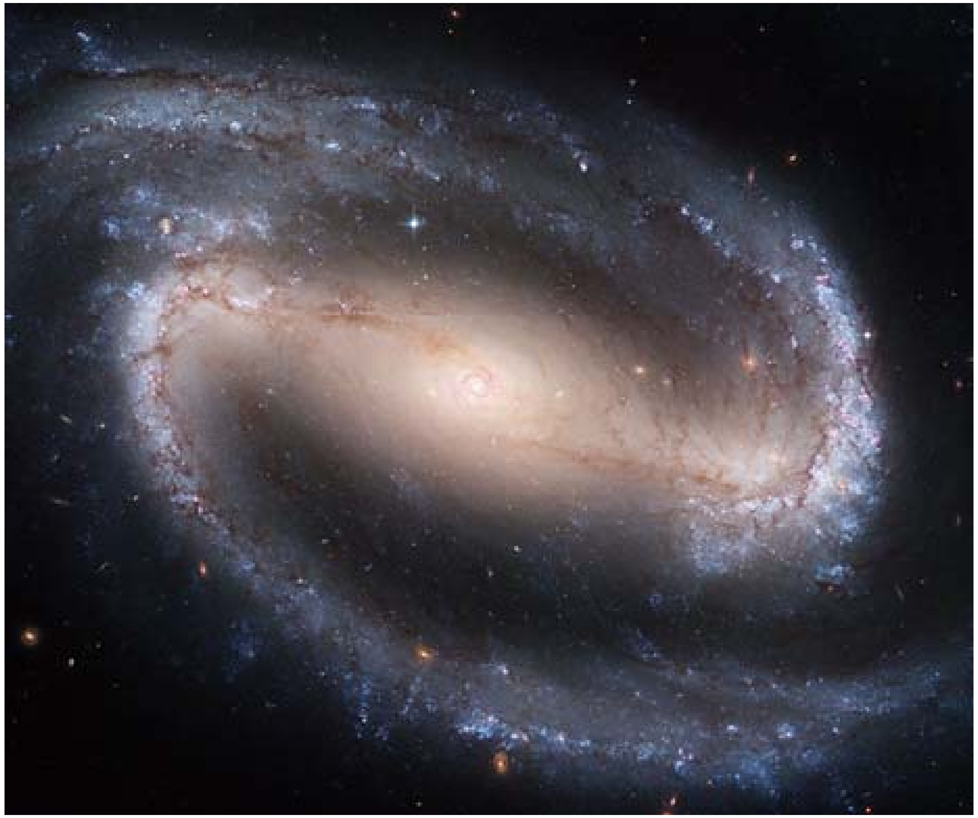
Physical Properties of Gaseous Features In Barred Galaxies: Effects of the Bar Strength

The 8th ASTRONUM@Biarritz, France

July 3, 2013



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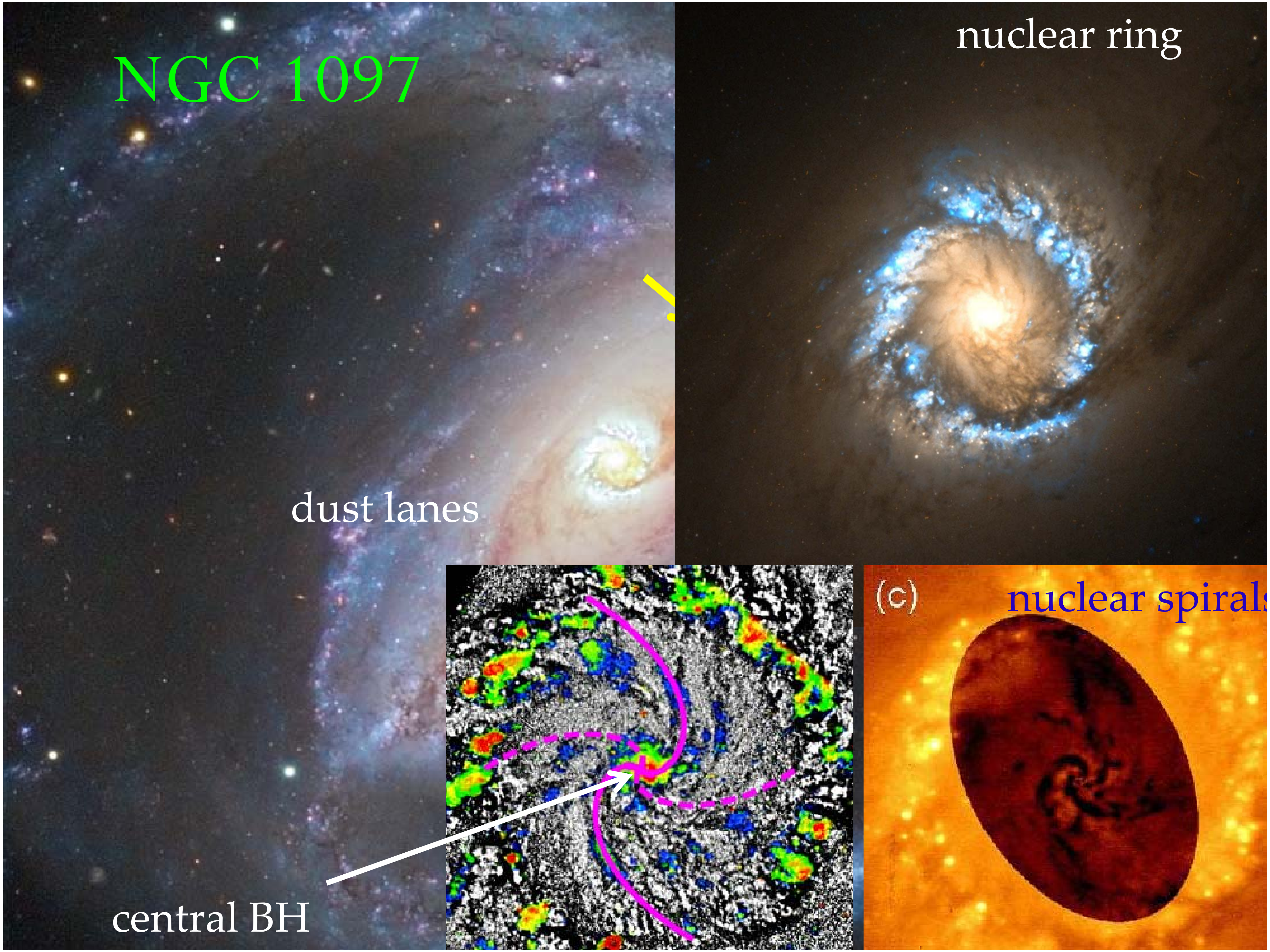
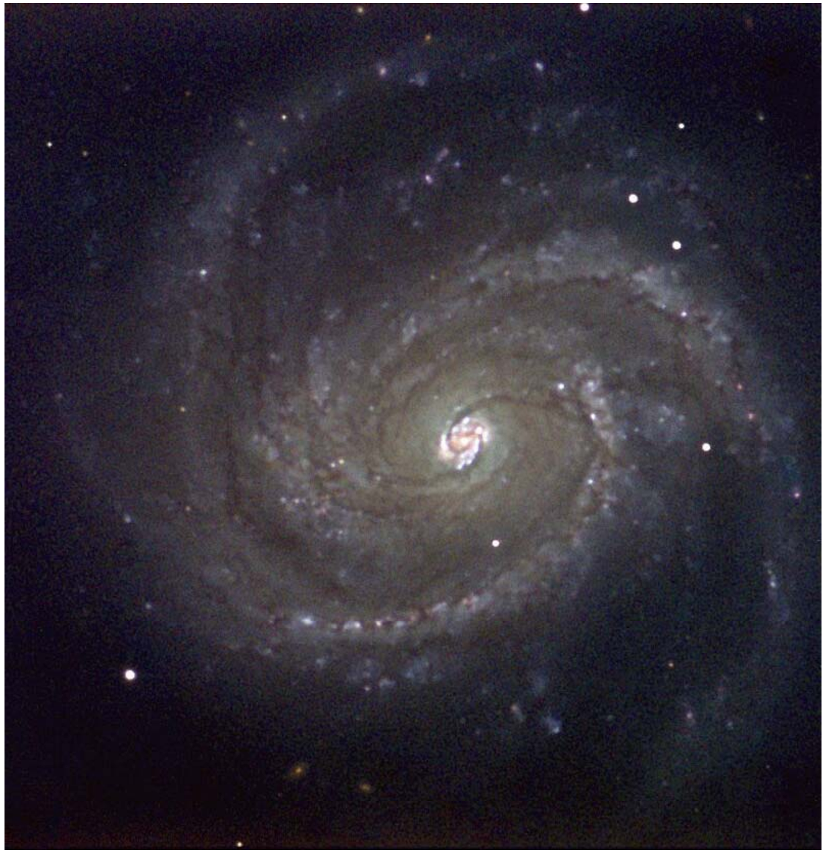

NGC 1097
nuclear ring
dust lanes
(c)
nuclear spirals
central BH

- Some galaxies have relatively straight dust lanes, while others have curved ones.

