The role of chaos in secular evolution of galaxies

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Plan of talk

- Non-integrability of motion in galactic models
- Methods of global analysis of phase space structure
- Resonant orbits and their importance for global dynamics
- Astrophysical applications
  - stability of triaxial cuspy galaxies
  - centrophilic orbits and feeding of supermassive black holes
- A novel method for simulating slow collisionless evolution

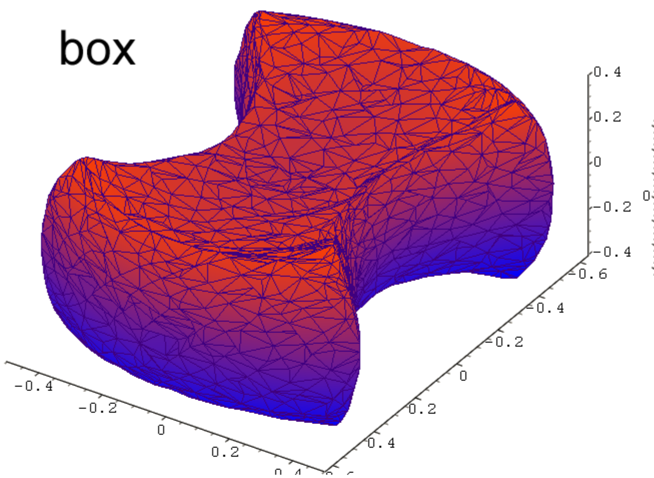
Chaos in galactic dynamics

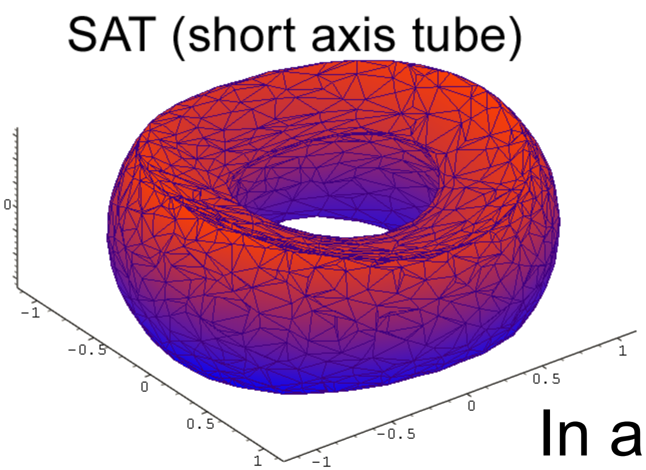
It is often assumed that any reasonable potential is (nearly) integrable. However, there are several important cases when it is not true:

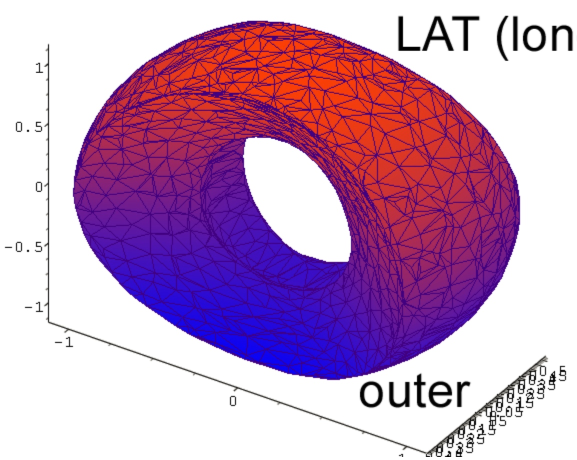
- Triaxial elliptical galaxies with cuspy density profiles
- Spiral non-axisymmetric galaxies around resonances
- Time-dependent potentials

