Star Formation in Nuclear Rings of Barred Galaxies

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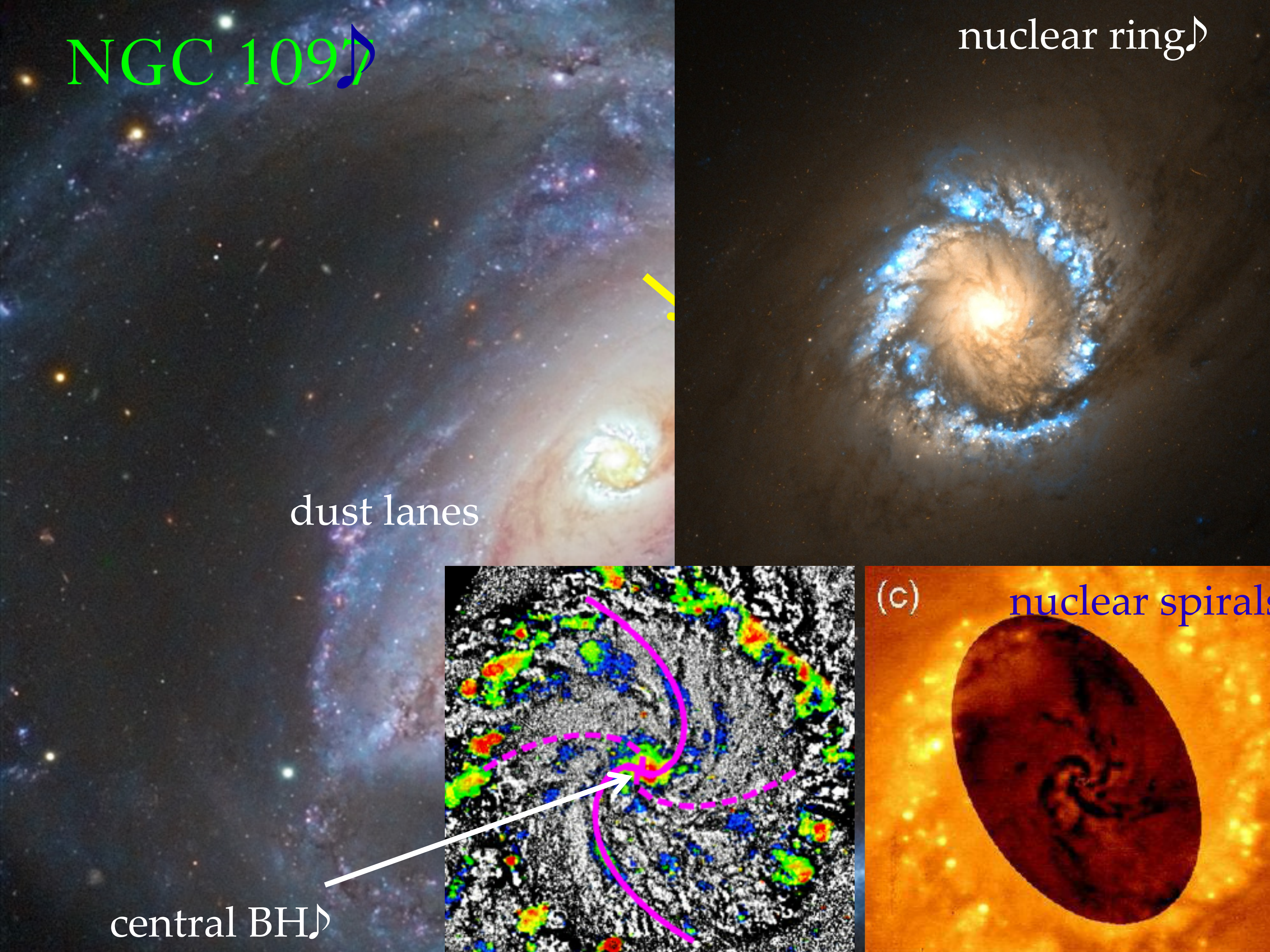
Outline

- Formation of Nuclear Rings
- Star Formation in Nuclear Rings



NGC 1097
nuclear ring
dust lanes
(c)
nuclear spiral
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♪

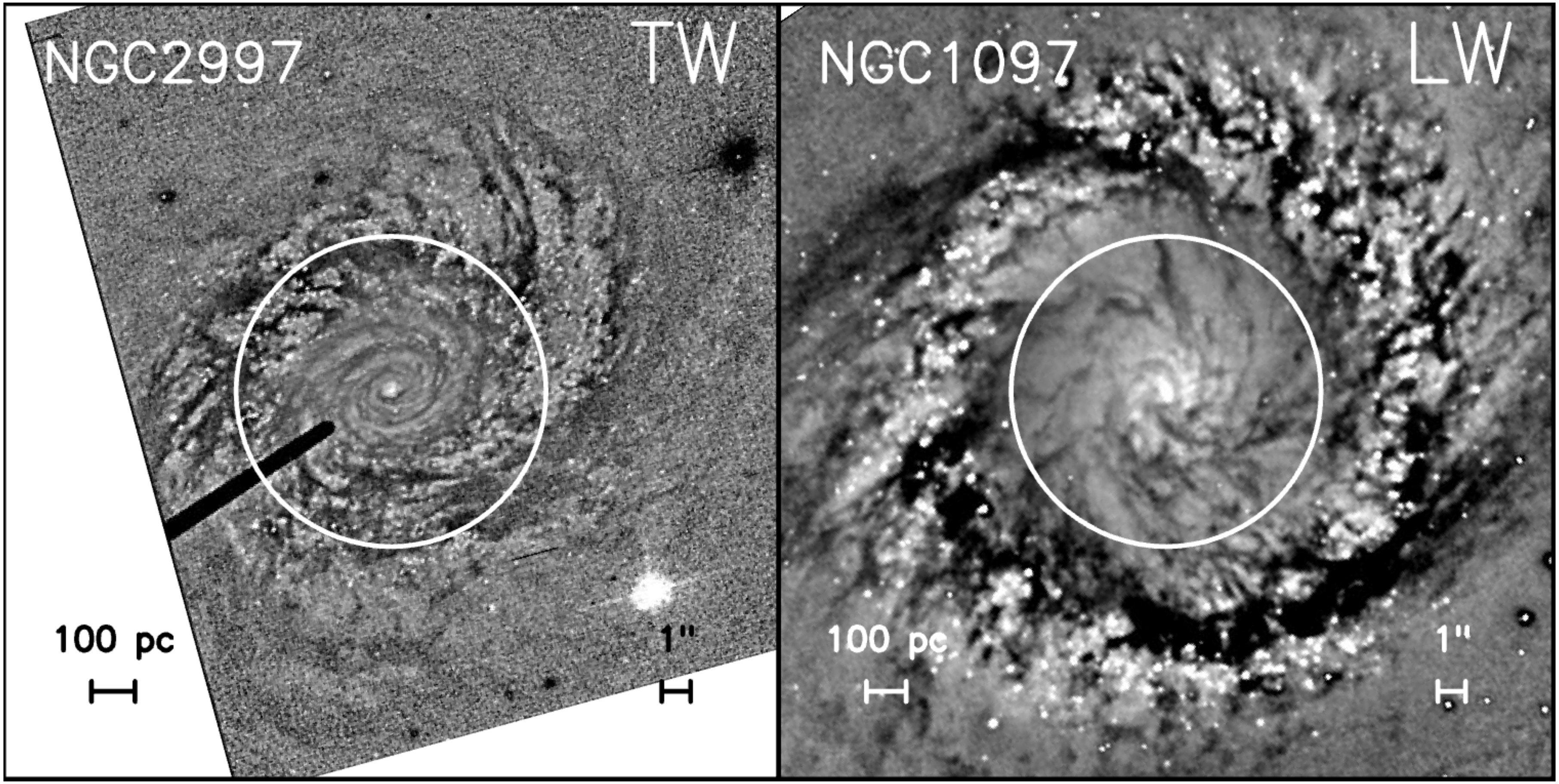
- Some galaxies have a relatively large nuclear ring, while others have smaller one.♪

