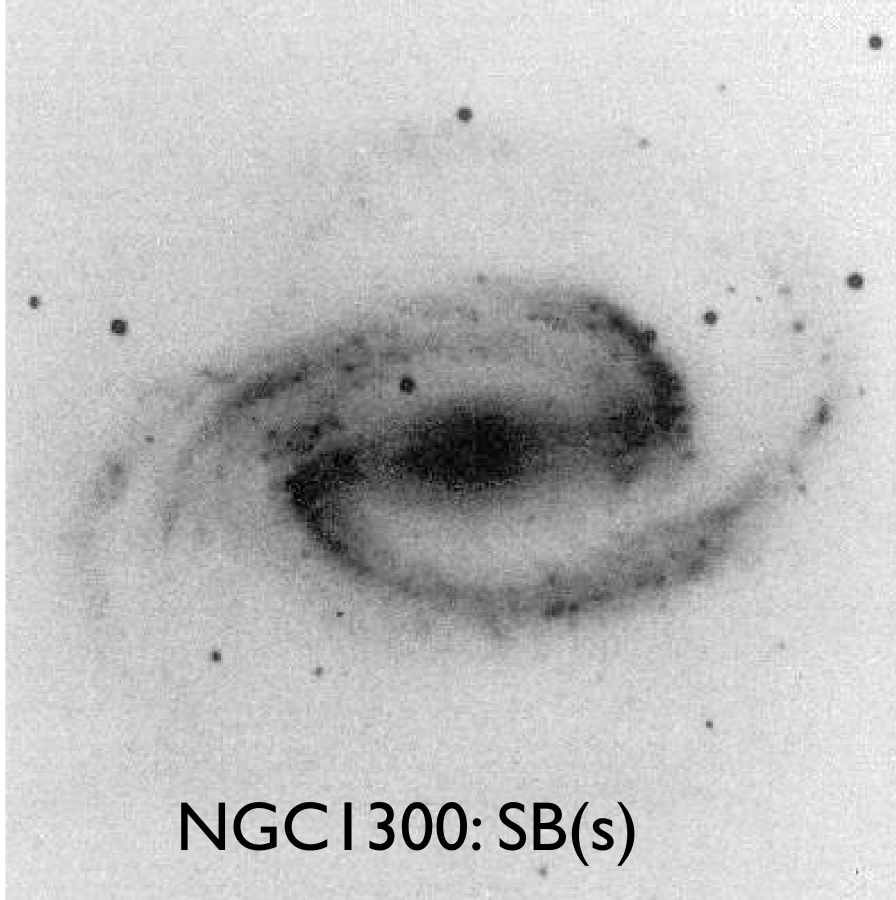
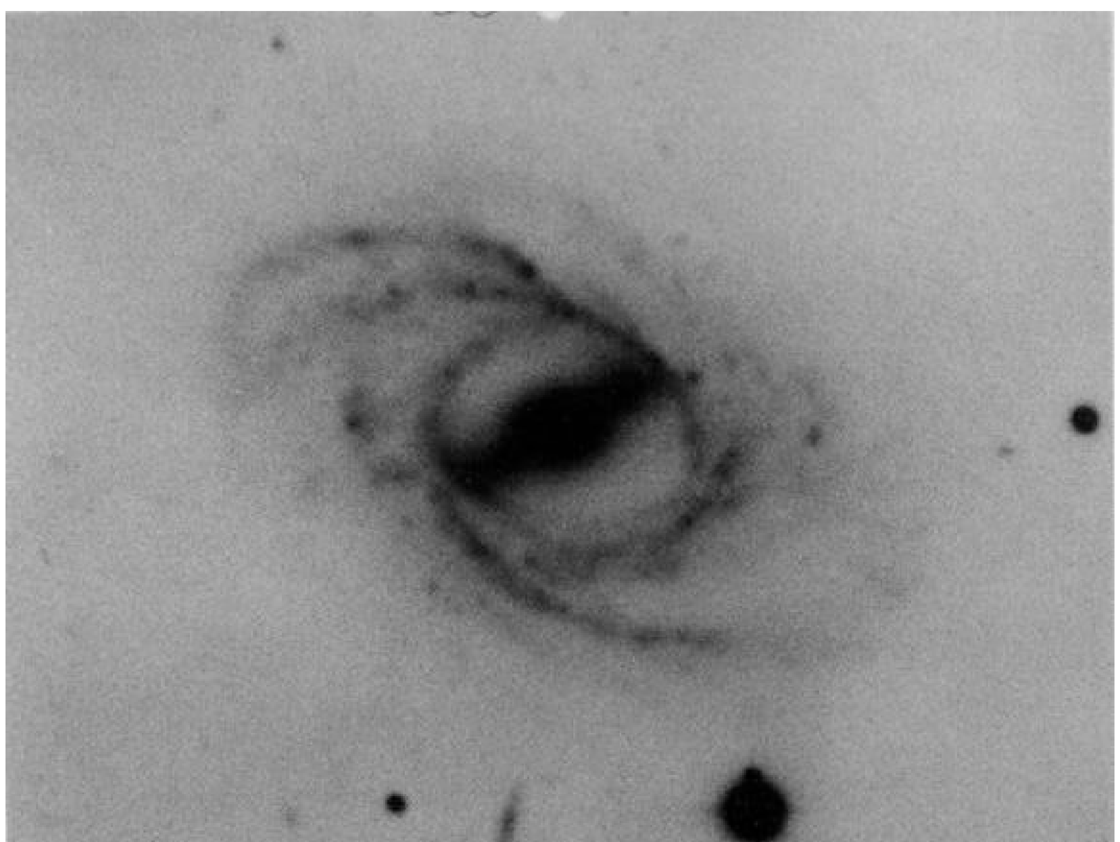
Barred Galaxies

Morphology
Gas in barred galaxies
Dynamics: pattern speed
Theory: secular evolution, resonances



NGC1300: SB(s)

fig.6



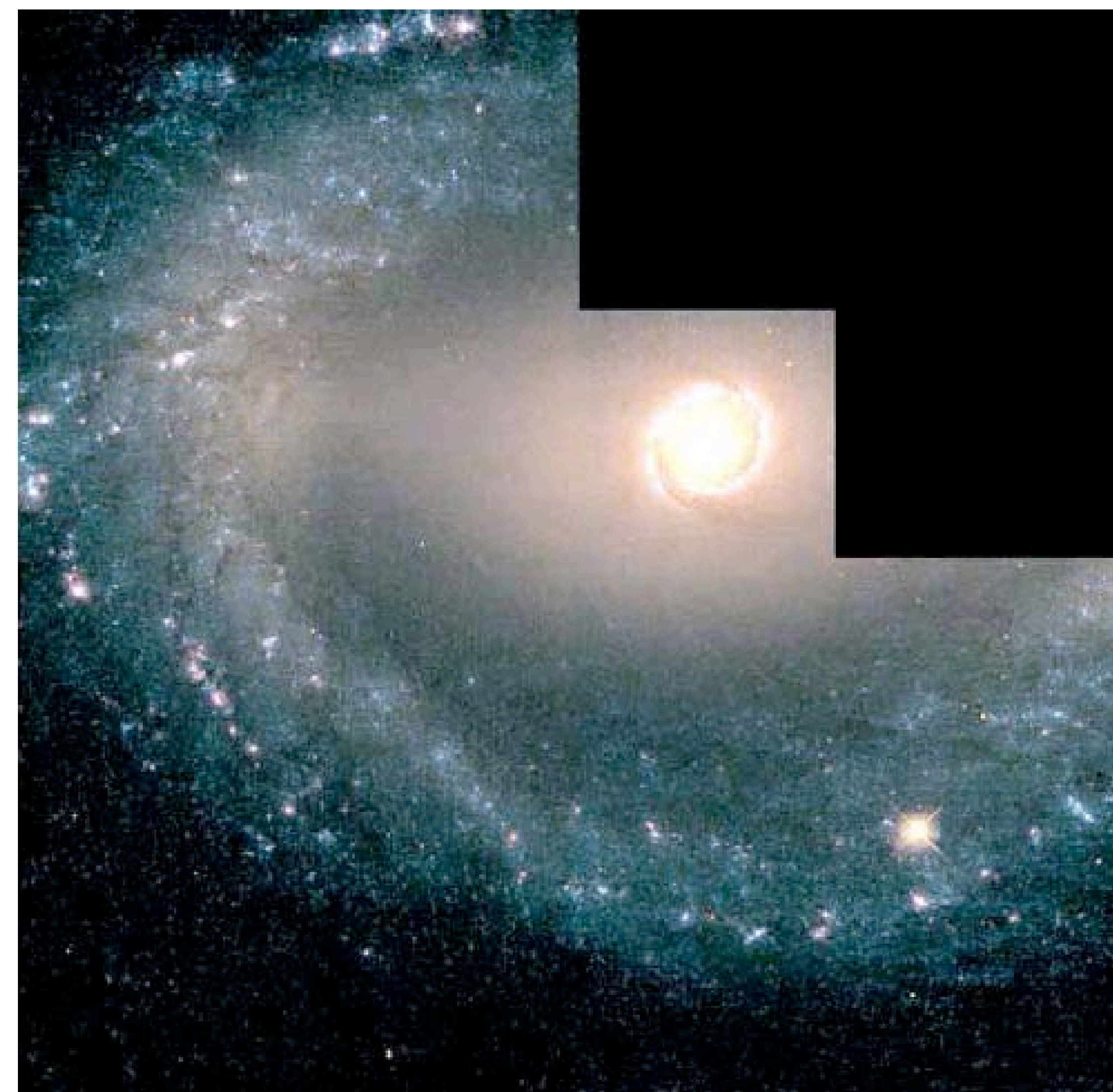
NGC2523: SB(r)

1. Barred spiral galaxies are divided into subclasses SB(s), in which the spiral arms begin at the ends of the bar, and SB(r), in which a complete "inner ring" of stars connects the ends of the bar. In the latter case, the spiral arms start somewhere on the ring, "often downstream from the ends of the bar" (Sandage & Bedke 1994). SB(r) and SB(s) galaxies are contrasted in Figure 6; additional SB(r) galaxies are shown in Figures 3 and 5, and additional SB(s) galaxies are shown in Figure 7.

2. Some barred and oval galaxies have "outer rings" (R) that are 2.2 ± 0.1 times the diameter of the bar or inner disk. Outer rings in barred and unbarred galaxies are similar (Fig. 2, 5). Inner and outer rings are different; there is no size overlap. Some galaxies contain both (Fig. 5).

NGC1512: SB(r)

fig.3



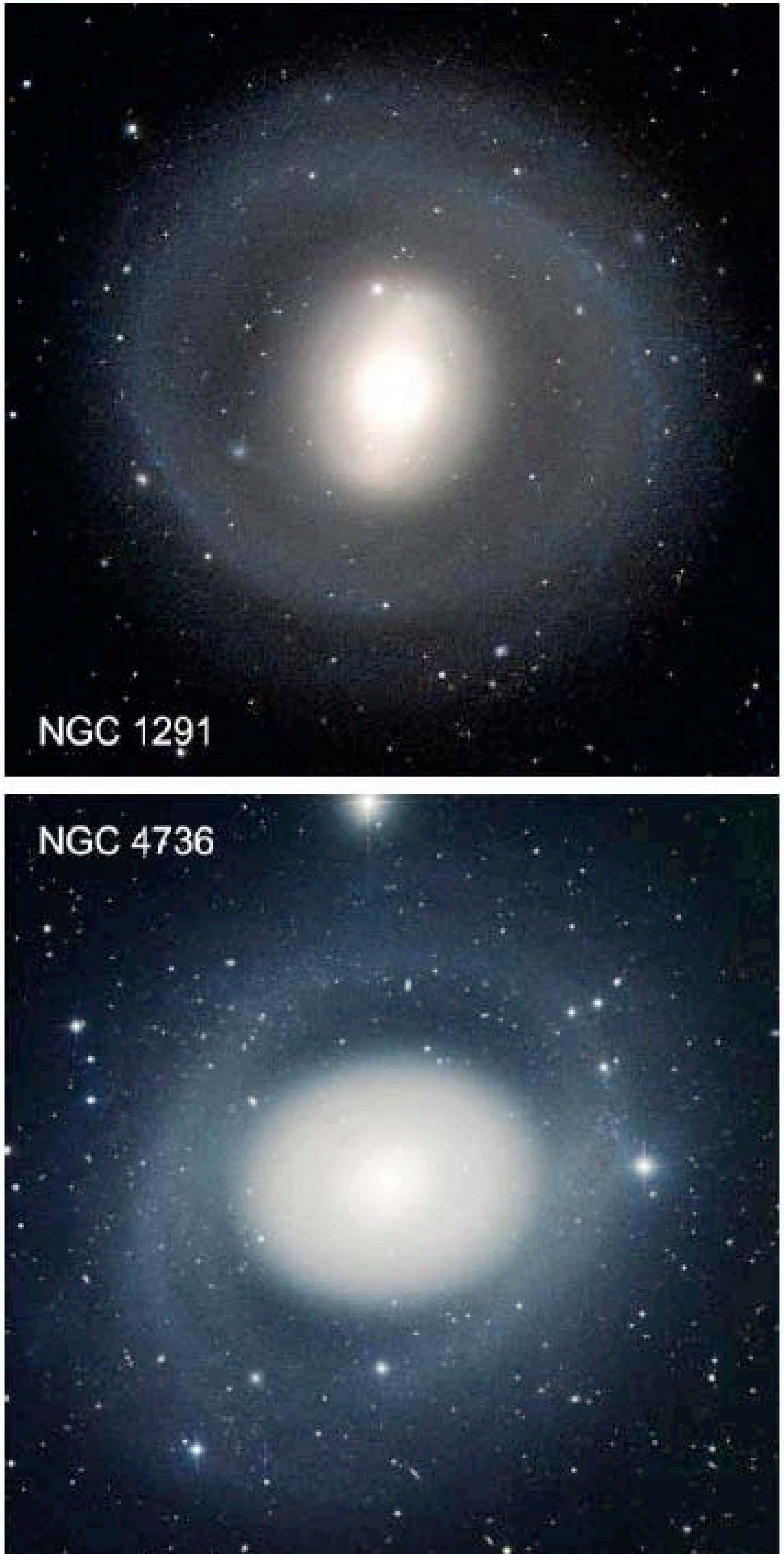


fig.2

3. At intermediate Hubble types, when the bar is made mostly of old stars and the disk contains many young stars, the stellar population of inner and outer rings is like that of the disk, not like that of the bar (Figures 2 and 3). Inner and outer rings generally contain gas.

4. In SB(s) galaxies, an almost-straight dust lane parallels the ridge line of the bar but is displaced slightly forward in the direction of galactic rotation. Such dust lanes are analogous to and connect up with the prominent dust lanes seen on the trailing side of the arms in global-pattern spirals. Examples are shown in Figures 6, 7, and 8. These dust lanes are almost never present in SB(r) galaxies (Sandage 1961). NGC 1512 in Figure 3 is a rare exception.

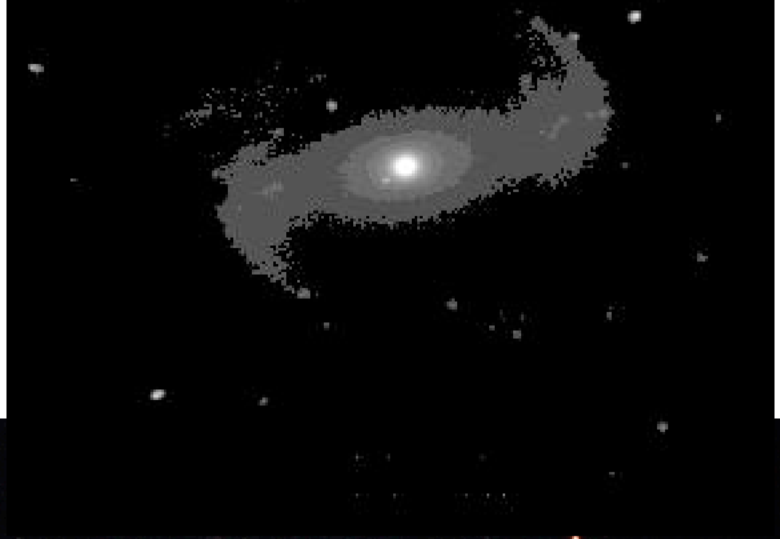
5. Many barred and oval galaxies have very active star formation near their centers, in what is conventionally identified as the bulge. Often the star formation is concentrated in a ring. Figures 3, 7, and 8 show examples.

6. Many barred galaxies have "bulges" that are themselves elongated into a structure resembling a bar. Examples are shown in Figure 14.

7. Many early-type SB galaxies contain a "lens" in the disk – a shelf of slowly decreasing surface brightness with a sharp outer edge. Lenses have intrinsic axial ratios of ~ 0.85; the bar usually fills the longest dimension. These properties are discussed in Kormendy (1979a, b, 1981, 1982a) and in Athanassoula et al. (1982). Lenses are sometimes seen in unbarred galaxies; NGC 1553 is the best example (Freeman 1975; Kormendy 1984). Lenses in early-type galaxies look similar to oval disks in late-type galaxies (Section 3.2); it is not clear whether or not they are physically similar. Lenses are illustrated in Figures 2 and 5.

NGC 1300

- Dust lanes
- Star formation regions
- Old stellar bar



Barred Galaxies: overall properties

- Barred galaxies are numerous: 1/3 of all spirals have strong bars and 1/3 has a weaker inner bar
- Our Galaxy and Andromeda are barred galaxies
- LMC is a barred galaxy
- Typically star formation inside the bar is suppressed (but not in nucleus)
- Barred galaxies sometimes have rings: inner and outer rings
- Length of a bar is typically close to the exponential scale-length of the disk. Yet, there is substantial spread
- Bars have boxy shape:

  $(x/a)^c + (y/b)^c = 1$ with $c=2.5\text{-}5.5$

- Bars rotate, with a pattern speed that is close to the angular circular speed in the disk near the bar ends. If R_{bar} is the radius of the bar and $R_{corotation}$ is the radius of corotation, than:

$$R_{bar} \approx R_{corotation} / 1.3$$

Morphology of surface brightness profiles

- Early Type: flat inner profile
- Late Type: double exponential

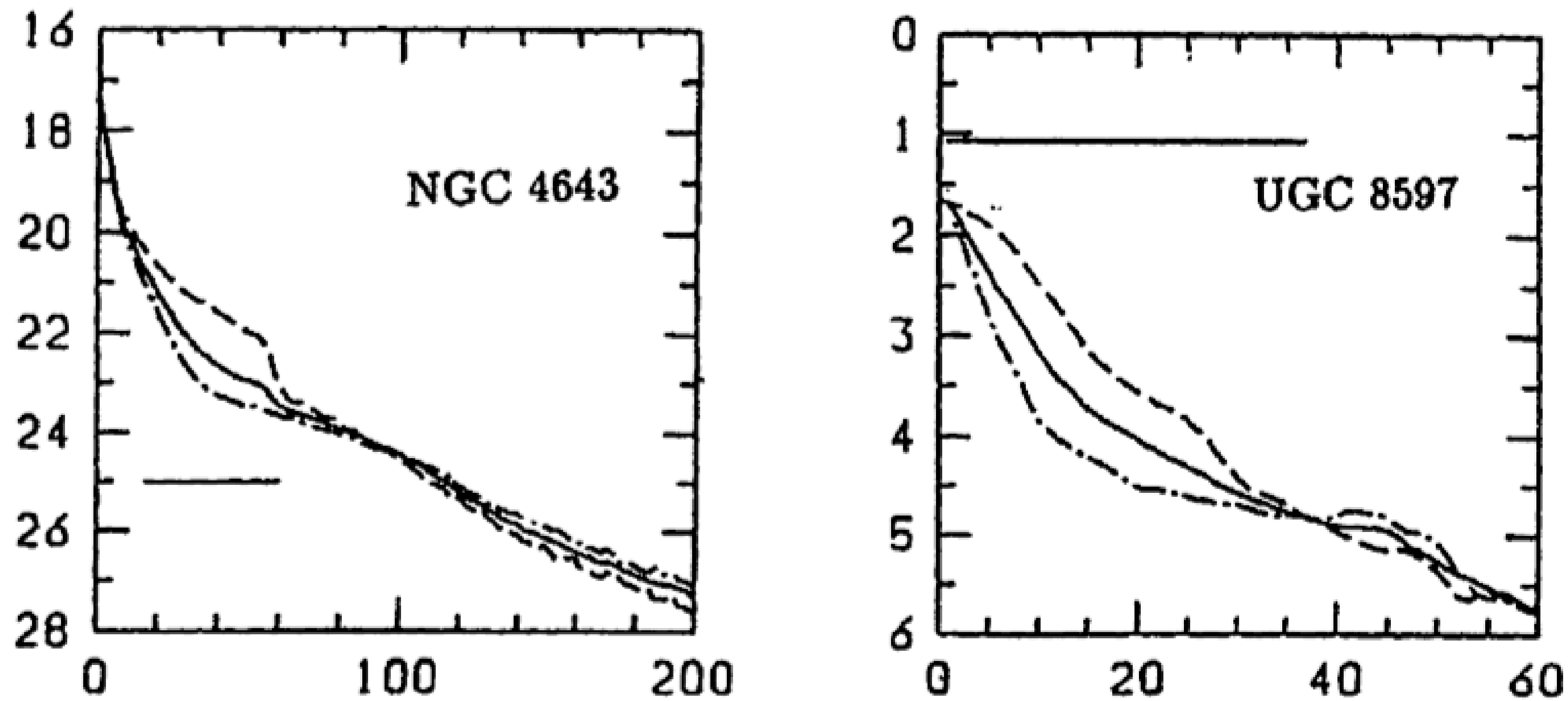
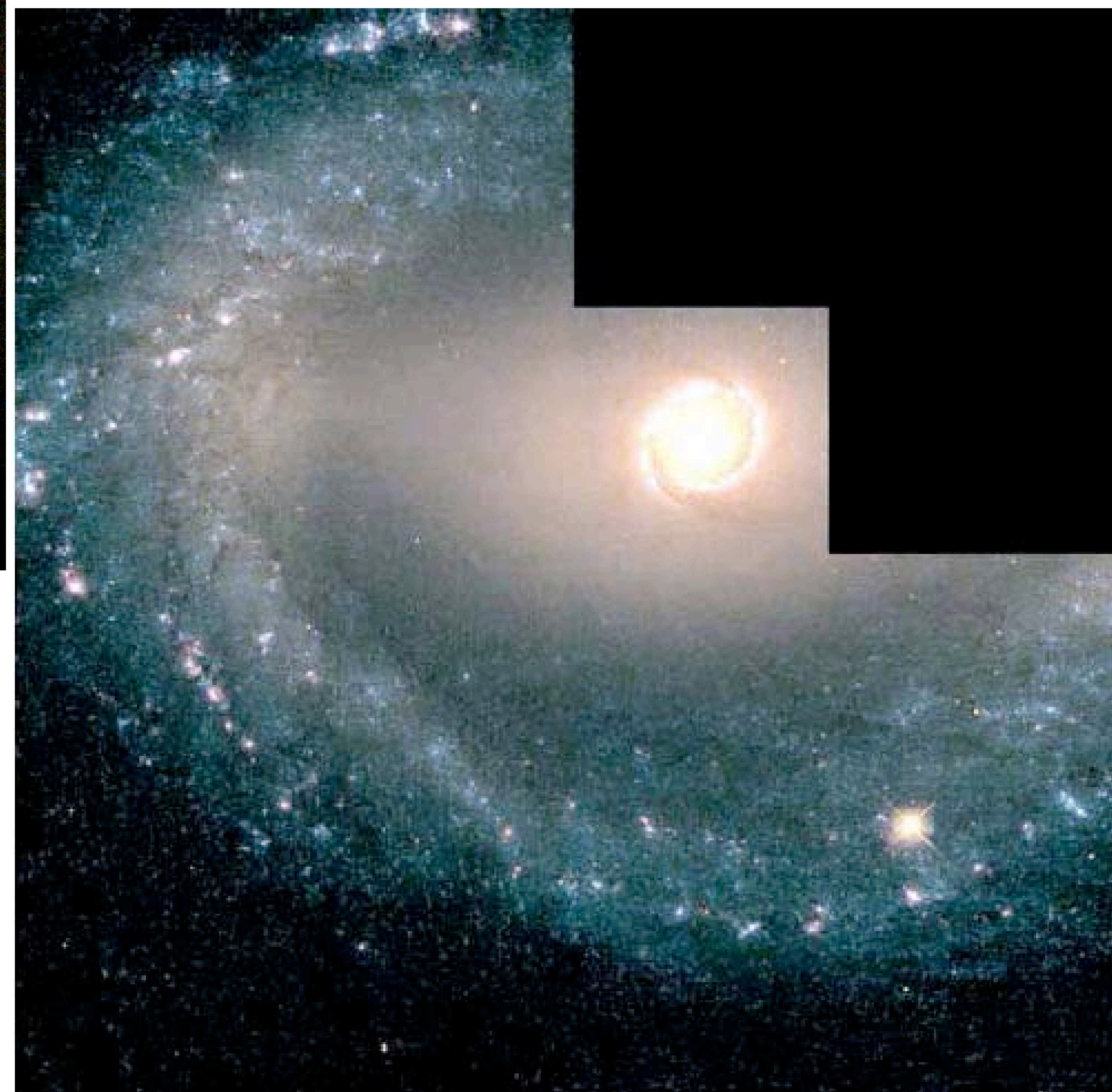


Figure 3. Radial profiles of an early-type (left panel) and a late-type (right panel) barred galaxy. The ordinate is surface brightness in magnitude scale and the abscissa is radius in arcsec. Solid lines, dashed lines, and dot-dashed lines represent azimuthally averaged profiles, profiles along the bar major axis, and profiles along the bar minor axis, respectively. A horizontal line in each panel shows the bar region.

