

The suppression of the matter power spectrum: strong feedback from X-ray gas mass fractions, kSZ effect profiles, and galaxy–galaxy lensing

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ABSTRACT

Baryon feedback redistributes gas relative to the underlying dark matter distribution and suppresses the matter power spectrum on small scales, but the amplitude and scale dependence of this effect are uncertain. We constrain the impact of baryon feedback on the matter power spectrum by jointly analysing X-ray gas mass fractions from the eROSITA and HSC–XXL samples and Sloan Digital Sky Survey (SDSS)/Dark Energy Spectroscopic Instrument (DESI) + Atacama Cosmology Telescope (ACT) kinetic Sunyaev–Zel’dovich (kSZ) effect profiles; the samples are characterized with galaxy–galaxy lensing and together span group and cluster masses ($13 < \log_{10} \frac{M_{500}}{M_{\odot} h^{-1}} < 14$) at $0 < z < 1$. Using the baryonification framework, our joint eROSITA and kSZ model gives precise constraints on the suppression of the matter power spectrum: 10 ± 2 per cent at $k = 1 h \text{ Mpc}^{-1}$. The inferred gas profiles are more extended and the power suppression is stronger than predicted by the fiducial models of recent hydrodynamical simulation suites, including FLAMINGO and BAHAMAS. The HSC–XXL gas mass fractions, which the fiducial simulations were calibrated to reproduce, prefer more moderate power suppression than the kSZ and eROSITA data: 5 ± 4 per cent at $k = 1 h \text{ Mpc}^{-1}$. With a simulated LSST Year 1 weak lensing analysis, we demonstrate a framework for next-generation surveys: calibrating feedback models with multiwavelength gas observables to recover the small-scale statistical power of cosmic shear.

Key words: methods: numerical – galaxies: formation – large-scale structure of Universe – cosmology: theory.

1 INTRODUCTION

Baryon feedback processes, particularly energy injection by active galactic nuclei (AGNs), redistribute gas relative to the underlying dark matter distribution. This redistribution suppresses the matter power spectrum on small, non-linear scales by tens of per cent relative to dark matter-only predictions (e.g. M. P. Daalen et al. 2011; N. E. Chisari et al. 2019; S. N. B. Debackere, J. Schaye & H. Hoekstra 2020). Testing the cosmological model on small scales requires accurate modelling of the non-linear matter power spectrum (e.g. E. Semboloni et al. 2011). However, the precise amplitude and scale dependence of matter power suppression due to baryon feedback remains unclear. This uncertainty directly translates to a loss of cosmological precision. Modelling of baryonic feedback and the intrinsic alignment of

galaxies (correlations between galaxy shapes not introduced by weak lensing, e.g. N. E. Chisari 2025) limit cosmological precision by more than a factor of 2 for cosmic shear (A. Amon et al. 2022) – the weak gravitational lensing of background galaxies by large-scale structure. With recent analyses partially lifting the uncertainty from intrinsic alignments by limiting shear studies to blue galaxy populations that are found to weakly align (J. McCullough et al. 2024), baryonic feedback is now the limiting systematic for cosmic shear (e.g. DES Collaboration 2026; N. C. Robertson et al. 2026).

There is no consensus from modern hydrodynamical simulations on the impact of baryon feedback on the matter power spectrum. Simulations include a variety of baryonic feedback processes (e.g. AGNs, supernovae, and stellar winds) and are increasingly in agreement with the observed stellar-to-halo mass relation, cosmic star formation density, and cluster scaling relations (e.g. I. G. McCarthy et al. 2017; R. Davé et al. 2019; R. Pakmor et al. 2023; J. Schaye et al. 2023; K. Dolag et al.

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2025; J. Schaye et al. 2025; L. Bigwood et al. 2025a). However, they lack the resolution to treat feedback processes from first principles and instead adopt ‘sub-grid’ prescriptions for the behaviour of stars and AGNs. Different sub-grid physics recipes result in markedly different predictions for the suppression of the matter power spectrum (e.g. M. P. Daalen et al. 2011; M. P. Daalen, I. G. McCarthy & J. Schaye 2020; L. Bigwood et al. 2025a).

Without a precise prediction from simulations for the impact of feedback on the matter power spectrum, weak lensing analyses often adopt conservative scale cuts: excluding the small-scale modes most sensitive to baryonic physics. Although it can reduce bias, this approach discards a large fraction of the available signal. An alternative method is to retain the small scales and account for matter power suppression by baryon feedback using flexible models: e.g. the halo model (E. Semboloni et al. 2011; E. Semboloni, H. Hoekstra & J. Schaye 2013; A. J. Mead et al. 2021), the baryonification of dark matter-only simulations (A. Schneider & R. Teyssier 2015; R. E. Angulo et al. 2021; G. Aricò et al. 2021; A. Schneider et al. 2025), Principal Component analysis (PCA; H.-J. Huang et al. 2021), the resummation model (M. L. Loon & M. P. van Daalen 2024; M. P. Daalen et al. 2025), simulation-based analytic models (J. Salcido et al. 2023; M. Schaller & J. Schaye 2025), simulation based emulators (e.g. M. Schaller et al. 2025), and effective field theory (e.g. A. Bartlett, J. DeRose & M. White 2025; J. DeRose & S.-F. Chen 2025). Without calibration from external probes of baryon feedback (e.g. the hot gas mass fractions of groups and clusters), the flexibility of these models effectively downweights the small scales, degrading the cosmological precision similarly to scale cuts (G. Aricò et al. 2023; L. Bigwood et al. 2024; D. Anbajagane et al. 2025).

In this work, we use multiwavelength gas observations and galaxy–galaxy lensing (GGL) to directly constrain the distribution of baryons relative to the underlying dark matter. We then relate these constraints to the suppression of the matter power spectrum, producing data-driven priors that can be incorporated into weak lensing analyses. This approach transforms feedback modelling from a source of systematic uncertainty to an observationally calibrated component of cosmological inference.

By tracing how much gas is expelled from haloes and how far it extends, observations of the intracluster medium (ICM) are valuable probes of baryon feedback. Recent studies have inferred the impact of baryon feedback on the matter power spectrum using a variety of observations, including X-ray gas mass fractions (A. Schneider et al. 2022; L. Bigwood et al. 2024; S. Grandis et al. 2024; M. P. Daalen et al. 2025; M. Kovač et al. 2025), diffuse X-ray emission (T. Ferreira et al. 2024; A. La Posta et al. 2025), the thermal and kinetic Sunyaev–Zel’dovich effects (tSZ and kSZ; A. Schneider et al. 2022; T. Tröster et al. 2022; L. Bigwood et al. 2024; N. Dalal et al. 2025; M. Kovač et al. 2025; F. A. Roper, Y.-C. Cai & J. A. Peacock 2025; S. Pandey et al. 2025a), and fast radio bursts (R. Reischke & S. Hagstotz 2025). The matter power spectrum is indirectly benchmarked by comparing hydrodynamical simulations to gas observables (I. G. McCarthy et al. 2018, 2025; J. Schaye et al. 2023; B. Hadzhiyska et al. 2025; B. Ried Guachalla et al. 2025; J. Siegel et al. 2025; L. Bigwood et al. 2025b). The suppression of the non-linear matter power spectrum has also been constrained directly from the cosmic shear data, either with or without assuming the Lambda cold dark matter (Λ CDM) cosmology preferred by the cosmic microwave background (CMB; e.g. H.-J. Huang et al. 2021; A. Amon & G. Efstathiou 2022; A. Chen et al. 2022; G.

Aricò et al. 2023; C. Preston, A. Amon & G. Efstathiou 2023; C. García-García et al. 2024; C. Preston, A. Amon & G. Efstathiou 2024; J. C. Broxterman et al. 2025; K. P. Sarmiento et al. 2025; R. Terasawa et al. 2025; J. Xu et al. 2025). Overall, there is a growing consensus that feedback indeed suppresses the matter power spectrum on small scales, and more recently there is evidence that suppression may be stronger than realized in many state-of-the-art hydrodynamical simulations. In addition to the effects of feedback, deviations of the non-linear matter power spectrum from the Λ CDM expectation could be signs of new physics (e.g. D. C. Hooper et al. 2022; V. Poulin et al. 2023; K. K. Rogers et al. 2023; C. Preston et al. 2025). Motivated by these previous studies, we address key uncertainties in the study of baryon feedback and deliver precise priors for next-generation cosmic shear analyses.

Cosmic shear is sensitive to baryon feedback over a wide range of halo mass and redshift (e.g. L. Lucie-Smith et al. 2025). At $0.1 < k h \text{ Mpc}^{-1} < 10$ and $0 < z < 1$, suppression of the matter power spectrum is strongly correlated with the baryon properties of groups and clusters (J. Salcido et al. 2023). However, no single observation probes the full regime: X-ray gas mass fractions probe the inner regions ($< R_{500}$) of low redshift clusters, while existing kSZ measurements constrain the outskirts (beyond several R_{500}) of higher redshift group mass haloes. Building a complete picture of baryon feedback thus requires a multiprobe approach. In this work, we jointly analyse stacked measurements of the kSZ effect from SDSS/DESI+ ACT (E. Schaen et al. 2021; B. Ried Guachalla et al. 2025) and X-ray gas mass fractions from the first eROSITA All-Sky Survey catalogue (RASS1; E. Bulbul et al. 2024; M. Kluge et al. 2024) and the HSC–XXL sample (D. Eckert et al. 2016; M. Pierre et al. 2016; D. Akino et al. 2022). For the kSZ and eROSITA samples, we adopt the galaxy–galaxy lensing mean halo mass measurements of J. Siegel et al. (2025); the HSC–XXL sample includes the weak lensing halo mass measurements of K. Umetsu et al. (2020). Weak lensing halo mass constraints resolve a key source of uncertainty, because the implied magnitude of gas expulsion by a kSZ or X-ray observation is degenerate with the halo mass (e.g. I. G. McCarthy et al. 2025).

In Section 2, we describe the multiwavelength data sets. We review the baryonification model in Section 3 and validate the framework in Section 4. We present the model fits in Section 5. In Section 6, we compare our results with state-of-the-art hydrodynamical simulations and demonstrate how the model constraints can be implemented as data-driven priors for cosmic shear, using a forecast of the Legacy Survey of Space and Time (LSST) Year 1 data. We conclude in Section 7.

2 DATA

In this work, we infer the impact of baryons on the matter power spectrum by jointly analysing kSZ effect profiles and X-ray hot gas mass fractions, with mean halo mass constraints from GGL. We describe the kSZ and X-ray measurements in Sections 2.1 and 2.2, respectively.

2.1 SDSS/DESI + ACT kSZ effect profiles

The kinetic Sunyaev–Zel’dovich (kSZ) effect is a CMB secondary anisotropy, arising from the inverse-Compton scattering of CMB photons off the ionized gas around galaxies and clusters. Due to the bulk motion of the gas, these scatterings impart a Doppler

shift to the CMB photons (R. A. Sunyaev & Y. B. Zeldovich 1980). The apparent change in temperature induced by the kSZ effect ΔT_{kSZ} is therefore proportional to the electron number density and the peculiar velocity of the gas

$$\frac{\Delta T_{\text{kSZ}}}{T_{\text{CMB}}} = \frac{\sigma_T}{c} \int_{\text{los}} e^{-\tau} n_e v_p dl, \quad (1)$$

where σ_T is the Thomson scattering cross-section, c is the speed of light, n_e is the free-electron number density, v_p is the peculiar velocity along the line of sight, and $\tau = \sigma_T \int n_e dl$ is the optical depth to Thompson scattering. Because the gas of interest is optically thin, we assume $e^{-\tau} \approx 1$ (see E. Schaan et al. 2021; B. Ried Guachalla et al. 2025). For one galaxy, the kSZ effect is approximately

$$\frac{\Delta T_{\text{kSZ}}}{T_{\text{CMB}}} \approx -\tau_{\text{gal}} \frac{v_{p,\text{gal}}}{c}. \quad (2)$$

To achieve a high signal-to-noise ratio measurement, the kSZ signal must be stacked across many galaxies. We consider the kSZ effect profile measurements of E. Schaan et al. (2021) and B. Ried Guachalla et al. (2025), which employ compensated aperture photometry (CAP) filters. For a galaxy located at $\vec{\theta}$ on the sky, the CAP filter sums the temperature fluctuation within θ_d of the galaxy and background subtracts the temperature fluctuations between θ_d and $\sqrt{2}\theta_d$ (equations 8 and 9 of E. Schaan et al. 2021).

Because the kSZ effect is proportional to the velocity of the gas, the stacked kSZ signal is measured by a combination of velocity and inverse-variance weighting (E. Schaan et al. 2021; B. Ried Guachalla et al. 2025)

$$\hat{T}_{\text{kSZ}}(\theta_d) = -\frac{1}{r_{v,\text{bias}}} \frac{v_{\text{rec}}^{\text{rms}}}{c} \frac{\sum_i \mathcal{T}_i(\theta_d) \left(\frac{v_{i,\text{rec}}}{c}\right) \sigma_i^{-2}}{\sum_i \left(\frac{v_{i,\text{rec}}}{c}\right)^2 \sigma_i^{-2}}, \quad (3)$$

where $\mathcal{T}_i(\theta_d)$ is the CAP filtered signal for the i th galaxy, σ_i^2 is the variance in $\mathcal{T}_i(\theta_d)$, $v_{i,\text{rec}}$ is the reconstructed line of sight peculiar velocity, and $v_{\text{rec}}^{\text{rms}}$ is the standard deviation of the reconstructed peculiar velocities. For existing measurements, the galaxies' three-dimensional peculiar velocities were reconstructed from the galaxy number overdensity field by the linearized continuity equation (N. Padmanabhan et al. 2012; M. Vargas-Magaña et al. 2017). To account for biases in the peculiar velocity reconstruction, E. Schaan et al. (2021) and B. Ried Guachalla et al. (2025) scale the profile amplitudes by the correlation between the true and reconstructed velocities in mock catalogues

$$r_{v,\text{bias}} = \frac{\langle v_{\text{true}} v_{\text{rec}} \rangle}{v_{\text{true}}^{\text{rms}} v_{\text{rec}}^{\text{rms}}}. \quad (4)$$

Using the ABACUSSUMMIT dark matter-only N -body simulation suite, B. Hadzhiyska et al. (2024) report the reconstruction quality for DESI-like spectroscopic samples: $r_{v,\text{bias}} \sim 0.7$ with < 5 per cent uncertainties. In Appendix D, we compare the corrected line-of-sight RMS of the reconstructed velocities with matching samples from the FLAMINGO simulations, finding agreement within 10 per cent. For our modelling, we assume a conservative uncertainty of 10 per cent for $r_{v,\text{bias}}$.

In this work, we consider the stacked kSZ effect profiles of E. Schaan et al. (2021) and B. Ried Guachalla et al. (2025), which used spectroscopic redshift tracers from SDSS and DESI, respectively. The ACT + *Planck* CMB temperature maps and galaxy samples underlying these measurements are described in Sections 2.1.1 and 2.1.2, respectively. Because the kSZ stacks are constructed with common CMB temperature maps (ACT DR5 for SDSS and DR6 for DESI), the different measurements (e.g. SDSS

LOWZ and CMASS) are formally covariant. The SDSS and DESI spectroscopic samples also share common objects (A. G. Adame et al. 2025a). For our analysis, we assume the kSZ measurements are independent; the galaxy selections occupy distinct comoving volumes and mass/redshift regimes, so map-level covariance contributes negligibly to the parameter uncertainties relative to kSZ measurement noise. Investigation of measurement covariances with forward modelling is warranted.

2.1.1 SDSS BOSS: LOWZ and CMASS

E. Schaan et al. (2021) measured the stacked kSZ effect profiles for the LOWZ and CMASS samples from the Baryon Oscillation Spectroscopic Survey (BOSS) DR10 release (C. P. Ahn et al. 2014). The LOWZ ('low redshift') sample consists of red galaxies at $0.15 < z < 0.4$, and the CMASS ('constant mass') sample includes massive galaxies at $0.4 < z < 0.8$ (C. P. Ahn et al. 2012). The CMB temperature map is derived from ACT DR5 (J. W. Fowler et al. 2007; D. S. Swetz et al. 2011; S. W. Henderson et al. 2016; R. J. Thornton et al. 2016) and *Planck* (Planck Collaboration VI 2020). E. Schaan et al. (2021) measured the kSZ effect in both the 90 and 150 GHz frequency ACT maps; we consider both measurements. From the mock BOSS catalogues (M. Manera et al. 2013, 2015), E. Schaan et al. (2021) report a peculiar velocity bias factor of $r_v = 0.7$ and quote uncertainties of a few per cent.