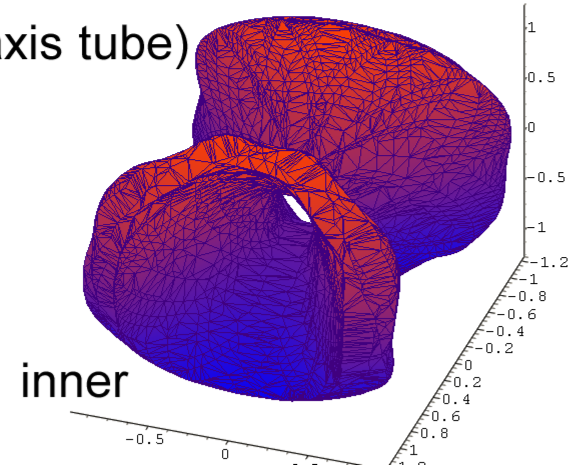
Chaotic orbits exist in 2d potentials, but in 3d they are much more diverse

Types of orbits in 3d integrable potential



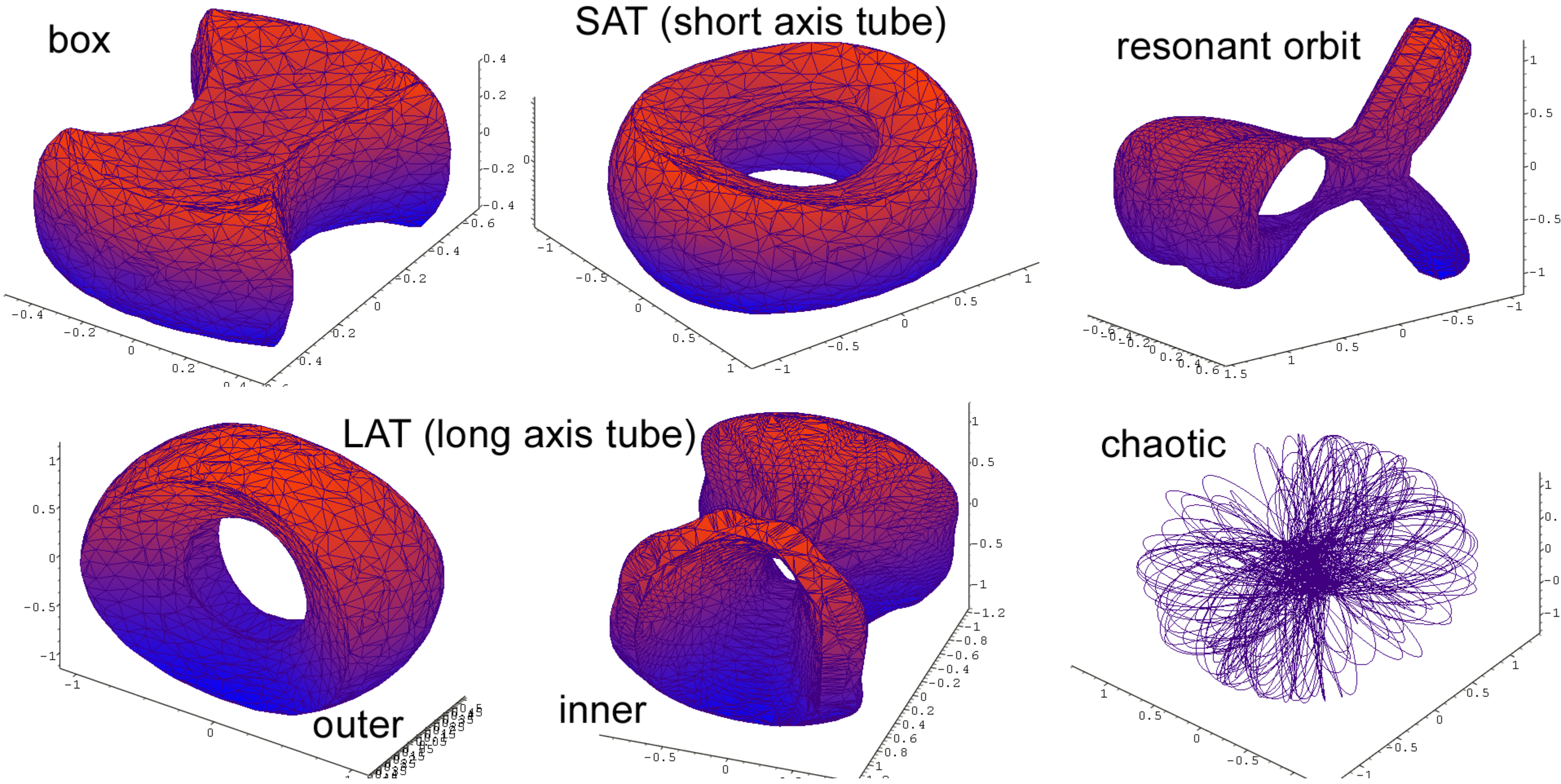




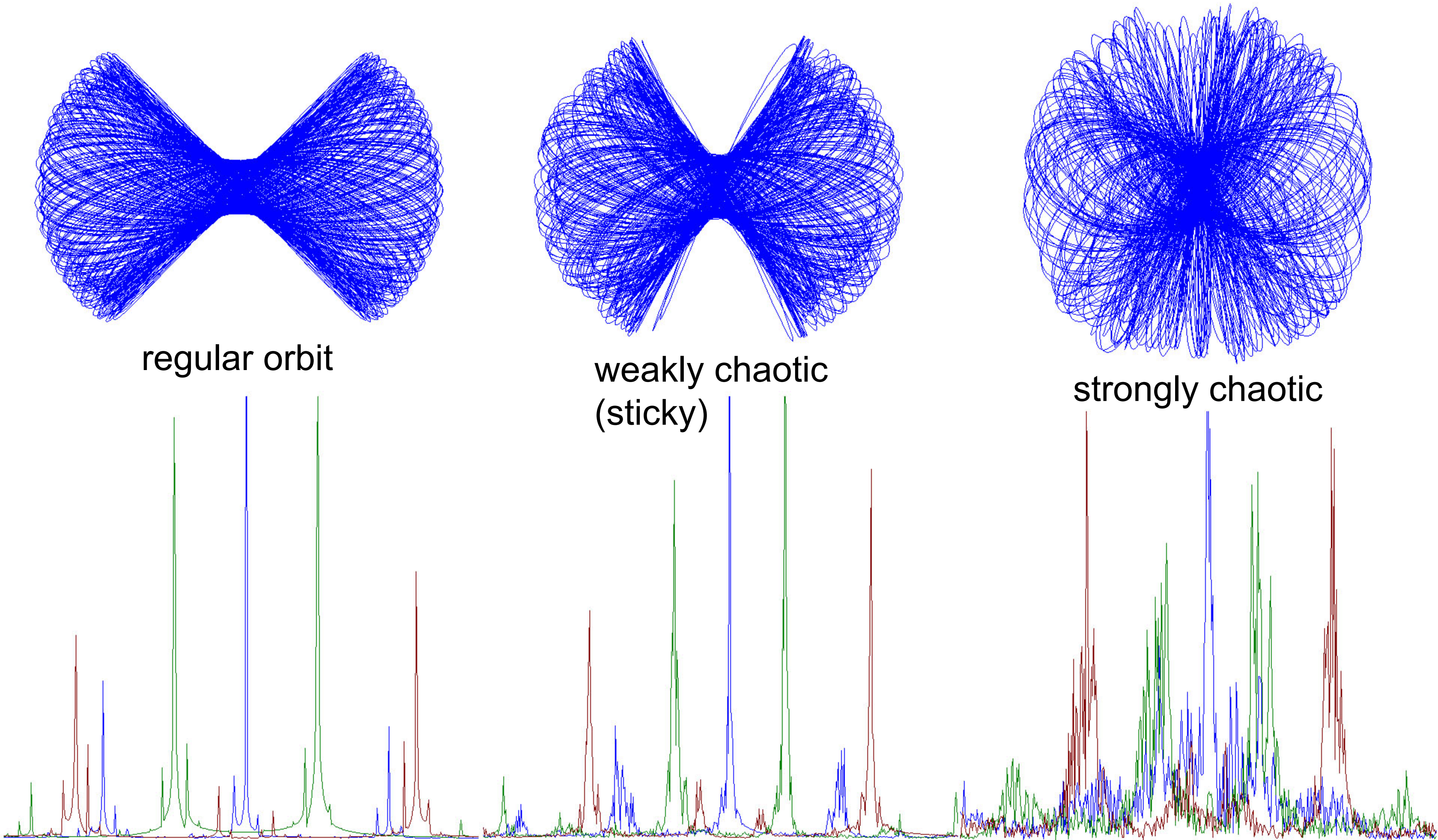


In an integrable