NGC 6951: $\Delta\alpha=9^o$

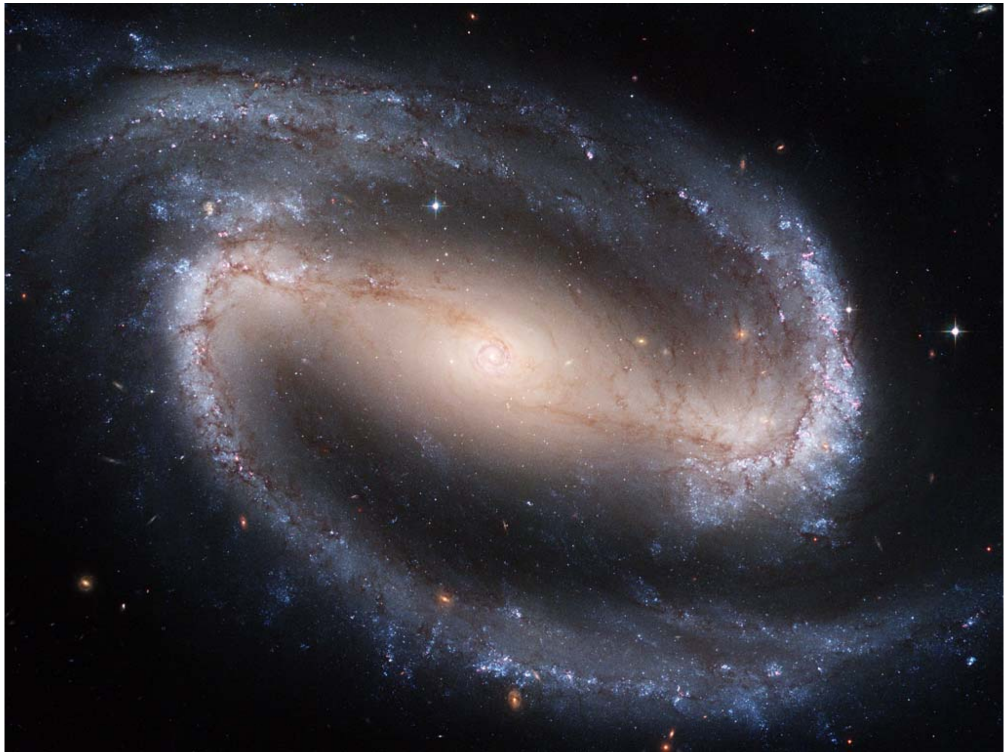


NGC 4321: $\Delta\alpha=73^o$

Comeron et al. (2009)

- Some galaxies have a relatively large nuclear ring, while others have smaller one.

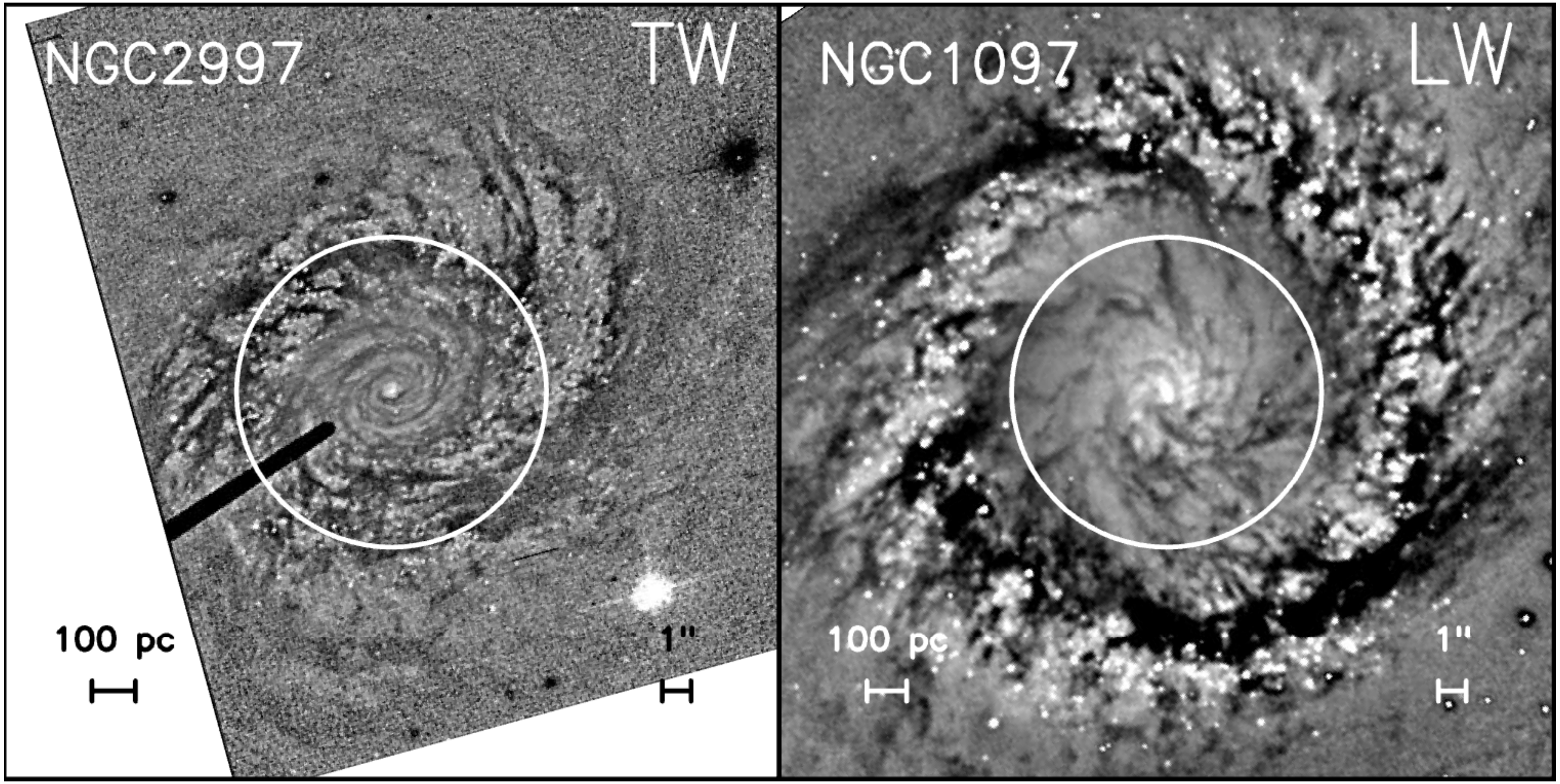
NGC 1343: 1.2kpc × 0.9kpc



NGC 1300: 0.3kpc × 0.2kpc

Mazzuca et al. (2009)

- Some galaxies have tightly wound nuclear spirals, while others have loosely wound ones.



Peeples & Martini (2006)

Nuclear Rings

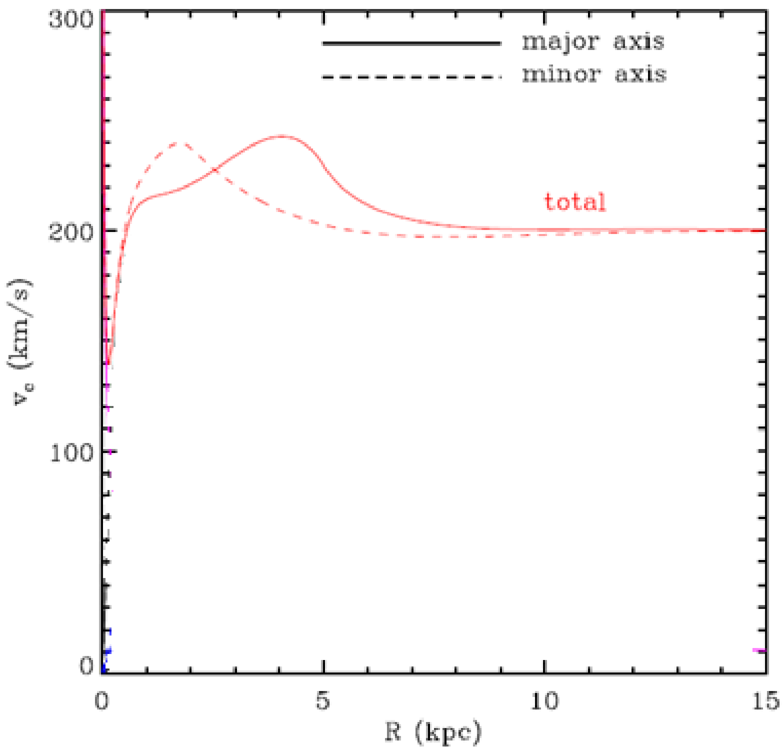
- Regarding nuclear rings, it has been widely accepted that rings form via **resonant interactions** of the gas with the bar potential.
  - This notion was driven by the fact that observed nuclear rings are located near the **inner Lindblad resonances** (e.g., Combes & Gerin 1985; Knapen et al. 1995; Comeron et al. 2010).
- Yet, there is no convincing theoretical argument.
  - Bar torque is very week near the ILRs.
  - Resonance is a secular process, occurring over a very long time scale.
  - Resonance tends to disperse the material, rather than gathering it (e.g., gaps in planetary rings and the asteroid belt).

