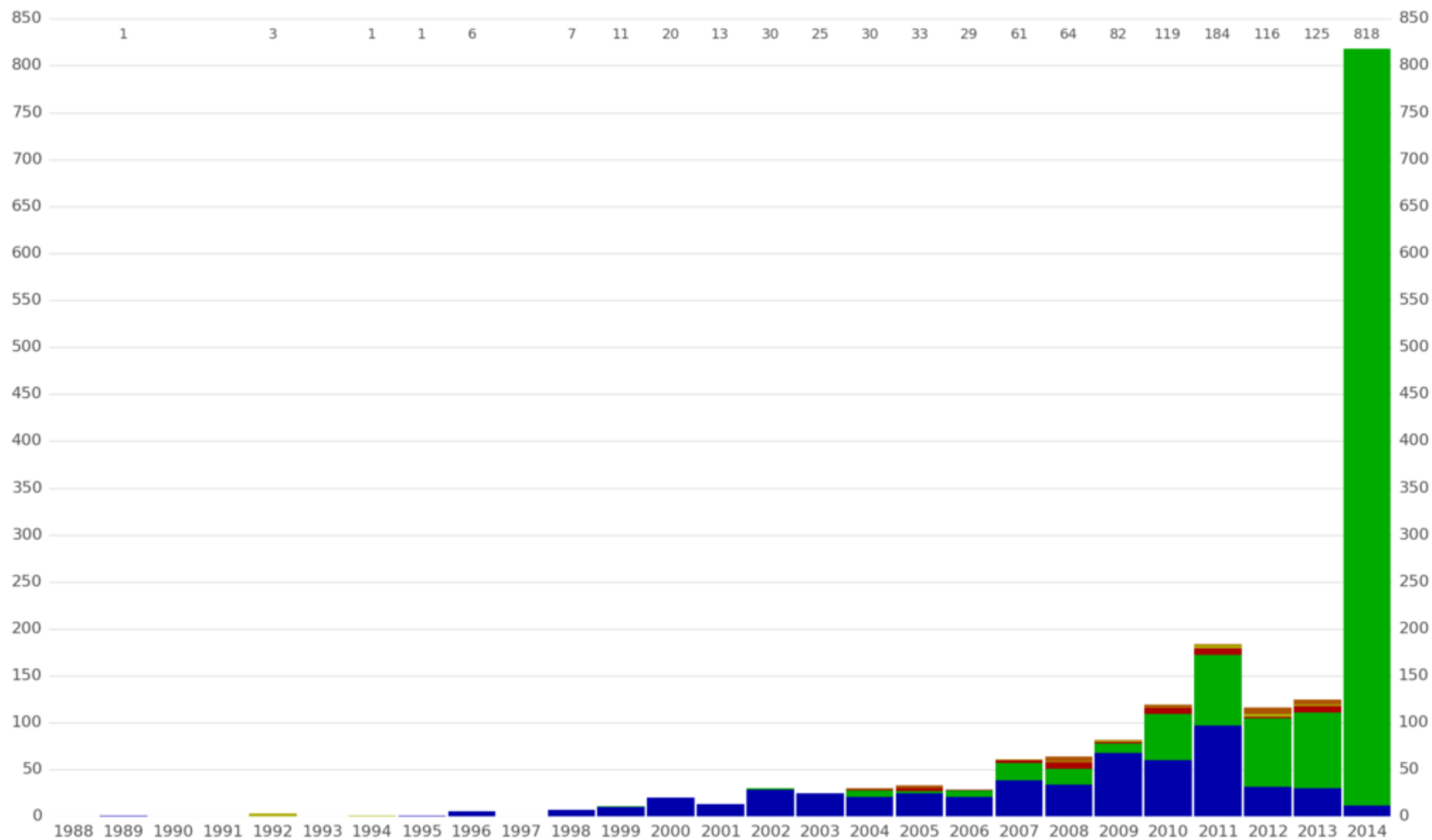
Extreme Exoplanetary Systems

Hot Jupiters, Star-Disk-Binary Interactions,
Spin Chaos, Circumbinary Planets

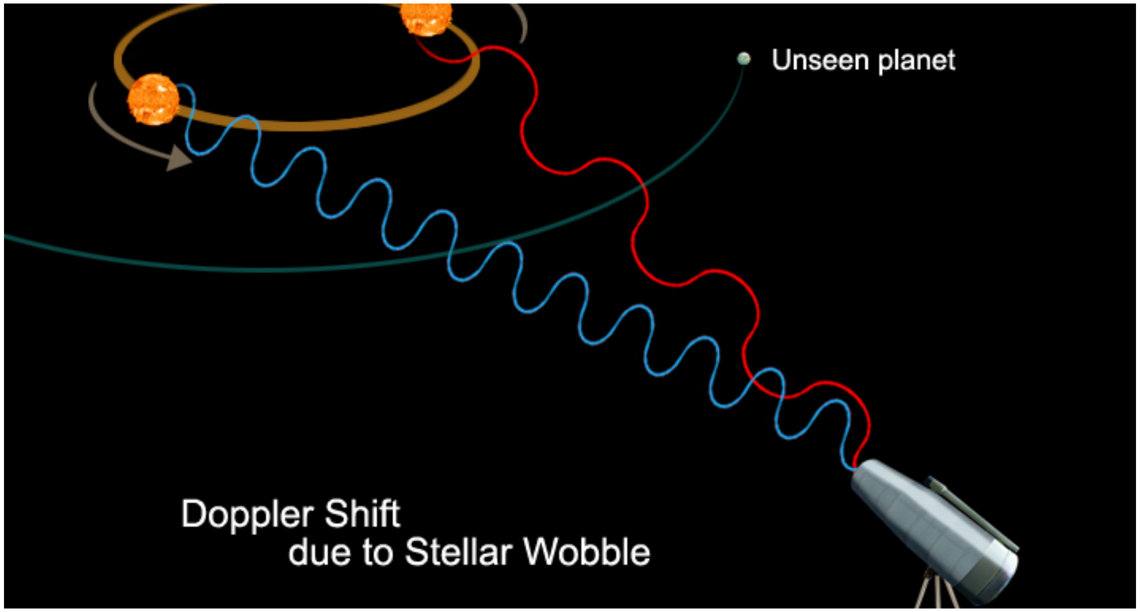
Dong Lai
Cornell University

Astronomy Colloquium, UCSC, April 1, 2015

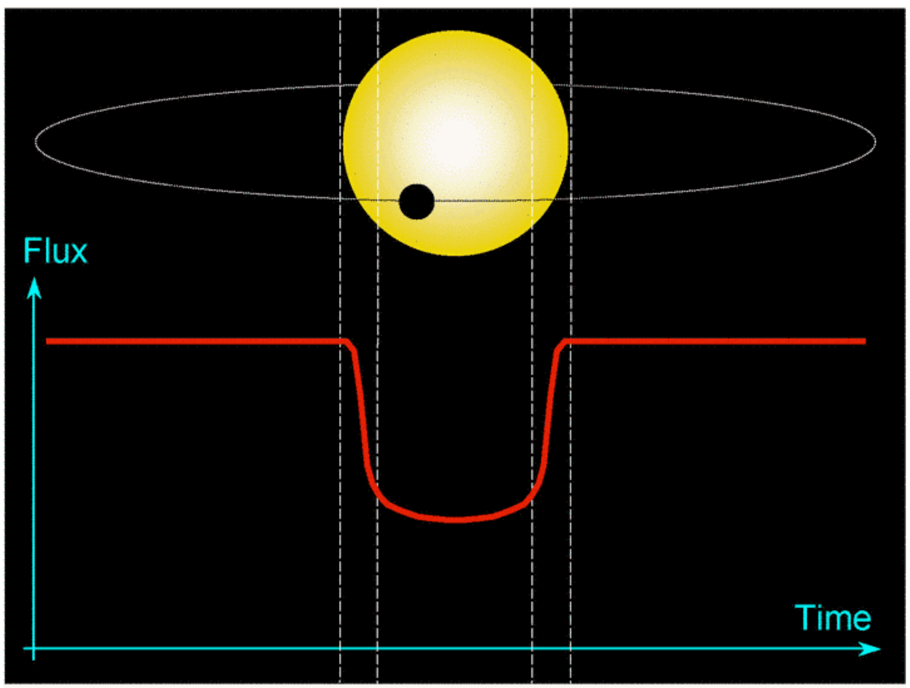
Number of planets by year of discovery



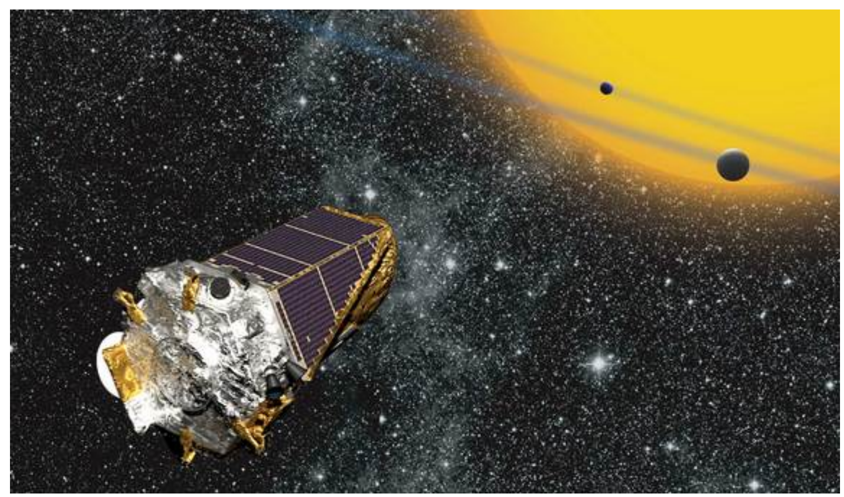
1500+ confirmed, ~4000 Kepler candidates

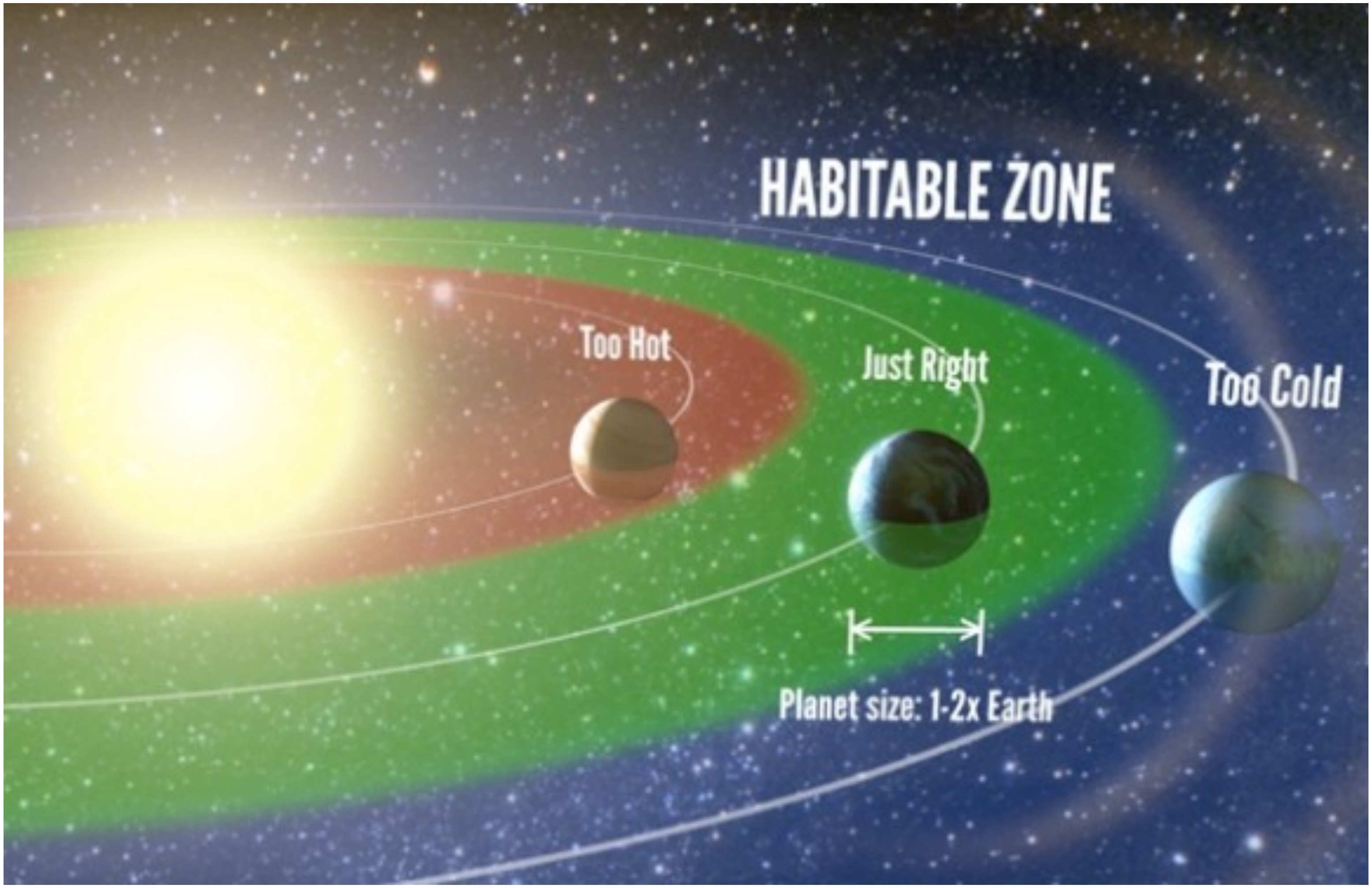


Radial Velocity Method



Transit Method



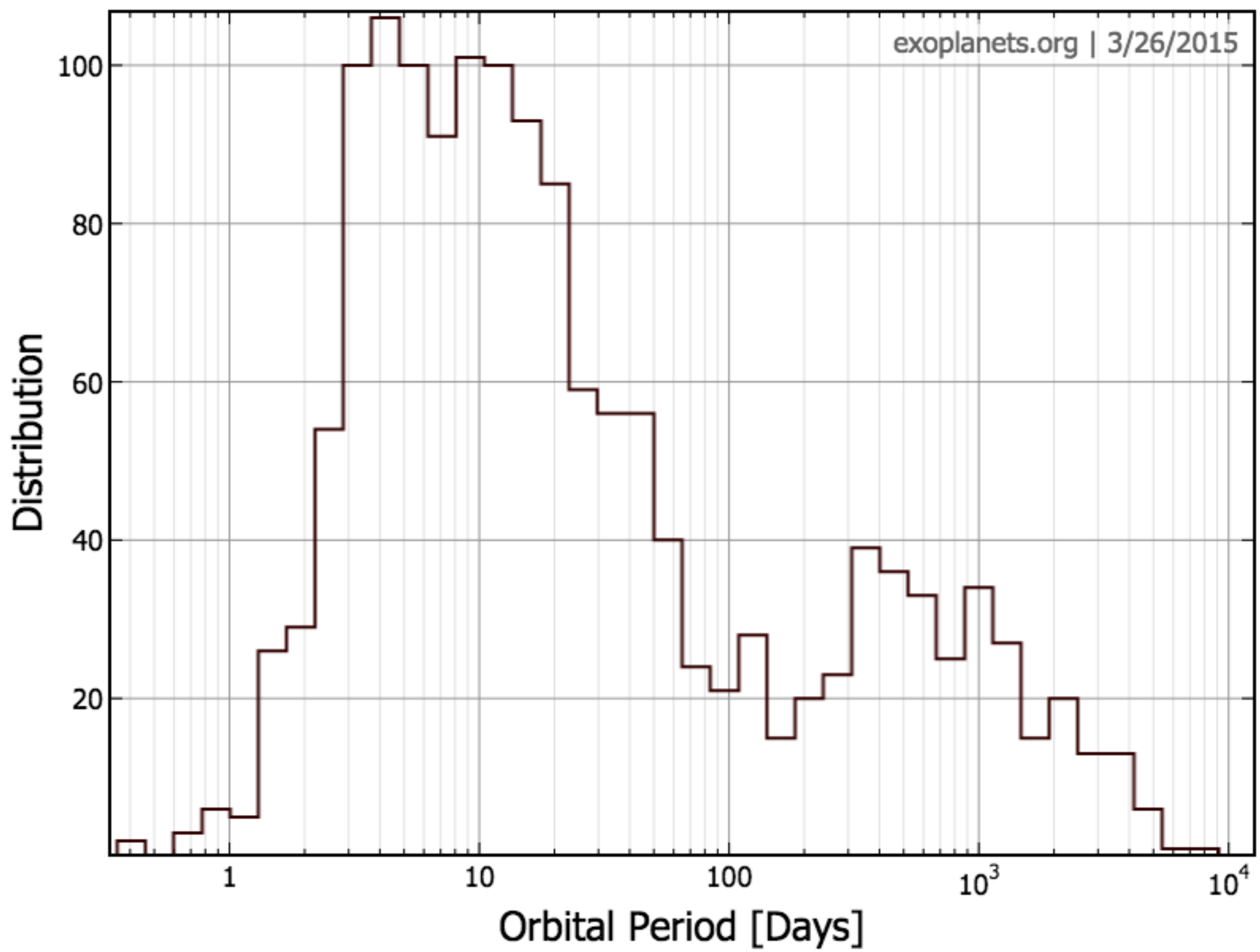


~10% of Sun-like stars have habitable Earth-size planets

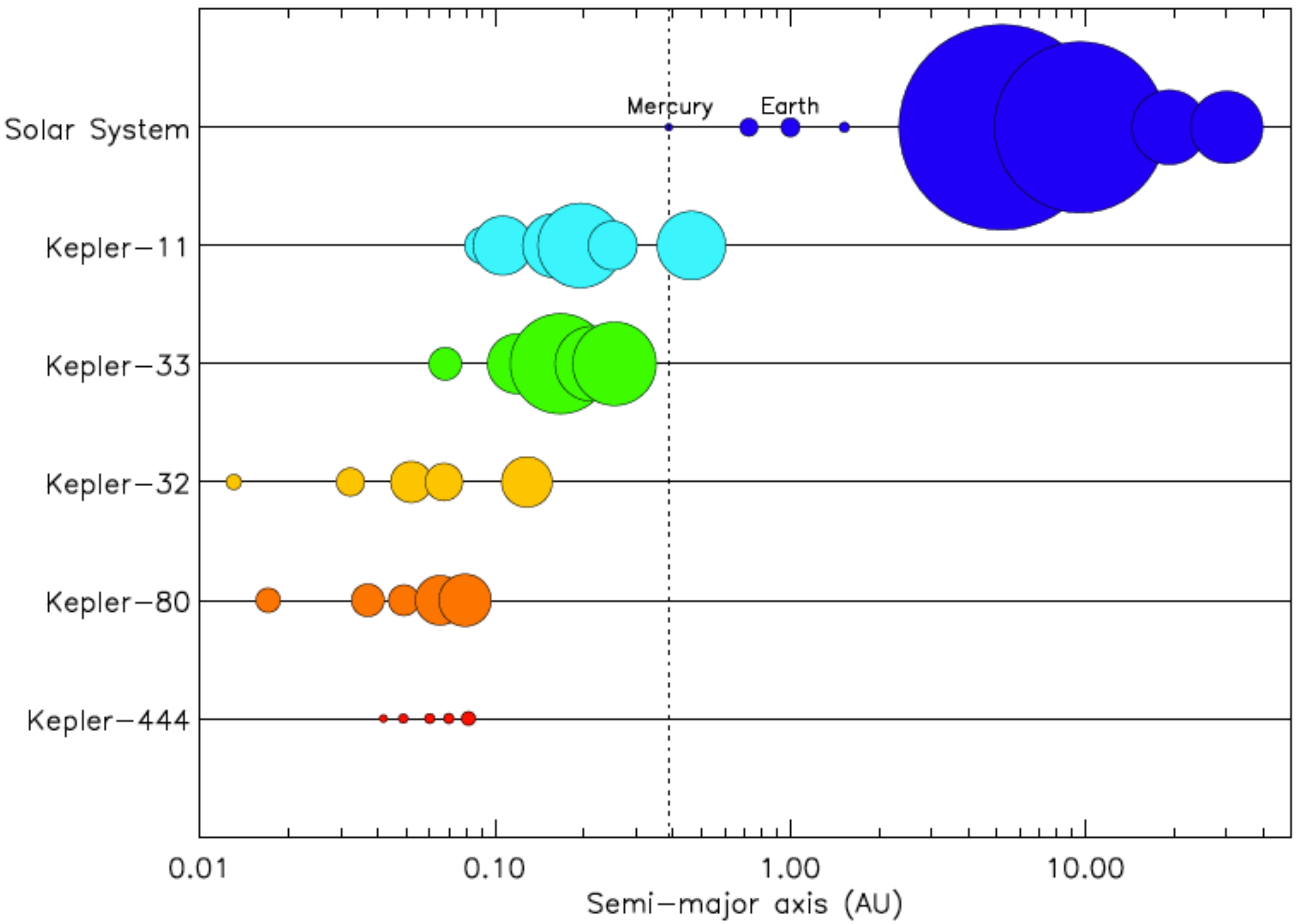
Petigura et al 2014: 42000 stars->603 planets,10 in habitable zone (1-2 R_e, ¼-4 Flux_e)

Surprises and Puzzles in Exoplanetary Systems

Orbital period puzzle

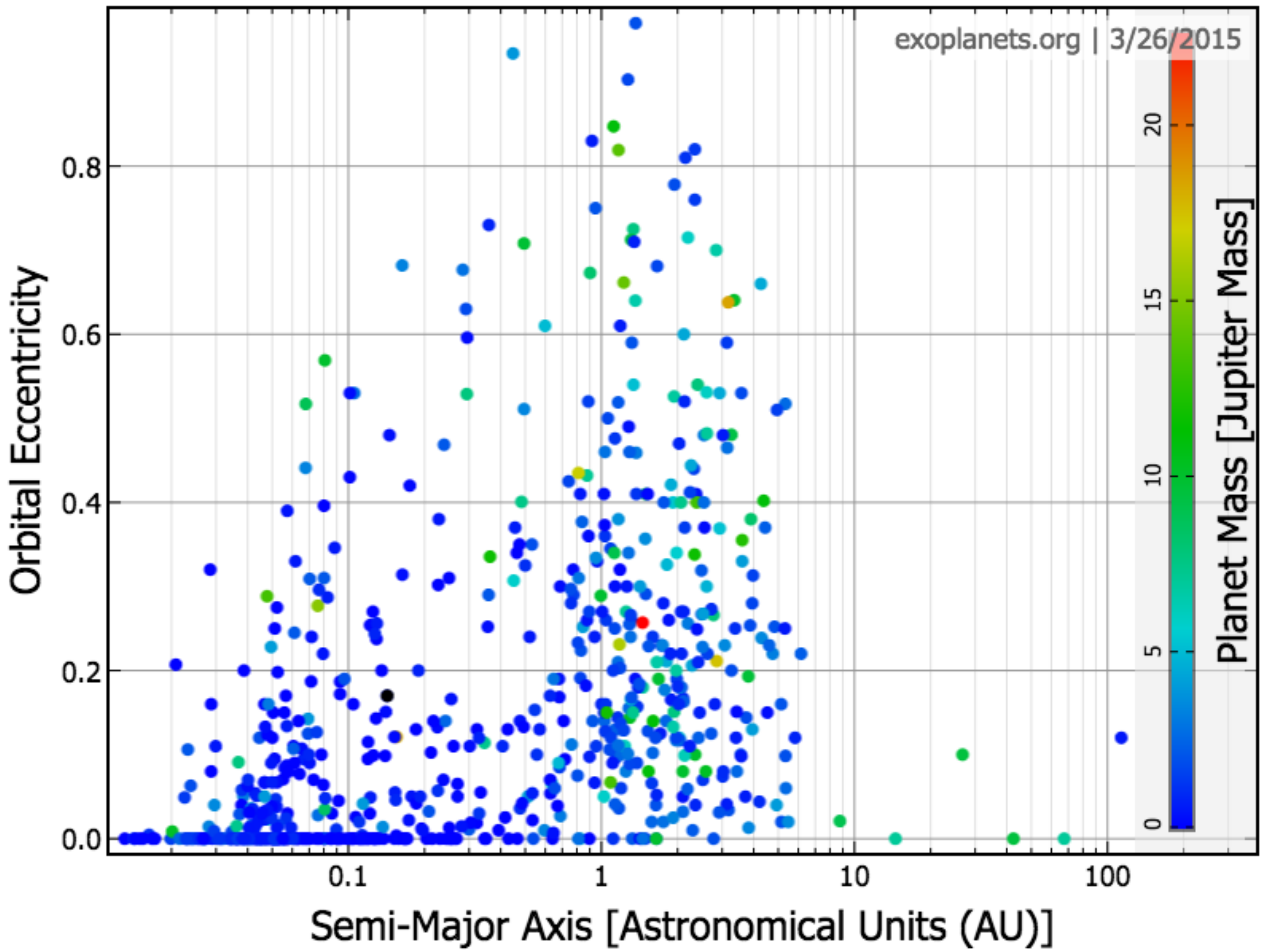


Kepler Compact Planetary Systems:

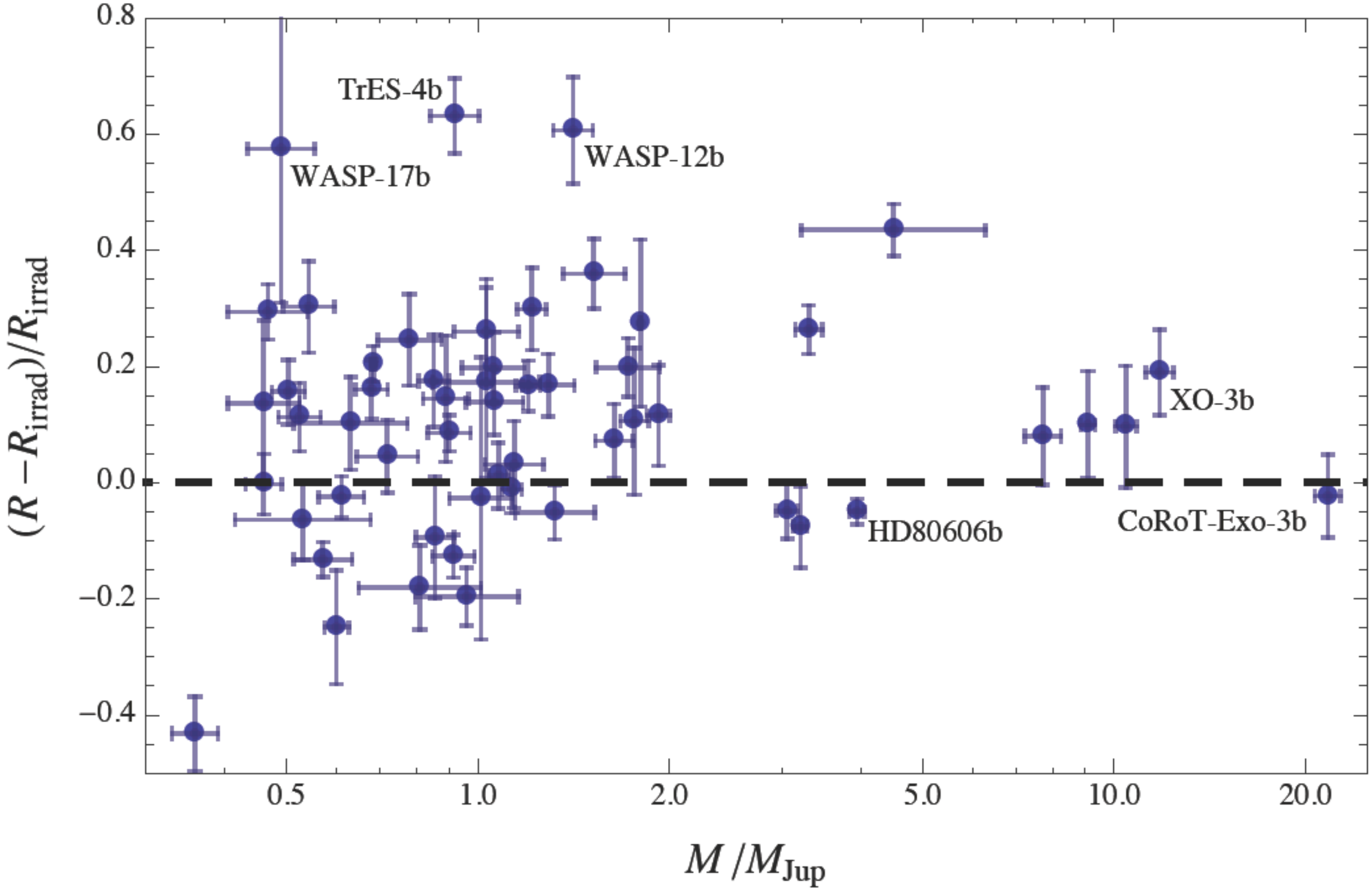


Campante et al. 2015

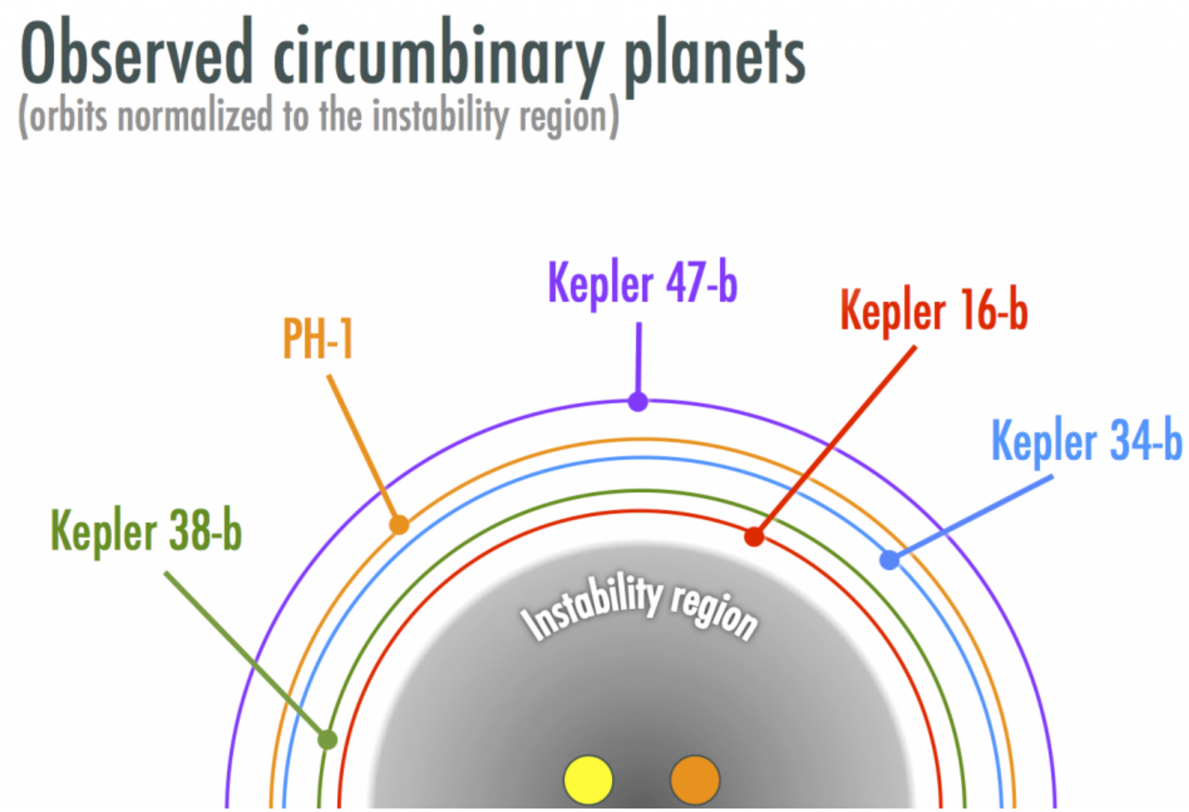
Eccentricity Puzzle



Planet Radius Inflation Puzzle



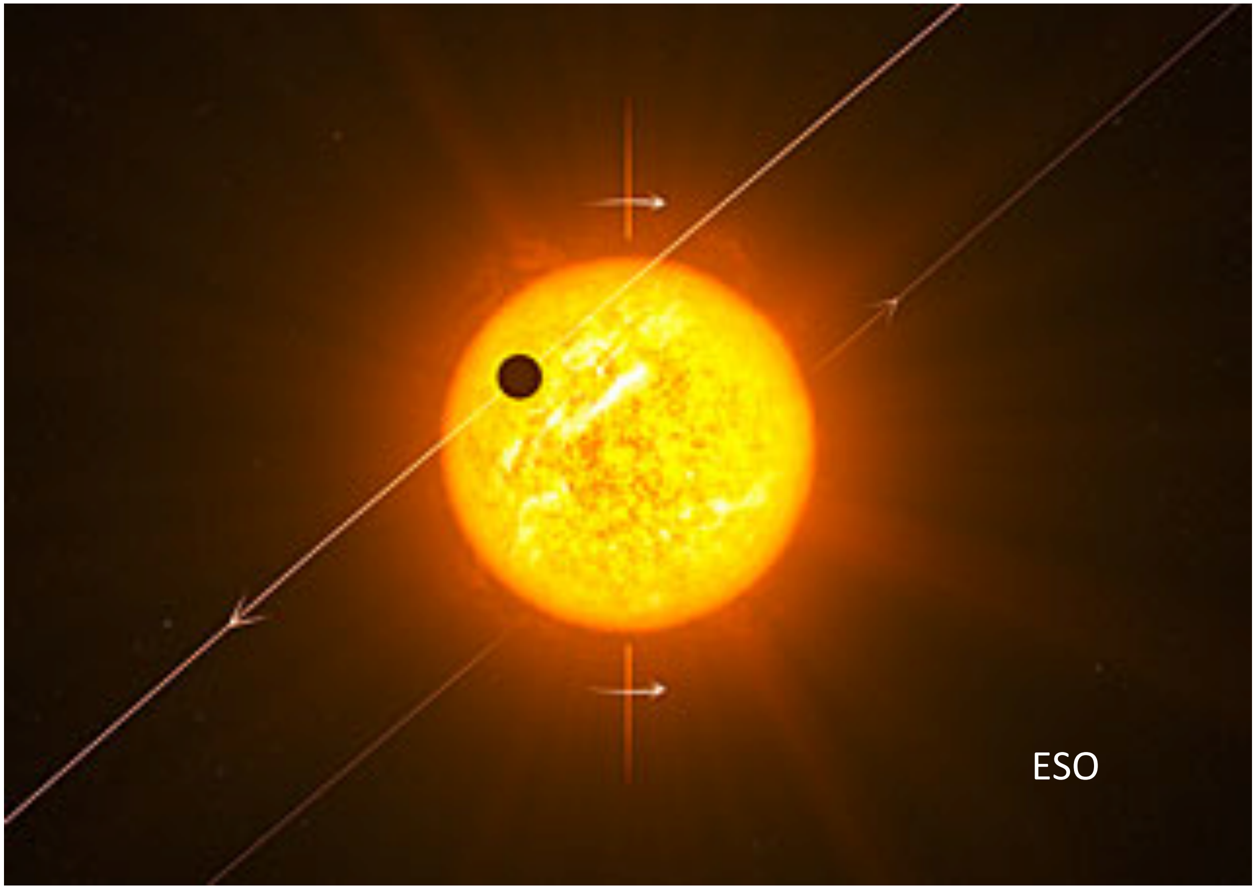
Planets around binary stars



stefanom.org

Planets around binary stars ("Tatooines")

