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Galactic bars in cosmological context

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Abstract. Galactic disks can form in asymmetric potentials of the assembling dark matter (DM) halos, giving rise to the first generation of gas-rich bars. Properties of these bars differ from canonical bars analyzed so far. Moreover, rapid disk growth is associated with the influx of clumpy DM and baryons along the large-scale filaments. Subsequent interactions between this substructure and the disk can trigger generations of bars, which can explain their ubiquity in the Universe. I provide a brief summary of such bar properties and argue that they fit naturally within the broad cosmological context of a hierarchical buildup of structure in the universe.

Key words. cosmology: dark matter – galaxies: evolution – galaxies: formation – galaxies: halos – galaxies: interactions – galaxies: kinematics and dynamics

1. Introduction

Among various approaches to galaxy formation, two stand out — those that deal with isolated and open systems. In the former *modus operandi,* angular momentum, J, and mass of a system are conserved. Thus, for example, one deals with a finite reservoir of gas, galaxy interactions are treated in maximally-controlled experiments, and, in most such cases, the amount of substructure present is quite limited, if it exists at all. The modeled galaxies quickly use up the available gas and show a single splash of gas influx to fuel the central starburst or active galactic nuclei (AGN) activity. As a result, there are numerous difficulties in reproducing the observed phenomena in isolated systems: they start with simplified initial conditions, e.g., an axial symmetry (in disk galaxies) which is broken spontaneously by the bar instability. In many ways these systems are too idealized to explain the evolutionary tracks of real galaxies, but they serve as excellent educational tools. The perennial question about these systems remains: why should nature create 'equilibrium' systems and immediately 'destroy' them by various dynamical instabilities?

Here we shall take an alternative approach and treat an assembling disk–halo as an open system whose evolution is driven by both extrinsic (i.e., environmental) and intrinsic factors. In this context, 'open' is synonymous with 'cosmological.' The cosmological caveats include the redshift dependence of gas and dark matter (DM) influx along the large-scale filaments which feed the growing disk inside an assembling halo. Thus, conditions which are associated with a disk-halo growth are those of

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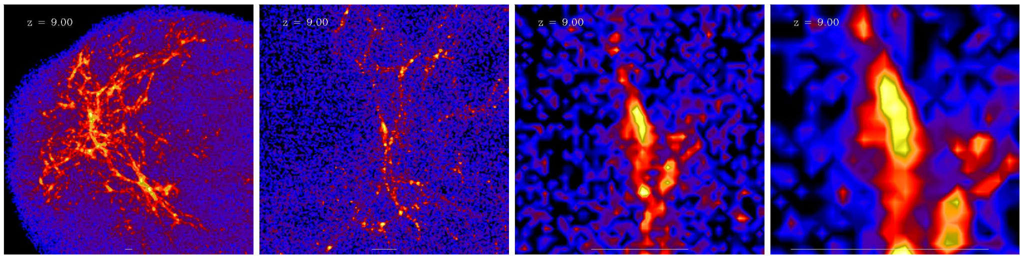

Fig. 1. Snapshots of gas density (color-coded) evolution in the BDM model at $z = 9$ (based on Romano-Dìaz et al. 2008a). The panels are from left-to-right 600 kpc, 200 kpc, 50 kpc and 25 kpc across.

an asymmetric background DM potential and clumpy mix of DM and baryons. This asymmetry of the potential comes from the surrounding filaments(s) and from the virialized triaxial DM mass distribution. The accretion process itself is highly inhomogeneous and potentially responsible for various dynamical phenomena in the disk and its immediate surroundings — few of these will be discussed here.

Galactic bars appear as dominant morphological features in nearby disks (e.g., Sellwood & Wilkinson 1993; Knapen et al. 2000; Marinova & Jogee 2007). At intermediate redshifts of $z \sim 0.2 - 1$, this picture is a subject to controversy (Jogee et al. 2004; Elmegreen et al. 2004; but see Sheth et al. 2008). At even higher z we know very little about the disk evolution. However, the importance of bars goes well beyond morphology — they serve as a fundamental channel of angular momentum redistribution in a galaxy. Hence bar formation and evolution should be tied to the overall process of galaxy formation and evolution in the CDM universe. Here we attempt to pursue this argument.

