Based on
- Zhang et al. to be submitted (circumcluster environment)
- Zhang et al. 2024 (cosmic filaments)

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eROSITA view of the hot baryon beyond r_{200c} of massive halos

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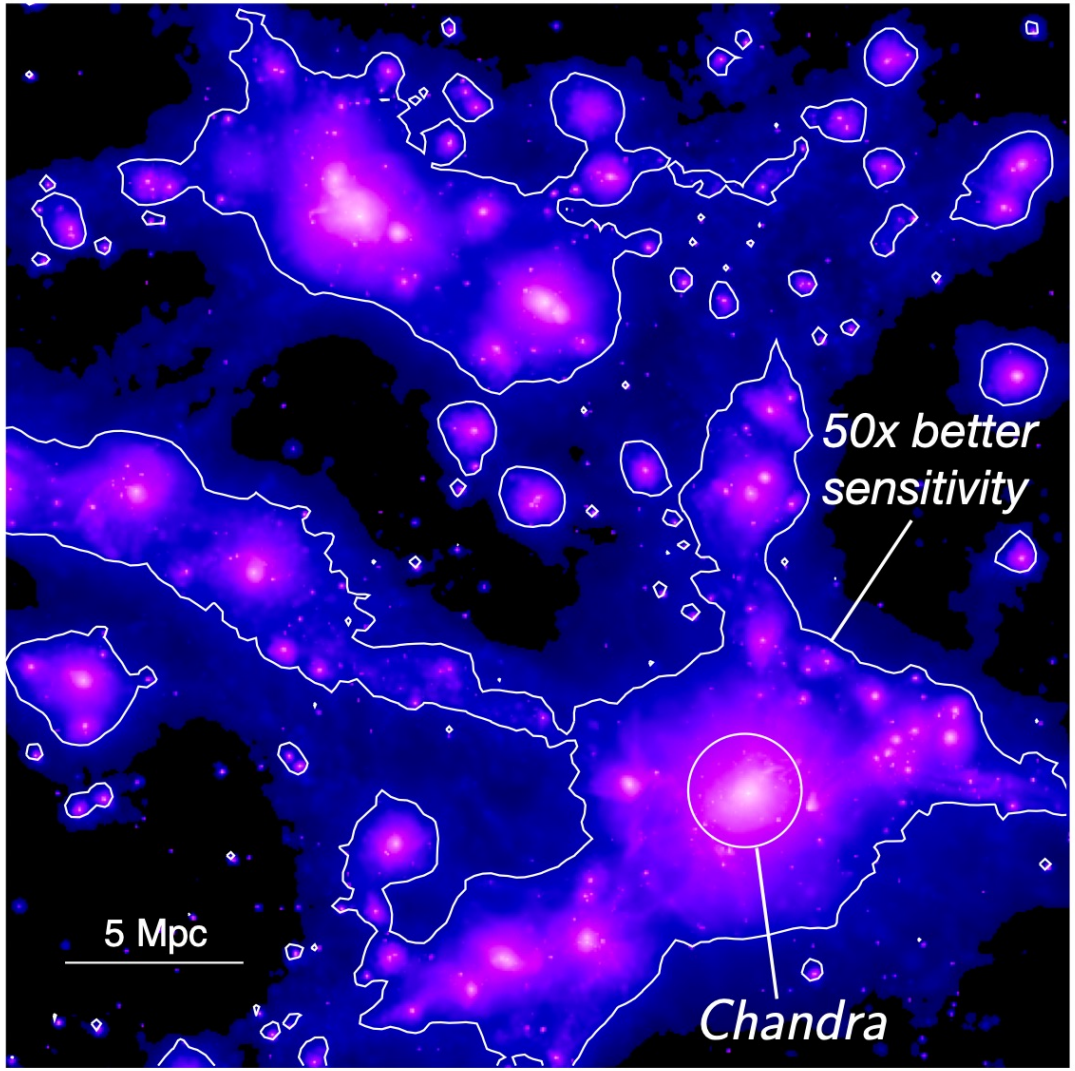
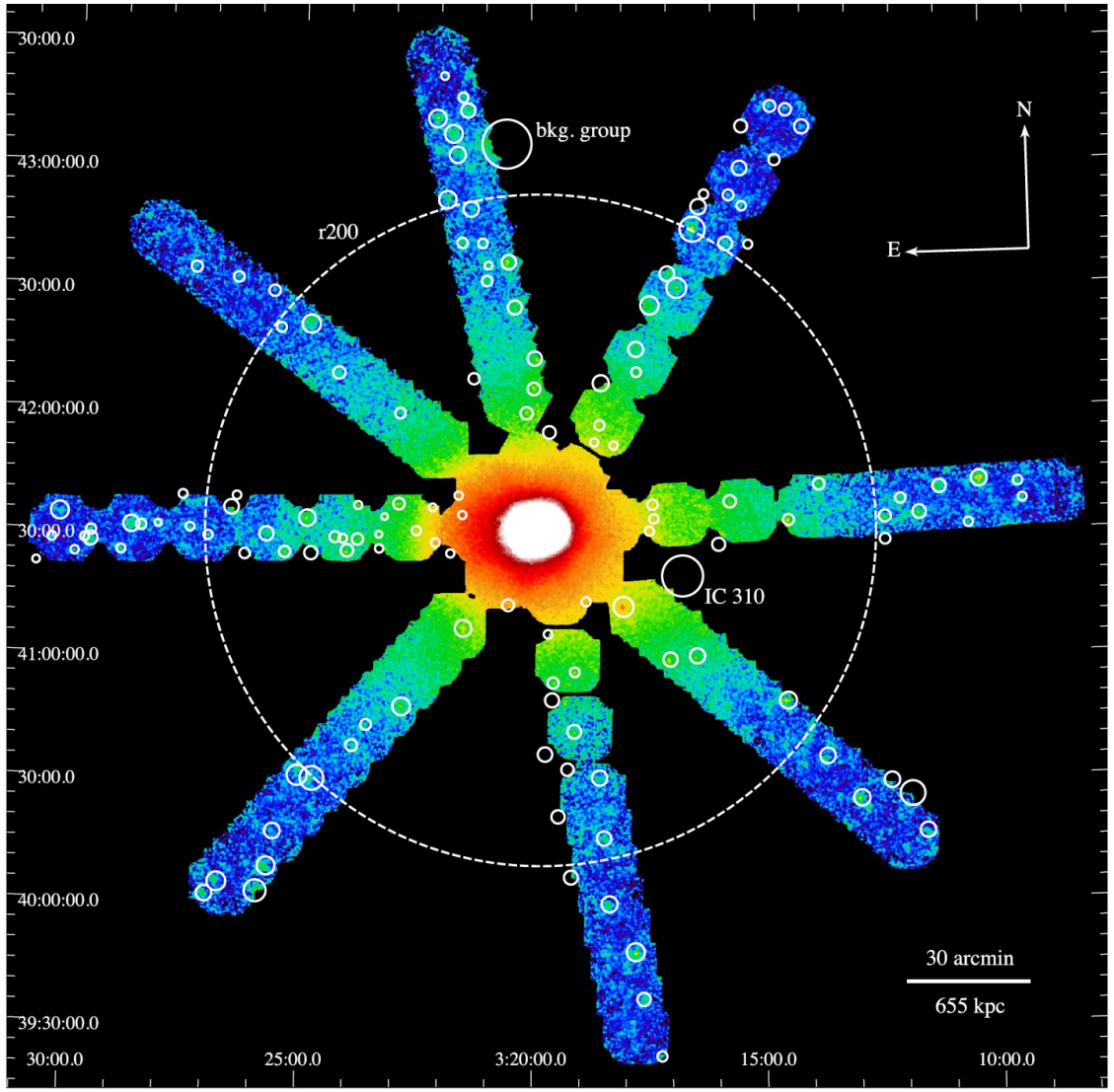
We are interested in baryon reservoirs



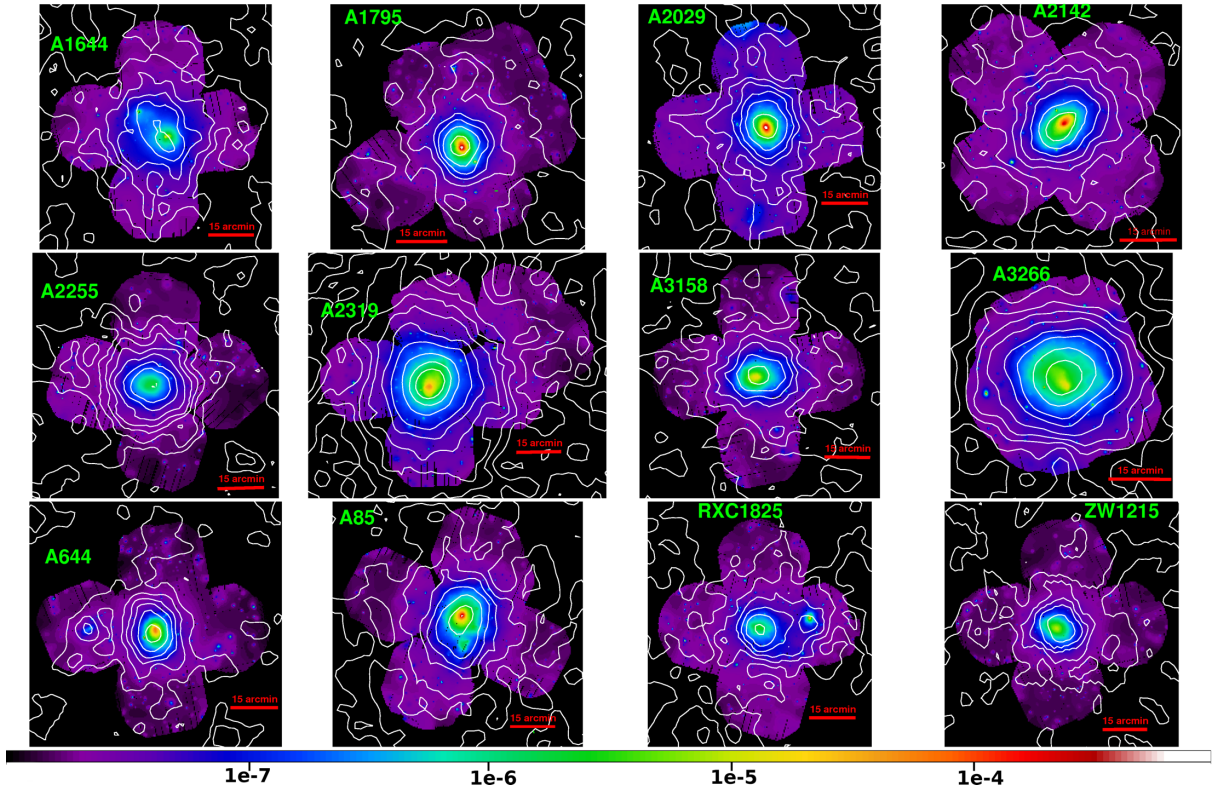
However,

- Telescopes have sensitivity limit
- X-ray fore/background is complicated

Walker+19

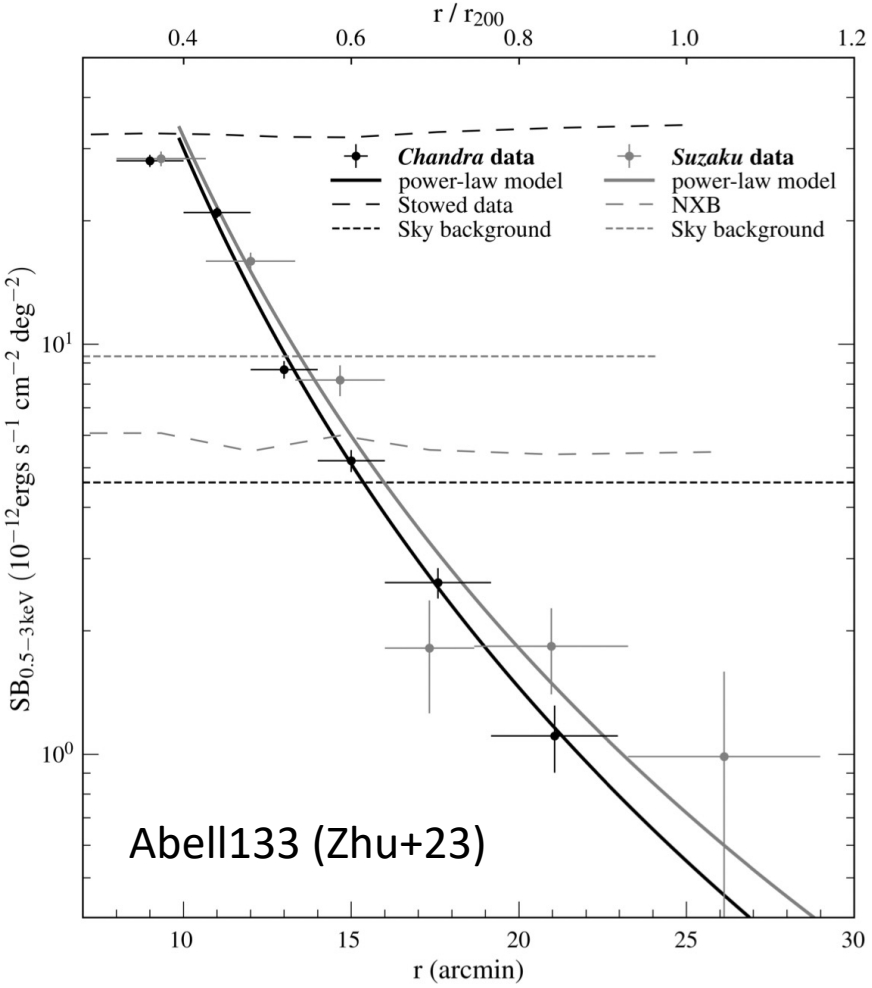


Suzaku mapping of the Perseus outskirts (Urban+17)

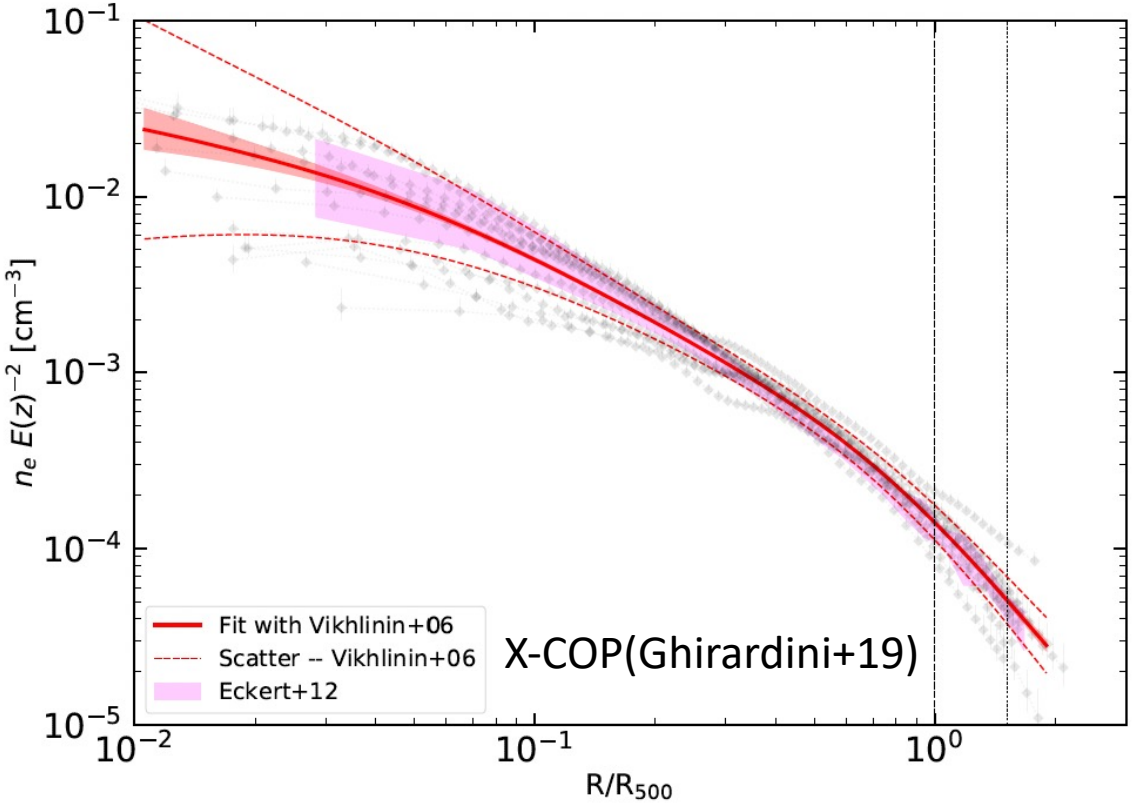


XMM-Newton X-COP
(Eckert+17, image credit: Vittorio Ghirardini)

X-ray SB & ICM density at r_{200c}

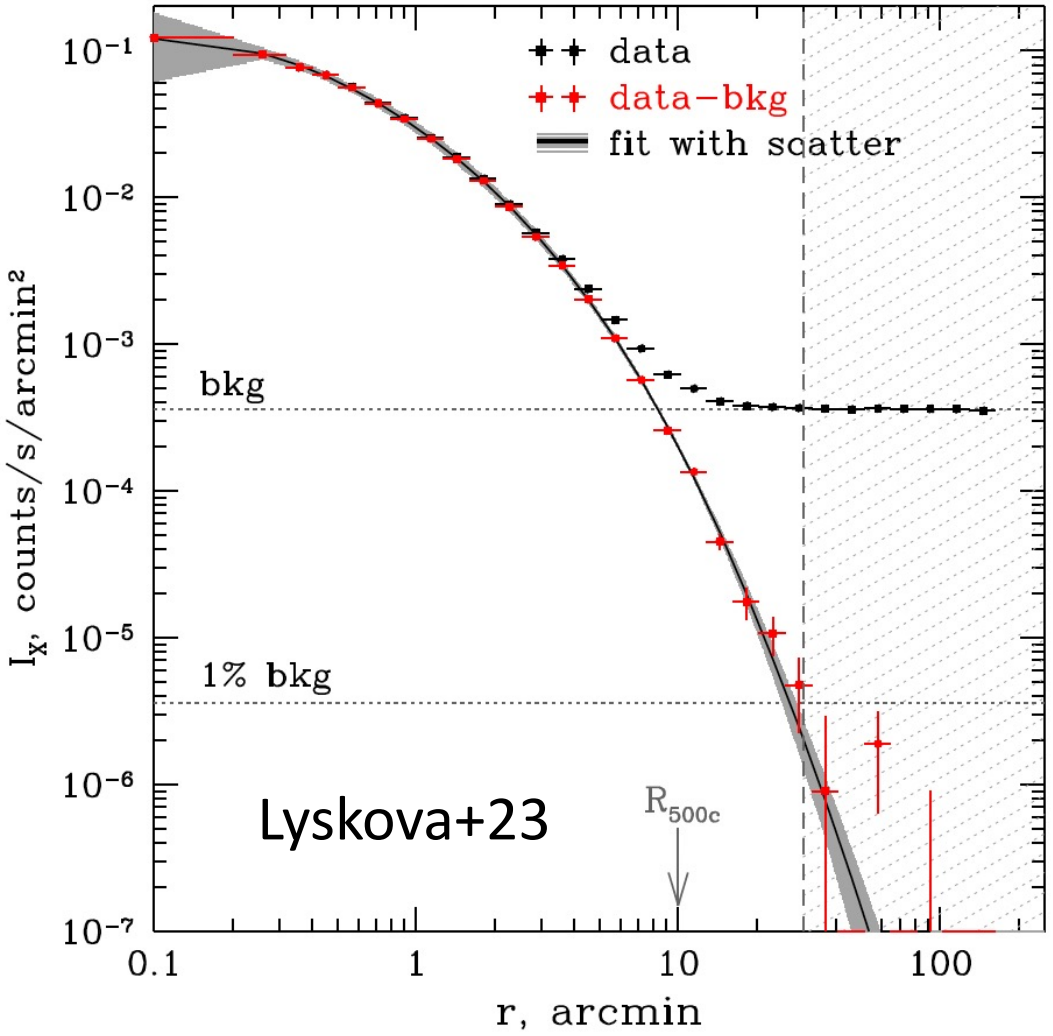


- $S_x < 10\% S_{x,sky}$

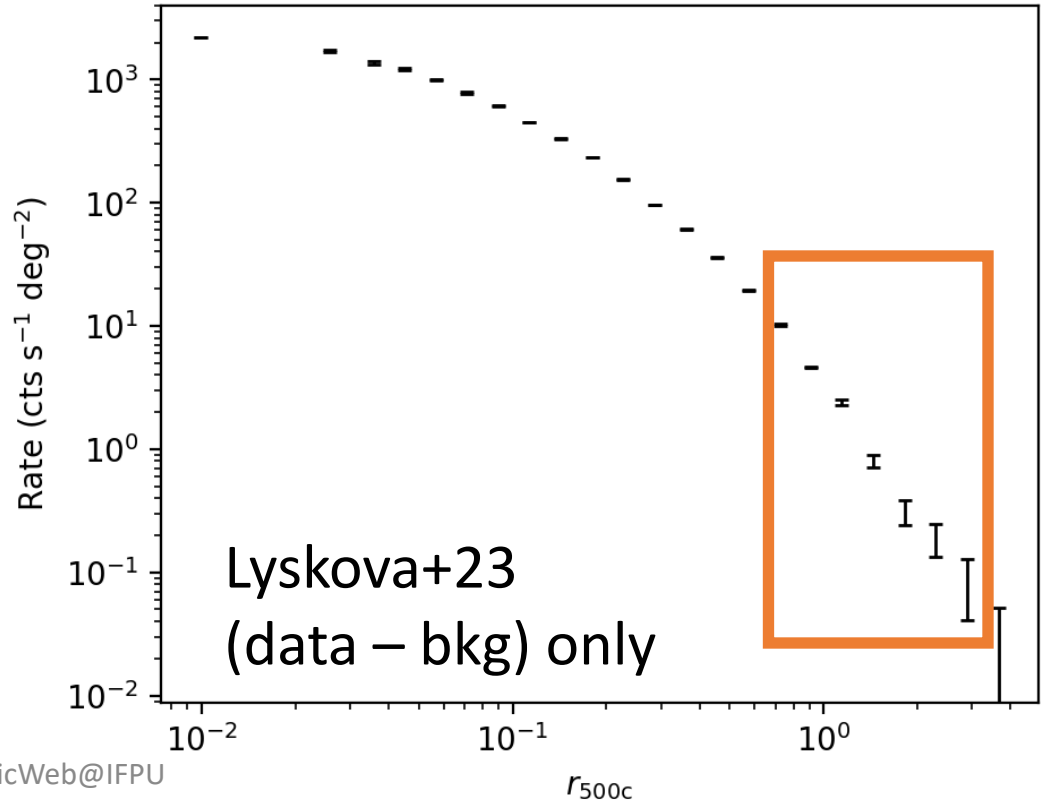


- $n_e \sim 5\times10^{-5}$ cm^{-3} -> $\Delta_b \sim$ **120**
- A **dense** environment
- Outskirts but not boundary

eRASS stacking of 38 PSZ (CHEX-MATE) clusters



- Stray light removed
- Modified Vikhlinin06 profile (3+ parameters)



Questions to be addressed

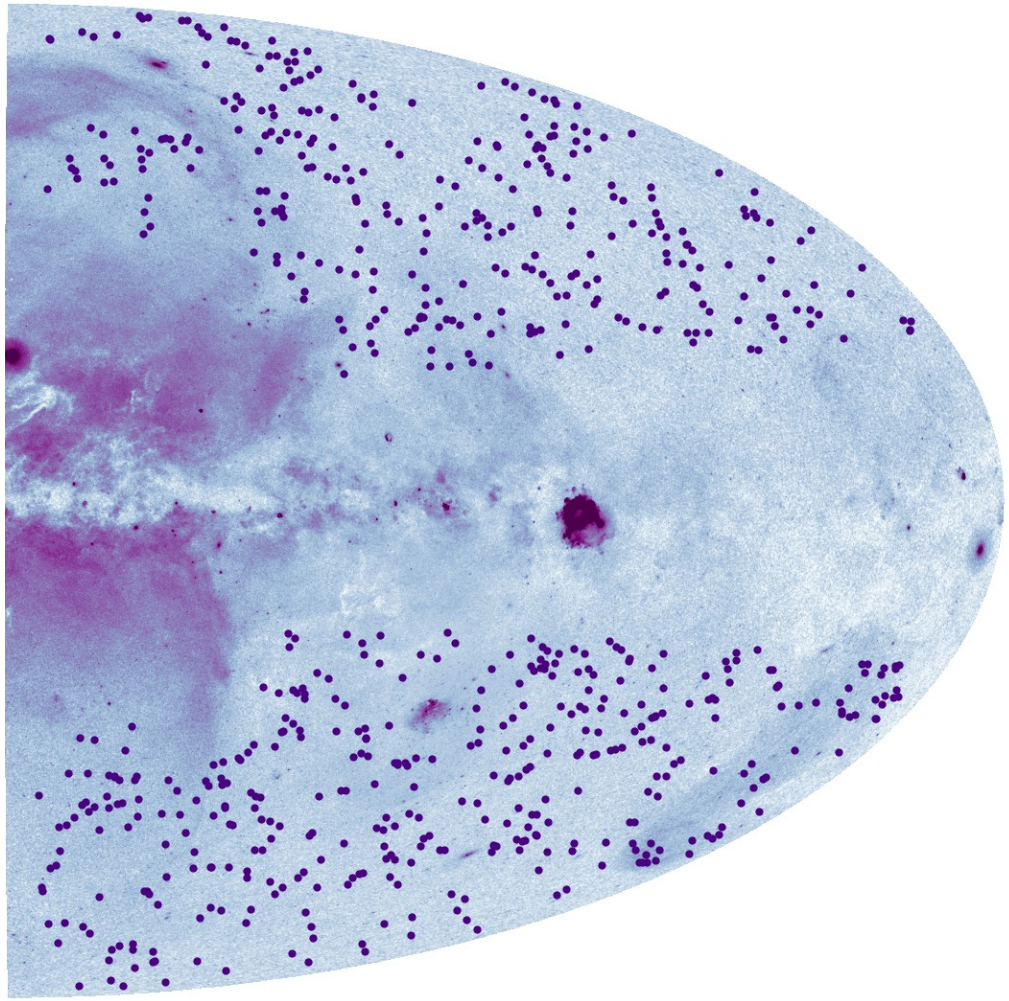
- Where is the boundary of a (gaseous) halo?
  - Where do halo – filament connections happen?
- What are the spatial & thermodynamic structures of gas around & beyond halo boundary?
- Baryon budget in halos & halo baryon budget in the Universe

