

Spiral density waves in M81



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Outline

- observations
- our plans for M81
- stellar density waves
- substructures and effects of gaseous self-gravity
- summary

M81 (NGC3031)

Object type:

Spiral galaxy: SA(s)ab

Position (J2000):

RA: 09h 55m 33.20s Dec: 69° 3' 55.00"

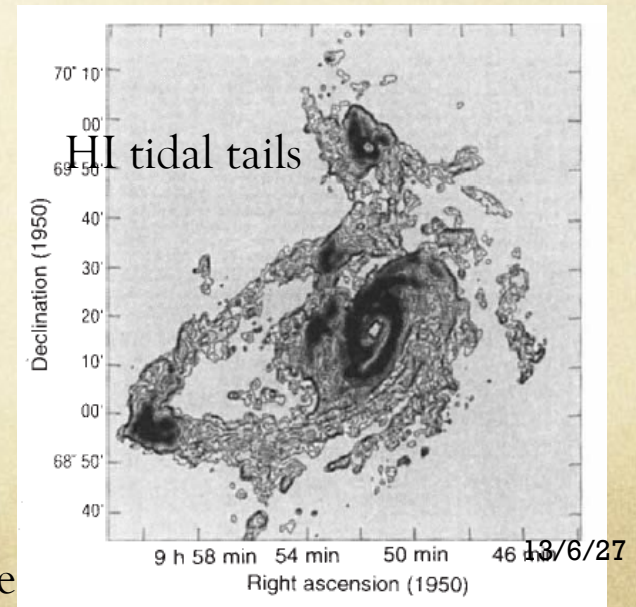
Distance:

12,000,000 light-years (3.6 Mpc)

Constellation:

Ursa Major (the Big Bear)

Major companions: M82, NGC3077

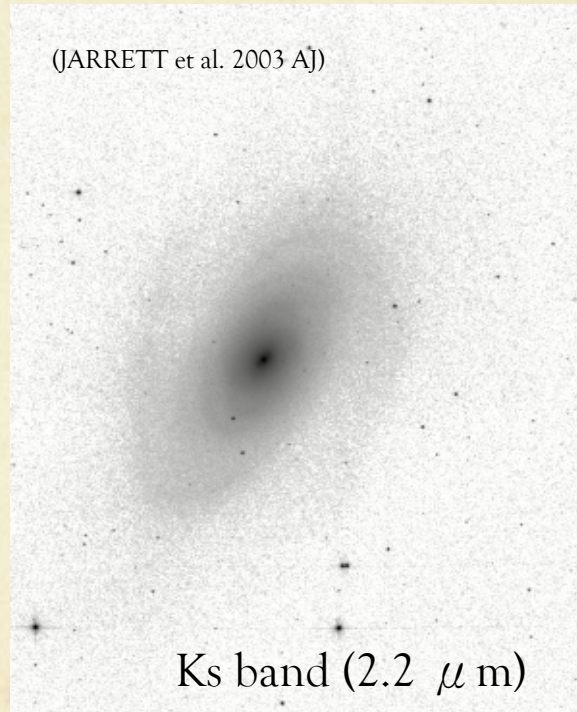


observations (I)

(Credit: N.A. Sharp (NOAO/AURA/NSF))



(JARRETT et al. 2003 AJ)



smooth stellar spirals; bulge/
old disk stars

(Braun 1995)



Tidal interaction; rotation
curve; large structures

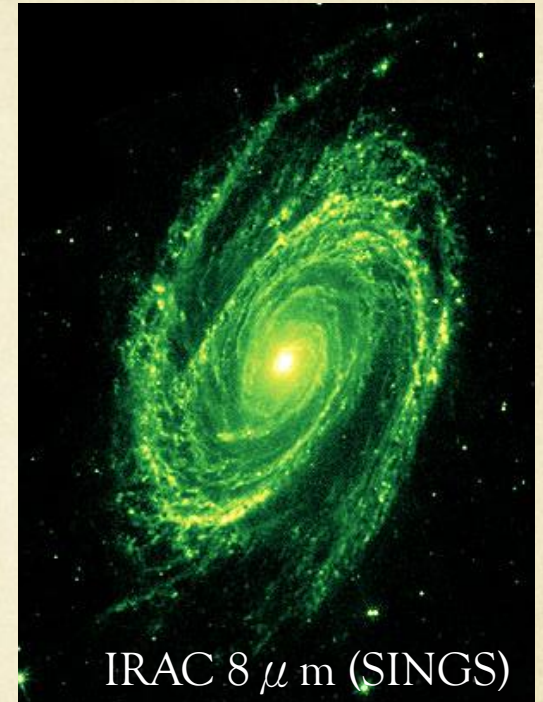
observations (II)



GALEX FUV-NUV
Gil de Paz et al. 2007
hot, young stars



IRAC 3.6 μ m (SINGS)
old stellar population

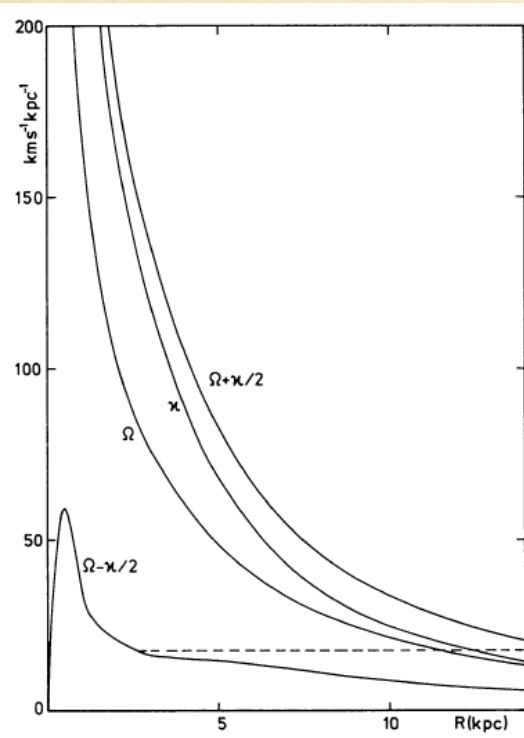


IRAC 8 μ m (SINGS)
dust; tracer of shocks

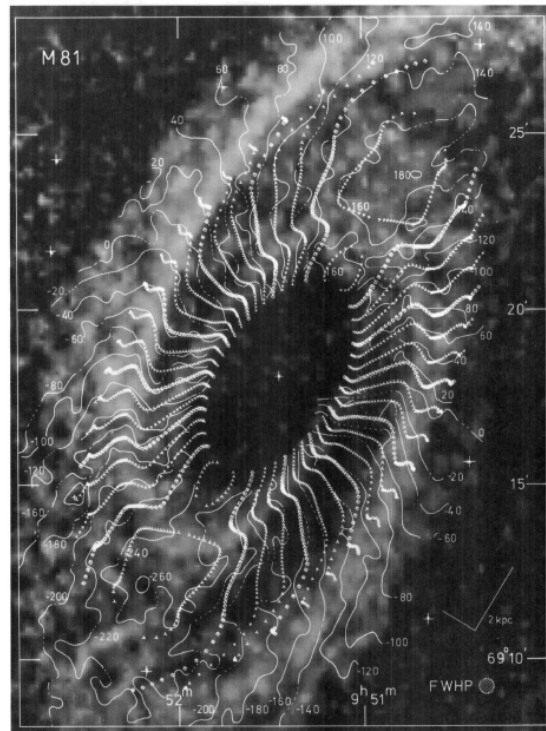
Models for M81

Visser 1980a,b

Without dark halo, heavy stellar disk is required to sustain the rotation curve

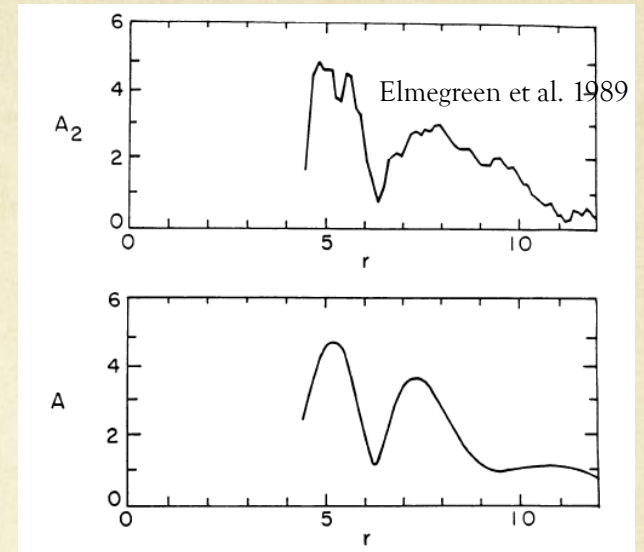


$\Omega_p = 18 \text{ km/s/kpc}$

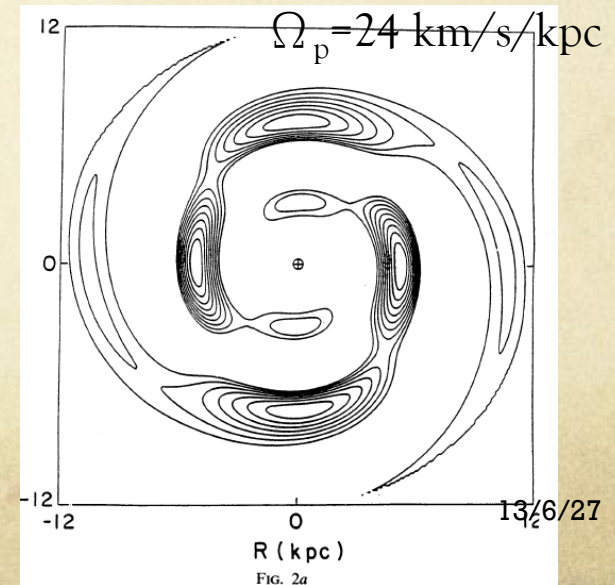


radial velocity field

Lowe et al. 1994 (the 3rd paper of modal approach: application to M81)