2. First generation of bars in open systems

Cold stream-fed growth emerges as the dominant mode of DM and baryonic assembly in massive galaxies (e.g., Dekel et al. 2009). In the following discussion, we rely on representative models which run from identical initial conditions at $z = 120$ in ΛCDM Universe — pure DM (PDM) simulations and simulations with WMAP3 fraction of baryons, the BDM models (Romano-Dìaz et al. 2008a). Fig. 1 displays snapshots of gas density evolution in the BDM model on scales from 600 kpc to 25 kpc. The latter scale is relevant for disk formation and it is significant that the filamentary structure extends down to this size at high z. The resulting halo shapes will be substantially triaxial (e.g., Allgood et al. 2006), partly because of the assembly process and partly as a result of the radial orbit instability. Baryons act to wash out the equatorial ellipticity and to reduce the flatness of the DM distribution (Fig. 2; also e.g., Kazantzidis et al. 2004; Berentzen & Shlosman 2006; Shlosman 2007).

One of the crucial differences between the local and high-z universes lies in that the latter is much more cold gas-rich. Gas-dominated disks that form in the asymmetric potentials cannot maintain axial symmetry — stars and especially gas will respond dramatically producing a standing density wave and a shock, respectively. Simulations have demonstrated that early bars will form under these conditions and that these bars will have properties different from the canonical bars discussed in the literature so far (e.g., Heller et al. 2007b). Specifically, this first generation of bars (1) will form in disks with a low surface density and central mass concentration. Consequently, (2) they will exhibit low pattern speeds. (3) They will experience a rapid growth, concurrently with that of the host galactic disks. Finally, (4) both bars and disks will be aware of the DM halo orientation, i.e., position of its major axis. Importantly, the halo figure tumbling is exceedingly slow, whether it grows in

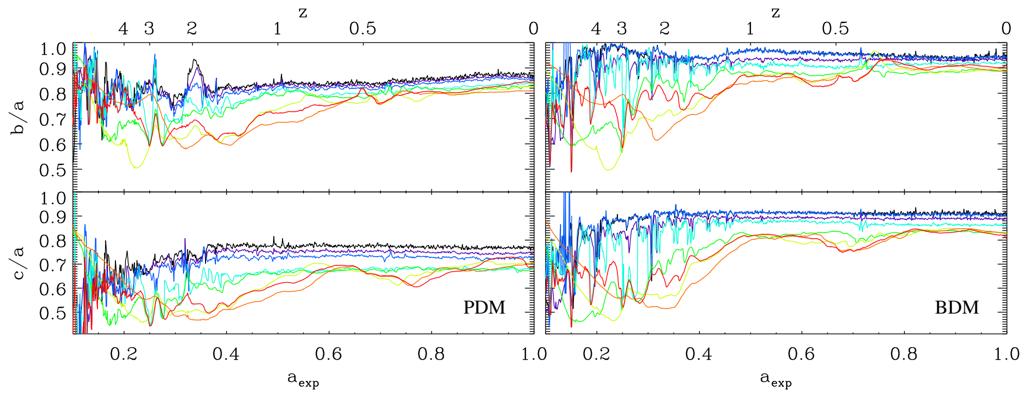

Fig. 2. Evolution of the axial ratios (shapes) for the prime DM halo at various representative radii in the PDM (left) and BDM (right) simulations. Top: halo b/a (stratified roughly from top to bottom) at $r = 10$ kpc, 20 kpc, the NFW radius, radius of maximal circular velocity, 100 kpc, 200 kpc, 300 kpc and the virial radius. Bottom: the same for c/a (Romano-Dìaz et al. 2008a).

a filament or in the field (Bailin & Steinmetz 2004; Heller et al. 2007b; Romano-Dìaz et al. 2008a,c). This will result necessarily in a double *inner* Lindblad resonance (ILR) — the outer ILR will move far out and the inner ILR to the center — between these resonances the baryonic response in the disk will be orthogonal to the major axis of the halo, reducing its equatorial ellipticity.

Thus, first bars are expected to form in the growing disks embedded in the triaxial halos. However, bars and triaxial halos are incompatible — a canonical bar tumbling within a stagnating halo will serve as a source of chaos and dissolve quickly (El-Zant & Shlosman 2002). The caveat lies in that the early bars are supposed to rotate very slowly (see above) and so the amount of chaos will be greatly reduced, prolonging the bar dissolution time to $\sim 1-2$ Gyr. During this time period, the disk growth can be appreciable. If the disk response to the halo forcing (see above) can successfully wash out the inner halo equatorial ellipticity over this timescale, it will remove the main source of chaos and open the possibility for the bar to strengthen. Future work can confirm whether this indeed what is happening.

