How Gas Accretion Feeds Galactic Disks

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Abstract

Numerous observations indicate that galaxies need a continuous gas supply to fuel star formation and explain the star formation history. However, direct observational evidence of gas accretion remains rare. Using the EAGLE cosmological hydrodynamic simulation suite, we study cold gas accretion onto galaxies and the observational signatures of the cold gas kinematics. For EAGLE galaxies at $z = 0.27$, we find that cold gas accretes onto galaxies anisotropically with typical inflow speeds between 20 and 60 km s$^{-1}$. Most of these galaxies have comparable mass inflow rates and star formation rates, implying that the cold inflowing gas plausibly accounts for sustaining the star-forming processes of the galaxies. As motivation for future work to compare the cold gas kinematics with measurements from quasar sightline observations, we select an EAGLE galaxy with an extended cold gas disk, and we probe the cold gas using mock quasar sightlines. We demonstrate that by viewing the disk edge on, sightlines at azimuthal angles below 10° can detect cold gas that corotates with the galaxy disk. This example suggests that cold gas disks extending beyond the optical disks possibly explain the sightline observations that detect corotating cold gas near galaxy major axes.

Key words: galaxies: evolution – galaxies: formation – galaxies: halos – quasars: absorption lines

1. Introduction

Observations have indicated the need for gas accretion onto galaxies. Infalling gas prolongs the gas consumption times of galaxies, or else the star formation of galaxies would exhaust the gas within a few gigayears (Gyr; Bigiel et al. 2008, 2011; Leroy et al. 2008, 2013; Rahman et al. 2012). Gas infall helps regulate galaxy star formation and is responsible for the color of galaxy disks along the Hubble sequence (Kennicutt 1998). Continuous accretion of metal-poor gas explains the relative paucity of low-metallicity stars in the disk, known as the G-dwarf problem in the solar neighborhood (van den Bergh 1962; Schmidt 1963; Sommer-Larsen 1991), and is also observed in other galaxies (e.g., Worthey et al. 1996). These observations strongly suggest the need for galaxy gas accretion.

However, direct observation of gas accretion onto galaxies remains sparse (Putman et al. 2012). Although the Milky Way (MW) is accreting gas (e.g., the Magellanic Stream; Fox et al. 2014), our location in the MW makes it difficult to detect inflowing gas besides high-velocity clouds (Zheng et al. 2015). Beyond the local universe, the detection rate of net inflow identified from galaxy spectra stays low at roughly 5% (Martin et al. 2012; Rubin et al. 2012). These down-the-barrel galaxy observations have been challenged by the fact that inflowing gas can be identified only if the Doppler shift can be distinguished from the velocity dispersion of the interstellar medium (ISM). Otherwise, the inflowing gas will produce absorption that overlaps with the dense ISM in wavelength (or velocity) space, and the true inflow mass flux will be underestimated.

In contrast to down-the-barrel observations, transverse sightlines through the circumgalactic medium (CGM; Tumlinson et al. 2017) eliminate the problem of overlapping absorption from the intervening CGM and the ISM. Transverse sightlines probe the CGM against bright background sources such as quasars. Recent quasar sightline studies use a series of metal absorption-line systems to provide better constraints on the significant cool ($\sim 10^4$–$10^5$ K) gas mass in the CGM. Together with the warm-hot phase, the CGM potentially accounts for at least half and up to all of the missing baryons associated with galaxy halos (Werk et al. 2014; Prochaska et al. 2017; also see Stocke et al. 2013).

Recent measurements of circumgalactic absorption along quasar sightlines draw attention to the inhomogeneous distribution of baryons in the CGM. Sightlines along the galaxy major or minor axes frequently detect absorption systems with large equivalent widths and broad velocity ranges, but these strong absorbers are largely absent from sightlines that do not align with either of the two axes (Bouché et al. 2012; Kacprzak et al. 2012, 2015; Nielsen et al. 2015). This bimodality in spatial geometry suggests that the position of the sightline relative to the galactic disk potentially distinguishes the origin of the circumgalactic absorption.

Sightlines along galaxy major axes often detect circumgalactic absorption with the Doppler shift sharing the same sign as the galactic disk. This implies that the CGM corotates with the galaxy disks out to large radii (Steidel et al. 2002; Kacprzak et al. 2010, 2011; Bouché et al. 2013, 2016; Diamond-Stanic et al. 2016; Ho et al. 2017; Martin et al. 2019). However, a simple rotating disk poorly reproduces the broad velocity ranges spanned by the absorption (Steidel et al. 2002; Kacprzak et al. 2010, 2011; Ho et al. 2017). Some studies even demonstrate that the corotation can be modeled as inflowing gas with a disk-like geometry (Bouché et al. 2016; Bowen et al. 2016; Ho et al. 2017). Hence, probing the CGM along galaxy major axes provides a promising strategy to explore how galaxies obtain their gas.

From the theoretical perspective, circumgalactic gas, especially for gas accreted in “cold mode,” has significant angular momentum, which can lead to corotation. In contrast to the “hot mode,” where shock-heated gas cools and accretes onto the central galaxies isotropically (Full & Efstathiou 1980; Mo et al. 1998), cold-mode gas has a cooling time shorter than the time needed to establish a stable shock (Kereš et al. 2005; Dekel & Birnboim 2006). Recent hydrodynamical simulations
emphasize the importance of cold-mode accretion. In addition to accreting along filamentary streams, cold-mode gas has a higher specific angular momentum than its dark matter and hot-mode gas counterparts (Kereš et al. 2009; Brook et al. 2011; Kimm et al. 2011; Stewart et al. 2011, 2013, 2017; Teklu et al. 2015; Stevens et al. 2017).

In hydrodynamical simulations, galactic disks grow by accreting cooling, high angular momentum gas from the CGM. As gas streams fall toward a galaxy, torques generated by the disk align the infalling gas with the pre-existing disk (Danovich et al. 2012, 2015). The newly accreted gas forms an extended cold flow disk, which corotates with the galaxy out to large radii (Stewart et al. 2011, 2013). With gas accreted at later times having higher specific angular momentum, galaxy disks thereby grow inside out (Kimm et al. 2011; Pichon et al. 2011; Lagos et al. 2017; El-Badry et al. 2018).

This paper presents results from the EAGLE simulation suite (Crain et al. 2015; Schaye et al. 2015; McAlpine et al. 2016). EAGLE has been found to produce a realistic galaxy population and broadly reproduce a number of observations. These include the $z \sim 0$ galaxy stellar mass function and the Tully–Fisher relation (Schaye et al. 2015), the evolution of galaxy masses (Furlong et al. 2015), the color bimodality of galaxies (Trayford et al. 2015, 2016), and the atomic (Bahé et al. 2016; Crain et al. 2017) and molecular gas (Lagos et al. 2015) content of galaxies. Similar to other hydrodynamical simulations that show cold gas with high specific angular momentum, Stevens et al. (2017) have demonstrated that both cooling gas and hot gas in EAGLE have higher specific angular momentum than the dark matter halo. Previous works using the EAGLE simulations (and OWLS; Schaye et al. 2010) have also demonstrated the importance of cold gas accretion onto galaxies (van de Voort et al. 2011; Correa et al. 2018a, 2018b). Turner et al. (2017) have compared EAGLE mock spectra with metal-line absorption data of $z \approx 2$ star-forming galaxies (Turner et al. 2014) in the Keck Baryonic Structure Survey (KBSS; Rudie et al. 2012; Steidel et al. 2014). The comparison has found evidence of infalling gas that explains the observed redshift-space distortions.

Using the EAGLE simulations, we examine how cold gas accretes onto galaxies and relate the gas kinematics to measurements in quasar sightline observations. We identify the inflowing gas particles using two methods: (i) the analytical ballistic approximation that predicts the motion of particles under the influence of gravity, and (ii) tracking particles through time in EAGLE, which includes full hydrodynamic calculations. We study and compare the inflow properties from identifying inflow particles using the two methods, and we gain insight into the factors that affect whether a cold gas particle reaches the inner galaxy within a disk rotation period. To motivate the use of EAGLE simulations to explain the CGM observations in the future, we use mock sightlines to probe the cold gas around one of the EAGLE galaxies. We identify the structural features that can reproduce the corotation signature and the broad velocity ranges detected in quasar sightline observations. We defer the spectral analysis and the use of a large galaxy sample to a future paper.

We present the paper as follows. Section 2 describes the EAGLE galaxy selection at $z = 0.27$, and we demonstrate that the short gas consumption time demands an external gas supply. Then we identify the cold inflowing gas that feeds the inner galaxies and examine the inflow properties. We show the results of using the ballistic approximation and particle tracking in Sections 3 and 4, respectively. In Section 5, we probe the cold gas around an EAGLE galaxy using mock quasar sightlines, and we focus on the gas structures that corotate with the disk and span broad velocity ranges. Finally, we summarize our results in Section 6.