NGC1512: SB(r): Central active region



Motion of Gas

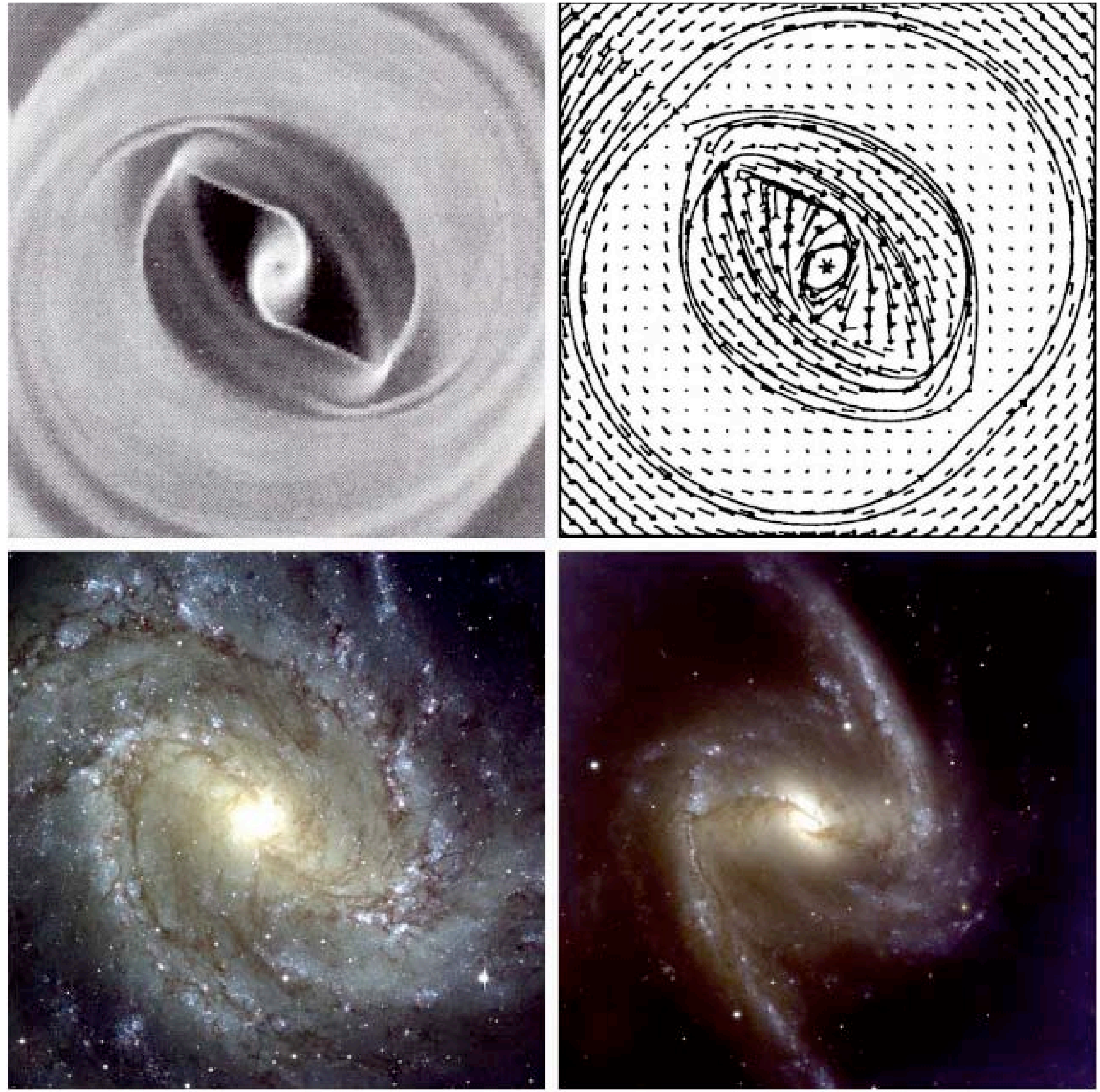
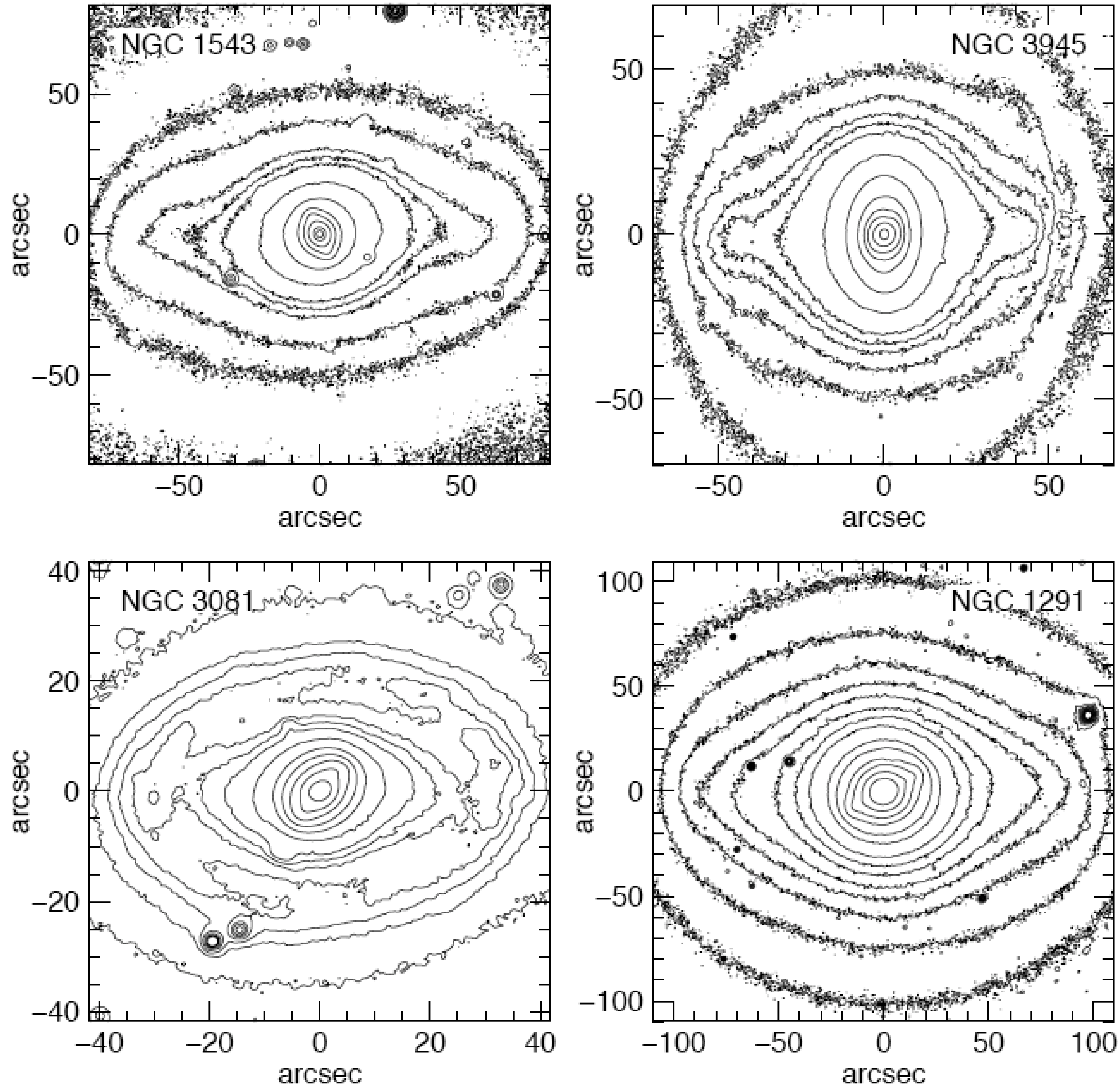


Figure 7 Comparison of the gas response to a bar (Athanassoula 1992b model 001) with NGC 5236 (left) and NGC 1365 (right). The galaxy images

Nuclear bars



Peanut-shape bulges

Peanut-shape bulges: sign of a bar

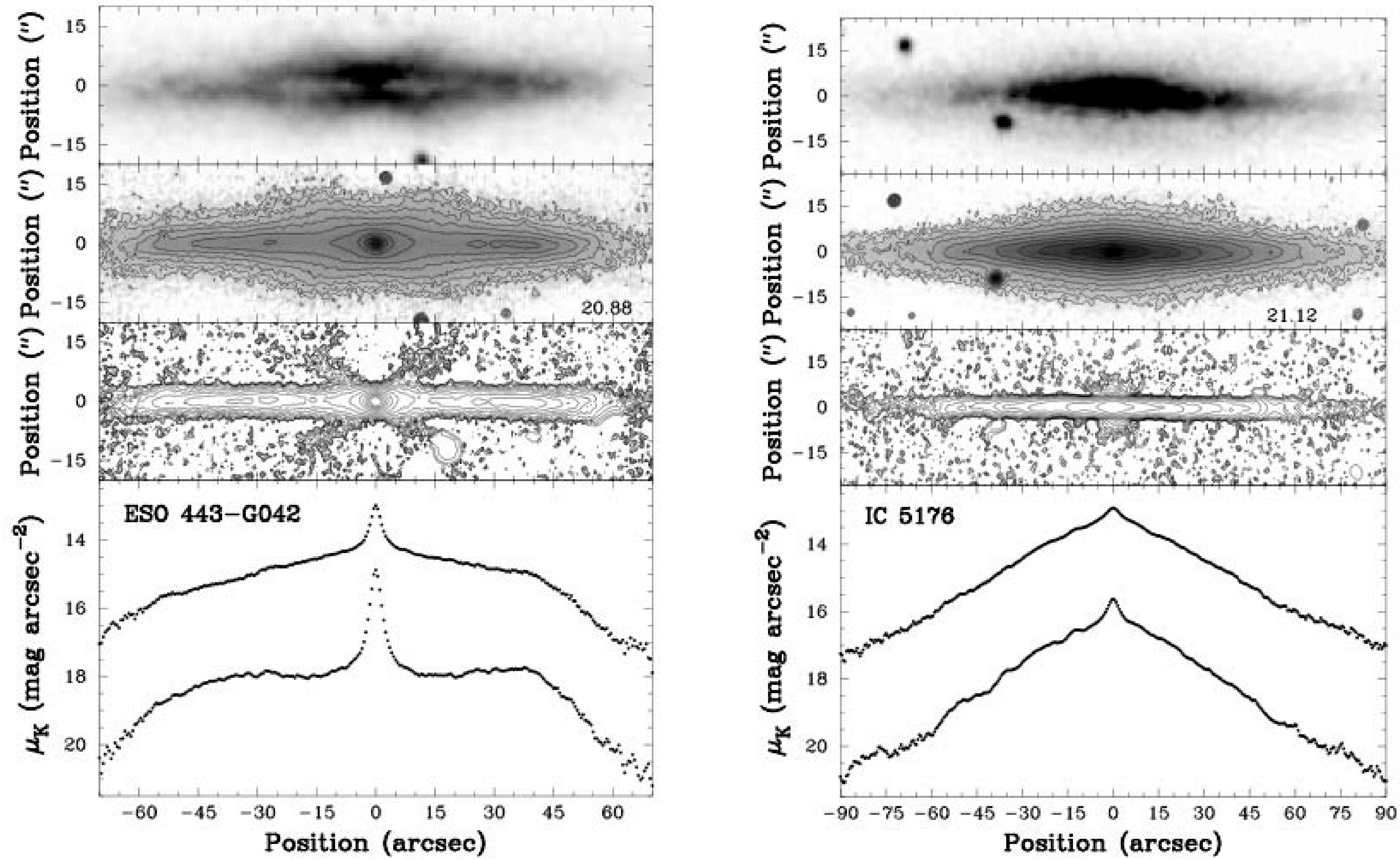


Figure 1. Images and surface brightness profiles of the galaxies ESO443-G042 (left), with a B/PS bulge, and IC5176 (right), with a nearly pure disc. From top to bottom, each panel shows first a DSS image of the galaxy, second our *K*n-band image, third an unsharp-masked *K*n-band image, and last the major-axis (fainter) and vertically-summed (brighter) surface brightness profiles, all spatially registered.

Azimuthal variations of surface brightness

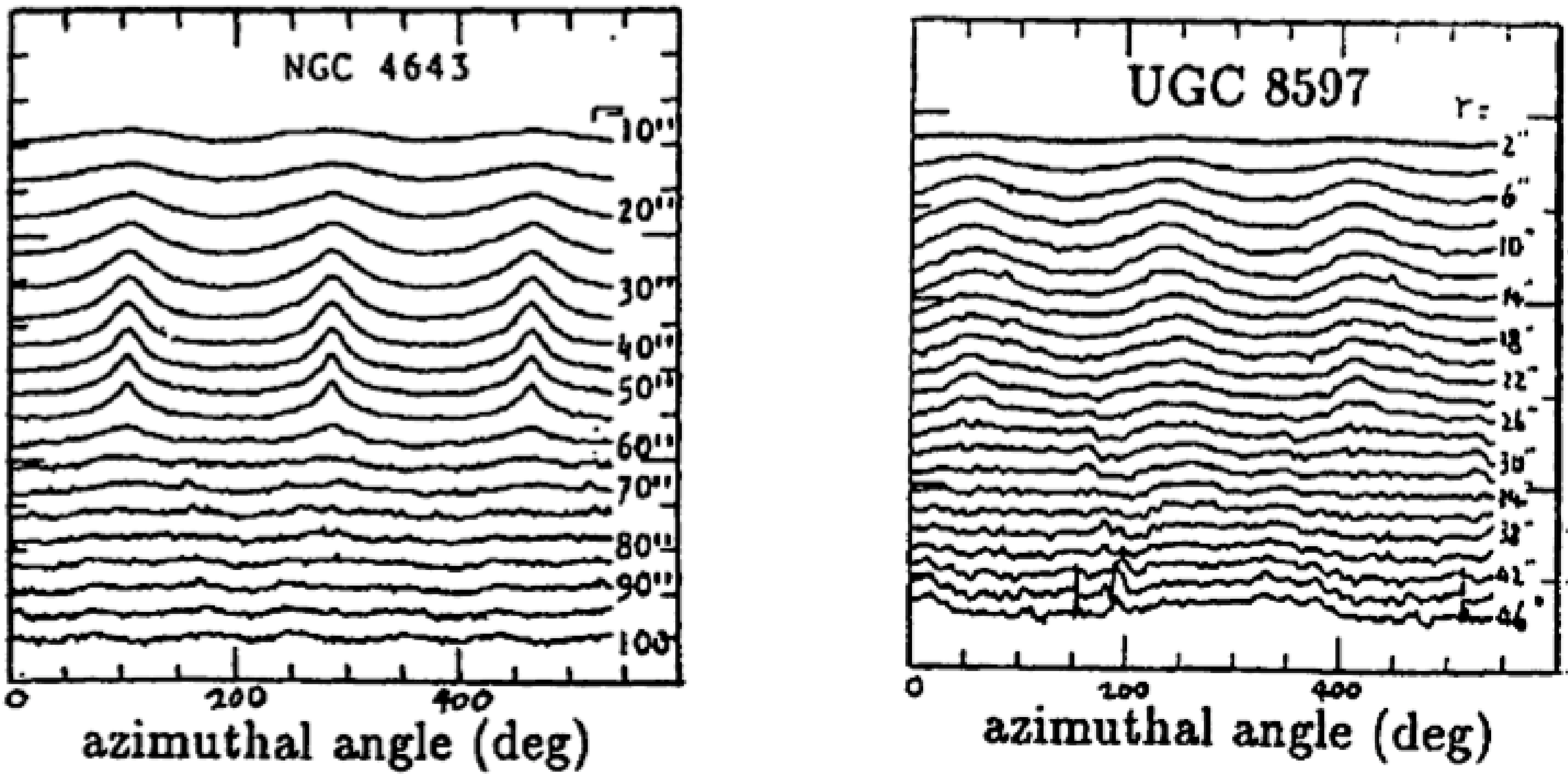


Figure 1. Azimuthal profiles of an early-type (left panel) and a late-type (right panel) barred galaxy. The ordinate and the abscissa are surface brightness in arbitrary units and azimuthal angle, respectively. The upper part in each panel shows profiles in the bulge region, the middle part shows profiles in the bar region, and the lower part shows profiles in the outer disk region.

Unlike spiral arms, bars have very large variations of the stellar mass: a factor of 2-3 for innner/out bar regions

Figure 2 shows the results of the Fourier decomposition. The Fourier components are defined as follows,

$$I(r,\theta) = A_0(r)/2 + \sum_m [A_m(r)\cos m\theta + B_m(r)\sin m\theta],$$

where

$$A_m(r) = \frac{1}{\pi}\int_0^{2\pi} I(r,\theta)\cos m\theta \mathrm{d}\theta, \quad \text{and} \quad B_m(r) = \frac{1}{\pi}\int_0^{2\pi} I(r,\theta)\sin m\theta \mathrm{d}\theta.$$

The Fourier amplitude of the m-th component is defined as

$$I_0(r) = A_0(r)/2, \quad I_m(r) = [A_m(r)^2 + B_m(r)^2]^{1/2},$$

and the relative amplitude of the m-th component is defined as $I_m(r)/I_0(r)$. In both early- and late-type barred galaxies, the amplitudes of the m=2 component are the largest, but in the early-type barred galaxies the contributions of m=4, m=6, and m=8 components are also large, while in the late-type barred galaxies only the amplitudes of m=4 are significant and contributions from higher components are negligible.

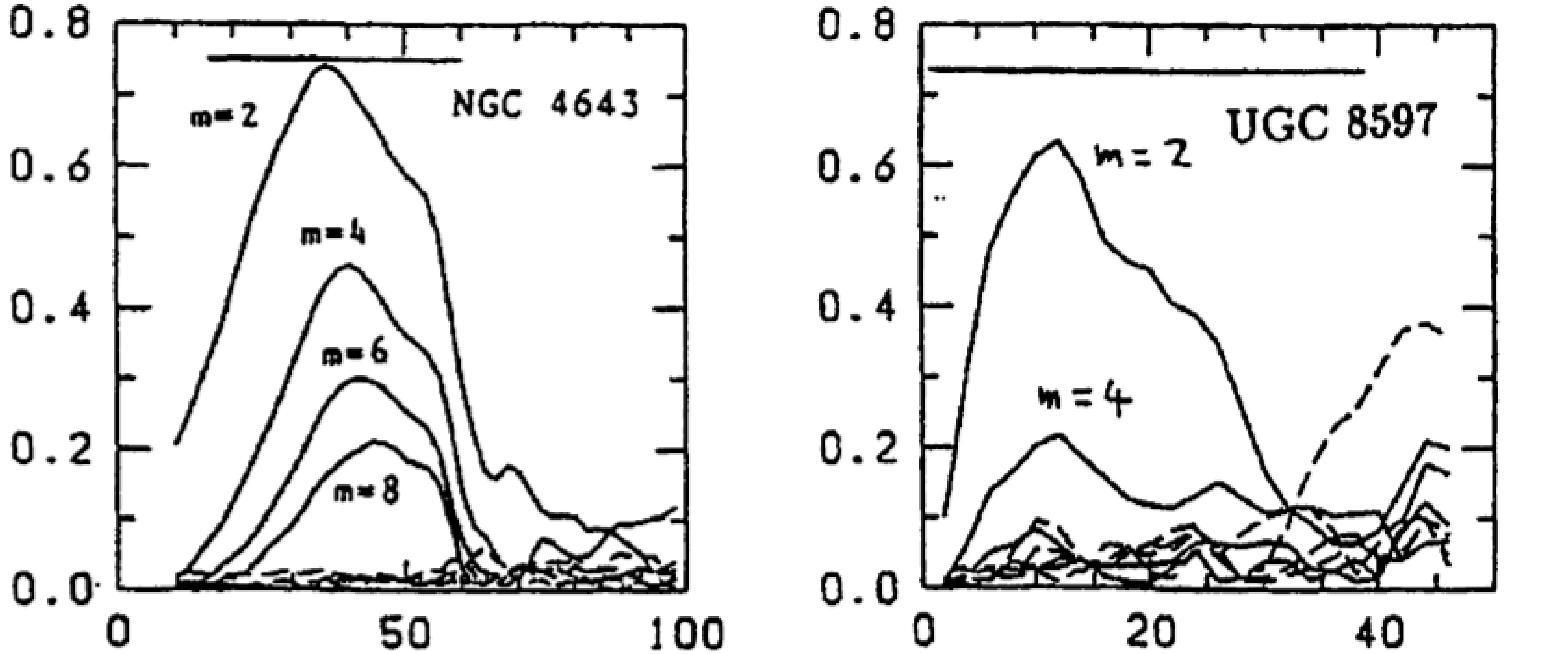
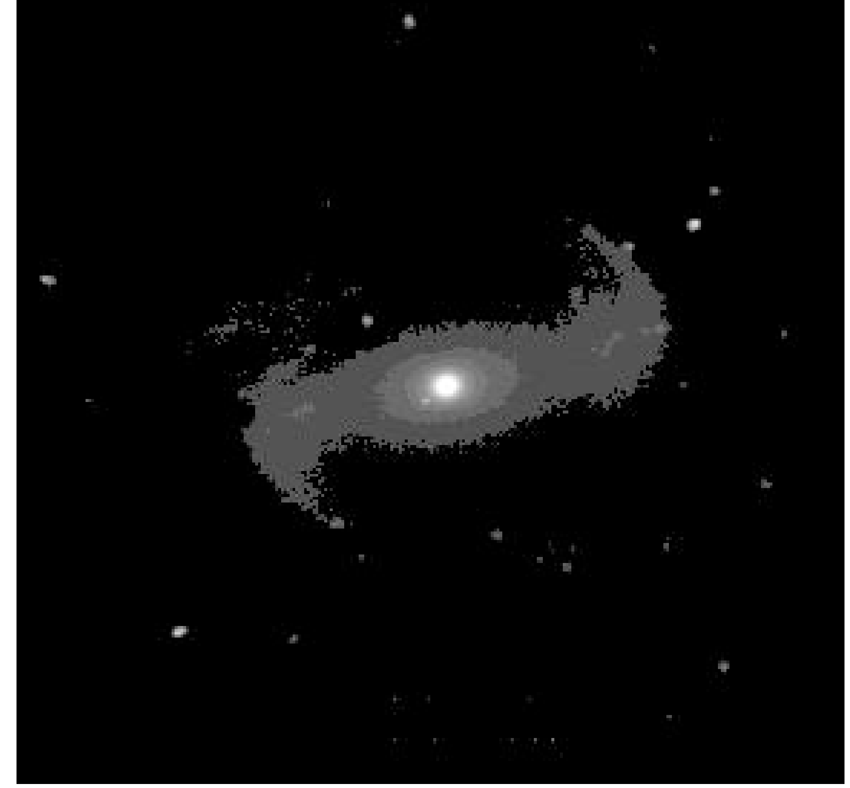


Figure 2. Relative Fourier amplitude of an early-type (left panel) and a late-type (right panel) barred galaxy. The ordinate is the relative amplitude of the Fourier component and the abscissa is radius in arcsec. A horizontal line in each panel represents a bar region.

