Hints and insights from the simulations of tidal stirring of dwarf galaxies

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dIrr versus dSph galaxies

NGC 6822

Leo I

dIrr	dSph
irregular/disky	elliptical
rotating	non-rotating
contain gas	do not contain gas
forming stars	not forming stars

Morphology-density relation: dSph galaxies are found closer to the big galaxies, while dIrrs occupy isolated regions at the outskirts of the LG

Tidal stirring scenario

- All dwarf galaxies were initially disks embedded in dark matter haloes
- In the vicinity of a big galaxy they are strongly affected by tidal forces
- Tidal forces cause strong mass loss and the formation of tidal tails
- The evolution involves morphological transformation, from a disk to a bar and then a spheroid
- Streaming motions of stars change to random motions

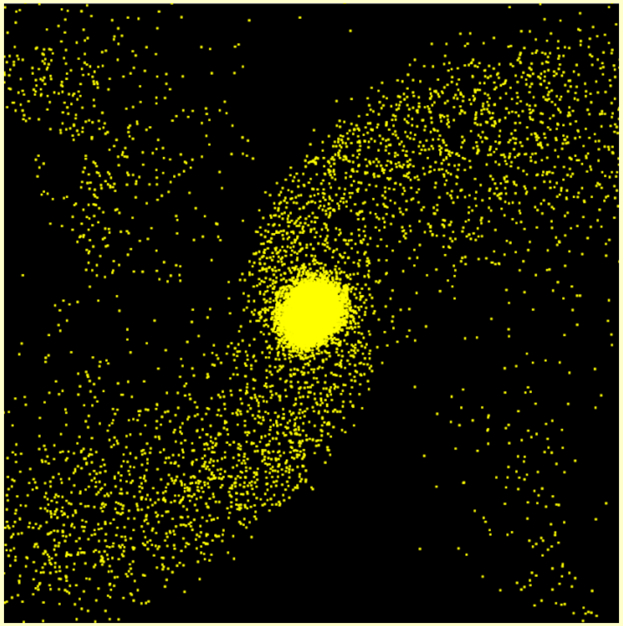
Mayer et al. 2001

If dSphs formed via tidal stirring:

- They are not spherical
- The stellar orbits are not isotropic
- They have some remnant rotation
- The kinematic samples are contaminated by tidally stripped stars

Examples of simulations

- The simulations traced the evolution of a two-component dwarf galaxy on an eccentric orbit around the Milky Way for 10 Gyrs
- The dwarf initially had a stellar disk and an NFW-like dark matter halo
- The dwarf was modelled with 1.2 x 10^6 stellar and 10^6 dark matter particles
- The progenitor had an initial mass of 10^9 $M_\odot$



20 kpc

Klimentowski et al. 2007

Kazantzidis et al. 2011

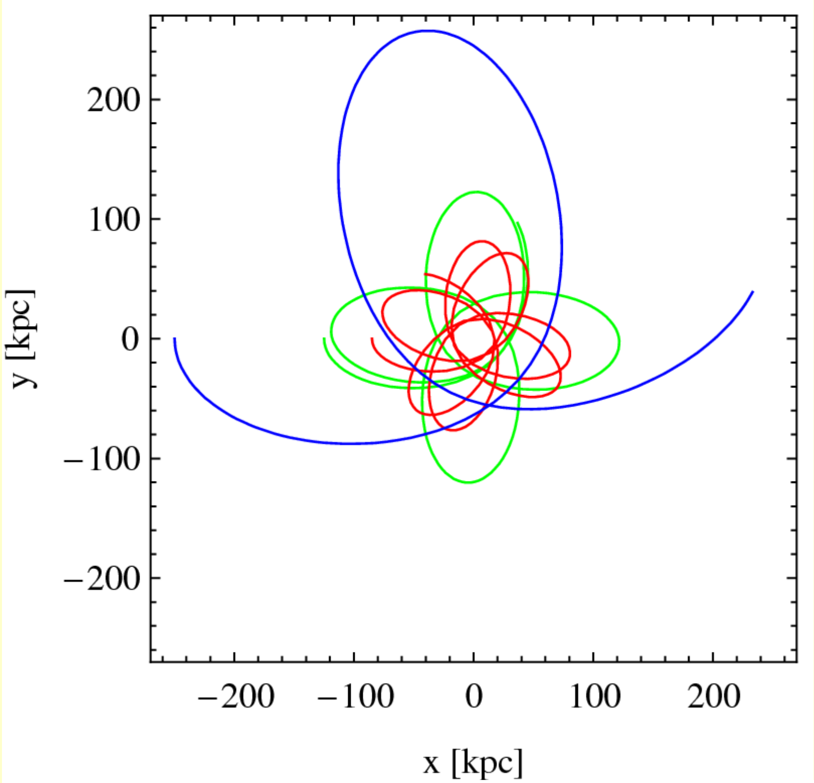
All simulations

PROPERTIES OF THE SIMULATED DWARFS.

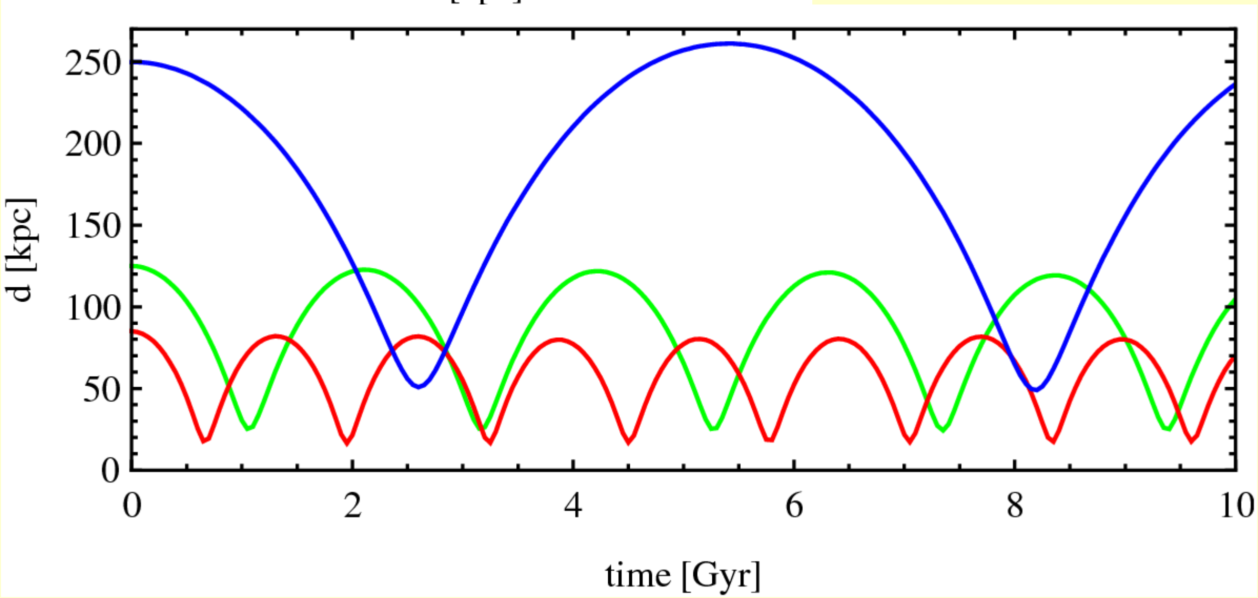
Simulation	Varied parameter	r_{apo} [kpc]	r_{peri} [kpc]	T_{orb} [Gyr]	t_{la} [Gyr]	r_{lim} [kpc]	M_V [mag]	$r_{1/2}$ [kpc]	μ_V [mag arcsec^{-2}]	V/σ	$e = 1 - b/a$	Color
O1	orbit	125	25	2.09	8.35	6.28	−11.7	0.36	23.4	0.36	0.20	green
O2	orbit	87	17	1.28	8.95	6.28	−10.2	0.33	24.6	0.08	0.03	red
O3	orbit	250	50	5.40	5.40	6.28	−12.8	0.44	22.5	1.30	0.66	blue
O4	orbit	125	12.5	1.81	9.05	6.28	−10.4	0.60	24.7	0.50	0.05	orange
O5	orbit	125	50	2.50	10.00	6.28	−12.3	0.41	22.9	0.81	0.55	purple
O6	orbit	80	50	1.70	8.50	6.28	−12.3	0.47	23.3	0.37	0.35	brown
O7	orbit	250	12.5	4.55	9.10	6.28	−11.8	0.46	23.6	0.62	0.39	black
S6	$i(-45°)$	125	25	2.09	8.35	6.28	−11.8	0.30	22.7	0.18	0.20	green
S7	$i(+45°)$	125	25	2.09	8.35	6.28	−12.0	0.45	23.3	0.25	0.26	red
S8	$z_d/R_d(-0.1)$	125	25	2.09	8.35	6.28	−11.8	0.34	23.2	0.62	0.27	blue
S9	$z_d/R_d(+0.1)$	125	25	2.09	8.35	6.28	−11.7	0.38	23.7	0.55	0.17	orange
S10	$m_d(-0.01)$	125	25	2.09	8.35	6.28	−10.9	0.38	24.5	0.45	0.09	purple
S11	$m_d(+0.02)$	125	25	2.09	8.35	6.28	−12.8	0.37	22.4	0.71	0.42	magenta
S12	$\lambda(-0.016)$	125	25	2.09	8.35	3.78	−12.3	0.22	21.8	0.64	0.25	cyan
S13	$\lambda(+0.026)$	125	25	2.09	8.35	6.94	−11.1	0.50	24.8	0.26	0.12	pink
S14	$c(-10)$	125	25	2.10	8.40	6.28	−11.4	0.35	23.7	0.31	0.14	black
S15	$c(+20)$	125	25	2.08	8.30	6.28	−12.2	0.37	23.2	0.96	0.32	gray
S16	$M_h(\times 0.2)$	125	25	2.14	8.55	3.67	−10.1	0.25	24.4	0.37	0.17	brown
S17	$M_h(\times 5)$	125	25	1.88	9.40	7.00	−13.1	0.48	22.8	0.63	0.18	yellow