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 85; Knapen+95; Comeron+10).
- 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 Strength

- We argue that it is the **bar strength** that controls the properties of bar substructures.
- Bar strength parameter $\boldsymbol{Q_b}$

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

where F_T = tangential force due to a bar

F_R = radial force due to mass distribution

  – SA(Q_b <0.1); SB (Q_b > 0.15) (Buta & Block 2001)

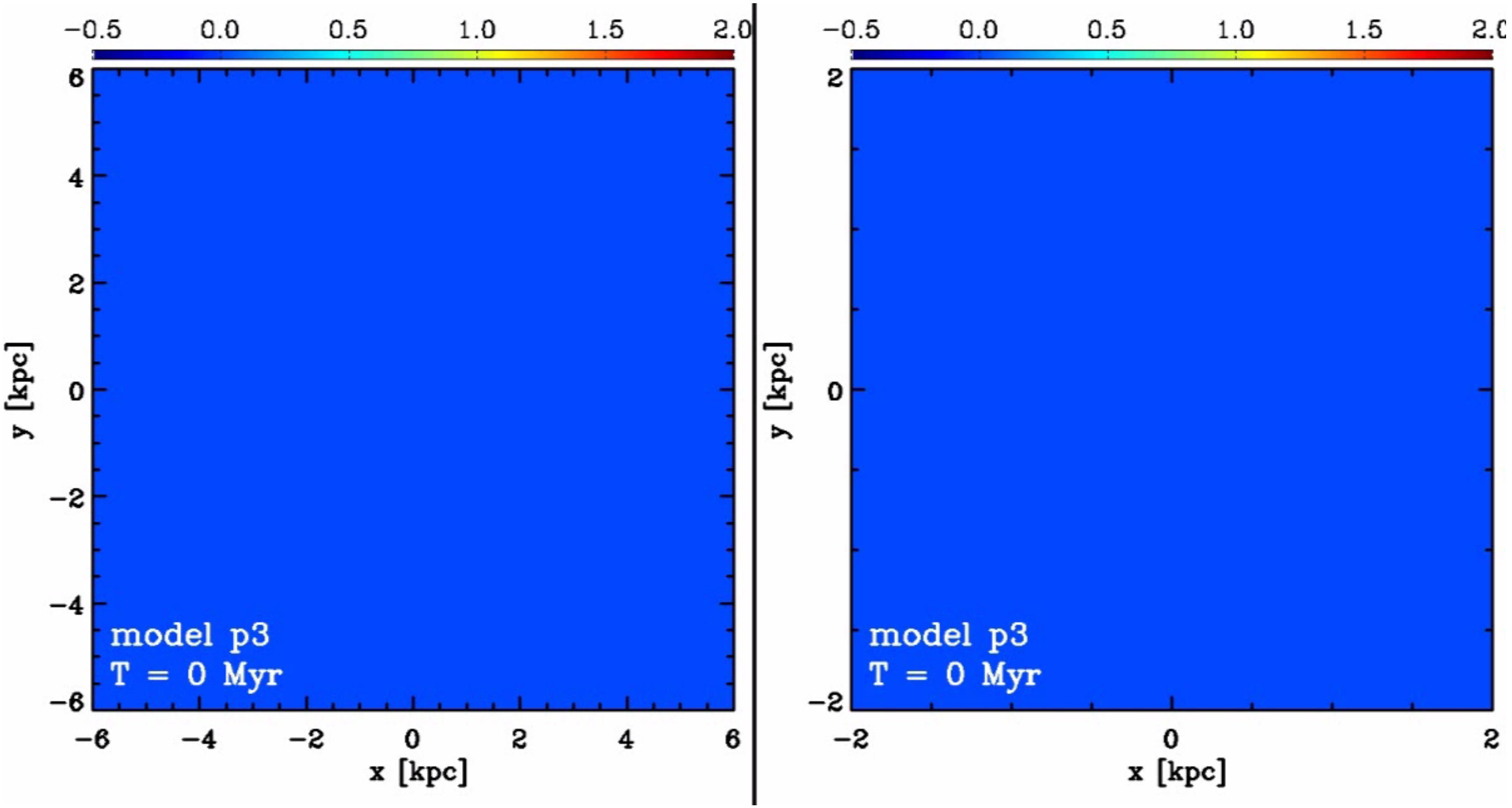
Numerical Models

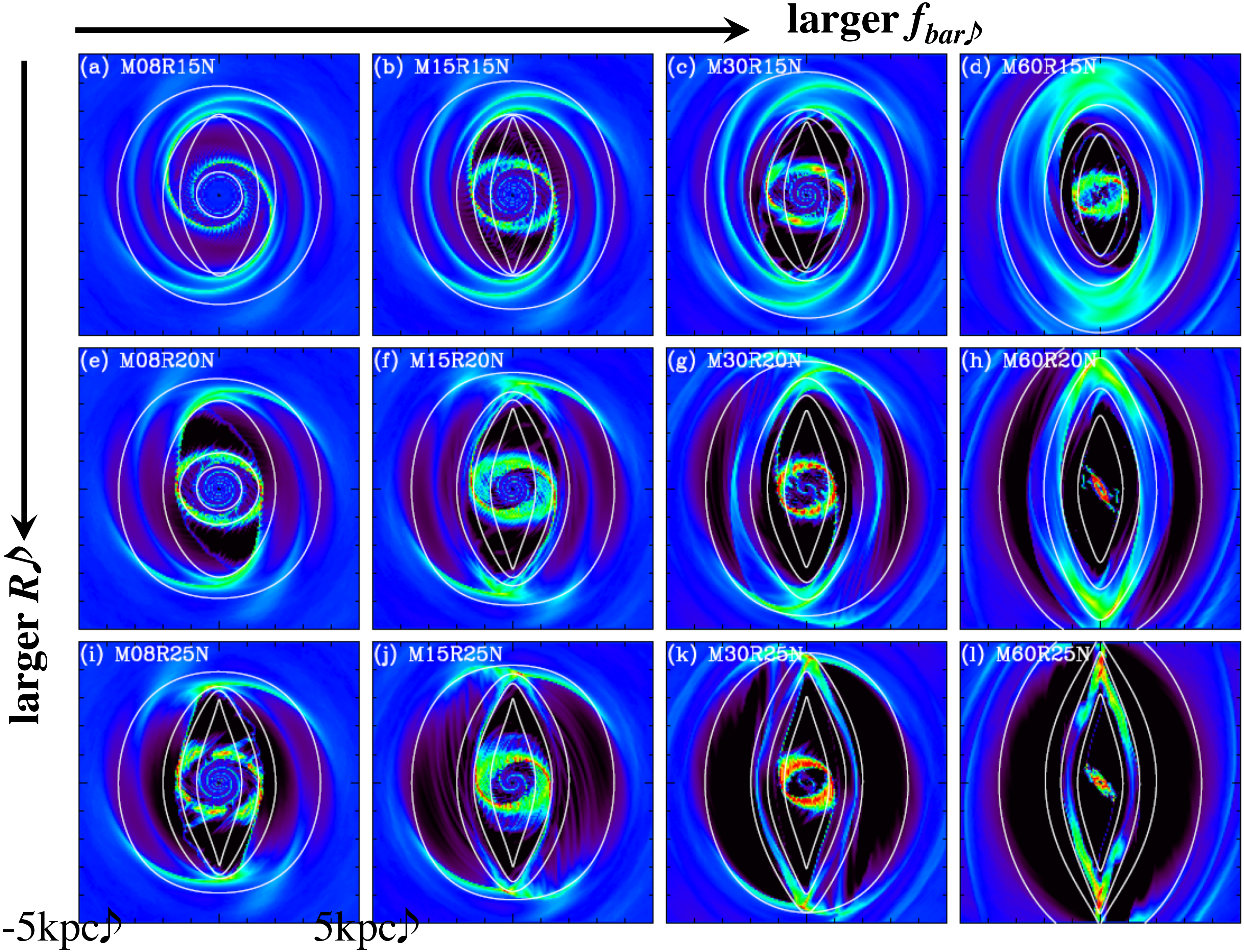
- To study the effect of bar strength on the properties of bar substructure, we run numerical hydrodynamics simulations.
- Consider a 2D gaseous disk that is isothermal (c_s=10 km/s) and self-gravitating, and study its response to a non-axisymmetric bar potential.
  - Flat rotation curve corresponding to normal disk galaxies.
- Bar potential is modeled by **Ferrers prolates** that are characterized by two parameters:
  - Bar mass fraction: $f_{\rm bar} = \dfrac{M_{\rm bar}}{M_{\rm bar} + M_{\rm bulge}} \sim 8 - 60~\%$
  - Aspect ratio: $\mathcal{R} = a/b \sim 1.5 - 3.5$