Bar Model

- A normal galaxy with flat rotation at v_c~200 km/s in outer parts
  - M_{BH}= 4x10^7 $M_\odot$
- Bar : **a Ferrers ellipsoid**

$$\rho = \begin{cases} \rho_{\rm bar}\left(1-g^2\right)^n & \text{for } g<1, \\ 0 & \text{elsewhere,} \end{cases}$$
$$g^2 = y^2/a^2 + (x^2+z^2)/b^2$$

  - n=1 (cental density concentraion)
  - Semi-major axis ***a*=5 kpc**
  - Aspect ratio ***R*=*a*/*b* = 1.5 – 3.5**
  - Bar mass $\boldsymbol{f_{bar}}$ = **$M_{bar}/(M_{bar}+M_{bulge})$ = 8%– 60%**
  - Ω_b = 33 km/s/kpc (R_{CO}=6kpc)



f_{bar}=30%
R=2.5,
M_{BH}=4x10^7 $M_\odot$

Bar Strength

- The most important parameter that controls the properties of bar substructures is the **bar strength Q_b** defined by

$$Q_b = \left.\frac{F_T}{F_R}\right|_{\max}$$

where F_T = tangential force due to a bar

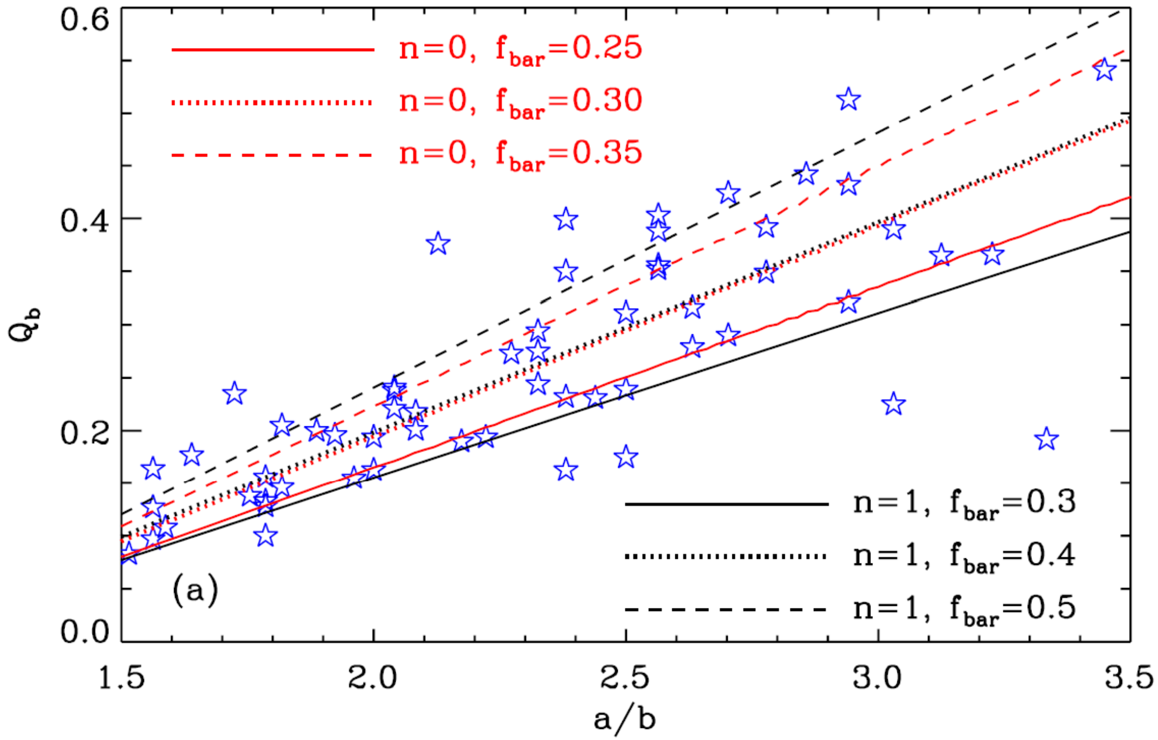
F_R = radial force due to mass distribution

(e.g., Combes & Sanders 1981; Laurikainen & Salo 2002; Block et al. 2004; Laurikainen et al. 2004, 2006; Peeples & Martini 2006; Comeron et al. 2009, 2010)

- For our galaxy models with Ferrers bar,

$$Q_b = \begin{cases} 0.58 f_{\rm bar}^{0.89}(a/b-1), & \text{for } n=0, \\ 0.44 f_{\rm bar}^{0.87}(a/b-1), & \text{for } n=1, \\ 0.38 f_{\rm bar}^{0.79}(a/b-1), & \text{for } n=2 \end{cases}$$

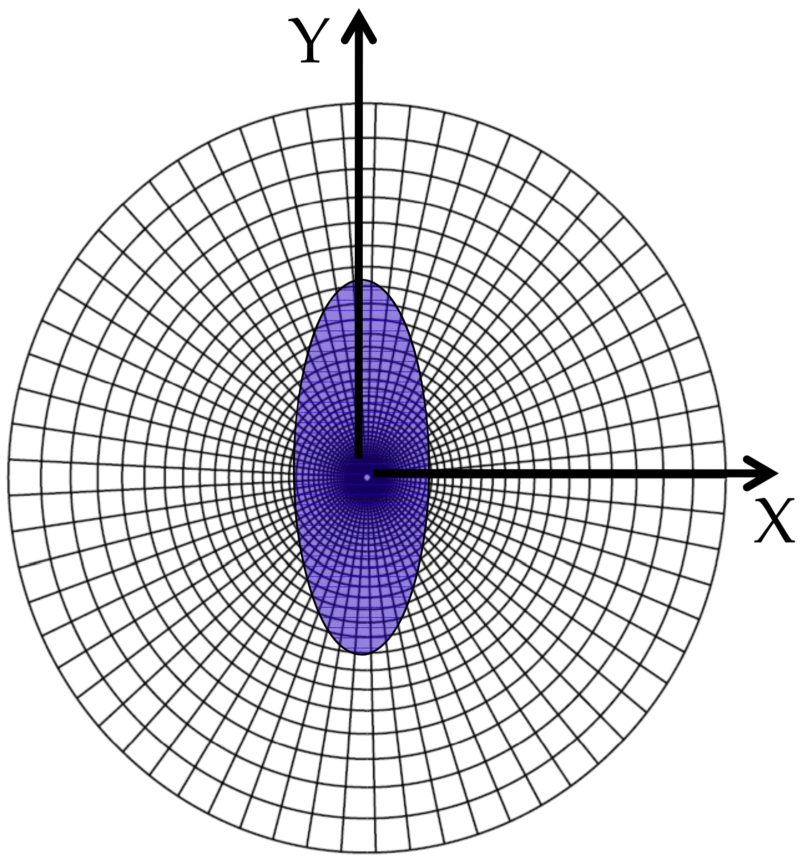
Bar Strength of Model Galaxies vs. Observations



- The trend of Q_b becoming larger for a more longated bar in the observational estimates (Comeron et al. 2010) is consistent with the results of our galaxy models.
  - $f_{bar} = 0.3–0.5$ for $n = 1$
  - $f_{bar} = 0.25–0.35$ for $n = 0$

Numerical Method

- **CMHOG** Code (**C**onnection **M**achine **H**igher **O**rder **G**odunov)
  - Grid-based code in cylindrical geometry
- Logarithmically-spaced cylindrical grid with 1024x480 zones
- The bar is oriented along the *y*-axis.
- The gaseous disk is self-gravitating and isothermal (c_s=10 km/s) without magnetic fields.
- The ideal HD equations are solved in a frame rotating with the bar.
- No back reaction of the gas to the stellar bar.
- In order to avoid strong trasients, the amplitude of the bar potential is slowly incrased over ~200 Myr.



