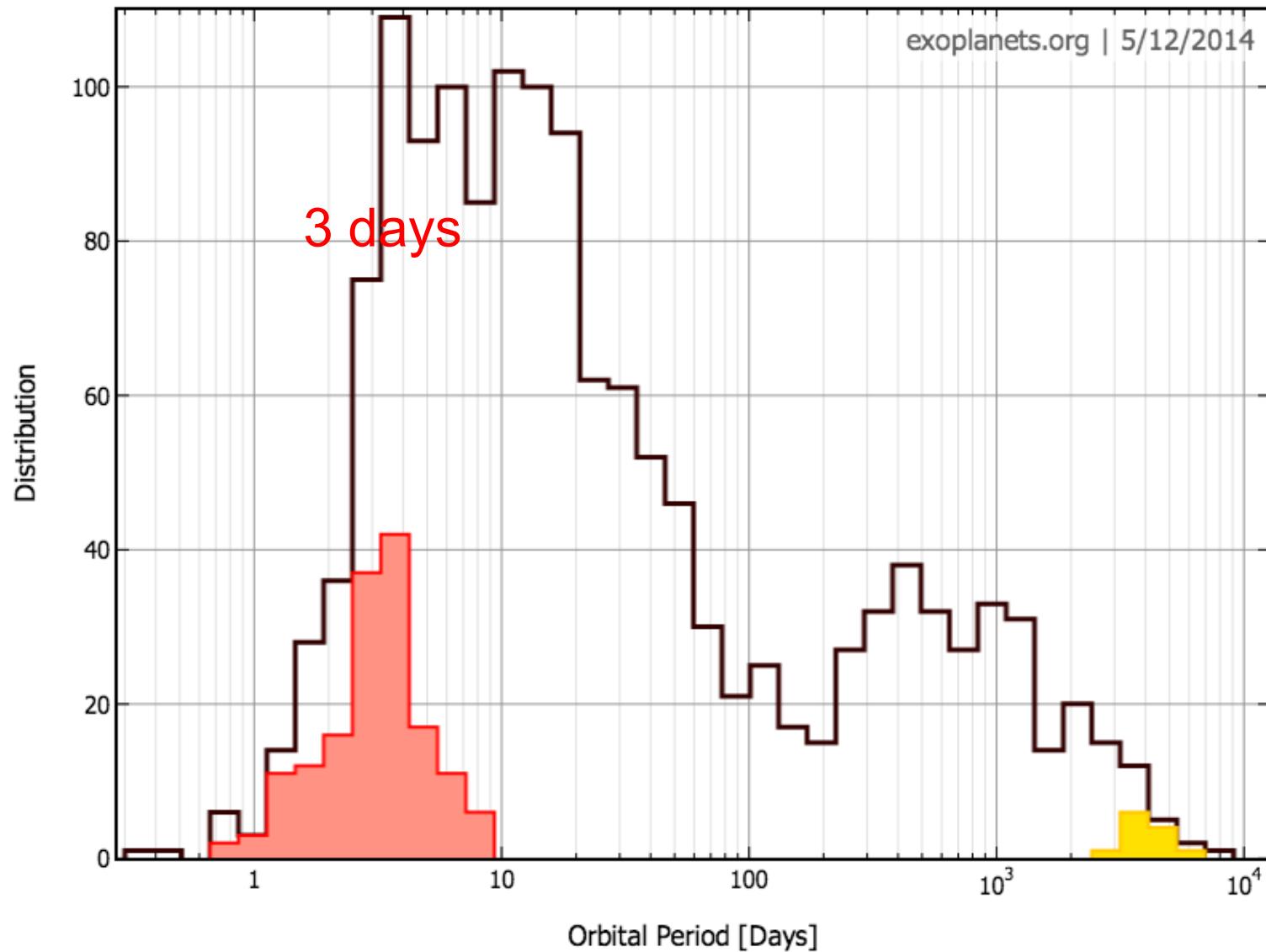


Star-Disk-Binary Interactions & Primordial Spin-Orbit Misalignment

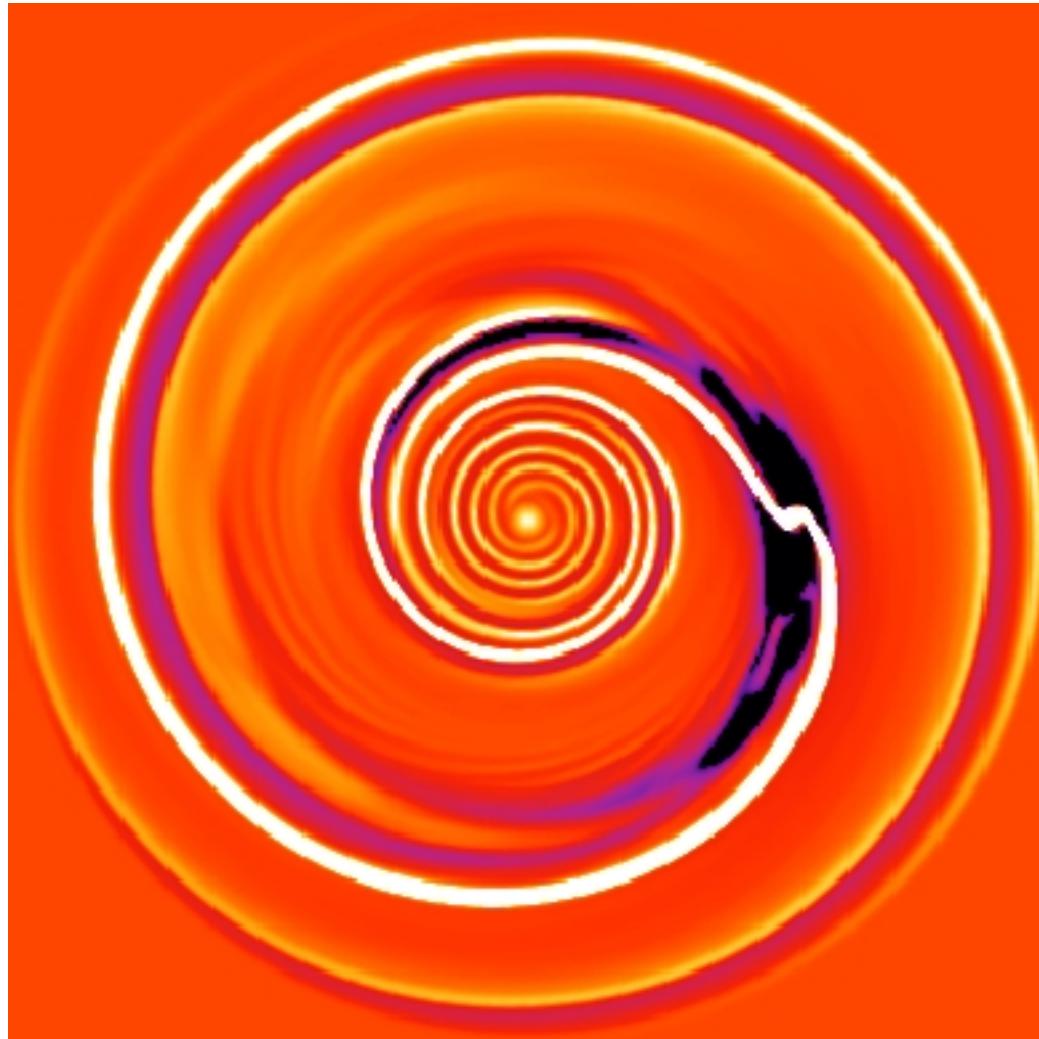
Dong Lai
Cornell University

Caltech, Astronomy, 5/12/2014

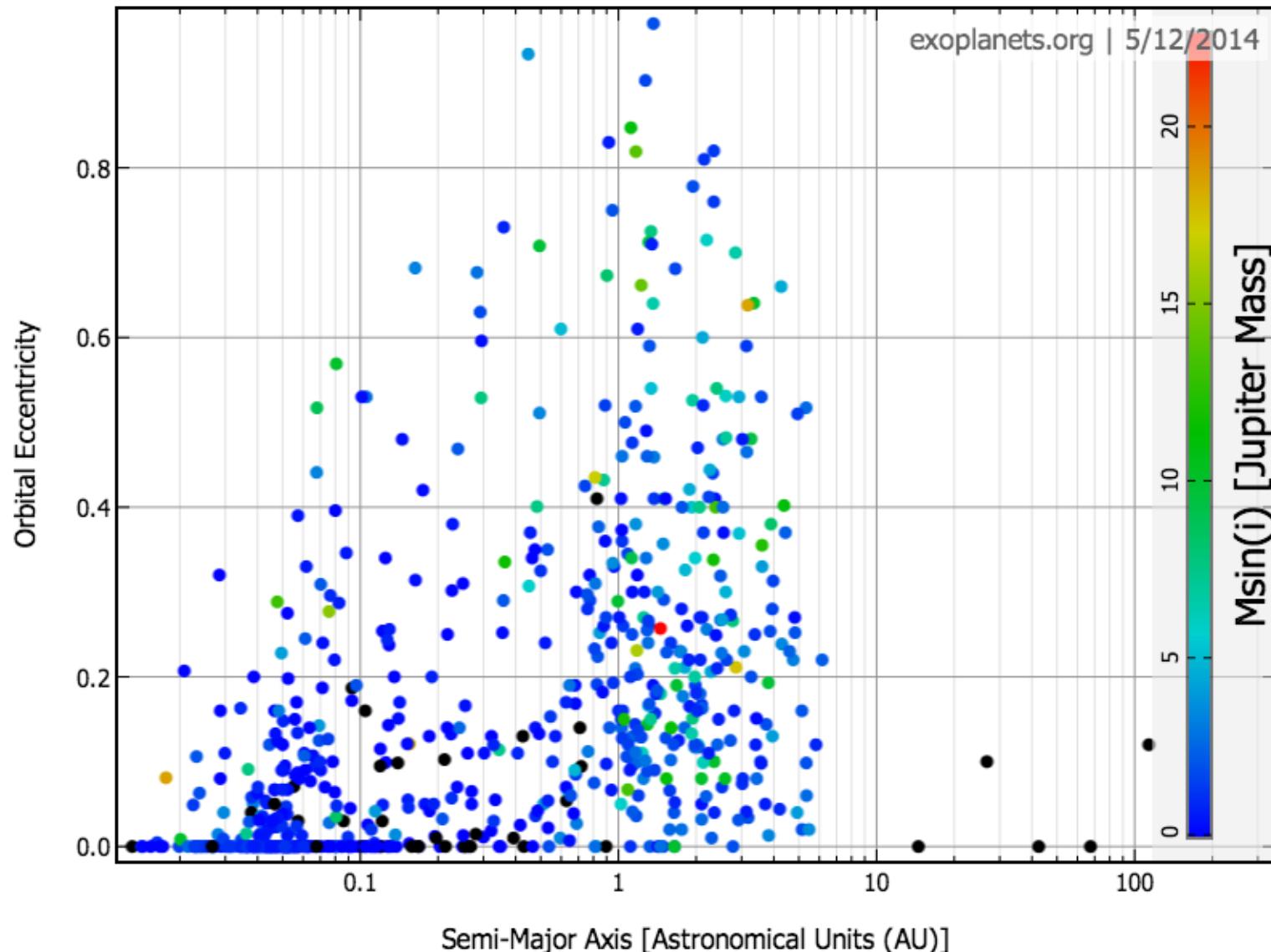
Orbital period puzzle



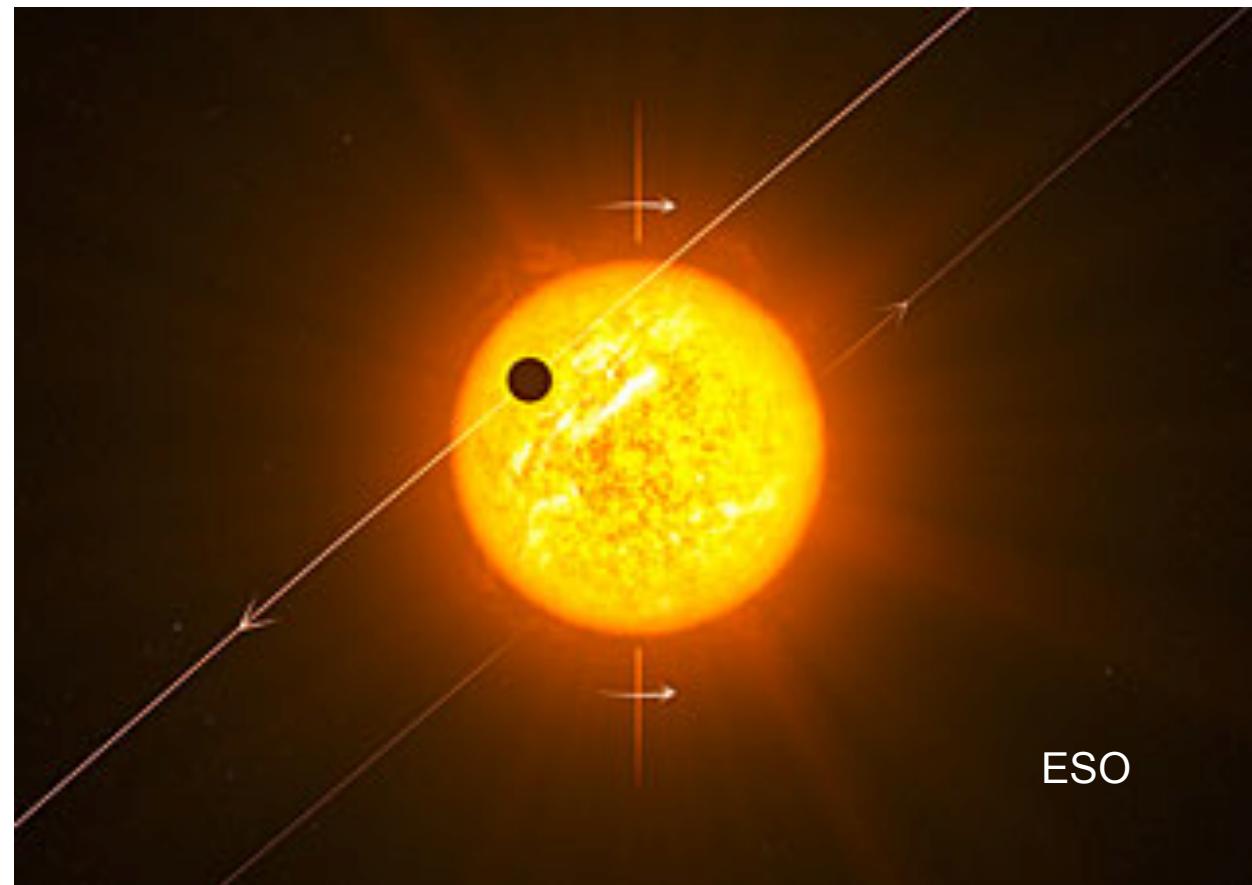
Disk-Driven Migration

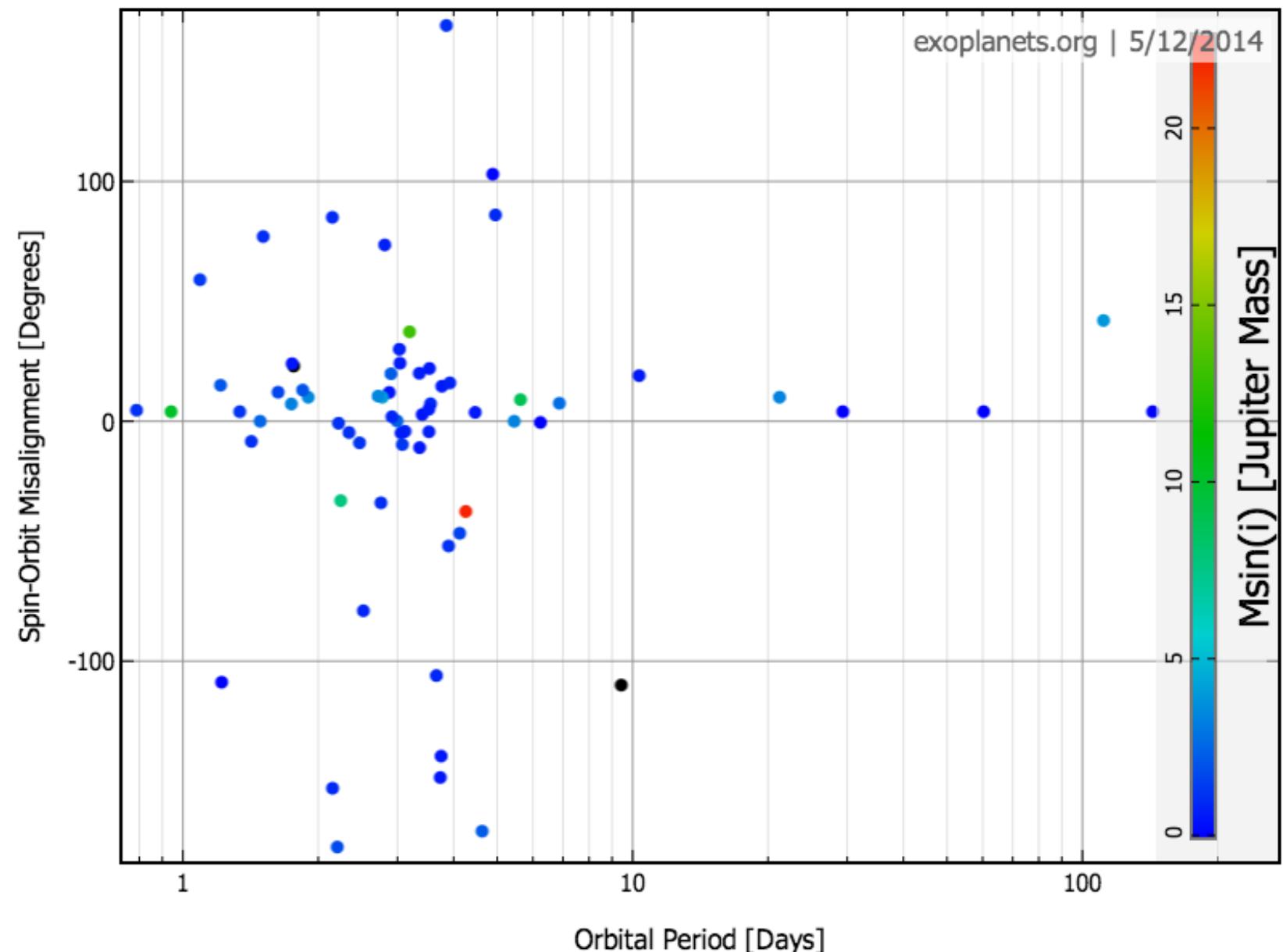


Eccentricity Puzzle

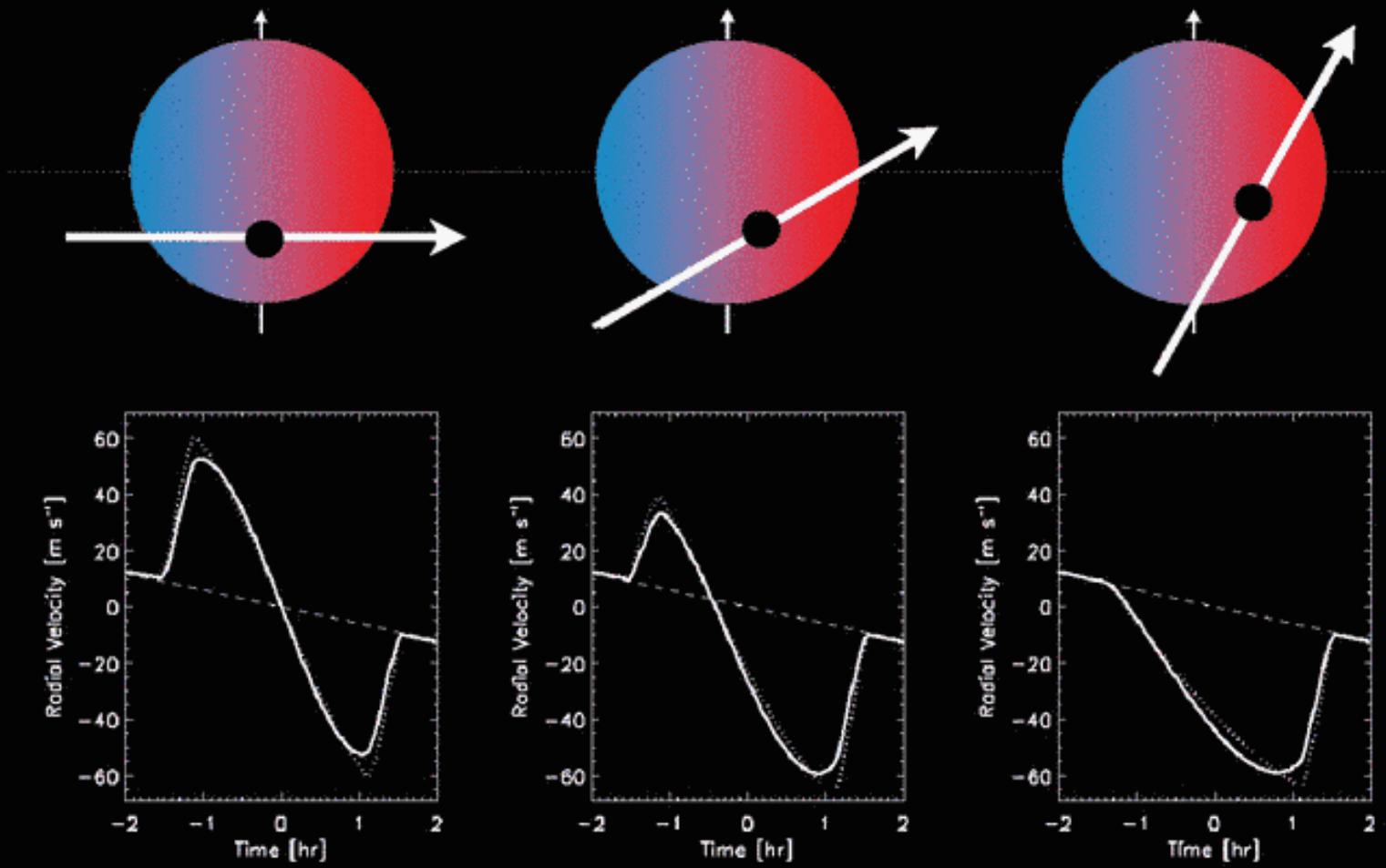


Spin-Orbit Misalignment Puzzle

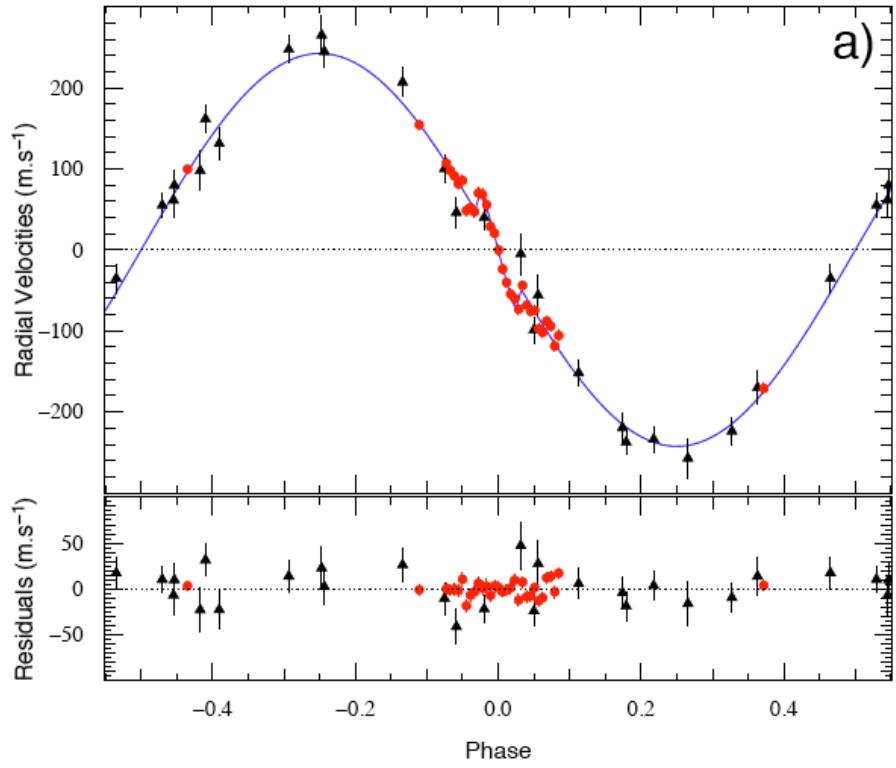




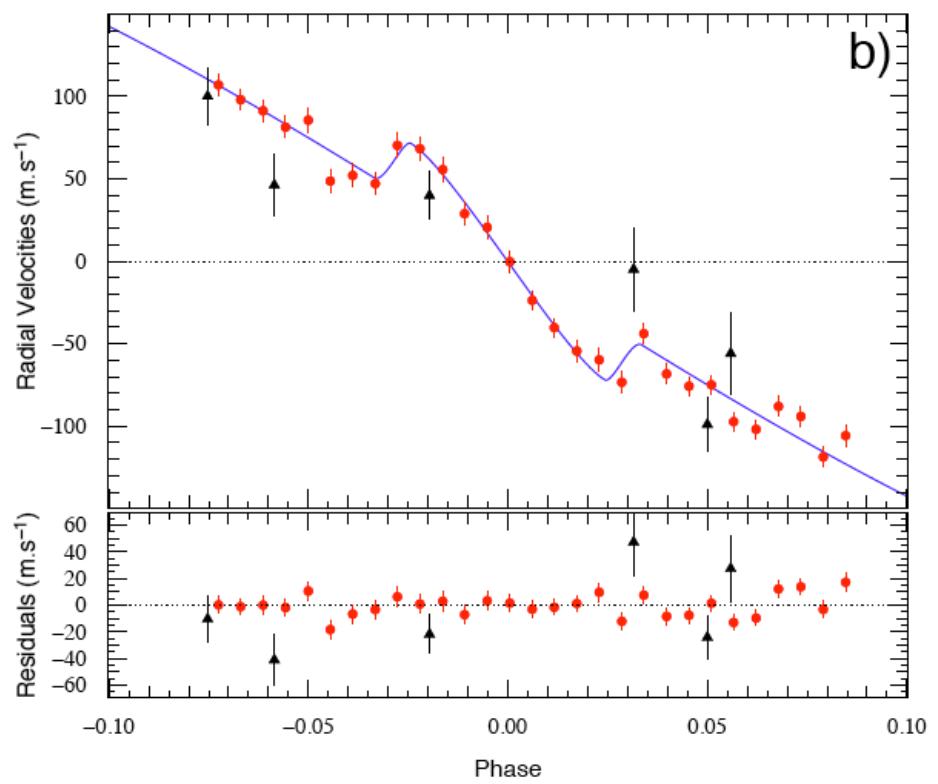