Boxy shapes of isophotes

NGC1300



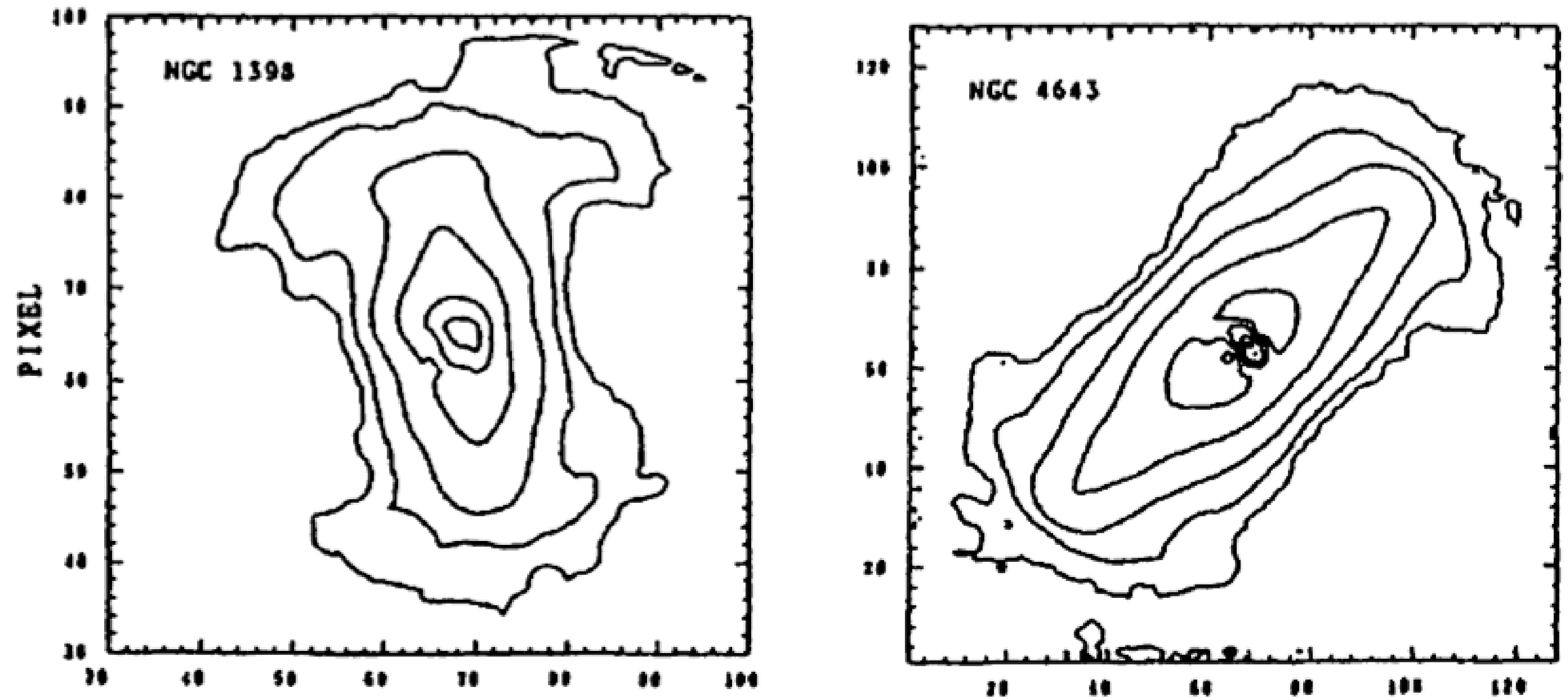
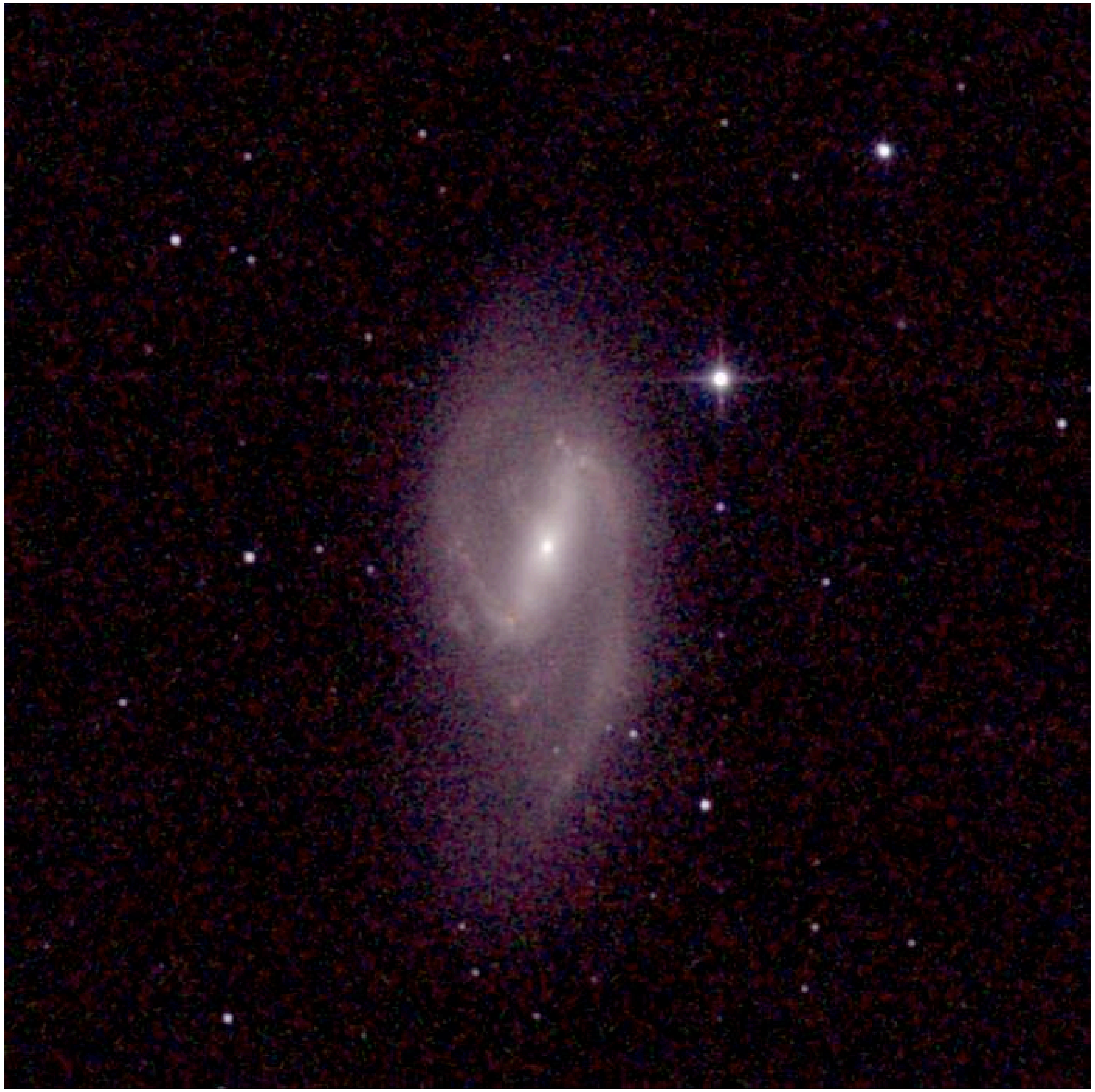
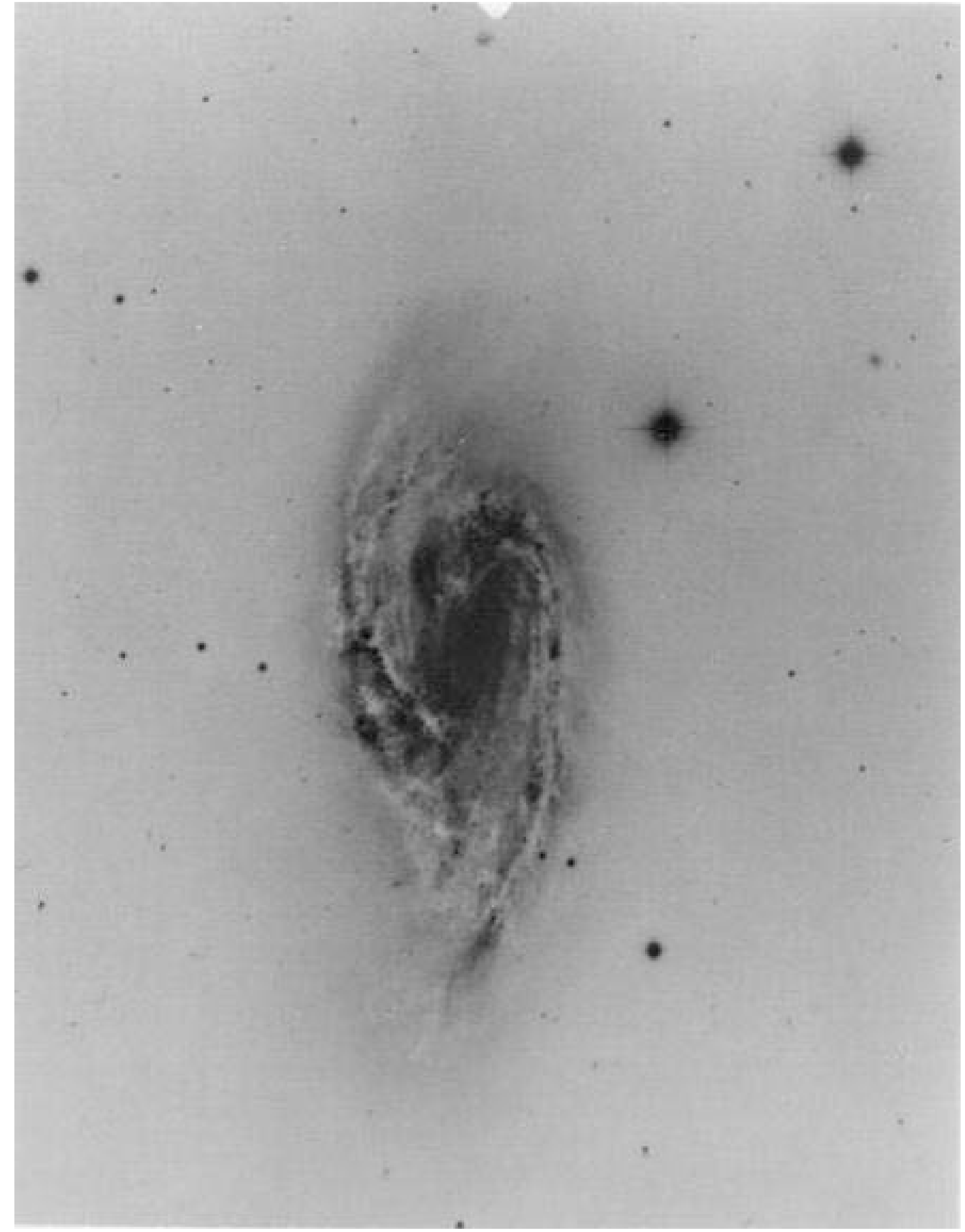


Figure 4. Examples of the isophotal map of the bar component itself in the early-type barred galaxies (NGC 1398 and NGC 4643). The outermost contour is 25.0 mag arcsec^{-2}, and the interval is 1.0 mag arcsec^{-2}.

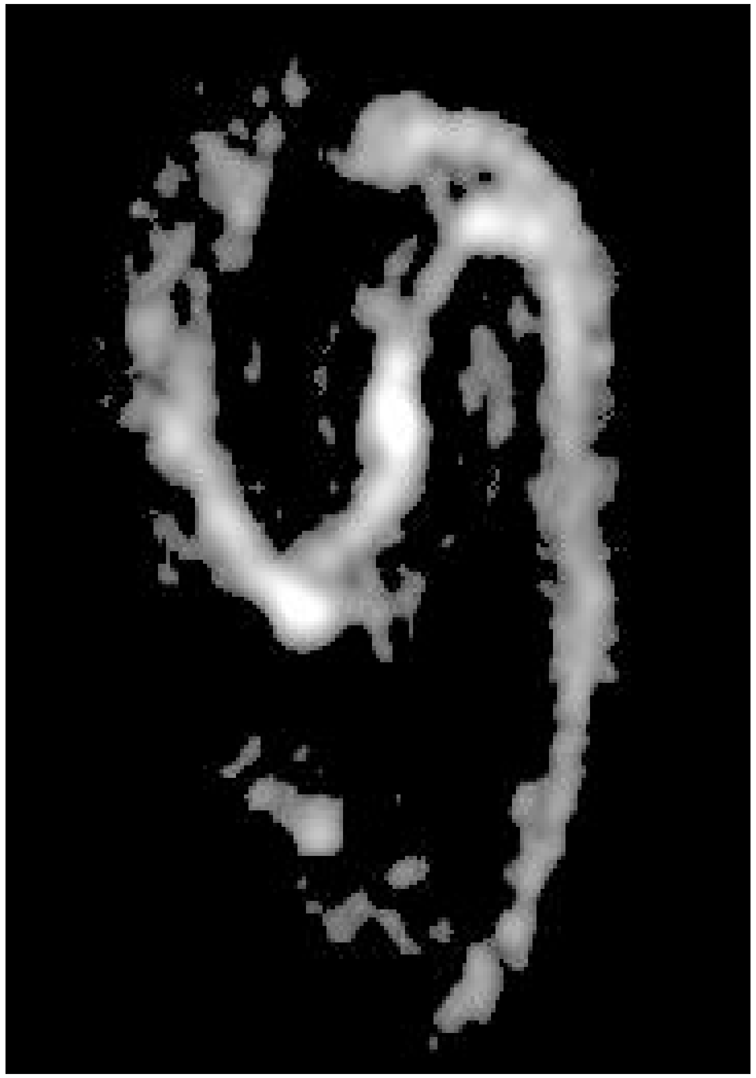
NGC 3627



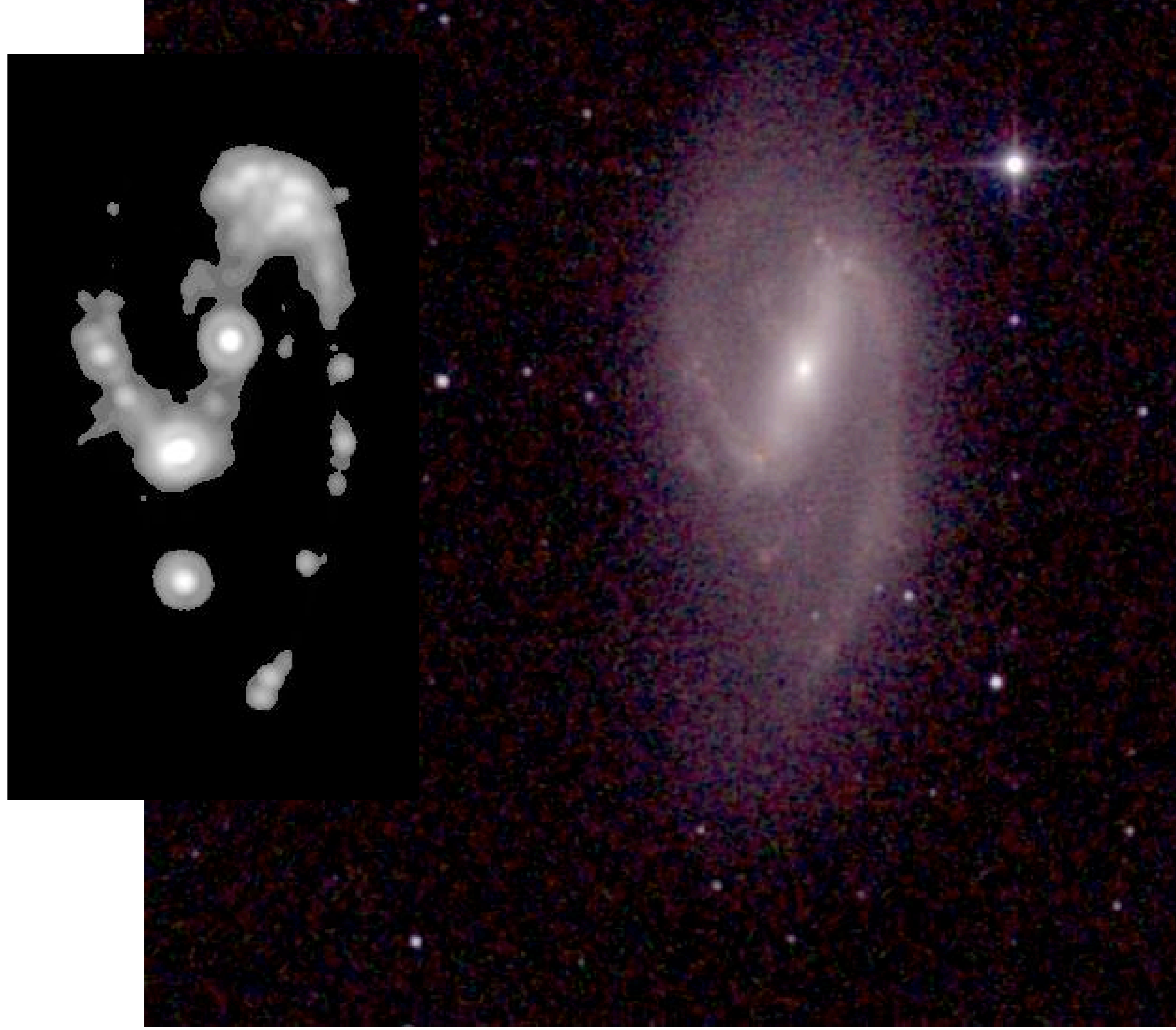
2MASS



Palomar



CO



Spitzer (infrared)

2MASS: old stars

NGC 3627: different wavelengths

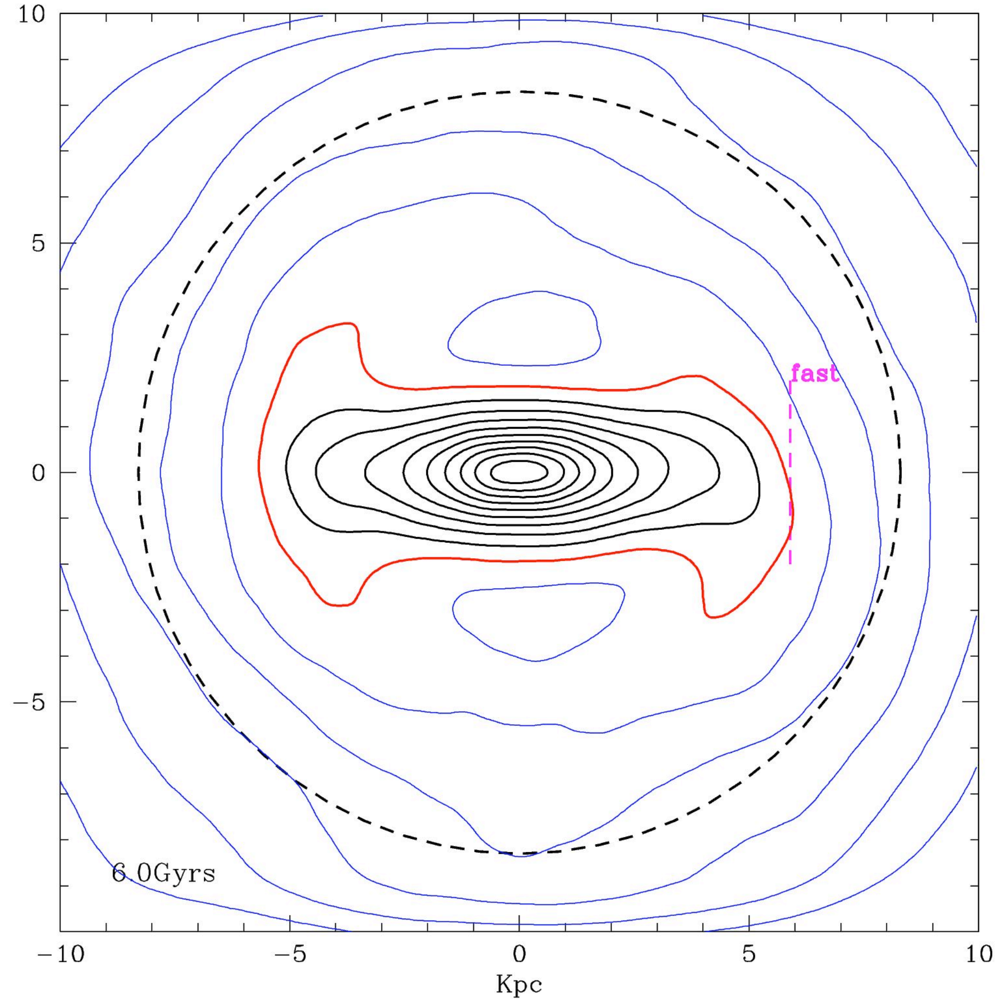
Star formation in barred galaxies

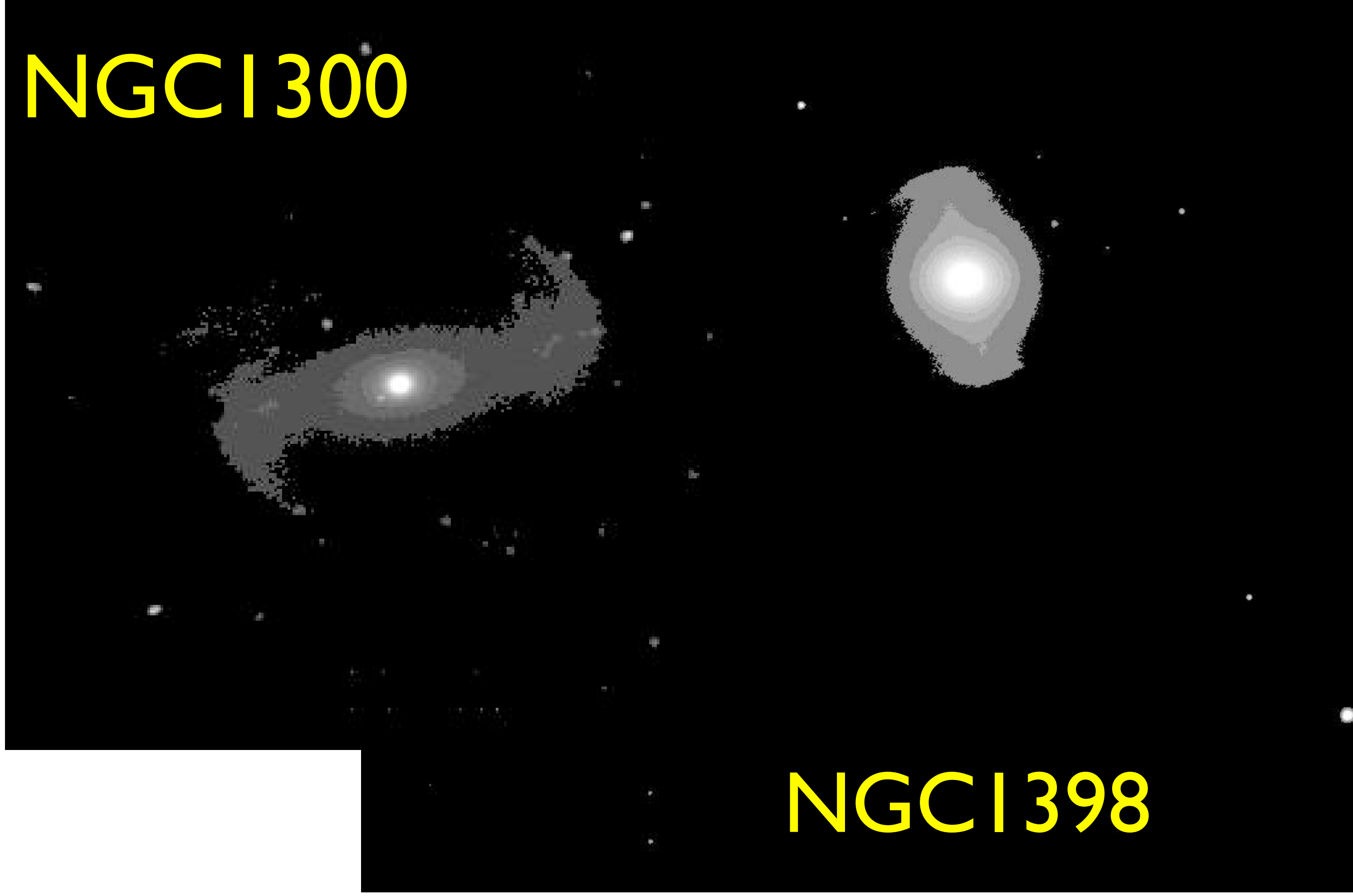
In general, global star formation rates and other properties are consistent with non-barred spials of comparable Hubble class.

