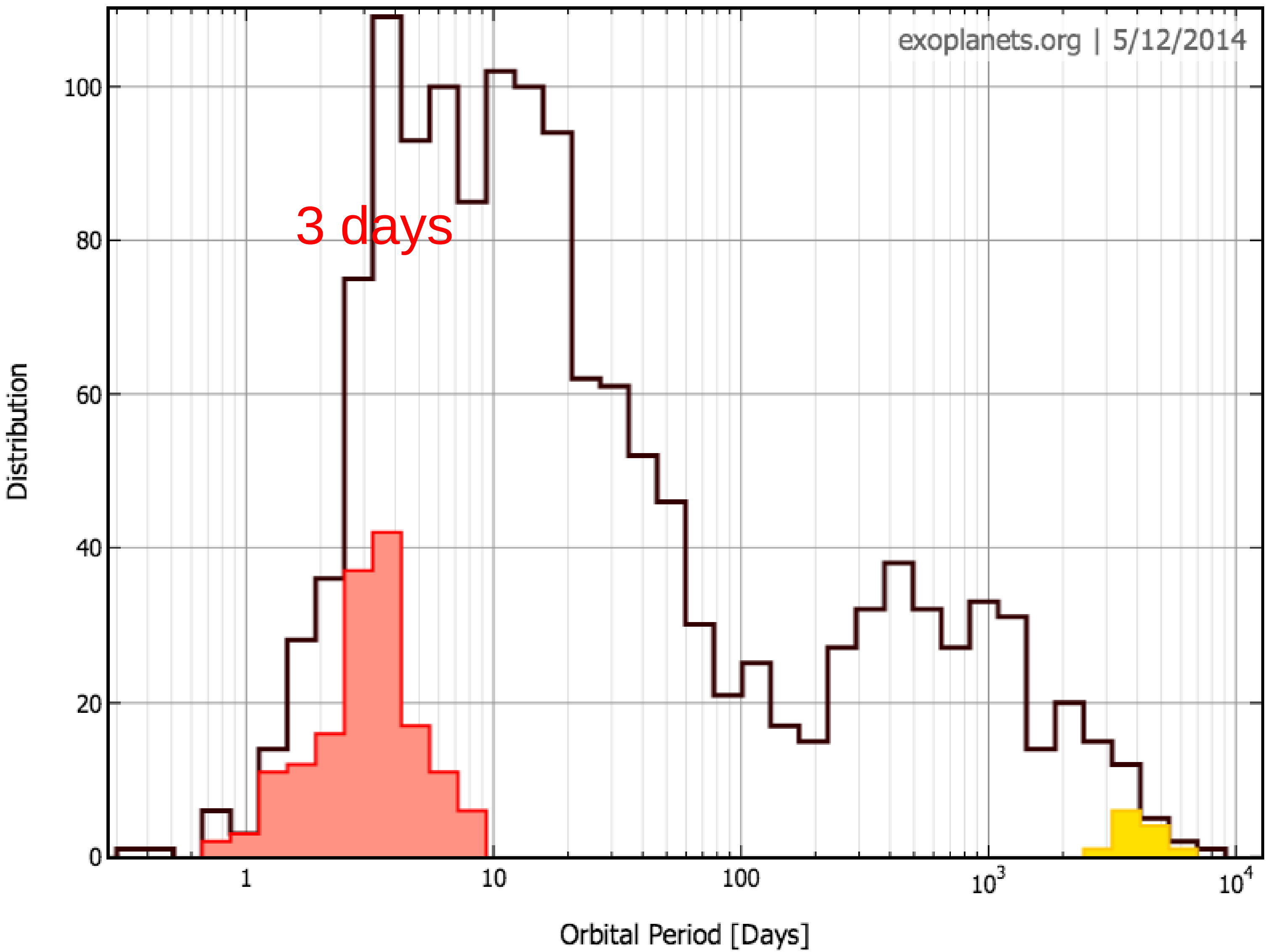
Star-Disk-Binary Interactions
& Primordial Spin-Orbit Misalignment

