BINARY BLACK HOLE DYNAMICS

DAVID MERRITT

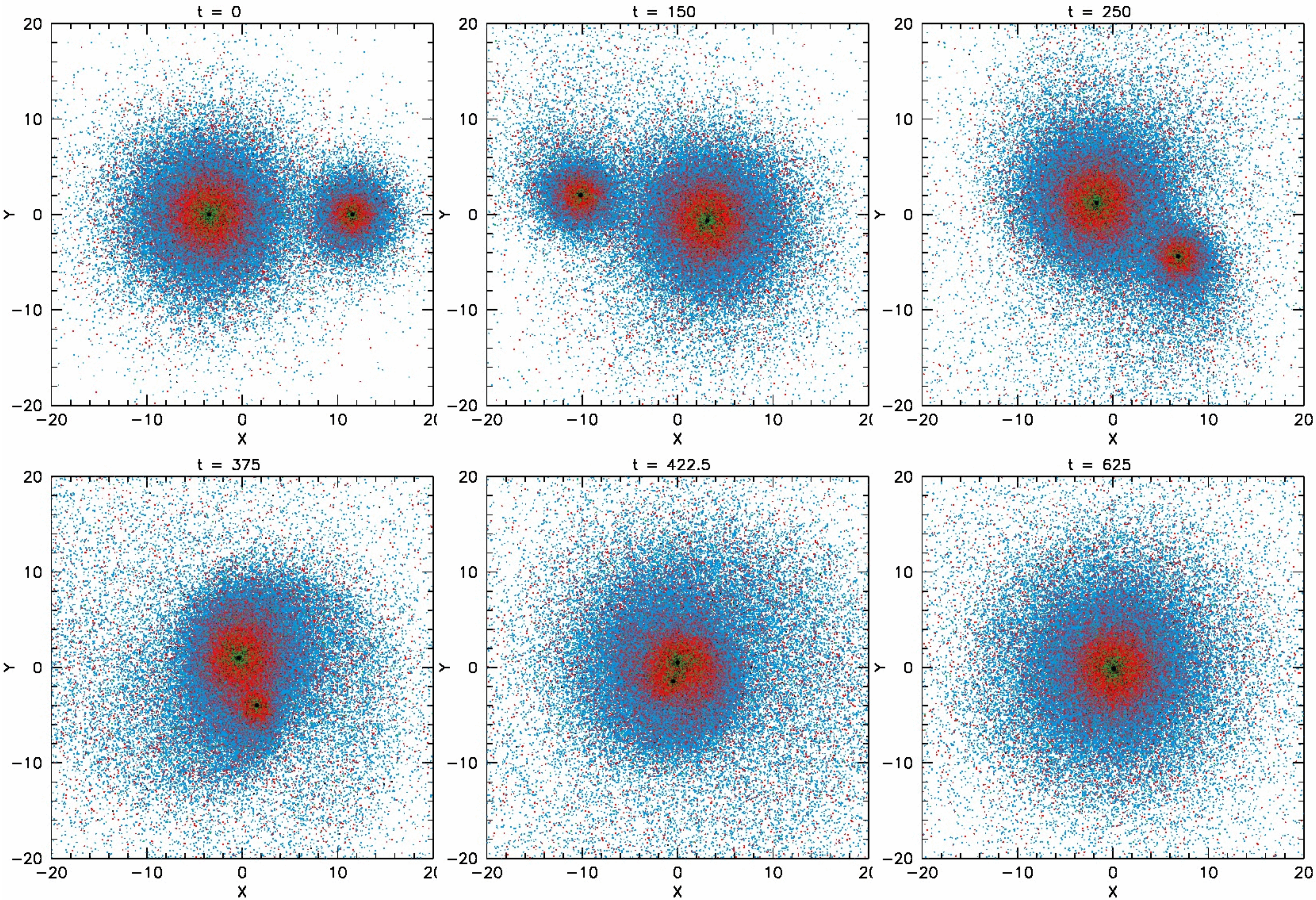
"BINARY BLACK HOLES & DUAL AGN:
A WORKSHOP IN MEMORY OF DAVID S. DE YOUNG"

TUCSON, ARIZONA
NOVEMBER 29-30, 2012

I. Final-Parsec Problem

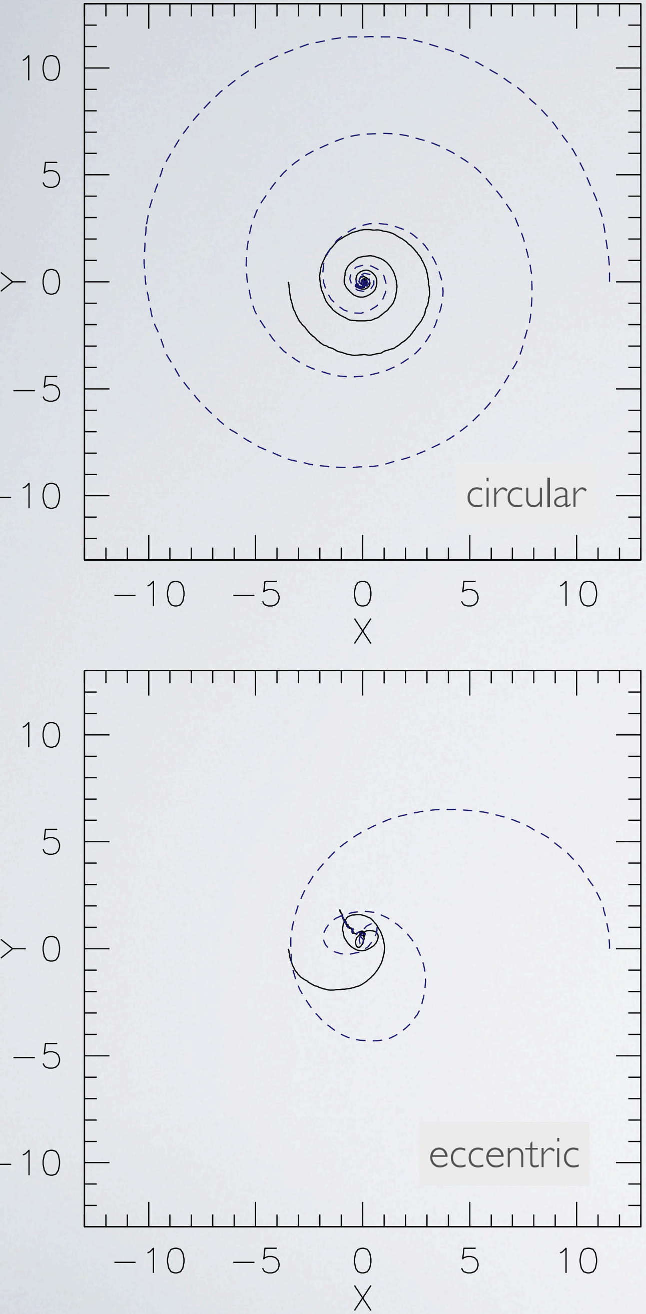
II. Binary Evolution in Rotating Nuclei

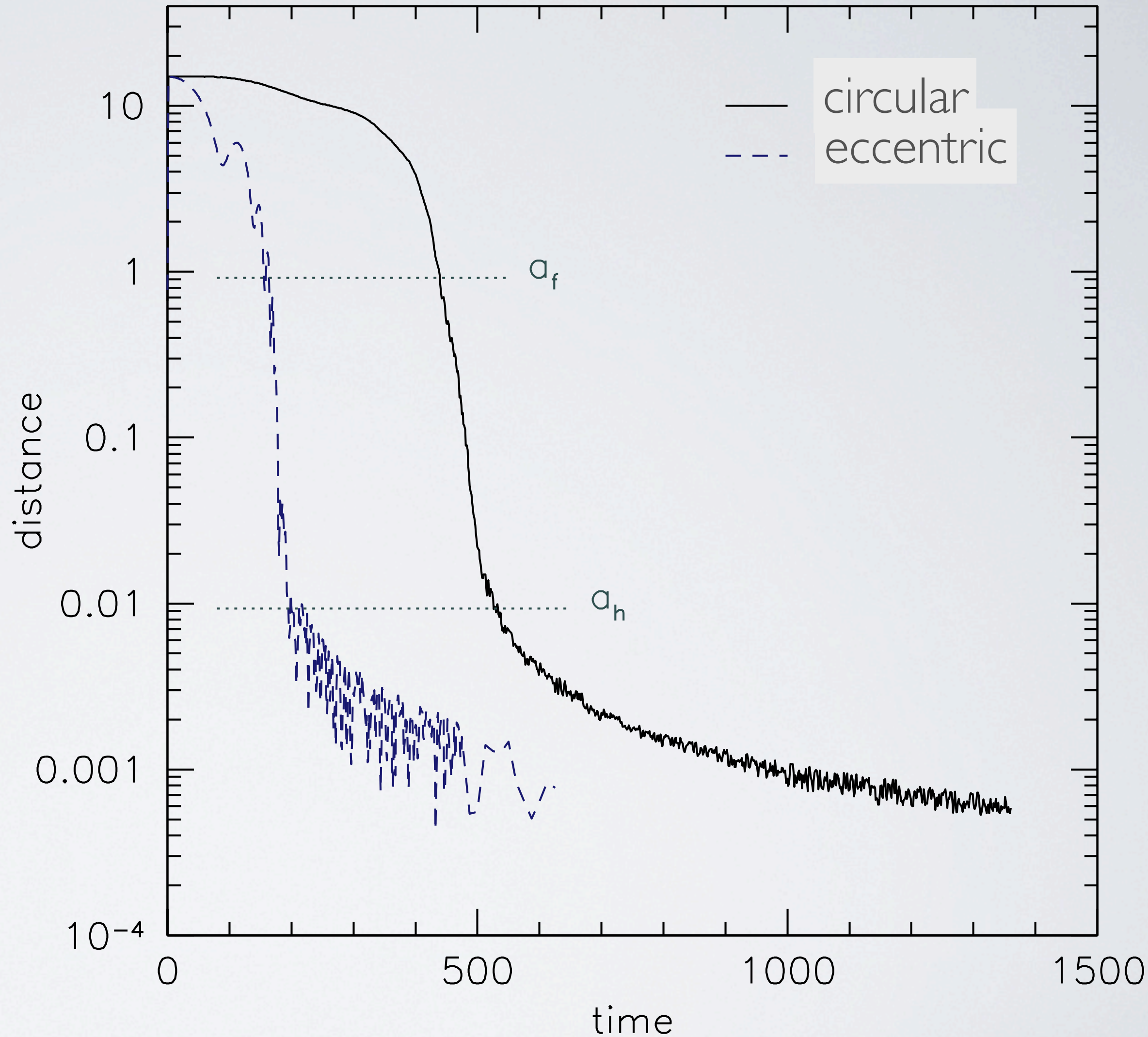
III. Post-Binary Evolution in Rotating Nuclei



