The tidal stirring model and its application to the Sagittarius dwarf

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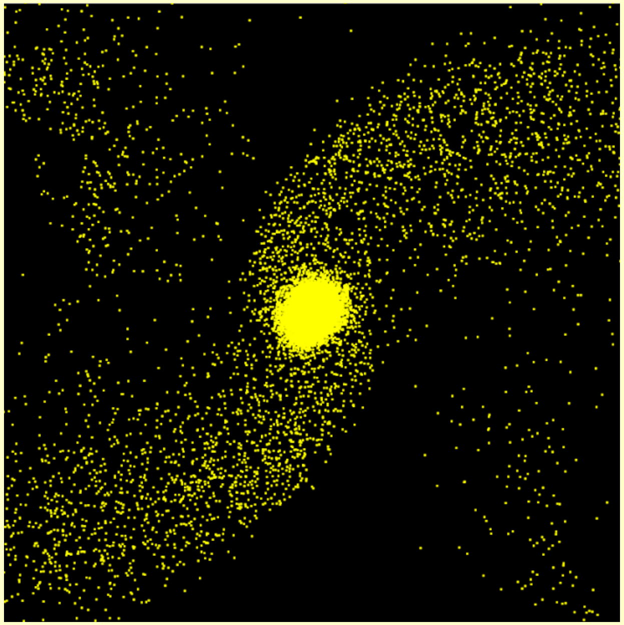
Tidal stirring scenario

- 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

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 $M_\odot$
- 19 simulations for different orbits and dwarf structure

