Inner and outer kinematics and dynamics of merger remnants → Galactic Archaeology

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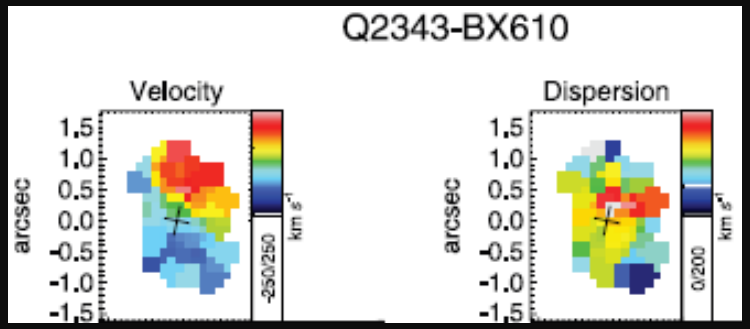
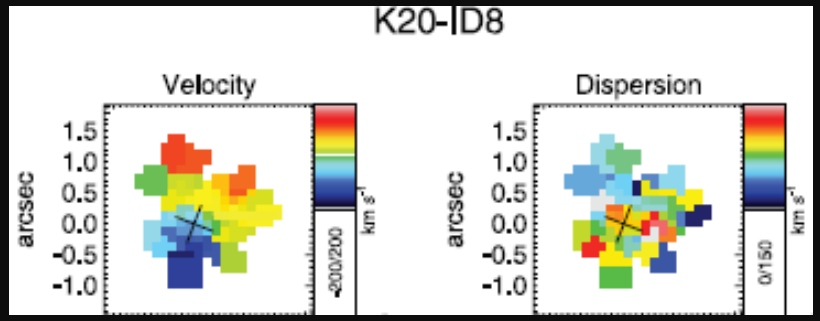
Motivation

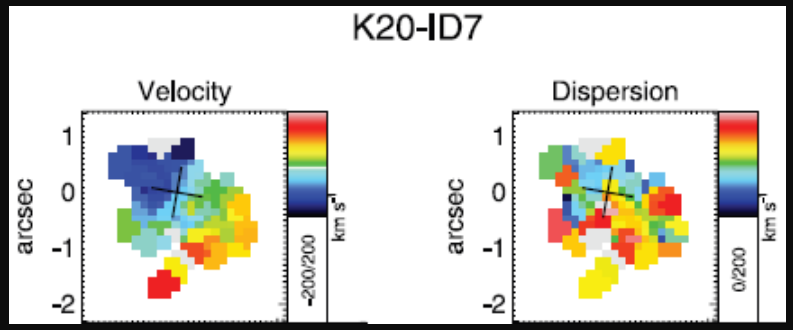
- How did local elliptical galaxies form? How did GCs form inside them?

- Incomplete violent relaxation in mergers -> Galactic archeology in a *statistical* sense

- SAURON, GC/PNe kinematics -> full 6D distribution functions of local ellipticals







KINEMETRY OF SINS HIGH-REDSHIFT STAR-FORMING GALAXIES: DISTINGUISHING ROTATING DISKS FROM MAJOR MERGERS[1]

Shapiro et al. 2008

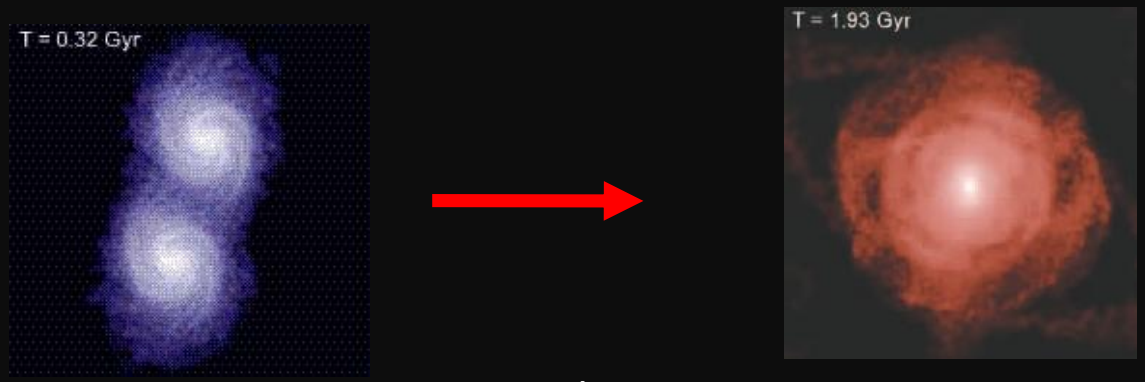
Elliptical galaxies as mergers of spirals

Toomre & Toomre 1972; Toomre 1977

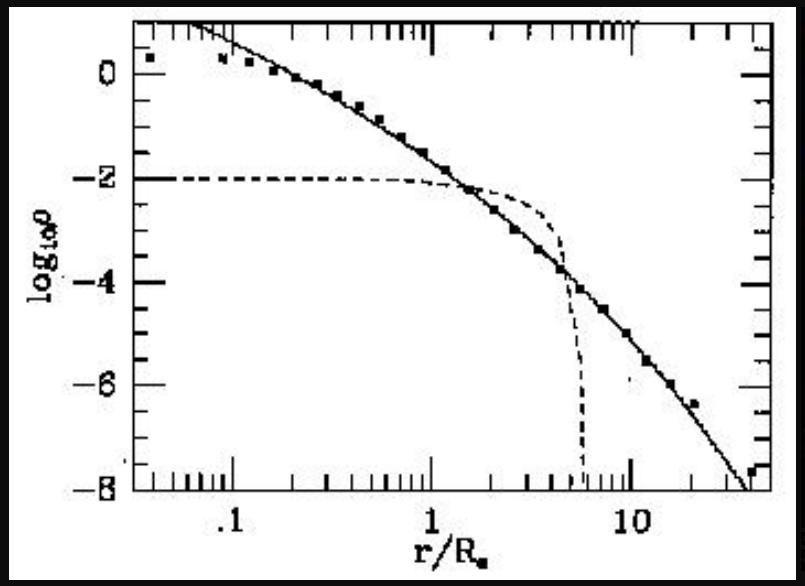
- ellipticals are well-mixed systems → violent relaxation

- "bridges and tails" can be explained by tidal interactions between galaxies

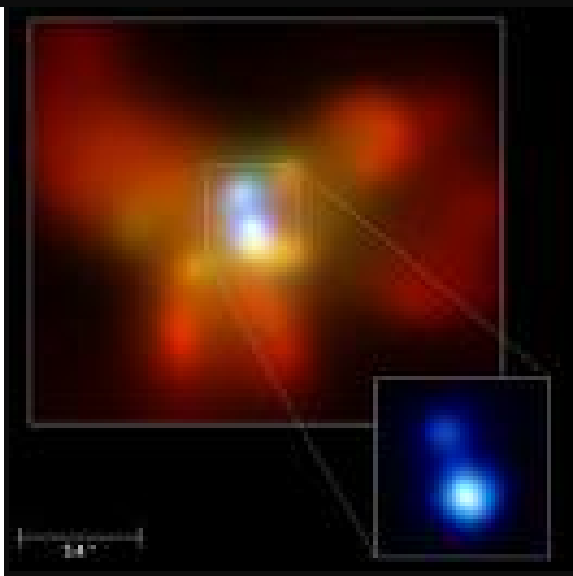
- extrapolating the number of observed ongoing mergers over the age of the universe predicts the right number of local ellipticals



Hopkins et al., astro-ph/0506398



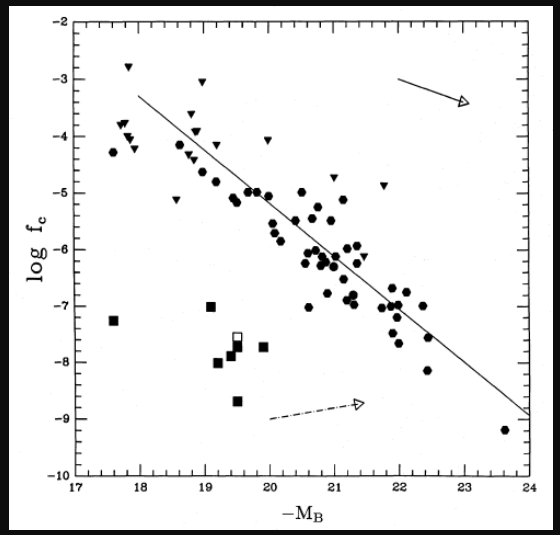
Binney & Tremaine 1987, p. 277



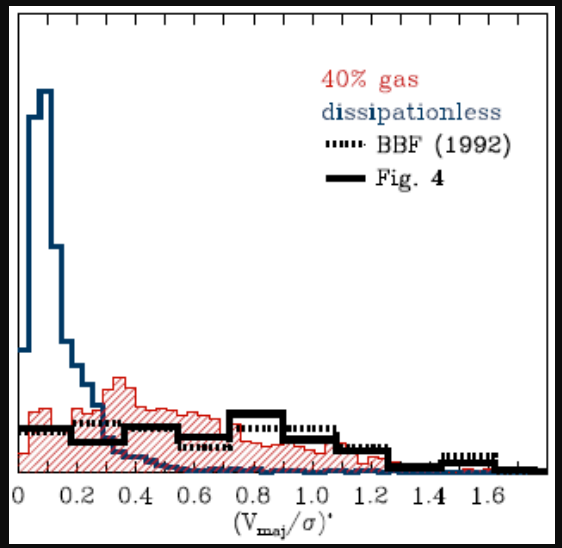
- Numerical simulations of violent relaxation produce remnants following the " $r^{1/4}$ " law, like observed elliptical galaxies

