Orbital Dynamics of Simulated Galaxy Merger Remnants

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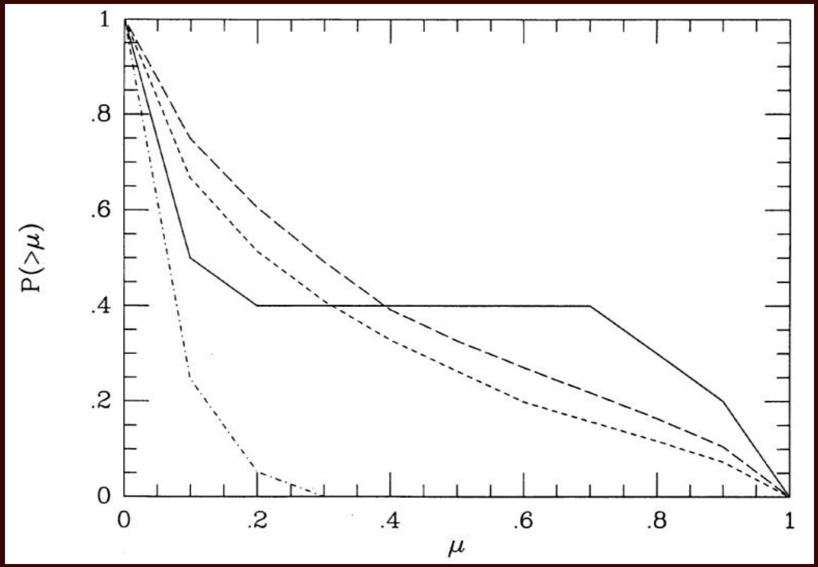
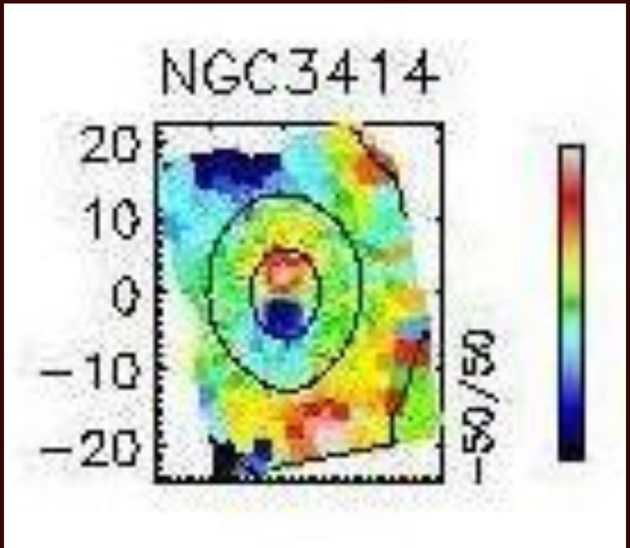
The complexity of observed elliptical galaxies

- major and minor axis rotation
- isophote twists
- kinematically distinct components
- embedded disks
- velocity anisotropy
- coherent streams
- tidal tails, rings



Jedrdejewski & Schechter 1989



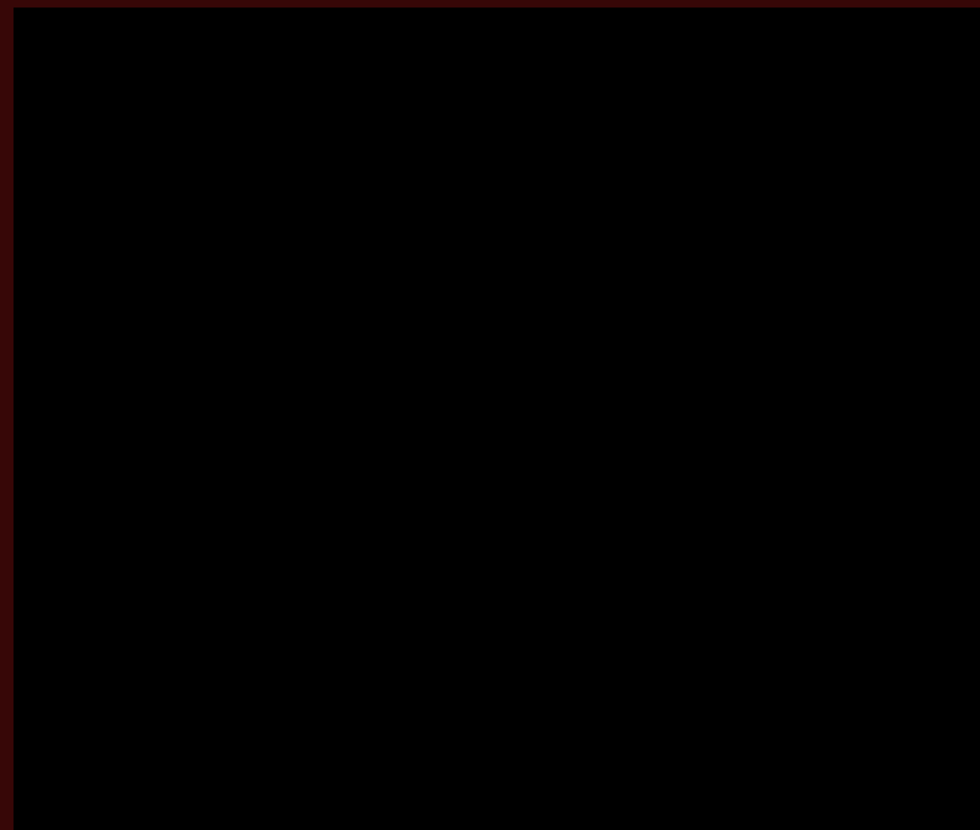
Krajnovic et al. 2008

☹ Structure of elliptical galaxies cannot be (fully) explained by simple theory.

☺ Information about formation history encoded in complex features.

The role of simulations

- How to parse the available information on formation history?
- Stronger constraints on formation theories when more detailed features matched by simulated remnants.
- How well can we *really* reconstruct the 3D distribution function from 2D observables?



Galaxies as collisionless systems

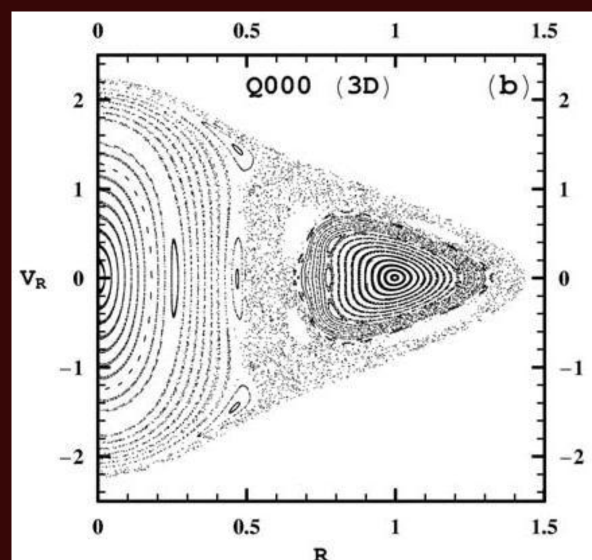
$$t_{relax} \approx \frac{NR}{(8\ln\Lambda)v} \gg t_{Hubble}$$

Governed by Collisionless Boltzmann Eq'n,

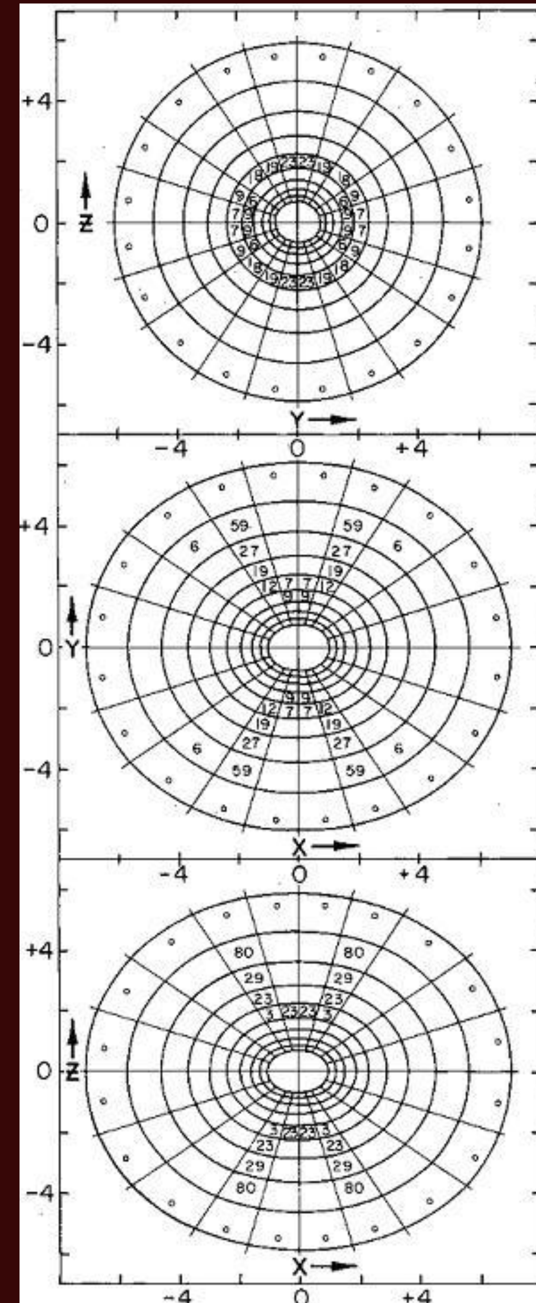
$$\frac{\partial f}{\partial t} + \vec{v}\cdot\vec{\nabla} f - \vec{\nabla}\Phi \cdot \frac{\partial f}{\partial \vec{v}} = 0 \, ,$$

and Poisson's Eq'n $\vec{\nabla}^2 \phi(\vec{r}) = 4\pi G \rho(\vec{r})$.

- Orbits do not uniformly fill their energy hypersurfaces, since they are confined by (approximate) isolating integrals of motion. Orbits conserving three or more such integrals are called *regular* .



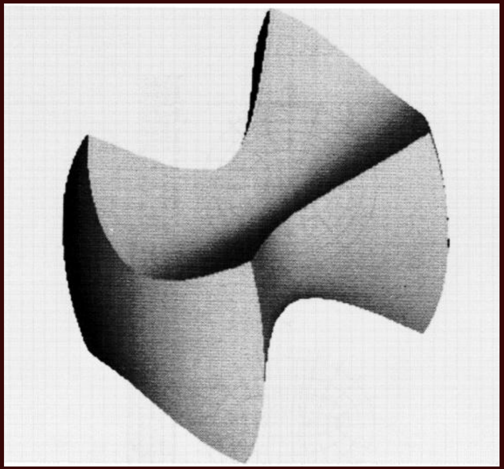
Kalapotharakos et al. 2004

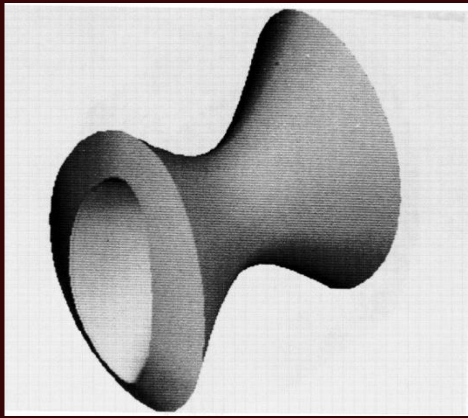


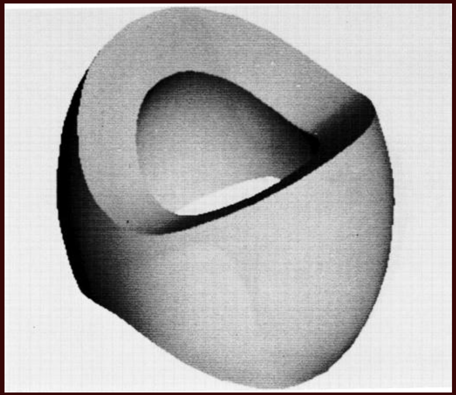
Schwarzschild 1979

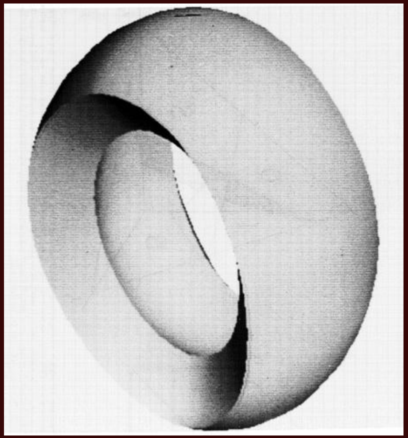
Regular orbits in triaxial potentials

Four major orbit classes in flat-cored, integrable triaxial potential:


Box


Inner long-axis tube

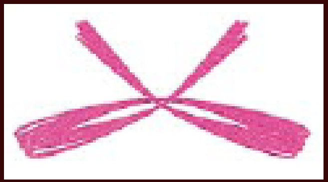

Outer long-axis tube


Short-axis tube

Statler 1987

Resonant orbits (cusps):

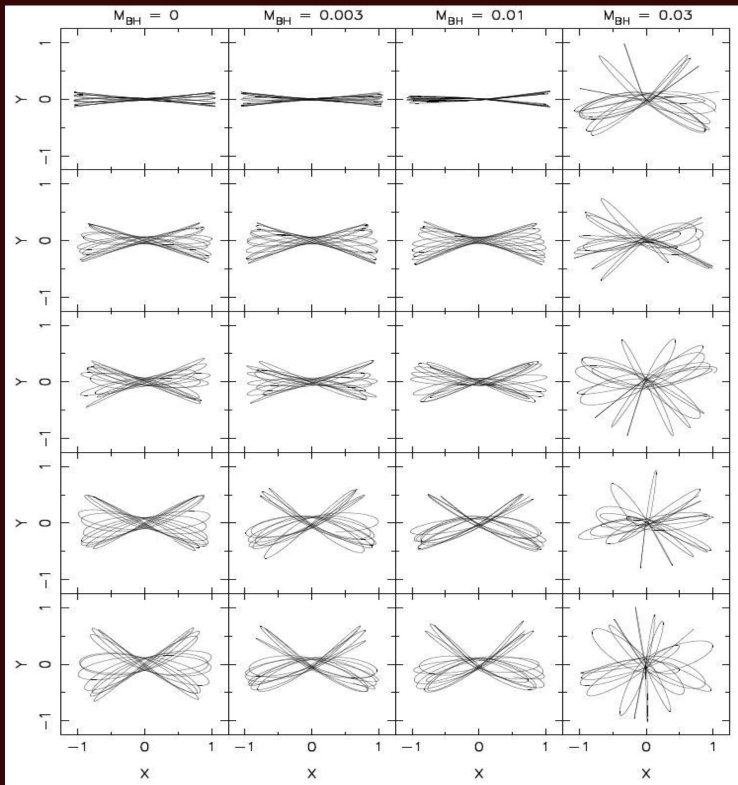
$$l\omega_x + m\omega_y + n\omega_z = 0$$



