ARTICLE

Stellar Bars in Isolated Gas-Rich Spiral Galaxies Do Not Slow Down

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Elongated bar-like features are ubiquitous in galaxies, occurring at the centers of approximately two-thirds of spiral disks[1,2]. Due to gravitational interactions between the bar and the other components of galaxies, it is expected that angular momentum and matter will redistribute over long (Gyr) timescales in barred galaxies [3-5]. Previous work ignoring the gas phase of galaxies has conclusively demonstrated that bars should slow their rotation over time due to their interaction with dark matter halos [6-15]. We have performed a simulation of a Milky Way-like galactic disk hosting a strong bar which includes a state-of-the-art model of the interstellar medium and a live dark matter halo. In this simulation the bar pattern does not slow down over time, and instead remains at a stable, constant rate of rotation. This behavior has been observed in previous simulations using more simplified models for the interstellar gas but its explanation has remained elusive[16,17]. We propose that the gas phase of the disk and the dark matter halo act in concert to stabilize the bar pattern speed and prevent a bar from slowing down or speeding up. We find that in a Milky Way-like disk, a gas fraction of only about 5% is necessary for this mechanism to operate. This result naturally explains why nearly all observed bars rotate rapidly[18-20] and is especially relevant for our understanding of how the Milky Way arrived at its present state.

It has long been known that non-axisymmetric features in a stellar disk act to redistribute mass and angular momentum.[3] The interaction between a bar and a spheroid (either a dark matter halo or stellar bulge) has received considerable interest.[4,5] Stellar disks in isolation are prone to developing bars, [21] but the presence of a strong spherical potential (e.g., from a stellar bulge or dark matter halo) acts to stabilize the disk against bar formation.[22,23] Many numerical simulations have confirmed that a live dark matter halo generically exerts a negative torque on a bar, causing its pattern speed to decrease and its length and strength to increase[6-15]. Intuitively, the bar excites a wake of resonant material in a dark matter halo in a manner akin to dynamical friction. This wake lags a bar and thus exerts a negative torque on it.

The expectation that a dark matter halo acts to slow down a bar is in conflict with observational estimates of bar pattern speeds. Bar rotation rates are typically classified by the dimensionless ratio

$$\mathcal{R} = R_{\mathrm{CR}}/R_b, \tag{1}$$

where R_{CR} is the radius of corotation and R_b is the length of the bar.[†] Galaxies with $\mathcal{R} < 1.4$ are considered "fast rotators" while galaxies with $\mathcal{R} > 1.4$ are considered "slow rotators."[7] Galaxies with $\mathcal{R} < 1$ are not thought to be stable.[24] Observational estimates of the pattern speeds of bars indicate that nearly all galaxies have $1 < \mathcal{R} < 1.4$.[18-20,25]

The role of gas on the evolution of the bar is less well-understood. Since the gas phase typically only contributes about $10 - 20\%$ of the mass of a galaxy at the present day, one might naively expect it to have a subdominant effect on the bar. However, because gas is collisional, it can participate in non-resonant angular momentum exchange with the bar.[26] Thus, numerical work has shown that the gas phase can have a stronger influence on a bar than its contribution to the mass of a galaxy would suggest.[17,27]

We have performed a simulation of a disk galaxy using the finite-volume gravito-hydrodynamics code AREPO.[28] In AREPO, the fluid is discretized as a moving Voronoi mesh. We use the additional physics in the galaxy formation module Stars and MUltiphase Gas in GaLaxiEs (SMUGGLE) [29]. SMUGGLE is a comprehensive and self-consistent galaxy formation model with a wide range of physical processes, including radiative heating/cooling, star formation, and stellar feedback. More detailed information on SMUGGLE is given in the Methods section. Our disk galaxy is a modified version of the GALAKOS model[30], which consists of a stellar disk, stellar bulge, and dark matter halo. After ~ 2.5 Gyr of evolution, the GALAKOS disk forms a bar consistent with the Milky Way bar in terms of pattern speed and length (~ 40 km/s/kpc and ~ 4.5 kpc, respectively). We modify this setup to include a gas phase, the details of which are provided in the Methods section.

A face-on surface density projection of our simulations is shown in Fig. 1. The upper three panels show the disk in the N-body run while the lower three panels show the disk in the SMUGGLE run. Each column shows the disk ~ 1 Gyr apart in time. There is a large qualitative difference in the evolution of the bar pattern between the two runs. We see that in the N-body case, the bar lengthens in time and grows in strength. In