Evidence for dissipation in mergers

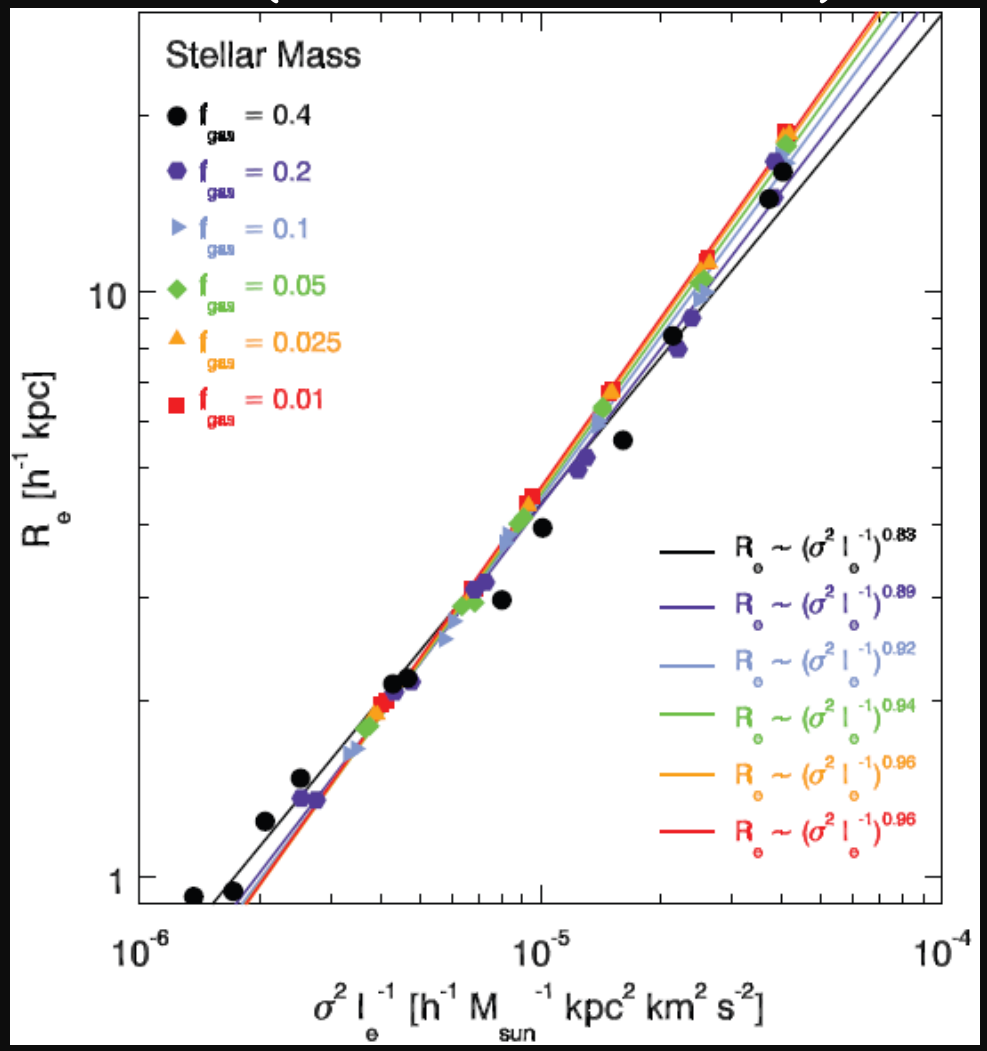
- core phase space densities (Carlberg 1986)



- kinematics (Cox et al. 2006)

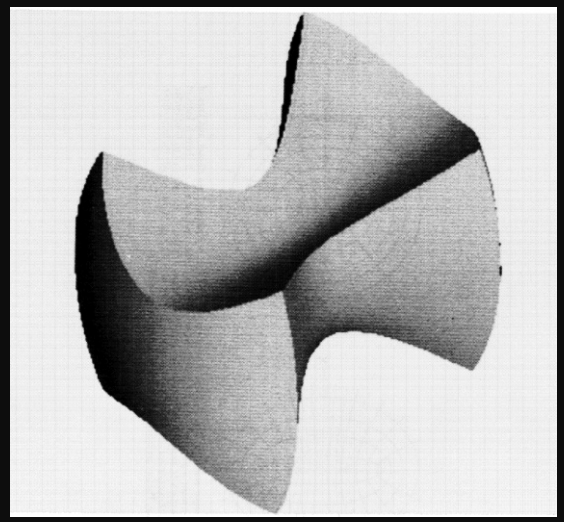


- FP tilt → $f_{gas} \geq 30\%$ (Robertson et al. 2006)

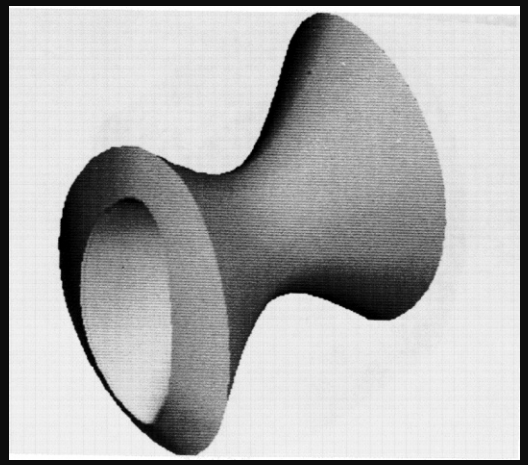


Regular orbits in triaxial potentials

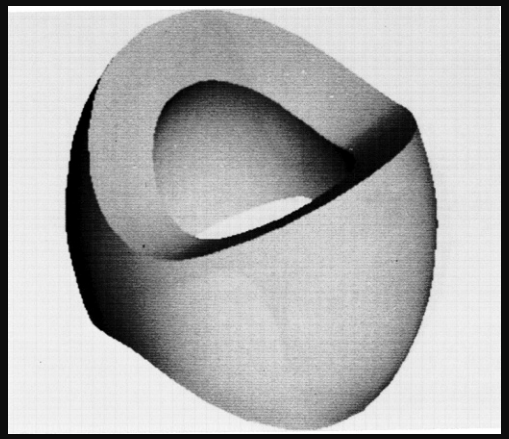
Four major orbit classes in flat-cored, integrable triaxial potential:



