eROSITA view of the WHIM emission in cosmic filaments

Xiaoyuan Zhang

on behalf of the eROSITA-DE consortium

xzhang@mpe.mpg.de

Based on
Zhang et al. 2024, A&A, 691, A234

NewAthena Science Webinar, 22 April 2025

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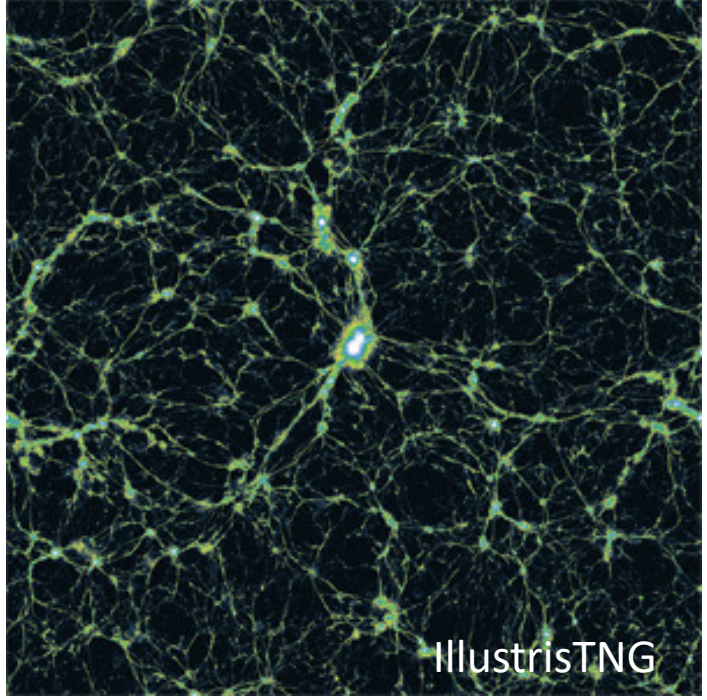
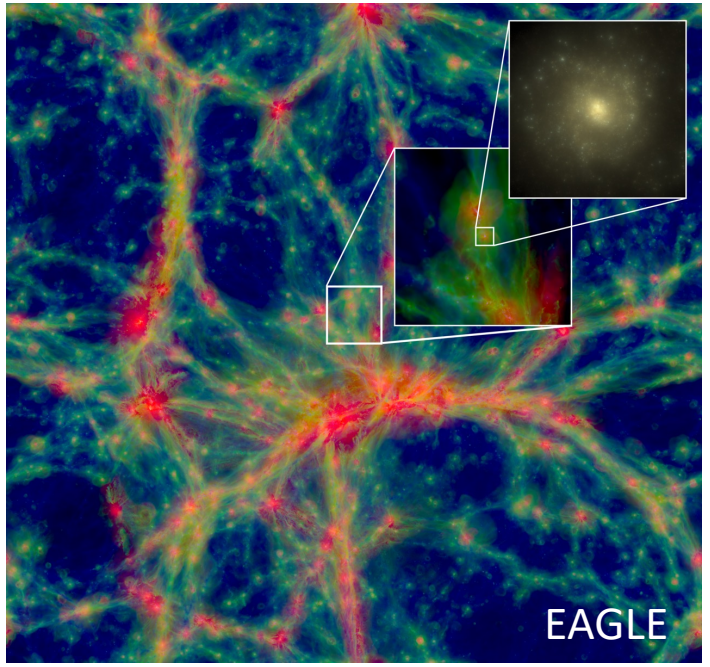
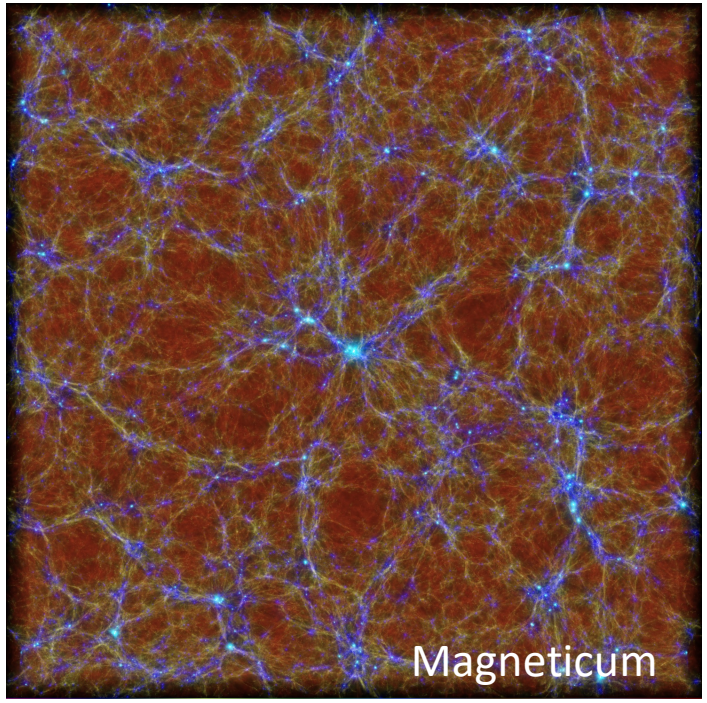
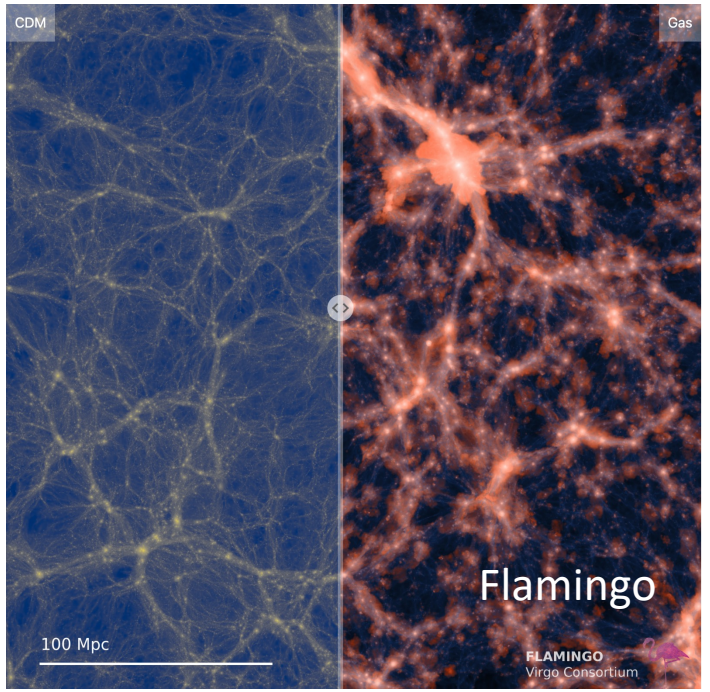




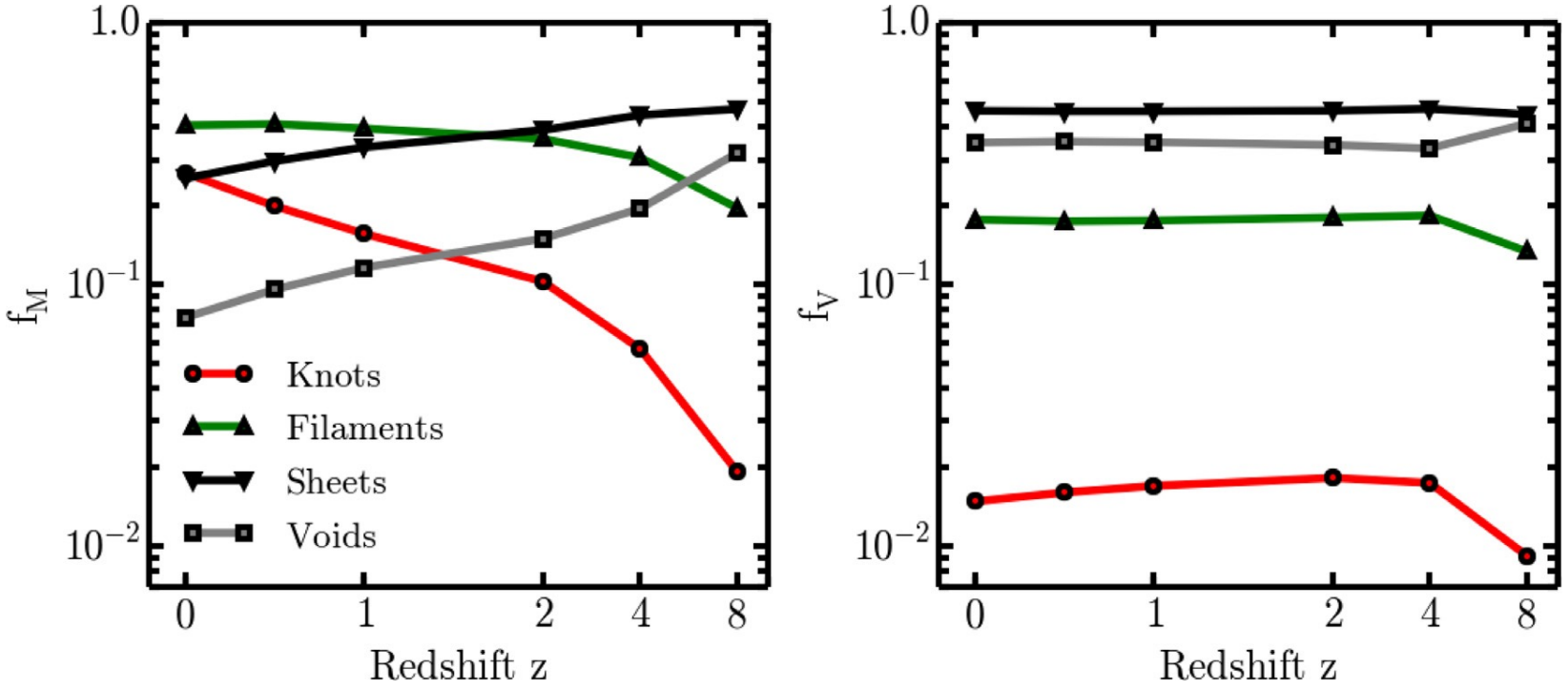




Large scale structure

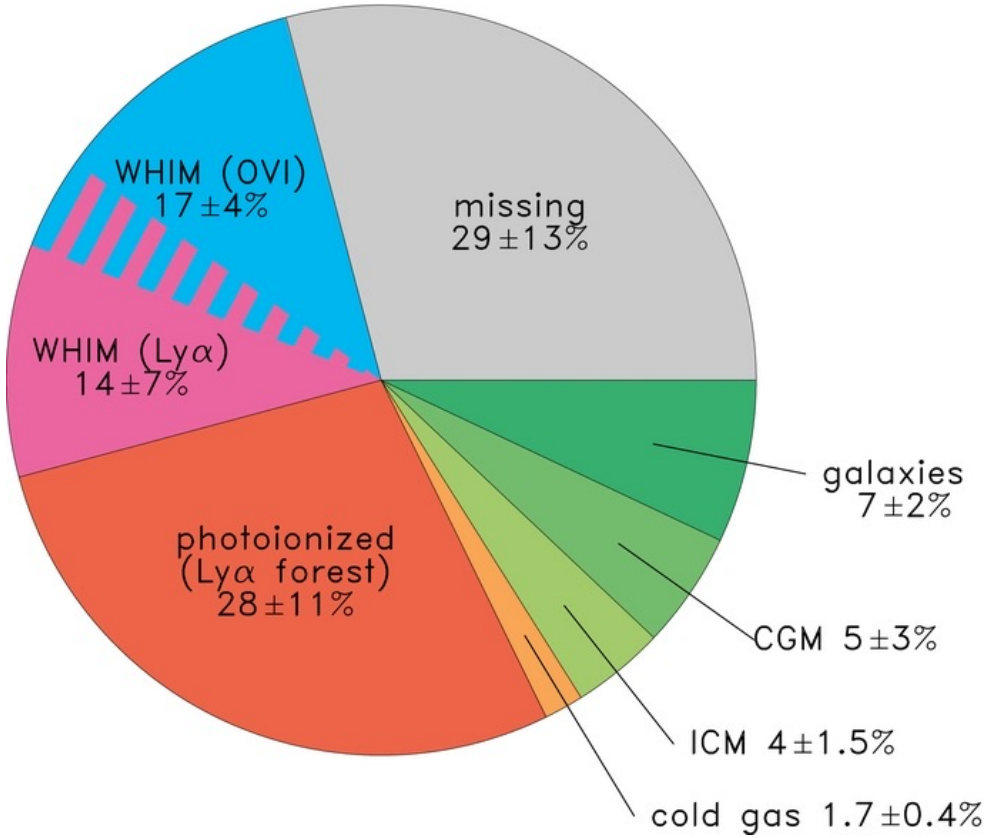
- Voids
- Sheets
- Filaments
- Nodes

40% of total mass is in cosmic filaments



Mass and comoving volume evolution (Martizzi+2019)

Mass accretion: Voids & sheets -> filaments + knots



Shull+12

Table 2. Hot gas ($\log T(\mathrm{K}) > 5.5$) fraction of the total baryon content within the EAGLE simulation.

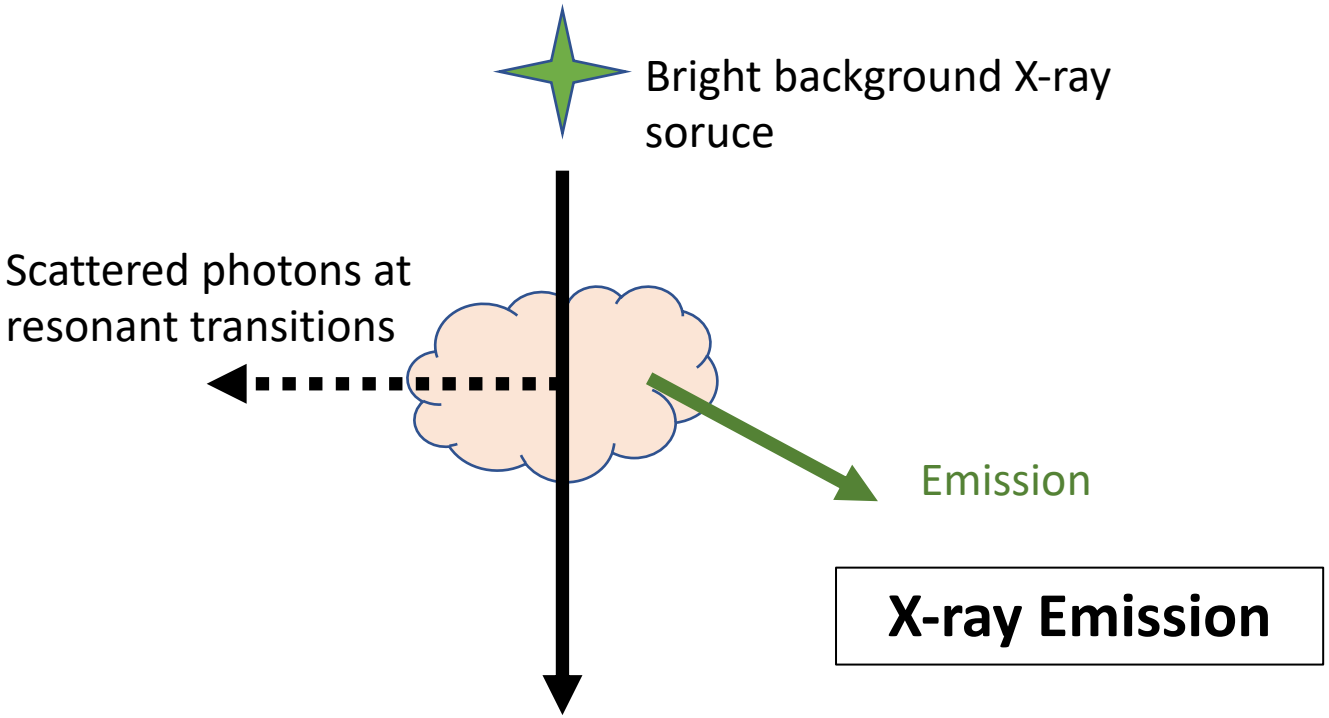
Component	$\Omega_{b,i}$ / $\Omega_{b,planck}$
Total	42%
Within R_{200}	13%
Hot WHIM [a]	29%
Outskirts [b]	5%
Bisous filaments [c]	25%
NEXUS+ filaments [c]	23%

Notes. [a]"Total" – "Within R_{200}". [b]Gas outside R_{200} but within FoF halo. [c]Outside R_{200}, including outskirts.

