Gas Structures and Star Formation in the Central Regions of Barred-Spiral Galaxies

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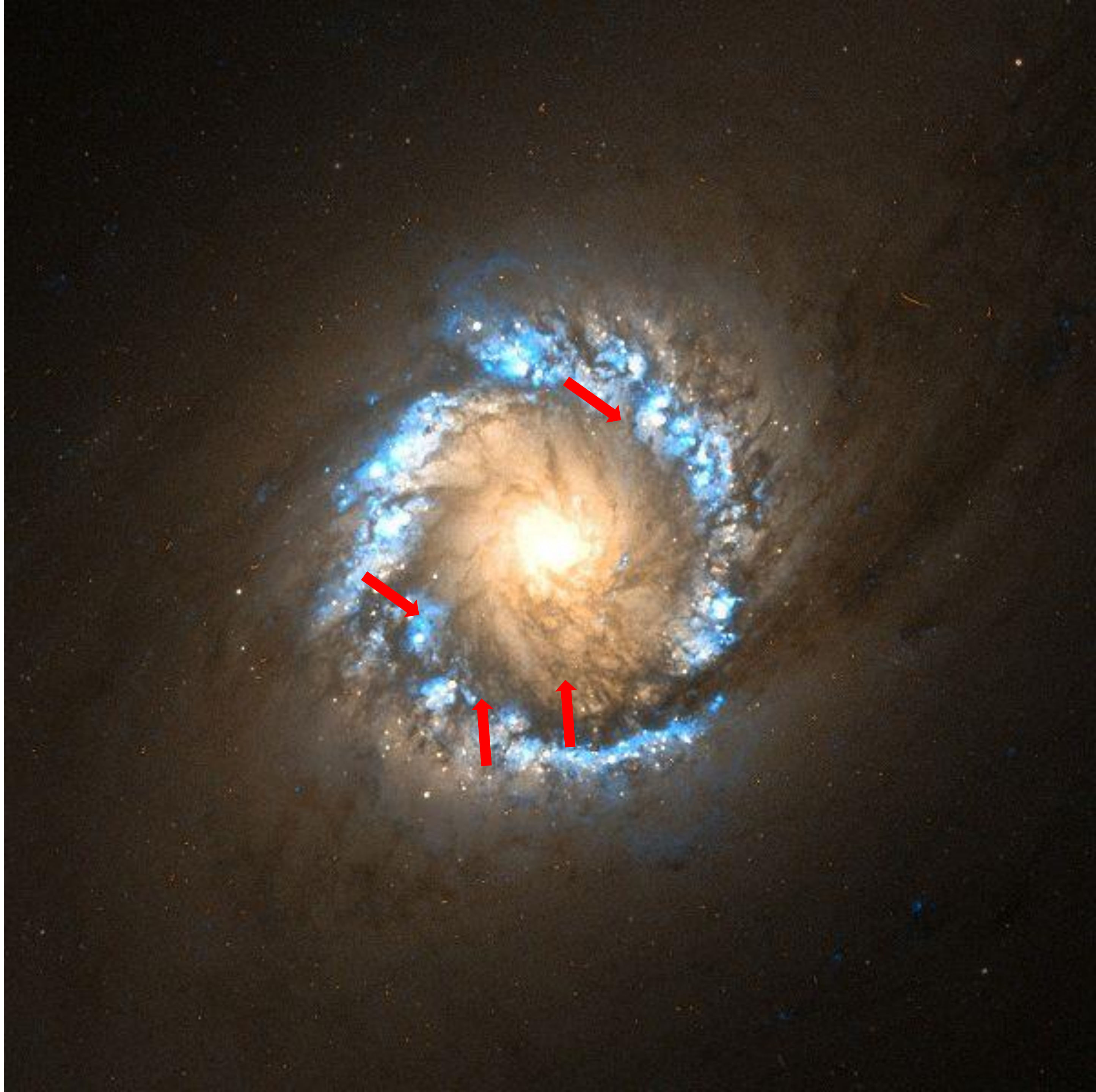
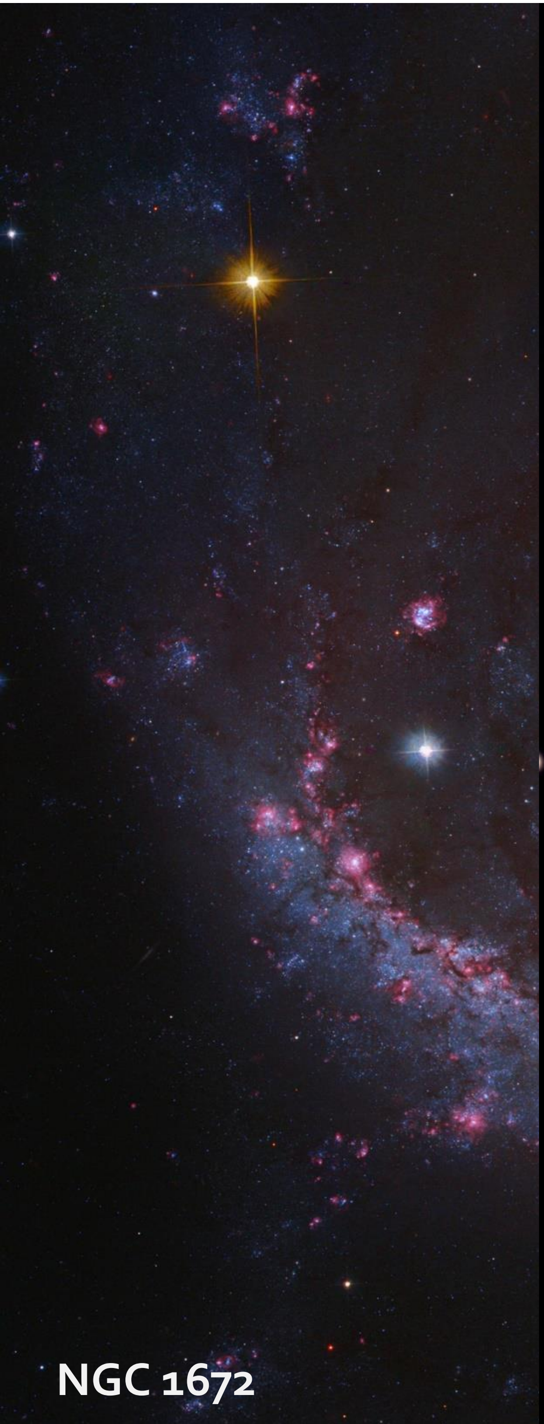
Introduction

