drives the other. We conclude that more research is needed to firmly establish the roles the CGM plays in galaxy evolution.

2.2. Angular Momentum

We now expand on what is known about the AM content and exchange processes in the CGM. The motivation for this is twofold. First, in the standard cosmological picture, galaxies inherit their AM from gas accreted from their host halos (e.g., Fall & Efstathiou 1980, Dalcanton et al. 1997, Mo et al. 1998). In this picture, the AM of halos is first acquired via gravitational torques during structure formation (e.g., Peebles 1969, White 1984), though the AM of a particular halo fluctuates substantially over time due to mergers (e.g., Vitvitska et al. 2002). Although on sufficiently large scales the baryons are expected to have AM properties similar to that of the dark matter, hydrodynamic forces and feedback processes experienced by the baryons during galaxy formation can potentially strongly affect the AM content of both the CGM as well as galaxies. Second, observations indicate that in many systems the CGM has substantial rotation (e.g., Bouché et al. 2013, Hodges-Kluck et al. 2016, Ho et al. 2017), and we would like to understand these CGM observations.

A useful basis to understand the AM properties of the CGM is to start with scalings derived from dark matter–only simulations. Dark matter halos can be characterized by a dimensionless spin parameter $\lambda \equiv \frac{J}{\sqrt{2}MRV}$, where J is the total AM inside a sphere of radius R containing mass M, and $V = \sqrt{GM/R}$ is the circular velocity at R (Bullock et al. 2001). We adopt the standard choice of setting R to the virial radius. With these definitions, numerical simulations have shown that dark matter halos have a lognormal distribution of spin parameters, nearly independent of mass and redshift, with a median $\lambda \approx 0.035$ (e.g., Bett et al. 2007, Zjupa & Springel 2017). Defining the sAM $j \equiv J/M$ and noting that $R_{\rm vir} \propto M_{\rm h}^{1/3}/(1+z)$ (for halos defined to have constant overdensity relative to the mean matter density) implies $j \propto M_{\rm h}^{2/3}/\sqrt{1+z}$. Thus, at fixed redshift j increases with halo mass $\propto M_{\rm h}^{2/3}$, whereas at fixed halo mass j increases with time $\propto 1/\sqrt{1+z}$ as redshift decreases. Although these scalings apply to dark matter–only simulations, DeFelippis et al. (2020) find that the same scalings roughly describe the CGM AM trends with halo mass and redshift in the `IllustrisTNG` hydrodynamic simulation, which includes feedback from galaxy formation. Assuming that the sAM of the CGM is comparable with that of the dark matter halo (though with significant differences discussed below), the small spin parameters $\lambda \sim 0.035$ imply that AM support is negligible in most of the CGM, becoming only important at a circularization radius $R_{\rm circ} \approx \sqrt{2}\lambda R_{\rm vir} \sim 0.05 R_{\rm vir}$. The small contribution of rotation to the support of halo gas has been confirmed by a systematic analysis of different support terms in `EAGLE` simulations (Oppenheimer 2018).

Next, we summarize some key results concerning how the CGM AM relates to other components, including the dark matter halo and the central galaxy. We also review physical explanations for the differences found between the different components. We refer to **Figure 6** for some quantitative results on spin parameters of the gas and the dark matter around simulated galaxies with a halo mass $M_{\rm h} \sim 10^{12}$ M$_\odot$ at $z \sim 2$.

2.2.1. Angular momentum in the CGM versus the dark matter halo.

Within the virial radius, CGM gas has systematically higher sAM than the dark matter. Interestingly, this is the case even in nonradiative simulations, so part of the difference can be attributed to hydrodynamic interactions that do not involve cooling (e.g., Zjupa & Springel 2017). For example, when two halos merge, ram pressure causes the gas mass to become offset from the dark matter. Because the simulations also predict that the gas and dark matter spins are on average misaligned by ~35 deg, mergers could on average spin up gas more than the dark matter.