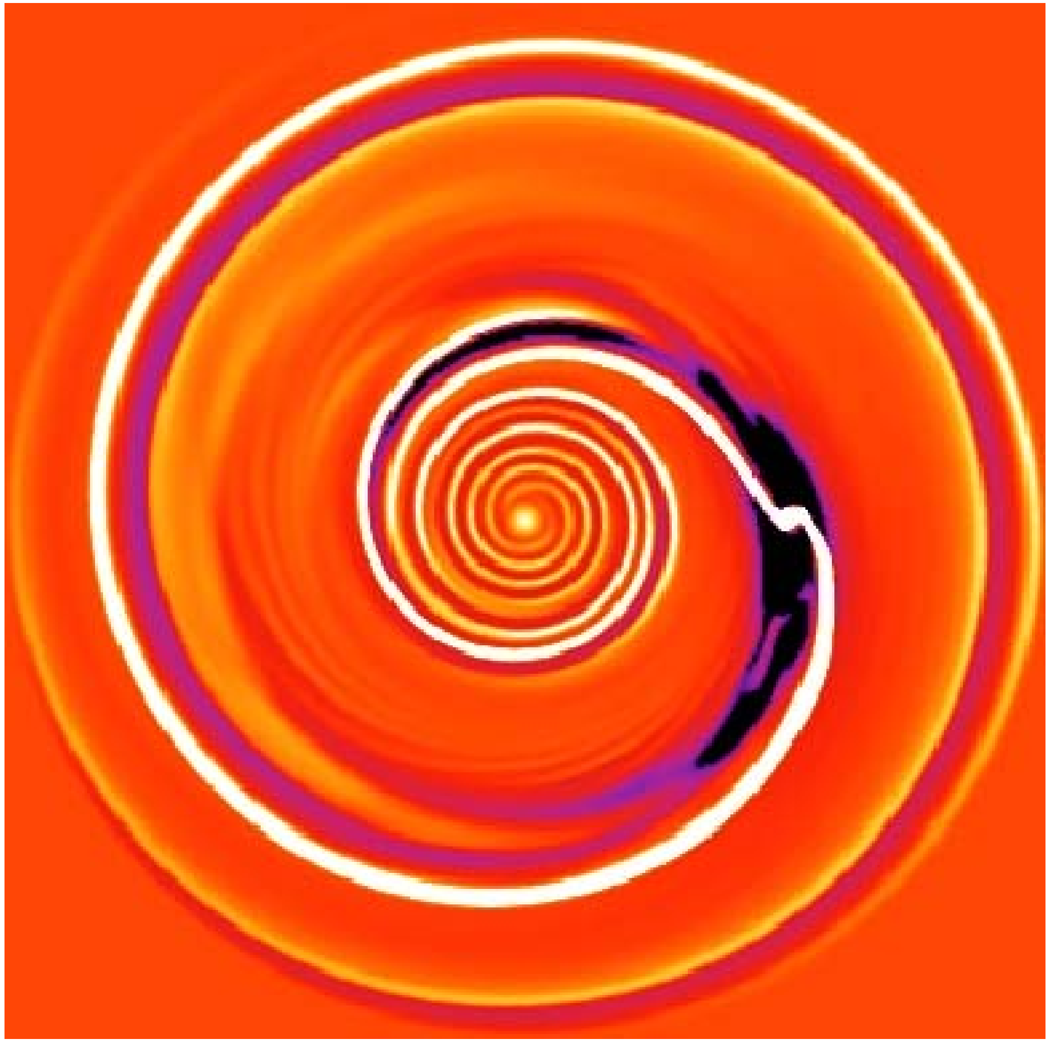
Dong Lai
Cornell University

Tsinghua 5/15/2014

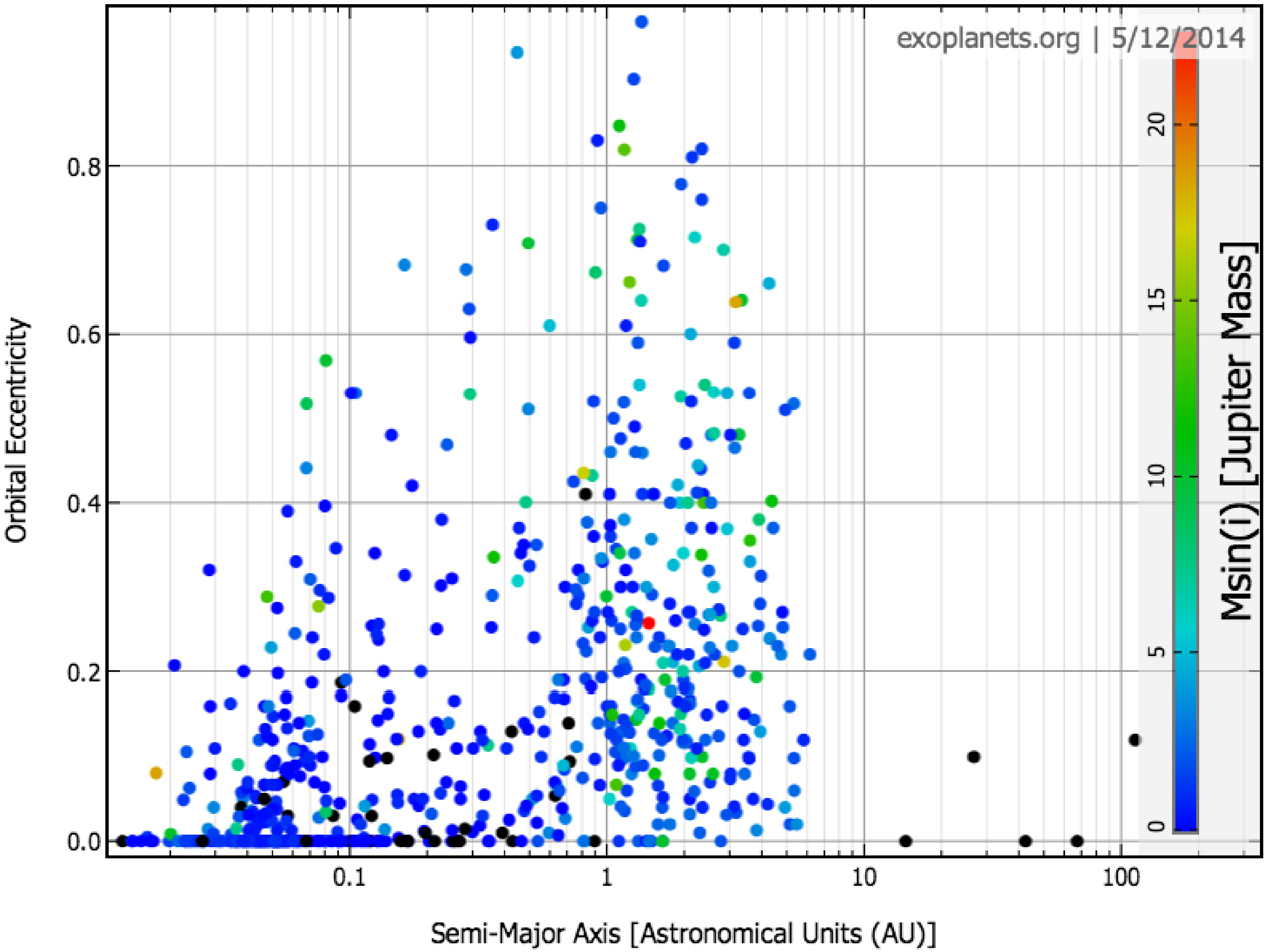
Orbital period puzzle



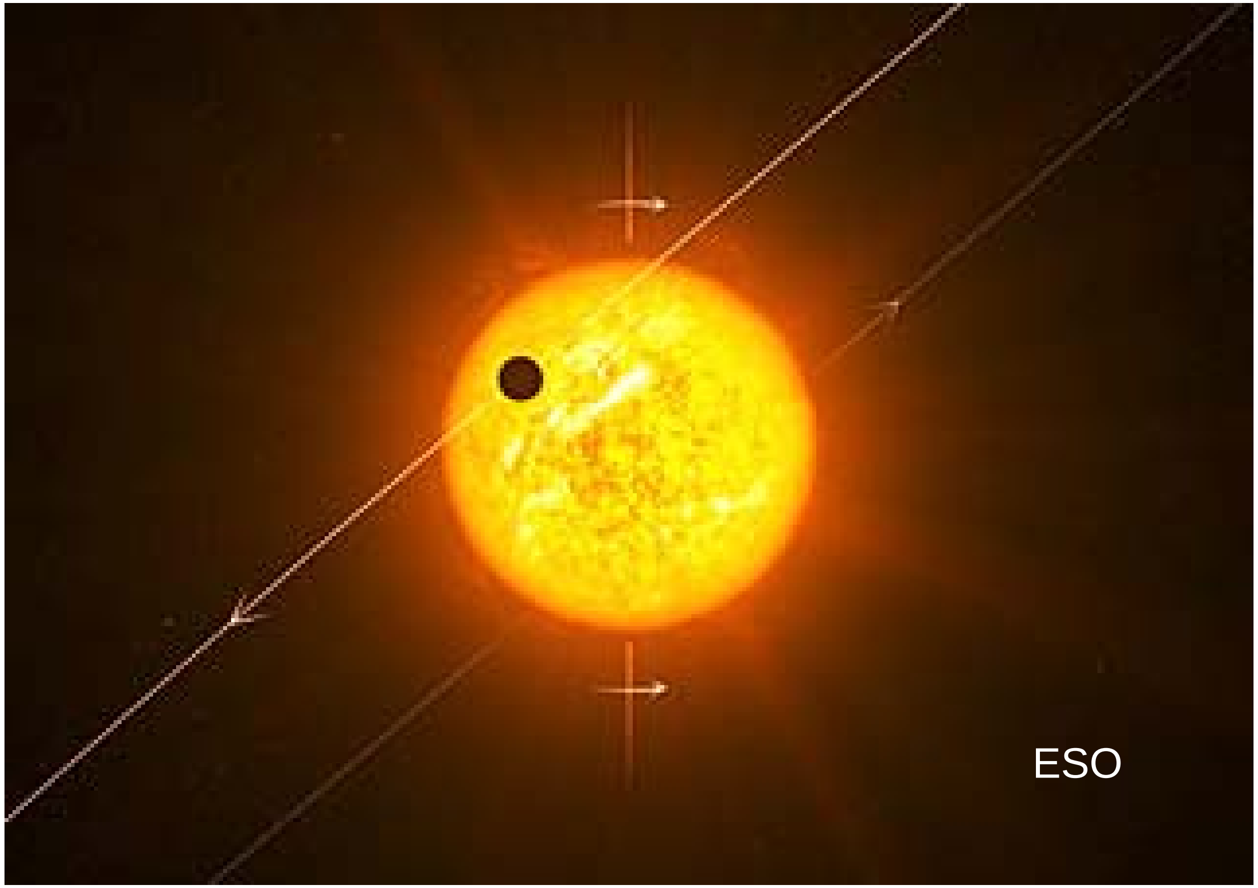
Disk-Driven Migration

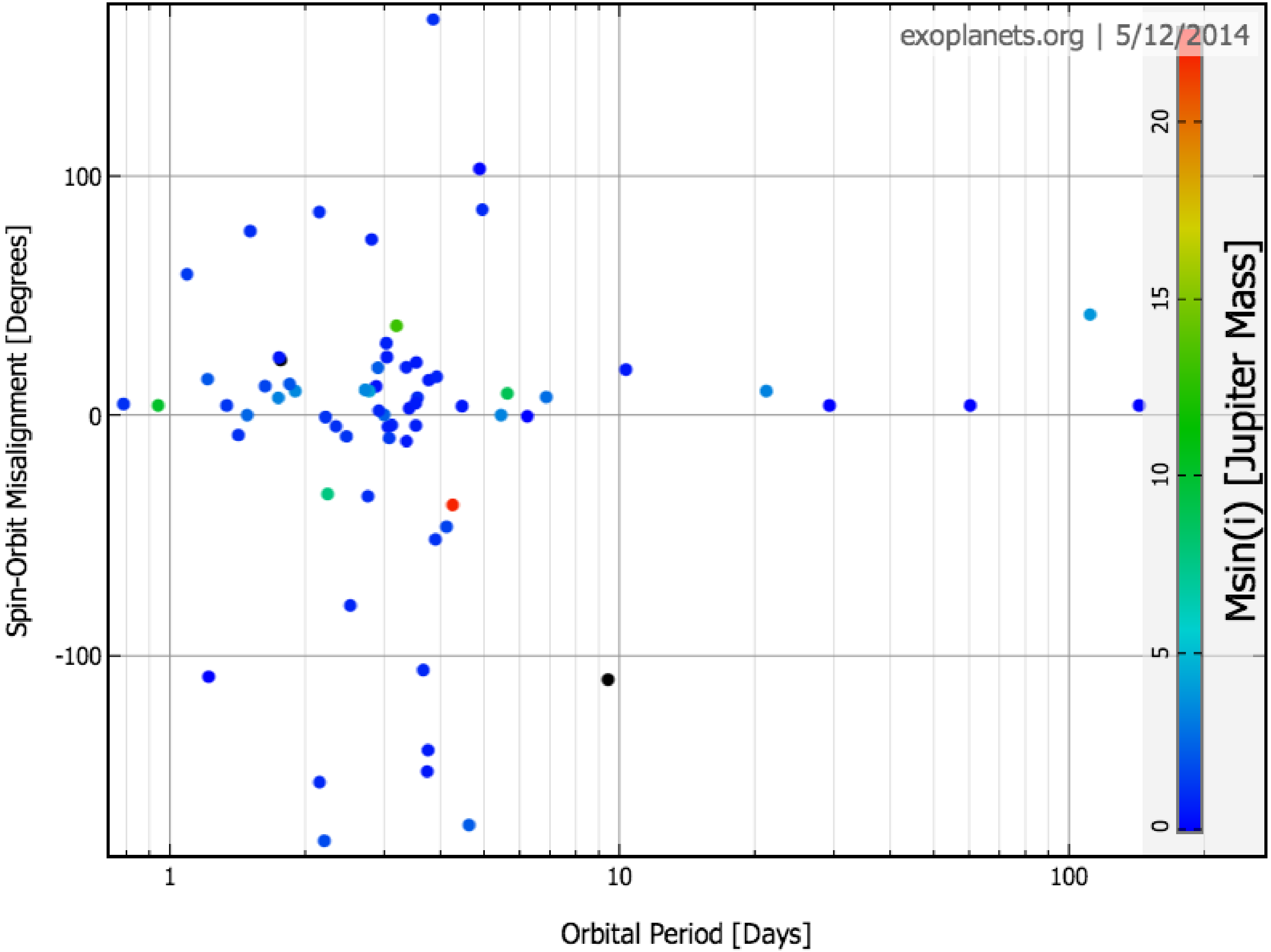


Eccentricity Puzzle

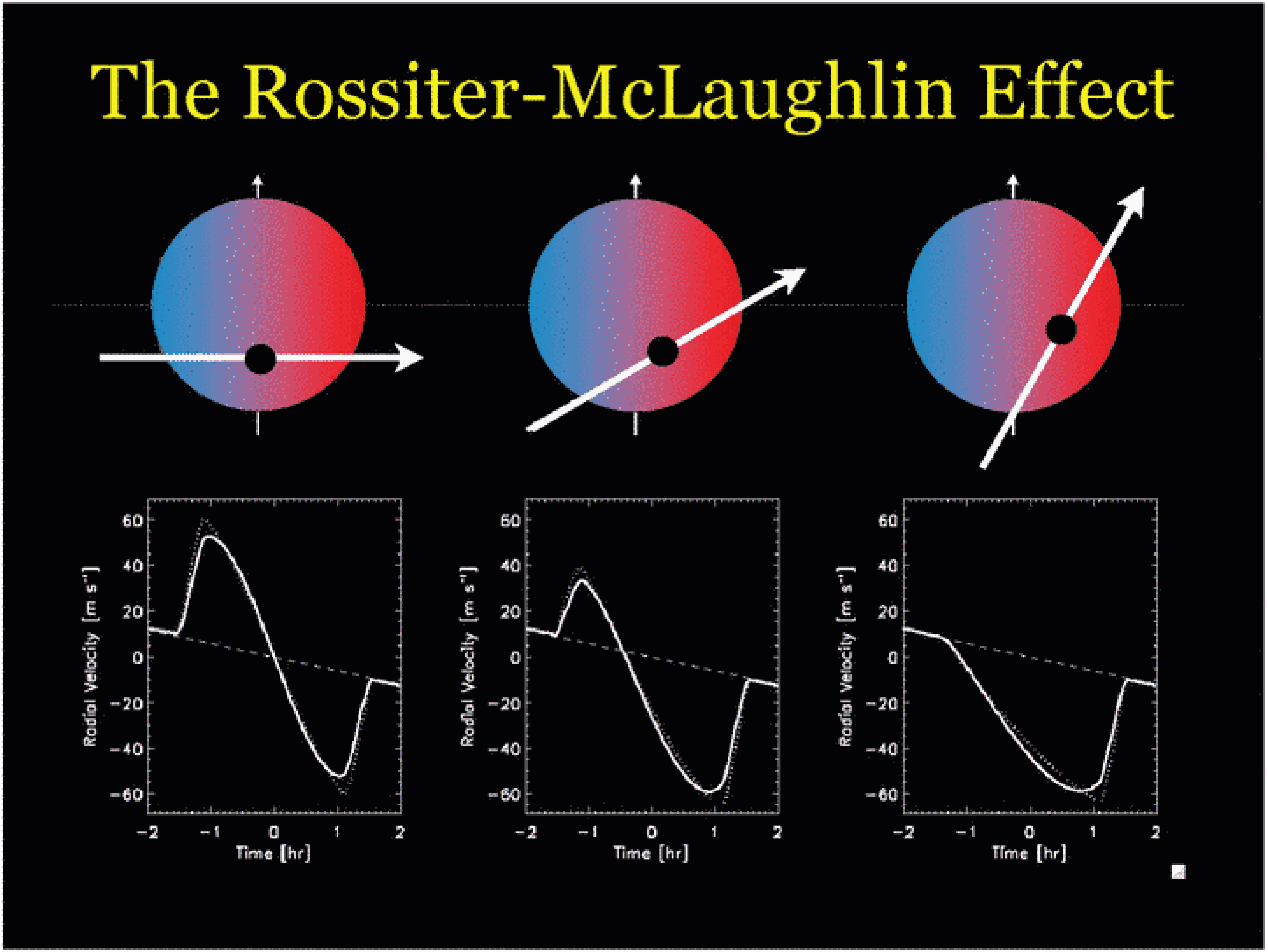


Spin-Orbit Misalignment Puzzle



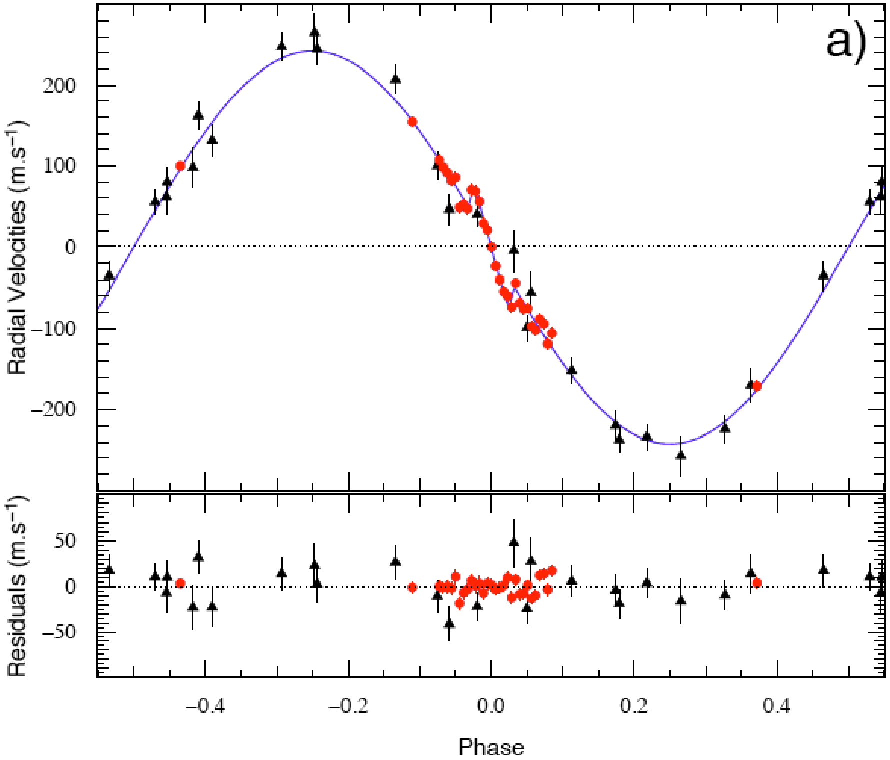


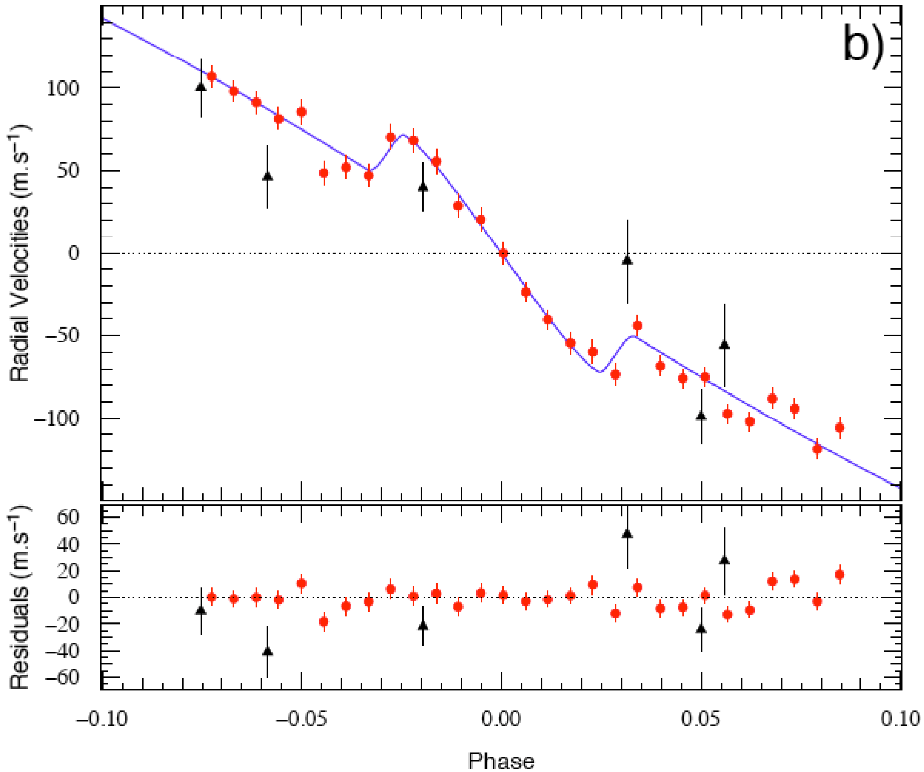
exoplanets.org | 5/12/2014
Spin-Orbit Misalignment [Degrees]
100
0
-100
1
10
100
Orbital Period [Days]
Msin(i) [Jupiter Mass]
0
5
10
15
20



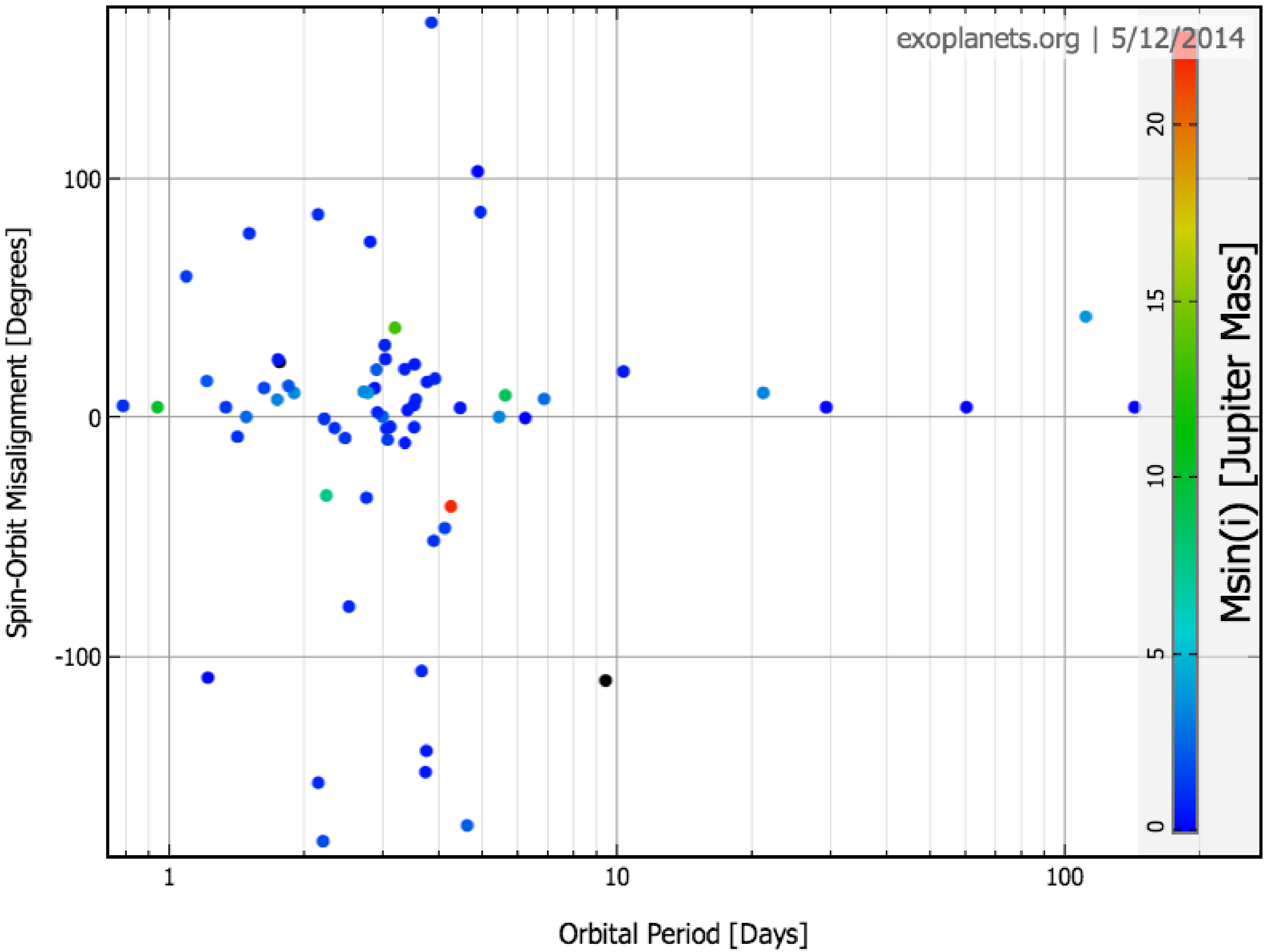
Slide from Josh Winn

WASP-4b





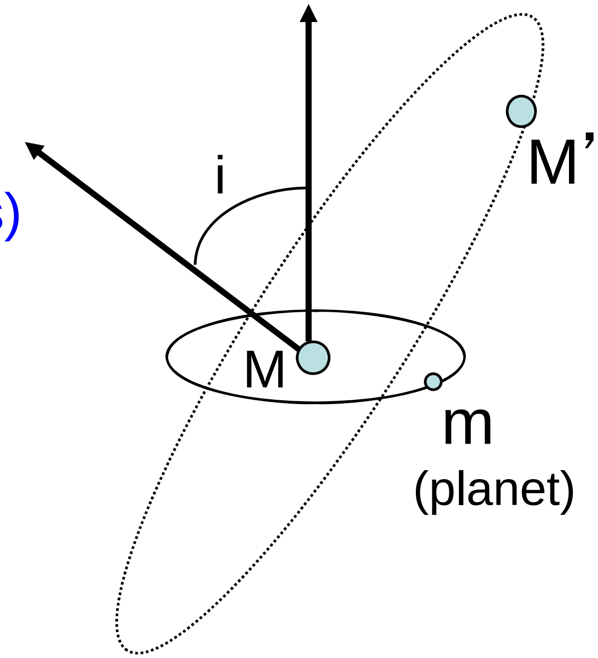
Triaud et al. 2010


exoplanets.org | 5/12/2014
Spin-Orbit Misalignment [Degrees]
Orbital Period [Days]
Msin(i) [Jupiter Mass]
100
0
-100
1
10
100
0
5
10
15
20