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[†] The radius of corotation R_{CR} is defined for circular orbits as the radius at which the orbital frequency is equal to the pattern speed, Ω_p, of a given non-axisymmetric feature. In a galaxy with a constant circular velocity V_c, it is given by $R_{\mathrm{CR}} = V_c/\Omega_p$.
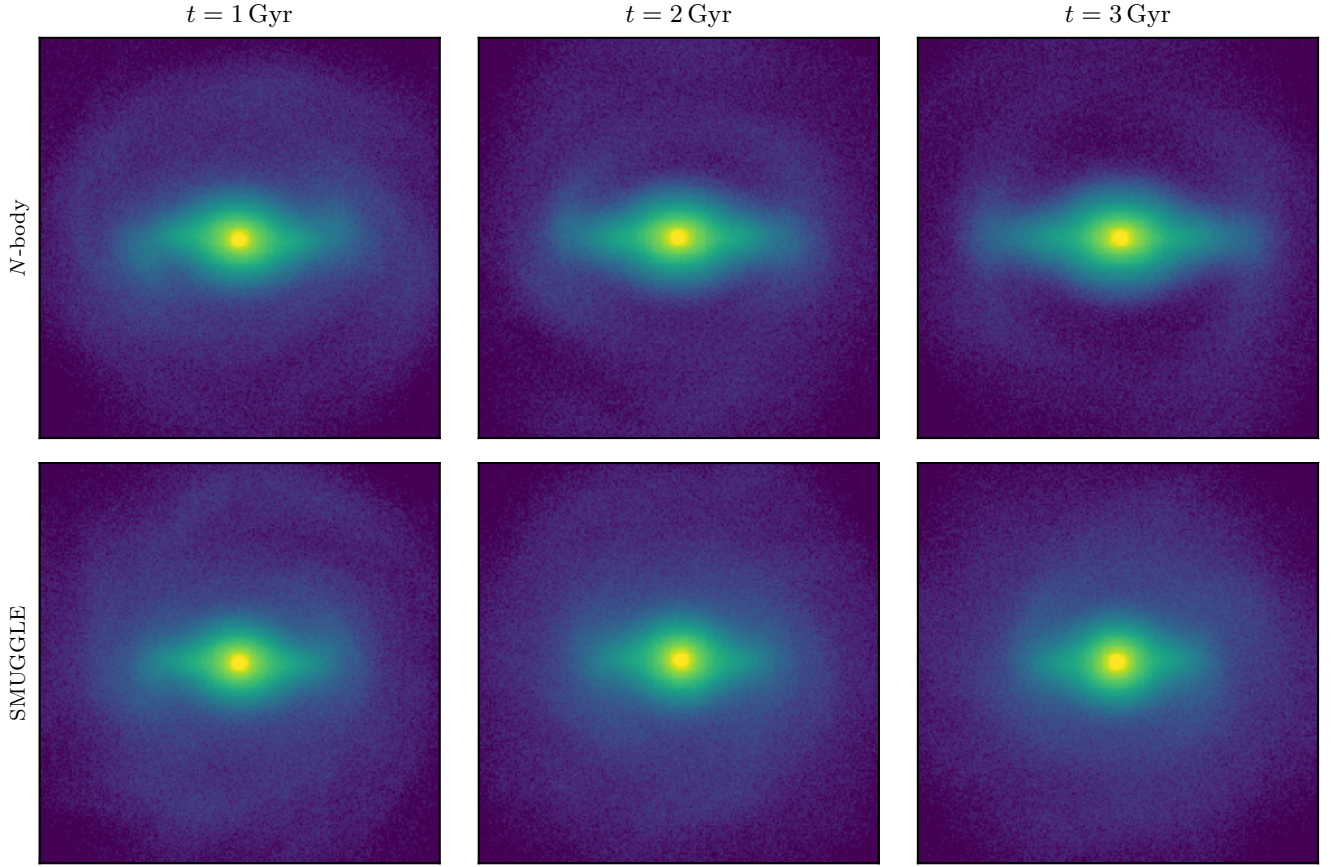
Figure 1 | Projected surface densities of simulated barred galaxies with and without the interstellar medium. The upper panels show an N-body only simulation while the lower panels show a simulation which includes the SMUGGLE model for the ISM. Columns show different points in time, separated by about 1 Gyr. We can see that in the N-body run, the bar grows in length and strength. In the SMUGGLE run, the bar remains at approximately the same length and strength over the course of the simulation. The N-body model is identical to the GALAKOS model, discussed in the text.

the SMUGGLE case, the bar retains a similar length and strength between panels.

We show the time evolution of different bar properties in Fig. 2. In the upper panel, we show the pattern speed over time in the N-body (blue) and SMUGGLE (orange) runs. The pattern speed in the N-body case slows down while the pattern speed in the SMUGGLE case remains roughly constant. The slowing down of the pattern speed in the N-body case is consistent with a long line of numerical research on bars in N-body simulations.[6–15] However, in the SMUGGLE case the pattern speed remains constant. After the first Gyr of evolution, we find that the pattern speed increases by only $\sim 10\%$ over the next 4 Gyr, compared to a $\sim 43\%$ decrease in the pattern speed for the N-body run over the same interval. As we saw qualitatively in Fig. 1, the length of the bar in the N-body case grows over time while it remains roughly constant in the SMUGGLE case. This is also consistent with previous numerical work, which found that bars tend to grow as they slow down and the radius of corotation increases.[7,10]

The bottom panel of Fig. 2 shows the torque exerted on the bar by different components. The solid lines indicate the torque on the bar by the dark matter halo, whereas the dashed line indicates the torque on the bar by the gas phase. In the N-body case, the halo exerts a steady negative torque on the bar, with an average

torque from 1 to 4 Gyr of -58.0 in units of $10^{10} M_\odot\,(\mathrm{km/s})^2$. The halo in the SMUGGLE case exerts a similar negative torque on the bar in the first Gyr of evolution, but after that the halo exerts a much smaller torque on the bar, averaging only -7.8 in the same units and over the same time interval. The gas in the SMUGGLE case exerts a steady positive torque averaging 11.7 over 1 Gyr in the same units.

The fact that the dark matter halo in the SMUGGLE case exerts a smaller negative torque on the bar can be understood in terms of the halo wake mechanism. In the N-body case, halo material which is resonant with the bar will form a wake which lags behind and exerts a negative torque on the bar, which slows it down.[4–6‡] As the bar slows down, the location of the resonances in phase space changes, allowing halo material newly resonant with the bar to participate in forming the wake. However, the gas is a reliable source of positive torque on the bar, speeding the bar up. This stops the resonance location from changing such that the halo cannot reinforce a wake, arresting the process by which the halo can slow the bar down.

We can test this interpretation by measuring the angle offset between the halo wake and the bar. If the wake and the bar are

