GASEOUS FLOWS AND STAR-FORMING DYNAMICAL MECHANISMS IN THE SPIRAL ARMS OF BARRED-SPIRALS

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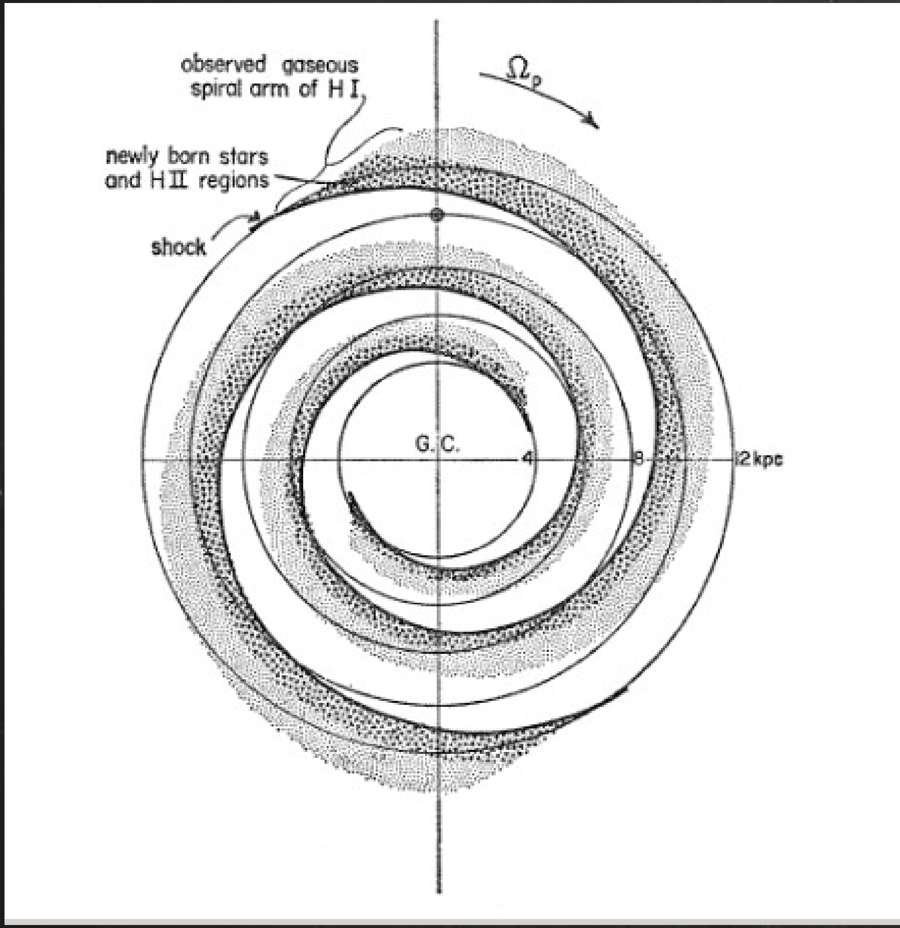
Gas flow in spiral arms. Textbook paradigms



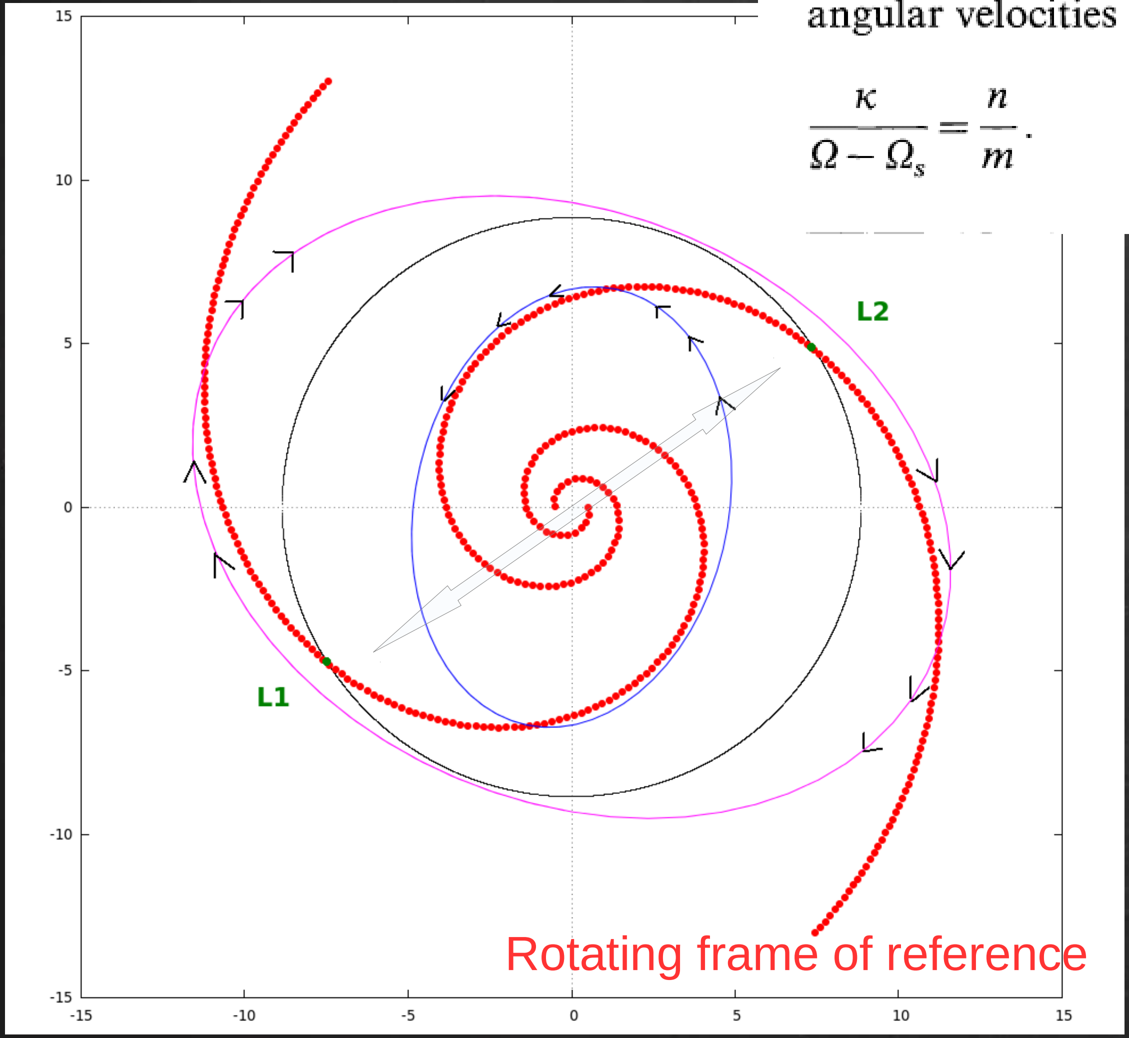
Implies that spirals extend:
Inside corotation

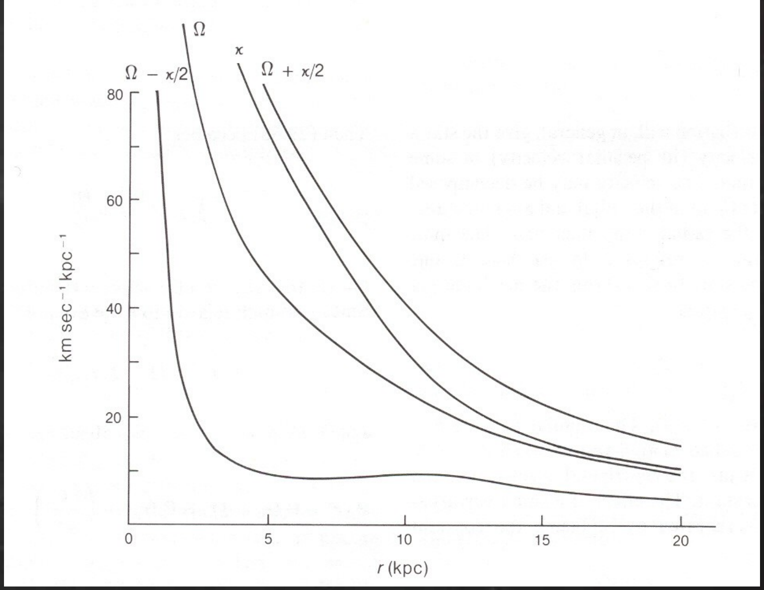
W.W. Roberts, 1969
ApJ 158,123

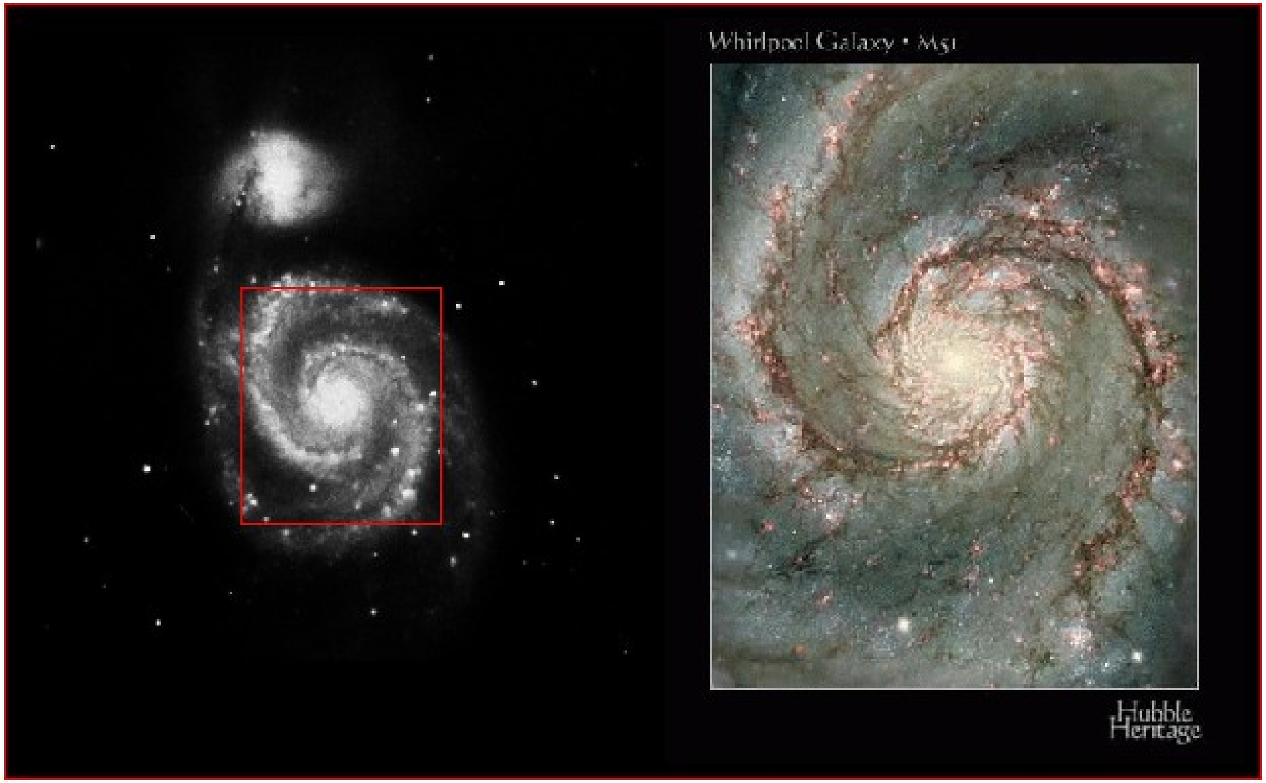
Resonances

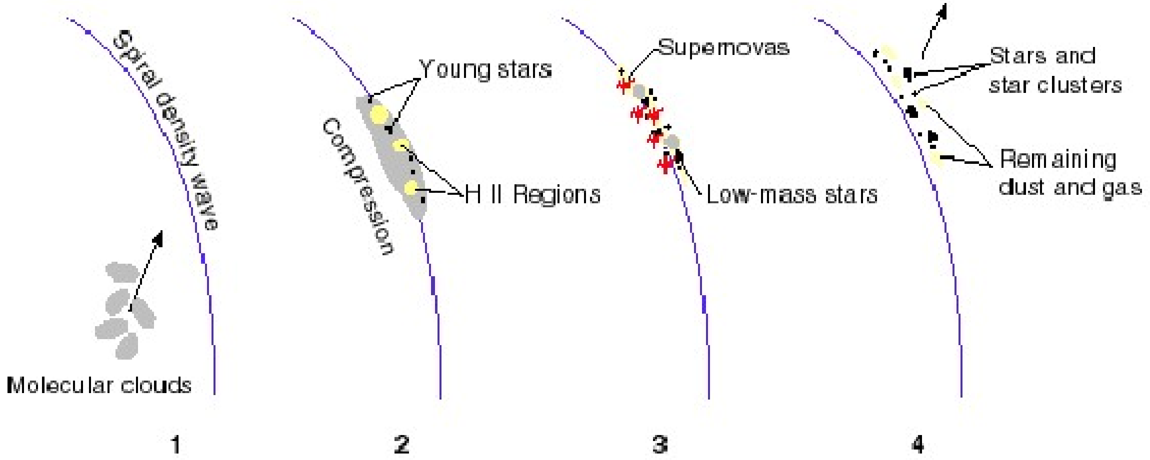
resonances between the epicyclic frequency κ and the angular velocity in the rotating frame $(\Omega - \Omega_s)$ (where Ω and Ω_s are the angular velocities of the stars and of the spiral pattern), i.e. when