### 2. Galaxy Selection from the EAGLE Simulation

#### 2.1. Simulation Overview

The EAGLE simulation suite consists of a large number of cosmological, hydrodynamic simulations (Crain et al. 2015; Schaye et al. 2015; McAlpine et al. 2016). EAGLE was run on a modified version of the $N$-body Tree-PM smoothed particle hydrodynamics (SPH) code GADGET–3 (last described in Springel 2005). State-of-the-art subgrid models were implemented to capture unresolved physics, including radiative cooling and photoheating, star formation, stellar evolution and enrichment, stellar feedback, black hole growth, and feedback from active galactic nuclei. The simulations also varied in cosmological volumes, resolutions, and subgrid physics, and the stellar feedback was calibrated to reasonably reproduce the sizes of disk galaxies and the galaxy stellar mass function at $z = 0$.

EAGLE defines galaxies as gravitationally bound subhalos identified by the SUBFIND algorithm (Springel et al. 2001; Dolag et al. 2009). In brief, first the friends-of-friends (FoF) algorithm (Davis et al. 1985) places dark matter particles into the same group if the particle separation is below 0.2 times the average particle separation. Baryons are associated with the same FoF halo (if any) as their closest dark matter particle. Then, within FoF halos, SUBFIND defines self-bound overdensity substructures as subhalos, and each subhalo represents a galaxy. Within each FoF halo, the subhalo that contains the particle with the lowest value of gravitational potential is the central galaxy. The remaining subhalos are classified as satellite galaxies.

In this pilot study, we use the simulation Ref-L012N0188 with a box size of 12.5 cMpc. In the future, we will expand our study to large simulations and with higher resolutions. We summarize the simulation parameters in Table 1. We use the particle data output\(^8\) and mainly focus on galaxies at a single “snapshot” of $z = 0.271$; this redshift is comparable to

| Simulation Property | Value |
|---------------------|-------|
| (1) Box size $L$ (cMpc) | 12.5 |
| (2) Number of particles $N$ | 188$^3$ |
| (3) Initial baryonic mass $m_b$ ($M_*$) | $1.81 \times 10^8$ |
| (4) Dark matter particle mass $m_{dm}$ ($M_*$) | $9.70 \times 10^8$ |
| (5) Gravitational softening length $\epsilon_{	ext{soft}}$ (kpc) | 2.66 |
| (6) Maximum softening length $\epsilon_{\text{sub}}$ (kpc) | 0.70 |

Note. (1) Convolving box size. (2) Number of dark matter particles (initially there is an equal number of baryonic particles). (3) Initial baryonic particle mass. (4) Dark matter particle mass. (5) Convolving Plummer-equivalent gravitational softening length. (6) Maximum proper softening length.

\(^8\) Particle data from snapshots can be downloaded from [http://icc.dur.ac.uk/Eagle/database.php](http://icc.dur.ac.uk/Eagle/database.php).
the galaxy redshifts in quasar absorption-line studies that measure the CGM kinematics of low-redshift galaxies (e.g., Ho et al. 2017; Martin et al. 2019). In Section 4, we also show results from particle tracking at time steps finer than consecutive snapshots; we use the reduced set of particle properties in “snapshots.”

2.2. Defining Cold Gas

In the simulation, we identify cold gas particles using temperature cutoffs. For most of this work, especially when we focus on cold inflowing gas (Sections 3 and 4), we select cold gas using a temperature cutoff of $2.5 \times 10^4$ K. This cutoff has been commonly used to distinguish between cold-mode and hot-mode accretion (Kereš et al. 2005, 2009; Stewart et al. 2013, 2017). However, when we compare cold gas kinematics to quasar sightline observations (Section 5), which detect absorption from low-ionization ions (e.g., Mg II, Si II, Fe II), we redefine the cutoff as $3 \times 10^4$ K. This is because low ions such as Mg II do not exist at $\sim 10^5$ K (Oppenheimer & Schaye 2013; Tumlinson et al. 2017).

In addition, we assign all star-forming gas as “cold” gas, because in EAGLE, the temperature of the star-forming (i.e., interstellar) gas is artificially increased to reflect the effective pressure. EAGLE lacks the resolution to resolve the interstellar gas phase of $T_{\text{gas}} \ll 10^5$ K. Hence, EAGLE imposes a temperature floor, such that the corresponding effective equation of state prevents numerical Jeans fragmentation, due to the finite resolution (Schaye & Dalla Vecchia 2008; also see Robertson & Kravtsov 2008 and Schaye & Dalla Vecchia 2008).

2.3. Galaxy Selection

We select galaxies at $z = 0.271$ with a stellar mass range of $\log(M_*/M_\odot)$ between 9.5 and 10.5, comparable to that of the galaxy samples in Ho et al. (2017) and Martin et al. (2019), who studied the CGM kinematics of low-redshift galaxies. To measure the stellar mass of each galaxy, we use a 3D aperture with a radius of 30 pkpc from the galaxy center$^4$ and sum over the masses of star particles that belong to the subhalo (as defined in Schaye et al. 2015). Figure 1 shows the selected galaxies on the SFR–$M_*$ plane, for which we use the same 30 pkpc aperture to measure the SFR. We show the SFR–$M_*$ main sequence from Peng et al. (2010), fitted to the star-forming galaxies in the Sloan Digital Sky Survey (SDSS) from Brinchmann et al. (2004). We also plot the line that divides star-forming and quiescent galaxies (Moustakas et al. 2013); the line comes from a redshift-dependent relation using $\sim 120,000$ galaxies with spectroscopic redshifts from the PRism MUlti-object Survey (PRIMUS; Coil et al. 2011; Cool et al. 2013) and SDSS. Figure 1 shows that our selected galaxies lie along the main sequence. Star-forming galaxies dominate our sample, with most of them being central galaxies.

The halo virial masses of our sample range from $\log(M_{\text{vir}}/M_\odot)$ of 11.5 to 12.6. We define the virial radius $r_{\text{vir}}$ as the radius that encloses an average density of $\Delta_{\text{vir}}(z)\rho_c(z)$, where $\rho_c(z)$ represents the critical density at redshift $z$, and the overdensity $\Delta_{\text{vir}}(z)$ follows the top-hat spherical collapse calculation in Bryan & Norman (1998)$^5$.

The galaxy center is defined as the location of the most-bound particle of the subhalo.

At $z = 0.271$, $\Delta_{\text{vir}}(z) = 124$.

![Figure 1. Galaxies on the SFR–$M_*$ plane. Black filled and red empty circles represent central and satellite galaxies, respectively. The brown dotted line and the shaded region show the star-forming main sequence and the 0.3 dex scatter from Peng et al. (2010), which fit the SDSS star-forming galaxies in Brinchmann et al. (2004). The cyan dashed line divides the sample into star forming or quiescent, depending on whether the galaxies lie above or below the line (Moustakas et al. 2013). The selected galaxies lie along the main sequence, and most galaxies are star forming.](image)

2.4. Global Gas Consumption Timescale

The gas consumption timescale is sometimes referred to as the “Roberts time” (Roberts 1963), which is defined using the following relation (Kennicutt et al. 1994, hereafter K94),

$$
\tau_R = \frac{M_{\text{gas}}/\text{SFR}}{1 - R},
$$

where $R$ is the returned gas fraction. The $(1 - R)^{-1}$ correction factor accounts for the gas re-cycling and future time dependence on SFR. K94 have analyzed how $(1 - R)^{-1}$ changes with different parameters, such as initial mass functions, star formation laws, and gas surface density, etc. From their time-dependent modeling of the gas return rate (from stars), they suggest that re-cycling gas extends the $\tau_R$ of typical star-forming disks by 1.5–4 times.

For our selected EAGLE galaxies, we calculate the gas consumption time $\tau_R$ using Equation (1). Including gas beyond the star-forming region will overestimate the actual gas depletion time in the inner galaxy regions, where star formation takes place. To avoid this overestimation, first we define the star-forming radius $r_{\text{SFR90}}$ as the radius that encloses 90% of the galaxy SFR, and we round it up to the closest 5 pkpc.$^6$ Then, we calculate $\tau_R$ using the gas mass and SFR within a 3D aperture of radius $r_{\text{SFR90}}$. In addition, we impose limits on gas temperature $T_{\text{gas}}$ while calculating the gas mass: all $T_{\text{gas}} \leq 2.5 \times 10^4$ K, and $T_{\text{gas}} \leq 3 \times 10^4$ K.

