Hot Jupiters and Super-Earths: Spin-Orbit Puzzles in Exoplanetary Systems

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With contributions from
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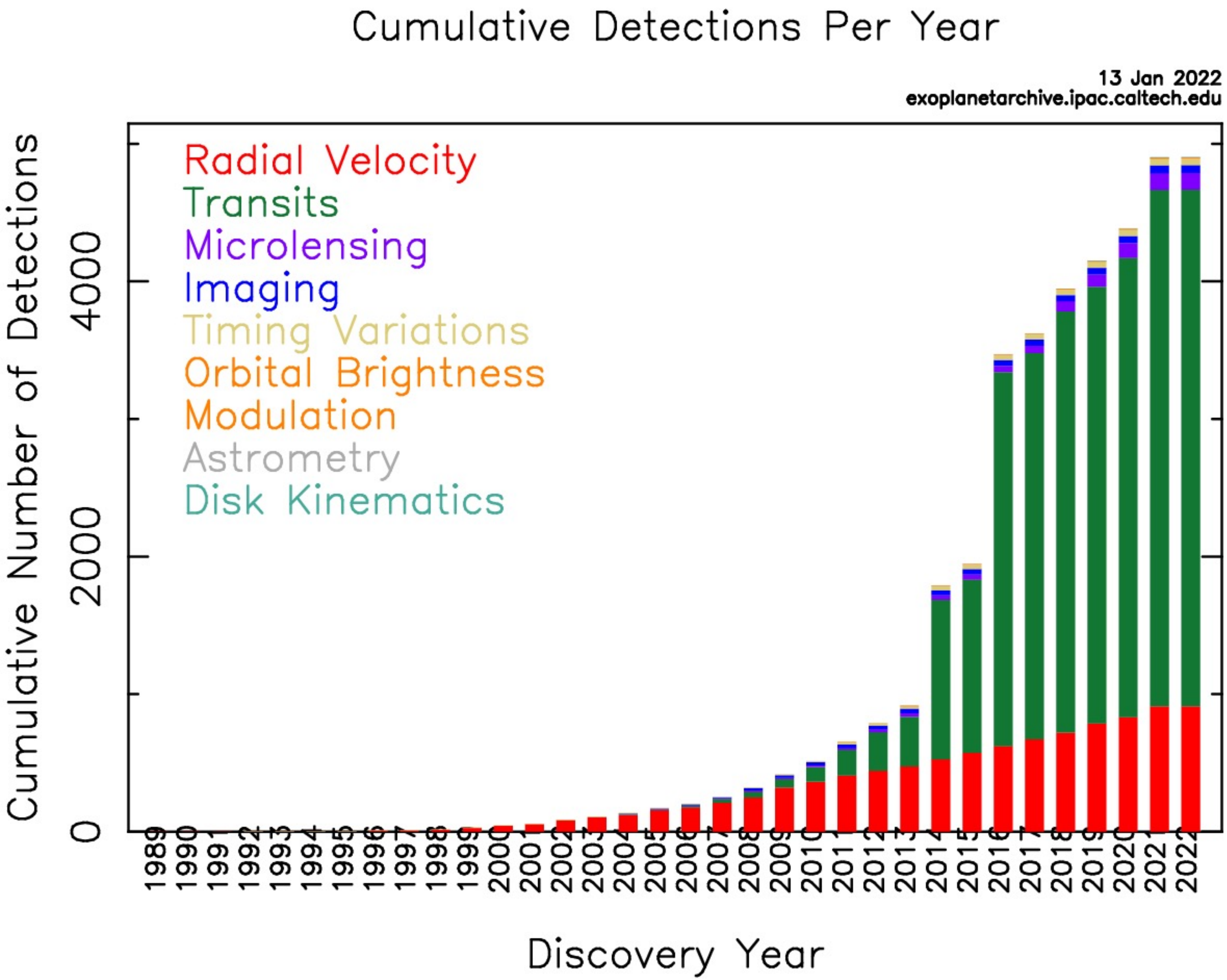
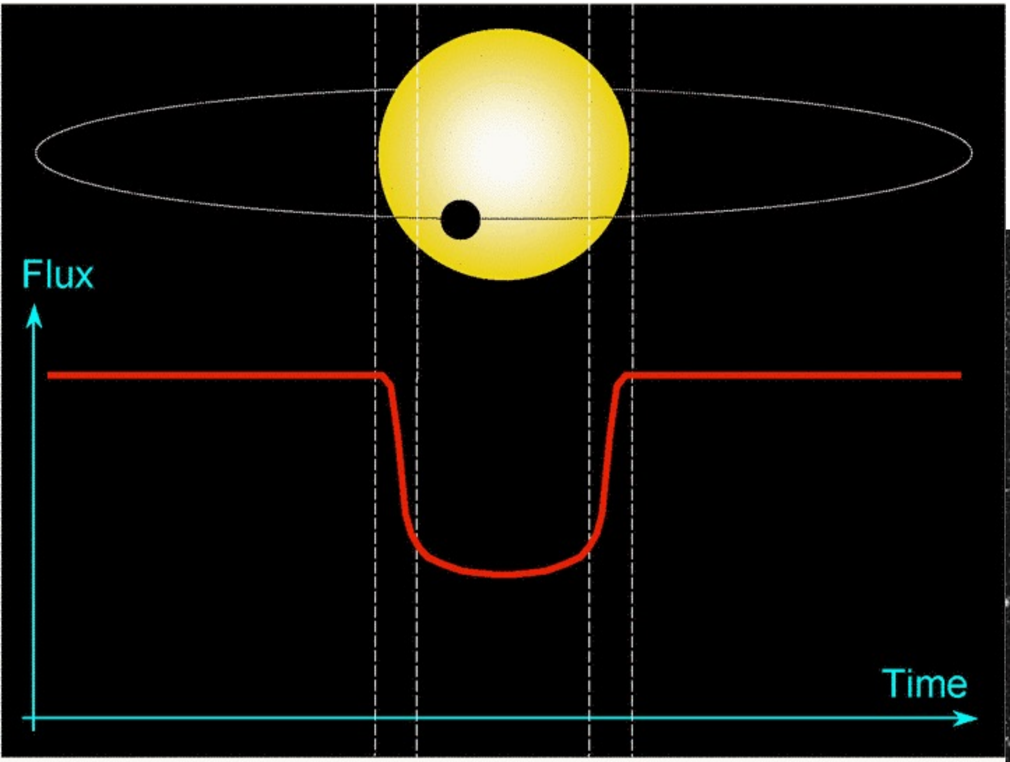
- Michelle Vick (Ph.D.20→Northwestern)
- Yubo Su (Ph.D.22→Princeton)
- Jiaru Li (Ph.D.23)

U Washington Astro Colloquium, 1/27/2022

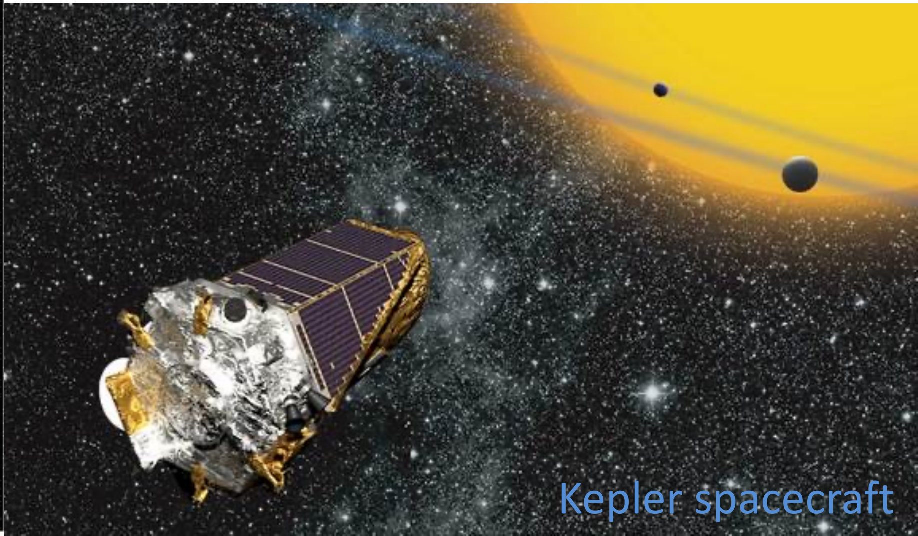


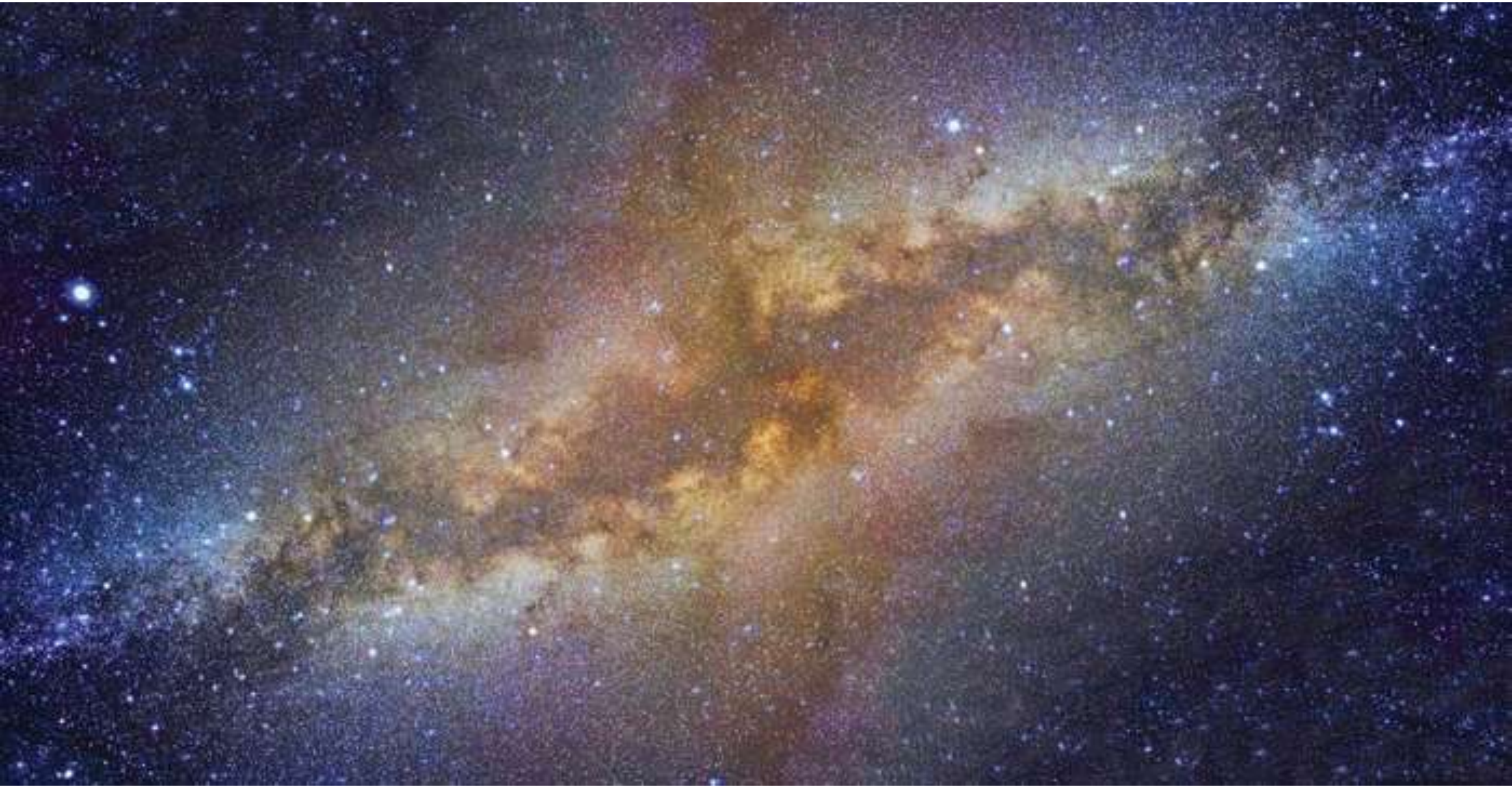
Cumulative Detections Per Year
13 Jan 2022
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
Astrometry
Disk Kinematics
Cumulative Number of Detections
0
2000
4000
Discovery Year

Doppler Method
("Radial Velocity")

