Radialization of satellite orbits in galaxy mergers

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(+ Vasily Belokurov, Wyn Evans; arXiv:2108.00010)

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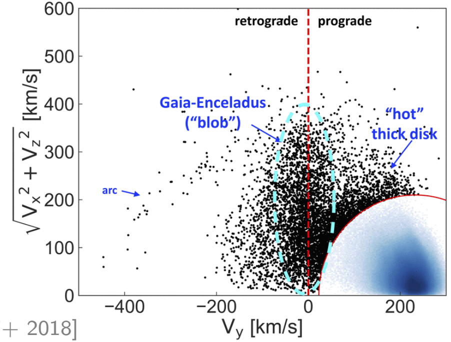
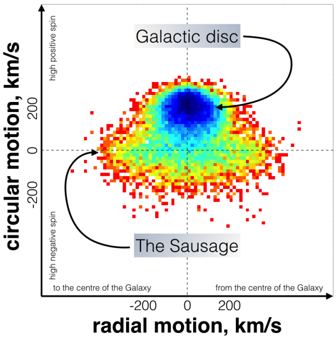
Motivation: the early merger in the Milky Way history



[Helmi+ 2018]



[Belokurov+ 2018]

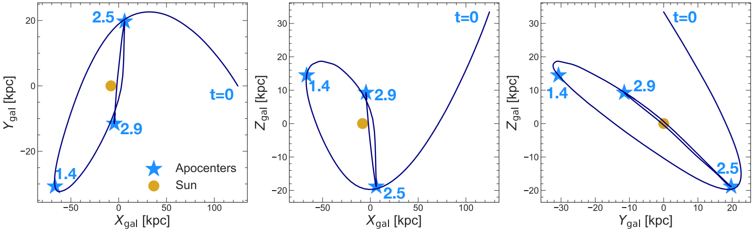
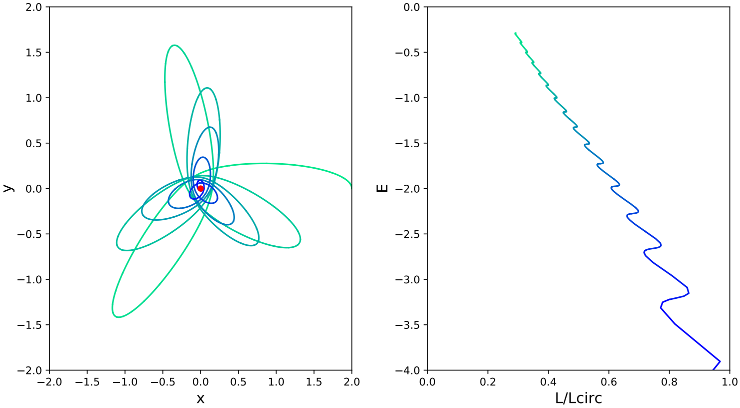


Figure 8. Orbit of our fiducial model. Apocenters are marked as stars along with their time of occurrence in Gyrs.

[Naidu+ 2103.03251: Reconstructing the last major merger of the Milky Way]

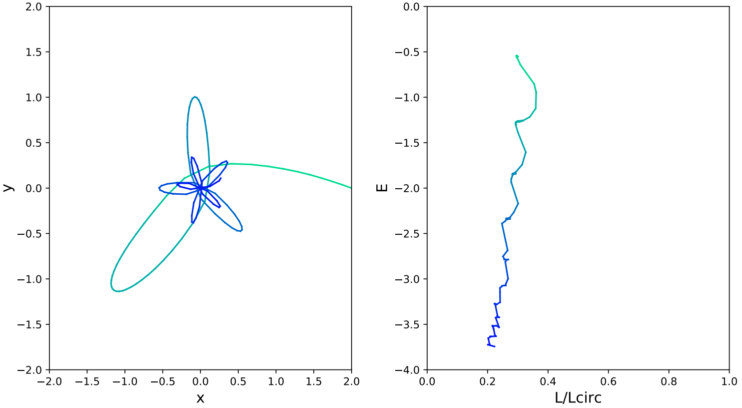
Classical picture: Chandrasekhar dynamical friction

- Friction force directed opposite to velocity
- $\Delta E_{\mathrm{drag}} = \mathbf{v} \cdot \Delta \mathbf{v}_{\mathrm{drag}}, \quad \Delta \mathbf{L}_{\mathrm{drag}} = \mathbf{r} \times \Delta \mathbf{v}_{\mathrm{drag}}$
- Most of the drag occurs at pericentre (small r, large v) $\Rightarrow$ a given Δv_{drag} affects energy more than angular momentum $\Rightarrow$ orbit circularizes



