Metal-rich Fuel for Supermassive Black Holes: Tracing the Origin and Properties of Accreted Gas in Cosmological Simulations.

2025-01-15

곽 동 윤

Introduction & Background (Observation).

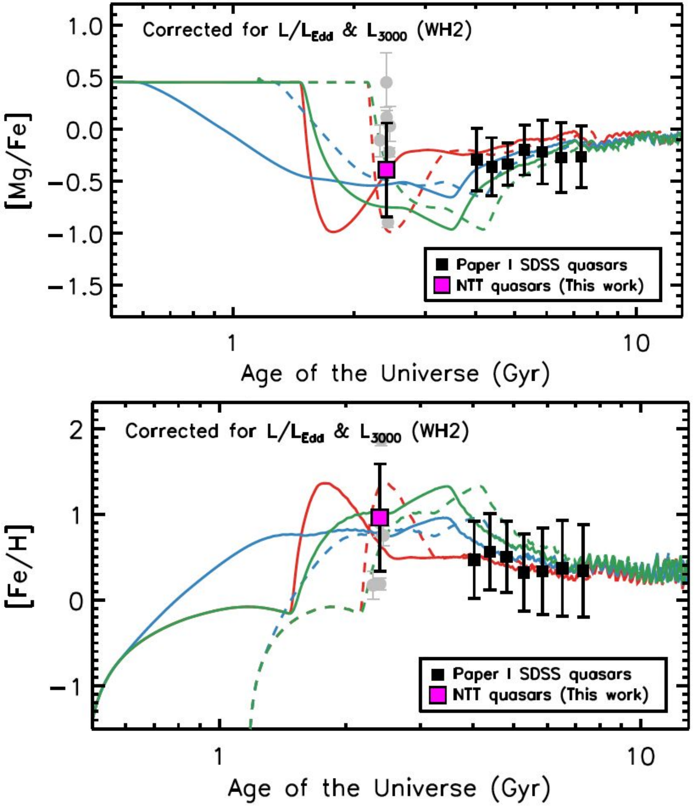
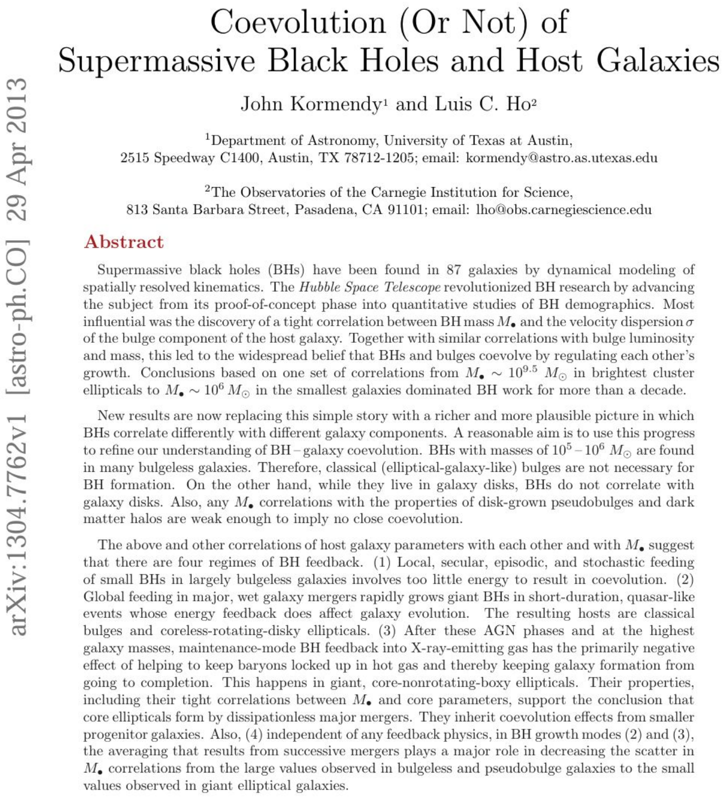


Figure in Sameshima et al. (2020)



arXiv:1304.7762v1 [astro-ph.CO] 29 Apr 2013

Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies

John Kormendy[1] and Luis C. Ho[2]

[1]Department of Astronomy, University of Texas at Austin, 2515 Speedway C1400, Austin, TX 78712-1205; email: kormendy@astro.as.utexas.edu

[2]The Observatories of the Carnegie Institution for Science, 813 Santa Barbara Street, Pasadena, CA 91101; email: lho@obs.carnegiescience.edu

Abstract

Supermassive black holes (BHs) have been found in 87 galaxies by dynamical modeling of spatially resolved kinematics. The *Hubble Space Telescope* revolutionized BH research by advancing the subject from its proof-of-concept phase into quantitative studies of BH demographics. Most influential was the discovery of a tight correlation between BH mass $M_\bullet$ and the velocity dispersion σ of the bulge component of the host galaxy. Together with similar correlations with bulge luminosity and mass, this led to the widespread belief that BHs and bulges coevolve by regulating each other's growth. Conclusions based on one set of correlations from $M_\bullet \sim 10^{9.5}\ M_\odot$ in brightest cluster ellipticals to $M_\bullet \sim 10^6\ M_\odot$ in the smallest galaxies dominated BH work for more than a decade.

New results are now replacing this simple story with a richer and more plausible picture in which BHs correlate differently with different galaxy components. A reasonable aim is to use this progress to refine our understanding of BH – galaxy coevolution. BHs with masses of $10^5 - 10^6\ M_\odot$ are found in many bulgeless galaxies. Therefore, classical (elliptical-galaxy-like) bulges are not necessary for BH formation. On the other hand, while they live in galaxy disks, BHs do not correlate with galaxy disks. Also, any $M_\bullet$ correlations with the properties of disk-grown pseudobulges and dark matter halos are weak enough to imply no close coevolution.

The above and other correlations of host galaxy parameters with each other and with $M_\bullet$ suggest that there are four regimes of BH feedback. (1) Local, secular, episodic, and stochastic feeding of small BHs in largely bulgeless galaxies involves too little energy to result in coevolution. (2) Global feeding in major, wet galaxy mergers rapidly grows giant BHs in short-duration, quasar-like events whose energy feedback does affect galaxy evolution. The resulting hosts are classical bulges and coreless-rotating-disky ellipticals. (3) After these AGN phases and at the highest galaxy masses, maintenance-mode BH feedback into X-ray-emitting gas has the primarily negative effect of helping to keep baryons locked up in hot gas and thereby keeping galaxy formation from going to completion. This happens in giant, core-nonrotating-boxy ellipticals. Their properties, including their tight correlations between $M_\bullet$ and core parameters, support the conclusion that core ellipticals form by dissipationless major mergers. They inherit coevolution effects from smaller progenitor galaxies. Also, (4) independent of any feedback physics, in BH growth modes (2) and (3), the averaging that results from successive mergers plays a major role in decreasing the scatter in $M_\bullet$ correlations from the large values observed in bulgeless and pseudobulge galaxies to the small values observed in giant elliptical galaxies.