- ~30% of the total baryon is missing
- In the $T > 10^{5.5}$ K **Warm-Hot Intergalactic medium** phase

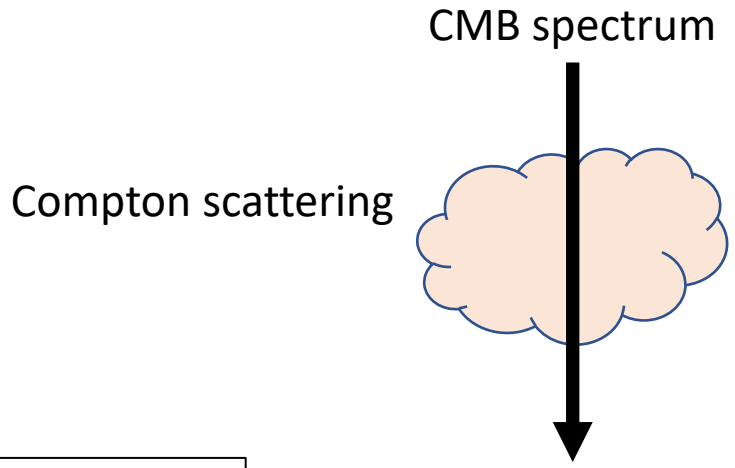
Analysis of EAGLE simulation (Tuominen+21)
~25% of baryon is
- $T > 10^{5.5}$ K
- Outside r_{200c}
- In cosmic filaments

How do we observe it?

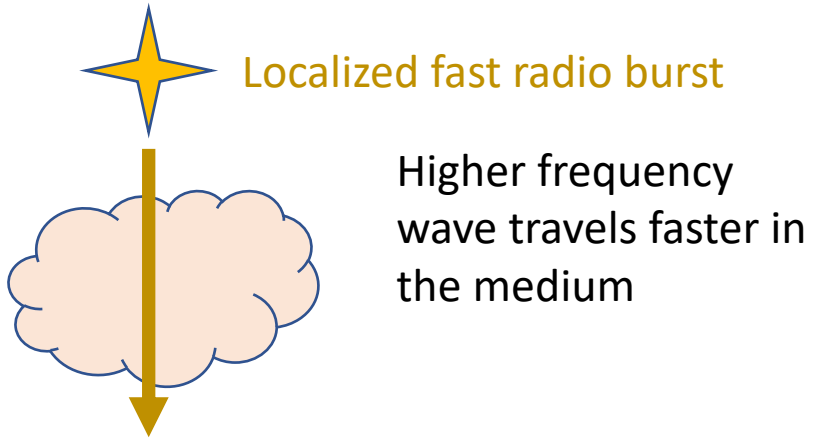


X-ray Emission

X-ray Absorption

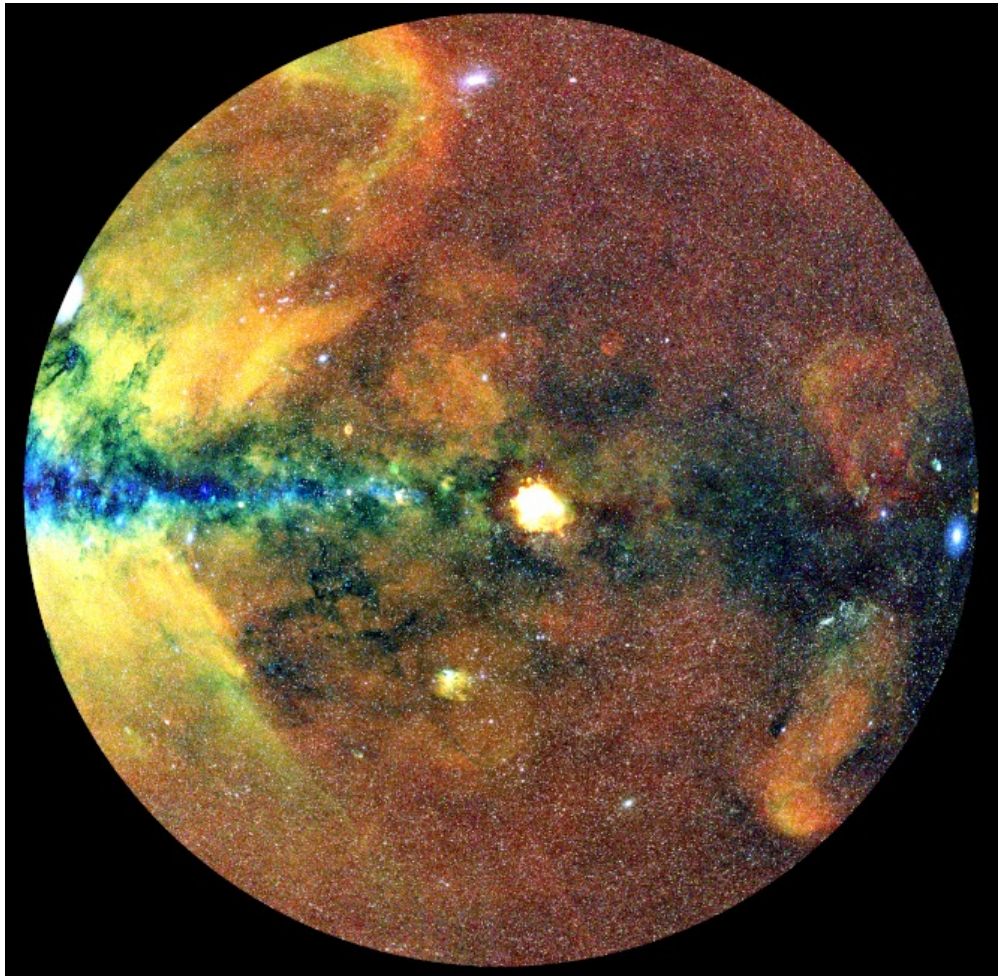


Thermal SZ



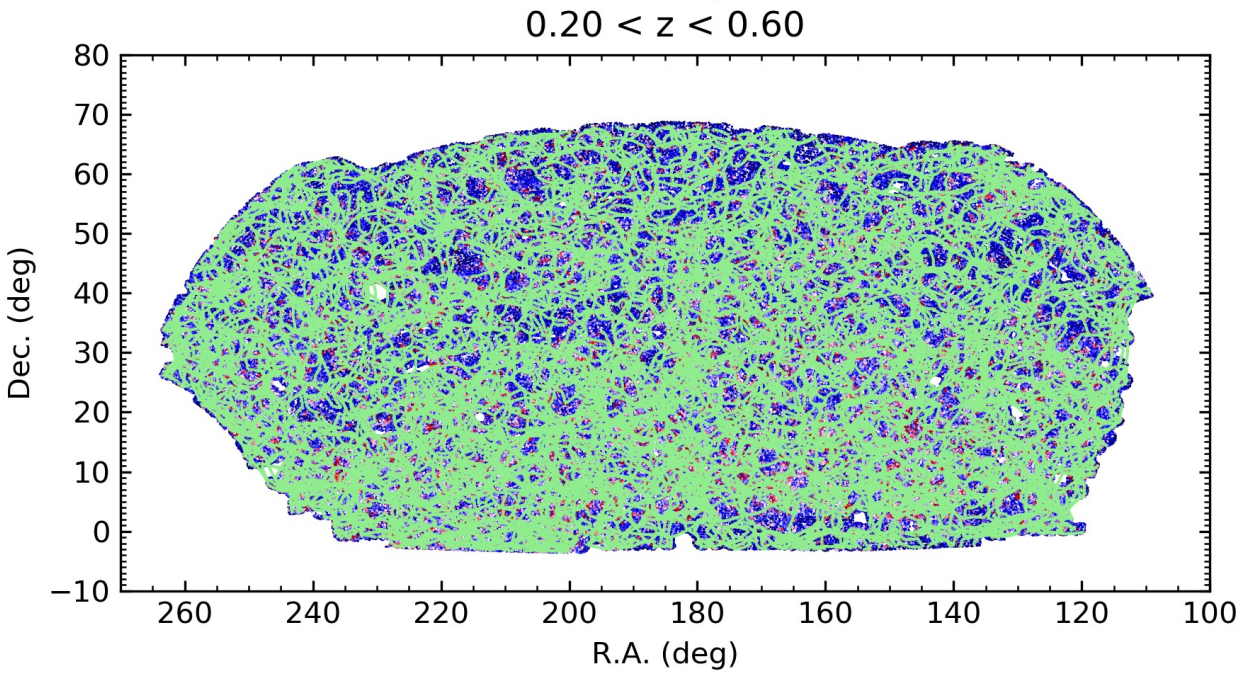
Dispersion Measure

About this work



eROSITA All-Sky Survey

+



Cosmic filament catalog

- SDSS BOSS galaxies + DisPerSE method (Malavasi+20)

Questions to be answered in this work

How much of the X-ray background emission is correlated with cosmic filaments?

What is the fraction of the signal from unbound WHIM?

What is the physical condition of the X-ray emitting WHIM

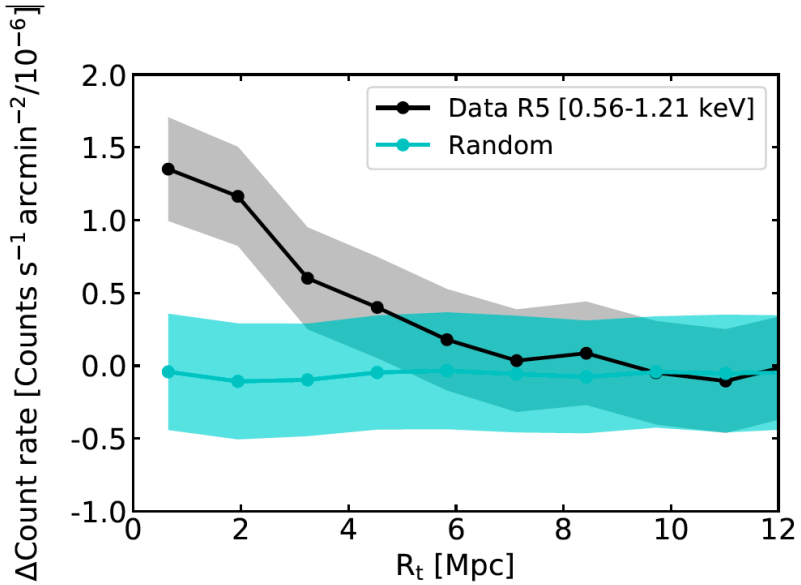
Stacking analysis

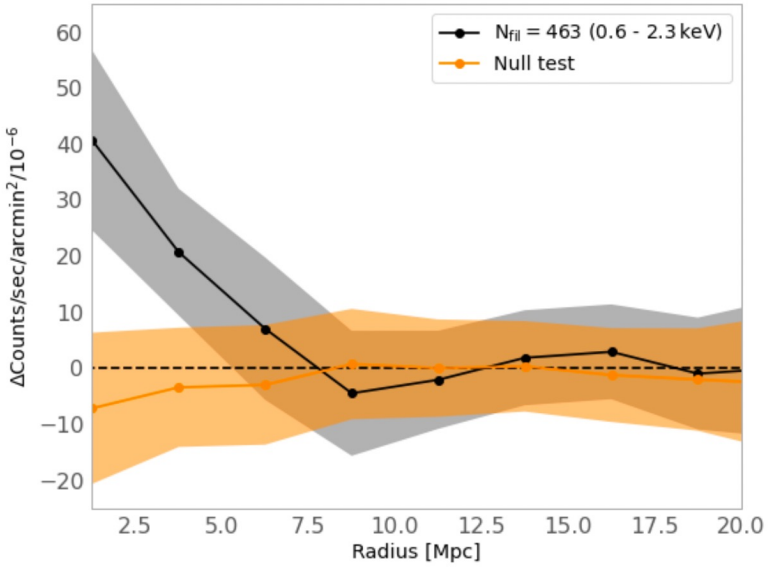
Halo emission (contamination) modeling

Spectral & profile modeling

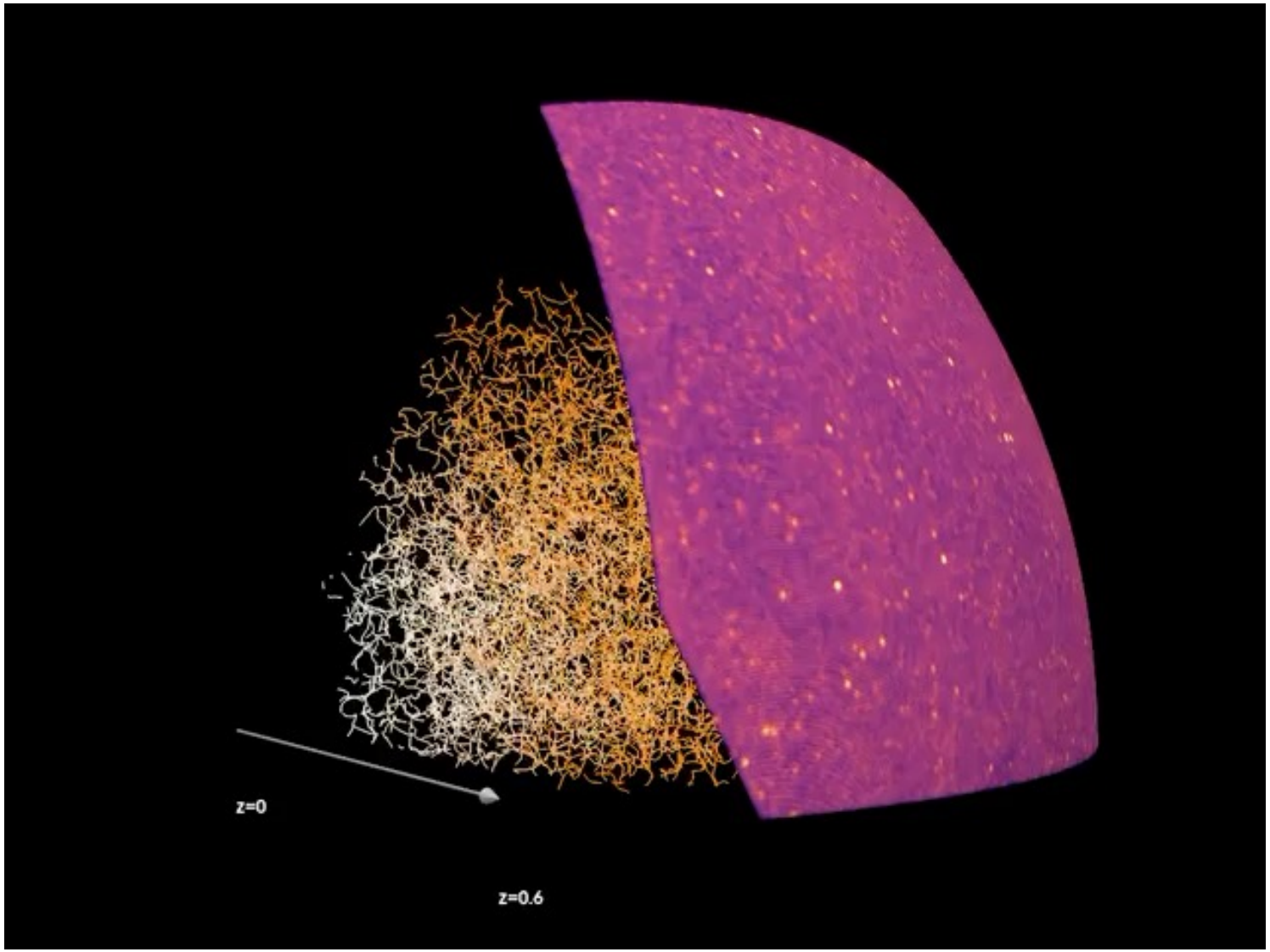
Stacking analysis

Filament emission stacking – searching for correlation





Stacking RASS & eFEDS + SDSS filament catalog
Signal significance: $\sim 4\sigma$ (Tanimura+20,22)



