Secular evolution and the formation of pseudobulges in disk galaxies — Introduction of galaxy bars

John Kormendy & Robert C. Kennicutt, Jr.

Hong Hui
05.25.2023

Introduction

bulge: an elliptical living in the middle of a disk
classical bulge<— merger

pseudobulge<— secular evolution
characteristics: memory of disks
(1) flatter shapes
(2) large V/sigma
(3) small velocity dispersion with respect to the Faber-Jackson relation
(4)spiral structures (nuclear bars)
(5) nearly exponential brightness profiles
(6) starbursts

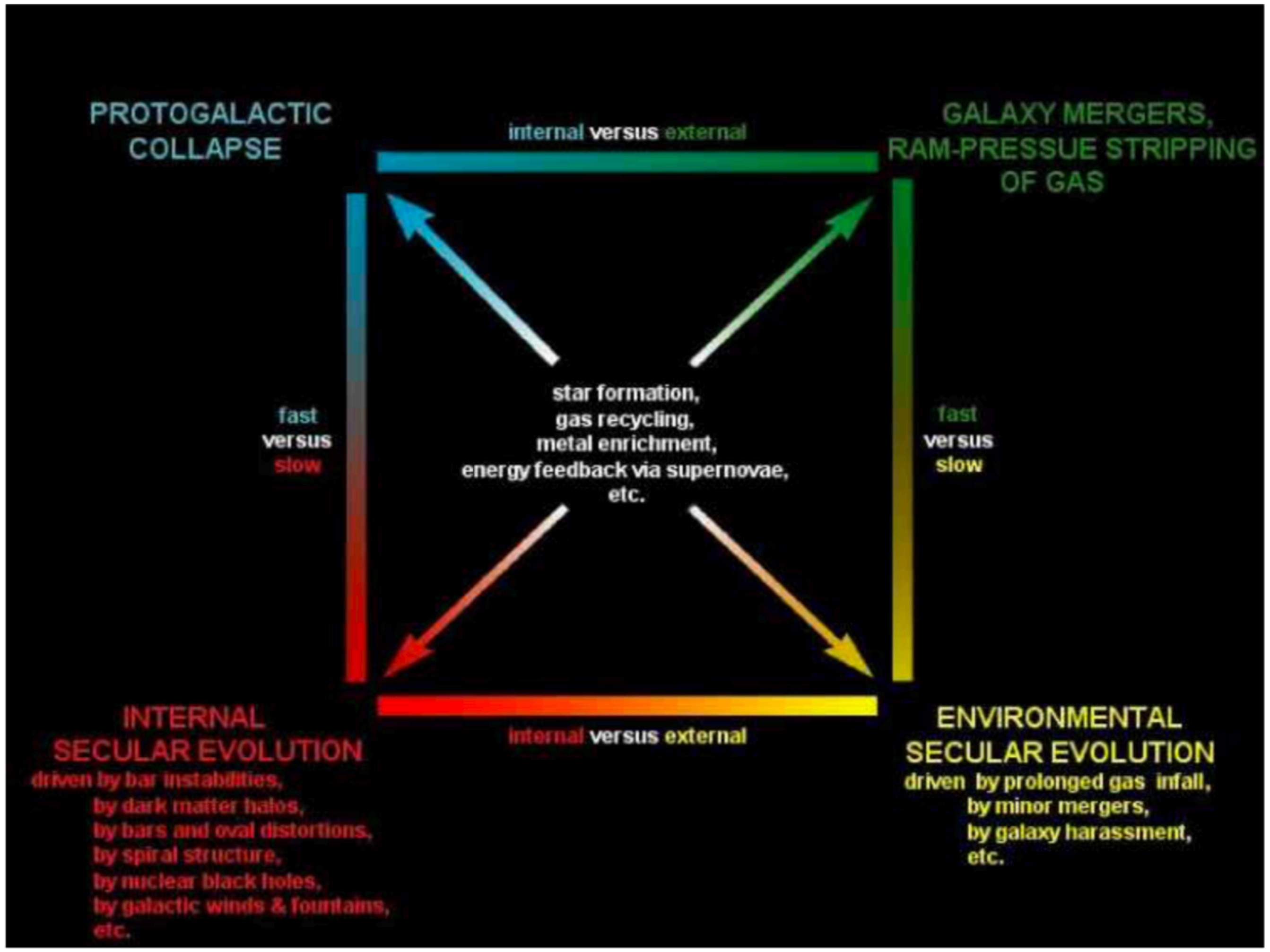


Figure 1 Morphological box (Zwicky 1957) of processes of galactic evolution updated from Kormendy (1982a). Processes are divided vertically into fast (top) and slow (bottom). Fast evolution happens on a free-fall ("dynamical") timescale, $t_{\rm dyn} \sim (G\rho)^{-1/2}$, where ρ is the density of the object produced and G is the gravitational constant. Slow means many galaxy rotation periods. Processes are divided horizontally into ones that happen purely internally in one galaxy (left) and ones that are driven by environmental effects such as galaxy interactions (right). The processes at center are aspects of all types of galaxy evolution. This paper is about the internal and slow processes at lower-left.