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)

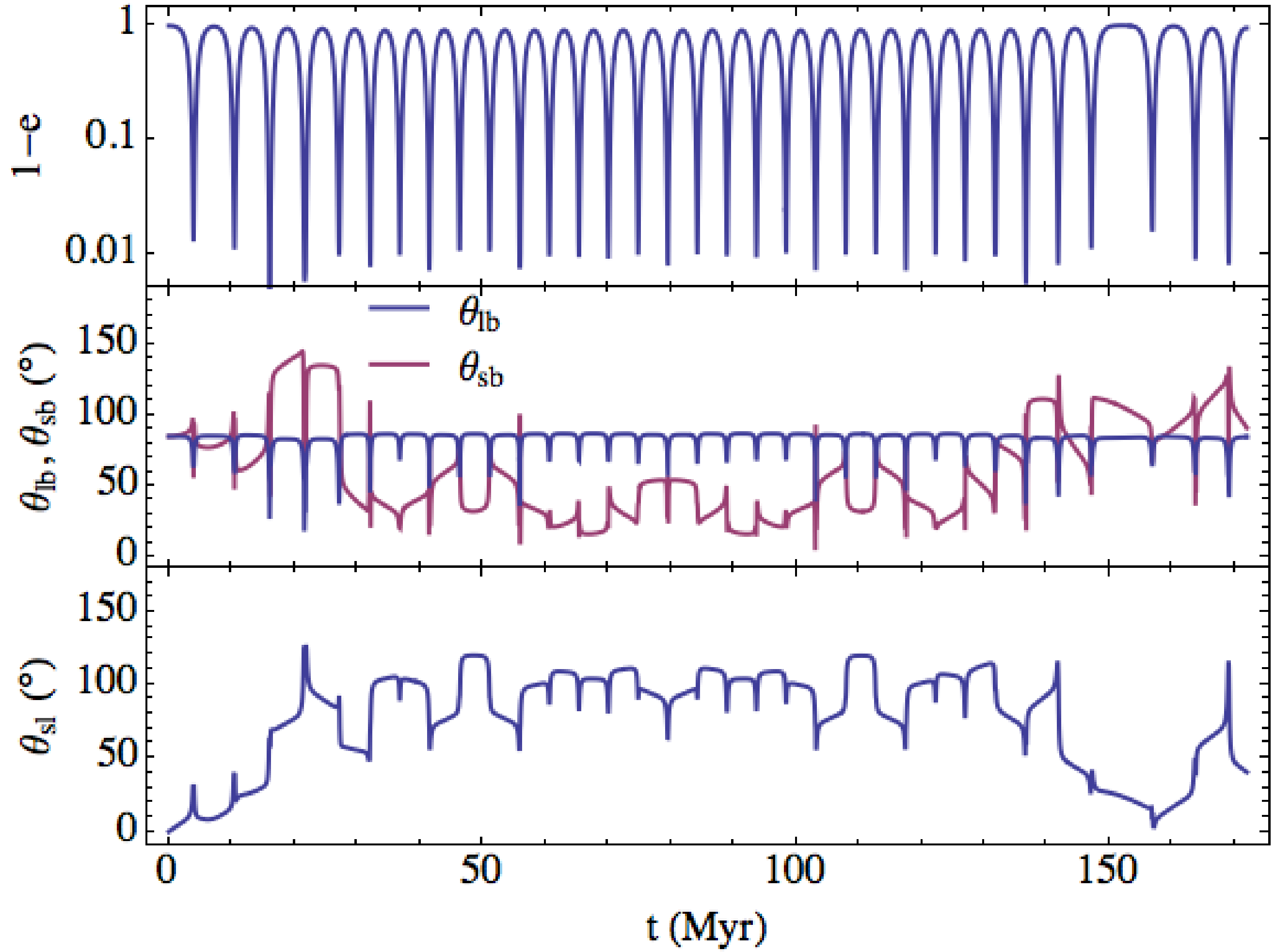
2. Planet-planet Interactions
   -- Strong scatterings
   (e.g., Rasio & Ford 96; Chatterjee et al. 08; Juric & Tremaine 08)
   -- Secular interactions ("Internal Kozai", chaos)
   (e.g Nagasawa et al. 08; Wu & Lithwick 11)



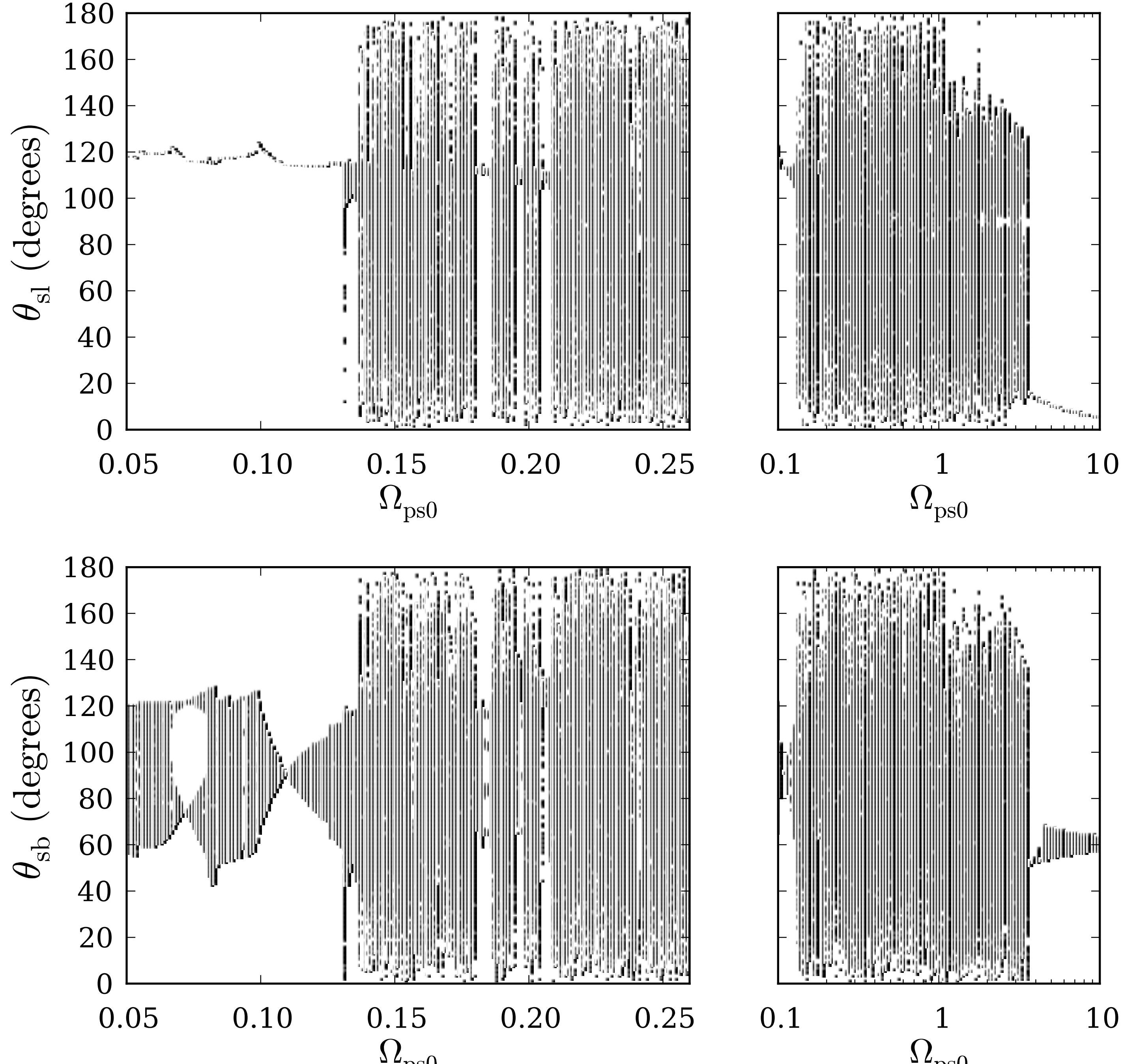
-- Chaotic stellar spin evolution during Kozai

(Storch, Anderson & DL 2014)

Chaotic Dynamics of Stellar Spin during Kozai cycle



Storch, Anderson & DL 2014



θ_{sl} (degrees)
θ_{sb} (degrees)
Ω_{ps0}
0
20
40
60
80
100
120
140
160
180
0.05
0.10
0.15
0.20
0.25
0.1
1
10

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

"High-Eccentricty 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.

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

Likely NO.

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

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

Likely NO.

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

-- Can produce distribution of period, ecc, misalignment? (Naoz+12,Petrovich+14)

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

Likely NO.

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

-- Can produce distribution of period, ecc, misalignment? (Naoz+12,Petrovich+14)

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

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

Likely NO.

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

-- Can produce distribution of period, ecc, misalignment? (Naoz+12,Petrovich+14)

-- 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)

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

Likely NO.

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

-- Can produce distribution of period, ecc, misalignment? (Naoz+12,Petrovich+14)

-- 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-55 (2 planets 10.5 & 21 days ➔40-55 deg from seismology; Huber et al 2013)

Kepler-9 (3-planets; Walkowicz & Basri 2013) ?

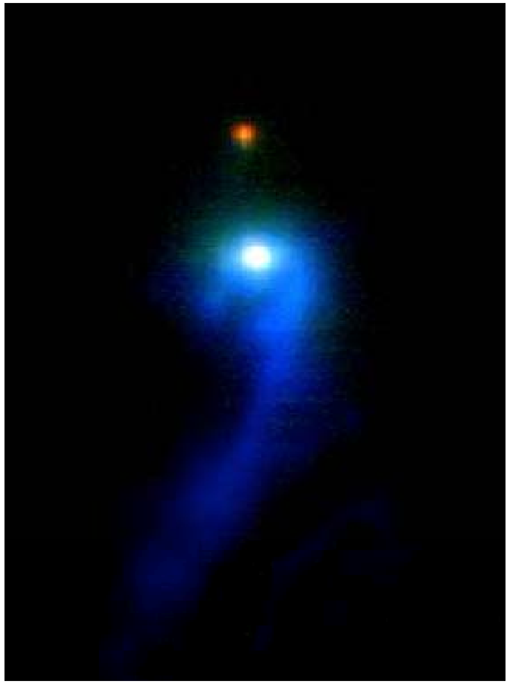
Other Candidates: Hirano et al. 2014

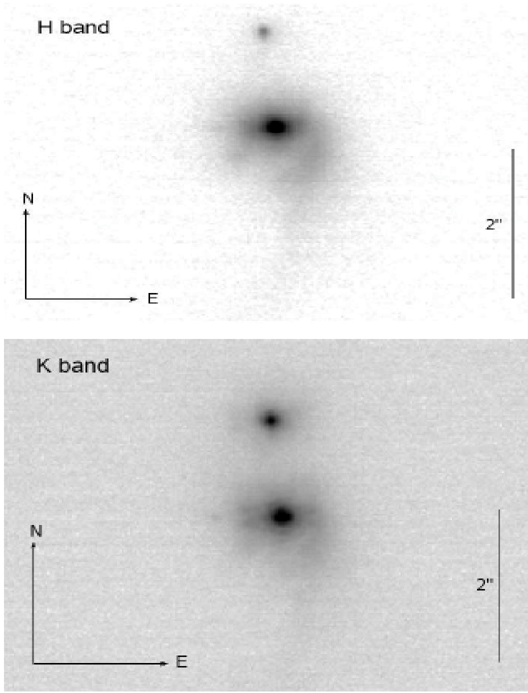
Hints of “Primordial” Misalignments

(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)

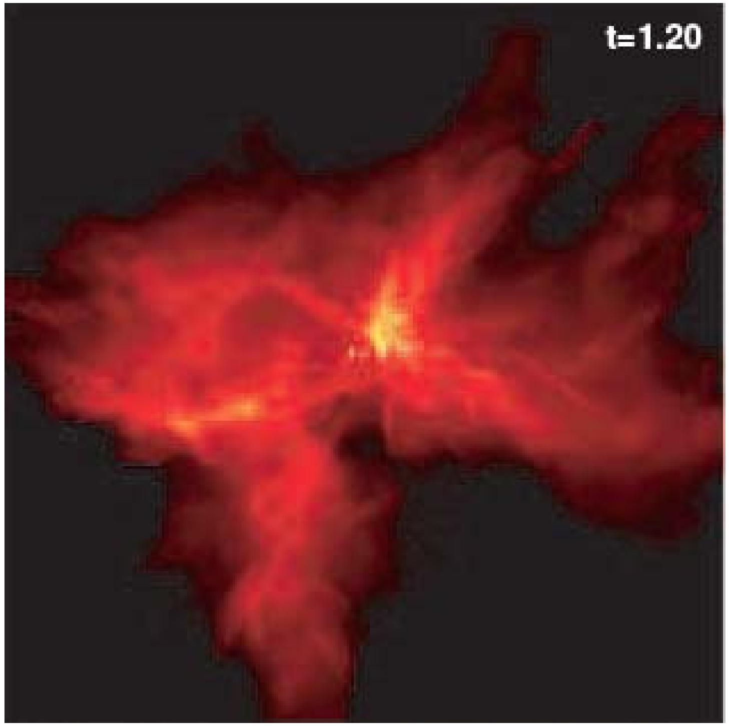
Ideas for Producing Primordial Misalignments

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)

