Observational signatures of secular evolution

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1 Introduction

The term 'secular evolution' becomes very popular for the last years as an alternative to the galactic evolution by discrete catastrophic events such as major mergers. What does it mean? It means *slow* smooth evolution, with the characteristic timescales of a few Gyrs. The great propagator of secular evolution of galaxies is John Kormendy, starting from his early studies of 70th. Now he has convinced the total community that the secular evolution is general, common, and not less important than fast collapses or merging. A lot of observational phenomena is now explained as consequences of secular evolution. Recently Kormendy & Kennicutt(2004) have reviewed a current state of this idea, with the numerous examples of the effects of secular evolution, and my goal here is to add some interesting facts/phenomena that have not received a proper attention yet.

What are mechanisms of secular evolution? Figure 1 represents a scheme for galaxy evolution mechanisms where all the known mechanisms are divided according to two characteristics: fast–slow and internal–external. The slow mechanisms ('slow' means those acting during many galaxy rotation periods) are the mechanisms of secular evolution; they may be internal or external. Internal mechanisms of secular evolution may be:

- bar instabilities in dynamically cold disk galaxies,
- deviations from circular rotation due to non-axisymmetric gravitation potential effect which may be produced by planar structures such as bars, lens, or spiral arms, or by triaxial ellipsoidal structures such as triaxial bulges and dark matter halos,
- complex, both gravitational and energetic, effects of nuclear supermassive black holes – they may provoke as attraction as well expansion,
- certain gas expansion by galactic winds and fountains, etc.

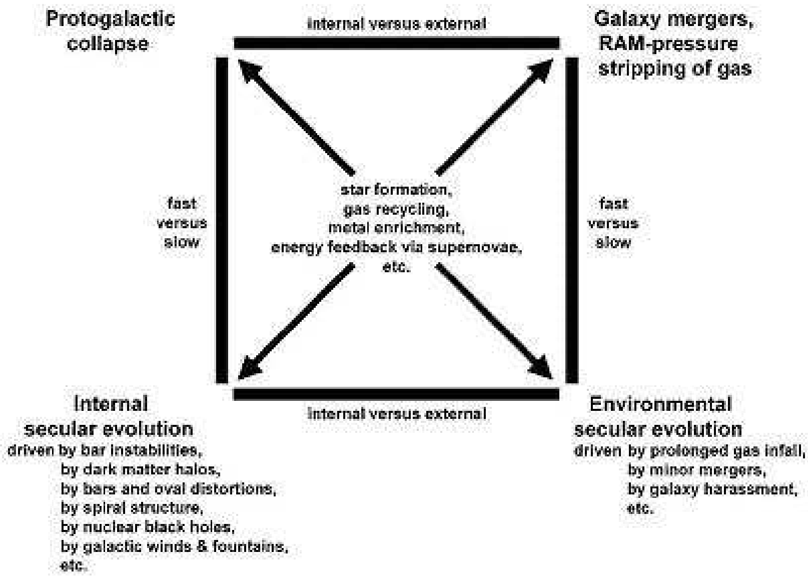

Figure 1: Classification scheme for evolution mechanisms of galaxies, originally from Zwicky (1957), adopted by Kormendy (1982a) and taken here from Kormendy & Kennicutt (2004)

External (environmental) mechanisms of secular evolution are:

- tidal effects from a neighboring galaxy,
- multiple minor mergers with satellites,
- gas accretion from the own gaseous halo or from gas-rich satellites, etc.

Historically, first attention for the effects of secular evolution was put by theoreticians dealing with bar investigations (e.g. Carnevali 1983, Weinberg & Tremaine 1983). But John Kormendy had early understood that bar-driven secular evolution might change the whole global structure of a galaxy. In his works, Kormendy (1979), Kormendy (1982b), Kormendy (1993), he introduced a term of 'pseudobulge' – large-scale spheroidal stellar component of a disk galaxy which had to be produced from the disk material by a bar-driven secular evolution. It takes more than twenty years for the community to estimate a global sense of the phenomenon of pseudobulges. Now a whole class of bulges – so called 'boxy/peanut bulges' which are especially spectacular when seen edge-on – are commonly recognized as a product of slow development of the bar vertical instabilities (Combes et al. 1990, Raha et al. 1991, Kuijken & Merrifield 1995, Bureau & Freeman 1999, Athanassoula 2005). Below let us discuss in detail a role of secular evolution in possible shaping of other types of bulges, a possible way to form different density profiles in the global stellar disks, and also a set of circumnuclear structures, mostly gaseous and stellar rings, which may originate from secular evolution.

