

Hot accretion onto spiral galaxies: the origin of extended and warped H I discs

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ABSTRACT

Gas accretion, hot ($\sim 10^6$ K) atmospheres, and a tilt between the rotation axes of the disc and the atmosphere are all robust predictions of standard cosmology for massive star-forming galaxies at low redshift. Using idealized hydrodynamic simulations, we demonstrate that the central regions of hot galaxy atmospheres continuously condense into cool ($\sim 10^4$ K) discs, while being replenished by an inflow from larger scales. The size and orientation of the condensed disc are determined by the angular momentum of the atmosphere, so it is large and often tilted with respect to the pre-existing galaxy disc. Continuous smooth accretion from hot atmospheres can thus both provide the necessary fuel for star formation and explain the observed ubiquity of extended and warped H I discs around local spirals. In this hot accretion scenario, cool gas observations cannot be used to trace the source of the H I warps out to halo radii, consistent with recent indications of a lack of 21 cm emission from the halos of nearby galaxies (the ‘H I desert’). Observations of H I warps formed via hot accretion can be used to constrain the angular momentum, accretion rate, and gas metallicity of hot galaxy atmospheres, important parameters for disc galaxy evolution that are hard to determine by other means.

Key words: keyword1 – keyword2 – keyword3

1 INTRODUCTION

The neutral hydrogen (H I) distribution in nearby spiral galaxies typically extends well beyond the stellar disc. Observations by [Broeils & Rhee \(1997\)](#) found a mean H I to optical radius ratio of $R_{\text{H I}}/R_{25} \approx 1.7$ with a dispersion of ≈ 0.5 , where $R_{\text{H I}}$ is defined at a surface density of $1 \text{ M}_{\odot} \text{ pc}^{-2}$ ($= 1.3 \cdot 10^{20} \text{ cm}^{-2}$) and R_{25} at surface brightness of $25 \text{ mag arcsec}^{-2}$ in the B-band (see also [Lee et al. 2025](#)). The extended H I thus provides valuable information about the dark matter distribution at radii where stellar emission is hard to detect. This H I observed beyond R_{25} typically occupies a tilted plane relative to the inner H I and stellar discs, forming an antisymmetric ‘integral sign’ H I warp (e.g., [Briggs 1990](#); [Sancisi et al. 2008](#)); the onset of the warp at $\approx R_{25}$ often coincides with the truncation of the stellar disc and a steep drop in the radial H I surface density ([van der Kruit et al. 2001](#); [van der Kruit 2007](#)). Early observations of the H I warp in the Milky Way date back to [Burke \(1957\)](#) and [Kerr \(1957\)](#), and surveys of external

disc galaxies have since revealed their prevalence. [García-Ruiz et al. \(2002\)](#) identified warps in 20 out of 26 edge-on galaxies, with warps present in every galaxy where H I extends beyond the stellar disc. The high occurrence of warps suggests their formation is independent of external perturbations, which are not as ubiquitous, and that the mechanisms that produce warps are common and long-lasting.

Proposed models for warp formation broadly fall into two classes (e.g., [Binney 1992](#)): torquing of a pre-existing outer H I disc or misaligned gas accretion onto the outskirts directly forming a tilted outer disc. Disc-torquing-based models require an external mechanism to generate the misalignment between the inner and outer discs, such as companions (e.g. [Gómez et al. 2017](#); [Wille & Machado 2024](#); [Deng et al. 2024](#)) or tilted dark halos (e.g. [Jiang & Binney 1999](#); [Shen & Sellwood 2006](#); [Han et al. 2023a,b](#)). Tilted dark halos appear to be prevalent in cosmological simulations, sustained either via misaligned accretion of dark matter ([Jiang & Binney 1999](#); [Shen & Sellwood 2006](#)) or by halo dynamics and merger histories (e.g. [Bailin et al. 2005](#); [Aumer & White 2013](#); [Emami et al. 2021](#); [Shao et al. 2021](#); [Han et al. 2023b](#); [García-Conde et al. 2024](#)), and thus potentially can explain the ubiquity of warps. [Sellwood & Debattista \(2022\)](#)

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argued that once a misalignment between the inner and outer discs is established, it can generate internally driven outward-propagating bending waves that sustain the warps for several Gyr.

In contrast with disc torquing-based models, accretion-based models propose that gas inflows deposit material onto disc outskirts with a misaligned angular momentum vector relative to that of the pre-existing disc (e.g., López-Corredoira et al. 2002; Sancisi et al. 2008; Roškar et al. 2010). Since continuous accretion is required to sustain star formation in spirals over cosmological timescales (e.g., Lilly et al. 2013), and the circumgalactic medium (CGM) that sources this accretion often has a tilted angular momentum vector relative to that of the disc (Zjupa & Springel 2017; DeFelippis et al. 2020; Huscher et al. 2021; Semenov et al. 2024), such models could in principle also explain the observed ubiquity and longevity of warps.

The accretion-origin scenario of H I warps could be tested by identifying the gas that sources the warp within the CGM. CGM accretion in Milky-Way mass halos at $z \sim 0$ is commonly assumed to proceed via cool ($\sim 10^4$ K) clouds sinking within a hot ($\sim 10^6$ K) and static volume-filling medium, where the clouds form as a result of either thermal instabilities in the hot phase (‘precipitation’, e.g., Donahue & Voit 2022) or direct accretion from the intergalactic medium (IGM) or satellite galaxies. Whether such clouds actually reach the galaxy or are evaporated into the hot phase due to hydrodynamic instabilities is a field of active research (Heitsch & Putman 2009; Armillotta et al. 2016; Tan et al. 2023; Afruni et al. 2023; Faucher-Giguère & Oh 2023). Moreover, recent deep 21cm images of local disc galaxies in the MHONGOOSE (de Blok et al. 2024) and FEASTS surveys (Wang et al. 2024) do not detect cool clouds down to a threshold of $N_{\text{H I}} \sim 10^{17} \text{ cm}^{-2}$ in the inner CGM ($\lesssim 100$ kpc) of nearby spirals (the ‘H I desert’, Healy et al. 2024; de Blok et al. 2024; Veronese et al. 2025; Marasco et al. 2025). To the extent that the low $N_{\text{H I}}$ is not a result of photoionization (Bland-Hawthorn et al. 2017), these observations imply that cool gas in the inner CGM is insufficient to sustain star formation in these discs, strengthening similar conclusions from earlier 21cm surveys (Sancisi et al. 2008; Sardone et al. 2021; Kamphuis et al. 2022). A lack of cool gas in the inner CGM of the Milky-Way is also suggested by observations that high velocity clouds (HVCs) are rare beyond ≈ 10 kpc (Wakker et al. 2007; Lehner et al. 2022), and by the tight upper limits on cool gas traced by C IV absorption ($N_{\text{C IV}} < 10^{13.4} \text{ cm}^{-2}$, Bish et al. 2021). M31 also exhibits a low cool gas content in its inner CGM with a total Si absorption column of $N_{\text{Si}} \lesssim 10^{14} \text{ cm}^{-2}$ (Lehner et al. 2020, 2025). These observations thus also challenge the sinking cool cloud model for galaxy accretion in nearby spirals.

An alternative possibility that could resolve the challenge posed by the H I desert is that the hot CGM condenses directly onto the warp, so the material source of the warp is hot gas that would be undetected by cool gas observations beyond the warp itself. The hot CGM tends to inflow at a rate where compressive heating balances radiative cooling, if the feedback heating rate is sub-dominant to the radiative cooling rate. This process is known as a ‘cooling flow’ in ICM literature (e.g. Fabian 1994), though note that despite the name, the gas remains hot while it inflows due to the heating-cooling balance. Recent studies using idealized and cosmological simulations show that such hot inflows spin up and flatten onto a thick disc geometry due to strong centrifugal forces at small radii, eventually cooling and accreting directly onto a thin disc (Stern et al. 2020, 2024; Hafen et al. 2022; Sultan et al. 2025). Growing observational evidence indicates that the CGM is indeed spinning (Hodges-Kluck et al. 2016; Ho et al. 2017; Juráňová et al. 2020; Ho & Martin 2020; Nateghi et al. 2024a; Nateghi et al. 2024b; Ho et al. 2025; Kacprzak et al. 2025) and simulations suggest CGM rotation axes with varying degrees

of tilts with respect to the rotation axes of the pre-existing discs (e.g., Zjupa & Springel 2017; DeFelippis et al. 2020; Huscher et al. 2021). The thin disc formed via this accretion process would thus be tilted and appear as an H I warp or a polar ring (e.g., Schechter & Gunn 1978). Furthermore, since hot CGM are expected to be prevalent in local massive star-forming galaxies (Kereš et al. 2005; Dekel & Birnboim 2006; Armillotta et al. 2016; Stern et al. 2020; Faucher-Giguère & Oh 2023), and evolve on cosmological timescales once formed (Bertschinger 1989; Pezzulli & Fraternali 2016), the resulting warps will be both prevalent and long-lived, consistent with H I observations.

In this work, we demonstrate that tilted hot CGM inflows indeed create long-lived H I warps, using an idealized simulation setup similar to Stern et al. (2024). We build on their results that showed hot rotating inflows cooling into a thin disc, by adding a tilt angle between the CGM and disc rotation axes to study the formation of H I warps. Our study is timely given recent observations with Square Kilometre Array (SKA) precursor telescopes such as MeerKAT and FAST, which have enabled detailed studies of extended H I structures at unprecedented resolution (e.g. Wang et al. 2024; Healy et al. 2024; Kurapati et al. 2025; Yang et al. 2025). These observations highlight the power of H I structures, including warps, in tracing physical processes that relate halo dynamics, gas accretion, and disc formation.

This paper is organised as follows. In section 2, we review previous results on the properties of hot rotating CGM inflows that are aligned with the disc, and provide analytic expectations for the misaligned case. In section 3, we introduce our numerical simulation setup of a misaligned hot and rotating CGM. We present the results from our simulations and establish the formation of warps under the paradigm of misaligned hot inflows in section 4. In section 5, we discuss the implications and predictions of our work, and in section 6, we summarize our key results.

2 MISALIGNED HOT INFLOWS

In this section, we summarize key aspects of hot rotating inflows derived by previous papers (Cowie et al. 1980; Stern et al. 2020, 2024; Hafen et al. 2022). We then use these results to establish our expectations for cases where hot CGM rotation is tilted with respect to the rotation axis of the disc (hereafter misaligned hot inflows).

Hot rotating inflows (also called ‘rotating cooling flows’) are subsonic solutions to the fluid equations of an inviscid ideal gas in an external gravitational potential Φ , in which ongoing feedback heating is negligible relative to radiative cooling:

$$\nabla \cdot (\rho \vec{v}) = -\frac{\partial \rho}{\partial t} \quad (1)$$

$$\left(\frac{\partial}{\partial t} + \vec{v} \cdot \nabla \right) \vec{v} = -\frac{1}{\rho} \nabla P - \nabla \Phi \quad (2)$$

$$\left(\frac{\partial}{\partial t} + \vec{v} \cdot \nabla \right) \ln K = -\frac{1}{t_{\text{cool}}} \quad (3)$$

where ρ , $\vec{v}$, and P are the gas density, velocity vector, and pressure, and $\ln K = \ln(P/\rho^\gamma)$ is the entropy with adiabatic index $\gamma = 5/3$. The cooling time is

$$t_{\text{cool}} = \frac{P}{(\gamma - 1)n_{\text{H}}^2 \Lambda} \quad (4)$$

where n_{H} is the hydrogen density and Λ is the cooling function which depends mainly on gas temperature T and gas metallicity Z .