Kormendy+2013

Introduction & Background (Simulation).

The Astrophysical Journal, 964:54 (10pp), 2024 March 20 https://doi.org/10.3847/1538-4357/ad245a

The Origins of Gas Accreted by Supermassive Black Holes: The Importance of Recycled Gas

Ena Choi[1], Rachel S. Somerville[2], Jeremiah P. Ostriker[3,4], Michaela Hirschmann[5,6], and Thorsten Naab[7]
[1] Department of Physics, University of Seoul, 163 Seoulsiripdaero, Dongdaemun-gu, Seoul 02504, Republic of Korea; enachoi@uos.ac.kr
[2] Center for Computational Astrophysics, Flatiron Institute, 162 5th Avenue, New York, NY 10010, USA
[3] Department of Astronomy, Columbia University, 550 West 120th Street, New York, NY 10027, USA
[4] Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA
[5] Institute for Physics, Laboratory for Galaxy Evolution and Spectral Modeling, Ecole Polytechnique Federale de Lausanne, Observatoire de Sauverny, Chemin Pegasi 51, 1290 Versoix, Switzerland
[6] INAF—Osservatorio Astronomico di Trieste, via G.B. Tiepolo 11, I-34143 Trieste, Italy
[7] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Strasse 1, 85741 Garching, Germany
Received 2023 August 21; revised 2024 January 25; accepted 2024 January 29; published 2024 March 14

Abstract

We investigate the fueling mechanisms of supermassive black holes (SMBHs) by analyzing 10 zoom-in cosmological simulations of massive galaxies, with stellar masses $10^{11-12}M_\odot$ and SMBH masses $10^{8.9-9.7}\,M_\odot$ at $z=0$, featuring various major and minor merger events. By tracing the gas history in these simulations, we categorize the gas accreted by the central SMBHs based on its origin. Gas that belonged to a different galaxy before accretion onto the BH is labeled as (i) "external," while smoothly accreted cosmic gas is classified as (ii) "smooth." Gas produced within the primary halo through stellar evolution and subsequently accreted by the SMBH is classified as (iii) "recycled." Our analysis, which includes stellar feedback, reveals that the primary fuel source for SMBHs is the recycled gas from dying stars. This recycled gas from stars in the inner region of the galaxy readily collapses toward the center, triggering starbursts and simultaneously fueling the SMBH. Galaxy mergers also play a crucial role in fueling SMBHs in massive galaxies, as SMBHs in massive halos tend to accrete a higher fraction of external gas from mergers compared to smoothly accreted gas. However, on average, it takes approximately 1.85 Gyr for external gas to enter the main galaxy and accrete onto the SMBH. Considering the presence of various other gas triggers for active galactic nucleus (AGN) activity alongside this time delay, the association between AGNs and mergers may not always be obvious.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); Hydrodynamical simulations (767); Supermassive black holes (1663); AGN host galaxies (2017)

1. Introduction

The strong connections between the cosmic evolution of supermassive black holes (SMBHs) and their host galaxies have been investigated for more than two decades. First of all, observational evidence has shown that almost every large galaxy has an SMBH at its center (e.g., Kormendy & Richstone 1995; Magorrian et al. 1998). The SMBH mass is strongly correlated with the spheroidal mass, velocity dispersion σ, and other properties of the galaxy (e.g., Gebhardt et al. 2000; Häring & Rix 2004; Kormendy & Ho 2013; Woo et al. 2013). Furthermore, the global cosmic star formation history and cosmic black hole (BH) accretion history follow each other remarkably closely, rising from the epoch of reionization to $z\sim2$–3, then steeply declining to the current epoch, suggesting that SMBHs and galaxies may have co-evolved.

Energetic feedback from accreting BHs, commonly called active galactic nucleus (AGN) feedback, has become a key ingredient in galaxy evolution simulations (Springel et al. 2005a; Sijacki et al. 2007; Somerville et al. 2008). AGN feedback prevents overcooling and excessive star formation in galaxies and also self-regulates the BH growth (e.g., Booth & Schaye 2009; Gaspari et al. 2011; Choi et al. 2012; Dubois et al. 2012; Appleby et al. 2020). Many contemporary large-volume simulations such as EAGLE, TNG, SIMBA, Horizon-AGN, and Magneticum all include the growth of BHs and feedback from them, and have been able to reproduce these gigantic $10^{8-9}\,M_\odot$ SMBHs at $z=0$ (Hirschmann et al. 2014; Schaye et al. 2015; Dubois et al. 2016; Weinberger et al. 2018; Davé et al. 2019). For a more detailed review of BH growth in cosmological simulations, see Somerville & Davé (2015) and Naab & Ostriker (2017).

How do SMBHs grow? The origin of SMBHs remains uncertain, but they are thought to grow primarily through two mechanisms: accretion and mergers. BHs grow by accreting matter from the surrounding gas, which spirals toward the BH and converts gravitational potential energy into heat, providing the principal source of radiation for AGNs. They also grow by merging with other BHs when two galaxies merge, bringing their respective BHs together. AGN pairs have been observed in X-ray, radio, and optical imaging and spectroscopy (e.g., Komossa et al. 2003), and more than 100 stellar-mass BH mergers have been discovered since the advent of the Laser Interferometer Gravitational-Wave Observatory. Based on the Soltan argument (Soltan 1982), it is expected that mass accretion plays a substantial role in BH growth. Moreover, the dominance of mass accretion as the primary source of BH mass is necessary to explain the evolution of the X-ray luminosity function of AGNs (e.g., Hirschmann et al. 2014). However, alternative studies suggest that the correlations between SMBH

Choi et al. (2024)

The Astrophysical Journal, 917:53 (30pp), 2021 August 20 https://doi.org/10.3847/1538-4357/ac09e8

Cosmological Simulations of Quasar Fueling to Subparsec Scales Using Lagrangian Hyper-refinement

