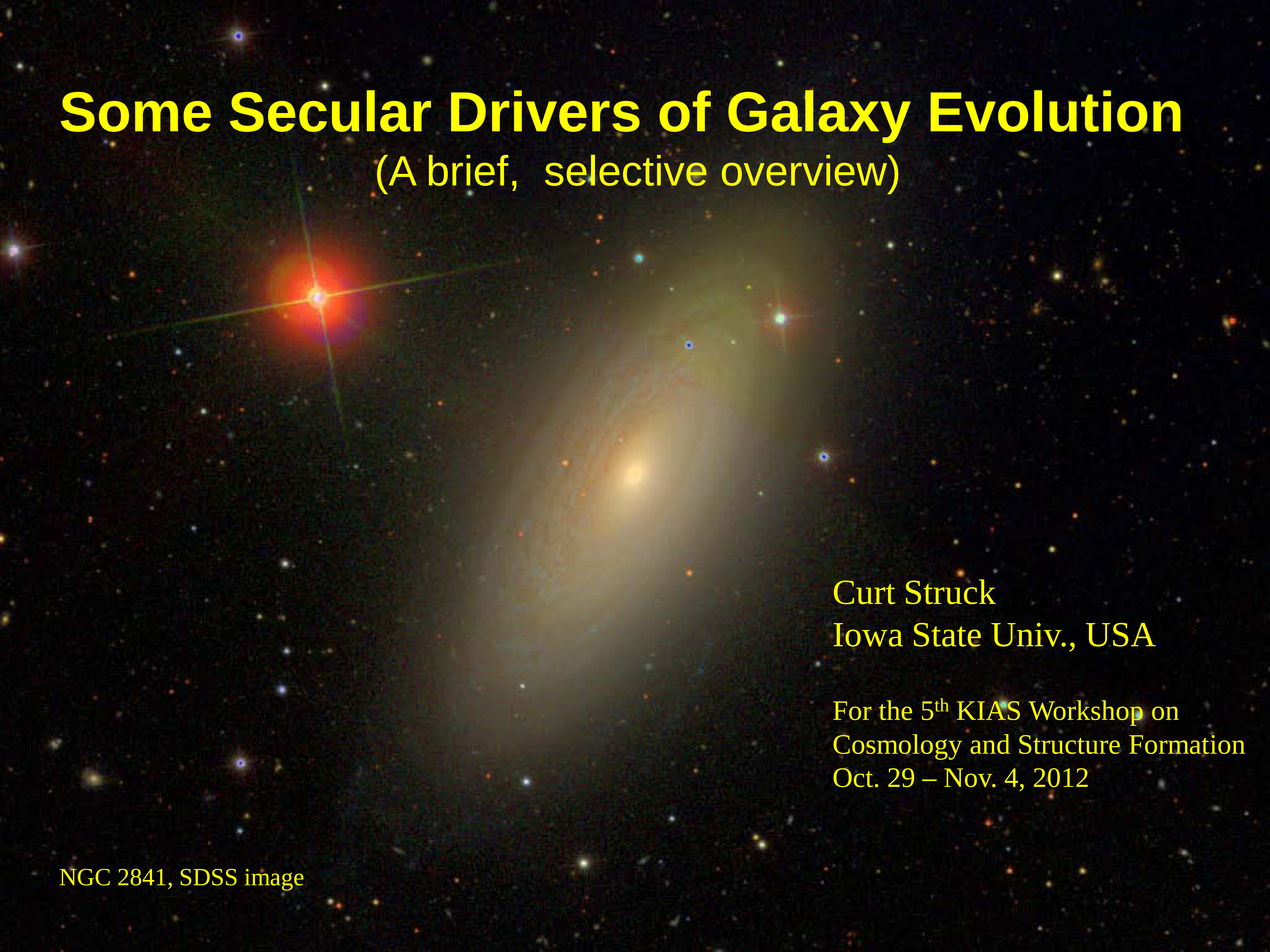
Some Secular Drivers of Galaxy Evolution

(A brief, selective overview)



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For the 5th KIAS Workshop on Cosmology and Structure Formation
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NGC 2841, SDSS image

Outline:

Secular – is a strange word for slow, continuous processes, but never mind.

1. Introduction
2. Starving and stressing disks: some environmental effects.
3. Exciting disks with waves.
4. A mish-mash of leftovers to feed disks: (tidal) halo infall.
5. To the bar… or not.
6. Summary

Including work with collaborators B. J. Smith, J.-S. Hwang and C. L. Dobbs.

1. Introduction

Historically, most studies of galaxy formation and development focused on impulsive drivers, e.g., large-scale collapse, major mergers, or rapid stripping.

However, several secular evolutionary processes have long been considered, including:

- gas consumption in disks,
- halo gas accretion/infall (more recently cosmological ‘cold’ accretion),
- bar formation – bar decay – secular bulge formation, and
- environmental effects like slow stripping/quenching.

Recently, some of these are being studied intensely within cosmological structure formation models.

Will highlight a couple of these and some less well-known secular processes, most of which are worthy of further attention.

2. Ram pressure & waves

• Baade & Spitzer (1951) first suggested that gas could be removed from galaxies by collisions, and later the idea was extended to stripping by the IGM in clusters.

• Rapid ram stripping in clusters was proposed by Gunn & Gott (1972) in a paper on galaxy cluster formation. (Subsequent history of subject reviewed in Schulz & Struck (2001).)

• Wholesale stripping is prompt in galaxies traversing the cores of large clusters at high velocities. However, in cluster outskirts, or in smaller groups with a lower density IGM, it is slower and less complete. The models of SS (2001) & more recent simulations affirm this the general point with the latter providing new details.

194 *S. Schulz and C. Struck*

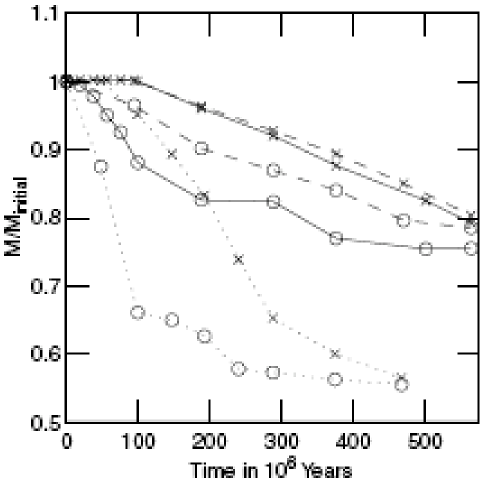
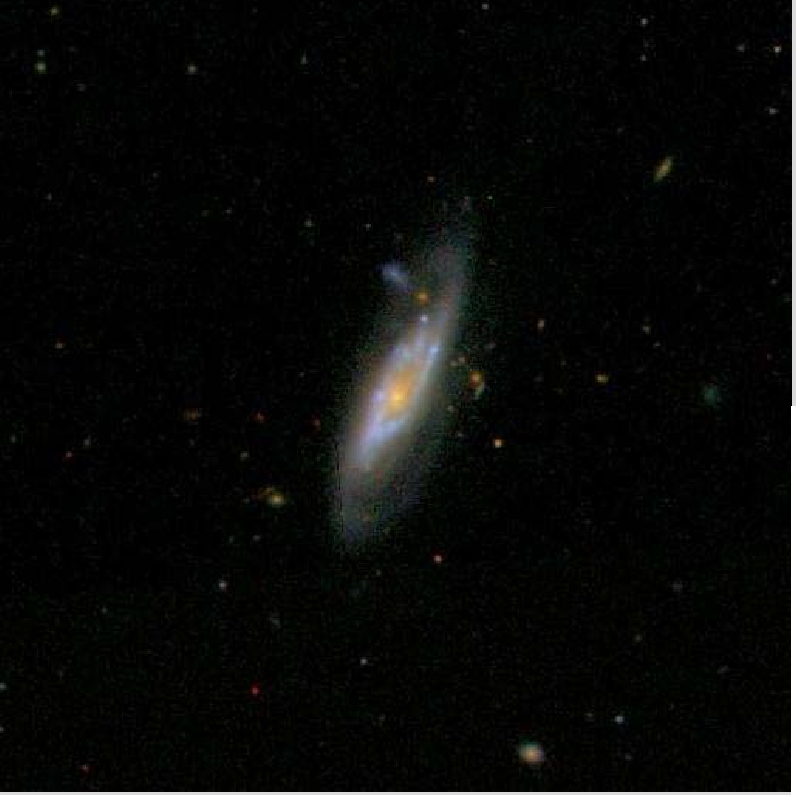