Spin-Orbit Misalignment Puzzle

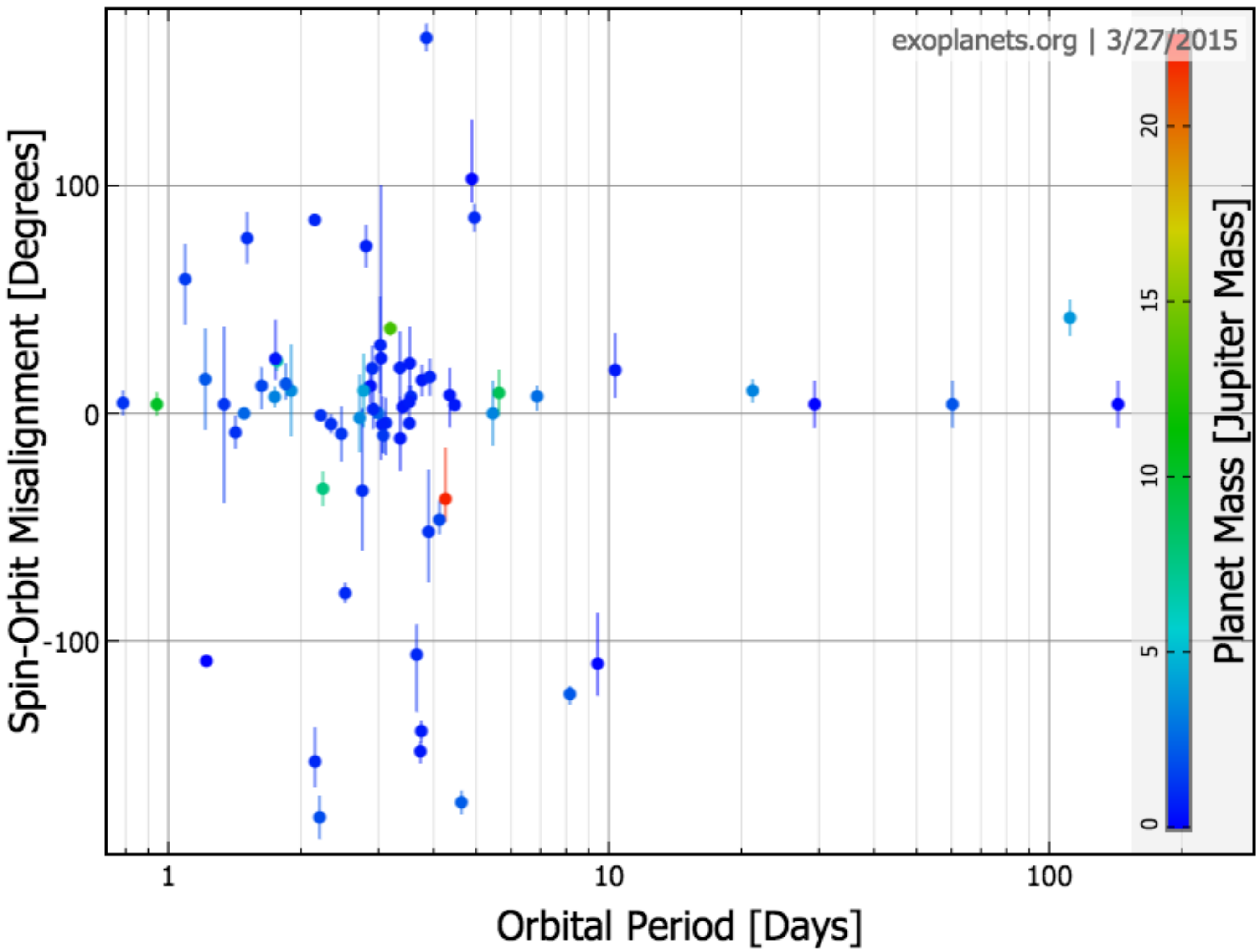


Solar System

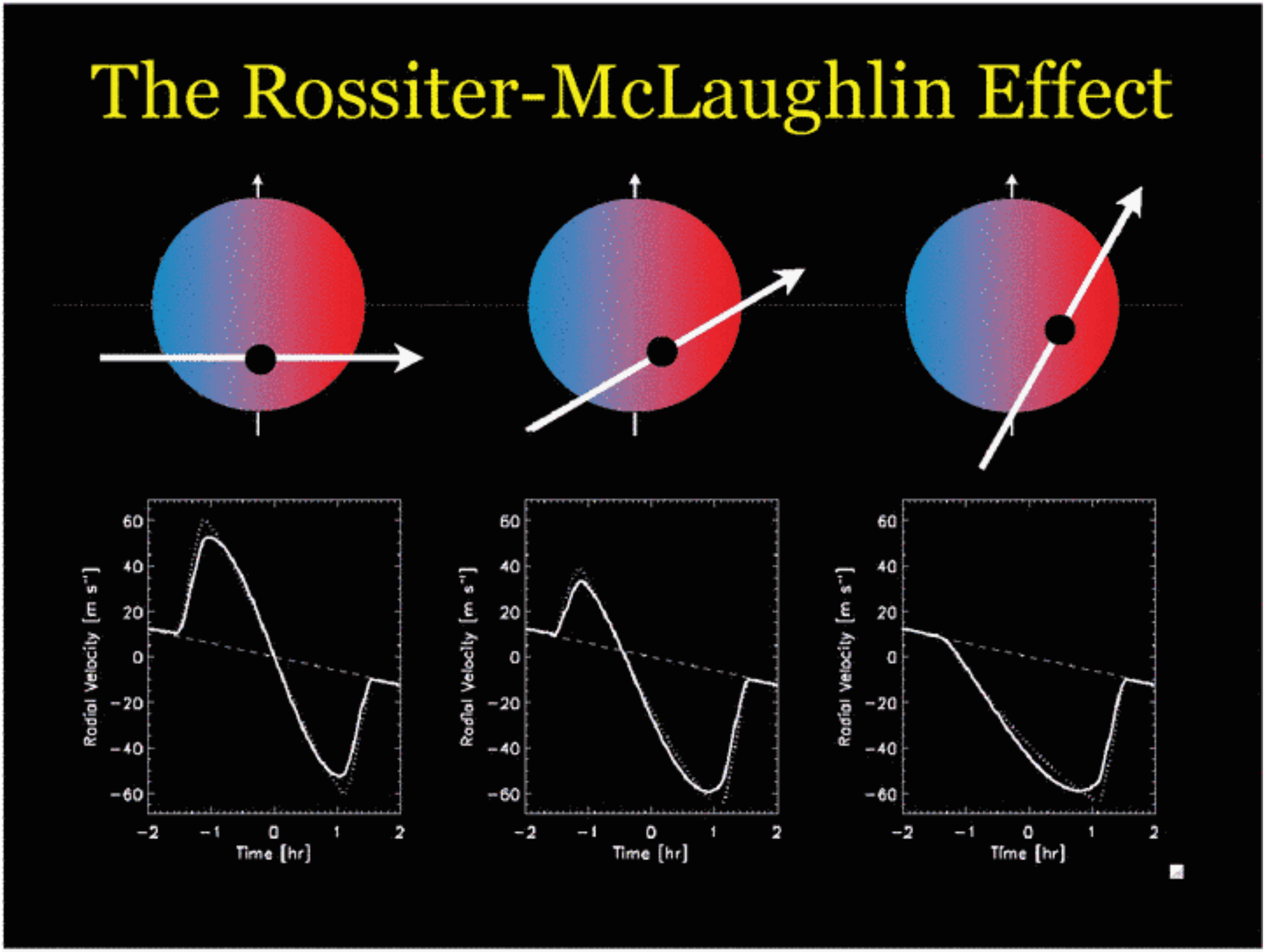
Orientation of planet's orbital plane

	ecliptic plane	Sun's equator
Murcury	7.005	3.38
Venus	3.394	3.86
Earth	0	7.15
Mars	1.850	5.65
Jupiter	1.303	6.09
Saturn	2.489	5.51
Uranus	0.773	6.48
Neptune	1.770	6.43

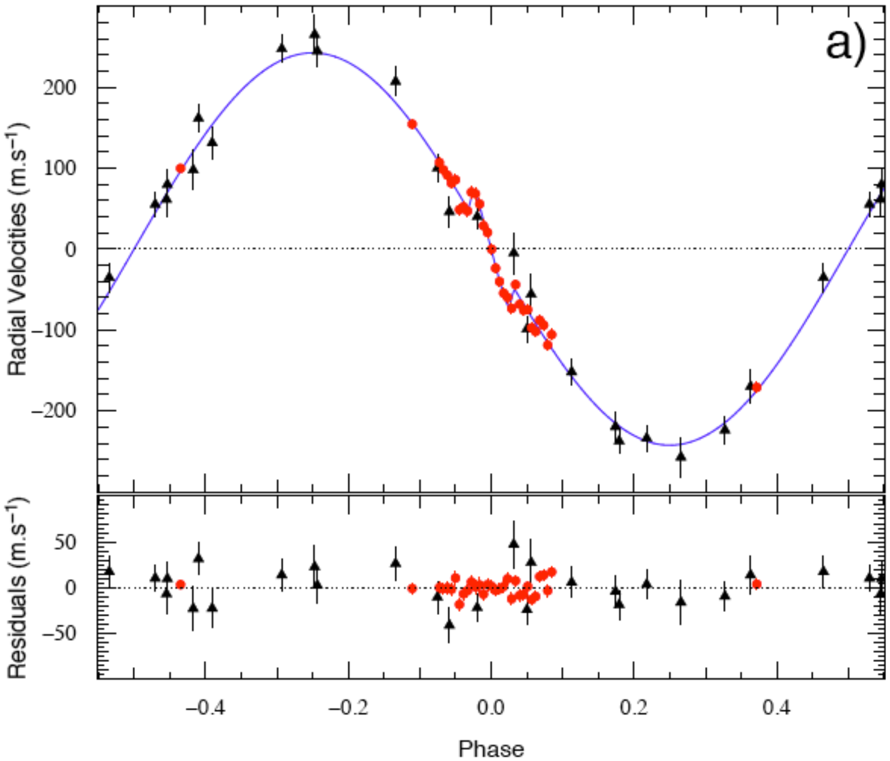
All major planets lie in the same plane (within 2 deg), which is inclinded to the Sun's equator by 7 deg.



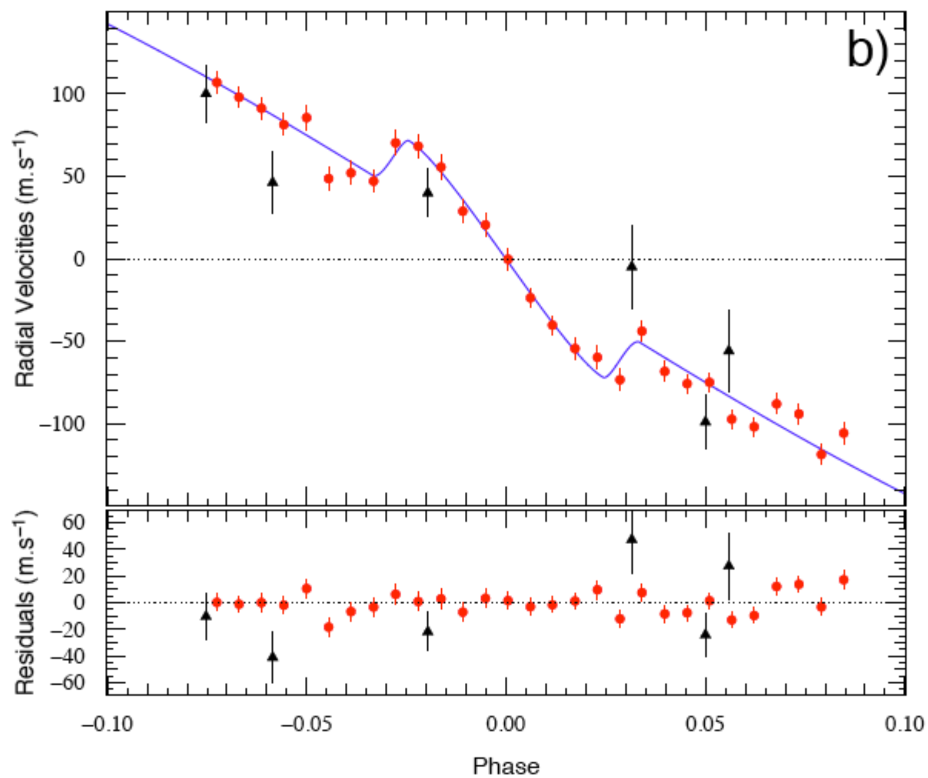
exoplanets.org | 3/27/2015
Spin-Orbit Misalignment [Degrees]
100
0
-100
1
10
100
Orbital Period [Days]
Planet Mass [Jupiter Mass]
0
5
10
15
20



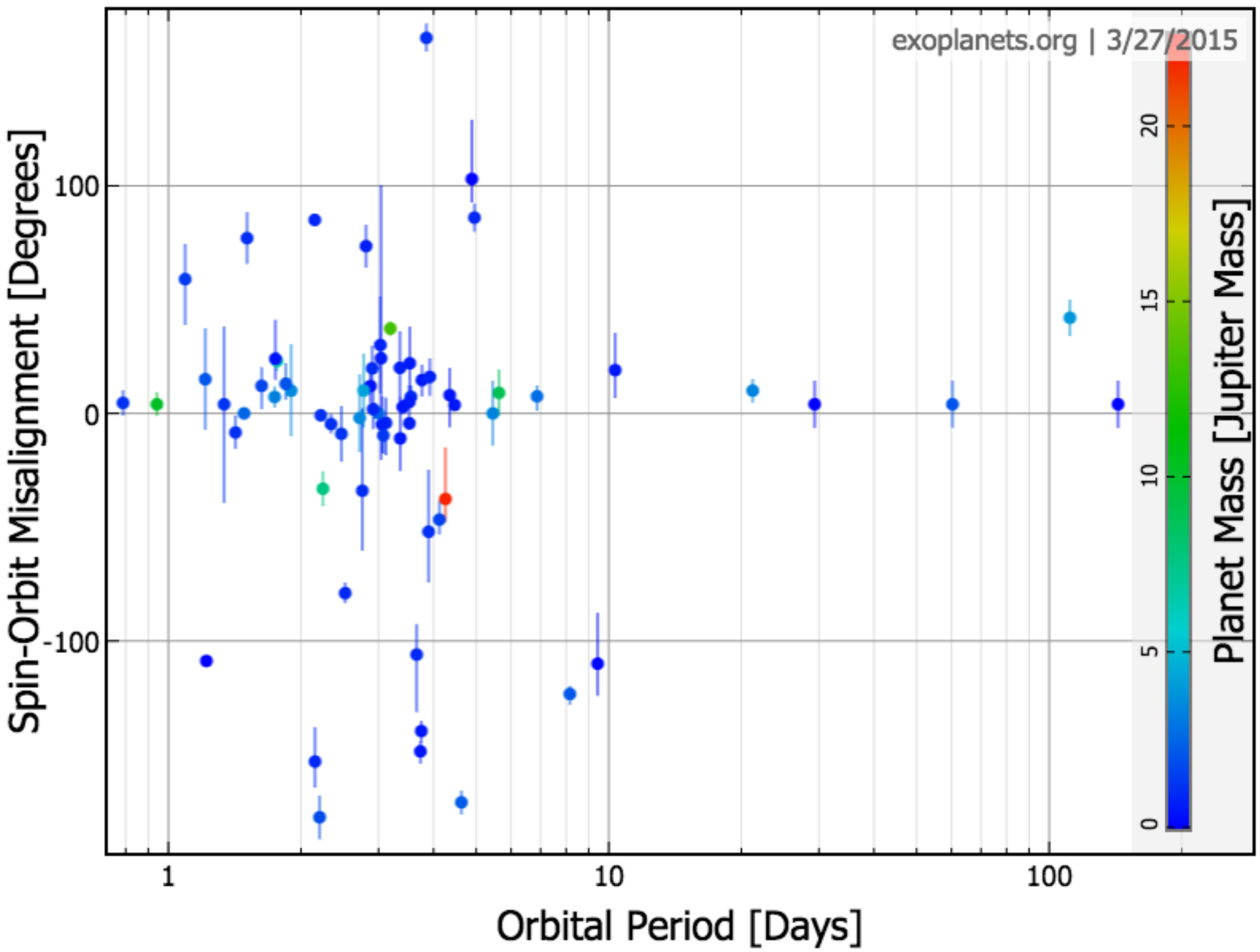
Slide from Josh Winn



WASP-4b



Triaud et al. 2010


exoplanets.org | 3/27/2015
Spin-Orbit Misalignment [Degrees]
100
0
-100
1
10
100
Orbital Period [Days]
Planet Mass [Jupiter Mass]
0
5
10
15
20

How to Form Misaligned Hot Jupiters?

Giant planets are formed in protoplanetary disks (gas + dust)

$t < 10$ Myrs

$R_{form} >$ a few AU

NASA

How to Form Misaligned Hot Jupiters?

Two coupled questions:

-- How did they migrate to < 0.05 AU?

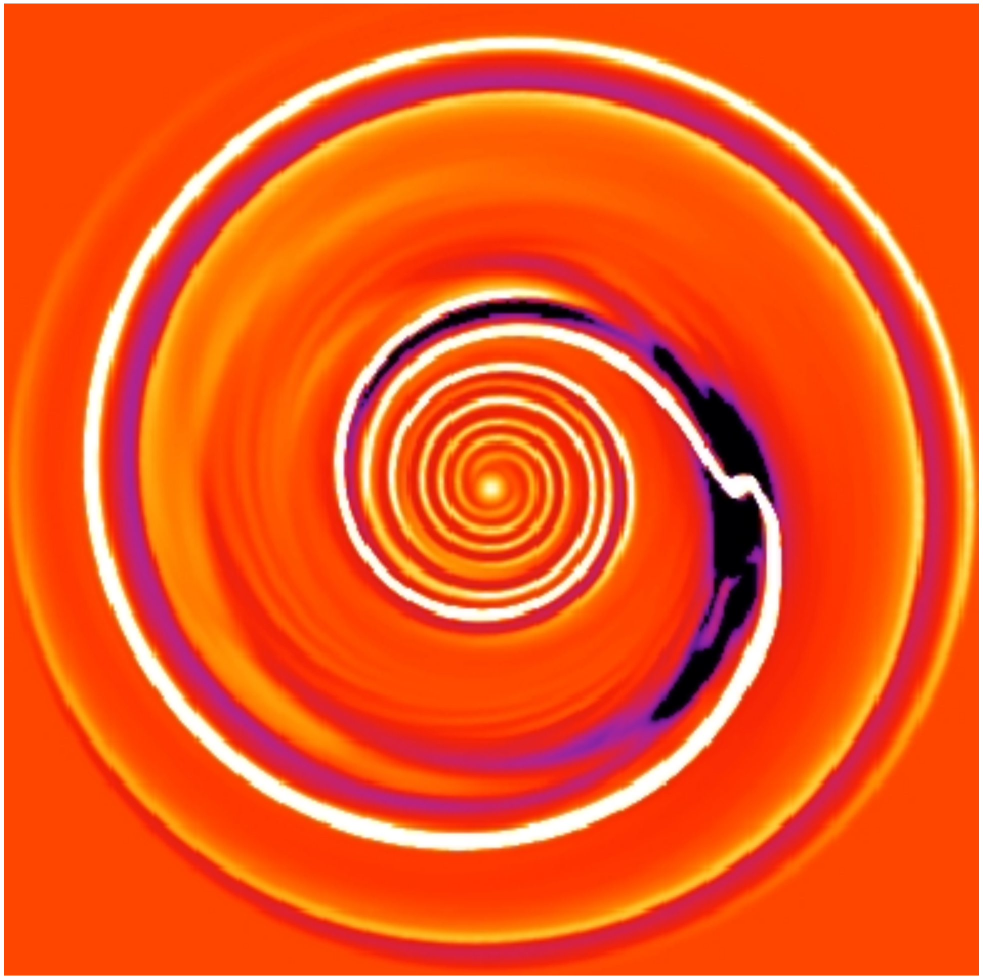
-- How did their orbits get misaligned with host star?

Likely multiple mechanisms (e.g. Dawson & Murray-Clay 2013)

This talk:

Two mechanisms… with surprising/interesting dynamics…

Disk-Driven Migration



Goldreich & Tremaine 1979
Lin et al. 1996

Ideas for Producing Primordial Misalignments

between Stellar Spin and Protoplanetary Disk

-- Star formation in turbulent medium (Bate et al. 2010; Fielding, Mckee et al 2014)

-- Magnetic Star – Disk Interaction (Lai, Foucart & Lin 2011, Foucart & Lai 2011)

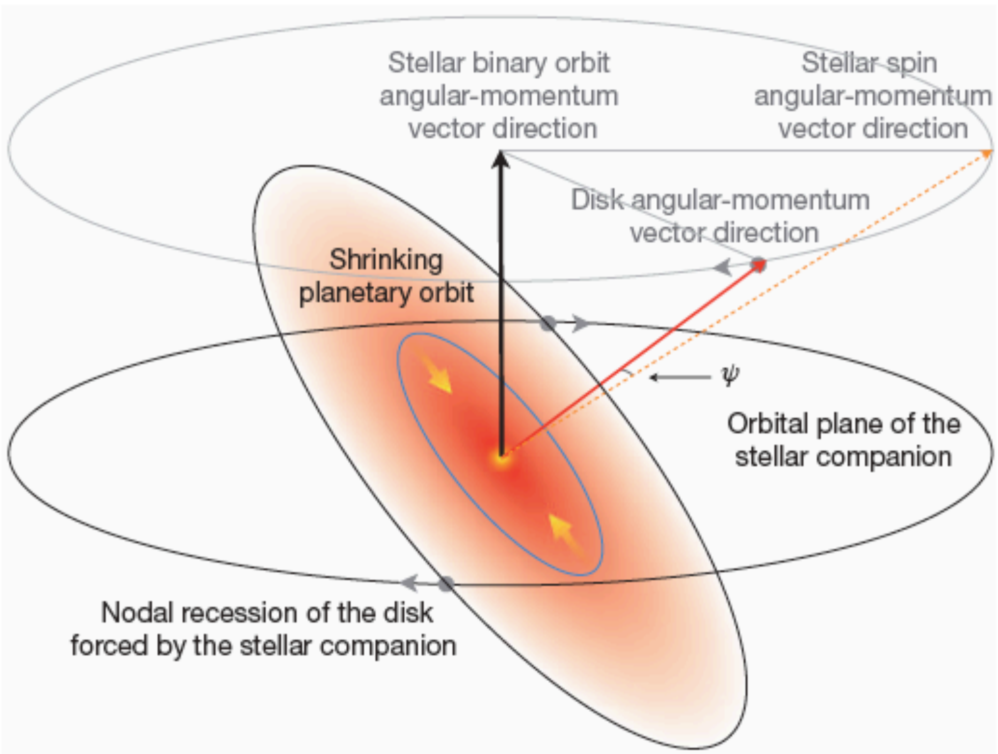
Ideas for Producing Primordial Misalignments

between Stellar Spin and Protoplanetary Disk

-- Star formation in turbulent medium (Bate et al. 2010; Fielding, Mckee et al 2014)

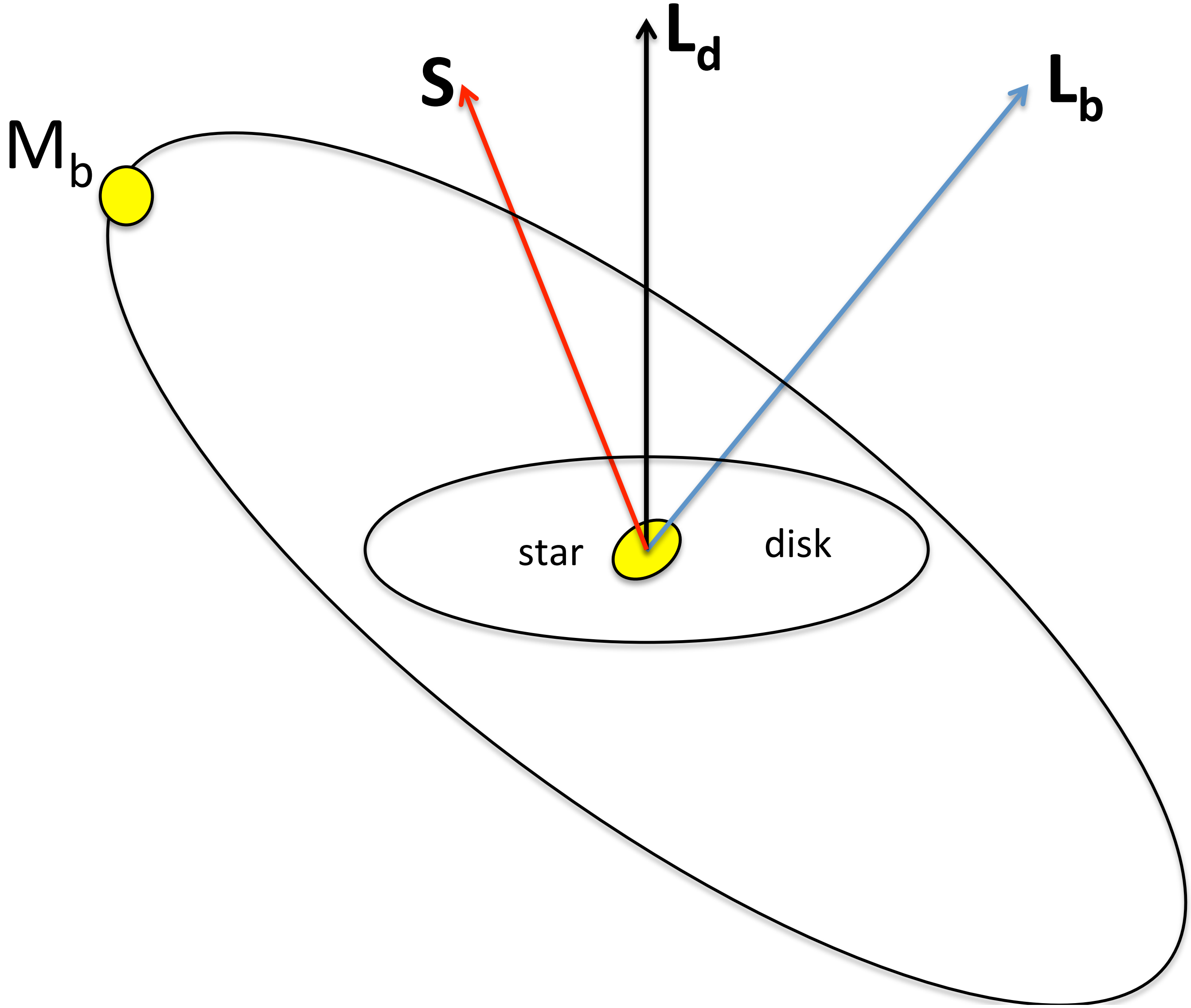
-- Magnetic Star – Disk Interaction (Lai, Foucart & Lin 2011, Foucart & Lai 2011)

-- Perturbation of Binary on Disk (Batygin 2012; Batygin & Adams 2014; **Lai 2014**)

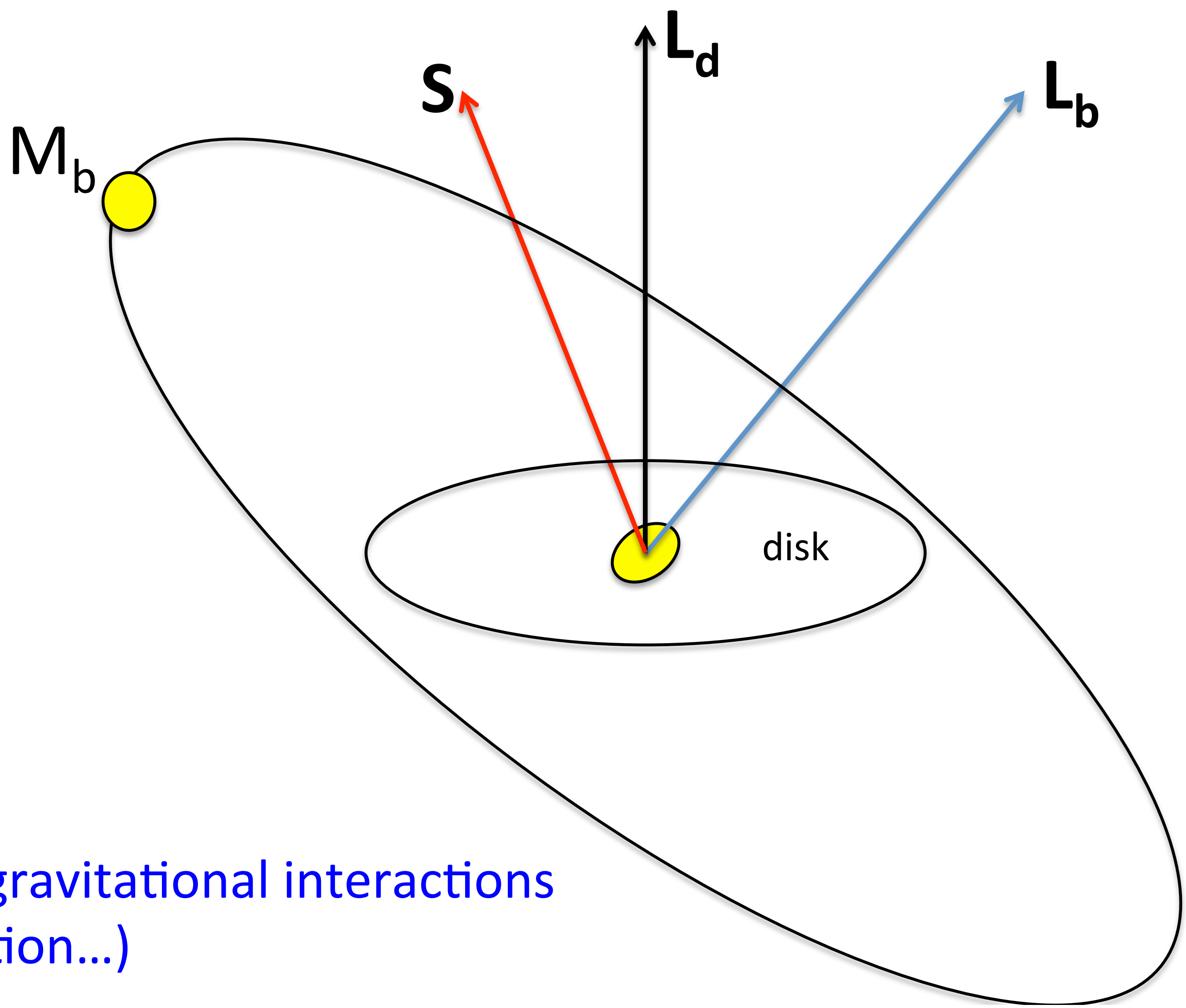


Star-Disk-Binary Interactions

DL 2014



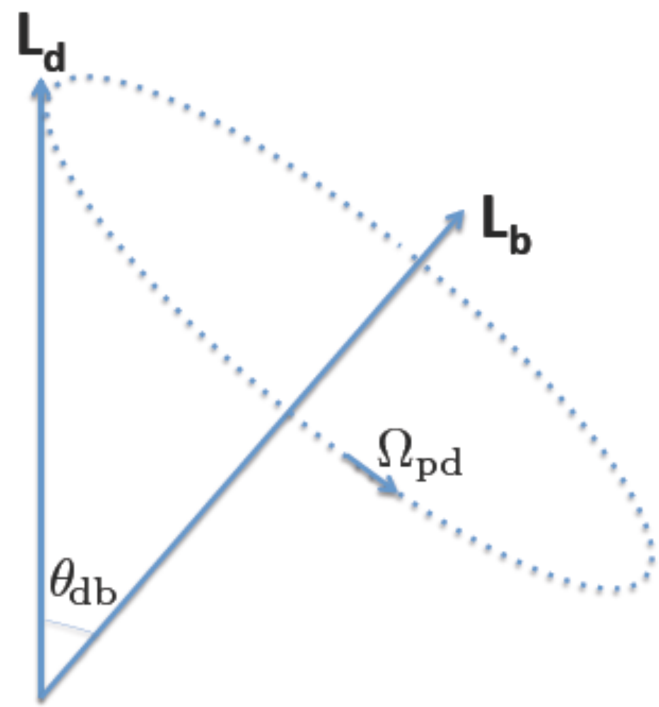
Star-Disk-Binary Interactions



First just gravitational interactions
(no accretion…)

Companion makes disk precess

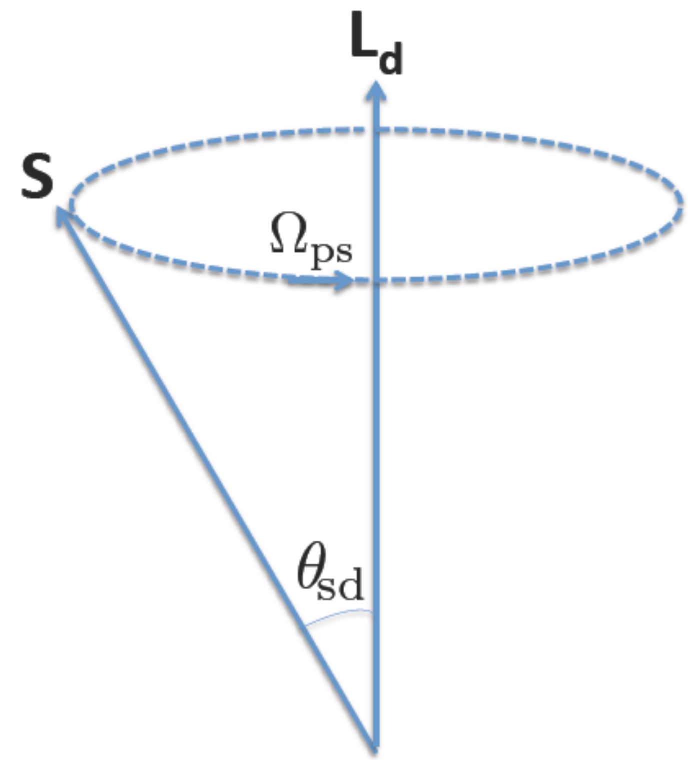
Disk behaves like a rigid body
(bending waves, viscous stress, self-gravity)



$$\Omega_{\rm pd} \simeq -5 \times 10^{-6} \left(\frac{M_b}{M_\star}\right) \left(\frac{r_{\rm out}}{50\,{\rm AU}}\right)^{3/2} \left(\frac{a_b}{300\,{\rm AU}}\right)^{-3} \times \cos\theta_{\rm db} \left(\frac{2\pi}{\rm yr}\right)$$

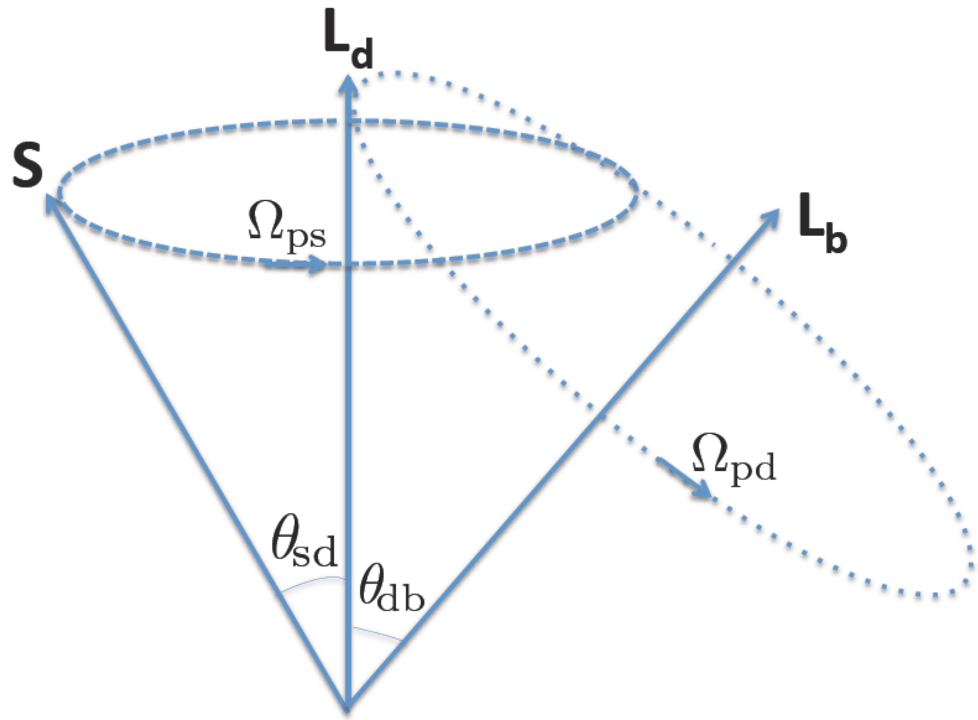
Disk makes the star precess

Due to gravitational torque from disk on rotating (oblate) star



$$\Omega_{\rm ps} \simeq -5\times 10^{-5}\left(\frac{M_d}{0.1M_\star}\right)\left(\frac{\bar{\Omega}_\star}{0.1}\right)\left(\frac{r_{\rm in}}{4R_\star}\right)^{-2}\left(\frac{r_{\rm out}}{50\ {\rm AU}}\right)^{-1} \times \cos\theta_{\rm sd}\left(\frac{2\pi}{\rm yr}\right)$$

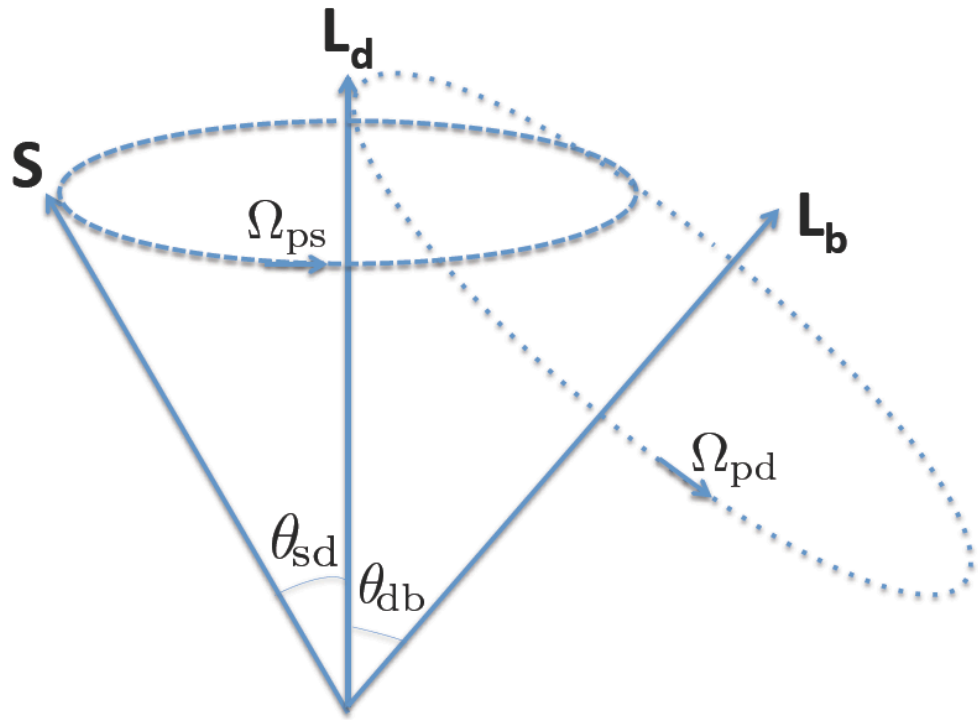
where $\Omega_\star = \left(\frac{2\pi}{3.3\ {\rm days}}\right)\left(\frac{\bar{\Omega}_\star}{0.1}\right)$