Daniel Anglés-Alcázar[1,2], Eliot Quataert[3,4], Philip F. Hopkins[5], Rachel S. Somerville[2,6], Christopher C. Hayward[2], Claude-André Faucher-Giguère[7], Greg L. Bryan[2,8], Dušan Kereš[9], Lars Hernquist[10], and James M. Stone[11]
[1] Department of Physics, University of Connecticut, 196 Auditorium Road, U-3046, Storrs, CT 06269-3046, USA; angles-alcazar@uconn.edu
[2] Center for Computational Astrophysics, Flatiron Institute, 162 Fifth Avenue, New York, NY 10010, USA
[3] Department of Astronomy and Theoretical Astrophysics Center, University of California Berkeley, Berkeley, CA 94720, USA
[4] Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA
[5] TAPIR, Mailcode 350-17, California Institute of Technology, Pasadena, CA 91125, USA
[6] Department of Physics and Astronomy, Rutgers University, 136 Frelinghuysen Road, Piscataway, NJ 08854, USA
[7] CIERA and Department of Physics and Astronomy, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208, USA
[8] Department of Astronomy, Columbia University, 550 West 120th Street, New York, NY 10027, USA
[9] Department of Physics, CASS, University of California at San Diego, 9500 Gilman Drive, La Jolla, CA 92093, USA
[10] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
[11] School of Natural Sciences, Institute for Advanced Study, 1 Einstein Drive, Princeton, NJ 08540, USA
Received 2020 August 26; revised 2021 April 26; accepted 2021 June 8; published 2021 August 17

Abstract

We present cosmological hydrodynamic simulations of a quasar-mass halo ($M_{\rm halo}\approx10^{12.5}\,M_\odot$ at $z=2$) that for the first time resolve gas transport down to the inner 0.1 pc surrounding the central massive black hole. We model a multiphase interstellar medium including stellar feedback by supernovae, stellar winds, and radiation, and a hyper-Lagrangian refinement technique increasing the resolution dynamically approaching the black hole. We do not include black hole feedback. We show that the subpc inflow rate (1) can reach $\sim6\,M_\odot\,{\rm yr}^{-1}$ roughly in steady state during the epoch of peak nuclear gas density ($z\sim2$), sufficient to power a luminous quasar, (2) is highly time variable in the pre-quasar phase, spanning 0.001–10 $M_\odot\,{\rm yr}^{-1}$ on Myr timescales, and (3) is limited to short ($\sim$2 Myr) active phases (0.01–0.1 $M_\odot\,{\rm yr}^{-1}$) followed by longer periods of inactivity at lower nuclear gas density and late times ($z\sim1$), owing to the formation of a hot central cavity. Inflowing gas is primarily cool, rotational support dominates over turbulence and thermal pressure, and star formation can consume as much gas as provided by inflows across 1 pc–10 kpc. Gravitational torques from multiscale stellar non-axisymmetries dominate angular momentum transport over gas self-torquing and pressure gradients, with accretion weakly dependent on black hole mass. Subpc inflow rates correlate with nuclear (but decouple from global) star formation and can exceed the Eddington rate by $\times10$. The black hole can move $\sim$10 pc from the galaxy center on $\sim$0.1 Myr. Accreting gas forms pc-scale, rotationally supported, obscuring structures often misaligned with the galaxy-scale disk. These simulations open a new avenue to investigate black hole–galaxy coevolution.

Unified Astronomy Thesaurus concepts: AGN host galaxies (2017); Quasars (1319); Galaxy nuclei (609); Galaxy formation (595); Galaxy evolution (594); Cosmological evolution (336); Black hole physics (159); Supermassive black holes (1663)