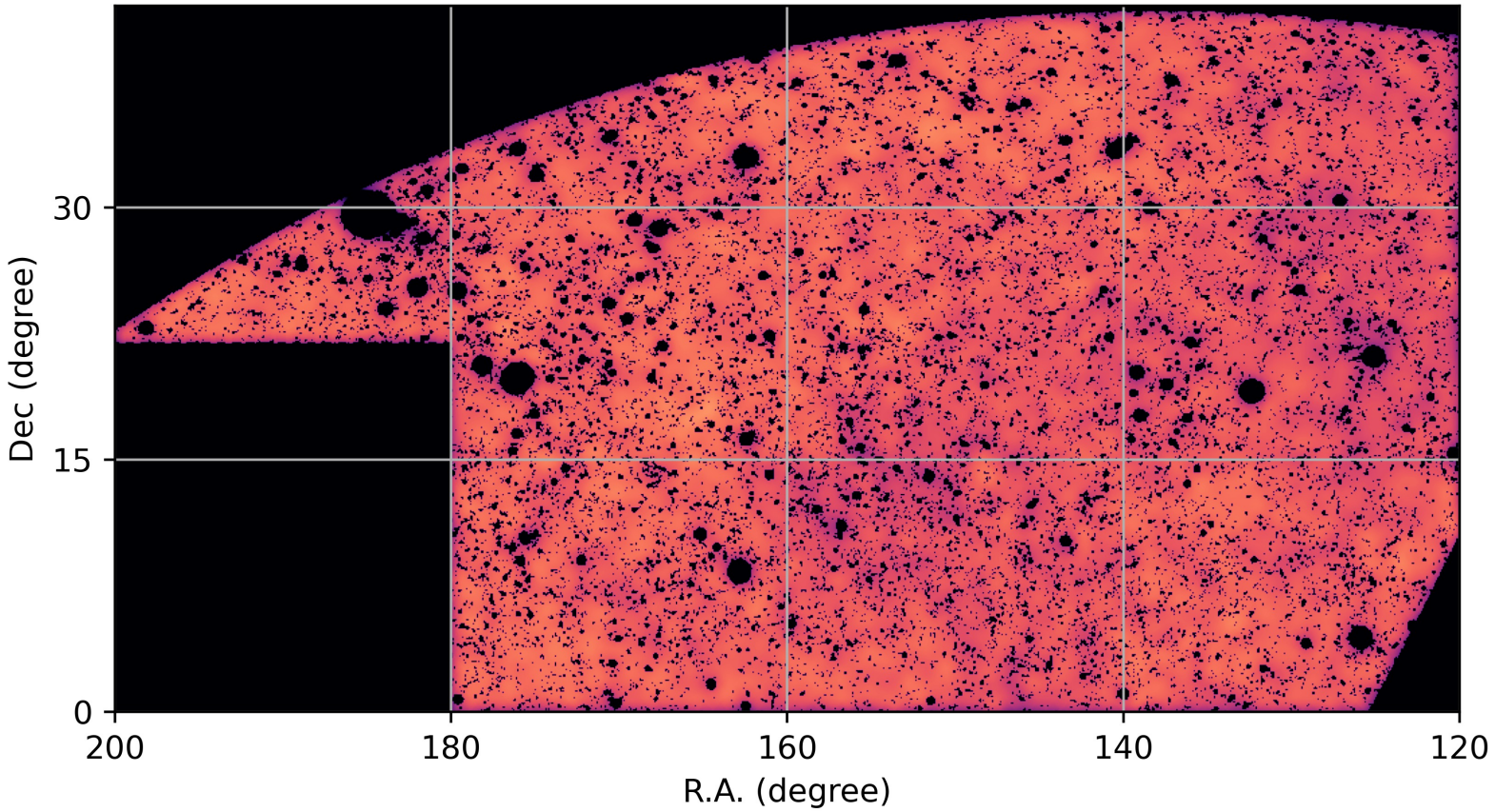
Malavasi+20 DisPerSE catalog (SDSS-BOSS based)