- Barred-spiral galaxy NGC 1097

- Dust lanes
- Spurs
- Nuclear ring
- Nuclear spirals



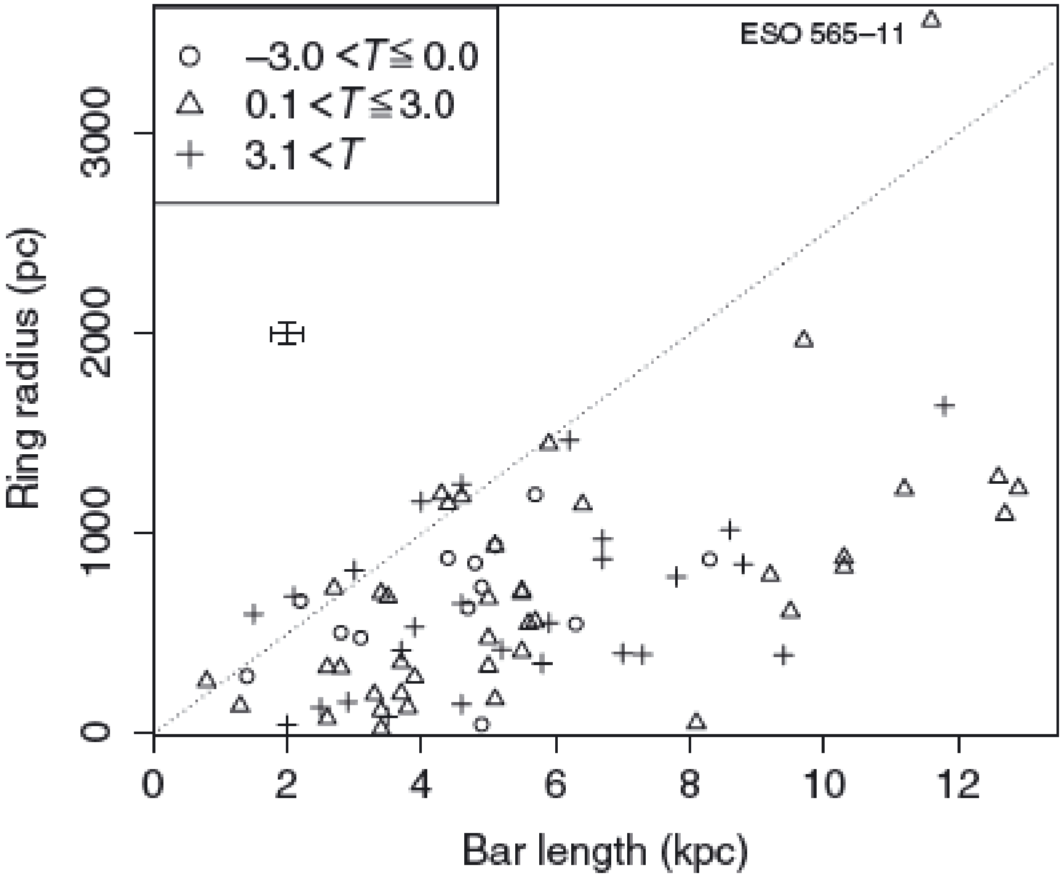
Observational Studies

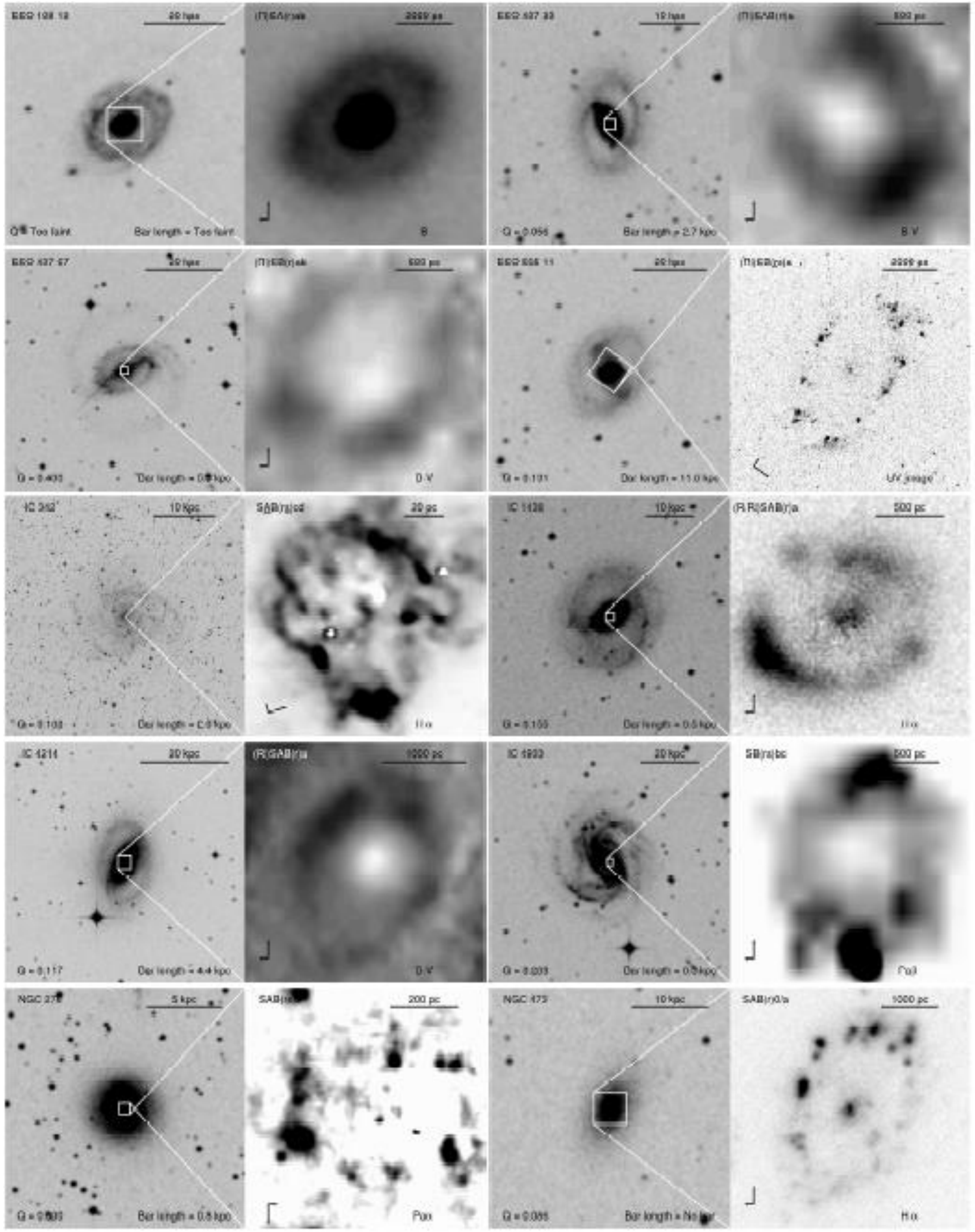

NGC 1672


NGC 613

Observational studies

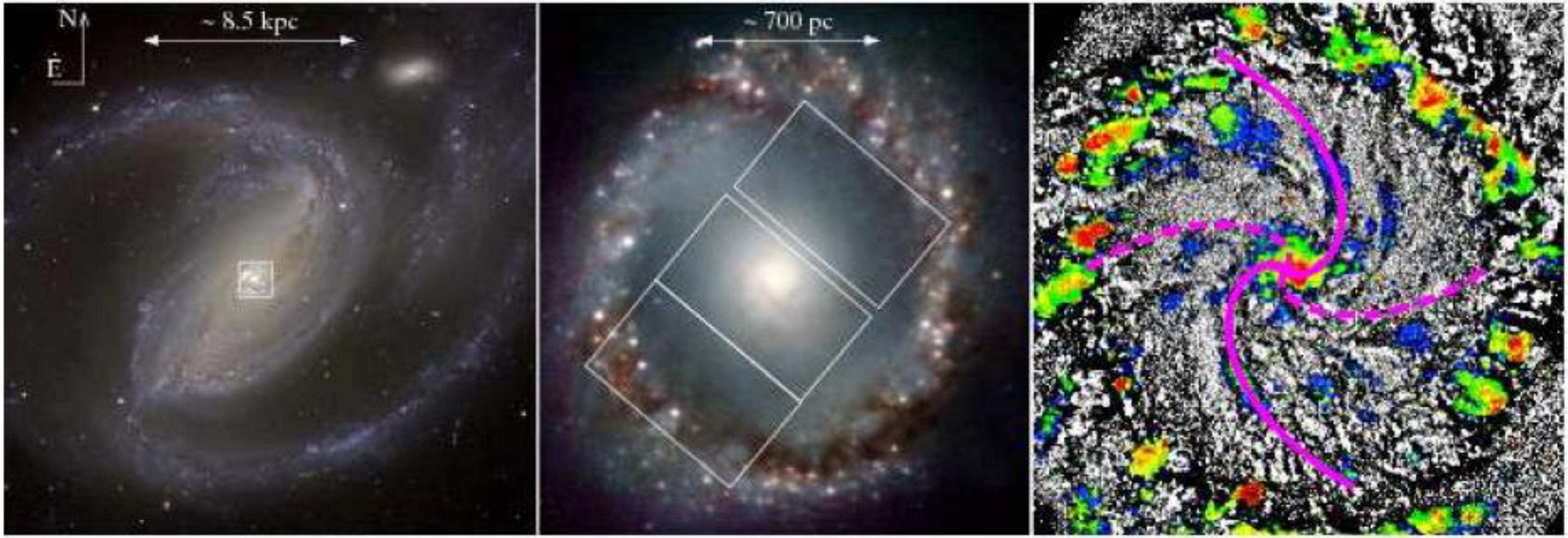
- Nuclear rings
  (Comeron et al. 2010)



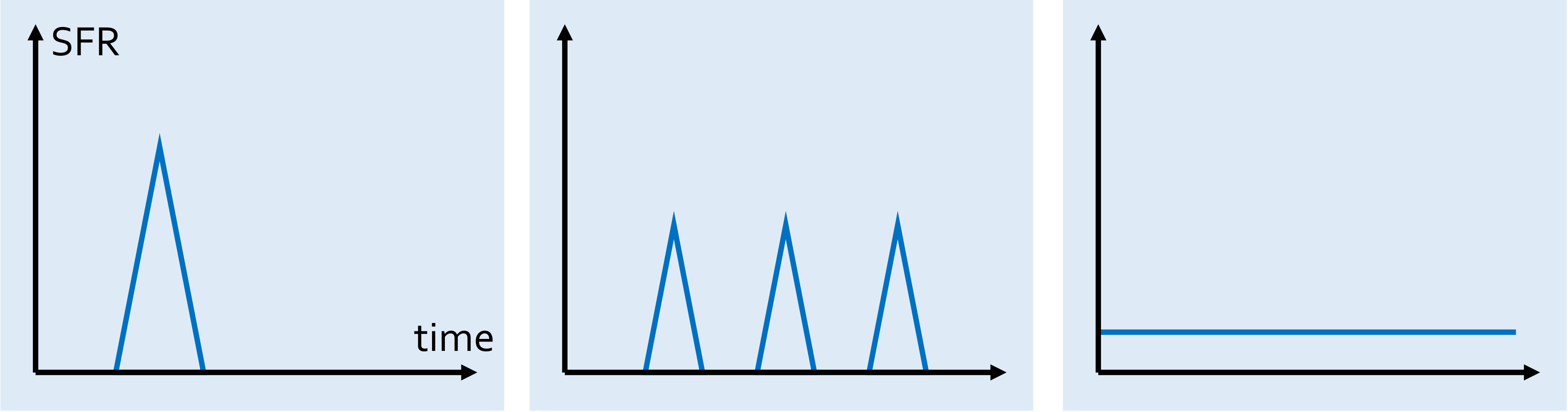


Observational studies

- Nuclear spirals (van de Ven & Fathi 2009)