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‡Since the bar is not a solid body, it is not guaranteed that a negative torque will slow it down - e.g. a negative torque could shred the bar, reducing its moment of inertia without changing its pattern speed. However, the bar seems to empirically respond to a negative torque induced by a halo wake by slowing down.
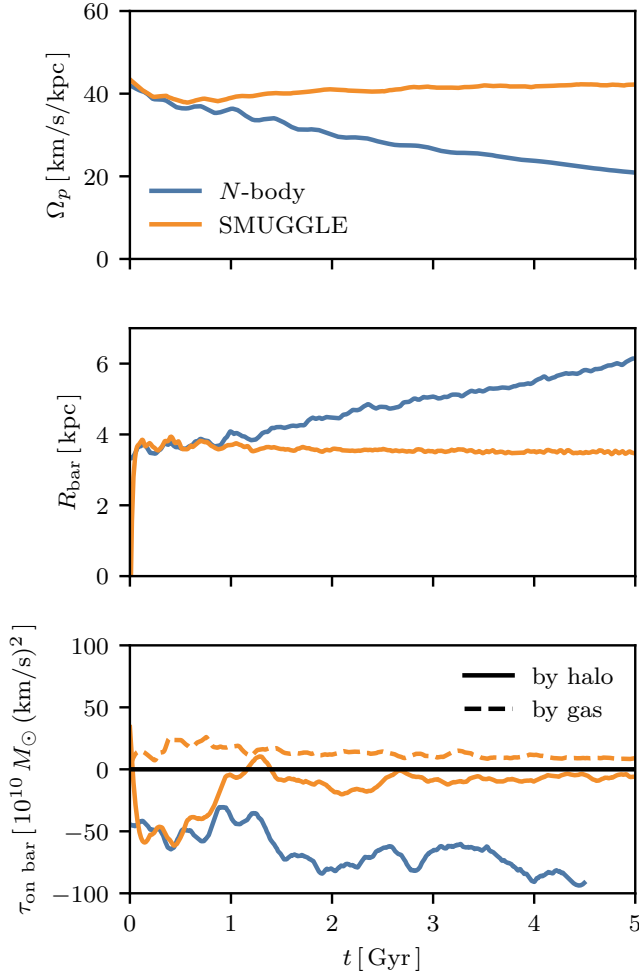
Figure 2 | Properties of the bar in our N-body and SMUGGLE simulations of a barred galaxy. The *upper panel* shows the evolution of the pattern speed. As expected, the bar in the N-body run slows down due to interactions between the bar and the dark matter halo. However, the bar in the SMUGGLE run does not slow down and instead remains at a constant pattern speed. The *middle panel* shows the evolution of the bar length. In the N-body case, the bar lengthens. This occurs because as the pattern speed drops, bar-like orbits at larger radii are possible. Stars are captured on these orbits, lengthening the bar. This process does not occur in the SMUGGLE cases since the bar pattern speed is not decreasing, and therefore the bar length remains constant. The *lower panel* shows the torque on the bar by different components. The solid lines show the torque exerted by the halo in both the N-body and SMUGGLE cases. The dashed line shows the torque exerted by the gas phase in the SMUGGLE run (there is no gas in the N-body run). Details on how these properties are calculated is given in the Methods section.

aligned (i.e., there is no angle offset), then the wake cannot exert a negative torque on the bar. This angle is plotted in the left panel of Fig. 3, which shows that the angle offset is larger in the N-body case than in the SMUGGLE case by about a factor of two. The center and right panels of Fig. 3 show the halo wake with respect to the location of the bar in the N-body (center) and SMUGGLE (right) cases.

The presence of the gas can arrest the process by which additional material in the dark matter halo can contribute to a wake. However, this does not explain why the pattern speed in the SMUGGLE case is nearly constant over several Gyr. Naively, it would be a coincidence that the bar pattern speed remains constant in the SMUGGLE case, resulting from a chance cancellation of the halo and gas torques. However, a constant pattern speed in the presence of gas has been observed in a few simulations of barred galaxies with gas.[16,17] Previous work has argued this is due to the bar torquing gas inwards, but no explanation has been given for why it might remain constant.

We propose that an equilibrium mechanism is responsible for the pattern speed remaining approximately constant. In this scenario, a torque must oppose changes in the pattern speed so that when the bar speeds up, a negative torque will slow it down and when the bar slows down, a positive torque will speed it up. It is simple to explain the first of these - when the pattern speed increases, the location of resonances will shift to regions of the dark matter halo phase space where no wake has been excited yet (e.g., the corotation radius will shrink).

When the bar slows down, we argue that this induces a larger positive torque from the gas phase. Only gas within corotation will flow inwards, while gas outside corotation will flow outwards.[26] Since the corotation radius is larger for more slowly rotating bars, it follows that more slowly rotating bars should be more efficient at driving gas inflows and thus experience a larger positive torque from the gas phase.

We performed an experiment to test this hypothesis by forcing the stellar disk in the SMUGGLE run to rotate at a constant angular rate and measuring the torque on the bar by the gas phase at different rotation rates. The result of this experiment is illustrated in Fig. 4, which shows that a more slowly rotating bar experiences a larger positive torque from the gas. We have therefore presented evidence for an equilibrium mechanism which keeps the pattern speed of the bar constant, resulting from the complex interplay between the dark matter halo and the gas phase.

We performed two additional tests to explore how our findings depend on the assumed model of the interstellar medium and the amount of gas present in the system. First, we performed a simulation of the same disk but with a simpler model of the interstellar medium[31], closer to standard methods used in cosmological simulations of galaxy formation. We find that the pattern speed evolution is nearly the same in this case, and so conclude that our result is not sensitive to the details of the model for the interstellar medium. The details of this experiment are given in the Methods section.

Second, we performed a set of simulations in which we decreased the initial gas mass of the disk. We essentially find for our disk, our proposed mechanism operates as long as the gas contributes about 5% of the total mass of the disk. If the gas available is below this threshold, then the pattern speed will decrease in a similar fashion to standard N-body simulations. Importantly, arbitrarily increasing the gas fraction does not cause the pattern speed to continuously increase. This is consistent with our proposed equilibrium mechanism and with previous studies of barred galaxies with varying gas fractions.[17] The exact critical gas fraction above which our mechanism operates is likely dependent on the properties of the bar, disk, and dark matter halo – further work is needed to characterize how this gas fraction varies with such properties. Details on this test in which we varied the gas mass of the disk are given in the Methods section.

