# Tracing hierarchical galaxy formation with stellar dynamics: From nuclei to halos

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# Dynamical imprint of galaxy formation

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

-Violent relaxation in mergers is incomplete (Lynden-Bell 1967).

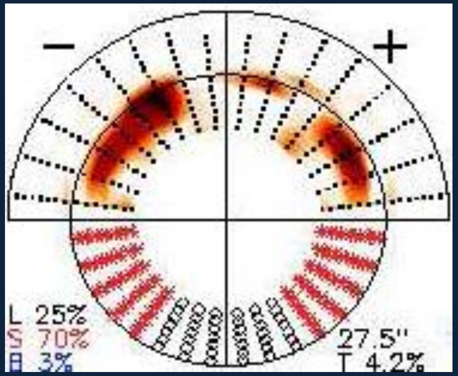
-Memory of ICs encoded in integrals of motion (IOM).

-Time-dependence/perturbations -> diffusion in IOM phase space.

-Crossing of orbital boundaries -> erasure of ICs (relaxation).

-To understand galactic structure and evolution, need to identify macroscopic groups of orbits that conserve qualitatively similar IOM.

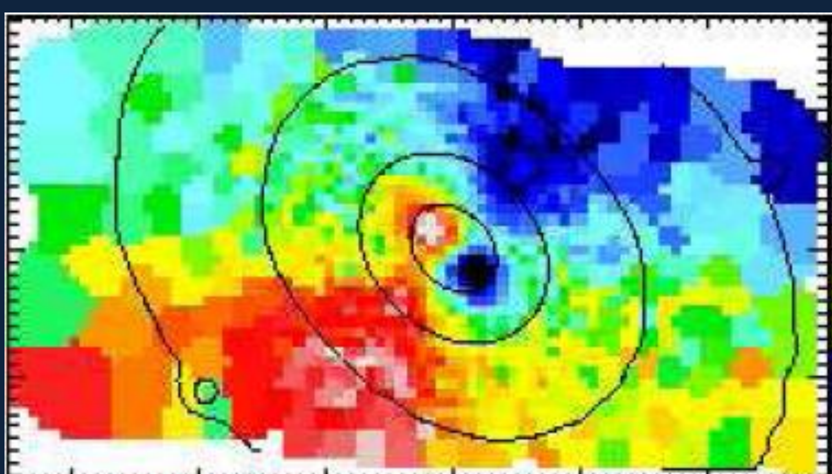
*Stellar orbits are the building blocks of galaxies (images: Poon & Merritt 2001).*




*Orbital phase space need not be uniformly populated (image: van den Bosch et al. 2008).*

# Dynamical information in real galaxies

Image: http://seds.org/~spider/ngc/ngc.cgi?NGC4365



NGC 4365: SAURON image

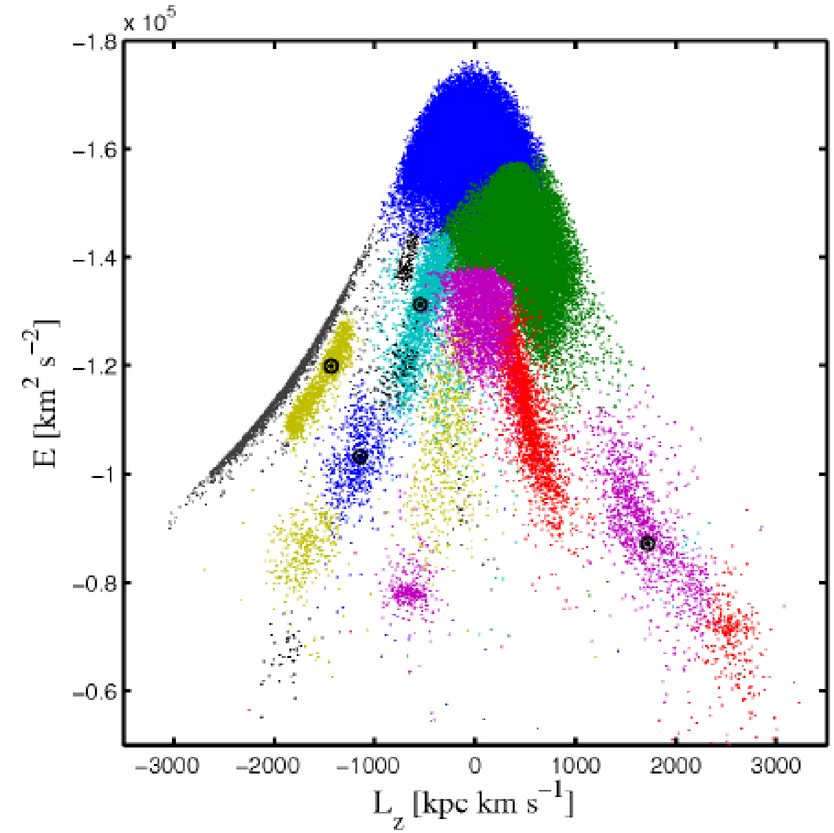


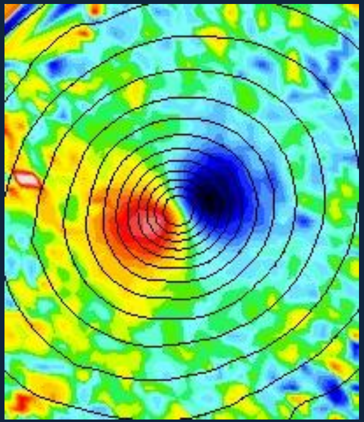

**Figure 11.** Distribution of stellar particles inside a sphere of 4 kpc radius at 8 kpc from the galactic centre in $E$ vs. $L_z$ space as would be observed by *Gaia*. The different colours show the groups identified by the Mean Shift algorithm. Black open circles denote those for which the time since accretion was successfully derived.

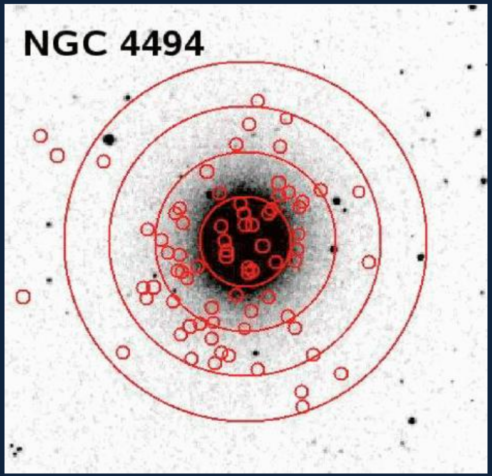
Gomez et al. 2010

The stellar population of the NGC 4365 KDC is indistinguishable from that of the outer galaxy.

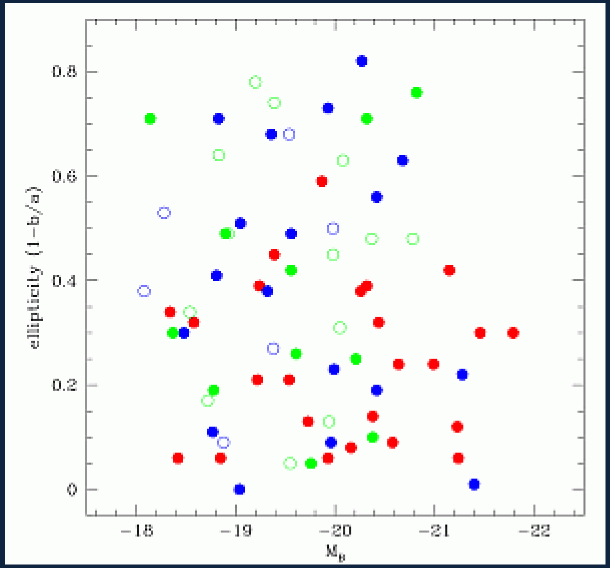
Sauron

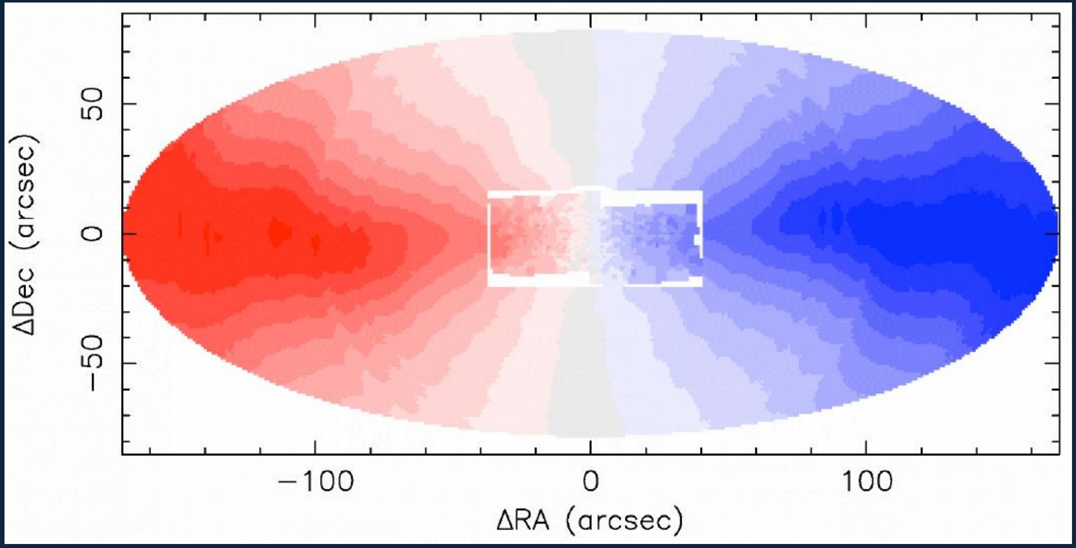
SMEAGOL



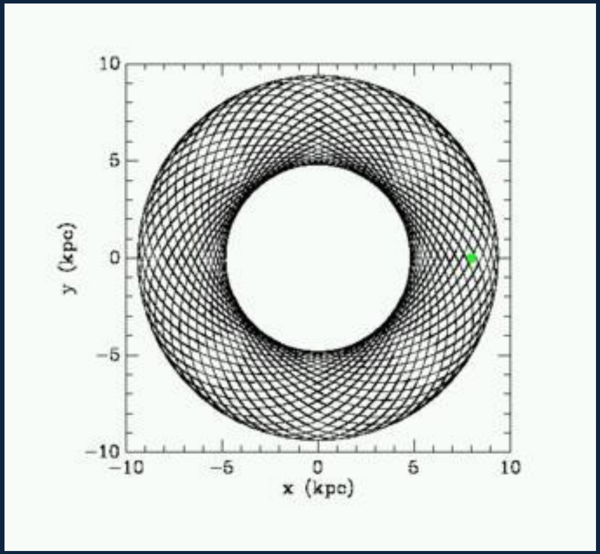



Proctor et al. 2009



## Spherical potentials

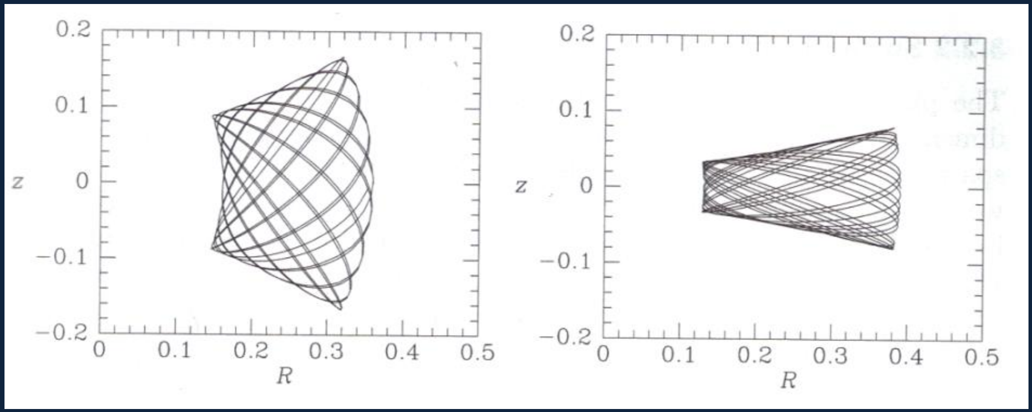


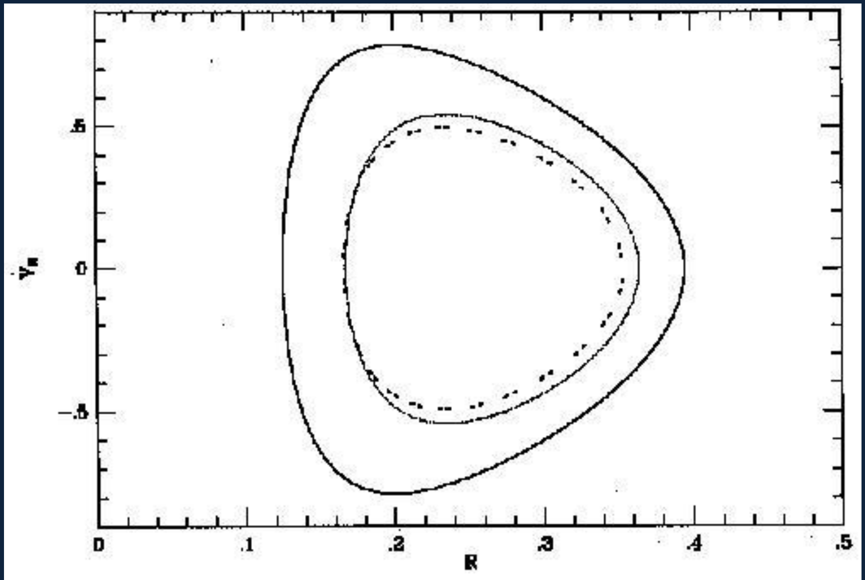

-Energy, angular momentum conserved -> orbit confined to plane

-Rosettes (precessing ellipses) uniformly fill annulus $r_0 < r < r_1$ over long times