$$\frac{\kappa}{\Omega - \Omega_s} = \frac{n}{m}. \tag{1}$$



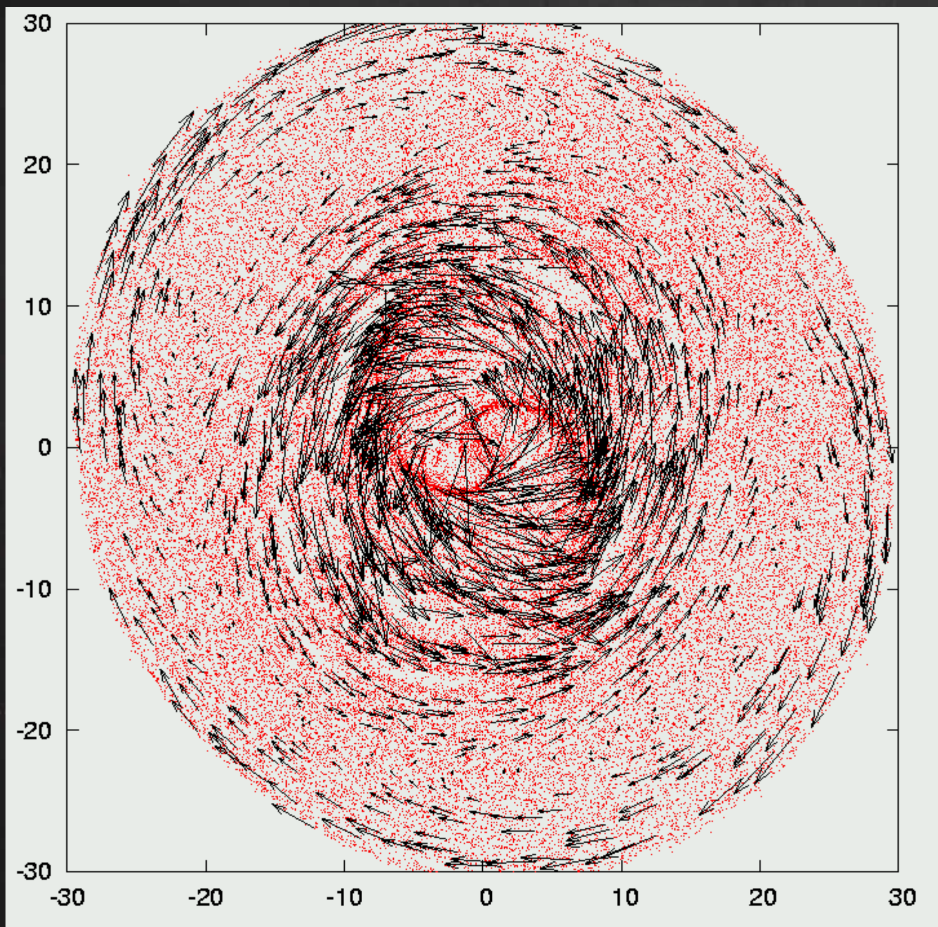



Whirlpool Galaxy • M51
Hubble Heritage

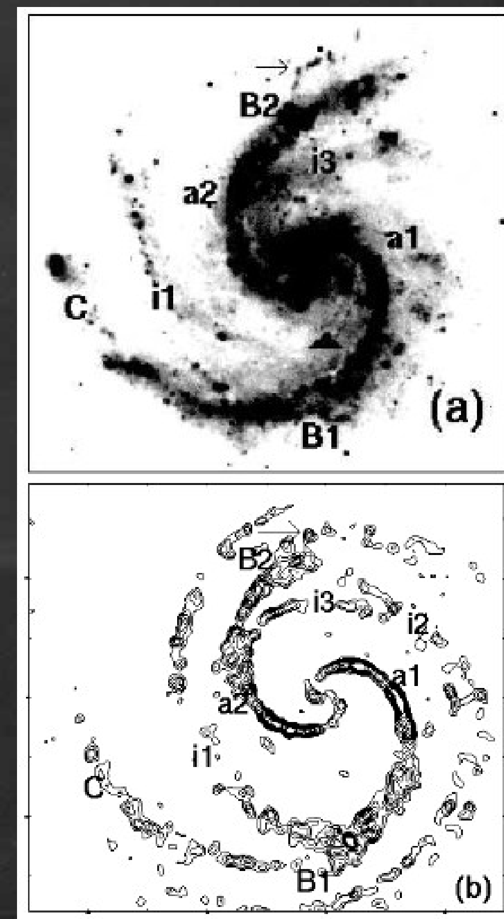

Spiral density wave
Molecular clouds
Young stars
Compression
H II Regions
Supernovas
Low-mass stars
Stars and star clusters
Remaining dust and gas
1
2
3
4

Normal (non-barred) spirals Models & Resonances I.

$V = V_0 + V_1$ $\quad V_0 = -v_{\max}^2 (f_b \exp(-\varepsilon_b r) - [\ln r + E_1(\varepsilon_d r)]),$ $\quad V_1(r,\theta) = Ar \exp(-\varepsilon_s r) \cos(2 \ln r / \tan i_0 - 2\theta)$

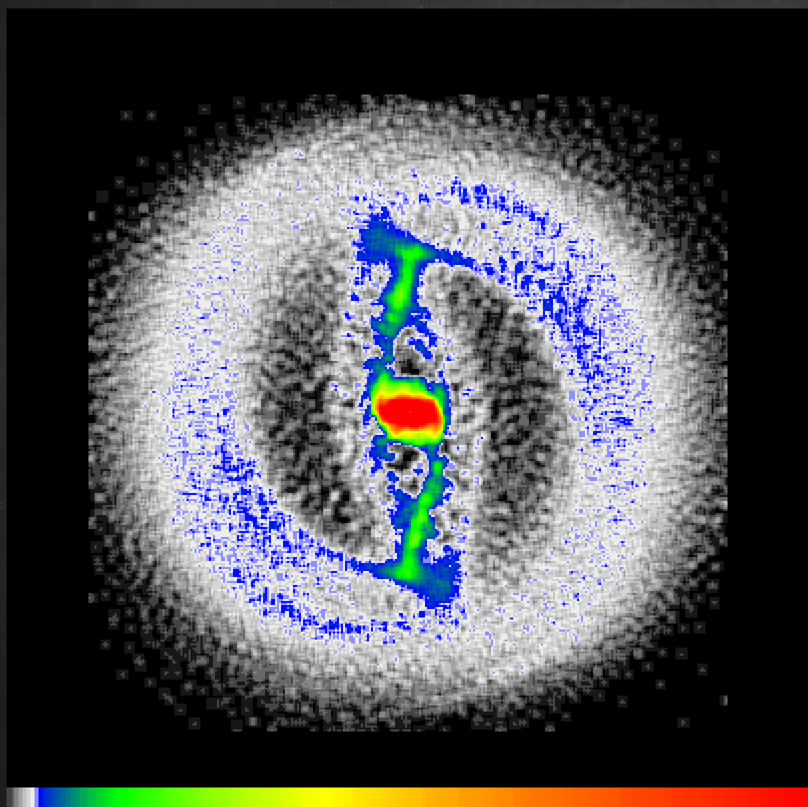


Rotating frame of reference

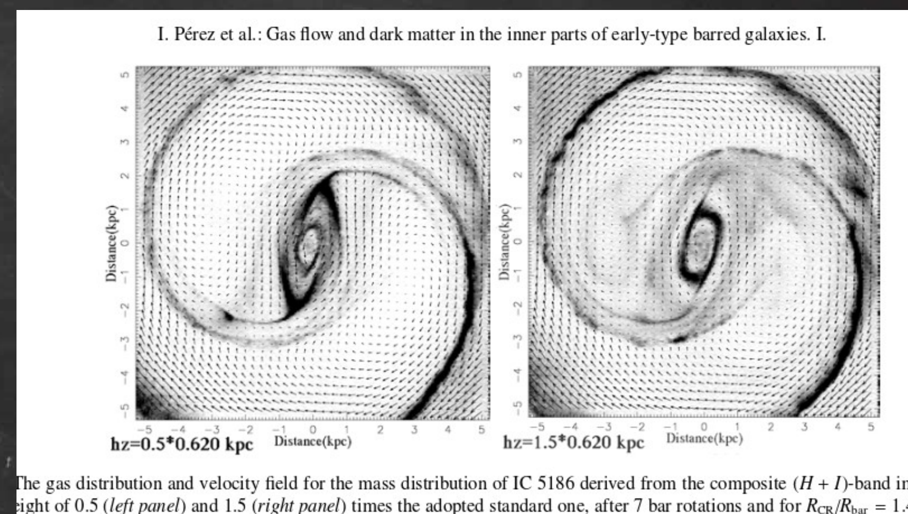


Patsis et al 1997, A&A

Barred-spirals
non/self-gravitating



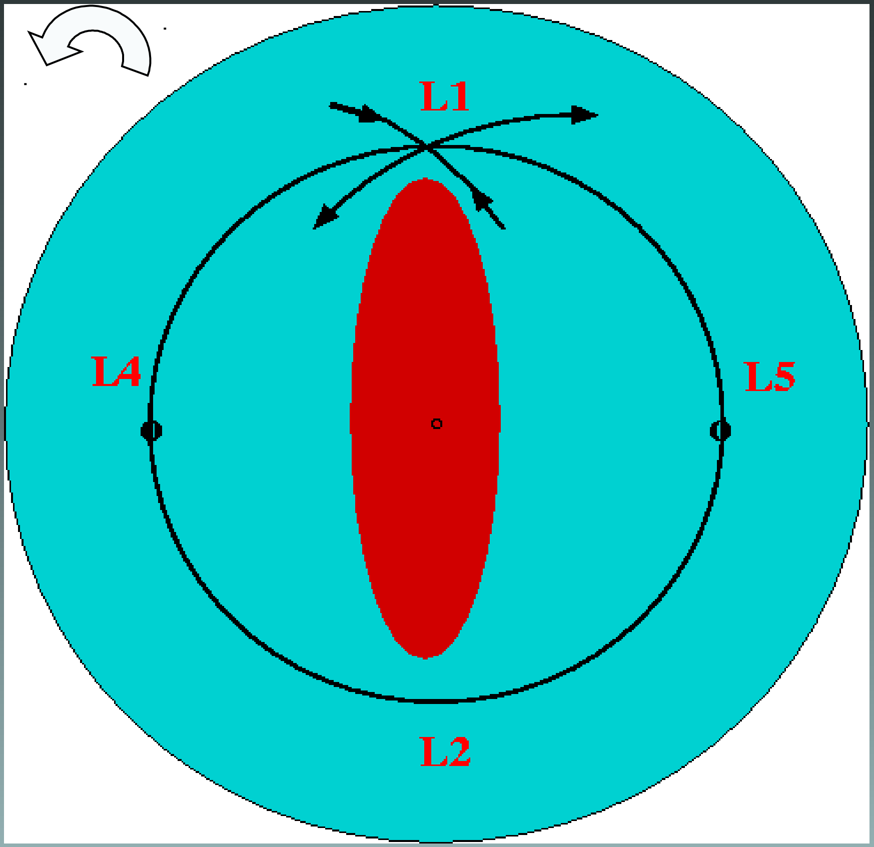
Patsis & Athanassoula 2000



Perez et al 2004, A&A

Lagrangian points

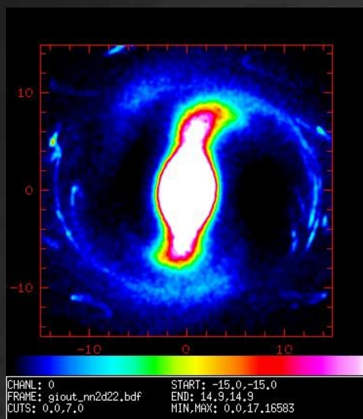
(in the case of a barred perturbation)

