Time-dependent Pattern Speeds in Barred Galaxies

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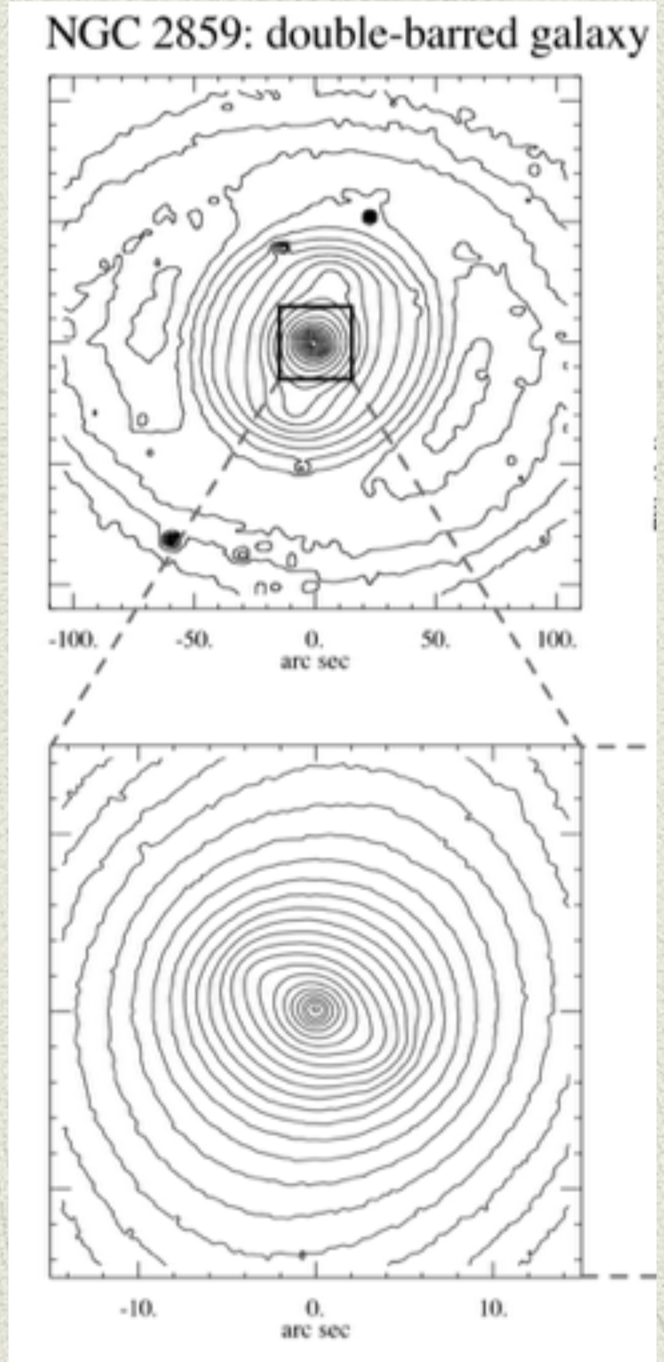
Outline

- Double-barred galaxies
- Formation scenarios
- Our simulation
- Summary

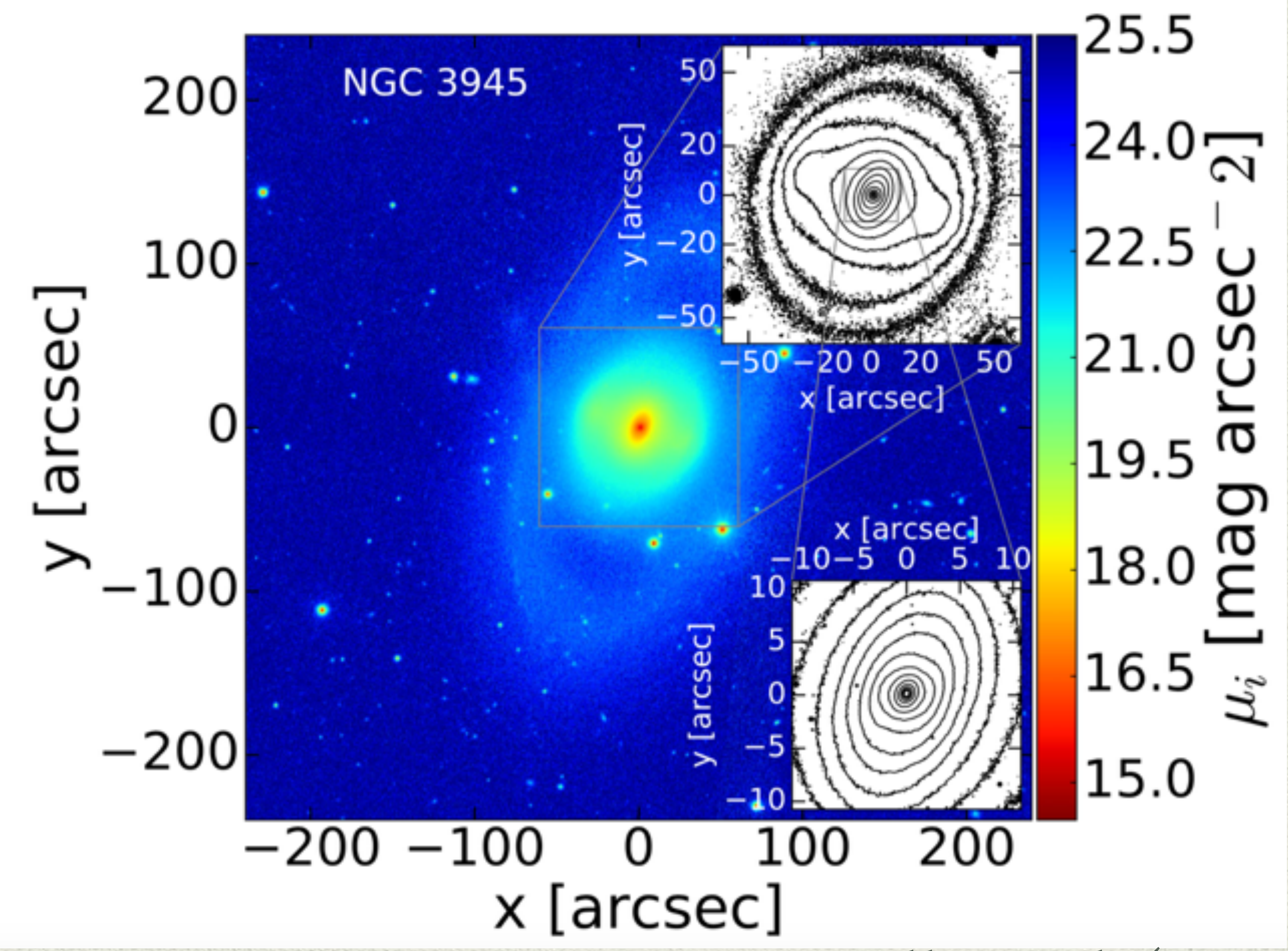
Double-barred Galaxies

R-band (WIYN)



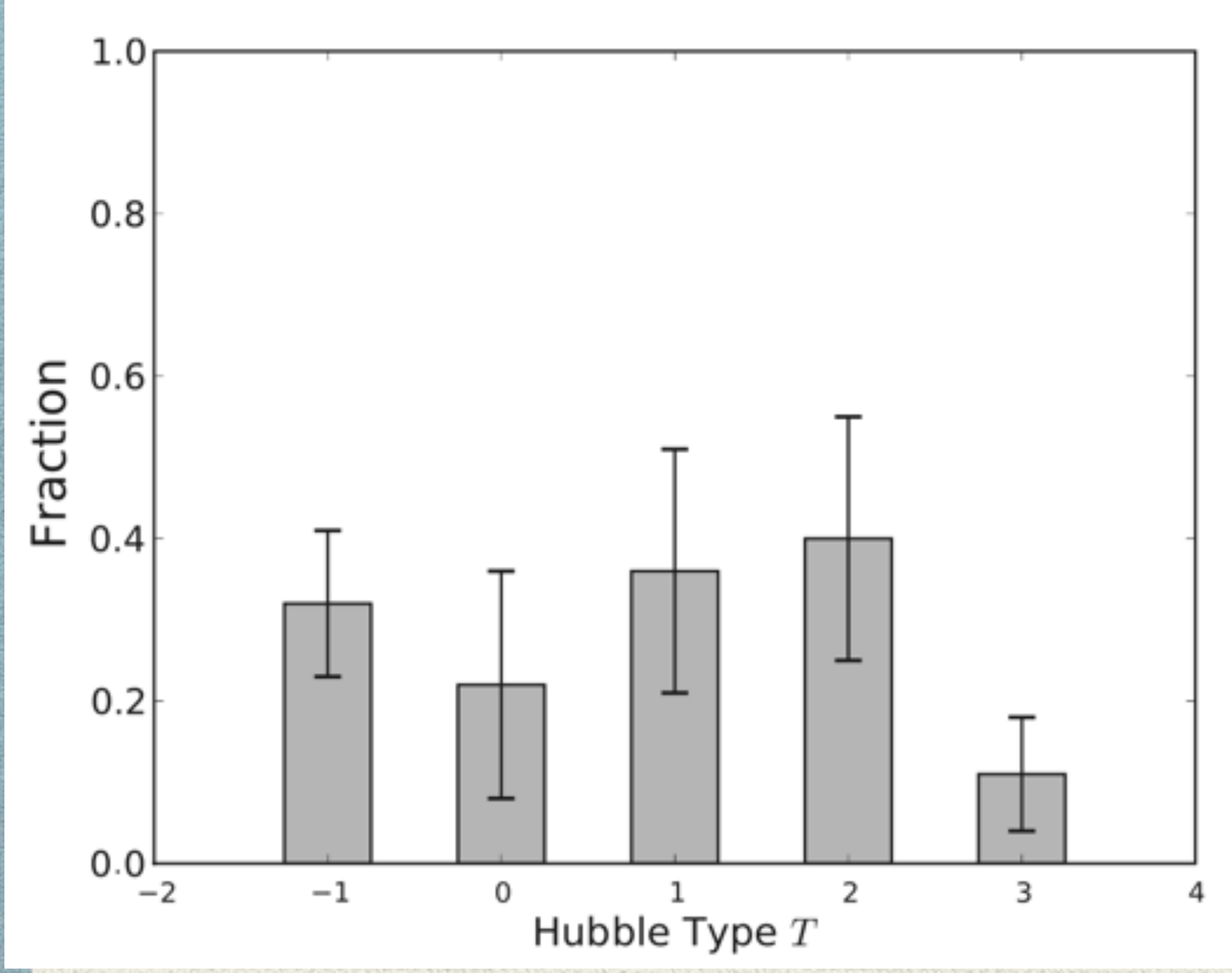
Erwin (2004)

