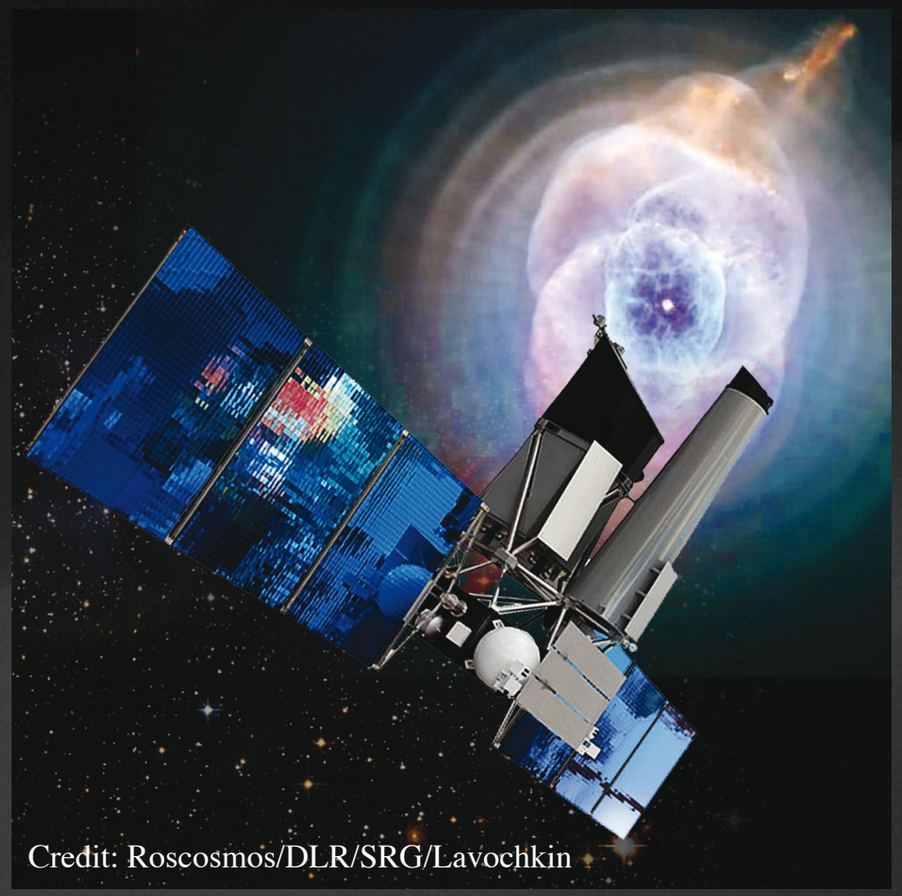
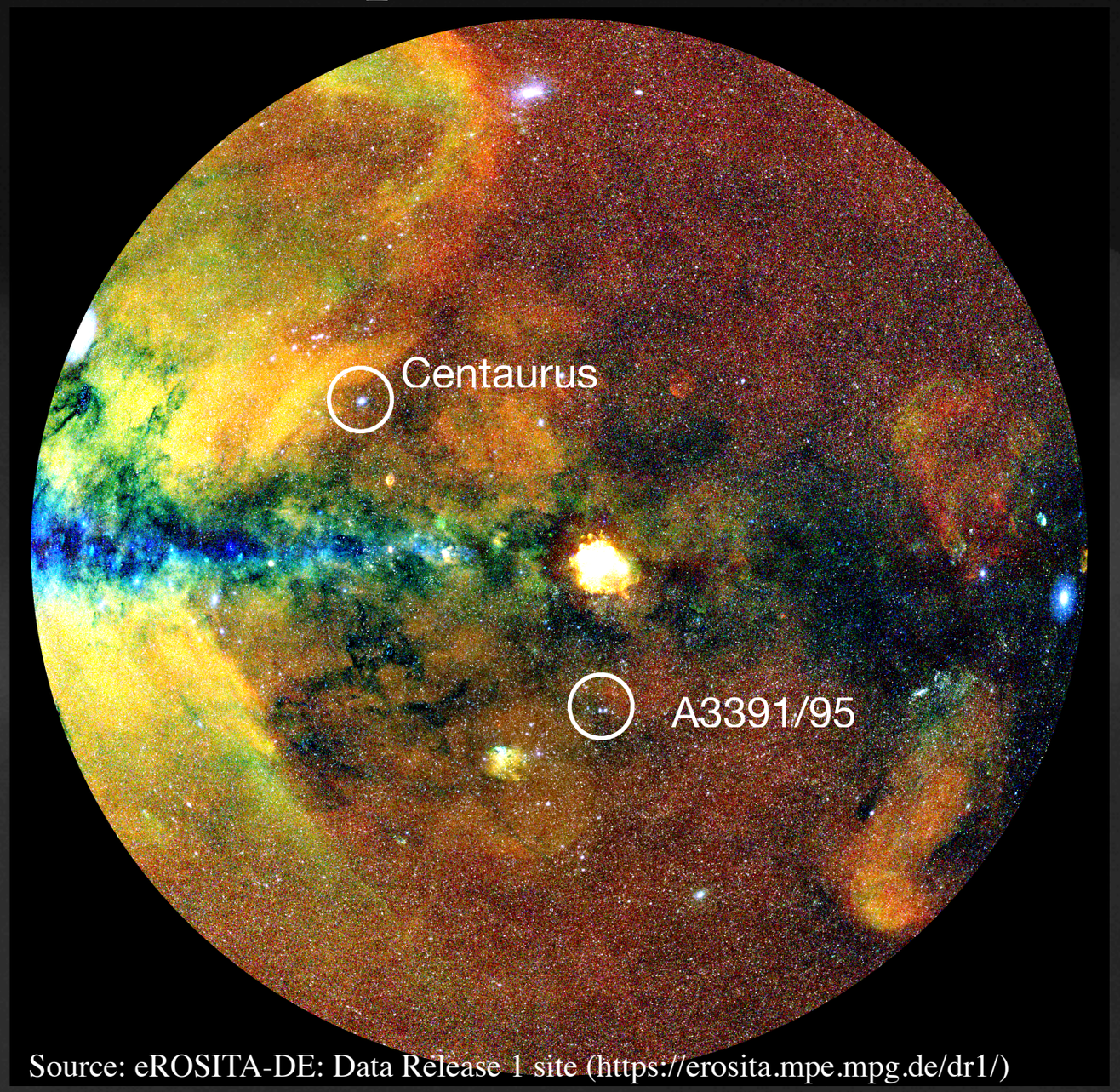
First Results from the SRG/eROSITA All-Sky Survey
Garching, 15-20 Sep 2024


Credit: Roscosmos/DLR/SRG/Lavochkin



Source: eROSITA-DE: Data Release 1 site (https://erosita.mpe.mpg.de/dr1/)

The eROSITA view of cluster outskirts and filaments

Angie Veronica et al. 2024a,b

UNIVERSITÄT BONN
Argelander-Institut für Astronomie
eROSITA

Centaurus Cluster

The SRG/eROSITA All-Sky Survey: Large-scale view of the Centaurus cluster

arXiv e-prints, arXiv:2404.04909

Angie Veronica, Thomas Reiprich, Florian Pacaud, Jeremy Sanders, Efrain Gatuzz, Michael Yeung, Esra Bulbul, Vittorio Ghirardini, Ang Liu, Caroline Mannes, Alexander Morelli, Naomi Ota

A3391/95 Cluster System

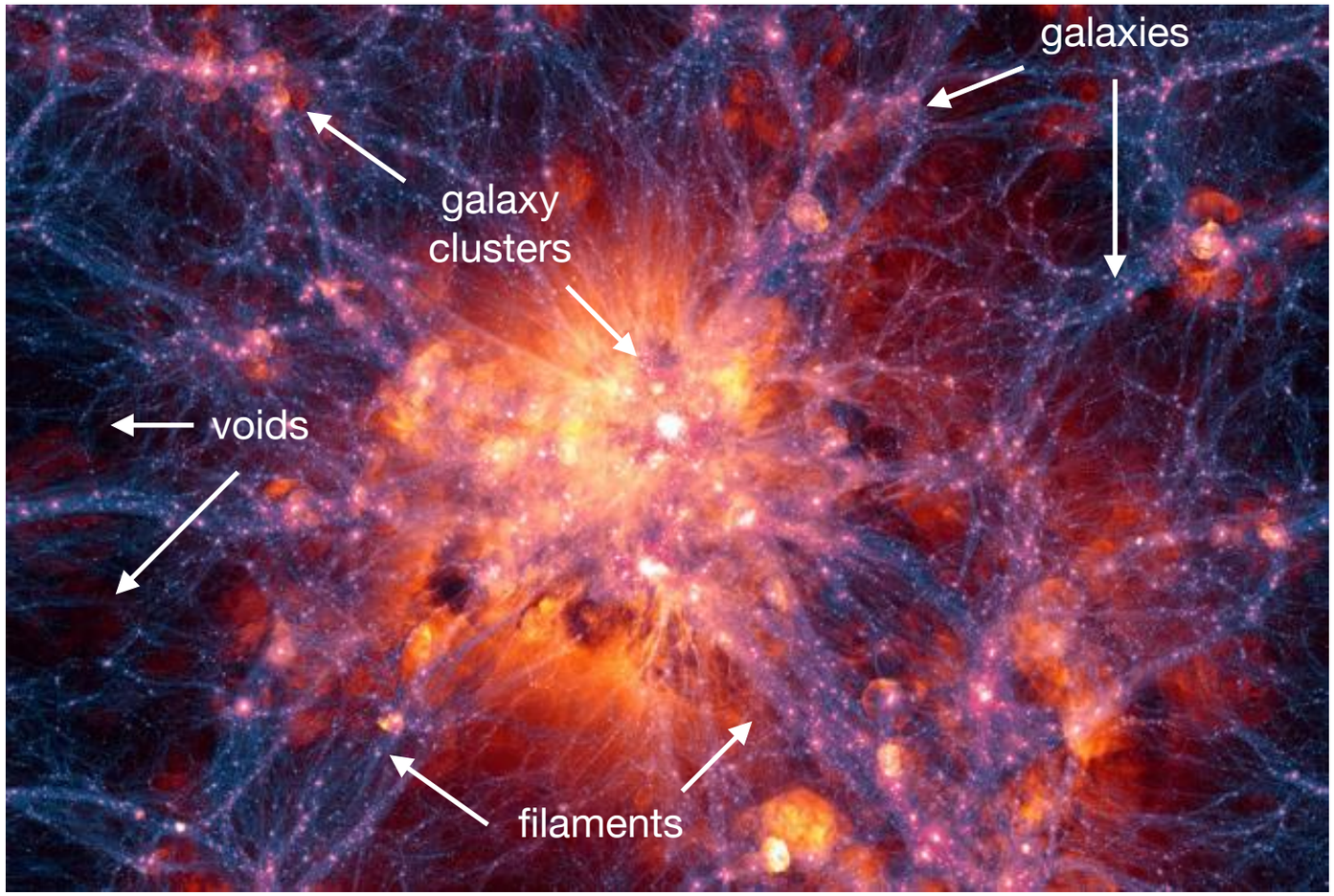
The eROSITA view of the Abell 3391/95 field: Cluster outskirts and filaments

A&A, 681, A108 (2024)

Angie Veronica, Thomas Reiprich, Florian Pacaud, Naomi Ota, Jann Aschersleben, Veronica Biffi, Esra Bulbul, Nicolas Clerc, Klaus Dolag, Thomas Erben, Efrain Gatuzz, Vittorio Ghirardini, Jürgen Kerp, Matthias Klein, Ang Liu, Teng Liu, Konstantinos Migkas, Miriam Ramos-Ceja, Jeremy Sanders, Claudia Spinelli

