A dark matter wake origin for an ever-present Gaia snail shell

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ABSTRACT

We perform a cosmological magnetohydrodynamic simulation of a Milky Way-like galaxy with $\gtrsim 10^8$ star particles to study the formation of out-of-equilibrium stellar disc structures in a full cosmological setting. In the plane defined by the coordinate and velocity perpendicular to the mid-plane (vertical phase space, \{\(Z, V_Z\)\}), stars in Solar-like volumes at late times exhibit clear spirals similar in shape and amplitude of the Gaia “Snail shell” phase spiral. We show that the phase spiral forms at a look back time of $\sim 6$ Gyr during the pericentric passage of a $\sim 10^{10} M_\odot$ satellite which stimulates the formation of a resonant wake in the dark matter halo. The magnitude of the wake-induced gravitational torque at the Solar radius at this time is $\sim 8$ times that from the satellite, and leads to the formation of a disc warp that wraps up into a vertical phase spiral over time. This link between dark matter wakes and the formation of the phase spiral is first explicitly established here, and contrasts with earlier studies favouring direct torques from a Sgr dwarf galaxy or buckled bar origin. Furthermore, the feature is ever-present during the epoch of disc evolution: the initial disc is never featureless and unperturbed as is ubiquitously assumed in non-cosmological models. Our results demonstrate the highly complex and substantial role of the dark halo and its population of satellites on the dynamical history of the Milky Way’s disc.

Key words: methods: numerical - Galaxy: structure - galaxies: spiral - Galaxy: kinematics and dynamics - Galaxy: disc - Galaxy: evolution

1 INTRODUCTION

Recent large Galactic surveys such as Gaia (Gaia Collaboration et al. 2018a) have now crystallized the idea that the Milky Way is in a state of dynamical disequilibrium. The Galactic disc(s) in particular harbours a great deal of structure indicative of this, including vertical asymmetries such as the warp and Monoceros Ring (e.g. Gómez et al. 2012; Slater et al. 2014; Xu et al. 2015; Poggio et al. 2018; Schönrich & Dehnen 2018) and planar stellar moving groups (see e.g. Gaia Collaboration et al. 2018b; Kawata et al. 2018; Antoja et al. 2018; Fragkoudi et al. 2019). These features are thought to originate from rich dynamical phenomena ranging from external perturbations (e.g. Widrow et al. 2012; Xu et al. 2015; Gómez et al. 2017b; Antoja et al. 2018; Laporte et al. 2022) to internal processes from bars and spiral arms (e.g. Monari et al. 2016; Fragkoudi et al. 2019; Trick et al. 2019, 2021). The detailed information now available from large Galactic surveys provide a unique opportunity to learn about these gravitational processes that have shaped the distribution of stars in our Galaxy. Given that gravity permeates the dark sector as well as the baryonic, it is also a window into the distribution of dark matter, and perhaps even its nature.

One of the most striking and recently discovered dynamical features discovered in the Galactic disc is the so-called Gaia “phase spiral” or “Snail shell” (Antoja et al. 2018; Tian et al. 2018): a spiral pattern in the vertical phase plane \((Z, V_Z)\) associated with oscillations perpendicular to the Galactic plane of nearby disc stars. This feature can be seen in both the density and planar velocity (either \(V_\phi\) or \(V_R\)) of stars in this plane, and is indicative of the phase mixing of a group of stars initially clumped together in the phase plane. The spiral shape occurs because the vertical period of oscillation is an increasing function of amplitude (anharmonic motion), therefore stars with larger oscillations in the initial clump would take longer to traverse a phase space ellipse compared to those with smaller oscillations (see Binney & Schönrich 2018, for a thorough explanation).

There has already been a surge in activity to try to understand the origin of the initial clump of stars. Several studies have linked the phase spiral to a perturbation from a dwarf satellite (e.g. Antoja et al. 2018; Binney & Schönrich 2018). Such a perturbation can qualitatively reproduce the phase spiral as seen in \(V_\phi\) or \(V_R\) by generating
correlated, coherent in-plane and vertical oscillations of stars entering the Solar neighbourhood from both the inner and outer disc; a clump of low-$V_\phi$, short vertical period inner disc stars shears into tighter spirals relative to a clump of high-$V_\phi$, long vertical period outer disc stars. An obvious candidate for the perturbing satellite is the Sagittarius dwarf galaxy (hereafter Sgr), which is thought to have undergone several close pericentric passages (Purcell et al. 2011; Ruiz-Lara et al. 2020) and induced gravitational perturbations on the disc (Gómez et al. 2013). Indeed, several idealised N-body simulations have shown that earlier passages of a more massive Sagittarius are able to qualitatively reproduce the phase spiral (Laporte et al. 2020) and induced gravitational perturbations on the disc (Gómez et al. 2020); these simulations have shown that earlier passages of a more massive Sagittarius are able to qualitatively reproduce the phase spiral (Laporte et al. 2018). Another class of perturbation arises from collective effects from resonant wakes generated in the dark matter halo by a passing satellite (e.g. Weinberg 1995, 1998; Vesperini & Weinberg 2000). Cosmological simulations have shown that these wakes can induce dynamical perturbations more than an order of magnitude larger than those from the satellite itself, and form galaxy-wide disc warps and corrugation patterns with features similar to those of the Milky Way’s Monoceros Ring (Gómez et al. 2016, 2021). Using tailored N-body simulations of the impact of a Sgr-like galaxy on an equilibrium stellar disc, Laporte et al. (2018) showed that even though a dark matter wave develops during the early pericentric passages of Sgr, its impact becomes negligible compared to the direct impact of Sgr at late times when the onset of the vertical phase spiral occurred. Thus the nature of the perturbation from which the feature grows is attributed directly to Sgr itself.