Observational studies

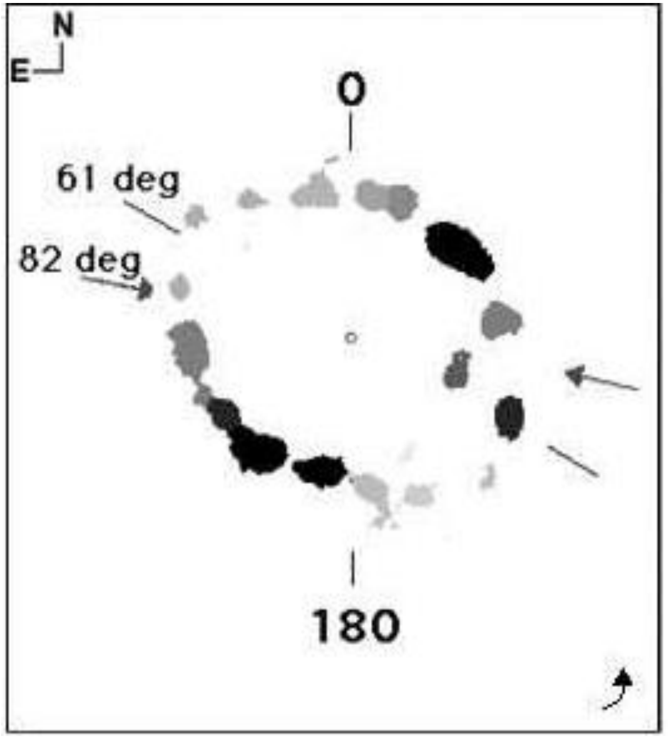


Single Burst Model · Multiple Bursts Model · Continuous Model

- 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) show 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

- Observations
  - 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)



Previous Numerical Studies

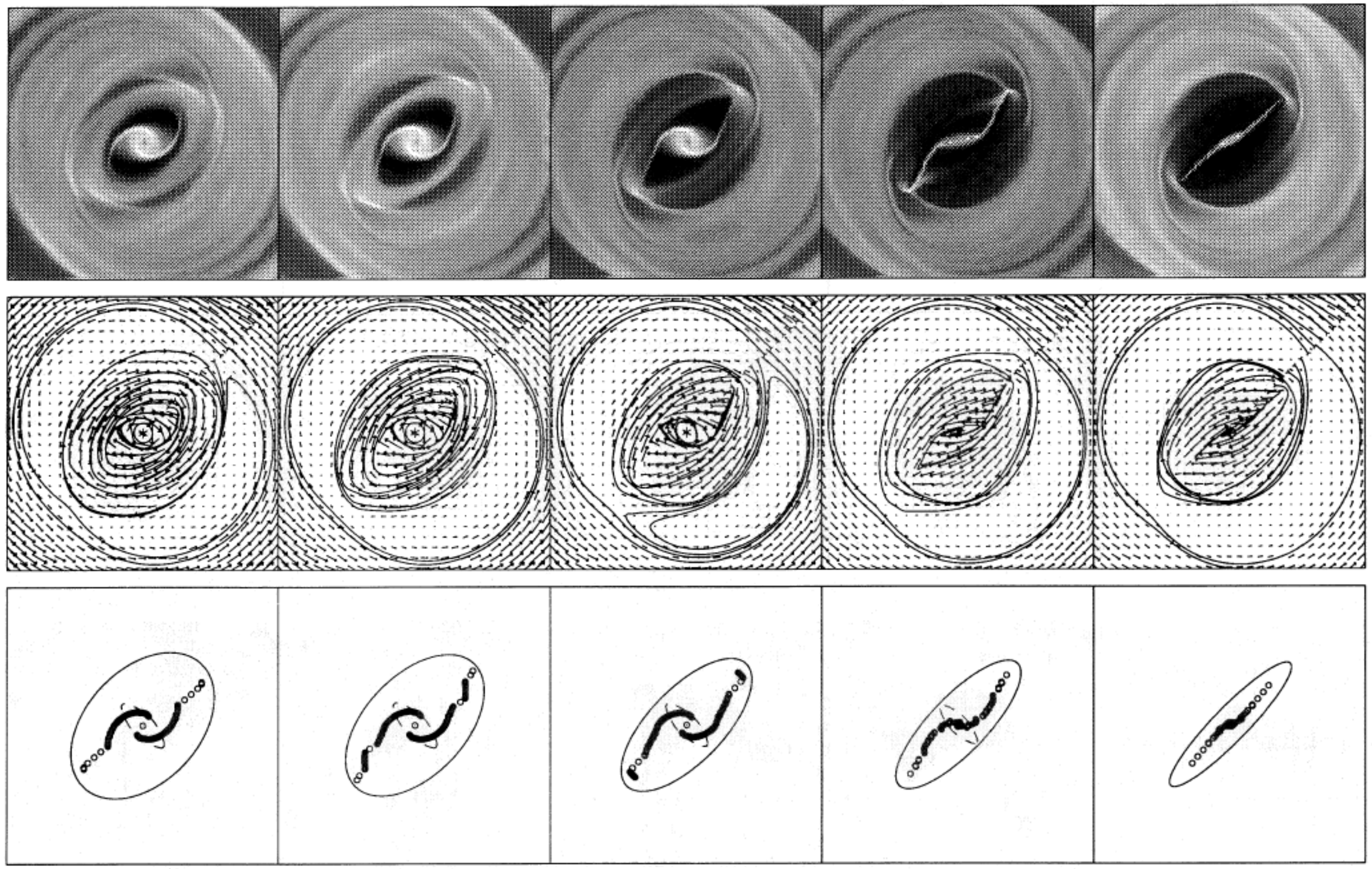
Previous Studies

- Grid-based simulations
  - Athanassoula 1992; Piner et al. 1995; Maciejewski et al. 2002; Maciejewski 2004; Regan & Teuben 2003, 2004; Kim et al. 2012a, 2012b; Kim & Stone 2013; Seo & Kim 2013, 2014

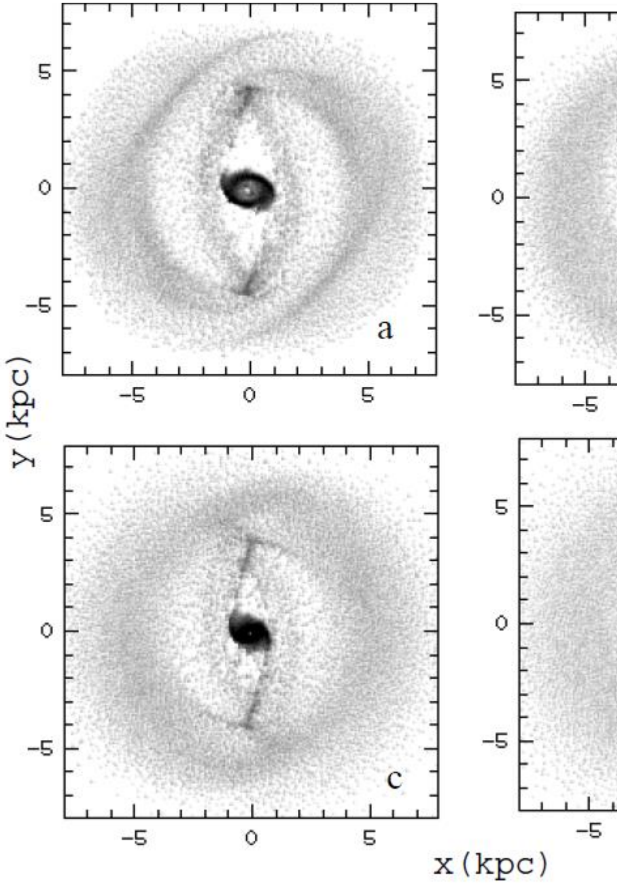
- SPH simulations
  - Englmaier & Gerhard 1997; Patsis & Athanssoula 2000; Ann & Lee 2000; Ann & Thakur 2005; Thakur et al. 2009

