Dynamical Friction in Dwarf Galaxy Cores

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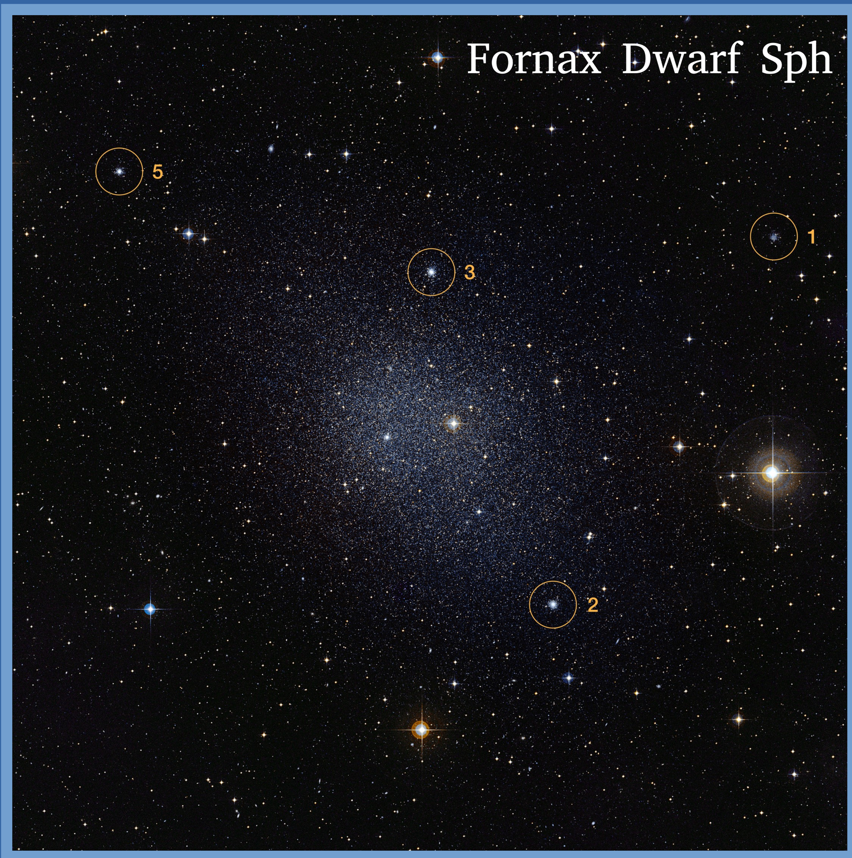
1. The Timing Problem

Low mass galaxies (masses < 10^9 $M_\odot$) containing globular clusters GCs offer an interesting dynamical puzzle. Fornax Dwarf Spheroidal is the classical example with 5 old GCs with ages > 10 Gyrs.

These galaxies with low background velocity dispersion, exert strong dynamical friction DF force (Chandrasekhar 1943) that leads to fast decay of angular momentum of orbiting GC, inspiralling it to the galaxy center within a few Gyrs. **So, by now, the Fornax GCs should have sunk to the galaxy center!**



3. Nature of Core Stalling- Partial or Complete?

Complete Stalling – Perturber's orbital radius stops to decay inside a critical radius r* ~ few 100 parsec ~ 1/3rd of galaxy core radius and the perturber keeps orbiting at this radius (Read et al 2006, Inoue 2011).

Partial Stalling – Perturber continues to inspiral inside r* with its orbital radius shrinking at a greatly reduced pace. Seen in recent simulations (Meadows et al 2020).

This behaviour also depends upon perturber's mass M_p with large (small) r* for heavier (low-mass) perturber.

High mass perturbers undergo partial stalling, while low-mass perturbers seem to completely stall inside a galaxy core. Peculiar feature observed in earliest simulations (Read et al 2006).

2. Core Stalling

Simulations indicated a suppressed DF for the "cored" background density profile of galaxy (Read+2006).

As perturber reaches inner core, rate of decay of its orbital radius is extremely slow (or even gets stalled). This phenomenon is termed "core stalling".

