Dynamical Evolution of a Supermassive Binary in a Rotating Nucleus

Alexander Rasskazov & David Merritt, Rochester Institute of Technology

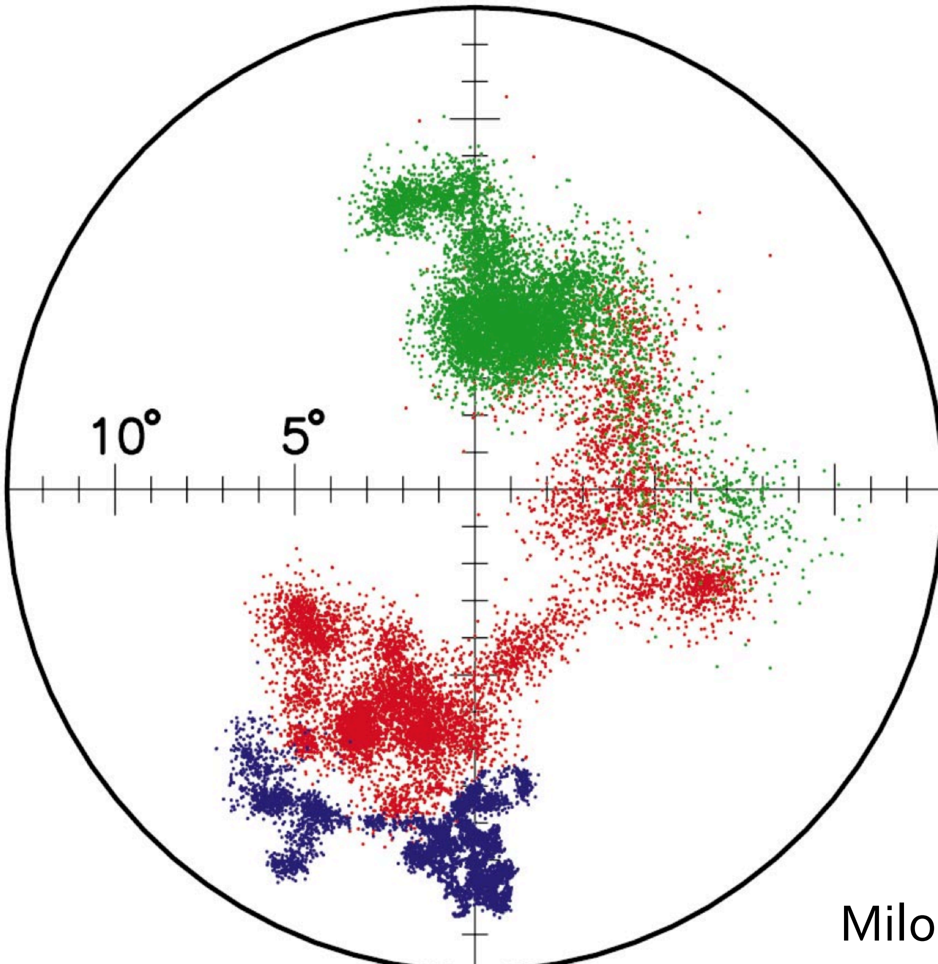
Supermassive binary's evolution

1) Unbound SMBHs, energy loss due to dynamical friction
2) Bound SMBHs, energy loss due to 3-body interactions with stars
3) Very close SMBHs, energy loss due to GW emission
4) Coalescence

(Begelman et al. 1980)

Reorientation in a Non-rotating Nucleus

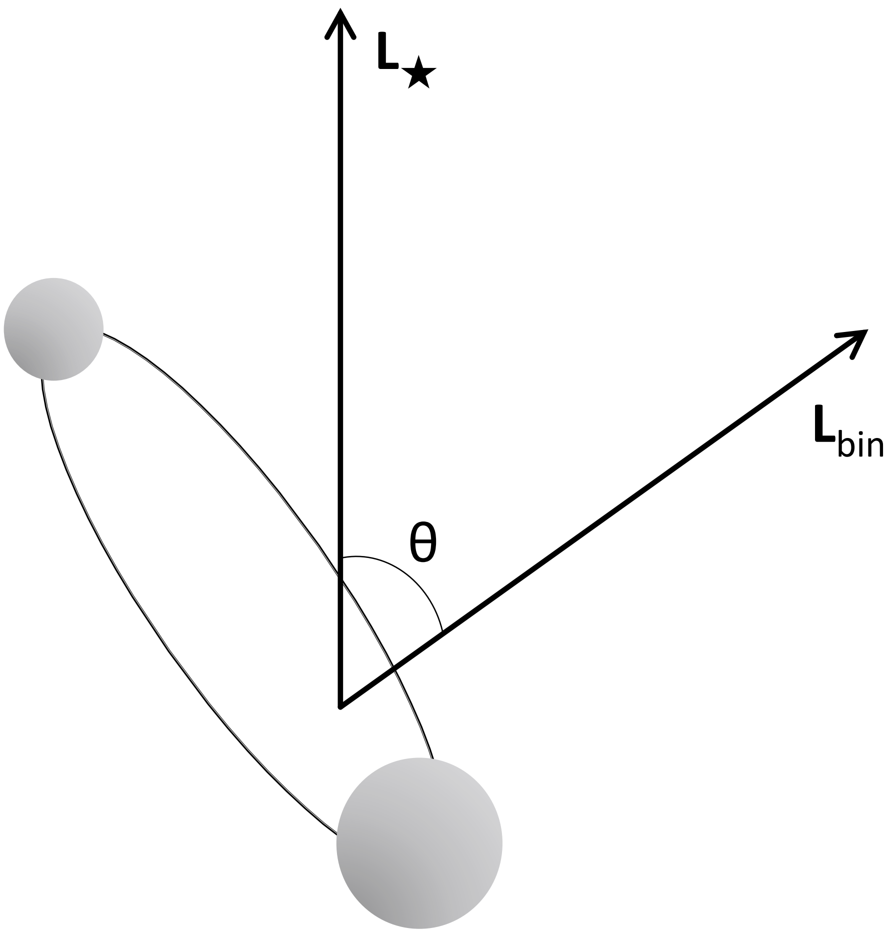
- Small (<1°) diffusion in random direction