Gualandris & DM (2012)

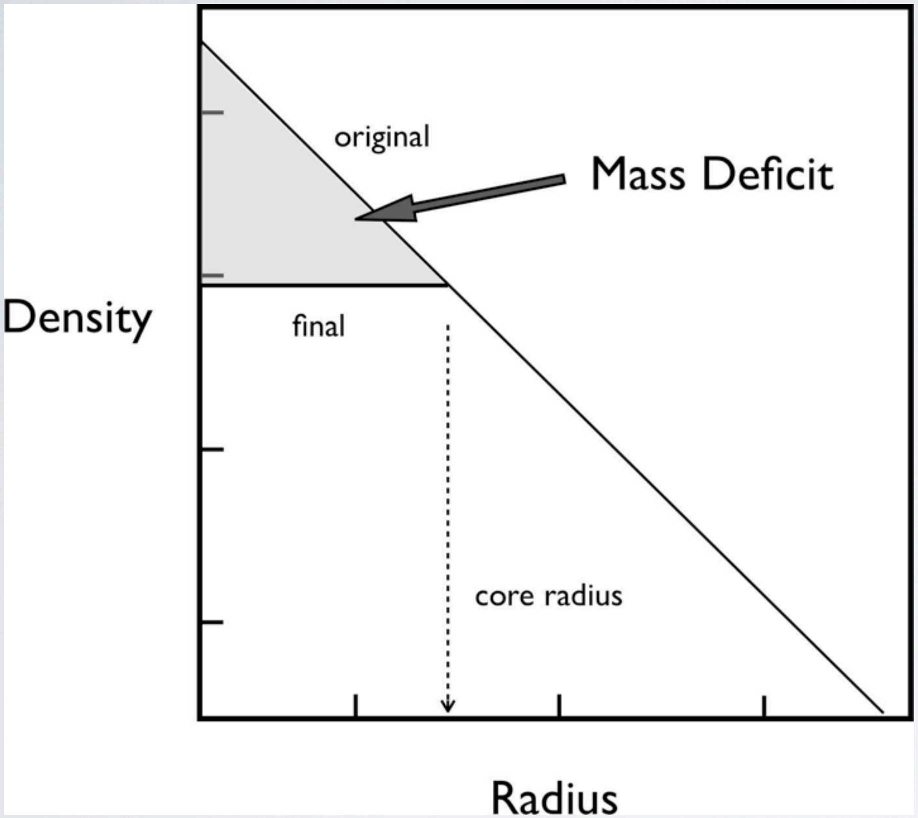
Separation Between SMBHs





Gualandris & DM (2012)

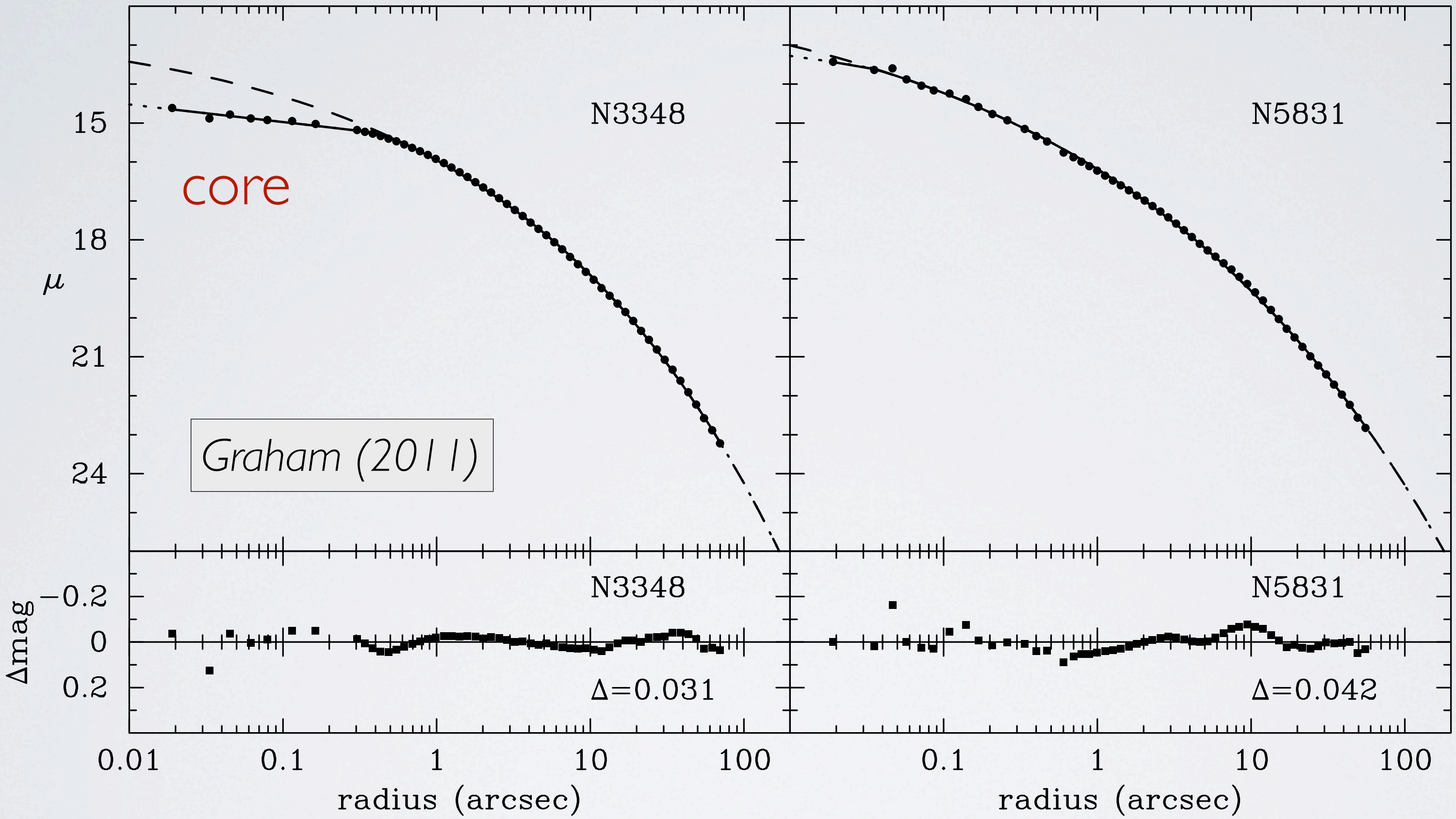
Mass Deficits



The **mass deficit** is defined as

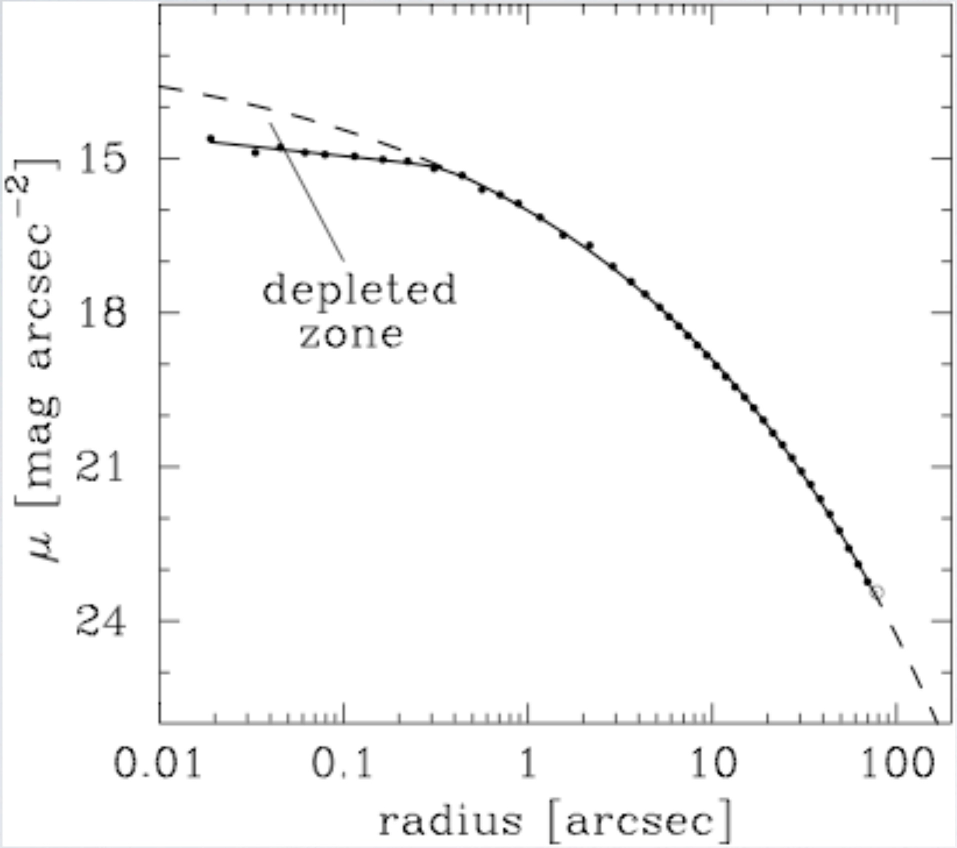
$$M_{\rm def} \equiv 4\pi \int_0^{r_{\rm max}} \left[\rho_{\rm init}(r) - \rho(r)\right] r^2 dr.$$