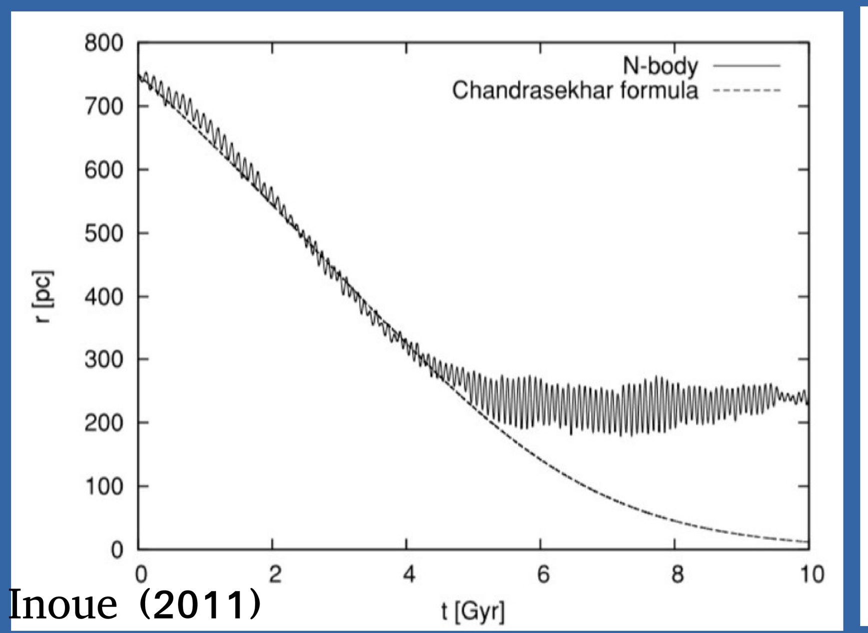
Some numbers!

Galaxy mass M ~ 10^9 $M_\odot$
Galaxy core radius b ~ 1 kpc

GC mass M_p ~ 2 x 10^5 $M_\odot$
GC core radius ~ 10 pc

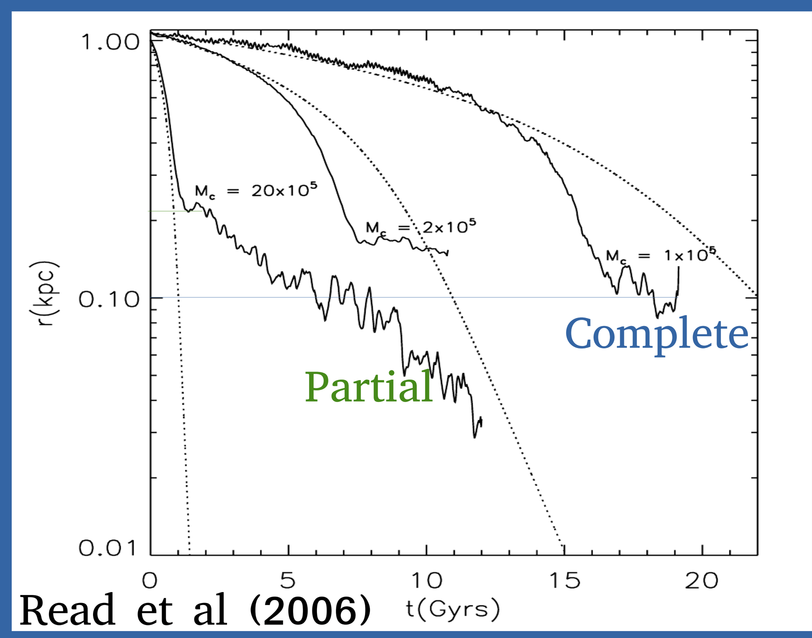
Stalling Radius r*~200 pc

Complete Stalling



Inoue (2011)

Mass Dependent Stalling



Read et al (2006)

Global Theory of Dynamical Friction & Core Stalling

4. The Global Theory

Chandrasekhar's DF formula assumes an infinite and homogeneous background density which implies straight-line orbits. The local DF results from hyperbolic interactions between perturber and stars.

