Star Formation in the Nuclear Region of Barred Galaxies

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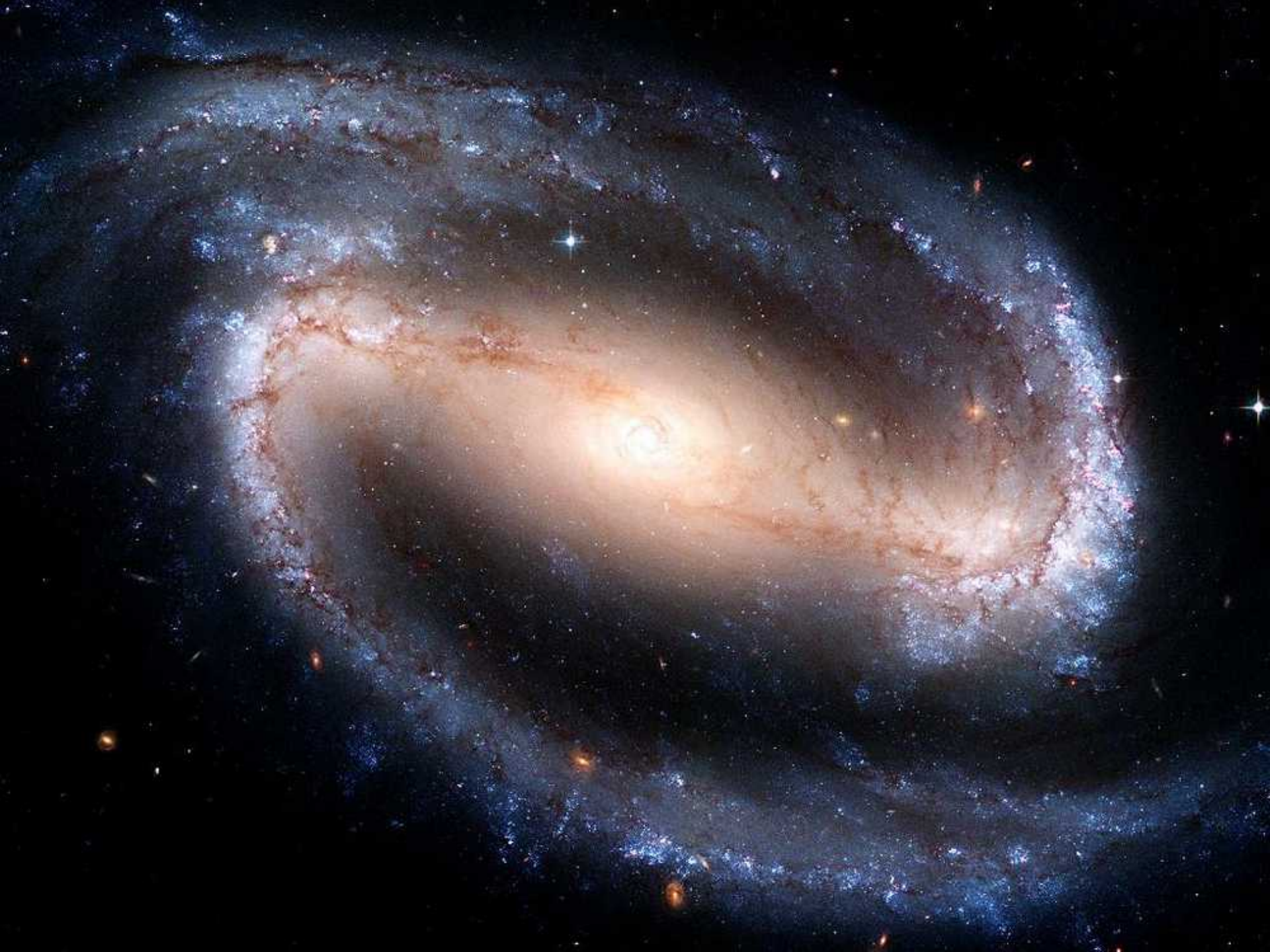
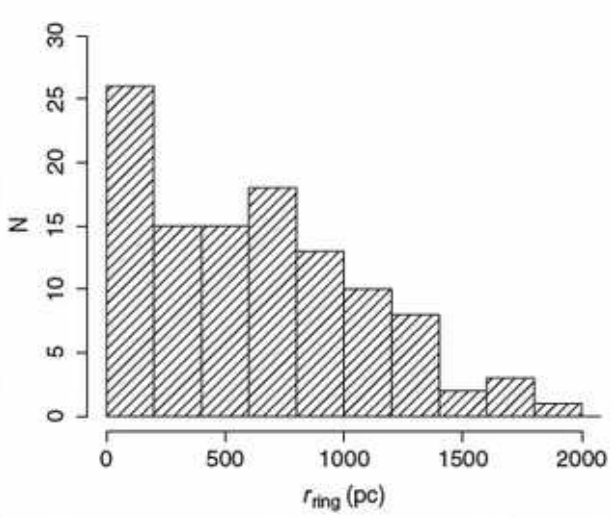


Observations

- Nuclear rings in barred galaxies are sites of intense star formation.
- Size of the nuclear rings varies from galaxy to galaxy (50pc ~ 2 kpc).
- The star formation rate (SFR) in the nuclear ring also differs fr



(Comeron et al. 2010)

Observations

- Nuclear ri
  s are
  sites of int

- Size of the
  from galax
  kpc).

NGC (1)	Morph. Type (2)	ϵ_{Ring} (3)	PA_{Ring} (deg) (4)	R_{Ring} (arcsec) (5)	R_{Ring} (kpc) (6)	PA_{Disk} (deg) (7)	PA_{bar} (deg) (8)	SFR ($M_\odot$ yr^{-1}) (9)
278	SAB(rs)b	0.06	120	4.4 × 4.1	0.2 × 0.2	...	No bar	0.5
473	SAB(r)0/a	0.37	160	12.2 × 6.9	1.7 × 1.0	153	164	2.2
613	SB(rs)bc	0.3	122	5.1 × 2.6	0.4 × 0.2	120	120	2.2
1300	(R)SB(s)bc	0.25	135	4.1 × 3.1	0.3 × 0.2	106	102	0.2
1343	SAB(s)b	0.25	60	8.8 × 6.6	1.2 × 0.9	80	82	6.8
1530	SB(rs)b	0.35	25	6.8 × 4.9	1.2 × 0.8	8	122	3.8
4303	SAB(rs)bc	0.14	88	3.3 × 2.8	0.2 × 0.2	...	10	1.4
4314	SB(rs)a	0.10	135	6.6 × 5.9	0.3 × 0.3	...	135	0.1
4321	SAB(s)bc	0.12	170	8.8 × 7.0	0.7 × 0.6	30	153	...
5248	(R)SB(rs)bc	0.3	115	6.6 × 4.6	0.7 × 0.5	110	137	4.2
5728	(R1)SAB(r)a	0.4	125	5.3 × 3.2	1.1 × 0.6	...	33	4.0
5905	SB(r)b	0.2	141	1.6 × 1.5	0.3 × 0.3	135	25	2.6
5945	SB(rs)ab	0.1	105	3.5 × 3.2	1.2 × 1.1	105	10	4.4
5953	SAa	0.1	192	6.1 × 5.5	1.0 × 0.9	169	no bar	9.9
6503	SA(s)cd	0.65	121	38.5 × 13.4	1.1 × 0.4	123	no bar	1.5
6951	SAB(rs)bc	0.2	146	4.6 × 3.7	0.5 × 0.4	170	85	1.4
7217	(R)SA(r)ab	0.20	89	11 × 8.8	0.8 × 0.7	95	no bar	0.6
IC 1438	SAB(r)a	0.10	130	3.3 × 3.0	0.5 × 0.5	...	124	1.3
7469	SAB (rs)a	0.09	38	1.6 × 1.5	0.5 × 0.5	135	56	...
7570	SBa	0.05	135	4.4 × 4.2	1.3 × 1.3	30	30	1.4
7716	SAB(r)b	0.2	30	6.3 × 4.2	1.0 × 0.7	35	34	3.2
7742	SA(r)b	0.05	133	9.9 × 9.4	1.0 × 1.0	...	no bar	4.3

