SRON
Netherlands Institute for Space Research

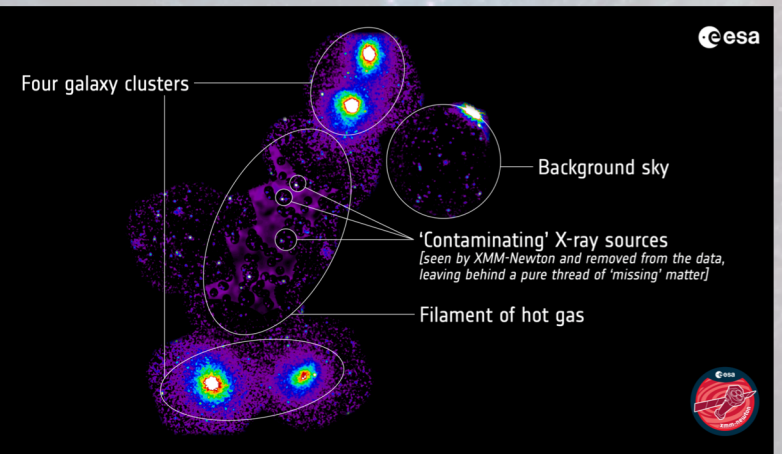
Universiteit Leiden
Leiden Observatory

eROSITA

A robust spectroscopic detection of the missing baryons in a cosmic filament

Konstantinos Migkas Oort Fellow – Leiden University

+ F. Pacaud, T. Tuominen, N. Aghanim



NewAthena webinar
03 July 2026

Migkas et al. (2025)
A&A, 698, A270

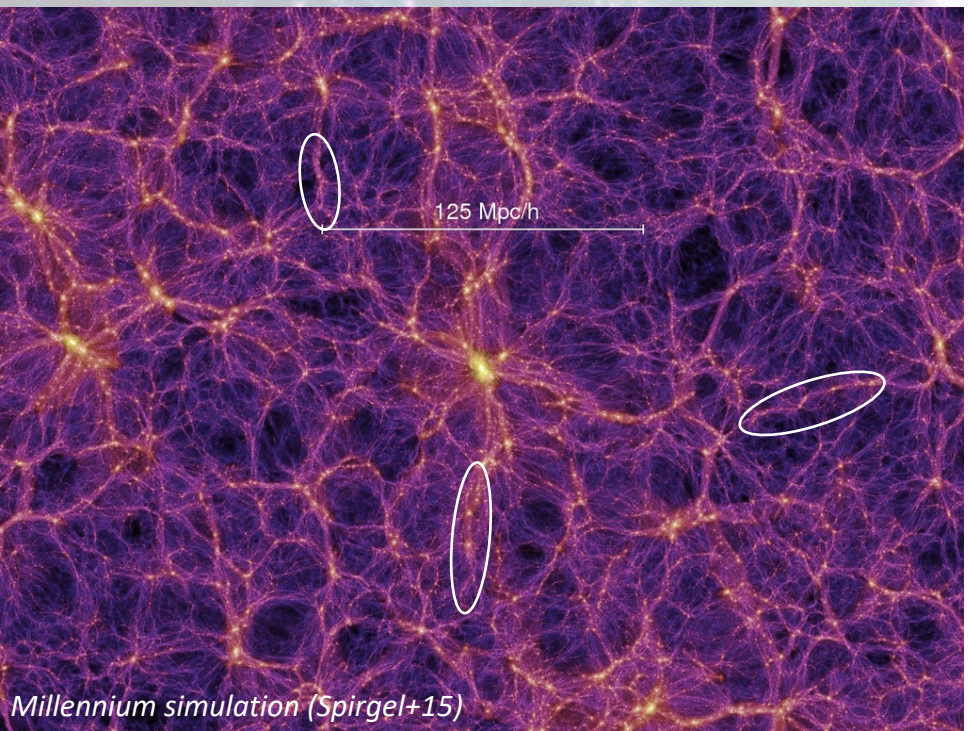
Missing baryon problem

30-40% of cosmic baryons at $z \sim 0$ have not been detected

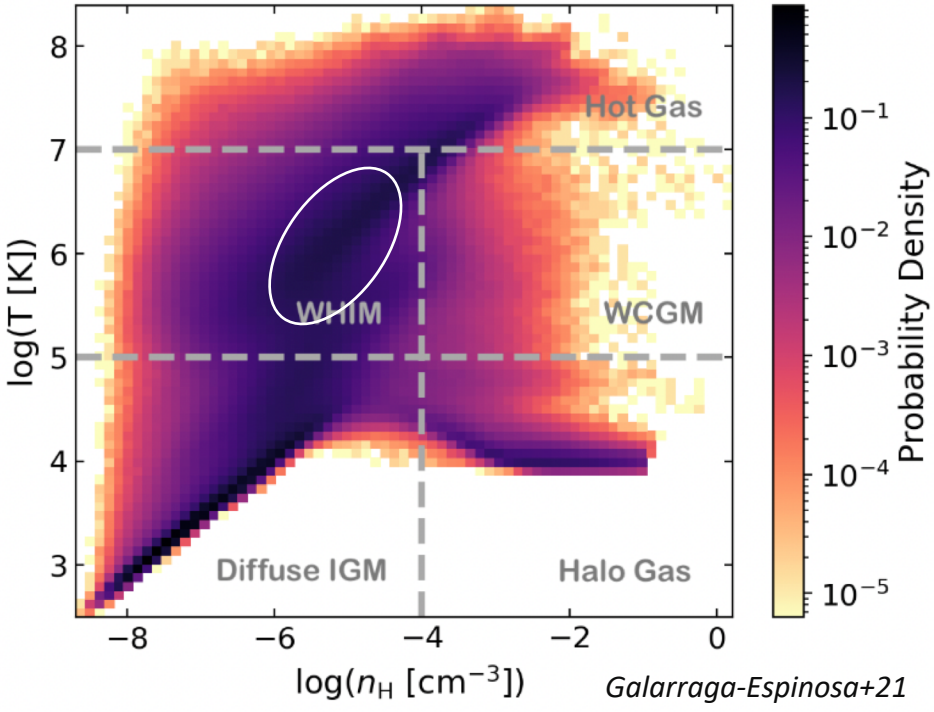
Simulations

They reside in filaments that connect clusters

Most in WHIM phase: $k_B T \sim 0.01 - 1$ keV, $n_H \leq 8\times10^{-5}/cm^3$



Millennium simulation (Spirgel+15)

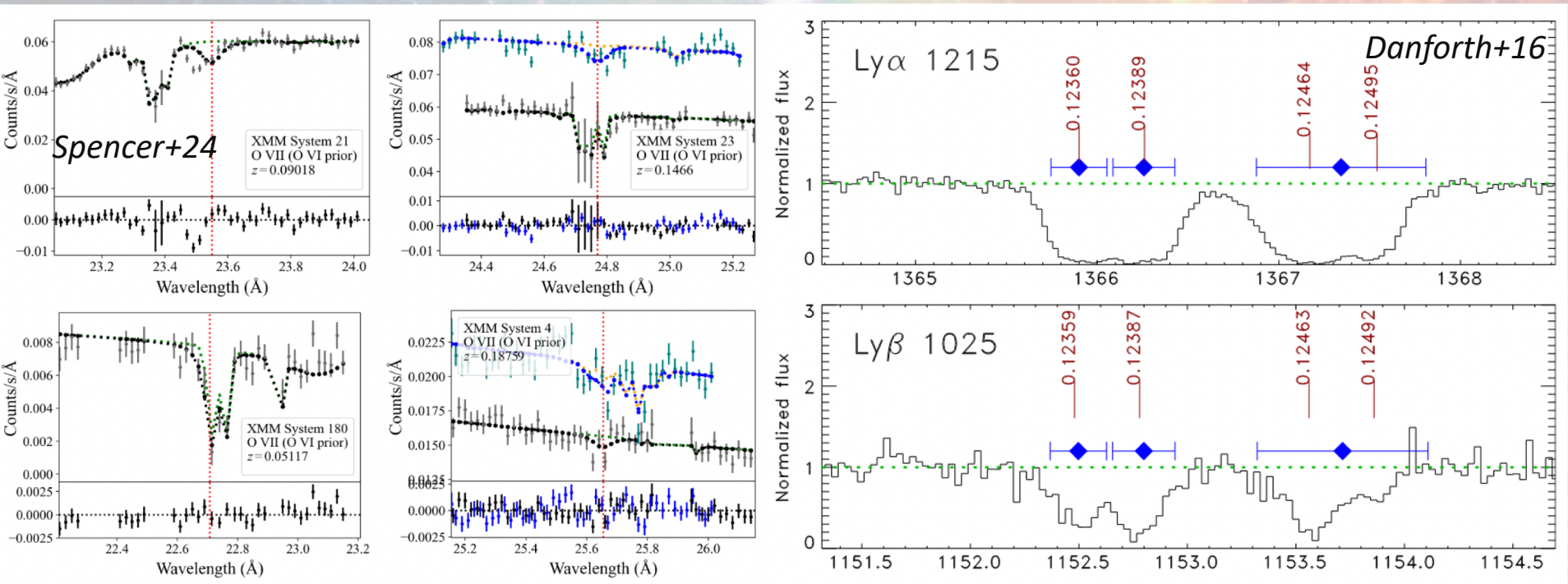


Galarraga-Espinosa+21

Detecting the missing baryons (WHIM)

UV and X-ray absorption lines from distant quasars (eg Danforth+16, Spencer+24)

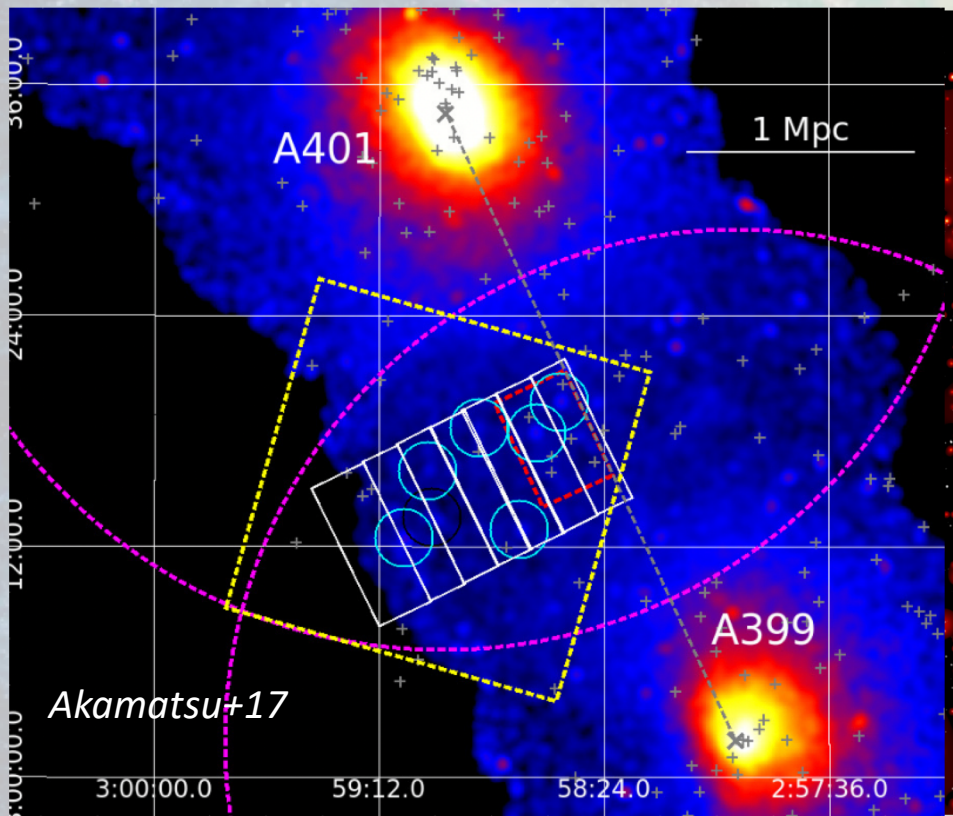
- Absorption from low-T gas in filaments
- Very difficult detection (only few systems show significant detection)
- Cannot robustly characterize n_e and T → not sure if it's "WHIM"

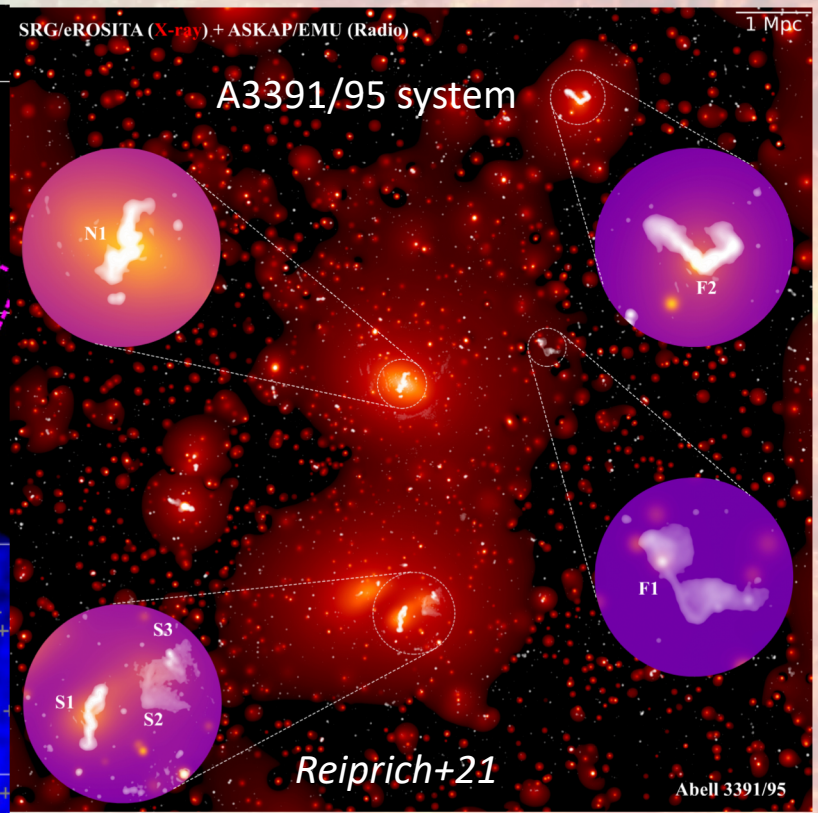


Detecting the missing baryons (WHIM)