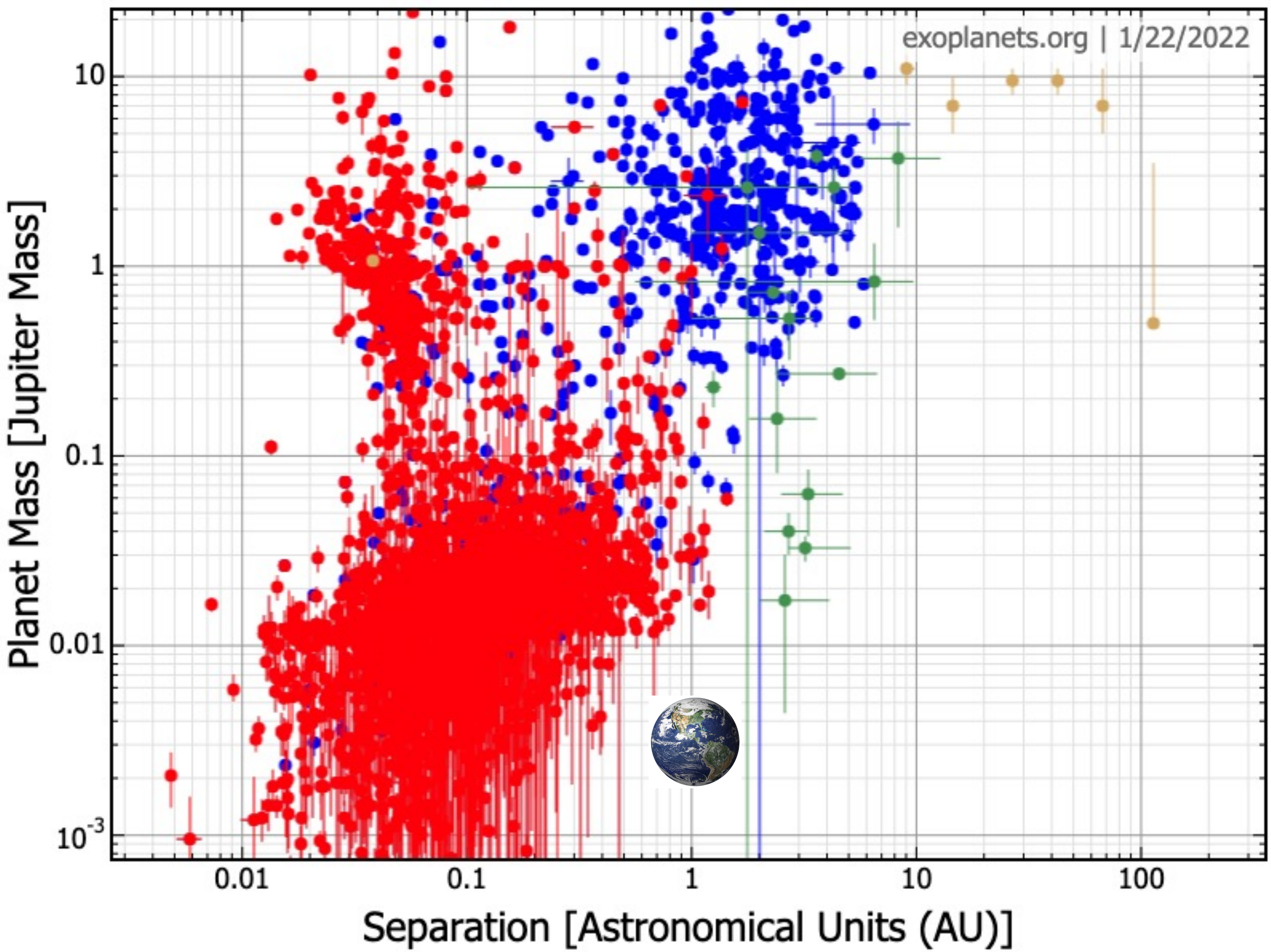


Transit Method



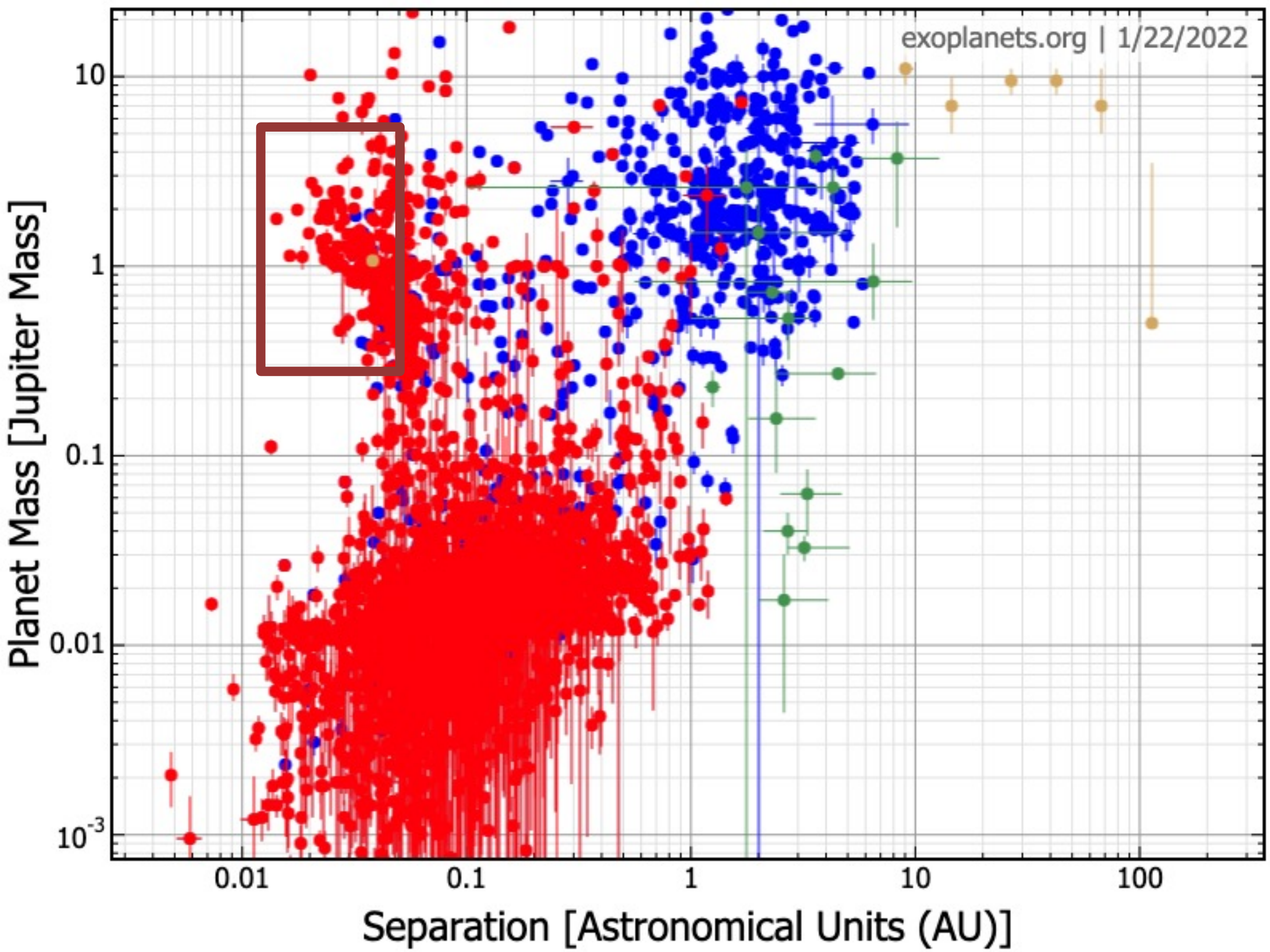


>~30% of stars in Galaxy have planetary system, each contains (on average) ~3 planets:
~10^{12} planets in the Galaxy

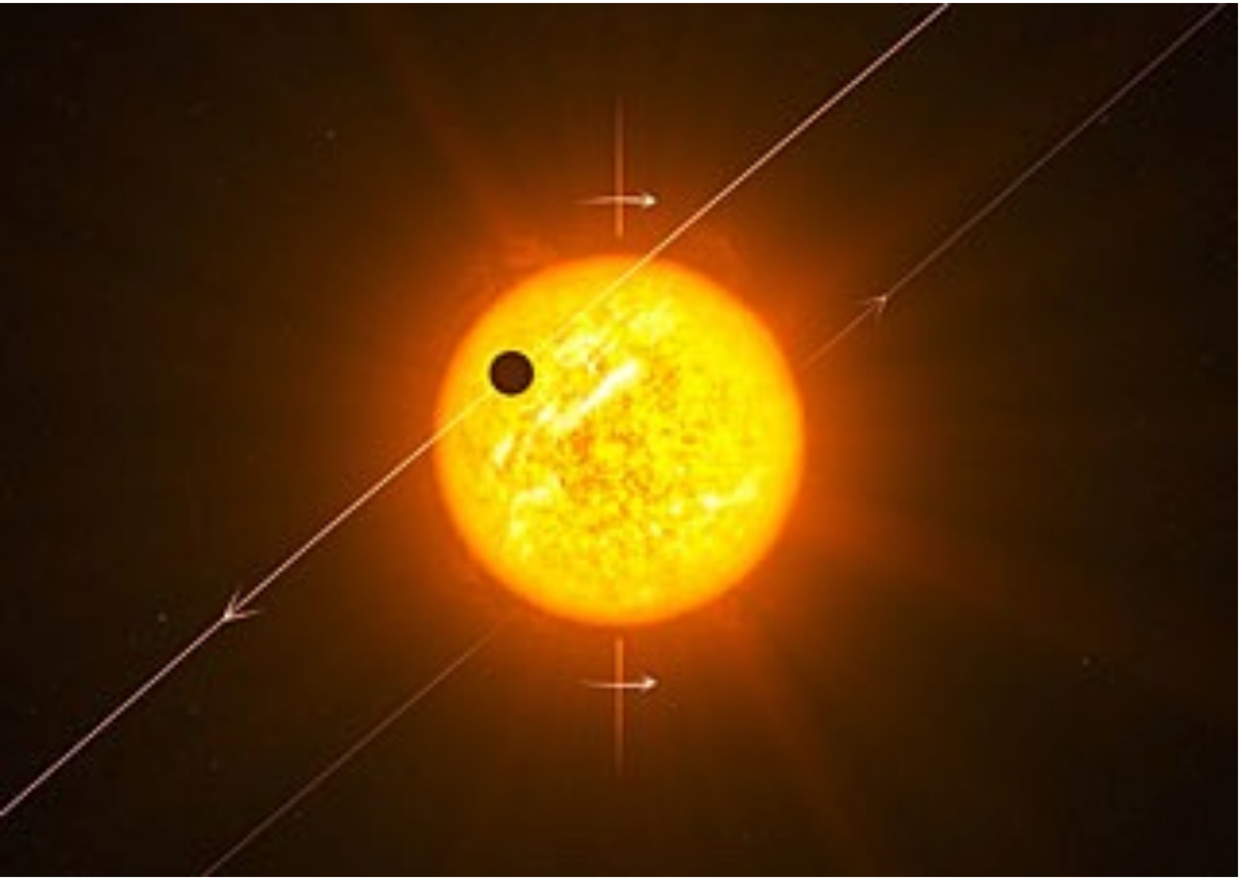


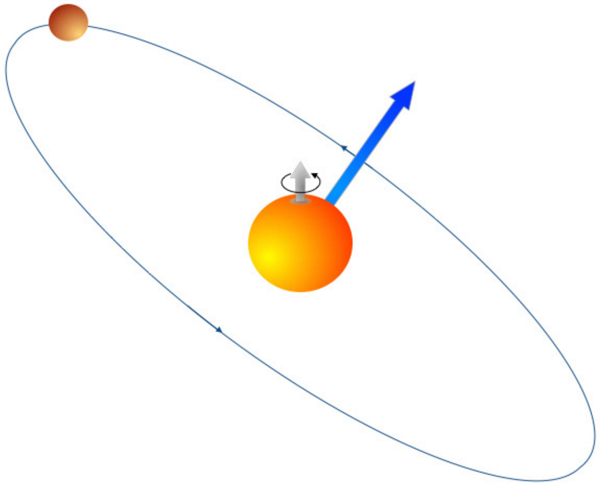
exoplanets.org | 1/22/2022
Planet Mass [Jupiter Mass]
10
1
0.1
0.01
10^{-3}
0.01
0.1
1
10
100
Separation [Astronomical Units (AU)]