From J. Siegel et al. (2025), we adopt GGL derived mean halo masses of $\log_{10} M_{500}/M_{\odot} = 13.51 \pm 0.01$ and 13.29 ± 0.02 for LOWZ and CMASS, respectively.

2.1.2 DESI: BGS and LRG

B. Ried Guachalla et al. (2025) measured the stacked kSZ effect profiles for two DESI DR1 samples: the Bright Galaxy Survey (BGS; C. Hahn et al. 2023) and the Luminous Red Galaxy sample (LRG; R. Zhou et al. 2023). The BGS sample is magnitude limited and spans $0 < z < 0.6$. Following DESI Collaboration (2024), B. Ried Guachalla et al. (2025) restricted the sample to $0.1 < z < 0.4$ and applied a luminosity selection as a function of redshift to create a sample with an approximately constant number density. The LRG sample includes massive quenched galaxies at $0.4 < z < 1.1$. Following J. Siegel et al. (2025), we consider two of the stellar mass bins defined by B. Ried Guachalla et al. (2025): $\log_{10} M_{*}/M_{\odot} = (10.5, 11.2), (11.2, 11.4)$; the mass selection is performed using the stellar masses from R. Zhou et al. (2023), which are derived from DESI Legacy Imaging photometry via a random forest algorithm. B. Ried Guachalla et al. (2025) adopt the harmonic-space Internal Linear Combination (hILC) CMB temperature map, which combines multiple ACT DR6 channels (90, 150, and 220 GHz) with *Planck* (W. Coulton et al. 2024); each channel is convolved with a Gaussian beam (1.6 arcmin FWHM) before the combination. To mitigate tSZ contamination, B. Ried Guachalla et al. (2025) masked temperature outliers in the ACT map. Peculiar velocities were adopted from A. G. Adame et al. (2025b), with reconstruction biases of $r_v = 0.64$ and 0.65 for the BGS and LRG samples, respectively (B. Hadzhiyska et al. 2024); the reported r_v uncertainties are approximately 3 per cent.

From J. Siegel et al. (2025), we adopt GGL derived mean halo masses of $\log_{10} M_{500}/M_{\odot} = 13.31 \pm 0.01$, 12.91 ± 0.02 , and 13.15 ± 0.01 for BGS, LRG M1, and M2, respectively.

2.2 X-ray gas mass fractions

X-ray observations of the ICM in groups and clusters are a well established tracer of baryon feedback. Stronger feedback processes are expected to expel gas beyond R_{500} , thereby lowering the typical gas fraction at a given halo mass. Indeed, the baryon fraction is found to increase as a function of radius and halo mass, approaching the universal baryon fraction at large radii of massive clusters (M. Sun et al. 2009; G. E. Bulbul et al. 2012; A. J. R. Sanderson et al. 2013; L. Lovisari, T. H. Reiprich & G. Schellenberger 2015; D. Eckert et al. 2016, 2019).

We consider X-ray gas mass fraction measurements from the *XMM-Newton* XXL sample (Section 2.2.1) and the eROSITA All-Sky Survey (Section 2.2.2). Weak lensing halo masses are available for both samples: K. Umetsu et al. (2020) and J. Siegel et al. (2025) for the XXL and eROSITA samples, respectively. The GGL derived halo masses resolve a long-standing uncertainty in the study of X-ray gas mass fractions. Previous studies often assumed hydrostatic equilibrium to estimate total masses, however, non-thermal pressure support can bias hydrostatic masses low by approximately 30 per cent (H. Hoekstra et al. 2015; D. Eckert et al. 2016; R. Kugel et al. 2023; M. Muñoz-Echeverría et al. 2024); further complicating matters, this bias is dependent on cluster mass (J. Braspennig et al. 2025).

2.2.1 HSC-XXL

The XXL survey targeted two 25 deg² patches of the sky with over 6 Ms of *XMM-Newton* observations (M. Pierre et al. 2016). The second XXL data release includes over 300 spectroscopically confirmed X-ray detected clusters at $0 < z < 1$ (C. Adami et al. 2018). For the approximately 100 clusters that overlap the HSC footprint, K. Umetsu et al. (2020) measured weak lensing masses with the first year HSC shear catalogue (R. Mandelbaum et al. 2018). Using the weak lensing masses, D. Akino et al. (2022) measured the gas mass within R_{500} for each XXL cluster in the HSC footprint and conducted a joint Bayesian analysis of the halo mass, gas mass, stellar mass, and X-ray luminosity scaling relations. The X-ray selection effects were modelled as a minimum luminosity selection function (appendix A1 of D. Akino et al. 2022).

With weak lensing halo masses and modelling of selection effects, the HSC-XXL scaling relations are particularly well characterized. The gas fraction scaling relation is broadly consistent with other pre-eROSITA X-ray gas fraction measurements (R. Kugel et al. 2023). Following R. Kugel et al. (2023), we approximate the HSC-XXL scaling relation as two halo mass bins: $f_{\text{gas}}(10^{13.5} \text{ M}_{\odot}) = 0.054 \pm 0.010$ and $f_{\text{gas}}(10^{14.5} \text{ M}_{\odot}) = 0.106 \pm 0.02$.

2.2.2 eROSITA All-Sky Survey

The eROSITA satellite (extended ROentgen Survey with an Imaging Telescope Array; P. Predehl et al. 2021) is a soft X-ray telescope onboard the Spectrum-Roentgen-Gamma observatory (SRG; R. Sunyaev et al. 2021). The first eROSITA All-Sky Survey catalogue (eRASS1; E. Bulbul et al. 2024) includes more than 12 000 optically confirmed X-ray groups and clusters in the Western Galactic Hemisphere between the local universe and $z < 1.5$ (E. Bulbul et al. 2024; M. Kluge et al. 2024). The publicly available

gas masses are measured by a parametric model fit to the X-ray images with a forward modelling calibration (J. S. Sanders et al. 2018; A. Liu et al. 2022; E. Bulbul et al. 2024). The eRASS1 reported halo masses M_{500} are estimated from a weak lensing calibrated scaling relation between redshift, X-ray count rate, and shear. The shear measurements include corrections for mis-centering and cluster member contamination, as well as calibration from forward modelling of simulated shear profiles (S. Grandis et al. 2024; F. Kleinebreil et al. 2025; N. Okabe et al. 2025).

Although eROSITA is more complete than previous X-ray selected samples (e.g. ROSAT; J. Truemper 1982; W. Voges et al. 1999), the sample is still shaped by selection effects. The completeness of the eRASS1 catalogue significantly falls at $M_{500} \lesssim 10^{14} \text{ M}_{\odot}$ (R. Seppi et al. 2022; I. Marini et al. 2024; P. Popesso et al. 2024b). We therefore limit our study to lower redshift ($z < 0.2$) massive haloes. Following J. Siegel et al. (2025), we define four bins of eROSITA clusters: $\log_{10} M_{500}/\text{M}_{\odot} = (13.3, 14.0)$ and $(14.0, 14.5)$ at $0.05 < z < 0.1$, and $\log_{10} M_{500}/\text{M}_{\odot} = (13.5, 14.0)$ and $(14.0, 14.5)$ at $0.1 < z < 0.2$. The four bins include a total of 2500 clusters. J. Siegel et al. (2025) independently measured the mean halo masses for each bin with GGL, validating the publicly reported eRASS1 masses. The GGL calibrated bins are consistent with the stacked X-ray gas mass fractions of optically selected haloes (P. Popesso et al. 2024a).

The eROSITA reported gas mass fractions suggest that groups and clusters are, on average, more gas-depleted than previously found (A. Dev et al. 2024; P. Popesso et al. 2024a; M. Kovač et al. 2025). At $M_{500} = 10^{14} \text{ M}_{\odot}$, the mean gas mass from the eRASS1 catalogue is approximately 40 per cent lower than the HSC-XXL scaling relation. We discuss potential explanations, including selection effects and modelling systematics, and avenues for further study in Section 6.1. Because the apparent discrepancy in the mean gas fractions is not fully understood, we consider both the eROSITA and pre-eROSITA measurements in this work.

3 BARYONIFICATION MODEL

The ‘baryonification’ model is a framework for relating the radial density profiles of gas, stars, and dark matter to the suppression of the matter power spectrum relative to a dark matter-only simulation. The method relies on perturbatively displacing particles in N -body simulations according to observationally motivated, spherically symmetric analytic density profiles, to mimic the impact of feedback on the matter distribution (A. Schneider & R. Teyssier 2015; S. K. Giri & A. Schneider 2021; A. Schneider et al. 2025). By calculating the power spectrum of the baryonified matter distribution, the suppression of the matter power spectrum can be related to the radial density profiles of gas, stars, and dark matter. Observational constraints on the gas distribution from X-ray and kSZ measurements can thus be transformed into constraints on the matter power spectrum (S. K. Giri & A. Schneider 2021; A. Schneider et al. 2022; G. Aricò et al. 2023; L. Bigwood et al. 2024; M. Kovač et al. 2025). Power suppression can also be inferred with a halo model (S. N. B. Debackere et al. 2020; N. Dalal et al. 2025; A. La Posta et al. 2025; S. Pandey et al. 2025b), see Section 6.2.

We outline the baryonification framework below and refer the reader to A. Schneider & R. Teyssier (2015) and S. K. Giri & A. Schneider (2021) for a detailed description. The baryonification particle displacements convert Navarro–Frenk–White (NFW)-

like profiles into baryonified haloes composed of hot gas $\rho_{\text{gas}}(r)$, a central galaxy $\rho_{\text{cga}}(r)$, and collisionless matter $\rho_{\text{clm}}(r)$

$$\rho_{\text{nfw}}(r) \rightarrow \rho_{\text{bfc}}(r) = \rho_{\text{gas}}(r) + \rho_{\text{cga}}(r) + \rho_{\text{clm}}(r). \quad (5)$$

The gas component is parametrized as a cored double-power law

$$\rho_{\text{gas}}(r) \propto \frac{\Omega_b/\Omega_m - f_{\text{star}}(M_{200})}{\left[1 + \left(\frac{r}{r_{\text{core}}}\right)\right]^{\beta(M_{200})} \left[1 + \left(\frac{r}{r_{\text{ej}}}\right)^{\gamma}\right]^{\frac{\delta - \beta(M_{200})}{\gamma}}}, \quad (6)$$

where Ω_b/Ω_m is the cosmic baryon fraction. Inside the core radius $r_{\text{core}} = 0.1R_{200}$, the slope of the density profile is determined by the power-law index

$$\beta(M_{200}) = \frac{3(M_{200}/M_c)^\mu}{1 + (M_{200}/M_c)^\mu}. \quad (7)$$

At group masses ($M_{200} \ll M_c$), the gas is efficiently expelled ($\beta \approx 0$), while for clusters ($M_{200} \gg M_c$), the gas is retained ($\beta \approx 3$); the sharpness of the transition between the low and high mass limits is set by μ . Beyond the ejection radius ($r_{\text{ej}} = \theta_{\text{ej}}R_{200}$), the slope of the density profile is dictated by the parameters γ and δ . The stellar fraction f_{sga} is parametrized as a power law $f_{\text{sga}}(M_{200}) = 0.055(M_{200}/M_s)^{-\eta}$, where $M_s = 2.5 \times 10^{11} M_\odot h^{-1}$ (B. P. Moster, T. Naab & S. D. M. White 2013).

The central galaxy component is parametrized as an exponentially truncated power law

$$\rho_{\text{cga}}(r) = \frac{f_{\text{cga}}(M_{200})}{4\pi^{3/2}R_h r^2} \exp\left[-\left(\frac{r}{2R_h}\right)^2\right], \quad (8)$$

where R_h is the stellar half-light radius (fixed to 0.015 times the virial radius) and $f_{\text{cga}}(M_{200})$ is the fraction of stars in the central galaxy: $f_{\text{cga}}(M_{200}) = 0.055(M_{200}/M_s)^{-(\eta+\eta_\delta)}$

The collisionless matter component, including dark matter, satellites, and halo stars, is parametrized as

$$\rho_{\text{clm}}(r) = \left[\frac{\Omega_{\text{dm}}}{\Omega_m} + f_{\text{sga}}(M_{200})\right] \rho_{\text{nfw}}(r), \quad (9)$$

where $\Omega_{\text{dm}}/\Omega_m$ is the cosmic dark matter fraction and $f_{\text{sga}} = f_{\text{star}} - f_{\text{cga}}$ is the stellar fraction in satellite galaxies and halo stars.

The seven free parameters $\Theta = \{M_c, \mu, \theta_{\text{ej}}, \delta, \gamma, \eta, \eta_\delta\}$ are summarized in Table 1. We show how each parameter affects the suppression of the matter power spectrum, the kSZ signal, and the hot gas mass fractions of groups and clusters in Fig. 1. In this parametrization of the baryonification model, the feedback parameters are redshift independent. For a given set of model parameters Θ , the comoving density profile of each component only depends on halo mass and radius. However, predictions of the baryonification model (e.g. gas mass fractions, kSZ effect profiles, or suppression of the matter power spectrum) still depend on redshift, because the clustering and scale factor of the underlying N -body simulation evolves with redshift. The current data does not require redshift dependent model parameters (Section 5.1), however, further study of redshift dependent models is warranted.

In this work, we constrain the free parameters using GGL characterized X-ray and kSZ observations. Stellar fraction measurements are not readily available for our bins of eROSITA clusters. Measurements are available for other cluster samples (e.g. A. Vikhlinin et al. 2006; A. H. Gonzalez et al. 2013; A. J. R. Sanderson et al. 2013; L. Lovisari et al. 2015; A. V. Kravtsov, A. A. Vikhlinin & A. V. Meshcheryakov 2018; D. Akino et al. 2022),

however, it is non-trivial to account for differences in sample selection and halo mass estimation between these studies and our eROSITA bins. To ensure internal consistency, we refrain from modelling the stellar fraction for either the eROSITA or HSC-XXL X-ray samples. Following M. Kovač et al. (2025), we fix the stellar parameters to $\eta = 0.1$ and $\eta_\delta = 0.2$ for our fiducial analysis (see B. P. Moster et al. 2013). In Appendix A, we show that the parameter constraints are weakly sensitive to the adopted stellar parameters. We repeat the fitting process for four different stellar parameter treatments, including conservative Gaussian priors instead of fixed values, and demonstrate that at the current statistical uncertainty, the effect of varying stellar priors is negligible. We adopt wide top hat priors for the other five baryonification parameters. For our fiducial analysis, we fix the baryon fraction to the maximum likelihood cosmological parameters of the DES Y3 ‘3× 2pt + All Ext.’ flat Λ CDM cosmology (T. M. C. Abbott et al. 2022); we show our results are insensitive to this choice in Appendix A.

While the baryonification of a dark matter-only simulation is significantly faster than evolving a full hydrodynamical simulation, displacing particles in N -body simulations is still computationally expensive. We therefore rely on the BCEMU emulator (S. K. Giri & A. Schneider 2021), trained on 2700 baryonified simulations, for our Bayesian inference. The underlying N -body simulation consisted of 512^3 particles in a $256 (\text{Mpc } h^{-1})^3$ box with a Λ CDM cosmology: $\Omega_m = 0.315$, $\Omega_b = 0.049$, $h_0 = 0.674$, $n_s = 0.96$, $\sigma_8 = 0.811$. Along with the seven radial profile parameters, the baryon fraction Ω_b/Ω_m was varied between 0.10 and 0.25. BCEMU has been demonstrated to be per cent level accurate at $10^{-1} < k [h \text{ Mpc}^{-1}] < 10^1$ and $0 < z < 2$ (S. K. Giri & A. Schneider 2021). A baryonification emulator is also publicly available from the BACCO simulation project (R. E. Angulo et al. 2021; G. Aricò et al. 2021). A. Schneider et al. (2025) recently introduced an updated version of the baryonification framework, including modified formulations of the density profiles and treatment of the dark matter, gas, and stellar components as independent fields; an emulator was not publicly available at the time of writing. In this work, we consider the original baryonification framework and reserve investigation of alternate formulations for future work (Shavelle et al. in preparation).

