Star Formation in Nuclear Rings of Barred-Spiral Galaxies

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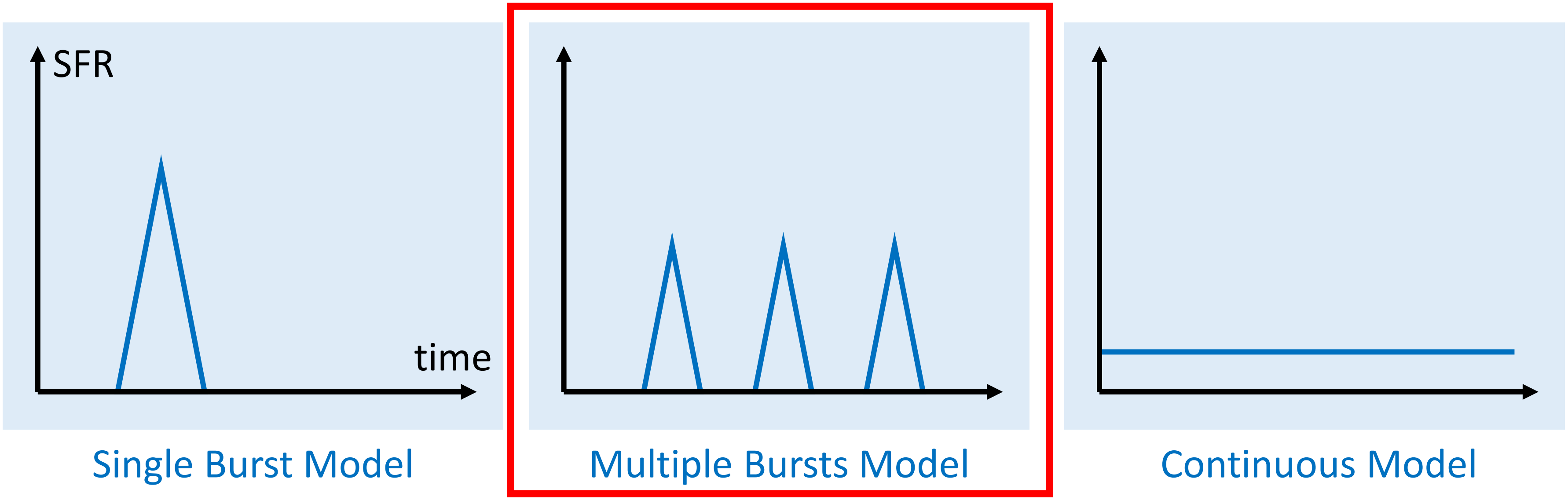
NGC 1097

- Nuclear rings in barred-spiral galaxies are sites of intense star formation.
- Observations indicate that the star formation rate in nuclear rings differs from galaxy to galaxy and is widely distributed in the range of 0.1-10 $M_{\odot}$ yr^{-1} .