Figure 2 shows the distribution of the gas consumption time $\tau_R$ of the galaxies. We show $\tau_R$ before and after applying the $(1 - R)^{-1}$ correction factor, i.e., set $(1 - R)^{-1} = 1$ or use an

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$^4$ The galaxy center is defined as the location of the most-bound particle of the subhalo.

$^5$ At $z = 0.271$, $\Delta_{\text{vir}}(z) = 124$.

$^6$ We round up to the closest 1 pkpc, if the star-forming radius is below 5 pkpc.
accretion, the accreted gas will remain cold during accretion. Therefore, we focus on the accretion of cold gas onto galaxies. In Section 4, by identifying inflowing gas through tracking particles, we will verify that, at least for our selected central galaxies in EAGLE, inflow from hot gas is negligible. That will justify our focus on only cold gas in this section.

We want to identify the cold gas particles that will fall into the galactic disk within a rotation period. In principle, we can do so by tracking particles through time. However, the simulation only produces snapshot output at coarse redshift (i.e., time) intervals typically larger than a rotation period. And in general, tracking the particle positions at time steps finer than the default simulation output requires rerunning the simulation, which may be impossible if one only has access to output at preset time intervals. Running future cosmological simulations will also become more computationally expensive, making it hard or even impossible to save the full simulation output at fine time steps. As a result, the reconstruction of gas infall rates by tracking particles through time will be difficult. Therefore, in this section, we introduce a procedure to estimate the infall from the simulation output at a single time step.

We ignore pressure forces on the cold gas and calculate the orbits of gas particles in the gravitational potential. Orbits that reach pericenter beyond the galactic disk cannot feed the disk. We are interested in the orbits that intersect the galactic disk, because the collision of the cloud with the gas disk or the dense star-forming region will dissipate energy. We assume such gas will be incorporated into the disk as fuel. We then estimate a mean accretion rate and the average inflow speed over a disk rotation period. We also examine the distribution of the inflowing gas and its angular momentum. Then, in Section 4, we will discuss the validity and the caveats of this simple, analytical calculation of the ballistic approximation, and we will explore whether the ballistic approximation can reasonably reproduce the inflow properties. For the analysis in this section and Section 4, we will only focus on the central galaxies and exclude the satellite galaxies.

### 3. Identification of Inflowing Cold Gas

We aim to understand how galaxies get the gas to fuel star formation. Hot, virialized gas does not directly accrete onto galaxies. Even in the hot-mode accretion scenario, the virialized gas has to cool and condense, before being accreted to form stars. In the cold-mode scenario, the accreted gas remains cold during accretion. Therefore, we focus on the accretion of cold gas onto galaxies. In Section 4, by identifying inflowing gas through tracking particles, we will verify that, at least for our selected central galaxies in EAGLE, inflow from hot gas is negligible. That will justify our focus on only cold gas in this section.

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#### 3.1. Ballistic Approximation

To identify the inflowing cold gas ($T_{\text{gas}} \leq 2.5 \times 10^5$ K), we predict whether individual cold gas particles can reach the star-forming region within a rotation period. We define the star-forming region as a spherical region of radius $r_{\text{SFR0}}$ (defined in Section 2.4) from the galaxy center. We set the rotation period as $4 \times (3\pi)/(16G \langle \rho \rangle)$, where $\langle \rho \rangle$ represents the average density of the star-forming region. We calculate each particle orbit within a rotation period of the star-forming region. Each particle conserves energy and angular momentum, and the particle moves in a centrally directed gravitational field characterized by the dark matter. In the absence of hydrodynamical interactions between particles, the gravitational force determines the particle trajectory. Hence, we characterize the radial motion of each particle by

$$\ddot{r} = f_{\text{grav}}(r) + \frac{j^2}{r^3},$$  

(2)

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5 \((1 - R)^{-1} = 2.5\) is also adopted in other publications, e.g., Boselli et al. (2001).

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Figure 2. Distribution of gas consumption time. We calculate the gas consumption time using the gas mass and SFR within the star-forming radius $r_{\text{SFR0}}$. Within each histogram bin, different colors of the filled histograms distinguish the use of gas masses with different temperature limits. The bottom and top axes show the timescale before and after applying the gas re-cycling correction factor, i.e., $(1 - R)^{-1} = 1$ or 2.5. The black histogram shows the gas consumption time distribution of nearby galaxies in Kennicutt et al. (1994), and their calculation includes only the gas mass within the star-forming disk. Even with the $(1 - R)^{-1}$ correction factor, at least half of the EAGLE galaxies have gas consumption timescales shorter than the Hubble time.

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(2)

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5 \((1 - R)^{-1} = 2.5\) is also adopted in other publications, e.g., Boselli et al. (2001).
\( e = \frac{1}{2} f^2 + \frac{j^2}{2r^2} + \Phi_{\text{grav}}(r), \)

where \( f_{\text{grav}}(r) = -\frac{\partial \Phi_{\text{grav}}(r)}{\partial r} \) represents the gravitational force per unit mass at radius \( r \), and \( j \) and \( \varepsilon \) represent the constant specific angular momentum and energy of the particle. If the particle orbit ever intersects the star-forming region, then we consider the particle as inflowing.

We justify our assumption of gravitational force dominating over the pressure force on the cold gas as follows. Analogous to a multiphase ISM model, gases of different phases, e.g., cold (\( \sim 10^3 \) K) and hot (\( \sim 10^6 \) K) gas, reach pressure equilibrium and thereby share a similar pressure gradient, i.e., \( \nabla P_{\text{cold}} \approx \nabla P_{\text{hot}} \). The cold gas has a higher density, i.e., \( \rho_{\text{cold}} \gg \rho_{\text{hot}} \), because gas density scales inversely with temperature. As a result, the cold gas experiences a smaller pressure force because
For the virialized hot gas, the pressure force balances the gravitational pull and prevents the gas from collapsing, due to its own gravity. Because the cold gas experiences a smaller pressure force than the hot gas, the pressure force on the cold gas is negligible compared to gravity. Hence, for the cold gas, the gravitational force dominates.

We expect the ballistic approximation to break down under the following circumstances. First, if the cold gas clouds...
intercept hot gas with a comparable mass column density, then the cold gas will be suspended by the hot gas, which prevents the cold clouds from falling in. Because this scenario violates the assumption of the ballistic approximation that the gravitational force dominates over the pressure force, the ballistic approximation becomes invalid. Second, although we assume any gas that reaches the star-forming region will be incorporated into the disk, this ignores the presence of galactic winds. Not only can winds remove gas that has once accreted onto the star-forming disk, they can also push out gas that would otherwise be accreted. Consequently, whether the gas remains in the disk as fuel is sensitive to feedback, which the ballistic approximation ignores. Third, gas particles may lose angular momentum, due to the interactions and collisions between them, e.g., with other cold infalling gas particles or with the pre-existing disk (Danovich et al. 2015; Stevens et al. 2017).

The angular momentum dissipation thereby depends on the distribution of the gas particles and the frequency of particle collision, which the ballistic approximation ignores. Keeping these caveats in mind, we will identify the inflowing gas and predict the inflow properties using this analytical calculation. Section 4 will explore the validity of the ballistic approximation. We will show that although the ballistic approximation can estimate the mass inflow rate to within a factor of 2 compared to that from particle tracking, the prediction is less accurate for the average radial inflow speed. Our analysis will thereby suggest that generally, the reconstruction of gas inflow properties, including inflow rates and inflow speeds, will benefit from simulation output at higher time cadence, e.g., at the order of the rotation timescale of $\sim 100$ Myr.

### 3.2. Geometry of the Inflowing Cold Gas

In this section, we examine the distribution and the morphological structure of the inflowing cold gas. As an example, we show a galaxy (ID: 37448) in Figure 3, and we project the cold gas particles ($T_{\text{gas}} \lesssim 2.5 \times 10^6$ K) onto 2D planes. First, panels (a) to (c) indicate that the galaxy has a rotating structure. The blueshifted and redshifted particle projected velocities clearly show that the galaxy has an approaching and a receding side. Second, panel (a) also illustrates that most particles reside in a thin structure, and the galaxy resembles a disk morphology. To visualize the distribution of the inflowing gas, in panels (d) to (f), the colors of the gas particles show whether the particles will reach the star-forming region, i.e., inflowing. Most inflowing gas particles (red dots) reside in the outer spiral arms.