X-ray emission (eg Werner+08, Eckert+15, Akamatsu+17, Reiprich+21, Zhang+24):

- Surface brightness increases between clusters (or @ cluster outskirts) compared to BG
- T_X remains unknown, n_e only loosely connstrained under assumptions



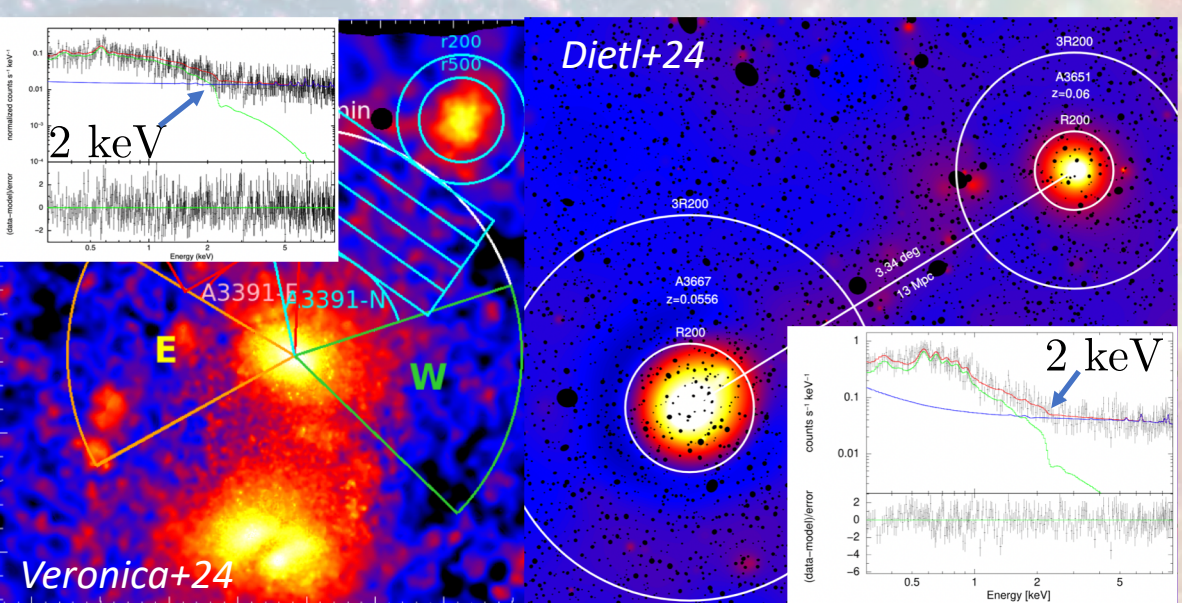


Detecting the missing baryons (WHIM)

- **X-ray spectroscopy analysis** of filament emission is **necessary** to accurately characterize WHIM
- **Only 2 WHIM detections from X-ray continuum** from individual filaments before this work, from eROSITA (Dietl+24, Veronica+24, eRASS:4 & eROSITA-PV respectively)

For different filament environments, both find

$$T \sim 1 \text{ keV}$$
$$n_e \sim 5 \times 10^{-5}/\text{cm}^3$$
$$\delta_{\text{bar}} \sim (120 - 240)$$



Detecting the missing baryons (WHIM)

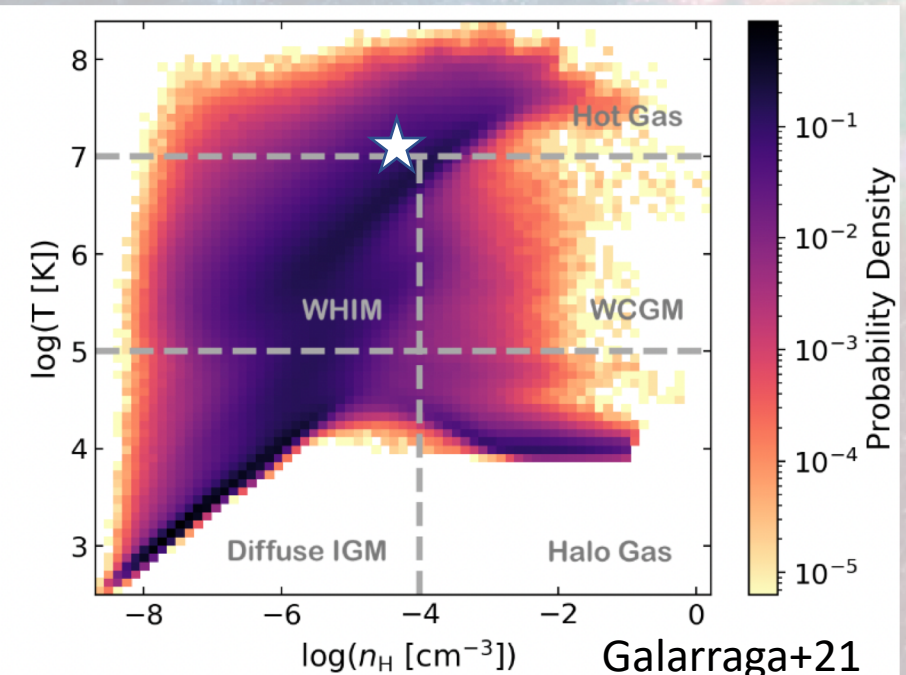
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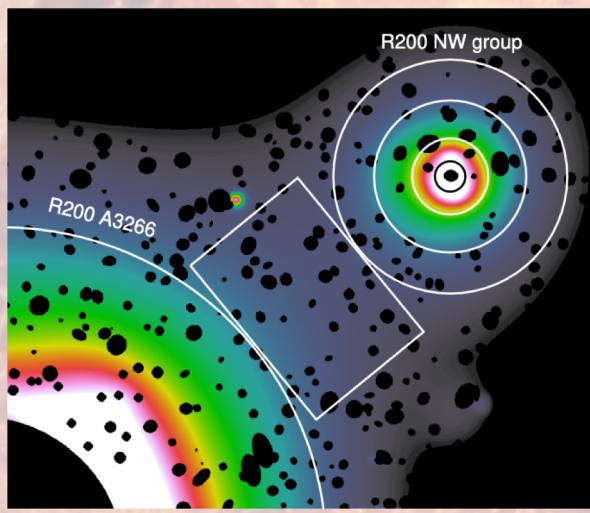
Marginally consistent with simulations for the densest filaments

Unexpectedly high..?



- Selection effects (survivorship bias)?
- Residual AGN+halo contamination?
- ΛCDM tension?

Detecting the missing baryons (WHIM)

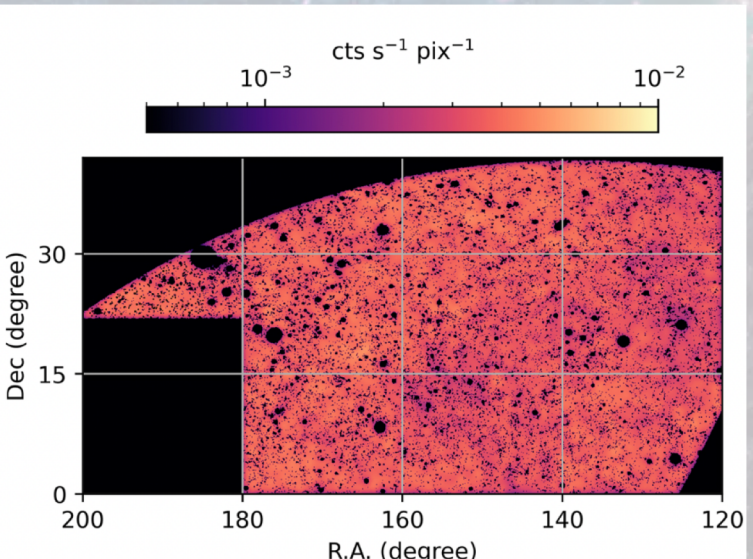


- **Dietl+26:** eRASS:5 for z=0.06 filament

$$T \sim 1.2 \text{ keV}, \ \delta_{\rm bar} \sim 320$$

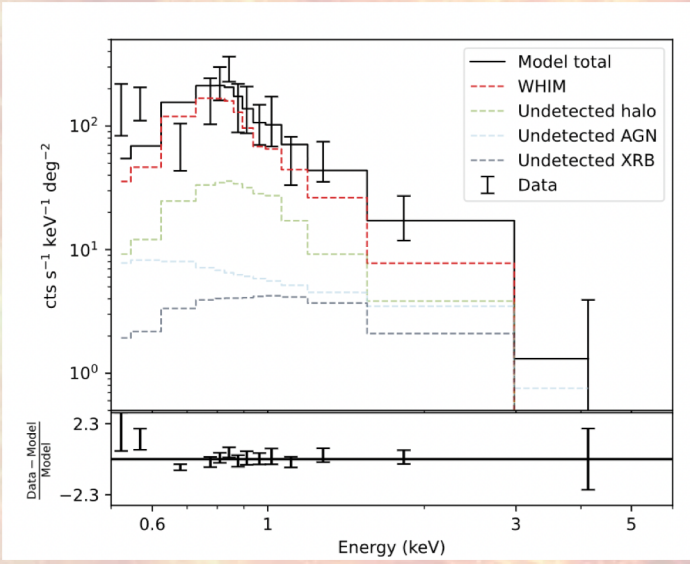
- **Zhang+24**: eRASS:4 **stacking of ~8,000 optically detected filaments**

  Note: 40% of the signal comes from contamination (unresolved halos, AGN etc).



$$T \sim 0.6 \text{ keV}$$

$$\delta_{\rm bar} \sim 80$$

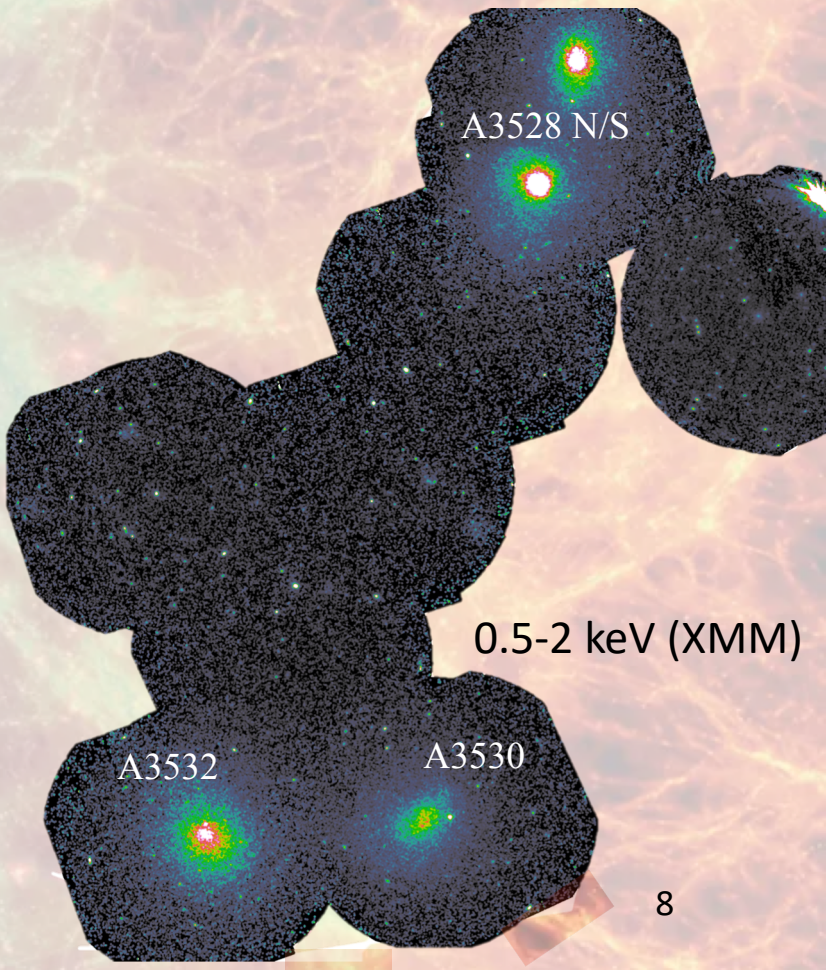


Goal of this work

- Carefully search for **X-ray thermal emission** in a Shapley supercluster **filament** (A3528 N/S, A3530, A3532) using deeper X-ray data

- **Determine WHIM** phase (T_X and n_H) with **improved accuracy**

- Compare with **cosmological simulations**

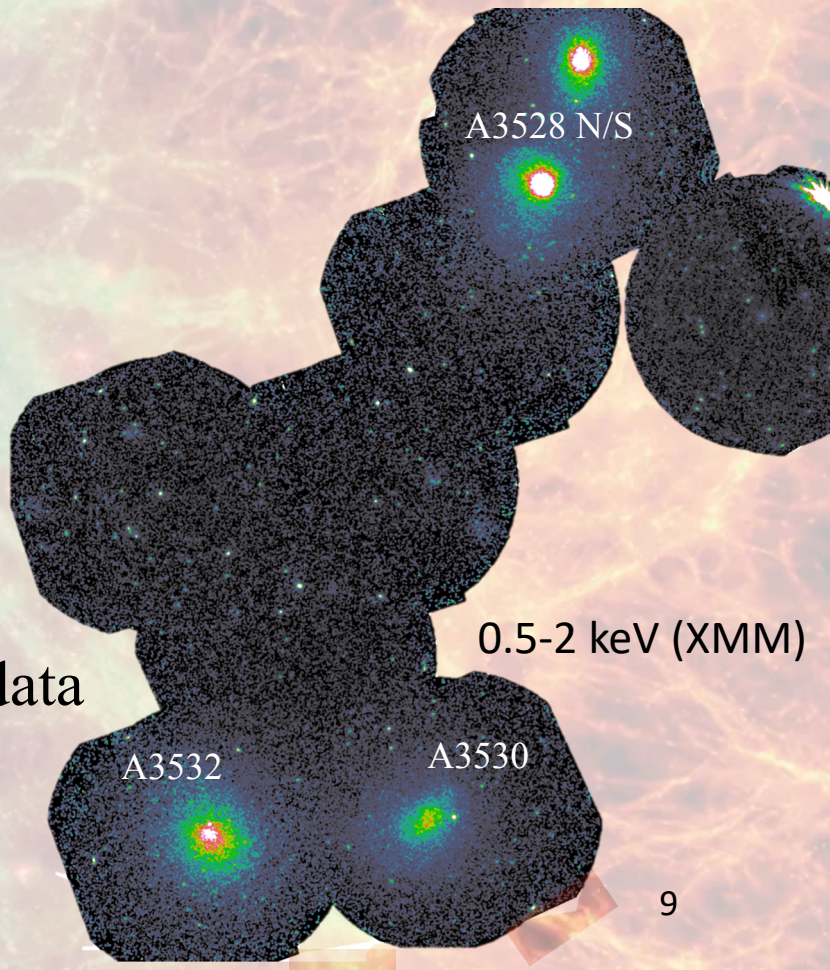


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- Carefully search for **X-ray thermal emission** in a Shapley supercluster **filament** (A3528 N/S, A3530, A3532) using deeper X-ray data

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How..?