Previous Studies

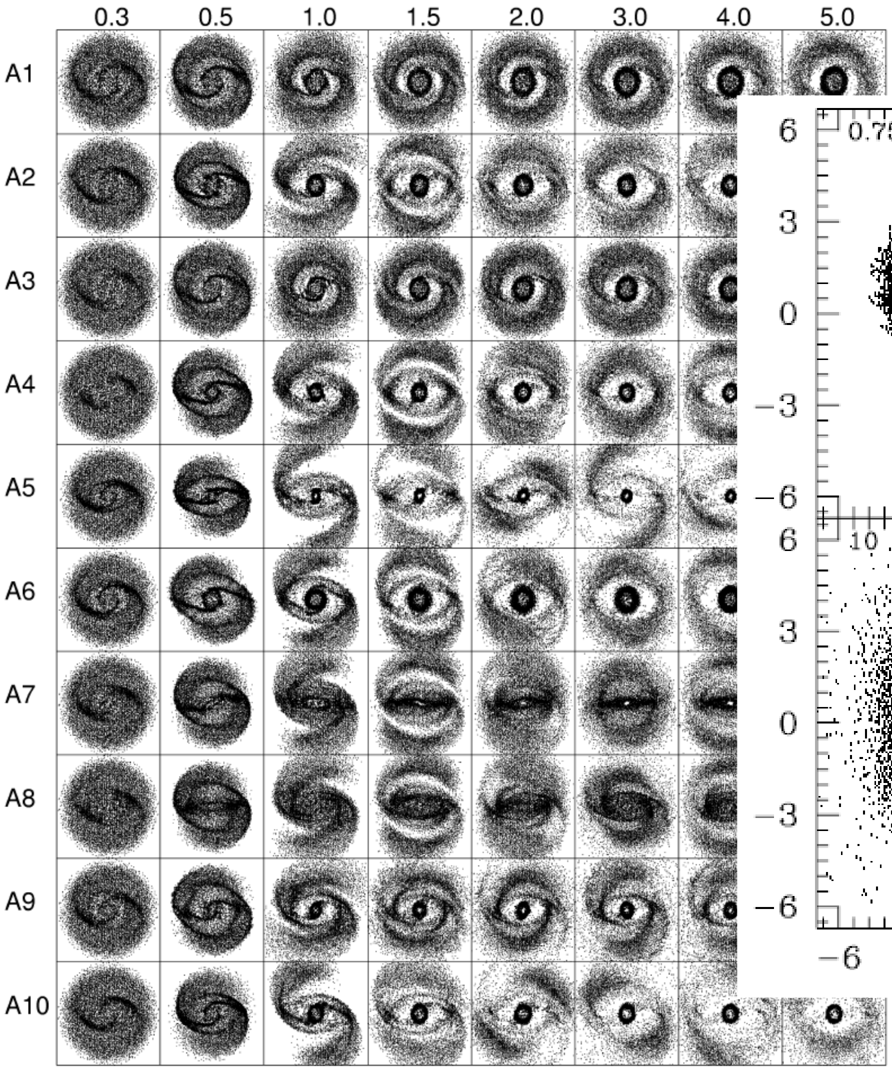
- Athanassoula (1992)
  - Dust lanes are shocks in the gas flows
  - Dust lanes are straighter when the bar potential is stronger
  - Grid resolution : 100 pc
  - Resolution is not enough to resolve the central region



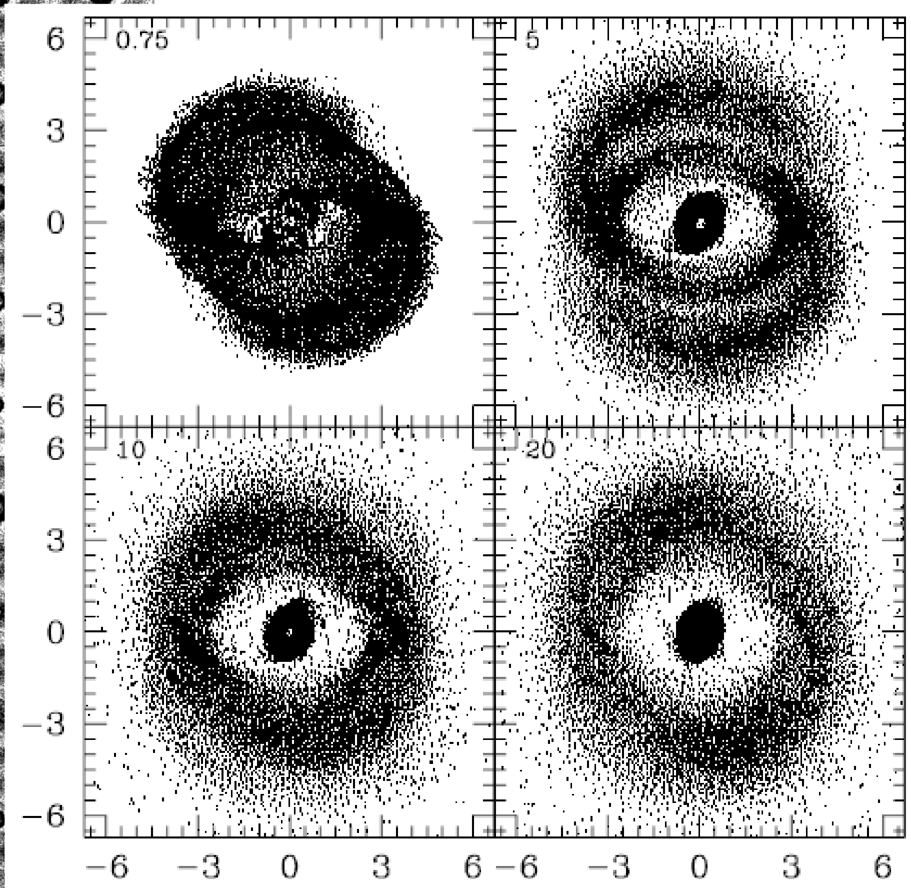
Previous Studies



Patsis & Athanassoula (2000



Ann & Lee (2000)



Thakur et al. (2005)

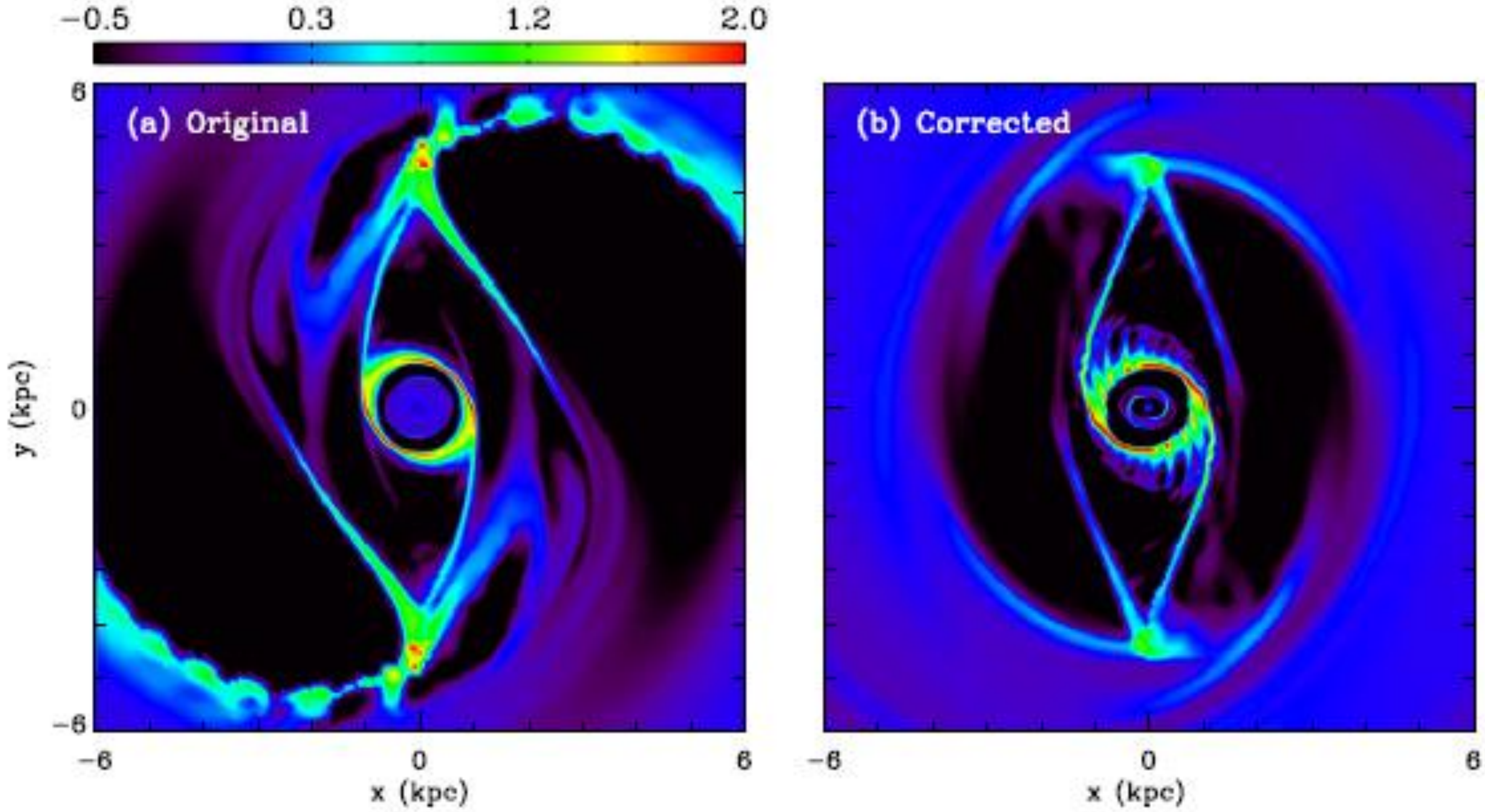
Previous Studies

- To focus on central region, Piner et al. (1995) used the CMHOG code on a cylindrical grid.
  - Grid resolution at 1kpc : 20 pc
  - Grid resolution at inner boundary (0.1 kpc) : 2pc
  - Maciejewski et al. 2002; Maciejewski 2004; Regan & Teuben 2003,2004