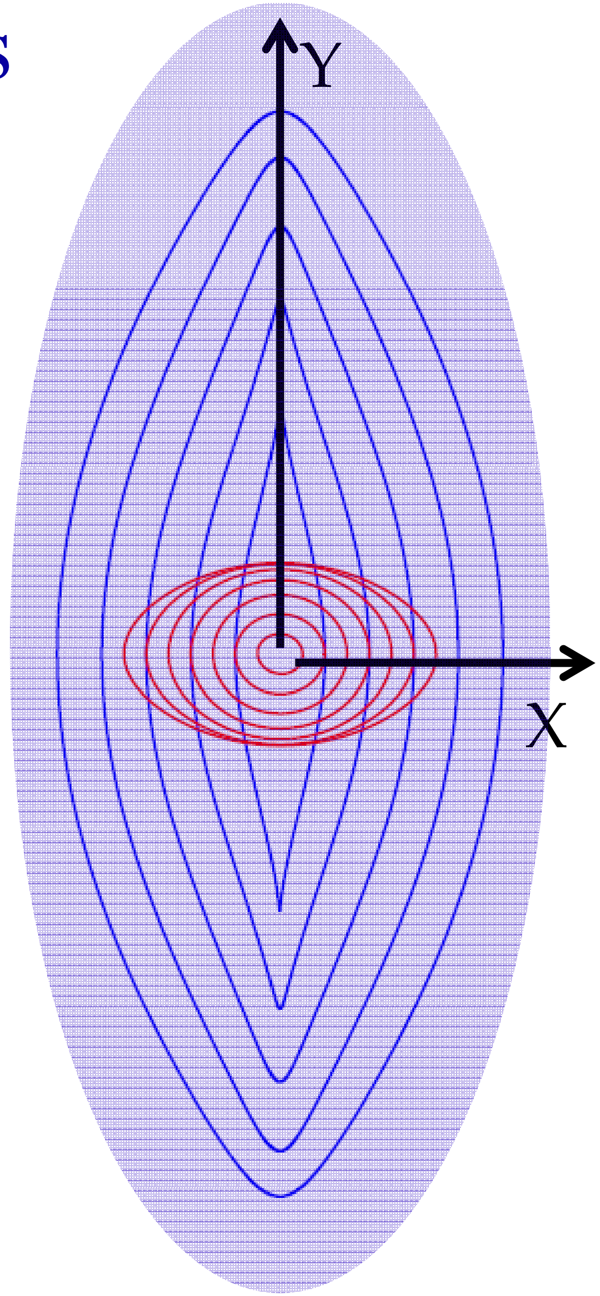
x_1 and x_2 Orbits

- In the presence of an non-axisymmetric potential, angular momentum is not conserved, while **Jacobian integral** defined by

$$E_J = \frac{1}{2}|\dot{r}|^2 + \Phi_{\rm eff}$$

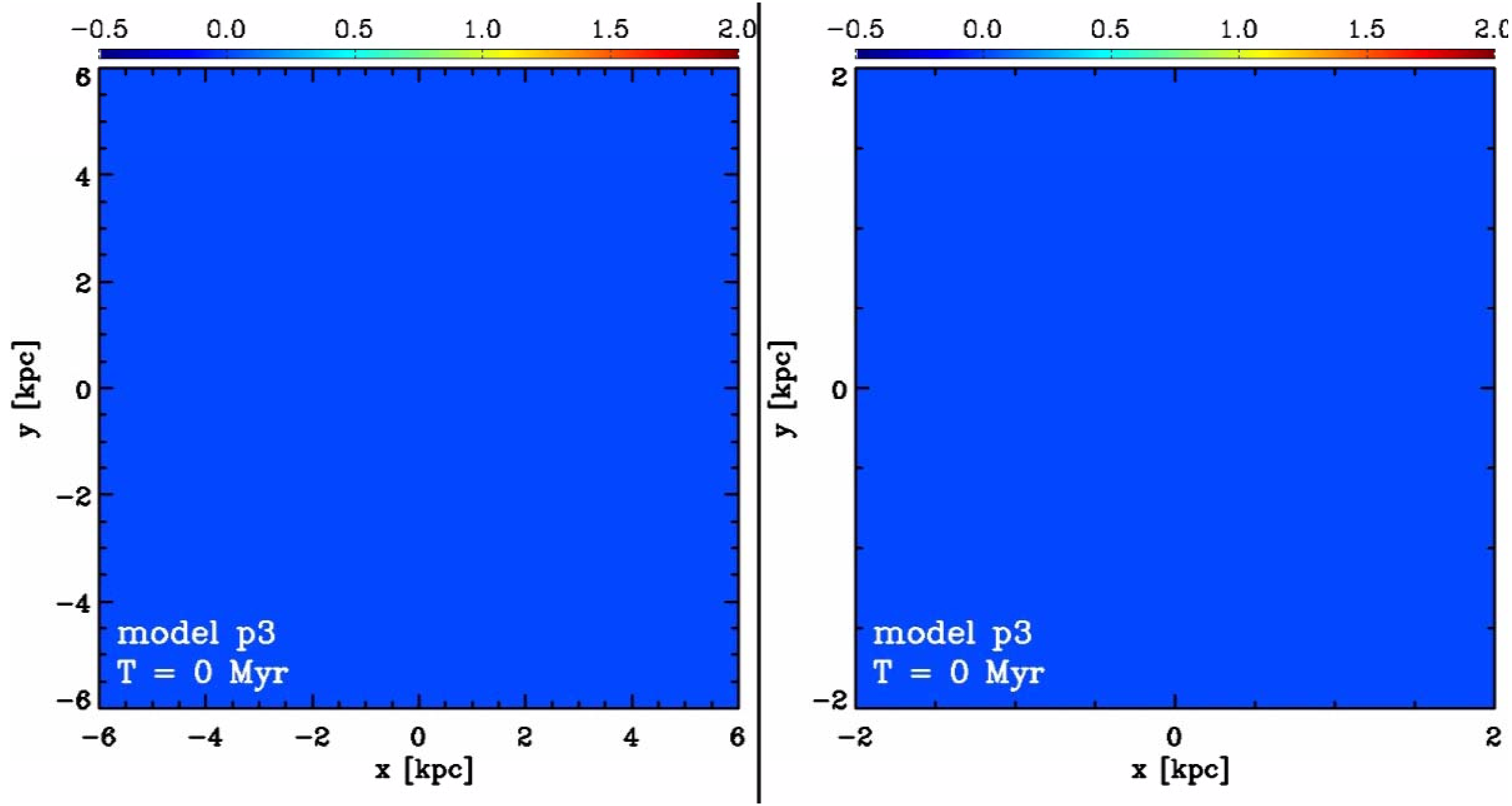
 is conserved.

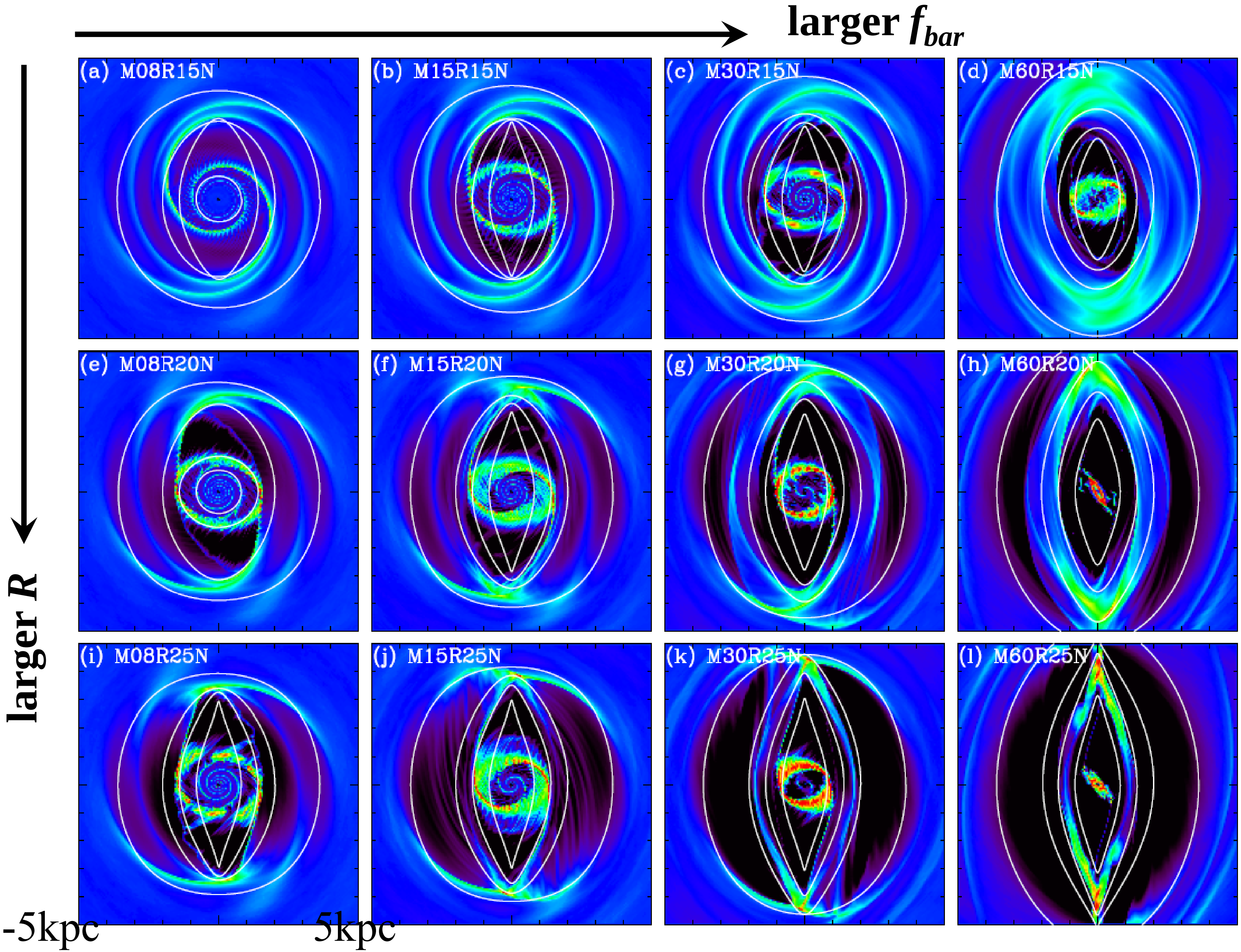
- Two (prograde) closed-orbit families in the rotating frame (Contopoulos & Papayannopoulos 1980):
  - **x_1 orbits** elongated along the bar major axis
    - Support the bar potential.
    - Associated with dust lanes.
  - **x_2 orbits** aligned along the bar minor axis
    - Associated with nuclear rings.



