Evolution of Stellar Spin in Binaries and the Production of Misaligned Hot Jupiters

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In collaboration with Natalia Storch, Dong Lai

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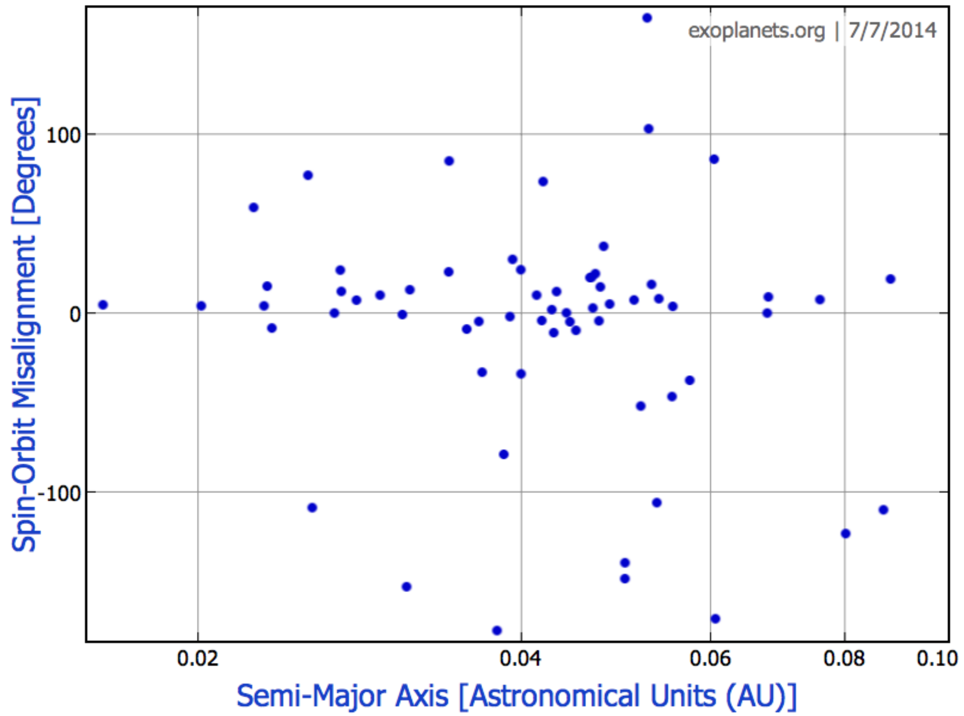
Based on:
Storch, Anderson, & Lai 2014, submitted;
Anderson, Storch, & Lai 2014, in preparation

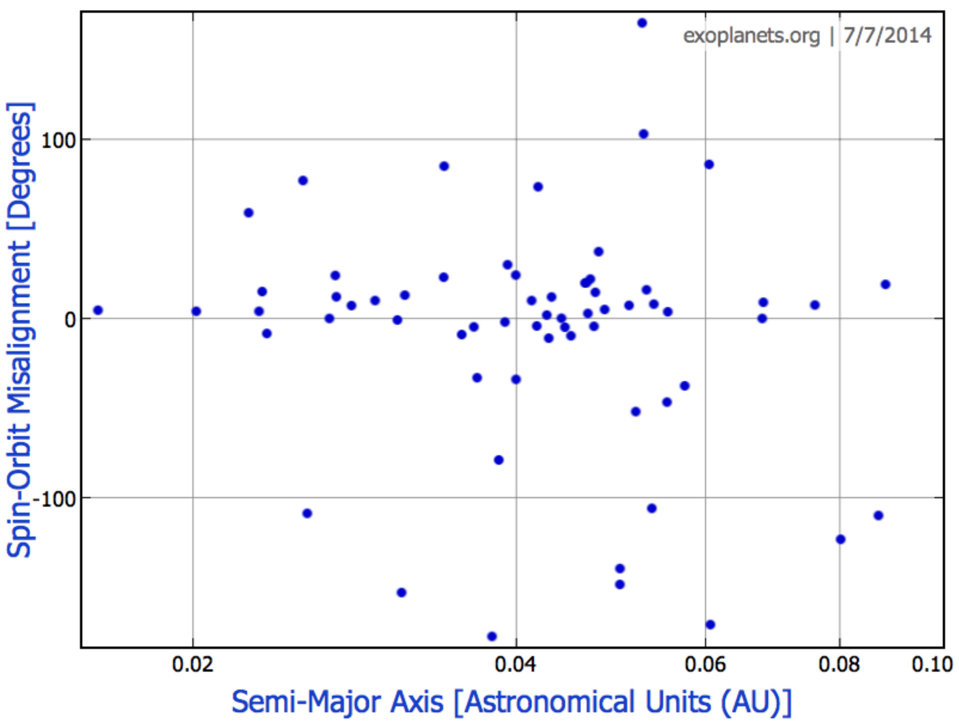
Outline

- Motivation/background: the Kozai - Lidov mechanism and production of hot Jupiters
- Stellar spin-orbit dynamics
- Observational implications

Spin-Orbit Misalignment in Hot Jupiter Systems

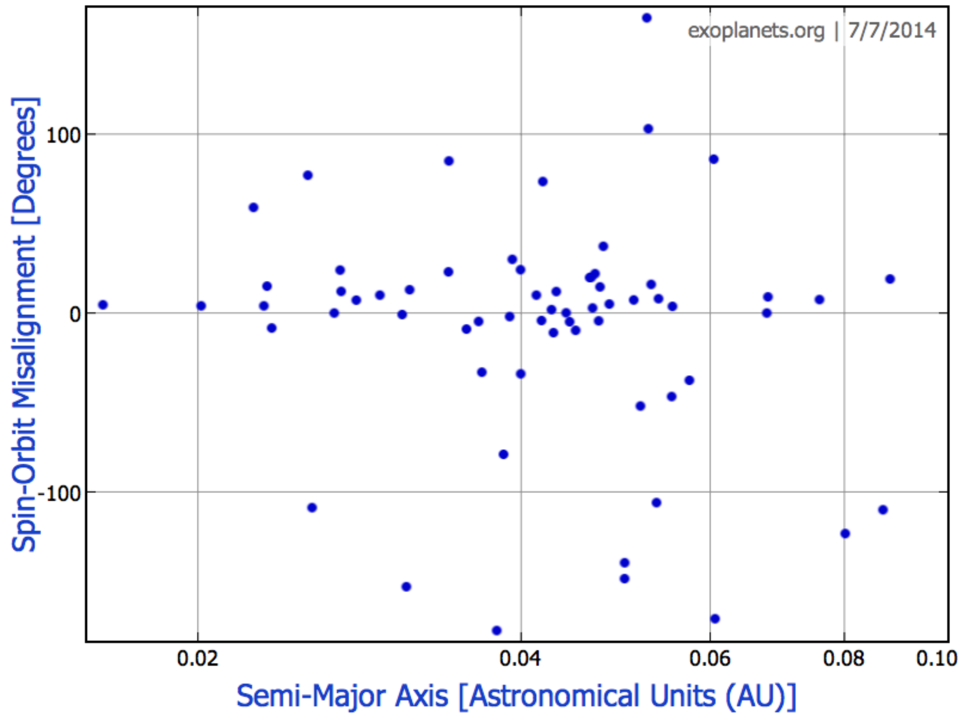


Spin-Orbit Misalignment in Hot Jupiter Systems



Possible causes for misalignment:

Spin-Orbit Misalignment in Hot Jupiter Systems



Possible causes for misalignment:

- Primordial disk misalignment

  (e.g. Bate et al. 2011, Lai et al. 2011, Batygin & Adams 2013, Lai 2014)

- Planet-planet interactions:

  - scattering (e.g. Ford & Rasio 2008, Wu & Lithwick 2011)