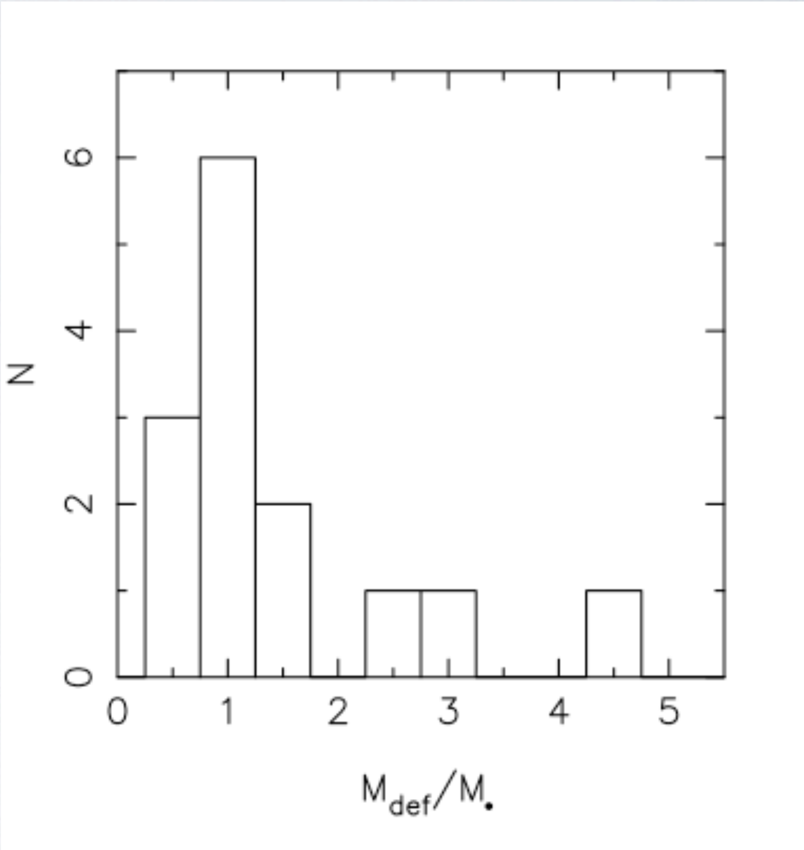
Nuclear Structure of Bright Galaxies



$M_{\rm gal} \gtrsim 10^{10}\ M_{\rm Sun}$ $M_{\rm gal} \lesssim 10^{10}\ M_{\rm Sun}$

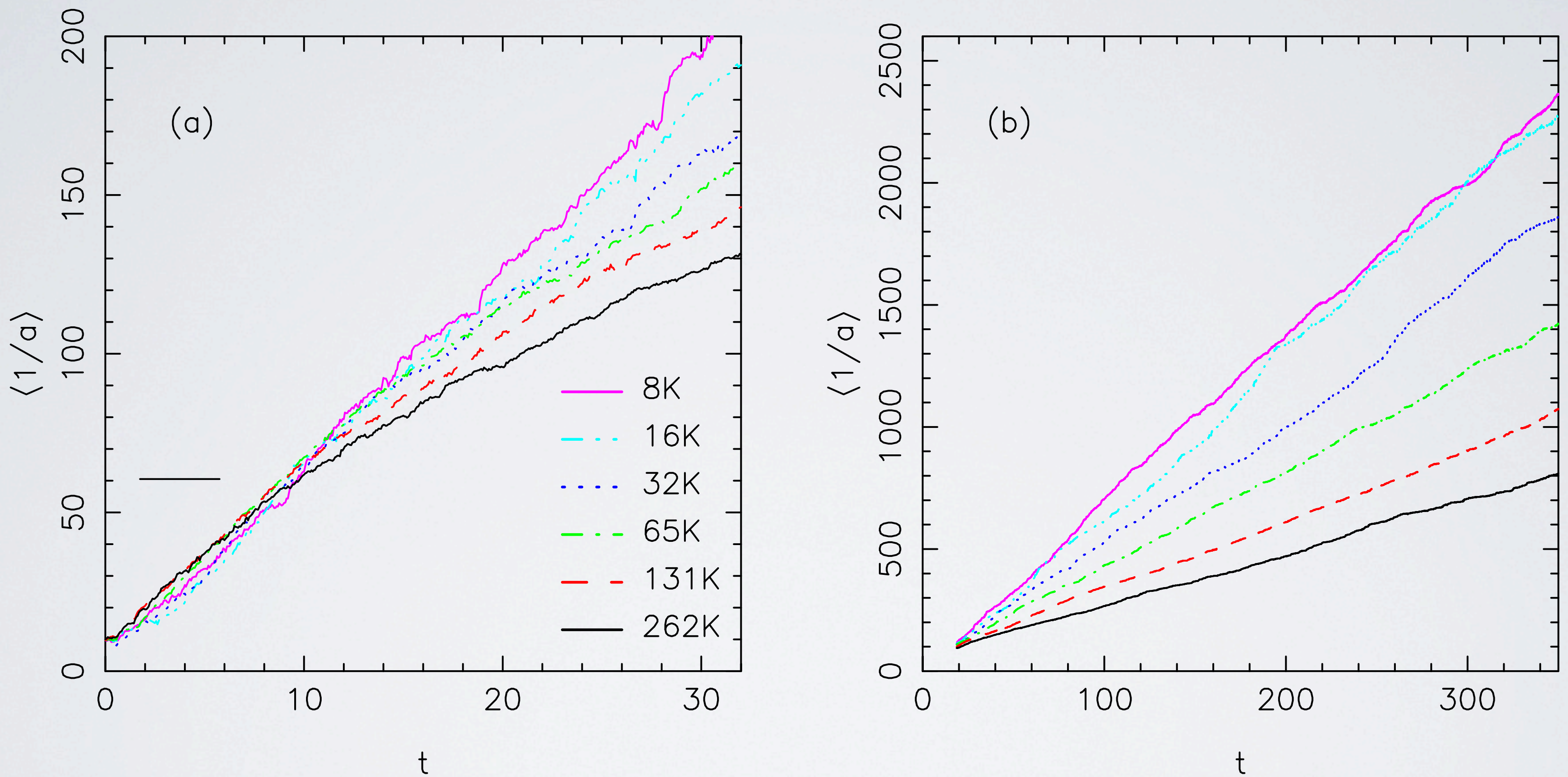
Observed Mass Deficits



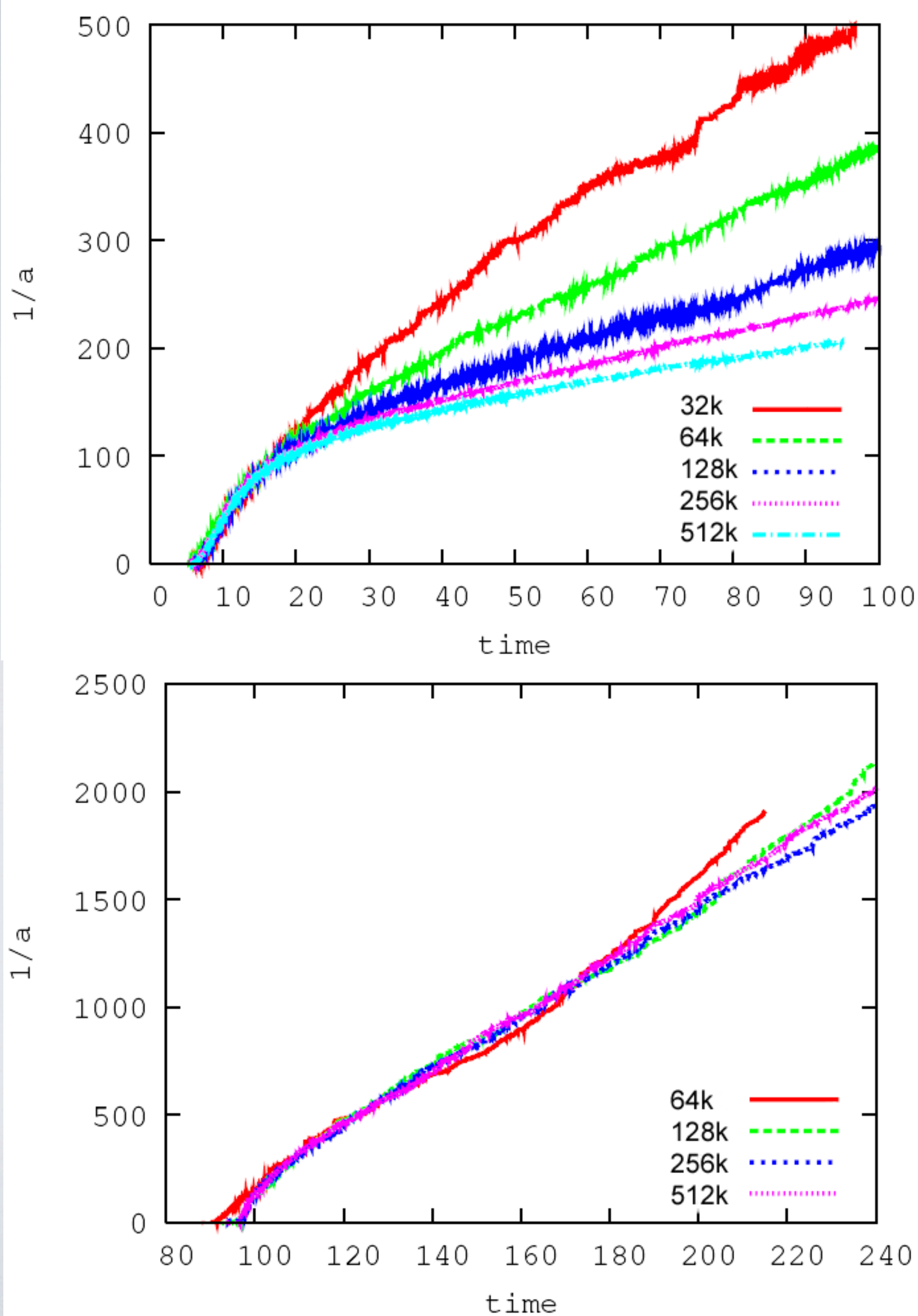


Graham (2004)

Stalling of the Binary in Spherical Galaxies



DM, Mikkola & Szell (2007)



Spherical galaxy: Stalling

Non-spherical galaxy: No stalling?