(Mazzuca et al. 2008)

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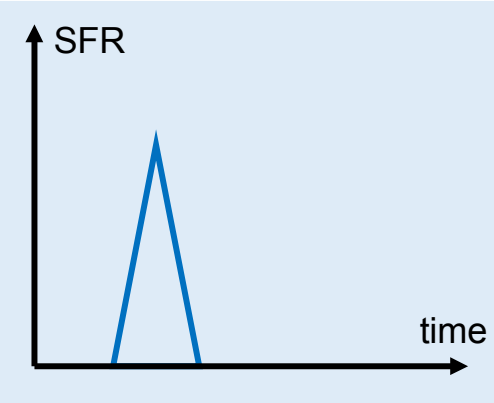
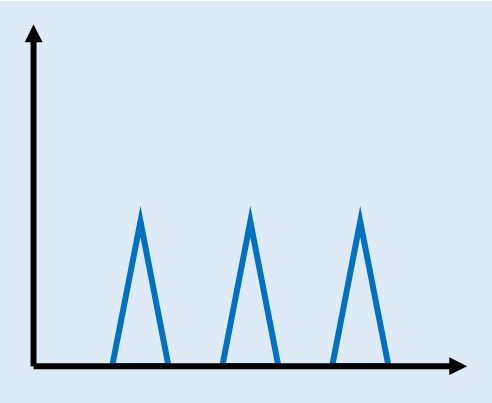
Observations



Single Burst Model



Multiple Bursts Model

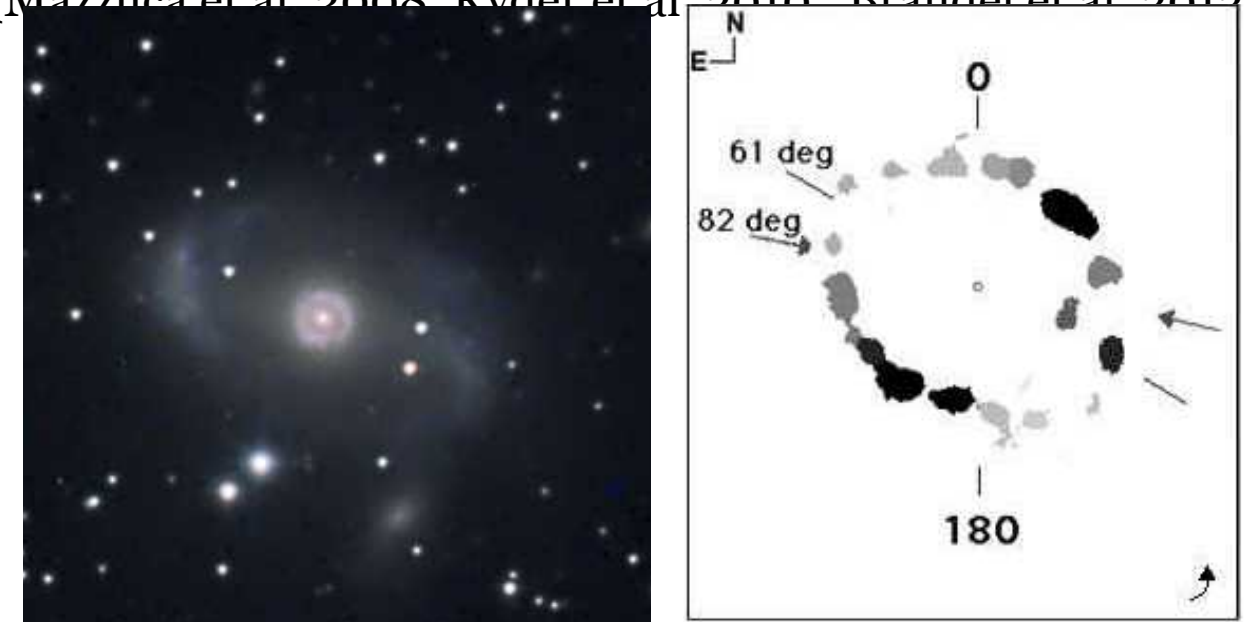
Continuous Model

- Continuous SF
  - van der Laan et al. (2013) found that the circumnuclear ring in NGC 6951 has b een forming stars for recent ~1Gyr.
- Multiple-burst SF
  - Using stellar population synthesis models Allard et al. (2006) estimated that M1 00(NGC 4321) shows multiple-burst type SF.
  - Sarzi et al. (2007) showed two galaxies (NGC4314 and NGC 7217) also have exp erienced multiple-burst SF using the same method.

Observations

- Locations of star formation
  - Some galaxies show an azimuthal age gradient.
  - Some galaxies do not show a noticeable age gradient.

(Mazzuca et al. 2008, Ryder et al. 2010, Brandel et al. 2012)



NGC 1343 (Mazzuca et al. 2008)

Previous Simulations

- Hydrodynamic simulations
  - Athanassoula 1992; Maciejewski et al. 2002; Maciejewski 200 4; Regan & Teuben 2003,2004
  - Englmaier & Gerhard 1997; Patsis & Athanssoula 2000; Ann & Lee 2000; Ann & Thakur 2005; Thakur et al. 2009
- N-Body (+SPH) simulations
  - Bournaud et al. 2005; Martinez-Valpuesta 2006; Berentzen et al. 2007; Manos et al. 2010; Minchev et al. 2012; Athanssoula 2012; Roca-Fabrega et al. 2013; Kwak et al. 2017

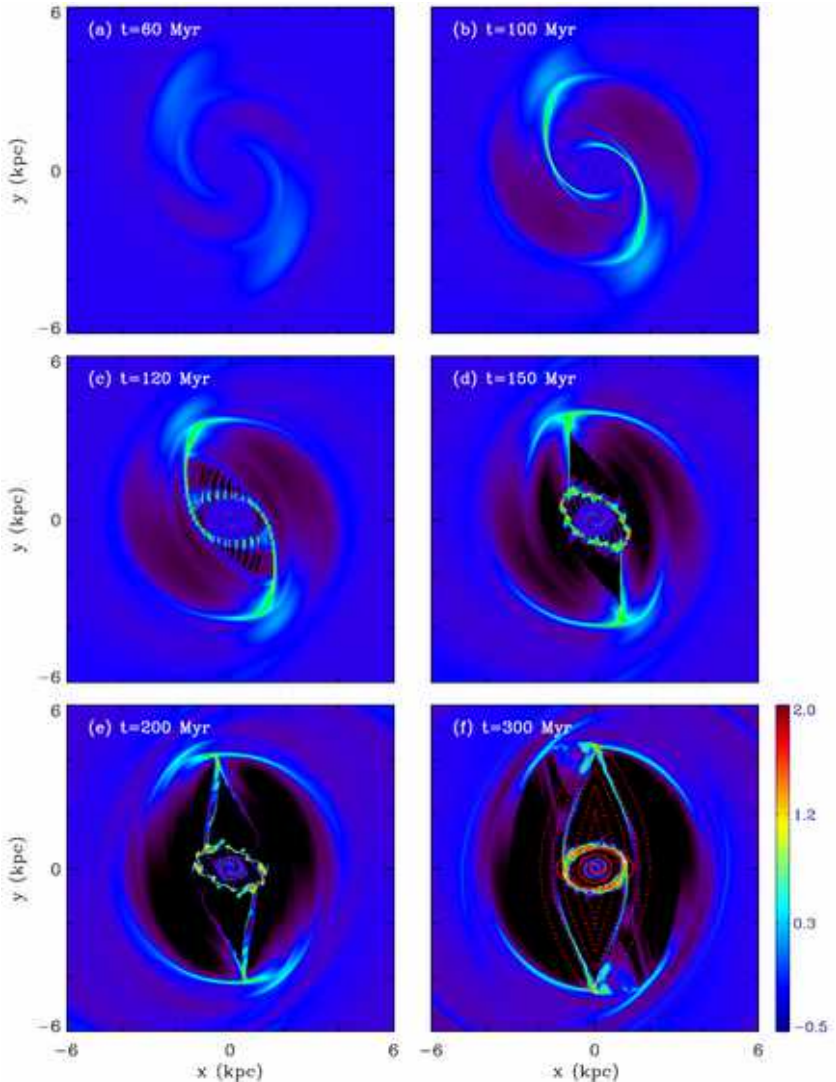
2D simulations

- Two dimensional cylindrical, non-uniform radial grid c ode, CMHOG2
- The gaseous disk is assumed to be isothermal and infini tesimally thin.
- The stars and dark matter are represented by a static gr avitational potentials.
  - Stellar bar potential is modeled by a Ferrers (1877) prolate.
  - Semi-major / minor axes : 5 kpc / 2 kpc
  - Pattern speed : 33 km/s/kpc