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

Length is directly from DisPerSE

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

Source masking

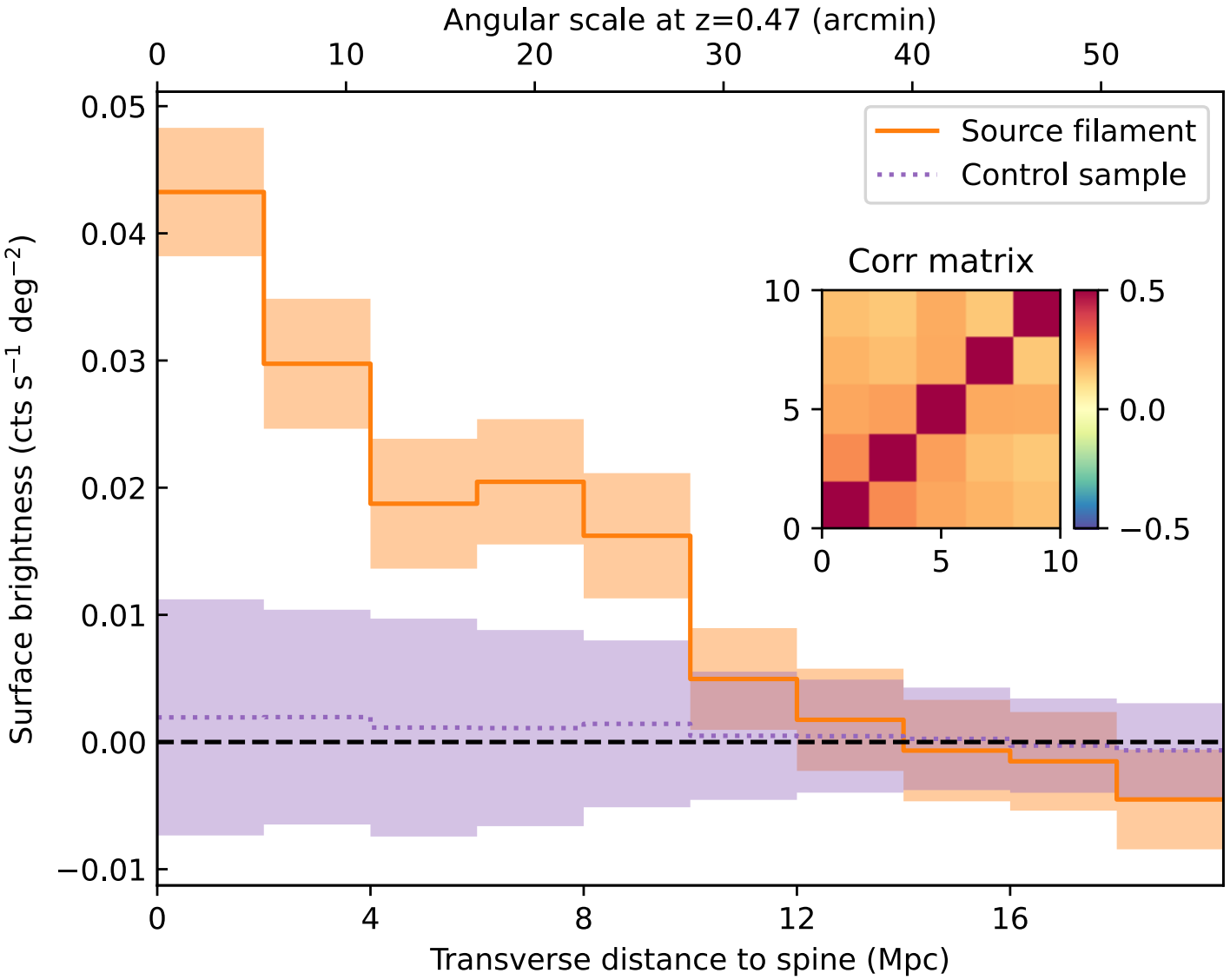


0.3-1.2 keV eRASS:4 map

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

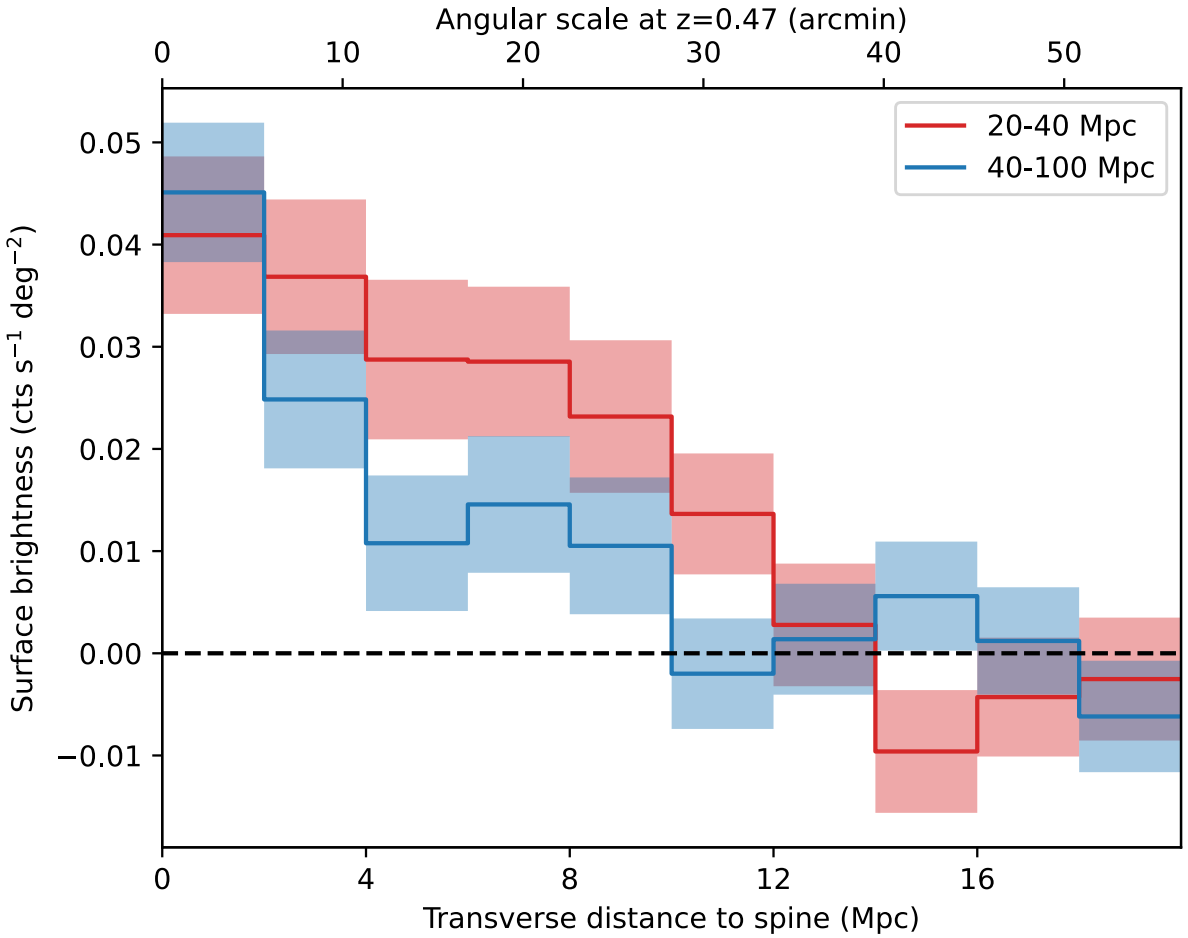
Stacked profile

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



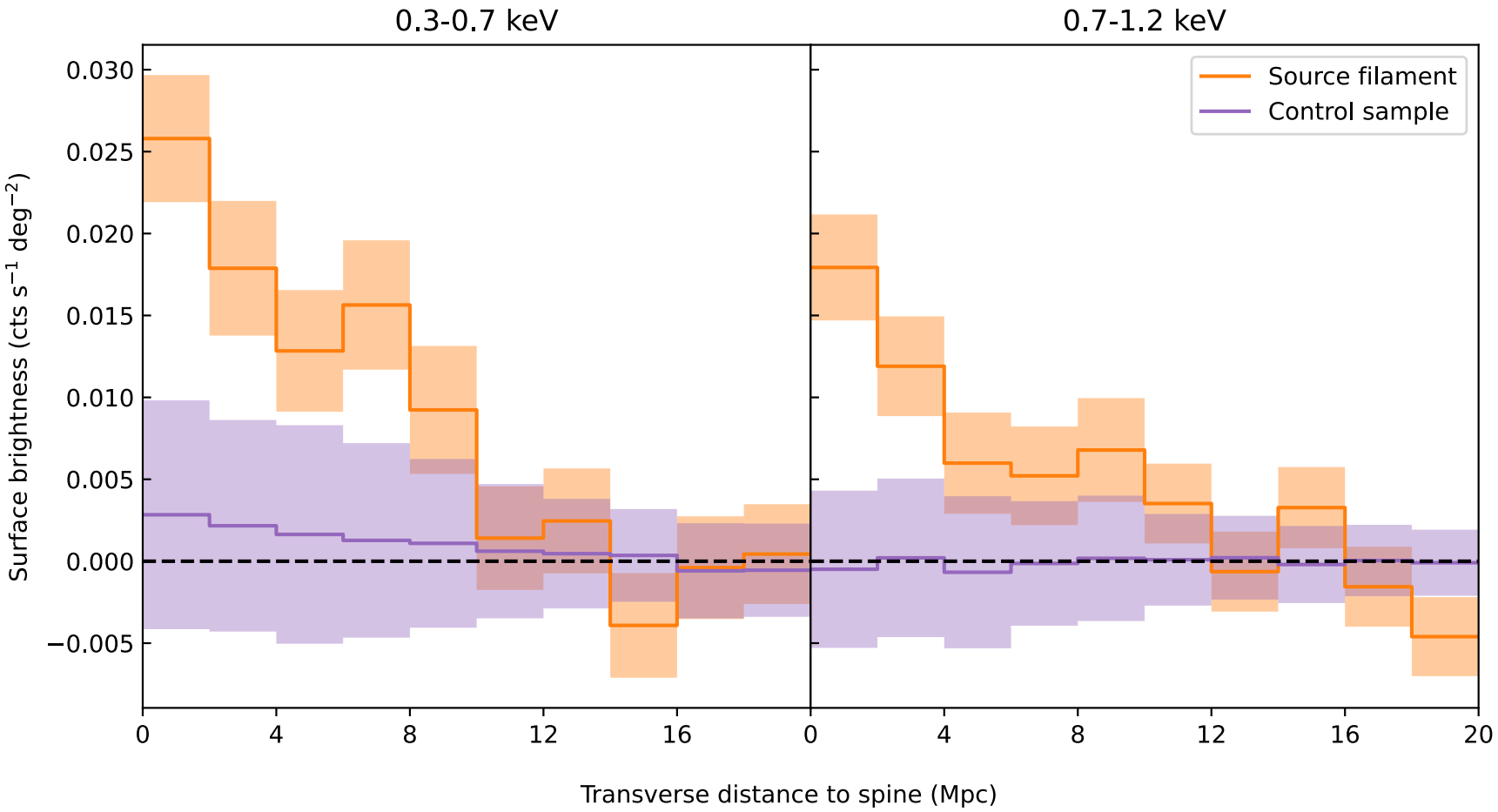
2300 deg^2 2-year eRASS: **9-σ** significance

Grouped by length



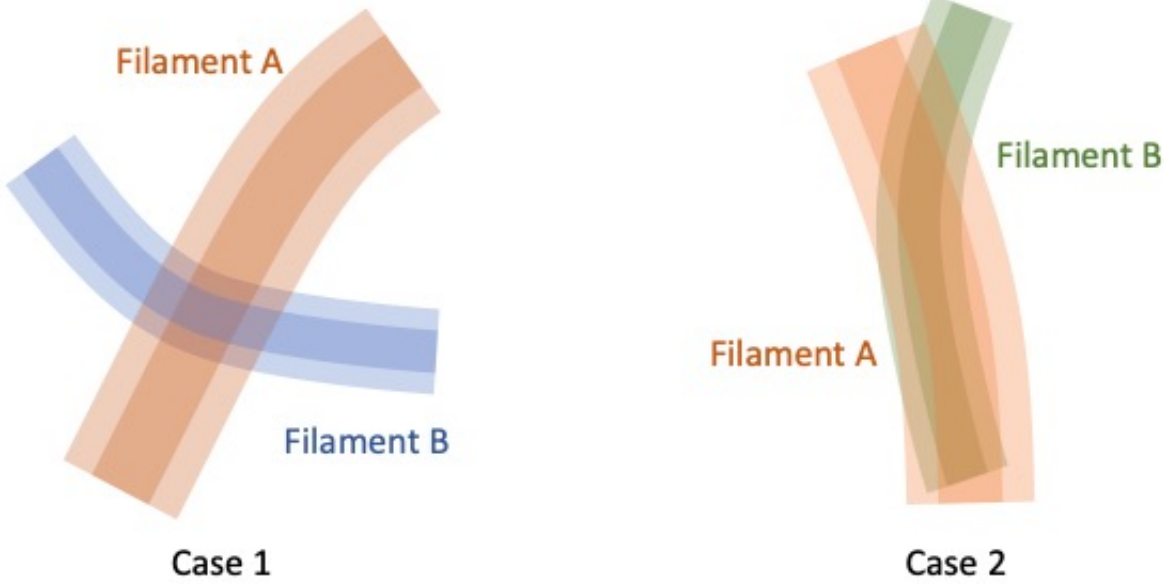
Stacked signal of short filaments is wider than long filaments

In different bands



Stacking validation

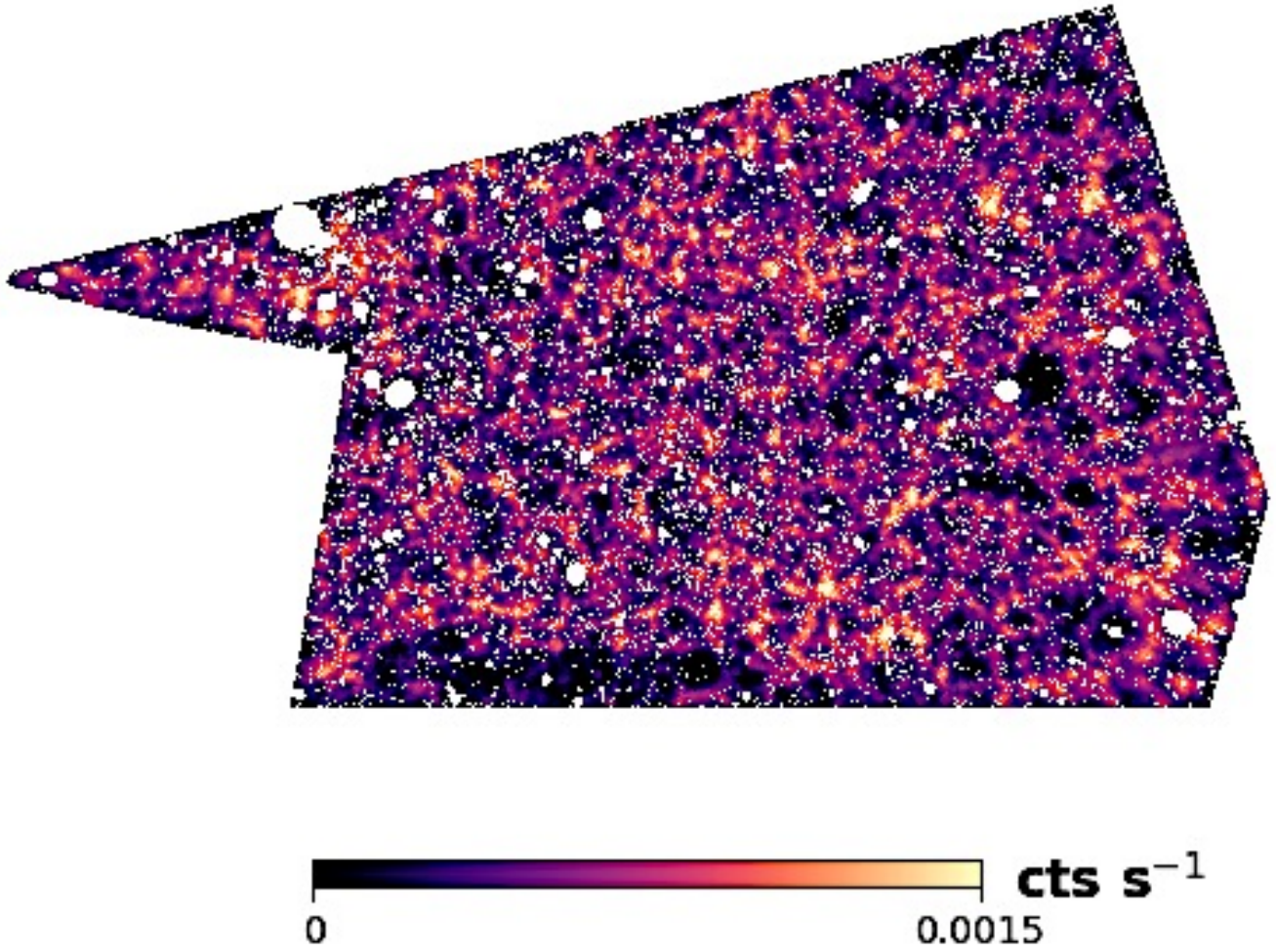
- Filament emission < 1% of Sky background
- Filaments from different redshifts projected at the same position
- Stacking supposes to only recover *correlated* signals



Possible signal boosting

- Case 1: no signal boosting
- Case 2: doubled signal

Stacking validation - mock filament emission map

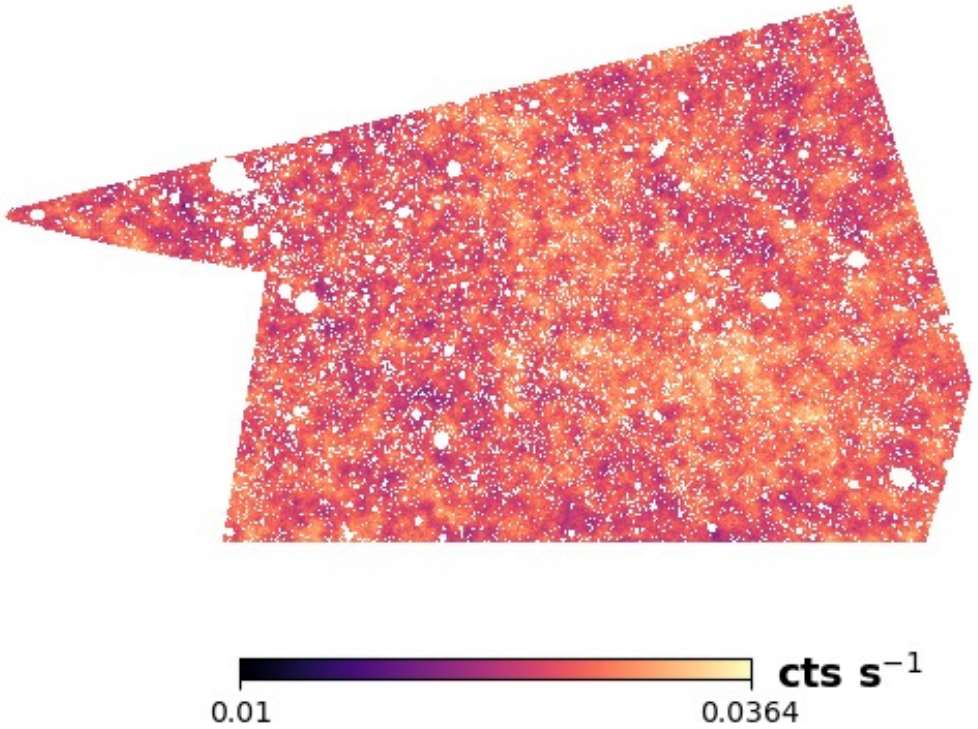


Based on

- Configurations of the selected filaments
- Injected SB profile

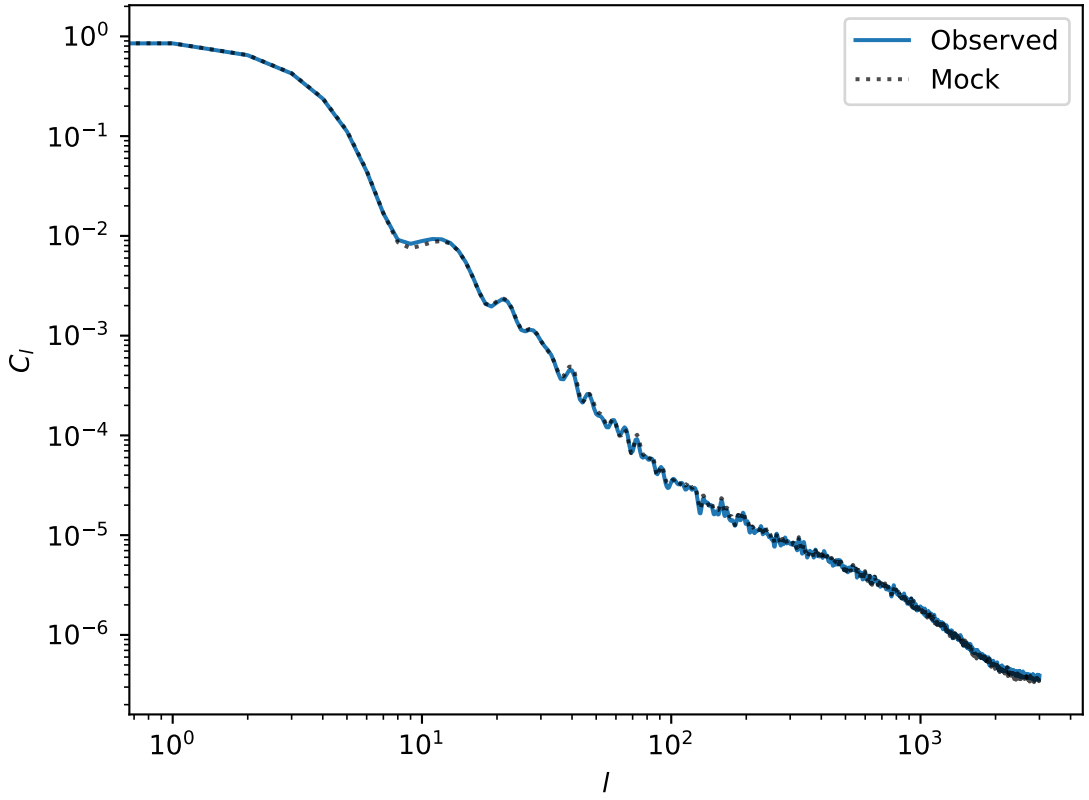
Selected filament emission (< 1% of the total)