Analogous to Figure 3, Figure 4 shows the remaining 10 central galaxies, and we use the same color scheme as in Figures 3(d) to (f) to distinguish the inflowing particles. A similar figure with particles color-coded by the particle projected velocities can be found in the Appendix. The particle projection plots in Figures 3 and 4 (and the Appendix) show that despite the different morphologies among galaxies, most galaxies have rotating structures. The infalling gas particles are distributed anisotropically and form a variety of structures, e.g., particles are concentrated along streams or are located near the thin, “disk-like” structures as in Figure 3.

![Figure 5. Spatial distribution of cold inflowing gas particles relative to warped disk planes. The left and the right panels show the cumulative mass profiles of the inflowing gas in the radial $R$ and perpendicular $Z$-directions relative to the disk planes (i.e., in cylindrical coordinates), respectively. Both $R$ and $Z$ are normalized by the galaxy virial radius $r_{\text{vir}}$, and the mass profiles are normalized by the total mass of the inflalling gas. The thin cyan lines represent individual central galaxies, and the thick orange solid and dashed lines show the median and the 68% confidence level. As measured from the median profiles, enclosing 90% of the inflowing gas mass requires $R \approx 0.35 r_{\text{vir}}$ and $|Z| \approx 0.2 r_{\text{vir}}$ (black dotted lines). The inflowing gas particles extend farther in the $R$-direction compared to the $|Z|$-direction.](image)

To quantify the spatial distribution of inflowing gas particles, we calculate their positions relative to the plane of the cold gas disk. For each galaxy, we define the disk plane using the net angular momentum vector of cold gas. We allow the disk plane to change with radius, because H1 observations often find warped gas disks (e.g., Heald et al. 2011; Zschaechner et al. 2012), and we measure the net angular momentum vector in concentric shells with thickness of $\Delta r = 10$ pkpc. Figure 5 shows the cumulative mass profiles of the inflowing gas relative to the warped disk planes. The thin cyan lines represent individual central galaxies, and the thick orange solid and dashed lines represent the median and the 68% confidence levels of the sample. The profiles show that the inflowing particles extend farther in the $R$-direction on the disk plane than in the $|Z|$-direction perpendicular to the disk plane. As an illustration, the black dotted lines show that from the median profiles, $R \approx 0.35 r_{\text{vir}}$ encloses 90% of the inflowing gas mass, in contrast to 0.2$r_{\text{vir}}$ in the $|Z|$-direction. On the one hand, 0.2$r_{\text{vir}}$ or tens of pkpc (Table 2 shows $r_{\text{vir}}$ of each galaxy) along the $|Z|$-direction implies that the infalling particles do not just lie on a thin disk. But on the other hand, as the inflowing gas particles extend farther in the $R$-direction than in the $|Z|$-direction, the gas tends to have a cylindrical structure, instead of an isotropic distribution.

### 3.3. Angular Momentum of Inflowing Gas

Figures 3(g) and (h) show the specific angular momentum $|j|$ of each cold gas particle. To be rotationally supported, each particle requires a specific angular momentum of $|j|/|k_{\text{circ}}| = |r| r_{\text{circ}}$ (solid line), where $r_{\text{circ}}$ is the circular velocity at radius $r$. Except for the inflowing gas at $r \approx r_{\text{SFR90}}$, most inflowing particles have $|j|/|k_{\text{circ}}| < 1$. Thus, these particles lack sufficient angular momentum to be on circular orbits. The inflowing gas of other central galaxies also show the same characteristics.

Without angular momentum, a particle will fall radially toward the galaxy center due to gravity. Angular momentum provides rotational support for a particle. Under the assumption of angular momentum conservation, the particle $|j|$ defines the pericenter of the particle orbit, and only particles with pericenters smaller than the star-forming radius $r_{\text{SFR90}}$ can...
possibly be considered inflowing. In reality, however, a particle may lose angular momentum, due to tidal interactions with the existing disk. Hence, the predicted pericenter represents an upper limit, and more particles than predicted may reach \( r_{\text{SFR}90} \) within a rotation period.

### 3.4. Average Mass Inflow Rate and SFR

Unless galaxies replenish their gas, galaxies will eventually quench due to the lack of fuel. The inflow rate provides an important clue of whether a galaxy can sustain its star formation rate. To calculate the average mass inflow rate \( M_{\text{in}}^{\text{ballistic}} \), we sum over the mass of the inflowing cold gas and divide it by the rotation period of each galaxy. We list the \( M_{\text{in}}^{\text{ballistic}} \) for individual galaxies in Table 2. Figure 6 compares \( M_{\text{in}}^{\text{ballistic}} \) to the galaxy SFR (blue circles), and the figure shows that \( M_{\text{in}}^{\text{ballistic}} \) exceeds the SFR for all central galaxies.

Equality between the average mass inflow rate and the galaxy SFR does not imply a sustainable star formation rate. Gas outflows remove gas from the galaxy and thereby demand a higher inflow rate to support star formation, whereas the recycling stellar gas reduces the need for new gas supply. In a self-sustaining evolution model, i.e., an equilibrium model, a galaxy reaches equilibrium when the gas inflow rate is equal to a linear combination of the SFR and the gas outflow rate (Bouché et al. 2010; Davé et al. 2012). Under the equilibrium condition, we express the inflow rate \( M_{\text{gas,in}} \) as

\[
M_{\text{gas,in}} = (1 - R) M_* + M_{\text{gas,out}}.
\]

where \( M_{\text{gas,out}} \) and \( M_* \) represent the mass outflow rate and SFR, respectively. The \( (1 - R) \) factor corrects for the gas re-cycling fraction, and hence \( (1 - R)M_* \) represents the corrected net SFR. The mass outflow rate scales with the SFR according to the mass-loading factor, \( \eta = M_{\text{gas,out}}/\text{SFR} \). For simplicity, we use \( R = 0.52 \) as in Bouché et al. (2010).\(^9\) While \( \eta \) is not well constrained in observations, due to the uncertainties in mass outflow rates, we adopt \( \eta \sim 1 \) and 2 (dotted and dotted–dashed lines, respectively, in Figure 6), typically inferred from observations for galaxies with stellar masses similar to our EAGLE galaxies (Martin et al. 2012; Kacprzak et al. 2014; Heckman et al. 2015), as well as dwarf galaxies (Martin et al. 1999) and infrared-luminous galaxies (Rupke et al. 2005). Figure 6 shows that the inflow rates are comparable to that expected from the equilibrium models, suggesting that the cold inflowing gas plausibly accounts for sustaining the galaxy star formation activities. We further discuss the comparison between inflow rates and SFRs and the implication in Section 4.2.

### 3.5. Mass-weighted Average Inflow Speed

To estimate the average inflow speed over the rotation period, we take the mass-weighted average of the inflow speeds of individual inflowing cold gas particles. First, for each inflowing cold gas particle, we calculate its inflow speed from the change in radial distance from the galaxy center, \( \Delta r \), and divide it by the rotation period. However, the ballistic approximation breaks down when the particle enters the star-forming region. Once the gas particle collides with the dense gas clouds in the star-forming region and dissipates energy, our assumption of energy conservation no longer holds. Therefore, we estimate \( \Delta r \) by differentiating the initial particle radial position and the star-forming radius \( r_{\text{SFR}90} \); we assume the particle halts once it reaches \( r_{\text{SFR}90} \). Then, we weight the inflow speeds of all inflowing gas particles by their particle masses, and we obtain the mass-weighted average inflow speed \( \langle v_{\text{in}}^{\text{ballistic}} \rangle \) for each galaxy.

Table 2 lists the mass-weighted average inflow speed \( \langle v_{\text{in}}^{\text{ballistic}} \rangle \) for the central galaxies, which ranges from 17 to 62 km s\(^{-1} \). Although most particles have low inflow speeds, resulting in low \( \langle v_{\text{in}}^{\text{ballistic}} \rangle \), the particle inflow speeds often span a large range, and the distribution has a high-velocity tail. To characterize the spread in individual inflow speeds, we also estimate the mass-weighted average inflow speed using the subset of particles with the highest inflow speeds; this particle subset accounts for 10% of the total inflowing gas mass. We

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9 Adopting \( R = 0.6 \) as in Section 2.4 will have a negligible effect on the equilibrium expectation in Figure 6.
show this average inflow speed from the “high-speed tail” as \( \langle v_{\text{in,ballistic}} \rangle_{\text{in,top10\%}} \) in Table 2. For most galaxies, \( \langle v_{\text{in,ballistic}} \rangle_{\text{in,top10\%}} \) exceeds 100 km s\(^{-1}\). The significant difference between \( \langle v_{\text{in}} \rangle_{\text{in,top10\%}} \) and \( \langle v_{\text{in,ballistic}} \rangle_{\text{in,top10\%}} \) demonstrates the large spread in particle inflow speeds despite the low mass-weighted average.