- Combine **Suzaku** + **XMM** + **ROSAT** data

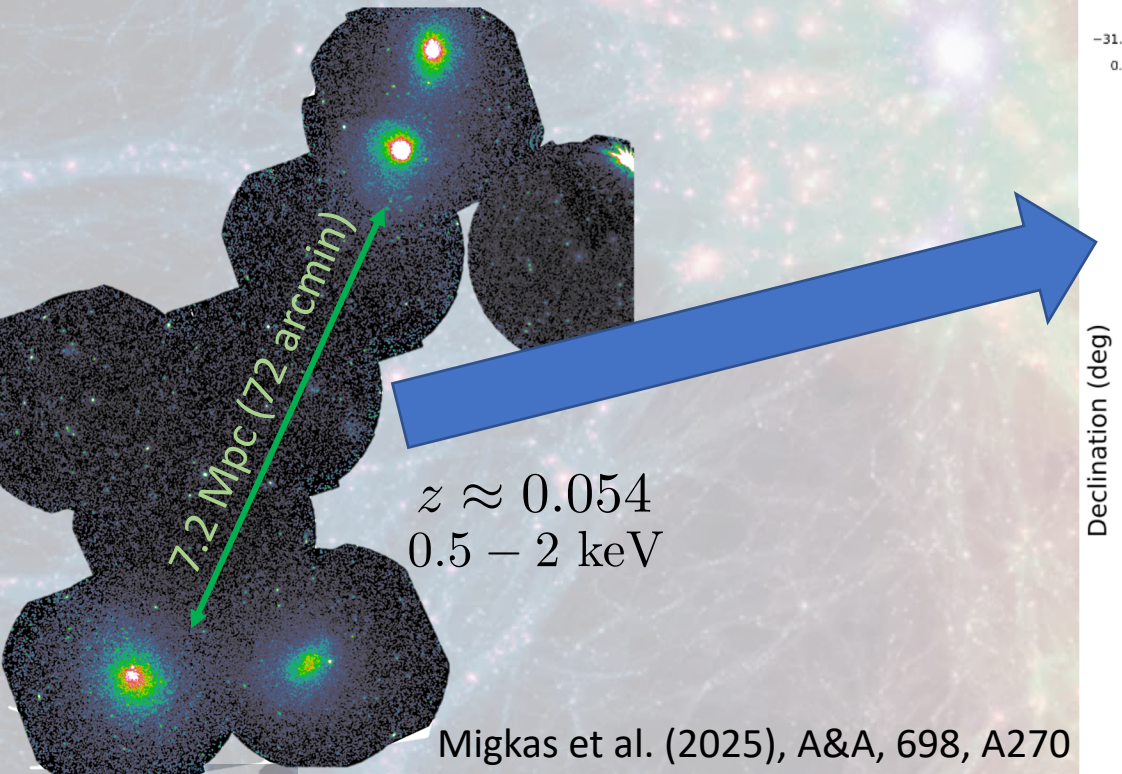
WHIM

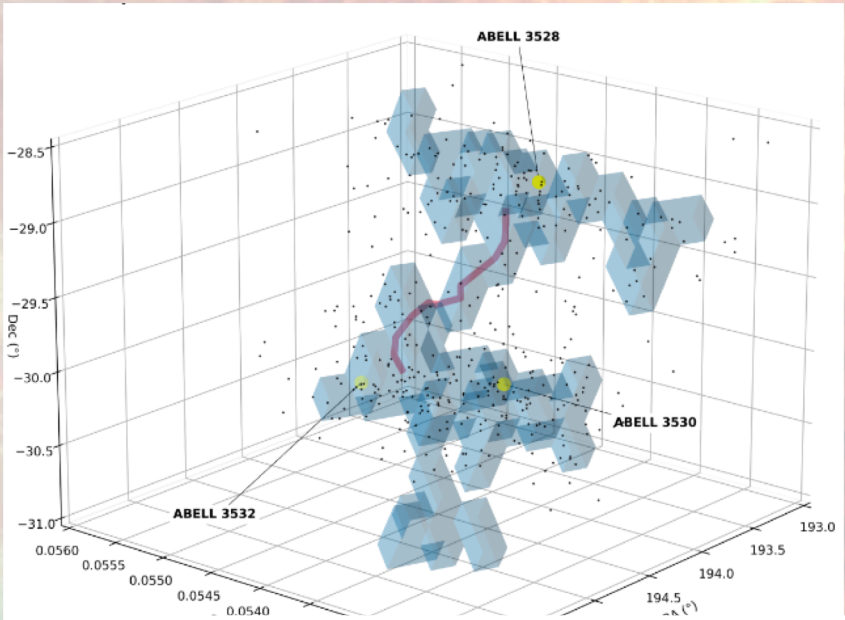
AGN+BG

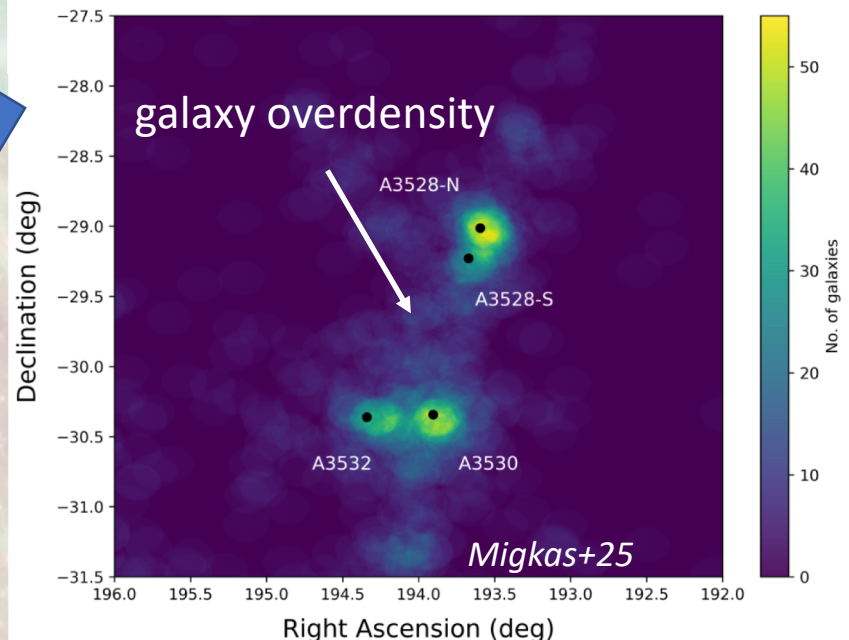
BG

Optical detection of the filament

- **Detected in optical** (spec-z) in Aghanim+24 in the Shapley Supercluster velocity Database, **correcting for peculiar velocities**
- Inclination with sky plane = 53°
- **3D length: 7.2 Mpc**