Absent rotation, and under the assumptions of spherical symmetry, steady-state, and $t_{\text{cool}} \gg t_{\text{ff}}$ where $t_{\text{ff}} = \sqrt{2}r/v_c$ is the free-fall time with a circular velocity $v_c = \sqrt{r\nabla\Phi}$, the above equations have an analytic solution for an isothermal potential (e.g., [Fabian et al. 1984](#); [Stern et al. 2019](#)):

$$\begin{aligned} T &= 2.0 \cdot 10^6 v_{c,200}^2 \text{ K} \\ n_{\text{H}} &= 0.8 \cdot 10^{-3} r_{10}^{-1.5} v_{c,200} \dot{M}_1^{0.5} \Lambda_{-22}^{-0.5} \text{ cm}^{-3} \\ -v_r &= \frac{r}{t_{\text{cool}}} = 27 r_{10}^{-0.5} v_{c,200}^{-1} \dot{M}_1^{0.5} \Lambda_{-22}^{0.5} \text{ km s}^{-1} \end{aligned} \quad (5)$$

where v_r is the radial velocity and we normalize the variables by $r_{10} = r/10 \text{ kpc}$, $v_{c,200} = v_c/200 \text{ km s}^{-1}$, $\dot{M}_1 = \dot{M}/1 \text{ M}_{\odot} \text{ yr}^{-1}$, and $\Lambda_{-22} = \Lambda/10^{-22} \text{ erg cm}^3 \text{ s}^{-1}$. The mass inflow rate $\dot{M} = -4\pi r^2 \rho v_r$ is independent of radius, and is the only free parameter of the solution for a known cooling function and potential. This parameter could also be cast in terms of the total CGM mass via the relation between $\dot{M}$ and n_{H} in eqn. (5). The constant temperature of the solution is a result of the balance between radiative cooling and compressive heating in the inflow, while the subsonic inflow velocity implies that deviations from a hydrostatic pressure profile are small, of order $(v_r/v_c)^2 = 0.5(t_{\text{ff}}/t_{\text{cool}})^2 \ll 1$. The inflow timescale is

$$t_{\text{flow}} \equiv \frac{r}{v_r} = t_{\text{cool}}, \quad (6)$$

indicating that linear thermal instabilities do not have time to develop despite that the hot atmosphere is thermally unstable ([Balbus & Soker 1989](#); [Stern et al. 2019](#)). [Stern et al. \(2019\)](#) demonstrated using idealized hydrodynamic simulations that an initially static hot CGM converges onto these solutions within a timescale t_{cool} , and [Sultan et al. \(2025\)](#) showed that this solution provides a good approximation of the hot CGM phase in the FIRE-2 cosmological zoom simulations without black hole feedback, for halo masses $\gtrsim 10^{12} \text{ M}_{\odot}$ at which the $t_{\text{cool}} > t_{\text{ff}}$ assumption is valid.

When accounting for some initial rotation in the hot CGM, the inflow is expected to spin up as it accretes, and eventually halt and cool at the radius where the inflow becomes rotation supported known as the ‘circularization radius’ R_{circ} ([Cowie et al. 1980](#); [Stern et al. 2020](#)), which is comparable to the galaxy scale in standard disc formation theory (e.g., [Mo et al. 1998](#)). The main signature of this accretion mode is thus that cooling from $\sim 10^6 \text{ K}$ to $\sim 10^4 \text{ K}$ in the accreting gas occurs near the galaxy disc and is simultaneous with achieving rotation support ($v_{\phi} \rightarrow v_c$), a prediction that has been borne out in gas accreting onto $z \sim 0$ Milky-Way mass galaxies simulated in FIRE-2 ([Hafen et al. 2022](#)).

A mean value for R_{circ} can be estimated from

$$\bar{R}_{\text{circ}} = \sqrt{2} \lambda_{\text{hot}} f_{\text{vc}}^{-1} r_{\text{vir}} = 0.08 f_{\text{vc}}^{-1} \left(\frac{\lambda_{\text{hot}}}{0.06} \right) r_{\text{vir}}, \quad (7)$$

where λ_{hot} is the spin parameter of the hot CGM defined in [Bullock et al. \(2001\)](#) as

$$\lambda_{\text{hot}} \equiv \frac{j_{\text{hot}}}{\sqrt{2} v_{\text{vir}} r_{\text{vir}}}, \quad (8)$$

r_{vir} , $v_{\text{vir}} = \sqrt{GM_{\text{vir}}/r_{\text{vir}}}$ and M_{vir} are respectively the halo virial radius, virial velocity, and virial mass, while j_{hot} is the hot CGM specific angular momentum and $f_{\text{vc}} \equiv v_c(\bar{R}_{\text{circ}})/v_{\text{vir}} \gtrsim 1$. We assume the average $\lambda_{\text{hot}} \approx 0.06 - 0.08$ found in cosmological simulations ([Teklu et al. 2015](#); [Danovich et al. 2015](#); [Stewart et al. 2017](#); [Oppenheimer 2018](#); [DeFelippis et al. 2020](#); [Huscher et al. 2021](#)), a factor of ≈ 2 larger than the mean spin of the halo. These simulations

also exhibit a halo-to-halo dispersion in λ_{hot} of $\approx 0.25 \text{ dex}$. We thus expect $\bar{R}_{\text{circ}} \approx 20 \text{ kpc}$ for $r_{\text{vir}} = 250 \text{ kpc}$.

The estimate of $\bar{R}_{\text{circ}}$ in eqn. (7) can be compared to typical stellar disc sizes of

$$R_{25} \approx 4R_{\text{d}} \approx 0.05 r_{\text{vir}} \quad (9)$$

where we assumed a factor of four between R_{25} and the disc scale length R_{d} ([Kregel et al. 2002](#); [van der Kruit & Freeman 2011](#); [Comerón et al. 2012](#); [Martín-Navarro et al. 2012](#)), and the relation between R_{d} and r_{vir} derived from abundance matching by [Kravtsov \(2013\)](#). Comparison of eqns. (9) and (7) implies that $\bar{R}_{\text{circ}}$ is on average $\approx 60\%$ larger than $4R_{\text{d}}$, so most of the accreting gas circularizes and cools somewhat beyond the edge of the stellar disc.¹ A similar argument was made by [Stewart et al. \(2013\)](#) and [Stewart et al. \(2017\)](#) in the context of circularization of cold flows accreting onto $z > 1$ galaxies.

[Stern et al. \(2024\)](#) used an idealized 3D hydrodynamic simulation setup to study how a quasi-spherical hot inflow at radii $r > \bar{R}_{\text{circ}}$ transitions to a cool disc at $\approx \bar{R}_{\text{circ}}$, thus going beyond 1D arguments employed by previous idealized studies. They showed that the hot inflow first flattens into a thick hot disc geometry when centrifugal forces become substantial, and then cools from $\sim 10^6 \text{ K}$ to $\sim 10^4 \text{ K}$ at the disc-halo interface when the gas becomes fully rotation supported. Each fluid element cools at the disc radius corresponding to its own R_{circ} , which in turn depends on its specific angular momentum as in eqn. (7).

How would a hot rotating inflow cool if the stellar disc rotation axis is tilted by an angle θ_{tilt} ? If we can disregard gravitational torques by the disc at radii $\bar{R}_{\text{circ}}$, most of the accreting gas will cool as if there is no pre-existing disc, forming a disc oriented according to the CGM rotation axis. This outer gaseous disc will have a radius $\bar{R}_{\text{circ}}$ and will be tilted by an angle θ_{tilt} relative to the pre-existing inner disc, so it would appear as a warp. Therefore, in a typical galaxy, most of the accretion from a hot rotating inflow will occur onto a warp with size $\approx 50\%$ larger than the pre-existing disc. We verify this conclusion using hydrodynamic simulations below.

Our assumption that the torquing of the hot inflowing CGM prior to cooling can be neglected is justified as follows. For a fluid element with a tilted rotational axis relative to the pre-existing disc, the minimum timescale for alignment is $t_{\text{align}} = \omega_{\text{pre}}^{-1}$ where ω_{pre} is the precession frequency of an inclined orbit at this radius. [Binney \(1992\)](#) estimated ω_{pre} for moderately inclined orbits with radius $R > 4R_{\text{d}}$ in an axisymmetric potential of an exponential disc, and derived (their eqn. 9)

$$\omega_{\text{pre}}(R) \approx 11 \Omega (R/R_{\text{d}})^{-3} \quad (10)$$

where $\Omega = v_c/r = \sqrt{2}/t_{\text{ff}}$ is the angular frequency of a circular orbit. Using $R = R_{\text{circ}}$ in eqn. (10) we get

$$t_{\text{align}} \approx 22 t_{\text{ff}} \left(\frac{R_{\text{circ}}}{7R_{\text{d}}} \right)^3. \quad (11)$$

where we normalized by $7R_{\text{d}}$ due to the expected relation between $\bar{R}_{\text{circ}}$ and R_{d} suggested by eqns. (7) and (9). This timescale can be compared to the flow time

$$\frac{t_{\text{align}}}{t_{\text{flow}}} \approx 3.7 \left(\frac{R_{\text{circ}}}{7R_{\text{d}}} \right)^3 \left(\frac{t_{\text{cool}}/t_{\text{ff}}}{6} \right)^{-1} \quad (12)$$

¹ In [Stern et al. \(2024\)](#) we did not account for the high CGM spin relative to that of the dark matter halo as seen in cosmological simulations, so we concluded $\bar{R}_{\text{circ}} \approx 4R_{\text{d}}$ (see section 6.5 there), rather than $\bar{R}_{\text{circ}} > 4R_{\text{d}}$ as deduced here. The high dispersion in CGM spin between halos hints that both cases are relevant, though the latter is likely more common.

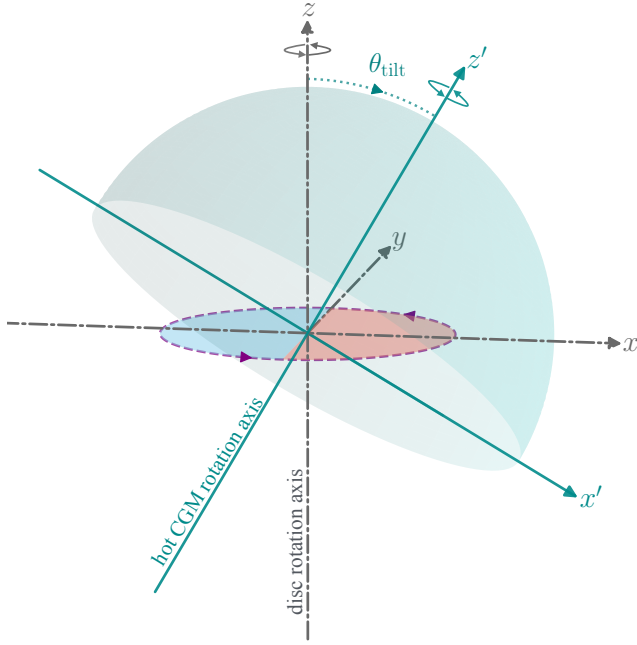


Figure 1. Illustration of the initial conditions in the simulations: a galactic disc surrounded by a hot rotating CGM with a tilted axis. The primed and non-primed coordinate systems respectively describe the CGM and disc orientations, with z and z' along the rotation axes. The $y = y'$ axis is oriented along the line of nodes, and the tilt angle is marked by θ_{tilt} .

where we used eqn. (6) and the estimate of $t_{\text{cool}}/t_{\text{ff}}$ in the inner CGM of Milky-Way mass halos from [Stern et al. \(2024\)](#). The alignment time is thus longer than the flowtime for most of the gas that accretes at radii above the average of $\bar{R}_{\text{circ}} = 7R_d$, and thus to first-order can be neglected. This calculation justifies our expectation that cooling occurs in the midplane defined by the CGM rotation axis, and would thus appear as an extended warp in observed H I discs. In the next section, we test this conclusion using hydrodynamic simulations.

We note that the calculation above neglects any torque due to the inner dark matter halo, which could have a triaxial shape and principal axes that are tilted with respect to the disc and the outer halo (e.g., [Bailin et al. 2005](#); [Shao et al. 2021](#); [Emami et al. 2021](#); [Han et al. 2023b](#)). [Trapp et al. \(2024\)](#) compared the torques applied by the halo and by the disc on accreting gas in Milky Way mass FIRE-2 simulations at $z = 0$, and found that in some cases the dark matter torque can dominate. In this case, the hot CGM may cool in a plane which is intermediate between its own and that of the inner halo, though this plane would still likely be tilted with respect to that of the disc. The disc of accreted gas would thus still appear as a warp, though with $\theta_{\text{warp}} < \theta_{\text{tilt}}$. Our assumption below of a constant gravitational potential also implies the dark matter halo is not growing or growing slowly as expected at late times ([Diemer et al. 2013](#); [Mo et al. 2024](#), see, e.g.,).

3 SIMULATION SETUP

In this section, we describe the numerical simulation setup we use to study warp formation under the paradigm of misaligned hot inflows. Our simulation setup closely follows that described in [Stern et al. \(2024\)](#), which demonstrated how a thin disc forms out of a hot

rotating CGM. We now assume the hot rotating CGM surrounds a pre-existing disc with a tilted rotating axis.