    (a, b = semi-major and semi-minor axes of the bar)
  - Resulting the bar strength is in the range $Q_b \sim 0.02$–0.7.

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

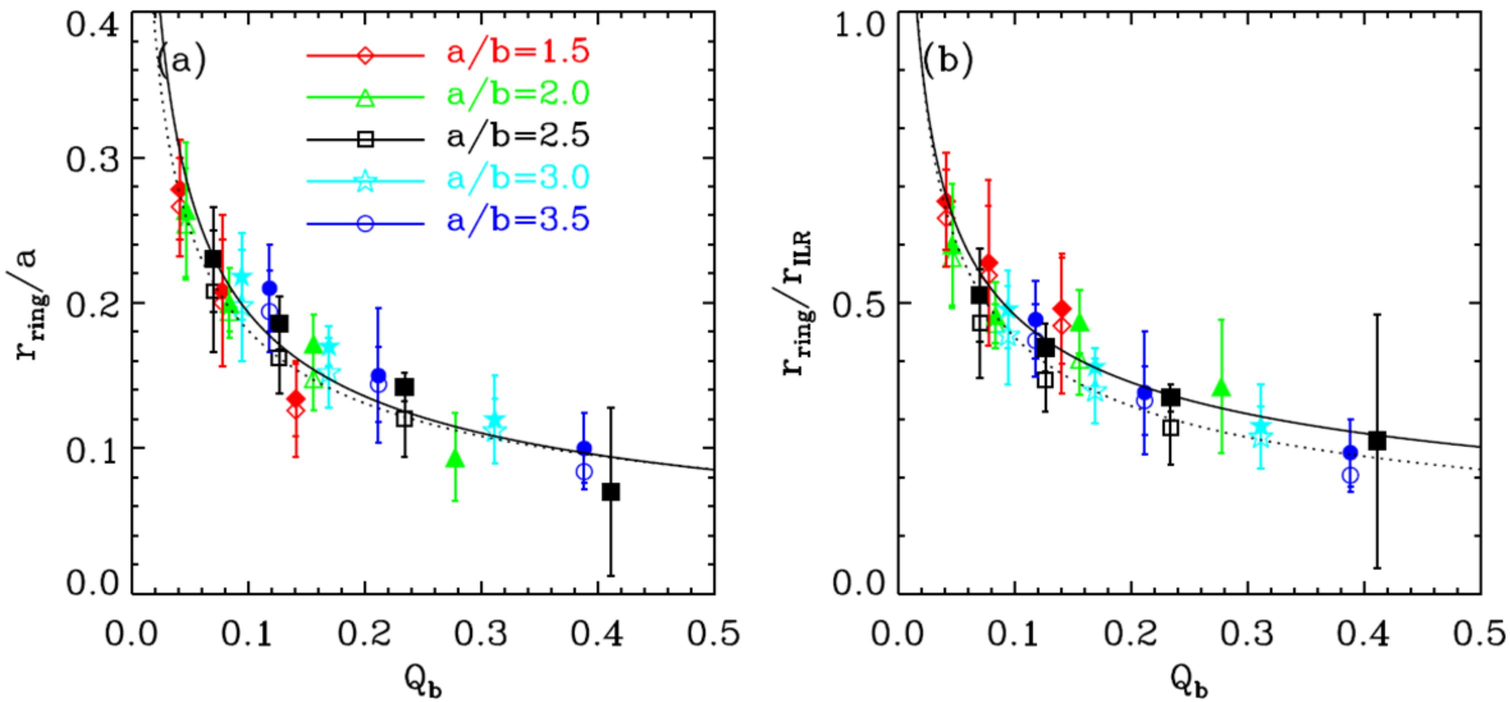
Kim et al. (2012)





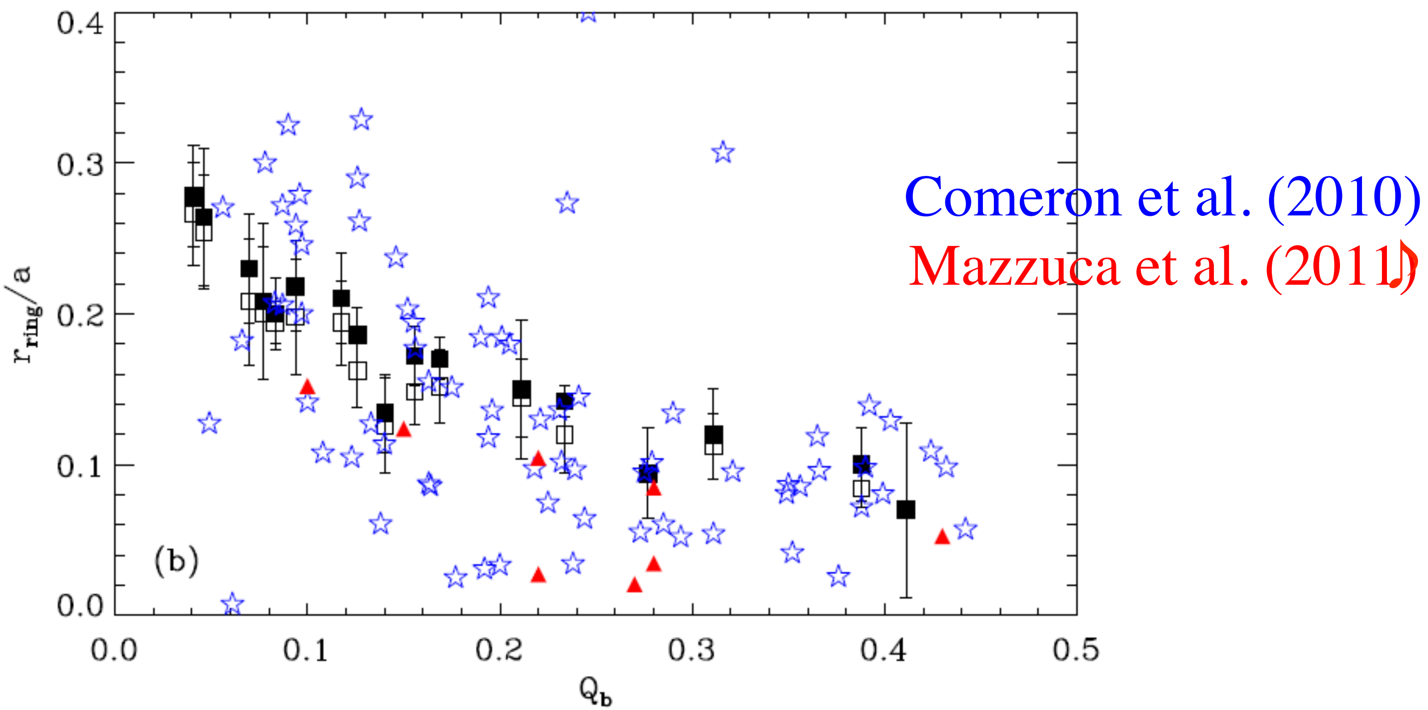
larger f_{bar}
larger R
(a) M08R15N
(b) M15R15N
(c) M30R15N
(d) M60R15N
(e) M08R20N
(f) M15R20N
(g) M30R20N
(h) M60R20N
(i) M08R25N
(j) M15R25N
(k) M30R25N
(l) M60R25N
-5kpc
5kpc

