Binary supermassive black holes and the final parsec problem: is it a problem in real galaxies?

Eugene Vasiliev
David Merritt
Rochester Institute of Technology

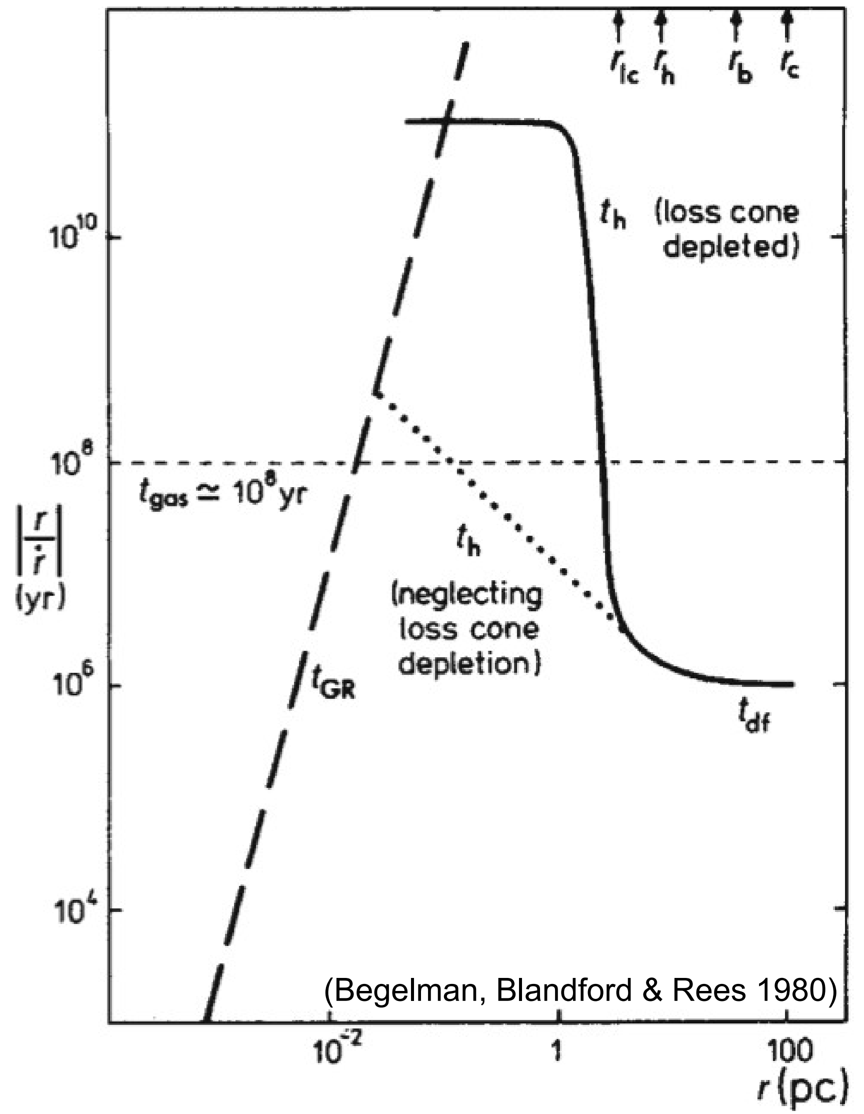
Fabio Antonini
Canadian Institute for Theoretical Astrophysics

Plan of the talk

- Evolution of supermassive black hole binaries
- Definition of the “final parsec problem”
- Possible solution in non-spherical galactic nuclei
- Is it a viable solution or a numerical artifact?

Evolution of supermassive black hole binaries

- Merger of two galaxies creates a common galactic nucleus
- Dynamical friction brings two black holes to a distance r_h where they form a bound binary
- The binary shrinks ("hardens") down to a separation at which gravitational radiation becomes effective
- GW emission finally drives the binary to coalescence



(Begelman, Blandford & Rees 1980)

Evolution of supermassive black hole binaries

- Dynamical friction timescale:

$$t_{\rm DF} \sim 10^6 \text{ yr} \left(\frac{r}{100 \text{ pc}}\right)^2 \left(\frac{\sigma}{200 \text{ km/s}}\right) \left(\frac{m_2}{10^8 \, M_\odot}\right)^{-1} \left(\frac{\ln \Lambda}{15}\right)^{-1}$$