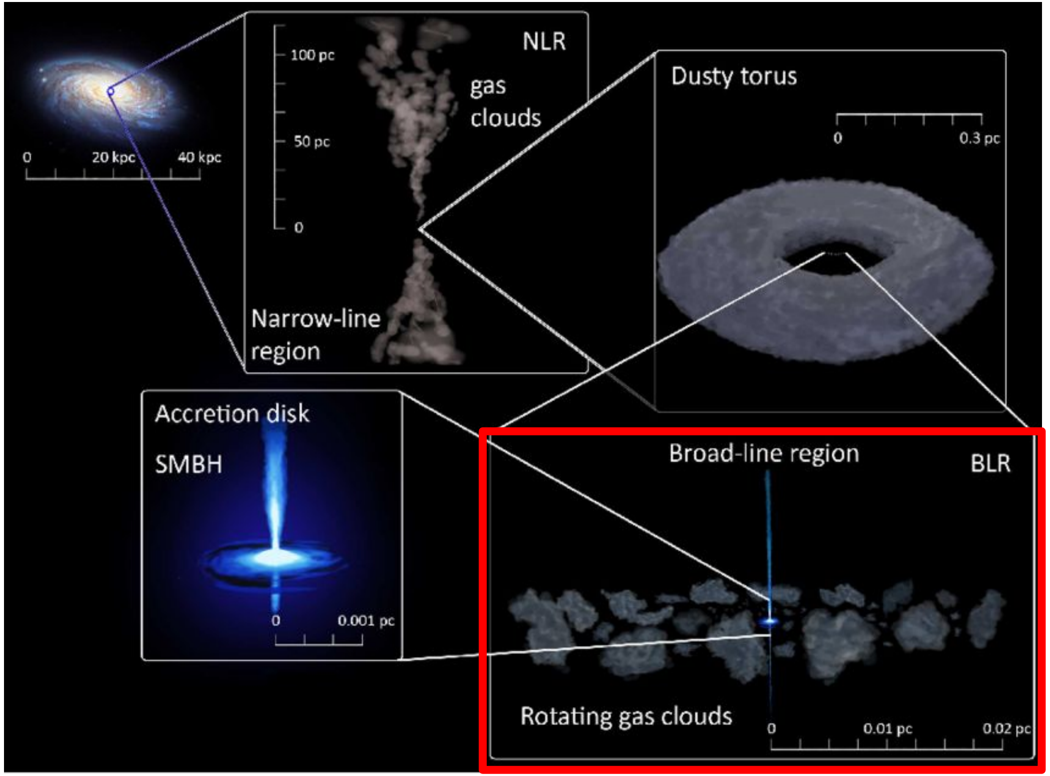
1. Introduction

The inflow of gas from large scales down to galactic nuclei plays a key role in galaxy formation, driving the growth of central massive black holes and a variety of related phenomena: from bright quasars (QSOs) that outshine their host galaxies (with bolometric luminosities reaching $L_{\rm bol}\sim10^{46}$–10^{48} erg s^{-1}, e.g., Fan et al. 2001; Mortlock et al. 2011; Trakhtenbrot et al. 2011; Bañados et al. 2018; Zakamska et al. 2019) to active galactic nuclei (AGNs) "feedback" in the form of fast nuclear outflows (e.g., Tombesi et al. 2013; Nardini et al. 2015), galaxy-scale winds (e.g., Rupke & Veilleux 2011; Greene et al. 2012; Liu et al. 2013; Cicone et al. 2014; Harrison et al. 2014; Zakamska & Greene 2014; Ramos Almeida et al. 2017; Wylezalek et al. 2020), and radio-emitting jets (Fabian 2012; Hlavacek-Larrondo et al. 2012) that may have a significant impact on galaxy evolution (e.g., Silk & Rees 1998; Di Matteo et al. 2005; Murray et al. 2005; Faucher-Giguère & Quataert 2012; Richings & Faucher-Giguère 2018). The scaling relations between the masses of central black holes and the properties of their host galaxies (e.g., Häring & Rix 2004; Hopkins et al. 2007; Bentz et al. 2009; Bennert et al. 2011; Kormendy & Ho 2013; McConnell & Ma 2013; Reines & Volonteri 2015; Graham 2016), as well as the similarity between the global cosmic histories of star formation and black hole accretion (Silverman et al. 2008; Aird et al. 2010; Rodighiero et al. 2010; Heckman & Best 2014; Madau & Dickinson 2014), further suggest some form of black hole–galaxy coevolution over cosmological timescales. It is thus crucial to understand the mechanisms driving gas inflows from galactic scales down to the black hole accretion disk in a full cosmological context, which remains a major challenge.

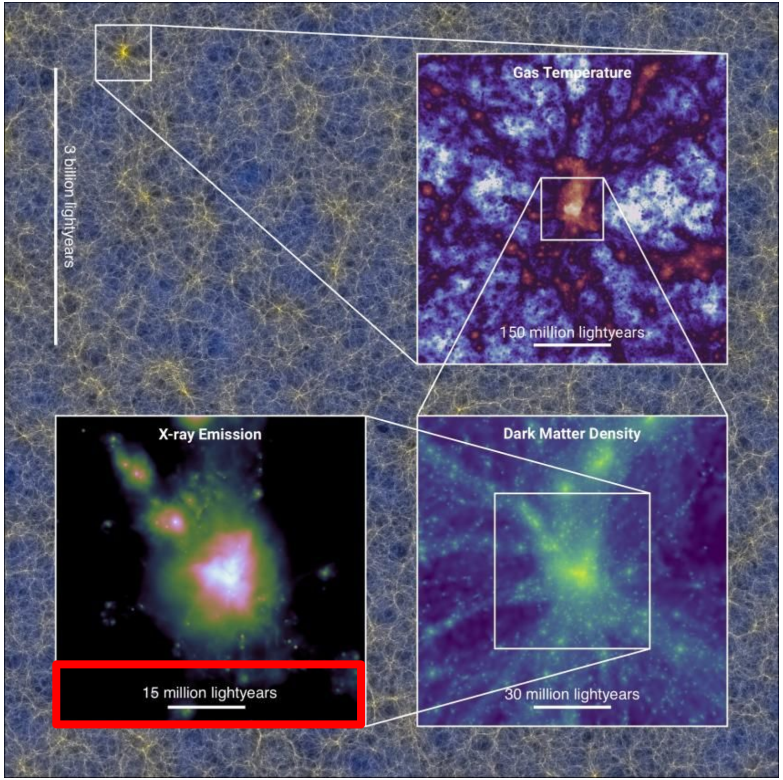
Modern large-volume cosmological hydrodynamic simulations such as Magneticum (Hirschmann et al. 2014), Horizon-AGN (Dubois et al. 2014b; Volonteri et al. 2016), Eagle (Schaye et al. 2015; Rosas-Guevara et al. 2016), Illustris (Genel et al. 2014; Vogelsberger et al. 2014a, 2014b; Sijacki et al. 2015), BlueTides (Feng et al. 2016), Romulus (Tremmel et al. 2017; Sharma et al. 2020), IllustrisTNG (Weinberger et al. 2017; Pillepich et al. 2018; Habouzit et al. 2019), and SIMBA (Davé et al. 2019; Thomas et al. 2019; Borrow et al. 2020) have implemented subgrid models of black hole growth and feedback with increasing success at reproducing global galaxy properties and black hole observables (see Habouzit et al. 2021, for a recent comparison). However,

Alcázar et al. (2021)

Introduction & Background.