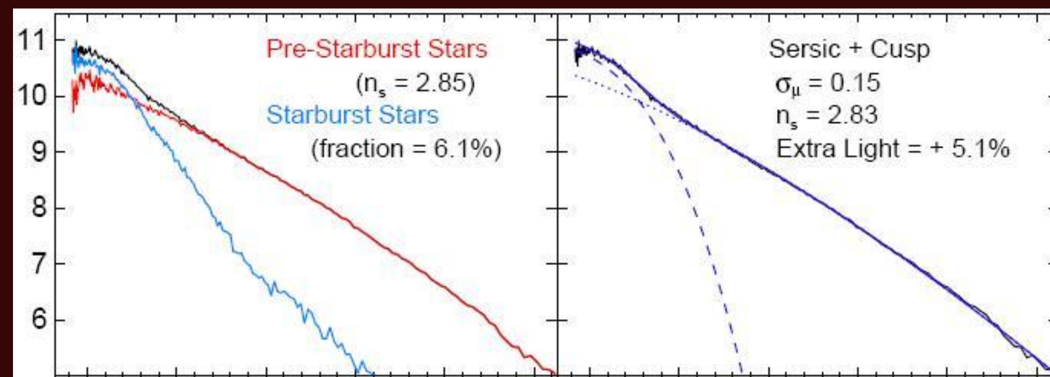
Poon & Merritt 2001

Effect of a central mass concentration

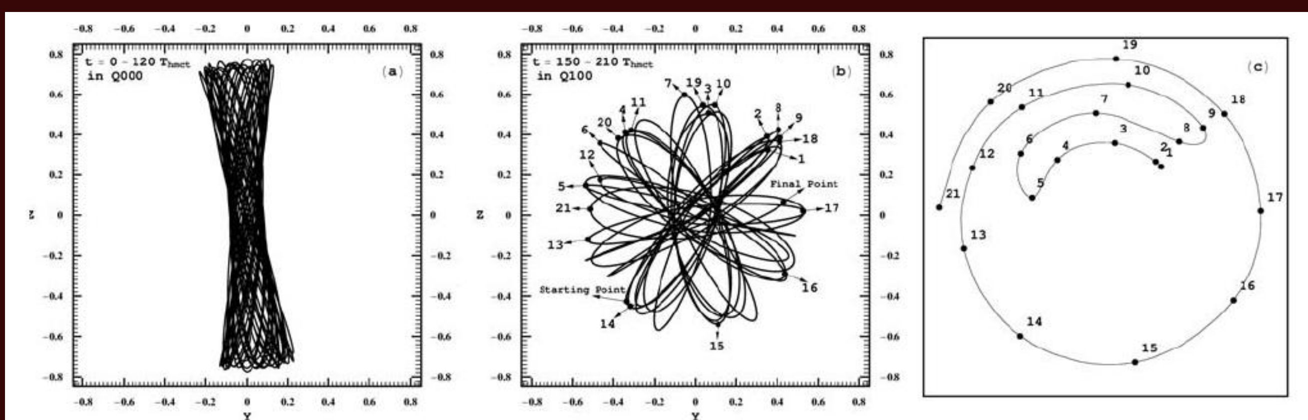
A central mass concentration destabilizes centrophilic box orbits and drives the potential toward oblate axisymmetry.



Valluri & Merritt 1997



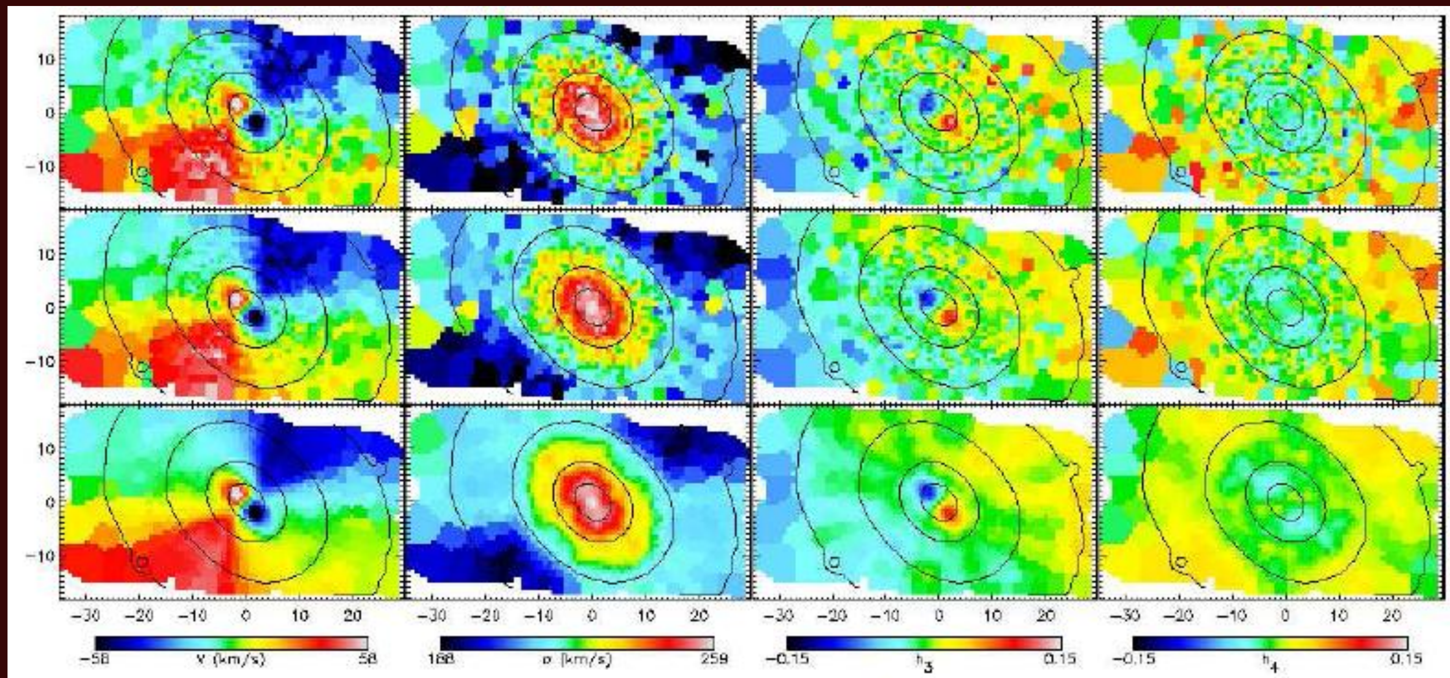
Hopkins et al. 2008

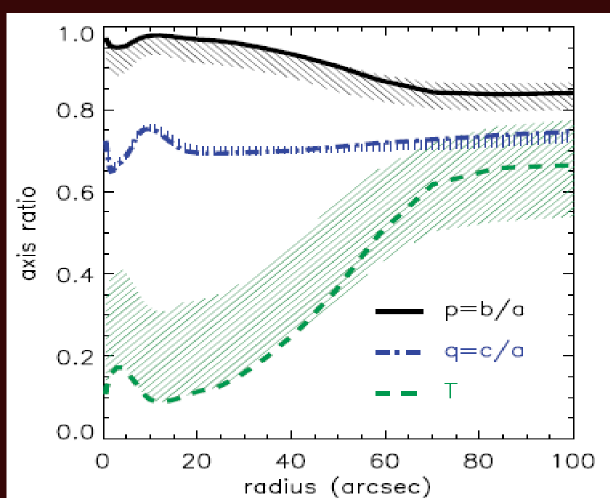


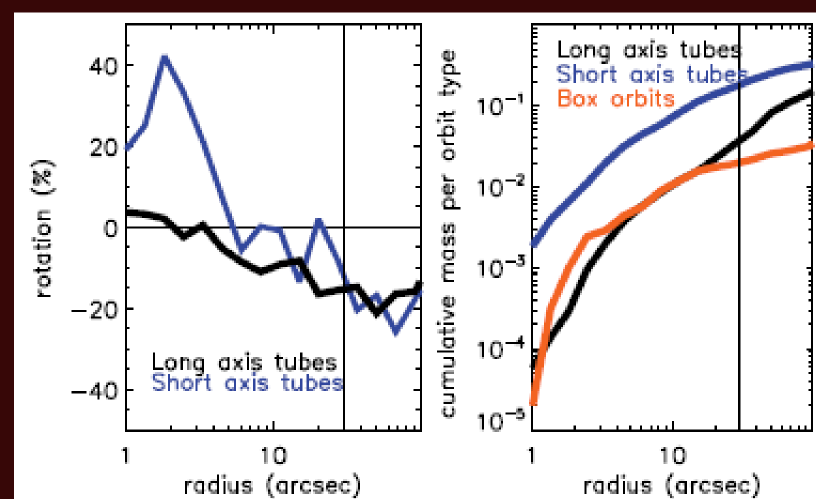
Kalapotharakos et al. 2004

Hopkins et al. 2006

Dynamical modelling of observed galaxies
(e.g. NGC4365: van den Bosch, et al., astro-ph/0712.0113)







SCF expansion of galactic potential & orbit integration

$$\rho(r) = \sum_{nlm} A_{nlm}\rho_{nlm}(\vec{r}) \qquad \Phi(r) = \sum_{nlm} A_{nlm}\Phi_{nlm}(\vec{r})$$

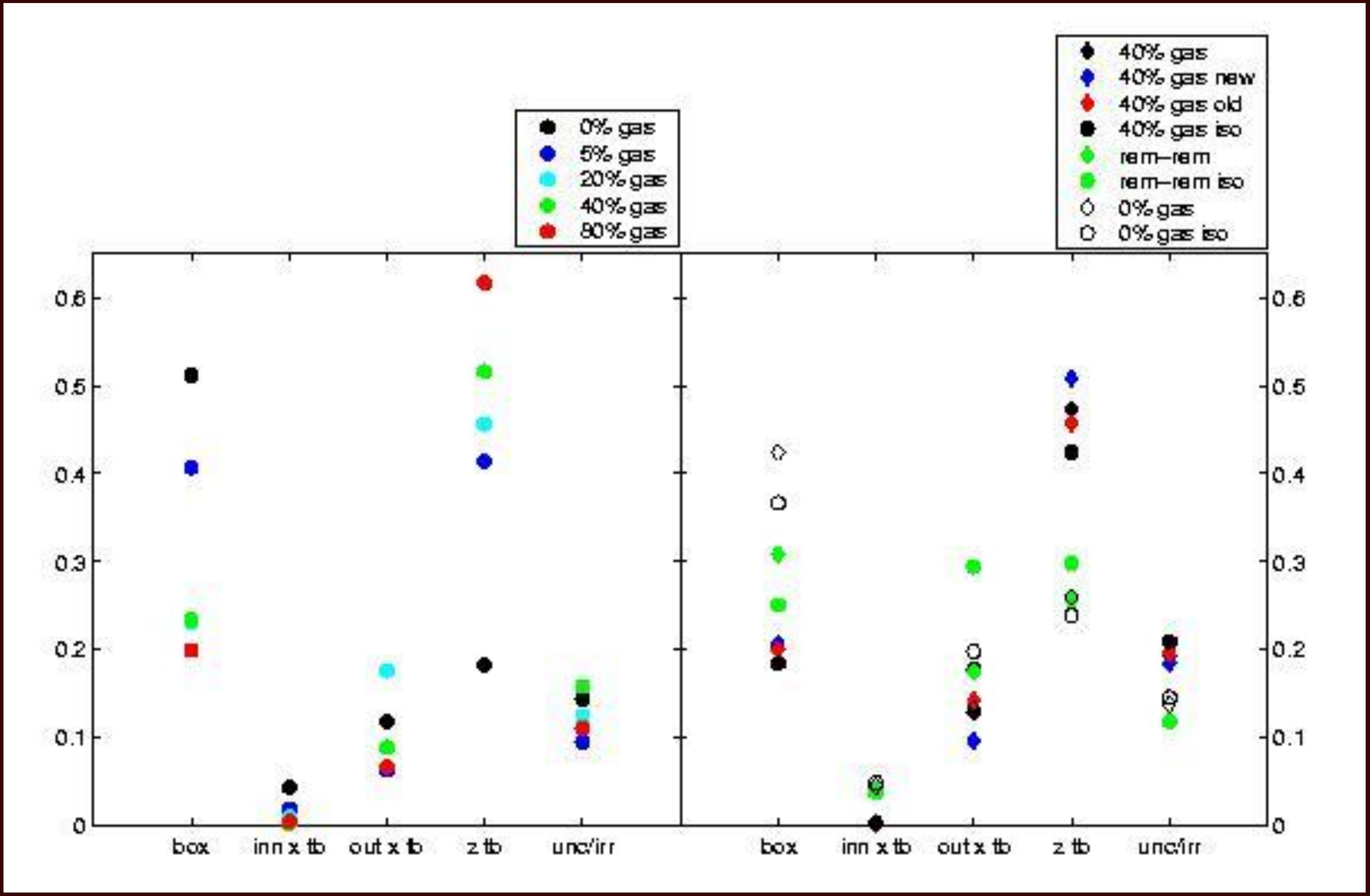
$$\vec{\nabla}^2\Phi_{nlm}(\vec{r}) = 4\pi G\rho_{nlm}(\vec{r})$$

$$\begin{bmatrix}\rho(r,\theta,\phi)\\ \Phi(r,\theta,\phi)\end{bmatrix} = \sum_{n=0}^{\infty}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\begin{bmatrix}\tilde{\rho}_{nl}(r)\\ \tilde{\Phi}_{nl}(r)\end{bmatrix} P_{lm}(\cos\theta)\left[A_{nlm}\cos(m\phi) + B_{nlm}\sin(m\phi)\right]$$

$$\begin{pmatrix}A_{nlm}\\ \\ B_{nlm}\end{pmatrix} = N_{lm}\tilde{A}_{nl}\sum_{k=0}^{N} m_k\tilde{\Phi}_{nl}(r_k)P_{lm}(\cos\theta_k)\begin{bmatrix}\cos(m\phi_k)\\ \\ \sin(m\phi_k)\end{bmatrix}$$

- $(\Phi, \rho)_{000}$ term is just a Hernquist profile.
- Each orbit integrated through 150 periapsis passages using Bulirsch-Stoer method, coordinates evaluated at 4096 points equally spaced in time, then classified.