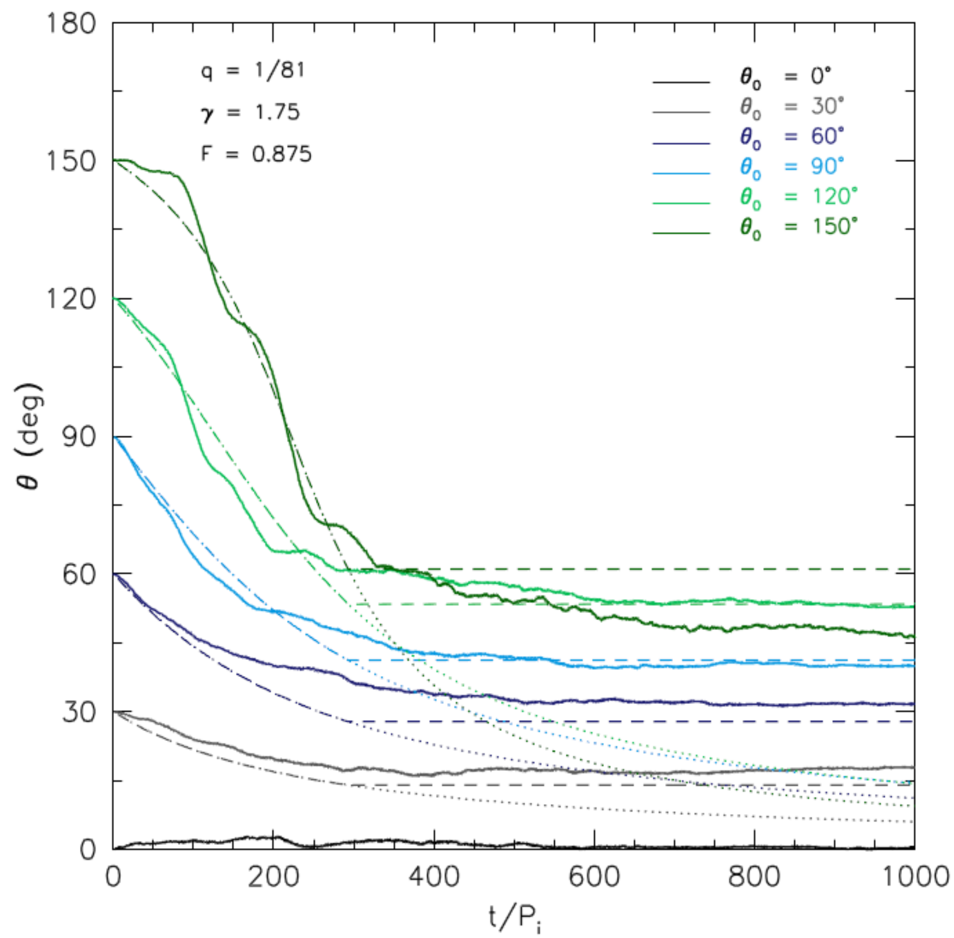


Milosavljevic & Merritt (2001)

Reorientation in a Rotating Nucleus

- A much stronger drift in a certain direction





Gualandris et al. (2012)

Fokker-Planck Equation

$$\frac{\partial F}{\partial t} = \frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left[\sin\theta\left(\frac{\langle\Delta\theta^2\rangle}{2}\frac{\partial F}{\partial\theta} - \langle\Delta\theta\rangle F\right)\right]$$

$F(\theta,t) -$ probability density distribution in θ

$\langle\Delta\theta^2\rangle \sim (\Delta\theta)^2/\Delta t -$ "Random walks", "Diffusion"

$\langle\Delta\theta\rangle \sim \Delta\theta/\Delta t -$ "Drift", "Friction"

Debye (1929)

Scattering Experiments

$$\langle \Delta\theta \rangle, \left\langle \Delta\theta^2 \right\rangle = \text{average of } \delta\theta,\ \delta\theta^2 \text{ over all interactions}$$