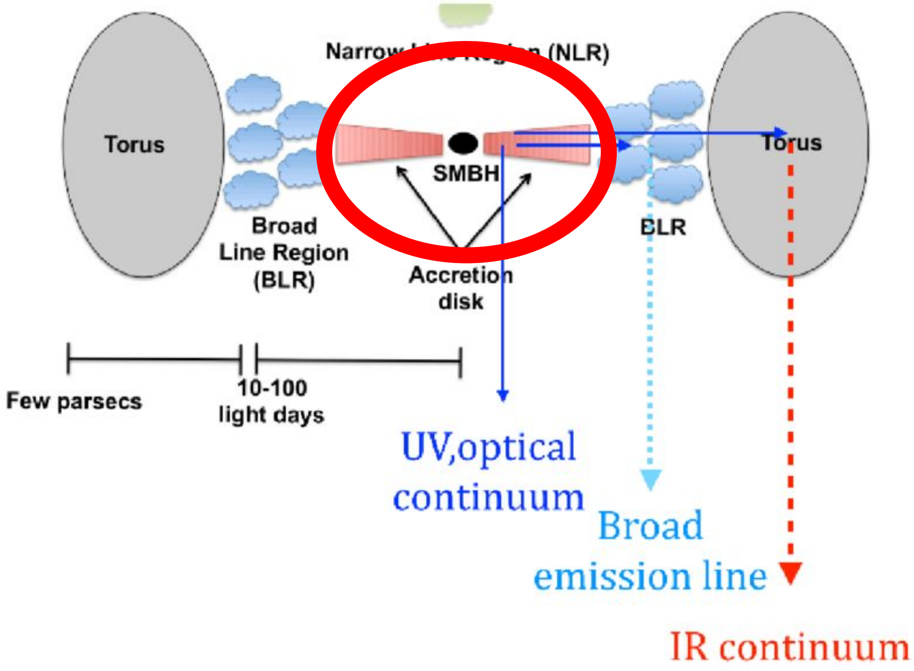


Observation



Zoom-in simulation

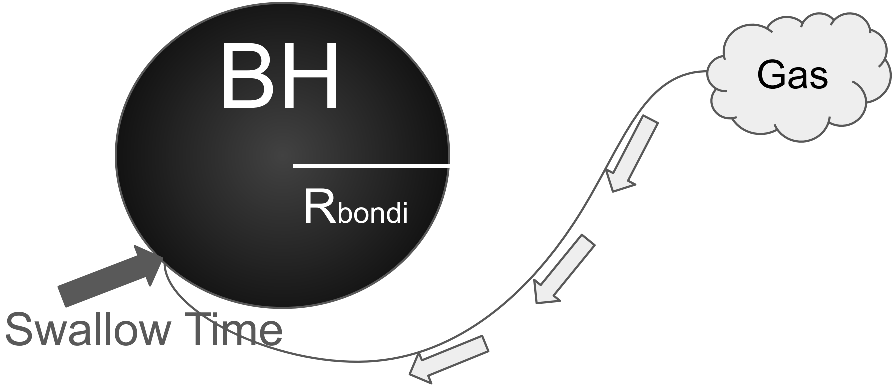
Introduction & Background.



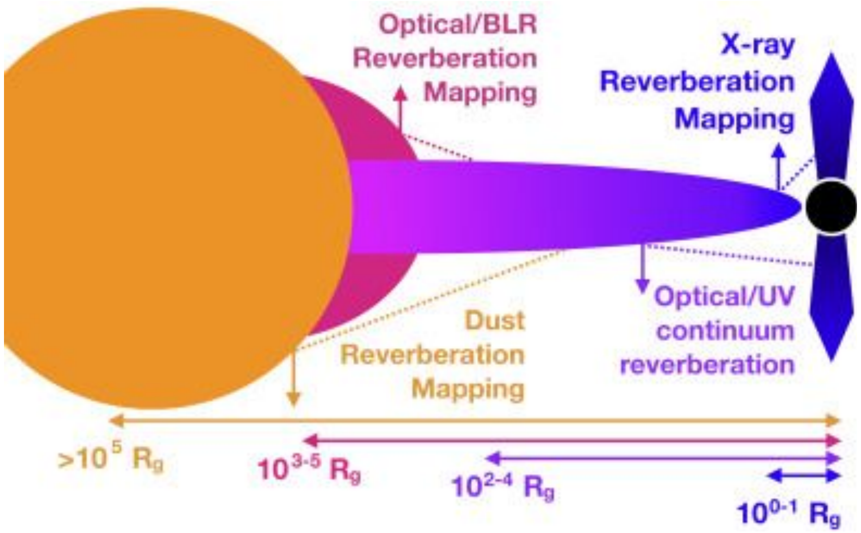
AGN Unification model

Why “Swallow”?

- **Comparable length scale of a few tens of parsecs**



$$r_{\rm Bondi} \equiv \frac{2GM_{\rm BH}}{{v_i}^2}, \text{ where } {v_i}^2 = c^2 + {v_{\rm rel}}^2$$



(Simulation) **(Observation)**

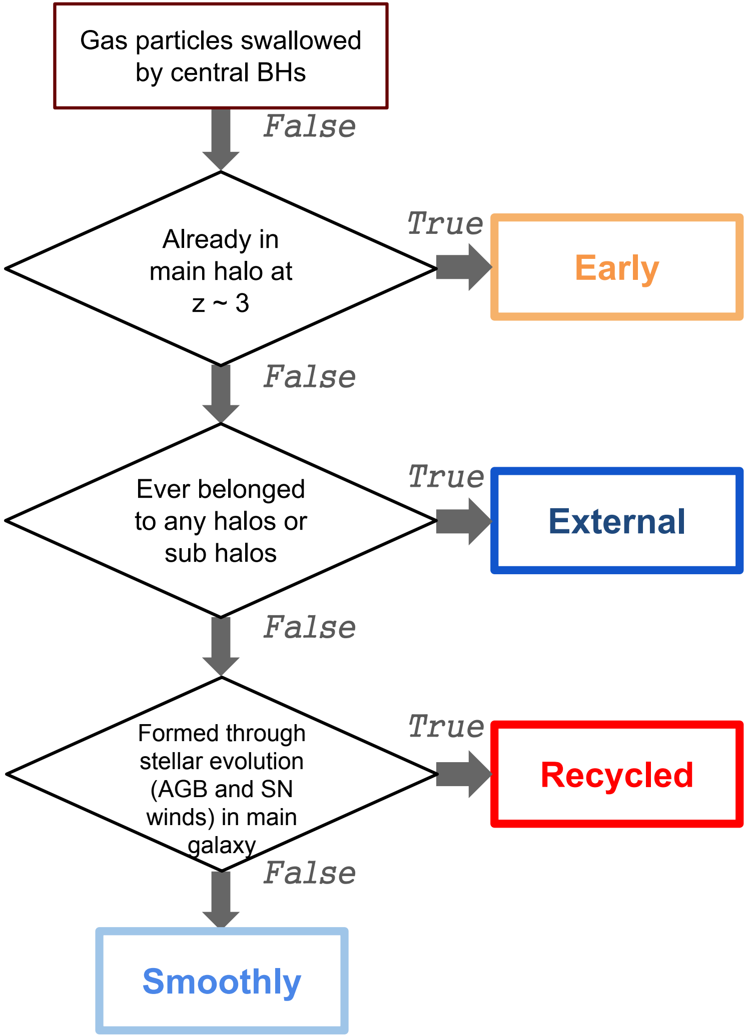
Introduction & Background.

- In particular, we aim to compare the metallicity of black hole-swallowed gas with observational data, and to trace the origin of this gas—whether it is pristine, externally acquired, or recycled through internal stellar evolution processes.

- By using **gtrace**, a zoom-in simulation center-finder tool, we find the $R200$ and central position.