Observational studies

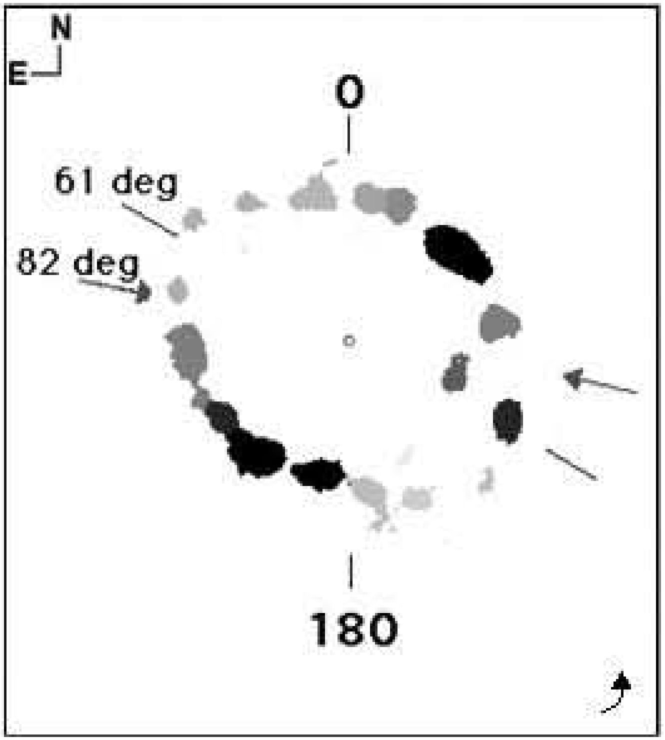


- Continuous SF
  - van der Laan et al. (2013) find that the circumnuclear ring in NGC 6951 has been forming stars for ~1Gyr.

- Multiple-burst SF
  - Using stellar population synthesis models Allard et al. (2006) estimate that M100(NGC 4321) shows multiple-burst type SF.
  - Sarzi et al. (2007) show two more galaxies (NGC4314 and NGC 7217) also have multiple-burst SF using same method.

Observational studies

- Age gradient of young star clusters in nuclear rings
  - Some galaxies show an age gradient along the azimuthal direction.
  - Some galaxies do not show a gradient.
    (Mazzuca et al. 2008, Ryder et al. 2010, Brandel et al. 2012)



Galaxy Model and Methods

- Consider a 2D gaseous disk that is isothermal (c_s=10 km/s) and self-gravitating (**CMHOG code**).
- Use an exponential gaseous density profile (Bigiel & Blitz, 2012) .
- Bar potential is modeled by **Ferrers prolate.** (Athanassoula, 1992)
  - Bar fraction f = 30%, Major axis = 5kpc, Axis ratio a/b = 2.5
  - Pattern speed of a bar = 33 km/s/kpc
- Take models both with and without spirals.

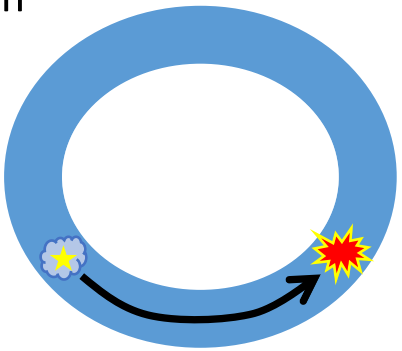
Galaxy Model and Methods

- Star formation
  - SF critical density comes from Jeans criterion : Σ_{th} ~ 1160 $M_\odot pc^{-2}$
  - SF efficiency ~ 1% (Krumhlz & Tan, 2007)
  - SF probability in a time interval Δt is given by