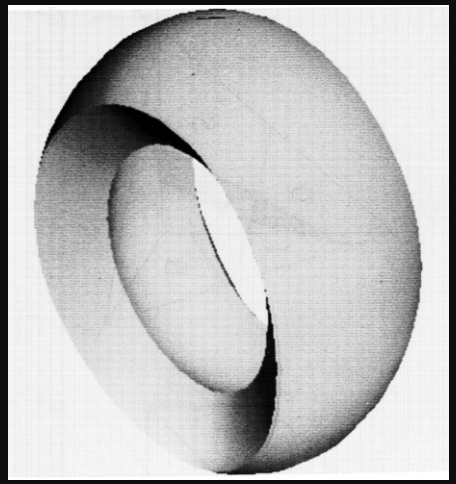
Box



Inner long-axis tube



Outer long-axis tube

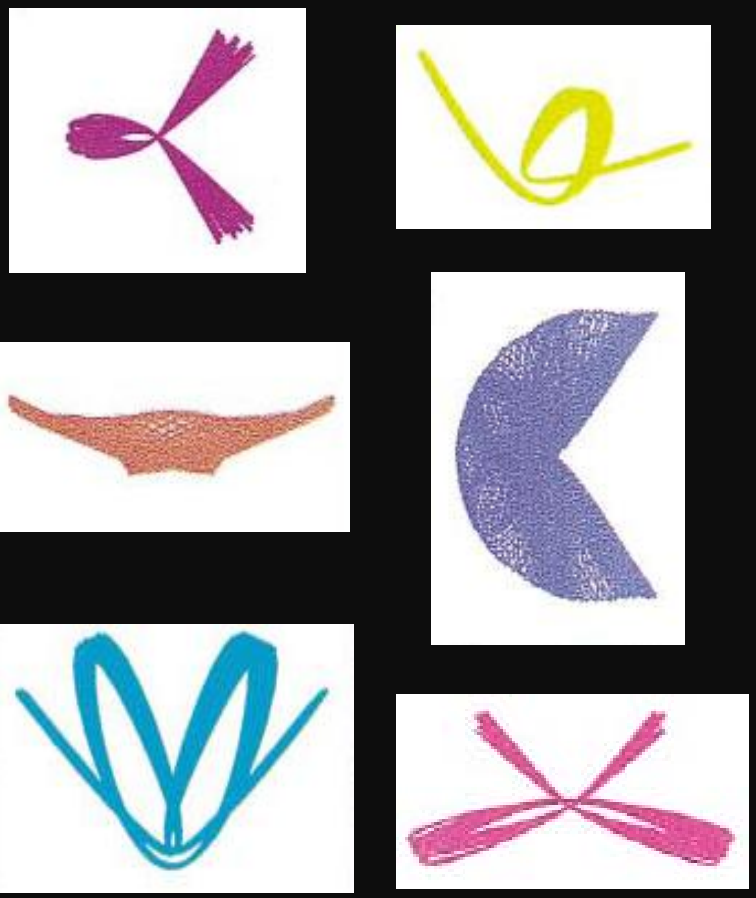


Short-axis tube

Statler 1987

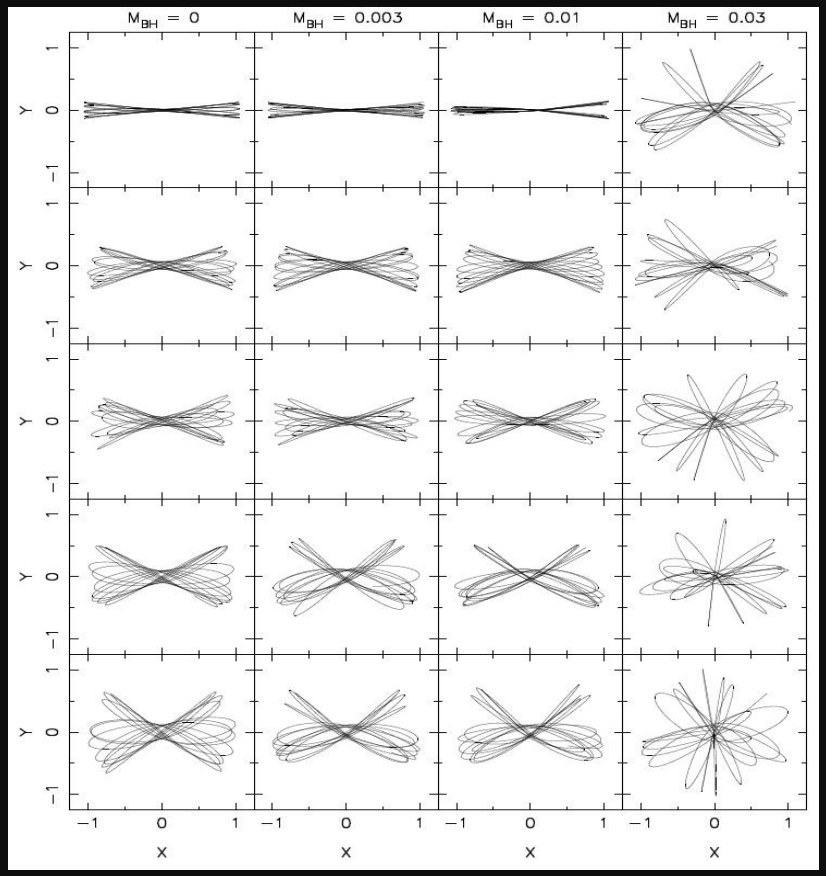
Resonant orbits (cusps):

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



Poon & Merritt 2001

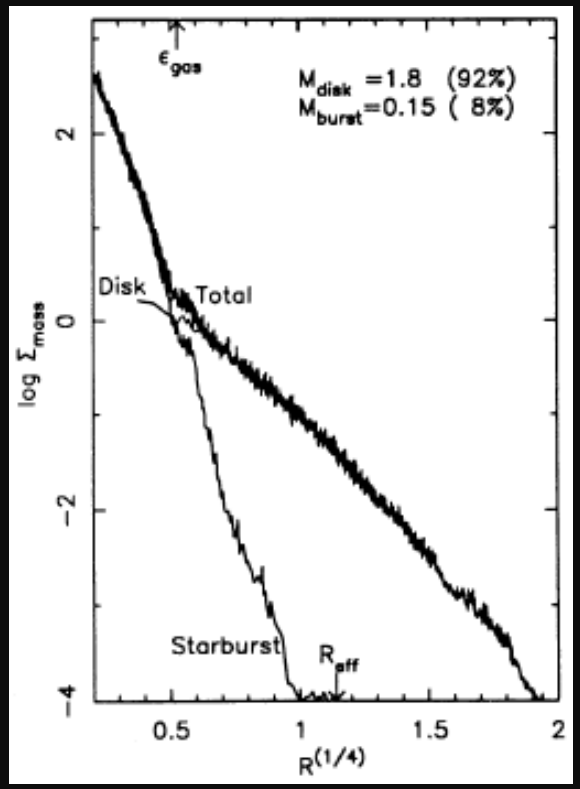
Effect of a central mass concentration



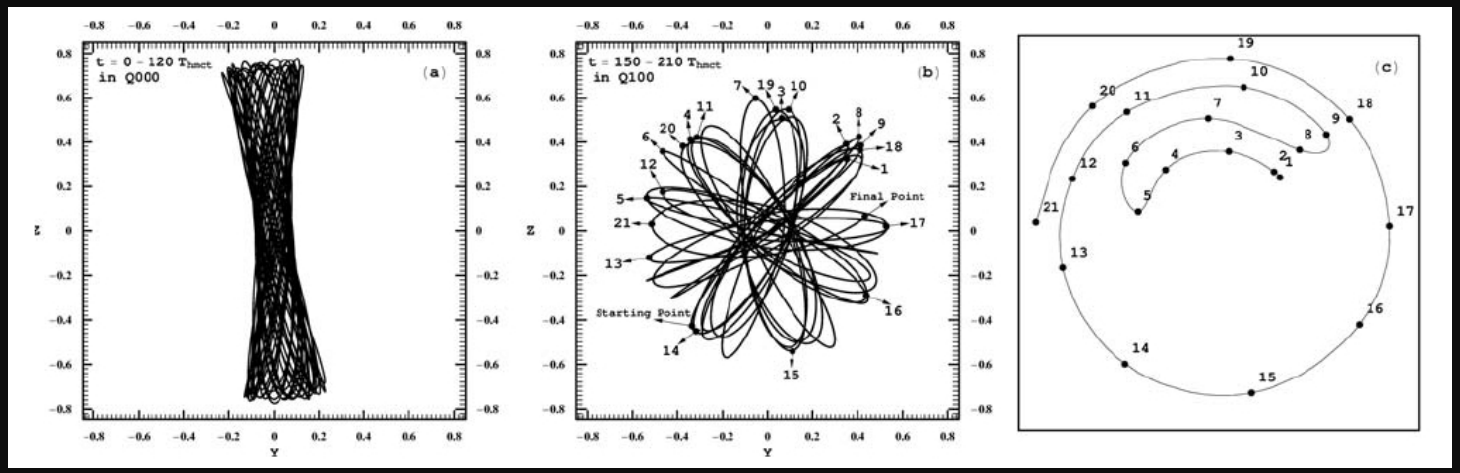
Valluri & Merritt 1997

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

In a merger, tidal torques drive the gas into the center, where it forms a compact starburst component.