2 Coupling between bulges and disks – consequence of secular evolution?

Now a point of view has dominated that bulges of disk galaxies have different types and different origins. Roughly, they are usually divided into 'classic' bulges which are thought to be similar to elliptical galaxies and 'pseudobulges' which are thought to be formed from disk material (e.g. Athanassoula 2005). Consequently, the formers are thought to form *before* disks and the latter – *after* the disk formation. Also there is a common opinion that the formers dominate in early-type disk galaxies and so are more massive and the latters – in late-type ones and are small.

Observational data which stimulates this division is mainly statistics of the surface brightness radial profiles. When the photometric model fitting began to use Sersic profiles $\mu \propto r^{1/n}$ with the power n as a free parameter, it became clear that there is an anticorrelation between the (numerical) morphological type of a disk galaxy and its bulge's n: in late-type spiral galaxies the bulges have exponential brightness profiles, $n = 1$, and in early-type spirals, Sa-Sb, the mean n is close to 2, with the most massive bulges demonstrating de Vaucouleurs' profiles with $n = 4$ (e.g. Andredakis et al. 1995, Graham 2001, Mollenhoff 2004). Exponential bulges can be obtained in simulations of secular evolution of stellar disks (e.g. Pfenniger & Friedli 1991), and the tight relation between the scalelengths of bulges and disks, $h_b/h_d = 0.13$, found by Courteau et al. (1996) helps the impression that they are genetically related. The magic similarity of the brightness profile shapes between ellipticals and massive bulges is in fact a less convincible prove of their similar formation mechanisms. In particular, massive bulges are known as fast rotators (Kormendy & Illingworth 1982), and their dynamical properties including high phase density in the centers cannot be easily explained in the frame of the formation by major mergers.

Recently several new photometric surveys have been published and statistically analysed, and the correlations found there, to my opinion, contradict the hypothesis of 'classical' bulges being formed before the disks. Aguerri et al. (2005) demonstrate an excellent correlation of disk exponential scalelengths and bulge effective radii for a sample of *lenticular*, so very early-type, galaxies. MacArthur et al. (2004) have found a tight correlation of bulge and disk integrated colours for *all* types of disk galaxies, from Sm to S0; it means that the properties of stellar populations, in particular, mean age, are also related. Bars are thought to be main drivers of pseudobulges growth in the centers of late-type spirals. But when Laurikainen et al. (2007) have divided their sample of disk galaxies into 'barred' and 'non-barred', the difference among statistics of n and bulge luminosity contributions has been revealed only for early-type disk galaxies, namely for S0-Sb, and no difference has been shown by late-type galaxies. Interestingly, the bulges in early-type *barred* galaxies are smaller and closer to exponential profiles than the bulges in non-barred galaxies. This fact may be treated as an evidence for recent morphological-type transformations toward earlier types of the galaxies possessing bars. And it is the brightest demonstration of secular evolution consequences.

If both types of the bulges, massive in early-type galaxies and small in late-type galaxies, are products of secular evolution, the difference in their brightness profiles and mean sizes can be the result of different contributions of various mechanisms of secular evolution into their shaping. Recent simulations by Eliche-Moral et al. (2006) have shown that multiple *minor* mergers re-form the bulges of disk galaxies in such a way that their Sersic parameter n can be increased from 1 to 2 and in some models even to 4. So if a galaxy is initially late-type one with a small exponential bulge, multiple minor mergers, which are one of the mechanisms of secular evolution, may affect it simultaneously in three directions: they heat and thicken the stellar disk making spiral arms weaker, they drop their stars into the center increasing the bulge mass, and they reform the bulge exponential brightness profile into a more steeper one. As a result, the late-type spiral galaxy may be transformed into an early-type spiral galaxy and even into a S0.