The Rossiter-McLaughlin Effect



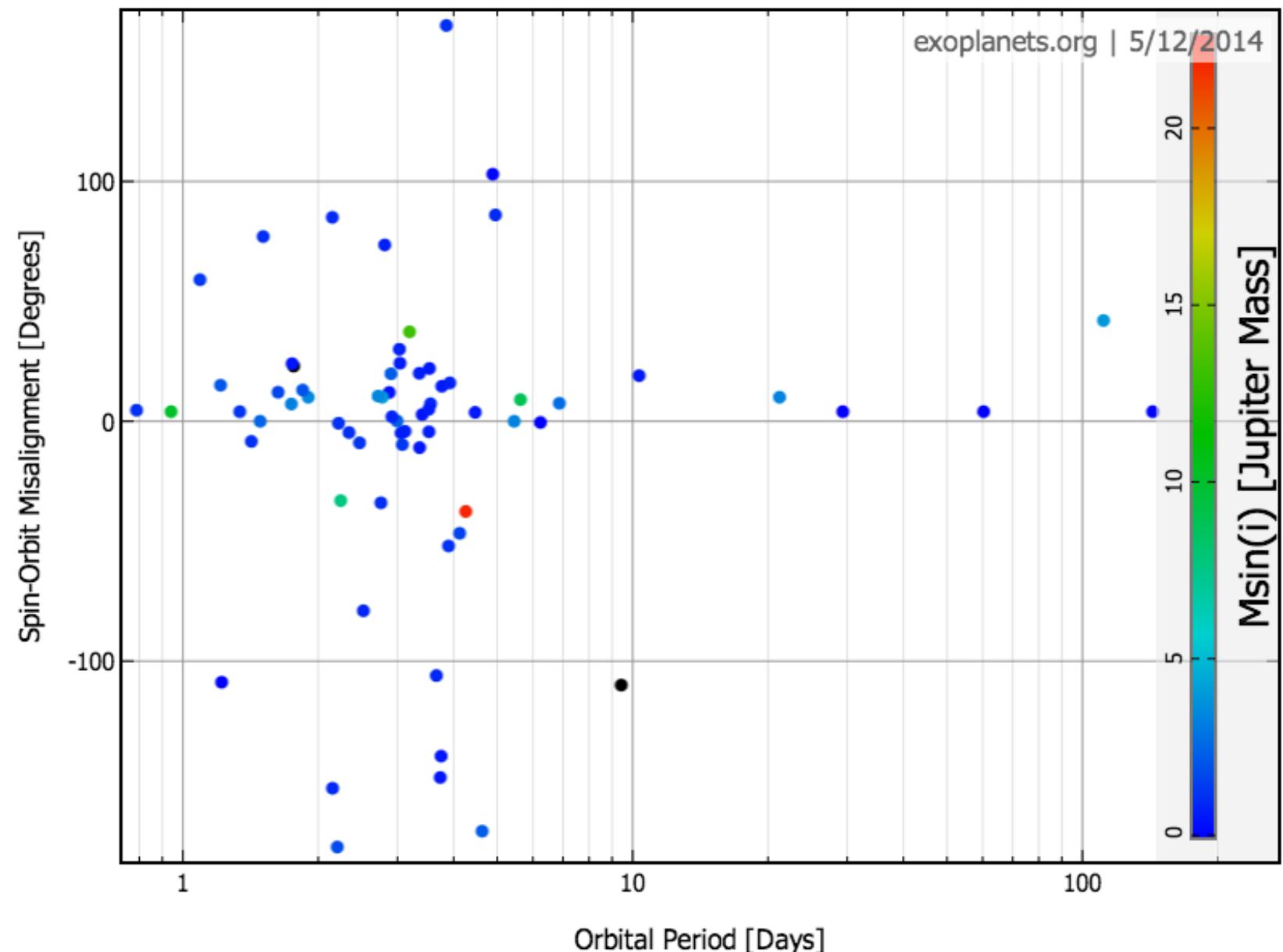
Slide from Josh Winn



WASP-4b



Triaud et al. 2010



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

1. Kozai + Tide migration by a distant companion star/planet

(e.g., Wu & Murray 03; Fabrycky & Tremaine 07; Naoz et al.12, Katz et al.12)

2. Planet-planet Interactions

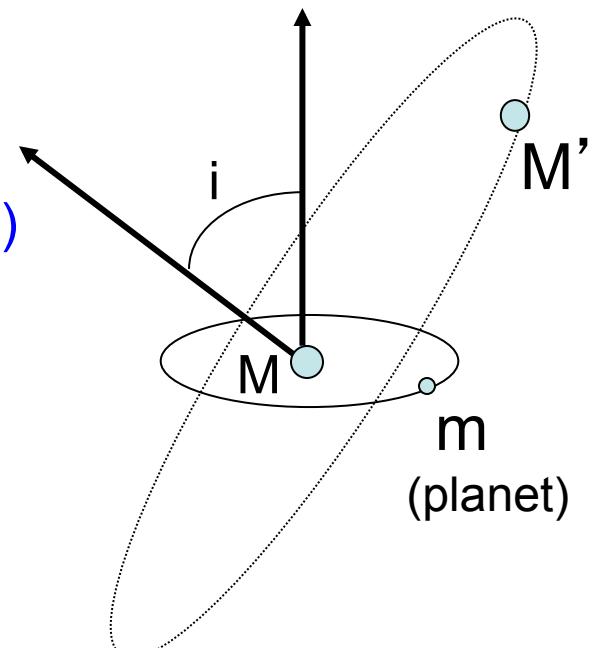
-- Strong scatterings

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

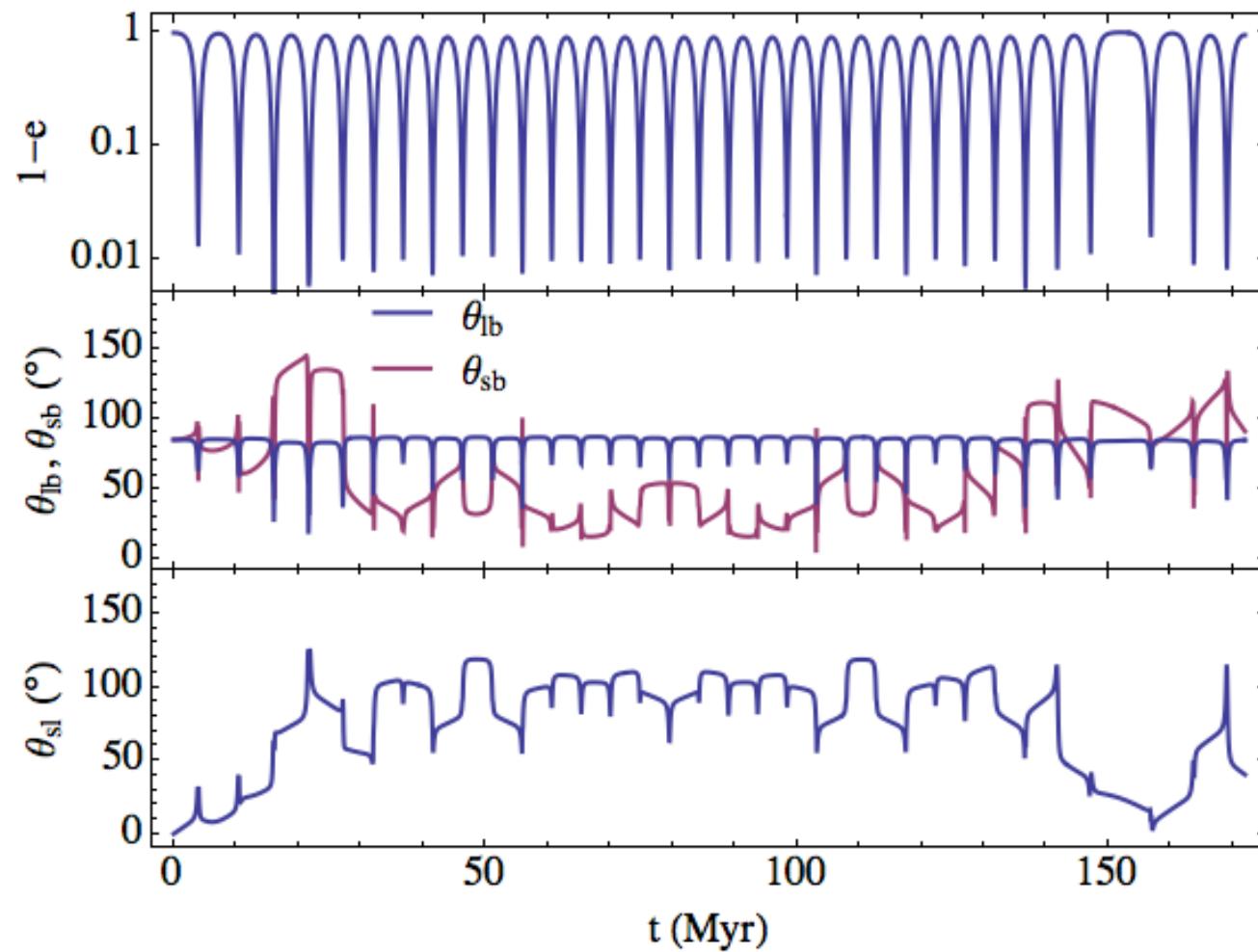
-- Secular interactions (“Internal Kozai”, chaos)