4. Ballistic Approximation versus Hydrodynamic Calculations

Instead of tracking particles through continuous time, the ballistic approximation provides an alternate method to predict the properties of gas inflows. To understand how the gas inflow properties from the ballistic approximation compare to those from the hydrodynamic calculations in \textsc{Eagle}, we track the gas particles through “snipshots.” Snipshots are output from the same \textsc{Eagle} run, sampled at finer time intervals but with less information per particle compared to the full “snipshot” output. This allows us to select the time slice around the rotation period of a galaxy. In Section 4.1, we explain how we track particles to define inflowing cold gas. Section 4.2 compares the average mass inflow rate obtained from both the ballistic approximation and particle tracking, whereas Section 4.3 compares the mass-weighted average inflow speed using the two methods. In Section 4.4, we explore how the newly accreted gas contributes to recent star formation. Section 4.5 discusses the limitations of the ballistic approximation and the caveats of comparing its inflow prediction to the outcome of \textsc{Eagle}’s hydrodynamical calculations.

4.1. Tracking Gas Particles to Identify Inflowing Gas

We follow each gas particle through \textsc{Eagle} snipshots, sampled at every \(~\sim 70 \) Myr around \( z \sim 0.271 \). To identify the inflowing cold gas particles for each galaxy, first we choose the snipshot for which the time evolved from \( z = 0.271 \) is closest to the galaxy rotation period. Hence, we use different snipshots for different galaxies. We define cold gas using the same criteria in Section 2.2. To classify a gas particle as inflowing, the particle has to reside beyond \( r_{\text{SFR90}} \) at \( z = 0.271 \) and have reached \( T_{\text{gas}}(z = 0.271) \) or deeper after the rotation period in the selected snipshots. If this particle has been converted into a star, we still classify it as an inflowing gas particle. Because only a tiny fraction of inflowing gas particles have turned into stars after a rotation period, our conclusions will not change even if we exclude this inflowing particle subset.

In our ballistic approximation, we have assumed that inflow from hot gas is negligible and only focused on cold gas with \( T_{\text{gas}} \lesssim 2.5 \times 10^3 \) K. Figure 7 justifies this assumption. Through particle tracking, comparing the inflow mass with and without applying a temperature cutoff \( T_{\text{gas}}(z = 0.271) \) (red hexagons and gray diamonds) shows that over 95% of the tracked inflowing gas (by mass) is cold. This implies that for our selected \textsc{Eagle} galaxies, inflow from cold gas dominates.

Using the results of particle tracking and the prediction of the ballistic approximation, Figure 7 compares the inflowing gas mass from both methods. The inflow mass from the ballistic approximation generally exceeds the traced inflow mass by a factor of 1.5–2 (blue circles). To understand what contributes to this factor of 2 overestimation, we subdivide the gas particles into three categories: (I) predicted cold inflow from the ballistic
The top panel shows the ratio between each of these quantities and the tracked gas at all temperatures. The gray diamonds show the tracked inflow rate from cold gas using the ballistic approximation, and the particles have reached an average radial distance relative to the galaxy center. Second, we divide the horizontal axis shows the average radial distance from the star-forming region, resulting in a low average inflow speed. We will discuss how feedback affects the average mass inflow rate in Section 4.5.

We also compare the tracked inflow rates to the galaxy SFRs in Figure 6 (red hexagons). Although the inflow rates from particle tracking are lower than those from the ballistic approximation, Figure 6 still shows that most galaxies have comparable inflow rates and SFRs. This suggests that even without other types of inflows, such as satellite accretion and hot gas accretion (negligible as deduced in Figure 7), the cold gas inflow alone can account for most of the fuel needed to sustain the star formation in galaxies.

4.3. Mass-weighted Average Inflow Speed from Particle Tracking

We calculate the average inflow speed as in Section 3.5, but with two differences. First, instead of assuming the inflowing gas particles halt at \( r_{SFR0} \), we calculate \( \Delta r \) as the change in radial distance relative to the galaxy center. Second, we divide \( \Delta r \) by the time evolved from \( z = 0.271 \) to the selected snapshot, instead of the galaxy rotation period. In Table 2, \( \langle v_{\text{in}} \rangle_{\text{tracking}} \) shows the mass-weighted average inflow speed, and \( \langle v_{\text{in, top10\%}} \rangle_{\text{tracking}} \) shows the mass-weighted average from only the top 10% of particles by mass that have the highest particle inflow speeds. Figure 9 shows these two sets of average inflow speeds calculated from the cold gas and compares them with the predicted inflow speeds from the ballistic approximation.

The average inflow speeds calculated from particle tracking share similar characteristics to those from the ballistic approximation: (1) low mass-weighted average inflow speed of \( \lesssim 60 \text{ km s}^{-1} \), (2) large range of individual particle inflow speeds
with a “high-speed tail,” and (3) if we only consider 10% of the particles by mass with the highest individual inflow speeds, then the mass-weighted average \((v_{\text{in, top10\%}}^{\text{tracking}}) / \text{in, top10\%})\) often exceeds 100 km s\(^{-1}\). In addition, for both sets of average inflow speeds, i.e., either from all cold gas or only cold gas particles at the high end of inflow speeds, the ballistic approximation overestimates the average inflow speeds for most galaxies. The differences in inflow speeds from the ballistic approximation and particle tracking mostly stay within a factor of 2. The only exception is the galaxy (ID: 48386) with feedback removing most of the gas from the star-forming region (see Sections 4.2 and 4.5).

However, unlike the mass inflow rate, which shows a correlation between the prediction from the ballistic approximation and the calculation from particle tracking, inflow speeds do not reveal the same characteristic. While one possible explanation is the mismatch of inflowing particles identified by the two methods, another reason is due to the assumption of the ballistic approximation. When we calculate the average radial inflow speed for the ballistic approximation, because the approximation breaks down when a particle interacts with the dense clouds in the star-forming region, we assume the particle halts when it reaches the star-forming region. However, in reality, where the particle ends up depends on the density and the distribution of cold gas within the star-forming region, both of which the ballistic approximation ignores. Therefore, even though the average radial inflow speeds from ballistic approximation and particle tracking agree within a factor of 2, the lack of correlation suggests that the ballistic approximation does not provide a satisfactory estimate of the inflow speed. Hence, this suggests that inflow speed estimation and, generally, the reconstruction of inflow properties require tracking particles at series of simulation output with higher time cadence, preferably of the order of \(\sim 100\) Myr, i.e., around (or shorter than) the rotation period of a galaxy.

4.4. Star Formation from Gas Accreted onto the Inner Galaxy

Gas accreted onto galaxies eventually forms stars. For each galaxy, we identify the gas at \(z = 0.271\) that has turned into stars at the selected snapshot after a rotation period. Although most of these particles reside within \(r_{\text{SFR90}}(z = 0.271)\) at both times, on average, around 10% of the new stars are formed from the newly accreted gas that originally resided outside of \(r_{\text{SFR90}}\).

Figure 10 shows two galaxy examples, and the red points illustrate the gas particles that have turned into stars after a rotation period. Most of these particles originally resided along the spiral arms. After a rotation period, these particles become more concentrated near each galaxy center, where some of these particles are newly accreted from outside of \(r_{\text{SFR90}}\). This demonstrates the fueling of star-forming activity from newly accreted gas. Moreover, some stars are formed outside the star-forming radius, which indicates the growth of the star-forming disk and the stellar disk. This qualitatively supports the picture of inside-out galaxy growth.

4.5. Limitations of the Ballistic Approximation

Using the ballistic approximation, both predicted inflow rate and mass-weighted average velocity generally agree with those from particle tracking to within a factor of 2. In addition to the breakdown conditions of the ballistic approximation stated in Section 3.1, here we describe another cause of discrepancies between the two sets of inflow properties. We also discuss two caveats of comparing predictions from ballistic approximation to the outcome from the hydrodynamical calculations in EAGLE.

By following the gas particles in continuous time steps, i.e., at multiple times for each galaxy, we find that feedback plays an important role. The ballistic approximation ignores the effect of feedback and predicts each particle trajectory by considering only gravity. But within a rotation period, feedback and winds expel some recently accreted gas particles to large radii. In the most extreme case (galaxy ID: 48386), not only does the feedback expel the newly accreted gas, but the feedback also disrupts the star-forming region and disperses all of the cold gas.