- A binary is called hard if its orbital velocity exceeds that of the field stars, or the separation is less than a_h:

$$a_h = \frac{G\mu}{\sigma^2} \approx 2.7 \text{pc} (1+q)^{-1} \left(\frac{m_2}{10^8 \, M_\odot}\right) \left(\frac{\sigma}{200 \text{km/s}}\right)^{-2}, \qquad \mu \equiv \frac{m_1 m_2}{m_1 + m_2}, \; q \equiv \frac{m_2}{m_1}$$

- The timescale for coalescence due to GW emission is (Peters 1964)

$$t_{\rm GW} = \frac{5}{256 \, F(e)} \frac{c^5}{G^3} \frac{a^4}{\mu (m_1 + m_2)^2} \approx 7 \times 10^8 \text{yr} \frac{q^3}{(1+q)^6} \left(\frac{m_1 + m_2}{10^8 \, M_\odot}\right)^{-0.6} \left(\frac{a}{10^{-2} a_h}\right)^4$$

$$F(e) \equiv (1 - e^2)^{7/2} \left(1 + \frac{73}{24} e^2 + \frac{37}{96} e^4\right)$$

Gravitational slingshot and binary hardening

A star passing at a distance $\lesssim 3a$ from the binary will experience a complex 3-body interaction which results in ejection of the star with velocity $v_{\rm ej} \sim \sqrt{\frac{m_1 m_2}{(m_1+m_2)^2}}\, v_{\rm bin}$.

These stars carry away energy and angular momentum from the binary, so that its separation decreases:

$$\frac{d}{dt}\left(\frac{1}{a}\right) \approx 16 \frac{G\,\rho}{\sigma}$$

Thus, if density of field stars ρ remains constant, the binary hardens with a constant rate.

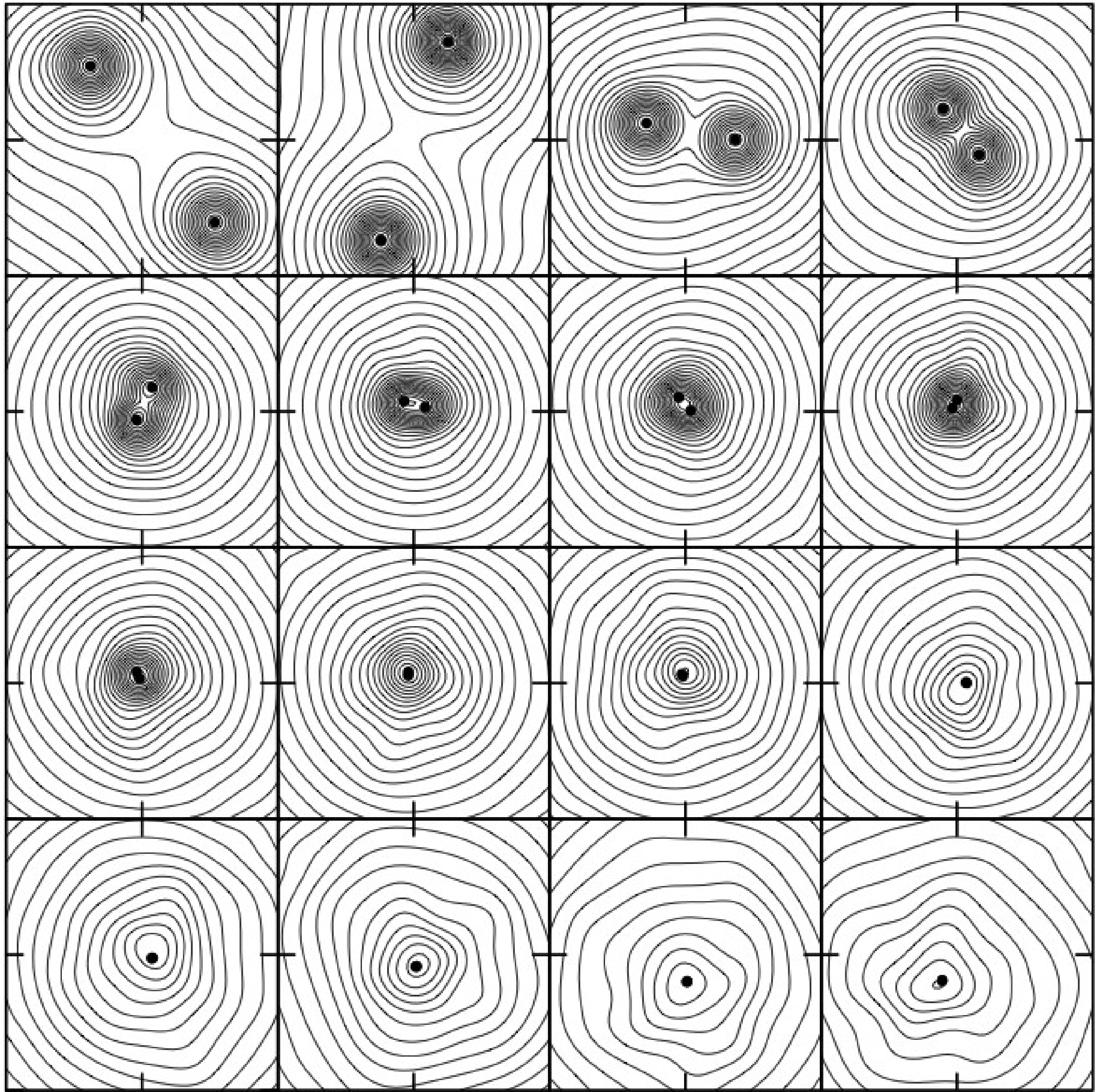
However, the reservoir of low angular momentum stars which can be ejected is finite and may be depleted quickly, so that the binary stalls at a radius $a_{\rm stall} \sim (0.1-0.4)a_h$.