3.1 Modelling X-ray and kSZ measurements

We constrain the free parameters of the baryonification model by jointly modelling the X-ray gas mass measurements (eROSITA or HSC-XXL) and the SDSS/DESI + ACT kSZ effect profiles.

At a given halo mass, we predict the X-ray gas mass by integrating the gas component $\rho_{\text{gas}}(r, M)$ to R_{500} . Previous studies often assumed hydrostatic equilibrium to derive cluster halo masses and therefore included a hydrostatic equilibrium bias parameter (e.g. A. Schneider et al. 2022; M. Kovač et al. 2025); we bypass this uncertainty by considering GGL halo masses: K. Umetsu et al. (2020) and J. Siegel et al. (2025) for the HSC-XXL and eROSITA samples, respectively.

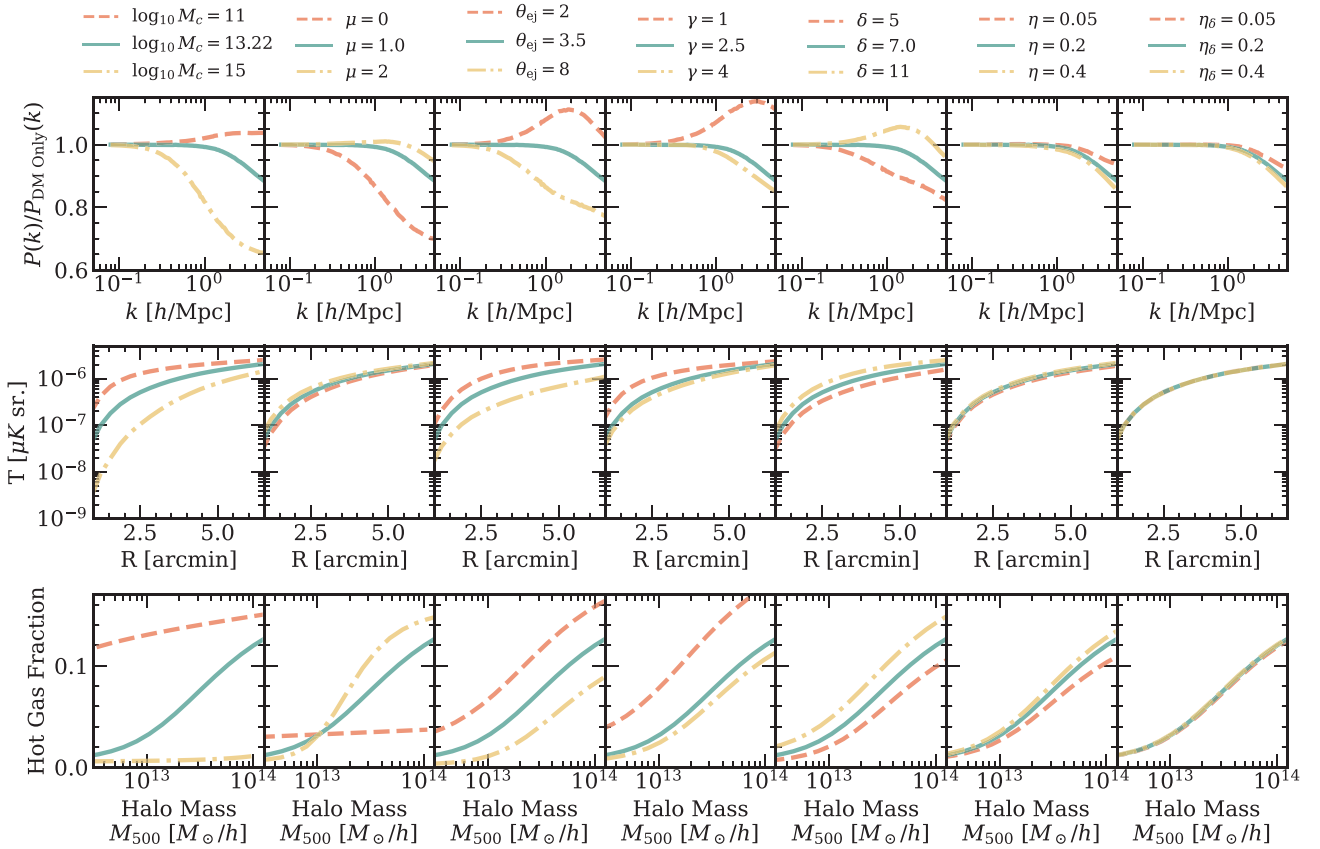
To predict kSZ profiles from the model, we convert the gas density profile $\rho_{\text{gas}}(r)$ to an electron density profile $n_e(r)$ assuming a fully ionized medium with primordial abundances

$$n_e(r) = \frac{(X_H + 1) \rho_{\text{gas}}(r)}{2 m_{\text{amu}}}, \quad (10)$$

where m_{amu} is the atomic mass unit and $X_H = 0.76$ is the hydrogen mass fraction. The electron density $n_e(r)$ is then integrated

Table 1. Qualitative descriptions of the model parameters, assumed priors, and posteriors from fitting the kSZ and X-ray data. We exclude the posteriors from the joint kSZ and HSC-XXL fit because of the poor goodness of fit; the posteriors are presented in Appendix B.

Parameter	Description	Prior	Posterior			
			f_{gas} HSC-XXL	f_{gas} eROSITA	kSZ	Joint kSZ and eROSITA f_{gas}
$\log_{10} \frac{M_c}{M_\odot h^{-1}}$	The characteristic mass scale at which the slope of the gas profile becomes shallower (equation 7).	U[11.0, 15.0]	$12.8^{+0.6}_{-0.8}$	$13.3^{+0.8}_{-0.8}$	$13.8^{+0.6}_{-0.5}$	$13.6^{+0.2}_{-0.2}$
θ_{ej}	Specifies the characteristic radius of gas ejection: $r_{\text{ej}} = \theta_{\text{ej}} R_{200}$ (equation 6).	U[2.0, 8.0]	$5.0^{+2.0}_{-2.0}$	$5.0^{+2.0}_{-2.0}$	$6.0^{+1.0}_{-1.0}$	$6.0^{+1.0}_{-1.0}$
μ	Defines how fast the slope of the gas profile becomes shallower towards small halo masses (equation 7).	U[0.0, 2.0]	$0.5^{+0.6}_{-0.3}$	$0.5^{+0.3}_{-0.2}$	$0.4^{+0.6}_{-0.3}$	$0.9^{+0.2}_{-0.1}$
γ	Exponent in the gas profile parametrization (equation 6)	U[1.0, 4.0]	$3.0^{+1.0}_{-1.0}$	$2.6^{+0.9}_{-1.0}$	$2.0^{+1.0}_{-1.0}$	$2.0^{+1.0}_{-1.0}$
δ	Exponent in the gas profile parametrization (equation 6)	U[5.0, 11.0]	$8.0^{+2.0}_{-2.0}$	$8.0^{+2.0}_{-2.0}$	$7.0^{+2.0}_{-2.0}$	$8.0^{+2.0}_{-2.0}$
η	Specifies the total stellar fraction within a halo (equation 8)	Fixed: 0.1				
η_δ	Specifies the stellar fraction of the central galaxy: $\eta_\delta = \eta_{\text{cga}} - \eta$ (equation 8)	Fixed: 0.2				

**Figure 1.** The impact of the baryonification model parameters on the suppression of the matter power spectrum relative to a dark matter universe, $P(k)/P_{\text{DM only}}(k)$ (top), the stacked kSZ effect profile as a function of angular radius for a $\log_{10}[M_{500}/M_\odot h^{-1}] = 13.1$ halo at $z = 0.3$ (middle), and the hot gas mass fraction within R_{500} as a function of halo mass (bottom). Each panel varies one baryonification parameter, within the prior bounds (Table 1). For the leftmost column, M_c is reported in units of $M_\odot h^{-1}$.

along the line-of-sight to yield the optical depth

$$\tau_{\text{gal}}(\theta) = 2\sigma_T \int n_e(\sqrt{l^2 + d_A(z)^2\theta^2}) dl, \quad (11)$$

where d_A is the angular diameter distance. To mirror the observations, we convolve $\tau_{\text{gal}}(\theta)$ with a Gaussian beam and employ CAP filtering. For the DESI samples, the CMB temperature map is convolved with a Gaussian beam of 1.6 arcmin full width at half-maximum (FWHM) prior to stacking (B. Ried Guachalla et

al. 2025). For the SDSS samples, the 90 and 150 GHz beams are approximately Gaussian with FWHM of 2.1 arcmin and 1.3 arcmin, respectively (E. Schaan et al. 2021). The amplitude of the kSZ effect profile is determined by the standard deviation of the line-of-sight gas velocities (equation 3). We therefore scale the model kSZ profiles by the reported standard deviation of the galaxy peculiar velocities v_p^{rms}/r_v (E. Schaan et al. 2021; B. Ried Guachalla et al. 2025); in Appendix D we find that v_p^{rms}/r_v is in agreement with the selection of FLAMINGO galaxies that best fits the measured GGL for each kSZ sample. By multiplying the kSZ profiles by v_p^{rms}/r_v , we assume that the standard deviation of the line-of-sight gas velocities is independent of angular separation from the galaxies θ_d . However, in Appendix D we demonstrate that this approximation is only valid for small angular separations. Our kSZ fits are therefore limited to $\theta_d < 2.5'$.

The adoption of conservative scale cuts ($\theta_d < 2.5'$) limits the radial information from the kSZ effect profiles. For the 150 GHz LOWZ/CMASS measurements and the DESI measurements, the scale cut restricts our modelling to radii less than $2\times$ the beam size. For the 90 GHz LOWZ/CMASS measurements, we only keep scales up to the beam size. Because the kSZ measurements are cumulative profiles and the outer radial bins are highly correlated, the signal is dominated by the innermost radial bins, even without scale cuts. While a single kSZ measurement provides limited radial information on its own, the combination of all the SDSS/DESI + ACT measurements together probes the comoving gas distribution from approximately $0.1\text{--}1.0$ comoving Mpc h^{-1} , see Section 5.2.

4 MODEL VALIDATION: INJECTION-RECOVERY

In this work, we infer the suppression of the matter power spectrum relative to a dark matter-only simulation by jointly fitting kSZ and X-ray observations with the baryonification model. Previously, S. K. Giri & A. Schneider (2021) demonstrated that the baryonification model successfully predicts the suppression of the matter power spectrum from the mean $f_{\text{gas}}\text{--}M_{500}$ and $f_{\text{star}}\text{--}M_{500}$ relations for the BAHAMAS, OWLS, Illustris, and Horizon simulations. The model was also able to predict the gas and stellar mass fractions from the matter power spectrum. To further validate the model, we use the FLAMINGO simulations to perform a series of injection-recovery tests designed to mirror our kSZ and X-ray samples.

The FLAMINGO suite consists of 16 hydrodynamical simulations of varied resolution, box size, sub-grid modelling, and cosmology (R. Kugel et al. 2023; J. Schaye et al. 2023). We consider the 1 Gpc^3 intermediate resolution simulations ($m_{\text{gas}} = 1.09 \times 10^9 M_\odot$) with the maximum likelihood cosmological parameters of the DES Y3 ‘ $3\times 2\text{pt} + \text{All Ext.}$ ’ flat Λ CDM cosmology (T. M. C. Abbott et al. 2022). The sub-grid physics (stellar and AGN feedback) is calibrated to reproduce the observed $z = 0$ galaxy stellar mass function and the gas mass fractions of groups and clusters from pre-eROSITA X-ray surveys (R. Kugel et al. 2023); the calibrated simulations successfully predict the stellar to halo mass relation, the central black hole–stellar mass relation, the cosmic star formation rate history, and cluster scaling relations (J. Schaye et al. 2023; J. Braspennig et al. 2024). The suite includes variants with stronger (weaker) baryon feedback that were calibrated to gas fraction measurements shifted down (up) by $N\sigma$, where σ is the observational uncertainty on the mean gas fraction relation and $N \in [+2, -2, -4, -8]$. For our tests, we consider the

fiducial feedback (L1_m9) and strongest feedback ($f_{\text{gas}} - 8\sigma$) simulations. Both simulations use thermal AGN feedback following C. M. Booth & J. Schaye (2009); the $f_{\text{gas}} - 8\sigma$ simulation realizes stronger feedback by more powerful but less frequent AGN outbursts.

4.1 Predicting the gas observables from the power suppression

We first assess whether the baryonification framework can predict the properties of haloes from the suppression of the matter power spectrum, $P(k)/P_{\text{DM Only}}(k)$. For the fiducial and strongest feedback FLAMINGO simulations, we fit $P(k)/P_{\text{DM Only}}(k)$ at $z = 0$ and $0.1 < k < 5\text{ h Mpc}^{-1}$. We adopt uniform priors for all seven free parameters and assume 5 per cent uncertainty in $P(k)/P_{\text{DM Only}}(k)$. The parameter posteriors are shown in Appendix C.

The model successfully fits the shape of the power suppression for both simulations (left column of Fig. 2). From only $P(k)/P_{\text{DM Only}}(k)$, the fits accurately predict the baryon content of groups and clusters. In Fig. 2, we compare the gas mass fractions of groups and clusters with the model predictions, finding strong agreement; the model also reproduces the stellar fractions, shown in Appendix C for brevity. In addition to integrated properties (e.g. f_{gas}), the model accurately predicts the radial extent of the gas. For a representative group mass halo ($\log_{10} M_{500}/M_\odot h^{-1} = 13.1$), we compare the gas density profile and the kSZ effect ($z = 0.3$ and 0.75) from the simulations with the model predictions (Fig. 2); the model and simulation are consistent within 1σ .

The baryonification model successfully predicts the kSZ effect profiles at $z > 0$ from the $z = 0$ suppression of the matter power spectrum, even though the model parameters are redshift independent (Section 3). This result is consistent with A. Schneider et al. (2025), where the best-fitting baryonification parameters for the fiducial and strongest feedback FLAMINGO simulations were found to be weakly dependent on redshift to at least $z = 1.5$. For other simulations (e.g. cosmo-OWLS), the best-fitting baryonification parameters vary significantly with redshift (S. K. Giri & A. Schneider 2021). Further investigation of redshift dependent models is key, although we note that the current observational data does not appear to require redshift dependent model parameters (Section 5.1).

4.2 Predicting the power suppression from the gas observables

We infer the power suppression of the FLAMINGO simulations by fitting mock kSZ effect profiles and hot gas fractions with the baryonification framework. The simulated kSZ effect profiles are calculated from the FLAMINGO light-cones following I. G. McCarthy et al. (2025). To reflect the SDSS/DESI + ACT kSZ measurements (E. Schaan et al. 2021; B. Ried Guachalla et al. 2025), we stack the kSZ effect profile for group mass haloes $13.1 < \log_{10} M_{500}/M_\odot h^{-1} < 13.2$ at $z = 0.3$ and 0.75 , using a Gaussian beam of FWHM = 1.6 arcmin and CAP filtering. For the gas mass fraction observables, we calculate $f_{\text{gas}} = M_{\text{gas}}/M_{500}$ from the stacked density profile of $z = 0.3$ clusters: $13.95 < \log_{10} M_{500}/M_\odot h^{-1} < 14.05$. We assume uncertainties of 15 and 5 per cent on the simulated kSZ and gas mass measurements, respectively; these uncertainties are approximately twice the signal-to-noise ratio of the real data.