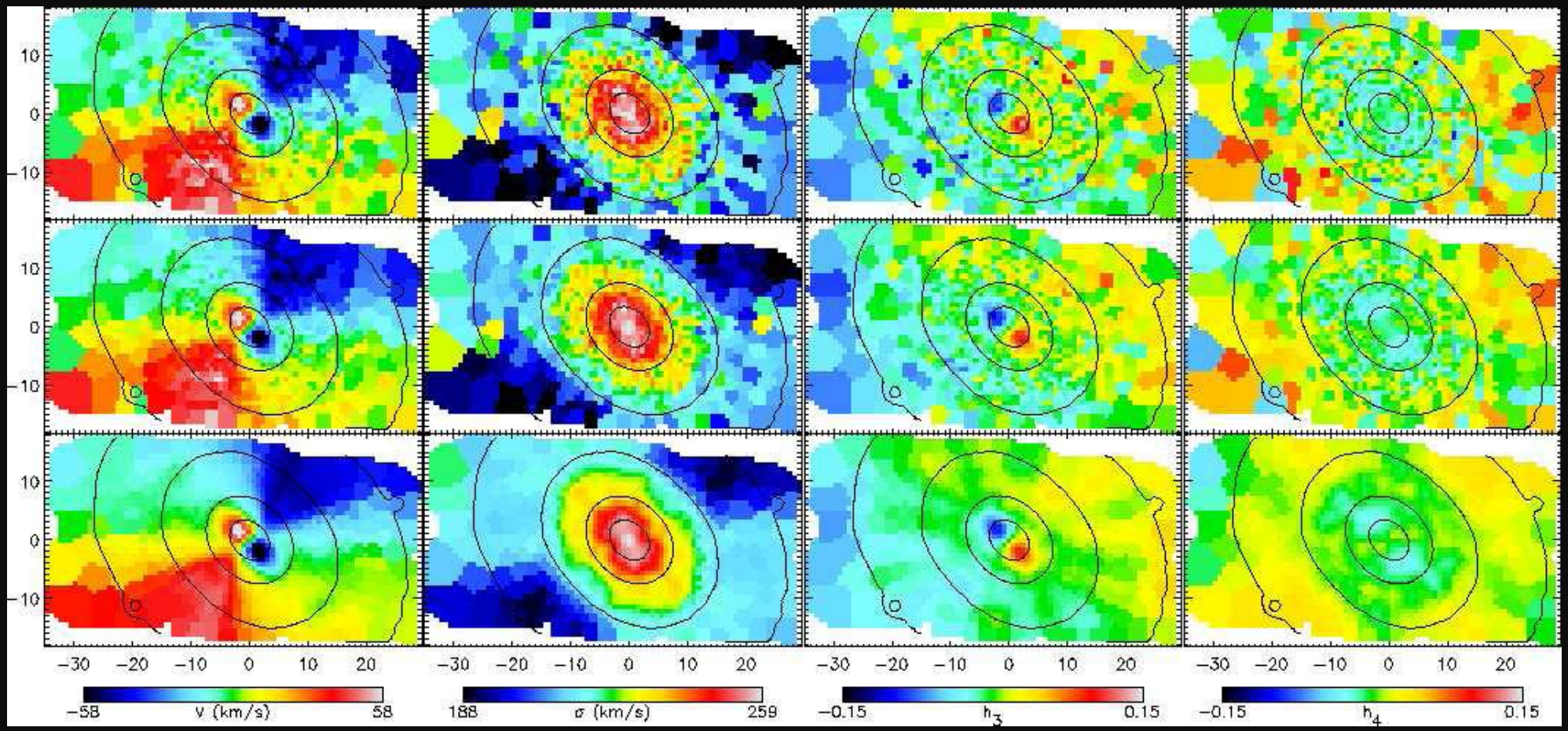


Mihos & Hernquist 1994



Kalapotharakos et al. 2004

Schwarzschild modeling of NGC4365



Statler et al. 2004, Van de Ven et al. 2008, Van den Bosch et al. 2008

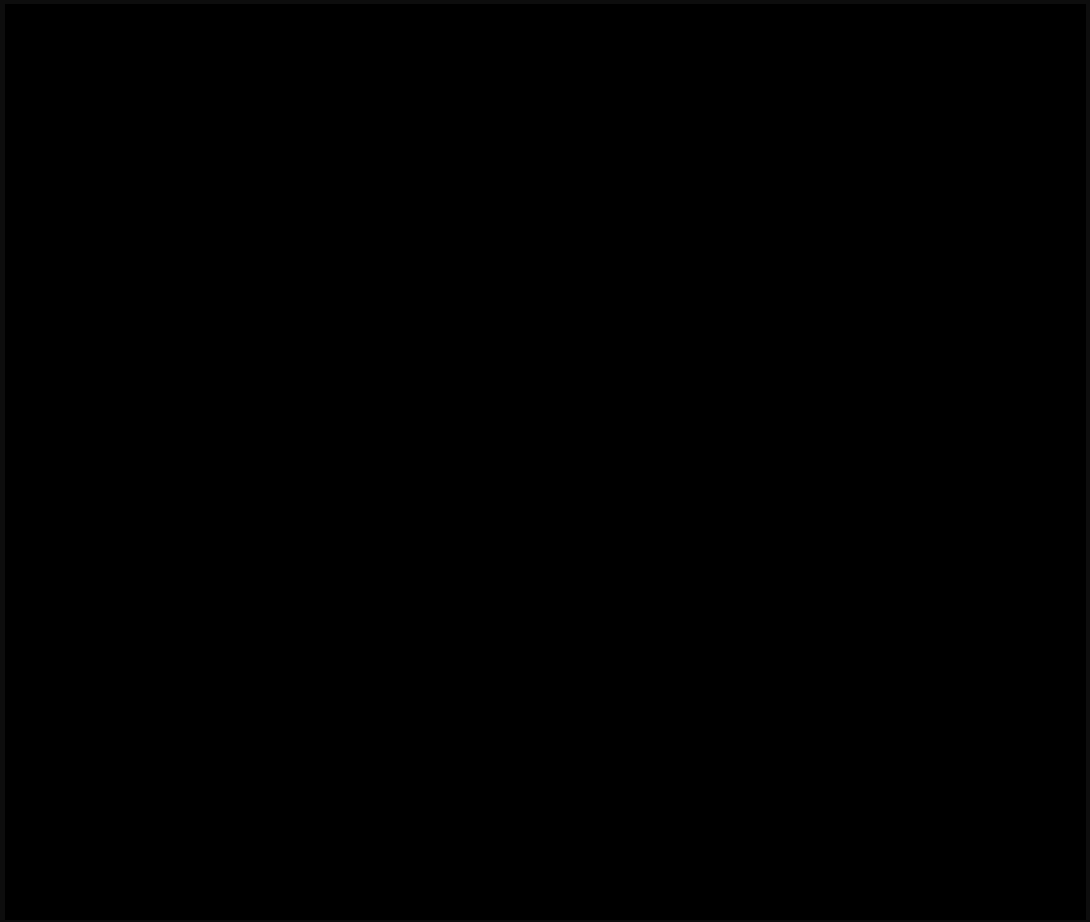
Full 6D stellar distribution function can be unambiguously recovered from h_0-h_4 maps, except in unusual cases.

Our simulations

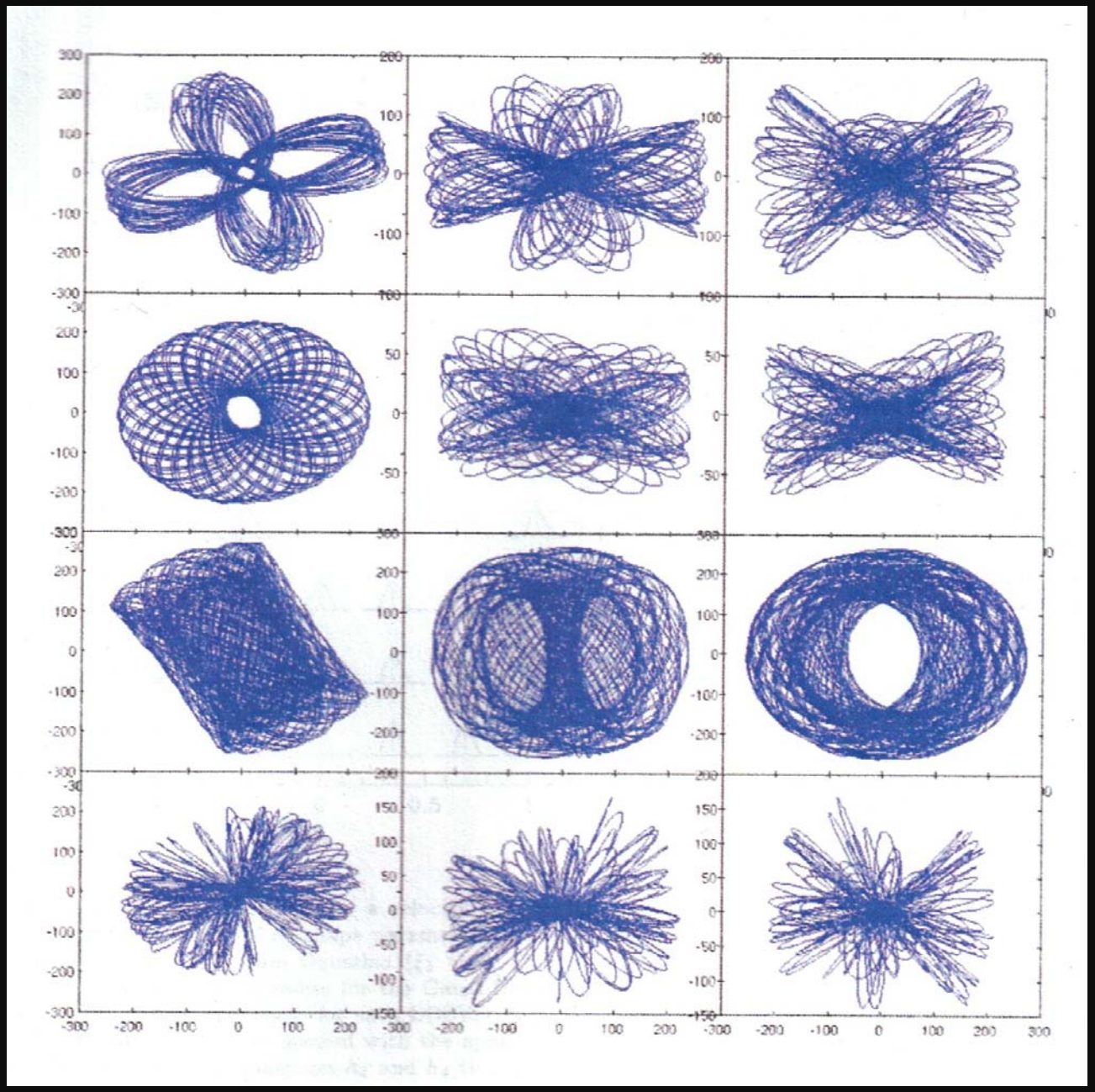
- Standard Gadget-2 (tree-SPH) simulations of 1:1 mergers, including star formation, radiative heating & cooling, SF and AGN feedback

- Disk-disk mergers at 0, 5, 10, 15, 20, 30, and 40% gas , each on eight uniformly sampled merger orbits

- Re-mergers of 20 and 40% gas disk merger remnants ("dry" mergers)