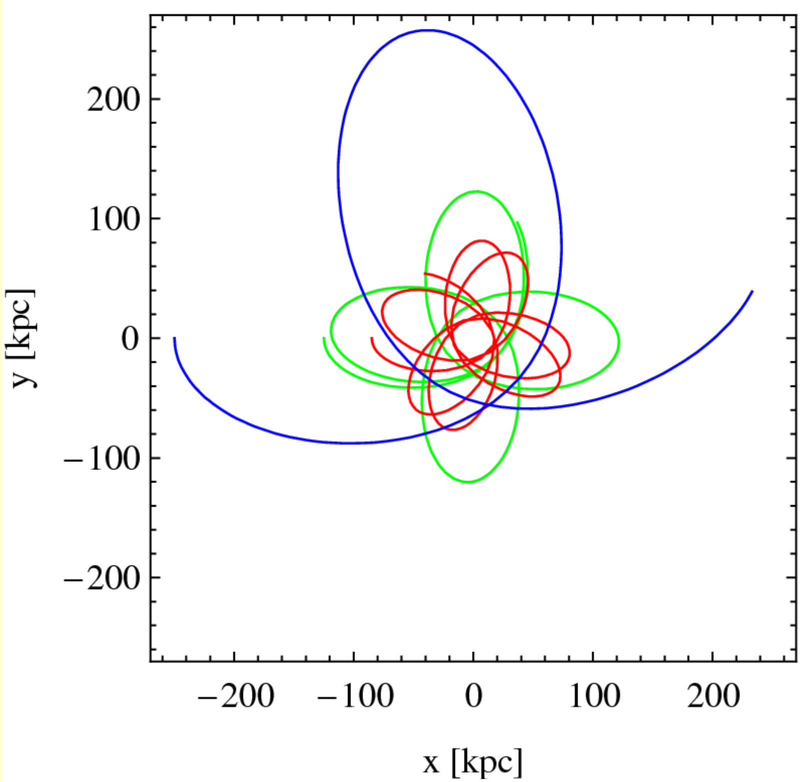


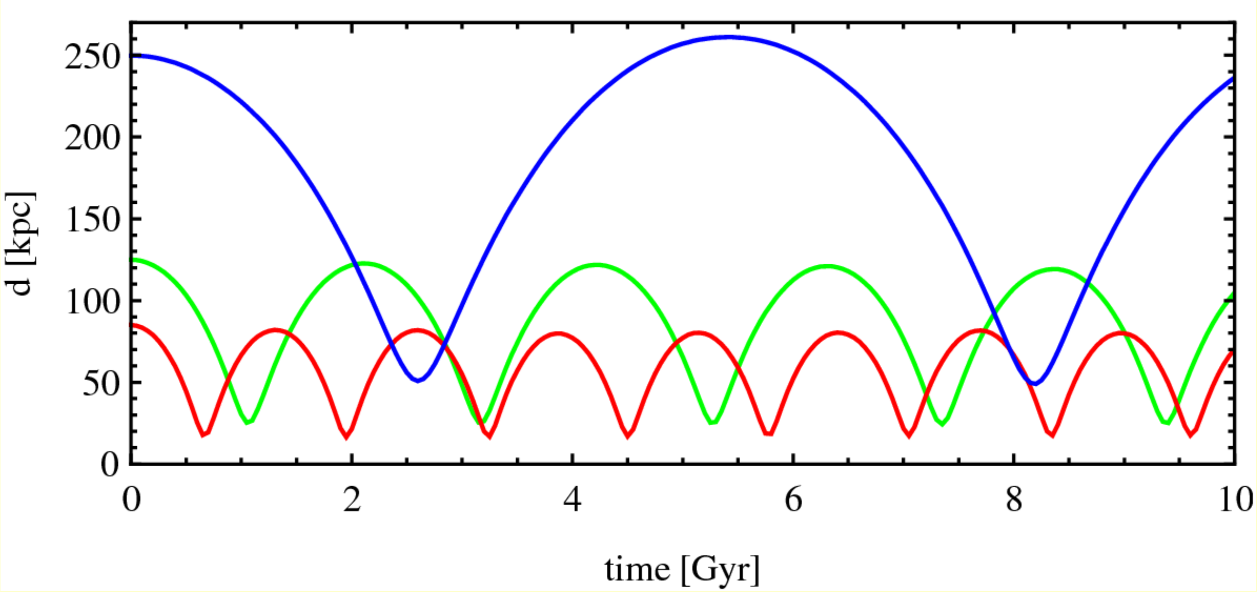
20 kpc

Three simulated cases

Three orbits of different size, other parameters unchanged

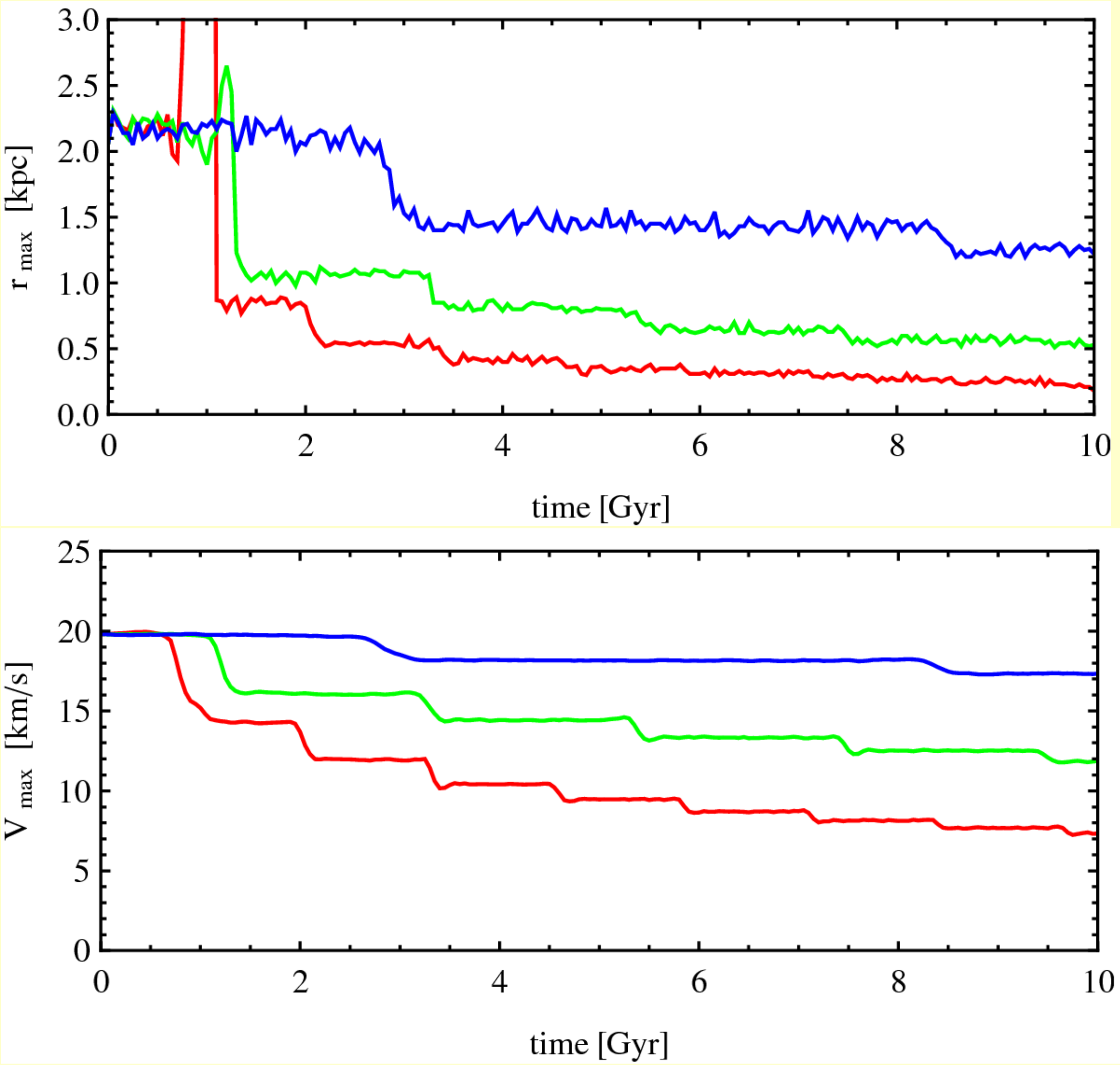
$r_{apo} / r_{peri} = 5$



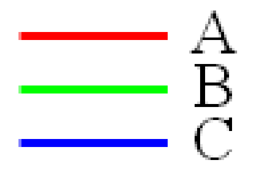


Kazantzidis et al. 2011

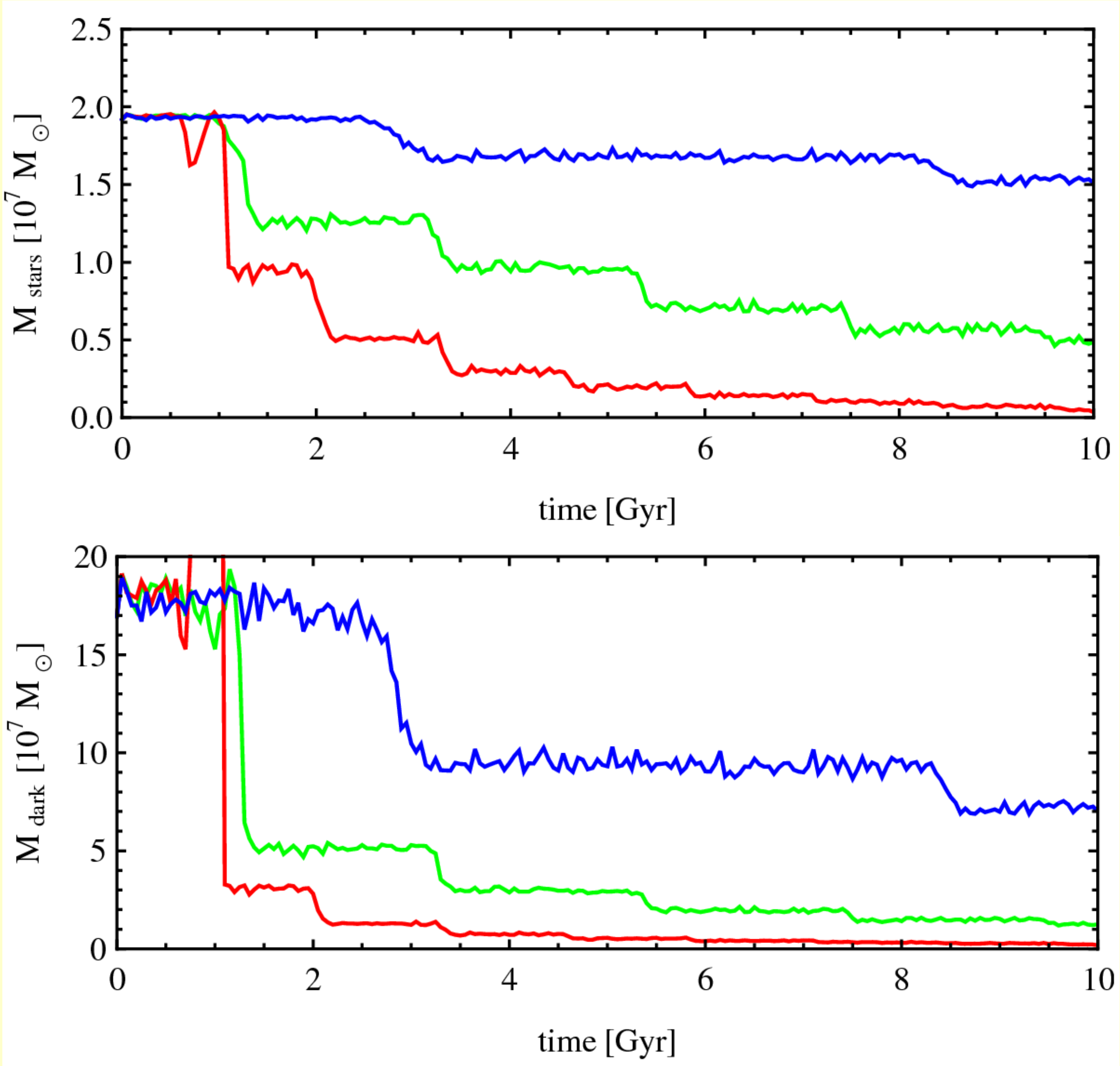
Mass and size evolution



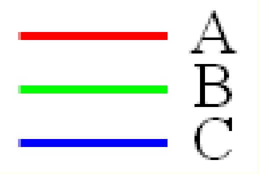
- r_{max} is a characteristic radius where V_{circ} has a maximum
- V_{max} is a good measure of the mass



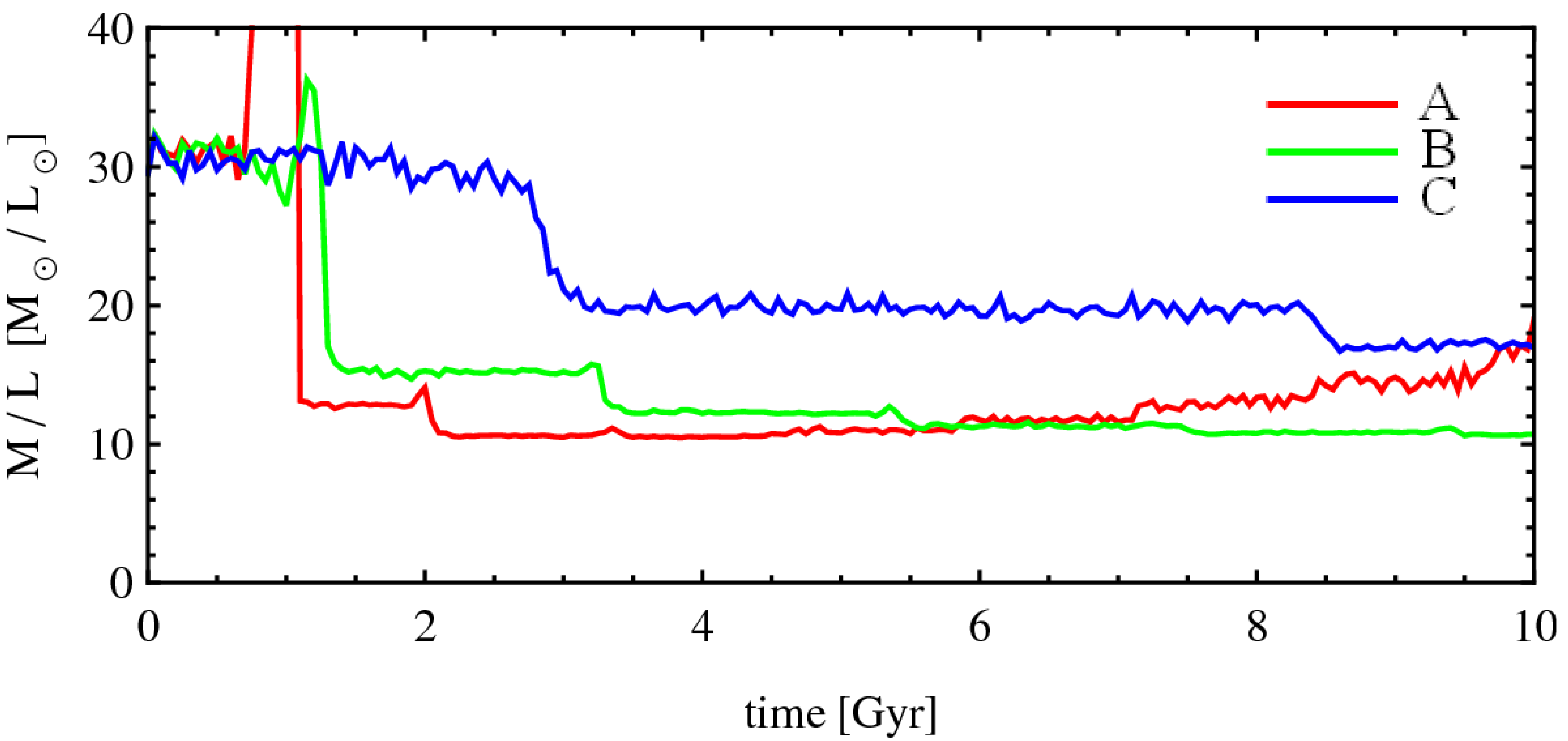
Masses of stars and dark matter



- The mass loss is strongest at pericenters
- The profile of dark halo is affected more strongly and its shape is not preserved