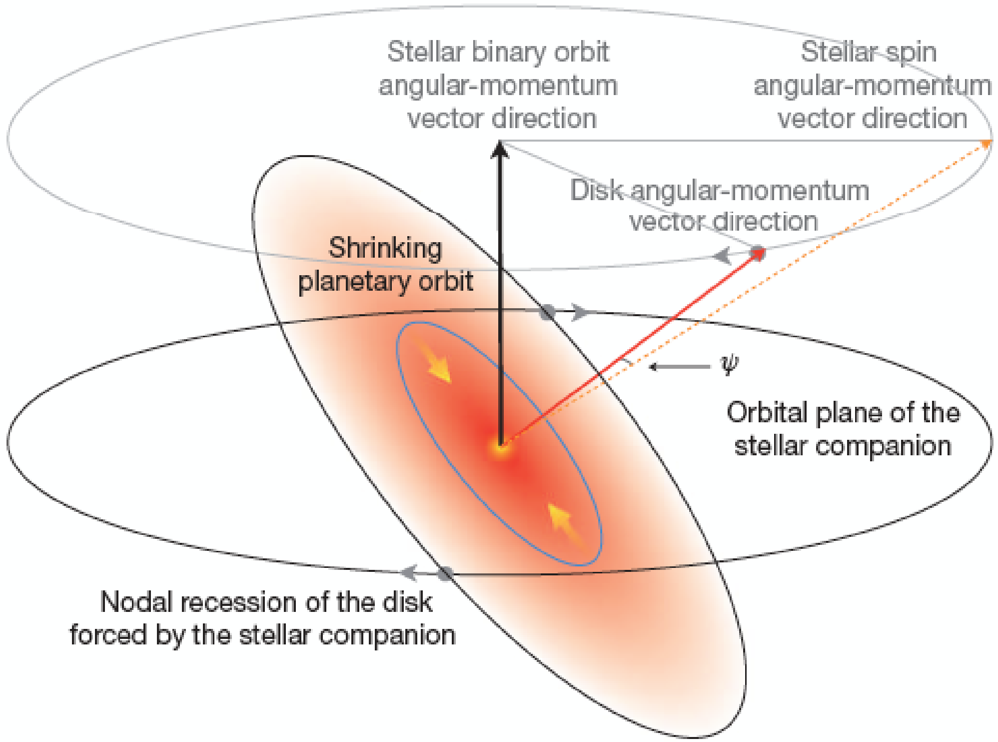
Ideas for Producing Primordial Misalignments

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**)

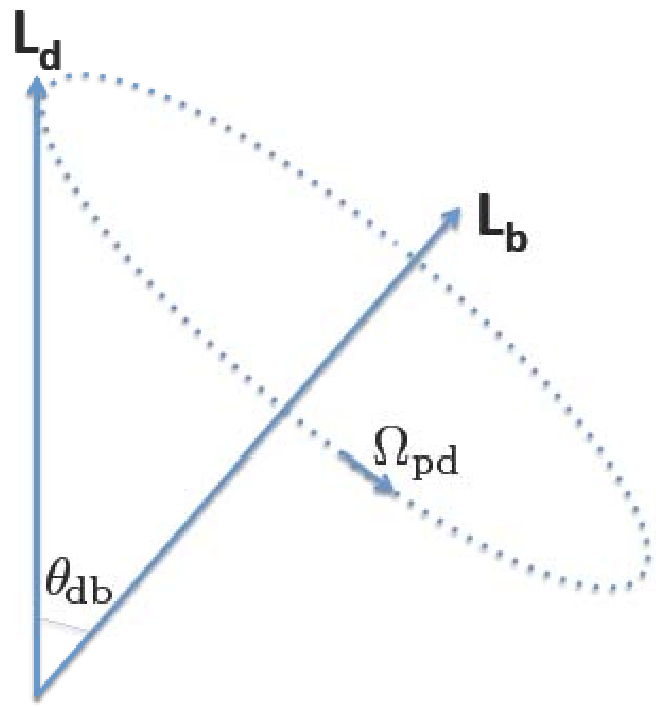


Star-Disk-Binary Interactions

Star-Disk-Binary Interactions

First no accretion, just gravitational interactions…

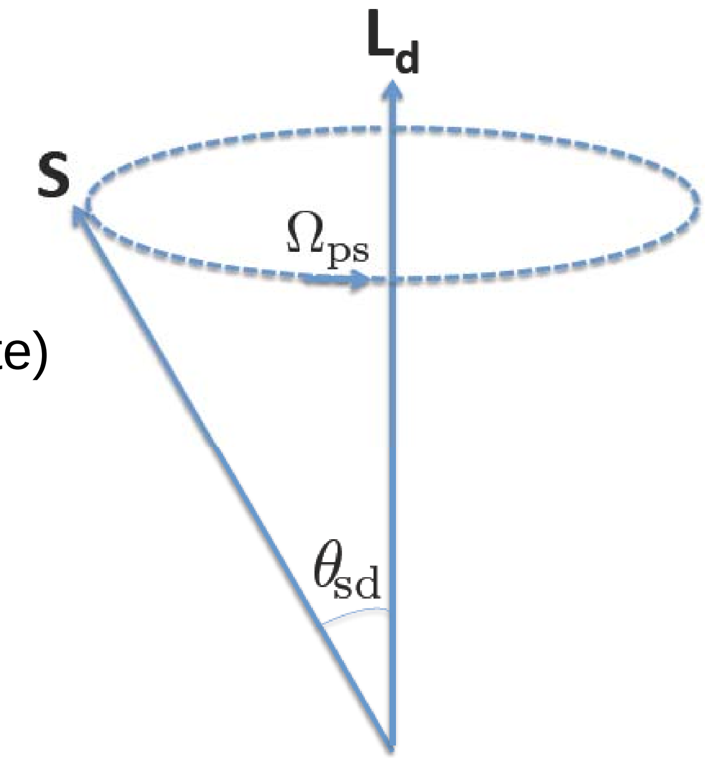
Companion makes disk precess



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

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

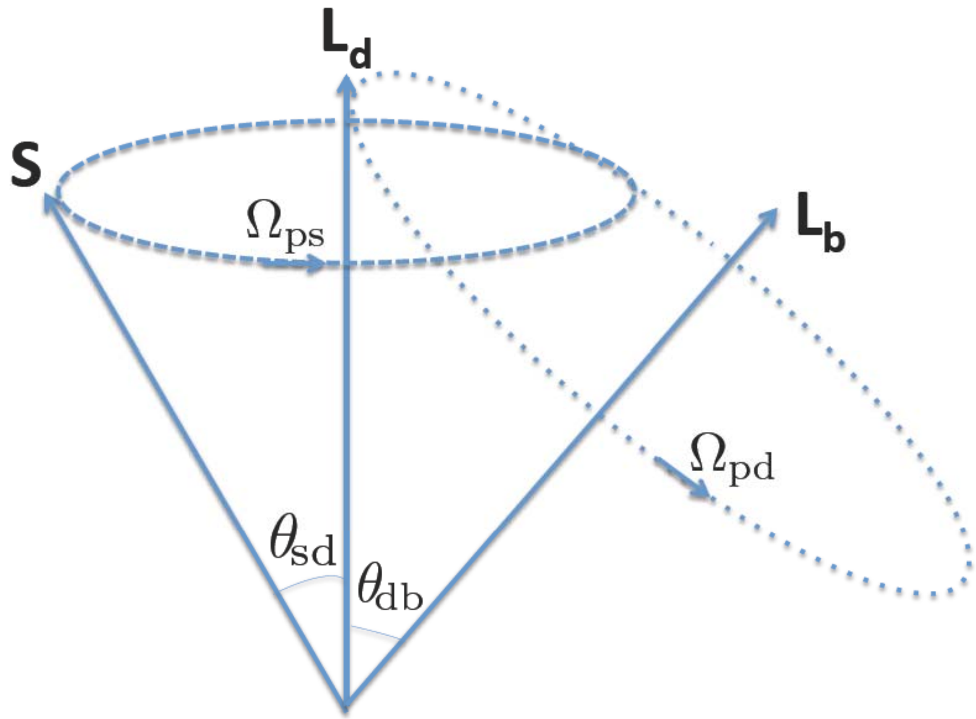
Disk makes the star precess



Gravitational torque on rotating star (oblate)
Mutual precession, but L_d>>S

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

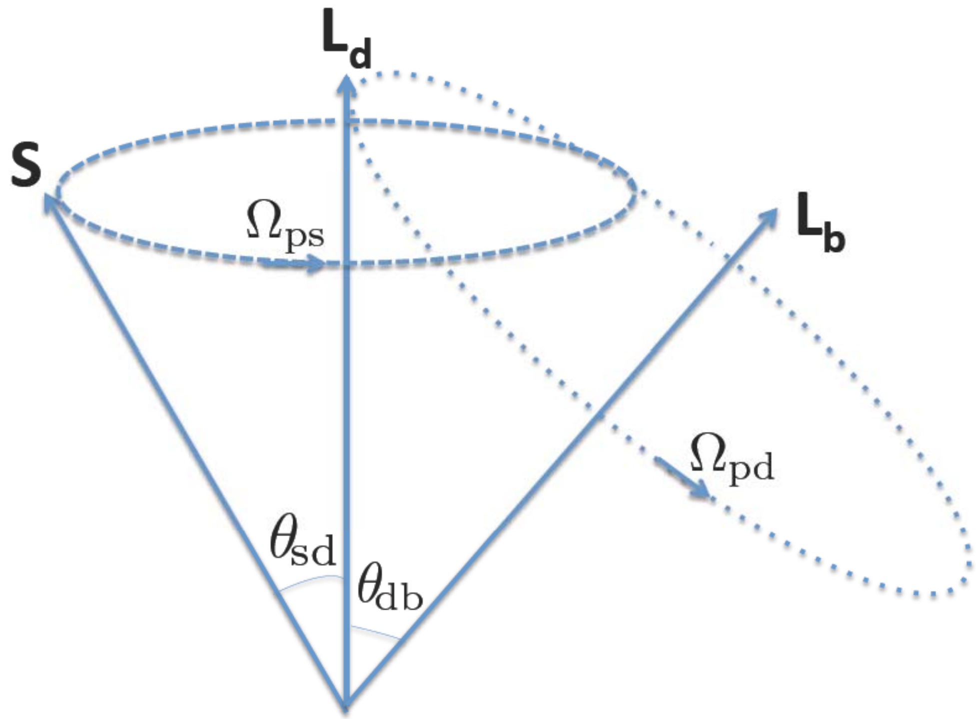
where $\Omega_\star = \left(\frac{2\pi}{3.3\ \mathrm{days}}\right)\left(\frac{\bar{\Omega}_\star}{0.1}\right)$



Two limiting cases:

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

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



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

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

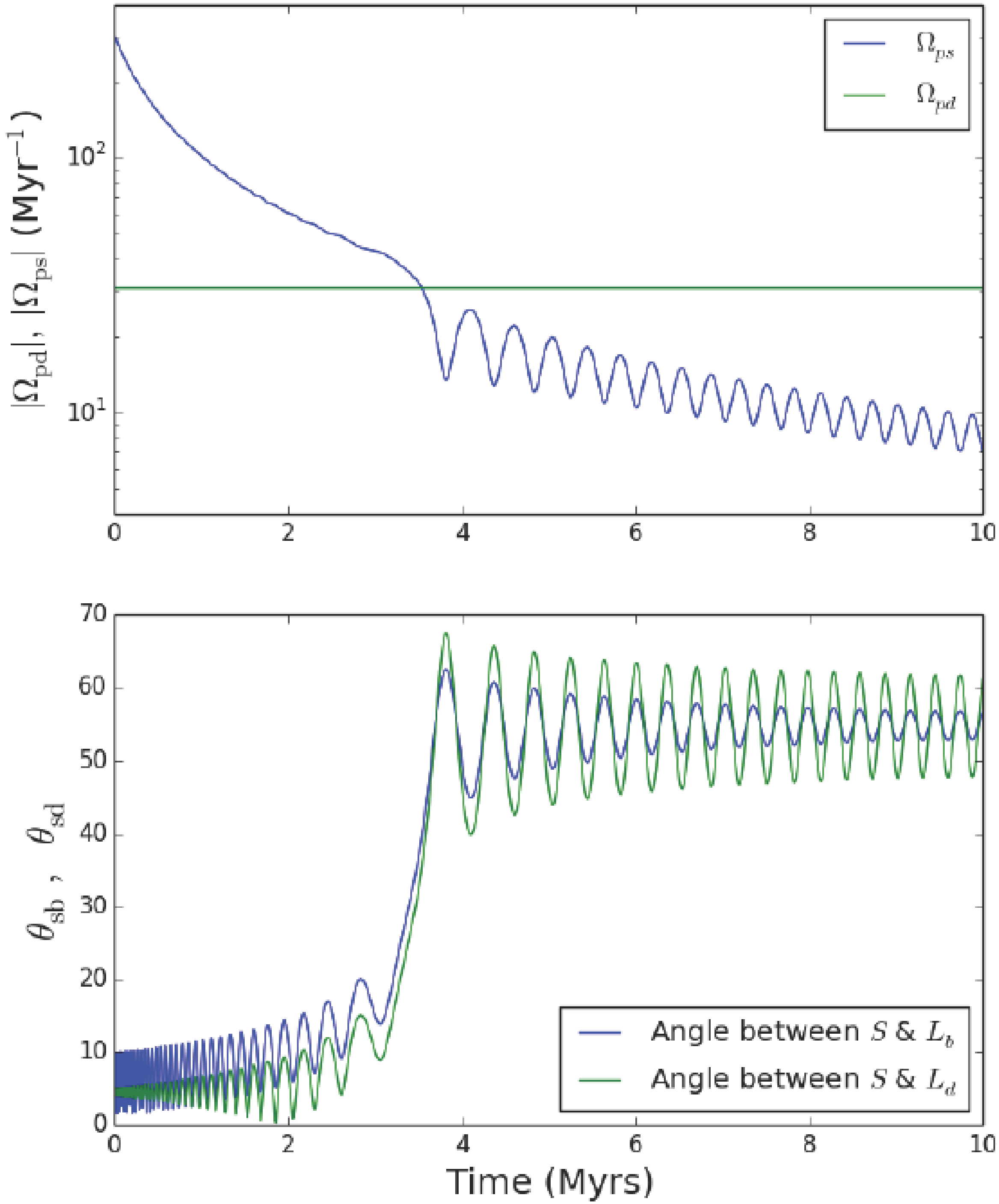
Simple model:

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

Initial:

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

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

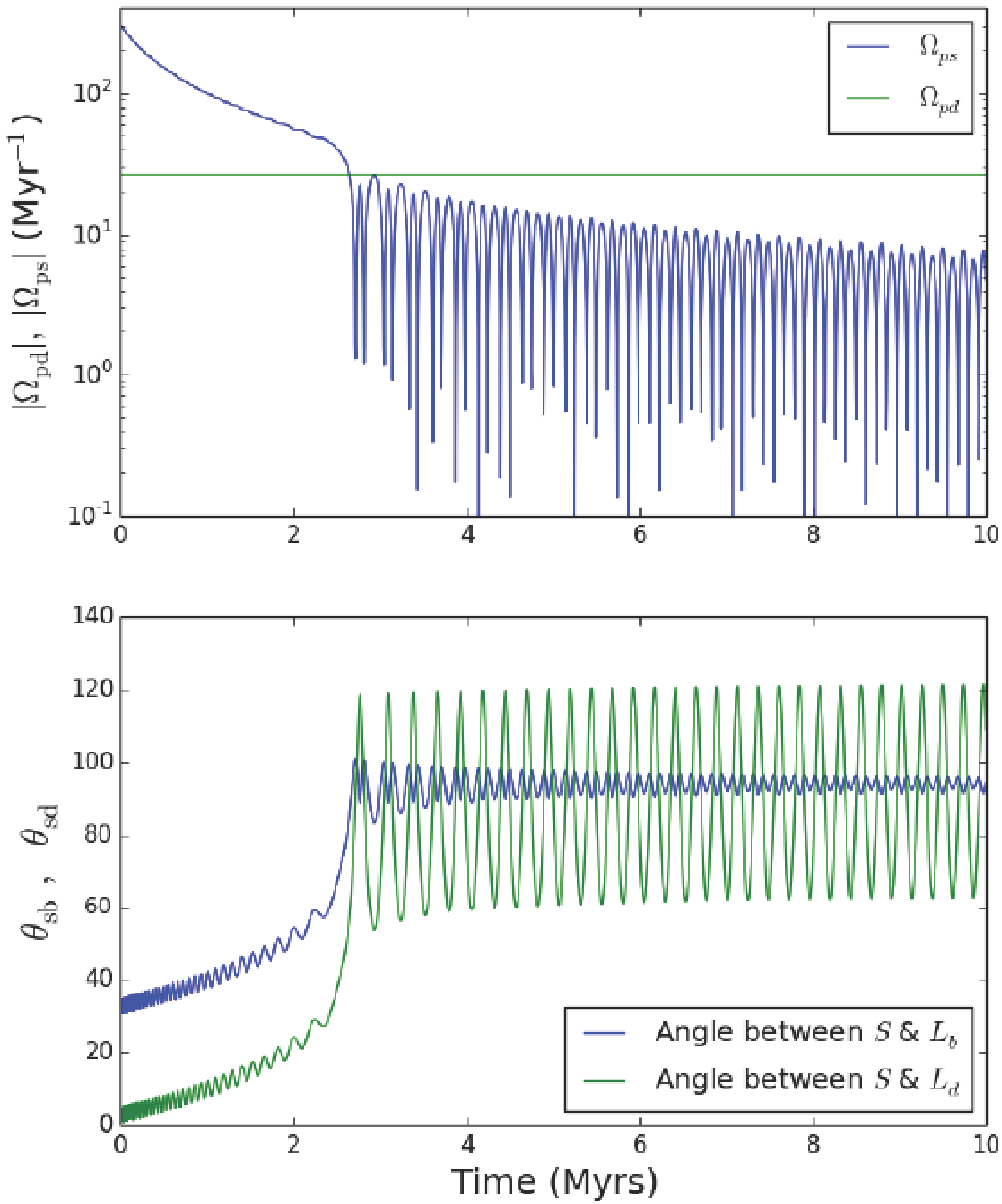


DL2014

Initial:

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

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



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

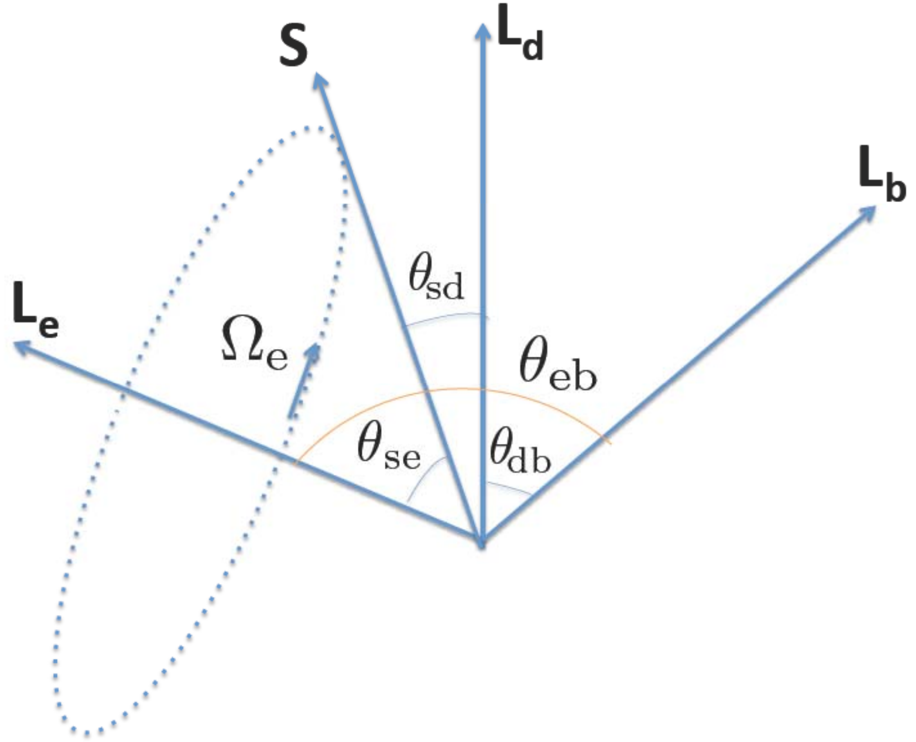
$$\frac{d\hat{\boldsymbol{S}}}{dt} \simeq \Omega_{\rm ps}\, \hat{\boldsymbol{L}}_{\rm d} \times \hat{\boldsymbol{S}}$$

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

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

$\uparrow$

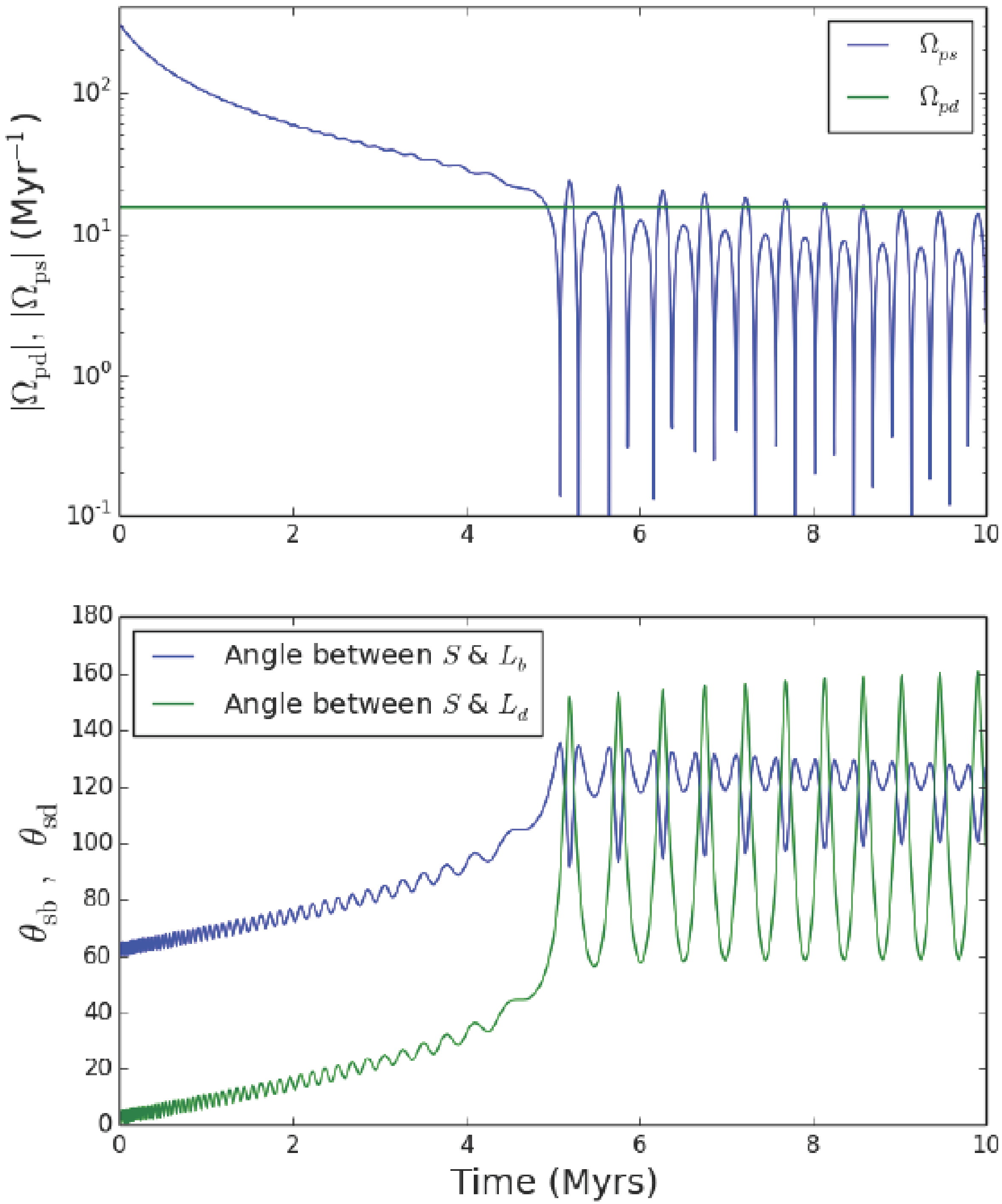
$\Omega_e \hat{\mathbf{L}}_e$



Initial:

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

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



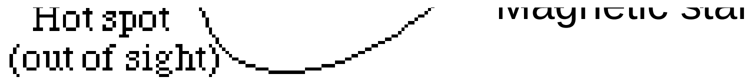
Now consider

Isolated Star-Disk Systems:
Accretion and Magnetic Interaction

Magnetic Star - Disk Interaction: Basic Picture

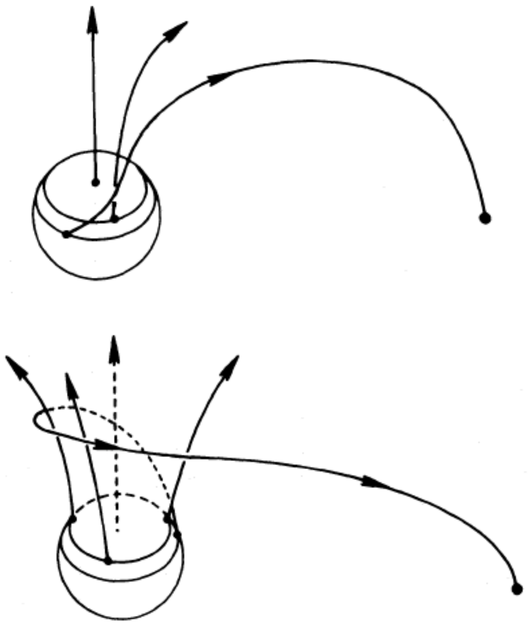
$)^{1/7}$

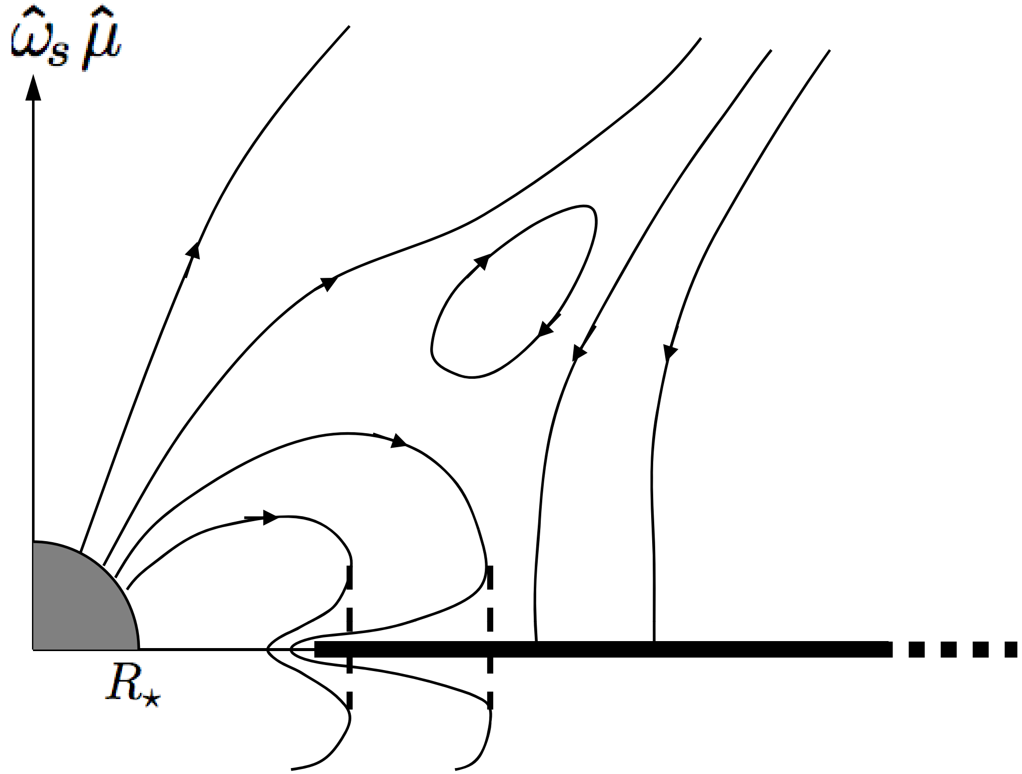
$.5 - 1$

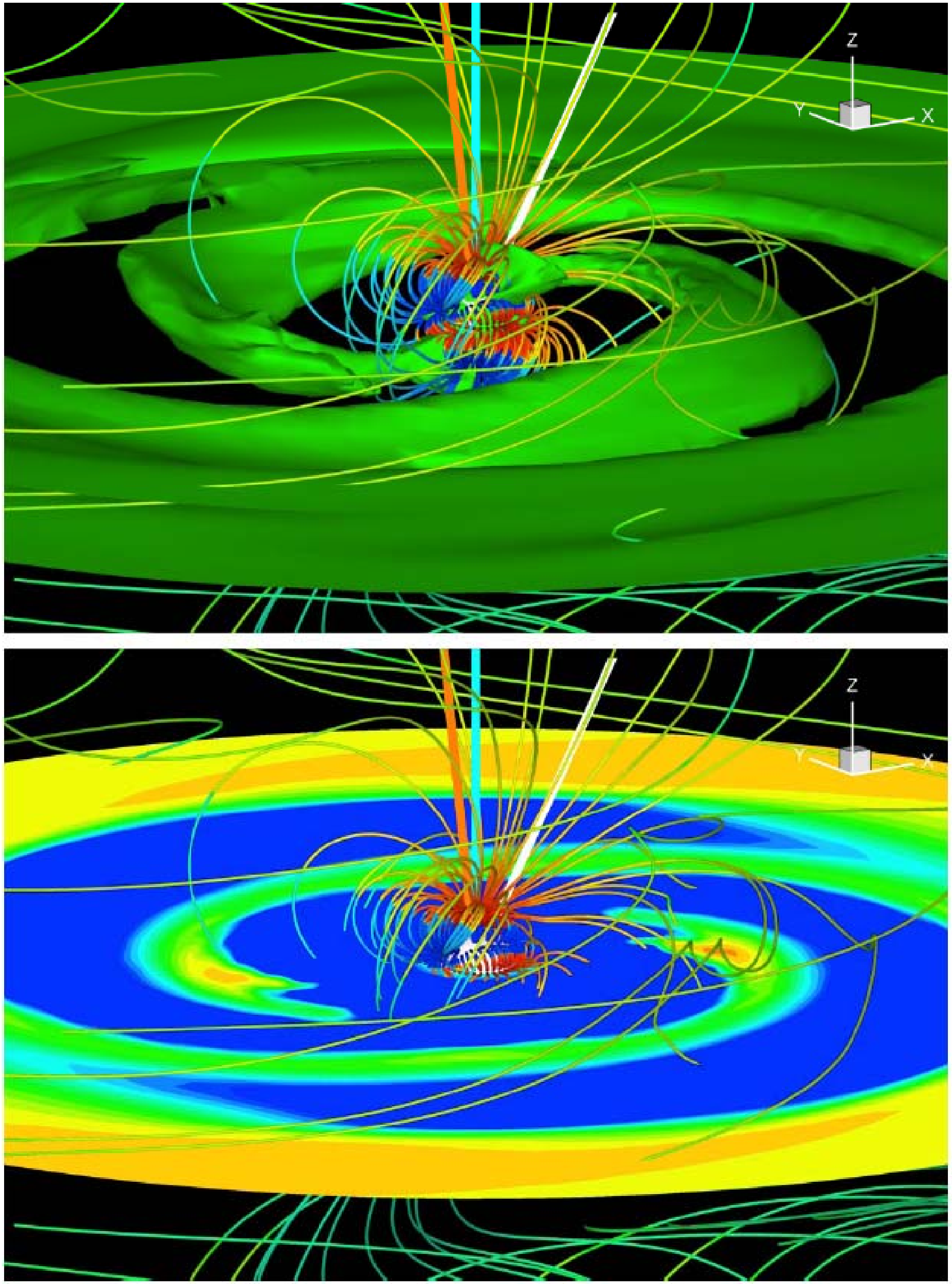


Magnetic Star - Disk Interaction: Physical Processes

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 >> dynamical time (rotation/orbital period)