-Centrifugal barrier shields star from center of potential

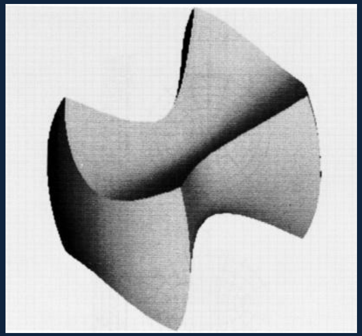
## Axisymmetric potentials



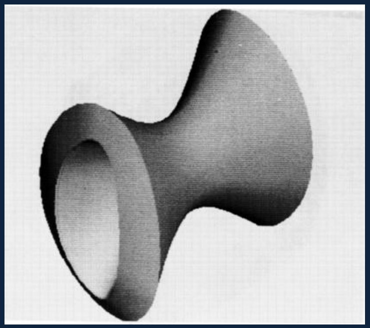




Binney & Tremaine 2008

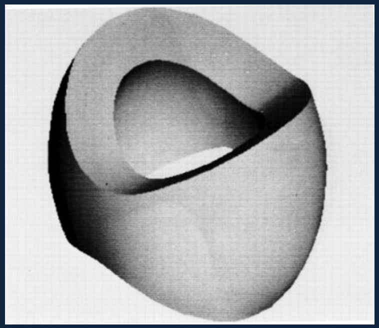
# 3D triaxial potentials



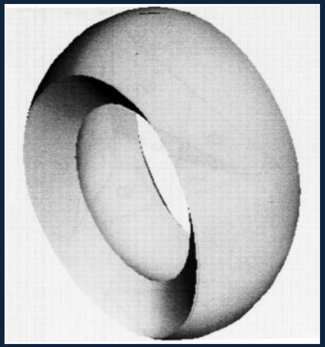
Box



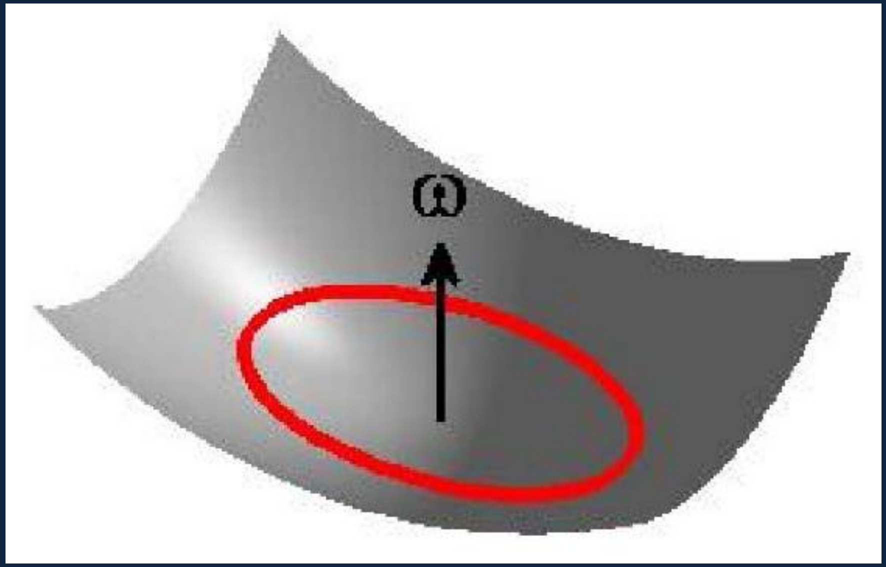
Inner long-axis tube



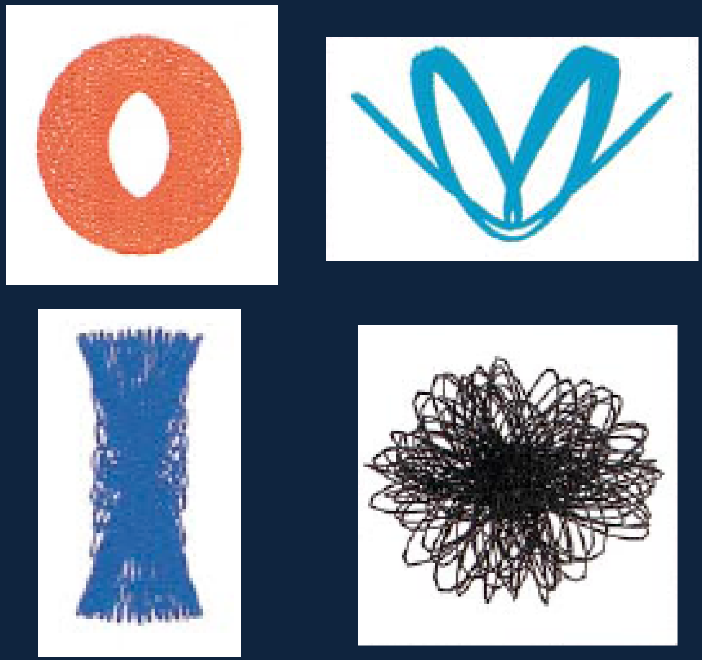
Short-axis tube



Outer long-axis tube

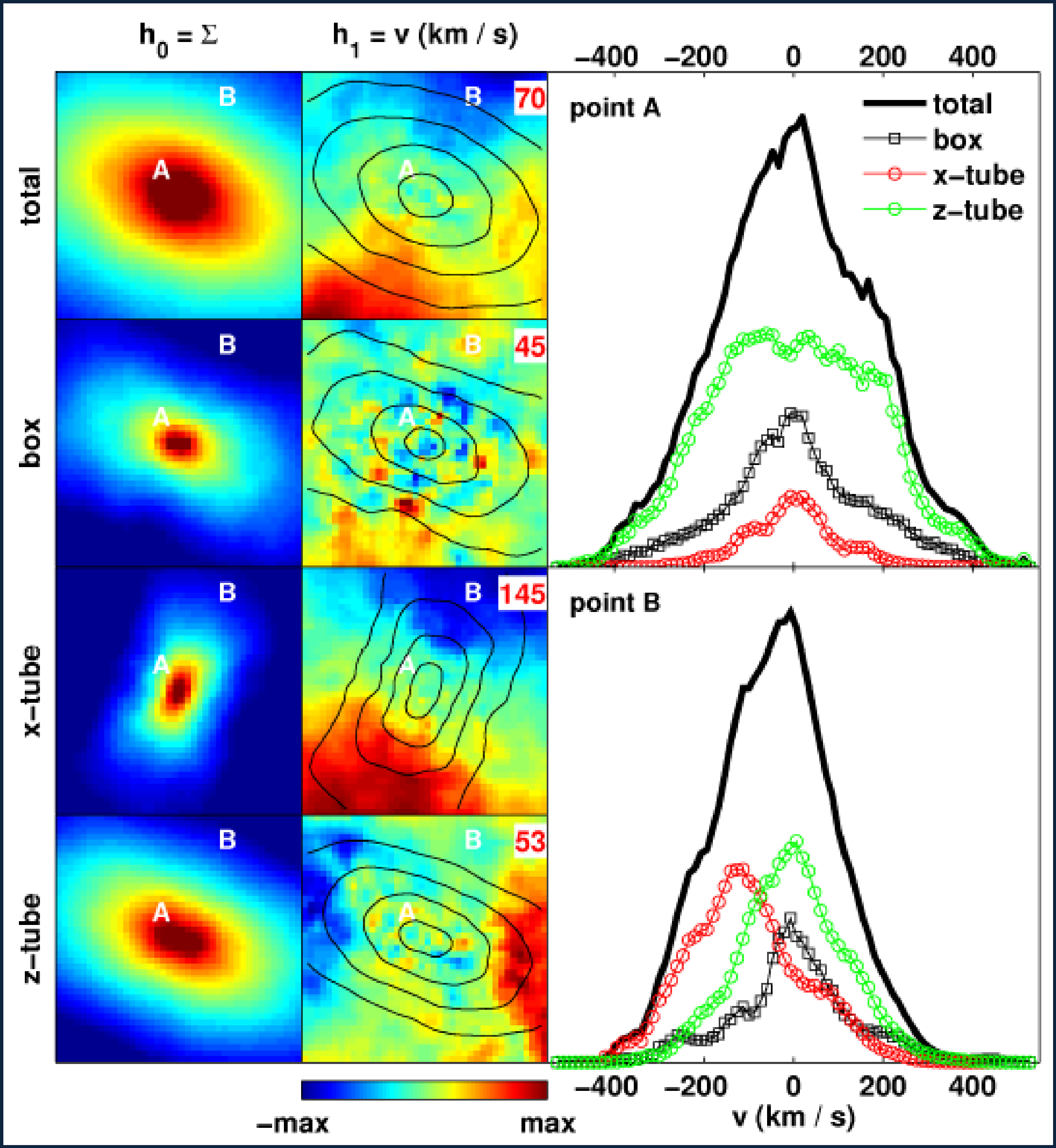


Binney and Spergel 1982;
figure from Hoffman et al. 2010

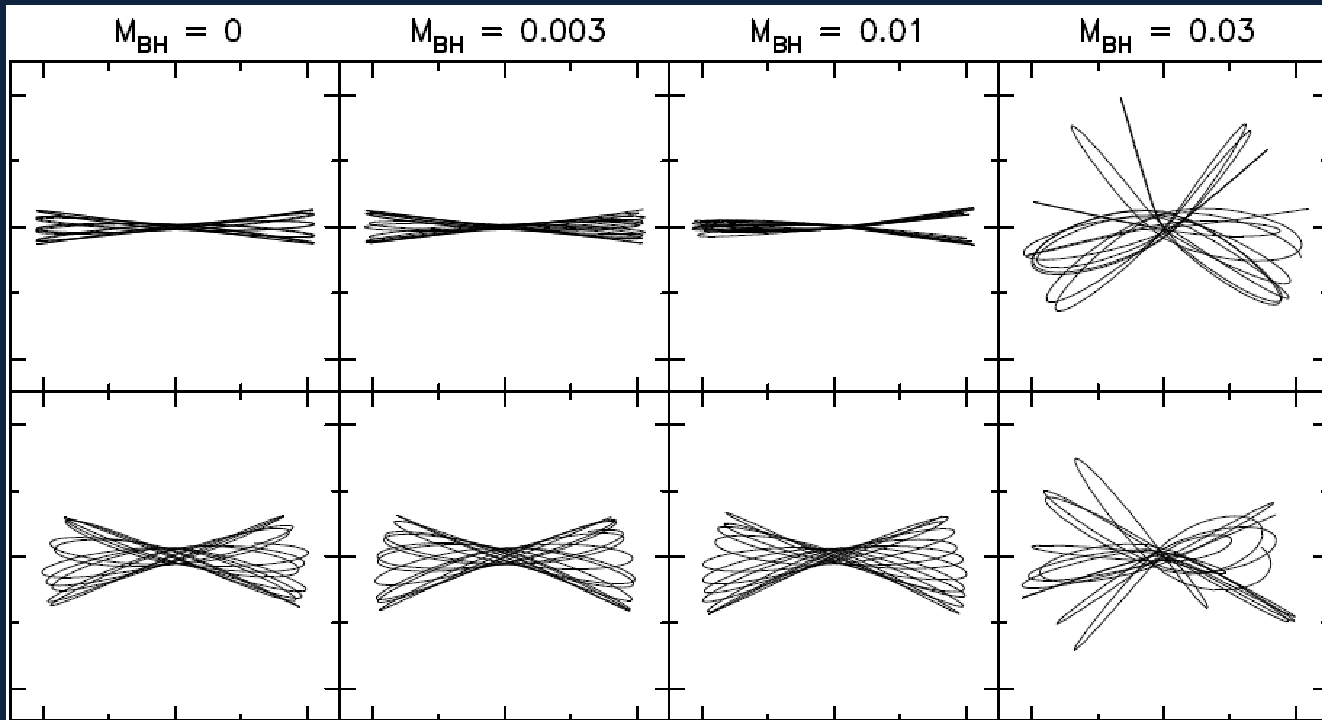


Poon & Merritt 2001

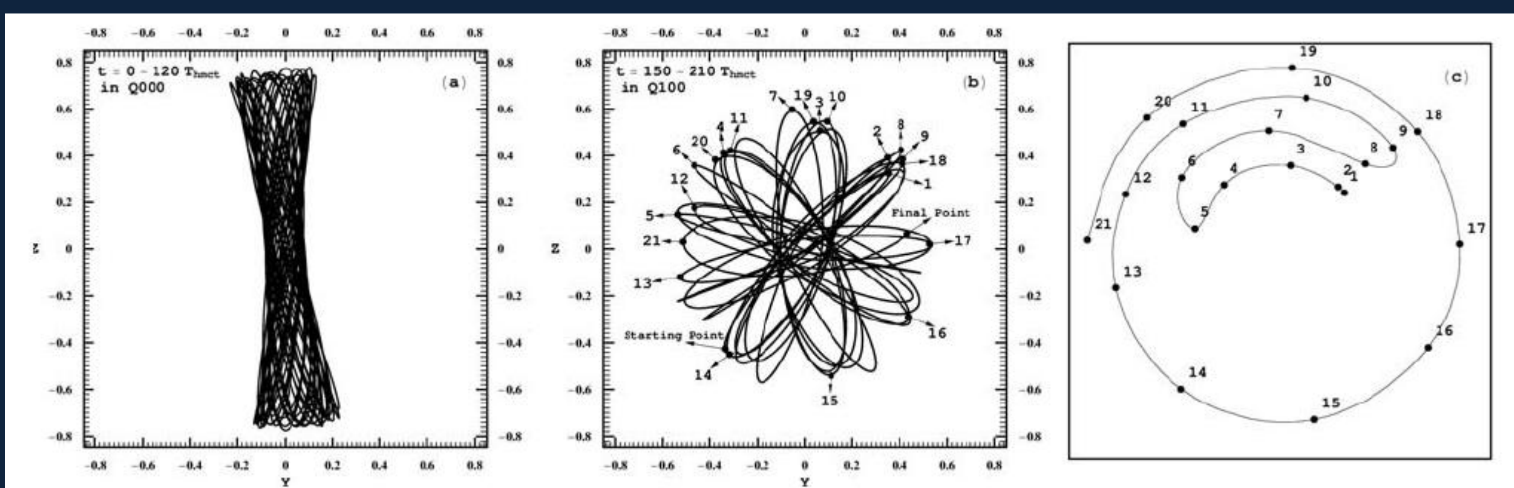
Imprint of orbital structure on kinematics