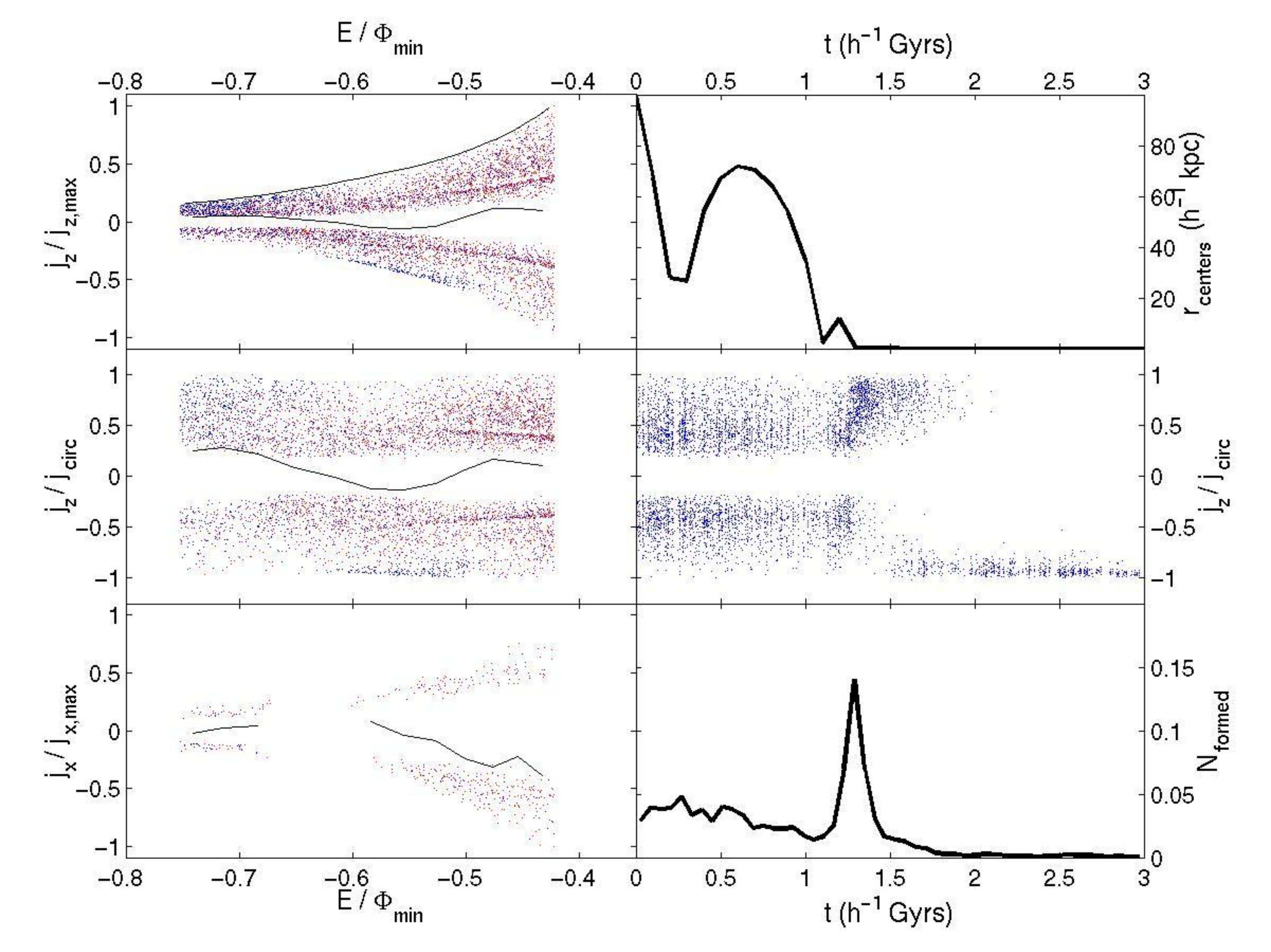
Orbit classification statistics, averaged over merger remnants within ~ the half-light radius



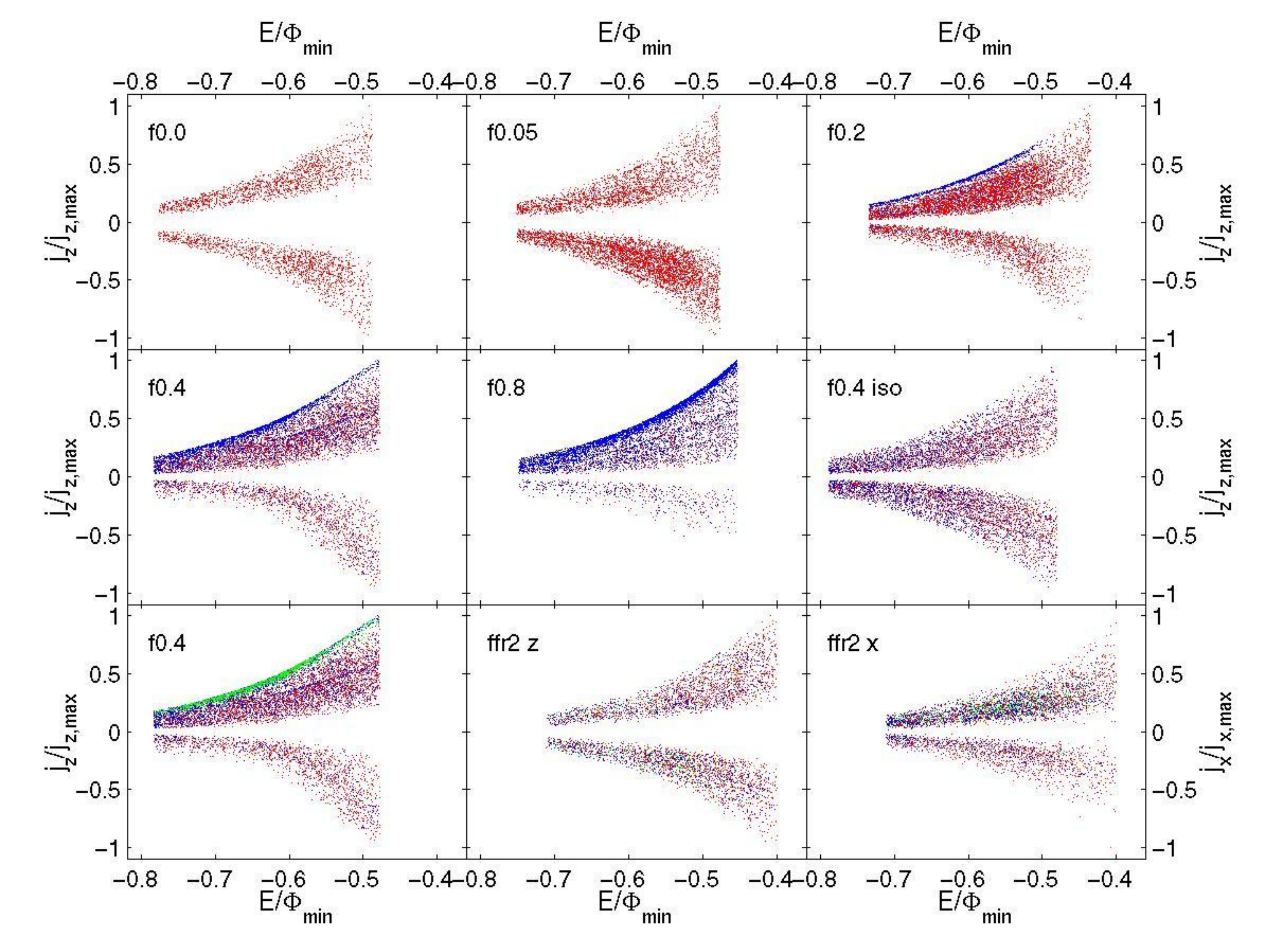
By gas fraction

Collisionless, 40% gas, & re-merger remnants

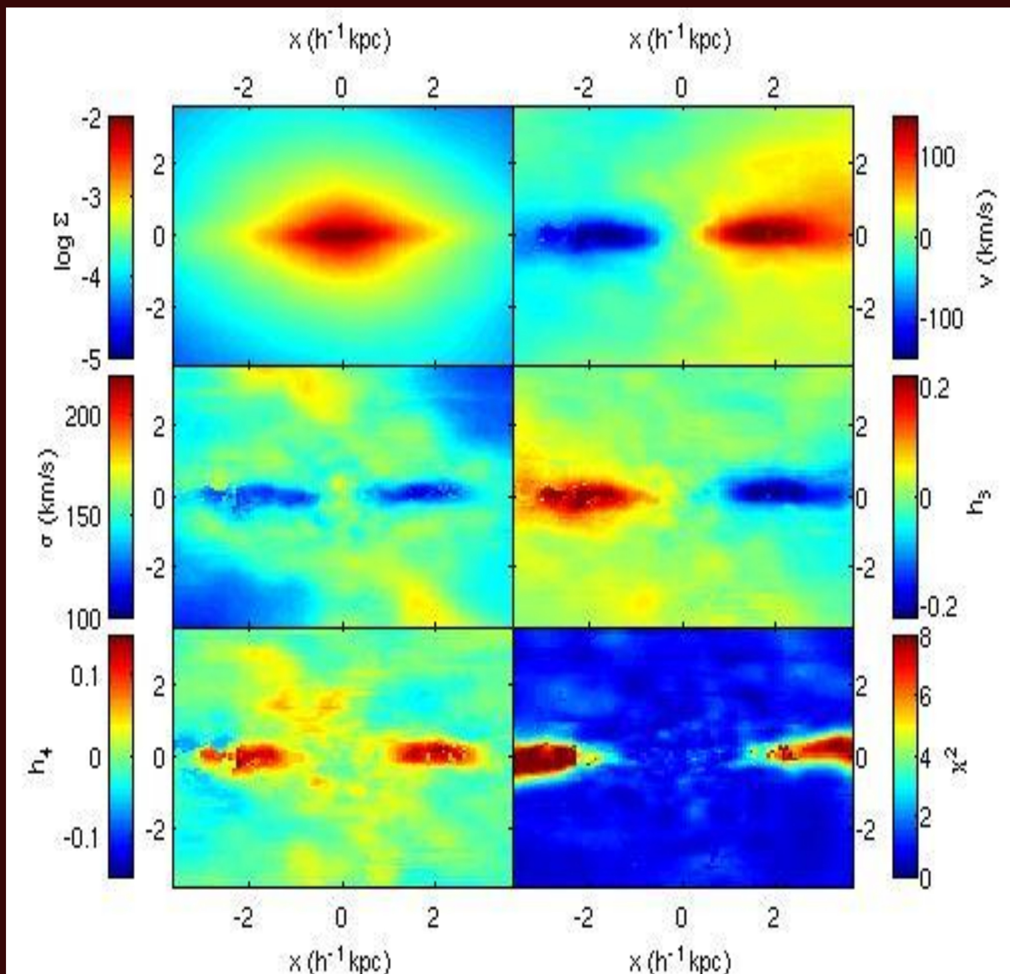
The role of when stars form during the merger (importance of including real time star formation)

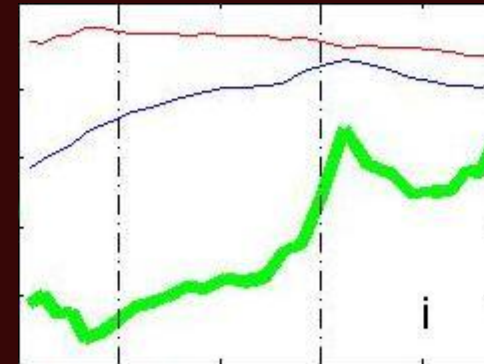


E – J phase space as a function of gas fraction

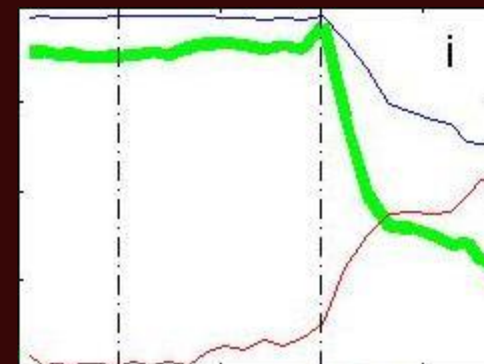


Orbit "i": $(\theta_1, \varphi_1) = (0, 0)$
$(\theta_2, \varphi_2) = (71, 30^\circ)$

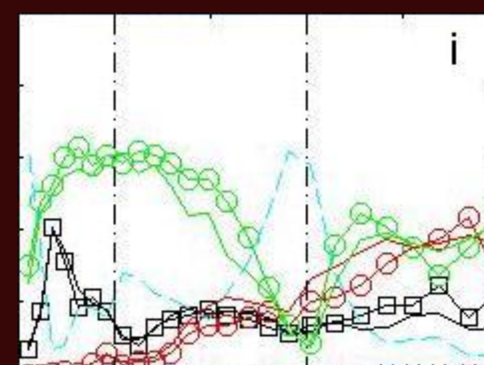




shape

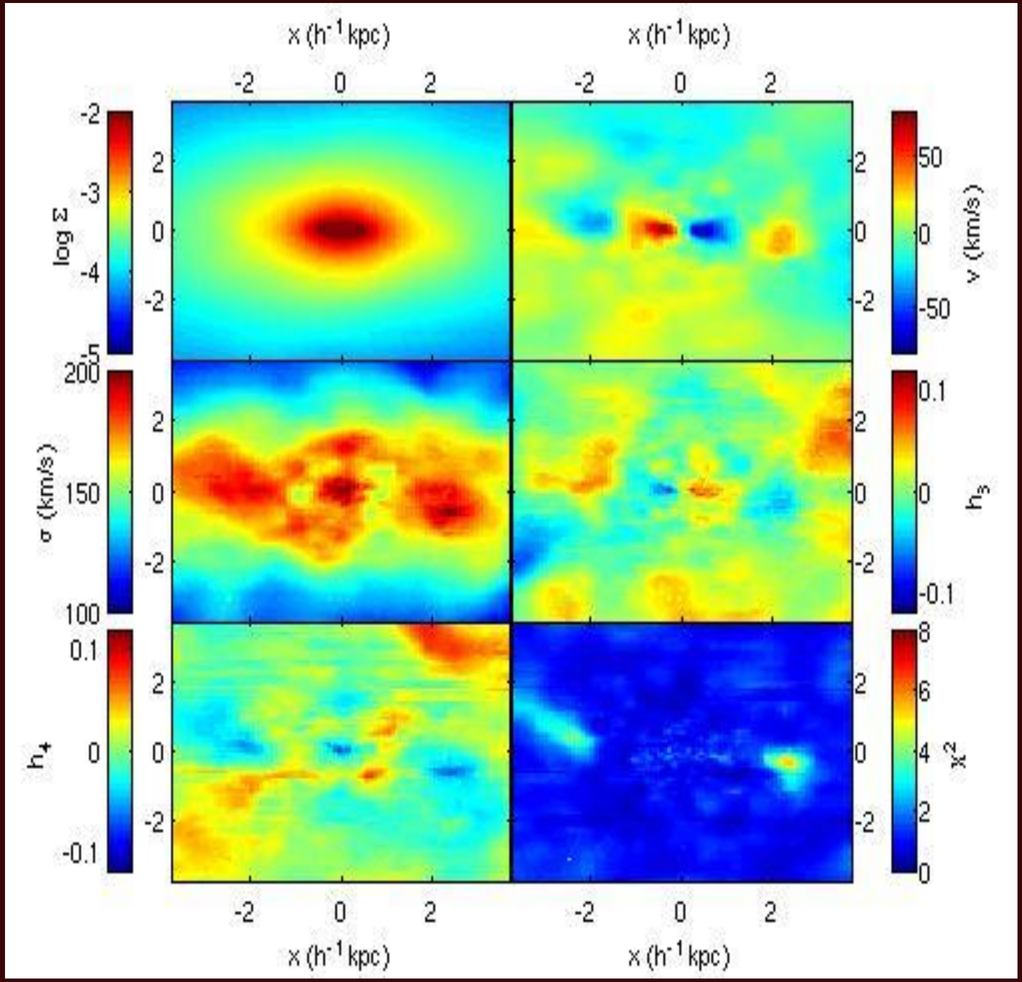


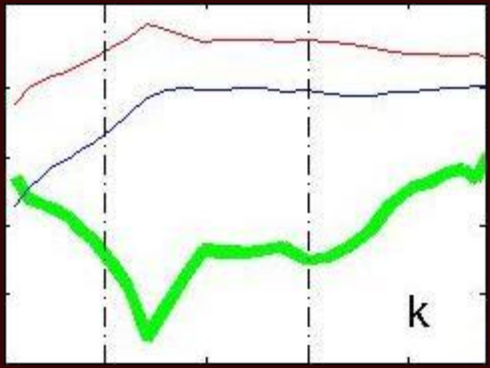
orientation



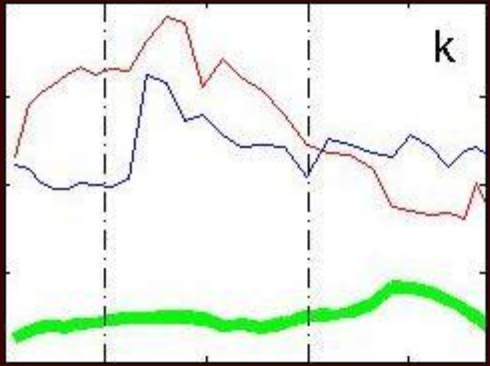
orbit structure

Orbit "k": $(\theta_1, \varphi_1) = (-109, -30^\circ)$
$(\theta_2, \varphi_2) = (71, -30^\circ)$

