Modeling the morphology of disk galaxies by means of the orbital theory

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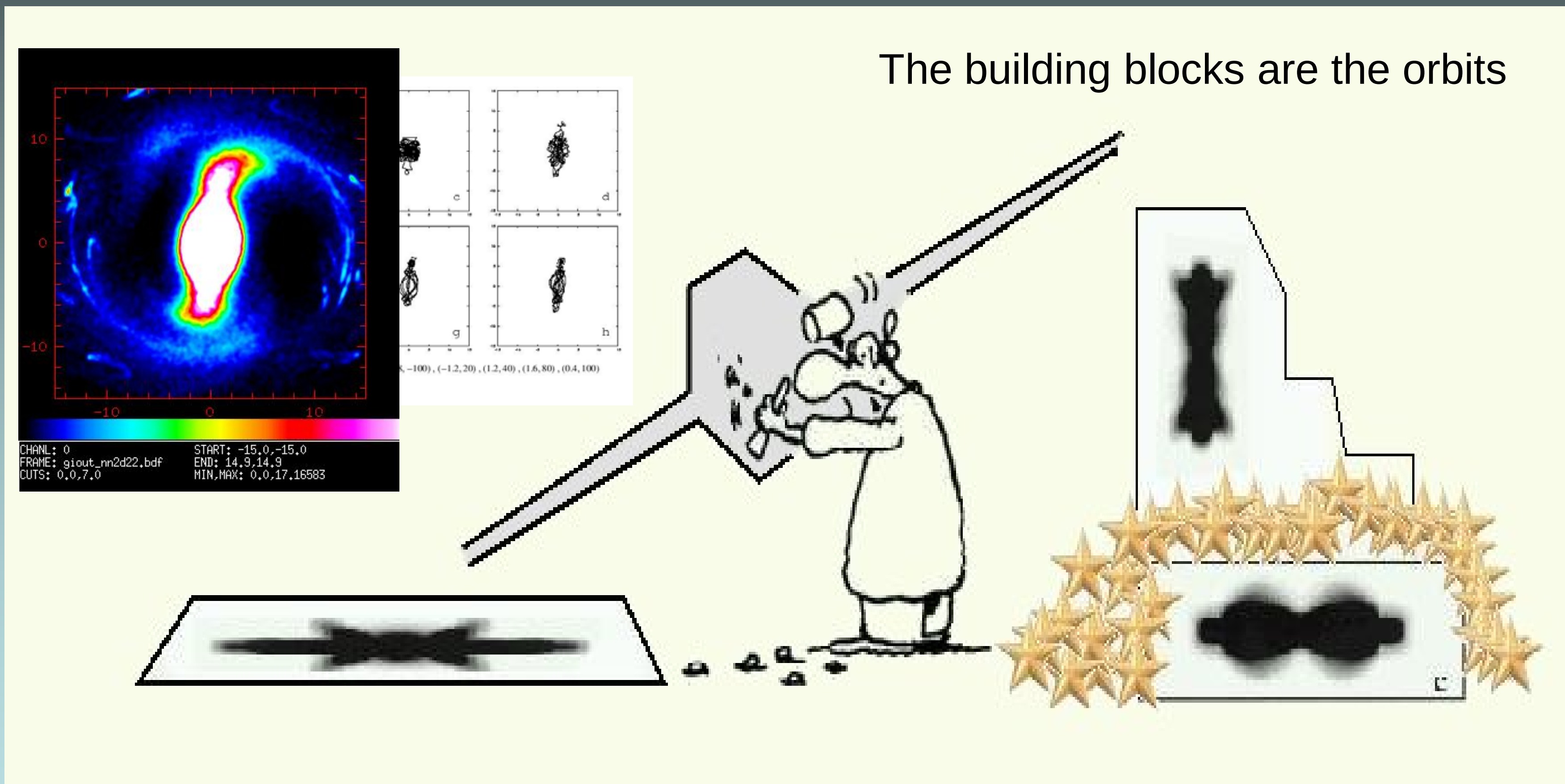
“Modeling is neither science nor mathematics; it is the craft that builds bridges between the two.”

F. Morrison, “The art of modeling dynamic systems” (1991)



(…vaguely speaking)

- A model is an object you compare with observations.

  For a galaxy you compare its photometry and kinematics with observational data.
- If you succeed in a good reproduction of the basic dynamical features then you *may have* a good insight of the dynamics of the galaxy.

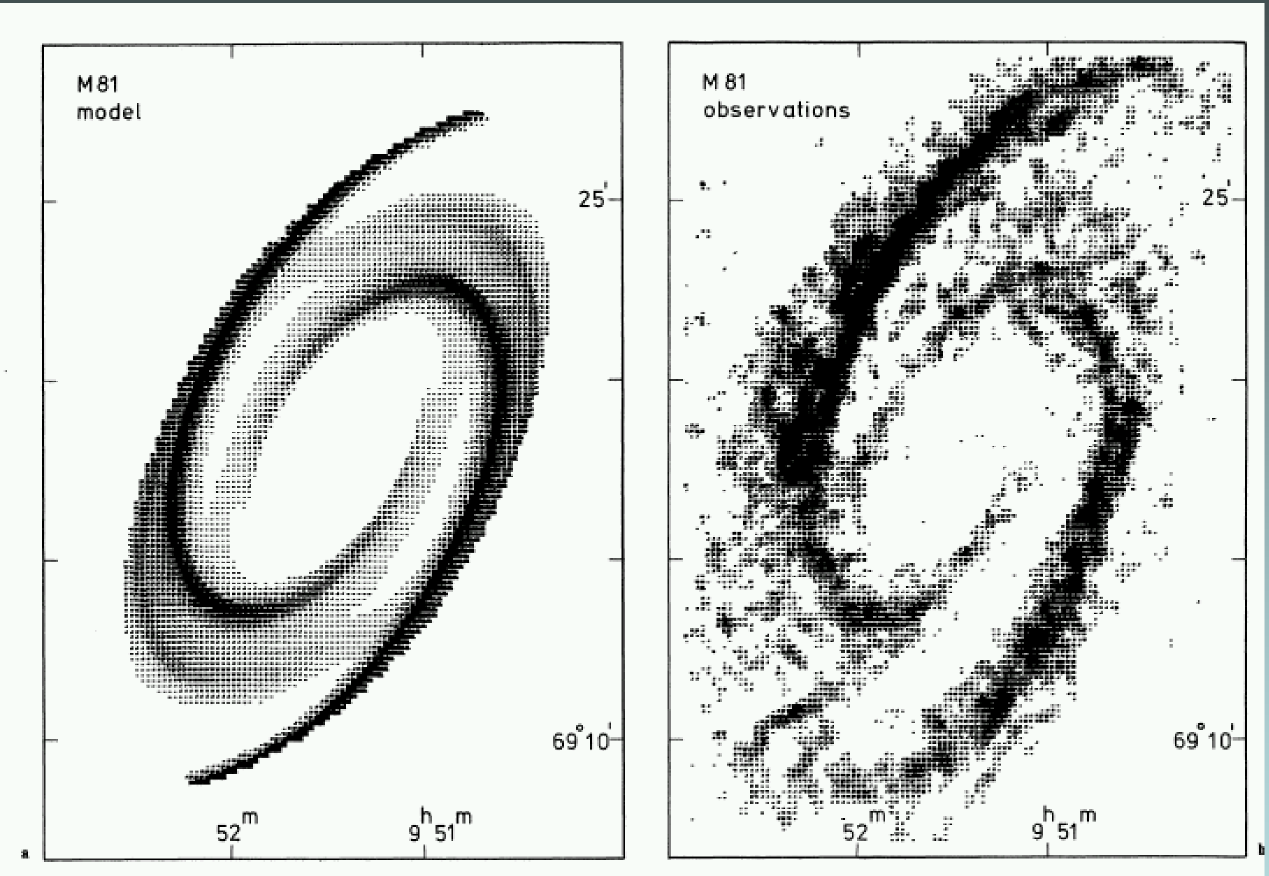
It is not easy to find a unique solution.

- Galaxies (especially disks) are *complicated* systems, characterized by many interrelated parameters (stellar, gas and DM dynamics, ☼-formation etc.).
- Observations (although continuously progressing) do not offer all needed information (e.g. spiral kinematics in the near-infrared).

However,…

- …we can foresee tendencies, check basic hypotheses and exclude possible solutions.

HI dustribution (Visser 1980, AA 88, 149)



Streamlines

H. C. D. Visser: The Dynamics of the Spiral Galaxy M 81. II 161

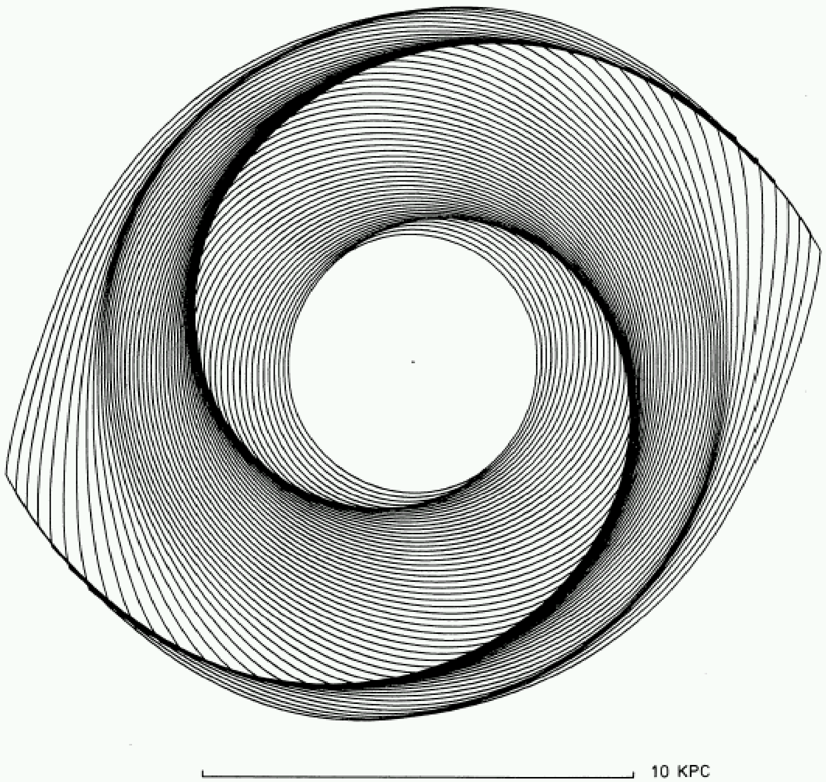
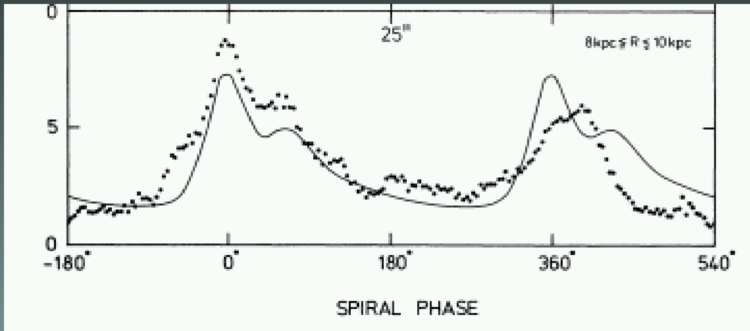


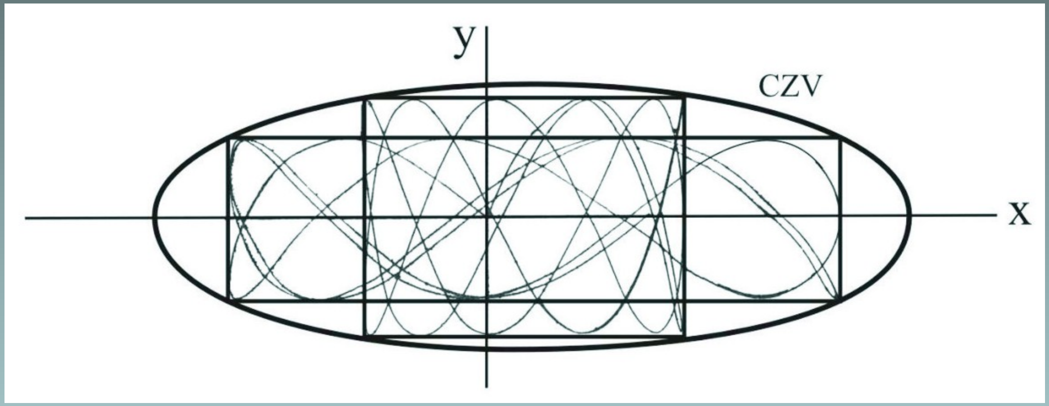
Fig. 2. Streamlines of the final model with an increment of 0.1 kpc in mean radial distance, seen face-on. Note that the number of streamlines crossing a unit area is a measure of the (unsmoothed) perturbed surface density of the gas. In the outer regions the density enhancement due to the growing importance of the second harmonic resonance can be seen. The line showing the length scale in the plane of the galaxy is in the major-axis direction



precessing ellipses flow to the end of the spiral structure.