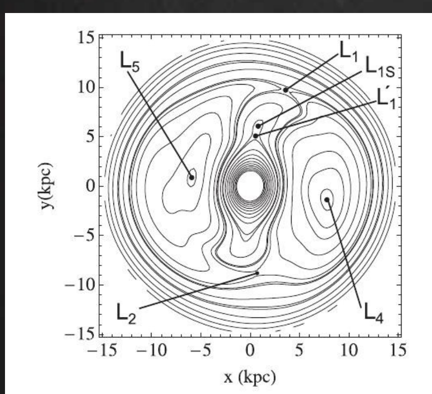


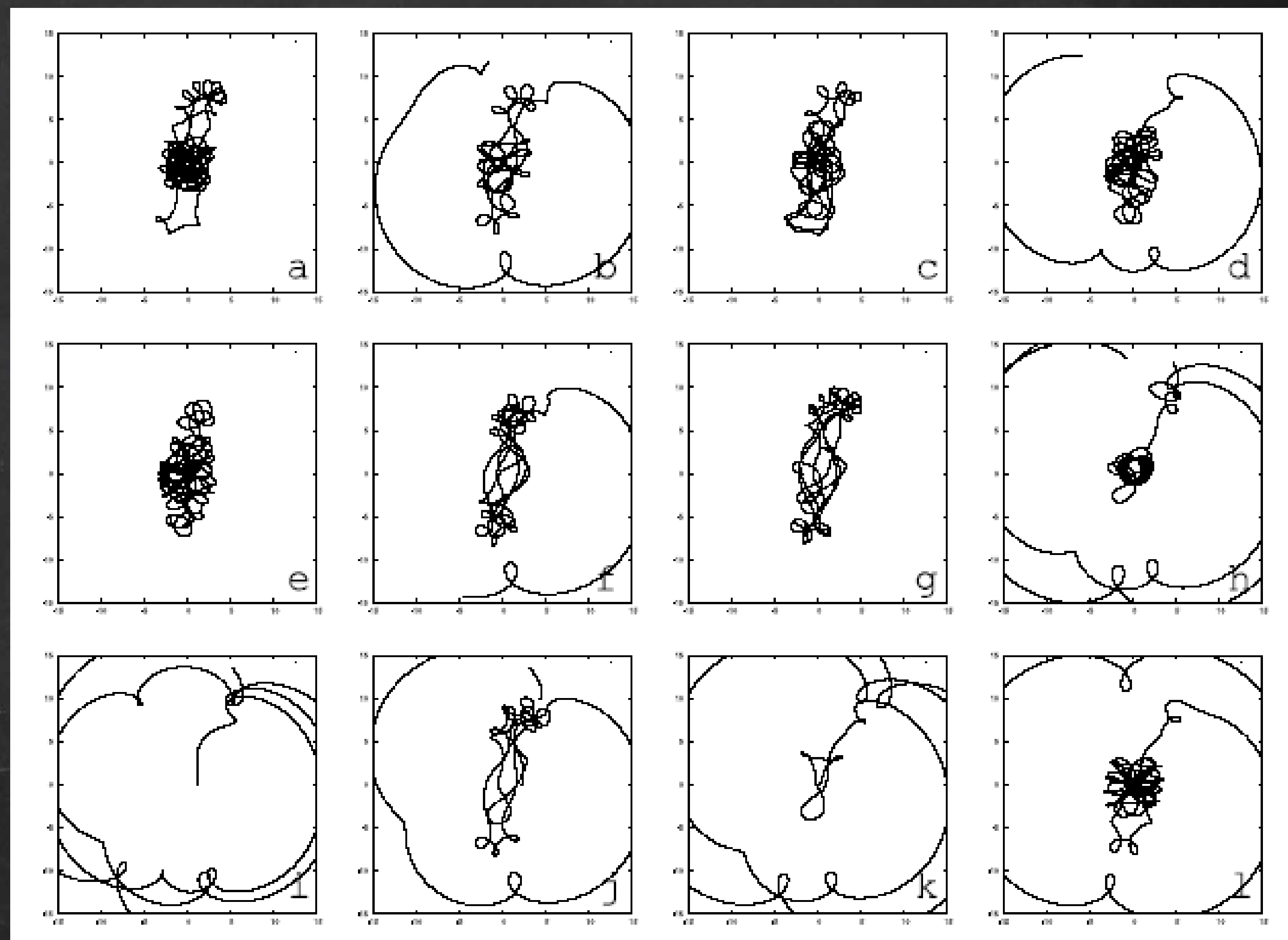
"Chaotic" spirals:

Voglis+, Athanassoula+, Romero-Gomez+, etc. 2006 → ….

In the presence of bars new kinds of stellar flows exist...







What about gas?

- An alternative viewpoint which does not consider the spiral arms as density waves has also been discussed in a series of papers by Romero-Gómez et al. (2006, 2007); Athanassoula et al. (2009a,b, 2010). Their theory, which is more directly applicable to stars than to gas, is based on the observation that orbits in the vicinity of unstable Lagrangian points can be trapped into invariant manifolds whose morphology can reproduce the spiral arms.

Sormani, Binney, Magorrian, 2015, MNRAS

What about gas?

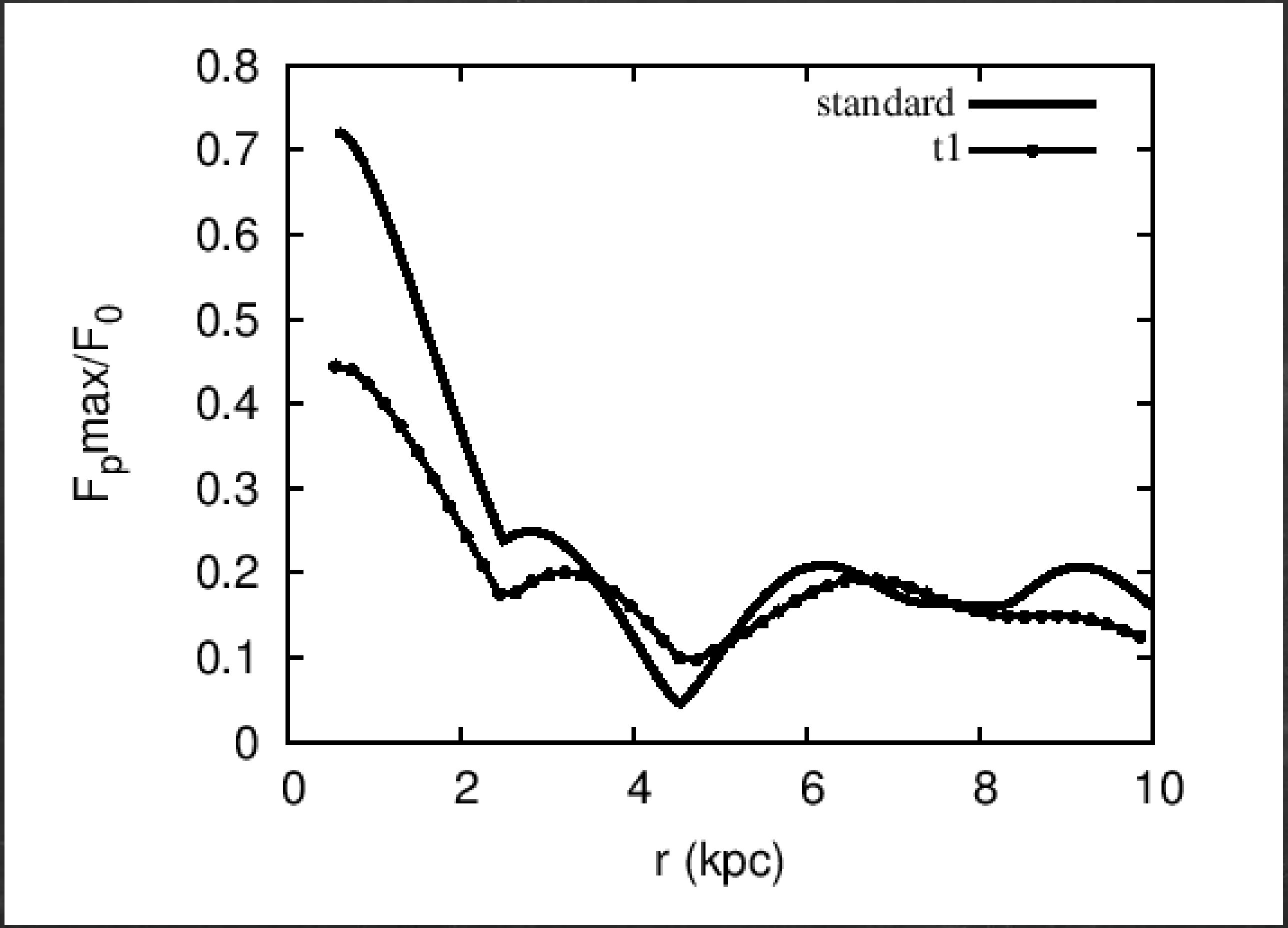
- Flows of gas in barred-spiral potentials
- Flow in the “chaotic spirals” region
- Comparison between stellar and gaseous flows
- Comparison with flows in non-barred potentials

2 THE GENERAL MODEL

In our study we follow stellar and gaseous responses in 2D barred-spiral potentials which can be written in polar coordinates (R, φ), in the general form:

$$\Phi(R, \varphi) = \Phi_0(R) + \sum_{k=2,4,6} \left[\Phi_{kc}(R)\cos(k\varphi) + \Phi_{ks}(R)\sin(k\varphi)\right]. \quad (1)$$

$\Phi_0(R)$ is the axisymmetric term, while the sum in the right side of equation (1) is the perturbing term $\Phi_p(R, \varphi)$ The components $\Phi_0(R)$, $\Phi_{kc}(R)$, and $\Phi_{ks}(R)$ in equation (1) are polynomials of the form $\sum_n a_n r^n$, $n = 0 \ldots 8$. The specific models studied in the present paper, as well as those in Tsigaridi & Patsis (2013) and Tsigaridi & Patsis (2015), use as basis a potential estimated for NGC 3359 (Boonyasait 2003; Patsis et al. 2009). The coefficients



standard
t1
$F_p max/F_0$
r (kpc)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
2
4
6
8
10

1.9 < R_c / R_b < 3

$$H \equiv \frac{1}{2}\left(\dot{x}^2 + \dot{y}^2\right) + \Phi(x, y) - \frac{1}{2}\Omega_p^2(x^2 + y^2) = E_J, \tag{2}$$

where (x, y) are the coordinates in the Cartesian frame of reference, rotating with angular velocity Ω_p. $\Phi(x, y)$ is the potential in Cartesian coordinates. E_J is the numerical value of the Jacobi constant. Hereafter, we will refer to it in the paper as "the energy". Dots denote time derivatives. The Ω_p values used are such as to secure $1.9 \lessapprox R_{L_{1,2}}/R_b \lessapprox 3$, where $R_{L_{1,2}}$ is the radius of the unstable Lagrangian points and R_b is the length of the response bar. These are the assumptions under which we investigate the dynamical mechanisms acting for building a barred-spiral morphology.