Orbits in the simulated remnants



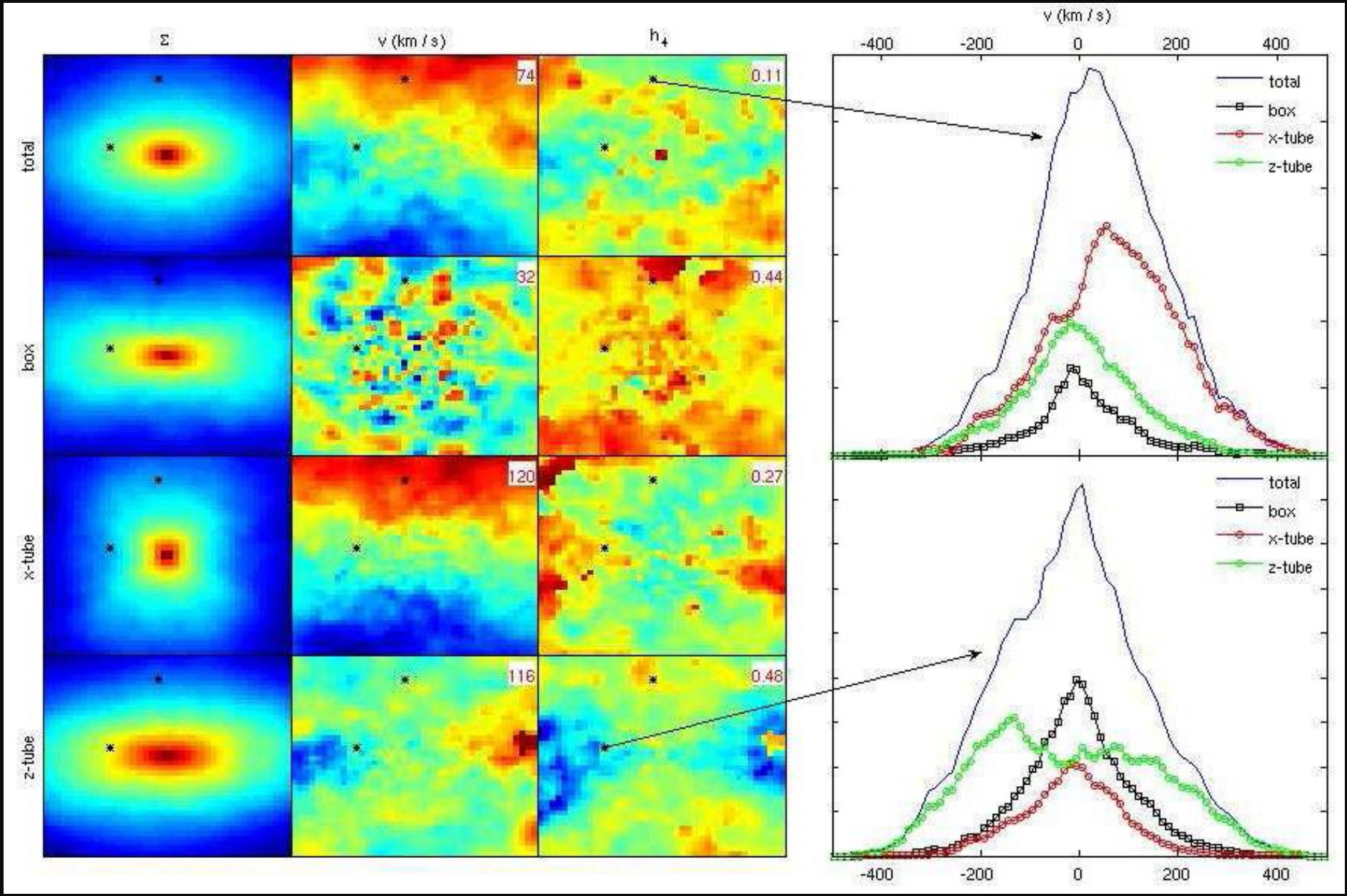
From Gaspard Clozel's senior thesis.

- Froze the potential ~ 2Gyrs after the merger and represented it with a truncated SCF expansion.

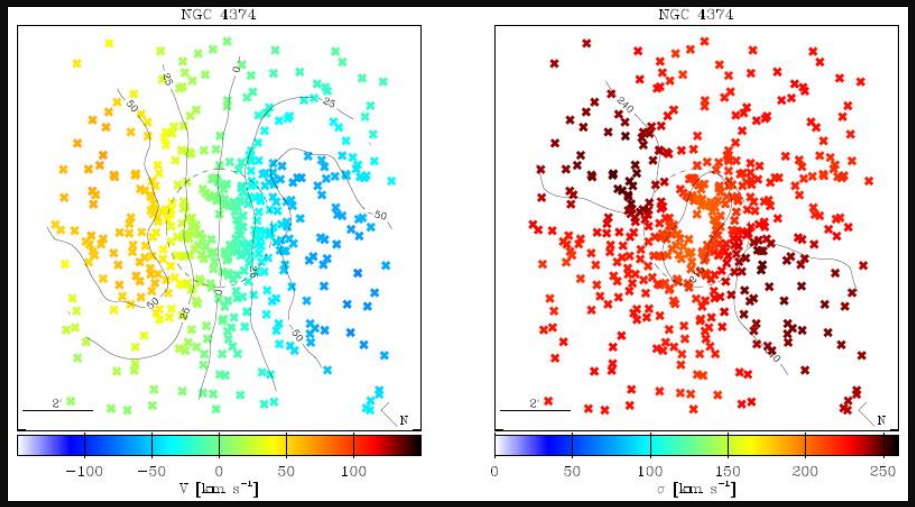
- Integrated orbits of all stars for 150 dynamical times and classified them as x-tubes, z-tubes, or boxes.

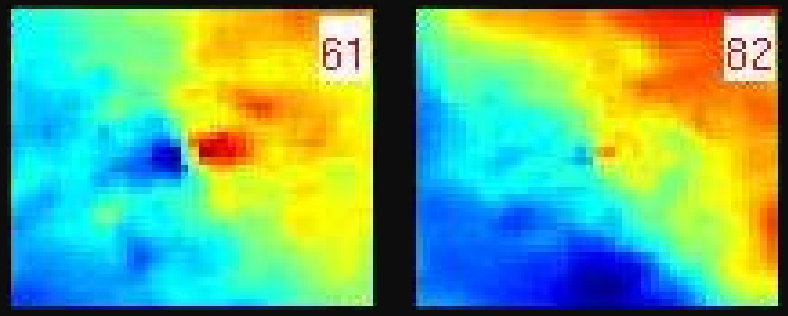
- Constructed 2D (SAURON-like) kinematic maps of the first four Gauss-Hermite moments h_1-h_4.

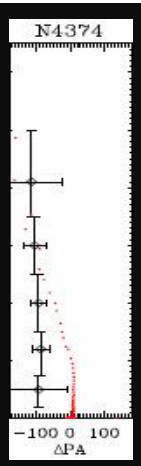
A typical example, showing the contribution of the three orbit classes to the observed kinematics

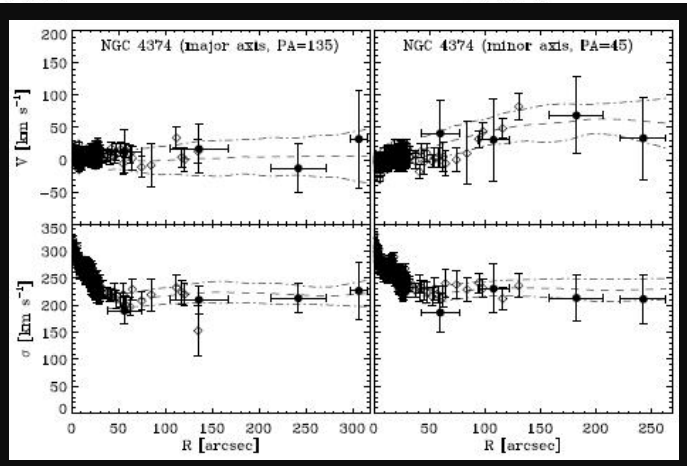


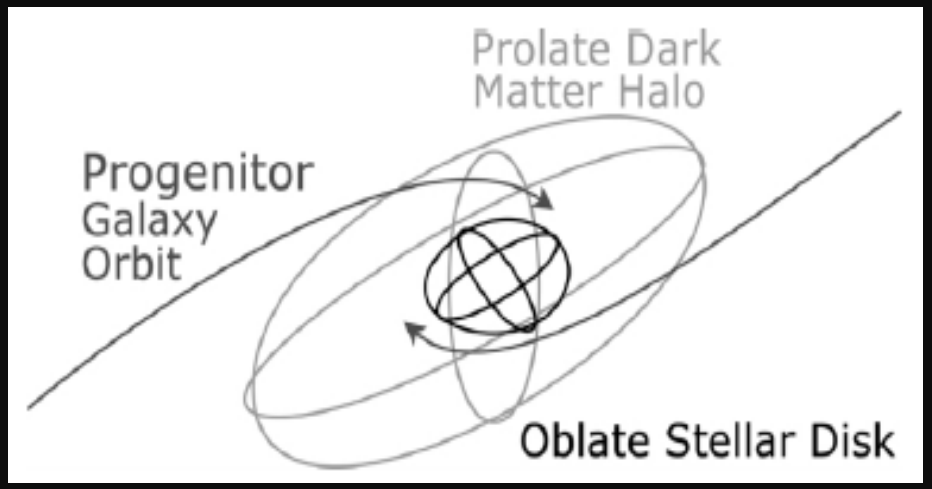
Outer kinematics from planetary nebulae and globular cluster systems