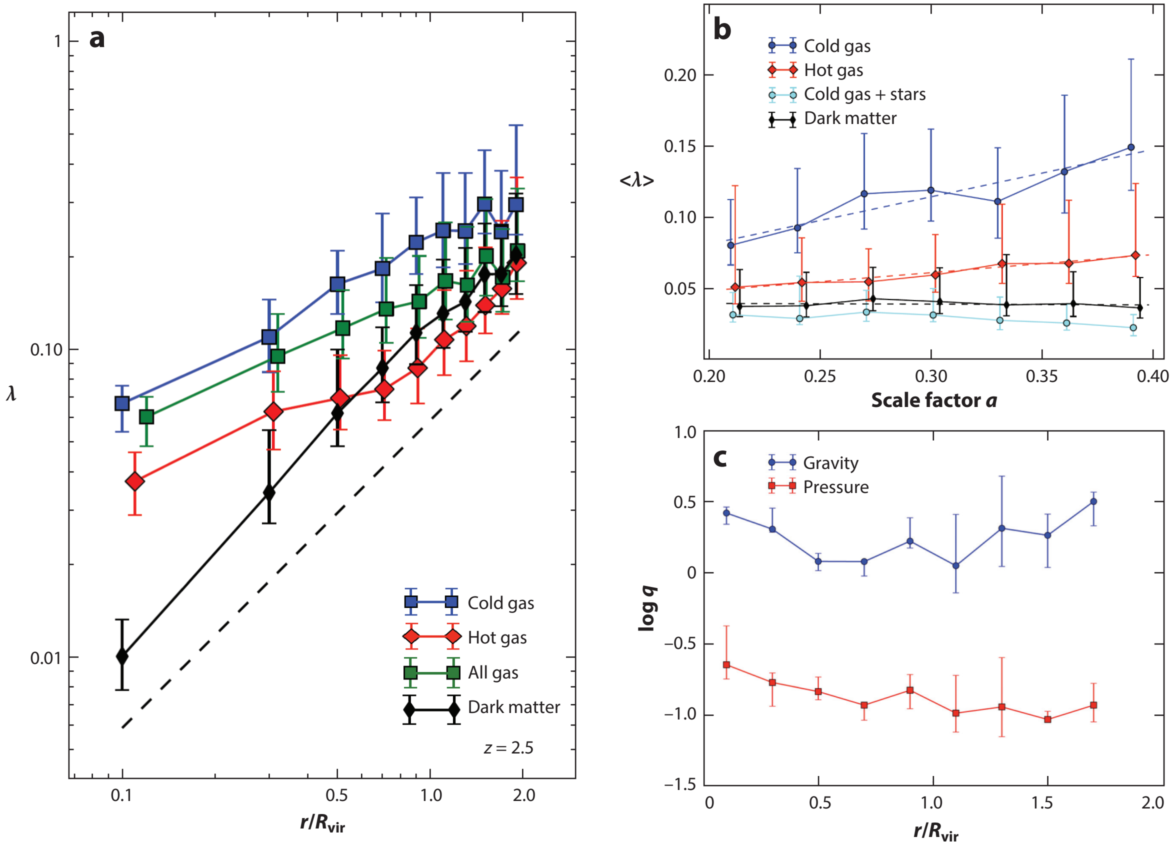

Figure 6

(*a*) Radial profiles for the spin parameter of different mass components in 29 simulated halos analyzed by Danovich et al. (2015). The halo mass ranges from $10^{11.5}$ to $10^{12.5}$ $M_\odot$ at $z \sim 2$. The total gas mass is divided between cold and hot components, corresponding to $T < 10^5$ K and virial-temperature gas, respectively. The symbols show the mean spin in each shell, whereas the error bars show the standard deviation. The dashed line shows a slope of unity. Several trends are apparent: First, for all components, the mean spin parameter increases from the inside out; second, the spin parameter of the gas is systematically higher than that of the dark matter; and third, the higher spin in the gas is primarily driven by the cold gas. (*b*) Evolution of the mean spin parameters inside the virial radius as a function of the cosmological scale factor $a = 1/(1 + z)$. Here the cyan "cold gas + stars" component corresponds to $<0.1R_{\mathrm{vir}}$, a proxy for the evolution of galactic baryons. Averaged within the virial radius, the sAM of the cold gas exceeds that of the dark matter by a factor of ∼2–3. (*c*) Comparison of the radial profiles of torques on cold halo gas due to gravity versus torques due to gas pressure, for simulation snapshots ranging from $z \sim 1.6$ to $z \sim 3.2$. The q parameter is proportional to $|\boldsymbol{\tau}|/|\boldsymbol{l}|$, showing that gravitational torques are more important for the cold gas. Figure adapted with permission from Danovich et al. (2015). Abbreviation: sAM, specific angular momentum.