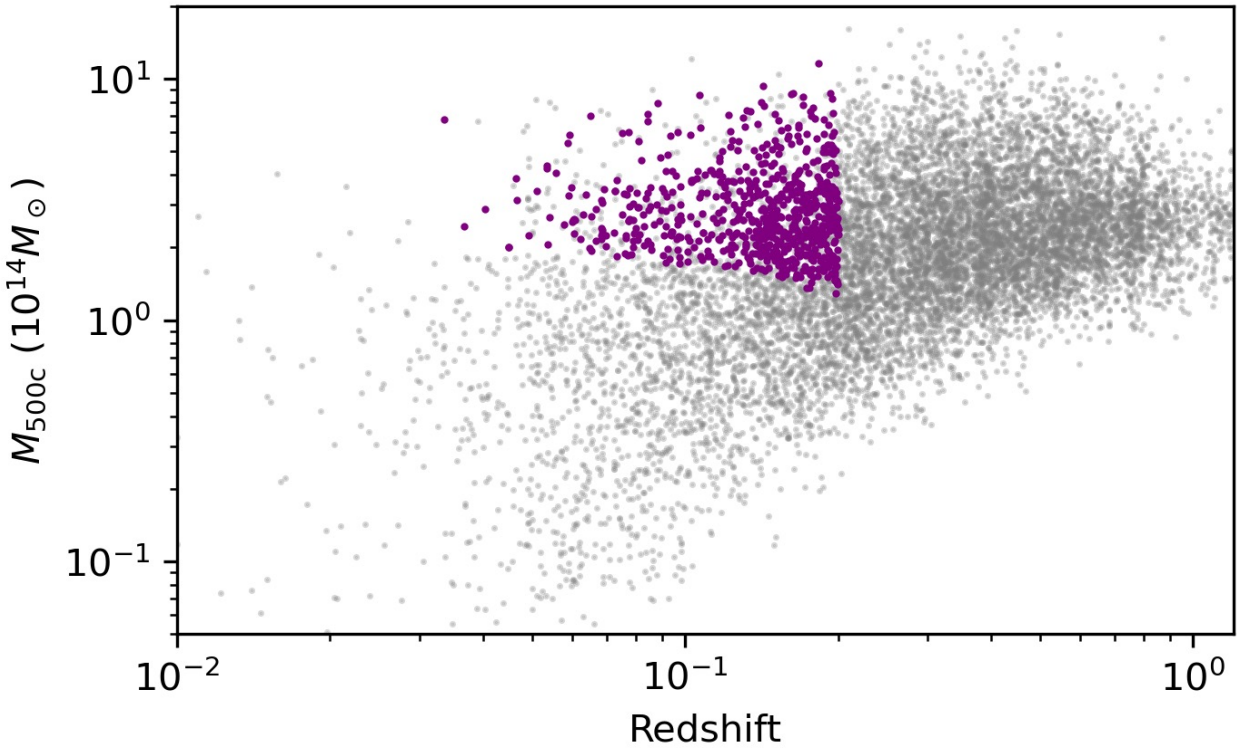
Stacking eRASS X-ray events

- Given a set of objects with positions $P(\boldsymbol{x})$, and a field $F(\boldsymbol{x})$
  - $\xi_{PF}(r) = \langle P(\boldsymbol{x})F(\boldsymbol{x}+\boldsymbol{r})\rangle$
- $P(\boldsymbol{x})F(\boldsymbol{x}+\boldsymbol{r})$: profile $F(r)$ around position $\boldsymbol{x}$

- Searching for **correlated** signal from input objects and the observed events

680 galaxy clusters

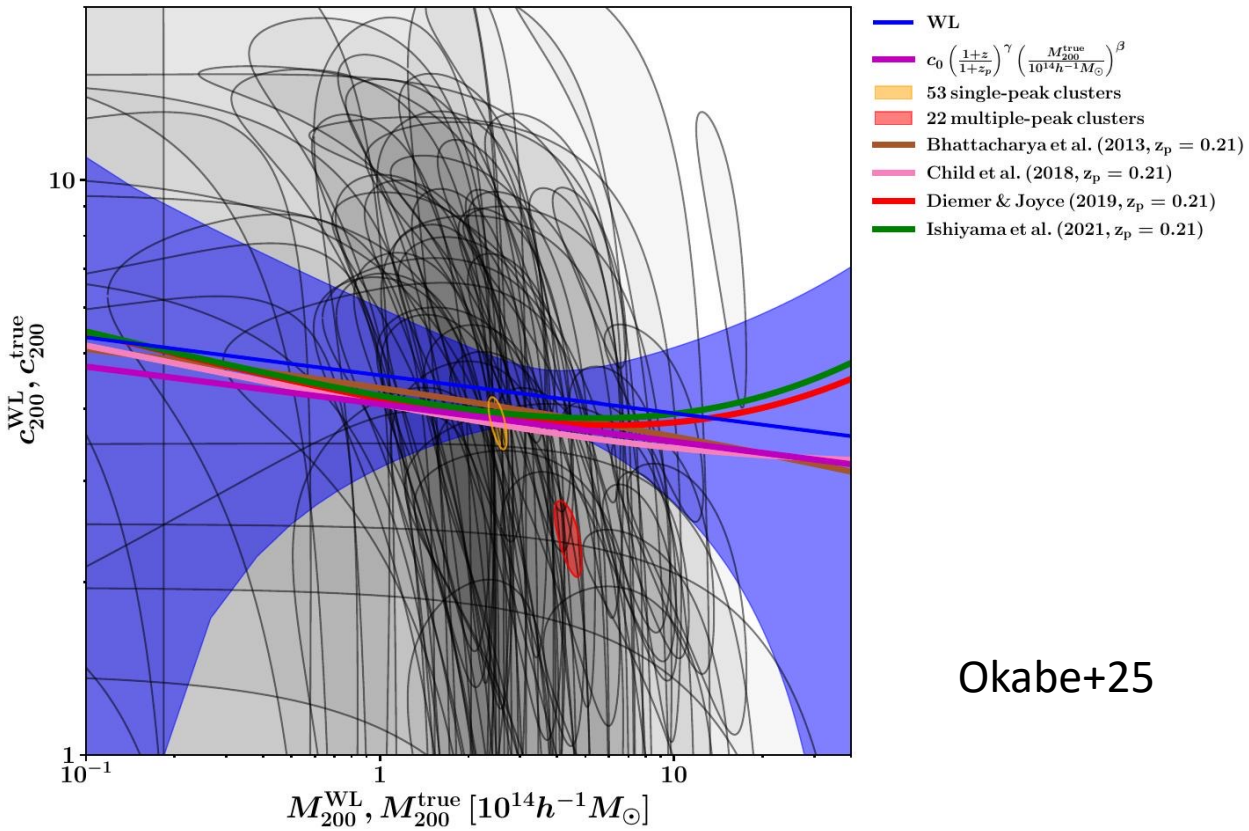




- eRASS1 X-ray selected clusters (Bulbul+24)
- $0.03 < z < 0.2$
- $L_{0.5\text{-}2keV} > 2\times10^{43}$ erg s^{-1}

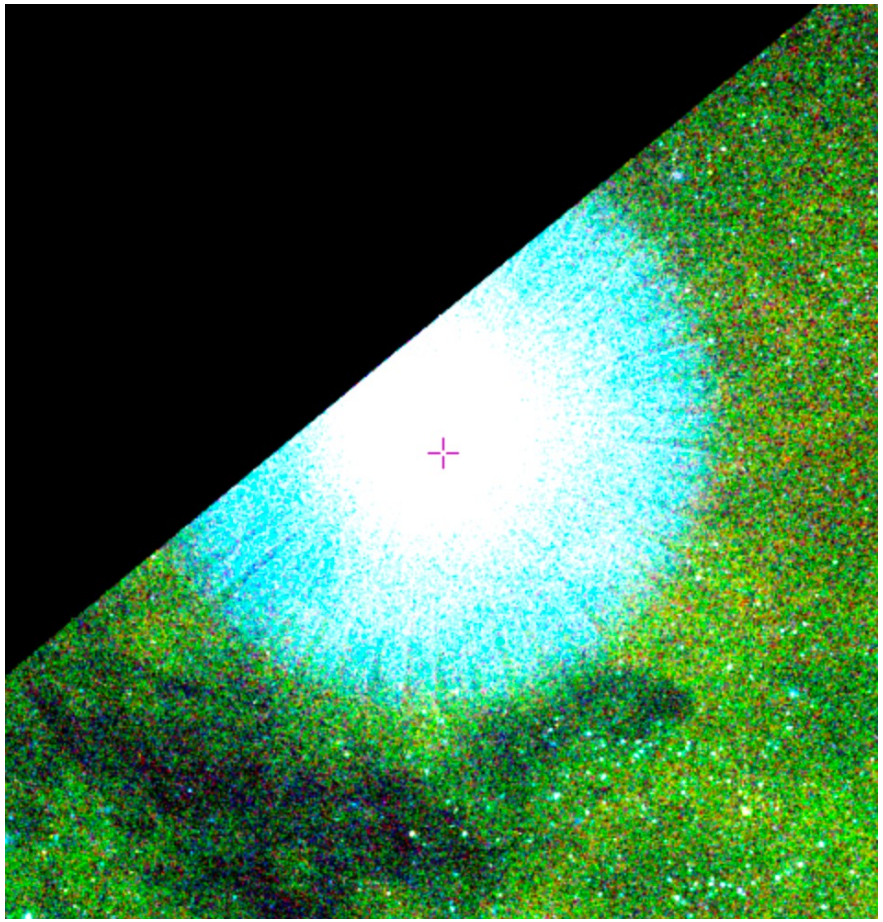
r_{200m} based scaled radius

- $c_{200c} = 4$ for r_{500c} to r_{200m} conversion

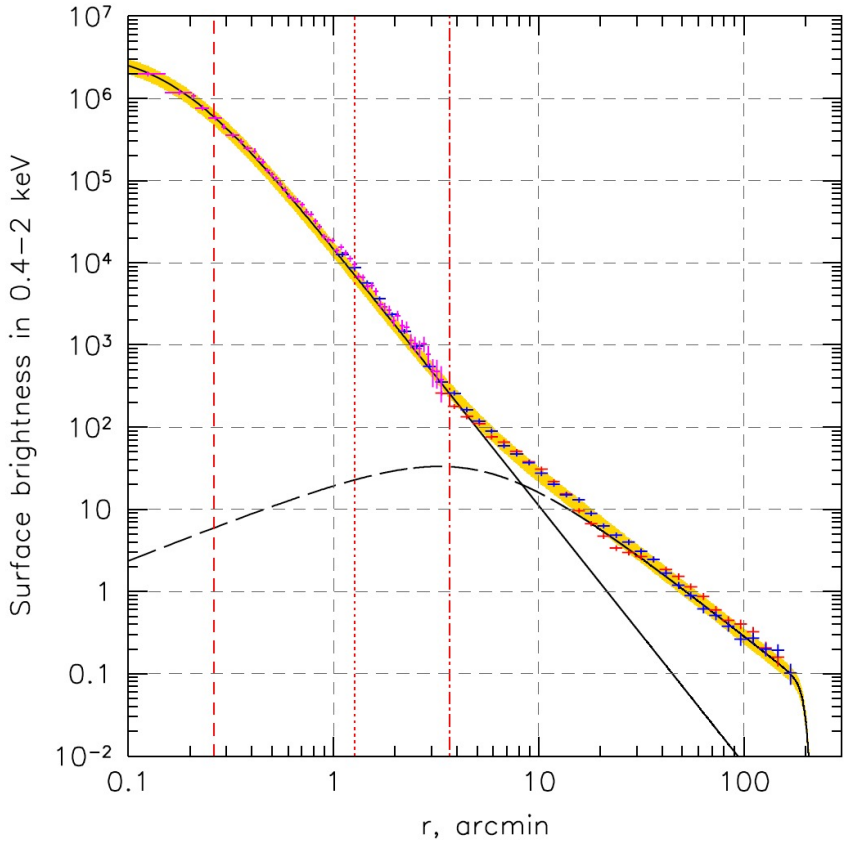


Okabe+25

eROSITA stray light (~200’ radius)



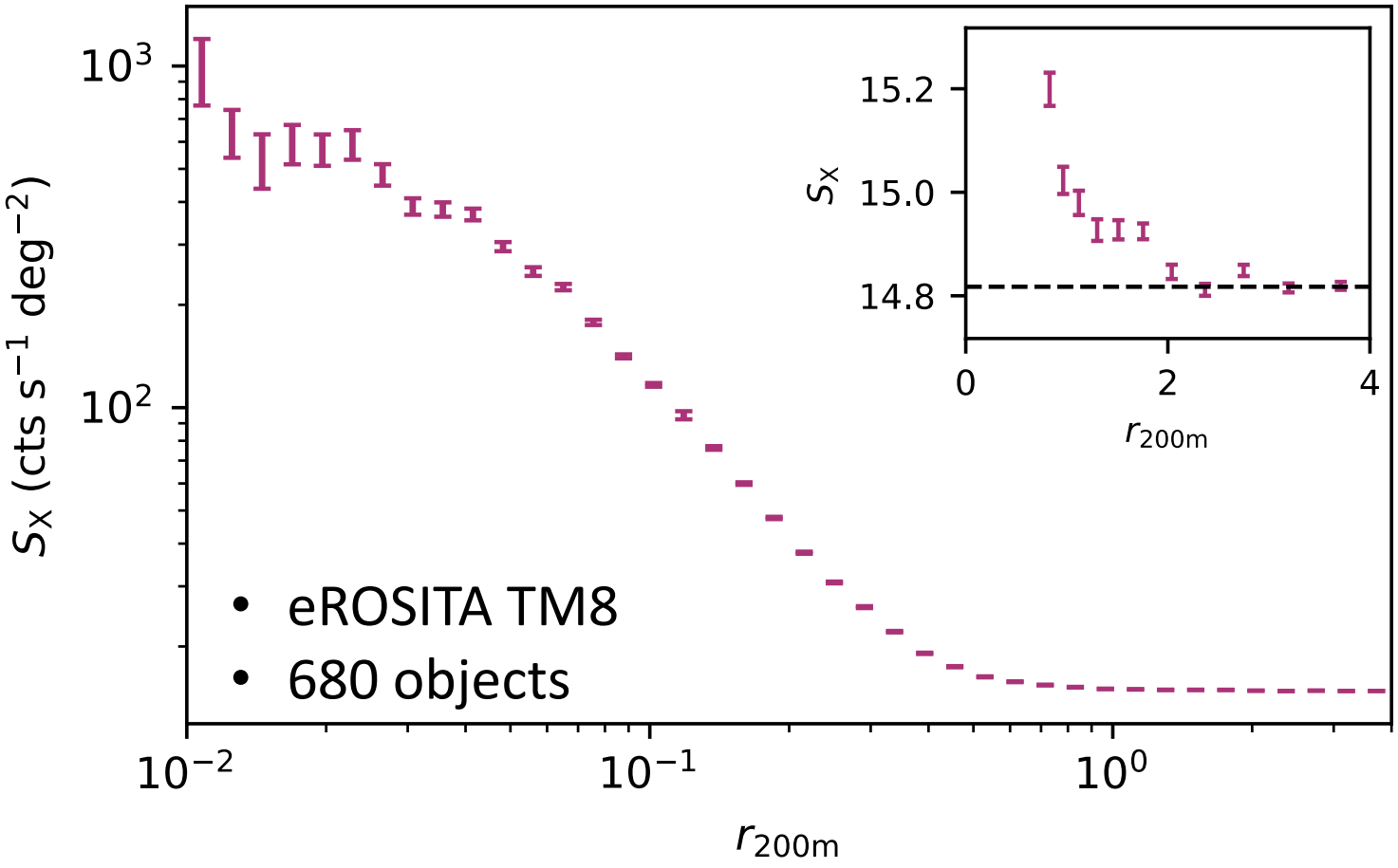
Stray light of Scorpius X-1



SL profile (dashed line)
(Churazov+22)

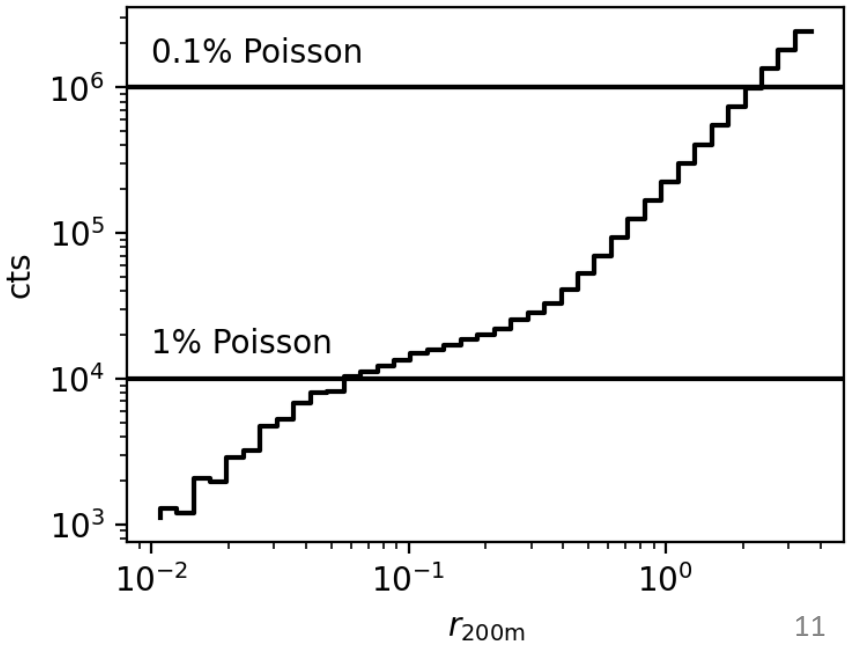
1st order removal:
SL ~ net map ∗ SL profile

SB with background (SL removed)

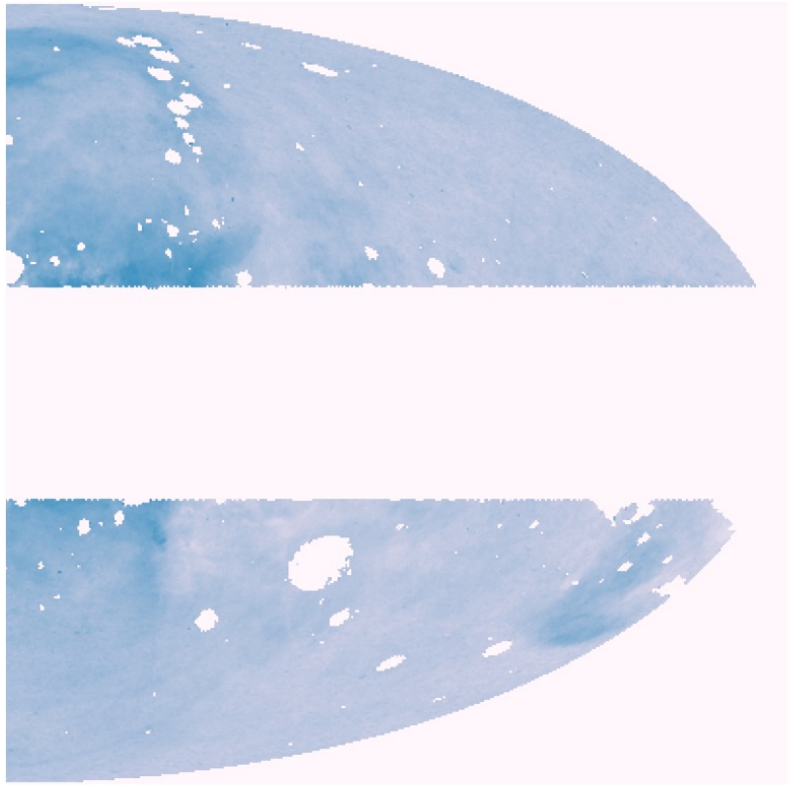


Strong X-ray “background”

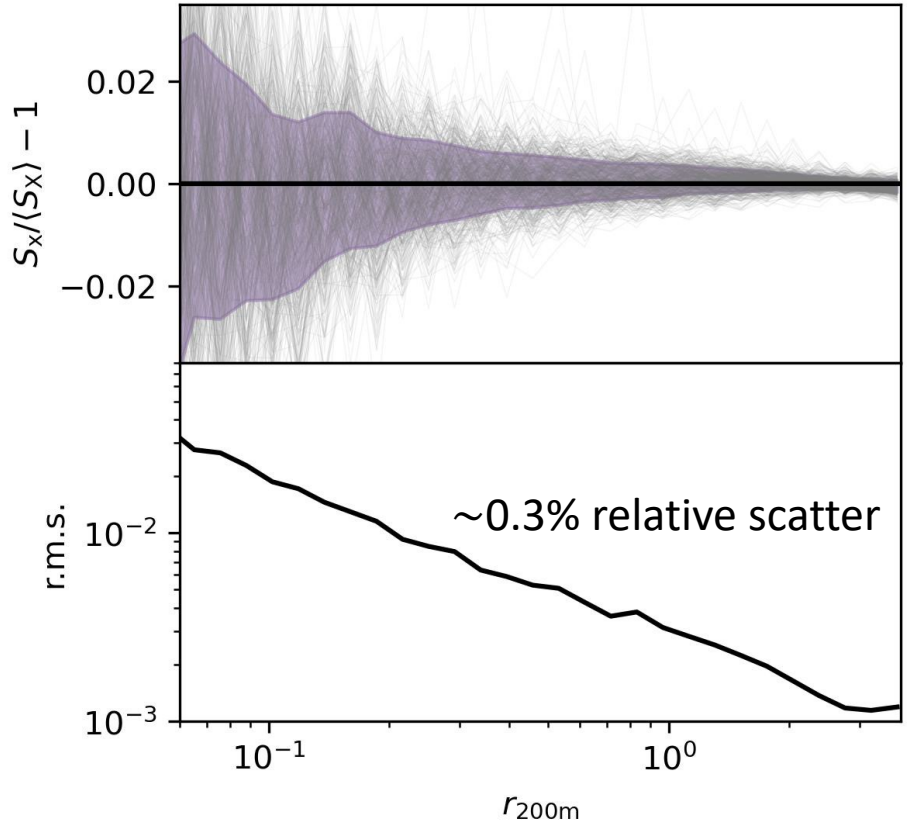
- 15 cts s^{-1} deg^{-2} for TM8
- Mostly from Milky way