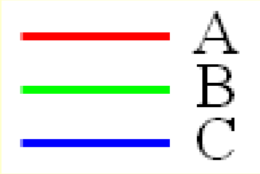
Łokas et al. 2011

Three simulated cases



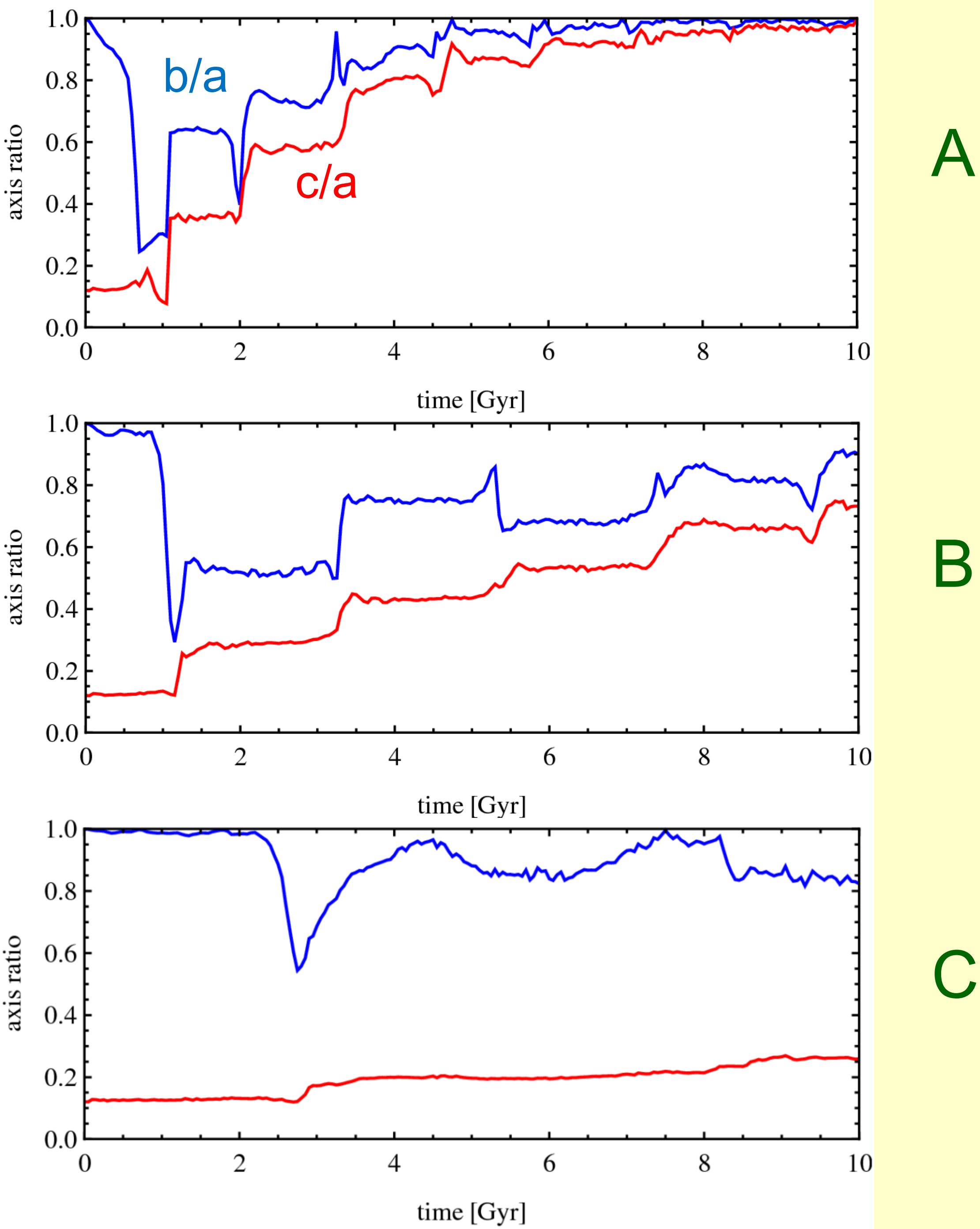
Three orbits of different size, other parameters unchanged





