Baryon Pasting: A Novel Framework for Interpreting Next-Generation SZ and X-ray Observations

Erwin Lau

Akos Bogdan, Daisuke Nagai, Nico Cappelluti, Masato Shirasaki

(2025 ApJ 983, 8, arXiv:2410.22397)

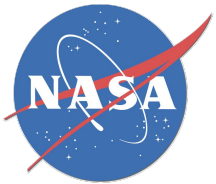
and the Baryon Pasting Team

(2025 ApJ 980, 122, arXiv:2411.00108)

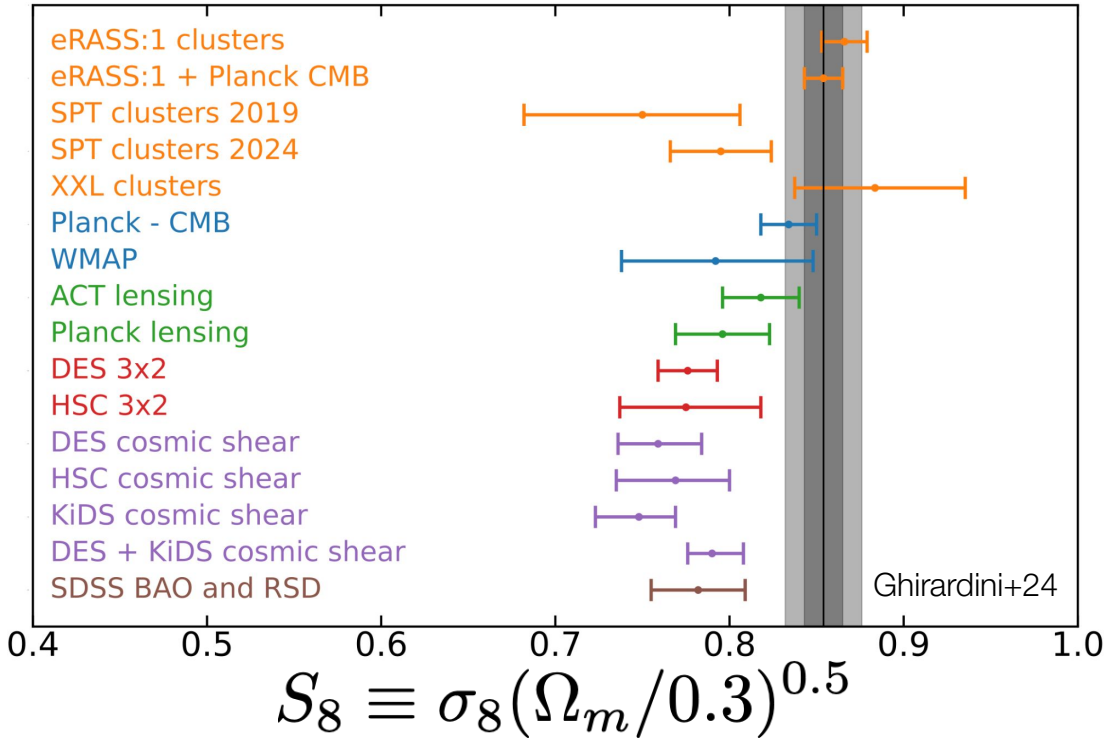
mm Universe 25

The University of Chicago

June 26 2025



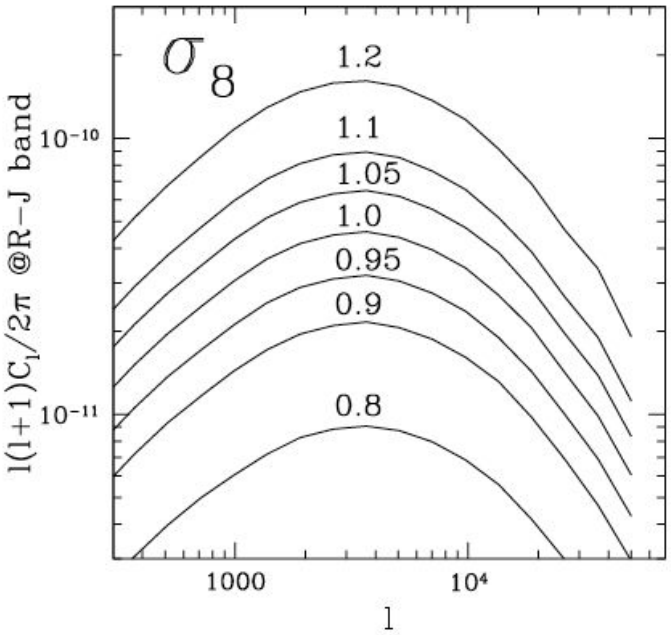
The S_8 Tension



Tensions in cosmic matter density fluctuations between Planck CMB measurements and low-z large-scale structure probes: CMB lensing/cosmic shear/galaxy clustering and cluster abundances

Cosmology
with Thermal SZ Angular Power Spectrum

tSZ power spectrum - Komatsu & Seljak 02



Also
Hill & Pajer 13,
Horowitz+17,
Hurier+15,17,
Salvati+18,
Bolliet+19,
Osato+18,20,
Tanimura+21,etc.

$$C_\ell \sim (\sigma_8)^8 (\Omega_m)^3$$

Alternative to cluster abundances:

- Don’t need mass calibration
- Insensitive to selection function

Cosmology and Astrophysics with Angular Power Spectrum of Groups and Clusters

$$C_\ell^{1h} = \int dz \frac{dV}{dz d\Omega} \int dM \frac{dn}{dM} \left| S_\ell(M,z) \right|^2$$

Halo number counts: Cosmology

Halo gas profiles: Astrophysics

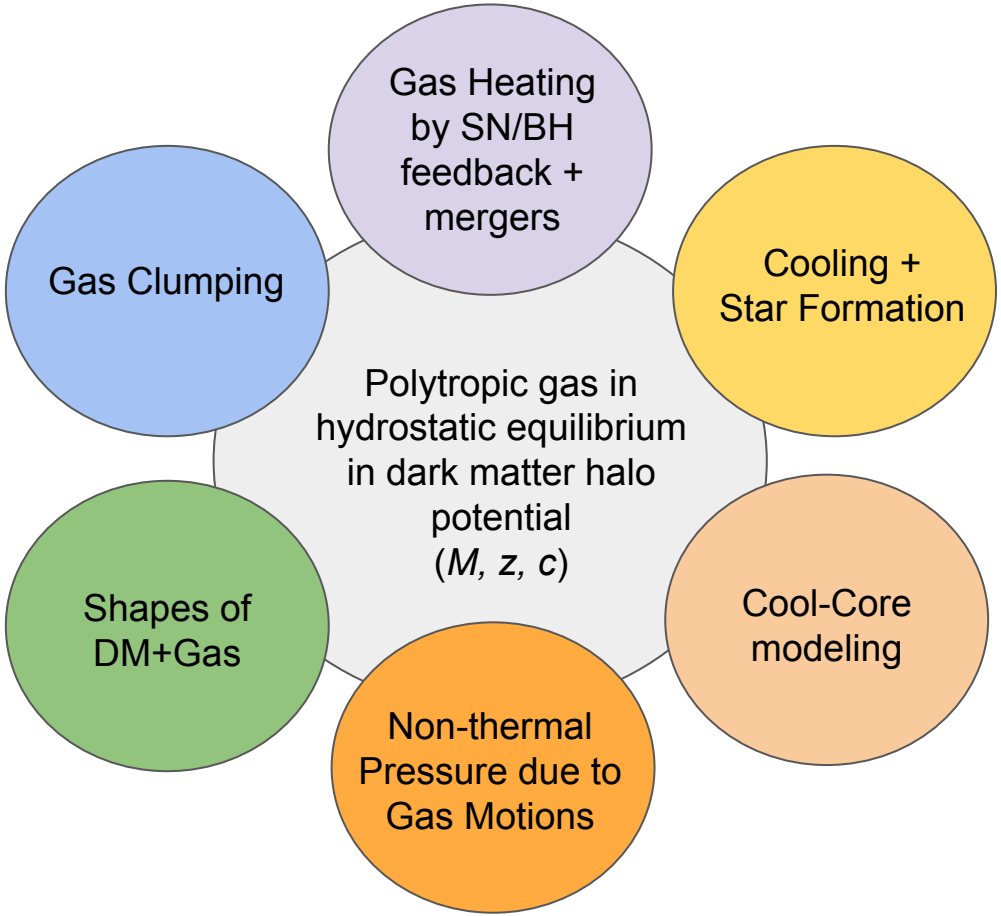
Angular power spectrum of clusters/groups is a unique probe of both cosmology (cosmic volume and halo mass function) and astrophysics (ICM profiles).