N-body simulations

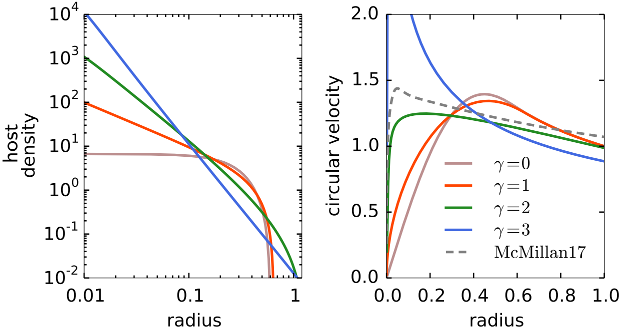
- Satellites typically lose mass as they sink in
- Host galaxy moves in response to satellite gravity
- “Friction” force not strictly antiparallel to velocity
- In many cases the orbit radializes rather than circularizes



N-body simulations

We conducted a large grid of simulations with different

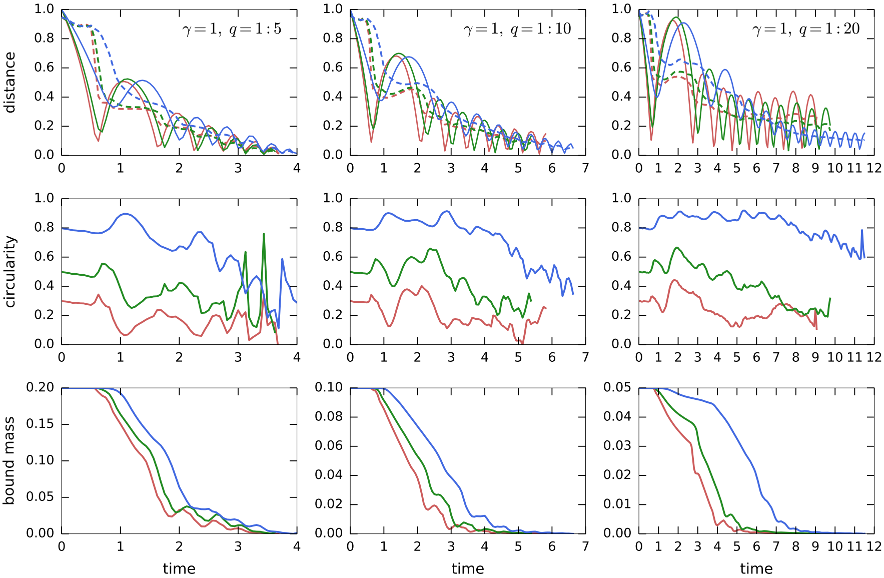
- host density profiles: $\rho \propto r^{-\gamma}$, $\gamma = 0, 1, 2, 3$
- satellite mass ratios: $q \equiv M_{\mathrm{sat}}/M_{\mathrm{host}} = 1{:}5,\ 1{:}10,\ 1{:}20$
- initial circularities: $\eta \equiv L/L_{\mathrm{circ}}(E) = 0.3,\ 0.5,\ 0.8$



We used the FMM code GYRFALCON [Dehnen 2000, 2002], developing a Python interface for its Poisson solver: `https://github.com/GalacticDynamics-Oxford/pyfalcon`

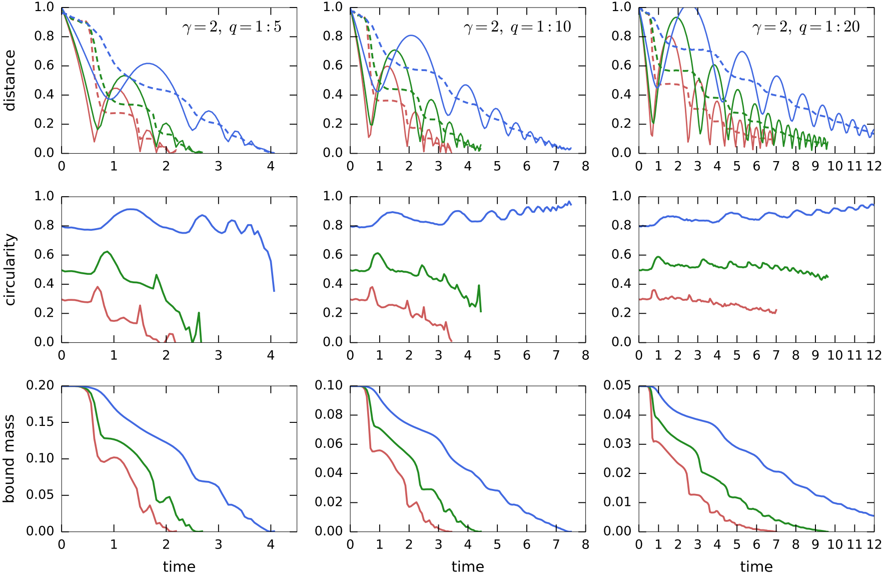
Evolution in the case of a $\gamma = 1$ host galaxy