Merit of all-sky stacking - remove uncorrelated components

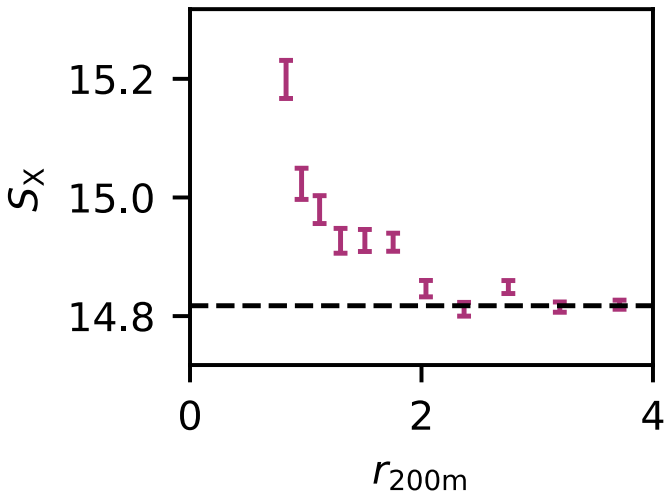


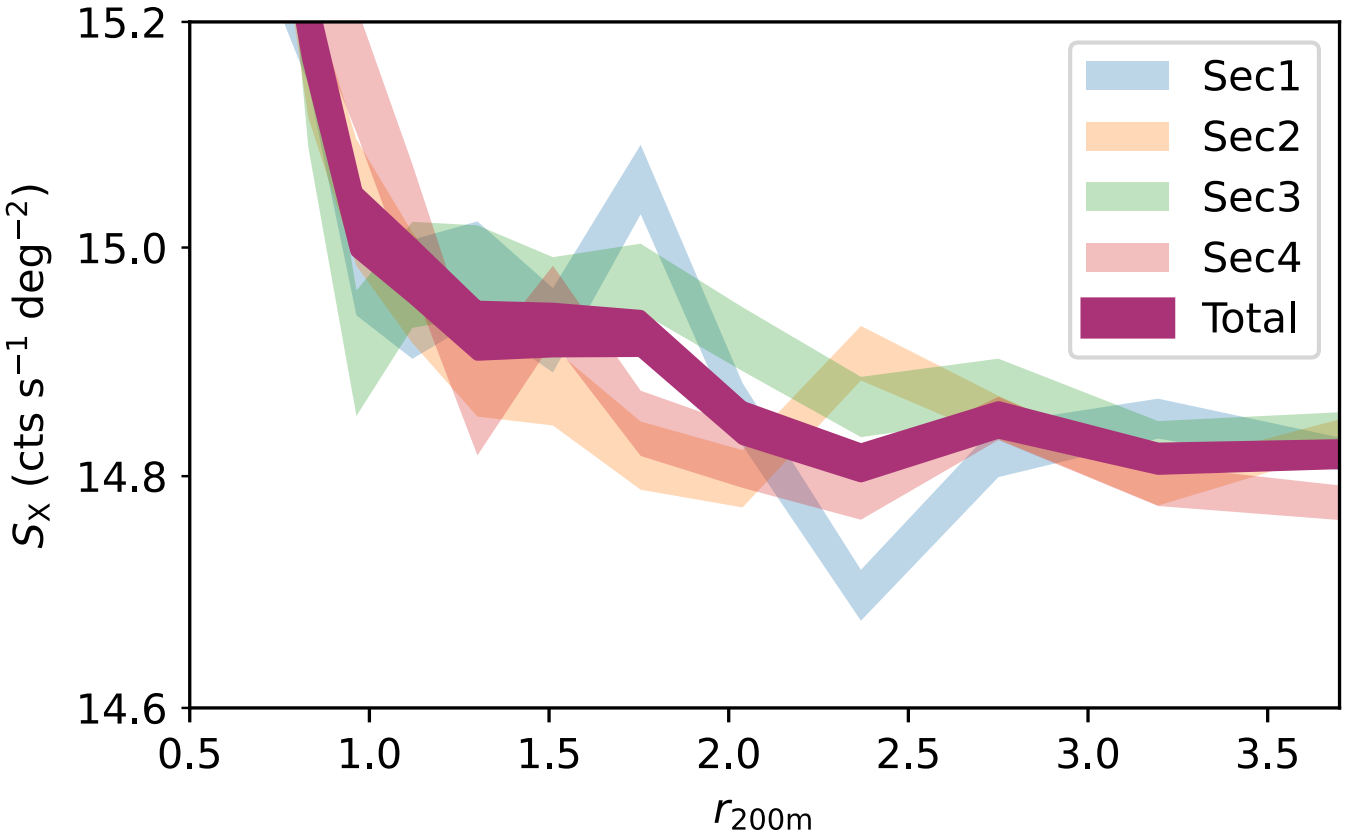
Source free eRASS:4 field



500 realizations of randomized cluster positions

Profiles in four individual sectors

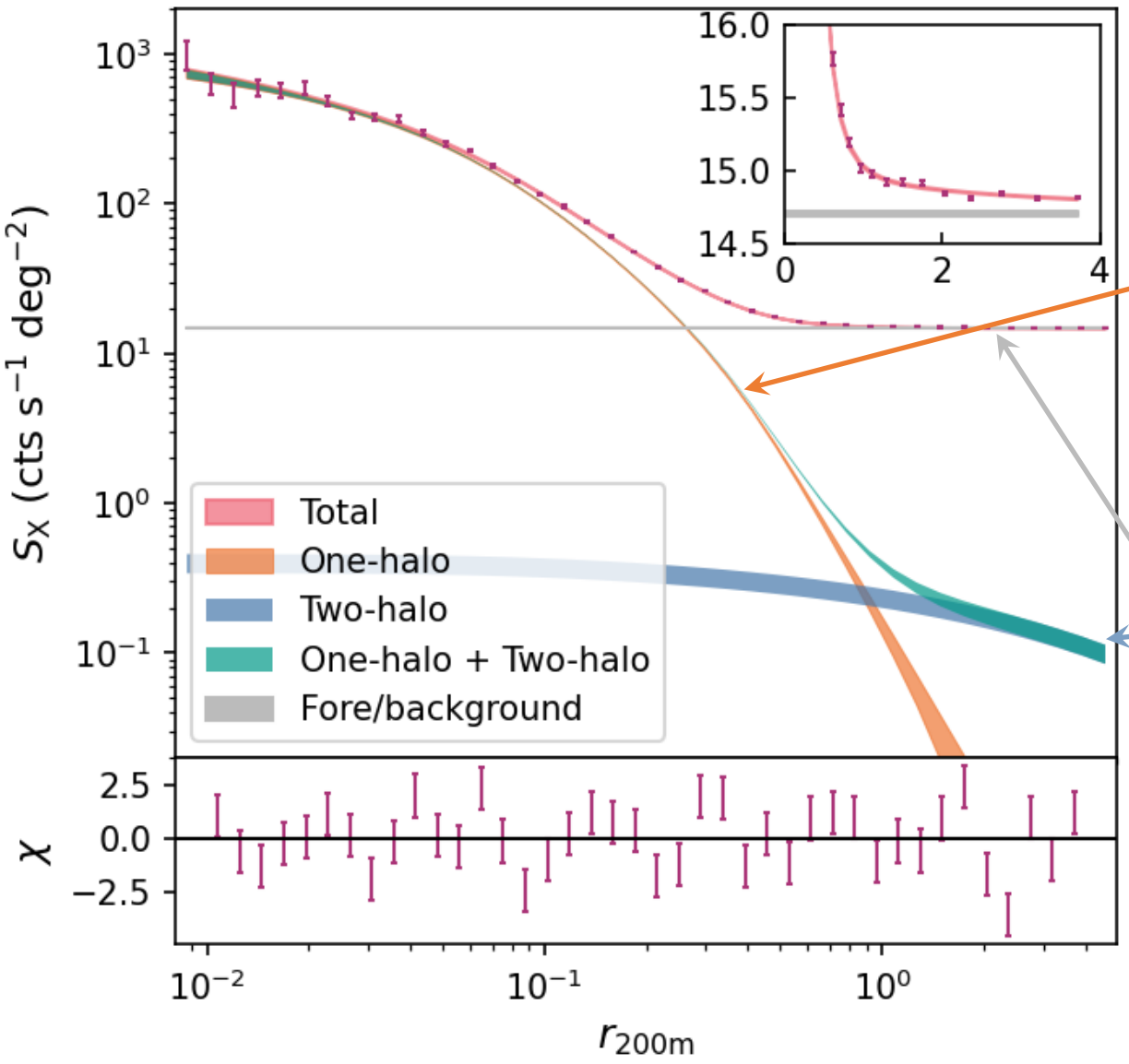




Decomposing correlated and uncorrelated components

Component	Formalism
One-halo	$\epsilon_{1\mathrm{h}}(r) = n(r)^2\Lambda;$ $n(r) = \frac{n_0}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}$ (gNFW, Nagai+07)
Two-halo	$\epsilon_{2\mathrm{h}}(M,r) = A\times\xi(r)b(M)\int n(M')b(M')L(M')\mathrm{d}M'$
Background	Constant model

Note: there is additional non-halo gas emission in 2-h

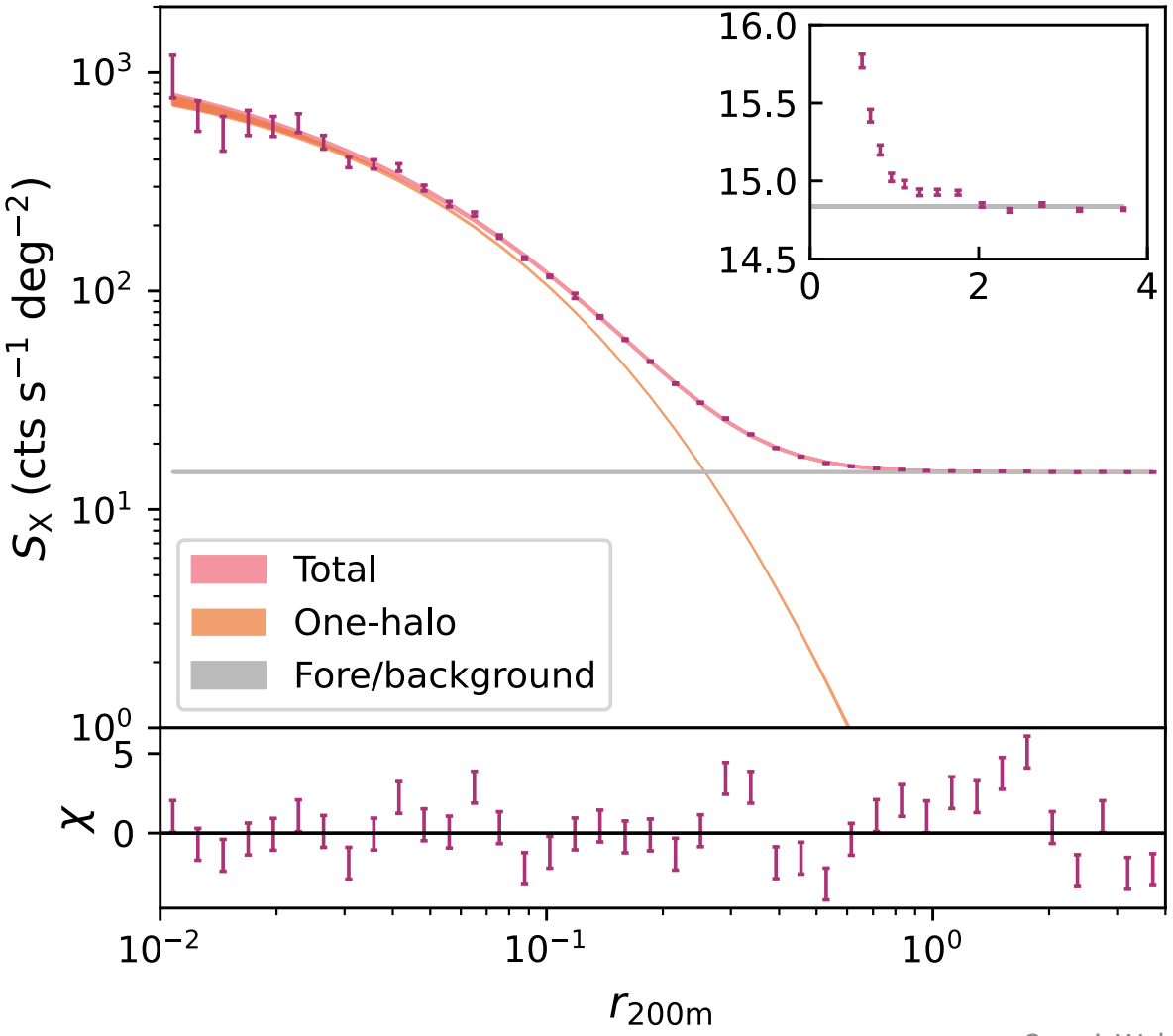


Inner profile: Cluster emission itself (1-h)

Outer profile: Emission from nearby objects that *correlated* with the cluster (2-h)

Uncorrelated background

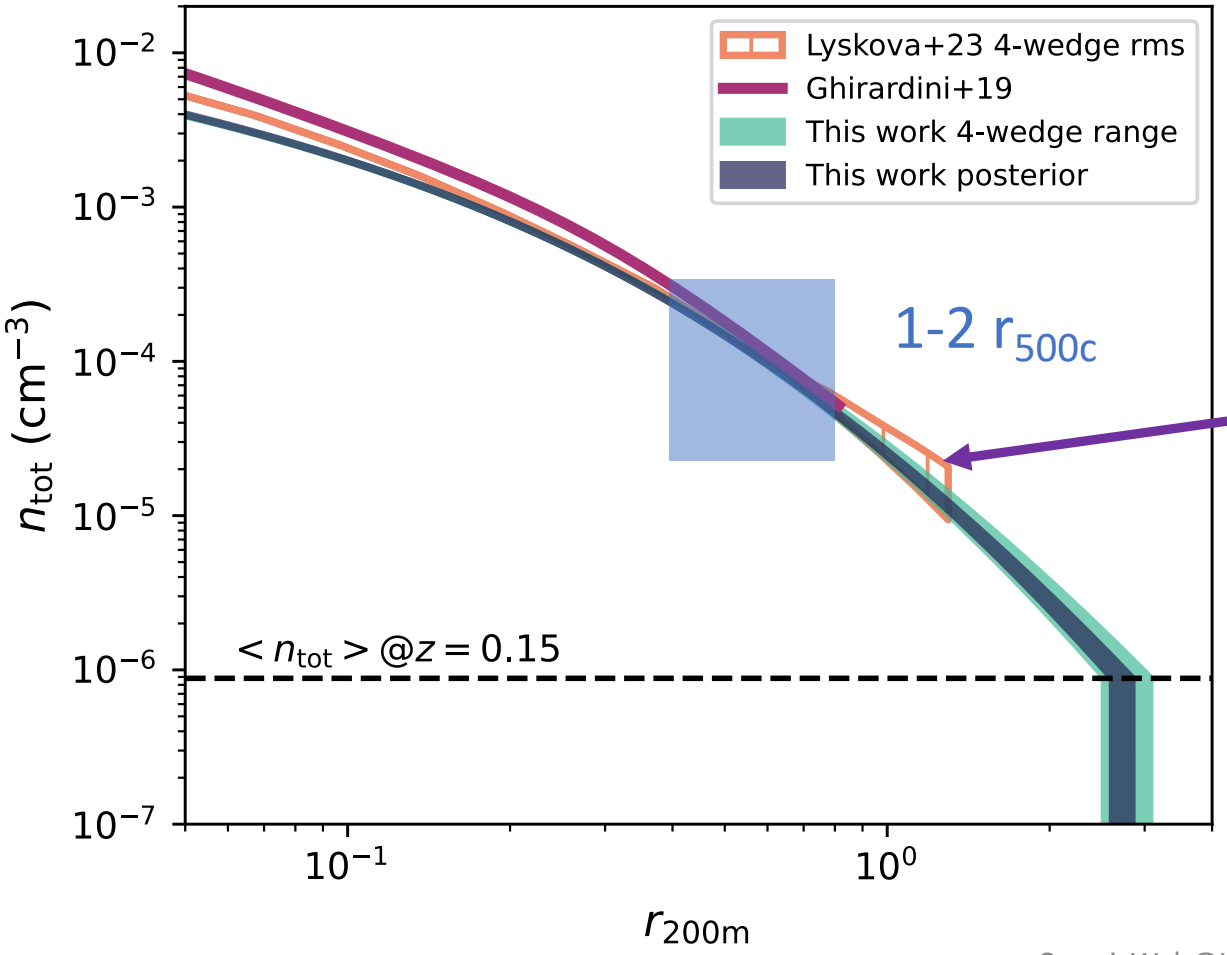
Fitting with only 1-h?



There is an additional flatter slope component…

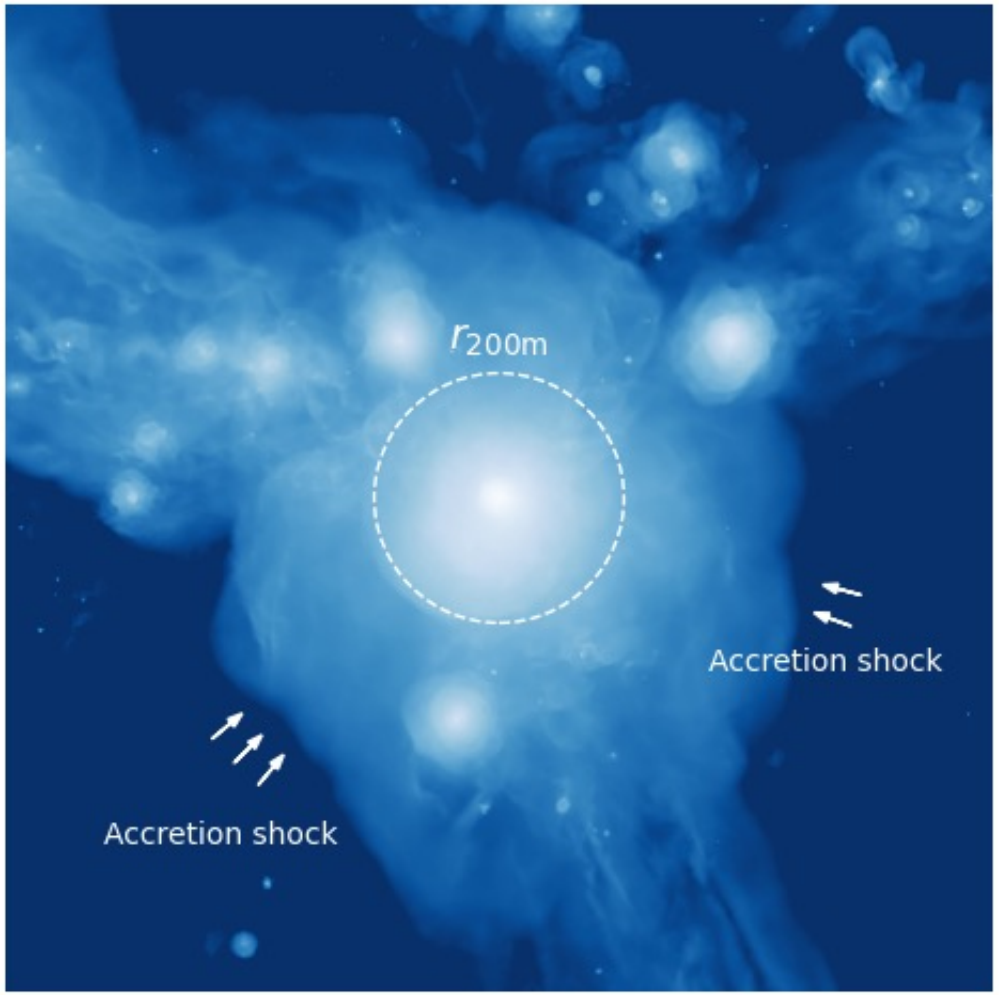
Model comparison: w/ & w/o 2-h
Bayes Factor = exp(11)

Deprojected gas density profile (gNFW)