Large-Scale Structures of the Universe

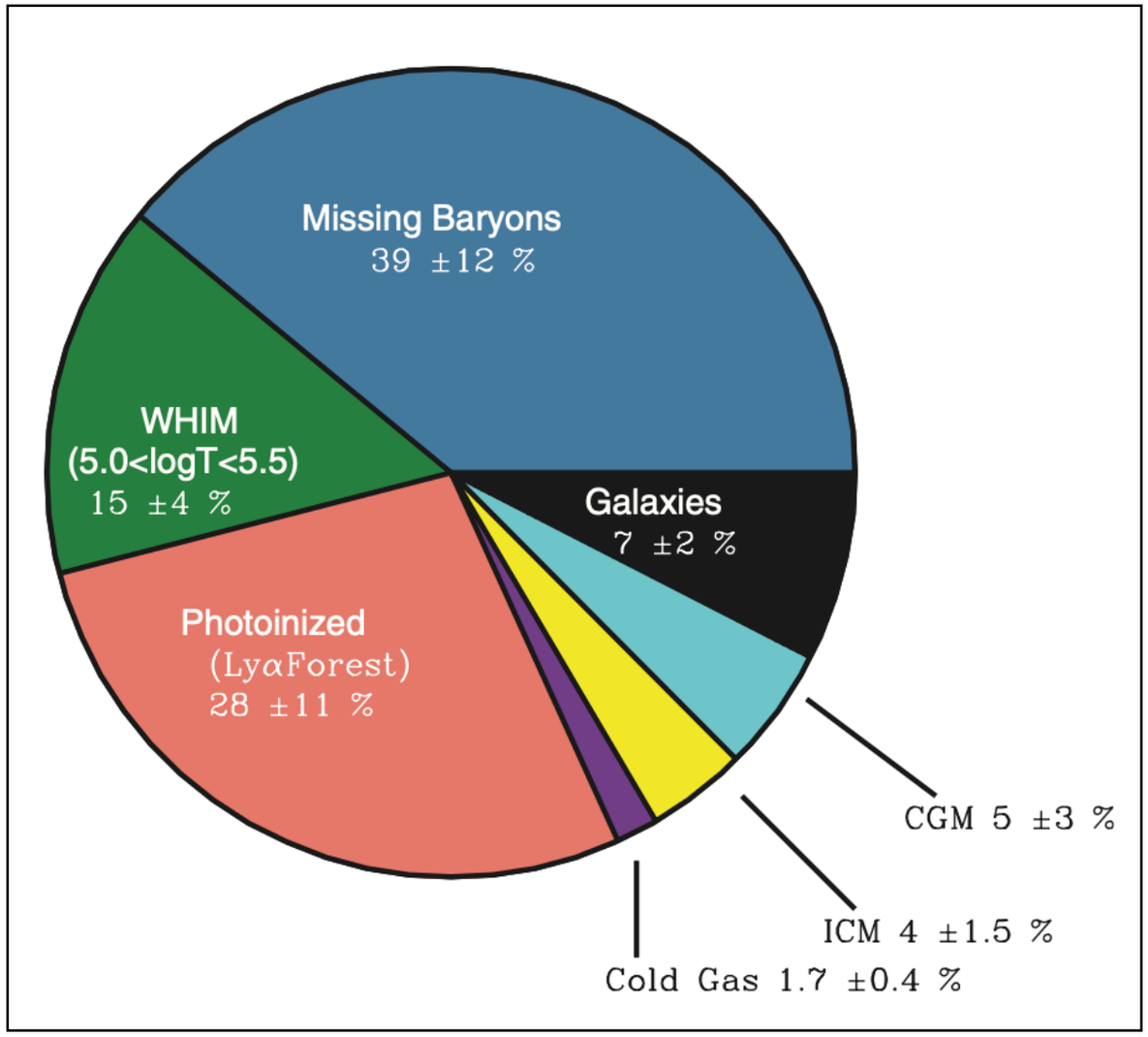
- Galaxy clusters sit in the nodes of the cosmic web, connected by comic filaments
- They form and grow from accretion and mergers of small structures (e.g., galaxies)
  - Imprints of these accretion processes are embedded in the cluster outskirts (e.g., caustics in the dark matter density profile, inhomogeneous gas density distribution, gas motions, etc.)
- Galaxy clusters are tracers of LSS



A computer model of the LSS of the universe using the Illustris simulator. This image depicts the dark matter and gas involved in forming galaxies and galaxy clusters, as well as the filaments connecting them.
Credit: Illustris (labelled)

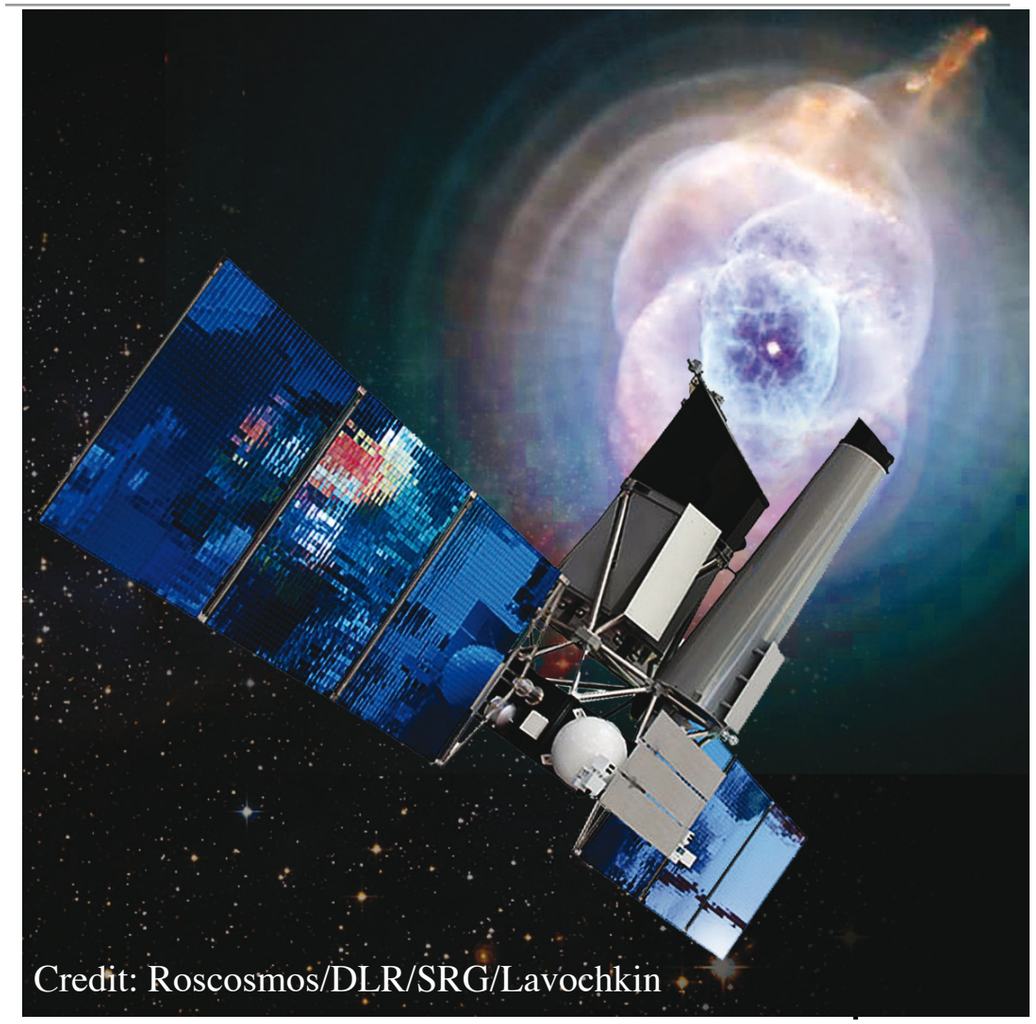
Large-Scale Structures of the Universe

- **Missing baryon problem:**
  - in the local Universe, we are still missing about 30-40% of the total baryons
- **Solution**: they are in the cosmic-filaments in the so-called the Warm-Hot Intergalactic Medium (WHIM)
  - $n_e \approx 10^{-6}$–10^{-4} cm^{-3}
  - $T \approx 10^5$–10^7 K ($k_B T \approx 0.009$–0.9 keV)
    - faint!

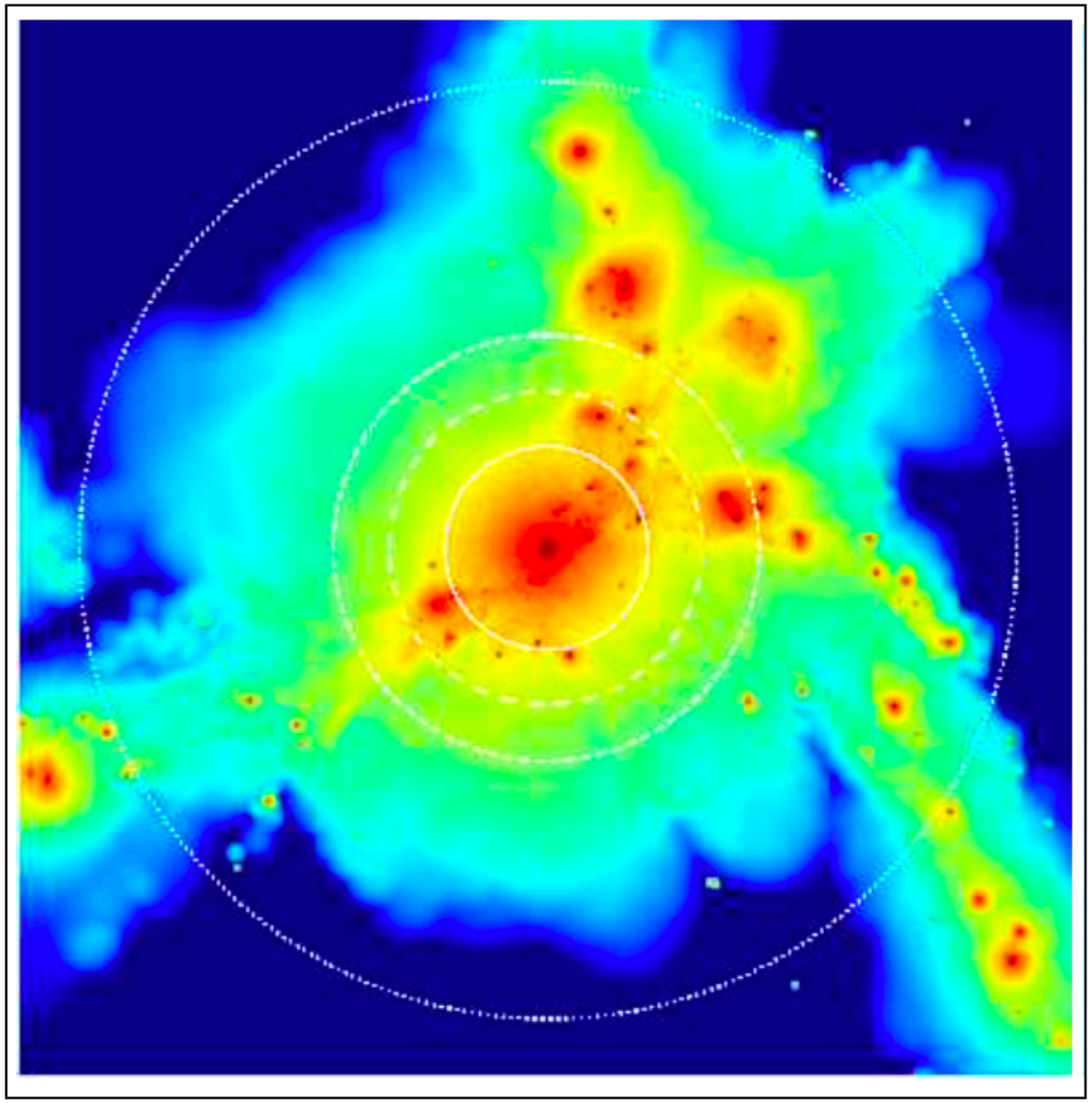


Baryon budget of local Universe ($z = 0$)
(Nicastro et al. 2017)