Ring Formation

(Kim et al. 2012)

- Off-axis shocks are produced by growth of a non-axisymmetric bar potential.
- Gas loses its angular momentum when it passes through dust lanes and moves in ward.
- The nuclear ring forms in the position w here the centrifugal force balances the ex ternal gravity.
- In the static bar potential models, the nu clear rings shrink in radius with time bec ause of an addition of gas with lower ang ular momentum.



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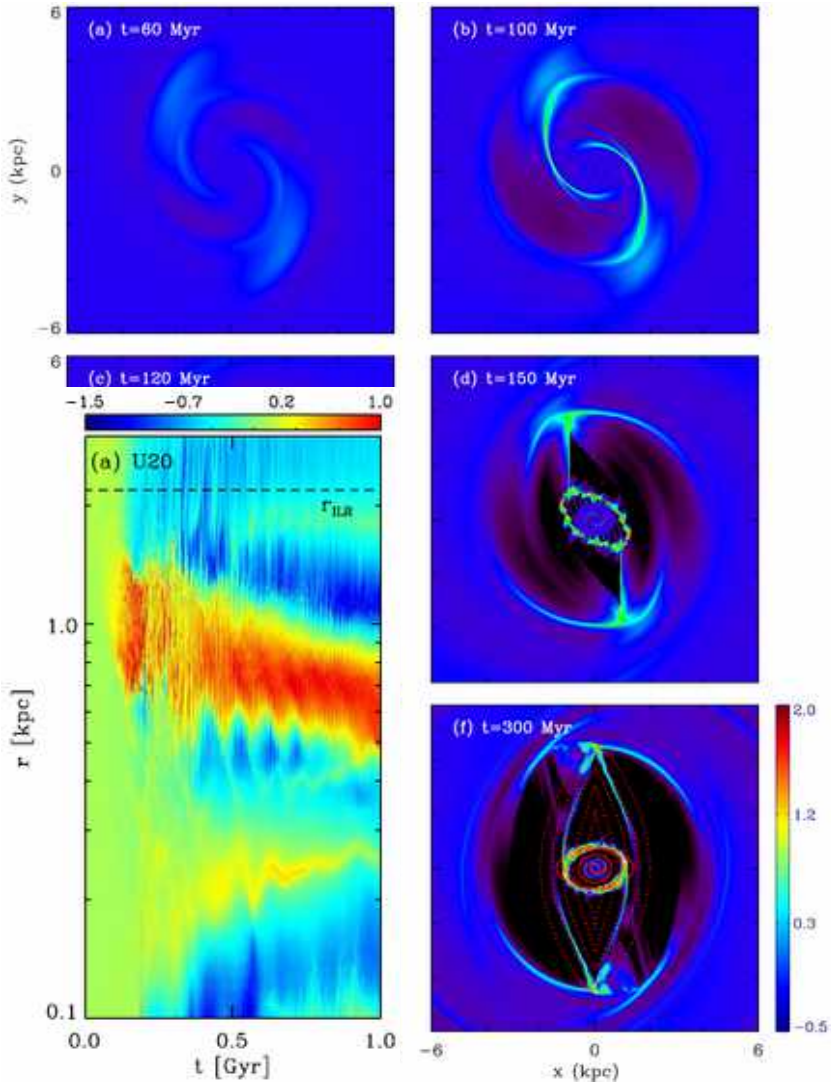
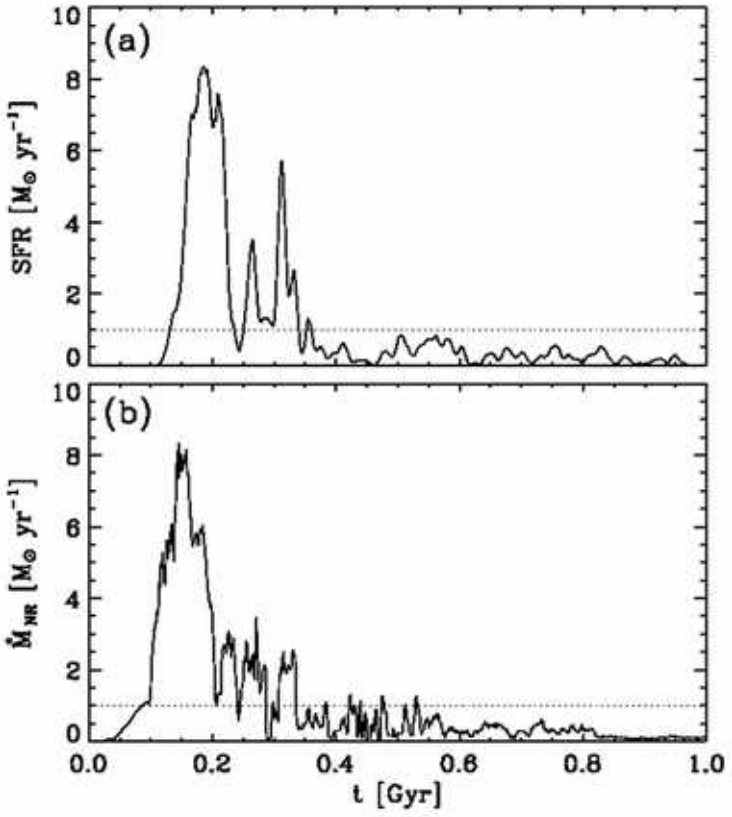


Star Formation Rate

(Kim et al. 2013)

- The SFR shows a strong primary burst cau sed by the rapid gas infall to the ring due to the bar growth.
- After a few bursts, the SFR decreases rapidl y since the bar region becomes almost emp ty due to gas inflows.
- The SFR in the nuclear ring is roughly equa l to the mass inflow rate to the ring.



Star Formation Rate

(Kim et al. 2013)