3.1 Code and physics

We use the meshless finite-mass (MFM) mode of the GIZMO code ([Hopkins 2015](#)). MFM is a Lagrangian hydrodynamics solver that combines many advantages of traditional smooth particle hydrodynamics (SPH) and grid-based methods. This allows us to track each resolution element and study its evolution as it inflows from the hot CGM onto the warp. The simulations are initialized with a disc galaxy embedded in a rotating hot CGM as detailed below, where the axis of rotation of the CGM is misaligned with that of the disc by an angle θ_{tilt} (see Figure 1). We refer to the disc and halo coordinate frames as (x, y, z) and (x', y', z') , respectively, with $y = y'$ oriented along the line of nodes. The corresponding spherical coordinates are (r, θ, ϕ) and (r', θ', ϕ') with $r = r'$. We run four idealised 3D hydrodynamic simulations with $\theta_{\text{tilt}} = 0^\circ, 15^\circ, 30^\circ$, and 60° , where $\theta_{\text{tilt}} = 0^\circ$ corresponds to no misalignment. Radiative cooling is calculated using the redshift $z = 0$ optically thin cooling tables from [Wiersma et al. \(2009\)](#) with a gas metallicity $Z = 0.3 Z_\odot$ as estimated for the Milky-Way CGM ([Bregman et al. 2018](#)), while disabling optically thick radiative cooling to temperatures lower than 10^4 K. Since our study is focused on the idealised geometry and thermodynamics of gas outside the ISM, the results are not sensitive to the lack of low-temperature cooling. We also disable feedback processes in order to focus on the regime where radiative cooling in the CGM dominates over feedback heating (see discussion). ‘Star formation’ is implemented by converting all gas resolution elements with densities $n_{\text{SF}} > 10 \text{ cm}^{-3}$ into stellar particles. Last, simulated gravitational forces include self-gravity between simulated gas and stars and an additional spherical acceleration term $-(v_{c,0}^2/r)\hat{r}$ with $v_{c,0} = 200 \text{ km s}^{-1}$, in order to approximate the gravitational field due to the inner dark matter halo. The effects of a non-spherical and potentially tilted halo potential (see section 2) are left for future study. We run the simulations for 3 Gyr, with snapshots saved every 5 Myr. We analyse snapshots after the flow converges into a steady state where the inner hot CGM phase continuously inflows and spins up, cools, and accretes onto the disc. This steady state is achieved typically after ≈ 300 Myr as shown below.

3.2 Initialising a galaxy

We initialise a galaxy disc using the MAKEDISK code ([Springel et al. 2005](#)), adopting parameters of a typical main-sequence Milky-Way mass galaxy ([Catinella et al. 2018](#)). The stellar disc is initialized with a mass of $M_\star = 4.5 \times 10^{10} M_\odot$, a radial scale length of $R_d = 2.5 \text{ kpc}$ and a vertical scale length of $0.1 R_d$. The stellar disc spans $0.03 - 4 R_d$ and connects to a bulge of mass $M_{\text{bulge}} = 2 \times 10^8 M_\odot$, modelled with a Hernquist profile and a scale length of 0.1 kpc . We initialise the cold gaseous disc with a mass $M_{\text{gas}} = f_{\text{gas}} M_\star$ with $f_{\text{gas}} = 0.1$, following the total gas fraction scaling relation from [Catinella et al. \(2018\)](#). The gas disc is initialised with the same exponential distribution as the stellar disc. In the MAKEDISK calculation, we also include the isothermal gravitational field with circular velocity $v_{c,0} = 200 \text{ km s}^{-1}$ used in our simulations, ensuring that v_c is consistent with the baryonic Tully-Fisher relation ([Lelli et al. 2019](#)). Resolution elements mass is $m_b = 8 \times 10^4 M_\odot$, resulting in a total of 6×10^5 and 6×10^4 elements for the initial stellar and gaseous discs, respectively.

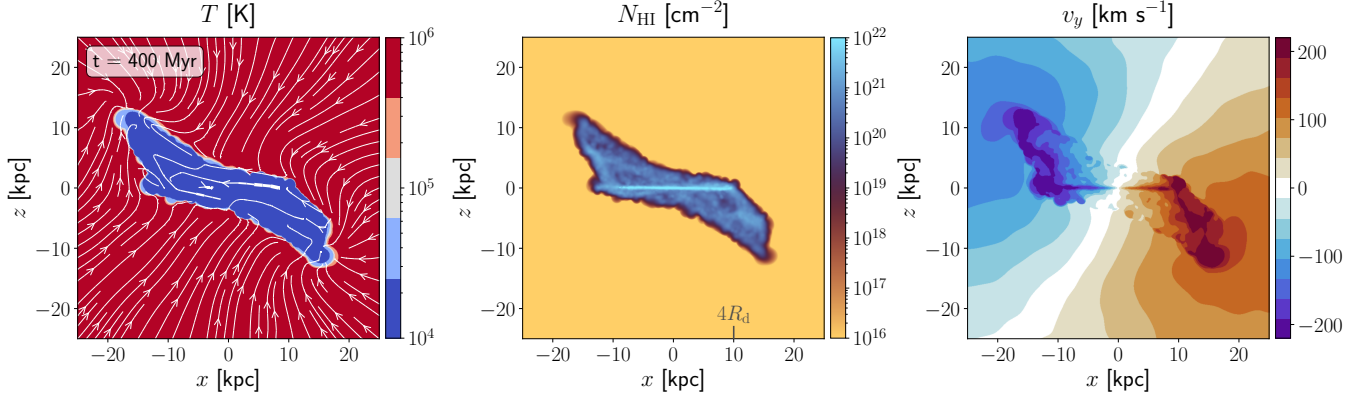


Figure 2. An H_I warp condensing out of a tilted hot CGM. Panels show edge-on projections of the $\theta_{\text{ilt}} = 30^\circ$ simulation at $t = 400$ Myr, after the hot inflow reached a steady state. Gas temperature is shown on the left, H_I column density in the centre, and velocity along the projected axis on the right. White streamlines in the left panel trace the velocity field in the projected plane. The pre-existing disc is apparent in the $z = 0$ plane with a maximum extent of $4R_d = 10$ kpc. A cool, integral-sign H_I warp is apparent, aligned with the 30° -tilted midplane of the hot CGM. The streamlines demonstrate that the hot CGM is inflowing towards the disc and is the source of the warp. Cooling of the hot CGM from $\approx 10^6$ K to $\approx 10^4$ K at the warp boundary increases N_{HI} by orders of magnitude.

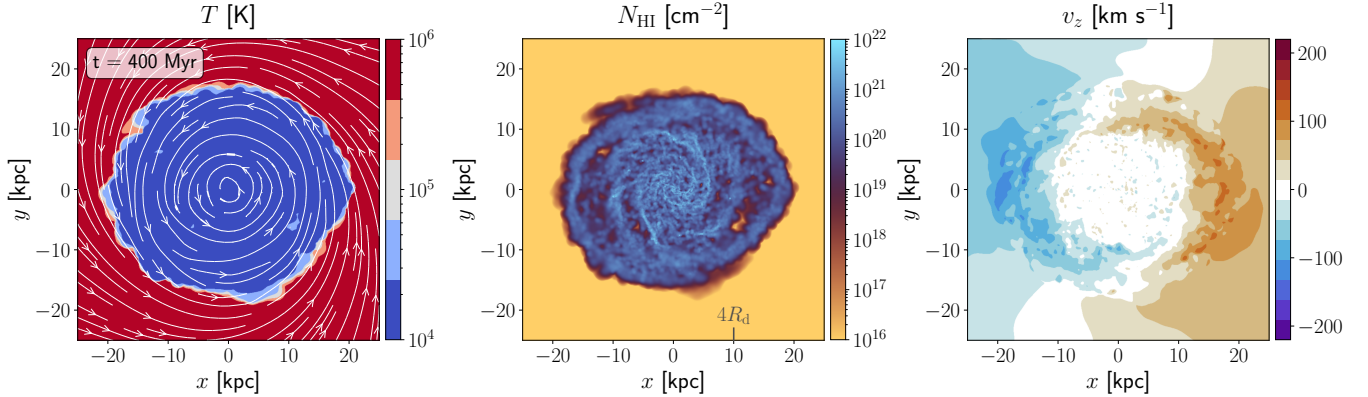


Figure 3. Similar to Fig. 2, for a face-on projection. White streamlines on the left demonstrate how the hot CGM spirals inward toward the disc, cooling abruptly from $\approx 10^6$ K to $\approx 10^4$ K at the warp boundary. The right panel shows that at $|x| \gtrsim 10$ kpc the warp is inflowing towards the disc midplane.

3.3 Initialising a rotating, inflowing hot CGM

We initialise the density, temperature, and radial velocity of the CGM with a non-rotating spherical hot inflow solution from [Stern et al. \(2019\)](#) with $\dot{M} = 0.5 M_\odot \text{ yr}^{-1}$. We integrate the 1D spherically symmetric and steady-state flow equations to obtain this solution, starting at the sonic radius of $r_{\text{sonic}} = 0.05$ kpc and proceeding outward. The integration uses the same $v_{c,0} = 200 \text{ km s}^{-1}$ and cooling function with $Z = 0.3 Z_\odot$ as in the simulation. We then randomly assign initial locations of gas resolution elements in the GIZMO simulation in a way that ensures a radial mass distribution equal to that in the 1D solution. Subsequently, we add a net rotation to the gas by initialising all resolution elements with an angular momentum

$$j_{z'}(t=0) = 4000 \sin^2 \theta' \text{ kpc km s}^{-1}, \quad (13)$$

where we remind the reader that the primed coordinates are defined with respect to the rotation axis of the CGM. This angular momentum distribution is independent of radius and implies that each radial shell has a uniform angular frequency as expected based on the arguments in [Stern et al. \(2024\)](#), equal to $\Omega = 10 (r/20 \text{ kpc})^{-2} \text{ Gyr}^{-1}$. The implied mean circularization radius is $\bar{R}_{\text{circ}} = 13 \text{ kpc}$, as can be

derived from eqns. (7) – (8) and the value of $v_c = 230 \text{ km s}^{-1}$ that we get at disc radii (see below).

The ICs are not in a steady state, since the pressure structure in the integrated solution does not account for rotation support or for the gravity of the disc. The simulation adjusts to a new steady state within several hundreds of Myr, with a somewhat higher $\dot{M}$ in the range $1.4 - 2 M_\odot \text{ yr}^{-1}$.

CGM resolution elements at $r < 100$ kpc have the same mass of $m_b = 8 \times 10^4 M_\odot$ as stars and gas in the disc, which implies a characteristic resolution size of $\approx (3m_b X / (4\pi n_{\text{H}} m_p))^{1/3} \approx 0.8 n_{-3}^{-1/3} \text{ kpc}$ where m_p is the proton mass, X is the hydrogen mass fraction, and $n_{-3} \equiv n_{\text{H}} / 10^{-3} \text{ cm}^{-3}$. This density normalization is typical for hot gas hydrogen densities near the disc. The ~ 100 times denser cool gas has characteristic sizes of $\approx 40 \text{ pc}$. For comparison, the height of the $\approx 10^4 \text{ K}$ gaseous disc that forms from the cooling of the hot gas is $\approx (10^4 \text{ K} / T_{\text{hot}})^{1/2} \bar{R}_{\text{circ}} \approx 1 \text{ kpc}$, where $T_{\text{hot}} \approx 2 \cdot 10^6 \text{ K}$ is the temperature of the hot gas. We use a lower mass resolution for gas beyond $r = 100$ kpc since it does not participate in the inflow due to its long cooling times. It nevertheless needs to be included in the simulation to confine the gas at smaller radii from expanding outward. The assumed mass resolution becomes coarser by a factor

of three every factor of $\sqrt{2}$ in radius beyond 100 kpc, out to 3.2 Mpc where the sound crossing time equals 10 Gyr. The CGM is initialised with a total of 2×10^5 resolution elements.