Two limiting cases:

(1) $|\Omega_{\rm ps}| \gg |\Omega_{\rm pd}|: \quad \Longrightarrow \quad \theta_{\rm sd} \simeq \text{constant}$

(2) $|\Omega_{\rm ps}| \ll |\Omega_{\rm pd}|: \quad \Longrightarrow \quad \theta_{\rm sb} \simeq \text{constant}$

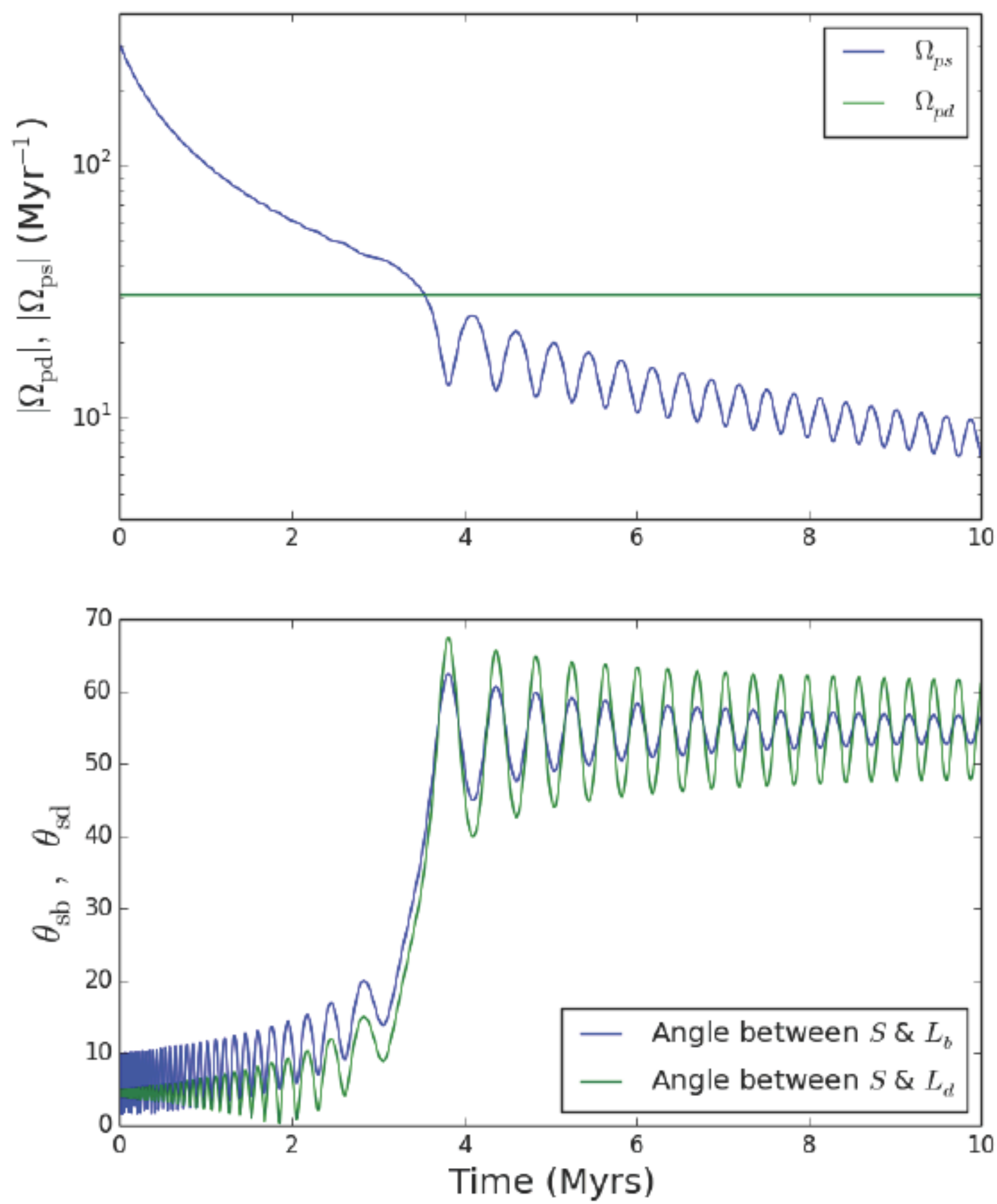


$$\Omega_{\rm pd} \simeq -5\times10^{-6}\left(\frac{M_b}{M_\star}\right)\left(\frac{r_{\rm out}}{50\,{\rm AU}}\right)^{3/2}\left(\frac{a_b}{300\,{\rm AU}}\right)^{-3} \times \cos\theta_{\rm db}\left(\frac{2\pi}{\rm yr}\right)$$

$$\Omega_{\rm ps} \simeq -5\times10^{-5}\left(\frac{M_d}{0.1M_\star}\right)\left(\frac{\bar{\Omega}_\star}{0.1}\right)\left(\frac{r_{\rm in}}{4R_\star}\right)^{-2}\left(\frac{r_{\rm out}}{50\,{\rm AU}}\right)^{-1} \times \cos\theta_{\rm sd}\left(\frac{2\pi}{\rm yr}\right)$$

Simple model:

$$M_d = \frac{0.1M_\odot}{1+(t/0.5\ {\rm Myrs})}$$



Initial:

$\theta_{\rm db} = 5^\circ$

$\theta_{\rm sd} = 5^\circ$

DL2014

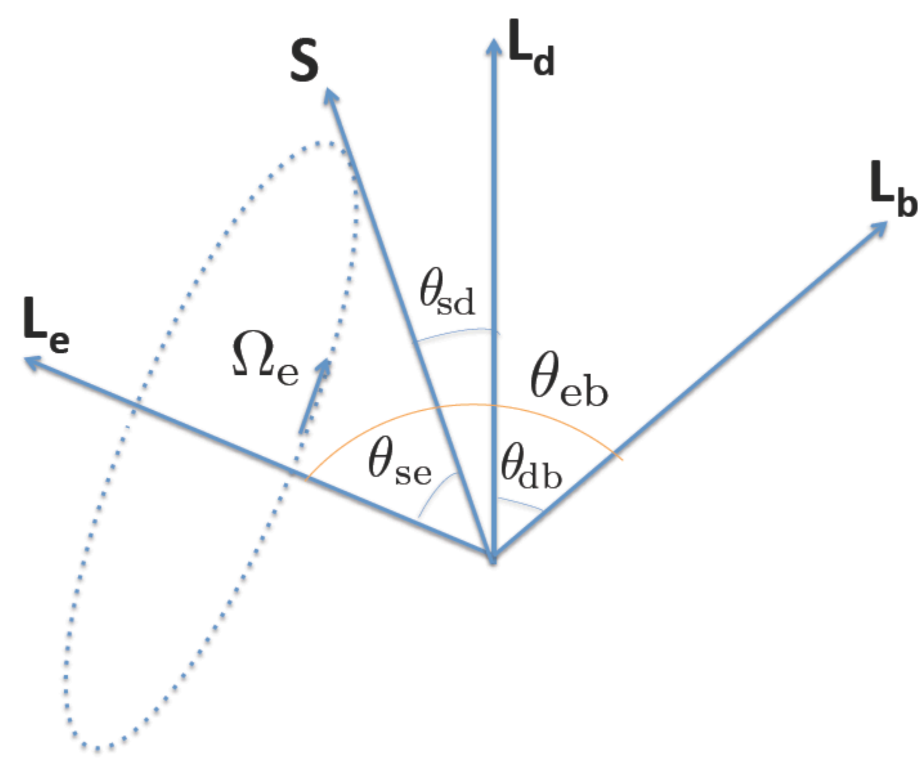
Resonance $\Omega_{\rm ps} = \Omega_{\rm pd}$

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

In the frame rotating at rate $\Omega_{\rm pd}\hat{\mathbf{L}}_{\rm b}$

$$\left(\frac{d\hat{\mathbf{S}}}{dt}\right)_{\rm rot} = \Omega_{\rm ps}\hat{\mathbf{L}}_{\rm d} \times \hat{\mathbf{S}} - \Omega_{\rm pd}\hat{\mathbf{L}}_{\rm b} \times \hat{\mathbf{S}}$$

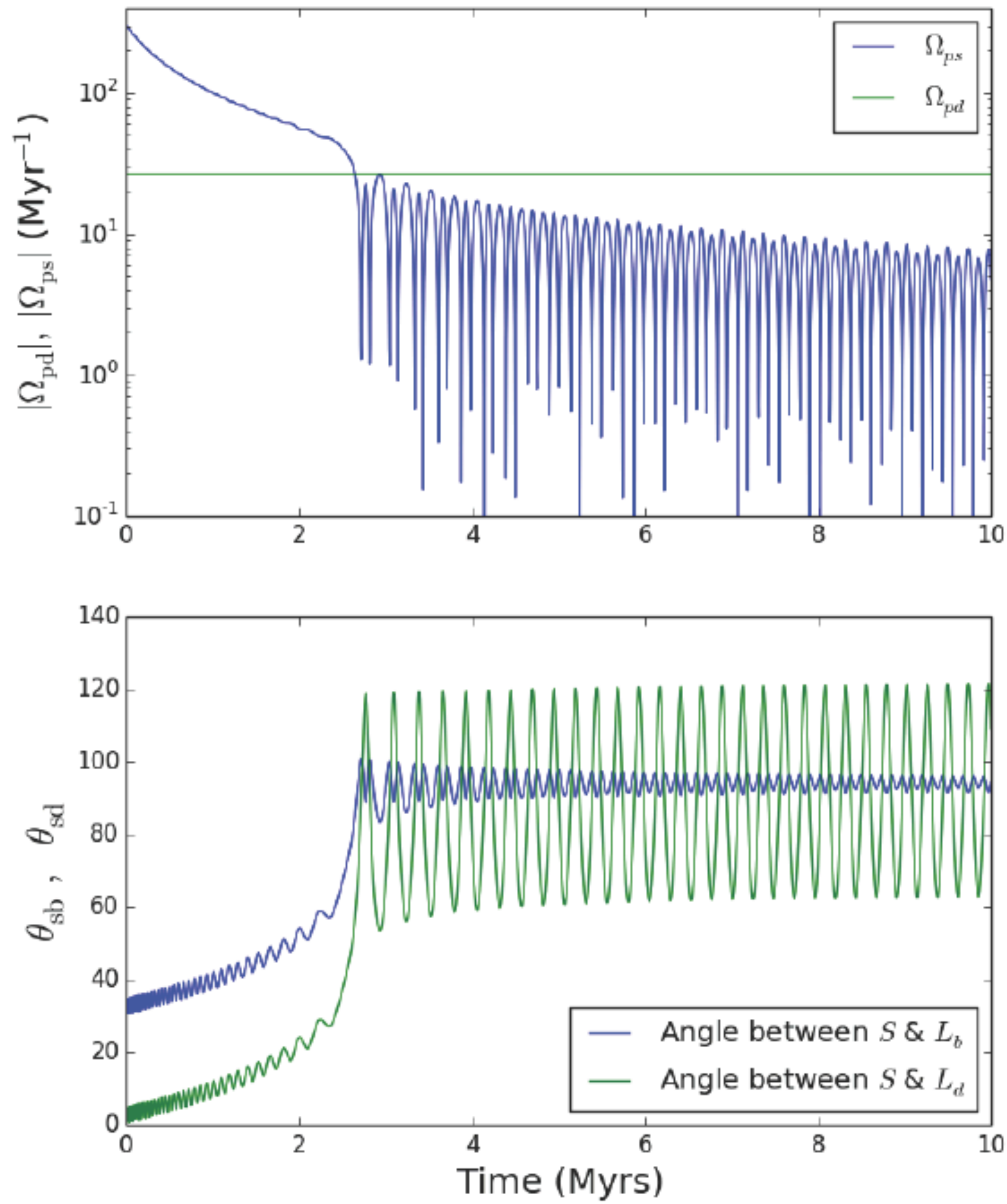
$$= \underbrace{\left(\Omega_{\rm ps}\hat{\mathbf{L}}_{\rm d} - \Omega_{\rm pd}\hat{\mathbf{L}}_{\rm b}\right)}_{\Omega_e\hat{\mathbf{L}}_e} \times \hat{\mathbf{S}}$$

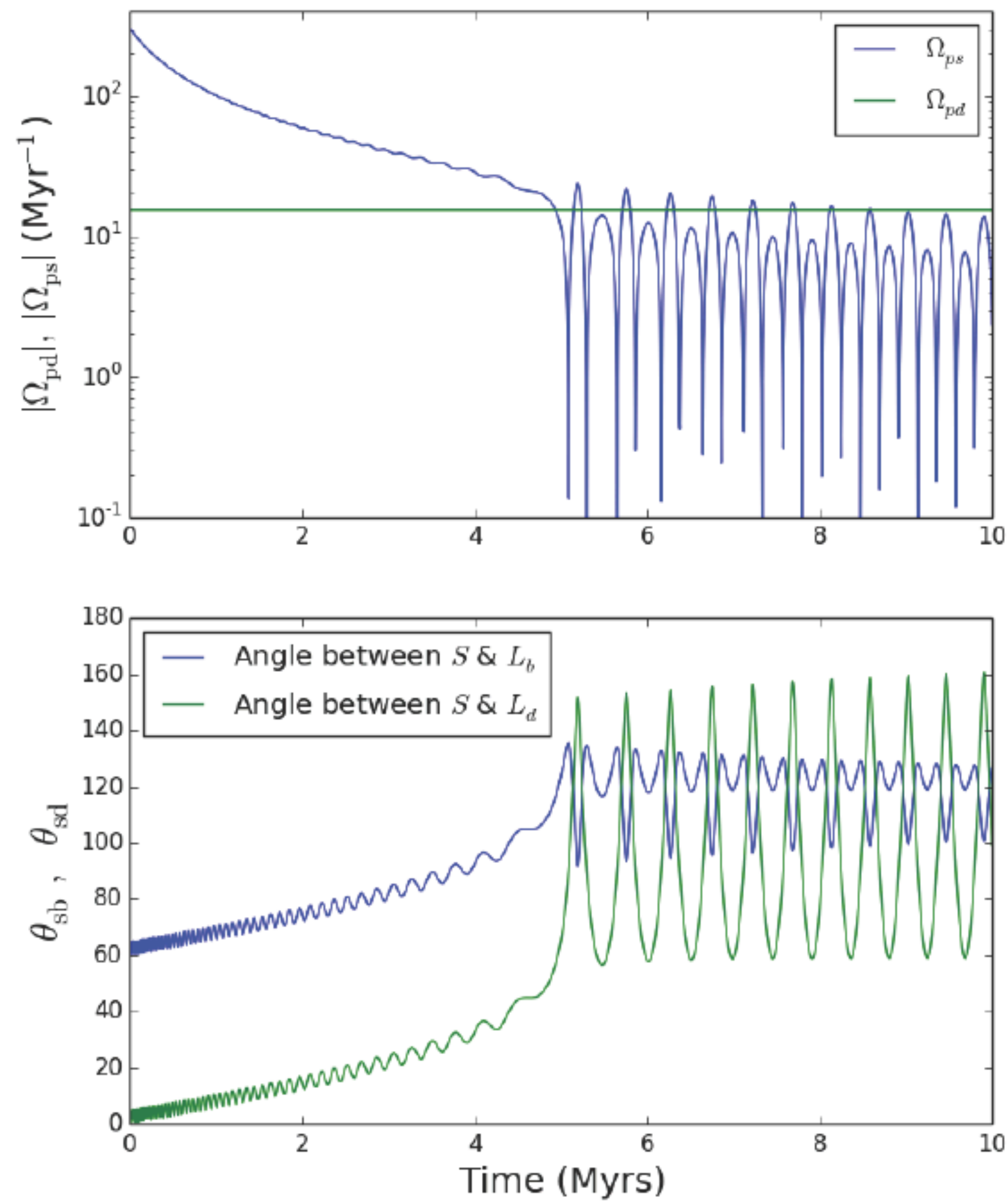


Initial:

$\theta_{\mathrm{db}} = 30^\circ$

$\theta_{\mathrm{sd}} = 5^\circ$





Initial:

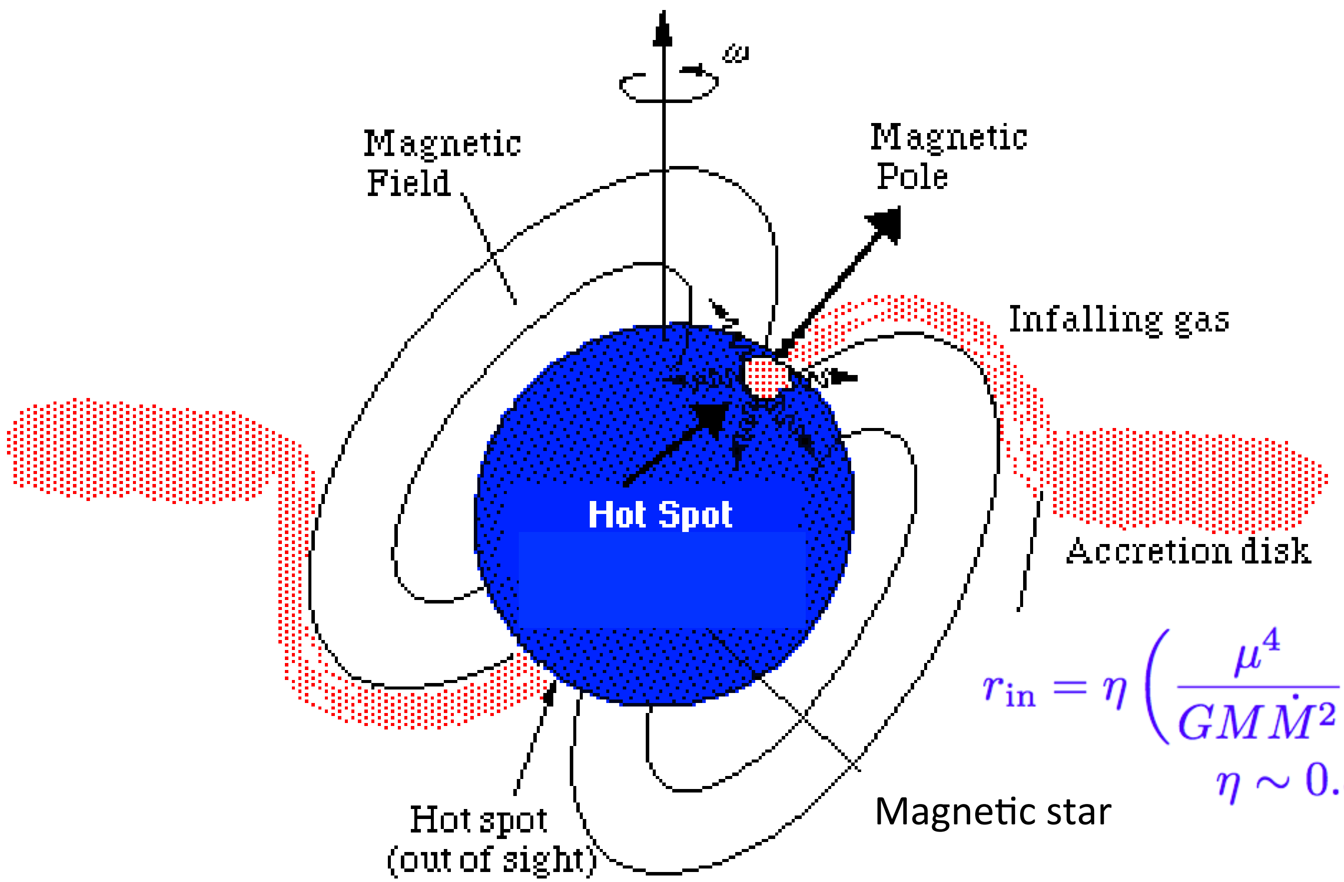
$$\theta_{\rm db} = 60^\circ$$

$$\theta_{\rm sd} = 5^\circ$$

Complications:

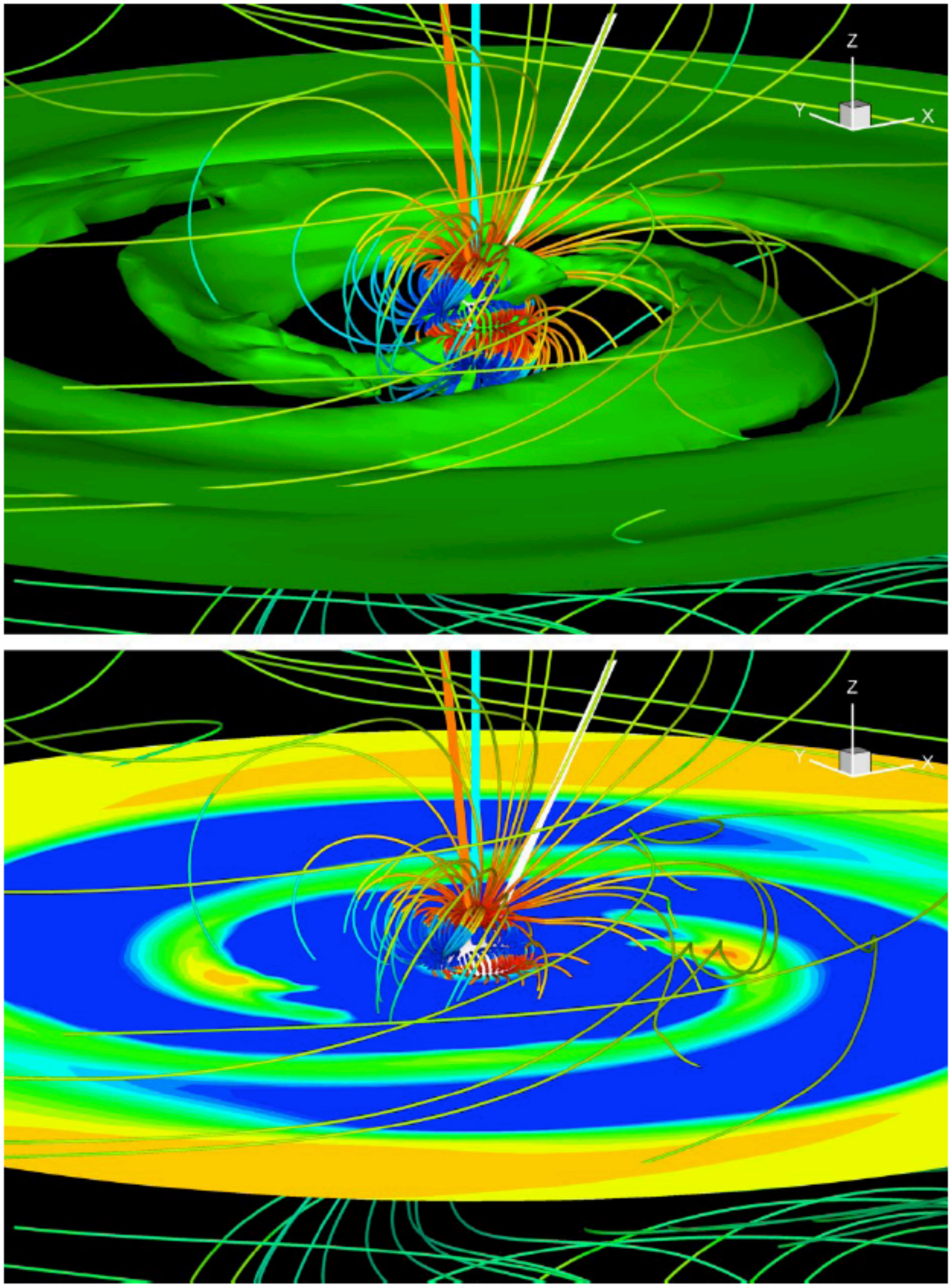
Accretion and magnetic interaction

Magnetic Star - Disk Interaction: Basic Picture



$$r_{\rm in} = \eta \left(\frac{\mu^4}{G M \dot{M}^2} \right)^{1/7}$$

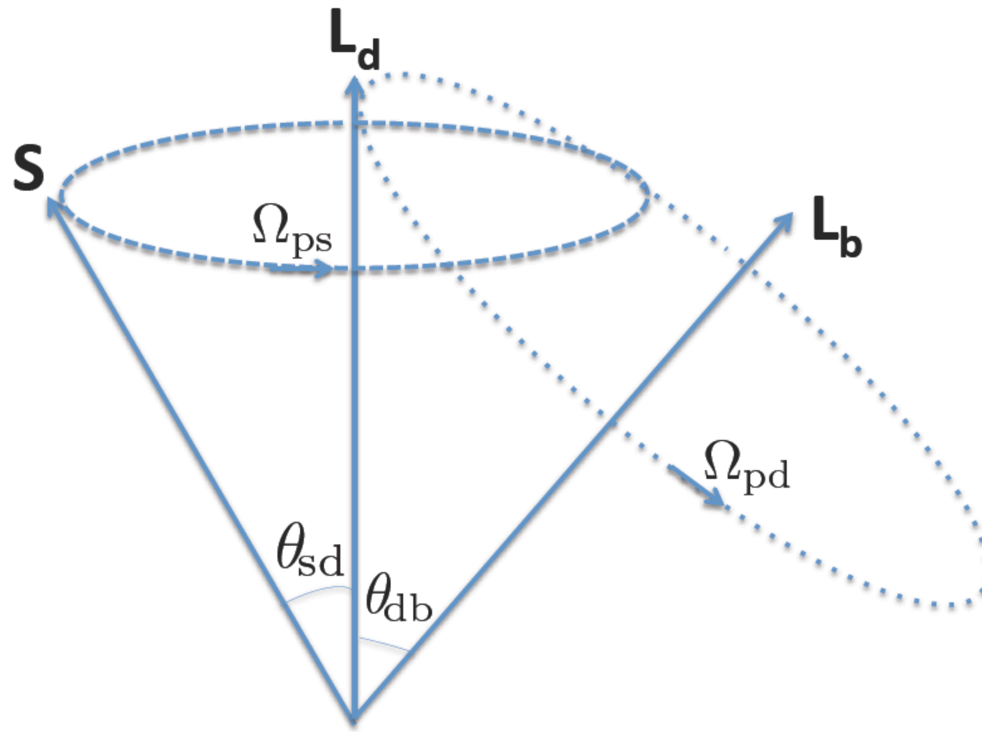
$$\eta \sim 0.5 - 1$$



Romanova, Long, Lovelace, et al. 2012

Star-Disk-Binary Interactions

Gravitational interactions…

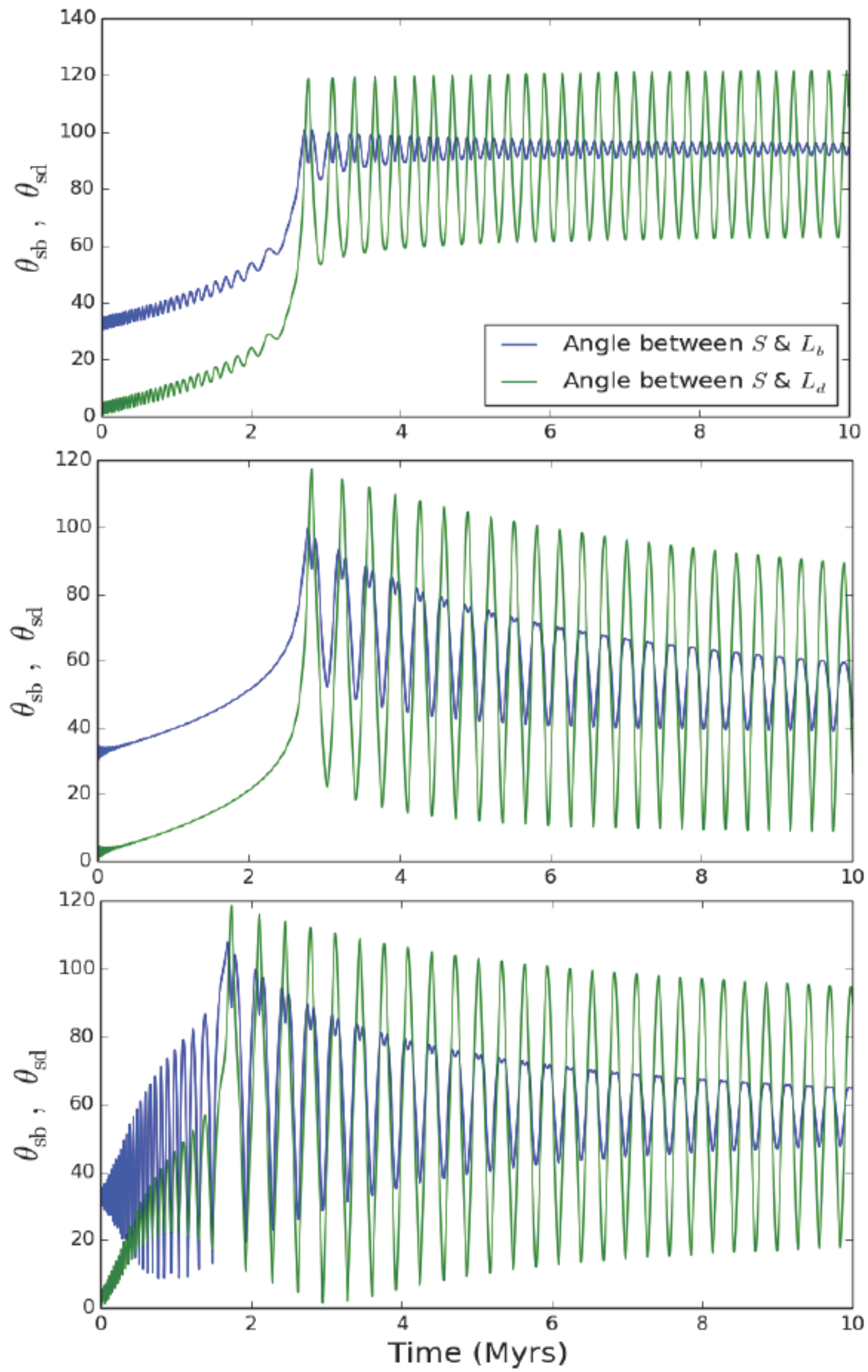


Now include Accretion and Magnetic Torques

No accretion/magnetic

Accretion/magnetic damps SL-angle

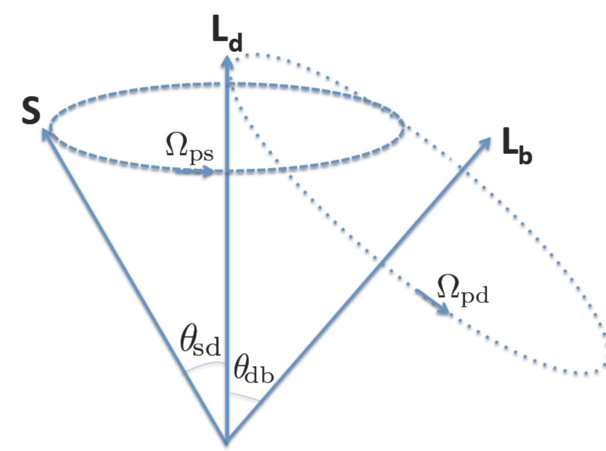
Accretion/magnetic increases SL-angle



DL2014

Summary (#1)
Star-disk-binary interactions

- With a binary companion, spin-disk misalignment is "easily" generated
- The key is "resonance crossing"
- Accretion/magnetic torques affect it, but not diminish the effect

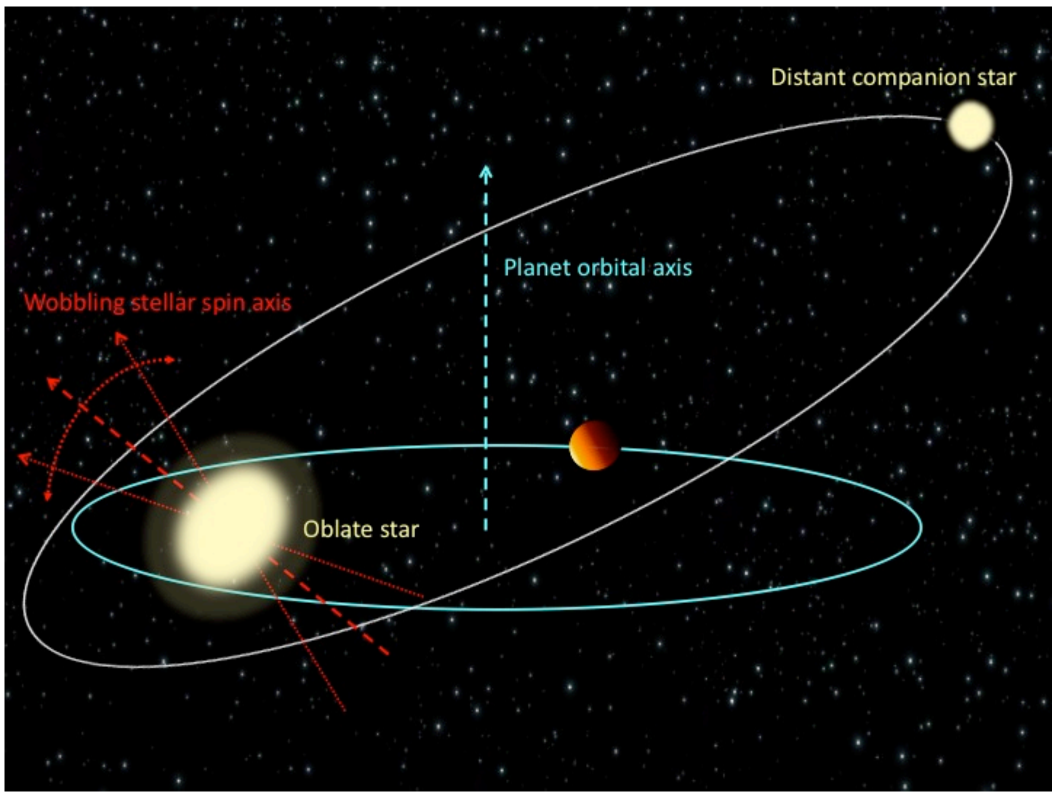


➔ **"primordial" misalignment of stellar spin and disk**

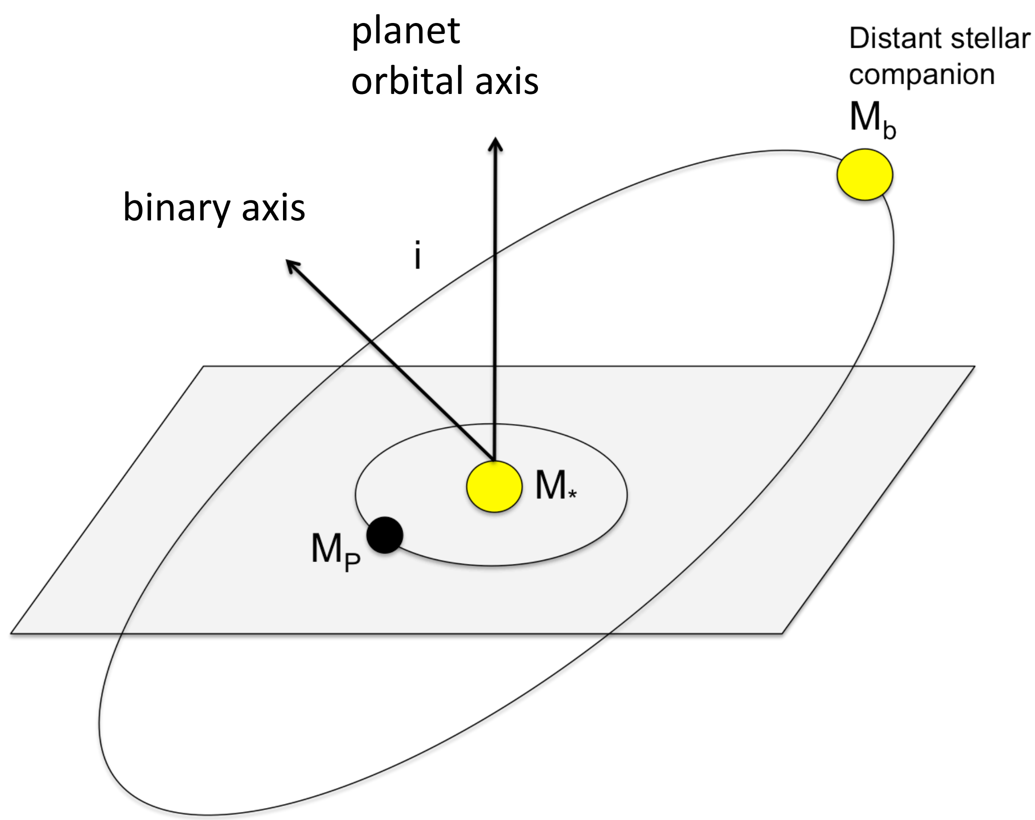
How to Form Misaligned Hot Jupiters?

How to Form Misaligned Hot Jupiters?