Morphology of barred galaxies

SB ring
SB spiral

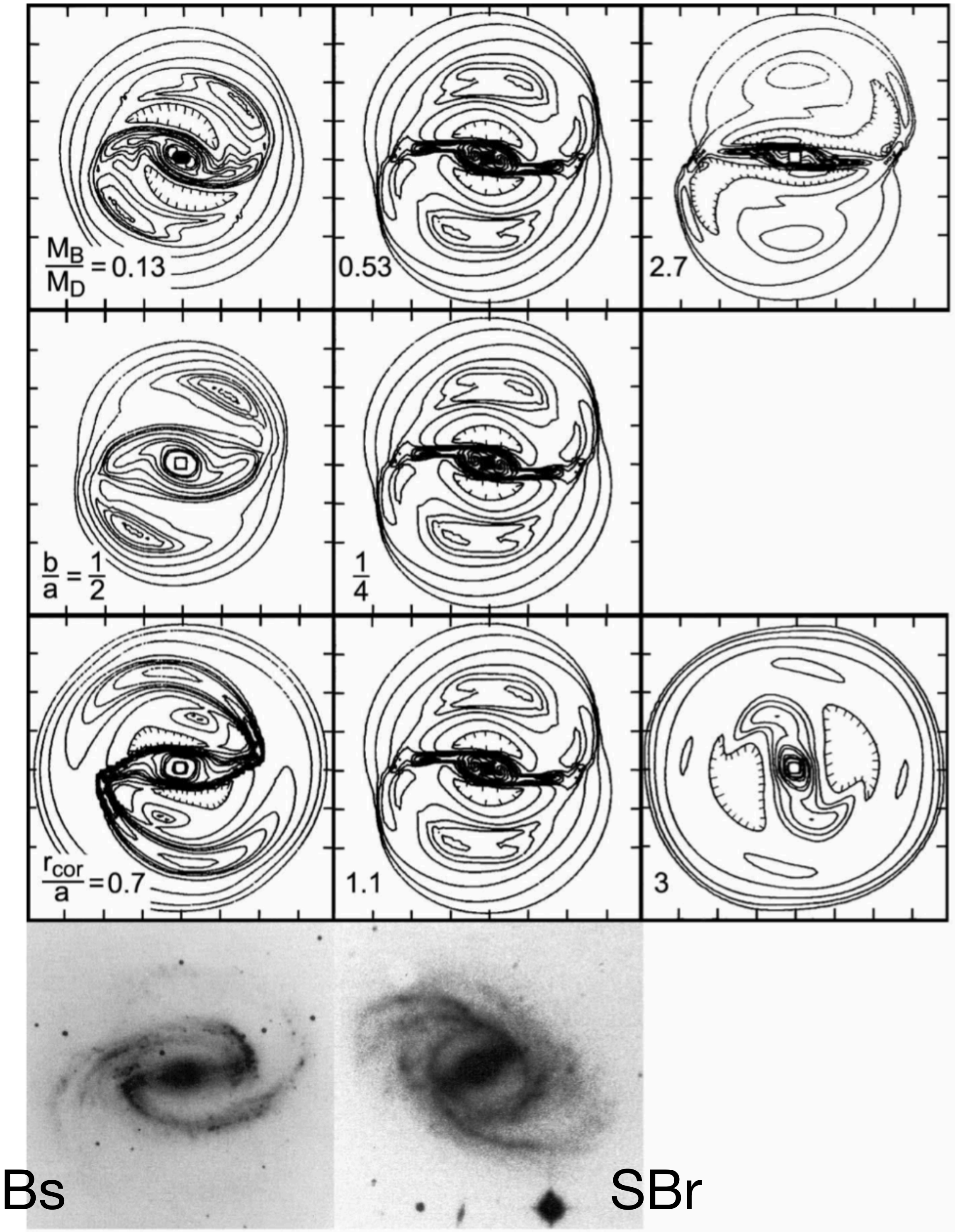


Figure 6 Contours of steady-state gas density in response to a ba
(adapted from Sanders & Tubbs 1980, who also show intermediate cases
The bar is horizontal and has a length equal to four axis tick marks. Th
top row explores the effect of varying the ratio M_B/M_D of bar mass to dis
mass. The second row varies the bar's axial ratio b/a. The third row varie
the bar pattern speed, parametrized by the ratio $r_{\rm cor}/a$ of the corotatio
radius to the disk scale length. The middle column is the same standar
model in each row; it approximates an SB(r) galaxy such as NGC 2523
(bottom center). The left panels resemble SB(s) galaxies such as NGC
1300 (bottom left). The right panels carry the parameter sequences to
unrealistic extremes; they do not resemble real galaxies.

SBr

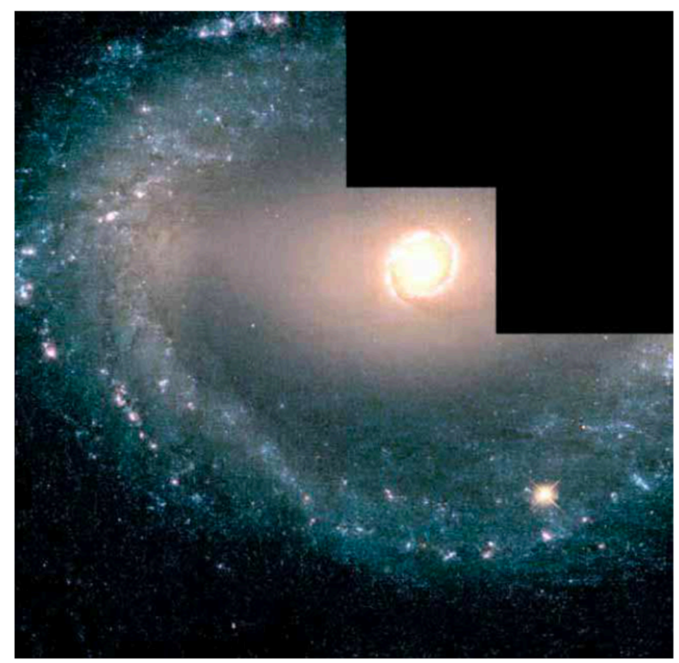


Figure 3 NGC 1512, an SB(r)ab galaxy imaged with HST by Maoz et al. (2001). This figure (courtesy NASA and ESA) illustrates the stellar population of inner rings. As is common in intermediate-Hubble-type galaxies, the bar in NGC 1512 is made of old, red stars and the disk is made of young, blue stars. The point of this figure is that the inner ring has the same stellar population as the disk, not the bar. Also seen at center is a nuclear star formation ring that is shown at higher magnification in Figure 8 and the start of a well developed, curved dust lane (cf. Figures 6 – 8) that extends out of the field of view to the right. The corresponding dust lane on the other side is visible near the central ring but not at larger radii. The outer parts of NGC 1512 are illustrated by Sandage & Bedke (1994), who note that NGC 1512 is morphologically normal except for some distortion of its outer spiral structure (not shown here) by a tidal encounter with neighboring NGC 1510.