4 SIMULATION RESULTS

4.1 Formation of H I warps from misaligned hot inflows

Figure 2 shows edge-on maps of gas temperature (T ; left panel), neutral hydrogen column density (N_{HI} ; middle), and projected velocity (v_y ; right) in the $t = 400$ Myr snapshot of the $\theta_{\text{tilt}} = 30^\circ$ simulation. This snapshot is after the accretion flow has converged onto a steady state, as shown below, while the projected plane is chosen to be perpendicular to the line of nodes (the $y = y'$ axes). A cool ($T \approx 10^4$ K) ‘integral sign’ warp is apparent in the outer parts of the cool gas disc, where the warp is in the $+z$ direction on the left and in the $-z$ direction on the right. The value of N_{HI} is about 1–2 orders of magnitude lower in the warp than in the central disc, though still at detectable levels of $N_{\text{HI}} > 10^{19} \text{ cm}^{-2}$. The warp is also evident in the distinction between the kinematic position angles of the inner and outer discs, as can be seen in the right panel, where the kinematic position angle is defined as the angle of the line that maximizes the gradient of the projected velocity. The panels show that the warp is roughly perpendicular to the symmetry axis of the velocity field of the hot gas, evident as the $v_y = 0 \text{ km s}^{-1}$ contour. This indicates that the warp forms in the plane perpendicular to the hot CGM rotation axis, as further demonstrated below.

Streamlines in the v_x, v_z plane are plotted as white contours in the left panel of Fig. 2. These streamlines demonstrate that the hot CGM is inflowing towards the disc, as expected in hot gas where radiative cooling dominates over feedback heating. The panel shows that streamlines that are away from the symmetry axis tend to converge onto the warp, indicating that most of the accretion flows onto the warp. Note also that despite that gas in the cool warp originates from the CGM, N_{HI} in the CGM is negligible since the accreting gas is hot ($\gtrsim 10^6$ K) and highly ionized prior to joining the warp.

Figure 3 shows face-on projections of the same snapshot shown in Fig. 2. The projected streamlines plotted in the left panel demonstrate that the hot gas is spiralling onto the cool disc, remaining hot until it joins the cool disc edge, as also found by [Stern et al. \(2024\)](#) in simulations where the disc and hot CGM are aligned. The right panel of Fig. 3 demonstrates that the warp is evident as an asymmetric pattern in the projected velocity (v_z) when viewed face on.

Figure 4 shows edge-on N_{HI} maps and projected streamlines in the $t = 400$ Myr snapshots of the four simulations. The simulations differ in the tilt angle between the disc and CGM rotation axes, as noted on top of the panels and evident from the directions of the projected streamlines. Warps are clearly apparent in the N_{HI} maps of the three simulations with non-zero tilt angles, with the plane of warp roughly perpendicular to the rotation axis of the hot CGM. Our main result that warp plane traces the midplane of hot CGM rotation is thus independent of the tilt angle. We note also that the accreting warp in the simulation with $\theta_{\text{tilt}} = 60^\circ$ may be observationally classified as a polar ring galaxy ([Schechter & Gunn 1978](#)), which are observed to have an incidence rate of 1–3% in the local universe ([Deg et al. 2023](#); [Mosenkov et al. 2024](#)).

The tendency of warps to track the midplane defined by the hot CGM rotation axis is demonstrated in Figure 5, where we plot specific angular momentum profiles of the snapshots shown in Fig. 4. The top and bottom panels show the specific angular momentum magnitude and angle, respectively, while solid and dashed lines show cool ($T <$

10^5 K) and hot gas ($T > 10^5$ K), respectively. Profiles are measured using a mass-weighted average of all resolution elements in shells with thickness 1 kpc. Different simulations are noted with different colors, with the tilt angles noted in the legend. We also mark the maximum radius of the pre-existing disc ($4R_d = 10$ kpc) and the specific angular momentum of a circular orbit $v_c r$. The value of $v_c(r)$ is calculated in the simulation assuming a spherical potential

$$v_c^2(r) = v_{c,0}^2 + \frac{GM(<r)}{r} \quad (14)$$

where $v_{c,0} = 200 \text{ km s}^{-1}$ is the analytic potential in the simulations (section 3.1) and $M(<r)$ includes all simulated star and gas particles within radius r . The calculation is done in the same $t = 400$ Myr snapshot, though the difference between different snapshots is minor.

The top panel of Fig. 5 shows that the specific angular momentum of the cold gas follows that expected for rotation-supported gas (gray line) out to the edge of the disc at 10 kpc. At larger radii of 10–22 kpc, the cool gas rotates somewhat more slowly than circular orbits, and there is no cool gas beyond ≈ 22 kpc since the CGM is purely hot in our idealized setup. The hot gas specific angular momentum also increases at $r < 20$ kpc, but its rotation velocity is $\approx 0.5v_c$ less than that of the cool gas, likely since any hot gas that approaches full rotation support immediately cools (see below). At $r > 20$ kpc, the specific angular momentum profile of the hot gas flattens and is approximately equal to the mean value in the initial conditions of $3000 \text{ kpc km s}^{-1}$ (section 3.3).

The bottom panel of Fig. 5 shows the transition between the inner disc at $r < 10$ kpc, where the rotation axis of the cold gas is in the direction of the z axis (0°), and the hot CGM at $r > 20$ kpc where the rotation axis of the hot gas is at an angle θ_{tilt} . The warp is evident at intermediate radii of ≈ 10 –22 kpc where the angle of rotation of the cold gas changes between 0° and θ_{tilt} . The angle of rotation of the hot gas also changes at warp radii, though more gradually than the cold gas, and remains offset from 0° even at small radii (except in the $\theta_{\text{tilt}} = 0^\circ$ simulation).

In Figure 6 we demonstrate that the H I warp is long-lived in our simulations. In the first three columns, we plot the edge-on projections of N_{HI} at times $t = 0, 400, 800$ Myr for the $\theta_{\text{tilt}} = 15^\circ, 30^\circ$, and 60° simulations. The panels show that the warp and hot inflow form within a few hundred Myr and remain roughly steady afterwards. We also plot in the rightmost panels the radial profiles of the angle of the cold gas specific angular momentum vector at different times, similar to the bottom panel of Fig. 5. These panels also show that the warps form within 300 Myr and remain roughly steady afterwards. After ≈ 1.5 Gyr the inner disc also tilts, as a result of the accreted gas mass ($\approx 2 \cdot 10^9 M_\odot$ at $t = 1.5$ Gyr) becomes comparable to the initial ISM mass of $4.5 \cdot 10^9 M_\odot$.

We note that Fig. 6 also demonstrates a high-density ring structure in the warps, evident mainly in the $t = 800$ Myr panels. This is potentially a result of the idealized nature of our simulations, wherein there is a discontinuity in the angular momentum distribution between the ISM and CGM gas, where, in practice, it is likely more continuous.

4.2 Tracking the accretion flow

In this subsection, we analyse the accretion flow and warp formation from a Lagrangian viewpoint, complementing the Eulerian viewpoint explored in the previous subsection. To this end, we track gas resolution elements that form the accretion flow in a manner similar to [Hafen et al. \(2022\)](#) and [Stern et al. \(2024\)](#). We choose resolution elements that start within a 2 kpc-thick spherical shell centred at $r_0 = 40$ kpc at $t_0 = 300$ Myr and are subsequently accreted onto

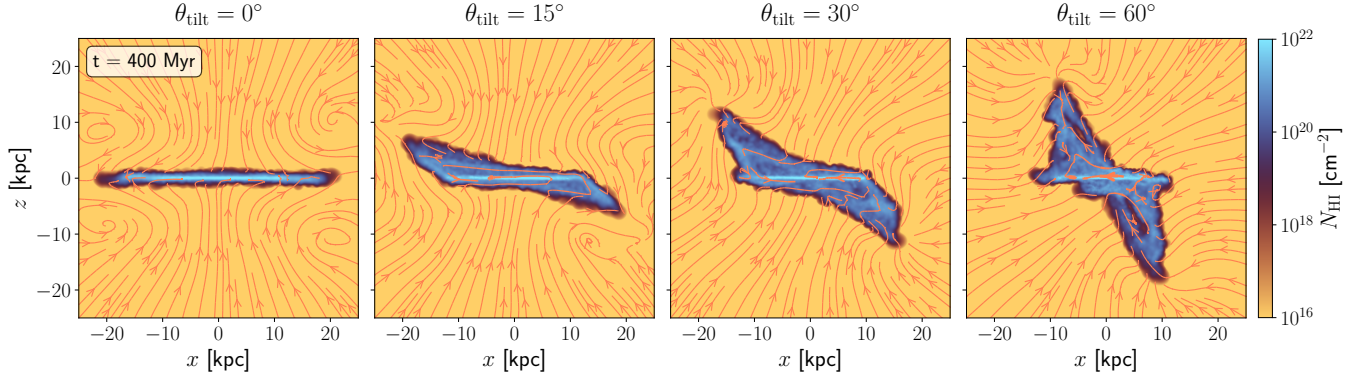


Figure 4. Formation of H_I warps from rotating hot CGM with different tilt angles. Panels show edge-on projections of H_I column density in the $t = 400$ Myr snapshots of the four simulations, with red streamlines tracing the velocity field in the projected plane. Tilt angles are noted on top and are evident from the symmetry axis of the streamlines. The hot inflow cools in the midplane of the tilted CGM in all four cases, creating a H_I warp when $\theta_{\text{tilt}} \neq 0^\circ$. Observed angles of H_I warps thus trace the rotation axis of the hot CGM.

the galaxy at any time up to $t_{\text{accreted,max}} = 1.5$ Gyr. Here, ‘accreted’ implies that the gas has cooled below $T \lesssim 10^5$ K by $t_{\text{accreted,max}}$ and remains cool, potentially forming a star particle. This results in 1895 tracks for the fiducial $\theta_{\text{tilt}} = 30^\circ$ simulation. For each track, we mark the time $t_{10^5 \text{ K}}$ when the gas cools to $T = 10^5$ K, and measure times in the track relative to $t_{10^5 \text{ K}}$. We note that there is no refinement scheme in our simulations, so resolution elements preserve their identity throughout the simulation time.

Example tracks of accreting gas particles are shown in Figure 7. To avoid making the plot too congested, we show only tracks satisfying the following conditions: the gas cools in the halo midplane ($\theta'_{10^5 \text{ K}}$ within $90^\circ \pm 10^\circ$) and outside the pre-existing disc $R_{10^5 \text{ K}} > 12$ kpc. We demonstrate below that most of the accretion satisfies these conditions. Red lines plot all tracks with $-15^\circ < \phi(t = 10^5 \text{ K}) < 15^\circ$ while blue lines plot all tracks with $165^\circ < \phi(t = 10^5 \text{ K}) < 195^\circ$. The median trajectories of each group are plotted with thick lines with borders, where the dashed border corresponds to where the median track is hot and the solid line to where the median track is cool.

In Figure 8 we plot Aitoff projections of accreting gas at the time of cooling in the three simulations with finite tilt angles. Left panels show the solid angle in the frame of the pre-existing disc, while right panels show the frame of the CGM. Each point marks the solid angle at the time of cooling ($\theta_{10^5 \text{ K}}, \phi_{10^5 \text{ K}}$ or $\theta'_{10^5 \text{ K}}, \phi'_{10^5 \text{ K}}$) of a different track. The figure demonstrates that most of the accreting gas cools in the midplane of the CGM, forming an S-shaped locus in the left panel and a straight locus at $\theta'_{10^5 \text{ K}} \approx 90^\circ$ in the right panel. In all three simulations, a fraction of 83%–88% of all tracks cool within 10° of the halo midplane. Fig. 8 thus implies that the *drop in temperature from $\approx 10^6$ K to $\approx 10^4$ K occurs in the CGM midplane*, suggesting that the balance between radiative cooling and compressive heating, which keeps the accreting gas hot, is maintained at all times until the flowlines reach the midplane. Observationally, this result implies that the gas that feed the warps is hot and thus hard to observe until it joins the warp. Additional locii of points are evident in Fig. 8 just above and below the pre-existing discs, suggesting that for these tracks, cooling is a result of direct interaction of the accreting gas with the pre-existing discs. These tracks are subdominant, with 12%–17% of all tracks cooling within 10° of the disc midplane. We thus conclude that in a rotating CGM, cooling from the hot phase onto warps occurs at the plane of the warp, and that this plane is the midplane of the

rotating hot CGM. Warps formed this way thus trace the rotation axis of the hot CGM.

Figure 9 shows the distribution of $R_{10^5 \text{ K}}$ in the $\theta_{\text{tilt}} = 30^\circ$ simulation, which is the cylindrical radii at which the hot inflow cools. We color tracks that cool within 10° of the halo midplane in coral and those that cool away from this midplane in turquoise. The figure shows that all gas that cools beyond 15 kpc cools at the halo midplane, as does almost all the gas that cools beyond the pre-existing disc at 10–15 kpc. This reinforces the conclusion from Figure. 8 that H_I warps that extend beyond the stellar disc trace the rotation axis of the hot CGM.