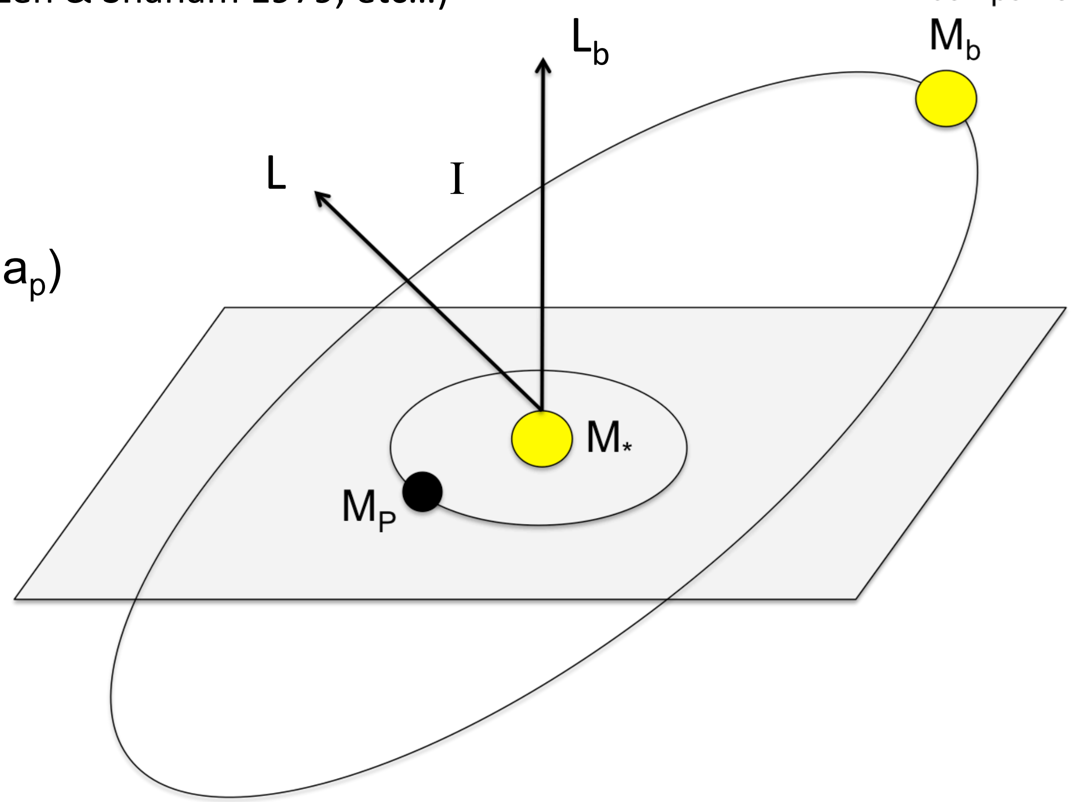
  - Secular chaos (e.g. Wu & Lithwick 2011)

- **Kozai oscillations** due to a distant stellar companion (e.g. Wu & Murray 2003, Fabrycky & Tremaine 2007, Naoz et al. 2012)

Kozai - Lidov Mechanism

(Lidov 1962, Kozai 1962, Mazeh & Shaham 1979, etc…)

Hierarchical system ($a_b >> a_p$)

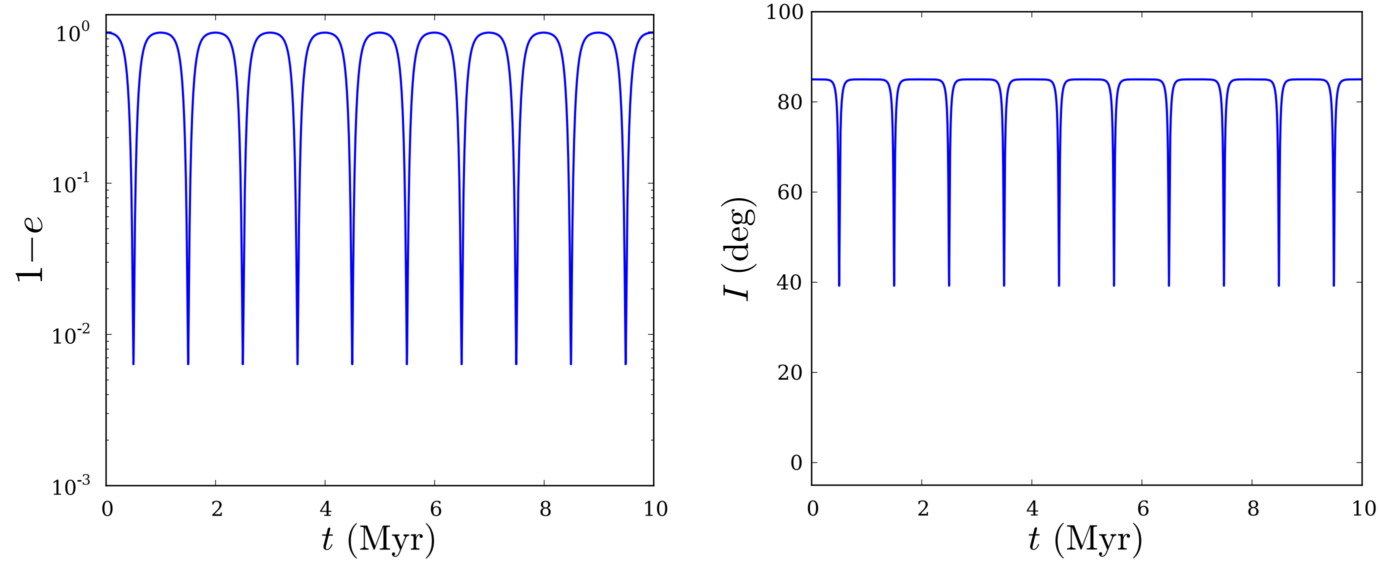


Planetary orbit is perturbed by quadrupole potential of companion (secular perturbation)

If binary inclination greater than ~40 degrees, get long term variations in eccentricity & inclination

Kozai Mechanism

Conserved quantity $\Theta = (1 - e^2)\cos^2(I)$



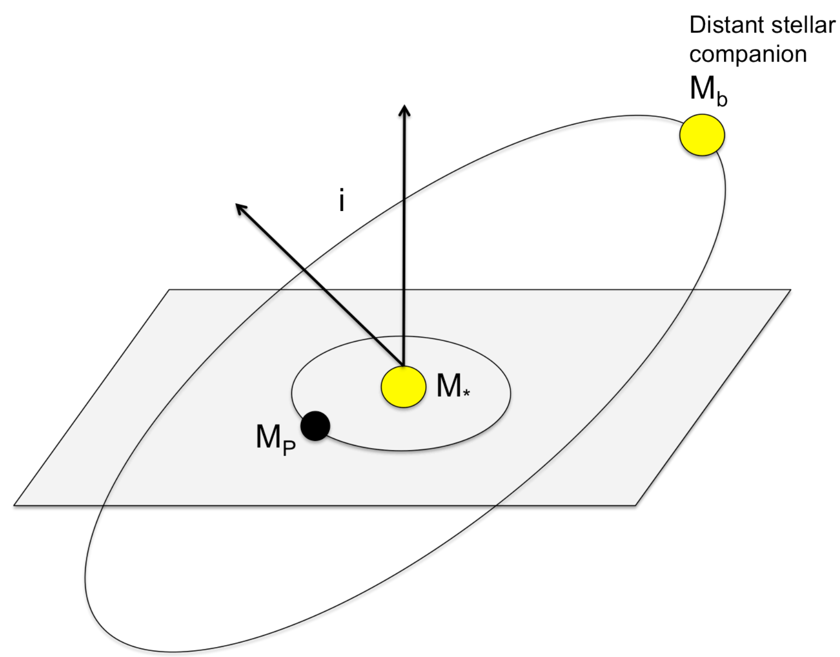
If inclination is high (~85 deg), max eccentricity > 0.99

$$\dot{\omega}_k \sim \frac{1}{t_k} = \frac{M_b}{M_\star}\left(\frac{a}{a_b}\right)^3 \Omega_p \qquad \text{where} \qquad \Omega_p = \left(\frac{GM_\star}{a^3}\right)^{1/2}$$

Corrections to Kozai

- Additional periastron precession due to GR, static tides, oblateness

- **Tidal dissipation in planet**



Hot Jupiter formation via high eccentricity migration

- Kozai oscillations pump planet into high-e orbit and changes orbital inclination
- Tidal dissipation in planet during high-e phases causes orbital decay
- Combined effects can result in planets in ~ few days orbit from host star (a hot Jupiter is born!)