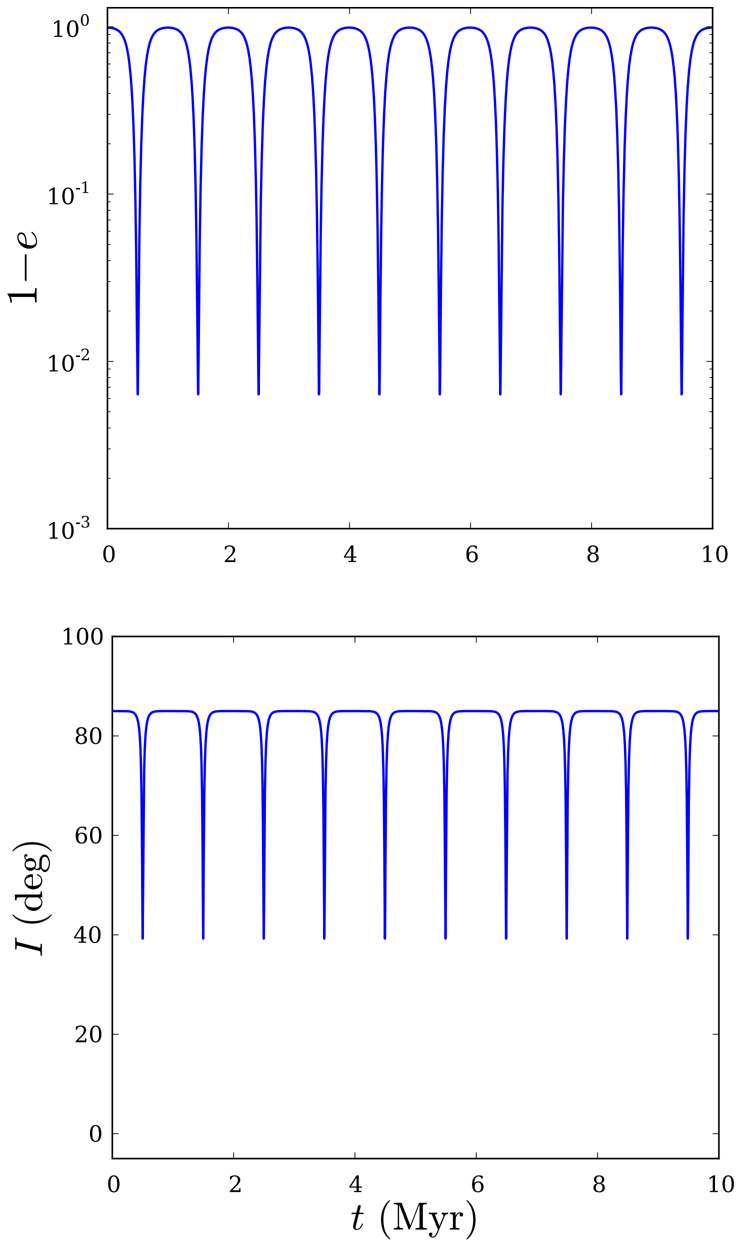
Gradual (secular) perturbation from a distant stellar companion
+ Tidal dissipation.....(> 100’s Myrs)

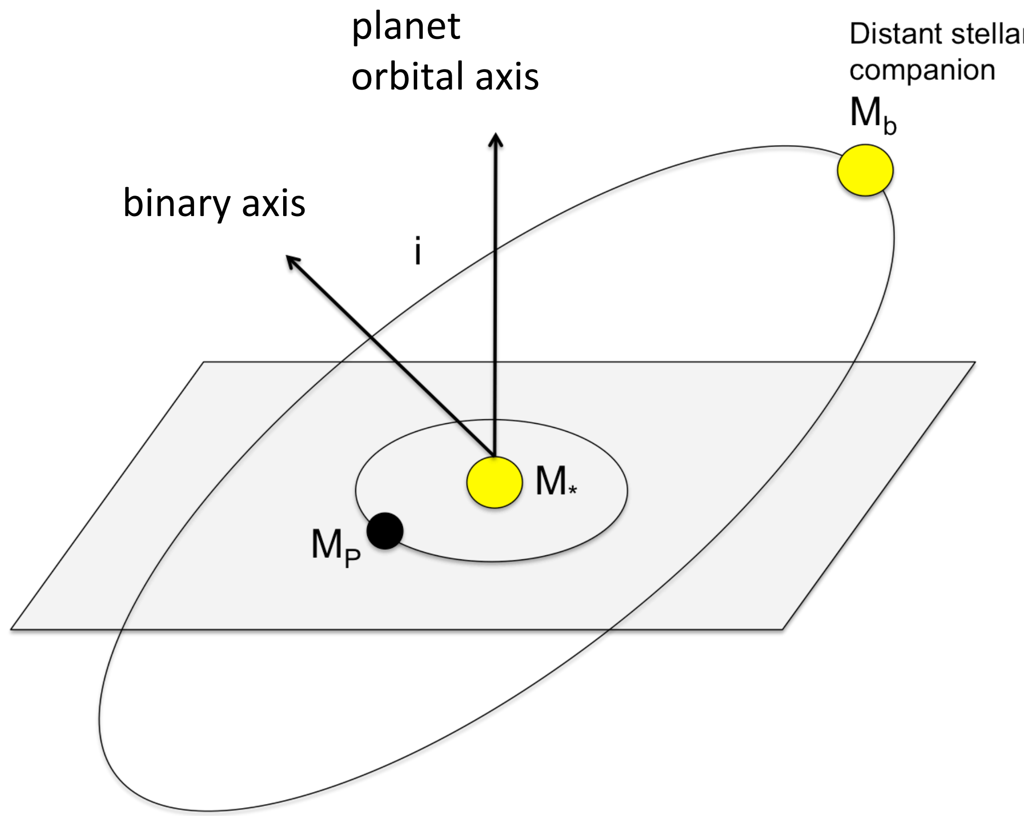


Lidov-Kozai Oscillations



Lidov-Kozai Oscillations





- Eccentricity and inclination oscillations induced if i > 40 degrees.
- If i large (85-90 degrees), get extremely large eccentricities (e > 0.99)

Hot Jupiter formation

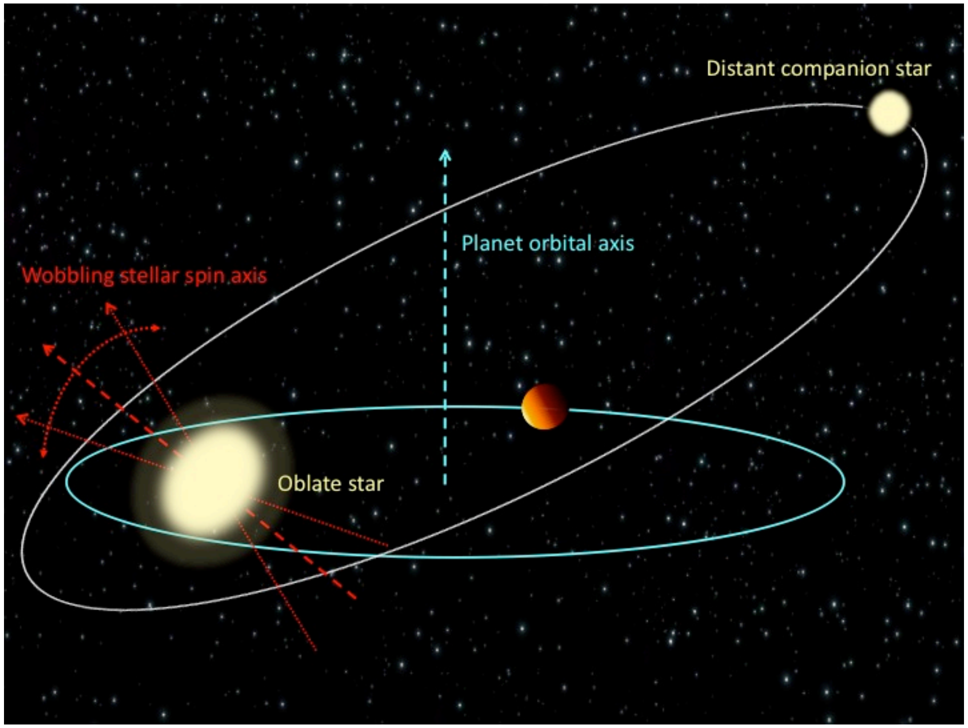
Holman et al. 97; Wu & Murray 03; Fabrycky & Tremaine 07; Naoz et al.12, Katz et al.12; Petrovich 14

- Planet forms at ~ a few AU
- Companion star periodically pumps planet into high-e orbit (Lidov-Kozai)
- Tidal dissipation in planet during high-e phases causes orbital decay

➔ Combined effects can result in planets in ~ few days orbit

Q: What is happening to the stellar spin axis ?

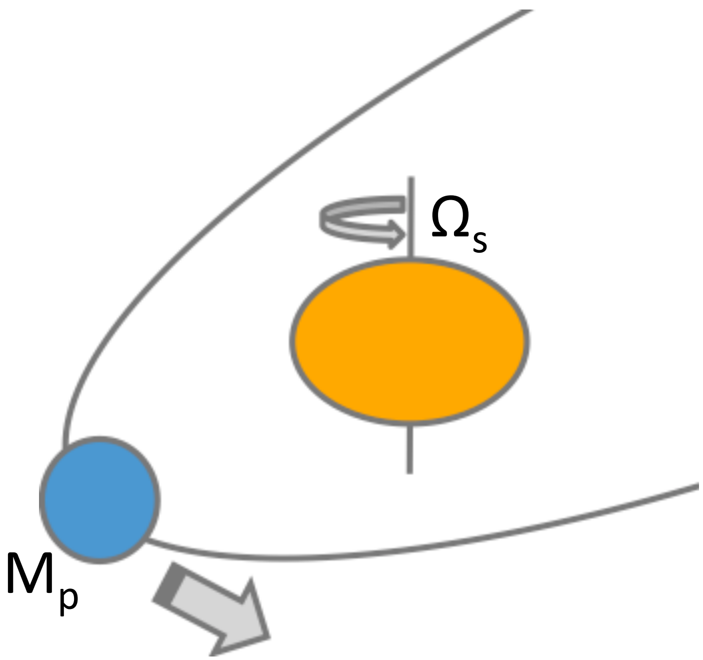
Chaotic Dynamics of Stellar Spin Driven by Planets Undergoing Lidov-Kozai Oscillations



With
Natalia Storch
(Ph.D.15→ Caltech)
Kassandra Anderson

Storch, Anderson & DL 2014, Science
Storch & DL 2015a,b
Anderson, Storch, DL 2015

Precession of Stellar Spin



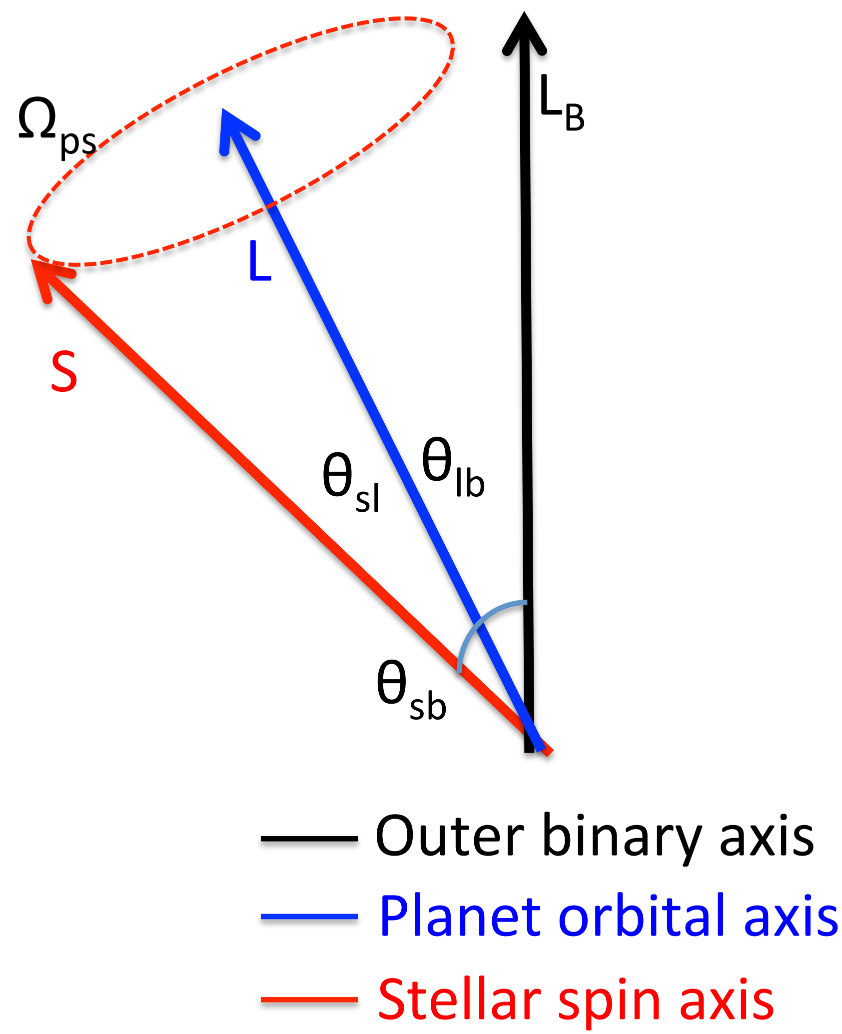
- Star is spinning (3-30 days) → oblate → will precess

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

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

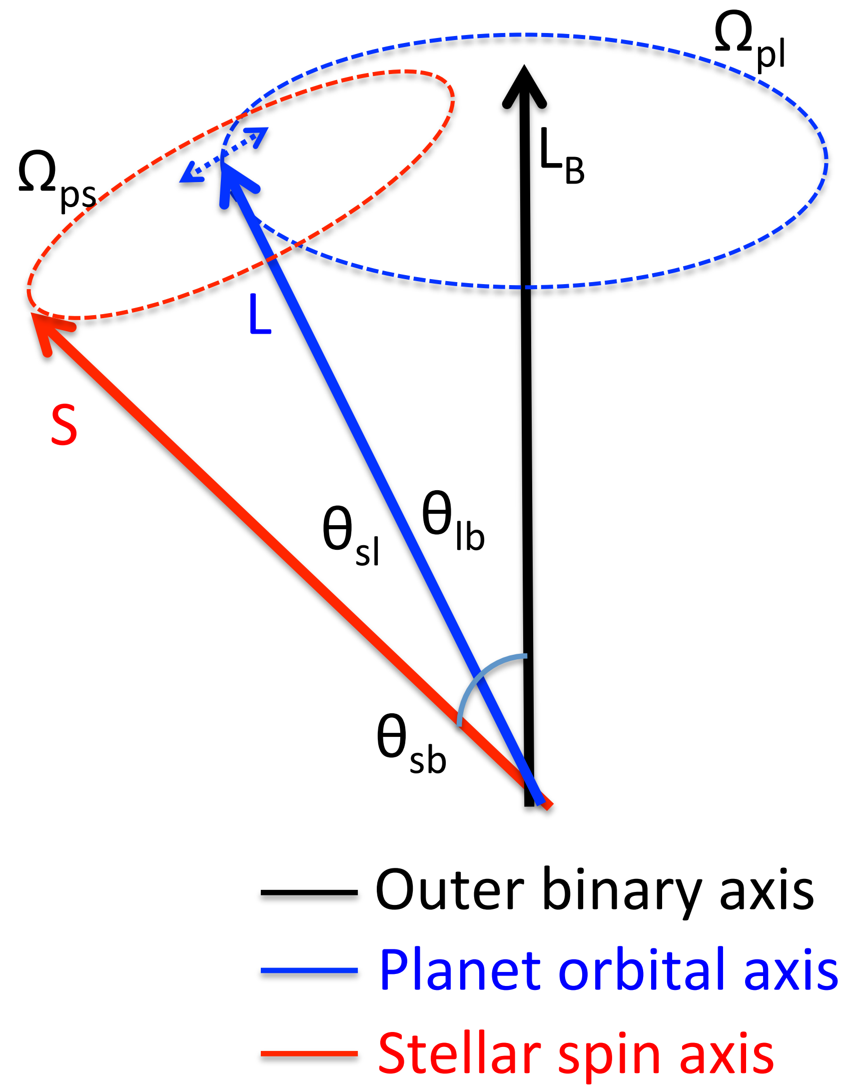
Spin Dynamics

- Stellar spin axis S wants to precess around planet orbital axis L.



Spin Dynamics

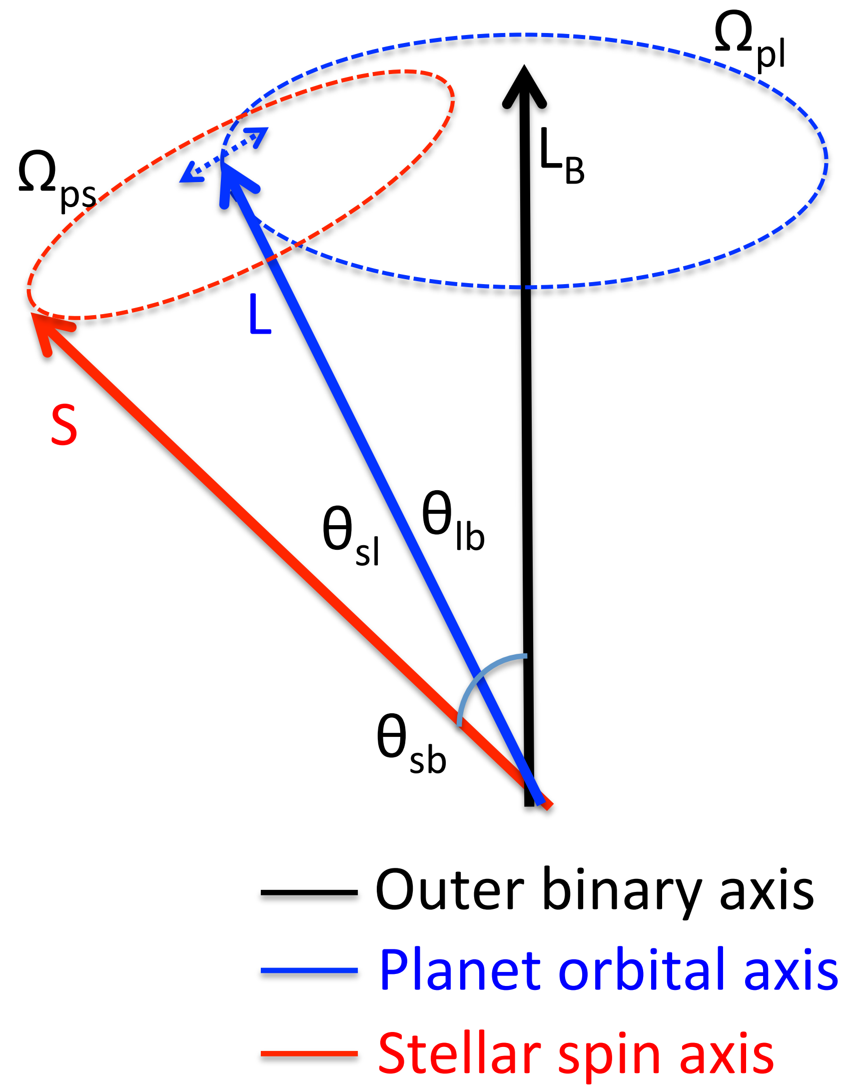
- Stellar spin axis S wants to precess around planet orbital axis L.
- But L itself is moving:
  - Nodal precession (L precesses around binary axis L_b)
  - Nutation (cyclic changes in inclination of L relative to L_b)



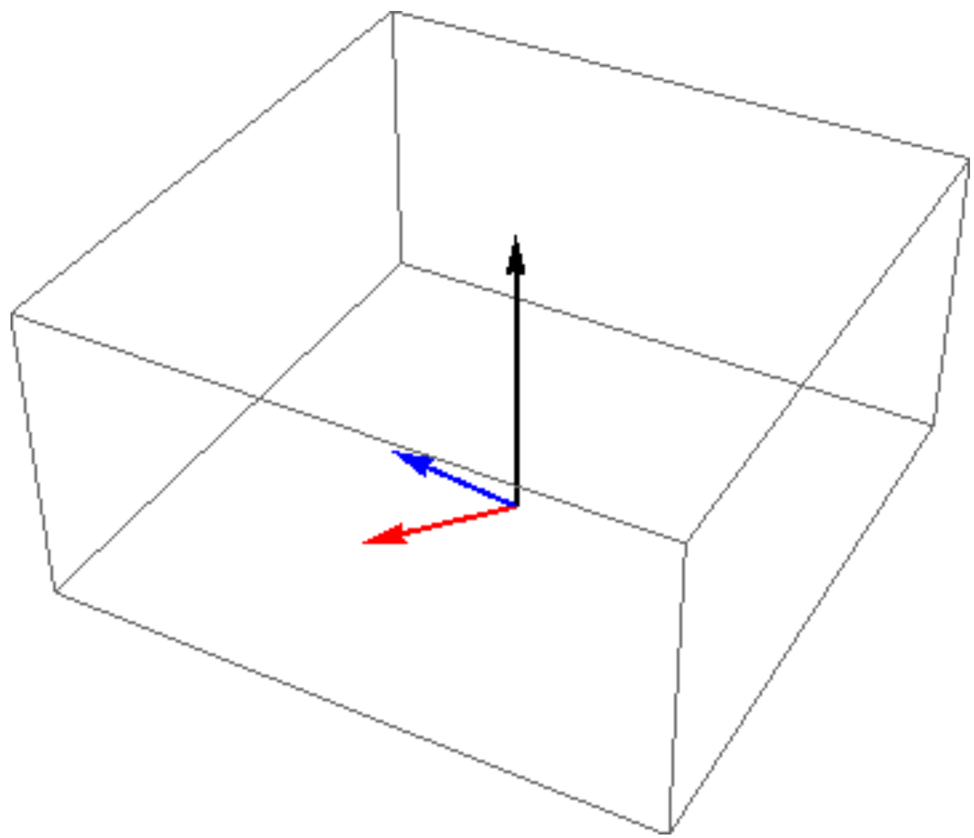
Spin Dynamics

- **Q: Can S keep up with L?**
- Answer depends on

$$\Omega_{\rm ps} \quad \text{vs} \quad \Omega_{\rm pl}$$



If $|\Omega_{ps}| >> |\Omega_{pl}|$: YES ("adiabatic")

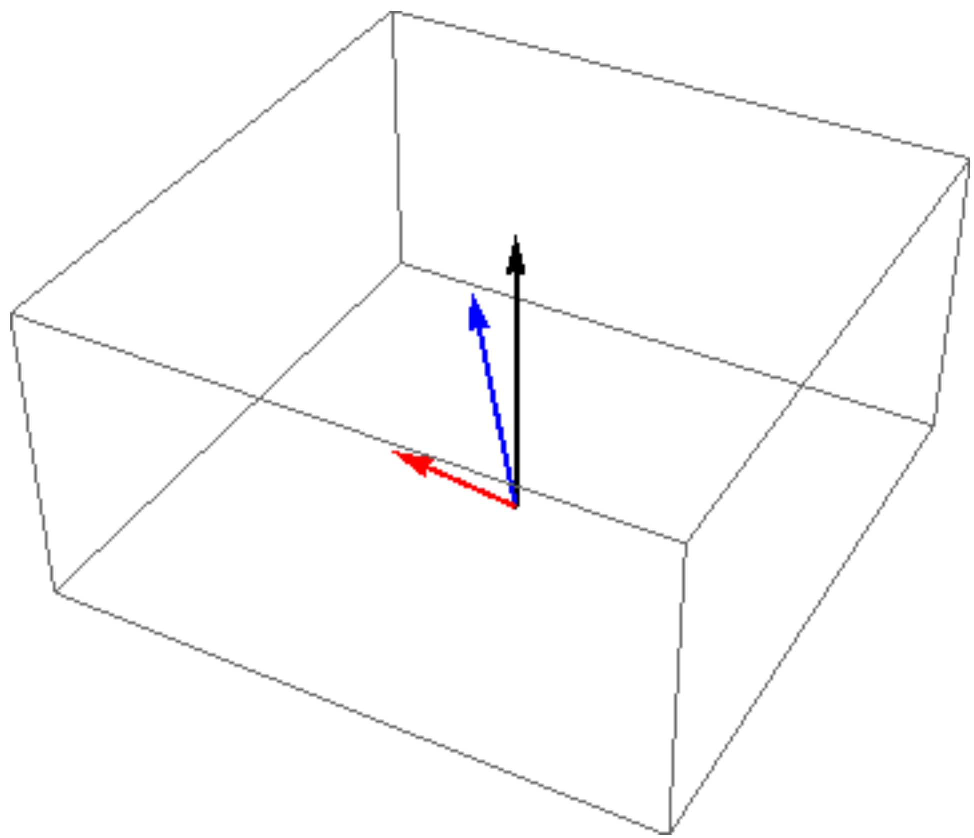


N. Storch

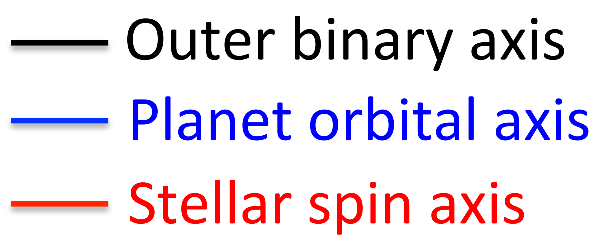
θ_{sl} = constant, i.e. initial spin-orbit misalignment is maintained for all time

Outer binary axis
Planet orbital axis
Stellar spin axis

If $|\Omega_{ps}| \ll |\Omega_{pl}|$: NO ("non-adiabatic")



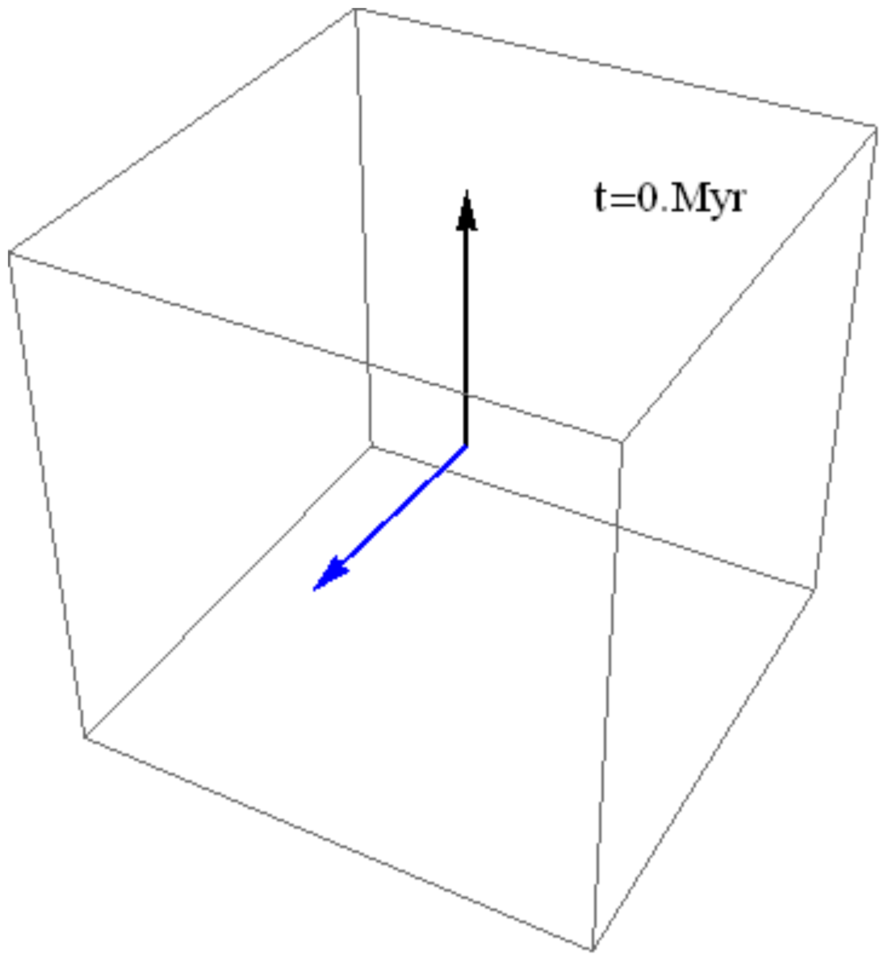
N. Storch



If $|\Omega_{ps}| \sim |\Omega_{pl}|$: “trans-adiabatic”

To answer, need to solve orbital evolution equations together with spin precession equation….

If $|\Omega_{ps}| \sim |\Omega_{pl}|$: "trans-adiabatic"

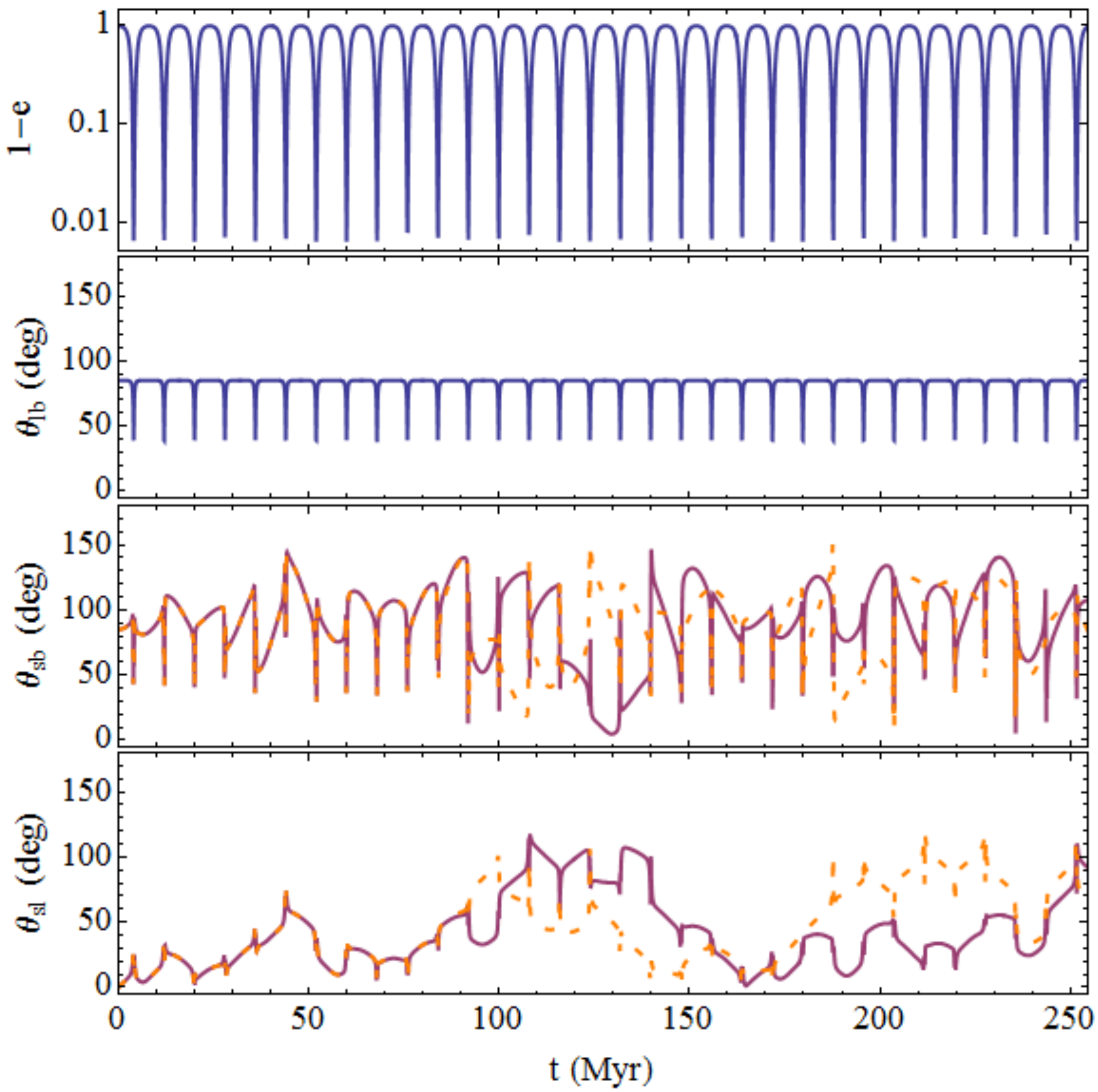


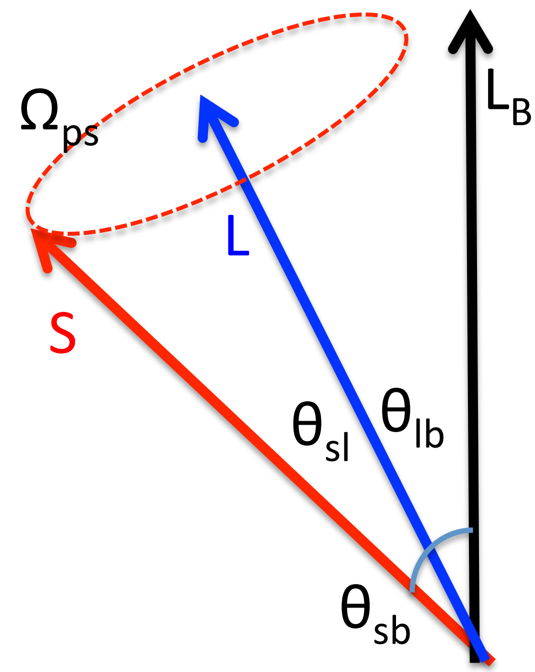
N. Storch

Outer binary axis
Planet orbital axis
Stellar spin axis

Q: Is it really chaotic?