Global theory of DF, by Tremaine & Weinberg (1984) for Spherically symmetric galaxies, considers real rosette orbits of stars. This is a secular perturbation theory and resulting frictional torque is only contributed by resonant stellar orbits.

5. Orbital Resonances

Stellar Rosette Orbital Frequencies:
Ω_w = Mean motion frequency
Ω_g = Apsidal precession frequency

Perturber's Circular Frequency:
Ω_p = Two-body frequency of perturber and enclosed galactic mass. Ω_p ↑ as r ↓

General Resonance:
$n\ \Omega_w + l\ \Omega_g - m\ \Omega_p = 0$

Corotating (CR) Resonances: n = m
$\Omega_w \approx \Omega_p >> \Omega_g$

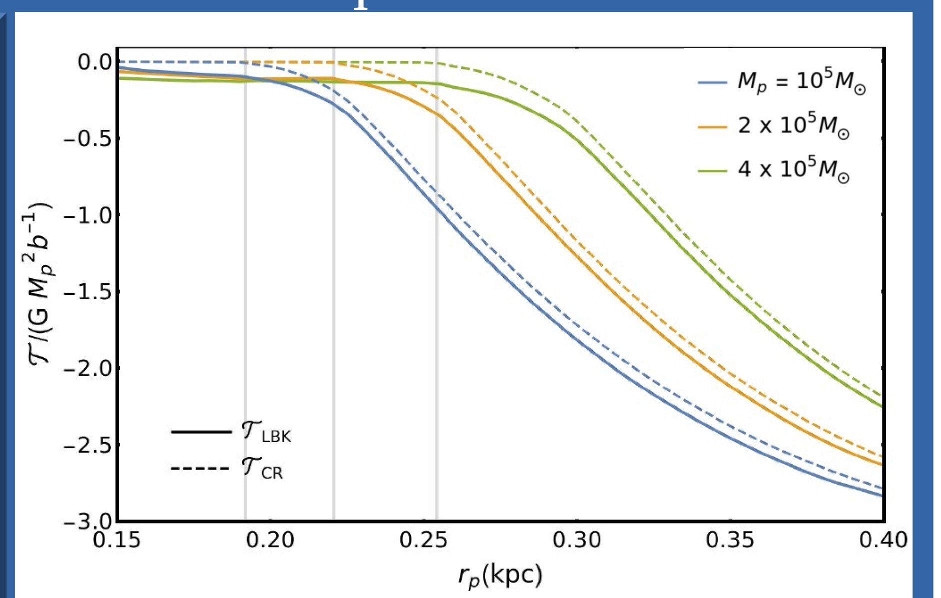
9. DF Torques

Total LBK torque $\tau_{LBK} = \tau_{CR} + \tau_{nCR}$
Non-CR torque $\tau_{nCR} \sim -0.1 G\ M_p^2/b$
CR torque τ_{CR} vanishingly small inside r*

Outside filtering radius r >> r*,
$\tau_{LBK} \approx \tau_{CR} >> \tau_{nCR}$

Inside filtering radius r < r*,
$\tau_{LBK} \approx \tau_{nCR}$ with $\tau_{CR} \approx 0$