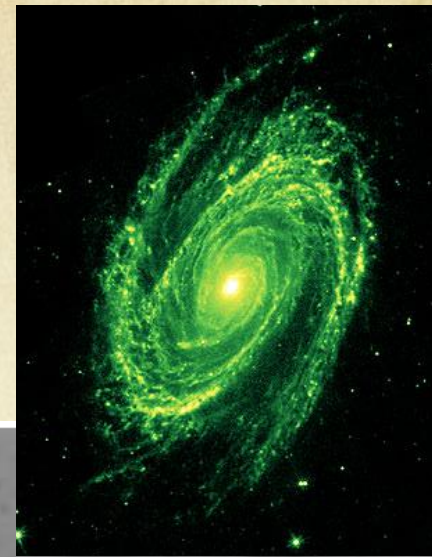


Interference pattern of leading and trailing waves traveling in opposite directions

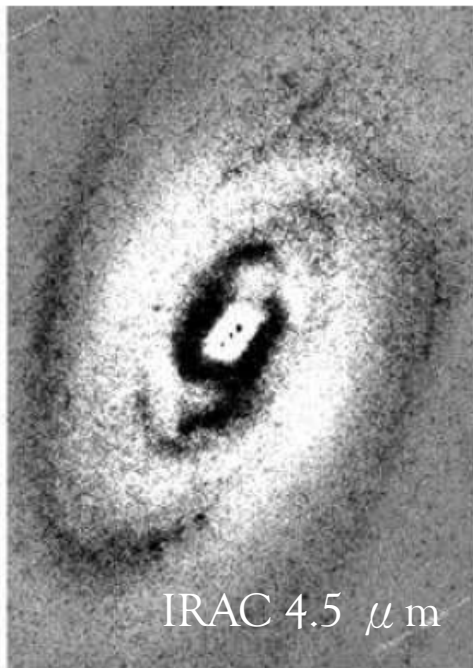


Inner spirals

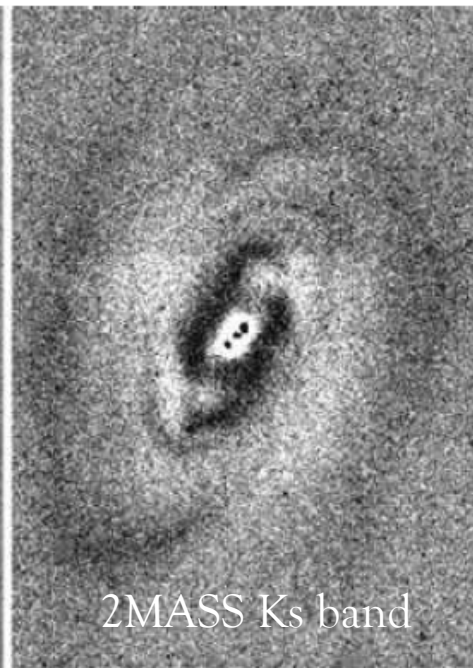
Non-axisymmetric residuals Kendall et al. 2008, MNRAS, 387, 1007



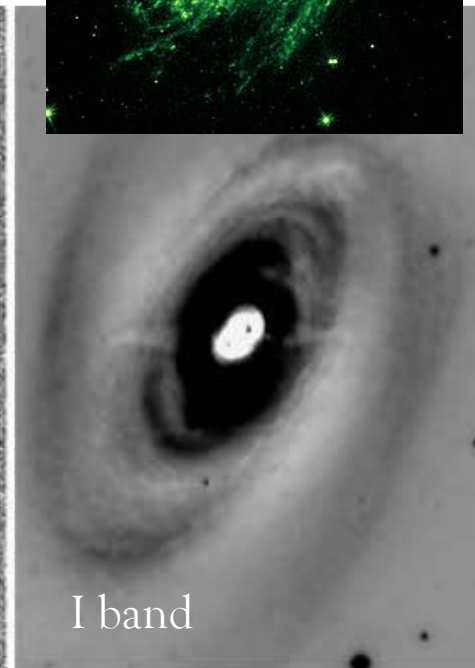
IRAC 3.6 μ m



IRAC 4.5 μ m



2MASS Ks band



I band

Questions:

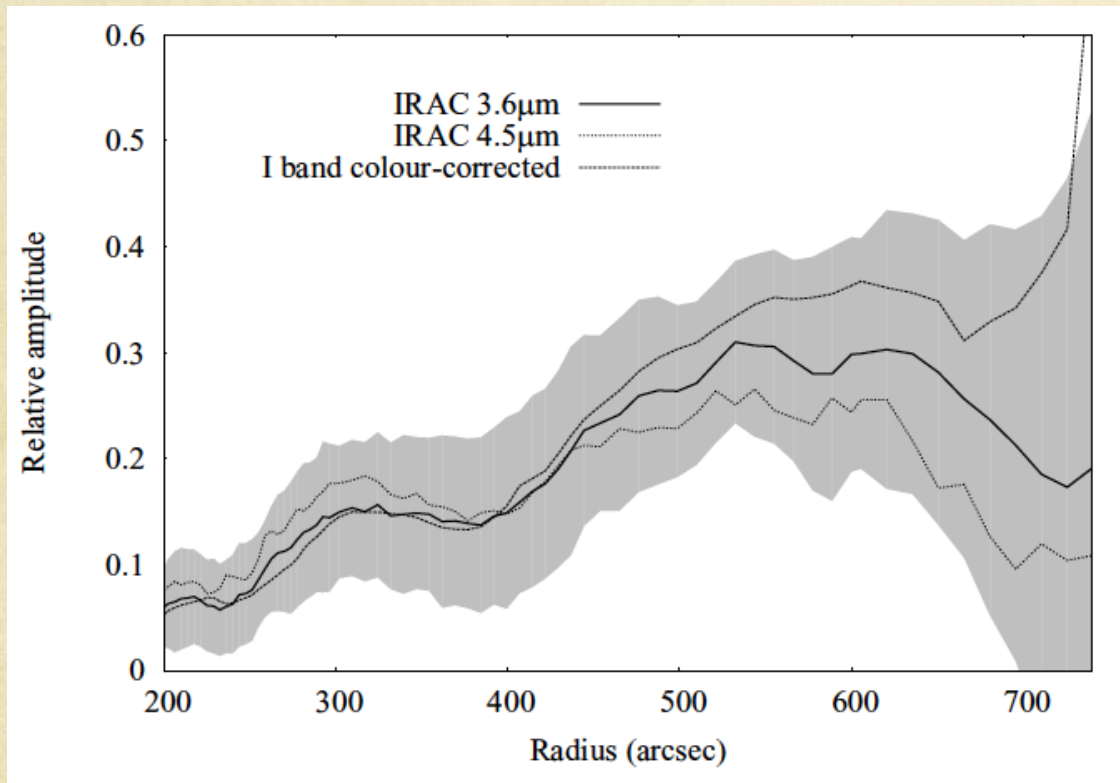
1. A pair of stellar spiral situated well inside the radius of ILR (2.5 kpc)?
2. What is the origin and the pattern speed of inner spirals?
3. Can spiral density wave theory explain the origin of inner spirals?
4. Stellar spirals induced by gaseous spirals? (Kendall et al. 2008)

Scientific goals

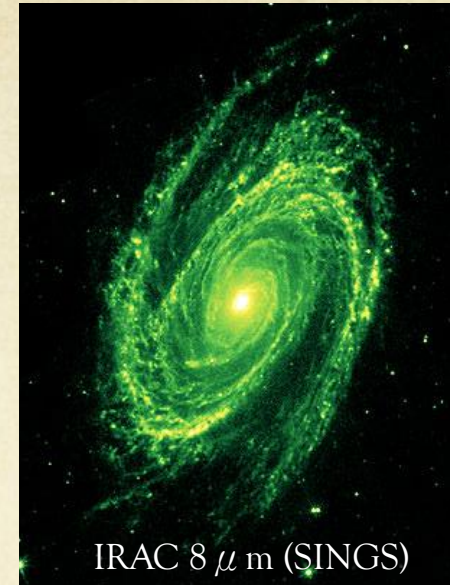
Study the **stellar structure** and the **gas response** in **M81** thoroughly within the framework of **density wave theory**

observations (III)

Amplitude of the stellar spiral (mass variation)



Kendall et al. 2008, MNRAS, 387, 1007



Questions:

1. Can the spiral density wave theory explain the amplitude of spirals?
2. How does gas react to the stellar spiral? Can the gas response explain the sub-structures seen in the images?
3. What's the effects of gaseous self-gravity?