If $|\Omega_{ps}| \sim |\Omega_{pl}|$: "trans-adiabatic"





Lyapunov time ~ 6 Myrs

Storch, Anderson & DL 14

Complication & Richness

Ω_{ps} & Ω_{pl} are strong functions of eccentricity (and time)

$$\Omega_{\rm ps} = -\frac{3GM_p(I_3 - I_1)}{2a^3 S} \frac{\cos\theta_{\rm sl}}{(1-e^2)^{3/2}} = -\Omega_{\rm ps0} \frac{\cos\theta_{\rm sl}}{(1-e^2)^{3/2}}$$

$$\Omega_{\rm ps0} \propto \frac{M_p \Omega_s}{a^3}$$

$$\Omega_{\rm pl} = -\Omega_{\rm pl0}\, f(e)$$

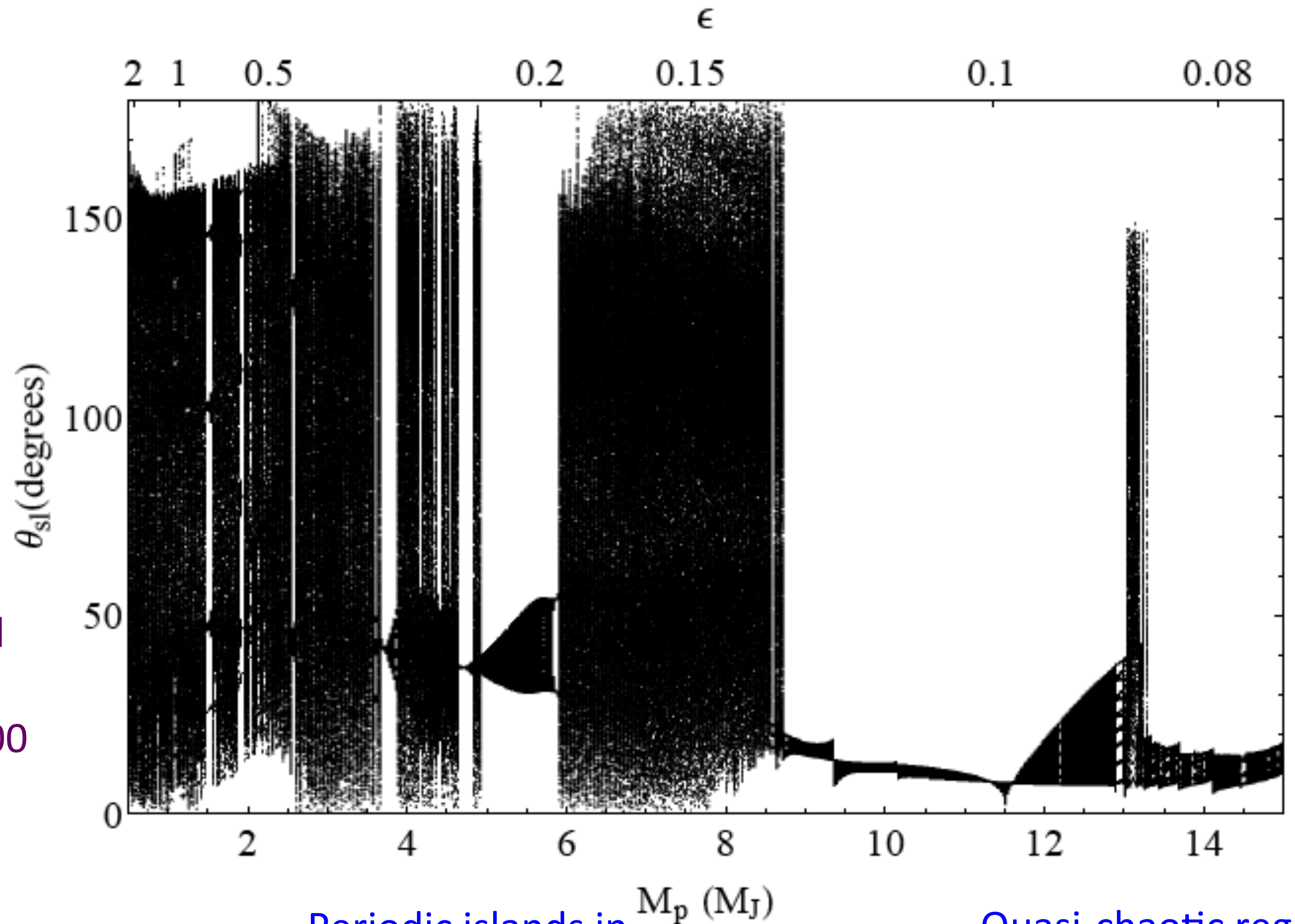
$$\Omega_{\rm pl0} \sim n \left(\frac{M_b}{M_\star}\right) \left(\frac{a}{a_b}\right)^3 \cos\theta_{\rm lb}^0$$

Key parameter:

$$\epsilon = \frac{\Omega_{\rm pl0}}{\Omega_{\rm ps0}} \propto \frac{a^{9/2}}{M_p \Omega_s}$$

The ratio of orbital precession frequency to spin precession frequency at zero eccentricity

Bifurcation Diagram



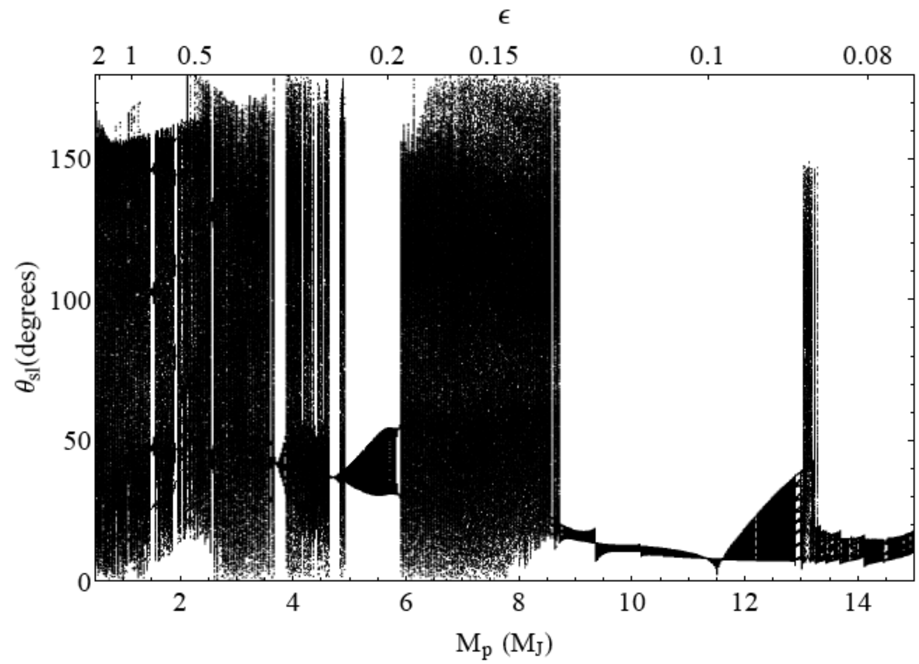
Values recorded at eccentricity maxima, for 1500 LK-cycles

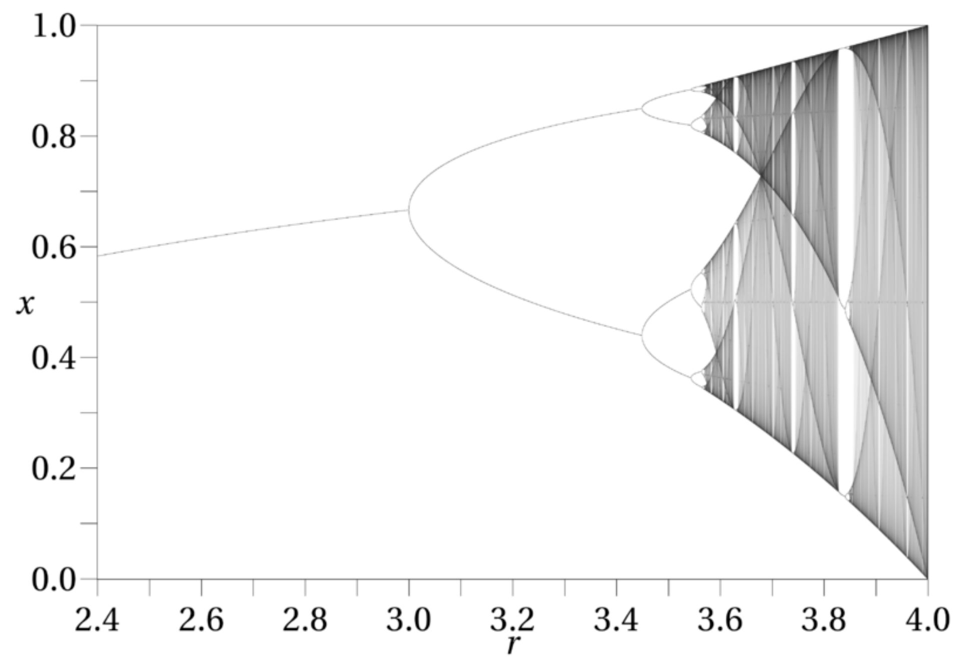
Periodic islands in the ocean of chaos

Quasi-chaotic regions in the “calm” sea

Storch, Anderson & DL 14; Storch & DL 15

Bifurcation Diagram





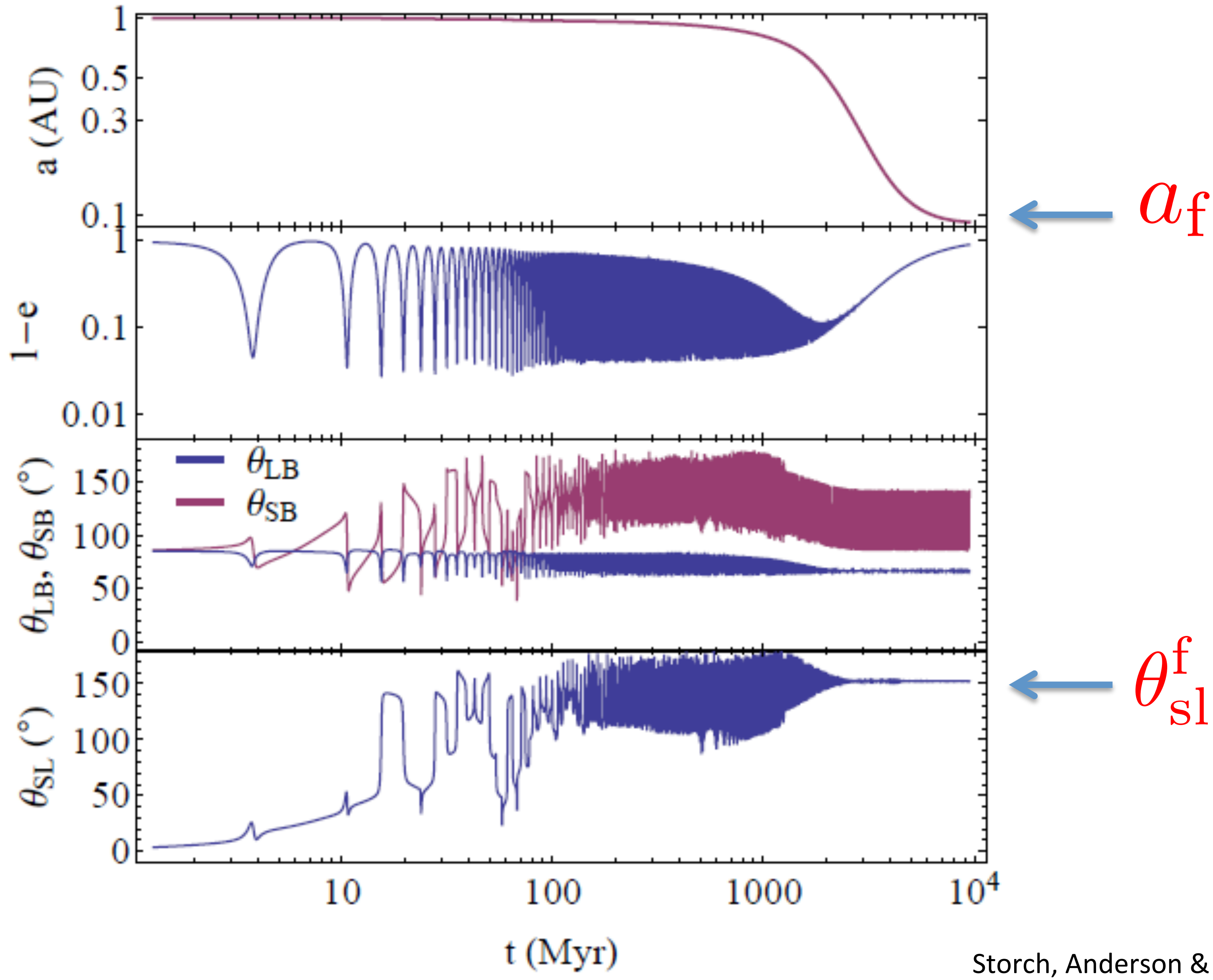
Logistic Map:

$$x_{n+1} = r x_n (1 - x_n)$$

R.May (1976): Discrete time population model

What about tidal dissipation?

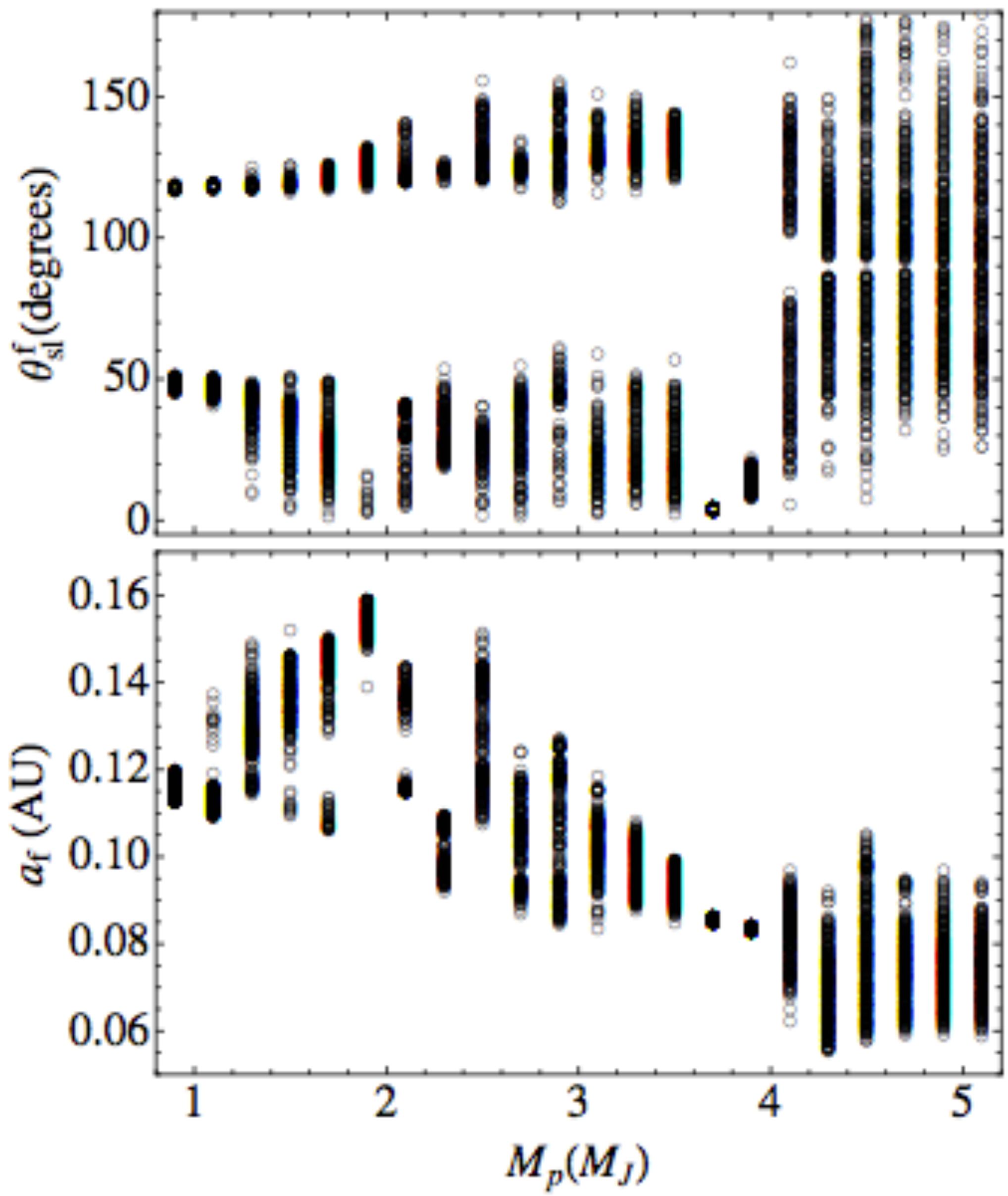
Lidov-Kozai + Tidal Dissipation



Storch, Anderson & DL 14

Memory of Chaos

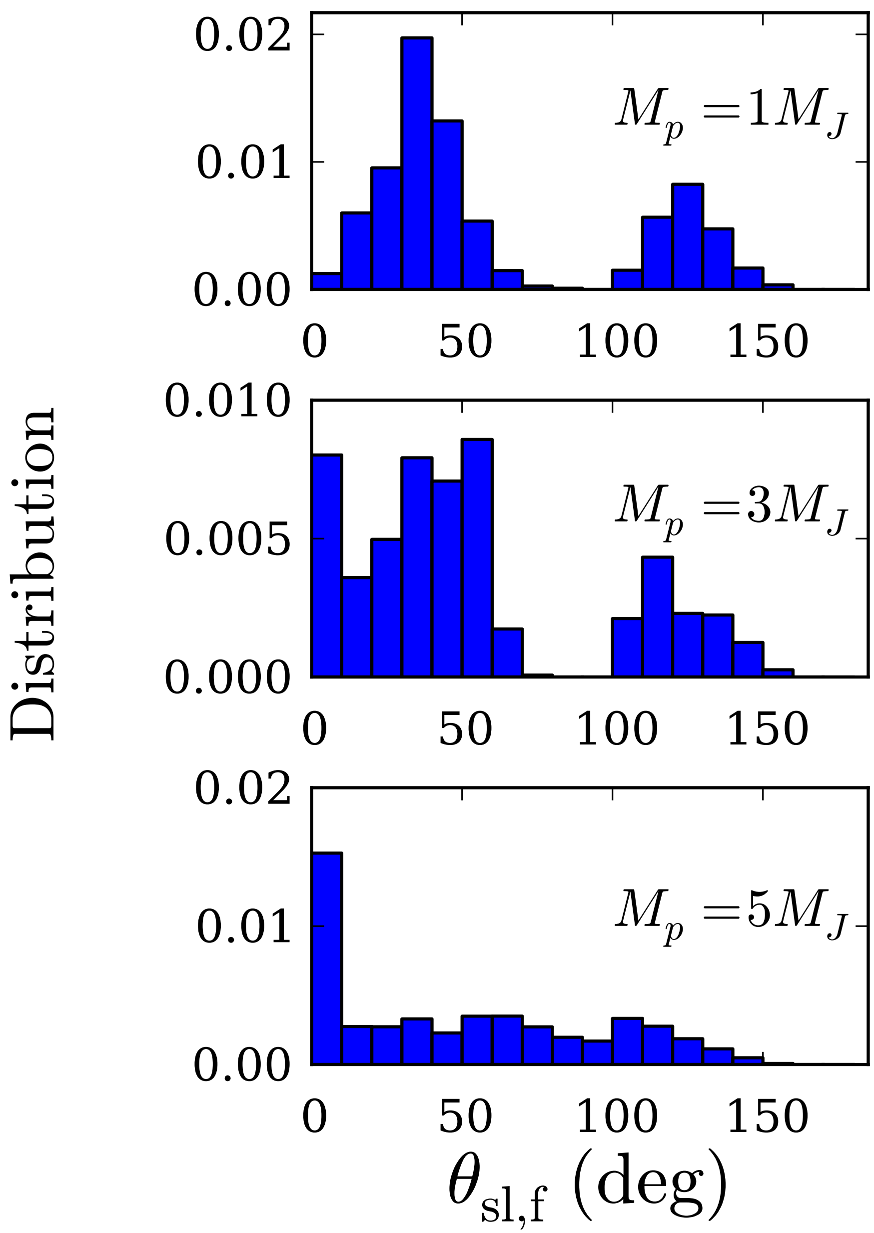
A tiny spread in initial conditions can lead to a large spread in the final spin-orbit misalignment



Initial orbital inclination θ_{lb}=85± 0.05°, with spindown

Storch, Anderson & DL 14

Distributions of the final spin-orbit angle



Parameters:

a_b = 200 AU
$M_* = M_b = 1\ M_{sun}$

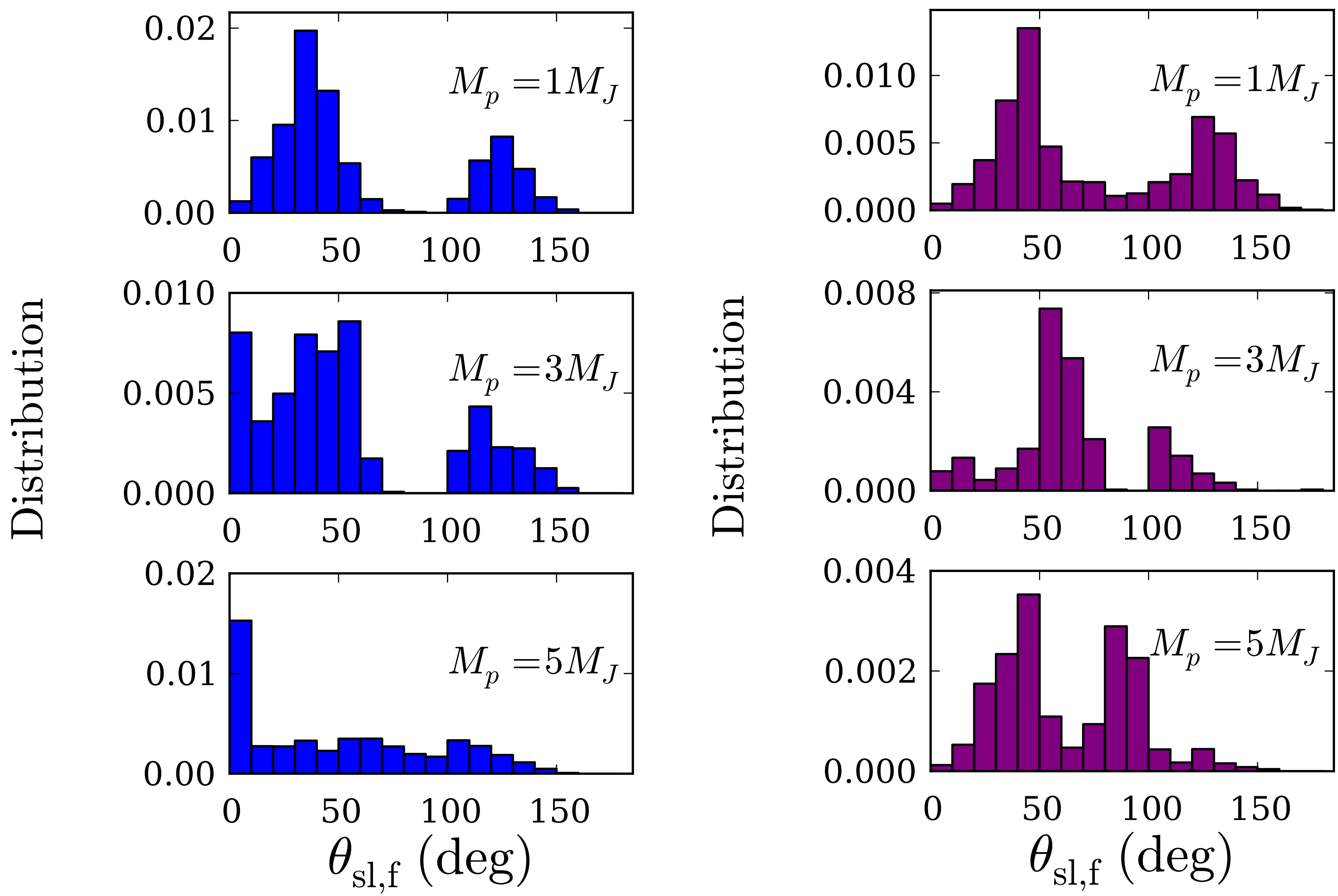
Stellar spin-down calibrated such that spin period = 27 days at 5 Gyr (Skumanich law)

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

Anderson, Storch & DL 15

Solar-type star

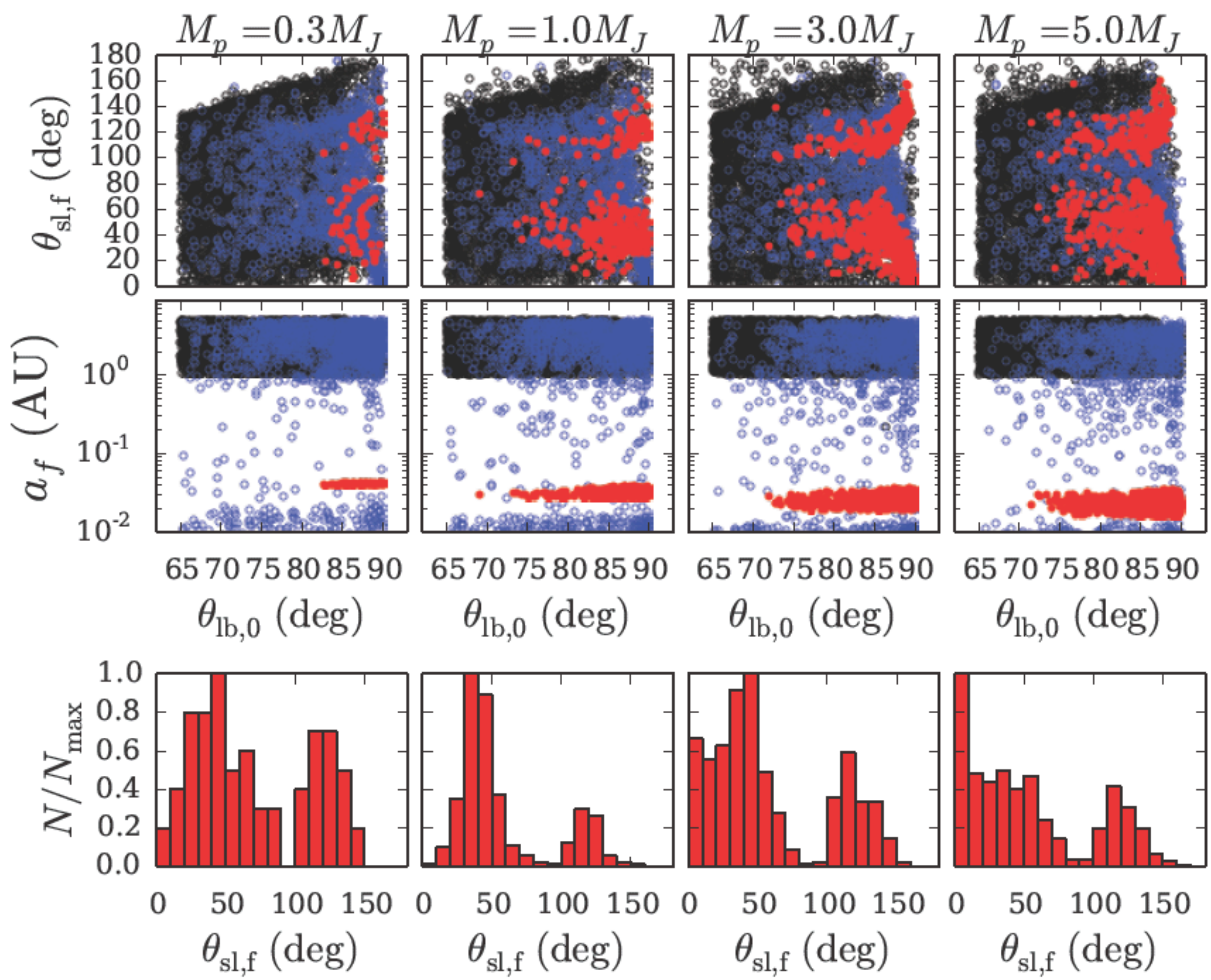
F Star (1.4 M_{sun})



Anderson, Storch & DL 15

Formation of Hot Jupiters in Stellar Binaries

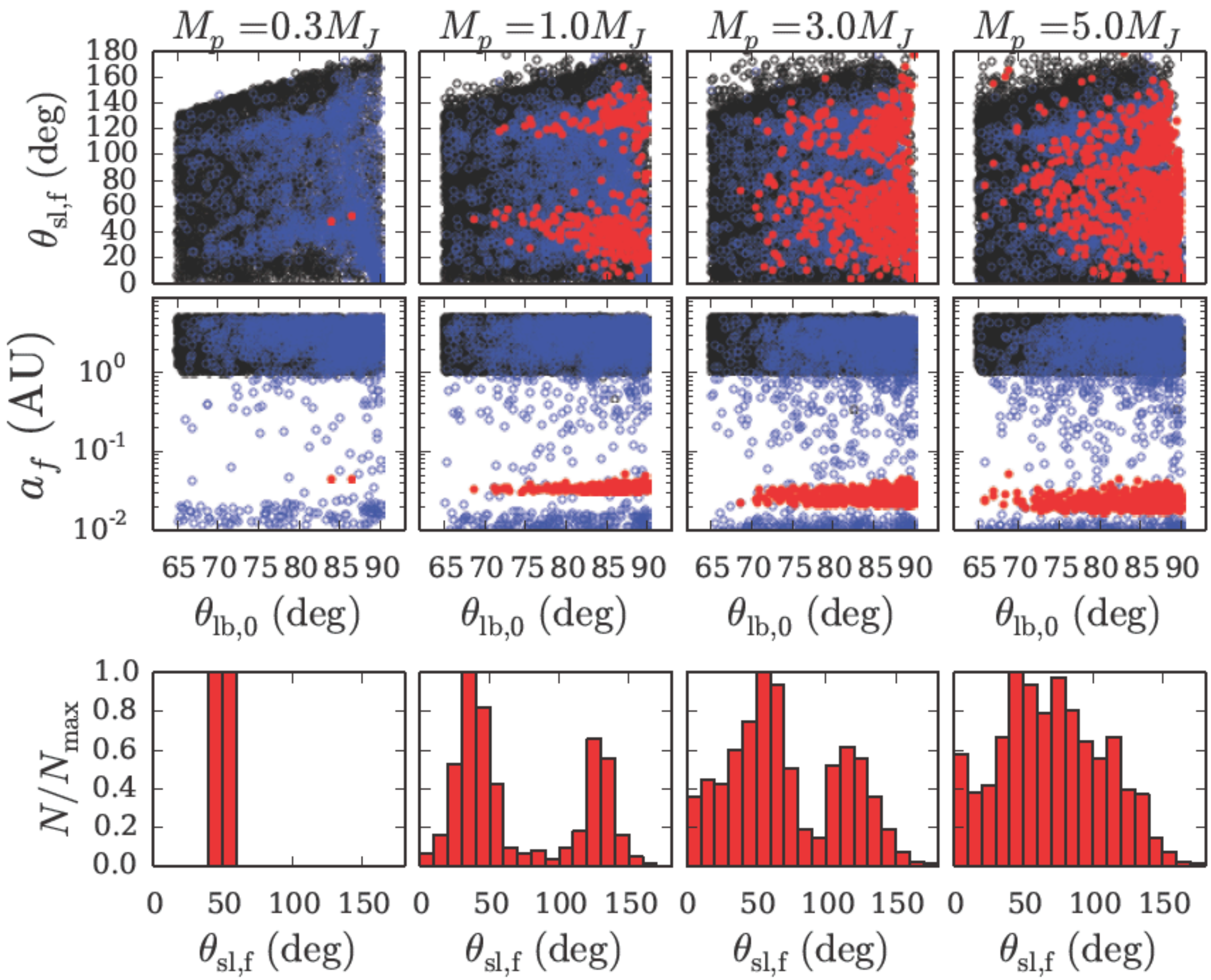
Anderson, Storch & DL 2015



G Stars

Formation of Hot Jupiters in Stellar Binaries

Anderson, Storch & DL 2015



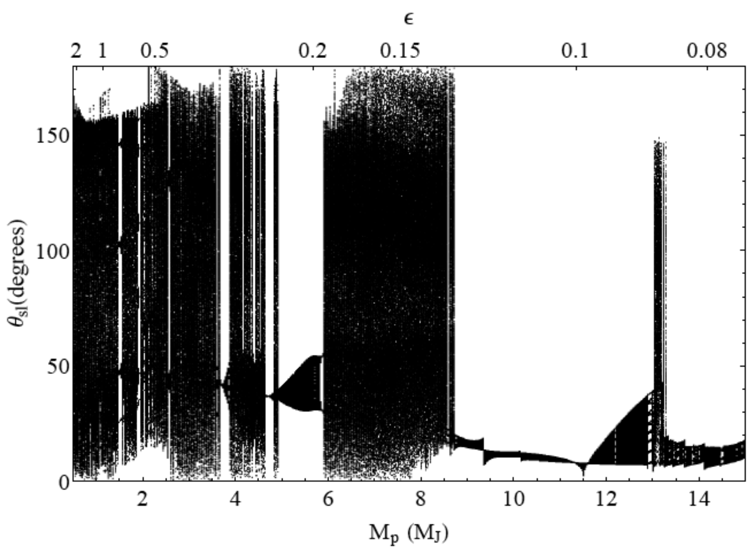
F Stars

Recap:

- Chaotic stellar spin dynamics has potentially observable consequences (spin-orbit misalignment, formation efficiency, etc).
- Depends on planet mass, stellar rotation rate/history, etc.

  (Anderson, Storch & DL 2015)

Theory of Spin Chaos

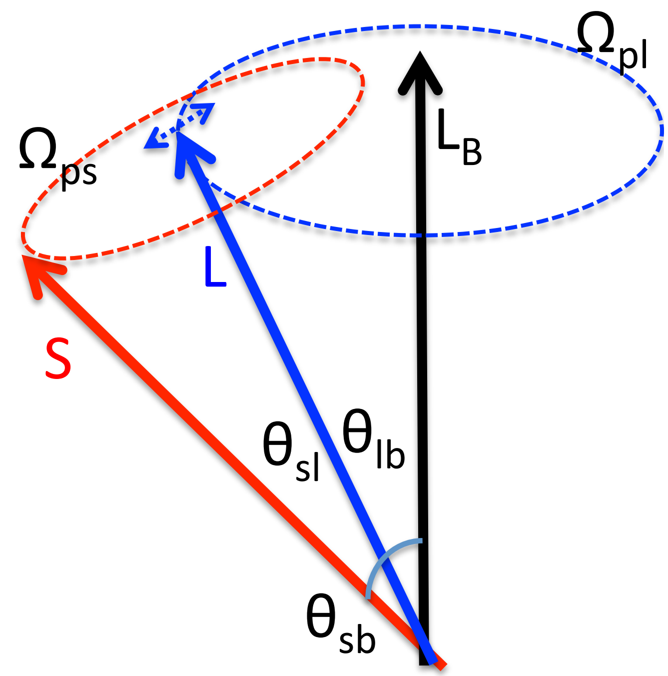


N. Storch & DL 2015

In Hamiltonian system, Chaos arises from **overlapping resonances** (Chirikov criterion; 1979)

Ω_{ps} & Ω_{pl} are strong functions of e and t (with period P_e)

What resonances??



Hamiltonian Perturbation Theory

$$H = \underbrace{-\frac{1}{2}\alpha(t)\cos^2\theta_{\rm sl}}_{\text{Spin precession}} - \underbrace{\Omega_{\rm pl}(t)\left[\cos\theta_{\rm lb}(t)\cos\theta_{\rm sl} - \sin\theta_{\rm lb}(t)\sin\theta_{\rm sl}\cos\phi\right]}_{\text{Orbit's nodal precession}} - \underbrace{\dot\theta_{\rm lb}(t)\sin\theta_{\rm sl}\sin\phi}_{\text{Orbit's nutation}},$$

$\rightarrow$ $$H' = \frac{\bar\alpha}{n_e}\left(-\frac{1}{2}p^2 + \psi(\tau)p - \sqrt{1-p^2}\left[\beta(\tau)\cos\phi + \gamma(\tau)\sin\phi\right]\right)$$

$$\begin{aligned}
\beta(\tau) &= -\frac{\Omega_{\rm pl}(\tau)}{\alpha(\tau)}\sin\theta_{\rm lb}(\tau),\\
\gamma(\tau) &= \frac{\dot\theta_{\rm lb}(\tau)}{\alpha(\tau)},\\
\psi(\tau) &= -\frac{\Omega_{\rm pl}(\tau)}{\alpha(\tau)}\cos\theta_{\rm lb}(\tau).
\end{aligned}$$

$\rightarrow$ $$\begin{aligned}
H' &= \frac{\bar\alpha}{n_e}\left(-\frac{1}{2}p^2 + \epsilon\,\psi_0\,p + \epsilon\,p\sum_{M=1}^{\infty}\psi_M\cos Mt\right.\\
&\quad\left. -\frac{\epsilon}{2}\sqrt{1-p^2}\sum_{M=0}^{\infty}\left[(\beta_M+\gamma_M)\cos(\phi - M\tau) + (\beta_M-\gamma_M)\cos(\phi+M\tau)\right]\right)
\end{aligned}$$

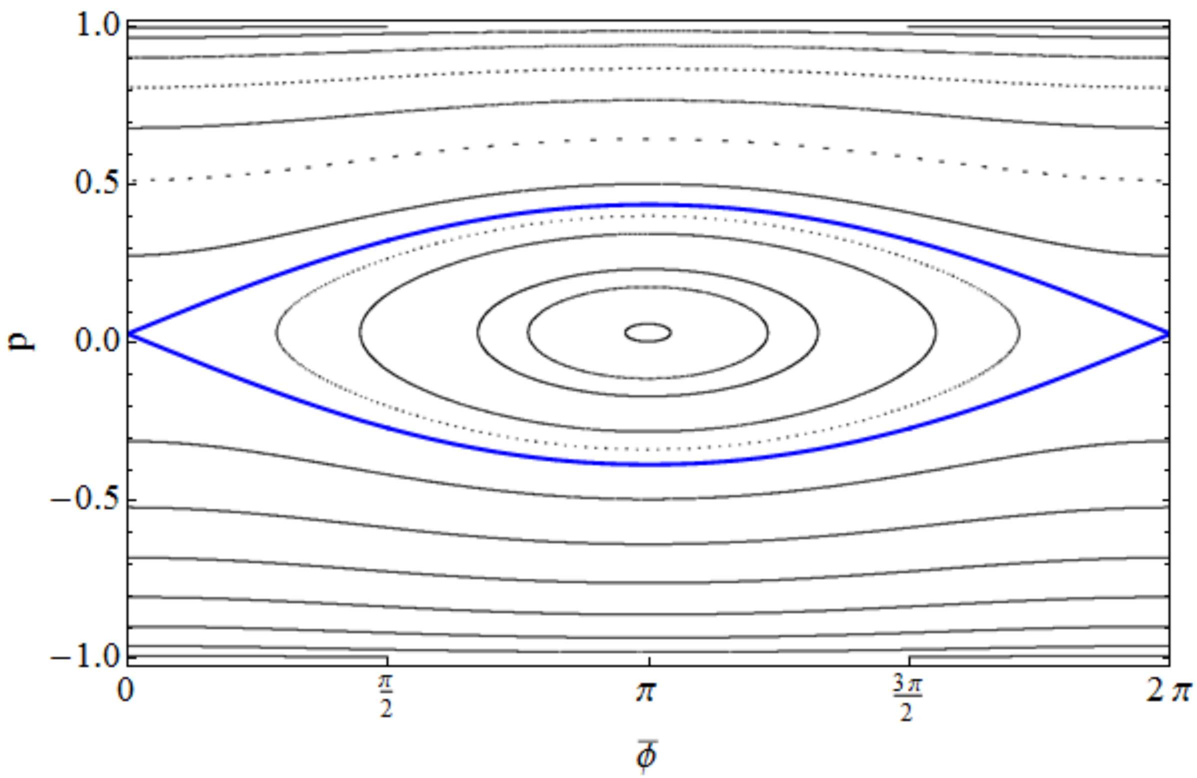
Spin-Orbit Resonances

$$\bar{\Omega}_{\rm ps} = -\bar{\alpha}\cos\theta_{\rm sl} = N\,\frac{2\pi}{P_e}$$