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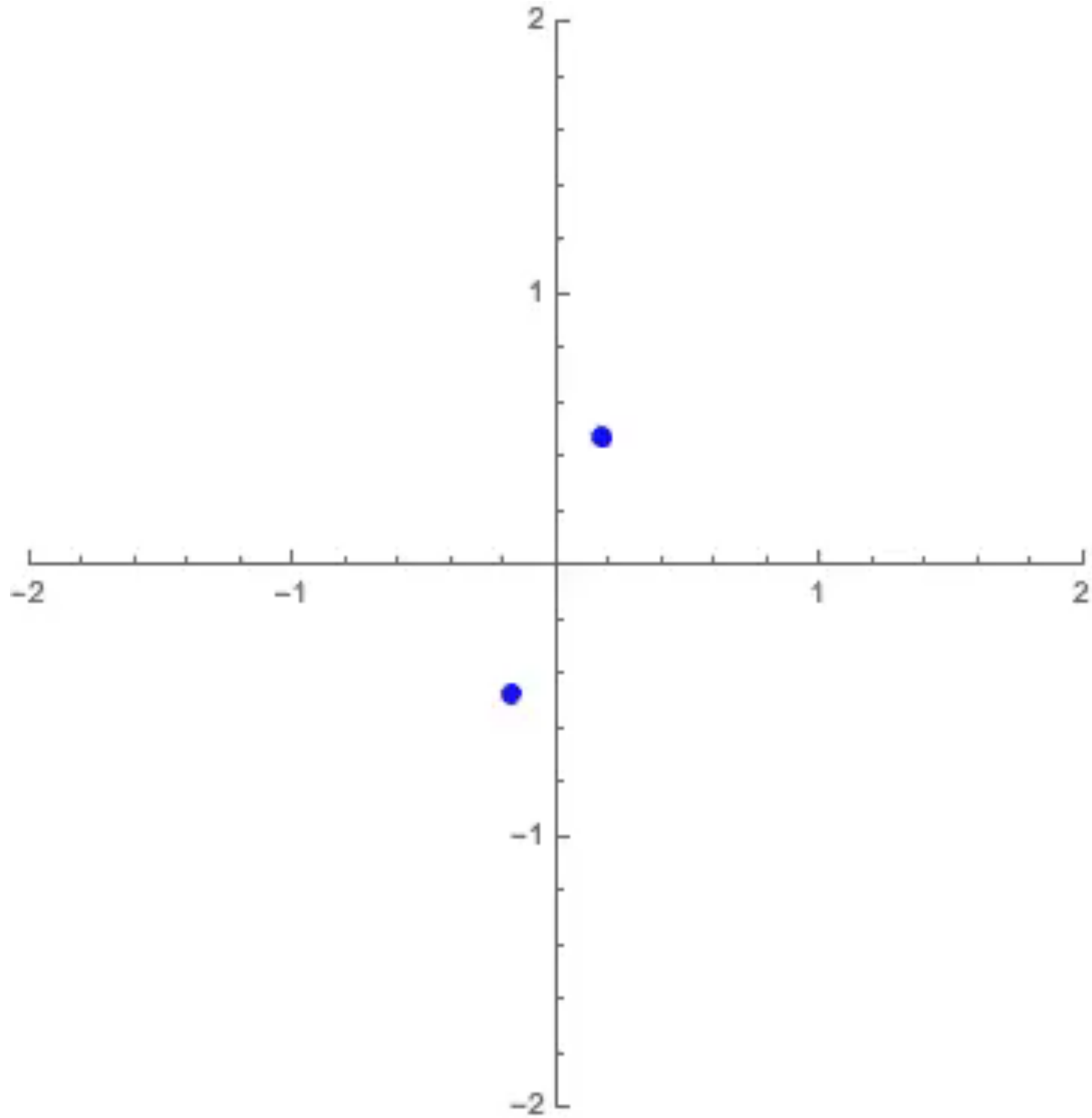
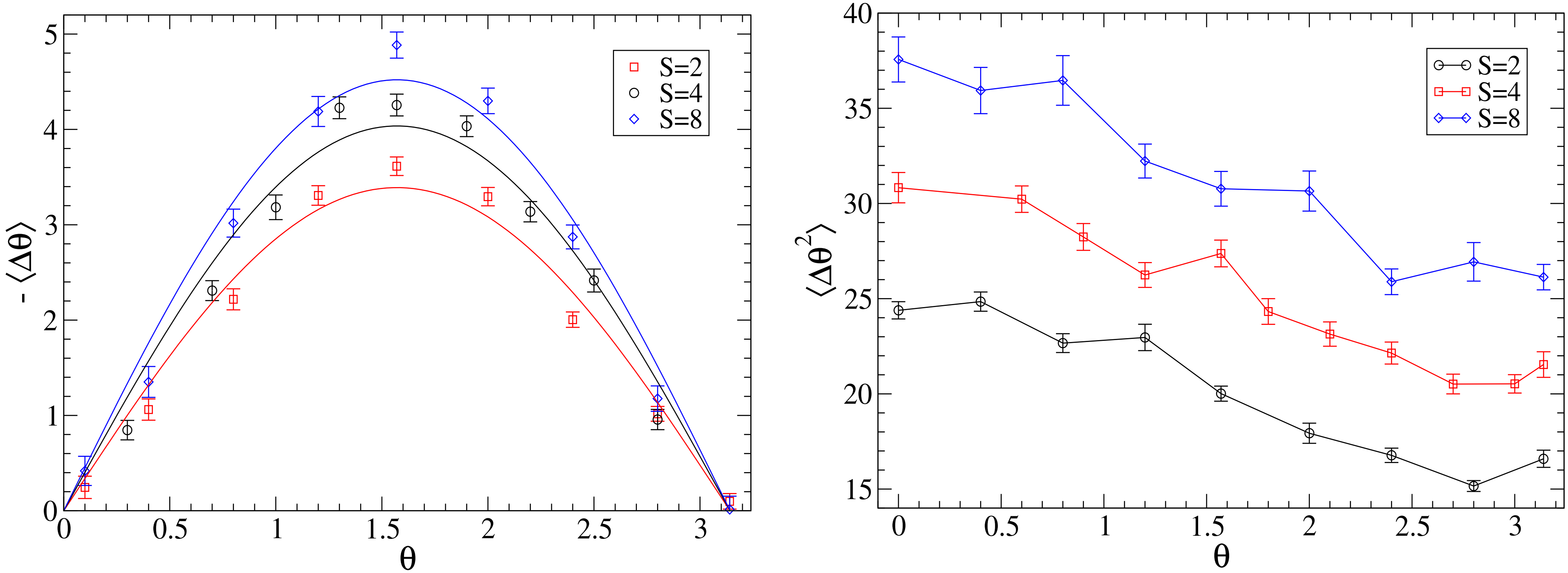
$$\langle \Delta\theta^2 \rangle \sim \langle \Delta\theta \rangle \frac{m}{M_1 + M_2} \ll \langle \Delta\theta \rangle$$