The distribution of $R_{10^5 \text{ K}}$ in Fig. 9 is bimodal, with a peak at 21 kpc and another peak at 13 kpc. For comparison, the gray line denotes the distribution of R_{circ} in our initial conditions which peaks at 12 kpc, calculated using $v_c(R_{\text{circ}})R_{\text{circ}} = j \cos \theta_{\text{tilt}}$, where j is given by eqn. (13) and v_c is given by eqn. (14). The $R = 21$ kpc peak of the bimodal distribution thus indicates cooling somewhat prior to achieving full rotation support, as also suggested by the sub-centrifugal velocities of cold gas shown Fig. 5. Fluid elements which cool with $R_{10^5 \text{ K}} > R_{\text{circ}}$ at a given time in the simulation also tend to have a narrow range in $\phi_{10^5 \text{ K}}$, suggesting some rotation instability promotes cooling at these radii. We defer exploring this behaviour and the bimodality in $R_{10^5 \text{ K}}$ to future work.

Figure 10 demonstrates how the accretion flow proceeds as a function of time relative to the time of cooling, in the $\theta_{\text{tilt}} = 30^\circ$ simulation. We focus in this figure on gas which cools at $R_{10^5 \text{ K}} > 15$ kpc, corresponding to the right peak in Fig. 9 and including 59% of all accreting gas. Corresponding tracks of accreting gas with $R_{10^5 \text{ K}} < 15$ kpc are shown in the appendix. We group the accretion tracks by the azimuthal angle at the time of cooling, with bins spanning 30° and centred on the values noted in the legend. Lines and bands plot the mean and dispersion of properties of each bin in $\phi_{10^5 \text{ K}}$.

Panel a in Fig. 10 demonstrates that cooling from 10^6 K to 10^4 K is rapid ($\lesssim 100$ Myr) relative to cooling times farther out in the halo, due to the high densities of $n_{\text{H}} \approx 10^{-3} \text{ cm}^{-3}$ at the time of cooling (panel f). Cooling occurs in the halo midplane ($z' = 0$, panel b) and at $R'_{\text{cyl}} < 25$ kpc as indicated by Fig. 9 for gas with $R_{10^5 \text{ K}} > 15$ kpc. Note also that j'_z remains constant prior to cooling (panel e), indicating torques on the hot gas are weak in our simulation as derived using analytic arguments in section 2.

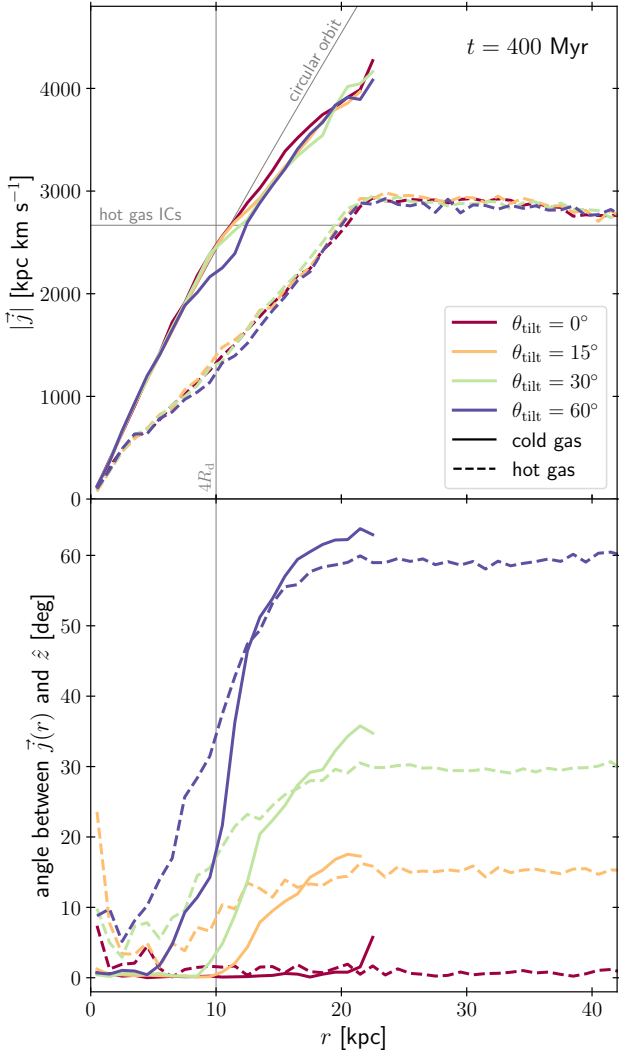


Figure 5. Angular momentum profiles of cool and hot gas in CGM inflows. Panels show the magnitude (*top*) and angle to the disc axis (*bottom*) of the mean specific angular momentum vector at each spherical radius, for both cool gas ($T < 10^5$ K, solid) and hot gas ($T > 10^5$ K, dashed). Colors denote the four simulations, which differ in CGM tilt angle, as evident in the hot gas profiles in the bottom panel at large radii. The 10 kpc size of the pre-existing disc is marked. The H I warp is evident as an increase in cool gas angle from $\approx 0^\circ$ at $r \lesssim 10$ kpc to $\approx \theta_{\text{tilt}}$ at $r \approx 20$ kpc. The cool warp rotates somewhat slower than circular orbits (gray line in top panel), while hot gas rotates slower than cool gas at all radii.

We mark $v_c(t)$ in panels *d* and *i* of Fig. 10, by calculating v_c at the mean $R'(t)$ and $R(t)$ shown in panels *c* and *h*. At the time of cooling, the rotation support is comparable but somewhat lower than the circular velocity ($v_\phi \approx 0.7v_c$), indicating substantial but incomplete rotation support. The cooled gas thus infalls from the radius at which it cools $R_{10^5 \text{ K}} \approx 20$ kpc to $R \approx 12$ kpc at which full rotation support is achieved within $\lesssim 100$ Myr. Cooling thus occurs closely in time with achieving full rotational support as expected in the rotating hot inflow scenario and as identified in the FIRE-2 simulations by Hafen et al. (2022). Note that in the ideal non-tilted case, achieving full rotation support and cooling occur simultaneously within 10 Myr (Stern et al. 2024). During the brief infall phase, the gas density increases by two orders of magnitude (panel *f*), and the cool gas is mildly torqued with

j_z' decreasing from ≈ 3500 kpc km s $^{-1}$ to ≈ 3000 kpc km s $^{-1}$ (panel *e*).

After rotation support is achieved at $t > t_{10^5 \text{ K}} + 100$ Myr, the flow settles on a tilted circular orbit which is stable for at least the next 500 Myr. The orbit is tilted by 20° relative to the disc and 10° relative to the CGM, and has a high gas density of $\approx 0.3 \text{ cm}^{-3}$. We note though that simulating the evolution of gas after cooling requires more realistic disc physics than implemented in our simulations.

Similar tracks for gas with $R_{10^5 \text{ K}} < 15$ kpc are shown in the appendix, separated into tracks that cool in the halo midplane ($\theta'_{10^5 \text{ K}} = 90^\circ \pm 10^\circ$, Fig. A1) and outside the halo midplane (Fig. A2). The inner halo midplane tracks shown in Fig. A1 include 27% of all accreting gas and mostly have $11 < R_{10^5 \text{ K}} < 15$ kpc as shown in Fig. 9. These tracks are significantly torqued prior to cooling with j_z and j_z' increasing by a factor of 1.5 – 2, in contrast with the tracks shown in Fig. 10 with $R_{10^5 \text{ K}} > 15$ kpc, which are not torqued prior to cooling. The difference is likely a result of the stronger gravitational and hydrodynamic torques when cooling radii are smaller (eqn. 11). Correspondingly, these tracks achieve rotation support simultaneously with cooling, and there is no cool infall phase.

The tracks that cool outside the halo midplane constitute 15% of all accreting gas and all cool at small radii of 0 – 15 kpc (Fig. 9). Panel *g* in Fig. A2 demonstrates that they mainly cool in the disc plane ($z = 0$ kpc), as also suggested by Fig. 8. It thus seems plausible that cooling of this accreting gas is a result of direct interaction with the pre-existing disc.

5 DISCUSSION

In this work, we demonstrate that hot CGM rotating around an axis tilted with respect to the disc axis create extended H I warps. We show that the warp is the end result of the quasi-steady ‘rotating cooling flow’ process (Stern et al. 2020, 2024; Hafen et al. 2022; Sultan et al. 2025), wherein the hot CGM phase ($T \approx T_{\text{vir}} \sim 10^6$ K) flows inward while remaining hot and spinning up, eventually cooling to $T \approx 10^4$ K in the plane perpendicular to the rotation axis and at a radius comparable to the circularization radius. This model therefore shares the main principle of earlier models that attributed H I warps to misaligned accretion (e.g., Ostriker & Binney 1989; Jiang & Binney 1999; Shen & Sellwood 2006; Sancisi et al. 2008; Roškar et al. 2010), with the main distinction being that accreting gas is hot prior to joining the warp.

In this section, we discuss how our model compares with observations of low redshift massive spirals (section 5.1) and why our assumption of neglecting feedback heating of the hot CGM is plausible in these systems (section 5.2). We then discuss galaxies at higher redshifts or with lower masses (section 5.3).

5.1 Comparison to observations of $z \sim 0$ spirals

Our results suggest that cooling from the hot CGM is likely to occur in a disc that is extended and tilted with respect to the existing ISM. Observations of H I warps created via this scenario should thus trace the magnitude and orientation of the hot CGM angular momentum, and also the hot CGM metallicity. Such accretion at galaxy outskirts further requires radial inflows within the disc so the accreted gas reaches inner disc regions where star formation occurs. In this subsection, we compare these predictions with available observational constraints.

The predicted sizes of the extended H I discs in the model are $\gtrsim 1 - 2 \bar{R}_{\text{circ}} \approx 0.1 r_{\text{vir}}$ (Fig. 9), or roughly a factor of ≈ 2 larger than