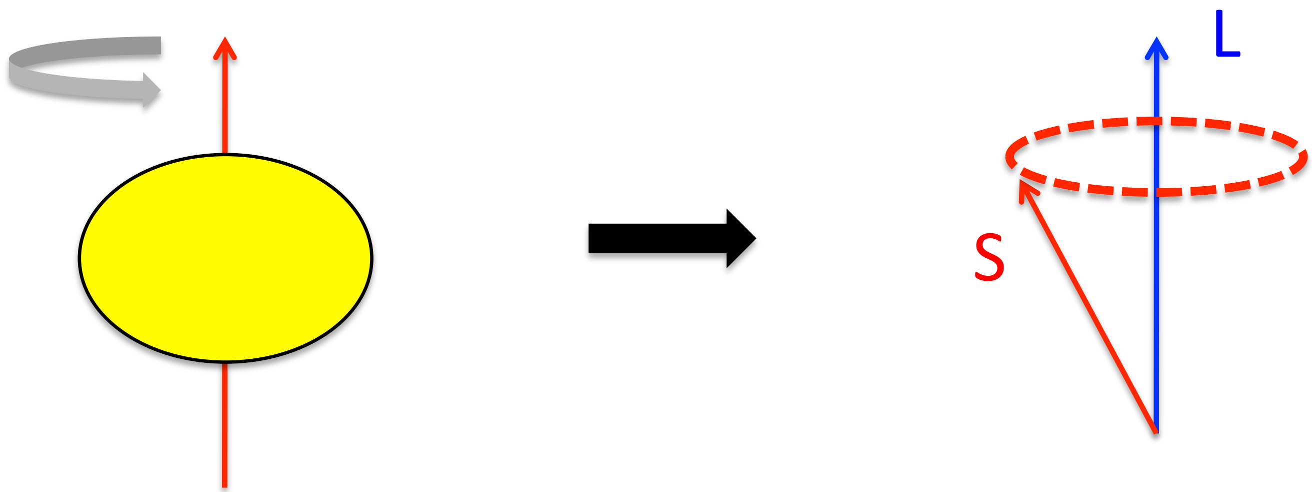
The spin in spin-orbit misalignment

During a Kozai cycle, planet orbit undergoes large variation in both **eccentricity** and **inclination** relative to the outer binary axis.

What happens to the stellar spin during this time?

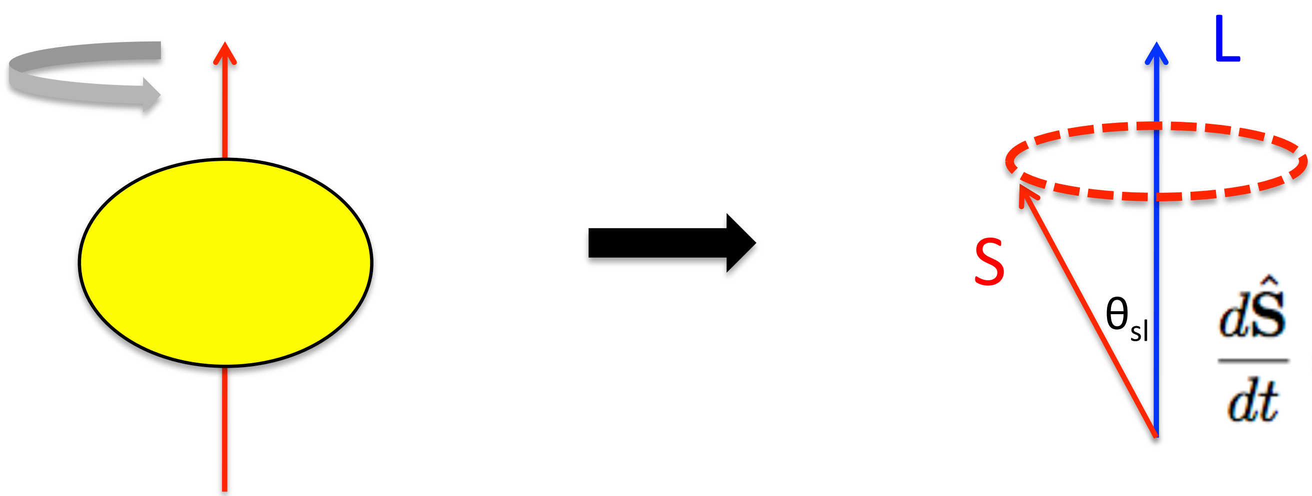
Stellar Spin Evolution

Star is oblate, experiences a torque from the planet, spin vector precesses at frequency Ω_{ps}



Stellar Spin Evolution

Star is oblate, experiences a torque from the planet, spin vector S precesses at frequency Ω_{ps}

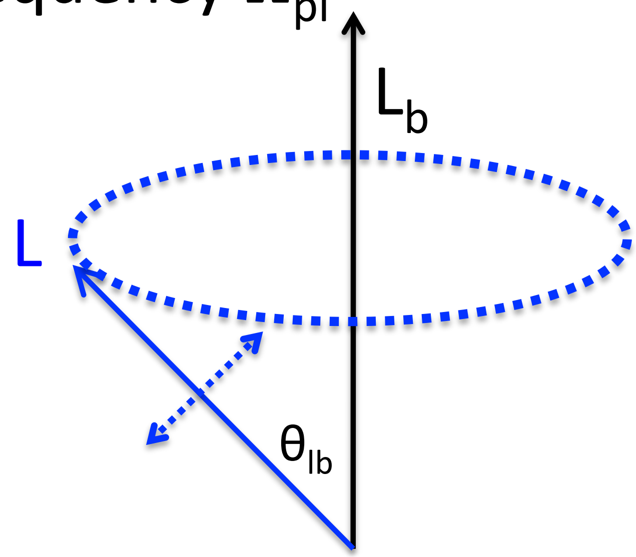


$$\frac{d\hat{\mathbf{S}}}{dt} = \Omega_{\rm ps}\hat{\mathbf{L}} \times \hat{\mathbf{S}}$$

$$\begin{aligned} \Omega_{\rm ps} &= -\frac{3GM_p(I_3 - I_1)}{2a^3(1-e^2)^{3/2}}\frac{\cos\theta_{\rm sl}}{S} \\ &\propto \frac{\Omega_{\rm s} M_{\rm p}}{a^3(1-e^2)^{3/2}} \end{aligned}$$

Planet Orbit Evolution

Orbital angular momentum axis L is precessing and nutating around the (fixed) binary axis L_b, with nodal precession frequency Ω_{pl}



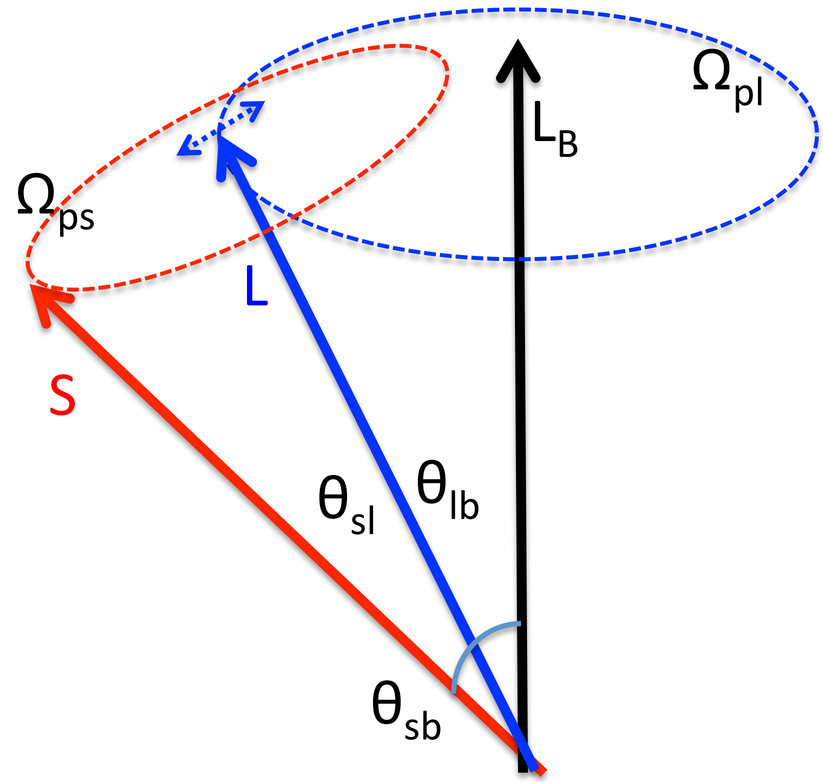
$$\Omega_{\rm pl} \approx \frac{1}{t_k(1-e^2)}$$

$$t_k = \frac{M_\star}{M_b}\left(\frac{a_b}{a}\right)^3 \frac{1}{\Omega_p}$$

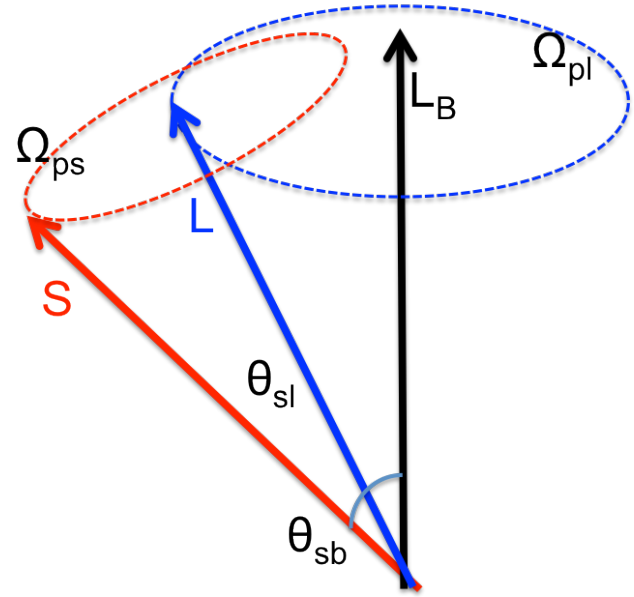
Spin-Orbit Evolution

- Kozai: eccentricity and inclination oscillations at frequency Ω_{pl}
- Mutual spin and orbital precession at frequency Ω_{ps}