Baryon Pasting (BP) Project

Era of large-scale surveys:
mm: SPT, ACT, SO, CMB-S4
X-ray: eROSITA
Optical: Euclid, Rubin, Roman

Challenge:
Not everyone have access to exascale computing resources at Argonne!

Baryon Pasting:
Simple, physical, computationally efficient method for modeling halo-gas connection



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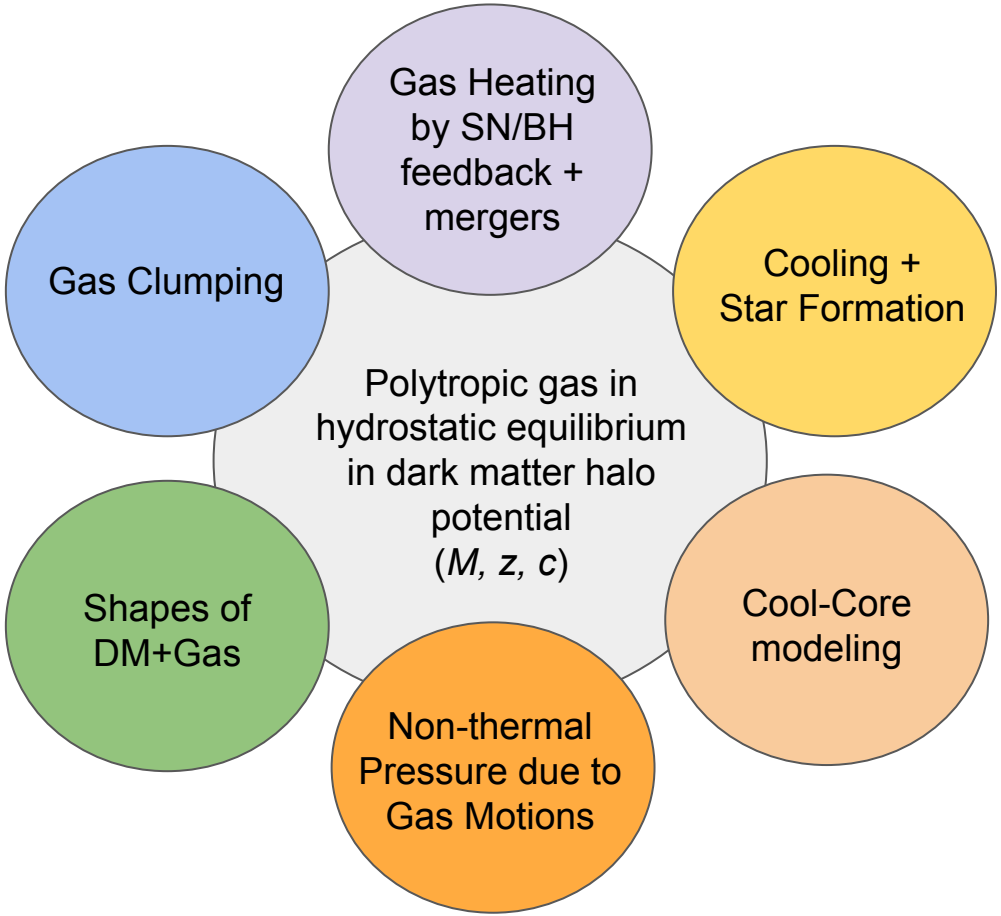
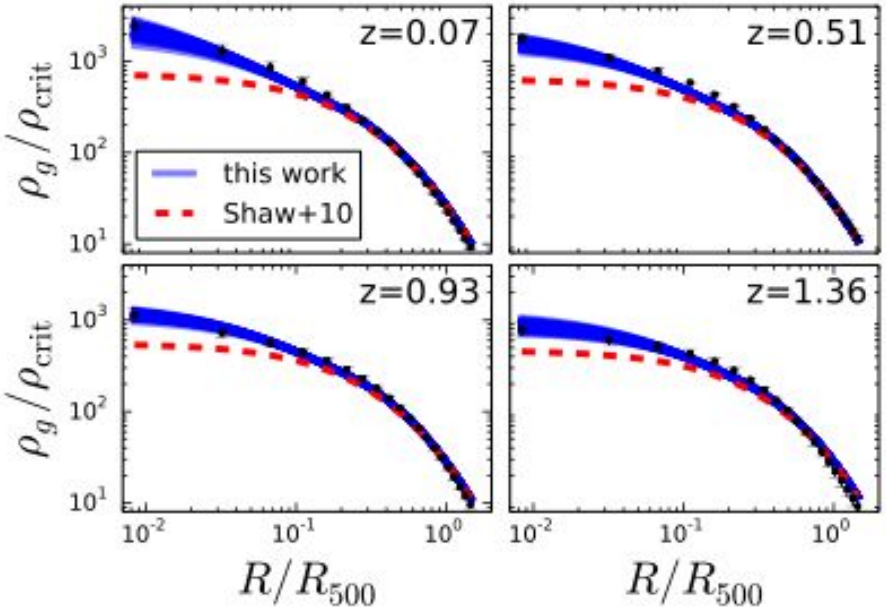
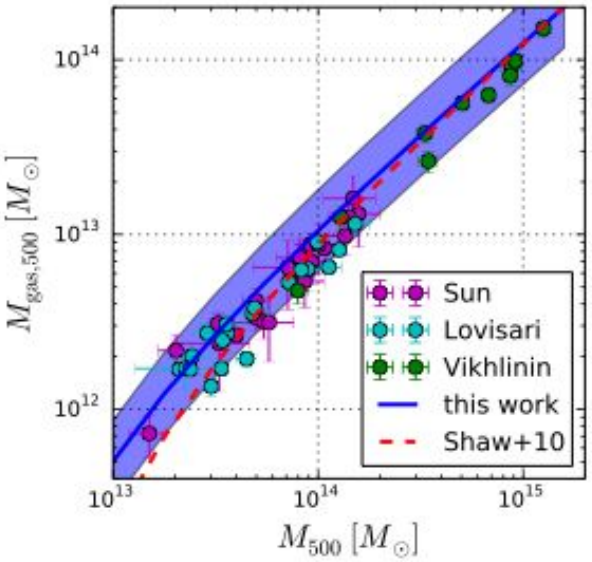
method for modeling halo-gas connection



BP Modeling of X-ray Clusters & Groups



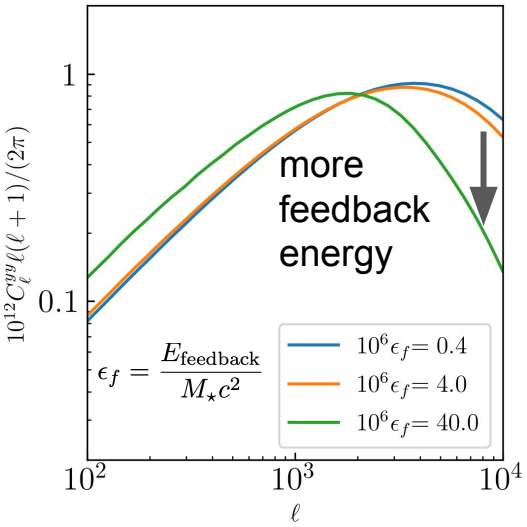
SPT-Chandra **gas density profiles** (McDonald+13,17)

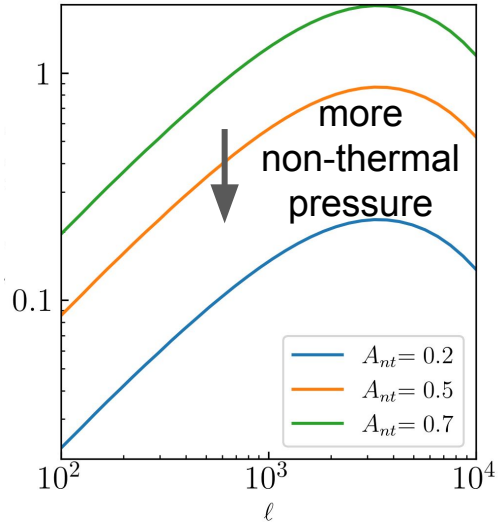


Scaling relation between gas mass and total mass (Vikhlinin+06, Sun+09, Lovisari+15)

BP gas model describes X-ray density profiles and gas mass well
(Flender, Nagai, McDonald+17)