(e.g Nagasawa et al. 08; Wu & Lithwick 11)

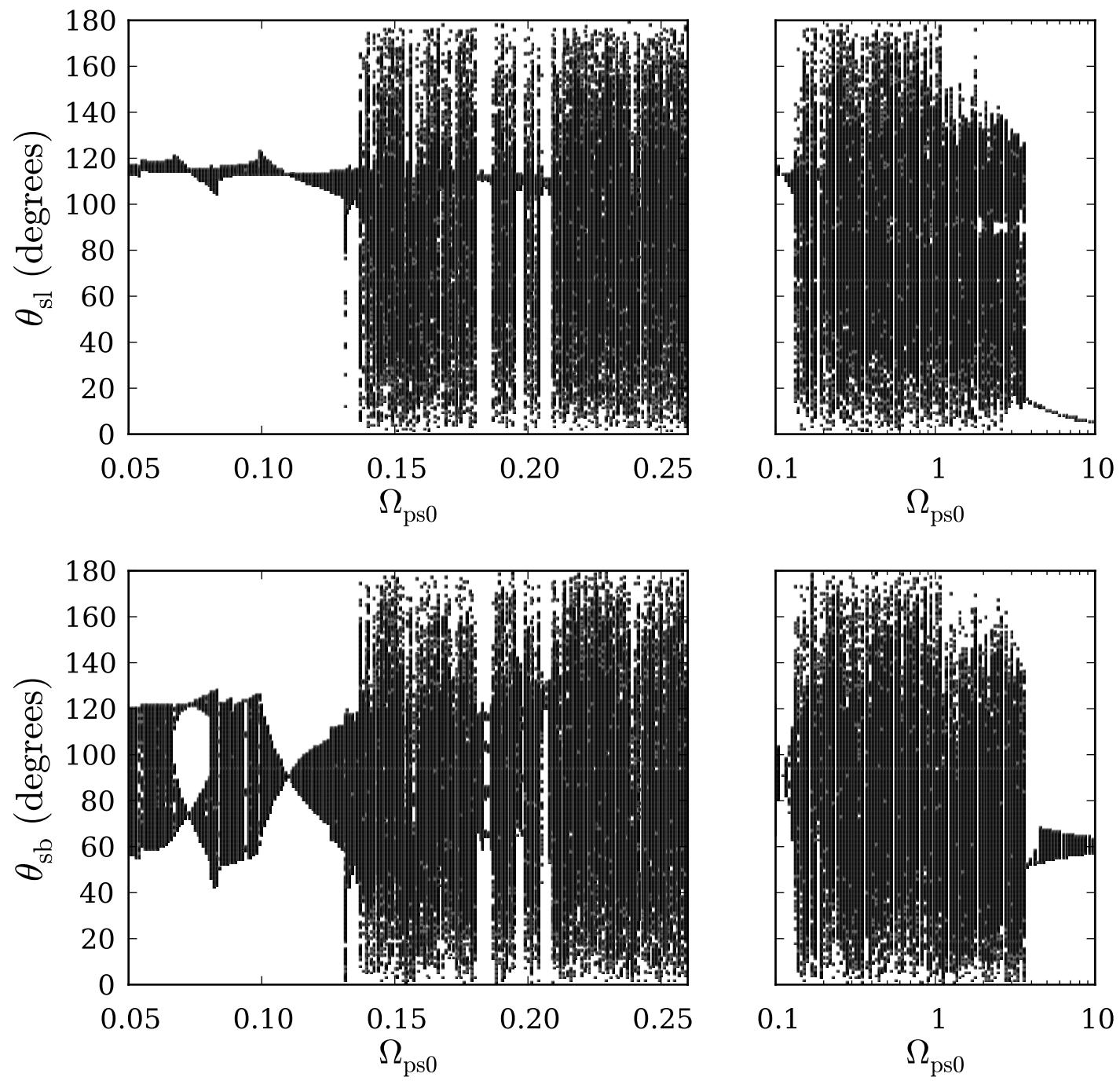
-- Chaotic stellar spin evolution during Kozai
(Storch, Anderson & DL 2014)



Chaotic Dynamics of Stellar Spin during Kozai cycle



Storch, Anderson & DL 2014



S^{*}-L_p misalignment in Exoplanetary Systems → The Importance of few-body interactions

“High-Eccentricity Migration”

- Planet forms at a few AUs
- Interaction with another body pumps it into high-e/inclined orbit
- Tidal dissipation on planet circularizes the orbit

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

Likely NO.

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- Misaligned multiplanet systems:
 - Kepler-56 (2 planets 10.5 & 21 days → 40-55 deg from seismology; Huber et al 2013)
 - Kepler-9 (3-planets; Walkowicz & Basri 2013) ?
 - Other Candidates: Hirano et al. 2014

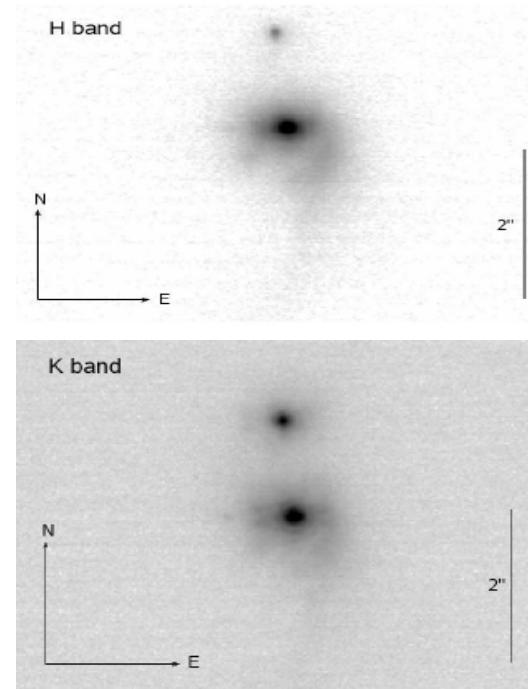
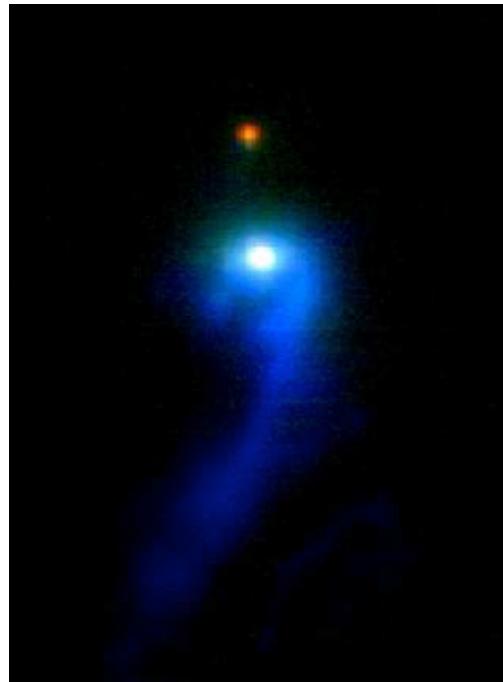
Hints of “Primordial” Misalignments

(before dynamical few-body interactions)

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)

- Misaligned multiplanet systems (Huber et al. 2013; etc)

Ideas for Producing Primordial Misalignments

between Stellar Spin and Protoplanetary Disk

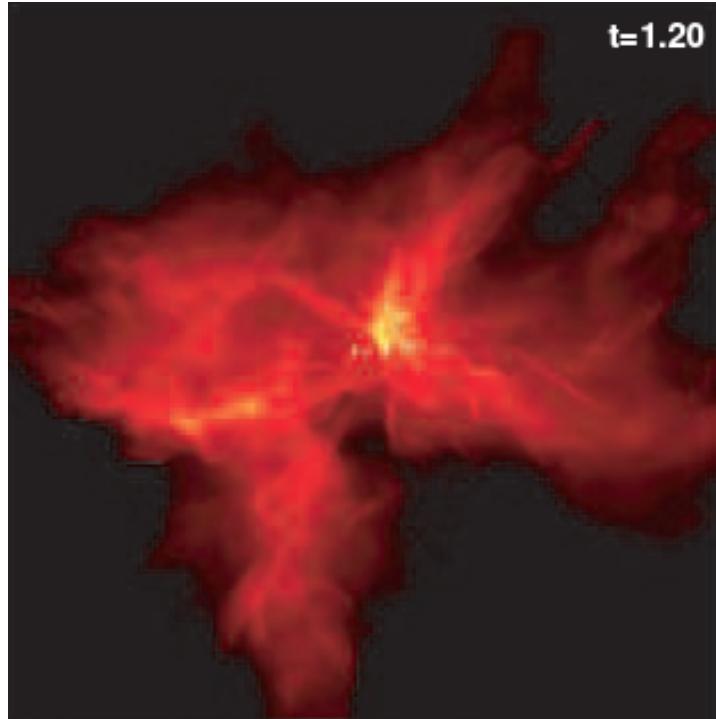
Ideas for Producing Primordial Misalignments

between Stellar Spin and Protoplanetary Disk

-- **Chaotic star formation** (Bate et al. 2010)

Supersonic turbulence --> clumps --> stars

Clumps can accrete gas with different rotation axes at different times



Ideas for Producing Primordial Misalignments

between Stellar Spin and Protoplanetary Disk

-- **Chaotic star formation** (Bate et al. 2010)

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

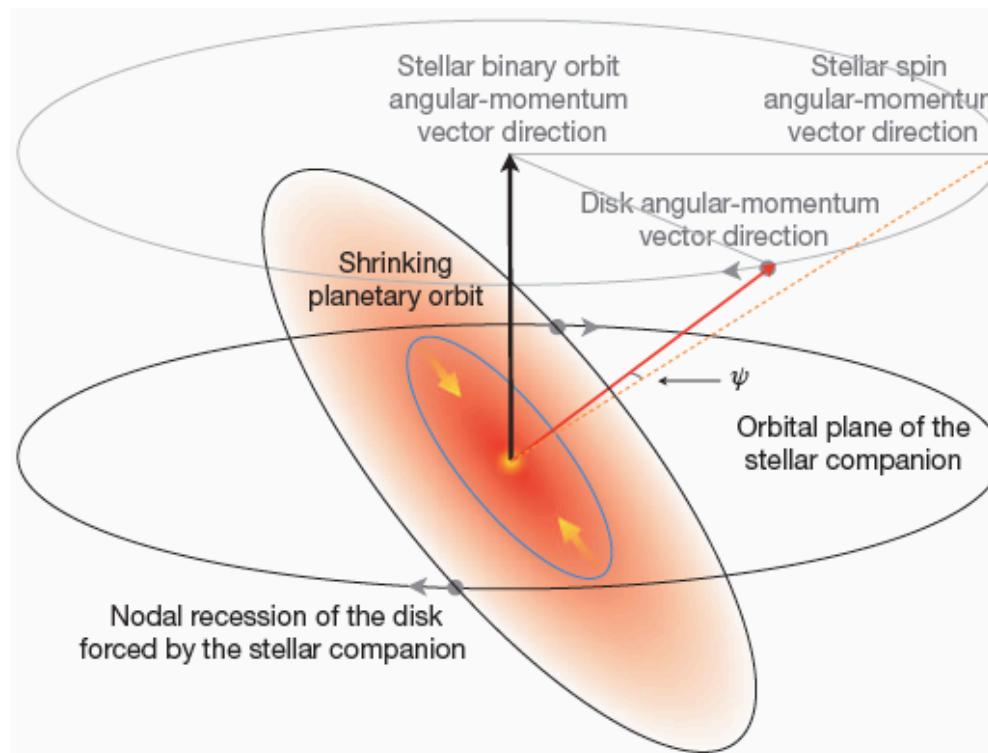
Ideas for Producing Primordial Misalignments

between Stellar Spin and Protoplanetary Disk

-- **Chaotic star formation** (Bate et al. 2010)

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

-- **Perturbation of Binary on Disk** (Batygin 2012; Batygin & Adams 2013; Lai 2014)



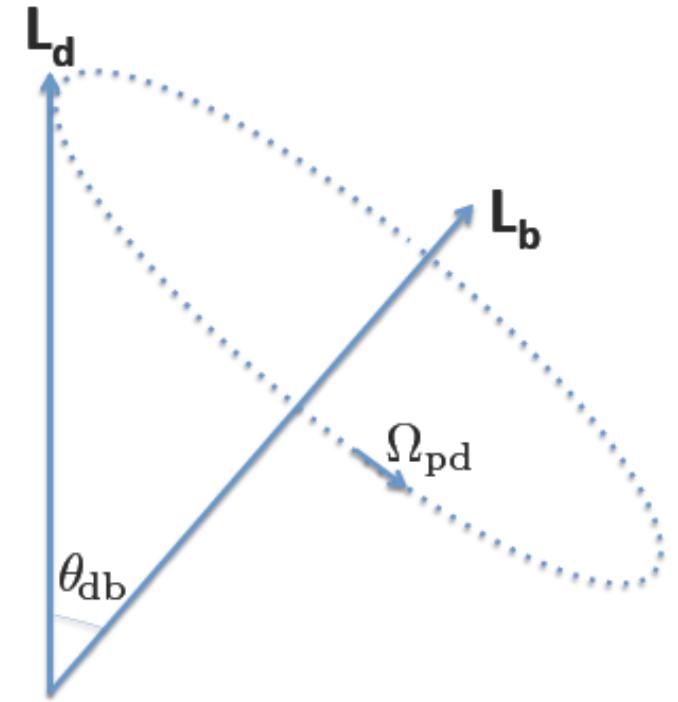
Star-Disk-Binary Interactions

Star-Disk-Binary Interactions

First no accretion, just gravitational interactions...

Companion makes disk precess

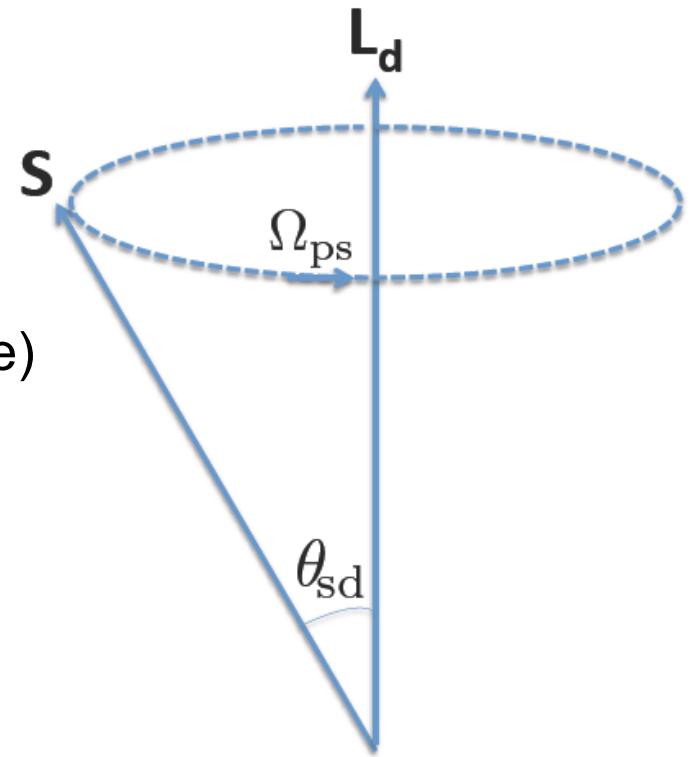
Disk behaves like a rigid body
(bending waves, viscous stress, self-gravity)