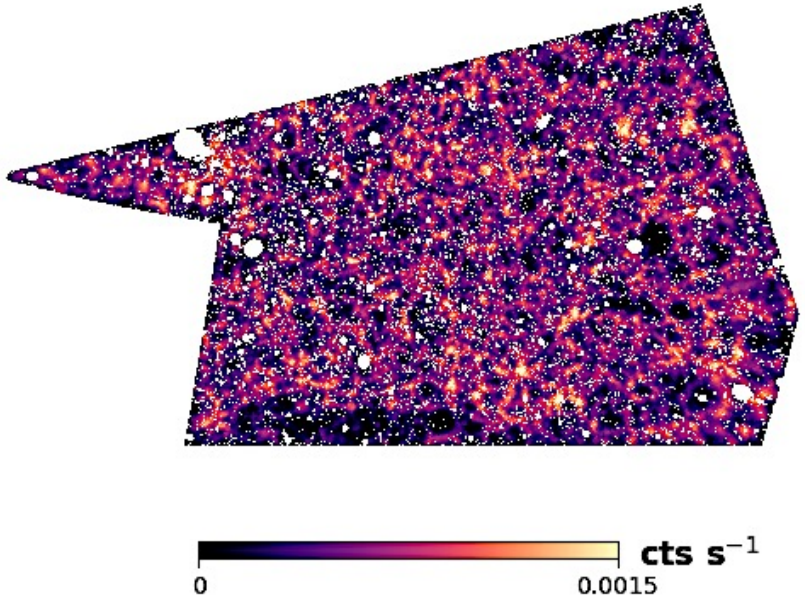
Simulated mock fore/background map



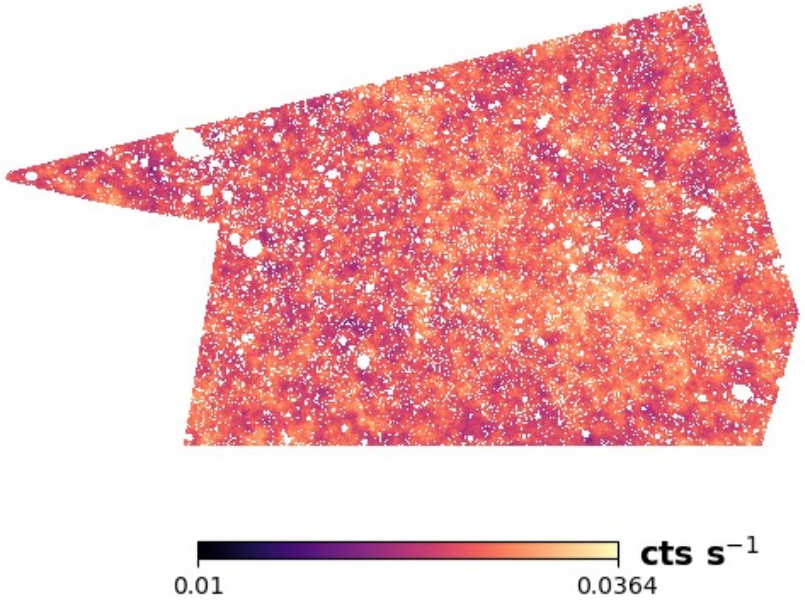
Based on the angular power spectrum of the field

Angular power spectrum



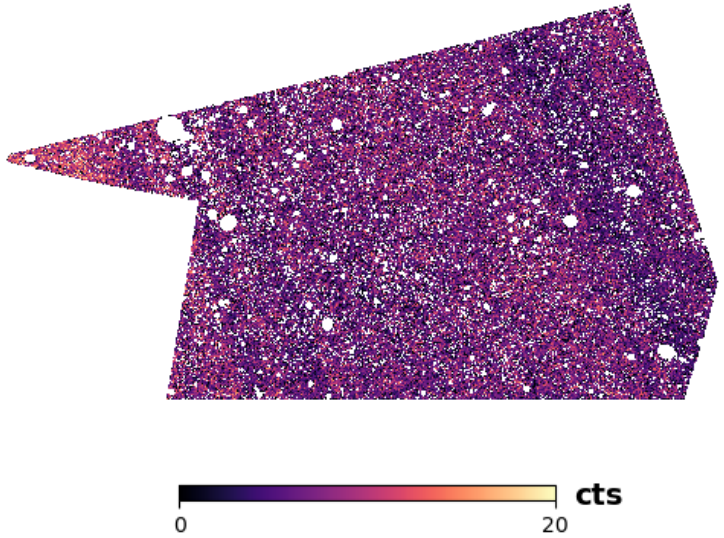


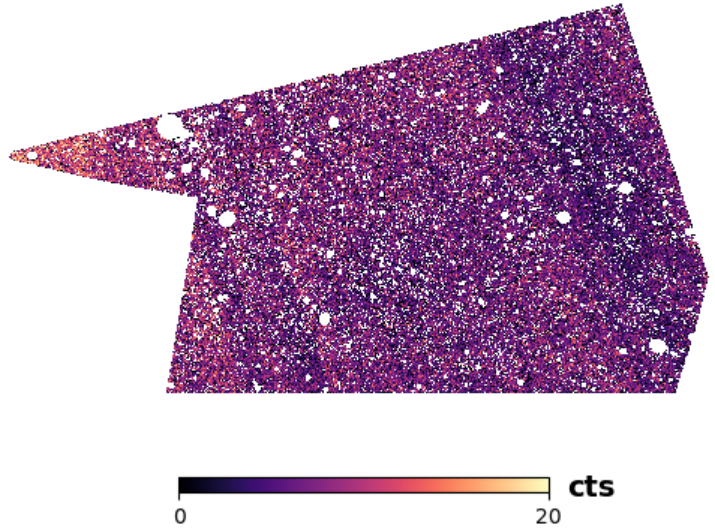
Filament emission (single map)



Fore/background emission (200 different maps)

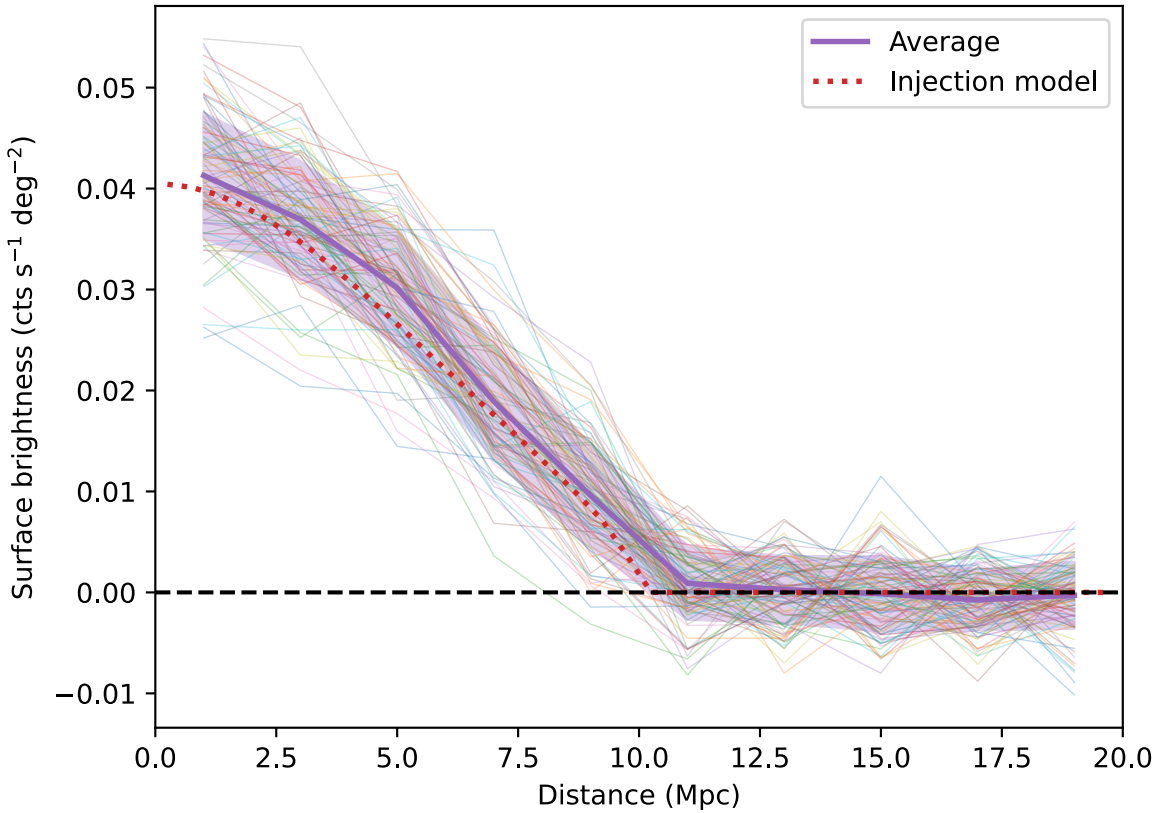
× exposure map





Observed map as comparison

Recovered profiles



With 200 different simulated background maps

Recovered profile matechs the injected profile with only 13% difference

Contamination modeling

X-ray sources in the Universe

Unbound		WHIM
Bound	Halo	Halo gas (ICM, IGrM, CGM)
	Halo & Subhalo (Galaxies)	Active Galactic Nuclei
		X-ray binaries
		Stars
		Supernova remnants

“Contamination signal”

Galaxy based contamination signal modeling

A catalog of galaxies
- RA, DEC
- z
- M_*

Scaling relation
$L_x(M_*, z) \rightarrow F_x(M_*, z, RA, DEC)$

Galaxy (halo) emission map

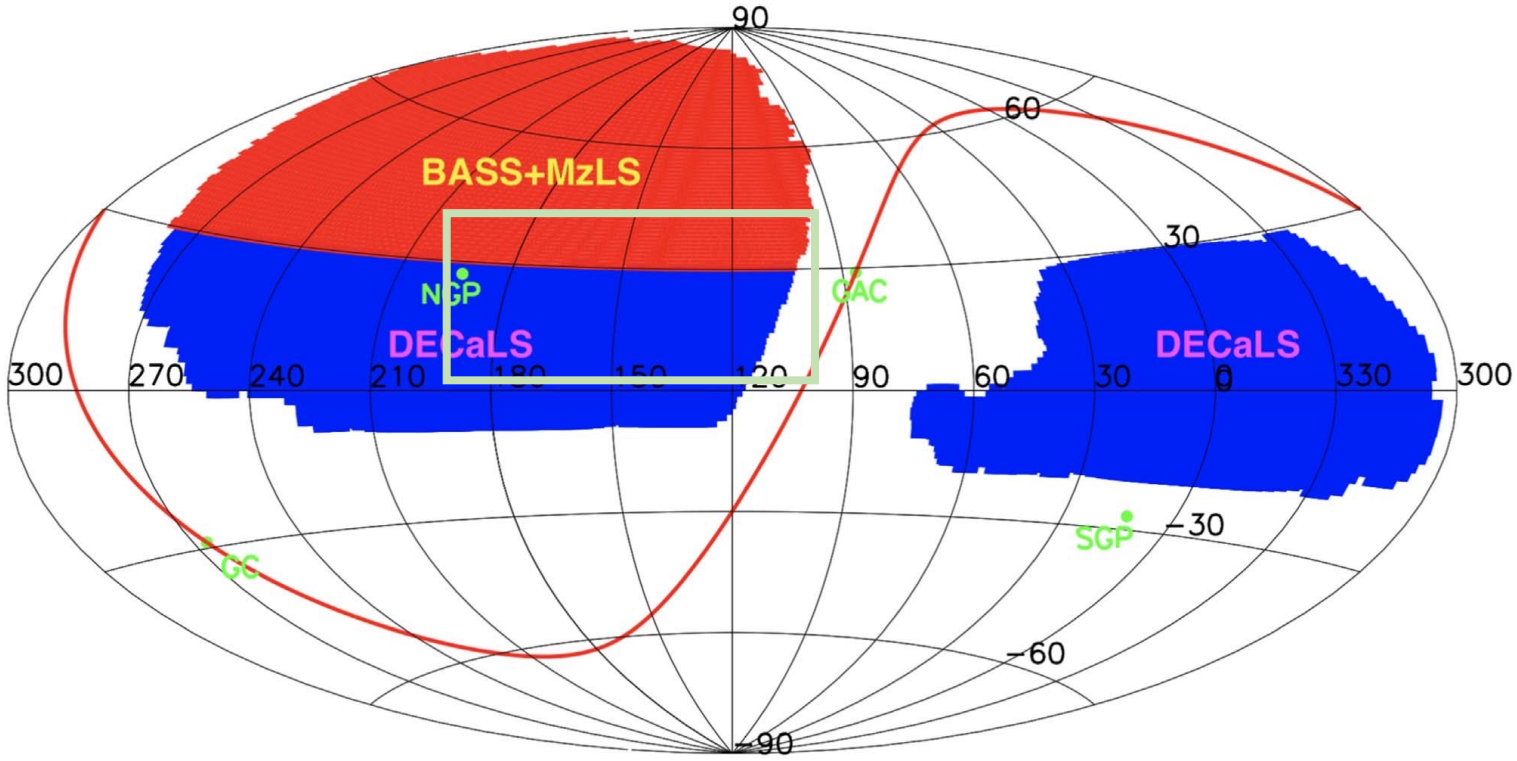
Stacking

Galaxy (halo) emission profile

Galaxy catalog

Legacy Survey photo-z catalog (Zou+19)

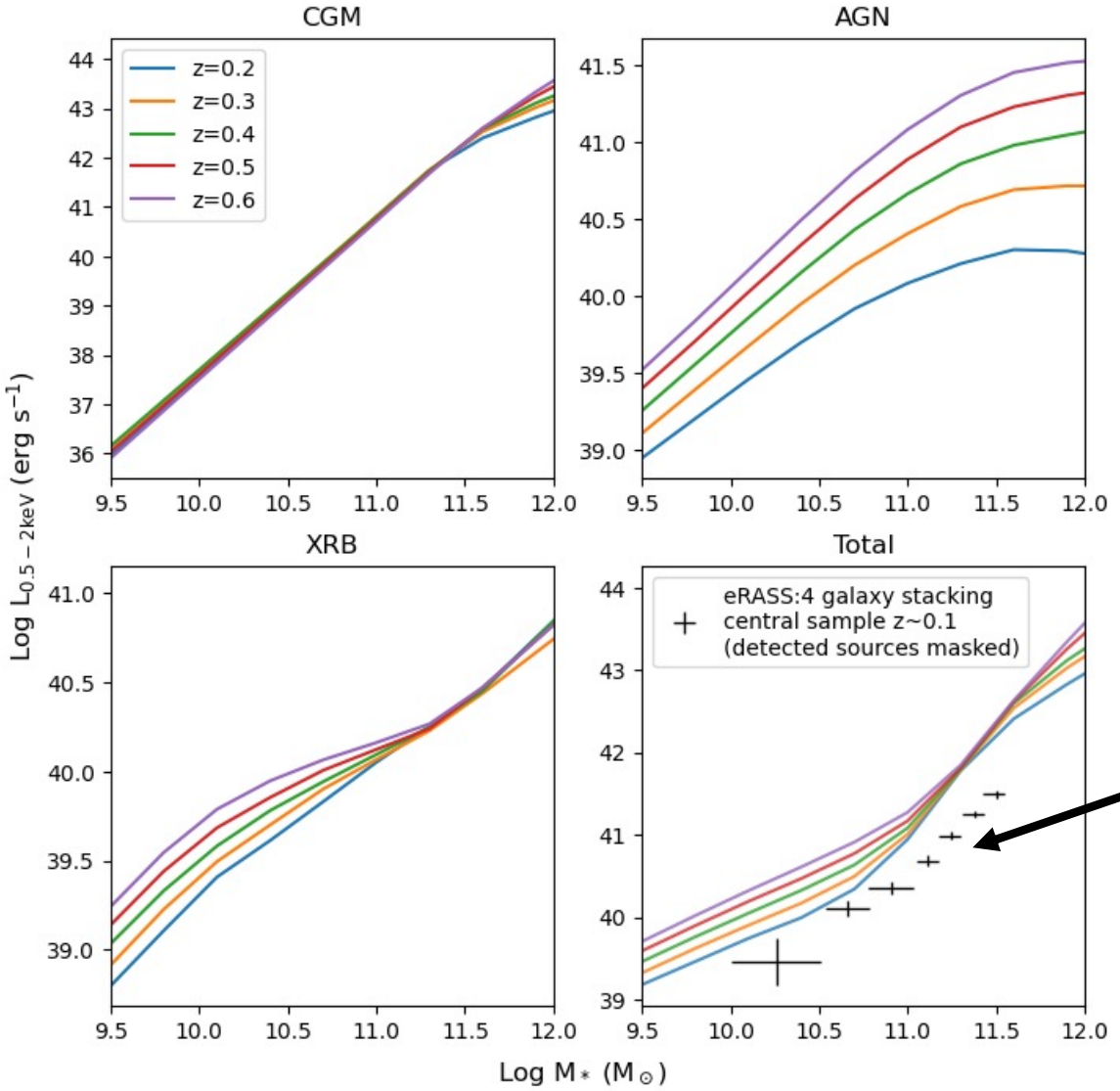
- RA, DEC
- z_{phot}
- M_*



Scaling relations

	Scaling relation	Spectral model
Halo gas	Anderson+15	CIE, kT from Bahar+22 Lx-T relation
AGN	Comparat+19,23 Xray mock catalog	Composite AGN model
XRB	Lehmer+19	Self absorbed powerlaw