ERROR

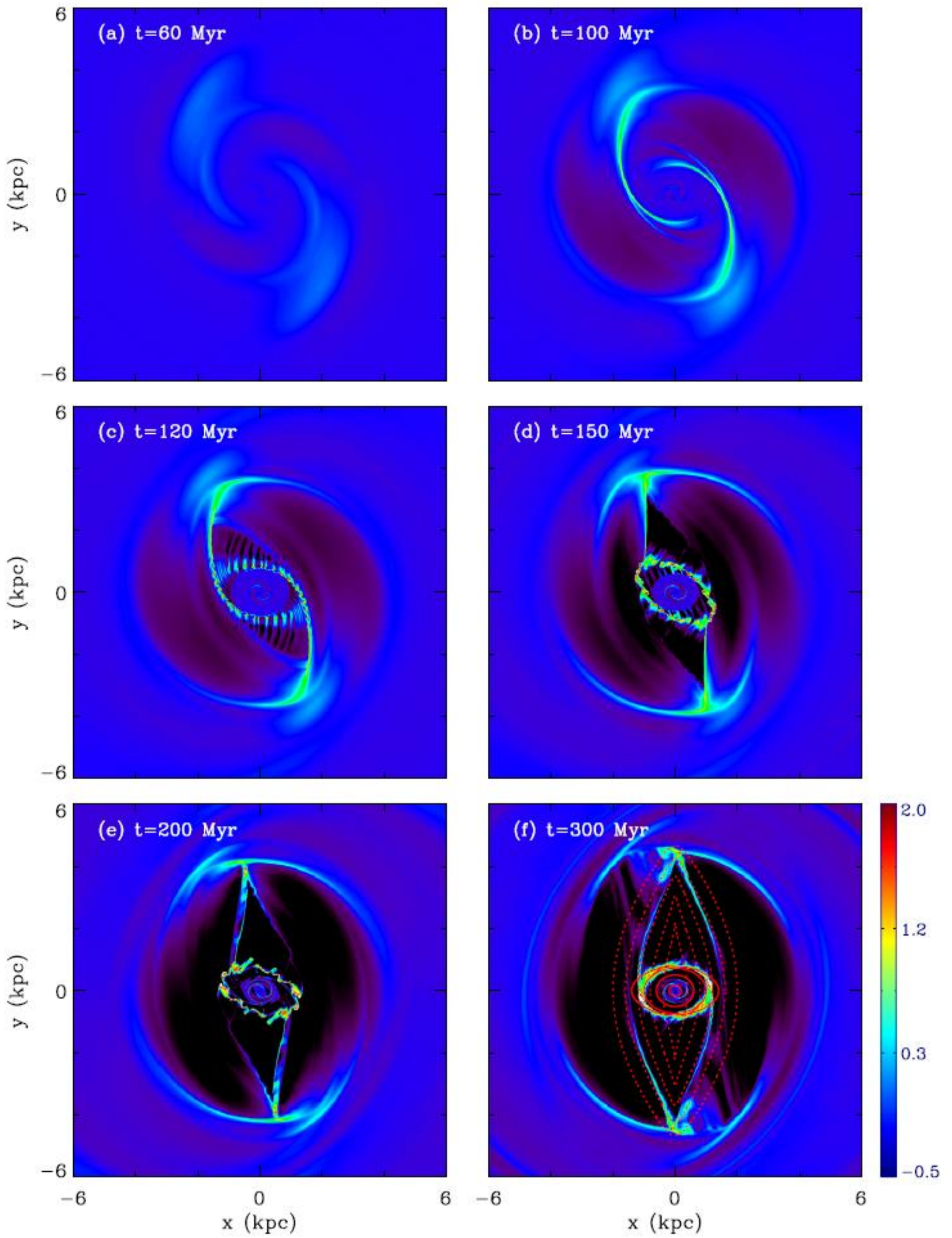
- Kim et al. (2012) corrected the error and revisited the issue of the substructure formation.
  - Grid resolution at 1kpc : 5 pc (1024x638)
  - A uniform Cartesian grid would require 6000x6000 zones to achieve the same resolution.

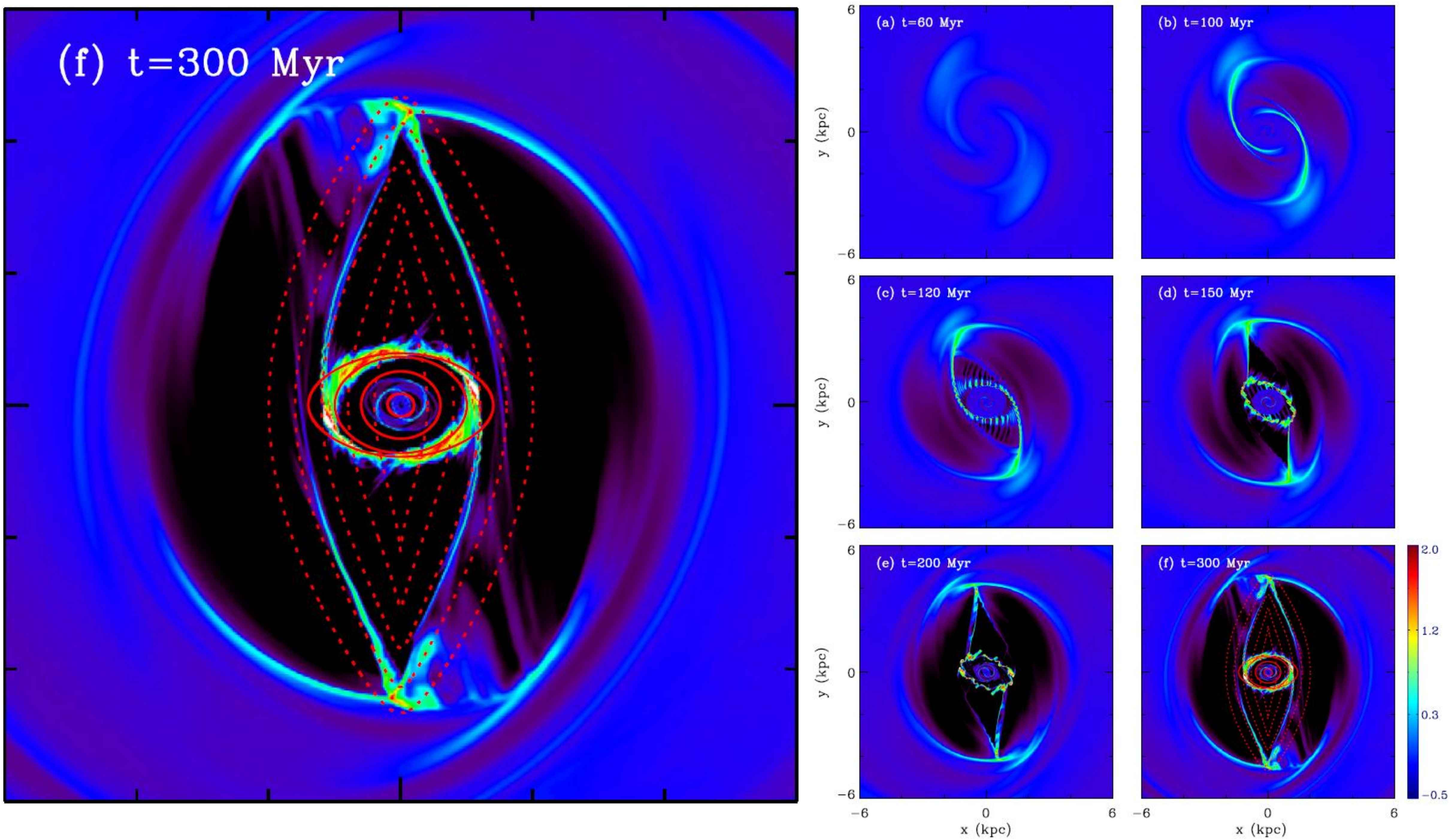
Previous Studies



Gas Structure Evolution

- Kim et al . (2012a)
  - Circular gaseous orbits perturbed by Gravitational torques induced by non-axisymmetric bar potential.
  - Overdense regions develop into off-axis shocks.
  - Gas loses angular momentum and forms a nuclear ring.
- Kim et al . (2012b)
  - Dust lanes are straighter and nuclear ring is smaller when the bar potential is stronger.