Key Results:

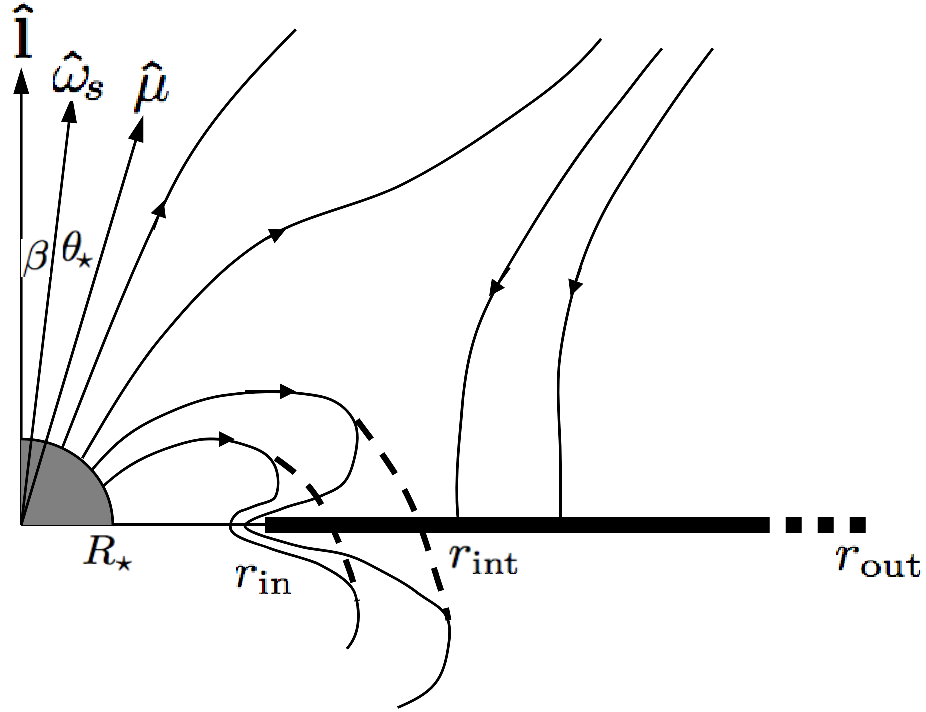
In general, there are magnetic torques which tend to make the inner disk (before disruption)

-- warp

-- precess

on timescale >> dynamical time (rotation/orbital period)

Consider two limiting cases
in general geometry…

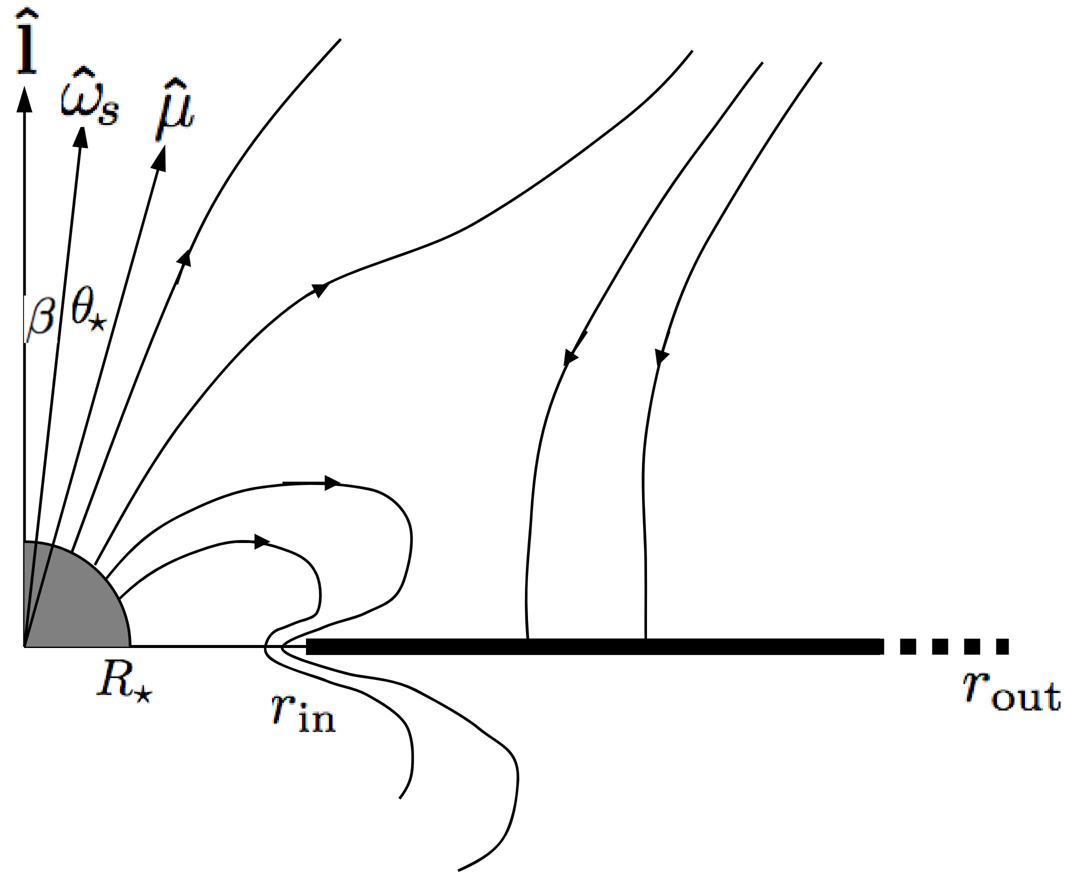


Perfect conducting disk:

Torque on disk (per unit area): $\mathbf{N} \propto \hat{\mu} \times \hat{\mathbf{l}}$

Averaging over stellar rotation: $\mathbf{N} \propto \hat{\omega}_s \times \hat{\mathbf{l}}$

Precessional Torque

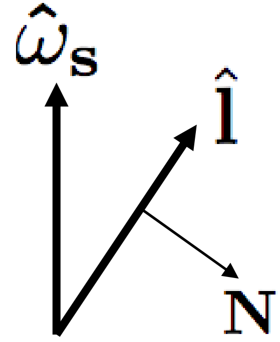


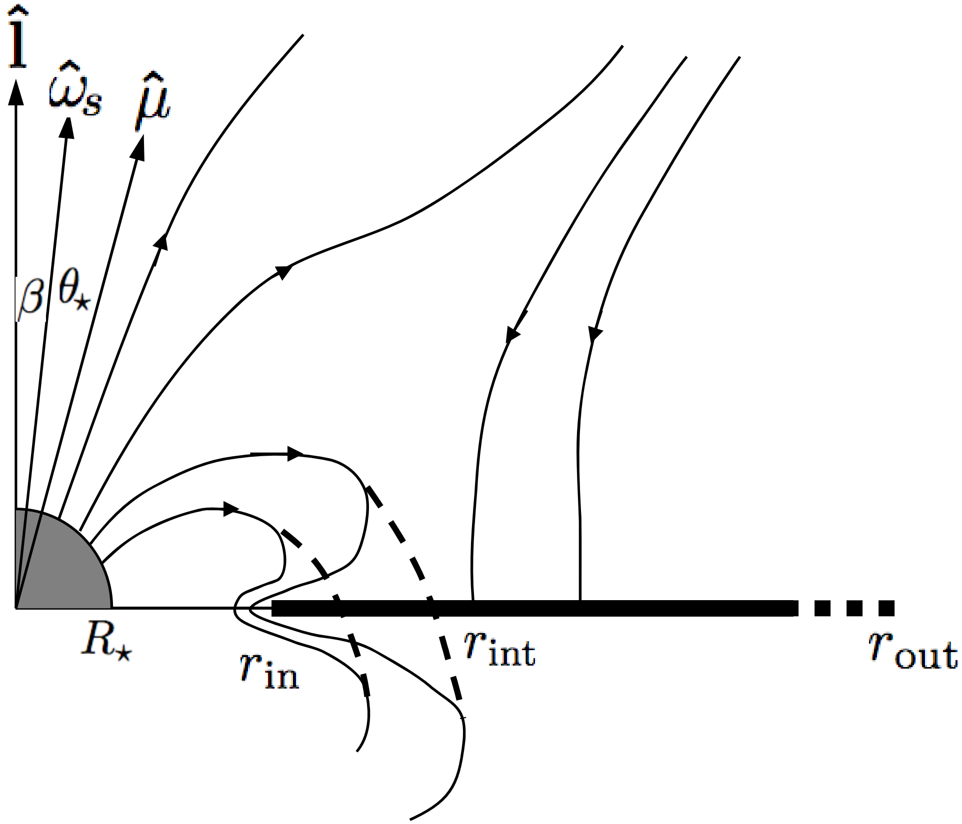
Poorly-conducting disk:

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

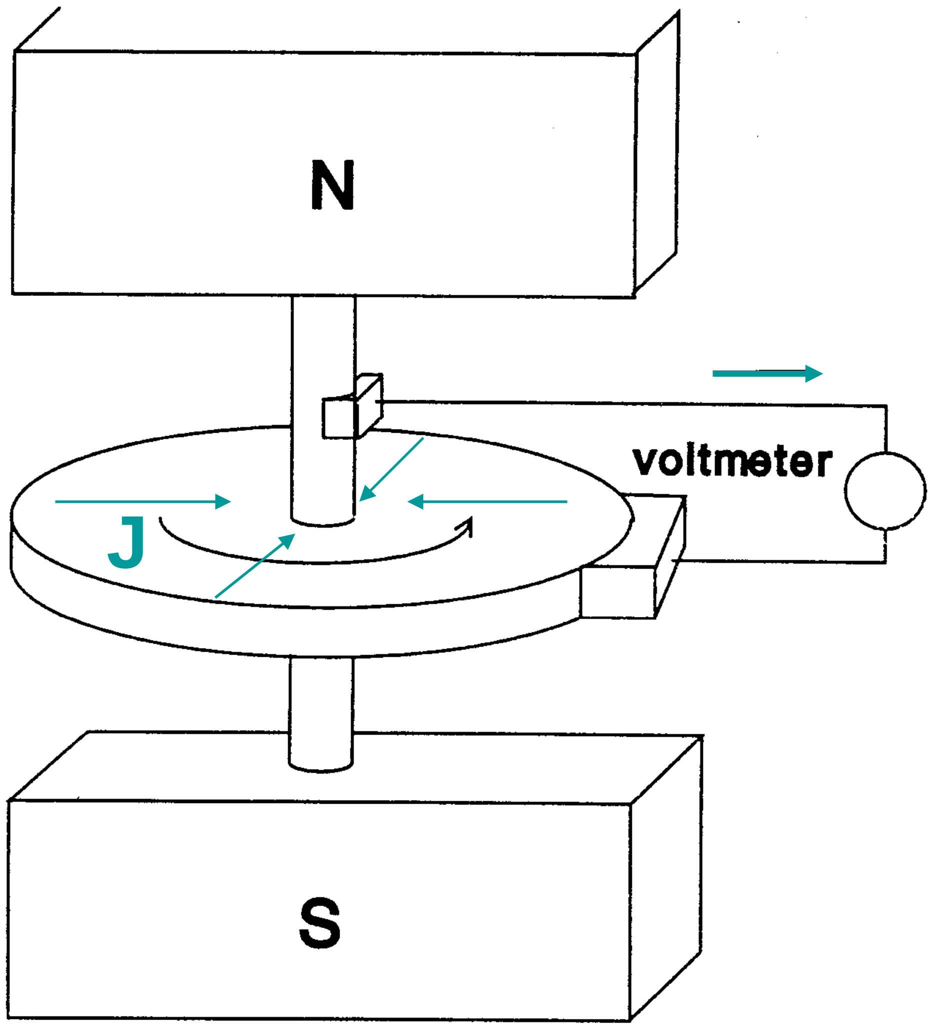
$$\Longrightarrow \quad \Delta B_\phi = \mp \zeta B_z$$