Figure 6. Comparison of mass loss in three models. The circles connected by the solid line segments represent the gas in the fiducial model retained in a rectangular volume around the original gas disc as a function of time (see text for details of the box bounds). The circles connected by dashed and dotted lines represent the gas retained within the same box in the 40° tilt and 2000 km s^{-1} models, respectively. The solid, dashed dotted curves connecting depict gas mass remaining on the crosses any part of the computational grid, in the fiducial, 40° tilt and 2000 km s^{-1} models, respectively.



Example I: NGC 4848, SDSS & Halpha

The images show stripping of the outer disk, but also waves of SF in the inner disk. (Also see recent work of Yoshida, et al. on other Coma cluster galaxies.)

M. Fossati et al.: Hα tail behind NGC 4848

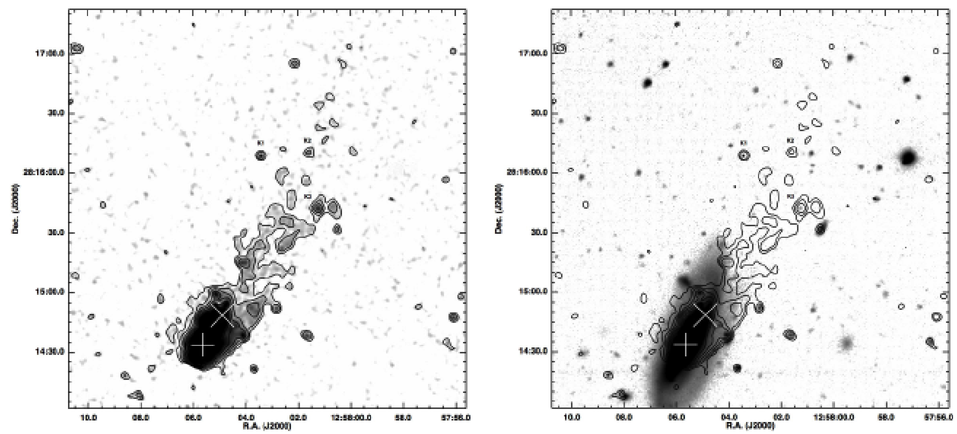


Fig. 1. *Left panel*: grayscale representation of the Gaussian-smoothed (three-pixel-kernel) NET image of NGC 4848, with contours of the same image (contours are from 1 to 320 $\times$ 10^{-17} erg cm^{-2} s^{-1} arcsec^{-2} in 10 logarithmic intervals). The white cross marks the center of the molecular hydrogen given by Vollmer et al. (2001), while the white X marks the center of the HI given by Bravo Alfaro et al. (2001). Three knots of NET emission with associated stellar continuum are marked K1-3. *Right panel*: grayscale representation of the OFF image of NGC 4848, with contours of the Gaussian-smoothed (three-pixel-kernel) NET image (same as left panel). Note the angle between the major axis of the galaxy and the direction marked by the tail, which points toward the center of the Coma cluster.

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Astronomy & Astrophysics

65 kpc of ionized gas trailing behind NGC 4848 during its first crossing of the Coma cluster*

Matteo Fossati[1], Giuseppe Gavazzi[1], Alessandro Boselli[2], and Michele Fumagalli[3]

Example II: The truncated disks of the Virgo cluster.

Kenney & Koopmann's (2004) study of truncated disks found a variety of types, including a set of truncated disks with enhanced SF. The fact that disk truncation does not necessarily reduce net SF is confirmed & extended by Vollmer, et al. (2012).

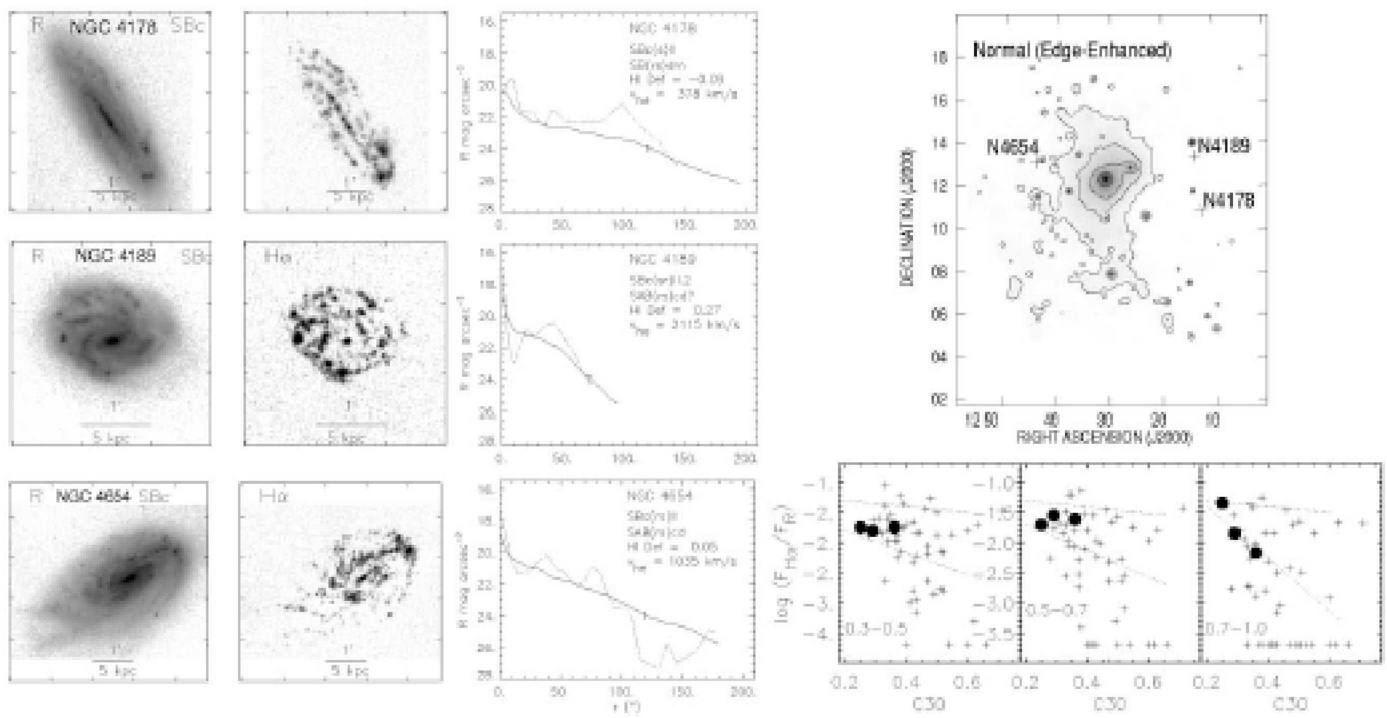

FIG. 10.—Three Virgo Cluster galaxies that show locally enhanced Hα emission in asymmetric arcs near the edge of the star-forming disk. NGC 4380 (Fig. 8) and the pair of galaxies NGC 4298 and NGC 4647 (Fig. 11) also show similar outer arcs of star formation. However, this local enhancement is not significant enough to increase the NMSFR over the whole radial bin, as shown at bottom right. (See Fig. 4 for details on the plot, but note that, unlike preceding figures, the plot at bottom right depicts the NMSFRs within three smaller radial bins: $0.3r_{24} < r < 0.5r_{24}$, $0.5r_{24} < r < 0.7r_{24}$, and $0.7r_{24} < r < 1.0r_{24}$.)