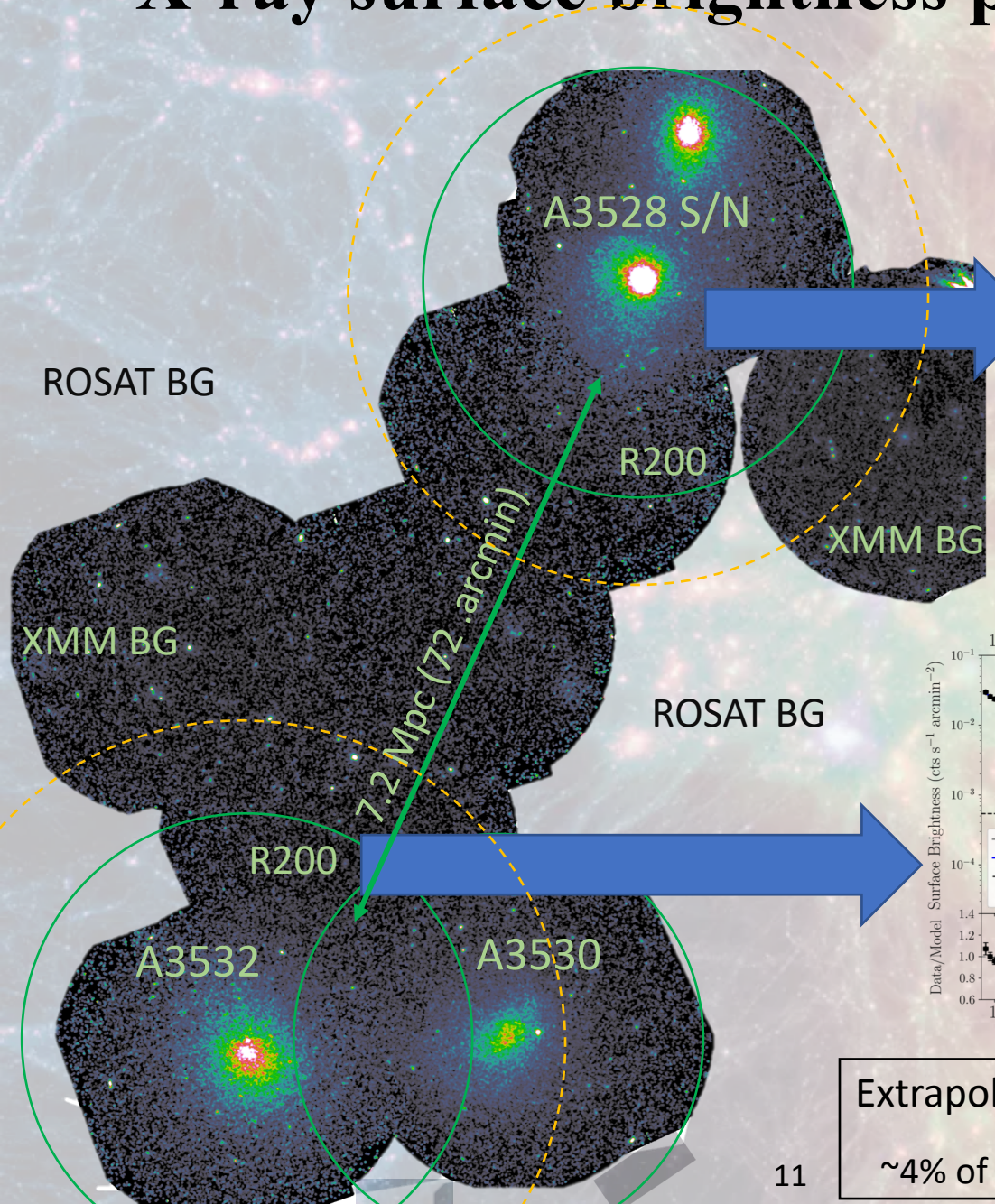


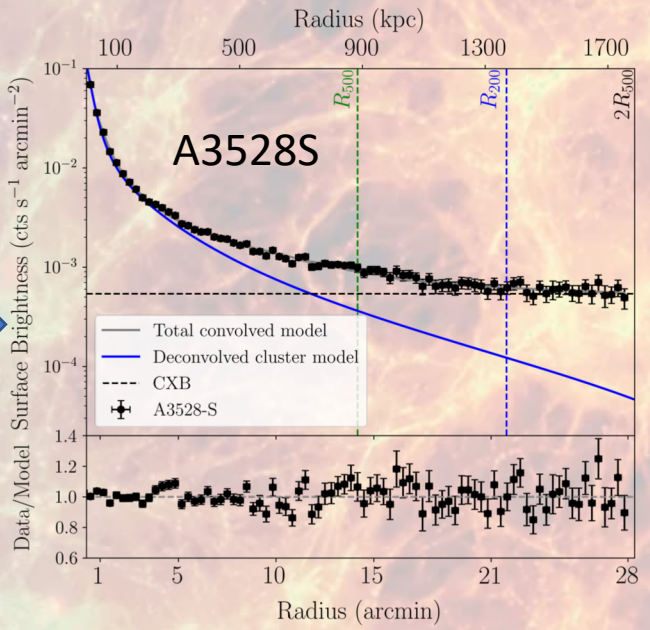


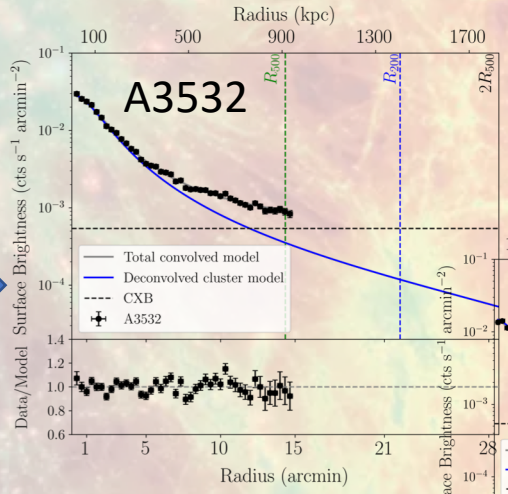


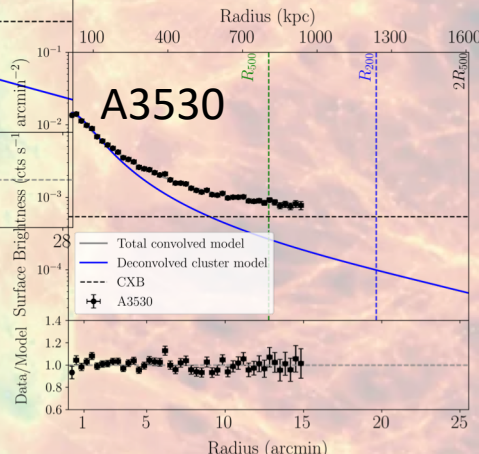
Migkas et al. (2025), A&A, 698, A270

X-ray surface brightness profiles of clusters





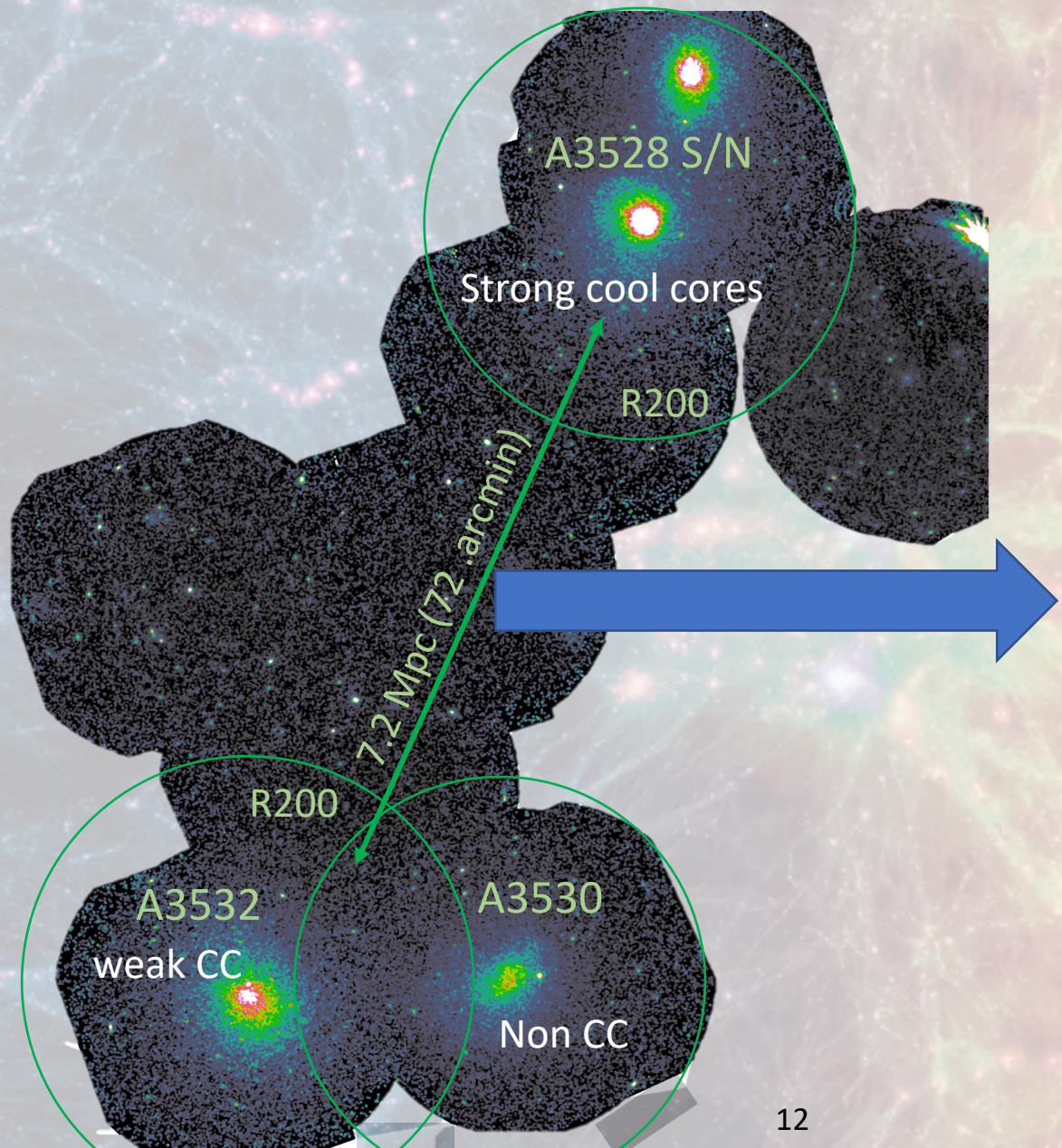


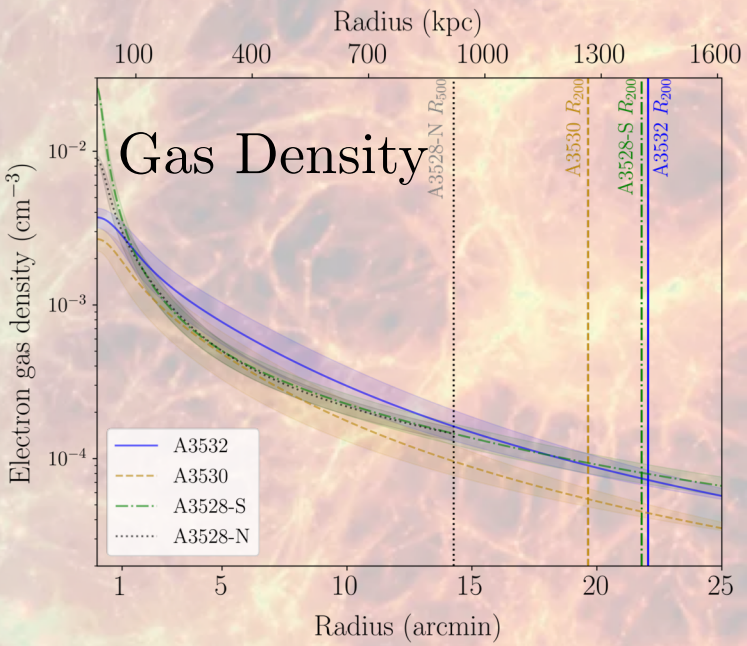


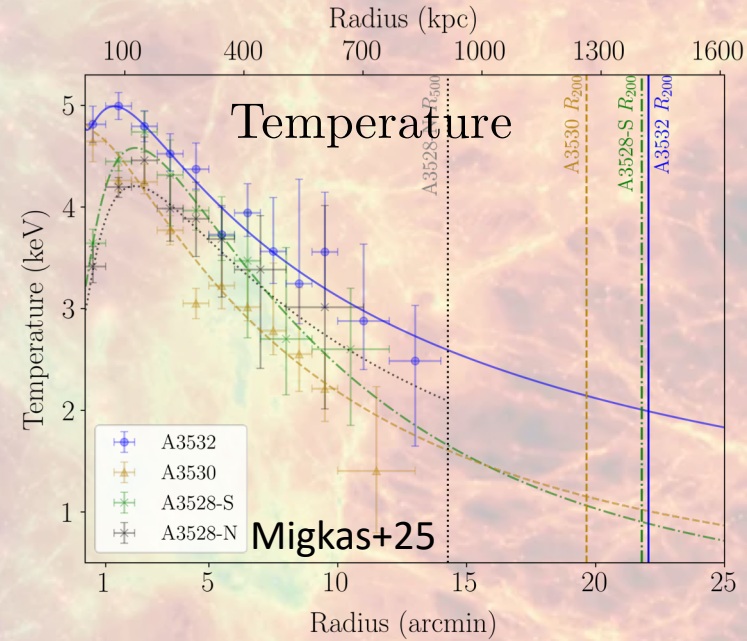
Extrapolate to $2R_{500}$

~4% of background

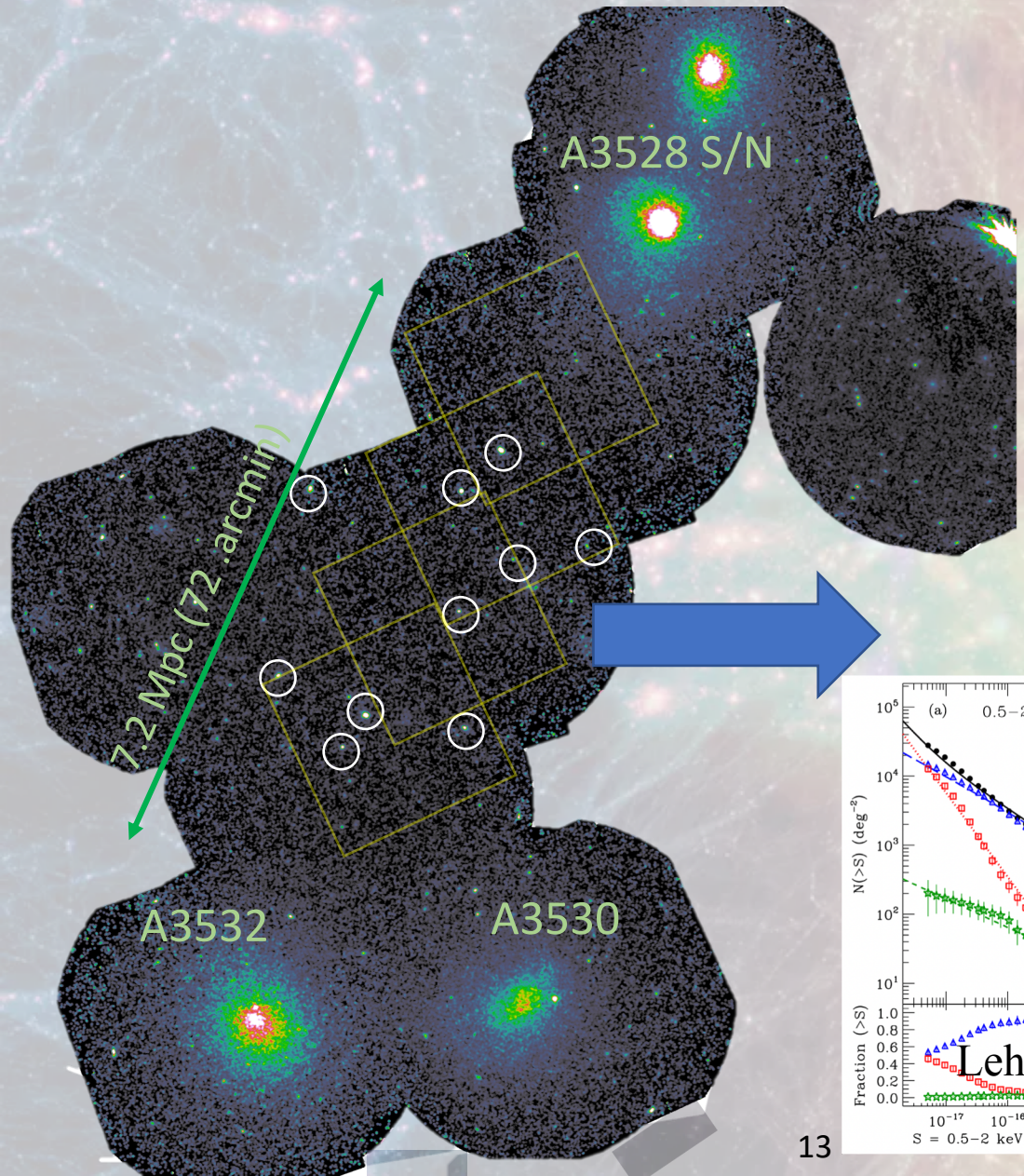
Gas density and Temperature profiles of clusters