SDSS *i*-band and *HST* WFPC2 *F814W*



Dullo et al. (2016)

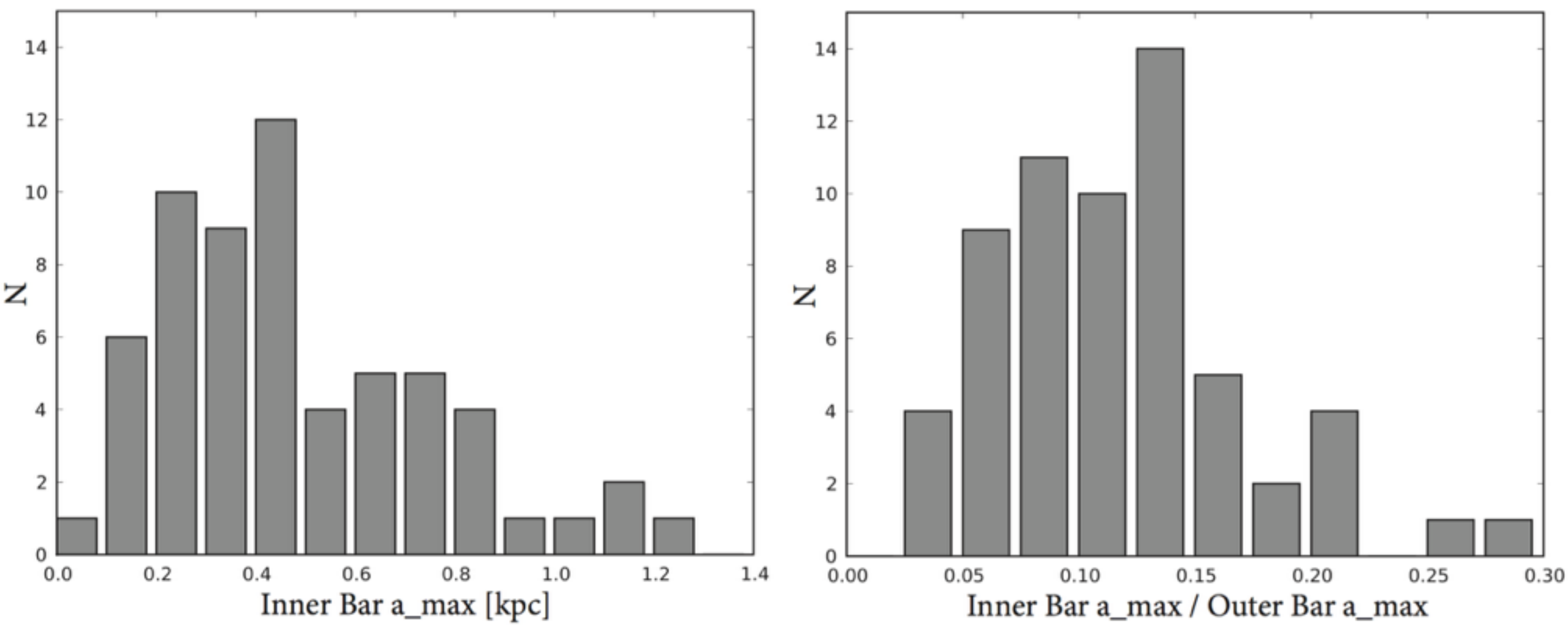
- The double-bar frequency is ~ 30% of barred galaxies



early type → late type

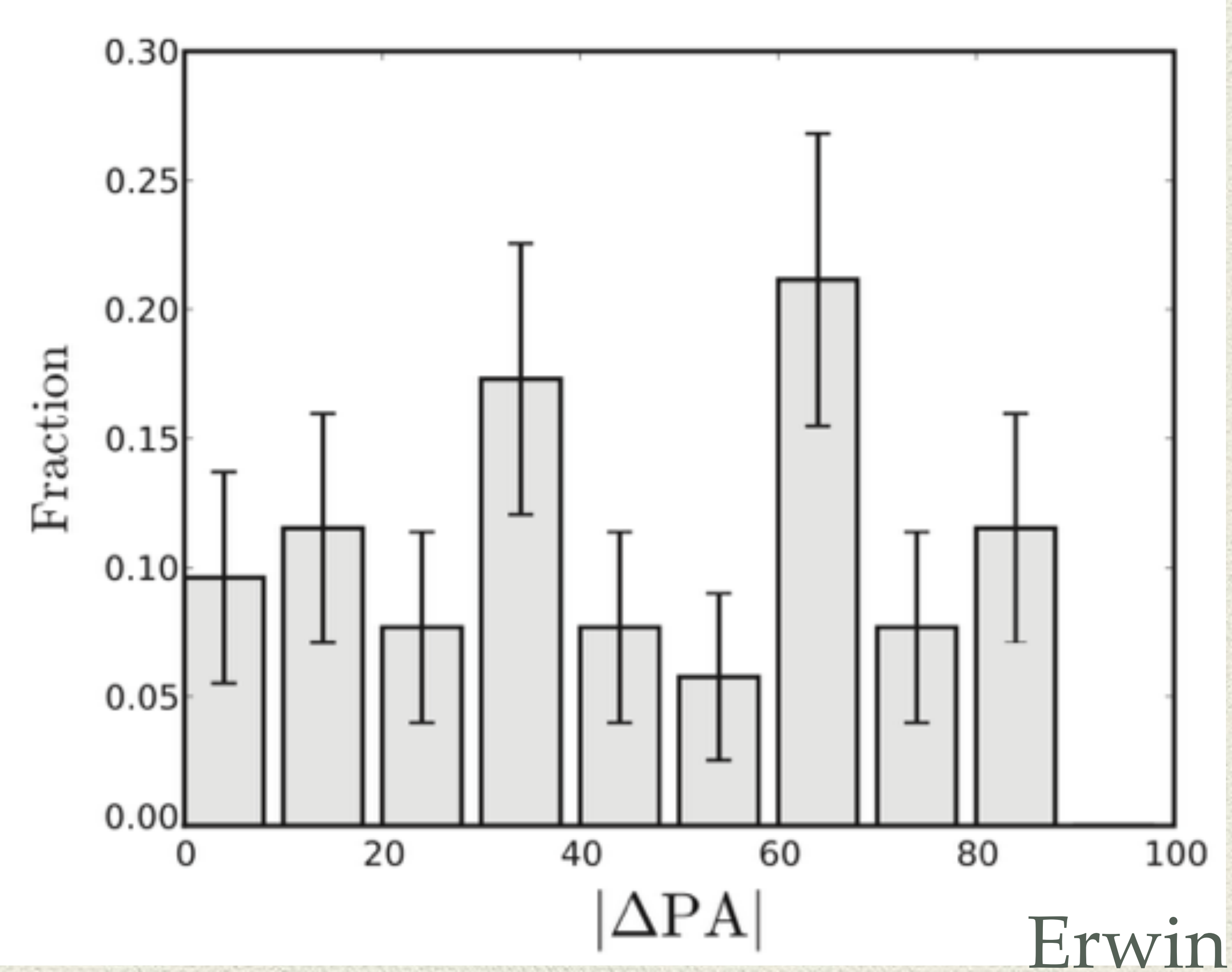
Erwin (2011)

- The double-bar frequency is ~ 30% of barred galaxies.
- The median size of inner bars is ~ 500 pc
- The median size ratio is ~ 0.12



Erwin (2011)

- The double-bar frequency is ~ 30% of barred galaxies.
- The median size of inner bars is ~ 500 pc
- The median size ratio is ~ 0.12
- The relative angles appear to be randomly distributed