Hot Jupiters: Giant Planets with P < 10 days



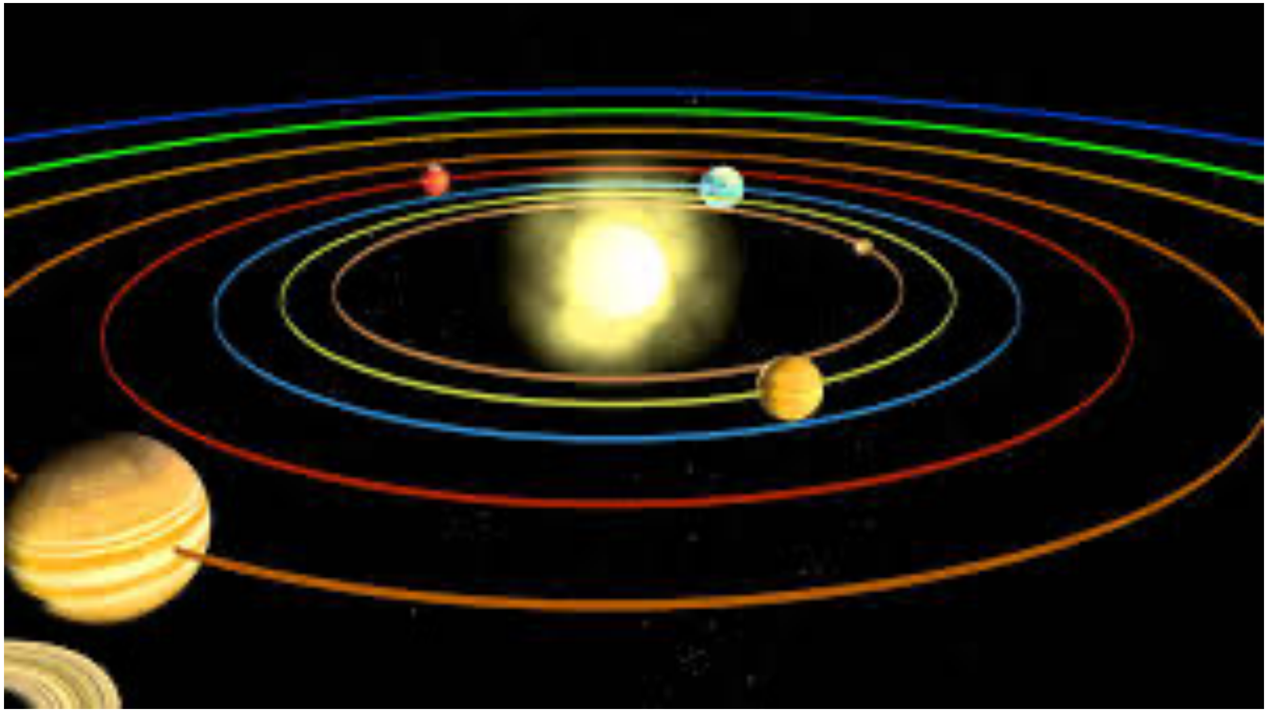
Spin-Orbit Misalignment Puzzle

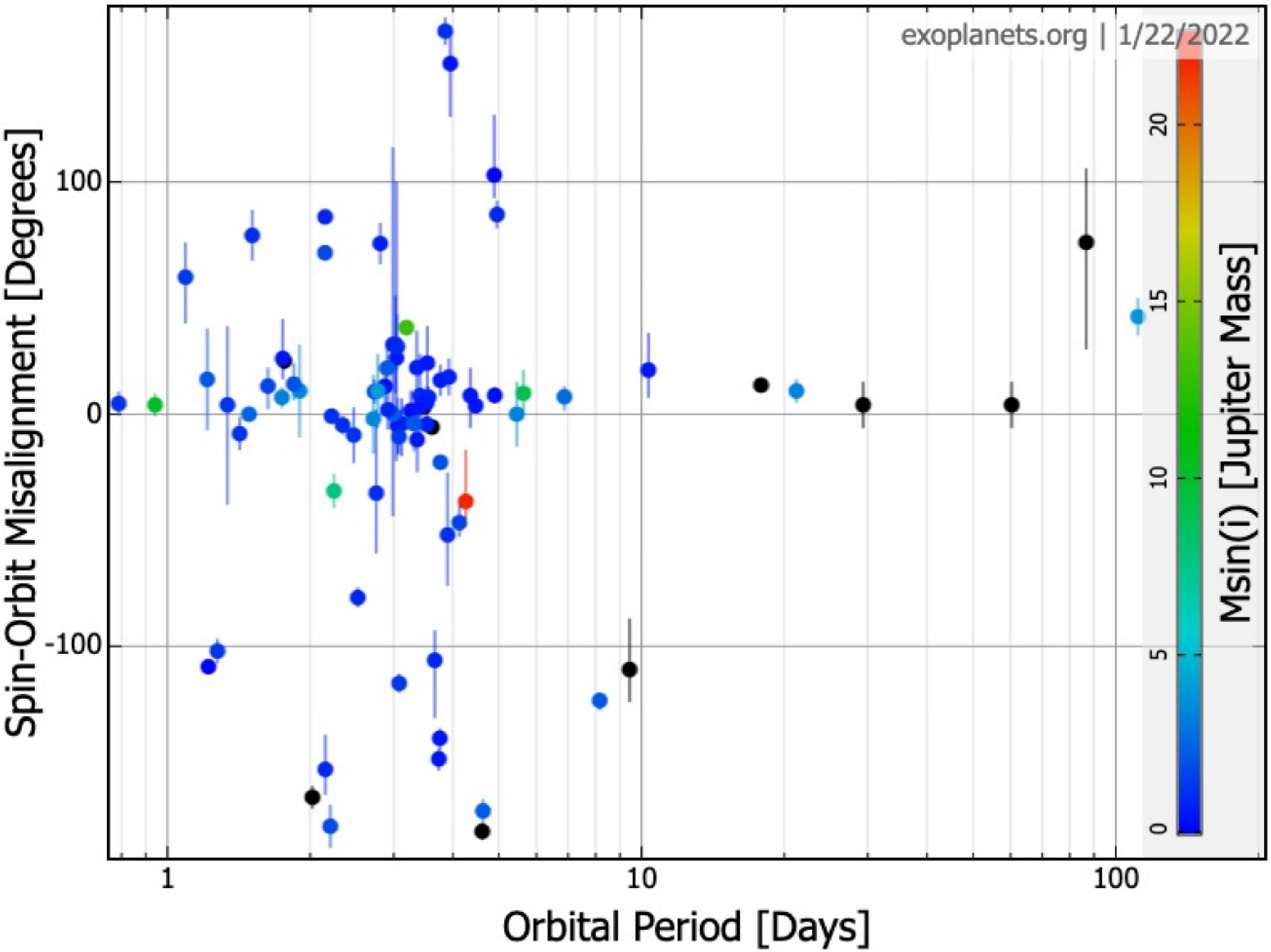




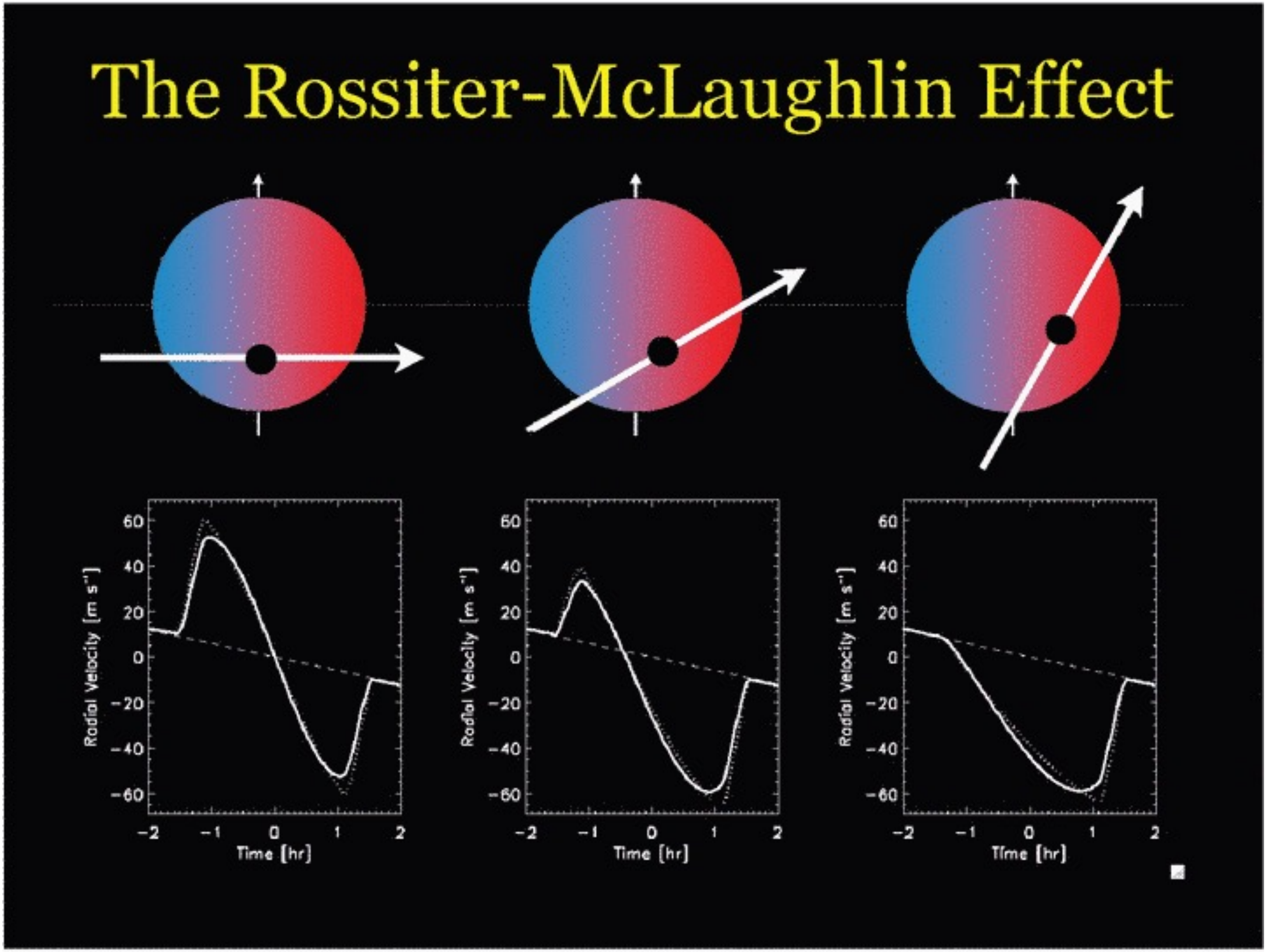
Solar System

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





exoplanets.org | 1/22/2022
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

How to Form Misaligned Hot Jupiters?

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

$t < 10$ Myrs

$R_{form} >$ a few AU

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?

High-Eccentricity Migration:

Lidov-Kozai effect induced by an external companion

Lidov-Kozai Effect

Can perturbation from the Moon make Earth's satellites fall?

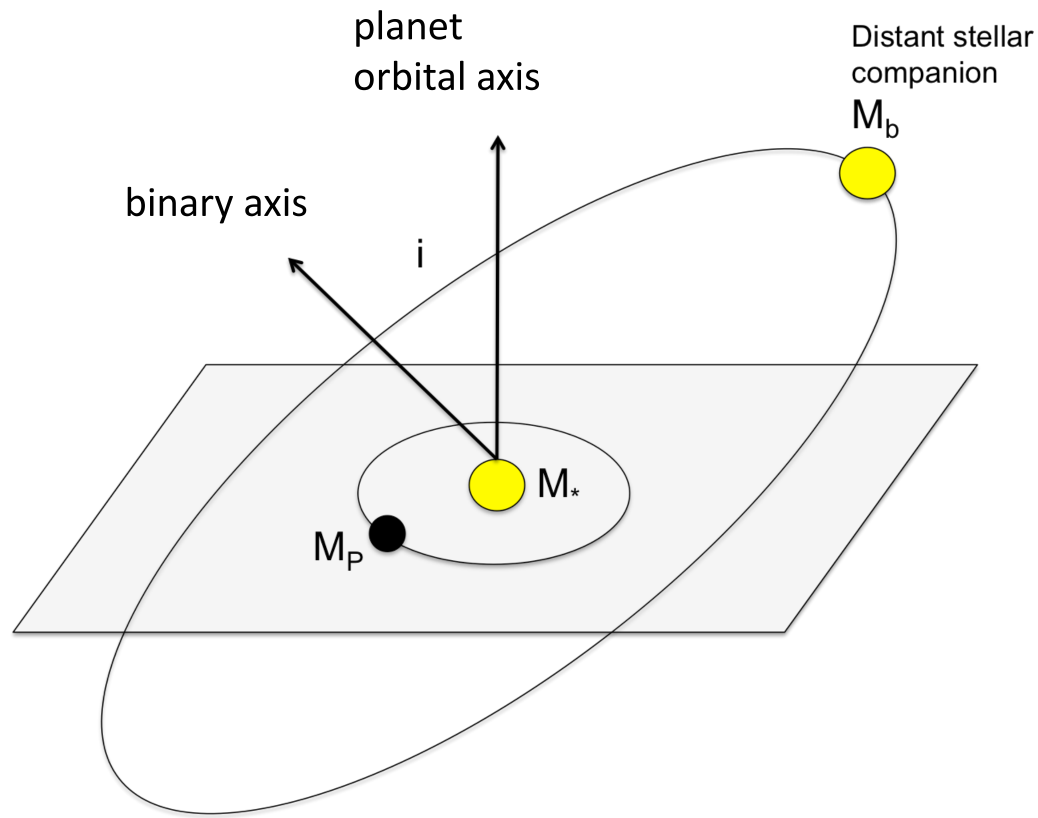
Planet. Space Sci., 1962, Vol. 9, pp. 719 to 759. Pergamon Press Ltd. Printed in Northern Ireland

THE EVOLUTION OF ORBITS OF ARTIFICIAL SATELLITES OF PLANETS UNDER THE ACTION OF GRAVITATIONAL PERTURBATIONS OF EXTERNAL BODIES

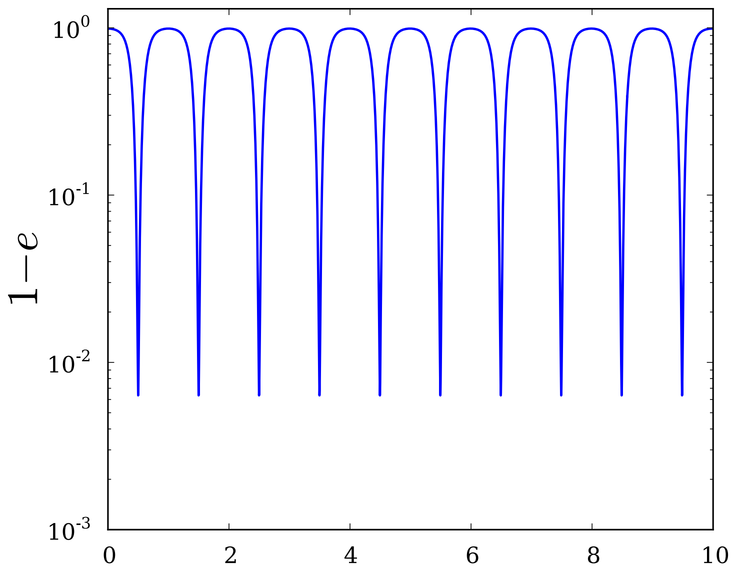
M. L. LIDOV

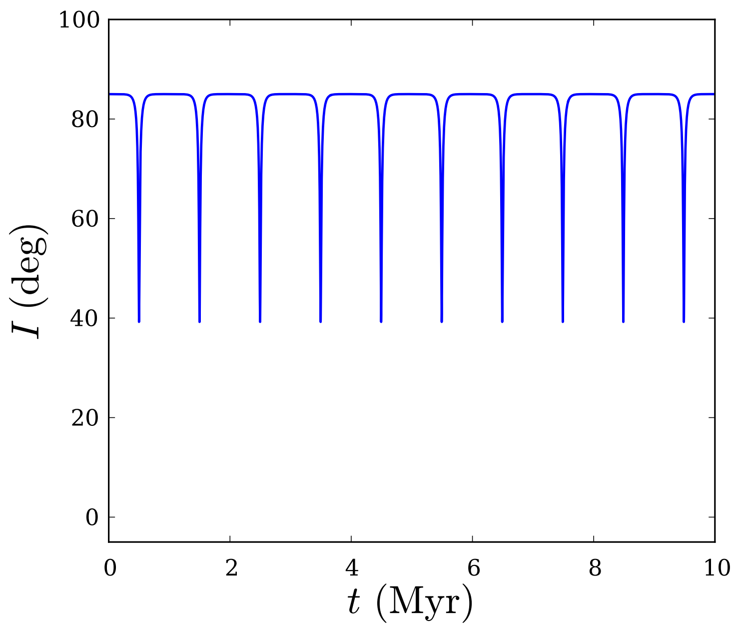
Translated by H. F. Cleaves from *Iskusstvennye Sputniki Zemli*, No. 8, p. 5, 1961.