- Sinking time insensitive to initial eccentricity
- Orbits radialize for any initial eccentricity



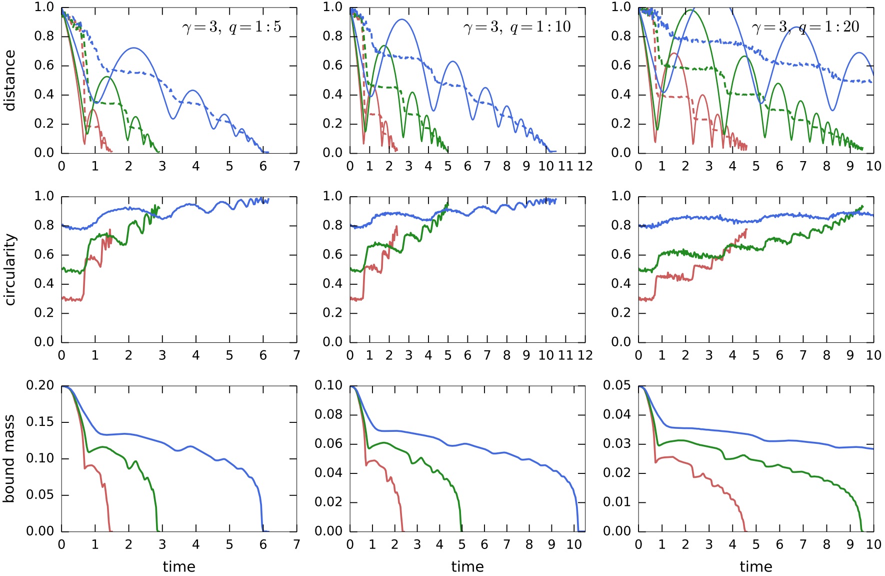
Evolution in the case of a $\gamma = 2$ host galaxy

- Sinking time somewhat longer for more circular orbits
- Orbits radialize for high-mass satellites or high initial eccentricity



Evolution in the case of a $\gamma = 3$ host galaxy

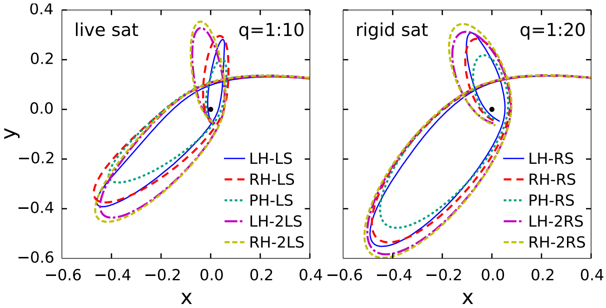
- Sinking time much longer for more circular orbits
- Orbits always circularize



Variation of simulation setup

- replace a disrupting (live) satellite with a point-like (rigid) one
  (examining the self-friction by the stripped material)
- replace the live host potential with a rigid initial profile
  (testing the role of host deformability)
  - fix the host potential at origin (pinned host, PH)
  - allow the rigid host potential (RH) to move around a common centre of mass
- put two identical satellites on diametrally opposite orbits
  (eliminate the reflex motion of the host without unphysical alterations)

In all alternative setups, the orbit is less likely to radialize or even circularizes compared to the baseline (physically realistic) case