Our plans for M81 (I)

A three-component (dark halo, bulge, stellar disk) basic model for M81.

observational constraints:

rotation curve, scale-length, masses in bulge and stellar disk

not good

Stellar density waves

Applying the method described in Lau & Bertin (1978) to solve the spiral structure

assumptions:

- (1) inner/outer boundary conditions
- (2) Toomre's Q profile (sound speed)

we get:

- (1) pattern speed of the unstable spiral modes
- (2) the shape of stellar density waves

comparison with observations:

- (1) the shape of stellar spirals (including the inner and the outer spirals)
- (2) the trend of the amplitude of density waves

Our plans for M81 (II)

Would the gas response fit observations?

questions:

- (1) how well is the assumption of QSSS? Phase offset between gaseous shocks and the potential minimum.
- (2) Are the density waves strong enough to cause sub-structures?
- (3) Is the self-gravity of gas important to the formation sub-structures?

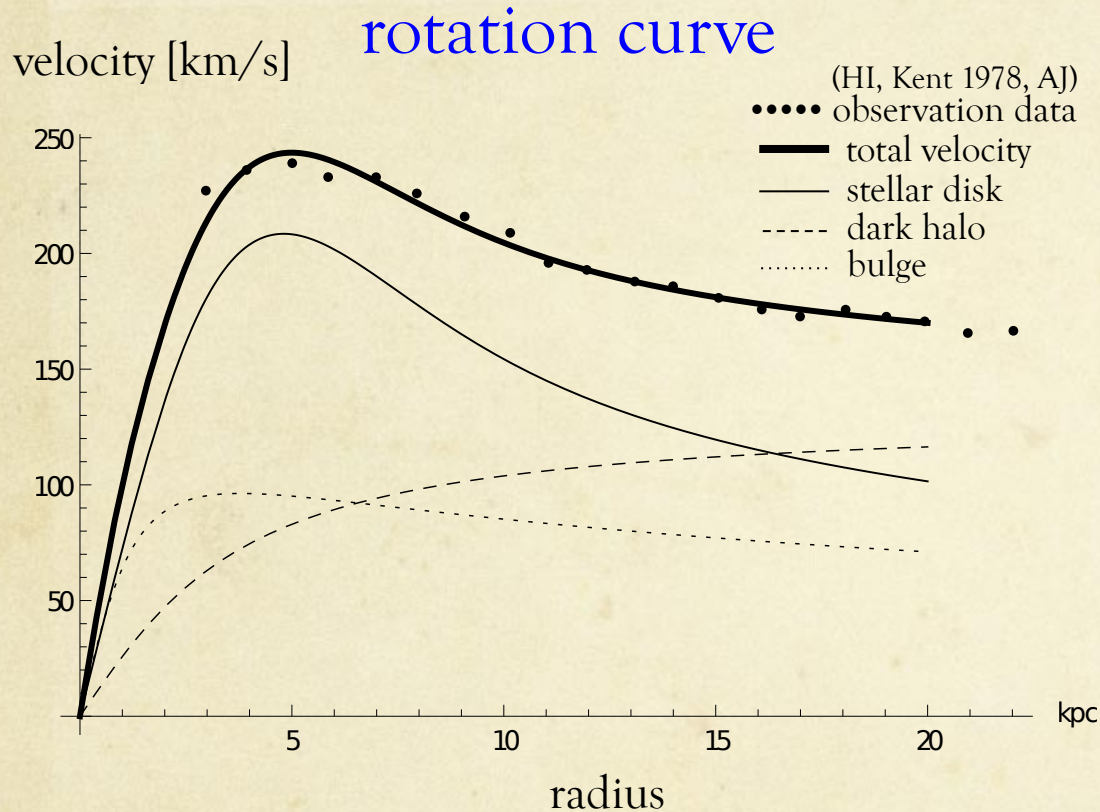
method:

- (1) Implement the stellar spirals just obtained in the hydrodynamic code, Antares.
- (2) Scale the amplitude of spirals to fit observation
- (3) under the assumption of QSSS, we rotate the density wave rigidly with the calculated pattern speed

objectives:

- (1) non-linear gas response
- (2) formation of substructure: higher harmonic resonances, formation of spurs, the effect of gaseous self-gravity
- (3) phase offset between stellar potential minimum and the gas shocks
- (4) comparison with observations

A three-component model for M81



* Lowe et al. 1994, ApJ. 427, 184

§ Toomre's disk 1963, ApJ; Lau & Bertin 1978, ApJ

‡ Athanassoula 1992, MNRAS

mass [M_{\odot}]	our model	Lowe*
disk [§]	4.6×10^{10}	6.1×10^{10}
bulge [‡]	1.9×10^{10}	1.5×10^{10}
halo*	3.3×10^{10}	3.0×10^{10}

scale-length of the disk [kpc]

our model	3.33
Lowe*	2.83

With these models, the center part of M81 rotates rigidly as a solid body.

Discrete unstable spiral modes (I)

Based on the equations described by Lau & Bertin (1978), we solve the discrete unstable modes with the following equations

$$\frac{d^2 u}{dr^2} + \hat{k}_3^2 u = 0, \quad (1)$$

where

$$u = h_1 \left[\frac{\sigma_0 r}{\kappa^2 (1 - \nu^2)} \right]^{1/2} \exp \left(\int^r i \frac{\kappa}{aQ} dr \right), \quad (2)$$

$$\hat{k}_3^2 = \left[\frac{\kappa}{a} \right]^2 \left[\frac{1}{Q^2} - 1 + \nu^2 + \frac{1}{4} \mathcal{J}^2 Q^2 \right]. \quad (3)$$

Here the dimensionless quantities Q , ν , \mathcal{J} are defined as

$$Q = \kappa a / \pi G \sigma_0, \quad (4)$$

$$\nu = (\omega - m\Omega) / \kappa, \quad (5)$$

$$\mathcal{J} = 2m \left(\frac{\pi G \sigma_0}{\kappa^2 r} \right) / \left(\frac{1}{s} - \frac{1}{2} \right)^{1/2}, \quad (6)$$

$$s = -d \ln \Omega / d \ln r. \quad (7)$$

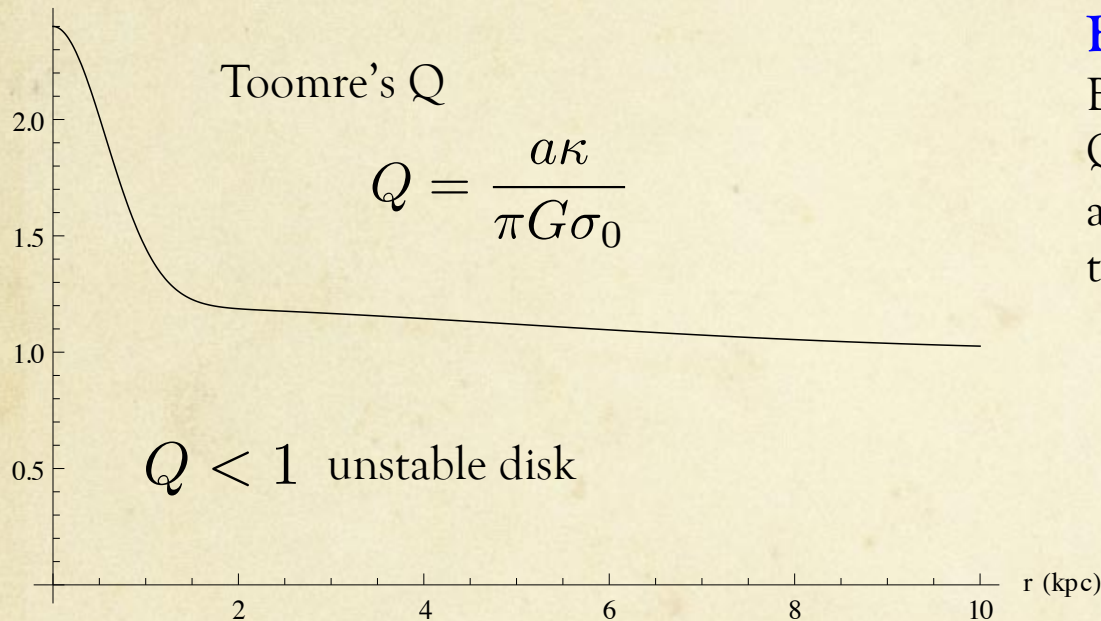
$$h_1 = a^2 \sigma_1 / \sigma_0$$

Equation (1) is an equation of harmonics oscillator, with k_3^2 (complex function) being a function of Q & the basic model of M81

- We assume these equations are valid all the way to the center
- Rigid body rotation is important to avoid the singularity in Eq. (6)

Discrete unstable spiral modes (II)

Based on the equations described by Lau & Bertin (1978), we solve the discrete unstable modes with the following input of Toomre's Q and boundary conditions