We note that ref.[25] found that the rotation parameter $\mathcal{R}$ posi-
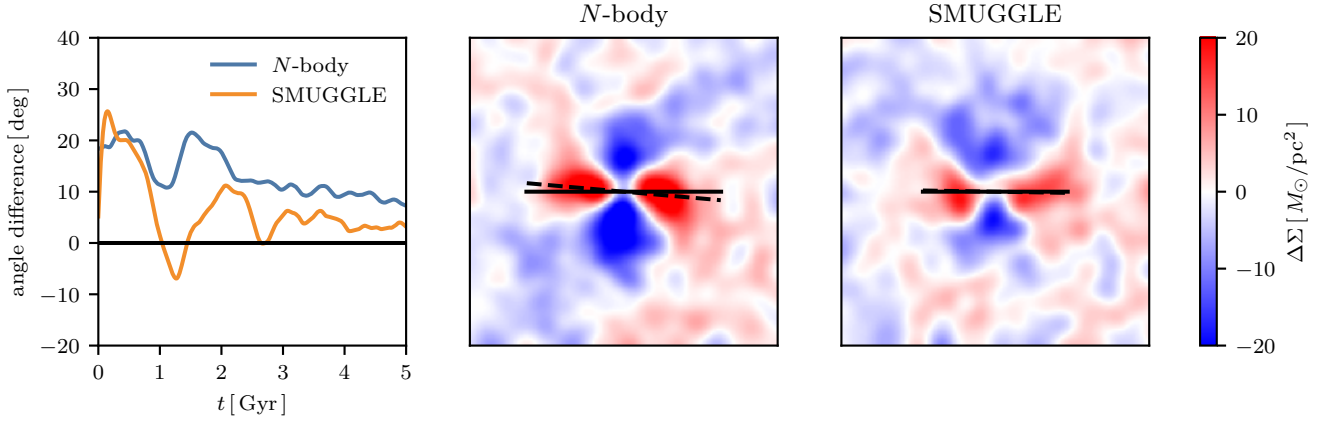
Figure 3 | The wake excited in the dark matter halo. The dark matter halo wake is shown in the N-body case (*middle panel*) and SMUGGLE case (*right panel*) after 2.6 Gyr of evolution. The *middle* and *right panels* show a surface density projection in the x-y plane of the dark matter halo after an axisymmetric average has been subracted. The solid line indicates the direction of the bar while the dashed line indicates the direction of the halo wake (both measured by taking the second Fourier component within a sphere of all material within a radius of 4 kpc). The *left panel* shows the time evolution of the angle difference between the bar and the halo wake, as measured from the second Fourier component. After the first Gyr, the angle difference in the SMUGGLE case is smaller than in the N-body case by about a factor of two, reflecting how the dark matter halo in the SMUGGLE case is unable to exert as negative a torque on the bar as in the N-body case.
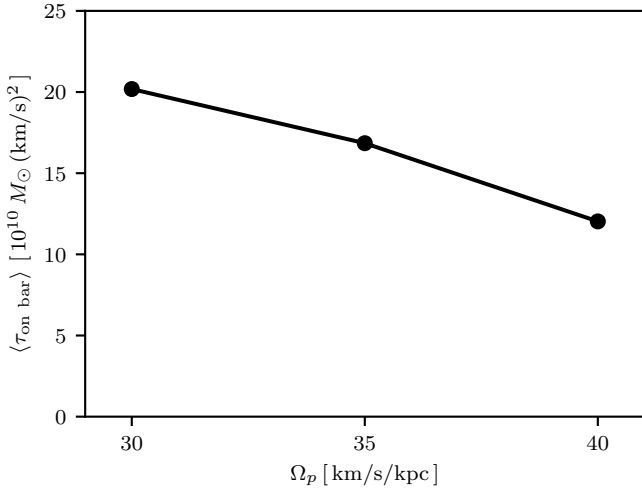

Figure 4 | Average torque exerted by gas on a bar which rotates at a fixed pattern speed. Since only gas within the corotation radius is able to infall and slower bars have larger corotation radii, slower bars experience a larger net torque than faster bars. The setup of the simulations used here is identical to the SMUGGLE case discussed earlier and in the Methods section, except the N-body disk is rotated as a solid body with a constant angular velocity.

without requiring the inner regions of dark matter halos to be underdense[7,33] or requiring new physics.[34,35] Second, we show that the role of gas is of paramount importance in studies which attempt to uncover the nature of dark matter from its effect of slowing down the bar.[36,37] Third, we provide an explanation for how the Milky Way's bar could be both long-lived and a fast rotator, of which there is some observational evidence.[38] And finally, we complicate the picture of radial mixing expected to sculpt the Milky Way's disk [39,40], a process which relies upon the pattern speed of the bar to change with time (though our work does not alter expectations for radial mixing induced by spiral arms[41]).

Barred galaxies in cosmological simulations of galaxy formation continue to be in conflict with observations by producing bars which rotate too slowly.[42–44] However, the pattern speeds of bars in both cosmological simulations and the real universe can be affected by environmental processes not included in our simulation – e.g., satellite infall[45], non-sphericity[27] or rotation[46–49] in the dark matter halo, or perhaps even the gaseous circumgalactic medium. Naturally, extending our present work to account for such effects is a crucial next step in understanding the formation and evolution of galactic bars.

We found that below a certain gas fraction, bars should still be able to slow down. Therefore, we expect barred spiral galaxies which have been gas-poor for extended periods of time to be rotating very slowly. We therefore predict that observations which target such galaxies (e.g., lenticular barred galaxies[32]) would find slowly rotating bars. There does exist one such example of a galaxy which is known to be a slow rotator – the low surface brightness galaxy UGC 628.[50] This galaxy has been studied in detail by ref.[51], who note that it indeed has a low gas fraction for galaxies of its type. We predict a general trend that bars in gas-rich spiral galaxies should rotate quickly while bars in gas-poor spiral galaxies should rotate slowly.

tively correlates with gas fraction, such that galaxies with higher gas fractions are rotating more slowly. However, it is not obvious this is in tension with our result since the gas fraction of galaxies correlates with other galactic properties.[32] Furthermore, the measurement of pattern speeds is a delicate process still prone to large error bars.

The implications of our findings are numerous. First, we naturally explain why nearly all observed galaxies are fast rotators

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Author Contributions Foo.

Data Availability Foo.

Code Availability A public version of the AREPO code is available at `https://arepo-code.org/`.