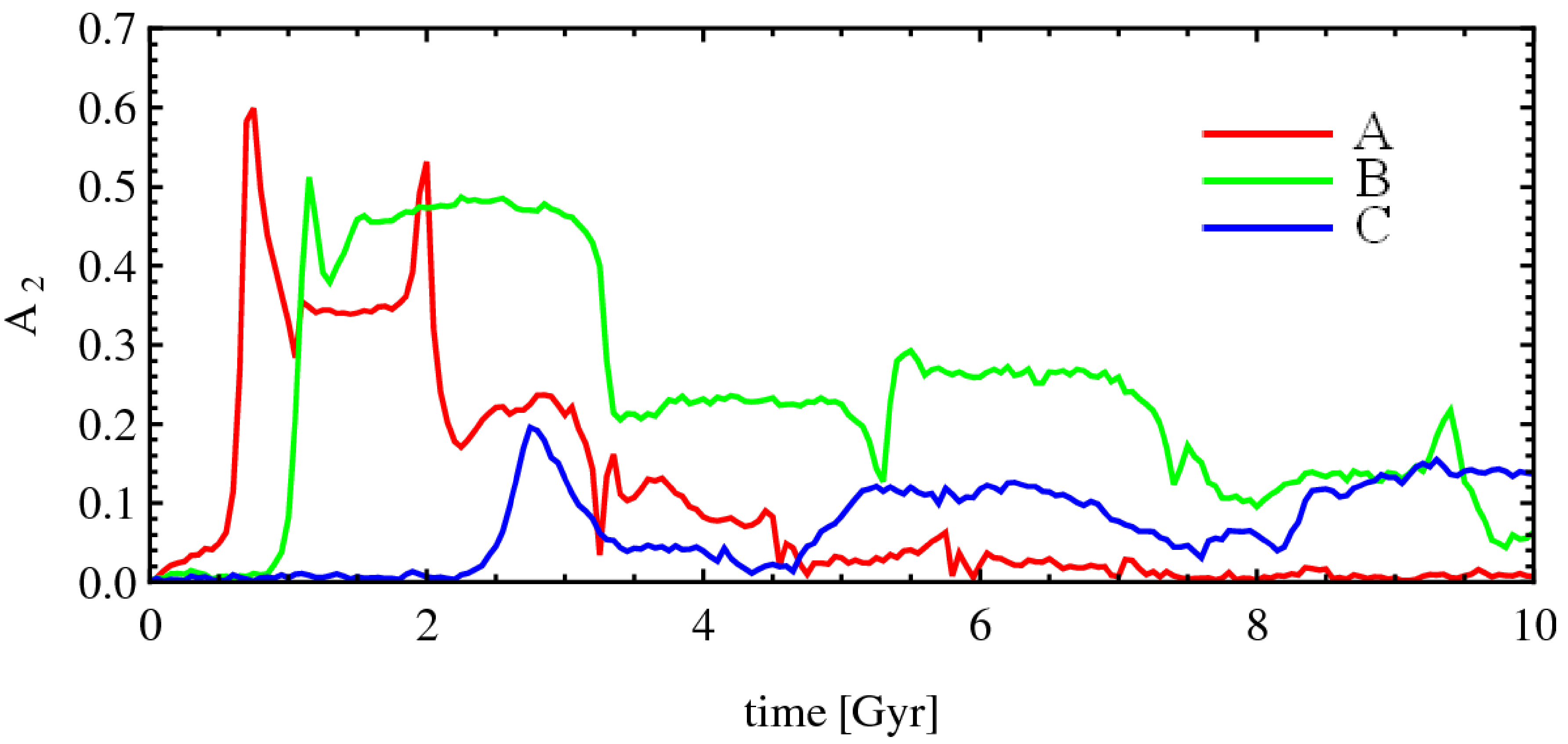


Mass-to-light ratio



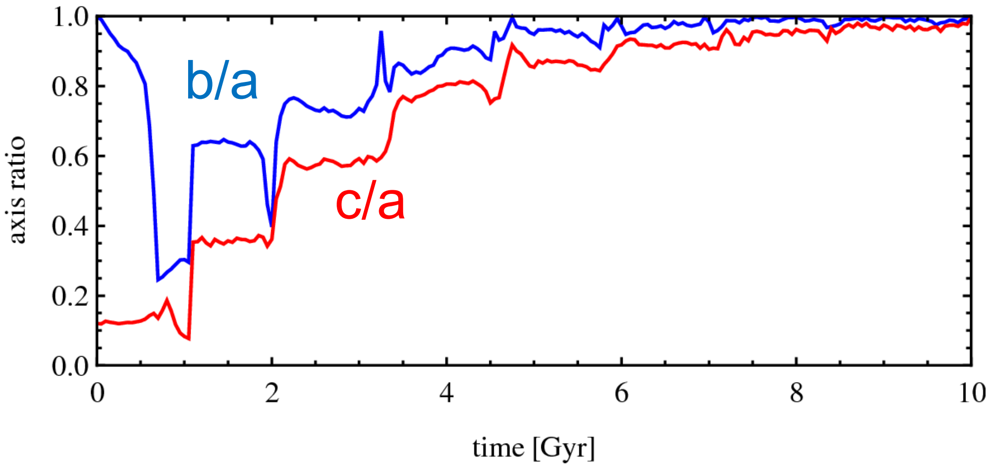
- Typically the mass loss in stars traces that in dark matter
- The M/L ratio can increase at later stages

Morphological evolution

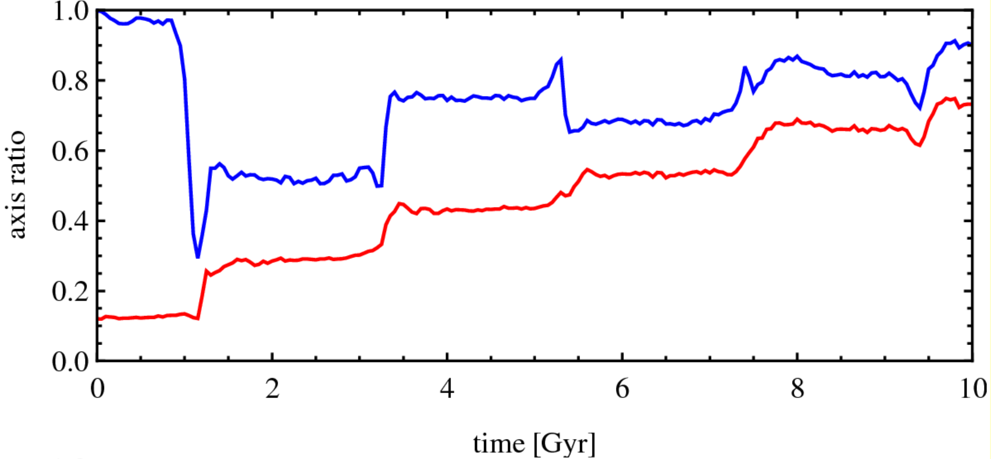


- The disk transforms into a bar which becomes more spherical with time
- The distribution of stars is in general not spherical