Erwin (2011)

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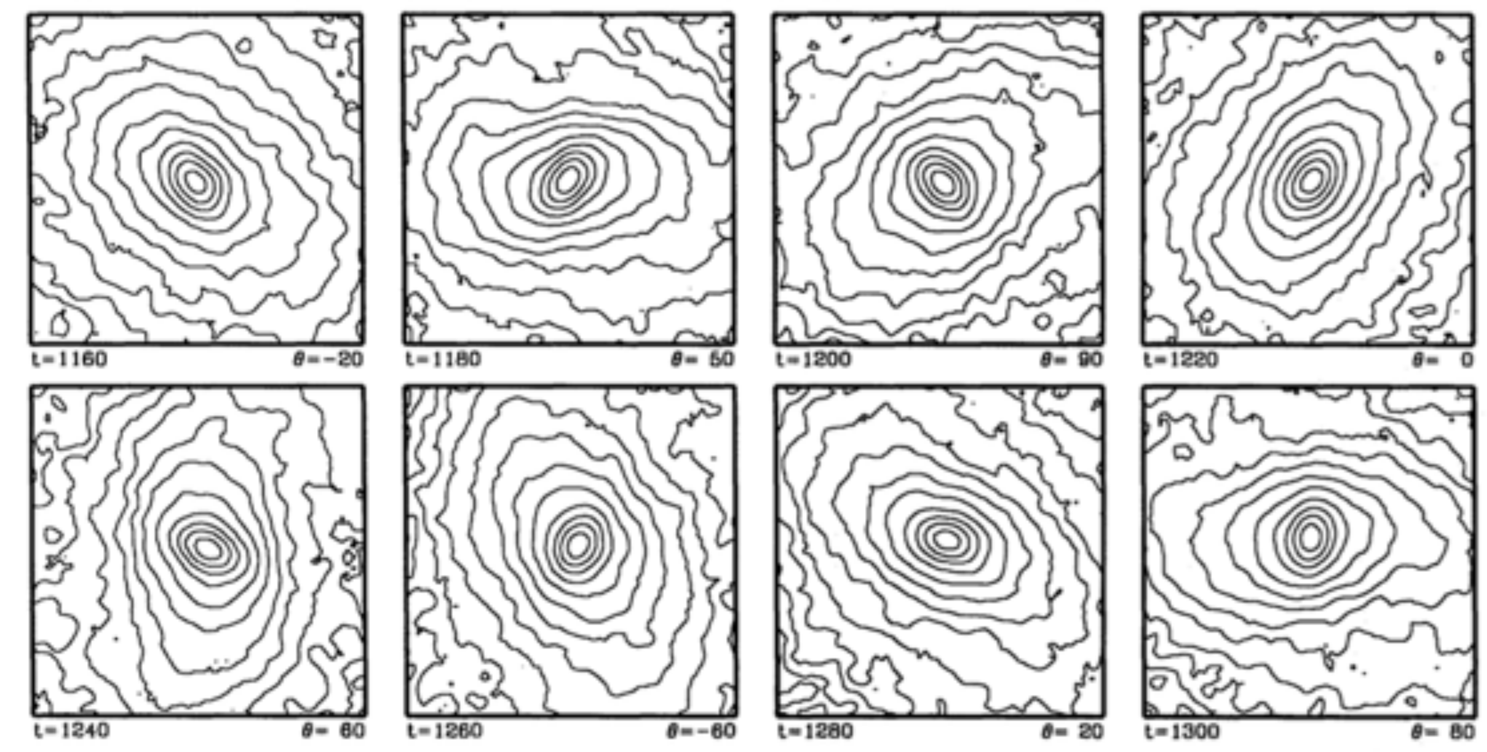
Formation Scenarios

- With gas:
  - form two bars simultaneously or form the outer bar first
  - different pattern speeds
  - need $M_{gas} \sim 10\%\ M_{total}$
- problem:
  - the short life time
  - gas dominated

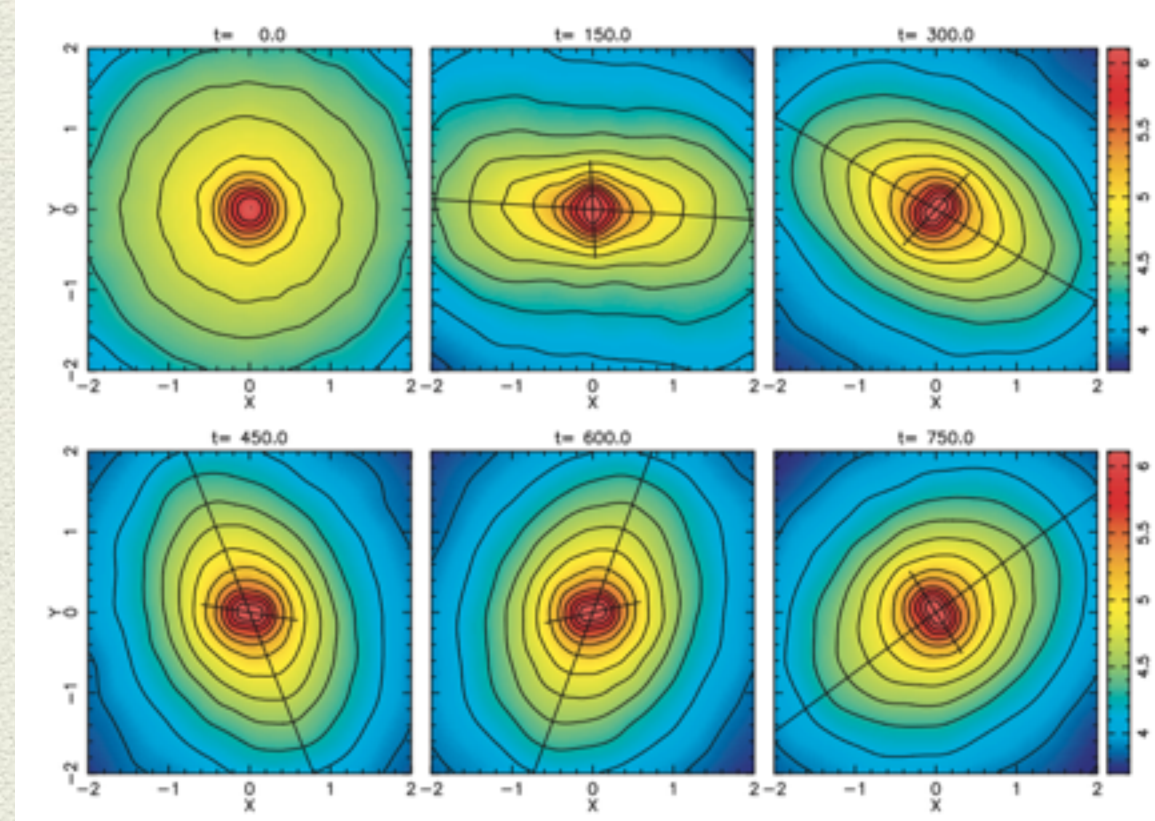


Friedli & Martinet (1993)

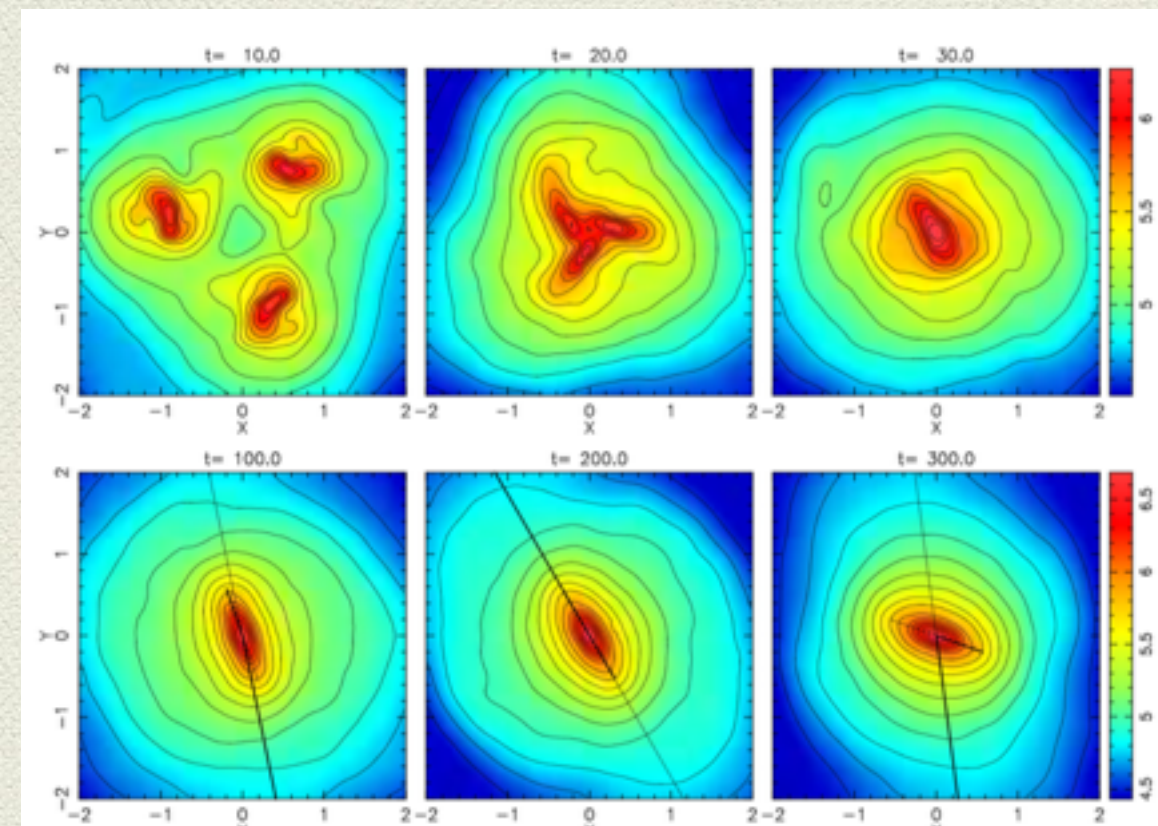
- Without gas:
  - need a rapidly rotating bulge
    - the inner bar forms first
    - the life time ~7 Gyr
  - dynamically cool inner disk

$$Q(R) = \begin{cases} (2.0 - b_Q)(\frac{R}{1.75})^2 + b_Q & (R \le 1.75) \\ 2.0 & (R > 1.75). \end{cases}$$