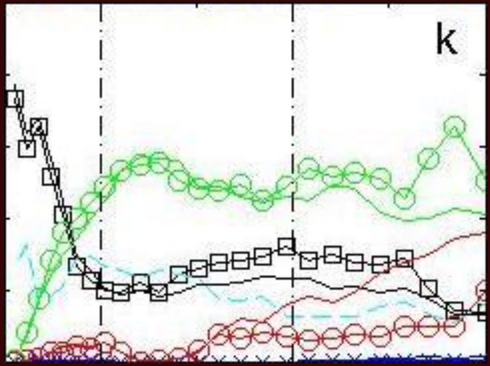




shape

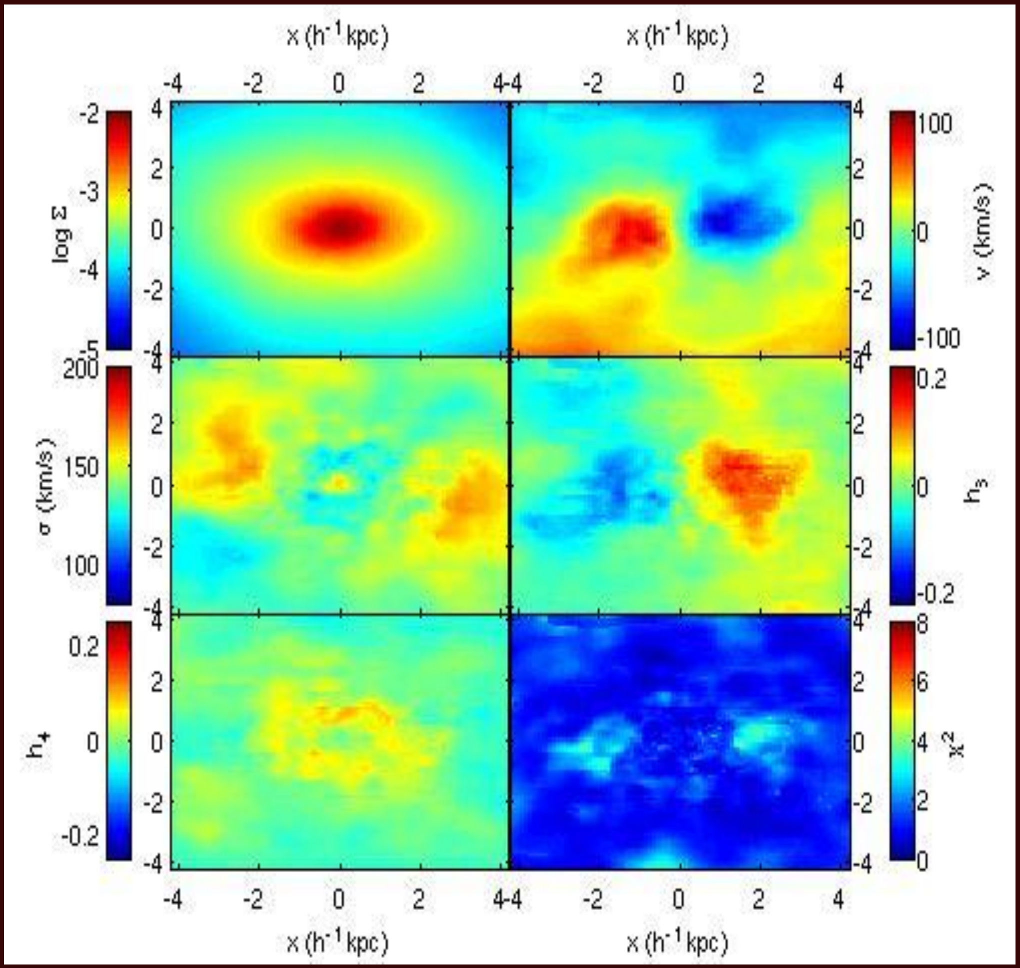


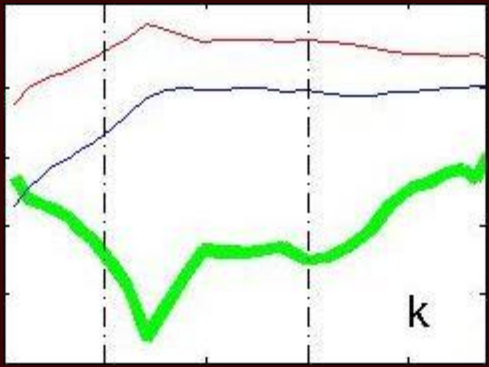
orientation



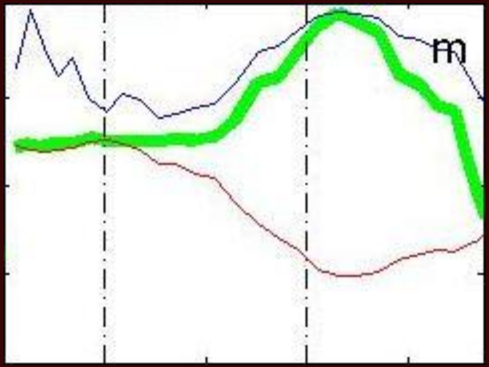
orbit structure

Orbit "m": $(\theta_1, \varphi_1) = (0, 0)$
$(\theta_2, \varphi_2) = (71, 90^\circ)$