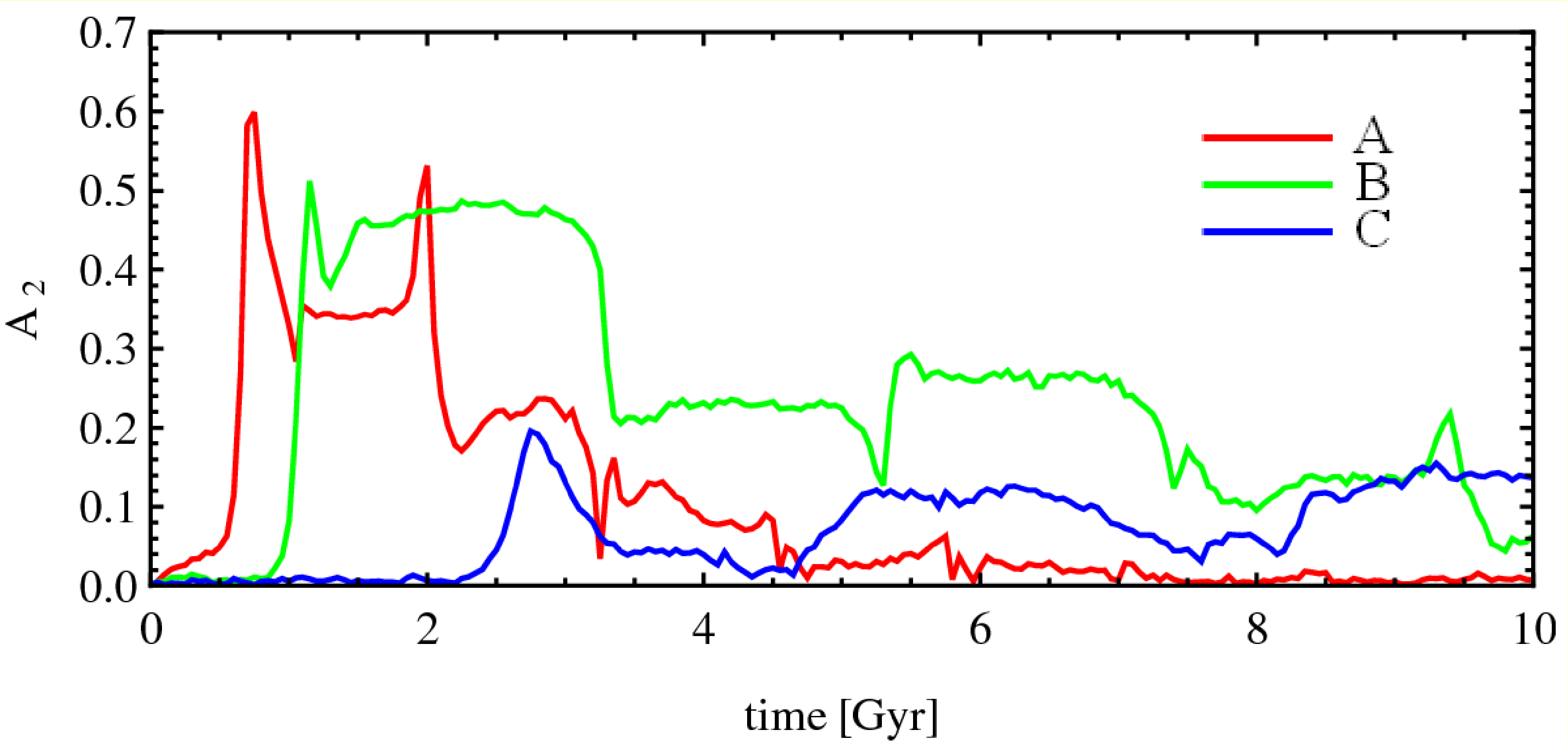
$r_{apo} / r_{peri} = 5$

Axis ratios

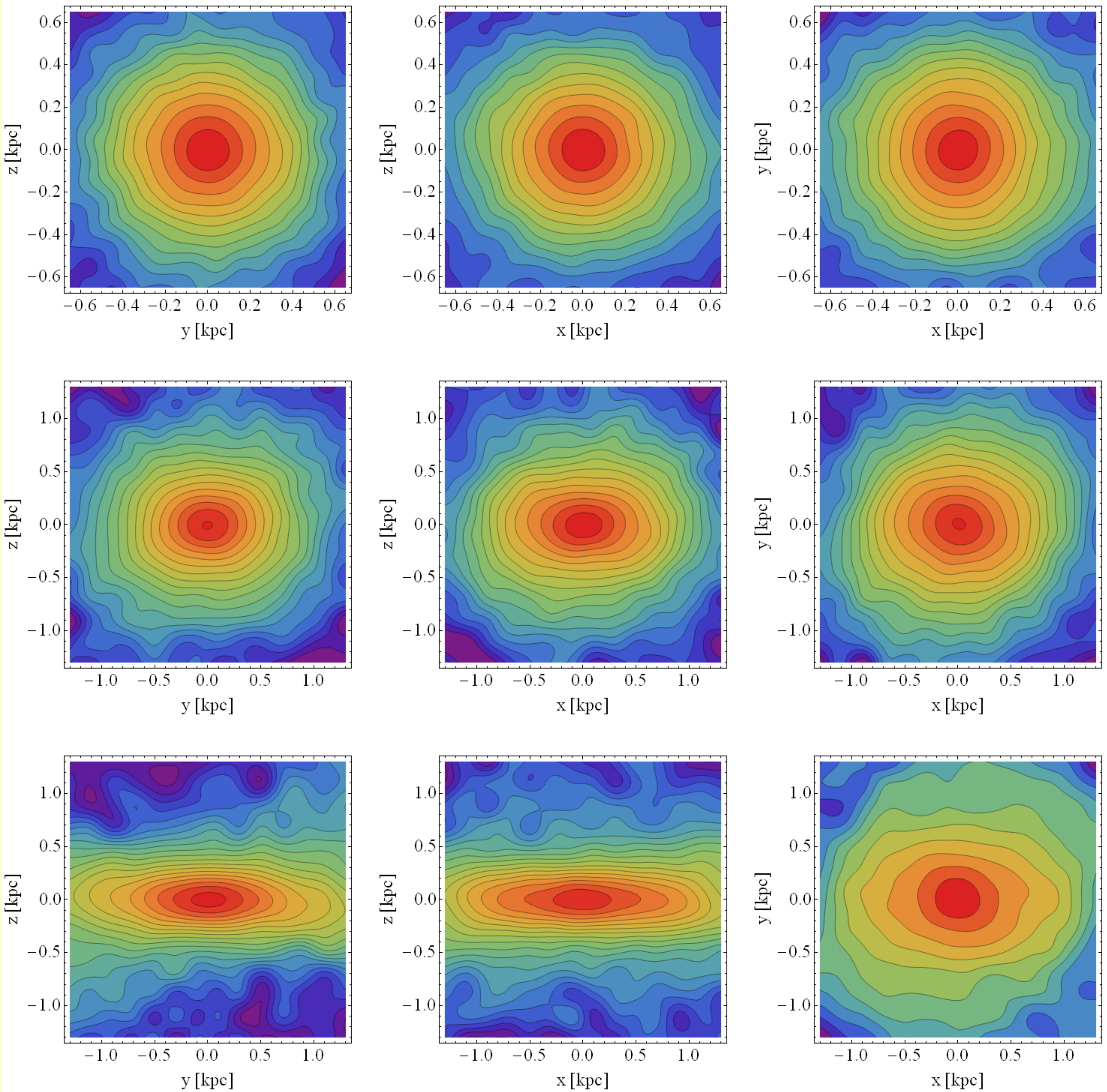


- Model A ends up spherical
- Model B is triaxial
- Model C remains disky

Morphological evolution



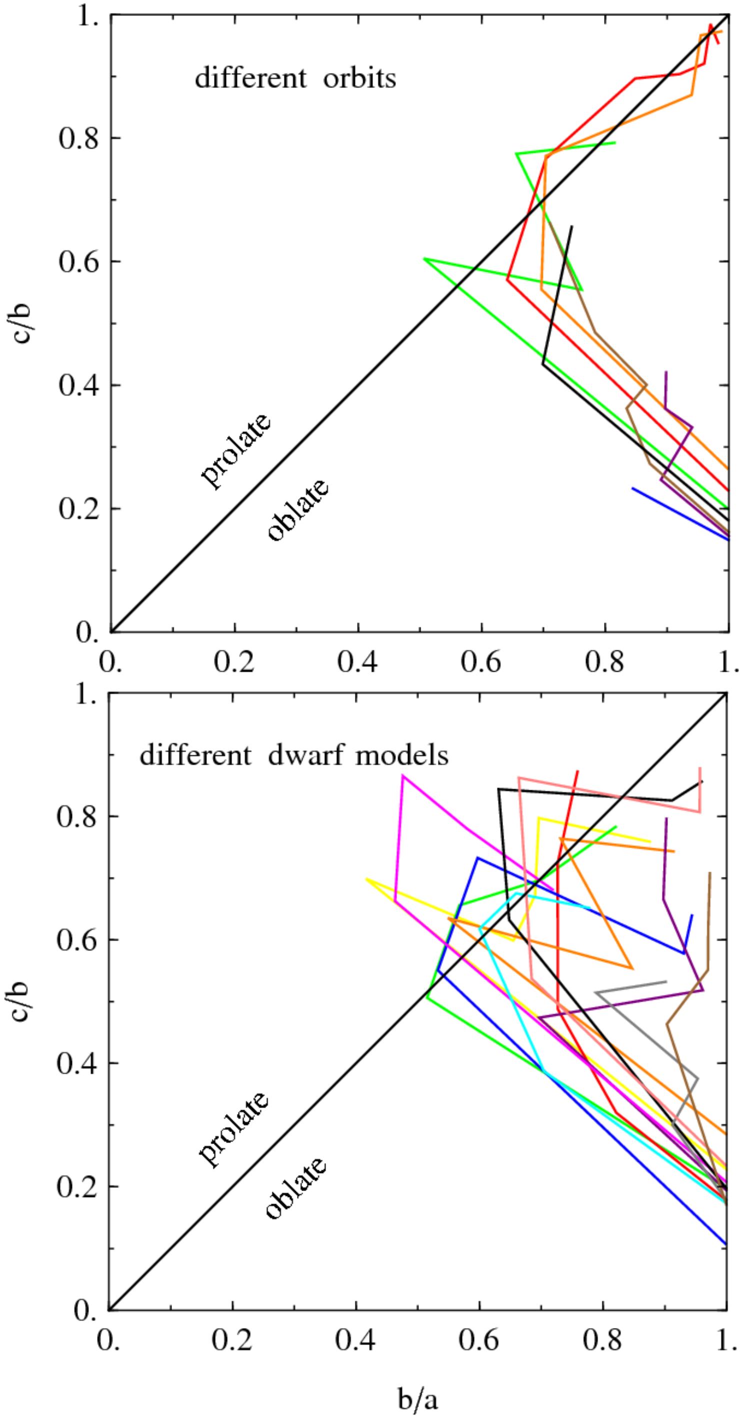
- The disk transforms into a bar which becomes more spherical with time
- The distribution of stars is in general not spherical