Bars living in growing disks are necessarily gas-rich (e.g., Heller et al. 2007a,b; Romano-Dìaz et al. 2008a,c), to the extent that was not contemplated in the literature so far. Shlosman & Noguchi (1993) found that, for gas fractions $f_g \gtrsim 10\%$ of the disk mass, the Jeans instability will lead to massive clumps which will spiral down to the central kpc as a result of a dynamical friction, leading to a nuclear starburst. Heating the stellar disk on their way, the clumps can damp the canonical bar instability or postpone it substantially. Bournaud et al. (2005) claimed that $f_g \sim 7.25\%$ is sufficient to trigger the bar dissolution due to the J transfer from gas to stars in the disk, in simulations with a rigid halo. Berentzen et al. (2007) compared the evolution of disks with $f_g \sim 0\%-8\%$, concluding that the apparent decrease in the bar strength is not related to the gas content but rather to the vertical buckling instability (e.g., Combes et al. 1990; Raha et al. 1991) in the bar, which weakens it substantially but allows for a secular rebuilding (e.g., Martinez-Valpuesta et al. 2004; 2006). Bars that are capable of growing typically appear as 'fast' bars, i.e., extending to near corotation, even in cuspy halos (Dubinski et al. 2009).

Gas fractions to be encountered at high z can be an order of magnitude higher than quoted above. Results, based on the equilibrium models, show that dependence of the bar strength on f_g is not so dramatic. As long as the Jeans instability in the gas is damped, J transfer from the gas to the stars is compensated by J lost by the stellar bar to the DM

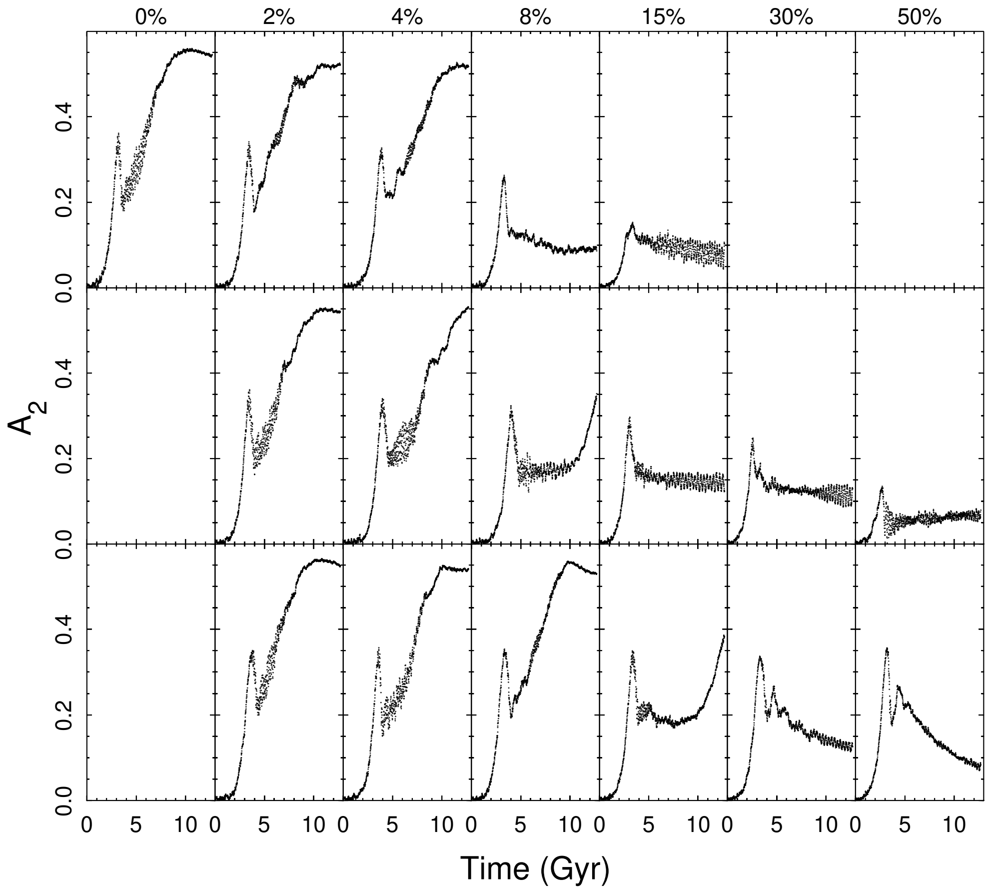

Fig. 3. Evolution of the stellar bar strength, given by the Fourier amplitude A_2 of the $m = 2$ mode, for various gas fractions, $f_g \sim 0\% - 50\%$ in the disk immersed in the live halo. The time is given in Gyrs. The Jeans instability is progressively damped from top to bottom models. The first peak defines the time of the vertical buckling in the bar. Note that A_2 shapes are very similar in all models up to the first peak (Villa-Vargas et al., in prep.).