potential these are the only possible orbit types

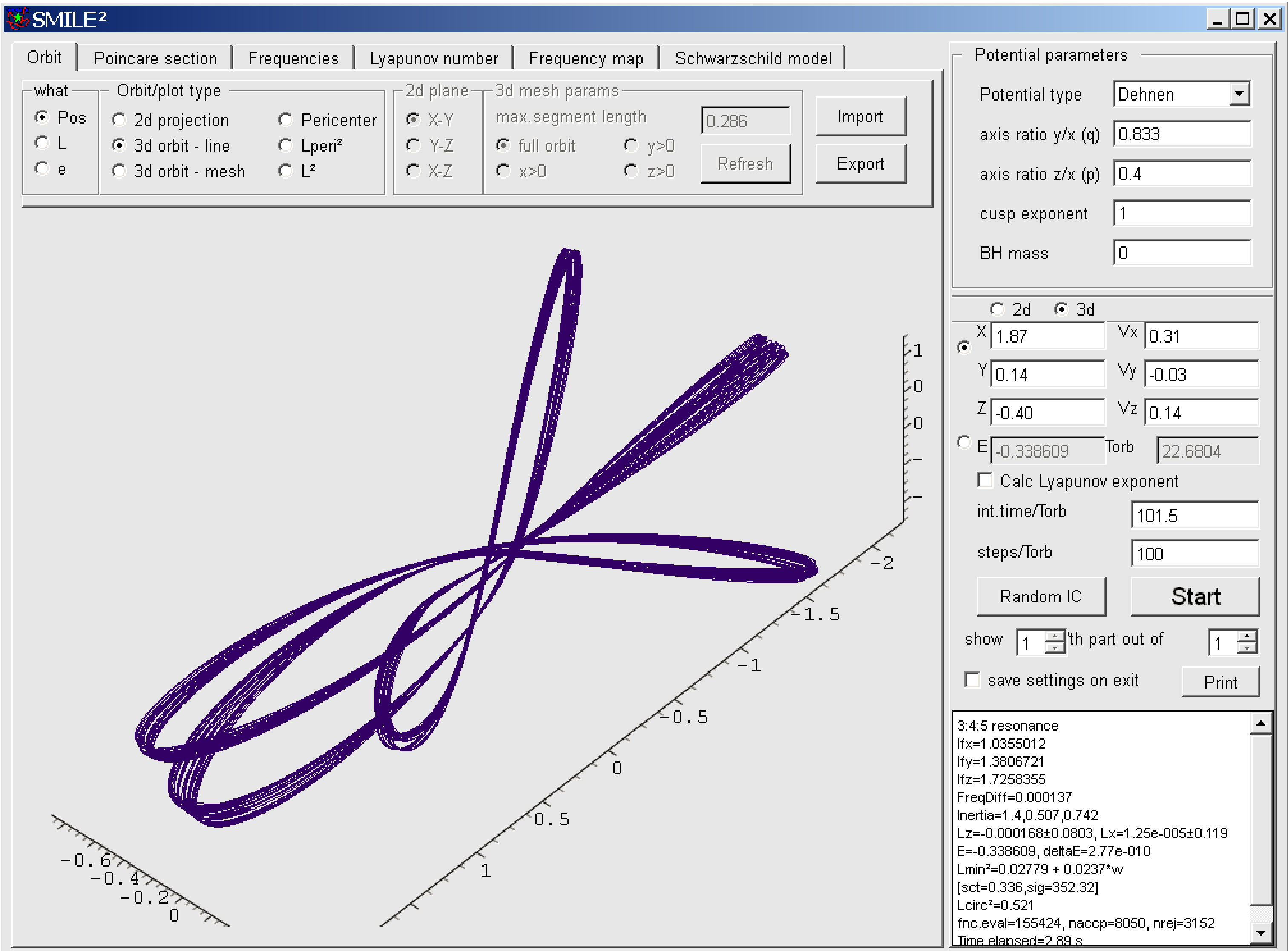
Types of orbits in 3d non-integrable potential