Density at r_{200m}: $\Delta_b \sim 20$

3D gas structure from IllustrisTNG

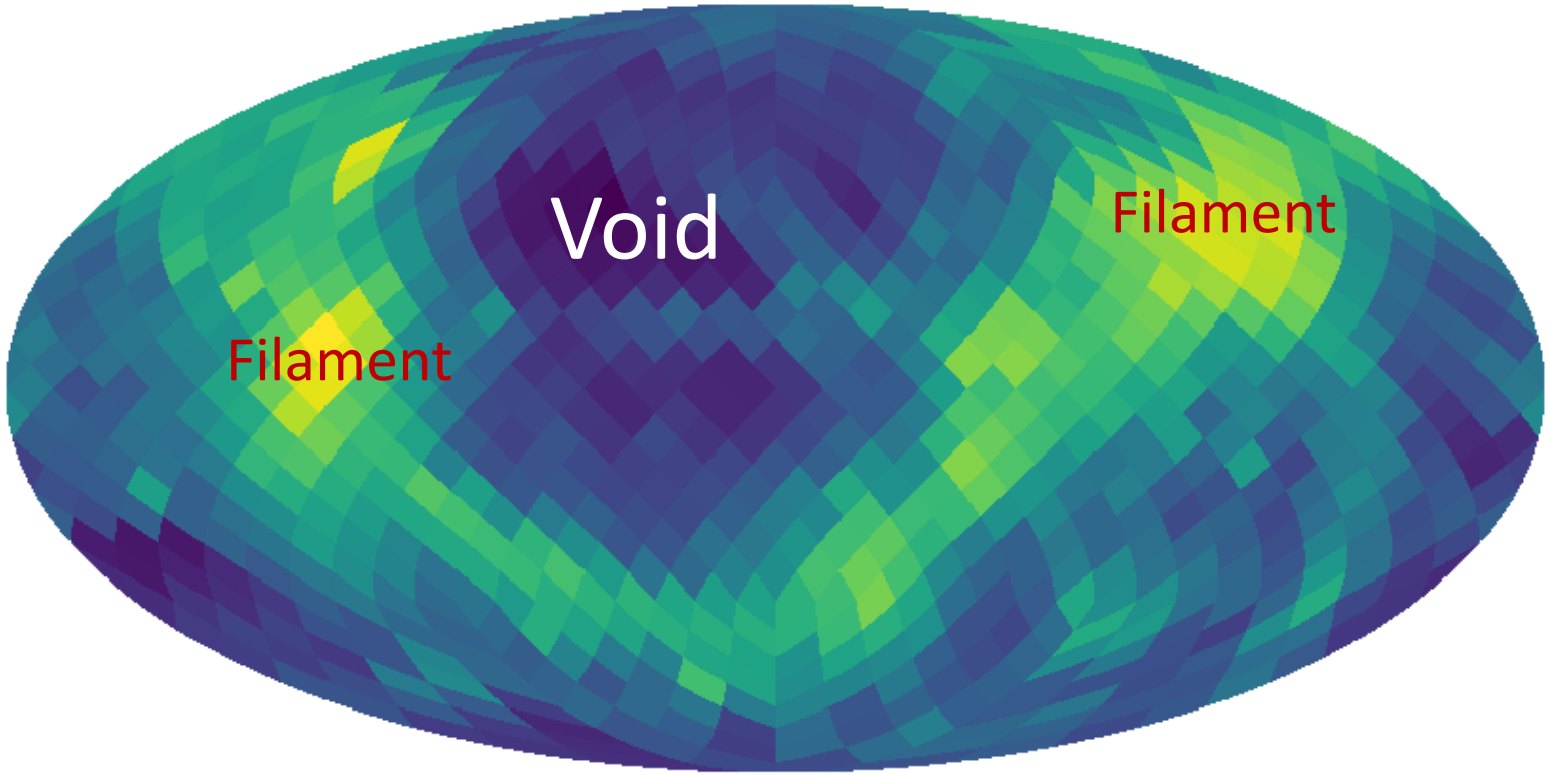


TNG300-1 z=0 snapshot

- 159 halos with $M_{500c} > 10^{14}\ M_{\odot}$

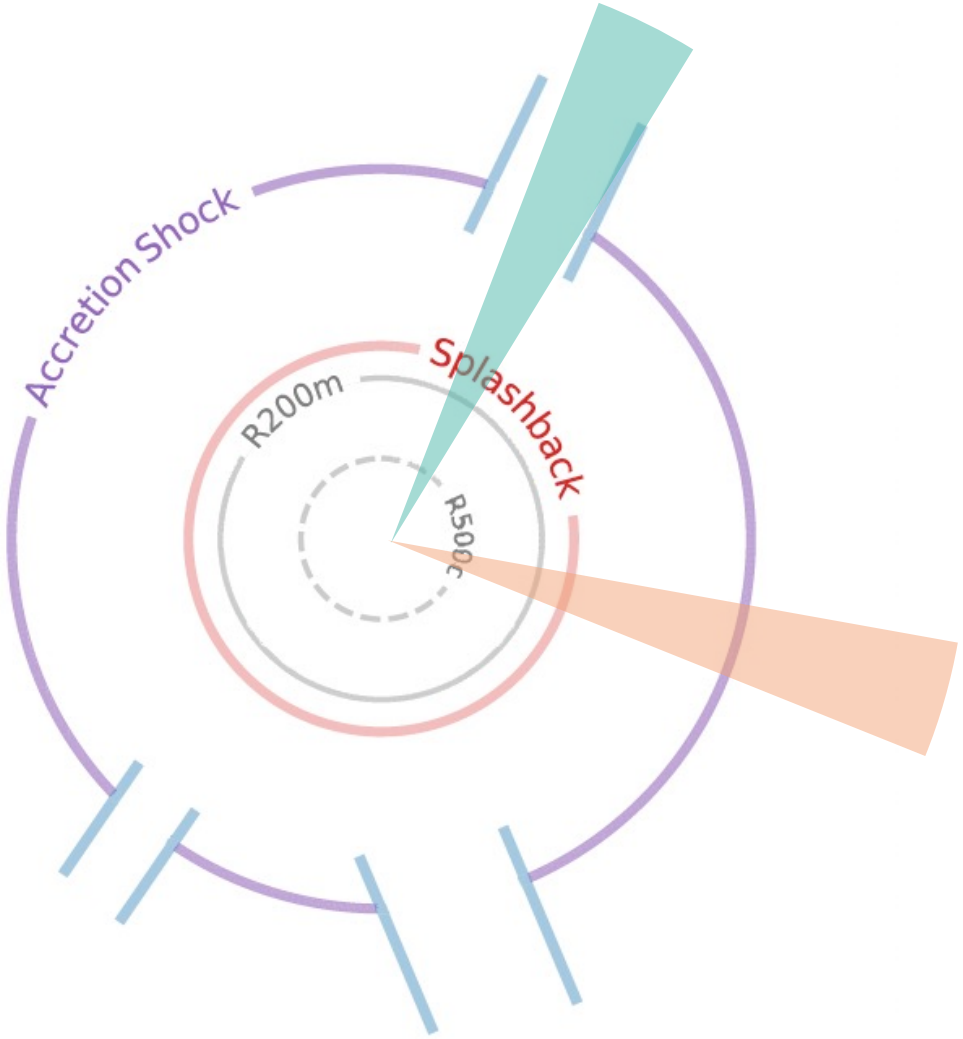
X-ray map of Halo id 32

Every cluster connects to filaments

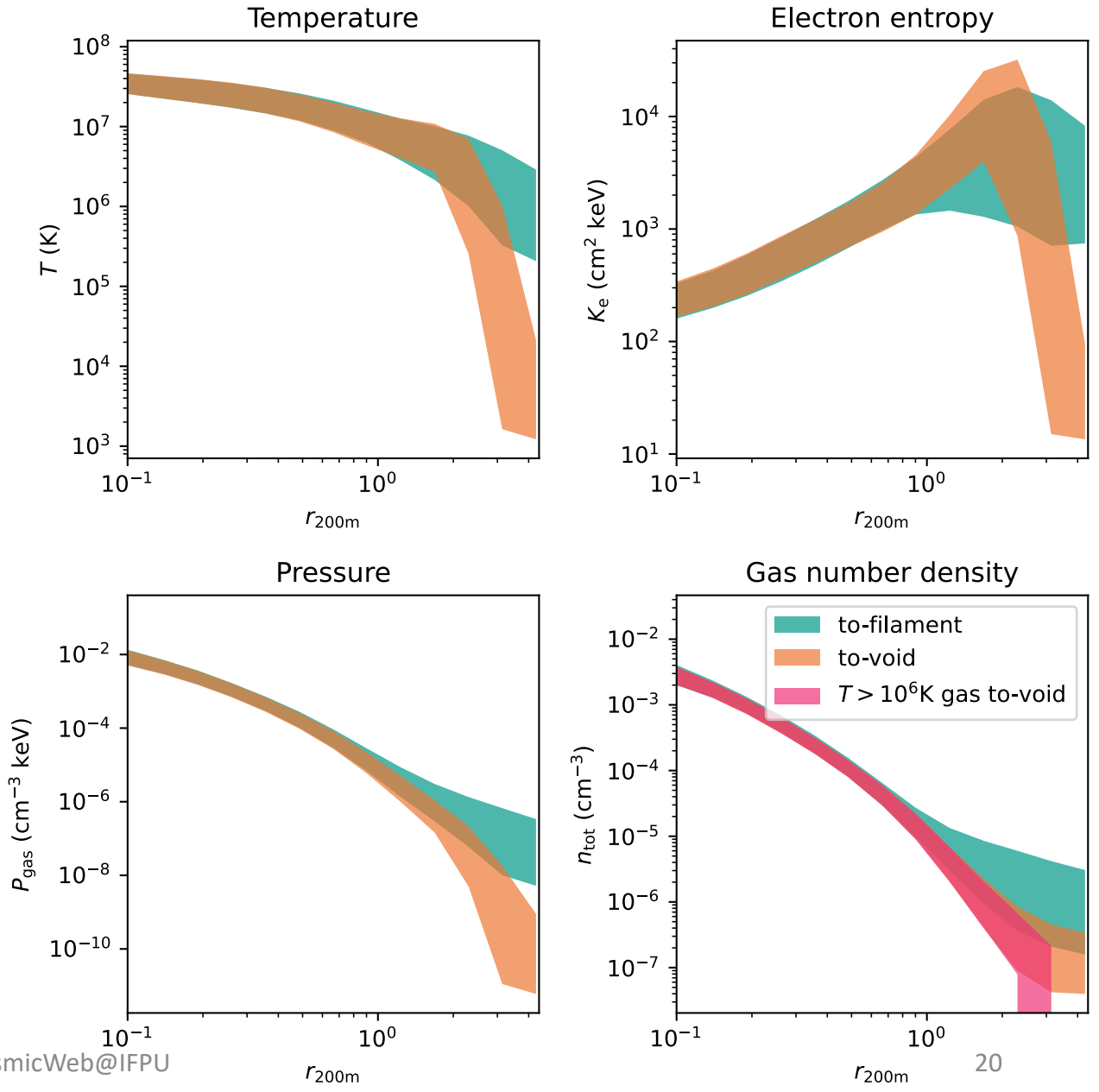


Example: Column density 768 (HEALPix NSIDE=8) l.o.s. from 1 to 5 r_{200m}

To-filament vs. to-void



Sketch from Anbajagane+22

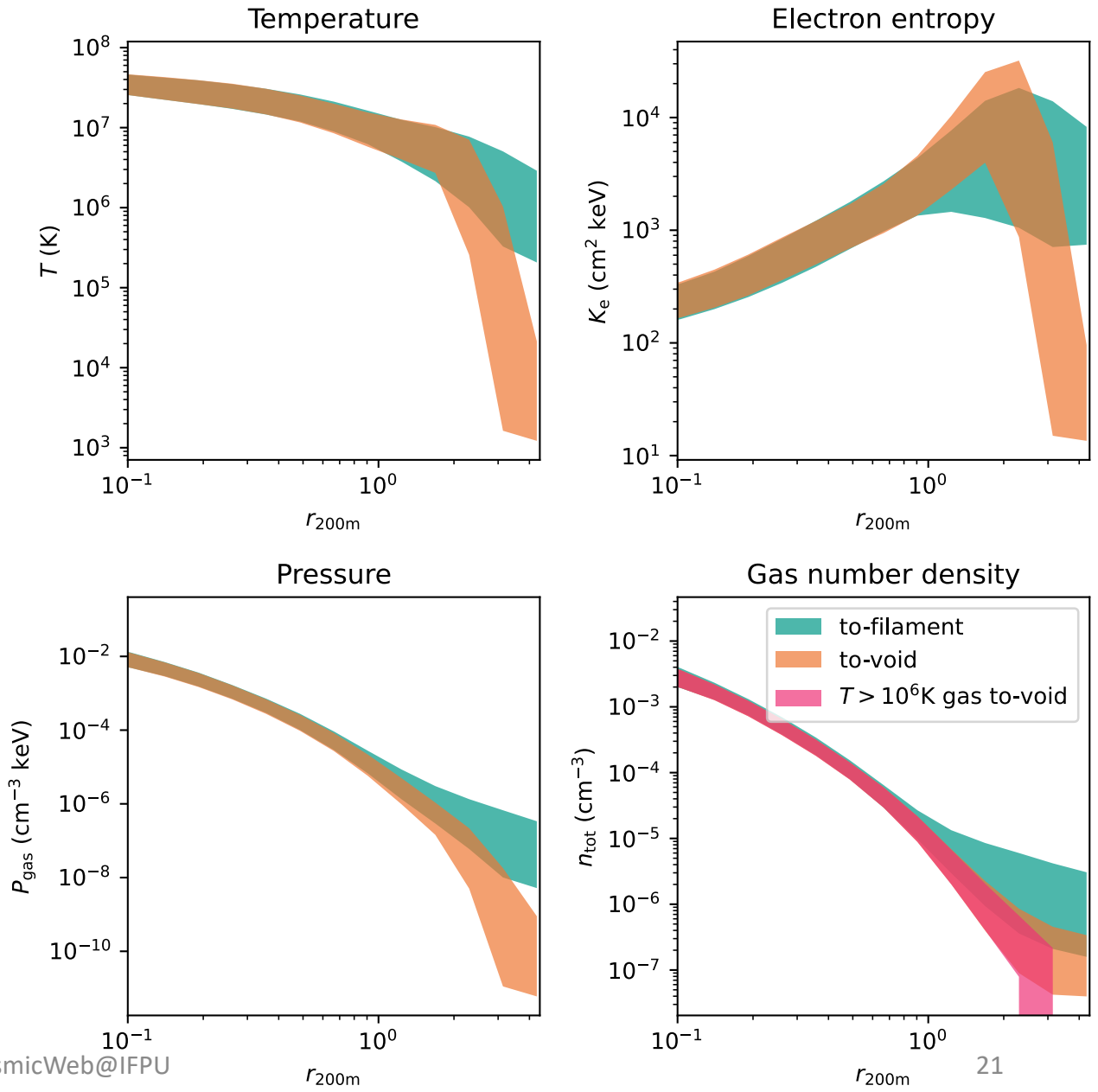


To-filament vs. to-void

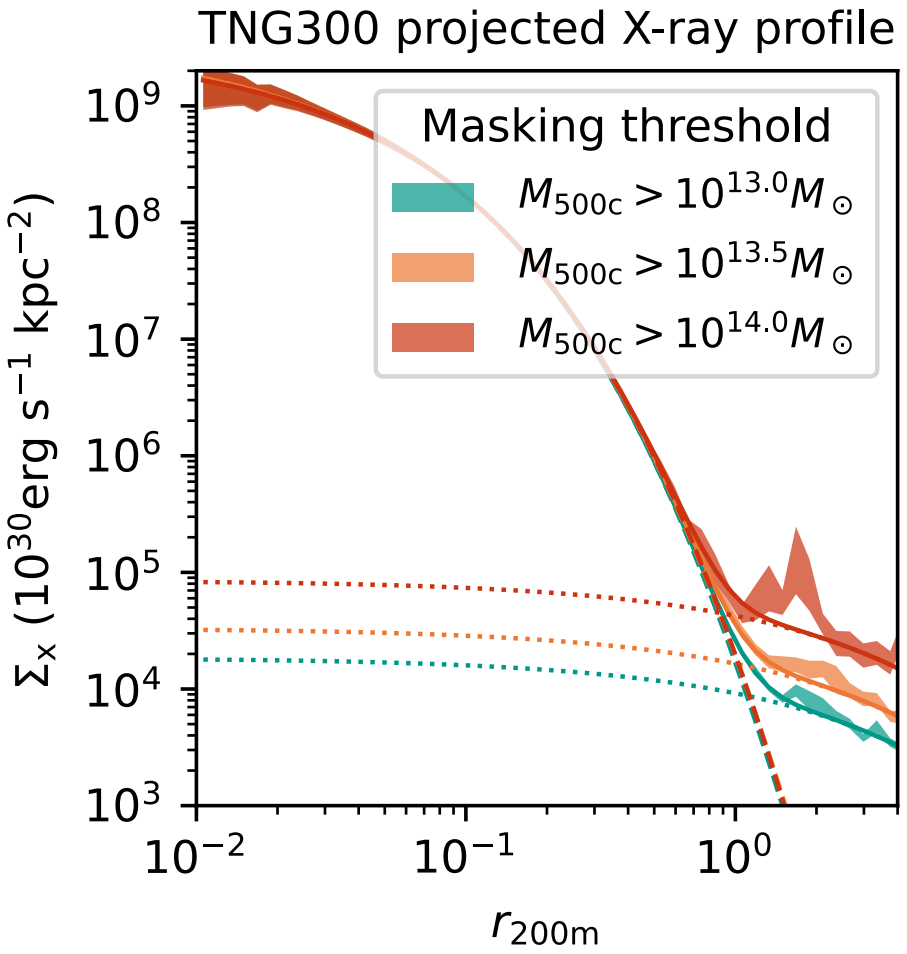
Where do to-fil thermodynamic profiles deviate from to-void profiles?

Temperature	$\sim$2-3R_{200m} (R_{shock})
Pressure	$\sim R_{200m}$
Entropy	$\sim R_{200m}$
Density	$\sim R_{200m}$

Δ_b at accretion shock $\lesssim 1$



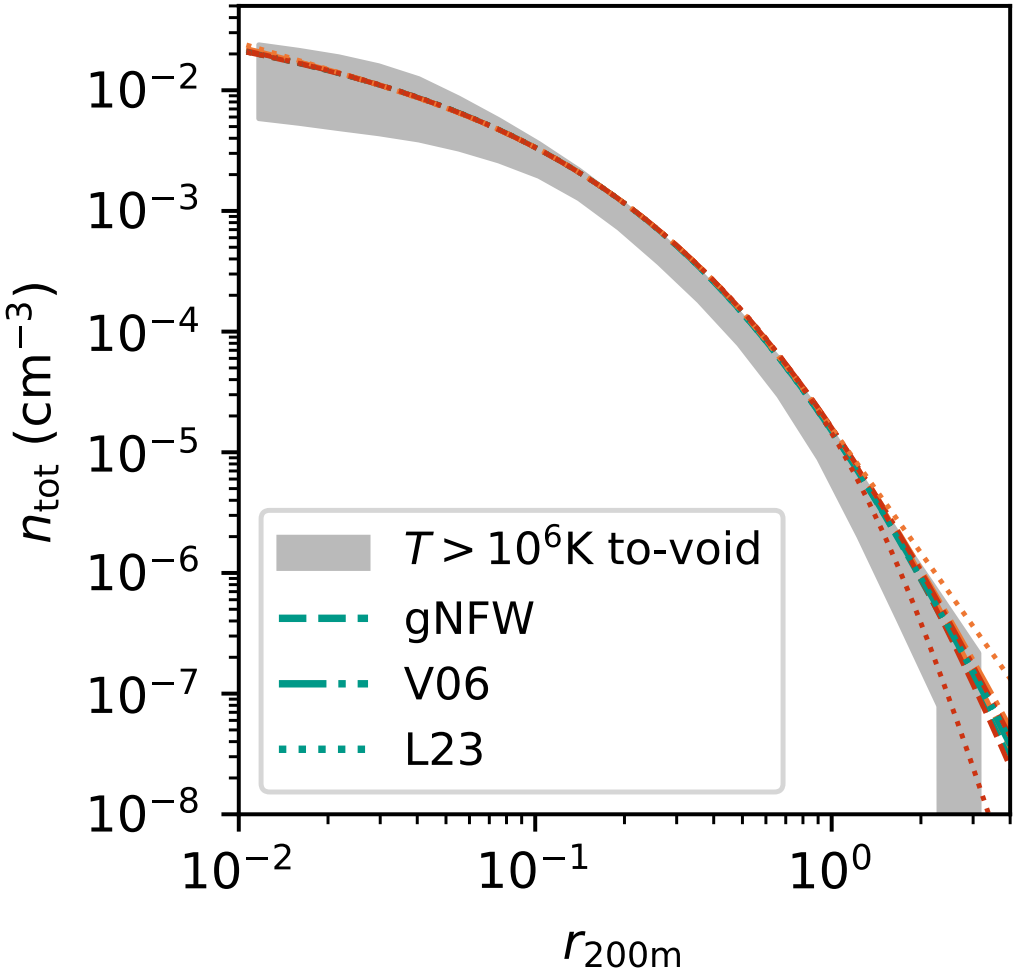
The 2-h in simulations: 2d emission profiles



- Rest-frame 0.2-2.3 keV band
- 20 Mpc projection depth

The 2-h formalism (or ξ_{mm}) can well fit the outer profile

Comparison between true & best-fit 1-h profile



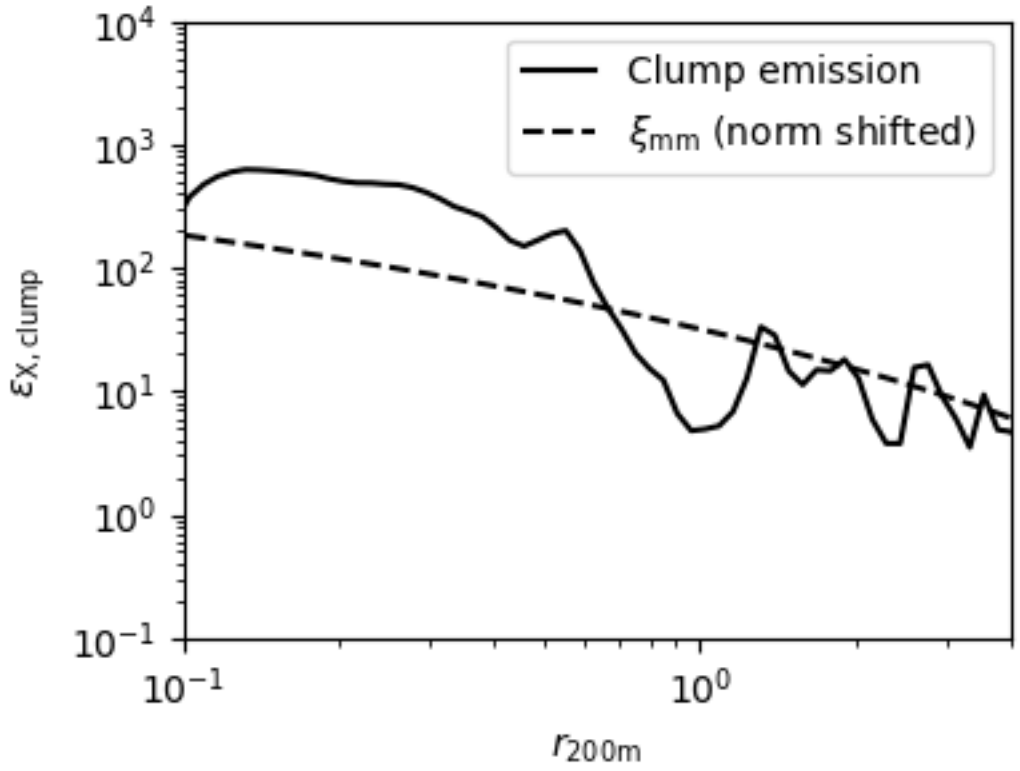
Radial variations of T & Z has little impact.

Tests on three profile models
- gNFW
- Vikhlinin06
- Lyskova+23 (modified V06)

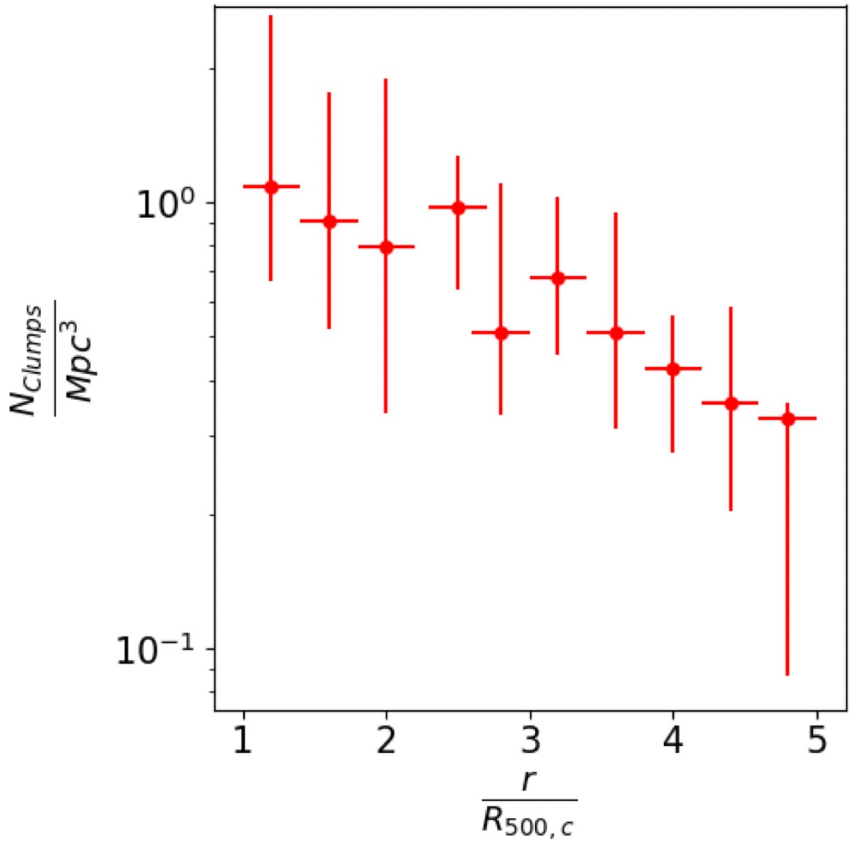
Should we worry about clumping?

- Clumping: inhomogeneity of halo atmosphere
  - Subhalos
  - Triaxiality
  - Shock/cold fronts
  - Density fluctuation due to turbulence

Clump radial profiles from simulations



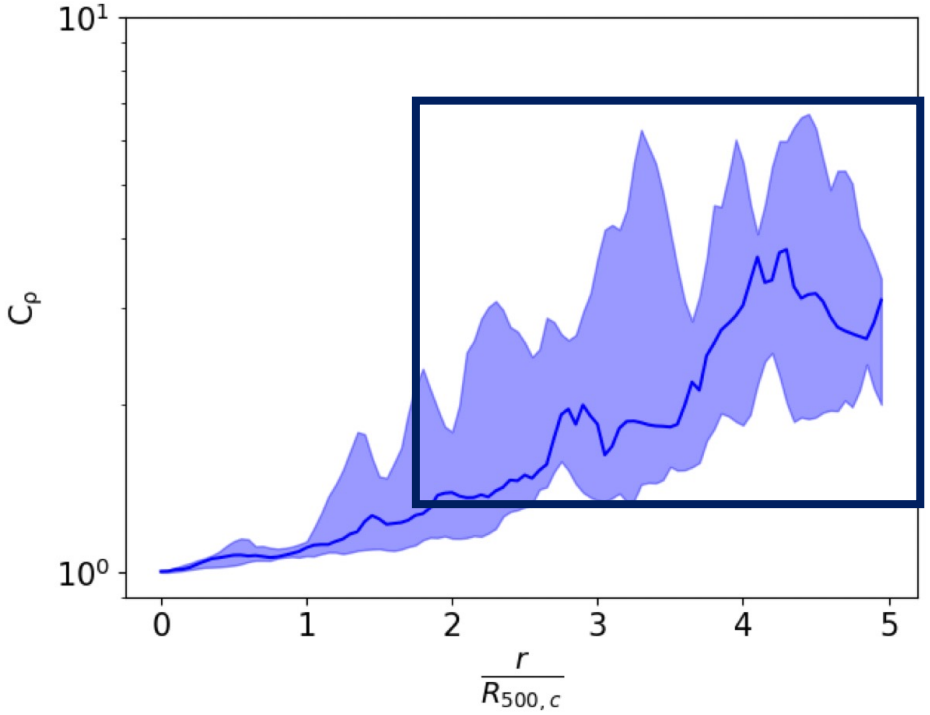
Volume weighted emission profile of associated Subfind halo (>10^{13} $M_\odot$) from TNG300



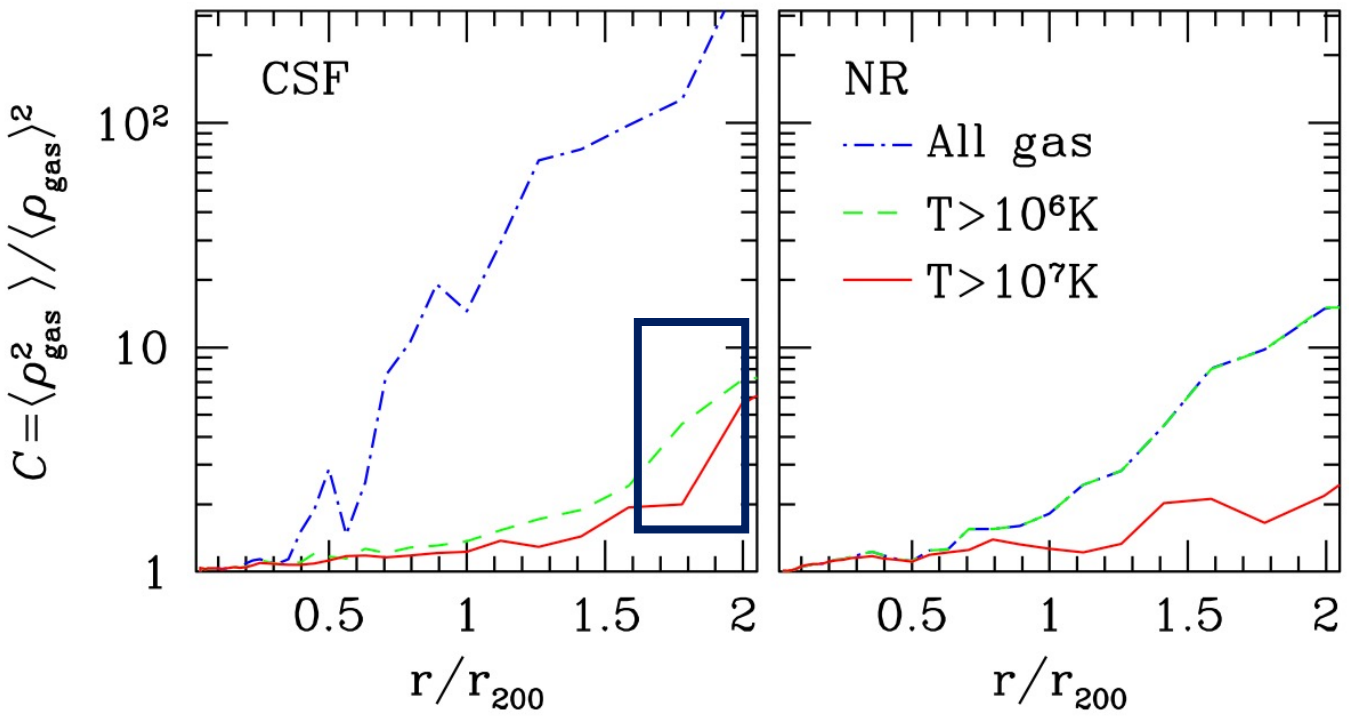
Magneticum clump number density (Angelinelli+21)

- 2-h term takes clumps into account

Should we worry about clumping?