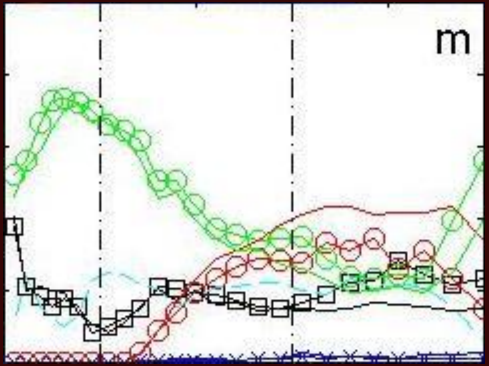




shape

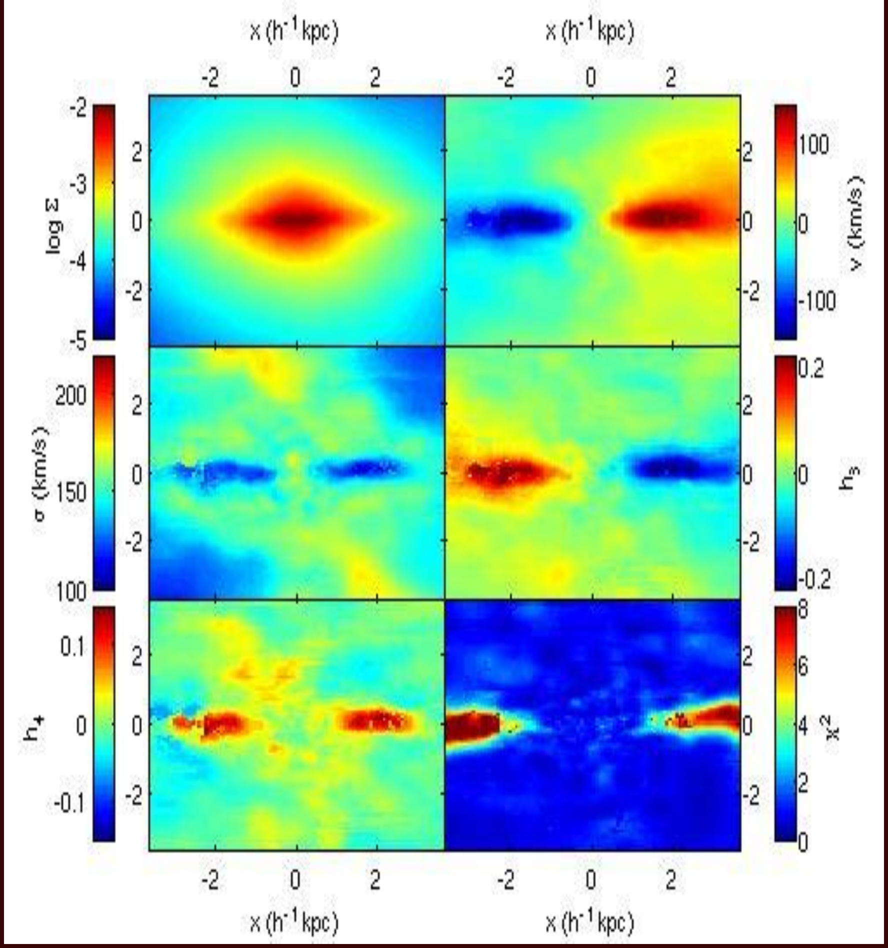


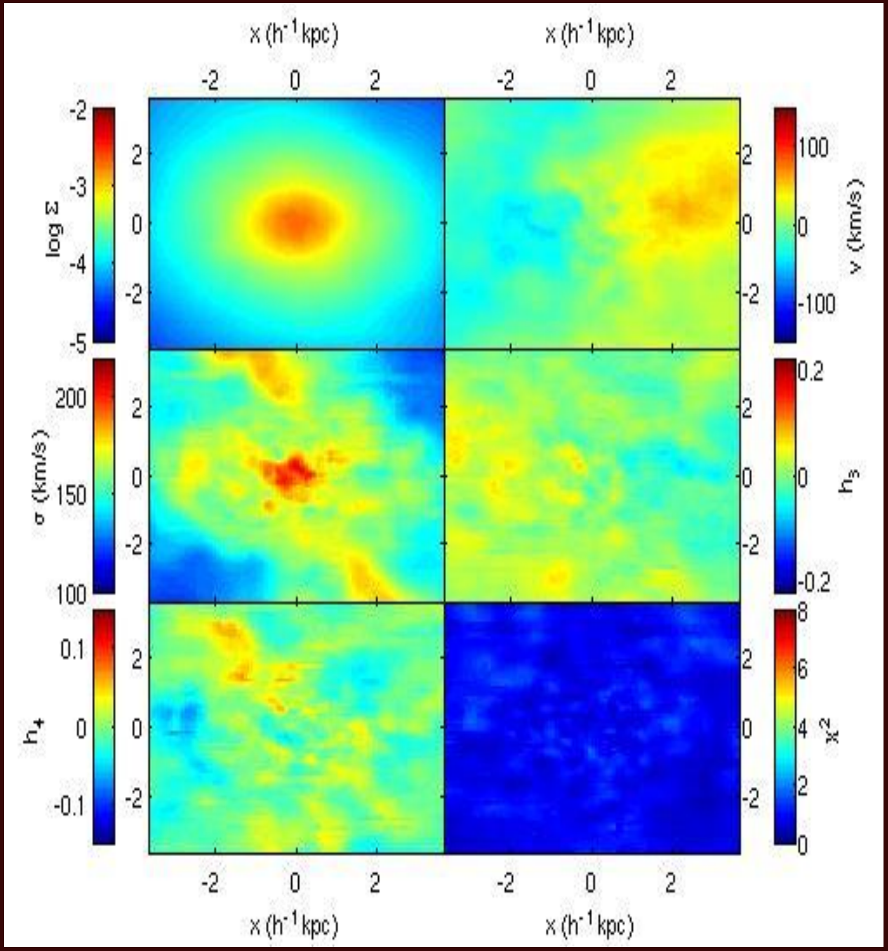
orientation



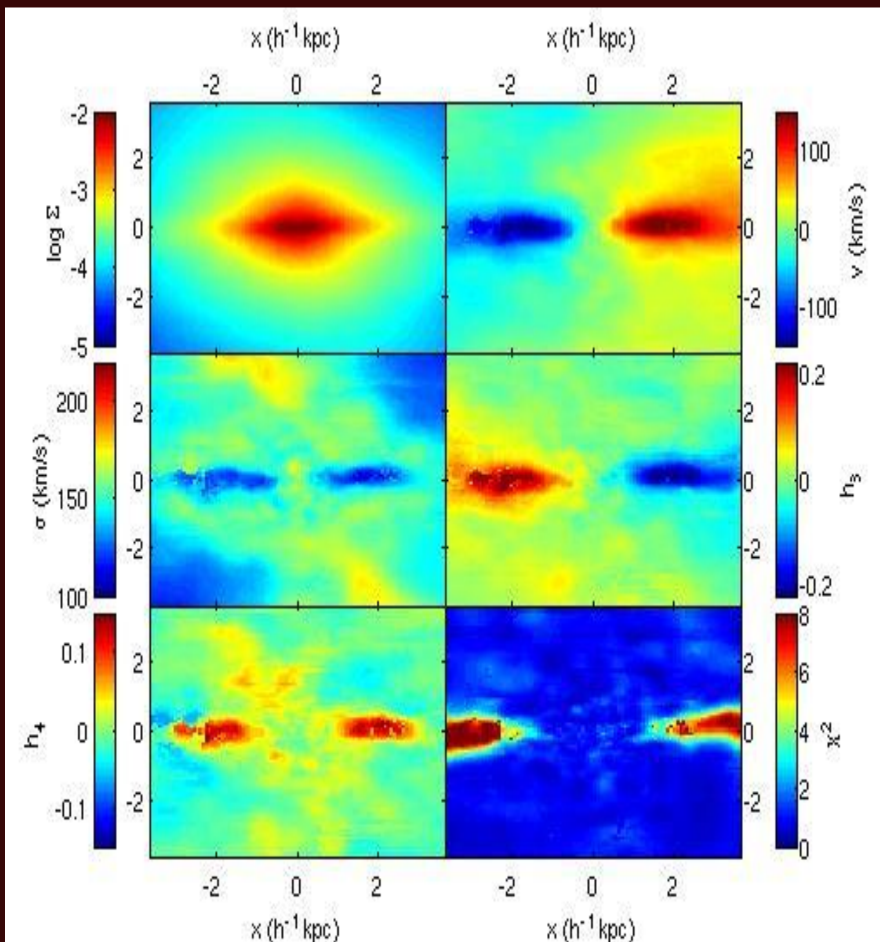
orbit structure

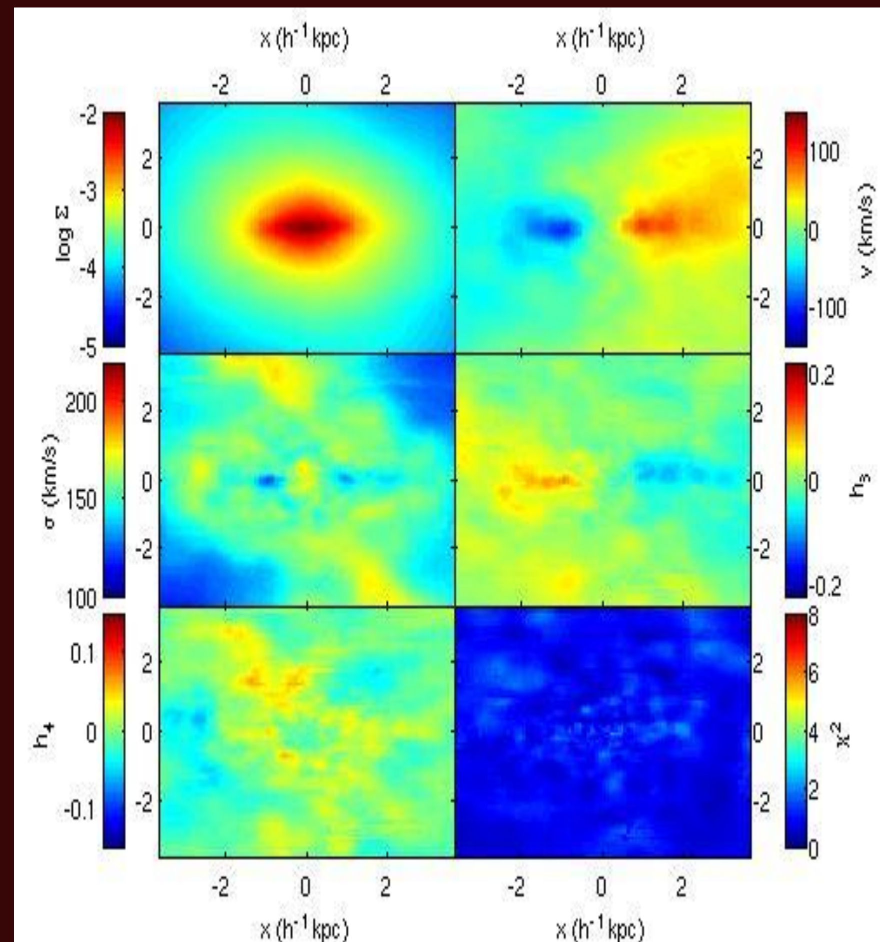
Orbit i – edge on: Contribution of new stars



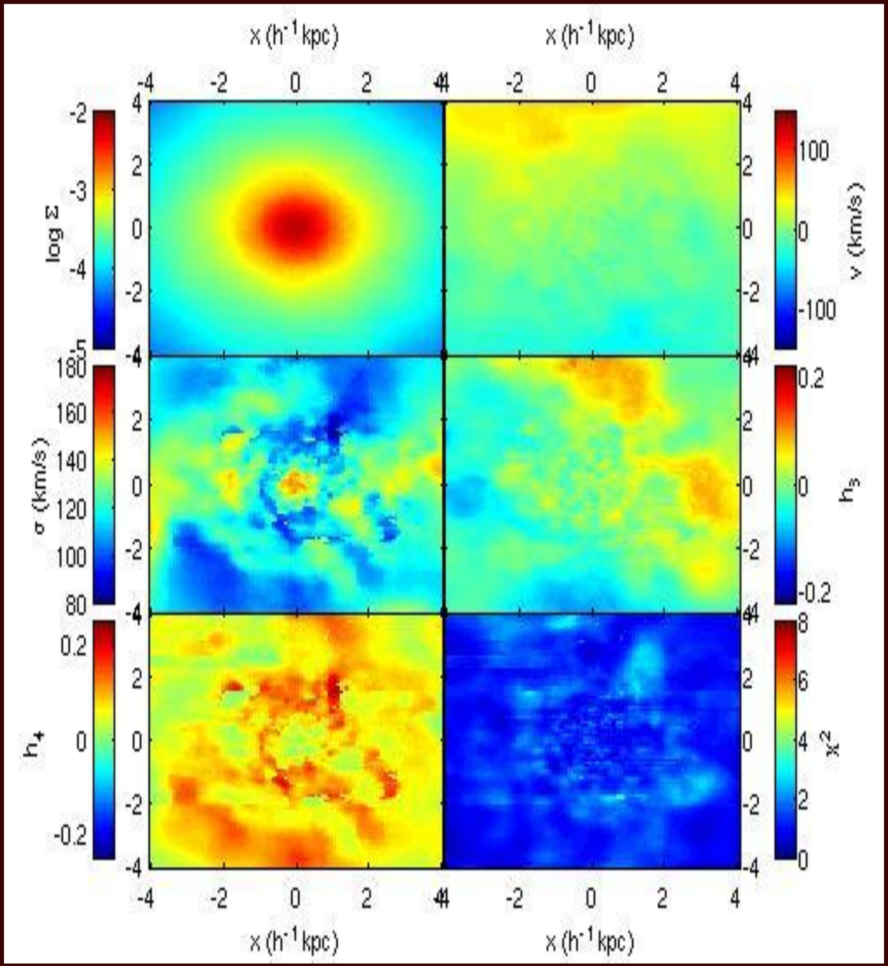


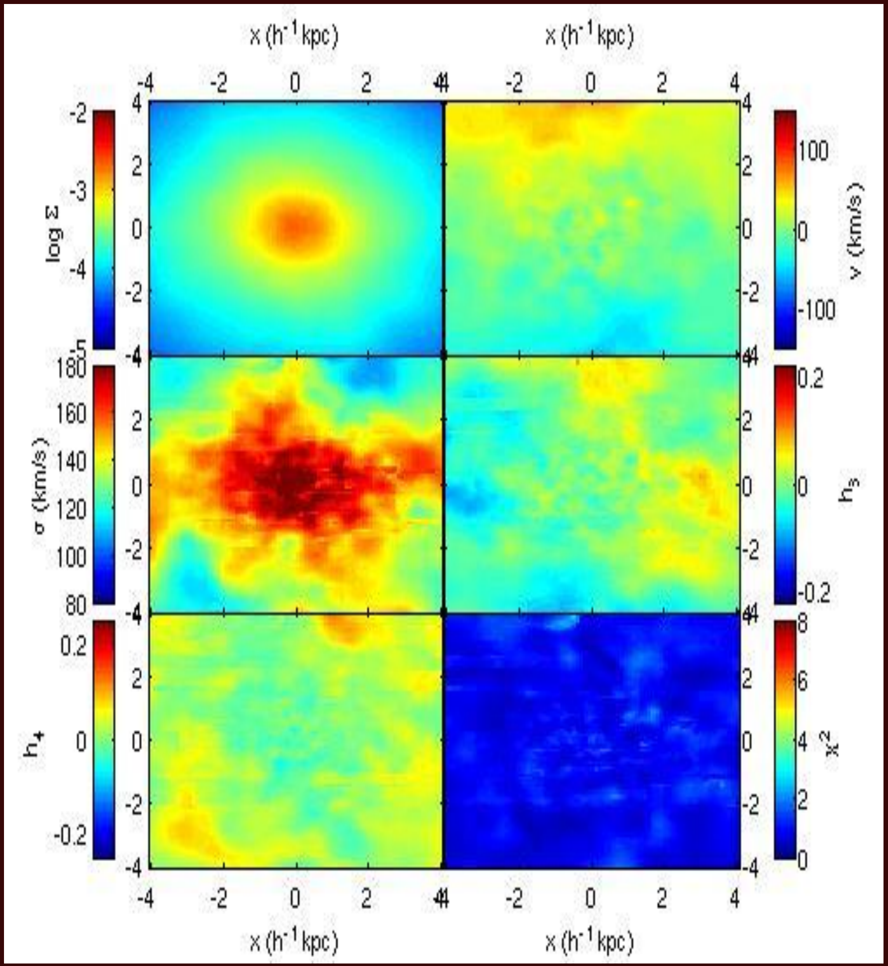
Orbit i – edge on: Contribution of last 15% of new stars to form



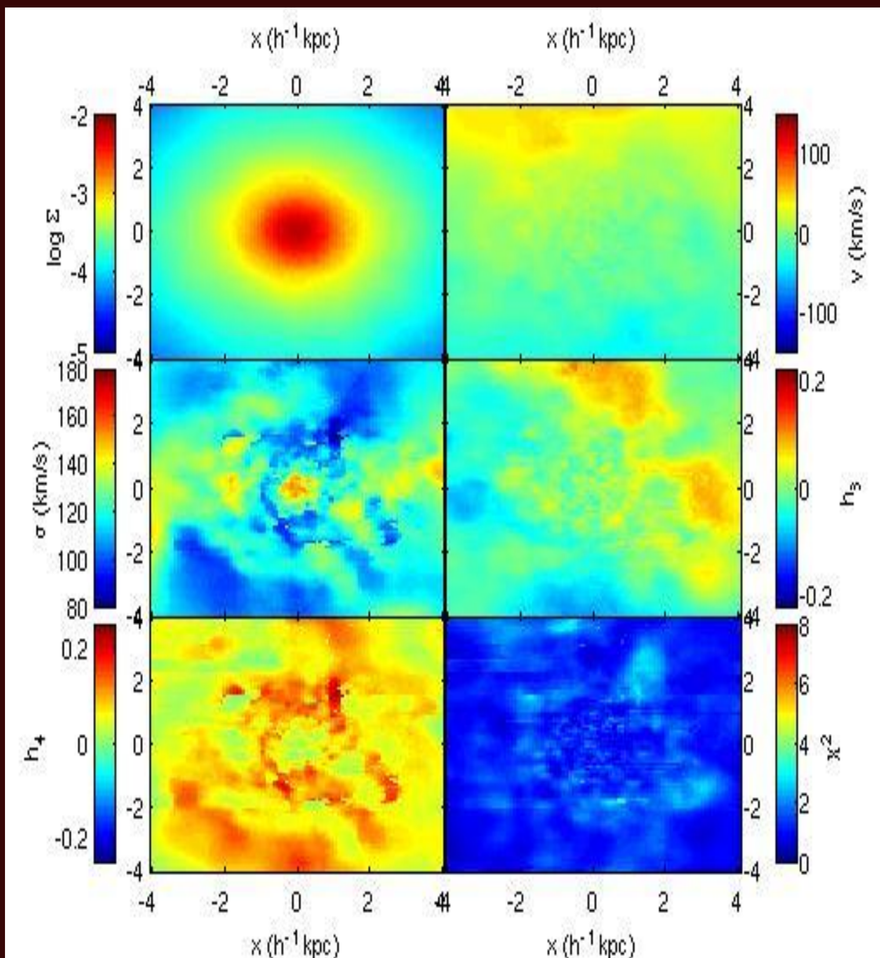


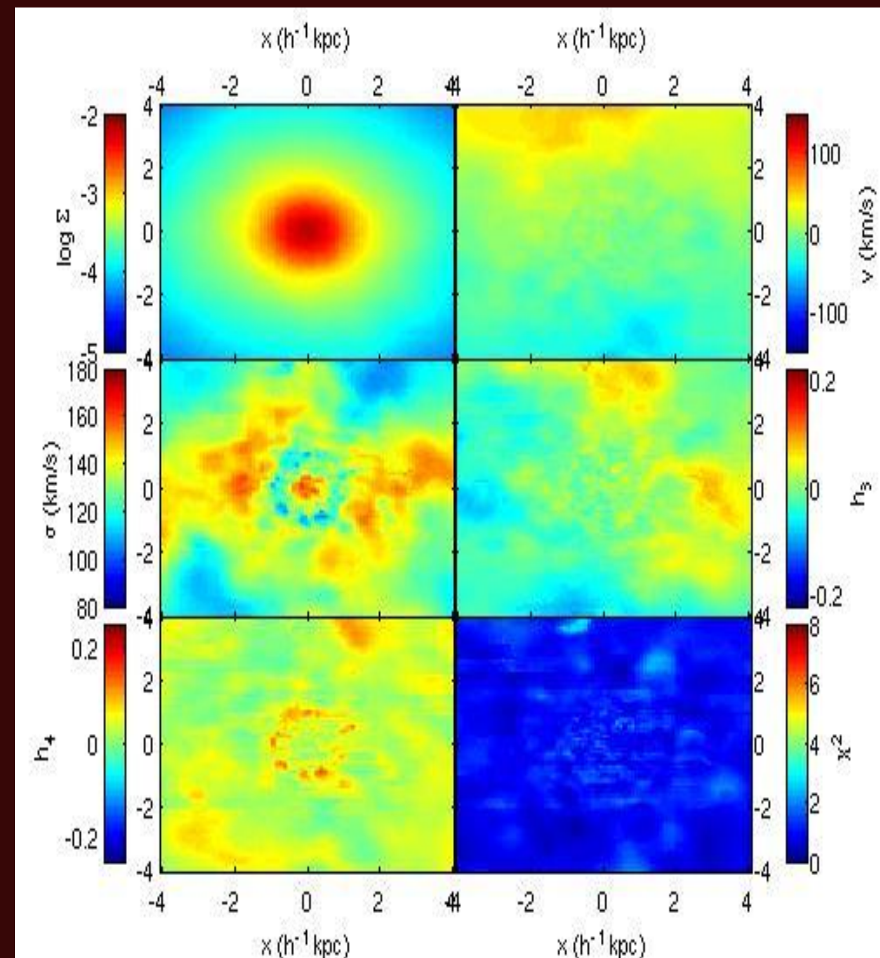
Orbit i – face on: Contribution of new stars