METHODS

Initial Setup

The initial setup of the galactic disk used in this work follows closely the GALAKOS model[30], which uses a modified version of `MakeNewDisk`.[52] The GALAKOS model has three components - a radially exponential and vertically isothermal stellar disk, and a stellar bulge and dark matter halo following a Hernquist profile.[53] All N-body runs in this work used the same setup parameters as the GALAKOS disk, more details of which can be found in the original paper.

The addition of the gas phase was done as follows. The version of `MakeNewDisk` used for the original GALAKOS model can generate a gas disk which is radially exponential and in vertical gravito-hydrodynamic balance. We modified the radial profile of this code in order to allow us to generate a disk with a constant surface density within some cut-off radius, and then exponentially declining beyond that radius with the scale-length of the stellar disk. We used an initial surface density of $20 \, M_\odot / \mathrm{pc}^2$ and a cut-off radius of $9.3 \, \mathrm{kpc}$.

After generating the gaseous disk in this way, we stitched the gas disk together with the GALAKOS N-body disk (and bulge and dark matter halo) after the GALAKOS disk has been allowed to evolve for $1.5 \, \mathrm{Gyr}$. The purpose of allowing the GALAKOS disk to evolve first for a short period of time is to allow for the bar to form unimpacted by the presence of the gas (which would normally disrupt the formation of the bar). Throughout this work, we consider $t = 0$ for the N-body run to be the time at which we added the gas phase for the SMUGGLE run (i.e. we ignore the first $1.5 \, \mathrm{Gyr}$ of evolution of the N-body disk when the bar is forming). We made one additional modification when stitching the gas disk together with the N-body disk - we created a hole within the central $4 \, \mathrm{kpc}$. This hole guards against an initial dramatic infall of gas within the bar region, which we found to destroy the bar. Models of the Milky Way's gas surface density profile indicate a reduction in gas in the bar region from ~ 1 to $\sim 4 \, \mathrm{kpc}$,[54] and so our practice of allowing the gas distribution to have a hole in the central region is consistent with our choice to begin the simulations with a bar already formed.

Our setup is initially out of equilibrium, but we found that after $\sim 500 \, \mathrm{Myr}$, the entire system has settled into a steady-state configuration and initial transients appear not to affect the results after this point. The constant surface density of the initial gas disk is important for ensuring the gas disk is dense enough in order for comparisons to real galaxies to be appropriate.

We computed the circular velocity curve of our model using the `AGAMA` package.[56] We fit the baryonic component (stellar disk, bulge, gas, and newly formed stars) with an axisymmetric cylindrical spline with 20 grid points in both the radial and vertical direction spanning 0.2 to $50 \, \mathrm{kpc}$ in the radial direction and from 0.02 to $10 \, \mathrm{kpc}$ in the vertical direction. We fit the dark matter halo using a spherically symmetric multipole fit with a maximum angular harmonic coefficient of $l = 2$. We plot the circular velocity curve in Extended Data Fig. 1 compared to observational estimates.[55] Our disk is slightly more massive than the Milky Way disk, and in the SMUGGLE run the addition of the gas phase results in a slightly higher circular velocity. We also show the evolution of the surface density profile in Extended Data Fig. 4 We find that in our simulation the atomic and molecular gas surface density and the SFR surface density is broadly consistent with the expected values for the Milky Way.[54,57] The discrepancy between 1 and $4 \, \mathrm{kpc}$ in the molecular and SFR surface density is likely due to the fact that the distances to molec-
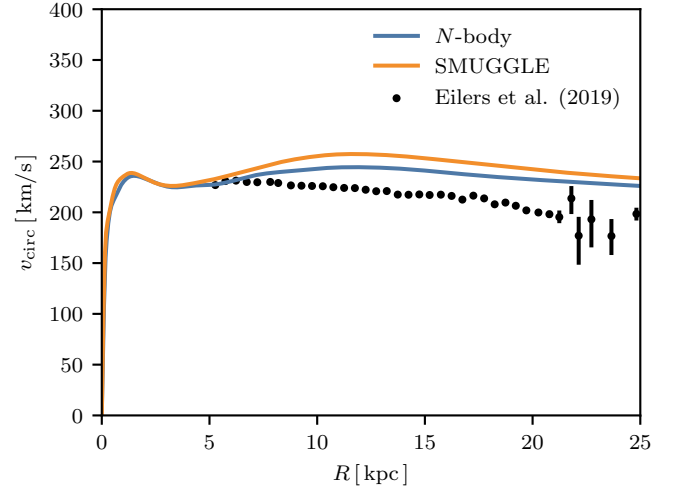
Extended Data Figure 1 | The circular velocity curve of our initial setups. This curve is shown for the N-body run (blue) and the SMUGGLE run (orange) compared to observational estimates for the Milky Way.[55] We see that the circular velocity curve for both runs is marginally larger than the Milky Way's, but still comparable. The SMUGGLE circular velocity curve is larger than the N-body curve due to the additional mass in the gas phase.

ular clouds which underlines this work used a simple kinematic distance based on an axisymmetric model of the Milky Way,[58] which is not accurate in the bar region where gas has large non-circular velocities.

We used a mass resolution of $7.5 \times 10^3 \, M_\odot$ for the baryonic components (initial stellar disk, stellar bulge, and gas) and a mass resolution of $3.75 \times 10^4 \, M_\odot$ for the dark matter halo. This mass resolution is closest to "level 3" in the AURIGA simulations.[59] This corresponds to approximately 6.4×10^6 particles in the stellar disk, 1.1×10^6 in the bulge, 1.2×10^6 in the gas disk, and 25.3×10^6 in the dark matter halo. We used a softening length of $0.02 \, \mathrm{kpc}$ for all components. Snapshots were saved at equal intervals of 0.005 in the time units of the simulation ($\mathrm{kpc}/(\mathrm{km/s}) \sim 1 \, \mathrm{Gyr}$).

SMUGGLE Model

We use the Stars and MUltiphase Gas in GaLaxiEs (SMUGGLE) model[29] implemented within the moving-mesh, finite-volume hydrodynamics and gravity code AREPO[28]. The SMUGGLE model additionally includes radiative heating and cooling, star formation, and stellar feedback. Explicit gas cooling and heating of the multi-phase interstellar medium is implemented, covering temperature ranges between 10 and $10^8 \, \mathrm{K}$.