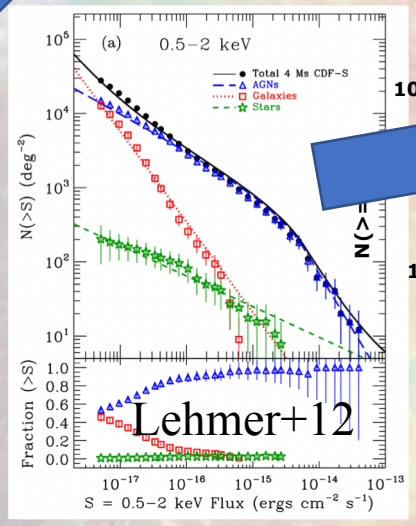


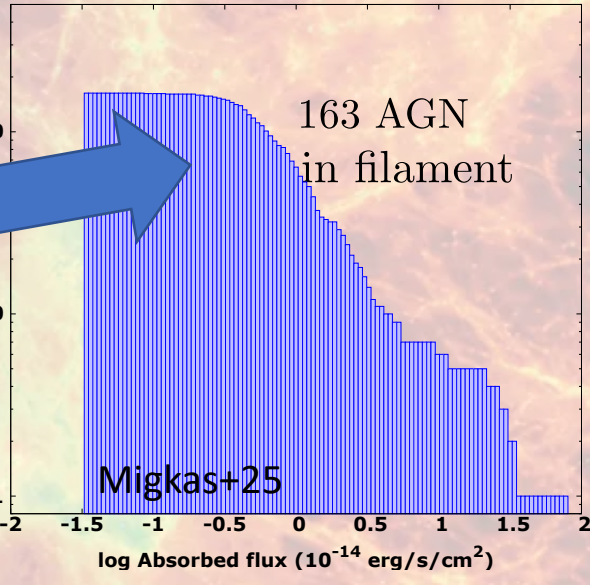
AGN across the filament with XMM



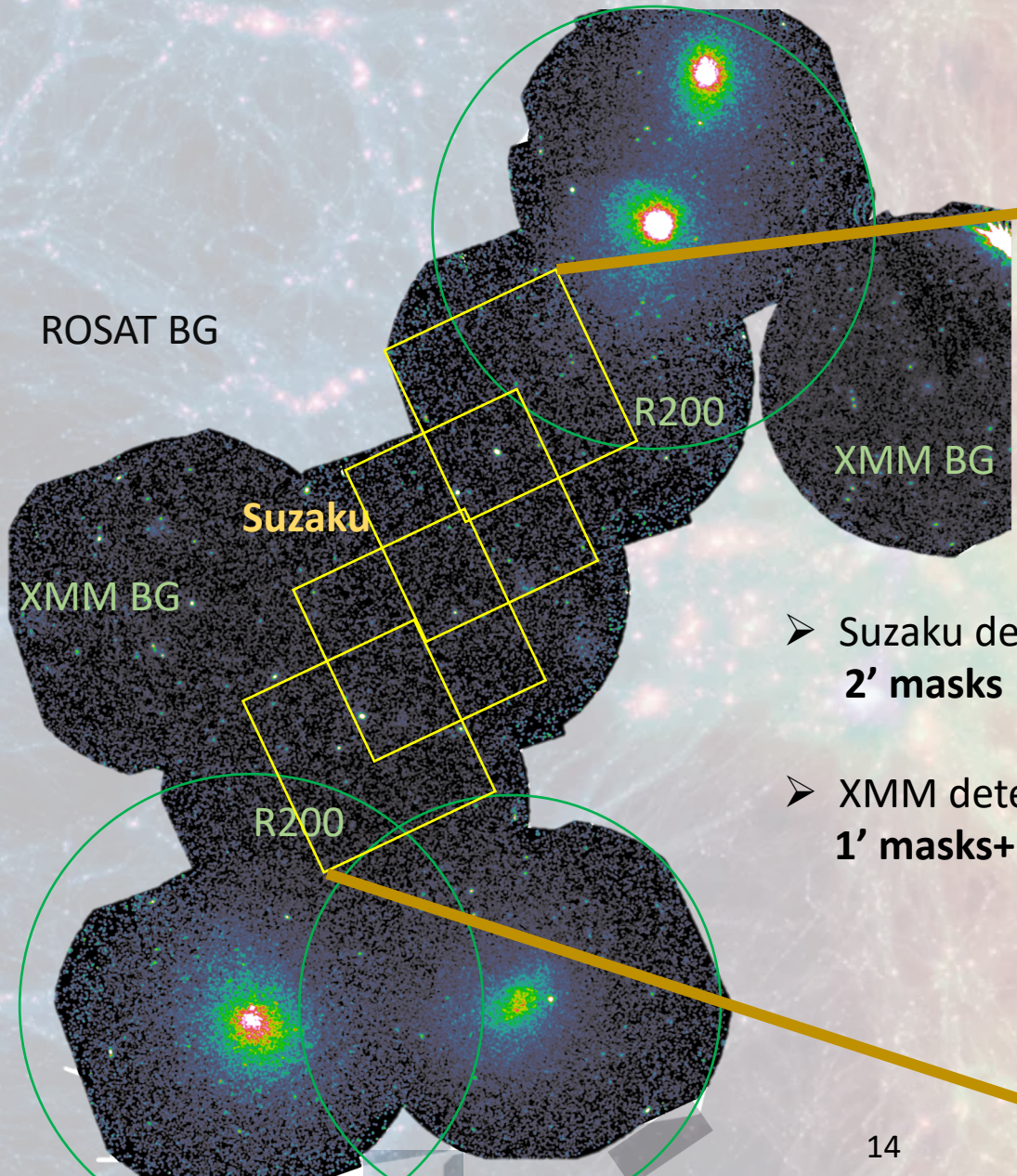
- Measure **flux of all resolved AGN** with XMM-Newton
- Compare with Chandra Deep Field
- **90% completeness** for AGN with $\geq 4.8\times10^{-15}$erg/s/cm^2
- **This is a game-changer in our analysis!**

$\log N - \log S$





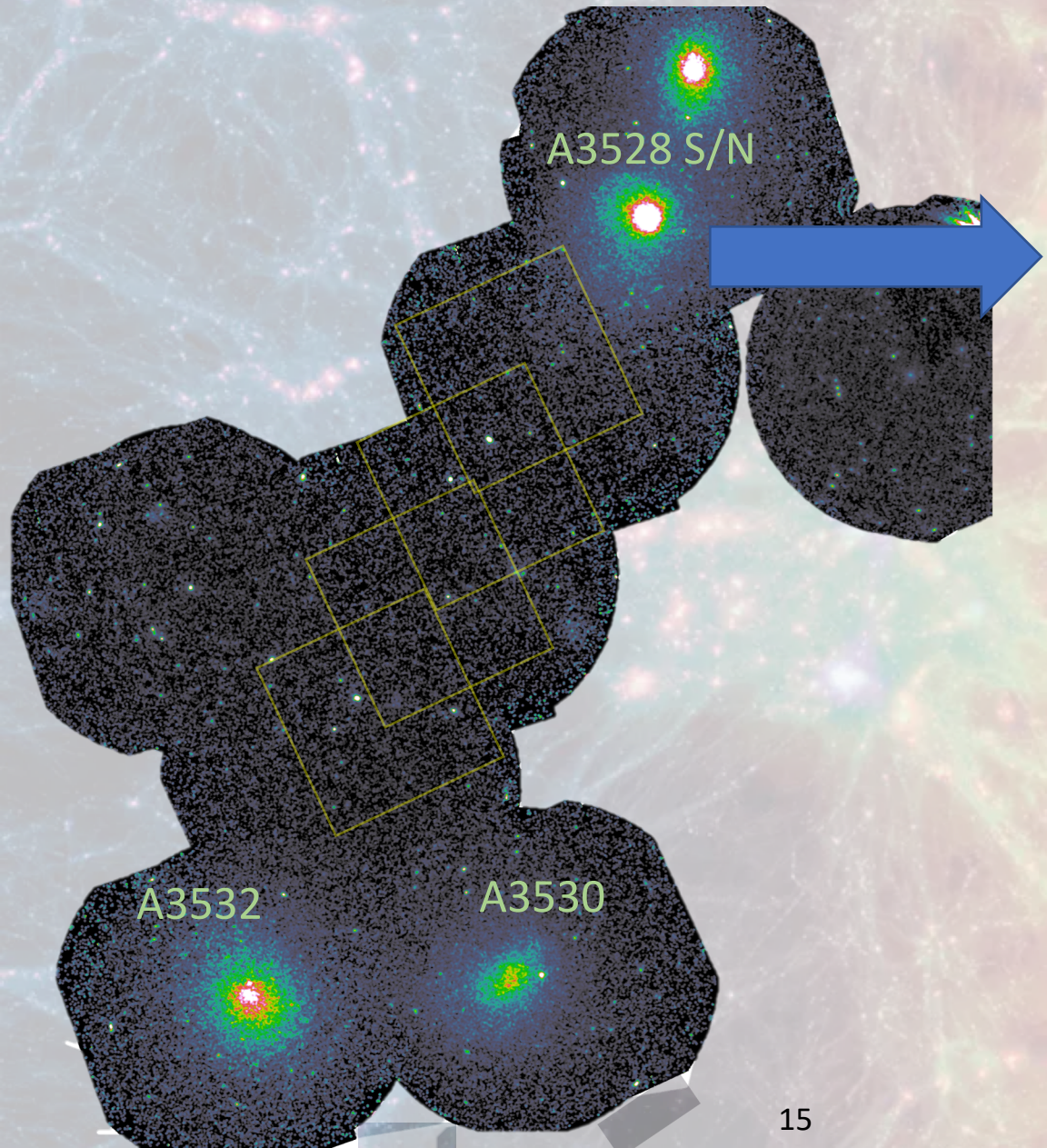
Suzaku view of the filament

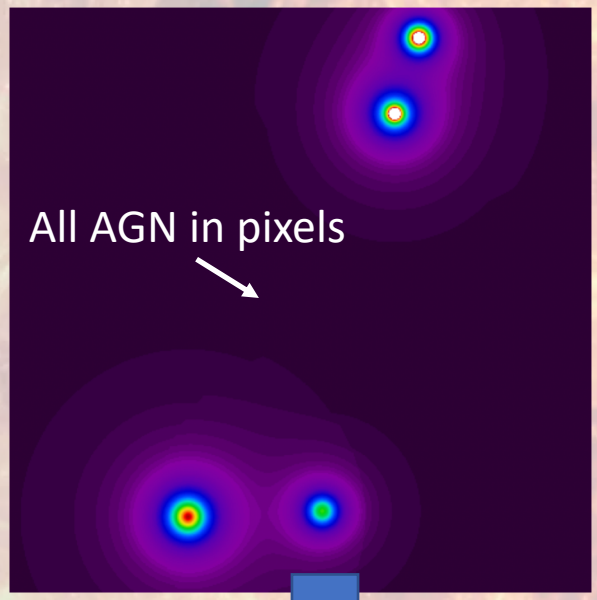


- Suzaku detection:
  2’ masks
- XMM detection:
  1’ masks+model



Simulated image to robustly isolate WHIM emission

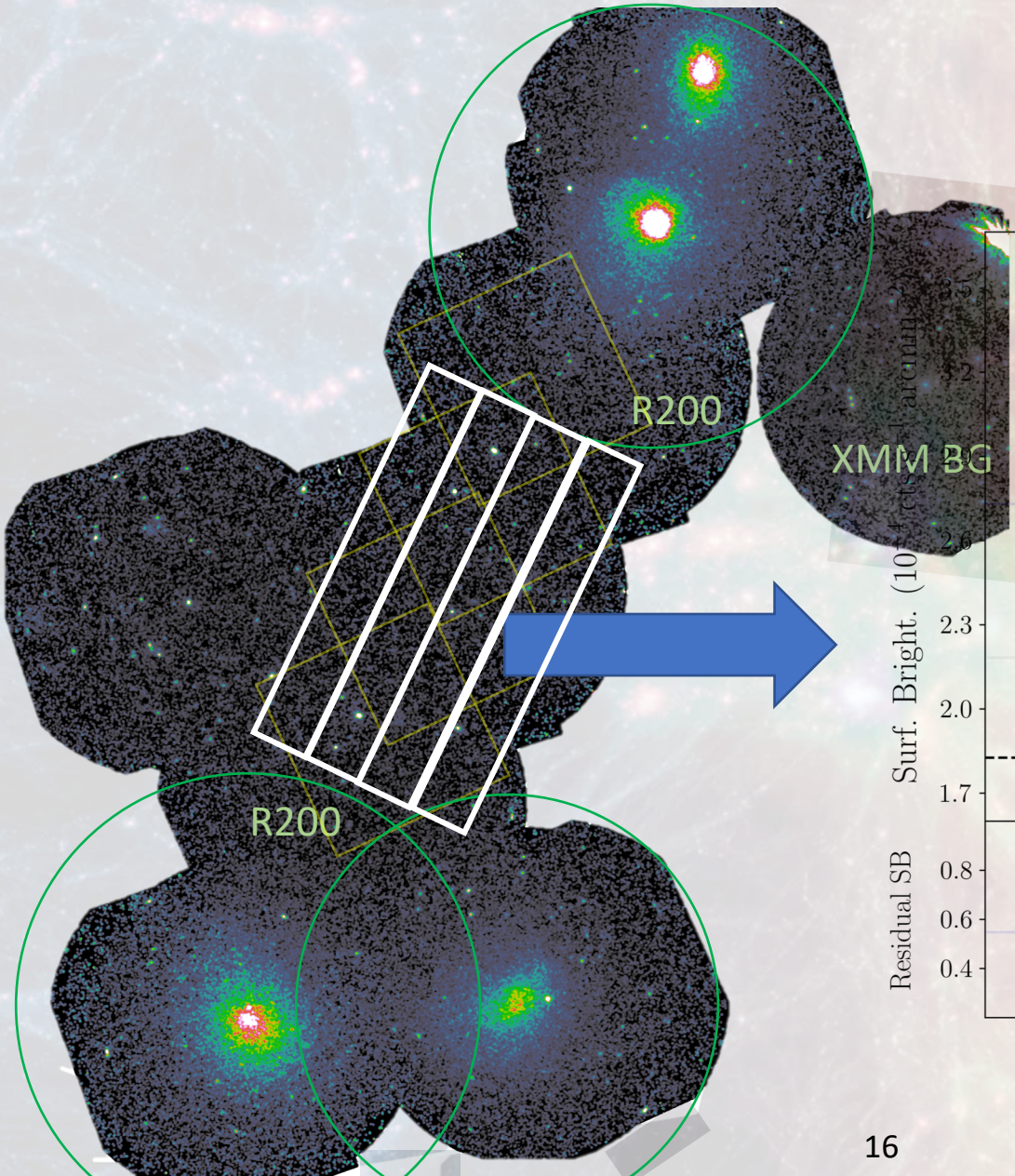




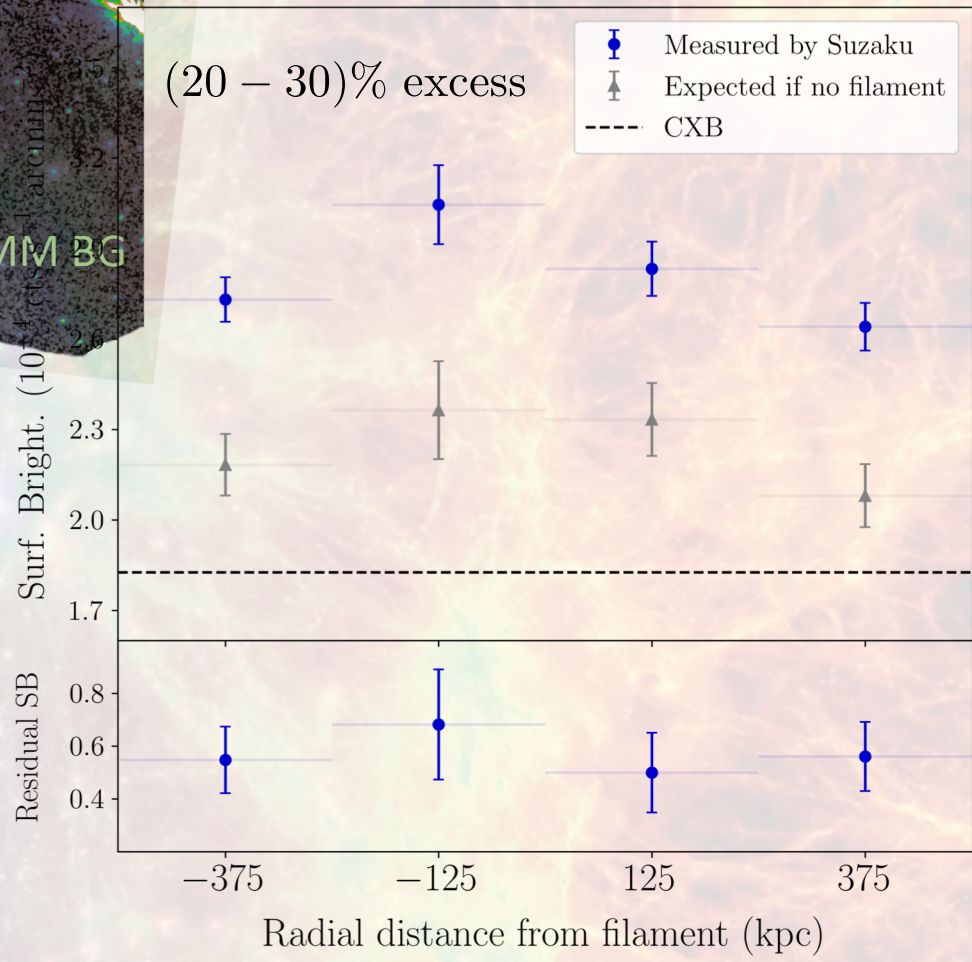
- Convolve with Suzaku PSF (1')
- Apply same masks as in data

