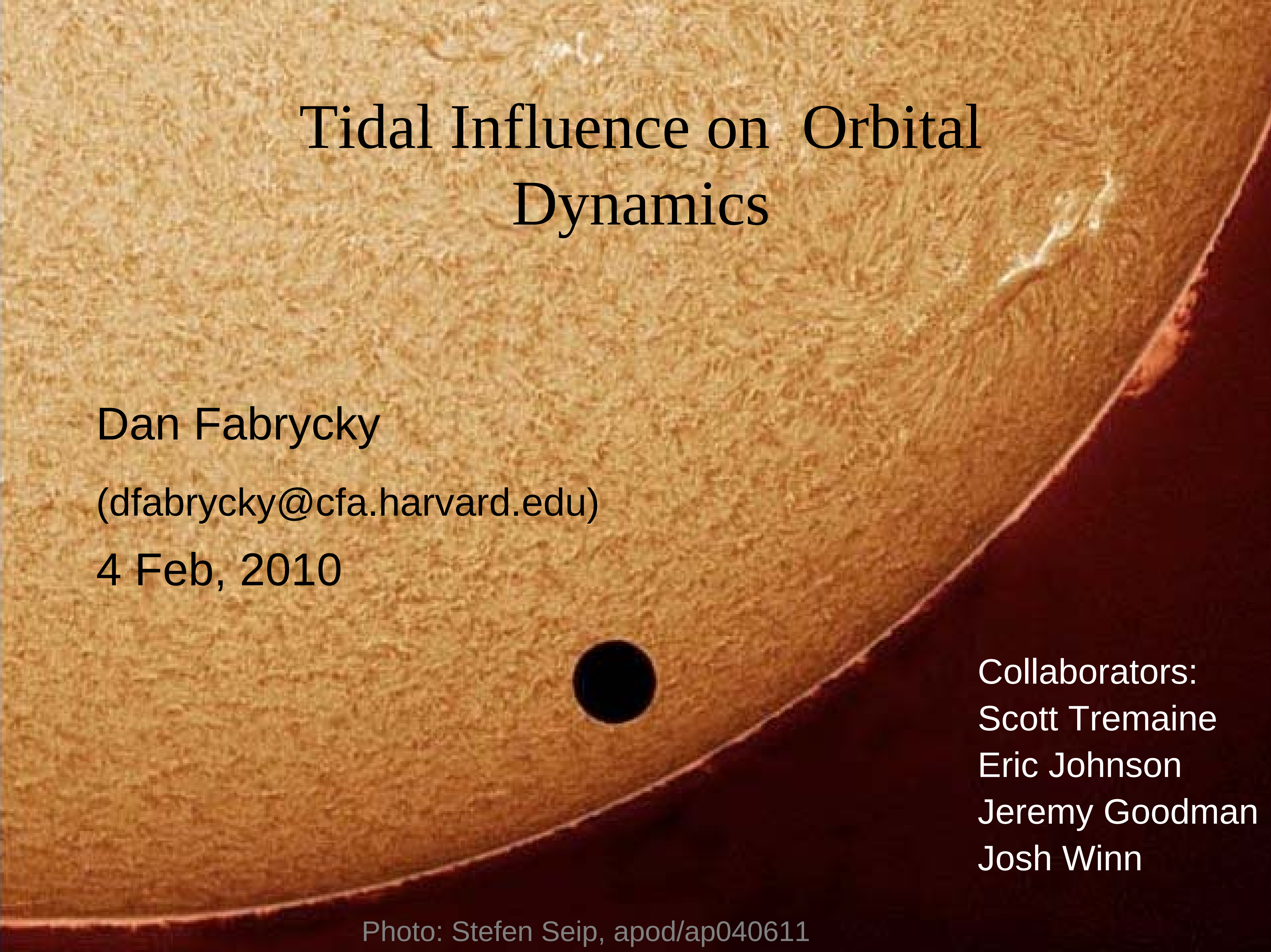

Tidal Influence on Orbital Dynamics

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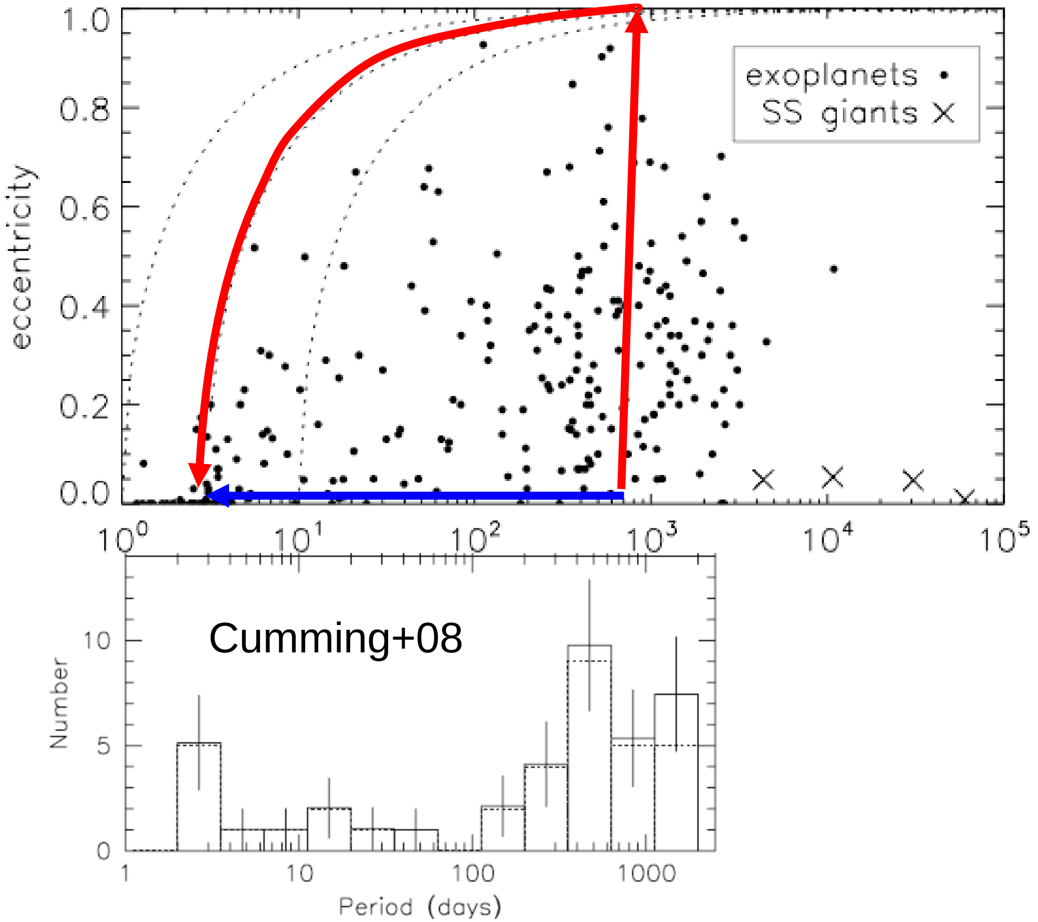
4 Feb, 2010

Collaborators:
Scott Tremaine
Eric Johnson
Jeremy Goodman
Josh Winn

Photo: Stefen Seip, apod/ap040611

Orbital Distribution



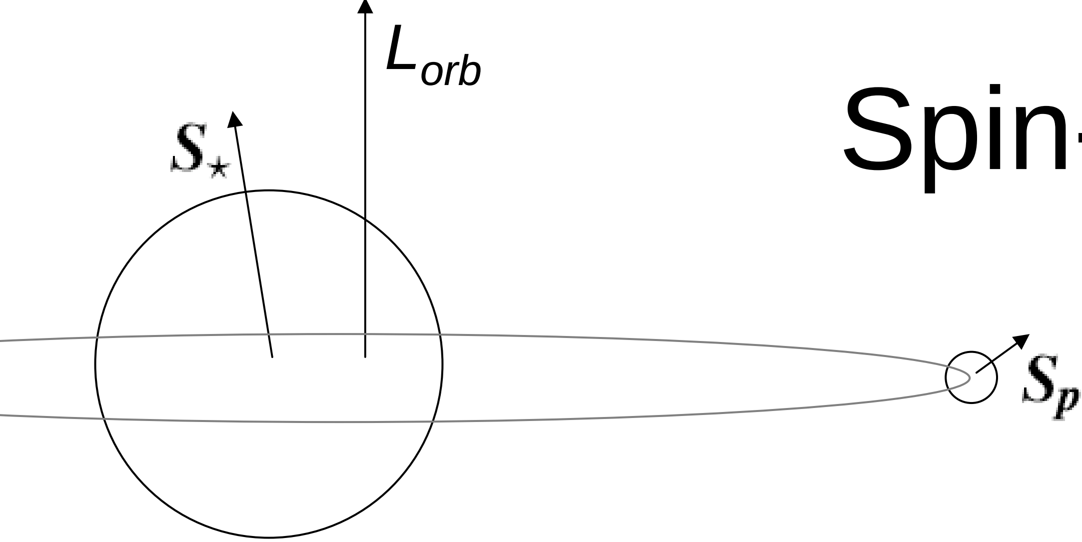
Inclination to stellar equator?

get misaligned

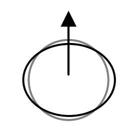
remain aligned

Hot Jupiters are a Sub-class

Spin-orbit evolution

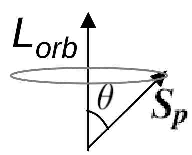


Hot Jupiters are spinning, gaseous bodies with oblate *rotational* bulges

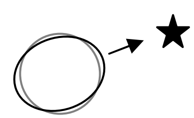


In the star's tidal gravitational field:

The spin vector precesses about the orbit normal

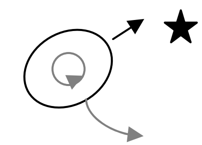


A prolate *tidal* bulge is raised, which tracks the star's position



Dissipating the energy of the tidal bulge:

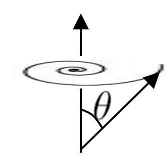
the spinning planet drags prolate bulge "downstream"



i) Parallelization; $\tau_{||} \approx 10^5$ yr

ii) Spin synchronization; $\tau_s = \tau_{||}/2$

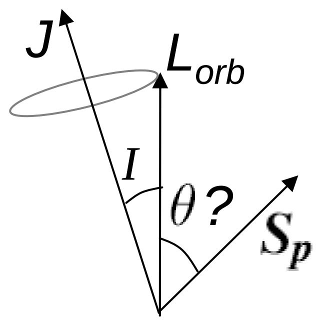
iii) Eccentricity damping; $\tau \approx 10^9$ yr



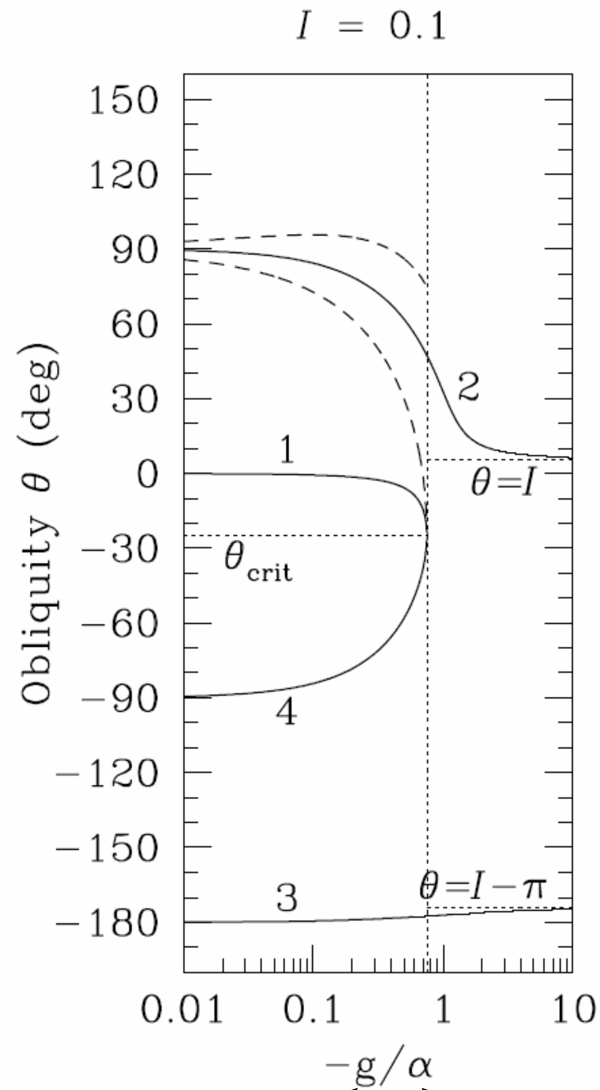
While i, ii, or iii are ongoing, tidal *heat* is generated in the planet

Cassini States

- Now suppose the orbital angular momentum ($L_{\rm orb}$) precesses due to a stellar rotational bulge or another planet that is non-coplanar



- Then: tidal damping on timescale $\tau_{||}$ produces a stable equilibrium obliquity $\theta \neq 0$, called a *Cassini state*.



orbit precession rate

spin precession rate

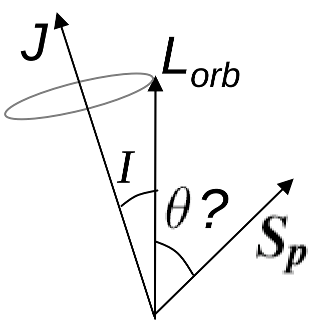
Moon’s spin

Lunation: Cassini's Laws

1) $P_{rotate} = P_{orbit}$

2) θ constant

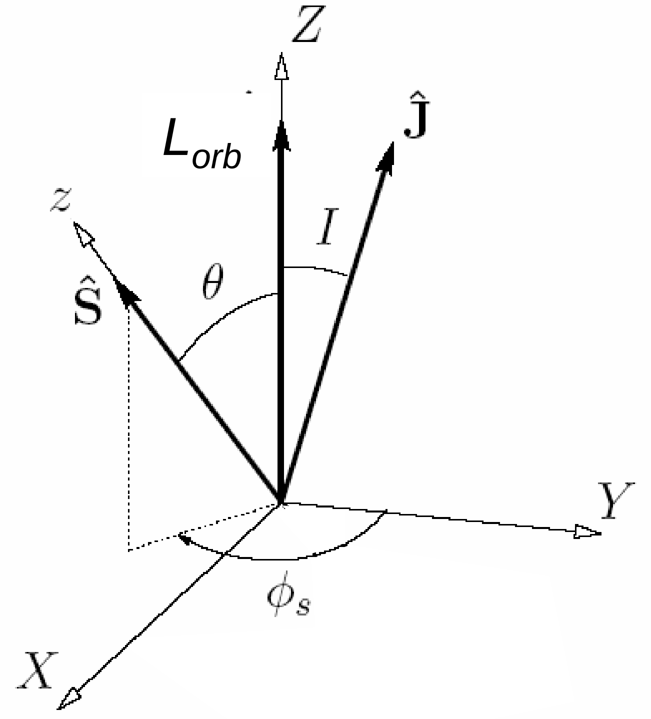
3) $\boldsymbol{S_p}$, L_{orb}, and J are coplanar

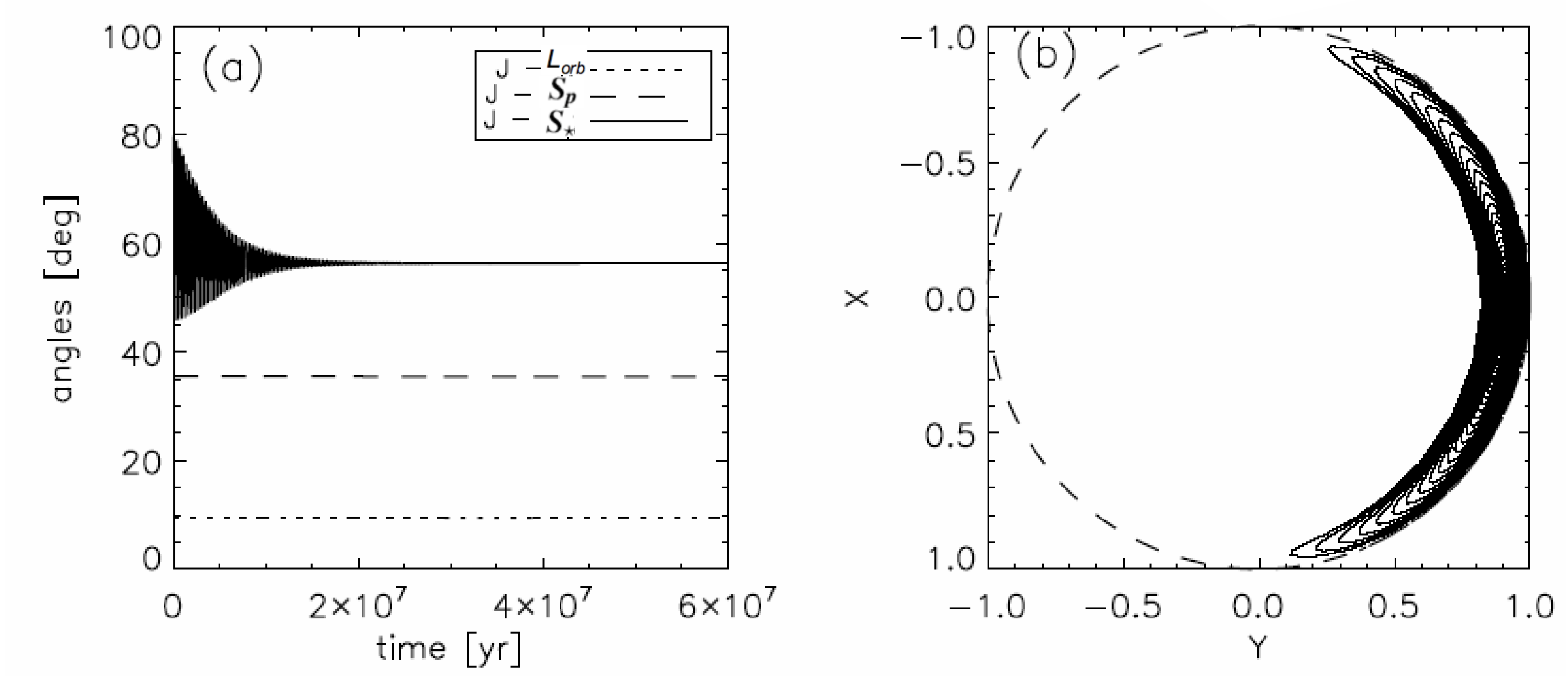


Settling into Cassini state 2

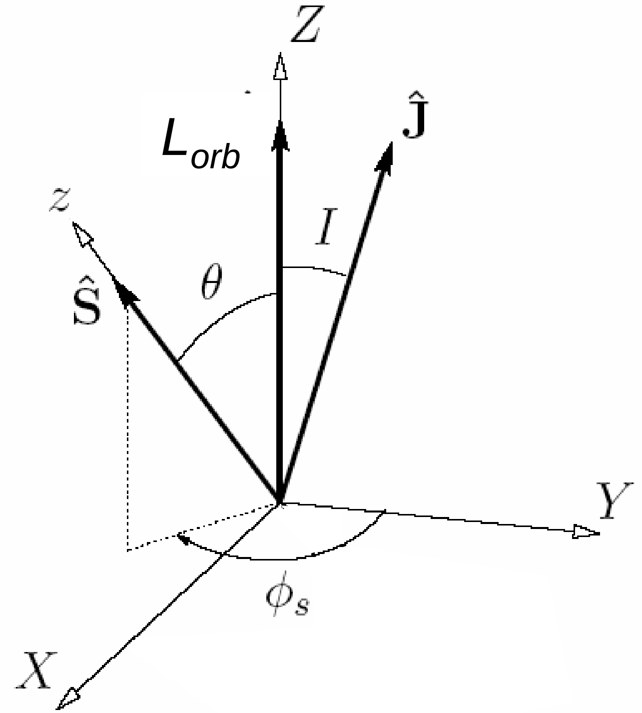
Oblique
| Pseudo-synch
(Levrard et al. 2007)