A

B

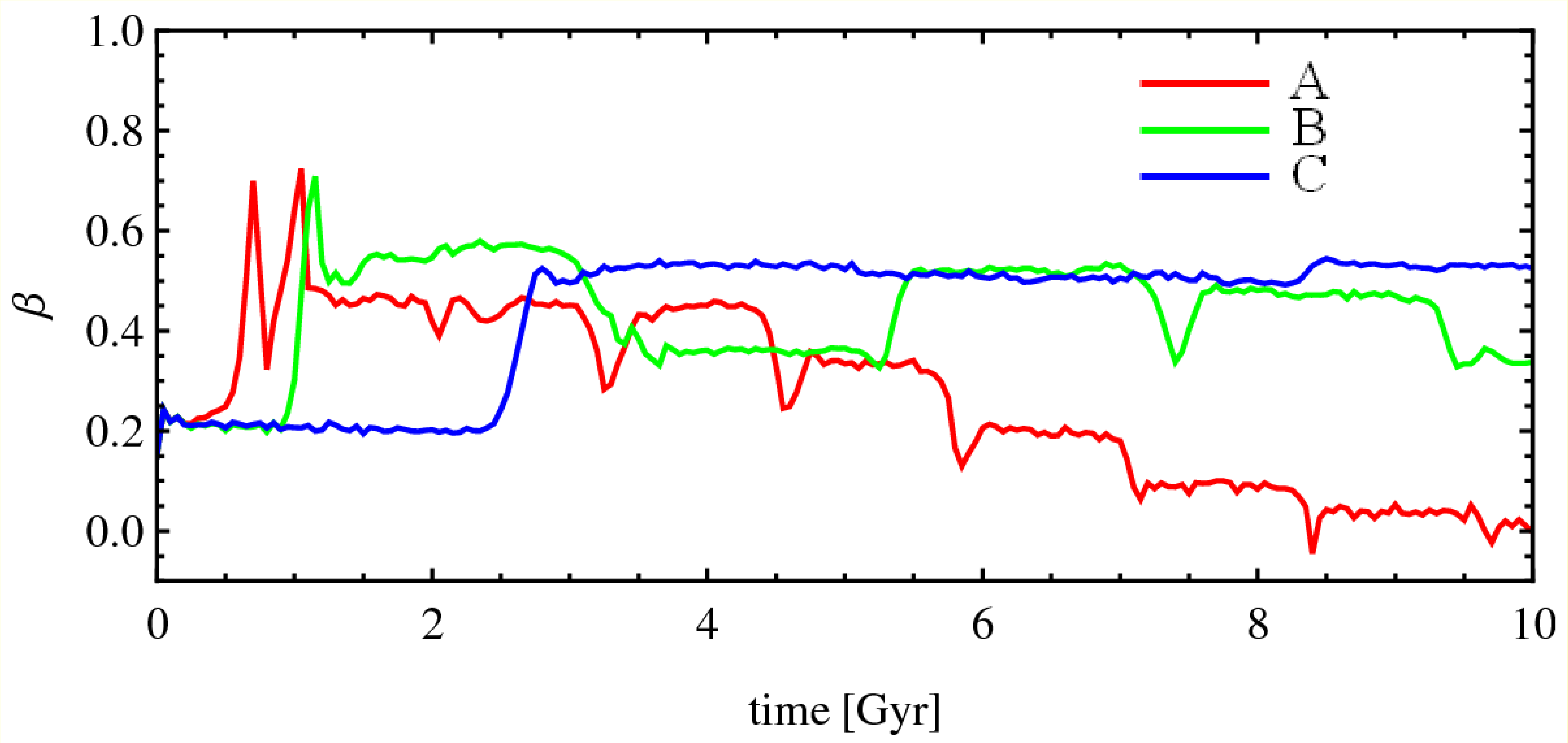
C



Prolate vs. oblate

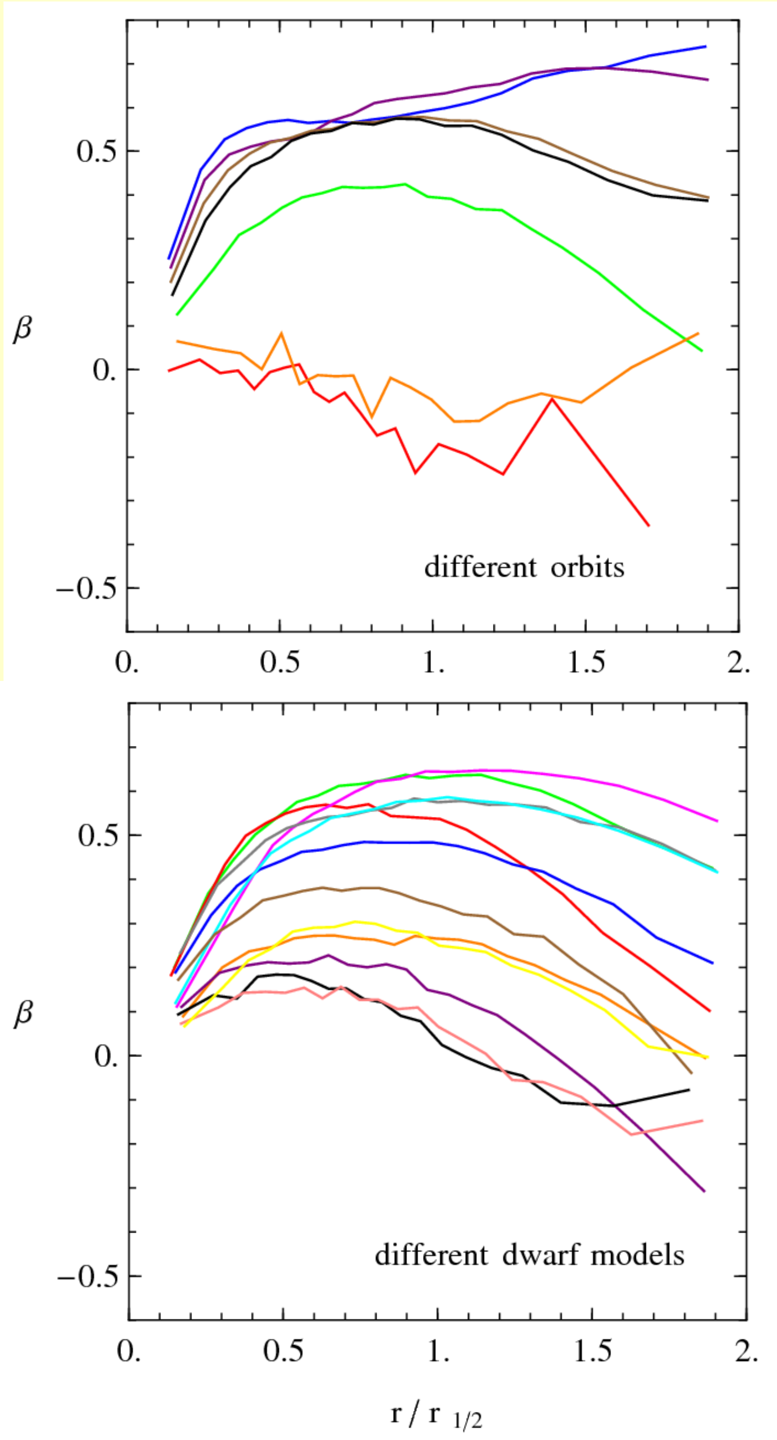
- Most dwarfs go through a prolate phase associated with bar formation at first pericenter
- Still, most dwarfs end up more oblate than prolate

