Innovations for a Sustainable Tomorrow

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Tracing the Coevolution of Gas and Black Holes in Cosmological Simulations

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Galaxy groups and clusters harbour a significant fraction of the Universe's baryonic matter, much of which exists in the form of hot, diffuse gas. Feedback mechanisms from supermassive black holes can heat, lift, and expel this gas from haloes, thus play a key role in shaping the cosmic distribution of baryons. We use the FLAMINGO cosmological hydrodynamical simulations to extend previous studies by probing a wider halo mass range, investigating the scatter and redshift dependence of $M_{BH} - M_{500} - f_{gas}$ relations of massive galaxies, groups, and clusters. At low halo masses, our findings align with earlier work. However, at higher halo masses we observe a reversal of the previously established trend. We explore a potential explanation for this reversal, with evidence that haloes reaccrete the gas they expelled earlier in cosmic history.

1. INTRODUCTION

A significant fraction of the Universe's baryons reside in galaxy groups and clusters as hot, diffuse gas. In these environments, supermassive black holes (BHs) generate feedback - via radiation, jets, and winds - which heats and redistributes this gas. Understanding the connection between AGN feedback and halo gas is therefore key to explaining the baryonic distribution of the universe. Previous work (e.g. Davies et al. 2019, 2020) found a **negative correlation** between BH mass and gas fraction in haloes with $M_{200} < 10^{13} M_{\odot}$, in the **EAGLE** and **IllustrisTNG** simulations. With the **larger volume** FLAMINGO simulations (Schaye et al. 2023), we extend this analysis to higher halo masses and larger samples, enabling a more detailed investigation of the BH–gas connection across cosmic time.

We use the high-resolution **fiducial FLAMINGO m8 run** (1Gpc^3). Our analysis uses: 13 snapshots, 78 halo catalogues, and 1 full-sky lightcone. BH subgrid physics follows Booth & Schaye (2009) and Bahe et al. (2022), and BHs are seeded with mass 10^5 $M_{\odot}$ in **central haloes above $2.757\times10^{11}\mathbf{M}_{\odot}$**.

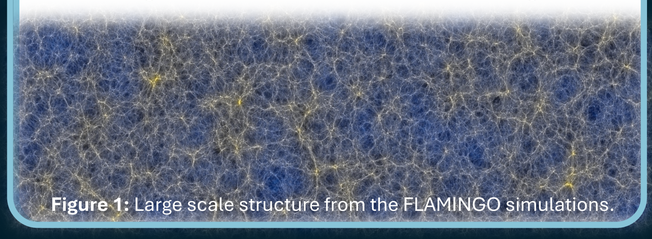

Figure 1: Large scale structure from the FLAMINGO simulations.

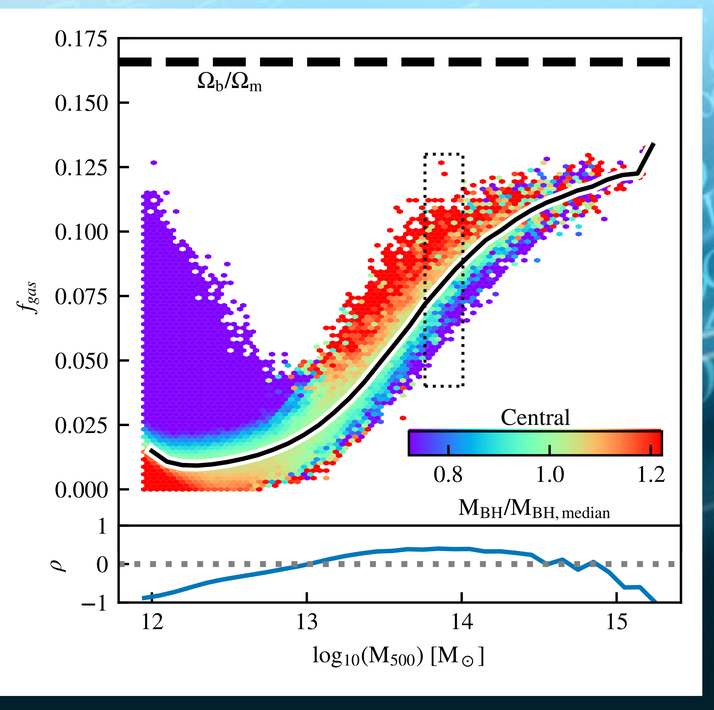

Figure 2: Present-day relation between gas fraction (f_{gas}) and halo mass (M_{500}), colour-coded by the ratio $M_{BH}/M_{BH,median}$ for central BHs. The solid black line indicates the running median, while the dashed black line marks the universal baryon fraction. The running Spearman rank correlation coefficient is shown below each main panel.