- First-order effects are usually much more important

Example of a 3-body interaction

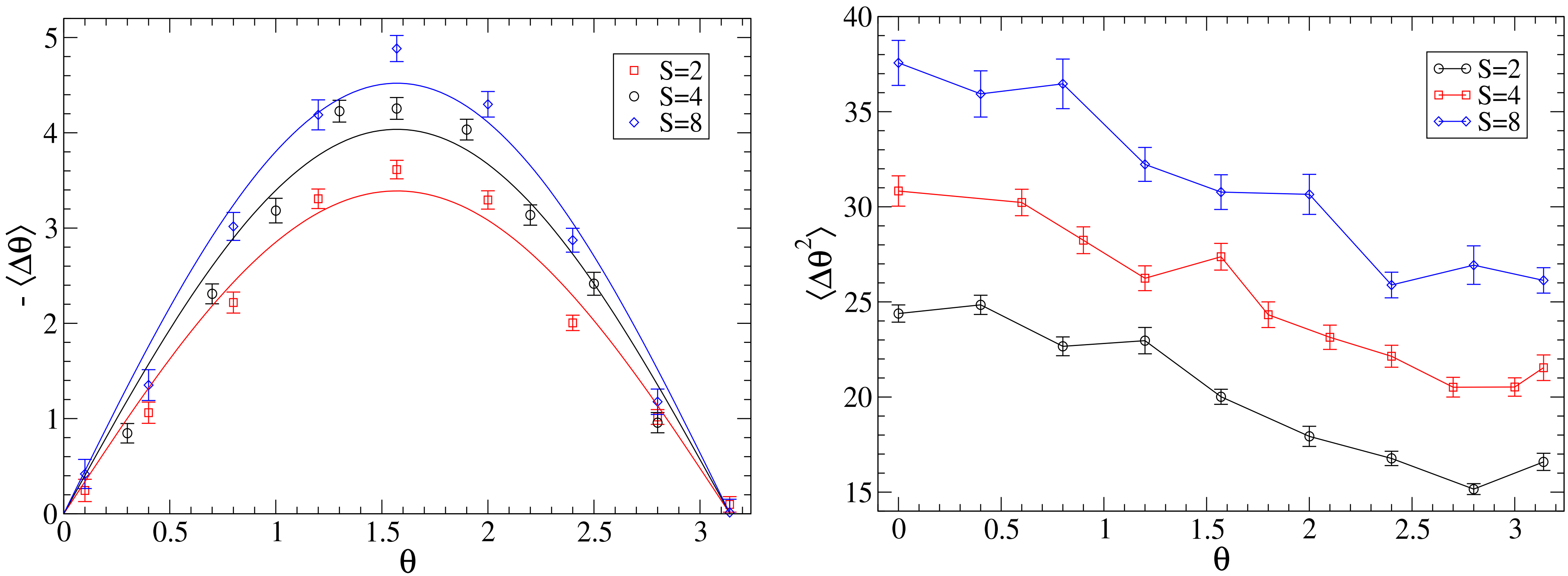


Diffusion coefficients: θ



$$\left(S \equiv \frac{V_{\mathrm{bin}}}{\sigma} = \frac{1}{\sigma}\sqrt{\frac{GM_{12}}{a}} \right)$$

Diffusion coefficients: θ

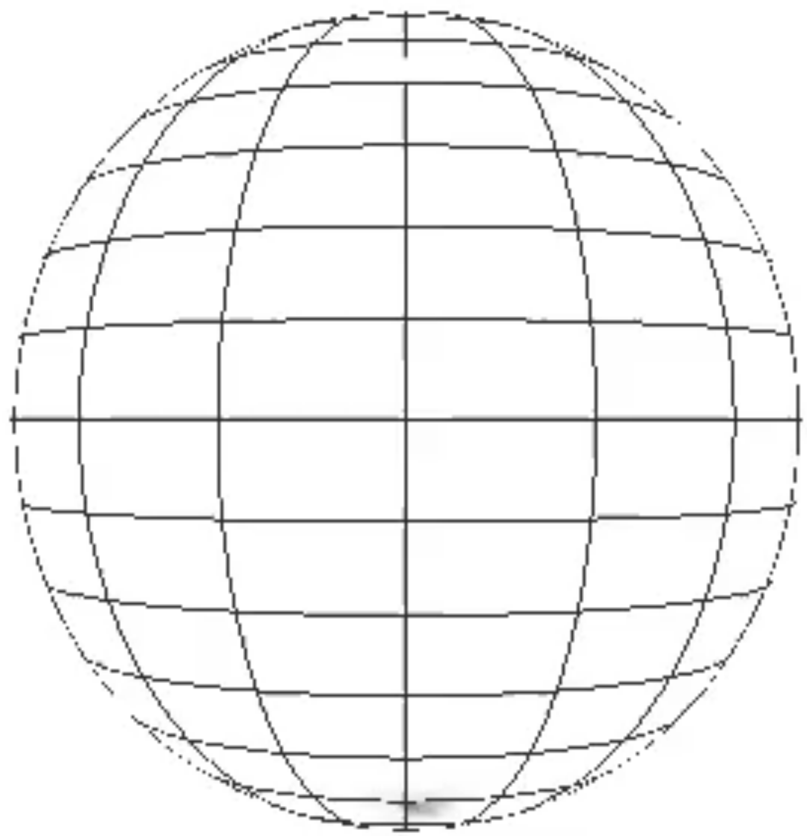


$$\left(S \equiv \frac{V_{\mathrm{bin}}}{\sigma} = \frac{1}{\sigma}\sqrt{\frac{GM_{12}}{a}} \right)$$

$$\left\langle \Delta\theta^2 \right\rangle \approx \mathrm{const}, \quad \left\langle \Delta\theta \right\rangle \sim -\sin\theta$$