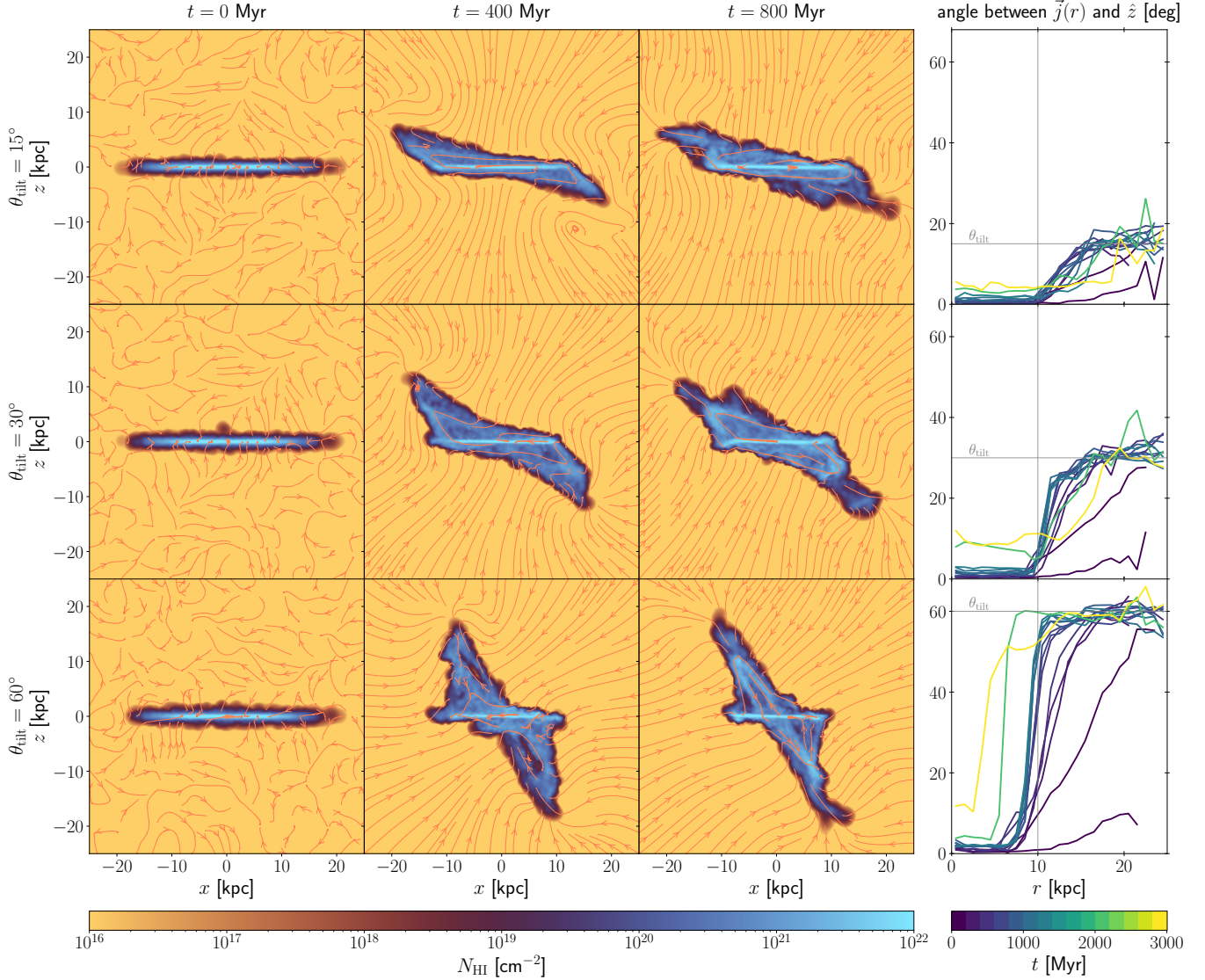


Figure 6. The longevity of H I warps condensing out of a rotating hot CGM for different tilt angles. Each row shows a simulation with different θ_{tilt} , where the three left panels show the edge-on (xz) projections of snapshots at $t = 0$, 400, and 800 Myr, respectively. The rightmost panel plots the angle of the mean specific angular momentum vector of cool gas as a function of radius and time. The size of the pre-existing disc is marked. Warps form within ≈ 300 Myr and remain steady afterwards. The tilts of the inner discs become evident after ≈ 1.5 Gyr, when the accreted gas mass becomes comparable to the initial ISM mass.

the stellar disc, due to the higher spin of the hot gas relative to that of the disc. This ratio is consistent with the relative extent of H I and stars observed in nearby spirals (e.g., Broeils & Rhee 1997; Lee et al. 2025), thus supporting the model. Crucially, H I gas is not required at larger distances, since the accreting gas cools only when reaching the circularization radius (Figs. 8–9), consistent with a lack of H I in the inner CGM of nearby spirals (Healy et al. 2024; de Blok et al. 2024; Wang et al. 2024; Lin et al. 2025; Veronese et al. 2025; Marasco et al. 2025). A similar argument on the size of accreted discs was made by Stewart et al. (2013) and Stewart et al. (2017), who posited that large cool discs at $z > 1$ are a result of the high spin of the cold flows that feed them. Our results thus demonstrate how the Stewart et al. argument applies at $z \sim 0$ when the hot accretion mode dominates, an epoch which is also more accessible to H I observations.

While observed H I warp sizes appear consistent with hot CGM spins expected from simulations, observed warp tilt angles may be

lower than misalignment angles of simulated hot CGM. García-Ruiz et al. (2002) observed warp angles of $3 < \theta_{\text{warp}} < 25^\circ$ with a median of 12° in edge-on galaxies, if we consider only the 16 out of 26 objects in their sample with $R_{\text{HI}}/R_{25} > 1.2$ where we expect $\theta_{\text{warp}} \approx \theta_{\text{tilt}}$ (see Section 2 and especially eqn. 12). Somewhat larger warp angles of $15^\circ - 20^\circ$ are measured in seven galaxies from the Local Volume H I survey (Wang et al. 2017), though they caution that their measurement method may somewhat overestimate true warp angles. For comparison, DeFelippis et al. (2020) looked at misalignments between the CGM and stellar disc in $z = 0$ MW-mass galaxies in the TNG100 simulations, and found a median $\theta_{\text{tilt}} = 15^\circ$ for galaxies in the upper quartile of the angular momentum distribution, and a larger $\theta_{\text{tilt}} = 40^\circ$ for galaxies in the lower quartile. Huscher et al. (2021) deduced a larger median $\theta_{\text{tilt}} = 56^\circ$ in the EAGLE simulations (Schaye et al. 2015). The simulated θ_{tilt} thus appear to be on average larger than observed θ_{warp} , though larger surveys, a more careful

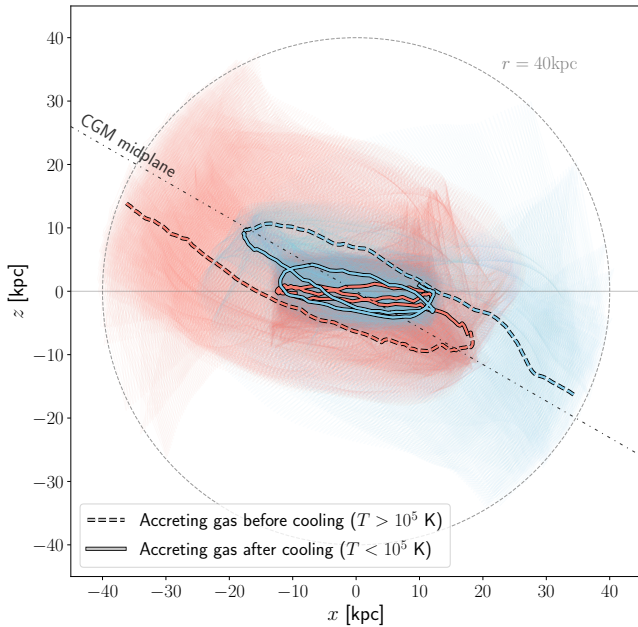


Figure 7. Example trajectories of gas in a hot rotating CGM which cools onto the warp. We show trajectories which cool either at $\phi_{10^5 \text{ K}} \approx 0^\circ$ (red) or at $\phi_{10^5 \text{ K}} \approx 180^\circ$ (blue), corresponding to cooling at the maximum vertical offset of the warp. Thick curves show the median trajectories, with dashed (solid) segments corresponding to when the inflow is part of the hot CGM (hi warp).

comparison that accounts for survey selection, and understanding how simulated θ_{tilt} depend on feedback parameters and simulation resolution are needed to test this conclusion.

Accretion onto galaxy outskirts also suggests that the gas metallicity in H I warps traces that of the hot CGM, since star formation within the warps is inefficient (Bigiel et al. 2010; Wang et al. 2017) and thus should not significantly alter the metallicity of accreted gas. In the Milky Way, Wenger et al. (2019) deduced $Z = 0.3 - 0.6 Z_\odot$ from H II regions at $R = 15$ kpc (the furthest of their measurements), similar to the $0.4 - 0.8 Z_\odot$ deduced in the outskirts of MANGA galaxies with similar mass (Pilyugin et al. 2019, at $R = R_{25}$). This metallicity in the Milky Way outskirts is consistent with the hot CGM metallicity of $\approx 0.5 Z_\odot$ deduced from X-ray and dispersion measure observations (Faerman et al. 2017; Qu & Bregman 2018; Bregman et al. 2018, with factor of ≈ 2 uncertainty). A handful of external galaxies also have metallicity estimates for their hot CGM, and show similar values as the Milky Way (Bregman et al. 2018). The hot CGM metallicity is thus consistent with the metallicity in galaxy outskirts within the observational errors, further supporting the validity of our hot accretion model.

Accretion at large radii, as suggested by the model above (Fig. 9), also requires radial inflows within the disc to sustain star formation at inner disc radii. This picture is consistent with the ‘modified accretion disc’ model for star-forming discs discussed in Wang & Lilly (2022a,b), a version of which is also observed in some simulations (Trapp et al. 2022; Barbani et al. 2025). In the modified accretion disc model, gas accretes mainly from the outer disc edge and flows inward, while some of the inflow turns into stars or is ejected by outflows at different radii. Observational evidence for these inflows in local discs is still inconclusive, since the low predicted inflow velocities of $1 - 5 \text{ km s}^{-1}$ in the inner disc imply that they are hard

to identify (e.g., Trapp et al. 2022). Di Teodoro & Peek (2021) argued that 21 cm observations rule out such disc inflows, though this result has been questioned in the outer parts due to known degeneracies between signatures of radial inflows and warps (Wang & Lilly 2023; Sylos Labini et al. 2025). In contrast, an observed correlation between mean gas metallicity and the slope of the disc metallicity gradient has been argued to support the existence of radial inflows (Lyu et al. 2025).

We note also that rotating and inflowing hot CGM have specific predictions for how the hot gas entropy, rotation velocity, and temperature depend on radius and polar angle relative to the hot CGM rotation axis, properties which have observational consequences for hot CGM observations. We refer the reader to previous papers on inflowing and rotating hot CGM for a thorough discussion (Stern et al. 2019, 2024; Wijers et al. 2024; Sultan et al. 2025, see also Sormani et al. 2018 who discussed radially-static rotating CGM).

5.2 Could galaxy feedback disrupt warp formation?

Our calculation above neglects heating of the hot CGM by galaxy feedback processes, and radiative losses are instead compensated by compressive heating in the inflow. Cooling of the hot CGM then occurs as a result of circularization at a radius $\gtrsim R_{\text{circ}} \approx 0.1 r_{\text{vir}}$, rather than as a result of thermal instability in the hot phase. If instead feedback heating offsets or exceeds cooling losses, then the hot CGM would not inflow but rather be radially static or form an outflow (Carr et al. 2023; Voit et al. 2024a,b). Galaxy accretion in this latter case would instead proceed via sinking cool clouds formed due to thermal instabilities (McCourt et al. 2012; Sharma et al. 2012; Voit et al. 2017). We argue here that neglecting feedback heating of the hot CGM is a plausible assumption in massive spirals at $z \sim 0$.

Main sequence SF discs at $z \sim 0$ exhibit weak stellar-driven winds (e.g., Heckman & Thompson 2017) which are unlikely to significantly offset CGM cooling losses. Significant heating by stellar feedback is more likely in starburst galaxies, which exhibit strong winds, though if bursts are separated by more than a cooling time, then the hot inflow would have time to reform. As t_{cool} is rather short in the inner CGM ($\lesssim 1$ Gyr, see section 2) this condition is plausibly satisfied. Feedback heating can also result from black hole activity, as is potentially suggested by the existence of the Fermi Bubbles in the Milky Way, though the amount of heating injected into the CGM by this process is highly uncertain (see review of Fermi bubble models in Sarkar 2024). Even if significant, feedback by the black hole mostly affects the hot CGM near the rotation axis (Truong et al. 2021), so it is unclear if it can disrupt the formation of H I warps near the disc edge as discussed here. We thus conclude that feedback heating of the hot CGM near the midplane is plausibly small in $z \sim 0$ main-sequence galaxies, supporting our calculation above.

We note that the relatively weak stellar-driven winds seen in local spirals, known as ‘fountain flows’, could also affect the hot CGM by promoting cooling at the disc-halo interface due to mixing of the cool winds with the hot gas (Marasco et al. 2012; Fraternali 2017; Li et al. 2023). The accretion rate via this fountain-driven accretion process will be limited by the rate at which a hot CGM inflow can replenish the disc-halo interface gas that has cooled and accreted. Our simulations suggest that most of the hot inflow ends up and cools beyond the disc edge (Fig. 9) rather than at small galaxy radii above sites of star formation where fountain flows are observed. The amount of hot gas available for cooling via fountain-driven accretion will thus be subdominant to accretion from disc outskirts.