    - b_Q<0.5: clumpy phase
    - the effect of random seed
- long-lived double-barred galaxies



Debattista & Shen (2007)



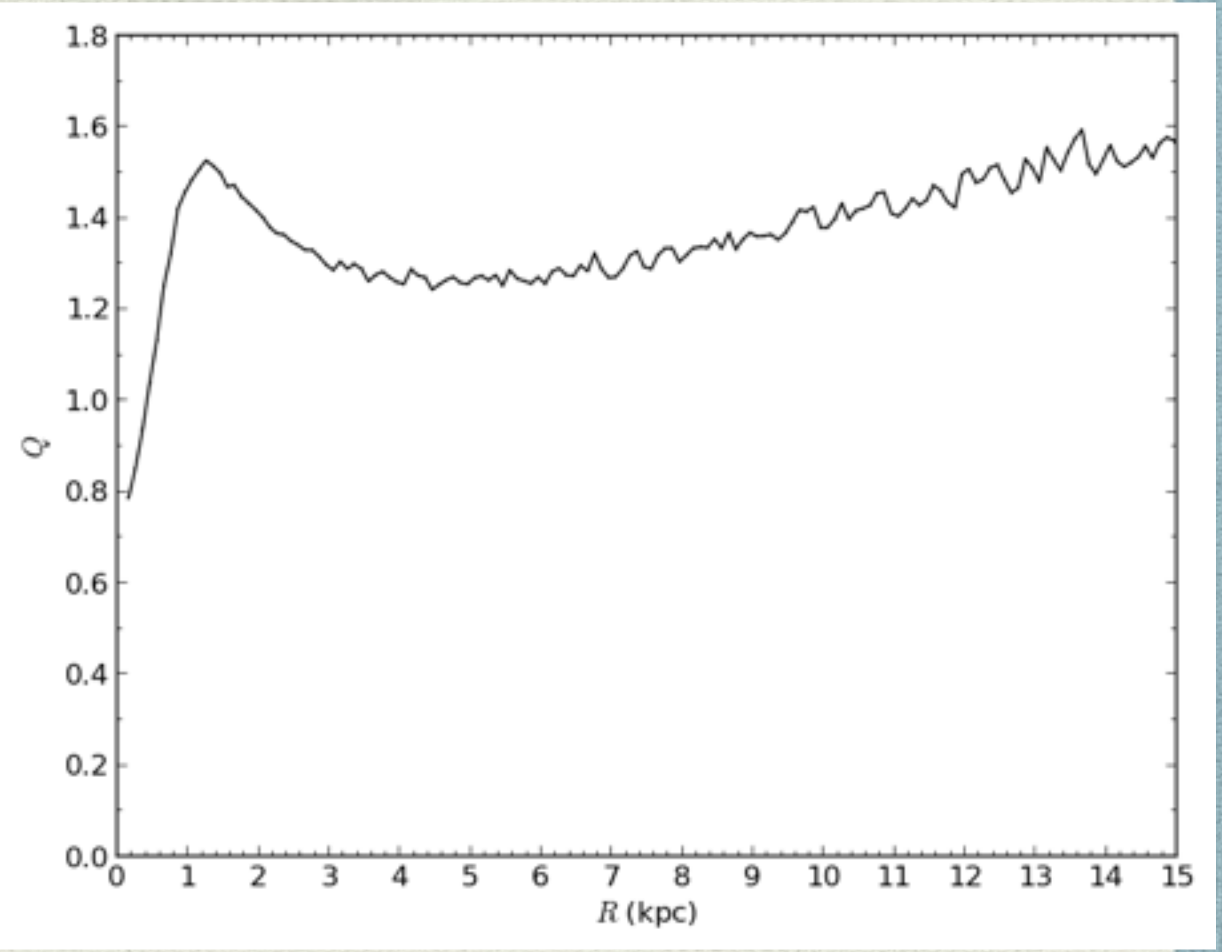
Du et al. (2015)

Model

- three Miyamoto-Nagai components

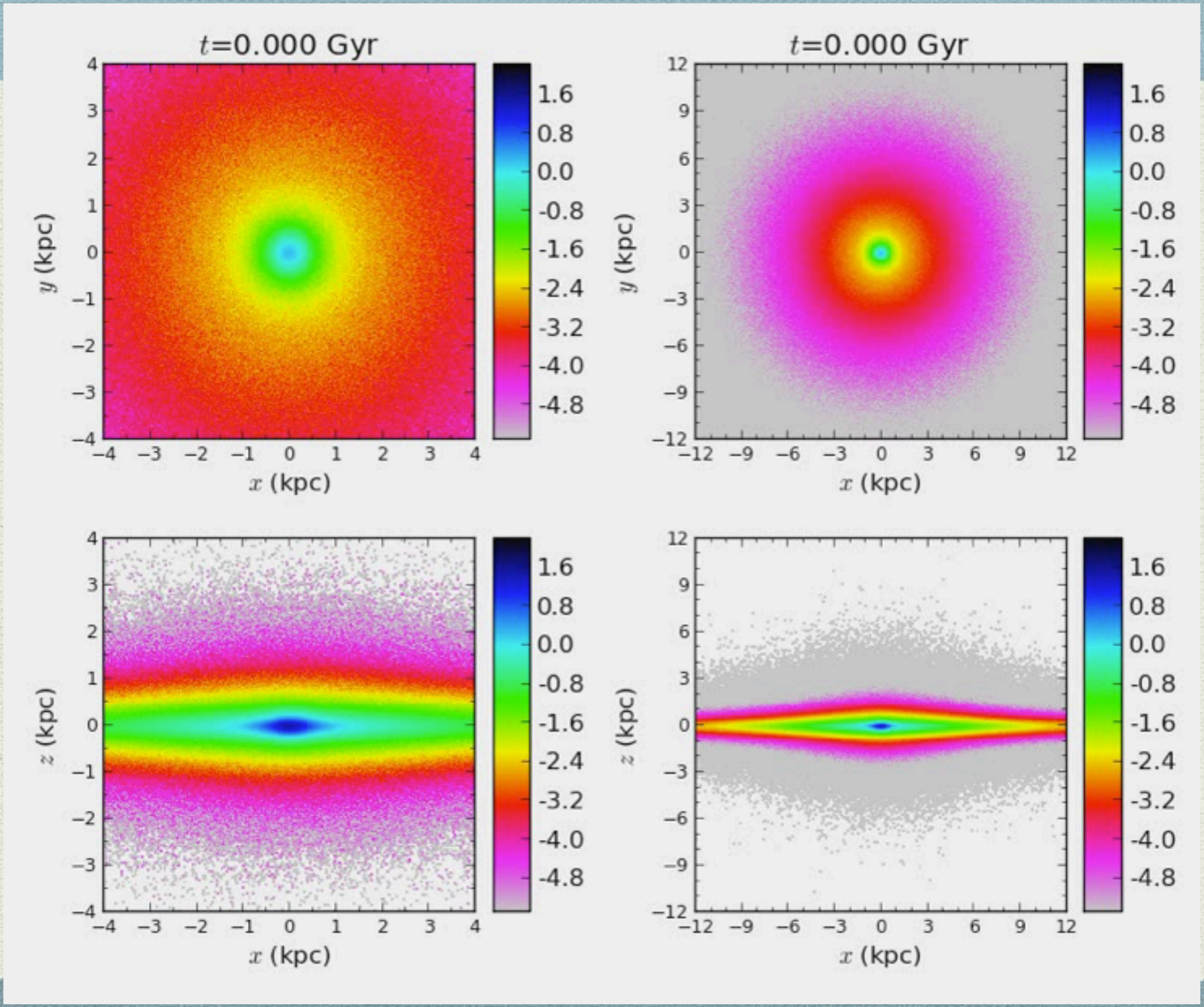
$$\rho_{MN}(R,z) = \left(\frac{b^2 M_{MN}}{4\pi}\right) \frac{aR^2 + (a + 3\sqrt{z^2+b^2})(a+\sqrt{z^2+b^2})^2}{\left[R^2 + (a+\sqrt{z^2+b^2})^2\right]^{5/2} (z^2+b^2)^{3/2}},$$