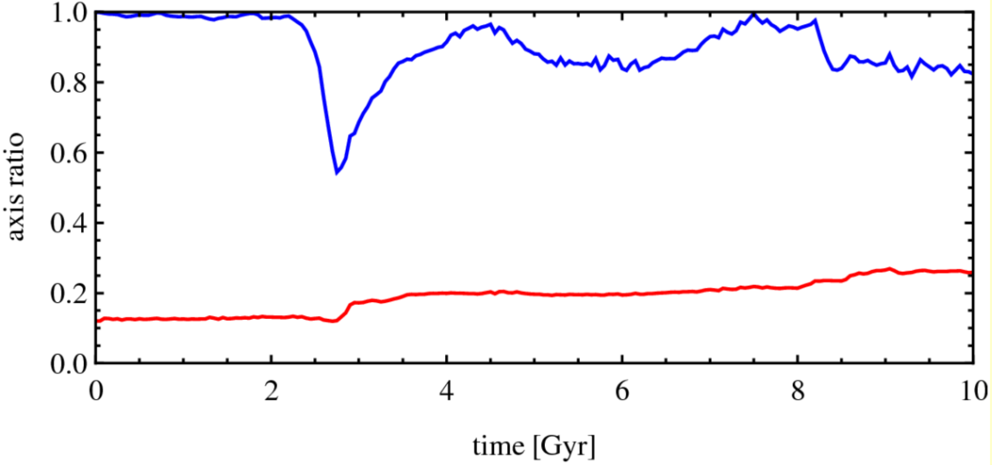
Axis ratios



A



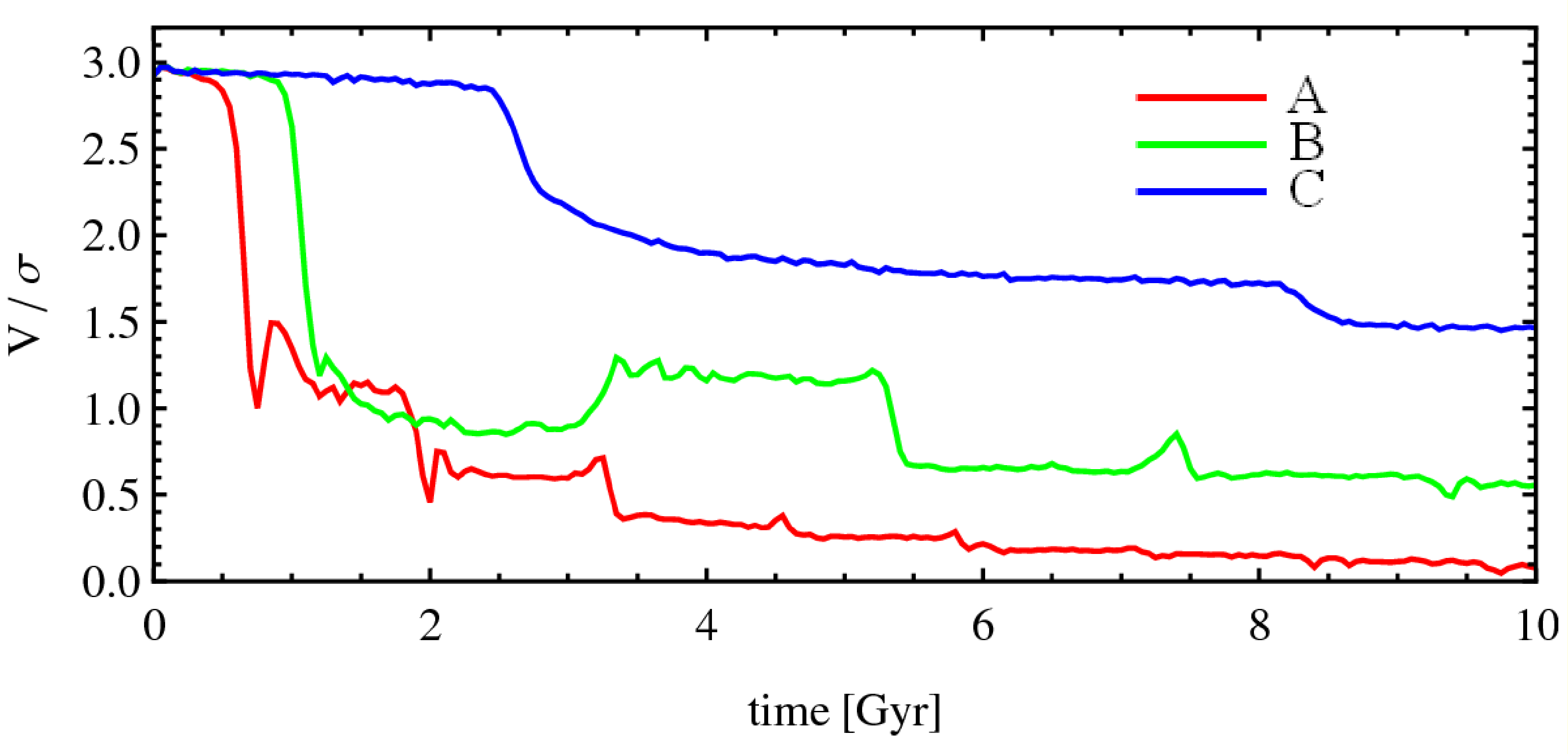
B



C

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

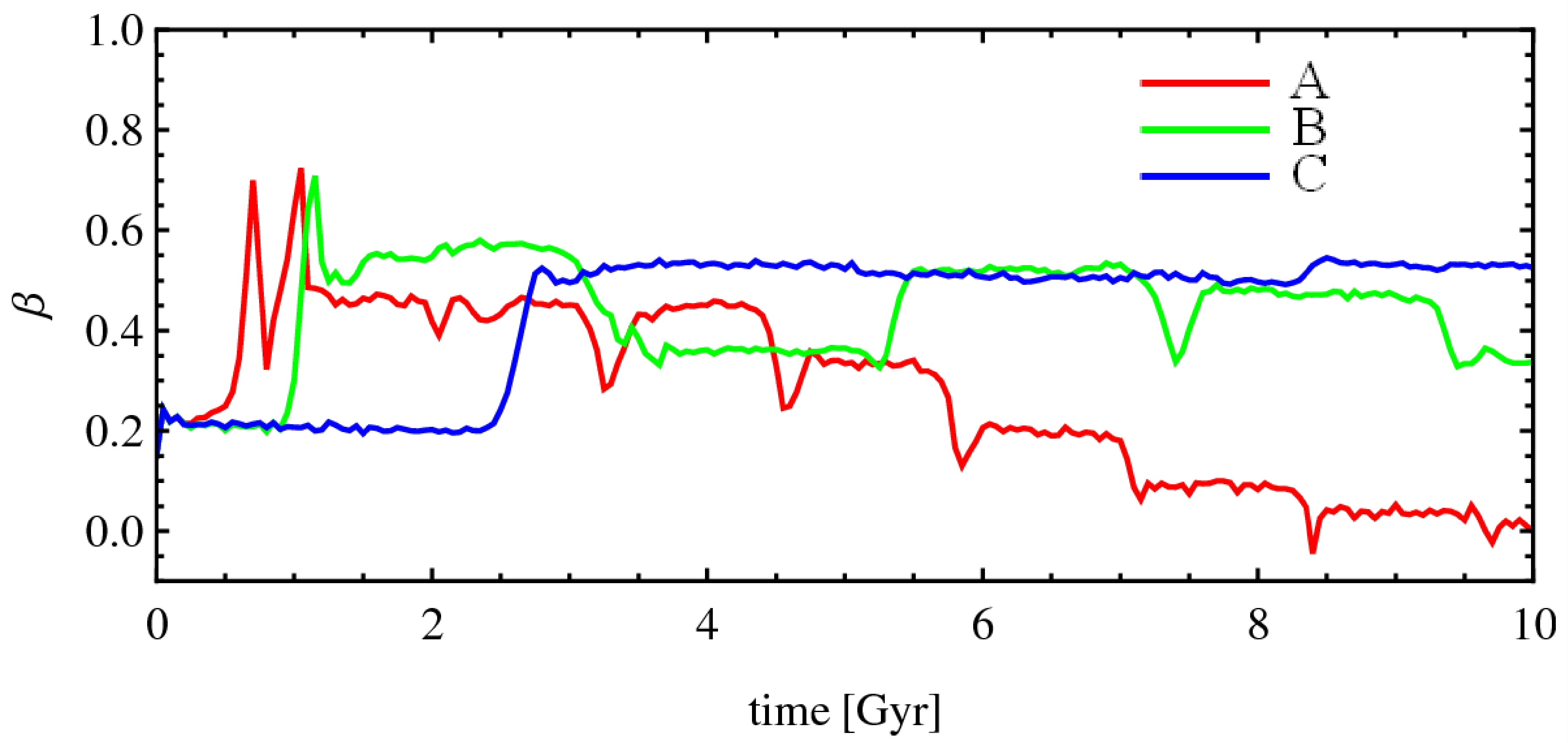
Streaming to random motion



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

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

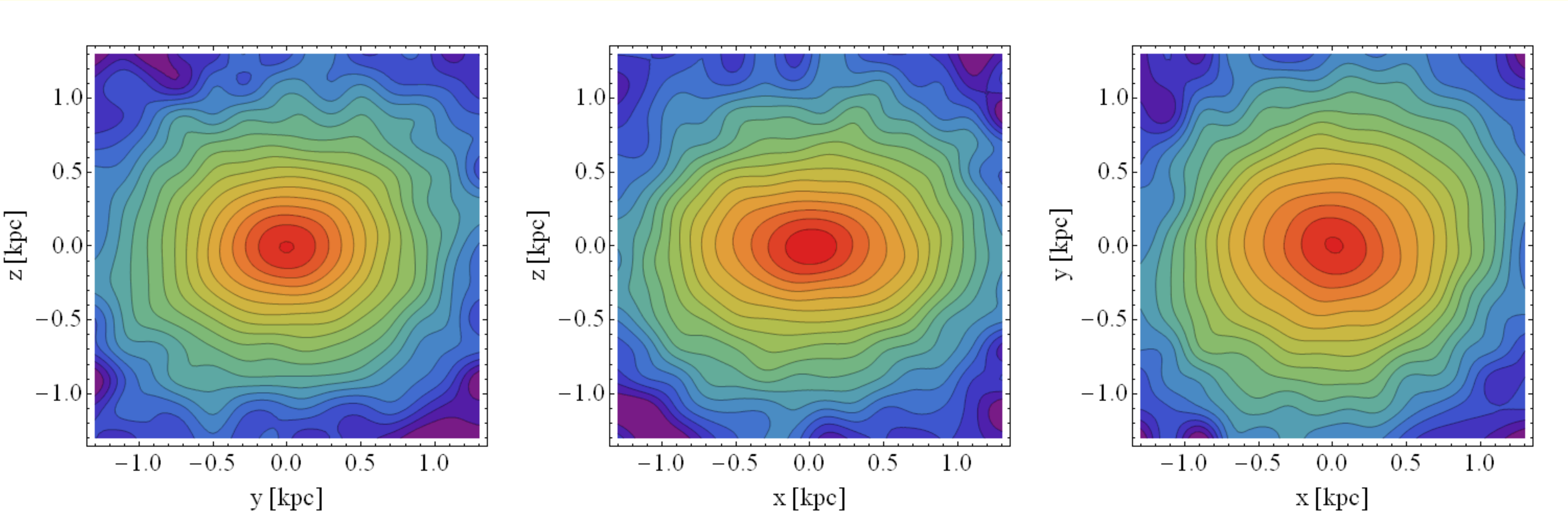
Anisotropy parameter



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

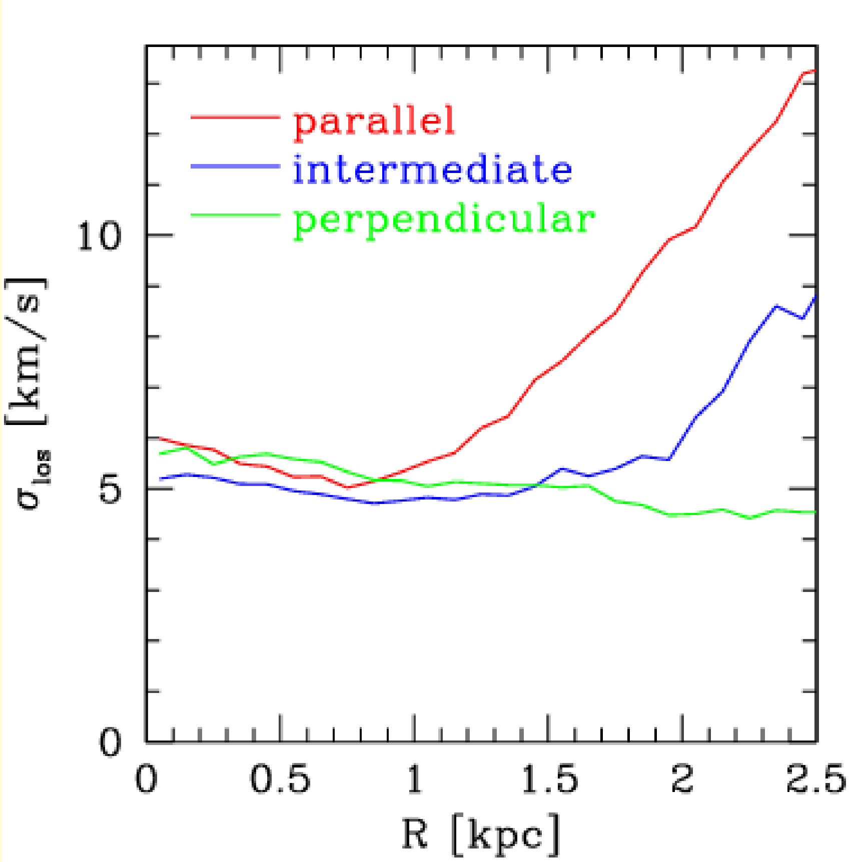
$\beta = 0$ isotropic distribution of orbits

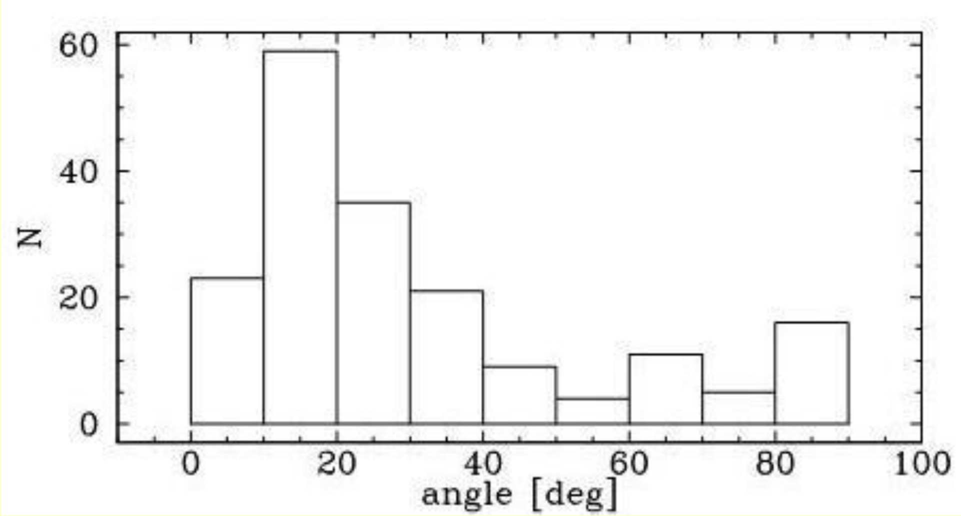
Line-of-sight view



Surface density distribution of the stars for the triaxial reference model B seen along the three axes