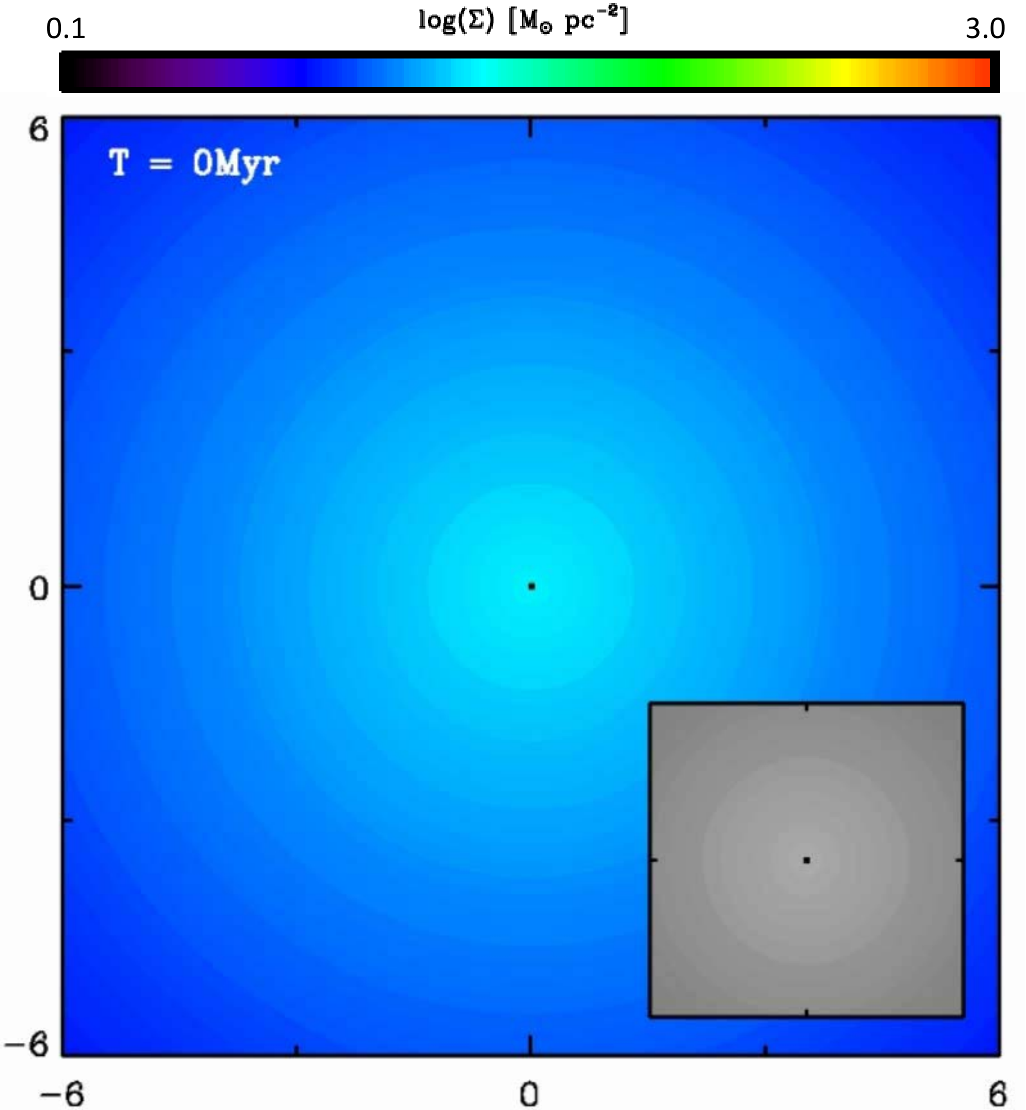
$$p \approx \epsilon_{\rm ff}\Delta t / t_{\rm ff} \sim 10^{-6} - 10^{-5}$$

  - 90% of gas turns into a particle that represents a star cluster (Typical Mass ~ $10^5 M_\odot$)

- Momentum Feedback
  - Consider only Type II SN events
  - Each SN drives total momentum to the surrounding medium amounting to P_{SN} = $3 \times 10^5 M_\odot$km/s (Kim et al. 2013)
  - Delayed explosion : delay time ~ 10Myr



Overall evolution of bar-only model



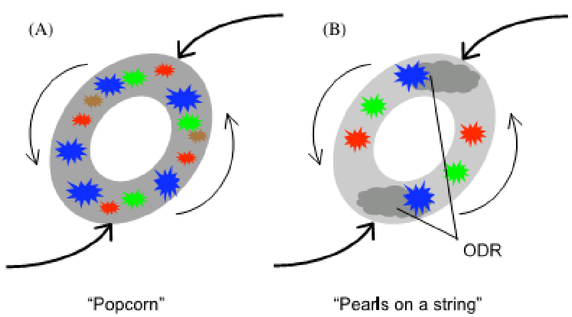
- Non-axisymmetric bar potential perturbs gas orbits to create overdense ridges at the downstream side from the major axis.