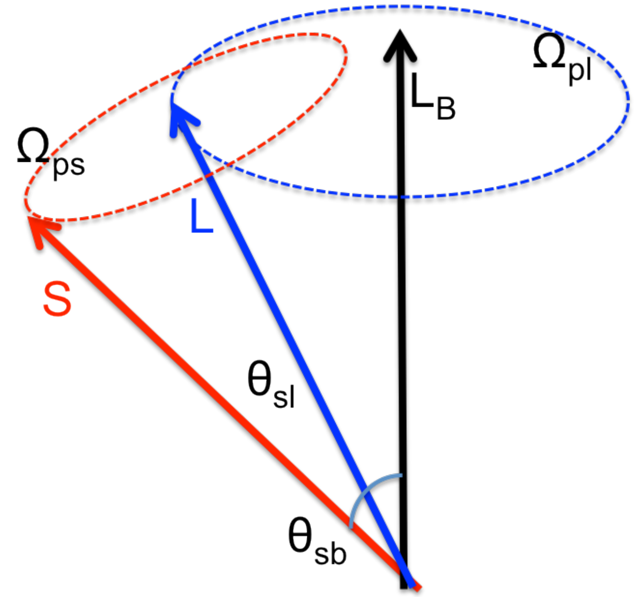
Throw them together → what happens?



Expect 3 qualitatively different regimes



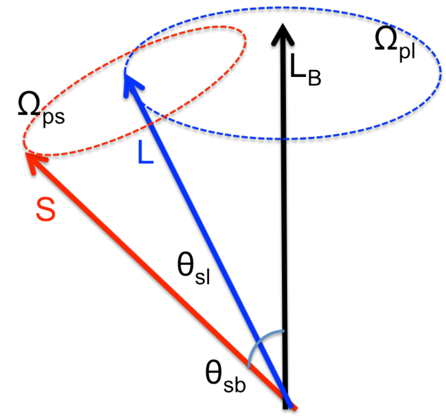
Expect 3 qualitatively different regimes



- Depends on the relative values of the precession rates Ω_{pl} and Ω_{ps}

- Both $\Omega_{pl} \sim (1-e^2)^{-1}$ and $\Omega_{ps} \sim (1-e^2)^{-3/2}$ are strong functions of eccentricity (and e changes during a Kozai cycle)

3 Regimes



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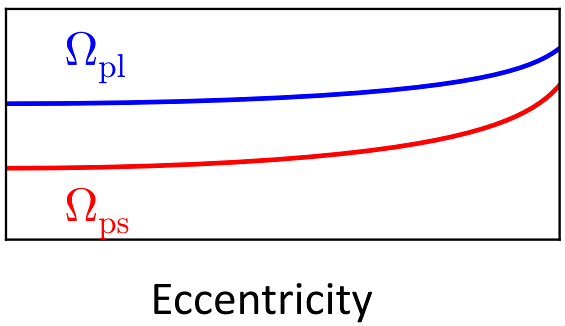
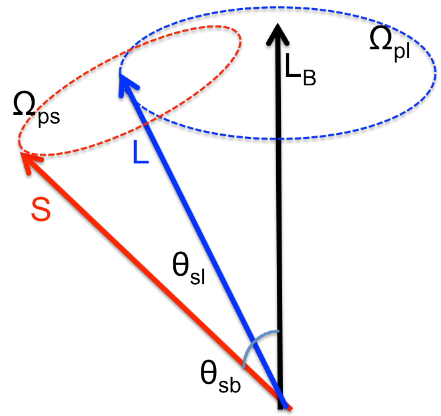


$$\left|\frac{\Omega_{ps}}{\Omega_{pl}}\right| < 1 \text{ throughout the Kozai cycle}$$

"Non-adiabatic"

$\theta_{sb} \approx$ constant

3 Regimes



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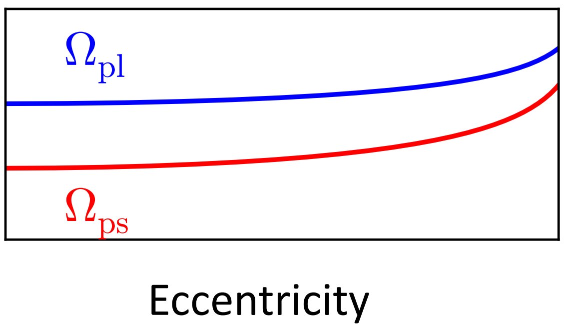

$$\left|\frac{\Omega_{ps}}{\Omega_{pl}}\right| < 1 \text{ throughout the Kozai cycle}$$

"<u>Non-adiabatic</u>"

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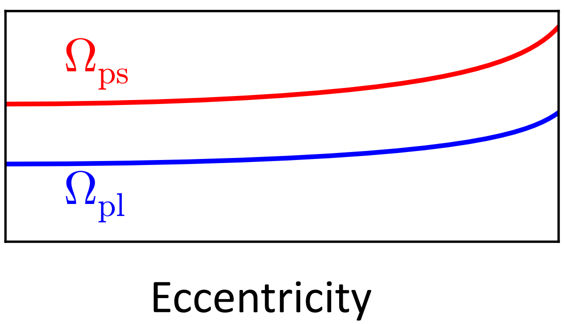
III

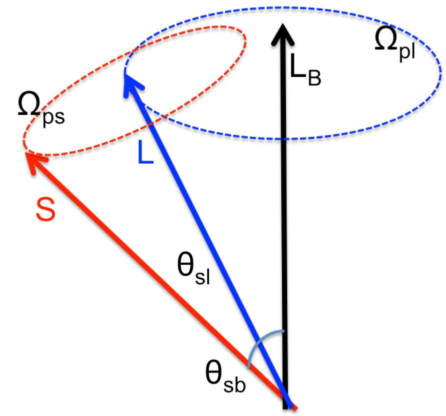


$$\left|\frac{\Omega_{ps}}{\Omega_{pl}}\right| > 1 \text{ throughout the Kozai cycle}$$

"<u>Adiabatic</u>"

$\theta_{sl} \approx$ constant

3 Regimes



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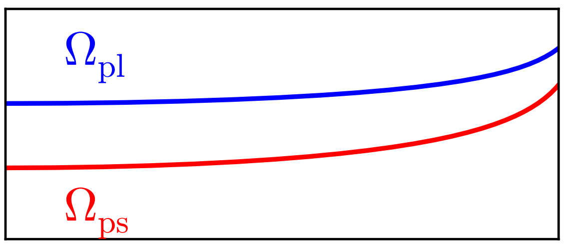
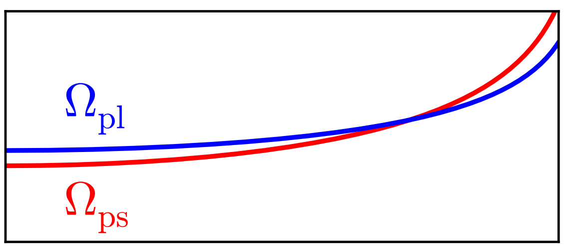


$$\left|\frac{\Omega_{ps}}{\Omega_{pl}}\right| < 1 \text{ throughout the Kozai cycle}$$

"Non-adiabatic"

$\theta_{sb} \approx$ constant

II

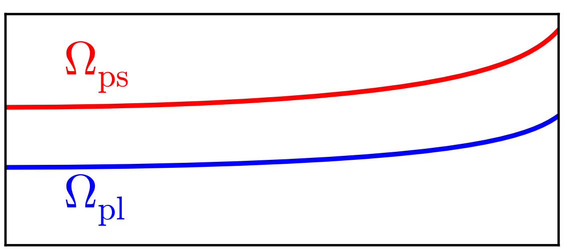


$$\left|\frac{\Omega_{ps}}{\Omega_{pl}}\right| = 1 \text{ during the Kozai cycle}$$

"Trans-adiabatic"

Complex behavior due to secular resonance!