Effects of Cluster Physics on tSZ Power Spectra

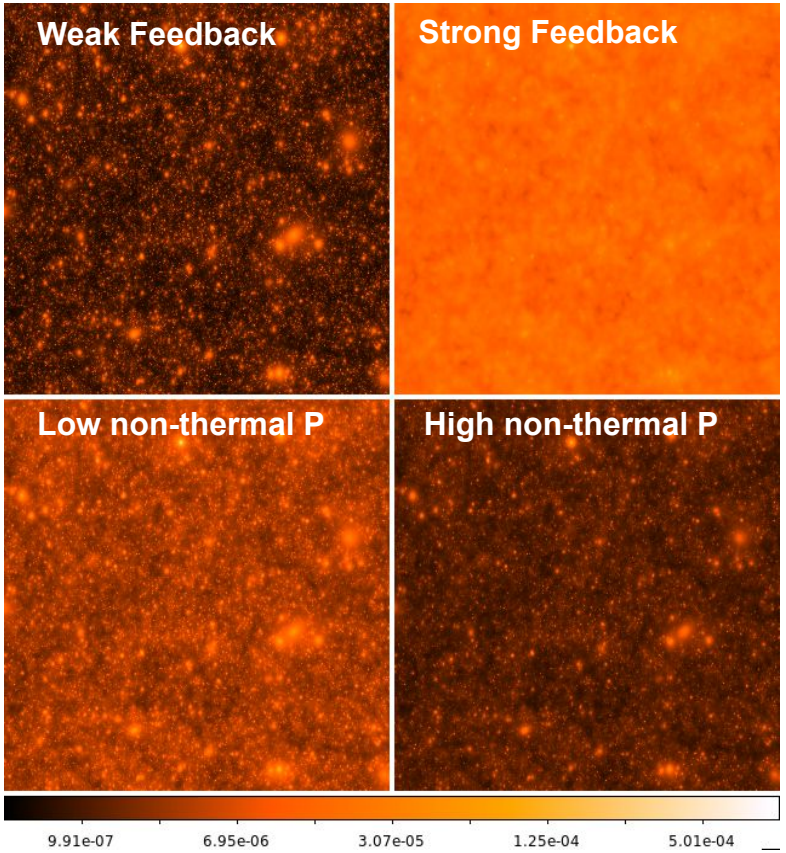




Feedback and ICM non-thermal pressure suppress tSZ power at different scales.

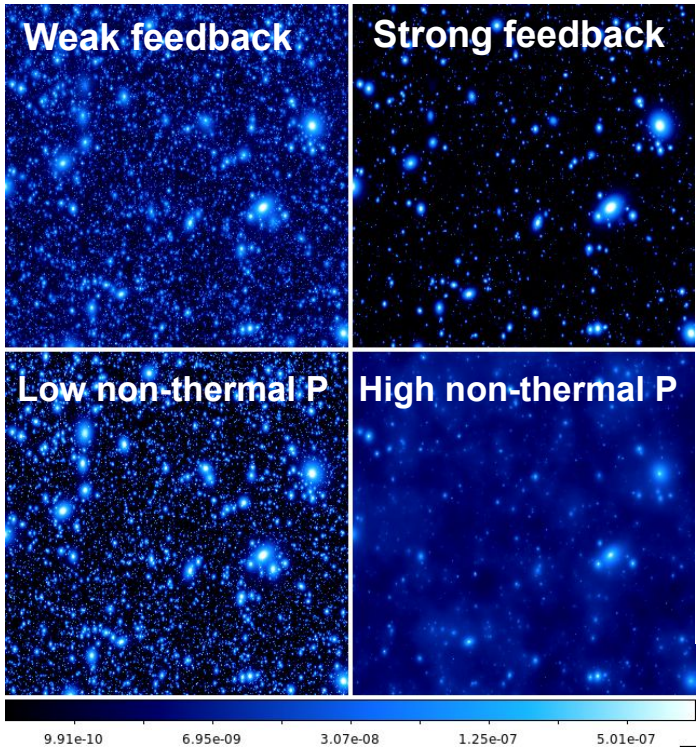
Also Shaw+10, Battaglia+12, Trac+11, etc.

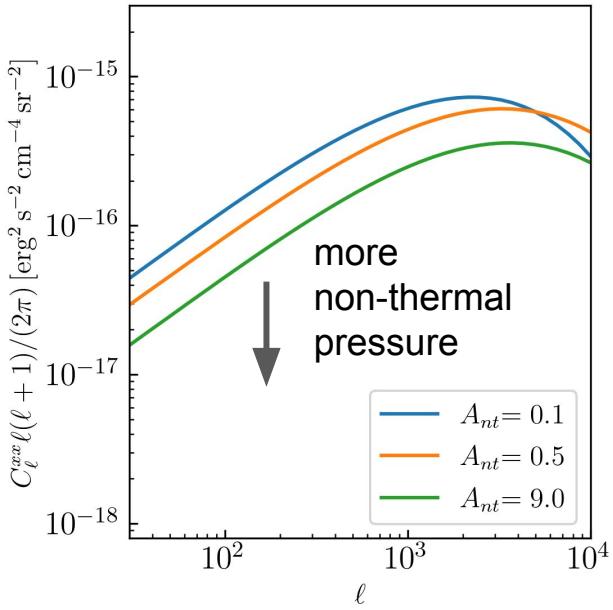
Baryon Pasted tSZ maps

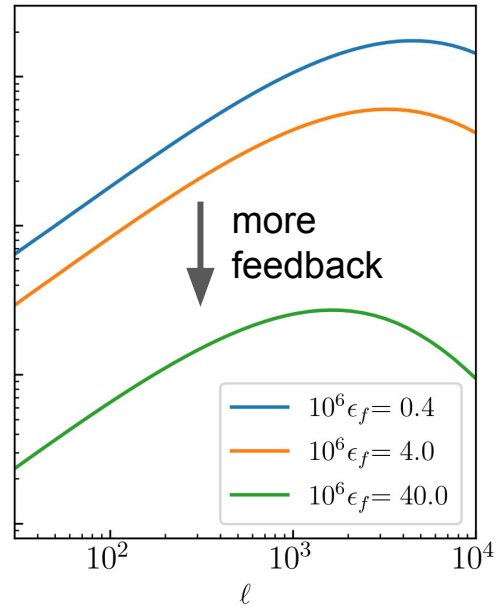


Effects of Cluster Physics on X-ray Power Spectra

Baryon Pasted X-ray map in [0.5, 2.0] keV band

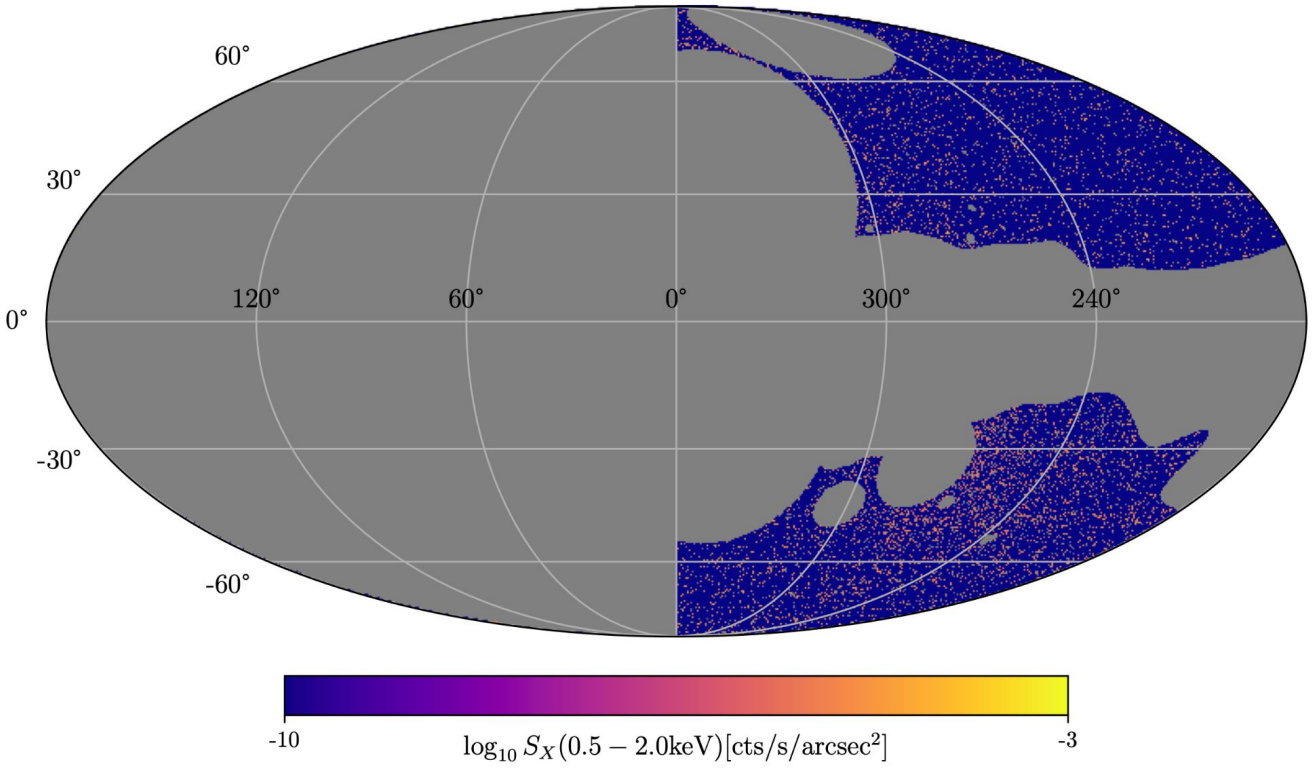






X-ray angular power spectrum is sensitive to feedback and non-thermal pressure, with different scale-dependence.