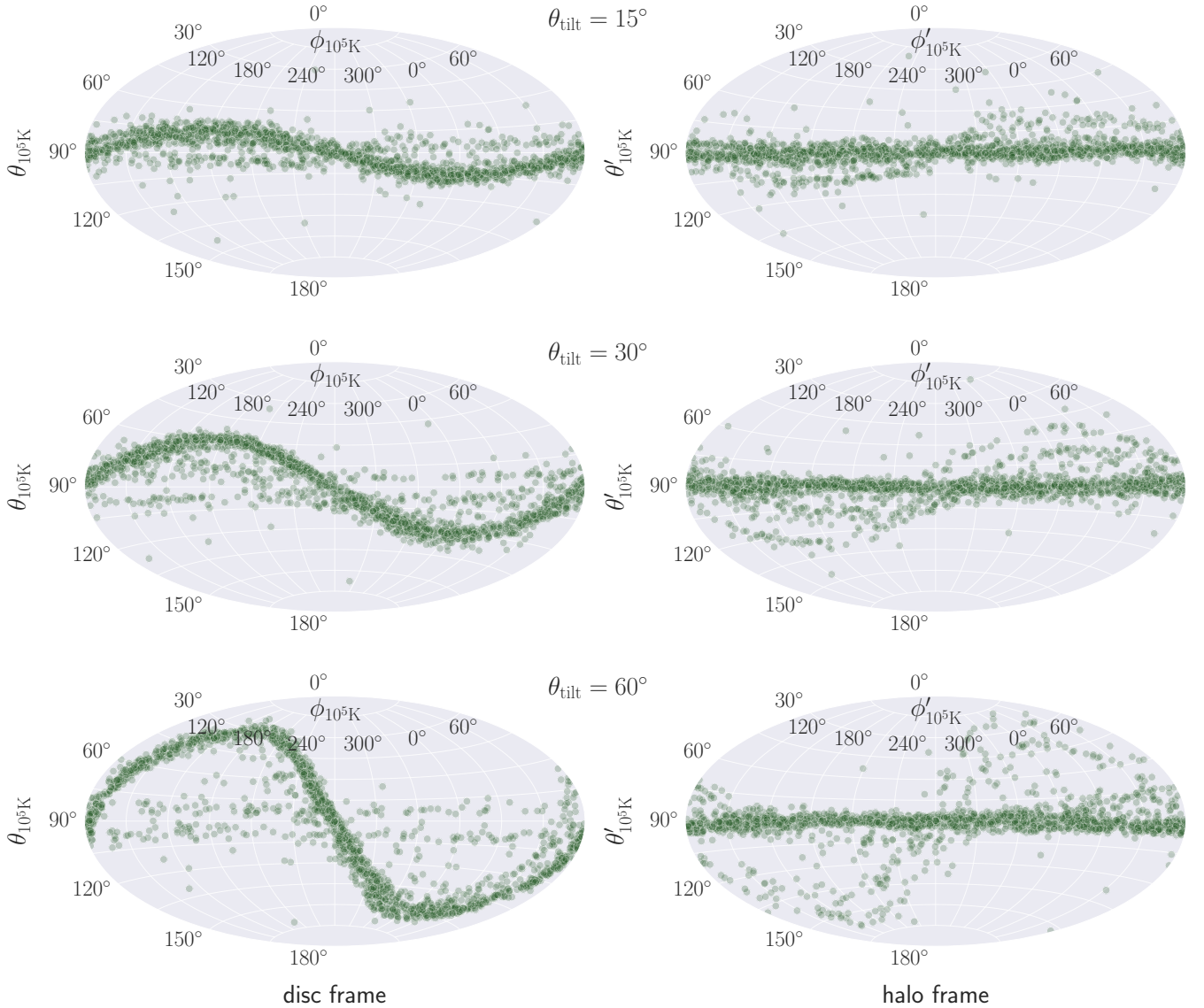


Figure 8. Polar and azimuthal angles at which the hot inflow cools from $\approx 10^6$ K to $\approx 10^4$ K, shown both in the disc frame (left) and in the halo frame (right) for the three simulations with $\theta_{\text{tilt}} = 15^\circ$ (top), $\theta_{\text{tilt}} = 30^\circ$ (middle), and $\theta_{\text{tilt}} = 60^\circ$ (bottom). Each point denotes the cooling angles of a single accreting resolution element. In all simulations, most of the accreting gas cools in the halo midplane ($\theta'_{10^5 \text{ K}} \approx 90^\circ$, straight locus in the right panels). A minority of the gas cools near the disc plane ($\theta_{10^5 \text{ K}} \approx 90^\circ$, two straight loci in the left panels).

5.3 At which masses and redshifts are H I warps formed via hot accretion expected?

Condensation of the hot CGM directly onto the warp requires that the hot CGM is stable and long-lived down to the circularization radius $R_{\text{circ}} \approx 0.1 r_{\text{vir}}$. It has long been argued that a stable hot CGM can exist only if its cooling time t_{cool} is longer than the halo dynamical or free-fall time t_{ff} , a condition satisfied for mean CGM densities above a halo mass threshold of $\sim 10^{11.5} M_\odot$ (White & Rees 1978; Birnboim & Dekel 2003; Kereš et al. 2005; Fielding et al. 2017; Pandya et al. 2023), with a secondary dependence on CGM mass and metallicity. Stern et al. (2020) showed that at inner halo radii near R_{circ} , the higher density and shorter cooling time imply a higher threshold mass than the outer CGM, of $\sim 10^{12} M_\odot$, for a CGM mass equal to half the halo baryon budget and characteristic metallicities of $0.3 Z_\odot$ (see also

fig. 2 in (Goldner et al. 2025)). This predicted ‘outside-in’ hot CGM formation scenario has been identified in the FIRE cosmological zoom simulations (Stern et al. 2021a,b; Gurvich et al. 2023; Kakoly et al. 2025) and potentially also in TNG50 (Semenov et al. 2024). It is this higher mass threshold that is required to be surpassed for the warp to condense directly out of the hot CGM. Furthermore, even if a stable hot phase exists down to R_{circ} , it may be subdominant in terms of accretion rate due to cold flows penetrating the halo and reaching the disc as expected at $z > 1$ (Dekel & Birnboim 2006). We thus expect H I warps condensing directly out of the hot CGM in Milky-Way mass spirals at $z < 1$, and potentially also at lower masses if the CGM is depleted in mass. This range of mass and redshift is also supported by the feedback-based arguments discussed in the previous section.

In principle, warps could also form due to misaligned cold ac-

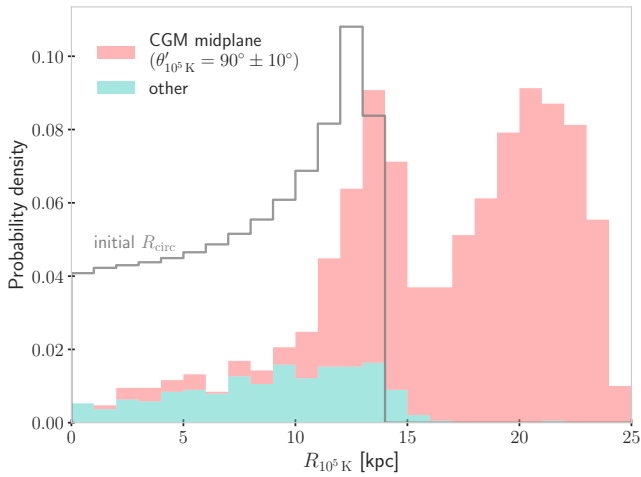


Figure 9. Distribution of radii at which the hot inflow cools from $\approx 10^6$ K to $\approx 10^4$ K in the $\theta_{\text{tilt}} = 30^\circ$ simulation. Color denotes whether cooling occurs in the CGM midplane (coral) or not (turquoise). The gray line denotes the PDF of circularization radii in the initial conditions. Note that almost all gas that cools beyond $4R_d = 10$ kpc cools in the CGM midplane, and not farther out in the halo or in the plane of the tilted stellar disc.

cretion, which is expected at lower masses and higher redshifts than hot accretion. It has, however, been argued that cold accretion drives turbulence in low mass and high-redshift discs, either directly by injecting momentum into the disc (Ginzburg et al. 2022), or indirectly by altering feedback properties and disc gas fractions (Stern et al. 2021a; Gurvich et al. 2023; Sun et al. 2025), characteristics which set the level of turbulence in the disc (e.g. Bland-Hawthorn et al. 2024, 2025). This connection between thin disc formation and hot accretion is supported by the tendency of thin discs to appear mainly in massive spirals at $z < 1$ (Kassin et al. 2012; Tiley et al. 2021), similar to when hot accretion is expected. Observed warps in local spirals surround discs which are sufficiently thin and kinematically cold that even mild warp angles of $\approx 3^\circ$ are identifiable (García-Ruiz et al. 2002). A gentle and smooth accretion process is thus preferred for explaining these systems, such as the hot accretion mode discussed herein.

6 SUMMARY

In this work, we use an idealized GIZMO simulation to demonstrate that an extended and warped H I disc forms out of hot CGM that has a tilted rotation axis with respect to that of the stellar disc. Our simulation setup includes a Milky Way-like pre-existing disc, a radiatively cooling hot CGM, and an analytic gravitational profile mimicking the dark matter halo potential similar to Stern et al. (2024), with the main distinction that the CGM and disc rotation axes are misaligned. Our study also differs in its focus on the formed H I discs, in contrast with predicted hot CGM properties discussed in Stern et al. (2024).

Our main findings can be summarized as follows.

(i) We demonstrate that extended H I discs can form through continuous and smooth cooling of the hot CGM, in the midplane defined by the rotation axis (θ' at cooling is $\sim 90^\circ \pm 10^\circ$, see Fig. 8) and at radii comparable to the circularization radius (Fig. 9). This is consistent with recent observations that gentle accretion and feedback

processes are required to produce regular and low-turbulent H I discs in the local universe (Marasco et al. 2025).

(ii) Accreting gas is hot and invisible to cool gas observations prior to joining the extended H I disc, consistent with recent deep 21 cm observations of local spirals that indicate H I in the halo is insufficient to explain gas accretion (de Blok et al. 2024; Wang et al. 2024; Lin et al. 2025).

(iii) Observed sizes of H I discs in the local Universe, which are roughly twice the stellar disc size (e.g. Broeils & Rhee 1997; Lee et al. 2025), are consistent with hot CGM spins seen in cosmological simulations (e.g. Stewart et al. 2017; DeFelippis et al. 2020; Huscher et al. 2021), supporting our model.

(iv) The cooling properties of hot CGM suggest that extended H I discs and warps probe the magnitude and orientation of the hot CGM angular momentum (Figs. 4, 5). This provides a new observational probe of hot CGM kinematics. Observed warp angles appear smaller than hot CGM-disc misalignment angles found in simulations (section 5.1).

(v) Warps are long-lived in our simulations, in the sense that warp angles evolve on the same timescale as the ISM angular momentum changes $t_{\text{warp}} \approx M_{\text{ISM}}/\dot{M} \sim$ a few Gyr (Fig. 6). We note that our simulations assume constant hot CGM properties, but these are also expected to evolve on $\gtrsim$ Gyr timescales once the hot CGM has formed.

The H I warp formation model discussed herein can be further tested by understanding warp formation in cosmological simulations. These simulations include explicit feedback models, more realistic dark matter potentials that are not perfectly spherical, and CGM spins and CGM-disc tilts that emerge self-consistently in a Λ CDM framework rather than being put in by hand as we do here. We expect our model to be valid in simulations in which accretion is dominated by inflows in the hot CGM, such as the FIRE-2 zoom simulations of Milky Way-mass galaxies at $z \sim 0$ (Hafen et al. 2022; Sultan et al. 2025). Simulations which account for disc physics could also allow studying additional properties of warps in the context of our warp formation model, such as radial inflows (see section 5.3), bending waves (e.g., Sellwood & Debattista 2022), corrugation patterns (e.g., Bland-Hawthorn & Tepper-García 2021), and line of nodes patterns (e.g., Briggs 1990; Józsa 2007). From the observational side, a more extensive sample of observed H I warps and their angles with respect to the inner disc would be useful for comparison against the hot CGM angular momentum properties found in simulations.