III



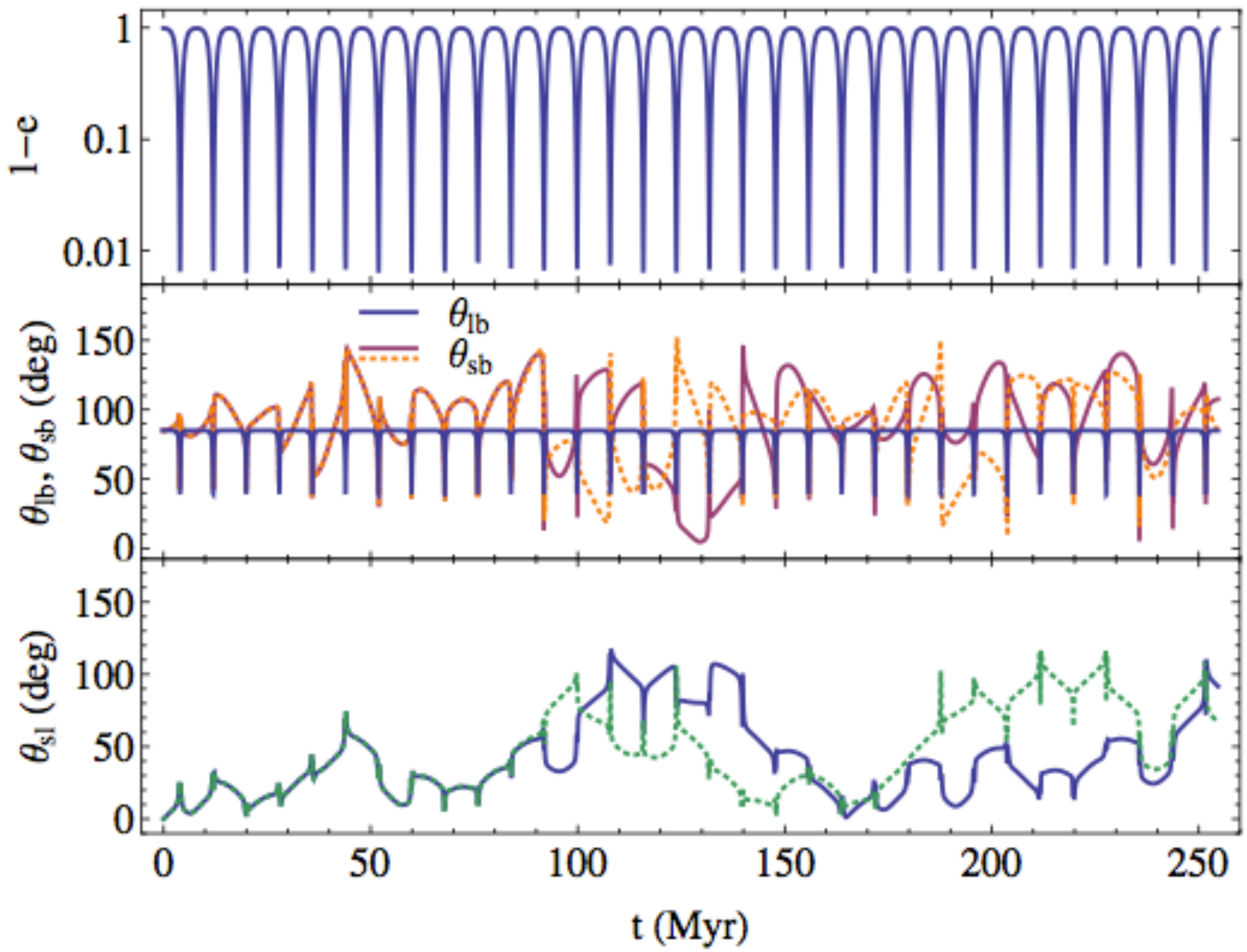
Eccentricity

$$\left|\frac{\Omega_{ps}}{\Omega_{pl}}\right| > 1 \text{ throughout the Kozai cycle}$$

"Adiabatic"

$\theta_{sl} \approx$ constant

Trans-adiabatic regime $\left|\frac{\Omega_{\rm ps}}{\Omega_{\rm pl}}\right| = 1$



N. Storch, from Storch, Anderson, & Lai 2014, submitted

Predicting the Regimes

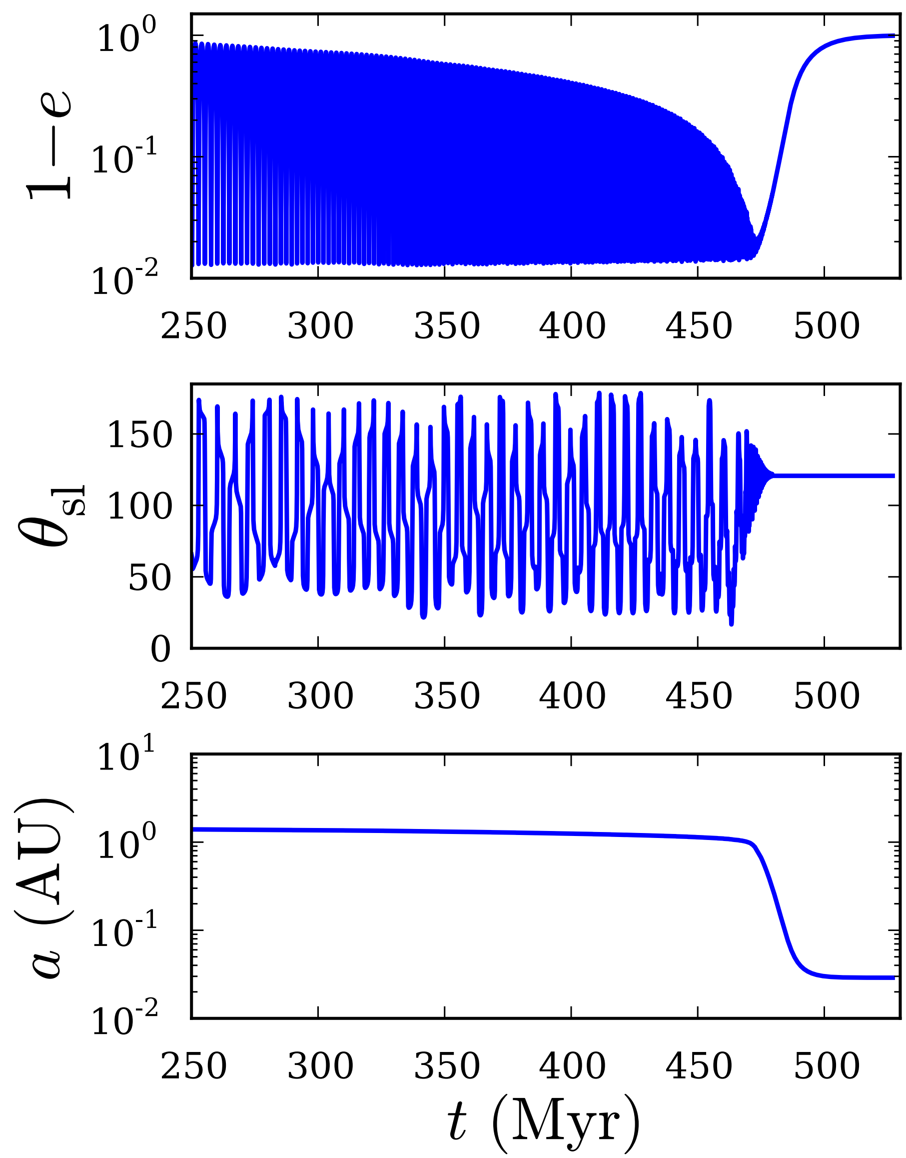
Predicting the Regimes

$$\frac{\Omega_{\rm ps}}{\Omega_{\rm pl}} \propto \frac{M_p \Omega_\star}{a^{9/2}}$$