The temperature increase of the cold gas particles also provides evidence for feedback; EAGLE implements the stellar feedback by stochastically heating particles to high temperature, known as the stochastic thermal feedback (Dalla Vecchia & Schaye 2008, 2012; Schaye et al. 2015). We focus on the change of temperature for particles that are predicted to reach the galaxy within a rotation period (by the ballistic approximation) but failed to do so (according to particle tracking). For the 11 central galaxies, around 50% of the particles that fail to be accreted have at least doubled their temperatures after a rotation period; the fraction varies among galaxies, from around 30% to 75%. For the most extreme case (galaxy ID: 48386), the particles have increased their temperatures by over 100 times to \(\sim 10^7\) K, indicating that the particles are strongly affected by feedback.

Because we identify inflowing gas using the location of particles after a rotation period, we have tracked the net inflow...
as the difference between the newly accreted gas and the gas expelled from the galaxy due to outflows. As some particles have once reached the star-forming region but have been expelled at later times due to feedback and winds, these particles explain the non-negligible fraction of predicted inflow particles that fail to be in the star-forming region after a rotation period (orange squares in Figure 7). In other words, whether or not a particle can accrete onto a galaxy and stay at the star-forming region without being expelled depends strongly on feedback. This phenomenon also qualitatively agrees with the results in Nelson et al. (2015) with AREPO and Correa et al. (2018b) with EAGLE: at $z \lesssim 5$ and $z \lesssim 2$, feedback suppresses the accretion rates onto galaxies with halo masses below $10^{12} M_\odot$.

We emphasize that the comparison between the ballistic approximation and particle tracking only explores whether or how well the former resembles the hydrodynamical calculations in EAGLE. This comparison, however, has two caveats: there exist at least two factors that will result in different inflow properties deduced from different hydrodynamical simulations. First, because whether the gas can accrete onto galaxies is sensitive to feedback, this means the method of feedback implementation and the feedback strength will alter the inflow properties deduced from hydrodynamical simulations. Second, the inflow properties may be code dependent. Nelson et al. (2013; also see Nelson et al. 2015) studied the cosmological gas accretion of $\approx 10^{11} M_\odot$ halos at $z = 2$. They found that compared to the SPH code GADGET-3, AREPO, a moving mesh code, produces an order of magnitude higher in the hot accretion rate, but a factor of 2 lower in the cold accretion rate. Therefore, this demonstrates that the properties of inflowing gas are affected by the nature of the numerical approach.

5. Interpreting Cold Gas Kinematics from Observations

Previous sections have demonstrated the ubiquitousness of gas accretion onto the EAGLE galaxies. In contrast, observations rarely detect inflowing gas directly, as down-the-barrel galaxy observations can identify inflowing gas only if its Doppler shift can be distinguished from the ISM velocity dispersion. As a result, quasar sightline observations have provided the best observational probe of gas inflows, and these sightline observations have advanced our understanding of the gas kinematics of the CGM.

Quasar sightline observations have revealed important results regarding the cold gas kinematics of the CGM. First, through quasar sightlines that probe the CGM near galaxy major axes, observations often show that the cold CGM ($\sim 10^4 K$), which is traced by low-ionization-state ions such as Mg II, corotates with the galaxy disks. Combining galaxy rotation curves and Mg II absorption profiles from quasar spectra, studies find cold absorbing gas that corotates with the disks at various redshifts: from low redshifts of $z \sim 0.1$ (Kacprzak et al. 2011) and $z \sim 0.2$ (Ho et al. 2017; Martin et al. 2019), to intermediate redshifts of $z \sim 0.5$ (Steidel et al. 2002; Kacprzak et al. 2010). While similar types of data rarely exist at higher redshifts, there exist evidence suggesting that the cold gas shows similar kinematic properties to the lower redshift counterparts. Using other low-ionization-state ions (e.g., Zn II, Cr II), Bouché et al. (2013, 2016) studied two galaxies at $z = 2.3283$ and $z = 0.9096$, respectively, and detected corotating cold gas out to 26 and 12 kpc. Second,
H I 21 cm observations, e.g., ~20 kpc in radius down to a H I column density of ~5 × 10^{19} cm^{-2} for NGC 5023 and UGC 2082 from the HALOGAS survey (Heald et al. 2011; Kamphuis et al. 2013), and ~30 kpc in radius for NGC 891 down to 10^{19} cm^{-2} (Sancisi & Allen 1979; Oosterloo et al. 2007). Third, the low-ion absorption typically spans over 100 km s^{-1}. Despite the corotation, a thin rotating disk fails to reproduce the broad velocity range. This problem demonstrates the need for additional components to describe the observed cold gas kinematics.

Inspired by these observations, we now observe the cold CGM kinematics in EAGLE using mock quasar sightlines. In this pilot study, limited by the galaxy sample size and resolution, our following discussion aims to encourage future work and focuses on one edge-on (i = 90°) galaxy. We will show that with this single galaxy, we can detect cold gas kinematics with characteristics similar to those detected in real quasar sightline observations. Therefore, this case study serves as motivation for future studies to “observe” the cold CGM using EAGLE simulations with larger box sizes and a higher resolution, and to include the analysis of mock absorption-line spectra.

Figure 11 shows the example galaxy to be studied in this section. This figure is similar to Figure 3, but in order to compare with cold gas traced by low-ionization-state ions, here we only show cold gas particles with \( T_{\text{gas}} \leq 3 \times 10^4 \) K. Not only do the particles form a structure with a redshifted and a blueshifted side, which thereby indicates rotation, but the more extended particle distribution in the radial than in the Z-direction implies the rotating structure morphologically represents a disk (panel (a)). Furthermore, out to around 60 pkpc, the majority of the cold gas particles have angular momenta comparable to those required to be on circular orbits (panel (c)). This suggests a rotating disk radius of around 60 pkpc. Therefore, from both morphological and kinematical perspectives, this selected galaxy clearly has a giant, rotating cold gas disk.

Panel (d) shows that this extended gas disk is warped. By finding the net angular momentum vector at each concentric 10 pkpc shell, we calculate the angle between the net vector at the \( i^{\text{th}} \) shell and that at the innermost shell, or at the \( (i - 1)^{\text{th}} \) shell. The small but nonzero variations of both angles out to 60 pkpc imply that the disk plane changes orientation with radius, i.e., the gas disk is warped. Warped gas disks are also commonly found in hydrodynamical simulations, a result of cooling gas accreting onto galaxies and aligning its angular momentum vector with the central disks (e.g., Roškar et al. 2010; Stewart et al. 2011). In particular with the EAGLE simulations, Stevens et al. (2017) showed that the angular momentum directions of both hot and cooling gas differ from that of the cooled gas by tens of degrees. This means that the gas particles precess as they cool, and their angular momenta align with the pre-existing cold gas in the galaxy. This leads to the formation of an extended, warped gas disk, similar to our example galaxy in Figure 11.

In this section, first we describe how we generate the mock sightlines in Section 5.1. In Section 5.2, by measuring the mean line-of-sight (LOS) velocities along sightlines, we explore which sightlines can detect cold gas that corotates with the galaxy disk. Then in Section 5.3, we study how the LOS velocity varies along sightlines, and we discuss the galaxy structures that can also produce velocity ranges comparable to those measured in real quasar sightline observations.

5.1. Creating Mock Quasar Sightlines

To create the mock quasar sightlines, first we define the disk plane of the galaxy. Within the innermost 10 pkpc of the galaxy, we calculate the net angular momentum vector of the cold gas and use this vector to define the disk plane. For a fixed galaxy inclination angle \( i \) (e.g., \( i = 90° \)), we generate sightlines with impact parameter \( b \) between 10 and 100 pkpc and azimuthal angle \( \alpha \) from 0° to 90°. Figure 12 illustrates the grid of sightlines relative to the galaxy major axis. Then, for each combination of \( i \), \( b \), and \( \alpha \), we produce 12 LOSs by changing the location of the observer; each sightline runs along a different direction relative to the simulation box, but as viewed from the “relocated” observer, the sightlines still intersect the disk at the given \( i \), \( b \), and \( \alpha \). Moreover, because in this work we are interested in the kinematic signatures of cold gas within the halo, we create each LOS to extend only to the galaxy virial radius \( r_{\text{vir}} \).