# Origin of the orbital structure – effect of a CMC

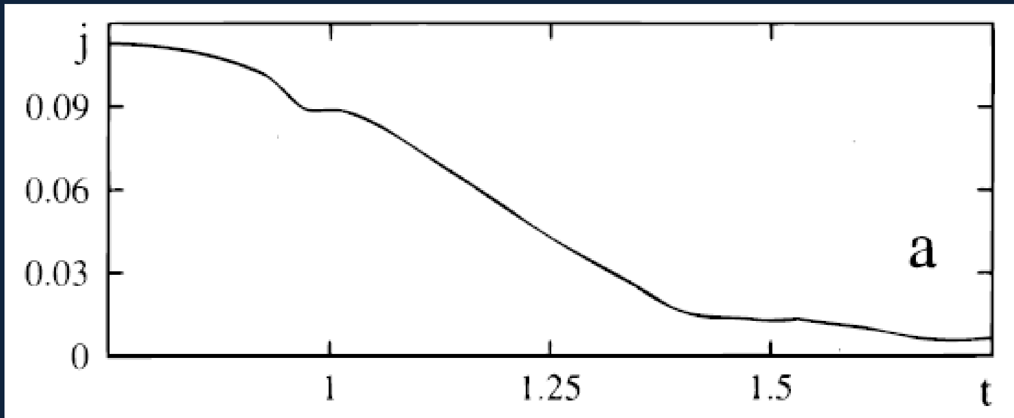


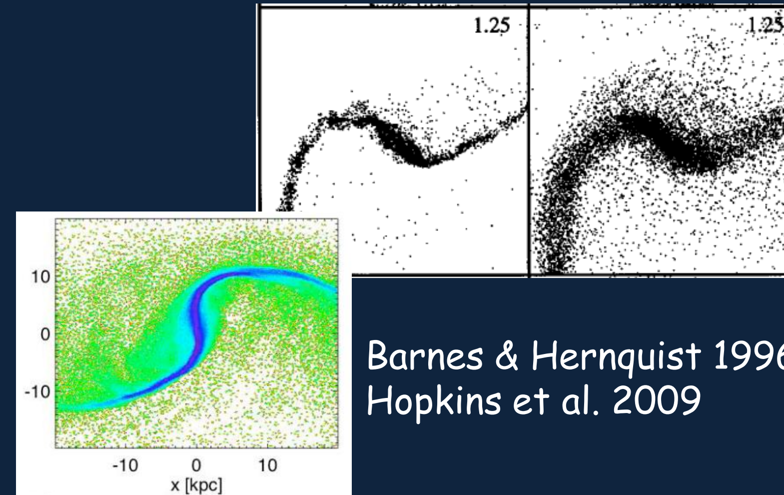

Merritt & Valluri 1997



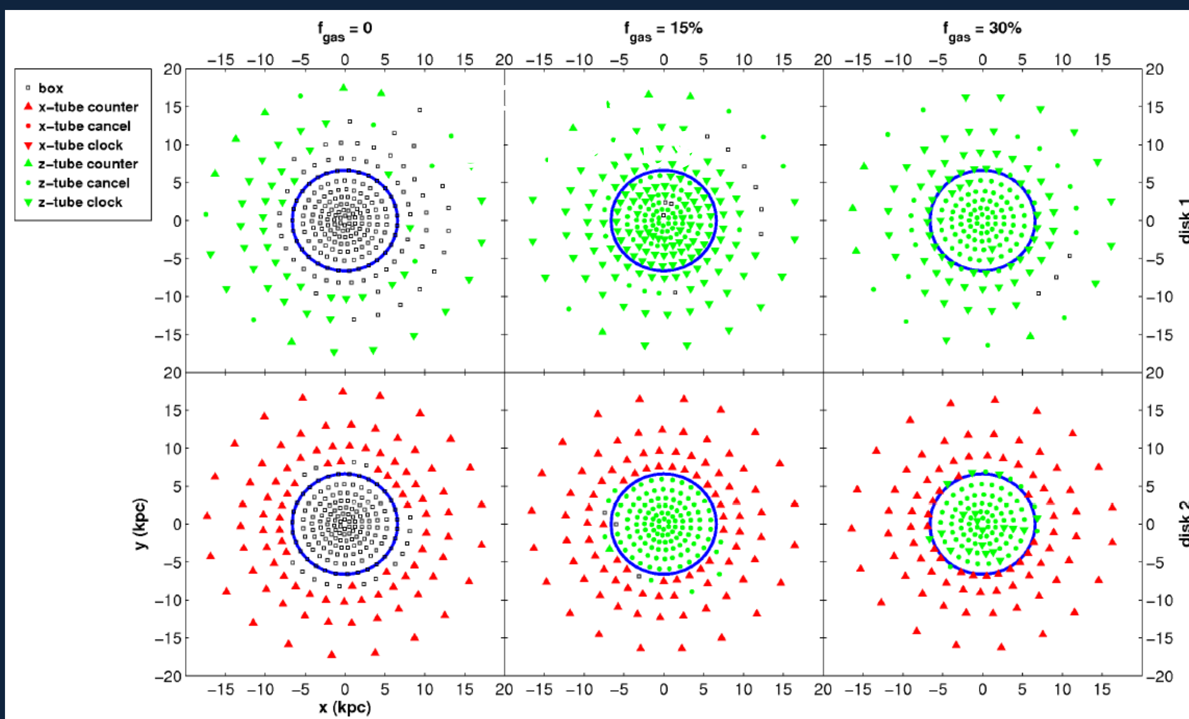

Kalapotharakos et al. 2004

# Origin of the orbital structure

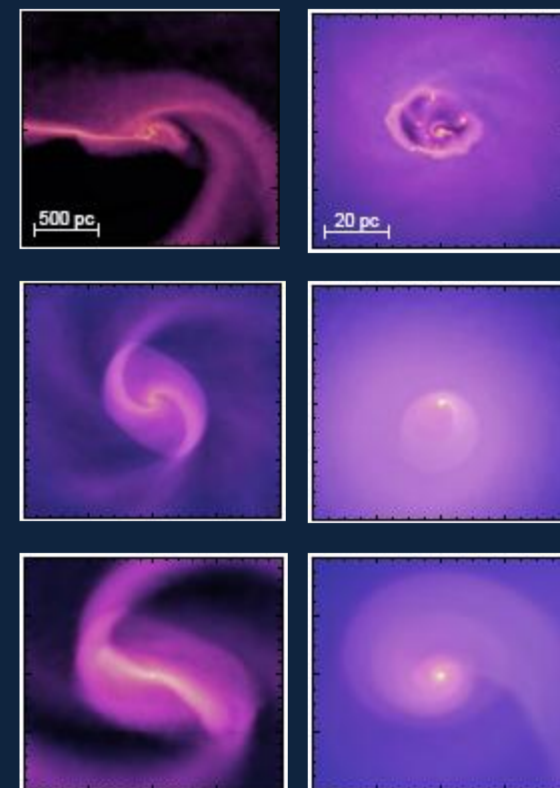



Barnes & Hernquist 1996, Hopkins et al. 2009

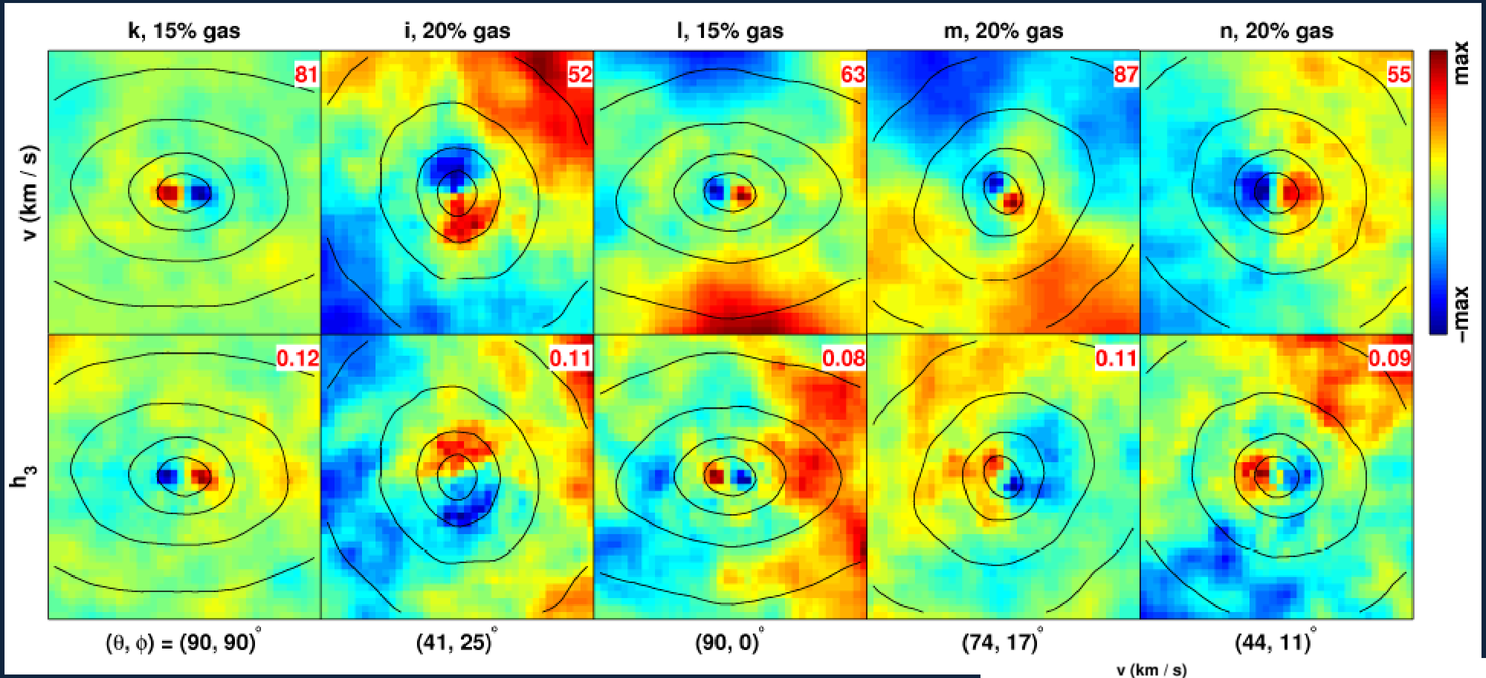


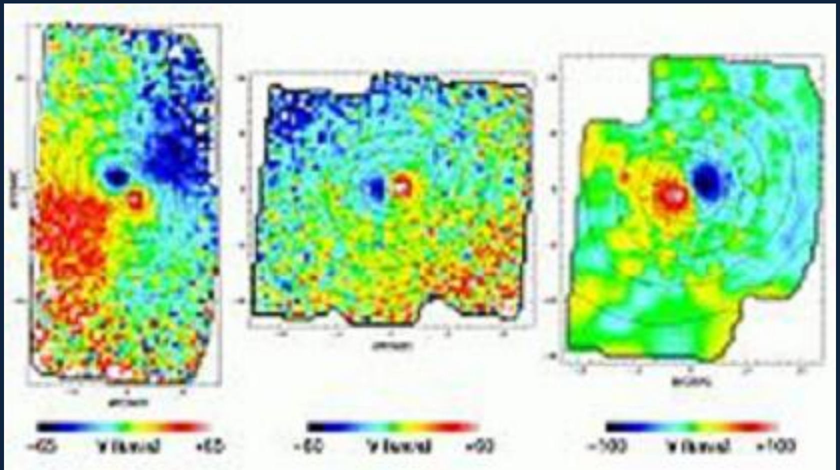

Hoffman et al. 2010



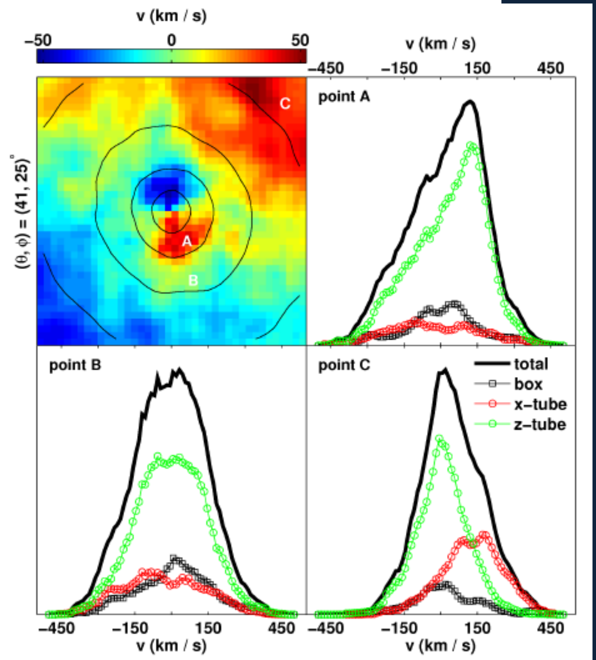