Nearly all of the theoretical work discussed above that explicitly studies the phase spiral adopts either toy or idealised N-body models (to the author’s knowledge, the single exception is García-Conde et al. 2022). These models do not include cosmologically-grown stellar discs (and therefore have no memory of stellar populations formed during past epochs) that could respond differently to perturbations relative to smooth equilibrium discs. Nor do they include the array of perturbations inherent to a cosmological setting, such as misaligned gas discs, the spectrum of subhaloes & satellites expected for the ΛCDM paradigm, and a non-axisymmetric dark matter halo. Cosmological zoom-in simulations model all of these processes, but their limited resolution typically precludes the study of delicate and detailed dynamical features like the phase spiral. For example, Gómez et al. (2016) globally characterized the vertical response of a galactic disc simulated on a fully cosmological context, but lacked the resolution to study its response in local Solar-like volumes. For cosmological simulations to match the detail provided by ~ 10⁸ star particles now attained by idealised models (Bland-Hawthorn & Tepper-García 2021; Hunt et al. 2021), tens of millions of cpu hours per simulation are required. Such substantial computational expense, which is mainly incurred by the hydrodynamic calculation involving large numbers of gas particles/cells, hinders the production of cosmological simulations capable of resolving detailed dynamical structures such as the spiral.

In this paper, we employ a new technique for star formation in cosmological simulations - called superstars, which significantly boosts the stellar resolution to ~ 10¹⁰ star particles without the need to increase the gas resolution. This approach yields significant advantages: it provides access to new dynamical scales for stars at a substantially reduced computational cost, and side-steps the most significant challenges to numerical convergence which are driven almost entirely by changes to gas resolution. We describe this technique in Section 2. In Section 3, we study the nature and origin of dynamical features analogous to the Gaia “Snail shell”. We show that the simulated disc develops a spiral structure in vertical phase space during the epoch of disc formation, and tie its origin to a dark matter halo wake. We show that this feature lasts until the present day, by which time its decayed to an amplitude and shape quantitatively similar to the Gaia phase spiral. In Section 4, we summarise our conclusions and discuss our findings in the context of earlier work.

2 SIMULATIONS

2.1 The Auriga model

The simulated galaxy presented in this paper is a re-simulation of one of the Milky Way-mass systems from the AURIGA project (Grand et al. 2017, 2018), specifically the halo presented in Grand et al. (2021) (referred to as Au 6 in AURIGA nomenclature). This halo has a mass of $M_{200} = 1.03 \times 10^{12}$ M⊙ at redshift zero, where $M_{200}$ is defined as the mass contained inside the radius at which the mean enclosed mass density equals 200 times the critical density of the universe. The parent dark matter only cosmological simulation has a comoving periodic box size 100 Mpc, and adopts the following parameters for the standard ΛCDM cosmology: $\Omega_m = 0.307$, $\Omega_b = 0.048$, $\Omega_{\Lambda} = 0.693$ and a Hubble constant of $H_0 = 100h$ km s⁻¹ Mpc⁻¹, where $h = 0.6777$, taken from Planck Collaboration (2014). At redshift 127 (the starting redshift), the resolution of the dark matter particles of the Lagrangian region from which this halo forms is increased and gas is added to create the initial conditions of the zoom simulation. At redshift zero, this high resolution region has a radius of the order ~ 1 Mpc.

The simulation was performed with the magneto-hydrodynamic code AREPO (Springel 2010; Pakmor et al. 2016), and the AURIGA galaxy formation model, which includes: primordial and metal line cooling; a uniform UV background that gradually increases to completion at $z = 6$; a model for star formation that activates for gas densities larger than 0.1 atoms cm⁻³ (Springel & Hernquist 2003); magnetic fields (Pakmor et al. 2014, 2017, 2018); gas accretion onto black holes and energetic feedback from AGN and supernovae type

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1 Few cosmological simulations have attained such a high stellar particle resolution, namely the Justice-League Mint Condition simulation (Applebaum et al. 2021) and a simulation from the Auriga project (Grand et al. 2021). The particle number of the simulation presented in García-Conde et al. (2022) is not stated, so it is unclear whether ~ 10⁸ star particles is achieved.
II (SNII, see Vogelsberger et al. 2013; Marinacci et al. 2014; Grand et al. 2017, for more details). Each star particle is treated as a single stellar population of given mass, age and metallicity. Stellar mass loss and metal enrichment from type Ia supernovae (SNIa) and Asymptotic Giant Branch (AGB) stars are modelled according to a delay time distribution, and metals from SNII are injected promptly. The AURIGA model has been shown to produce realistic spiral disc galaxies that are broadly consistent with a number of observations including star formation histories, stellar masses, sizes and rotation curves of Milky Way-mass galaxies (Grand et al. 2017), the distribution of HI gas (Marinacci et al. 2017), the stellar halo properties of local galaxies (Monachesi et al. 2019), stellar disc warps (Gómez et al. 2017a), and bulges (Gargiulo et al. 2019), the properties of magnetic fields in nearby disc galaxies (Pakmor et al. 2017, 2018), and the luminosity function of satellite galaxies (Simpson et al. 2018).