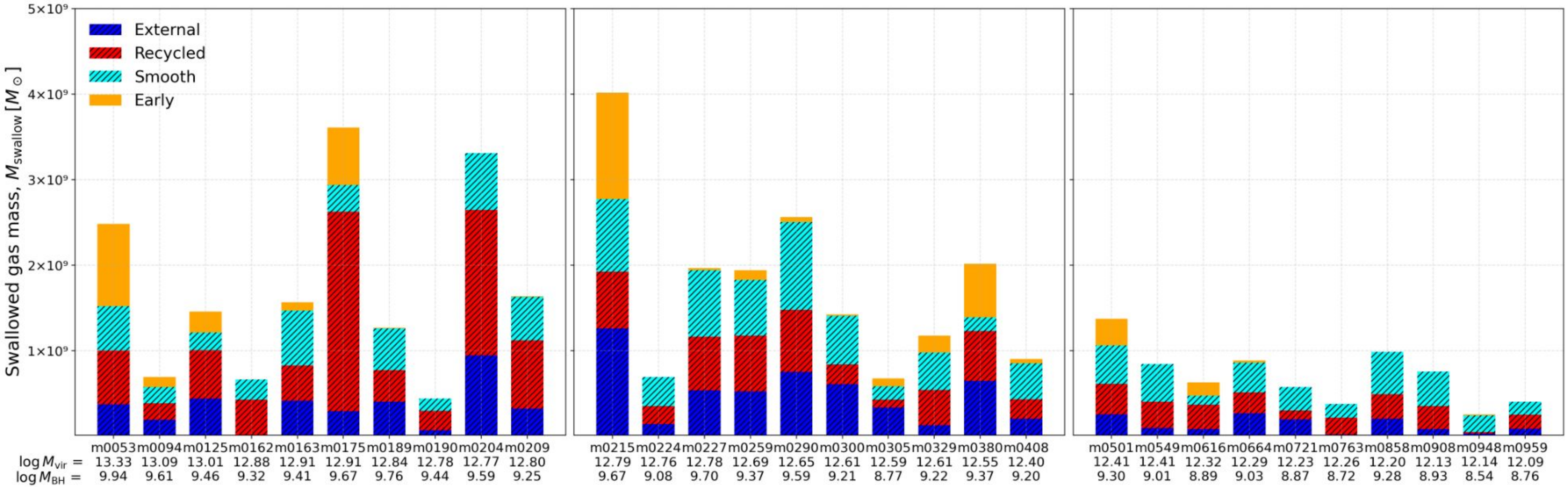
- In addition, we employ the **Rockstar** Halo Finder to obtain the properties of halos.