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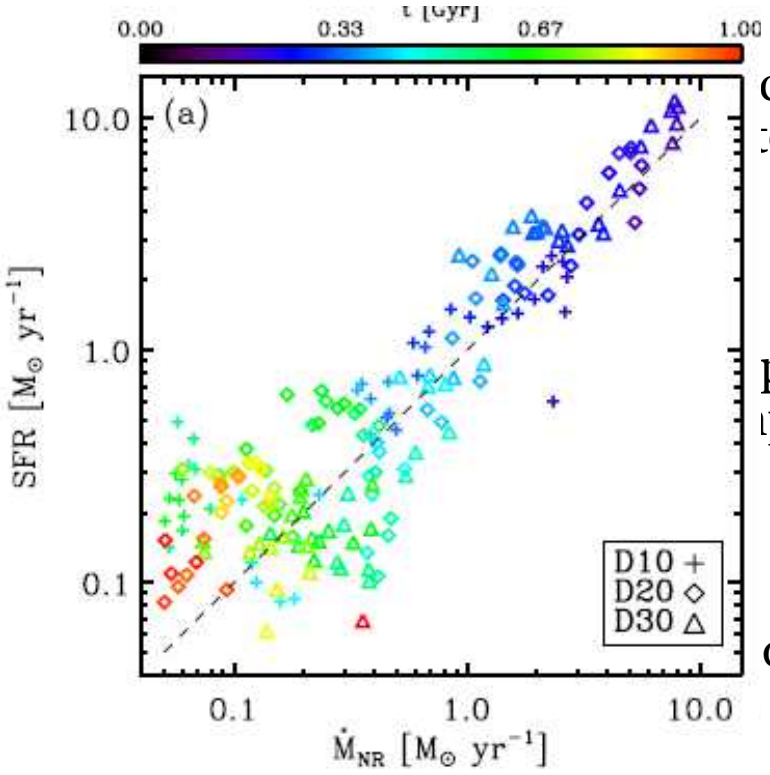
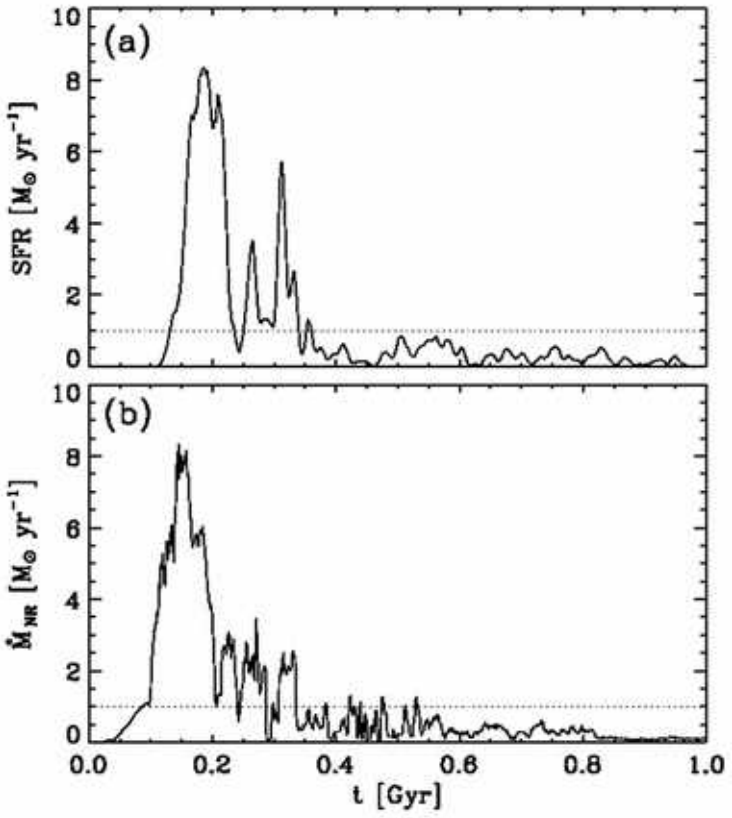
  ba :o the
- Af pidly
  sir pty d
  ue
- Th qual t
  o t





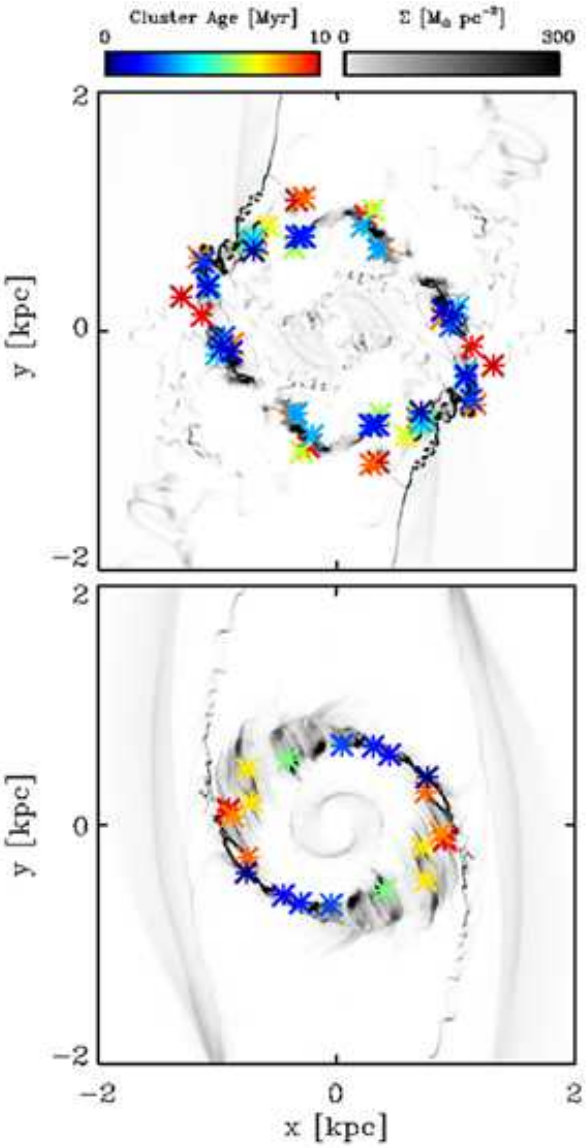
Age Gradient

(Kim et al. 2013)

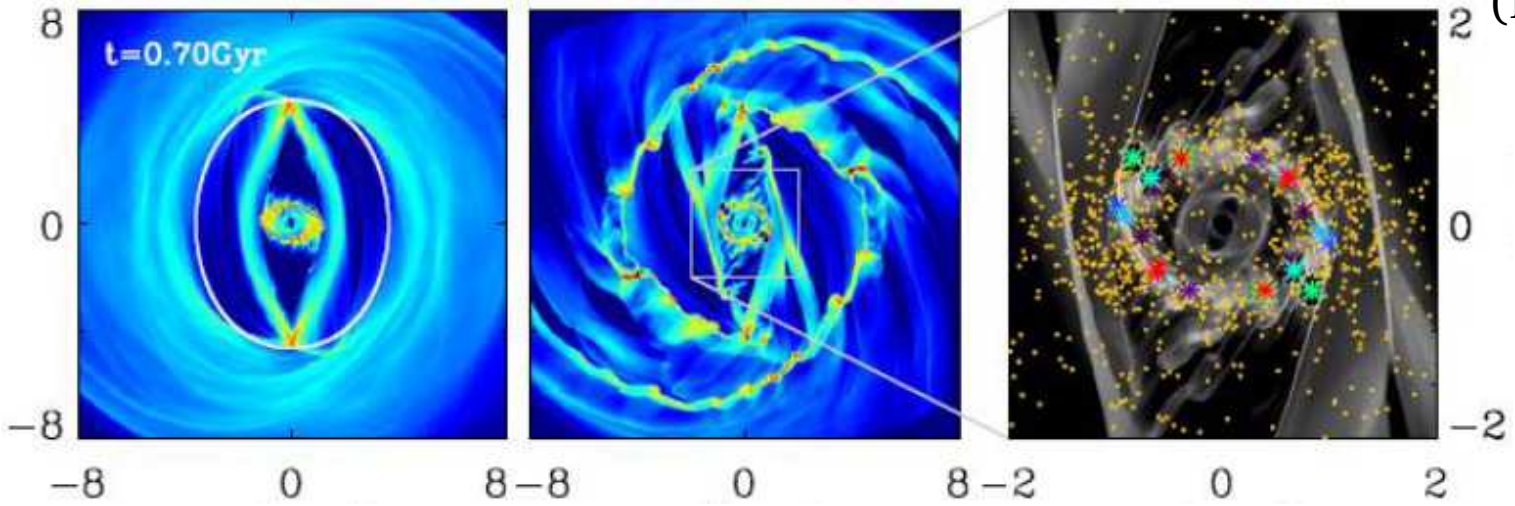
- When the SFR is larger than 1 Mz yr−1 :
  - Star formation events are widely distributed throughout the whole length of the ring.

- When the SFR is smaller than 1 Mz yr−1 :
  - Ages of young star clusters exhibit an azimut hal gradient along the ring, since star format ion events take place mostly near the contac t points.