Parameter	Halo	Disk	Bulge
Mass *M* (10^{10} $M_\odot$)	15.0	8.6504	1.3496
Scale length *a*+*b* (kpc)	15.0	4.5	0.5
Scale height *b* (kpc)	15.0	0.45	0.15



- $Q \equiv \frac{\sigma_R \kappa}{3.36 G\Sigma}$, where $\kappa^2 = R\frac{d\Omega^2}{dR} + 4\Omega^2$
- GalIC (Yurin & Springel 2014)
- gyrfalcON (Dehnen 2000)

Evolution



t=0.000 Gyr
t=0.000 Gyr
y (kpc)
x (kpc)
z (kpc)
x (kpc)
1.6
0.8
0.0
-0.8
-1.6
-2.4
-3.2
-4.0
-4.8

Methods for Determining the Phase/Pattern Speed

- Fourier Method

$$F_m = \sum_j m_j \left(\cos(m\theta_j) + i\sin(m\theta_j)\right)$$

$$\phi_m = \arctan(\Im(F_m), \Re(F_m))$$

$$\Omega_{\mathrm{F}m} = \frac{\dot{\phi}_m}{m}$$

$$\eta_m = \frac{\sqrt{\Im^2(F_m) + \Re^2(F_m)}}{N}$$

- Jacobi Integral Method

$$H = E - \mathbf{\Omega_J} \cdot \mathbf{L}$$

$$\Omega_J(t) = \frac{\dot{E}}{\dot{L}_z} = \frac{\mathbf{v(t)} \cdot \mathbf{a(t)} + \dot{\Phi}(\mathbf{x}(t))}{(\mathbf{x}(t) \times \mathbf{a}(t))_z}$$

- Moment of inertia

$$\mathbf{I} \equiv \begin{pmatrix} I_{xx} & I_{xy} \\ I_{xy} & I_{yy} \end{pmatrix} \equiv \begin{pmatrix} \sum_i m_i x_i^2 & \sum_i m_i x_i y_i \\ \sum_i m_i x_i y_i & \sum_i m_i y_i^2 \end{pmatrix}$$

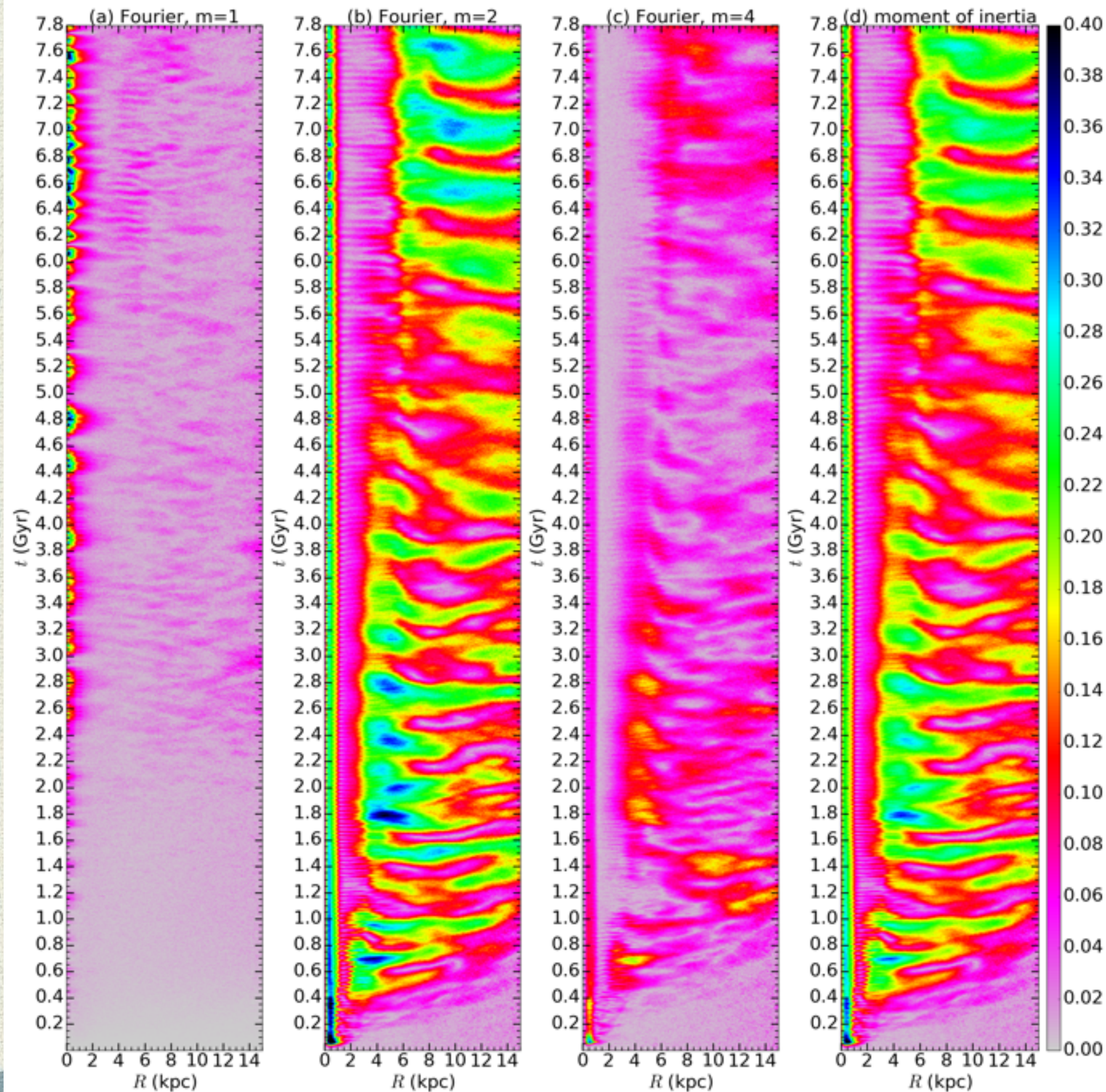
$$\phi_{\mathrm{I}} = \frac{1}{2}\,\mathrm{arctan2}\left(2I_{xy}, I_{xx} - I_{yy}\right)$$

$$\Omega_{\mathrm{I}} \equiv \dot{\phi}_{\mathrm{I}}(t)$$

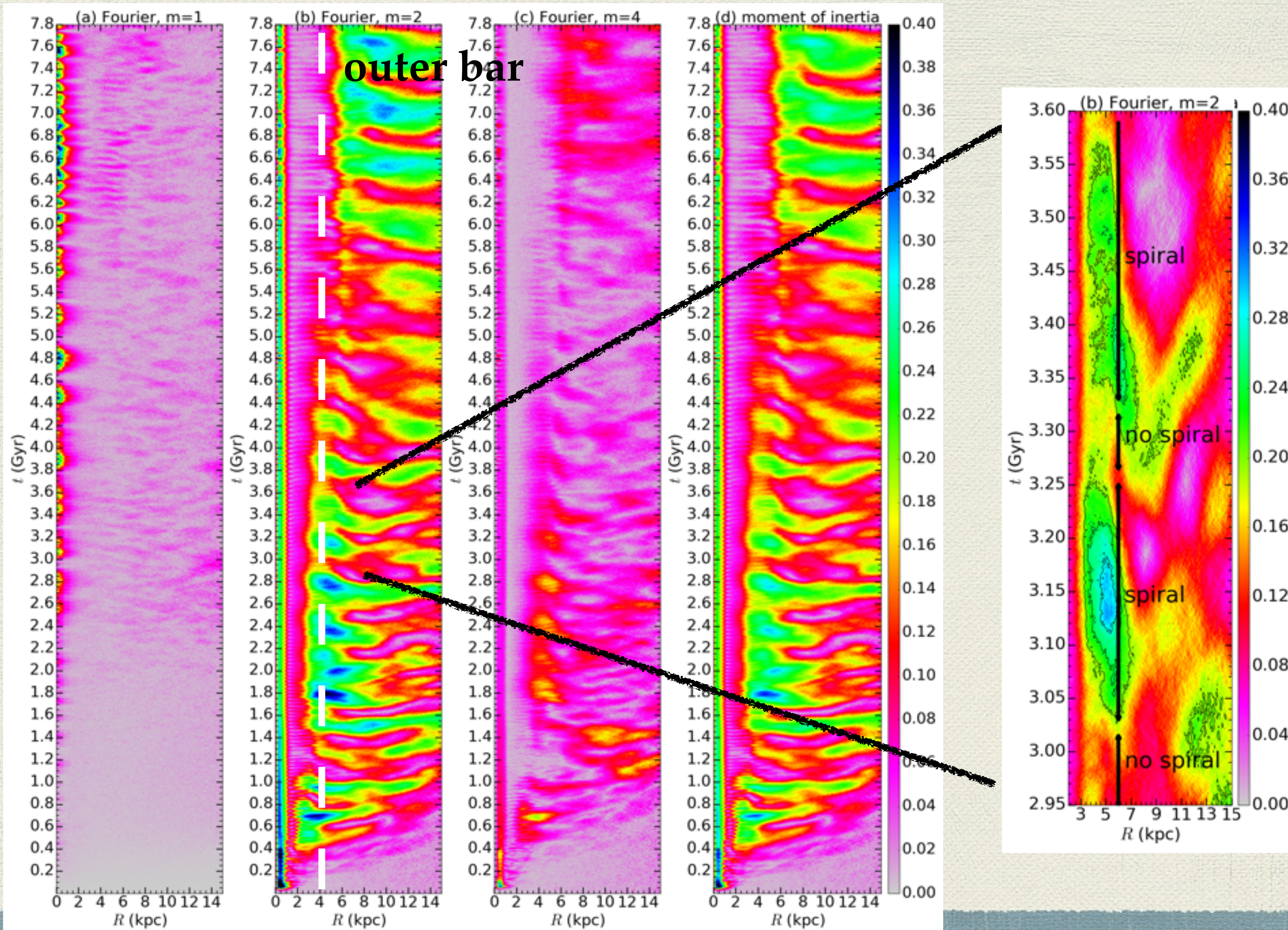
$$\eta_{\mathrm{I}} = 1 - \sqrt{\frac{\lambda_-}{\lambda_+}}$$

Pfenniger et al. (in prep.)