Model with Q_b=0.23 (f_{bar}=0.3, a/b=2.5)

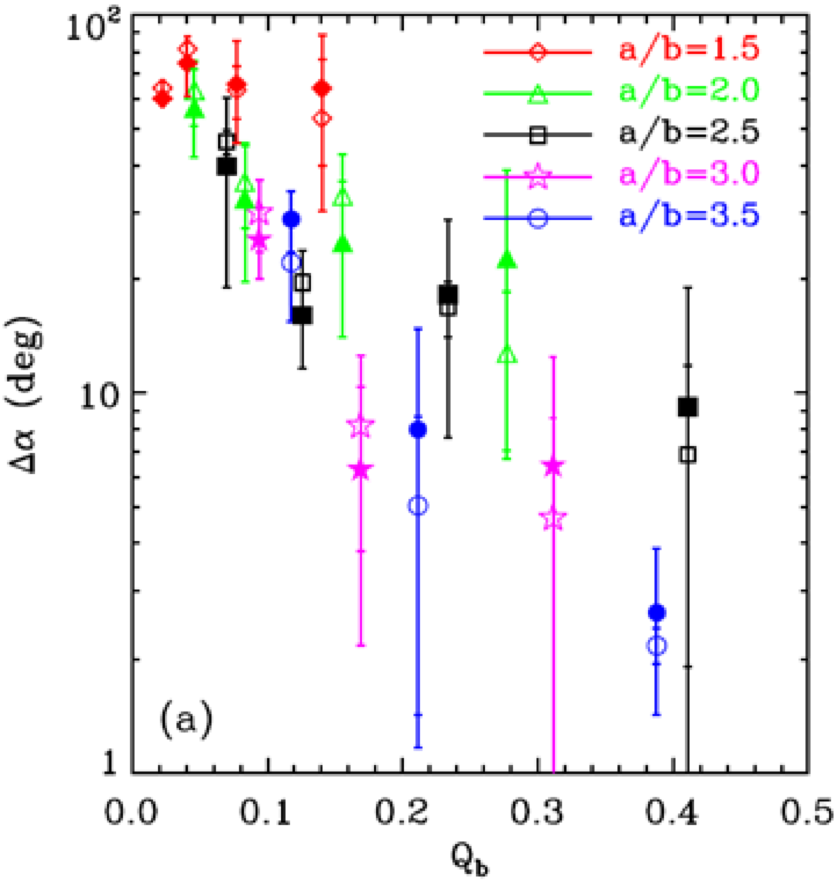
Kim et al. (2012)





larger f_{bar}
larger R
(a) M08R15N
(b) M15R15N
(c) M30R15N
(d) M60R15N
(e) M08R20N
(f) M15R20N
(g) M30R20N
(h) M60R20N
(i) M08R25N
(j) M15R25N
(k) M30R25N
(l) M60R25N
-5kpc
5kpc

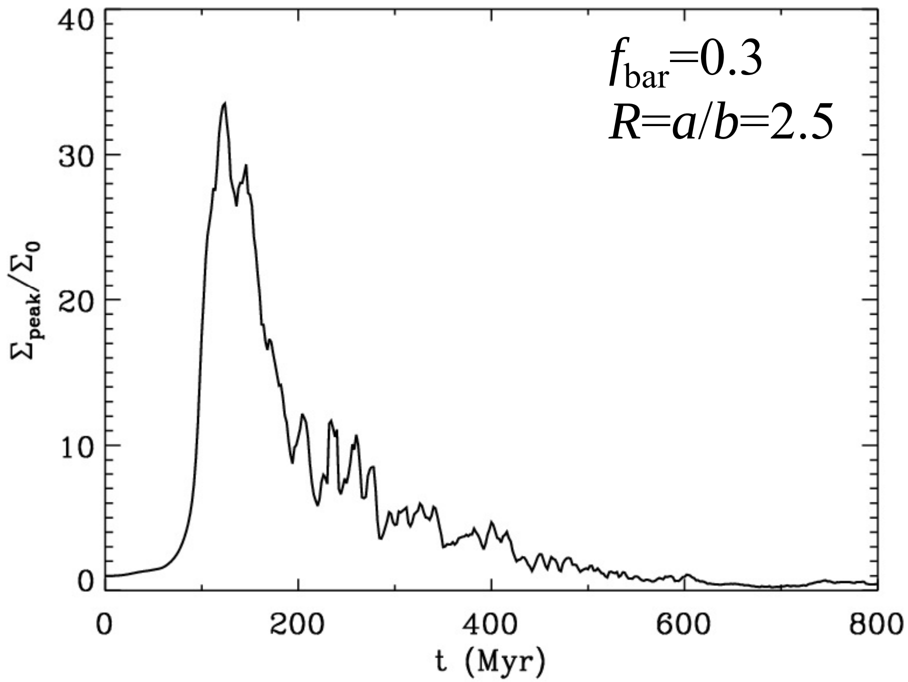
Curvature $\Delta\alpha$ of Dust Lanes



(Average is taken over 250-350 Myr)

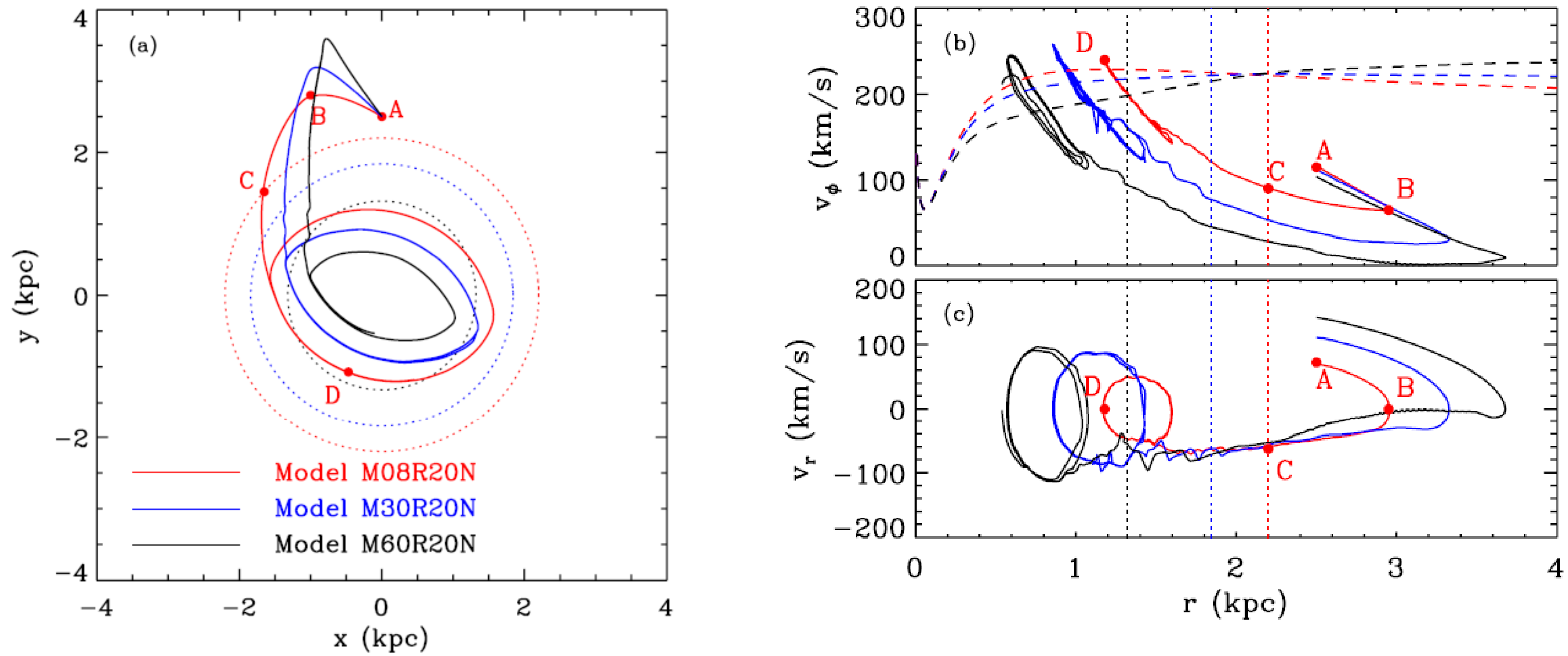
- Overall, the shape of dust lanes is well described by x_1 orbits.
- A stronger and more elongated bar has more straight dust lanes (Athanassoula 1992; Knapen et al. 2002; Comeron et al. 2009).