Evolution of density profile in the merger

Dynamical friction

Bound pair

Ejection of stars via gravitational slingshot



(Milosavljevic & Merritt 2001)

“Mass deficit” in observations of galactic nuclei

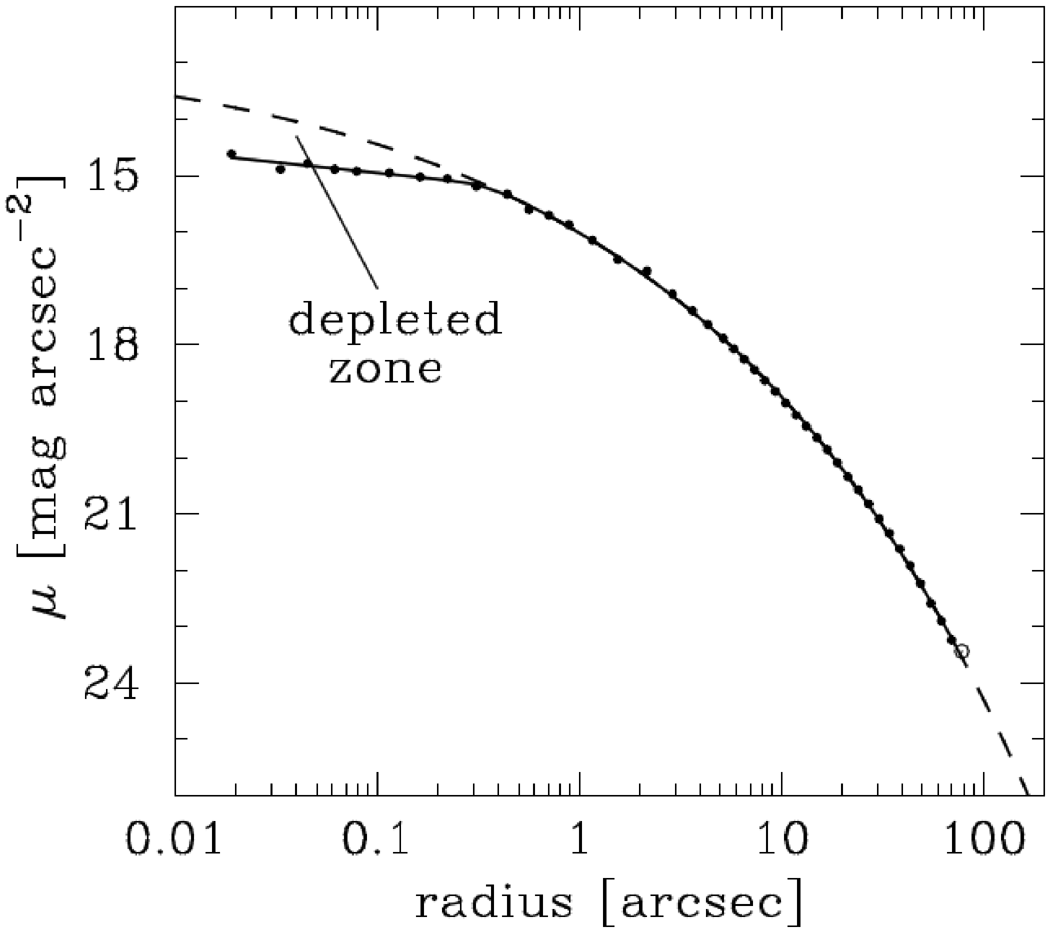


Figure 11: *Observed surface brightness profile of NGC 3348. The dashed line is the best-fitting Sersic model to the large-radius data. Solid line is the fit of an alternative model, the “core-Sersic” model, which fits both the inner and outer data well. The mass deficit is illustrated by the area designated “depleted zone” and the corresponding mass is roughly* $3 \times 10^8 M_\odot$ [Graham 2004]