Orbital theory

- An almost 60 years old tool …



(Contopoulos 1958, Stockholm **Ann. 20, no5)**

- … building models for galaxies since the mid 80's.

Galaxies in the Hamiltonian approximation

Equations of motion are derived from the Hamiltonian

$$H \equiv \frac{1}{2}\left(\dot{x}^2 + \dot{y}^2\right) + \Phi(x,y) - \frac{1}{2}\Omega_s^2(x^2+y^2) = E_J \qquad (4)$$

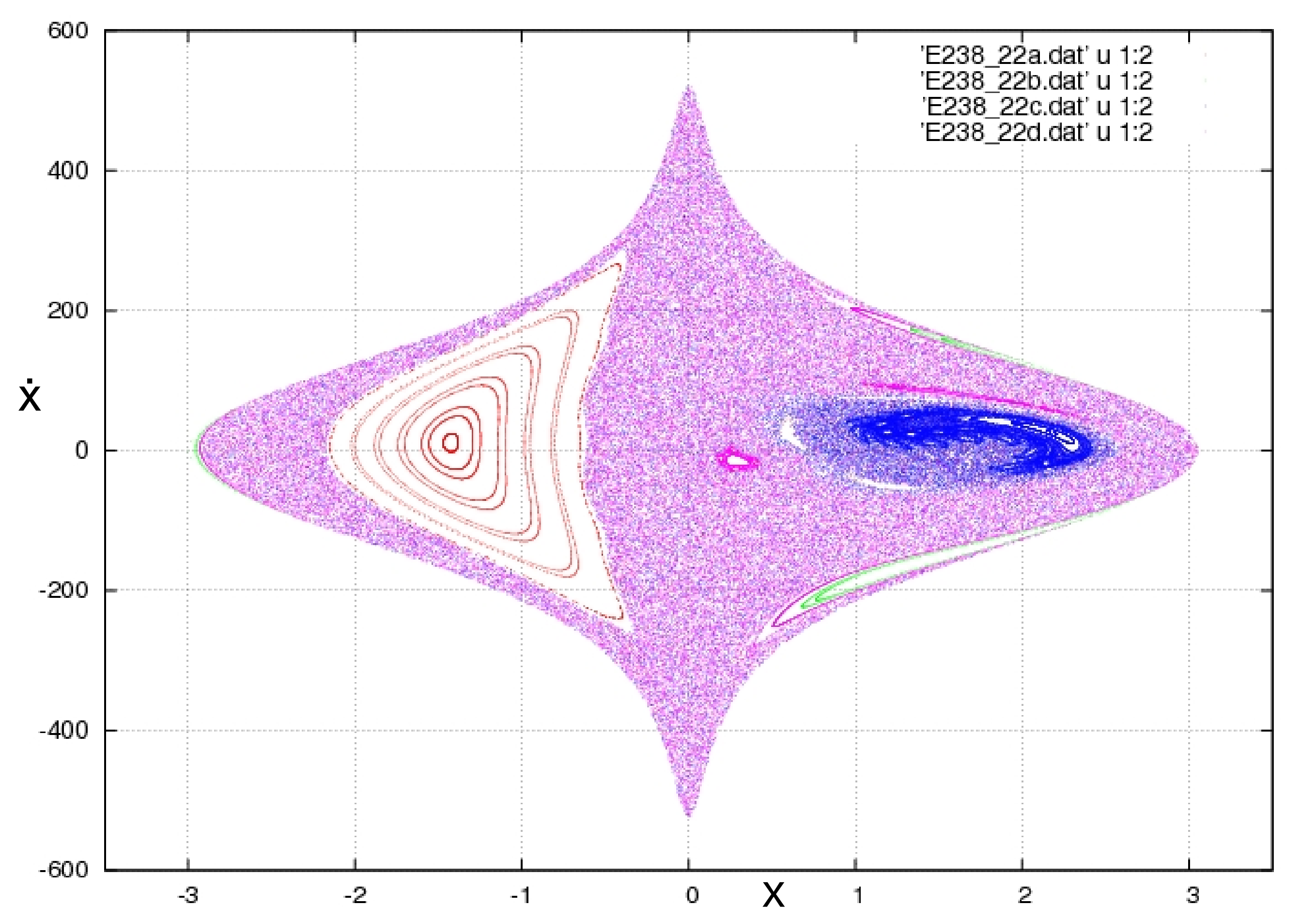
where (x,y) are the coordinates in a Cartesian frame of reference corotating with the spiral with angular velocity Ω_s. $\Phi(x,y)$ is the potential in Cartesian coordinates, E_J is the numerical value of the Jacobian integral and dots denote time derivatives.

$$H(x,y,z,\dot{x},\dot{y},\dot{z}) = \frac{1}{2}(\dot{x}^2+\dot{y}^2+\dot{z}^2) + \Phi(x,y,z) - \frac{1}{2}\Omega_b^2(x^2+y^2)$$

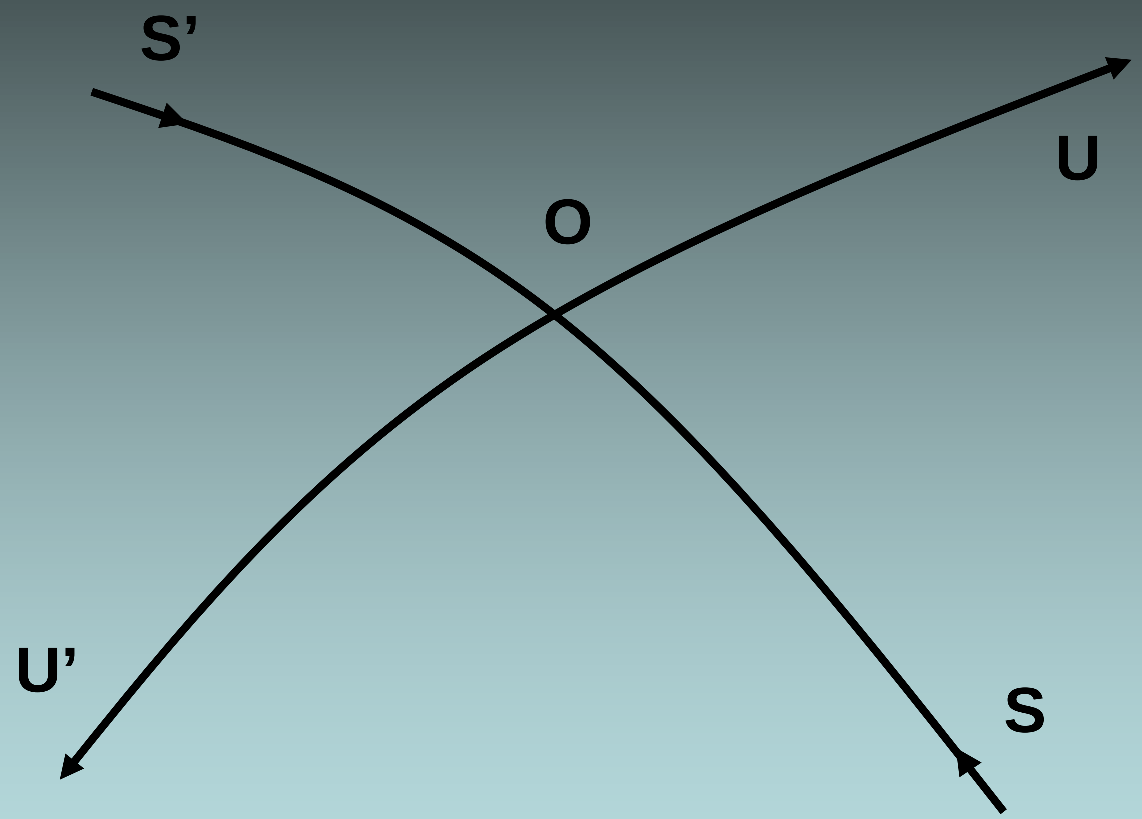
Potentials

- $\Phi(x,y,z) = \Phi_0 + \Phi_p$
- Reflect either general properties
- or estimated directly from near-infrared observations

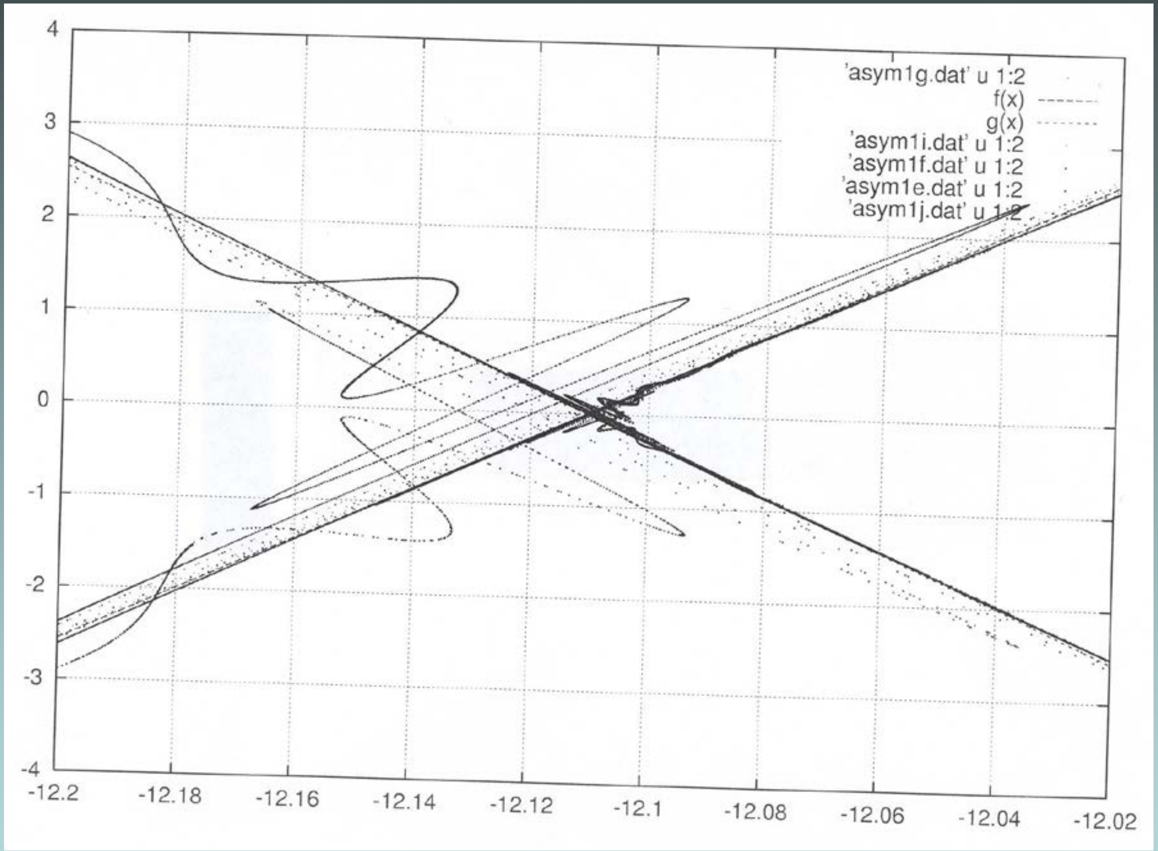
Order and Chaos in general coexist in the Hamiltonian systems – a 2D example
One has to select "energies" and orbits



