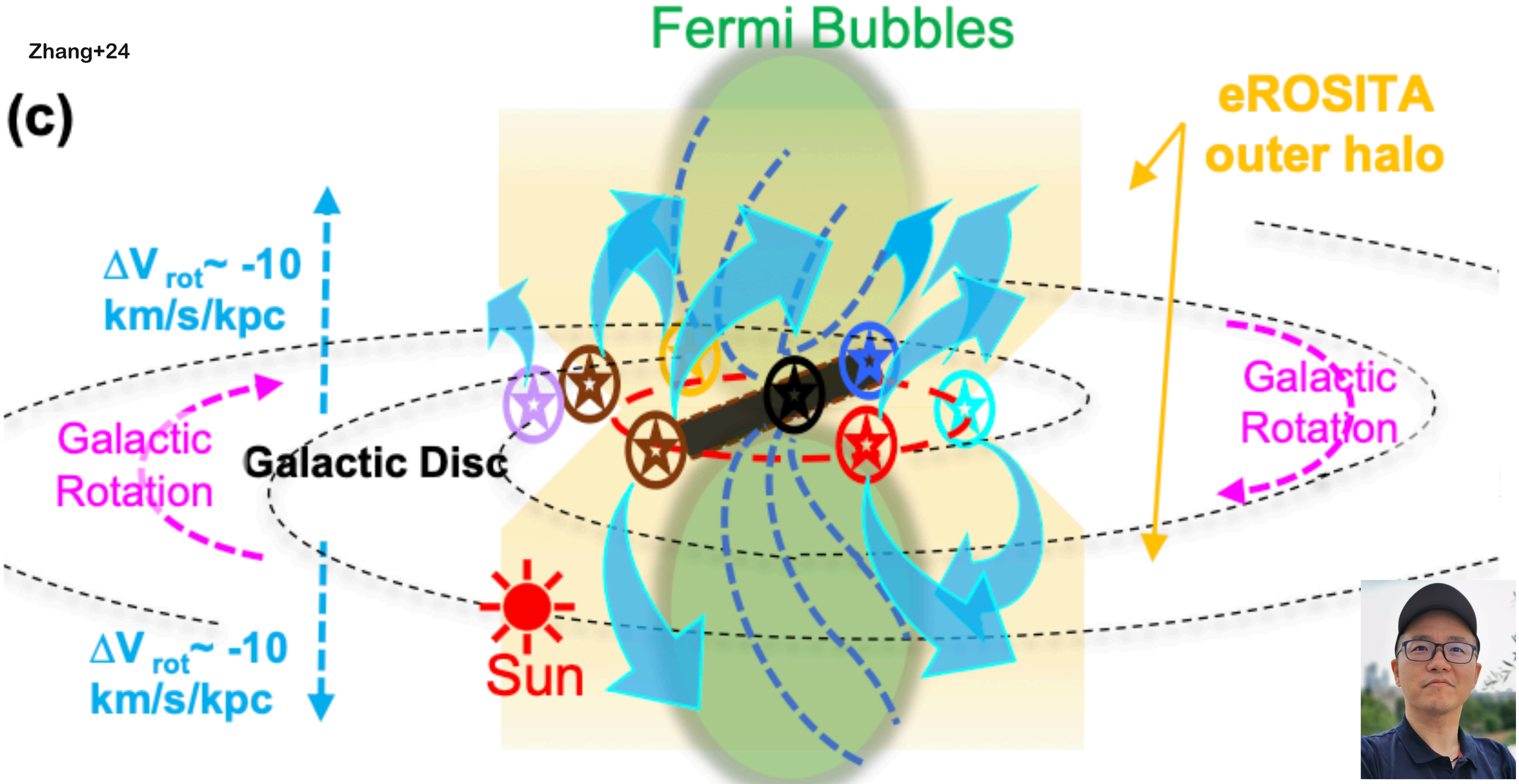


An updated picture of the Galactic outflow

Zhang+24



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