SBs

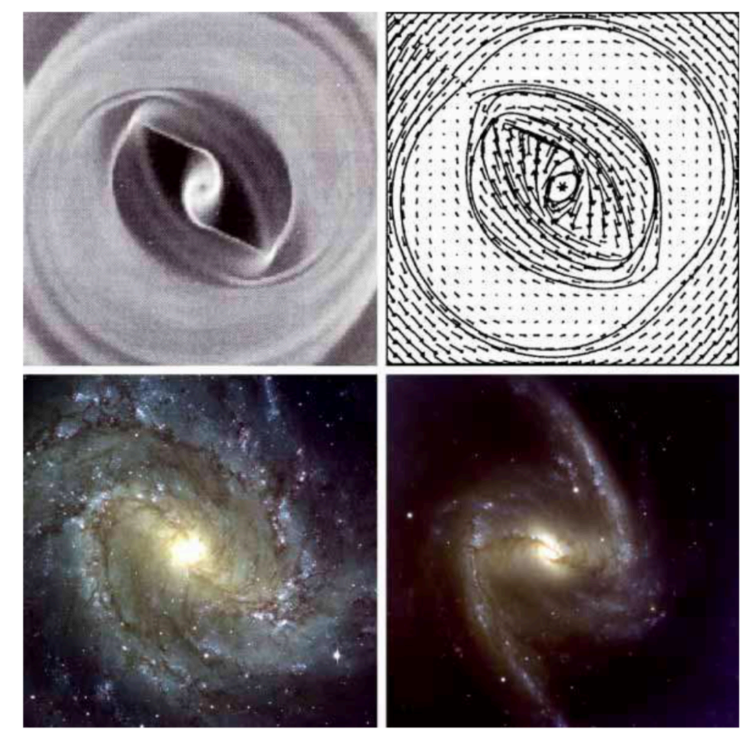


Figure 7 Comparison of the gas response to a bar (Athanassoula 1992b model 001) with NGC 5236 (left) and NGC 1365 (right). The galaxy images were taked with the VLT and are reproduced courtesy of ESO. In the models, the bar potential is oriented at 45° to the horizontal, parallel to the bar in NGC 5236. The bar axial ratio is 0.4 and its length is approximately half of the box diagonal. The top-right panel shows the velocity field; arrow lengths are proportional to flow velocities. Discontinuities in gas velocity indicate the presence of shocks; these are where the gas density is high in the density map at top-left. High gas densities are identified with dust lanes in the galaxies. The model correctly reproduces the observations (1) that dust lanes are offset in the forward (rotation) direction from the ridge line of the bar; (2) that they are offset by larger amounts nearer the center, and (3) that very near the center, they curve and become nearly azimuthal. As emphasized by the velocity field, the shocks in the model and the dust lanes in the galaxy are signs that the gas loses energy. Therefore it must fall toward the center. In fact, both galaxies have high gas densities and active star formation in their bright centers (e.g., Crosthwaite et al. 2002; Curran et al. 2001a, b).