Unstable points



“There is order in Chaos: Randomness has an underlying geometric form.”
J.P. Crutchfield et al. (1986), SciAm 254, No 12, 46



Using stability of periodic orbits

"building galaxies" by trapping a large number of non-periodic orbits

A 3D Model

$$\Phi = \Phi_D + \Phi_S + \Phi_B$$

component of the potential is a triaxial Ferrers bar, whose density $\rho(x)$ is:

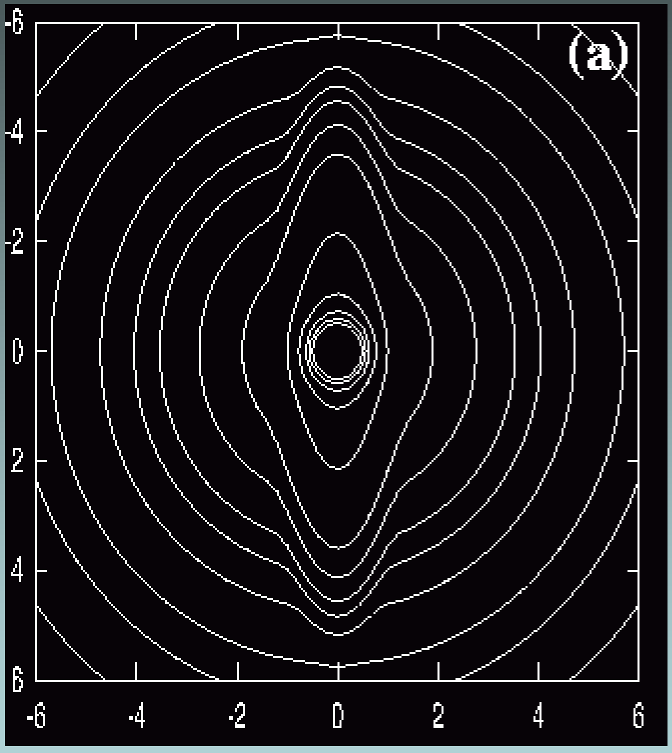
$$\rho(x) = \begin{cases} \frac{105 M_B}{32\pi abc}(1-m^2)^2 & \text{for} \quad m \le 1 \\ 0 & \text{for} \quad m > 1 \end{cases}, \tag{3}$$

where

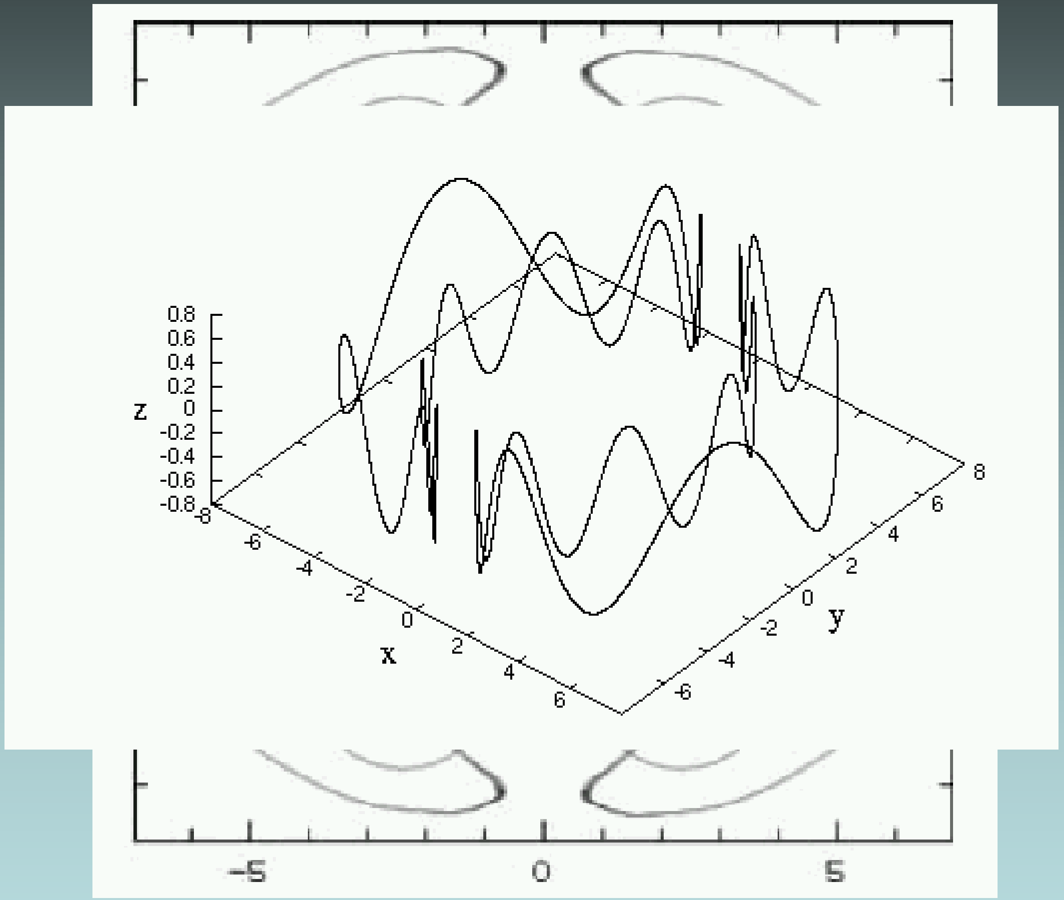
$$m^2 = \frac{y^2}{a^2} + \frac{x^2}{b^2} + \frac{z^2}{c^2}, \quad a > b > c, \tag{4}$$

a, b, c are the semi-axes and M_B is the mass of the bar component. For the Miyamoto disk the values A=3 and B=1 have been used, and for the axes of the Ferrers bar the values a:b:c = 6:1.5:0.6. The masses of the three components satisfy $G(M_D + M_S + M_B) = 1$. The length unit is taken as 1 kpc, the time unit as 1 Myr and the mass unit as $2 \times 10^{11} M_\odot$. Different values of the pattern speed, of the strength of the bar and of the parameters of the central bulge of the galactic model have been considered. A short description of the examined cases is given in Table 1. I will confine myself here to a brief outline of the main

isodensities



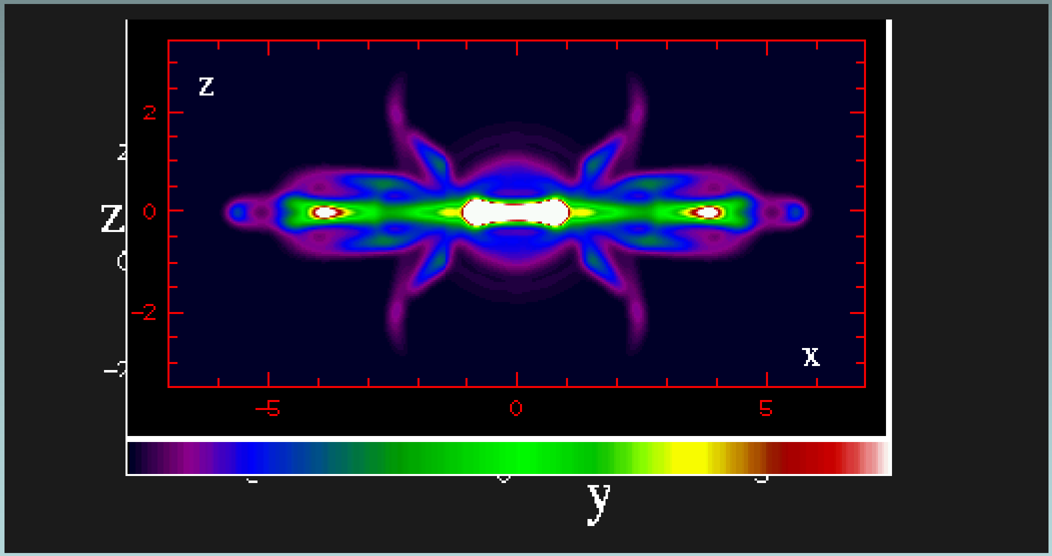
Periodic orbits and Resonances



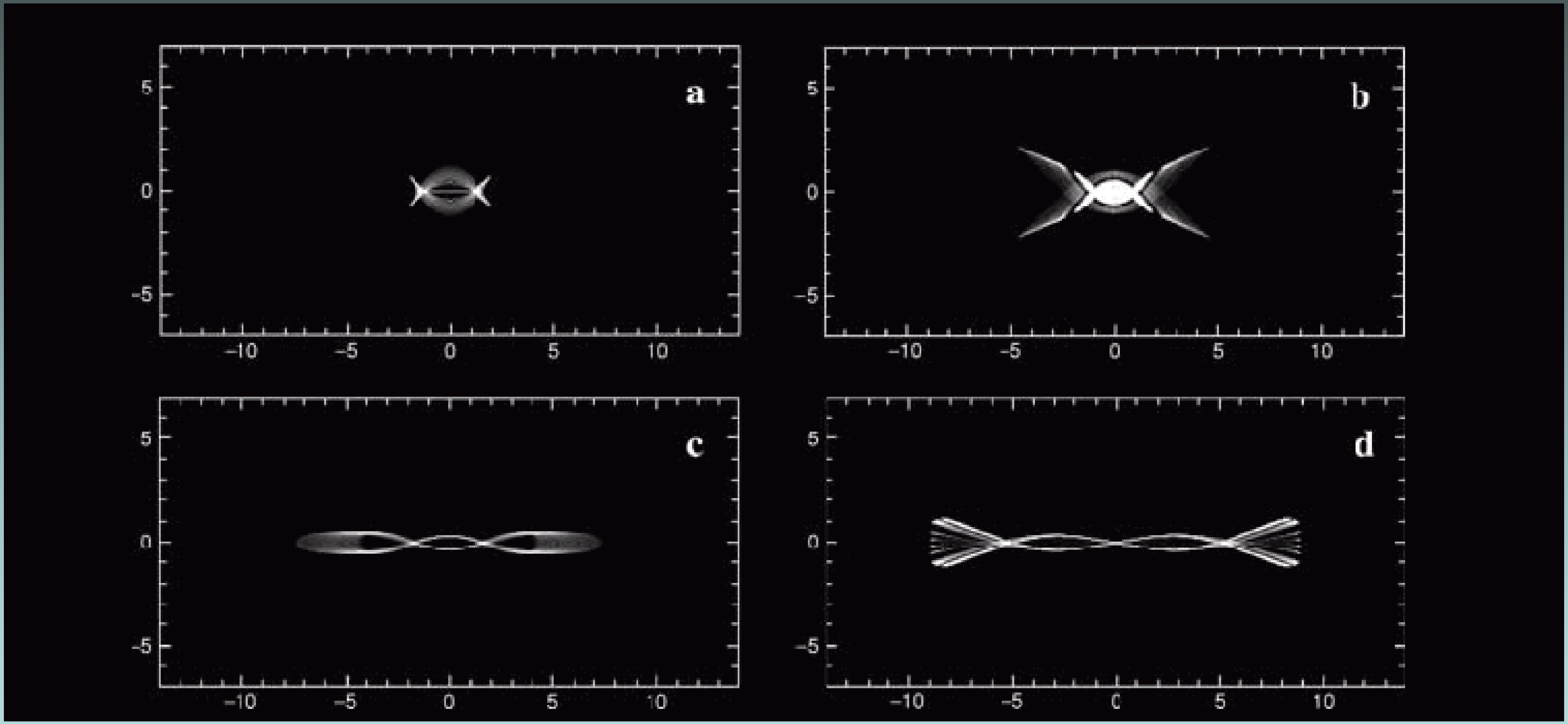
The relation between orbital shapes and morphological features

weighted profiles

(orbits from the stable parts of the families)