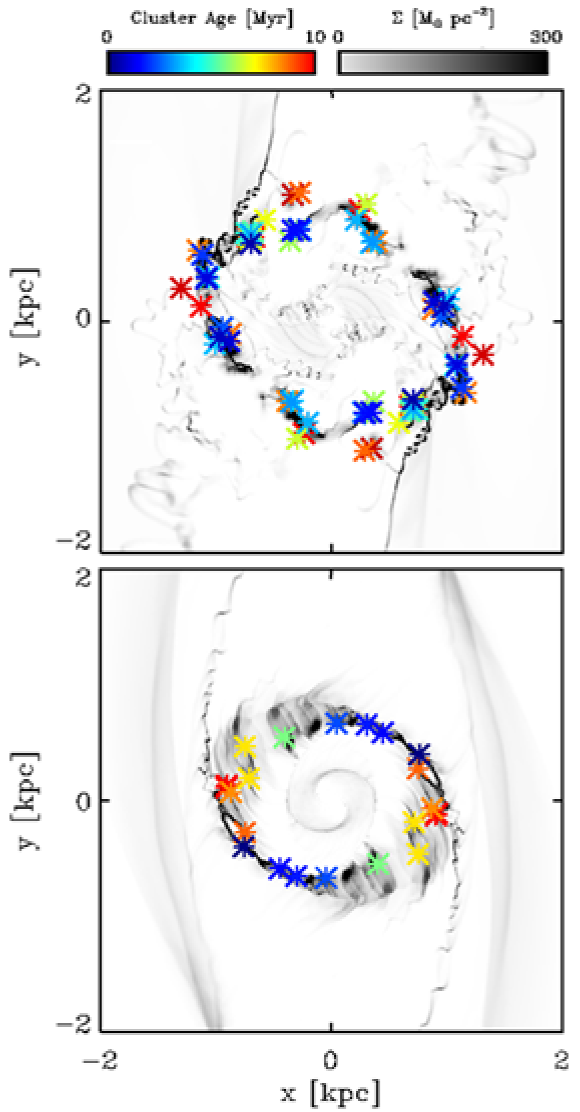
- The overdense ridges develop into dust-lane shocks and the gas moves radially inward along dust lanes.

- Only the gas inside bar region responds strongly to the bar potential, while the outer region is not much affected.
  → Gas outside the bar region do not move inward by the bar potential.

Age Gradient

- When the SFR is larger than 1 $M_\odot$ yr^{-1} :
  - Star formation events are widely distributed throughout the whole length of the ring.
- When the SFR is smaller than 1 $M_\odot$ yr^{-1} :
  - Ages of young star clusters exhibit an azimuthal gradient along the ring, since star formation events take place mostly near the contact points.
- Two models of star formation (Böker et al. 2008)
  - Popcorn & Pearls-on-a-string model





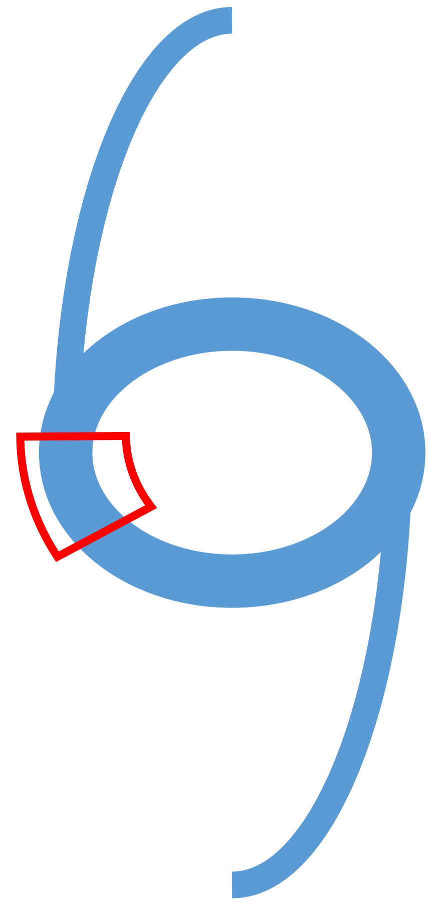
Age Gradient

- Inflowing gas moves into the ring through dust lanes.