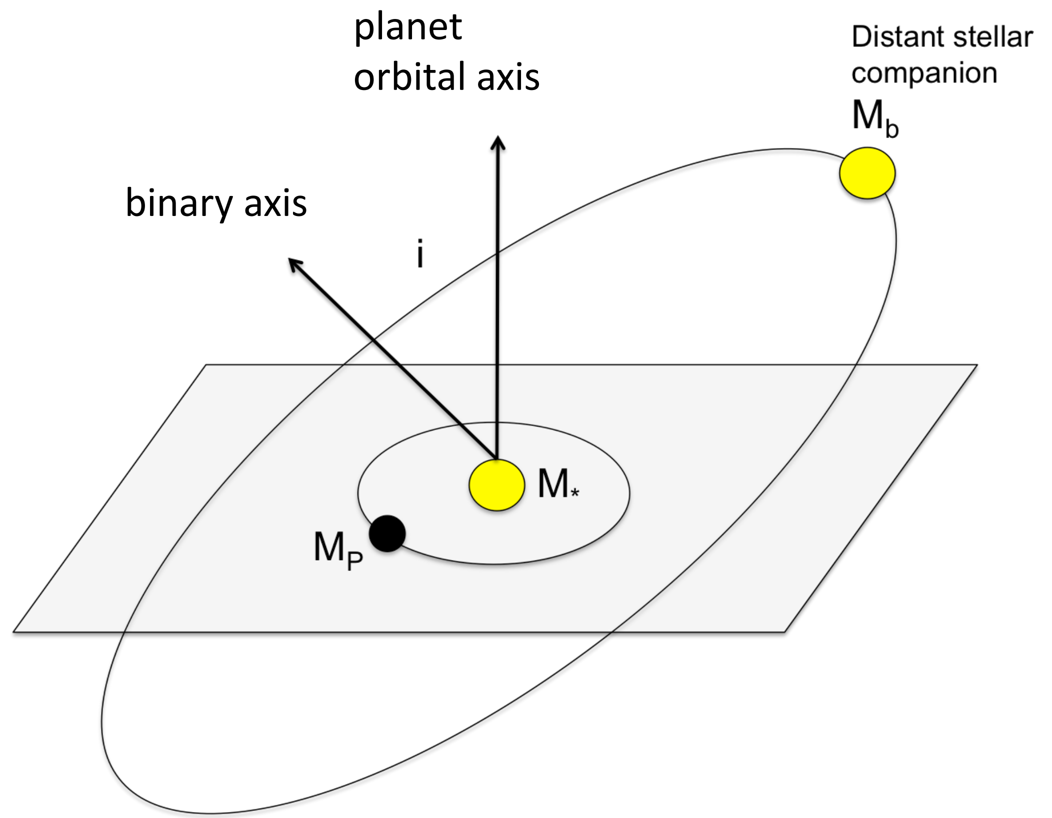
Lidov-Kozai Effect



Lidov-Kozai Effect







- 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: High-e Migration

- Planet forms at ~ a few AU
- Companion (star or another planet) 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

e.g. Eggleton+01; Wu & Murray 03; Fabrycky & Tremaine 07; Nagasawa+08; Wu & Lithwick 11; Beauge & Nesvorny 12; Naoz+12; Storch, Anderson & Lai 14; Petrovich 15a,b; Anderson, Lai +16; Munoz, Lai +16; Wu 18; Vick, Lai +19; Teyssandier, Lai+19

Main physics uncertainties:

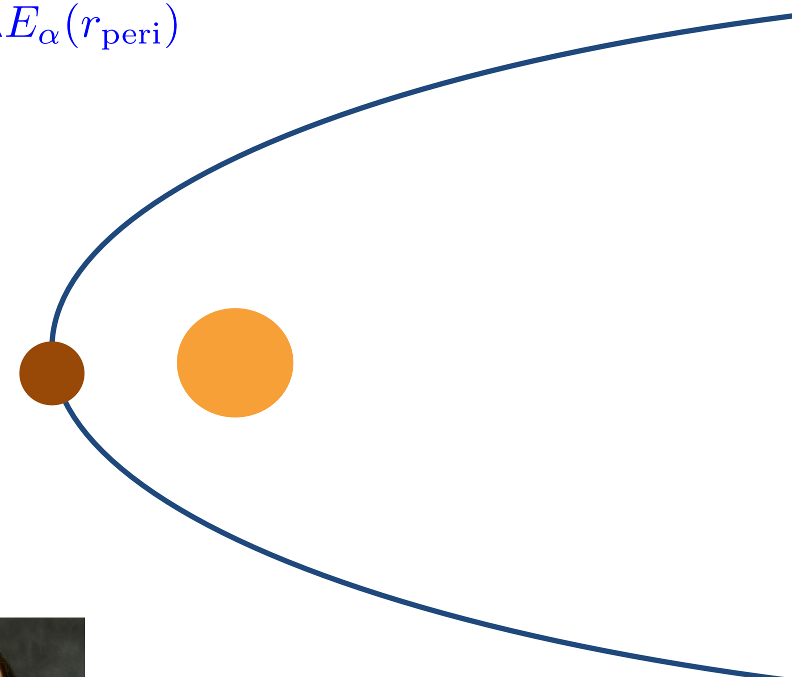
Need strong tidal dissipation; Can HJ survive tidal disruption? ...

Physics of Tidal Dissipation in Giant Planets: Dynamical/Chaotic Tides on high-e orbits

-- Near pericenter, the tidal potential of the star excites oscillation modes of the planet (f-modes, inertial modes, etc)

-- The energy transfer in each pericenter passage depends on the oscillation phase of mode

Typical scale of energy transfer in each passage $\pm\Delta E_\alpha(r_{\rm peri})$



For sufficiently small $r_{\rm peri}$ and large *e:*
Mode energy grows chaotically (quasi-diffusively)
to large values
When the mode energy reaches some fraction
of the planet binding energy
➔ rapid nonlinear dissipation

Vick & Lai 2018;
Vick, Lai & Anderson 2019
See also Wu 2018; Yu et al.2021

Michele Vick (Ph.D.2020 → Northwestern)

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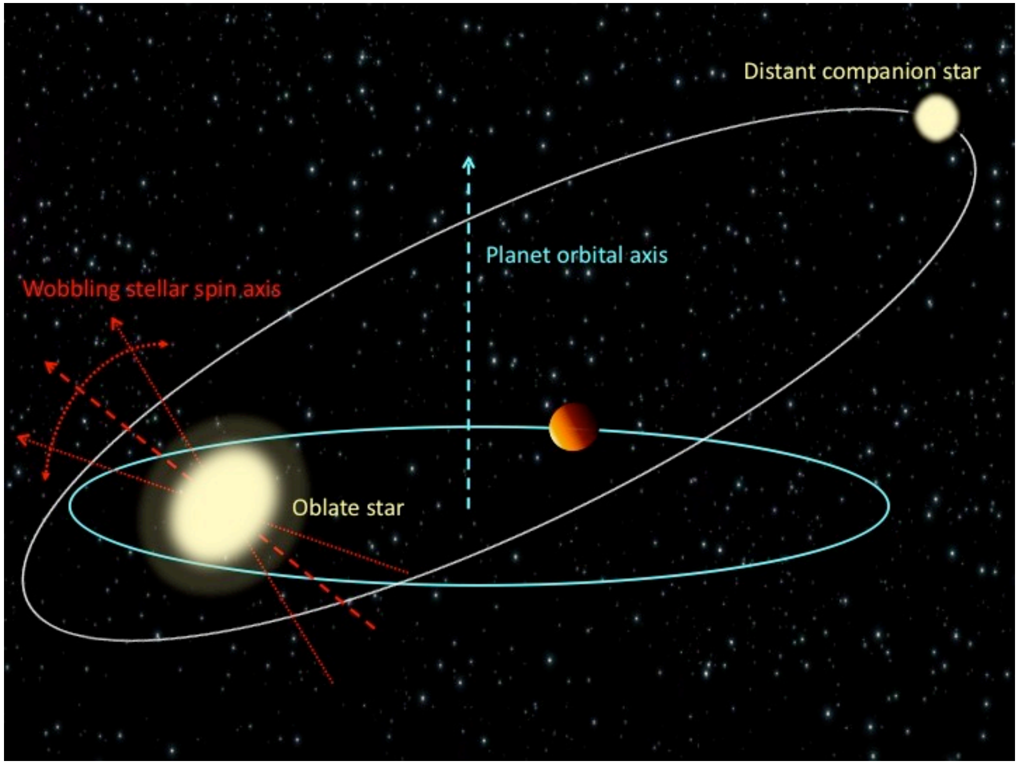
Question: How to produce misaligned stellar spin?

What happens to stellar spin axis as the planet undergoes Lidov-Kozai Oscillations ?



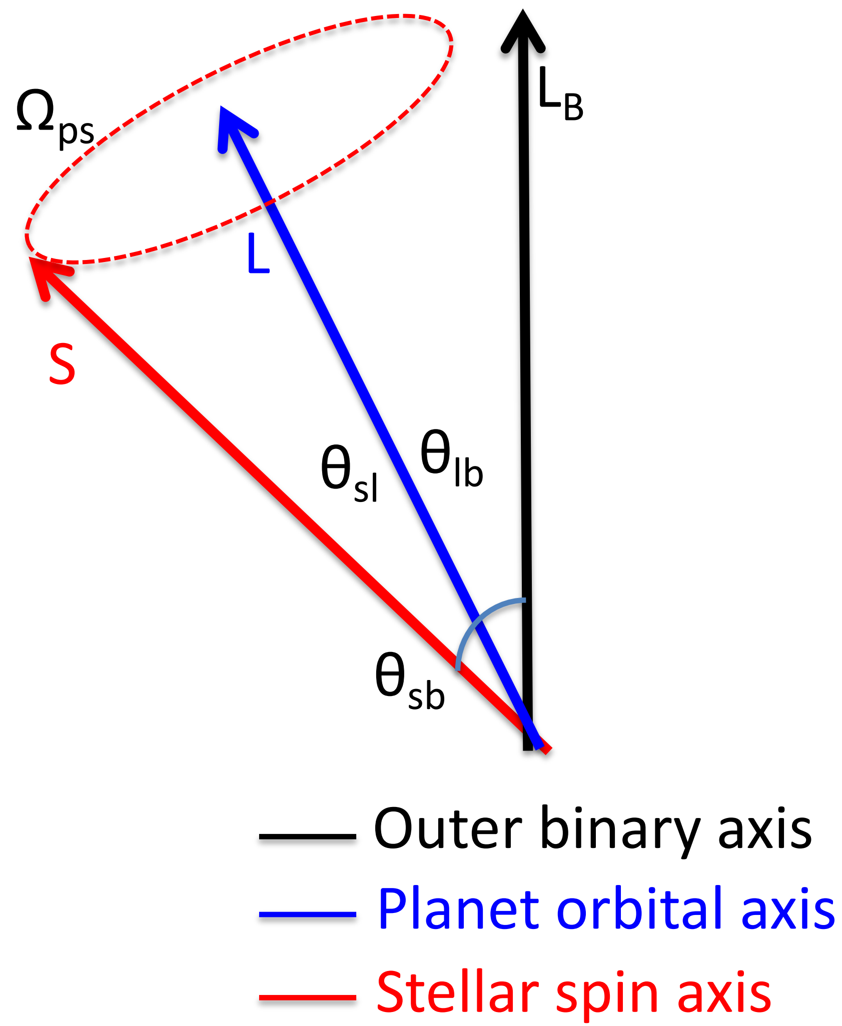
Star rotates ➔ oblate
➔ **S** precesses around **L**

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

Storch, Anderson & DL 2014, Science
Storch & DL 2015 MNRAS (Theory I)
Anderson, Storch, DL 2016 (Pop Study)
Storch, DL & Anderson2017 (Theory II)
Vick, DL & Anderson 2019