Star formation occurs in cells above a density threshold ($n_{\mathrm{th}} = 100 \, \mathrm{cm}^{-3}$) with a star-formation efficiency of $\epsilon = 0.01$. Star formation converts gas cells into star particles which represent single stellar populations with an initial mass function according to ref.[60] For each star particle, the deposition of energy, momentum, mass, and metals from stellar winds and supernovae is modeled. Photo-ionization and radiation pressure are modeled using an approximate treatment. A more detailed description of this model can be found in the flagship SMUGGLE paper.[29]

We used the fiducial model parameters, except that we increased the number of effective neighbors N_{ngb} for the deposition
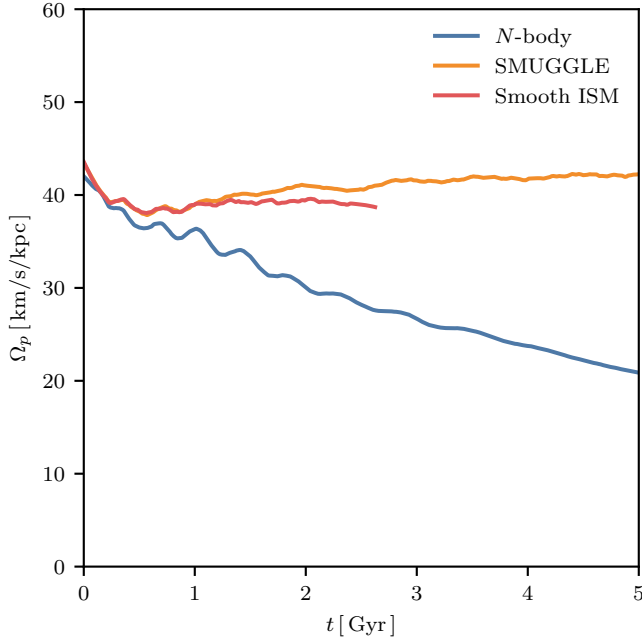
Extended Data Figure 2 | Pattern speed evolution of a smooth ISM model. This evolution is shown for the fiducial disk in the N-body (blue), SMUGGLE (orange), and smooth ISM (red) cases. The smooth ISM model is an older model for the ISM which treats its multiphase nature in a subgrid fashion.[31] This fundamentally differs from the SMUGGLE model, which explicitly resolve the hot and cold phases of the ISM.[29] The pattern speed in the smooth ISM case is broadly similar to the evolution in the SMUGGLE case. This shows that the stability of the pattern speed is not simply a result of our assumed model for the ISM.

of feedback from 64 to 512. We found that a lower value of $N_{\rm ngb}$ resulted in inefficient photo-ionization feedback since the photo-ionizing budget had not been exhausted after deposition into 64 neighboring cells. We also used an updated version of SMUG-GLE using a new mechanical feedback routine similar to the one described in ref.[61] This updated routine is a tensor renormalization which ensures linear and angular momentum conservation to machine precision.

Smooth Interstellar Medium Model
In addition to the SMUGGLE model, we considered a simpler model of the interstellar medium based upon ref.[31] In this model, the multiphase nature of the interstellar medium is modeled in a subgrid manner by allowing each resolution element to have a "cold" and "hot" component, with the equation of state of the gas suitably modified. Gas is allowed to interchange between the "cold" and "hot" components through processes such as cooling and stellar feedback. Cold gas is allowed to undergo star formation. The pattern speed evolution of this setup is given in Extended Data Fig. 2, which shows that the pattern speed evolves in a similar manner to the SMUGGLE case shown in Fig. 2.

Varying Gas Fraction
We also performed a test in which we varied the initial gas fraction of the disk. In our fiducial run, we set the surface density of the gas disk from $4\,\mathrm{kpc}$ to $\sim 9.3\,\mathrm{kpc}$ to be $20\,M_\odot/\mathrm{pc}^2$. We also
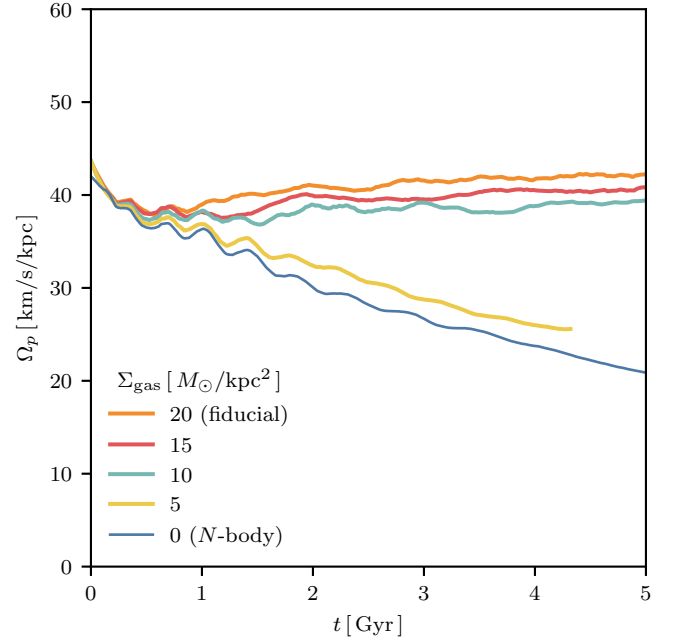
Extended Data Figure 3 | Pattern speed evolution with varying gas fractions. We explored the impact of lowering the initial gas surface density of our fiducial disk on the evolution of the pattern speed. The surface densities we tested of 20, 15, 10, and $5\,M_\odot/\mathrm{kpc}^2$ correspond to initial gas fractions of 16%, 10%, 7%, and 4%. We find that initial surface densities 20, 15, and $10\,M_\odot/\mathrm{kpc}^2$ result in bars which remain at a constant pattern speed, while an initial surface density of $5\,M_\odot/\mathrm{kpc}^2$ results in a bar which slows down in roughly the same manner as the N-body case.