- Maximum SFR at contact points is (Seo&Kim 2013)

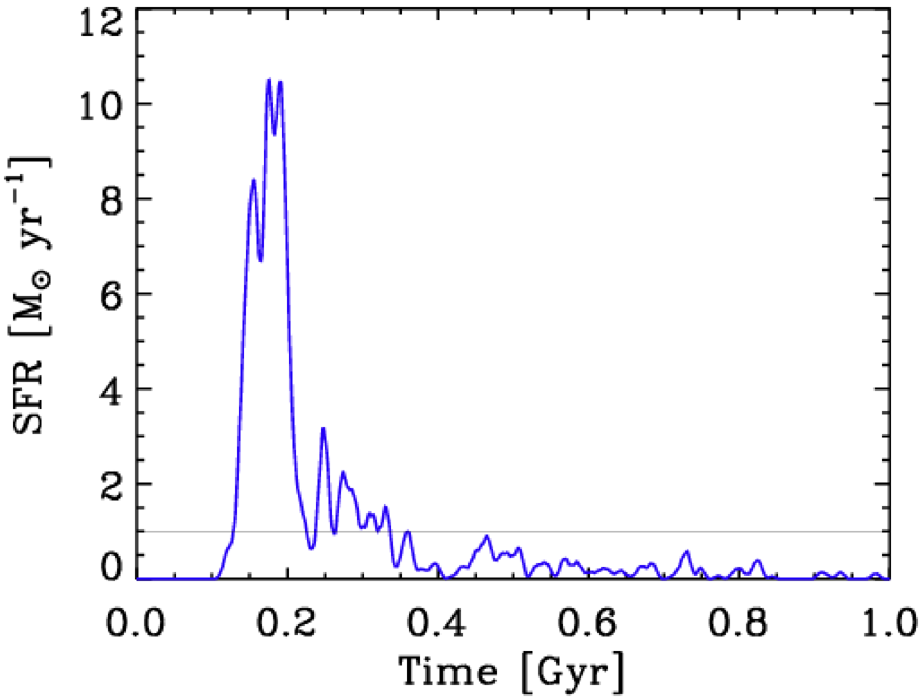
$$\dot{M}_{*,\mathrm{CP}} = \frac{2\epsilon_{\mathrm{ff}}\Sigma_{\mathrm{CP}} r_{\mathrm{NR}} \Delta r \Delta\phi}{t_{\mathrm{ff}}} \quad \sim 1\ M_{\odot}/\mathrm{yr}$$

$$\left(\begin{array}{l} \epsilon_{\mathrm{ff}} = 0.01 \\ \Sigma_{\mathrm{CP}} = 4000\ M_{\odot}\ \mathrm{pc}^{-2} \\ r_{\mathrm{NR}} = 1\ \mathrm{kpc} \end{array} \right. \qquad \dot{M}_{*,\mathrm{CP}} \propto c_s^3 r_{\mathrm{NR}}^2$$



- If mass inflow rate to the ring is small, most of the inflowing gas can be converted to stars at contact points.
- If mass inflow rate is large, all inflowing gas cannot be transformed at contact points.

Temporal variations of SFR



- At early time, the SFR displays a strong primary burst which is caused by the rapid gas infall to the ring.

- At late time, gas in the bar region is almost emptied, making mass inflow rate to the ring and ring SFR fairly small.