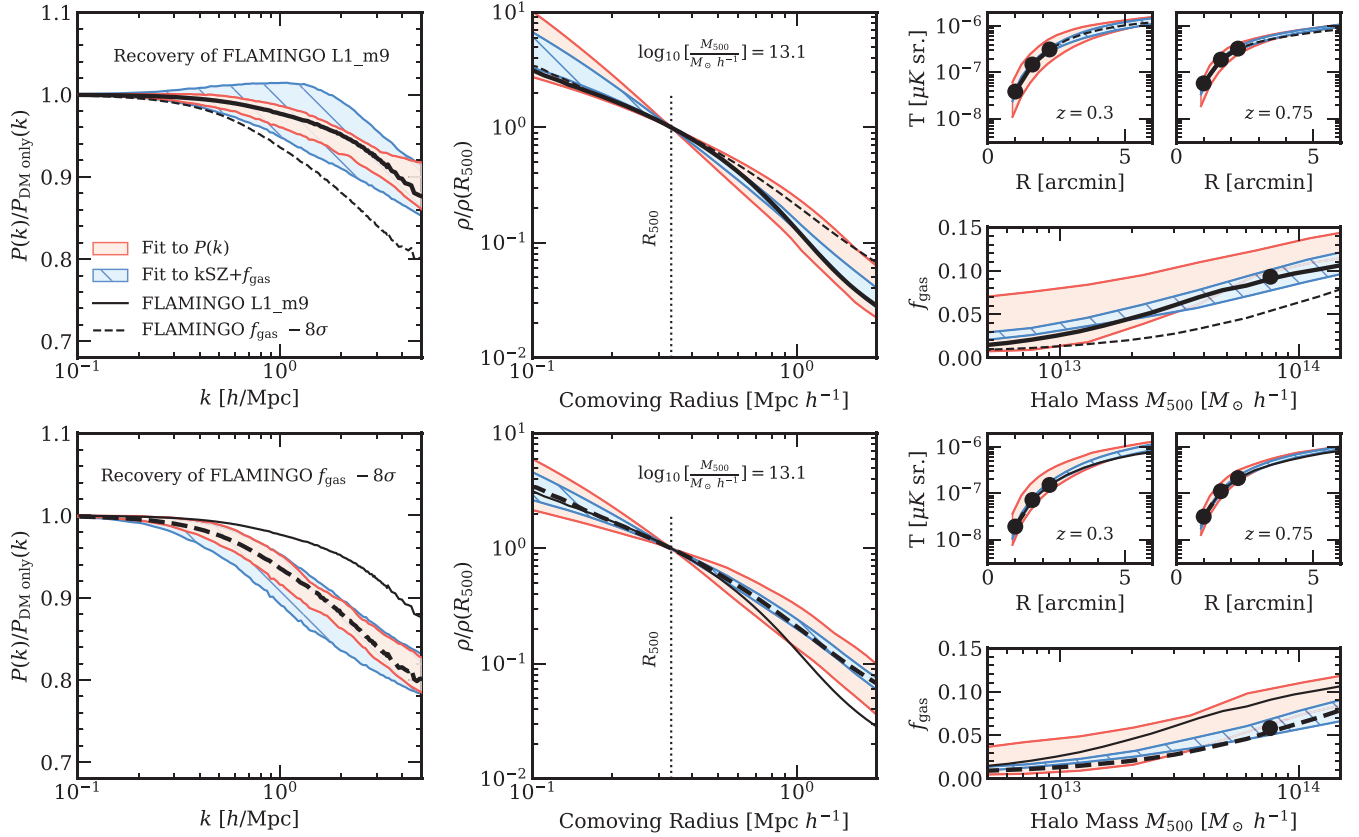


Figure 2. Injection recovery test: the baryonification model successfully predicts the suppression of the matter power spectrum, $P(k)/P_{\text{DM Only}}(k)$, from mock kSZ and gas fraction observations, and vice versa. The fits to mock kSZ and gas fraction observations are shown in blue (hatched), and the fits to $P(k)/P_{\text{DM Only}}(k)$ are shown in pink (no hatch); the shaded bands represent the 16th and 84th percentiles. The results for the fiducial (L1_m9) FLAMINGO simulation (solid black line) are shown in the *top* row, and for the strongest feedback ($f_{\text{gas}} - 8\sigma$) FLAMINGO simulation (dashed black line) in the *bottom* row. For each fit, we show $P(k)/P_{\text{DM Only}}(k)$ (*left*), the normalized hot gas radial density profile for a group mass halo (*centre*), the kSZ signal for the same representative halo mass at $z = 0.3$ and 0.75 (*upper right*), and the hot gas mass fraction as a function of halo mass at $z = 0$ (*lower right*). The mock kSZ and gas fraction observations are shown as black circles, with uncertainties of 15 per cent and 5 per cent, respectively; the uncertainties are smaller than the markers.

For each simulation, we fit the mock measurements with the baryonification model. Mirroring our analysis of the real data, we do not include stellar fractions in our fiducial simulation test. We demonstrate successful recovery of the power suppression from joint $f_{\text{gas}} + f_{\text{star}} + \text{kSZ}$ fits in Appendix C. The joint kSZ and gas fraction fits are presented in Fig. 2. For both simulations, the fit successfully describes the mock observables and accurately predicts the power suppression (within 1σ). The posteriors of the fits are included in Appendix C.

5 RESULTS: JOINT KSZ AND X-RAY FITS

We constrain the matter power spectrum from kSZ and X-ray observations of the gas distribution (Section 2): five stacked SDSS/DESI + ACT kSZ effect profiles of group mass haloes at $0.2 < z < 0.8$ (E. Schaan et al. 2021; B. Ried Guachalla et al. 2025) and X-ray gas mass measurements of clusters from eROSITA ($z \approx 0.1$; E. Bulbul et al. 2024) and HSC-XXL ($z \approx 0.3$; D. Akino et al. 2022). The mean halo mass of each sample is characterized with weak lensing: J. Siegel et al. (2025) for the kSZ and eROSITA samples, and K. Umetsu et al. (2020) for HSC-XXL.

The data are fit with the baryonification model, using wide top hat priors for the five gas parameters (M_c , μ , θ_{ej} , δ , γ). The poste-

rior probability distribution is sampled with EMCEE (D. Foreman-Mackey et al. 2013). We account for several sources of uncertainty in our analysis:

(i) Mean halo mass: for the kSZ and eROSITA samples, we adopt Gaussian priors on the halo mass, with the centres and standard deviations set by the GGL measurements; for the HSC-XXL data, halo mass uncertainties were propagated into the gas mass fractions through the Bayesian modelling of D. Akino et al. (2022).

(ii) X-ray gas mass: the statistical uncertainty on the mean gas mass of each eROSITA bin is < 1 per cent, however, we adopt a conservative 10 per cent uncertainty to reflect potential systematics (e.g. the 15 per cent flux offset between eROSITA and *Chandra* on common South Pole Telescope (SPT) sources, which approximately corresponds to 7 per cent in gas mass, E. Bulbul et al. 2024).

(iii) kSZ effect profiles: for the kSZ effect profiles, we consider the measurements' full covariance matrices. The amplitude of the kSZ effect is proportional to the RMS of the line-of-sight peculiar velocities, for which B. Hadzhiyska et al. (2024) report < 5 per cent uncertainty; we assume a conservative uncertainty of 10 per cent.

5.1 Consistency of the kSZ and X-ray data

First, we consider the three data sets independently, to assess their consistency and the feasibility of a joint fit: (i) SDSS/DESI + ACT kSZ effect profiles, (ii) eROSITA gas mass fractions, and (iii) HSC-XXL gas mass fractions. The fits are presented alongside the data in Fig. 3. The posteriors of each fit are reported in Table 1 and shown in Fig. B1.

The kSZ effect profiles and the eROSITA gas mass fractions favour similar feedback strengths, consistent with previous findings (M. Kovač et al. 2025; J. Siegel et al. 2025). The posteriors of the kSZ and eROSITA fits are consistent at the 1σ level for all parameters, allowing their joint analysis. Because the kSZ-only and eROSITA-only fits probe unique and relatively narrow ranges of halo mass, their predictions for the gas mass fraction relation should be interpreted with caution (Fig. 4); the kSZ-only fit is prior dominated at cluster masses, while the eROSITA-only fit is prior dominated at group masses. The joint fit to the kSZ and eROSITA data is presented in Fig. 3 and Table 1. Across group and cluster masses ($13 < \log_{10} \frac{M_{500}}{M_{\odot} h^{-1}} < 14$) and at $0 < z < 1$, the model describes the data well: reduced $\chi^2 = 1.2$.¹

The HSC-XXL X-ray measurements imply relatively weaker gas expulsion than the kSZ and eROSITA measurements; in particular, the kSZ and HSC-XXL fits differ at the 2σ level for M_c – the halo mass below which the gas density profile becomes shallower (equation 7). The baryonification model gives a poor joint fit to the kSZ and HSC-XXL data: reduced $\chi^2 = 2.5$.² The joint model is presented against the data in Fig. B2. Motivated by the tension between the CMASS kSZ measurement and the pre-eROSITA X-ray samples (L. Bigwood et al. 2024), previous studies proposed that the apparent discrepancy could result from the different radial scales, mean halo masses, and redshifts of the samples (L. Bigwood et al. 2024; L. Lucie-Smith et al. 2025). However, the SDSS LOWZ and DESI BGS kSZ measurements favour more gas expulsion than the lower mass bin of HSC-XXL, despite the samples having similar mean halo masses and redshifts (Fig. 3); at this mass ($\log_{10} M_{500}/M_{\odot} h^{-1} \approx 13.3$) and redshift ($z \approx 0.3$), the kSZ measurements probe the same radii as the X-ray measurements ($< R_{500}$). The disagreement between the kSZ measurements and the HSC-XXL scaling relation could stem from unaccounted for systematics in the X-ray or kSZ data (see Section 6.1). Simulation studies of the X-ray and kSZ measurements are warranted to investigate observational and modelling systematics.

The current X-ray and kSZ data do not require redshift dependent model parameters. The posterior constraints from the lower redshift kSZ samples (LOWZ and BGS, $z \approx 0.3$) are consistent with the higher redshift measurements (CMASS and LRG, $z \approx 0.5 - 0.8$), see Fig. B1. As discussed above, the model also successfully fits the eROSITA gas mass fractions ($z \approx 0.1$) jointly with the kSZ data ($z \approx 0.3 - 0.8$). While the kSZ data and the HSC-XXL model appear discrepant, it is difficult to resolve this difference with redshift evolution alone, because the BGS and LOWZ kSZ data probe the same mass, redshift, and radial scale as the HSC-XXL sample.

¹We also calculate the reduced χ^2 using the effective number of parameters: $p_D = -2(\log p(\text{data} | \theta)) + 2 \log p(\text{data} | \langle \theta \rangle)$, where $p(\text{data} | \theta)$ is the posterior probability of the parameters θ and the averages are over the MCMC posterior samples (D. J. Spiegelhalter et al. 2002). For the joint kSZ and eROSITA fit, we find $p_D = 10$ and $\chi^2/p_D = 0.9$.

²For the joint kSZ and HSC-XXL fit, $p_D = 10$ and $\chi^2/p_D = 2.1$.

Encouraged by the consistency of the data in analytic modelling and simulation comparisons, we primarily consider the joint kSZ and eROSITA model. However, we also investigate the HSC-XXL-only fit to reflect the uncertain state of the X-ray measurements.

5.2 Gas properties of groups and clusters

The kSZ and X-ray measurements probe a wide range of redshifts, halo masses, and radii: the kSZ measurements probe the gas distribution out to several R_{500} of group mass haloes at $0.3 < z < 1.0$, and the X-ray measurements are most informative for the inner regions ($< R_{500}$) of low redshift clusters ($z < 0.3$). The range of radii probed by each measurement is highlighted in Fig. 4. Together, the measurements probe all radii between 0 and 1 comoving Mpc h^{-1} .

In Fig. 4, we present the model constraints on the gas properties of groups and clusters: the radial density profile of a representative group mass halo at $z = 0$ and the hot gas mass fraction scaling relation. We show the results from fitting the kSZ, eROSITA, and HSC-XXL data separately, as well as the joint kSZ and eROSITA X-ray fit. As discussed in Section 5.1, the feedback constraints from the kSZ and eROSITA data are broadly consistent, but the HSC-XXL X-ray data favour weaker gas expulsion. It is difficult to quantitatively compare the gas property constraints from the separate kSZ and X-ray fits, because the kSZ-only fit is prior dominated at cluster masses, while the X-ray fits are prior dominated at group masses. The consistency of the independent fits is best ascertained from their posteriors and the quality of a joint fit.

The joint kSZ and eROSITA fit is highly constraining and yields precise predictions for the gas properties of groups and clusters, highlighting the benefit of constraining the gas distribution across a wide range of halo mass and redshift. In Section 6.3, we compare the model fits with recent hydrodynamical simulations.

5.3 Suppression of the matter power spectrum

With the BCEMU emulator (S. K. Giri & A. Schneider 2021), we map between the density profile parameters ($M_c, \mu, \theta_{ej}, \delta, \gamma, \eta, \eta_\delta$) and the suppression of the matter power spectrum. The posteriors on $P(k)/P_{DM \text{ Only}}(k)$ from the independent kSZ, eROSITA, and HSC-XXL fits are presented in Fig. 4, as well as our joint kSZ and eROSITA model.

Each gas observable favours suppression of the matter power spectrum relative to a dark matter-only simulation at $k > 1 h \text{ Mpc}^{-1}$. The $P(k)/P_{DM \text{ Only}}(k)$ constraints from fitting the kSZ and eROSITA X-ray data separately are statistically consistent with each other, and both are consistent with the joint fit at the 1σ level (Fig. 4). The posterior on $P(k)/P_{DM \text{ Only}}(k)$ is significantly narrowed by jointly fitting the kSZ and X-ray measurements. The model favours strong suppression of the matter power spectrum relative to a dark matter-only simulation: 10 ± 2 per cent at $k = 1 h \text{ Mpc}^{-1}$. Compared to the kSZ and eROSITA data, the HSC-XXL scaling relation implies weaker suppression. We compare our $P(k)/P_{DM \text{ Only}}(k)$ constraint with previous measurements and simulation predictions in Sections 6.2 and 6.3, respectively.

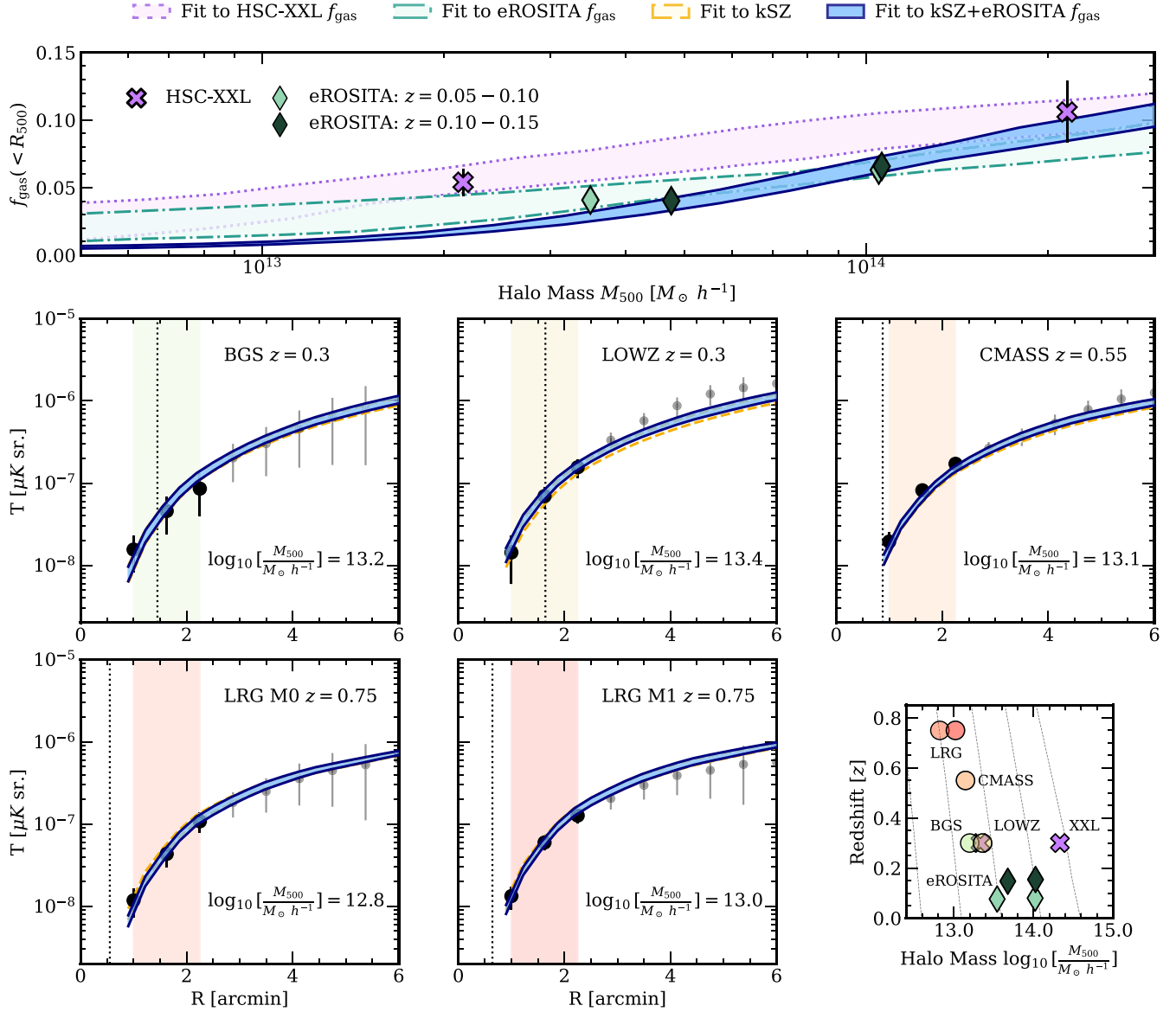


Figure 3. The joint fit to the kSZ and eROSITA X-ray measurements (solid blue), alongside fits to the kSZ (dashed yellow), eROSITA (dot-dashed green), and HSC-XXL (dotted purple) data separately. The top row compares the X-ray gas mass fraction measurements with the X-ray-only fits, and the lower two rows compare the kSZ effect profiles with the kSZ-only fit; the joint fit is presented in all panels. Because the kSZ only fit (dashed yellow) is not informed by the gas mass measurements, it is omitted from the top panel for clarity; the gas mass fraction relation inferred from the kSZ alone is shown in Fig. 4. The shaded bands represent the 16th and 84th percentiles of the model fits. For the kSZ measurements, we restrict our fits to the innermost data points (<2.5 arcmin), as indicated by the vertical shaded bars; at these scales the data are most constraining and least impacted by uncertain modelling (Appendix D). For each kSZ observation, we demarcate R_{500} as a vertical dotted line. The lower right panel presents the mean halo mass and redshift of each observable. The dotted lines show the mean growth histories of haloes, binned by their redshift zero mass.