3 Two-tiers ('antitruncated') large-scale stellar disks

Secular evolution must shape global stellar disks of the galaxies too. An interesting problem is an origin of the typically exponential profiles of disk surface brightness that has been demonstrated by Freeman (1970). Modern cosmological models deducing birth of a galaxy from condensation of gas previously distributed homogeneously over a sphere onto a disk, suggest that the exponential gas surface density profile is an initial condition of stellar disk formation. But there are other ideas, e.g., those of Lin & Pringle (1987), that there exist some long-acting mechanisms (in fact, mechanisms of secular evolution) that produce exponential *stellar* disks from *gaseous* disks with arbitrary initial radial density profiles. It can be, for example, viscous gas radial redistribution with a characteristic timescale equal to the star formation timescale (Yoshii & Sommer-Larsen 1989, Slyz et al. 2002).

But recently the attention of the astronomical community has been attracted to another type of global stellar disks which are *certainly* the product of secular evolution: these are so called 'antitruncated' disks. These disks are two-tiers: they consist of two exponential segments with different scalelengths, and the scalelenth of an outer segment is larger than that of an inner segment. When photometric surveys become deep enough, it becomes clear that the 'antitruncated' disks represent a substantial fraction of all disk galaxies: according to Erwin et al. (2007), they are found in one-third of nearby barred galaxies and in two-third of nearby unbarred galaxies.

During our investigation of disk galaxies with chemically distinct nuclei and other interesting circumnuclear structures such as inner polar gas rings, we met two-tiers global stellar disks in the host galaxies more than once. Sometimes, the two-tiers disks found by us were earlier mis-classified as extended bulges; but by measuring stellar velocity dispersion profiles, we proved that the inner exponential subsystems are in fact dynamically cold, so they are true disks (in NGC 7217 – Sil'chenko & Afanasiev 2000, in NGC 615 – Sil'chenko et al. 2001). We argued that the chemically distinct nuclei and/or polar gas rings in the very centers of the galaxies may be related to their two-tiers large-scale stellar disks by a common origin. For example, tidal perturbation may provoke eventual gas radial inflow over the whole galactic disk; such event would provide fuel for the circumnuclear star formation burst resulting in a chemically distinct nucleus and simultaneously would change (diminish) the radial scalelength of the gaseous, and subsequently of a future stellar, disk. Recently, Younger et al. (2007) have simulated a minor merger which can also produce a two-tiers stellar disk. But this time the outer extended disk form from the material which *outflows* toward the larger radii during the minor merger. Perhaps, the mechanism of Younger et al. (2007) is good to form an outer disk with low surface brightness; such are a two-tiers disk in NGC 5533 among our galaxies with chemically distinct nuclei (Sil'chenko et al. 1998) and the most barred galaxies of Type III from the sample of Erwin et al. (2008). But the catastrophique gas inflow is more suitable to form the compact inner disks of high surface brightness such as those in our galaxies NGC 7217, NGC 615, and also NGC 7742 (Sil'chenko & Moiseev 2006), and in NGC 4699 from the sample of Erwin et al. (2008). An interesting example is NGC 7742 (Fig. 2): it is unbarred Sb galaxy with a nuclear star forming ring and a large-scale gaseous disk counterrotating with respect to the stars. The key feature is that spiral arms and all the star formation in the galaxy is concentrated in the inner high surface brightness disk. And the outer stellar disk extended beyond $R = 5$ kpc up to at least $R = 11$ kpc, being the quite normal large-scale stellar disk as concerning its central surface brightness, $\mu_{V,0} \approx 21$ mag per sq. arcsec, and exponential scalelength, $h = 2.3$ kpc, has very smooth appearance, without any spiral arms or HII-regions. In our paper (Sil'chenko & Moiseev 2006) we have concluded that NGC 7742 had experienced a minor merger; but this time the minor merger has evidently resulted in gas concentration in the inner part of the galaxy, and the two-tiers configuration of the large-scale stellar disk is forming with the intense star formation in the inner part of the galaxy just under our looks.