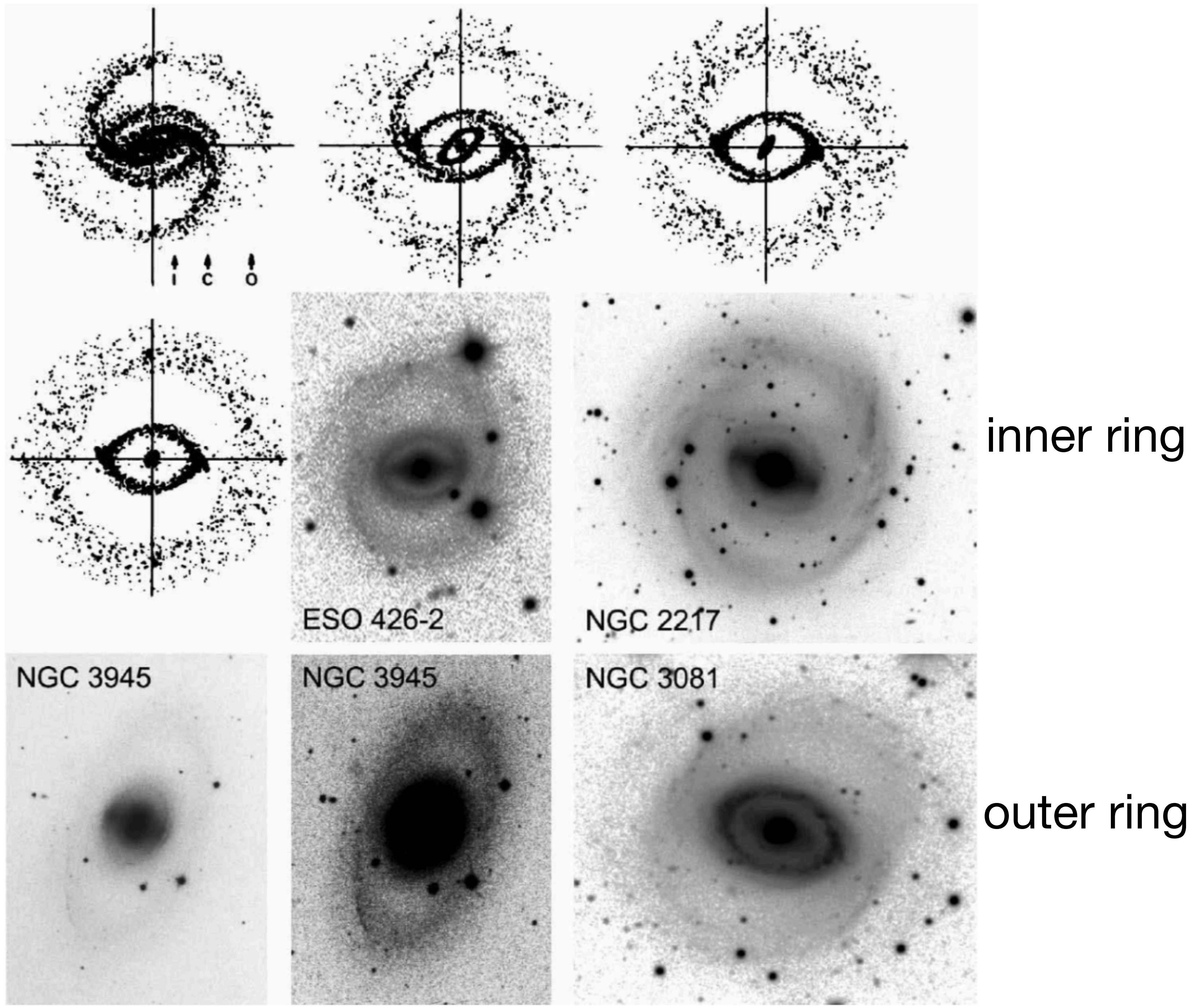


Figure 5 Evolution of gas in a rotating oval potential (Simkin, Su, & Schwarz 1980; see also Schwarz 1981, 1984). The gas particles in this sticky-particle n-body model are shown after 2, 3, 5, and 7 bar rotations (top-left through center-left). Arrows show the radii of ILR, corotation, and OLR. Four SB0 or SB0/a galaxies are shown that have outer rings and a lens (NGC 3945) or an inner ring (obvious in ESO 426-2 and in NGC 3081 but poorly developed in NGC 2217). Sources: NGC 3945 – Kormendy (1979b); NGC 2217, NGC 3081 – Buta et al. (2003); ESO 426-2 – Buta & Crocker (1991).

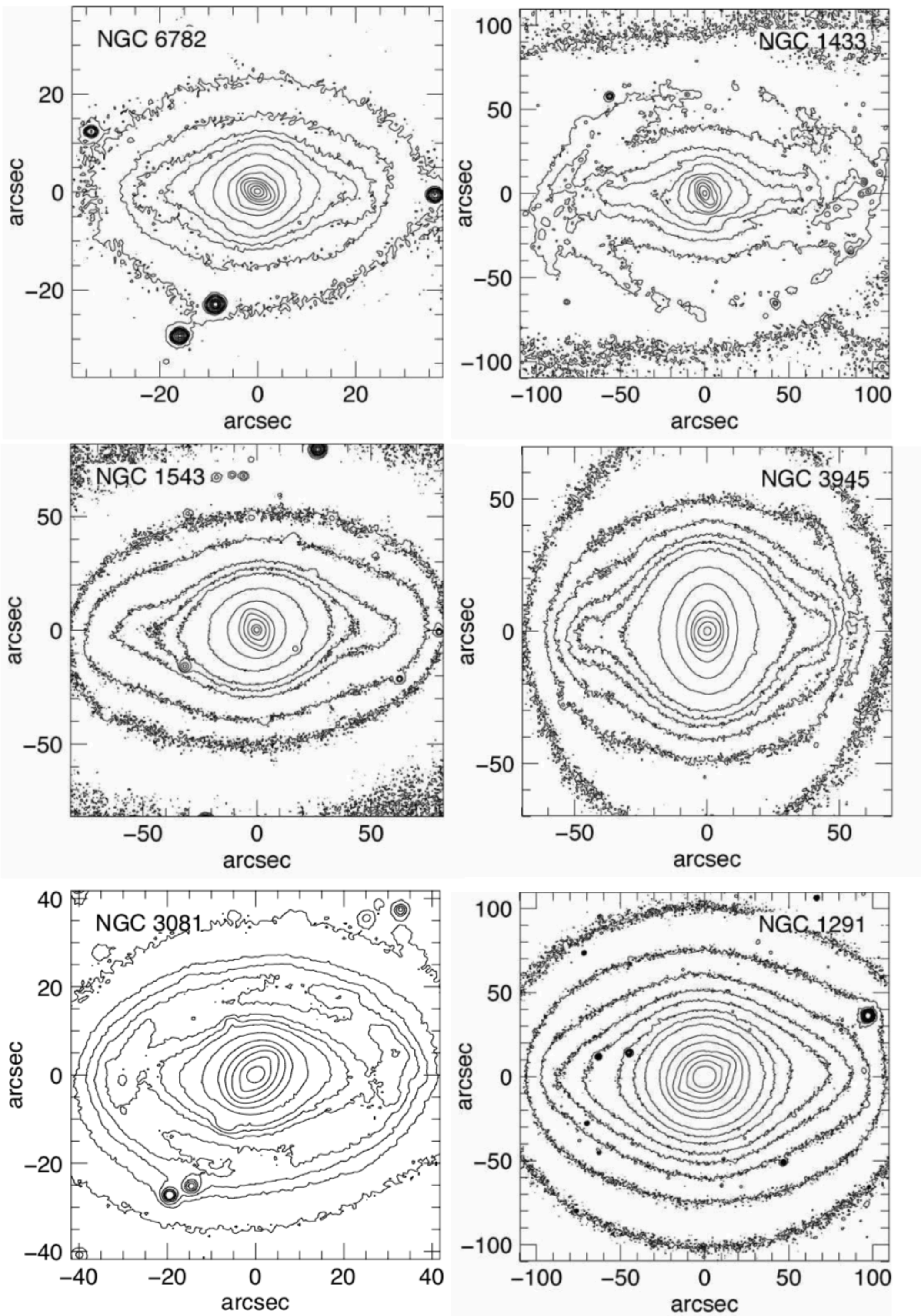


Figure 14 Bars within bars. Each galaxy image is rotated so that the main bar is horizontal. Contour levels are close together at large radii and widely spaced in the nuclear bars. NGC 3081 and NGC 1433 have inner rings. NGC 1291 is also shown in Figure 2, NGC 3081 and NGC 3945 in Figure 5, and NGC 6782 in Figure 8. The images are courtesy Ron Buta.