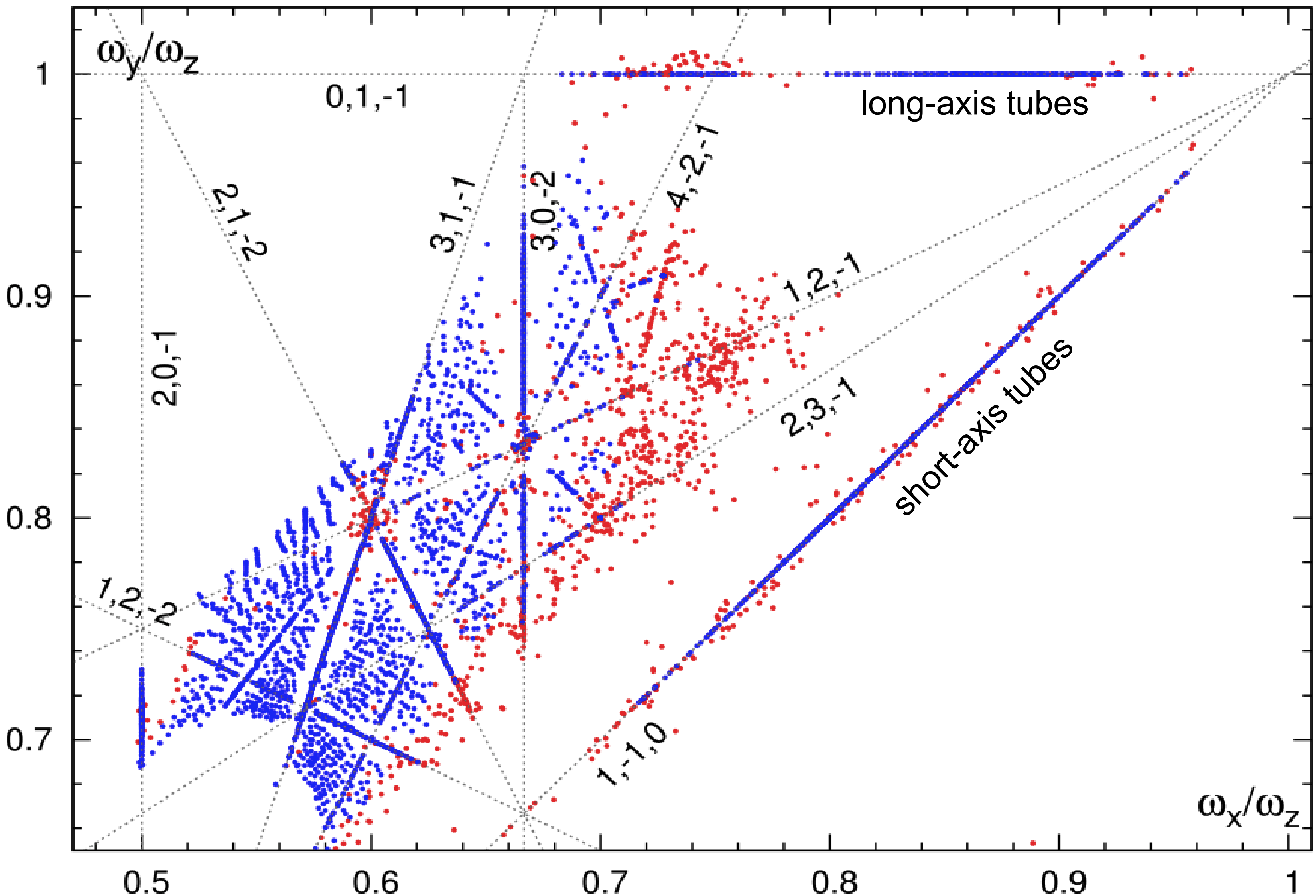
No well-defined transition to chaos



Resonant orbits

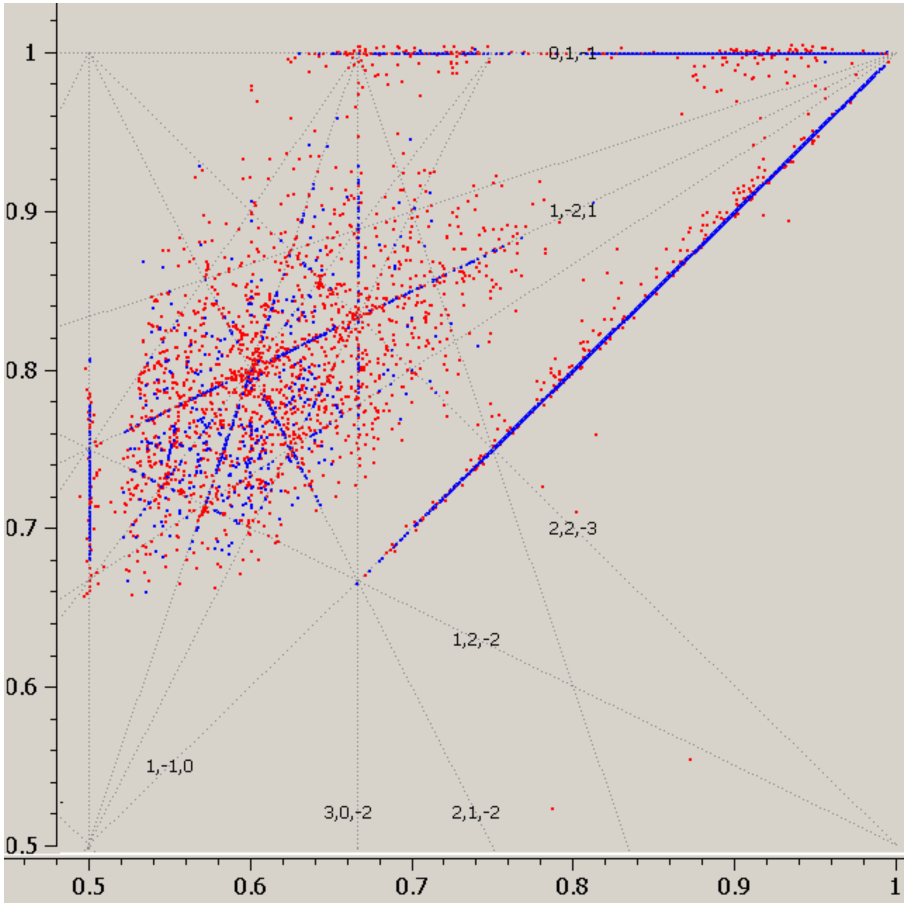


Frequency maps

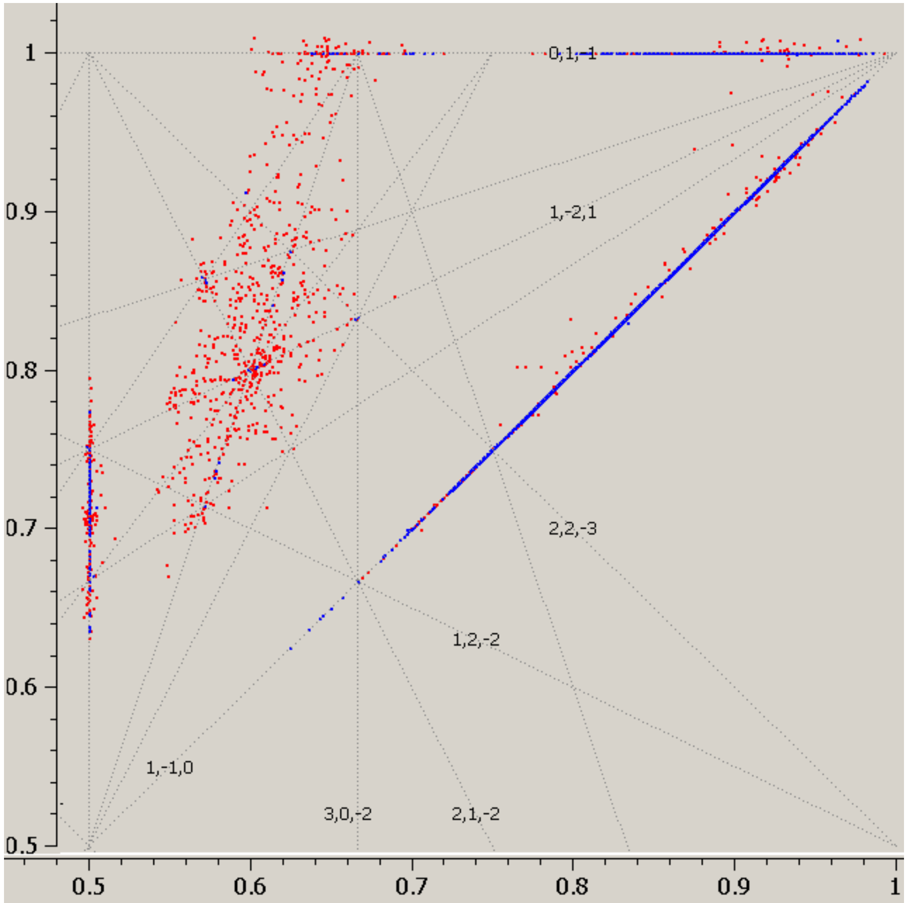


Frequency maps as tools for studying global dynamics

γ=1 Dehnen model
many resonant orbits that create the structure of the phase space



γ=2 Dehnen model:
almost all non-tube orbits are chaotic;
no global barriers to chaotic diffusion



Chaotic diffusion and secular evolution of triaxial cuspy galaxies with supermassive black holes

- Supermassive black holes are efficient "randomizers" of orbits that come close enough to the center of a galaxy
- Chaotic diffusion may lead to secular change of galactic shape
- The number of chaotic centrophilic orbits depends on the degree of triaxiality
- Rates of capture or disruption of stars by the black hole may be substantially enhanced in non-spherical galaxies (compared to spherical case) due to the presence of chaotic orbits
- Secular evolution rate does depend on the cusp slope and BH mass