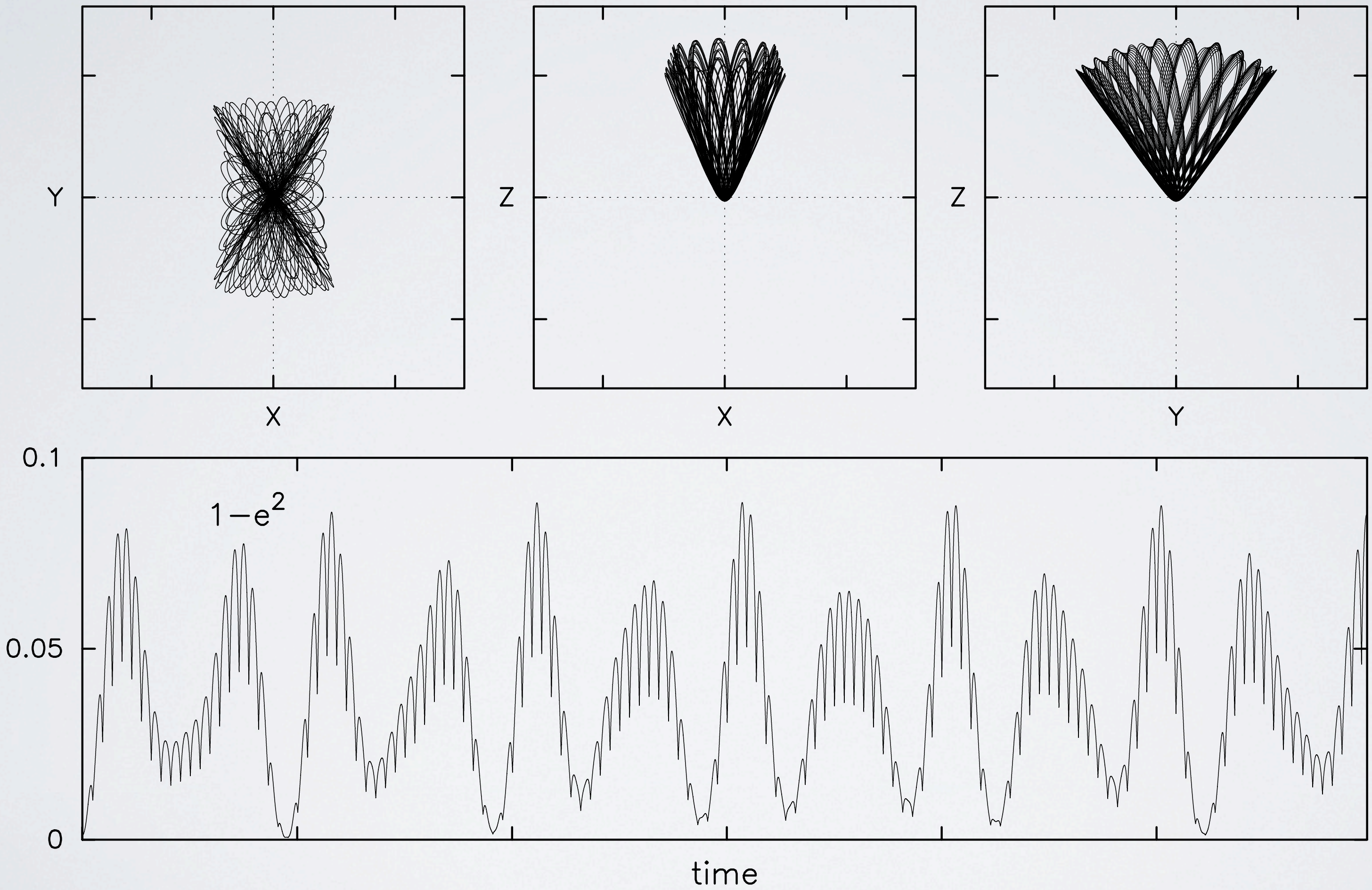
Khan et al. (2011)

Preto et al. (2011)

Possible Ways to Enhance the Hardening Rate

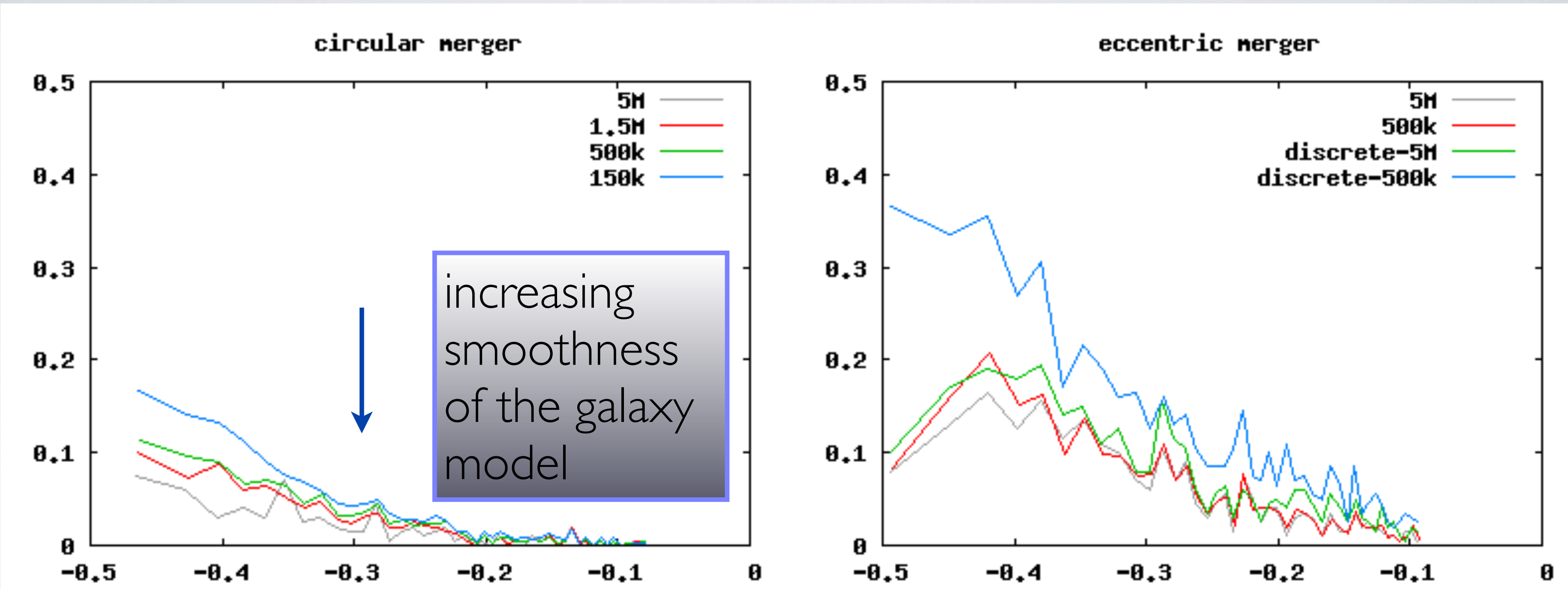
- Brownian motion of the binary (enables interaction with larger number of stars)
- Non-stationary solution for loss-cone repopulation
- Secondary slingshot (stars interact with binary several times)
- Gas physics
- Perturbations to the stellar distribution arising from transient events (infall of large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

“Pyramid” Orbits



Antonini, Vasiliev & DM (2013)

Centrophilic Orbits in the Merger Simulations?



∴ Not clear that efficient hardening of the binary is due to the presence of centrophilic orbits.

I. Final-Parsec Problem

II. Binary Evolution in Rotating Nuclei

III. Post-Binary Evolution in Rotating Nuclei

II. Binary Evolution in Rotating Nuclei

Evolution of a binary SMBH can be described in terms of dimensionless rate coefficients:

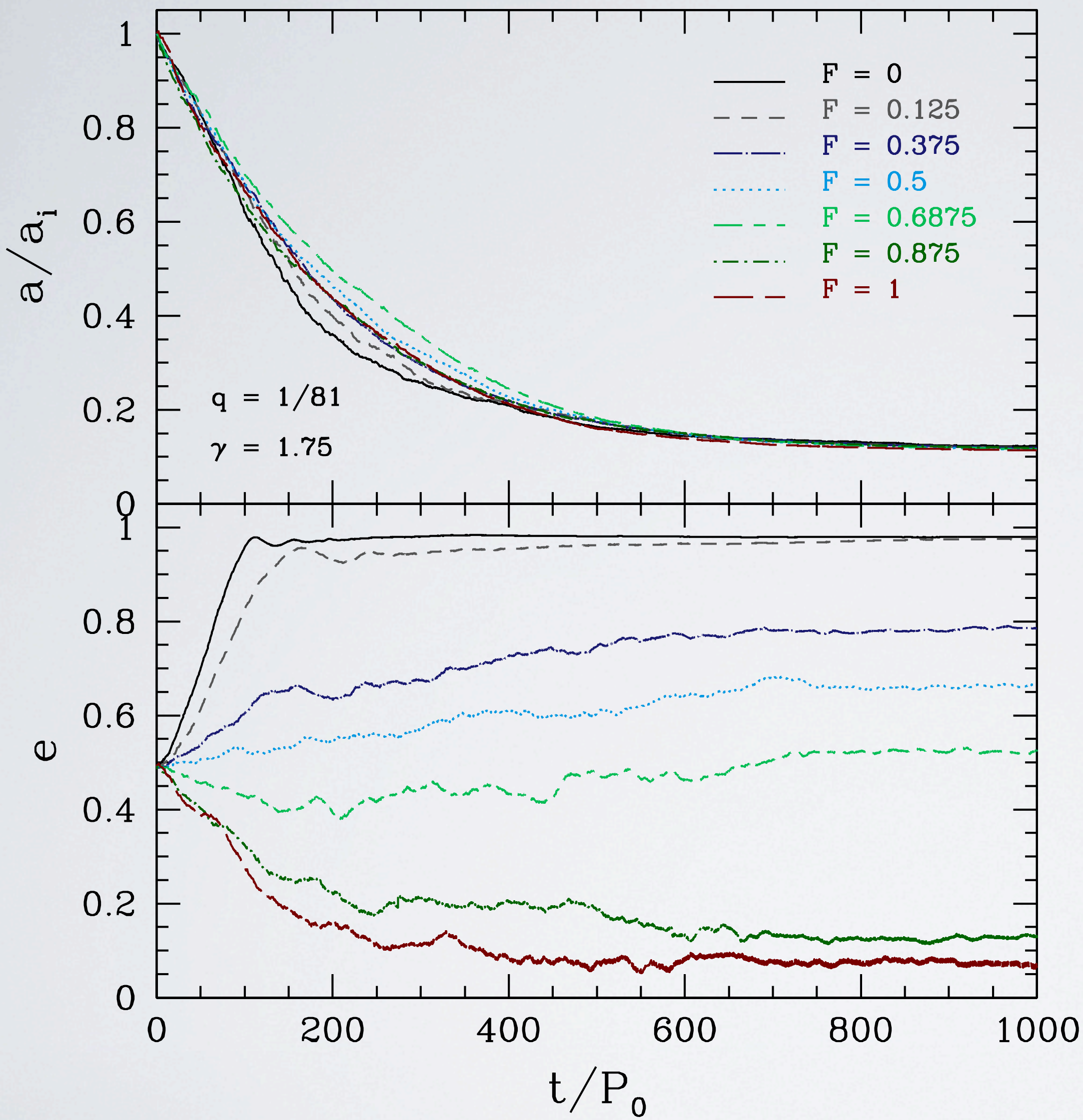
$$H \equiv \frac{\sigma}{G\rho}\frac{d}{dt}\left(\frac{1}{a}\right) \qquad \text{(energy)}$$

$$K \equiv \frac{de}{d\ln(1/a)} = \frac{\sigma}{G\rho a H}\frac{de}{dt} \qquad \text{(eccentricity)}$$

For a binary SMBH in an **isotropic** nucleus, K is small ($K \lesssim 0.15$) and positive (eccentricity increasing).