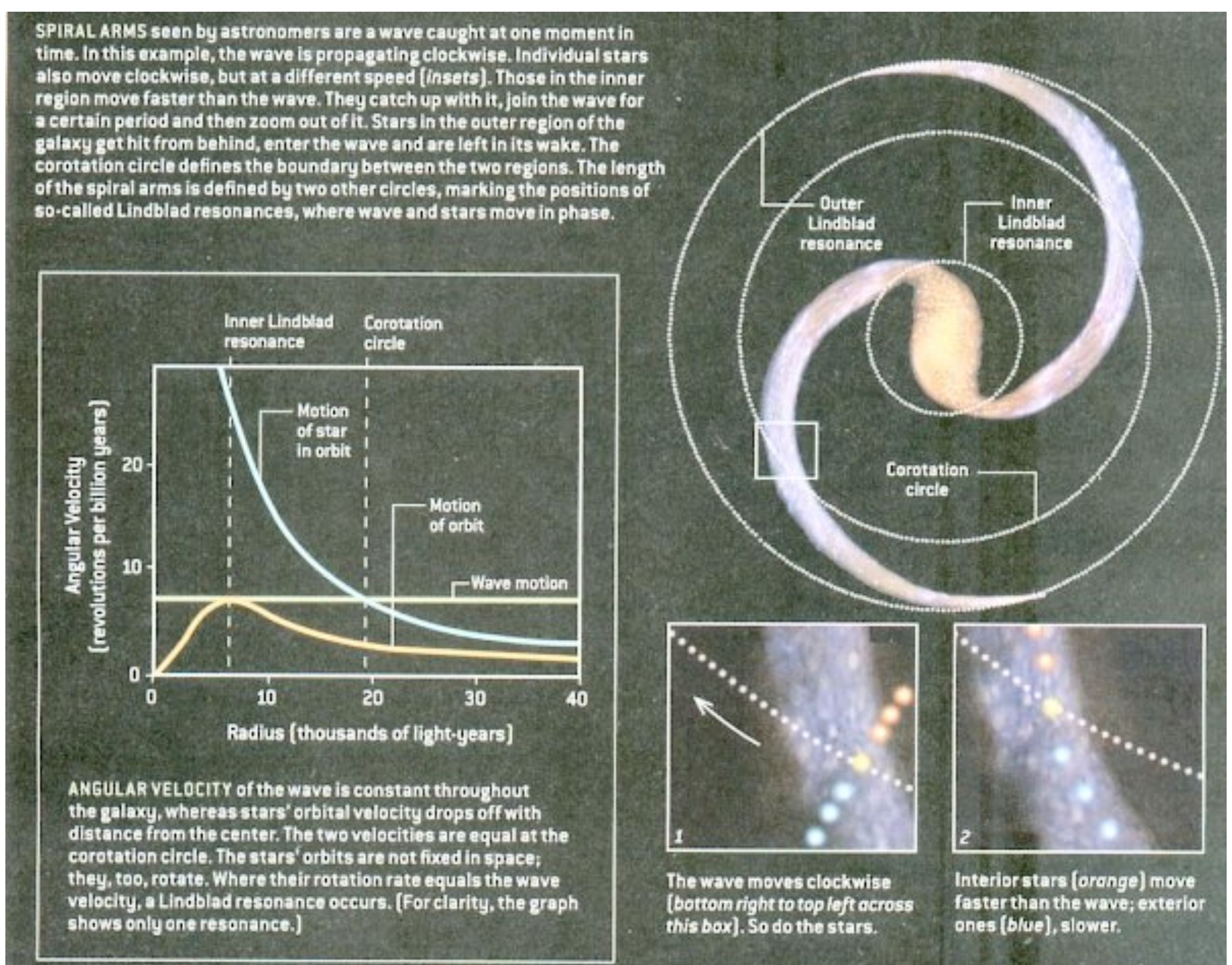
bulge + bar

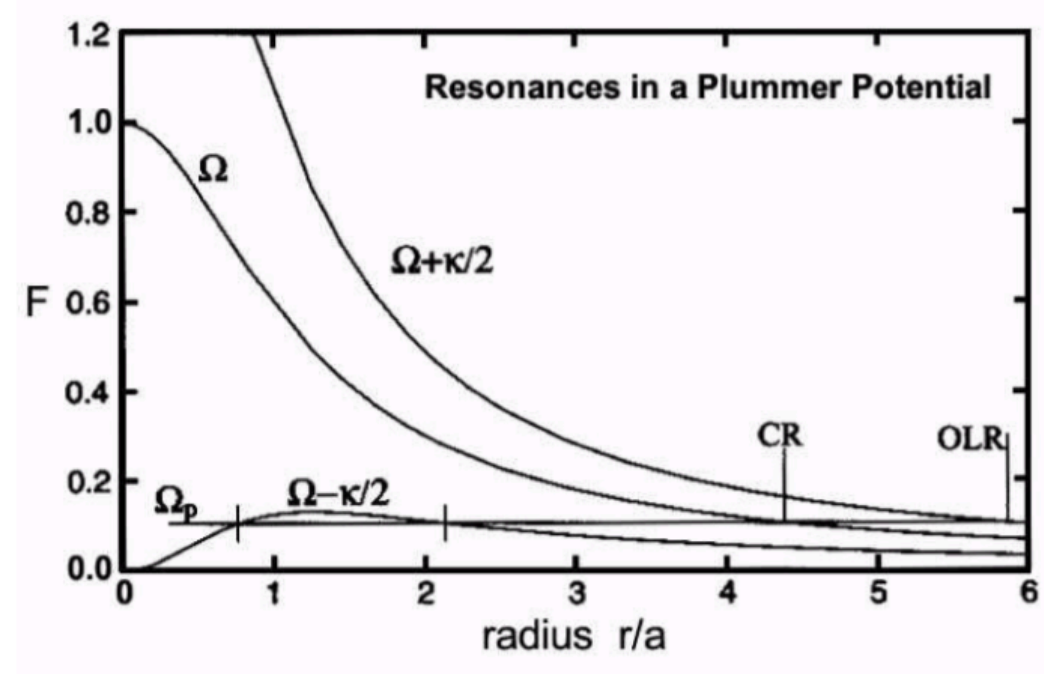
Dynamics of barred galaxies:

average velocity of stars: Ω
pattern velocity of bar: Ω_p
frequency of radial oscillation: κ