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



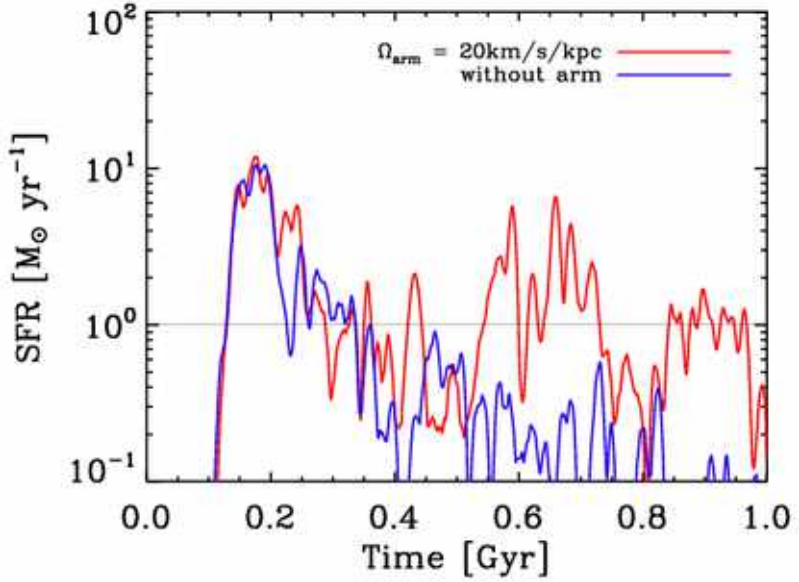
Star Formation with Spiral Arms



(Kim et al. 2014)

- Spiral arms can be efficient to transport t he gas from outside to the central bar regi on.

- The presence of spiral arms can make the SFR rejuvenated at t > 0.4 Gyr.

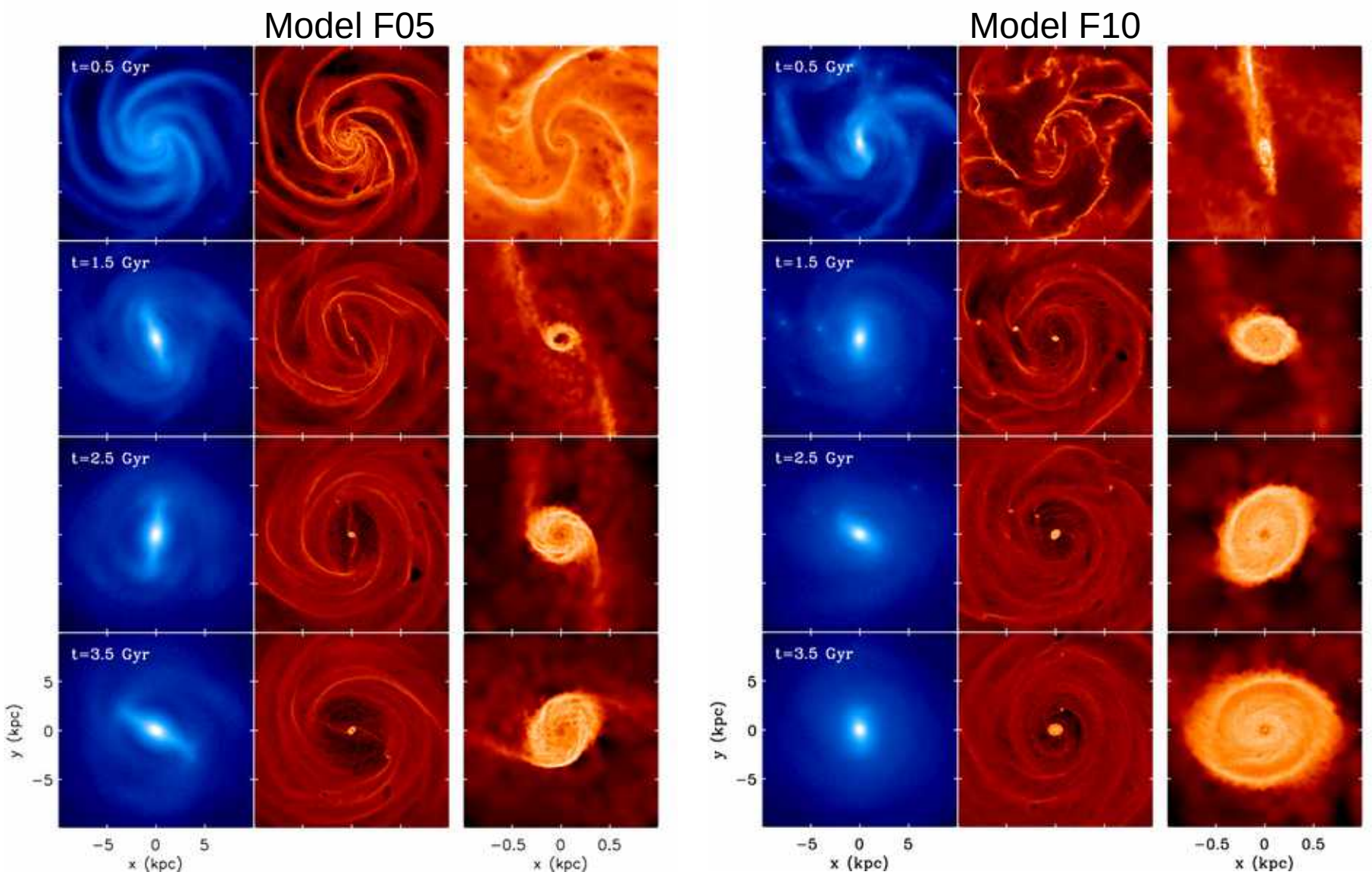


3D simulations

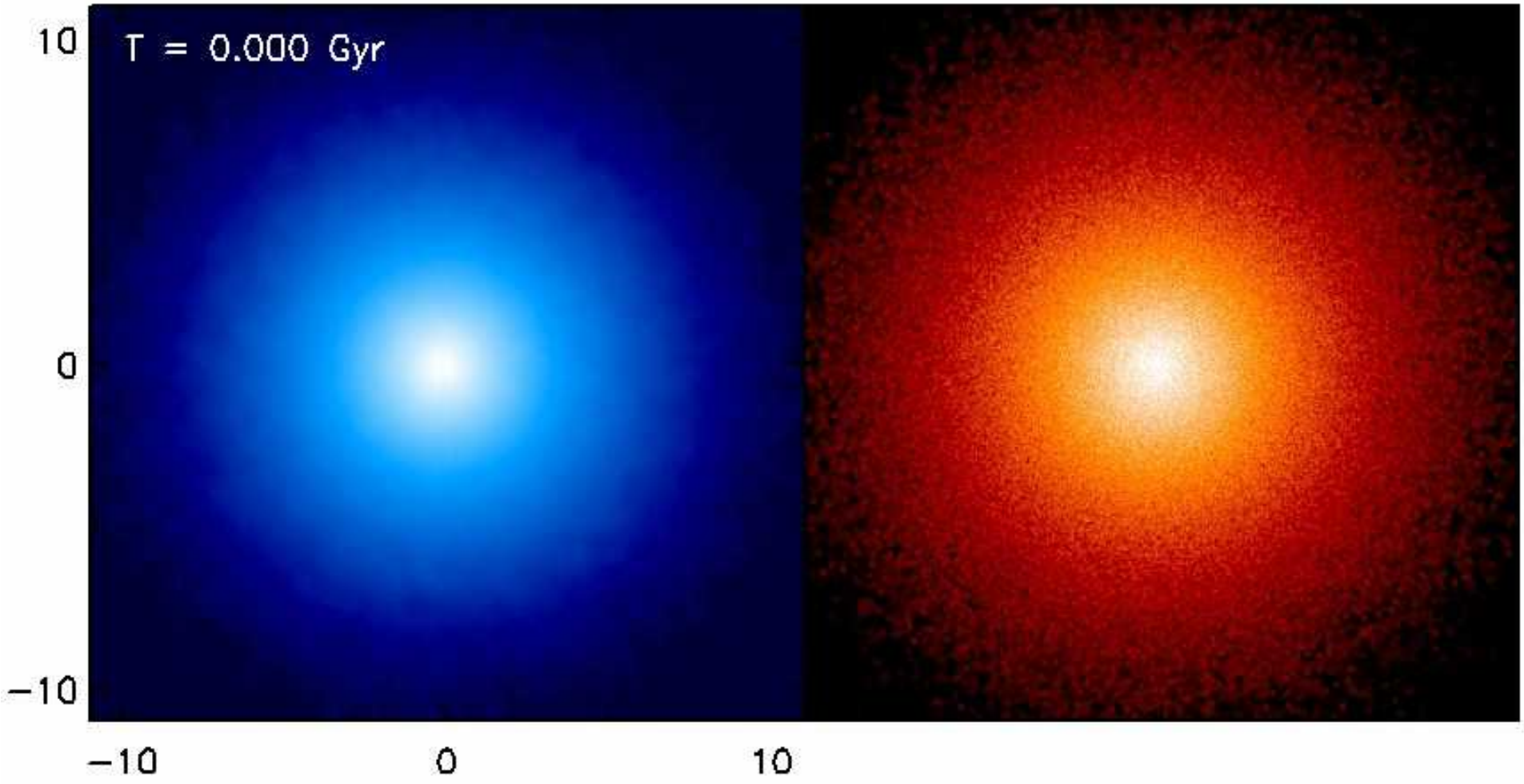
- We run fully self-consistent 3D simulations with live stellar disks a nd dark matters using the mesh-free hydrodynamic code GIZMO.
- The realistic star formation and feedback schemes (FIRE) include Type Ia/II supernovae, stellar winds, HII heating, etc.