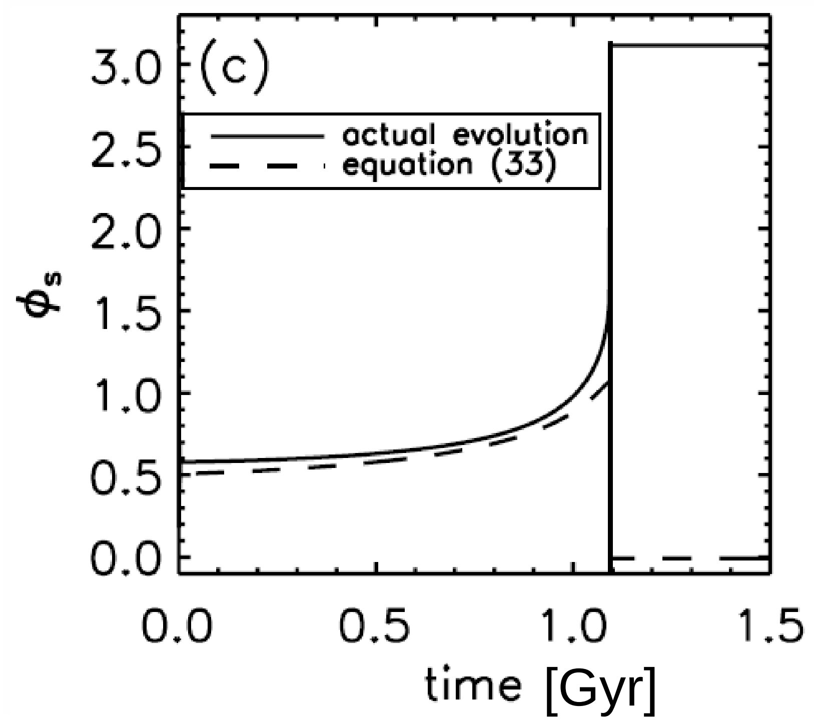
$$\Omega_p = \frac{2n}{\cos\theta + \sec\theta}$$