Hopkins et al. 2009

# KDCs in 15-20% gas remnants

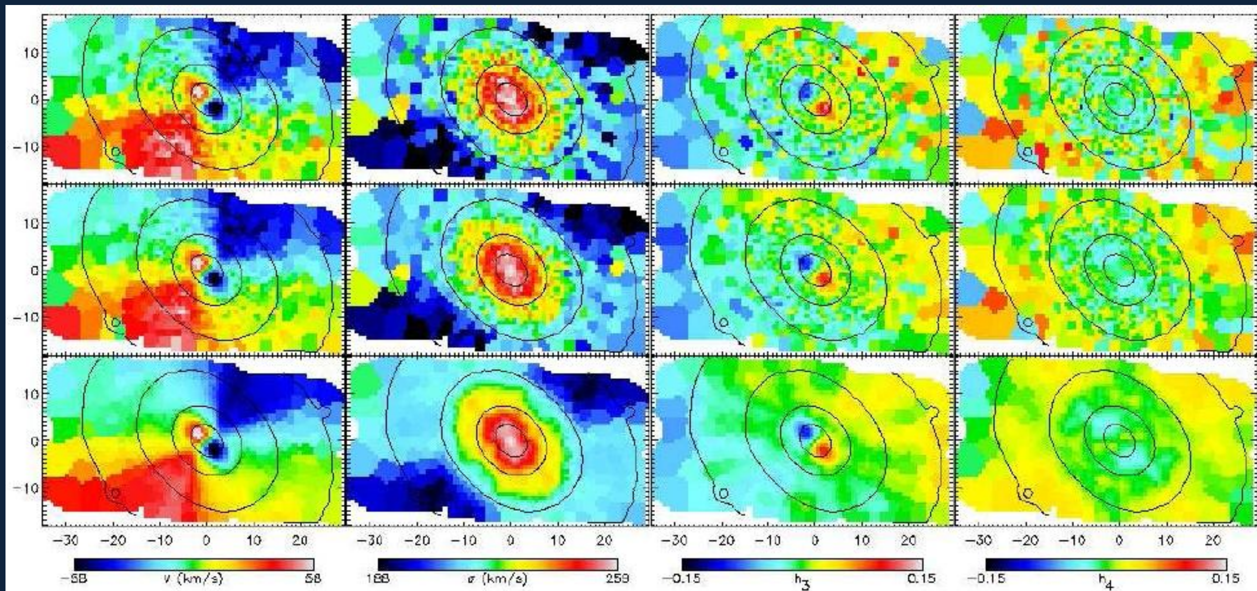


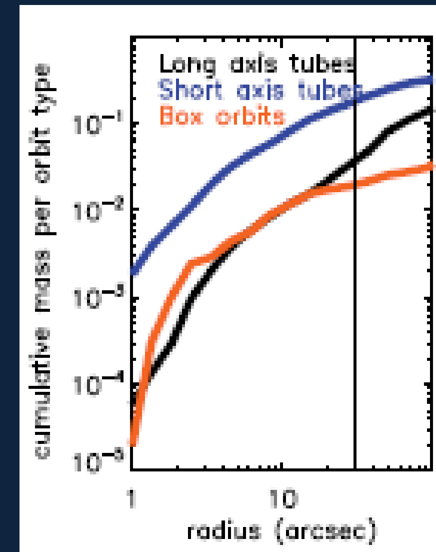



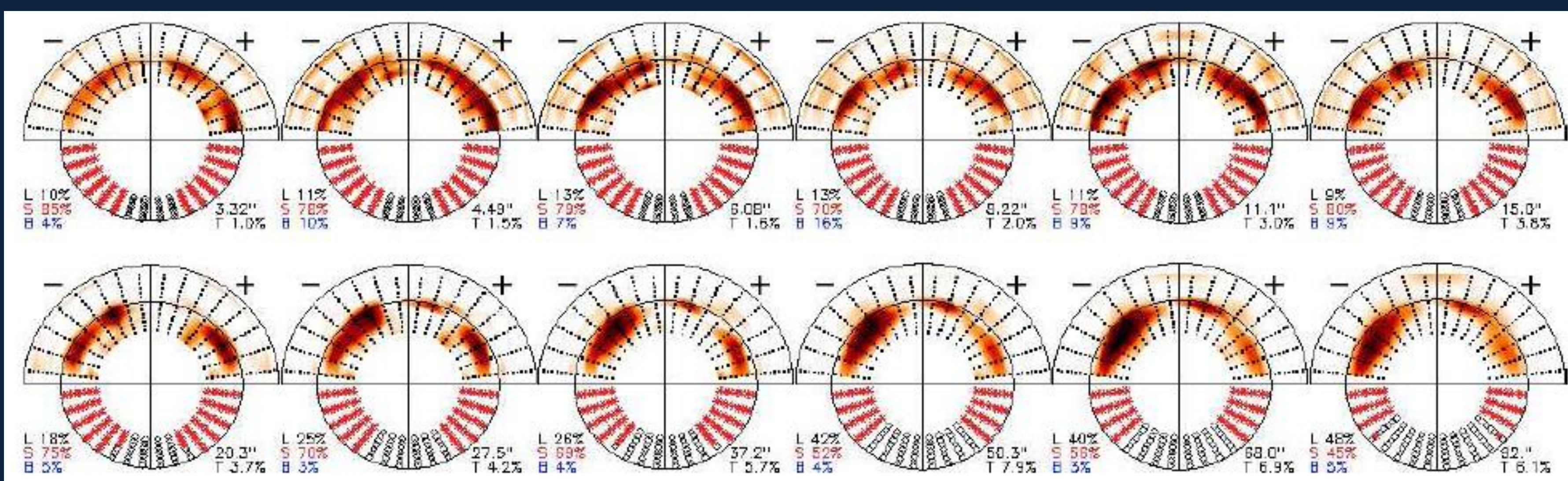
SAURON data



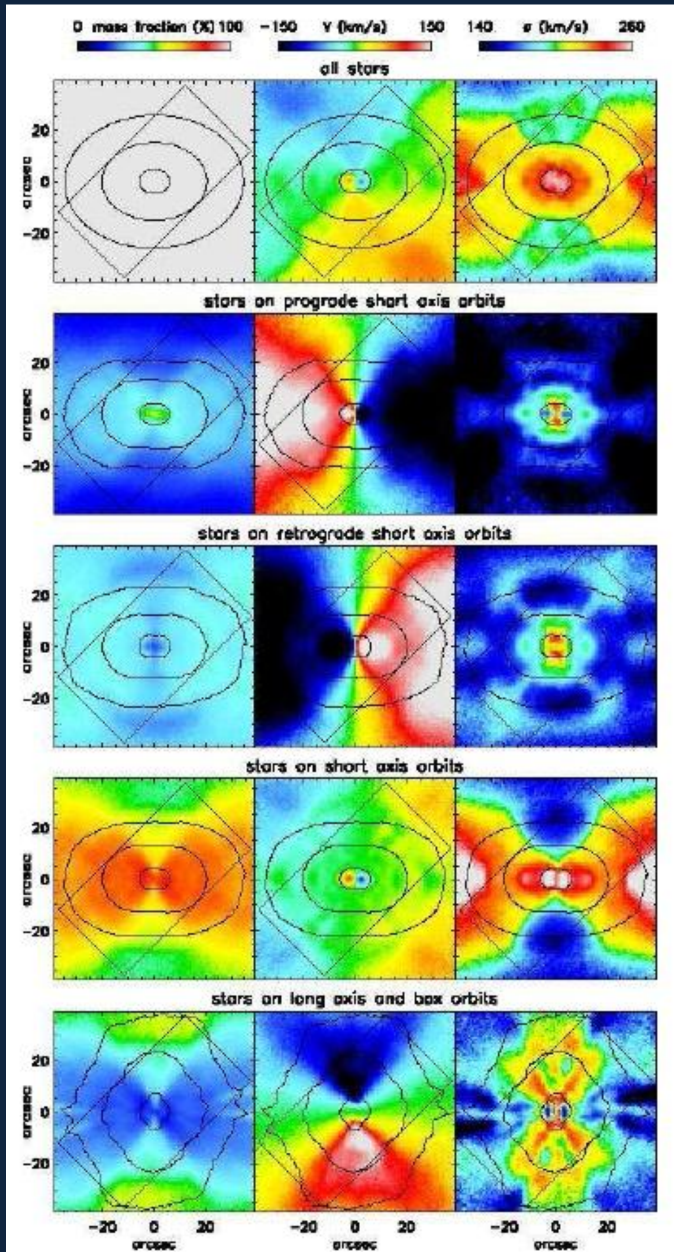
# NGC4365 – van den Bosch et al. 2008

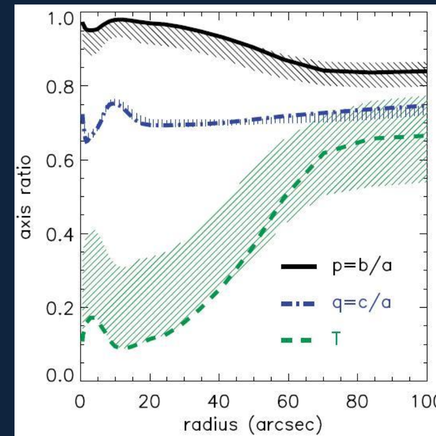


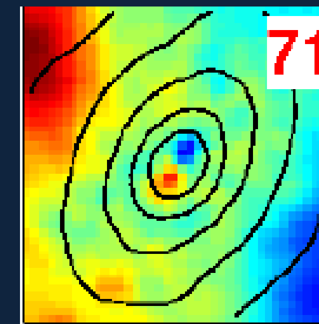



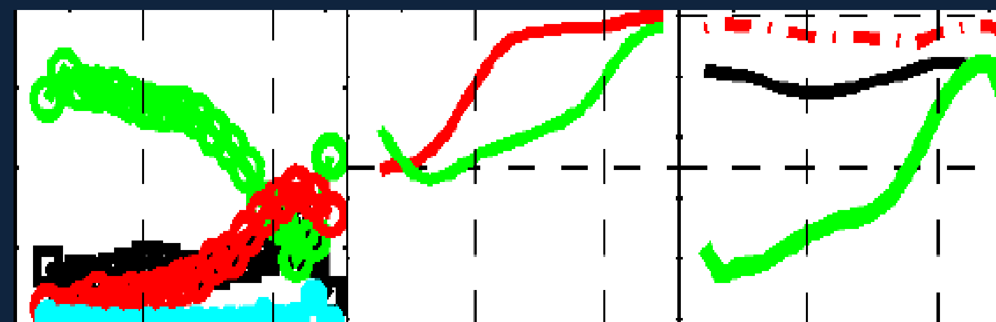



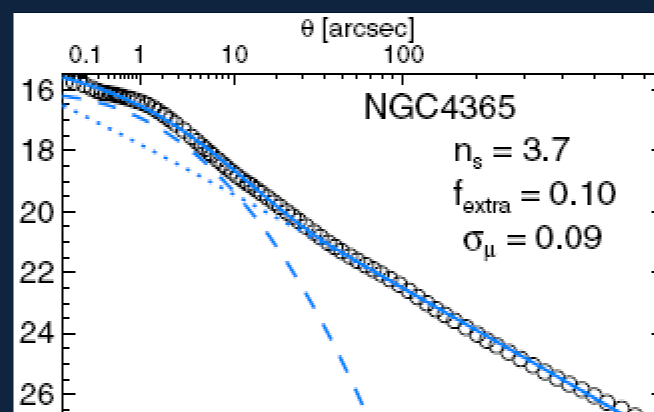
# NGC 4365 – comparison of 3D structure with simulations