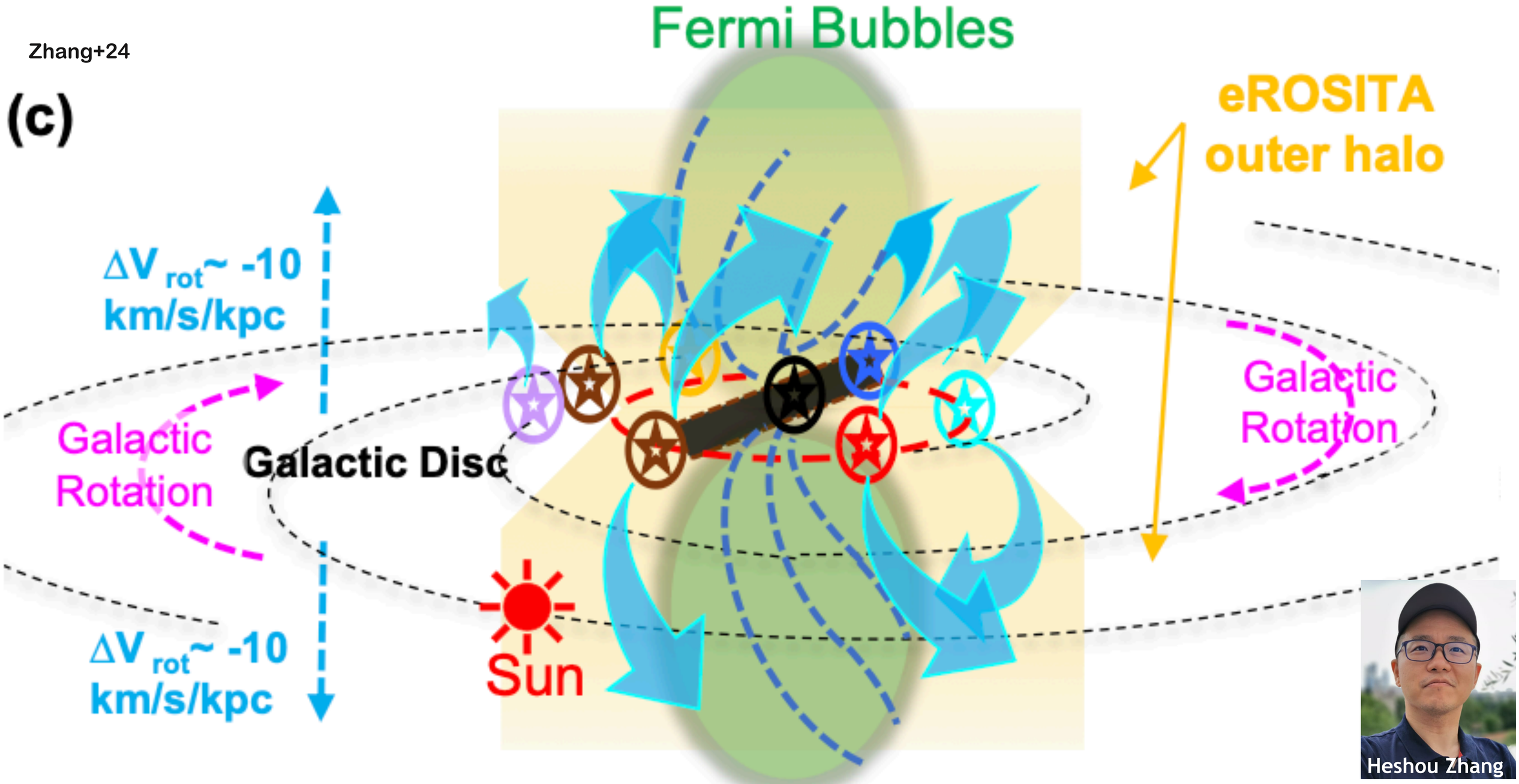

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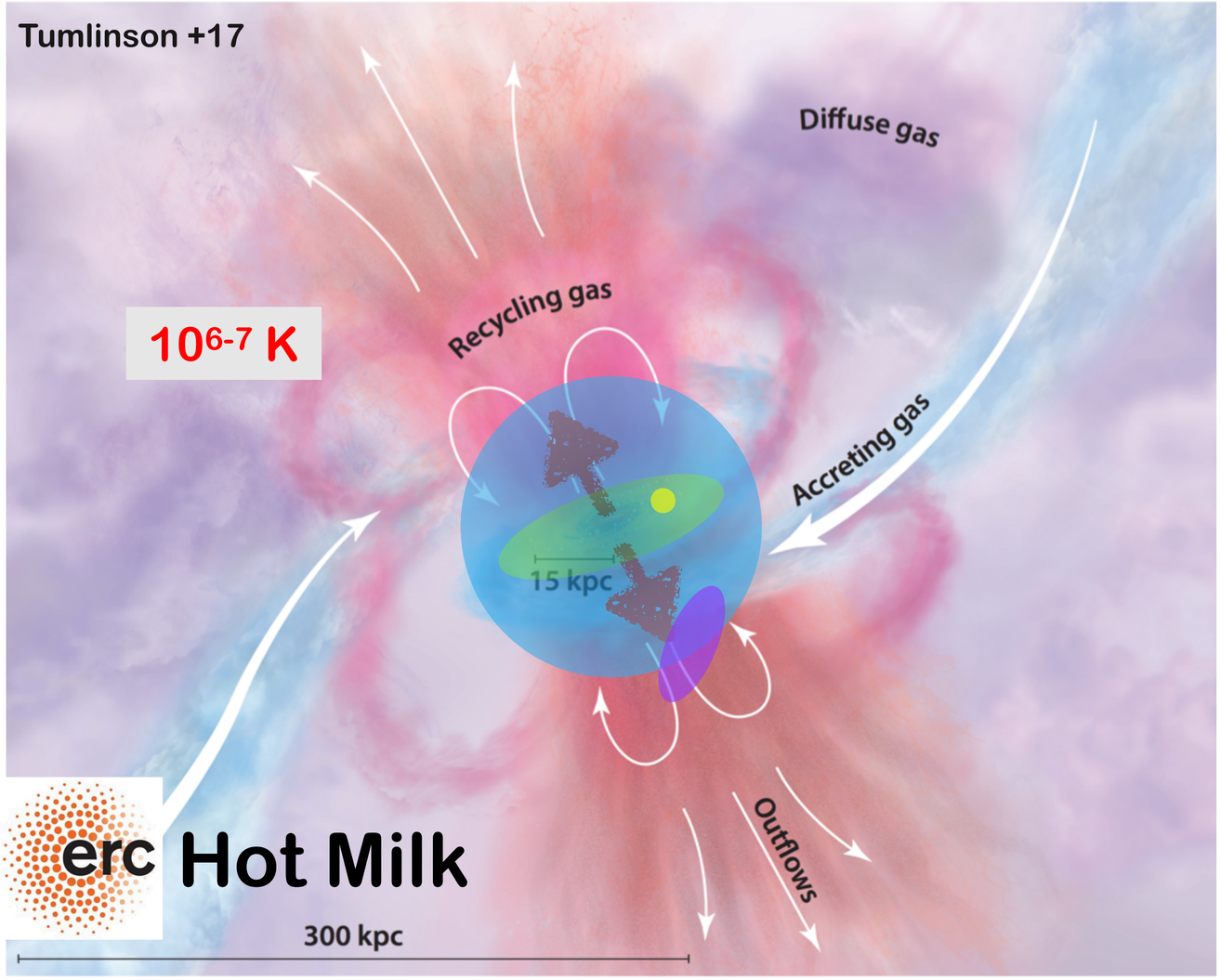