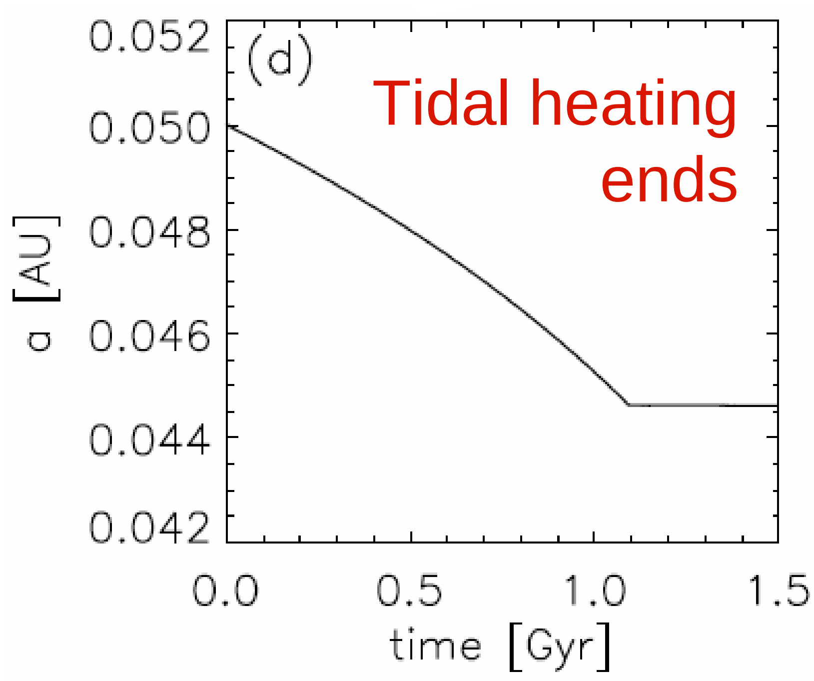




Breaking of Cassini state 2

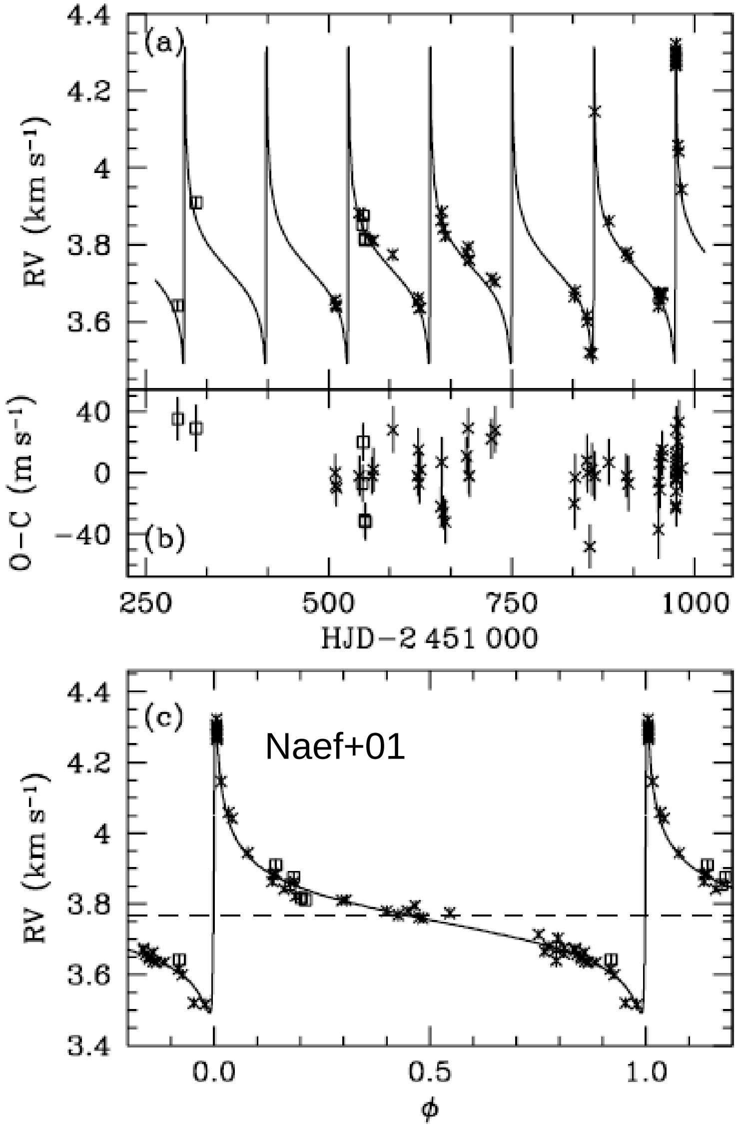




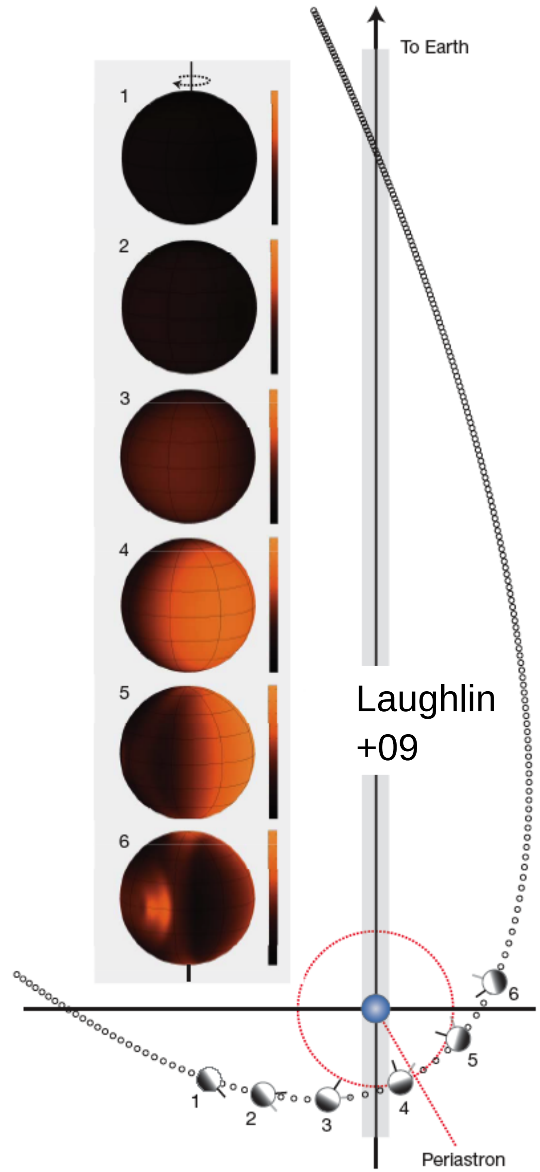


Tidal heating ends

‘606

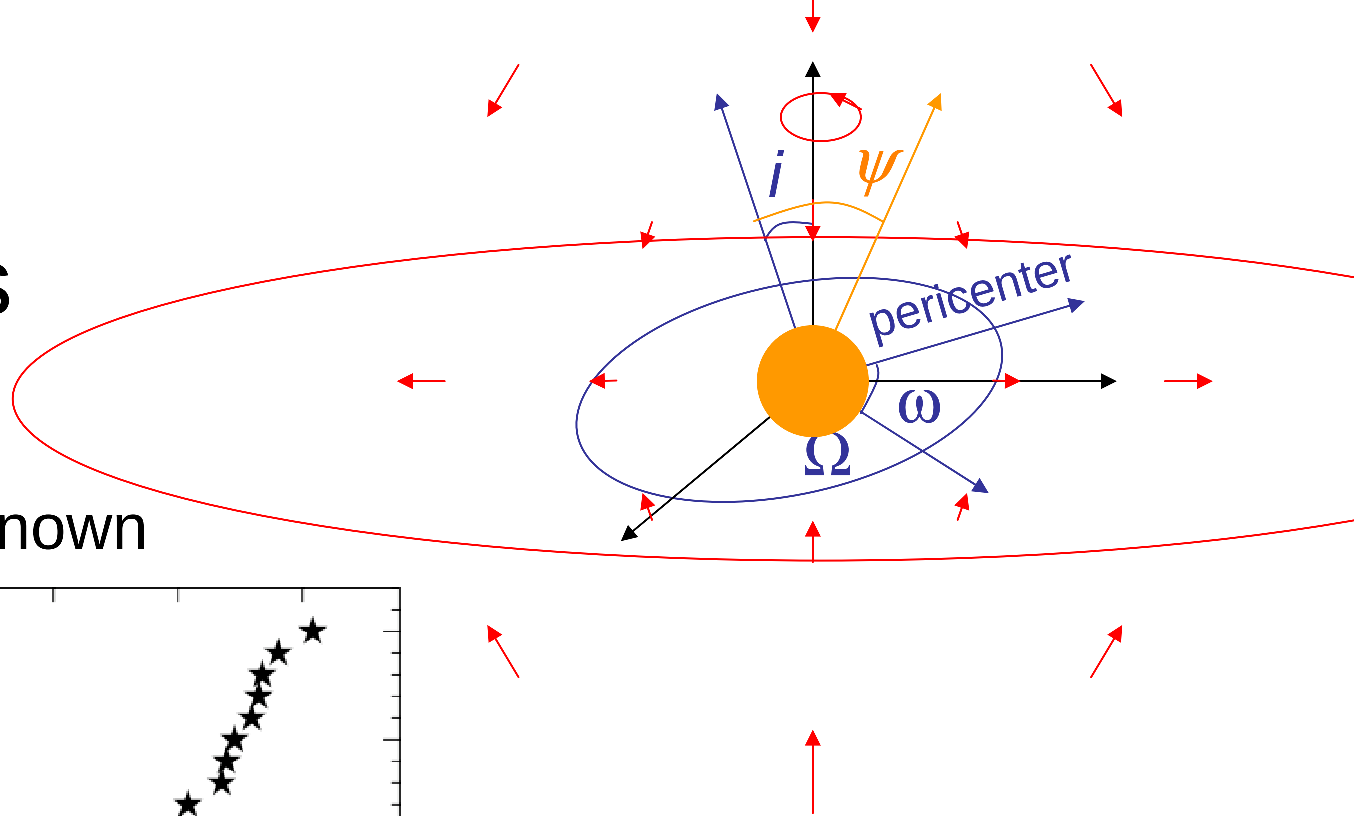


(a)
(b)
(c)
RV (km s⁻¹)
O−C (m s⁻¹)
HJD−2 451 000
ϕ
Naef+01

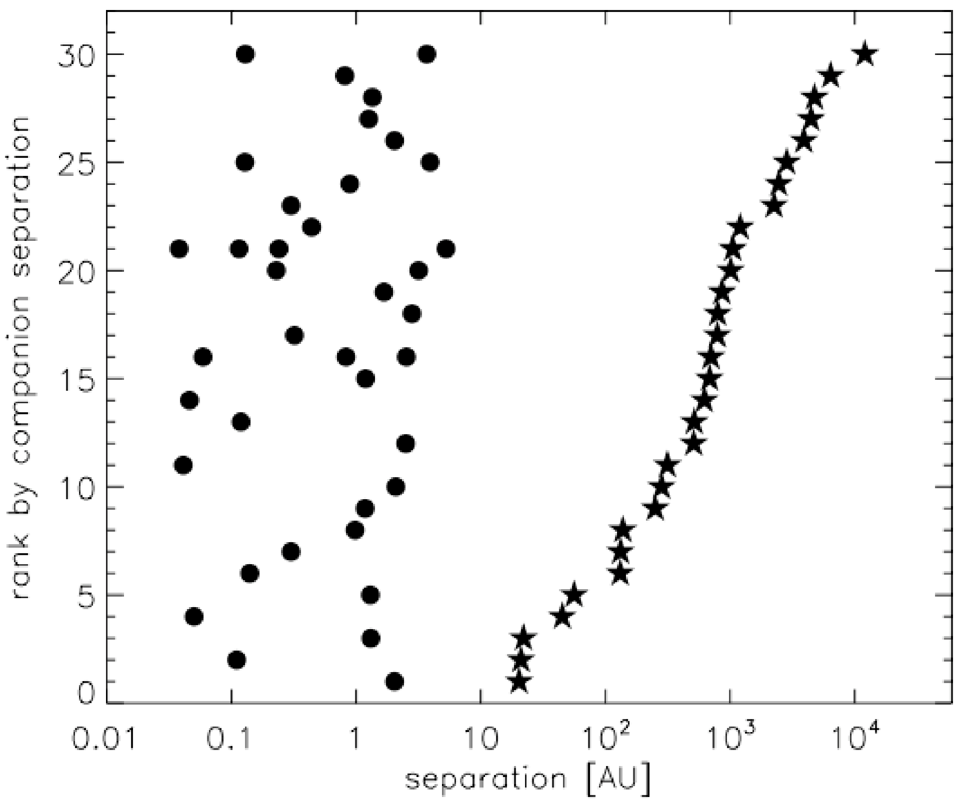


To Earth
Laughlin
+09
Periastron

Planets in Binaries



~40 systems known



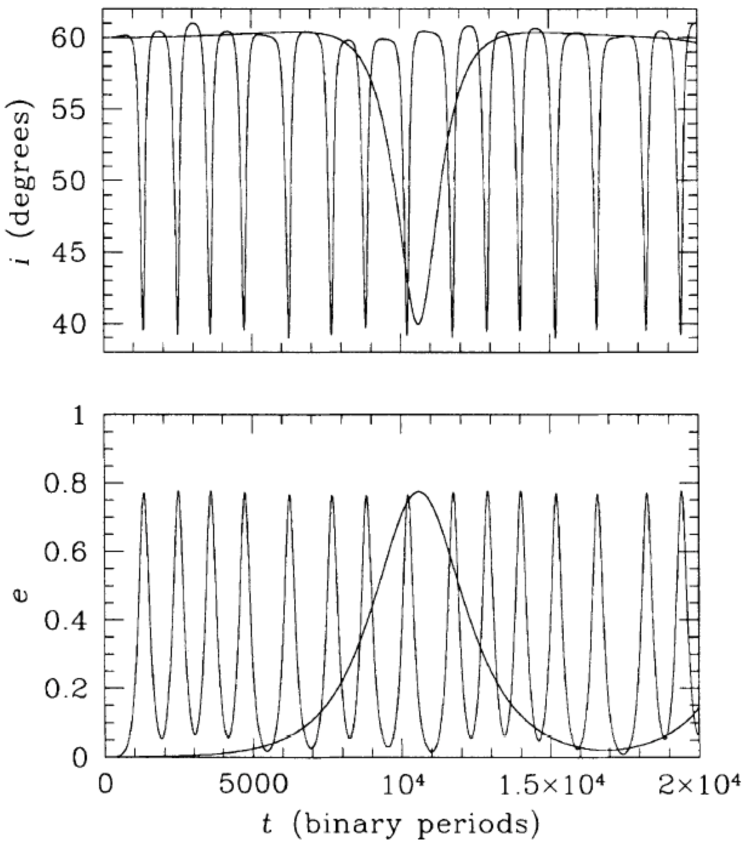
Orbital inclination (relative to stellar equator (a.k.a. stellar obliquity):

- varies for distant planets
- constant for hot Jupiters

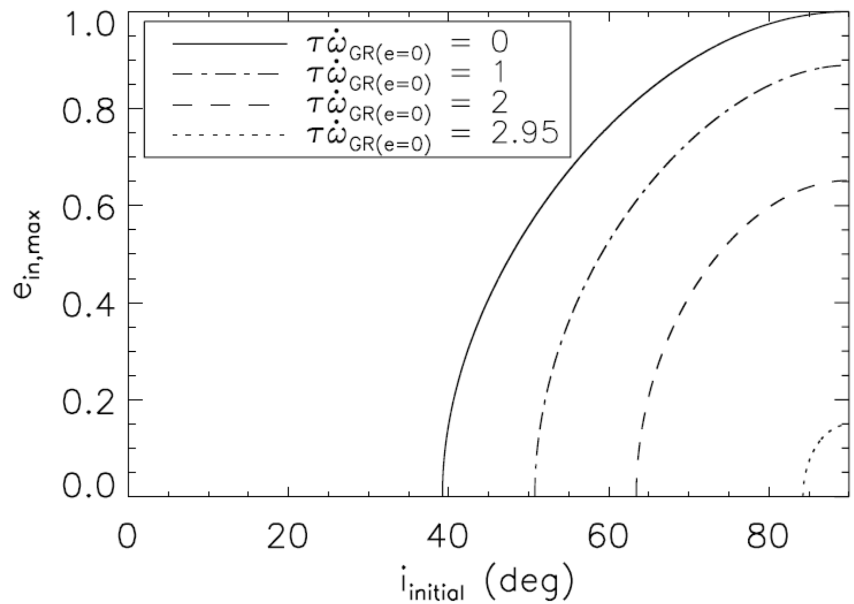
On long timescales (secular approx):