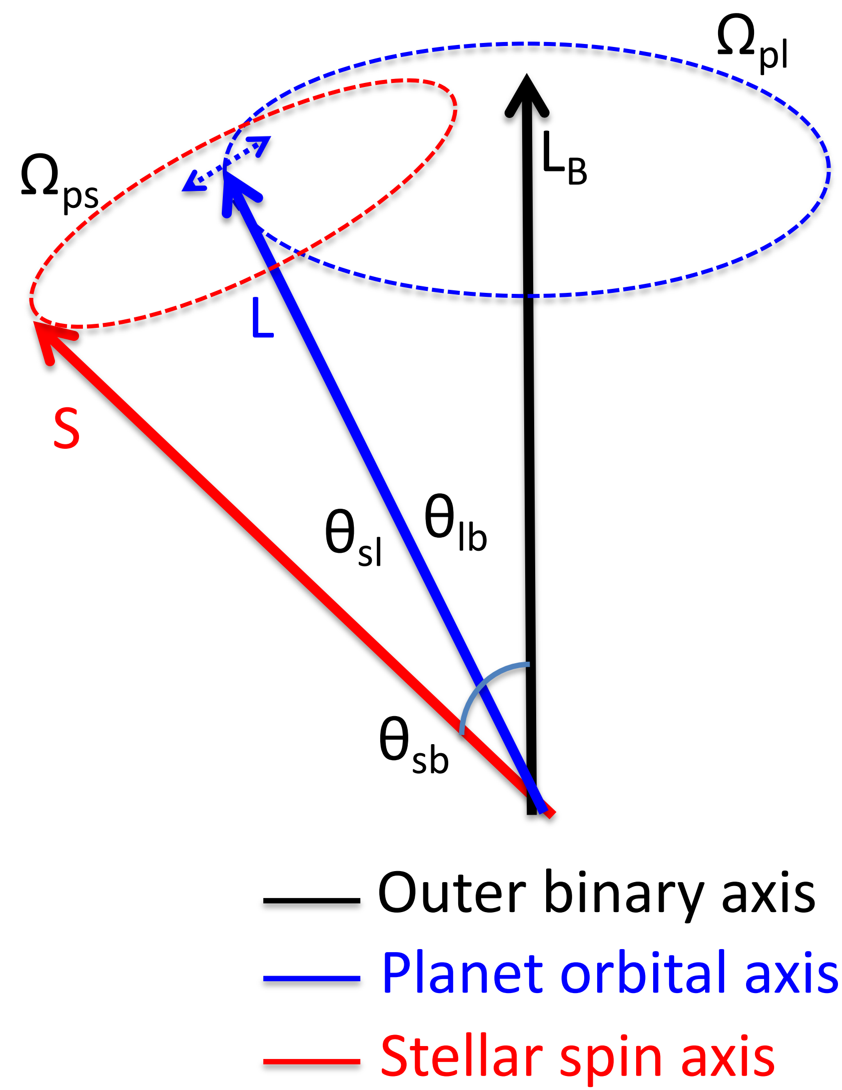
Spin Dynamics

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



Spin Dynamics

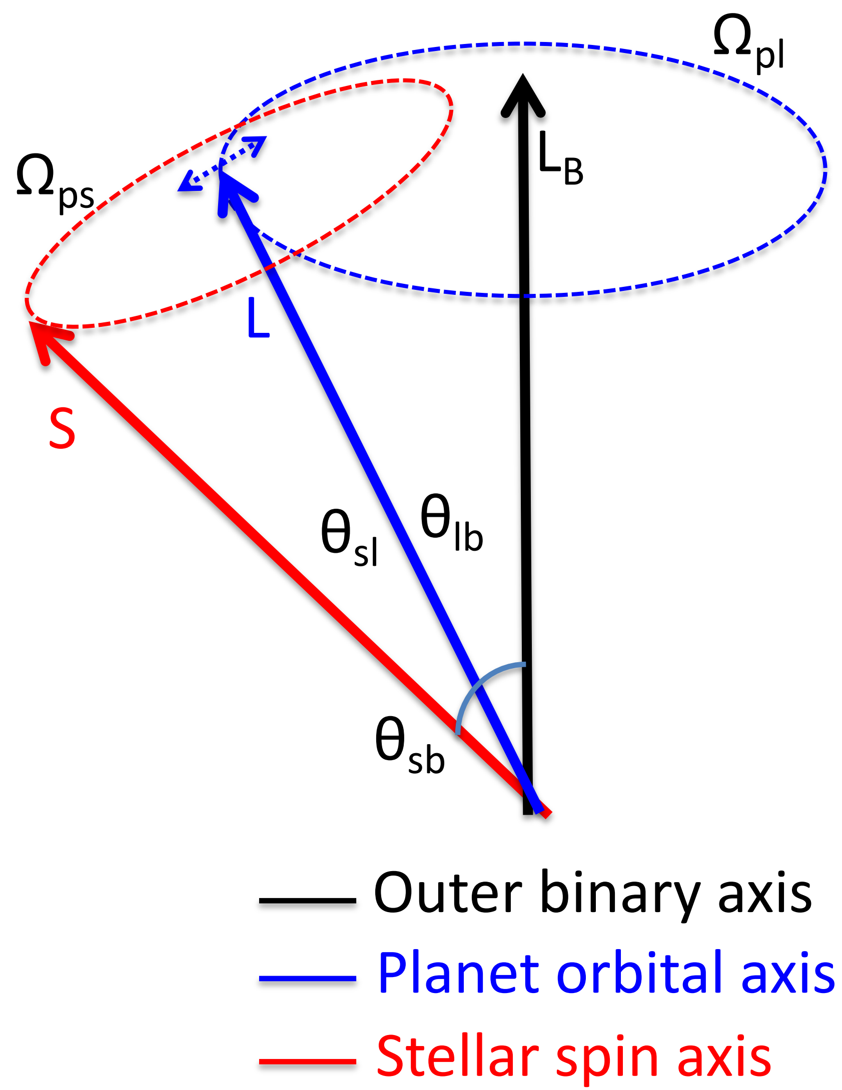
- Stellar spin axis S wants to precess around planet orbital axis L.
- But L itself is moving:
  - Nodal precession (L precesses around binary axis L_b)
  - Nutation (cyclic changes in inclination of L relative to L_b)



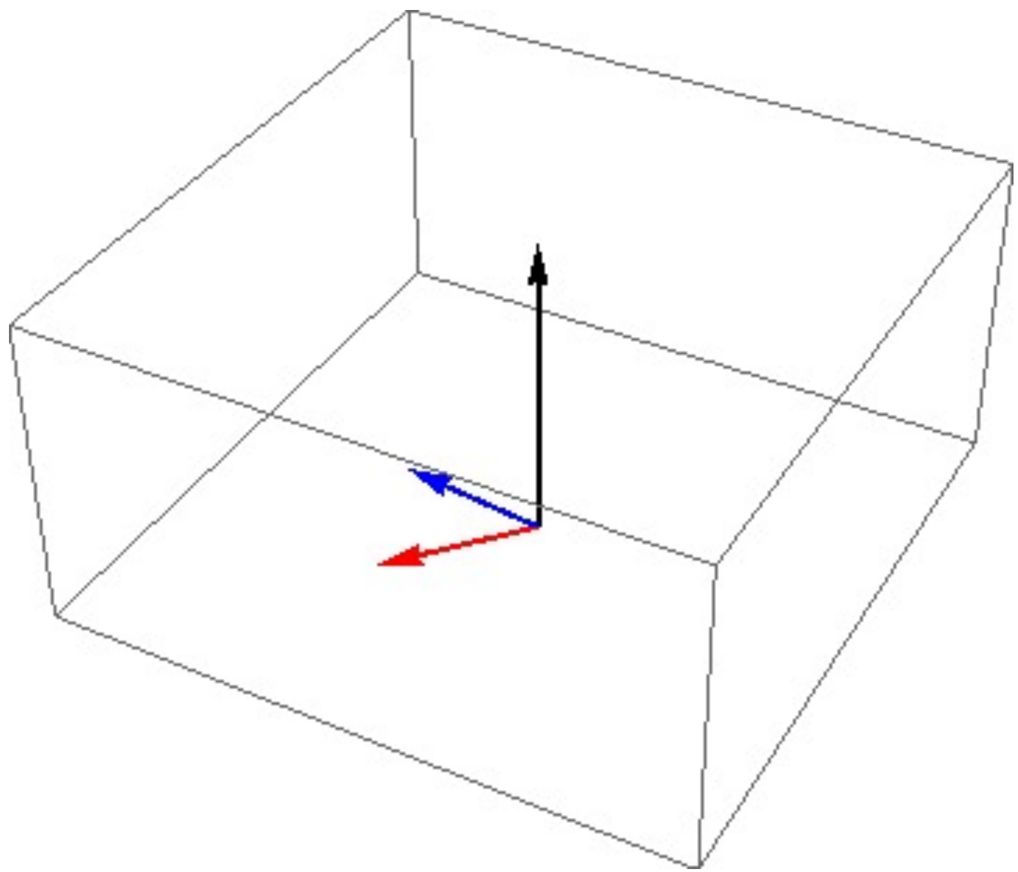
Spin Dynamics

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

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



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



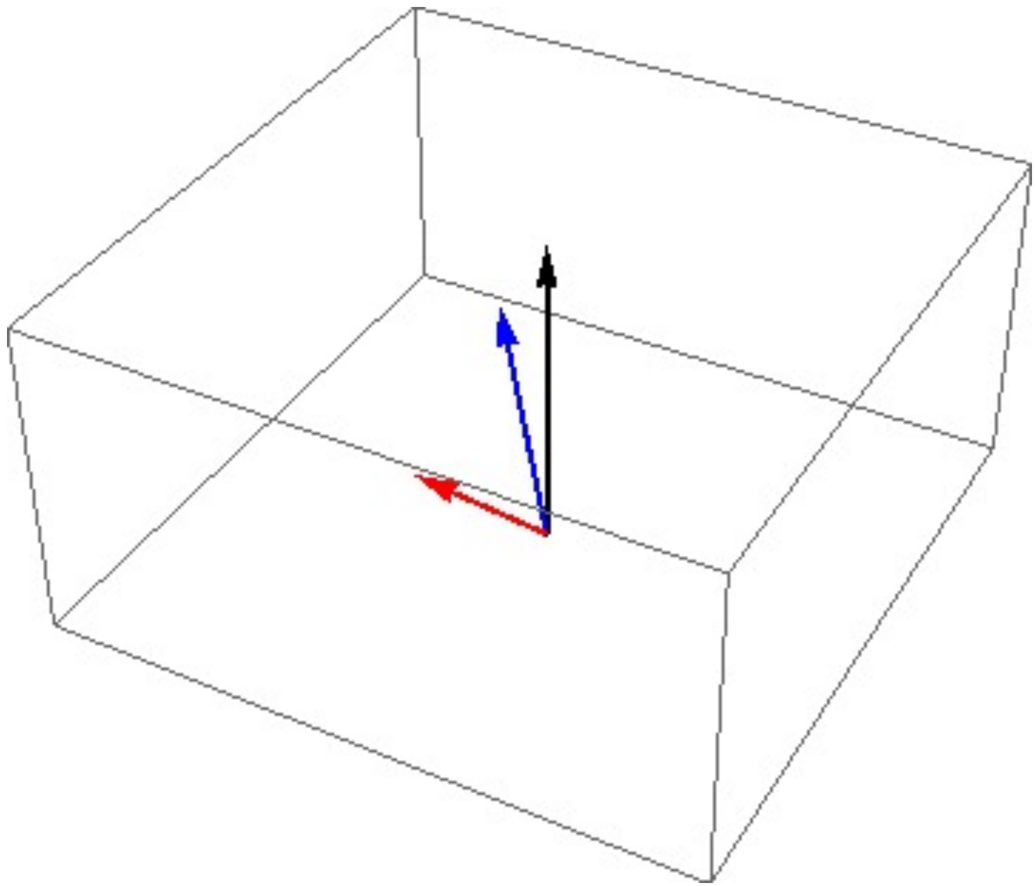
θ_{sl} = constant, i.e. initial spin-orbit misalignment is maintained for all time

Outer binary axis

Planet orbital axis

Stellar spin axis

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

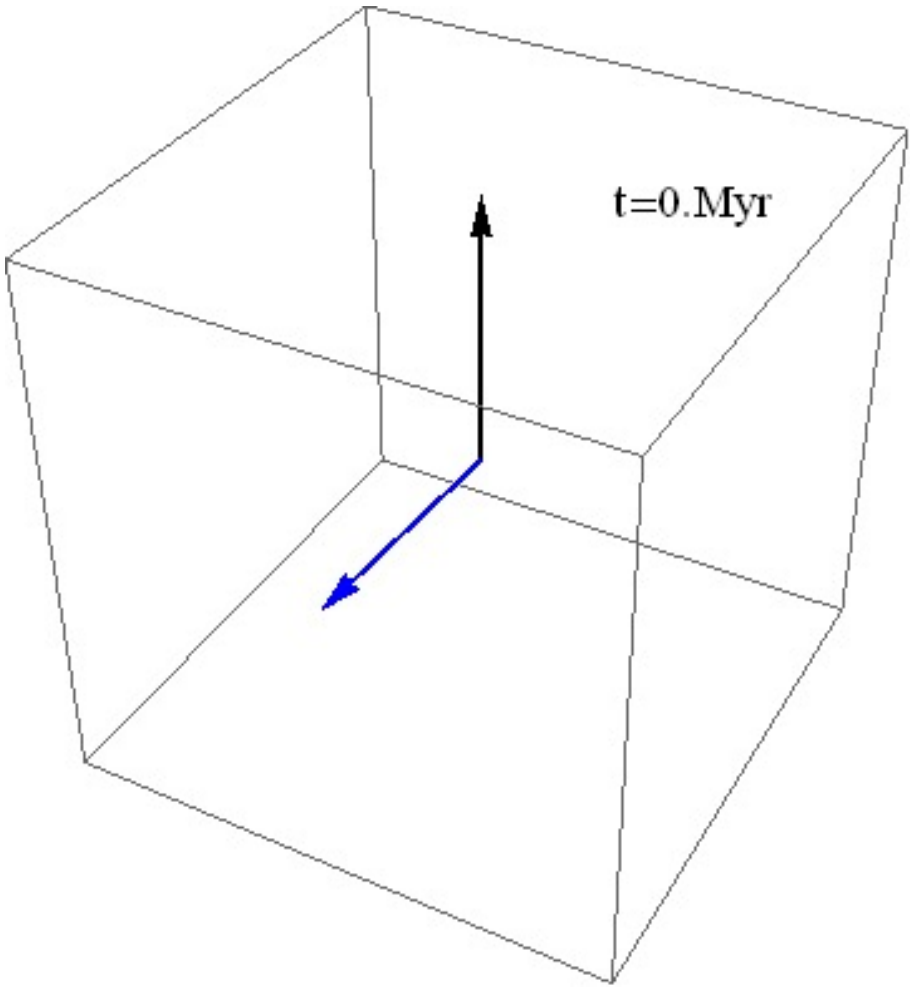


Outer binary axis
Planet orbital axis
Stellar spin axis

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

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

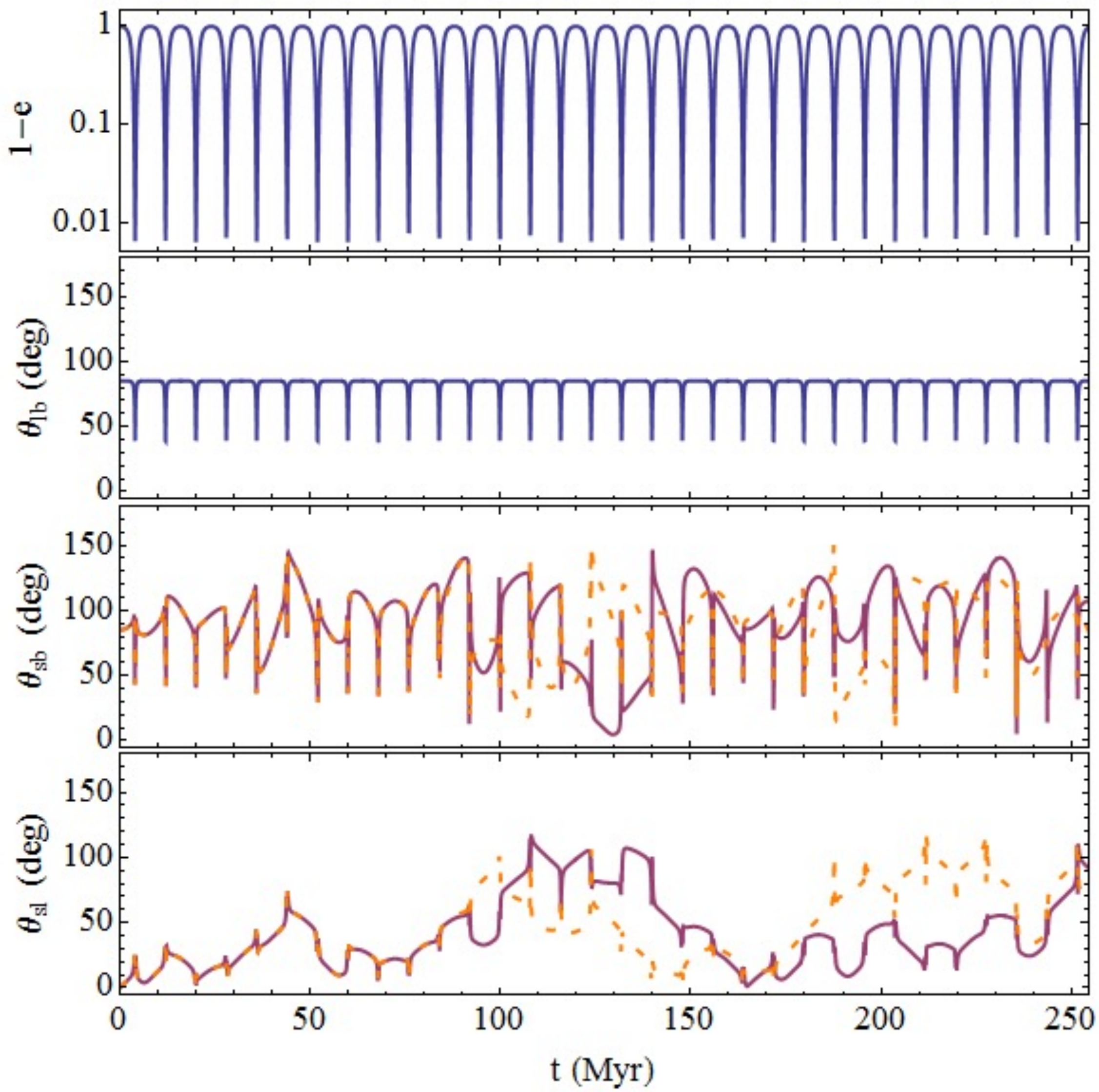
If $|\Omega_{ps}| \sim |\Omega_{pl}|$: “trans-adiabatic”