Implications for modelling

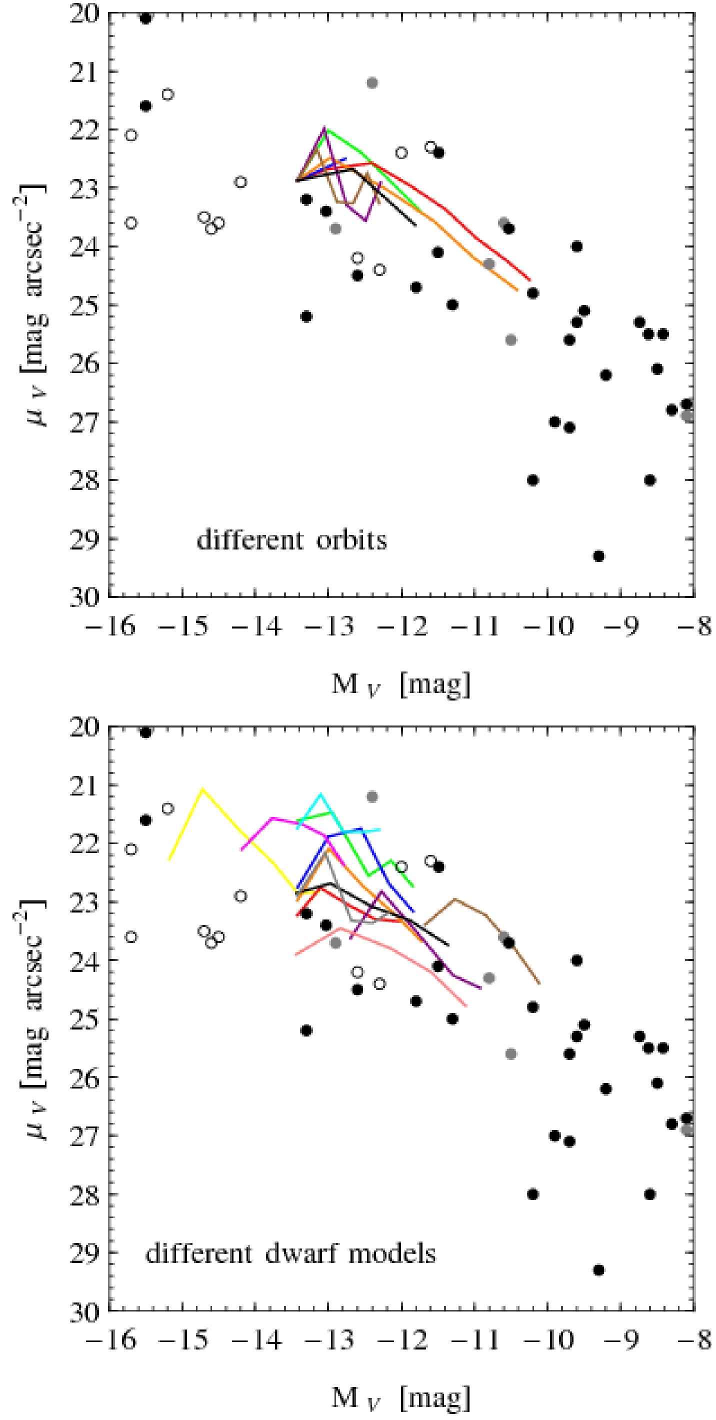




Tidal tails are typically oriented close to line of sight!

Klimentowski et al. 2007, 2009

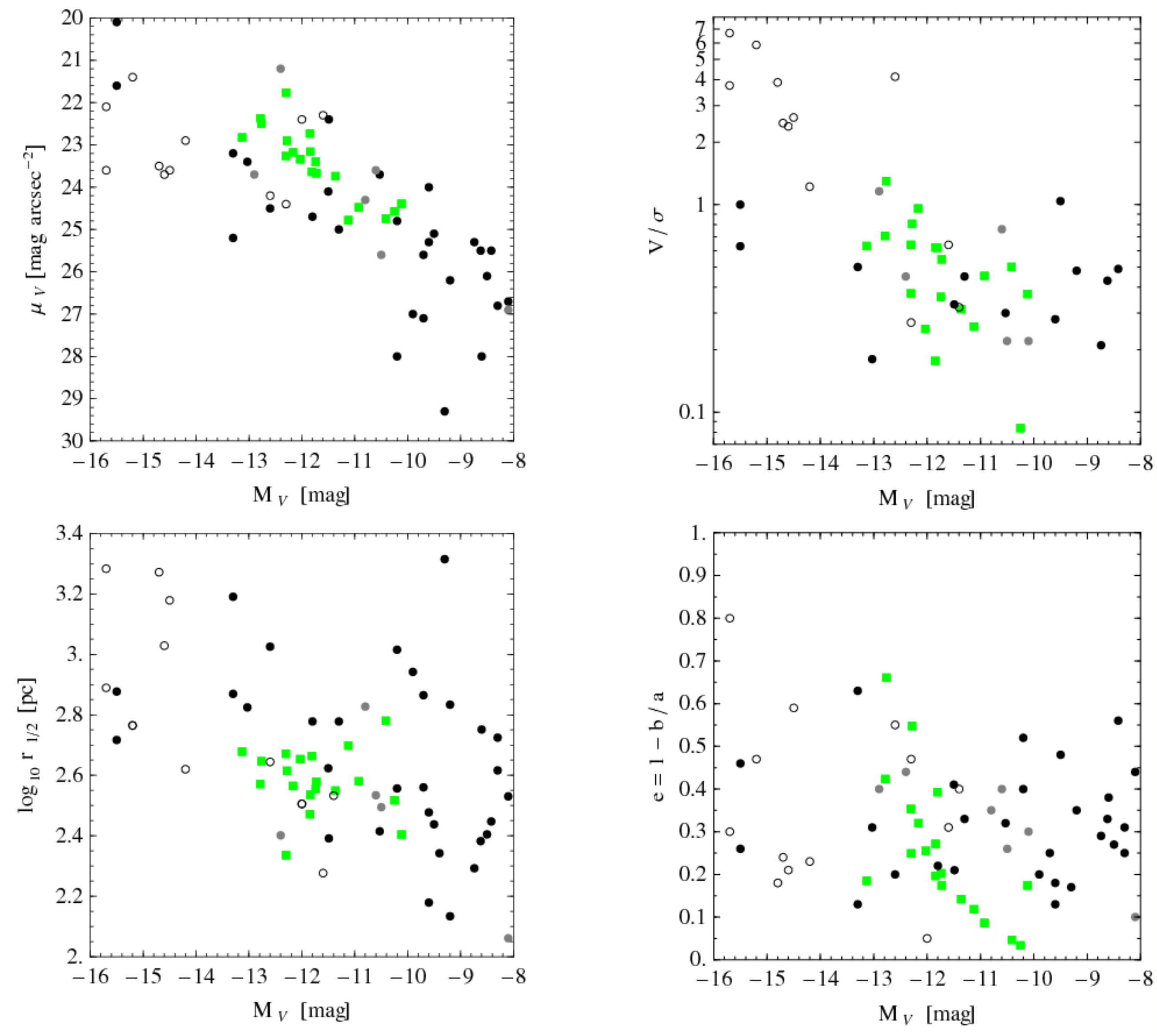
Evolutionary tracks



- Tracks in the M_V–μ_V plane move the dwarfs to fainter magnitudes and lower surface brightness
- The correlation suggests that dSph galaxies indeed formed from late-type progenitors

Łokas et al. 2011

Final properties



- Different properties at the last apocenter
- They match values for dSphs in the Local Group