4 Circumnuclear rings

4.1 Stellar rings

One of the recognized manifestation of the secular evolution driven by the bar presence in a disk of a galaxy, a very spectacular one, is circumnuclear

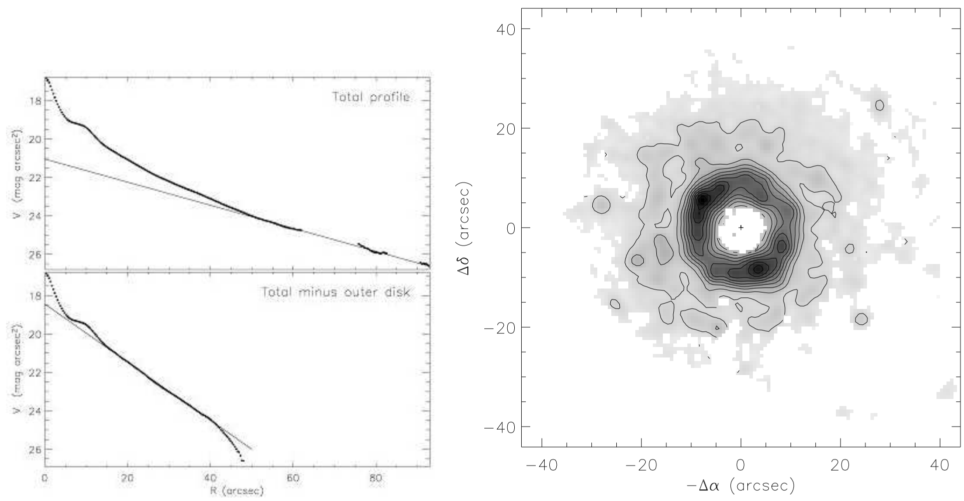

Figure 2: Comparison of the extensions of the stellar and gaseous disks in NGC 7742 (Sil'chenko & Moiseev 2006): *left* – the V-band surface brightness profile analysis of the stellar disk, *right* – 2D map of the Hα emission line intensity.

rings of star formation. Figure 3 presents a small collection of examples provided by the high-resolution imaging with the HST.

Circumnuclear star-forming rings are a well-established consequence of the bar Inner Lindblad resonance (ILR) in a large-scale gaseous disk (e.g. Buta & Crocker 1993), though there are known some cases of such rings in unbarred galaxies (for examples, NGC 7217 and NGC 7742 mentioned in the previous section). The gas which accretes onto the galactic center along the bar cannot penetrate through the area of chaotic orbits related to the ILR, because gas is a collisional dynamical system. So the gas accumulates at the ILR, and after its density becomes high enough, star formation starts. Observational estimates of the star formation effectiveness in the circumnuclear rings are quite impressive: according to Kormendy & Kennicutt (2004), it is 10% - 50% per 10^8 years, and so typical times of gas consumption by star formation in rings are less than 1 Gyr (compare to that in the large-scale disks with spiral arms, when the mean effectiveness of star formation is only 5% and timescales are a few Gyr). So the circumnuclear star forming rings may be very transient phenomenon – if external gas supply ceases due to some reasons and if the bars themselves are a transient phenomenon too.

During our investigation of the stellar population properties in the centers of lenticular galaxies we have found some structures which we think