Quinlan (1996)

Mikkola & Valtonen (1992)



In a **rotating** nucleus, changes in the binary's eccentricity can be much larger.

counter-rotating nucleus

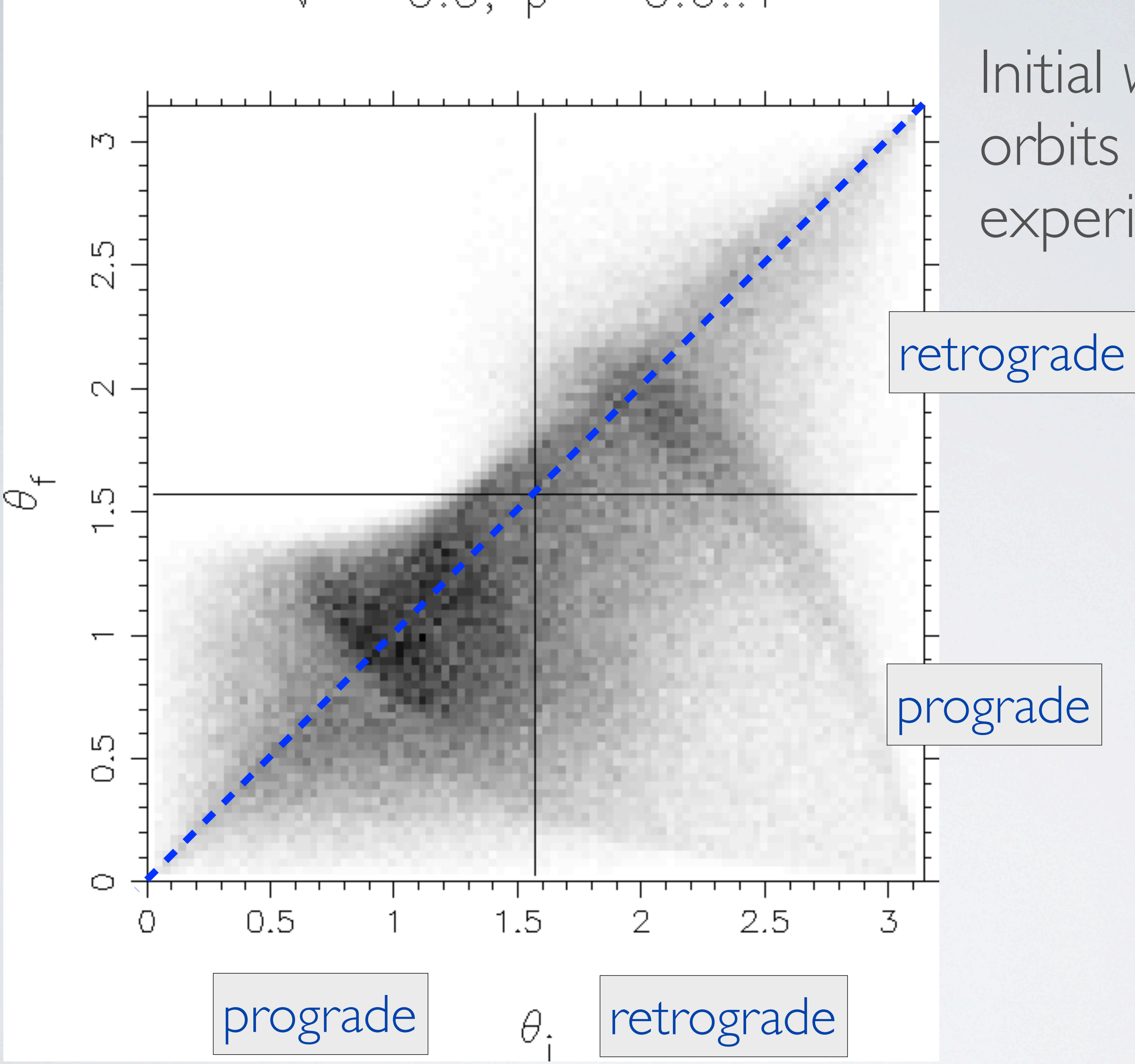
co-rotating nucleus

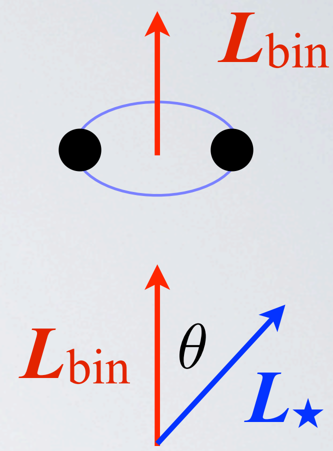
Sesana et al. (2011)

In a rotating nucleus, the number of **retrograde** and **prograde** encounters with the binary is different.

- Stars on **prograde** orbits interact strongly with the binary; stars on **retrograde** orbits avoid ejection during their initial encounter.
- If the binary is even mildy eccentric, the torque it exerts on a star can cause its orbit to "**flip**," from retrograde to prograde *(DM, Gulandris & Mikkola 2009)*.

Initial *vs* final stellar orbits in scattering experiments



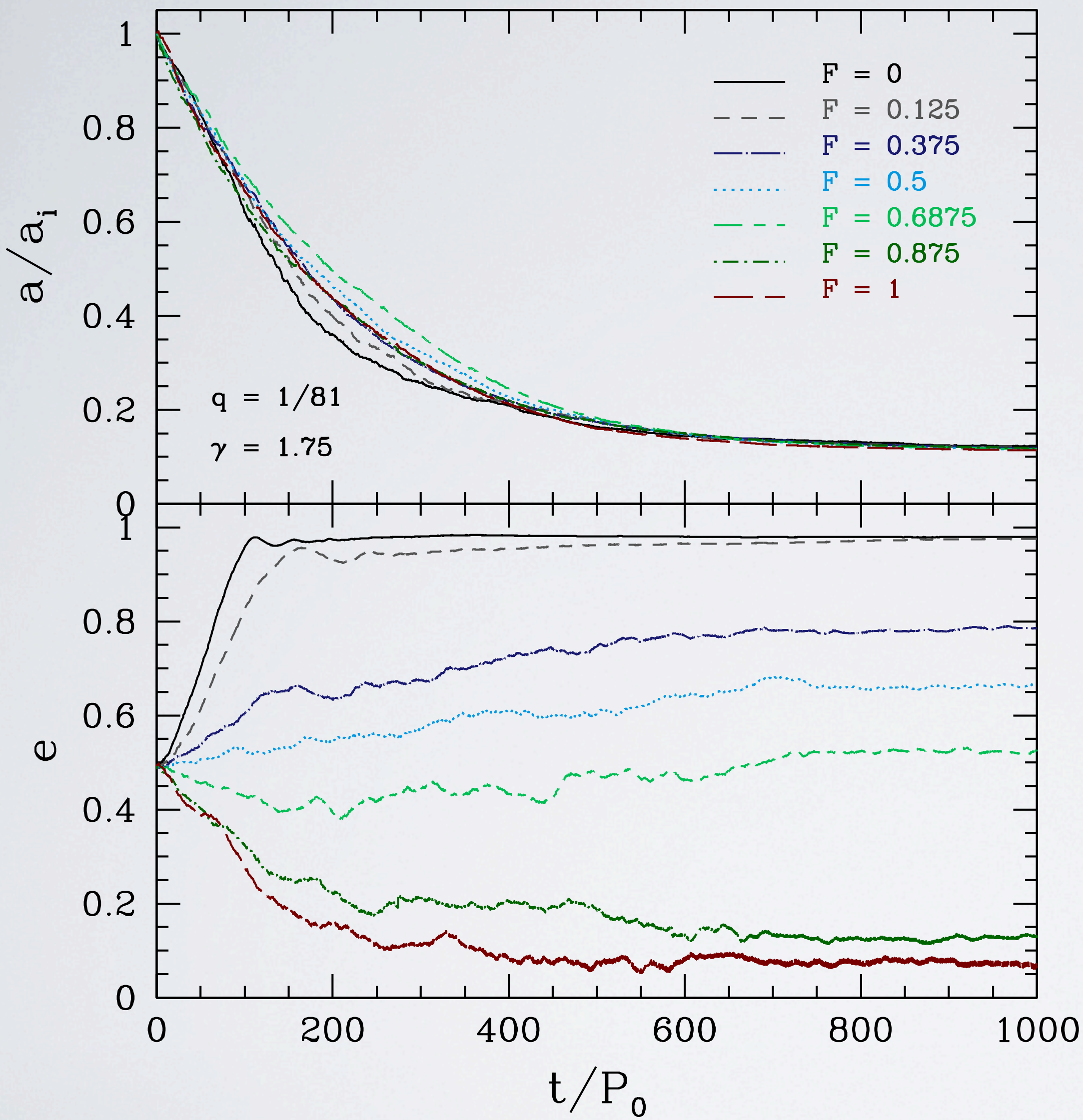


Rasskazov & DM (2012)

In a rotating nucleus, the number of **retrograde** and **prograde** encounters with the binary is different.

- Stars on **prograde** orbits interact strongly with the binary; stars on **retrograde** orbits avoid ejection during their initial encounter.
- If the binary is even mildy eccentric, the torque it exerts on a star can cause its orbit to "flip," from retrograde to prograde *(DM, Gulandris & Mikkola 2009)*.
- When such a star is finally ejected, it is likely to be on a prograde orbit; it has experienced a net *increase* in $\boldsymbol{L}$ that is in the same direction as the binary's $\boldsymbol{L}$.

$\boxed{\therefore\ \text{The binary's } L \textit{ decreases}\text{, i.e., its eccentricity increases.}}$



In a **rotating** nucleus, changes in the binary's eccentricity can be much larger.

counter-rotating nucleus

co-rotating nucleus

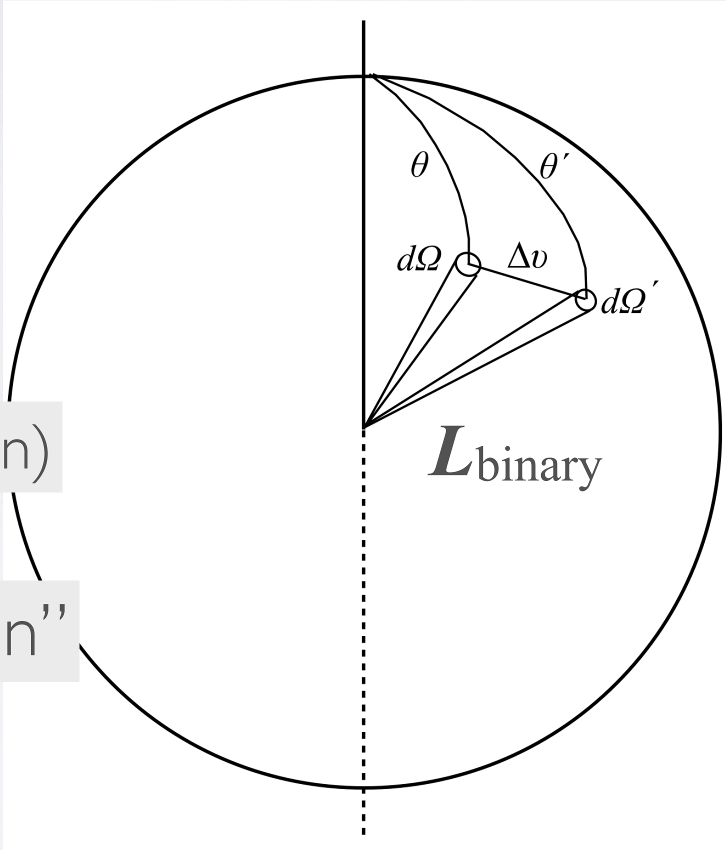
Sesana et al. (2011)

Angular momentum is a vector, and change of the binary's $\boldsymbol{L}$ implies changes also in its **orbital plane**.