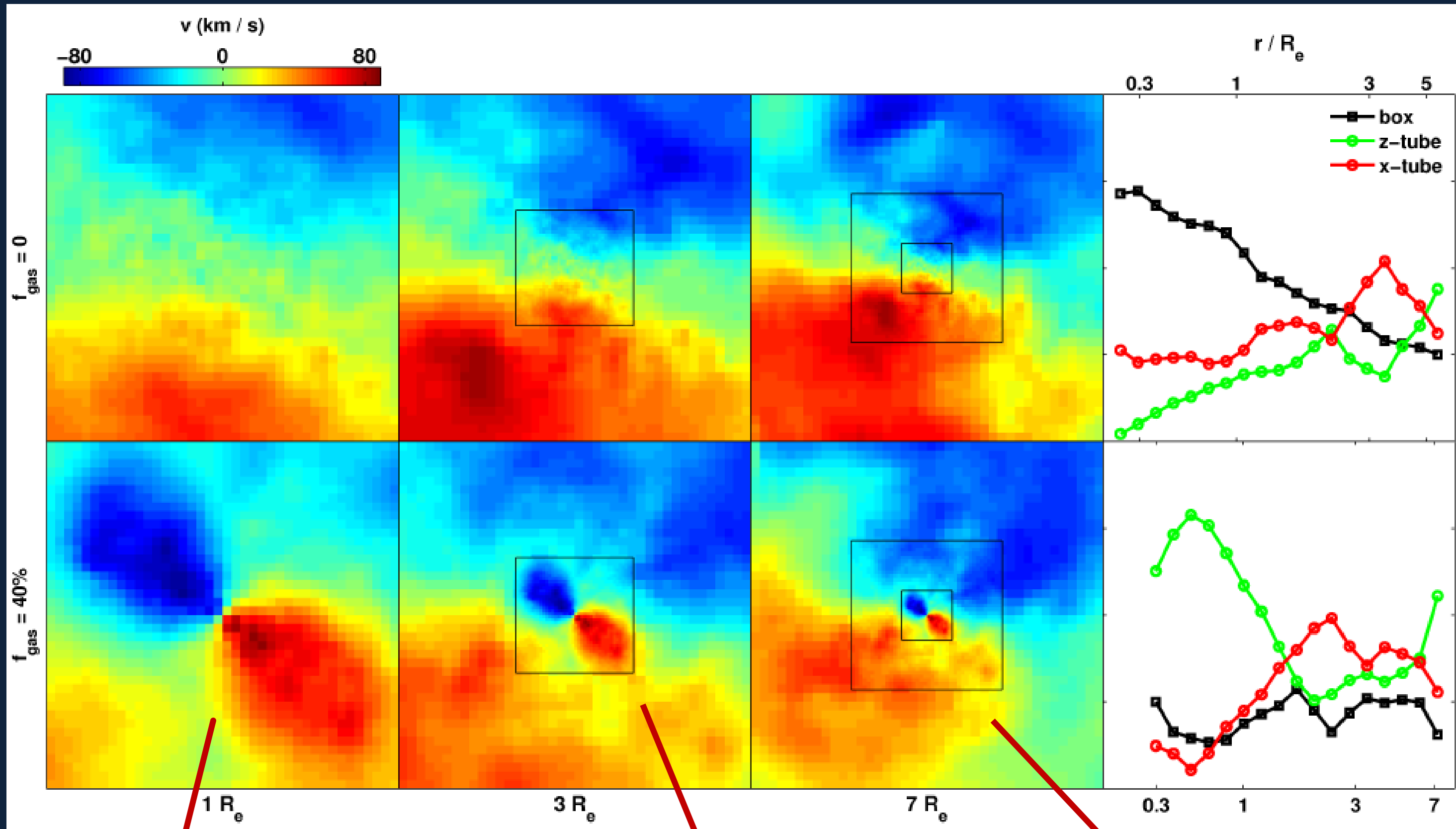



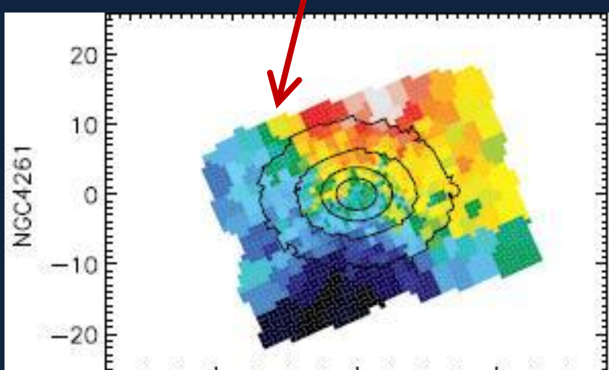





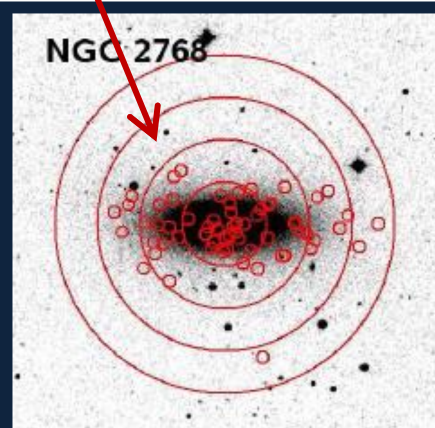

Hopkins et al. 2009:
10% "extra light" component in NGC 4365

# Constraints from outer kinematics

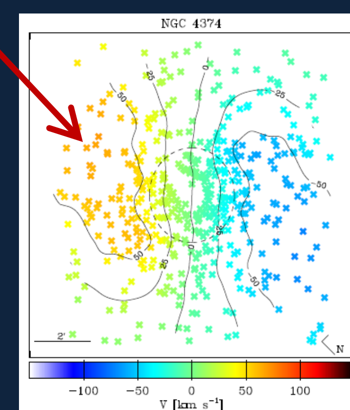



Emsellem et al. 2004

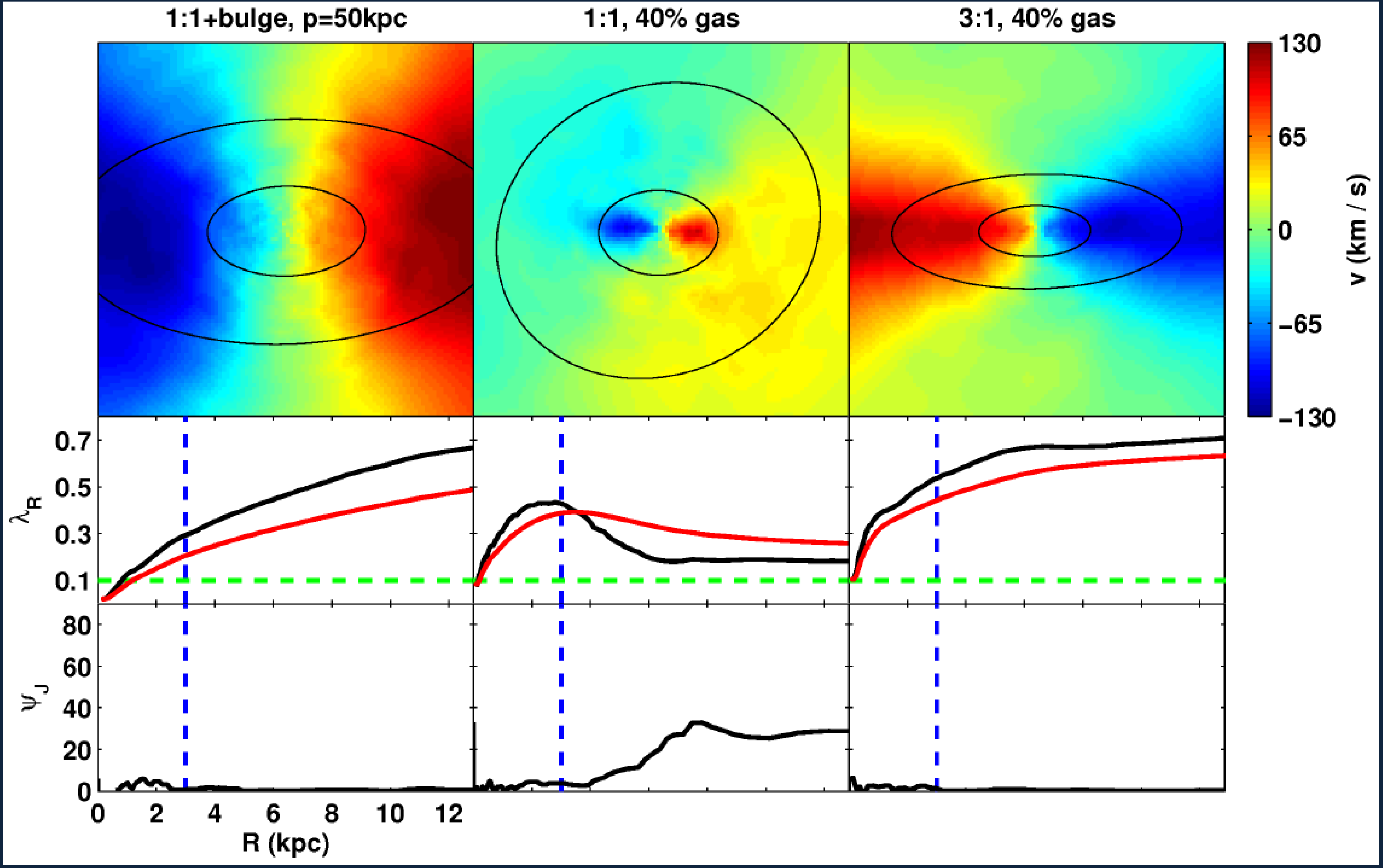



Proctor et al. 2009

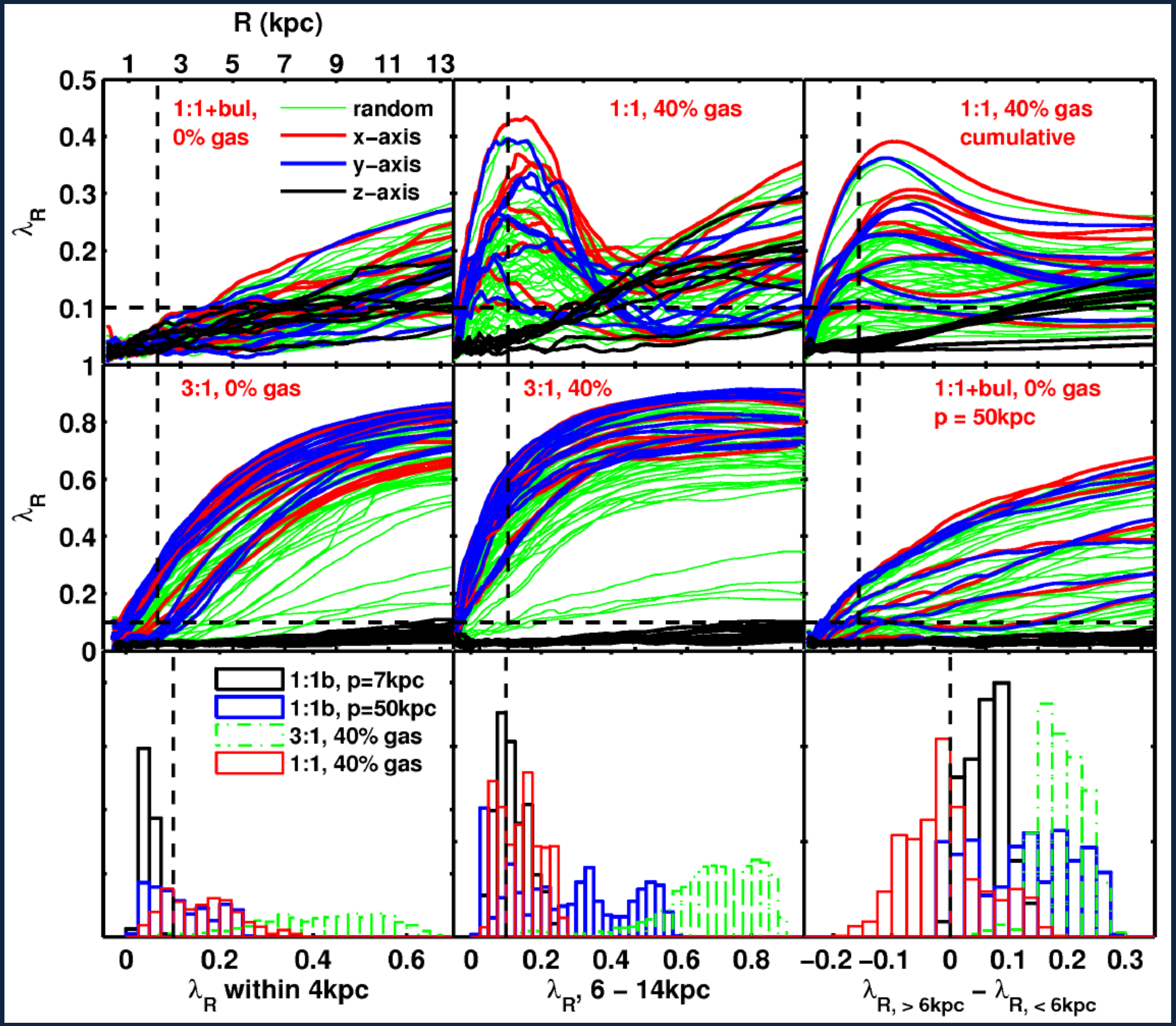



Coccato et al. 2009

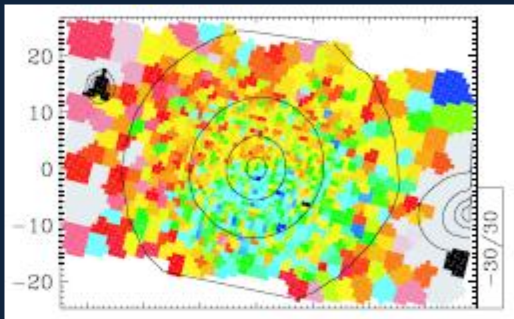
# Outer kinematics II



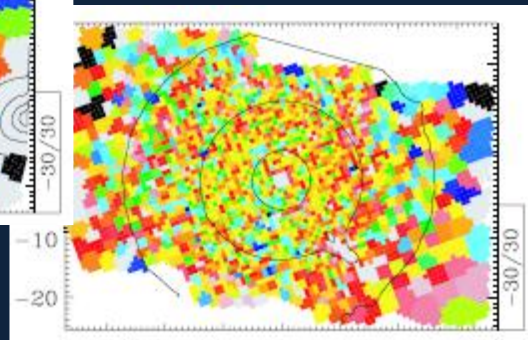