Ring Size



- A stronger bar induce stronger shocks and thus removes a larger amount of angular momentum from the gas, resulting in a smaller nuclear ring in size.
- The ring position is in general well inside the inner Lindblad resonance of the bar potential.
  - Ring formation is not by the resonances but by the centrifugal barrier.

Comparison With Observed Ring Sizes

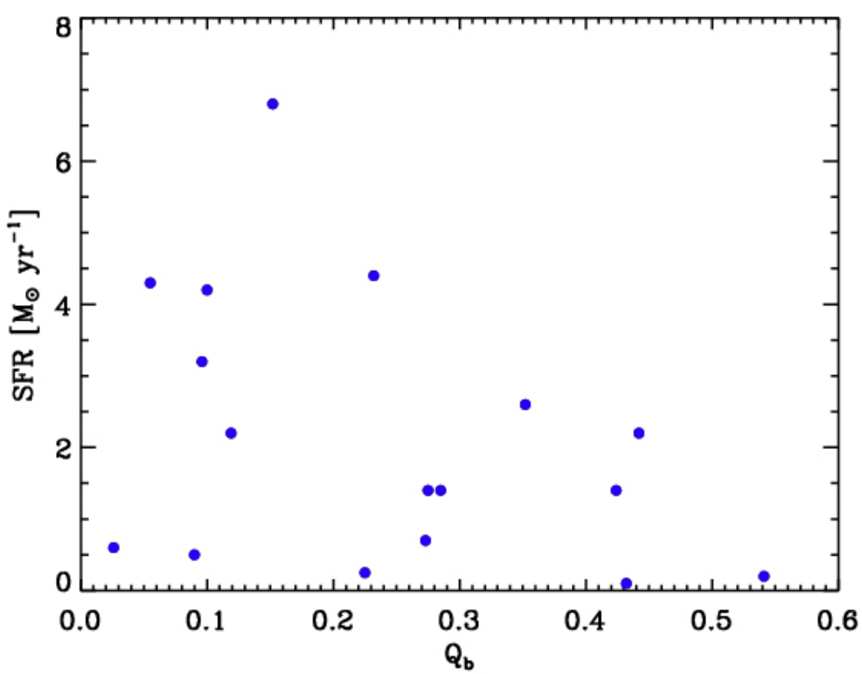


- Observational and numerical results are in good agreement.
  - Stronger bars can possess smaller rings.

Star Formation in Nuclear Rings

- Nuclear rings in barred galaxies are sites of intense star formation.
- Some important observational results that may provide clues as to how star formation occurs in nuclear rings.

1. The present star formation rate (SFR) vs Q_b
   - In the range 0.1–10 $M_\odot$ yr^{-1}, depending on the bar strength (Mazzuca+08).



Mazzuca+08
Comeron+10

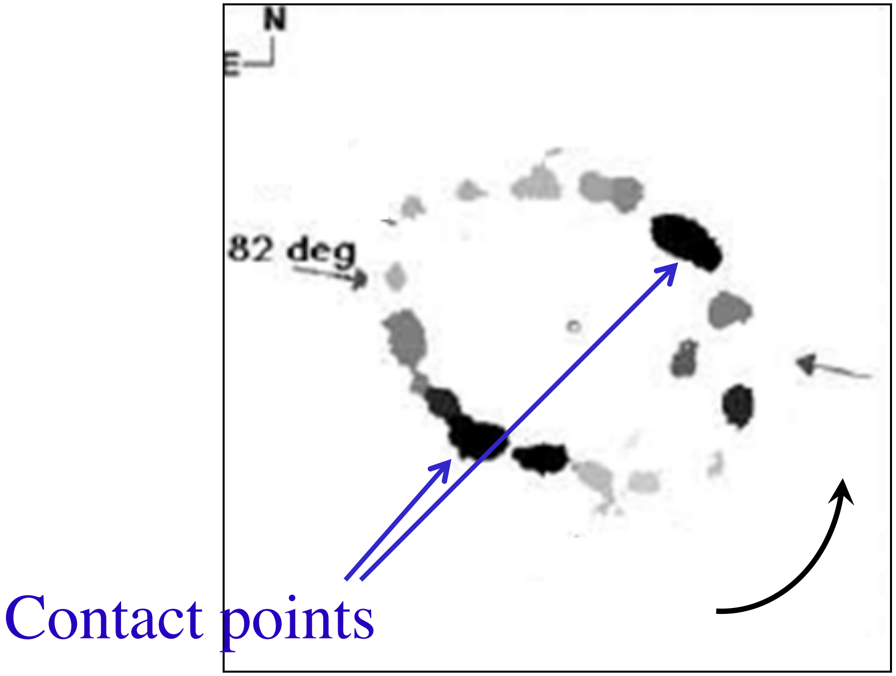
2. Longevity of Ring SFR

- Short-lived star formation: single burst
- Long-lived star formation
  - Multiple episodic bursts
  - Continuous SFR

- Population synthesis modeling favors long-lived star formation either with multiple episodic bursts (Allard+06, Sarzi+07) or continuous rates (van der Laan+13) rather than short-lived SF.

3. Azimuthal Age Gradient

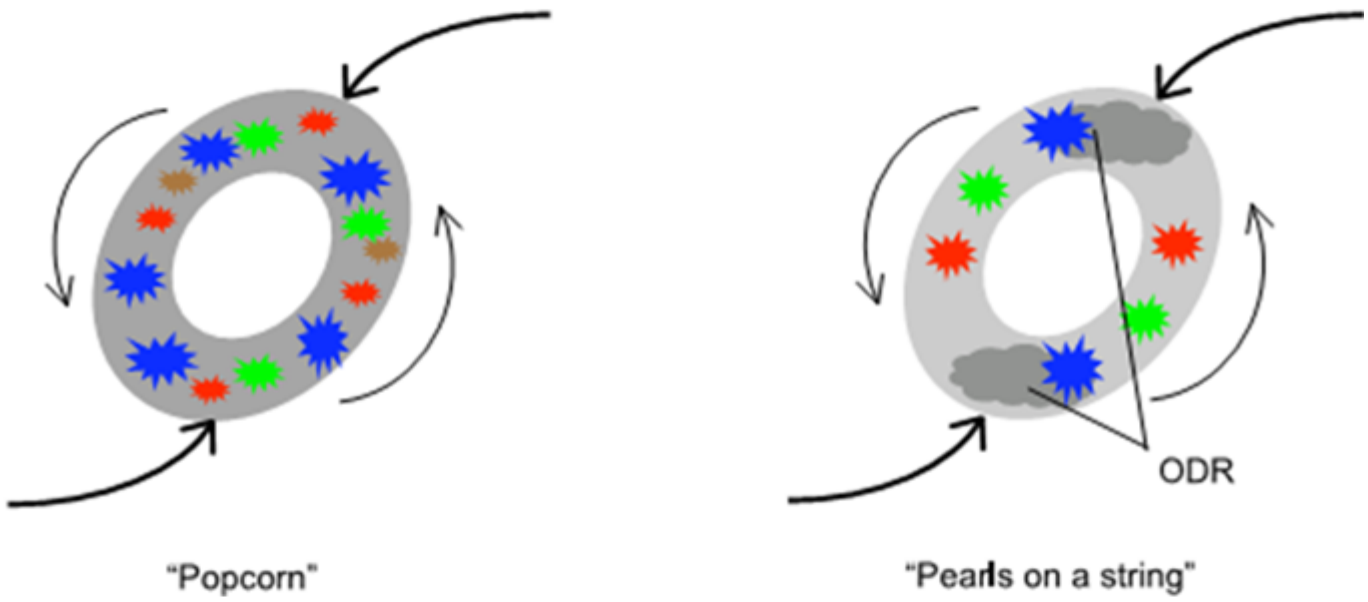
- Some galaxies (e.g., NGC 1343, IC 4933, NGC 7552) show an age gradient of star clusters along the azimuthal direction in nuclear rings (Mazzuca+08, Ryder+10, Brandel+12), while a majority of galaxies do not show apparent age gradients.