When the total CGM mass is divided between cold ($T < 10^5$ K) and hot (virial-temperature) gas, it becomes clear that higher gas sAM relative to the dark matter is primarily driven by the higher sAM of the cold gas, which can exceed that of the dark matter by a factor of ∼2–3 within R_{vir}. This indicates an important role for gas cooling. Danovich et al. (2015) analyzed the torques experienced by the dark matter and cold gas as they approach the virial radius of halos and argued that the excess quadrupole moment of the cold gas relative to the dark matter could explain the additional sAM acquired by the infalling cold gas as a result of more efficient tidal torquing. Specifically, the elongated, thin-stream geometry of the infalling cold gas (relative to the thicker dark matter distribution) enables the cold gas to acquire AM more efficiently via tidal torques. In other words, cold streams are where cold gas gets extra torque.

An additional timescale effect contributes to the higher sAM of the cold gas relative to the hot gas. Whereas the cold gas can accrete onto the central galaxy on a free-fall time, the hot gas is supported in the halo by thermal pressure for at least a cooling time. Thus, while much of the cold CGM has typically only recently entered the halo, the hot CGM has been built up over a longer period in the past. Because the sAM of matter accreting from large-scale structure increases with time, this timescale effect alone tends to enhance the sAM of the cold gas relative to the hot gas. The increasing sAM of matter accreting from large scales likely explains, at least in part, why the spin parameter of the different halo components increases systematically with radius in **Figure 6**.

Galaxy-formation feedback can also increase the sAM of the CGM relative to the dark matter. Namely, the ejection of gas from galaxies by star formation or AGN-driven outflows occurs primarily from the inner parts, where the baryons have relatively low sAM (Zjupa & Springel 2017). If sufficiently strong, feedback can eject some of the low-sAM gas not only from galaxies but from halos altogether. The preferential ejection from halos of low-sAM gas also tends to enhance the sAM of the remaining CGM relative to the dark matter.

Although the detailed quantitative predictions depend on the simulation code, including the feedback model, the high sAM of the CGM relative to the dark matter (especially for the cold gas) appears robust, as similar results have been found in cosmological simulations using different codes (e.g., Stewart et al. 2017, DeFelippis et al. 2020) and for halos in different mass ranges (e.g., Oppenheimer 2018). The high sAM of cold gas can produce extended rotating structures that have sometimes been called cold flow disks that may have observational signatures in low-ionization absorption systems corotating with central galaxies (e.g., Stewart et al. 2011, 2013).

2.2.2. Angular momentum in the CGM versus the central galaxy. The relationship between the sAM of galaxies and that of their host halos merits some comments. On one hand, observational studies (e.g., Kravtsov 2013, Somerville et al. 2018) and many numerical simulations (e.g., Genel et al. 2018, Rohr et al. 2022) find that on average the size of galaxies scales with the virial radius of the dark matter halo, with a normalization roughly consistent with that expected if the sAM of the galaxy is comparable with that of the dark matter halo. Furthermore, it is found in some simulations that at fixed stellar mass, halos with larger spin parameters on average host larger galaxies (Rodriguez-Gomez et al. 2022). On the other hand, some simulations that reproduce the average trend between galaxy size and halo size indicate that on a halo-by-halo basis, the spin parameter of the central galaxy is barely correlated with the spin parameter of the dark matter halo, when these are measured at the same final time (Garrison-Kimmel et al. 2018, Jiang et al. 2019). It is also noteworthy that the AM vector of the CGM is in general misaligned with that of the stars in the central galaxy by large angles $\sim$30–60 deg (DeFelippis et al. 2020).

These results could be understood if, to first order, the sAM of galaxies scales with the sAM of the host dark matter halo when the galaxy is assembled but there is order-unity scatter introduced between the sAM of the baryons and that of the dark matter over time. For example, Vitvitska et al. (2002) showed that the spin parameter of a dark matter halo fluctuates by factors up to $\sim$2–3 due to halo mergers. Because of the very different spatial distributions of matter, we expect galaxies to be torqued differently during mergers compared to the much larger halos. The partial decoupling of the spin parameter of galaxies from their host halos over time is consistent with the finding of Garrison-Kimmel et al. (2018) that the stellar morphologies and kinematics of simulated Milky Way–mass galaxies are poorly correlated with the properties of the final dark matter halos (including spin), but that the galaxy properties correlate better with dark matter halo properties evaluated at the time when 50% of the stars had formed.