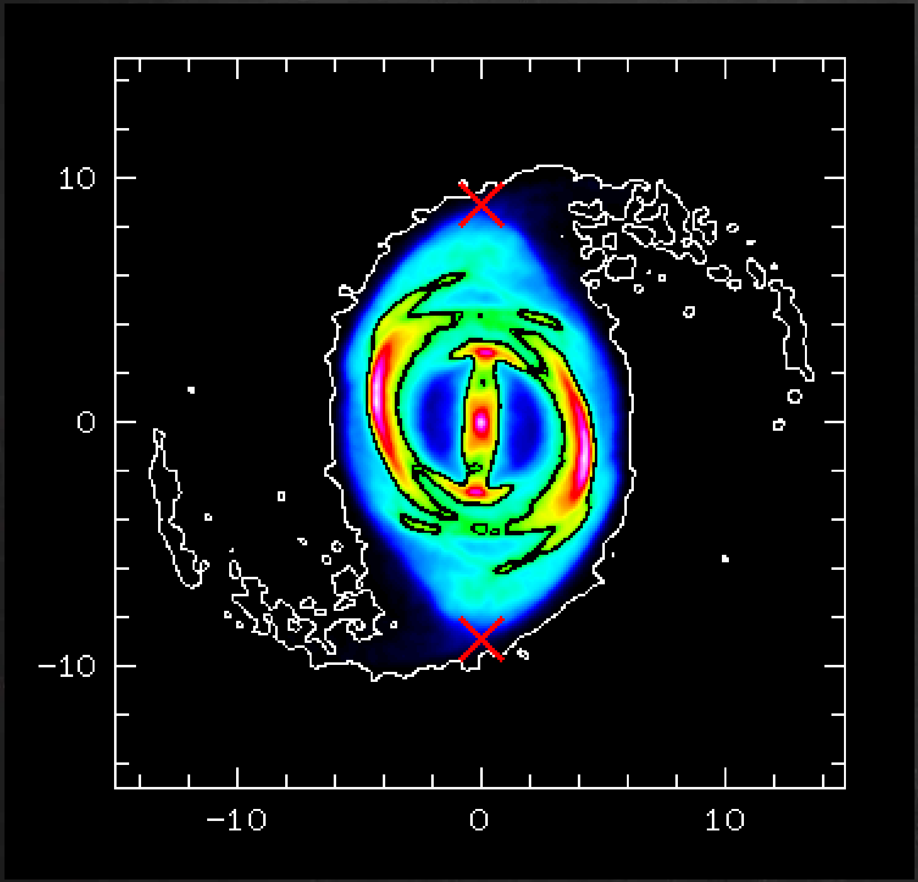
SPH

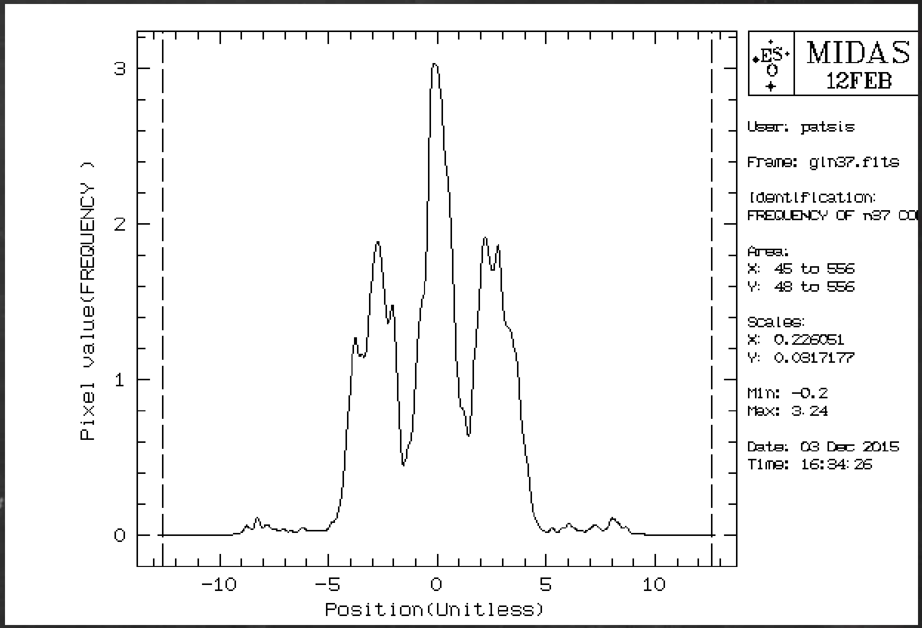
For the gaseous models, we follow the response of an an infinitesimally thin gaseous disc when we impose the gravitational potential described in section 2. The hydrodynamical response models are obtained with the use of the SPH scheme (Gingold & Monaghan 1977; Lucy 1977). The gas is assumed to be isothermal with a constant sound speed $c_s = 10$ km s^{-1}. Self-gravity of the gas, as well as star formation and magnetic fields are not taken into account. The code we used is a modified version of the one in Patsis & Athanassoula (2000). Test runs by means of the codes used in Patsis et al. (1994), Bate et al (1995) and Kitsionas & Whitworth (2002) have given essentially identical results.

In the majority of the simulations, typically 3×10^4 SPH particles are initially set in circular motion in the axisymmetric part of the potential (Φ_0). The non-axisymmetric part is introduced gradually and linearly within two pattern rotations to avoid strong transients. Then the response was followed until a time equal to 4-10 pattern rotations of the system, depending on the goals we have

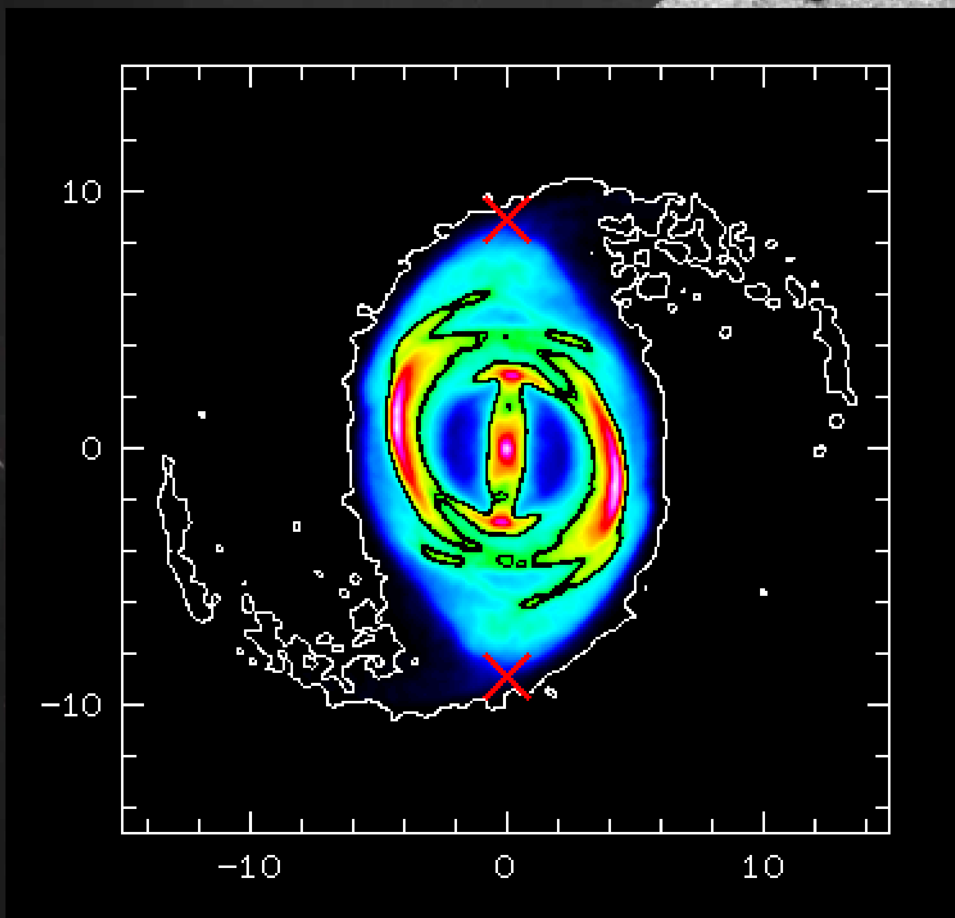
phase space, as will be described in section 4. For the artificial viscosity parameters of the SPH calculations we used the values $(\alpha, \beta) = (1, 2)$.

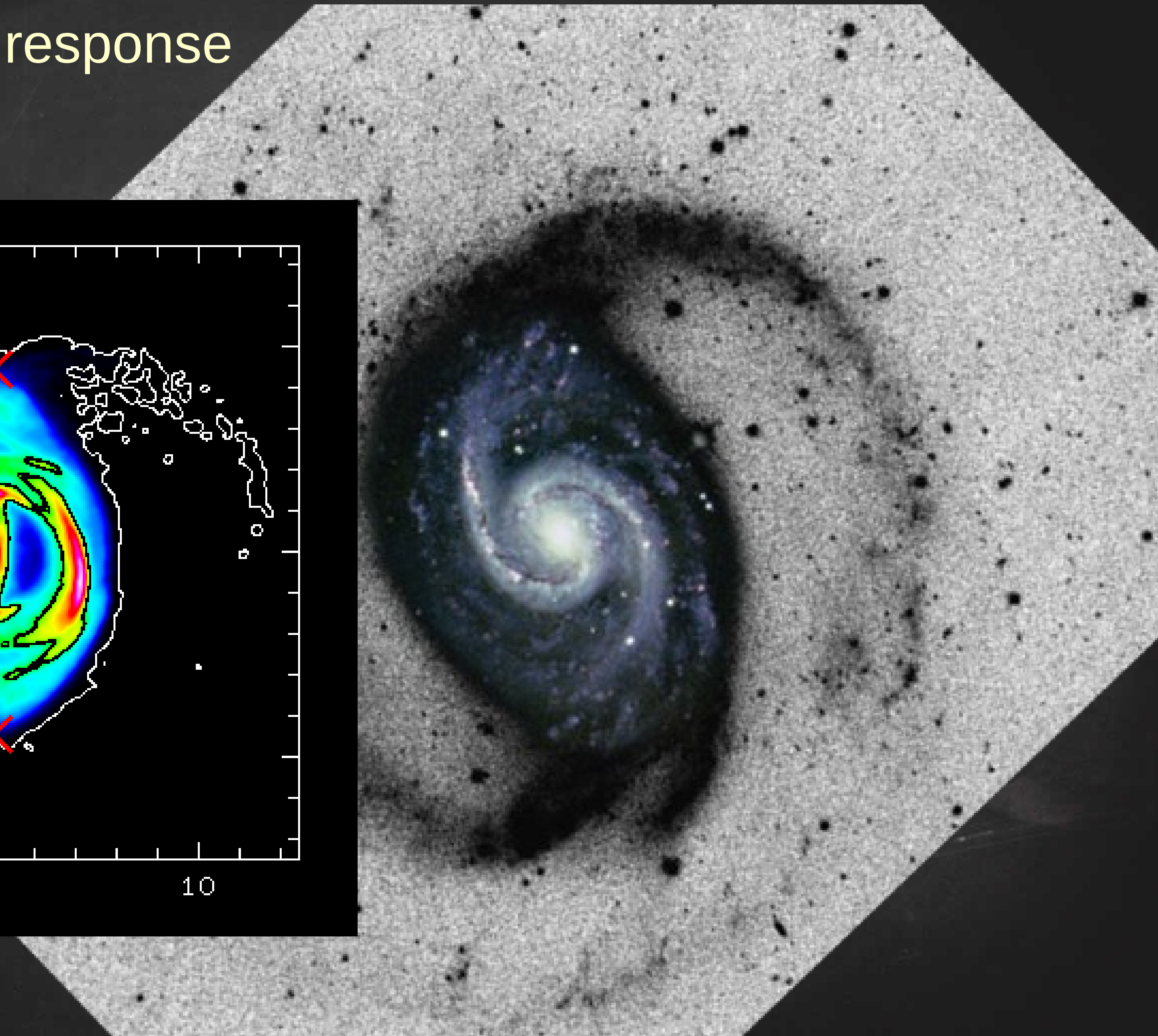
Fiducial **SLOW** case. Stellar response Ωp=15 km/s/kpc Rc/Rb=2.9