In barred spirals of intermediate class (SBb-SBc), the effects of the bar on star formation is clearly seen i the distribution of star forming sites. Two patterns: (a) star formation in rings(inner and nuclear rings for early-type bars) and (b) star formation in bar itself for late-type bars

Barred Galaxies: Theory

- Secular evolution
- Development of instabilities
- Transfer of angular momentum
- Evolution of density and velocity profiles
- Pattern speed
- Resonances



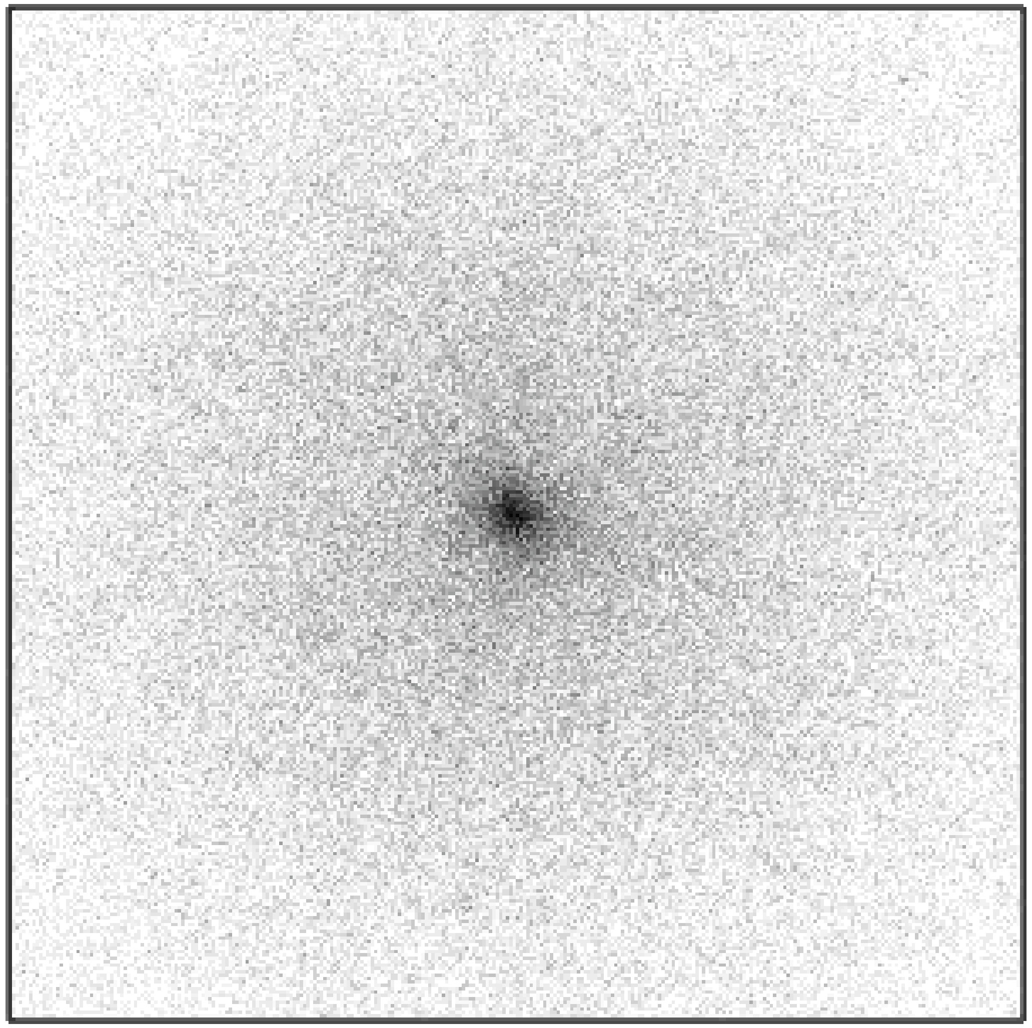


Bars in simulations and in real galaxies

Evolution of the stellar component

Bar forms though growth of instabilities. Once formed, it is a stable configuration, which evolves very slowly.

t=0



Two major instabilities:
- Bar (initial stage)
- Buckling (when bar is too strong)

Buckling of the bar results in much thicker central region (pseudo-bulge). Peanut-shape bulge is clearly seen.

t=0

Evolution of the stellar component

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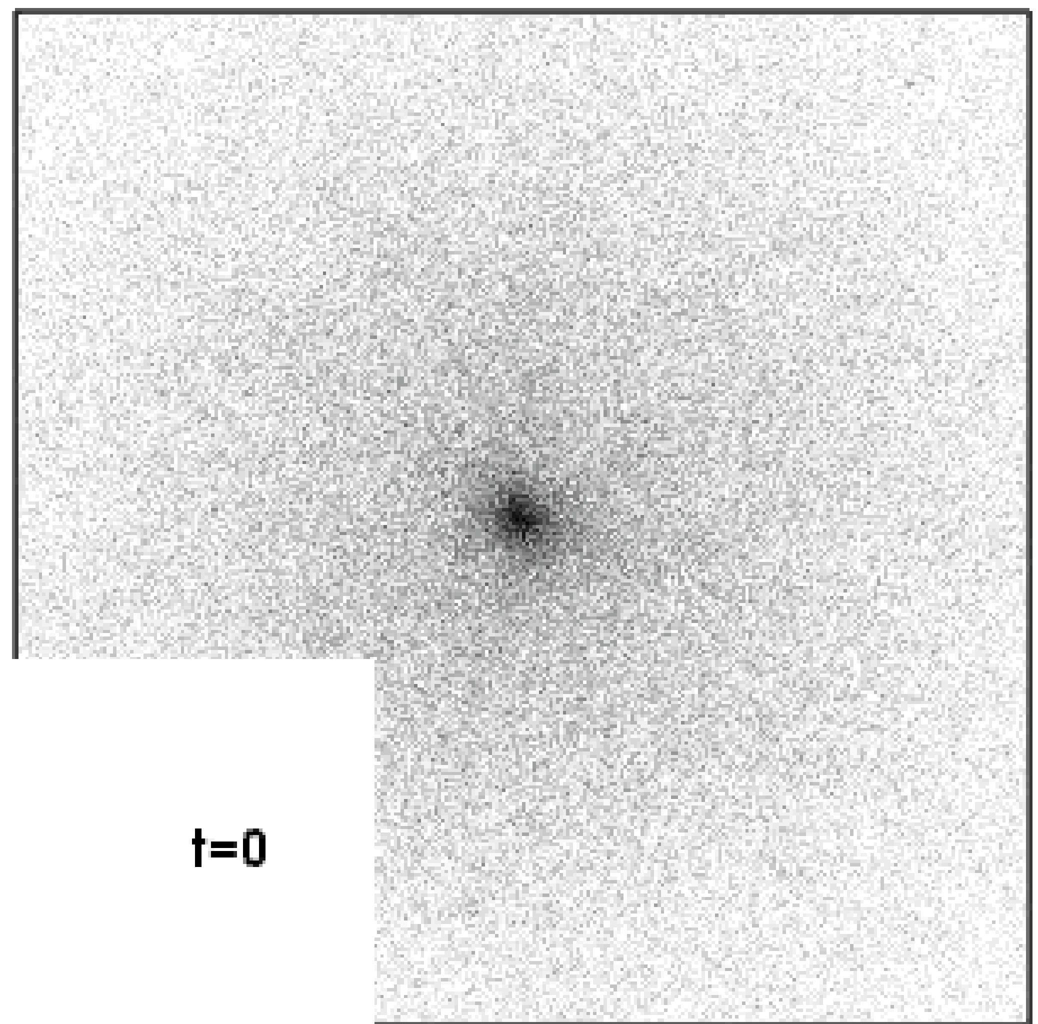

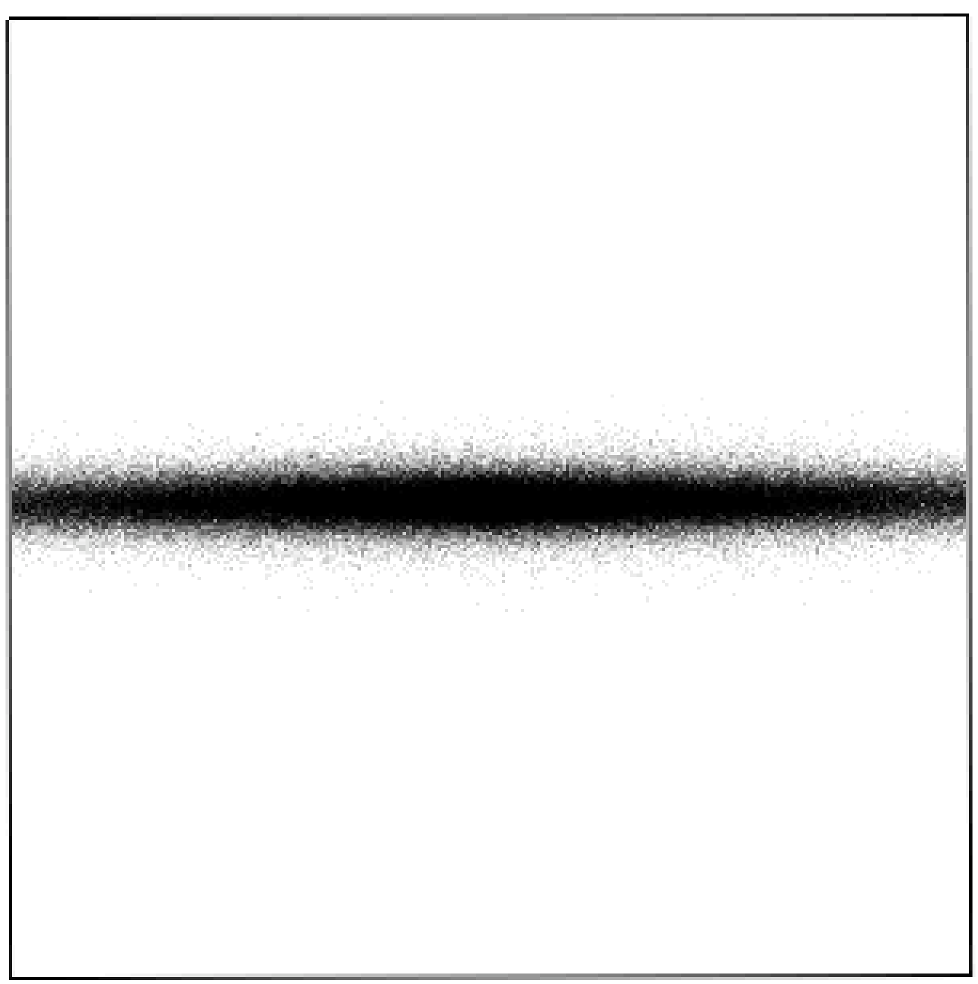

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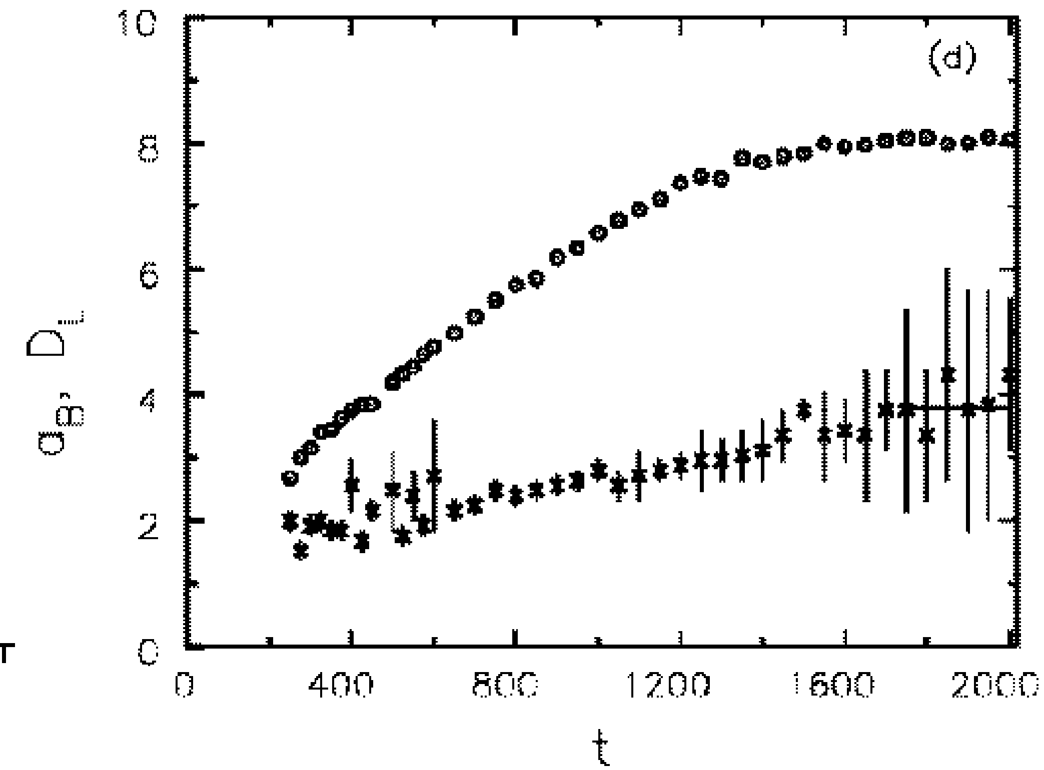
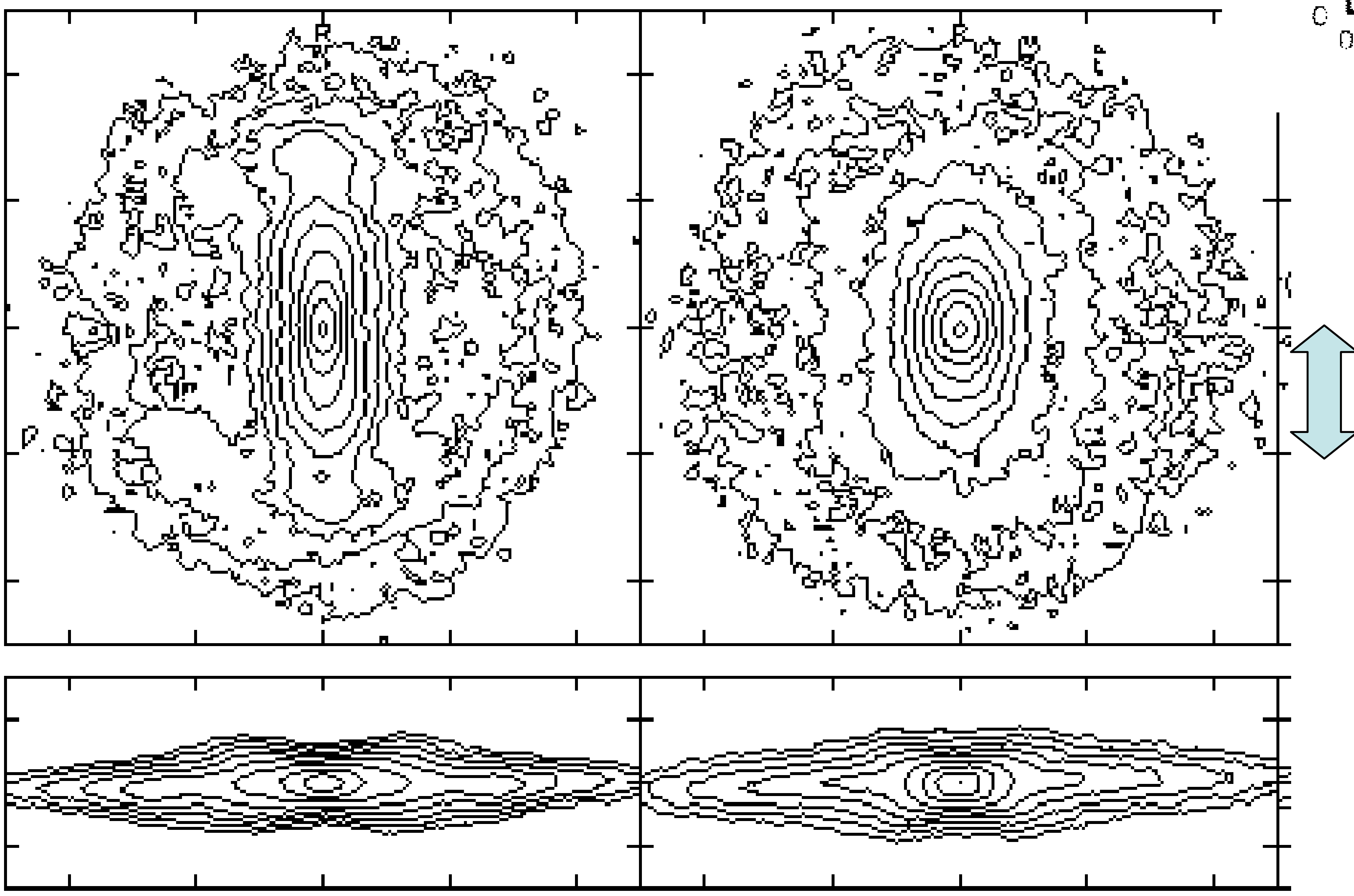


The truth is: Bars do not want to die.

If anything, they want to grow

Debattista&Sellwood 2000



2Rd=7kpc

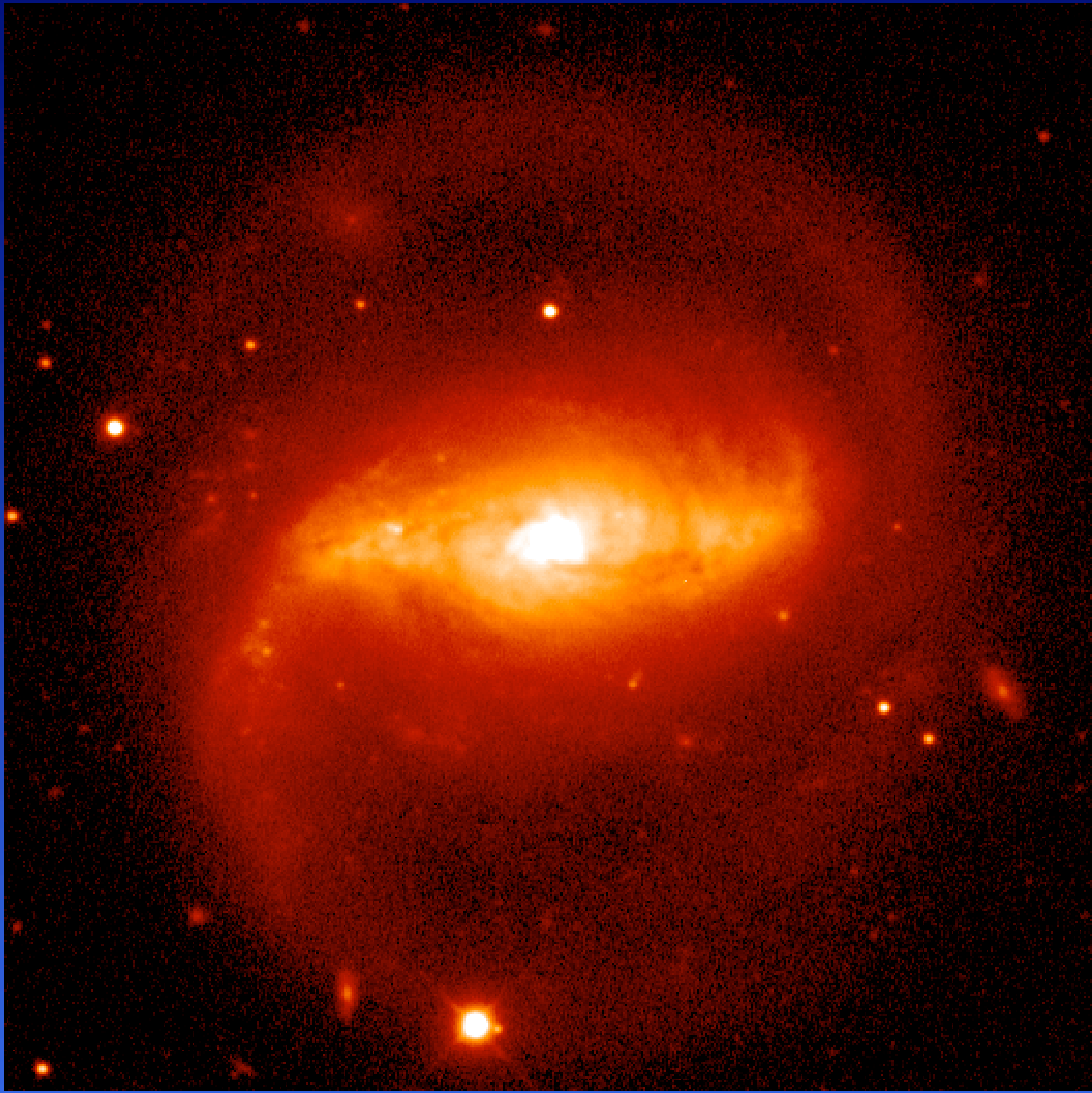
Athanassoula&Misiriotis 2002

GAS

Old hydro-simulations claimed that gas is important dynamically

Heller & Shlosman (1994)

Bournaud & Combes(2002)



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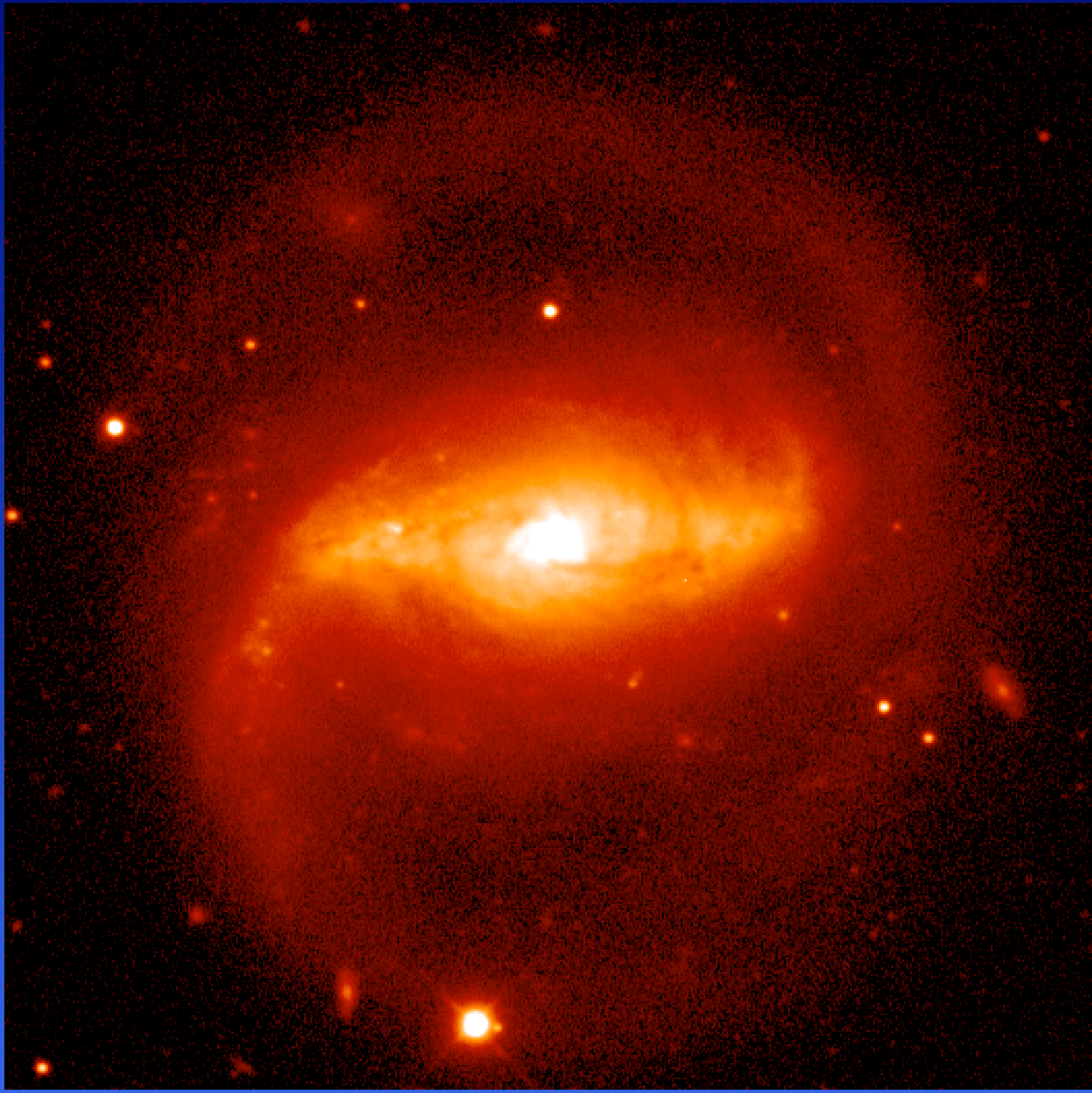


Recent hydro simulations with stellar feedback do not show destruction of bars

Often there is not enough gas mass to do the destruction (e.g. MW)