Example III: Evidence of slow quenching in groups….

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THE SUPPRESSION OF STAR FORMATION AND THE EFFECT OF THE GALAXY ENVIRONMENT IN LOW-REDSHIFT GALAXY GROUPS*

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ABSTRACT

Understanding the interaction between galaxies and their surroundings is central to building a coherent picture of galaxy evolution. Here we use *Galaxy Evolution Explorer* imaging of a statistically representative sample of 23 galaxy groups at $z \approx 0.06$ to explore how local and global group environments affect the UV properties and dust-corrected star formation rates (SFRs) of their member galaxies. The data provide SFRs out to beyond $2R_{200}$ in all groups, down to a completeness limit and limiting galaxy stellar mass of $0.06\ M_\odot\ \mathrm{yr}^{-1}$ and $1 \times 10^8\ M_\odot$, respectively. At fixed galaxy stellar mass, we find that the fraction of star-forming group members is suppressed relative to the field out to an average radius of $R \approx 1.5$ Mpc $\approx 2R_{200}$, mirroring results for massive clusters. For the first time, we also report a similar suppression of the specific SFR within such galaxies, on average by 40% relative to the field, thus directly revealing the impact of the group environment in quenching star formation within infalling galaxies. At fixed galaxy density and stellar mass, this suppression is stronger in more massive groups, implying that both local and global group environments play a role in quenching. The results favor an average quenching timescale of $\gtrsim 2$ Gyr and strongly suggest that a combination of tidal interactions and starvation is responsible. Despite their past and ongoing quenching, galaxy groups with more than four members still account for at least ~25% of the total UV output in the nearby universe.

Key words: galaxies: evolution – galaxies: groups: general – galaxies: star formation – ultraviolet: galaxies

Online-only material: color figures

Enhanced SF in galaxies that have been partially stripped? How does that work?

Schulz & Struck (2001) suggested a process nicknamed ‘annealing.’
- Behind the bow shock the pressure on the leading face of the disk is greater than the trailing face.
- The gas is pushed slightly out of the initial or stellar disk.
- As a result it feels a tidal compression from the stellar disk (and dark halo), in a direction perpendicular to the disk plane.
- There is also compression in the disk plane.

- The result is more gravitational instability in the truncated disk, and wave generation… and enhanced SF in some cases.

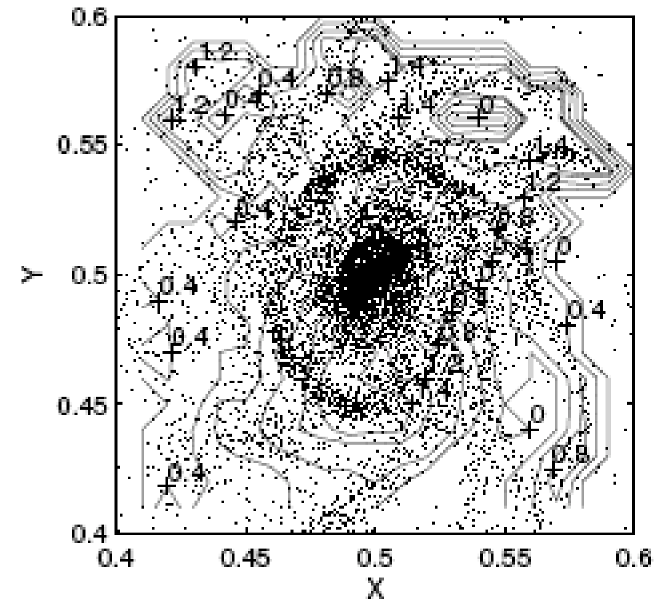


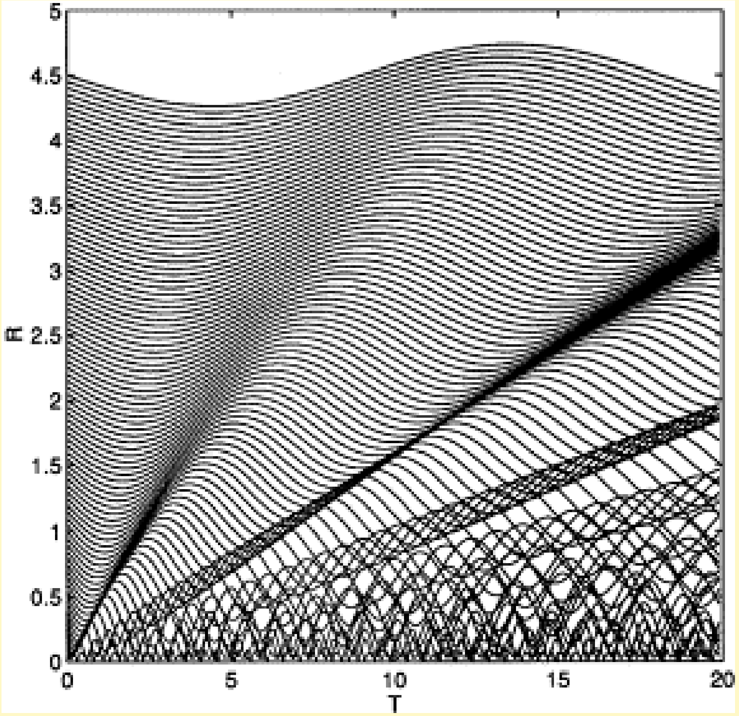
Figure 11. A galaxy tilted 40°, at $t = 0.94 \times 10^8$ yr. Contours of the z-component of the velocity of the gas disc particles, ranging from -1.6 to $+1.2$ (or -156 to $117\,\mathrm{km\,s^{-1}}$).

<u>This can be viewed as a secular by-product of a slow form of ram stripping.</u>

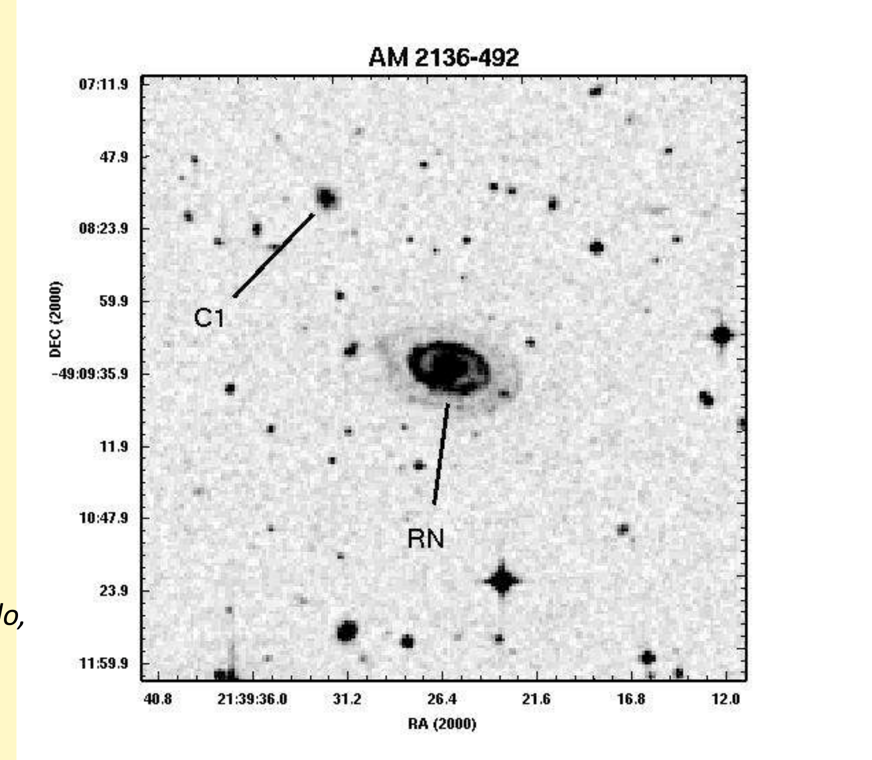
3. Slowly winding waves

• Classical spiral density wave theory, has long contended with the wind-up problem – in a typical shearing disk spiral waves do not maintain their form. They wind up within a few rotation periods.