Boundary conditions:

Because of the absence of ILR and Q-barrier in our model, waves are allowed to propagate all the way to the center.

at $r=0$:

In order to avoid singularity at the galactic center, we assume $r=0$ is a node of waves

at the radius of outer 4:1 resonance:
outgoing boundary condition

a : sound speed

κ : epicyclic frequency

G : gravitational constant

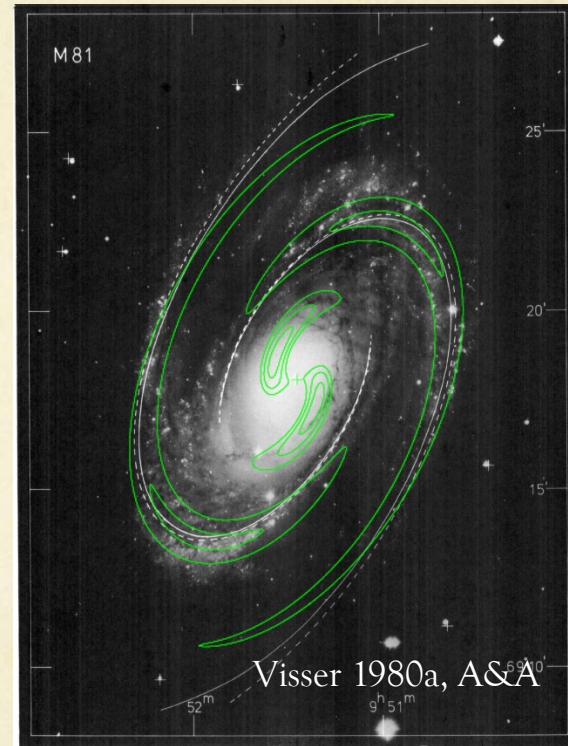
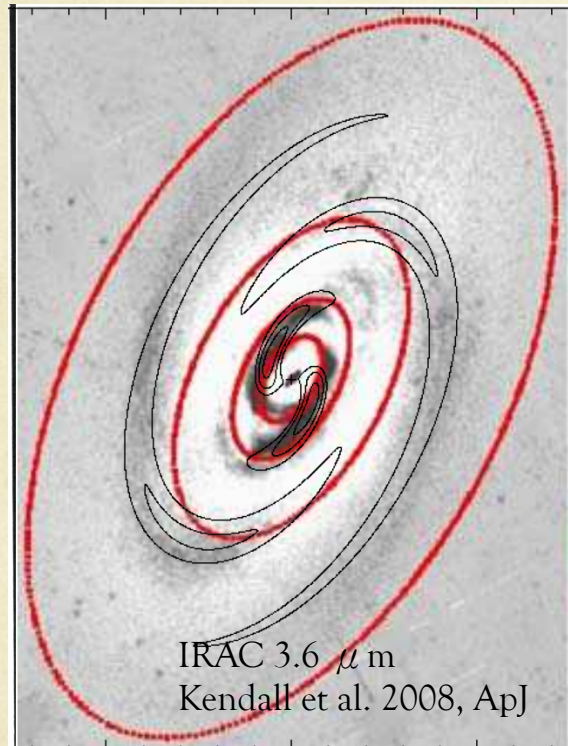
σ_0 : unperturbed surface density

Two dominate unstable modes are found

mode	pattern speed [km/s/kpc]	growth rate [km/s/kpc]
$n=0$	$\Omega_p = 41.4$	$\gamma = 0.10$
$n=1$	$\Omega_p = 31.1$	$\gamma = 0.11$

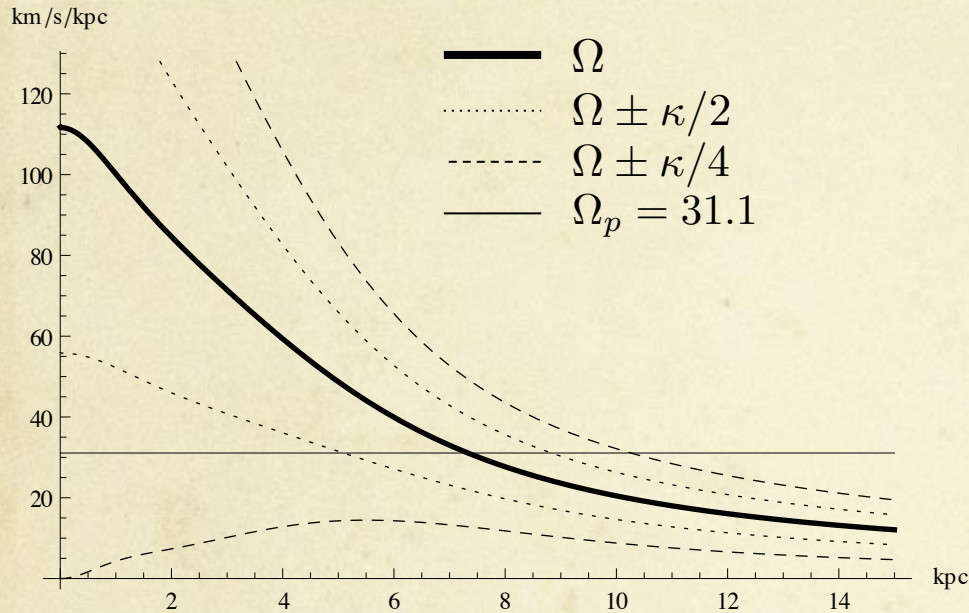
The density wave ($n=1$)

Contour: density waves calculated based on our model for the mode $n=1$

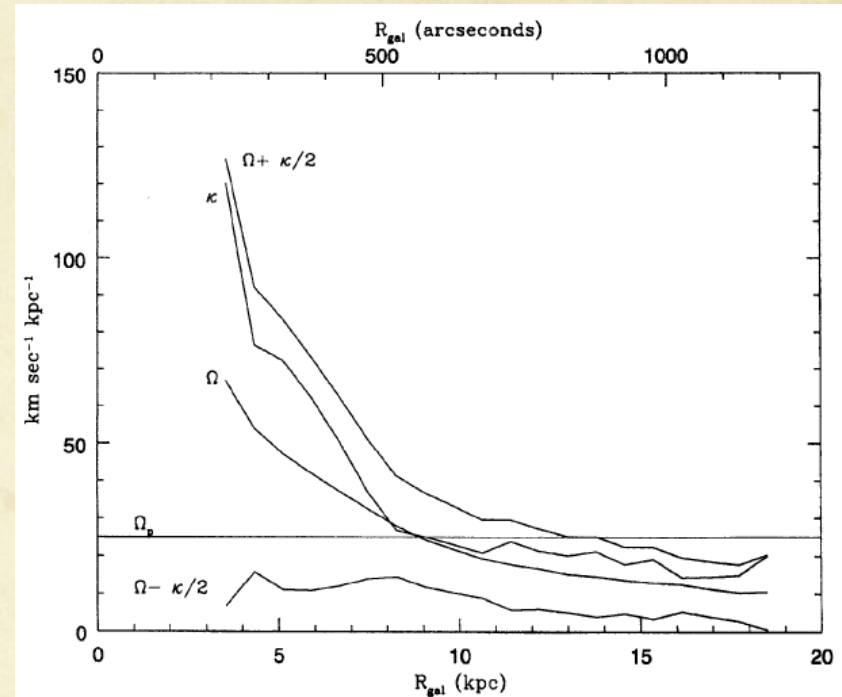


The inner spirals together with the outer spirals can be explained by a single spiral mode, rotating with the same pattern speed.

Resonances



Our model
 no ILR
 co-rotation: 7.33 kpc
 4:1 (inner): 5.1 kpc
 4:1 (outer): 8.8 kpc



HI observation

(Adler & Westfahl, 1996, AJ)