Strength

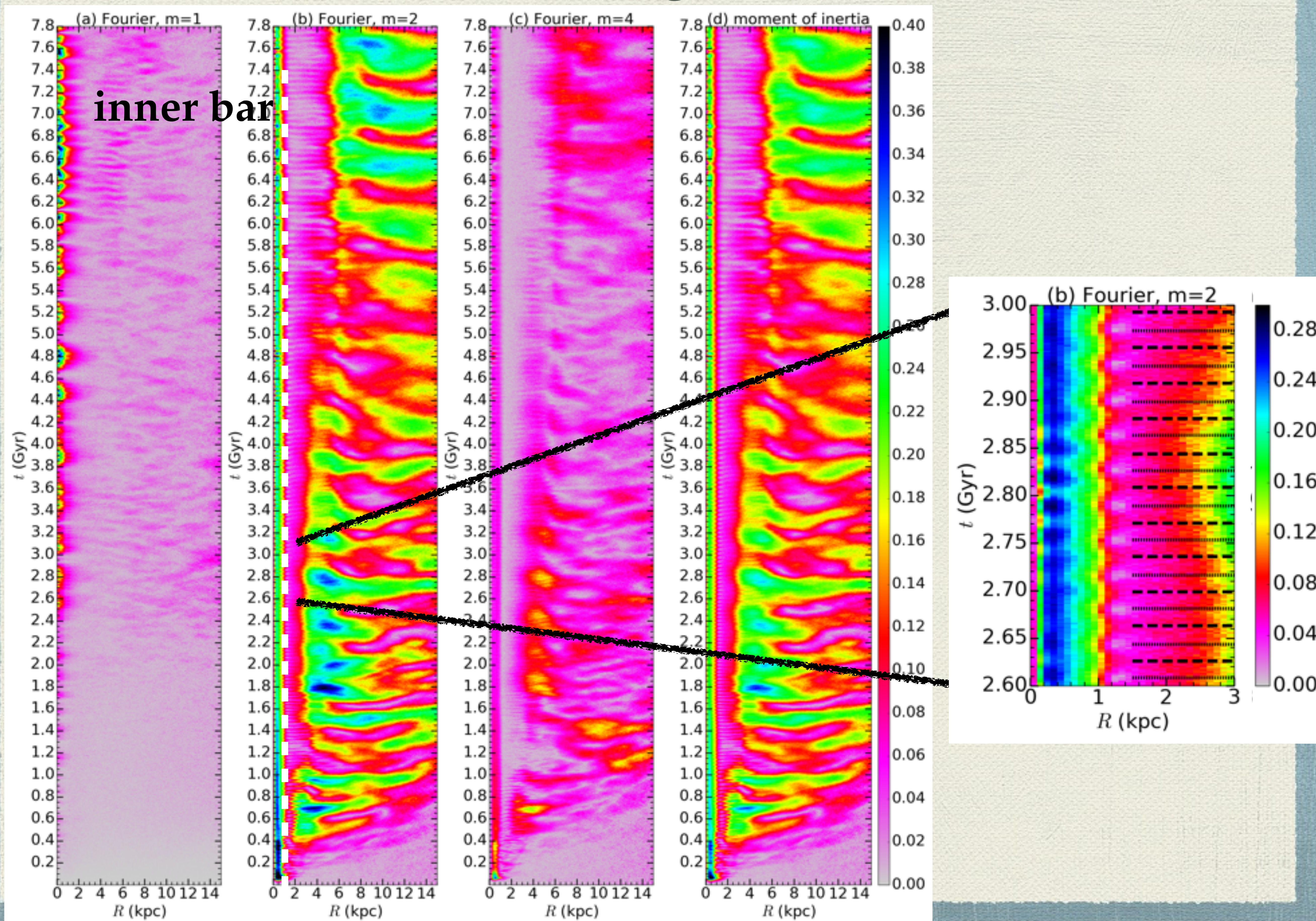

(a) Fourier, m=1
(b) Fourier, m=2
(c) Fourier, m=4
(d) moment of inertia
t (Gyr)
R (kpc)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
0.26
0.28
0.30
0.32
0.34
0.36
0.38
0.40

Strength



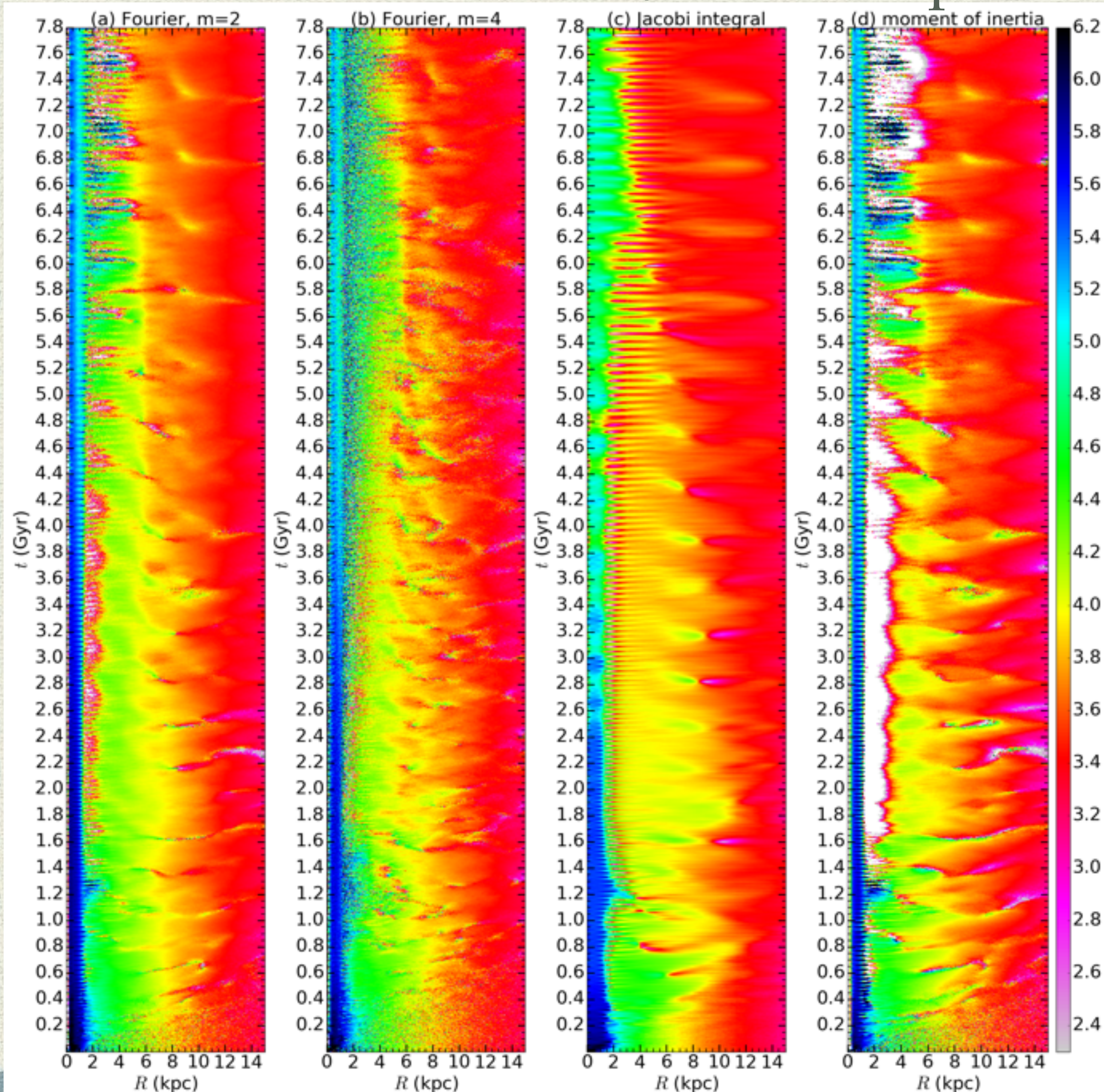
(a) Fourier, m=1
(b) Fourier, m=2
(c) Fourier, m=4
(d) moment of inertia
outer bar
t (Gyr)
R (kpc)
spiral
no spiral
spiral
no spiral