Anisotropy parameter



$\beta = 1 - (\sigma_\vartheta^2 + \sigma_\phi^2) / (2\,\sigma_r^2)$

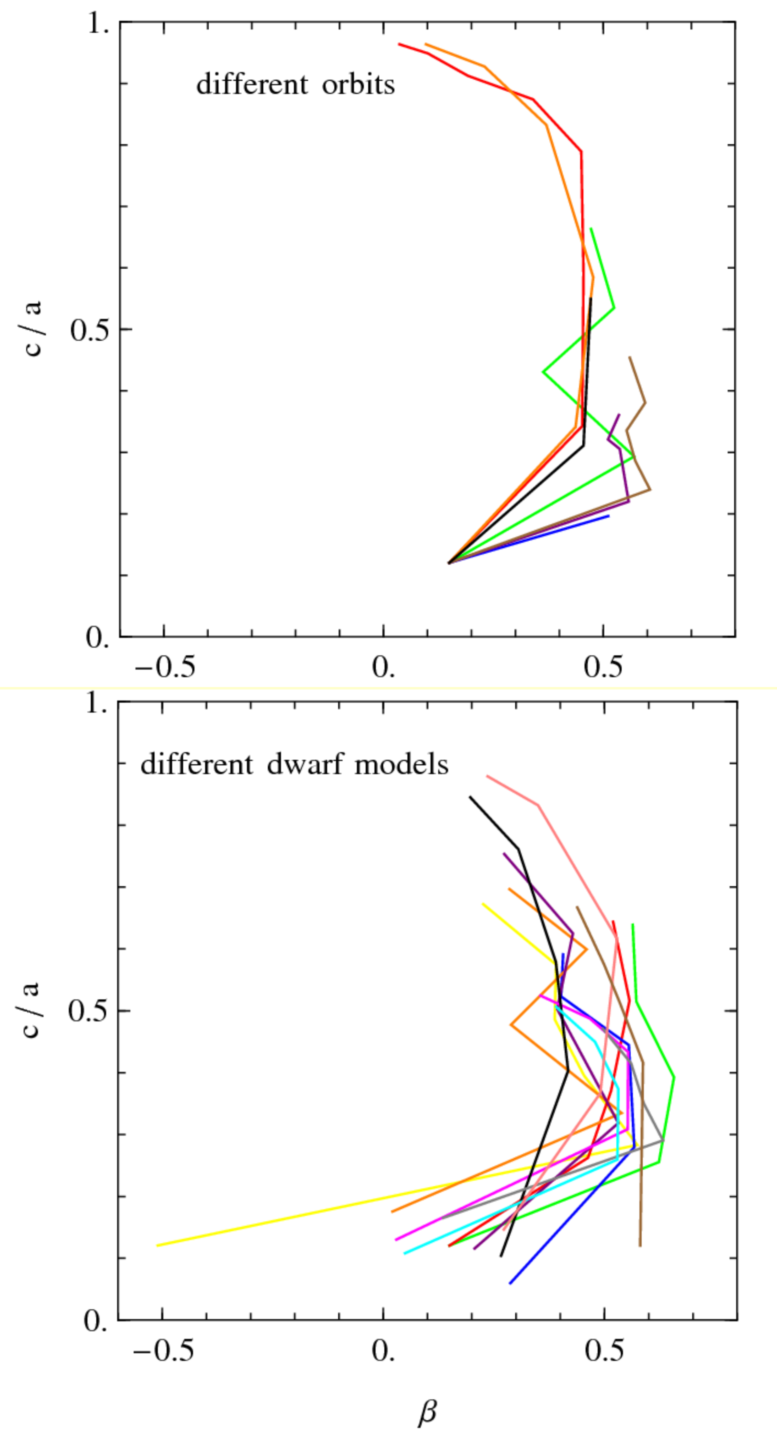
$\beta = 0$ isotropic orbits



Anisotropy profiles

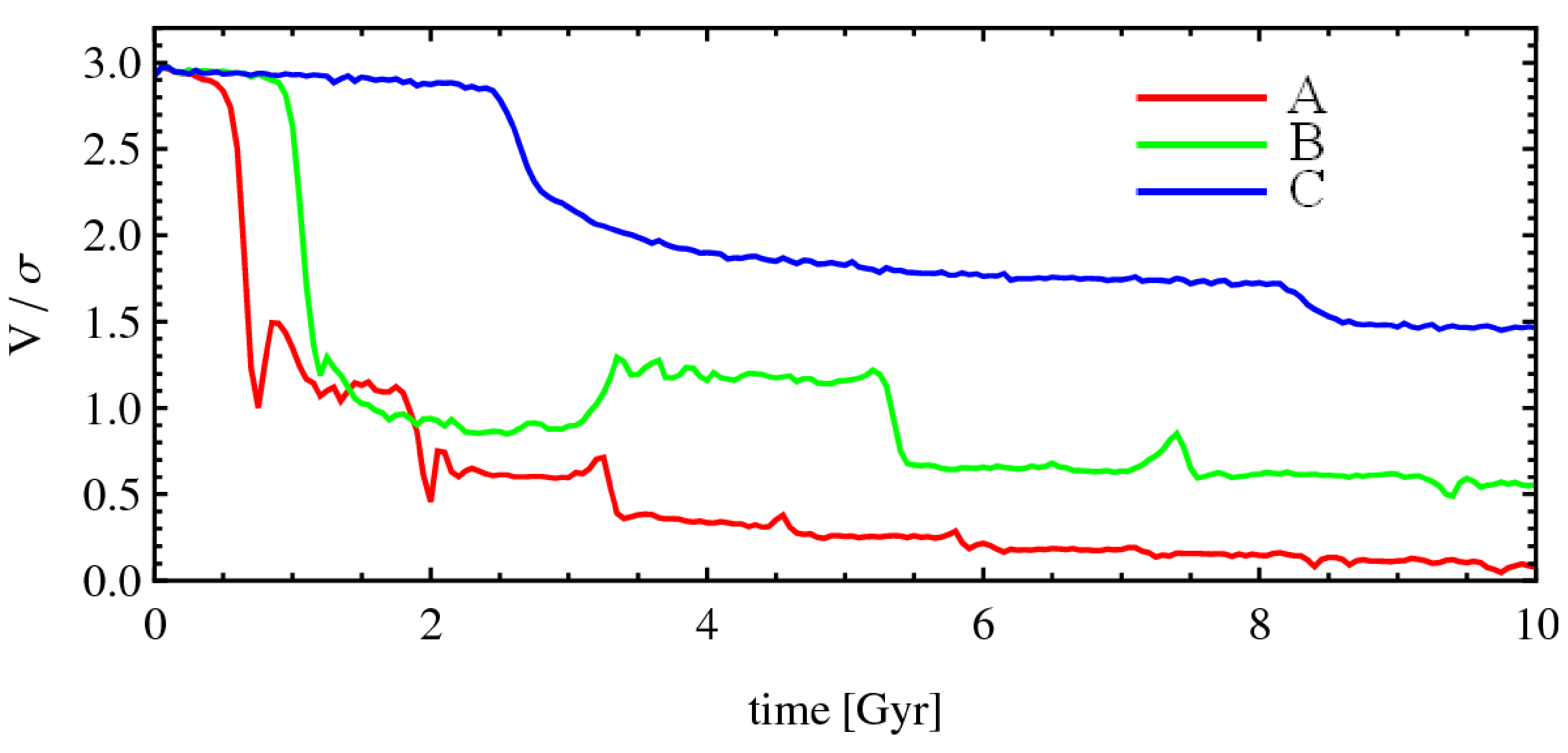
- Anisotropy profiles were measured at the final output of each simulation
- Radial orbits associated with the bar dominate except for very evolved dwarfs

Shape vs. anisotropy



- All dwarfs on all orbits go through a phase of radial anisotropy, no matter what initial value was
- Those dwarfs that end up more spherical also end up more isotropic