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

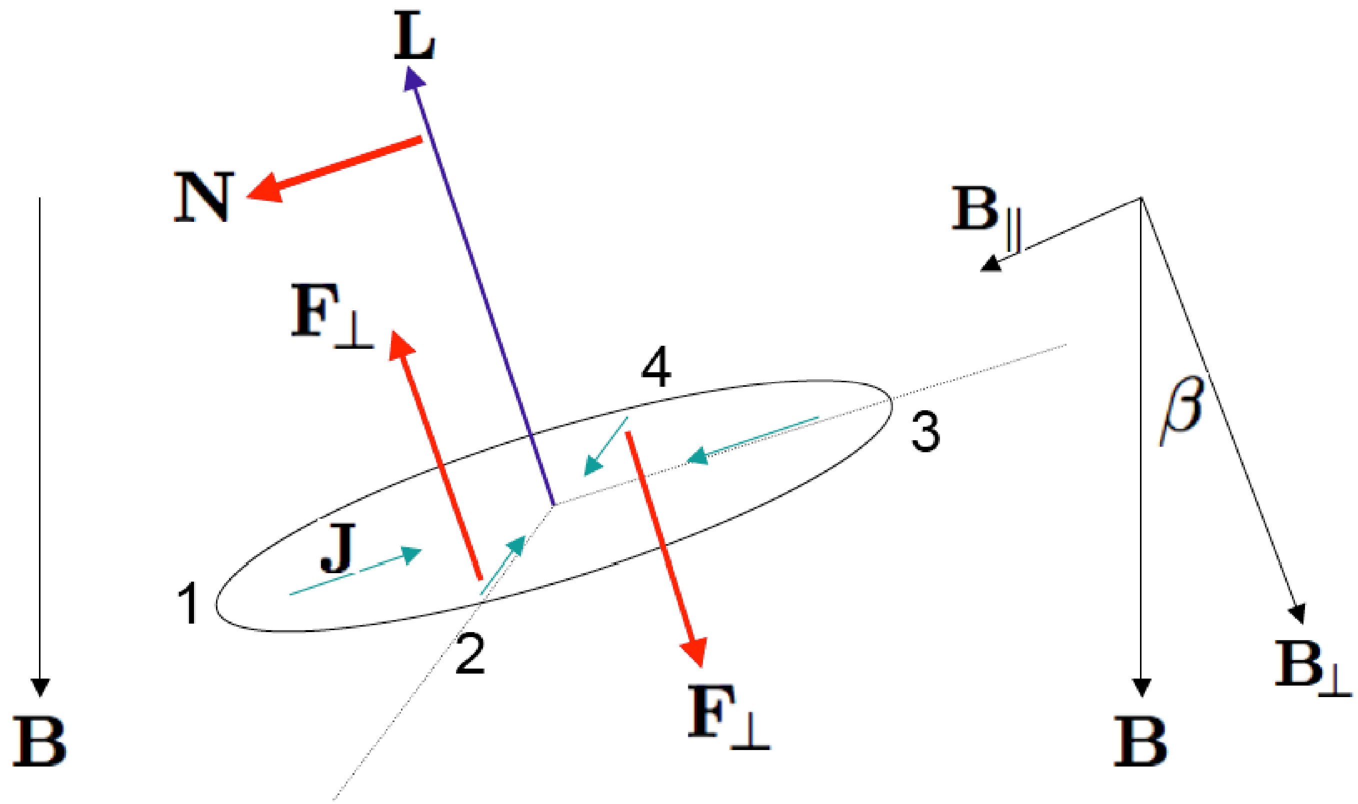
$$B_\phi^- = B_\phi^{(s)} + \zeta B_z$$

$$\Longrightarrow \quad F_z(\phi)$$

A Laboratory Experiment



A Laboratory Experiment



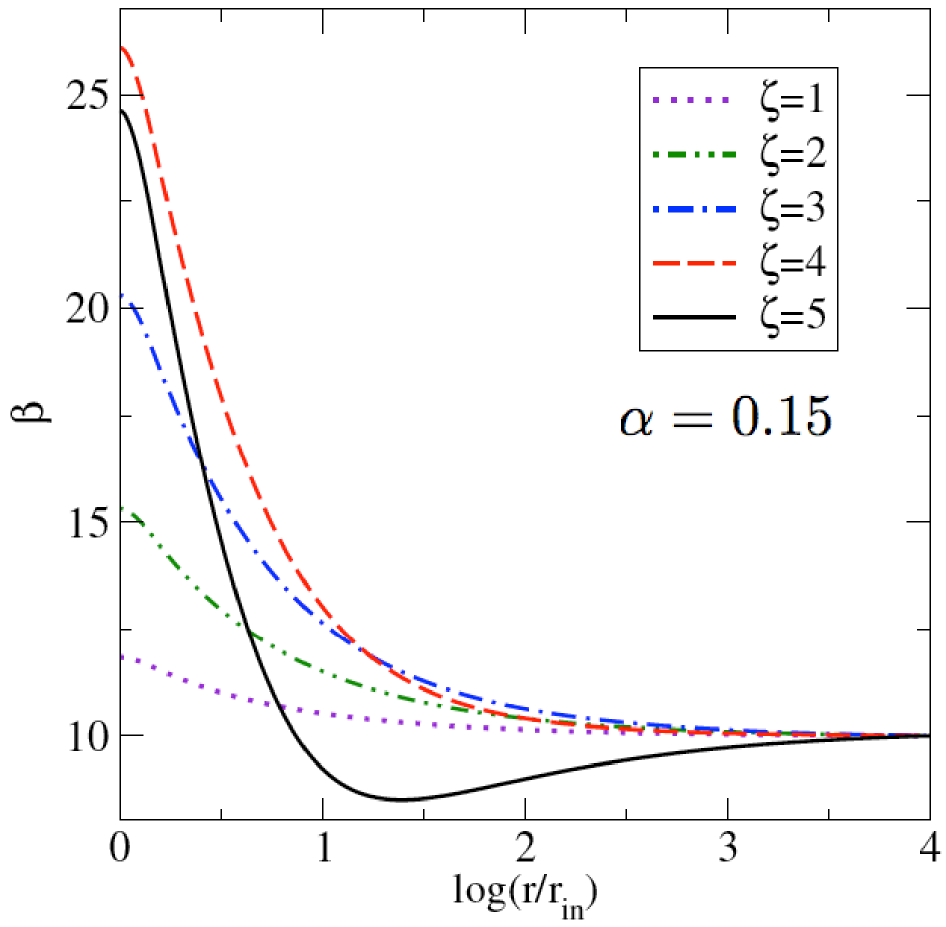
Recap:

Magnetic toques 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

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

Steady-state Disk Warp:



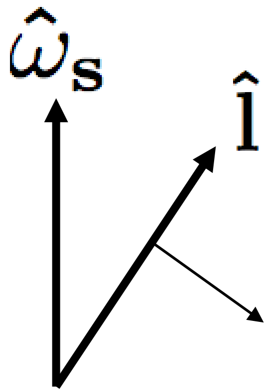
Foucart & DL 2011

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

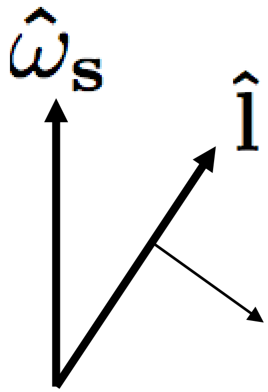
What is happening to the stellar spin direction?
(Is there secular change to the spin direction?)

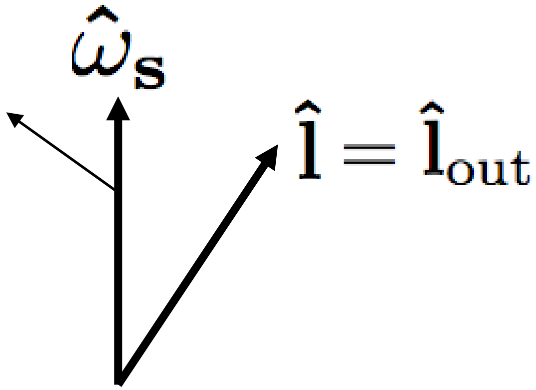
Need to consider:
Back-reaction torque on the stellar spin…
(for small warps --> flat disk)

What does magnetic warping torque do?



What does magnetic warping torque do?





Accretion tends to align S & L:

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

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

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

➔ $\mathcal{N}_{\rm acc} \sim \mathcal{N}_{\rm mag}$

Evolution of the stellar spin

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

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

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

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

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

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

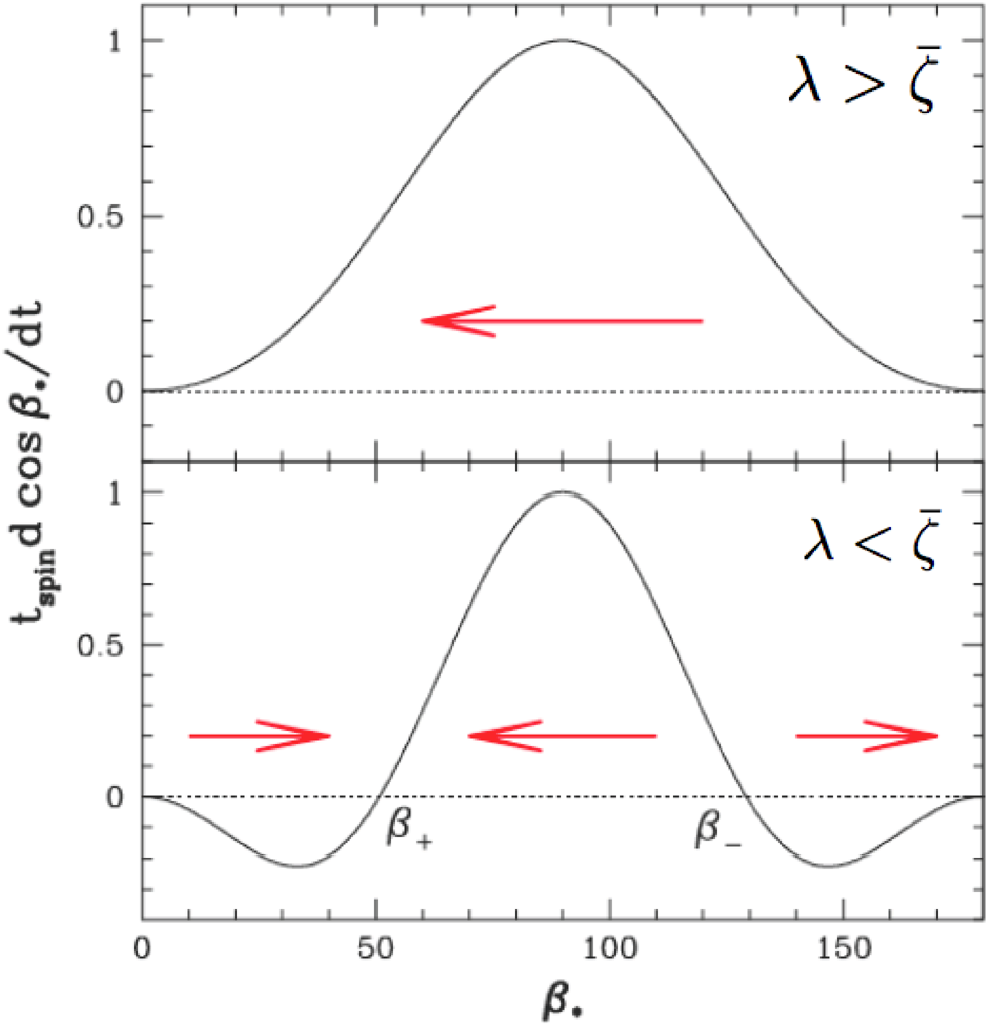
$$\bar{\zeta} = \frac{\zeta\cos^2\theta_\star}{6\eta^{7/2}} \quad (\sim 1)$$

Spin evolution timescale:

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

Evolution of the stellar spin

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



“weak” warping torque

“strong” warping torque

Summary:

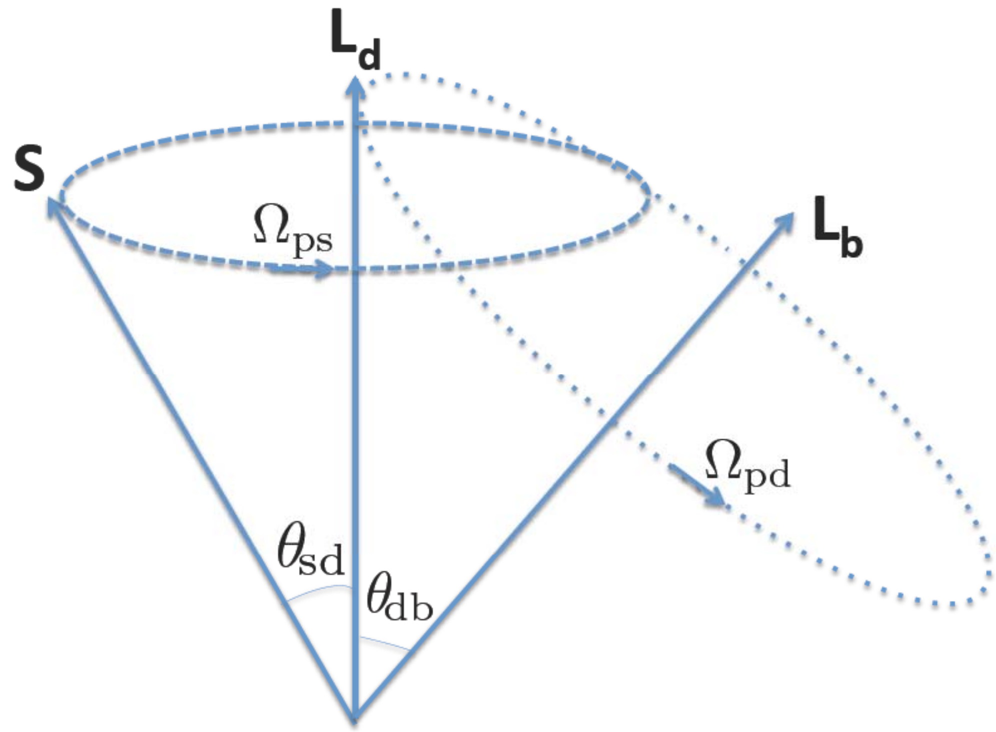
For Isolated star-disk systems:

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

$$\frac{d\boldsymbol{S}}{dt} = \lambda \mathcal{N}_0 \, \hat{\boldsymbol{L}}_{\rm d} - \mathcal{N}_{\rm s} \hat{\boldsymbol{S}} + \mathcal{N}_0 \, \bar{n}_w \cos\theta_{\rm sd} \, \hat{\boldsymbol{L}}_{\rm d} \times (\hat{\boldsymbol{S}} \times \hat{\boldsymbol{L}}_{\rm d})$$

$$+ \mathcal{N}_0 \, \bar{n}_p \cos\theta_{\rm sd} \hat{\boldsymbol{S}} \times \hat{\boldsymbol{L}}_{\rm d} + \Omega_{\rm ps} \hat{\boldsymbol{J}}_{\rm sd} \times \boldsymbol{S}$$