Diffusion coefficients:

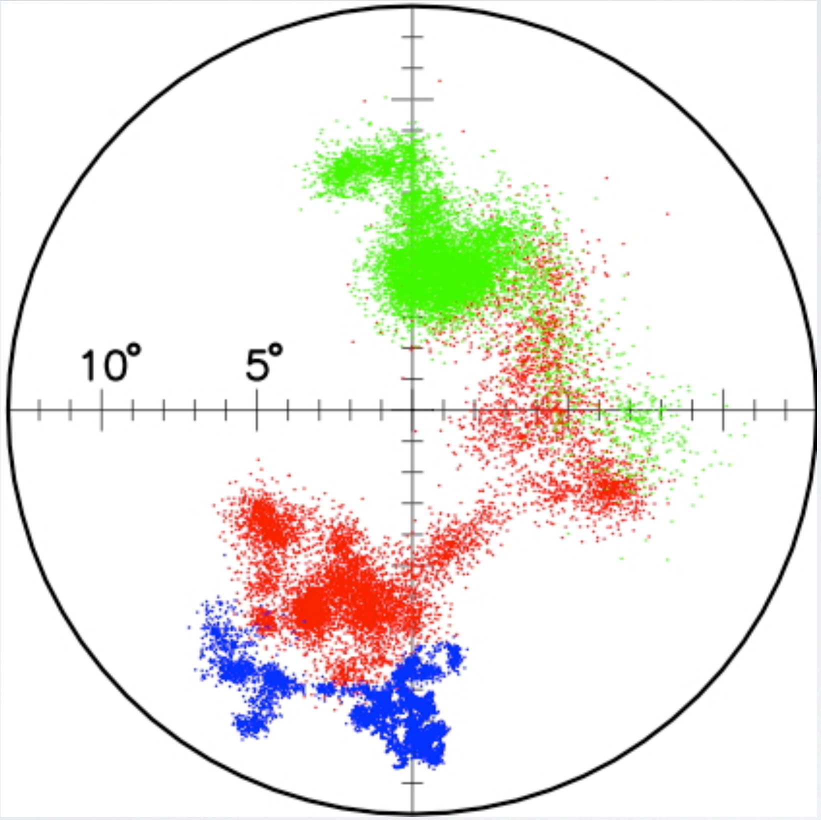
$$R_1 \equiv \frac{\sigma}{G\rho a}\langle \Delta\theta \rangle \qquad \text{(drift)}$$

$$R_2 \equiv \frac{M_{12}}{m_\star}\frac{\sigma}{G\rho a}\langle \Delta\vartheta^2 \rangle \quad \text{(diffusion)}$$



"Rotational Brownian motion"

Debye (1913, 1929)



- $M_{12}/m_\star = 164$
- $M_{12}/m_\star = 328$
- $M_{12}/m_\star = 655$

Milosavljevic & DM (2001)

Second-order rotational diffusion coefficient:

$$R_2 \equiv \frac{M_{12}}{m_\star}\frac{\sigma}{G\rho a}\langle\Delta\vartheta^2\rangle$$

$\approx$ 30-60 for "hard," equal-mass binaries

$$R_2 \propto q^{-1}(1-e^2)^{-1}$$

$$q \equiv M_2/M_1 \leq 1$$

DM (2002)

The **first-order** rotational diffusion coefficient:

$$R_1 \equiv \frac{\sigma}{G\rho a}\langle\Delta\theta\rangle$$

is zero, by symmetry, in a non-rotating nucleus.

But in a **rotating** nucleus, one expects the binary's $\boldsymbol{L}$ to align with that of the stars, at a rate that is independent of $m_\star/M_{12}$.

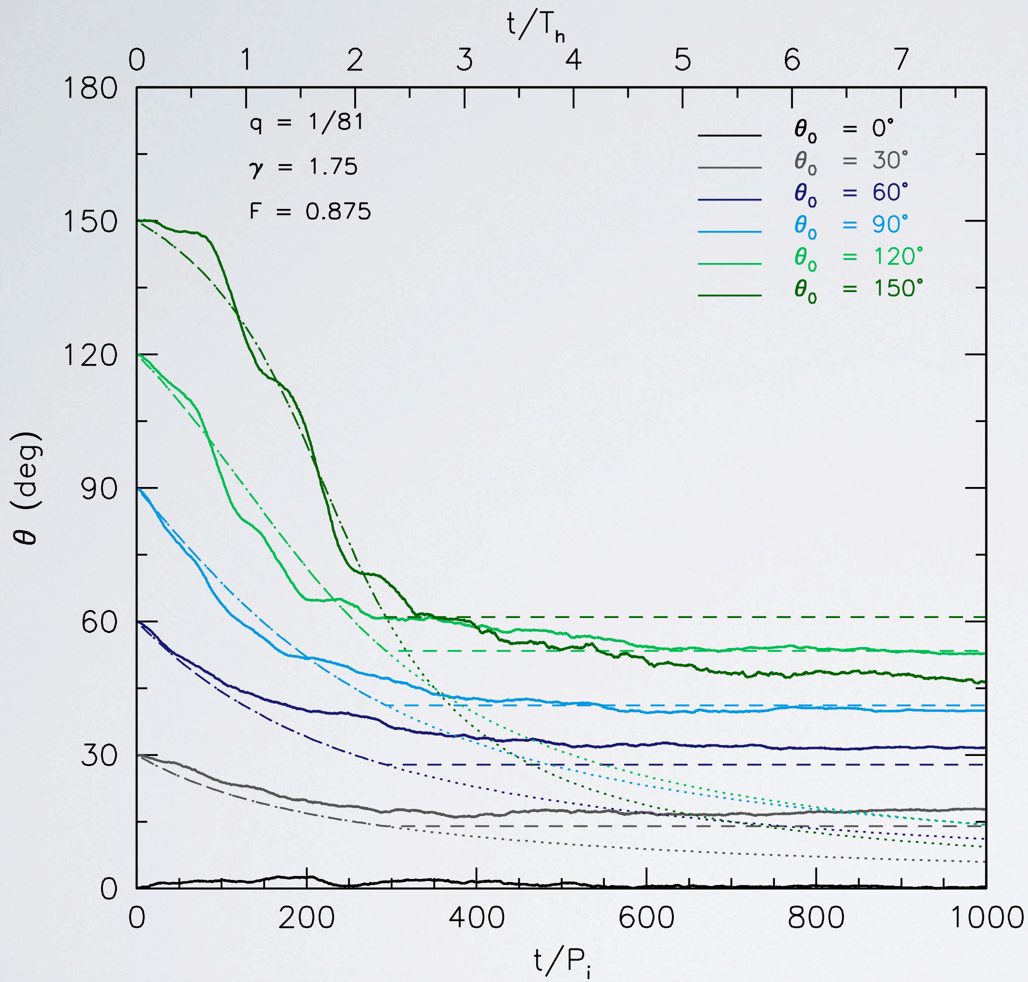
For instance, assume that stars are ejected from the binary in essentially random directions.

The average change in angular momentum of stars that impinge on the binary is then

$$\langle \Delta \boldsymbol{L}_\star \rangle = \langle \boldsymbol{L}_{\star,\mathrm{final}} - \boldsymbol{L}_{\star,\mathrm{initial}} \rangle$$

$$\approx -\langle \boldsymbol{L}_{\star,\mathrm{initial}} \rangle$$

Since the change in the binary's $\boldsymbol{L}$ is opposite in sign to $\langle \Delta \boldsymbol{L}_\star \rangle$, the binary's axis of rotation tends to align with that of the nucleus.



Gualandris et al. (2012)

Evolution of the angle θ between $\boldsymbol{L}_{\mathrm{binary}}$ and $\boldsymbol{L}_{\mathrm{cusp}}$.

$$R_1 \propto \sin\theta$$

I. Final-Parsec Problem

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III. Post-Binary Evolution in Rotating Nuclei

III. Post-Binary Evolution in Rotating Nuclei

Coalescence of two SMBHs results in a **spinning remnant**.

The spin, $\boldsymbol{S}$, can continue to evolve due to:

- Accretion of gas
- Capture of stars

} changes the magnitude, direction of $\boldsymbol{S}$

- Torquing by a gas disk
- **Torquing by stars**

} changes only the direction of $\boldsymbol{S}$

III. Post-Binary Evolution in Rotating Nuclei

Lense-Thirring torques cause orbital angular momenta, $\boldsymbol{L}_j$, to evolve as

$$\dot{\boldsymbol{L}}_j = \boldsymbol{\omega}_j \times \boldsymbol{L}_j, \quad \boldsymbol{\omega}_j = \frac{2G\boldsymbol{S}}{c^2 a_j^3 (1-e_j^2)^{3/2}}.$$

The same torques act back on the SMBH, causing its spin, $\boldsymbol{S}$, to evolve as

$$\dot{\boldsymbol{S}} = \boldsymbol{\omega}_S \times \boldsymbol{S}, \quad \boldsymbol{\omega}_S = \frac{2G}{c^2} \sum_j \frac{\boldsymbol{L}_j}{a_j^3 \left(1-e_j^2\right)^{3/2}}$$

III. Post-Binary Evolution in Rotating Nuclei

$$\dot{\boldsymbol{S}} = \boldsymbol{\omega}_S \times \boldsymbol{S}, \qquad \boldsymbol{\omega}_S = \frac{2G}{c^2}\sum_j \frac{\boldsymbol{L}_j}{a_j^3\left(1-e_j^2\right)^{3/2}}$$

$$\dot{\boldsymbol{L}}_j = \boldsymbol{\omega}_j \times \boldsymbol{L}_j, \qquad \boldsymbol{\omega}_j = \frac{2G\boldsymbol{S}}{c^2 a_j^3 (1-e_j^2)^{3/2}}.$$