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

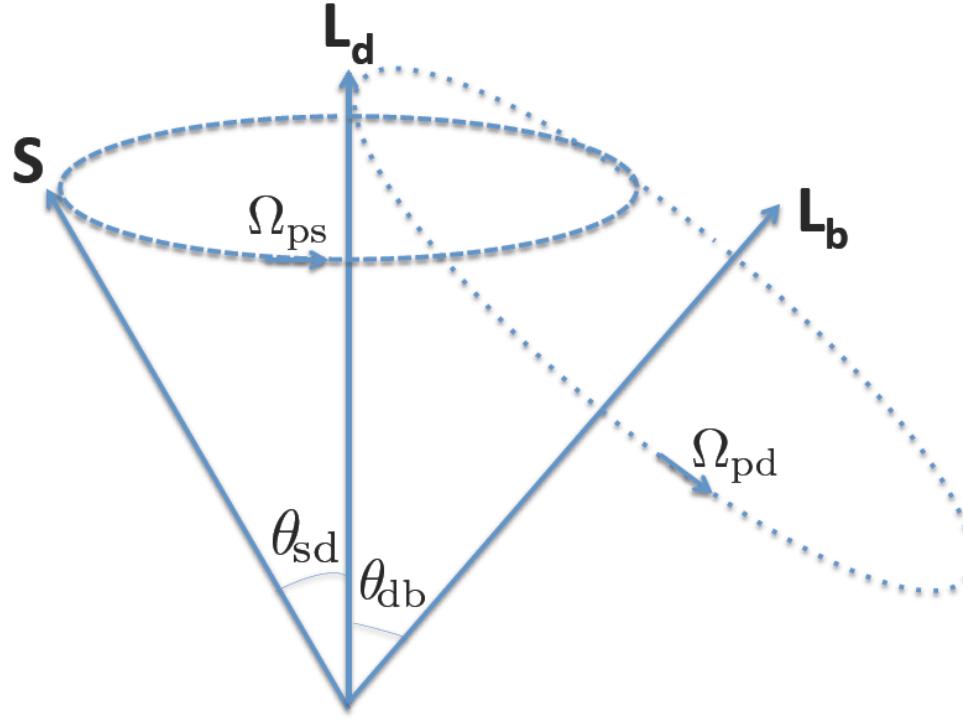
Disk makes the star precess

Gravitational torque on rotating star (oblate)
Mutual precession, but $L_d \gg S$



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

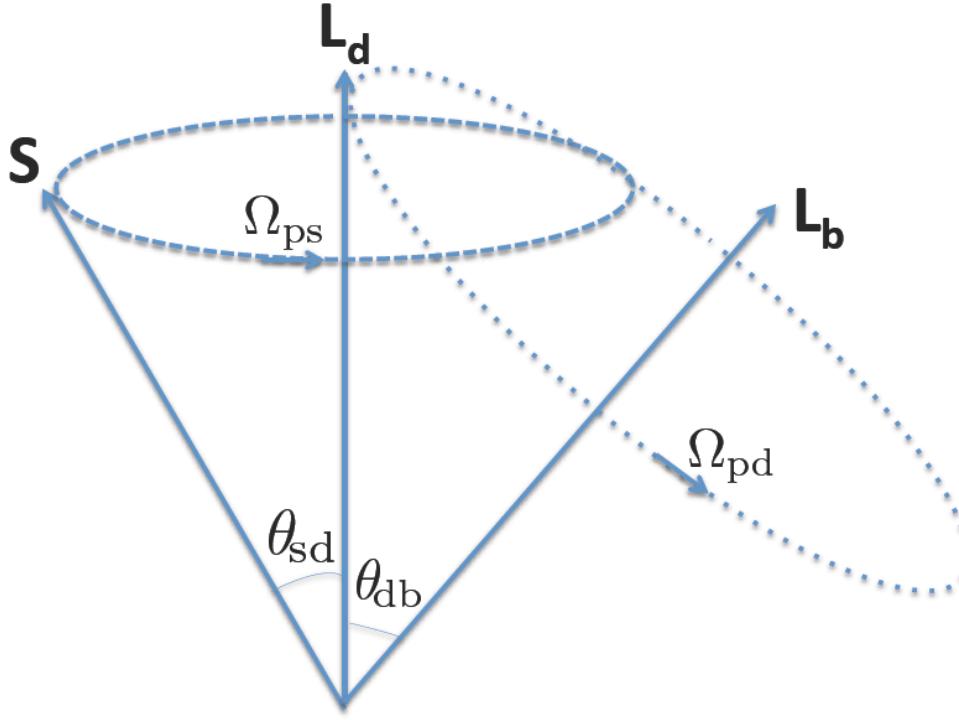
where $\Omega_\star = \left(\frac{2\pi}{3.3 \text{ days}} \right) \left(\frac{\bar{\Omega}_\star}{0.1} \right)$



Two limiting cases:

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

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



$$\Omega_{pd} \simeq -5 \times 10^{-6} \left(\frac{M_b}{M_\star} \right) \left(\frac{r_{out}}{50 \text{ AU}} \right)^{3/2} \left(\frac{a_b}{300 \text{ AU}} \right)^{-3}$$

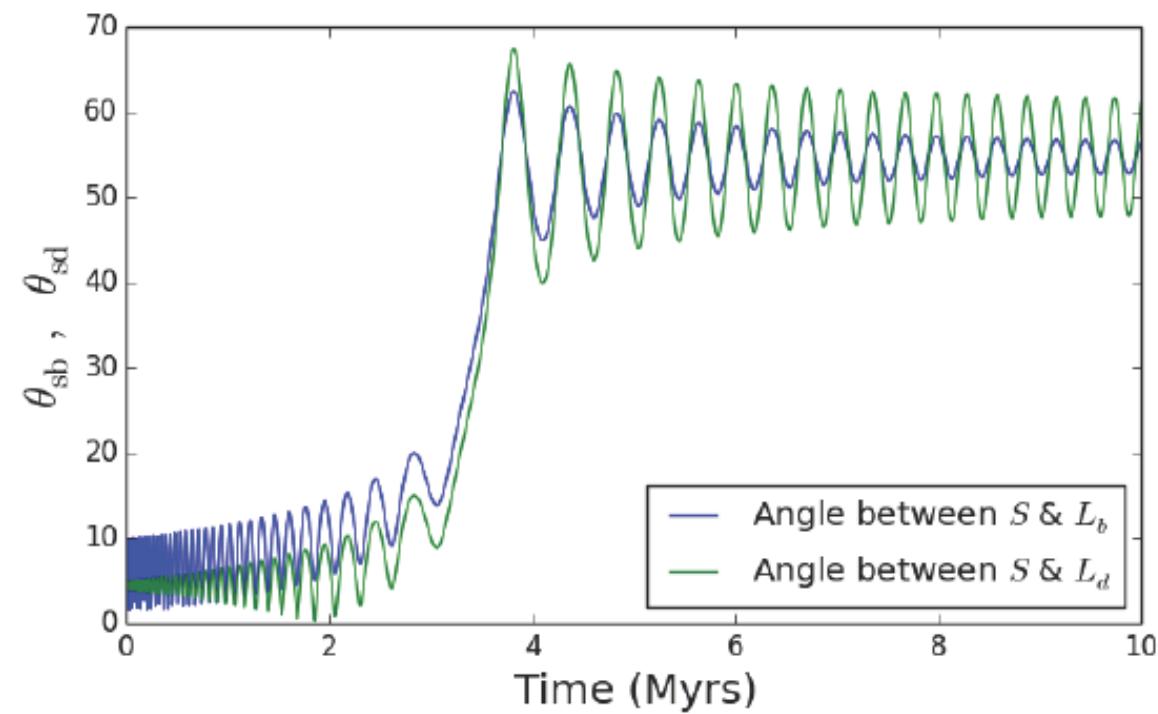
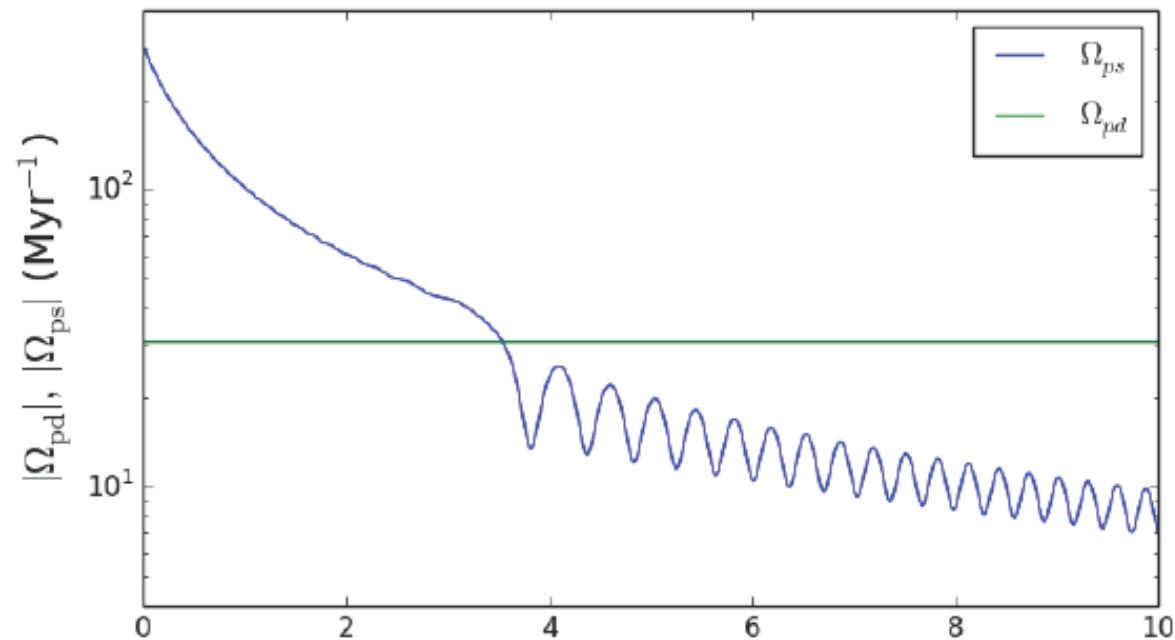
$$\times \cos \theta_{db} \left(\frac{2\pi}{\text{yr}} \right)$$

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

$$\times \cos \theta_{sd} \left(\frac{2\pi}{\text{yr}} \right)$$

Simple model:

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



Initial:

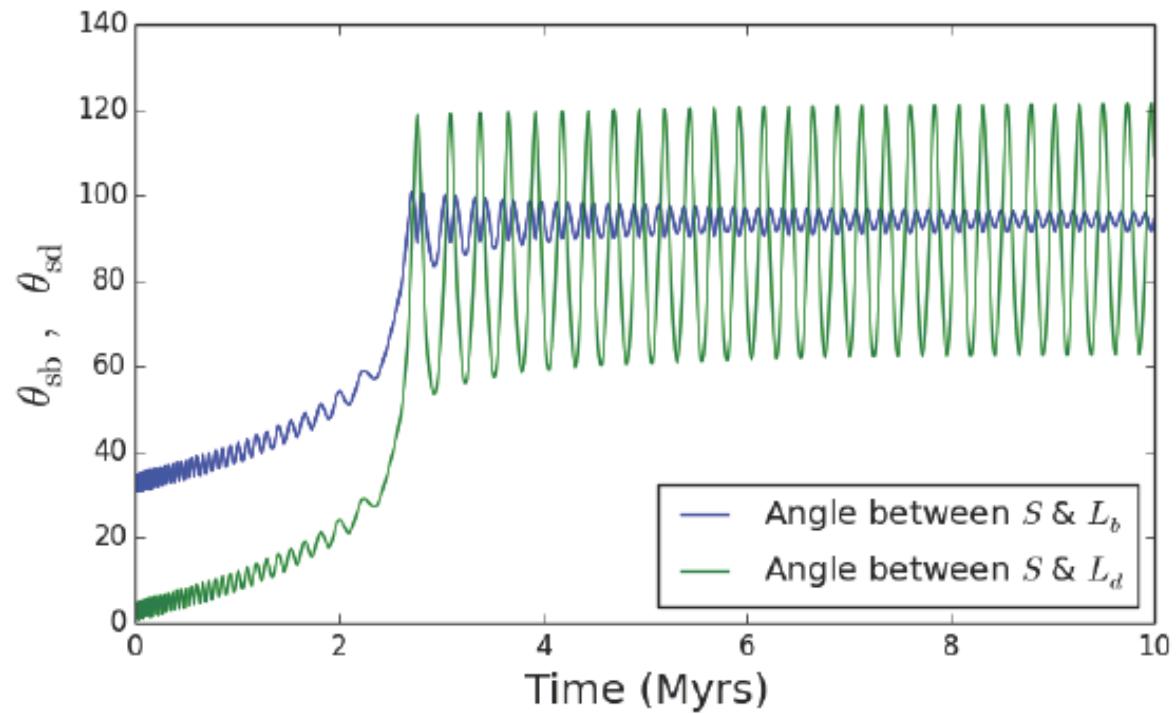
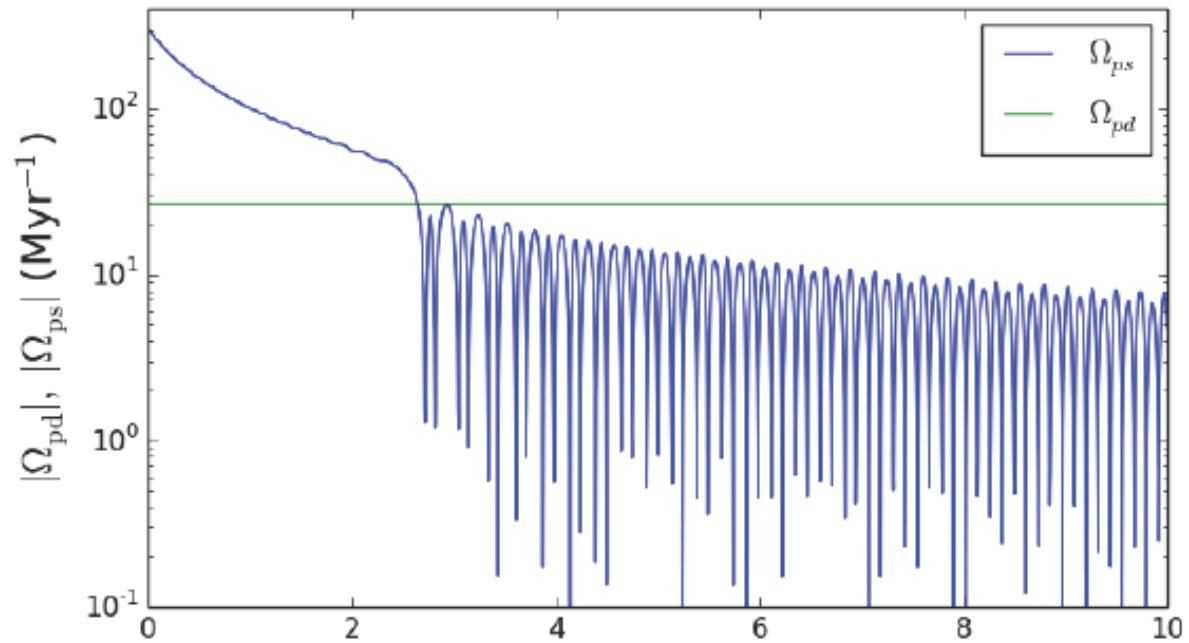
$$\theta_{db} = 5^\circ$$

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

Initial:

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

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



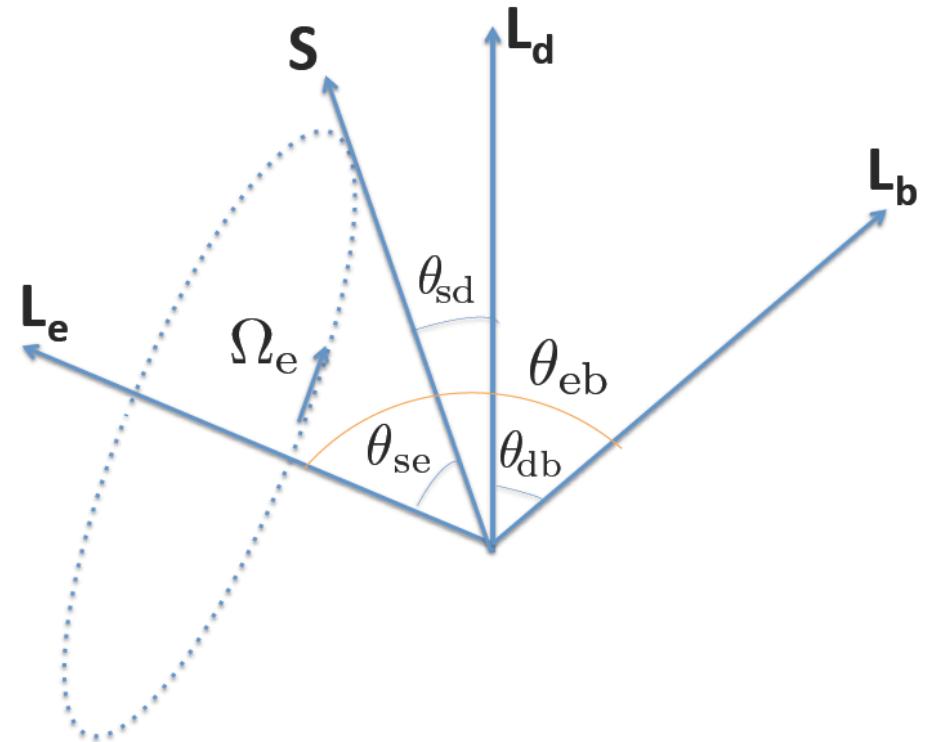
Resonance $\Omega_{\text{ps}} = \Omega_{\text{pd}}$