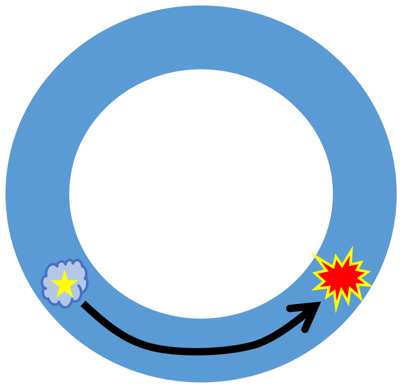
(f) t=300 Myr
(a) t=60 Myr
(b) t=100 Myr
(c) t=120 Myr
(d) t=150 Myr
(e) t=200 Myr
(f) t=300 Myr
y (kpc)
x (kpc)
6
0
−6
2.0
1.2
0.3
−0.5

Star formation in nuclear rings (Seo & Kim 2013, 2014)

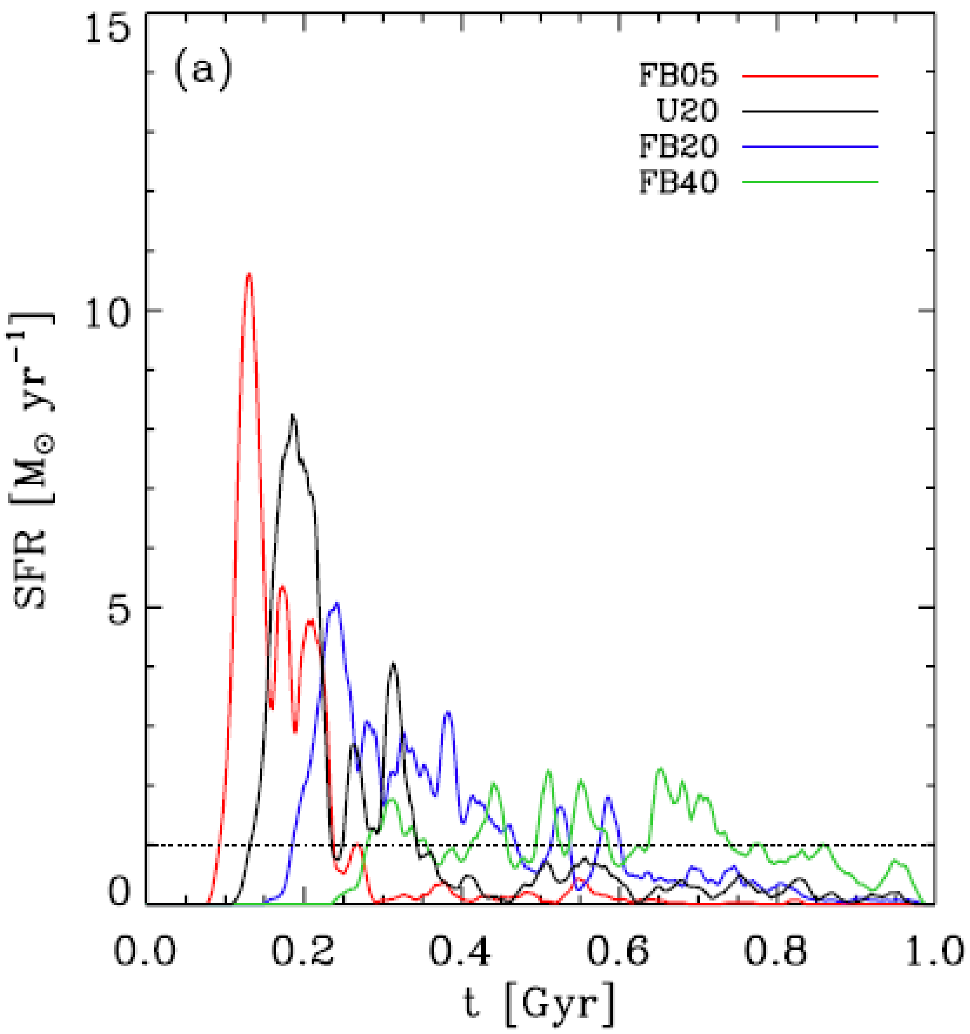
- CMHOG code
  - Self-gravitating disk
  - Star formation and feedback

- Star formation method
  - SF critical density comes from Jeans criterion : $\Sigma_{th} \sim 1160\ M_{\odot} pc^{-2}$
  - SF efficiency ~ 1% (Krumholz & Tan, 2007)
  - SF probability in a time interval Δt is given by $p \approx \epsilon_{ff} \Delta t / t_{ff} \sim 10^{-6} - 10^{-5}$
  - 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



Star formation in nuclear rings

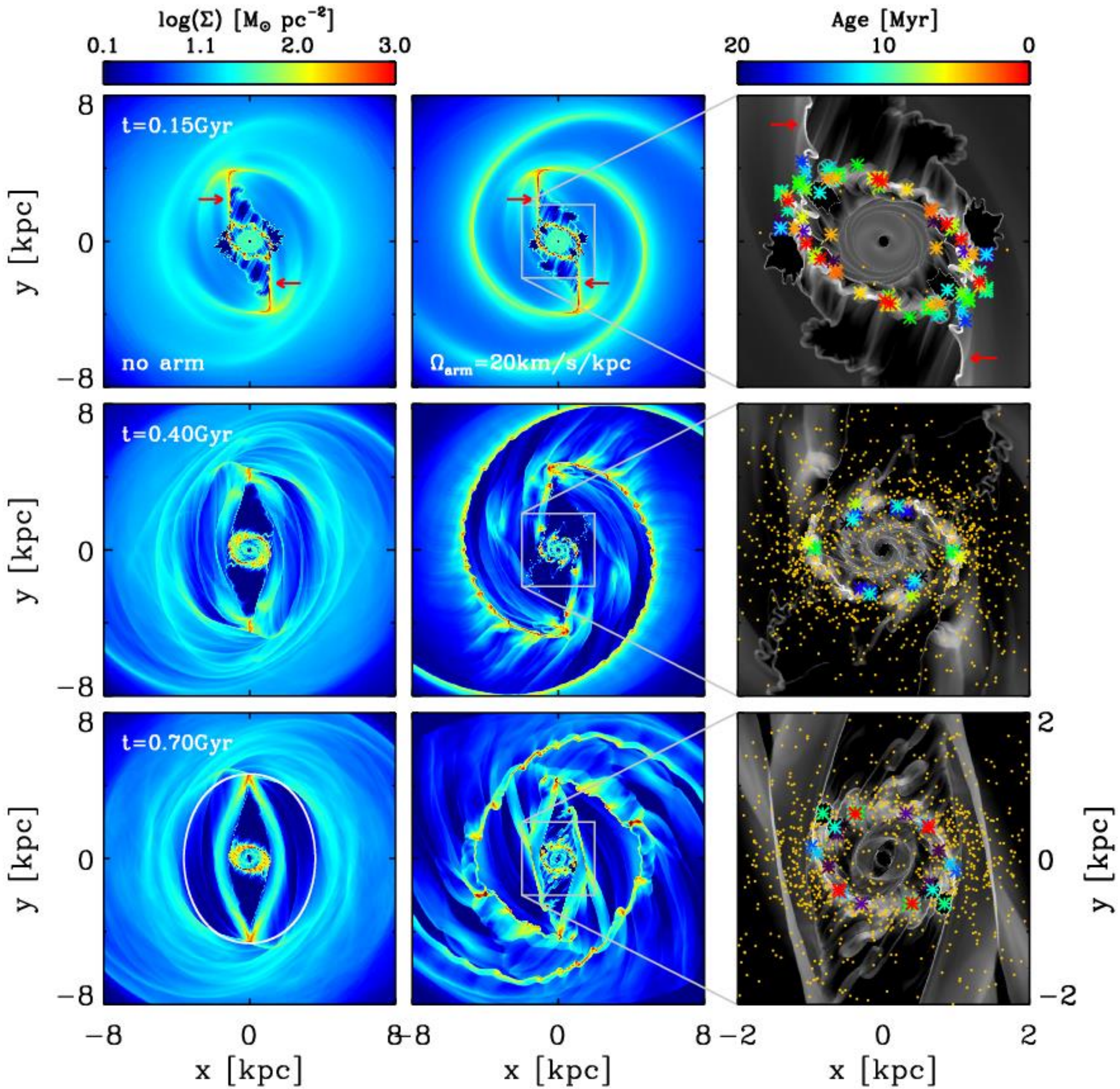


- Full bar strength : 0.5, 1, 2, 4 bartime. (1 bartime = 185 Myr)
- The primary burst is caused by the rapid gas infall due to the bar growth.
- The primary burst is caused by the rapid gas infall to the ring due to the bar growth.