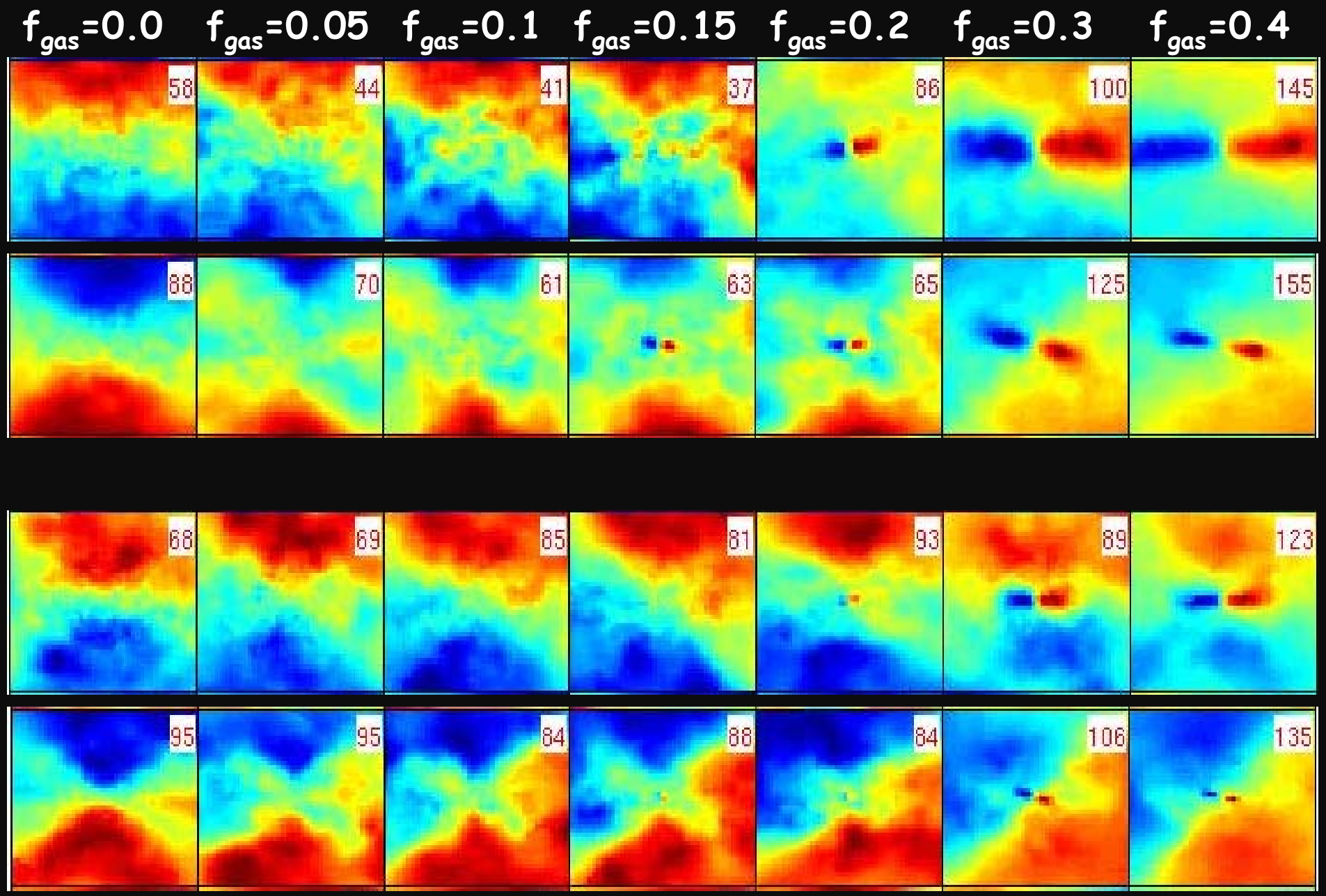




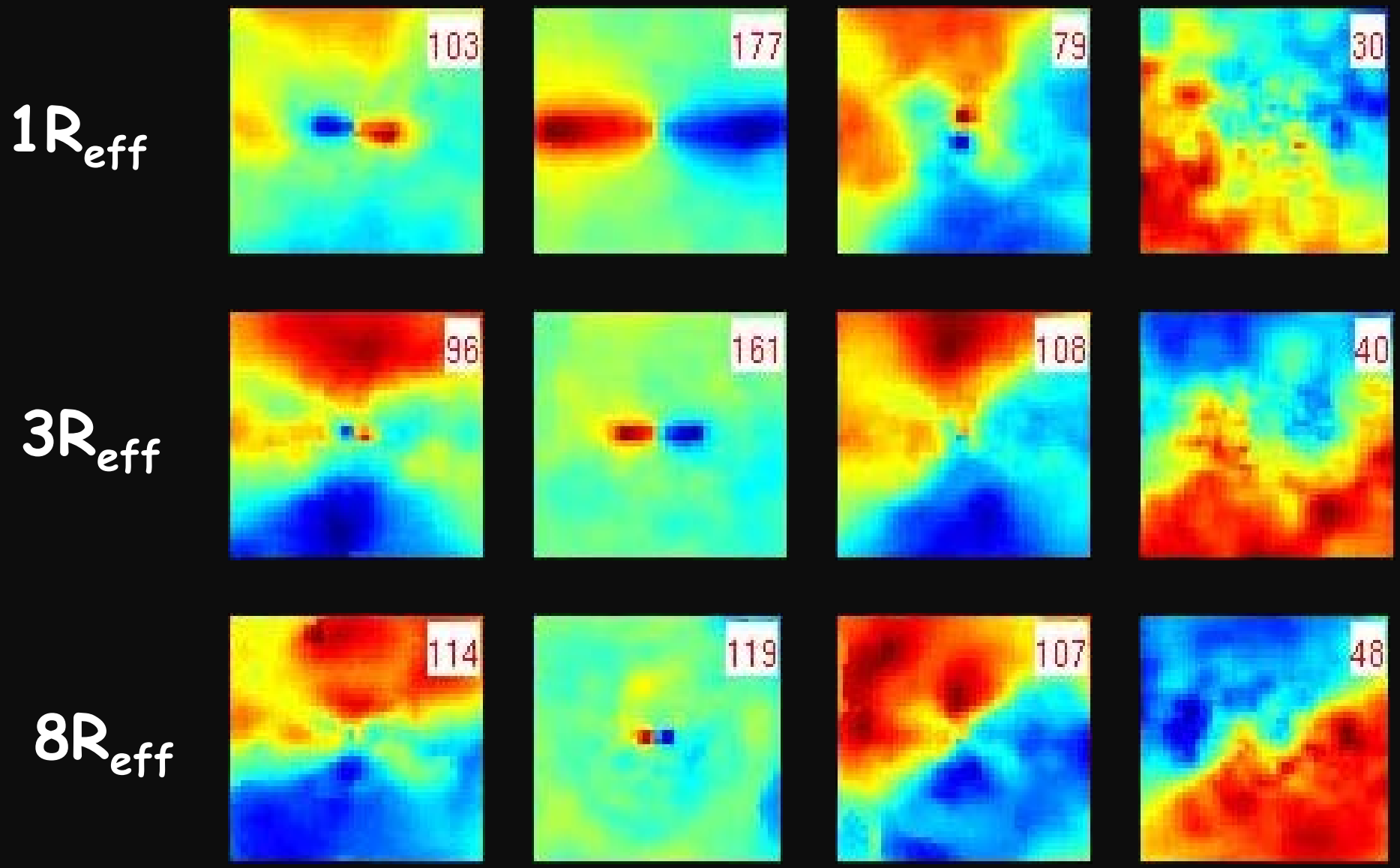
Cocatto et al. 2008:

- "twists and misalignments in the velocity fields are more frequent at large radii"
- "many objects are more rotationally dominated at large radii than in their central parts"