In the study of Grand et al. (2021), we presented the hitherto highest resolution cosmological hydrodynamic zoom simulation of a Milky Way-mass halo; the baryonic and dark matter mass resolution of the simulation is ~ 800 M☉ and 6 × 10⁶ M☉, respectively. In the AURIGA nomenclature, this resolution is given the shorthand “level 2”. Apart from the significant computational expense (~ 15 million CPU hours), this study highlighted two significant issues: i) a ~ 30% systematic increase in stellar mass of the main galaxy for each factor 8 increase in mass resolution (see Table 2 of Grand et al. 2021); ii) a break-down in the black hole centering algorithm at very high (level 2) gas resolution with negative consequences for disc formation. The former is a qualitatively generic problem for all hydrodynamic simulations, whereas the latter is a new obstacle. Both, however, are related to increases in gas resolution. This situation motivates a different approach to model stellar dynamics in cosmological simulations in which the mass resolution of collisionless components are enhanced relative to the gas.

2.2 The Superstars method

We adopt a newly developed method called Superstars which achieves both a very high stellar resolution and removes the issues described above, namely: i) the large computational cost; and ii) systematic changes with gas resolution. This method will be fully described in Pakmor et al. in prep, and the full suite of simulations will be presented in Fragkoudi et al. in prep. Here, we briefly summarise the essence of the method. Instead of forming a single star particle of a mass approximately equal to that of the gas cell from which it spawned, Superstars forms a group of lower-mass star particles instead. The birth positions are identical for each of the star particles in one group. Their velocities are set to the velocity of the parent gas cell plus a random isotropic component. The size of the isotropic component is drawn randomly from a Gaussian distribution with a width set by the minimum of the local sound speed and velocity dispersion of its neighbouring gas cells. We ensure that the total contributions of all random components of one group cancel to conserve total momentum in the simulation. The chemical evolution is handled in exactly the same manner as the original AURIGA simulations. The number of star particles formed per group is in principle arbitrary, but is naturally limited by the available computational resources. In the simulation discussed in this paper, we retain the level 4 gas resolution (~ 5 × 10⁴ M☉) and form 64 star particles per group and star-forming gas cell. This achieves the same stellar mass resolution (~ 800 M☉) as the simulation presented in Grand et al. (2021) with the highly desirable benefits of much improved numerical convergence (including a well-behaved black hole centering algorithm) and a more than 10 times reduction in the overall computational cost. As will be shown in Pakmor et al. in prep., the larger dark matter to stellar particle mass ratio that this technique entails does not enhance artificial scattering of particles found for lower resolution large cosmological volume simulations (Ludlow et al. 2019, 2021).

In the context of the present study, Superstars resolves detailed Galactic structure of the kind recently observed by large surveys such as Gaia in the presence of an array of complex dynamical phenomena inherent to galaxy formation. This is complementary to studies based on toy models and idealised N-body simulations that make up the vast majority of the current literature on the subject.

3 RESULTS

3.1 Present-day phase spiral properties

In this section, we present the properties of the disc and vertical phase spiral at redshift zero, with reference to the Gaia snail shell where appropriate. The top row of Figure 1 shows a face-on view of the present-day stellar disc colour-coded according to various properties: the azimuthal stellar over-density in the disc plane (left panel); the mean radial velocity (second panel); the mean vertical velocity (third panel); and the mean vertical height (fourth panel). Here, we note the presence of a weak bar and clear spiral structure stretching from the ends of the bar into the outer disc. In a similar morphological pattern, the mean radial velocity betrays streaming motions of magnitude ~ 10 km s⁻¹ correlated with the bar/spiral over-densities. A mild corrugation pattern is evident in the third and fourth panels of the top row of Fig. 1 as oscillations in Z and VZ along radial “spokes” of constant azimuth; the pattern appears to span from the Solar circle to the edge of the galaxy.

The second and third rows of Fig. 1 show the over-density of the VZ-Z distribution of star particles within 3 kpc of 8 Solar-like positions (spread equidistant in azimuth along a cylindrical radius of 8 kpc in the disc mid-plane), where each coordinate is normalised such that they are dimensionless (as done in Hunt et al. 2021, for example). For the normalisation factors, we calculate, for each snapshot, the standard deviation of the vertical position (and velocity (hZ and σZ, respectively) of star particles younger than 3 Gyr in a Solar annulus of width and height equal to 2 kpc. This selection ensures we calculate a reasonable normalisation for disc stars at Solar-like positions. At the present day, the values are: hZ = 530 pc and σZ = 23 km s⁻¹, respectively. To calculate the over-density value of each pixel in this surface of section, we first smooth the raw distribution with a 2D Gaussian kernel of width equal to 0.5 for both coordinates to yield a mean density map. Then we divide the original unsmoothed map by the mean density map and subtract 1 from each pixel, such that pixels with a positive (negative) value are over- (under-)densities. This reveals clear phase spirals with amplitudes of roughly 0.2-0.3 in some Solar-like positions (see, e.g., position 0), similar to what is reported by Laporte et al. (2019) for the Gaia snail shell. Although present at each Solar-like location, there is variation in the detailed

Note that this is not the same as the scale height, Z0, of a fitted density profile typically used to measure the thickness of discs, such as the sech²(Z/Z0) profile. For this simulated galaxy, the thin and thick disc scale heights are: Z0,thin = 363 pc and Z0,thick = 1107 pc, respectively. These values are consistent with current estimates for the Milky Way’s thin and thick discs (see Bland-Hawthorn & Gerhard 2016, and references therein).