Strength of Dust Lanes



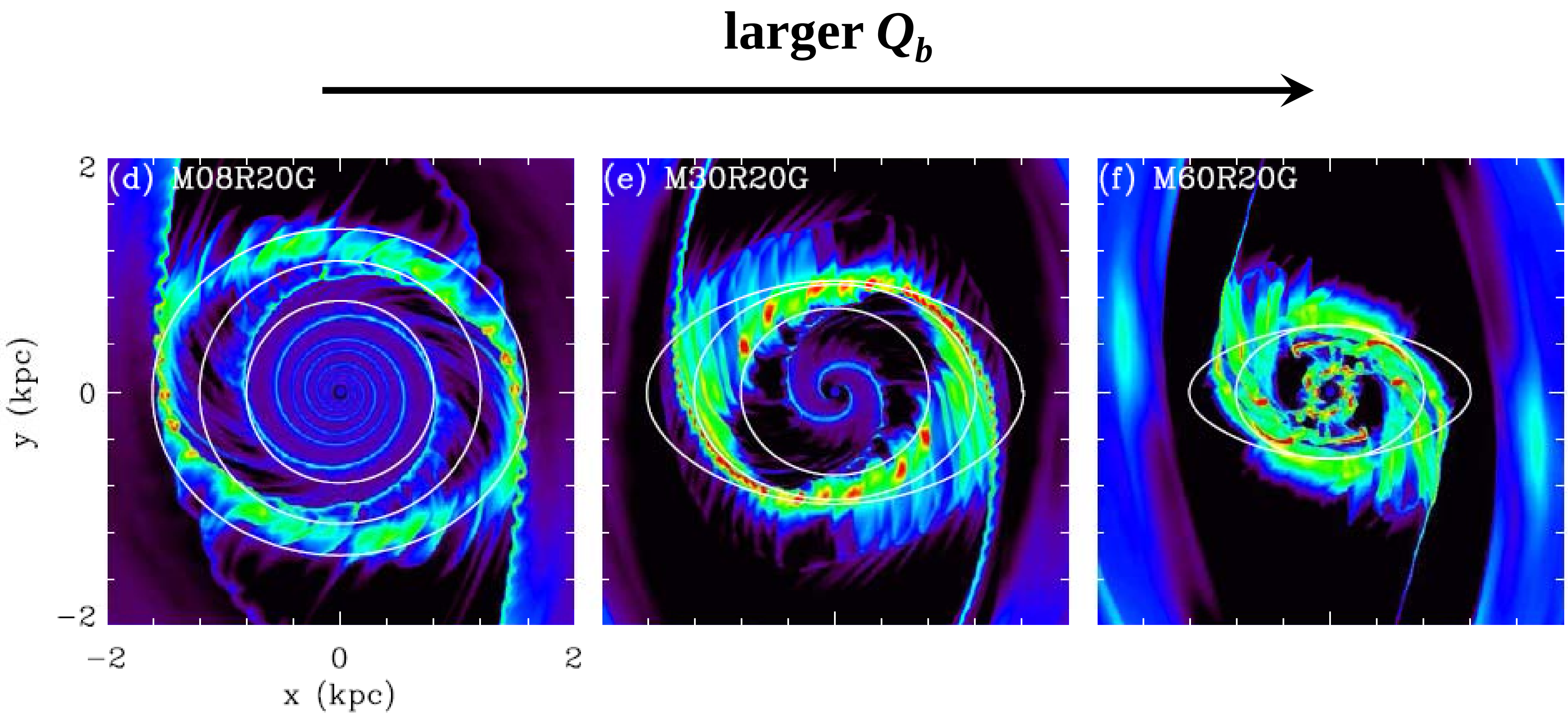
- Dust lanes remain strong only for 100 Myr around the time when the bar potential achieves the full strength.
  - The rapid decline of the strength of dust lanes is primarily due to the fact that the gas only inside the outermost x_1-orbit can respond strongly to the bar potential to lower its orbits.

Ring Formation

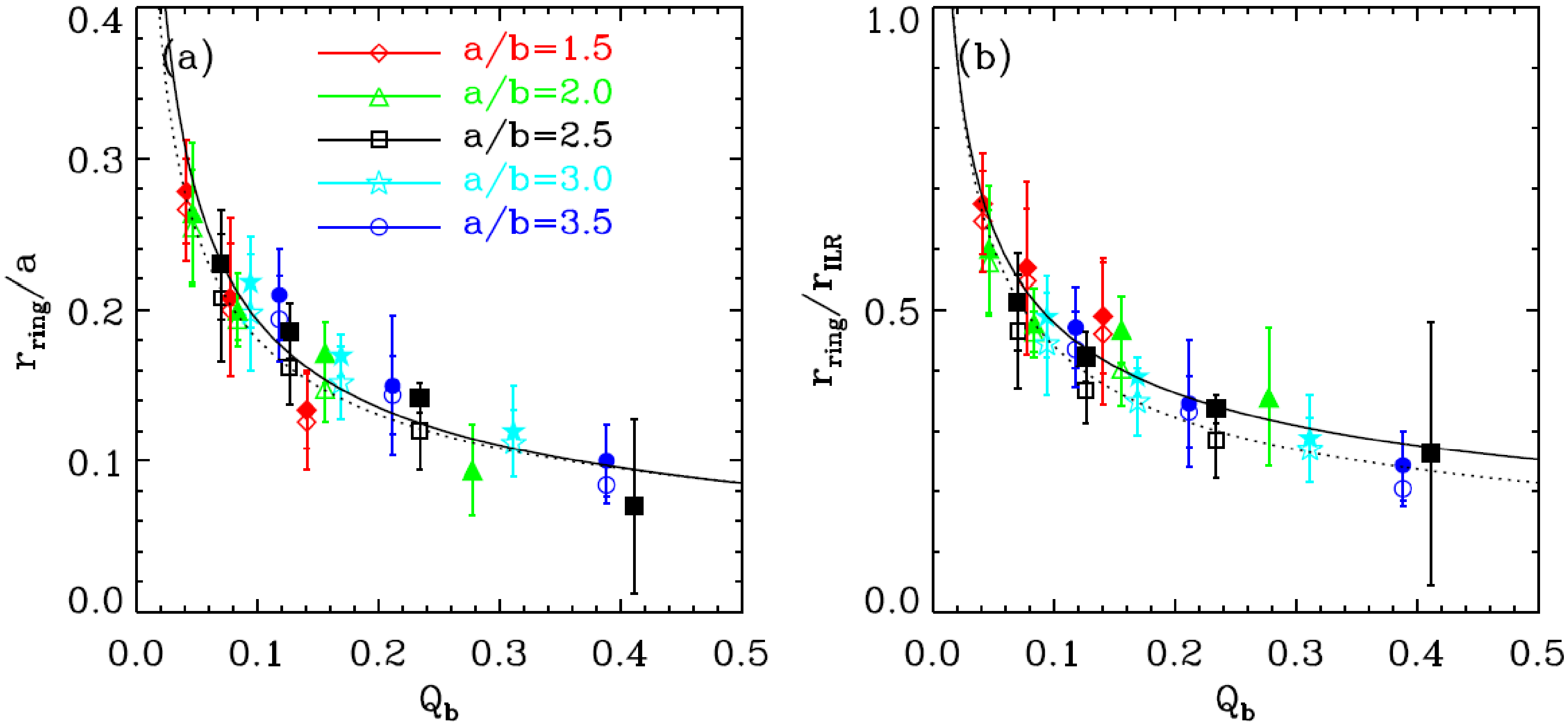


- The inflowing speed is so large that the bar torque cannot stop gas motions across the ILR.
- The inflowing gas keeps moving in and eventually forms a nuclear ring at the location where the centrifugal force balances the external gravitational force.