halo. Fig. 3 demonstrates that development of the canonical bar instability is nearly independent of the gas fraction, up to $f_g \sim 50\%$ at least, *if the Jeans instability in the gas is suppressed* (Villa-Vargas et al., in prep.). The buckling proceeds similarly independent of f_g. But the subsequent evolution of the bar strength differs — while 15% gas still allows for the secular growth of the bar, 30% reduces the bar strength by a factor of 2–3 over the Hubble time.

3. Dynamics of bars in open systems

When gas rich bars are triggered by the asymmetric DM potential, they can appear simultaneously on more than one spatial scale. By this we mean that bars on different scales will either have different pattern speeds or will be situated at different position angles (in fact, orthogonal to each other) and have the same speed. Most frequently they form on smaller scales of

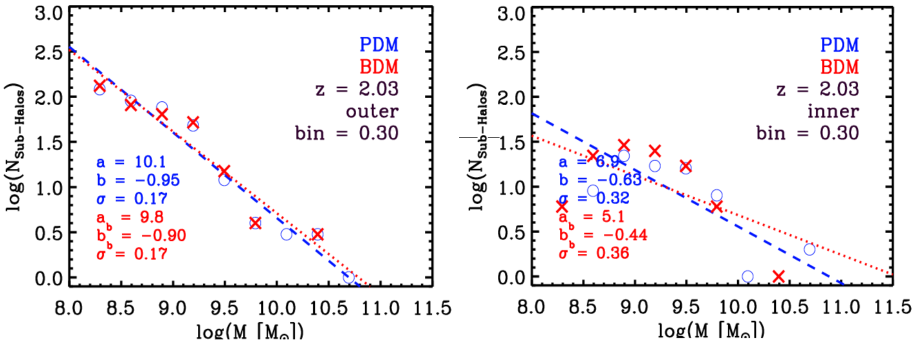

Fig. 4. Mass function $N(M_{\rm sbh})$ of the subhalo population at $z = 2$ in PDM (blue dashed) and BDM (red dotted) models. The minimal resolved subhalo mass is 10^8 $M_\odot$, which is about $10^{-4.3}$ of the prime halo virial mass at $z = 0$. Left: $N(M_{\rm sbh})$ for subhalos outside the virial radius of the prime halo; Right: $N(M_{\rm sbh})$ for subhalos inside the central $\sim$ 100 kpc $\times$ 50 kpc virialized region (defined by the isodensity contours) of the prime (Romano-Dìaz et al., in prep.).

a few×100 pc — so-called nuclear bars, and on the scales of a few kpc, so-called prime bars, although in some cases only one bar forms (Heller et al et al. 2007a,b). As we have stated above, *these bars do not form as a result of the canonical bar instability but rather constitute the disk response to the finite external perturbation*. Unlike most of the bars in the local universe, their young counterparts appear to be delineated by star formation which is present not only close to the ILR(s) but throughout the area of the bar. In a way they resemble inclined starbursting disks, unless distinguished kinematically.

As a first step, we discuss the behavior of single bars formed under these conditions, then comment on the evolution of double bars. Bar dynamics can be studied by inspecting their pattern speed, Ω_b, evolution. Here again the 'cosmological' bars differ from their low z gas-poor representatives. Those that are triggered by the asymmetric potential are characterized by strongly growing Ω_b, concurrently with the disk growth. An alternative way of triggering bars, also by a finite perturbation, was known for some time as a tidal triggering (e.g., Byrd et al. 1986; Noguchi 1987), but was never considered to be important enough to explain the observed bar fraction in the universe. As we discuss below and in the next section, within a somewhat modified framework, this picture may become more appealing.

It is important to emphasize here that the class of tidally triggered bars exhibit initial Ω_b which are determined by the orbital speeds and the impact parameters of the perturbers. But the subsequent evolution of Ω_b in all three types of bars (namely, canonical, triggered by the DM asymmetry or triggered tidally) is determined by the balance of angular momentum in the bar and by the central mass concentration, i.e., the shape of the inner rotation curve in a galaxy. Here, the role of gas, the only dissipative agent, cannot be overestimated. Either dynamically or secularly, the gas influx to the center contributes to the mass growth there and so, even under conservation of J in the bar, will cause an increase in Ω_b. The net effect on the bar tumbling can be estimated from the amount of J supplied by the disk gas to the bar within its corotation radius, the growth of the central mass concentration, and the amount of J lost by the bar to the outer disk and especially to the DM halo.