Note the Archimedean shape of these spirals (r = aθ), as opposed to logarithmic spirals (r = ae^θcosb) typically discussed in the context of galactic spiral arms (Binney & Tremaine 2008).
Figure 1. *Top row:* 40 kpc × 40 kpc face-on projections of various quantities for star particles within 1 kpc height above/below the midplane at redshift zero: the azimuthal over-density (leftmost panel); the mean radial velocity (km s\(^{-1}\), second panel); the mean vertical velocity (km s\(^{-1}\), third panel); and the mean vertical height (kpc, fourth panel). Black symbols mark the positions of 8 Solar-like positions placed equidistant along a ring of 8 kpc radius. *Second & third rows:* the over-density of star particles located within 3 kpc of each Solar-like position in the dimensionless vertical phase plane (see text for details). *Fourth & fifth rows:* as above, but coloured according to radial velocity (km s\(^{-1}\)). The phase-space spiral is visible at all eight Solar-like locations. A high-cadence (5 Myr time resolution) animation of this figure in the co-rotating frame (at \(R = 8\) kpc) can be viewed at [https://wwwmpa.mpa-garching.mpg.de/auriga/movies/multi_halo_6_sf64.mp4](https://wwwmpa.mpa-garching.mpg.de/auriga/movies/multi_halo_6_sf64.mp4). An equivalent figure for a “level 4” simulation can be seen at [https://wwwmpa.mpa-garching.mpg.de/auriga/images/multiplot_halo_6_sf1_r8_251-min.pdf](https://wwwmpa.mpa-garching.mpg.de/auriga/images/multiplot_halo_6_sf1_r8_251-min.pdf), which demonstrates that phase spirals are not resolved at that resolution.
This variation among different Solar-like positions, we deduce that the radial velocity amplitude of the phase spiral to be approximately 10 km s$^{-1}$, which is comparable to that of the observed phase spiral (e.g. Tian et al. 2018) dissected the vertical phase spiral as a function of age using LAMOST and Gaia data and showed that the phase spiral is present among groups of coeval stellar populations younger than 6 Gyr, except perhaps for the very youngest stars (that formed less than 500 Myr ago) which may not exhibit a clear spiral. As discussed by Tian et al. (2018) and elsewhere, this sort of dissection may help date the putative perturbation. To explore this idea in our simulation, we show in Fig. 2 the vertical phase space over-density for separate coeval stellar populations at two of the Solar-like positions shown in Fig. 1 (positions 4 and 6; separated in azimuth by 90 degrees). Star particles that formed between 2 and 6 Gyr ago (shown in the second and third rows of Fig. 2) show the strongest phase spirals. The oldest age group shows (at most) very faint signs of a phase spiral, because this population is kinematically hotter than the younger populations and therefore does not respond as coherently to dynamical perturbations as the latter. This is consistent with the work of Gómez et al. (2016), who showed that satellite perturbations excited global warp and corrugation structures which were strongest in the youngest stellar populations. A clear spiral is not evident for the stellar populations younger than 2 Gyr, in contrast to observations. We will discuss these results further in Section 4.

In Fig. 3, we show the vertical phase plane for star particles within 3 kpc spheres centred on positions along a ring of radius 14 kpc (but use the same normalisation factors as for the Solar-like positions in order to compare their relative shapes). The same age trends of the phase spirals described above for Solar-like positions hold also for the outer disc, therefore we show only star particles aged between 2 and 6 Gyr old in order to highlight the outer disc phase spiral properties clearly. We note two key differences compared to the spirals at Solar-like positions: i) the spirals are compressed along the vertical velocity axis relative to the vertical height axis, reflecting the lower vertical restoring force of the lower surface density outer disc; ii) the spirals are more loosely wound (fewer wraps) owing to the lower vertical frequencies and hence longer dynamical timescales of stars in the outer disc. These trends are consistent with those found in Gaia DR2 data and other simulations (see e.g., Laporte et al. 2019; García-Comde et al. 2022). Note also that these positions (4 - 7) span 135 degrees in azimuth (see the top-left panel of Fig. 1) and cover a downward and upward moving section of the corrugation pattern (see the third and fourth panels of the top row of Fig. 1). This translates to spirals in the $Z-V_z$ plane that move through approximately 180 degrees from position 4 to position 7, and provides a flavour of the kind of variation that could be present in future observations covering broader swathes of the disc.

### 3.2 The evolution of the phase spiral

Having shown that the morphology and strength of our simulated present-day phase spiral is similar to the Milky Way’s snail shell, we now focus on its formation and evolution. The top two rows of Fig. 4 shows a ~ 3 Gyr time sequence of the vertical height and velocity maps of the disc viewed face-on. The bottom row shows, for each snapshot, the vertical phase space over-density of star particles in a 3 kpc volume centred at a Solar-like location (indicated in each panel and selected to show the phase spiral particularly clearly). The first column shows this information for the snapshot $t_{\text{lookback}} = 6.5$ Gyr: the vertical height and velocity maps show a clear warp which stretches from the central disc to radii beyond the Solar-like positions (again marked by the black symbols). This warp manifests as an off-
Figure 3. Similar to Fig. 2, but for star particles between 2 and 6 Gyr old within 3 kpc spheres centred on positions along a ring of radius 14 kpc.