# Outer kinematics III



# The SAURON challenge

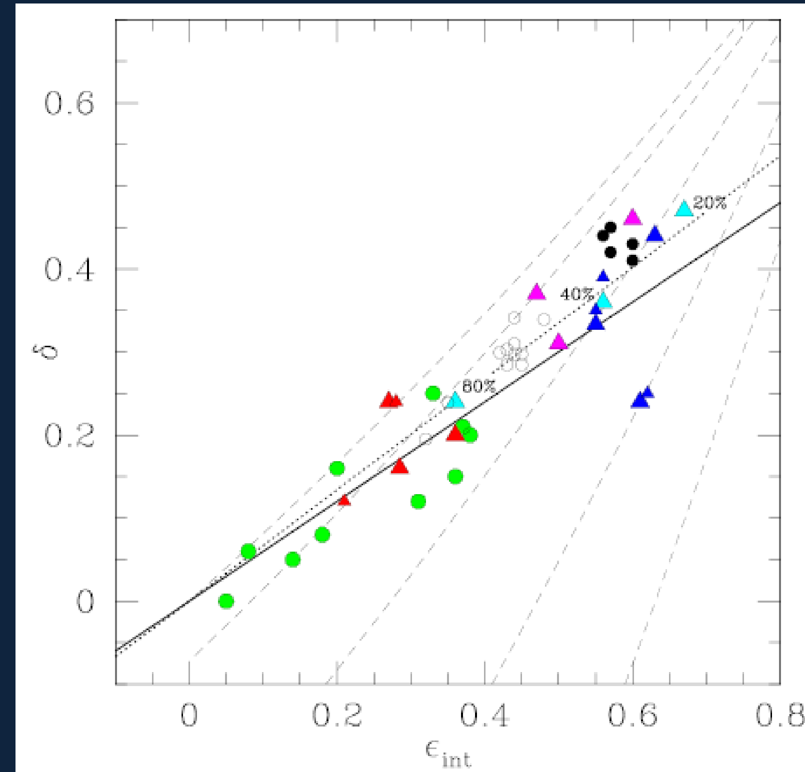


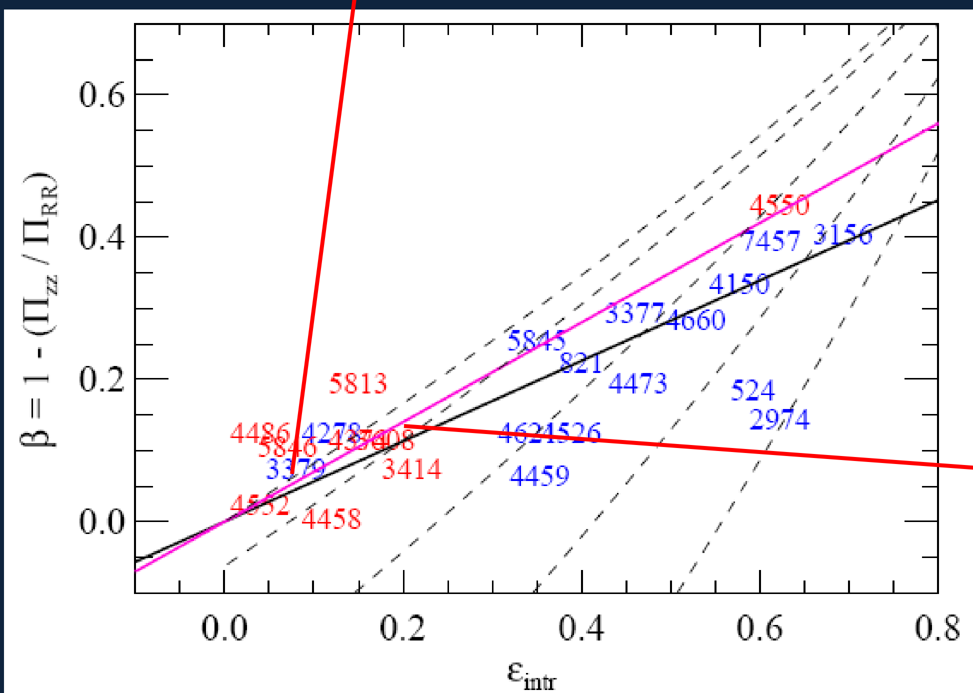
NGC 5846



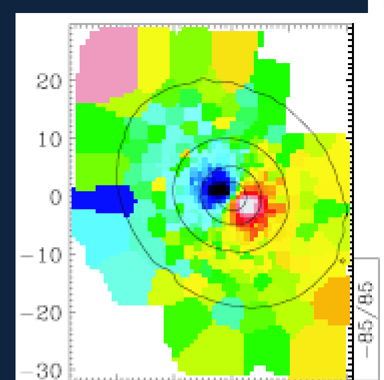
NGC 4486

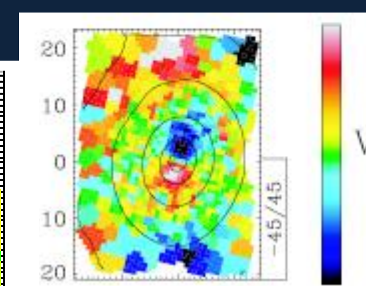
Burkert et al. 2008




Cappellari et al. 2007





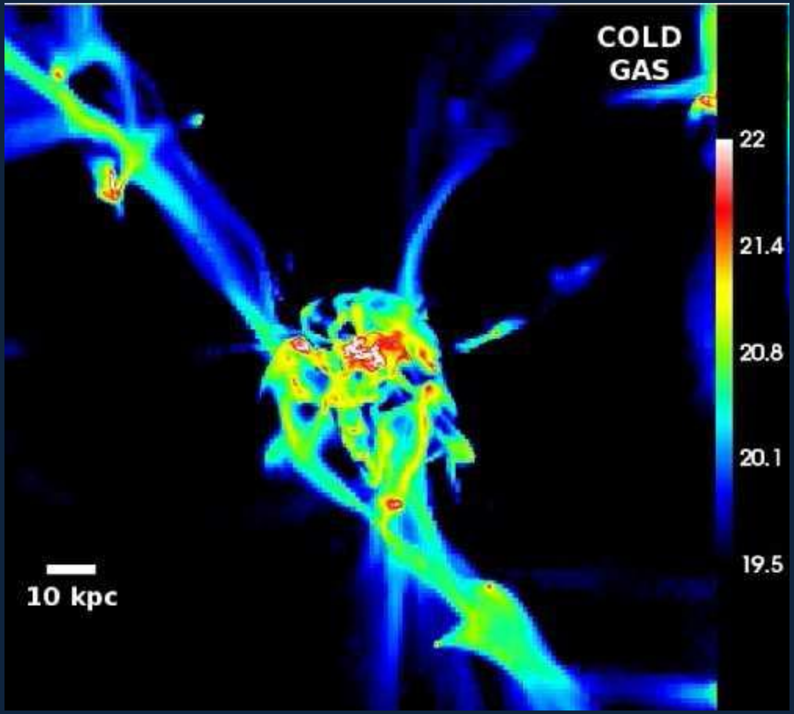

NGC 3414

NGC 5813

# More general formation scenarios

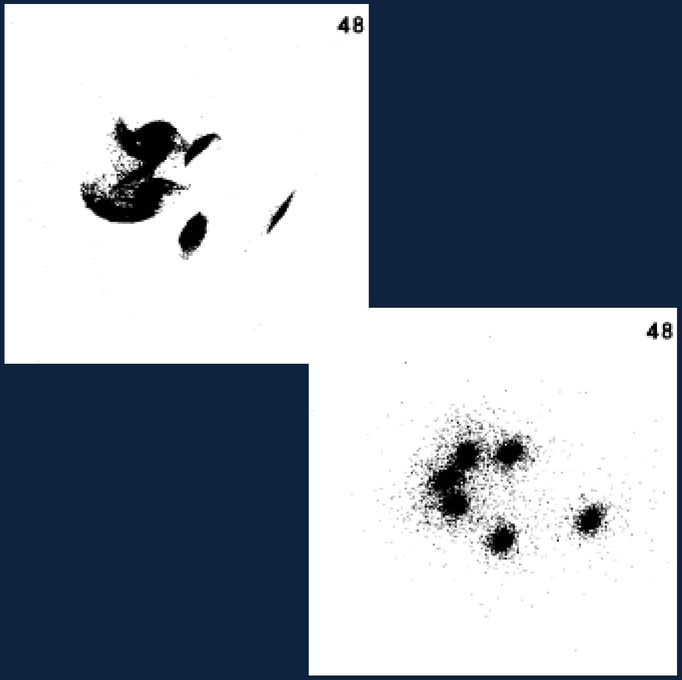
1) Complete exploration of merger phase space

2) Bulge formation through Clump migration in "wild disks"