Loss cone dynamics

The region of phase space with $L^2 < L^2_{\rm LC} \equiv 2G(m_1 + m_2)\,3a$ is called loss cone. In the absence of other processes, the loss cone is repopulated on a timescale

$$T_{\rm rep} \sim T_{\rm rel}\,\frac{L^2_{\rm LC}}{L^2_{\rm circ}}\ ,\ \text{where } T_{\rm rel} = \frac{0.34\,\sigma 3}{G^2\,m_\star\,\rho_\star\,\ln\Lambda}\ \text{is the relaxation time.}$$

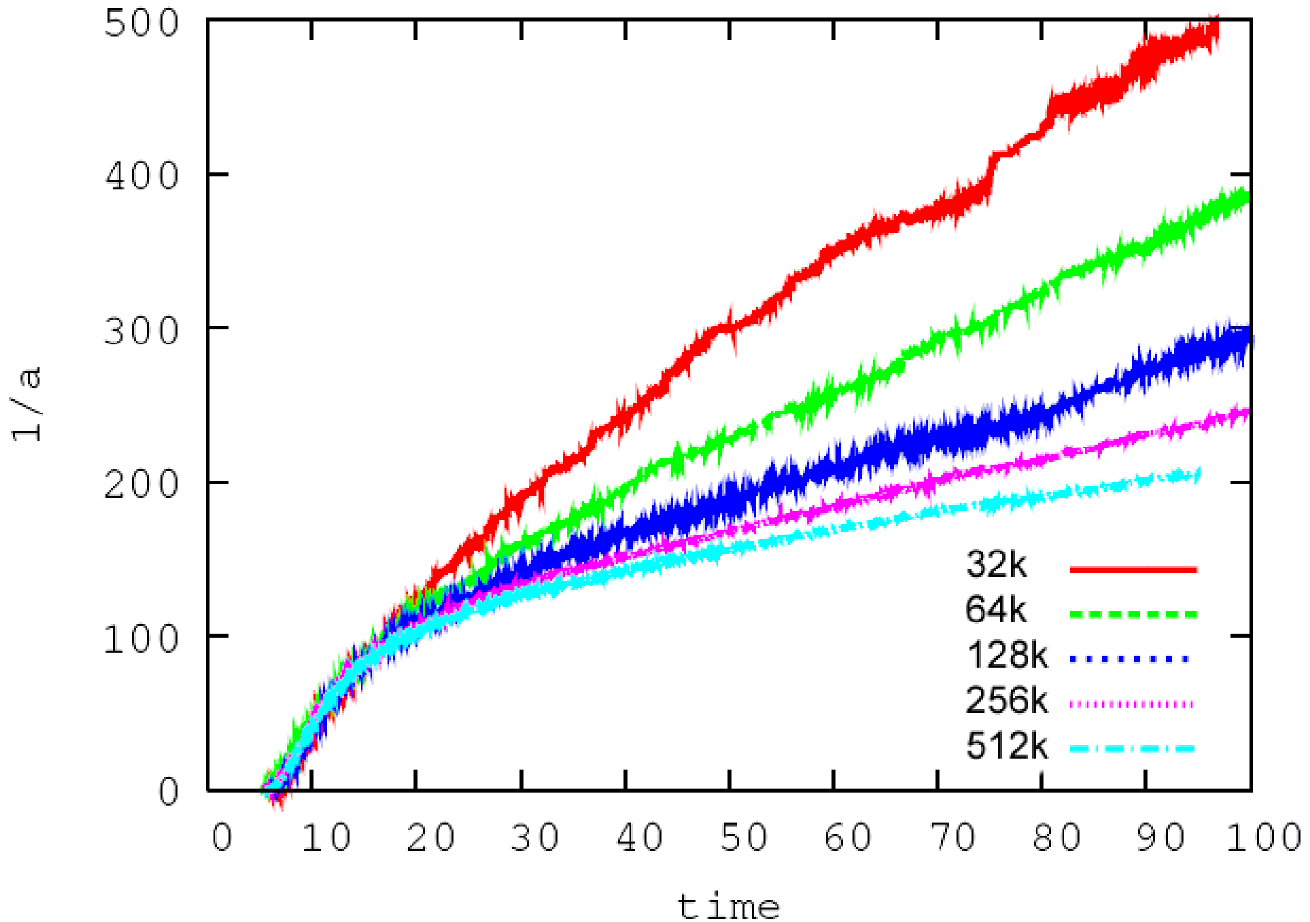
If $T_{\rm rep} \lesssim T_{\rm orb}$, the loss cone is essentially full – it is refilled faster than orbital period.