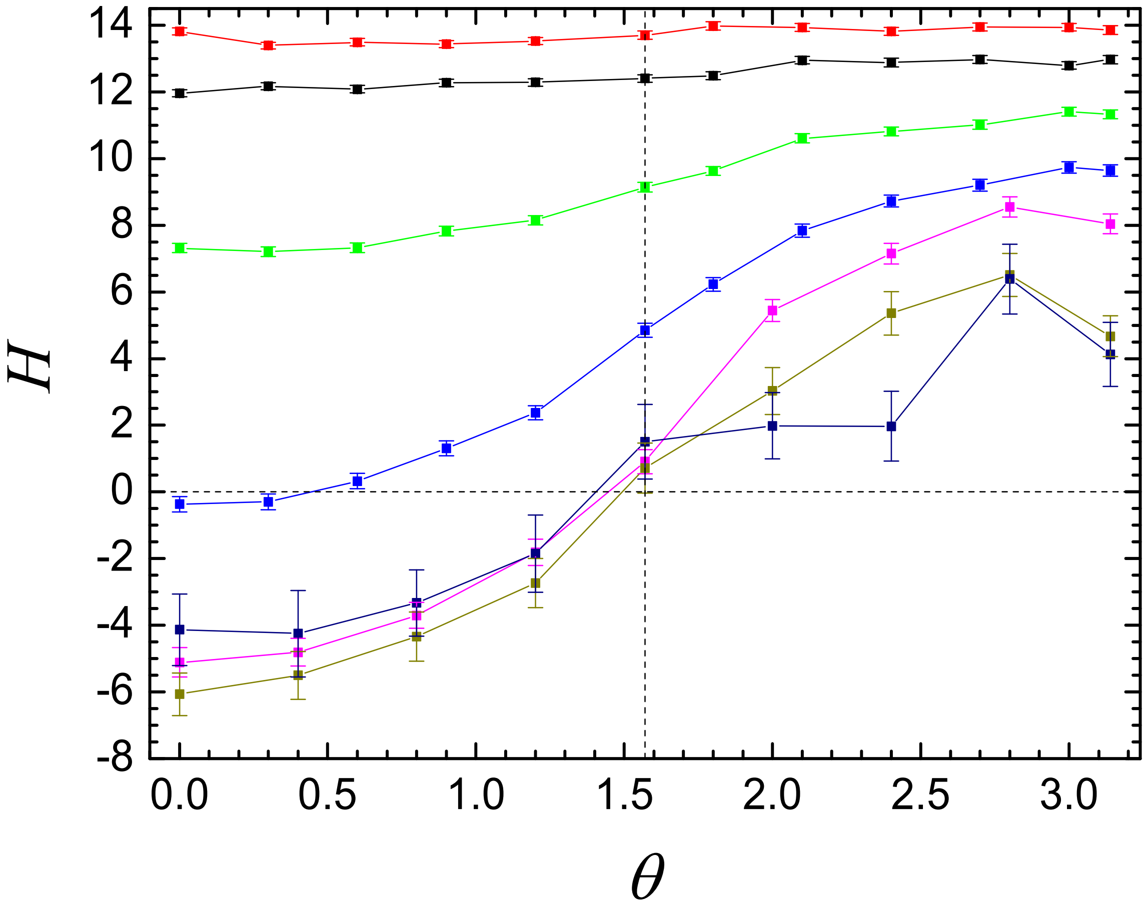
Orbital orientation evolution

- Diffusion in θ ≈ diffusion in ϕ
- Drift in θ is negative (towards co-rotation)
- No drift in ϕ



Diffusion coefficients: *a*

- No difference from non-rotating case (for binaries hard enough)