no ILR

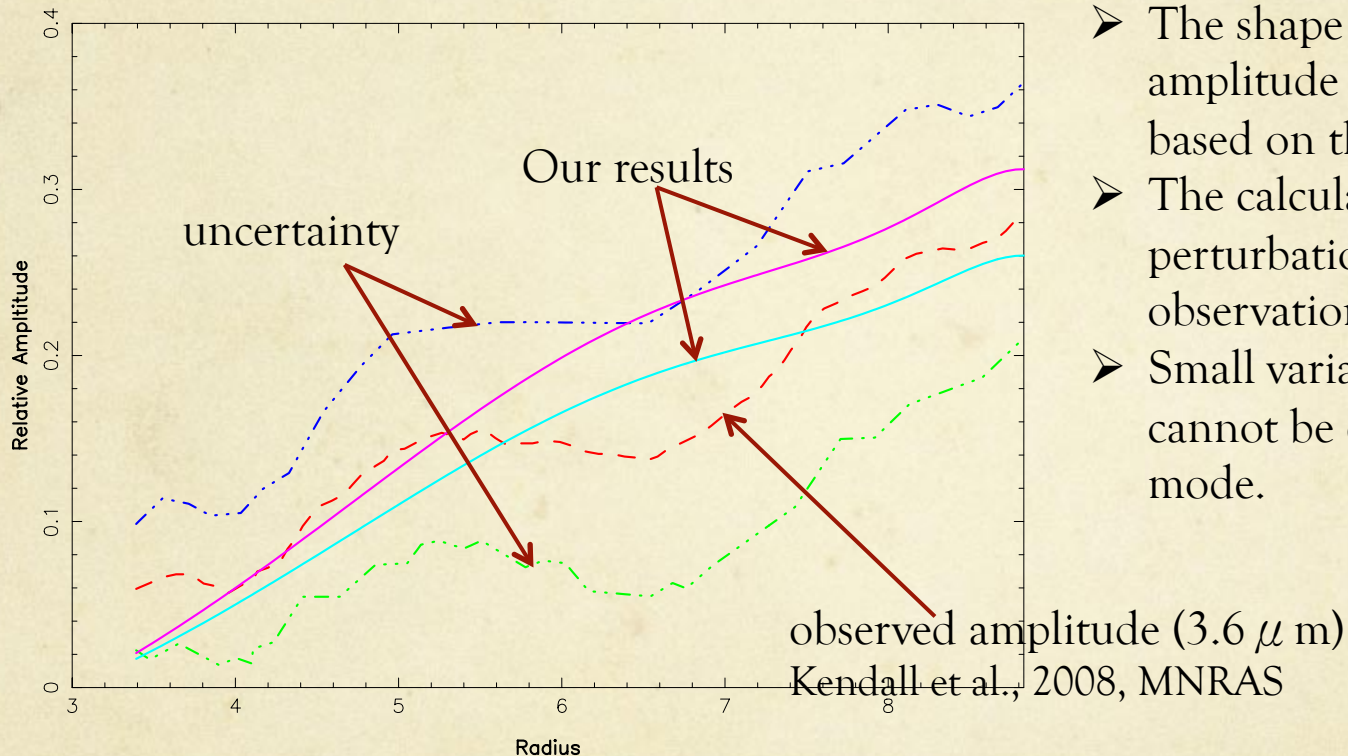
co-rotation = 9 kpc (Westfahl, 1998, ApJS)

$\Omega_p = 25$ [km/s/kpc] (Westfahl, 1995, ApJ)

Different methods give different values of pattern speed, ranging from 18 to 26 [km/s/kpc]

The amplitude of wave

Variation of amplitude in mass



- The shape and the trend of amplitude of spirals are calculated based on the density wave theory
- The calculated density perturbation is scaled to fit the observational amplitude
- Small variation in the amplitude cannot be explained by a single mode.

At co-rotation ($r=7.33$ kpc): 21% (25%) variation in the surface density corresponds to a 6.3% (7.3%) perturbation forcing compared to the axisymmetric force

The Antares code

2D hydrodynamic equations are solved numerically using high-order Godunov code

(Yuan & Yen 2005; Yen et al. 2012)

Governing equations

$$\frac{\partial \sigma}{\partial t} + \nabla \cdot (\sigma \mathbf{v}) = 0 \quad (\text{continuity equation, } \sigma : \text{surface density, } \mathbf{v}: \text{velocity vector})$$

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\frac{\nabla p}{\sigma} - \nabla V_{\text{total}} \quad (\text{equation of motion, } V_{\text{total}}: \text{total potential})$$

$$V_{\text{total}} = V_{\text{halo}} + V_{\text{disk}} + V_{\text{bulge}} + V_{\text{gas}} + V_{\text{spiral}}$$

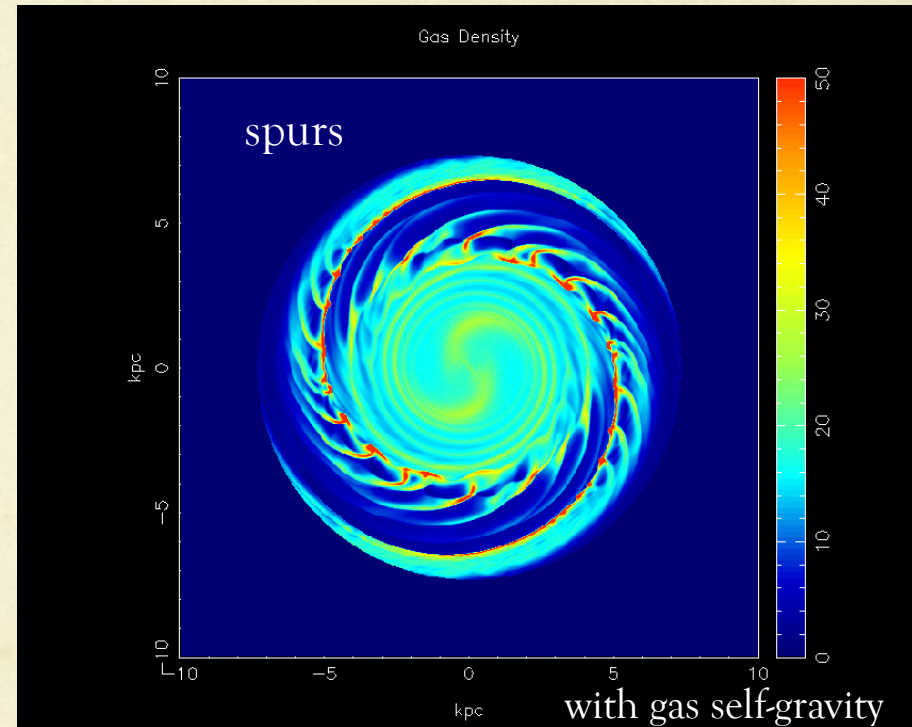
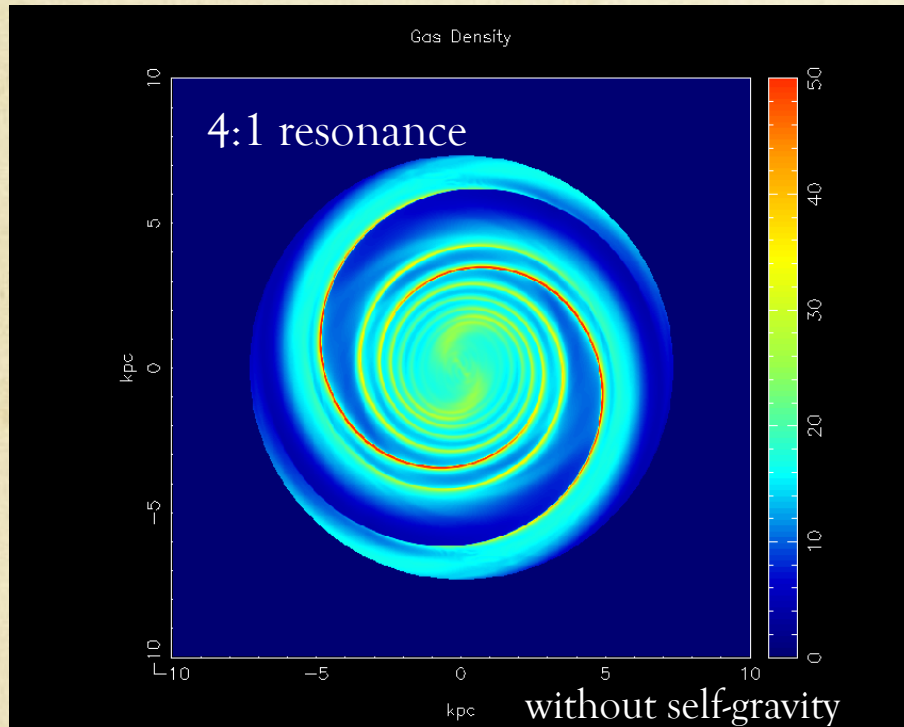
$$p = a^2 \sigma \quad (\text{isothermal equation of state; } a : \text{mean turbulent dispersion})$$

$$\nabla^2 V_{\text{gas}} = 4\pi G \sigma \delta(z)$$

(Poisson's equation, G : gravitational constant, δ Dirac delta function)

Gas response

Sub-structures (density maps)