In real galaxies, however, the opposite regime applies – the empty loss cone.

In this case the hardening rate $H \equiv \dfrac{d}{dt}(a^{-1}) \simeq \dfrac{T_{\rm orb}}{T_{\rm rep}} H_{\rm full}$.

In the N-body simulations, the full loss cone regime is manifested by independence of hardening rate on the number of particles, while the empty loss cone regime should have $H \propto m_\star \propto 1/N$.

N-dependence of hardening rate in simulations



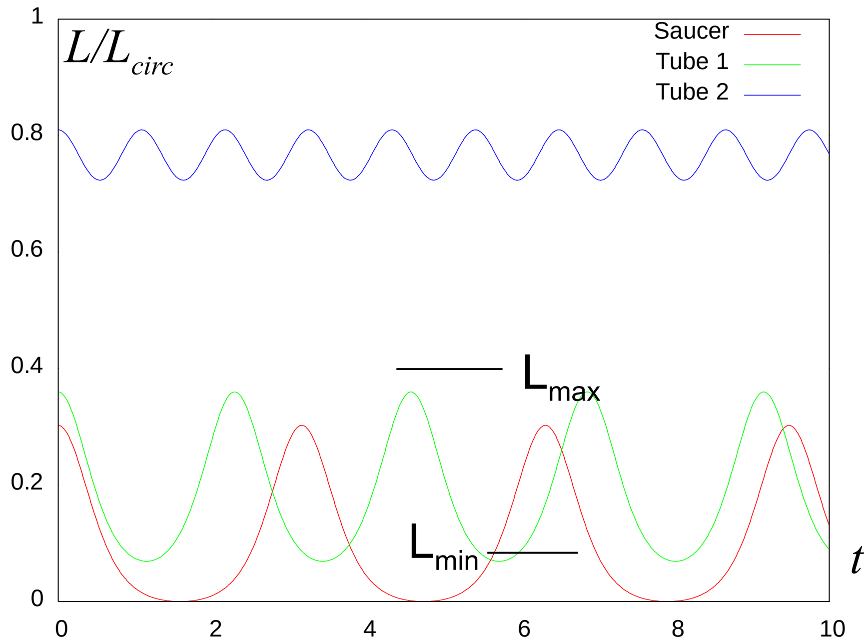
(Merritt et al.2007)

Possible ways to enhance the loss cone repopulation

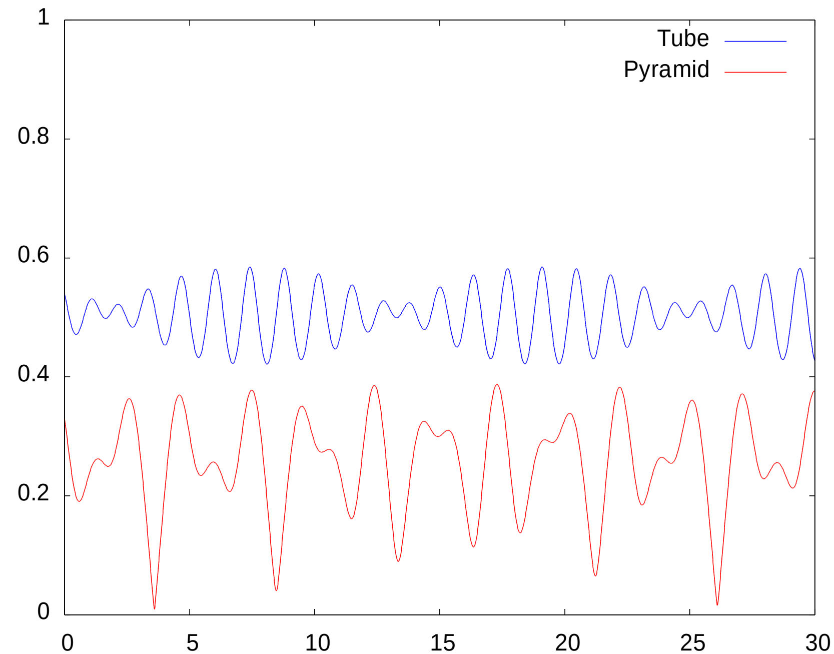
- Brownian motion of the binary (enables interaction with larger number of stars) [Milosavljevic&Merritt 2001]
- Non-stationary solution for the loss cone repopulation rate [Milosavljevic&Merritt 2003]
- Secondary slingshot (stars may interact with binary several times)
- Gas physics
- Perturbations to the stellar distribution arising from transient events (such as infall of large molecular clouds, additional minor mergers, …)
- Effects of non-sphericity on the orbits of stars in the nucleus