Processes other than mergers can also contribute to differences in the AM content between galaxies and their halos. One likely relevant factor is that the minority of baryons that end up in galaxies, relative to the cosmic baryon fraction, is not necessarily representative of the majority of halo baryons. The fraction of baryons found in galaxies peaks at $\sim$0.2 for Milky Way–mass halos and is as low as $\lesssim 10^{-3}$ for dwarf galaxies and for central galaxies in massive clusters (e.g., Behroozi et al. 2019). Another possibility is that the sAM of gas accreting through the CGM is not strictly conserved but rather experiences exchanges with other components.

2.2.3. Gravitational versus gas pressure torques. We do not yet have a detailed understanding of AM transport in the CGM, but several mechanisms can contribute. Danovich et al. (2015) decomposed the total Lagrangian torque on gas elements into three components, $\boldsymbol{\tau} = \mathrm{d}\boldsymbol{l}/\mathrm{d}t = \boldsymbol{\tau}_\Phi + \boldsymbol{\tau}_P + \boldsymbol{\tau}_s$, where $\boldsymbol{l}$ is the AM vector, $\boldsymbol{\tau}_\Phi = -\rho \boldsymbol{r} \times \nabla\Phi$ is the torque due to gravitational forces, $\boldsymbol{\tau}_P = -\boldsymbol{r} \times \nabla P$ is the torque due to pressure gradients, and $\boldsymbol{\tau}_s = -\boldsymbol{l}\nabla \cdot \boldsymbol{v}$ corresponds to viscous stresses. The viscous stress term is negligible in the ideal hydrodynamics limit. **Figure 6c** compares $\log q$ radial profiles for gravitational and pressure torques acting on cold gas for simulated halos at $z \sim 1.6$–3.2 from Danovich et al. (2015), where $q_{\Phi,P} \propto |\boldsymbol{\tau}_{\Phi,P}|/|\boldsymbol{l}|$. The results indicate that the torques on cold streams are dominated by gravity rather than gas pressure. These gravitational torques are sourced by anisotropies in the matter distribution, ranging from large-scale structure to central disks, which tend to align the infalling gas. It would be valuable to extend this kind of analysis to other regimes in the future. For example, the relative importance of gravitational torques versus pressure torques could be very different for hot gas, which tends to be more spherical in geometry and in approximate hydrostatic equilibrium throughout the halo. It would also be worthwhile to quantify the effects of magnetic fields on AM transport in the CGM. Magnetic fields play a key role in transporting AM in accretion disks around young stars and black holes, but their effects on AM exchanges in the CGM have not yet received attention to our knowledge.

After baryons are accreted by galaxies, gravitational torques due to asymmetric features in the potential (e.g., spiral arms, bars, or massive clumps) can strongly affect the AM distribution within galaxies, such as by forming central bulges (e.g., Shlosman et al. 1989). This would also contribute to differences between the AM of galactic components relative to what may be expected from strict conservation of AM inherited from the halo. Overall, AM acquisition and exchange processes in the CGM remain relatively understudied and more work on this topic would be highly valuable.

2.3. Galactic Winds

Galactic winds are commonly observed and are an essential ingredient of modern galaxy-formation theories. In most galaxies, these outflows are understood to be primarily driven by energy and/or momentum produced by massive stars, including via SNe (e.g., Chevalier & Clegg 1985) and/or radiation pressure (e.g., Murray et al. 2005). In galaxies with luminous AGNs, galactic winds can also be powered by accretion onto massive black holes (e.g., Faucher-Giguère & Quataert 2012, and references therein). Here, we focus on outflows powered by star formation. In current models, these outflows are critical to suppress star formation in galaxies up to $\sim L_\star$ by either ejecting gas from the ISM before it has time to turn into stars or preventing CGM gas from accreting onto galaxies in the first place (Somerville & Davé 2015, Naab & Ostriker 2017). However, because they originate on small scales and their driving mechanisms are not yet fully understood, the properties of galactic winds remain highly model dependent. Therefore, we limit our discussion below to general concepts and results that are useful for understanding the impact of galactic winds on the CGM, and vice versa, rather than the detailed predictions of specific models.

Figure 7 summarizes some key properties of galactic winds in simulations. One salient feature is that galactic winds are multiphase. This multiphase structure is clearly observed in