Strength

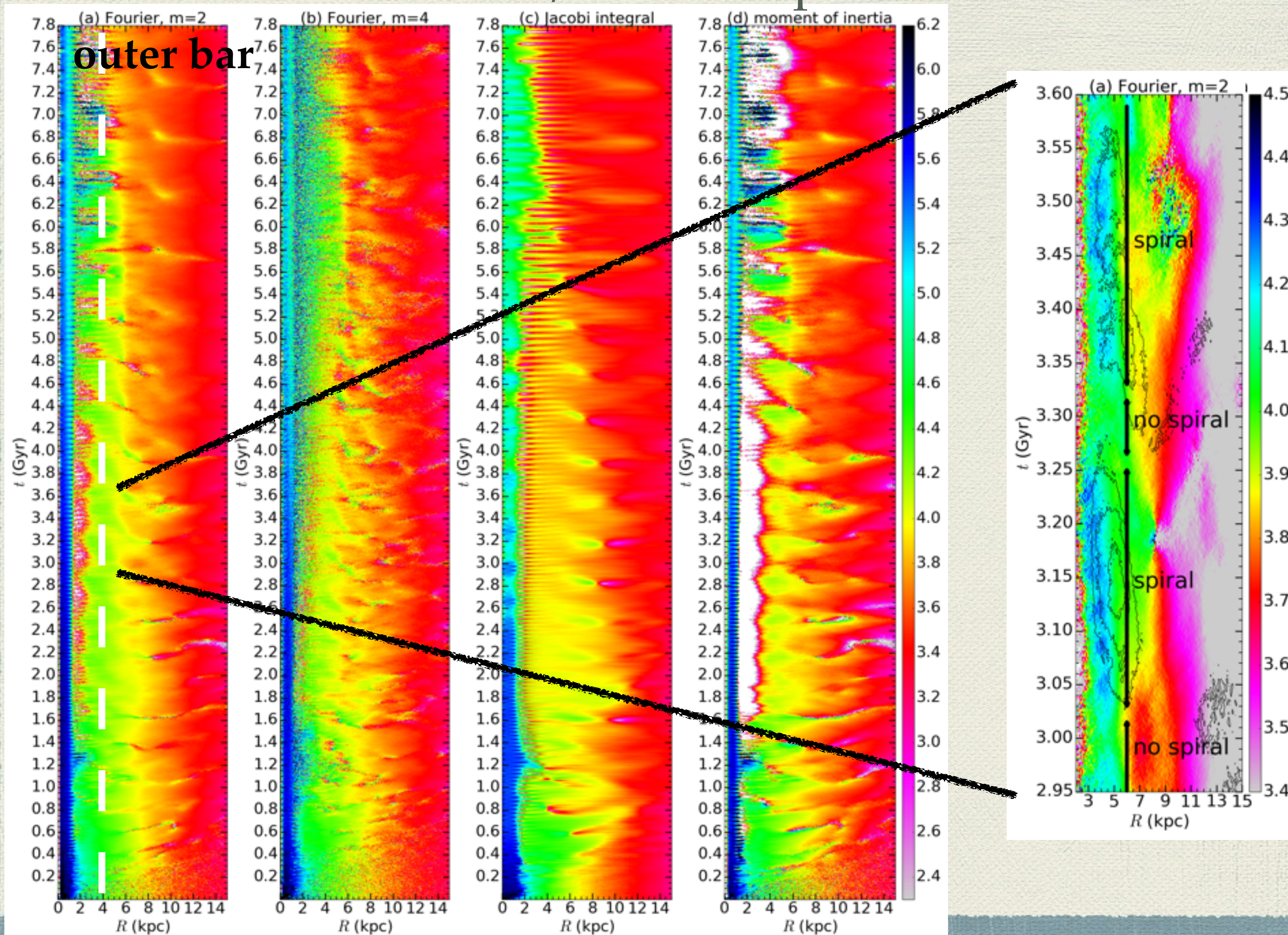


(a) Fourier, m=1
(b) Fourier, m=2
(c) Fourier, m=4
(d) moment of inertia
inner bar
t (Gyr)
R (kpc)
(b) Fourier, m=2
t (Gyr)
R (kpc)