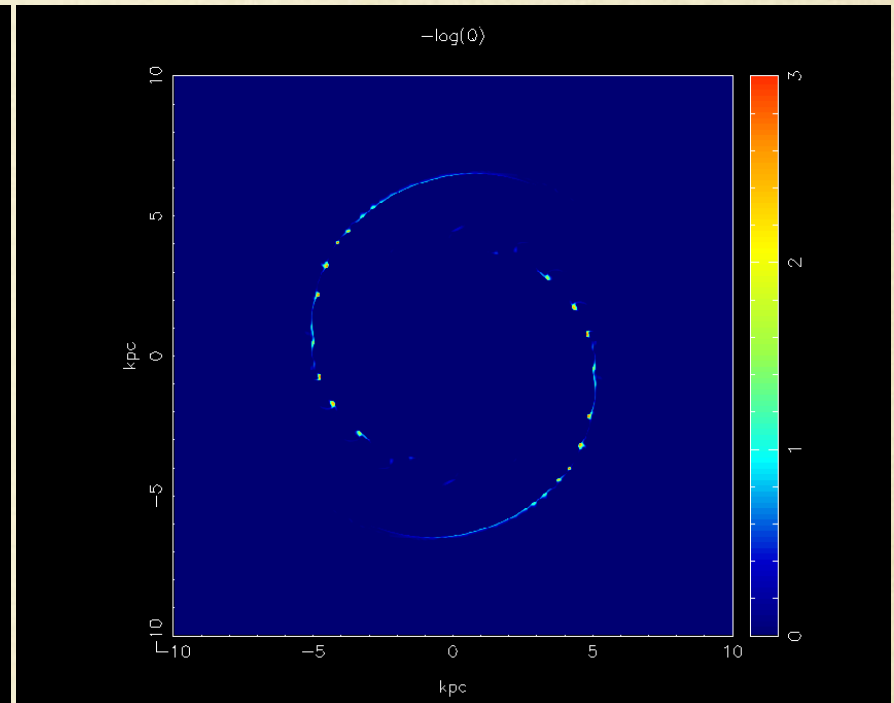
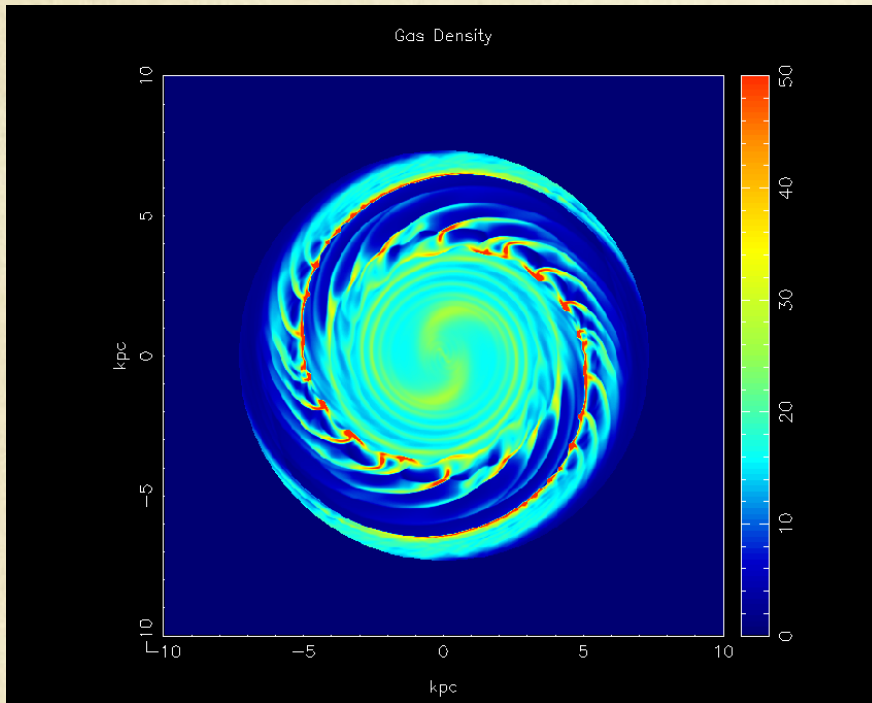
- 4:1 resonance is kept prominent in the simulation without self-gravity
- high density clumps form along shocks due to the gravitational instability
- The self-gravitating clumps are sheared apart in the post-shock region

In M81, self-gravity is crucial to the formation of spurs/wiggles.

Effects of gaseous self-gravity (I)

Gravitational instability

Toomre's Q

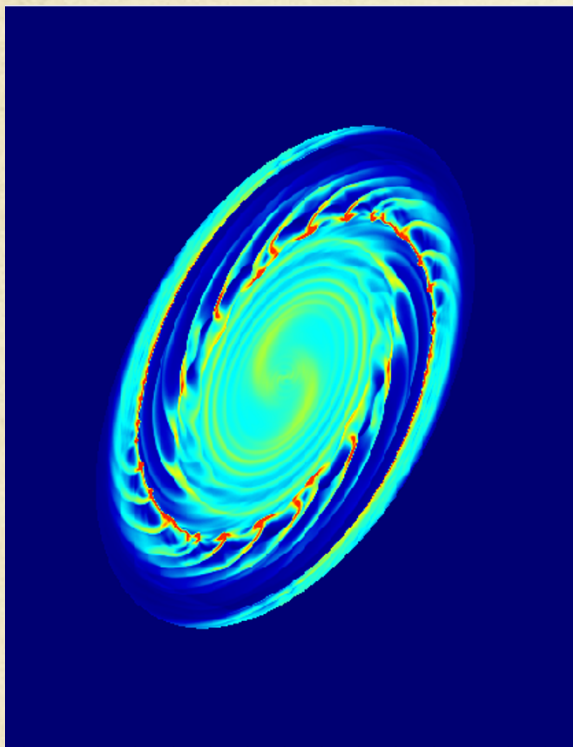


Surface density [M_{\odot}/pc^2]

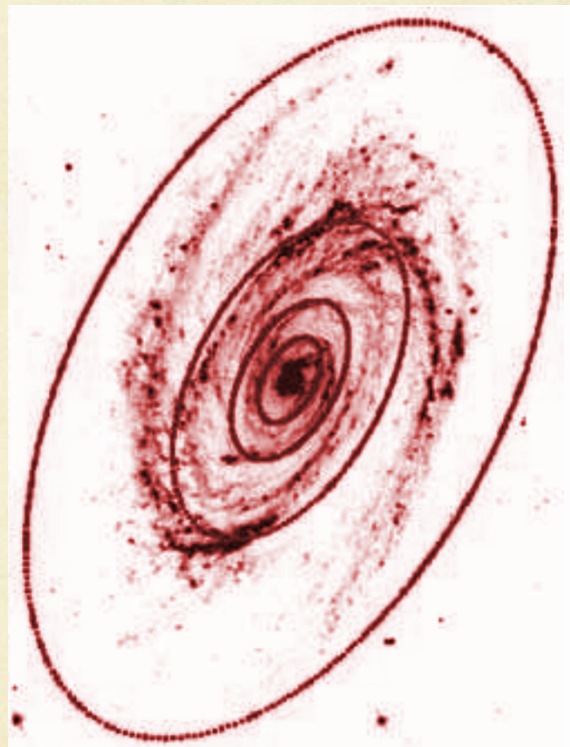
$-\log Q$

Only the dense clumps along the shocks are gravitationally unstable

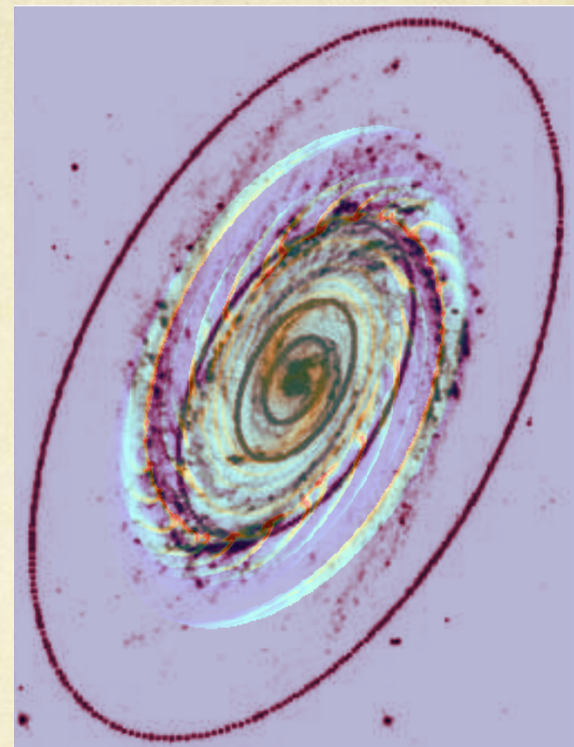
Comparison with M81



Numerical simulation



IRAC 8 μ m



Numerical simulation
+
IRAC 8 μ m

Formation of spurs

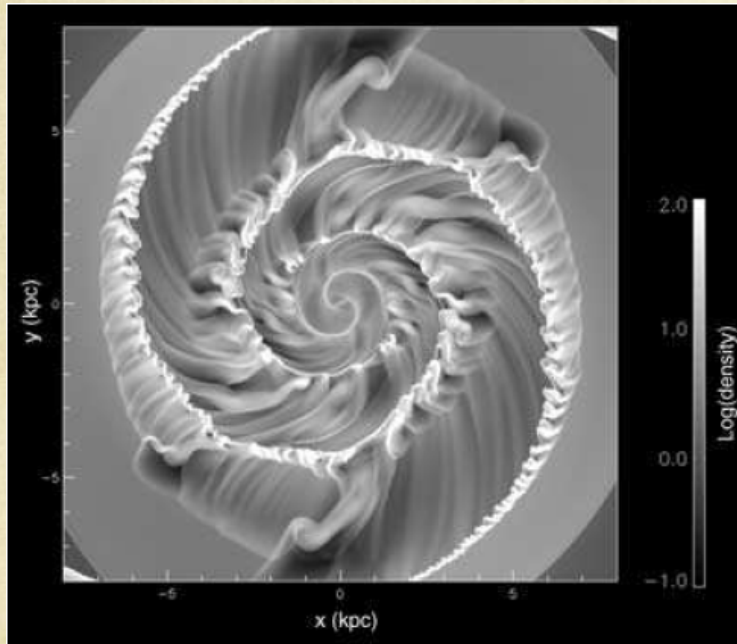
Feathering instability

Lee & Shu (2012)