Conserved quantities:

$$\boldsymbol{J} = \boldsymbol{S} + \sum_j \boldsymbol{L}_j \equiv \boldsymbol{S} + \boldsymbol{L}_{\rm tot}$$

$$|\boldsymbol{S}| \equiv S$$

$$|\boldsymbol{L}_j| \equiv L_j, \;\; j = 1, \ldots, N$$

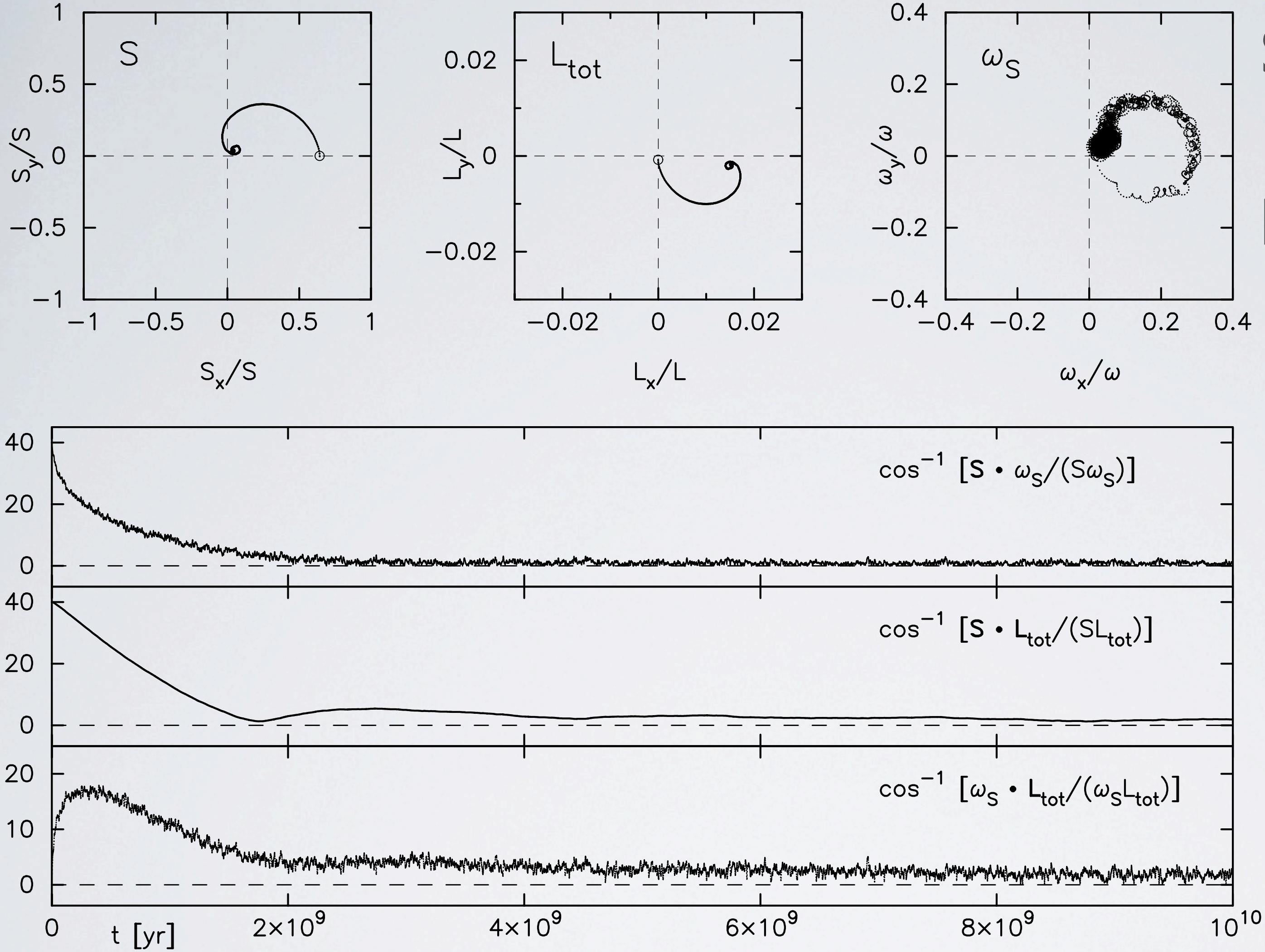
Not conserved:

$$\boldsymbol{L}_{\rm tot}, \boldsymbol{S}$$

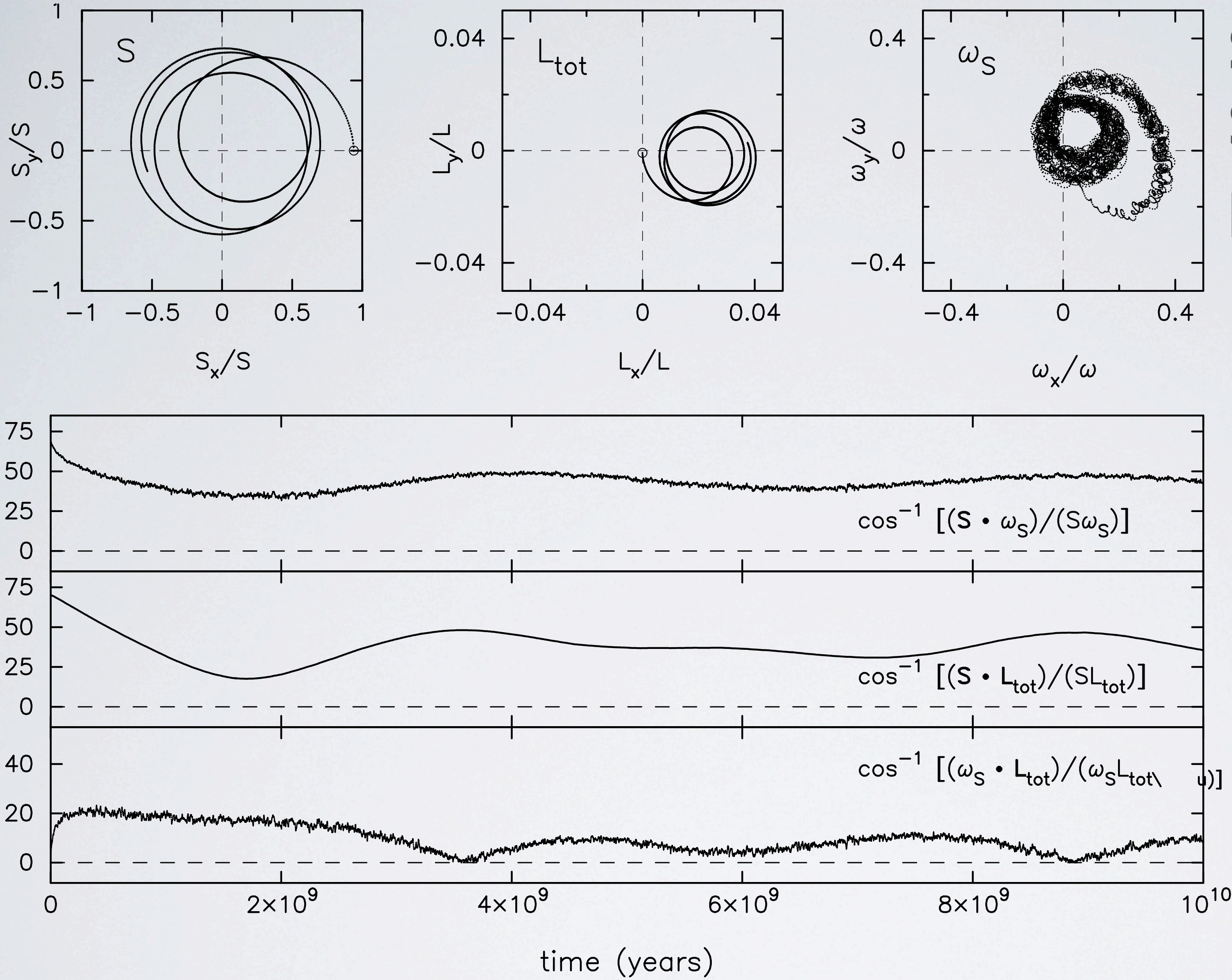
$$\boldsymbol{\omega}_S$$

DM & Vasiliev (2012)

Spin evolution I. Damped precession



Spin evolution II. Sustained precession



III. Post-Binary Evolution in Rotating Nuclei

There is a radius around the SMBH beyond which changes in the $\boldsymbol{L}_j$ are dominated by **star-star**, rather than spin-orbit, torques.

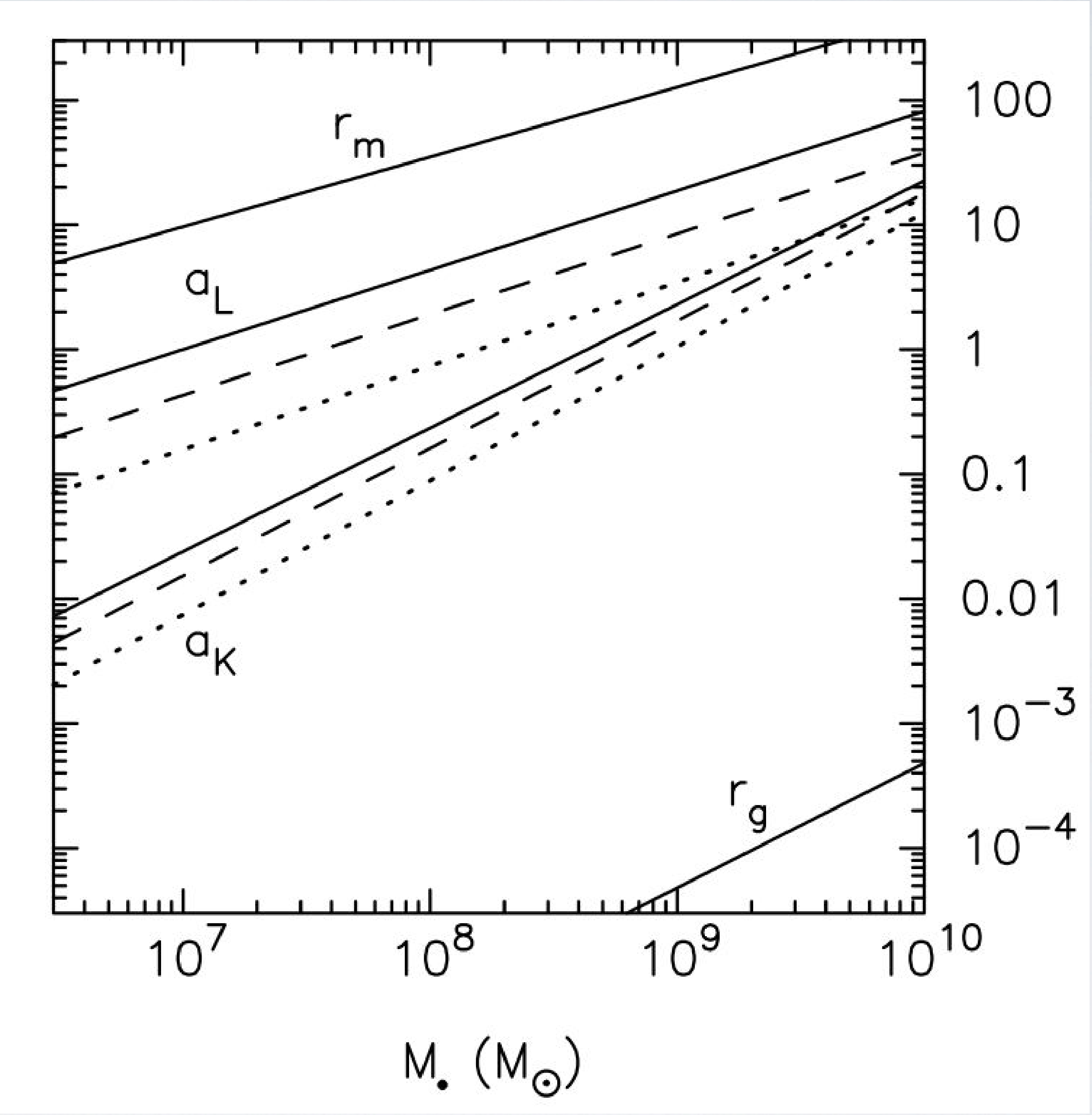
The "**radius of rotational influence,**" a_{K}, of a SMBH is defined by