- Initial conditions
  - Total disk mass : 5 × 1010 Mz
  - Disk scale length : 3 kpc
  - Vertical scale height : 300 pc
  - Gas fraction : 5, 10%
    - Gas mass inside 10 kpc ~ 2.5, 5 × 109 Mz
      (in case of 2D models ~ 4 × 109 Mz)

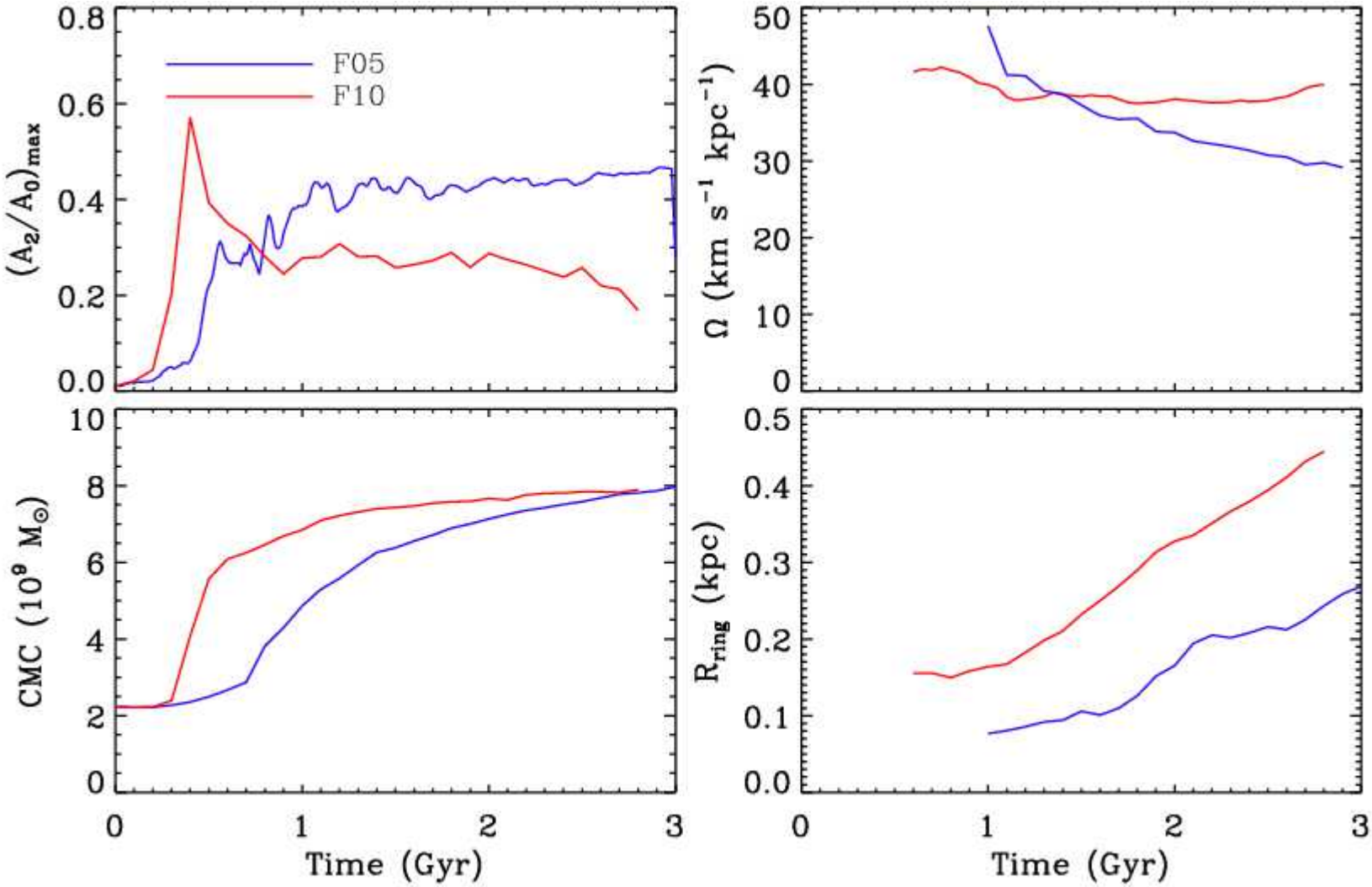
Overall Evolutions



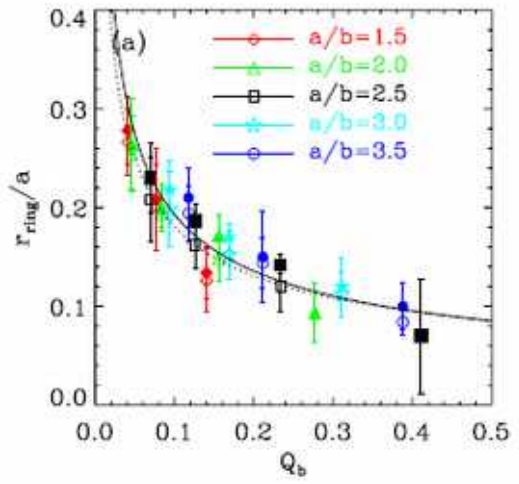
3D simulations



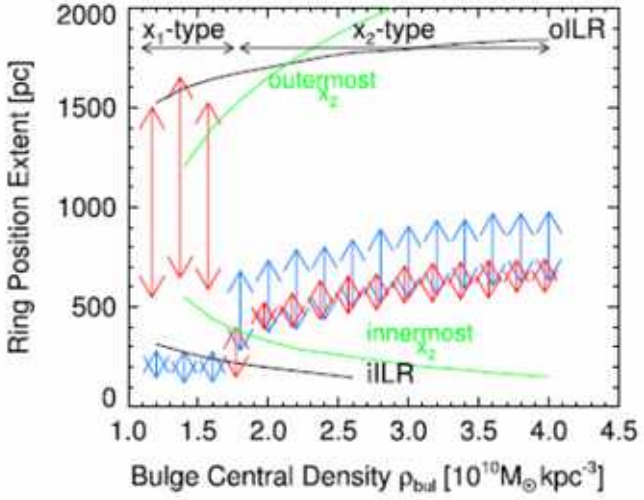
Bar Properties and Ring size

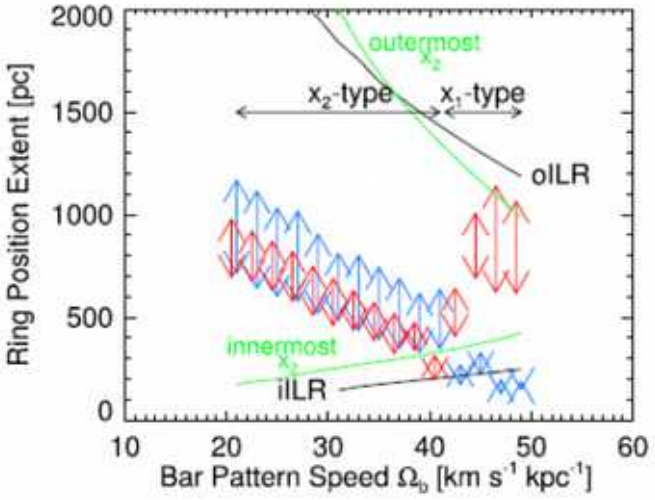


What controls size of the ring?