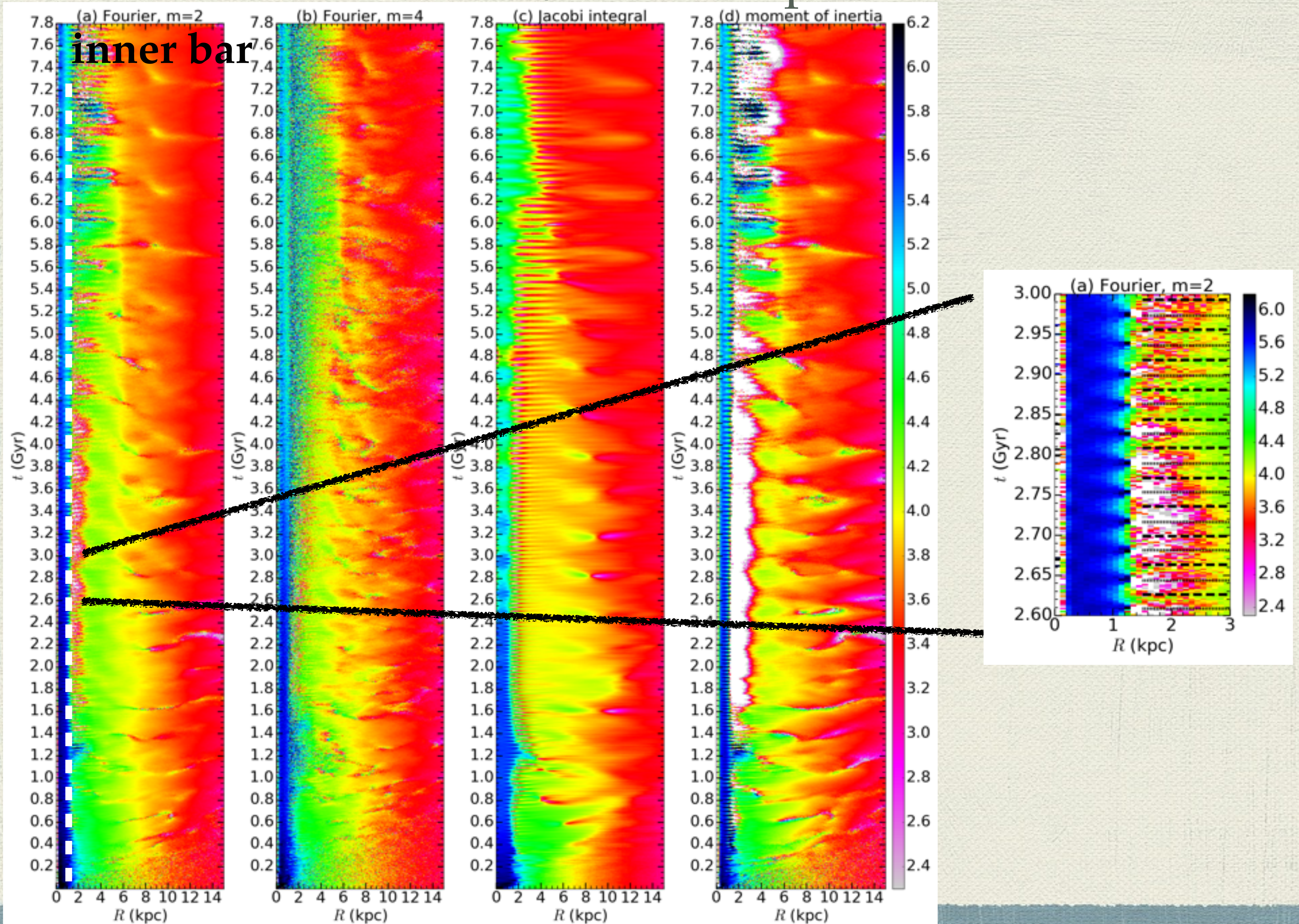
Phase / Pattern Speed



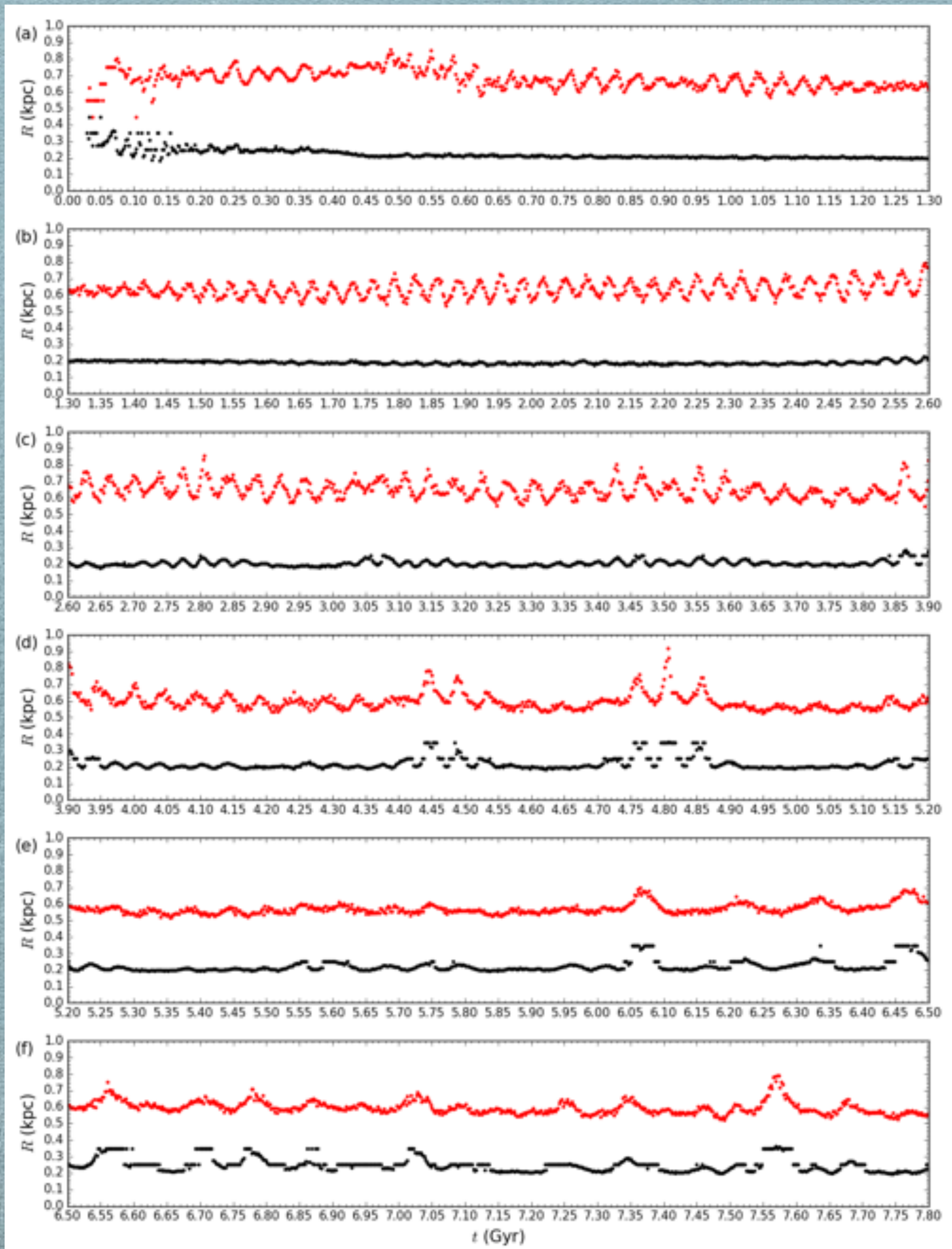
Phase / Pattern Speed



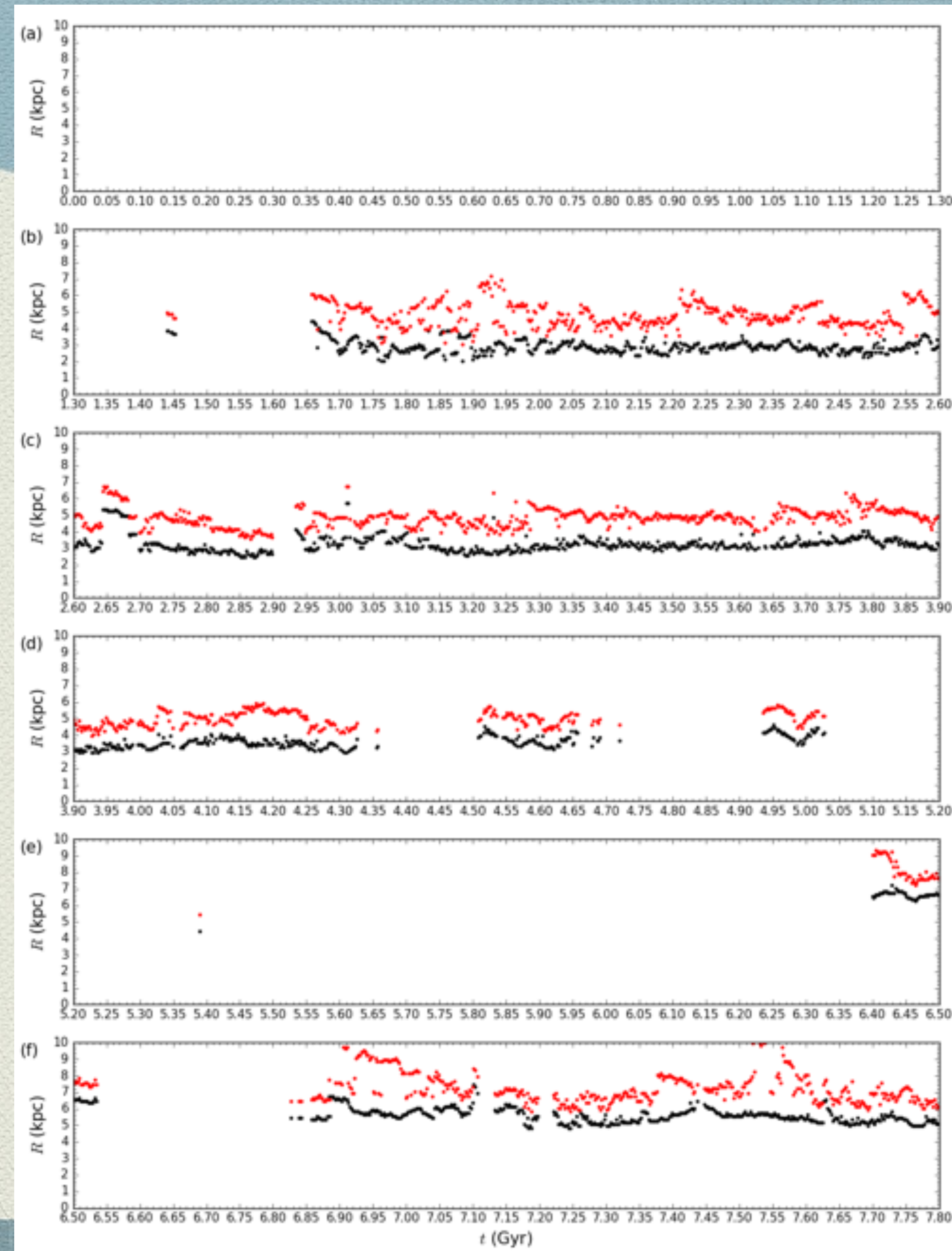
Phase / Pattern Speed



The size of the inner bar



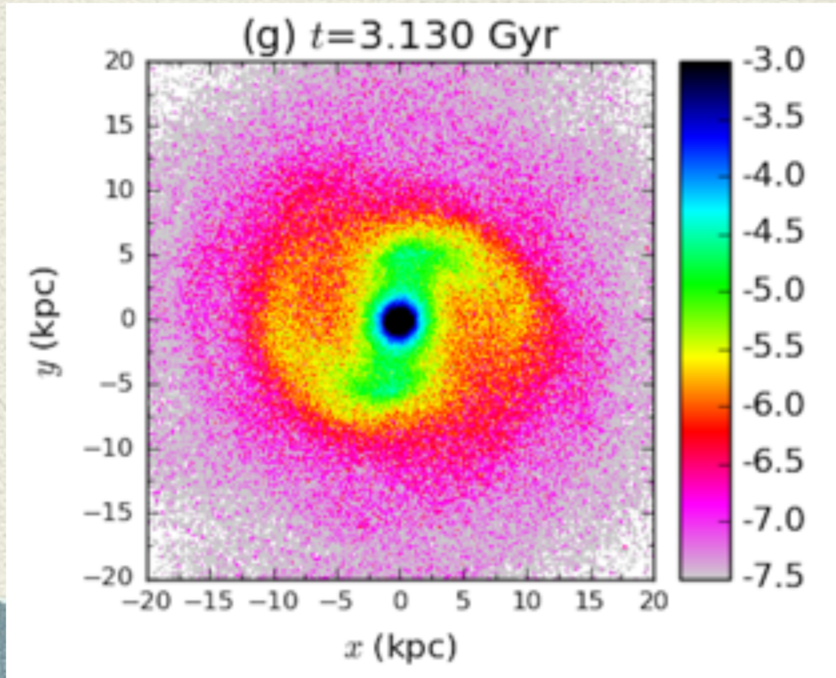
The size of the outer bar



Summary

- From observation:
  - About 1/3 early type barred galaxies have the inner bar
  - The size of the inner bar is ~10% of the outer bar
  - There is no preferred relative position angles between inner and outer bars
  - The pattern speed of two bars are different

- From our simulation
  - Generate long-lived double barred galaxies
  - Study the strength, instantaneous phase/pattern speed and size of the bars
  - Bars are flexible and time-dependent structures
  - Near the end of the bars, the assumptions of rigidity and constant pattern speed may be improper. The pattern speed made with stars samples located near it CR might need to be modified.



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