Nuclear Rings

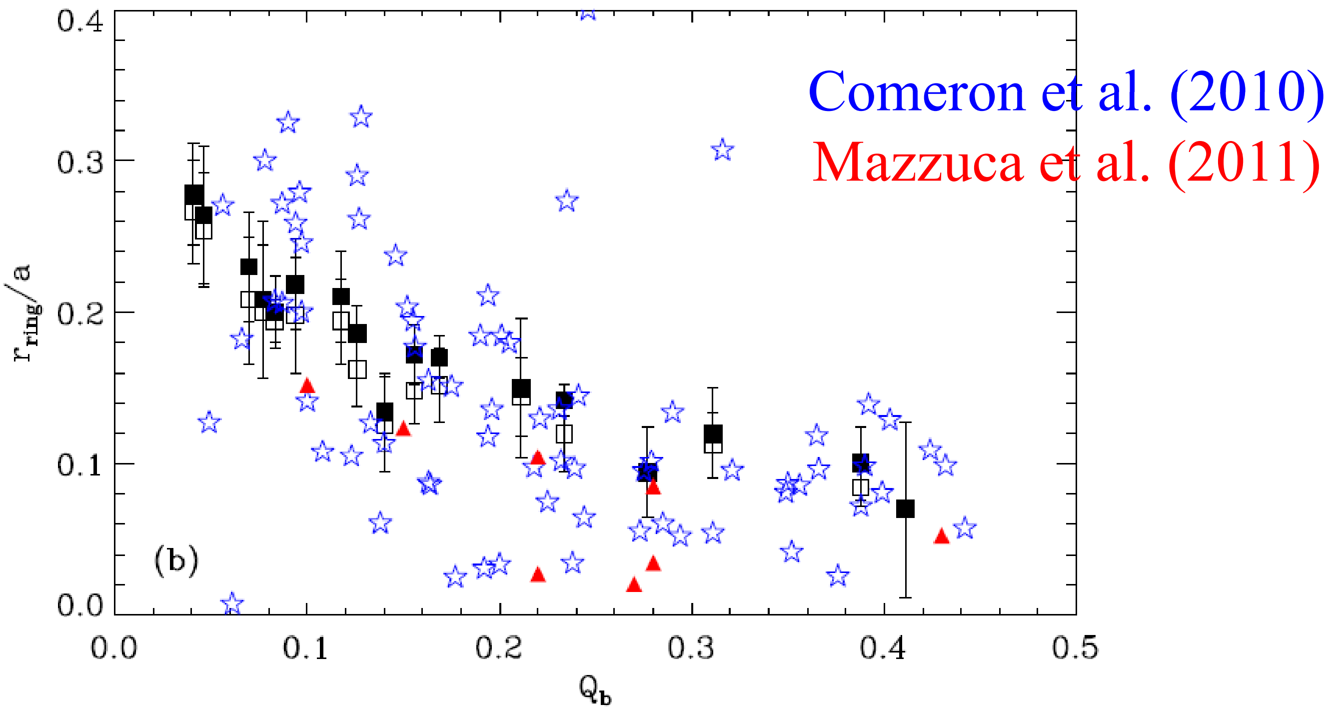


Ring Size



- The ring position is in general inside the inner Lindblad resonance of the bar potential.
- Rings are smaller in models with a stronger bar.

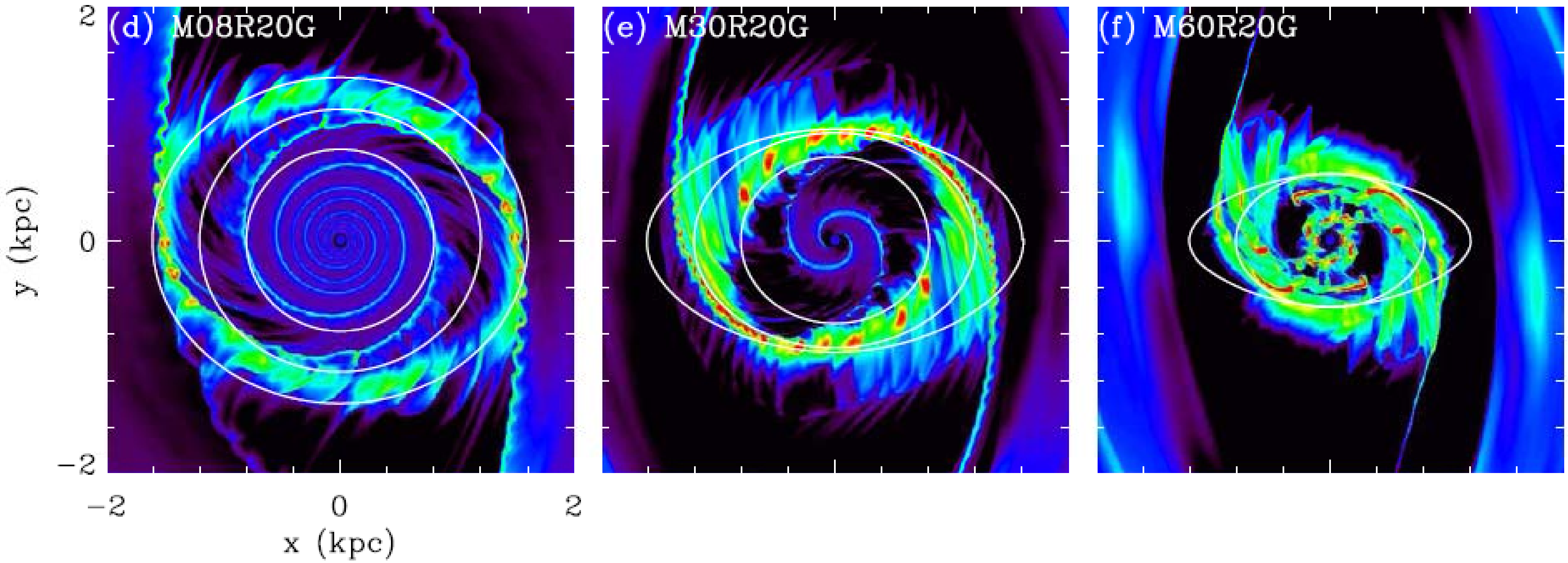
Comparison With Observed Ring Sizes



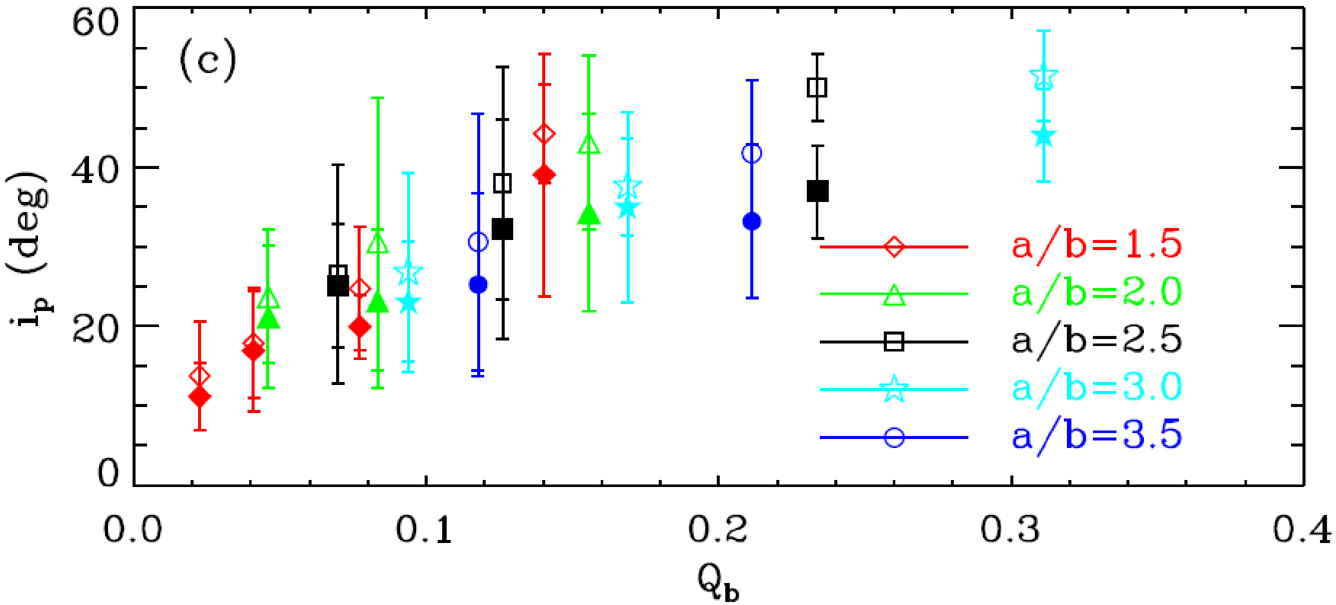
- Both observational and numerical results show that stronger bars can possess smaller rings.
- For $Q_b < 0.15$, the agreement between observational and numerical results is quite good.
- For $Q_b > 0.15$, the ring size in our models corresponds roughly to the upper envelope of the observational results.