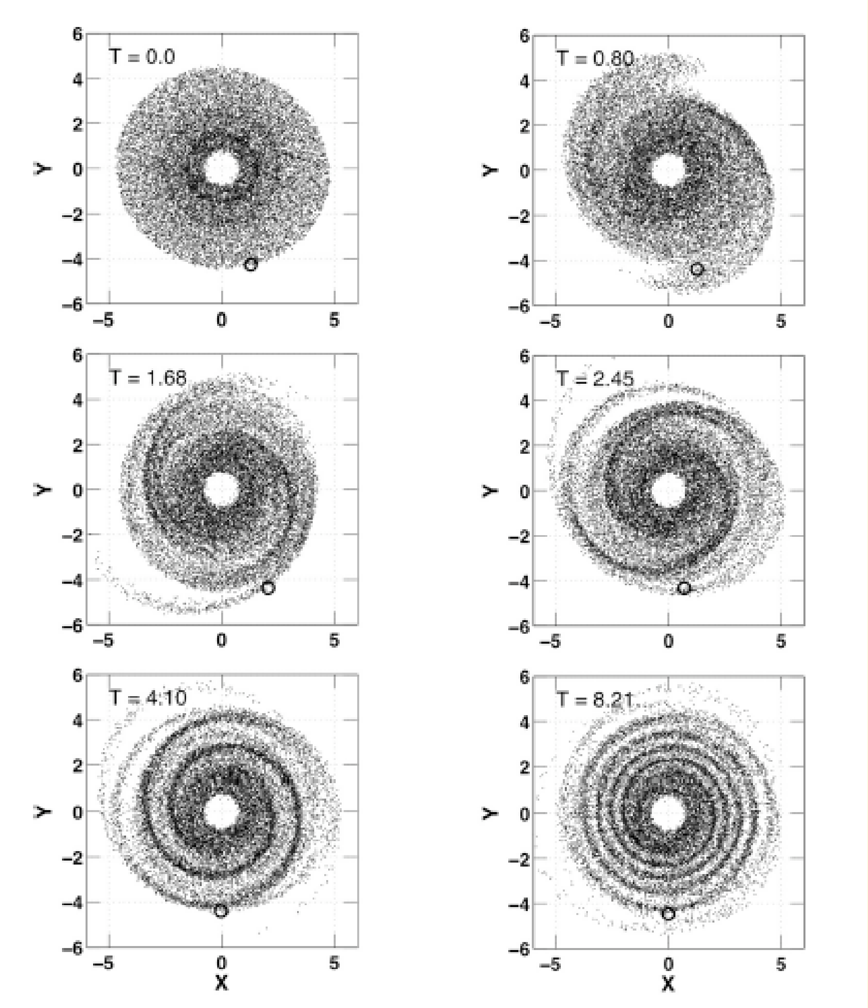
• A seemingly unrelated result of ring galaxy theory – in flat rotation curve disks the initial ring can be very weak; the strongest waves are the 2nd and 3rd rings. (Many of the rings we actually observe may be 2nd waves (see Struck 2010, Appleton & Struck-Marcell 1996).



From *Madore, Nelson, & Petrillo, 2009*

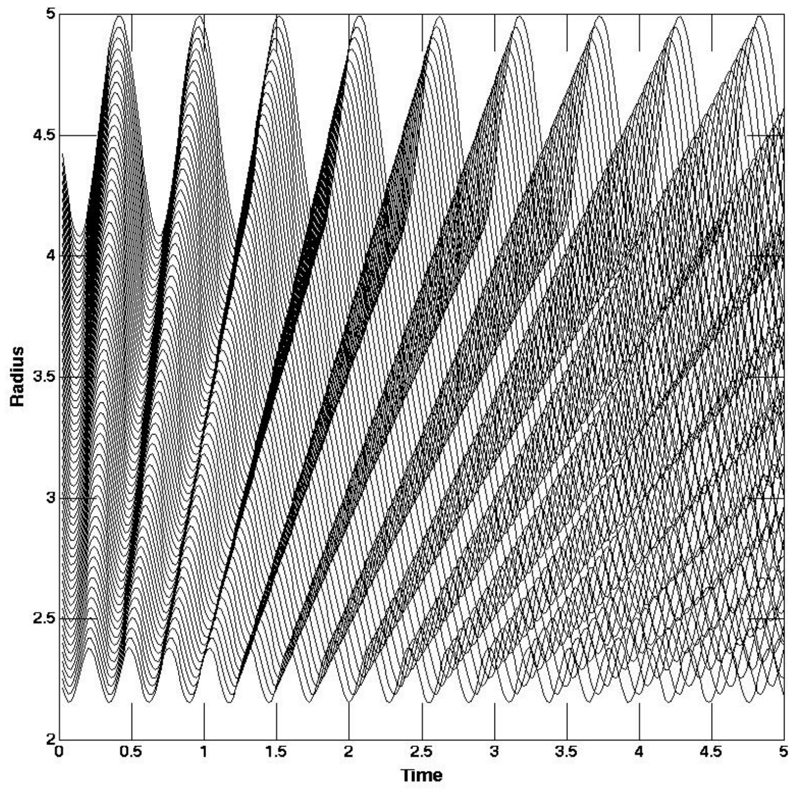


• In N-body/SPH models with two different codes Struck, Dobbs & Hwang (2011) found a phenomenon in spiral waves generated by weak (hyperbolic) flyby interactions with another galaxy that is a combination of the 2 effects.
Initially very weak spiral waves grow in strength with time, while also winding up.

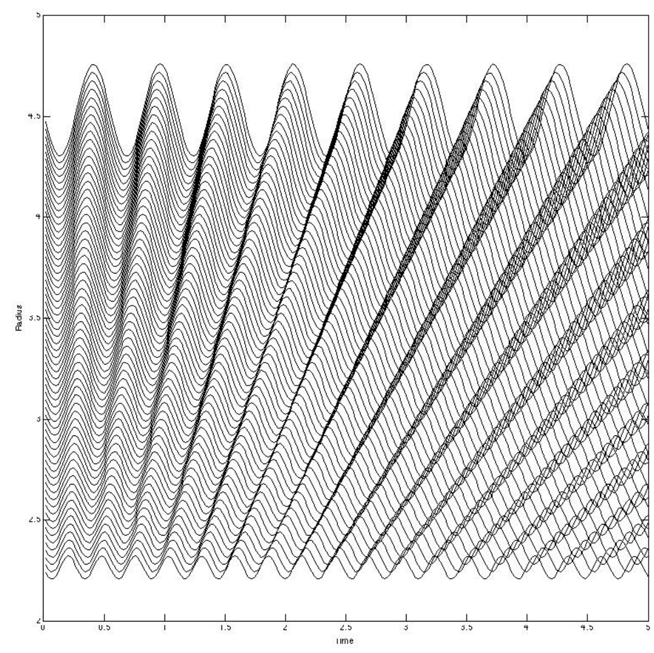


This can be understood with the help of a simple epicyclic model. Initially, the radial oscillations of stars at nearby radii are nearly synchronous. However, as their epicyclic phases drift, compressions and orbit crossings occur (see next slide).