Shen&Sellwood (2004): (i) central condensation does not kill the bar

(ii) Numerical effects were responsible for older results

Secular evolution

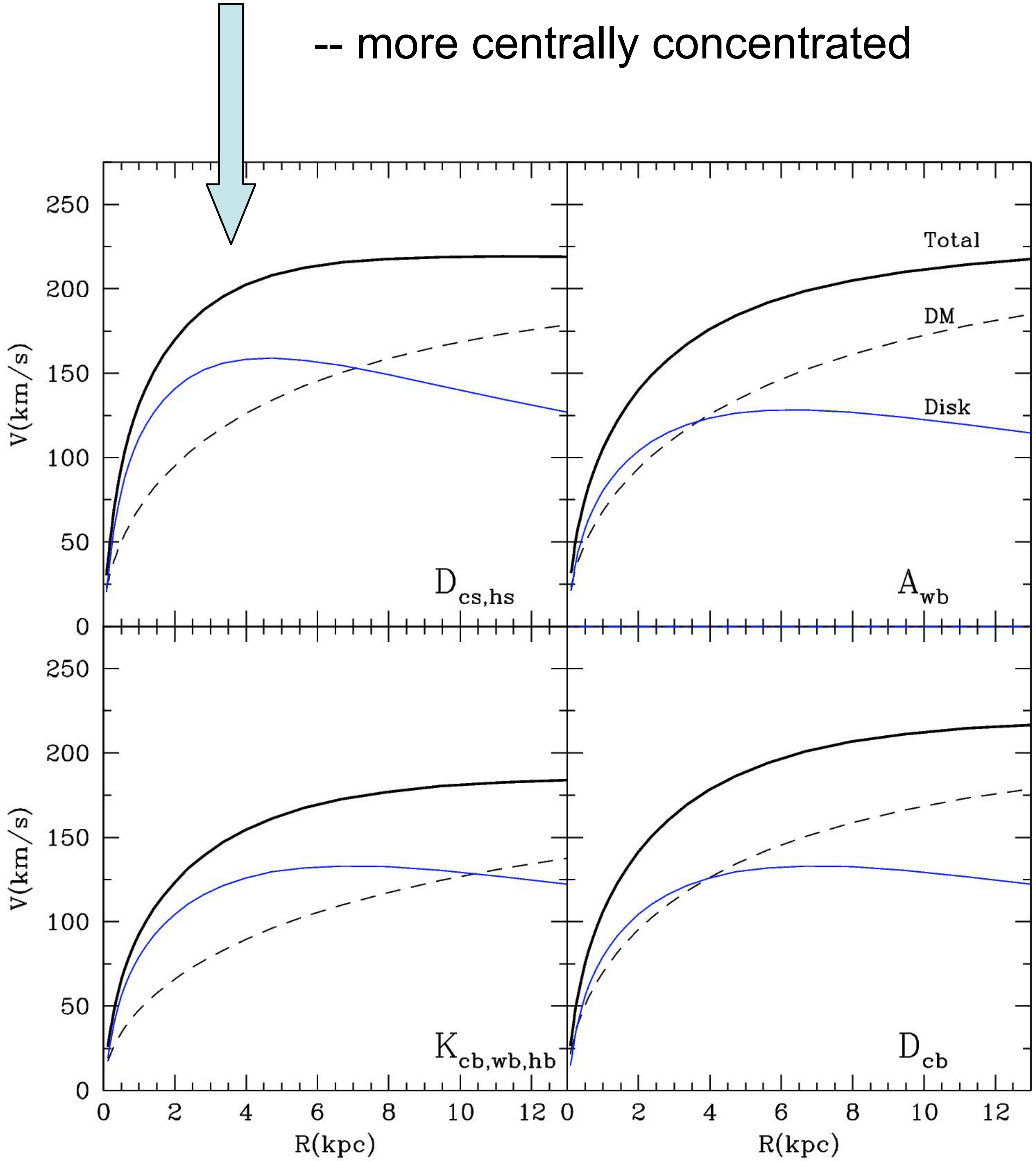
- Formation of "bulge" without merging of galaxies
- Typical setup: initially equilibrium (but unstable) stellar disk embedded in dark matter halo
- Disk is exponential with finite thickness. Toomre stability parameter Q=1.2-1.8
- Dark matter can be NFW or whatever

Initial Profiles

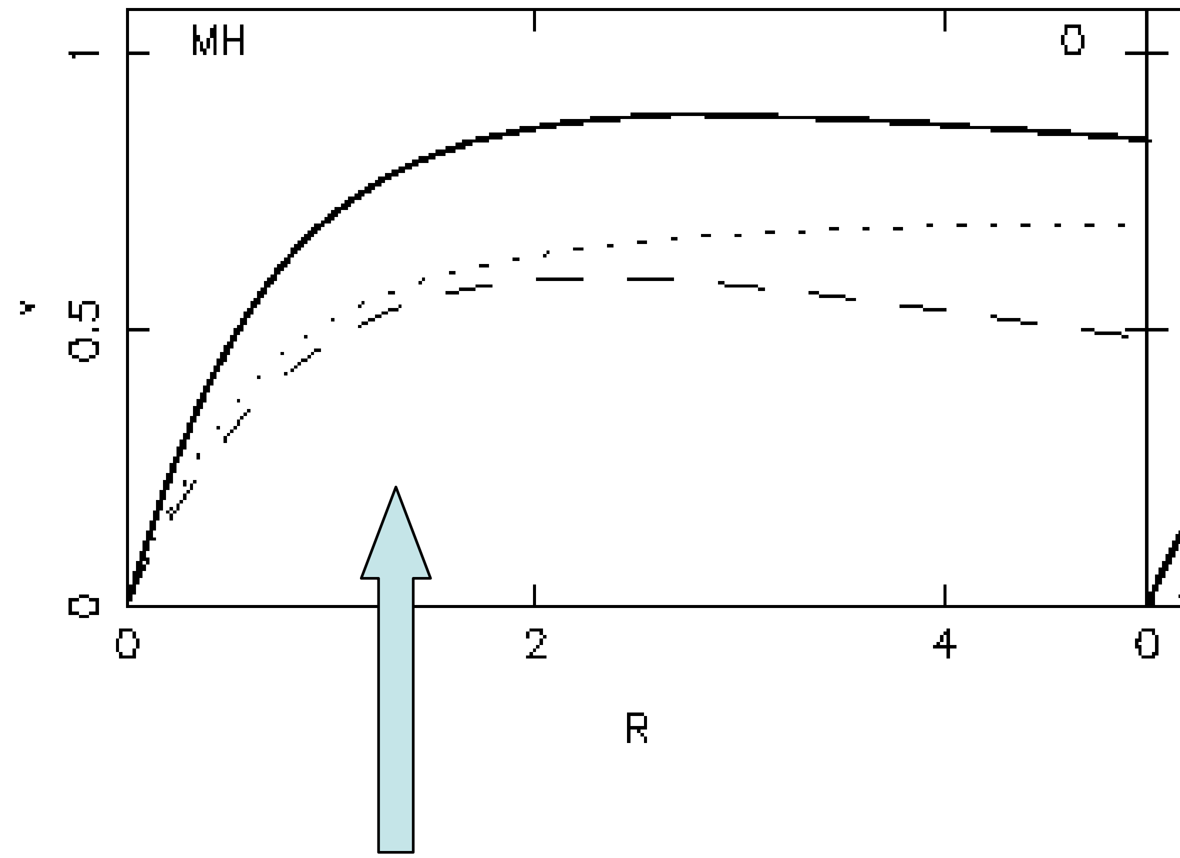
Expected DM/Disk ratio:

-- DM is below baryons

-- more centrally concentrated



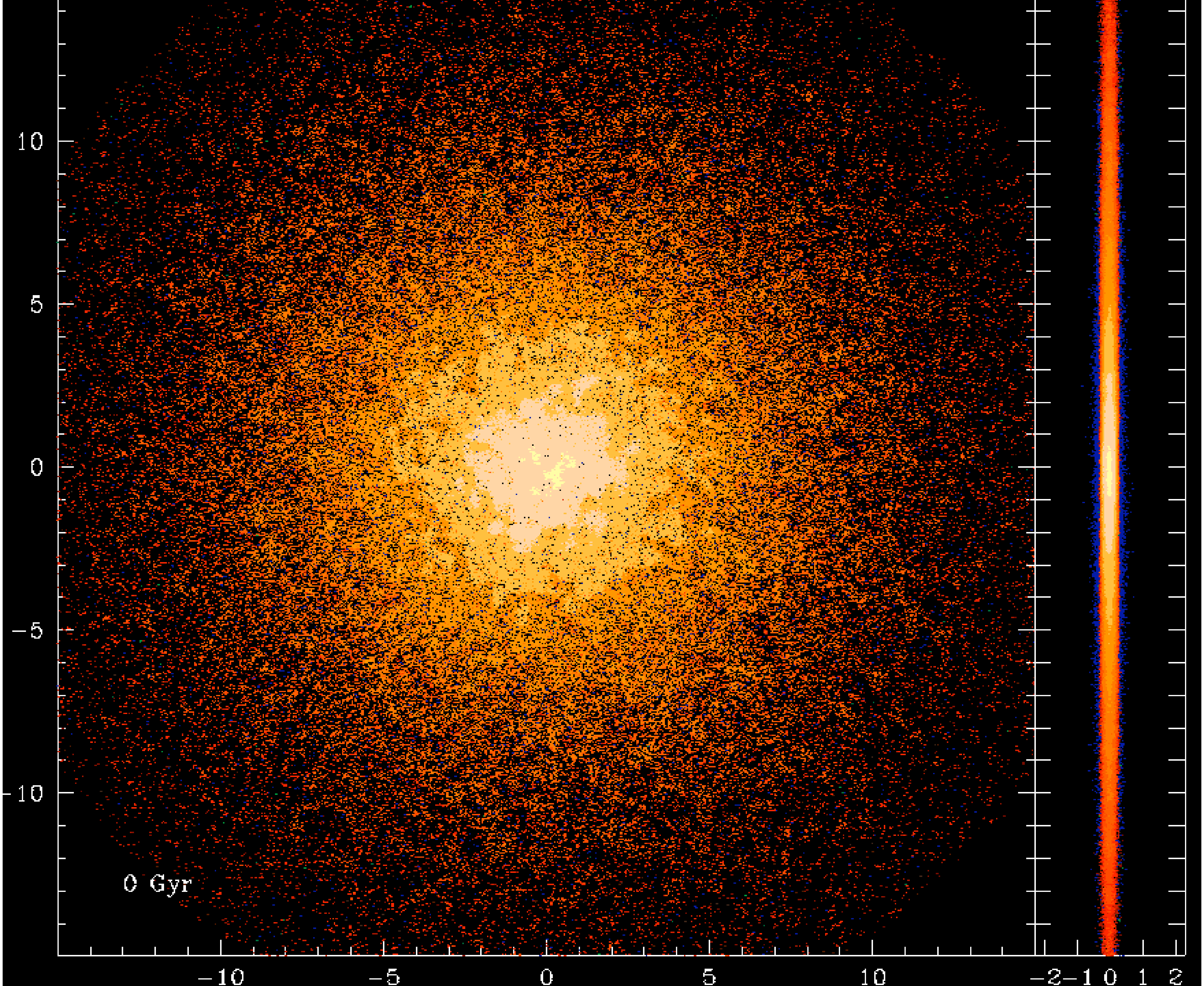
7kpc



Athanassoula&Misiriotis(2002):

--Too much DM at the center,

-- Less concentrated



10
5
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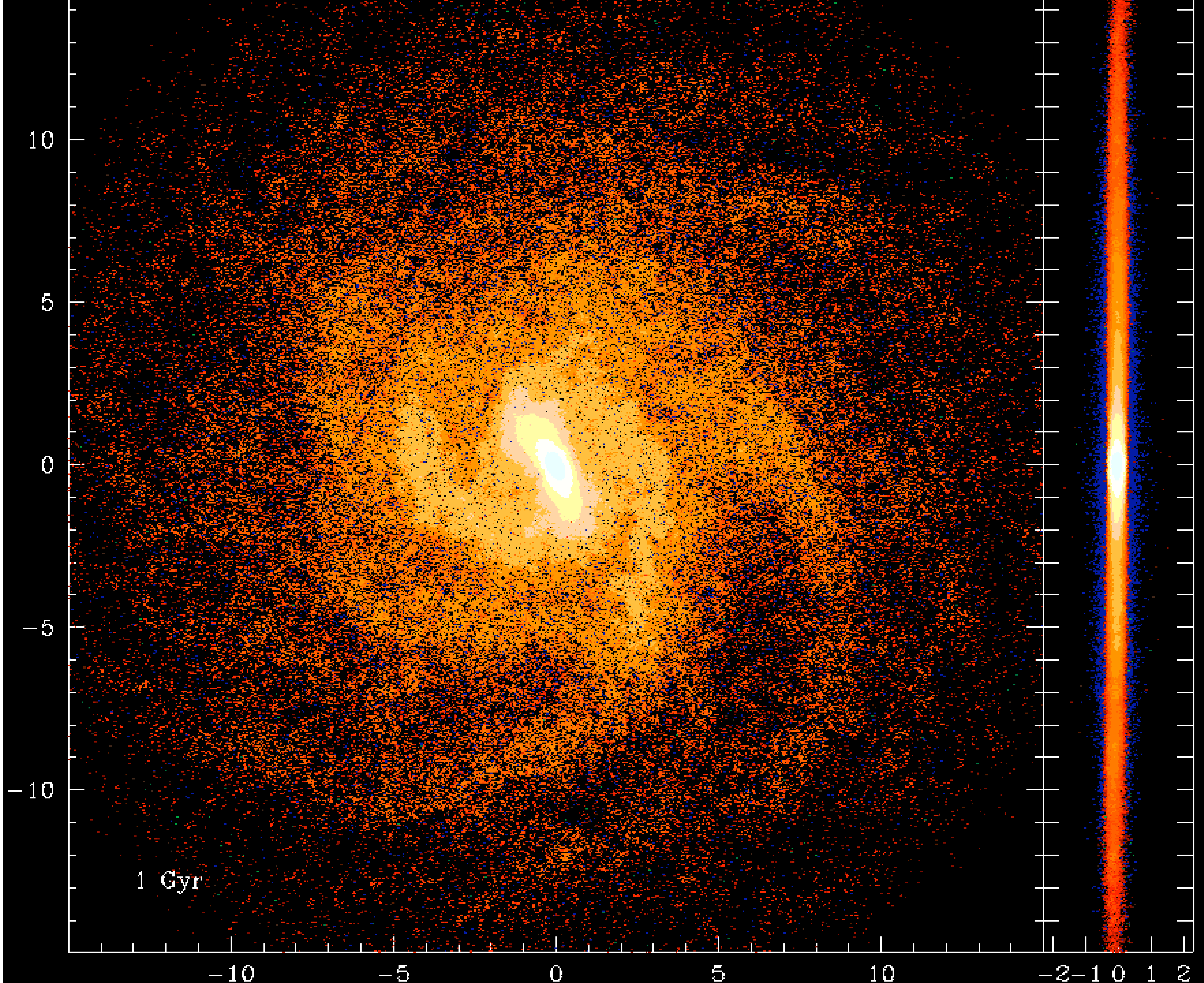
2



10
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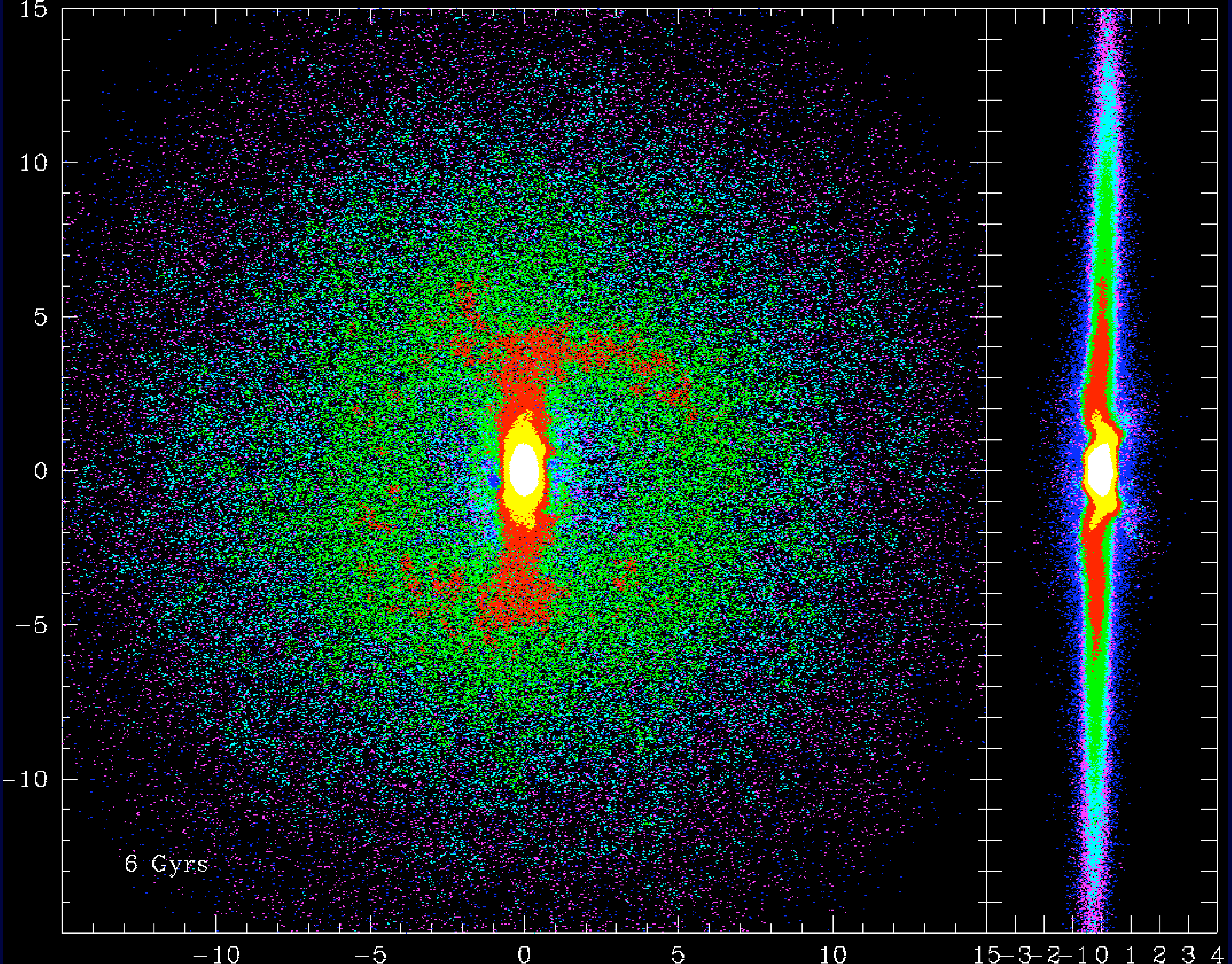
6 Gyrs
15
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−5
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15
−3
−2
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0
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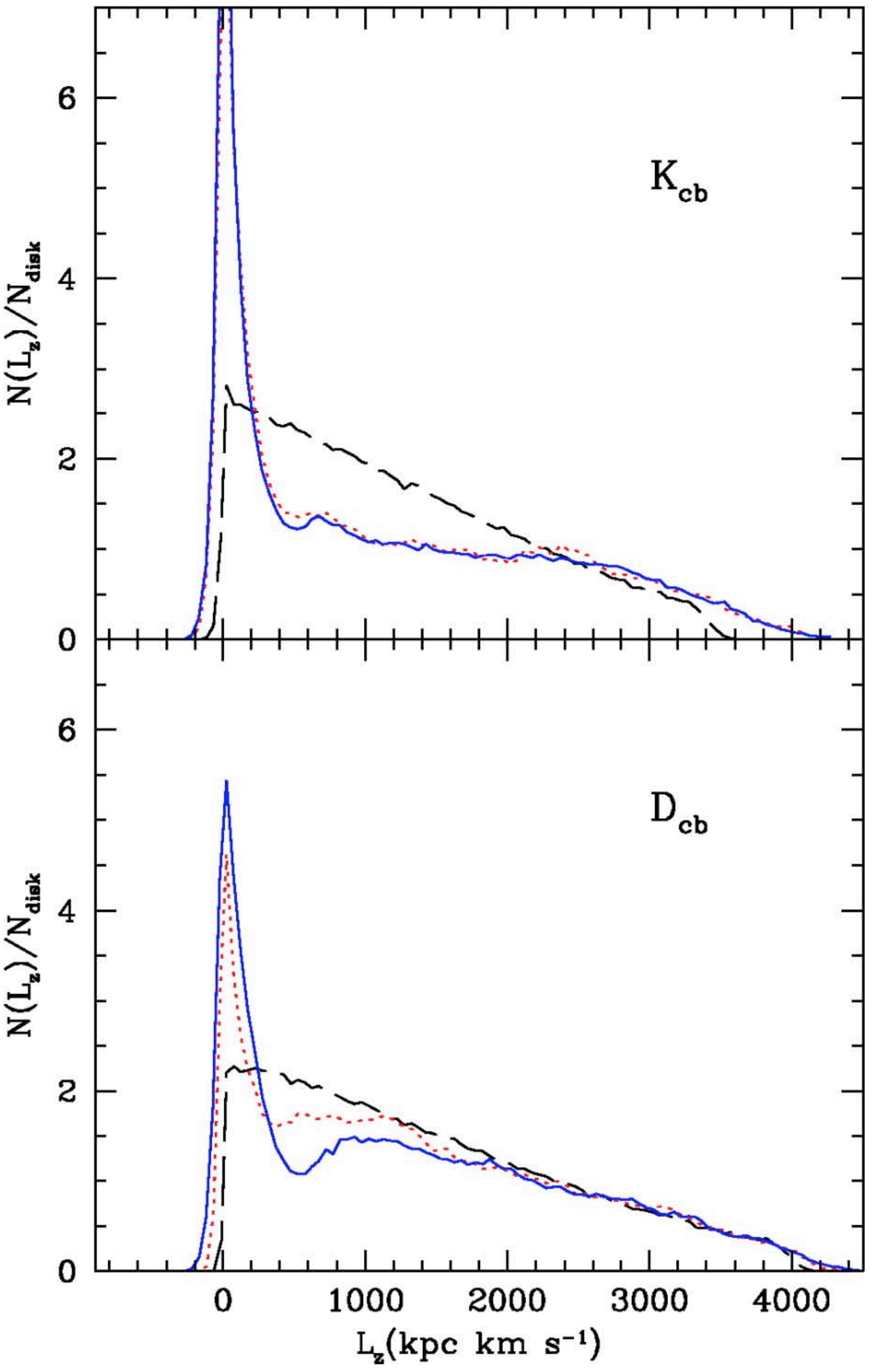
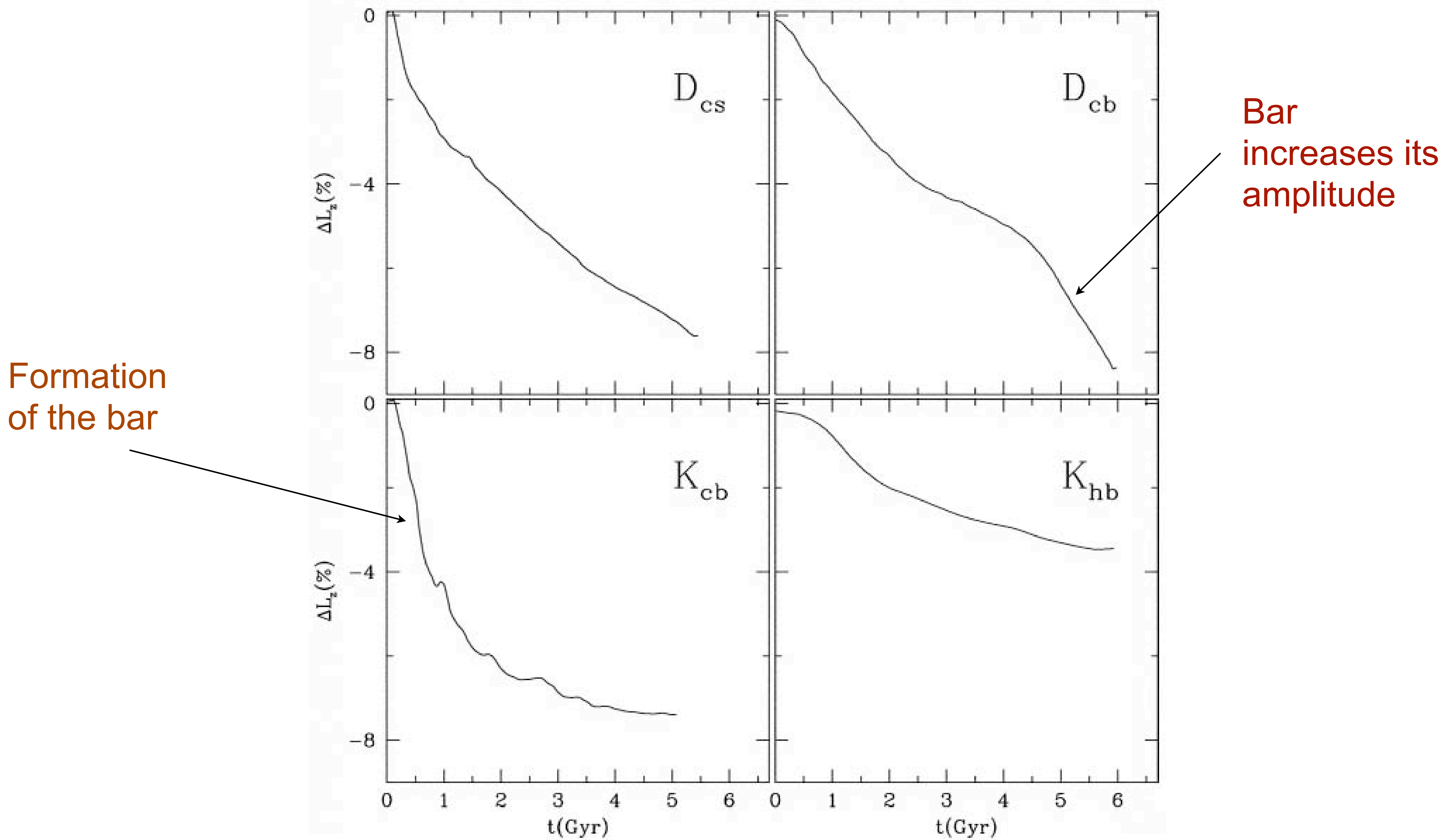
2
3
4

Evolution of the angular momentum

- Examples of different systems. Plots show distribution of z component at different moments. Dash curves are t=0. Dotted -> 1.6Gyrs. Full is for t=5Gyrs.
- Most of the change happens during the first 0.5Gyr when the bar forms. The peak at small Lz is the central part of the bar. It has very little rotation. It is made of stars, which initially had substantial angular momentum.
- Outer parts of the stellar disk increase the angular momentum because they absorb large fraction of Lz lost by the inner part. About 5% of the disk angular momentum is lost to the dark matter halo



Evolution of the disk angular momentum for four models. We show two models, D_{cb} and D_{cs}, that end up with strong bars at the end of the simulated period and two other models, K_{cb} and K_{hb}. Model D_{cb} presents an inflection point or zone, in which the rate of angular loss changes its decreasing trend to an increasing one. This time coincides with the second period of bar growth.