Star formation in nuclear rings

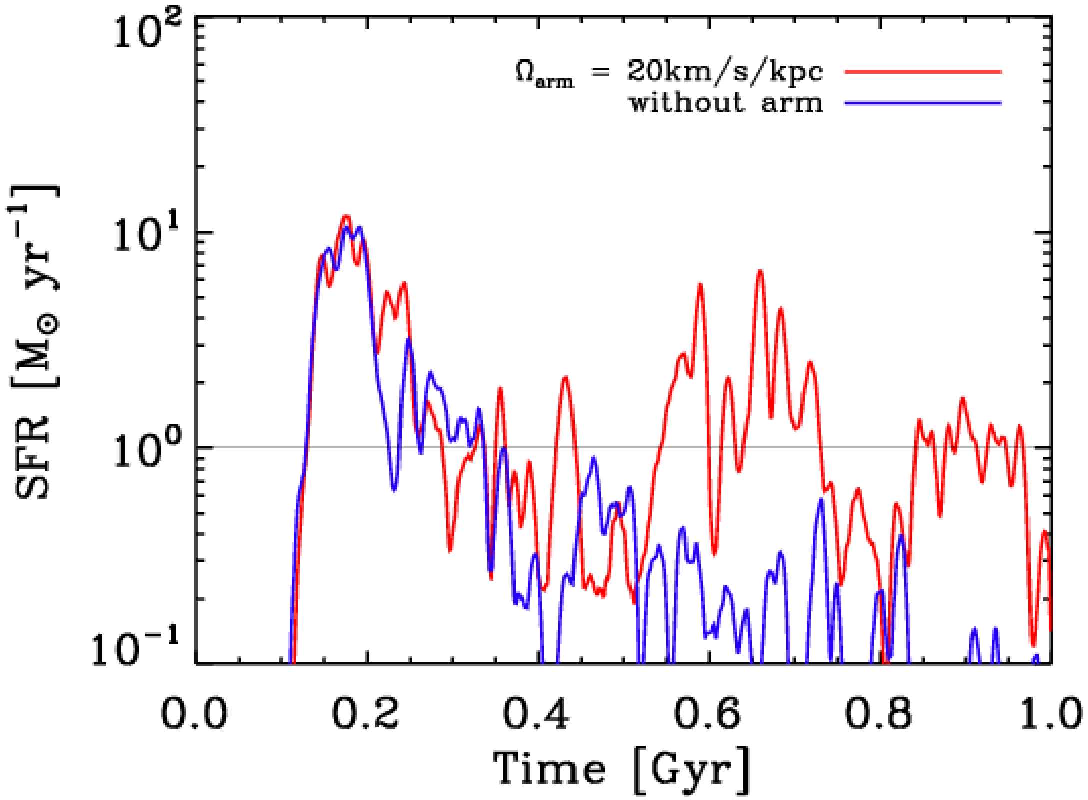
- Spiral arms can be efficient to transport the gas from outside to the central bar region.
  - Inside the co-rotation of the arms, gas loses angular momentum by passing through the spiral shocks.

- Kim & Kim (2014) found that spiral arms can transport the gas inward at a rate of ~0.05 – 3 $M_{\odot}$/yr .



- If the CR is enough 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.

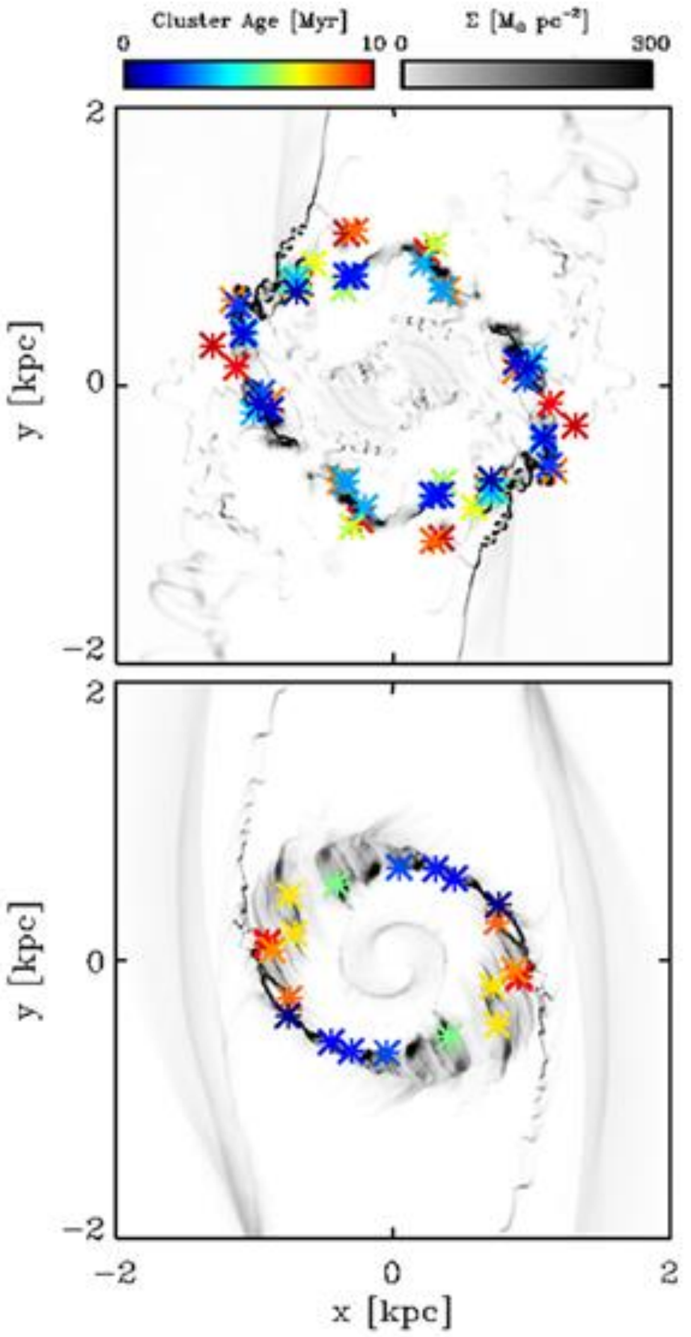
Star formation in nuclear rings



- 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.

Star formation in nuclear rings

- 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.



Star formation in nuclear rings

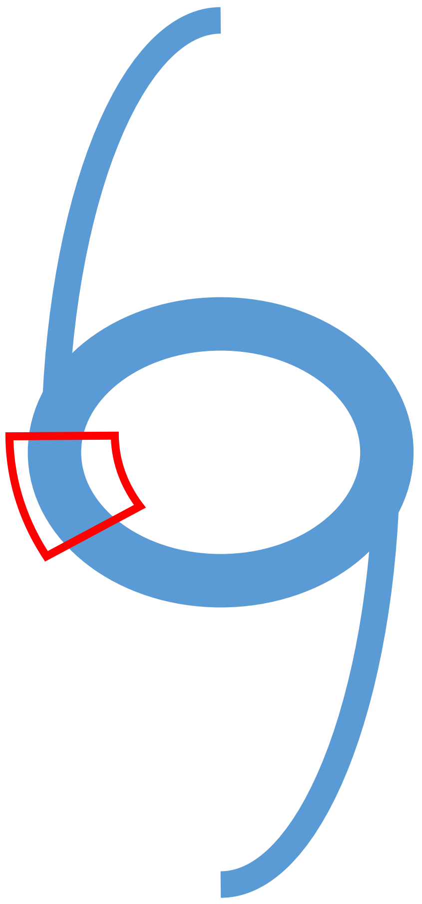
- Inflowing gas moves into the ring through dust lanes.

- Maximum SFR at contact points is

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

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

- 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.