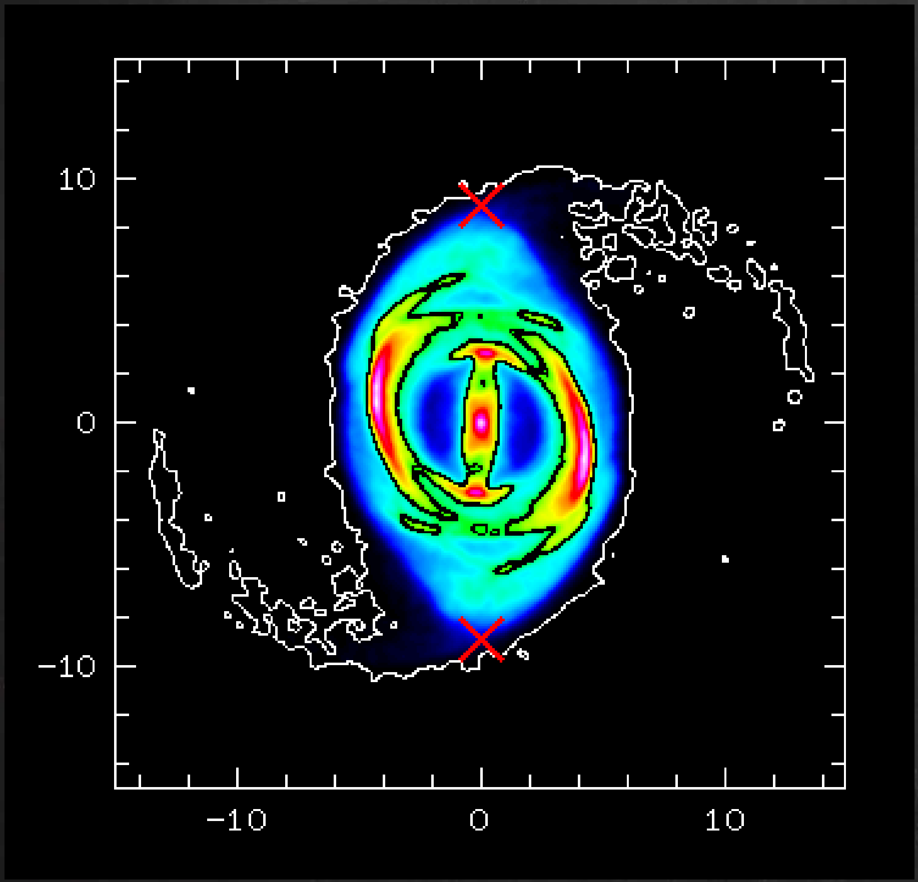


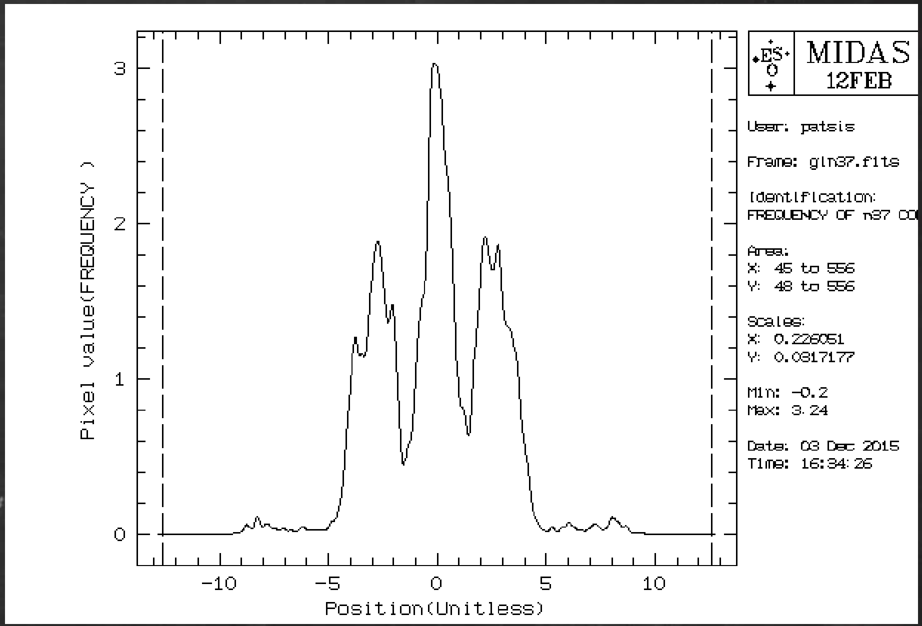
NGC1566-type response



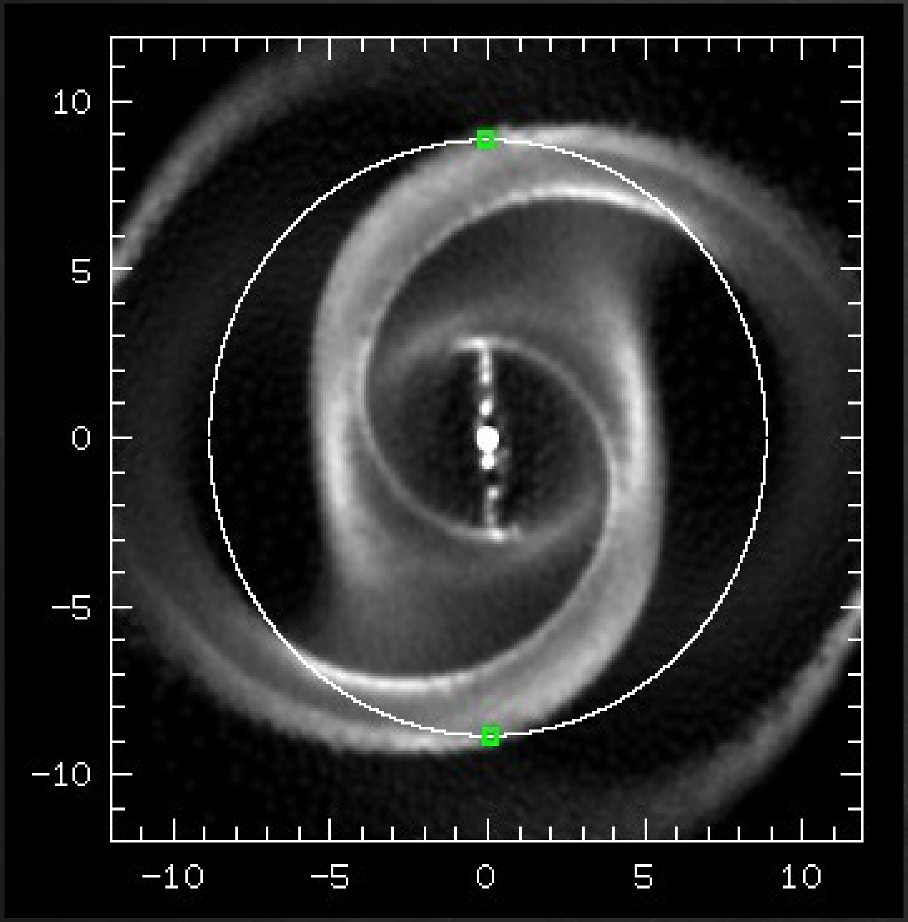


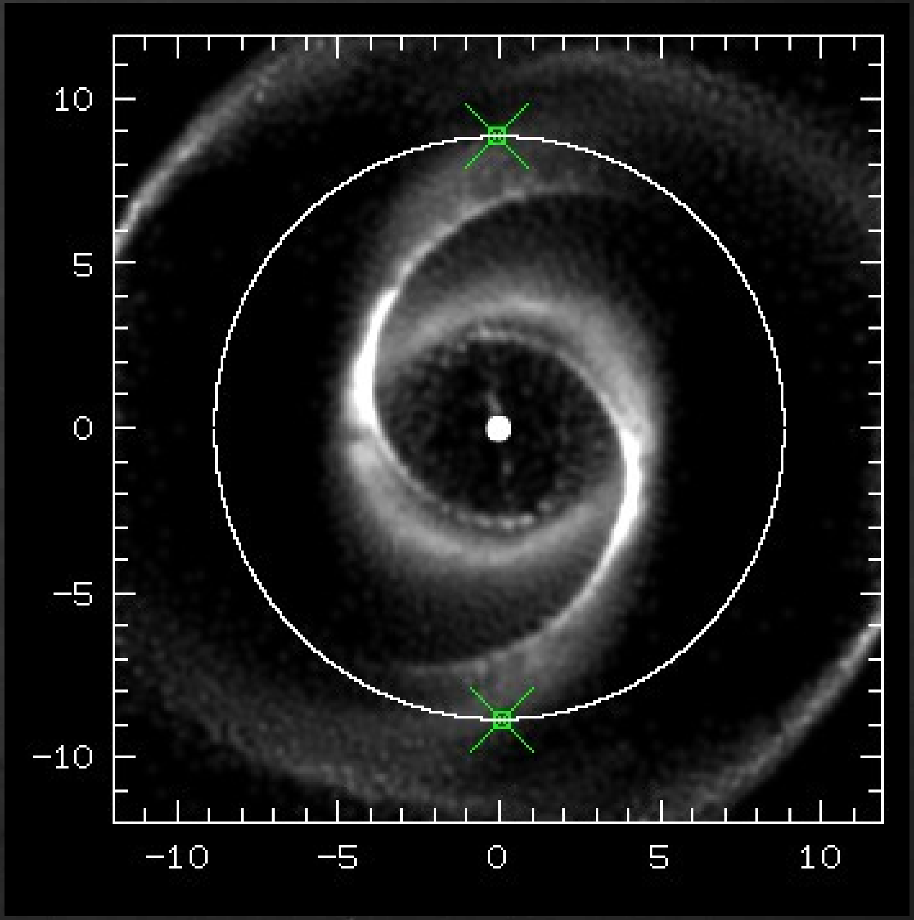
Fiducial case. Stellar response Ωp=15 km/s/kpc Rc/Rb=2.9

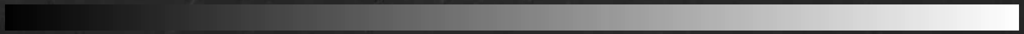




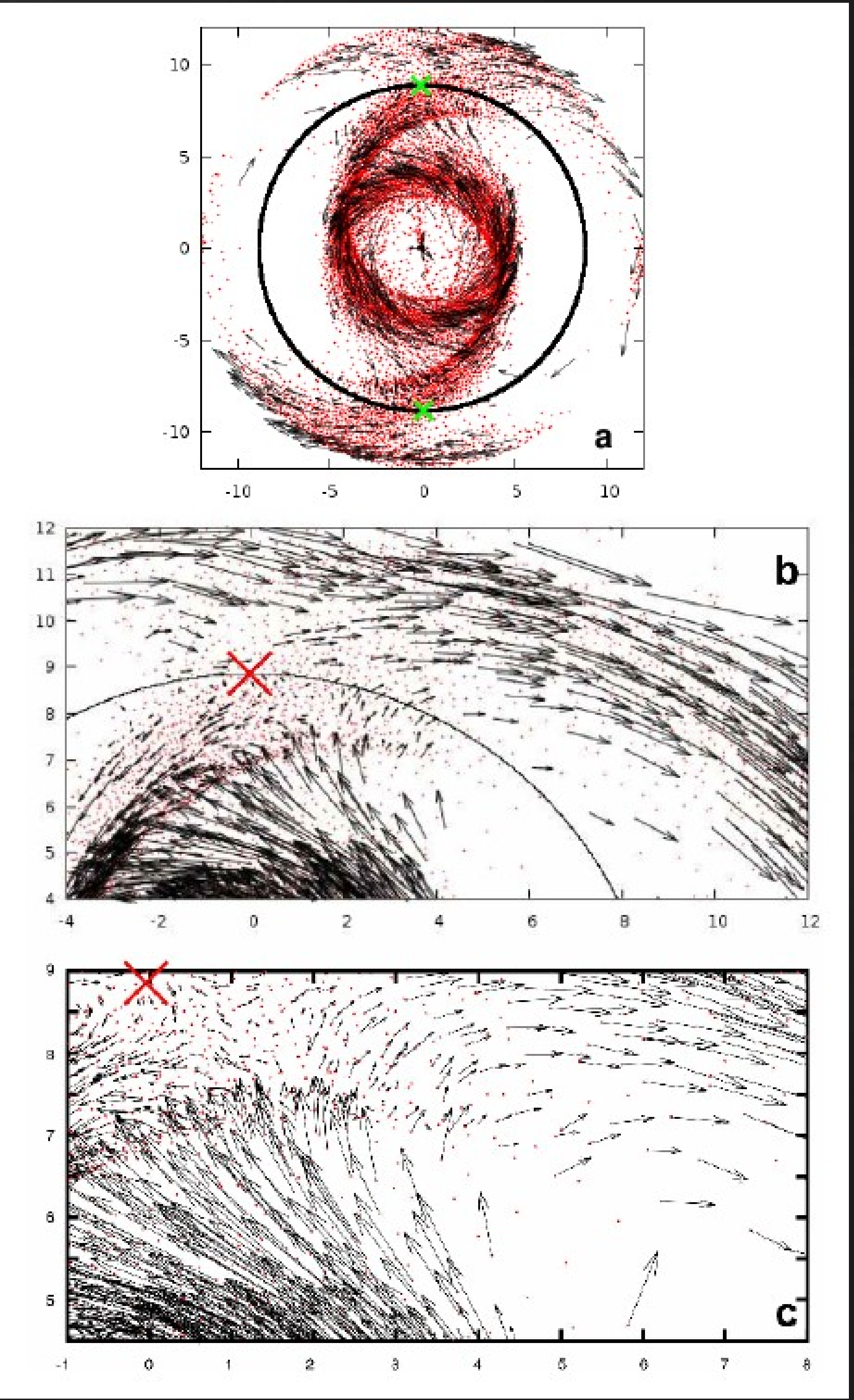
Fiducial case. Gaseous response Ωp=15 km/s/kpc Rc/Rb=2.9