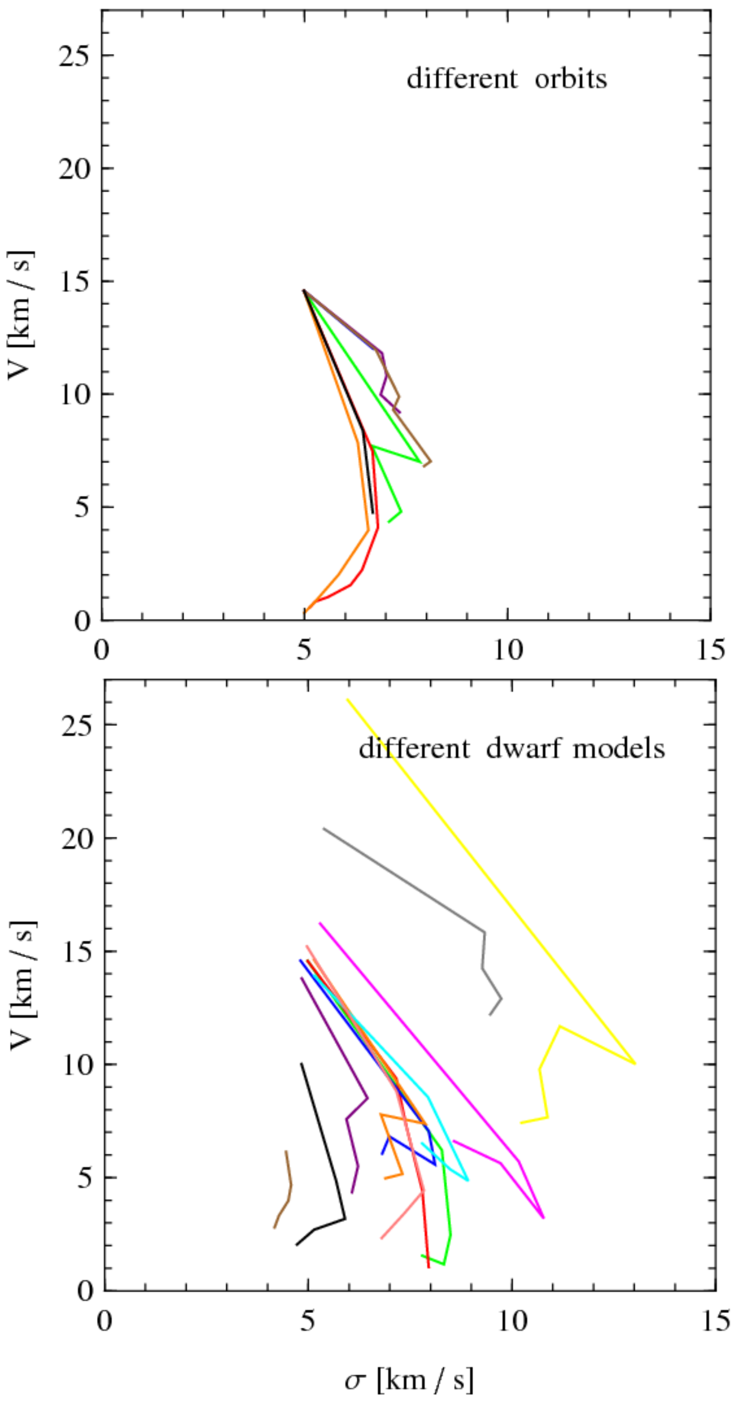
Streaming to random motion



$V = V_\phi$ – rotation around the shortest axis

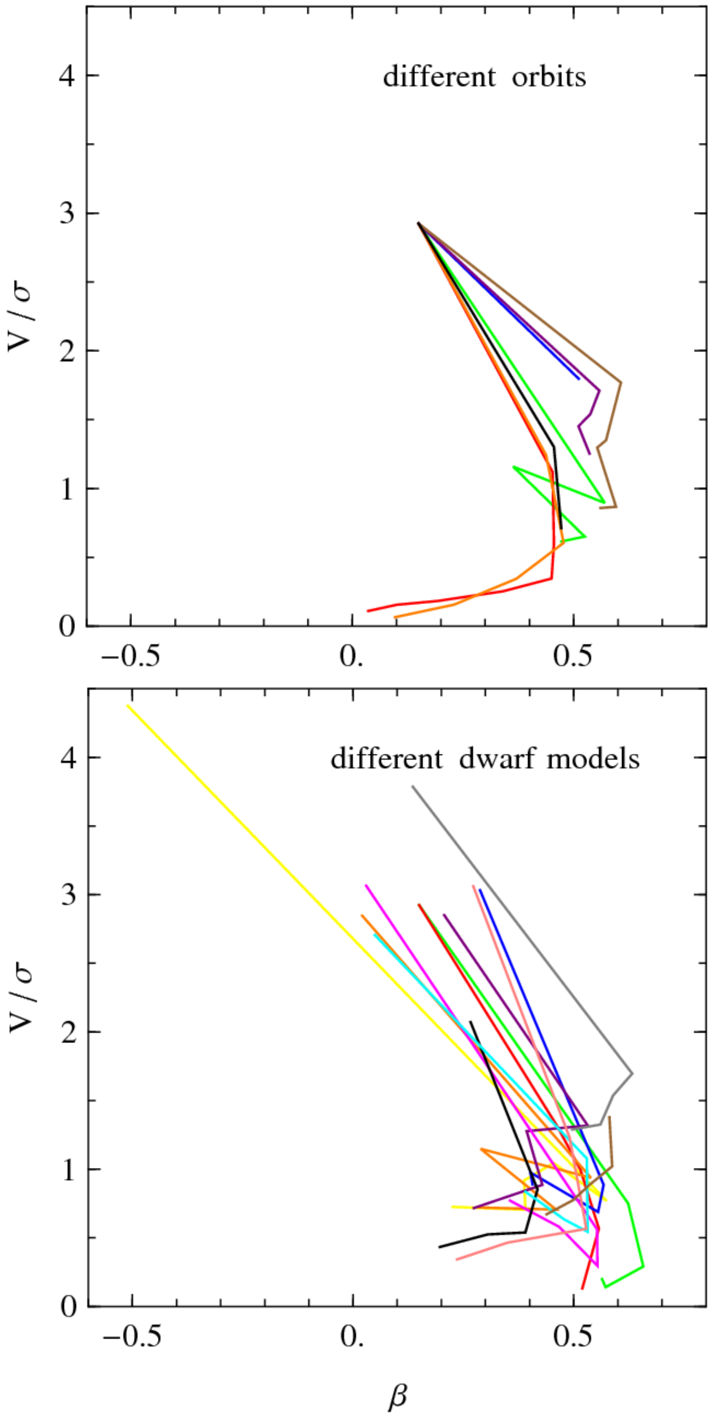
$\sigma = [(\sigma_r^2 + \sigma_\vartheta^2 + \sigma_\phi^2)/3]^{1/2}$ – 1D velocity dispersion

Streaming to random

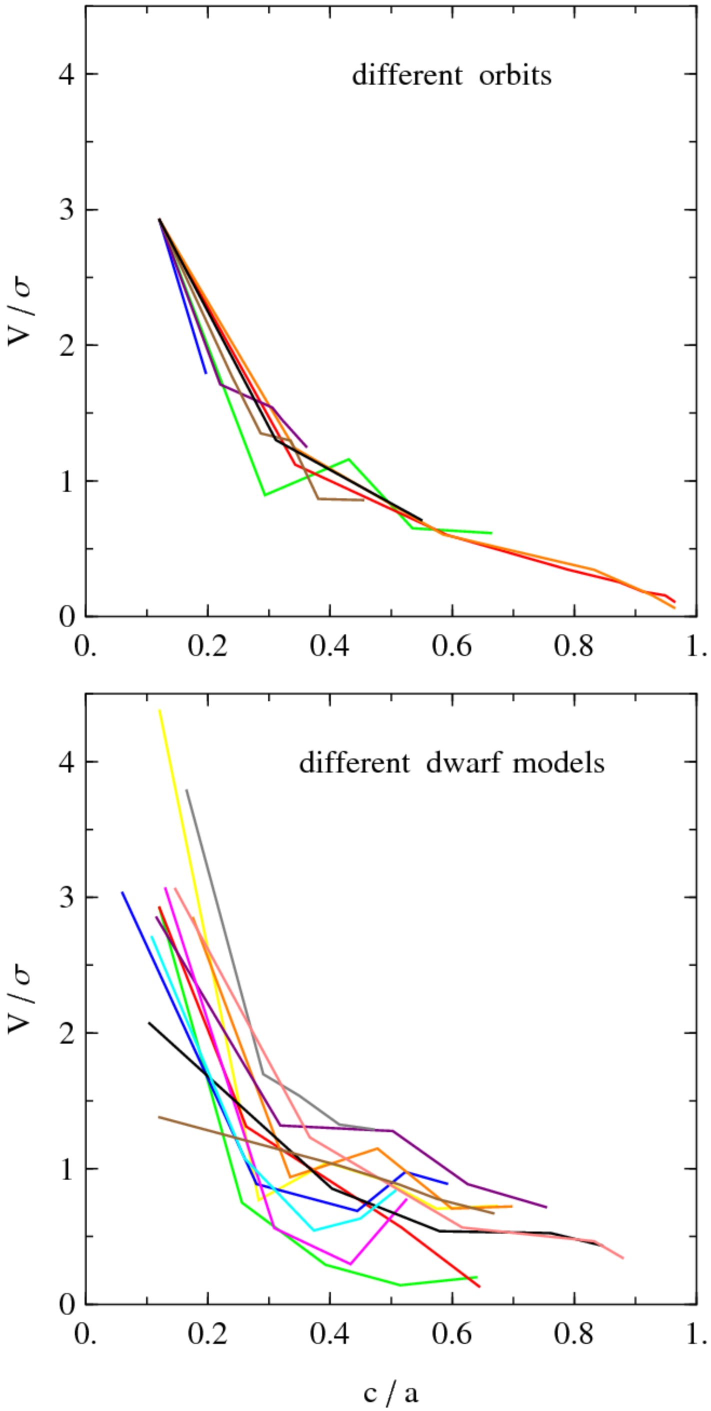


- All dwarfs on all orbits experience decrease of rotation velocity and increase of dispersion
- Most dwarfs retain rotation of the order of a few km/s

V/σ vs. anisotropy



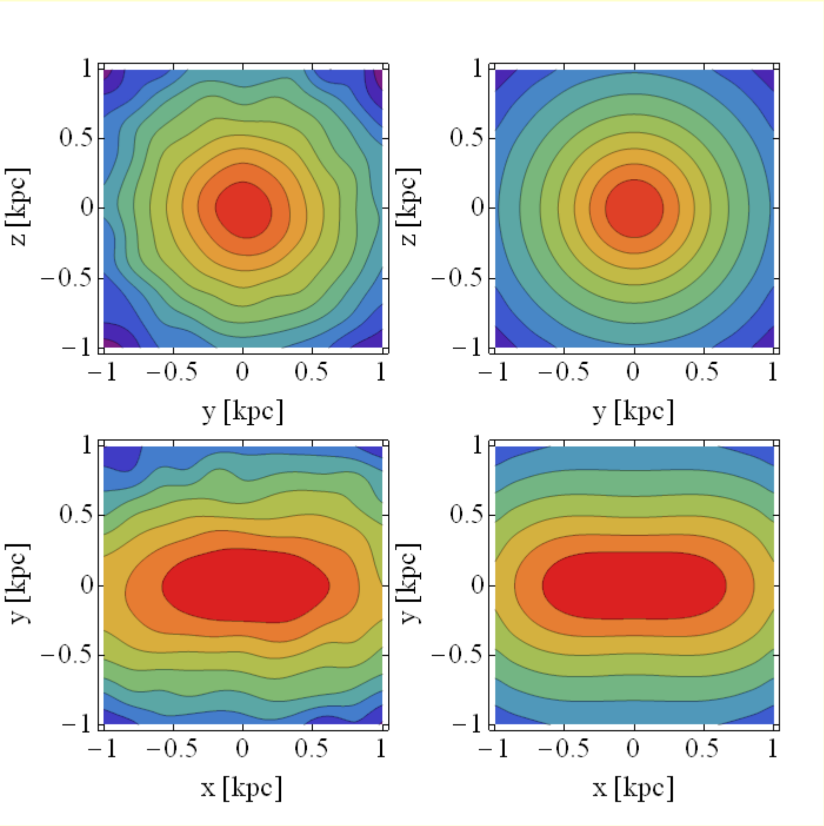
- At first pericenter passage all dwarfs lose much rotation and the bar is formed
- Those dwarfs that end up more isotropic also end up with less rotation