- Massive planets and/or rapidly rotating stars can be in the adiabatic regime ($\theta_{sl} \approx$ constant)

Tidal dissipation in planet + stellar spin-down

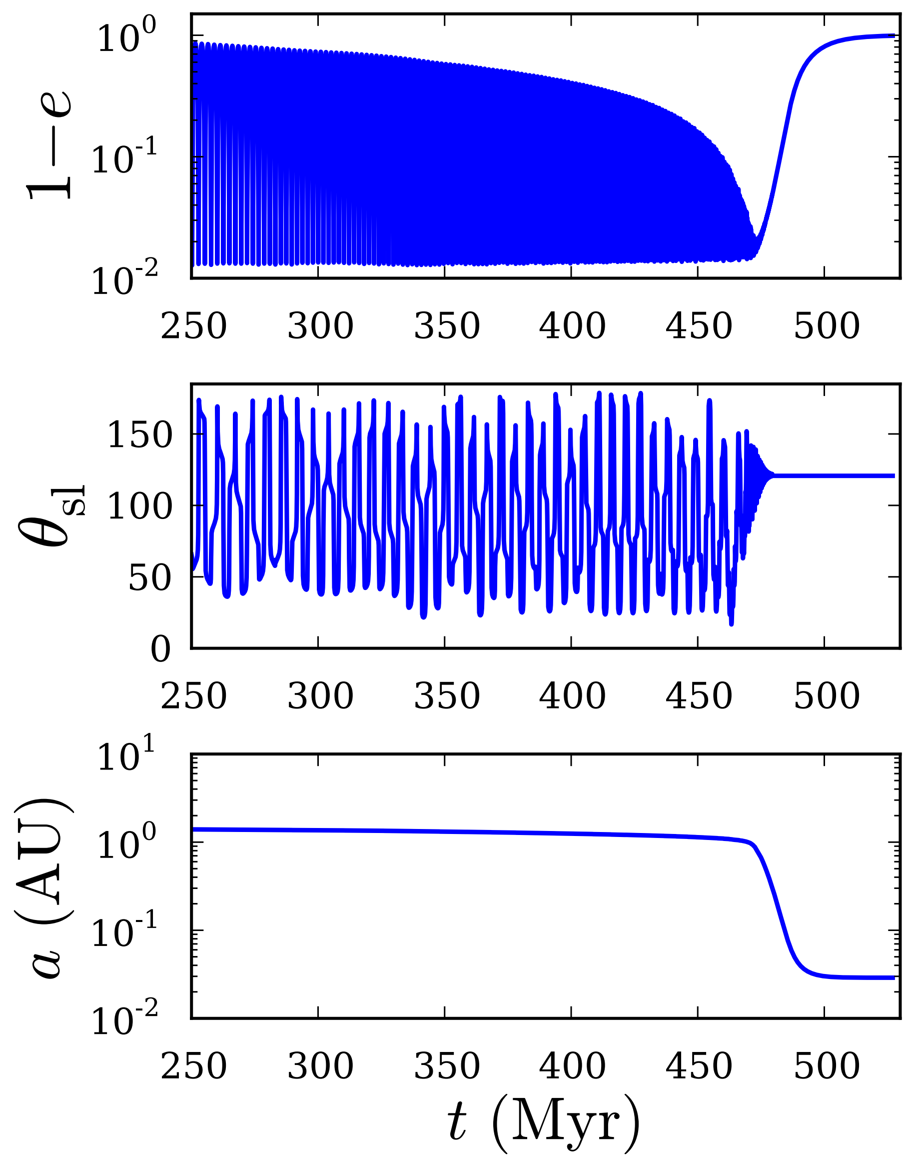
$$\frac{\Omega_{\rm ps}}{\Omega_{\rm pl}} \propto \frac{M_p \Omega_\star}{a^{9/2}}$$



Tidal dissipation in planet + stellar spin-down

$$\frac{\Omega_{\rm ps}}{\Omega_{\rm pl}} \propto \frac{M_p \Omega_\star}{a^{9/2}}$$

Once the semi-major axis decays, all systems end up in in the adiabatic regime

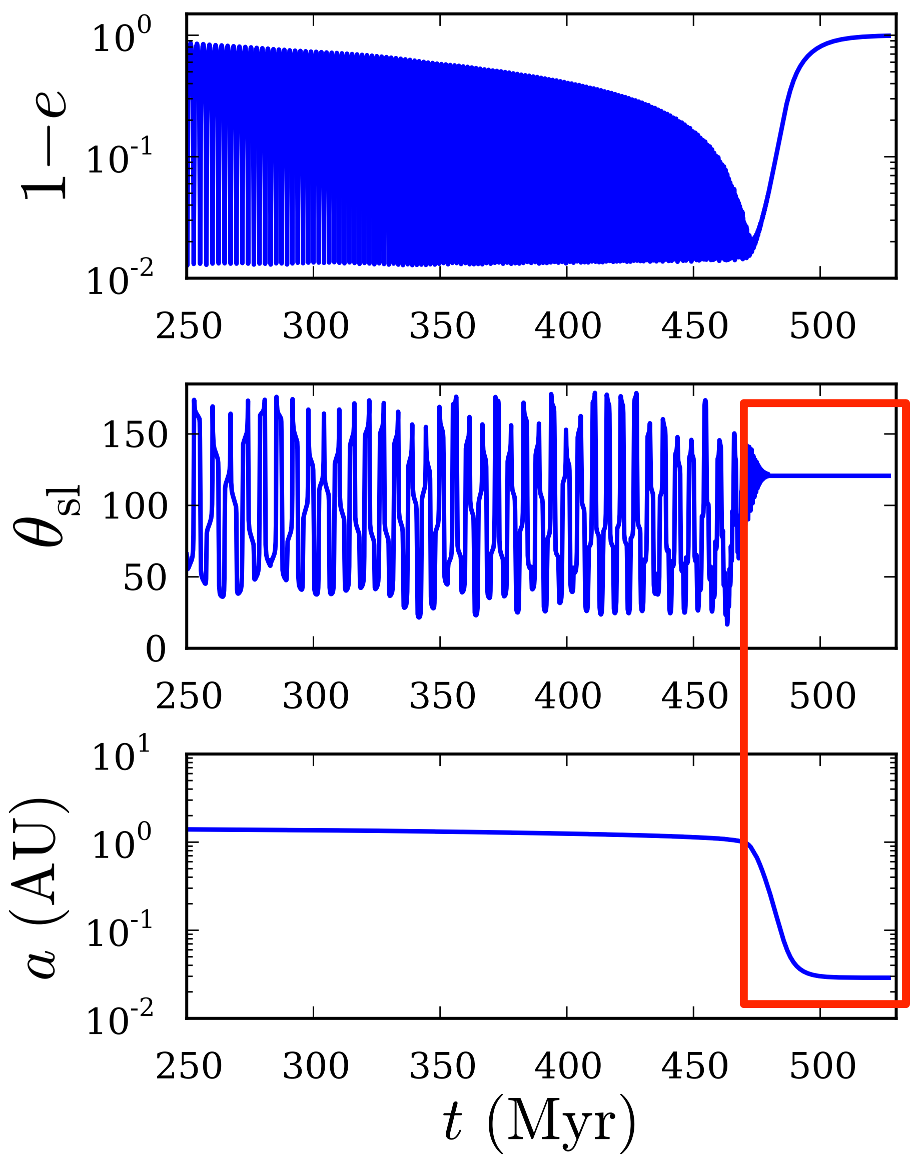


Tidal dissipation in planet + stellar spin-down

$$\frac{\Omega_{\rm ps}}{\Omega_{\rm pl}} \propto \frac{M_p \Omega_\star}{a^{9/2}}$$