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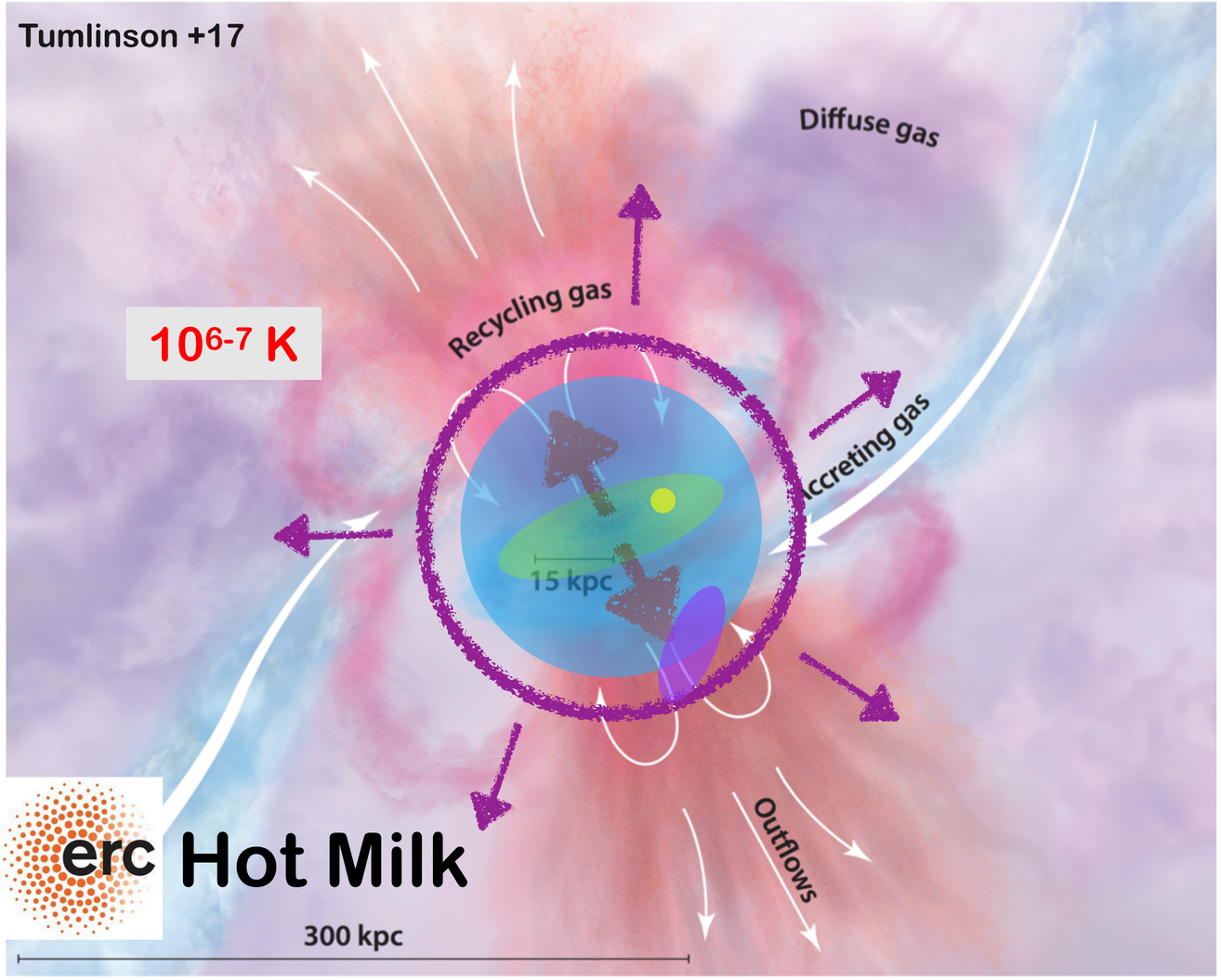