NGC 1343 (Mazzuca+08)
Hα Equivalent width

Two Modes of Ring SF (Böker+08)

- Popcorn model: SF occurs in dense clumps randomly distributed along a nuclear ring ➔ no age gradient
- Pearls-on-a-string model: SF takes place preferentially at the contact points between a ring and the dust lanes. ➔ age gradient.



- It appears that rings with age gradients have, on average, a smaller SFR than those without noticeable age gradients.♪

Numerical Methods

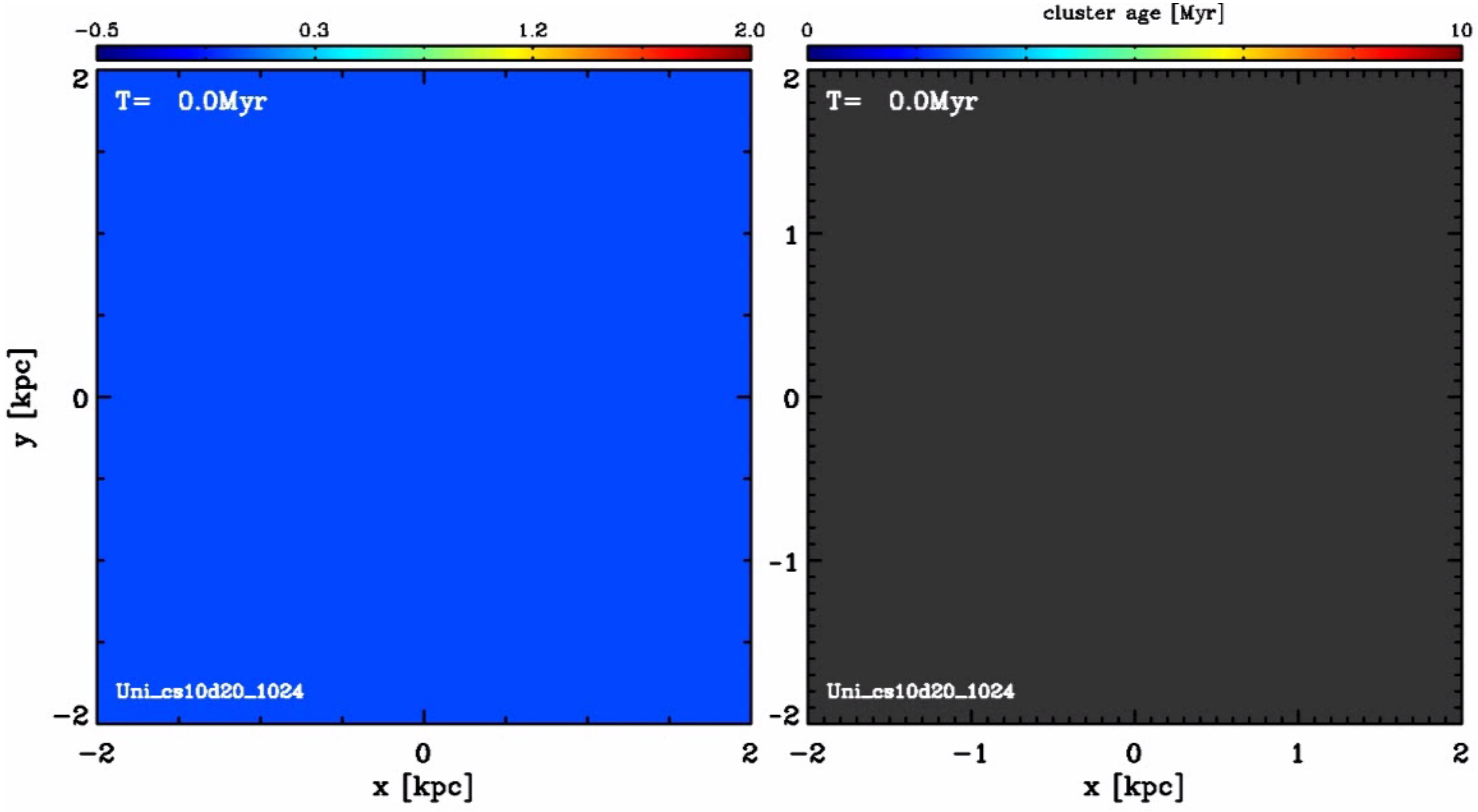
- SF Prescription
  - Critical density corresponding to the Jeans condition.
  - Star formation efficiency $\varepsilon \sim 1\%$ (Krumholz & Tan, 2007)
    - SF probability $P = \varepsilon \Delta t / t_{ff}$
  - 90% of gas turns into a particle that represents a star cluster
    - Typical Mass of each star cluster ~ $10^5 M_\odot$

- Delayed SF feedback via SN events
  - In the form of momentum injection
  - Delay time = 10 Myr.