Tracing large scale structures in the Universe



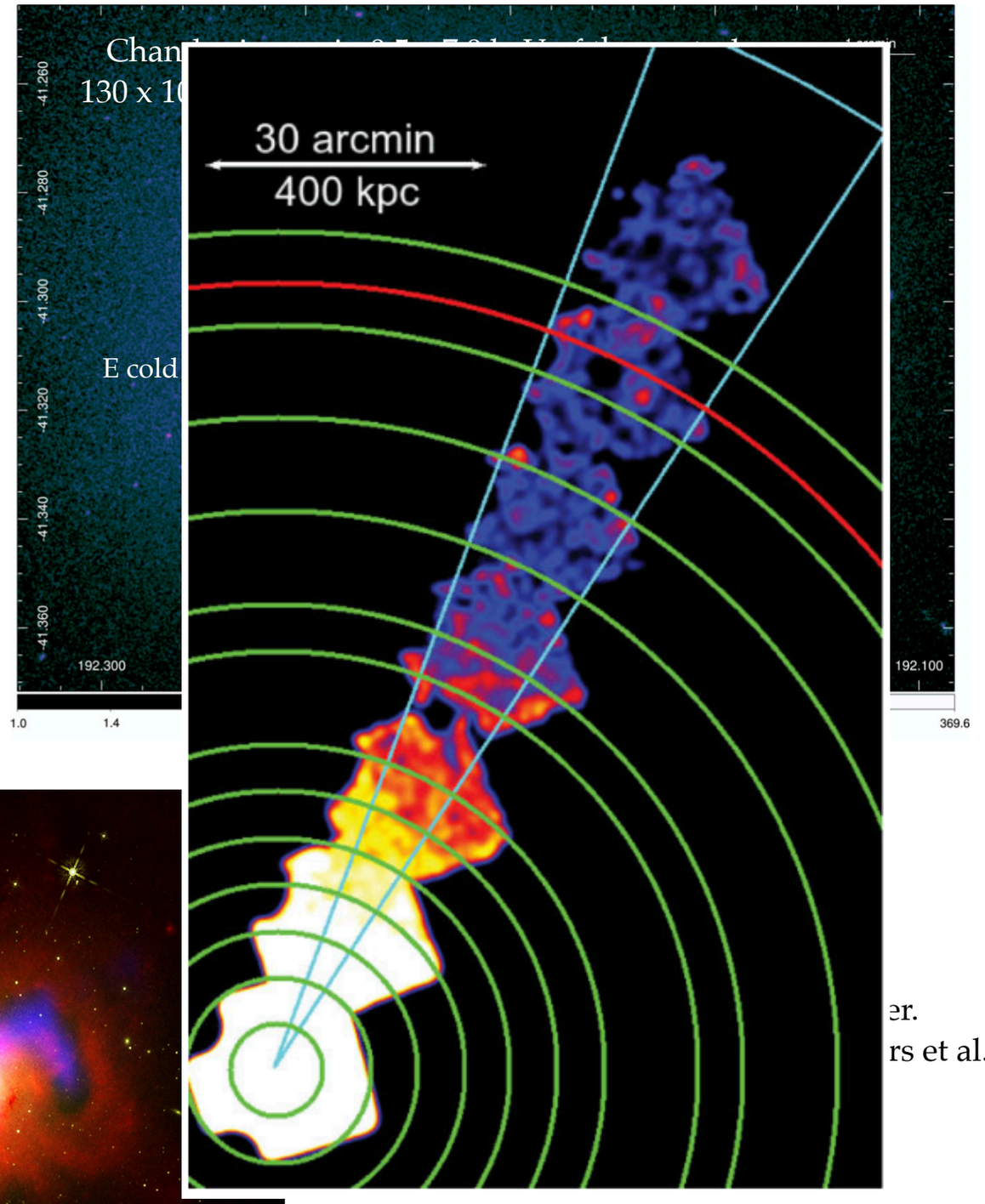
- Outskirts of nearby galaxy clusters
- Between galaxy cluster systems/complexes

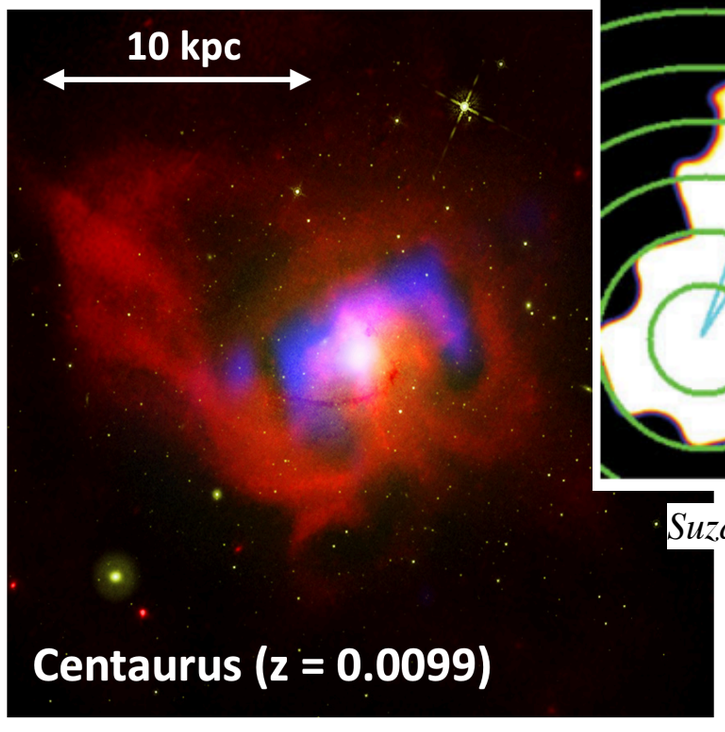


X-ray surface brightness image (0.5–2.0 keV) of a simulated galaxy cluster out to its outskirts (Roncarelli et al. 2006; Reiprich et al. 2013)

Centaurus Cluster

- One of the brightest and closest galaxy clusters in the sky
  - $f_{X,0.1-2.4\ \mathrm{keV}} = 2.7 \times 10^{-10}\ \mathrm{ergs/cm^2/s}$ (Reiprich & Böhringer+02),
  - z=0.0114.
- Extensive astrophysical studies using previous X-ray satellites (cores), small part in the outskirts.



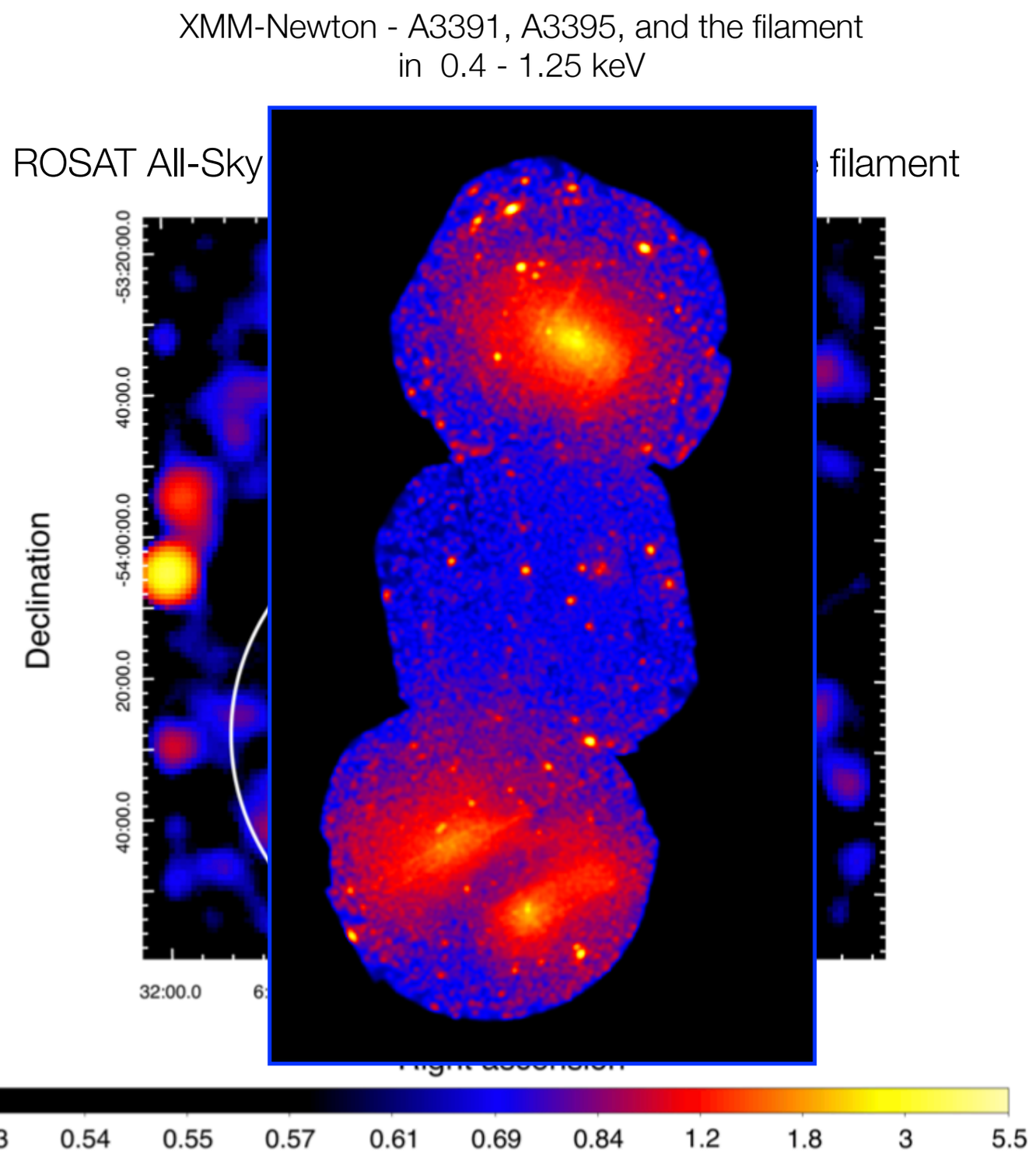


er.
rs et al.),

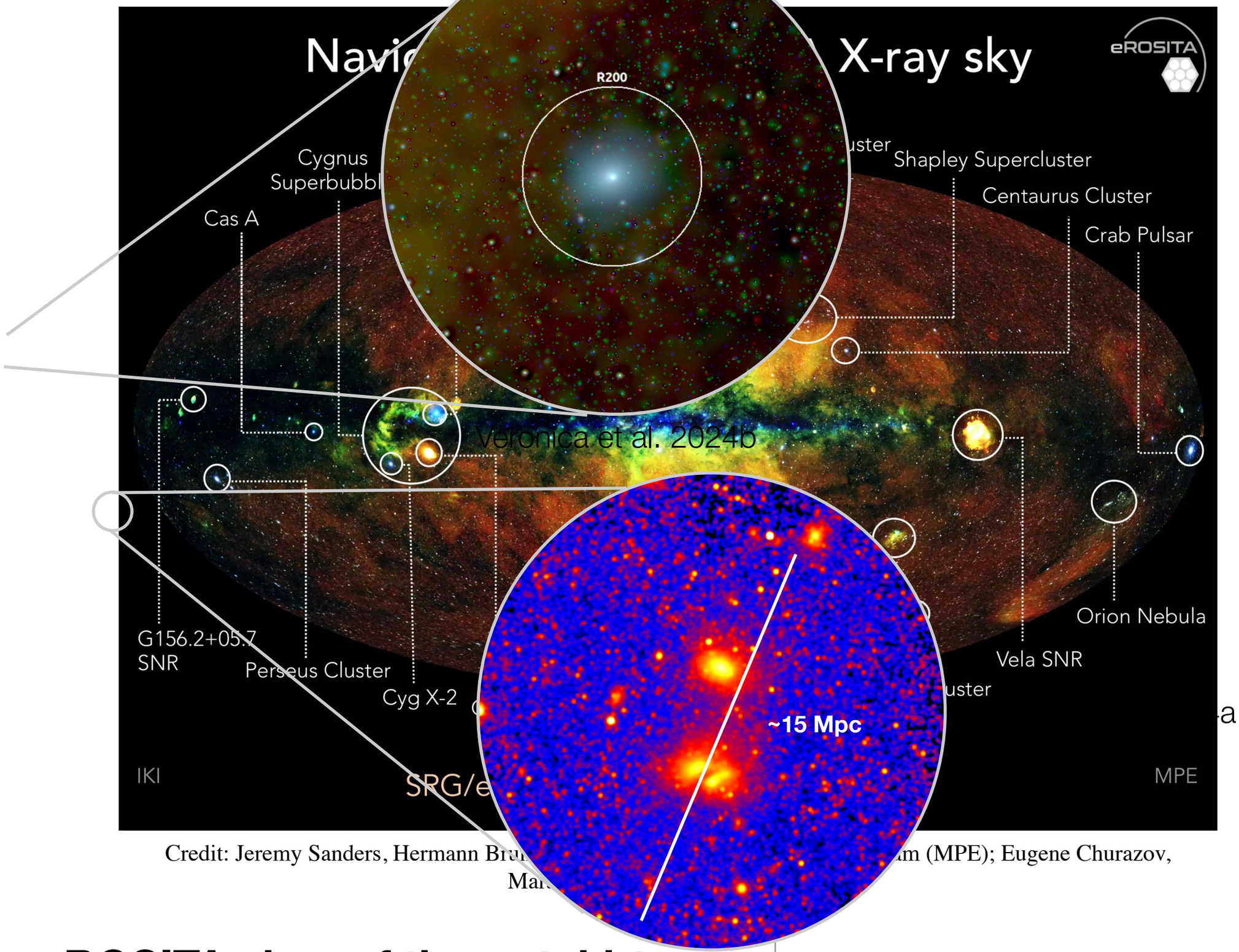
Suzaku observations of the Centaurus cluster.
Source: Walker et al. (2013).