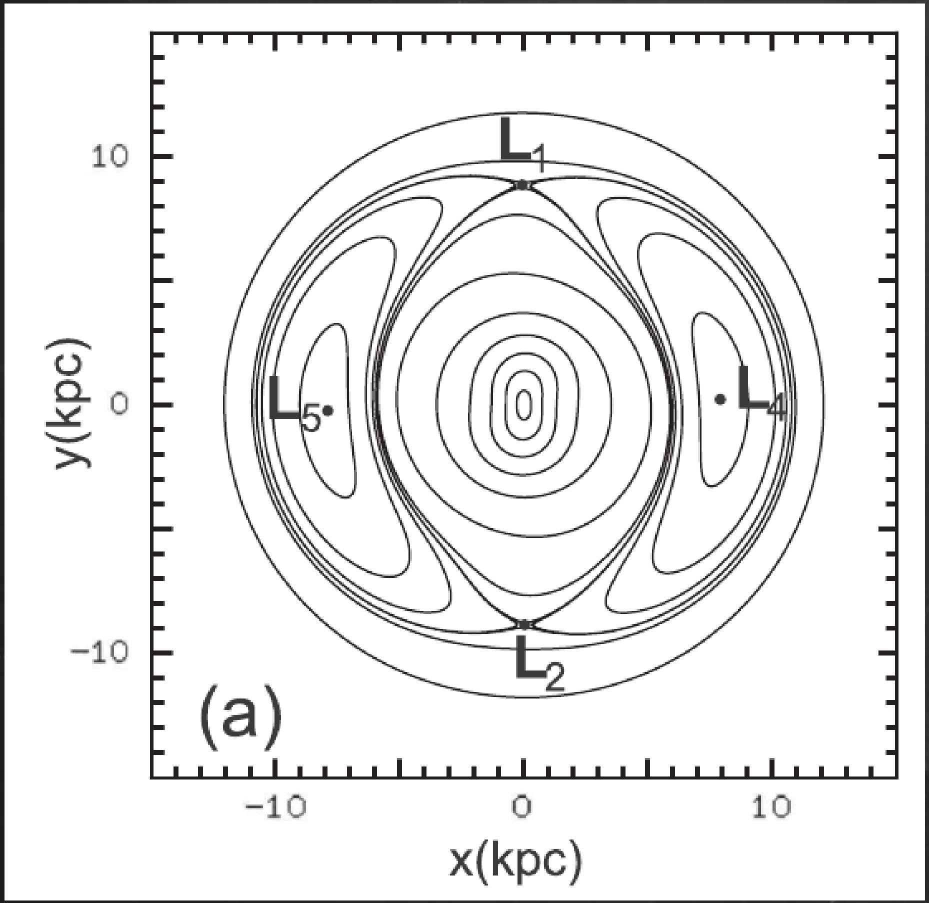
Fiducial case: Velocity Fields

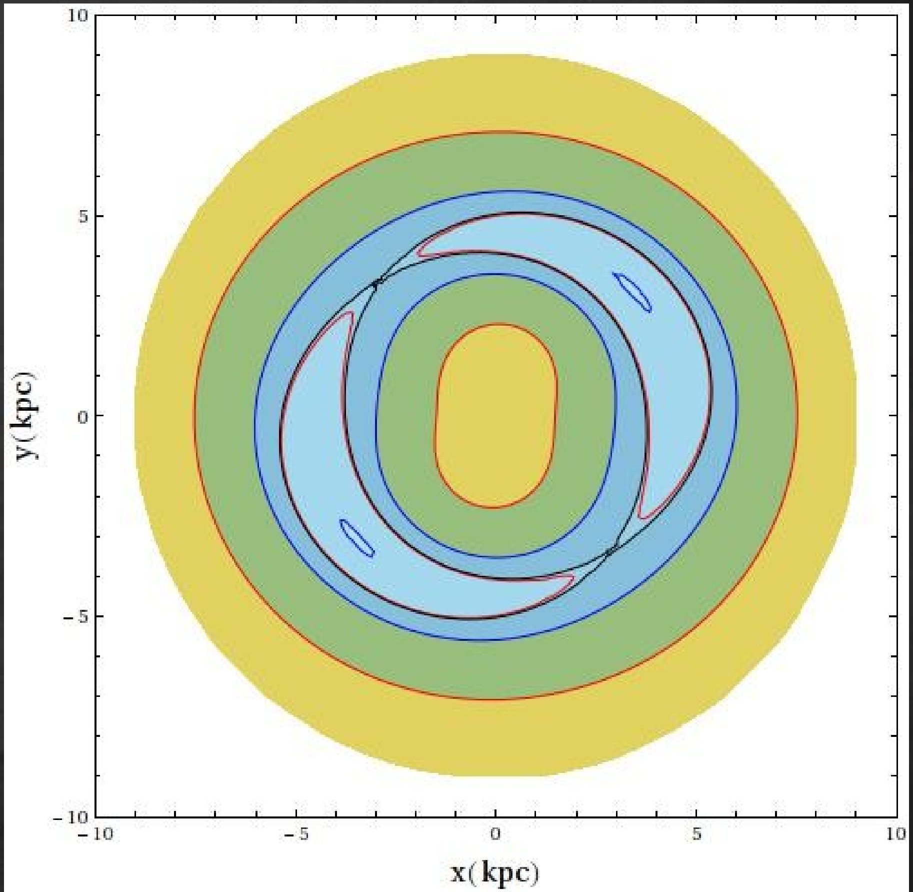


July 12, 2017

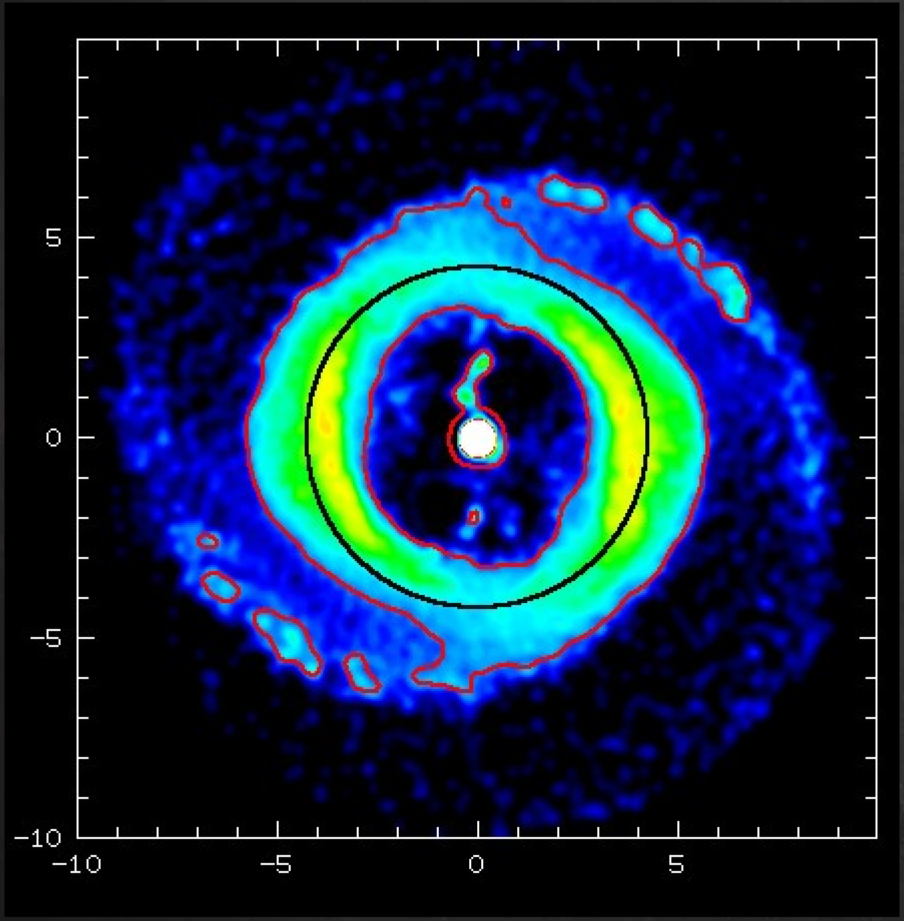
Rc/Rb=3.0

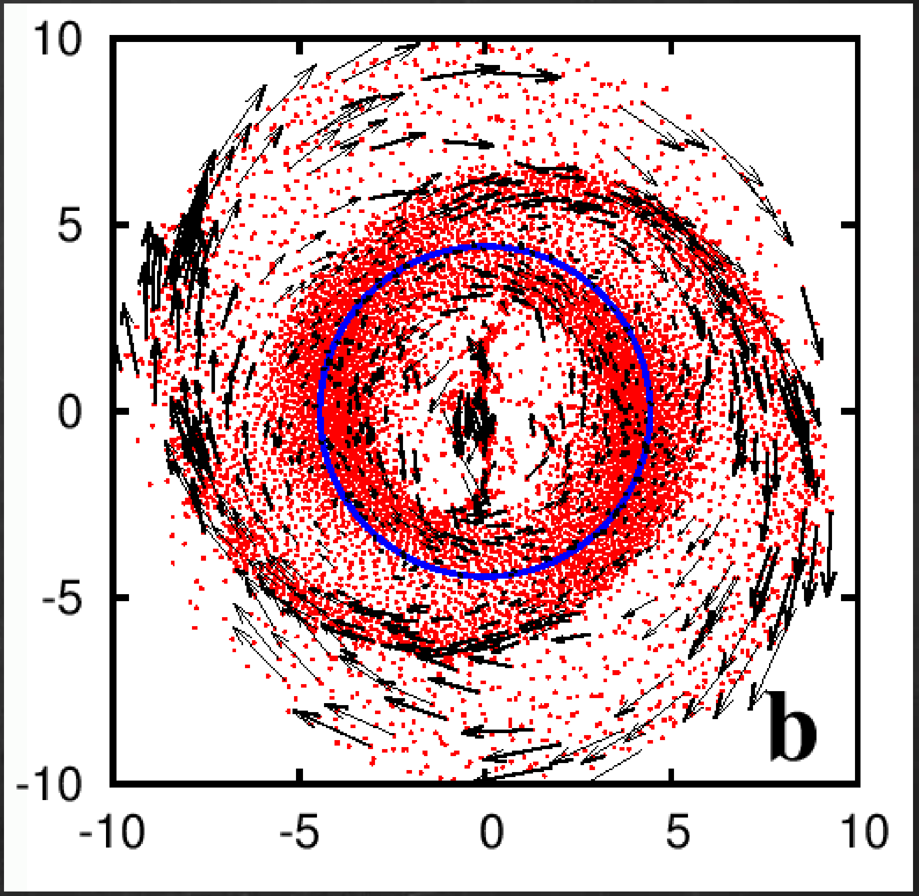
Rc/Rb=1.9



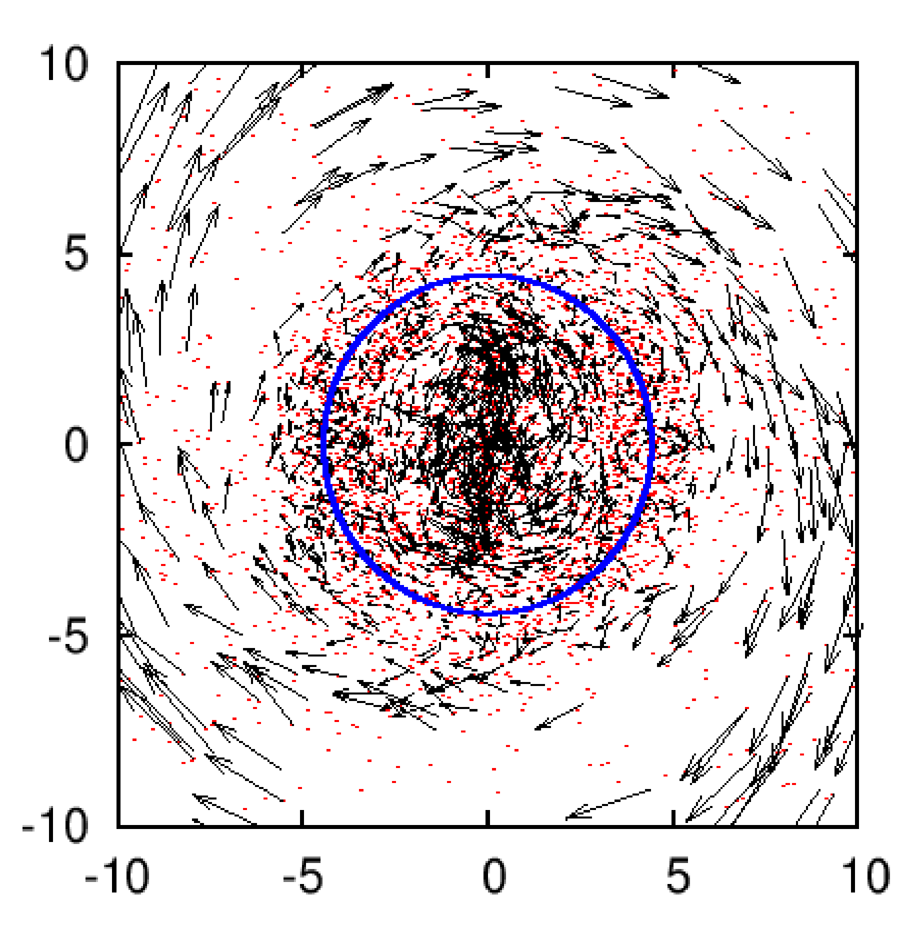


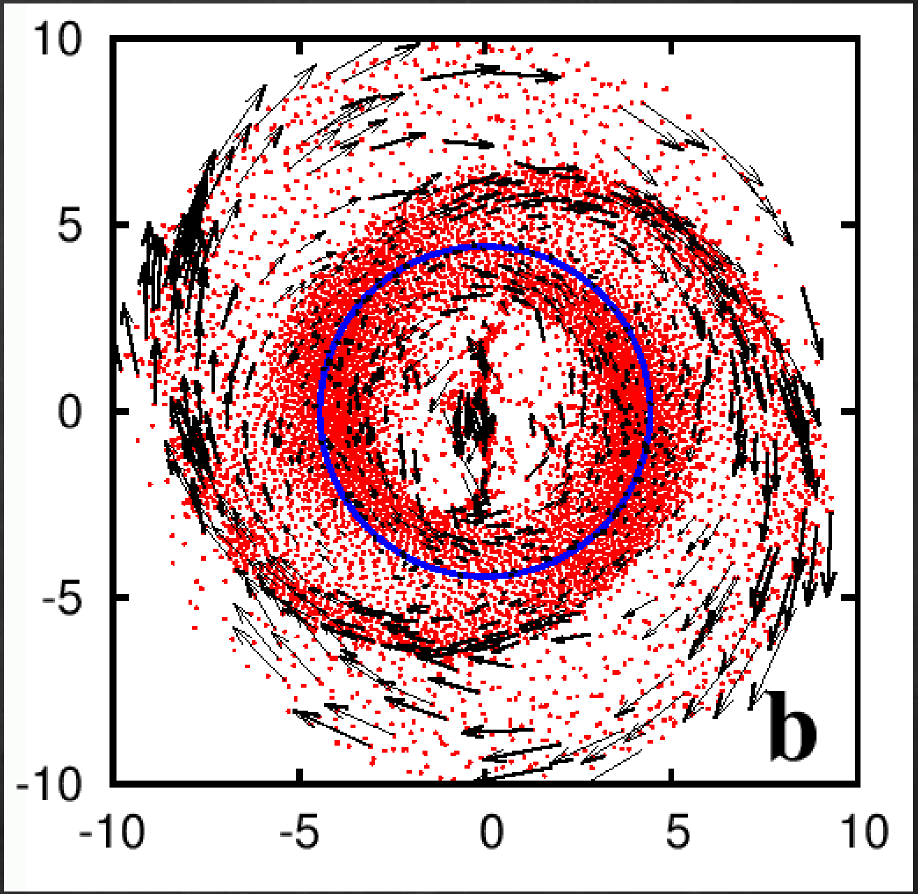
Gas: Rc/Rb=1.9



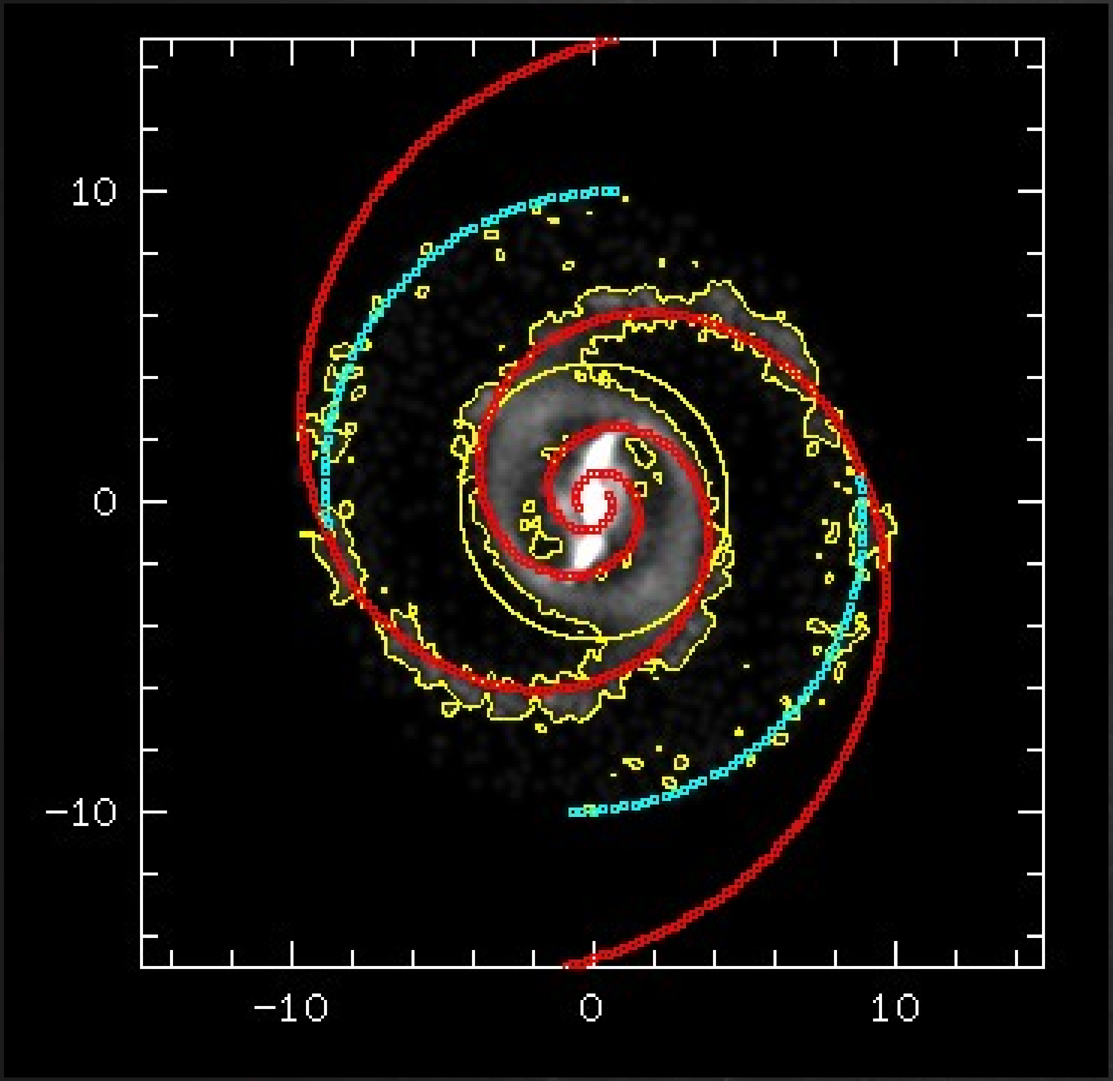


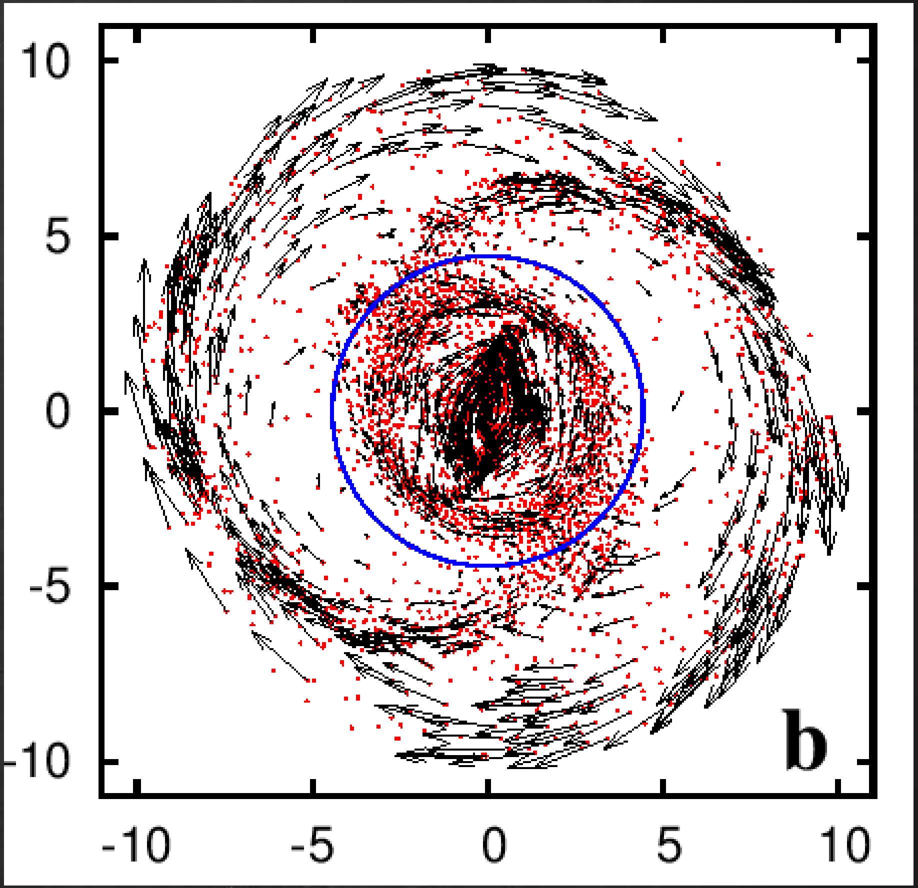
Stars vs Gas. Rc/Rb=1.9



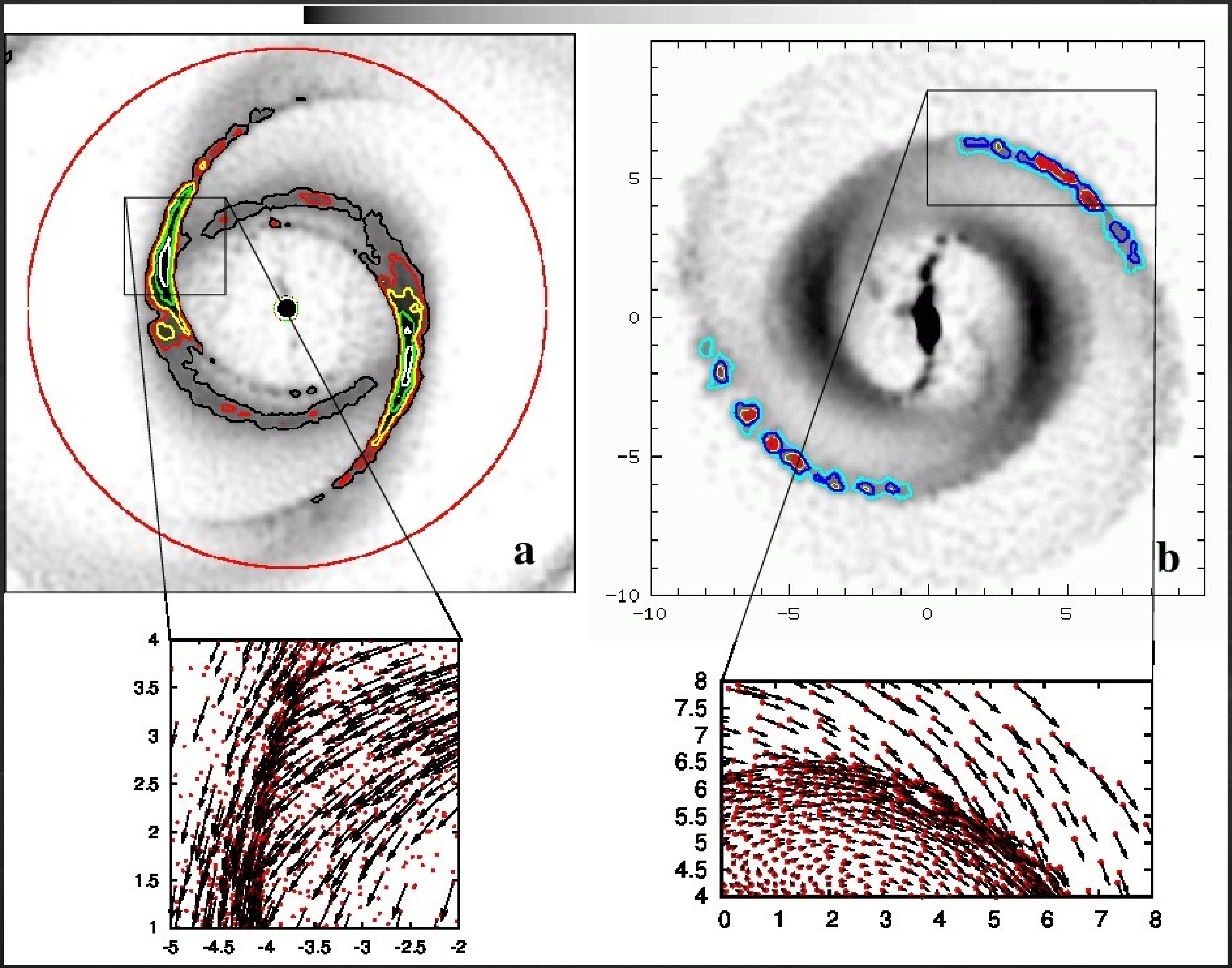


t1





Clumps


a
b
5
0
−5
−10
−10
−5
0
5
4
3.5
3