As the figure suggests, the result can be wave persistence for up to a few Gyr, though in real disks gas dissipation will damp it.



Radial oscillations of stars at different initial radii after the flyby impulse.



• This effect can account for the tightly wound spirals seen in some disks. A flyby companion would be long gone (or merged). The effect might also be triggered by an asymmetric halo, though this has not been studied.

• Given that minor interactions are more common than major interactions in low-density environs, this form of wave excitation may be important secular driver for a population of galaxies. (Of the 176 galaxies in the Hubble Atlas of about 10 or so have this morphology.)

More generally, this can be viewed, like ram-pressure annealing, as another low-level, but persistent environmental or “harrassment” effect.

NGC 2841,
WPC3 close up
from APOD

Recently, J. Sellwood has argued that a (self-gravitational) instability can amplify noise into spiral waves. The slow growth from small beginnings is similar to the “slowly breaking waves” idea, and the two may be related. They may be two aspects of ‘secular’ spiral formation.

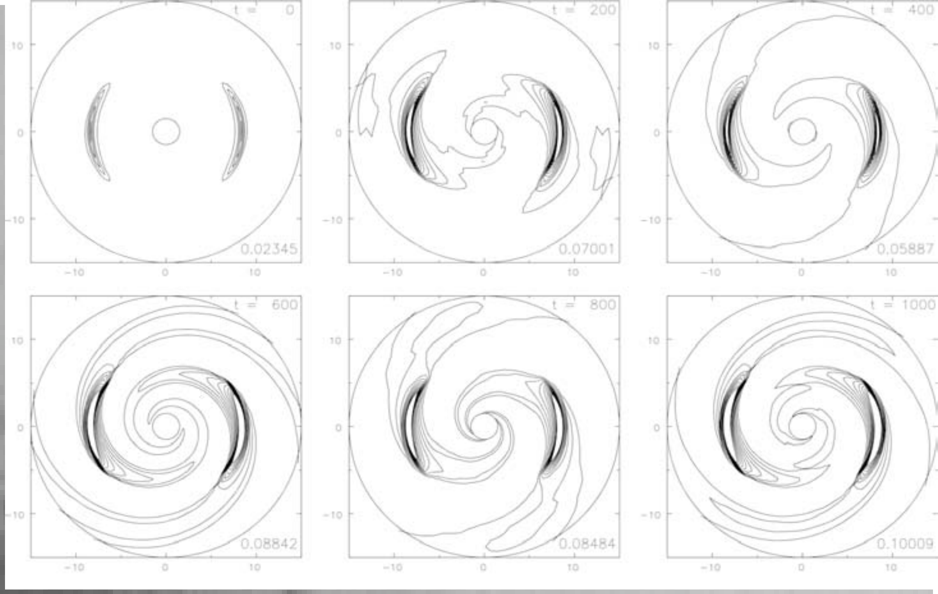
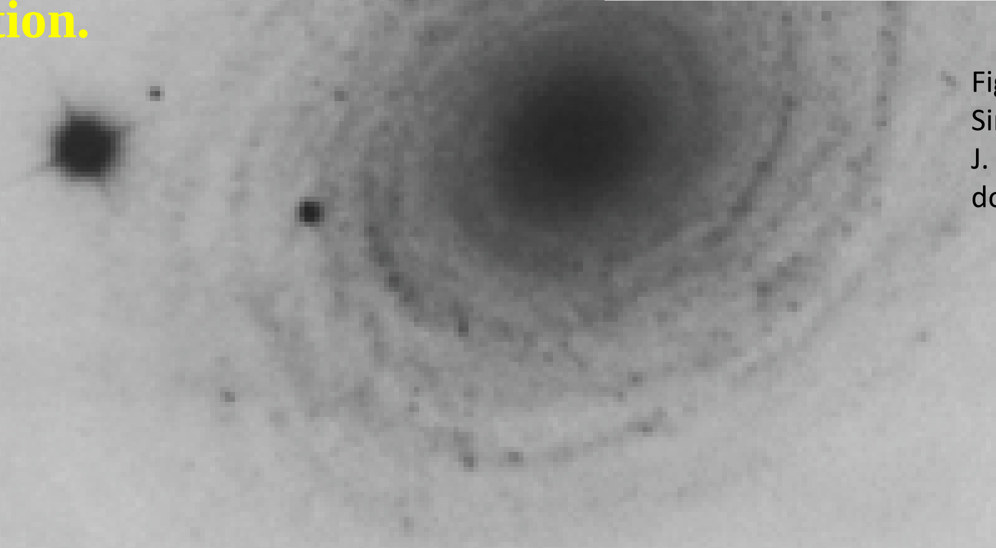


Figure 3 from Spiral Instabilities in N-body Simulations. I. Emergence from Noise
J. A. Sellwood 2012 ApJ 751 44
doi:10.1088/0004-637X/751/1/44



NGC 488

4. Slow accretion

There has been much discussion of cold accretion continuing out of cosmological filaments. I will not discuss this topic in detail (see L'Huillier talk in this session).

- Sancisi et al. (2008) presented a brief, but comprehensive review of accretion onto galaxies and found little evidence for cold, "galaxy-less" gas clouds. They concluded that the accretion due to gas-rich dwarfs and minor mergers is not sufficient to fuel the observed SF in galaxy disks.

- They note that there is a significant reservoir of gas in the outer disk regions, but how to mine it? (More on that in a moment….)

- Recent simulations suggest that cosmological accretion out of filaments has cold, warm and hot components. The latter two will not accrete directly into disks like the cold material. Ultimately some of that material may cool and fall onto the disk, i.e., in a secular fashion.

See review of Putman, Peek, & Joung (2012, AARA).

About mining the outer disk reservoir…

One way is the re-accretion of material torn out of galaxies in tidal interactions, e.g., in tails or splashes.

In major mergers we have the wholesale rearrangement, in a relatively short period of time, as in this example from Duc, Bournaud & Masset 2004.

With continued accretion over a somewhat longer timescale out of tails.