A3391/95

- Binary galaxy cluster system
- mean z ~ 0.053
- members: Abell 3391, Abell 3395, filament (ESO161)
- Observed by: RASS, Suzaku, Chandra, XMM-Newton, eROSITA, and others



Source: Sugawara et al. 2017



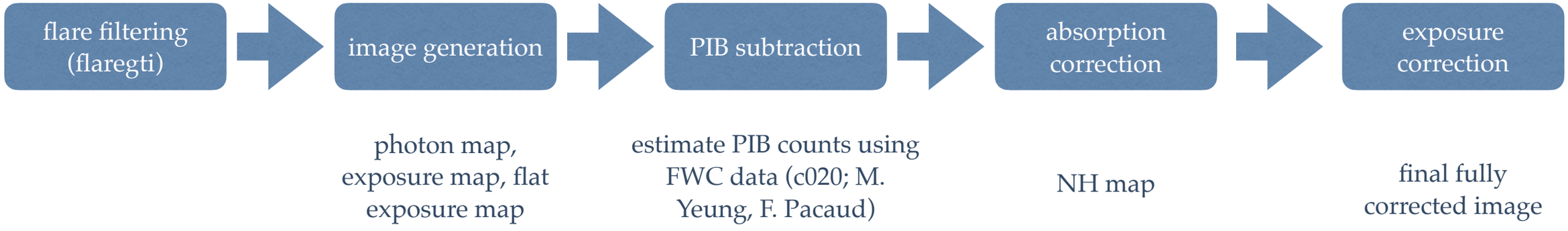
Credit: Jeremy Sanders, Hermann Bru m (MPE); Eugene Churazov, Mar

The eROSITA view of the outskirts and filaments

Centaurus cluster & A3391/95 cluster system

Analyses

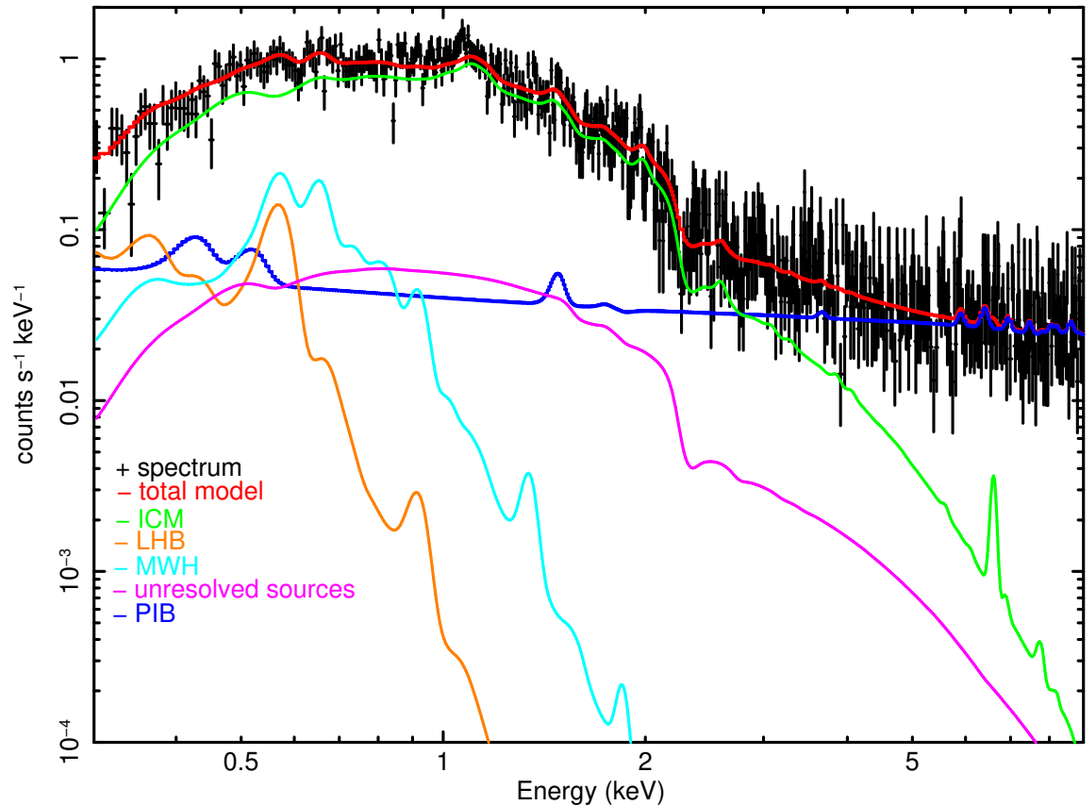
- Imaging analysis



- Spectroscopy

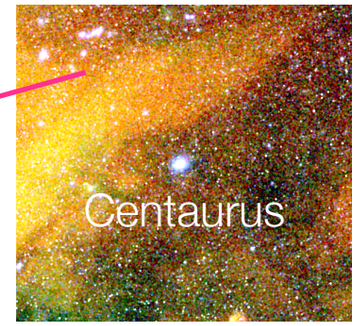
$$\text{Model} = \underbrace{\texttt{apec}_{\texttt{LHB}} + \texttt{TBabs} \times (\texttt{apec}_{\texttt{MWH}} + \texttt{powerlaw})}_{\text{CXB component}} + \underbrace{\texttt{TBabs} \times \texttt{apec}_{\texttt{clus}}}_{\text{cluster/filament emission}} + \texttt{PIB},$$

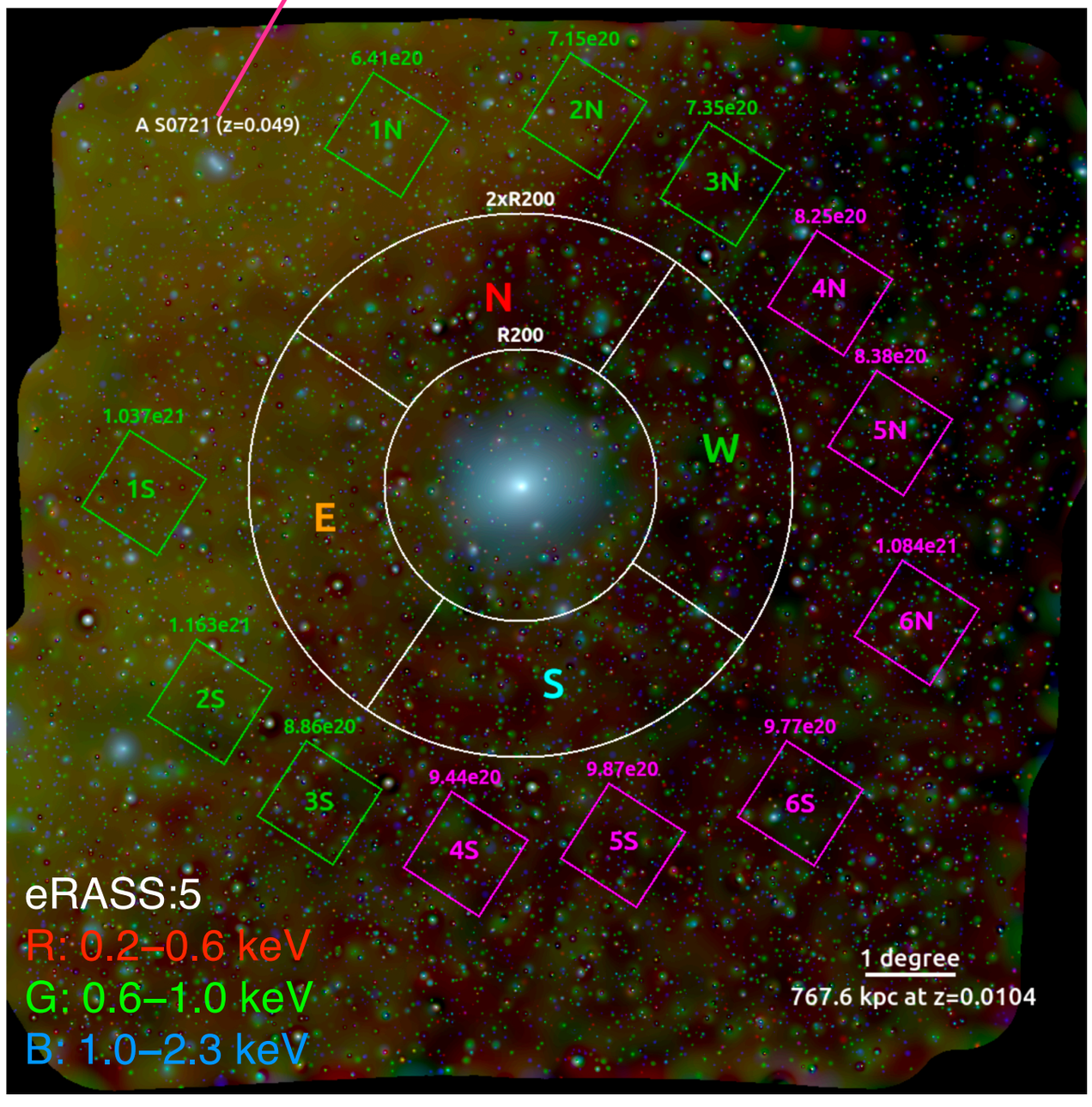
Central part of Centaurus cluster with the fitted total model and its components



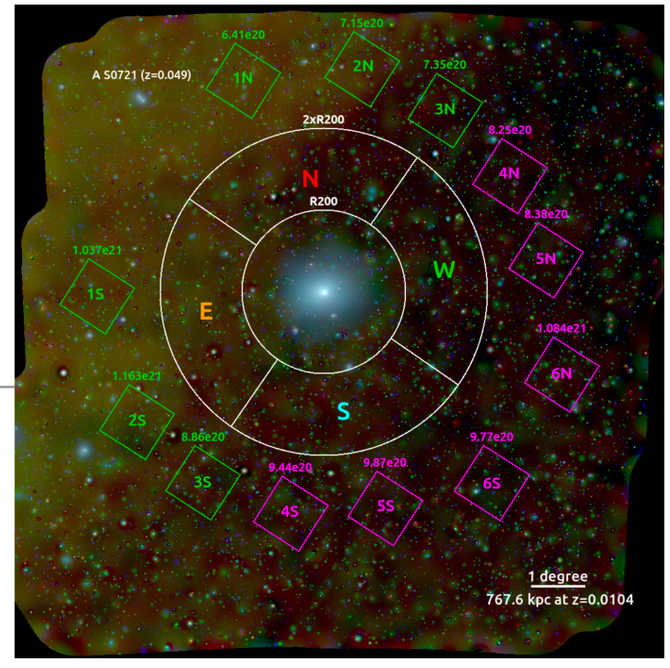
Centaurus Cluster with eRASS:5

- Additional foreground contamination by the *eROSITA Bubbles* (Predehl+20)