ran with surface densities of 15, 10, and $5\,M_\odot/\mathrm{pc}^2$. These correspond to initial gas fractions of approximately 16%, 10%, 7%, and 4%. The pattern speed evolution is shown in Extended Data Fig. 3 We find that the bar in disks with initial surface densities of 20, 15, and $10\,M_\odot/\mathrm{pc}^2$ evolve with a constant pattern speed while the bar in a disk with initial surface density of $5\,M_\odot/\mathrm{kpc}^2$ slows down at a similar rate to the N-body case.
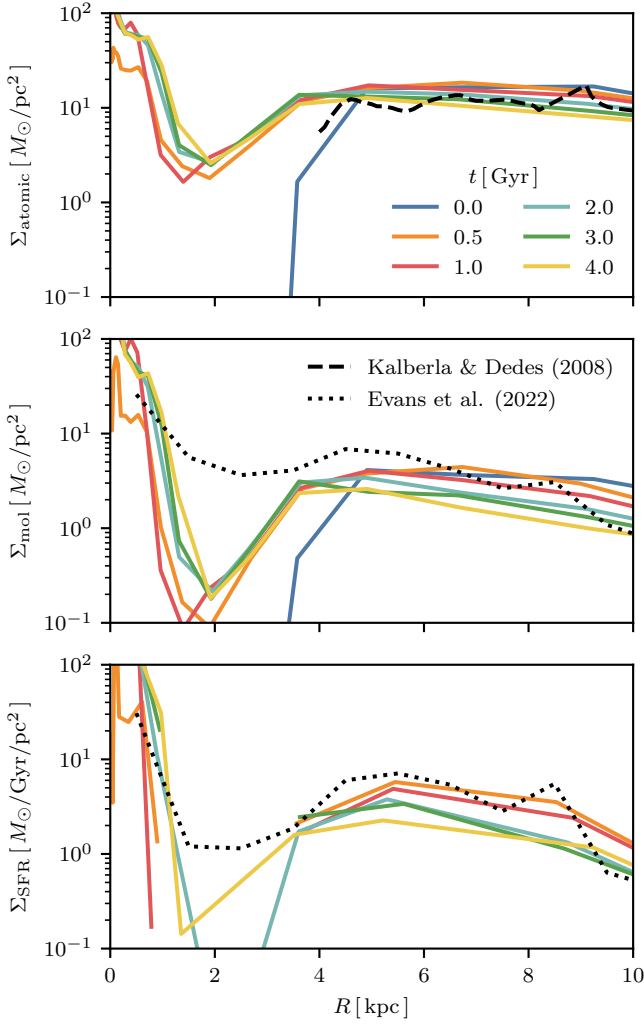
As a result, we conclude that for the disk, bar, and halo properties considered in this work, a gas fraction of only approximately 5% is necessary in order for the proposed stabilizing mechanism to operate.

Bar analysis
The analysis of various bar properties is performed as follows. First, the pattern speed is measured from the angle of the second Fourier component. We measured the second Fourier component by computing,

$$
\begin{aligned}
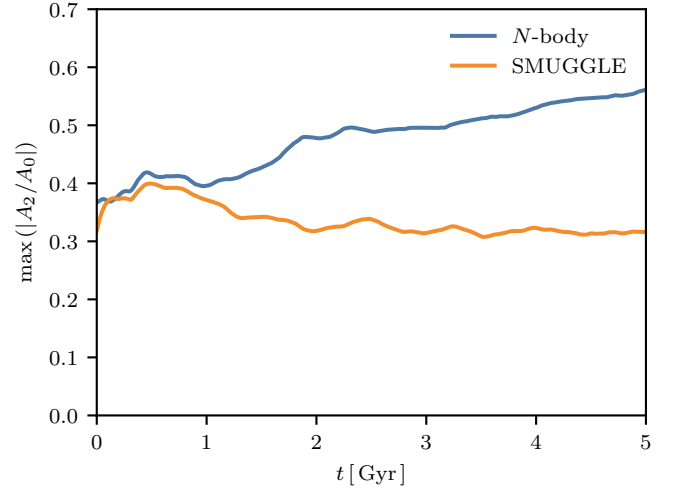A_2 &= \sum_i m_i e^{i2\phi_i} \\
A_0 &= \sum_i m_i,
\end{aligned}
\tag{2}
$$

where m_i and ϕ_i are the mass and azimuthal angle of each particle, respectively. We computed A_2 and A_0 in cylindrical bins of width $0.5\,\mathrm{kpc}$ from radii of 0 to $30\,\mathrm{kpc}$. We defined the angle of the bar ϕ_b to be twice the angle of the complex number A_2 as