$\Omega_\mathrm{p} = \Omega$: corotation (CR)
$\Omega_\mathrm{p} = \Omega - \kappa/2$: inner Lindblad resonance (ILR)
$\Omega_\mathrm{p} = \Omega + \kappa/2$: outer Lindblad resonance (OLR)

increase gas density and hence star formation





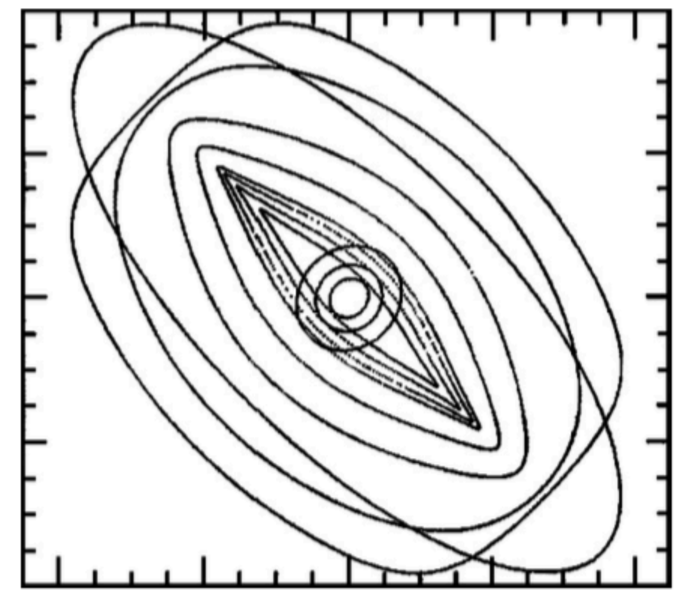


Figure 4 (Top) Frequencies $\Omega(r) = V(r)/r$ and $\Omega \pm \kappa/2$, where $\kappa^2 = (2V/r)(V/r + dV/dr)$ is the epicyclic frequency of radial oscillations for almost circular orbits. This figure (Sparke & Gallagher 2000) is for a Plummer potential, but the behavior is generic. For a pattern speed Ω_p, the most important resonances occur where $\Omega_p = \Omega$ (corotation), where $\Omega_p = \Omega + \kappa/2$ (outer Lindblad resonance OLR) and where $\Omega_p = \Omega - \kappa/2$ (two inner Lindblad resonances ILR, marked with vertical dashes). (Bottom) From Englmaier & Gerhard (1997), examples of the principal orbit families for a bar oriented at 45° as in Figure 7. The elongated orbits parallel to the bar are the x_1 family out of which the bar is constructed. Interior to ILR (or outer ILR, if there are two LRs), the x_2 family is perpendicular to the bar. Near corotation is the 4:1 ultraharmonic resonance; the almost-square orbit makes 4 radial oscillations during each circuit around the center. Since the principal orbits change orientation by 90° at each resonance shown, they must cross near the resonances.

Bar-driven radial transport of gas:

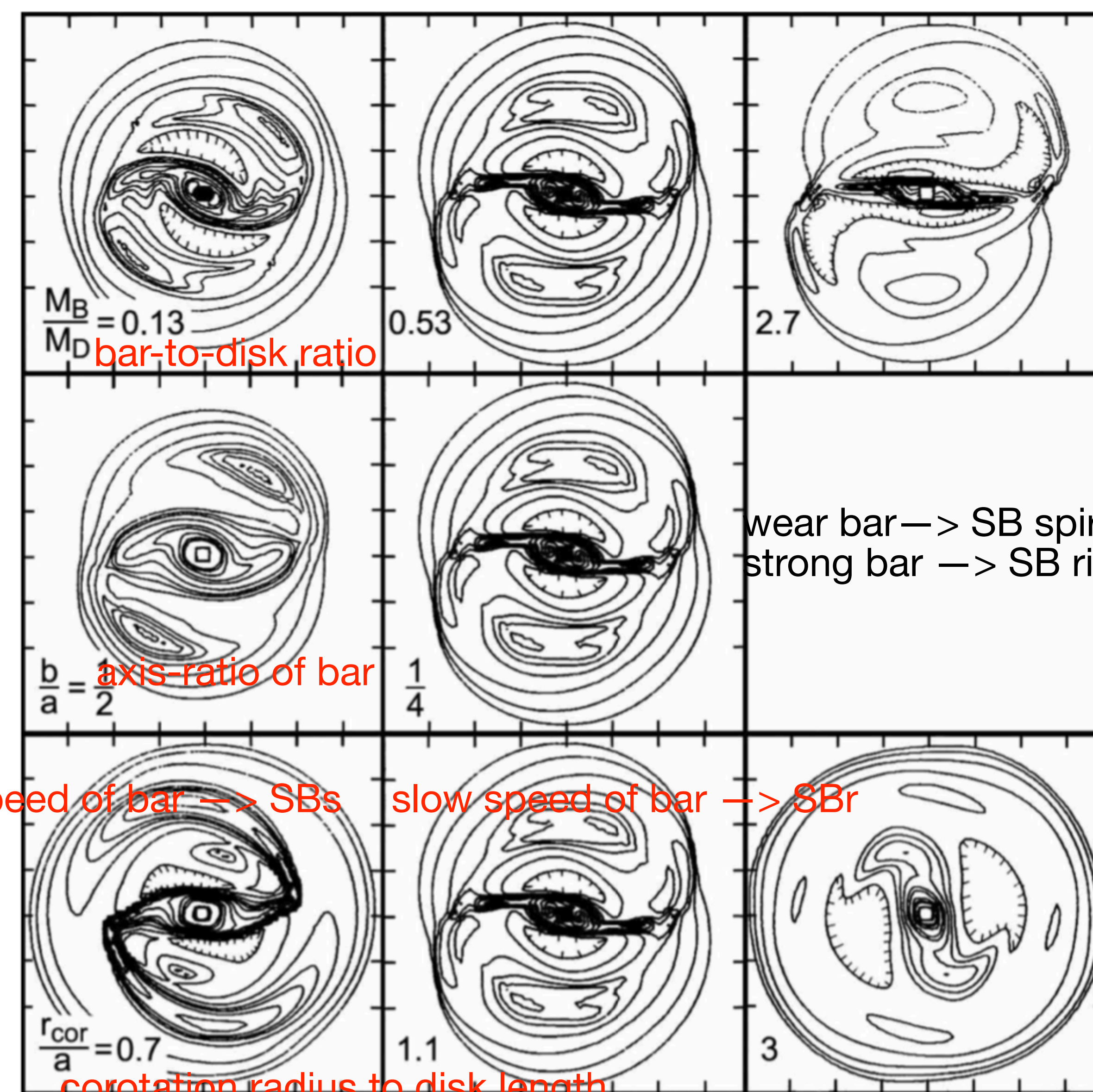
bar transfers angular momentum to the outer disk —> drive spiral structure —> bar gets more elongated, grows, the pattern slow down