Spin Direction Evolution

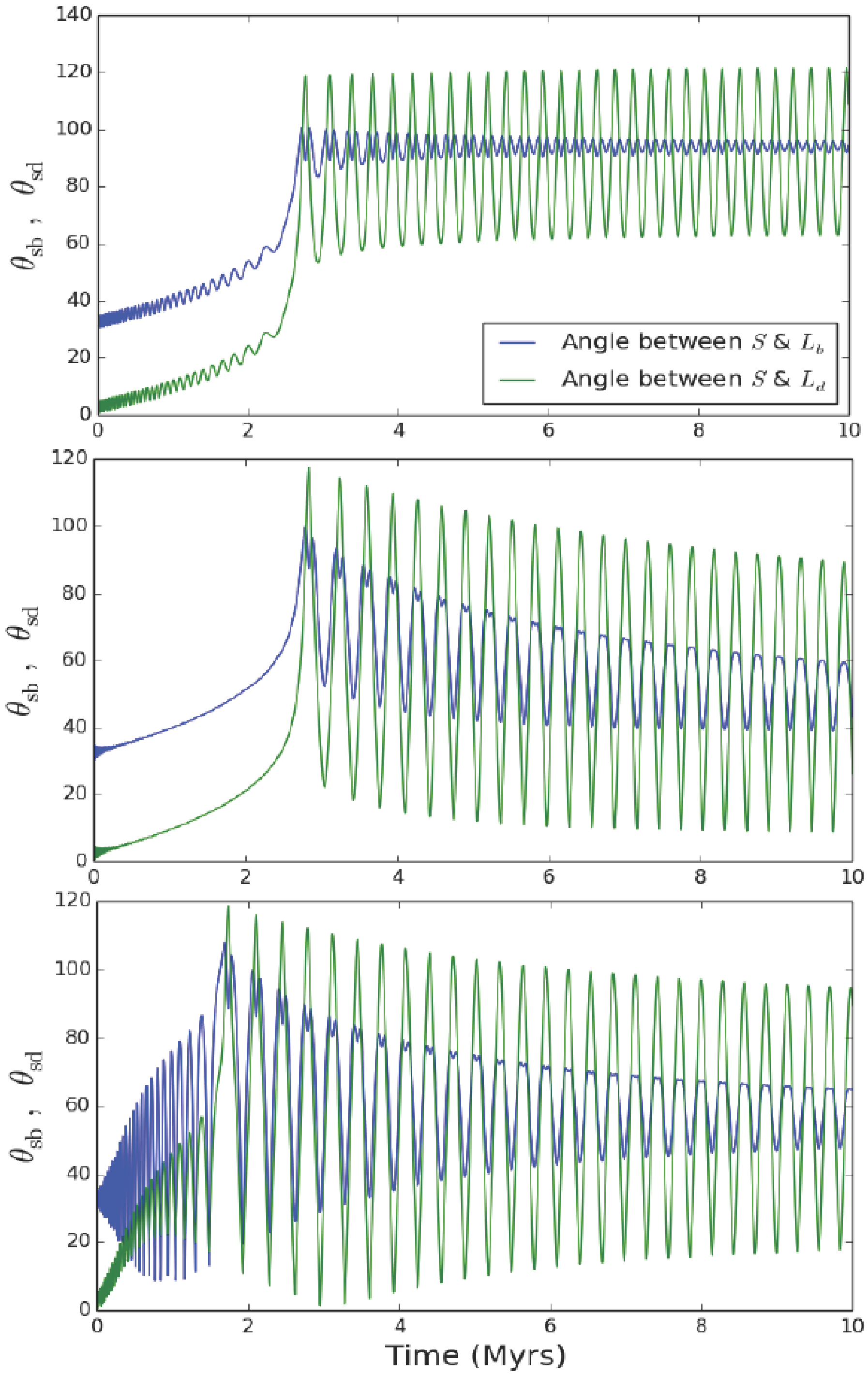
$$\frac{d\hat{\boldsymbol{S}}}{dt} \simeq \omega_0 \left(\lambda - \bar{n}_w \cos^2\theta_{\rm sd}\right) \left(\hat{\boldsymbol{L}}_{\rm d} - \cos\theta_{\rm sd}\hat{\boldsymbol{S}}\right) + \left(\Omega_{\rm ps}^{(m)} + \Omega_{\rm ps}\right) \hat{\boldsymbol{L}}_{\rm d} \times \hat{\boldsymbol{S}},$$

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

No accretion/magnetic

Accretion/magnetic damps SL-angle

Accretion/magnetic increases SL-angle

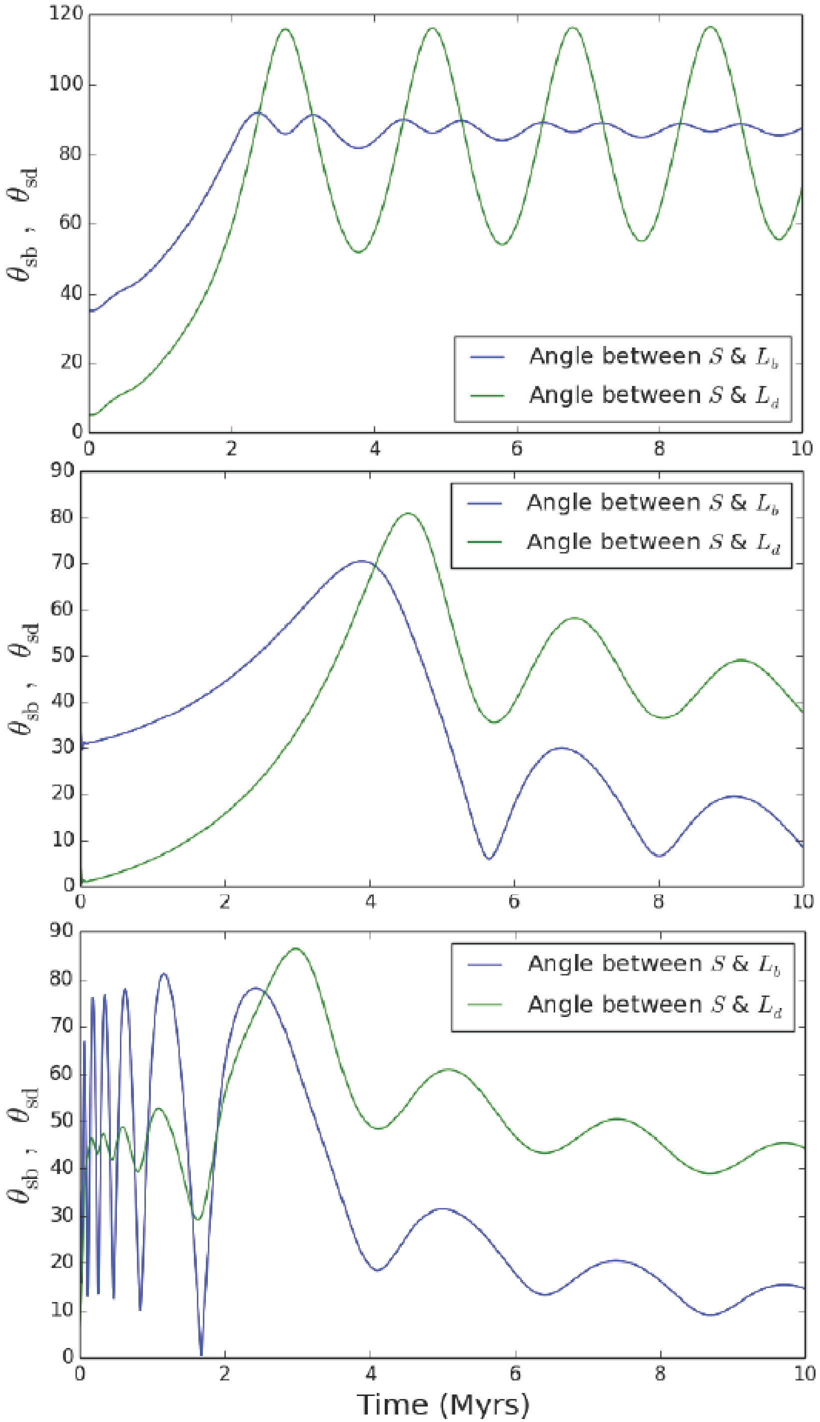


DL2014

No accretion/magnetic

Accretion/magnetic damps SL-angle

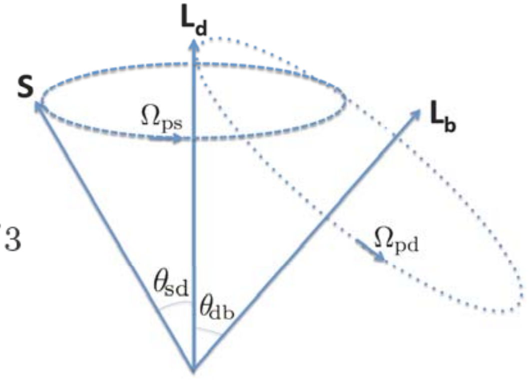
Accretion/magnetic increases SL-angle



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”



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

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

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

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

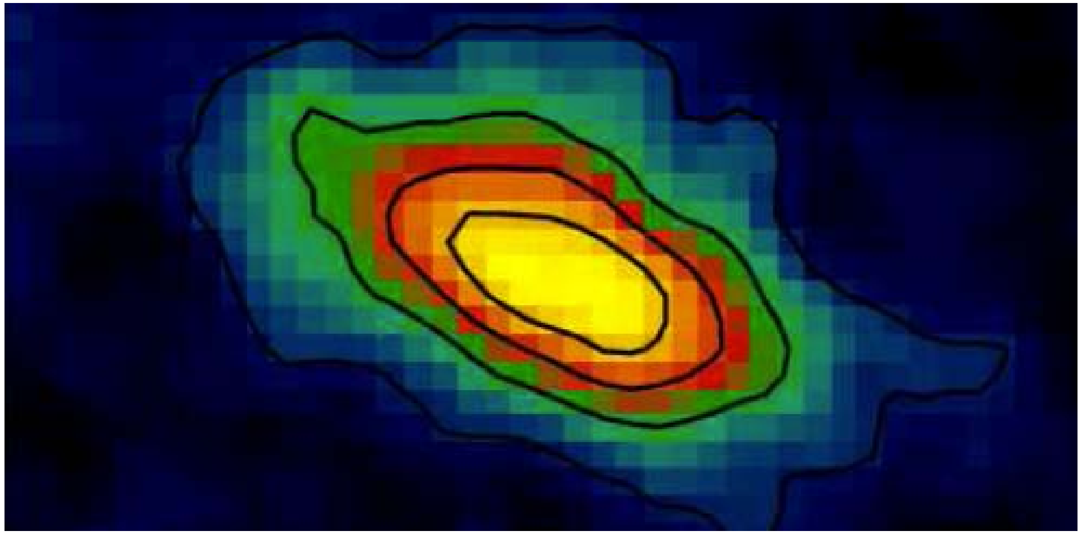
Implications for Hot Jupiter formation

-- 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…

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

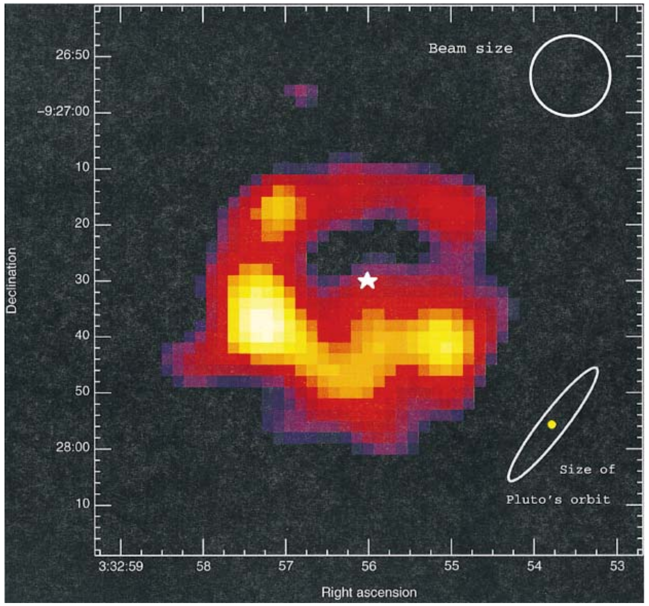


Greaves et al. 2013

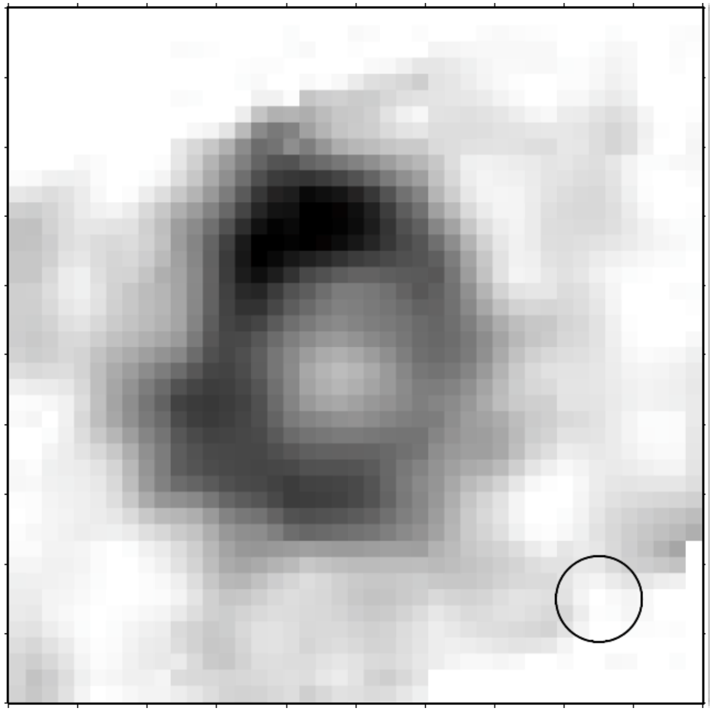
system names (UNS id)	notes	P (days)	$v \sin i_*$ (km/s)	R_* ($R_\odot$)	i_* (°)	i_d (°)	$\|\Delta i\|$ (°)
Vega, HD 172167 (A003)	planet?; 2 belts	—	—	—	3–6	10 ± 2	5.5 ± 2.5
HR 8799, HD 218396 (A—)	planets; 2 belts	—	—	—	$\gtrsim 40$	27 ± 10	$\gtrsim 3$
10 CVn, HD 110897 (F050)		13 [1]	3.4 ± 1.4	0.99	$63(\geqslant 33)$	56 ± 10	$7^{+29}_{(-7)}$
γ Dor, HD 27290 (F085)	2 belts	—	—	—	63–80	69 ± 5	$3^{+10}_{(-3)}$
Sun (G—)	*planets, 2 belts*	—	—	—	*7.3*	1.7 ± 0.2	5.6 ± 0.2
61 Vir, HD 115617 (G008)	planets	29 [2]	1.6 ± 0.5	0.97	$68(\geqslant 41)$	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	$0^{+12}_{(-0)}$
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	$88(\geqslant 63)$	54 ± 10	34^{+10}_{-27}
DE Boo, HD 131511 (K053)		10.4 [8]	4.5 ± 0.4	0.91	$\geqslant 70$	84 ± 10	$4^{+12}_{(-4)}$
HO Lib, GJ 581 (M056)	planets	94 [9]	0.3 ± 0.3	0.30	$\geqslant 0$	50 ± 20	—
AU Mic, HD 197481 (M—)		4.9 [10,11]	8.5 ± 0.6	0.77	$\geqslant 81$	$\geqslant 80$	$1^{+7}_{(-1)}$

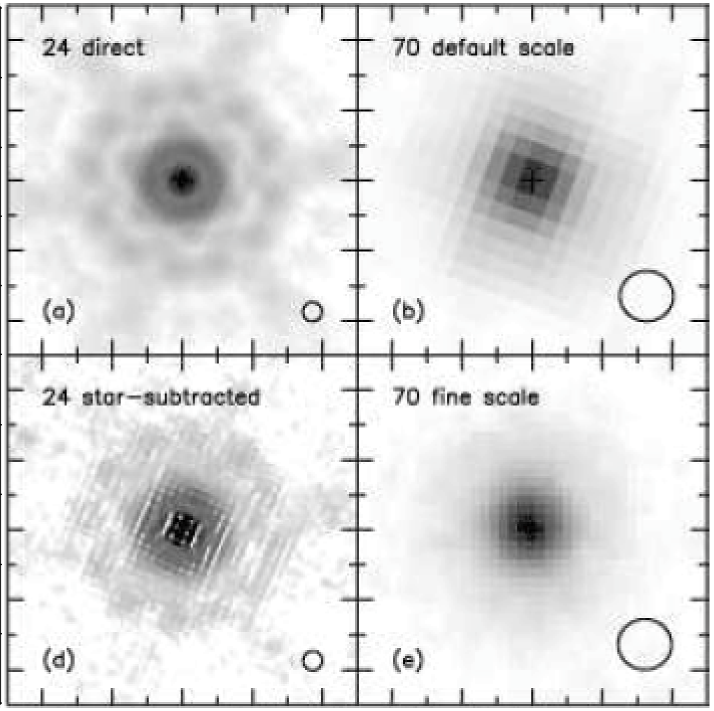
Watson et al 2011

HD	i_* (°)	i_{disk} (°)	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^o misalignemt 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
…

Thanks!