6 DISCUSSION

6.1 Uncertainties in the X-ray data

By probing the amount of gas depletion within R_{500} of groups and clusters, X-ray gas mass measurements are powerful probes of baryon feedback. In this work, we consider X-ray gas mass measurements from the eROSITA all-sky survey (E. Bulbul et al. 2024) and the HSC-XXL sample (D. Eckert et al. 2016; M. Pierre et al. 2016; K. Umetsu et al. 2020; D. Akino et al. 2022). The eROSITA observations suggest that groups and clusters are on average more gas depleted than indicated by the HSC-XXL scaling relation

(D. Akino et al. 2022). The average eROSITA gas mass fractions are also lower than those found by R. Kugel et al. (2023) from a collection of pre-eROSITA samples (without selection effect corrections): A. Vikhlinin et al. (2006); B. J. Maughan et al. (2008); J. Rasmussen & T. J. Ponman (2009); M. Sun et al. (2009); G. W. Pratt et al. (2010); Y.-T. Lin et al. (2012); A. H. Gonzalez et al. (2013); T. F. Laganá et al. (2013); A. J. R. Sanderson et al. (2013); H. Hoekstra et al. (2015); L. Lovisari et al. (2015); R. J. Pearson et al. (2017); S. L. Mulroy et al. (2019); L. Lovisari et al. (2020). This shift to lower mean gas mass fractions in the eROSITA data relative to pre-eROSITA samples was noted by several previous

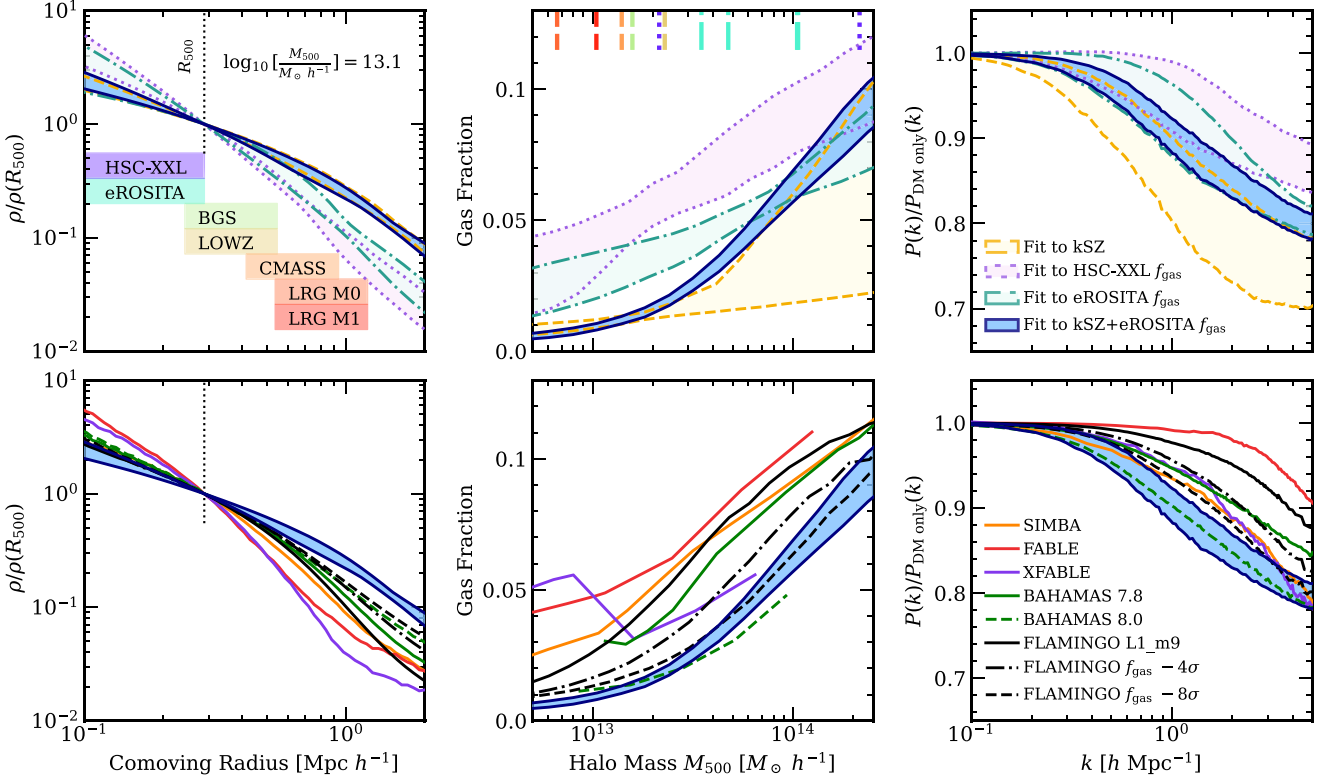


Figure 4. Constraints from SDSS/DESI +ACT kSZ effect profiles and X-ray gas fractions on the radial density profile of a group mass halo (*left*), the hot gas mass fraction as a function of halo mass (*centre*), and the suppression of the total matter power spectrum (*right*). *Top*: the results of the joint kSZ and eROSITA X-ray fit (solid blue), alongside fits to the kSZ (dashed yellow), eROSITA (dot-dashed green), and HSC-XXL (dotted purple) data separately. We note that the kSZ-only fit is prior dominated at cluster masses, while the X-ray fits are prior dominated at group masses. The shaded bands correspond to the 16th and 84th percentiles. In the leftmost panel, the range of comoving radii probed by each observation is indicated by the horizontal shaded bars. In the centre panel, the observations’ mean halo masses are shown as vertical lines (dashed for kSZ, dot-dashed for eROSITA, and dotted for HSC-XXL). *Bottom*: the joint kSZ and eROSITA fit alongside a selection of recent hydrodynamical simulations: BAHAMAS (I. G. McCarthy et al. 2017), SIMBA (R. Davé et al. 2019), FLAMINGO (J. Schaye et al. 2023), and FABLE/XFABLE (N. A. Henden et al. 2018; L. Bigwood et al. 2025a).

studies (A. Dev et al. 2024; P. Popesso et al. 2024a; M. Kovač et al. 2025; J. Siegel et al. 2025).

Selection effects are a potential explanation for the apparent discrepancy between the eROSITA measurements and the earlier samples (e.g. R. Seppi et al. 2022, 2025; N. Clerc et al. 2024; A. Dev et al. 2024; I. Marini et al. 2024; P. Popesso et al. 2024b). X-ray luminosity is proportional to density and gas mass (along with a temperature and metallicity dependence), causing X-ray selected samples to be biased to concentrated gas-rich haloes (S. Andreon et al. 2017; R. Seppi et al. 2022, 2025; N. Clerc et al. 2024; I. Marini et al. 2024). The lower mean gas mass fractions found by eROSITA could therefore reflect its greater completeness compared to previous X-ray selected samples (e.g. ROSAT; J. Truemper 1982; W. Voges et al. 1999). However, the HSC-XXL scaling relation analysis accounts for selection effects but still favours higher average gas mass fractions than reported by eROSITA. D. Akino et al. (2022) model the X-ray selection effect by truncating the parent distribution with a minimum X-ray luminosity threshold. The disagreement between the HSC-XXL scaling relation and the recent eROSITA measurements suggests that selection effects are not the only factor behind the discrepancy and/or the minimum luminosity threshold correction is insufficient (e.g. S. Andreon et al. 2017).

The eROSITA sample is also shaped by selection effects, with a significant drop in completeness for group mass haloes and below (e.g. I. Marini et al. 2024). To bypass X-ray selection, P. Popesso et al. (2024a) used eROSITA images to measure the gas mass fractions for stacks of optically selected groups and clusters (A. S. G. Robotham et al. 2011; S. P. Driver et al. 2022). These measurements mitigate the impact of X-ray selection but are subject to optical group finder contamination (>30 per cent; R. Seppi et al. 2025) and halo mass uncertainties. R. J. Pearson et al. (2017) similarly studied a sample of 10 groups from the GAMA friends-of-friends catalogue with *Chandra*. The mean gas mass fractions of our eROSITA cluster bins, which are limited to $z < 0.2$ to increase completeness, are consistent with these optically selected samples. Stronger feedback than previously assumed is also favoured from a comparison of the entropy of eROSITA detected groups with cosmological hydrodynamic simulations (MillenniumTNG, Magneticum, OWLS), including the effects of the eROSITA selection function (Y. E. Bahar et al. 2024). Studying the impact of the eROSITA selection function on the sample of gas mass fraction measurements is critical to understanding the extent of baryon feedback (Ding et al. in preparation).

The apparent discrepancy in mean gas mass fractions could stem from biased halo mass estimation. Previous studies often

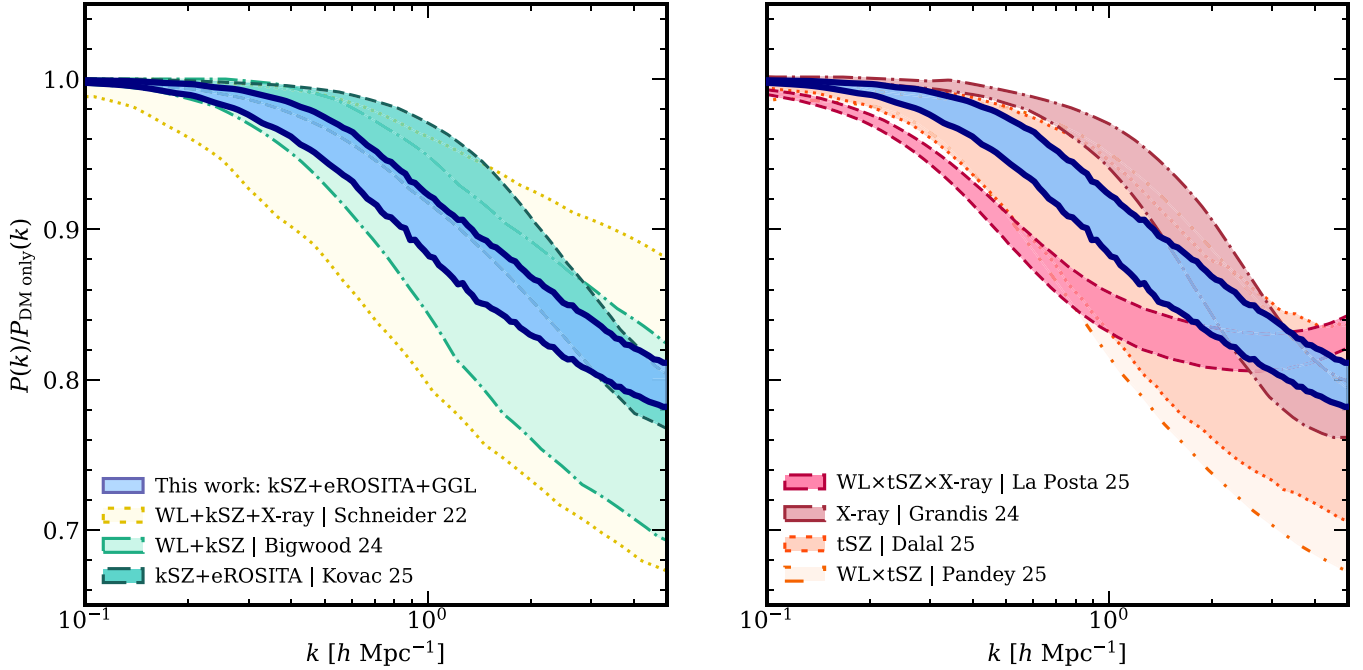


Figure 5. The constraints on the suppression of the matter power spectrum $P(k)/P_{\text{DM Only}}(k)$ from our joint fit to kSZ effect profiles and eROSITA X-ray gas mass fractions (solid blue), compared to constraints from the literature. *Left:* constraints derived (in part) from kSZ effect measurements (A. Schneider et al. 2022; L. Bigwood et al. 2024; M. Kovač et al. 2025). *Right:* constraints from pre-eROSITA X-ray and/or tSZ measurements (S. Grandis et al. 2024; N. Dalal et al. 2025; A. La Posta et al. 2025; S. Pandey et al. 2025a).

assumed hydrostatic equilibrium to estimate total masses, and such estimates can be biased by approximately 30 per cent due to non-thermal pressure support and/or deviations from hydrostatic equilibrium (H. Hoekstra et al. 2015; D. Eckert et al. 2016; R. Kugel et al. 2023; M. Muñoz-Echeverría et al. 2024; J. Braspennig et al. 2025). However, both the HSC-XXL scaling relation and the bins of eROSITA clusters that we consider include weak lensing halo mass constraints, from K. Umetsu et al. (2020) and J. Siegel et al. (2025), respectively.

Systematics in X-ray modelling also warrant further investigation. For a sample of SPT clusters, eROSITA derived luminosities are approximately 15 per cent lower than previously inferred with *Chandra* (E. Bulbul et al. 2024). Because X-ray luminosity is proportional to the gas density squared (at fixed temperature and metallicity), this flux offset corresponds to a 7 per cent skew in the gas mass. We include this source of uncertainty in our modelling (Section 5).

6.2 Landscape of feedback constraints

We present a selection of $P(k)/P_{\text{DM Only}}(k)$ measurements, alongside our joint kSZ and eROSITA result in Fig. 5 (A. Schneider et al. 2022; L. Bigwood et al. 2024; S. Grandis et al. 2024; N. Dalal et al. 2025; M. Kovač et al. 2025; A. La Posta et al. 2025; S. Pandey et al. 2025a). For brevity, we limit our comparison to studies that considered gas observables (e.g. X-ray and kSZ); hydrodynamical simulation predictions are shown in Fig. 4 and discussed in Section 6.3. The joint kSZ and eROSITA X-ray $P(k)/P_{\text{DM Only}}(k)$ constraint is consistent with the collection of previous studies at approximately the 1σ level (with the exception of A. La Posta et al. 2025, discussed below). The $P(k)/P_{\text{DM Only}}(k)$ constraints derived solely from the pre-eROSITA gas mass fractions (our HSC-XXL fit and S. Grandis et al. 2024) favour slightly weaker power sup-

pression than the other literature constraints and our joint kSZ and eROSITA model; however, the pre-eROSITA constraints are still broadly consistent with the other $P(k)/P_{\text{DM Only}}(k)$ posteriors.