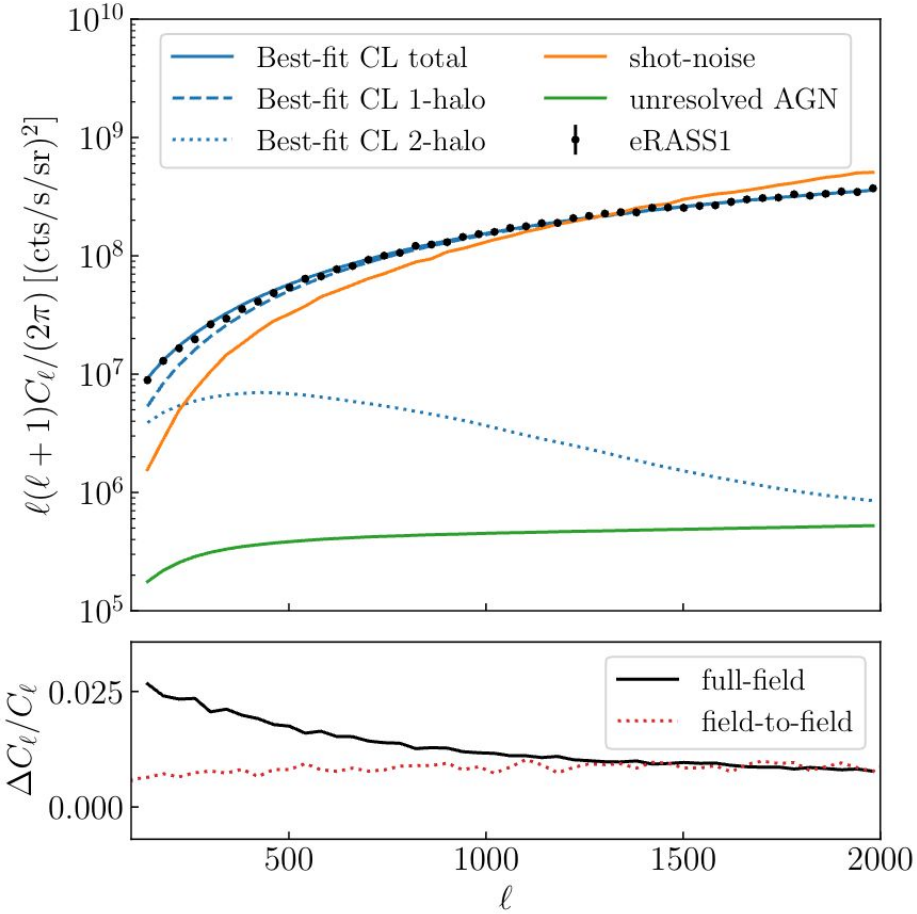
eRASS1 Map



- Half-sky map constructed from publicly available eRASS1 data (cf. Esra Bulbul's talk).
- Large sky coverage (fsky= 21%) means low *cosmic variance*.
- Masked out MW, eROSITA bubbles, resolved point sources, and z<0.1 clusters to mitigate non-Gaussian covariances.

Lau+2025a, ApJ 983, 8
arXiv:2410.22397

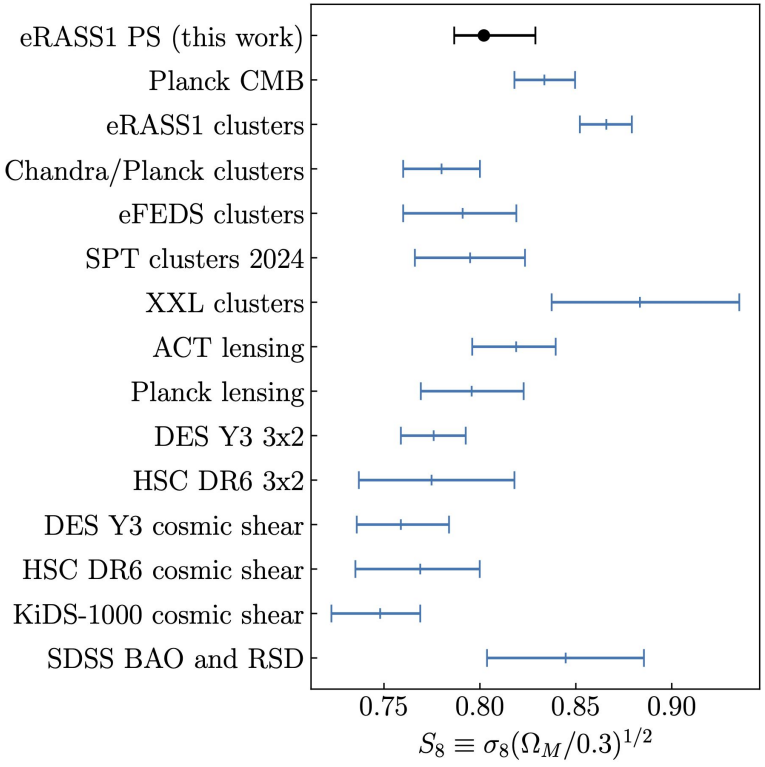
eRASS1 X-ray Power Spectrum of Clusters and Groups

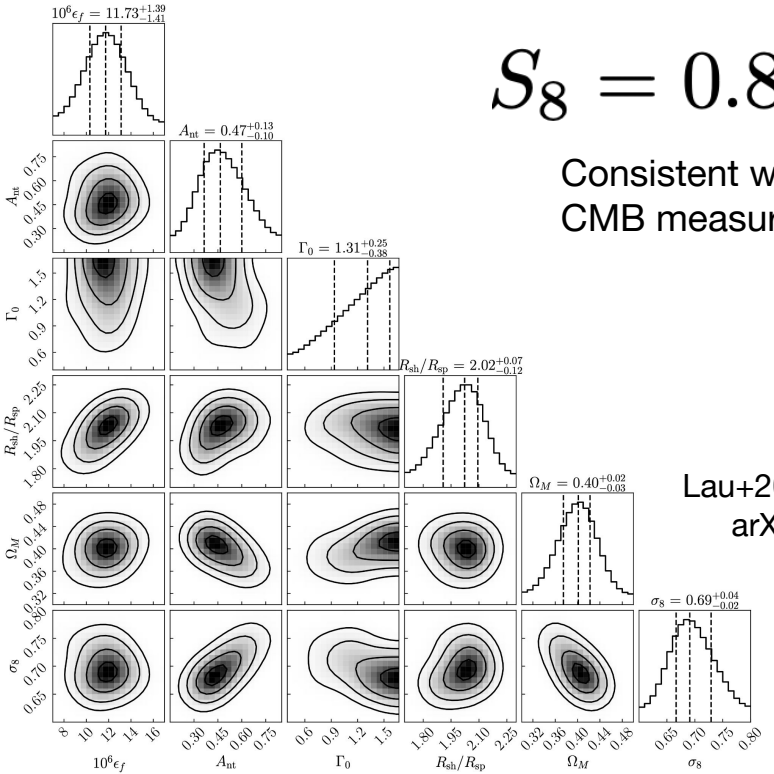


- BP model match well to eRASS1 at 100 $<\ell<$ 2000.
- Shot-noise becomes significant at $\ell >$ 1500 due to shallow exposure of eRASS1.
- Signal from unresolved AGN clustering is subdominant.