Simulations of isolated disks with an ad hoc addition of gas (Bournaud & Combes 2002) and cosmological simulations of growing disks embedded in large-scale filaments (Romano-Dìaz et al. 2008c) demonstrated that bars can accelerate over a prolonged time pe-

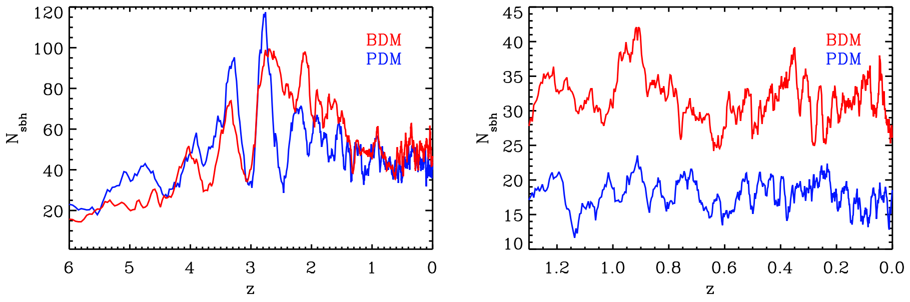

Fig. 5. Population of subhalos in PDM and BDM models within the inner 60 kpc (left) and inner 30 kpc (right) of the prime halo at lower redshifts (Romano-Dìaz et al. 2008b).

riod of a few Gyrs, during which the surface density of the disk, especially of its gas component, grows. This underlines the importance of the cold gas influx via filaments. With this, the strength, A_2, of the cosmological bars (anti)correlates with Ω_b — weakening bars accelerate, and vice versa, as shown first for the pure stellar bars in equilibrium models (Athanassoula 2003). Exceptions include the time periods of interactions between the developed bars and flybys, and the double bar systems (Romano-Dìaz et al. 2008c).

In the case of double bars, only the nuclear bars accelerate after formation, while the primary bar pattern speeds are quite steady over long time periods (Heller et al. 2007a). Both shapes and pattern speeds of nuclear bars vary with their orientation to the prime bar (Heller et al. 2001; Shlosman & Heller 2002; Englmaier & Shlosman 2004; Shen & Debattista 2009) and this is visible in models of cosmological double bars as well (Heller et al. 2007a). The latter work has also shown that double bars can lock their pattern speeds at various ratios of nuclear-to-primary Ω_n/Ω_p — an issue of mode coupling.

4. Bar triggering by DM substructure

The possibility of bar triggering via interactions with other galaxies hints at a strong dependence of bar fractions on the environment and redshift. However, bar fractions in clusters of galaxies and in the field appear comparable (Marinova et al. 2008; and this volume). This discrepancy between expectations and observations can be erased if bars can be triggered by interactions with DM substructure and not by a more rare interactions with their more massive neighbors. Existence of such DM subhalos is inherent to the hierarchical scenario of galaxy formation (e.g., White & Rees 1978). Hence, whether a halo is found in the cluster or in the field, it will grow by consuming the surrounding subhalos — those that survive the radial plunge can have a profound effect on the disk evolution.

Properties of a subhalo population have been studied in pure DM simulations (e.g., Ghigna et al. 1998; Klypin et al. 1999; Kravtsov et al. 2004; Diemand et al. 2007). Their mass distribution function was found to be nicely approximated by a power law $N_{\rm sbh} \sim M_{\rm sbh}^{-1}$, where $M_{\rm sbh}$ is the mass of a subhalo (e.g., Diemand et al. 2004). Much less is known about subhalos in the presence of baryons. Their power law distribution seems to be retained for DM halos above 10^{10} $M_\odot$ — the resolution limit (Weinberg et al. 2008). Fig. 4 displays the subhalo mass functions for PDM and BDM models at $z \sim 2$, for much higher resolution simulations resolving subhalos above 10^8 $M_\odot$ (Romano-Dìaz et al., in prep.). To emphasize the environmental effects, the population was divided into the outer one, situated in the computational box *outside* the virial radius of the prime halo, and the inner one, situated *within* the central virialized region delineated by density isocontours, ~100 kpc × 50 kpc. A number of trends can be seen: (1) for the ‘field’ subhalos, the difference between the PDM and