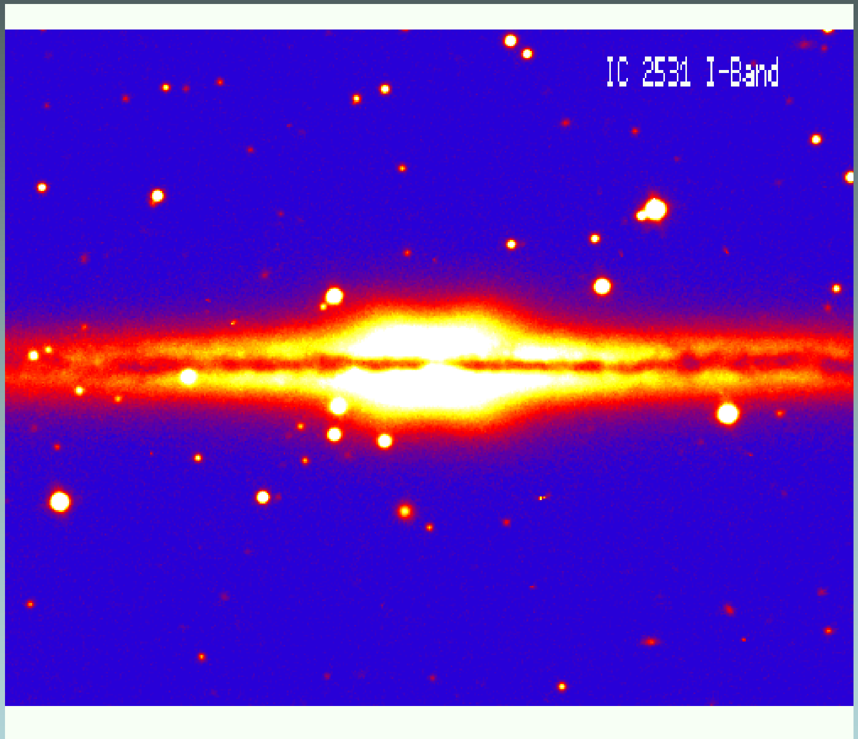


The relation between orbital shapes and morphological features



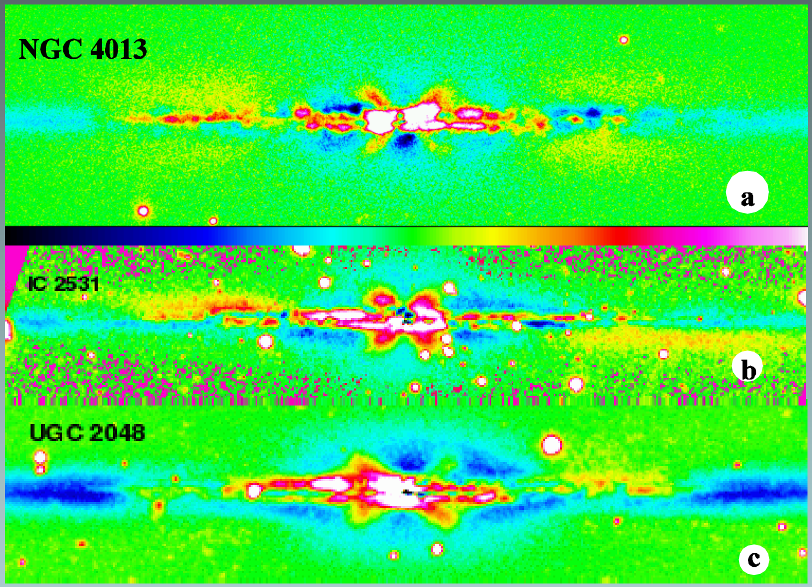
Revealing hidden structures

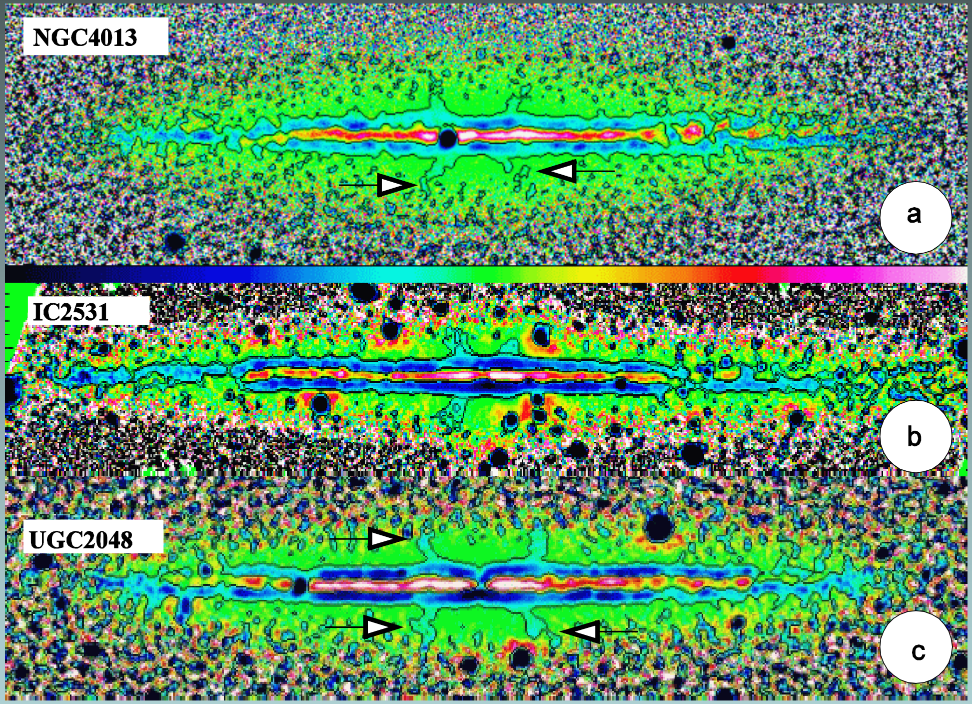
NGC 4013



Residual images

(Patsis & Xilouris 2006, MNRAS 366, 1121)

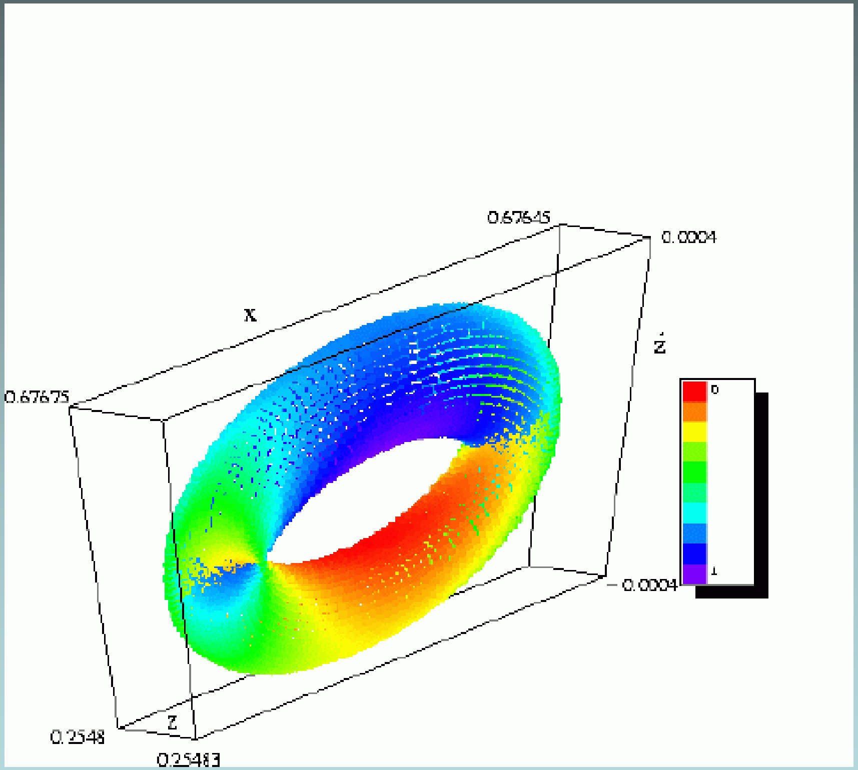




The role of Chaos

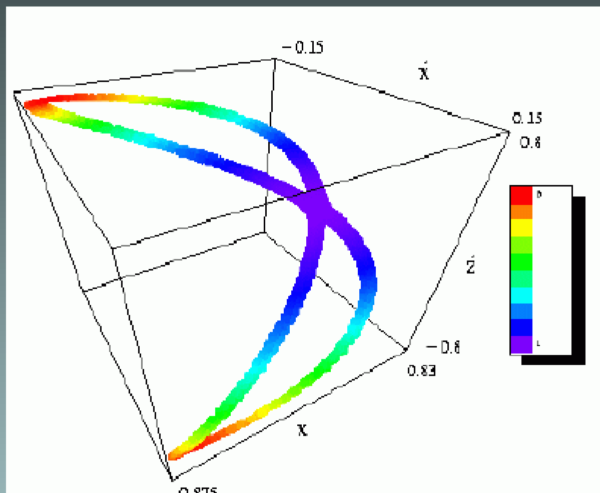
4D spaces of section – STABILITY
(Katsanikas & Patsis 2011, IJBC 21, 2, 467)

- three coordinates depicted in a 3D projection that can be viewed in a movie and the forth is given in color