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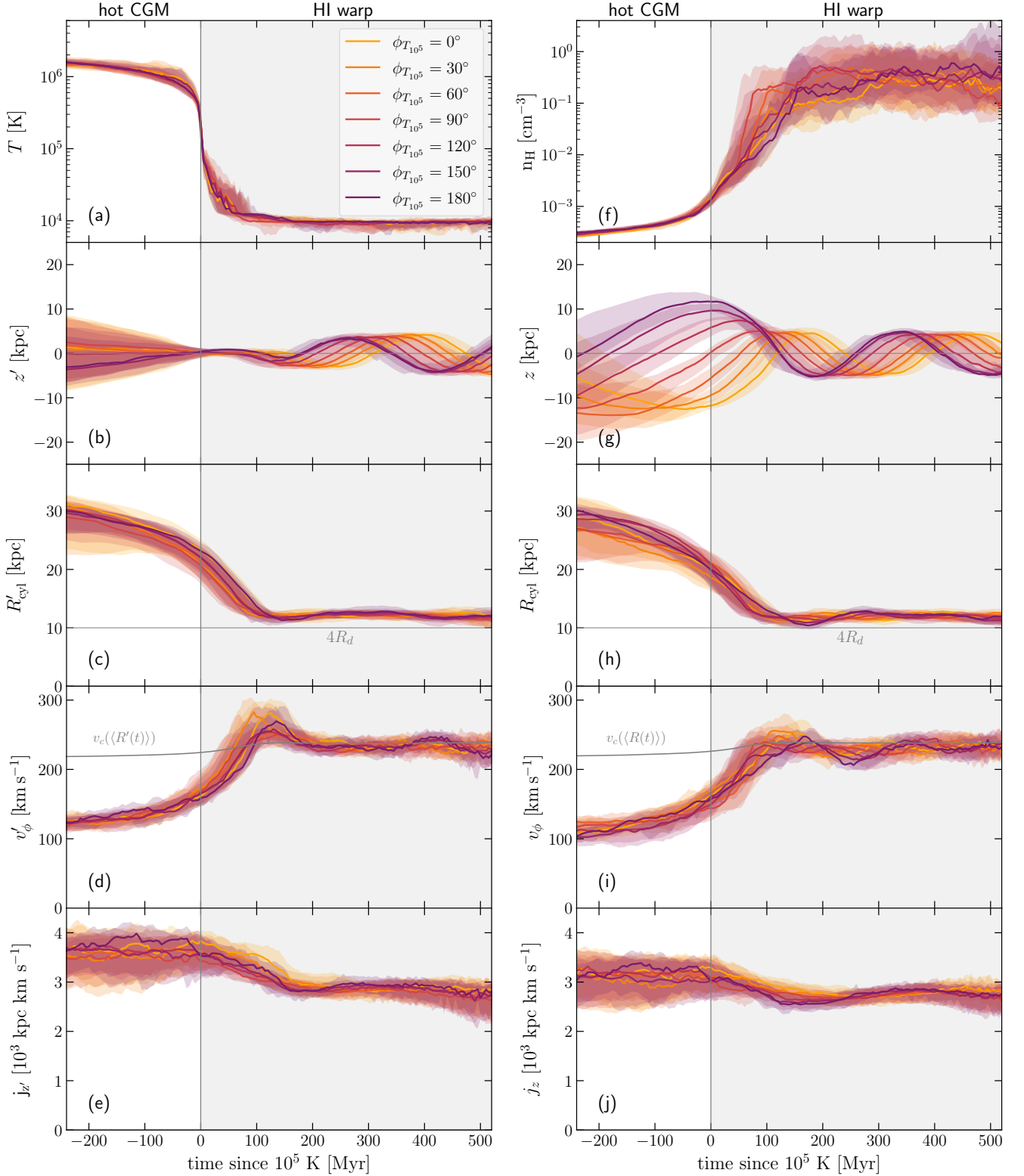


Figure 10. Lagrangian evolution of hot rotating CGM with a tilted rotation axis. Panels show different properties of accreting gas as a function of time since cooling, in the Θ_{30} simulation. Lines and bands plot the mean and dispersion of properties of all gas which cools at $R_{10^5\text{ K}} > 15\text{ kpc}$ (see Fig. 9), grouped by azimuthal angle at the time of cooling (see legend). Top row shows gas temperature (*left*) and density (*right*), while bottom four rows show z and R_{cyl} coordinates, rotation velocity, and specific angular momentum, both in the in the halo frame (*left*) and in the disc frame (*right*). Panel *a* demonstrates that cooling from 10^6 K to 10^4 K is rapid ($\lesssim 100\text{ Myr}$) and occurs in the halo midplane ($z' = 0$, panel *b*) as also indicated by Figs. 8–9. Rotation support with $v_\phi = v_c$ is achieved approximately 100 Myr after cooling (panels *d*, *i*), at which point the inflow stops (panels *c*, *h*) and the density ceases to increase (panel *f*). Similar tracks for gas with $R_{10^5\text{ K}} < 15\text{ kpc}$ are shown in the appendix.

DATA AVAILABILITY

The simulation data underlying this article will be shared on reasonable request to the corresponding authors. A public version of the GIZMO simulation code is available at <https://github.com/pfhopkins/gizmo-public>.

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APPENDIX A: ADDITIONAL ACCRETION TRACKS

Figures A1 and A2 are similar to Fig. 10, for fluid elements which cool in the halo midplane at $R_{10^5 \text{ K}} < 15 \text{ kpc}$ (27% of all accreting gas, Fig. A1), and for fluid elements which outside the halo midplane (15% of all accreting gas, Fig. 10). These tracks are discussed in section 4.2.

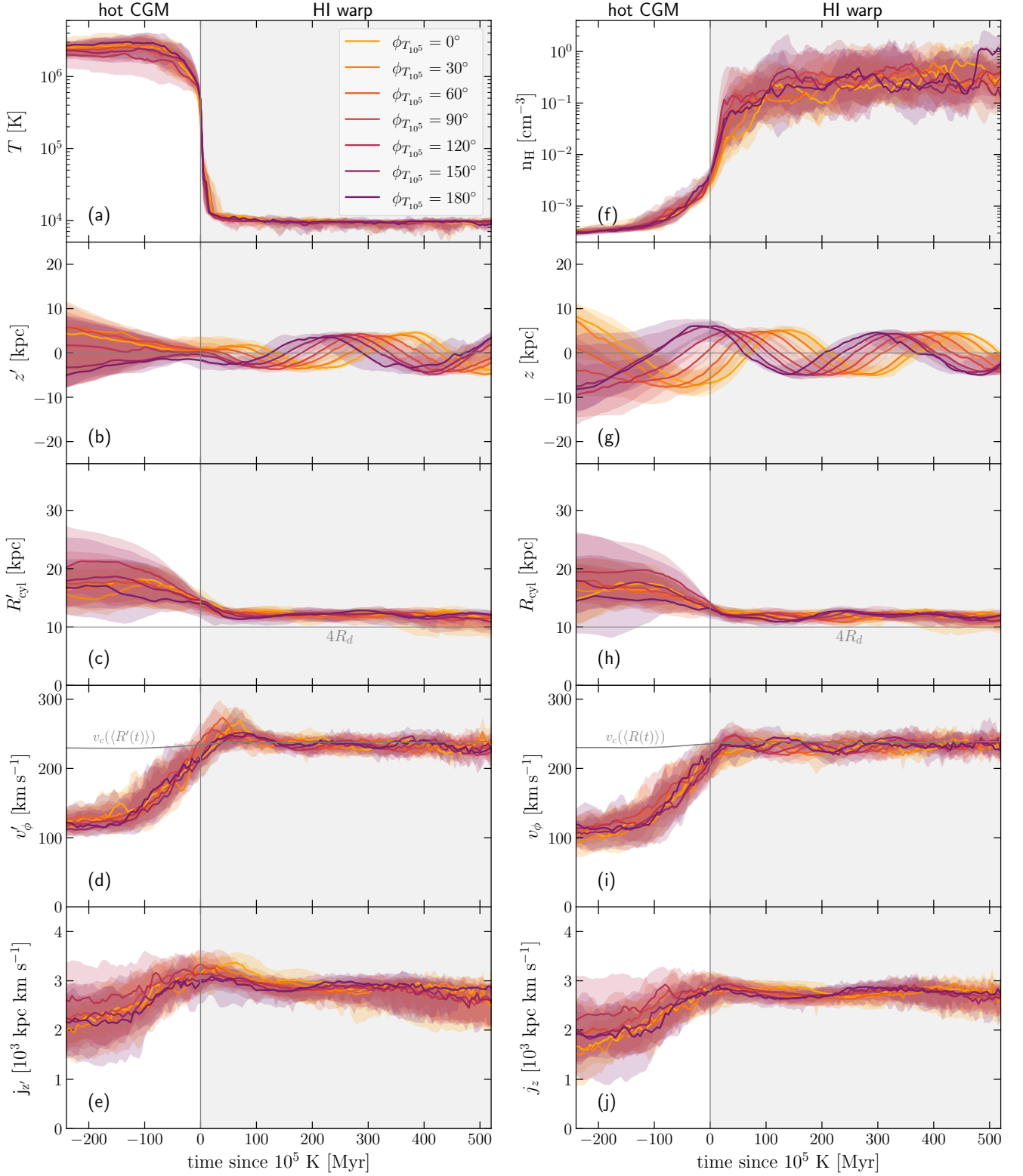


Figure A1. Similar to Fig. 10 for gas which cools in the halo midplane at $11 < R_{10^5 \text{ K}} < 15$.

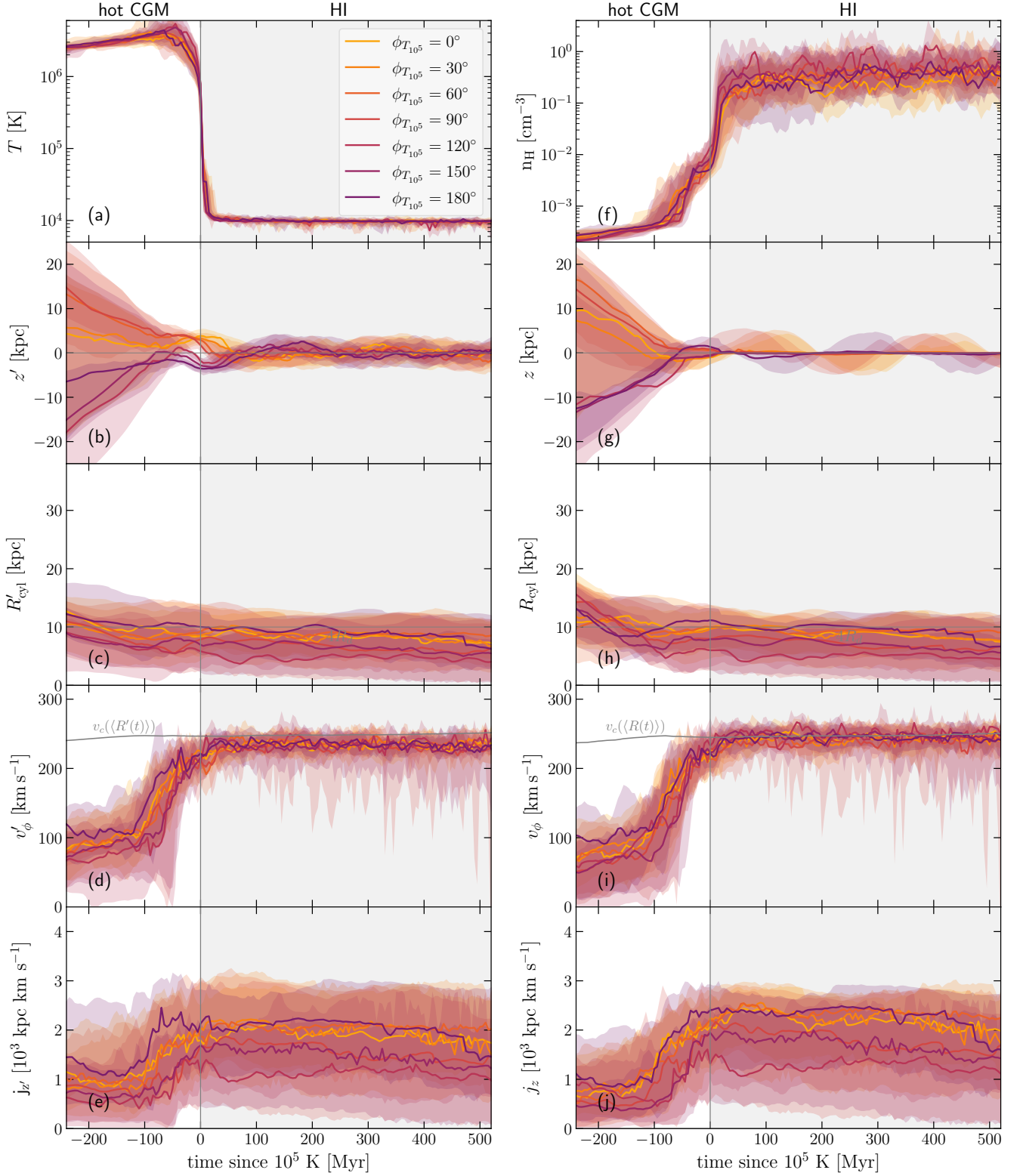


Figure A2. Similar to Fig. 10 for gas which cools away from the halo midplane.

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