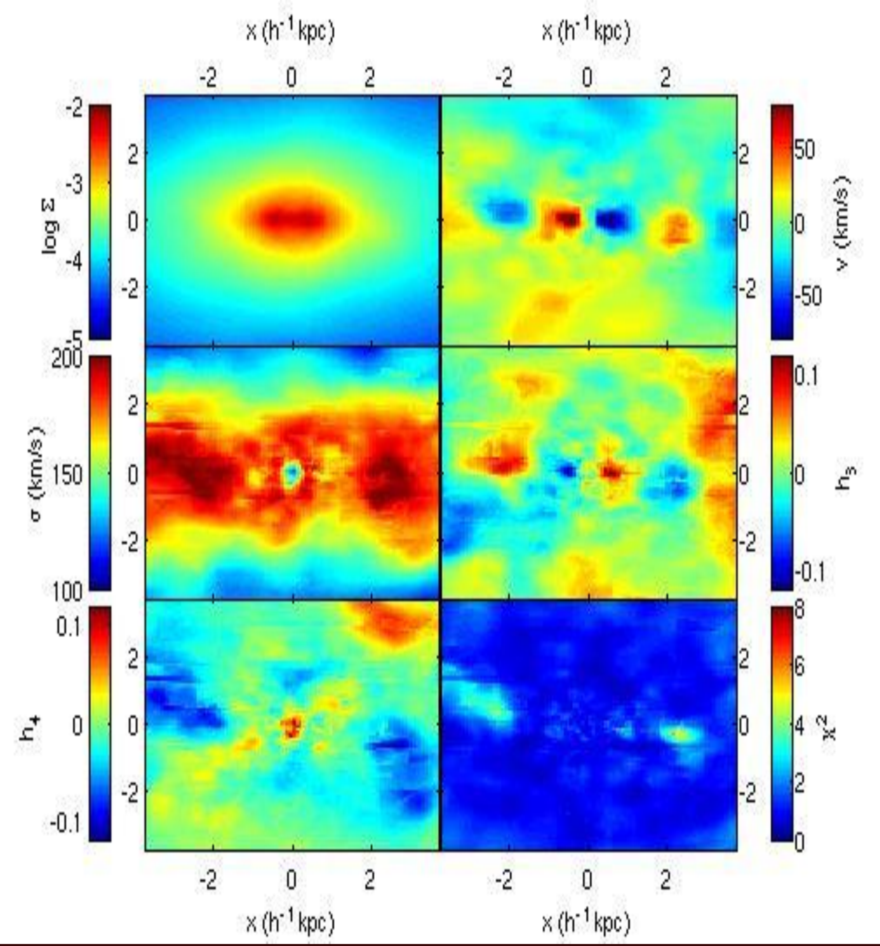


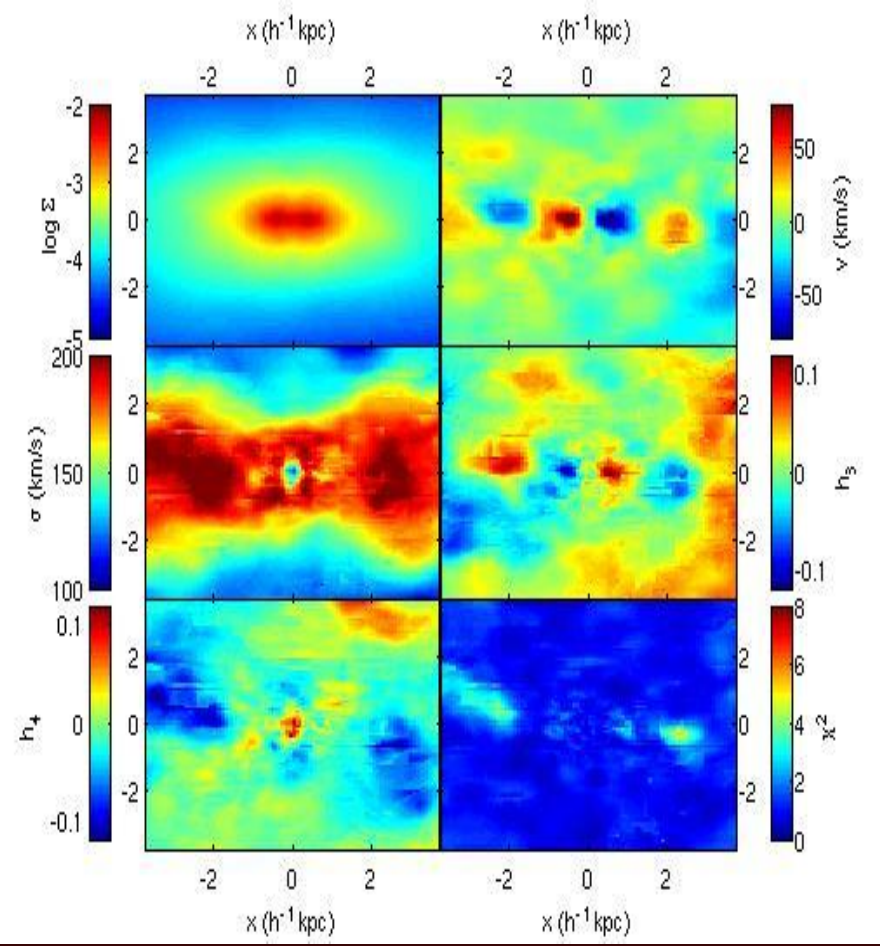
Orbit i – face on: Contribution of last 15% of new stars to form





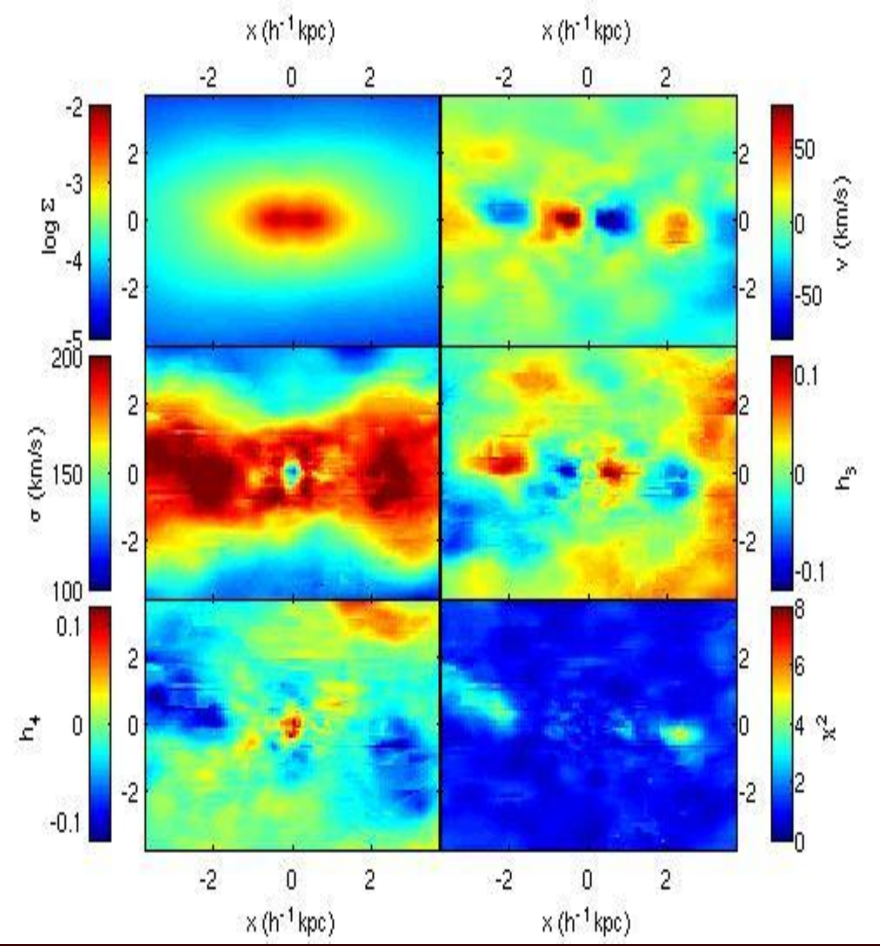
Orbit k – edge on: Contribution of x-tube orbits

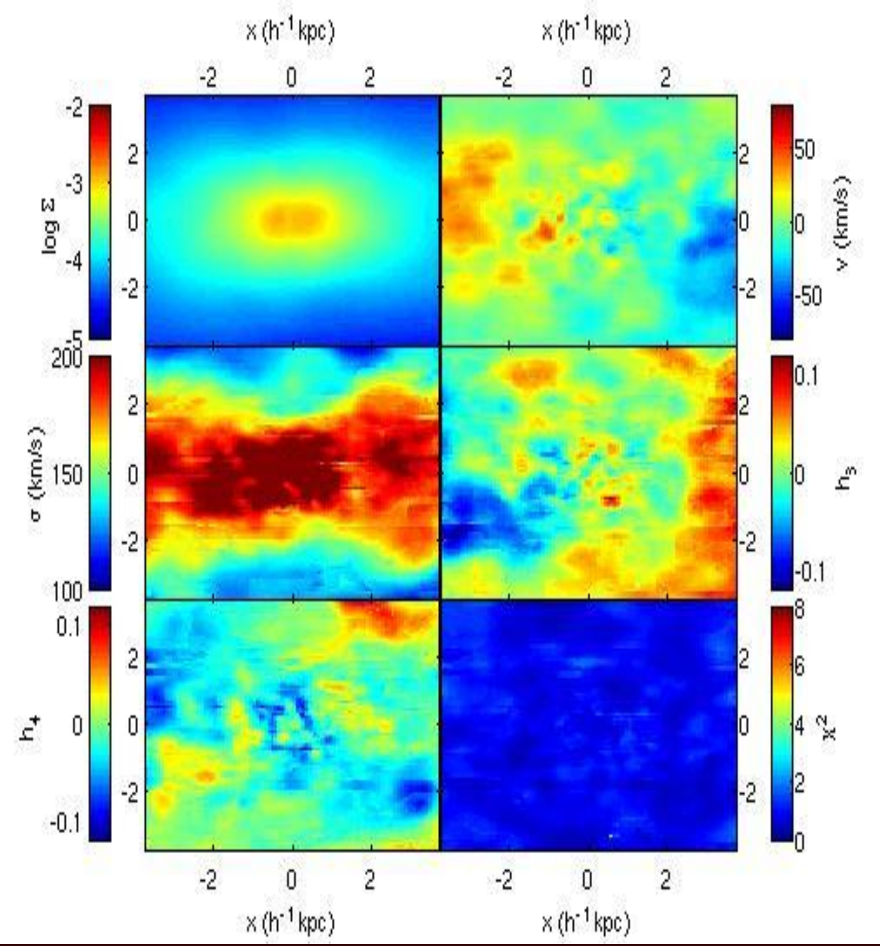




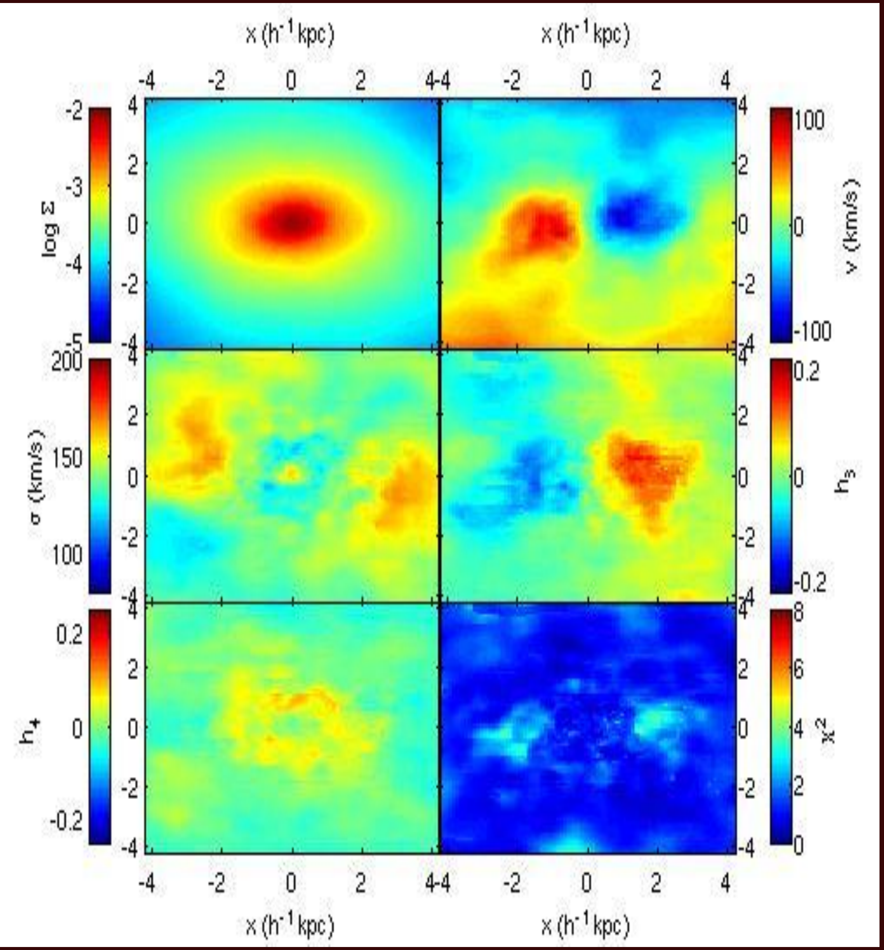
Boxes removed to emphasize rotation

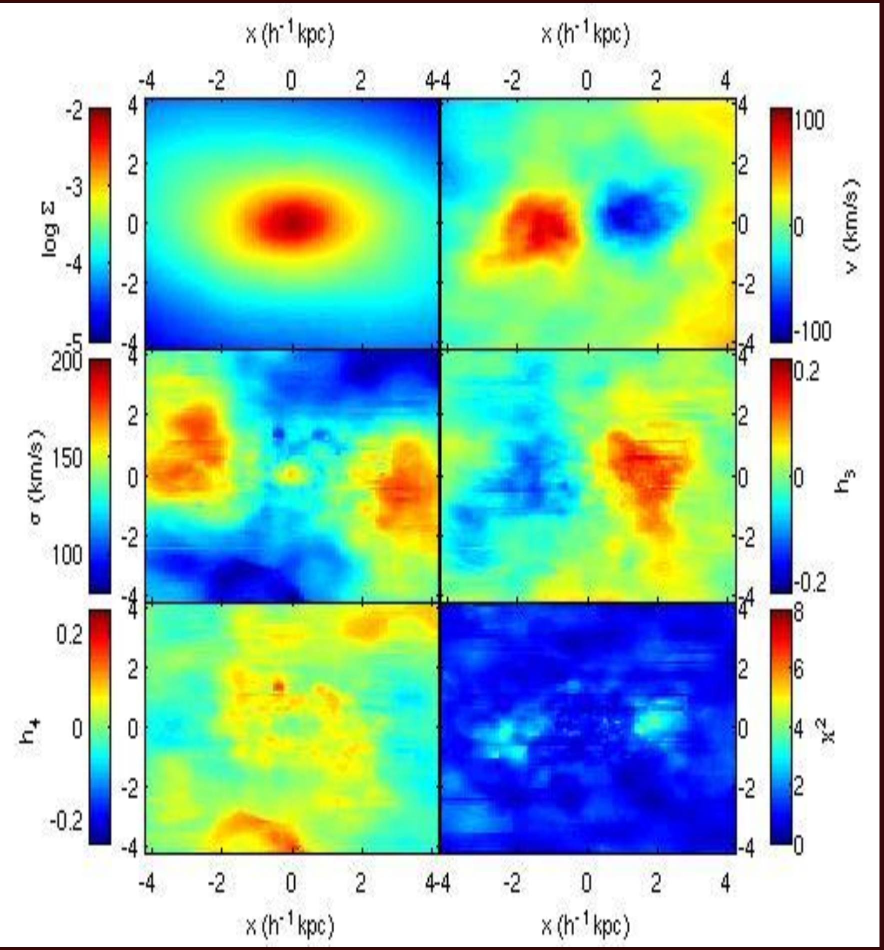
Orbit k – edge on: Contribution of “old” z-tube orbits