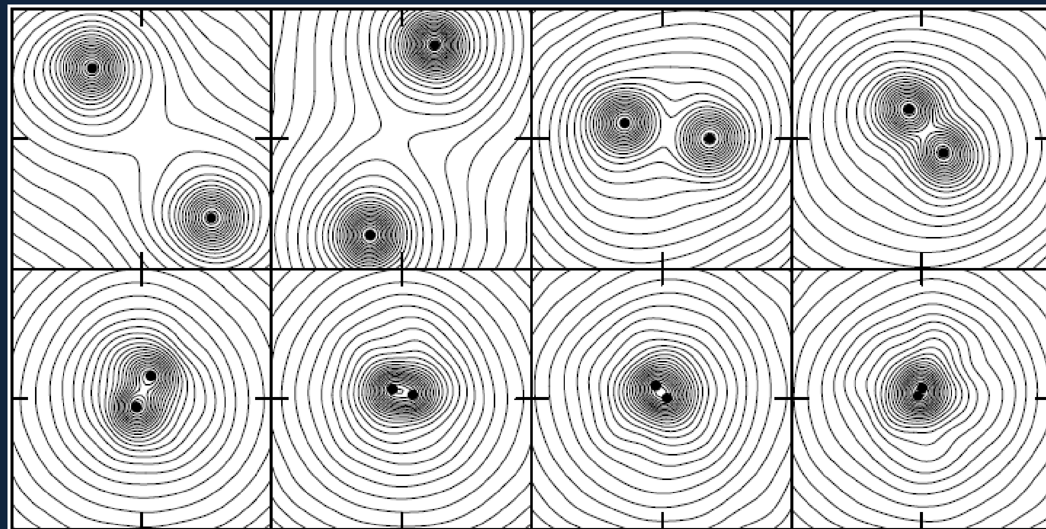

Ceverino et al. 2009

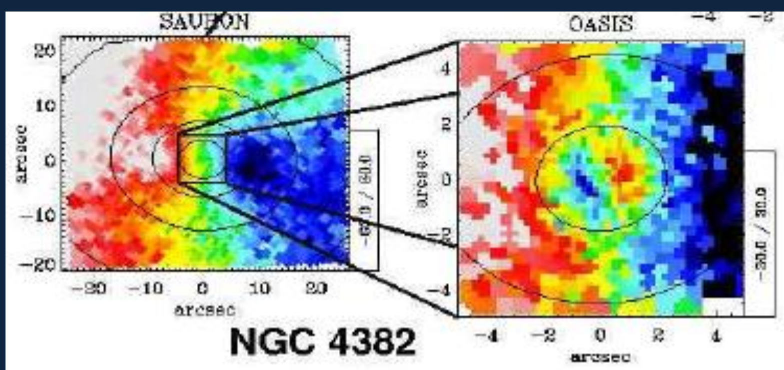
3) Multiple mergers / cosmologically motivated sequences

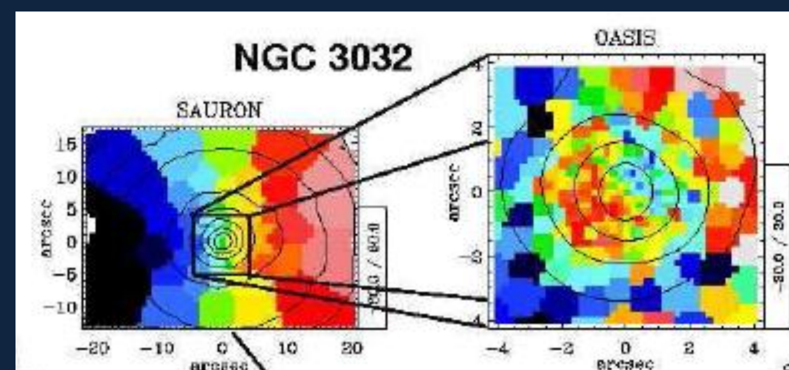



Weil & Hernquist 1996

# Binary SMBHs in collisionless galactic nuclei






Requirements: Integrate cuspy system with N ≈ $10^{7\text{-}8}$ for up to 500-1000 $t_{dyn}$ ; suppress relaxation enough to be in empty loss cone regime.

Ideal code: Pure triaxial NBSCF (no kicks) until initial spherical loss cone cleared out, switching to MCSCF after that.

# The Self-consistent field (SCF) method

$$\rho(r,\theta,\phi)=\sum_{l=0}^{\infty}\sum_{m=0}^{l}P_{lm}(\cos\theta)[A_{lm}(r)\cos m\phi+B_{lm}(r)\sin m\phi]$$

$$\Phi(r,\theta,\phi)=\sum_{l=0}^{\infty}\sum_{m=0}^{l}P_{lm}(\cos\theta)[C_{lm}(r)\cos m\phi+D_{lm}(r)\sin m\phi]$$

(A)

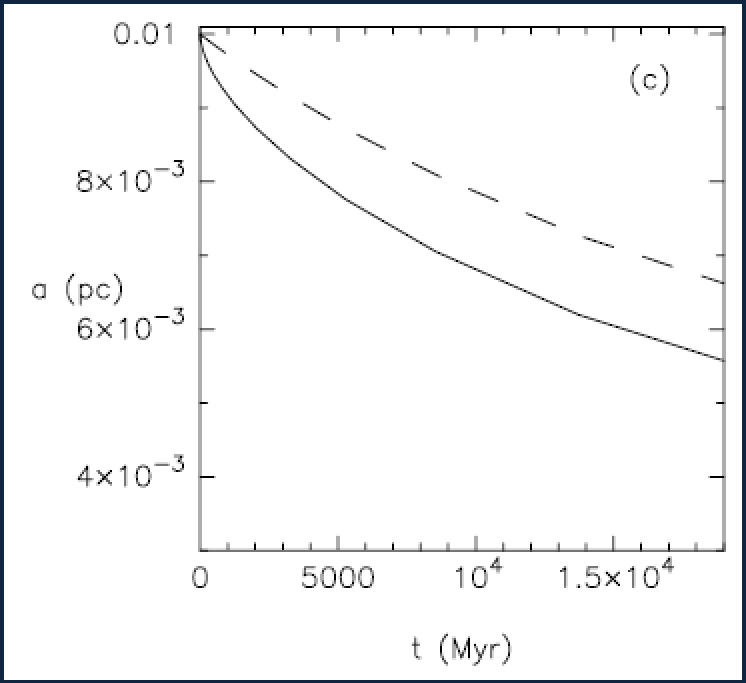
$$\begin{pmatrix}A_{lm}(r)\\B_{lm}(r)\\C_{lm}(r)\\D_{lm}(r)\end{pmatrix}=N_{lm}\sum_{n=0}^{\infty}\tilde{A}_{nl}\begin{pmatrix}\tilde{\rho}_{nl}(r)\\\tilde{\rho}_{nl}(r)\\\tilde{\Phi}_{nl}(r)\\\tilde{\Phi}_{nl}(r)\end{pmatrix}\sum_{k}m_k\,\tilde{\Phi}_{nl}(r_k)P_{lm}(\cos\theta_k)\begin{pmatrix}\cos m\phi_k\\\sin m\phi_k\\\cos m\phi_k\\\sin m\phi_k\end{pmatrix}$$

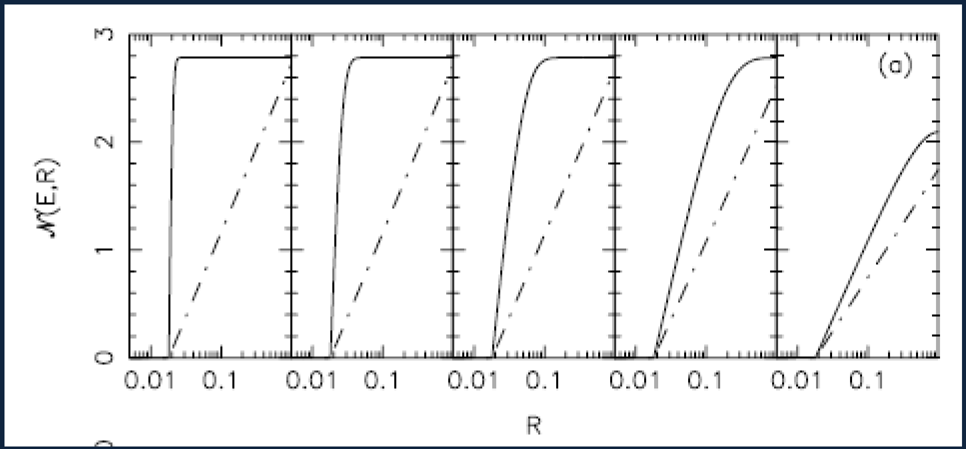
(B)

1) O(N)
2) Completely parallel
3) No Cartesian softening

Most astrophysical systems modeled with N-body simulations undergo brief episodes of rapid evolution, long periods of slow evolution ($t_{ev} \gg t_{dyn}$).

# Binary S/IMBHs in *collisional* nuclei




Milosavljevic & Merritt 2003
Sharp phase space gradients near the loss cone.

Requirements: Integrate cuspy system with $N \approx 10^7$ for up to 500-1000 $t_{dyn}$ ; suppress relaxation enough to be in empty loss cone regime *and* accurately treat 2-body relaxation.

Ideal code: Spherical, triaxial MCSCF *with Henon kicks* (note: unlike Spitzer MC, Henon method does not require a Maxwellian distribution!).