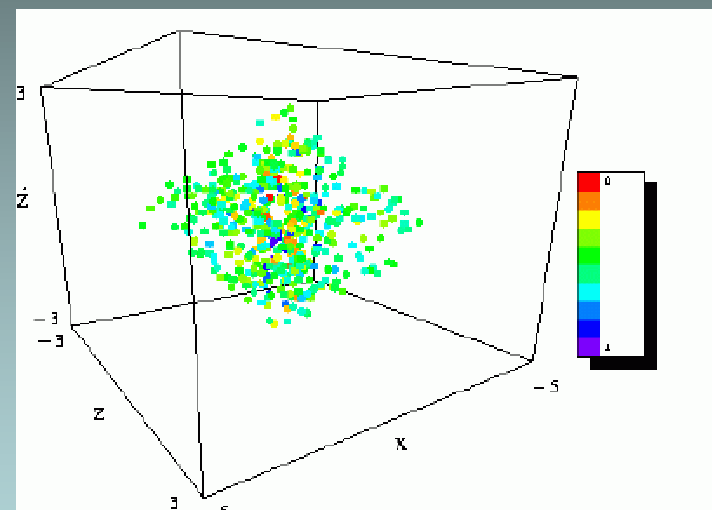


Katsanikas, Patsis & Contopoulos 2011 IJBC in press

A case of Simple Instability

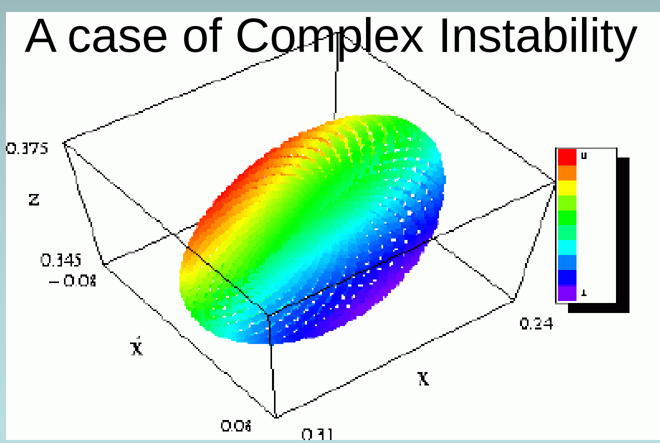


A case of Double Instability

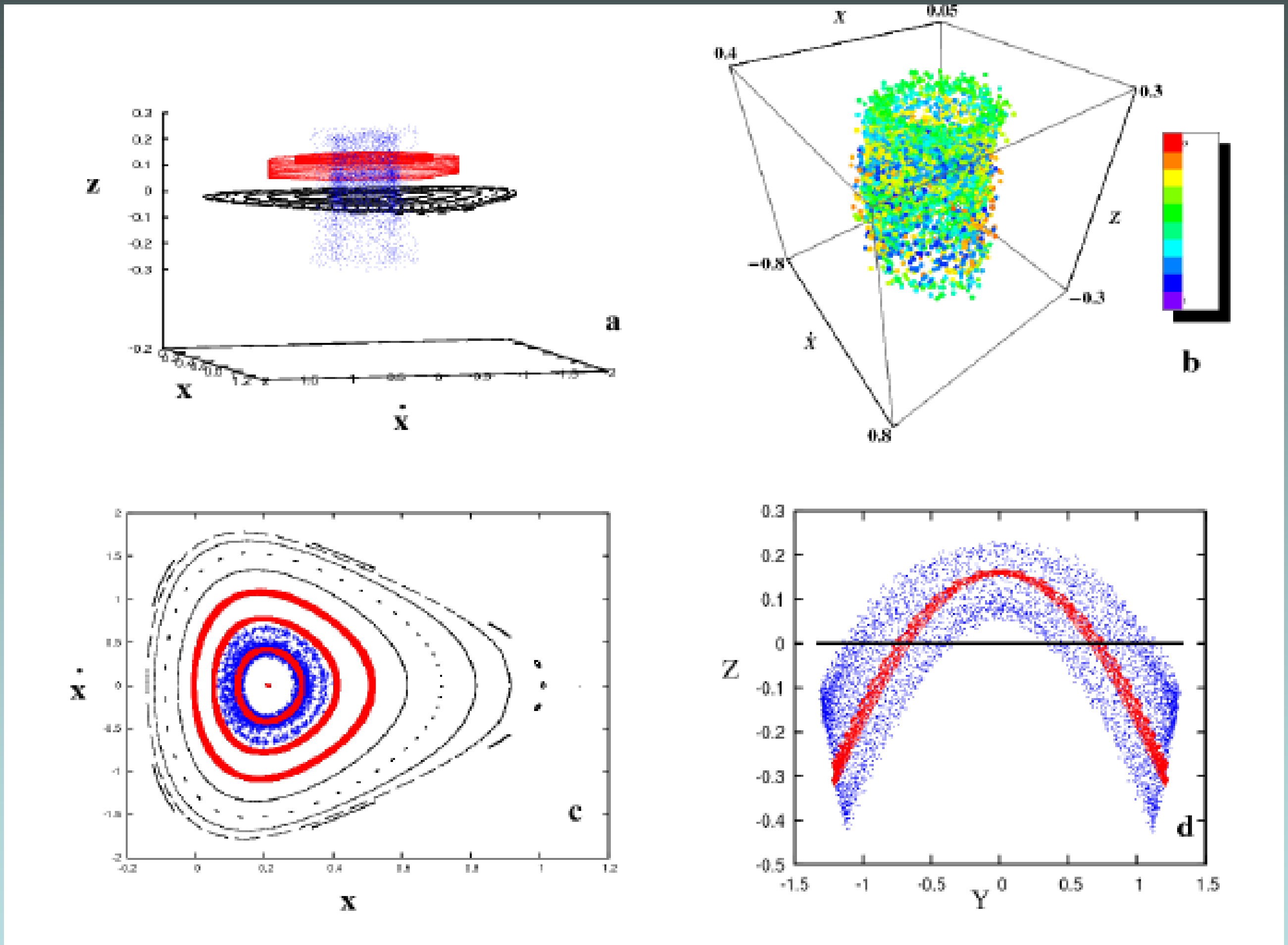


Looks like the general case

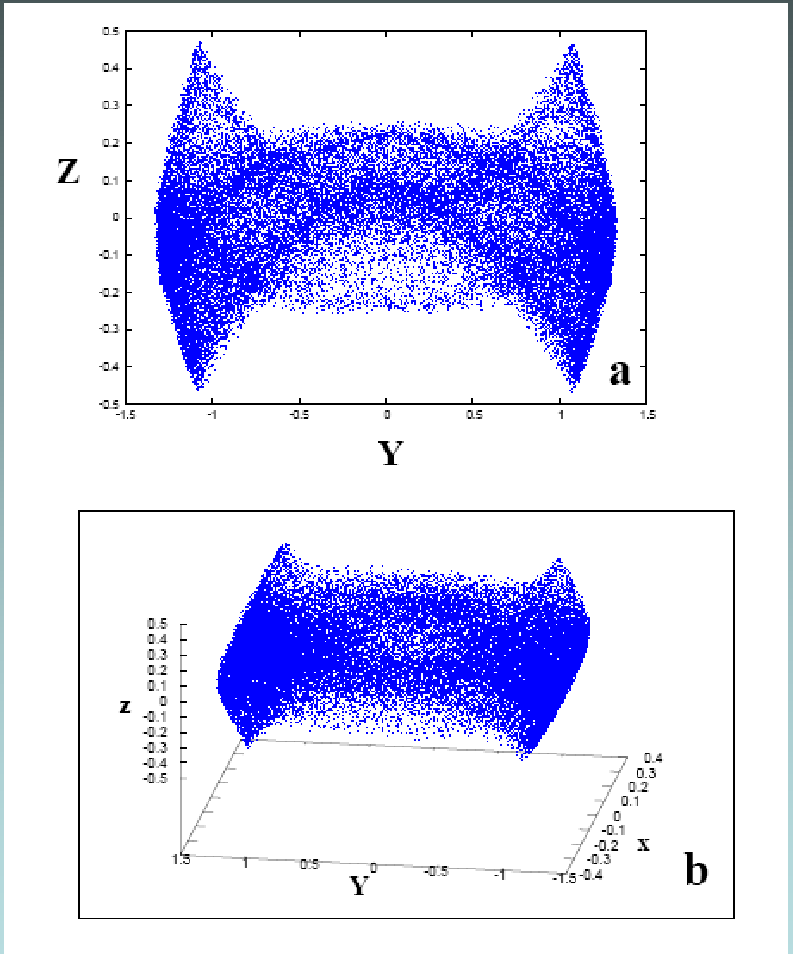
A case of Complex Instability



trapped chaotic orbit



more than the age of the universe



Structure out of Chaos

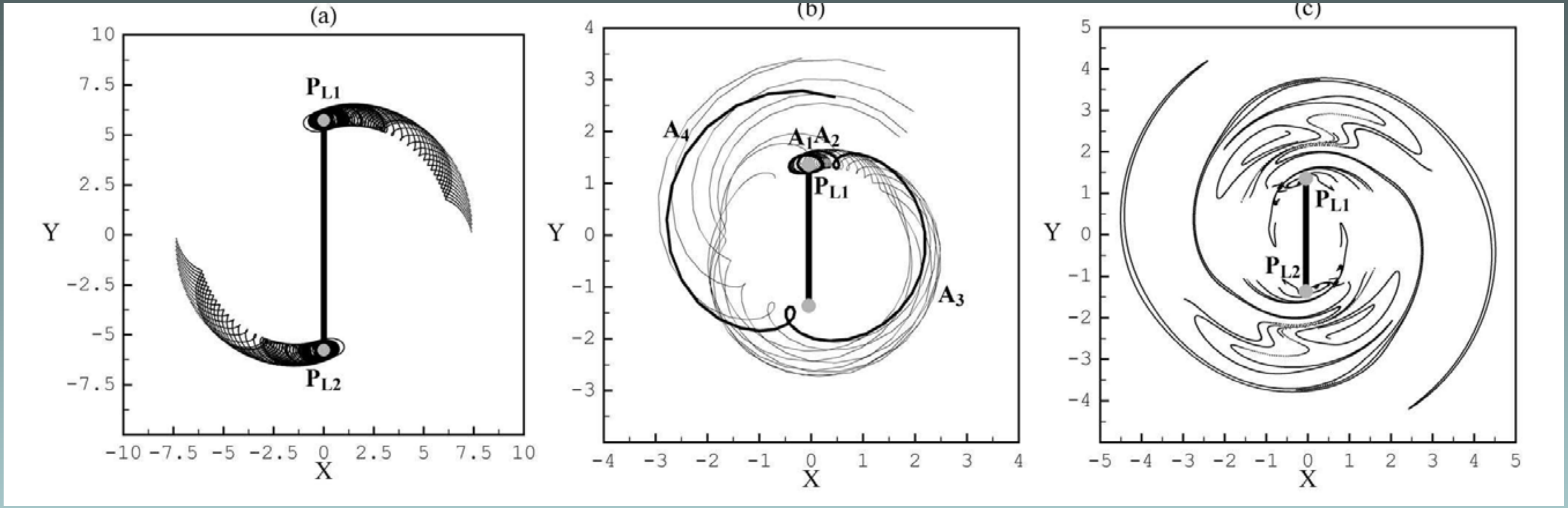
- In 3D there is work in progress, but in 2D there is a characteristic example:
- The spirals of the barred-spiral galaxies

Orbits in barred-spiral galaxies

- Contopoulos 1978, A&A 64,323
- Kaufmann & Contopoulos 1996, A&A 309, 381
- Patsis et al. 1997, ApJ 483, 731
- Voglis & Stavropoulos 2005, AIPC 848, 647
- Patsis 2006, MNRAS 369L, 56
- Voglis et al. 2006, MNRAS 372, 901
- Voglis et al. 2006, MNRAS, 373,280
- Romero-Gomez et al. 2006, A&A 453,59
- Voglis et al. 2007, MNRAS 381, 757
- Romero-Gomez et al. 2007, A&A 472, 63
- Tsoutsis et al. 2008, MNRAS 387, 1264
- “Chaos in Astronomy” 2009, SPRINGER
- Athanassoula et al. 2009, MNRAS 400, 1706
- Athanassoula et al. 2009, MNRAS 394,67

- Tsoutsis et al. 2009, A&A 495, 743
- Romero-Gomez et al. 2009, CNSNS 14.4123
- Patsis & Kalapotharakos 2008, MemSAIt, 2011
- Tsigaridi & Patsis 2010 PASP
- Kalapotharakos et al. 2010, MNRAS 403,83
- Kalapotharakos et al. 2010, MNRAS
- Patsis et al. 2010b, MNRAS
- Patsis et al. 2010c, MNRAS
- Chatzopoulos et al., 2011, MNRAS

Projection of invariant manifolds on the configuration space



Tsoutsis, Kalapotharakos, Efthymiopoulos, Contopoulos, 2009, MNRAS 495, 743

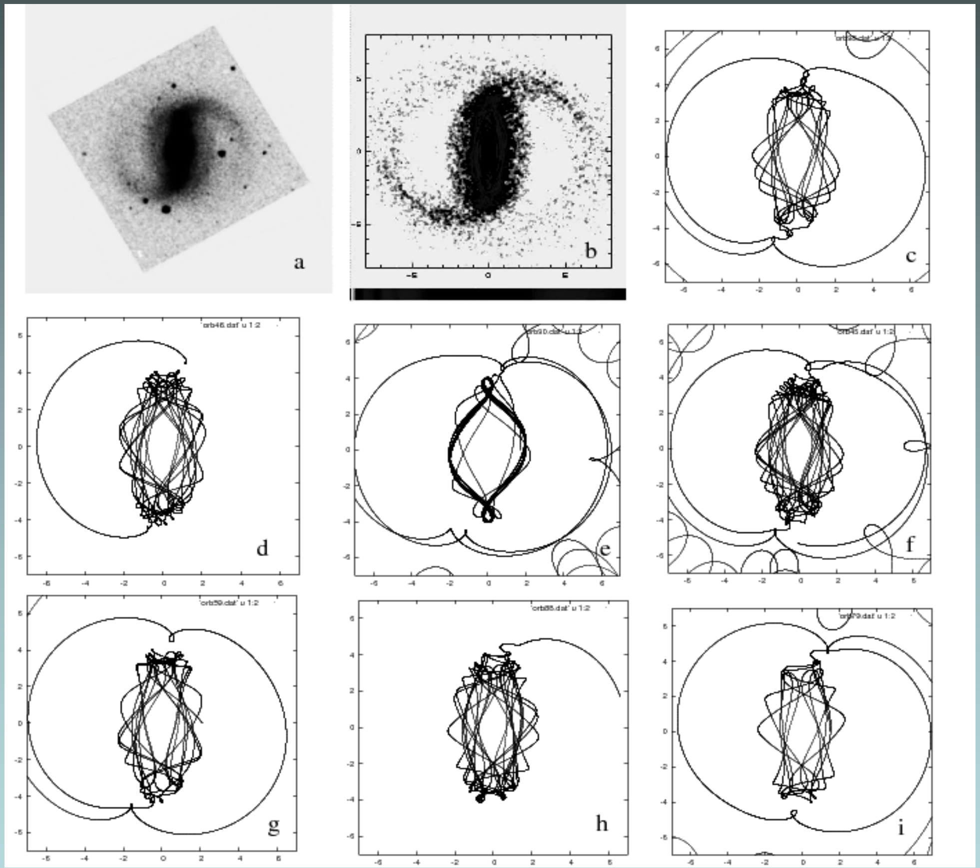
4:1 resonance-type chaotic orbits.
NGC 4314 - an early type barred galaxy