Spectral Analysis:
Profiles out to R_{200}

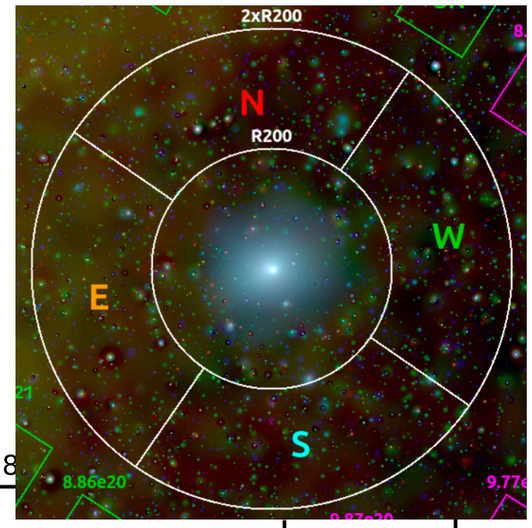


Total Model:

$$\text{Model} = \underbrace{\texttt{apec}_{\texttt{LHB}} + \texttt{TBabs} \times (\texttt{apec}_{\texttt{MWH}} + \texttt{apec}_{\texttt{eROBub}} + \texttt{powerlaw})}_{\text{CXB component}} + \underbrace{\texttt{TBabs} \times \texttt{apec}_{\texttt{clus}}}_{\text{cluster emission}} + \texttt{PIB}$$

X-ray spectroscopy in four directions.
The first to probe full azimuth out to R_{200}
(increasing the probed volume by a factor ~30)

Spectral Analysis:
Profiles out to R_{200}



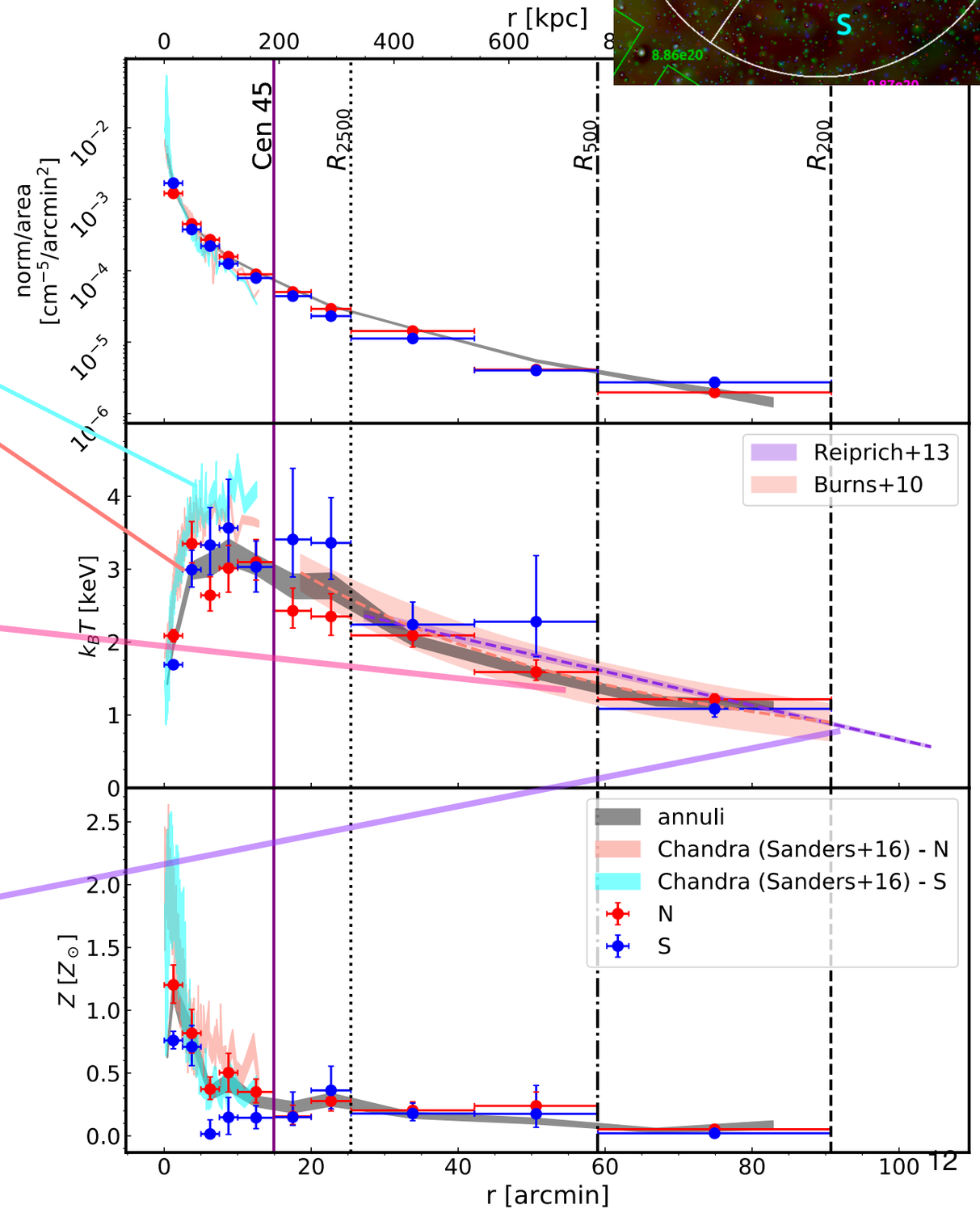
Chandra data points (Sanders+16)

T-profile from *Enzo* N-body+hydrodynamic simulations (Burns+10)

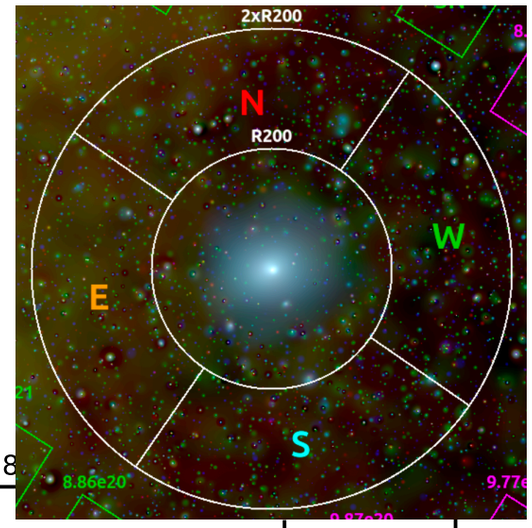
$$k_{\rm B}T(r) = A \cdot \langle k_{\rm B}T \rangle \left[1 + B\left(\frac{r}{R_{200}}\right)\right]^{\alpha}$$

T-profile from fit of Suzaku cluster outskirts measurements (Reiprich+13), for $0.3R_{200} < r < 1.15R_{200}$

$$k_{\rm B}T(r) = \left(1.19 - 0.84\frac{r}{R_{200}}\right) \cdot \langle k_{\rm B}T \rangle.$$



Spectral Analysis:
Profiles out to R_{200}

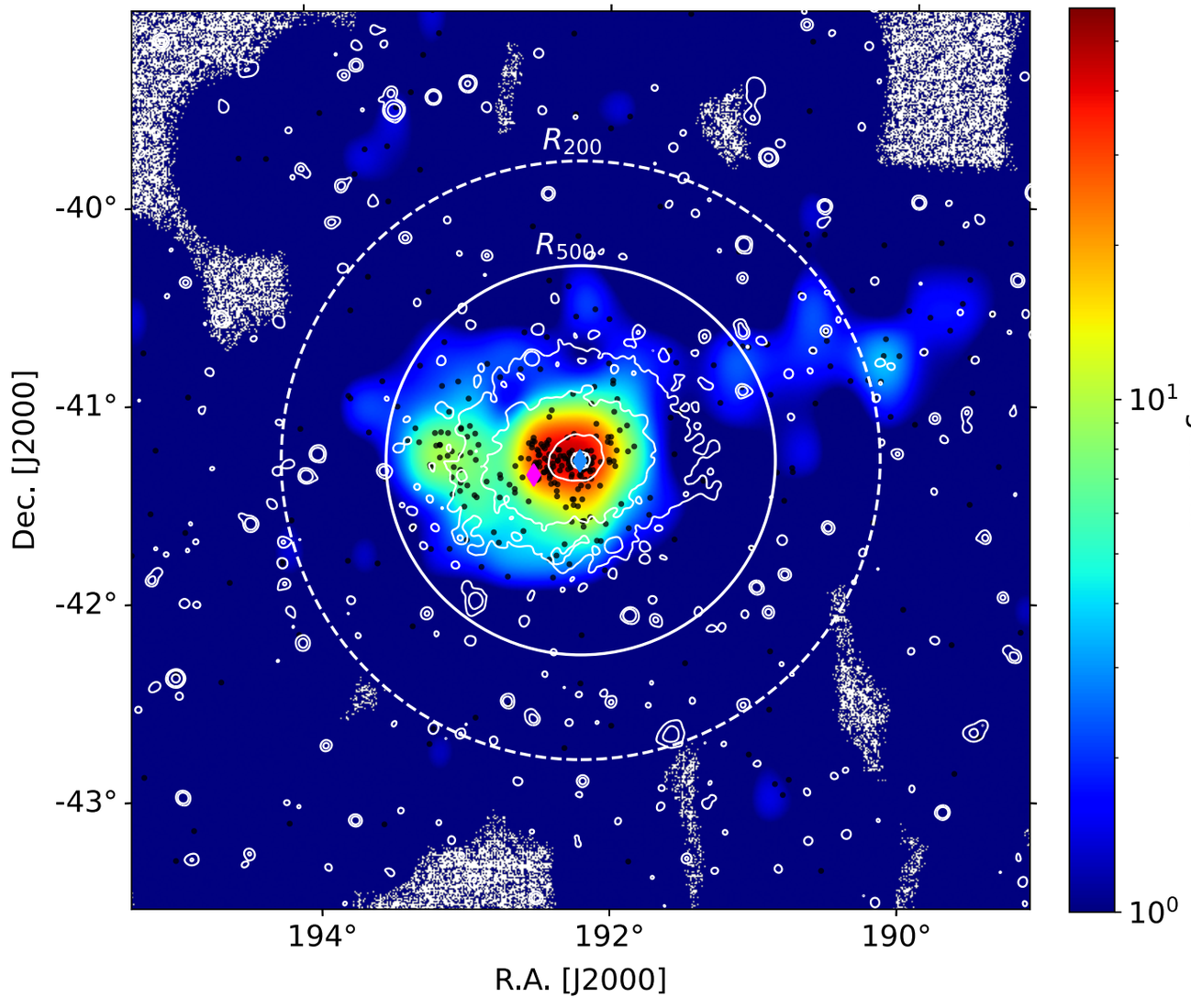


Chandra are systematically hotter
=> Cross-calibration (Migkas+24)

Good agreement with simulations and other outskirts measurements
=> absence of LSS?