Variation of kinematics with gas fraction → kinematic twists



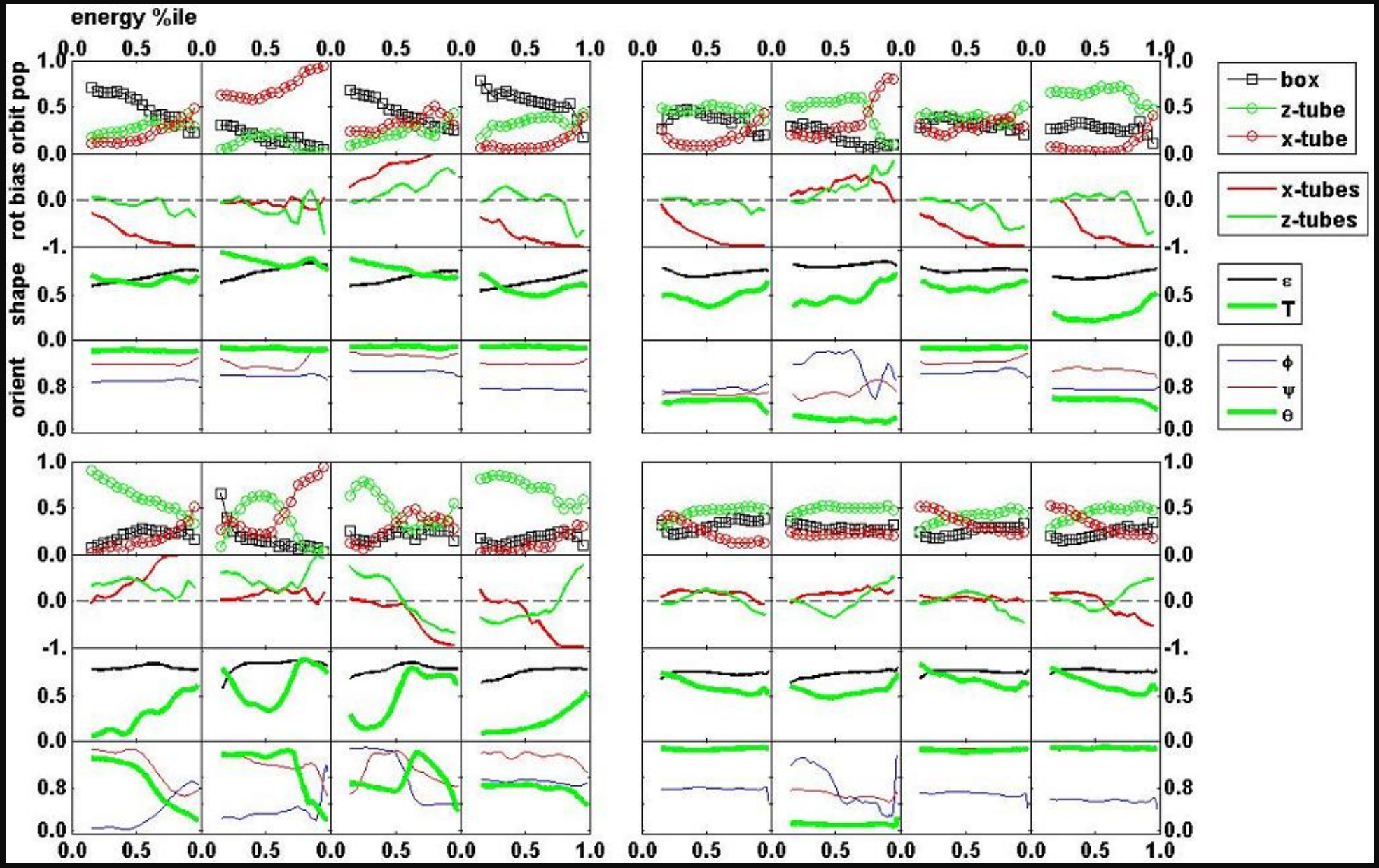
Inner and outer kinematics: four examples



Typical intrinsic structure of the simulated remnants

0% gas

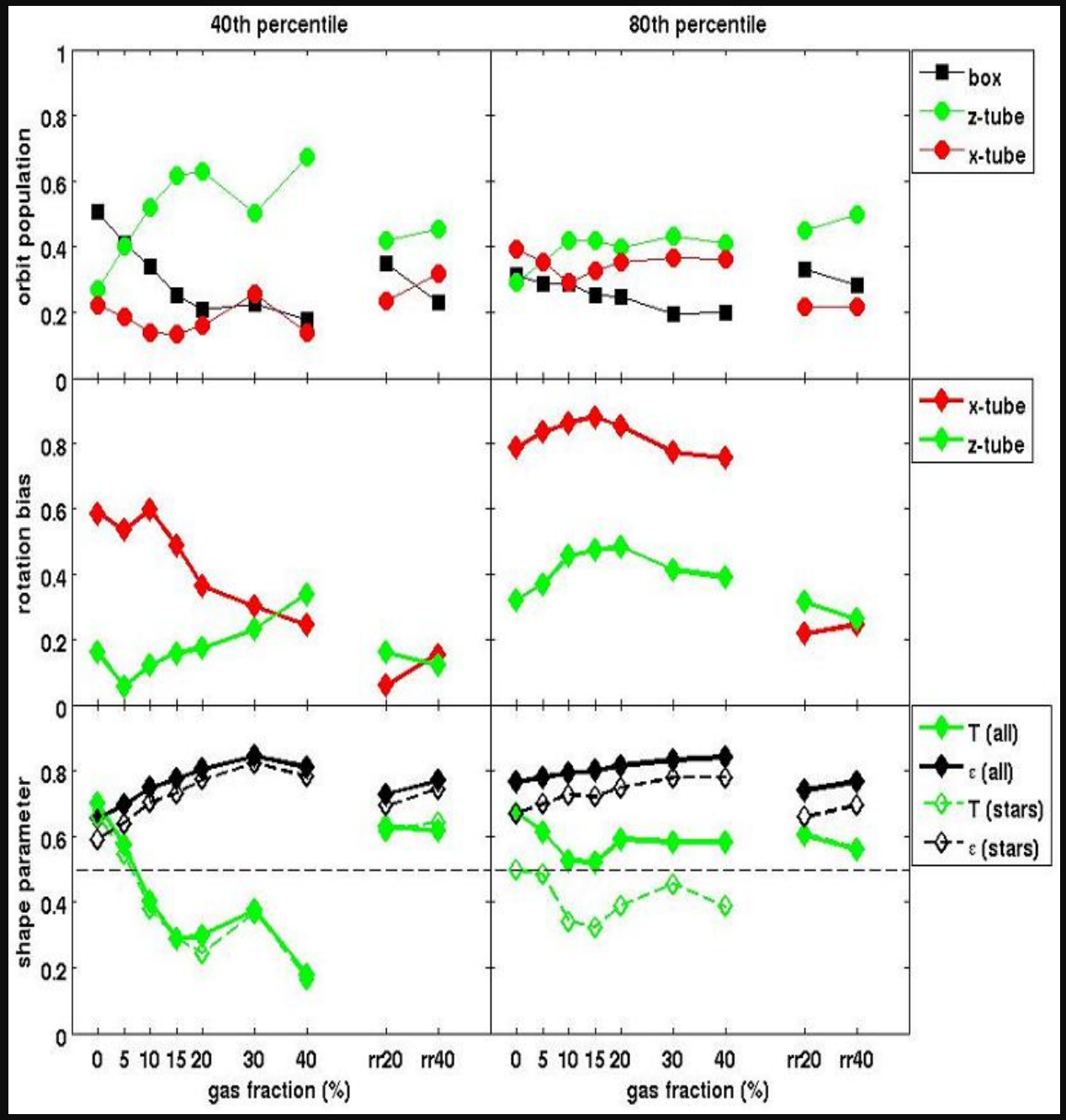
10% gas



40% gas

Re-mergers

Summary of the intrinsic structure trends



- As gas fraction ⬆, f_{box} ⬇ and $f_{z\text{-}tube}$ ⬆ in the inner regions. $f_{x\text{-}tube}$ is less strongly tied to f_{gas}.

- Tubes always dominate over boxes in the outer parts. Furthermore the tube orbits stream more in one preferred direction in the outskirts, resulting in an *increase in rotation with radius*.

- For gas fractions ≤ 20%, and in the outer regions for all f_{gas}, the x-tubes stream more than the z-tubes.

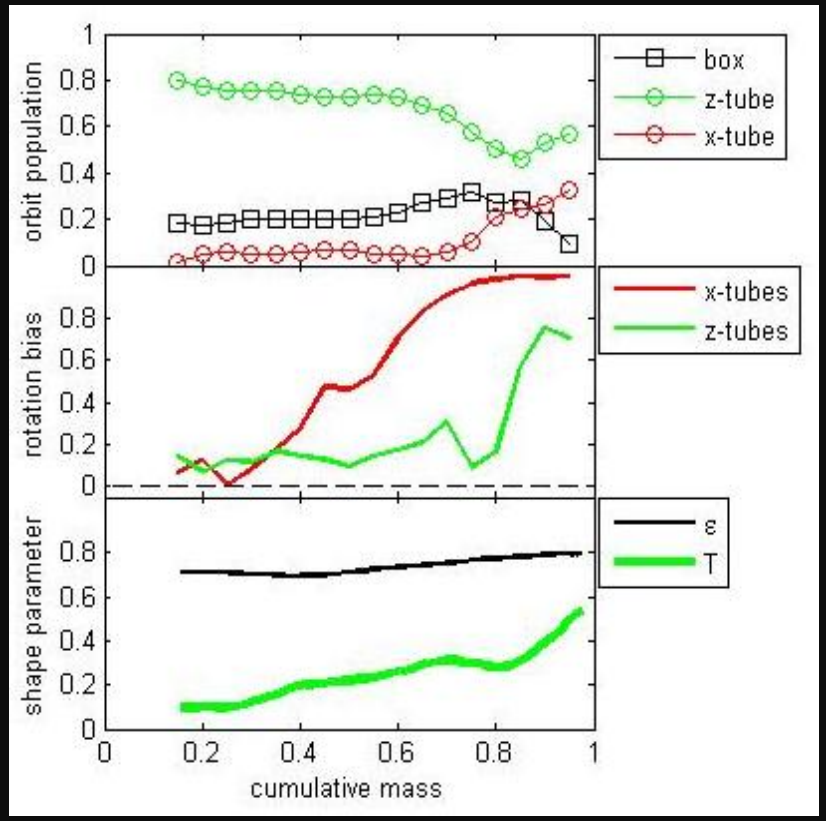
- There is a sharp distinction between disk and spheroid mergers in the amount of x-tube streaming in the halo.