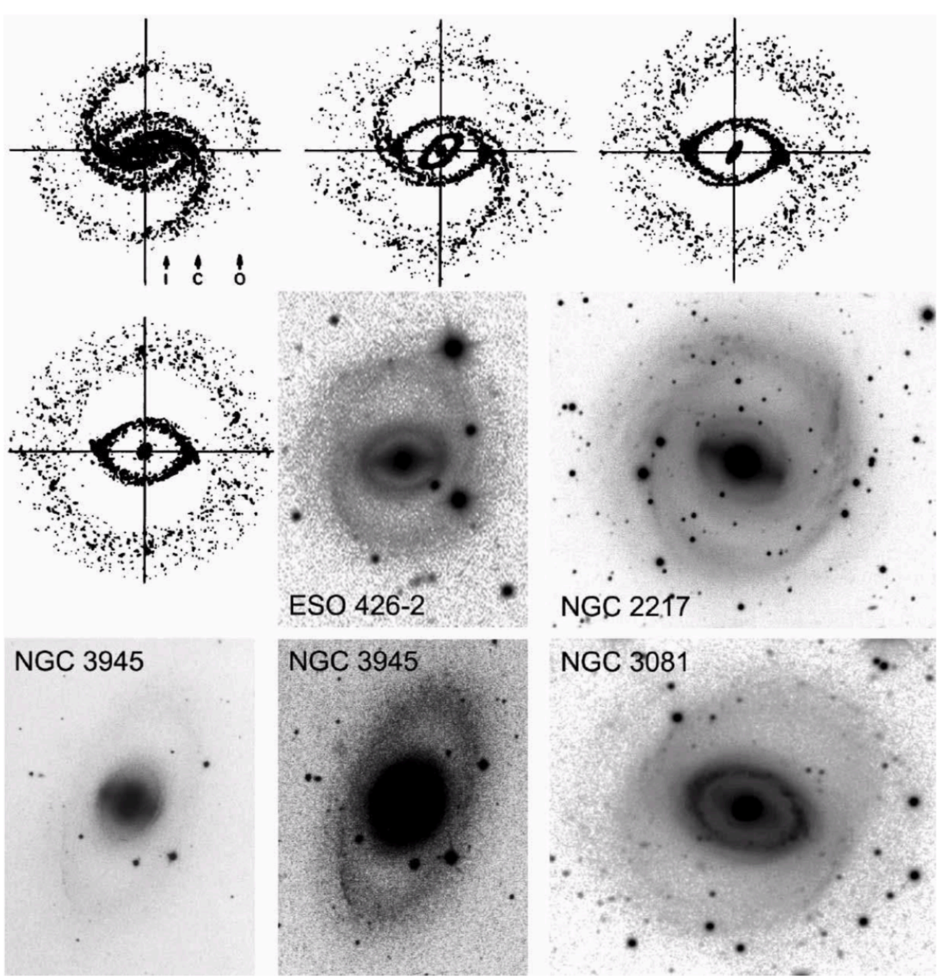
SBr
Outside corotation: gas collects into a outer ring near OLR
Inside corotation: gas falls toward the center —> pseudobulges
Around corotation: inner ring

SBs: dust lane, gas inflow

SBr galaxies are more mature than SBs galaxies

—>bar strength increase





Secular evolution of unbarred galaxies

1/3 disk galaxies look barred at optical wavelengths

many unbarred (optical) galaxies show bars in the infrared (2/3 galaxies look barred in IR)

Oval galaxies:
- less elongated than bars, nonaxisymmetric, evolve similarly as barred galaxies
- two ovals, different axial ratios and position angles, sometimes warped disks
- SAB or SA