Star Formation In Nuclear Rings

Model with SF feedback included

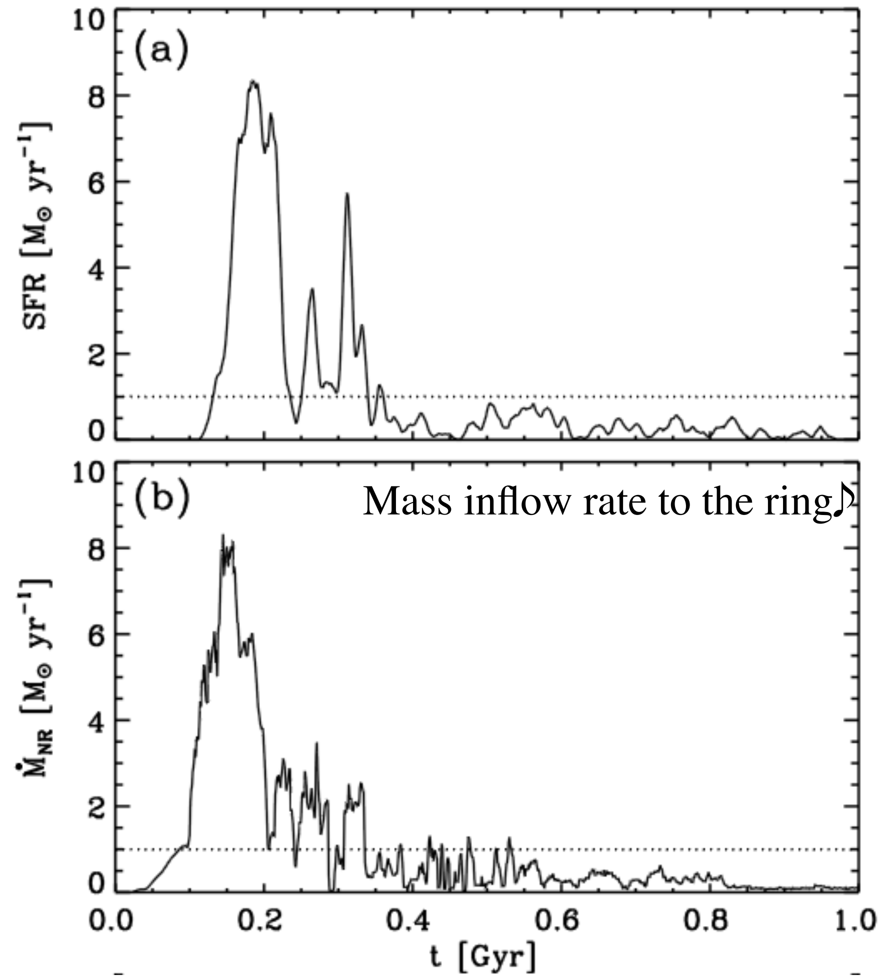
(Seo & Kim 2013)



Star Formation Rate♪

- SFR 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 ~ 1 $M_\odot$ yr^{-1}.
  - The primary burst is caused by the rapid gas infall due to the bar growth.
  - The secondary bursts are due to re-entry of the ejected gas from the primary burst.
- Contrast to observational results (Allard et al. 2006; Sarzi et al. 2007; van der Laan et al 2013)♪

(Seo & Kim 2013)♪



Azimuthal Age Gradient

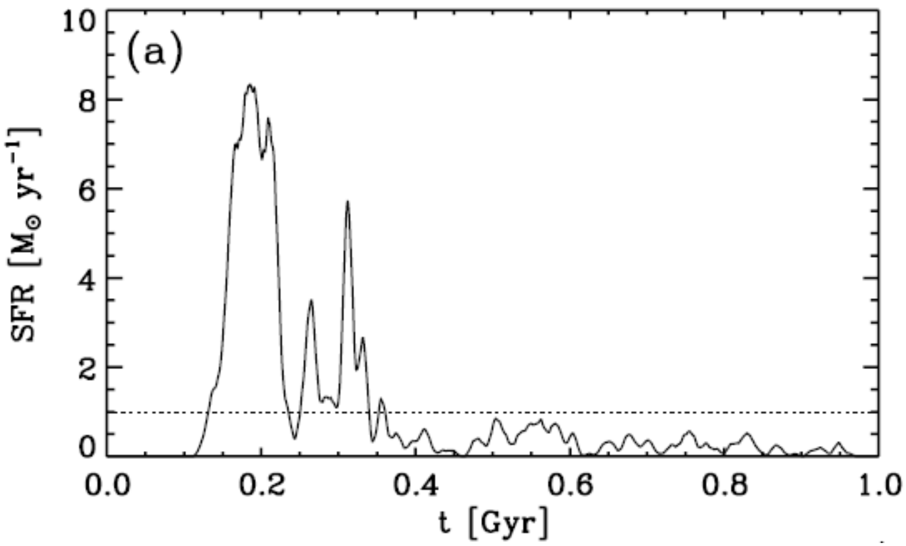
- The presence or absence of azimuthal age gradients of young star clusters in nuclear rings depends on the SFR.
  - No azimuthal age gradient if SFR > 1 $M_\odot$ yr^{-1}.
- The maximum SFR that can be afforded to two contact points

$$\dot{M}_{*,\mathrm{CP}} = 2\epsilon_{\mathrm{ff}}\Sigma_{\mathrm{CP}} r_{\mathrm{NR}} \Delta r \Delta\phi / t_{\mathrm{ff}} \sim 1 \mathrm{M}_\odot\ \mathrm{yr}^{-1} \left(\frac{r_{\mathrm{NR}}}{1\ \mathrm{kpc}}\right)^2 \left(\frac{c_s}{10\ \mathrm{km\ s}^{-1}}\right)^3$$

  - $\varepsilon_{\mathrm{ff}}$: SF efficiency (~1%)
  - Σ_{CP} : gas surface density at the contact points
  - r_{NR}, Δr, $\Delta\phi$: radius, width, angular extent of a nuclear ring
  - t_{ff}: free-fall time

Necessity of Gas Feeding to the Bar Region

- The gas in the bar regions should be replenished continuously or continually in order to make SF **prolonged** in nuclear rings.



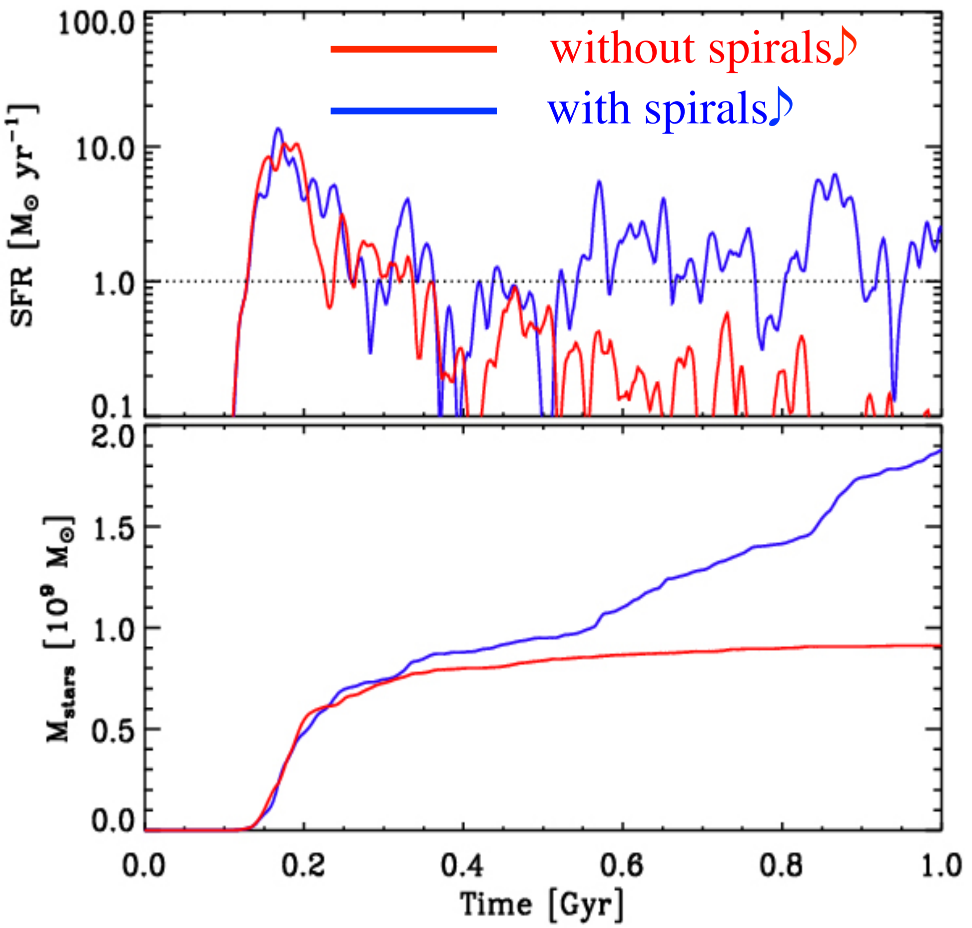
- Candidate mechanisms for gas feeding
  - angular momentum dissipation by spiral arms (Roberts & Shu 1972; Lubow et al. 1986; Hopkins & Quataert 2011)
  - galactic fountains (Fraternali & Binney 2006, 2008).
  - cosmic accretion of primordial gas (e.g., Dekel et al. 2009)
    - HVCs, ~ 0.7 $M_\odot$ yr^{-1} for M31/Milky-Way-type galaxies (Richter 2012)

Ring SF with Spiral Arms

Seo & Kim (in preparation)

- Spiral arms with moderate strength of can drive radial mass inflows of ~1 $M_\odot$ yr^{-1}, provided the corotation resonance of the arms is at large *R*.