Evolution of pattern speed and bar amplitude

Convergence study:

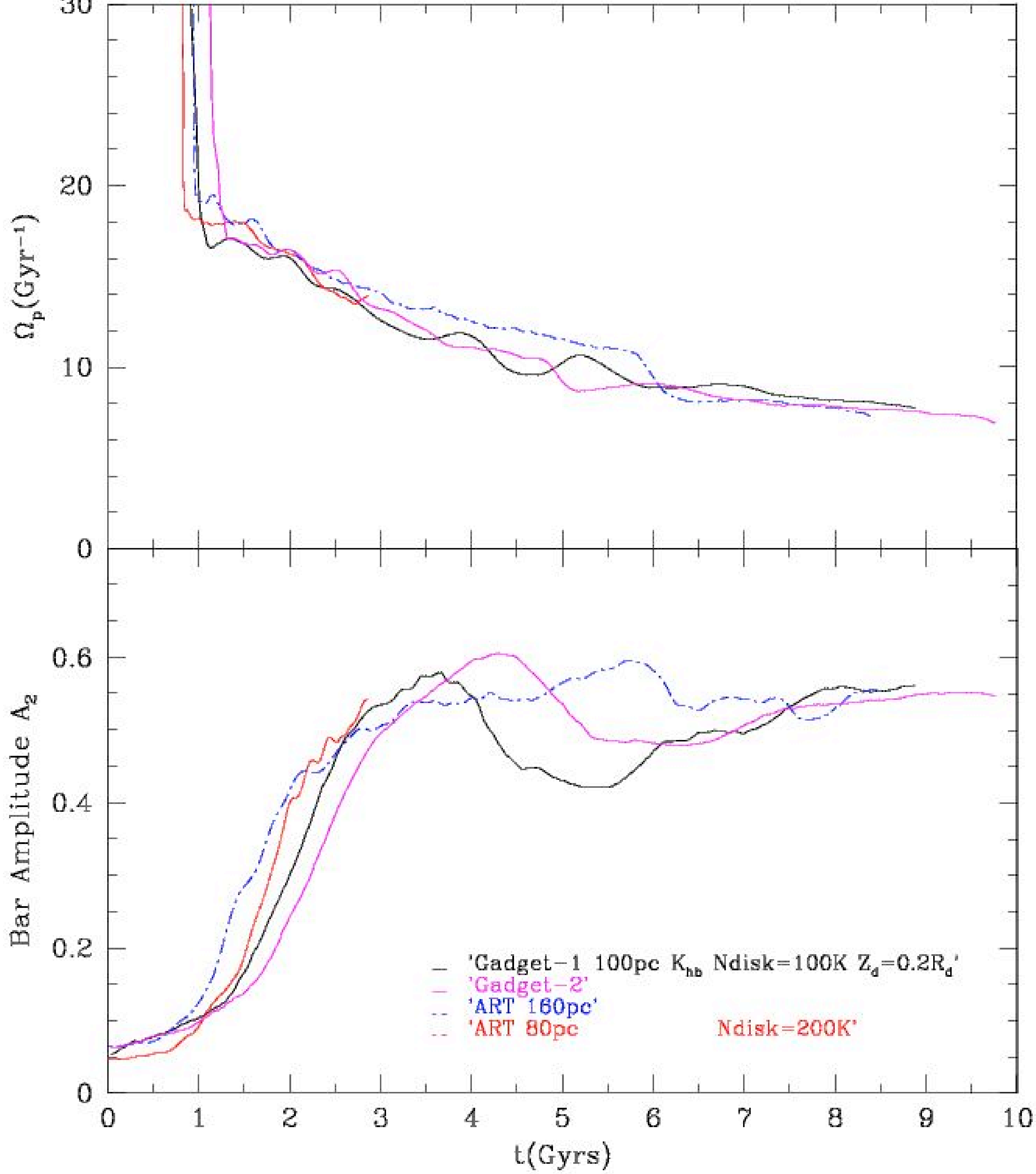
The same initial conditions run with different codes:

ART GADGET

System: Thick and Hot (Q=1.8) disk

Inside NFW halo.

Total: 2M particles



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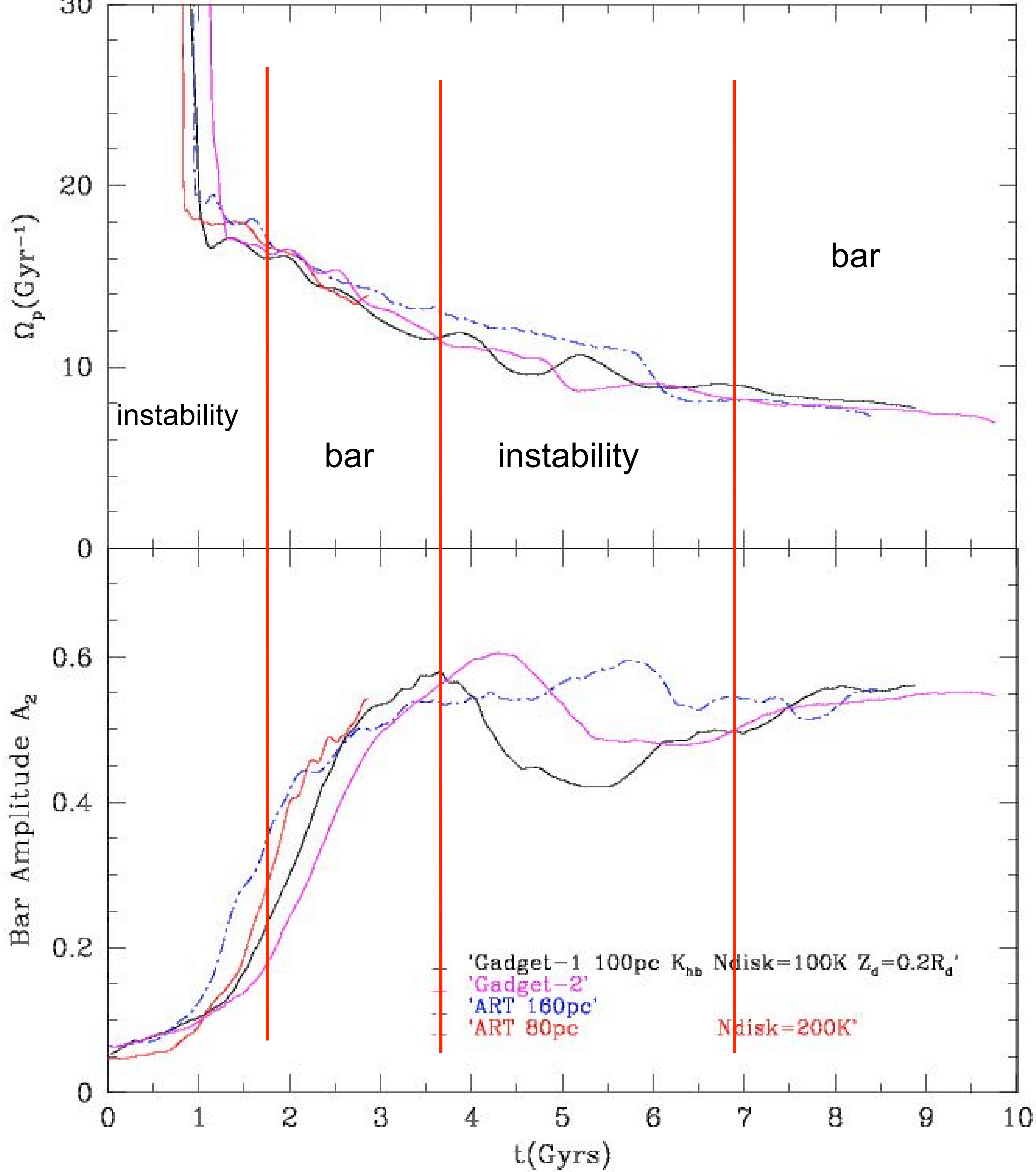
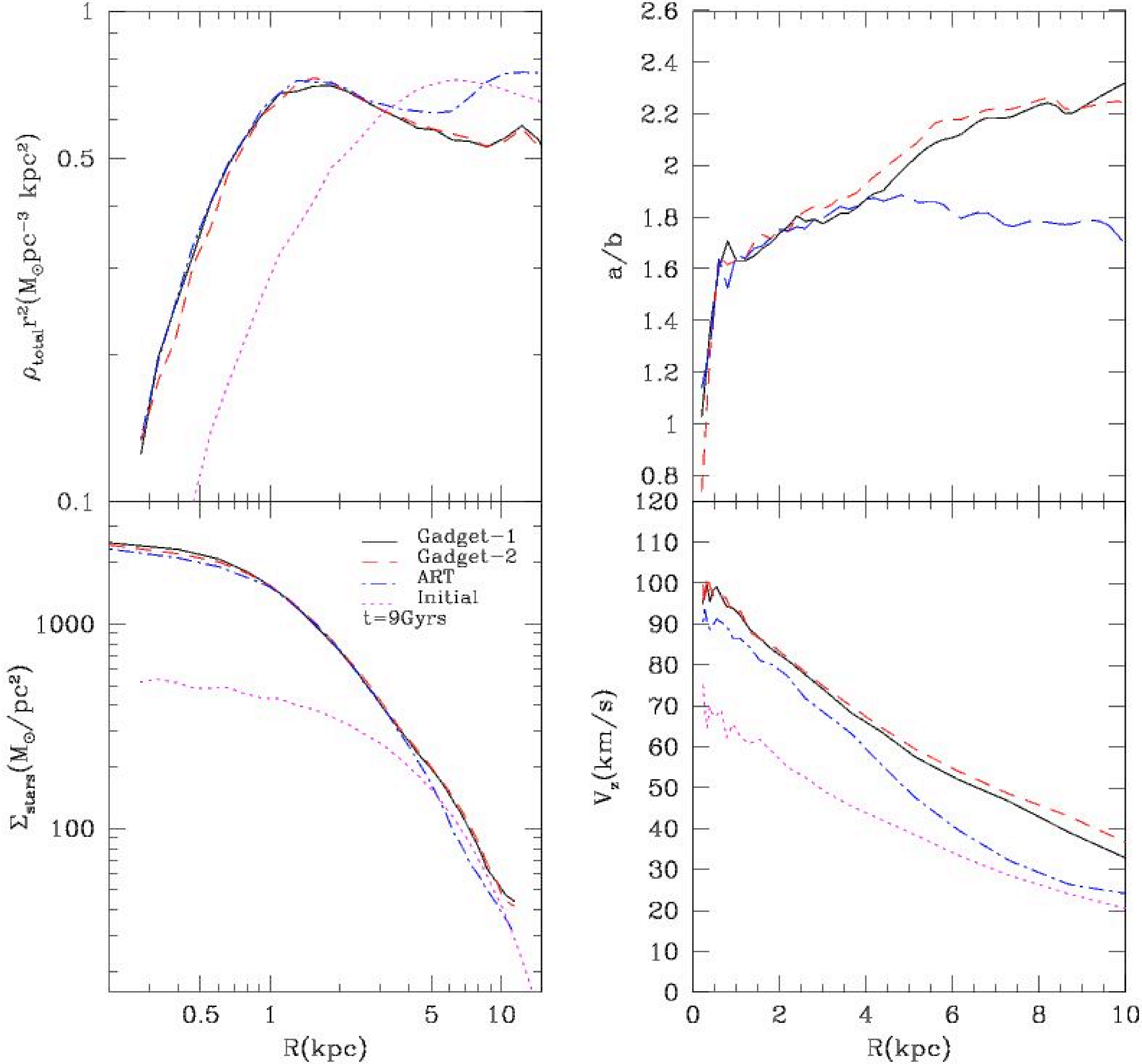


Changes in the structure of the disk

Example of a very long bar

a/b is the ratio of bar axes. Dotted curves are initial conditions

Most of the changes happen in the central 5kpc region

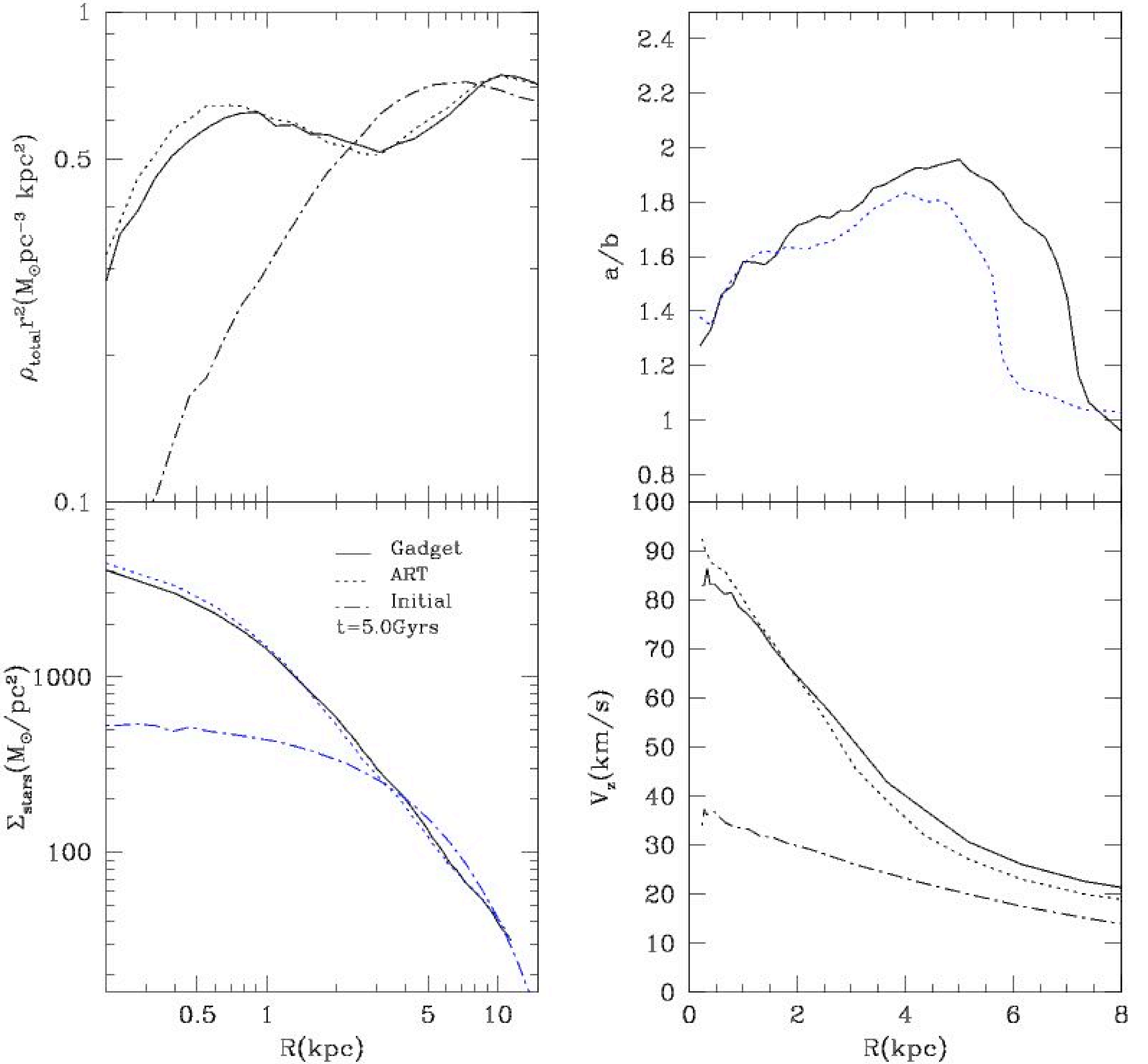


Changes in the structure of the disk

Example of a shorter and more dense bar

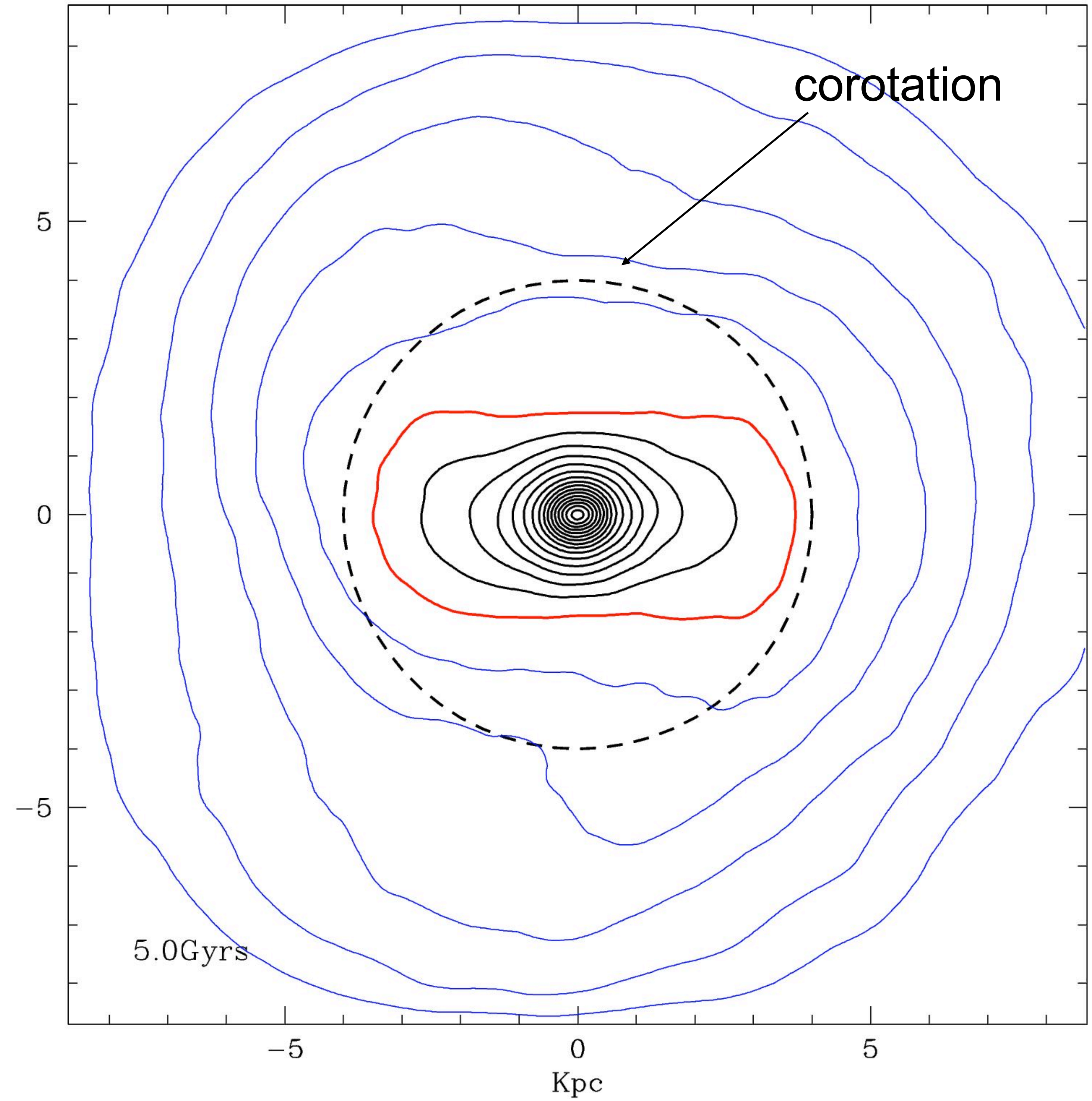
Features:

- Total density is almost r^{-2} starting from 0.5kpc and extending to 20kpc
- Center is getting denser and hotter.
- Very little change in the outer r>5kpc region
- Disk exponential length growth by factor 1.1-1.5



Comparison of one of the models with the Milky Way galaxy:

Model	MW
Rd=3kpc	2.5-3.5
Σ(8kpc)=54 Msun/pc^2	48±8 **Kuijken&Gilmore 89** 67 **Siebert etal 03**
V_r=47kms V_z =20km/s at 8kpc	40/17 kms Dehnen&Binney 98
Ω_{bar} =54Gyr^{-1}	Ω_{bar} =60±5Gyr^{-1} **Bissantz etal 03**



Mdm/Mtot =0.6 at 8kpc

Mdm/Mtot =0.35 at 3kpc

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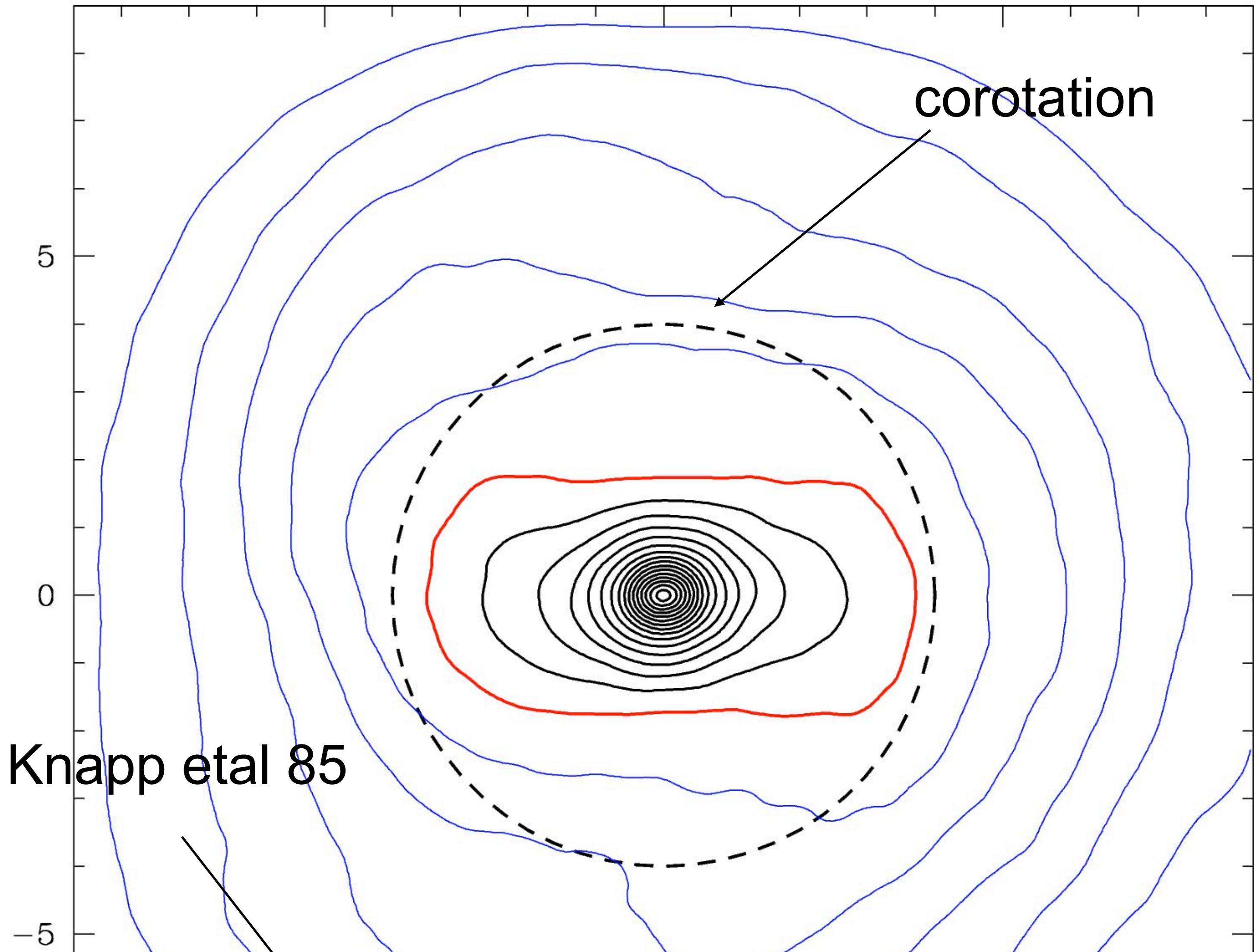