Lau+2025a ApJ 983,8
arXiv:2410.22397

S_8 & Astrophysics with eRASS1 Power Spectrum





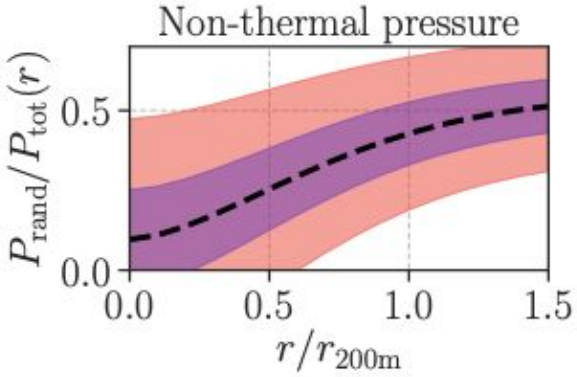
$$S_8 = 0.80^{+0.02}_{-0.01}$$

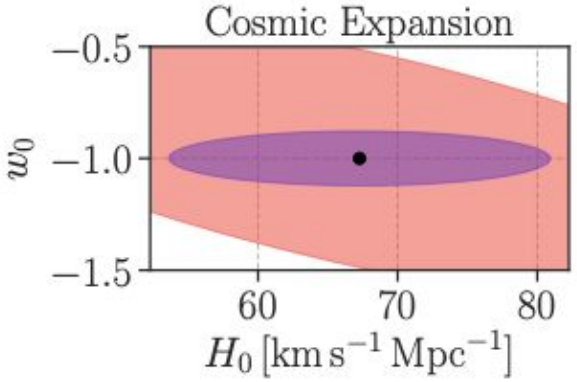
Consistent with *Planck* CMB measurements.

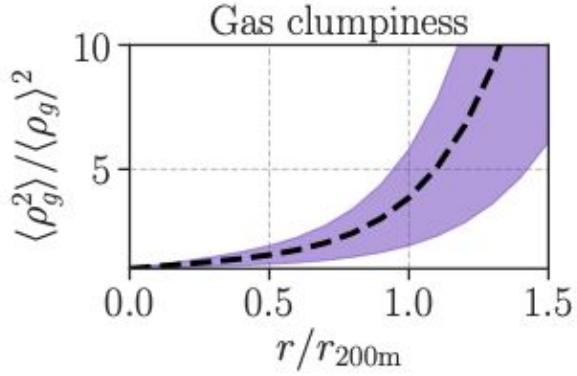
Lau+2025a, ApJ 983, 8
arXiv:2410.22397

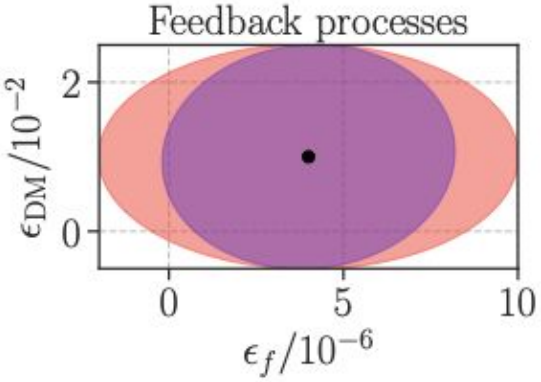
Provides the **first constraints on S8 and astrophysics** (feedback + non-thermal pressure support + outer accretion shock radius) of angular power spectrum of clusters and groups

Probing Cosmology and Astrophysics with X-ray/tSZ/Lensing Cross-Power Spectra







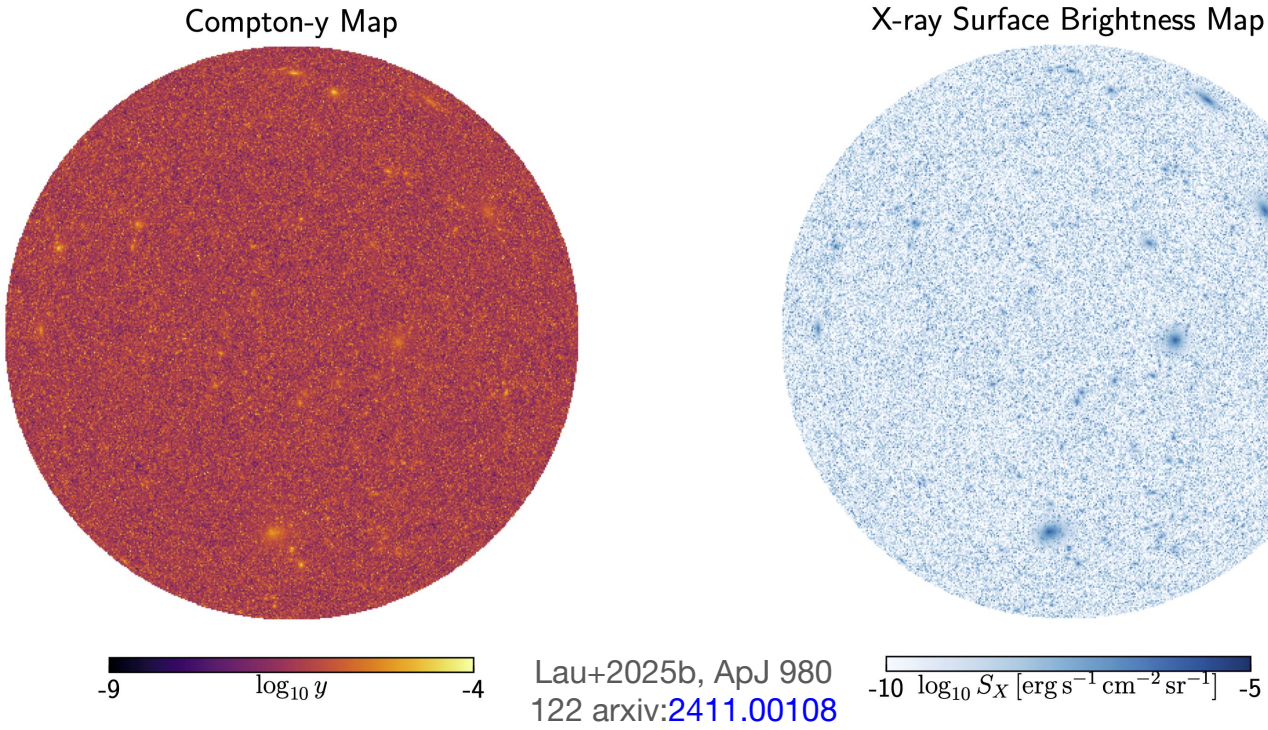


Microwave+Optical+X-ray

Measuring the **angular power spectra** in X-ray (eROSITA, microwave (CMB-S4), and optical (Rubin/LSST) lead to improved constraints on cosmology and astrophysics

Shirasaki, Lau, Nagai (2020)

Baryon Pasted Uchuu Half-Sky Lightcone Maps

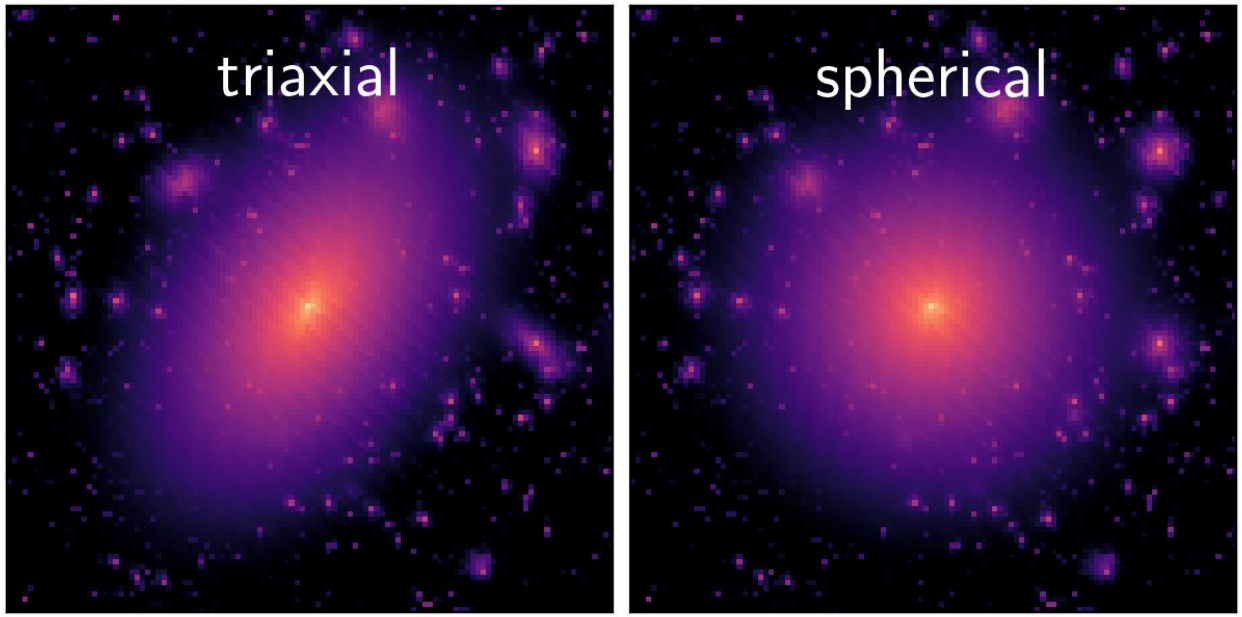


Lau+2025b, ApJ 980
122 arxiv:2411.00108

X-ray surface brightness and tSZ maps with half-sky lightcone from the 2.1 Gpc *Uchuu N*-body simulation (Ishiyama et al. 2021) with 75 million halos with $M_{500c} > 10^{13}$ Msun from z = [0,2]