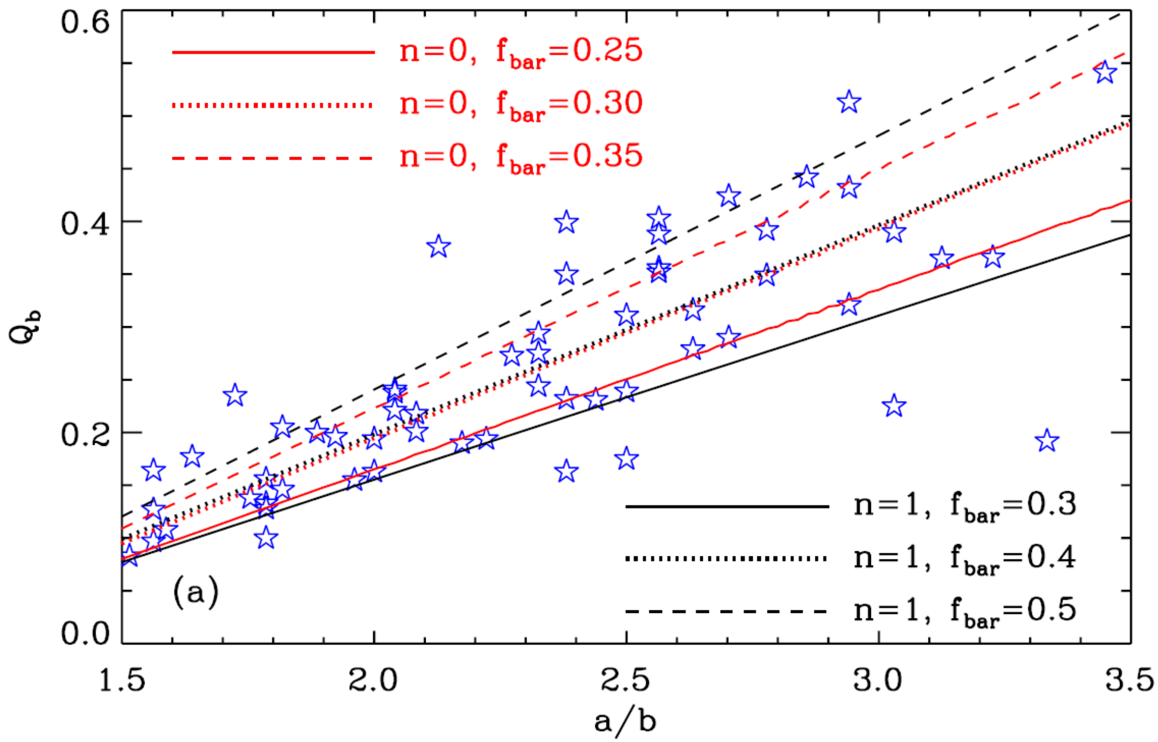
- Spiral arms can continuously transport fresh gas from outer regions to the bar region, capable of enhancing SFR at late time in the ring.



Summary

- Formation of nuclear rings
  - They form not by resonances but by the centrifugal barrier that the inflowing gas cannot overcome.
  - Galaxies with stronger bars host smaller nuclear rings
- Star formation in nuclear rings
  - In bar-only models, SF exhibits a strong primary burst followed by weak secondary bursts, before declining to very small values.
  - An azimuthal age gradient of star clusters is expected when SFR is low (less than 1 $M_\odot$ yr^{-1} in our models).
  - The bar potential alone is unlikely to be responsible for the gas supply needed for star formation in real nuclear rings.
    - For prolonged SFR, gas should be supplied to the bar region.
    - Spiral arms can be such a gas feeding mechanism.

Bar Strength of Model Galaxies vs. Observations

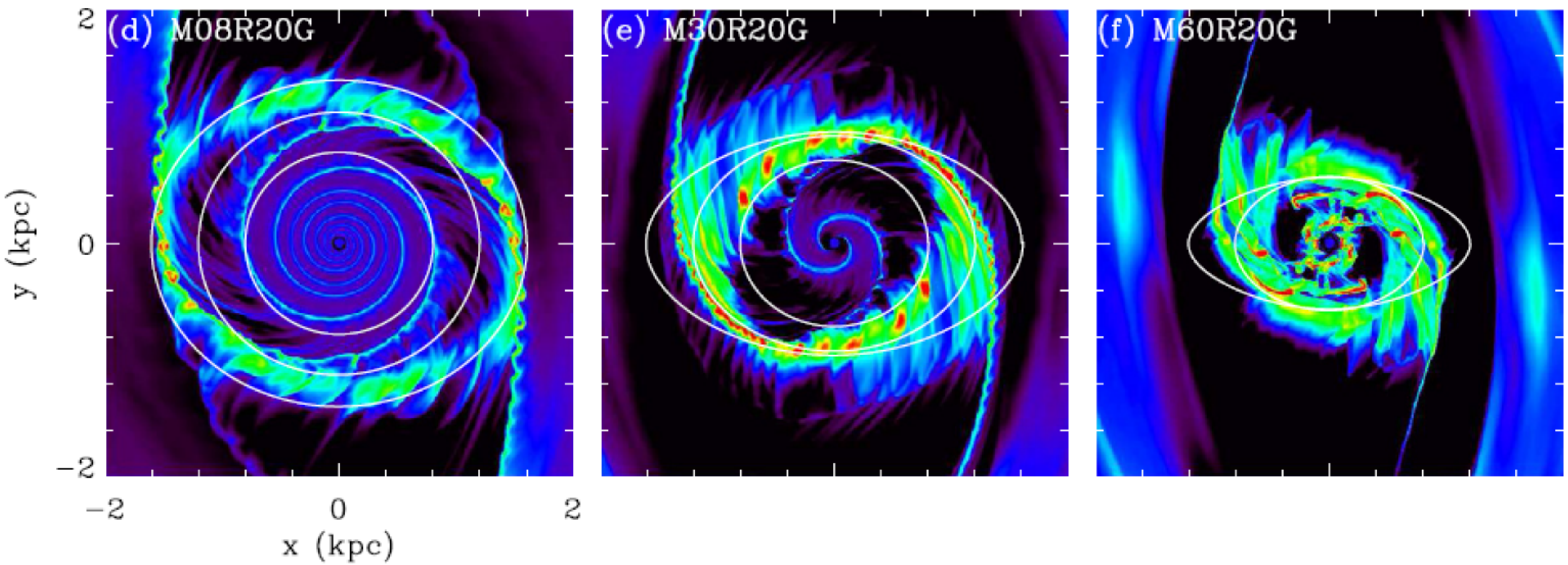


(Comeron et al.10)