V/σ vs. shape

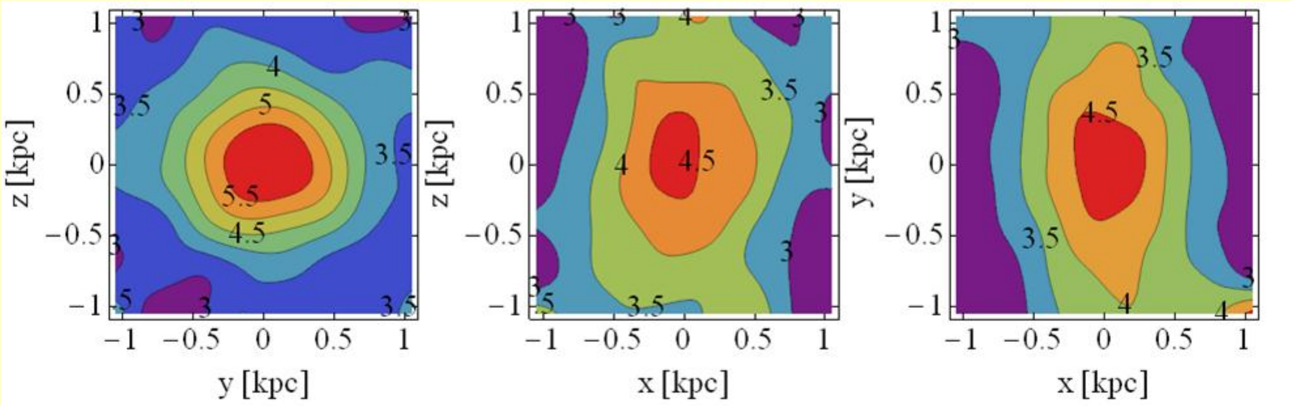
- At first pericenter passage all dwarfs lose much rotation and the bar is formed
- Those dwarfs that end up more spherical also end up with less rotation

Simple example



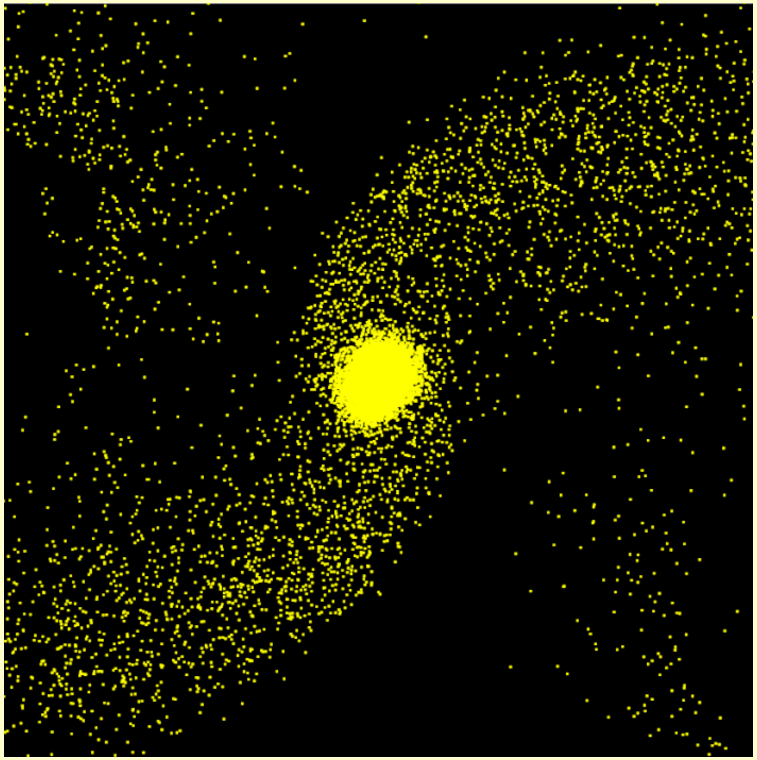
- A simulated prolate dSph galaxy
- When observed along the longest axis

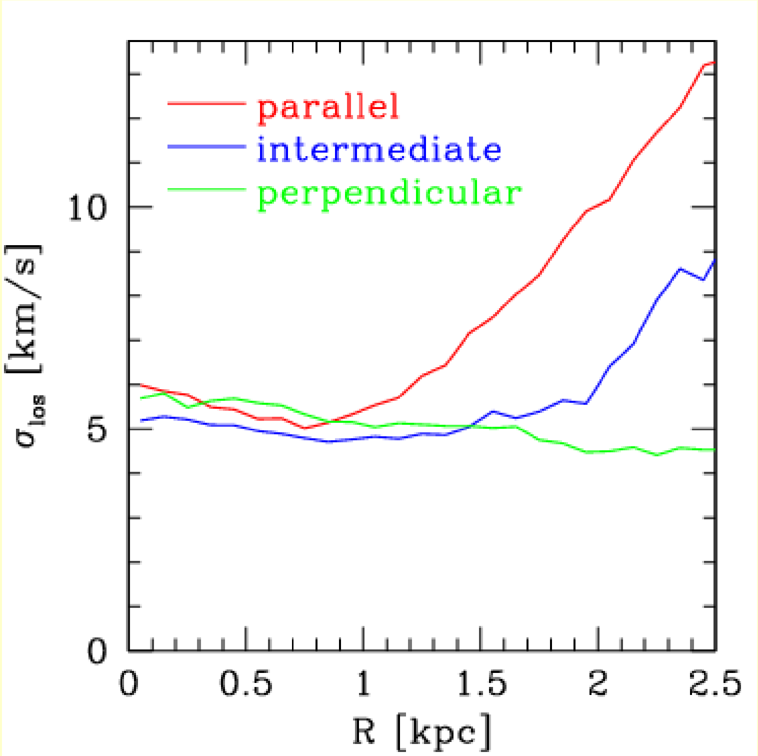
  $M_{fit} > M_{true}$
- When observed perpendicular to the bar $M_{fit} < M_{true}$



Łokas et al. 2010

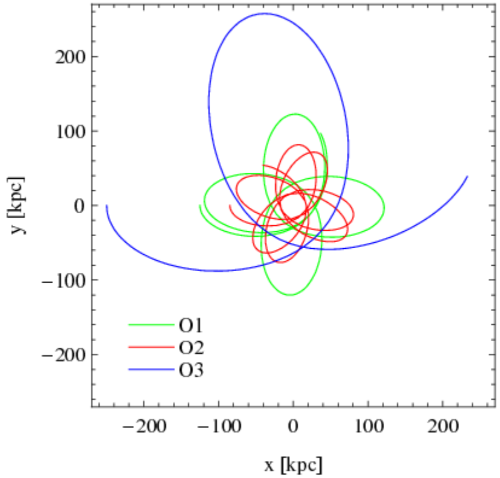
Contamination by stripped stars

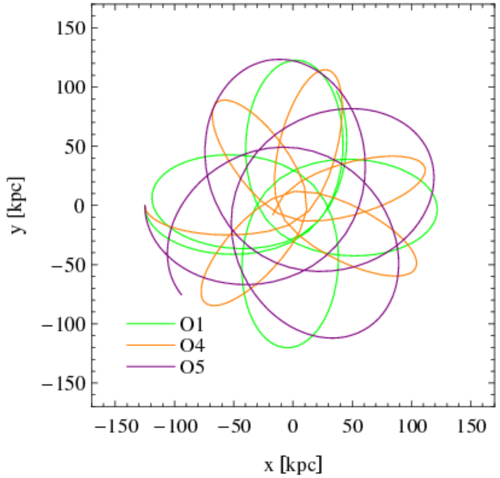


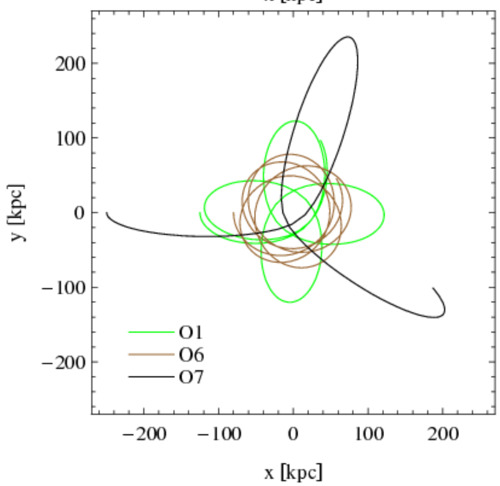


Klimentowski et al. 2007, 2009

- Number of contaminating stars depends on the line of sight
- Contamination is largest for the line of sight along the tails