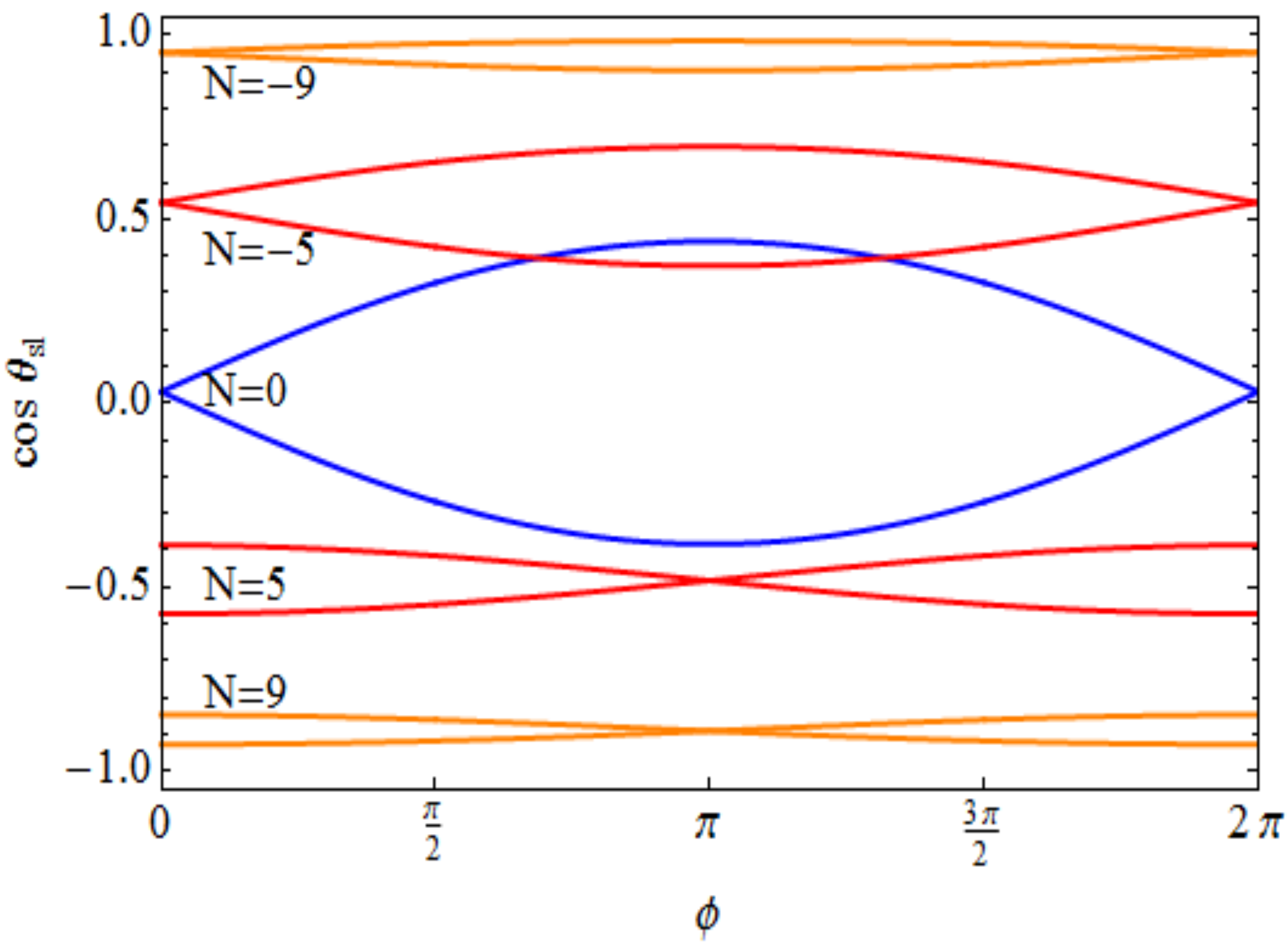
Average spin precession frequency	=	Integer multiple of mean Lidov-Kozai frequency

Individual Resonance

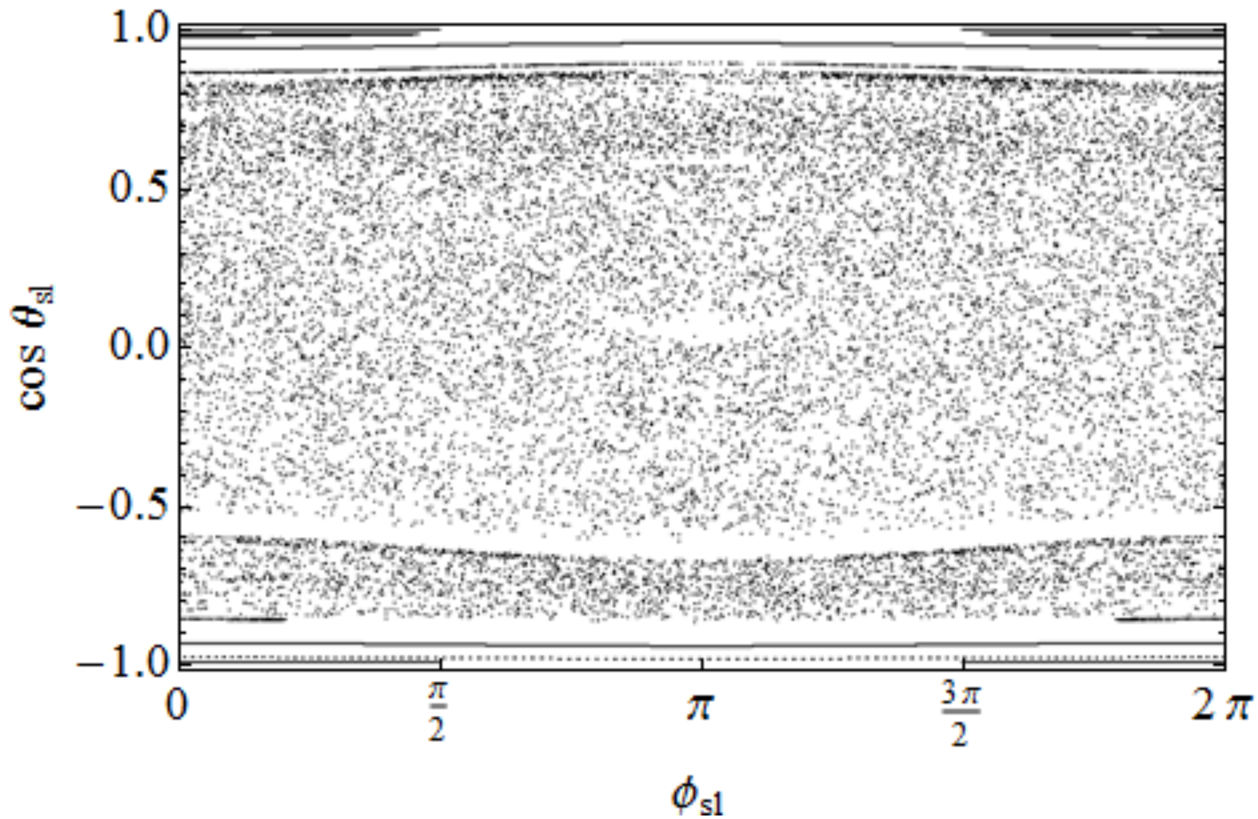
N=0



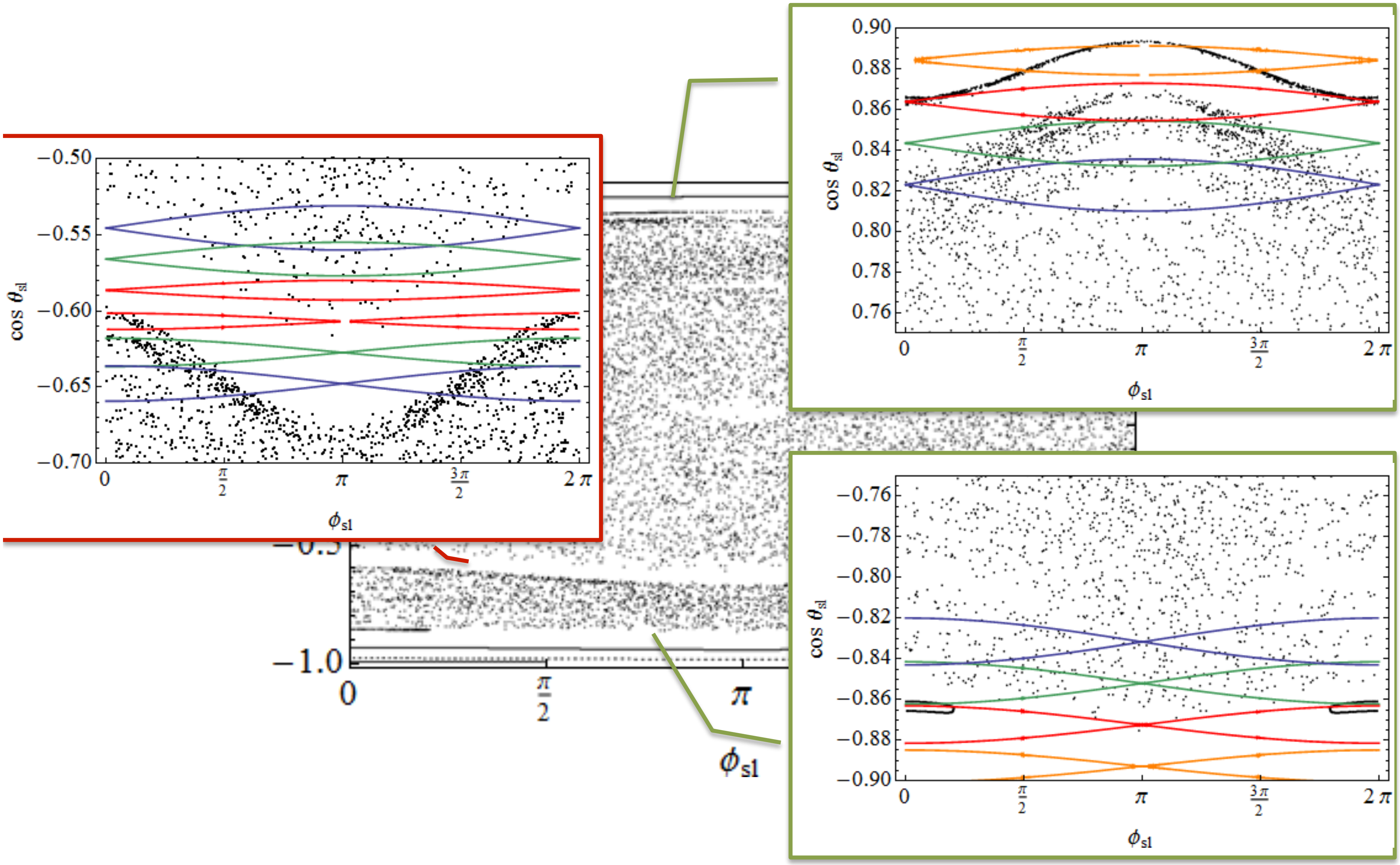
Individual Resonance



Poincare Surface of Section (Full System)

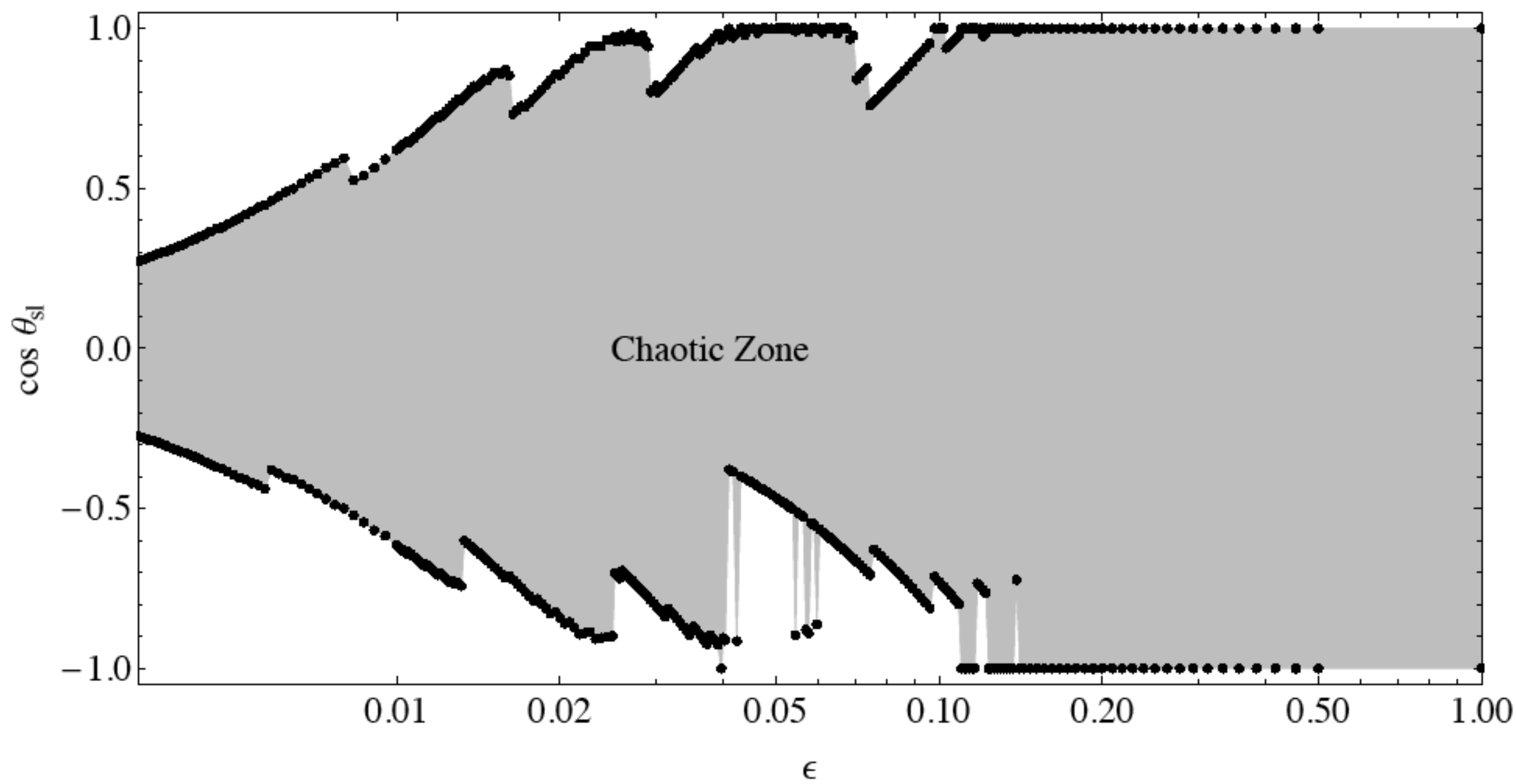


Poincare Surface of Section (Full System)



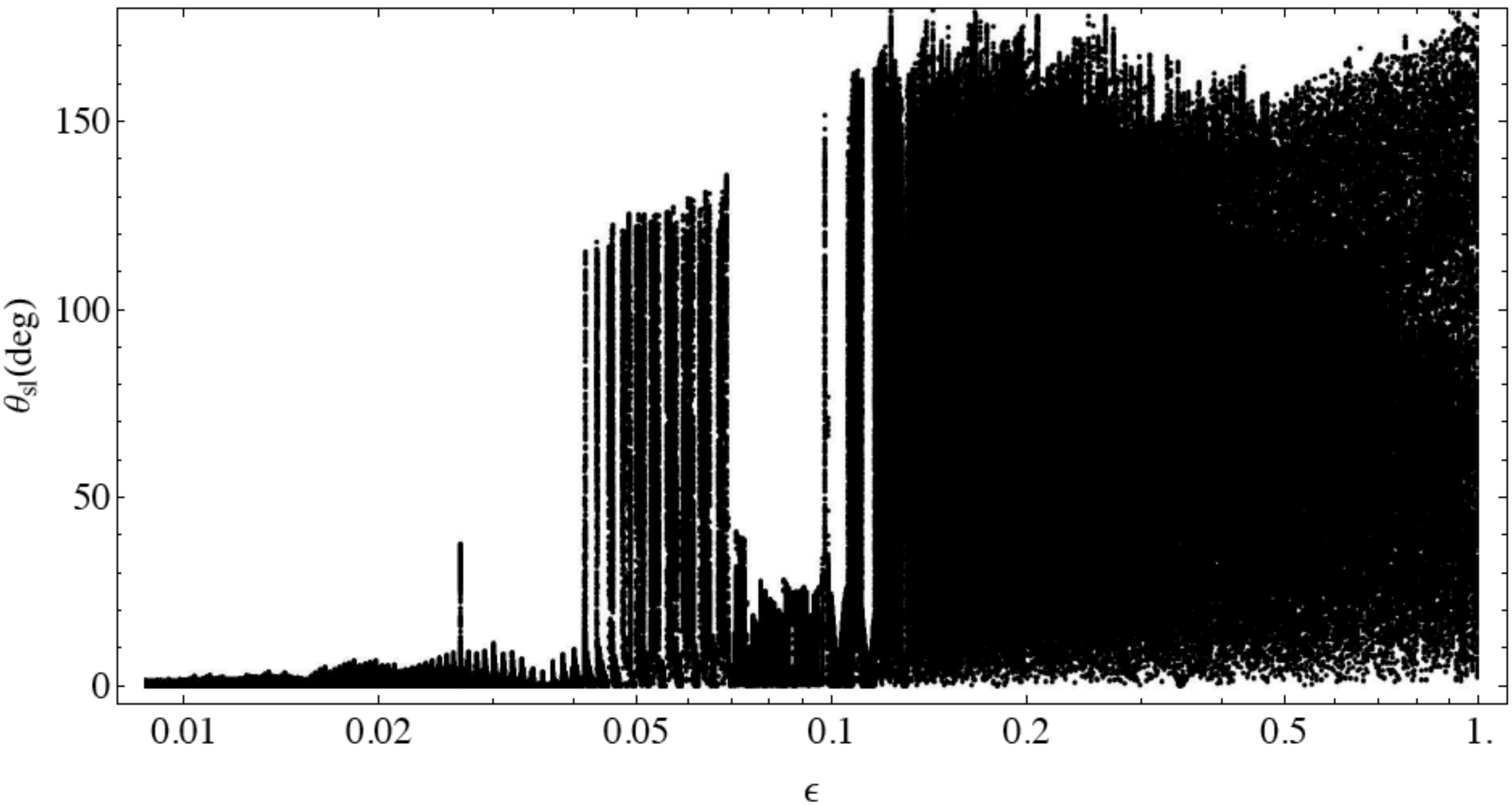
Boundary of Chaotic Zone

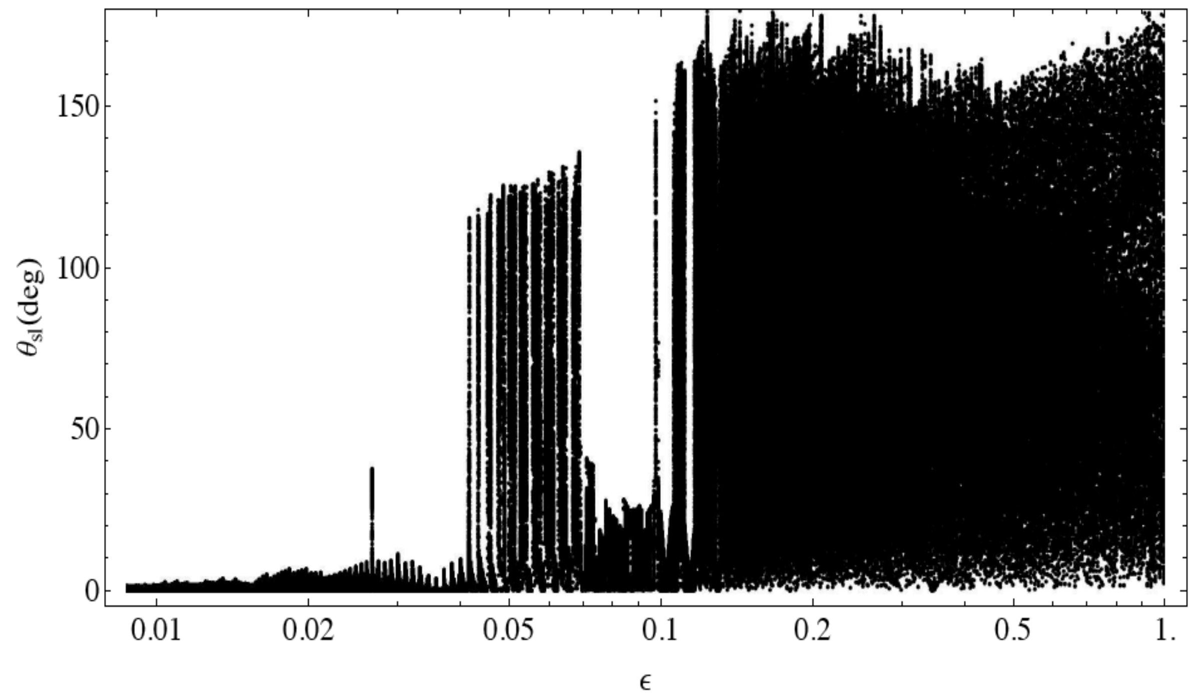
Analytical theory: From outmost overlapping resonances



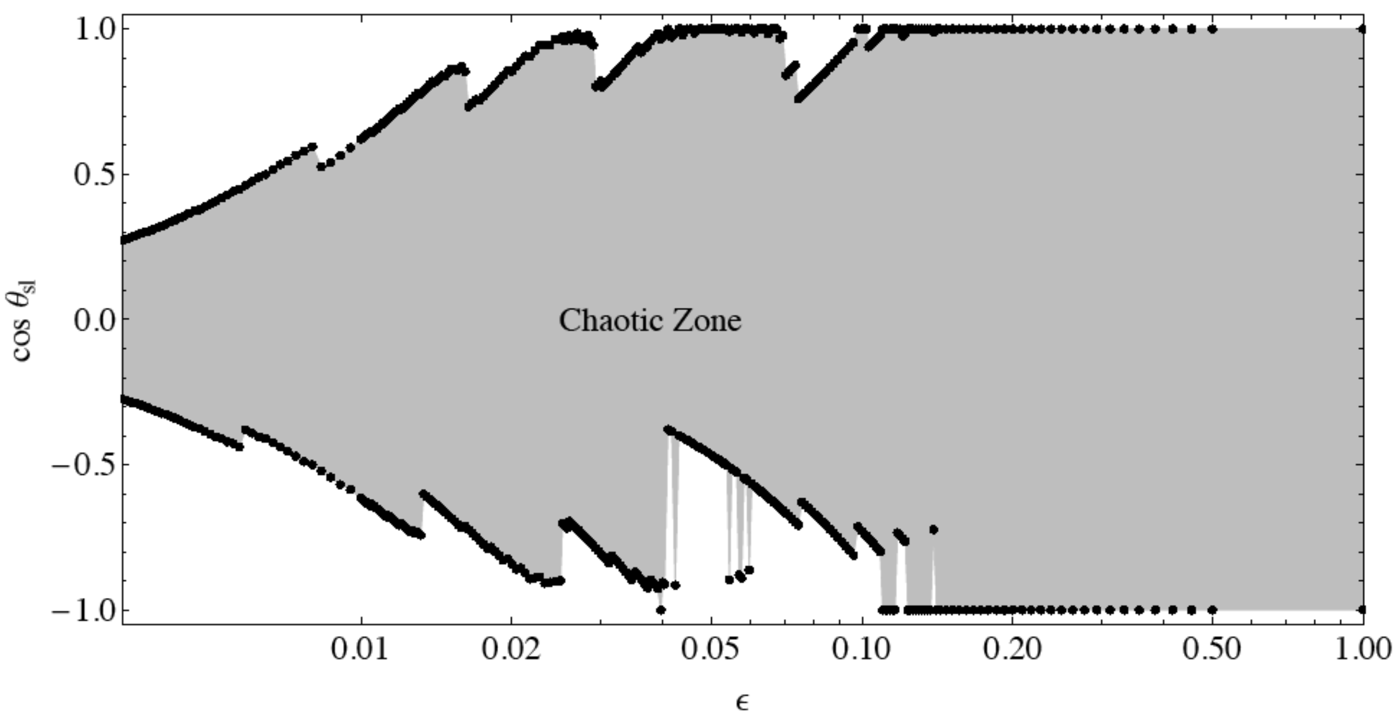
Numerical Bifurcation Diagram

Starting from zero spin-orbit angle





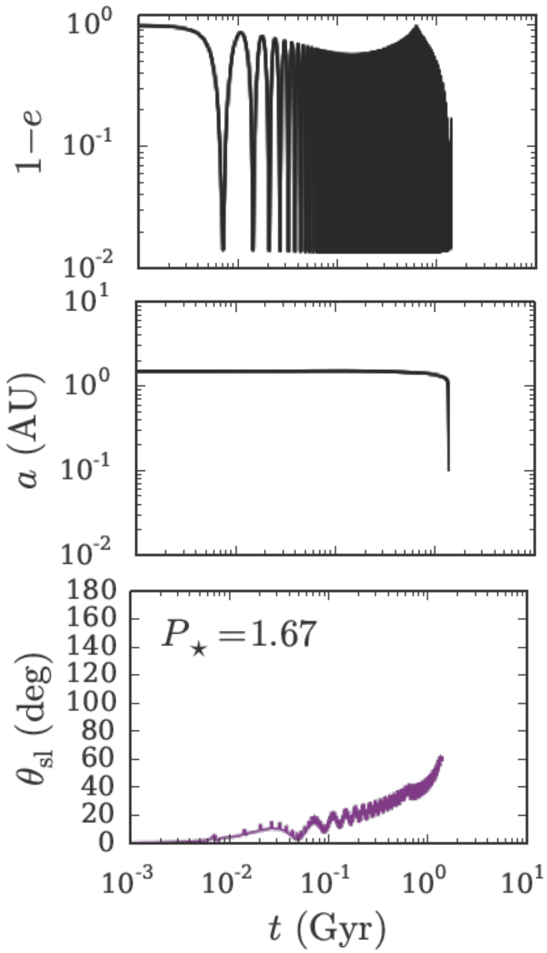
Numerical

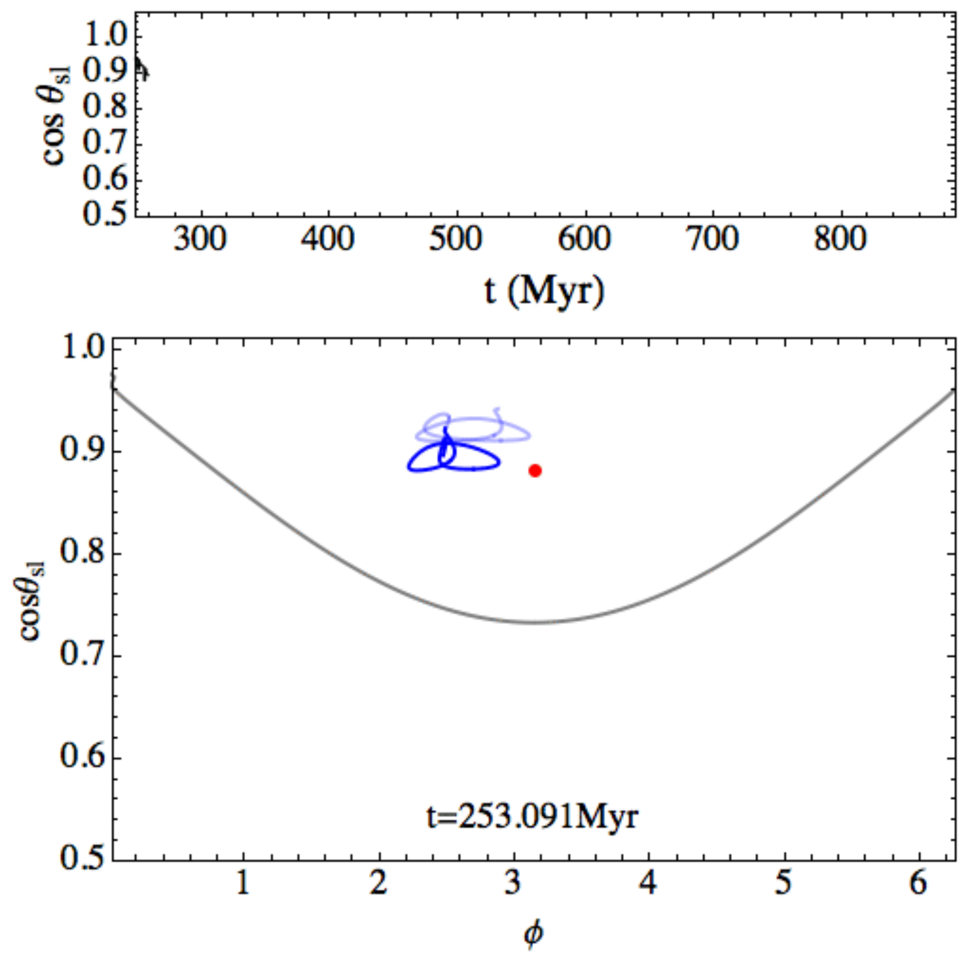


Theory

Storch & DL 2015

Effect of Dissipation: Adiabatic Resonance Advection





Anderson, Storch & DL 2015

N. Storch

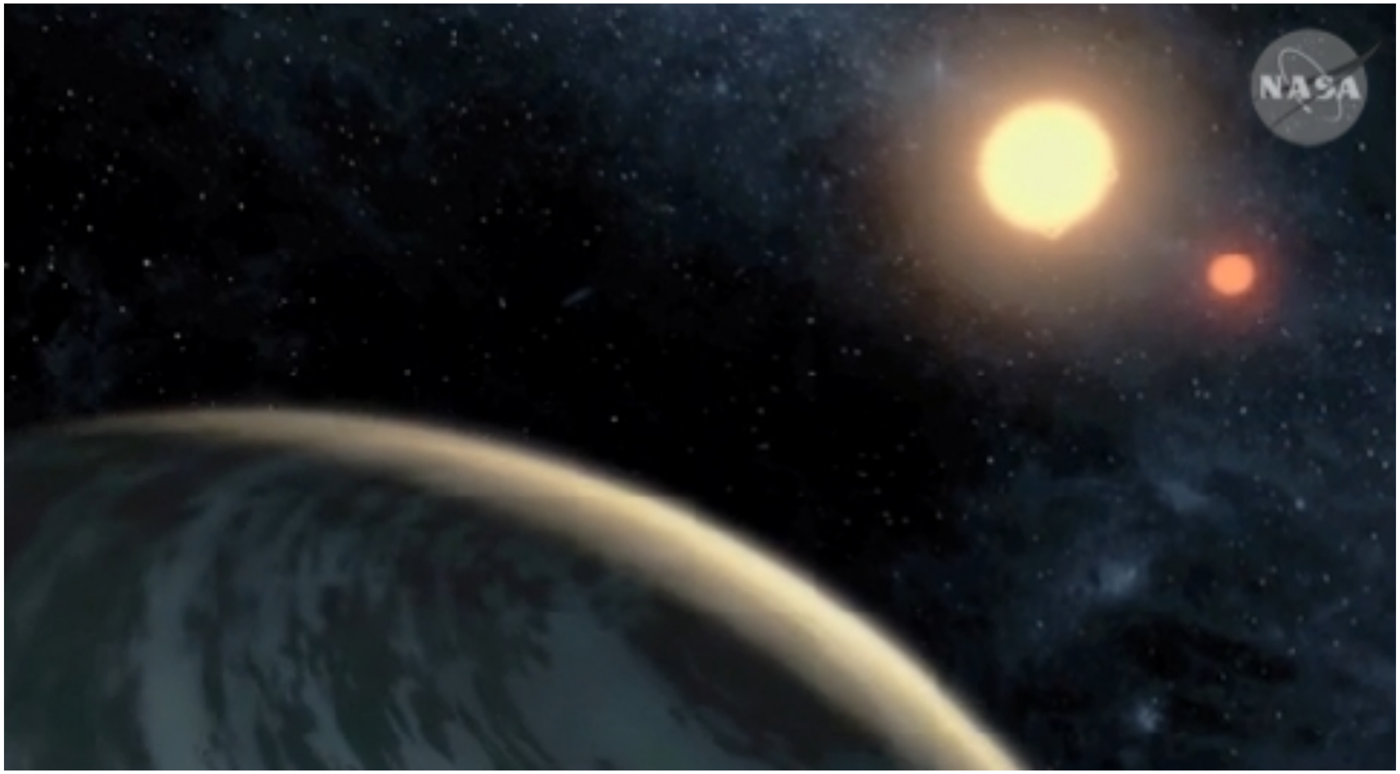
Summary (# 2)
Chaotic Stellar Spin and Formation of Hot Jupiters

- Dynamics of stellar spin is important for the formation of hot Jupiters, e.g. affects the observed spin-orbit misalignments (dependence on planet mass, stellar rotation/history etc)
- Spin dynamics can be chaotic
- Spin dynamics can be understood from resonance theory

Planets Around Shrinking Binaries

A new population of circumbinary planets?

Diego Munoz & DL 2015

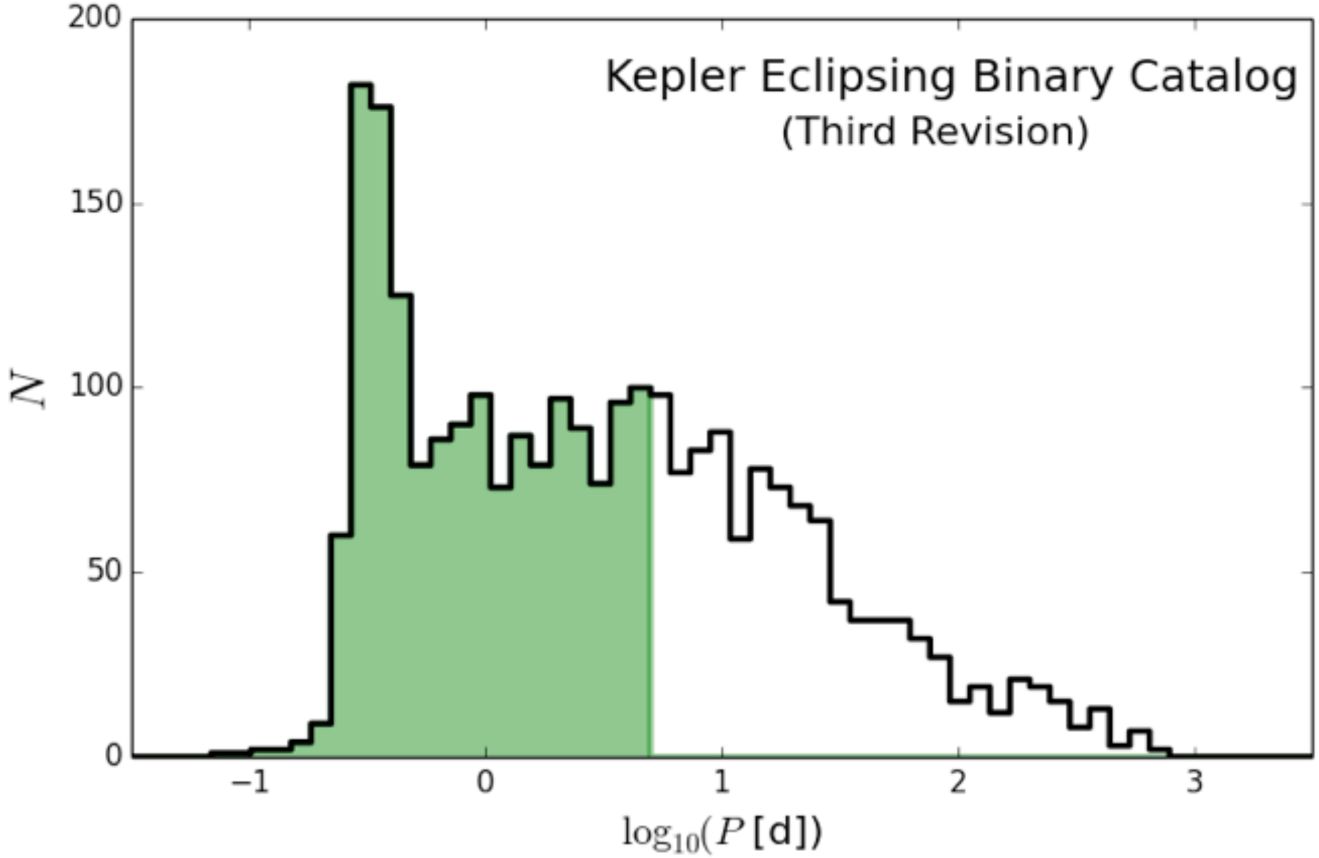


Kepler circumbinary planets

- Transiting ➔ coplanar
- Binary orbital period 7-40 days, planet orbital period 6-10 P_{bin}

Planet	P_p (days)	P_{bin} (days)	P_{crit} * (days)	P_p/P_{crit}	Ref.
Kepler-16 b	229	41.1	201	1.14	(a)
Kepler-34 b	289	27.8	194	1.49 †	(b)
Kepler-35 b	131	20.7	98.1	1.34 †	(b)
Kepler-38 b	106	18.8	81.0	1.30 †	(c)
Kepler-47 b	49.5	7.45	28.0	1.77	(d)
Kepler-47 c	303	”	”	10.8	(d)
Kepler-64 b	138	20.0	104/107 ‡	1.33 /1.29 ‡	(e,f)
Kepler-413 b	~ 66	10.1	41.4	1.59	(g)
KIC 9632895 b	241	27.3	100	2.41	(h)

Kepler eclipsing binaries



http://keplerebs.villanova.edu

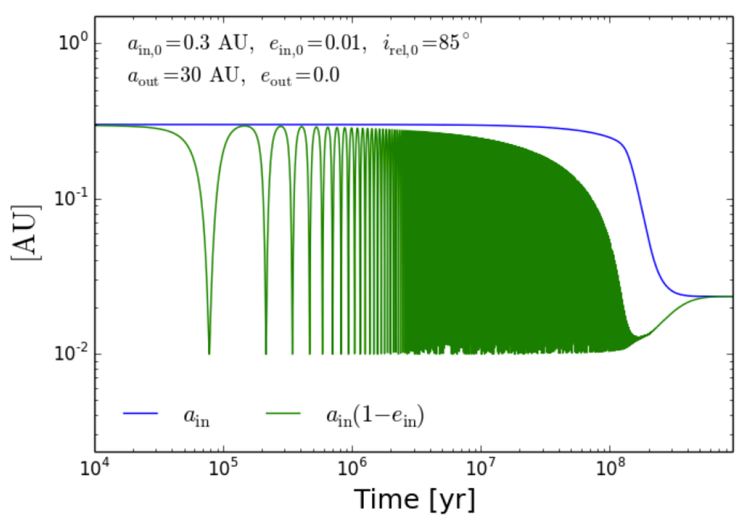
Puzzle: No transiting planet around compact binaries (P_{bin} < 5 days)

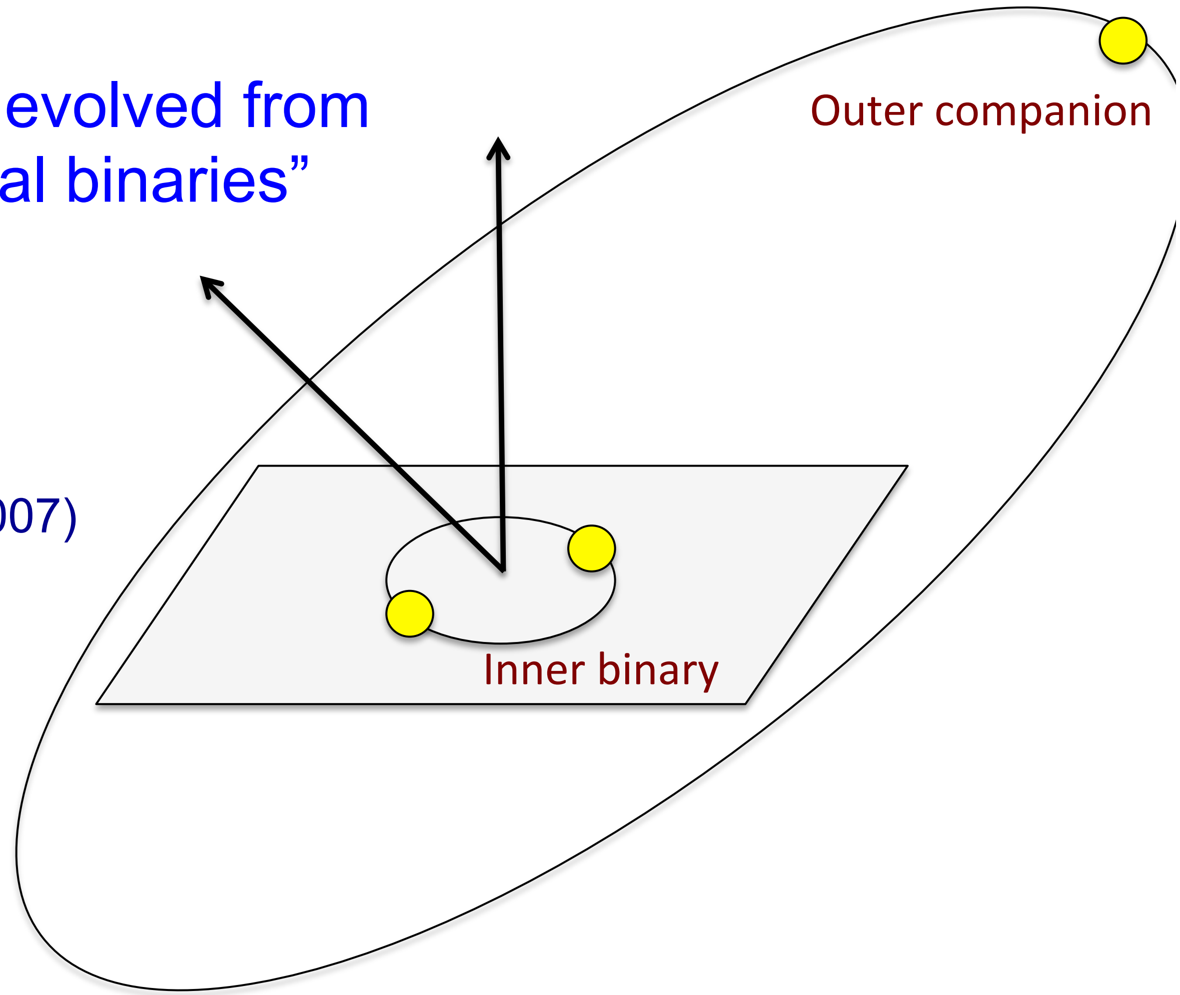
Question: Are there misaligned planets around compact binaries?