Method



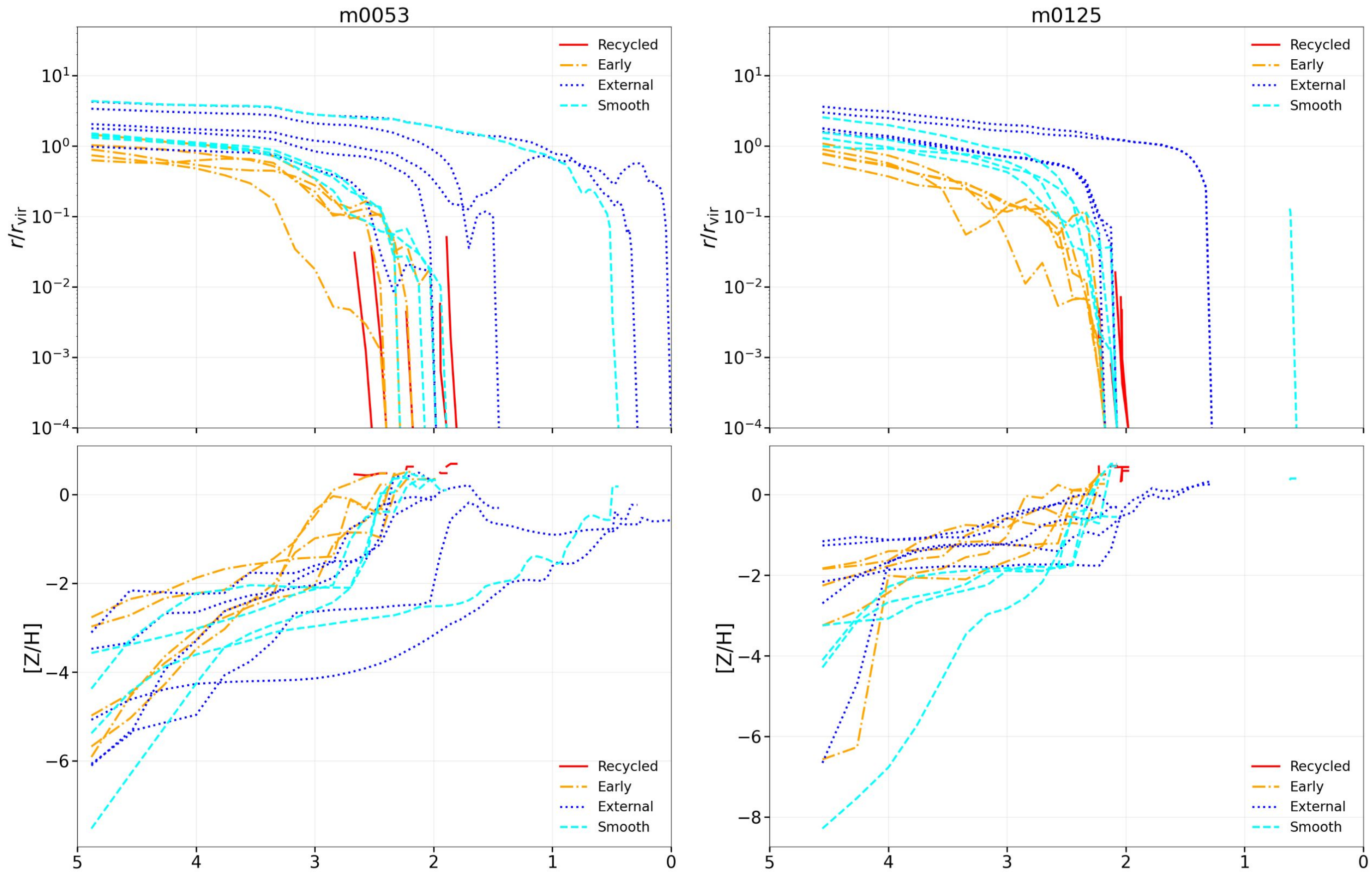
Flowchart

Result



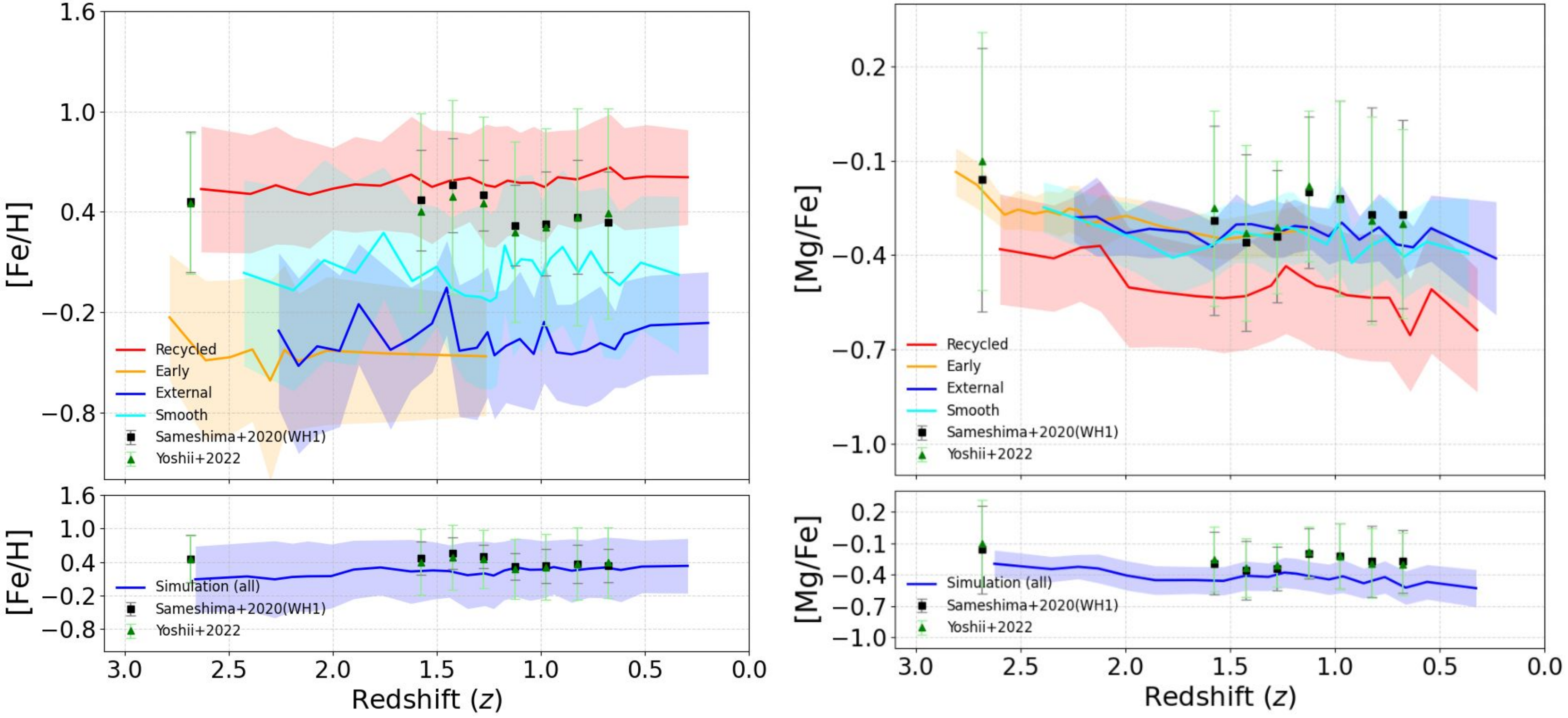
External
Recycled
Smooth
Early
Swallowed gas mass, $M_{swallow}$ [$M_\odot$]
5×10⁹
4×10⁹
3×10⁹
2×10⁹
1×10⁹
m0053 m0094 m0125 m0162 m0163 m0175 m0189 m0190 m0204 m0209
log M_{vir} = 13.33 13.09 13.01 12.88 12.91 12.91 12.84 12.78 12.77 12.80
log M_{BH} = 9.94 9.61 9.46 9.32 9.41 9.67 9.76 9.44 9.59 9.25
m0215 m0224 m0227 m0259 m0290 m0300 m0305 m0329 m0380 m0408
12.79 12.76 12.78 12.69 12.65 12.61 12.59 12.61 12.55 12.40
9.67 9.08 9.70 9.37 9.59 9.21 8.77 9.22 9.37 9.20
m0501 m0549 m0616 m0664 m0721 m0763 m0858 m0908 m0948 m0959
12.41 12.41 12.32 12.29 12.23 12.26 12.20 12.13 12.14 12.09
9.30 9.01 8.89 9.03 8.87 8.72 9.28 8.93 8.54 8.76

Result

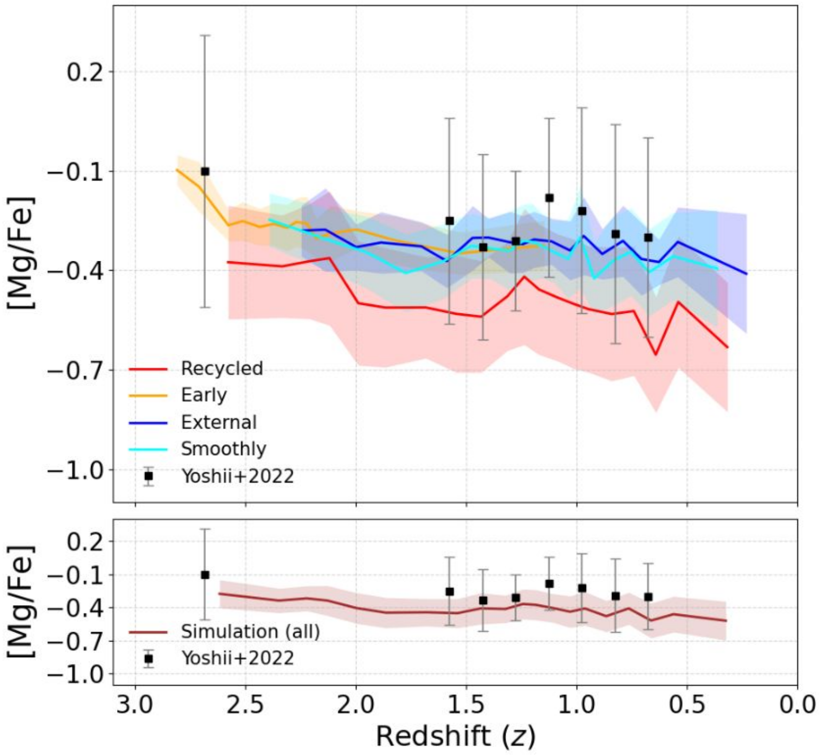


m0053
m0125
Recycled
Early
External
Smooth
r/r_{vir}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
[Z/H]
0
−2
−4
−6
−8
5
4
3
2
1
0