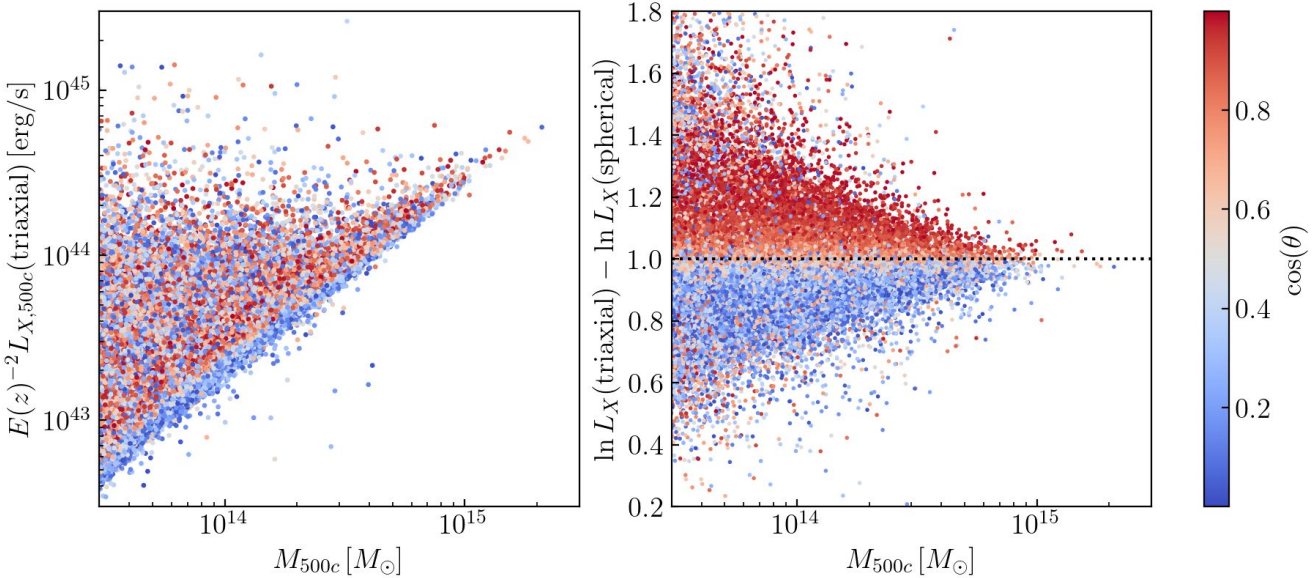
Beyond Spherical Cows: Triaxial Gas Halos

BP maps of the same halo: triaxial vs spherical



From DM-ICM shape relation calibrated with IllustrisTNG300

Extrinsic Scatter due to Gas Triaxiality & Orientation

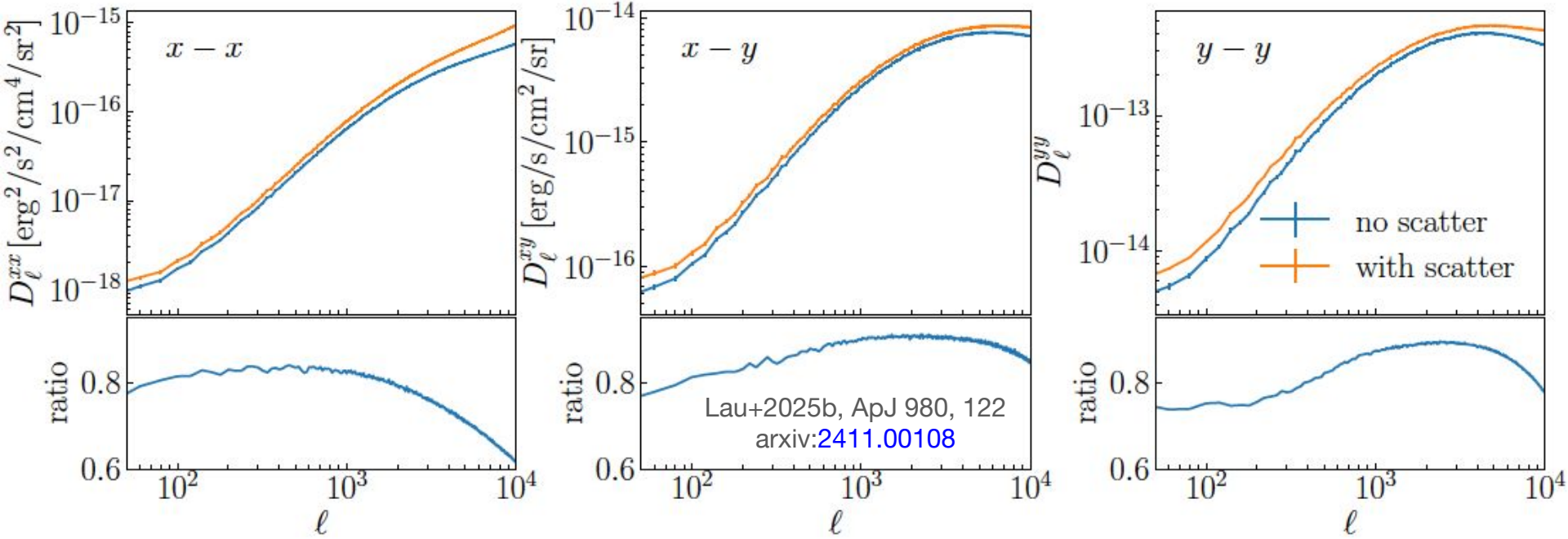


map type	$\log_{10}(M_{500c}/M_\odot)$ [13.5, 14.0]	[14.0, 14.5]	[14.5, 15.0]
Without core excision			
int	0.09	0.08	0.08
ext	0.29	0.22	0.20
int+ext	0.31	0.24	0.22
With core excision			
int	0.12	0.09	0.07
ext	0.22	0.15	0.11
int+ext	0.26	0.19	0.15

Lau+2025b, ApJ 980, 122
arxiv:2411.00108

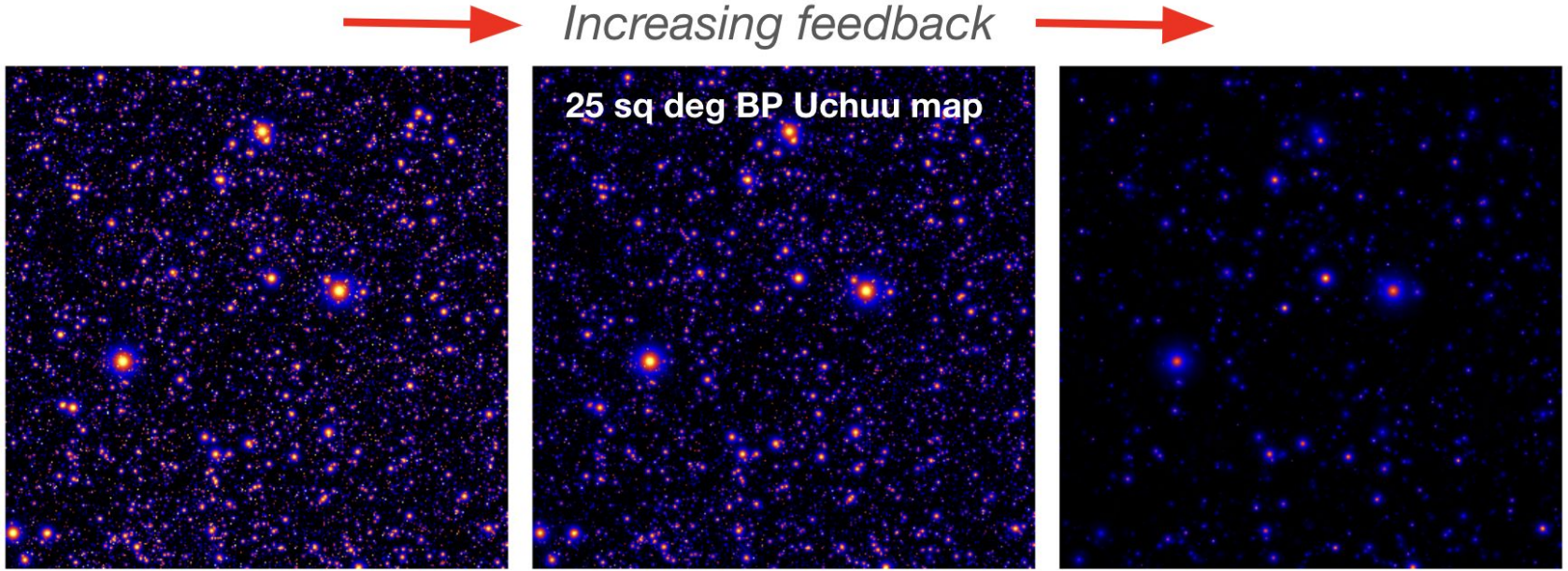
Extrinsic scatter due to ***projection effects and triaxiality*** accounts for **half** of total scatter (intrinsic+extrinsic) of X-ray luminosity-mass scaling relation.