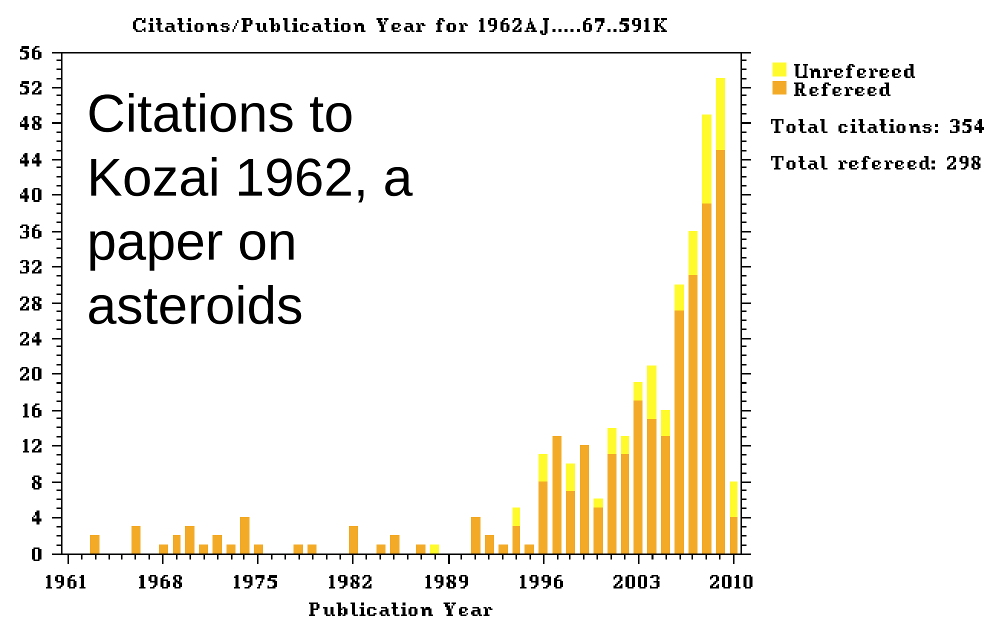
- Semimajor axis *a* is conserved
- *e* oscillates dramatically if $i_{crit}<i<180° - i_{crit}$
- $i_{crit} = \cos^{-1}[(3/5)^{1/2}] = 39.2°$
- ω and Ω both vary as well

Kozai Cycles



Holman, Touma, Tremaine 1997, on 16 Cyg B





Kozai Cycles with Tidal Friction

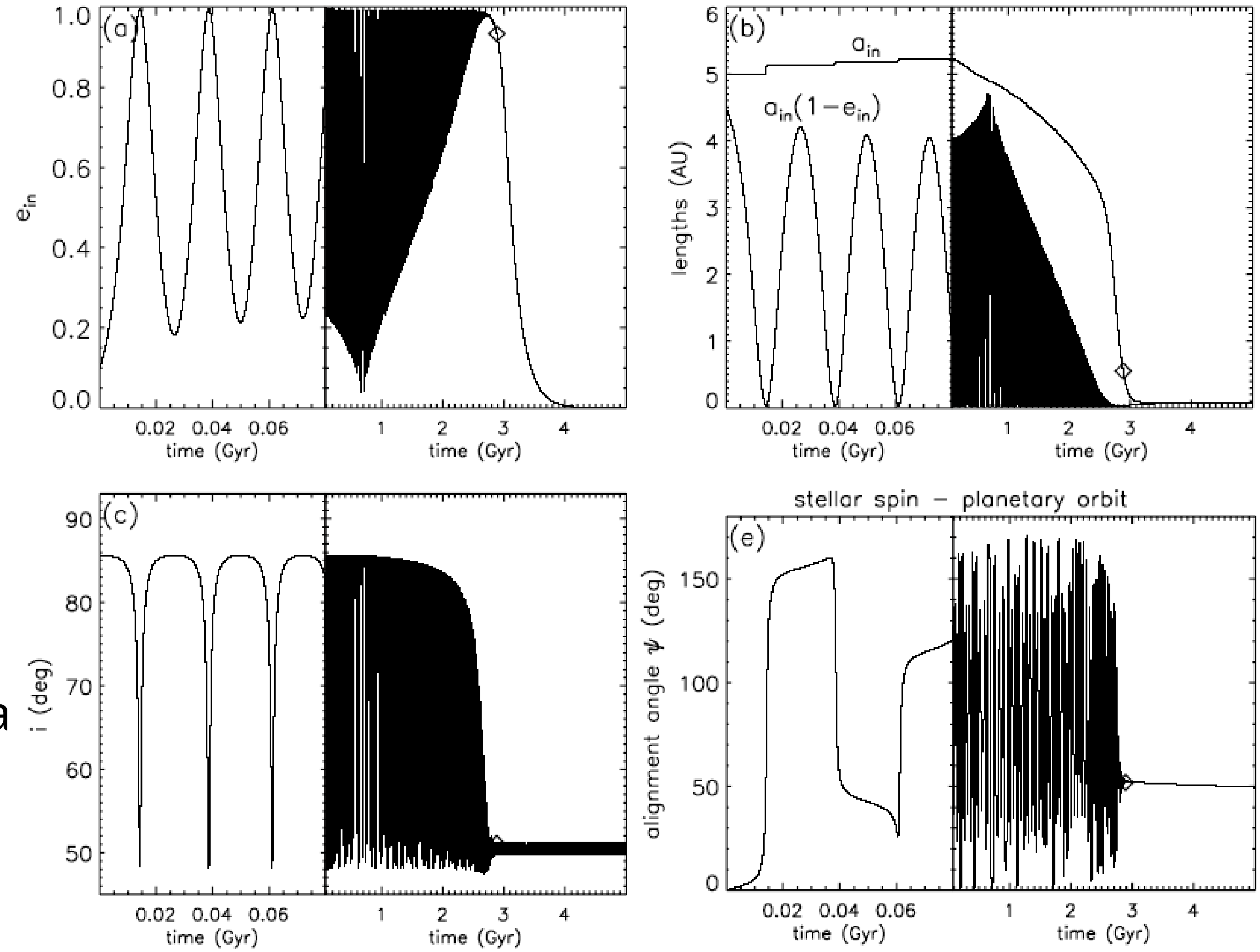
Adding…

- tidal effects:
  - time-shifted eq'm bulges
- spins:
  - rotational oblateness
- GR precession

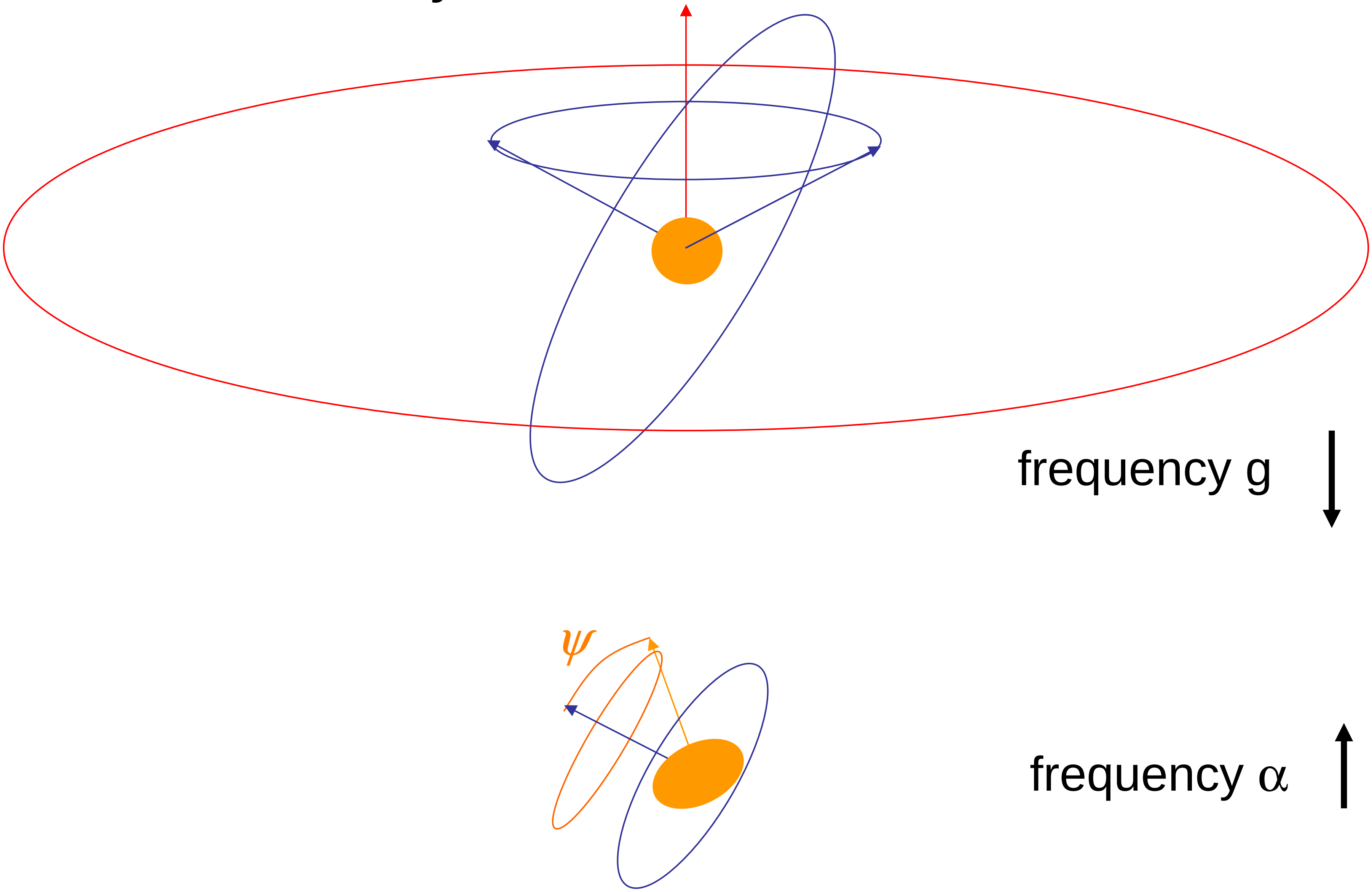
Equations from:

Eggleton & Kiseleva
Eggleton, 2001

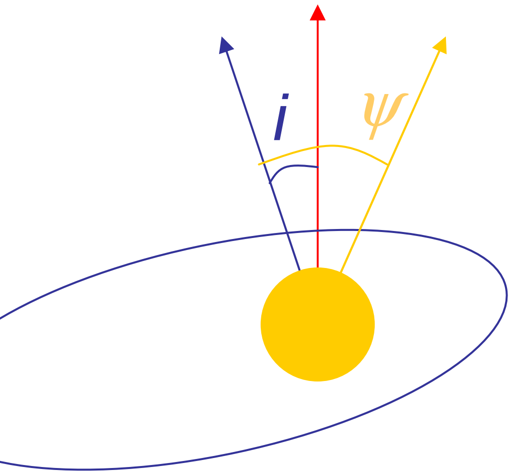
HD 80606b:

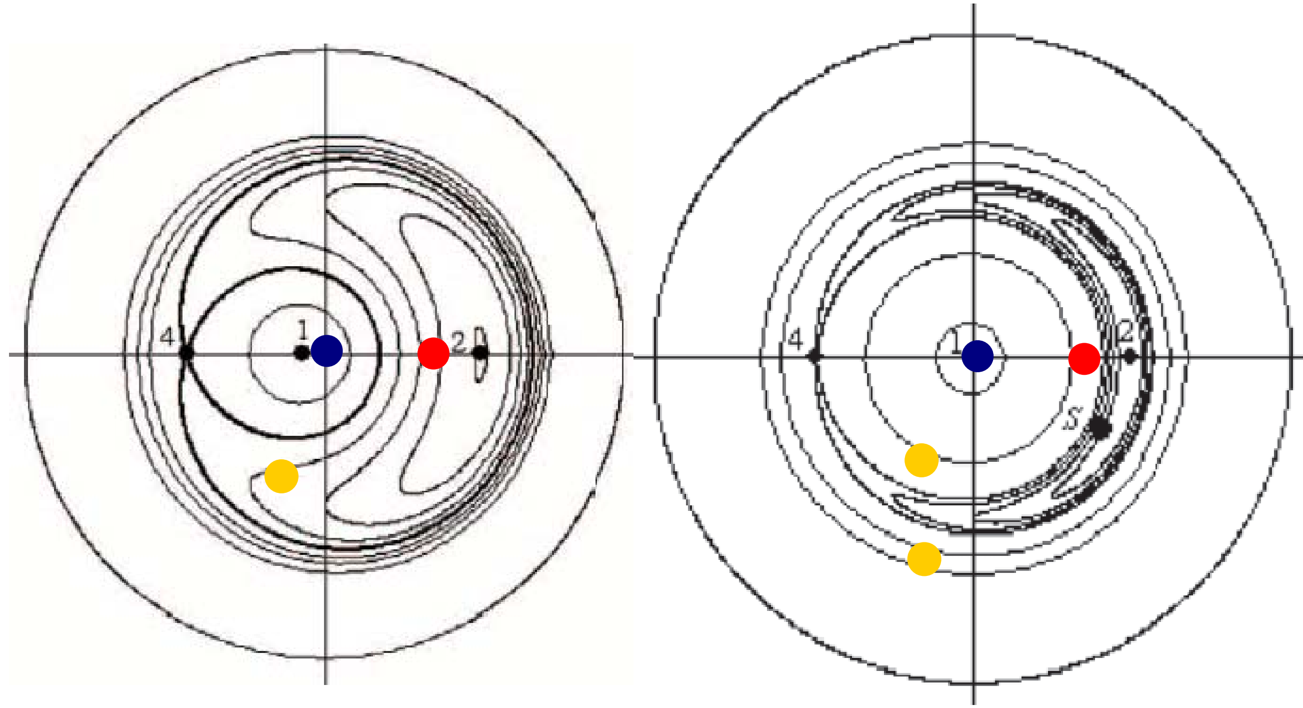


Theory of Secular Resonance

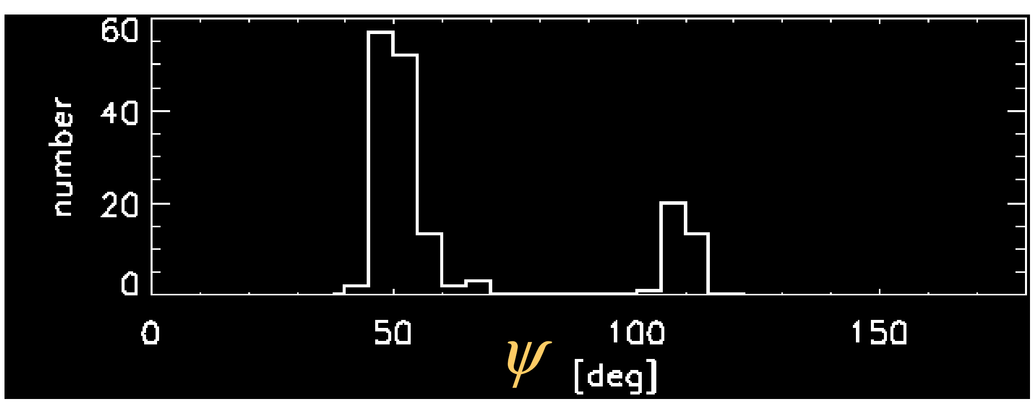


Secular Resonance during Kozai cycles with tidal friction

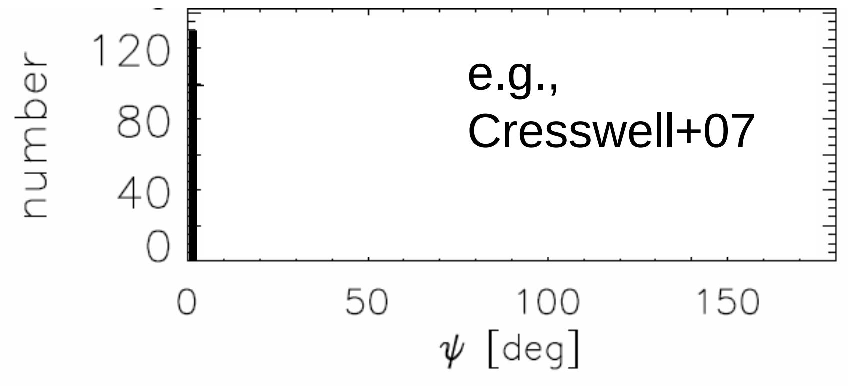




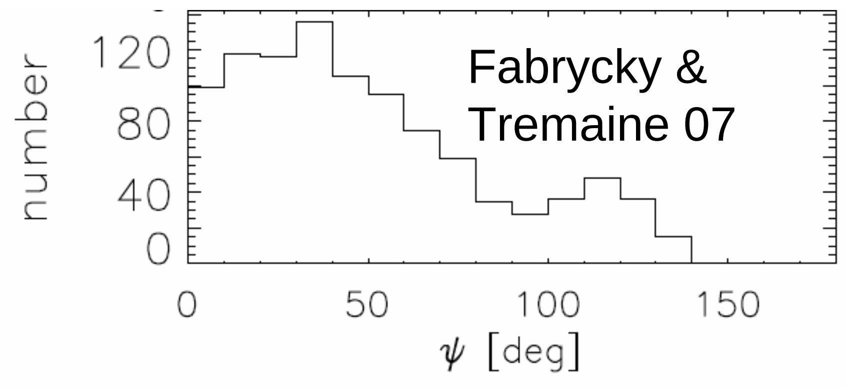
HD 80606:



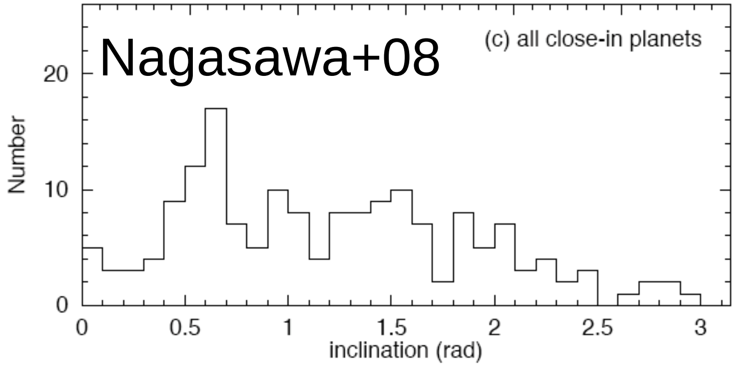
Theoretical Predictions



- Disk migration



- Kozai cycles with tidal friction

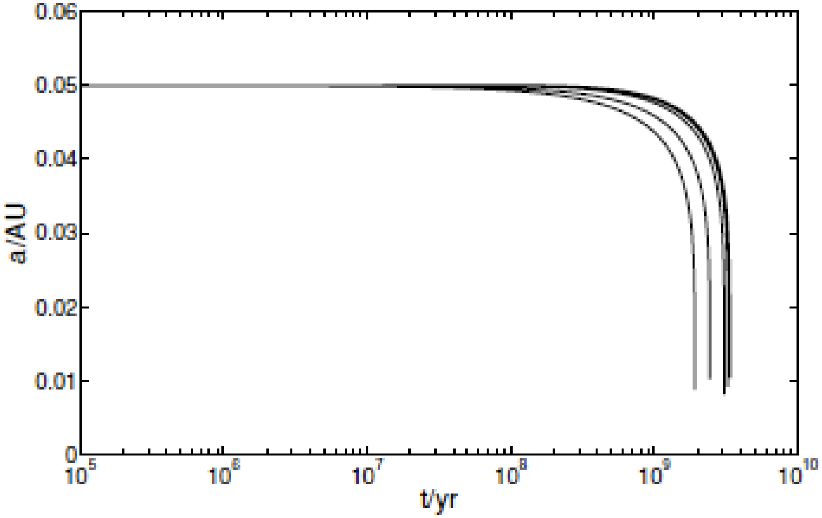


- Planet-planet scattering with tidal friction

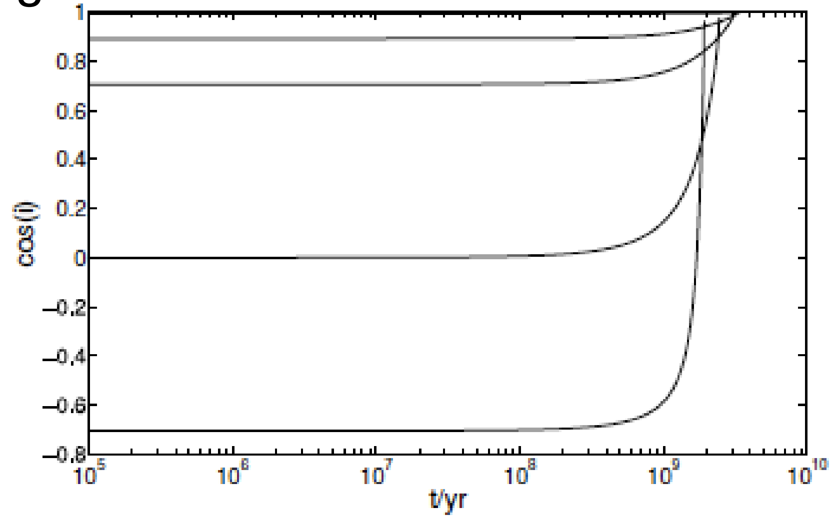
Also, resonant-pumping (Yu & Tremaine 01, Thommes & Lissauer 03)

Do Tides Realign the Star?