Get what Suzaku would see without emission from filament

Surface brightness profile of filament



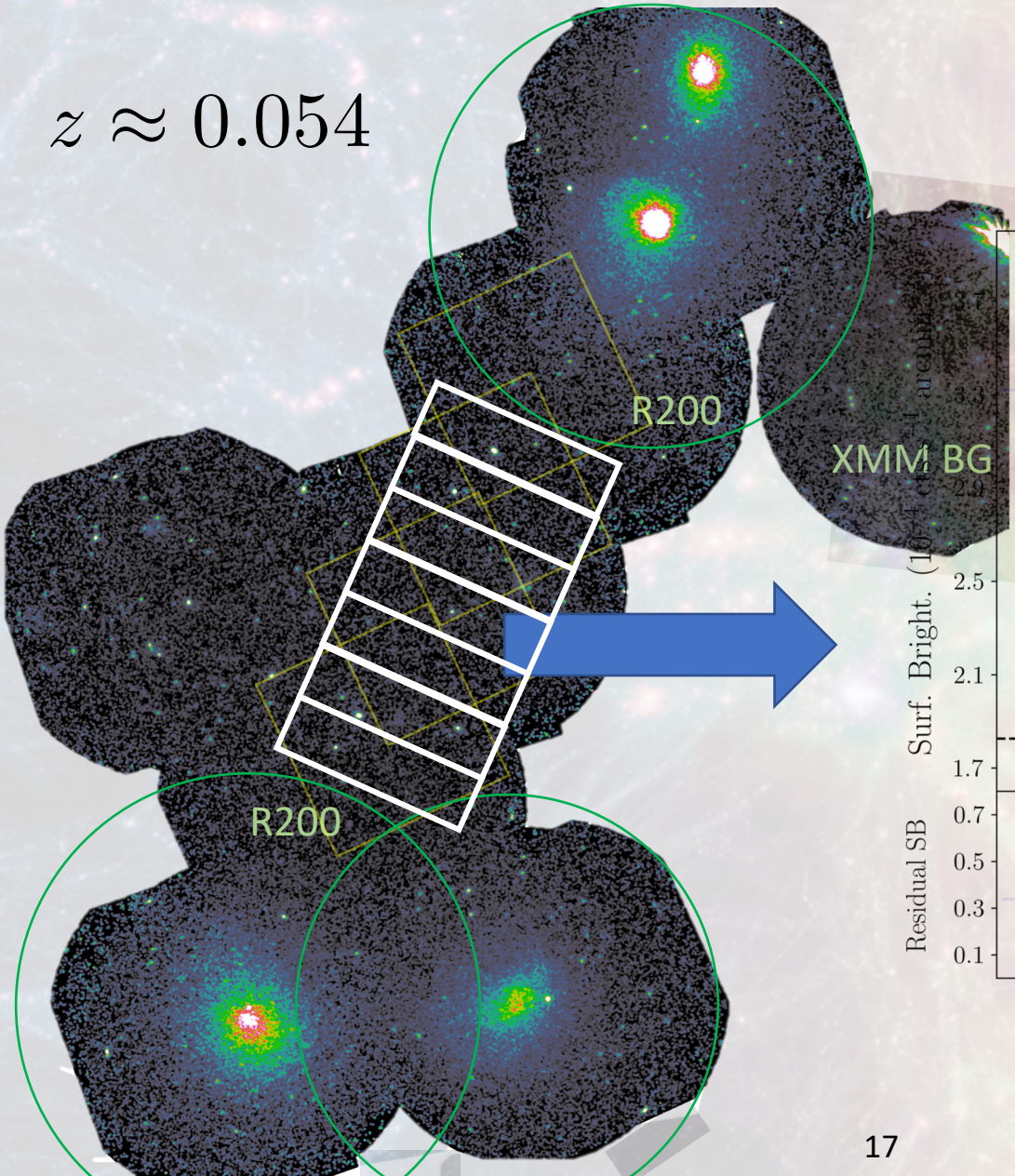
Excess emission at 6σ..!



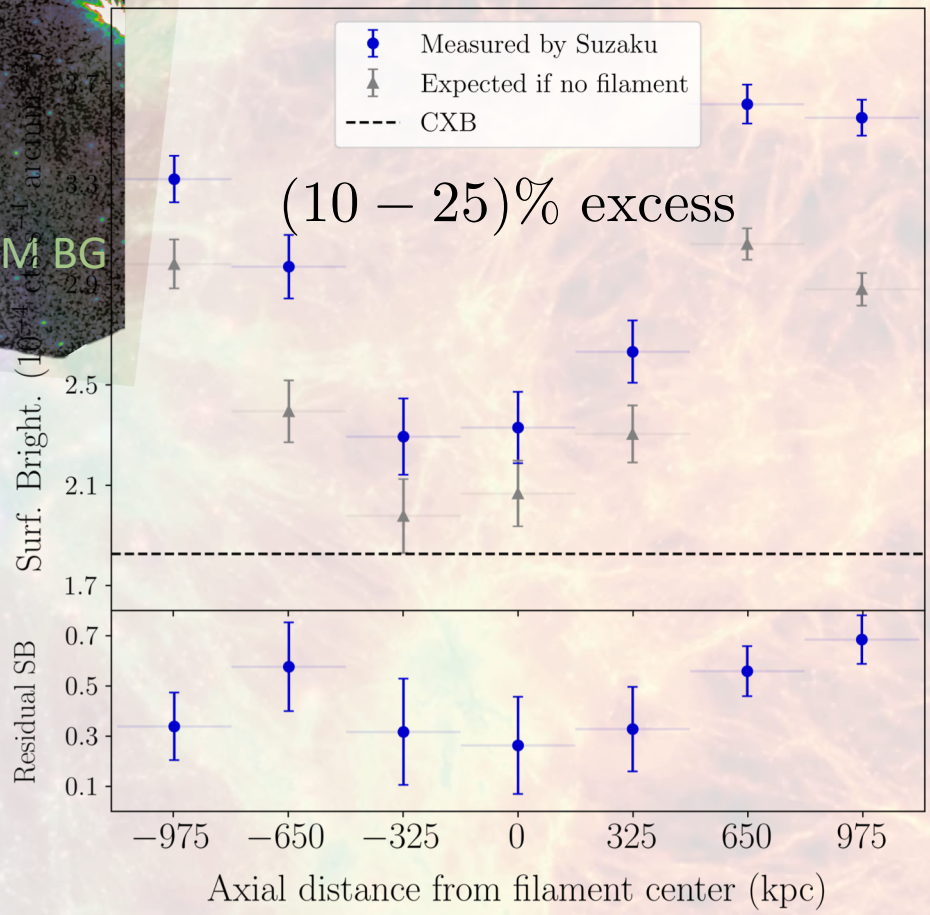
Migkas+25

Surface brightness profile of filament

$z \approx 0.054$



Excess emission at 6σ..!



Migkas+25

Fully cleaned mosaic image XMM+Suzaku



SCIENCE & EXPLORATION

"The models were right": astronomers find 'missing' matter

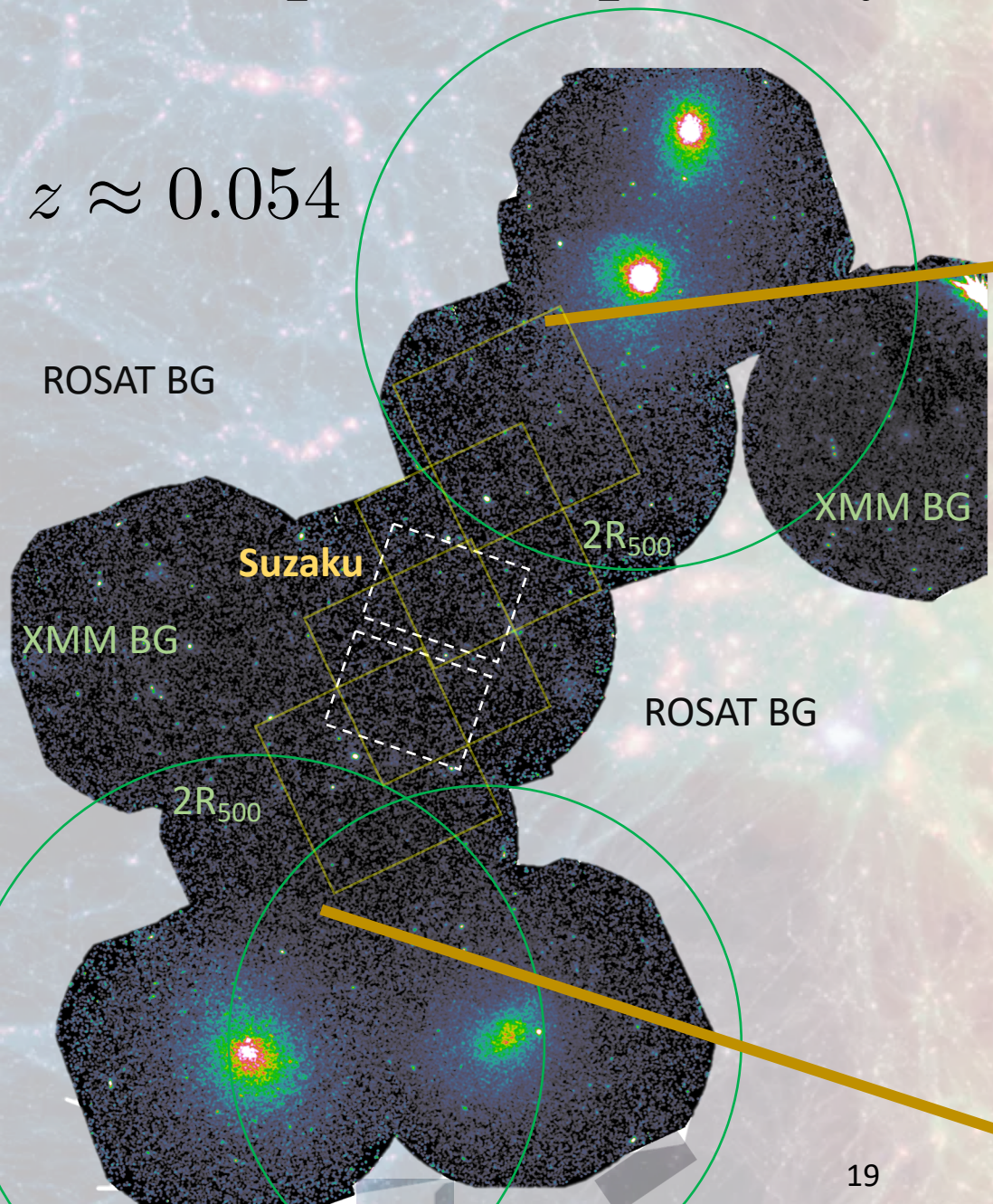
19/06/2025 22330 VIEWS 79 LIKES

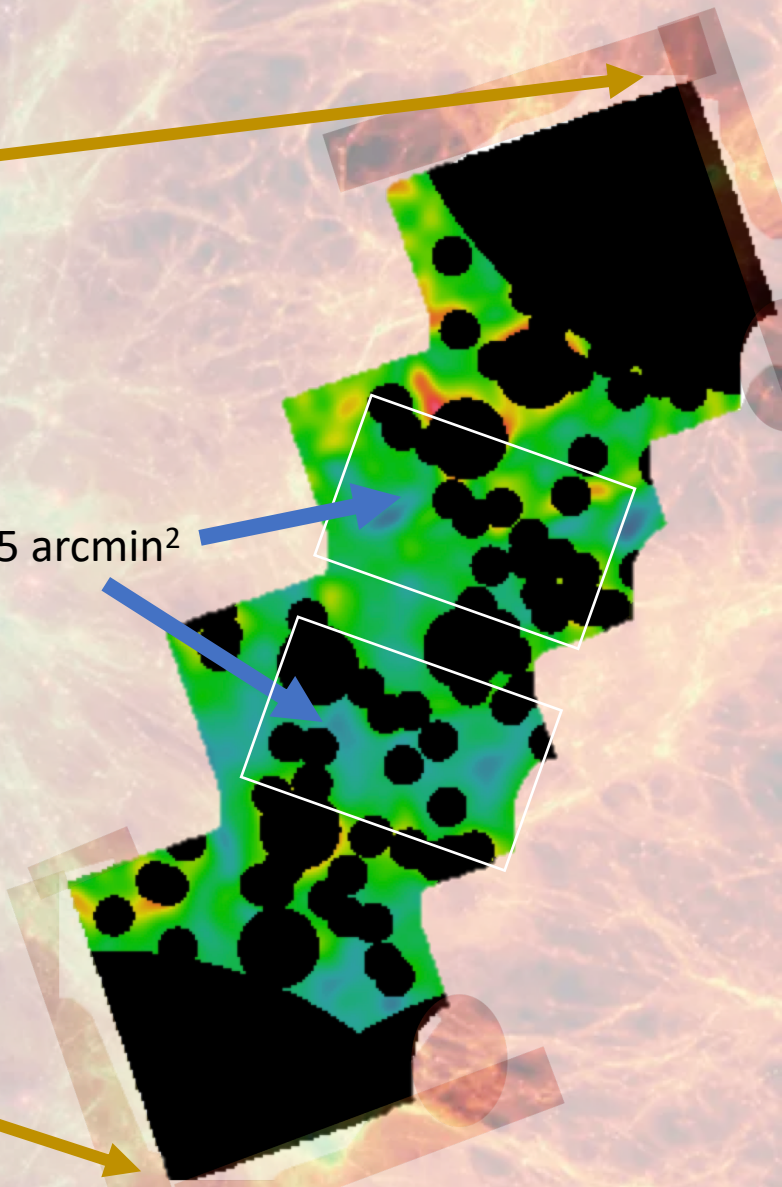
ESA / Science & Exploration / Space Science / XMM-Newton

- Residual AGN and cluster outskirts emission subtracted from Suzaku

Spectroscopic analysis of the filament

$z \approx 0.054$





Spectroscopic analysis of the filament



Detailed approach to account for AGN contamination

$$\texttt{Model} = \texttt{constant} \times [\texttt{apec}_1 + \texttt{tbabs} \times (\texttt{apec}_2 + \texttt{pow}_1)] + \texttt{gauss} + \texttt{tbabs} \times (\texttt{apec}_3 + \texttt{pow}_2)$$