The consistency of the recovered $P(k)/P_{\text{DM Only}}(k)$ between these studies is particularly encouraging because each observational probe is sensitive to different redshifts and halo masses. Several studies (A. Schneider et al. 2022; L. Bigwood et al. 2024; M. Kovač et al. 2025) analysed the CMASS kSZ effect profile ($z \approx 0.55$ and $\log_{10} M_{500}/M_{\odot} \approx 13$; E. Schaan et al. 2021), along with a selection of X-ray gas fraction measurements between $13 < \log_{10} M_{500}/M_{\odot} < 15$ at $z \lesssim 0.3$, including A. Vikhlinin et al. (2009), A. H. Gonzalez et al. (2013), A. J. R. Sanderson et al. (2013), L. Lovisari et al. (2015), A. V. Kravtsov et al. (2018), D. Akino et al. (2022), and P. Popesso et al. (2024a); the pre-eROSITA cluster hot gas mass fractions and radial density profiles analysed by S. Grandis et al. (2024) cover a similar mass and redshift range. The cross correlation of the tSZ effect with cosmic shear is also sensitive to $M_{500} \approx 10^{14} M_{\odot}$ haloes but over a wider redshift range ($z < 1$; A. Hojjati et al. 2015; S. Pandey et al. 2022, 2025a). The sample of tSZ selected clusters in N. Dalal et al. (2025) have a mean redshift of $z = 0.55$ and a mean halo mass of $M_{500} = 3 \times 10^{14} M_{\odot}$. In this work, we jointly analyse a selection of GGL calibrated kSZ and X-ray samples between group and cluster masses at $0 < z < 1$; the stacked measurements of the kSZ effect from DESI + ACT are vital for probing $z > 0.5$ (B. Ried Guachalla et al. 2025). By spanning a wide range of halo mass and redshift, joint modelling of kSZ and X-ray measurements significantly improves the constraining power of the model fit (Figs 4 and B1). Although our model considers the widest range of halo mass and redshift thus far, the inclusion of additional observables, particularly the unique mass and redshift space probed by the tSZ samples, is critical to building a complete picture of baryon feedback.

A quantitative assessment of the consistency of our results with those in Fig. 5 is limited, because different models have been used to constrain the suppression of the matter power spectrum. In this work, we adopt the BCEMU emulator (S. K. Giri & A. Schneider 2021); several previous studies also considered BCEMU (A. Schneider et al. 2022; L. Bigwood et al. 2024; S. Grandis et al. 2024) or similar BACCO emulators (G. Aricò et al. 2023; S. Grandis et al. 2024). M. Kovač et al. (2025) utilized the next generation baryonification model recently introduced by A. Schneider et al. (2025); the improved baryonification model includes updated formulations of the density profiles and treatment of the dark matter, gas, and stellar components as independent fields (an emulator is not yet publicly available). Other results use the halo model approach (S. N. B. Debackere et al. 2020; N. Dalal et al. 2025; A. La Posta et al. 2025; S. Pandey et al. 2025a). The power suppression constraints from the baryonification and halo model frameworks are largely consistent. The $P(k)/P_{\text{DM Only}}(k)$ posterior from A. La Posta et al. (2025) marginally deviates from the other constraints, potentially reflecting the relatively lower flexibility of their assumed density profiles (e.g. fixed ejection radius of unbound gas). As observational probes of baryon feedback become more precise, modelling systematics are increasingly significant. Future work comparing methods of constraining the suppression of the matter power spectrum and addressing modelling challenges (e.g. the effect of satellites and miscentering on the kSZ effect profile, Appendix D) is warranted.

6.3 Implications for feedback models

Cosmological hydrodynamical simulations reproduce a variety of galaxy and cluster observables, including the stellar-to-halo mass relation and cluster scaling relations (e.g. I. G. McCarthy et al. 2017; R. Davé et al. 2019; R. Pakmor et al. 2023; J. Schaye et al. 2023, 2025; K. Dolag et al. 2025), however, their predictions for the extent of gas expulsion from groups and clusters and the suppression of the matter power spectrum differ substantially. In Fig. 4, we present the gas mass fractions of groups and clusters and the suppression of the matter power spectrum from a selection of recent simulations: BAHAMAS (I. G. McCarthy et al. 2017), SIMBA (R. Davé et al. 2019), FLAMINGO (J. Schaye et al. 2023), FABLE (N. A. Henden et al. 2018), and XFABLE (L. Bigwood et al. 2025a). At $k = 1 \text{ h Mpc}^{-1}$, the predictions for the suppression of the matter power spectrum differ by >10 per cent.

In modern hydrodynamical simulations, the suppression of the matter power spectrum is primarily regulated by the AGN sub-grid model. SIMBA treats black hole accretion with a two-phase model: torque-limited accretion for cold gas and Bondi accretion for hot gas near the black hole (P. F. Hopkins & E. Quataert 2011; D. Anglés-Alcázar et al. 2017); AGN feedback is implemented with both kinetic and radiative modes. FABLE (Feedback Acting on Baryons in Large-scale Environments) also employs two-mode AGN feedback (following Illustris, D. Sijacki et al. 2015): the quasar-mode (high accretion rates), where the feedback energy is thermally coupled to the surrounding gas, and the radio mode (low accretion rates), where the feedback energy is injected through hot bubbles. XFABLE achieves stronger matter power suppression than FABLE, while remaining in agreement with observed galaxy and cluster properties, by modifying the AGN radio mode sub-grid model (L. Bigwood et al. 2025a): the hot bubbles are injected at 100 kpc/h (compared to $\sim 30 \text{ kpc/h}$ in FABLE), the accretion threshold for the radio mode is raised by $10\times$, only AGNs in massive haloes ($M_{500} \gtrsim 10^{13} M_{\odot}$) enter the radio mode,

and the energy content of the radio bubble is limited to $20\times$ the total energy in the ICM. The feedback models of FABLE and XFABLE were calibrated to match pre-eROSITA gas mass fractions; SIMBA was not calibrated to group and cluster scale properties. The fiducial FLAMINGO and BAHAMAS simulations implement AGN feedback through the radiative heating mechanism of C. M. Booth & J. Schaye (2009). To avoid numerical overcooling (C. Dalla Vecchia & J. Schaye 2012), the feedback energy is stored internally until it can heat at least one gas particle by ΔT_{AGN} ; increasing ΔT_{AGN} results in more powerful but less frequent AGN outbursts. The BAHAMAS suite includes a strong feedback variant with $\log_{10} \Delta T_{\text{AGN}} = 8.0$, compared to the fiducial BAHAMAS choice of $\log_{10} \Delta T_{\text{AGN}} = 7.8$. The FLAMINGO suite also includes variants with stronger (weaker) baryon feedback by calibrating to pre-eROSITA gas fraction measurements shifted down (up) by $N\sigma$, where σ is the observational uncertainty on the mean gas fraction relation and $N \in [+2, -2, -4, -8]$ (R. Kugel et al. 2023). For brevity, we only consider the fiducial intermediate resolution FLAMINGO simulation (L1_m9) and the strongest feedback variant ($f_{\text{gas}} - 8\sigma$). The FLAMINGO suite also includes variants with jet mode AGN feedback (F. Huško et al. 2022), however, these variants were only produced for a limited range of feedback strengths ($N \in [0, -4]$).

Joint modelling of kSZ and eROSITA X-ray data requires significantly more gas depletion within R_{500} than any of the fiducial feedback strength simulations predict. Only the simulation variants with particularly strong feedback, BAHAMAS 8.0 and FLAMINGO $f_{\text{gas}} - 8\sigma$, are consistent with our model. The comparison of hydrodynamic simulations to recent kSZ and eROSITA observations also favours strong feedback simulation variants (B. Hadzhiyska et al. 2025; I. G. McCarthy et al. 2025; B. Ried Guachalla et al. 2025; J. Siegel et al. 2025; L. Bigwood et al. 2025b).

The state of the ICM (e.g. temperature and pressure) is also sensitive to the AGN feedback. J. Braspenning et al. (2024) found that the fiducial FLAMINGO simulation and the more moderate feedback variants (e.g. $f_{\text{gas}} - 4\sigma$) are consistent with the observed cluster scaling relations and the radial profiles of massive clusters from a collection of the pre-eROSITA data. However, the strongest feedback variant ($f_{\text{gas}} - 8\sigma$) deviates from the cluster scaling relations, despite providing the best match to the kSZ measurements of all FLAMINGO variants. Exploring feedback models that can successfully reproduce all these observations simultaneously, including alternate formulations of AGN feedback (L. Bigwood et al. 2025a) or other mechanisms of gas expulsion (e.g. cosmic ray transport; E. Quataert & P. F. Hopkins 2025), is warranted.

6.4 Data-driven priors for weak lensing cosmology

Modelling the impact of baryon feedback on the matter power spectrum is a limiting systematic for weak lensing surveys. Here, we assess how our feedback constraints on the baryonification model parameters improve weak lensing cosmological precision and accuracy. We consider an LSST Year 1-like analysis (The LSST Dark Energy Science Collaboration 2018), comparing results with and without our calibrated model priors from current kSZ and eROSITA data.

To generate mock cosmic shear data, we follow the LSST Dark Energy Science Collaboration Science Requirements Document (The LSST Dark Energy Science Collaboration 2018). We adopt their specifications for source density, redshift binning, redshift distributions, and photometric redshift uncertainties. The data

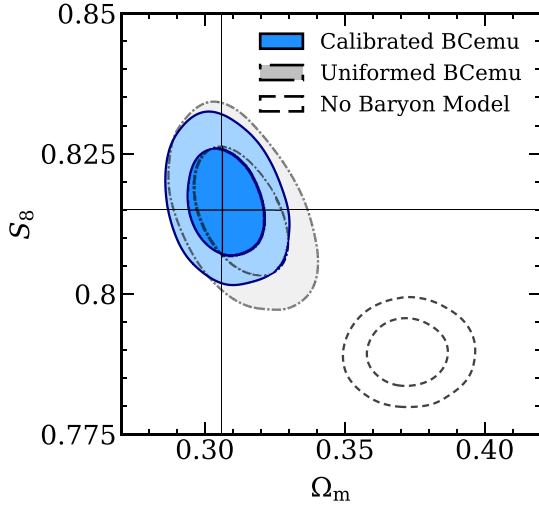


Figure 6. Simulated constraints on the matter density, Ω_m , and the lensing amplitude, S_8 , for an LSST Year 1 cosmic shear analysis (The LSST Dark Energy Science Collaboration 2018), demonstrating the improvement in precision and accuracy afforded by our calibrated model. Without a baryon feedback model, the inferred cosmology is significantly biased (dashed black); this constraint is unphysical but indicative of the available constraining power if feedback was precisely known. Due to its added flexibility, the uniformed baryonification model (dot-dashed black) degrades the constraining power by $2\times$, relative to the inference without a baryon model. Our kSZ and eROSITA calibrated baryonification prior (solid blue) recovers half the precision otherwise lost to the flexible baryon model.

vector is constructed using the COSMOSIS framework (J. Zuntz et al. 2015) as described in C. Preston et al. (2024). The non-linear matter power spectrum is treated with HMCODE (A. J. Mead et al. 2021). We assume the best-fitting baryonification parameters from the joint kSZ and eROSITA fit as the input level of feedback.

In Fig. 6, we report the constraints on Ω_m and S_8 for three different treatments of baryon feedback: (i) no baryon model, (ii) baryonification with uniform wide priors, and (iii) baryonification with kSZ and eROSITA calibrated priors. As expected, the inferred cosmology is significantly biased without a baryon model. Although unphysical, these constraints illustrate the expected cosmological precision if baryon feedback was perfectly known. The uninformed baryonification model recovers the input cosmology, however, the added model flexibility degrades the cosmological constraining power by $2\times$ relative to the inference without a baryon model. The kSZ and eROSITA calibrated baryonification model accurately constrains Ω_m and S_8 and recovers half the precision otherwise lost to the flexible baryon model. With data-driven constraints on baryon feedback, early LSST analyses can robustly exploit small-scale information.

7 CONCLUSIONS

We have presented the most comprehensive multiwavelength constraints to date on how baryonic feedback suppresses the non-linear matter power spectrum, a key uncertainty for cosmic shear cosmology. By jointly analysing SDSS/DESI + ACT kSZ effect profiles (E. Schaan et al. 2021; B. Ried Guachalla et al. 2025) and X-ray gas mass fractions from eROSITA (E. Bulbul et al. 2024) and HSC-XXL (M. Pierre et al. 2016; D. Akino et al. 2022), with weak lensing halo masses (J. Siegel et al. 2025), we

directly probe the distribution of gas in groups and clusters ($13 < \log_{10} \frac{M_{500}}{M_\odot h^{-1}} < 14$) at $0 < z < 1$. Using the baryonification framework (A. Schneider & R. Teyssier 2015; S. K. Giri & A. Schneider 2021), our joint constraints reveal that baryons significantly reshape the matter power spectrum on small scales.

Our main findings are:

(i) The kSZ effect profiles and eROSITA hot gas mass fractions independently and consistently favour strong feedback, implying a 10 ± 2 per cent suppression of the matter power spectrum at $k = 1 h \text{ Mpc}^{-1}$. This suppression exceeds the predictions of the fiducial models from recent hydrodynamical simulation suites, e.g. FLAMINGO and BAHAMAS, which were calibrated to reproduce pre-eROSITA X-ray measurements, including the HSC-XXL sample. We demonstrate the robustness of our results to observational systematics and perform successful injection recovery tests of the model’s ability to map between gas observables and matter power suppression.

(ii) The HSC-XXL X-ray scaling relation favours more moderate feedback than the kSZ and eROSITA data, corresponding to only 5 ± 4 per cent suppression at $k = 1 h \text{ Mpc}^{-1}$. Potential explanations include residual X-ray calibration differences, X-ray selection-function effects, X-ray modelling uncertainties, and/or unaccounted-for systematics in the kSZ velocity reconstruction. Cross-instrument calibration and forward modelling efforts will be critical to understanding this discrepancy. Nevertheless, all data sets consistently support non-zero suppression of the matter power spectrum, reinforcing the conclusion that constraining baryonic feedback is essential to modelling small-scale structure.

(iii) For upcoming surveys, such as LSST, Euclid, and Roman, observationally calibrated feedback models offer a path to unlocking small-scale cosmic shear. With a simulated LSST Year 1 analysis, we show that this framework can allow weak lensing analyses to safely extend to smaller angular scales, reducing the cosmological degradation associated with conservative scale cuts or flexible feedback models.

Understanding baryon feedback is not only an astrophysical problem but also a direct limitation on weak lensing cosmological constraining power. External constraints on the gas distribution are therefore an indispensable ingredient for next-generation analyses. X-ray and kSZ measurements will improve dramatically with upcoming data from eROSITA, Simons Observatory, and DESI (e.g. A. Laguë et al. 2025; B. Ried Guachalla et al. 2025; A. Wayland, D. Alonso & M. Zennaro 2025), requiring greater understanding of systematic uncertainties. Forward modelling studies of X-ray gas mass fractions and kSZ effect profiles will be crucial to understanding observational and modelling systematics. In the near future, additional measurements of the gas distribution will add complementary information to constrain baryon feedback (e.g. N. Dalal et al. 2025; K. Sharma et al. 2025; S. Pandey et al. 2025a). Feedback models that are calibrated with these upcoming multiwavelength observables can realize the small-scale statistical power of cosmic shear.

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DATA AVAILABILITY

The data underlying this article may be shared on reasonable request to the corresponding authors.

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APPENDIX A: SENSITIVITY TO MODELLING CHOICES

In this work, we constrain the suppression of the matter power spectrum, $P(k)/P_{\text{DM Only}}(k)$, by modelling kSZ effect profiles and X-ray gas mass fractions with the baryonification framework (A. Schneider & R. Teyssier 2015). Because stellar fraction measurements are currently unavailable for our eROSITA cluster sample, we set the stellar parameters to $\eta = 0.1$ and $\eta_s = 0.2$ for our fiducial analysis following M. Kovač et al. (2025). We also fix the universal baryon fraction, Ω_b/Ω_m , to the maximum likelihood cosmological parameters of the DES Y3 ‘3× 2pt + All Ext.’ flat Λ CDM cosmology (T. M. C. Abbott et al. 2022). In this appendix, we investigate the sensitivity of our results to these choices.