2. EXAMINING SCATTER

We define the **central** BH as the most massive BH within 30 kpc of the halo centre of potential, compute the **gas fraction** of haloes as: $f_{gas} = M_{gas}(r < R_{500})/M_{500}$ and quantify the **scatter** in BH mass as the ratio $M_{BH}/M_{BH,median}$. **Fig. 2** shows the gas fraction – halo mass relation, colour-coded by this scatter in central BH mass.

At **low halo masses**, a **strong negative correlation** is observed, were overmassive BHs correspond to low gas fractions, consistent with Davies et al. (2019, 2020). This aligns with physical expectations - more massive BHs produce stronger feedback, expelling gas and reducing the gas fraction. However, at **high halo masses**, we observe a **reversal** of this trend: **overmassive** BHs now correlate with **higher** gas fractions. This study aims to **understand the origin of this flip in correlation**.

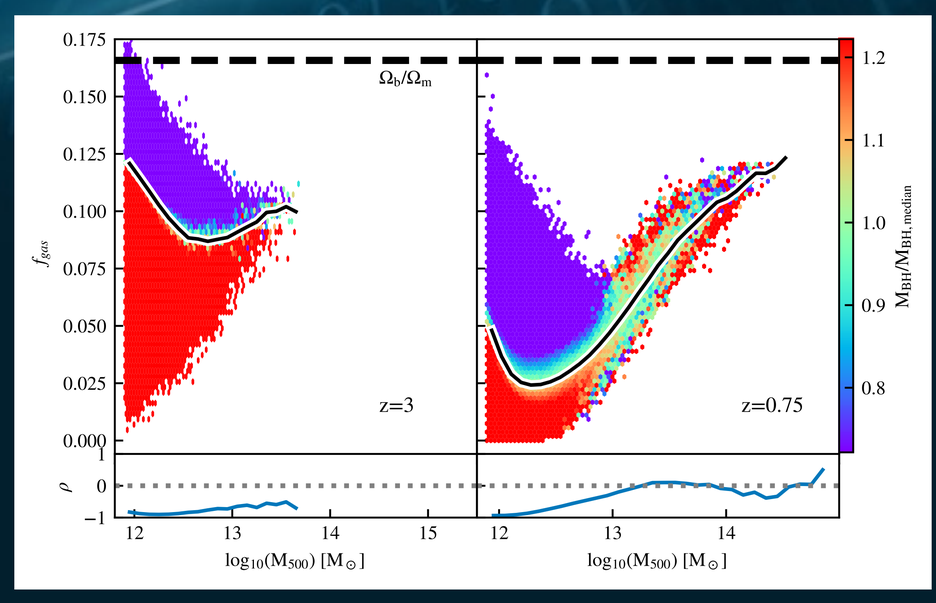

Figure 3: Gas fraction–halo mass relation, colour-coded by the ratio $M_{BH}/M_{BH,median}$ for central BHs. The left panel shows the relation at $z = 3$, and the right at $z = 0.75$. The solid black line indicates the running median; the dashed black line marks the universal baryon fraction, and the Spearman rank correlation coefficient is shown below each panel.