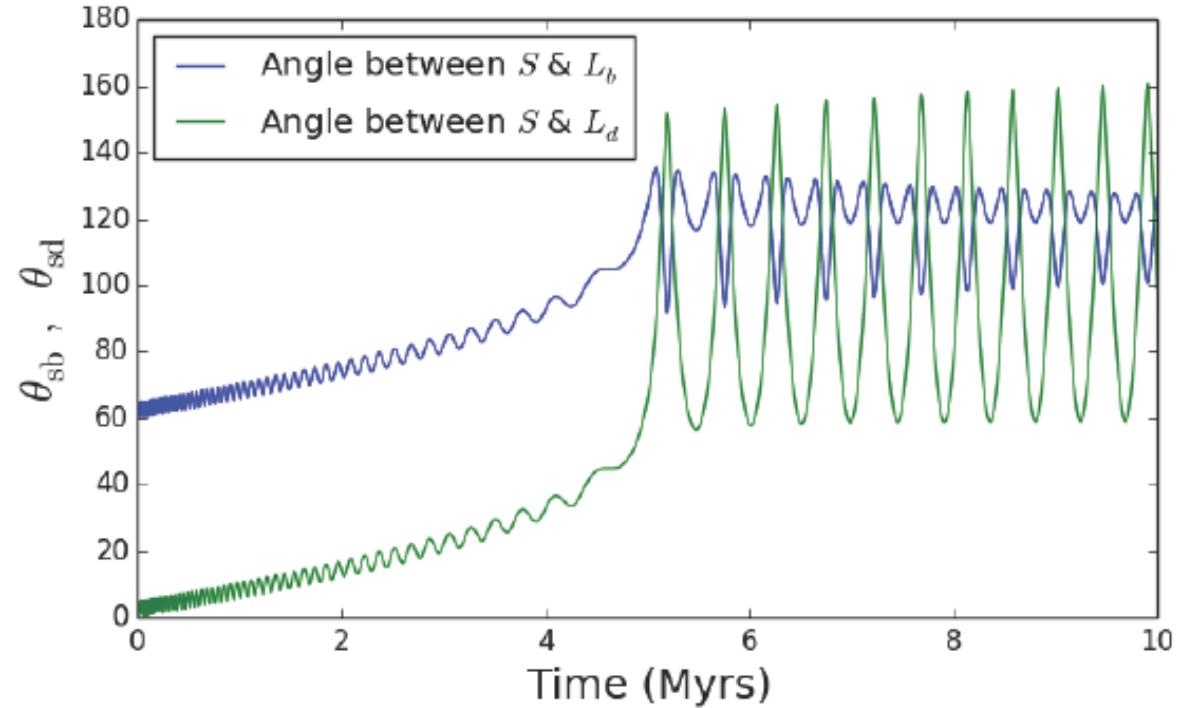
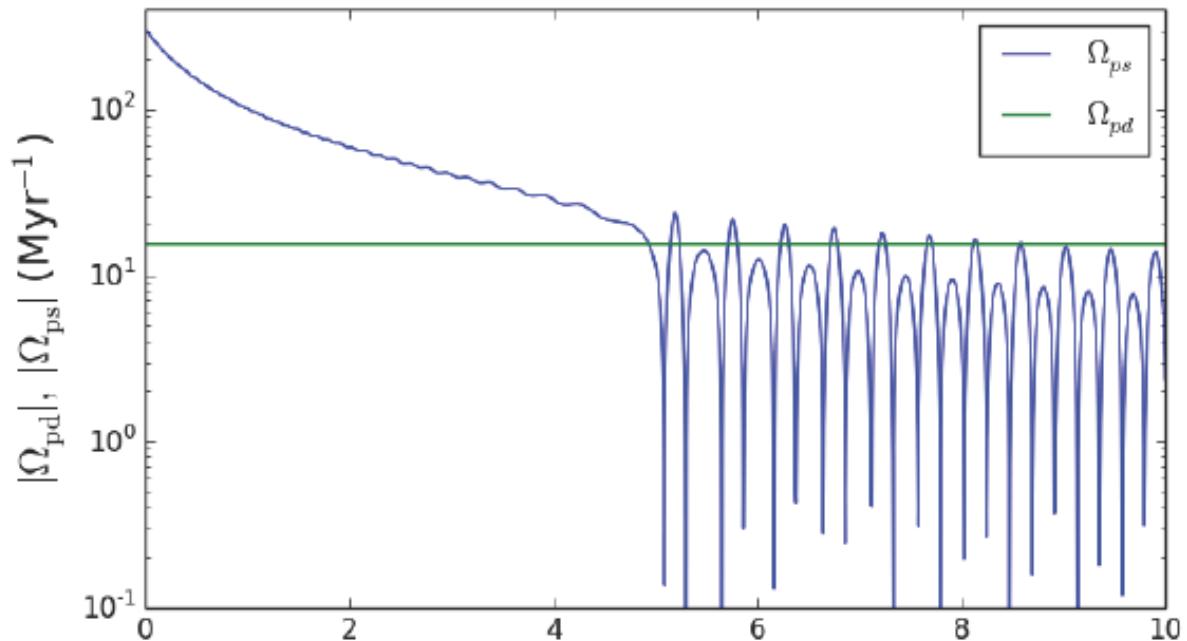
$$\frac{d\hat{\mathbf{S}}}{dt} \simeq \Omega_{\text{ps}} \hat{\mathbf{L}}_{\text{d}} \times \hat{\mathbf{S}}$$

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

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

$$\uparrow \\ \Omega_e \hat{\mathbf{L}}_e$$





Initial:

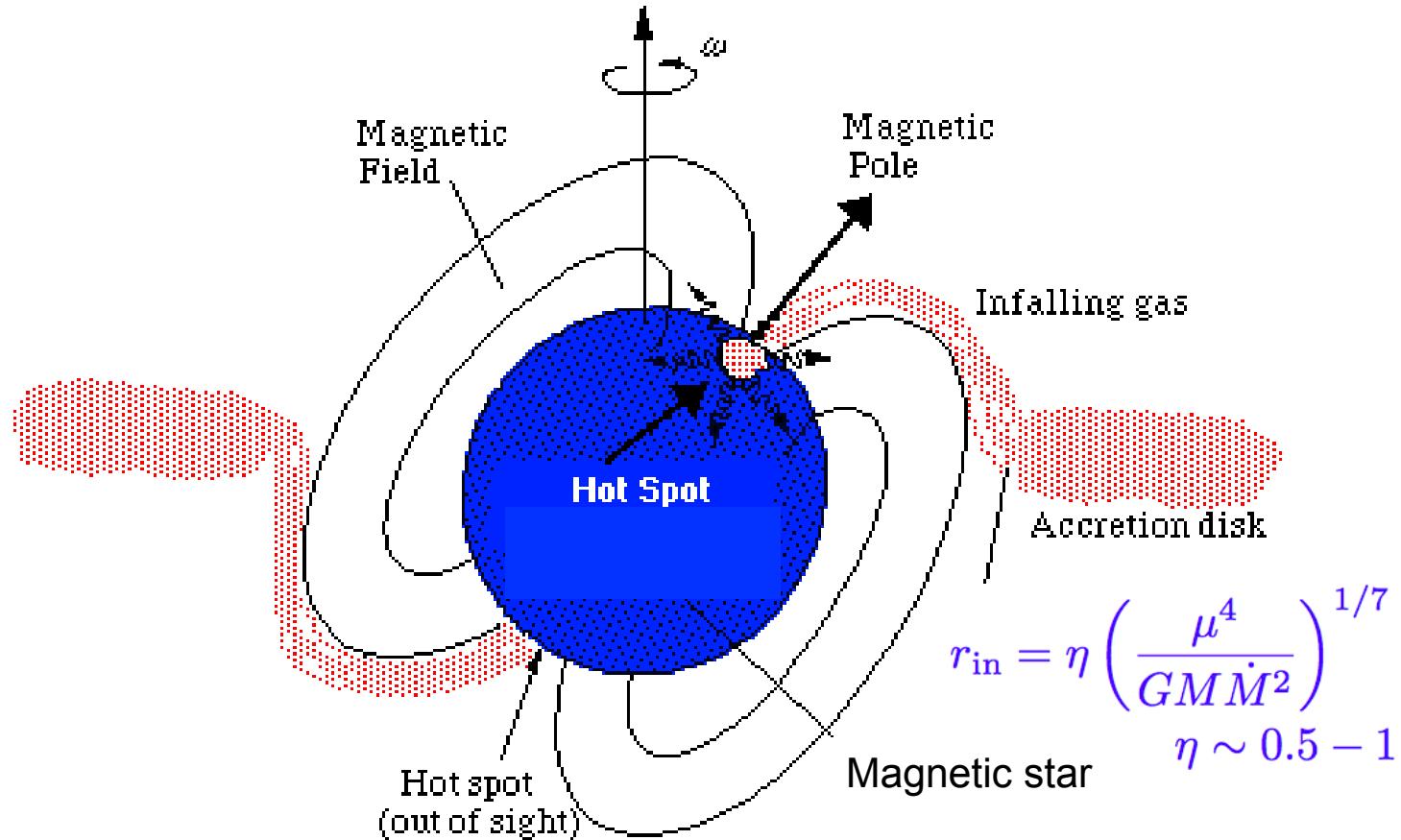
$$\theta_{db} = 60^\circ$$

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

Now consider

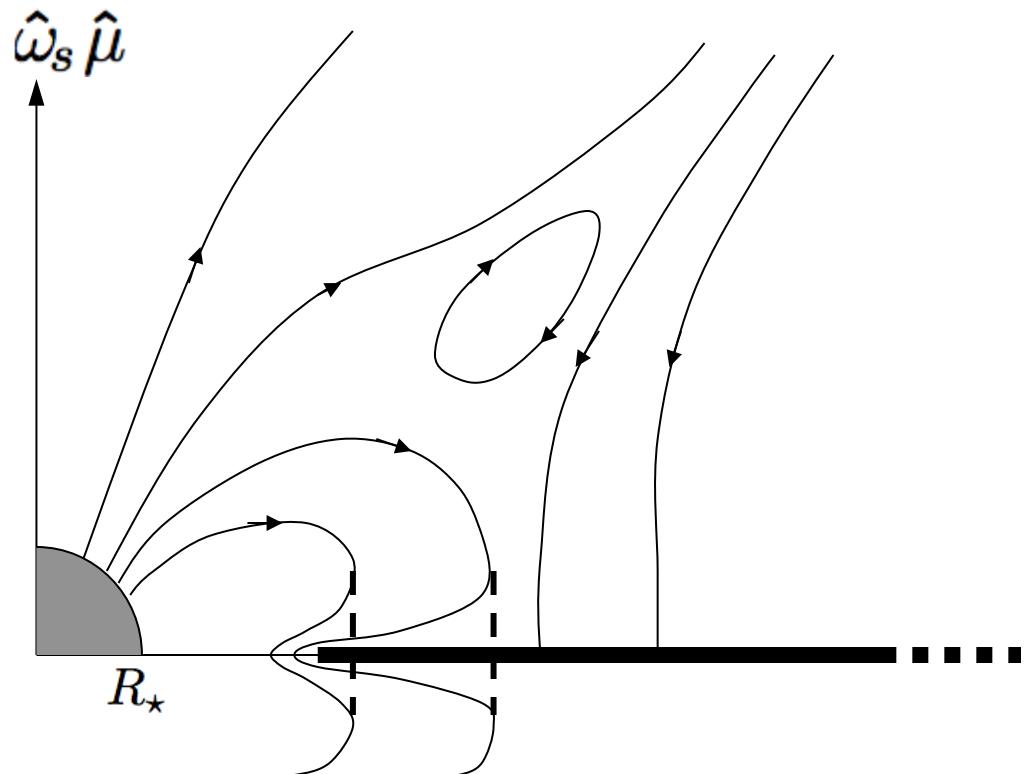
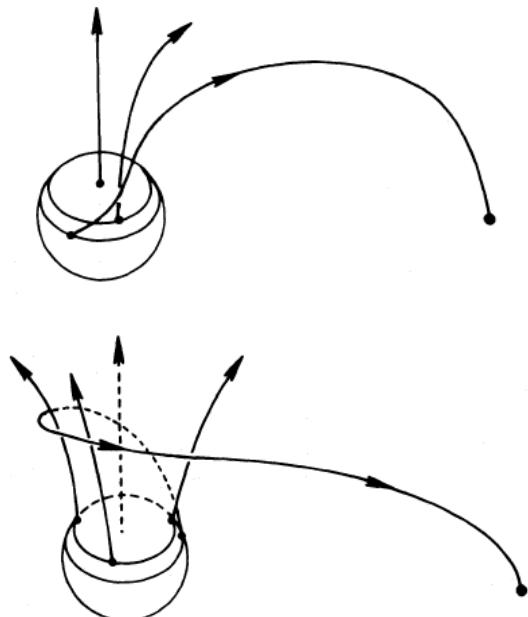
Isolated Star-Disk Systems: Accretion and Magnetic Interaction

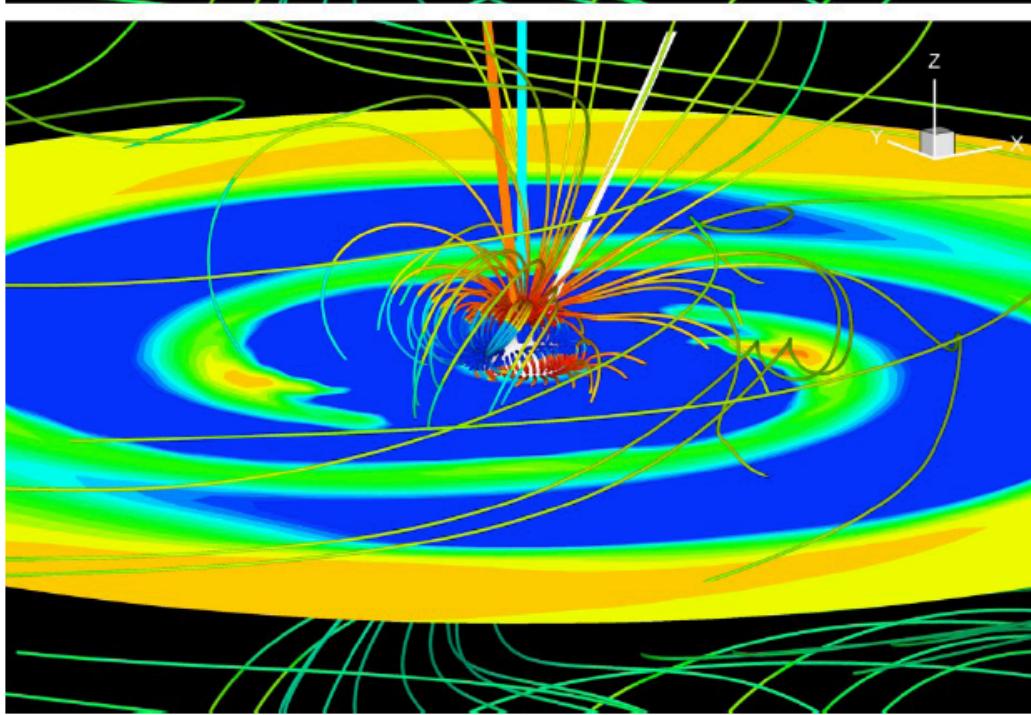
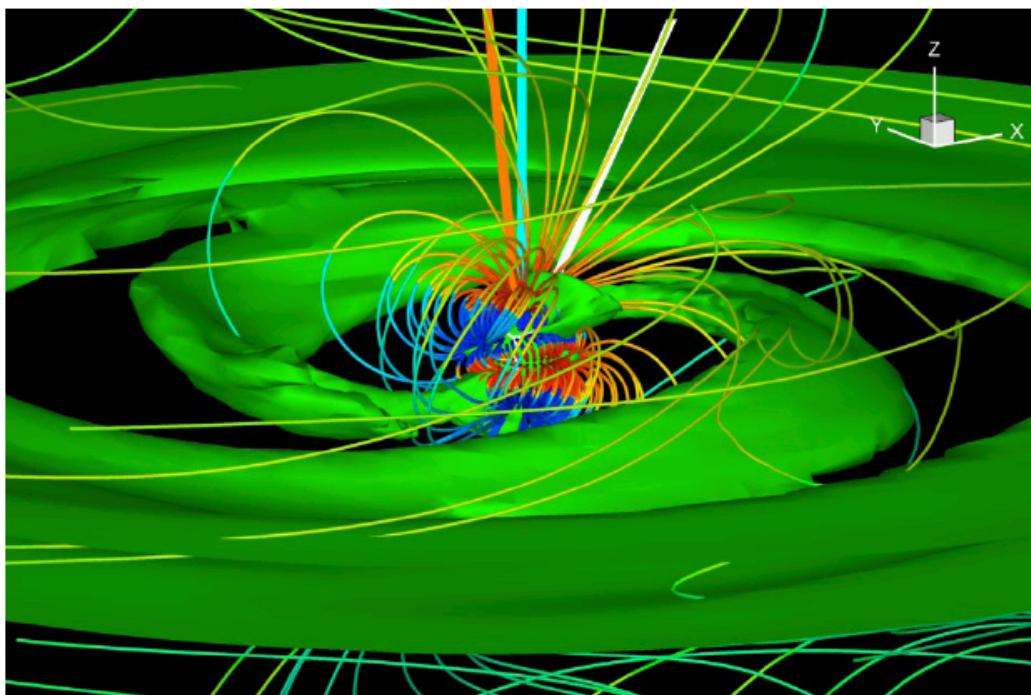
Magnetic Star - Disk Interaction: Basic Picture



Magnetic Star - Disk Interaction: Physical Processes

Magnetic field **reconnects** and penetrates the inner region of disk
Field lines linking star and disk are **twisted** --> toroidal field --> field **inflation**
Reconnection of inflated fields restore linkage





Romanova, Long, et al. 2010

Key Results:

In general, there are magnetic torques which tend to make the inner disk (before disruption)

- warp
- precess

on timescale \gg dynamical time (rotation/orbital period)

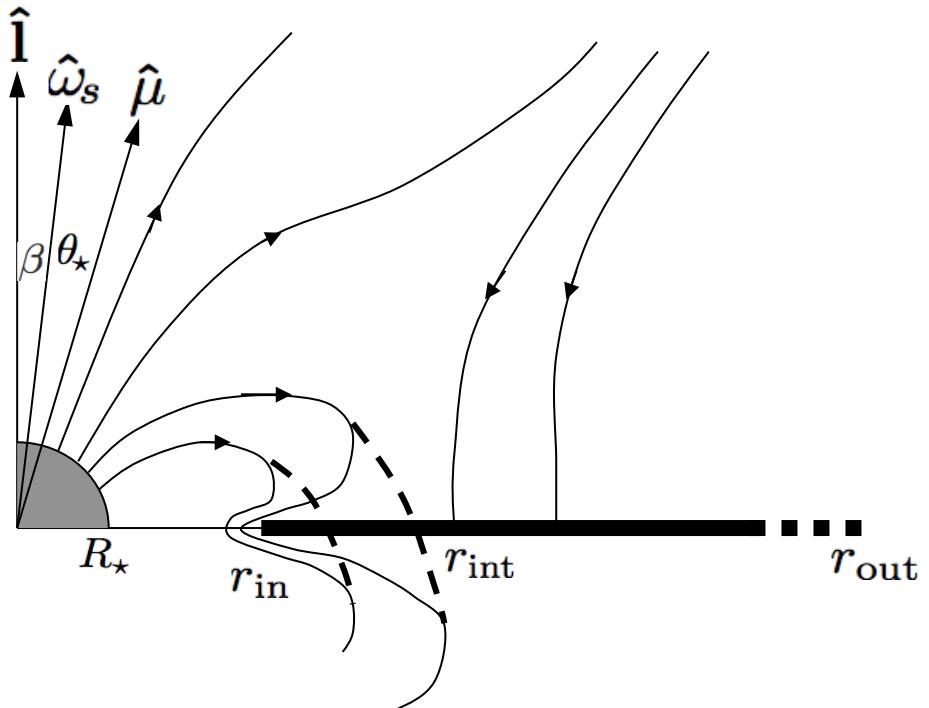
Key Results:

In general, there are magnetic torques which tend to make the inner disk (before disruption)

- warp
- precess

on timescale \gg dynamical time (rotation/orbital period)

Consider two limiting cases
in general geometry...