Extended Data Figure 5 | Evolution of bar strength. The bar strength is measured as the maximum of the second Fourier component divided by the zeroth Fourier component. We see that in the N-body case (blue) the bar strength increases with time, consistent with previous results showing that the bar strength increases as bars slow down. In the SMUGGLE case (orange), we see that the bar strength remains roughly constant, possibly slightly decreasing with time. This is also consistent with the expected relation between pattern speed and strength since the bar in this case is not slowing down.
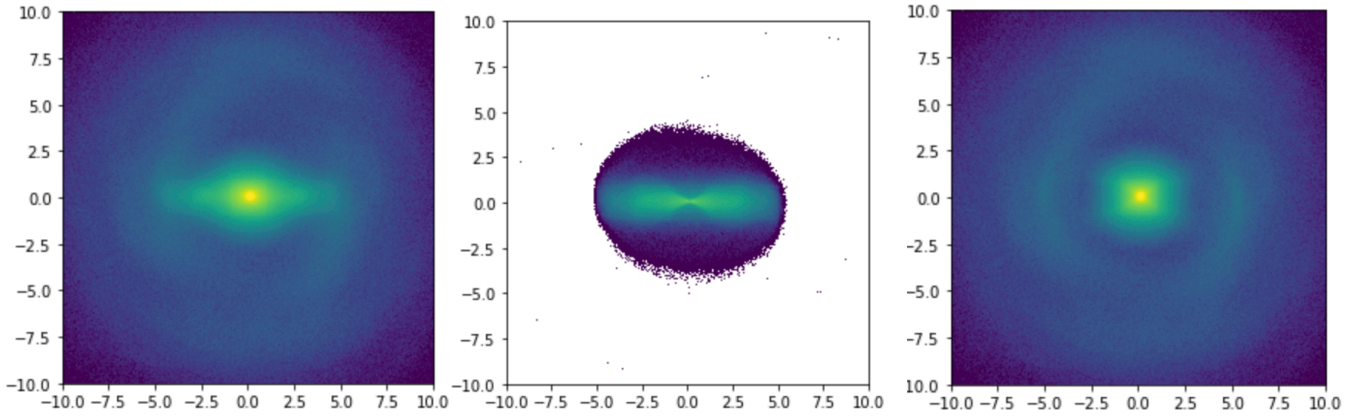
Extended Data Figure 4 | Evolution of gas and SFR surface density profiles. The time evolution of the atomic gas surface density (*upper*), molecular gas surface density (*middle*) and the star formation rate (SFR) surface density (*lower*) at various times during our fiducial simulation. Colored lines indicate the profiles at selected times during the simulation while the black dashed lines indicate observations for the atomic gas[57] and black dotted lines indicate a model which allows the CO-to-H$_2$ conversion factor X_{CO} to vary with metallicity.[54] Molecular gas surface densities were provided separately (N. Evans, private communication). We see that the molecular gas and SFR surface densities are within an order of magnitude of the Milky Way's typical values at all times. We see a sharp decrease in the gas and SFR surface densities along the extent of the bar from ~ 1 to ~ 4 kpc, related to the gas inflow in this region.

which showed a clear correlation between the bar pattern speed and the bar strength.[10] In the SMUGGLE case, we see that the bar strength has an initial drop but then remains at a roughly constant, but slightly decreasing, strength. This is consistent with the pattern speed in the SMUGGLE case being roughly constant or slightly increasing.

Computing the length of the bar and the torque on the bar by different components requires us to decompose the disk into a component which is trapped by the bar and a component which is untrapped. In order to do this, we follow closely the technique developed in ref.[62] We analyzed the orbit of each star particle (meaning initial disk, bulge, and newly formed stars) by extracting the x-y positions of the apoapse of each in a frame corotating with the bar (apoapses are defined as local maxima in r). For each apoapse, we searched for the 19 closest apoapses in time and applied a k-means clustering algorithm on this set of 20 points with $k = 2$. We then computed for each of the two clusters the average angle from the bar $\langle \Delta\phi \rangle_{0,1}$, the standard deviation in R of the points $\sigma_{R0,1}$, and the average radius of the cluster $\langle R \rangle_{0,1}$. At each apoapse, a particle was considered to be in the bar if it met the following criteria:

$$\max \left(\langle \Delta\phi \rangle_{0,1} \right) < \pi/8 \tag{3}$$

$$\frac{\sigma_{R0} + \sigma_{R1}}{\langle R \rangle_0 + \langle R \rangle_1} < 0.22 \tag{4}$$

These criterion are slightly different and simplified from the ones used in ref.[62], but we found them to empirically work well at decomposing the disk into a bar and disk component. In Extended Data Fig. 6, we show an example of this decomposition. The *left* panel shows a surface density projection of the stellar

measured in the bin extending from a radius of 2.5 to 3 kpc. After correcting for the periodicity of ϕ_b, we measured the pattern speed as the two-sided finite gradient of ϕ_b as a function of time.

The time evolution of the bar strength, defined as the maximum of $|A_2/A_0|$ as a function of radius, is shown in Extended Data Fig. 5. The quantity $|A_2/A_0|$ varies from 0 to 1, with larger values indicating a stronger bar pattern. We see that in the N-body case, $|A_2/A_0|$ increases over time as the bar pattern slows. This is consistent with previous N-body simulations

Extended Data Figure 6 | Disk decomposition into the bar and unbarred disk. This procedure is based on ref.[62] The *left panel* shows a surface density projection through the stellar component of the N-body simulation (disk and bulge). The *middle panel* shows the component of the disk identified as being trapped in the bar while the *right panel* shows the component of the disk identified as not being trapped in the bar. The fact that the untrapped stars form a roughly axisymmetric structure indicates our bar decomposition is sufficiently accurate. I will remake this figure - I ended up losing the files which stored the bar membership, so I just pulled these screenshots from an earlier presentation.

disk and bulge (including newly formed stars) from the SMUG-GLE model after $1\,$Gyr of evolution in a frame such that the bar is aligned with the x-axis. The *middle* panel shows a projection of the subset of stars that are identified as being trapped in the bar and the *right* panel shows a projection of the stars that are not identified as being trapped. The fact that the *right* panel is roughly axisymmetric indicates the bar decomposition is performing adequately.

After the disk has been decomposed into a trapped and untrapped component, we measured the bar length as being the radius R_b which encapsulates 99% of the stars identified as being trapped in the bar, allowing for some outliers. For the computation of the torque, we used the tree algorithm in `MakeNewDisk`[52] customized to be accessible from `Python` using `Cython`. This algorithm is based on the `TREESPH` code.[63] We constructed a tree using only the star particles identified as being trapped in the bar using an opening angle of 0.35. We then queried the tree at the locations of all resolution elements in the other components and computed the torque of the bar on such components. The torque on the bar by the other components is simply the negative of the torque on the other components by the bar. A similar method was applied in measuring the torque for the disk when the pattern speed is kept constant, as is done in Fig. 4.

Plotting Details

We saved snapshots in intervals of 0.005 in the time units of the simulation, kpc/(km/s), which is very nearly equal to $1\,$Gyr (it is $\sim 0.977\,$Gyr). Therefore, throughout this work we referred to the native code time unit as Gyr. None of our results are sensitive to this choice.

In order to remove numerical noise in several quantities we computed, we applied a Savitzky-Golay filter[64] as implemented in `scipy` using a window length of 81 and polynomial order of 3. This filter was applied to plots of pattern speeds, bar lengths and strengths, torques, and angle differences.

4