Intrinsic scatter in ICM profiles biases power spectra



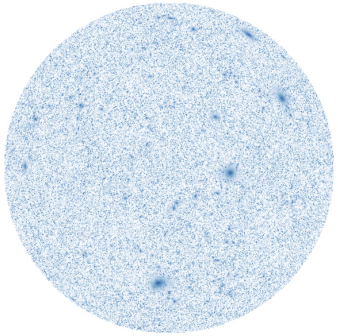
- **Intrinsic scatter** in density and pressure profiles -> **more fluctuations** in XSB and Compton-y from halo to halo-> **increases clustering signal**.
- Ignoring scatter in ICM profiles (as in simple halo model) underestimates angular power by 10%-40% depending on scale.

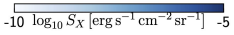
Forward Modeling Astrophysics in Cluster Selection

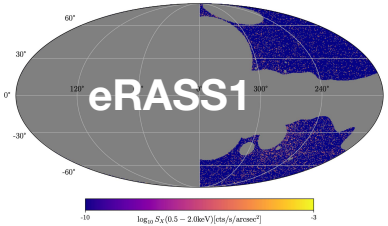


Forward model effects of feedback, non-thermal pressure, and morphology on cluster selection in X-ray surveys (e.g. FornaX) with BP maps.

X-ray Surface Brightness Map

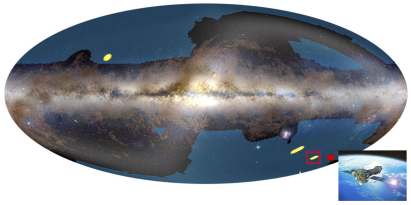






FornaX

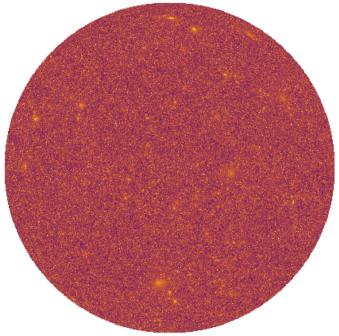
2024 Heritage Programme 2034

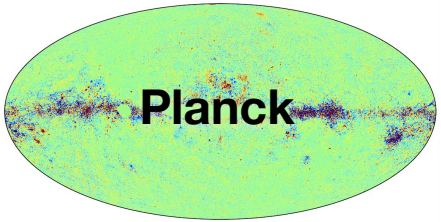


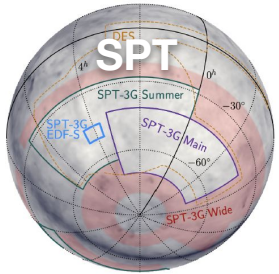
Summary

- Map-level analysis (e.g. angular power spectrum) is a promising alternative to cluster counting for doing cluster cosmology.
- We used Baryon Pasting to extract astrophysics and cosmology from maps, e.g., S_8=0.80 ± 0.02 with eRASS1.
  (Lau+ 2025a, ApJ 983,8 arXiv:2410.22397)
- We used Baryon Pasted-Uchuu maps to quantify previously unknown map-level intrinsic and extrinsic scatter in cluster observables.
  Maps and catalogs can be downloaded here.
  (Lau+ 2025b, ApJ 980 122 arXiv:2411.00108)
- BP is a promising tool for forward modeling and field-level inference on astrophysics and cosmology with multi-wavelength surveys in X-ray (eRASS, FornaX) and SZ (SPT, ACT, SO, CMB-S4).

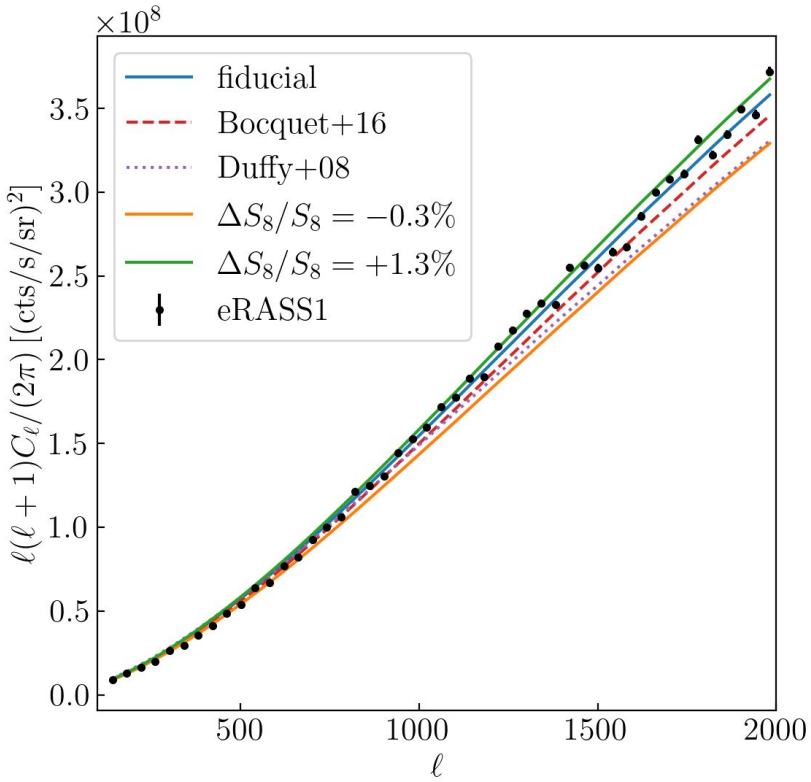
Compton-y Map







Potential Systematics



Differences due to HMF and M-c relation is small compared to uncertainties in S_8.

Baryon Pasting (BP) Gas Model

A physically-motivated parameterized model of gas in DM halos:

Polytropic equation of state in cluster cores and outskirts (Ostriker+05; Shaw+10, Flender+17)

$$P_{tot} = P_{th} + P_{nt} \propto \rho_g^{\Gamma} \qquad \Gamma(r,z) = \begin{cases} 1.2 & (r/r_{500} > 0.2) \\ \tilde{\Gamma}(1+z)^{\gamma} & (\text{otherwise}) \end{cases}$$

Star formation: stellar mass fraction (e.g., Giodini+09, Leauthaud+11, Budzynski+13)

$$\frac{M_*}{M_{500}} = f_* \left(\frac{M_{500}}{3 \times 10^{14}\, M_\odot} \right)^{-S_*}$$

Dynamical heating from DM and energy feedback from AGN and SNe

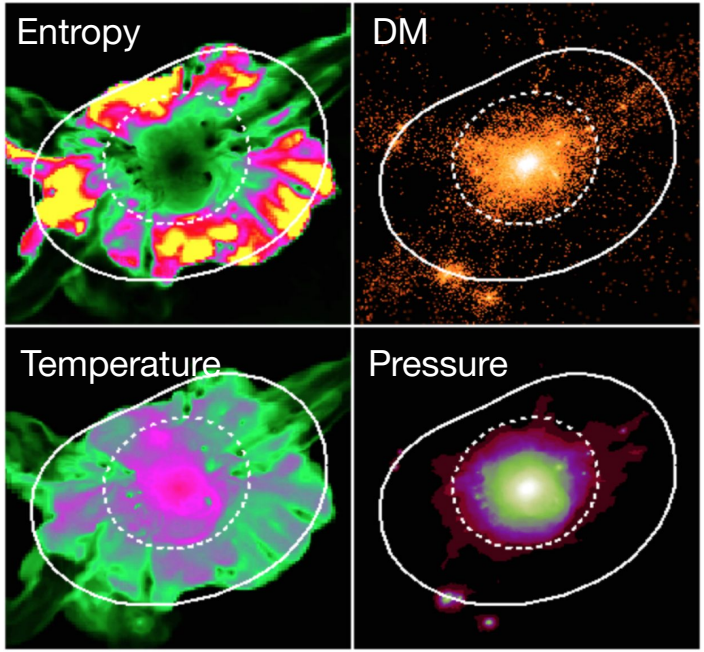
$$E_{g,f} = E_{g,i} + \epsilon_{\rm DM} |E_{\rm DM}| + \epsilon_f M_* c^2 + \Delta E_p$$