806 P.-A. Duc et al.: Formation of massive Tidal Dwarf Galaxies

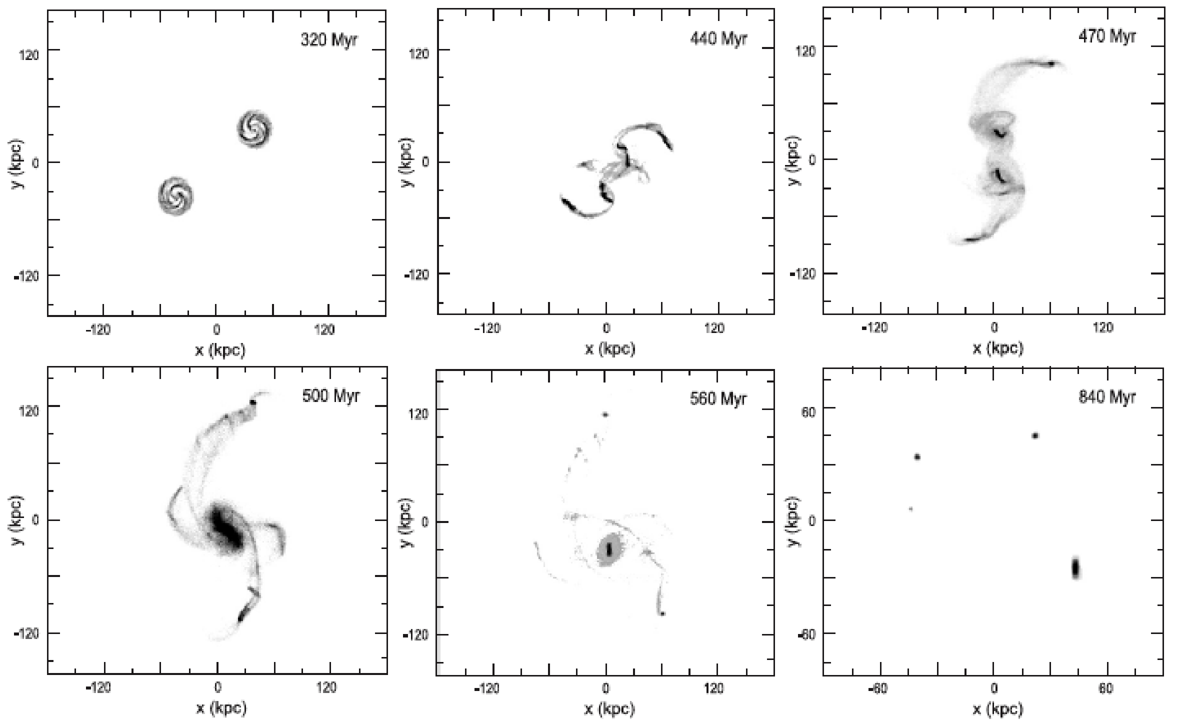


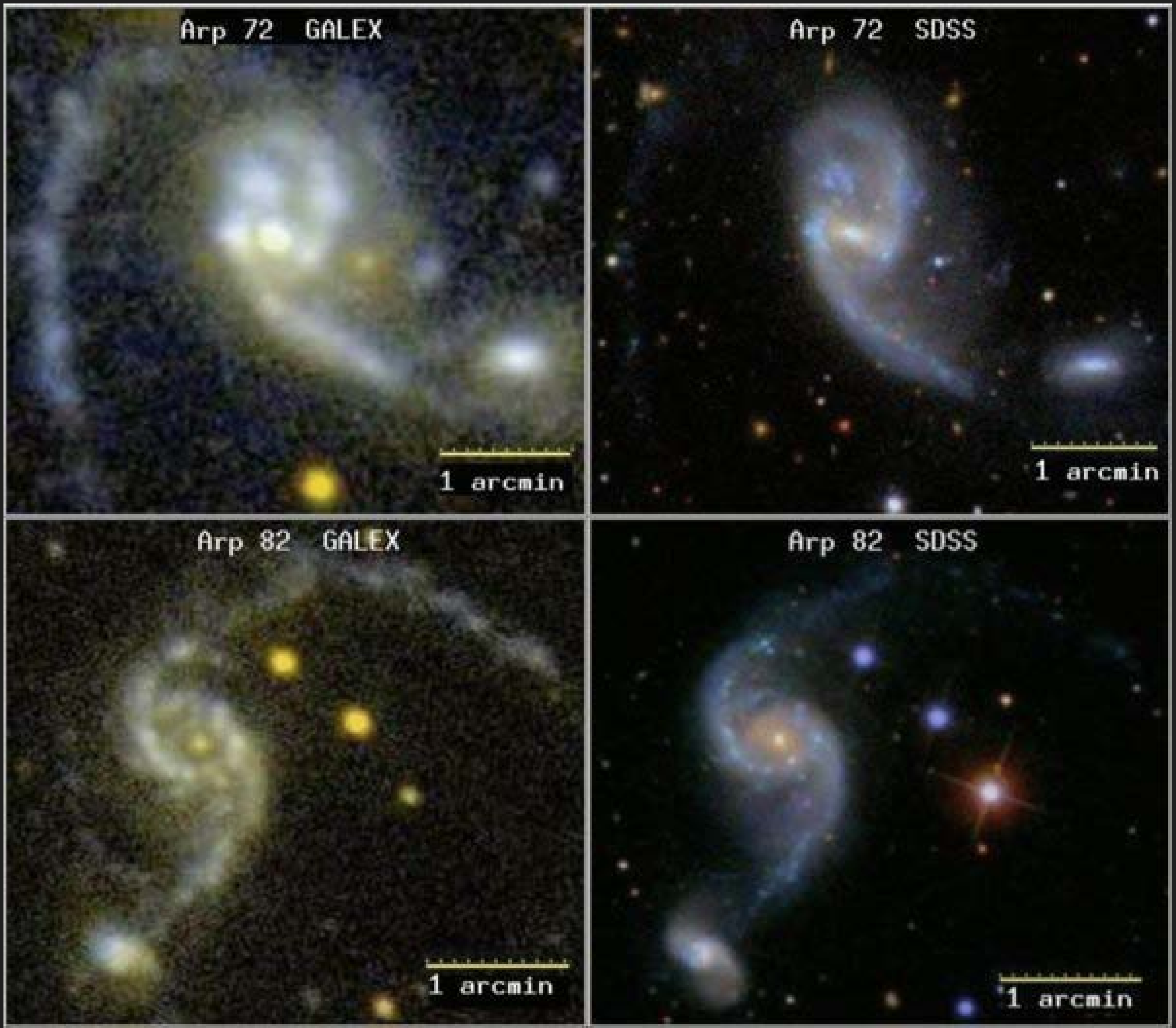
Fig. 1. Evolution of the gas distribution for the full *N*-body simulations of run A. The system is seen face-on. The gas is displayed with a logarithm intensity scale.

If the progenitor galaxies have extensive gas disks, then a great deal of material (e.g., $10^8 – 10^9$ solar masses) can be flung far out into tails, as shown in this image from the review of Duc & Renaud (2011).

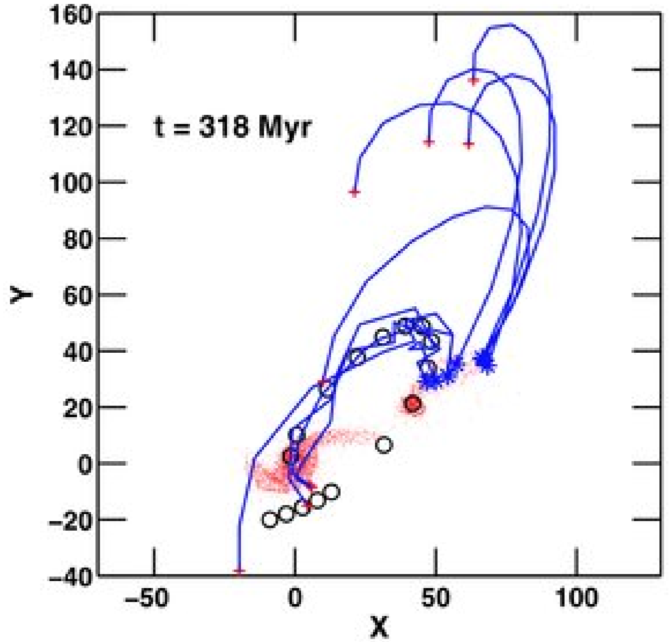
Fig. 7 A sample of interacting systems covering the various stages of major mergers, from the initial phases of the encounter (top left), to the last ones and formation of a relaxed object (bottom right). The gaseous component (atomic hydrogen) is superimposed on true color optical images of the galaxies, showing the distribution of the young and old stars. See Table 1 for details on the data.

Interestingly, those very long tails can often be seen in the ultraviolet as well as in 21 cm (From Smith, Giroux, Struck & Hancock 2010).