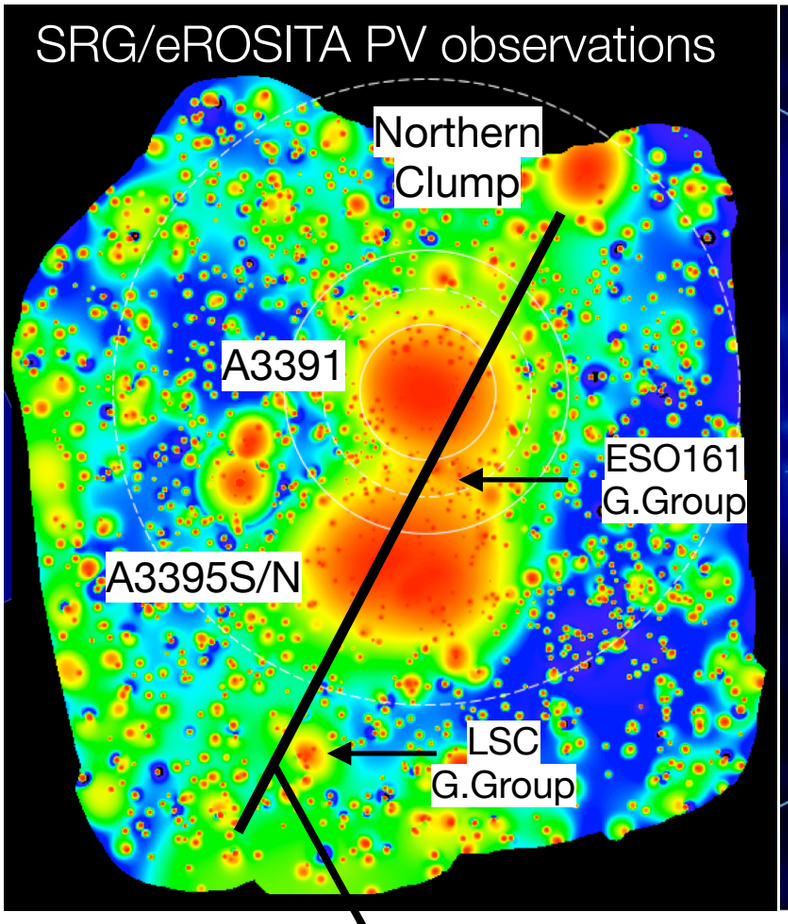
Centaurus Cluster

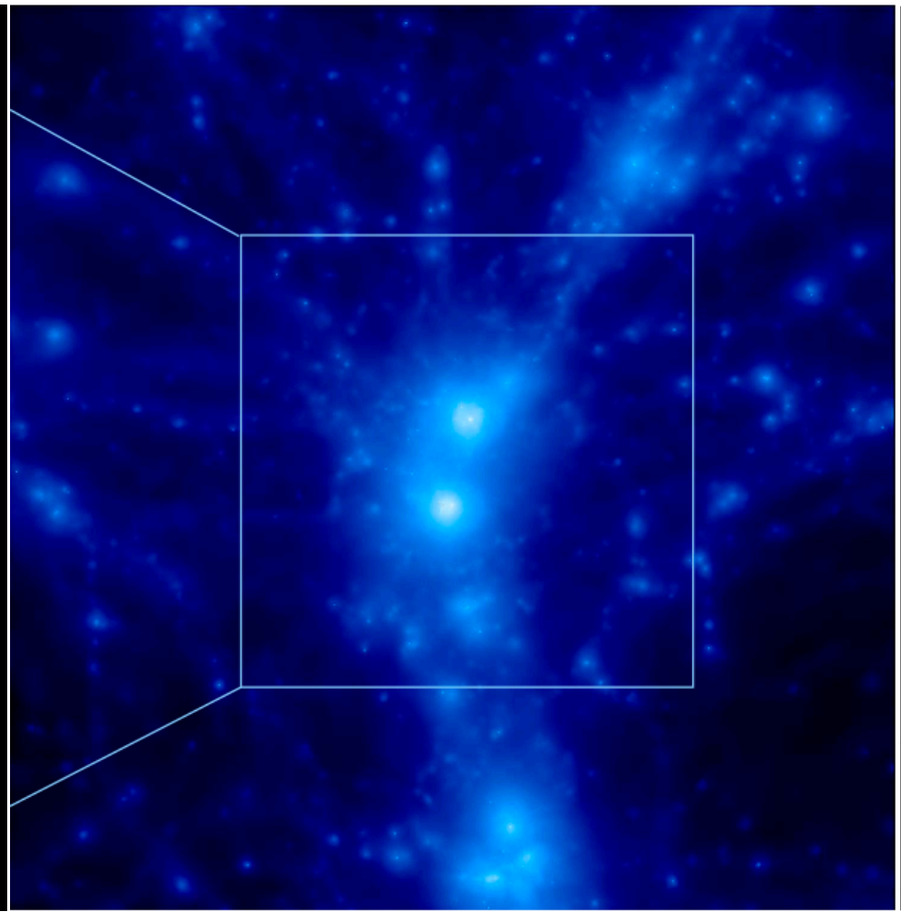
- The cluster appears relaxed/ regular at larger radii
- No large-scale structure found

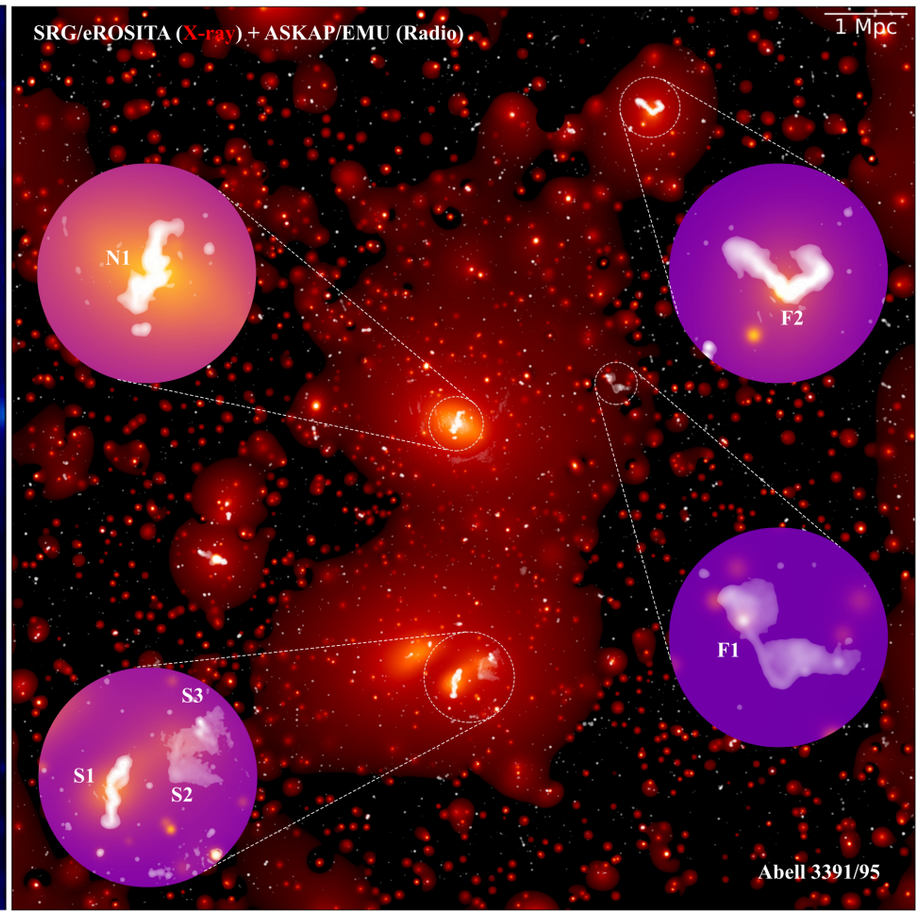


Galaxy number density map
Galaxy information is obtained from NED)

A3391/95 System







Discovery, Reiprich+21

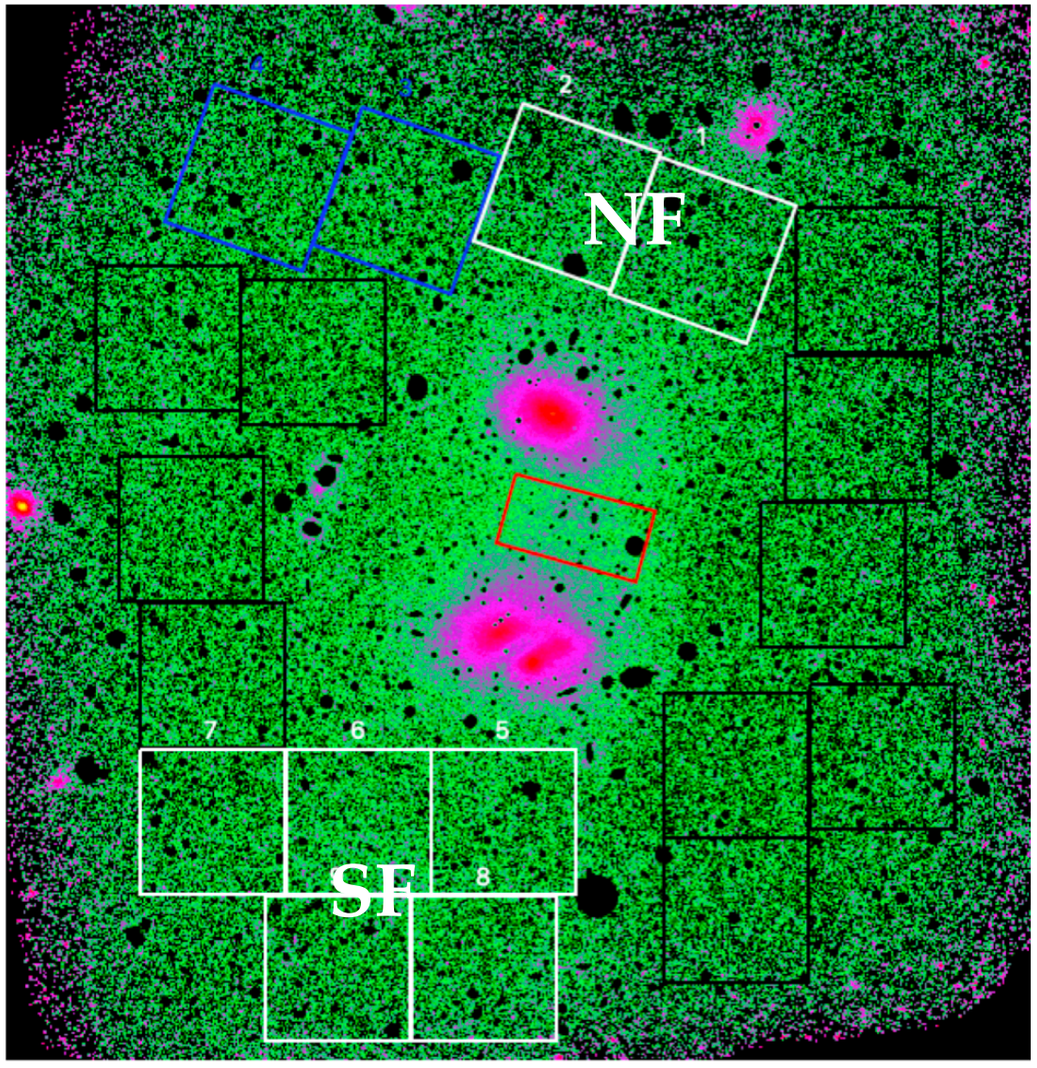
Magneticum Simulation, Biffi+22

ASKAP/EMU radio, Brüggen+21

15 Mpc Continuous Warm-Hot Emission

Surface brightness excess and significances of the detected filaments (Reiprich+21)