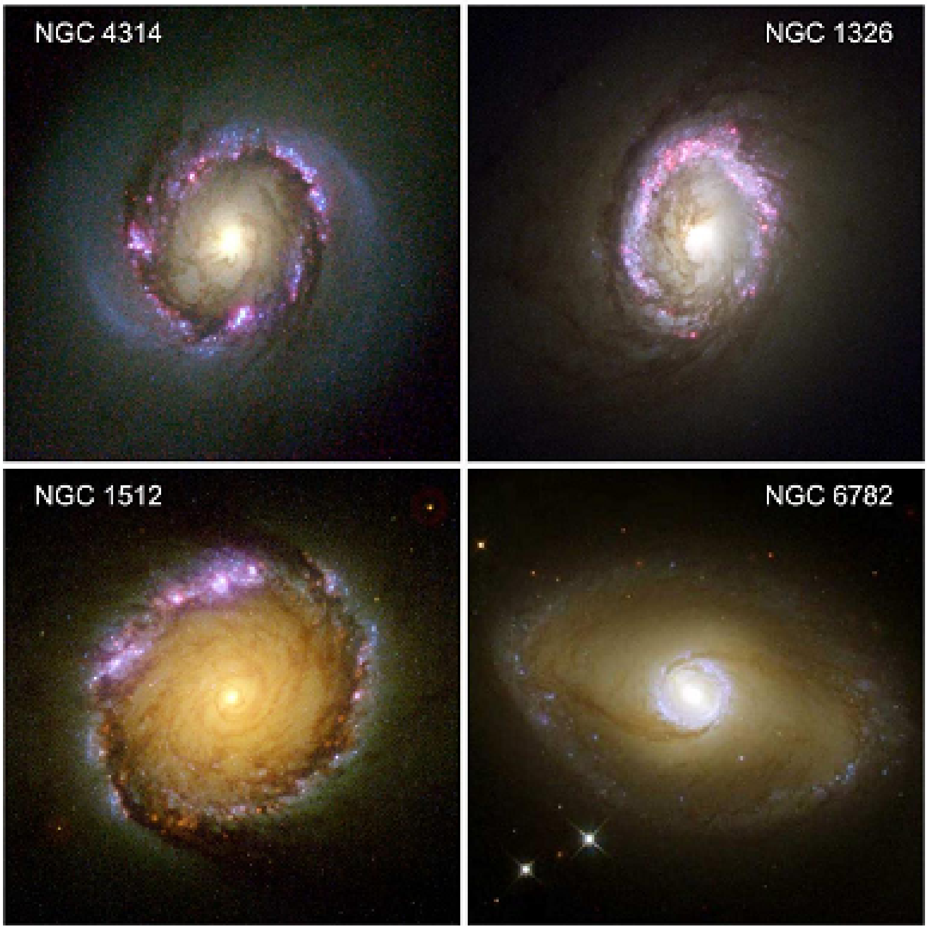

Figure 3: Examples of the circumnuclear starforming rings from the Hubble Space Telescope Heritage collection

to be relics of circumnuclear star forming rings. For example, in the giant lenticular galaxy NGC 80 which is located in the center of a massive galactic group and possesses a large exponential-profile 'pseudobulge' , we observe intermediate mean stellar age in the nucleus (6 Gyr) and in the ring at the radius of $5'' - 6''$ (5 Gyr); in between an old stellar population with the mean age of 10 Gyr is seen (Sil'chenko et al. 2003). The galaxy is projected face-on and looks perfectly axisymmetrical. Another interesting example is NGC 7013, S0/a galaxy with the outer spectacular elliptical ring of neutral hydrogen (Knapp et al. 1984). Here we may suspect a presence – not a bar, but an oval stellar lens. The center (except the nucleus) of this early-type galaxy is devoided of any form of gas – either cold neutral nor warm. Again, we observe rather young stellar nucleus, very old stellar population around the chemically distinct nucleus, and a ring of intermediate-aged stars at the radius of $6'' - 8''$ with the mean age of 3 Gyr (Sil'chenko & Afanasiev 2002). Lenticular galaxies may be the best place to search for the intermediate-aged relics of circumnuclear starforming rings because their origin by removing gas reservoirs of spiral galaxies a few Gyrs ago provides the necessary condition to stop star formation anywhere in a galaxy, including circumnuclear rings. From our 3D spectroscopic survey of 80 nearby lenticular galaxies (Sil'chenko 2008) we found 12 cases of circumnuclear intermediate-aged stellar rings. Interestingly, only one galaxy of these 12 demonstrates a noticeable bar, so the second necessary condition – bar dissolution - is perhaps also satisfied.

4.2 Gaseous inner polar rings

In this subsection I present a manifestation of the secular evolution of disk galaxies which is not discussed in detail and explained yet: inner polar gaseous rings. They must be discriminated from large-scale (outer) gas polar rings, such as is known in the famous Spindle-galaxy NGC 2685, which are well-understood as results of external accretion of the gas with initially orthogonal momentum. The inner polar rings, or disks, in non-interacting spiral galaxies, the first of which was found by us in NGC 2841 (Sil'chenko et al. 1997), are usually nested in the very centers of the galaxies with the large-scale gaseous disks co-planar and co-rotating to the large-scale stellar disks. Such are the cases of NGC 2841 (Rots 1980) and NGC 7217 (Buta et al. 1995), for example. Even *lenticular* galaxies where we have found inner polar rings (Sil'chenko & Afanasiev 2004) possess always massive extended neutral-hydrogen disks, and in those cases when we know their two-dimensional distribution and rotation the outer gas disks are far from being polar (e.g. NGC 2655 – Noordermeer et al. 2005, NGC 2787 – Shostak 1987). To explain the origin of a small central polar ring *inside* the normal large gaseous disk by external accretion, keeping in mind collisional dynamics of gas, we must force very fine tuning of the accreted satellite orbit: the accreted gas must fall into the very center of the recipient galaxy from its pole. Otherwise we must search for *internal* mechanism to put normally rotating gas onto polar orbits near the center of a galactic disk.