Figure 4. Time evolution of the warp/corrugation and snail shell. First and second rows: the mean vertical height and vertical velocity of stars for face-on apertures of 40 kpc × 40 kpc at a series of times. Colour bars indicate the colour scale in units of kpc and km s\(^{-1}\), respectively. Black symbols mark the locations of 8 Solar-like positions. Third row: the phase spiral over-density at a Solar-like position (indicated by the label in the top-left of each panel, and by the red circle in the first and second rows), selected to clearly show the structure at each time. The size of the phase plane is indicated by the scale bar in the lower-left corner of each panel; note that the aperture becomes larger from left to right as the normalisation factors (\(h_Z, \sigma_Z\)) decrease with time owing to upside-down formation (e.g. Grand et al. 2016). These snapshots illustrate: the formation of a global warp pattern (first column) that quickly starts to wind up (first two rows). As shown in the last row, a short-lived (~ 100 Myr) two-armed phase spiral emerges shortly after the onset of the warp (second column). Subsequently, a clear one-armed phase spiral develops (third column) and proceeds to wind-up and decrease in strength over time (fourth column). We remind the interested reader of the animation https://wwwmpa.mpa-garching.mpg.de/auriga/movies/multi_halo_6_sf64.mp4 which shows the evolution of the phase spiral at each Solar-like position.
centre over-density in $Z-V_Z$ space (lower-left panel). We will show in Section 3.3 that this occurs immediately after the close pericentric passage of a satellite galaxy of infall mass of $\sim 10^{10} \, M_\odot$. Over time, the disc warp winds into a corrugation pattern, the precise morphology of which evolves according to the radial dependence of vertical frequencies of stellar orbits and the relative strength of torques from the inner disc and outer halo (see Briggs 1999; Shen & Sellwood 2006; Gómez et al. 2017a, for detailed explanations). In the vertical phase plane at $t = 5.58$ Gyr, the distribution becomes more wrapped and a two-armed phase spiral is seen in $Z-V_Z$ space at the Solar location 4, which is in closest proximity to the disc crossing point of a satellite (we return to this in Section 4). However, this two-armed phase spiral is a local feature and lasts only approximately 100 Myr. The lower-third panel ($\sim 50$ Myr later) and lower-fourth panel (a further $\sim 1.3$ Gyr later) show clear one-armed vertical phase spirals: as phase mixing proceeds, the spiral becomes more tightly wound (characterised by more wraps) owing to the anharmonic motion discussed earlier. This time sequence clearly connects the phase spiral to an initially large-scale bi-symmetric warp, and thus supports the global nature of its origin.

To quantify the evolution of the phase spiral strength, we calculate the amplitude of the $m = 1$ and $m = 2$ terms of a discrete Fourier transform of the particles in the vertical phase plane:

$$A = \sqrt{W_c^2 + W_s^2},$$

where

$$W_c = \frac{N}{i} \cos m\theta_i / N; \quad W_s = \frac{N}{i} \sin m\theta_i / N,$$

and $N$ is the number of particles, and $\theta_i$ is the angular coordinate of the $i$-th particle in this plane. The phase spiral appears well-resolved in the dimensionless distance range of 0.5 and 2.5, therefore we consider particles within this region only in order to avoid spurious measurement effects. We bin star particles into 10 equally spaced bins in dimensionless distance, calculate the amplitude in each bin, and take the median amplitude across all bins for each Solar position. The evolution of the amplitudes of the $m = 1$ mode and the $m = 2$ mode are shown in Fig. 5: individual Solar-like positions are represented by circles and the medians of these values for each time are shown by solid curves. The $m = 1$ mode peaks at amplitude at $t_{\text{lookback}} \sim 6-7$ Gyr, then proceeds to gradually decay to its present day shape and strength depicted in Fig. 1. The $m = 2$ mode is weaker than that of the $m = 1$ mode at all times.

### 3.3 The nature of the perturbation

To understand the nature of the perturbation causing the phase spirals, we analyse the effects of possible perturbing sources, such as misaligned cold gas discs, dark matter, and satellites/subhaloes. As discussed earlier, the last of these has been extensively studied in the context of idealised simulations of the Sgr dwarf impact on a stellar disc. Dark matter halo torques (through, for example, dark matter wakes) has been found to have a significant impact on the stellar disc; it has been shown to be a key mechanism in the formation of galactic

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4 The values obtained for the median amplitude at a given time and Solar-like position do not depend heavily on bin size.
warps and corrugation patterns (e.g. Gómez et al. 2016, 2021; Laporte et al. 2018). In addition, prior cosmological simulations (e.g. Scannapieco et al. 2009) have shown that a misalignment between cold gas and the stellar disc can have a significant dynamical (even destructive) impact on the stellar disc. However, with the exception of the recent study of García-Conde et al. (2022), cosmological simulations have not explicitly resolved/studied “Snail shell”-like features, and therefore their connection to the aforementioned phenomena is unclear. In this section, we study the impact of each of these perturbing sources and isolate the main driver behind the phase spiral in our simulation.

First, we focus on the orientation of cold gas with respect to the disc as it grows over time. Fig. 6 shows the evolution of the cosine of the angle between the minor axis of the stellar disc and that of two different volumes of cold star-forming gas: that contained within 15 kpc, and that found at radii between 15 and 30 kpc. At times earlier than 4 Gyr, the edge of the stellar disc is smaller than 15 kpc. Up to this time, the cold gas inside 15 kpc is never more than 5 degrees out of alignment with the stellar disc. At t_{lookback} = 4 Gyr, the stellar disc reaches a size of 15 kpc and continues to grow as it sustains near complete alignment with the cold gas within 30 kpc for the remainder of the evolution. The near-perfect alignment between the cold gas disc and the stellar disc does not produce a significant large-scale torque, therefore we conclude that misaligned gas is not a driver of the phase spiral in this simulation.