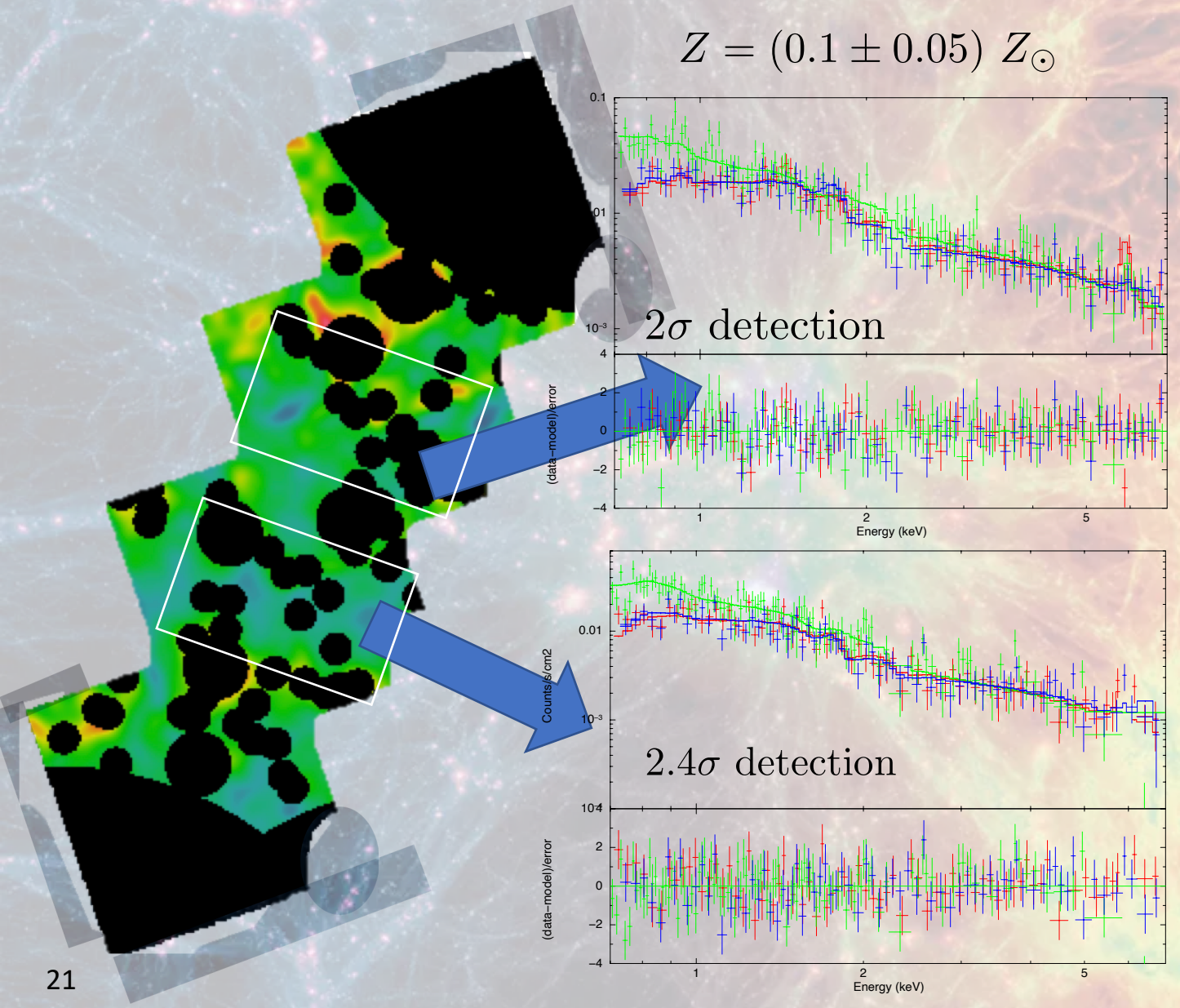
CXB from XMM

- Imperfectly masked AGN from Suzaku
- Constrained by XMM
- ±30% freedom in fit

Exploit deep XMM pointings + simulated Suzaku images to **precisely distinguish WHIM from AGN and cluster outskirts**

Spectroscopic analysis of the filament

$Z = (0.1 \pm 0.05)\ Z_\odot$



$T = 0.85^{+0.53}_{-0.34}$ keV

$n_e \approx 8 \times 10^{-6}/\mathrm{cm}^3$

$\delta_{\mathrm{bar}} = 31^{+6}_{-10}$

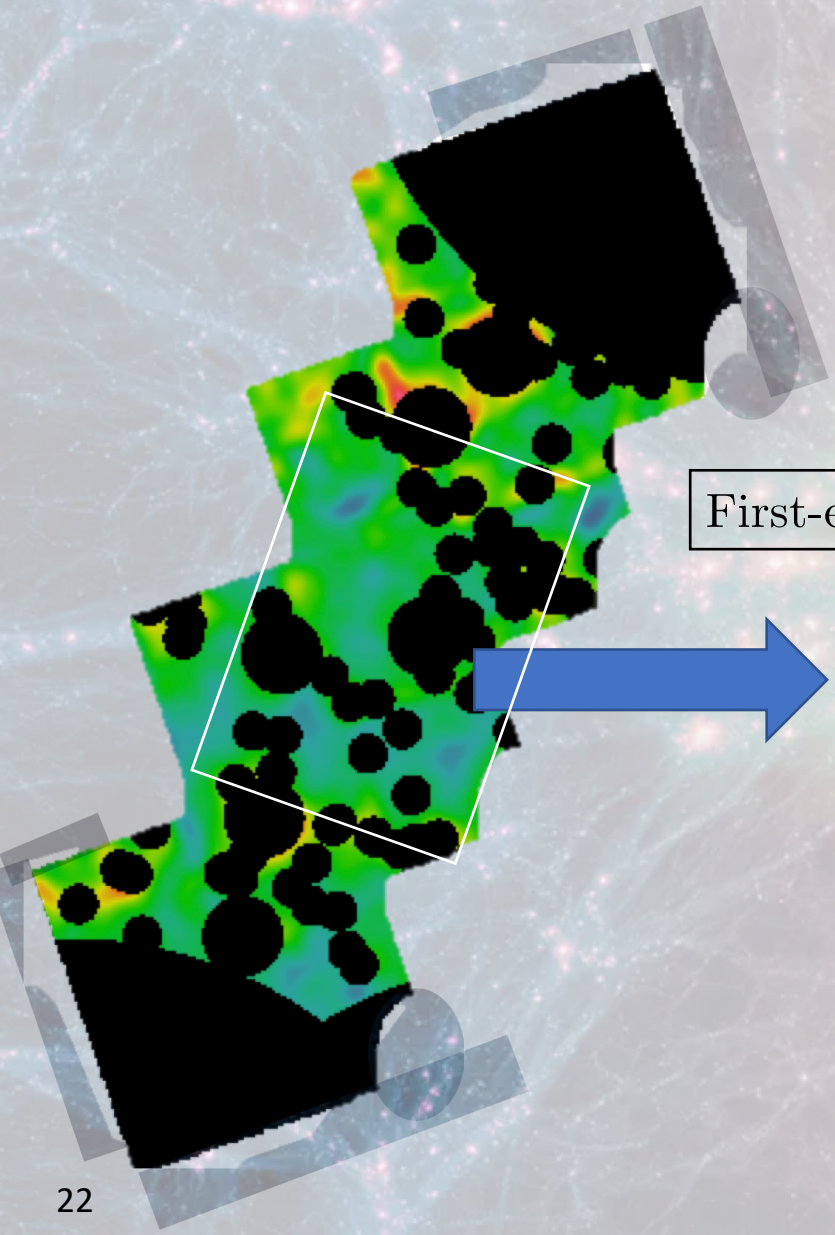
$T_{\mathrm{X}} = 1.09^{+0.31}_{-0.39}$ keV

$n_e \approx 10^{-5}/\mathrm{cm}^3$

$\delta_{\mathrm{bar}} = 37^{+6}_{-10}$

Migkas+25

Spectroscopic analysis of the filament

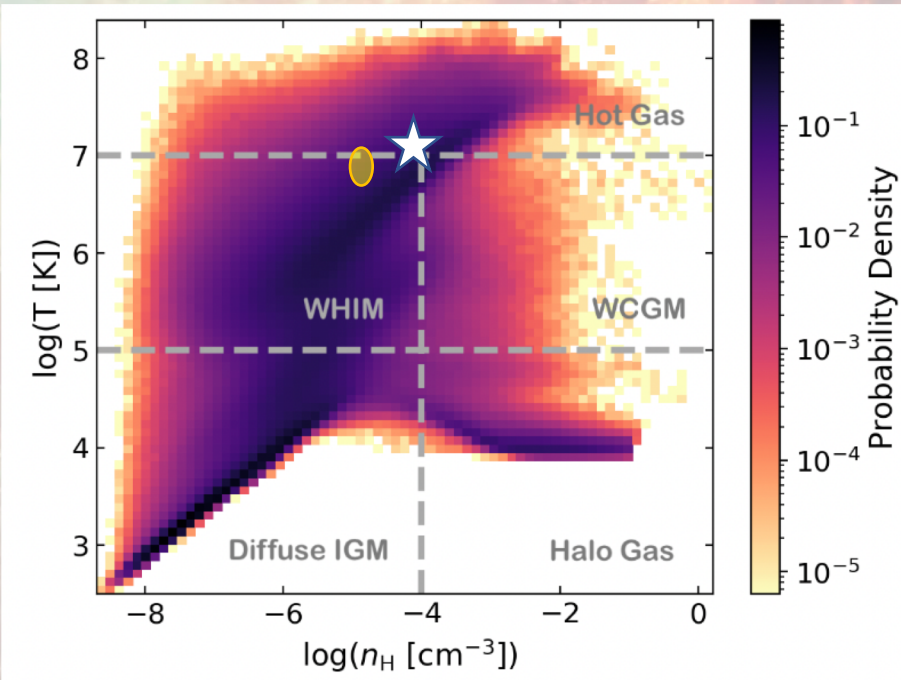


3.4σ detection

$$T_{\rm X} = 0.93^{+0.28}_{-0.32}\ {\rm keV}$$

$$\delta_{\rm bar} = 36^{+5}_{-7}$$

First-ever spectroscopic detection of "typical" WHIM(?)

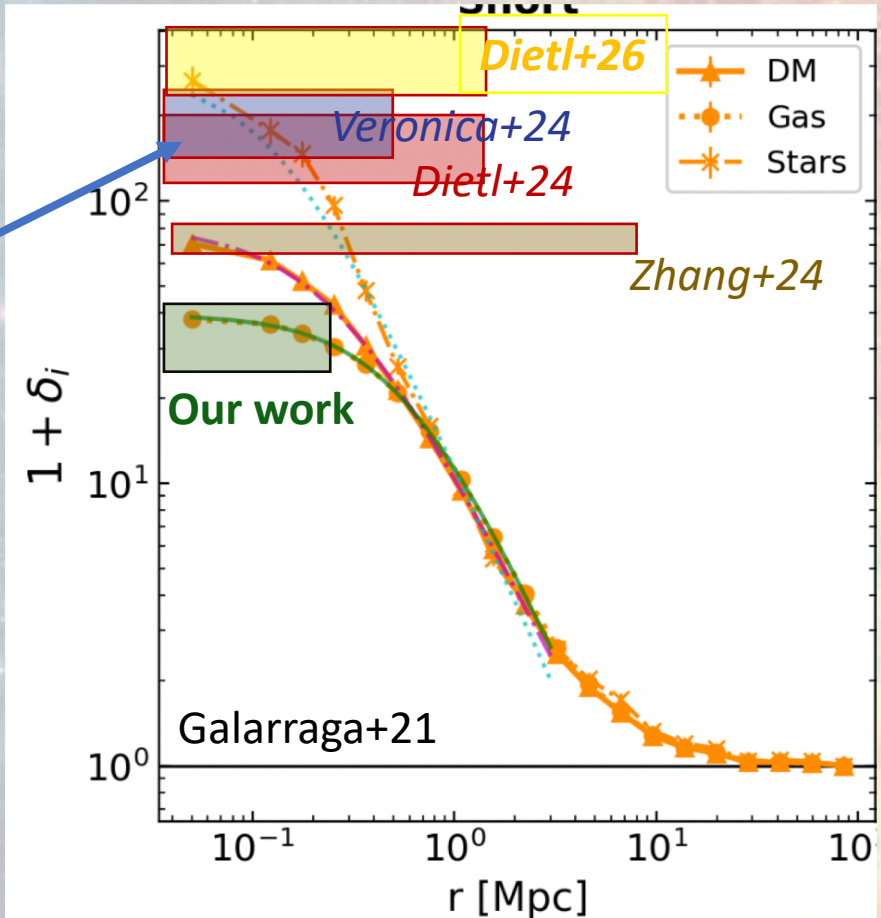


First characterization of pure WHIM

$$T_{\rm X} = 0.93^{+0.28}_{-0.32}\ {\rm keV} \qquad \boxed{\delta_{\rm bar} = 36^{+5}_{-7}}$$

First-ever spectroscopic detection of "typical" WHIM(?)

Marginally consistent with simulations for the densest filaments within the scatter



Detected, but barely characterized; where do we stand?

Study	Method	Result
Dietl+24, Veronica+24	eROSITA spectra	overdensity ≈ 120-240, kT ≈ 1.1 keV
Zhang+24	7,817 filaments, stacked	overdensity ≈ 78, kT ≈ 0.6 keV
Migkas+25	Suzaku + XMM, single filament	overdensity ≈ 37, kT ≈ 0.9 keV
Dietl+26	eROSITA spectra	overdensity ≈ 320 kT ≈ 1.2 keV

10–30%

Filament excess over the sky background: faint, soft, foreground-dominated

×8 spread

In overdensity: unresolved AGN, halos and cluster outskirts could bias the gas

0.7–1.1 keV

in every study so far: real heating, blind to cooler WHIM, or wrong assumptions?