Model of merger-induced non-thermal pressure fraction (Nelson, Lau, Nagai 14; Lau+09,13, Green+20)

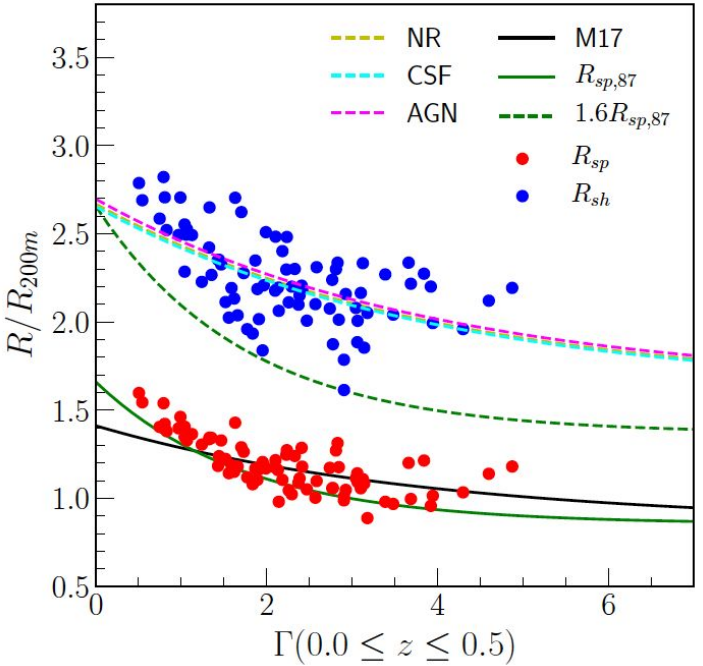
$$\frac{P_{\rm rand}}{P_{\rm total}}(r) = 1 - A \left\{ 1 + \exp\left[- \left(\frac{r/r_{200m}}{B} \right)^{\gamma} \right] \right\}$$

Halo Gas Boundary in BP Gas Model

DM splashback computed using SHELLFISH (Mansfield+17)



Aung, Nagai, Lau 2021



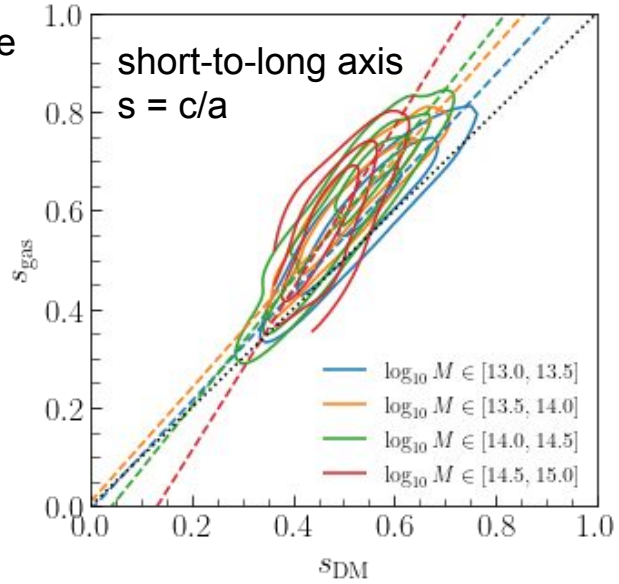
- Calibrate ratio of **outer accretion shock radius to splashback radius** with *Omega500* cosmological simulations (refer to Daisuke's talk for details) + R_{sp} model from More+15
- Sets the **halo gas boundary** needed for solving the ICM's equation of state!

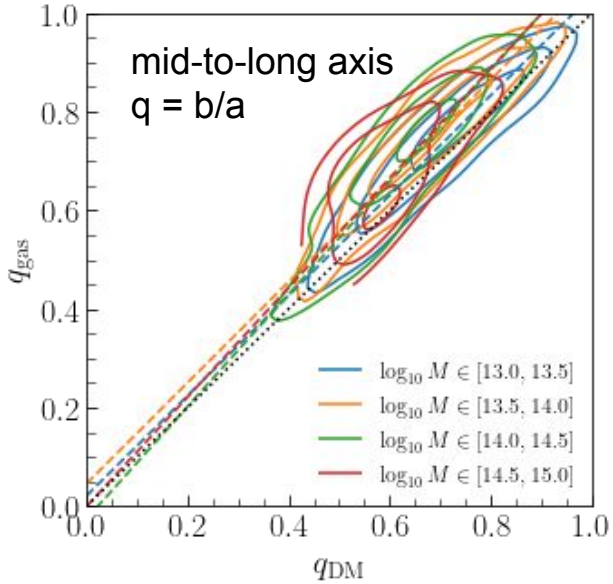
Beyond Spherical Cows: Triaxial Gas Halos

Calibrate relations between DM halo shape & gas shape with Illustris-TNG300 hydro simulations

s~ 1: more spherical

s~ 0: less spherical



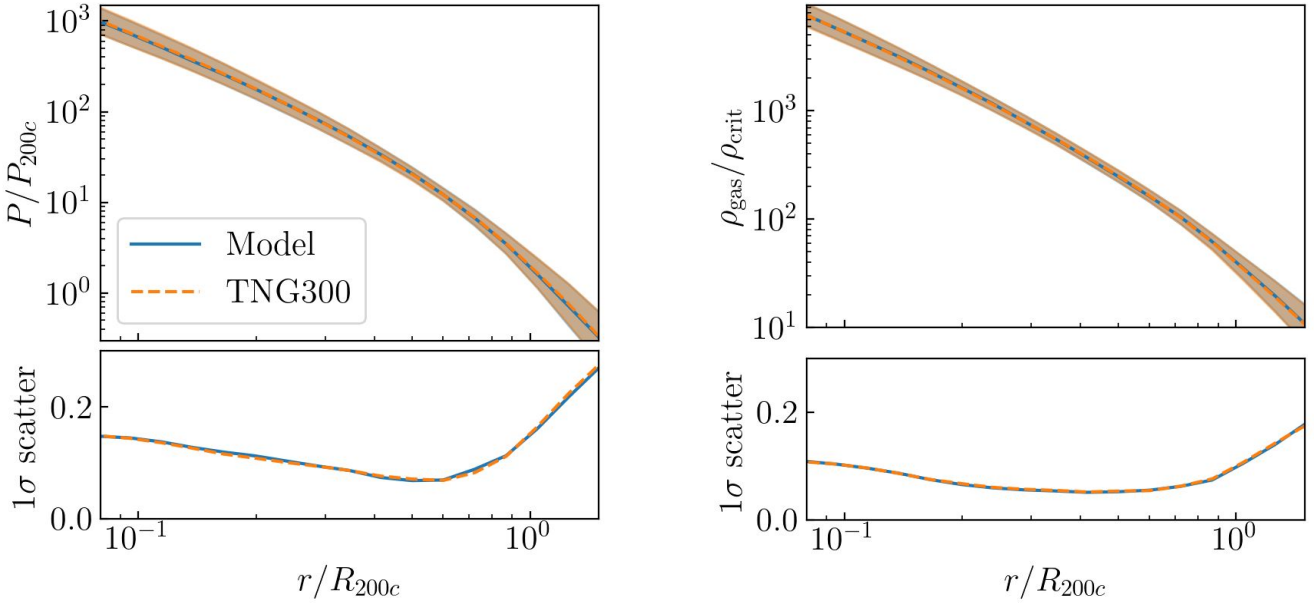


q~ 1: more spherical

q~ 0: less spherical

Gas shape more spherical than DM in clusters and groups

Model of Intrinsic Profile Scatter



- We model scatter in pressure and density profile by sampling profile covariance matrices measured in TNG300 simulations.
- Our model scatter matches the TNG300 simulations perfectly.