We now turn to the impact of satellites and dark matter. To calculate their effect, we follow the procedure of Gómez et al. (2016) which we briefly describe here for completeness. We define two rings with radii 14 kpc and 8 kpc, and, at every simulation snapshot, select disc particles within two separate galactocentric shells: 13.5 < r < 14.5 kpc and 7.5 < r < 8.5 kpc. We diagonalize the mass tensor associated with each of these particle subsets to obtain the orientation of the rings with respect to an inertial frame. For each case, the whole system is rotated such that a given ring’s plane is aligned with the X–Y plane. We then evenly sample 1000 positions along each ring and compute the torque on the ring from dark matter particles as

$$
\tau_{\text{shell}} = \sum_{i=1}^{1000} r_i \times F_i^{\text{shell}},
$$

(3)

where $r_i$ represents the galactocentric distance vector to the $i$-th test particle along a ring and

$$
F_i^{\text{shell}} = \sum_{j=0}^{N_{\text{shell}}} F_{ij},
$$

(4)

is the gravitational force vector imparted on the $i$-th test particle by $N_{\text{shell}}$ dark matter particles enclosed within a given spherical shell.
For our purpose of identifying the source responsible for driving the phase spiral, we shall concern ourselves with the magnitude of the torque in the directions parallel to the ring’s plane, $\tau_{XY}$, (i.e. the $X-Y$ component of torque that can tilt the disc plane; the $Z$-component of the torque only affects the magnitude of the angular momentum).

The results are shown in Fig. 7 for the test particle rings of 8 kpc (left panel) and 14 kpc (right panel) radii, respectively. We focus on the time period spanning from $t_{\text{lookback}} = 8$ Gyr to the present day because this period contains most of the evolution of the (thin) disc where phase spirals are expected to develop. The total torque from dark matter particles acting on each ring is clearly most dominant during the first half of this evolutionary period, and exhibits peaks approximately 6 Gyr ago. By subdividing the contributions from different spherical shells, we see that dark matter within 20 kpc of the galactic centre dominates the torque on the Solar ring, whereas the torque on the outer disc is dominated by material between 10 and 50 kpc. After $t_{\text{lookback}} = 4$ Gyr, the torque is much diminished, although remains ever-present until the present day. In Appendix A, we verify that this torque is numerically well-converged.

The circular symbols in Fig. 7 depict the torque imparted on each ring by satellite galaxies (multiplied by a factor of 4 to aid comparison to the dark matter-induced torque) and are coloured according to their total mass. Note that the spike in torque imparted by a satellite of $\sim 10^{10} M_\odot$ at around the look back time of 6.5 Gyr precedes the peak in dark matter torque by order $\sim 100$ Myr. Fig. 8 shows the evolution of the galactocentric distance (top panel), vertical height and cylindrical radius (middle panel), and the total mass (bottom panel) of the satellite. Interestingly, the orbit and mass-loss history of this satellite up to the third or fourth pericentric passage appears qualitatively consistent with some models of Sgr (e.g. Vasiliev & Belokurov 2020; Hunt et al. 2021), albeit occurring some gigayears prior to the real Sgr. Its mass is $3 \times 10^{10} M_\odot$ prior to infall at $t_{\text{lookback}} \sim 8.5$ Gyr. The next pericentric passage occurs $\sim 2$ Gyr later on a near-polar orbit with a relative vertical velocity of $\sim 400$ km s$^{-1}$, and corresponds to the time at which peak satellite-induced torque is attained. Incidentally, this rapid encounter correlates with the onset of the local two-armed phase spiral feature shown in the lower panel of the second column in Fig. 4: likely a manifestation of satellite-induced “breathing modes”\(^6\) (as described in e.g. Widrow et al. 2014; Hunt et al. 2022). Subsequent pericentric passages of this satellite register a decreasing magnitudes of $\tau_{XY}$, particularly on the outer disc ring, as its mass decreases owing to tidal stripping. We note that the peak in satellite torque on the outer ring at look back

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\(^6\) A breathing mode manifests as a two-armed spiral in the $Z-V_Z$ plane as the disc vertically expands and contracts symmetrically about the midplane, contrary to the one-armed bending mode where the disc is locally displaced as a whole into an asymmetric oscillation about the midplane.

Figure 8. The evolution of the distance (top panel), vertical height and cylindrical radius (middle panel), and total mass (bottom panel) of the satellite responsible for generating the dark matter wake. The vertical dashed line indicates the time at which dark matter-induced torque reaches its peak (see Fig. 7).

Figure 9. Over-density maps, $\delta \rho$, obtained from the dark matter particles contained within a shell defined by spheres of 12 and 16 kpc galactocentric distances. These maps are obtained after rotating the original density by $\pi$ in $\phi$ and flipping about $\theta = 0$, then subtracting this processed density map from the original in order to remove the quadrupolar triaxial halo feature. This enhances the dipolar signature of the wake, which is prominent at the time of maximum dark matter torque on the disc (upper panel) and inclined with respect to the disc midplane along $\theta = 0$ (dashed line). At the present day (lower panel), only a faint, patchy over-density map remains.
time \sim 2.5 \, \text{Gyr} is from a different satellite of mass a few times \(10^8 \, M_\odot\).