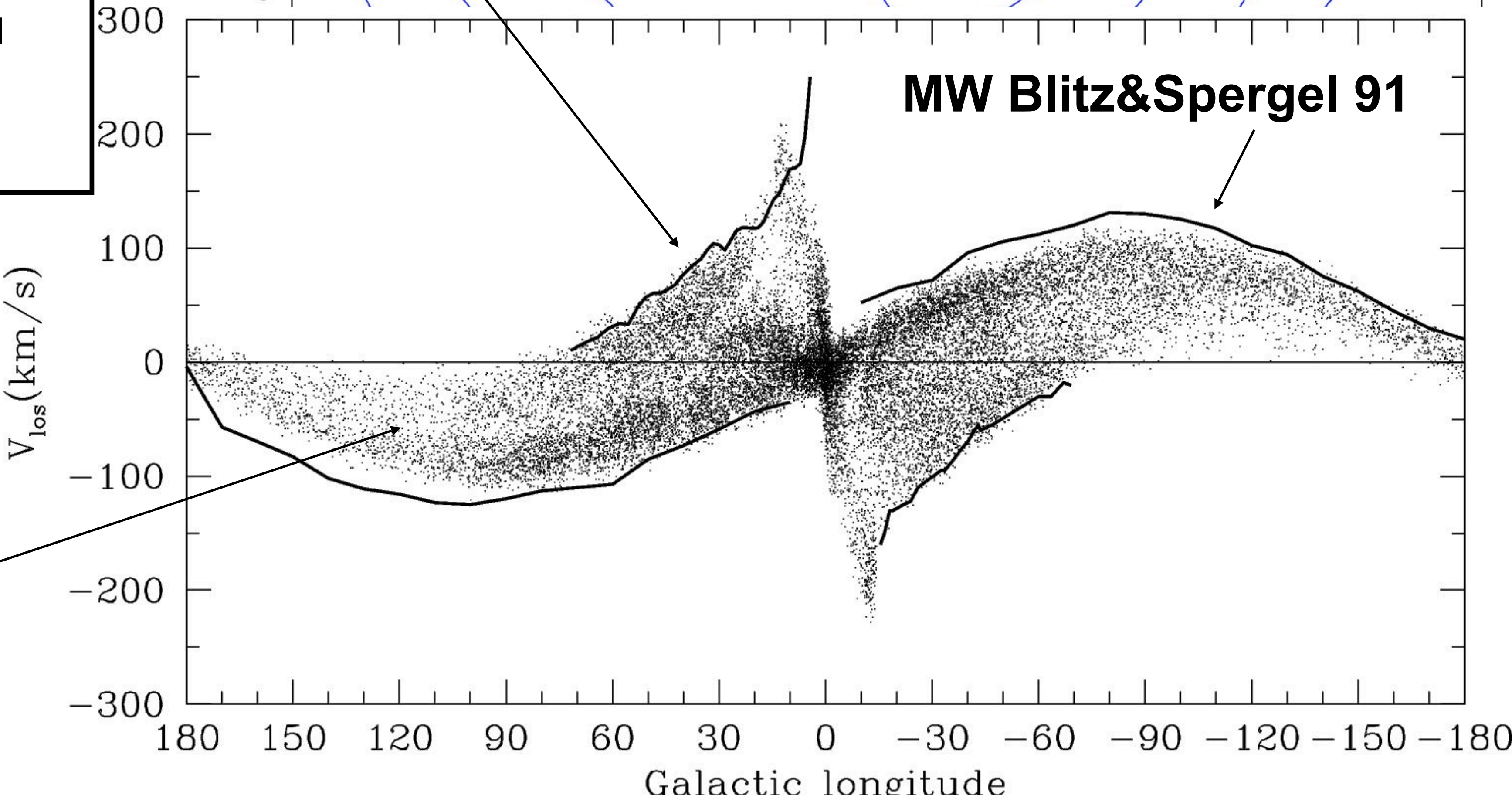

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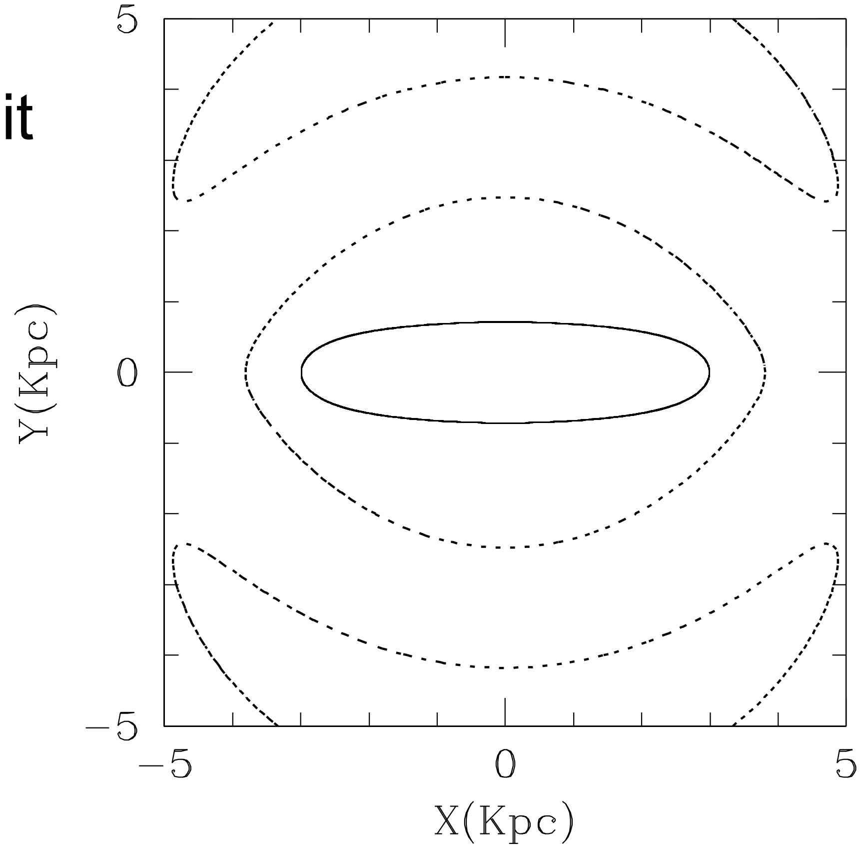
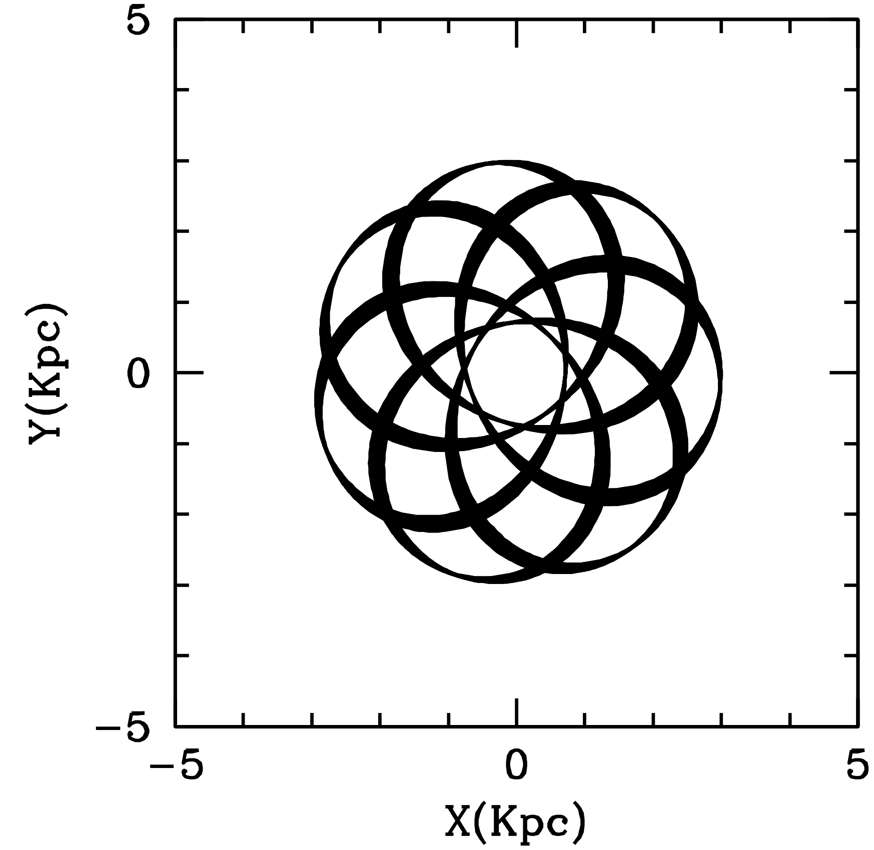
'cold' particles in model

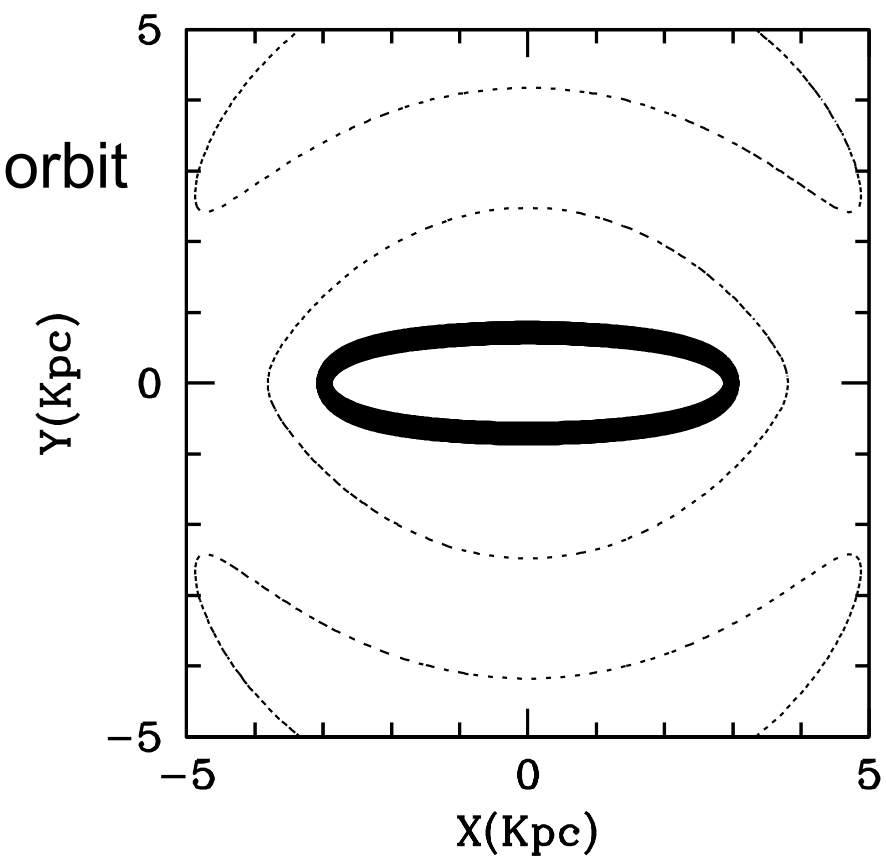
Orbits of stars in rotating and nonrotating frames

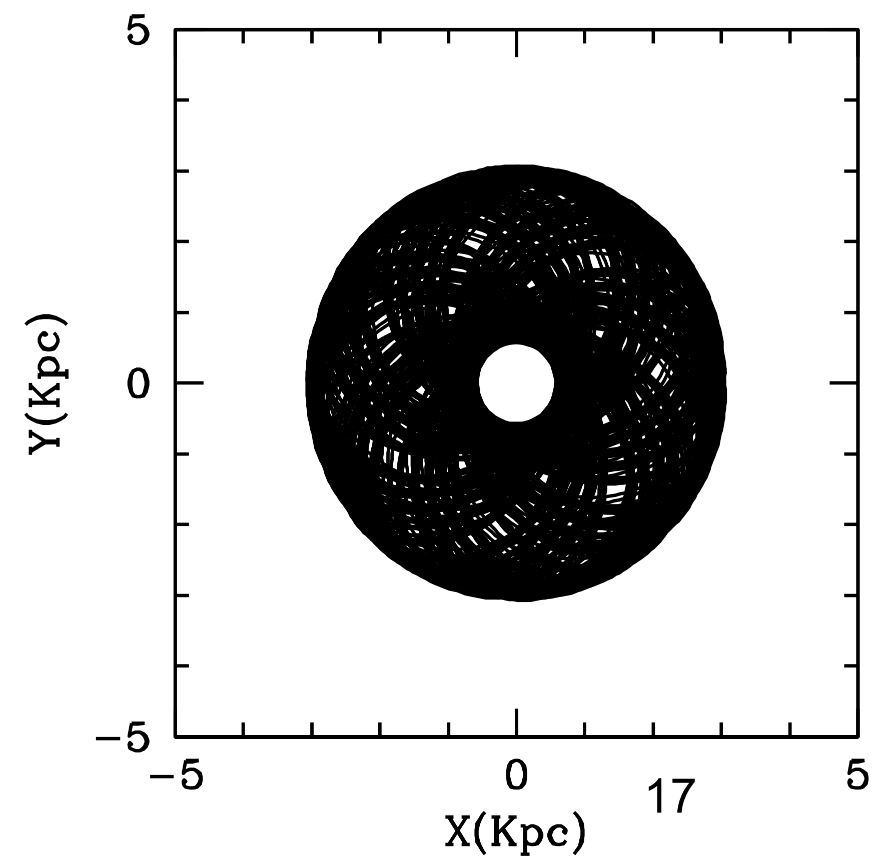
Closed (resonant) orbit





Tube (non-resonant) orbit





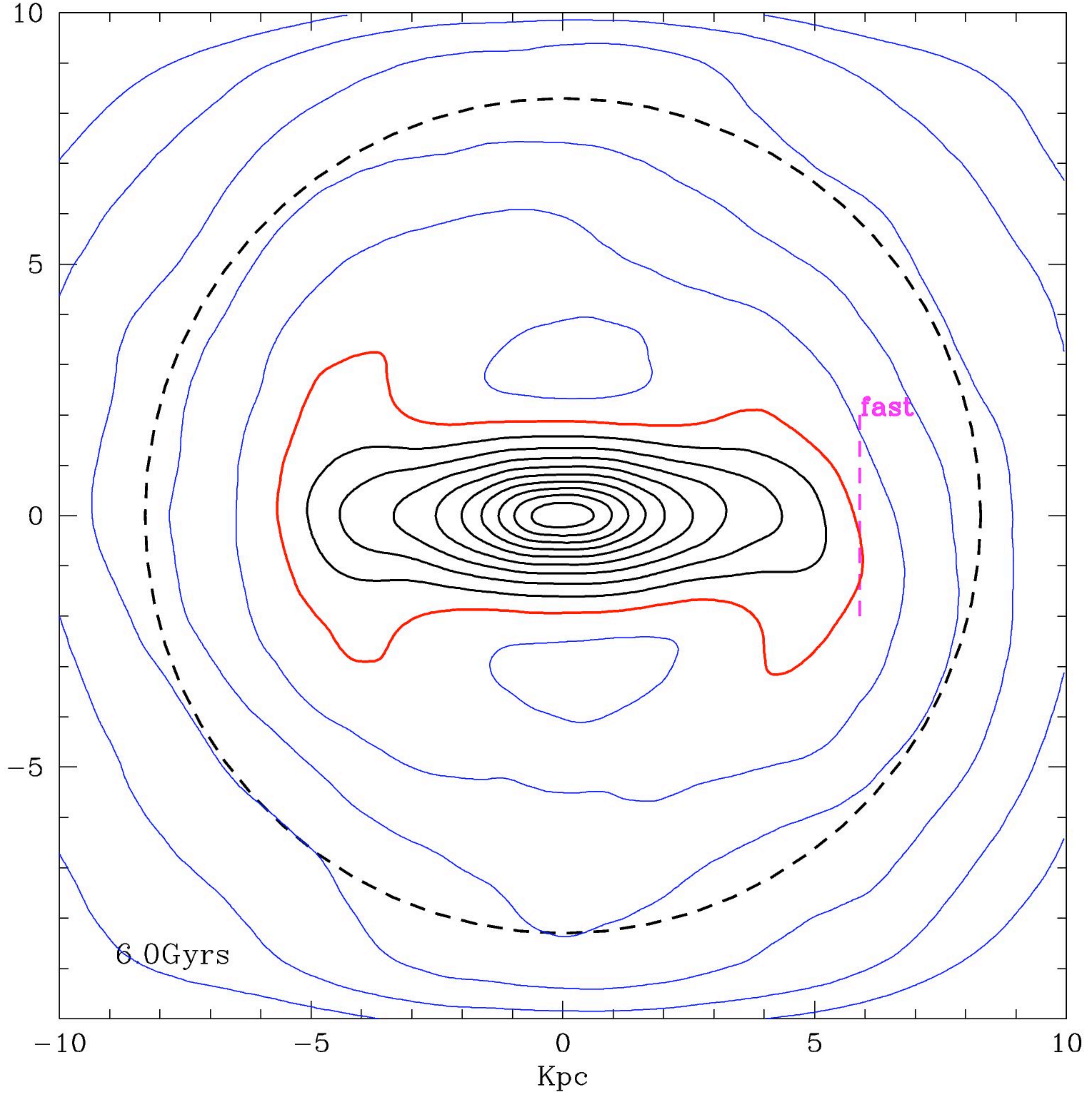
Resonances

- Each orbit has three frequencies:
  - radial (or epicycle) frequency κ
  - tangential Ω
  - vertical frequency κ_z
- An orbit is resonant if there are three integers l, m, n such that

$$l\kappa + m\Omega + n\kappa_z = m\Omega_p$$

  where Ω_p is the frequency of the bar (= pattern speed)
- For planar motions in the plane $n = 0$
- Different resonances:
  - Inner Lindblad resonance (ILR): l=-1, m=2
  - Corotation resonance (CR): l=0
  - Outer Lindblad resonance (OLR): l=1, m=2

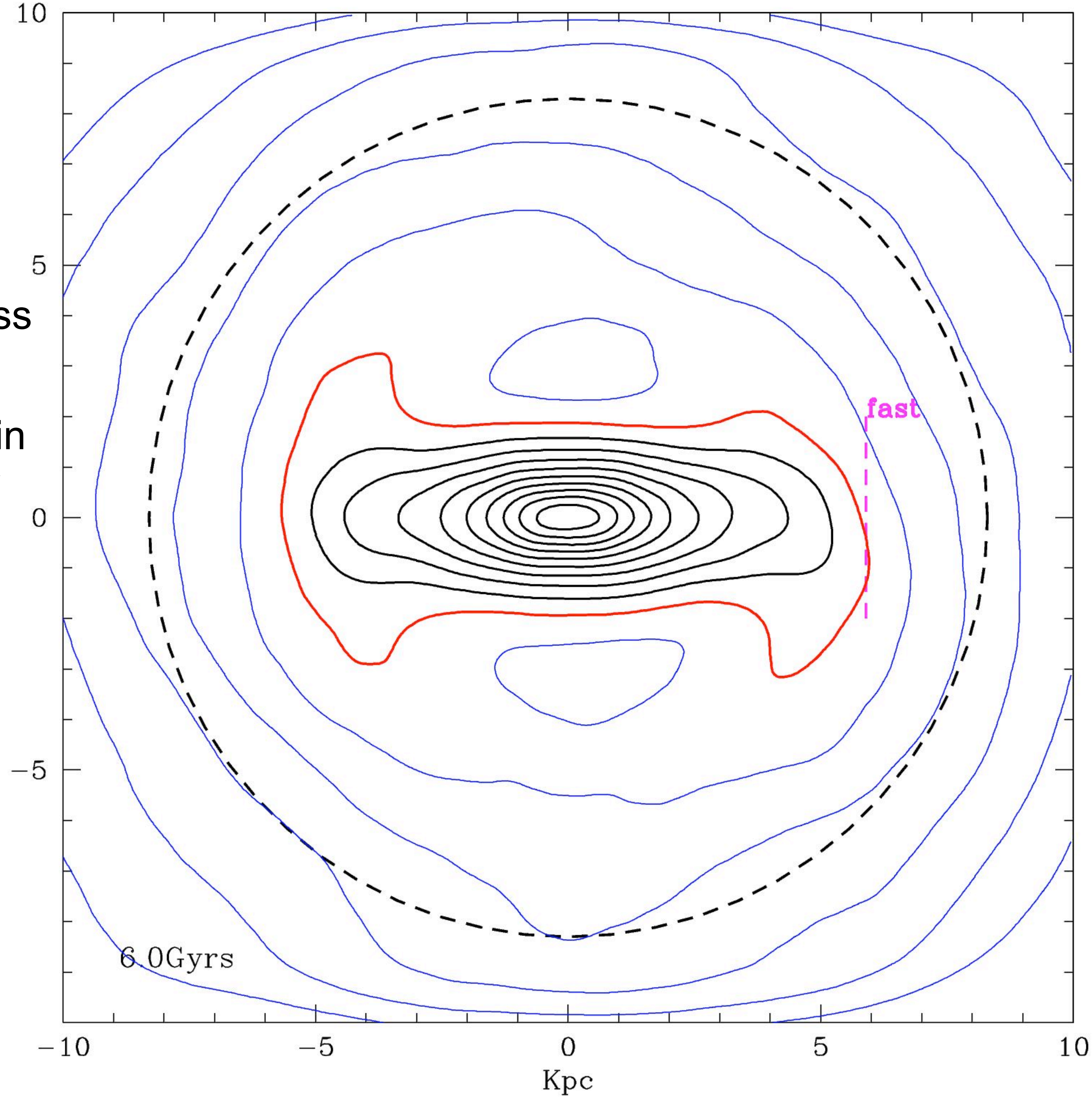
Resonances



Resonances

Misconcepts:

- Once at resonance, a particle experiences very strong gain or loss of energy and angular momentum
- Resonances are narrow regions in the phase-space, which can easily be missed
- A particle should stay a very long time at resonance to get an effect: “lingering of orbits”
- Corotation is a spesific radius

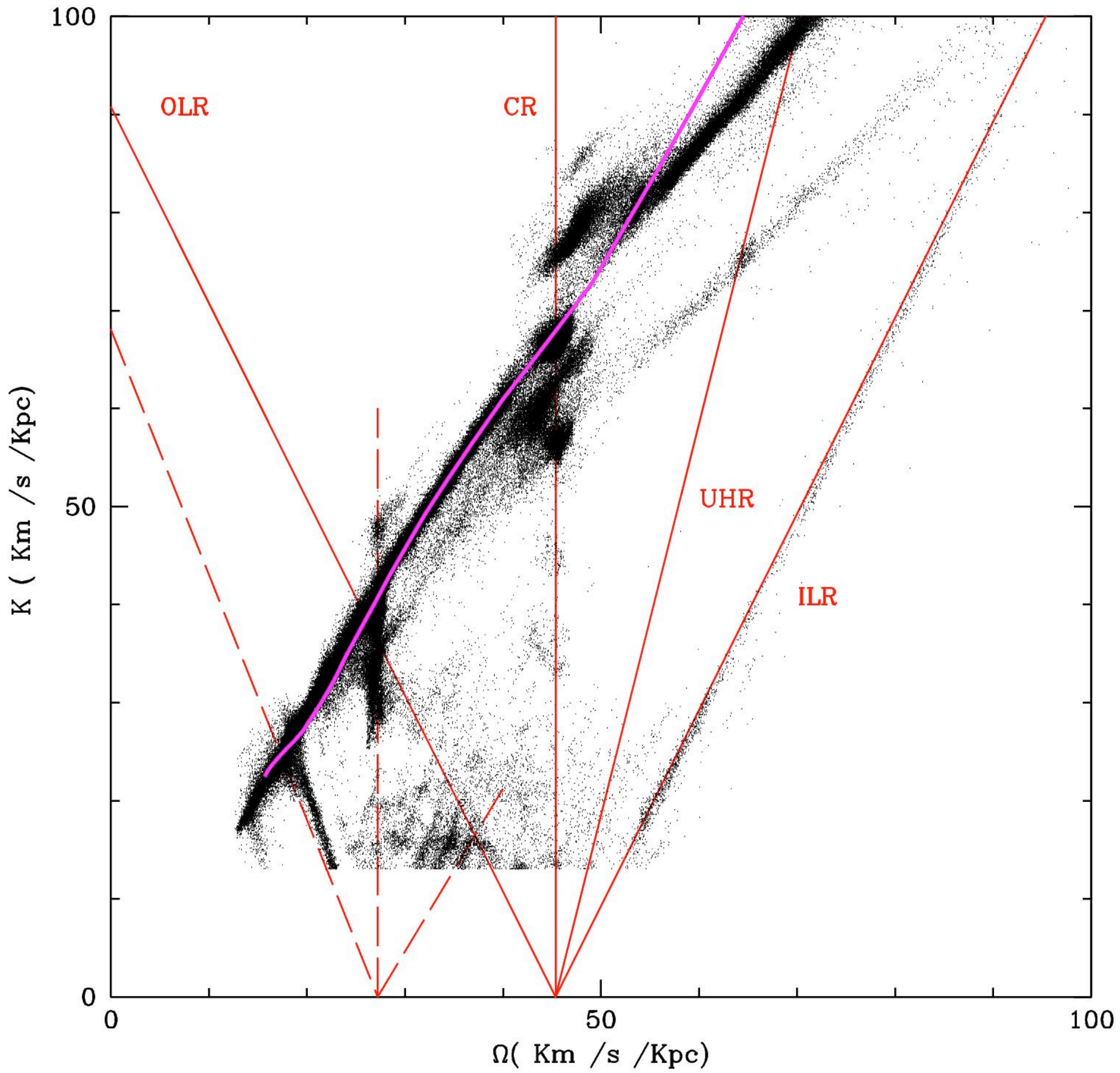


Resonances.