Perfect conducting disk:

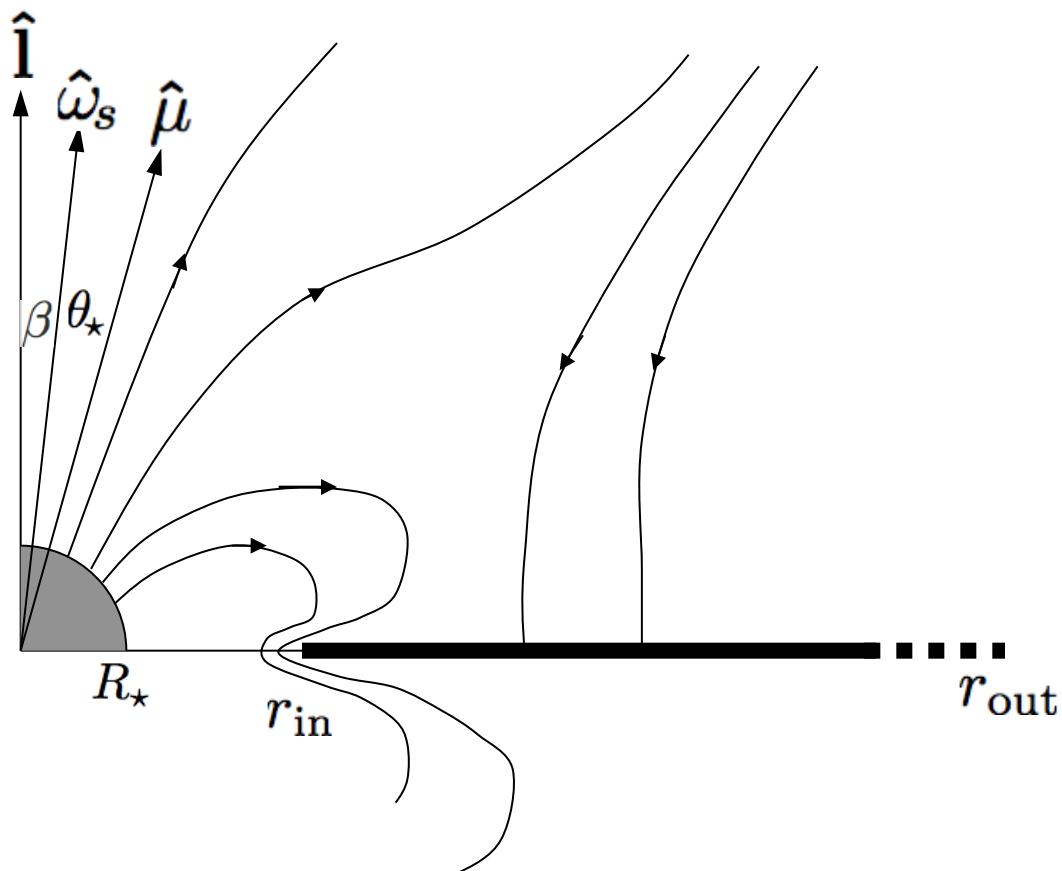
Torque on disk (per unit area):

Averaging over stellar rotation:

$$\mathbf{N} \propto \hat{\mu} \times \hat{\mathbf{i}}$$

$$\mathbf{N} \propto \hat{\omega}_s \times \hat{\mathbf{i}}$$

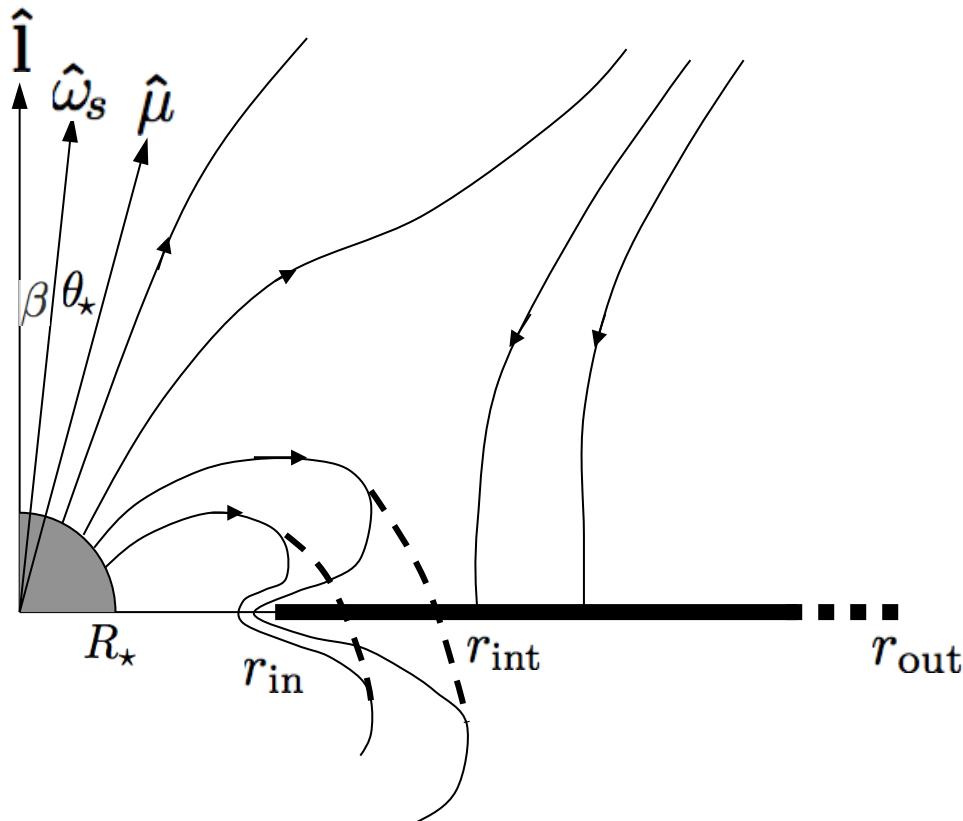
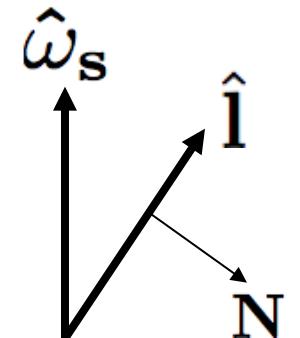
Precessional
Torque



Poorly-conducting disk:

Torque on disk (per unit area): $\mathbf{N} \propto -\hat{\mathbf{l}} \times (\hat{\mu} \times \hat{\mathbf{l}})$
 Averaging over stellar rotation: $\mathbf{N} \propto -\hat{\mathbf{l}} \times (\hat{\omega}_s \times \hat{\mathbf{l}})$

Warping torque



B_z threads the disk

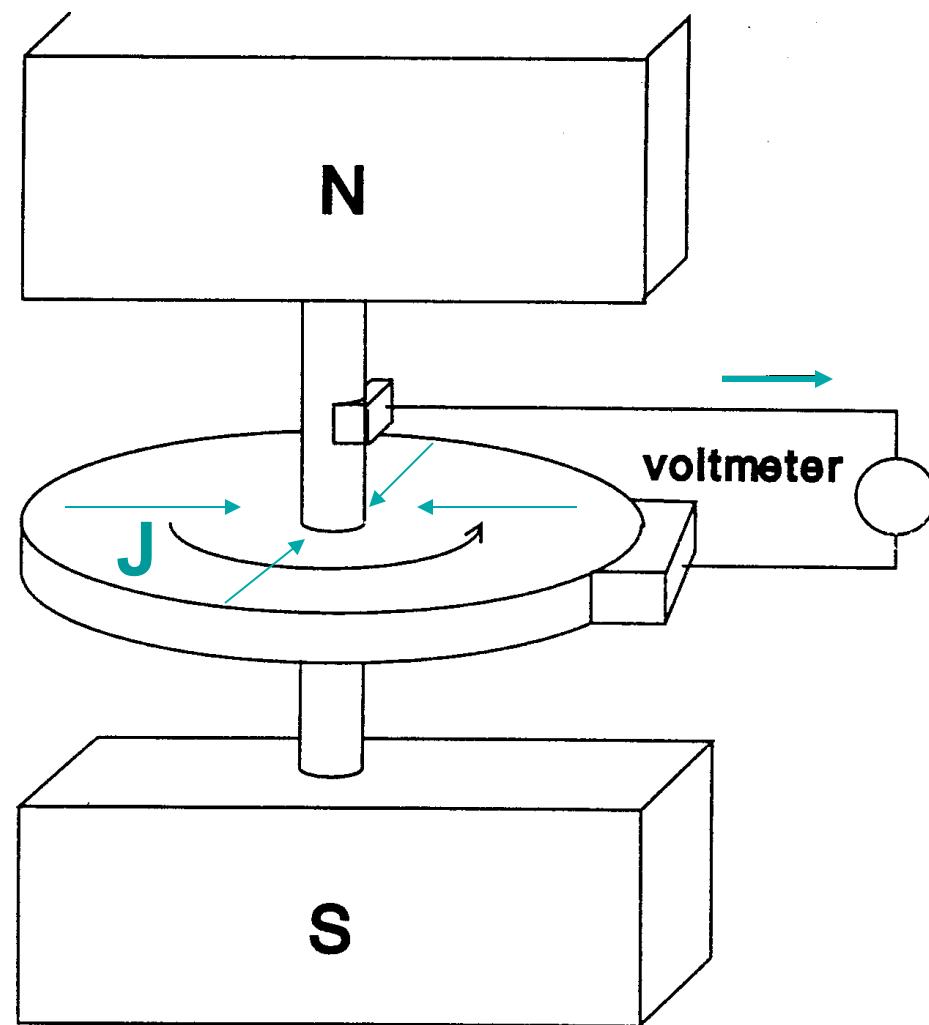
$$\implies \Delta B_\phi = \mp \zeta B_z$$

$$\implies B_\phi^+ = B_\phi^{(s)} - \zeta B_z$$

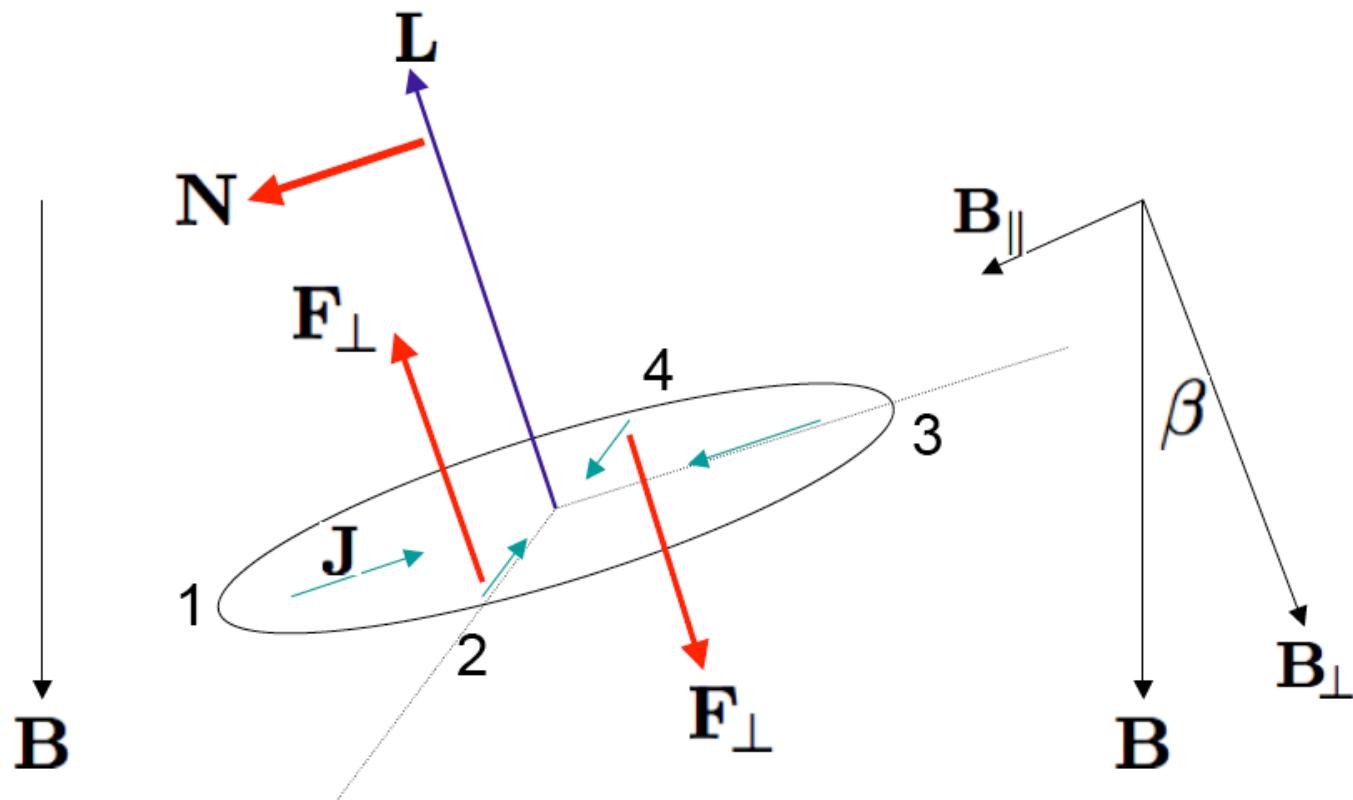
$$B_\phi^- = B_\phi^{(s)} + \zeta B_z$$

$$\implies F_z(\phi)$$

A Laboratory Experiment



A Laboratory Experiment



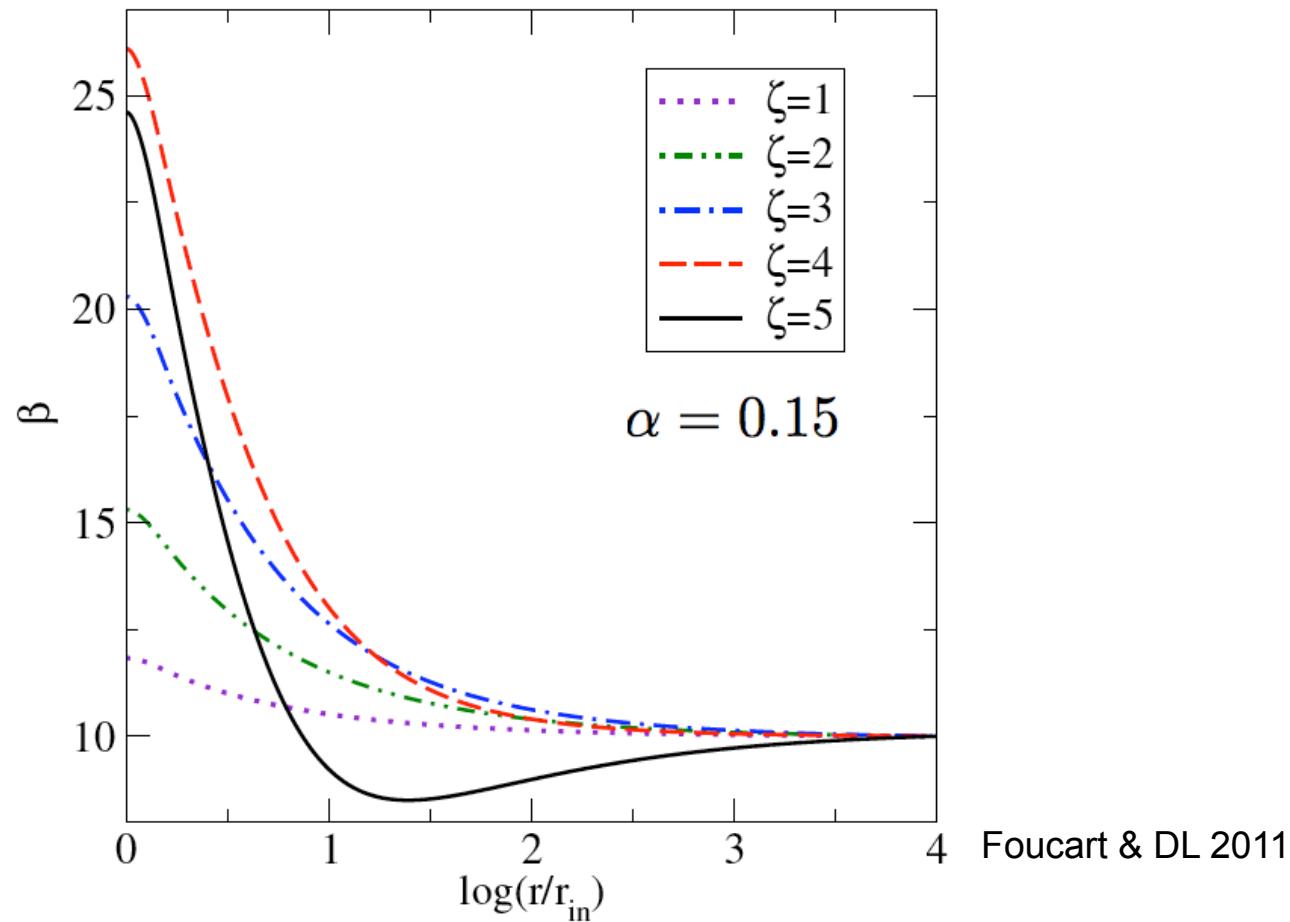
Recap:

Magnetic torques from the star **want** to make the inner disk warp and precess...