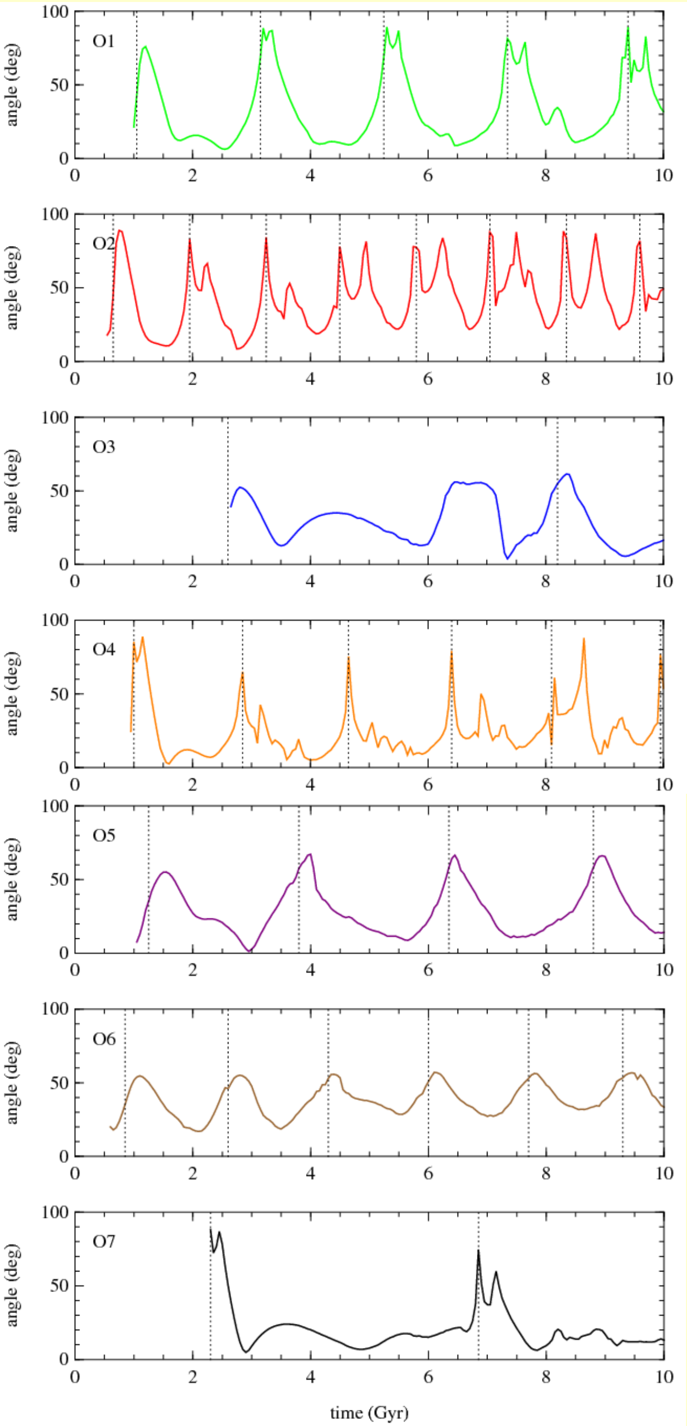
Tails on different orbits

Orbits of different size and eccentricity:

ORBITAL PARAMETERS OF THE SIMULATED DWARFS.

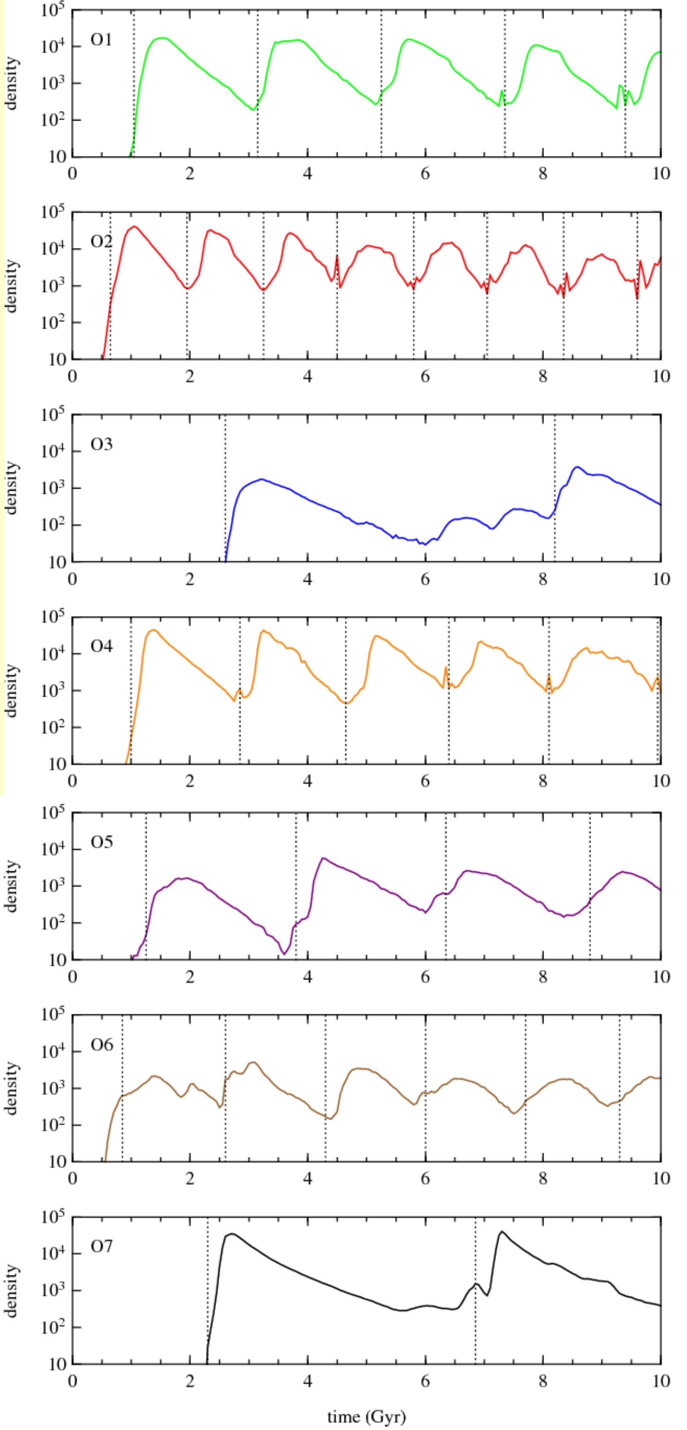
Orbit	r_{apo} (kpc)	r_{peri} (kpc)	r_{apo}/r_{peri}	T_{orb} (Gyr)	t_{la} (Gyr)	n_{peri}	Color
O1	125	25	5	2.09	8.35	5	green
O2	85	17	5	1.28	8.95	8	red
O3	250	50	5	5.40	5.40	2	blue
O4	125	12.5	10	1.81	9.05	6	orange
O5	125	50	2.5	2.50	10.00	4	purple
O6	80	50	1.6	1.70	8.50	6	brown
O7	250	12.5	20	4.55	9.10	2	black

Łokas & Kazantzidis, in prep.



Orientation of the tails

- Angle between tails at 9-10 kpc from the dwarf and the line of sight of an observer at GC
- For most of the time the tails are oriented close to the line of sight
- Tidally stripped stars must contaminate kinematic samples



Density of the tails

- Density of the tails in terms of the number of stars contained in a sphere at 9-10 kpc from the dwarf
- Density is largest on the way from the pericenter to apocenter
- Contamination is more important for dwarfs moving away from us

Conclusions

- Tidally formed dSphs are not spherical, stellar orbits are not isotropic (not β=const either), and they retain some rotation
- The dynamical properties are correlated: dwarfs that are more spherical also are more isotropic and retain less rotation
- Kinematic samples are most strongly contaminated for dwarfs approaching apocenters
- Density distributions of stars and dark matter are also strongly affected