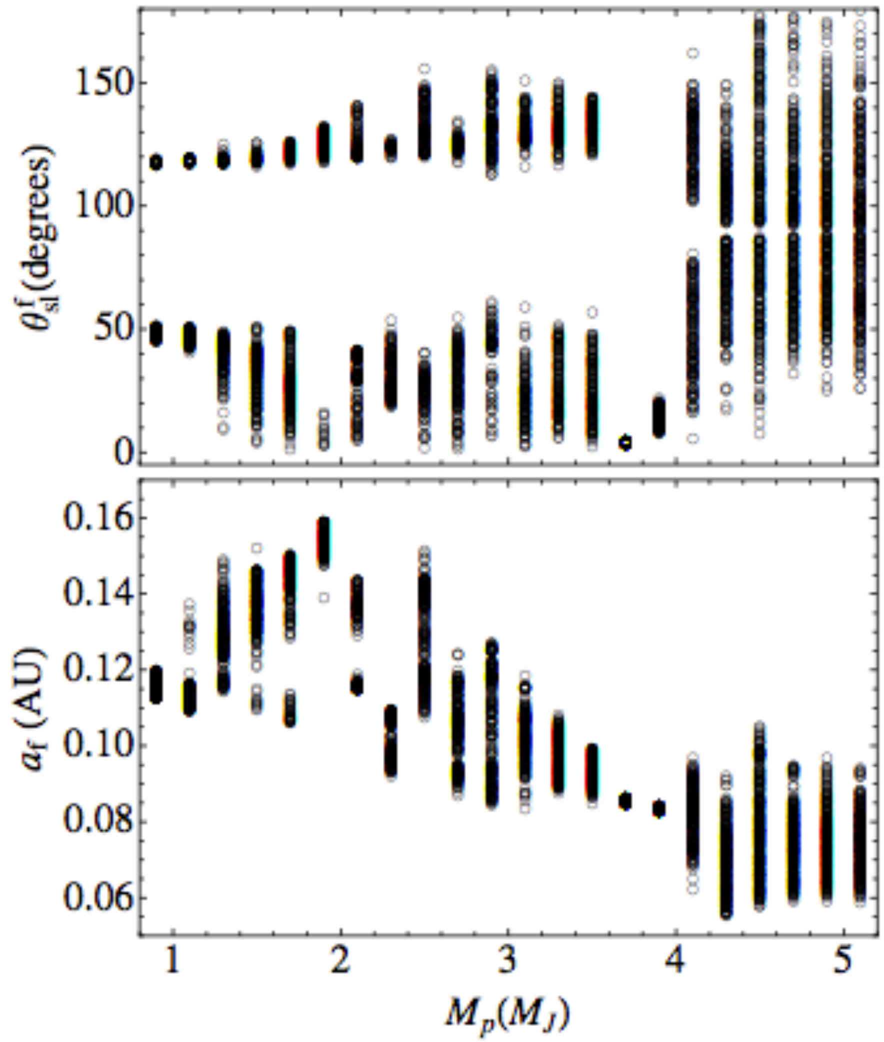
Once the semi-major axis decays, all systems end up in in the adiabatic regime

➔ spin-orbit angle settles to a final value



Memory of Chaos

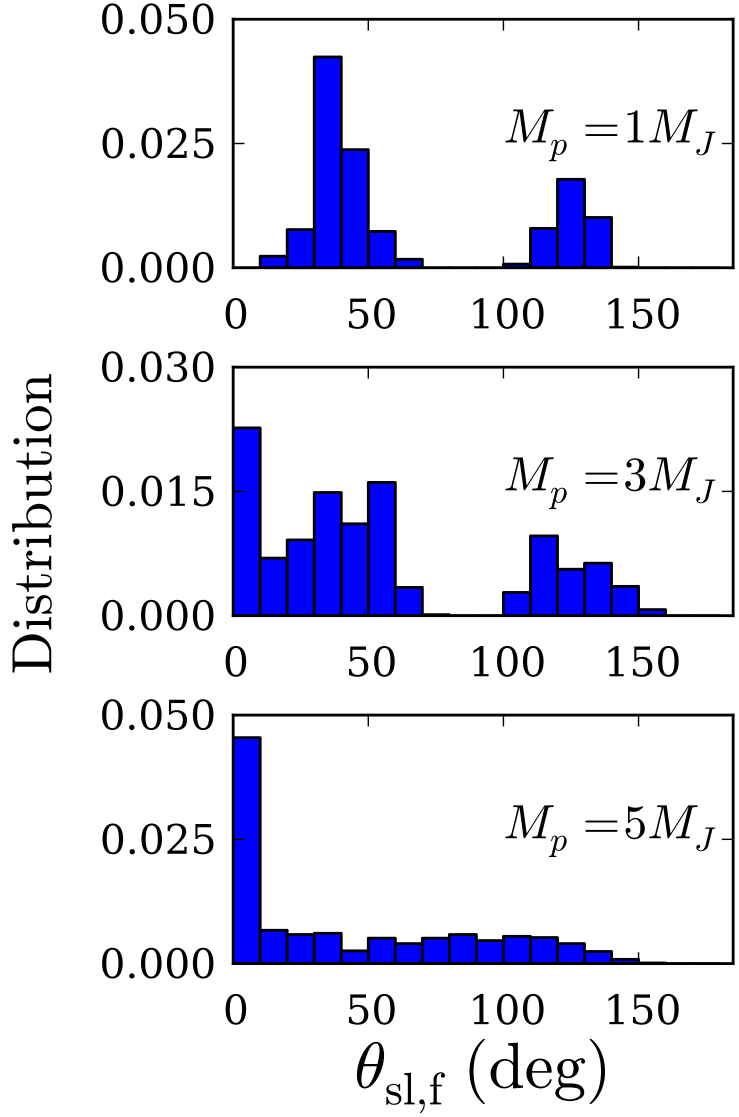
A tiny spread in initial conditions can lead to a large spread in the final spin-orbit misalignment