We repeat the joint kSZ and eROSITA gas mass fraction fit using five different stellar parameter priors: (i) $\eta = 0.1$ and $\eta_s = 0.2$ (fiducial), (ii) $p(\eta) = \mathcal{N}(0.1, 0.05)$ and $p(\eta_s) = \mathcal{N}(0.2, 0.05)$, (iii) $\eta = 0.25$ and $\eta_s = 0.25$ (motivated by S. Grandis et al. 2024), (iv) $p(\eta) = \mathcal{N}(0.25, 0.05)$ and $p(\eta_s) = \mathcal{N}(0.25, 0.05)$, and (v) $p(\eta) = \mathcal{U}(0.05, 0.40)$ and $p(\eta_s) = \mathcal{U}(0.05, 0.40)$. We also repeat the joint kSZ and X-ray fit for two alternate baryon fractions: 10 per cent lower and higher than the DES Y3 ‘3× 2pt + All Ext.’ flat Λ CDM maximum likelihood; assuming our fiducial stellar parameter choice ($\eta = 0.1$ and $\eta_s = 0.2$). The posteriors of each fit are presented in Fig. A1. The different stellar parameter and baryon fraction assumptions impact the posterior constraints below the 1σ level; this is consistent with prior baryonification modelling results (e.g. S. K. Giri & A. Schneider 2021; S. Grandis et al. 2024).

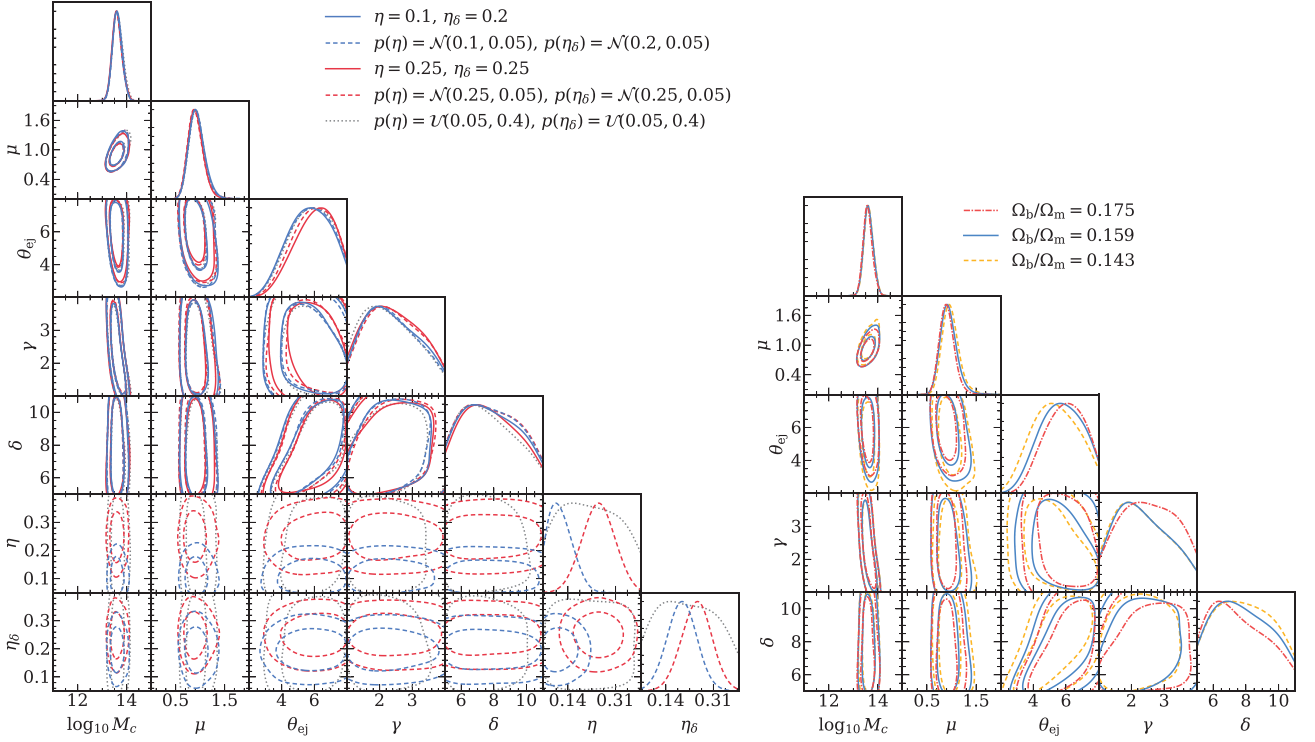


Figure A1. The posterior constraints on the baryonification parameters are weakly sensitive to the assumed stellar parameters (η, η_δ) and the universal baryon fraction (Ω_b/Ω_m). *Left:* the joint eROSITA X-ray and kSZ parameter constraints for four choices of stellar parameter priors. Our fiducial fit assumes $\eta = 0.1$ and $\eta_\delta = 0.2$ (solid blue). The dashed blue contours assume conservative Gaussian priors: $p(\eta) = \mathcal{N}(0.1, 0.05)$ and $p(\eta_\delta) = \mathcal{N}(0.2, 0.05)$. To test the sensitivity of the posteriors to the adopted prior, we also consider $\eta = 0.25$ and $\eta_\delta = 0.25$ (solid red); the dashed contours again correspond to Gaussian priors: $p(\eta) = \mathcal{N}(0.25, 0.05)$ and $p(\eta_\delta) = \mathcal{N}(0.25, 0.05)$. The grey dotted contour presents the posteriors assuming a uniform prior on the stellar parameters. *Right:* the posterior constraints for three choices of Ω_b/Ω_m . We present our fiducial choice in the solid contour (the maximum likelihood of the DES Y3 ‘3 × 2pt + All Ext.’ flat Λ CDM cosmology, T. M. C. Abbott et al. 2022) and show the results for 10 per cent lower and higher Ω_b/Ω_m in dashed and dot-dashed contours, respectively.

APPENDIX B: CONSISTENCY OF THE KSZ AND X-RAY DATA

To constrain the baryonification model, we consider SDSS/DESI + ACT kSZ effect profiles (E. Schaan et al. 2021; B. Ried Guachalla et al. 2025) and X-ray gas mass fraction measurements from the eROSITA (E. Bulbul et al. 2024) and HSC-XXL samples (M. Pierre et al. 2016; D. Akino et al. 2022). In Section 5.1, we compare the posterior constraints from fitting the kSZ, eROSITA, and HSC-XXL data separately. The posteriors of each fit are presented in Fig. B1. Consistent with previous studies, we find a slight tension between the strength of feedback implied by the kSZ effect profiles and pre-eROSITA X-ray gas mass fractions (L. Bigwood et al. 2024; M. Kovač et al. 2025; I. G. McCarthy et al.

2025). The posterior constraints from the kSZ and eROSITA X-ray gas mass fractions are statistically consistent, as are the posterior constraints from kSZ measurements at lower (LOWZ and BGS) and higher (CMASS and LRG) redshifts (bottom panel of Fig. B1).

Although the baryonification model provides an excellent joint fit to the kSZ and eROSITA measurements (Fig. 3), it struggles to simultaneously describe the kSZ and HSC-XXL data. Fig. B2 compares the joint kSZ and HSC-XXL fit with the data. The poor goodness of fit is primarily driven by the lower HSC-XXL mass bin and the BGS and LOWZ kSZ profiles; these measurements probe similar radii, redshift, and halo mass, but appear to require different levels of gas depletion. We discuss possible explanations for this discrepancy in Section 6.1.

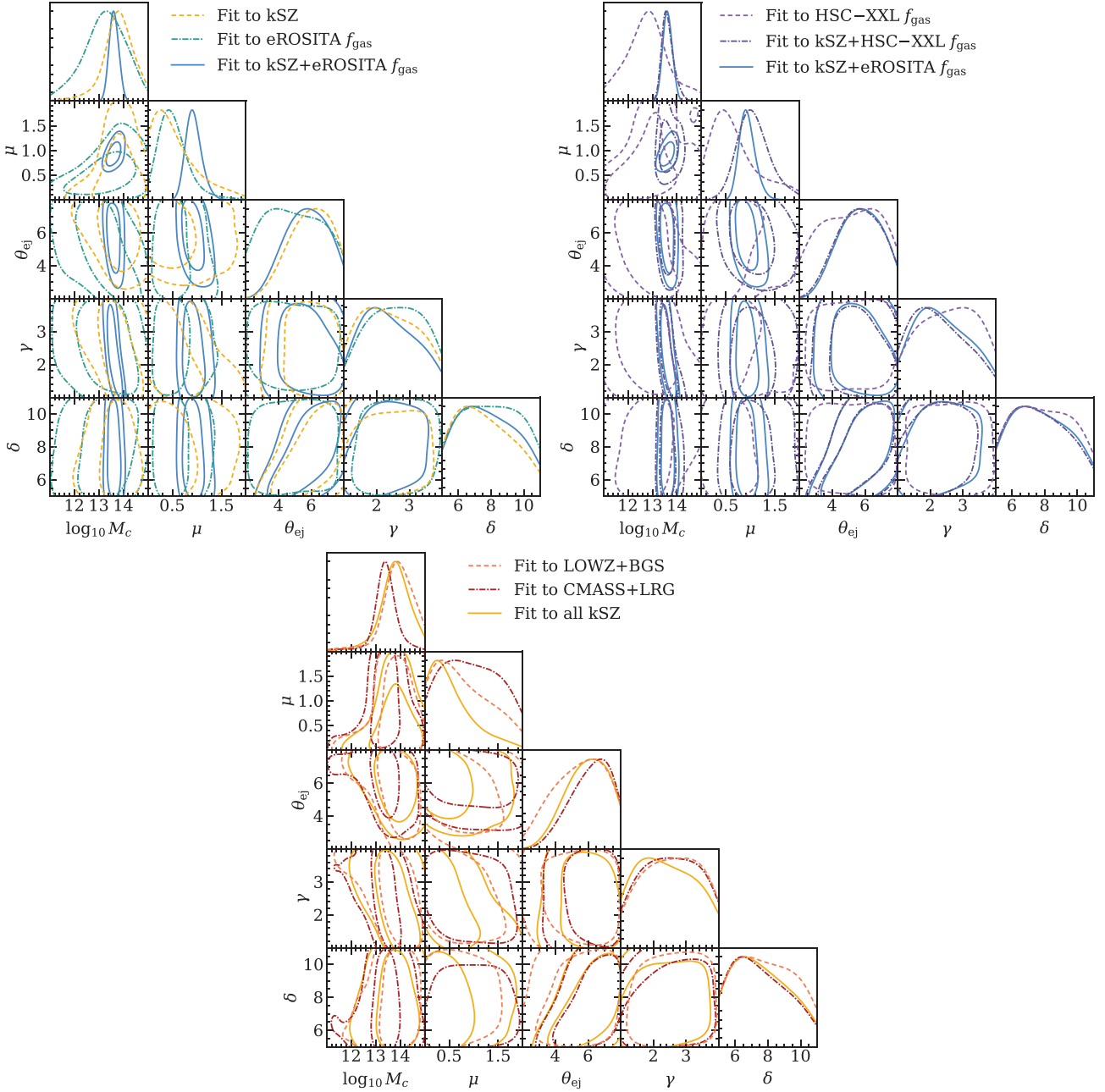


Figure B1. Posteriors on the baryonification parameters from fitting the kSZ and X-ray data. *Upper Left:* posteriors for the joint kSZ and eROSITA fit (solid), alongside the fits to the kSZ and eROSITA data separately (dashed and dot-dashed, respectively). *Upper Right:* posteriors from the HSC-XXL gas mass fractions alone (dashed) and jointly with kSZ (dot-dashed). For comparison, the joint kSZ and eROSITA posteriors are again shown in solid-blue. *Bottom:* posteriors from the combined kSZ fit (solid), alongside fits to the kSZ measurements at lower (LOWZ and BGS) and higher (CMASS and LRG) redshifts, in dashed and dot-dashed contours, respectively.

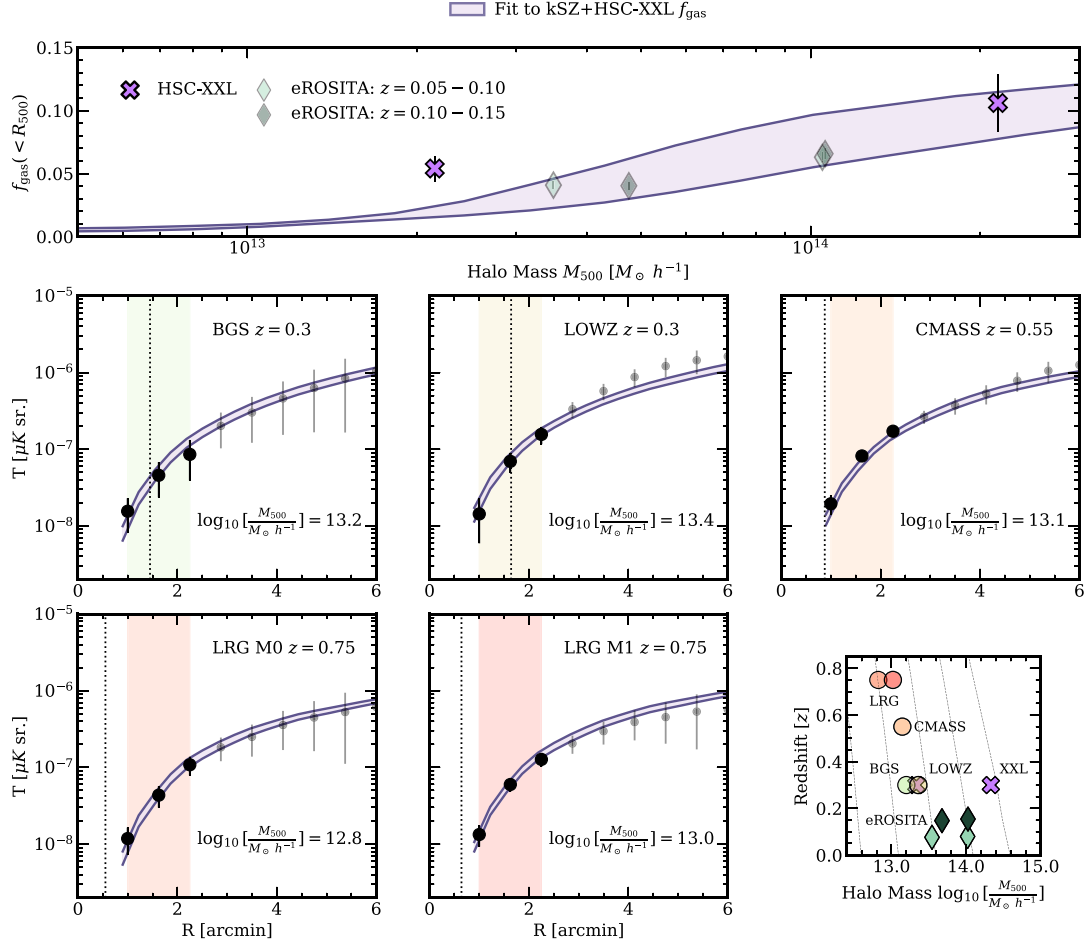


Figure B2. The baryonification model jointly fit to the kSZ and HSC-XXL X-ray measurements (solid purple), alongside the observations. Refer to Fig. 3 for a detailed description.

APPENDIX C: INJECTION RECOVERY

The baryonification framework relates gas observables (e.g. X-ray gas mass fractions) to the suppression of the matter power spectrum (A. Schneider & R. Teyssier 2015; S. K. Giri & A. Schneider 2021; A. Schneider et al. 2025). Using the BAHAMAS, OWLS, Illustris, and Horizon simulations, S. K. Giri & A. Schneider (2021) validated the BCEMU baryonification emulator by accurately predicting the suppression of the matter power spectrum from the gas and stellar mass fractions of simulated groups and clusters and vice versa. In this work, we further validate the framework using the FLAMINGO simulations (see Section 4); for brevity, we consider the fiducial (L1_m9) and strongest ($f_{\text{gas}} - 8\sigma$) feedback variants of the FLAMINGO suite.