An important feature seen in (particularly the right panel of) Fig. 7 is that peaks in dark matter torque either coincide with (or follow shortly after) peaks of satellite-induced torque. This is a smoking-gun signature of dark matter halo wakes that form behind satellite galaxies and amplify to produce a gravitational torque on the disc greater than that of the satellite behind which it formed. To show that a dark matter wake forms, we calculate an all-sky map of the dark matter over-density in a spherical shell between galactocentric radii of 12 and 16 kpc by performing the following steps (see Gómez et al. 2016, for a more thorough description):

- we apply a smoothing kernel to the dark matter particle distribution to estimate the density for each particle;
- we transform dark matter particle coordinates into spherical polar coordinates centred on the potential minimum of the galaxy, and for each particle in the spherical shell, calculate a polar grid of densities;
- we calculate an average density for the spherical shell to find the normalised dark matter over-density at each grid point:

\[
\hat{\rho} = \frac{\rho_{\text{grid}}(R, \phi, \theta) - \bar{\rho}_{\text{shell}}}{\bar{\rho}_{\text{shell}}} \quad (5)
\]

- to eliminate the triaxial halo signal from the map, we rotate the map by \(\pi \) in \(\phi\) and flip along the \(\theta = 0\) axis to produce \(\hat{\rho}_{\text{flip}}(R, \phi, \theta)\), then calculate dipolar wake over-density as

\[
\delta \rho = \frac{\hat{\rho} - \hat{\rho}_{\text{flip}}}{2} \quad (6)
\]

To better visualise the all-sky map, we perform the procedure above on a re-simulation of the original halo Au 6 with a factor 8 higher dark matter mass resolution (see Appendix A for more details). The all-sky map for \(\delta \rho\) at the time the dark matter-imparted torque reaches a maximum is shown in the upper panel of Fig. 9. The clear dipole observed is the signature of the wake, the major axis of which is misaligned with the \(\theta = 0\) vector that defines the mid-plane of the galactic disc. As shown by Gómez et al. (2017a), a dark matter wake with a similar such alignment creates gravitational forces that act vertically on the disc to deform it into a warp-like pattern. The lower panel of Fig. 9 shows the all-sky map for \(\delta \rho\) at \(z = 0\): the wake has clearly decayed and all that remains is a relatively weak (and somewhat patchy) over-density. This correlates with the sustained low and roughly constant torque at values \(\sim 5\) times lower than the peak wake activity seen in the last few Gyr of evolution in Fig. 7, but still dominates over satellite-induced torque at all times. The phase spiral is left to wind-up and decay during this late epoch into the comparatively weak pattern seen in Fig. 1.

### 4 CONCLUSIONS AND DISCUSSION

The Gaia phase spiral (Antoja et al. 2018), in addition to several other dynamical features (e.g. planar radial motions: Kawata et al. 2018), observed in the Milky Way is a sign that our Galaxy is in dynamical disequilibrium. The nature of the perturbation that set it in motion is the subject of much debate. Most of the theoretical work on the phase spiral has involved either very simplified toy models (Binney & Schönrich 2018) or idealised N-body simulations. Such numerical experiments sacrifice complex physics and cosmological environment for high resolution and/or a high-degree of control over the setup, and have provided several possible mechanisms including a buckling bar (Khoperskov et al. 2019) and the recent passages of Sgr (Laporte et al. 2019; Hunt et al. 2021).

In this paper, we have studied one of the first superstars cosmological magnetohydrodynamical simulations containing \(\sim 10^8\) disc star particles at \(z = 0\). This provides a complementary view of the problem by connecting it to a wide range of dynamical phenomena inherent to galaxy formation in the \(\Lambda\)CDM cosmological paradigm, such as continued gas accretion & star formation, satellite interactions, and feedback. Our main conclusions are as follows:

- At late times \((t_{\text{lookback}} \lesssim 3\, \text{Gyr})\) including the present day, our simulation shows a range of phase spiral features at multiple radii and azimuths over the stellar disc. At Solar-like positions, their amplitude and shape are similar to the Gaia Snail shell: 2-3 wraps with a radial velocity amplitude of \(\sim 10\, \text{km}\,\text{s}^{-1}\). The phase spirals are most clearly visible for coeval stellar populations of intermediate age (2-6 Gyr old), whereas older stars have a comparatively weak signal. These trends are similar to those seen in observations and models that predict the passages of Sgr as the main mechanism.
- For star particles located in the outer disc \((R \sim 14\, \text{kpc})\), phase spirals exhibit the same trends with age as for the Solar-like populations, but are “squashed” along the \(V_Z\)-axis owing to the lower disc surface density and vertical restoring force (in agreement with Laporte et al. 2019; García-Conde et al. 2022). They are also less-tightly wound than their Solar-position counterparts owing to their longer dynamical timescales, which indicates the outer Galactic disc is a promising place to look for signatures of past perturbations.
- We present new insights into a scenario for the formation of the phase spiral: first, a satellite of total infall mass \(\sim 10^{10}\, M_\odot\) generates the formation of a wake over-density in the dark matter halo (see also Gómez et al. 2016) during its first pericentric passage \(t_{\text{lookback}} \sim 6-7\) Gyr. This dark matter wake generates a strong gravitational torque parallel to the disc; it is approximately 8 times as strong as the direct torque imparted by the satellite at Solar radii. As a result, a strong warp forms in the disc which evolves into a global corrugation pattern. Locally, the oscillations associated to the corrugation pattern wrap up into spirals in the vertical phase plane.
- In our simulation, phase spirals first appear at the early epochs of disc formation/evolution, and are sustained by torques induced by the wake as it decays to a lower, constant amplitude. The wake-induced torque is larger than that imparted directly by any satellite at any time. Thus, the phase spiral is ever-present in our simulation.