Evolution of angular momentum of an orbit in a non-spherical nuclear star cluster

Total angular momentum squared, L^2, is not conserved but experiences regular oscillations due to torques from non-spherical stellar distribution.
Therefore, much larger number of stars can attain low values of angular momentum at some point in their regular precession
Especially in a triaxial nucleus, the fraction of centrophilic orbits may be large enough to sustain full loss cone regime for the entire evolution of the binary



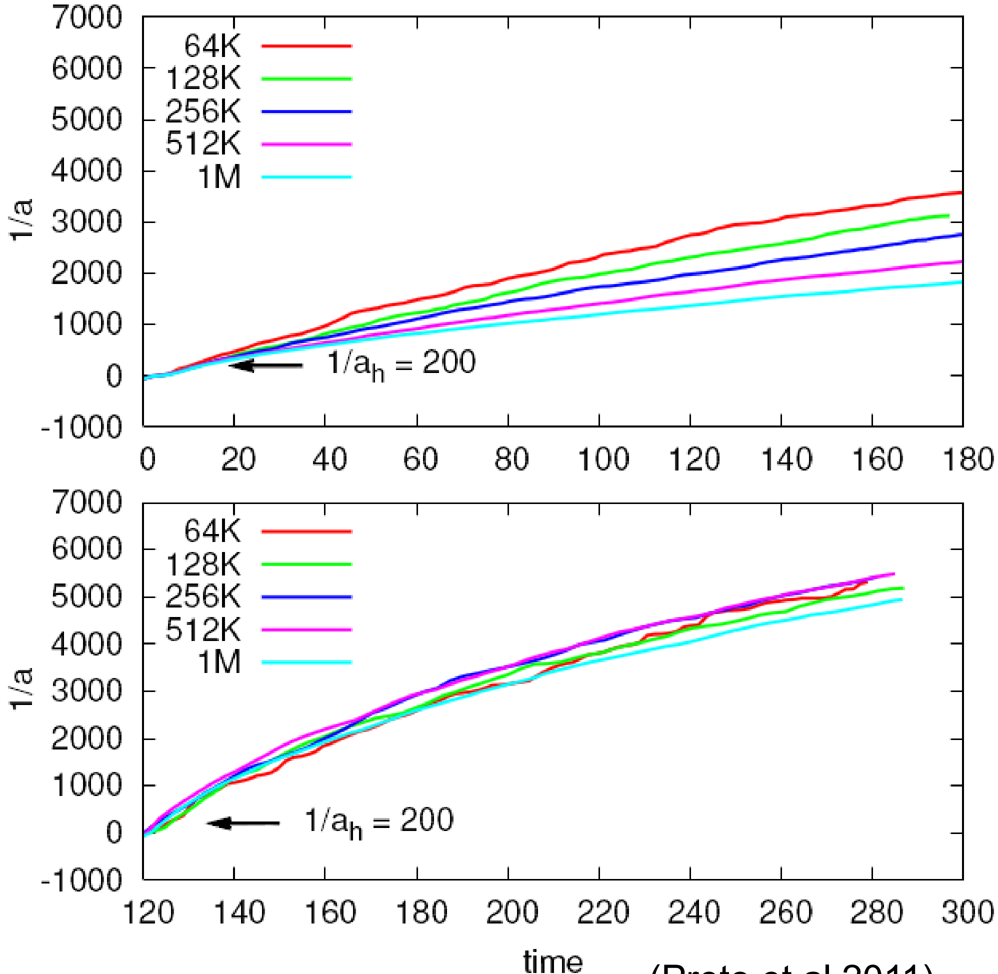
Axisymmetric system



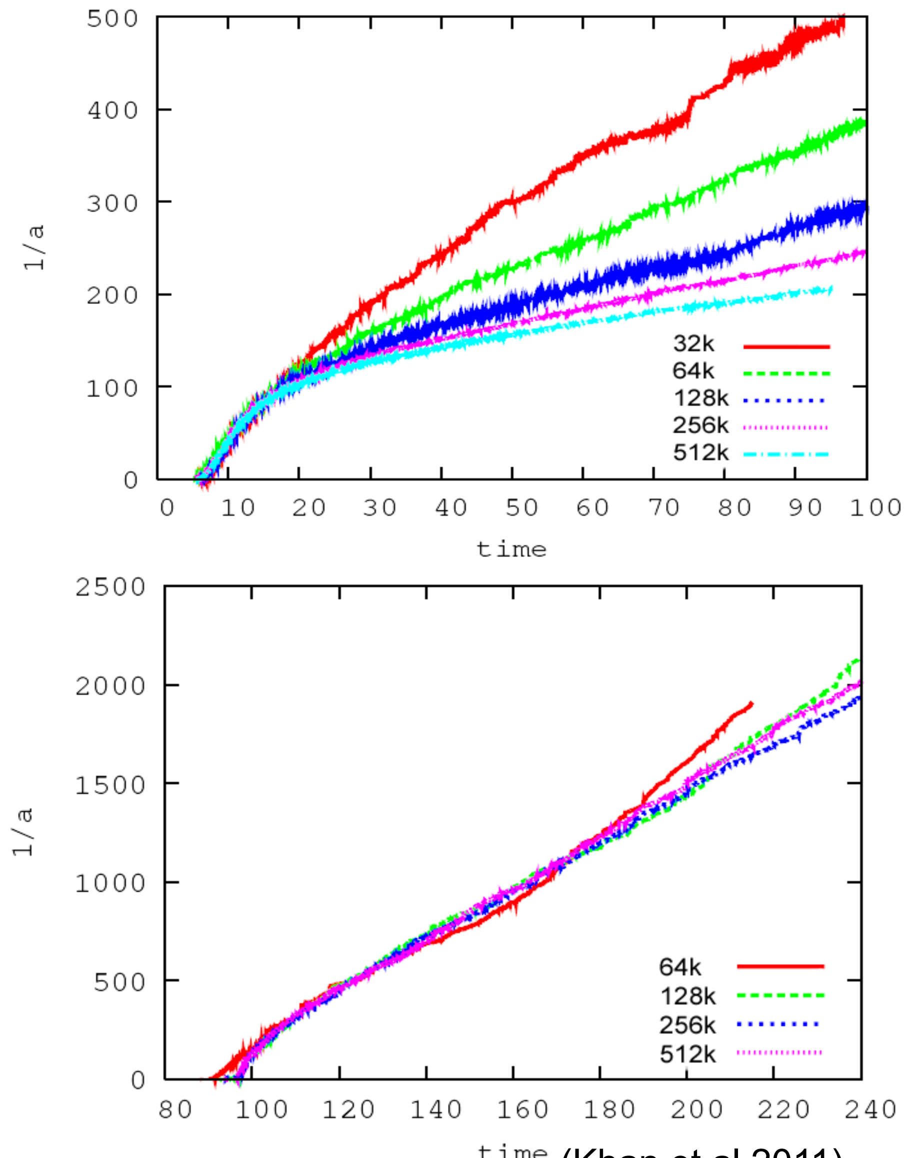
triaxial system

Hardening rates in non-spherical simulations

...were recently found to be N-independent

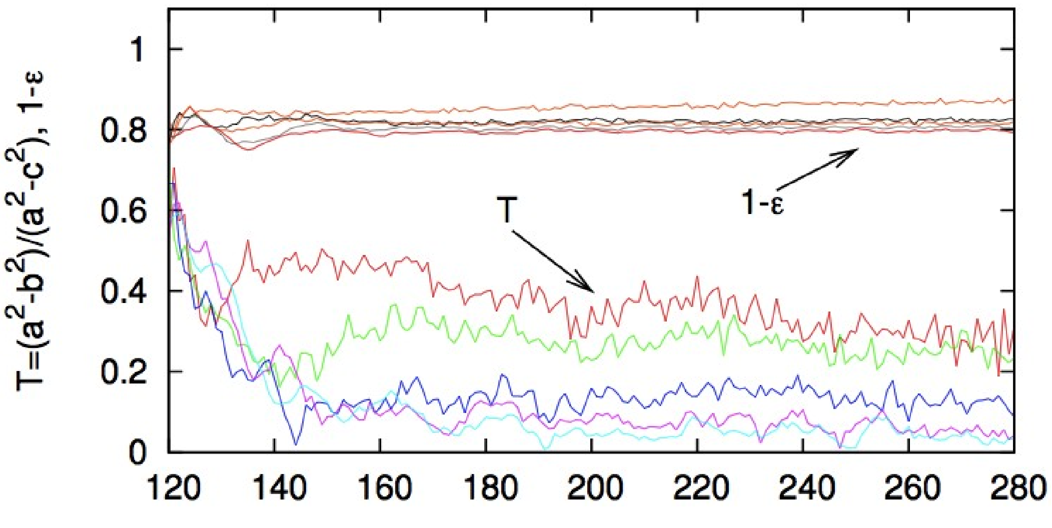


(Preto et al.2011)



(Khan et al.2011)

Are the merger remnants sufficiently non-spherical?