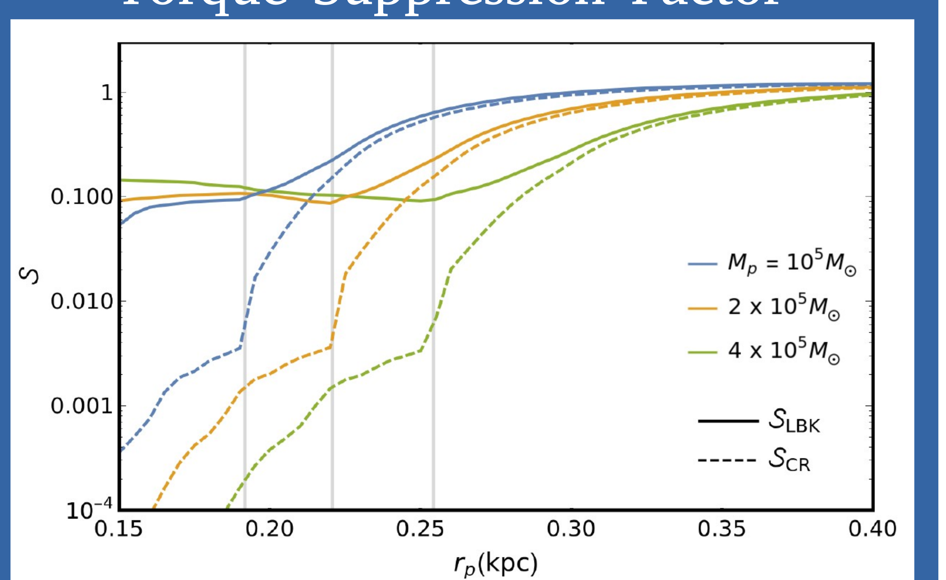
Torque Profiles



Suppression factor $S = \tau/\tau_{CS}$
For r >> r*, $S_{LBK} = \tau_{LBK}/\tau_{CS} \approx 1$, local and global theory are equivalent.

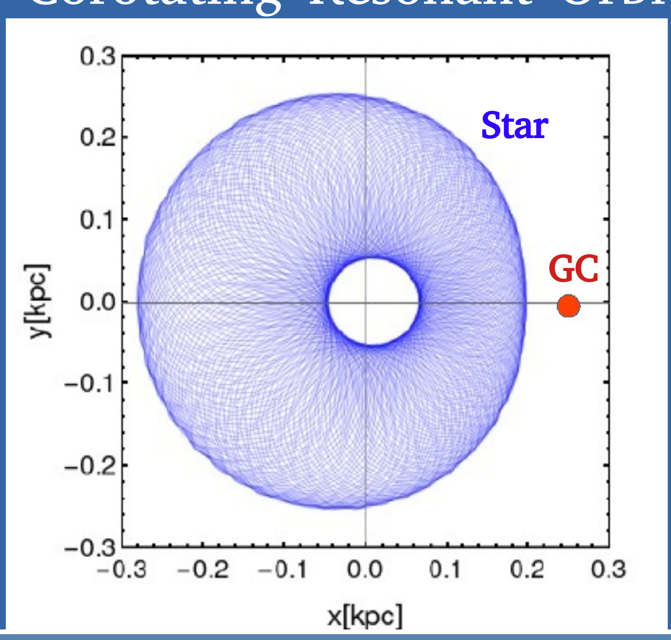
For r << r*, $S_{LBK} \sim 0.1 >> S_{CR}$
Non-CR resonances allow a remnant torque weaker than the local theory just by 10%.

Torque Suppression Factor



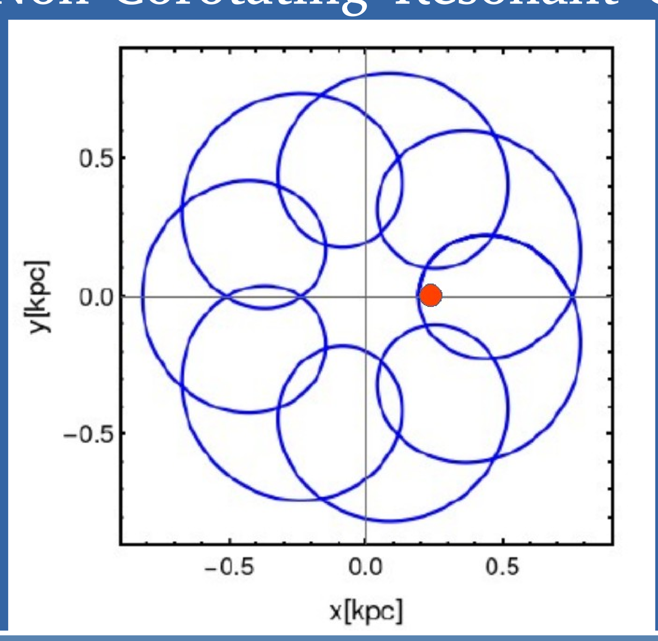
$S_{LBK} = \tau_{LBK}/\tau_{CS}$ $S_{CR} = \tau_{CR}/\tau_{CS}$