1. We isolate the particles found on the response spirals

2. We perform statistics on their Jacobi constants (Ej)

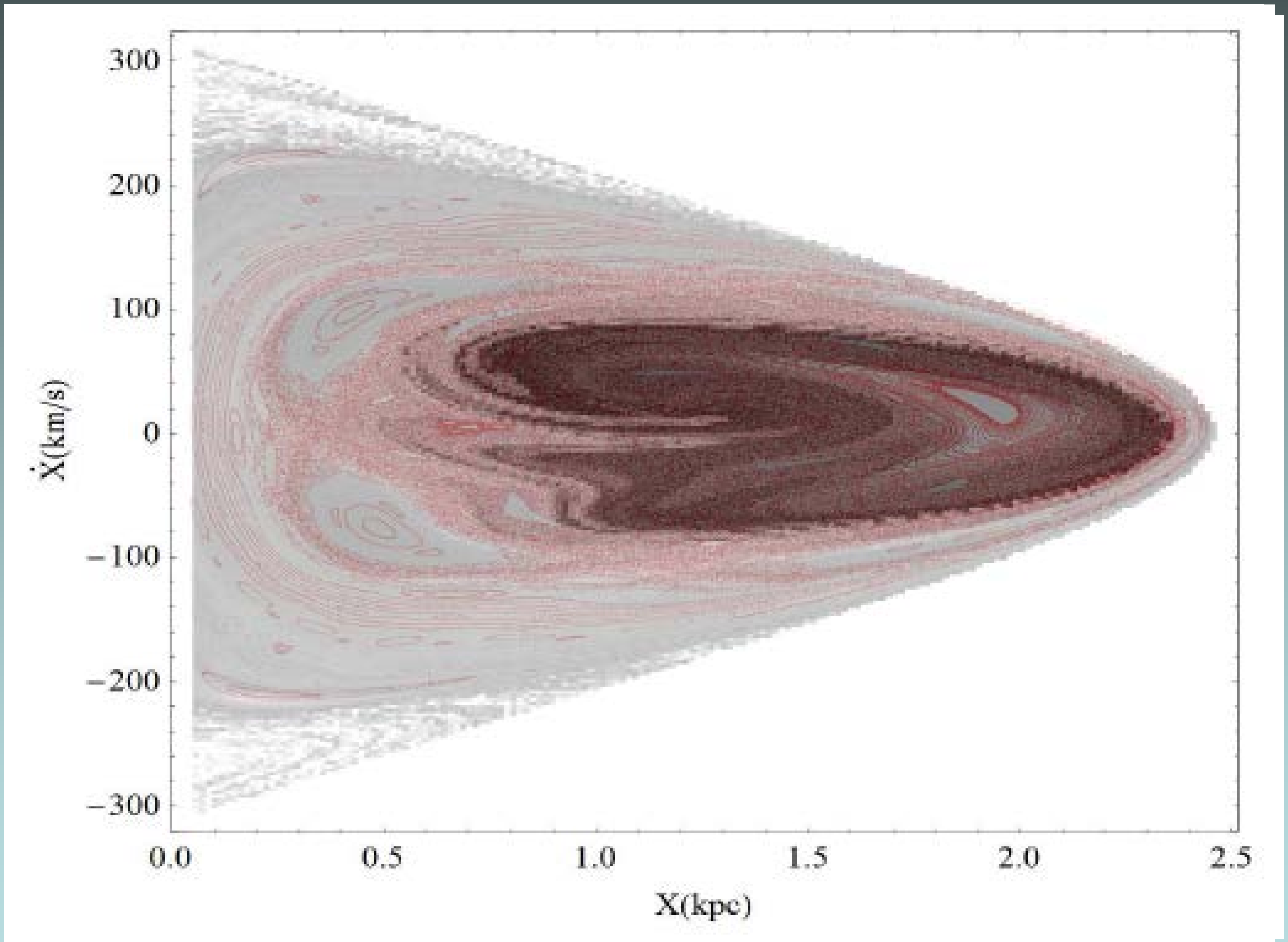
3. We realize that they belong to a narrow ΔEj interval, where chaos dominates on the surfaces of section

includes 4:1 family characte-ristic and L1,L2



Orbits supporting the boxy bar

Chatzopoulos, Patsis, Boily 2011, MNRAS 416, 479



NGC 1300
+C. Kalapotharakos, P. Grosbol

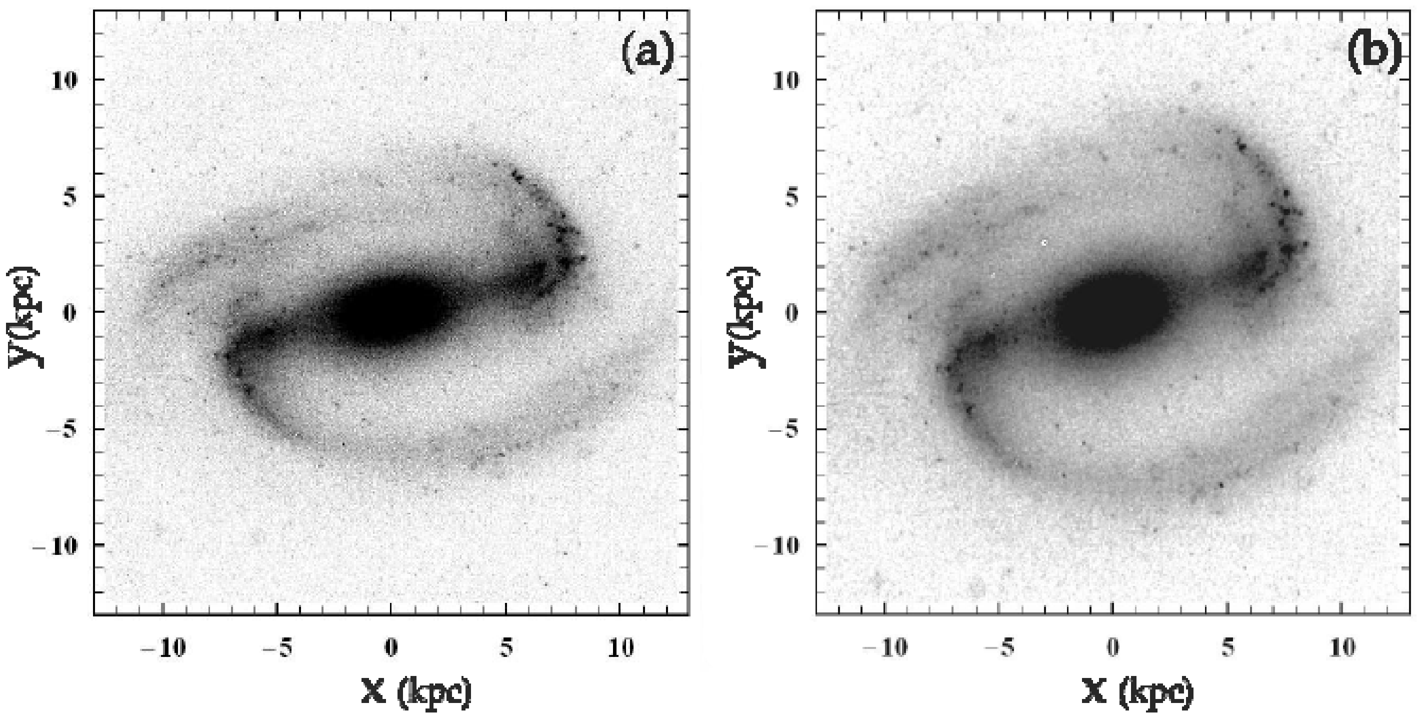
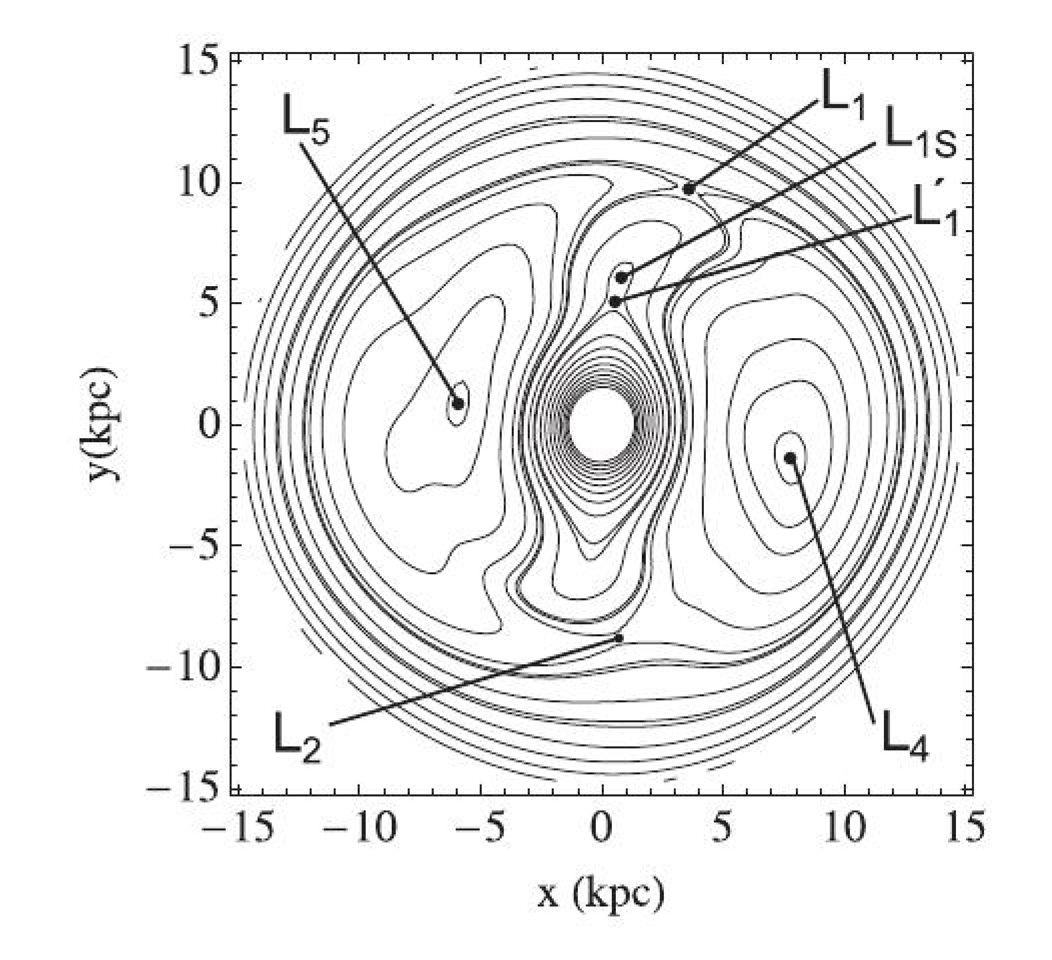


Figure 1. **(a)** The observed K band image of NGC 1300. **(b)** The deprojected K band image of NGC 1300 using (PA, IA)=(87°, 35°). The galaxy was observed with SOFI at the 3.5 m NTT telescope at ESO La Silla. The units on the axes are in kpc, assuming a distance to the galaxy D = 19.6Mpc. The images are in linear intensity scale.