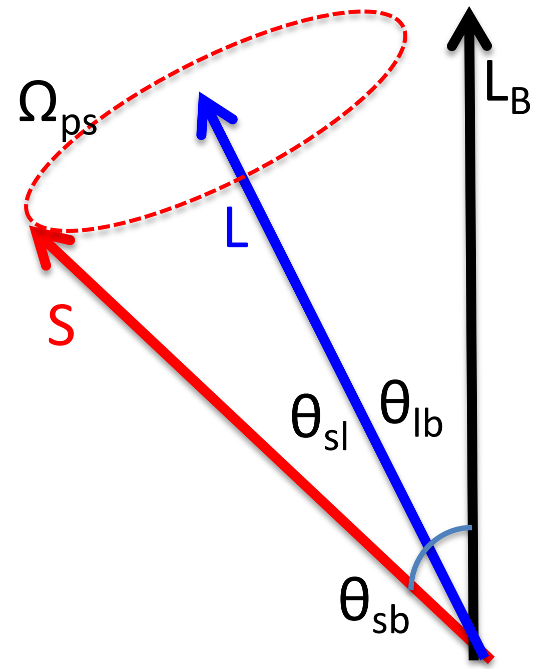


Q: Is it really chaotic?

Outer binary axis
Planet orbital axis
Stellar spin axis

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



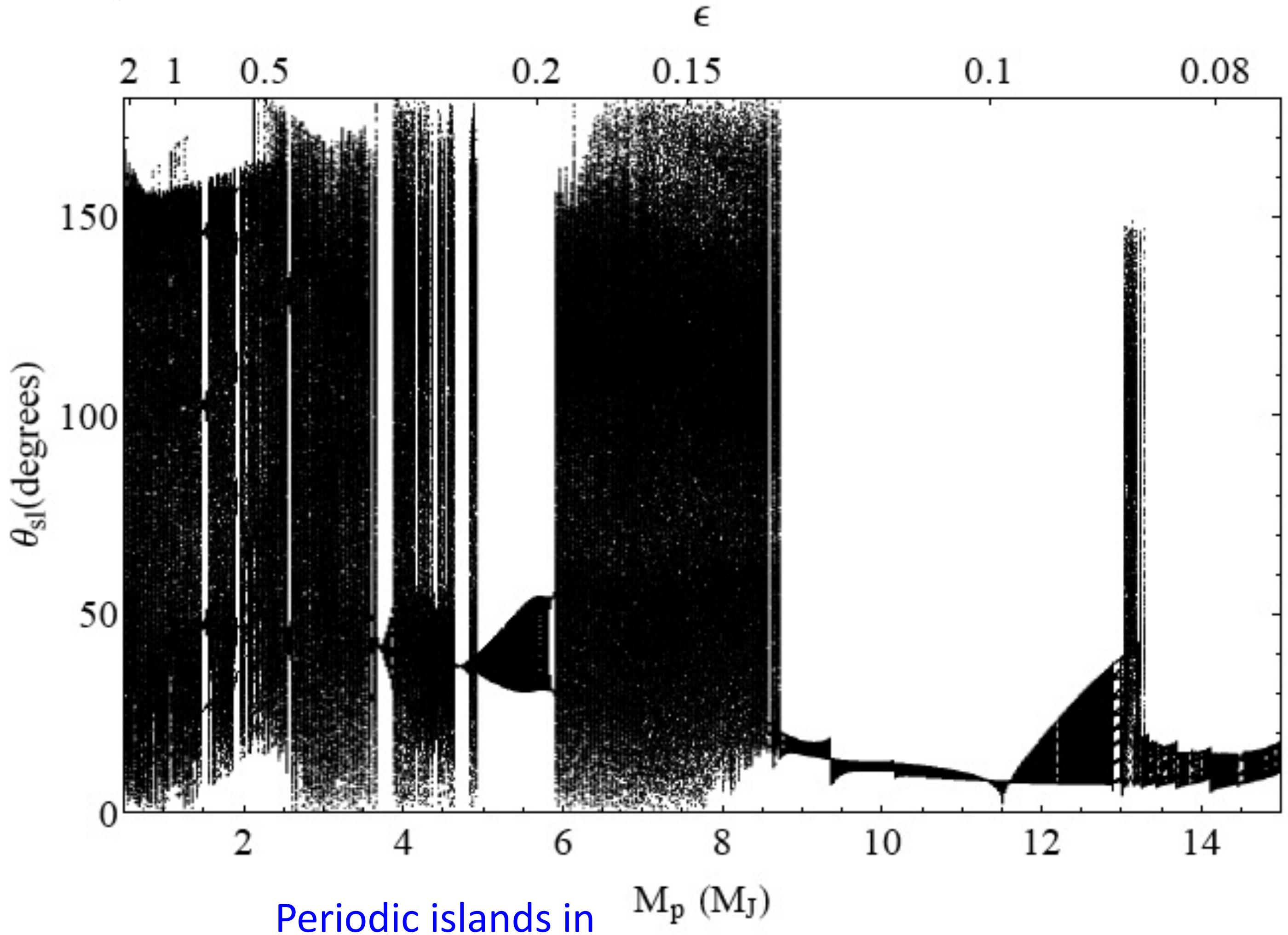


Lyapunov time ~ 6 Myrs

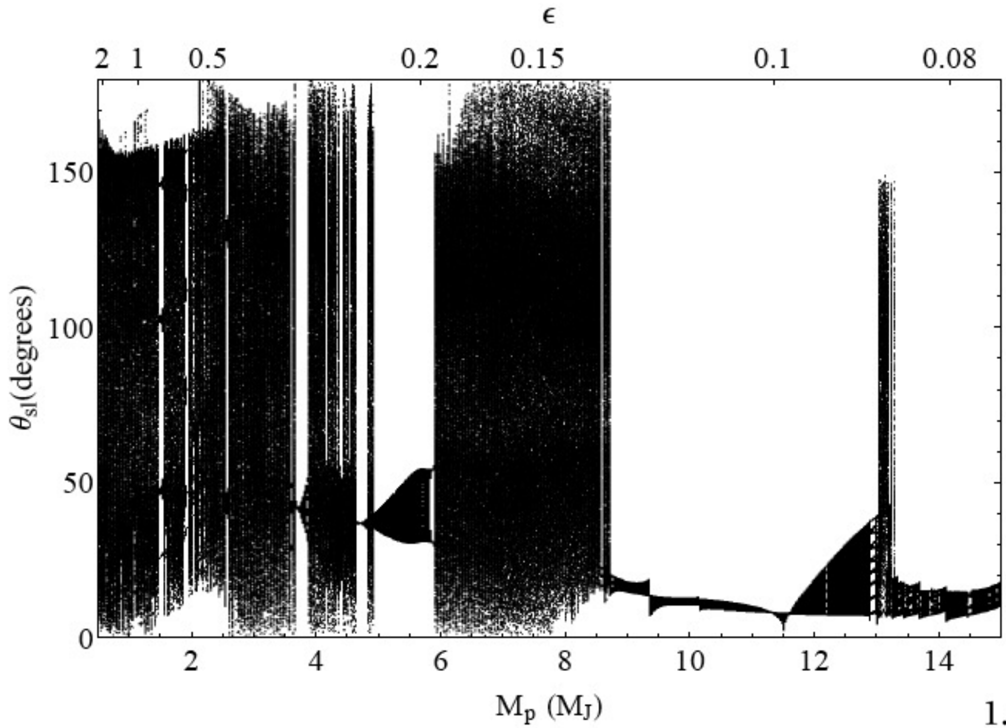
Ω_{ps} & Ω_{pl} are strong functions of eccentricity (and time)

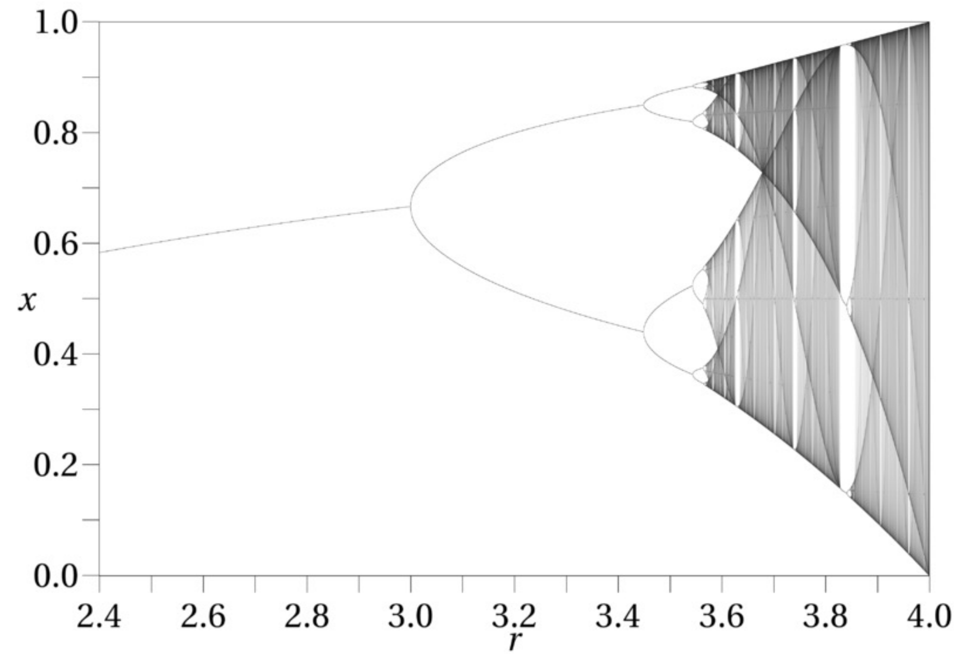
$$\epsilon = \frac{\Omega_{\rm pl0}}{\Omega_{\rm ps0}} \quad \propto M_p^{-1}$$

Spin-orbit angle recorded at eccentricity maxima



Periodic islands in the ocean of chaos



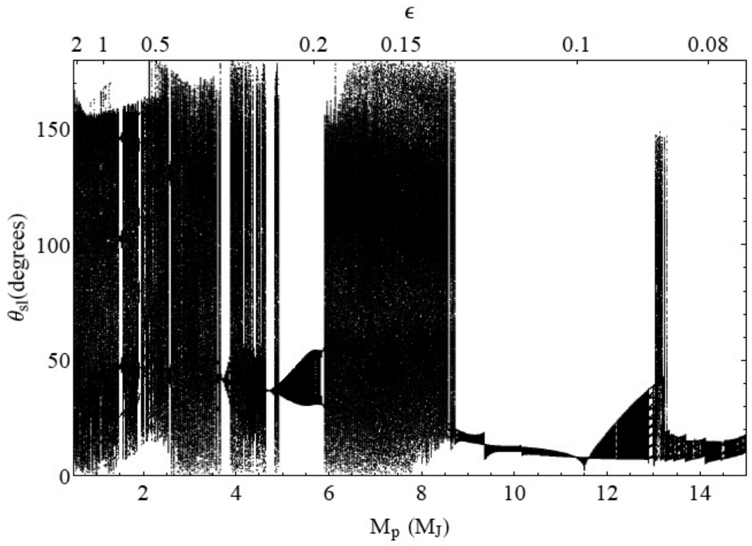


Logistic Map:

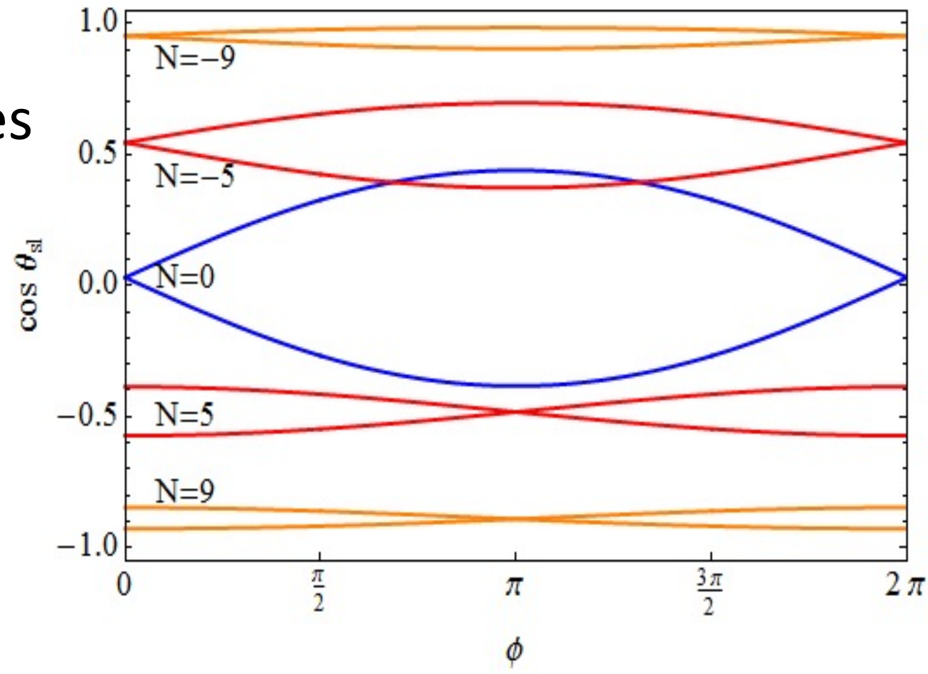
$$x_{n+1} = rx_n(1 - x_n)$$

R.May (1976): Discrete time population model

Theory of Spin Chaos

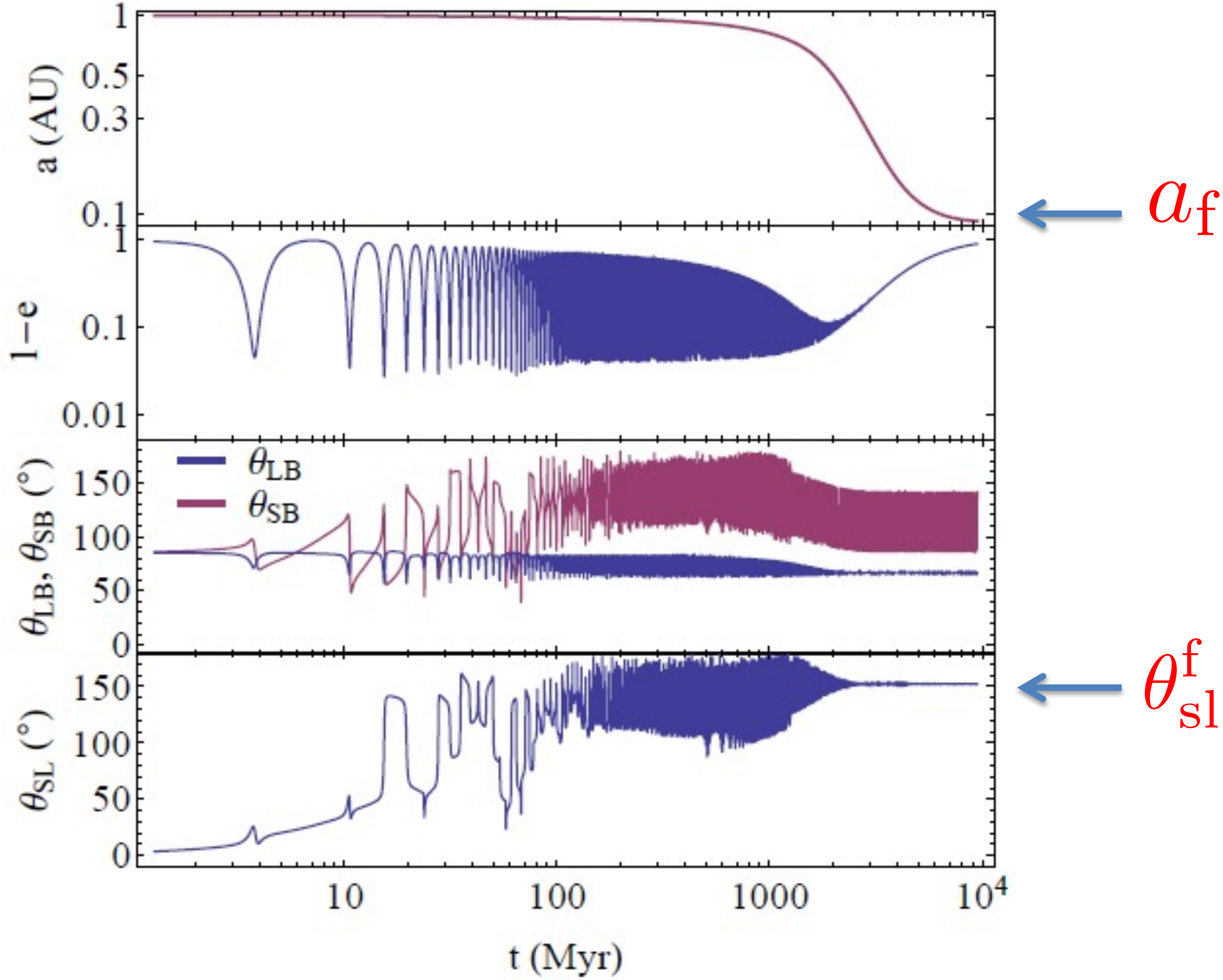


In Hamiltonian system, Chaos arises from **overlapping resonances** (Chirikov criterion; 1979)



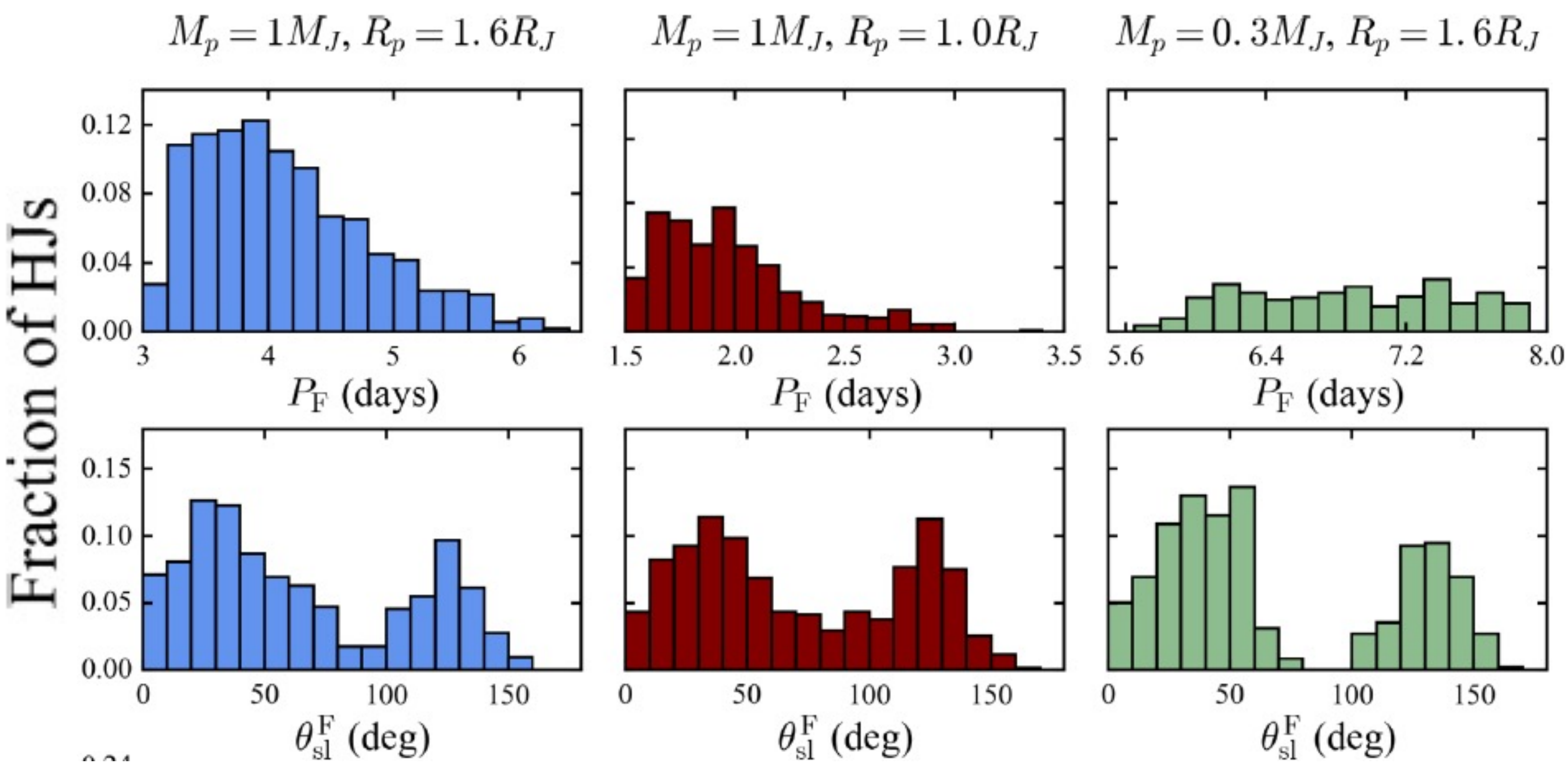
Add Tidal Dissipation….

Lidov-Kozai + Tidal Dissipation



Formation of Hot Jupiters via LK High-e Migration

Vick, DL & Anderson 2019



Hot Jupiter Formation Summary

High-Eccentricity Migration

Lidov-Kozai effect driven by external companion (planet or star) (see M.Vick+19)

-- Accounts for HJ pile-up at a few Roche radii

-- Explains the lack of nearby low-mass neighbors for most HJs (Huang+16)

-- Can naturally account for large stellar obliquities (spin-orbit dynamics important)

Early formation in protoplanetary disks

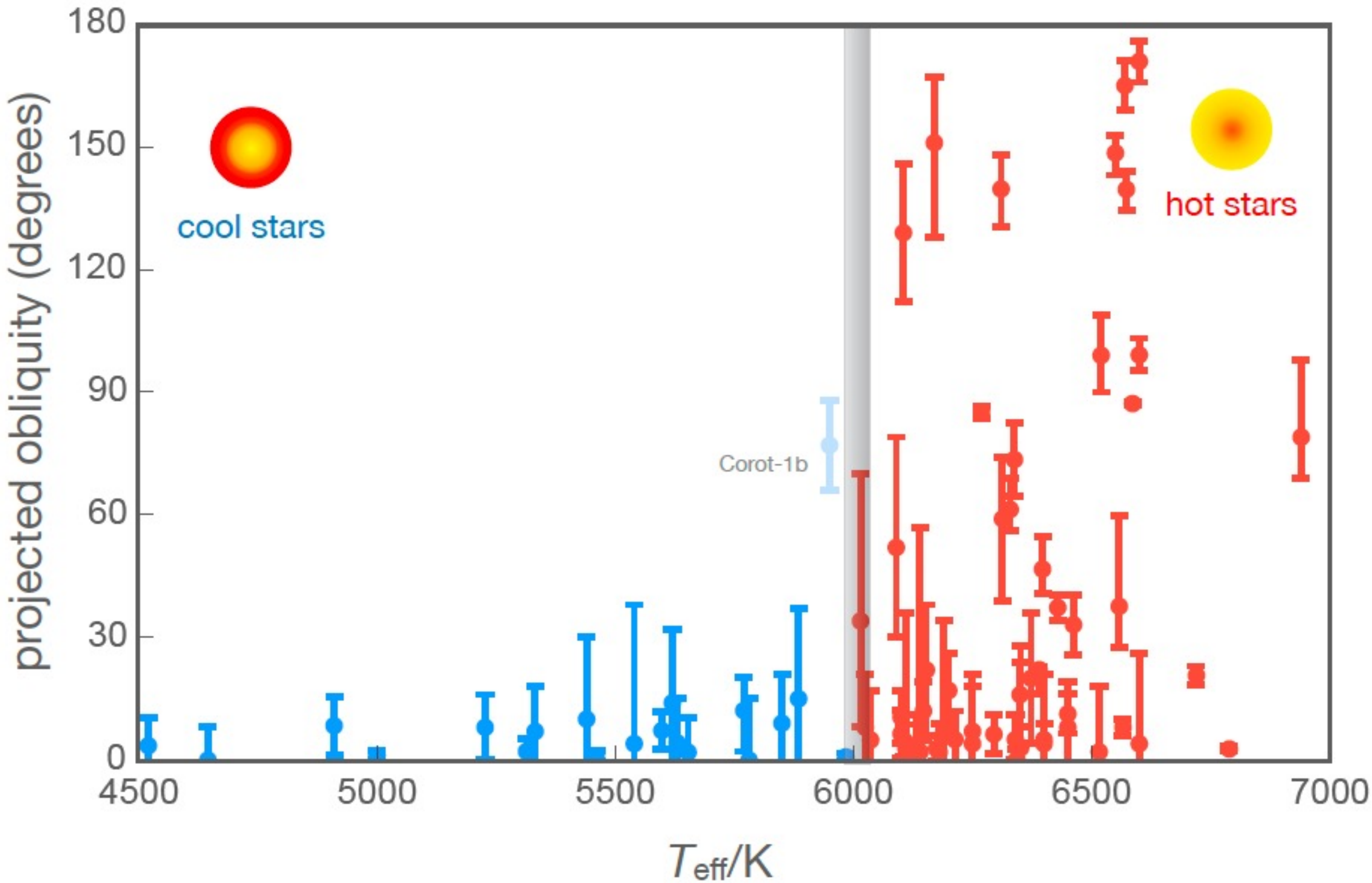
Disk-driven migration, in-situ formation

– Young proto-HJ candidates observed (e.g. CI Tau)

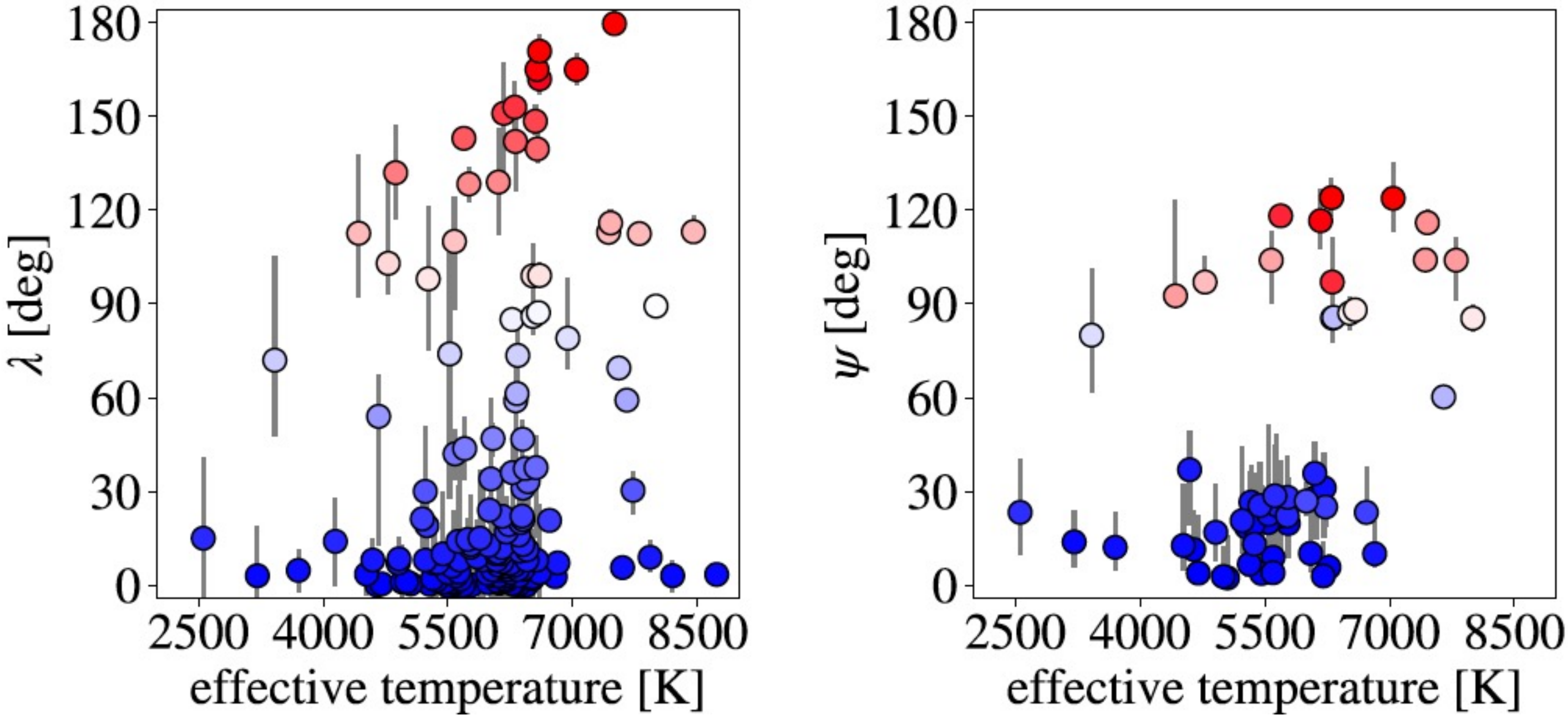
-- WASP-47b (HJ with small neighbors)

– Can misalignment (stellar spin vs orbit) be produced?