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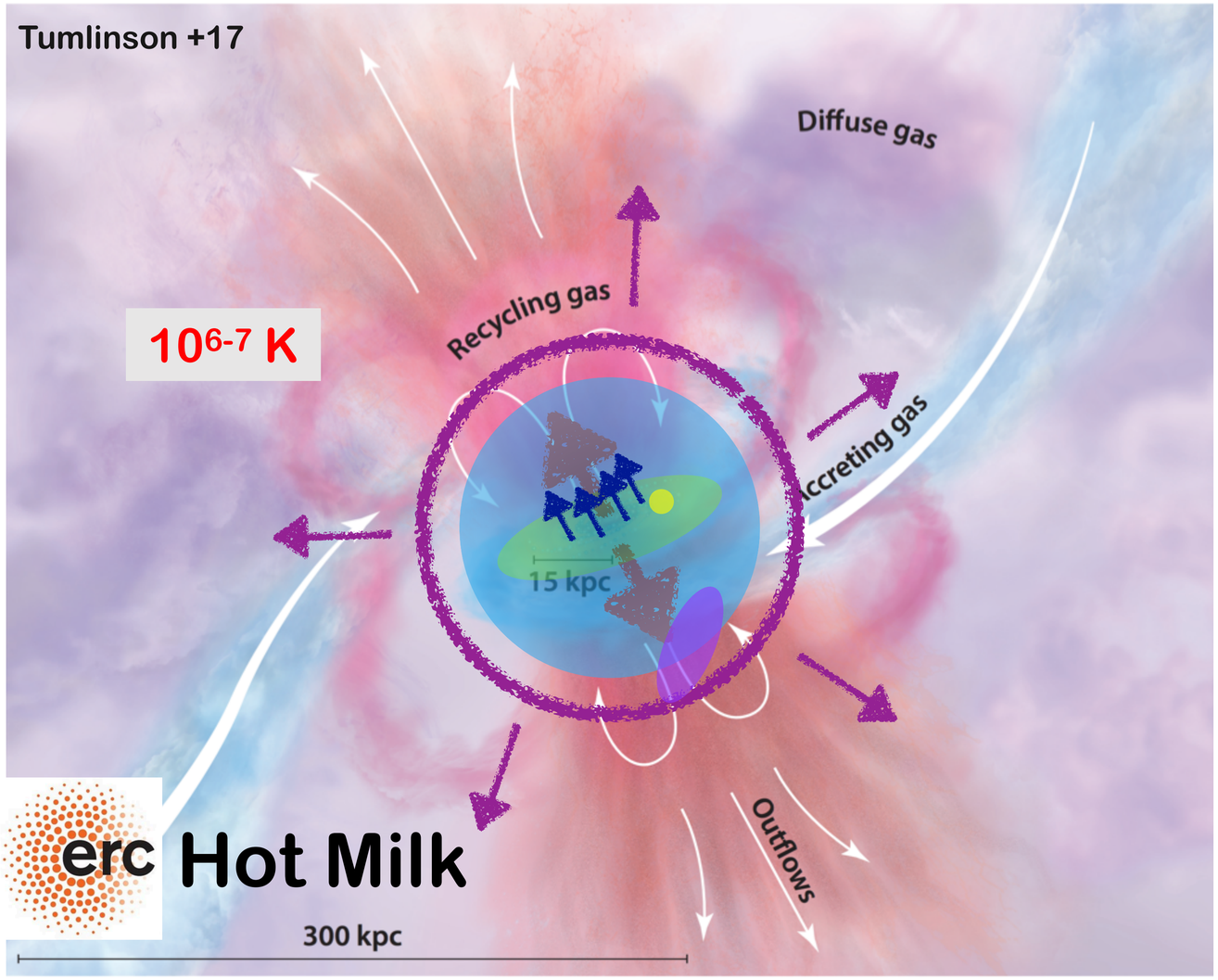

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The eROSITA bubbles have a non-thermal component

➜ The star forming ring at the end of the bar contributes to the Galactic outflow Zhang +24a