Interestingly, there was a single theoretical work where simulations have provided transition of a gas inflowing in a bar potential to inner polar orbits: the 3D simulations of a large-scale stellar-gaseous disk in an isolated galaxy by Friedli & Benz (1993). They obtained nice long-lived highly inclined central gaseous disks, if the initial gas of the large-scale disk *counterrotated* with respect to stars. So, to explain theoretically inner polar disks without external accretion, we need two additional conditions: a bar and globally counterrotating gas. When we begin to analyse our sample of galaxies with the inner polar disks, the picture is not so clear. For example, NGC 7742 (Sil'chenko & Moiseev 2006) has counterrotating large-scale gaseous disk, but has no bar. On the contrary, NGC 7217 (Sil'chenko & Afanasiev 2000) and NGC 2841 (Afanasiev & Sil'chenko 1999) have evidently triaxial (oval) inner component – bulge or lense, – but have no counterrotating gas. However, the latter galaxies have counterrotating *stellar* component, and if these stars drop their envelopes into ISM (they must do it!), we may have some weak but constant supply of counterrotating gas. Finally, we have now found a few fair examples of what we need: a bar plus gas counterrotation. Figure 4 present these examples: NGC 7280 (Sil'chenko 2005) and IC 1548 (Sil'chenko & Afanasiev 2008).

The study is supported by the grant of the Russian Foundation for Basic Research no. 07-02-00229a.

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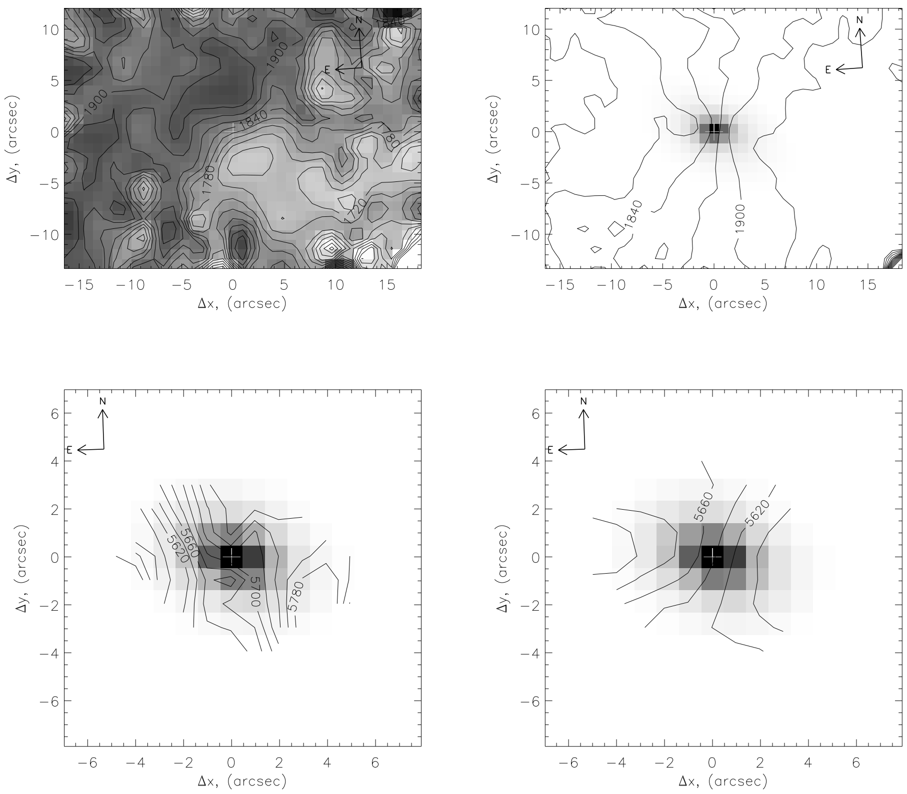

Figure 4: Examples of the inner polar rings inside counterrotating gaseous disks, with gas velocity fields to the left and stellar velocity fields to the right: *top* – NGC 7280, according to the SAURON data (Sil'chenko 2005), *bottom* – IC 1548, according to the MPFS data (Sil'chenko & Afanasiev 2008).

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