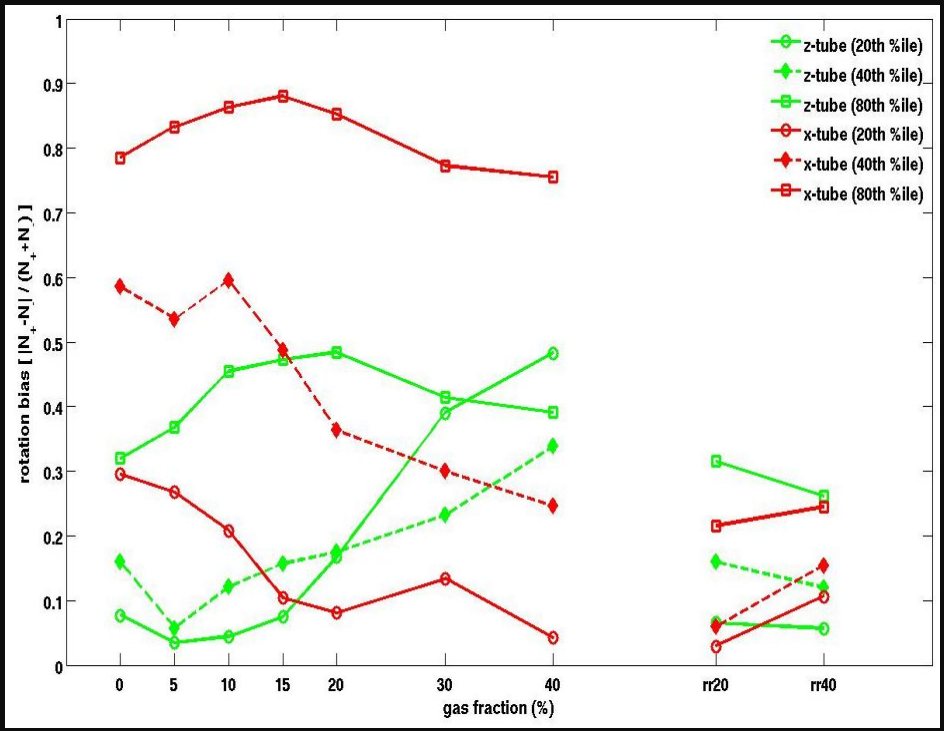
- The inner triaxiality of the disk-disk remnants decreases rapidly with f_{gas}, and their roundness peaks at f_{gas}≈30%. The high-f_{gas} remnants get more prolate in their outer parts.

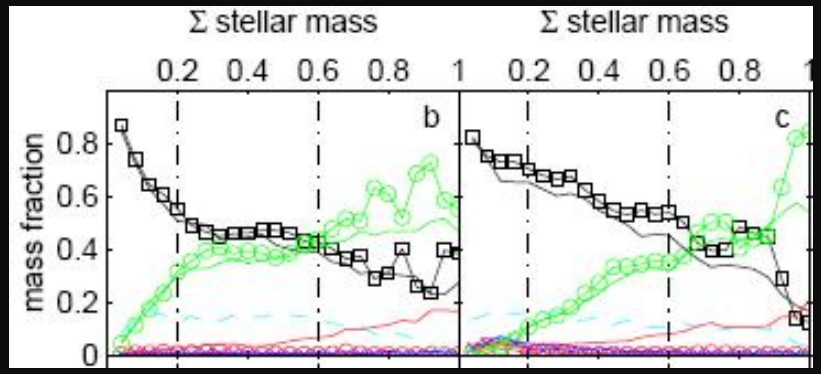
- The re-mergers are uniformly prolate.

- In the outskirts, the stars are more oblate and flattened than the dark matter.

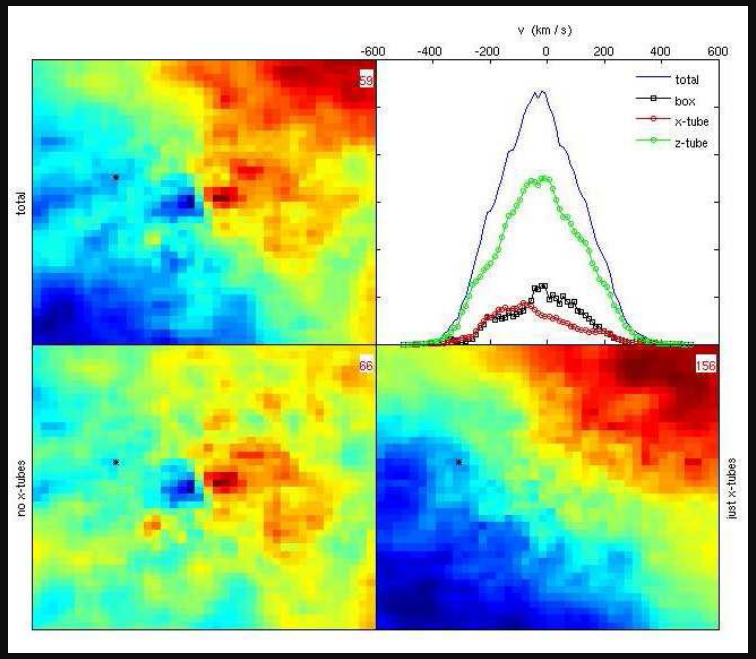
Kinematics can tell us where globular clusters formed: e.g. streaming about major axis.

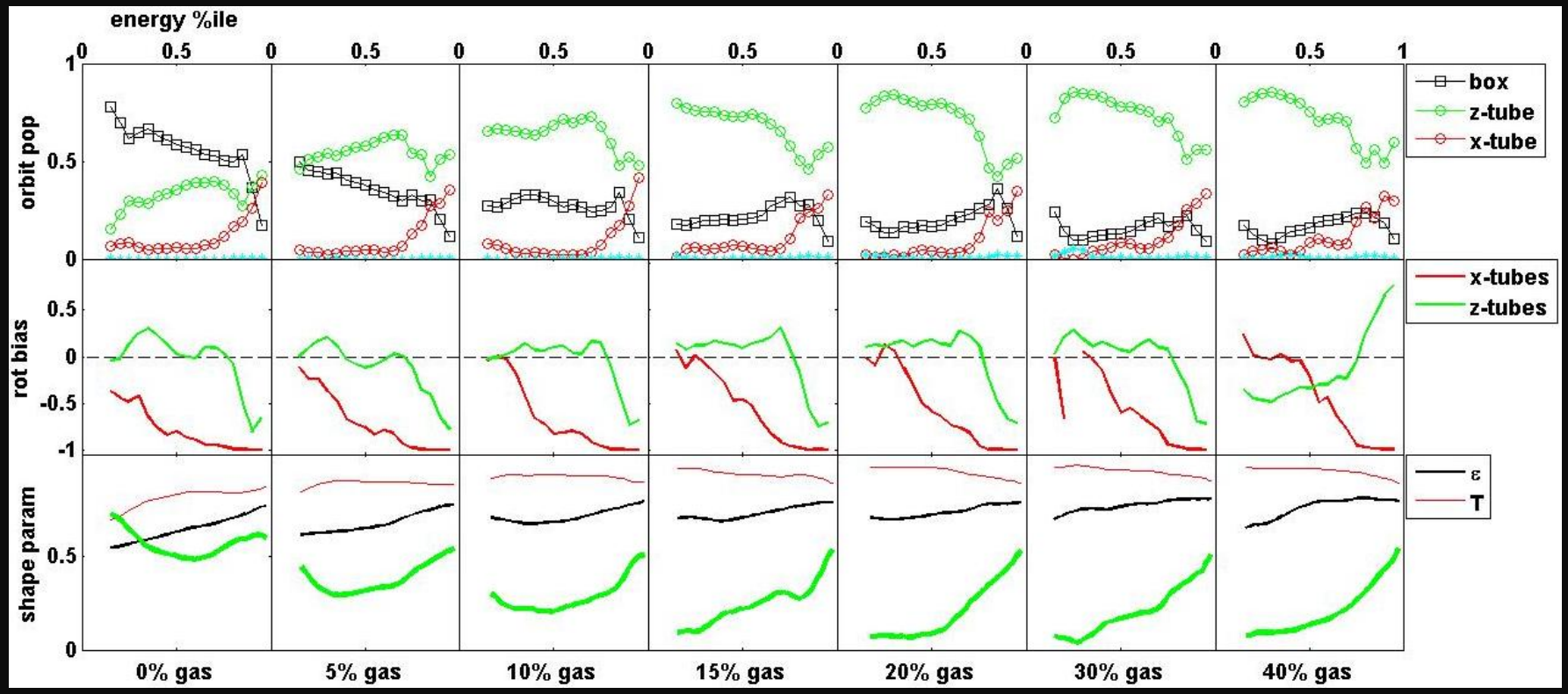






Cancelling rotation of the z-tube orbits – how we get KDC slow rotators at intermediate gas fractions





Conclusions/future

- Galaxy formation from GC kinematics
  - outer → merger orbits, morphologies
  - inner → dissipation, violent relaxation

- GC formation from GC kinematics
  - outer stellar, GC kinematics comparisons
  - correlations between MF and kinematics

- MASS FUNCTIONS (universal, insufficient evolution to get turnover)

Possibilities:
- GCs evolve primarily though internal processes
- Cosmological halo occupation history
- Orbital history in time-varying, triaxial potentials

Ongoing project: Tracking tidal histories of particles through merger simulations