$$H \equiv \frac{\sigma}{G\rho} \frac{-\langle \Delta a \rangle}{a^2}$$

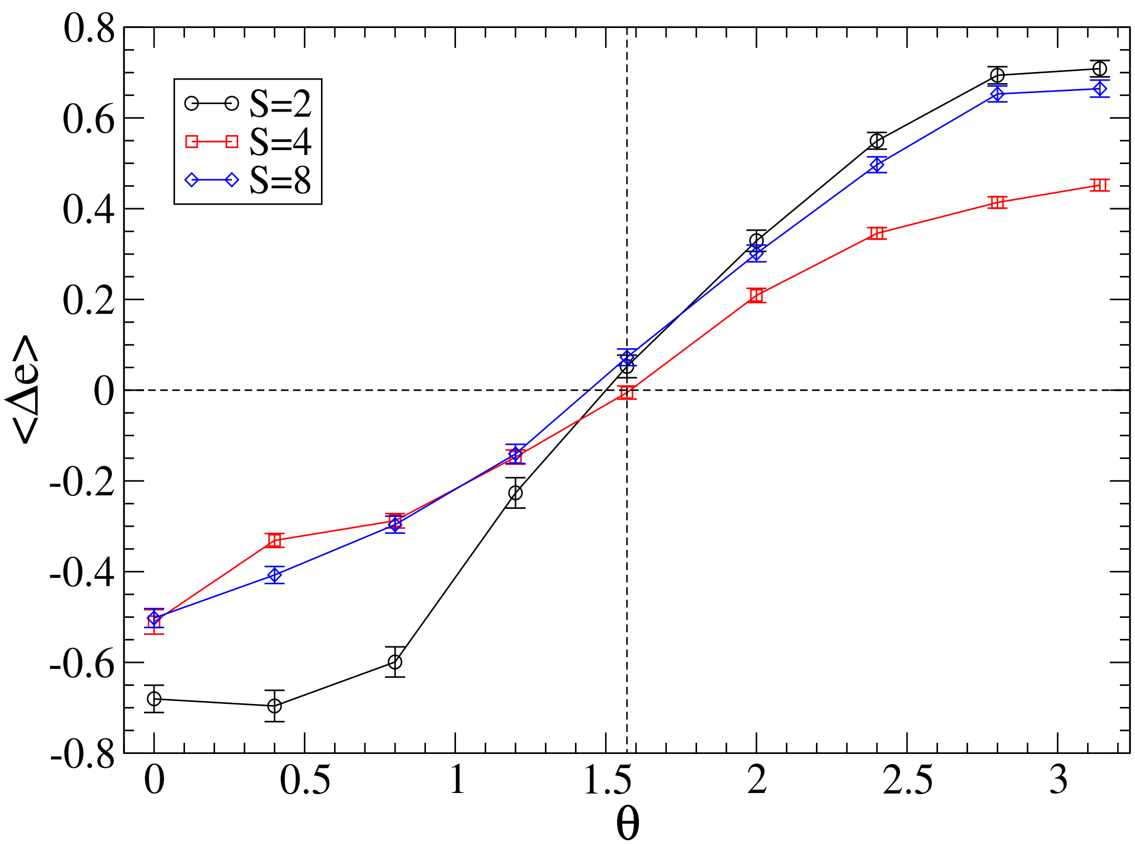
$$H = \text{const} \;\Rightarrow$$

$$\Rightarrow a(t) = \frac{a_0}{1 + t / t_h}$$

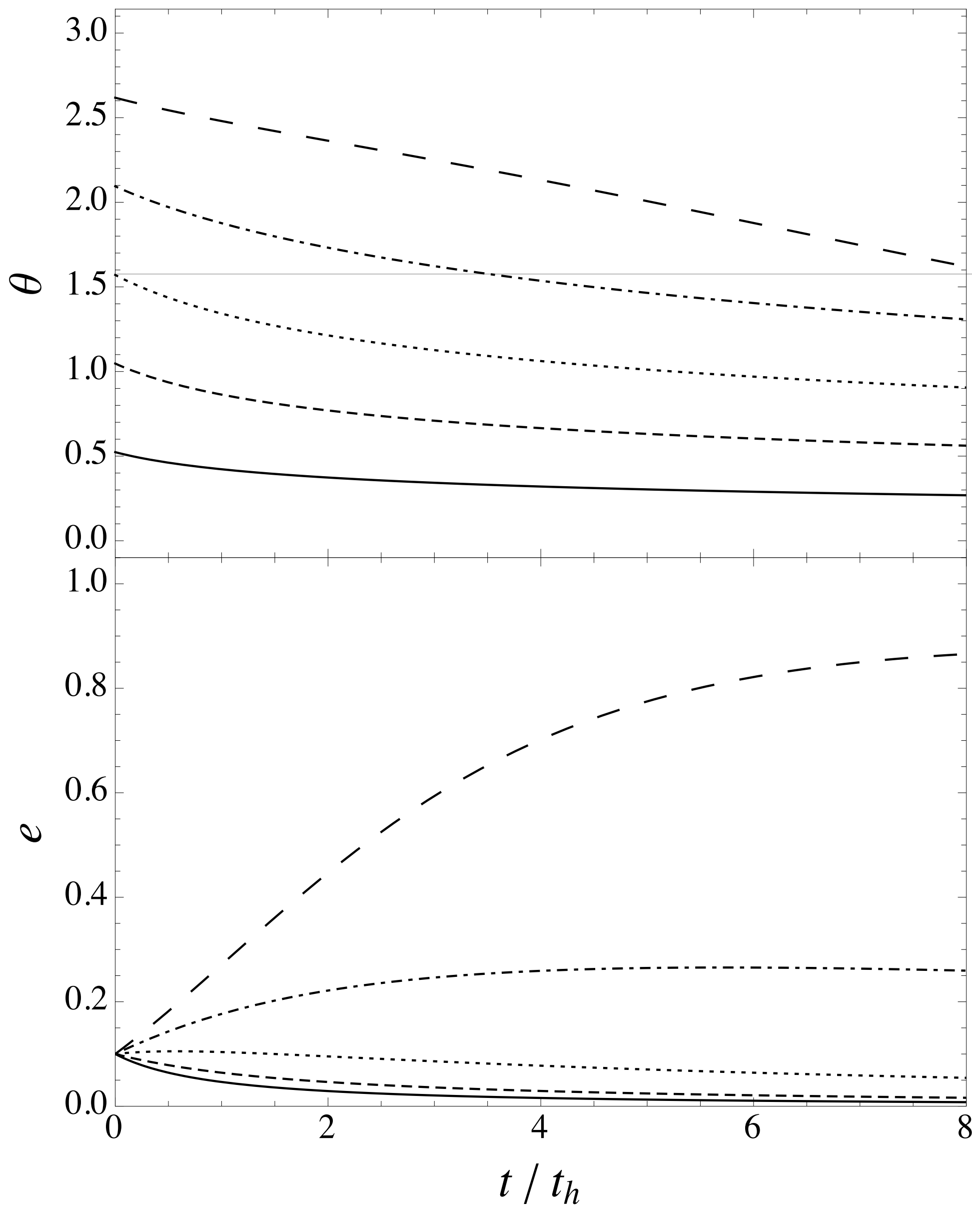
Diffusion coefficients: *e*

$$L_{\rm bin} \uparrow\uparrow L_\star : \quad e \to 0$$

$$L_{\rm bin} \uparrow\downarrow L_\star : \quad e \to 1$$



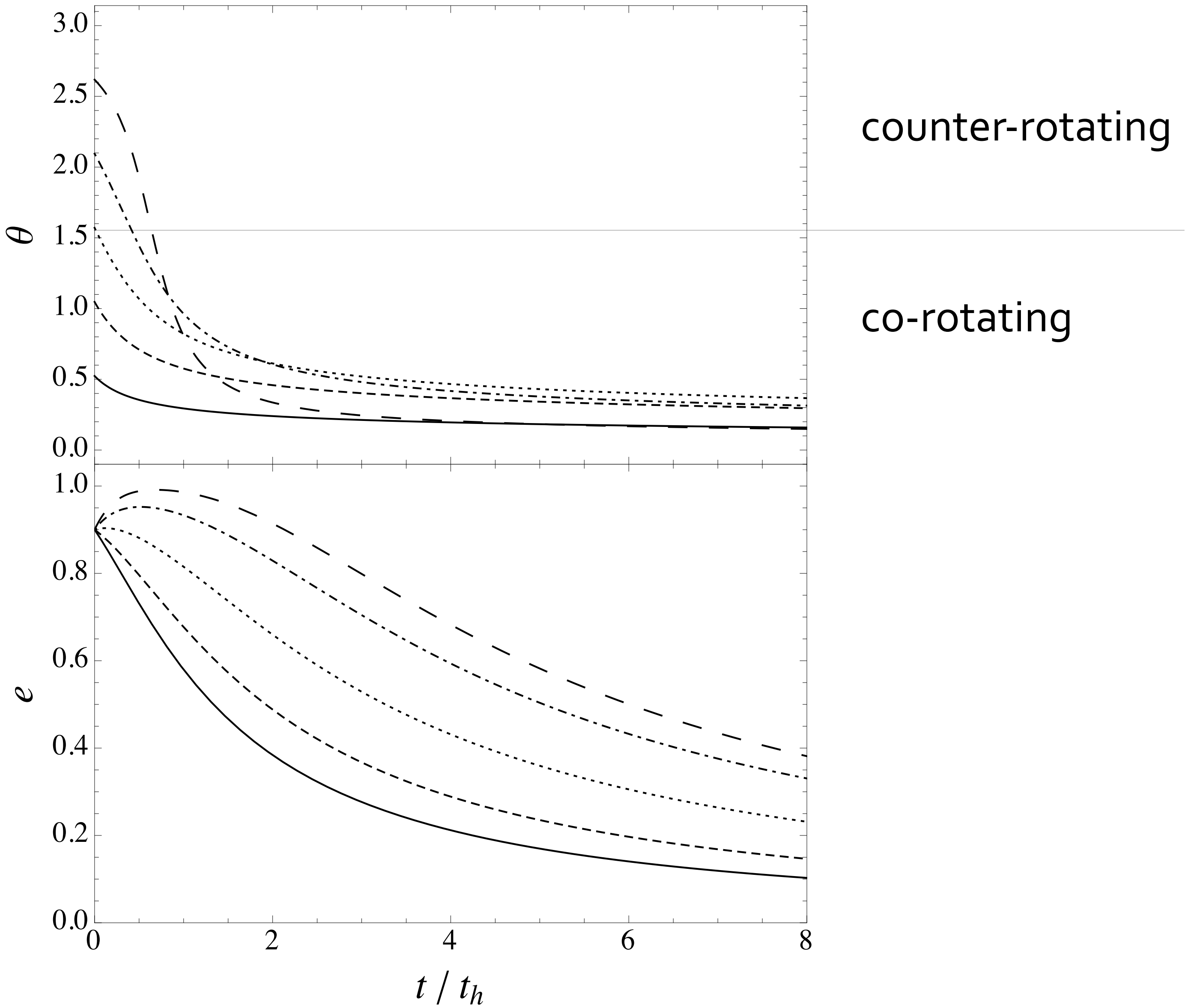