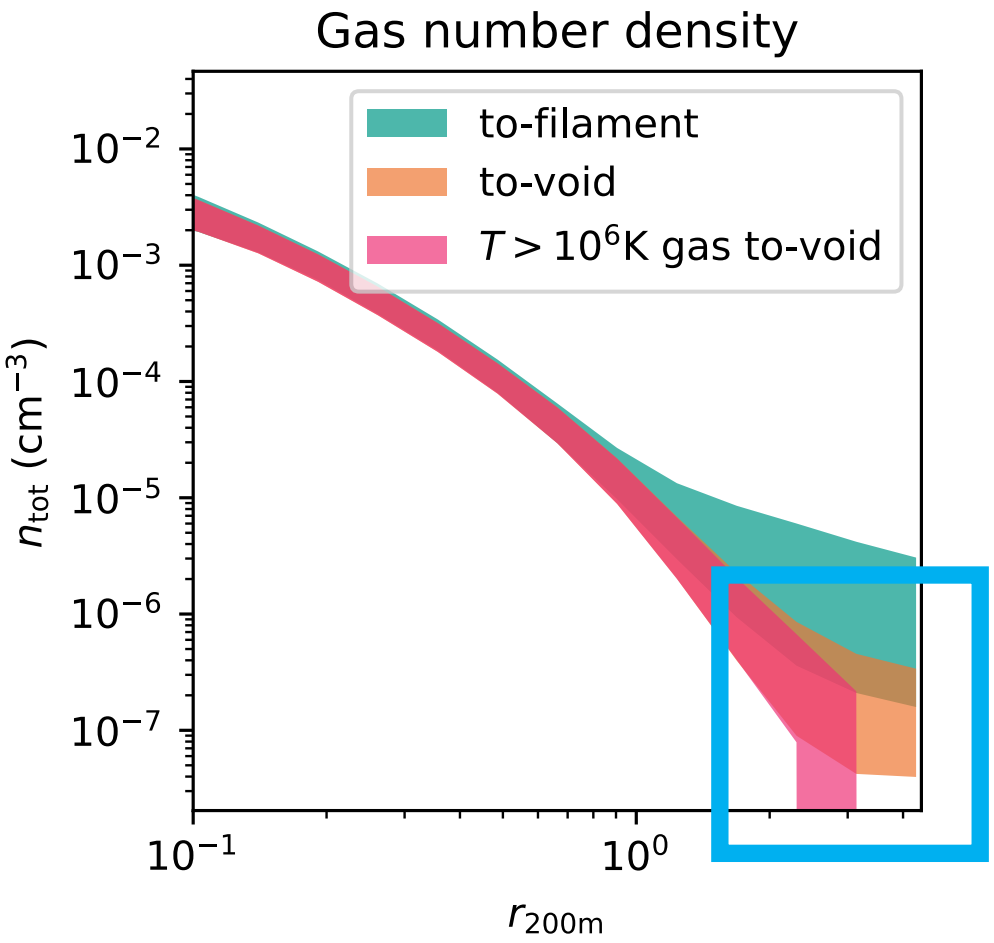
Angelinelli+21

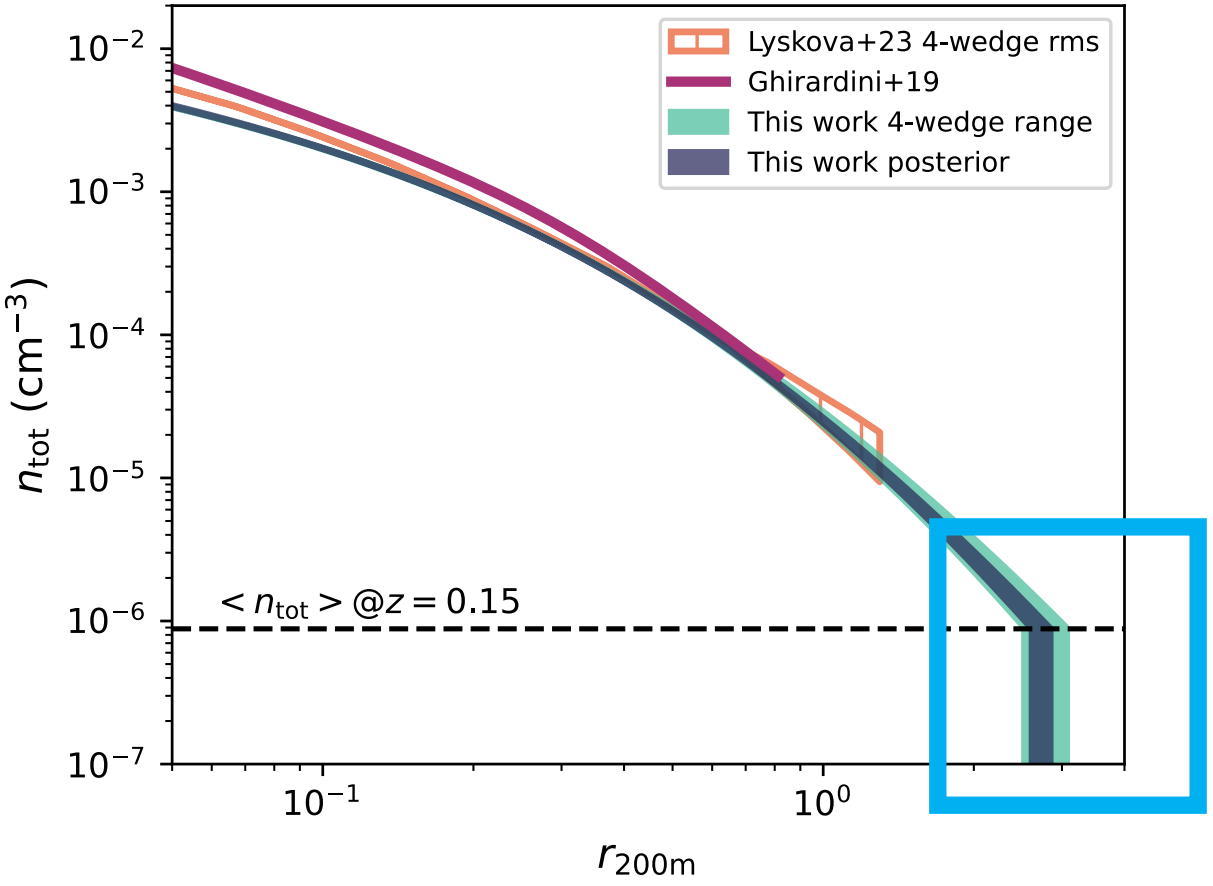


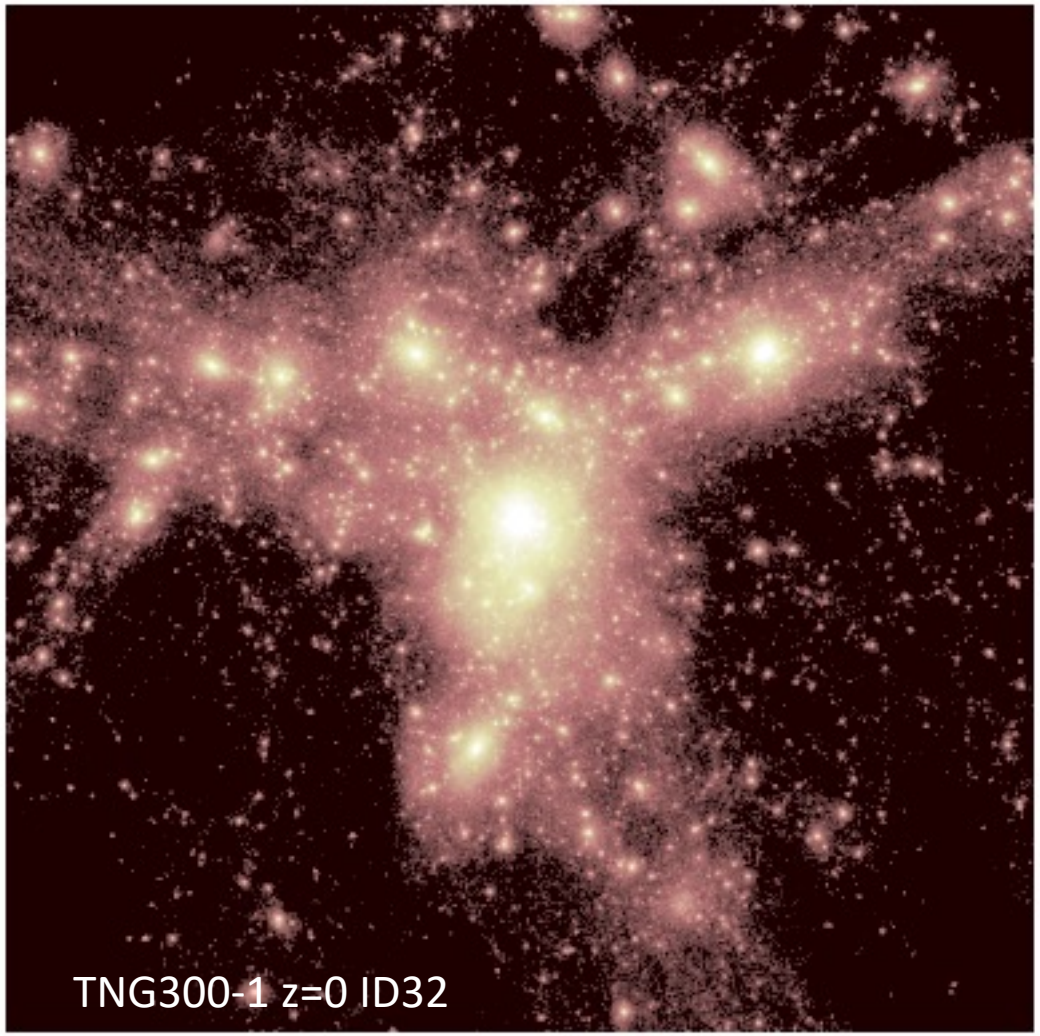
Nagai+11

Emergence of cosmic filaments

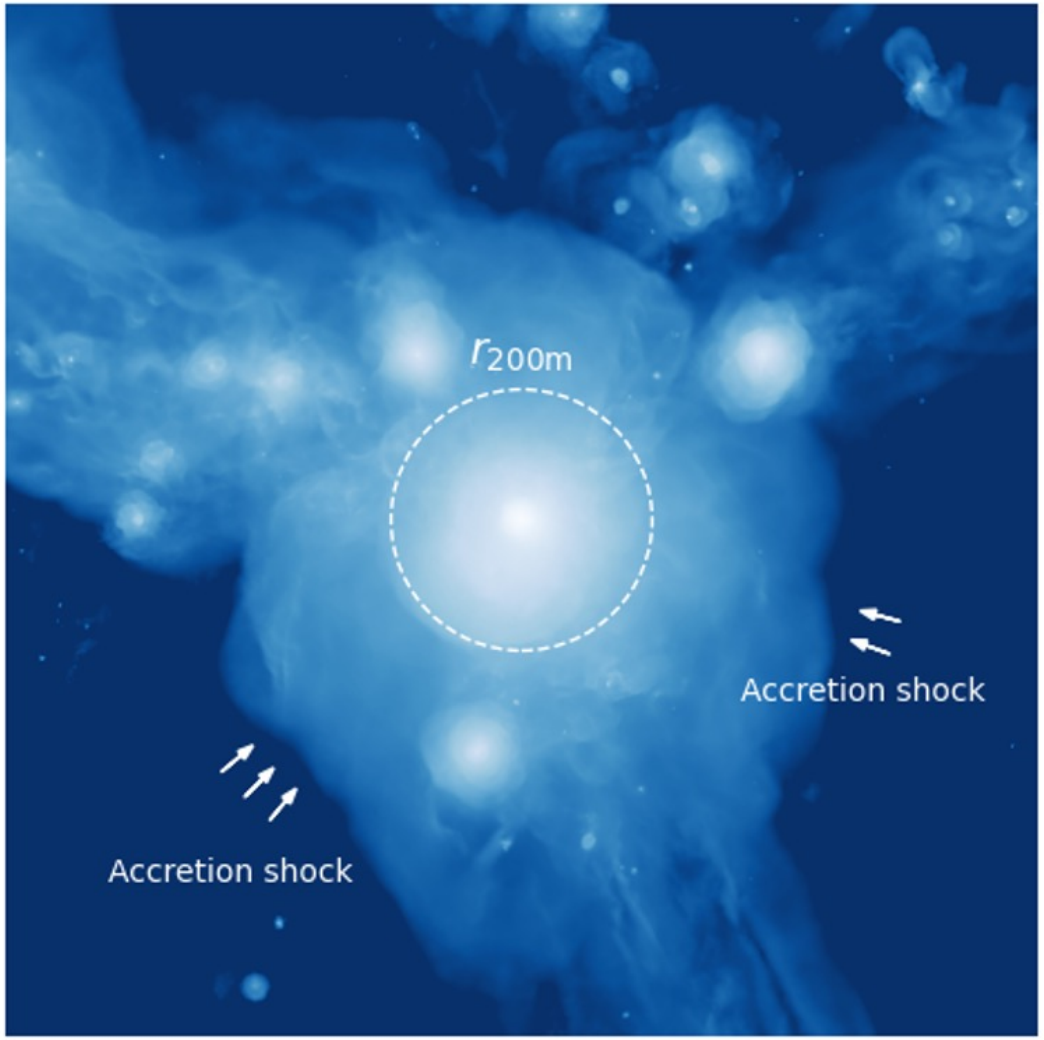
Estimation of r_{shock}





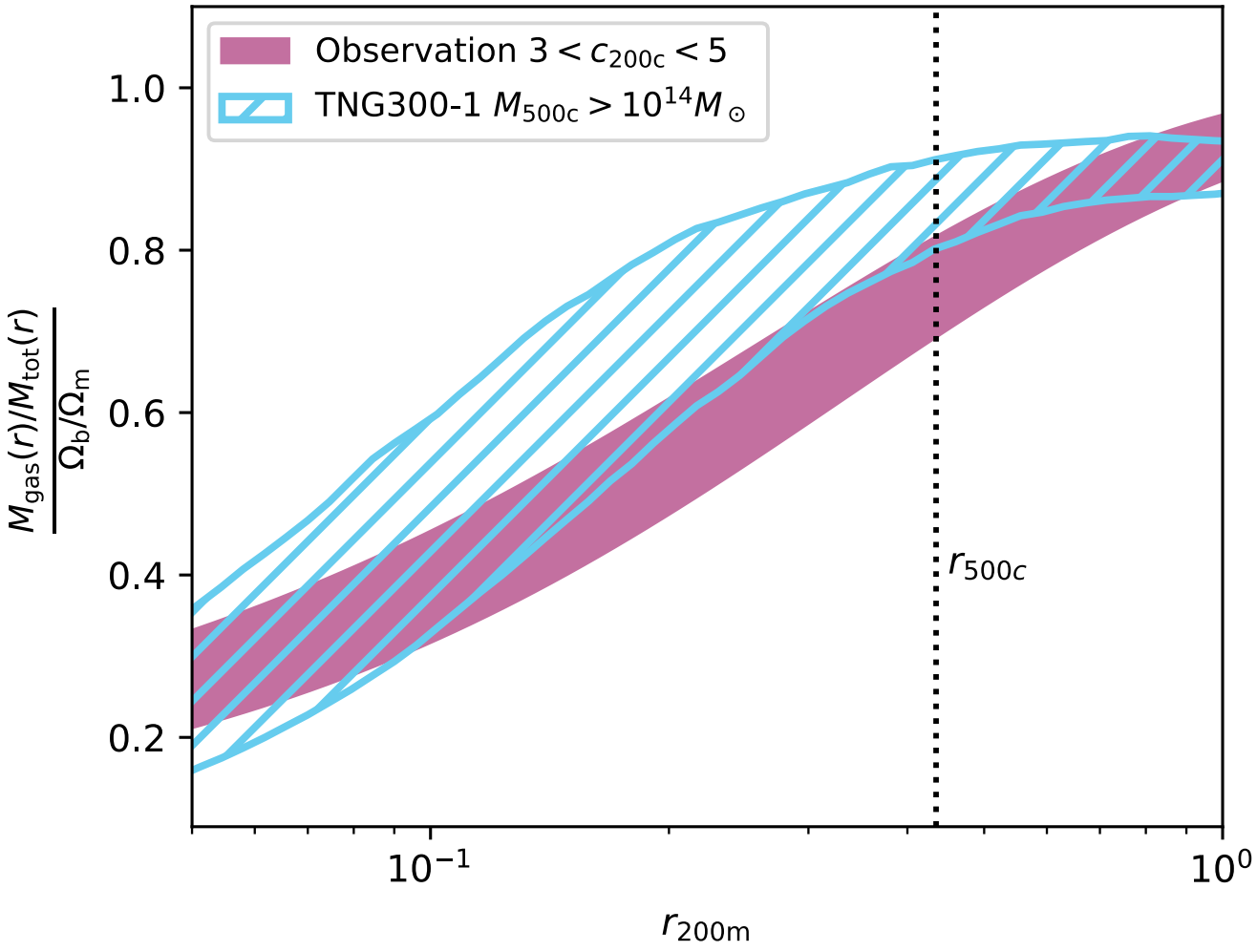


DM



X-ray (gas)

Baryon depletion & gas fraction



Flatter than TNG model

r_{200m} is the baryon enclosure radius

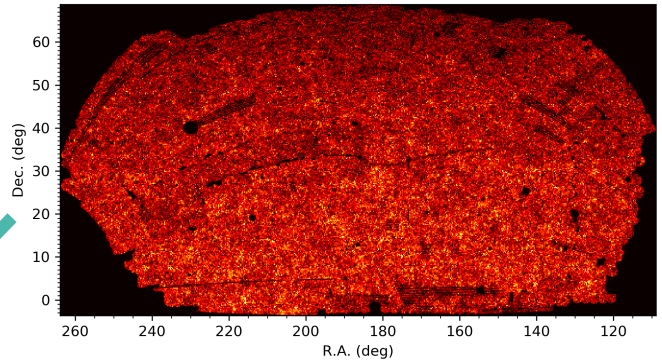
Assume that every halo has complete baryon

- For log M/Msun > 10 halos
- $\frac{\frac{\Omega_{\rm b}}{\Omega_{\rm m}} \int n(M) {\rm d}M}{\rho_{\rm b}} = 0.067$

- Cosmic filaments are the right place to search for the missing baryon.

Stacking of cosmic filaments

Extracting LSS information from different surveys

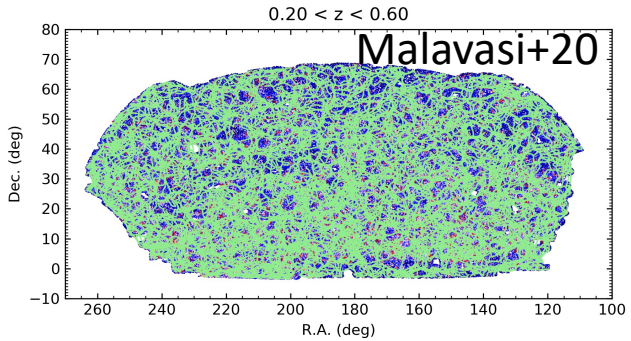


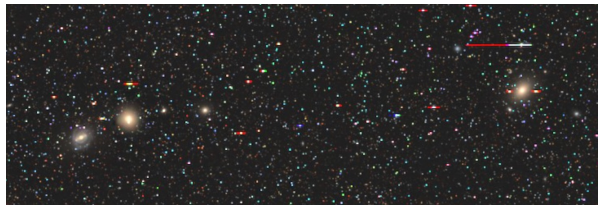
Galaxy sample
e.g., SDSS BOSS

Sample of cluster pairs

Planck Collaboration+13, Isopi+25

Filament finder(s)

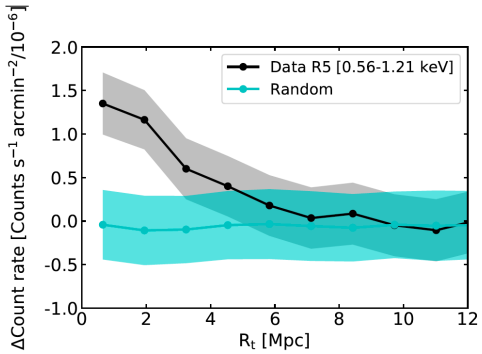




Sample of LRG pairs

Maps of:
- X-ray
- Radio
- Compton-y
- WL convergence
- Galaxy distribution
- etc.

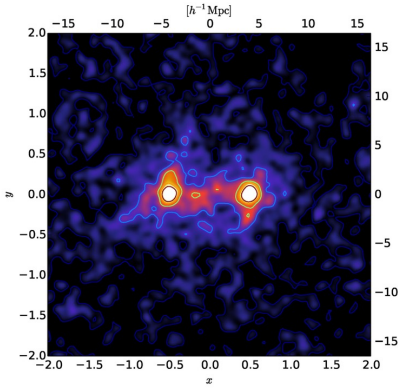
Stacking



Tanimura+20a

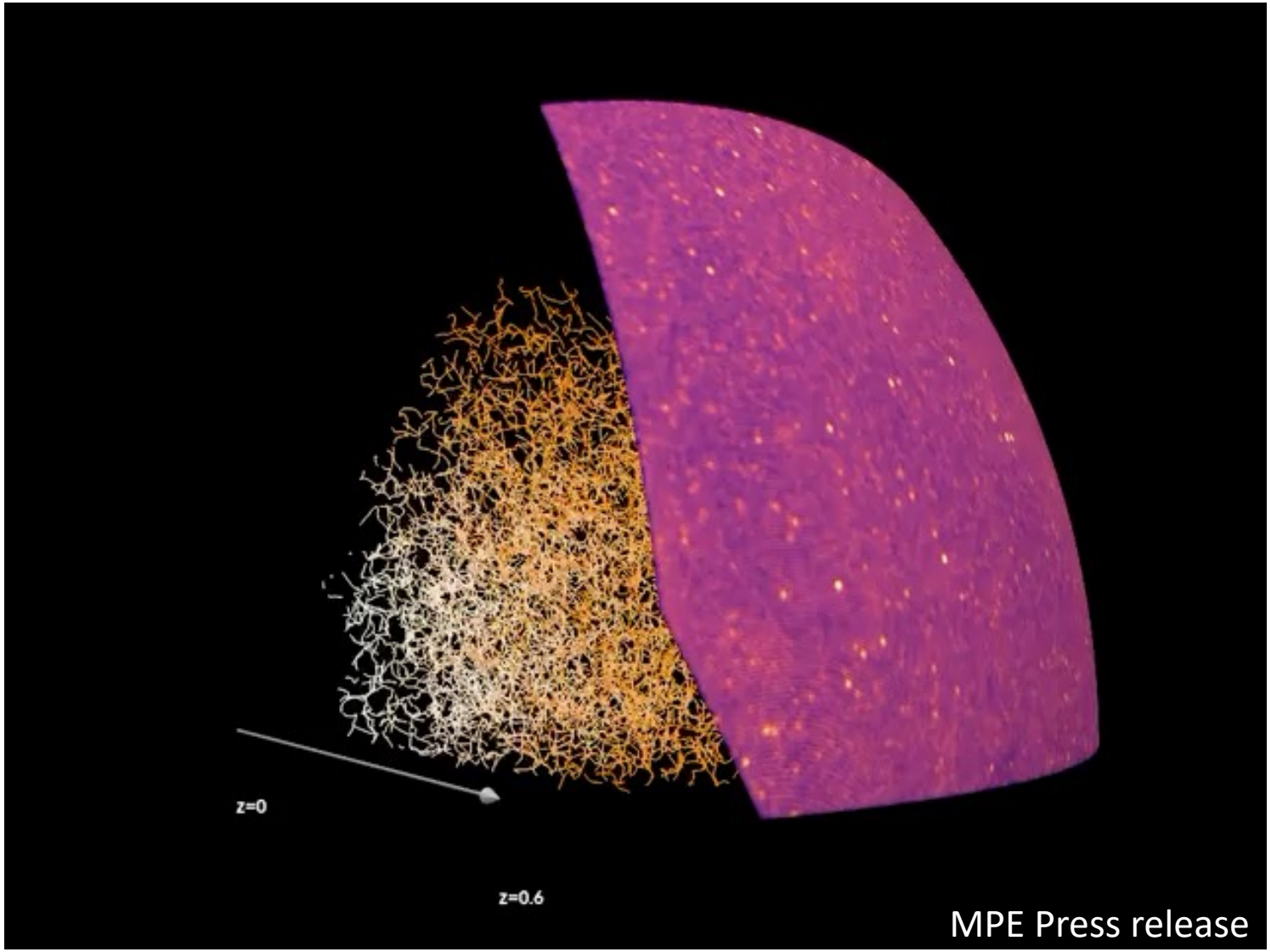
Also
Bonjean+20,
Tanimura+20b,
Tanimura+22, etc.