2.5
2
1.5
1
-5
-4.5
-4
-3.5
-3
-2.5
-2
8
7.5
7
6.5
6
5.5
5
4.5
4
0
1
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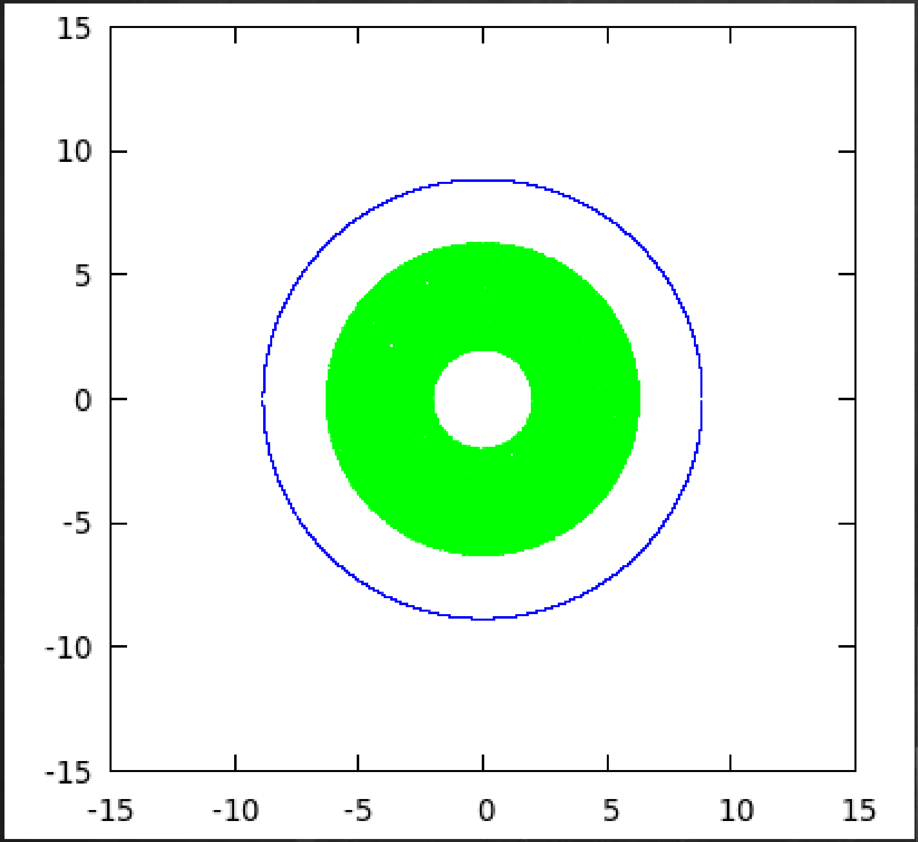
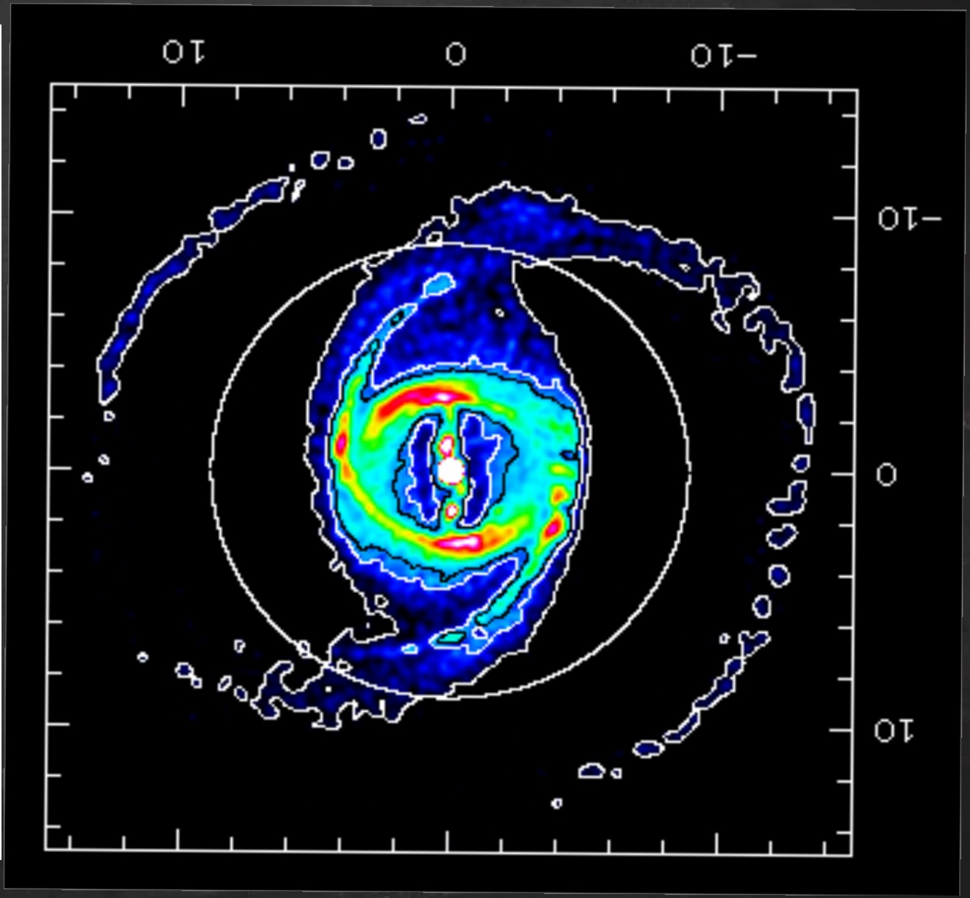
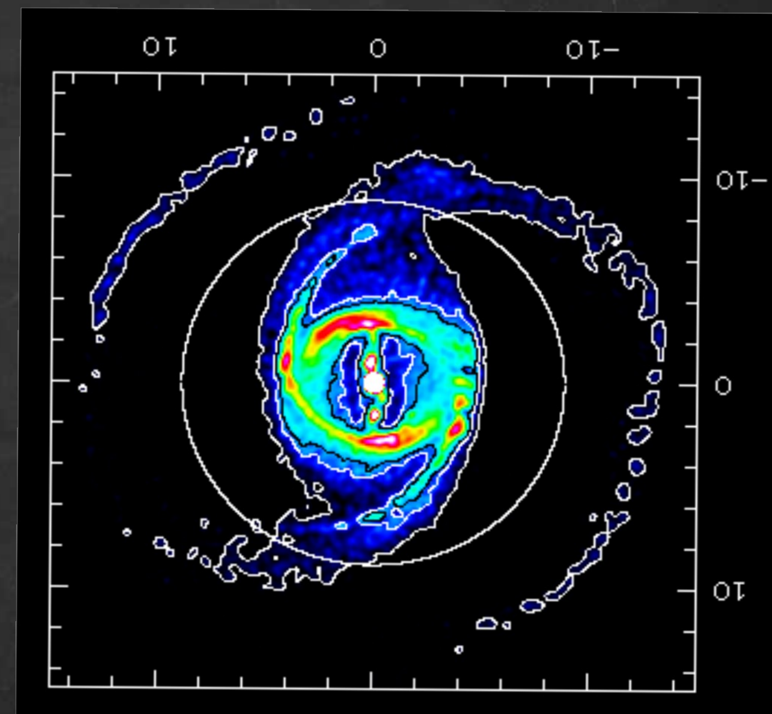
4
5
6
7
8


15
10
5
0
-5
-10
-15
-15
-10
-5
0
5
10
15




10
0
−10
−10
0
10

CONCLUSIONS

- The “NGC-1566” type of morphology is encountered under the simple assumption that we have a single low pattern speed in the model. Regular flows shape the inner spirals, while the outer spirals are supported by chaotic orbits and we have flows along the arms.
- Clumps are formed in both sets of spiral arms, inside and outside corotation, by means of two different dynamical mechanisms.

CONCLUSIONS

- There is in general a discontinuilty between the inner and the outer. The discontinuity is emphasized by the presence of a weak bar or oval distortion surrounding the inner barred-spiral structure.
- The pitch angle of the inner regular spiral is more sensitive to the variation of the pattern speed than the pitch angle of the outer chaotic spirals.