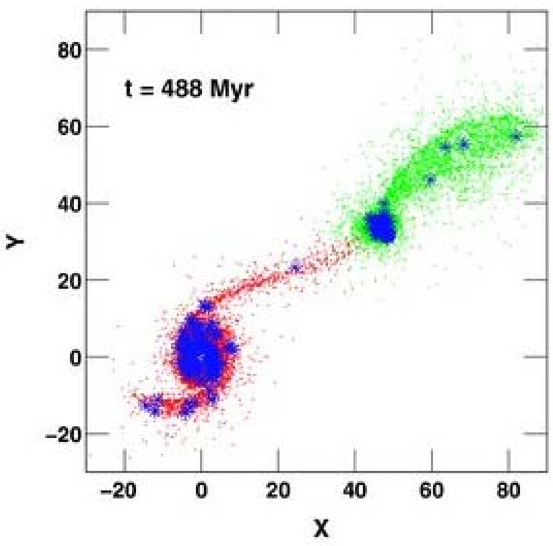
Note the relatively small companions – fairly minor mergers can produce long tails, and extended-time infall too.

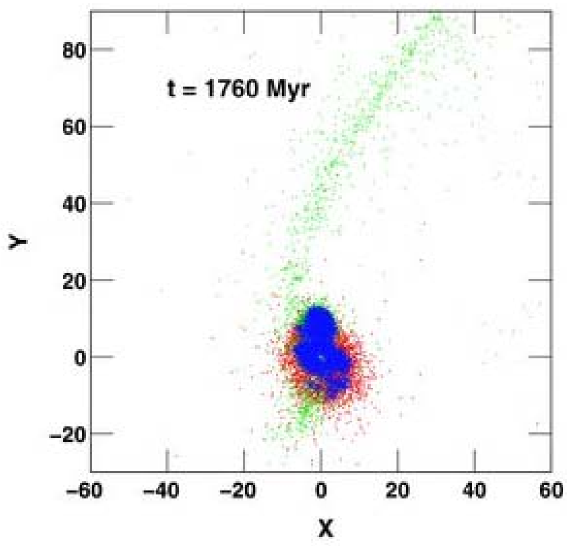


How long? Potentially, quite a long-time for tails produced in prograde encounters. E.g., this example from a model for Arp 305 from Hancock, et al. 2009.



The late time tail remnants look like a cosmic filament.





Aside: just as spiral waves can be modeled analytically with epicyclic orbit approximations, tidal tails can be modeled with ensembles of particles following precessing ellipse orbits.

In a spherical halo potential with a power-law acceleration of the form - $g(r) = \frac{-\mu}{r^{1+2\delta}}$. (where the exponent of r equals 1 for a flat rotation curve), "p-ellipse" orbits described by the equation,

$$\frac{1}{r} = \frac{1}{p}\left[1 + e\cos((m\phi)\right]^{1/2+\delta}, \quad \text{with } m = \sqrt{2(1-\delta)},$$

have been shown to give quite accurate approximations to the true orbits in these potentials, see Struck (2006) and S. R. Valluri, et al. (2012), and thus, provide a useful basis for simple models.

E.g., analytic models of tidal tails as a function of various parameters, see Struck & Smith (2012).

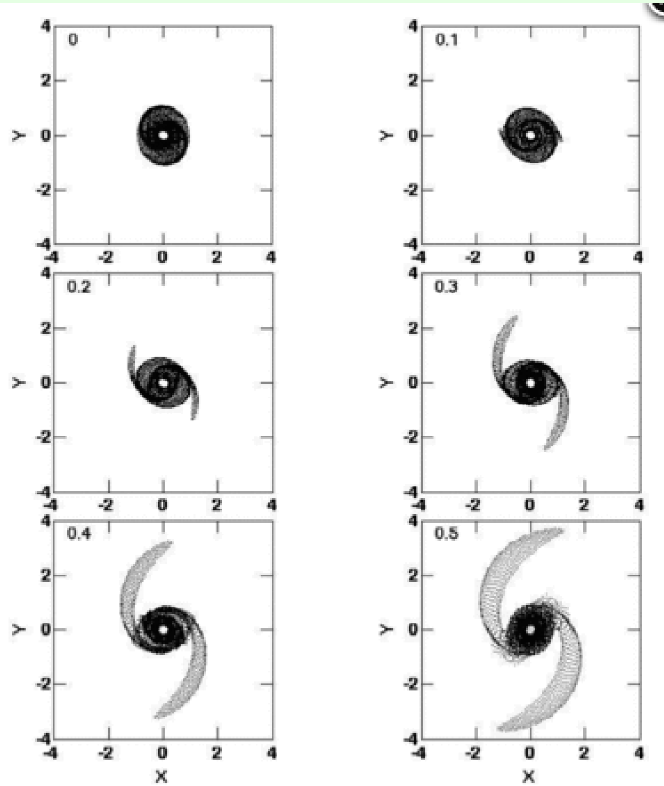


Figure 9. Analytic model discs formed from a tidal perturbation of amplitude A'= 0.35 (at q= 1.0). Each panel shows a model with a different value of the potential exponent δ, which is given in the upper left-hand corner. In all cases the model is shown at a time of 5.0 units.

[In compact groups] gas can be pulled out of galaxies (to slowly accrete later or be shocked to high temperatures) in even more dramatic ways. The poster child for this situation is Stephan's Quintet.

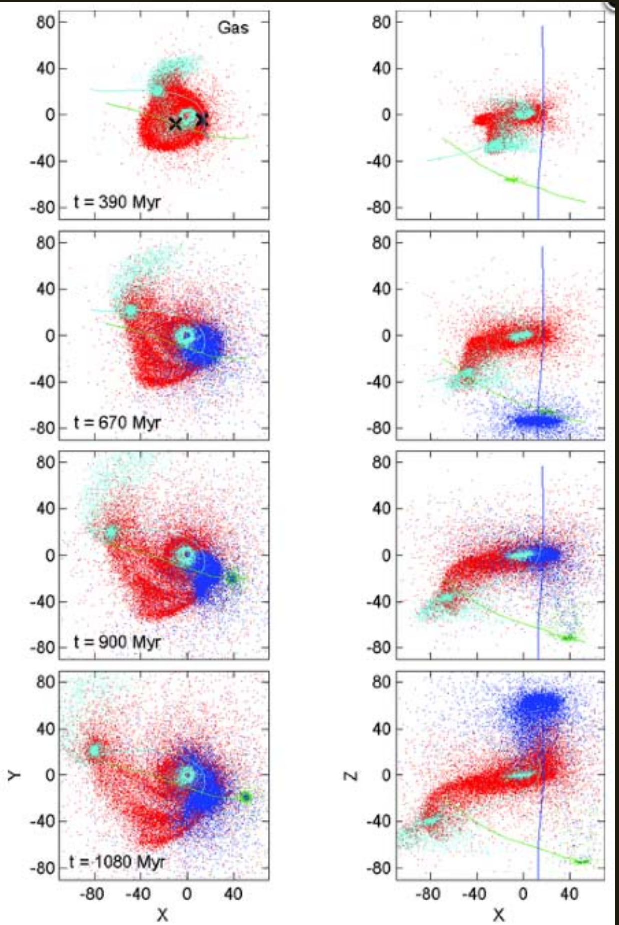


Figure 6. Four snapshots from the fiducial model of gas particles projected on to the x–y plane (left-hand column) and the x–z plane (right-hand column). These snapshots are