Model - observation comparison



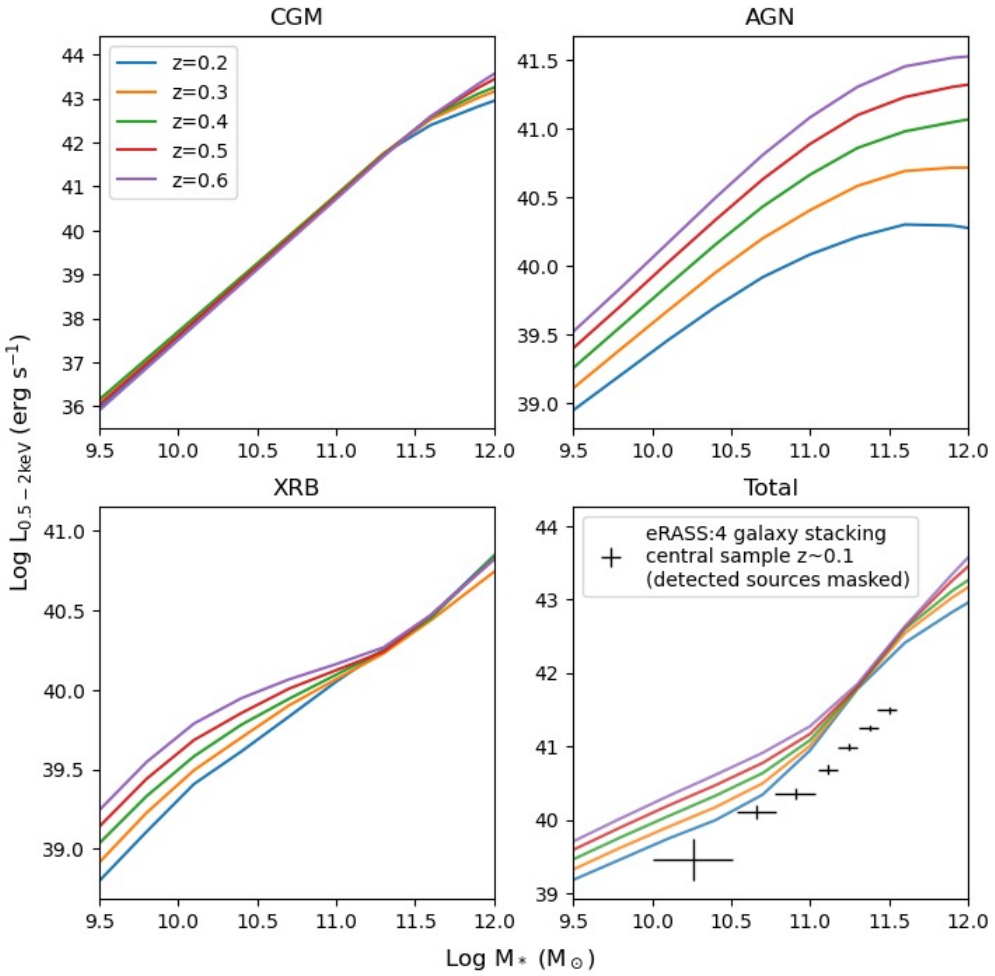
Evolution of AGN luminosity function

Evolution of SFR

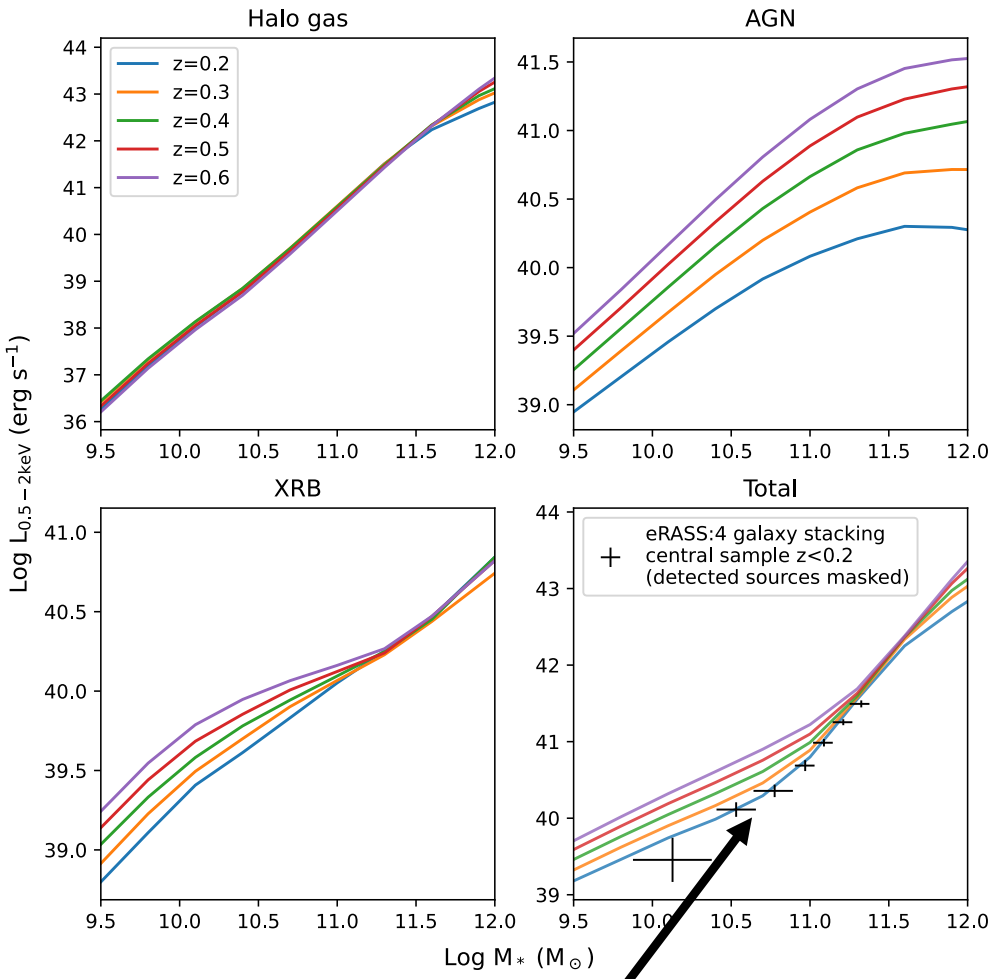
Significant discrepancy

Additional M_* calibration

Scaling relation	**M_* adoption**
Anderson+15	Blanton+07
Y. Zhang+24 observation	Chen+12
This work	Zou+19



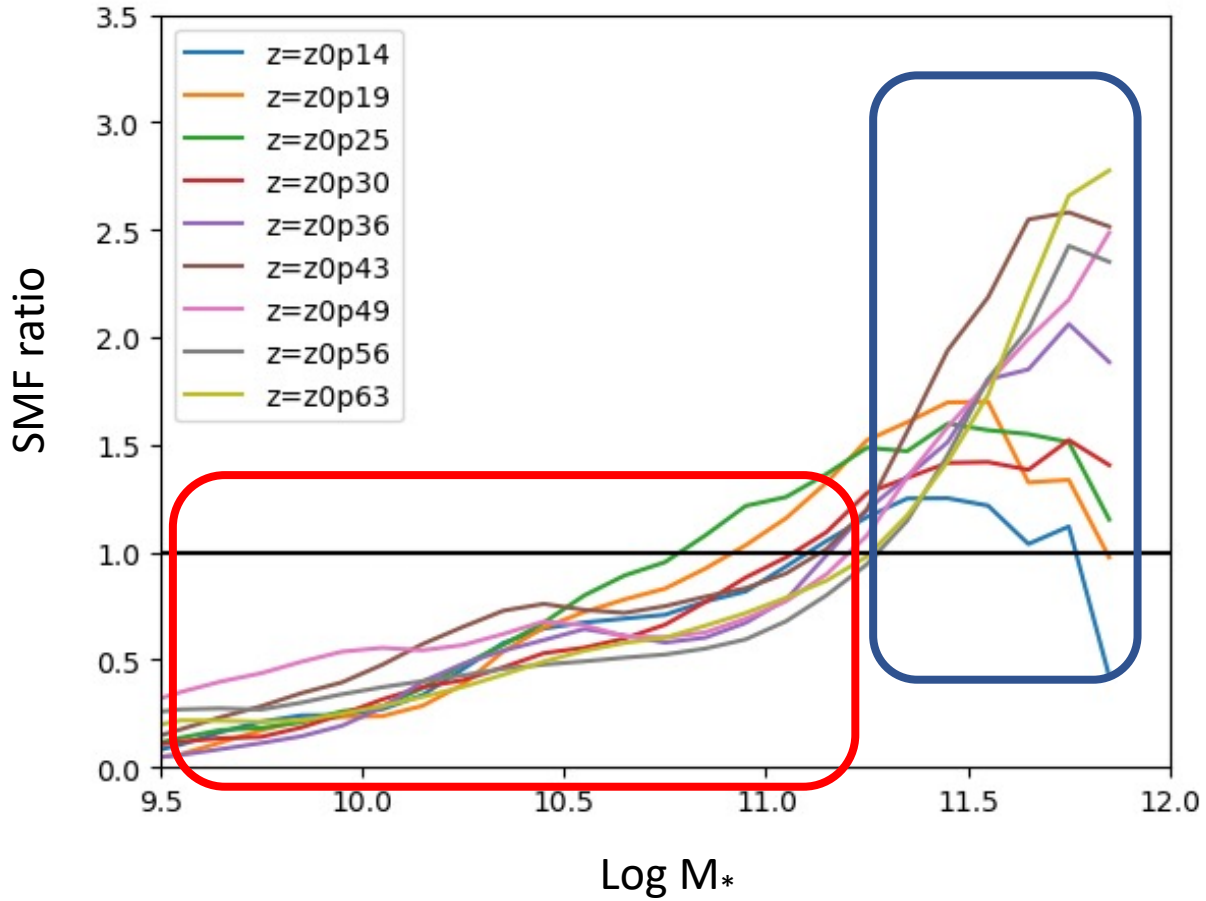
Calibrated M_*



Good agreement

Legacy survey completeness

Stellar mass function ratio Zou+19 / UniverseMachine

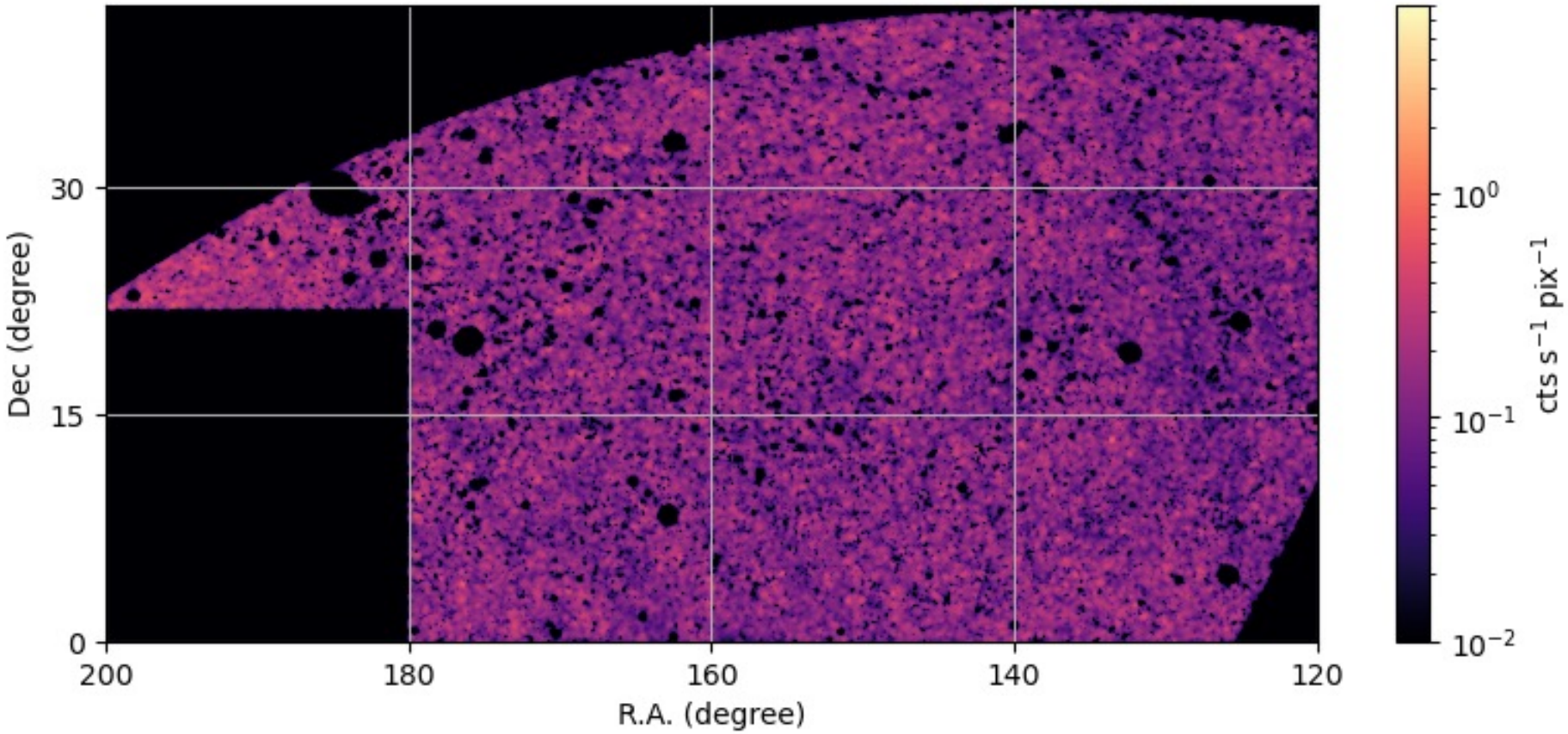


$M_* > 10^{11.2}\ M_\odot$:
SMF slope inconsistency, sensitive to M_* measurement