6. Corotating Resonant Orbit



CR resonant orbits are generally of smaller size. Slow libration in perturber's rest frame.

7. Non-Corotating Resonant Orbit



Non-CR orbits have high eccentricity and are bigger in size. Fast libration as $\Omega_w \sim \Omega_g$

8. The Filtering Radius r*

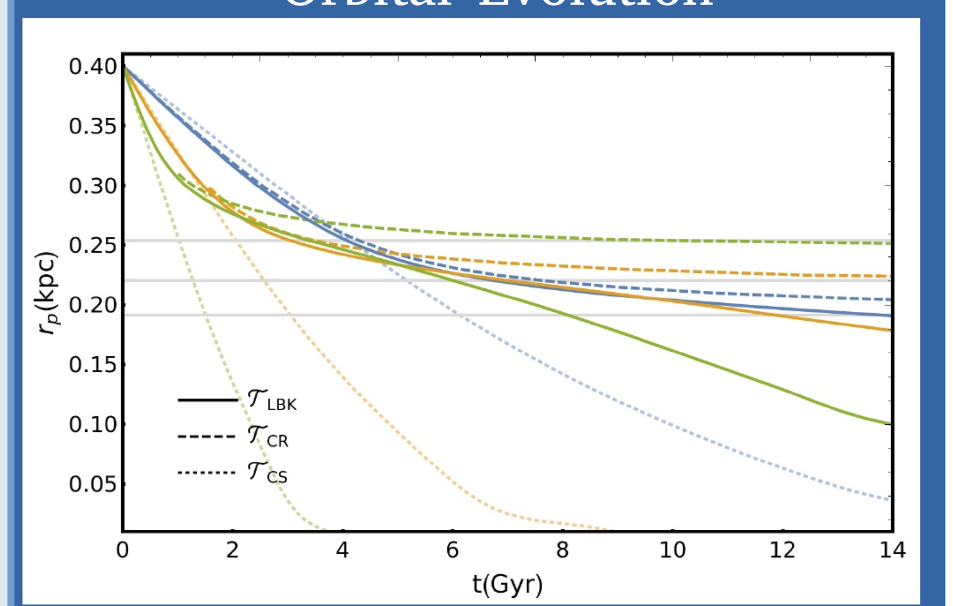
As perturber reaches r = r*, its orbital frequency $\Omega_p = \Omega_w(r=0)$ the maximum possible orbital frequency of a star (Kaur & Sridhar 2018). As perturber sinks inside r*, the CR resonances are highly suppressed.

10. Orbital Decay of perturber

Inside r < r* partial stalling occurs due to remnant non-CR resonances.
Only CR torques leads to complete stalling.
High mass perturbers have higher Ω_p and nearby low order non-CR resonances and stronger remnant torques. Partial Stalling behaviour.

Low mass perturbers appear to stall completely due to weak non-CR torques.

Orbital Evolution



11. Comparisons with Simulations

Pros : 1) Qualitative nature of orbital evolution of perturber - partial or complete stalling – inside galactic cores matches with simulations.
2) The filtering radius r* agrees amazingly well with simulations.

Cons : Some simulations show anti-frictional behaviour deep inside the core (Cole+2012). This can not be explained by our secular model. More general non-secular model of Banik & van den Bosch (2021) can explain this effect.

12. What lies ahead?

1) Role of non-corotating resonances needs to be explored in N-body simulations.
2) Generalizing theory to distinguish between these two regimes of stalling.

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