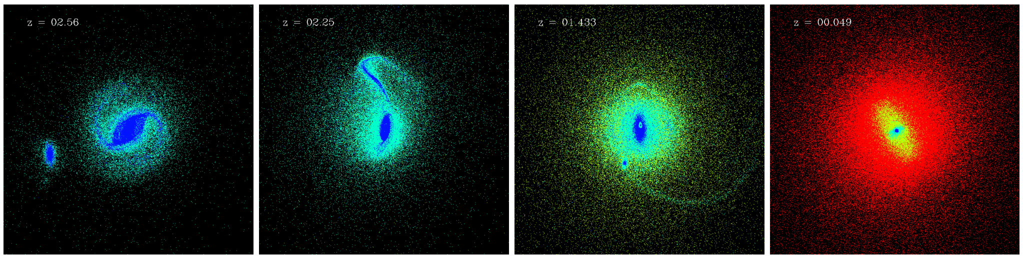

Fig. 6. Snapshots of disk evolution and its stellar population. Stellar ages are 0–0.2 Gyr (blue), 0.2–2 Gyr (blueish), 2–5 Gyr (yellow) and older than 5 Gyr (red). In this model, a long-lived stellar bar is triggered by the interaction with an inclined prograde subhalo (hosting another disk) at $z \sim 2.56$ (left). Numerous interactions with additional subhalos (e.g., middle panels) leave the bar intact. A nuclear bar develops after $z \sim 0.1$, orthogonally to the prime bar (right). From Romano-Dìaz et al. (2008c).

BDM models is minimal at these redshifts. (2) the log-log slope is about (−0.9) – (−0.95) and quite stable at other z. (3) Evolutionary trends are present in the inner subhalo population — their integrated number is lower by a factor of a few, both in the PDM and BDM. (4) the BDM slope is shallower than the PDM one — more massive BDM subhalos survive better than the PDM ones in the central dense region of the prime halo.

Our main interest in subhalo populations lies in its impact on the disk evolution. Specifically, we focus on the comparison between the PDM and BDM models. The environmental effects are clearly seen in the overall decrease in $N_{\rm sbh}$, both with and without baryons. This trend accelerates with z and especially for the innermost massive PDM subhalos. Hence we expect an excess of *inner* BDM subhalos over the PDM ones at lower redshifts. Fig. 5 shows that indeed the BDM subhalos dominate that inner 30 kpc region of the prime halo at low z, well after the epoch of major mergers which ends by $z \sim 1.5$ in these models. The time variable influx of the subhalos is clearly visible in Fig. 5. The maxima at $z \sim 4 - 2$ (left panel) are associated with the major mergers. The subhalo population at $z \lesssim 1$ (right panel) is much more steady, still one can observe 'waves' of subhalos that penetrate the inner 30 kpc. A more careful analysis shows that these subhalos have been accreted via filament(s). They appear to cluster within the filament but their merging there is suppressed. The ability of these subhalos to penetrate the central region of the prime halo is enhanced because they are 'glued' by the baryons and hence can withstand larger tides. Interactions between the DM substructure and stellar bars can be classified very roughly into flybys and direct hits (those include mergers). Prograde encounters can excite bars, retrograde can only cause lopsidedness, while direct hits weaken existing bars. Like the canonical bars formed as a result of the intrinsic instability, tidally-induced bars are very resilient. They avoid a number of difficulties associated with the linear stage of the bar instability. An example of such a long-lived bar triggered by a DM subhalo on a prograde inclined orbit is shown in Fig. 6. Interactions with the surrounding substructure leave it intact (Gauthier et al. 2006; Romano-Dìaz et al. 2008c). Without much exaggeration, one can say that in order to destroy this bar, one should largely destroy the disk which hosts it, although it does go through phases when it is quite weak.

To summarize, there is a clear advantage to processes which involve tidal triggering of galactic bars, at least at high to intermediate, and possibly low z. This triggering can result either from an asymmetric DM distribution or from interactions with the surrounding substructure. Such a triggering constitutes a finite amplitude perturbation and is independent of a number of problems associated with the canonical (spontaneous) bar instability. Recent numerical simulations involving baryons show a more dominant population of subhalos in the innermost DM halo, in the regions which host growing galactic disks, and after the epoch of major mergers. Finally, the availability of substructure around field and cluster galaxies points to the bar fractions being (reasonably) independent of the environment.

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