Formation of Compact (<5 days) Binaries

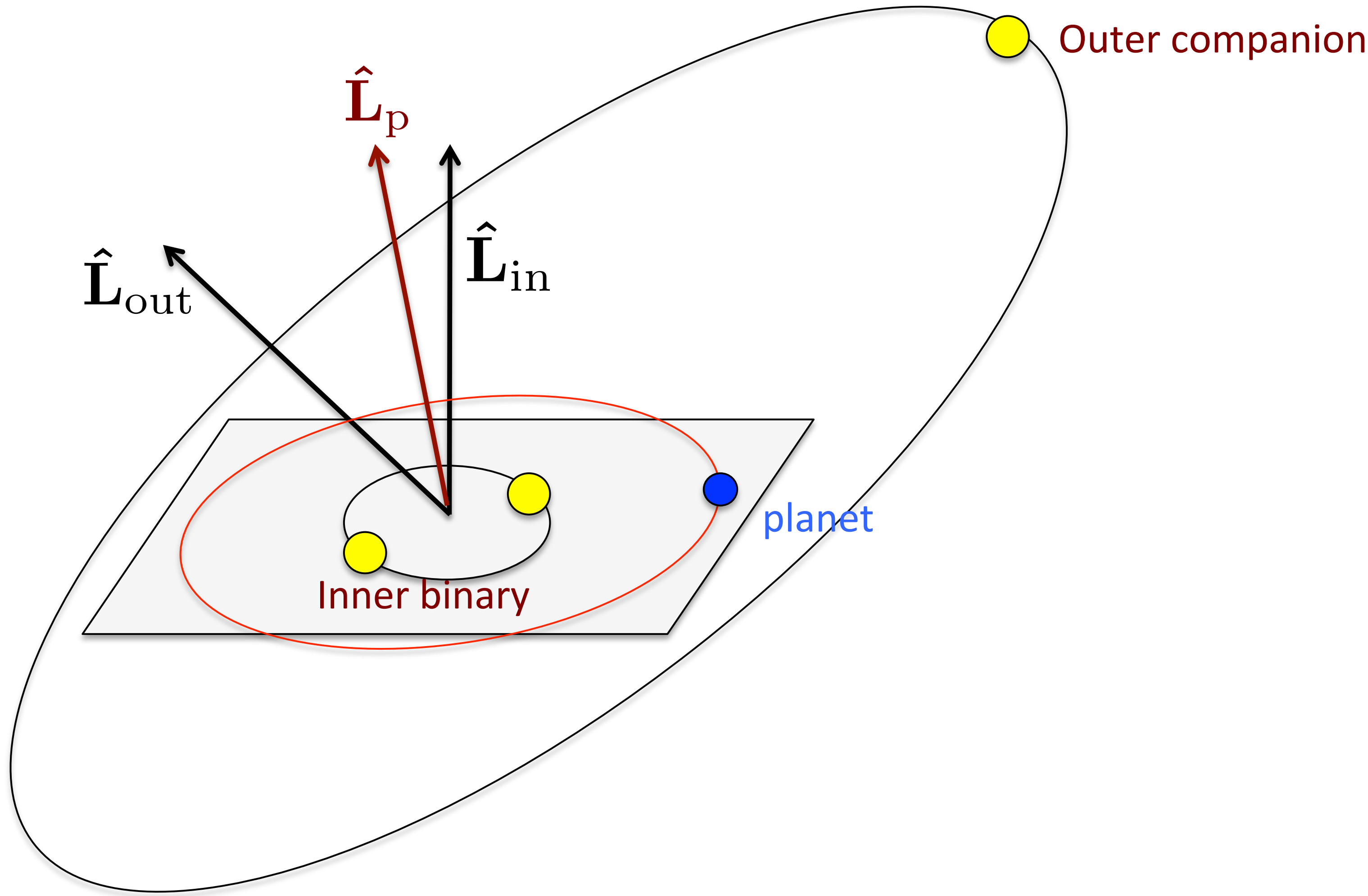
Compact binaries are evolved from orbital decay of "normal binaries"

-- Lidov–Kozai oscillation induced by an outer companion
-- Tidal dissipation
(e.g. Fabrycky & Tremaine 2007)



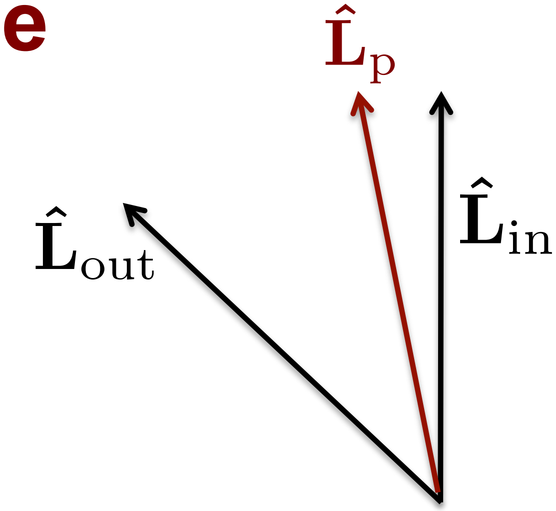


A planet "inside" a stellar triple



A planet "inside" a stellar triple

(Laplace 1805,… Tremaine et al. 2009)



Precessional (Coupling) Rates:

L_p around L_{in} : $$\Omega_{p\text{-in}} \equiv \frac{1}{2} n_p \left(\frac{\mu_{\mathrm{in}}}{M_{\mathrm{in}}}\right)\left(\frac{a_{\mathrm{in}}}{a_p}\right)^2$$

L_p around L_{out} : $$\Omega_{p\text{-out}} \equiv n_p \left(\frac{M_{\mathrm{out}}}{M_{\mathrm{in}}}\right)\left(\frac{a_p}{a_{\mathrm{out}}}\right)^3$$

When $\Omega_{\mathrm{p-in}} \gg \Omega_{\mathrm{p-out}}$ ➡ $\hat{\mathbf{L}}_p$ "obeys" $\hat{\mathbf{L}}_{\mathrm{in}}$

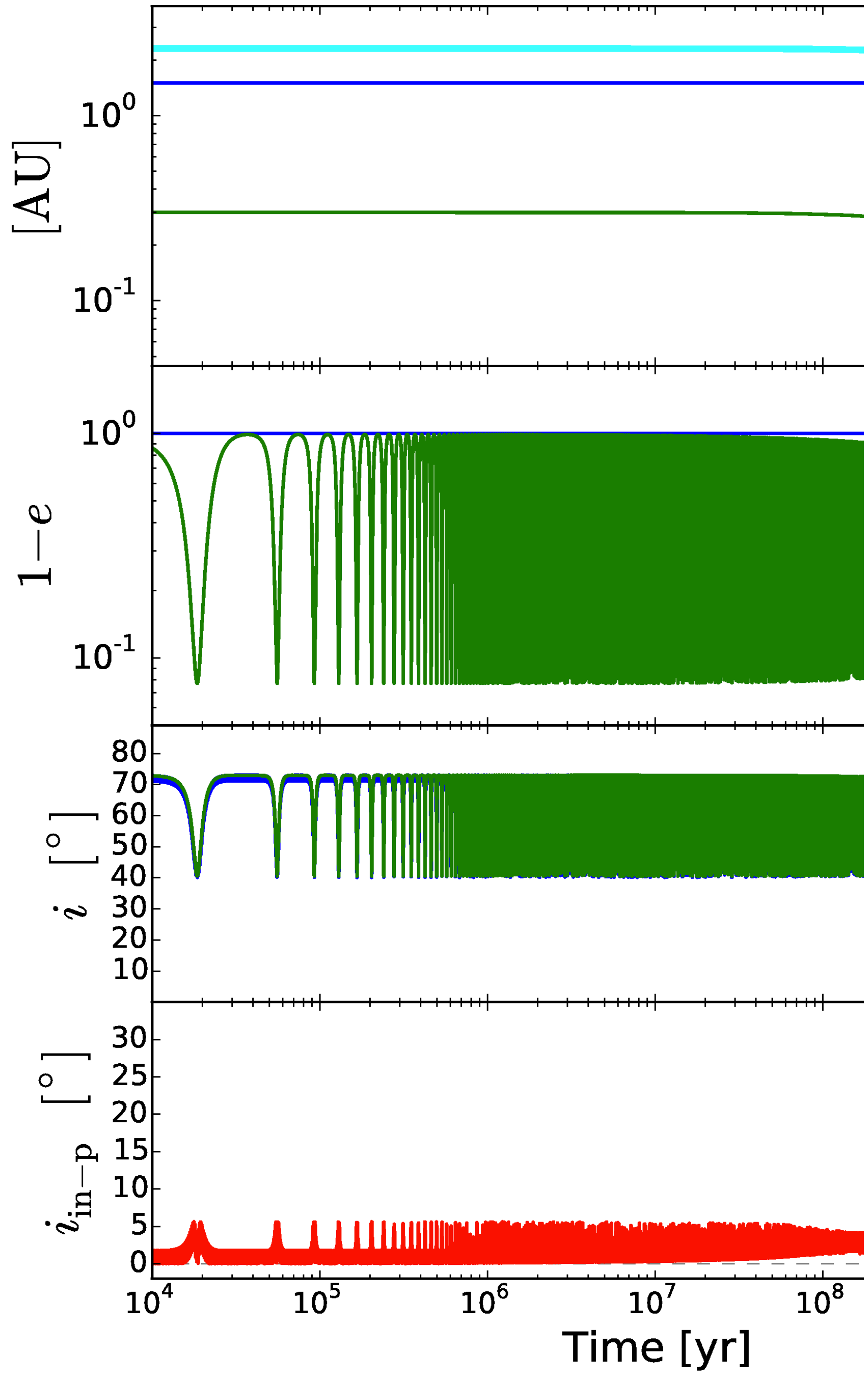
e.g., $a_p = 1.5$ AU, $a_{\mathrm{in}} = 0.3$ AU, $a_{\mathrm{out}} = 18$ AU, $M_{\mathrm{in}} = M_{\mathrm{out}} = 1\ M_\odot$

$\hat{\mathbf{L}}_{\mathrm{in}}$ changes slowly, at the rate $$\Omega_{\text{in-out}} \equiv n_{\mathrm{in}} \left(\frac{M_{\mathrm{out}}}{M_{\mathrm{in}}}\right)\left(\frac{a_{\mathrm{in}}}{a_{\mathrm{out}}}\right)^3$$

➡ $\hat{\mathbf{L}}_p$ follows $\hat{\mathbf{L}}_{\mathrm{in}}$ adiabatically

Green: binary

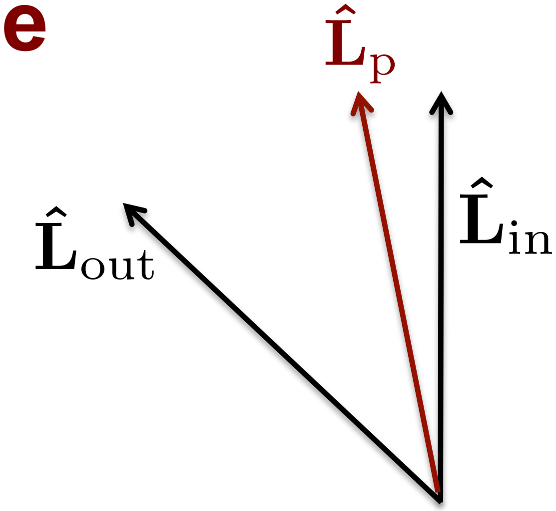
Blue: planet



$i_{\text{in-out},0} = 73^\circ$

A planet "inside" a stellar triple

(Laplace 1805,… Tremaine et al. 2009)



Precessional (Coupling) Rates:

L_p around L_{in} : $$\Omega_{p\text{-in}} \equiv \frac{1}{2} n_p \left(\frac{\mu_{\rm in}}{M_{\rm in}}\right)\left(\frac{a_{\rm in}}{a_p}\right)^2$$

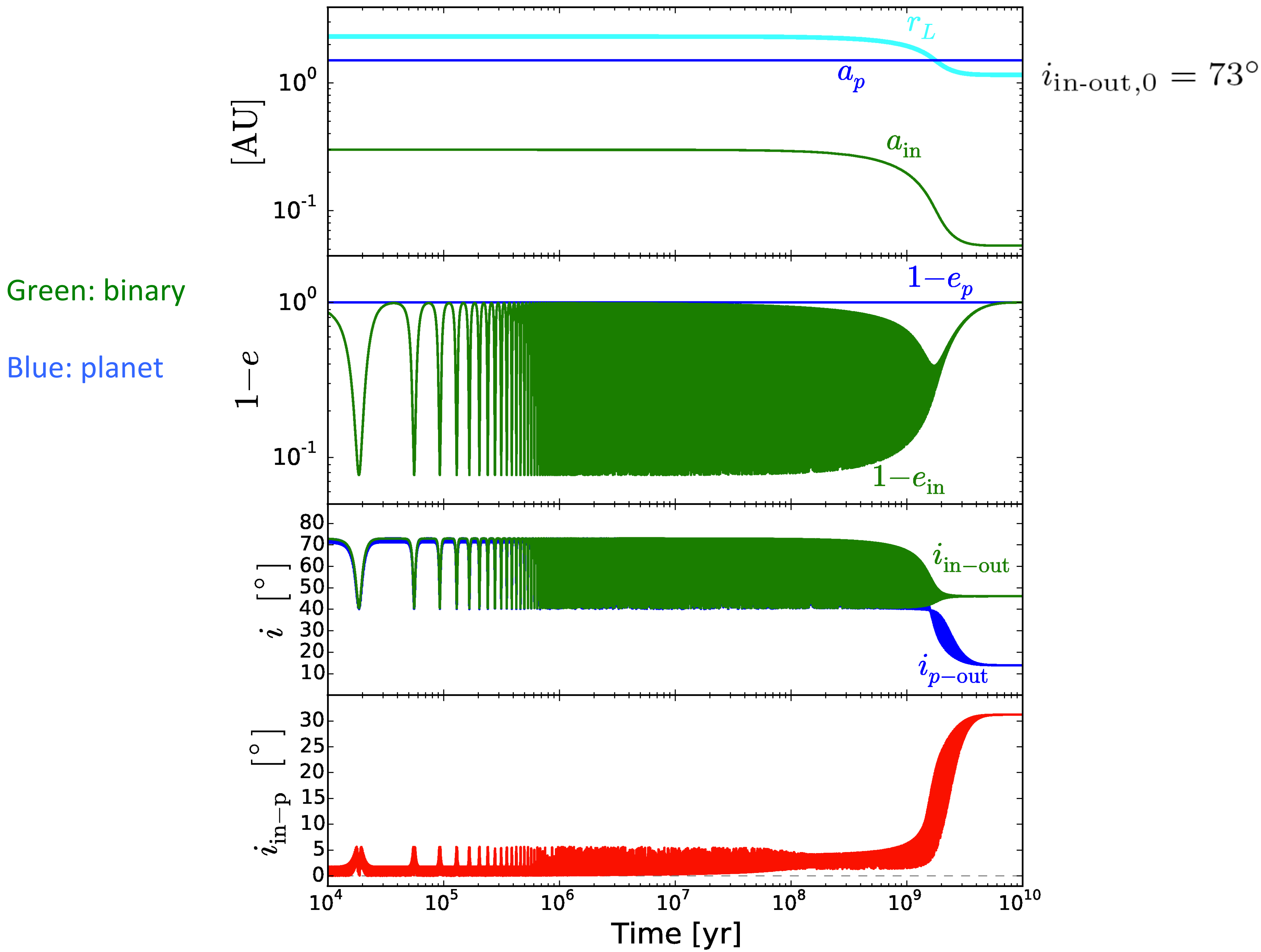
L_p around L_{out} : $$\Omega_{p\text{-out}} \equiv n_p \left(\frac{M_{\rm out}}{M_{\rm in}}\right)\left(\frac{a_p}{a_{\rm out}}\right)^3$$

When $\Omega_{\rm p-in} \gg \Omega_{\rm p-out}$ $\Rightarrow$ $\hat{\mathbf{L}}_p$ "obeys" $\hat{\mathbf{L}}_{\rm in}$

e.g., $a_p = 1.5$ AU, $a_{\rm in} = 0.3$ AU, $a_{\rm out} = 18$ AU, $M_{\rm in} = M_{\rm out} = 1\ M_\odot$

$\hat{\mathbf{L}}_{\rm in}$ changes slowly, at the rate $$\Omega_{\text{in-out}} \equiv n_{\rm in} \left(\frac{M_{\rm out}}{M_{\rm in}}\right)\left(\frac{a_{\rm in}}{a_{\rm out}}\right)^3$$

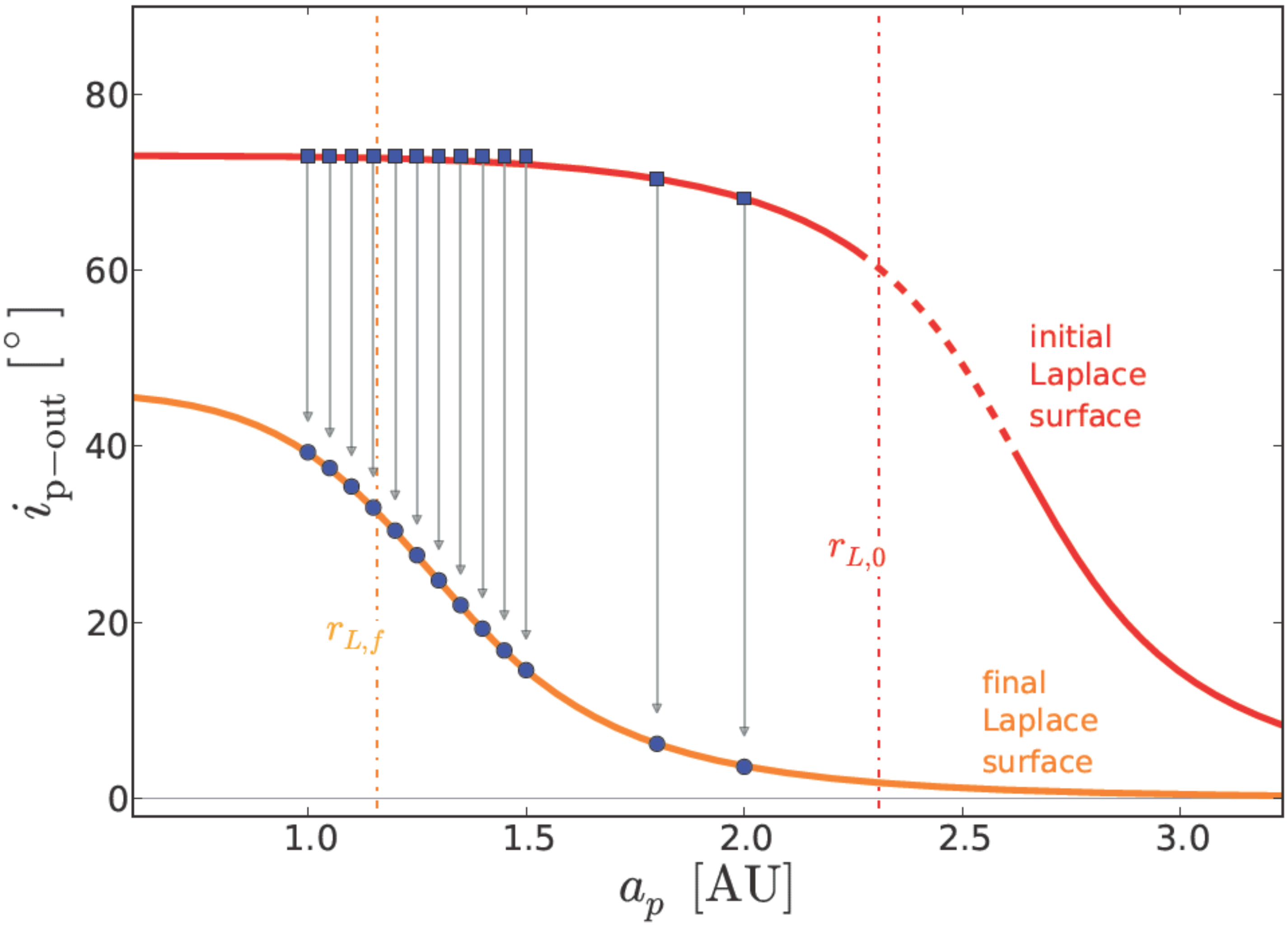
$\Rightarrow$ $\hat{\mathbf{L}}_p$ follows $\hat{\mathbf{L}}_{\rm in}$ adiabatically



Green: binary
Blue: planet
$i_{\text{in-out},0} = 73^\circ$
r_L
a_p
a_{in}
[AU]
10^0
10^{-1}
$1-e_p$
$1-e_{\text{in}}$
$1-e$
$i_{\text{in-out}}$
$i_{p\text{-out}}$
i [°]
$i_{\text{in-p}}$ [°]
Time [yr]
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}

Laplace Equilibrium

triple with $i_{\text{in-out},0}$=73°



$a_{\text{in},0} = 0.3$ AU, $i_{\text{in-out},0} = 73°$, $a_{\text{in},f} = 0.053$ AU, $i_{\text{in-out},f} = 46.1°$ and $a_{\text{out}} = 18$ AU

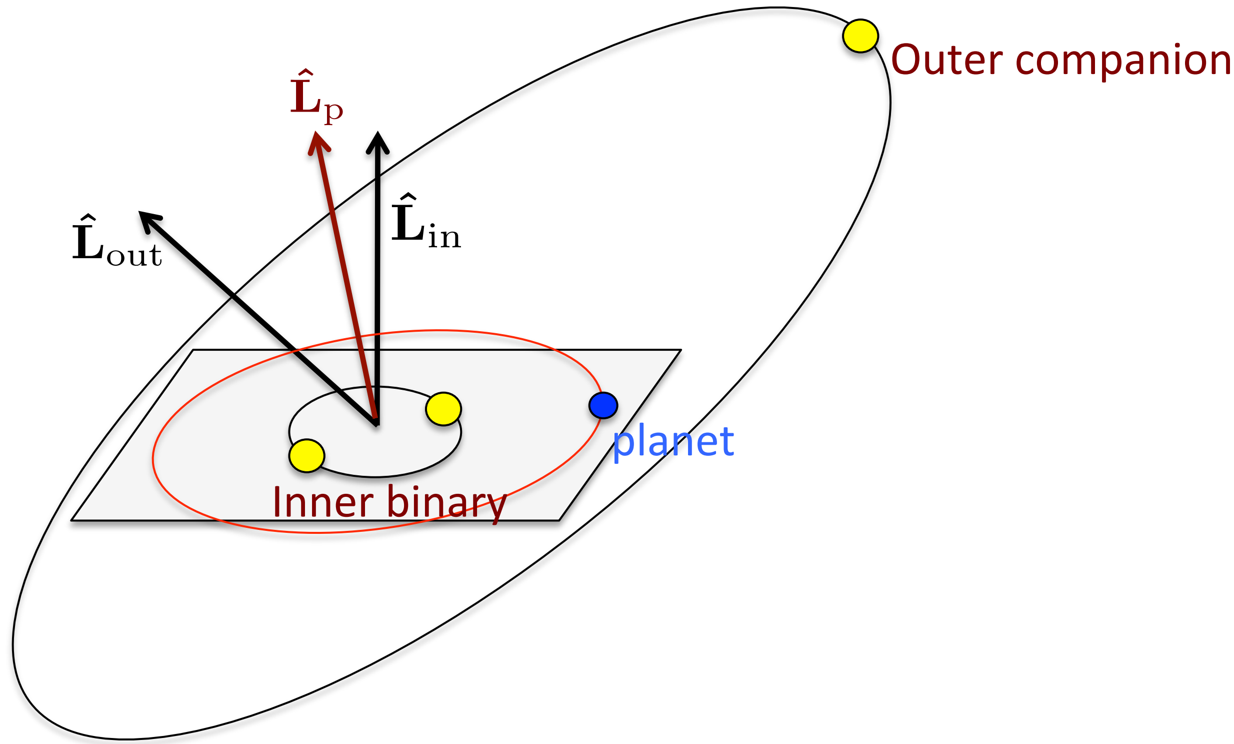
Prediction:

- Suppose planets exist around "normal" binaries (e.g., Kepler circumbinary planets) in stellar triples
- As the binary orbit shrinks (due to Lidov-Kozai oscillation + tide), planet can survive, but will be misaligned with the binary

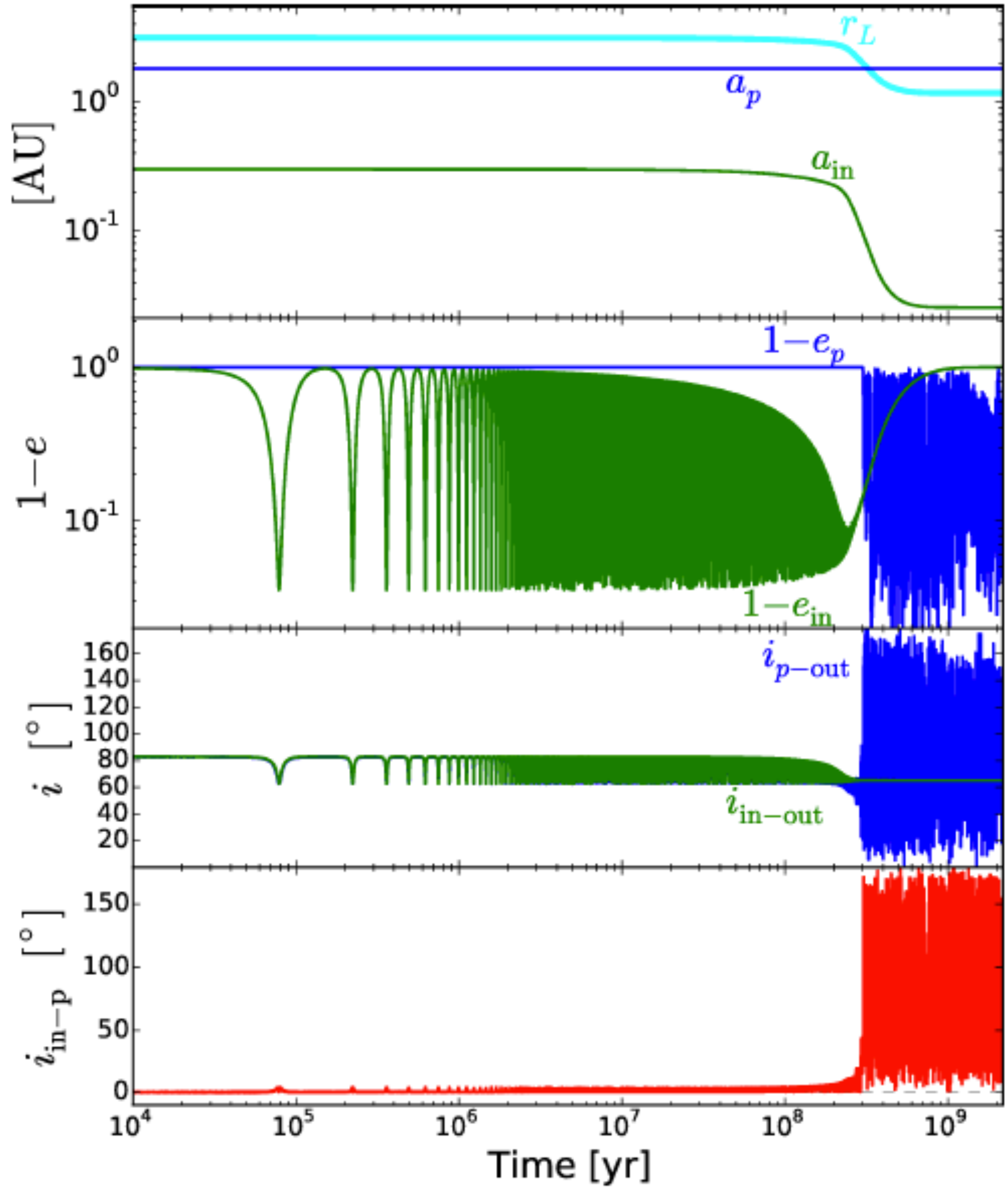
Misaligned planets around compact (<5 days) binaries

Misalignment angle increases with planet orbital period

Caveat:



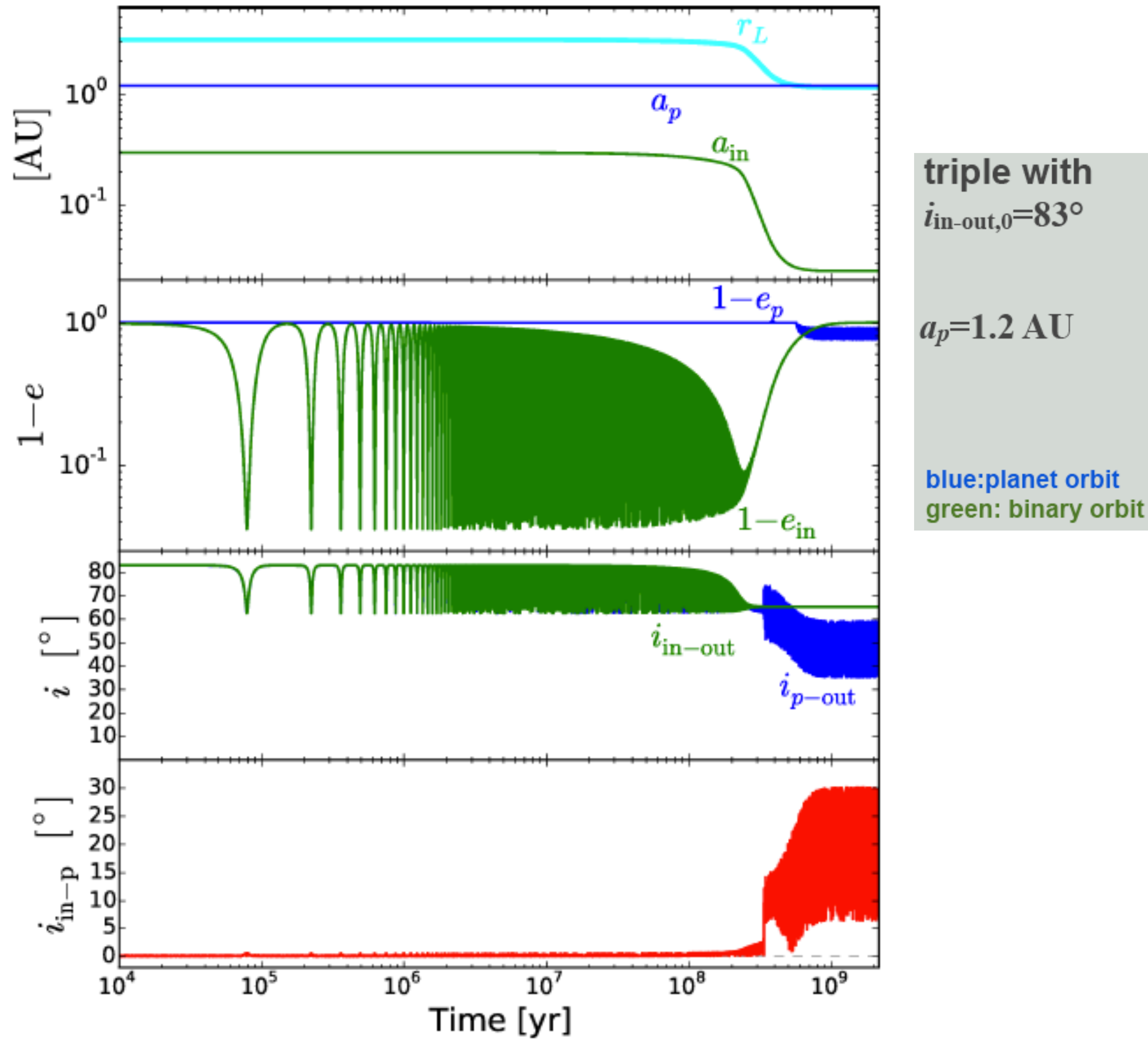
If the outer companion is extremely inclined relative to the inner binary (>80^{o}) the planet may not survive as the inner binary shrinks