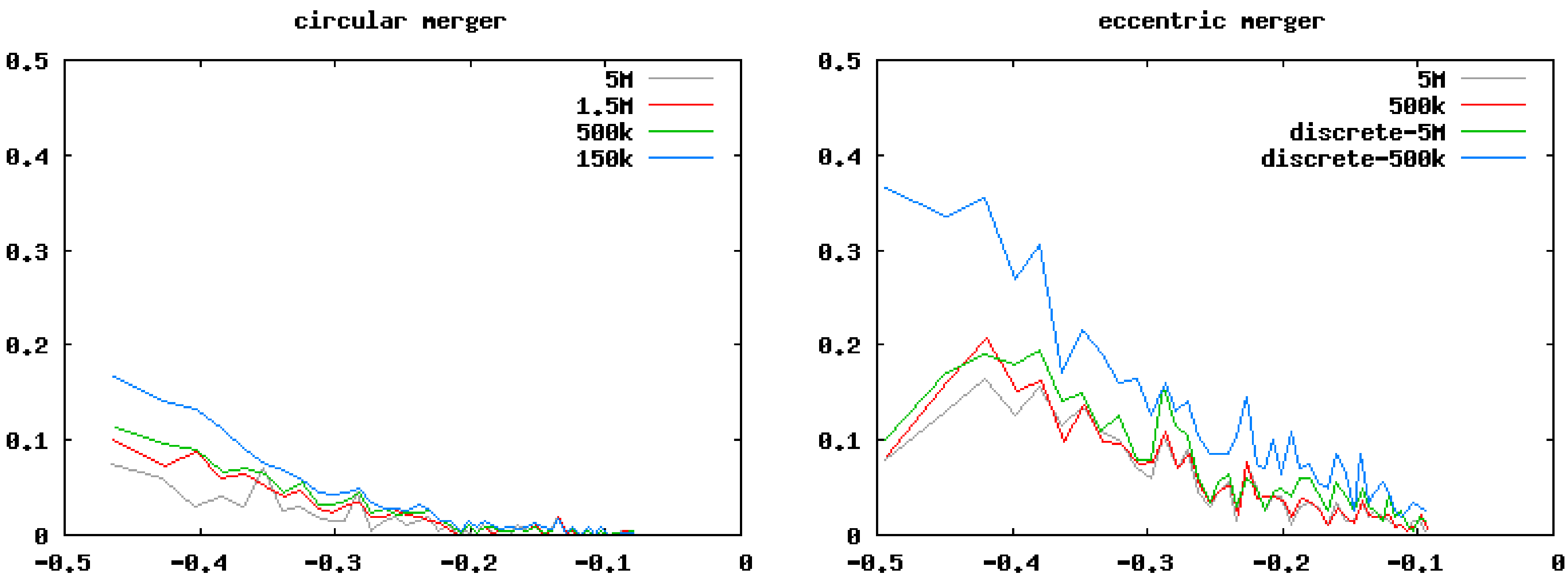
Degree of flattening and triaxiality as a function of time (Preto et al.2011)

But: this is an “average” measure.

More important is the radial dependence and amount of triaxiality in the very center.

That may still be dominated by shot noise ~$(1/N)^{1/2}$.

Analysis of particle orbits in merger remnants



Fraction of centrophilic orbits as a function of energy,
for varied degree of 'smoothness' of the potential.

In the two merger simulation, this fraction is substantially different and exhibits different dependence on the number of particles,
yet both simulations seem to be in the full loss cone regime!

This may mean that we haven't yet reached sufficient numerical resolution

Conclusions

- Formation of binary supermassive black holes results in their coalescence in a reasonable time only if there is a continuous supply of low angular momentum stars which can interact with the binary and make it shrink.
- The standard loss cone theory for a spherical galaxy predicts that this reservoir is quickly depleted and very slowly repopulated – this is the final parsec problem.
- In the case of realistic, non-spherical merger remnants, this problem is believed to be alleviated because of existence of large amount of stars on centrophilic orbits, which can overwhelm the loss cone depletion.
- It is not yet clear whether we may simulate this process reliably.