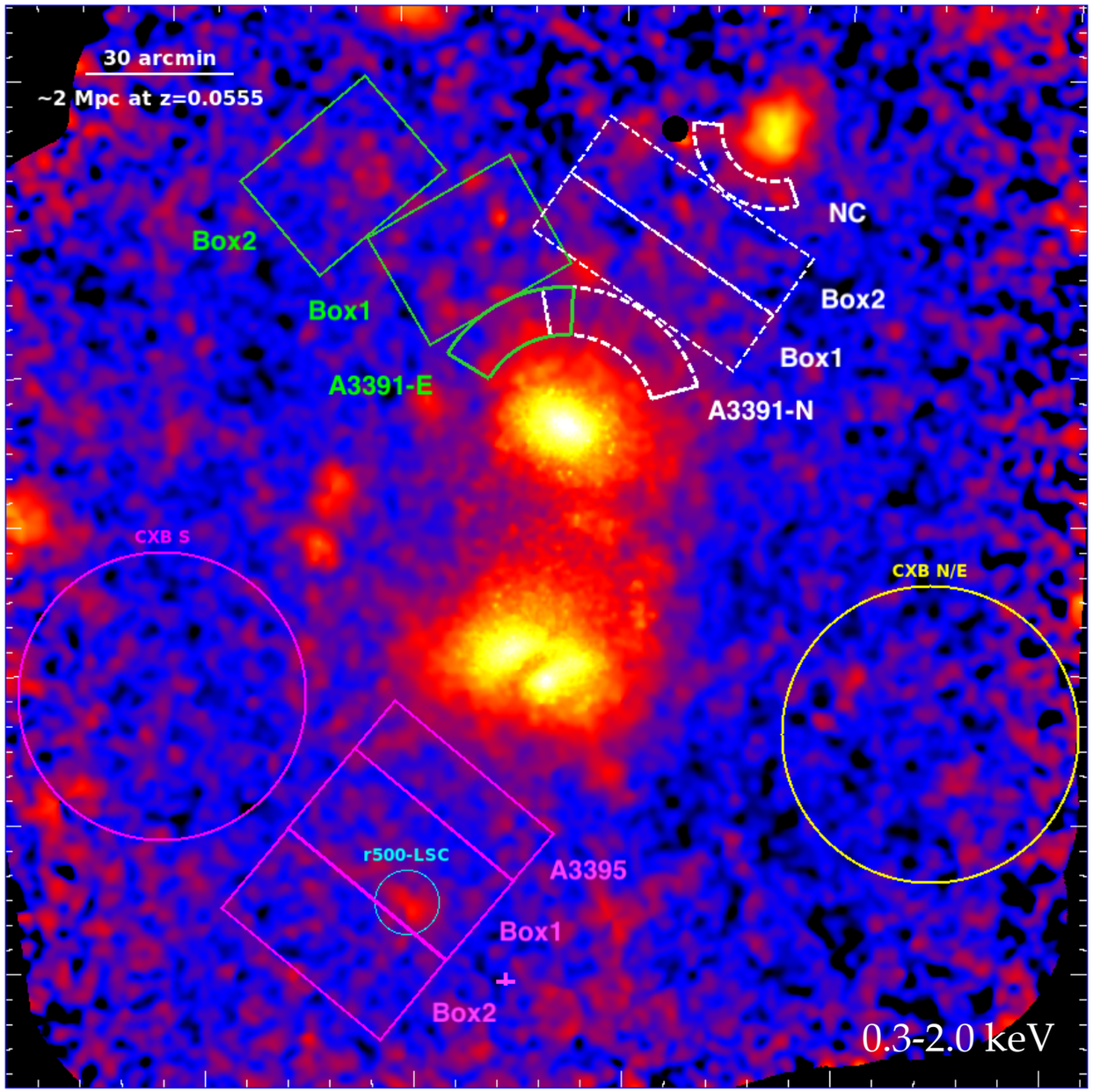
(Reiprich+21)



Filament	Surface brightness excess	Significance
Northern Filament	$\left(23.5^{+2.7}_{-2.6}\right)\%$	$\left(4.6^{+1.5}_{-1.3}\right)\sigma$
Southern Filament	$\left(20.7^{+2.4}_{-2.3}\right)\%$	$\left(4.1^{+1.3}_{-1.1}\right)\sigma$
Eastern Filament	$\left(14.4^{+2.5}_{-2.4}\right)\%$	$\left(2.8^{+1.0}_{-0.8}\right)\sigma$
Bridge	$\left(137.0^{+7.2}_{-6.7}\right)\%$	$\left(26.9^{+8.2}_{-7.0}\right)\sigma$

Fig. F.1. Box selection for the determination of excess surface brightnesses and significances. All rectangular boxes have a side length of 0.5 deg. See text for details.

Spectral Analysis



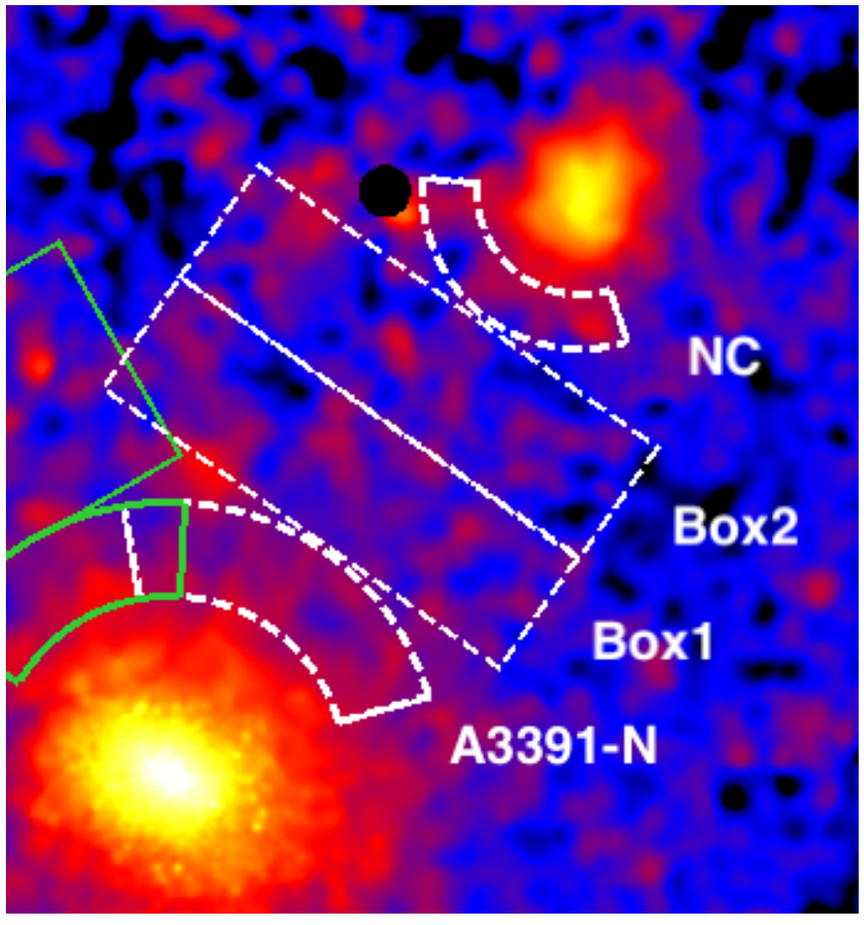
Definitions:

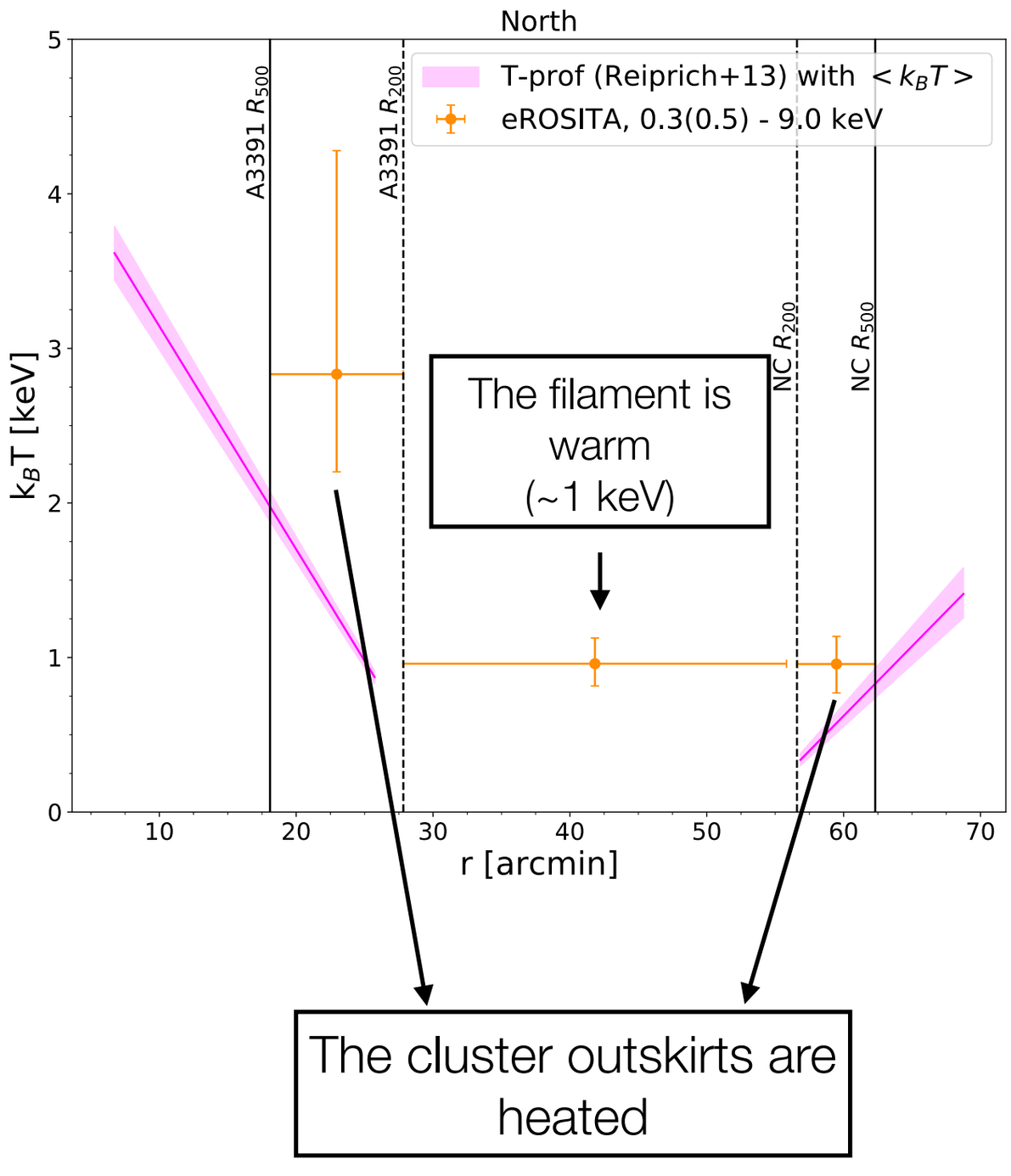
- Outskirts: $R_{500} < r < R_{200}$
- Filament: $> R_{200}$

Filament lengths:

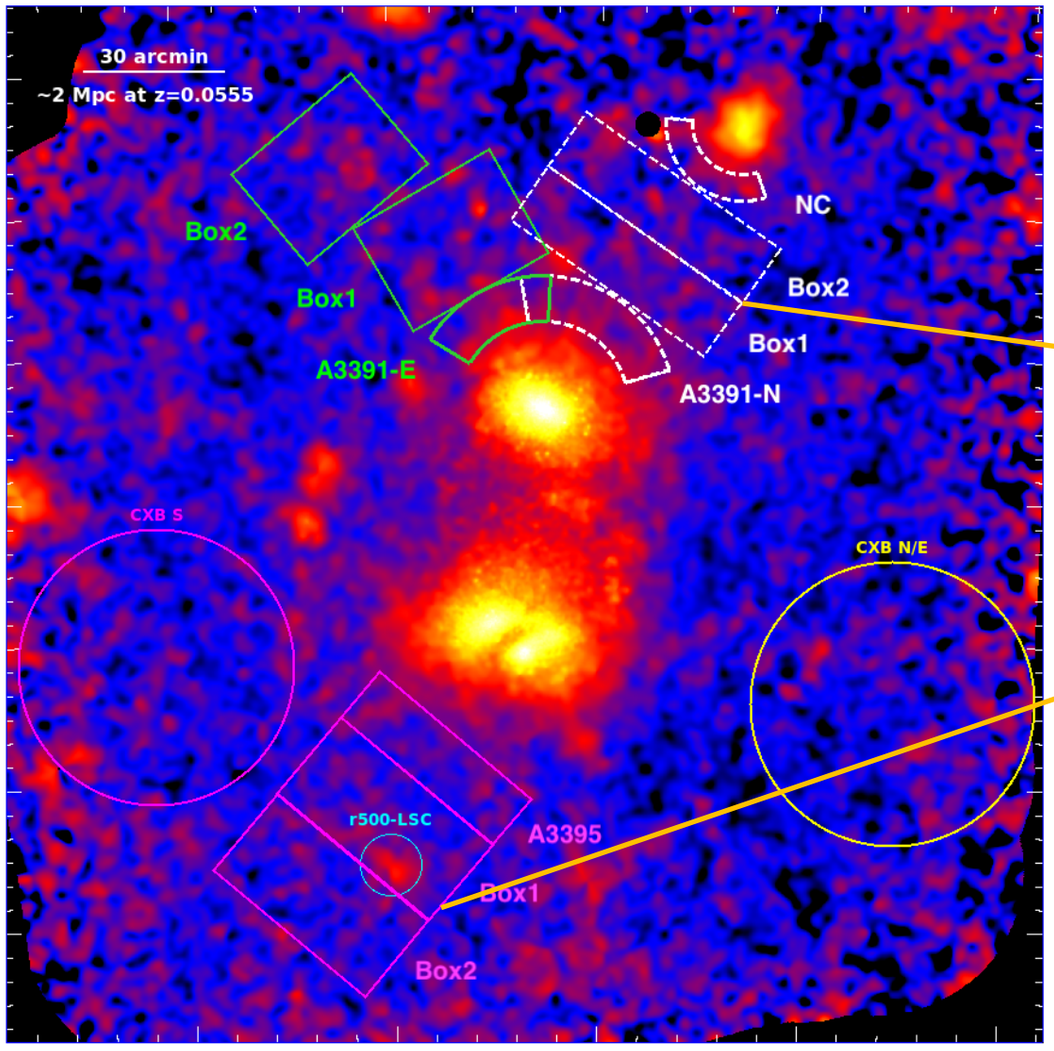
- NF: 1.8 Mpc
- SF: 2.7 Mpc

Results: Outskirts





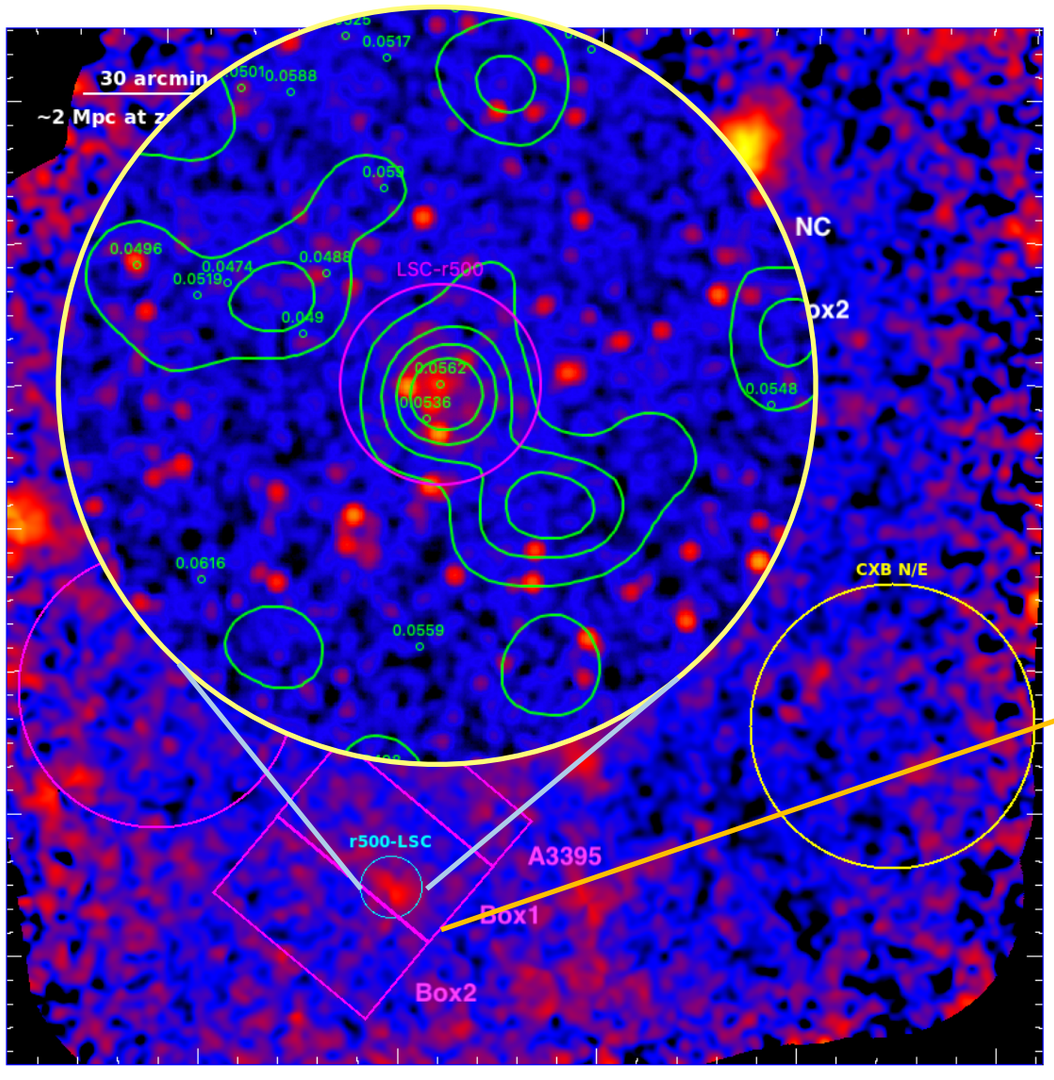
Results: Filaments



Temperatures:

$k_{\mathrm{B}}T \sim 1\,\mathrm{keV}$

Results: Filaments



Baryon overdensity:

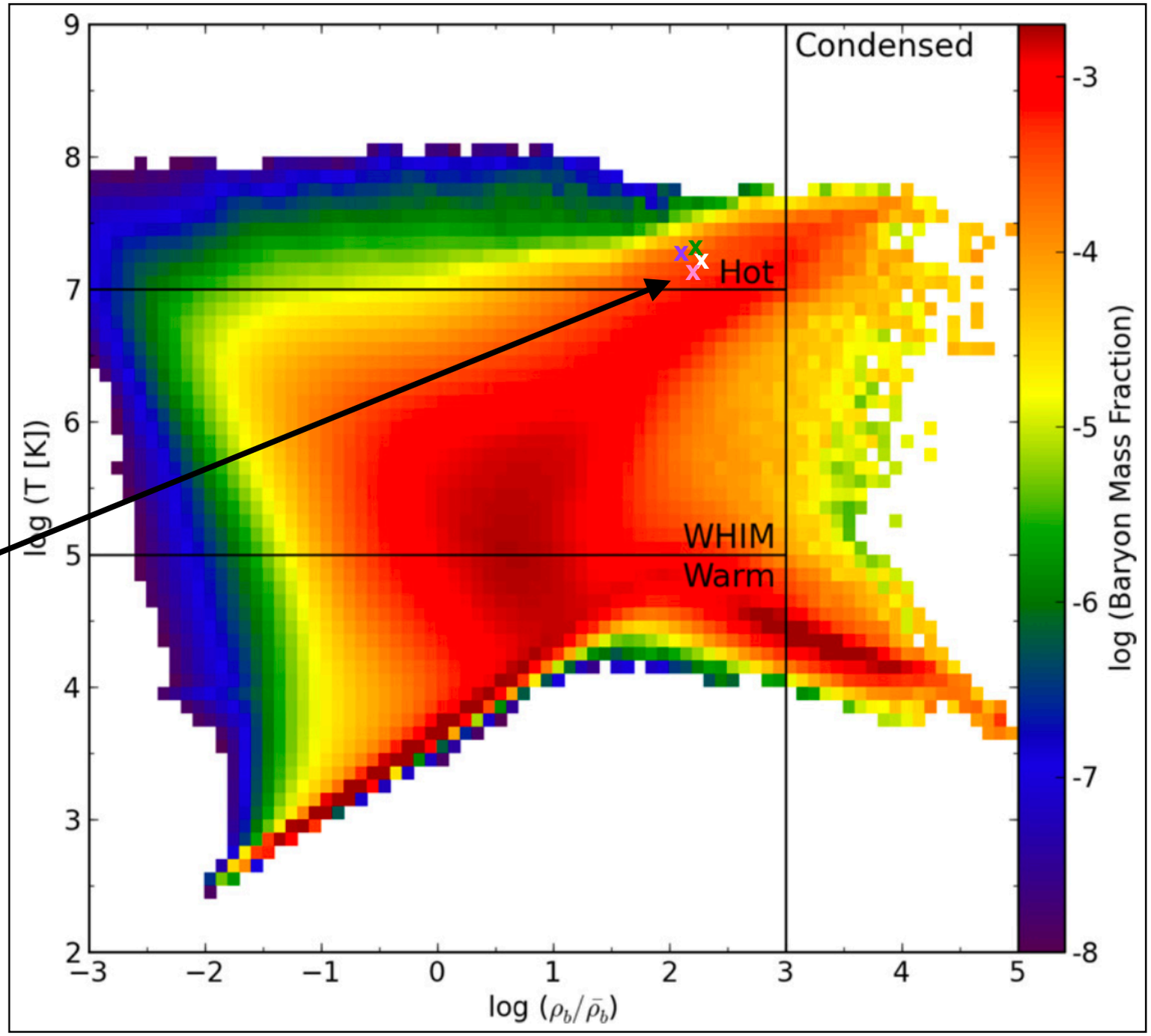
$$\delta_b = 166 \pm 14$$

~30% decreases

$$\delta_{b,\mathrm{woLSC}} = 117^{+17}_{-19}$$

Baryon distribution in the 2D phase space of baryon temperature and baryon over-density (Shull+12).

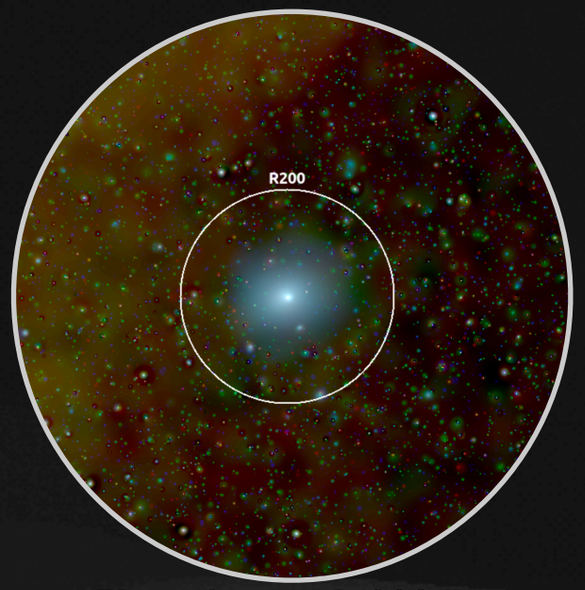
A3391/95 filaments:
$98 \leq \delta_b \leq 238$



Summary & Outlook

- **Outskirts**:
  - Presence of LSS can induce temperature deviation (e.g., shock heating).
- **Filaments**:
  - The n_e of the filaments are consistent with the predicted WHIM properties, but the **temperatures** are higher.
    - As both filaments are short (< 3 Mpc) and located in a denser environment, stronger gravitational heating may be responsible for this temperature enhancement.
  - The **metallicities** are low, but still within the expected range.
  - It is important to account for clumps as to not bias the density measurements.

- More such sample in eRASS data:
  - astrophysics in outskirts,
  - filament properties,
  - resolving small clumps/groups residing in filaments.



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Thank You!

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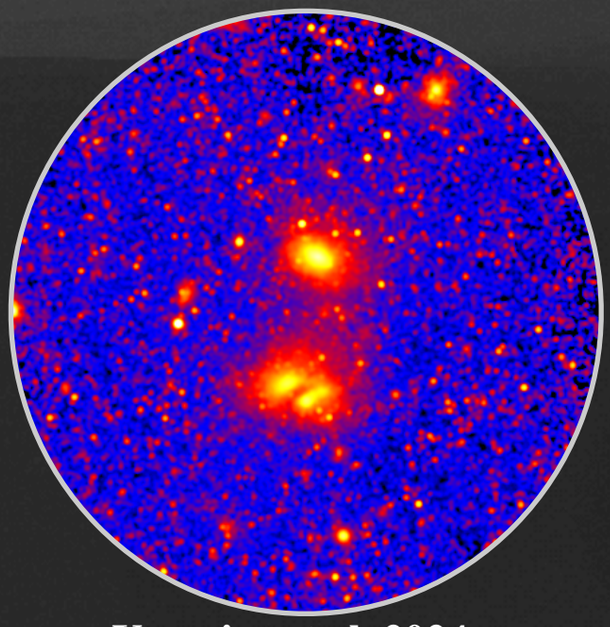

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