- Bar-only model cannot explain multiple bursts of star formation.
  → Additional mass inflows are required

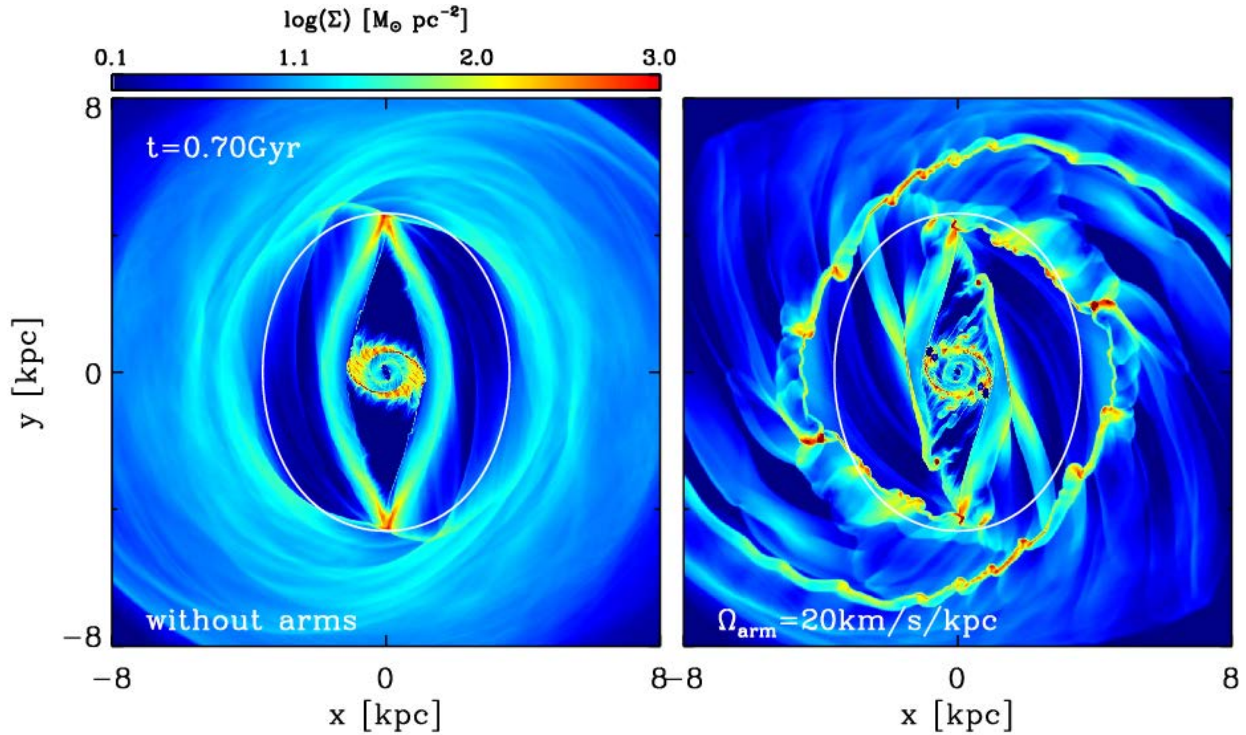
Necessity of Gas Feeding to the Bar Region

- Candidate mechanisms for gas feeding :
  - Angular momentum dissipation by spiral arms (Roberts & Shu 1972; Lubow et al. 1986; Hopkins & Quataert 2011; Kim&Kim 2014)
  - Galactic fountains (Fraternali & Binney 2006, 2008).
  - Cosmic accretion of primordial gas (e.g., Dekel et al. 2009)

- Mass inflow by spiral arms (Kim&Kim 2014)
  - Inside the Co-rotation radius(CR) of arms, gas can lose angular momentum by passing through spiral arms, while the gas outside the CR of arms move radially outward.
  - Spiral shocks are strong when the arm strength F is large and/or pattern speed Ω_{arm} is small.
  - Spiral arms can transport the gas inward at a rate of ~ 0.05-3.0$M_{\odot}$ yr^{-1}.