# Relaxation in N-body simulations

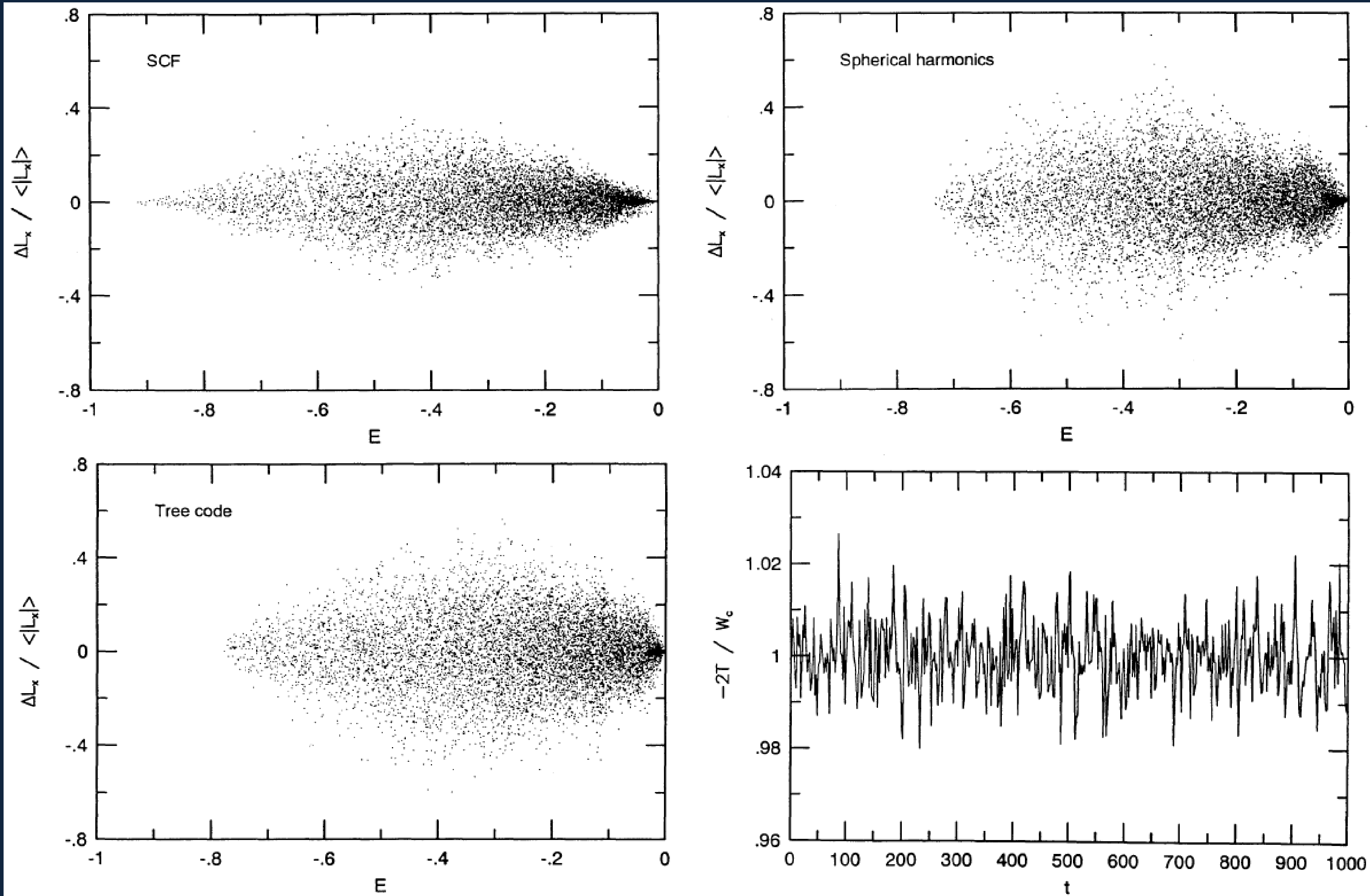


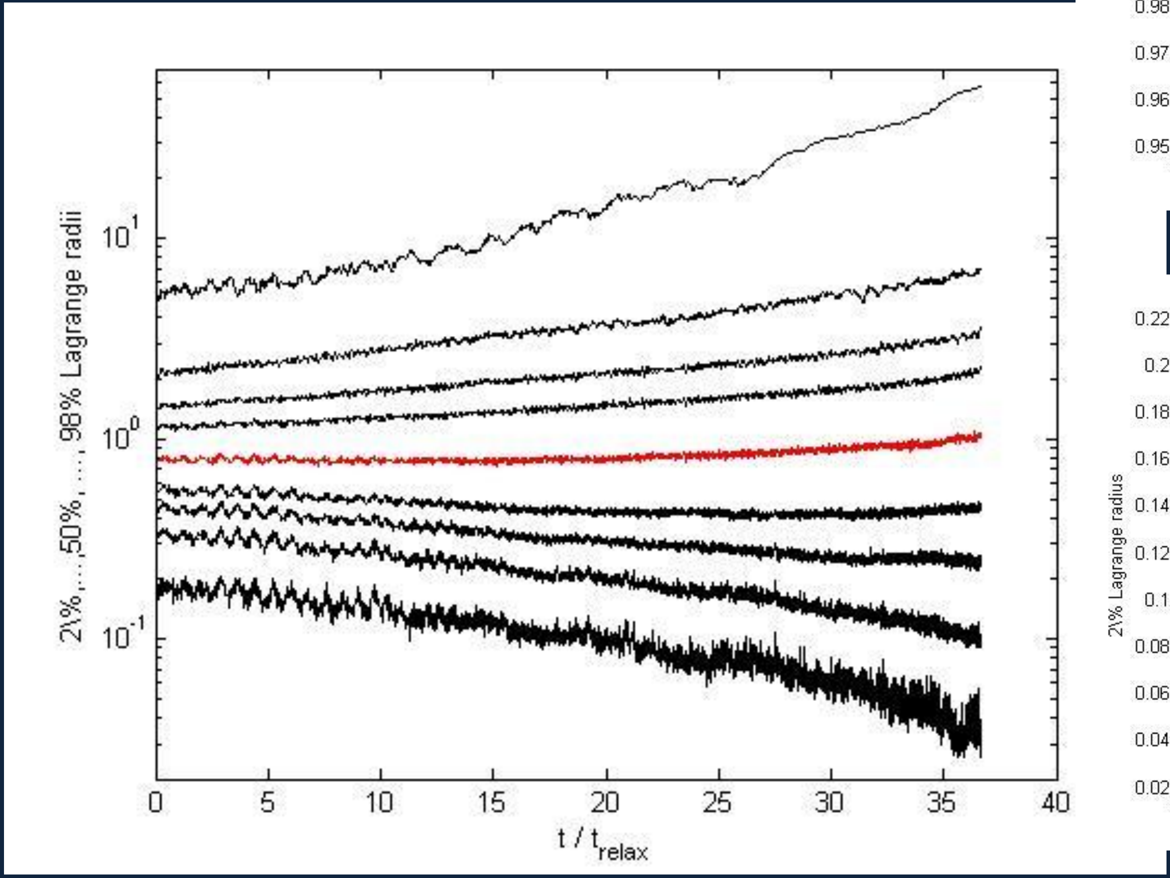

FIG. 12

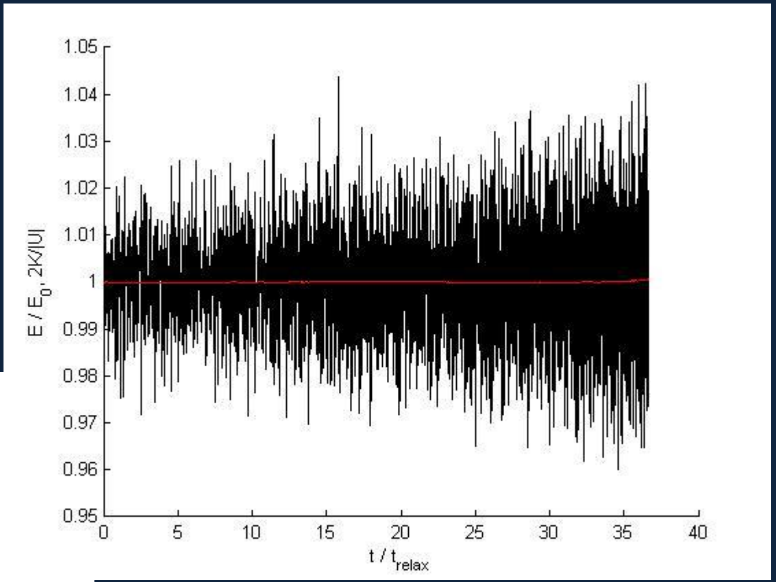
FIG. 13

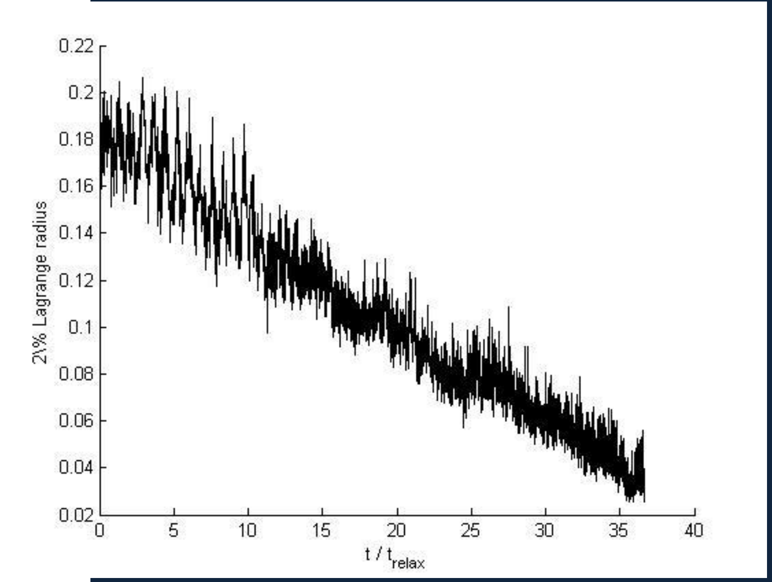
Hernquist & Ostriker 1992

# Evolution owing to time fluctuations of coefficients

$N = 2.5 \times 10^3$
$N_{max} = 6,\ l_{max} = 4$



# Temporal smoothing

Figure 14 motivates a modification to the SCF method that would be impossible or, at best, very difficult to implement in $N$-body codes, which we refer to as "temporal smoothing." That is, one could imagine setting $A'_{000}$ equal to the global time-average of the values plotted in Figure 14, and then integrating particle orbits in this fixed potential. As implied earlier, particle energies would

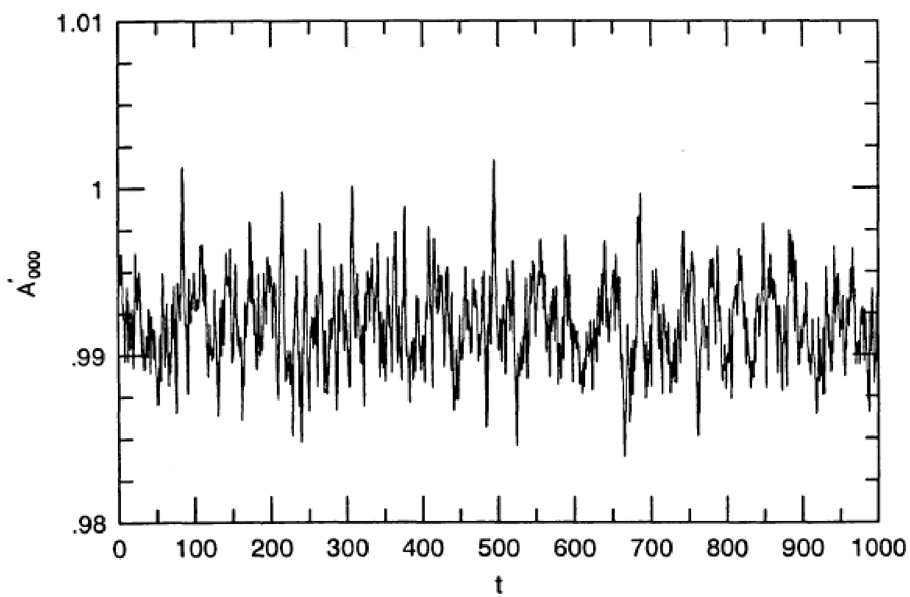
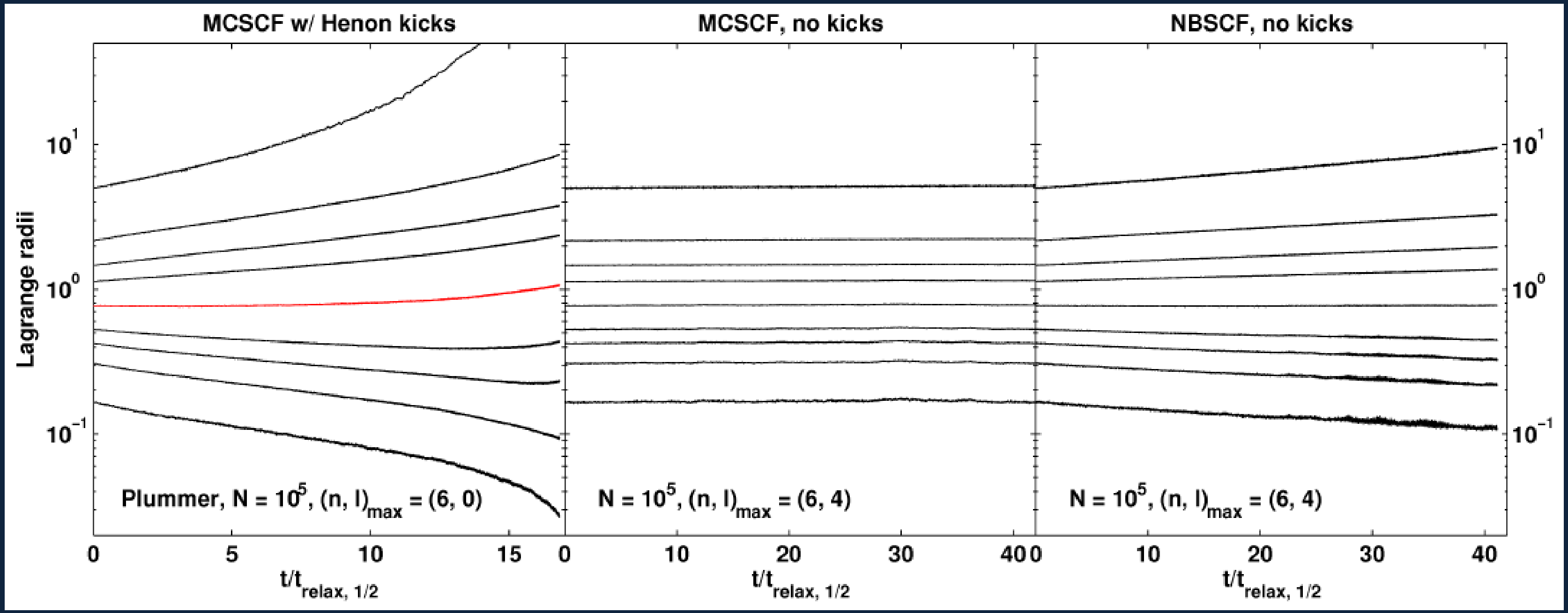


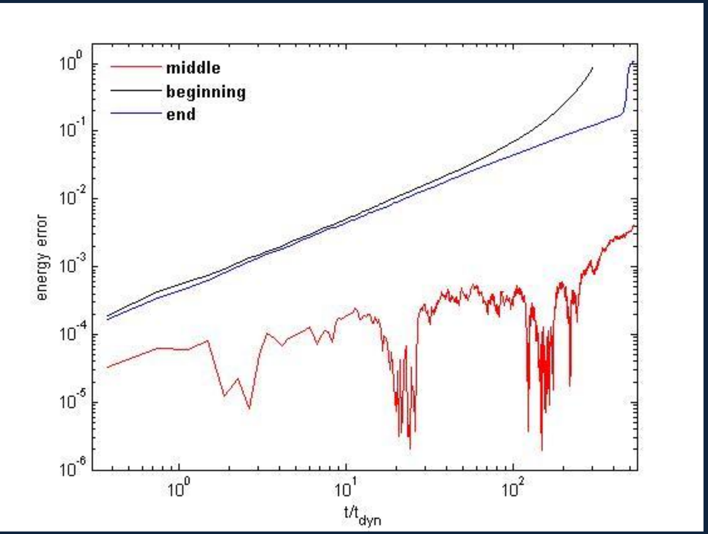

FIG. 14.—Expansion coefficient in a purely radial version of the run shown in Fig. 10, as a function of time. $A'_{000}$ differs from the value of $A_{000}$ given by eq. (2.33) by a constant factor so that $A'_{000}$ would be precisely one in the continuum limit.

"Monte-Carlo" implementation

1) Initialize $\{m_k, \mathbf{r}_k, \mathbf{v}_k\}$.
2) Compute $\mathbf{a}(\mathbf{r})$ from eq'n (B).
3) Integrate each particle's orbit *separately* through $\delta t = \varepsilon t_{relax,}$.
4) Apply Henon kicks.
5) Go back to step 2.

# Suppressing relaxation with rare potential updates




Energy conservation is currently an issue for long-term integrations of $10^4$– $10^5$ dynamical times.

# Summary

-Merger model predicts a characteristic, physically intuitive orbital structure (though not necessarily unique), observable with SAURON + SMEAGOL

-Power of direct comparisons with dynamical models of observed systems: Physical intuition, some features detectable only this way

-Need for extension to more general formation models – cosmological merger trees, smooth/clumpy gas accretion, …

-SCF / MC technique ideal for studying nuclear kinematics of SMBH binary nuclei; code under development.