The model accurately predicts the gas and stellar content of groups and clusters from $P(k)/P_{\text{DM Only}}(k)$, for the fiducial and strongest feedback FLAMINGO simulations. The framework also successfully predicts $P(k)/P_{\text{DM Only}}(k)$ from group and cluster observables. To reflect our data fits, in Section 4 we considered the stacked kSZ profiles of group mass haloes at $z = 0.3$ and 0.75 and the gas mass fractions of clusters. For completeness, here we consider a joint kSZ, gas mass fraction f_{gas} , and stellar mass fraction f_{star} fit with uniform priors for all 7 baryonification parameters (Fig. C1). Both the kSZ + f_{gas} fit and the kSZ + f_{gas} + f_{star} fit accurately predict the matter power suppression. The posteriors of the $P(k)/P_{\text{DM Only}}(k)$, kSZ + f_{gas} , and kSZ + f_{gas} + f_{star} fits are presented in Fig. C2. The recovered parameters are consistent between all three fits.

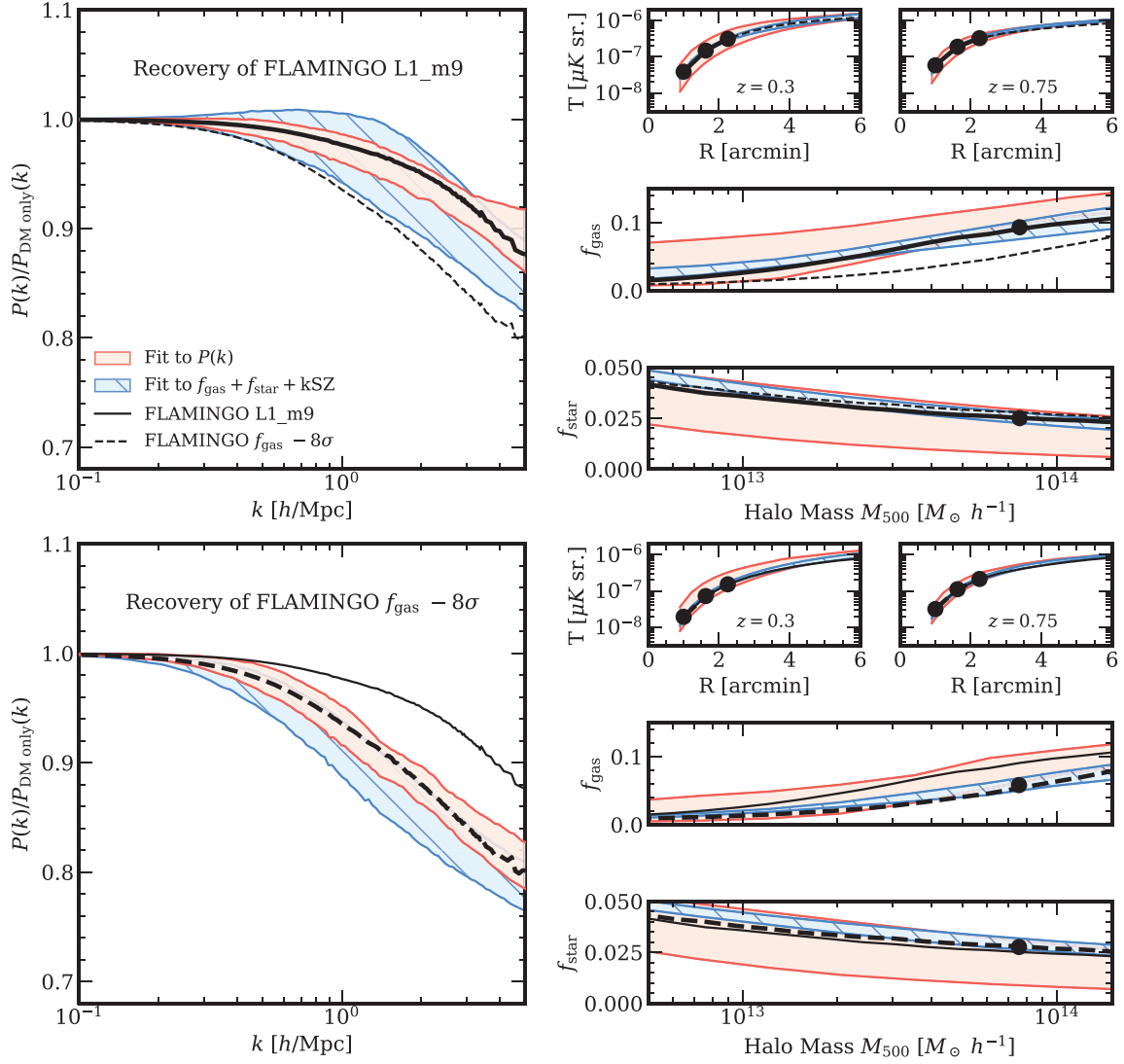


Figure C1. The baryonification model successfully predicts the suppression of the matter power spectrum $P(k)/P_{\text{DM Only}}(k)$ from mock kSZ, gas mass fraction, and stellar mass fraction observations, and vice versa. Refer to Fig. 2 for a detailed description.

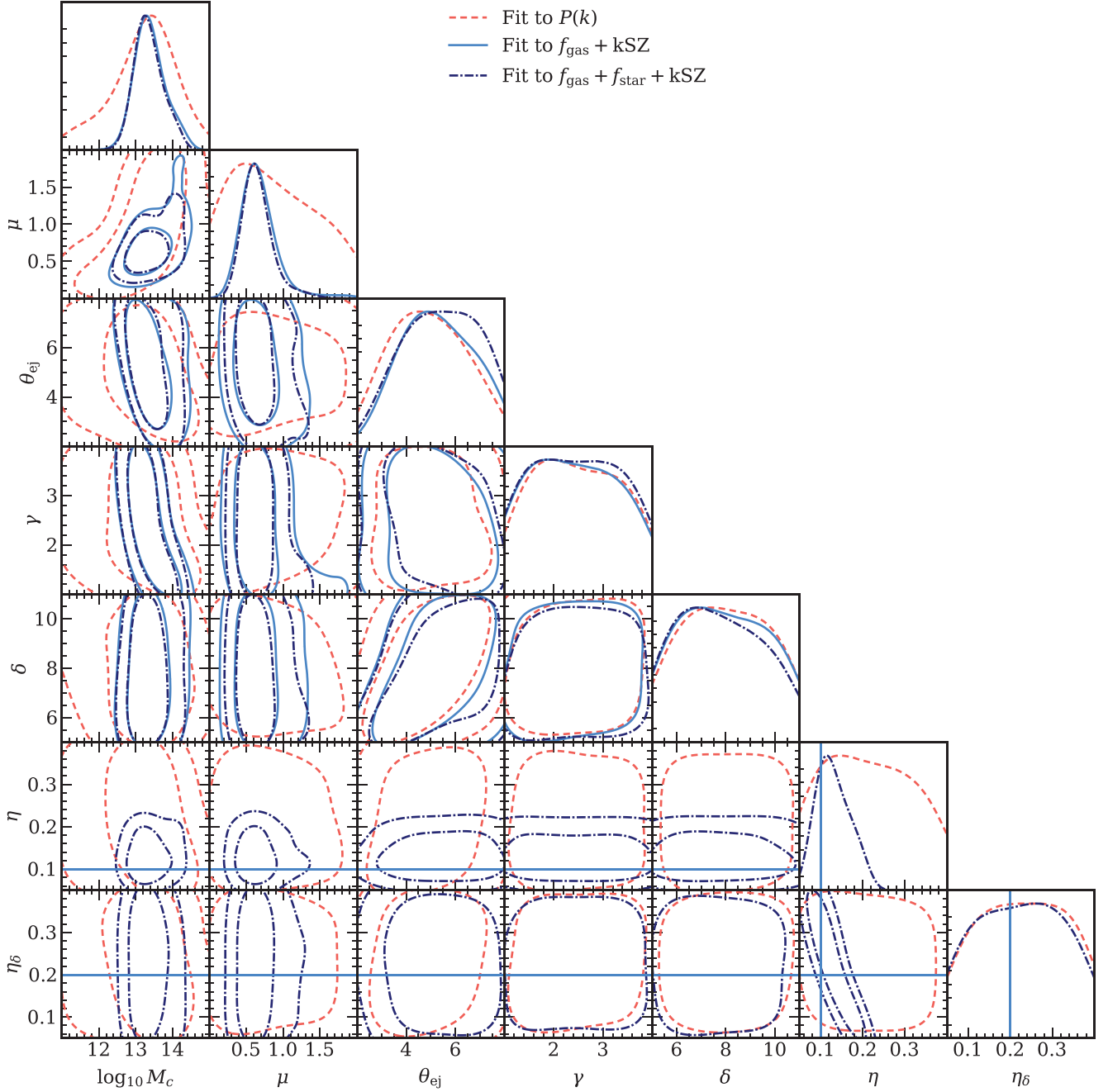


Figure C2. Posteriors on the baryonification parameters from the FLAMINGO simulation injection-recovery tests. The constraints from fitting the matter power suppression, $P(k)/P_{\text{DM Only}}(k)$, are shown in pink (dashed). The joint kSZ and X-ray gas mass fraction fit is shown in blue (solid); following our analysis of the data, we fix the stellar parameters to $\eta = 0.1$ and $\eta_\delta = 0.2$. The joint kSZ, gas mass fraction, and stellar mass fraction fit is shown in purple (dot-dashed). For brevity, we present the results from the strongest feedback FLAMINGO variant ($f_{\text{gas}} - 8\sigma$), because it matches the SDSS/DESI + ACT kSZ data best (I. G. McCarthy et al. 2025; J. Siegel et al. 2025).

APPENDIX D: CHALLENGES OF KSZ MODELLING

The temperature change induced by the kSZ effect is proportional to the density and velocity of the gas along the line of sight (equation 1). For an idealized halo – spherically symmetric gas distribution moving at the same velocity as the central – the conversion between the gas density profile and the kSZ effect profile

is well-defined. The presence of satellite galaxies and two-halo interactions complicates this picture.

Satellites potentially impact the measurement of the kSZ effect in several ways (I. G. McCarthy et al. 2025). Satellites will be miscentered from the centrals, thereby lowering the kSZ signal relative to a galaxy at the centre of the gas distribution. Satellites also occupy more massive haloes than expected from stellar mass alone; because halo mass and gas mass are approximately

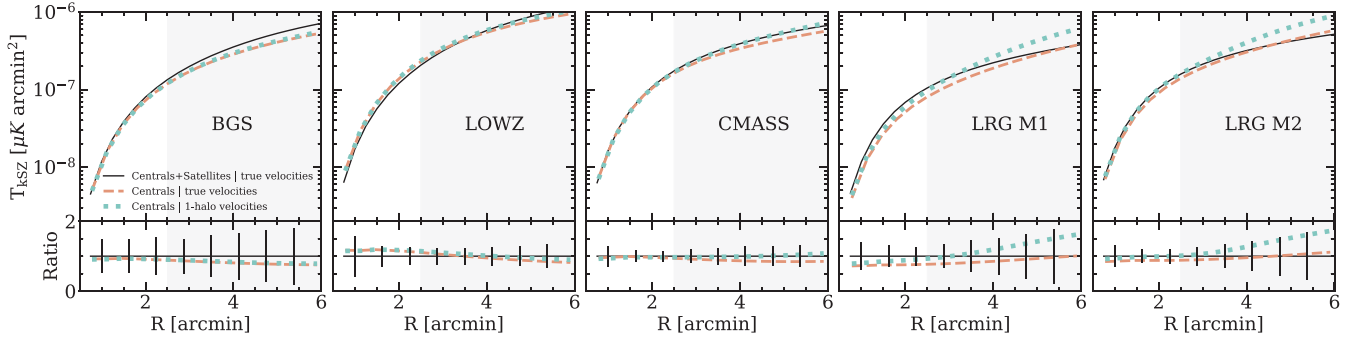


Figure D1. Demonstration of how satellites and two-halo interactions alter the kSZ effect profile in FLAMINGO; for brevity, we present the results from the strongest feedback FLAMINGO variant ($f_{\text{gas}} - 8\sigma$), because it matches the SDSS/DESI+ACT kSZ data best. We present the simulated kSZ effect profile for samples with (solid) and without (dashed) satellites. The simulated galaxies are selected by matching the measured GGL profiles of each SDSS/DESI + ACT sample (J. Siegel et al. 2025). We also test the approximation that the peculiar velocity of the gas distribution is the same as the velocity of the central galaxy. For the centrals only samples, the dotted lines present the kSZ profile where the gas particle velocities are fixed to the central halo velocity. Each column corresponds to a different SDSS/DESI + ACT measurement, and the bottom row presents the ratio of the different kSZ signals with the fiducial calculation. The measurement uncertainties are shown alongside the residuals for context. The shaded region (> 2.5 arcmin) demarcates the scales omitted from our analysis due to modelling uncertainties.

proportional, satellites potentially boost the kSZ signal relative to a sample of all centrals. For a fixed stellar mass selection (i.e. all galaxies above a minimum stellar mass cut), I. G. McCarthy et al. (2025) found that the kSZ effect signal from a sample of centrals is lower than with satellites. The effect is approximately 30 per cent for a low mass selection ($\log_{10} M_*/M_\odot > 11$) and only 5 per cent for $\log_{10} M_*/M_\odot > 11.6$. This effect is partially a result of the different mean halo masses between the samples with and without satellites. For each SDSS/DESI + ACT kSZ stack, J. Siegel et al. (2025) identified the selection of simulated galaxies that best fits the measured GGL signal. To isolate the impact of satellites, we compare the mock kSZ effect signals for the best-fitting selection of centrals and the best-fitting selection of centrals and satellites in Fig. D1. For small angular scales (< 2.5 arcmin), the two selections agree well. On larger scales, the kSZ effect signal from the centrals only selection is lower than the sample with satellites, potentially reflecting differences in the underlying gas distribution.

To predict the kSZ effect from a given gas density profile, we assume that the gas distribution has the peculiar velocity of the central galaxy. This assumption is reasonable on small scales, but on larger scales the gas velocity is not necessarily dominated by a single central potential. To test this approximation, we calculate the kSZ effect profile from FLAMINGO using either the true per-particle velocities or assigning the gas particles the peculiar velocity of the central host. We compare the true and approximate kSZ effect profiles in Fig. D1; the kSZ profiles are calculated for the selection of central haloes that best fit the measured GGL signal for each SDSS/DESI + ACT kSZ stack. As expected, the true and approximate kSZ effect profiles are identical on small scales, where it is reasonable to assume that the gas velocity is the same as the central galaxy velocity, but the approximation breaks

down on larger scales. The difference is most pronounced at high redshift ($z = 0.75$), because the kSZ profile is probing beyond several R_{500} .

For a given sample of galaxies, the kSZ effect is typically measured by a weighted stack of the CMB temperature map (E. Schaan et al. 2021; B. Hadzhiyska et al. 2025; B. Ried Guachalla et al. 2025), where the weights are the galaxies' reconstructed peculiar velocities. The fidelity of the velocity reconstruction is a potential source of uncertainty. To account for non-linearities and shot noise uncertainties, current studies calculate a correction factor based on mock catalogue velocity reconstructions (E. Schaan et al. 2021; B. Hadzhiyska et al. 2025); for the DESI samples, the correlation between the true and reconstructed velocities is approximately 0.7 with quoted uncertainties of less than 5 per cent (B. Hadzhiyska et al. 2024). For each SDSS/DESI + ACT kSZ stack, the selection of simulated galaxies that best fits the GGL signal has a peculiar velocity RMS within 10 per cent of the bias corrected linear theory reconstruction (J. Siegel et al. 2025). Systematics could be further investigated by reconstructing the simulated galaxy velocities using the same method as the observations.

To mitigate uncertainties, particularly the effect of satellites and two-halo interactions, we restrict our kSZ analysis to small scales < 2.5 arcmin. Because the kSZ effect measurement is highly correlated at larger angular separations (B. Ried Guachalla et al. 2025), these scale cuts do not significantly reduce the signal-to-noise ratio of the data. Future work addressing these uncertainties is critical to unlocking the full potential of the SDSS/DESI + ACT measurements.

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