Weak points of previous simulations

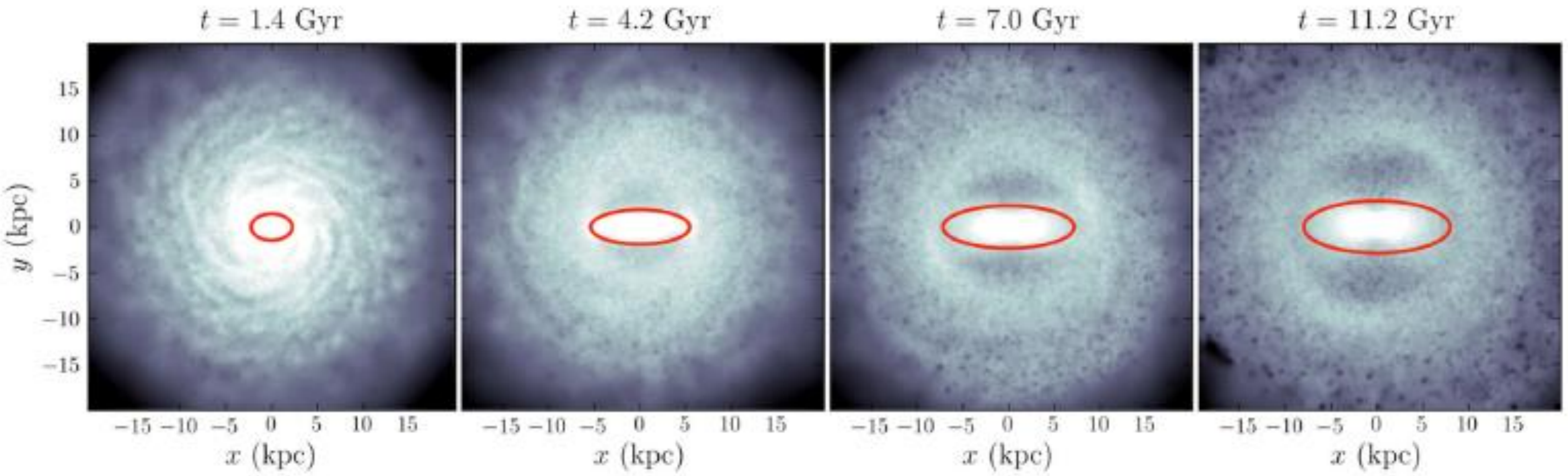
- 2-Dimensional thin disk
  - z-direction stellar feedback

- Isothermal condition
  - Star formation criteria
  - Momentum feedback

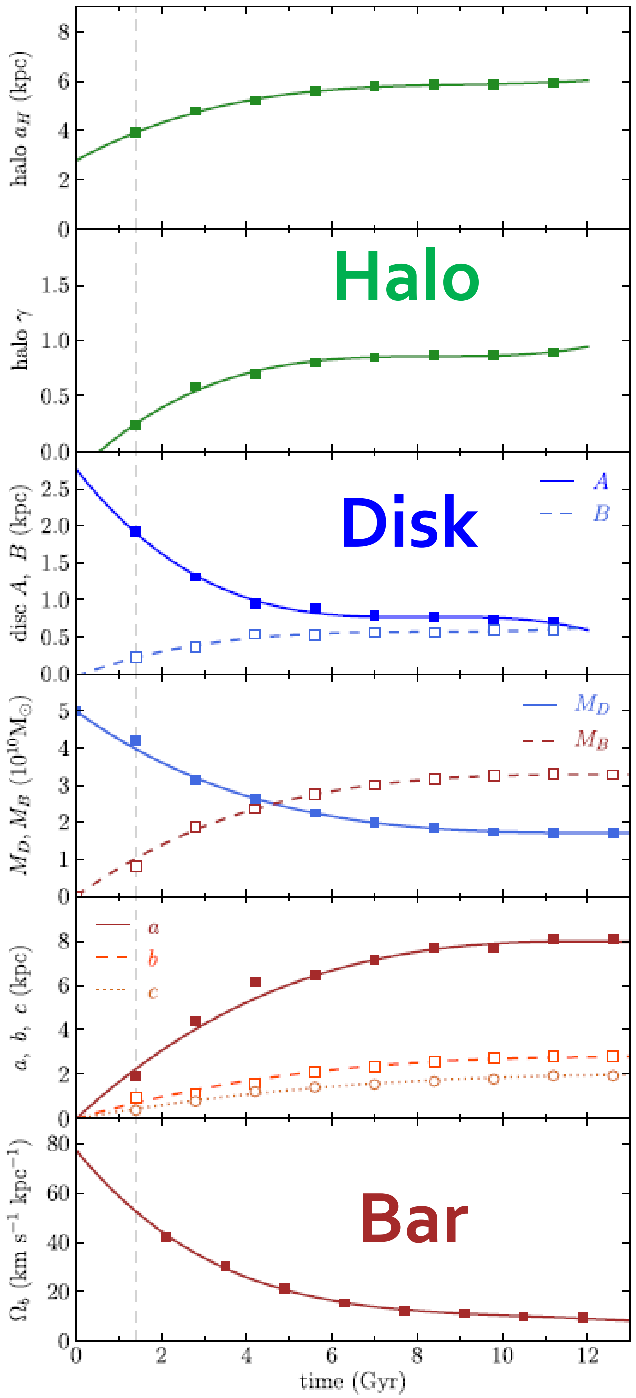
- Fixed stellar bar/spiral potential
  - Growth of bars

N-Body simulations

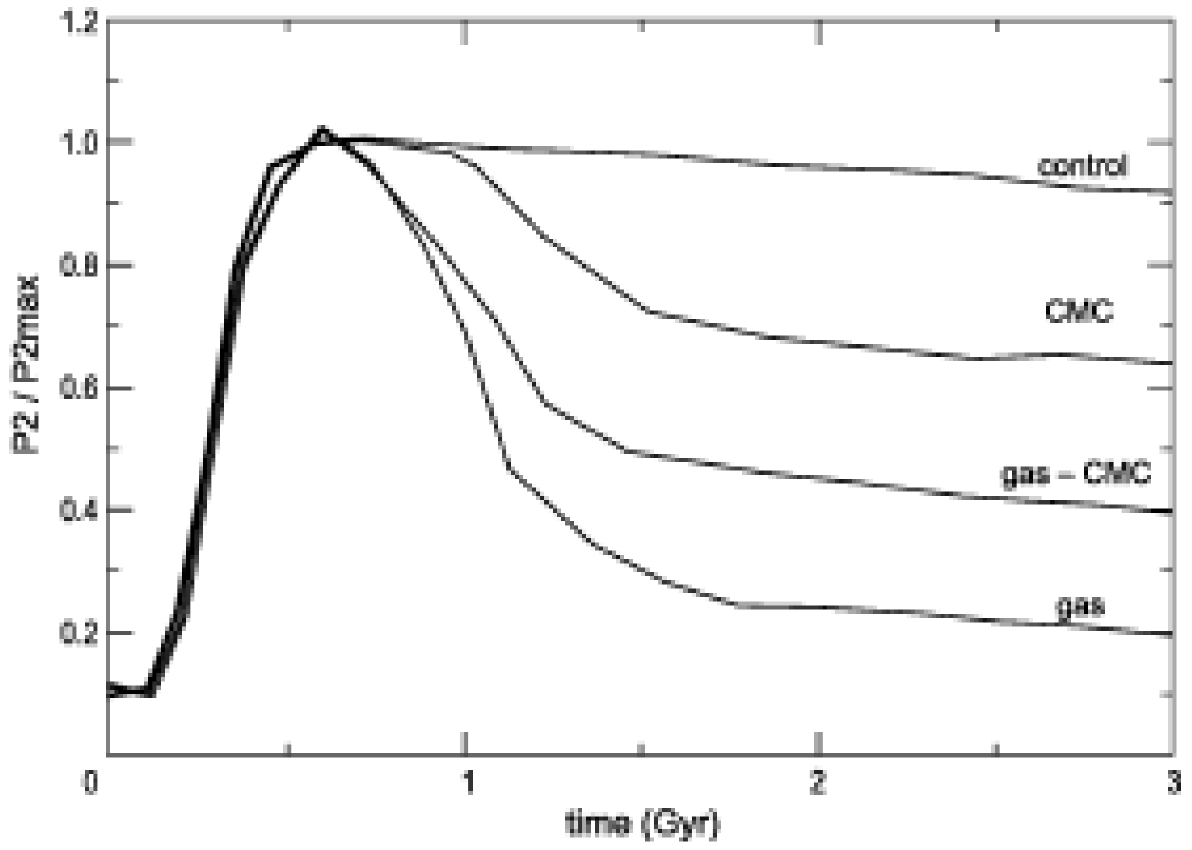
- N-Body simulations show that physical parameters of stellar components vary with time (Bournaud et al. 2005; Berentzen et al. 2007; Manos et al. 2010; Minchev et al. 2012; Athanssoula 2012; Roca-Fabrega et al. 2013)



Manos et al. (2010)



N-Body simulations



- Bournaud et al. (2005)
- Bars in gas-rich spiral galaxies are short-lived.

Ongoing work…

- Enzo code
  - Adaptive Mesh Refinement (AMR) code
  - Gas cooling/heating
  - Including N-Body dynamics
  - Star formation
    - + Temperature criterion
  - Feedback
    - Radiative feedback (+ stellar winds)

Thank You