Analogous to observations, which trace cold gas using low ions (e.g., Mg II, Si II, Fe II), we redefine the cold gas temperature cutoff to be \( 3 \times 10^4 \) K (see Section 2.2). We use \( y_\tau \) (Turk et al. 2011) to convert the cold gas particle fields to grid-based fluid quantities. We extract the cold gas density and velocity at cells intersected by each sightline. Then, we calculate the mean LOS velocity, and we explore how the LOS velocity changes along sightlines in Sections 5.2 and 5.3, respectively.

\[^{10}\text{The observed H I disk size (diameter) depends on the depth of the observation; deeper observations measure H I emission down to a lower column density limit, resulting in a larger H I disk size. As an example, for NGC 5023, the H I diameter is 19 kpc at a column density limit of 10^{19} \text{ cm}^{-2}, but the disk extends to about 27 kpc in diameter at 2 \times 10^{19} \text{ cm}^{-2} (Kamphuis et al. 2013).}\]

\[^{11}\text{Measured from the galaxy center, the azimuthal angle \( \alpha \) is the angular separation of the sightline from the galaxy major axis. A sightline at \( \alpha = 0° \) lies on the major axis, whereas a sightline at \( \alpha = 90° \) lies on the minor axis.}\]
the colors gas at high $\alpha$ to 60 pkpc and 40 pkpc, respectively. In particular, if the gas had moved only shows the sightlines along which we rule out random gas motion at the 1 level of confidence. The latter criterion prevents mis-detecting corotating gas. The bottom panel of Figure 13 isolates the sightlines in the $b$-$\alpha$ plane with $p_{\alpha,11} > 0.5$; within the 1 level of confidence, it is unlikely that these sightlines have randomly moving cold gas detected. This is because with random gas motion, sightlines will detect corotation half of the time, and the probability of detecting corotating gas at one sightline will be $p = 0.5$. This probability, however, is excluded at the 1 level of confidence if $p_{\alpha,11} > 0.5$. Then, among these sightlines in the $b$-$\alpha$ plane, we also ask the following question: if the gas moves randomly, what is the probability of having $\geq N_{\alpha}$ LOSs that detect corotating gas among the $N_{\text{cold}}$ LOSs. We show this probability using the color scale in the bottom panel of Figure 13. Among the selected $b$-$\alpha$ locations, the chances of detecting $\geq N_{\alpha}$ sightlines with corotating gas lie below 12%. In particular, at $b = 10$ pkpc and 20 pkpc, the probabilities at both $\alpha = 0^\circ$ and $10^\circ$ lie below 5%. Thus, the calculation suggests that sightlines shown in the lower panel of Figure 13, i.e., sightlines at $\alpha = 0^\circ$ and $10^\circ$ out to 60 pkpc and 40 pkpc, respectively, have unlikely intersected randomly moving gas. In other words, we can detect corotating cold gas along these sightlines.

Our edge-on galaxy example demonstrates that quasar sightlines are more likely to detect corotating cold gas near the galaxy disk plane—at sightlines with $b \leq 60$ pkpc and low $\alpha$ of $\leq 10^\circ$. This can be naturally explained by sightlines intersecting the rotating gas disk as shown in Figure 11(a). Because real quasar sightline observations often detect corotating cold gas along sightlines near the galaxy major axes, our example suggests that these sightlines have likely intersected cold gas disks that extend beyond the optical disks.

While we use one EAGLE galaxy to demonstrate the possibility of detecting corotating cold gas using mock quasar sightlines, the presence of rotating structures, which can give rise to corotating gas detection, is not unique to this galaxy. Figure 14 shows the cold gas distribution of the remaining 10 central galaxies, and we color each particle by its projected LOS velocity. Although the spatial distribution of particles indicates that not all galaxies have thin-disk-like morphologies, at least half of the galaxies have cold gas structures that show signs of rotation, i.e., an approaching side and a receding side. Rotating gas structures are not only common among our selected galaxies—simulated galaxies with halo mass $\geq 10^{12} M_\odot$ from the FIRE project also show clear signs of rotation, even though the gas distribution is not morphologically “disky” (El-Badry et al. 2018). Hence, sightlines through all these galaxies may also detect corotating cold gas as in our example, and this may imply that corotation detection is not a rare phenomenon.

5.2. CGM Corotation with Galactic Disk

We pose the question of which sightlines can detect cold gas that corotates with the inner galaxy disk. Using the mock sightlines that probe the edge-on galaxy, for each of the 12 LOSs at different $b$ and $\alpha$, we calculate the mean LOS velocity (column density weighted). If this mean LOS velocity has the same sign as the disk rotation and is at least 10 km s$^{-1}$ away from the galaxy systemic velocity, then we classify the LOS as detecting corotating gas. The latter criterion prevents mis-assigning cold gas that moves randomly within thermal and turbulent velocity as corotating.

Before discussing the detection of cold corotating gas, we note that not all LOSs intersect cold gas. The top panel of Figure 13 shows that among the 12 LOSs per $b$-$\alpha$ combination, the number of LOSs that intersects cold gas decreases with increasing $b$ and $\alpha$. This can be explained by the decreasing cold gas density when the radial separation from the galaxy center increases (e.g., see the cold gas distribution in Figure 11(a)).

Using the sightlines that have intersected cold gas, we explore what ranges of $b$ and $\alpha$ can detect corotating gas. At each $b$-$\alpha$ combination, first we find the number of LOSs that intersects cold gas $N_{\text{cold}}$ and the number of LOSs with corotating cold gas detected $N_{\alpha}$. Using binomial statistics (Gehrels 1986), we calculate the 1 lower limit of the rate of detection of corotating cold gas $p_{\alpha,11}$. The bottom panel of Figure 13 isolates the sightlines in the $b$-$\alpha$ plane with $p_{\alpha,11} > 0.5$; within the 1 level of confidence, it is unlikely that these sightlines have randomly moving cold gas detected. This is because with random gas motion, sightlines will detect corotation half of the time, and the probability of detecting corotating gas at one sightline will be $p = 0.5$. This probability, however, is excluded at the 1 level of confidence if $p_{\alpha,11} > 0.5$. Then, among these sightlines in the $b$-$\alpha$ plane, we also ask the following question: if the gas moves randomly, what is the probability of having $\geq N_{\alpha}$ LOSs that detect corotating gas among the $N_{\text{cold}}$ LOSs. We show this probability using the color scale in the bottom panel of Figure 13. Among the selected $b$-$\alpha$ locations, the chances of detecting $\geq N_{\alpha}$ sightlines with corotating gas lie below 12%. In particular, at $b = 10$ pkpc and 20 pkpc, the probabilities at both $\alpha = 0^\circ$ and $10^\circ$ lie below 5%. Thus, the calculation suggests that sightlines shown in the lower panel of Figure 13, i.e., sightlines at $\alpha = 0^\circ$ and $10^\circ$ out to 60 pkpc and 40 pkpc, respectively, have unlikely intersected randomly moving gas. In other words, we can detect corotating cold gas along these sightlines.

5.3. Velocity Range along the LOS

Quasar sightline observations often detect broad LOS velocity ranges that cannot be explained by a thin rotating
Figure 14. Projected LOS velocities of cold gas particles with $T_{\text{gas}} \leq 3 \times 10^4$ K. Each panel projects the cold gas particles of each central galaxy onto a 2D plane. Every particle is color-coded by its projected LOS velocity. Red and blue represent redshifted and blueshifted cold gas particles, respectively, and we use the same velocity scale as in the top row of Figure 3. The gray arrow shows the direction of the net angular momentum of the cold gas, which is measured within an aperture of 10 pkpc from the galaxy center. More than half of the galaxies show signs of rotation. Each panel has the same spatial scale of 200 pkpc.

Figure 15 shows the variation of LOS velocity and cold gas density along selected sightlines of the example edge-on galaxy (galaxy ID: 37448). The top and the bottom panels show how the LOS velocity and cold gas density vary along sightlines that individually intersect three structural components: a thin disk (red), a thick disk (orange), and a gas stream (yellow). A positive LOS velocity indicates that cold gas is not intersected by that section of the sightline. We only show $|D_{\text{los}}| \leq 80$ pkpc along the path, beyond which all three sightlines rarely intersect any cold gas.

disk model. Therefore, using our example galaxy that has an extended rotating disk, we investigate the velocity ranges that this galaxy can produce. By examining how LOS velocity varies along different sightlines, we discuss the resultant velocity ranges that can possibly be created by different gas structures.

We choose individual sightlines that intersect different components of the cold gas structure: (1) the thin disk—at small $b$ and along the galaxy major axis ($\alpha = 0^\circ$), (2) the thick disk—at small $b$ and at least several kiloparsecs above the disk plane (e.g., $\alpha = 20^\circ$), and (3) a gas stream. Specifically for our edge-on galaxy example, a sightline that intersects the disk midplane represents the thin-disk component. Because EAGLE imposes a temperature floor of 8000 K to prevent metal-rich gas particles from cooling to very cold, interstellar gas (Crain et al. 2015; Schaye et al. 2015), this sets a minimum disk height, considerably larger than the physical scale height for observed edge-on galaxies (de Grijs 1998; Kregel et al. 2002).