But disk will **want** to resist it by internal stresses
(viscosity, bending waves) or self-gravity

$$\begin{aligned}\frac{\partial}{\partial t} \left(\Sigma r^2 \Omega \hat{\mathbf{l}} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(\Sigma V_R r^3 \Omega \hat{\mathbf{l}} \right) &= \frac{1}{r} \frac{\partial}{\partial r} \left(Q_1 I r^2 \Omega^2 \hat{\mathbf{l}} \right) \\ &\quad + \frac{1}{r} \frac{\partial}{\partial r} \left(Q_2 I r^3 \Omega^2 \frac{\partial \hat{\mathbf{l}}}{\partial r} + Q_3 I r^3 \Omega^2 \hat{\mathbf{l}} \times \frac{\partial \hat{\mathbf{l}}}{\partial r} \right) + \mathbf{N}_m\end{aligned}$$

Steady-state Disk Warp:

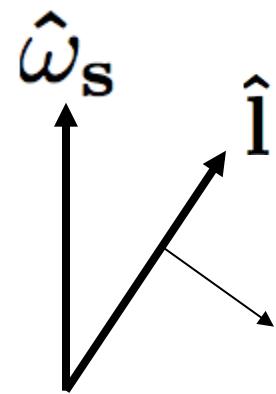


For most disk/star parameters, the disk warp is small

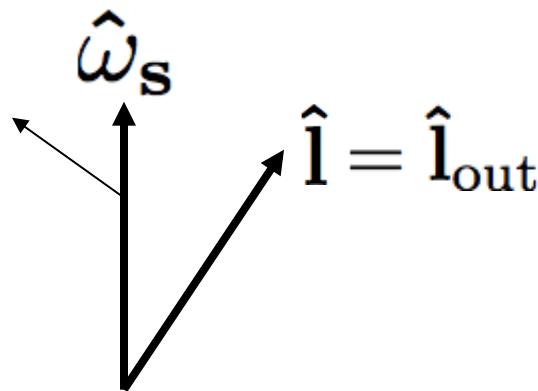
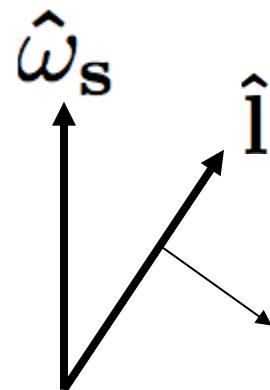
What is happening to the stellar spin direction?
(Is there secular change to the spin direction?)

Need to consider:
Back-reaction torque on the stellar spin...
(for small warps --> flat disk)

What does magnetic warping torque do?



What does magnetic warping torque do?



Accretion tends to align S & L:

Accretion torque $\mathcal{N}_{\text{acc}} \simeq \dot{M} \sqrt{GM_{\star}r_{\text{in}}}$

Magnetic misalignment torque: $\mathcal{N}_{\text{mag}} \sim \mu^2/r_{\text{in}}^3$

For $r_{\text{in}} \sim \left(\frac{\mu^4}{GM_{\star}\dot{M}^2} \right)^{1/7}$

→ $\mathcal{N}_{\text{acc}} \sim \mathcal{N}_{\text{mag}}$

Evolution of the stellar spin

$$\frac{d}{dt} (J_s \hat{\omega}_s) = \mathcal{N} = \mathcal{N}_{\text{acc}} + \mathcal{N}_m + \mathcal{N}_{\text{sd}}$$

$$\mathcal{N}_{\text{acc}} = \lambda \dot{M} \sqrt{GMr_{\text{in}}} \hat{l}_{\text{in}}, \quad \lambda \sim 1 \text{ (or less)}$$

\mathcal{N}_m = backreaction of magnetic (warping & precessional) torques

$$\mathcal{N}_{\text{sd}} = -|\mathcal{N}_{\text{sd}}| \hat{\omega}_s$$

(Each term is of order $\mathcal{N}_0 = \dot{M} \sqrt{GMr_{\text{in}}}$)

$$\Rightarrow \frac{d \cos \theta_{\text{sd}}}{dt} = \frac{\mathcal{N}_0}{J_s} \sin^2 \theta_{\text{sd}} \left(\lambda - \tilde{\xi} \cos^2 \theta_{\text{sd}} \right)$$

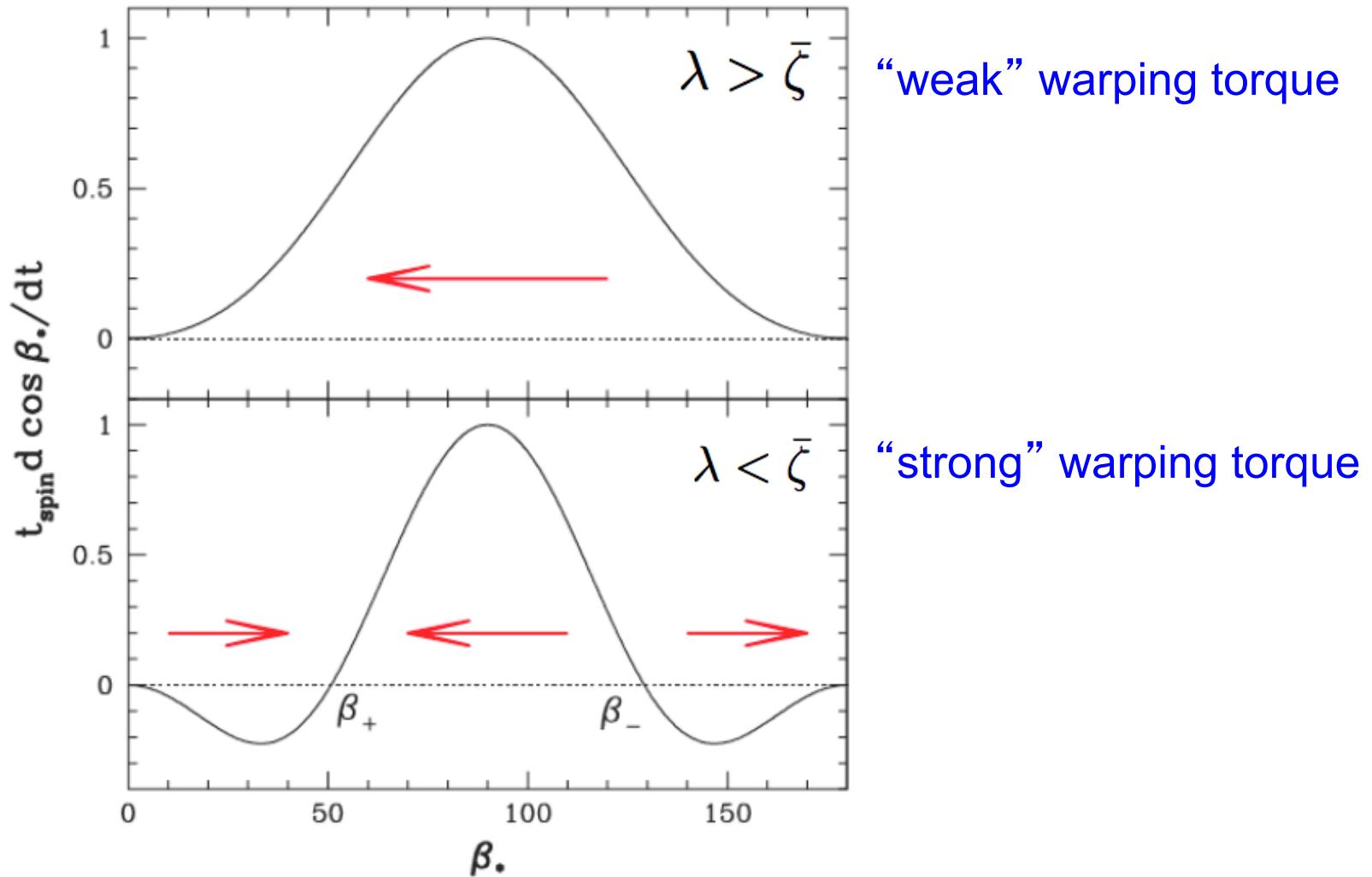
$$\bar{\zeta} = \frac{\zeta \cos^2 \theta_\star}{6\eta^{7/2}} \ (\sim 1)$$

Spin evolution timescale:

$$t_{\text{spin}} = (1.25 \text{ Myr}) \left(\frac{M_\star}{1 M_\odot} \right) \left(\frac{\dot{M}}{10^{-8} M_\odot \text{yr}^{-1}} \right)^{-1} \left(\frac{r_{\text{in}}}{4R_\star} \right)^{-2} \frac{\omega_s}{\Omega(r_{\text{in}})}$$

Evolution of the stellar spin

$$\frac{d \cos \theta_{\text{sd}}}{dt} = \frac{\mathcal{N}_0}{J_s} \sin^2 \theta_{\text{sd}} \left(\lambda - \tilde{\xi} \cos^2 \theta_{\text{sd}} \right) \quad \bar{\zeta} = \frac{\zeta \cos^2 \theta_\star}{6\eta^{7/2}} (\sim 1)$$



Summary:

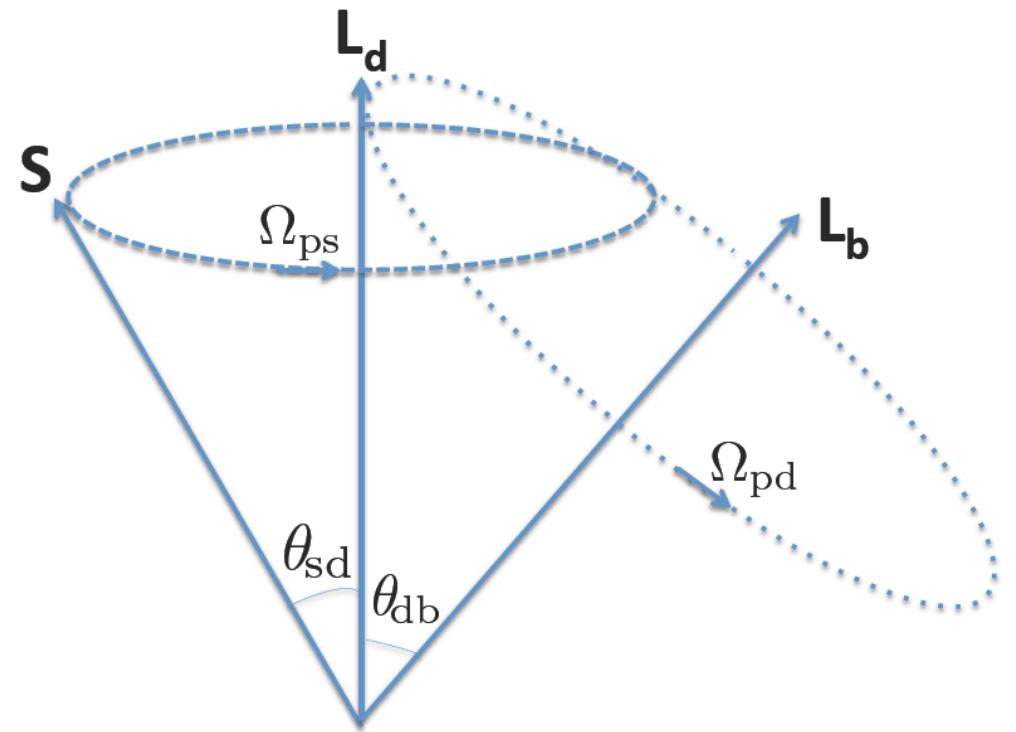
For Isolated star-disk systems:

Magnetic torque tends to produce spin-disk misalignment,
But competes with accretion

→ May or may not produce small/modest misalignment
(e.g., Solar system 7 degree?)

Star-Disk-Binary Interactions

Gravitational interactions...



Now include Accretion and Magnetic Torques

Spin Evolution

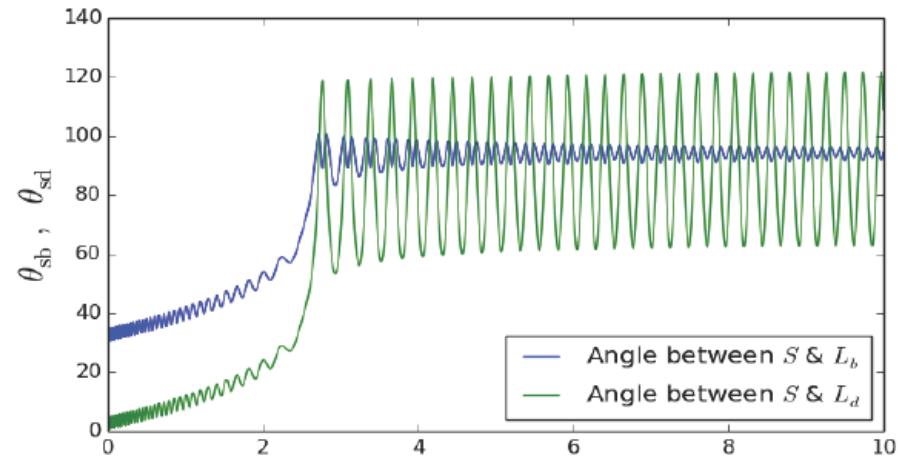
$$\begin{aligned}\frac{d\mathbf{S}}{dt} = & \lambda \mathcal{N}_0 \hat{\mathbf{L}}_{\text{d}} - \mathcal{N}_{\text{s}} \hat{\mathbf{S}} + \mathcal{N}_0 \bar{n}_w \cos \theta_{\text{sd}} \hat{\mathbf{L}}_{\text{d}} \times (\hat{\mathbf{S}} \times \hat{\mathbf{L}}_{\text{d}}) \\ & + \mathcal{N}_0 \bar{n}_p \cos \theta_{\text{sd}} \hat{\mathbf{S}} \times \hat{\mathbf{L}}_{\text{d}} + \Omega_{\text{ps}} \hat{\mathbf{J}}_{\text{sd}} \times \mathbf{S}\end{aligned}$$

Spin Direction Evolution

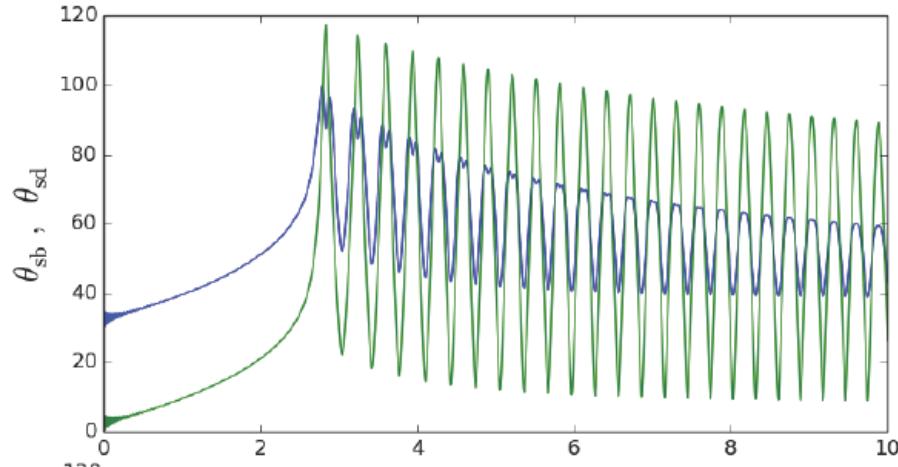
$$\begin{aligned}\frac{d\hat{\mathbf{S}}}{dt} \simeq & \omega_0 \left(\lambda - \bar{n}_w \cos^2 \theta_{\text{sd}} \right) \left(\hat{\mathbf{L}}_{\text{d}} - \cos \theta_{\text{sd}} \hat{\mathbf{S}} \right) \\ & + \left(\Omega_{\text{ps}}^{(m)} + \Omega_{\text{ps}} \right) \hat{\mathbf{L}}_{\text{d}} \times \hat{\mathbf{S}},\end{aligned}$$

$$t_{\text{spin}} = \frac{1}{\omega_0} = (1.25 \text{ Myr}) \left(\frac{M_\star}{1 M_\odot} \right) \left(\frac{\dot{M}}{10^{-8} M_\odot \text{yr}^{-1}} \right)^{-1} \left(\frac{r_{\text{in}}}{4 R_\star} \right)^{-2} \frac{\omega_s}{\Omega(r_{\text{in}})}$$