Barker & Ogilvie 2009



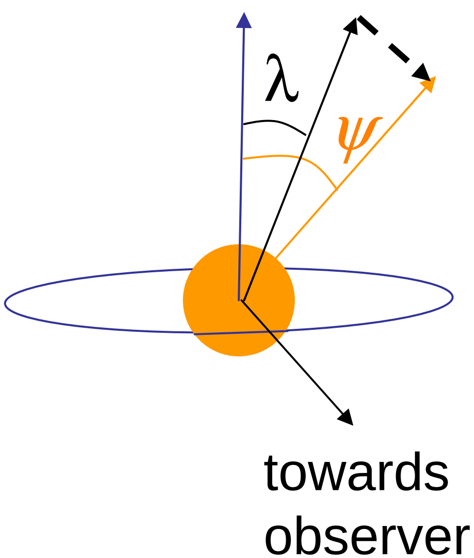
(a) a evolution for $a = 0.05$ AU



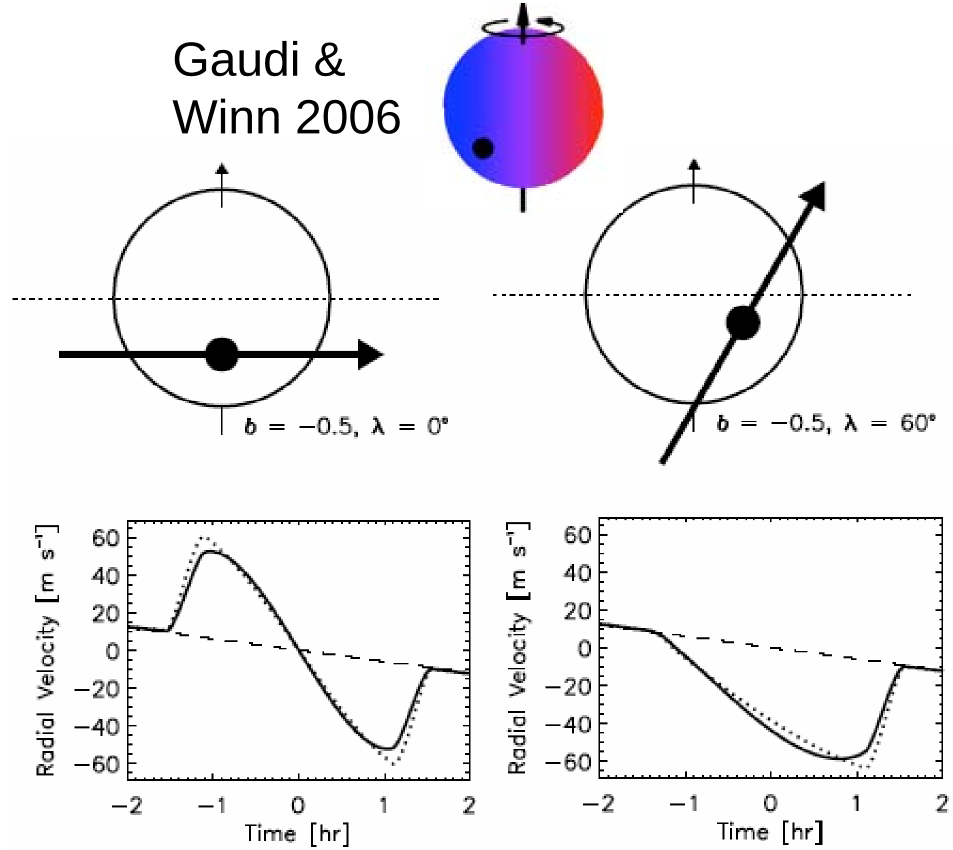
(b) $\cos i$ evolution for $a = 0.05$ AU

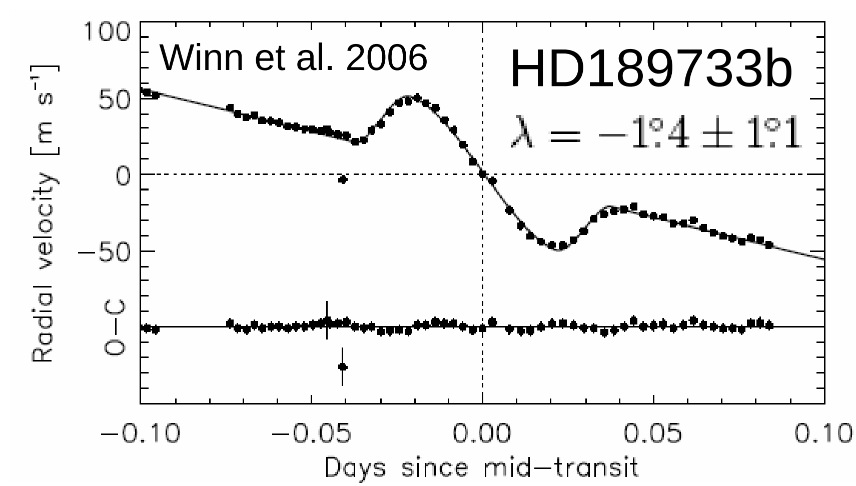
Only if the planet is in the run-away process of being tidally consumed.