(Kim, Seo, Kim 2012)

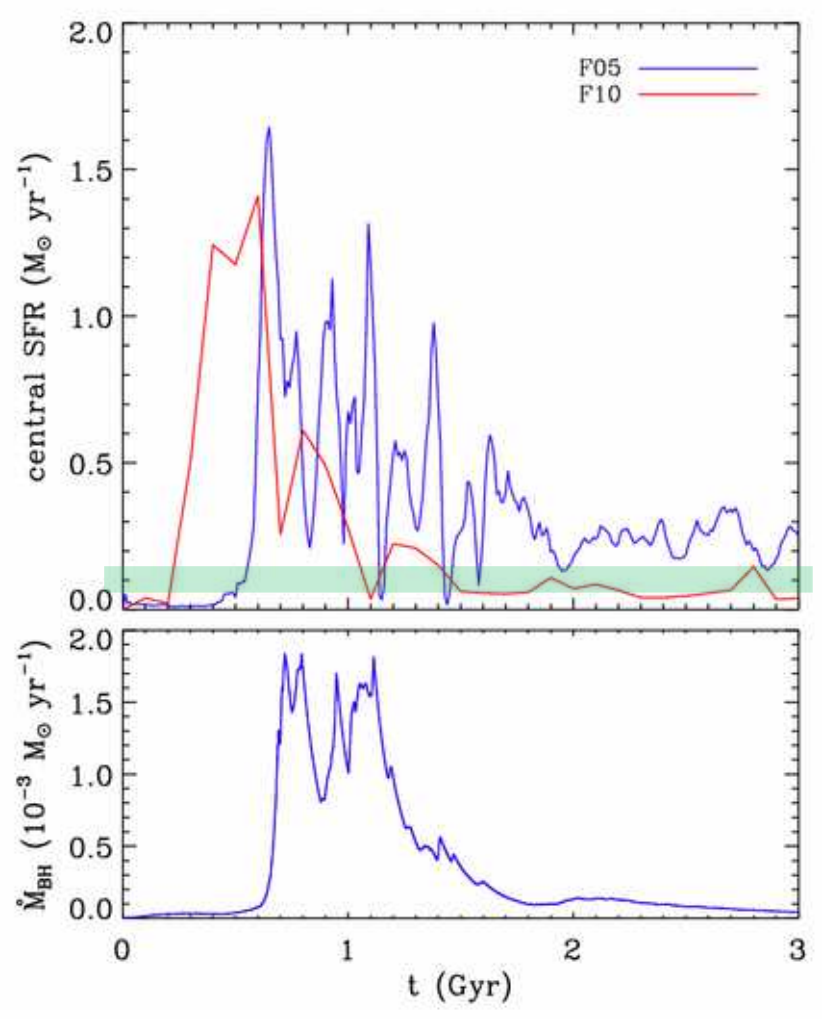




(Li, Shen, Kim 2015)

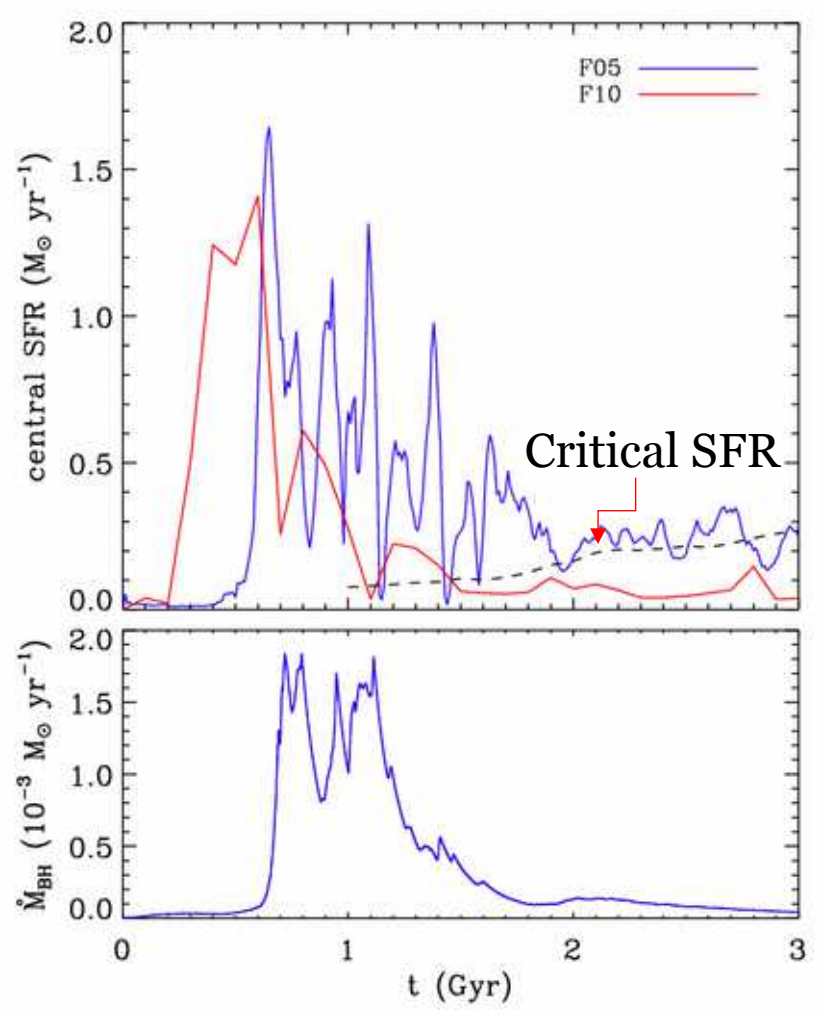
- Size of the nuclear ring increases with decreasing bar strength and pattern speed, and increasing CMC.

Star Formation in 3D Models



- Model F05 (Blue) :
  - The phase of active star formation period is longer than the 2D Models since the bar forms more slowly.
  - Several sudden drops in SFR at the stage of active star formation are due to supernovae feedback in the center.
  - After the clear ring is formed, the mass inflow rate to the black hole becomes very small.
- Model F10 (Red) :
  - The overall shape of the SFR is similar to that of the 2D simulations.