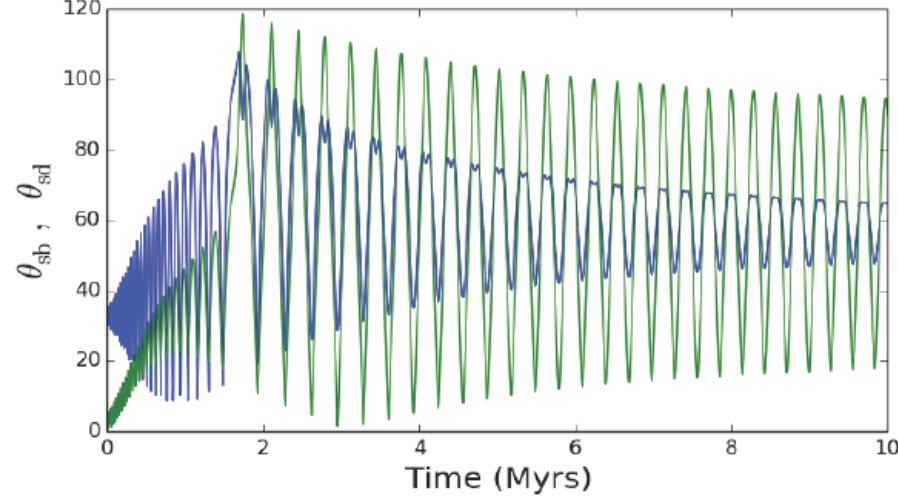
No accretion/magnetic



Accretion/magnetic
damps SL-angle

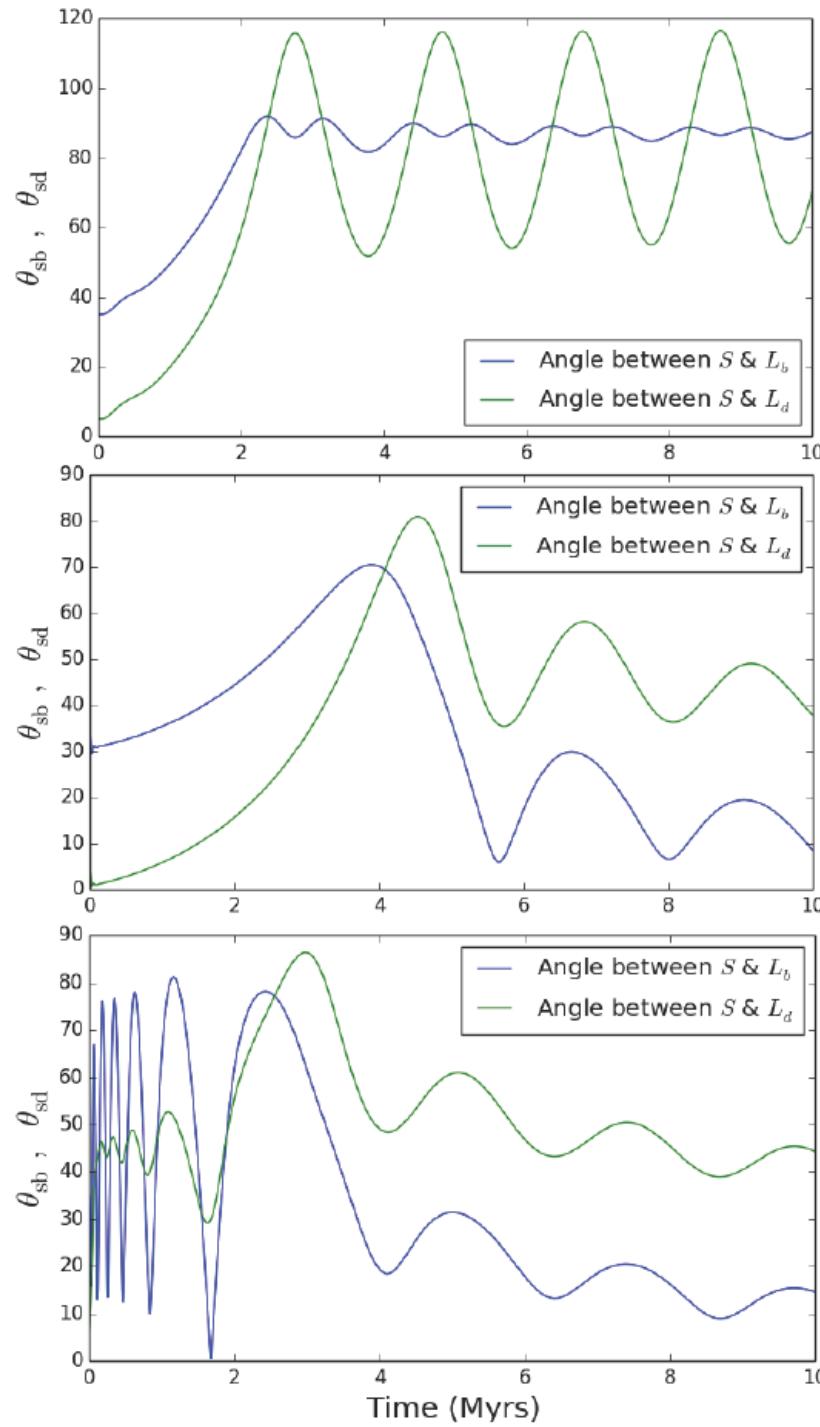


Accretion/magnetic
increases SL-angle



DL2014

No accretion/magnetic



Accretion/magnetic
damps SL-angle

Accretion/magnetic
increases SL-angle

DL2014

Recap the Key Findings:

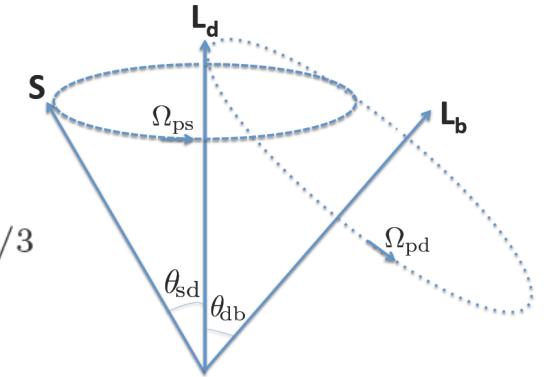
- With a binary companion, spin-disk misalignment is “easily” generated
- Accretion/magnetic torques affect it, but not diminish the effect
- The key is “resonance crossing”

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

$$\rightarrow \frac{a_b}{r_{\text{out}}} \gtrsim 2.8 \left(\frac{M_b}{M_\star} \right)^{1/3} \left(\frac{r_{\text{out}}}{50 \text{ AU}} \right)^{-1/6} \left(\frac{\bar{\Omega}_\star}{0.1} \right)^{-7/9} \left(\frac{M_{\text{di}}}{0.1 M_\star} \right)^{-1/3}$$

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

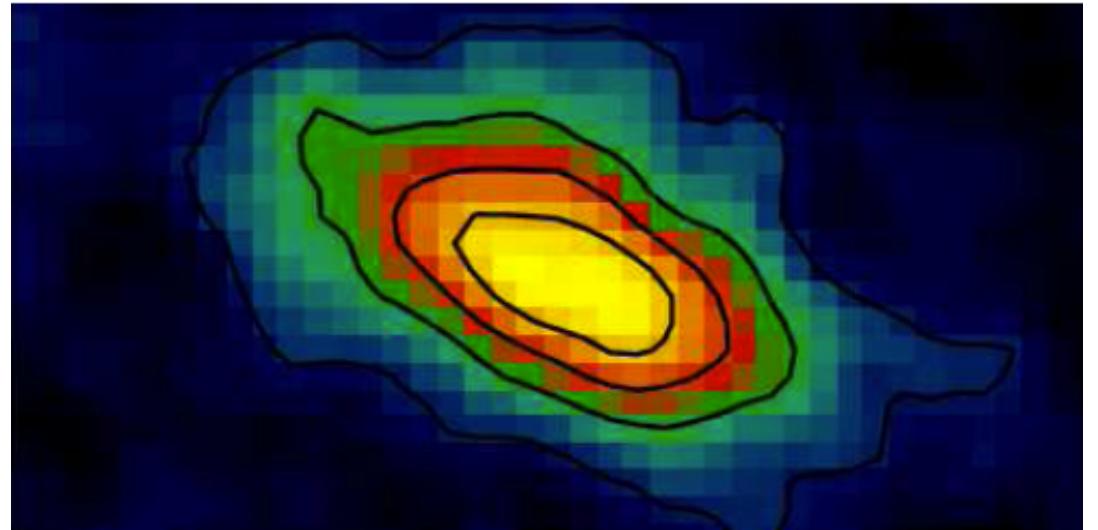
$$\rightarrow \frac{a_b}{r_{\text{out}}} \lesssim 7.6 \left(\frac{M_b}{M_\star} \right)^{1/3} \left(\frac{r_{\text{out}}}{50 \text{ AU}} \right)^{-1/6} \left(\frac{\bar{\Omega}_\star}{0.1} \right)^{-7/9} \left(\frac{M_{\text{df}}}{0.005 M_\star} \right)^{-1/3}$$



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...

Star-Debris Disk Systems: $i_{\text{star}} \approx i_{\text{disk}}$

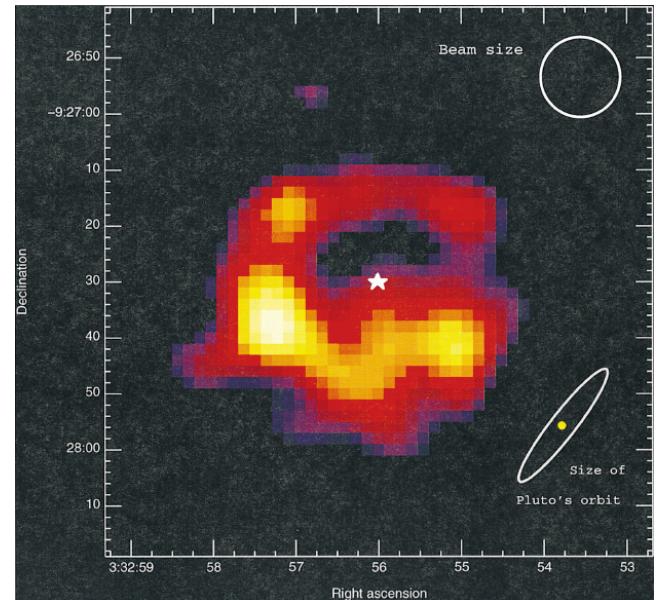


Greaves et al. 2013

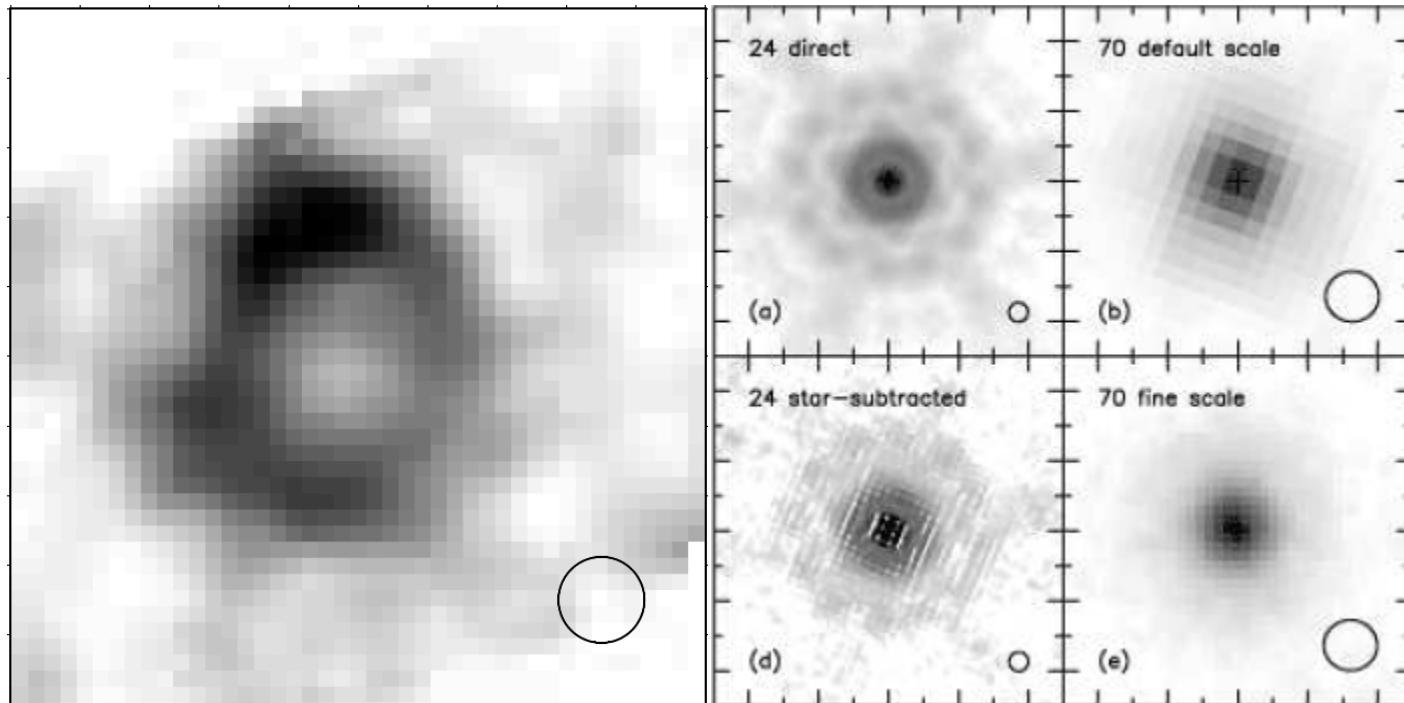
system names (UNS id)	notes	P (days)	$v \sin i_*$ (km/s)	R_* (R_\odot)	i_* ($^\circ$)	i_d ($^\circ$)	$ \Delta i $ ($^\circ$)
Vega, HD 172167 (A003)	planet?; 2 belts	—	—	—	3–6	10 ± 2	5.5 ± 2.5
HR 8799, HD 218396 (A—)	planets; 2 belts	—	—	—	$\gtrsim 40$	27 ± 10	$\gtrsim 3$
10 CVn, HD 110897 (F050)		13 [1]	3.4 ± 1.4	0.99	$63 (\gtrless 33)$	56 ± 10	$7^{+29}_{(-7)}$
γ Dor, HD 27290 (F085)	2 belts	—	—	—	63–80	69 ± 5	$3^{+10}_{(-3)}$
<i>Sun</i> ($G-$)	<i>planets, 2 belts</i>	—	—	—	7.3	1.7 ± 0.2	5.6 ± 0.2
61 Vir, HD 115617 (G008)	planets	29 [2]	1.6 ± 0.5	0.97	$68 (\gtrless 41)$	77 ± 4	$9^{+22}_{(-9)}$
58 Eri, HD 30495 (G029)			11.3 [2,3,4]	3.4 ± 0.3	0.97	51 ± 6	51 ± 10
V439 And, HD 166 (G030)	2 belts?	5.7 [3,5]	4.8 ± 0.7	0.87	39 ± 6	50 ± 10	$11^{+12}_{(-11)}$
ϵ Eri, HD 22049 (K001)	planet(s); 2 belts	11.6 [6]	2.3 ± 0.3	0.74	46 ± 8	38 ± 10	$8^{+13}_{(-8)}$
EP Eri, HD 17925 (K035)			6.9 [2,6,7]	5.8 ± 0.6	0.79	$88 (\gtrless 63)$	54 ± 10
DE Boo, HD 131511 (K053)			10.4 [8]	4.5 ± 0.4	0.91	$\gtrless 70$	84 ± 10
HO Lib, GJ 581 (M056)	planets	94 [9]	0.3 ± 0.3	0.30	$\gtrless 0$	50 ± 20	—
AU Mic, HD 197481 (M—)			4.9 [10,11]	8.5 ± 0.6	0.77	$\gtrless 81$	$\gtrless 80$
							$1^{+7}_{(-1)}$

Watson et al 2011

HD	i_* ($^{\circ}$)	i_{disk} ($^{\circ}$)	ref.
10647	49^{+17}_{-11}	≥ 52	(Liseau et al. 2008)
10700	45^{+24}_{-15}	60–90	(Greaves et al. 2004)
22049	31^{+5}_{-5}	25	(Greaves et al. 1998)
61005	90^{+0}_{-26}	80	(Maness et al. 2009)
92945	65^{+21}_{-10}	70	(Krist et al. 2005)
107146	21^{+8}_{-9}	25 ± 5	(Ardila et al. 2004)
197481	90^{+0}_{-20}	90	(Krist et al. 2005)
207129	47^{+22}_{-13}	60 ± 3	(Krist et al. 2010)



Greaves et al. 1998



CSO and Spitzer
(MIPS) image
Backman et al 2009

Consistent with
face-on
(Stapelfeldt 2010)

Summary

-- Hints/Needs for primordial star-disk misalignments

-- Isolated star-disk systems:

Magnetic torque may produce small/modest misalignments;

May explain the 7° misalignemnt in solar system

-- Binary-disk-star interactions:

Easy to generate promordial misalignments

“Secular resonance”

Take place before few-body interactions (e.g. Kozai)

Disk-driven migration can produce misaligned hot Jupiters

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Thanks!