From J.-S. Hwang et al., 2012

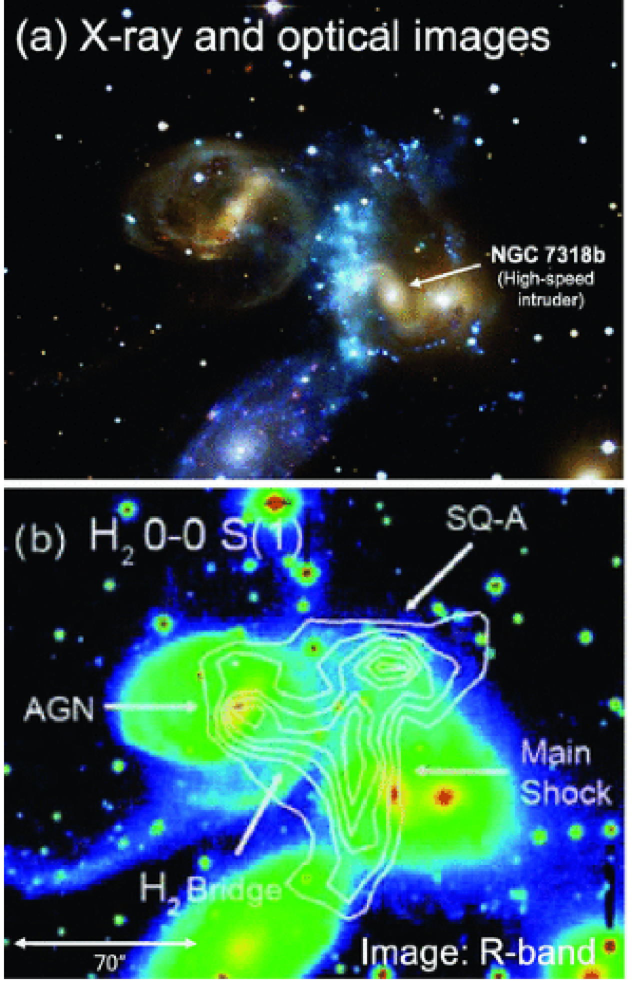


Figure 3. Central region of Stephan's Quintet seen in multiwavebands. (a) A *Chandra X-ray Observatory* image (cyan) is superimposed on an optical image from the Canada–France–Hawaii Telescope (CFHT). A large-scale shock feature appears as a curved, elongated X-ray ridge in the middle of the image. The shock-heated X-ray gas is thought to be generated by NGC 7318b colliding through the core of the group at high speed. [Credit: X-ray (NASA/CXC/CfA/E.O'Sullivan), optical (CFHT/Coelum)] (b) H_2 contours (white; adopted from Cluver et al. 2010) detected by using *Spitzer* are overlaid on an *R*-band image (from Xu, Sulentic & Tuffs 1999). The warm molecular gas shows a distribution similar to that of the hot X-ray-emitting plasma. (North is up and east to the left.) The group-wide shock elongated in the north–south direction ('main shock') and a second feature running eastwards ('H_2 bridge') are also seen in H_2 emission as in X-ray emission.

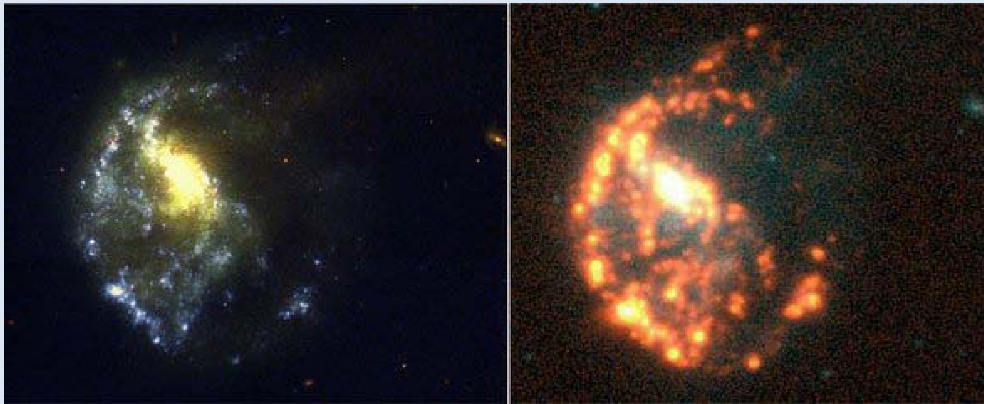
5. Bar formation/evolution - the classical driver of secular evolution.

Will note only one aspect of this aspect of this huge topic, i.e., recent work seems to indicate that tidal bar formation is difficult. E.g.,

- Casteels, et al. (2012) – sample of 148,291 “Galaxy Zoo 2” galaxies, found – “the likelihood of identifying a bar decreases significantly in pairs with separations < 30 h_{70}^{-1} kpc, suggesting that bars are suppressed by close interactions between galaxies of similar mass.”
- Lee, Park, Lee & Choi (2012) – sample of 33,391 SDSS, DR7 galaxies, found – “ f_{SB1} *decreases as the separation to the nearest neighbor galaxy becomes smaller than 0.1 times the* virial radius of the neighbor regardless of neighbor’s morphology. These results imply that strong bars are likely to be destroyed during strong tidal interactions…”

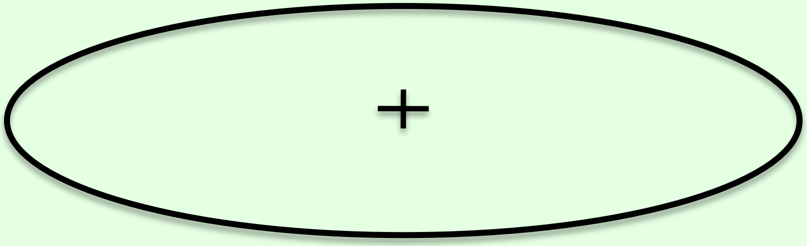
• These results contradict <u>expectations</u> from classic numerical models (e.g., Noguchi, Athanassoula, and others), but don’t necessarily contradict the results. The models did not generally show long-lived bars.

• The questions of whether, when and how long-lived tidal bars might form seems wide open right now. Also the questions of what effects a transient bar might have after it has disappeared?

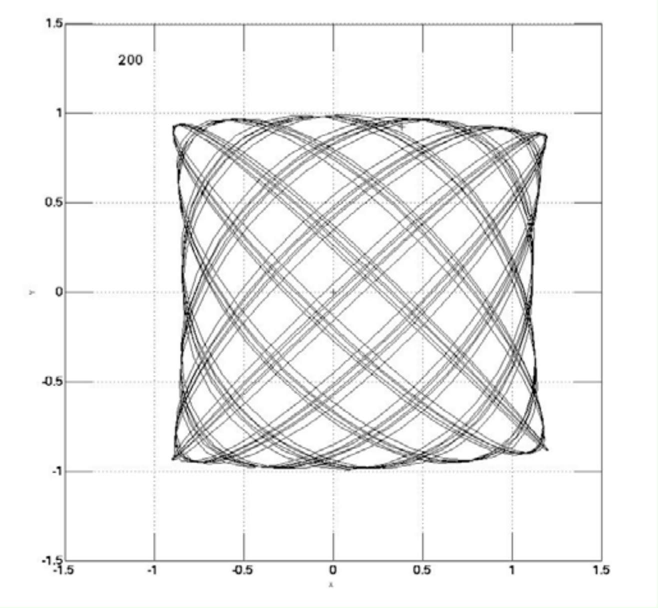


NGC 922, ring/bar, from Pellerin, et al. (2010)

As an illustrative example, a typical orbit in the rising rotation curve inner disk of an isolated galaxy might look something like this -



While with the addition of a modest tidal potential, e.g., in a companion flyby, the (numerically integrated) orbit becomes -



In both cases, the orbits are in the disk plane. In the case of the box orbit, note the offset from the center at (0,0).

Even if the companion, and its tidal potential disappear, the ensemble of stellar orbits left at random points on box orbits, will be very different than the initial ensemble.

6. Conclusions

• In addition to strong impulsive events, a number of slower, secular processes play a role in galaxy evolution. Those discussed above are only a sample.

• Galaxies have a strong tendency to settle into steady states described by simple scaling relations (“fundamental planes,” etc.).

• Disturbances enhance SF, but the frequency of strong impulsive events decreases rapidly with cosmological time.

→ At late times, a diverse range of secular processes are left to “fan the flames” of galaxy evolution.

Many of these deserve further study.

Some will may ultimately be incorporated in large-scale models (e.g., delayed stripping) others will not, but are still important in individual systems.

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