Stacking



Epps+17

Also
de Graaff+19,
Tanimura+19,
Vernstrom+21,
Hodgeson+22, etc.



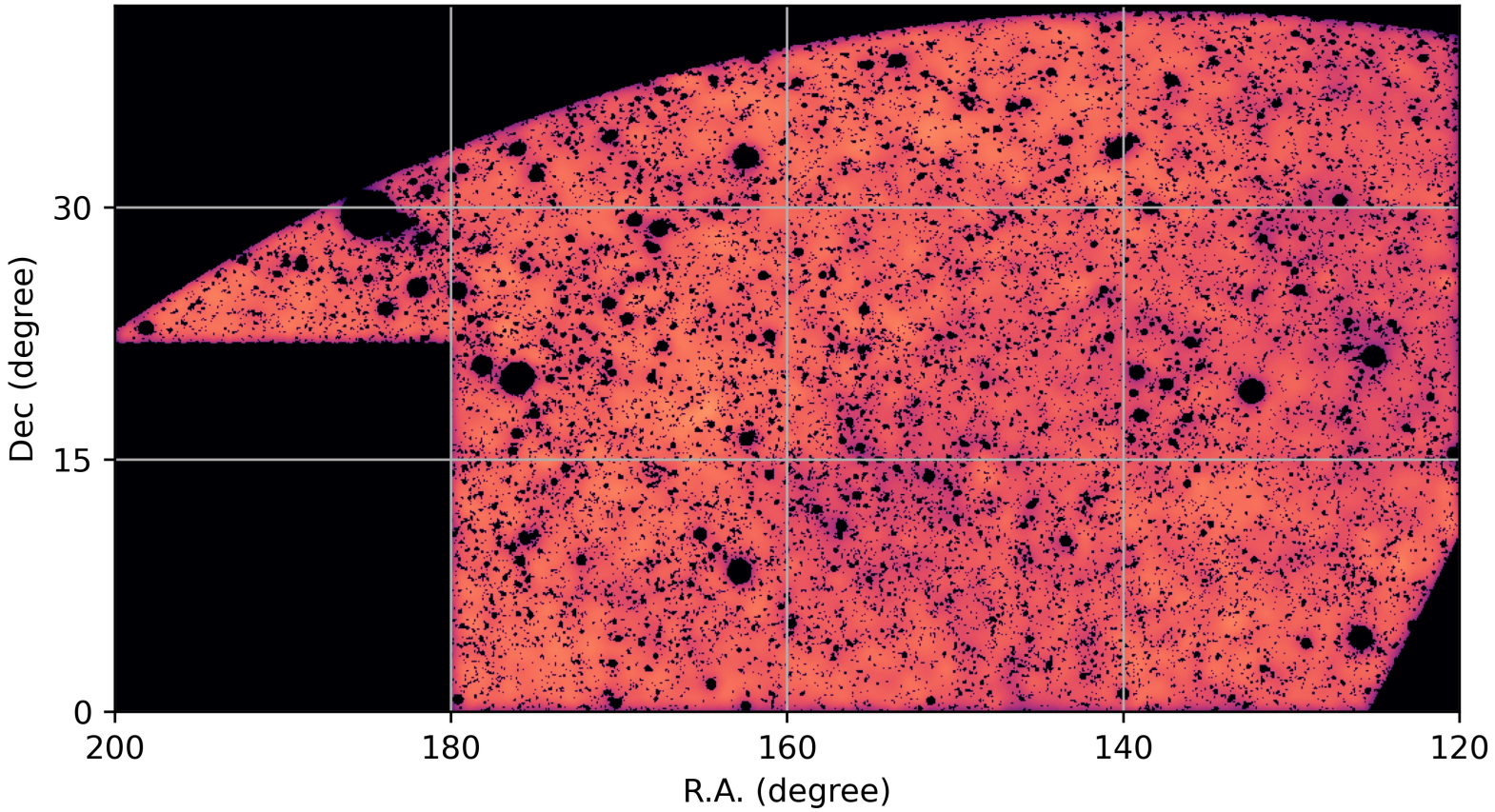
- 2300 deg^2 eRASS:4 X-ray sky
- 3D structure of the 7817 cosmic filaments

Malavasi+20 DisPerSE catalog (SDSS-BOSS based)

- 20 < Length (Mpc) < 100
- 0.2< z < 0.6

Length is directly from DisPerSE

Source masking

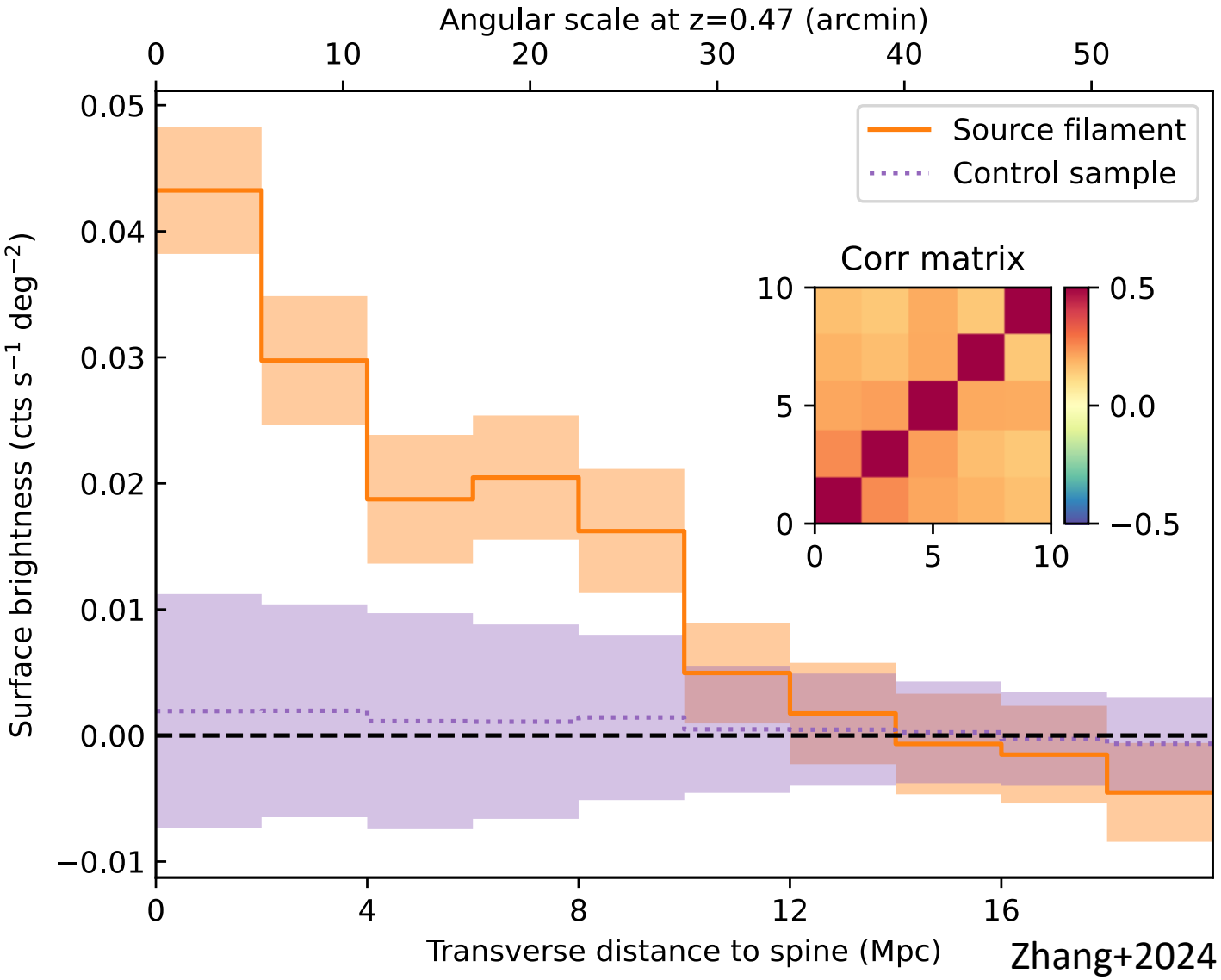


0.3-1.2 keV eRASS:4 map

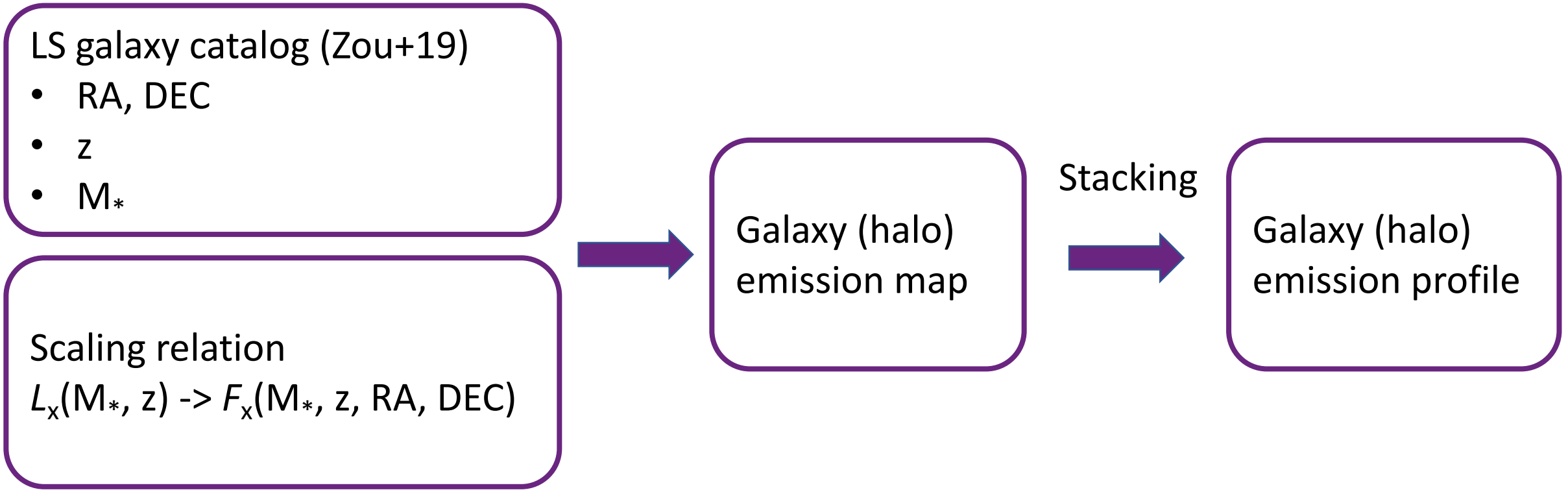
eRASS:4 detections
eRASS1 clusters (Bulbul+24)
redMaPPer λ>20 clusters (Kluge+24)
Foreground groups (Tinker+21)

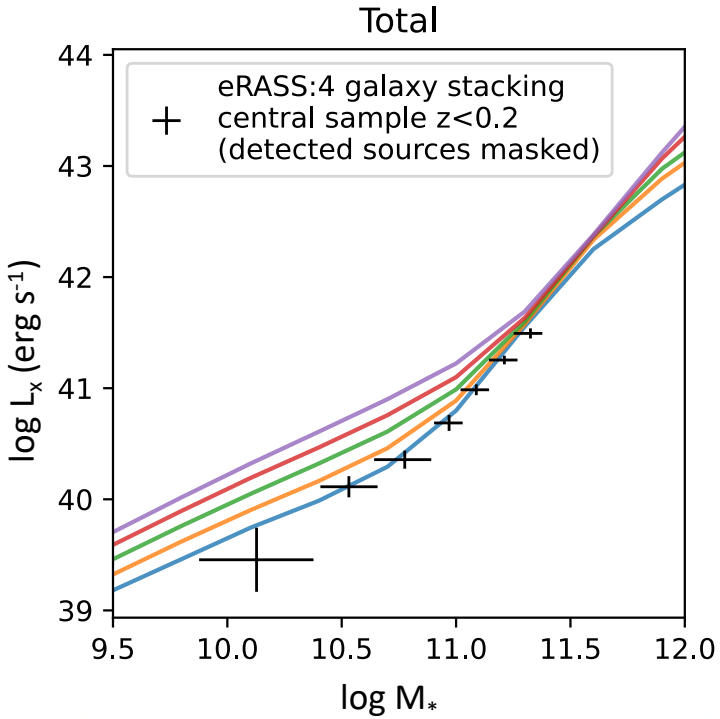
Stacked profile

- Stacking weight: exposure
- Local background subtracted
- Uncertainty: sky pixel bootstrapping
- Control sample: randomized filament positions

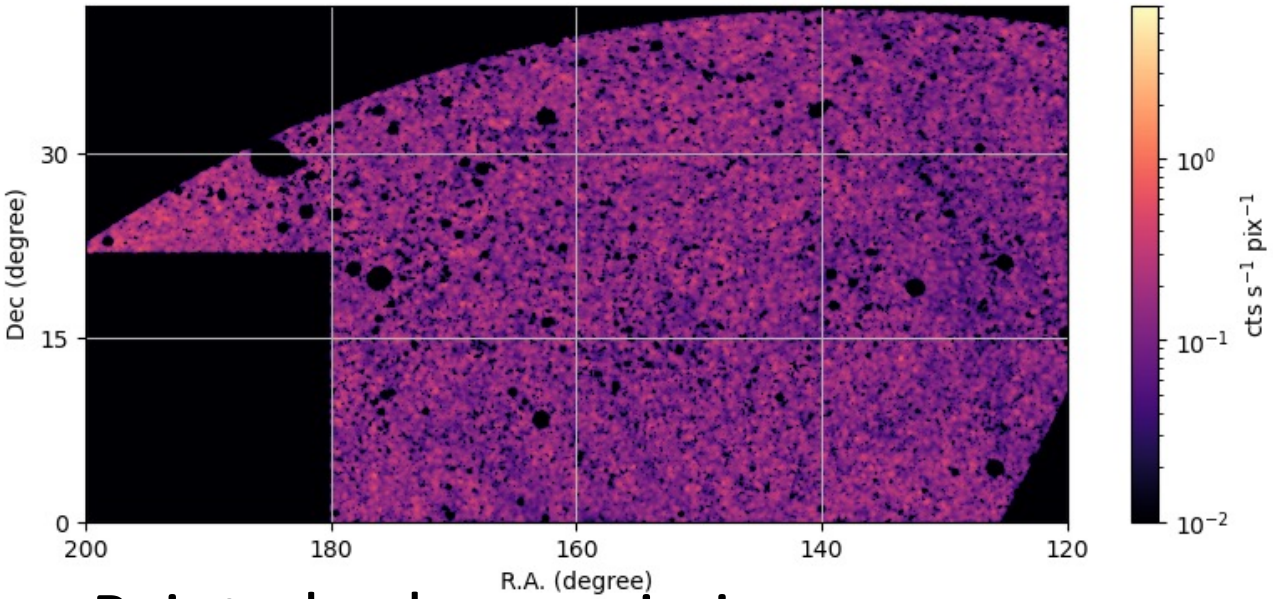


Galaxy based contamination signal modeling

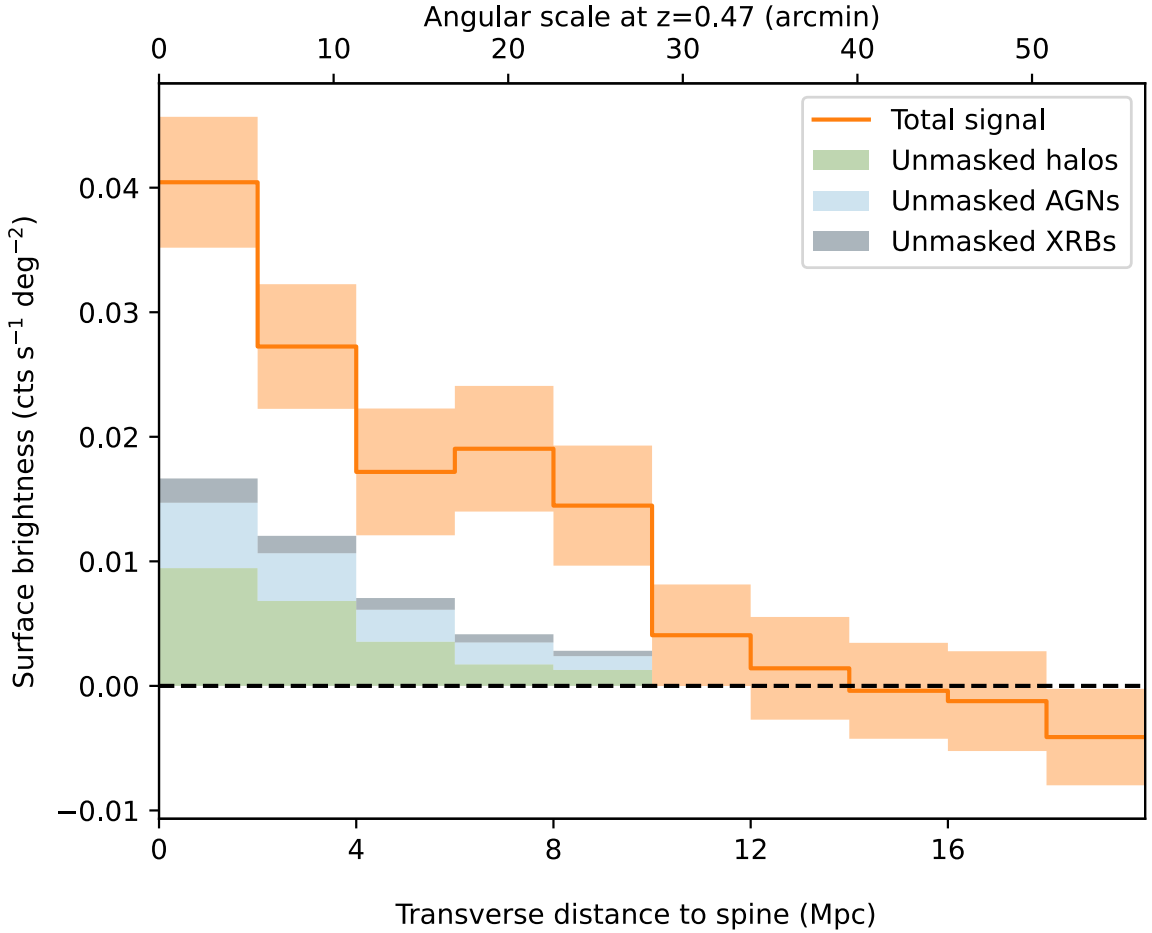




Model scaling relation
CGM:Anderson+15
AGN:Comparat+19,23
XRB: Lehmer+19



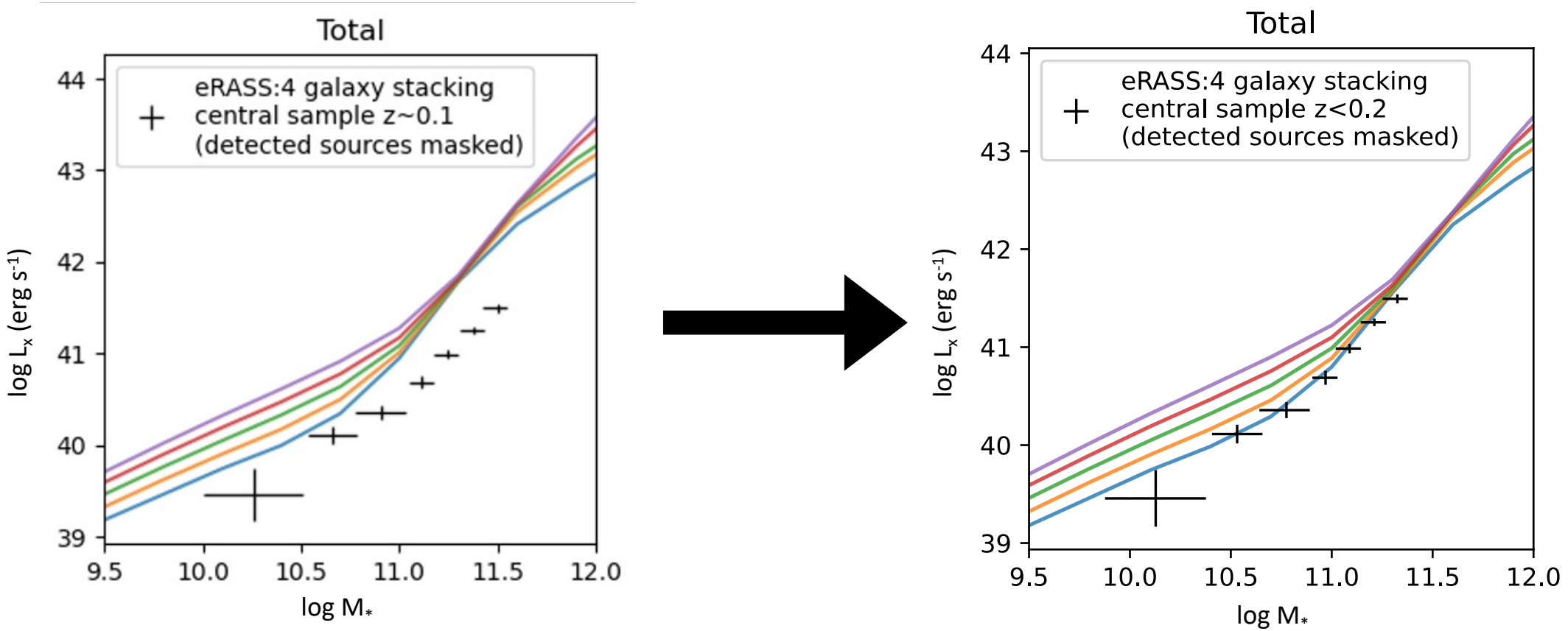
Painted galaxy emission map



Stacked profiles from the galaxy emission map

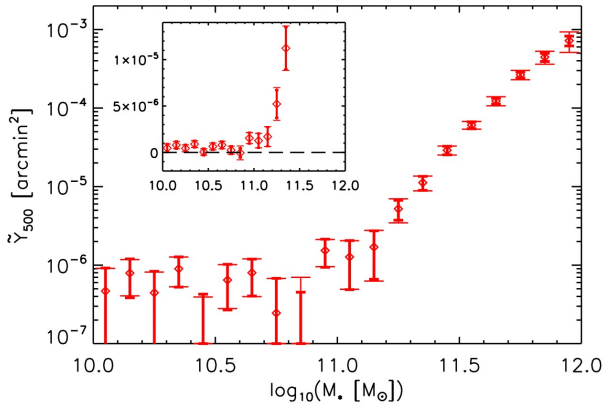
- ~40% “contamination”

Stellar mass measurement **discrepancy**



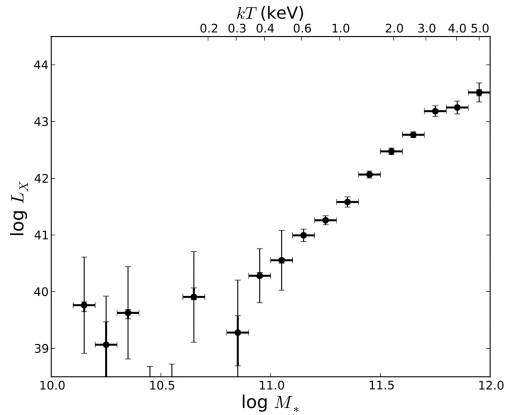
Version 04.2024

M∗



y-M∗ relation (Planck collaboration+13)

M∗: NYU-VAGC (Blanton&Roweis07)



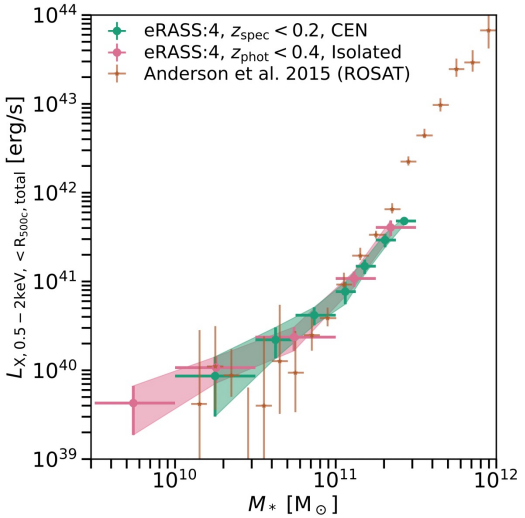
RASS Lx-M∗ relation (Anderson+15)