Our findings have significance for the Sgr interpretation of the phase spiral: by fortuitous circumstance, the wake-inducing satellite shares many similar properties to the inferred orbit and mass-loss history of some dynamical models of Sgr (e.g Vasiliev & Belokurov 2020). The main difference is that, in our simulation, its orbit is offset several gigayears into the past with respect to the real Sgr. A crude accounting of this offset would correspond to a “present day” satellite mass of \(\sim 3 \times 10^8\, M_\odot\), and a phase spiral like the one shown in the lower-right panel of Fig. 4 which would also be visible in the youngest stars as is observed by Gaia (e.g. Tian et al. 2018). Thus, it seems plausible that a dark matter wake associated with the initial passages of Sgr could be playing a major role in the formation and propagation of the Gaia snail shell. This contrasts somewhat with the findings of recent idealised N-body simulations: for example, Laporte et al. (2018, 2019) showed that their Sgr analogue created a dark matter wake that dominated the torque on its first pericentric passage, but then subsequently decayed to a negligible level before direct torques from Sgr stimulate the onset of the phase spiral pattern. We speculate that the relatively durable dark matter wake found in our simulation could be linked to a cosmological satellite distribution (compared to
a single object set on a prescribed orbit) and/or the differences in the properties of the dark matter halo and its ability to support wake amplification processes (Vesperini & Weinberg 2000; Gómez et al. 2016).

Importantly, a non-negligible role of a dark matter wake in the formation of the phase spiral could complicate the mapping between the phase spiral properties and those of Sgr. Indeed, the $\sim 10^{10} \, M_{\odot}$ infall mass of our wake-inducing satellite is somewhat less massive than that favoured by some idealised models (Laporte et al. 2019; Bland-Hawthorn & Tepper-García 2021), but may help alleviate some of the discrepancies between the mass of the Sgr remnant and phase spiral properties discussed by Bennett et al. (2022).

With respect to other cosmological simulations, García-Conde et al. (2022) found that pericentric passages of a satellite of infall mass similar to that of our Sgr-like satellite correlated with the emergence of phase spirals in their simulation. However, they remark that the pericentre of this satellite is larger than that of Sgr and conclude that it is unlikely to be the sole contributor to the perturbation responsible for their phase spirals. We speculate that the dark matter halo wake mechanism established in this work is present also in their simulation.

Finally, we remark that the dynamical response of the disc to perturbations has a dependency on the kinematics of newborn coeval stellar populations which is in turn governed by our galaxy formation model. We note also that our simulation does not appear to produce the recently discovered two-armed phase spiral in the inner disc Hunt et al. (2022); however, this may not be surprising because its origin is speculatively linked to bar/spiral structure, whereas our simulation does not contain a bar according to typical definitions (e.g. Athanassoula 2002; Algorry et al. 2017; Fragkoudi et al. 2020). Thus many questions remain open. Nevertheless, our results underline the difficulty in interpreting the complex dynamical history of the Galaxy, and expose a new link between phase spiral features like the Snail shell and the dark matter distribution around the Galaxy. To make further progress on the phase spiral, future cosmological simulations with calibrated Sgr analogues will need to be performed.

More generally, our study highlights the potential for a suite of superstars simulations (Fragkoudi et al. in prep) to scrutinise galactic dynamics in the cosmological context, such as the nature of galactic spiral arms and bar formation and evolution. We defer these tasks to future work.

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DATA AVAILABILITY

High level data underlying this article will be shared on reasonable request to the corresponding author.

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APPENDIX A: CONVERGENCE STUDY

Because dark matter wakes develop over large volumes in the halo, it is logical to ask whether the dark matter particle resolution is high enough (and noise low enough) to capture the dynamics (e.g. Garavito-Camargo et al. 2019). To demonstrate that the torques induced by the dark matter wake are robust to resolution changes, Fig. A1 shows a reproduction of the right hand panel of Fig. 7 for the Superstars simulation (here denoted “Superstars64”) as well as a re-simulation of the same system, “DM8” with 8 times as many dark matter particles (but with the standard single star particle formed per gas cell, i.e., “level 4” stellar resolution). It is evident that, for each radial shell considered, the salient features of the evolution of the torque acting perpendicular to the disc minor axis are preserved at both resolution levels. The main appreciable difference is that the strength of the torque decays more slowly after the peak at ~ 6 Gyr for the DM8 run compared to the Superstars64 run. However, the difference is slight and could potentially be accounted for by minor stochastic variations in, for example, the precise infall time, mass, and orbit of the wake-generating satellite; such variations can arise from the “butterfly effect” phenomenon (e.g. Genel et al. 2019; Grand et al. 2021) or resolution changes (although we note that the evolution of the putative satellite in the Superstars64 and DM8 simulations is almost identical). Nevertheless, the convergence seen in Fig. A1 indicates that the torque imparted by the dark matter wake is captured in our Superstars simulation.

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