Evolution of *e* and θ



counter-rotating

co-rotating

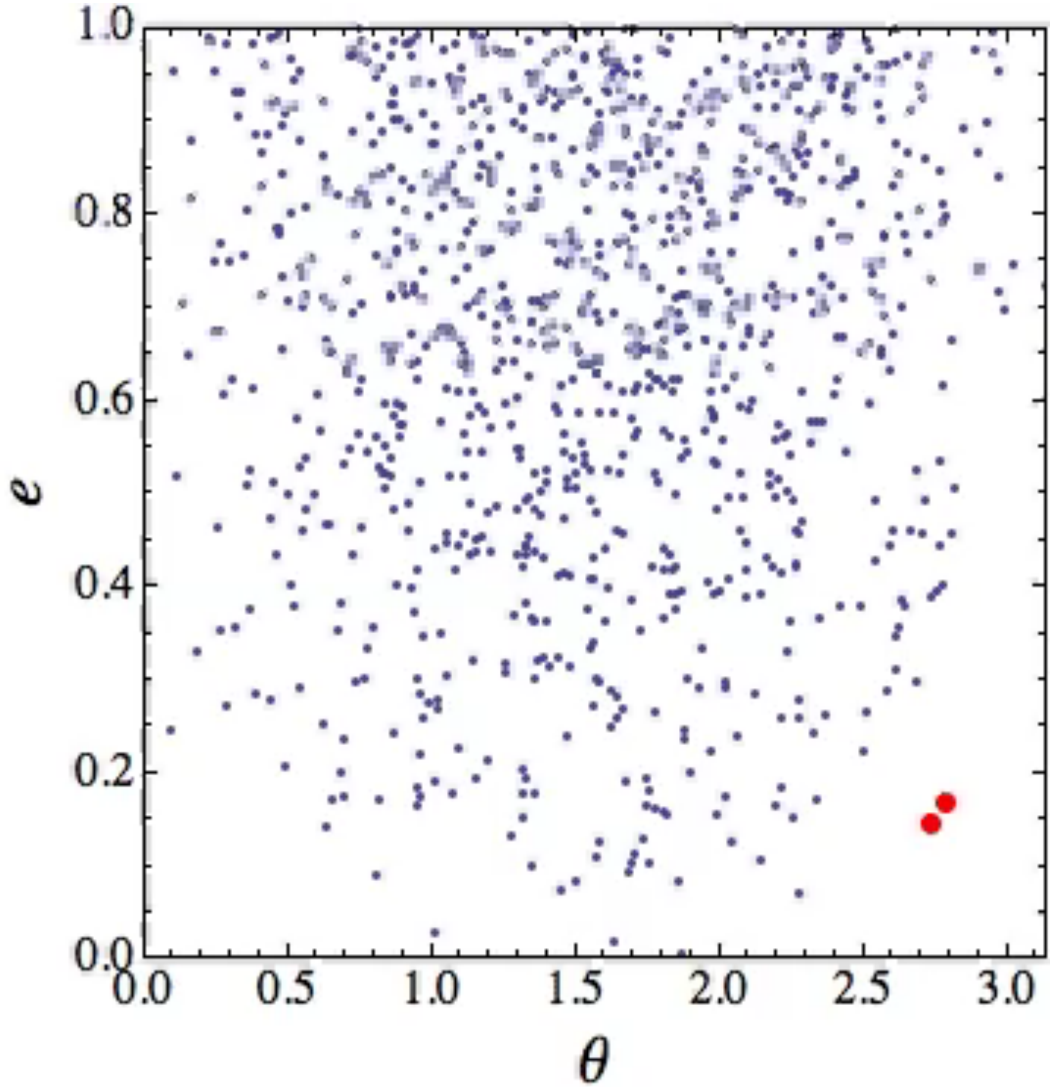
Evolution of *e* and θ



counter-rotating

co-rotating

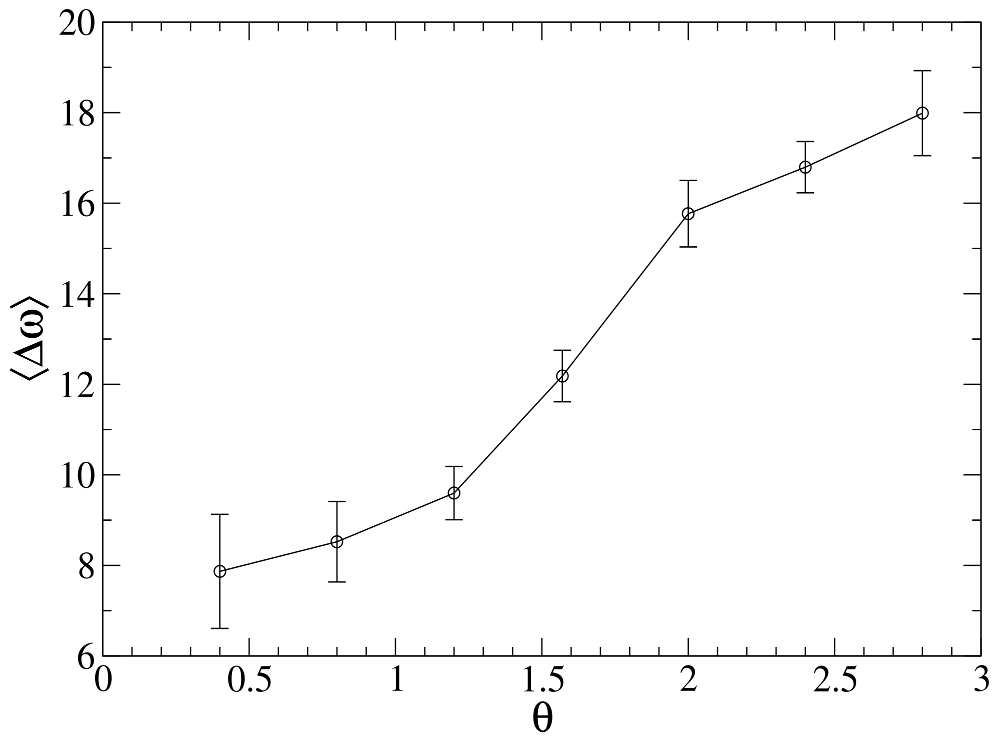
Evolution of *e* and θ

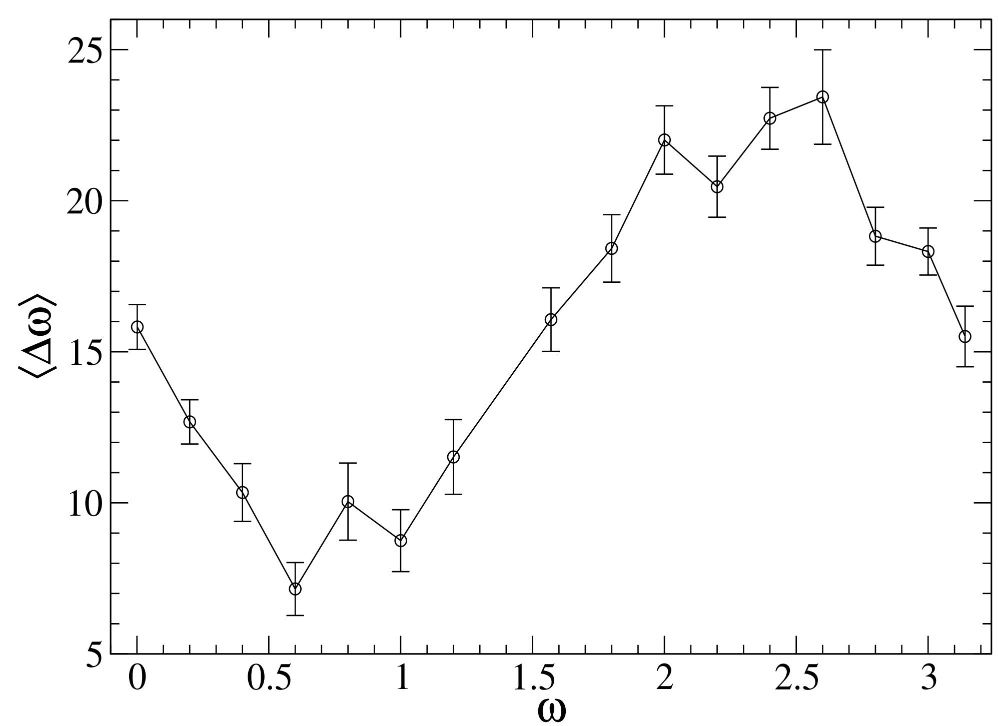


Binary's argument of periapsis

$$\langle \Delta\omega \rangle \neq 0$$

- Apsidal precession due to 3-body, even in non-rotating nuclei





Conclusions

- In rotating nuclei the orbital reorientation is
  - much stronger
  - $\theta \to 0$ rather than random walk
- No significant difference in hardening rate
- $e \to 0$ if co-rotating, $e \to 1$ if counter-rotating
- Possible applications:
  - Orbital plane $\Rightarrow$ gas dynamics, spin of merger remnant (Lousto & Zlochower 2014)
  - Eccentricity $\Rightarrow$ GW emission

Thank you!