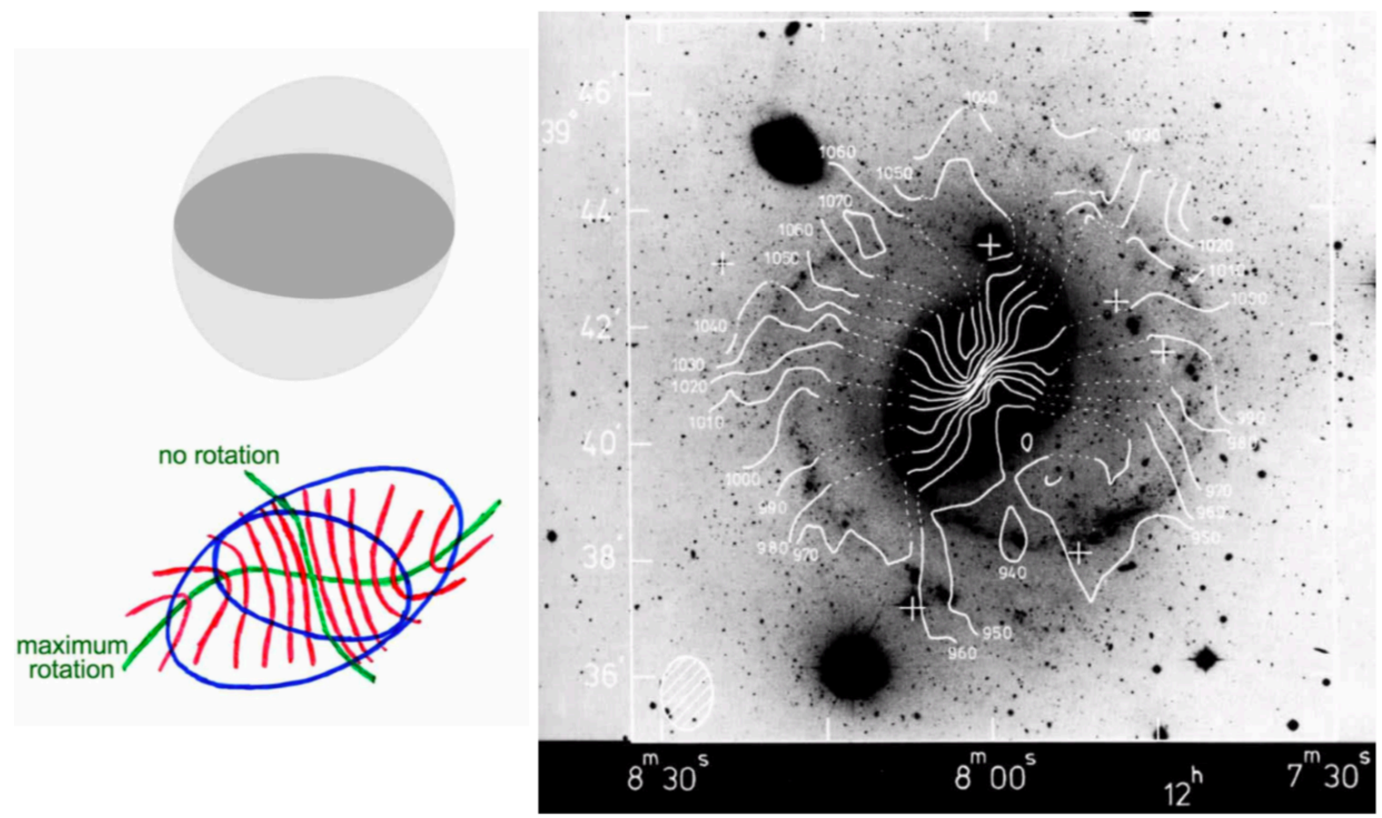


Figure 9 Criteria for recognizing strongly oval but unbarred galaxies shown schematically at left and with observations of NGC 4151 at right. This figure is adapted from Kormendy (1982a). The NGC 4151 H I velocity field is from Bosma, Ekers, & Lequeux (1977a).

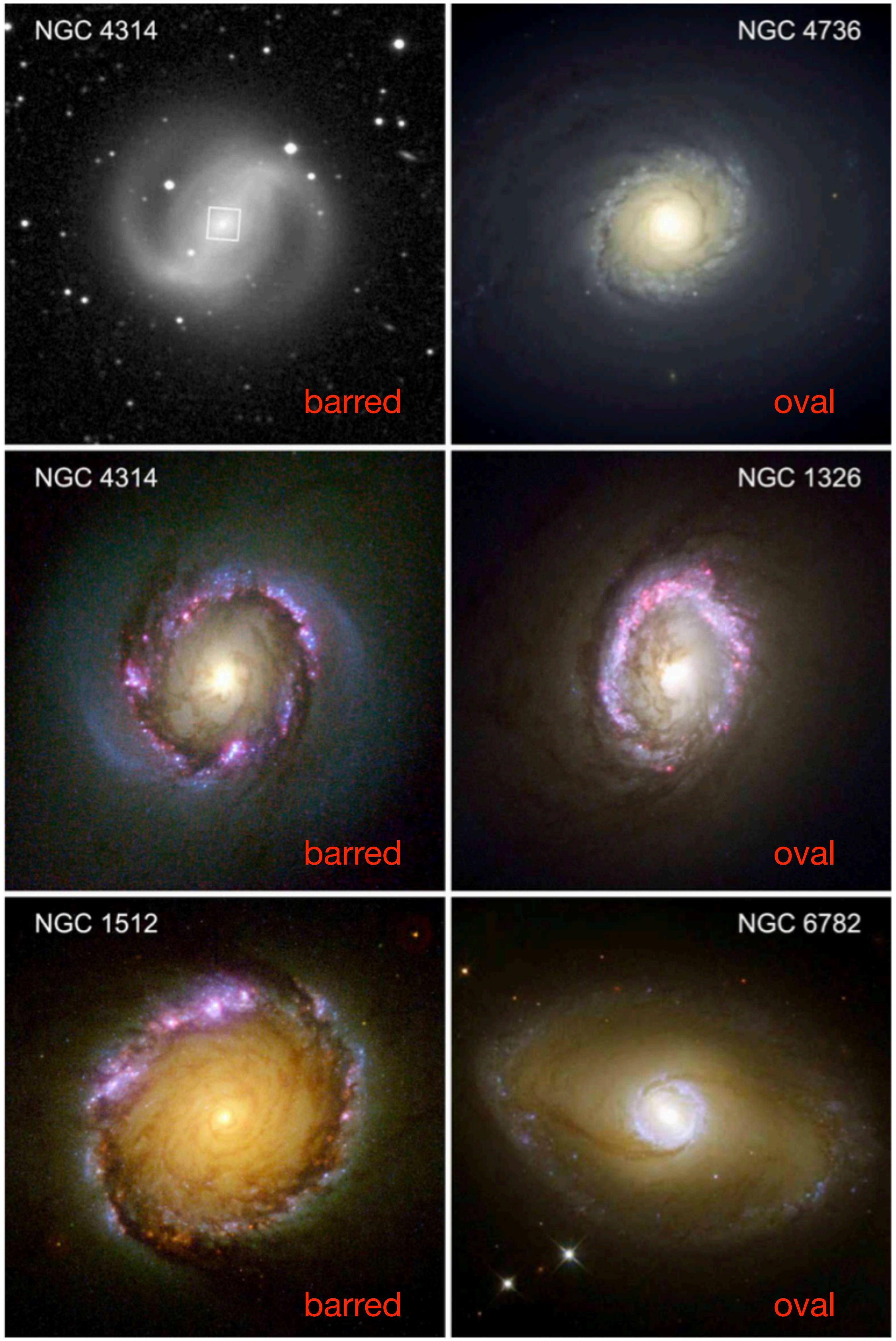


Figure 8 Nuclear star formation rings in barred and oval galaxies. For NGC 4314, a wide-field view is at top-left; for NGC 4736, the wide-field view is in Figure 2. Sources: NGC 4314 – Benedict et al. (2002); NGC 4736 – NOAO; NGC 1326 – Buta et al. (2000) and Zolt Levay (STScI); NGC 1512 – Maoz et al. (2001); NGC 6782 – Windhorst et al. (2002) and the Hubble Heritage Program.

infalling gas to center —> enhanced
star formation concentrate in rings ~0.5 kpc

barred and oval galaxies evolve similarly

The death of bars

bars die as gas inward and build up a large concentration

ILR radius increases ($\Omega - \kappa/2$ increases, $\Omega_{\rm p}$ decreases as bar slow down)

a dead bar looks like a lens component

galaxies without bars, bar-driven secular evolution may have happened in the past