As a result, EAGLE cannot produce very flat galaxies (also see Lagos et al. 2018 for a related discussion). We select our sightline that intersects the thick disk component $\sim$10 pkpc above the disk midplane, avoiding the “unresolved” thin disk. We call this the “thick disk” component also because the 10 pkpc thickness is comparable to that of modeled rotating gas disks (tens of kiloparsecs tall) in explaining the measured CGM kinematics (e.g., Steidel et al. 2002; Ho et al. 2017; Ho & Martin 2019).

Figure 15 shows the variation of the LOS velocity and cold gas density along each of the three sightlines. Along the path of each sightline, $D_{\text{los}} = 0$ pkpc separates the near side and the far side of the edge-on disk. Although our sightlines extend to $r_{\text{vir}}$, we only plot $|D_{\text{los}}| \leq 80$ pkpc. Beyond this path length, the sightlines rarely intersect any cold gas within $r_{\text{vir}}$. Even if cold gas is intersected, it has orders-of-magnitude lower density than the intersected cold gas within $|D_{\text{los}}| \leq 80$ pkpc. In addition, a positive LOS velocity indicates that it has the same sign as the disk angular momentum, i.e., the intersected cold gas corotates with the galaxy disk. For each of the three sightlines that
intersect the three structures, the LOS velocities stay positive. This indicates that the intersecred cold gas always shares the same sense of rotation as the inner galaxy disk. In the following, we briefly discuss the velocity variation along individual sightlines.

First, the sightline that intersects the thin disk detects the broadest LOS velocity range. The LOS velocity $v_{\text{los}}$ reaches 210 km s$^{-1}$ at $D_{\text{los}} = 0$, where the cold gas density also peaks (red line in Figure 15). The large $v_{\text{los}}$ is produced by the circular motion of the gas on the disk, and the rotation velocity vector is tangent to the sightline at $D_{\text{los}} = 0$. Increasing $|D_{\text{los}}|$ then reduces the magnitude of $v_{\text{los}}$ significantly, because the LOS no longer runs in parallel with the rotation velocity vector. Along this sightline, because the LOS velocity varies from around 30 to 210 km s$^{-1}$, this sightline can detect a broad LOS velocity range of 180 km s$^{-1}$.

Second, the sightline that intersects the thick disk component produces a narrower velocity range. The LOS velocity reaches maxima of around 70 and 110 km s$^{-1}$ (orange line in Figure 15). The density peaks at the two locations of the velocity maxima, which indicates that the thick disk component does not comprise a uniform disk. This is evident from the gas distribution in Figure 3, which shows the gas having spiral structures instead of being a solid disk. Because this sightline detects LOS velocity that varies from around 30 km s$^{-1}$ to a maximum of 110 km s$^{-1}$, the velocity range reaches 80 km s$^{-1}$, which significantly exceeds the thermal line width.

As for the sightline that intersects a gas stream, only discrete sections along the sightline have intersected cold gas. The sightline intersects the gas stream at around $D_{\text{los}} = -40$ pkpc (yellow line in Figure 15). At the far side of the disk of $D_{\text{los}} = 20$ pkpc, the sightline intersects cold gas with density 100 times lower. The higher density gas stream produces LOS velocities from around 30 km s$^{-1}$ to a maximum of 100 km s$^{-1}$. Therefore, this sightline produces an LOS velocity range comparable to that of the thick disk component.

Using the three cases of our example edge-on galaxy, we have demonstrated that velocity ranges of over 100 km s$^{-1}$ in observations can be produced by a sightline that intersects a thin rotating disk edge on. Sightlines that intersect the thick disk component or a gas stream can detect LOS velocity ranges that are significantly broader than the thermal line width. All these gas structures likely contribute to the broad line profiles in real observations, especially because the observed profiles broadened by instrumental resolution are expected to consist of multiple velocity components.

However, we emphasize that while the three example sightlines can produce broad velocity ranges in principle, such sightlines are extremely rare. As a result, they cannot explain the large number of broad absorption systems observed. Moreover, the observed velocity range of the absorption depends on the column density and thereby the ionization state of the gas, which is beyond the scope of this paper. Therefore, in the future, we will conduct the ionization analysis and use mock sightlines to study the absorption-line profiles of different ionic species. This will provide us deeper insight into the circumgalactic gas kinematics measured in quasar sightline observations.

6. Summary and Conclusions

Galaxies grow and fuel star formation by accreting gas, yet direct observation of gas inflows onto galaxies remains sparse. In this pilot study, we have studied the properties of cold inflowing gas around EAGLE galaxies at $z = 0.27$. We have identified the cold inflowing gas using two methods: (i) a ballistic approximation that calculates the trajectories of particles moving under gravity, and then predicts which particles accrete onto the inner galaxy within a rotation period, and (ii) tracking particles through the same time interval in EAGLE, which includes full hydrodynamic calculations. We have compared the two sets of deduced inflow properties and discussed the limitations of the ballistic approximation. To gain insight into understanding cold gas kinematics measured from quasar sightline observations, we have probed the cold CGM ($\sim 10^5$ K) using mock quasar sightlines. Our analysis has focused on the CGM corotation with the galactic disk, as well as the velocity ranges produced by different galaxy structures.

Using either the ballistic approximation or particle tracking, we find that the galaxies typically have low inflow speeds of around 20–60 km s$^{-1}$. The mass inflow rates deduced from the two methods agree to within a factor of 2, and the ballistic approximation often overestimates. We have attributed the major cause of the discrepancy to feedback, which has removed the newly accreted gas or can even disrupt the star-forming regions. In other words, feedback reduces the overall amount of cold gas accreted and thereby suppresses the mass inflow rates. Nevertheless, the mass inflow rates are generally comparable to the galaxy SFRs. This suggests that the cold inflowing gas plausibly sustains the galaxy star formation activities and thereby prolongs the disk lifetimes.

Inspired by recent observational measurements of cold gas kinematics along quasar sightlines, we have used mock quasar sightlines to probe the cold gas within $r_{\text{vir}}$ around a selected EAGLE galaxy. This galaxy has an extended cold gas disk, and the measurements of its cold gas kinematics share similar characteristics to sightline observations. This motivates future work using larger simulation boxes with a higher resolution to “observe” the cold gas kinematics in detail.

We have posed the question of which sightlines can detect cold gas that corotates with the inner galaxy disk. By viewing the selected EAGLE galaxy edge on, we have found that sightlines with azimuthal angles of $\alpha = 0^\circ$ and $10^\circ$ can detect corotating cold gas out to 60 pkpc and 40 pkpc, respectively. Because quasar sightline observations often detect corotating cold gas near the galaxy major axes, our results suggest that it is possible that the observed sightlines have intersected cold gas disks that extend beyond the optical disks.

Because quasar sightline observations also often detect broad velocity profiles, we have explored whether sightlines that individually intersect a thin-disk component, a thick disk component (i.e., above the disk plane), and a gas stream can produce comparable velocity ranges. We have demonstrated that sightlines intersecting these three gas components can produce velocity ranges of over 70 km s$^{-1}$, significantly broader than the thermal line width. All these structures possibly contribute to the broad line profiles in observational measurements, especially because the observed line profiles are expected to consist of multiple velocity components.

In the future, we will use EAGLE simulations with large box sizes and higher resolutions to study cold gas kinematics. With larger cosmological volumes, we can increase the sampling size...
of galaxies. This will produce better statistics on the probabilities of detecting corotating cold gas along sightlines and finding galaxies with extended cold gas disks. Using simulations with better resolution will allow us to generate high-resolution, mock absorption-line spectra and compare them to quasar sightline measurements. This will allow us to interpret quasar sightline observations using EAGLE simulations and thereby gain insight into the measured cold gas kinematics.

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Appendix

The top row of Figure 3 shows the projected line-of-sight velocities of the cold gas particles $T_{\text{gas}} \leq 2.5 \times 10^5$ K of one galaxy (ID: 37448). In his Appendix, Figure 16 shows the cold gas distribution of the remaining 10 central galaxies. Each particle is color-coded by its projected velocity, and we use the same velocity scale as in the top row of Figure 3. Most galaxies have an approaching (blueshifted) side and a receding (redshifted) side, indicating that the cold gas structures show signs of rotation.
Figure 16. Particle projection plots showing the projected line-of-sight velocities of cold gas particles ($T_{\text{gas}} \leq 2.5 \times 10^5$ K). Each particle is color-coded by its projected velocity, and we use the same velocity scale as in the top row of Figure 3. This figure follows the same format as in Figure 4. Each galaxy occupies 3 rows × 1 column, enclosed by the thick black lines. For individual galaxies, from top to bottom, each panel represents the cut in the x, y, and z planes, respectively. The side length of each panel is 200 pkpc. The plotted central galaxies are ordered in decreasing stellar masses, from left to right, and top to bottom.