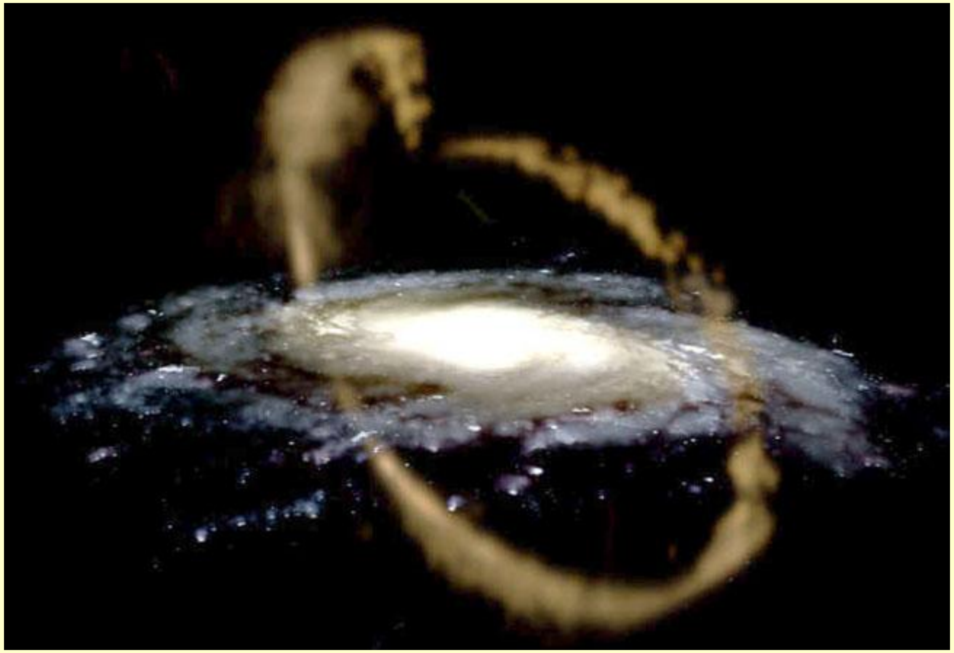
🟩 simulated

○ dIrr

● dSph/dIrr

● dSph

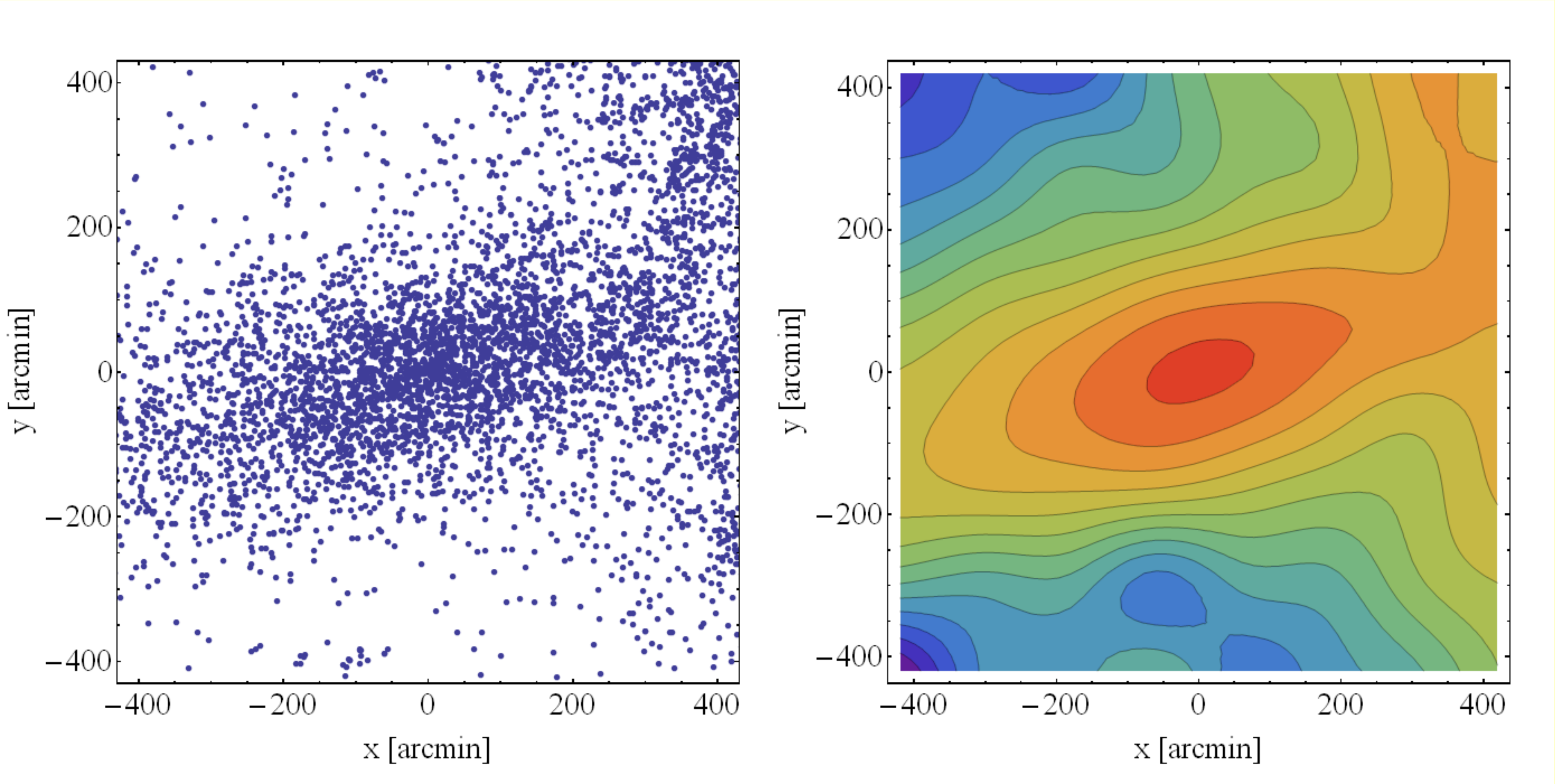
Application to Sagittarius



Due to its proximity to the Milky Way Sgr must be strongly affected by tides!

- Position: RA=18h55m, Dec=-30d30m
- Distance from the Sun: d=24 kpc,
- Orbital pericenter ~20 kpc, apocenter ~60 kpc
- Radial velocity measured from the Sun: 171 km/s
- Velocity perpendicular to the line of sight: 230-330 km/s

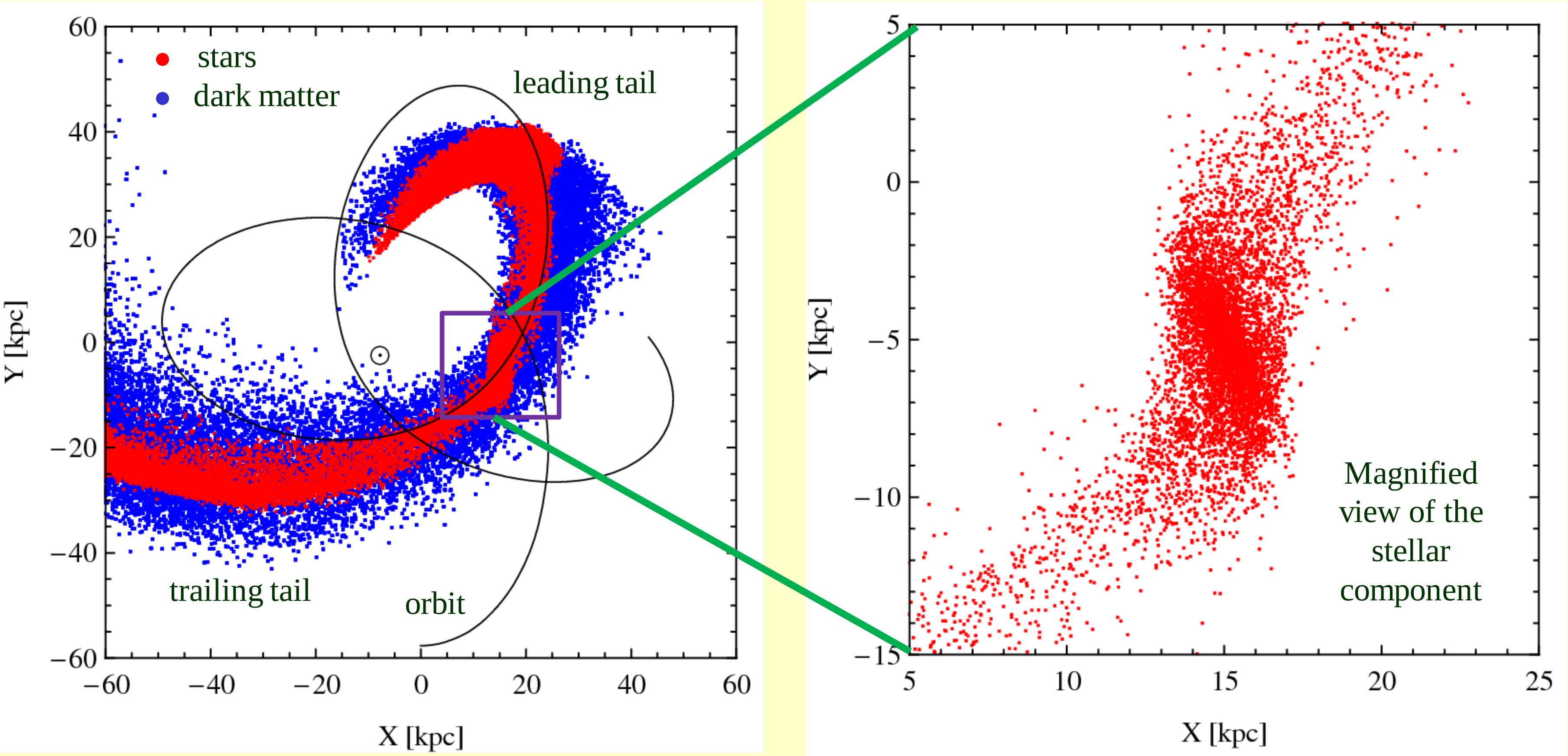
Distribution of M giant stars in Sgr



Majewski et al. 2003

Can this be reproduced from the tidally stirred spherical object?

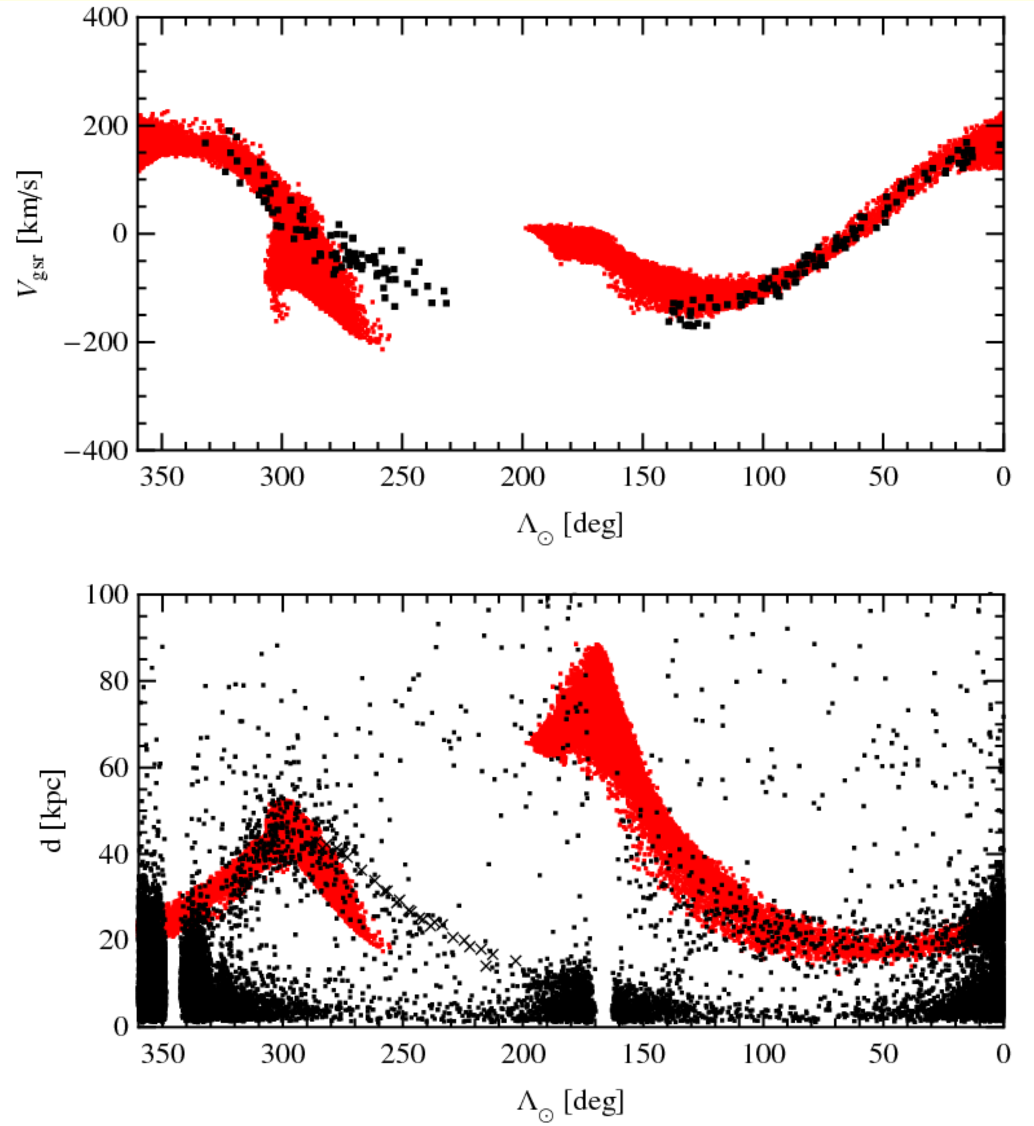
Simulation of Sgr



Dwarf galaxy with initial mass of 1.6 x 10^{10} $M_{\odot}$, composed of a disk and dark halo, evolving on a tight orbit (apo/peri=58/17 kpc) around the Milky Way; after 1.3 Gyr has just passed the second pericenter