Star Formation in 3D Models



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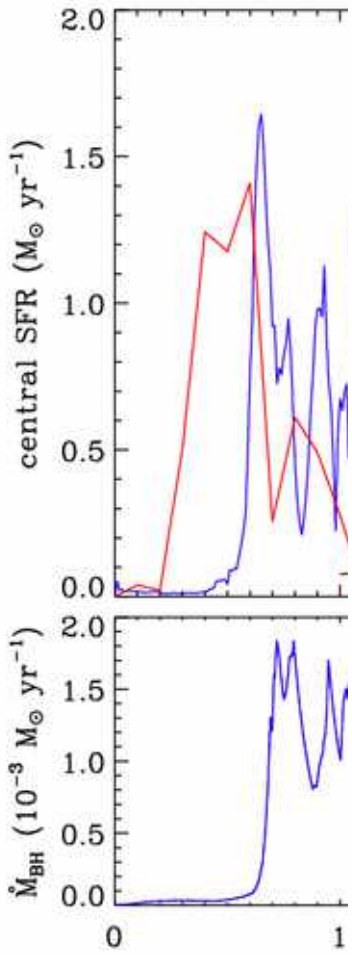
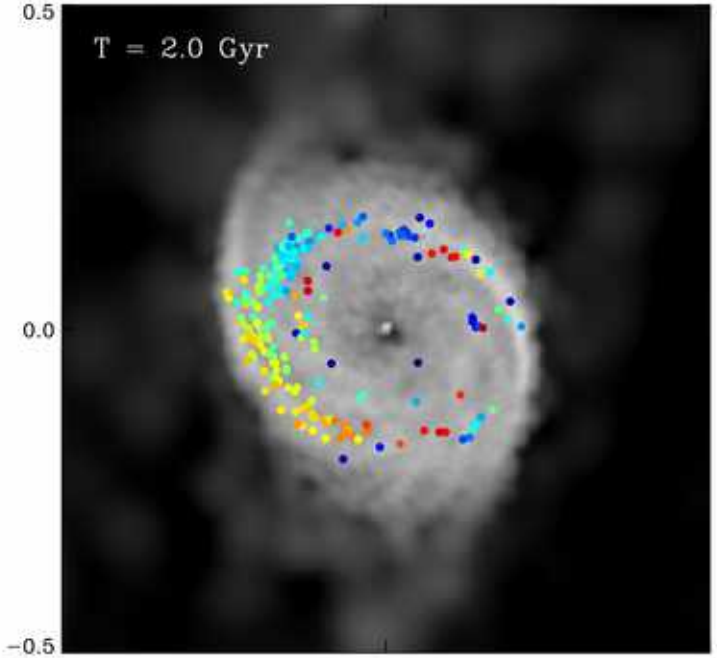
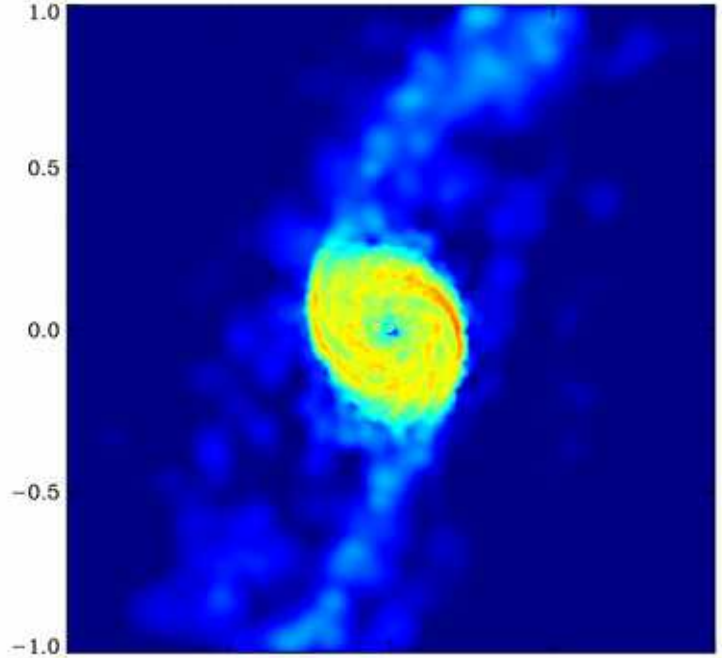
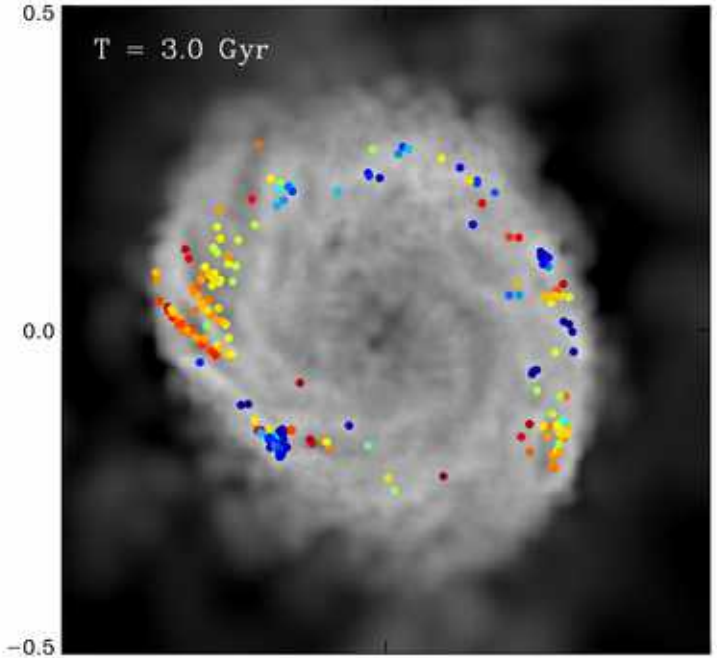
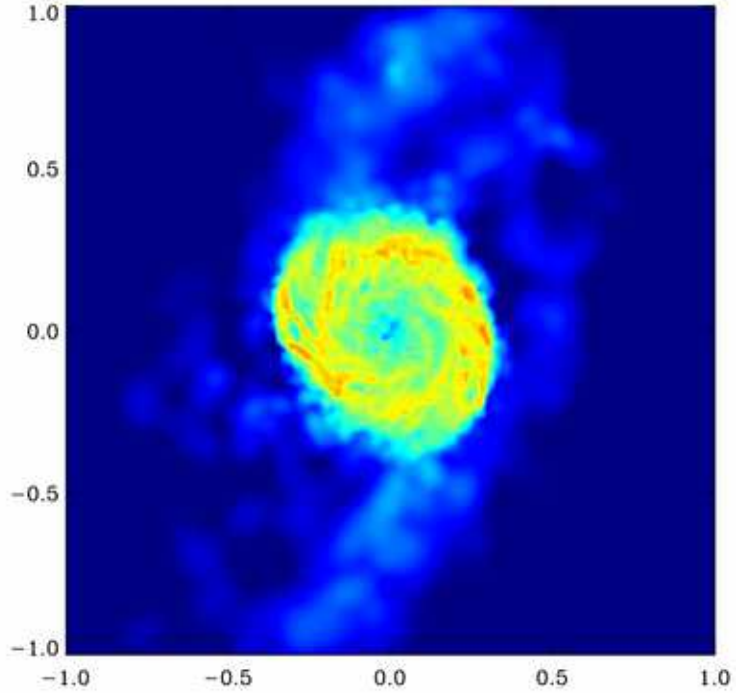
Star F


central SFR ($M_\odot$ yr^{-1})
2.0
1.5
1.0
0.5
0.0
$\dot{M}_{BH}$ (10^{-3} $M_\odot$ yr^{-1})
2.0
1.5
1.0
0.5
0.0
0
1


T = 2.0 Gyr
0.5
0.0
−0.5


1.0
0.5
0.0
−0.5
−1.0


T = 3.0 Gyr
0.5
0.0
−0.5
−0.5
0.0


1.0
0.5
0.0
−0.5
−1.0
−1.0
−0.5
0.0
0.5
1.0

Compare with Milky Way

- Physical parameters of the Milky Way (compare with Model F05 at t ~ 2 Gyr)
  - Mass of molecular gas in the CMZ ~ 2-5 × 107Mz . (~ 3 × 107Mz) (Launhardt et al. 2002; Molinari et al. 2011)
  - The star formation rate ~ 0.07-0.15 Mz /year (~ 0.14 Mz /year) (An et al. 2011; Immer et al. 2012)
  - Half-length of the bar ~ 3.0 kpc (~ 4-4.5 kpc)
  - Pattern speed of the bar ~ 43±9 km/s/kpc (~ 37 km/s/kpc)
  - Stellar mass in the bulge region ~ 1.4-1.7 × 1010Mz
  - Stellar mass of Galactic thin bar ~ 7±1 × 109Mz (Bland-Hawthorn&Gerhard 2016) (Total stellar mass inside 5 kpc ~ 2.3 × 1010Mz)

Summary

- We ran numerical simulations to study gaseous structures and star formation activities in the nuclear regions of barred galaxies.
- The SFR shows a few strong bursts before declining to small values.
- Only when the SFR is smaller than the critical value, the ages of young star clusters exhibit an azimuthal gradient.
- Additional gas feeding due to spiral arms can enhance the SFR at late time.
- Size of the ring slightly decreases with time in 2D simulations, whereas it increases in 3D models.