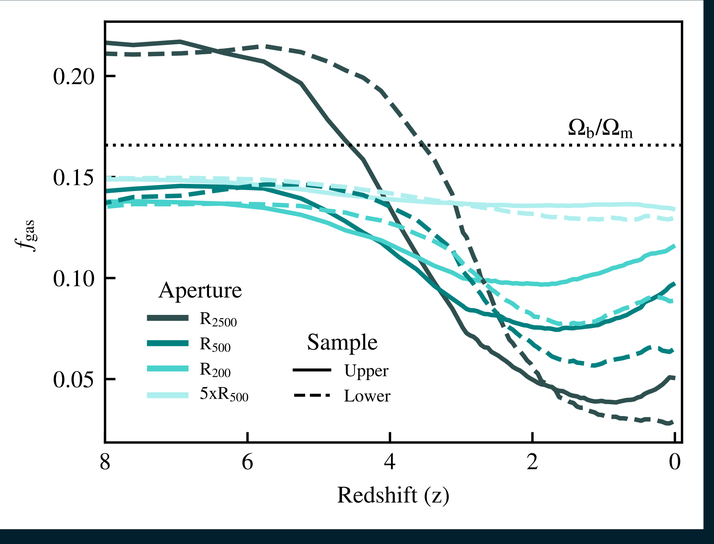

Figure 5: Evolution of f_{gas} with redshift for the upper (solid) and lower (dashed) tracked samples. Gas fractions are computed in various apertures ($R_{2500}, R_{500}, R_{200}, 5\times R_{500}$), with darker colours representing increasingly smaller aperture sizes.

3. REDSHIFT DEPENDENCE

Fig. 3 illustrates the redshift evolution of the relationship between halo gas fraction and central BH mass ratio.

- **Left: z = 3** A strong negative correlation is observed: haloes with overmassive central BHs consistently show low gas fractions, regardless of halo mass.
- **Right: z = 0.75** The reversal of this correlation begins to emerge around z∼1.5, as some haloes with overmassive BHs retain or reacquire higher gas fractions. By z=0.75, haloes with $M_{500} \sim 10^{13-14}\, M_{\odot}$ hosting over-massive BHs now appear both above and below the median gas fraction. More massive haloes $M_{500} \sim 10^{14-15}\, M_{\odot}$ still show suppressed gas fractions when hosting overmassive BHs.

By z=0 **(Fig.2),** the correlation has fully reversed in high-mass haloes, demonstrating a clear redshift dependence in the coupling between BH mass and gas content.