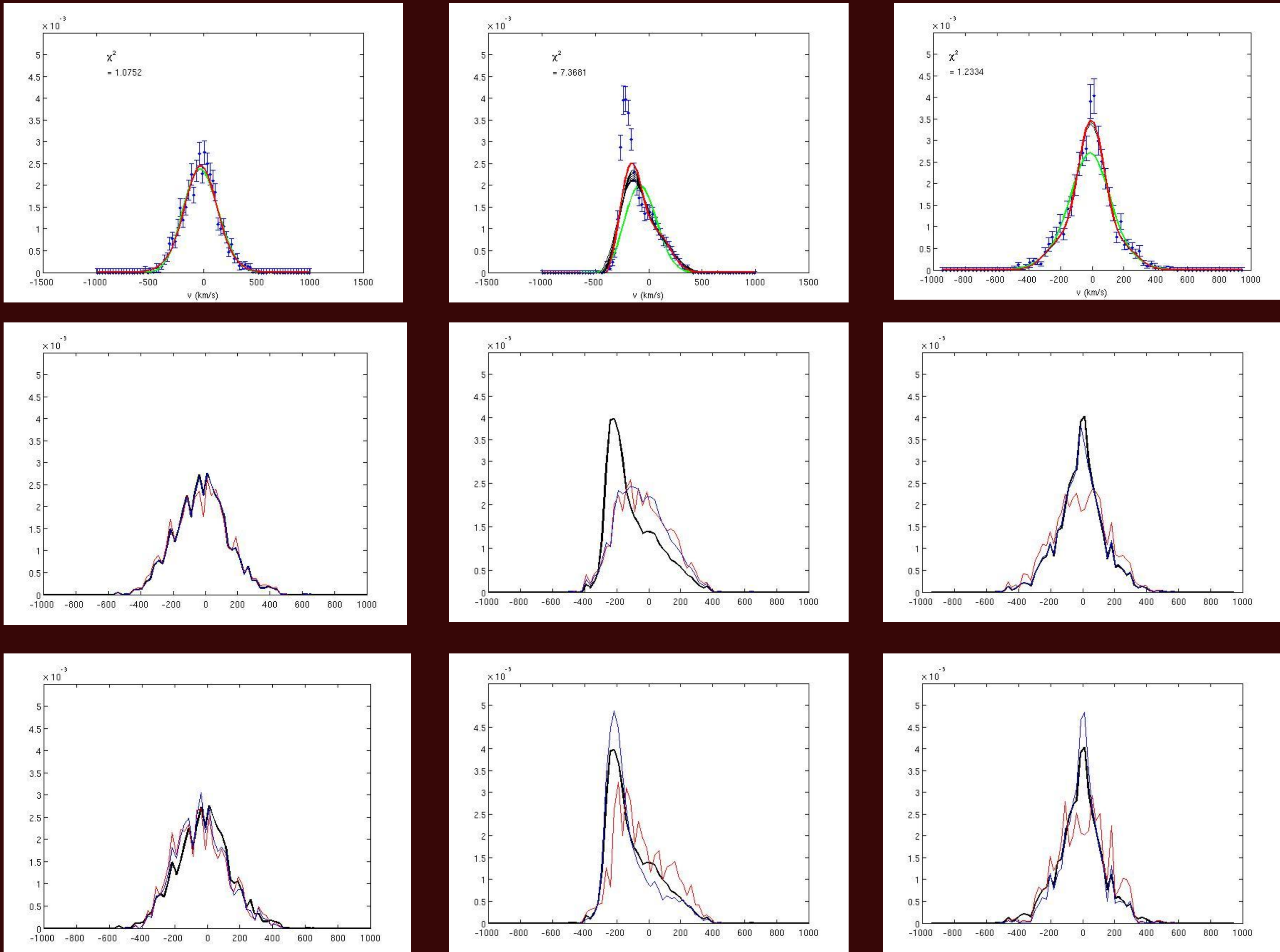




Orbit m – θ ~ 60°: Contribution of x-tube orbits

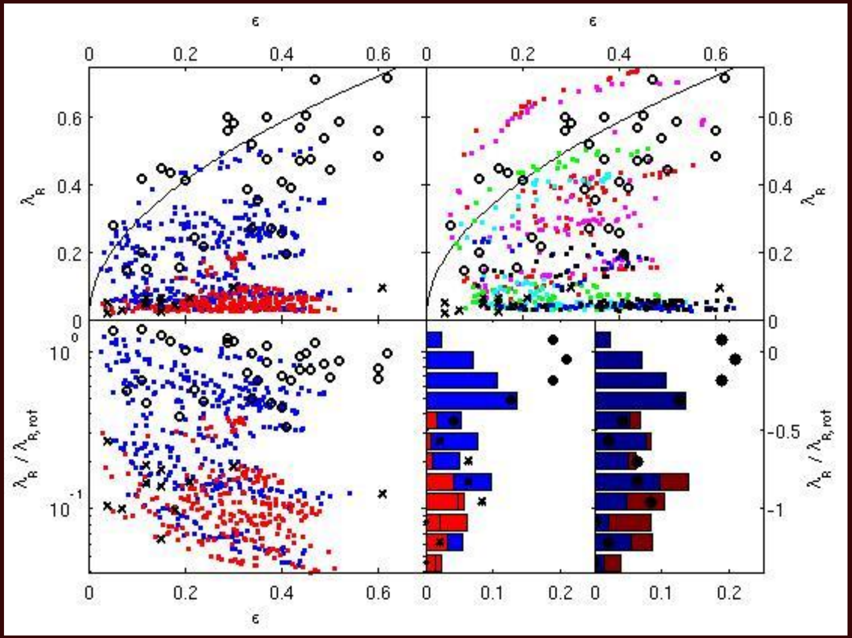




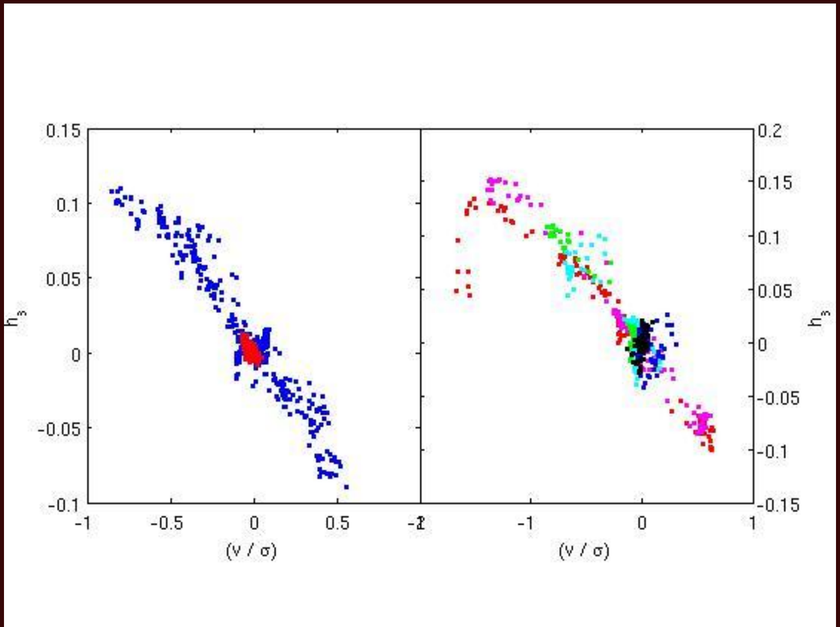


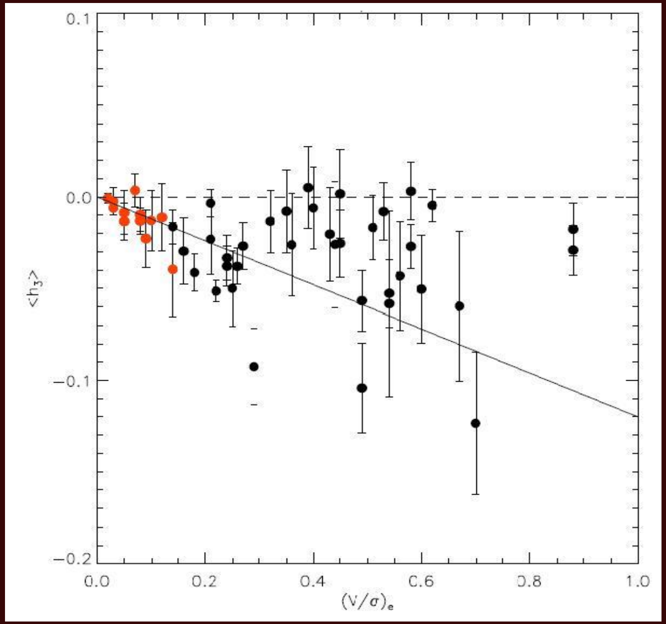
χ²
= 1.0752
χ²
= 7.3681
χ²
= 1.2334
× 10⁻³
v (km/s)

Global properties of remnants derived from 2D maps



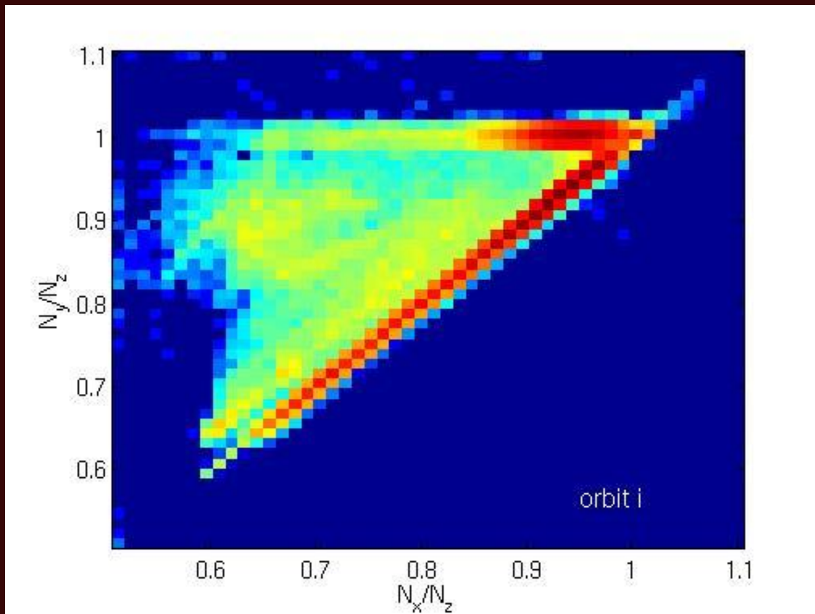
- Gas-rich disk-disk merger remnants are much faster rotators than re-merger remnants.
- Both sets of remnants show negative correlations between h_3 and v/σ, but the disk-disk remnants have far more extreme values of both quantities.