2D response $\Omega_p = 22$ km s^{-1} kpc^{-1}



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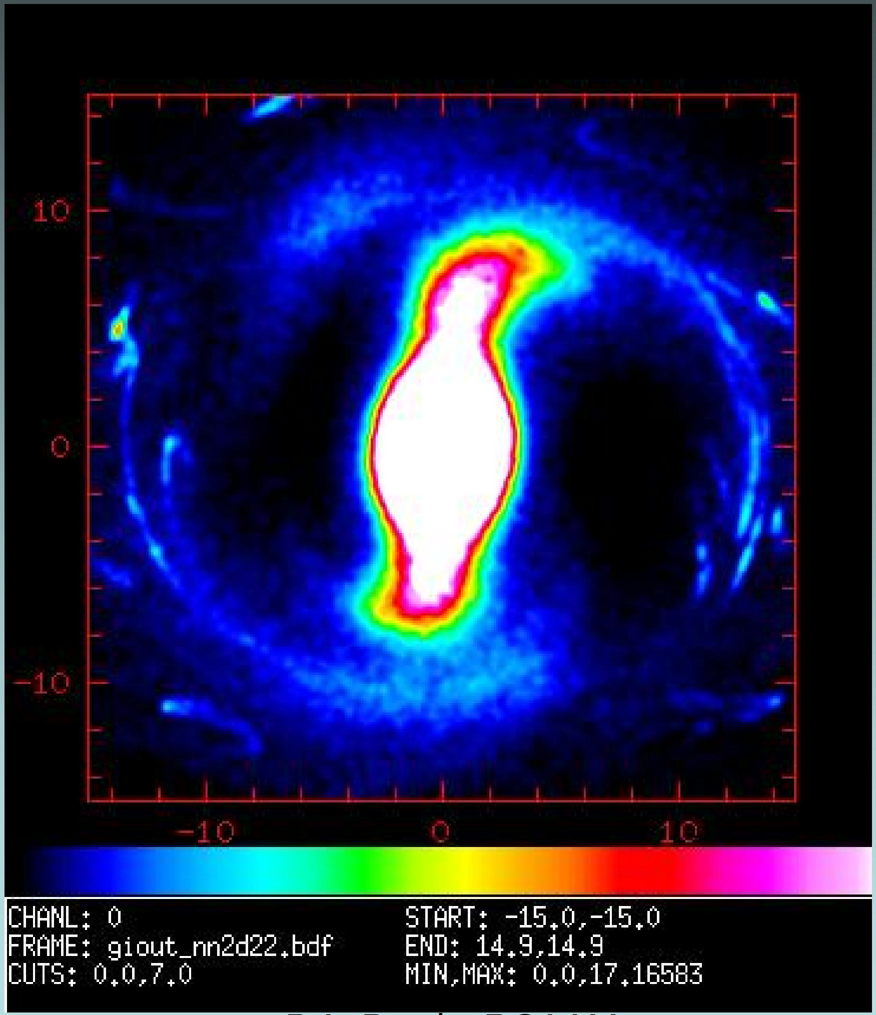
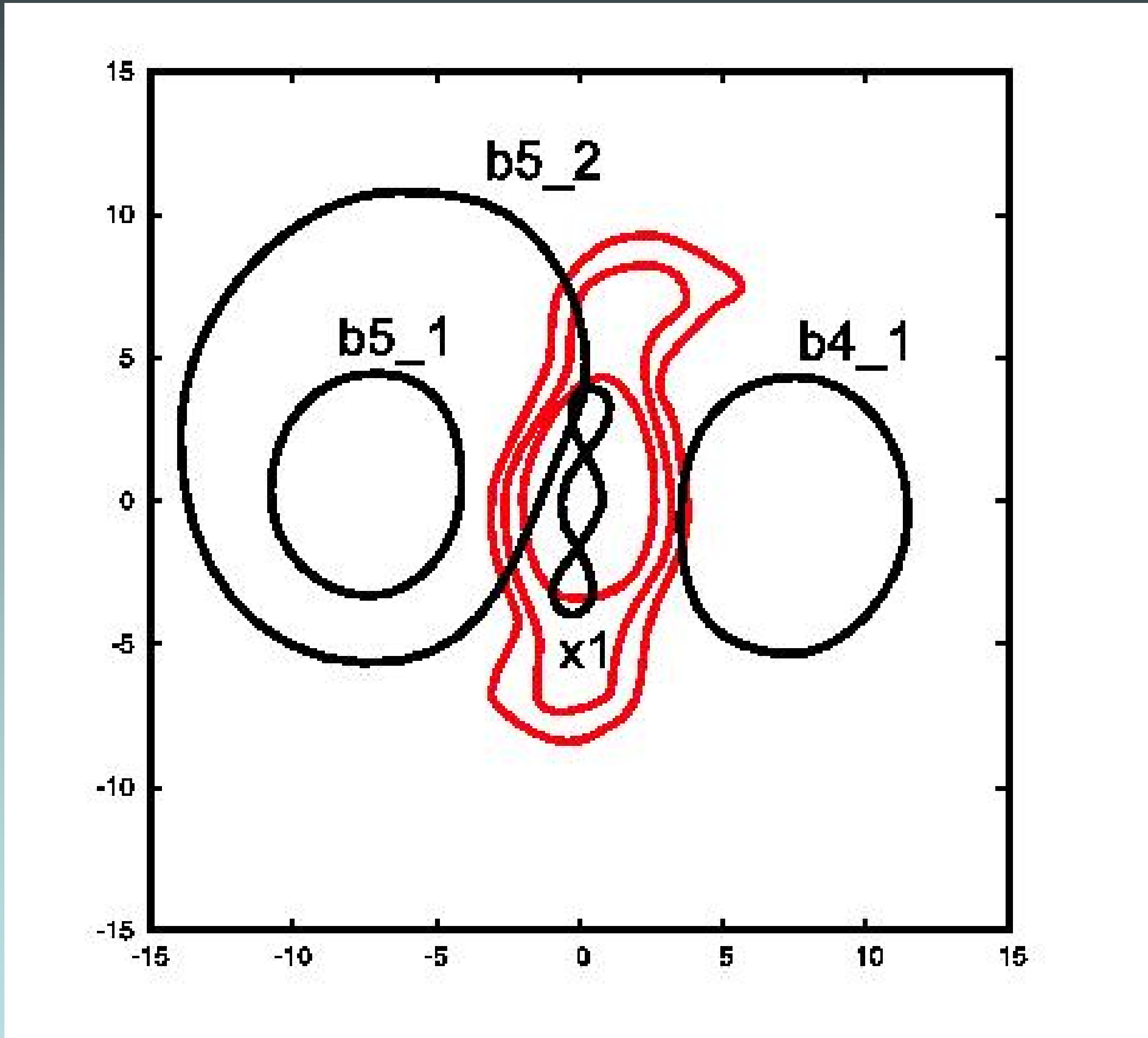
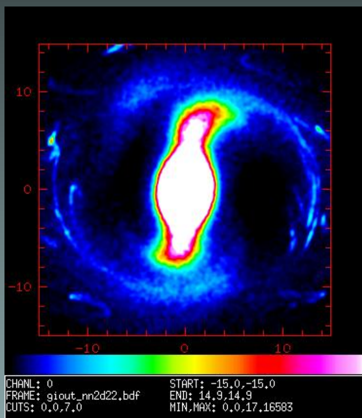
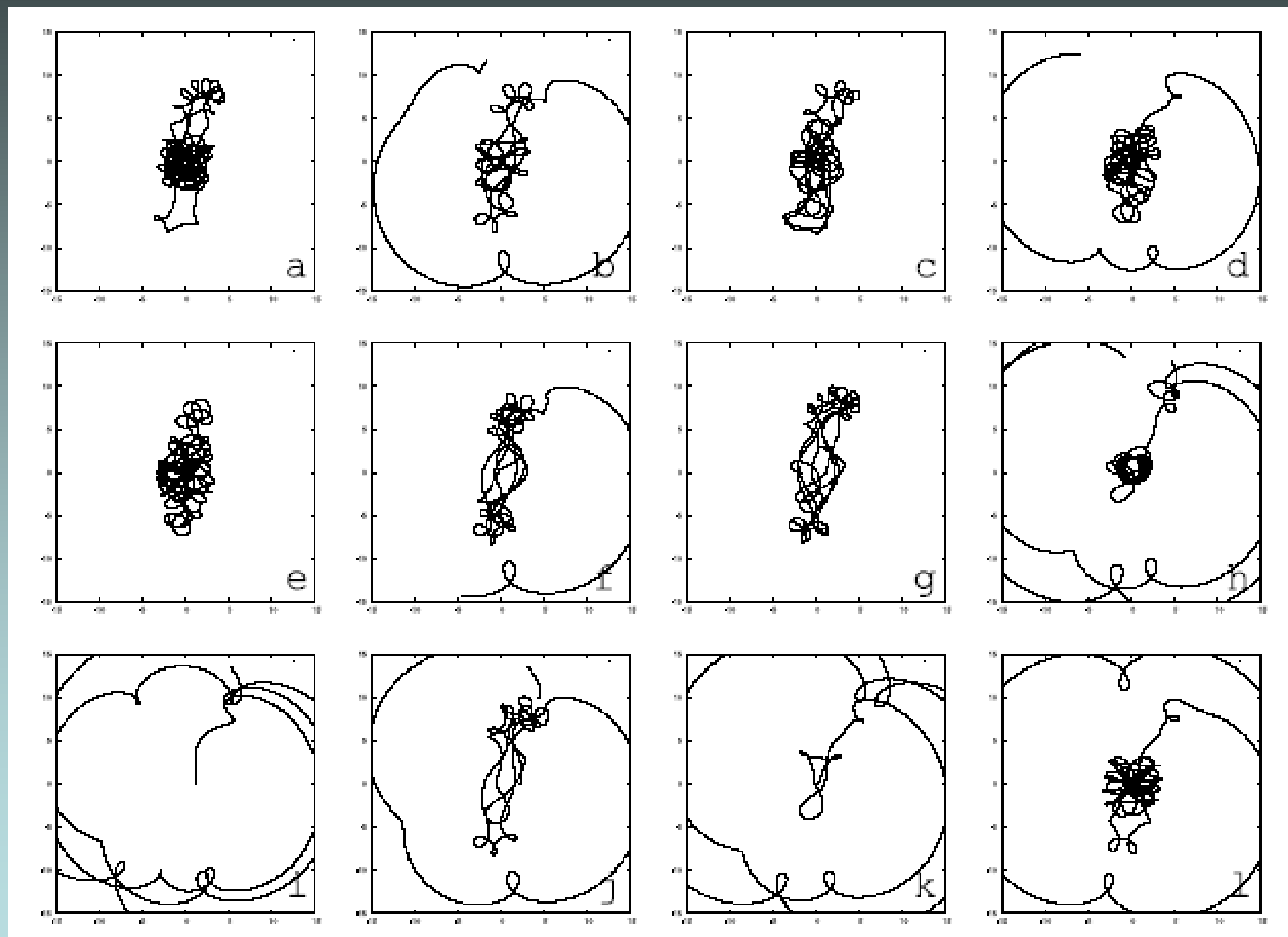