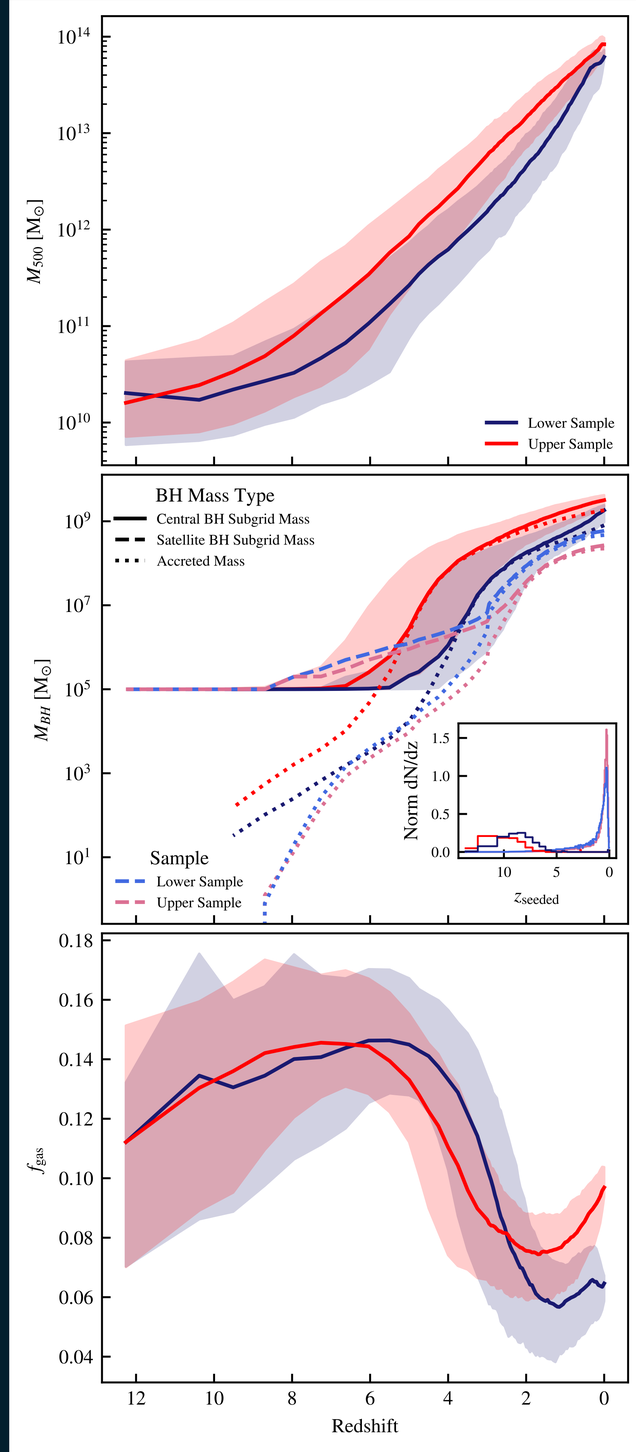

Figure 4: Redshift evolution tracks for central BHs and host haloes within the mass range shown as the dotted region of Fig. 1, split into the 90th (upper, red) and 10th (lower, navy) percentiles of f_{gas} at $z = 0$. Shaded regions indicate the 16th–84th percentile range. **Top:** Halo mass (M_{500}) versus redshift. **Middle:** BH mass versus redshift; solid lines represent central BHs, dashed lines represent satellite BHs, and dotted lines show the total accreted mass. The inset panel displays the normalised probability distribution function of seed redshifts for each BH population. **Bottom**: f_{gas} versus redshift.

4. BH TRACKING

High-mass haloes hosting **overmassive** BHs begin to show **increasing gas fractions at z∼1.5**. To investigate the cause of this, we first select haloes at z=0 within the mass range $10^{13.75} \leq M_{500}\ [M_{\odot}] < 10^{14}$ (corresponding to the highlighted region in Fig. 2). From this subset, we identify the **upper and lower 10th percentiles** of the fgas distribution, forming two distinct samples of 710 haloes:

- the **upper fgas sample** (high f_{gas} at z=0)
- the **lower fgas sample** (low f_{gas} at z=0)

We identify the **central BHs** of these haloes at z=0 and track their evolution through cosmic time. **Fig. 4** shows the median evolutionary tracks for properties of the **upper** (red) and **lower** (navy) samples.

Top Panel: $M_{500} - z$ Relation

The upper sample reaches higher halo masses earlier, crossing the halo seed mass threshold ($2.757\times 10^{11} M_{\odot}$) sooner and thus seeds its central BHs earlier.

Middle Panel: $M_{BH} - z$ Relation

- Upper sample central BHs seed as early as z∼11, with significant growth starting around z∼6.
- Lower sample central BHs seed later, as their host haloes reach the threshold seed mass at later times.
- This BH growth remains accretion-dominated until about z∼2.

Bottom Panel: $f_{gas} - z$ Relation

High- f_{gas} systems show early quenching starting around z∼5, followed by a notable **rise in gas fraction around z∼1.5** - consistent with the flip in correlation observed in **Fig. 3**. The lower sample exhibits a similar trend but with later, therefore more efficient, quenching and gas re-accretion. We explore the increase in gas fraction further by examining the evolution of f_{gas} within multiple apertures in **Fig.5**. In an **outside-in accretion** scenario, we expect **larger apertures** to **lose gas later** and **reaccrete it earlier**. This is indeed observed: $f_{\rm gas}\,(R_{500})$ declines last and reaccretes first. For both samples, even the largest aperture, $5\times R_{500}$, shows a noticeable decrease in f_{gas}, suggesting that central BH feedback can affect gas content even on these **large scales**.

5. CONCLUSIONS

WHAT CAUSES THE FLIP IN CORRELATION?

High mass haloes tend to have grown earlier in cosmic time (Fig.4, top)...

...so seed their central BHs at higher redshifts, enabling prolonged accretion-driven growth and allowing them to become overmassive (Fig.4, middle).

Strong AGN feedback from the central expels a significant fraction of halo gas, out to even $5xR_{500}$ (Fig.4, bottom; Fig.5), and quenches itself (Fig.4, middle).

The halo then reaccretes the previously ejected gas at z ~ 1.5 (Fig.4, bottom; Fig.5) such that overmassive central BHs correlate with high gas fractions (Fig.2).

Future Work: Studying BH feedback with state-of-the-art observations.

Bahé, Y.M. *et al.* (2022), *MNRAS*, 516(1), pp. 167–184.
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