Filament emission with NewAthena

WFI: find and map them

0.86 m² effective area

at 1 keV: an order of magnitude beyond current X-ray observatories

40′ × 40′

Large field of view: more and fainter filaments around and between clusters, even with single pointings

9″

resolves the AGN and halos that inflate filament densities today

X-IFU: weigh and characterize them

4 eV spectral resolution

separates the O VII triplet from Milky Way lines for any $z \geq 0.04$ filament and lets us measure other lines

1–3

WHIM emission lines per pixel at >3σ (simulation forecast, Cruise+25)

Z, v, z not possible before

metallicity, velocity and redshift from lines, not assumed in the fit, potentially even filament orientation without optical

Filament emission with NewAthena

10–30%

Filament excess over the sky background: faint, soft, foreground-dominated

×8 spread

In overdensity: unresolved AGN, halos and cluster outskirts could bias the gas

0.7–1.1 keV

in every study so far: real heating, blind to cooler WHIM, or wrong assumptions?

WFI

Discover and map many more fainter filaments, free of AGN contamination

X-IFU

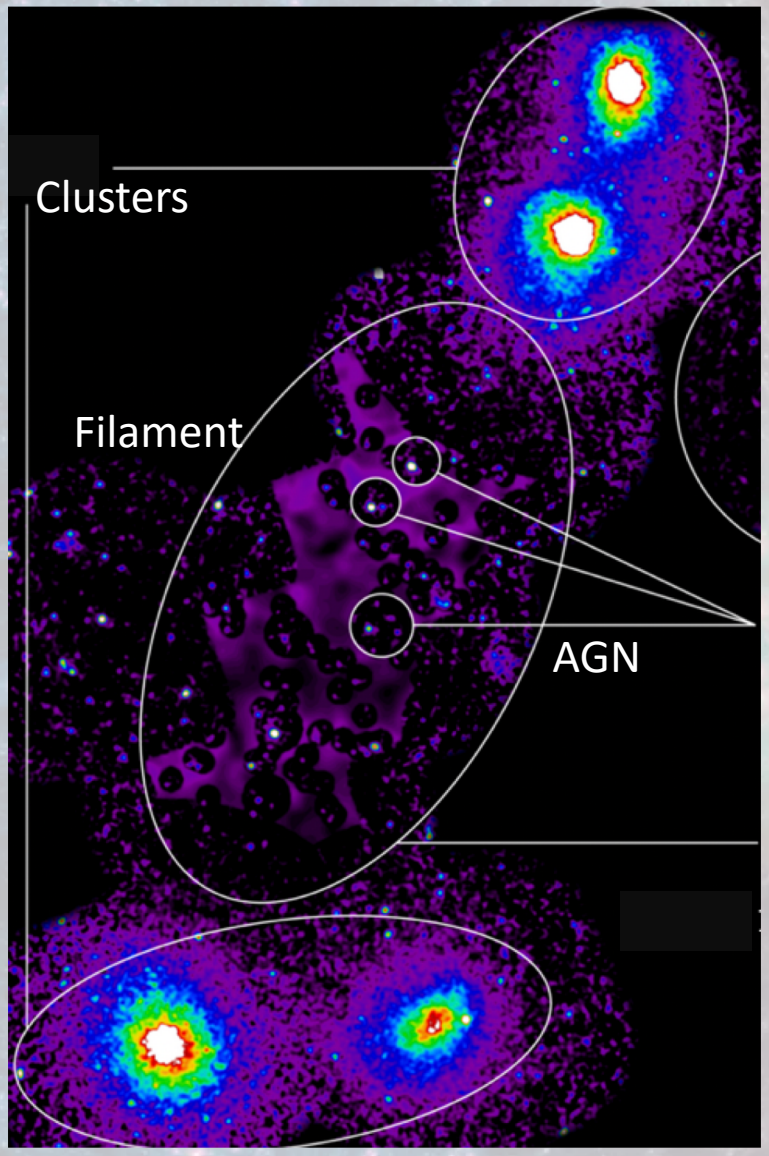
lines reach cooler, lower-density gas, metallicity and kinematics from emis. lines

Lower Temperatures

Absorption at $z > 0.1$ adds the cooler, more diffuse phase (Fisher+26)

Together, NewAthena will provide a complete census of the missing baryons throughout cosmic filaments

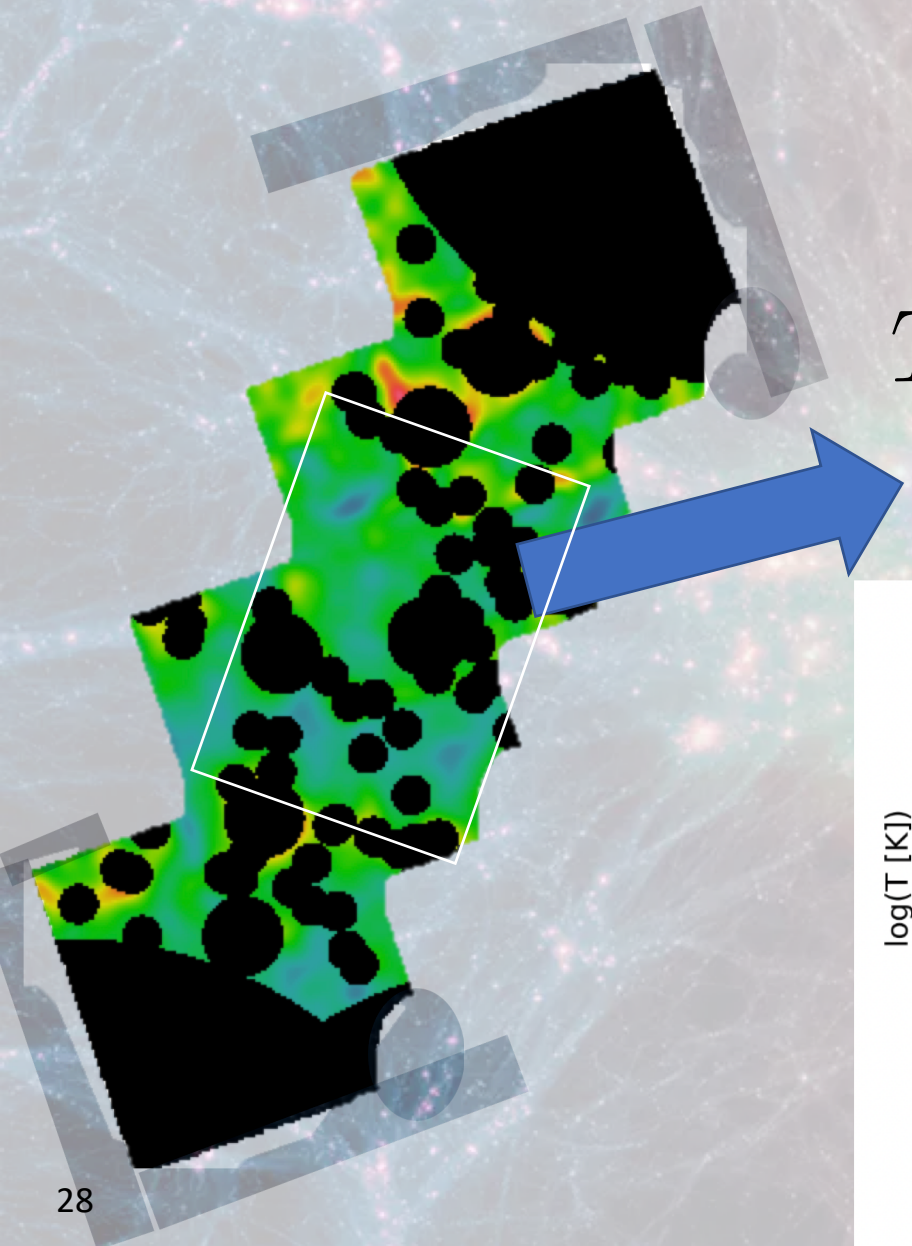
Summary



- **Spectral detection** of filamentary (WHIM) thermal emission **is very rare**
- Combined **Suzaku, XMM, ROSAT + careful modelling** to detect emission from Shapley filament
- Detected both through a **21% SB jump** along the axis + **3.4σ spectral detection**
- $T_X \sim 0.9$ keV, $\delta_b \sim 40$ (**averagely dense WHIM**)
- Unambiguous X-ray detection of **pure WHIM** throughout a single filament and the **first to agree well with simulations**
- Such studies set the stage for unmatched **newAthena** constraints on filaments

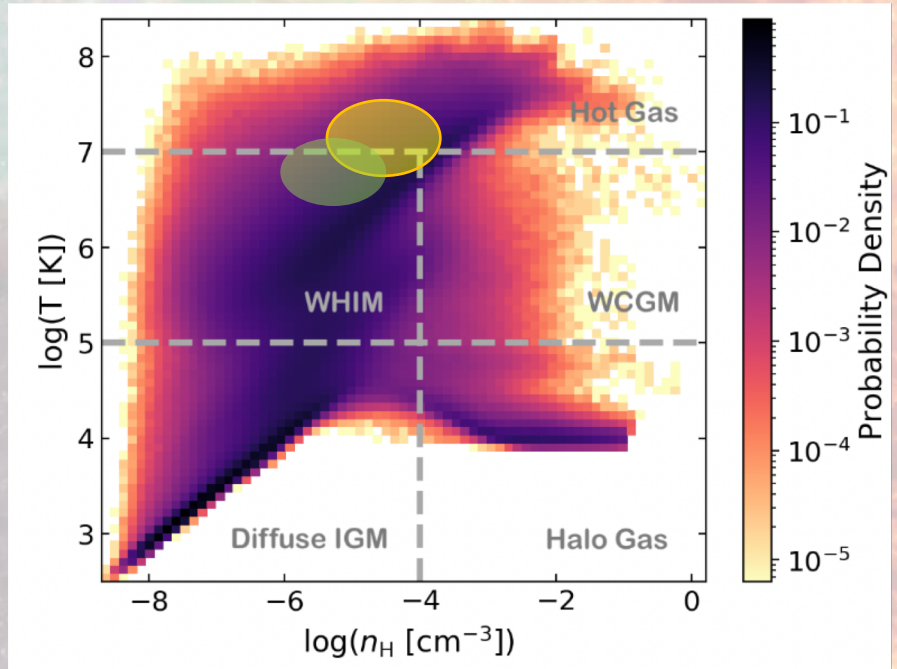
Thanks for your attention!

Overestimation if only Suzaku

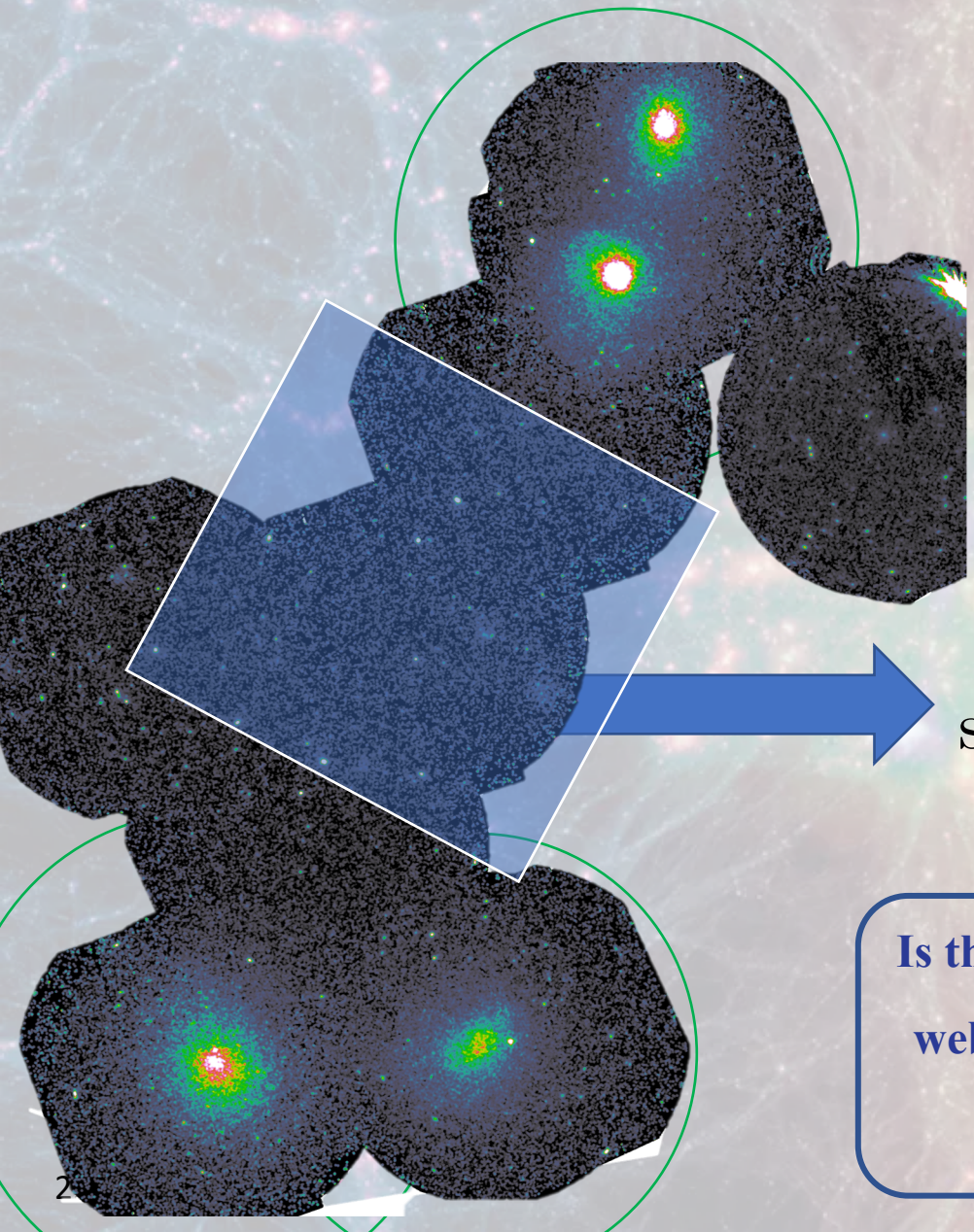


Only mask AGN that Suzaku resolves

$$T_{\rm X} \sim 1.8 \quad \delta_{\rm bar} \approx 80$$



Filament gas mass



Cylinder with R_{200} radius

$$M_{\rm gas} \sim 2.1 \times 10^{13}\ M_\odot$$

similar to surrounding clusters

Is the hidden (baryonic) part of the cosmic web affecting the local gravitational field and peculiar velocities?