M∗: NYU-VAGC (Blanton&Roweis07)

J. Comparat's Mock

(Comparat+20,23)

- Anderson+15 Lx-M∗ relation
- UniverseMachine SMF (Behroozi+19)



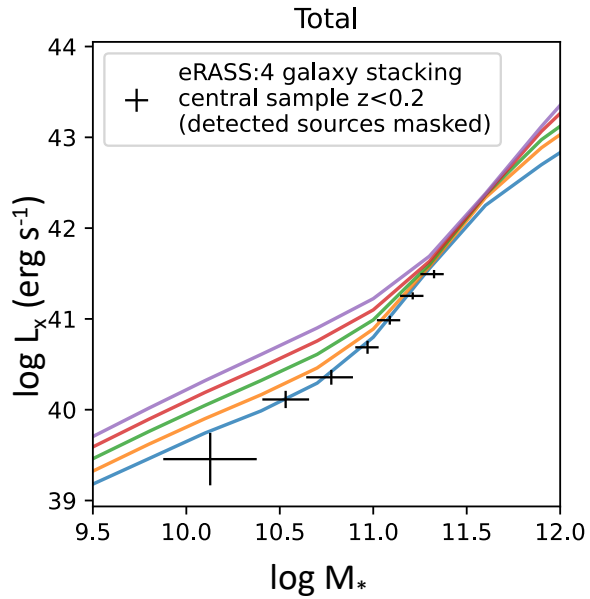
eRASS Lx-M∗ relation (Zhang+24)

M∗: Chen+12

The 4th version of M∗:

LS galaxy catalog (Zou+19)

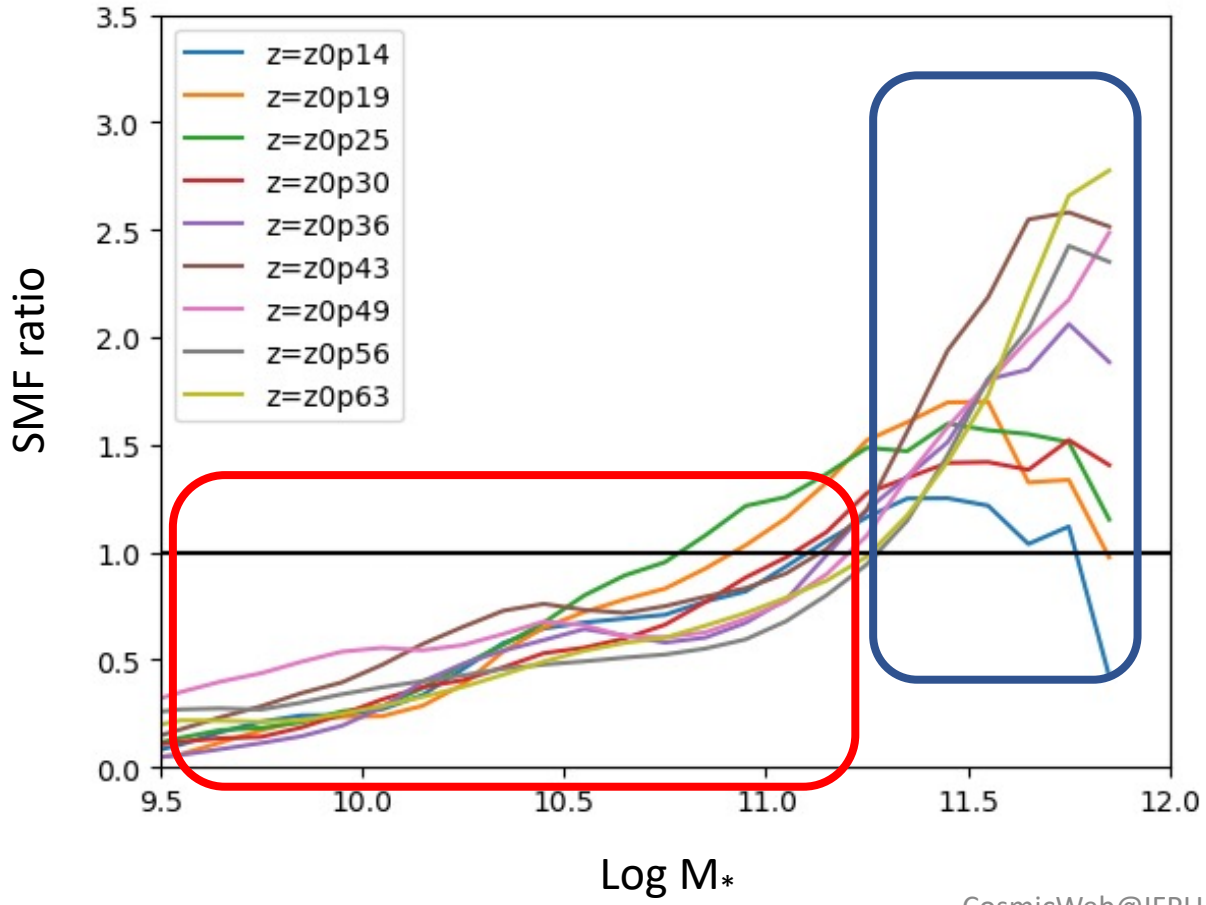
for galaxy emission map painting in this work



Use Zou+19 as a reference

Galaxy completeness & SMF discrepancy

Stellar mass function ratio Zou+19 / UniverseMachine

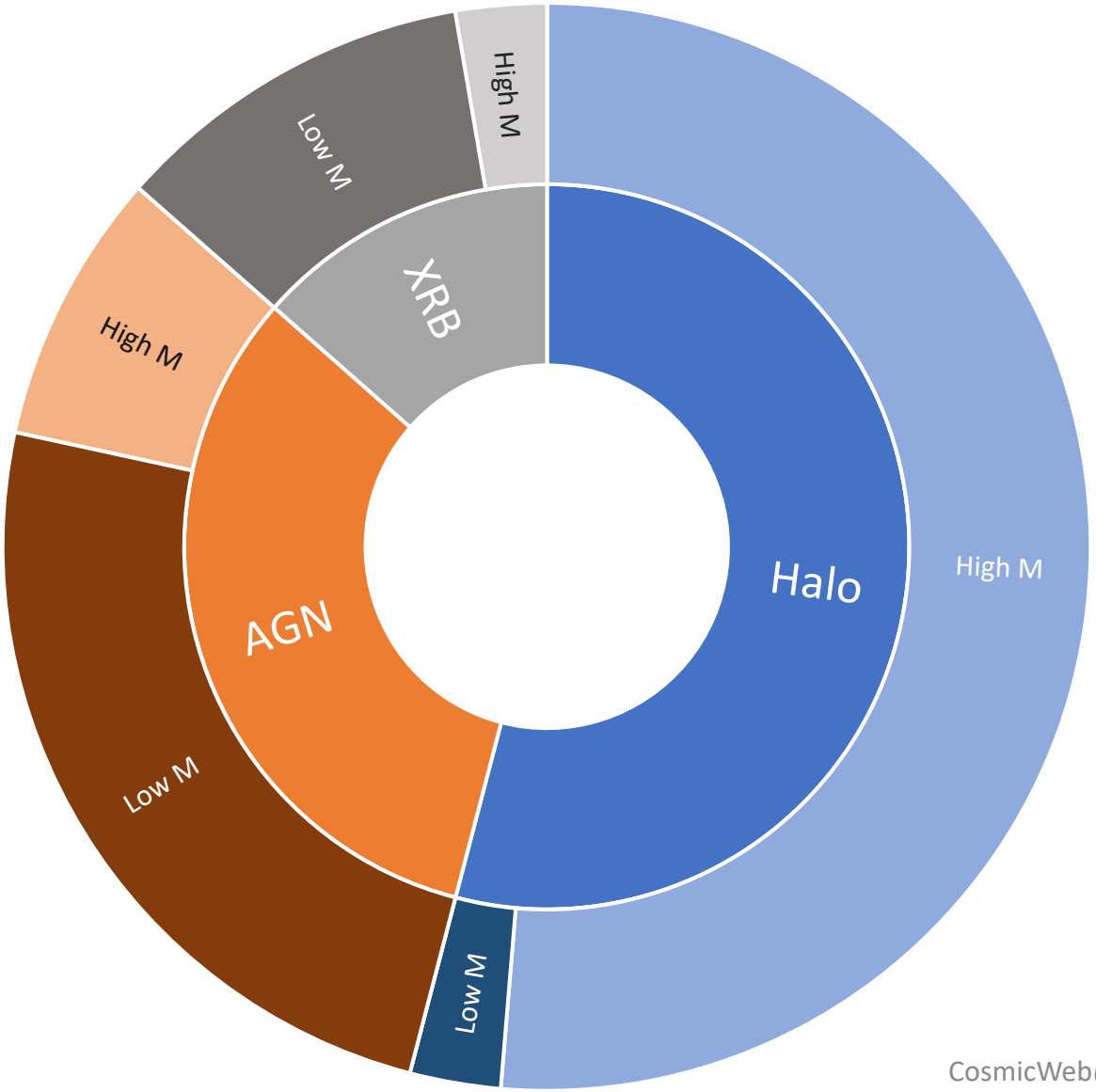


$M_* > 10^{11.2}\ M_\odot$:
SMF slope inconsistency, sensitive to M_* measurement

Conservative decision:
No further M_* correction

$M_* < 10^{11.2}\ M_\odot$:
Observed galaxies are incomplete
$F_{paint} = F_{predict}$ / completeness

Contamination fractions

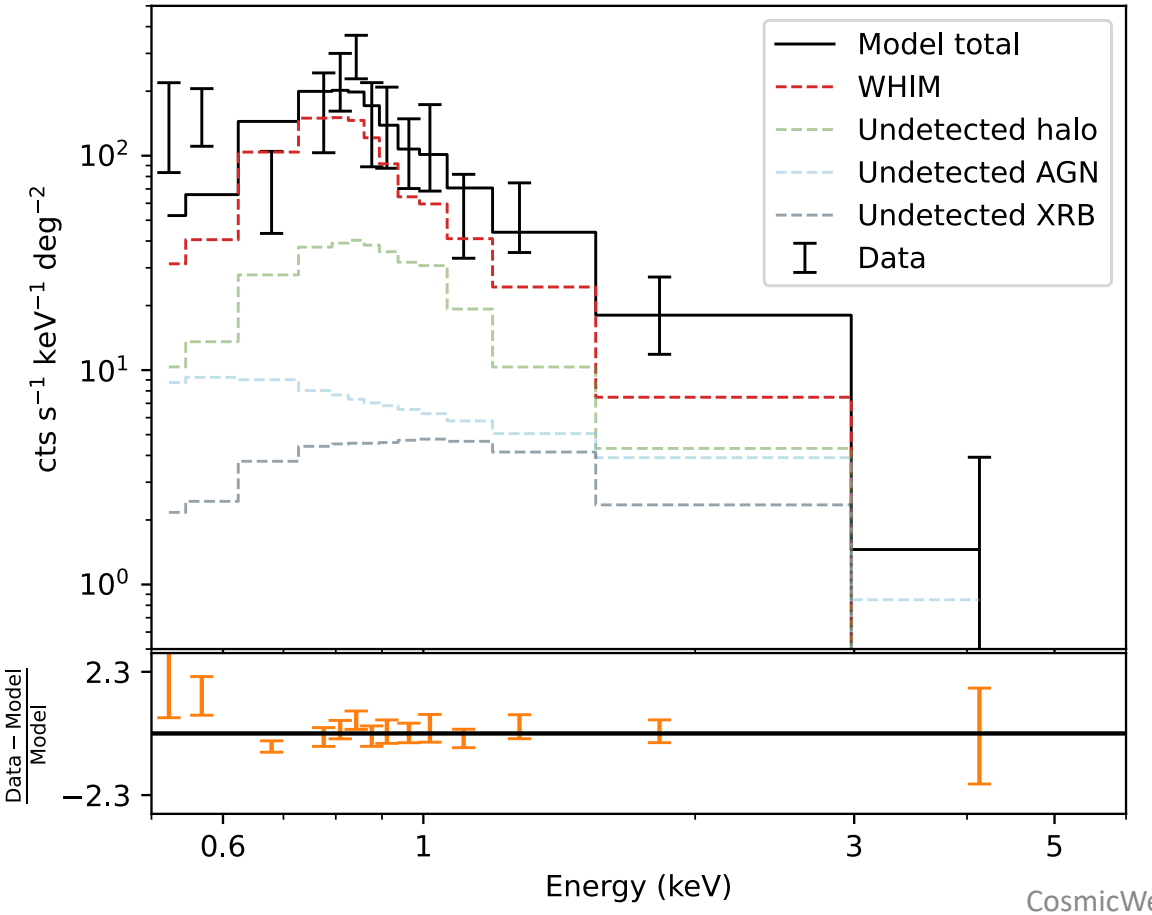


- Over half contamination is from X-ray halos (group size)

High M: $M_* > 10^{11}\ M_\odot$
Low M: $M_* < 10^{11}\ M_\odot$

Stacked rest-frame spectra

- Approach of blueshift & stack (Bulbul+14)



Components:

- APEC ($Z = 0.2 \times Z_{\odot}$) [Norm, kT]
- Contamination sources [Norm]
  - Halo gas
  - AGN
  - XRB

Best-fit "representative" temperature
0.58 ± 0.1 keV ($10^{6.8}$ Kelvin)

0—10 Mpc region with
10—20 Mpc local bkg subtracted

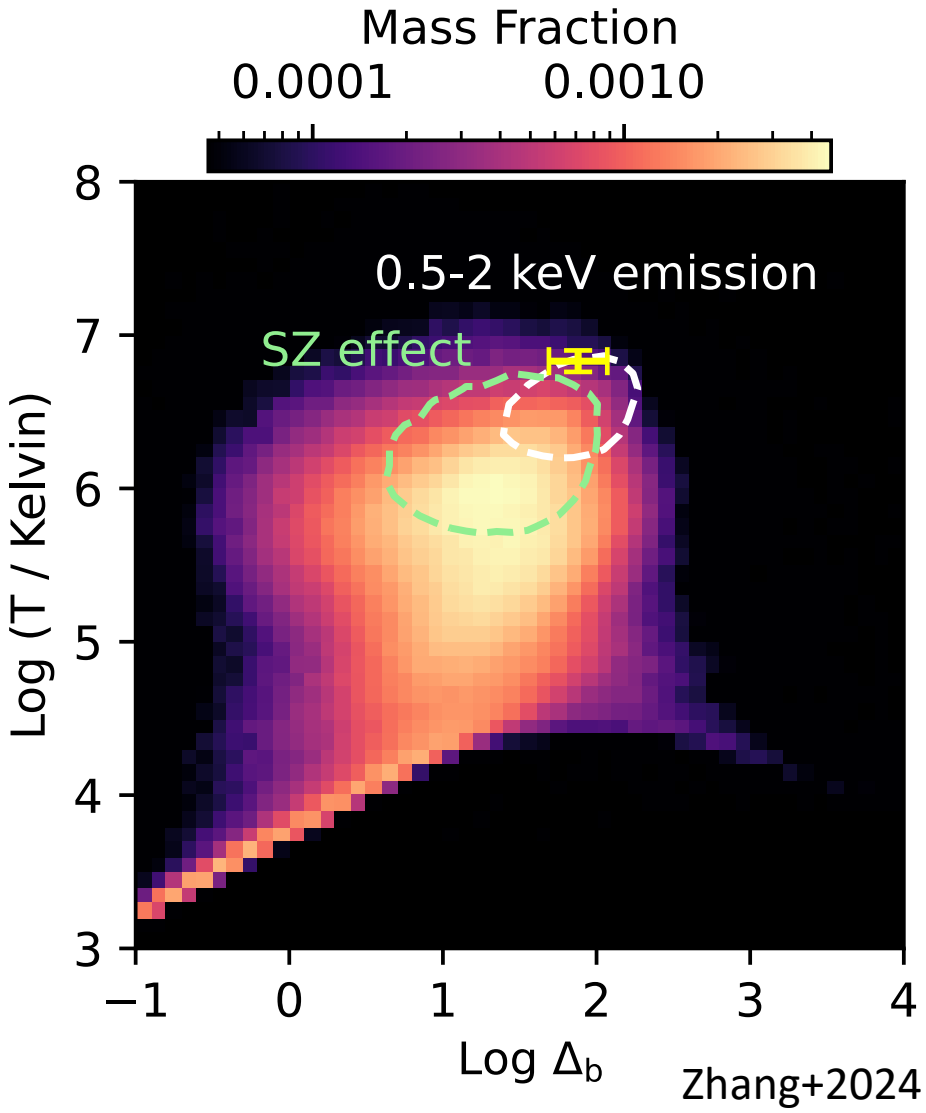
Profile modeling

Two-phase modeling:
Volume filling phase + X-ray emitting phase

Assumptions for X-ray emitting phase:

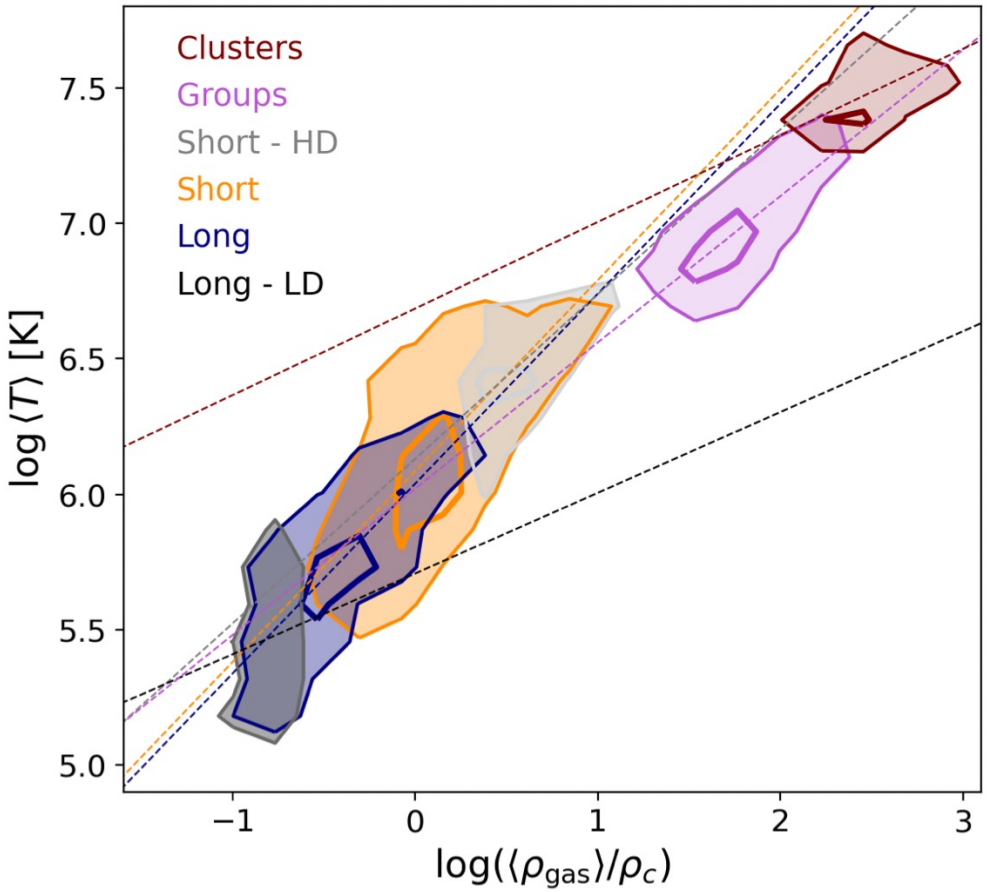
- King-profile
- log y_{sz} : -8.5
- Isothermal gas

- $\mathrm{Log}\,\overline{\Delta}_{\mathrm{b}} = 1.88 \pm 0.2$ (volume averaged)
- only ~1% of the total volume



All Subfind halos removed
Contour: 50% enclosed contribution

What phase do we stack?



Galarraga-Espinosa+22

The broad phase distribution comes from:

- Multiphase in individual filaments
- Phase “scaling relation” of different filament population

Take-home messages

Cluster stacking

- Galaxy clusters are not isolated
- $\sim r_{200m}$:
  - Intersection between 1-h and 2-h
  - Baryon enclosure radius
- r_{shock} can be indirectly estimated

Filament stacking

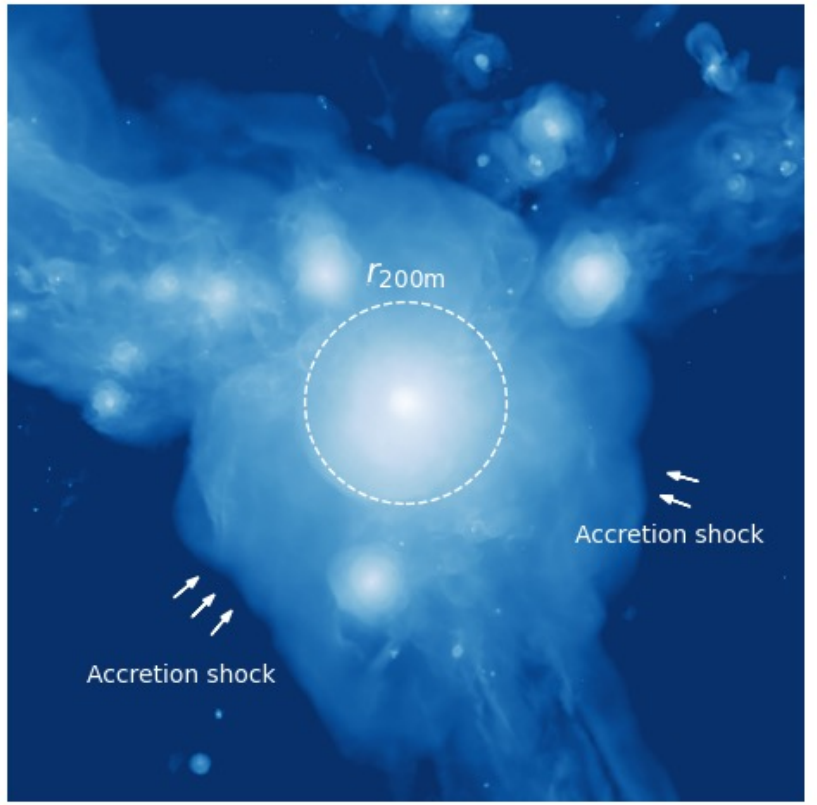
- Understand halo contamination is more difficult than getting signal
- X-ray is mostly from high density hot gas

Open discussions

1. Is there a clear boundary between gaseous halos and the cosmic web environment?
2. Can accretion (external) shocks be directly observed with X-ray?
3. Regarding to splashback radius measurements, are we talking about the splashback feature or 1h-2h intersection? Are they same?
4. What is the minimal halo-halo separation to define a “filament”?
   - Double r_{200m} or double r_{shock}?
   - Is a 7 Mpc bridge between two clusters a filament?
5. Better way to remove contamination from filament stacking?

Halo – environment boundary?