Measuring stellar obliquity

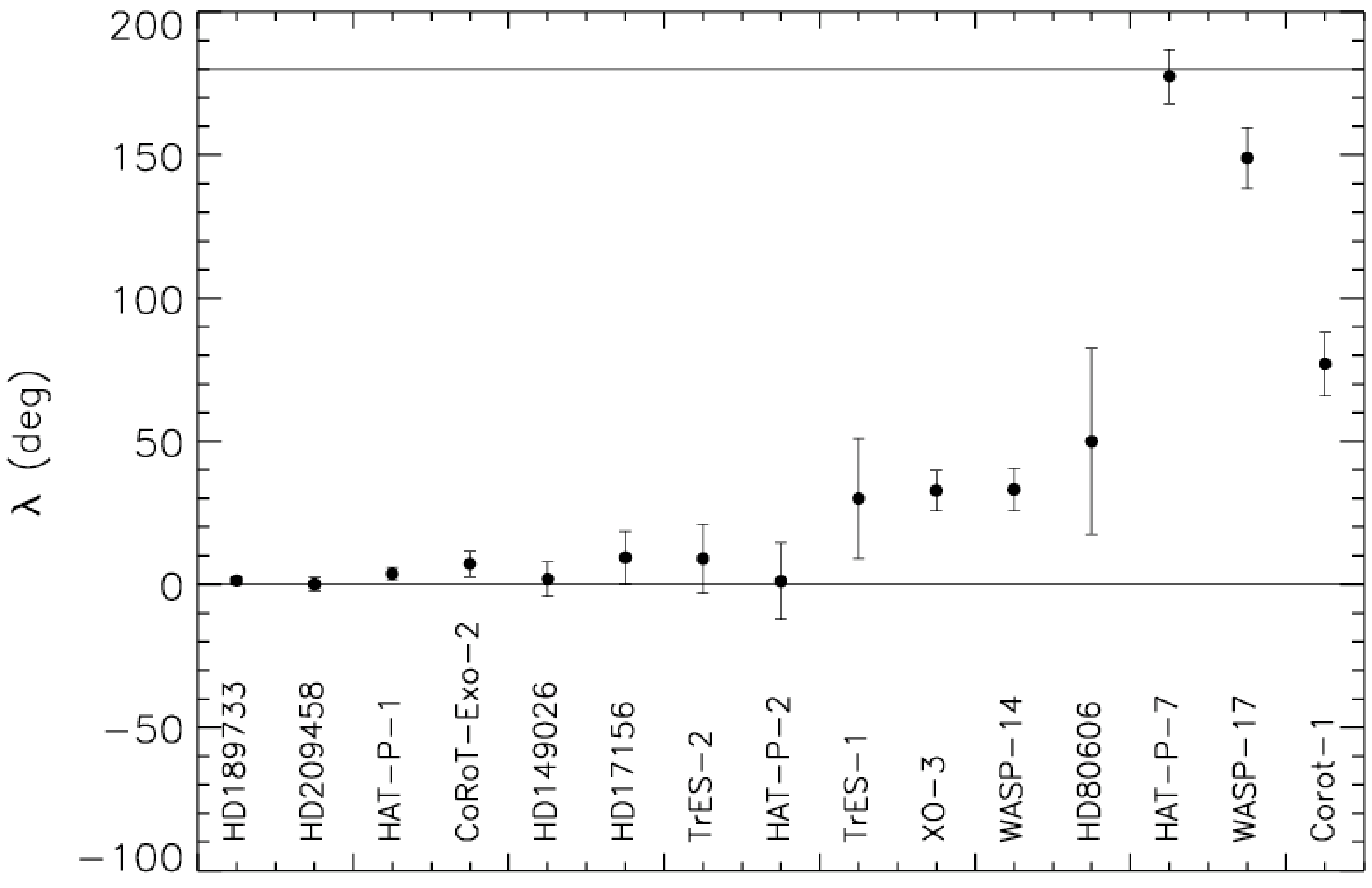


Gaudi & Winn 2006



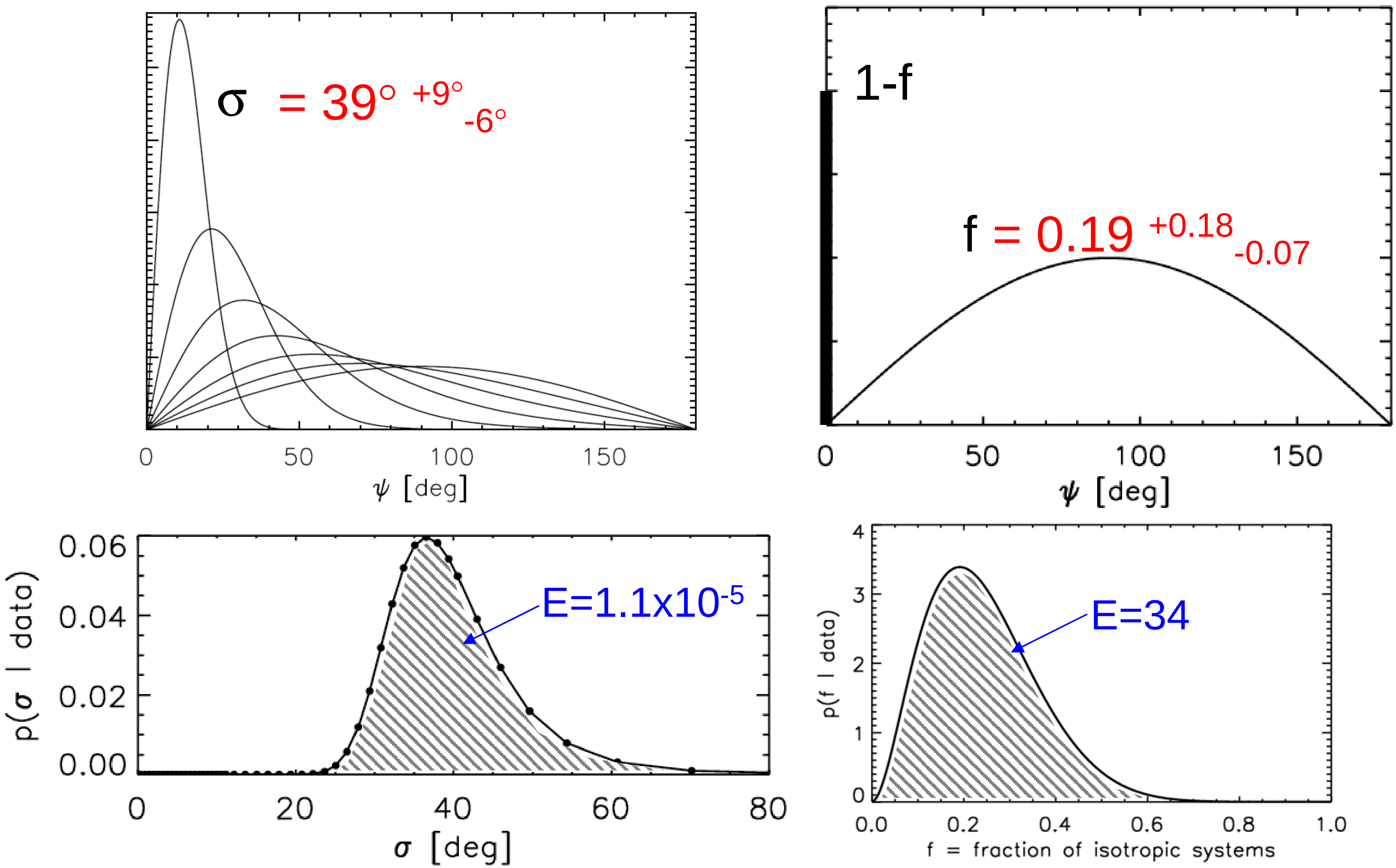


Spin-orbit observations…



(excluding WASP-3b: λ=15±10° ; Kepler-8b: λ=-27±5°)

ψ distributions

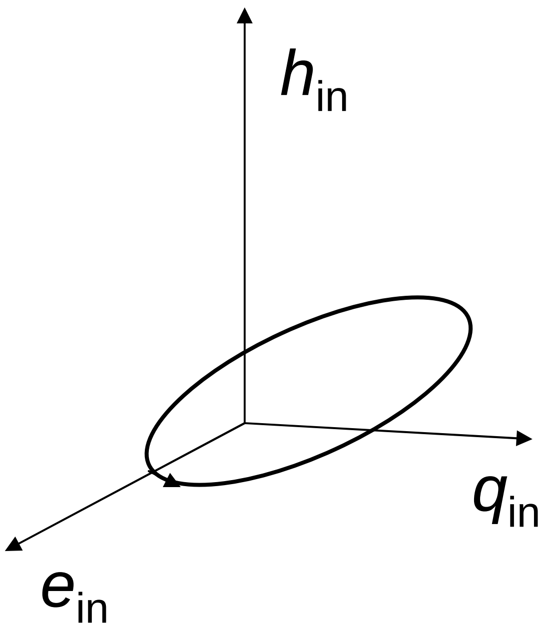


Two migration mechanisms?   Fabrycky & Winn 2009

Topics

- Spin states stabilized dynamically
- Origin of hot Jupiters
- Spin-orbit misalignment
- Didn't touch on:
  - Tides and mean-motion resonances
    - Theory (Terquem & Papaloizou 2007)
    - 55 Cnc b-c (Novak et al. 2003)
    - HD 40307 (Lin et al. in prep)
  - Tides and apsidal alignment
    - Mardling 2007, 2010
    - Batygin et al. 2009ab - particular systems

Eggleton equations



$$\frac{1}{e_{\rm in}}\frac{d\boldsymbol{e}_{\rm in}}{dt} = (Z_1 + Z_2 + Z_{\rm GR})\hat{\boldsymbol{q}}_{\rm in} - (Y_1 + Y_2)\hat{\boldsymbol{h}}_{\rm in} - (V_1 + V_2)\hat{\boldsymbol{e}}_{\rm in} - \left(1 - e_{\rm in}^2\right)\left[5S_{\rm eq}\hat{\boldsymbol{e}}_{\rm in} - \left(4S_{ee} - S_{qq}\right)\hat{\boldsymbol{q}}_{in} + S_{qh}\hat{\boldsymbol{h}}_{\rm in}\right],$$

$$\frac{1}{h_{\rm in}}\frac{d\boldsymbol{h}_{\rm in}}{dt} = (Y_1 + Y_2)\hat{\boldsymbol{e}}_{\rm in} - (X_1 + X_2)\hat{\boldsymbol{q}}_{\rm in} - (W_1 + W_2)\hat{\boldsymbol{h}}_{\rm in} + \left(1 - e_{\rm in}^2\right)S_{qh}\hat{\boldsymbol{e}}_{\rm in} - \left(4e_{\rm in}^2 + 1\right)S_{eh}\hat{\boldsymbol{q}}_{\rm in} + 5e_{\rm in}^2 S_{\rm eq}\hat{\boldsymbol{h}}_{\rm in},$$

$$I_1\frac{d\boldsymbol{\Omega}_1}{dt} = \mu h_{\rm in}\left(-Y_1\hat{\boldsymbol{e}}_{\rm in} + X_1\hat{\boldsymbol{q}}_{\rm in} + W_1\hat{\boldsymbol{h}}_{\rm in}\right),$$

$$I_2\frac{d\boldsymbol{\Omega}_2}{dt} = \mu h_{\rm in}\left(-Y_2\hat{\boldsymbol{e}}_{\rm in} + X_2\hat{\boldsymbol{q}}_{\rm in} + W_2\hat{\boldsymbol{h}}_{\rm in}\right),$$

Dissipative:

$$V_1 = \frac{9}{t_{F1}}\left[\frac{1 + (15/4)e^2 + (15/8)e^4 + (5/64)e^6}{(1-e^2)^{13/2}} - \frac{11\Omega_{1h}}{18\omega}\frac{1 + (3/2)e^2 + (1/8)e^4}{(1-e^2)^5}\right],$$

$$W_1 = \frac{1}{t_{F1}}\left[\frac{1 + (15/2)e^2 + (45/8)e^4 + (5/16)e^6}{(1-e^2)^{13/2}} - \frac{\Omega_{1h}}{\omega}\frac{1 + 3e^2 + (3/8)e^4}{(1-e^2)^5}\right],$$

$$\frac{1}{t_{F1}} = \frac{9}{t_{V1}}\frac{R_1^8}{a^8}\frac{MM_2}{M_1^2}\frac{1}{(1-Q_1)^2}.$$

Non-Dissipative:

$$X_1 = -\frac{M_2 A_1}{2\mu\omega a^5}\frac{\Omega_{1h}\Omega_{1e}}{(1-e^2)^2} - \frac{\Omega_{1q}}{2\omega t_{F1}}\frac{1 + (9/2)e^2 + (5/8)e^4}{(1-e^2)^5},$$

$$Y_1 = -\frac{M_2 A_1}{2\mu\omega a^5}\frac{\Omega_{1h}\Omega_{1q}}{(1-e^2)^2} + \frac{\Omega_{1e}}{2\omega t_{F1}}\frac{1 + (3/2)e^2 + (1/8)e^4}{(1-e^2)^5},$$

$$Z_1 = \frac{M_2 A_1}{2\mu\omega a^5}\left[\frac{2\Omega_{1h}^2 - \Omega_{1e}^2 - \Omega_{1q}^2}{2(1-e^2)^2} + \frac{15GM_2}{a^3}\frac{1 + (3/2)e^2 + (1/8)e^4}{(1-e^2)^5}\right].$$

…