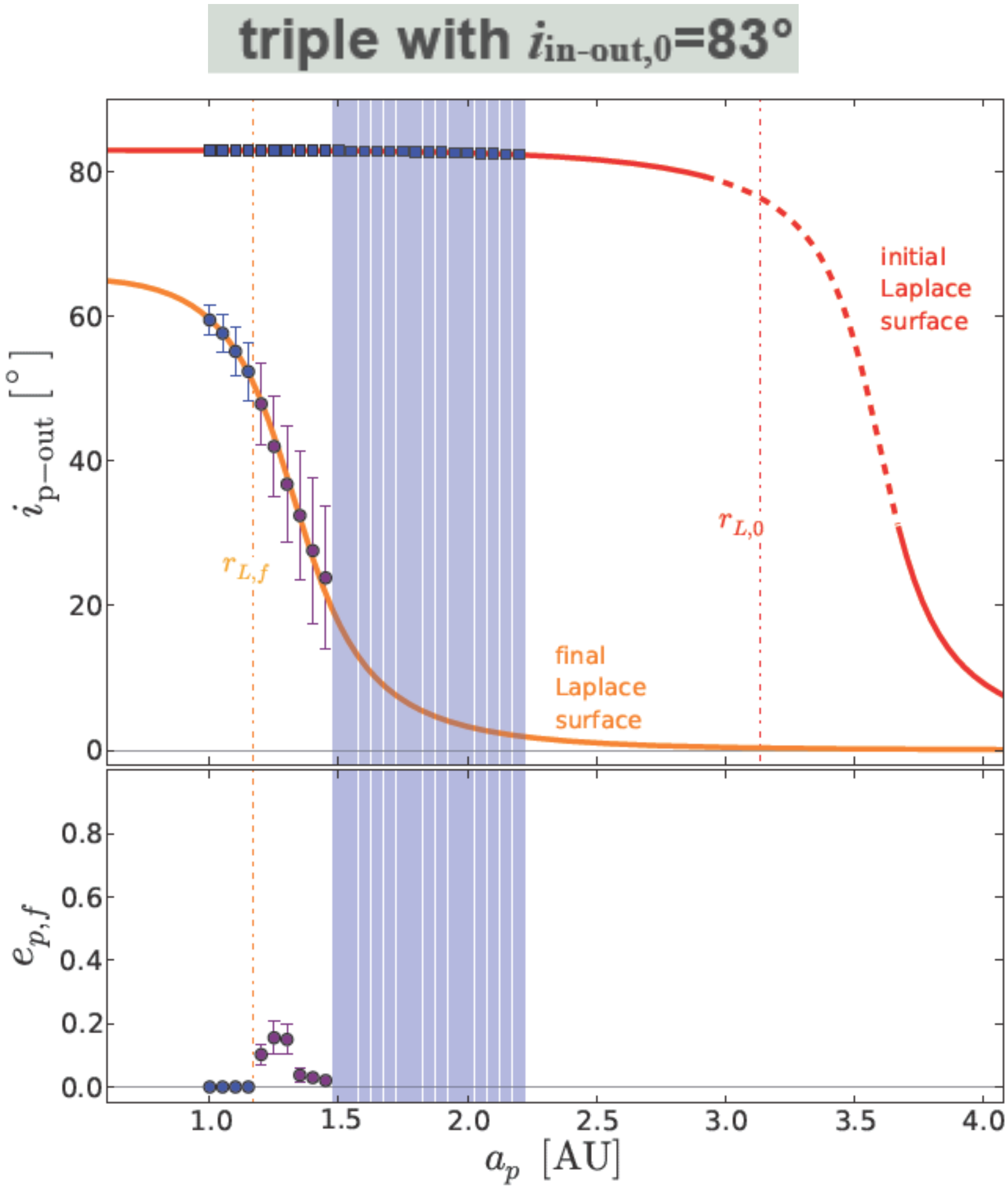
triple with
$i_{\text{in-out},0}$**=83°**

a_p**=1.8 AU**

blue:planet orbit
green: binary orbit



r_L
a_p
$a_{\rm in}$
[AU]
$1-e_p$
$1-e$
$1-e_{\rm in}$
$i_{\rm in-out}$
$i_{p-{\rm out}}$
i [°]
$i_{\rm in-p}$ [°]
Time [yr]
triple with
$i_{\text{in-out},0}$=83°
a_p=1.2 AU
blue:planet orbit
green: binary orbit



triple with $i_{\text{in-out},0}$=83°
initial Laplace surface
final Laplace surface
$r_{L,0}$
$r_{L,f}$
$i_{\text{p-out}}$ [°]
$e_{p,f}$
a_p [AU]
80
60
40
20
0
0.8
0.6
0.4
0.2
0.0
1.0
1.5
2.0
2.5
3.0
3.5
4.0

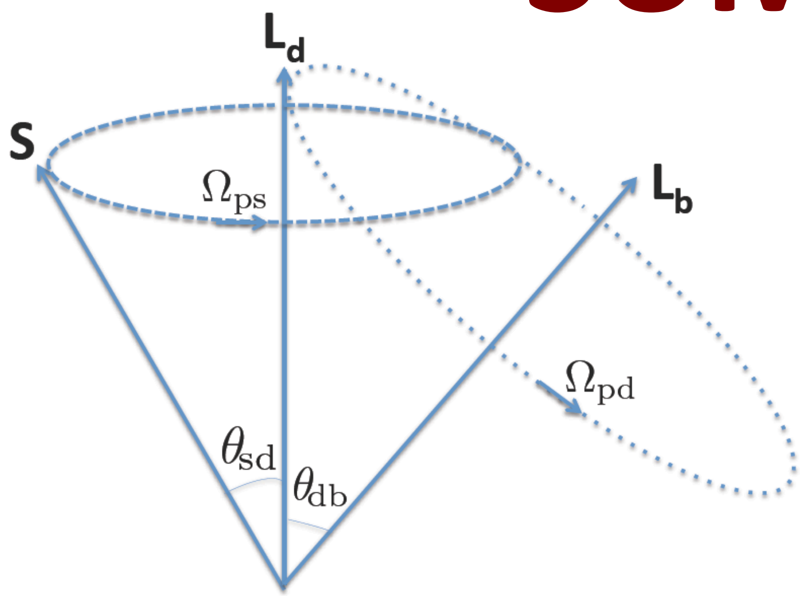
Summary (#3)
Survival of Planets in Shrinking Binaries

- Suppose planets exist around “normal” binaries (e.g., Kepler circumbinary planets) in stellar triples
- As the binary orbit shrinks (due to Lidov-Kozai oscillation + tide), planet can survive, but will be misaligned with the binary

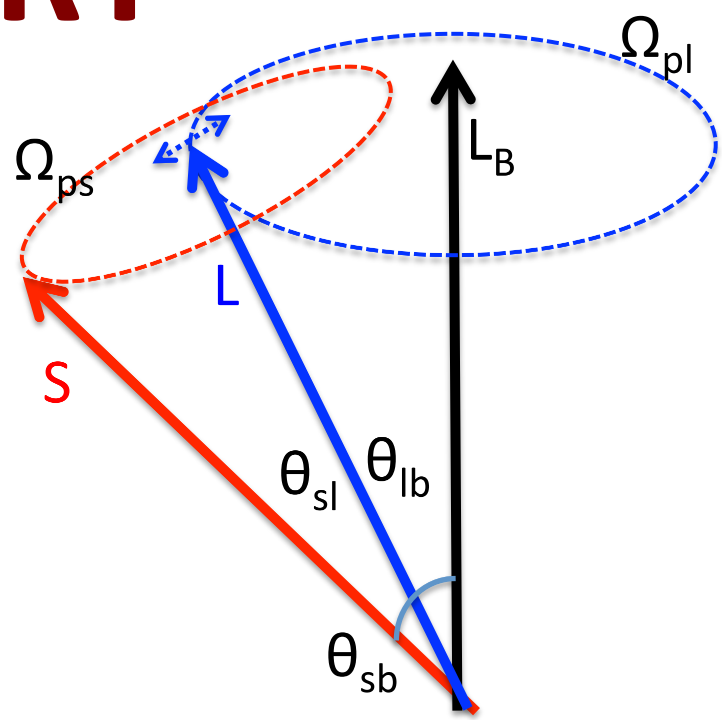
Misaligned planets around compact (<5 days) binaries

Misalignment angle increases with planet orbital period

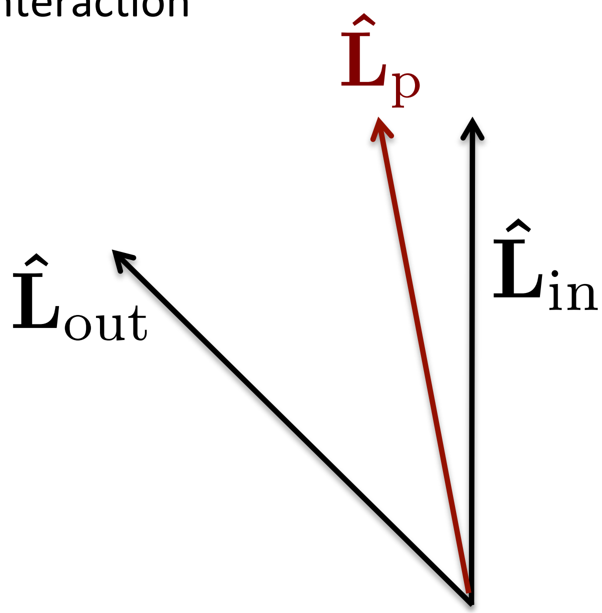
SUMMARY



Star-disk-binary interaction



Spin dynamics of host star of planet
Undergoing Lidov-Kozai



Planets in shrinking binaries

Thanks!

Is “High-e Migration” the whole story for producing hot Jupiters and S-L misalignments?

Likely NOT.

-- Companion? Initial conditions? (e.g., Knutson et al. 2014)

-- Paucity of high-e proto-hot Jupiters (Socrates et al.2012; Dawson et al.2012)

-- Stellar metallicity trend of hot Jupiters ➔ Two mechanisms of migrations (Dawson & Murray-Clay 2013)

-- Misaligned multiplanet systems:

Kepler-56 (2 planets 10.5 & 21 days ➔40-55 deg from seismology; Huber et al 2013)
Kepler-25 (2 transiting planets, one non-transiting; Benomar et al 2014)
55 Cancri (?? Bourrier & Hebrard 2014; Lopez-Morales et al. 2014)
Other Candidates: Hirano et al. 2014; Kepler-9 (?? Walkowicz & Basri 2013)

See Boue & Fabrycky 2014

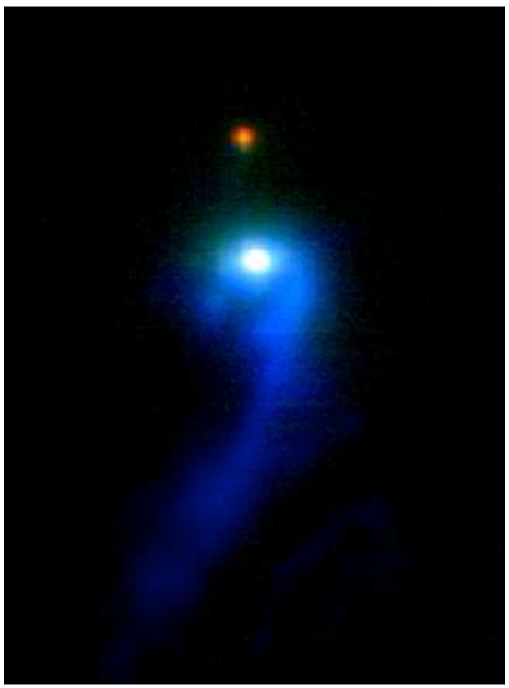
Hints of "Primordial" Misalignments

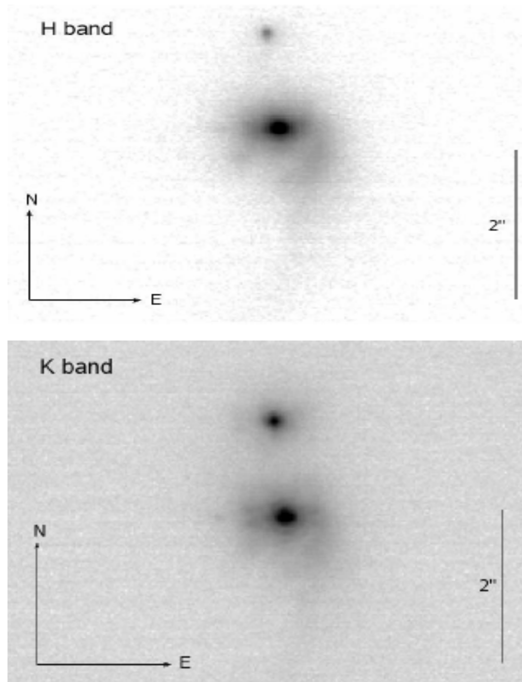
(before dynamical few-body interactions)

-- Solar system: 7 degree

-- Stellar spin axes in a>40 AU binaries: Misaligned (Hale 1994)

-- PMS/YSO binaries: Misaligned protostellar disks measured from jets or disks

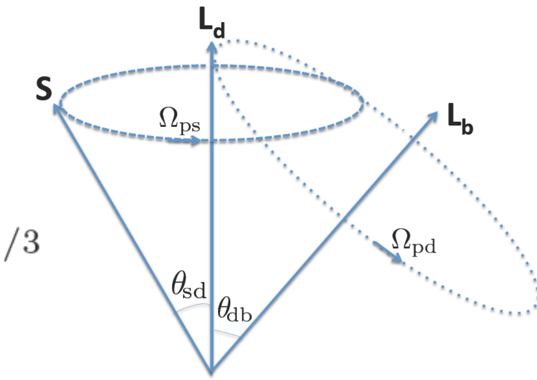




Haro 6-10:
Two disks: one edge-on, one face-on
(Roccatagliata et al. 2011)

Recap the Key Findings:

-- With a binary companion, spin-disk misalignment is "easily" generated
-- Accretion/magnetic torques affect it, but not diminish the effect
-- The key is "resonance crossing"



$$|\Omega_{\rm ps}/\Omega_{\rm pd}| \gtrsim 1 \ \text{at}\ t = 0$$

➔ $$\frac{a_{\rm b}}{r_{\rm out}} \gtrsim 2.8 \left(\frac{M_{\rm b}}{M_\star}\right)^{1/3} \left(\frac{r_{\rm out}}{50\,{\rm AU}}\right)^{-1/6} \left(\frac{\bar{\Omega}_\star}{0.1}\right)^{-7/9} \left(\frac{M_{\rm di}}{0.1 M_\star}\right)^{-1/3}$$

$$|\Omega_{\rm ps}/\Omega_{\rm pd}| \lesssim 1 \ \text{at}\ t = 10\ \text{Myrs}$$

➔ $$\frac{a_{\rm b}}{r_{\rm out}} \lesssim 7.6 \left(\frac{M_{\rm b}}{M_\star}\right)^{1/3} \left(\frac{r_{\rm out}}{50\,{\rm AU}}\right)^{-1/6} \left(\frac{\bar{\Omega}_\star}{0.1}\right)^{-7/9} \left(\frac{M_{\rm df}}{0.005 M_\star}\right)^{-1/3}$$

Implications for Hot Jupiter formation

-- If hot Jupiters are formed through Kozai induced by a companion, then primordial misalignment likely already present

-- Even when Kozai is suppressed, misaligned planets can be produced

-- Disk driven migration is quite viable…

S*-L_p misalignment in Exoplanetary Systems
➔ The Importance of few-body interactions

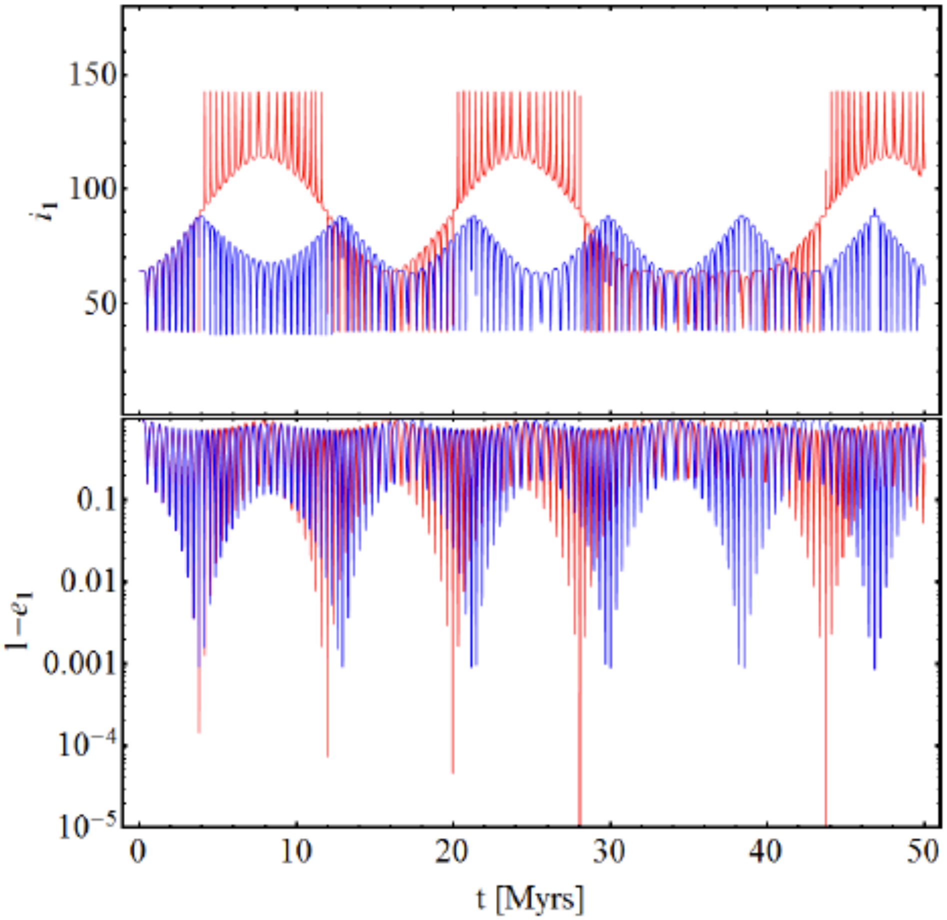
1. Planet-planet Interactions

   -- Strong scatterings
   (e.g., Rasio & Ford 96; Chatterjee et al. 08; Juric & Tremaine 08)

   -- Secular interactions/chaos
   (e.g Nagasawa et al. 08; Wu & Lithwick 11)

2. Lidov-Kozai oscillations induced by a distant companion star/planet
   (e.g., Holman et al. 97; Wu & Murray 03; Fabrycky & Tremaine 07; Naoz et al.12, Katz et al.12; Petrovich 14)

High-Order Lidov-Kozai Effects:



Liu, Munoz & DL 2015

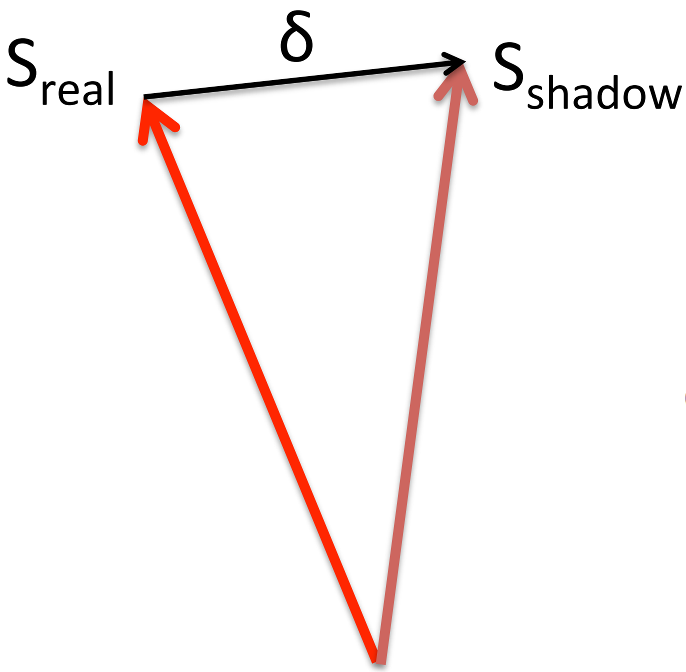
Suppression of extreme orbital evolution in triple systems with short range forces

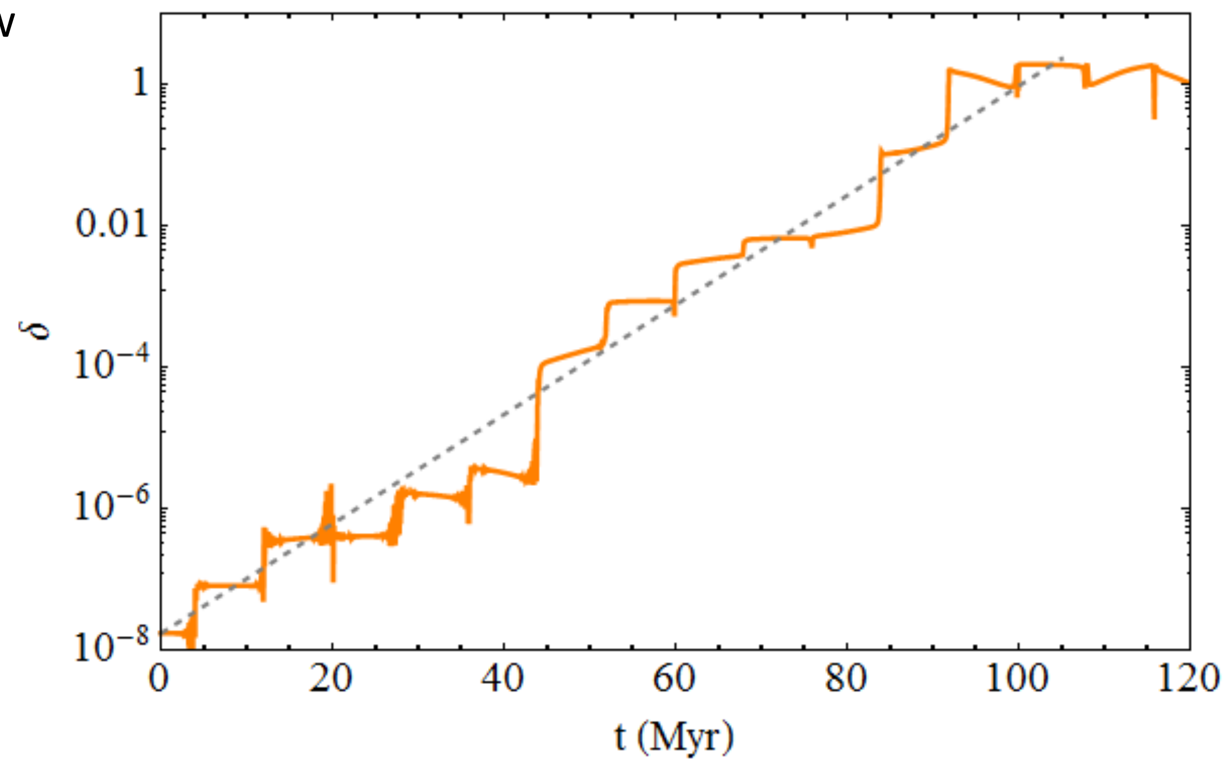
Bin Liu[1,2⋆], Diego J. Muñoz[2] and Dong Lai[2]

[1] *Center for Astrophysics, University of Science and Technology of China, Hefei, Anhui 230026, People's Republic of China*

[2] *Center for Space Research, Department of Astronomy, Cornell University, Ithaca, NY 14853, USA*

If $|\Omega_{ps}| \sim |\Omega_{pl}|$: “trans-adiabatic”





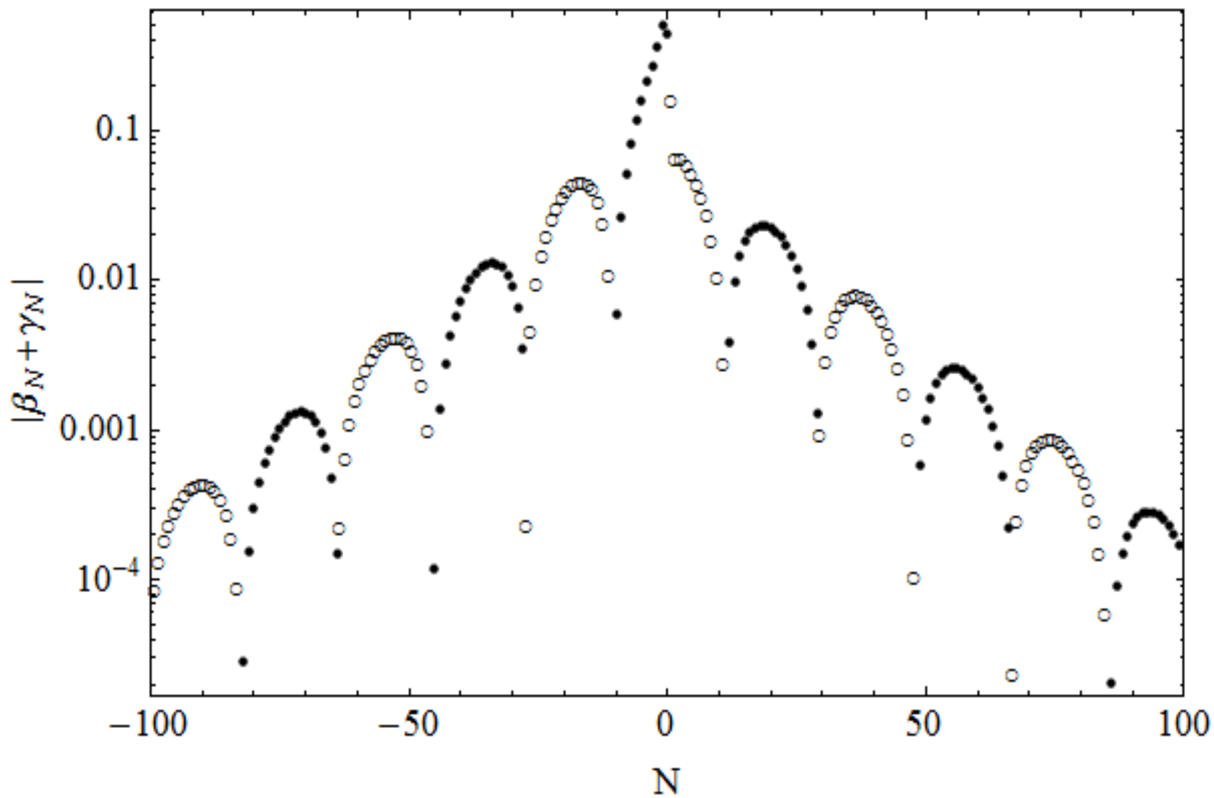
Lyapunov time ~ 6 Myr

Storch, Anderson & DL 14

Boundary of Chaotic Zone

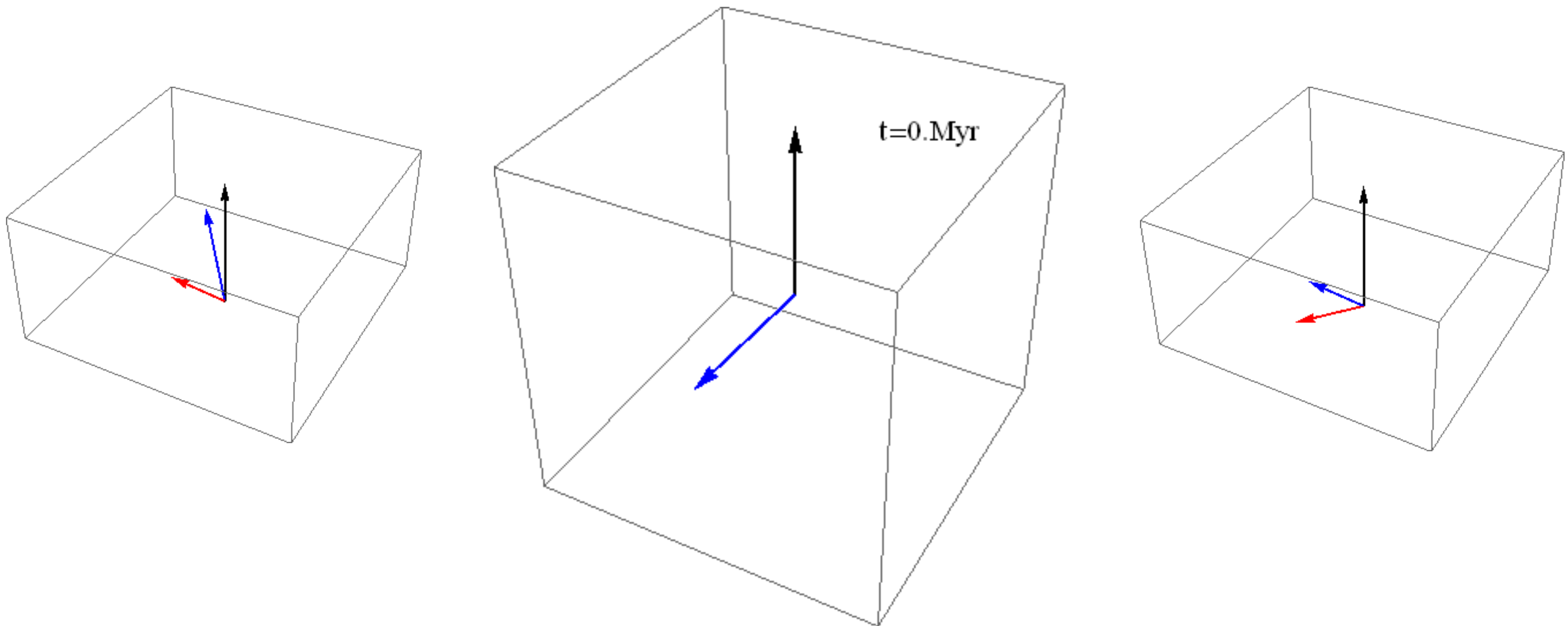
From outermost overlapping resonance

$$w_N \sim 2 \left[2 \underbrace{\|\beta_N + \gamma_N\|} \epsilon \sqrt{1 - p_N^2} \right]^{1/2}$$



N. Storch

Outer binary axis
Planet orbital axis
Stellar spin axis



ε decreases

Physically: planet mass increases or stellar spin rate increases or semi-major axis decreases

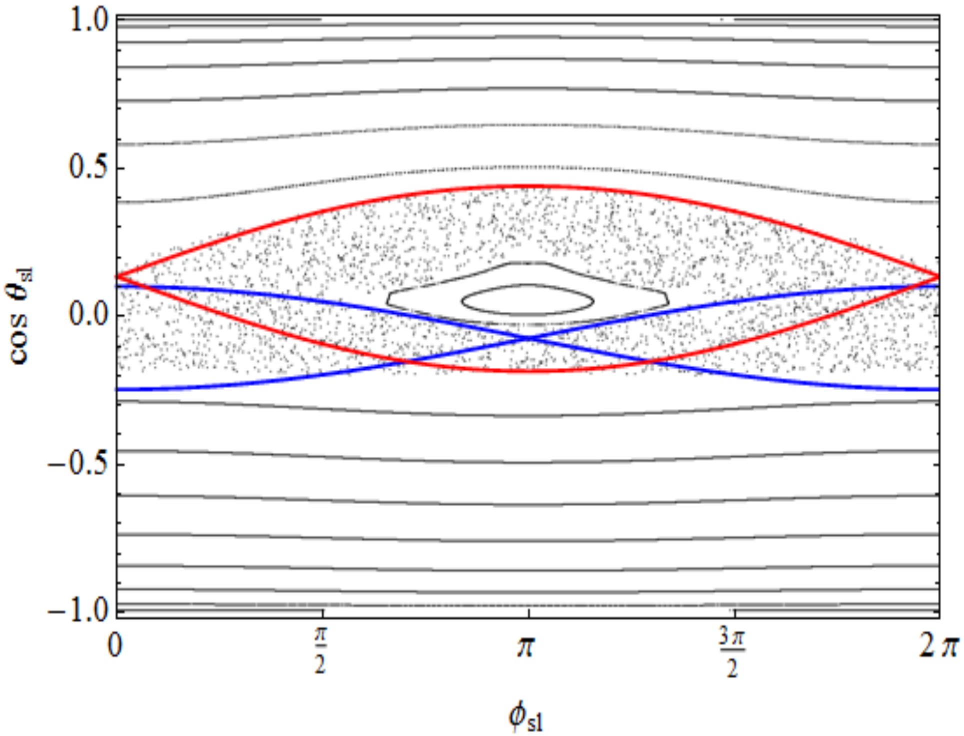
Lidov-Kozai + Tidal Dissipation

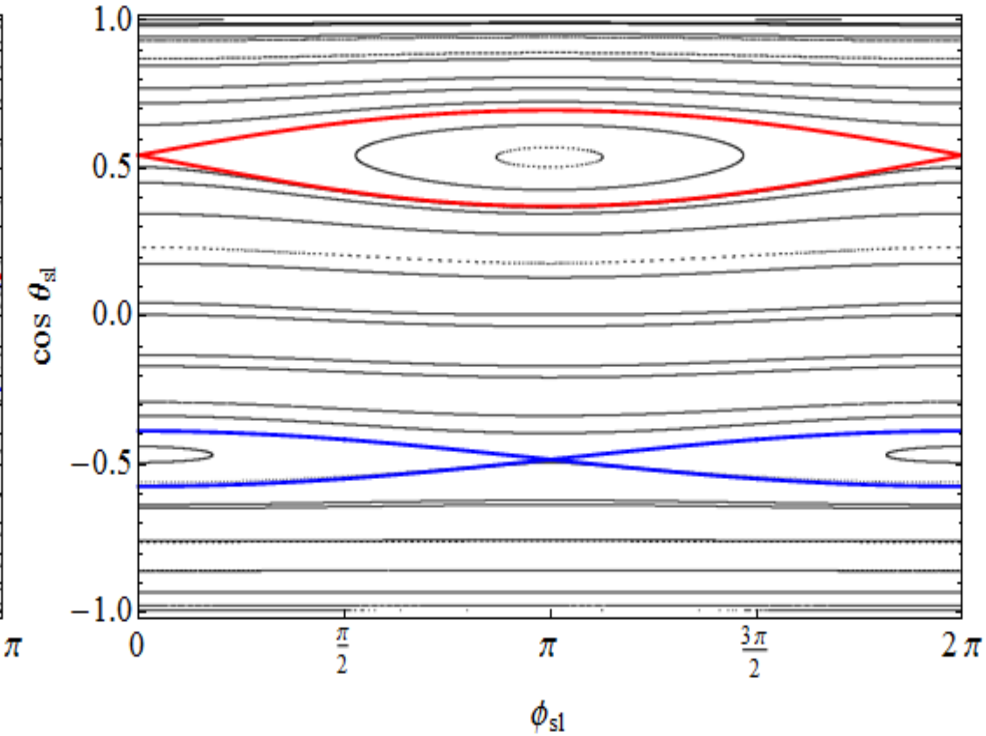
Recall $\epsilon = \dfrac{\Omega_{\mathrm{pl0}}}{\Omega_{\mathrm{ps0}}} \propto \dfrac{a^{9/2}}{M_p \Omega_s}$

➔ As orbit decays, even if the initial state is in the non-adiabatic regime, it will end up adiabatic

➔ Chaos always has a chance to influence S-L angle (unless the system starts out very adiabatic)

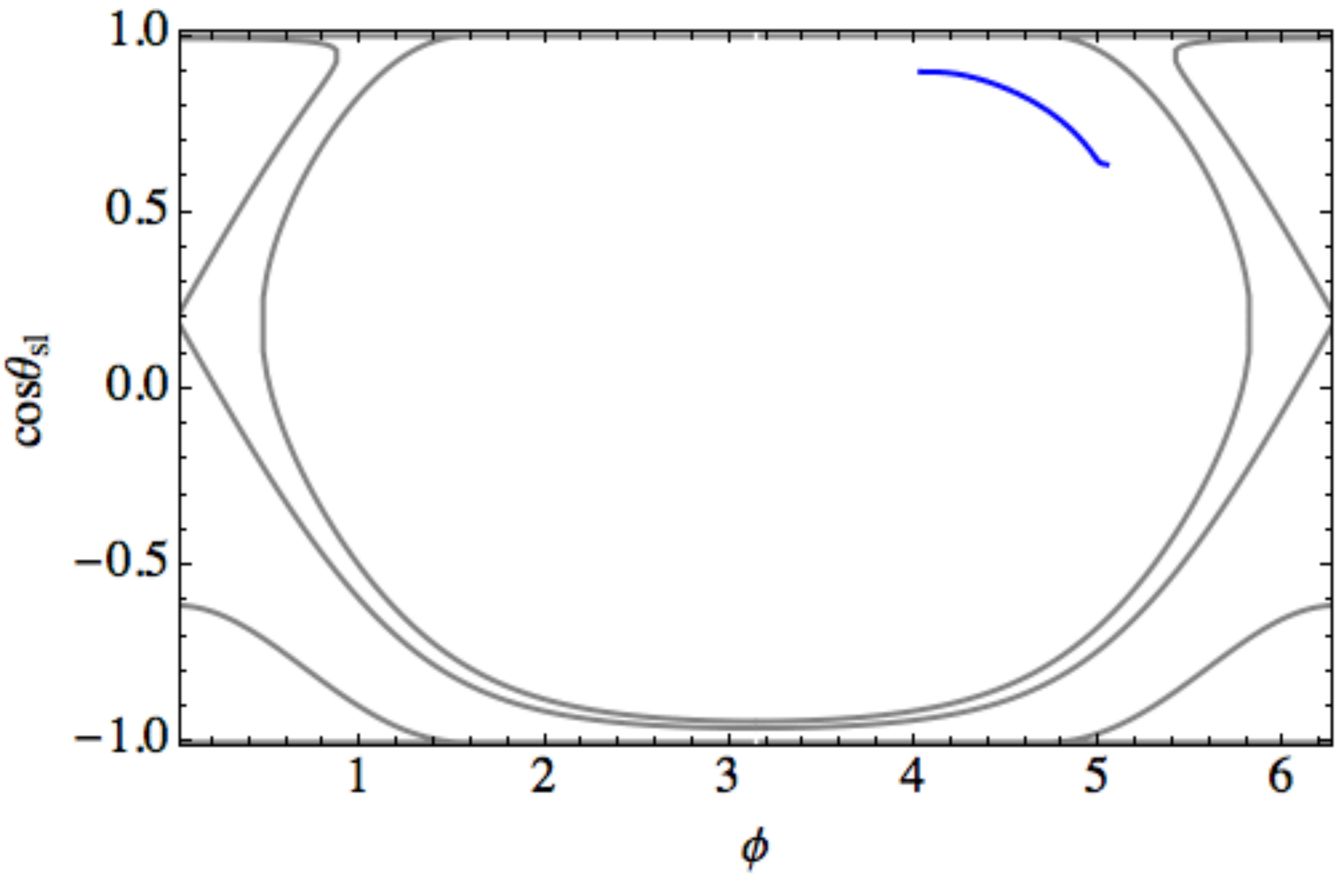
Multiple Resonances Together





Condition for chaos:
resonance overlap

Effect of Dissipation: Bifurcation



N. Storch

Summary of HJs

- Many exoplanetary systems are quite different from the Solar syetem
- **Formation of misaligned Hot Jupiters:**

  (1) Disk driven migration

  Star-disk-binary interactions ➔ primordial misalignment between star and disk

  (2) Lidov-Kozai oscillations + tide ➔ high-e migration

  chaotic dynamics of stellar spin during LK cycles:

  -- important for the observed spin-orbit misalignments, depend on planet mass, stellar rotaton/history etc.

  -- Spin dynamics can be understood from resonance theory