Nuclear Spirals

larger Q_b



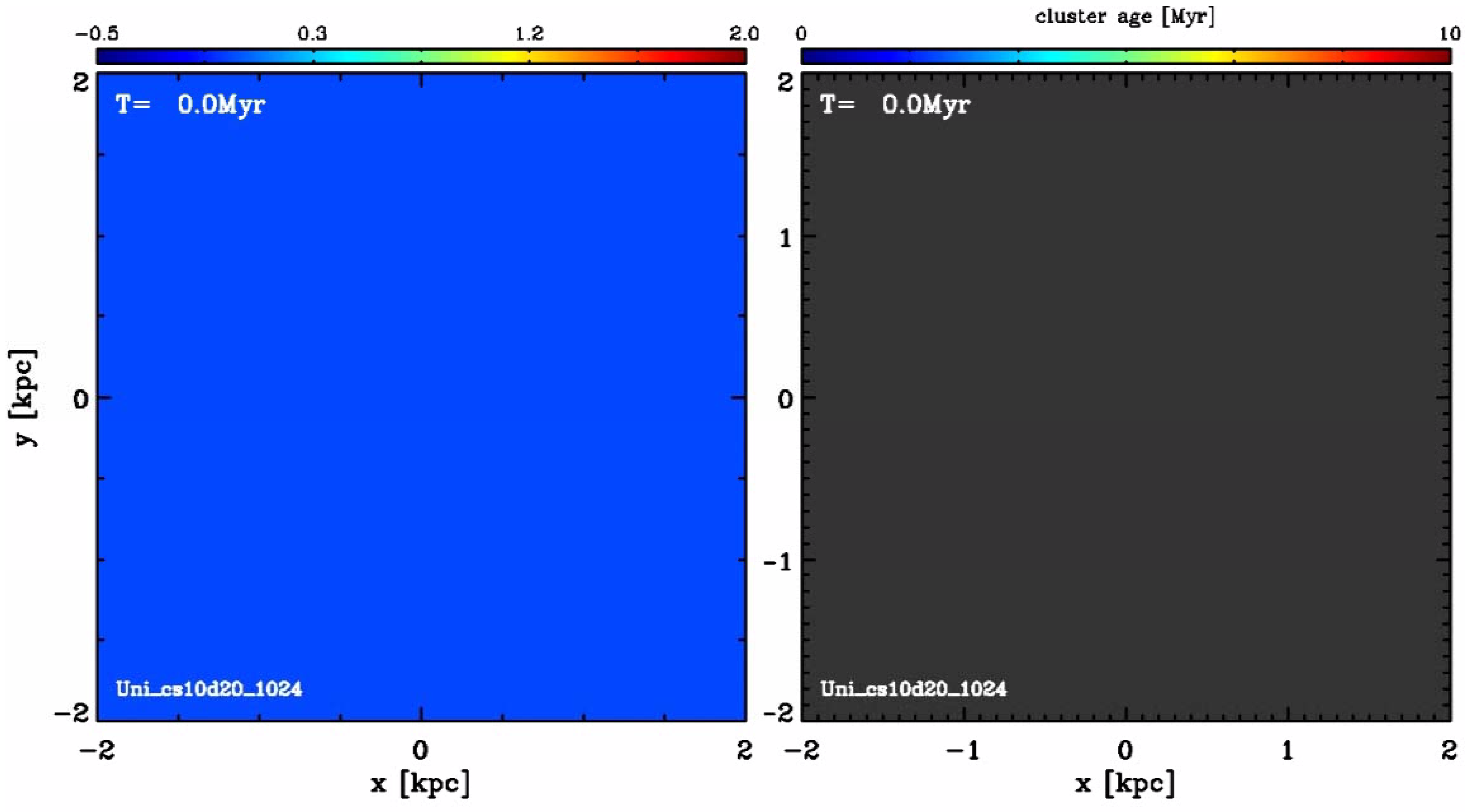
averaged over t = 0.3–0.5 Gyr



- Since nuclear spirals grow and unwind faster as Q_b increases, the probability of having more tightly-wound and weaker spirals is larger for galaxies with a weaker bar torque.
  - consistent with the observational results that tightly wound spirals are found primarily in weakly barred galaxies, while loosely wound spirals are more common in strongly barred galaxies (Peeples & Martini 2006; Martini et al. 2003a,b).

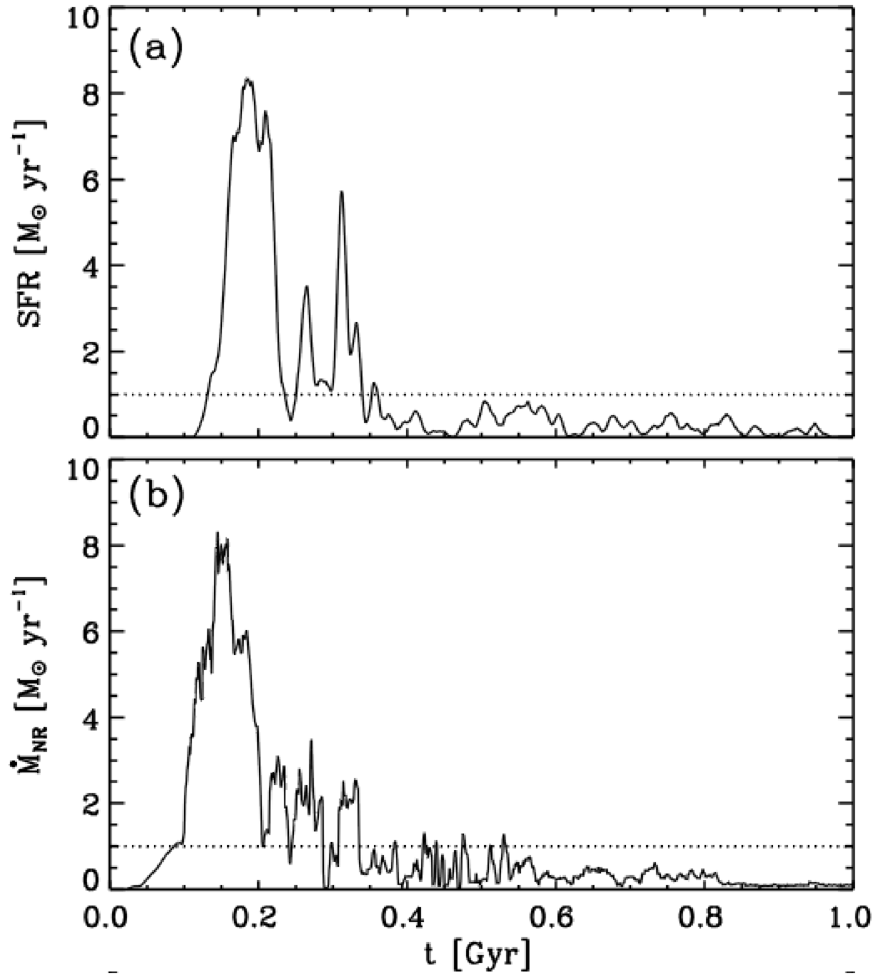
Star Formation In Nuclear Rings

(Seo & Kim 2013)



Ring Star Formation Rate

- Star formation rate in the nuclear rings is well correlated with the mass inflow rate to the rings.
- SFR shows a strong primary burst lasting for about 100 Myr and then decays to small values below $\sim 1\ M_\odot\ yr^{-1}$.
  - Contrast to observational results that show that ring star formation is long lived lasting for 1-1.5 Gyr, with multiple episodes (Allard et al. 2006; Sarzi et al. 2007; van der Laan et al 2013)



Summary

- The bar strength Q_b is the most important parameter in governing the physical properties of gaseous substructures in barred galaxies.
  - Dust lanes tend to be more straight under a stronger and more elongated bar.
  - The ring position is determined not by the resonance but by the bar strength.
  - Nuclear spirals unwind faster in more strongly barred galaxies.
- It appears that the gas in the bar regions should be replenished continuously or continually in order to explain observed **strong dust lanes** as well as **prolonged SF** in nuclear rings of barred galaxies.