Łokas et al. 2010

Tidal debris

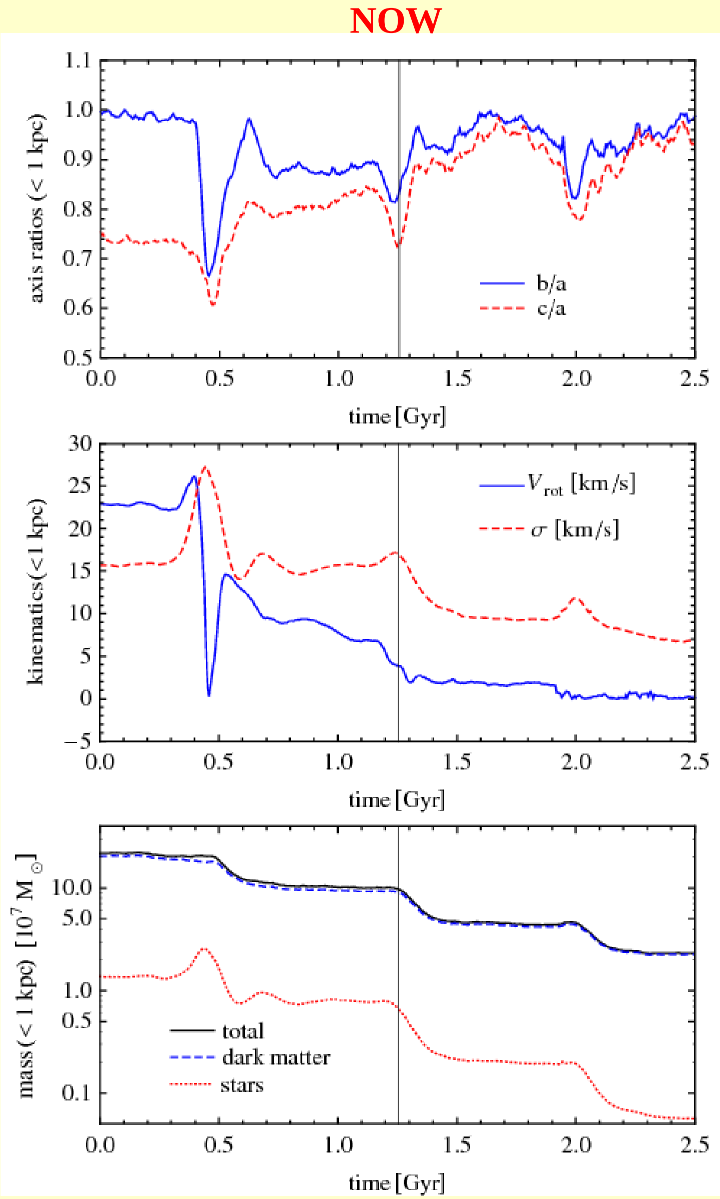


We reproduce the velocities and distances of stars in the tails reasonably well

● simulation

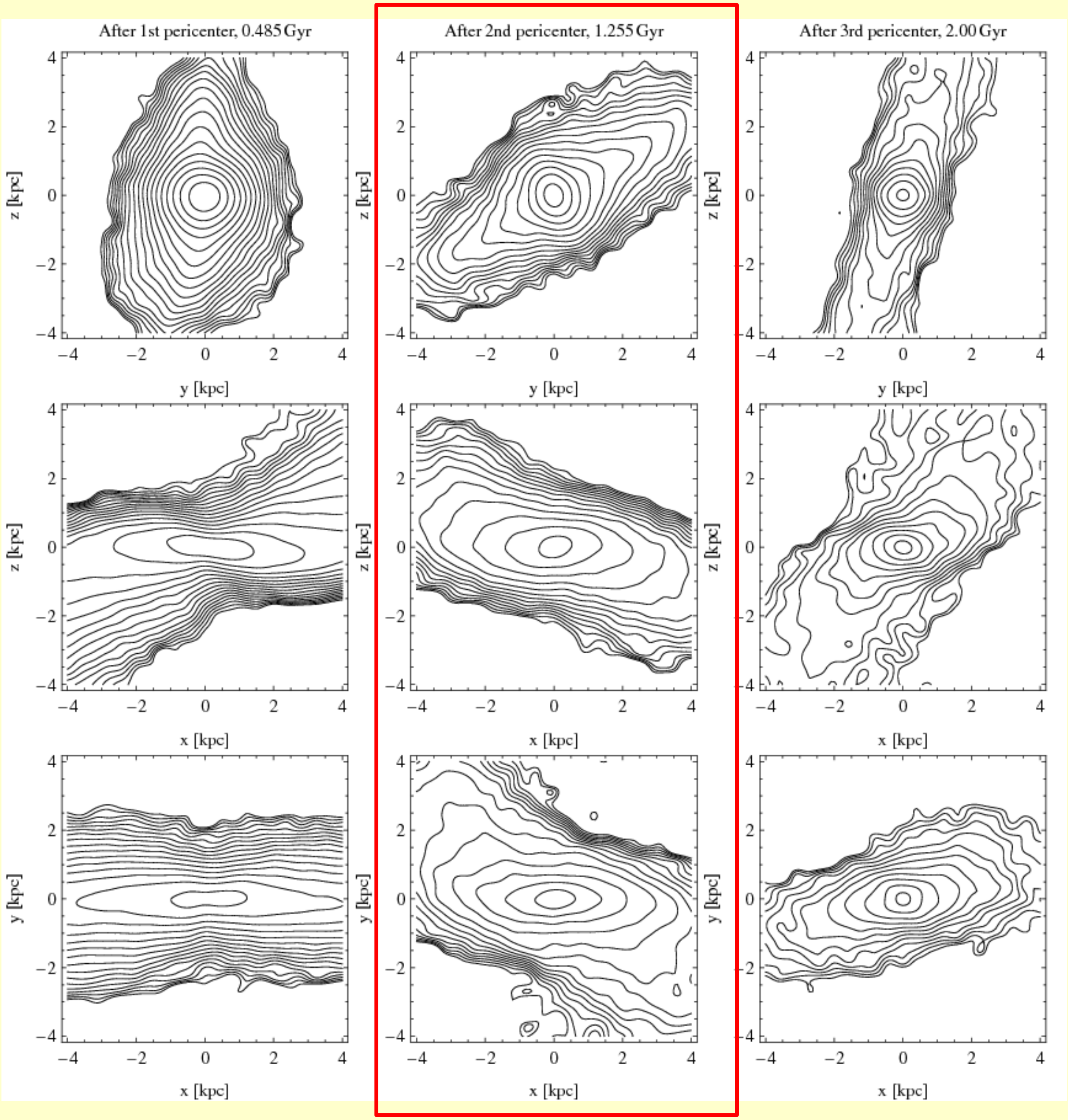
● real data

Tidal evolution



- The stellar component of the dwarf undergoes strong morphological evolution from a disk to a bar and then a spheroid
- Ordered motion (rotation) becomes dominated by random motion
- The dwarf experiences a significant mass loss
- The mass loss in stars traces that in dark matter

Morphological evolution

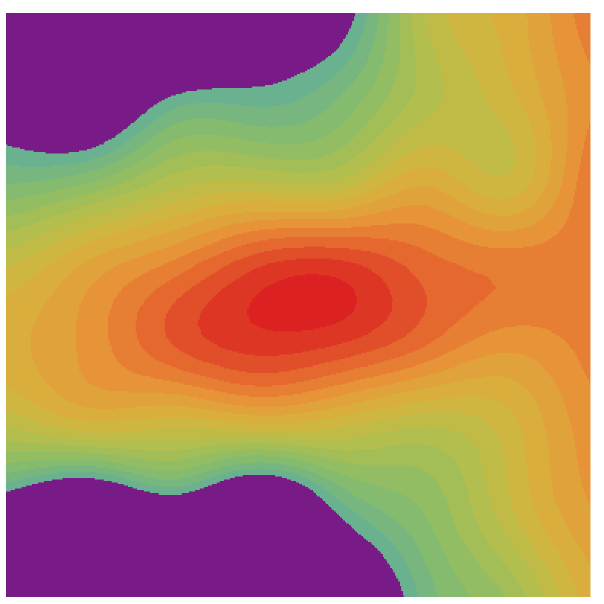


NOW

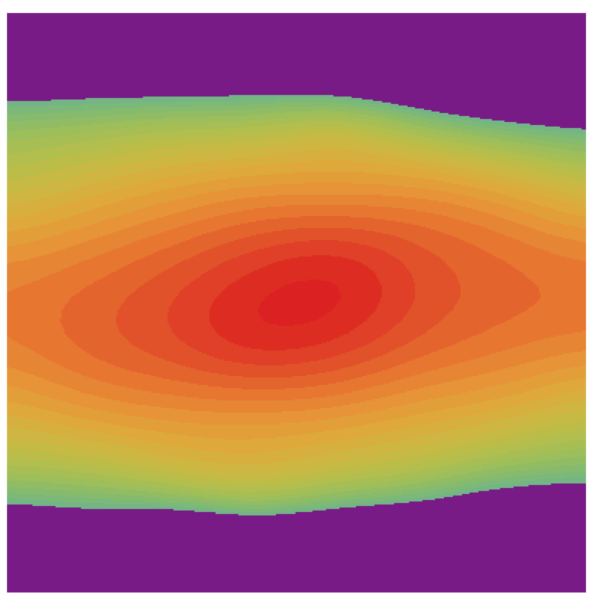
Surface density contours of the stellar component of the simulated Sgr after the 1st, 2nd and 3rd pericenter, seen along principal axes