$$(1-e^2)^3\left(\frac{a_K}{r_g}\right)^3 < \frac{16\chi^2}{N(a)}\left(\frac{M_\bullet}{m_\star}\right)^2 \qquad r_g \equiv \frac{GM_\bullet}{c^2}.$$

Beyond this radius, the stellar $\boldsymbol{L}_j$ evolve stochastically, on the "resonant relaxation" timescale.

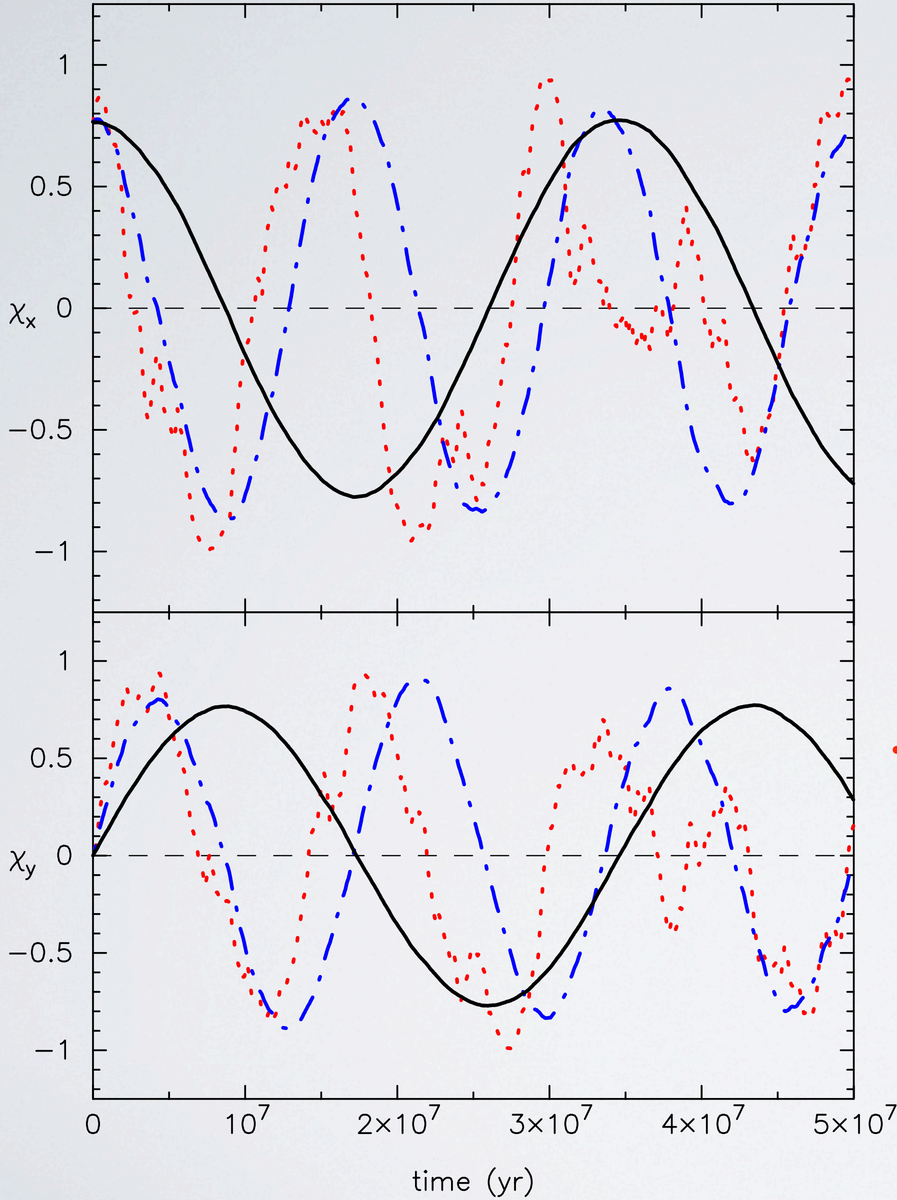
DM & Vasiliev (2012)

Radii associated with SMBH spin



Radius (pc)

DM & Vasiliev (2012)



Response of $\boldsymbol{\chi} \equiv \boldsymbol{S}/(GM_\bullet/c^2)$ to torquing by stars, some of which lie outside the radius of rotational influence.

$m_\star = 0.1\ M_\odot$

$m_\star = 1.0\ M_\odot$

$m_\star = 10.\ M_\odot$

DM & Vasiliev (2012)

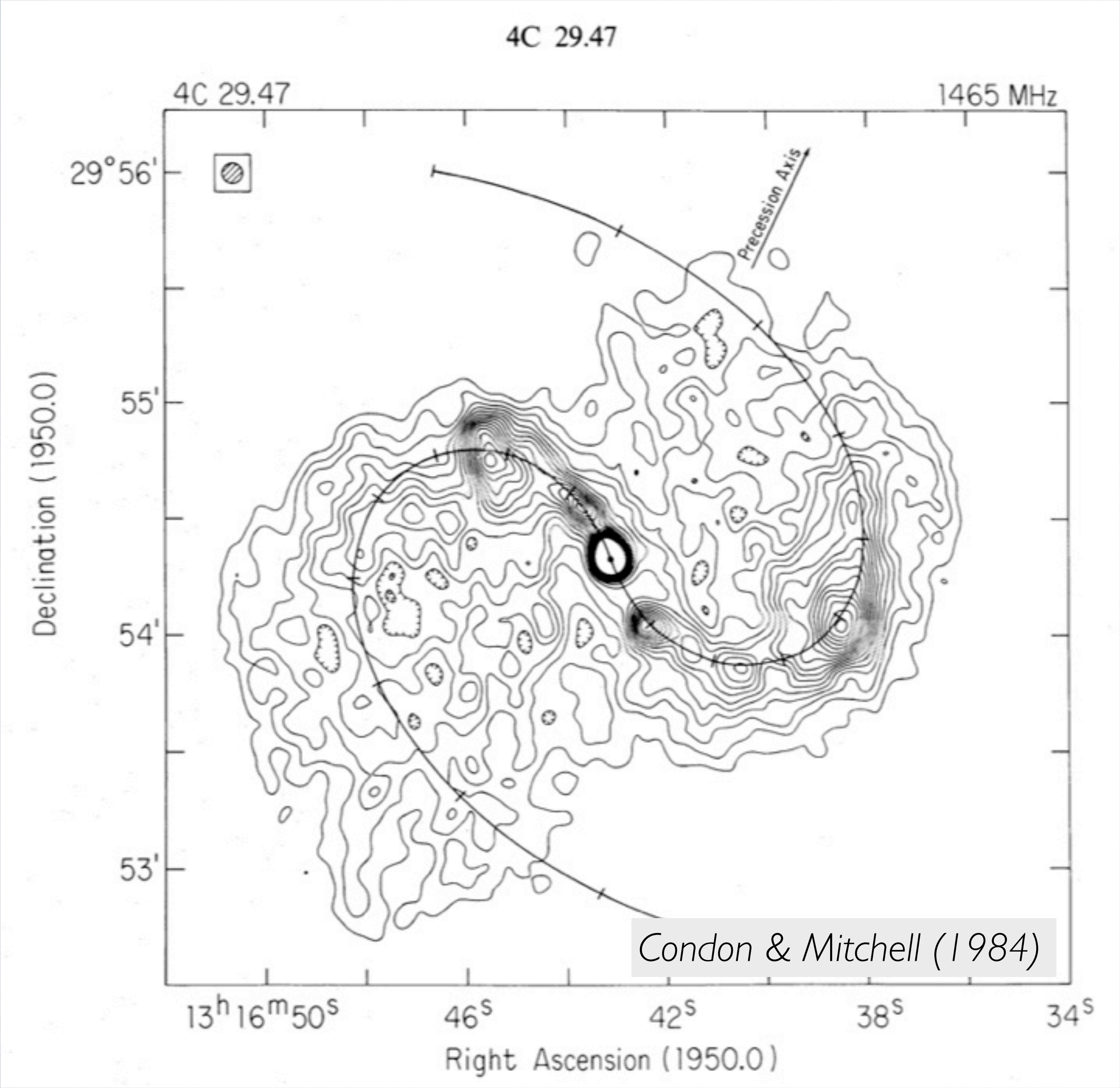
Accretion disk

- Dissipative
- Gas near SMBH in thin disk
- Torque determined by gas at ~warp radius*
- $\boldsymbol{S}$ aligns with $\boldsymbol{L}_{\mathrm{gas}}$

Stars

- Dissipationless
- Stars near SMBH can have any distribution
- Torque determined by stars at ~rotational influence radius*
- $\boldsymbol{S}$ may, or may not, align with $\boldsymbol{L}_{\mathrm{stars}}$

*after matter near the SMBH has aligned with it



S-shaped radio source