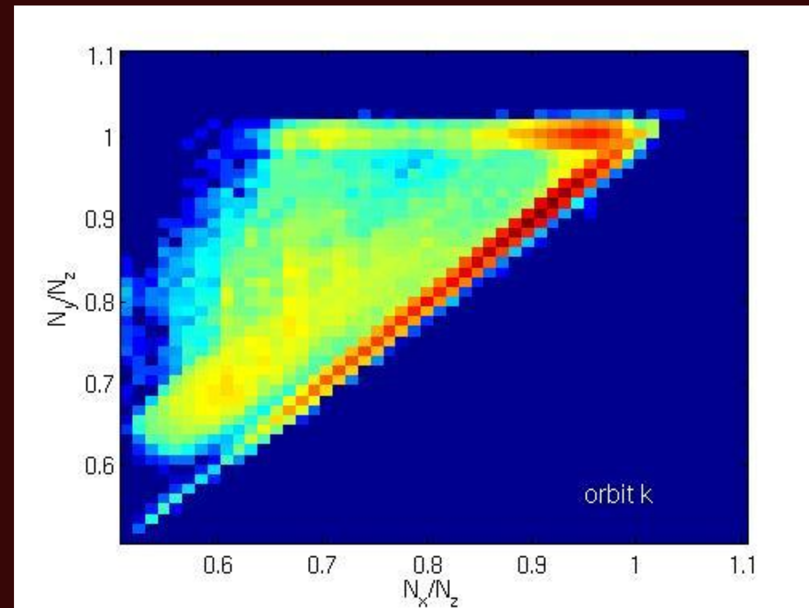


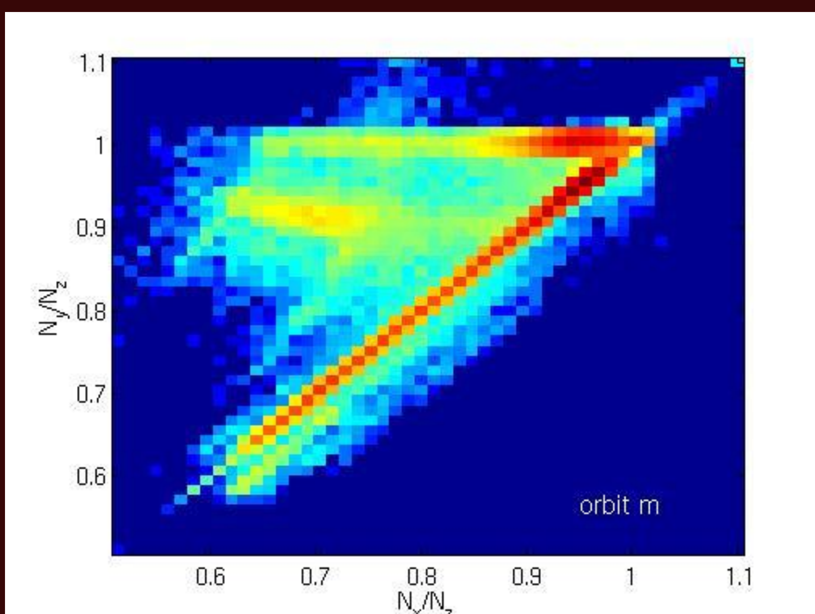


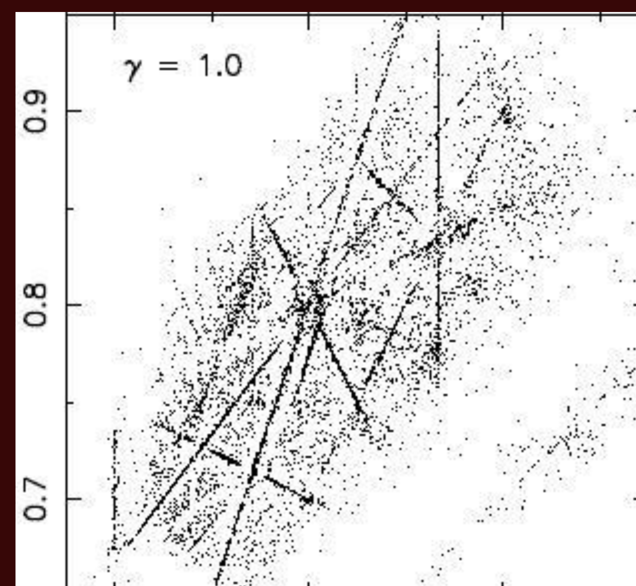
Krajnovic et al. 2008

Resonance structure



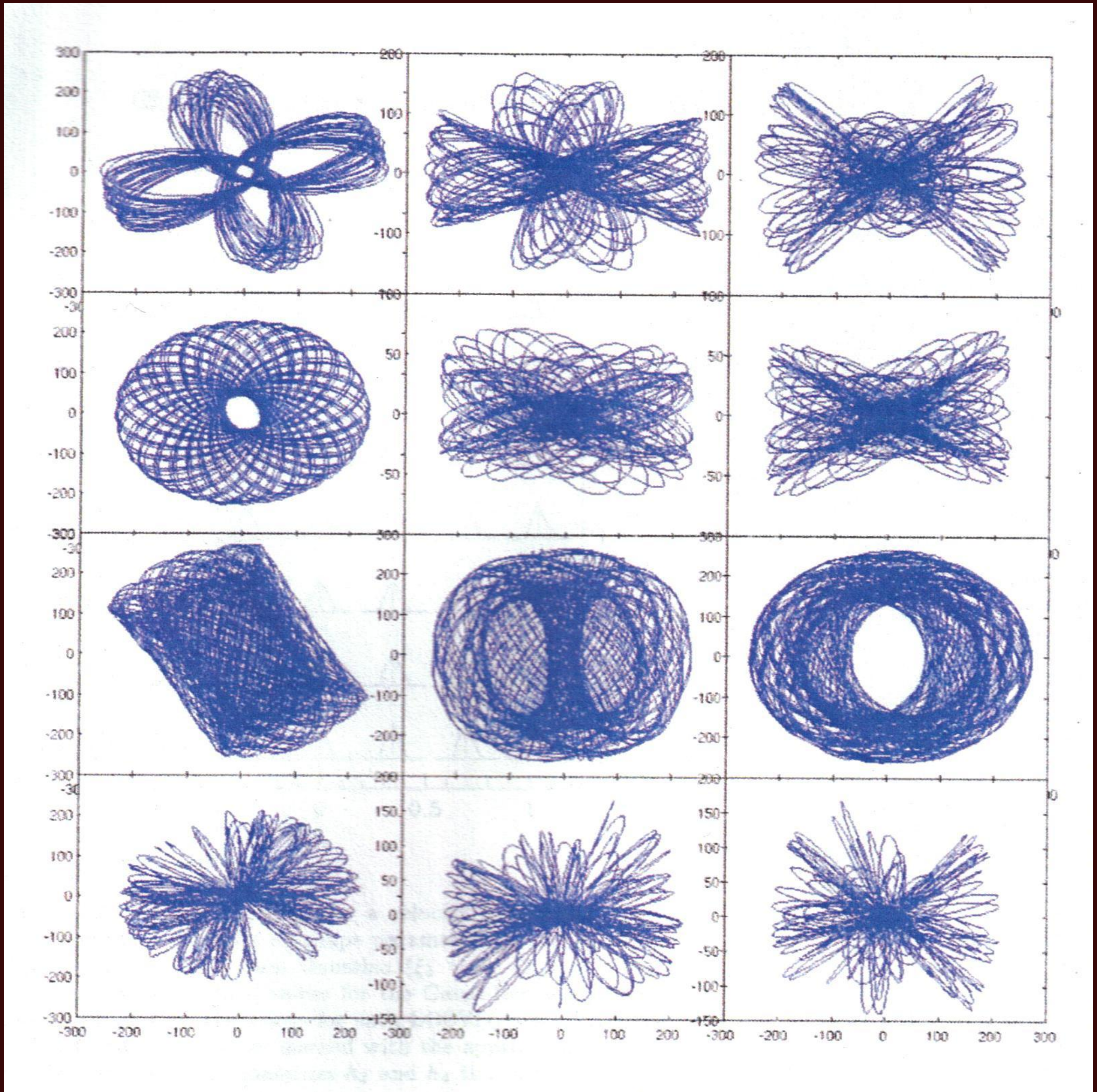






Valluri & Merritt 1997

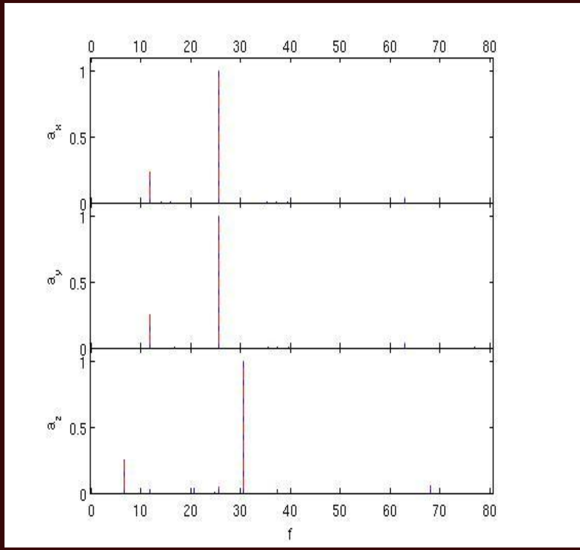
Noisy orbits in simulated merger remnants

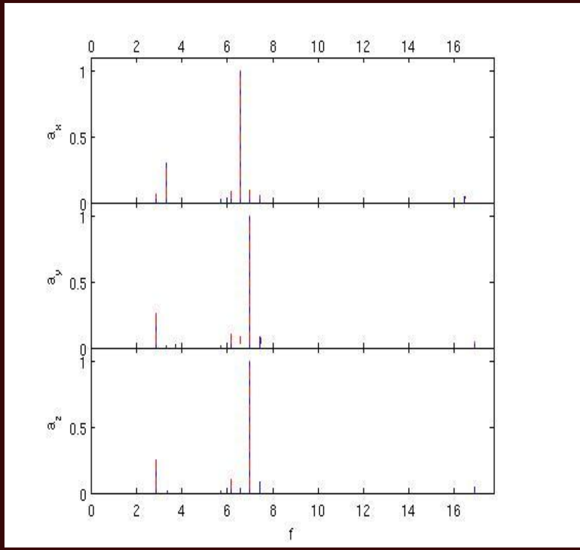


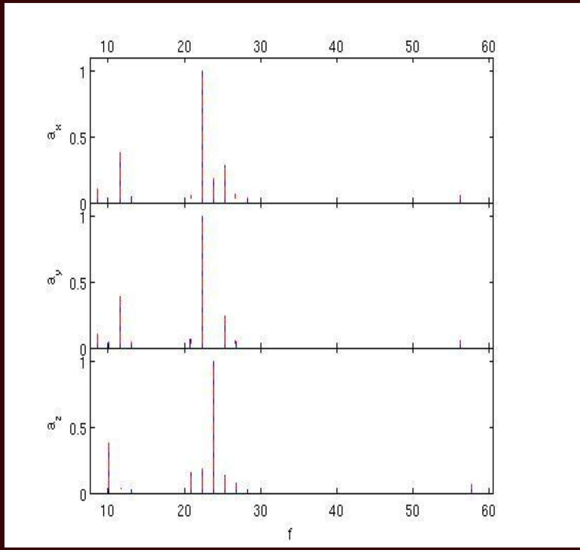
From Gaspard Clozel's senior thesis

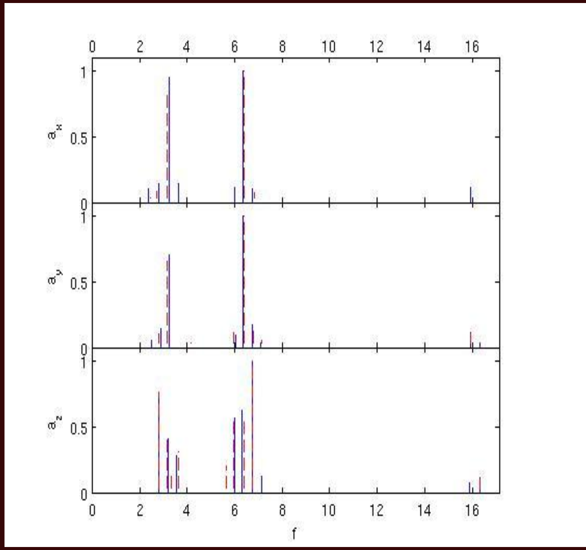
- Physical or Numerical?
- Numerical perturbations:
  - particle discreteness
  - truncation of SCF expansion
- Physical perturbations:
  - radial variation of ellipticity/orientation
  - central mass concentrations
  - streams, embedded disks, etc.

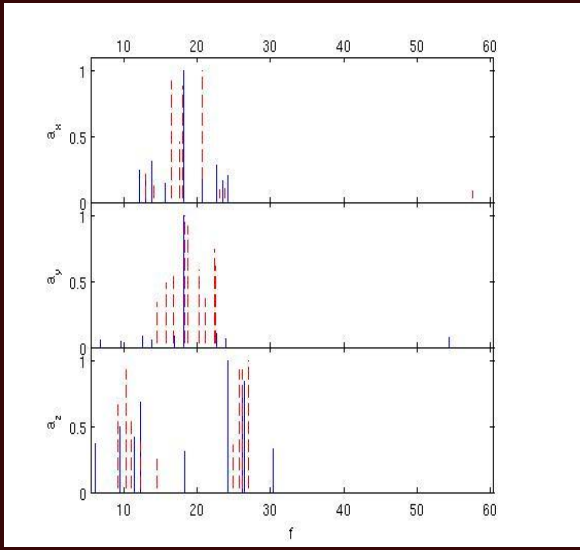
Quantifying the noise with spectral analysis

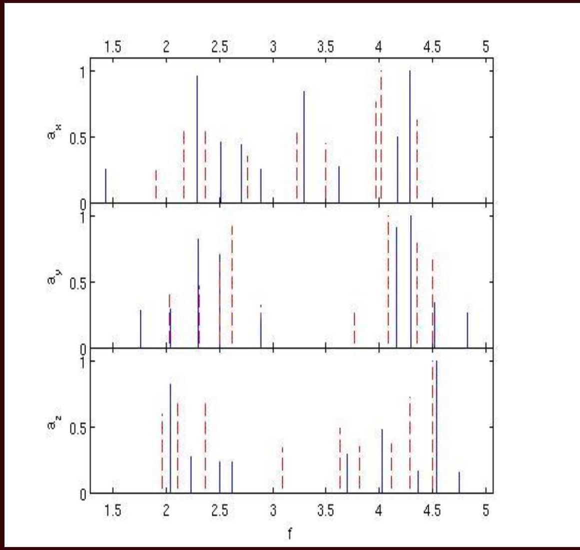




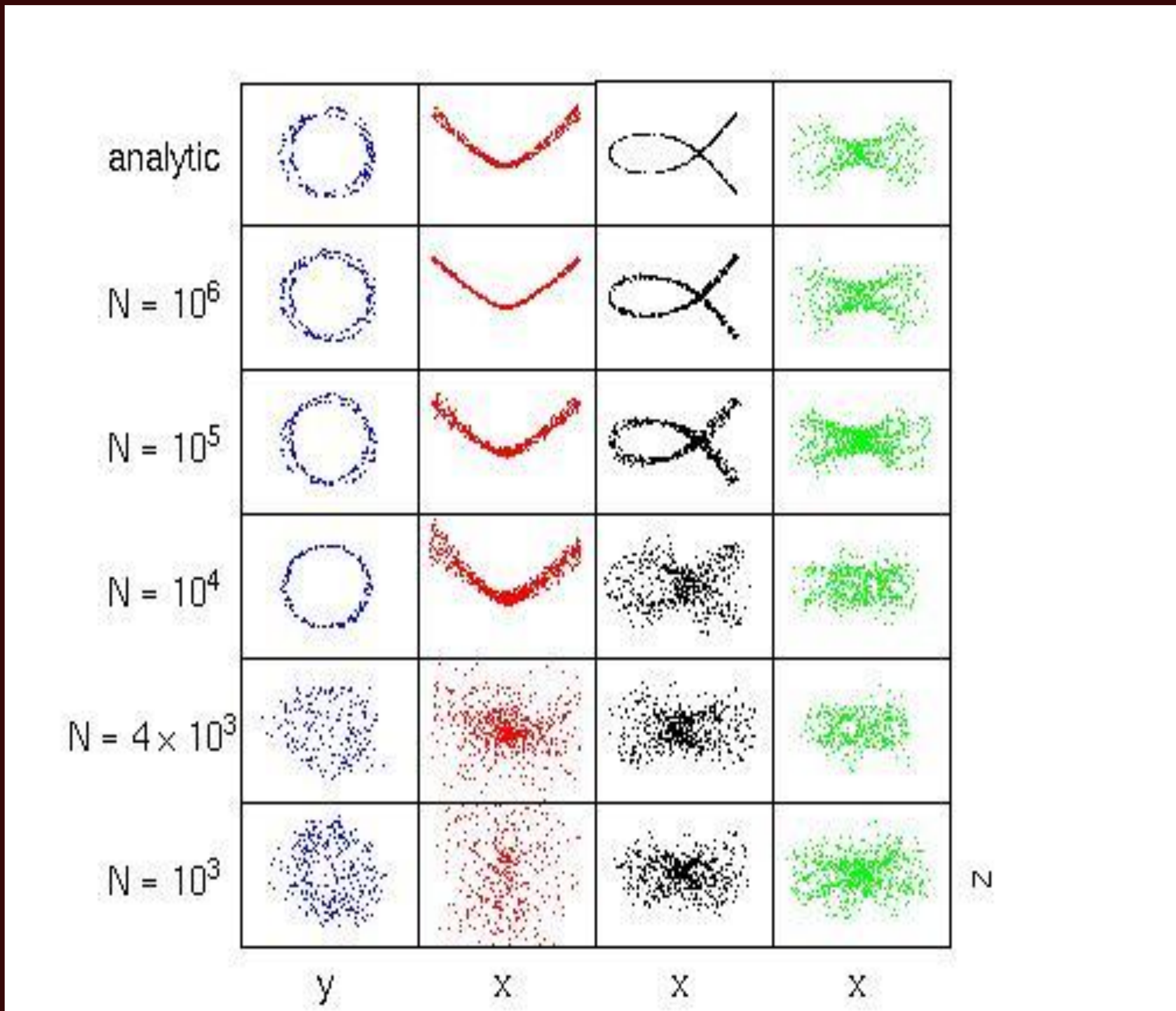








Effect of particle discreteness – SCF does not mitigate two-body relaxation!



Plot by Josh Glaser (summer student)

n_{relax}

$\approx N / (8 \ln \Lambda)$

$\rightarrow N \approx 4000$

Summary

• Elliptical galaxies display complex distribution functions that contain a wealth of information about their formation history. N-body simulations are an important tool to parse this information.

• For instance, a gas component in a disk-disk merger leads to a more oblate remnant with a higher fraction of short-axis tube orbits.

• Qualitative trends in 2D kinematic data are reproduced in simulated merger remnants.

• The orbits in simulated remnants are noisy; the (physical/numerical) perturbations that are primarily responsible for this stochasticity deserve further study.

Future work

• Quantitative comparison with SAURON data.

• Schwarzschild modelling of simulated remnants. Do we get it right? Degeneracies?

• More simulations, covering wider range of ICs; cosmologically motivated ICs; effect of environment.

• Exploration of sources of orbital stochasticity in simulated remnants. Influence on galactic structure/evolution?