2d22: stable periodic orbits

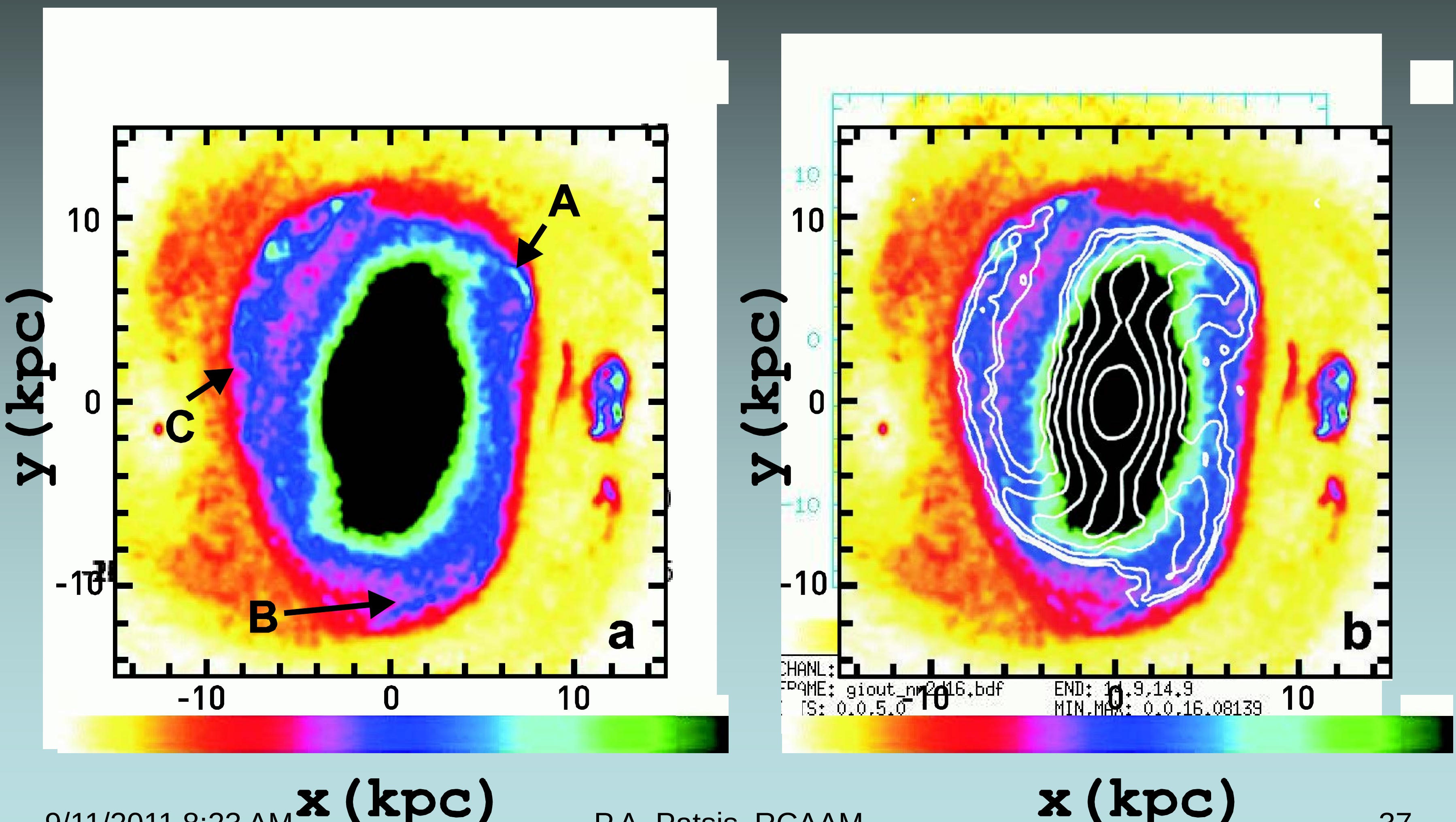


“chaotic” spirals

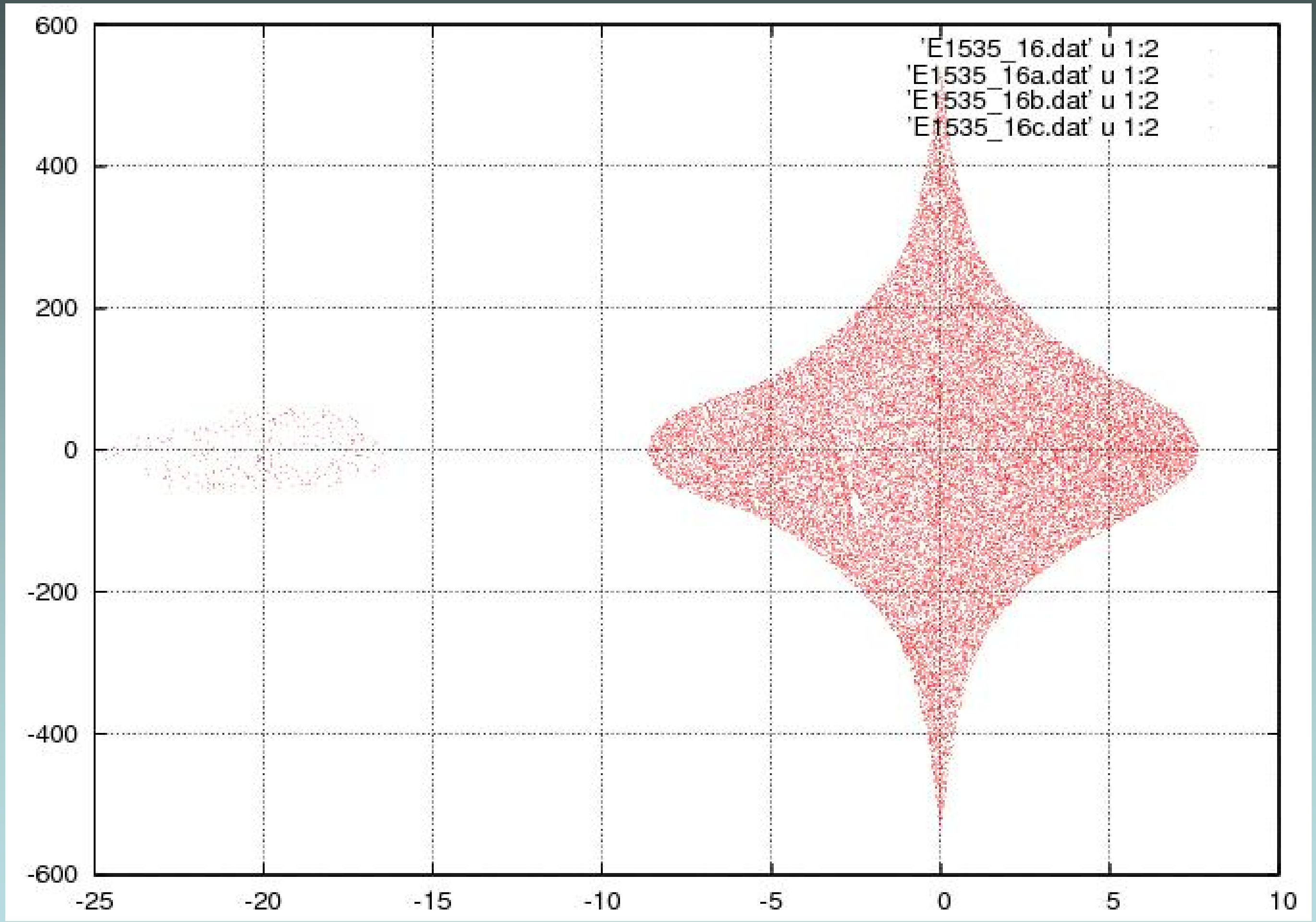


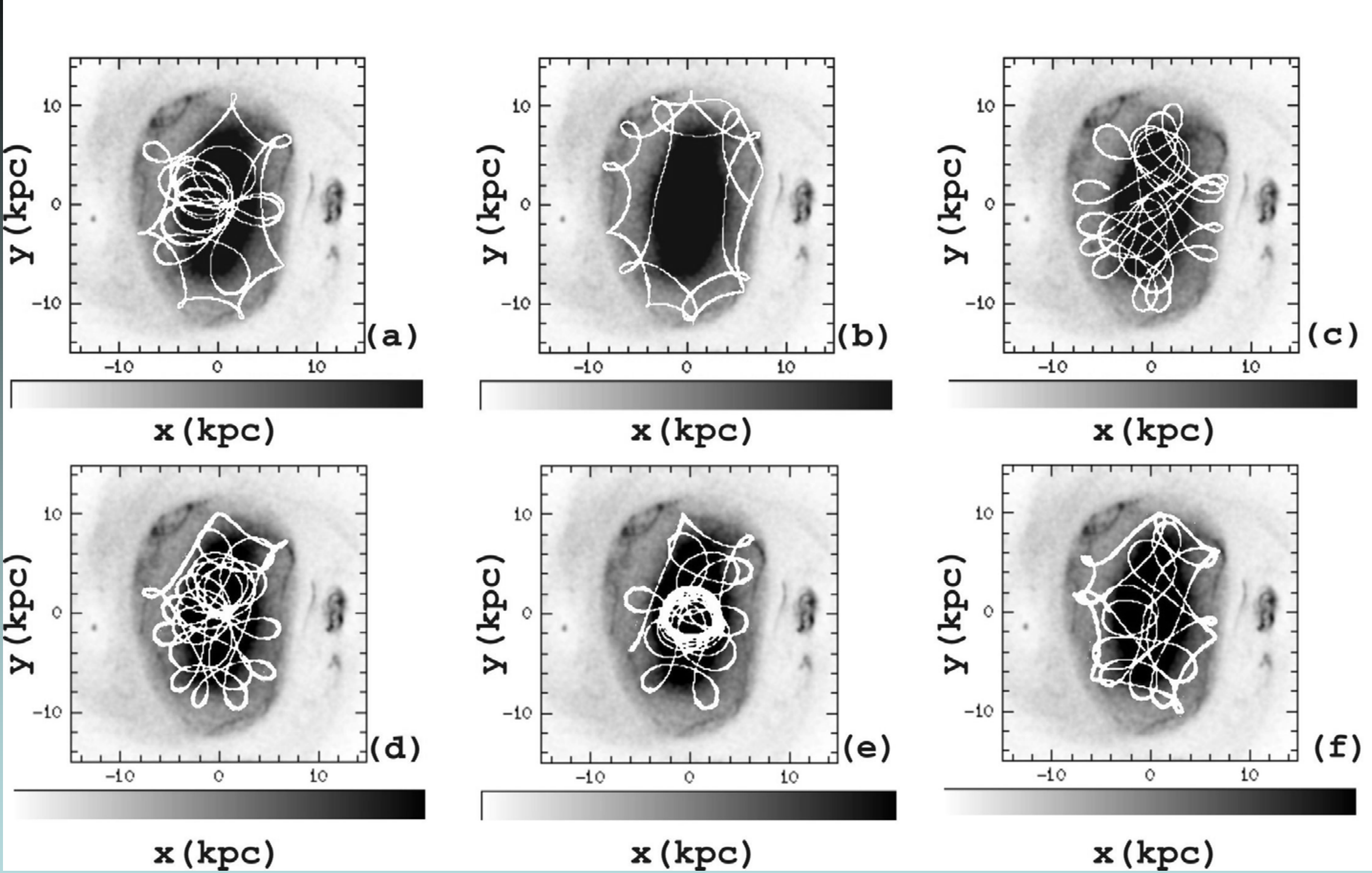


2d: $\Omega_p = 16$ km s^{-1} kpc^{-1}



2d16: Ej= -1.535×10^5




(a)
(b)
(c)
(d)
(e)
(f)
y (kpc)
x (kpc)
10
0
-10

Summary

- Using orbits one can find solutions for the dynamics of disk galaxies that match the observed photometry and kinematics, as if the potentials were time-independent.
- Not only regular but also chaotic orbits participate in building these models.

Example of a gaseous flow in a double spiral system (Tsigaridi & Patsis –in preparation)