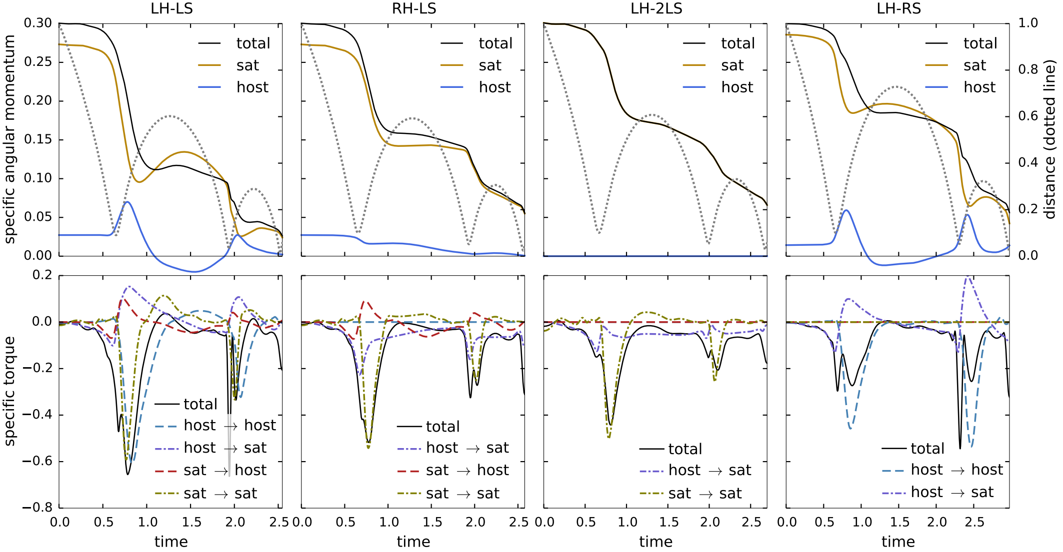


Decomposing the forces and torques

relative distance $\Delta\mathbf{x} \equiv \mathbf{x}_s - \mathbf{x}_h$; relative velocity $\Delta\mathbf{v} \equiv \mathbf{v}_s - \mathbf{v}_h$;

acceleration of the host centre $\mathbf{a}_h = \mathbf{a}_h^h + \mathbf{a}_h^s$ induced by the host $\mathbf{a}_h^h$ and the satellite $\mathbf{a}_h^s$;

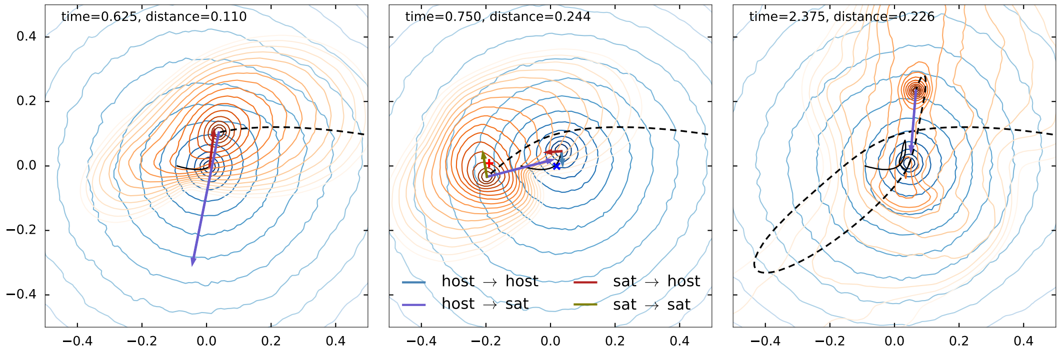
specific angular momentum $\mathbf{L} \equiv \Delta\mathbf{x} \times \Delta\mathbf{v}$; specific torque $\mathbf{T} \equiv \dot{\mathbf{L}} = \Delta\mathbf{x} \times (\mathbf{a}_s - \mathbf{a}_h)$



Curious events after the pericentre passage (second panel)

sign of
torque

- + "Classical" dynamical friction torque (by the host on the satellite) actually changes sign and increases the angular momentum
- – Self-friction by the stripped satellite debris due to asymmetric tidal tail
- – Torque caused by the host self-gravity appears due to the offset of the host centre-of-density relative to its centre-of-mass (i.e. its distortion)

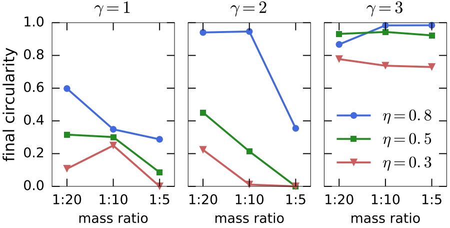


Summary: factors contributing to radialization

1. Self-friction by the tidally stripped satellite debris
   (stronger shocks for more eccentric orbits)

2. Motion of the host galaxy's dense central region towards the satellite pericentre, displacing it relative to the host centre of mass
   (stronger for more easily deformable shallow host density profiles) – both reflex motion *and* global response.

   We are witnessing this effect now in the MW–LMC interaction! [Erkal+ 2021, Petersen & Peñarrubia 2021, Garavito-Camargo+ 2021]



- ▶ Debris of massive accreted satellites are deposited onto highly eccentric orbits [e.g. Amorisco 2017]

- ▶ Chandrasekhar's formula fails to reproduce the eccentricity evolution