A bar forms at 1st pericenter, is still present at 2nd, but is destroyed at 3rd

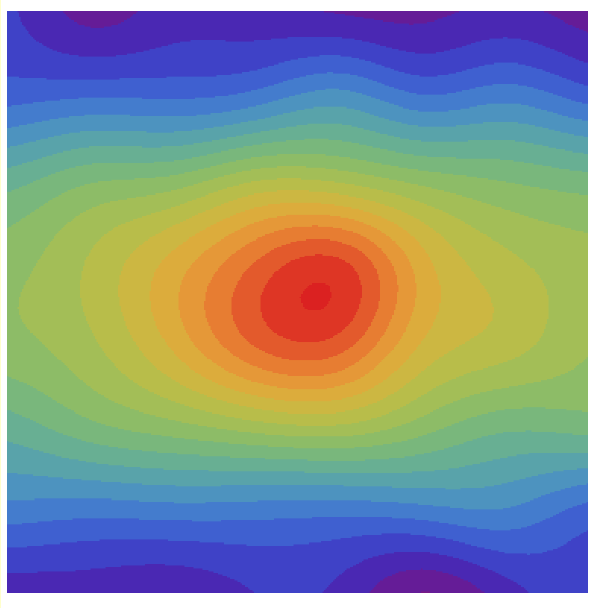
View from the Sun at present



real data
M giant stars



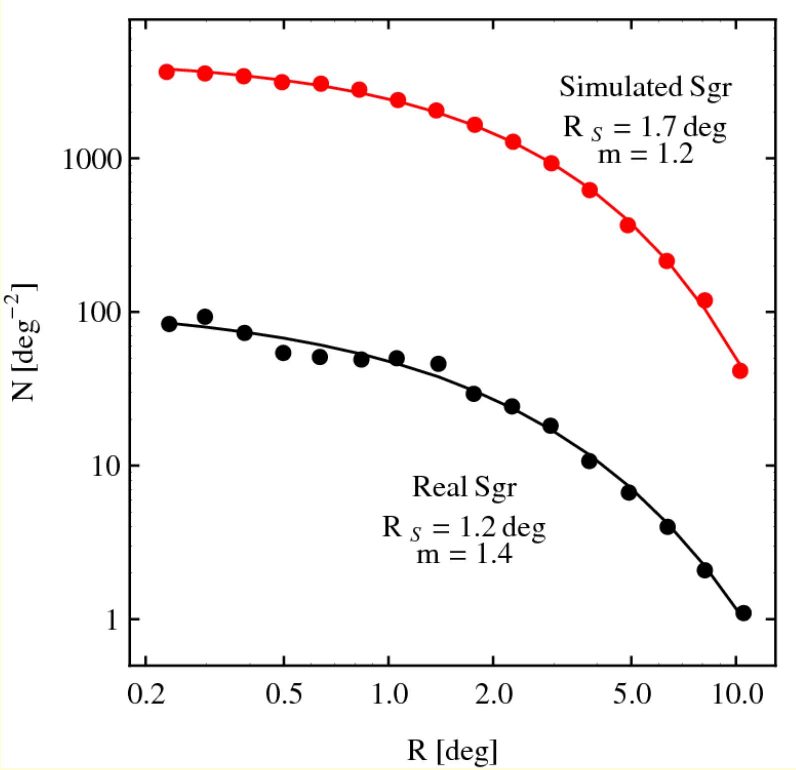
simulated
stellar component

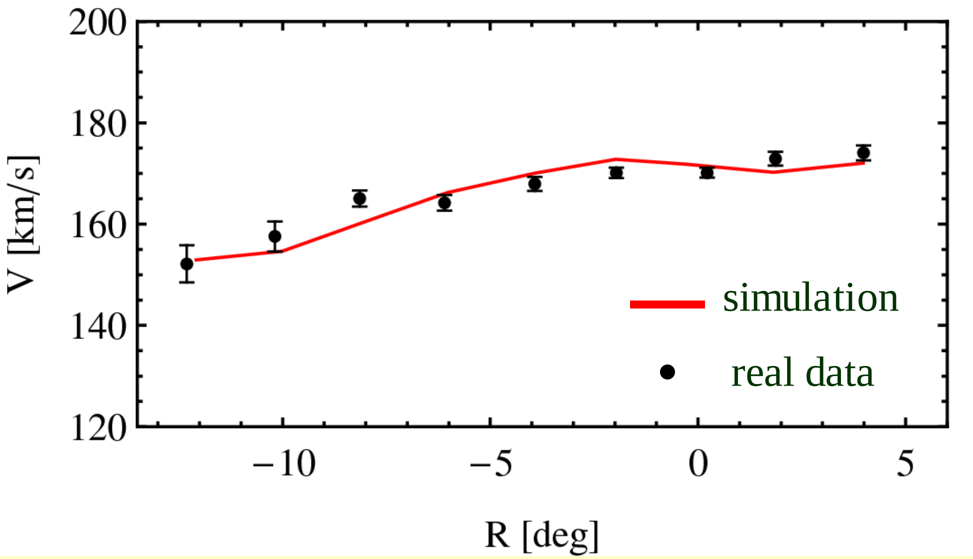


simulated dark
matter component

The shape of the observed stellar component can only be reproduced if we start with a disk almost coplanar with the orbit.

Distribution of stars and rotation

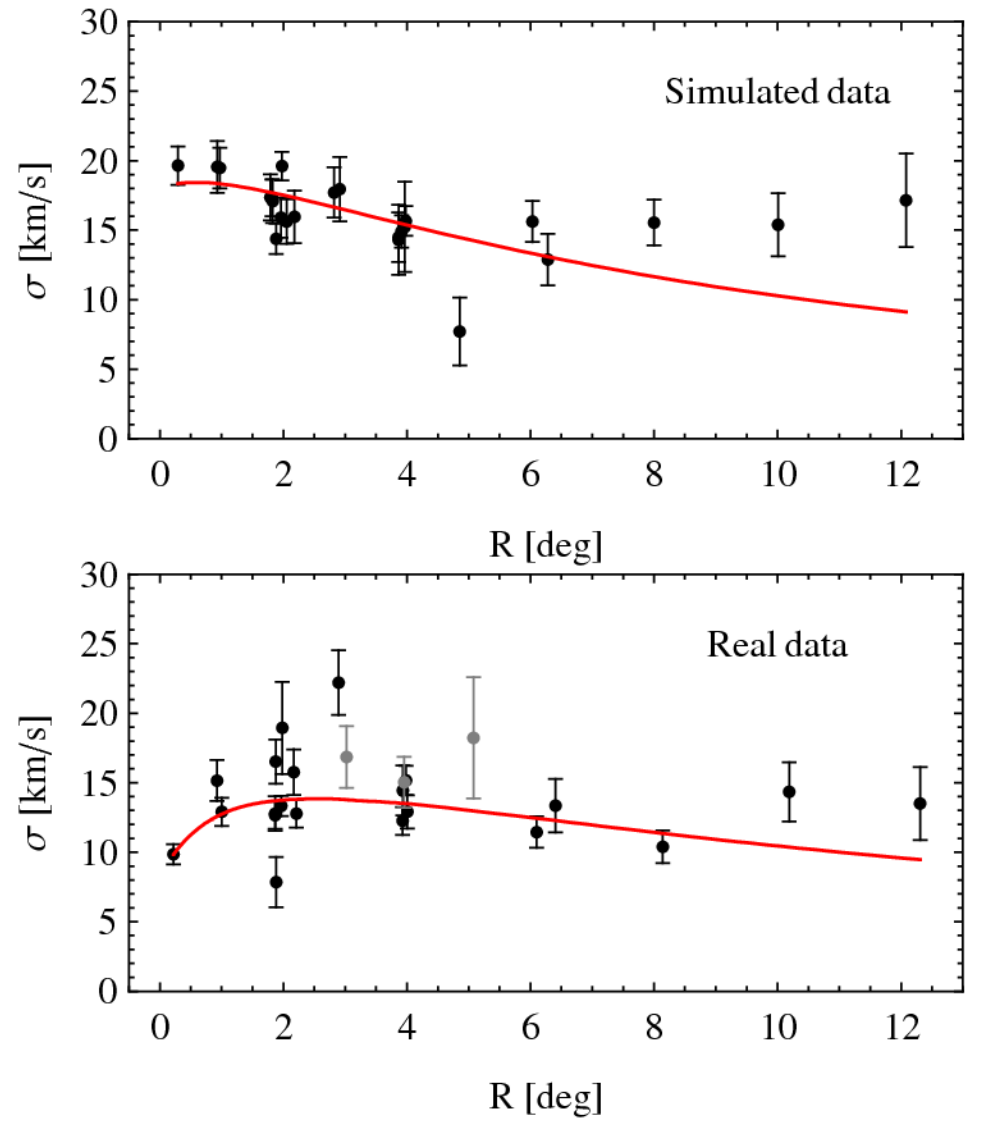




The density profile of stars is well reproduced

Very little intrinsic rotation remains in the stellar component, the velocity gradient is mainly of tidal origin

Kinematics and mass



The velocity dispersion profiles were fitted with the solutions of the Jeans equation assuming that mass traces light and the anisotropy parameter is constant with radius.

Present mass of Sgr:
$6 \times 10^8 \, M_\odot$
$M/L = 30 \, M_\odot/L_\odot$

Conclusions

- Tidal stirring is the most important gravitational process by which dwarf galaxies evolve
- Tidal stirring results in strong mass loss and morphological transformation of rotating disks into spheroids dominated by random motions
- Final products of tidal stirring are typically non-spherical and radially anisotropic
- The Sagittarius dwarf (and the LMC!) fit the tidal stirring scenario very well
- The present shape and inclination of Sgr can be reproduced if we start with a disk almost coplanar with the orbit and the dwarf has not passed more than two pericenters on its present orbit