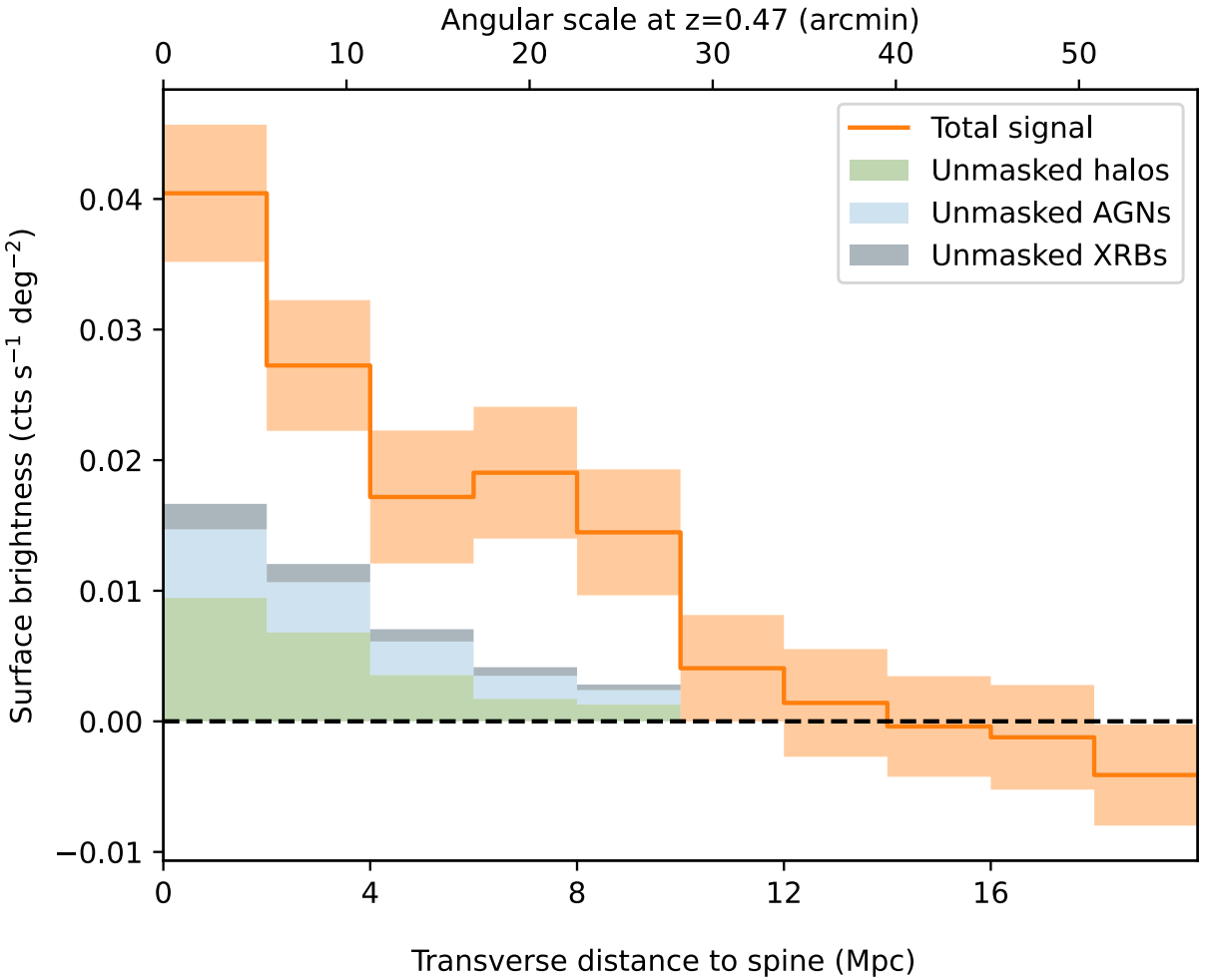
Conservative decision:
No further M_* correction

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

Painted galaxy emission map

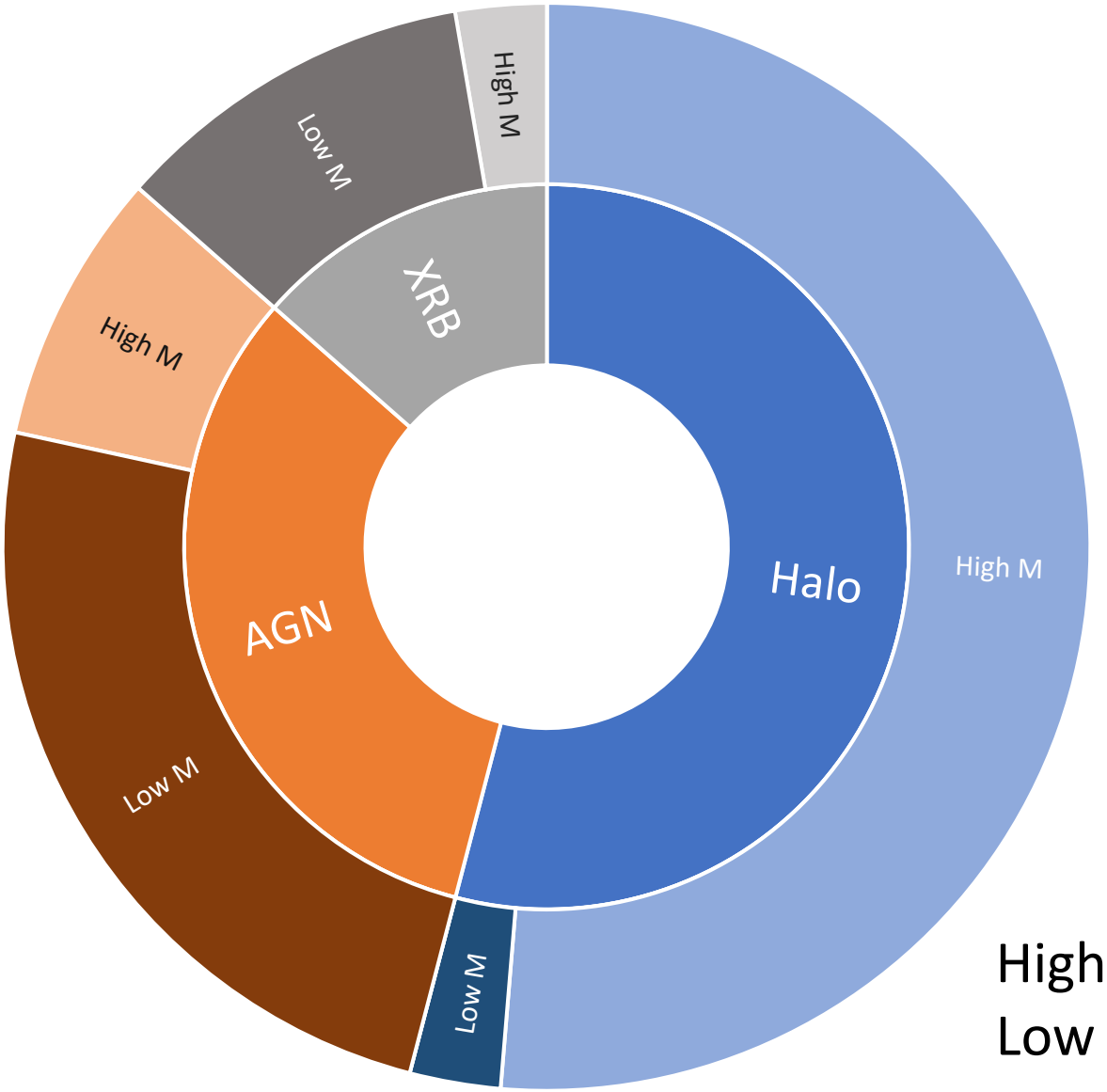


Profiles of the three contamination sources



- 37% of total by this method

Contamination fractions



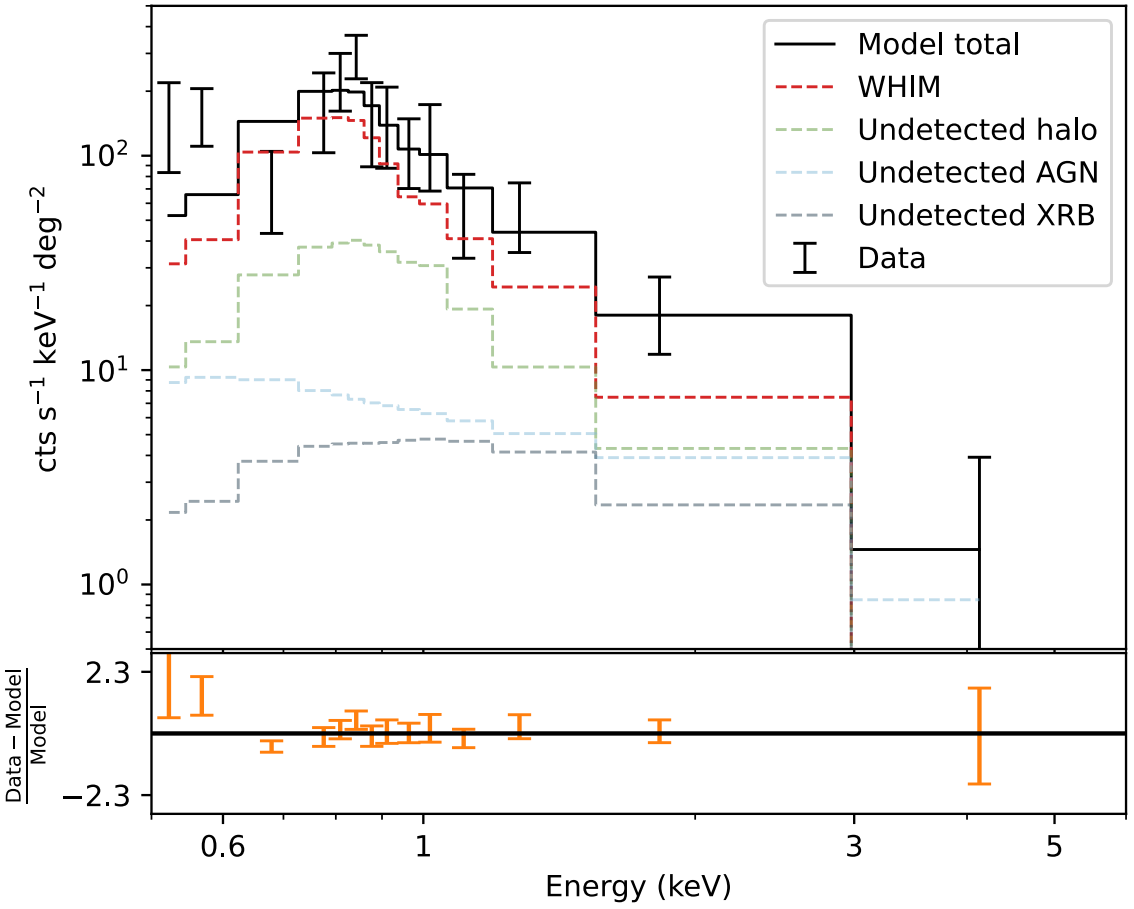
- 37% of total by this method
- Over half contamination is from X-ray halos (group size)

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

WHIM properties modeling

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

Modeling SB profile -> WHIM density

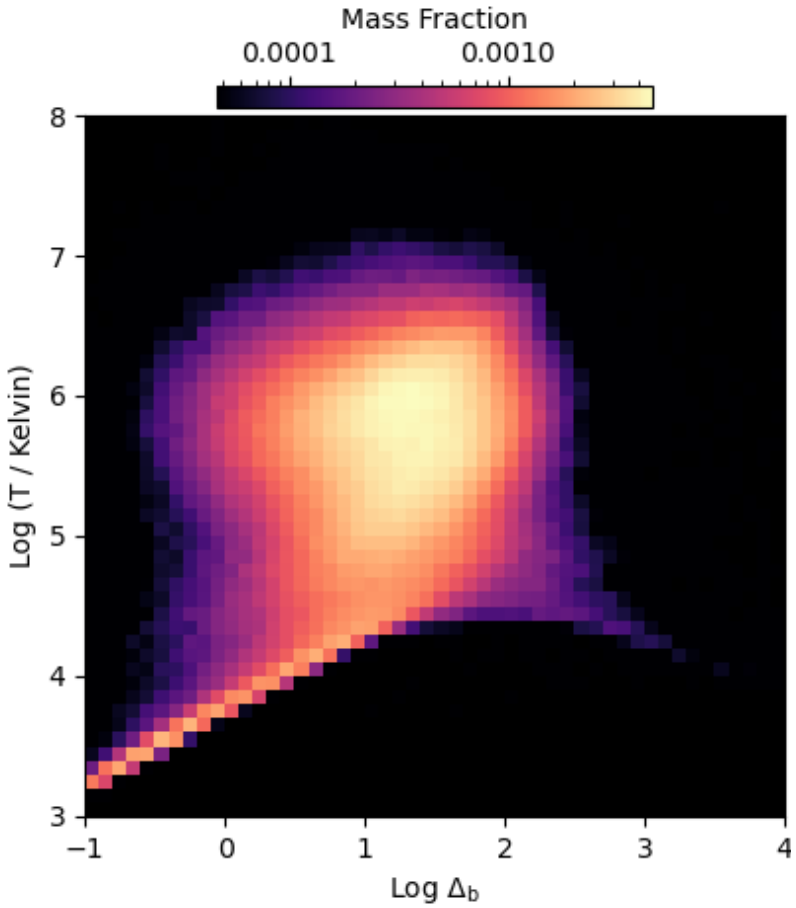
A few assumptions

1. Multiphase nature
   - Volume filling fraction $f_{\rm vol} \equiv \frac{V_{\rm det}}{V_{\rm filament}}$
   - King-profile for both $n(r)$ & $f_{\rm vol}(r)$
   - However, still assume the `representative` T
2. Universal Δ_b profile -> $\rho(z) \propto (1+z)^3$
3. Smoothing effects on the observed profile
4. Predicted Compton-y < Tanimura+20 stacking results

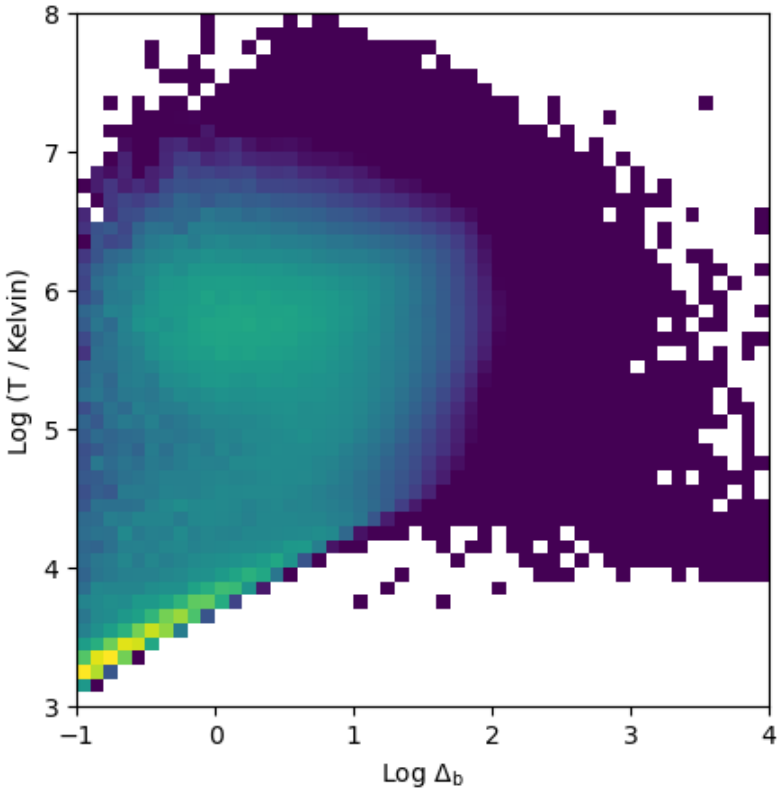
Multiphase nature

Simulation analysis:

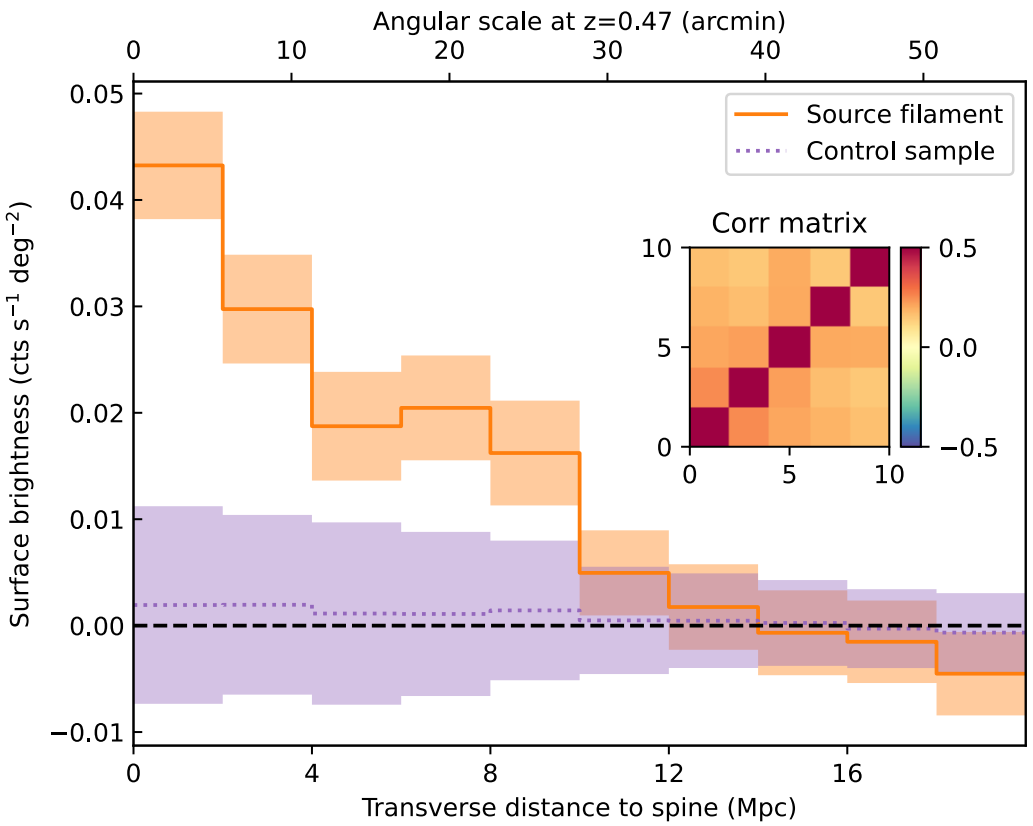
- TNG300-1 z=0.48 snapshot
- DisPerSE filaments constructed using 10^9 $M_\odot$ <M_* < 10^{12} $M_\odot$ galaxies
- Gas particles around filaments within 1 Mpc distance
- Halo bound particles excluded, nodes particles r < 2 Mpc excluded



Volume distribution



Smoothing effects

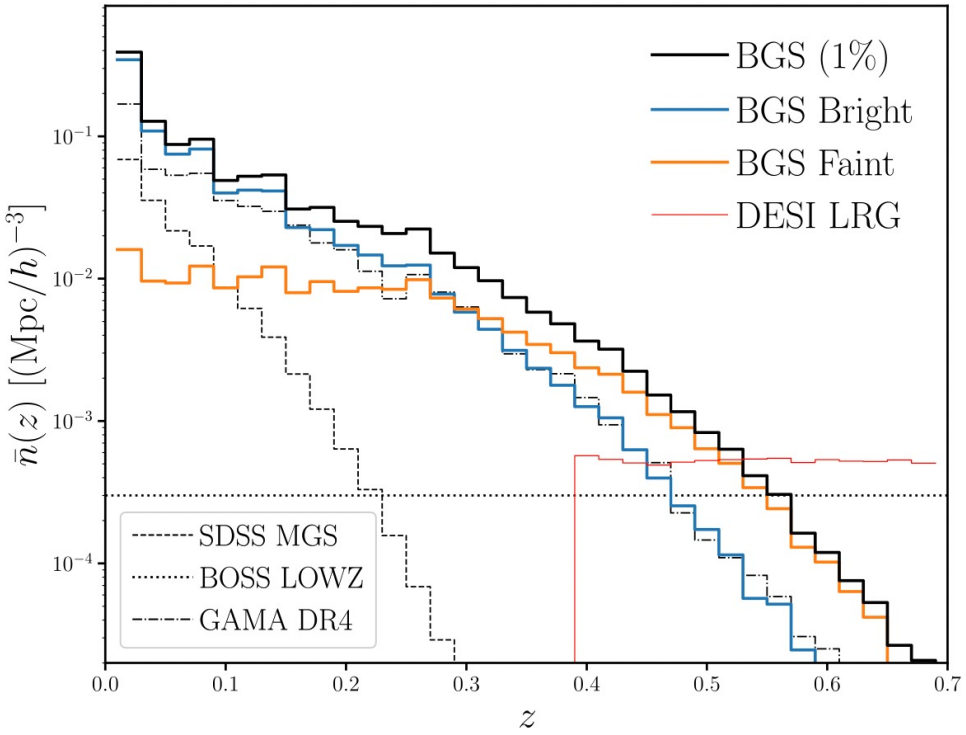


Observed width: 20 Mpc

Intrinsic width: a few Mpc

Incomplete galaxy sample for filament catalog construction

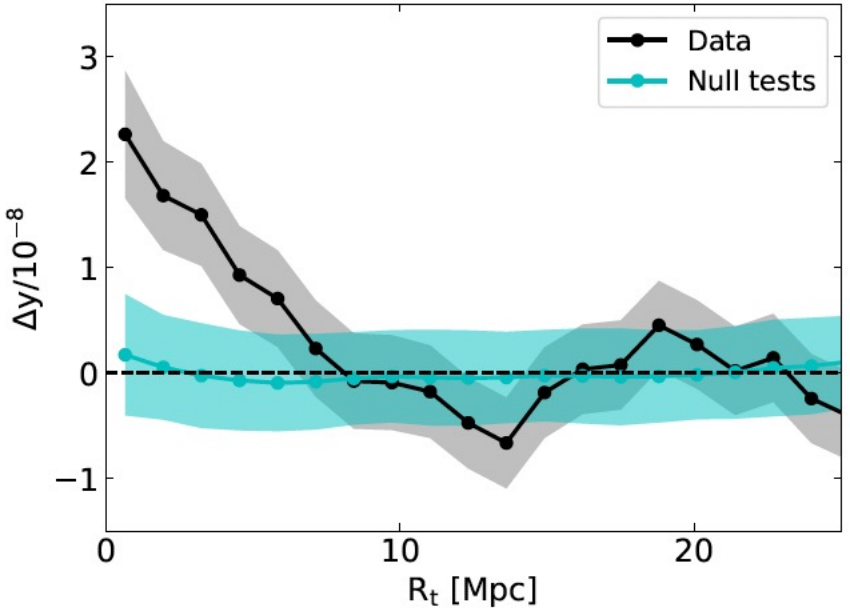
- $\sim 10^{-4}$ Mpc^{-3}
- Skeleton uncertainty
- Will be significantly improved by DESI



DESI vs SDSS (Hahn+23)

f_{vol} – density degeneracy

- $EM \sim \int f_{\rm vol} n^2 {\rm d}V$
- $y \sim \int f_{\rm vol}\, nT {\rm d}l$
- y from X-ray emitting gas < y_{tot}
- Our log y term in the likelihood N(-8.3, 0.5)



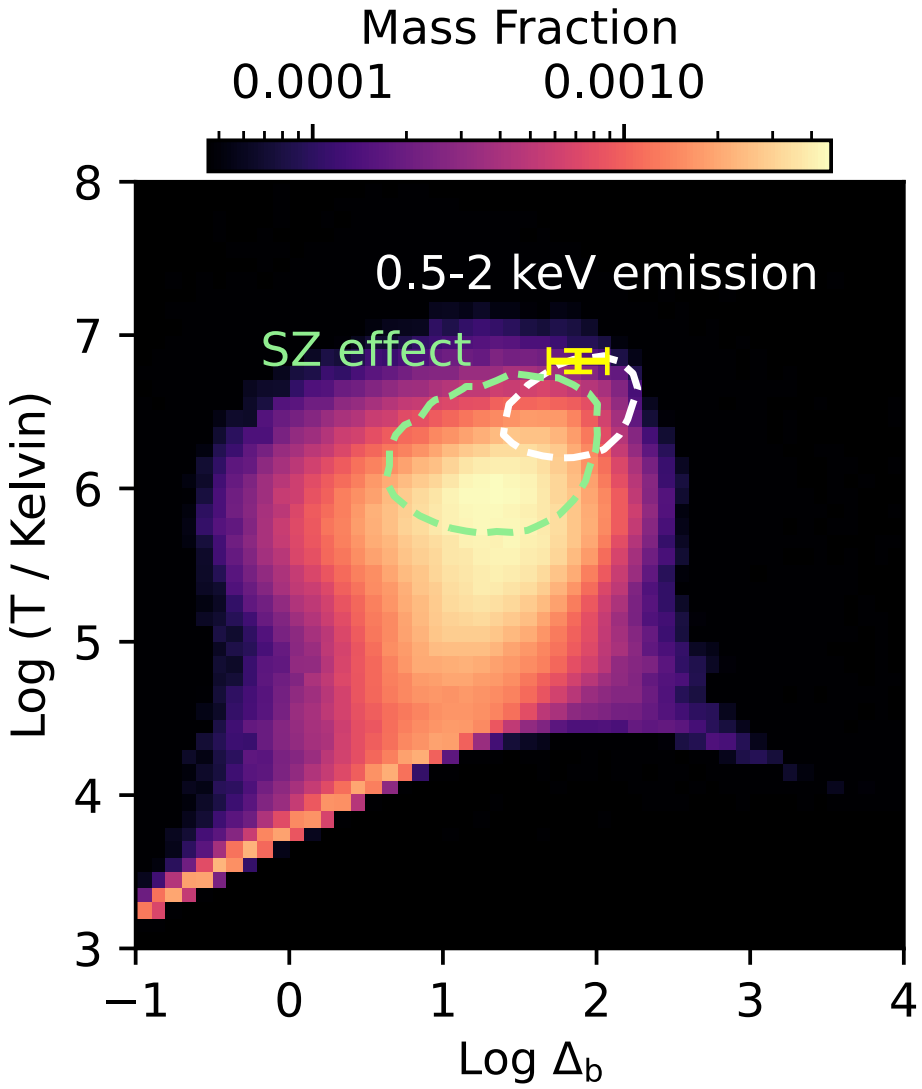
Planck SZ stacking (Tanimura+19)

Best-fit parameters

- $\mathrm{Log}\,\overline{\Delta}_{\mathrm{b}} = 1.88 \pm 0.2$

  (volume averaged)

- only ~1% of the total volume



Contour: 50% enclosed contribution

Our answers to the three questions

How much of the X-ray background emission is correlated with cosmic filaments?

- 9σ
- $\sim$0.5% of the background
- Depends on survey configurations and source masking

What is the fraction of positive correlation from unbound WHIM?

- $\sim$60%
- Uncertainty origin:
  - Scaling relation
  - High mass end of SMF

What is the physical condition of the X-ray emitting WHIM

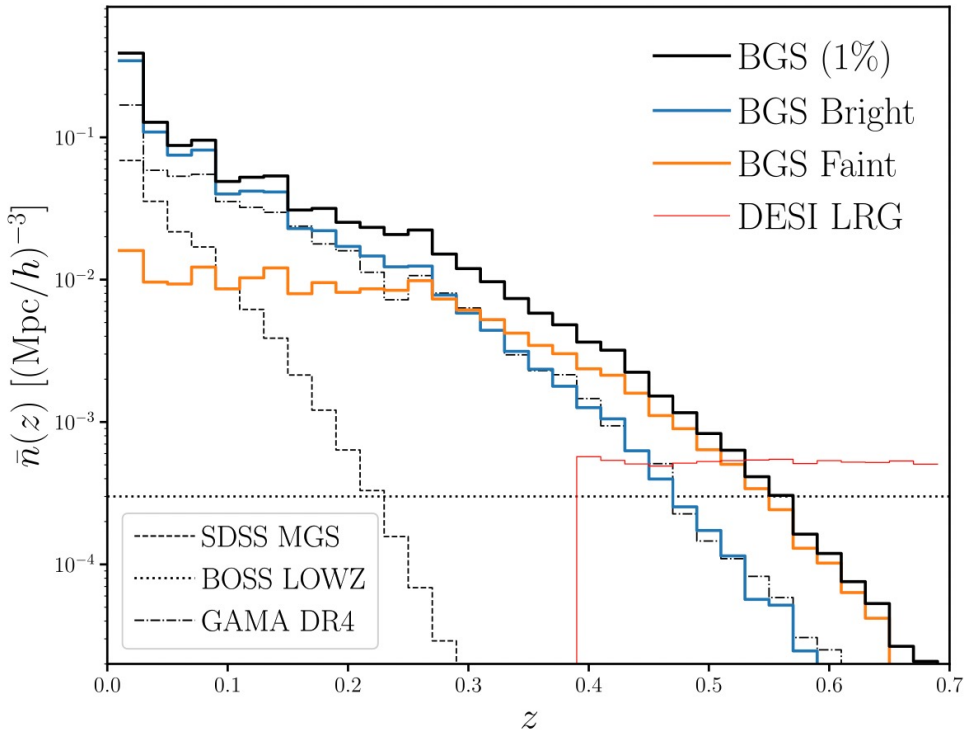
- $\Delta_b \sim 80$
- $T \sim 6 \times 10^6$ K
- X-ray emission from high density and high temperature gas

Scope beyond eROSITA and SDSS filaments

Optical galaxy surveys

- DESI
- 4MOST

- Higher galaxy density
  Better filament precision & completeness



Scope beyond eROSITA and SDSS filaments

In the high-resolution X-ray spectroscopy era
With future DESI & 4MOST filament catalog

X-ray absorption
(*NewAthena*)

- Foreground structure distribution of all bright blazars
- Multi-absorber stacking

X-ray emission
(*HUBS*)

- High density structures for pointing
- Probing photoionized WHIM