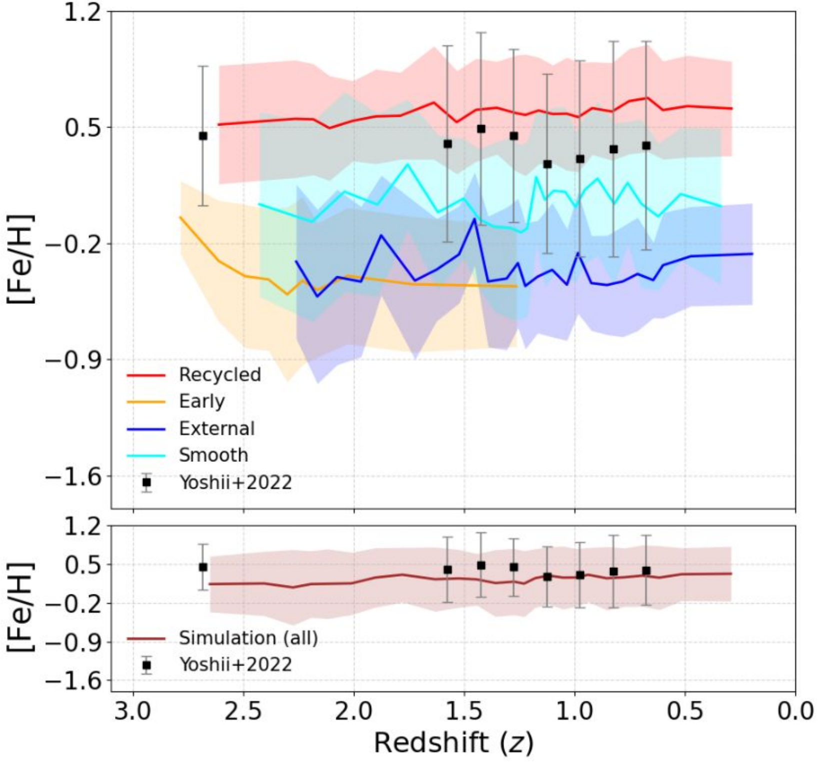
Result w/wo Sameshima+2020



Result



[Mg/Fe]
0.2
−0.1
−0.4
−0.7
−1.0
Recycled
Early
External
Smoothly
Yoshii+2022
[Mg/Fe]
0.2
−0.1
−0.4
−0.7
−1.0
Simulation (all)
Yoshii+2022
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Redshift (z)



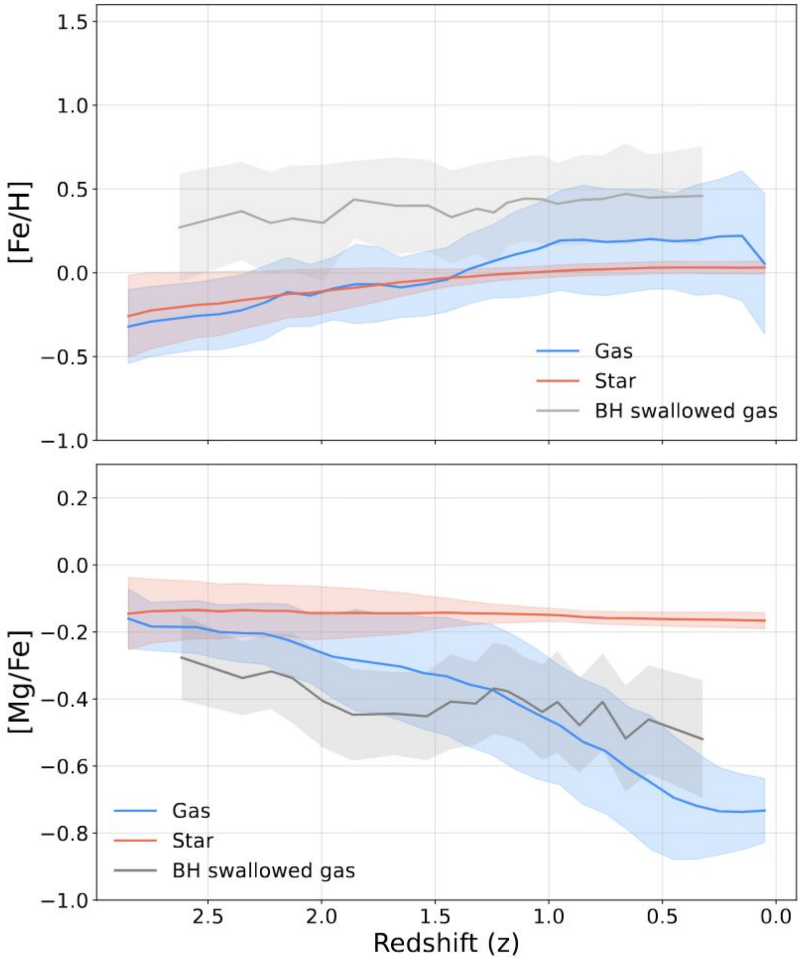
[Fe/H]
1.2
0.5
−0.2
−0.9
−1.6
Recycled
Early
External
Smooth
Yoshii+2022
[Fe/H]
1.2
0.5
−0.2
−0.9
−1.6
Simulation (all)
Yoshii+2022
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Redshift (z)

Result

Table 1. Spearman rank-order correlation between swallow redshift and abundance ratios of swallowed gas particles. r_s is the Spearman correlation coefficient and p is the two-sided p-value for the null hypothesis of no correlation. N_s denotes the number of swallowed particles in each category.

	[Fe/H]		[Mg/Fe]		
Category	r_s	p	r_s	p	N_s
Early	−0.10	10^{-12}	0.45	10^{-33}	630
Recycled	0.09	10^{-2}	0.26	10^{-70}	4340
External	0.04	5×10^{-1}	0.13	10^{-7}	1269
Smooth	−0.04	5×10^{-2}	0.13	10^{-8}	1826
Total	−0.11	10^{-23}	0.24	10^{-108}	8065

Result


[Fe/H]
1.5
1.0
0.5
0.0
−0.5
−1.0
Gas
Star
BH swallowed gas
[Mg/Fe]
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
Gas
Star
BH swallowed gas
2.5
2.0
1.5
1.0
0.5
0.0
Redshift (z)

Take home message

High-z Metal-rich AGNs

Even at high redshift, gas swallowed by central black holes is **already metal-rich**, indicating early chemical enrichment consistent with **Yoshii et al (2022).**

Recycled Gas Enrichment

Recycled gas from old stellar populations is a major source of BLR metal enrichment.

Comparison with Observations

Simulation **[Mg/Fe]** values are comparable in order of magnitude to the observed [Mg/Fe] ratios, showing quantitative consistency.

Q&A