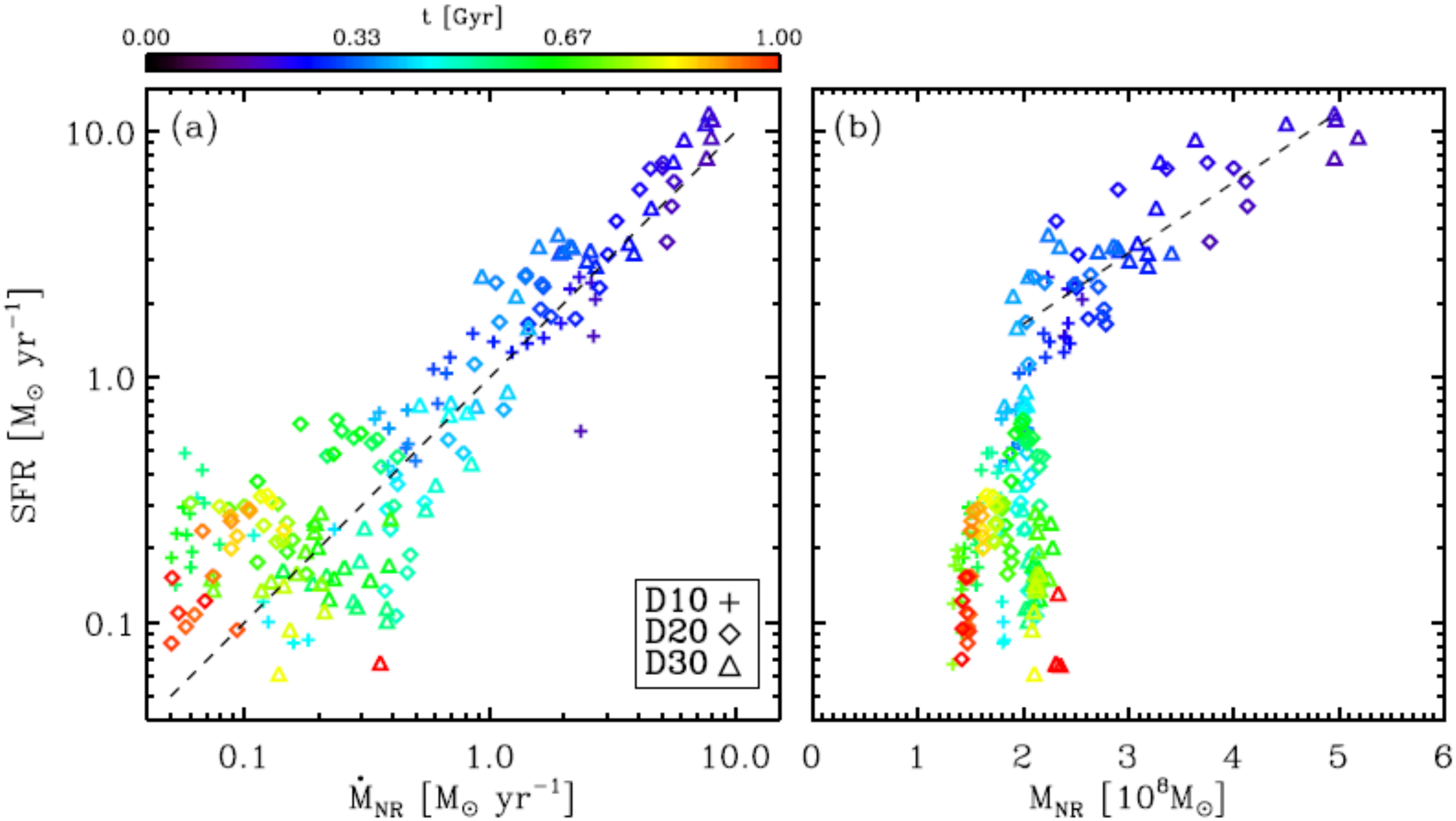
- The trend of Q_b becoming larger for a more elongated bar in the observational estimates is consistent with the results of our galaxy models.
  - f_{bar} = 0.25–0.35 for a homogenous bar

Nuclear Rings

larger Q_b



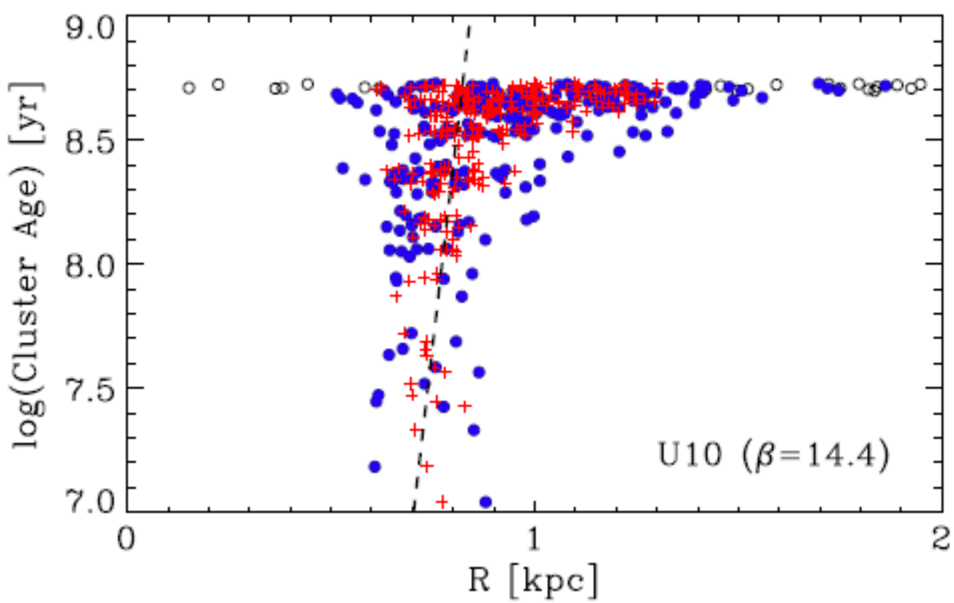
What Controls Ring SF?



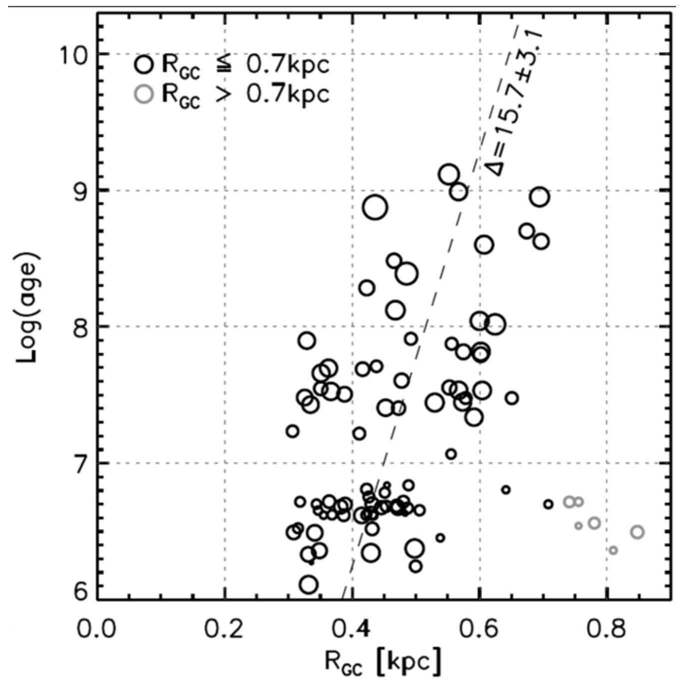
- The ring SFR has a tight linear correlation with the mass inflow rate $\dot{M}_{\rm NR}$ to the ring, and has a weak dependence on the total gas mass $M_{\rm NR}$ in the ring.

Radial Age Gradient

Seo & Kim 2013



NGC 1672 (Jang & Lee 13)



- The star clusters produced exhibit a positive radial age gradient
  - Young clusters are located close to the nuclear ring, while old clusters are found away from the ring.
  - Due to a temporal decrease in the ring size