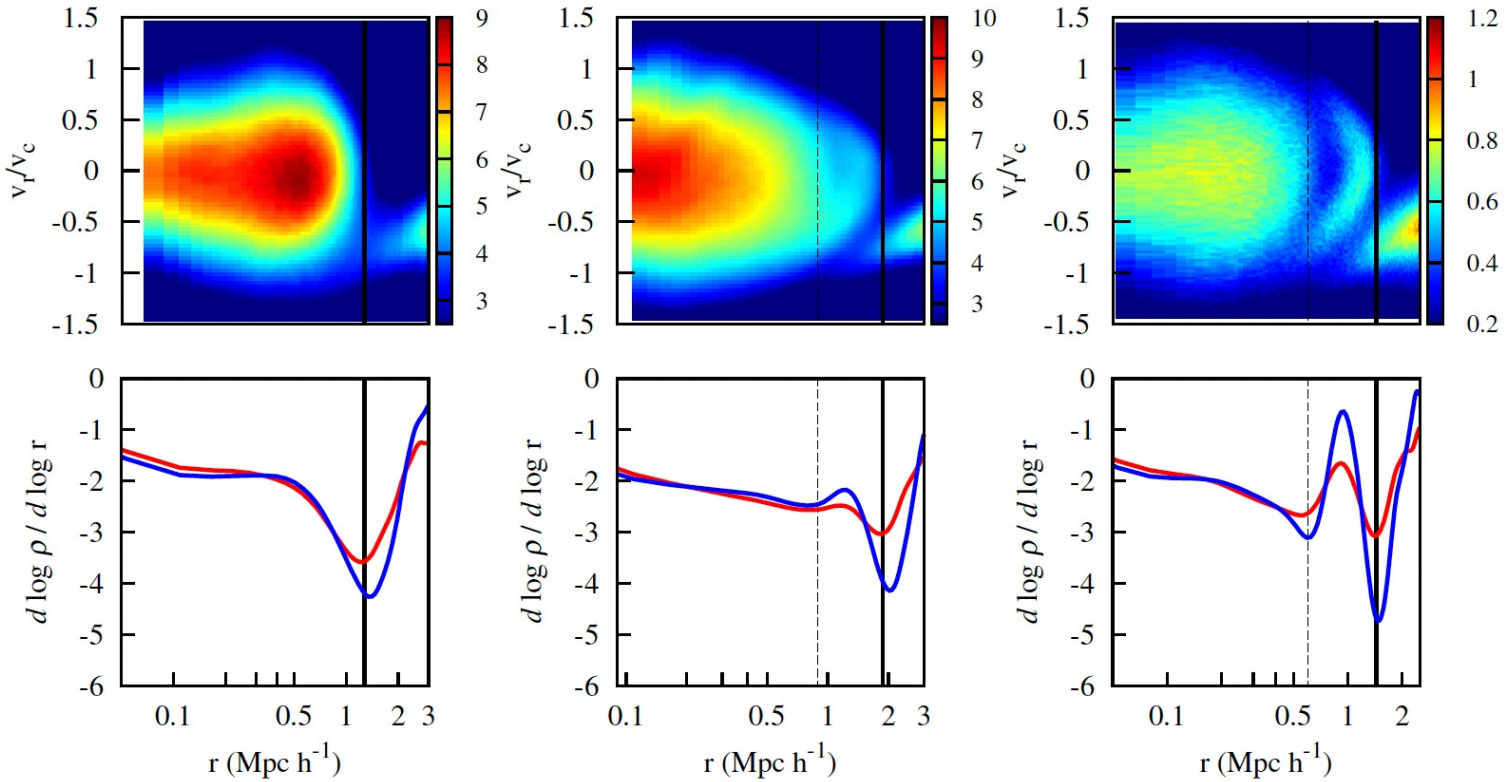
1. Is there a clear boundary between gaseous halos and the cosmic web environment?
2. Is there a boundary between ICM and WHIM?



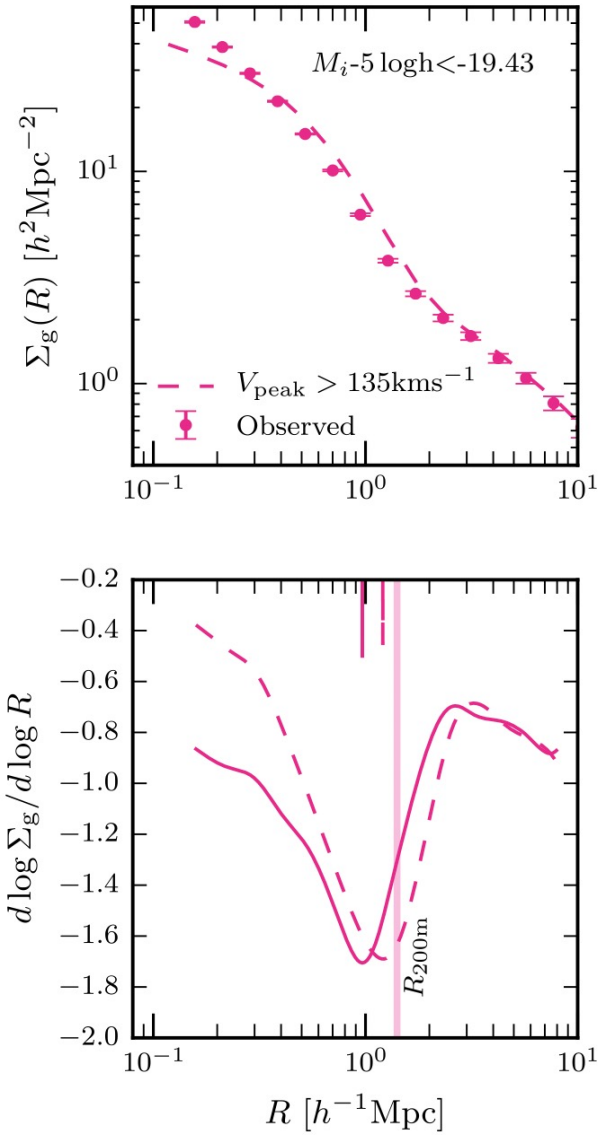
Can accretion (external) shocks be directly observed with X-ray?

- Post-shock density is about cosmic mean baryon density
- Post-shock SB: ∼1/100 of 2-h SB, ∼1/10,000 of sky SB.

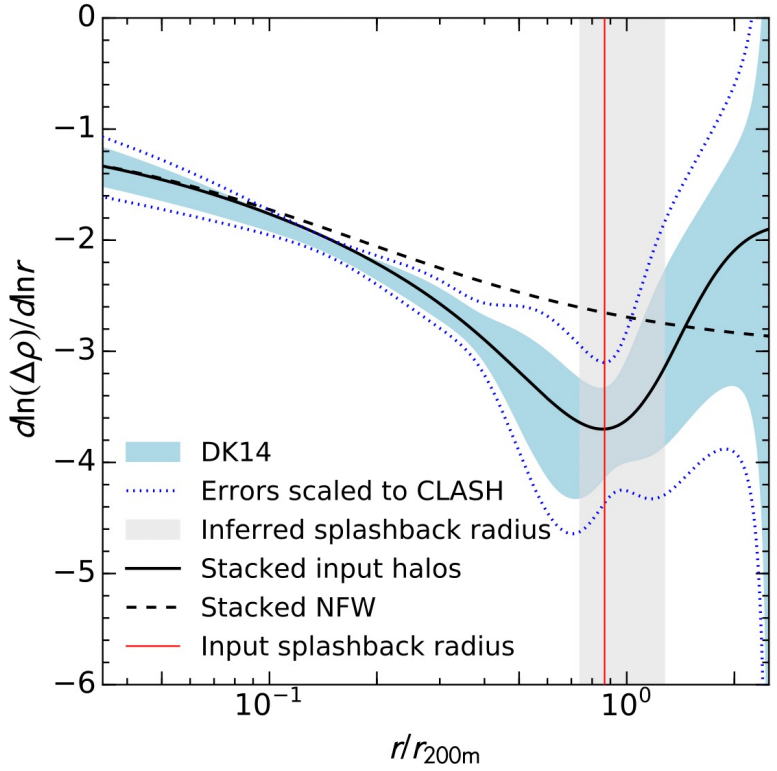
Splashback radius measurements: true splashback feature or 1h-2h intersection?



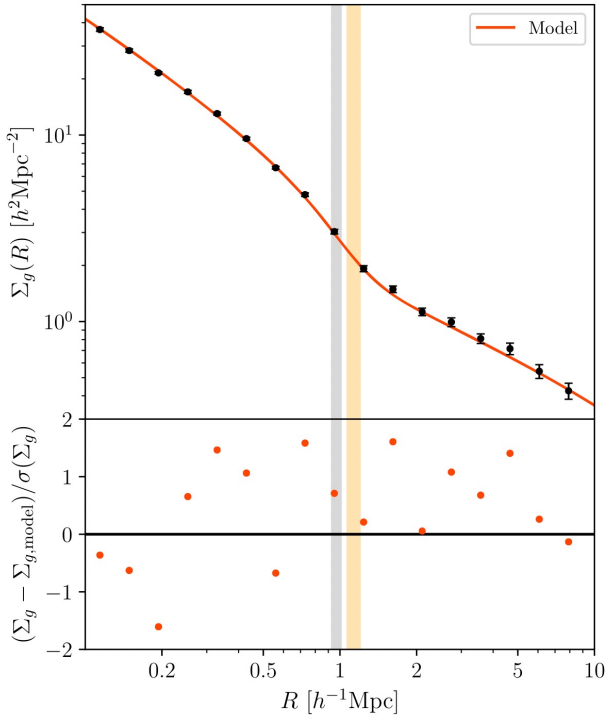
Widely used log-slope method (Adhikari+14)



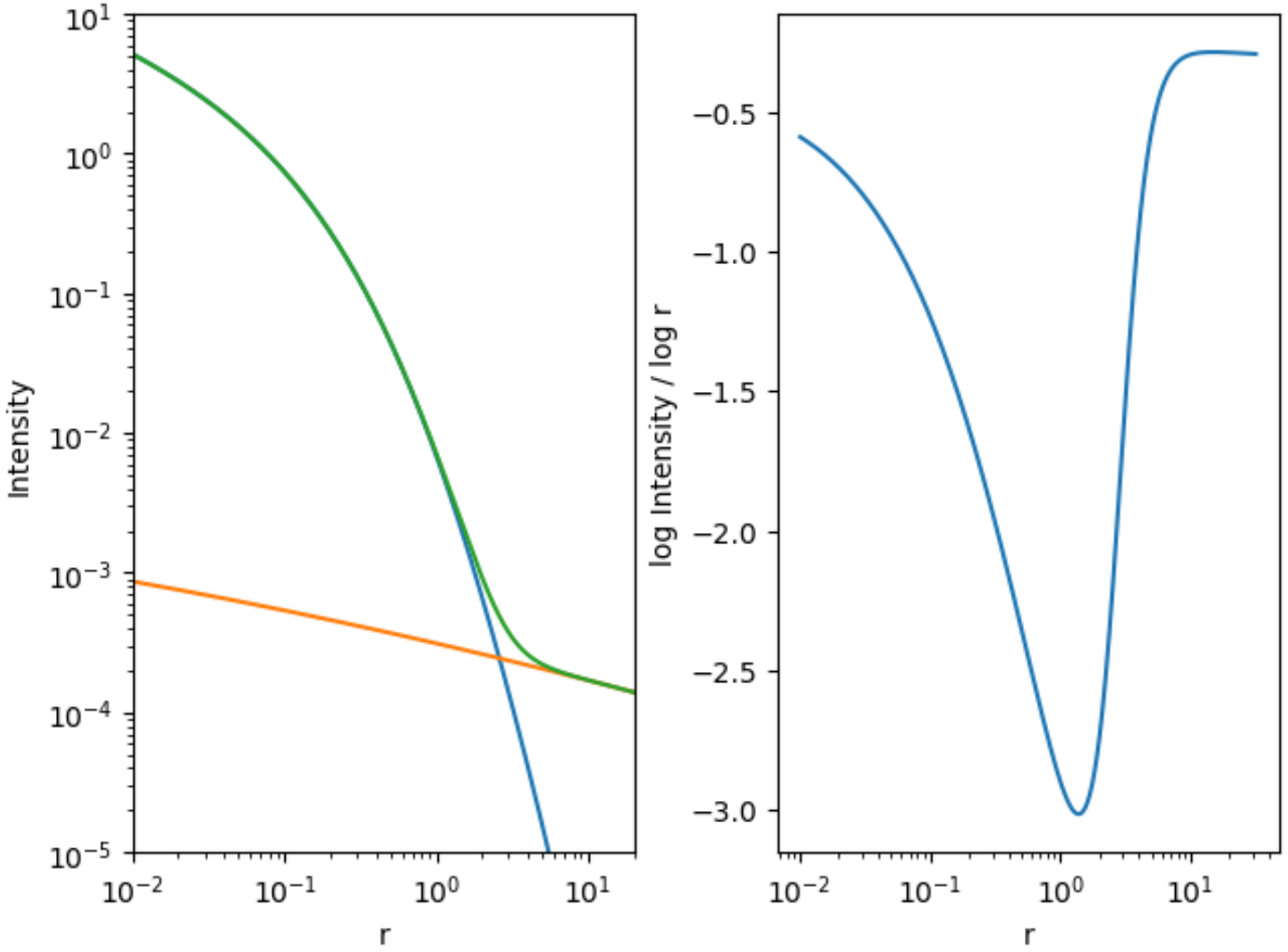
More+16



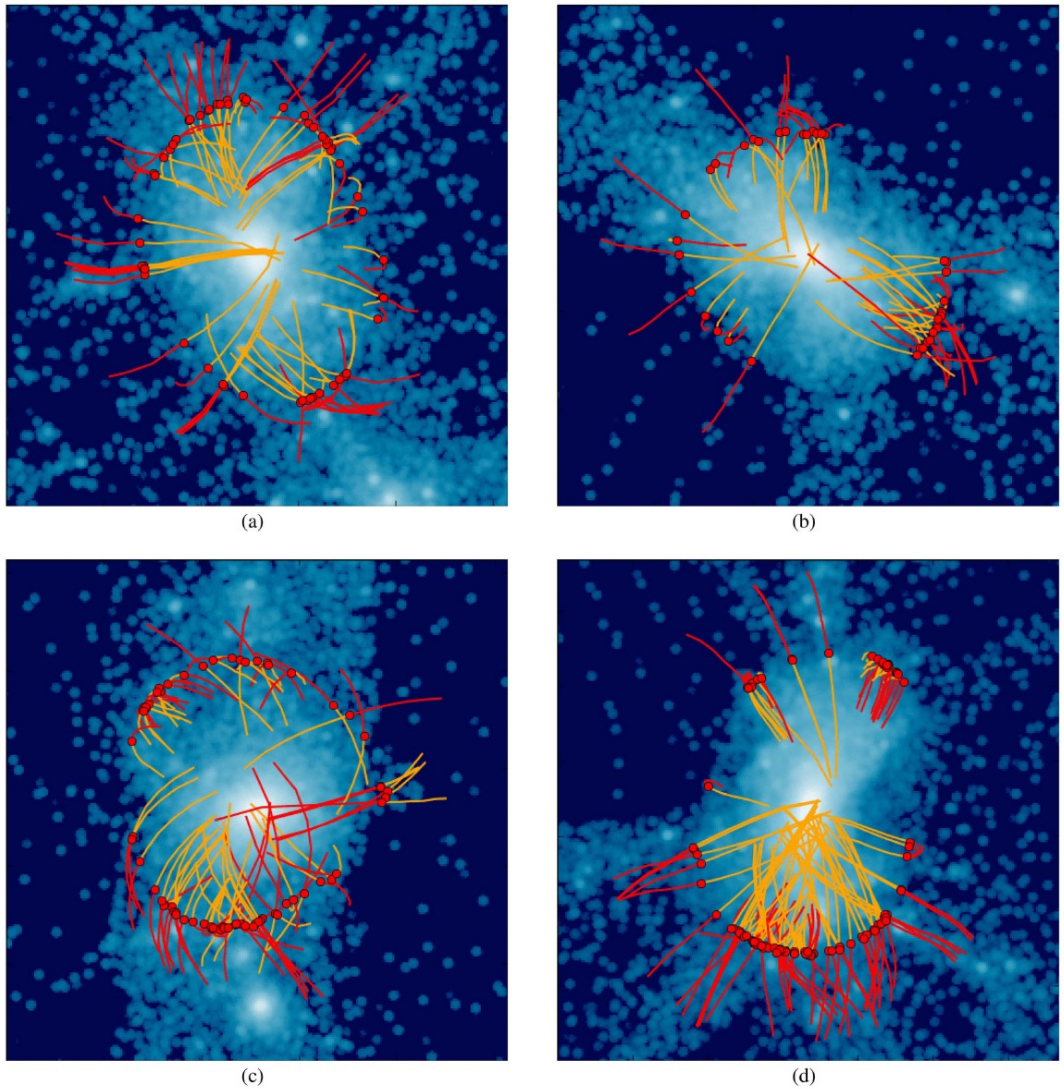
Umetsu+17



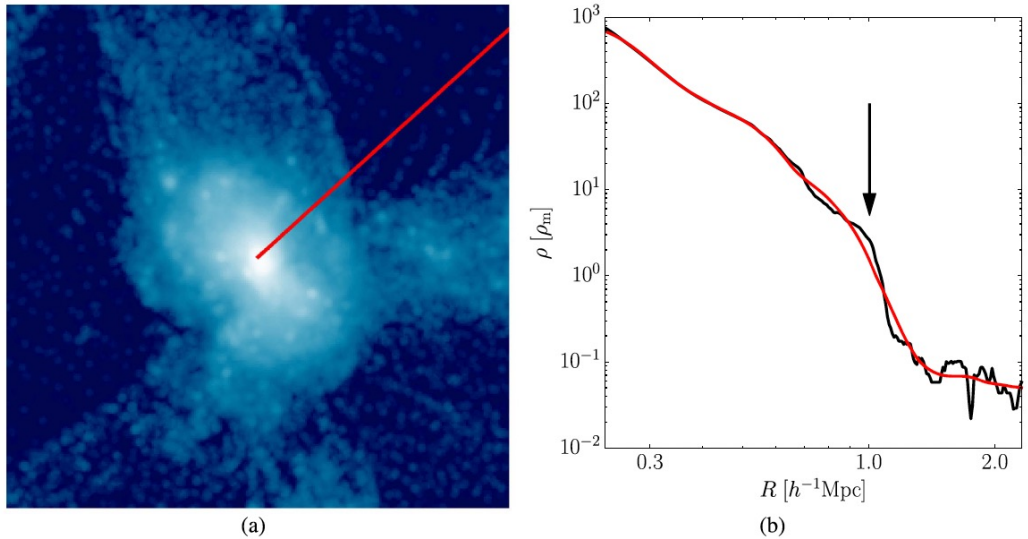
Chang+18



- The log-slope valley can be easily produced by a gnfw + flat power law combination

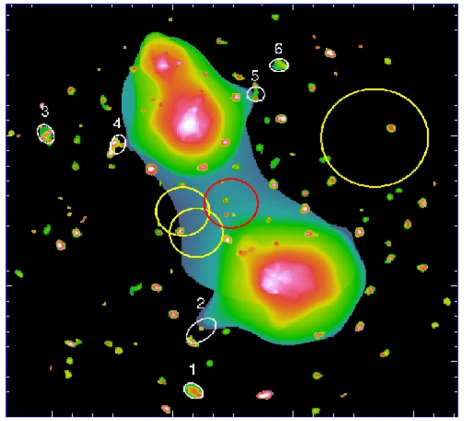


Trajectories of DM particles (Mansfield+17)

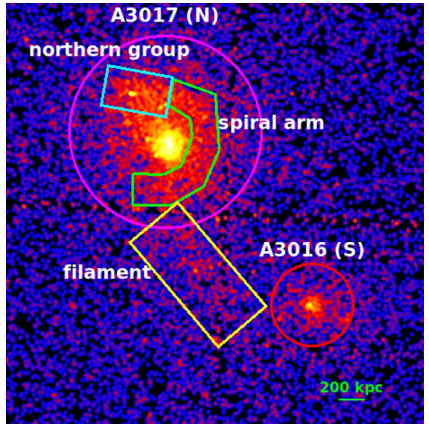


Splashback: Sharp edge of DM

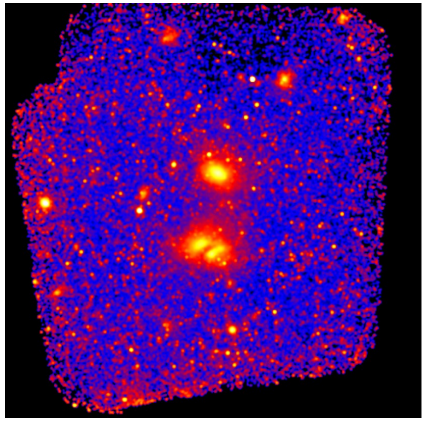
Are those filaments?



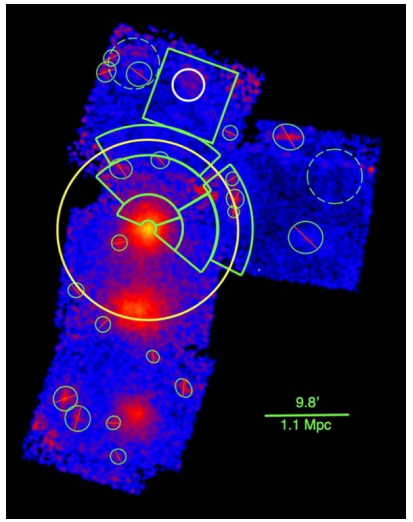
A222-223: 2.8 Mpc
(Werner+08)



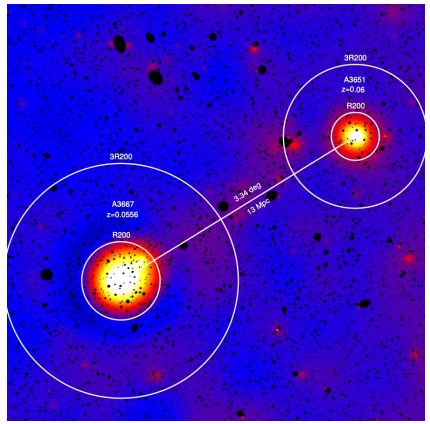
A3016-3017: 1 Mpc
(Parekh+17, Chon+19)



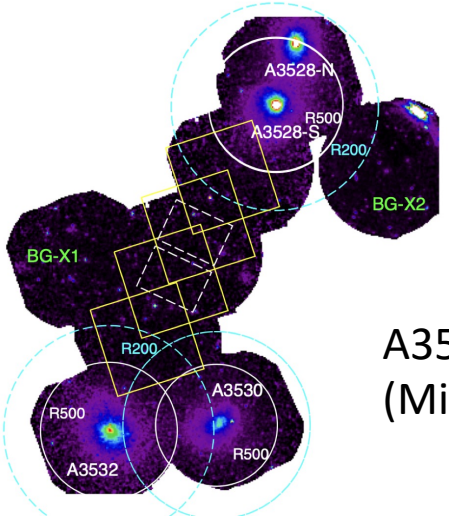
A3391-3395: 2.6 (15) Mpc
(Sugawara+17, Alvarez+18,
Reiprich+21, Veronica+24)



A98NS
(Alvarez+22)



A3667-3651: 13 Mpc
(Dietl+24)



A3532-3528: 4.3 Mpc
(Migkas+25)

What are filaments?

Cluster A	GLon	GLat	z	θ_{500} (′)	Cluster B	GLon	GLat	z	θ_{500} (′)	θ_{12} (′)
A0399	164.315	−39.458	0.0722	13.53	A0401	164.184	−38.869	0.0739	14.73	35.8
A3391	262.377	−25.148	0.0514	14.91	A3395	263.243	−25.188	0.0506	15.67	47.0
A2029	6.437	50.53	0.0766	15.32	A2033	7.308	50.795	0.0817	9.94	36.6
MKW3s	11.393	49.458	0.0442	18.14	A2063	12.811	49.681	0.0355	21.29	56.8
A2147	28.970	44.535	0.0353	22.19	A2152	29.925	43.979	0.0370	13.12	52.9
A2256	111.014	31.759	0.0581	16.62	A2271	110.047	31.276	0.0584	10.55	57.3
A0209	159.878	−73.507	0.2060	5.60	A222	162.494	−72.221	0.21430	4.35	89.9
A0021	114.819	−33.711	0.0940	8.74	IVZw015	114.953	−34.357	0.0948	8.00	39.3
RXJ	271.597	−12.509	0.0620	13.86	RXJ	272.087	−11.451	0.0610	11.67	69.6
RXJ	303.215	31.603	0.0535	13.72	RXJ	304.324	31.534	0.0561	10.98	56.8
A3558	311.987	30.726	0.0480	19.50	A3562	313.329	30.358	0.0490	16.09	72.7
A2259	50.385	31.163	0.1640	6.23	RXJ17.33+26.62	49.221	30.859	0.1644	7.18	62.5
A3694	8.793	−35.204	0.0936	9.19	A3695	6.701	−35.547	0.0894	10.62	104.4
A3854	8.456	−56.330	0.1486	6.80	A3866	9.408	−56.946	0.1544	7.23	48.5
MS2215	58.636	−46.675	0.0901	9.44	RXJ	59.757	−46.262	0.0902	8.00	52.5
RXJ	59.757	−46.262	0.0902	8.00	A2440	62.405	−46.431	0.0906	9.58	110.1
A222	162.494	−72.221	0.2143	4.35	A223	162.435	−72.006	0.2108	4.61	12.9
A3528N	303.709	33.844	0.0542	12.67	A3528S	303.784	33.643	0.0544	13.94	12.6
A3530	303.990	32.532	0.0541	12.73	A3532	304.426	32.477	0.0554	14.24	22.2
RXJ	109.848	53.046	0.3320	3.04	Zw1358.1+6245	109.941	52.846	0.3259	3.71	12.4
A2061	48.130	57.161	0.0777	11.06	A2067	48.548	56.776	0.0756	8.46	26.8
NPM1G+30.0	58.259	18.810	0.0717	9.42	RXJ	58.309	18.547	0.0645	12.71	16.0
A2384B	33.321	−48.441	0.0963	7.87	A2384A	33.540	−48.431	0.0943	8.98	8.7
A2572a	93.857	−38.800	0.0422	15.34	A2572	94.232	−38.933	0.0403	14.67	19.2
PLCK12.8+49.7	12.818	49.699	NA	NA	PLCK11.3+49.43	11.368	49.431	NA	NA	58.68

Cluster pairs in Planck Collaboration+13

What are filaments?

- A typical cluster pair with their r_{200m} touched: $\gtrsim$ 5 Mpc
- Can pairs solve the “missing baryon problem”?
- Is a filament a chain of halos?

Better way to remove contamination from filament stacking?