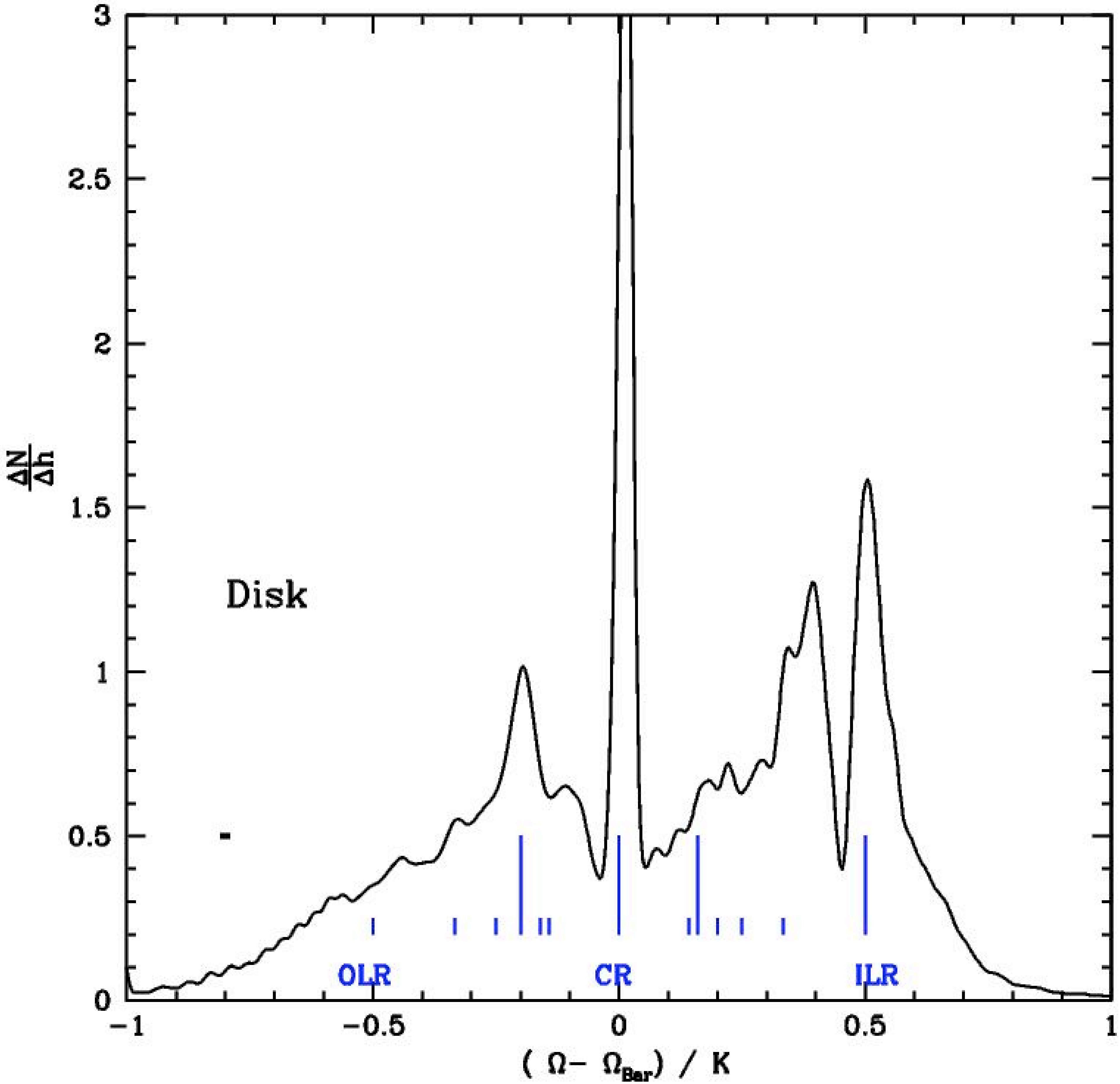
Frequencies of orbits:

Radial (K) and tangential (Ω) of orbits

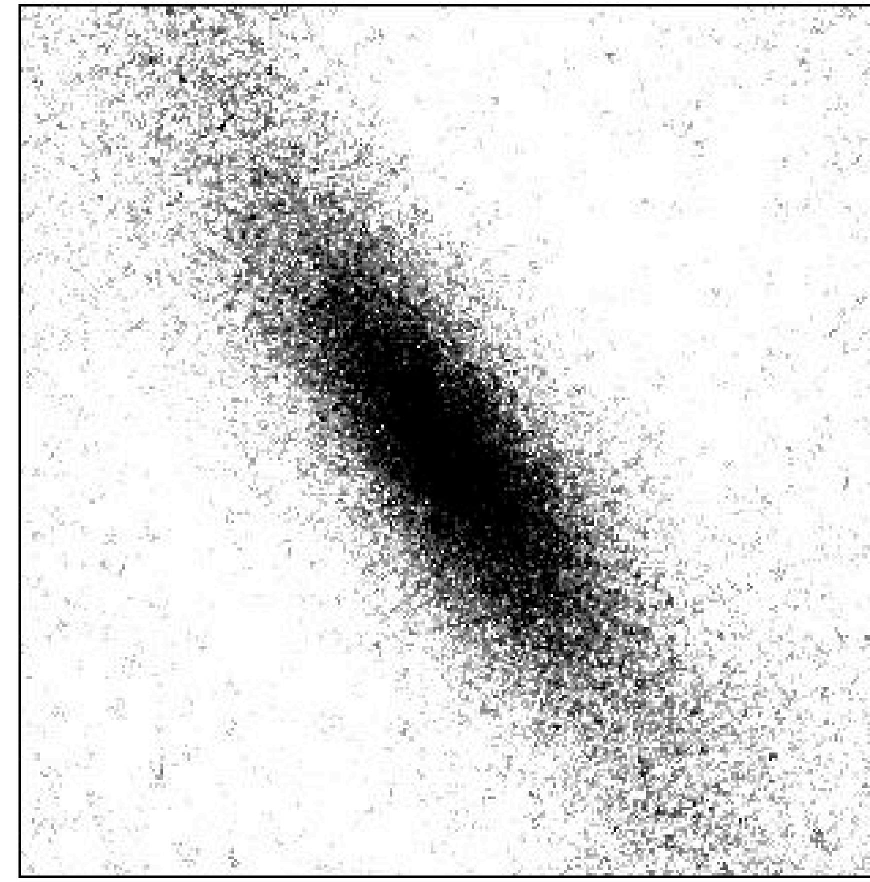
Frequency of Bar



Resonances: distribution of frequencies indicates that resonances are trapping: orbits accumulate at resonances

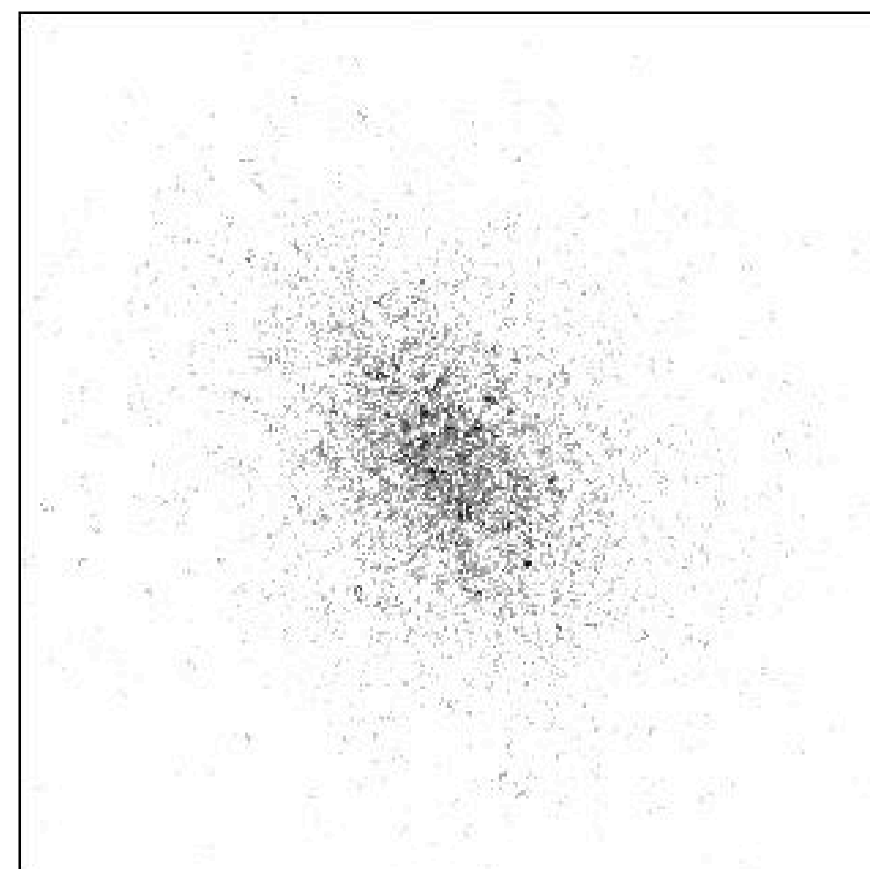


Stellar Bar: 10kpc frame

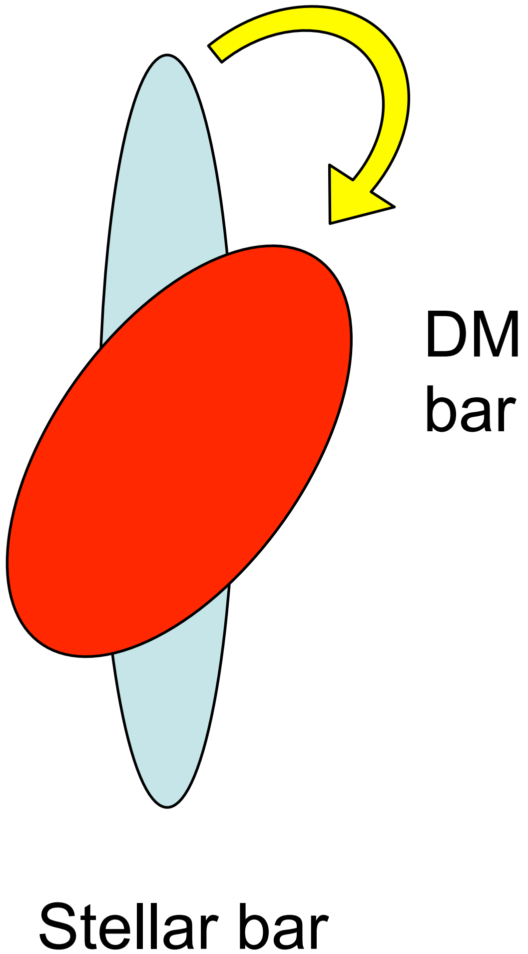


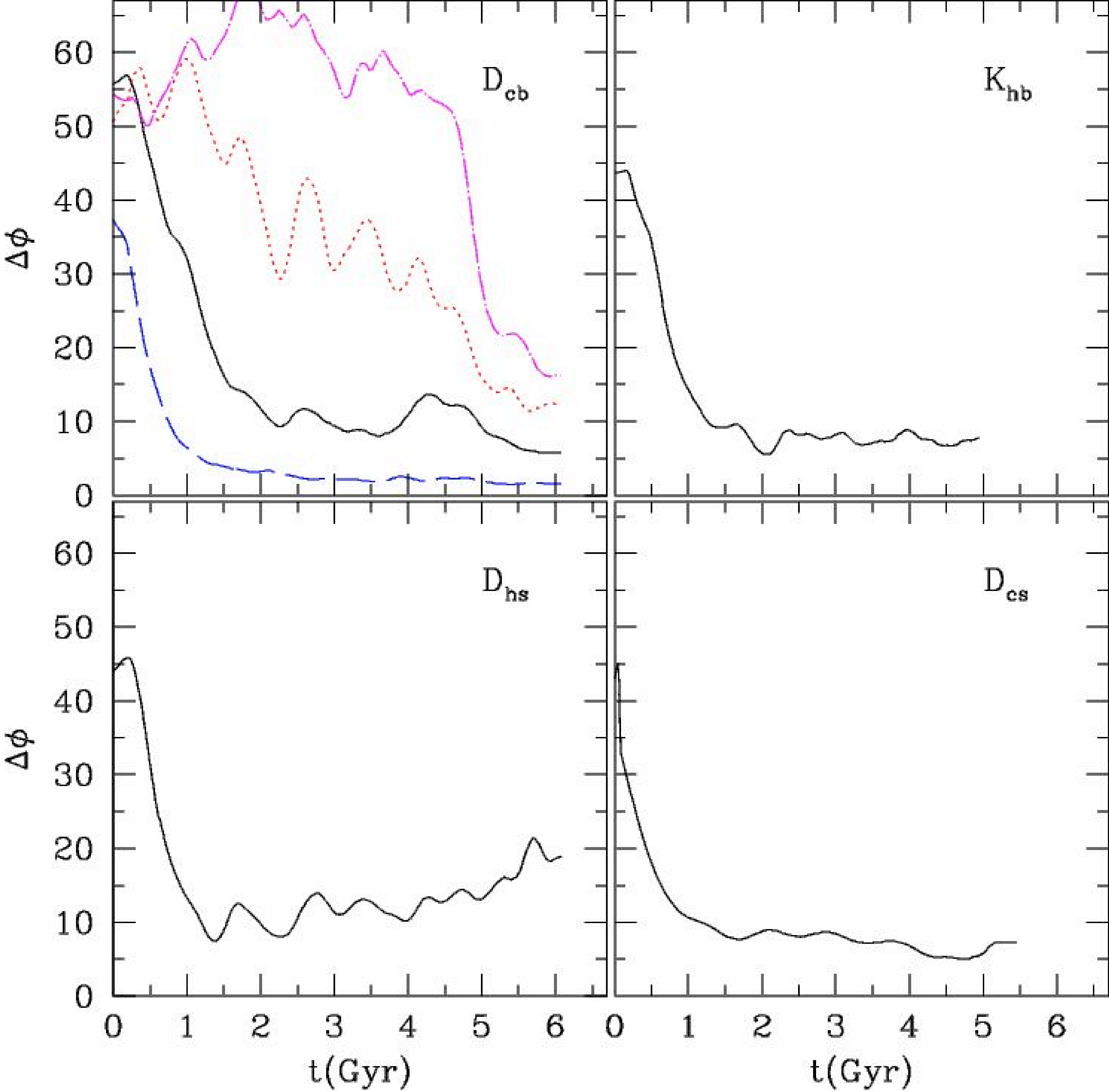
Dark matter forms a BAR, which rotates and tracks the stellar bar

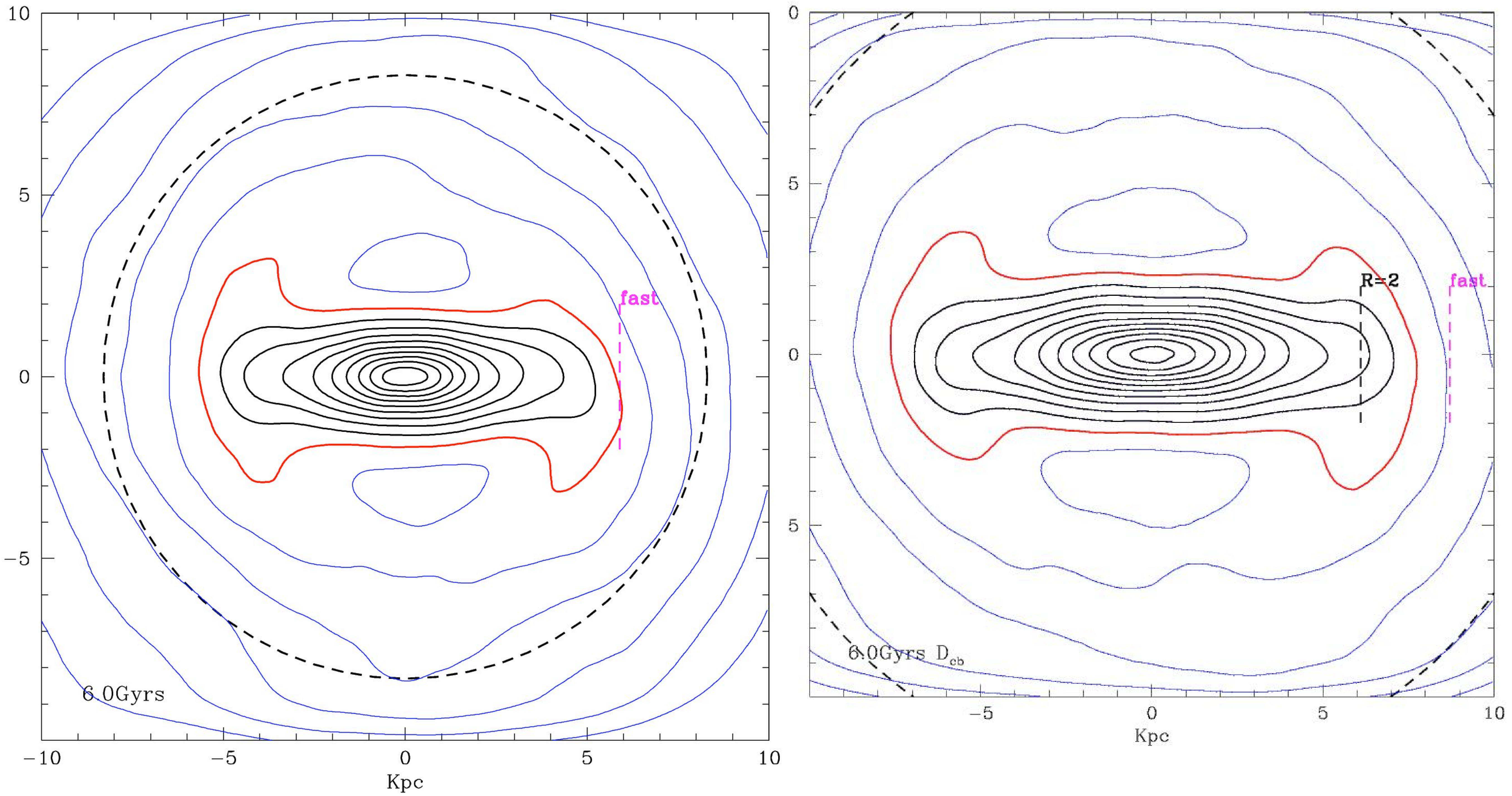
Dark matter Bar: rotates with the stellar bar with a small lag



Evolution of the phase lag between the stellar and the DM bars



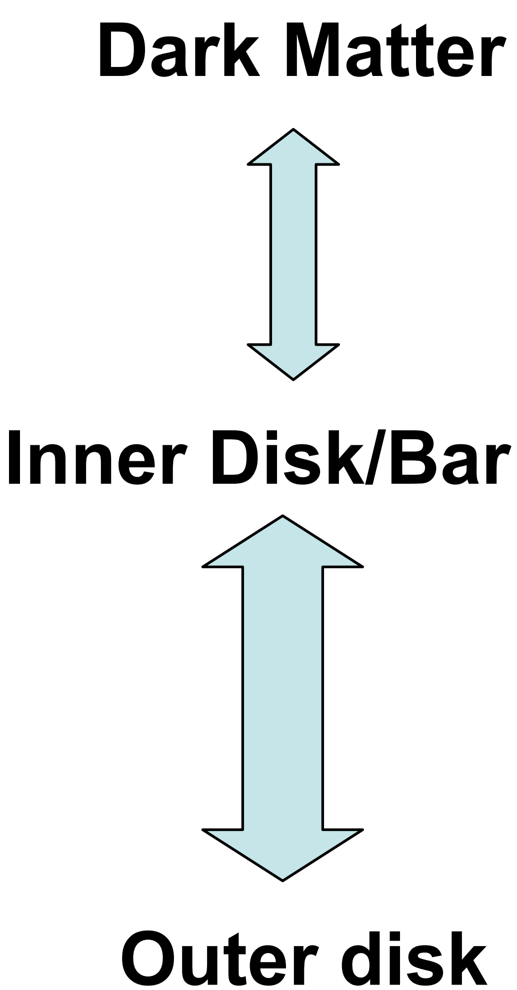




Fast or Slow Bars?

Trends:

- **Dynamical friction makes slower bars (M.Weinberg 85, D&S 2000)**
- **Stronger bars are longer (Athanassoula&Misiriotis 2002)**
- **More concentrated bars are weaker**
- **Hotter halos and disks experience less friction**



Friction slows the bar

Trends:

- **Dynamical friction makes slower bars (M.Weinberg 85, D&S 2000)**
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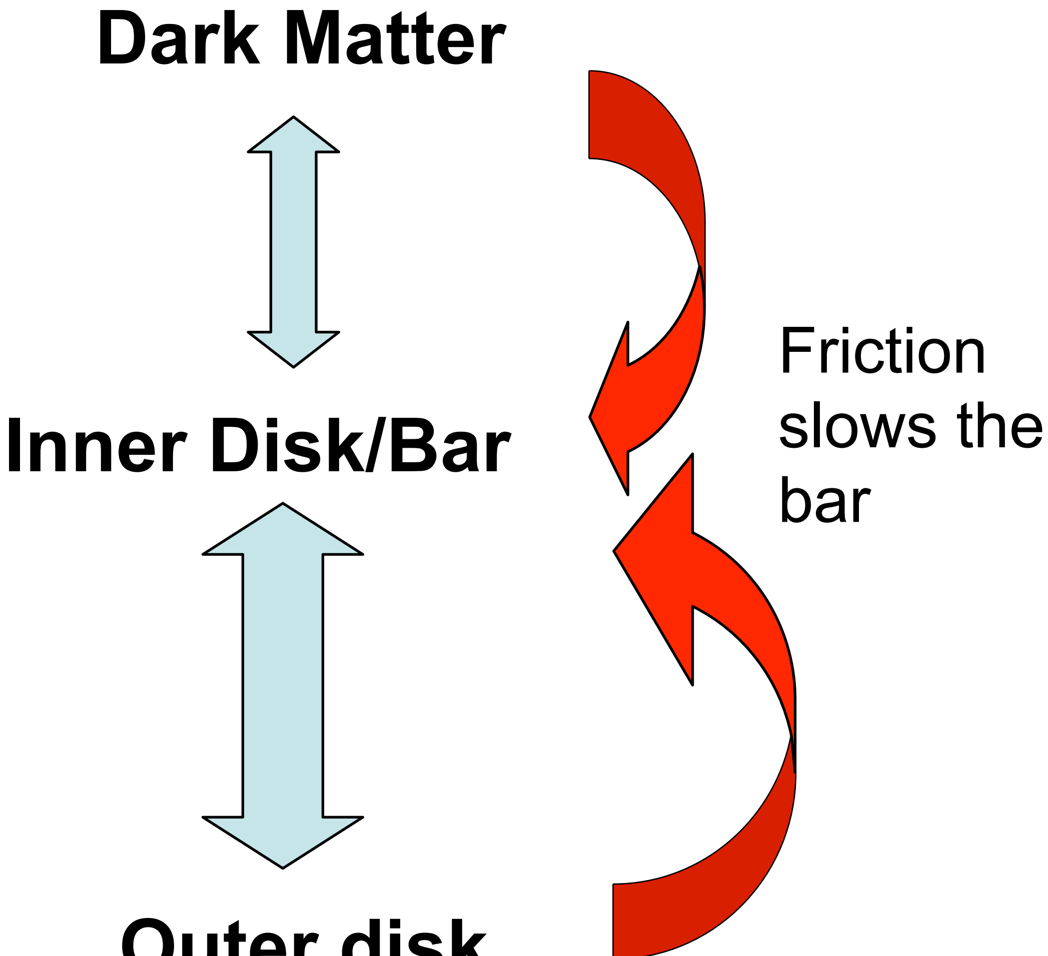

Trends:

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