[Merritt&Quinlan 1998, Valluri&Merritt 1998, Merritt&Poon 2004, Holley-Bockelmann&Sigurdsson 2006, Vasiliev&Athanassoula 2012]

Interplay between collisional and collisionless effects

- Discreteness noise accelerate diffusion of chaotic orbits through phase space [Kandrup+ 2000s]
- Two-body relaxation in non-spherical potentials enhances the rate of loss-cone repopulation for a supermassive black hole [binary]

  [Vasiliev&Merritt 2013, Vasiliev,Antonini&Merritt 2013]

- Bottom line: difficult to control collisional effects in simulations of primarily collisionless processes

A novel method of studying slow collisioness evolution of near-equilibrium models

- Consider evolution of ensemble of **N** *orbits* (not just *particles*) in the slowly changing potential generated by the time-averaged density of these orbits
- Each orbit is represented by **m** points sampling its trajectory
- Potential and density are evaluated as basis-set expansions with coefficients computed from N*m points
- Orbits are computed on the time interval $T >> T_{orb}$
- New coefficients of expansion are evaluated from trajectories during the entire integration interval T

A novel method of studying collisioness evolution

CONS

- Only suitable for slow evolution of near-equilibrium systems

PROS

- Beat down discreteness noise in potential
  (N*m instead of N points are used to compute coefs)
- Time smoothing of potential variation ($T \gg T_{orb}$ => adiabatic evolution)
- Computational cost linear in N
- May impose particular form of symmetry (reflection, triaxial, axisymmetric)
- May add random perturbations to velocities during orbit integration that would mimick two-body relaxation rate for a desired $N_{star} \neq N$
  (Monte-Carlo collisional evolution code in Spitzer's formulation for **arbitrary geometry**)

Conclusions

- Chaotic effects are important for many problems of galactic dynamics
- Resonant orbits are important for the global structure of phase space and for the rate of chaotic diffusion
- Frequency map is a useful tool for visualizing this structure
- Possibility of simulating the slow, collisionless evolution in time-smoothed mean-field dynamics