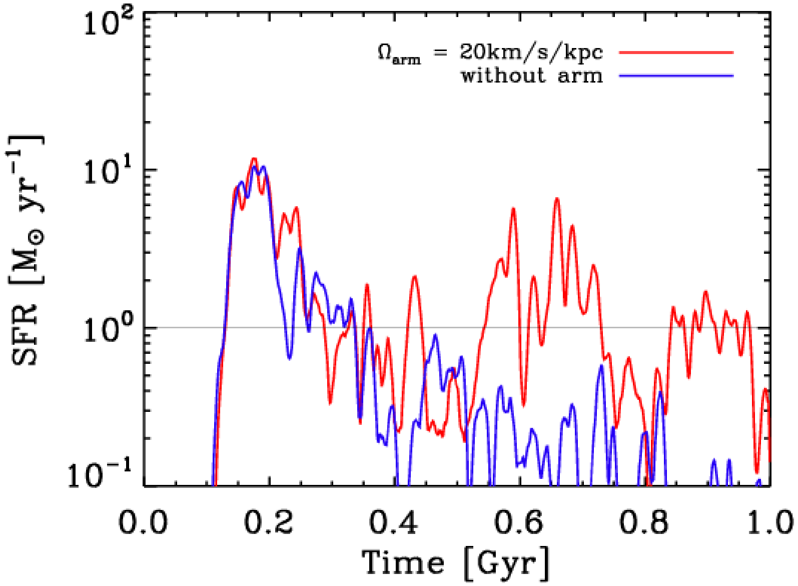
- Spiral arm potential
  - m = 2, pitch angle = 20^{o}
  - F = 5~20%, Pattern speed of arms = 10, 20, 33km/s/kpc (Co-rotation Radius : 20, 10, 6kpc)

Effects of spiral arms

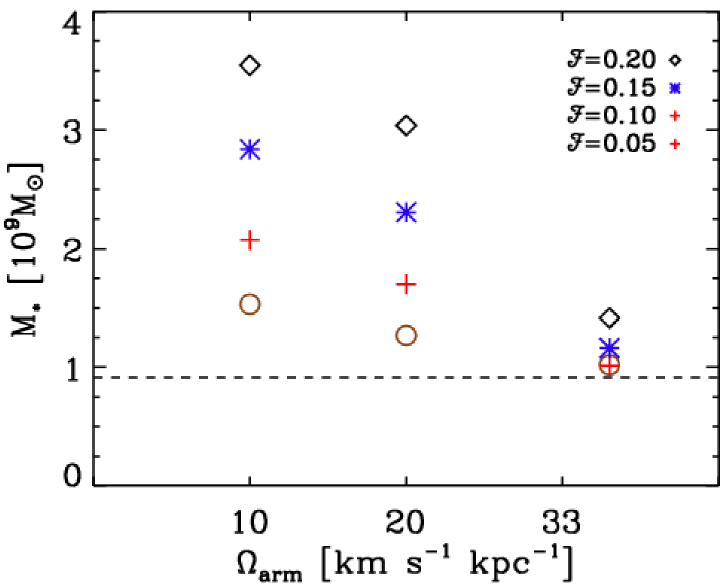


- If the CR is located to far from the bar region, spiral arms can drive gas toward the bar region.
- This inflowing gas moves on along x1 orbits after entering the bar region and piles up at the bar ends where x1 orbits crowd.
- Mutual collisions of gas orbits and interaction between the bar and spirals take away angular momentum from the gas
  → Gas blobs move along the dust lanes to the nuclear ring, intermittently.

Enhanced SF by Arms



- The presence of spiral arms can make the SFR rejuvenated at t > 0.4 Gyr.
- Episodic star formation bursts occur at late time, since the mass infalls from the bar ends to the ring occur intermittently.



- Total converted mass is larger for models with larger F and smaller Ω_{arm}.
- Enhanced mass in models with Ω_{sp} = 33km/s/kpc is not much, since the co-rotation radius is 6kpc.

Summary

- Our results show that an azimuthal age gradient of young star clusters is expected when the SFR is low (less than 1 $M_{\odot}$ yr^{-1} in our models).

- We find that spiral arms can supply gas to nuclear rings of barred-spiral galaxies, giving rise to multiple bursts of star formation at late time.