N. Storch, from Storch, Anderson, & Lai 2014, submitted

Observational Consequences

Distributions of the final spin-orbit angle

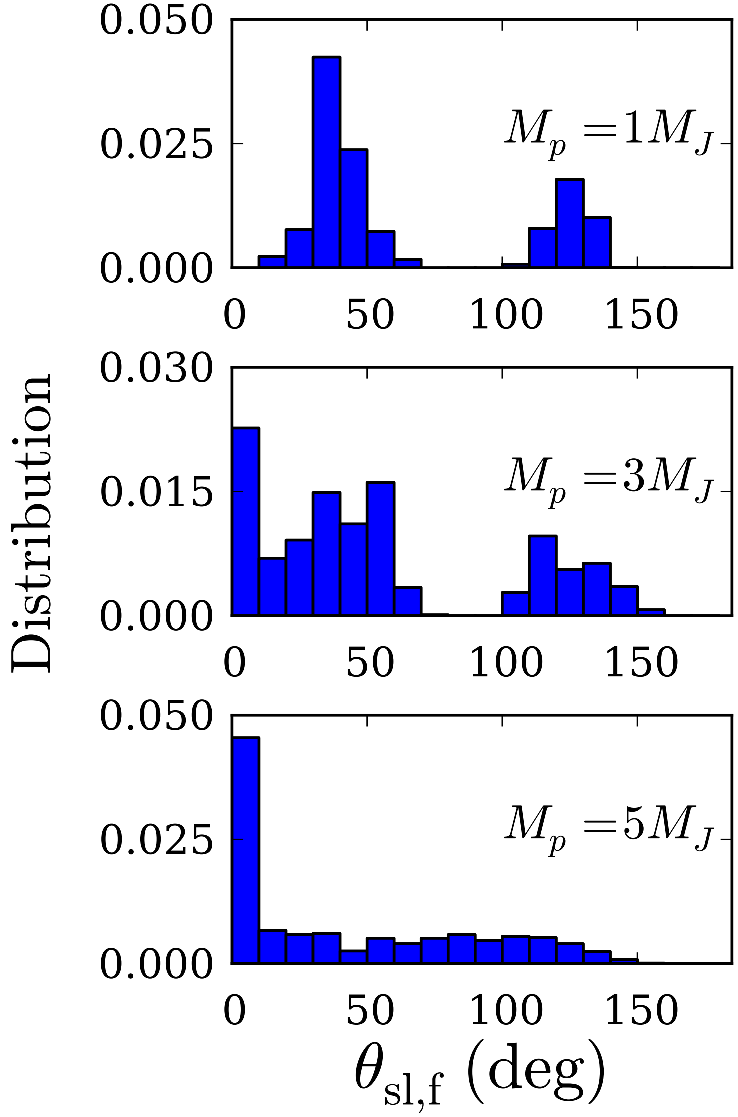


Parameters:
a_b = 200 AU

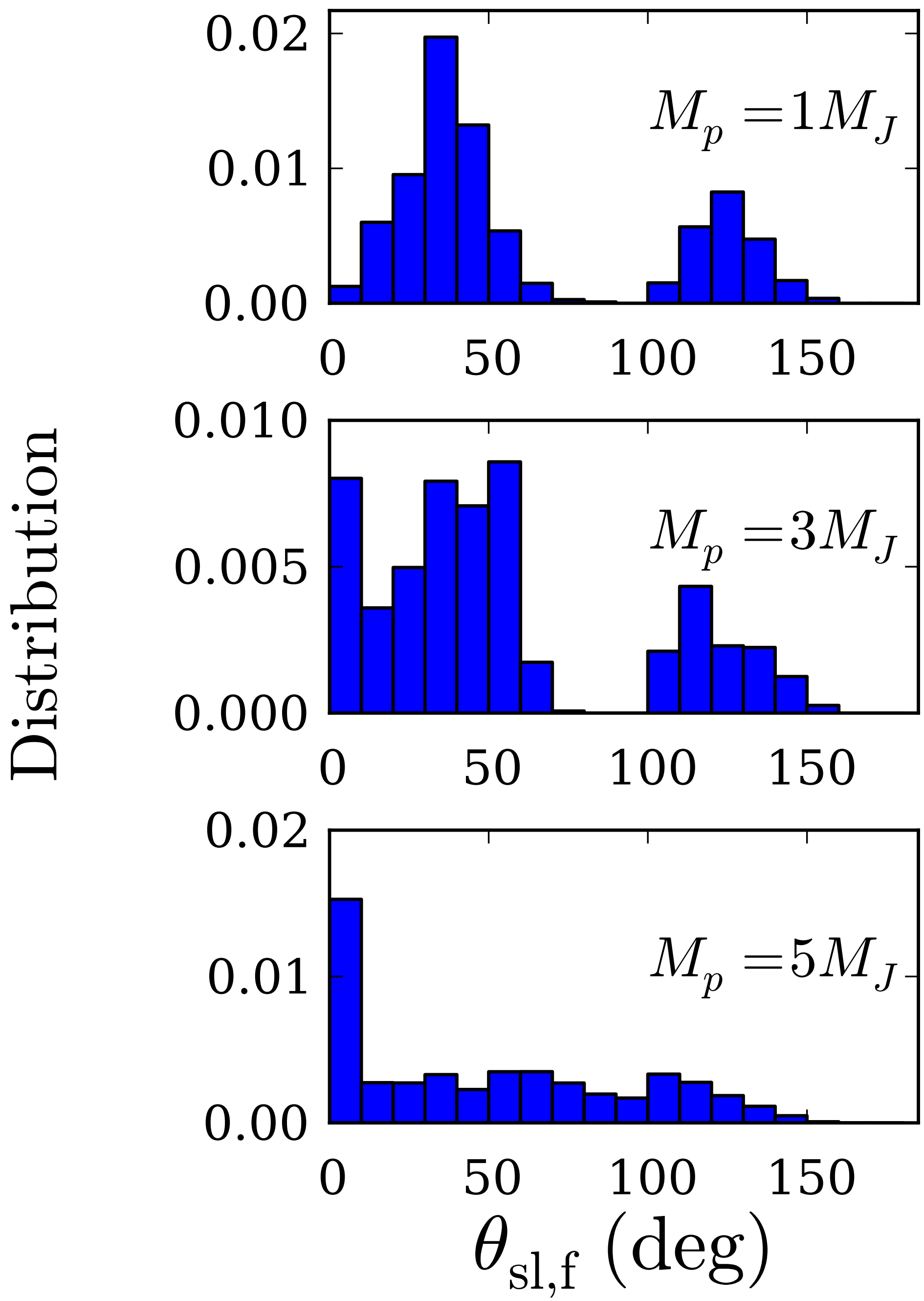
M_* = M_b = 1 M_{sun}

Stellar spin-down calibrated such that spin period = 27 days at 5 Gyr (Skumanich law)

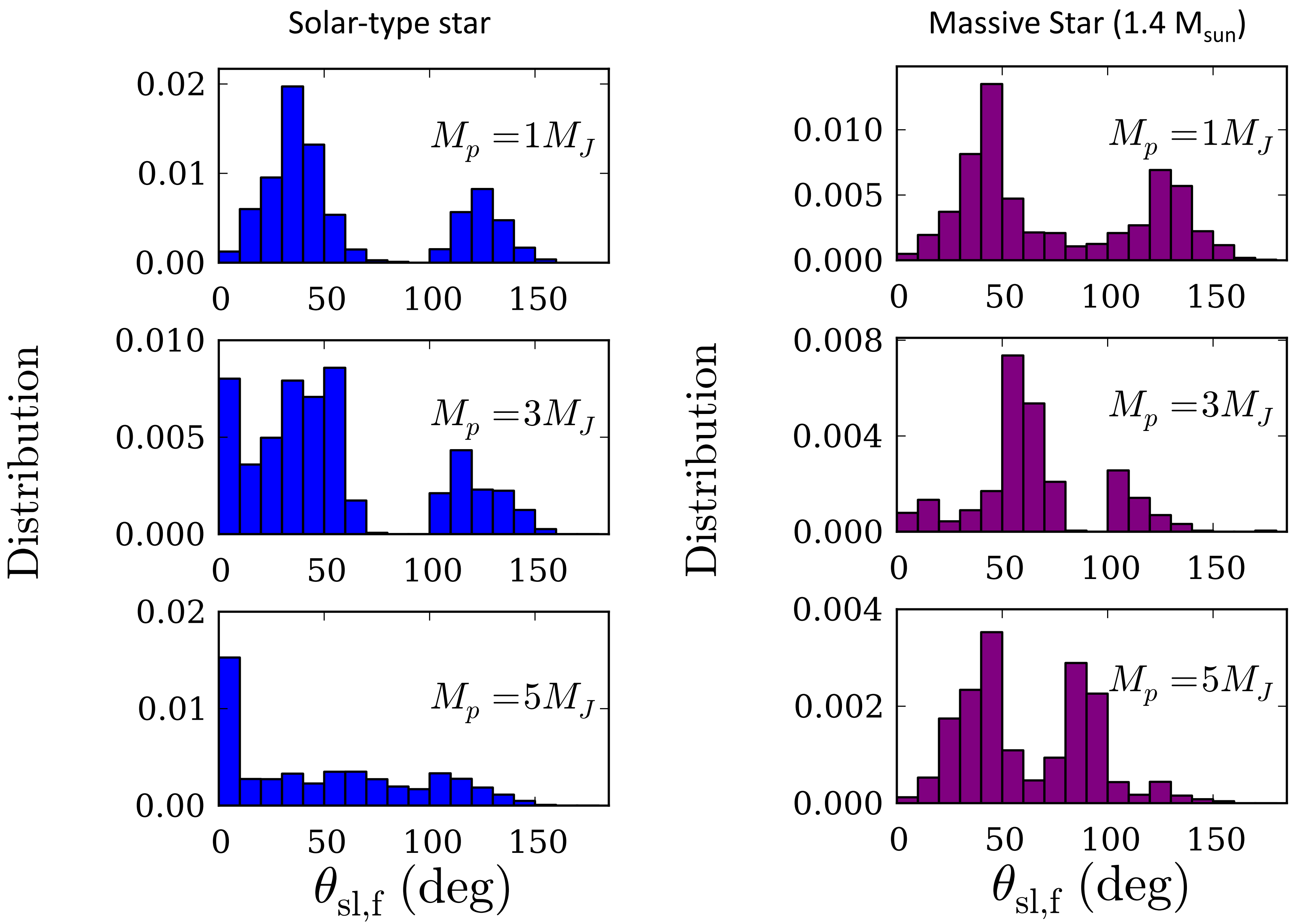
a = 1.5 AU



$$\frac{\Omega_{\rm ps}}{\Omega_{\rm pl}} \propto \frac{M_p \Omega_\star}{a^{9/2}}$$



Uniform distribution of initial semi-major axes (a = 1.5 – 3.5 AU)


Solar-type star
Massive Star (1.4 M$_{sun}$)
$M_p = 1M_J$
$M_p = 3M_J$
$M_p = 5M_J$
Distribution
$\theta_{\rm sl,f}$ (deg)
0.02
0.01
0.00
0.010
0.005
0.000
0.008
0.004
0.002
0
50
100
150

Conclusions

- Stellar spin plays a starring role in the spin-orbit evolution
- 3 qualitatively distinct regimes, with the possibility of chaos
- Final distribution depends on the planet mass, stellar properties, and spin history

Measuring Chaos

Define a “real” system with set of initial conditions, and “shadow” system with initial conditions differing by a small amount

$$\delta \equiv |\hat{\mathbf{S}}_{\rm real} - \hat{\mathbf{S}}_{\rm shadow}|$$

$$\delta(t) = \delta_0 e^{\gamma t}$$