2D global simulations

Kelvin-Helmholtz instability

Wada & Koda (2004)

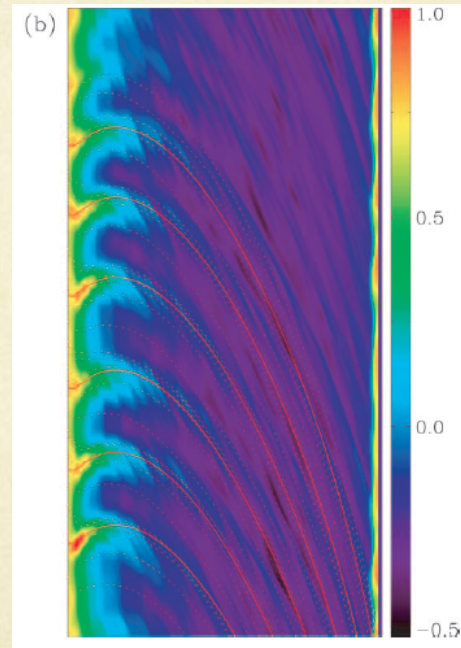


pure hydrodynamical simulation

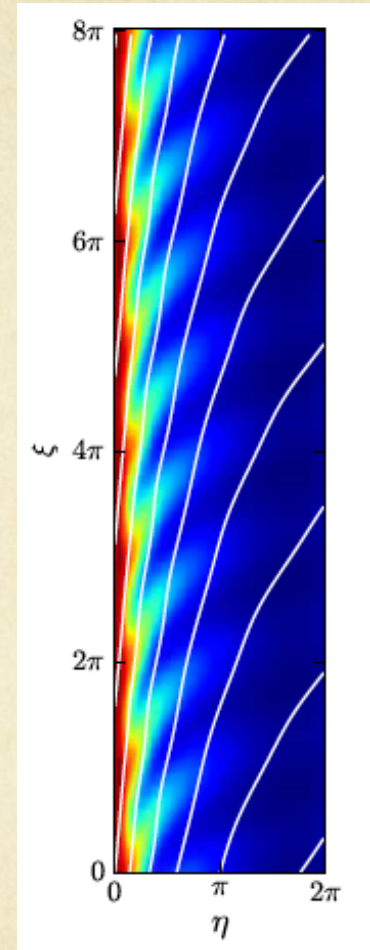
2D/3D local simulations

Manegto-Jeans instability

Kim & Ostriker(2002, 2006), Kim, Ostriker & Stone (2002)



Including self-gravity & magnetic field



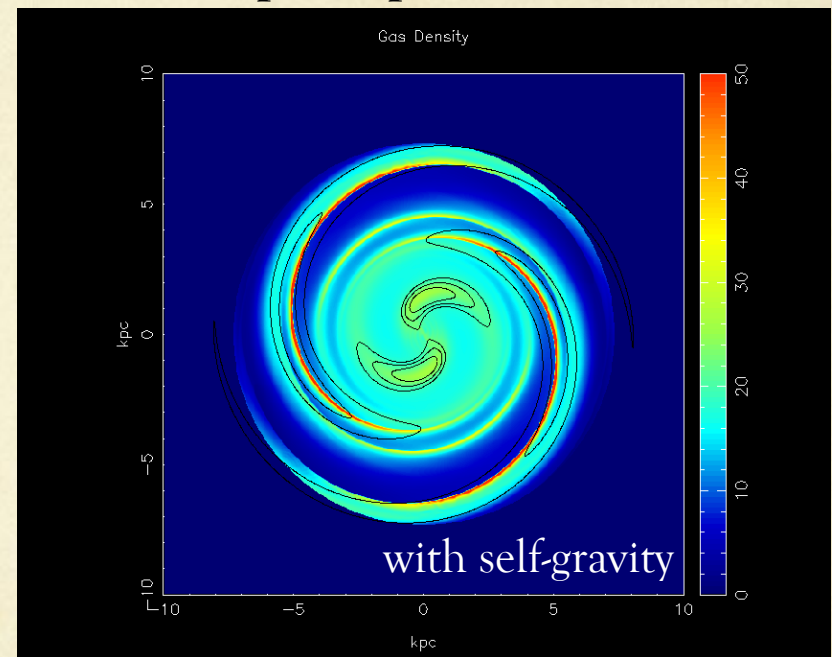
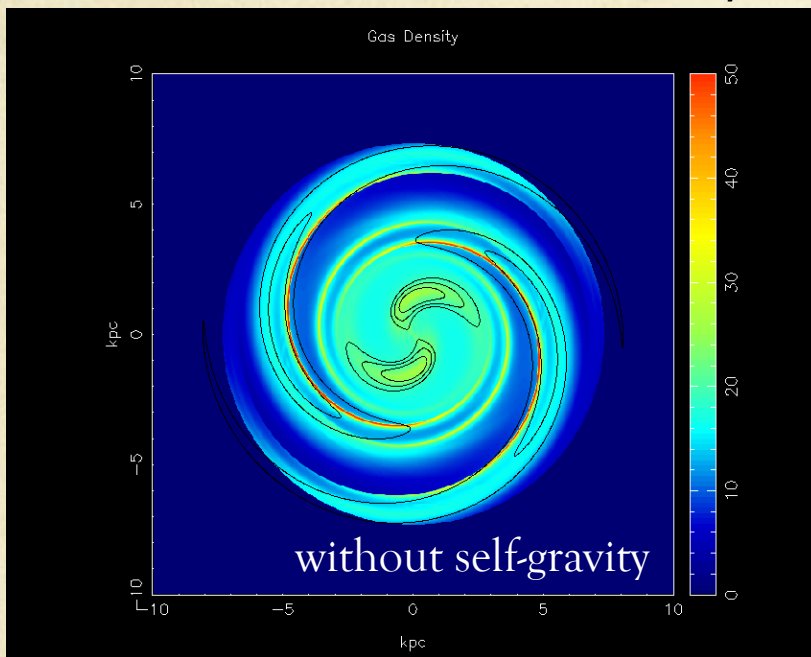
- Within the error bar of forcing, Kelvin-Helmholtz instability is not likely at work in M81
- In M81, gravitational instability sets in before the pure hydrodynamic instability occur

Effects of gaseous self-gravity (II)

Phase offsets between potential minima and spiral shocks

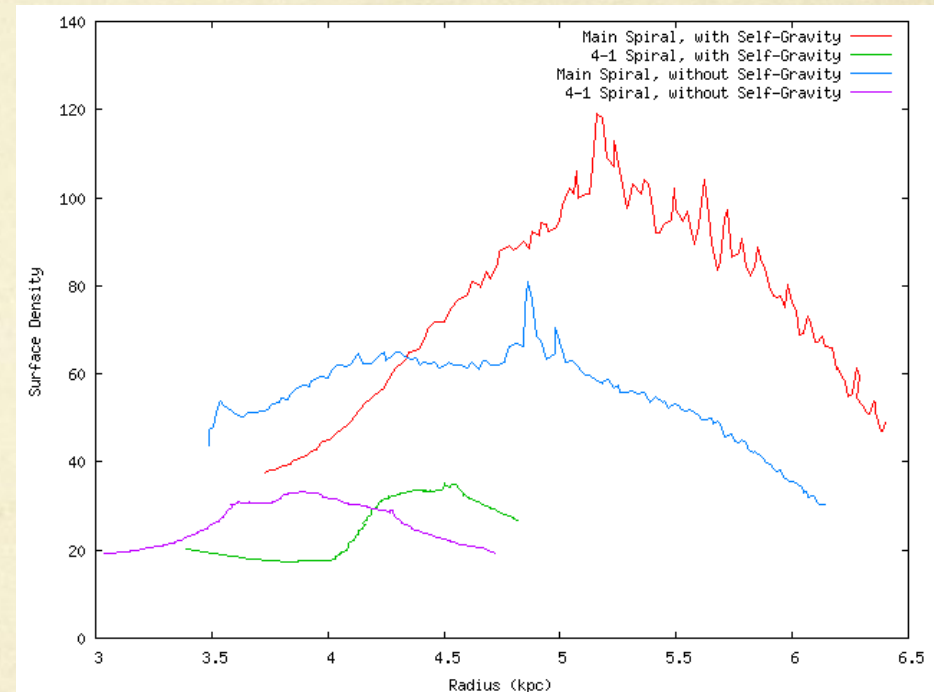
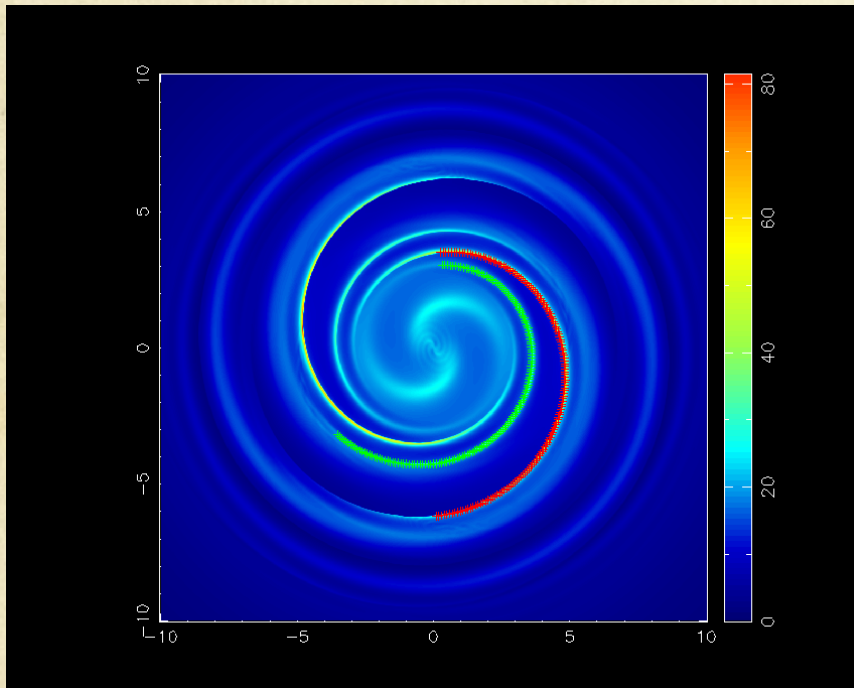
colors: surface density

contours: spiral potential



- The overall structures expand radially outward in the model with self-gravity
- Self-gravity shifts the positions of shocks downstream toward the potential minimum
- The phase offset between potential minimum and shocks is useful in determining the radius of co-rotation (Gittins & Clarke, 2004, MNRAS, Kendall et al. 2008, MNRAS)

Effects of gaseous self-gravity (III)

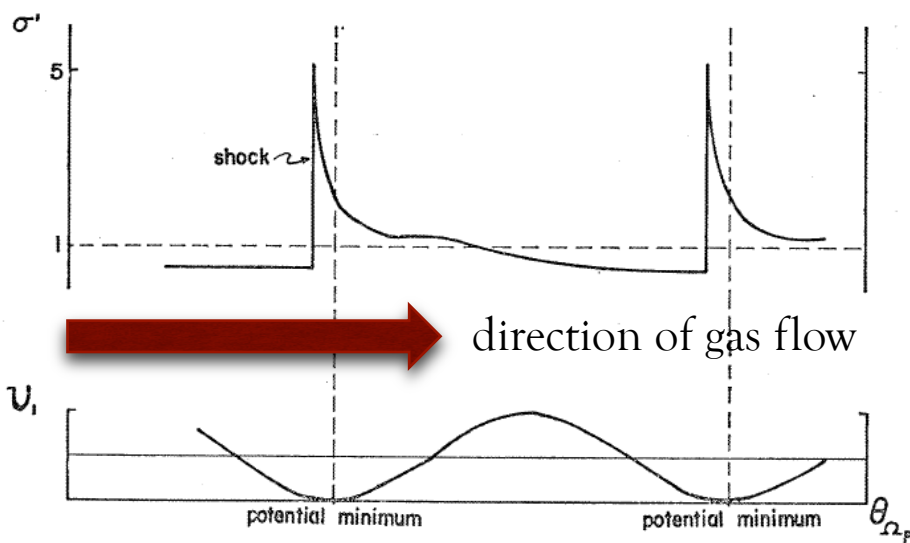


- Self-gravity significantly enhances the density of the major shocks
- Structures (Major shocks & 4:1 resonances) are enlarged by the self-gravity of gas

Effects of gaseous self-gravity (IV)

Phase offset $\Delta\theta(r)$

W. W. Roberts 1969, ApJ



- Gittins & Clarke (2004, MNRAS) performed the asymptotic analysis (Shu et al. 1972, 1973) and numerical simulations to investigate the phase shift as a function of sound speed and the strength of forcing.

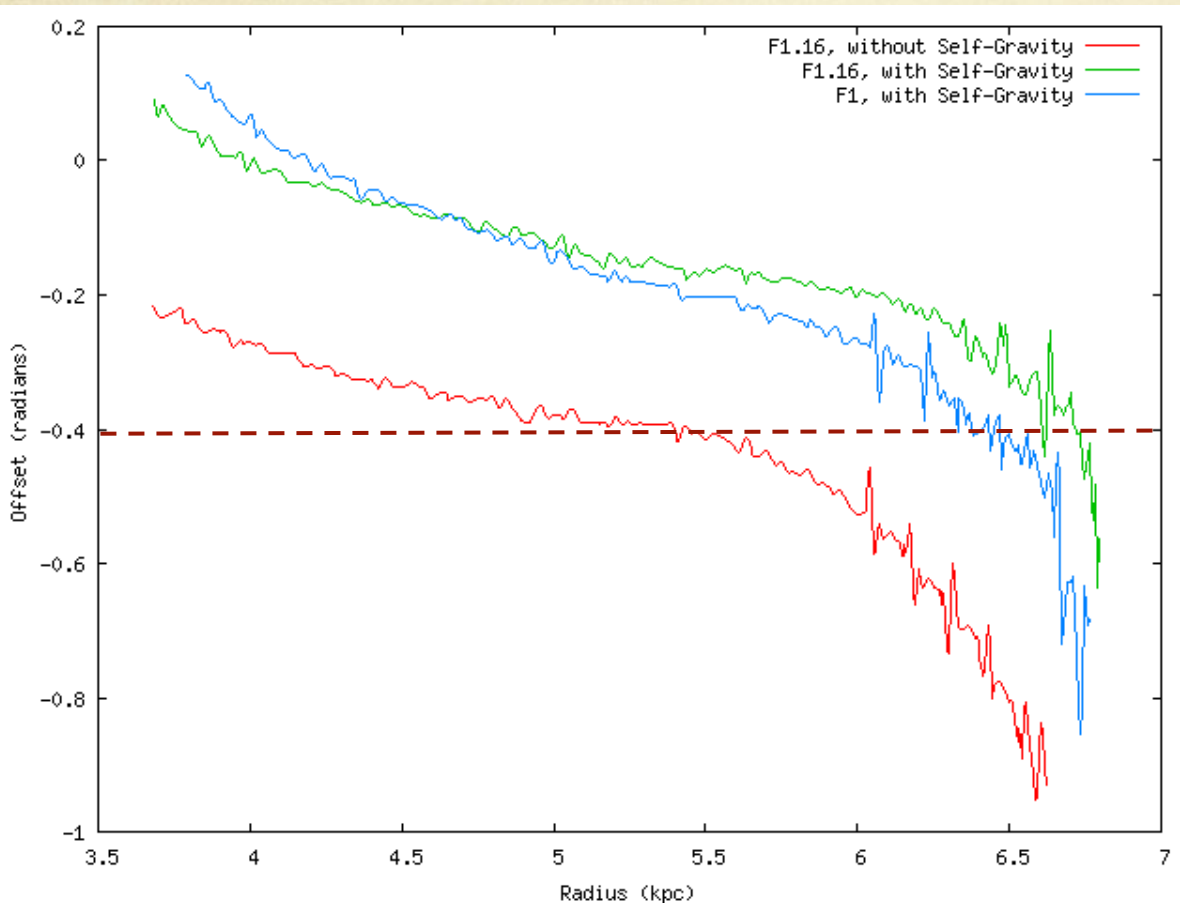
sound speed \uparrow $\Delta\theta(r)$ \updownarrow
 Forcing \uparrow $\Delta\theta(r)$ \downarrow

For $m=2$, given $\Delta\theta > 22.5^\circ$, co-rotation is constrained within uncertainty of 25%

- Based on Gittins & Clarke (2004), Kendall et al. constrained the co-rotation of M81 at 12 ± 3 kpc (However, Kendall adopted a strength of forcing 22.5% at 8.5 kpc; Gittins & Clarke used 5% for their calculation)

Effects of gaseous self-gravity (V)

Phase offsets between potential minima and spiral shocks



The self-gravity of gas significantly reduces the phase offset

with self-gravity
 $\Delta \theta = 23^\circ \rightarrow 10\%$

without self-gravity
 $\Delta \theta = 22.5^\circ \rightarrow 25\%$

Summary

- The inner spirals together with the outer spirals seen in M81 can be explained by a single unstable spiral mode ($n=1$) calculated from the density wave theory. They share the same pattern speed $\Omega_p = 31.1$ [km/s/kpc].
- For M81, Kelvin-Helmholtz instability cannot be the cause of spurs within the uncertainty of the strength of forcing.
- Self-gravity of gas enhances the density along shocks significantly and trigger gravitational instability to form dense gas clumps, which are sheared apart in the post shock regions in the form of spurs.
- Self-gravity significantly reduces the angular offset between the major shocks and potential minima.
- Self-gravity enlarges the overall structures of gas.

Lots of works remain to be done for M81

- The effect of the disk thickness (gas & stellar disks)
- Variation in the amplitude of spiral waves
- Systematic study on the phase offset. This could be useful for determining the radius of co-rotation and the pattern speed for more disk galaxies.
- Would magnetic fields important for the formation of sub-structures?

Thank you!!