(e.g. Bate+10; Lai+11; Batygin 12; Batygin & Adams 12; Lai 14; Spalding & Batygin 14; Zanazzi & Lai 18)

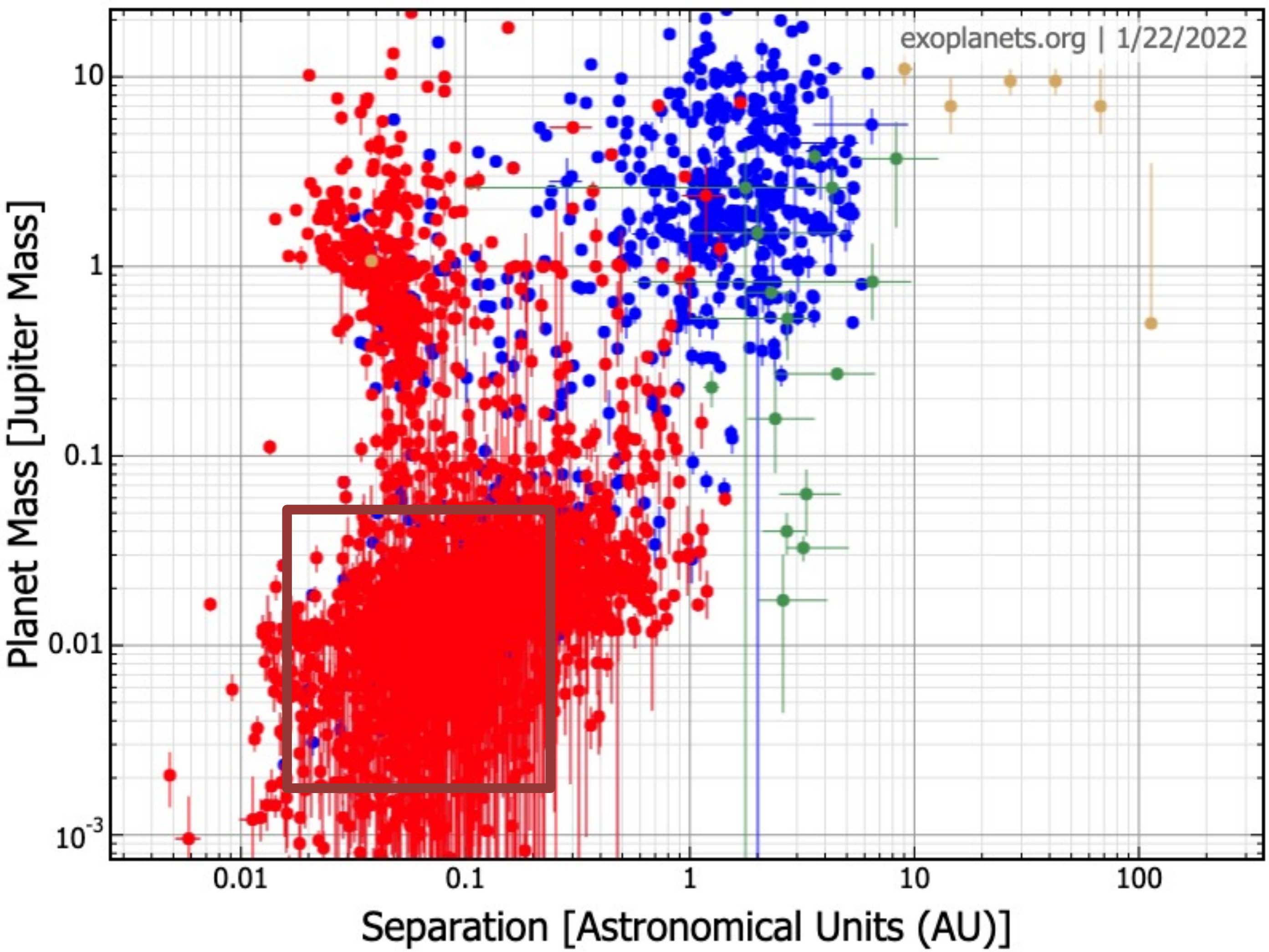


Spalding & Winn 2022

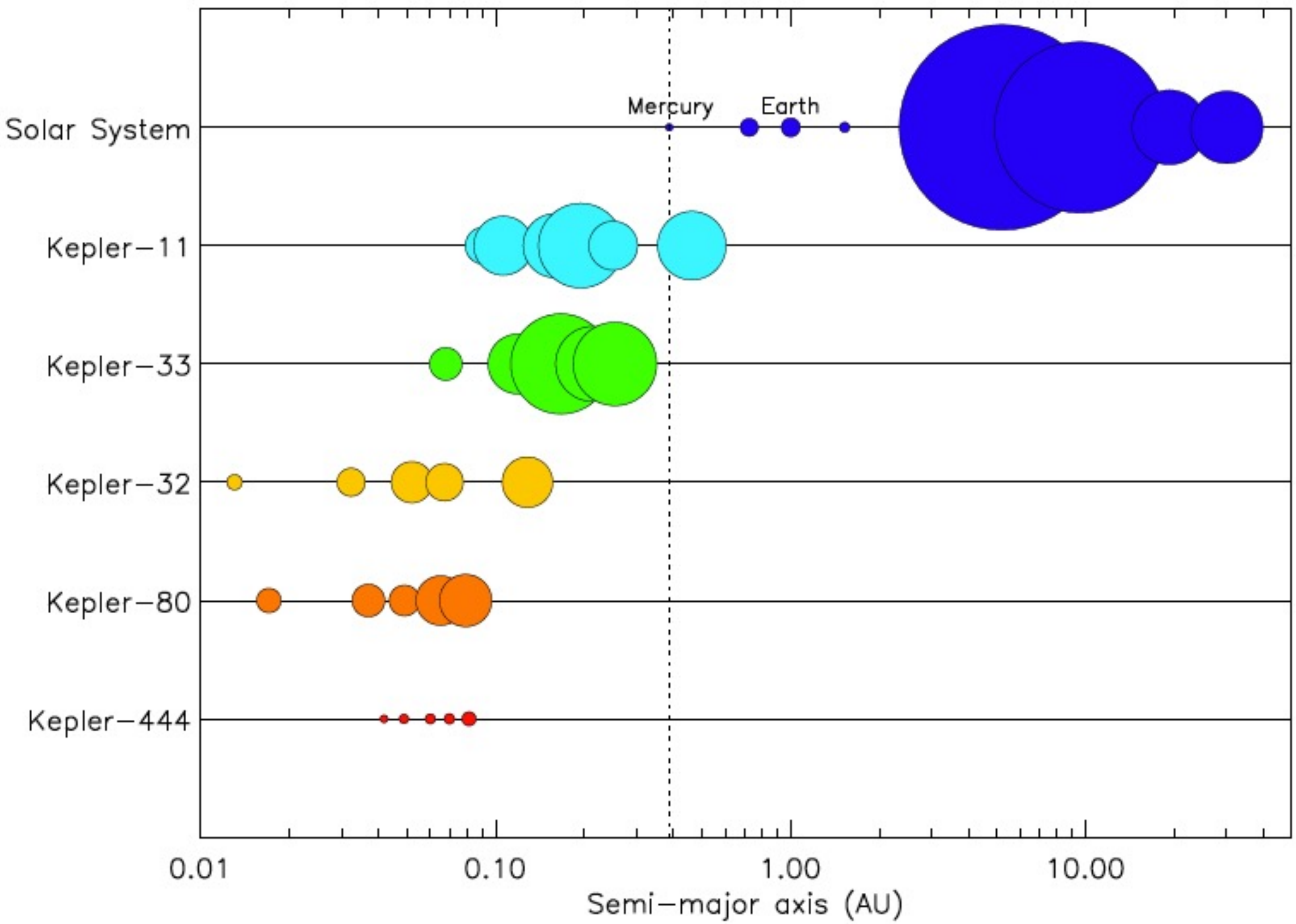


Albrecht et al. 2021

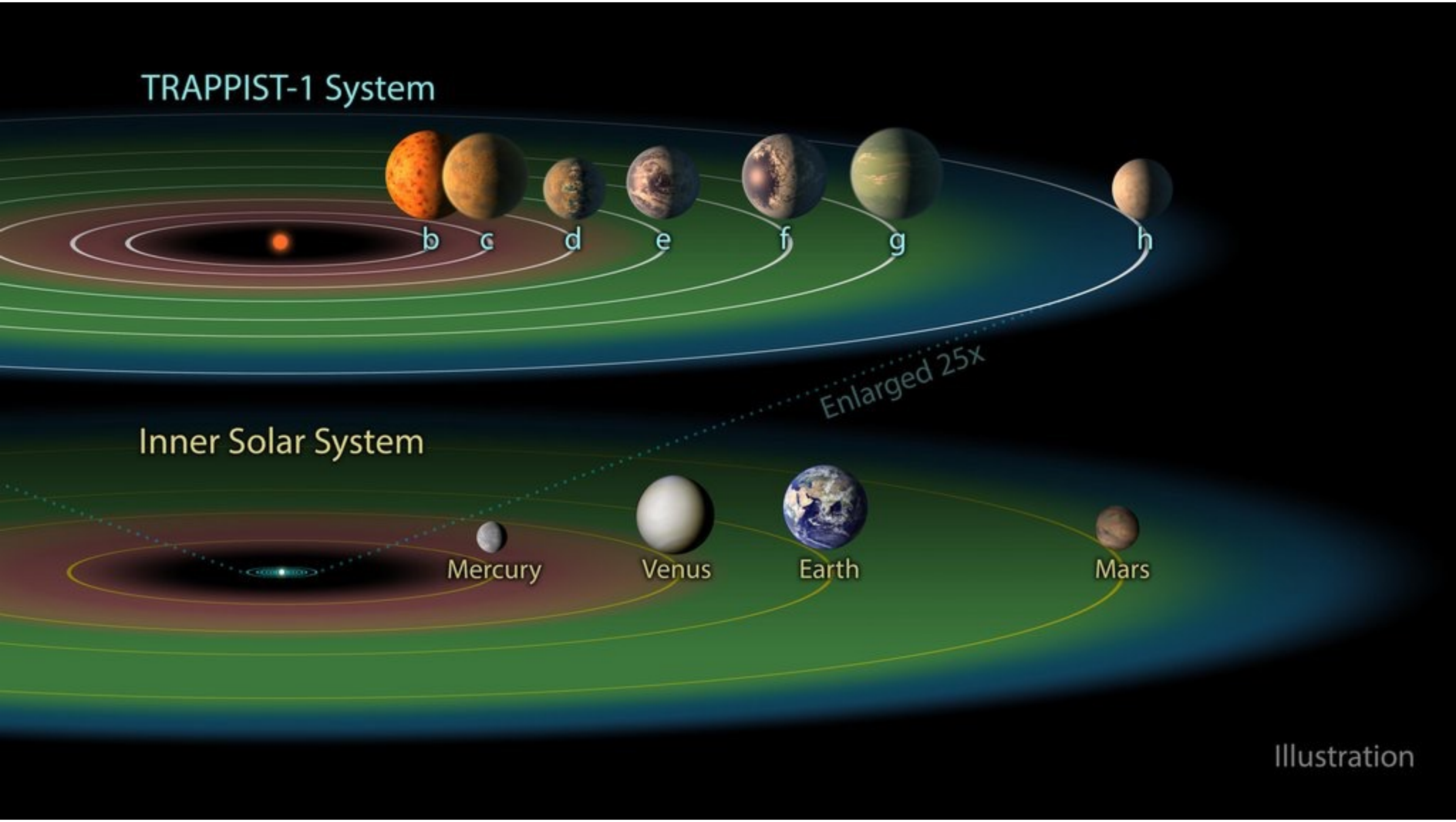
Super-Earths: 1-5 $R_{E,}$ P<100 days



Super-Earths (1-5 R_E) in Compact Systems (P<100 days)



Earth-like planets around M stars



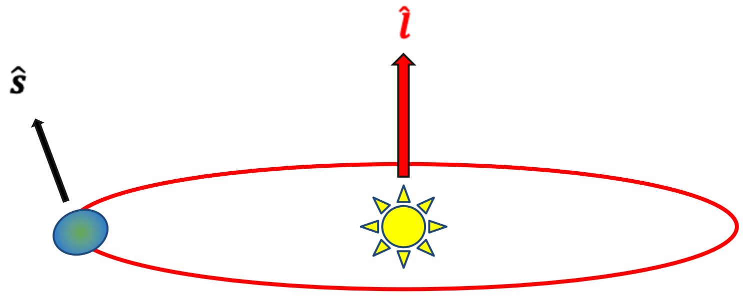
Formation of Close-in Super-Earths

-- Large-scale migration

-- In-Situ Formation

Characterizations: atmospheres…

What are the (expected) spin obliquities of Super-Earths?



Take-home message:

Super-Earths in multi-planet systems can have significant obliquities (despite strong tidal alignment torque)

Planetary Obliquities

Mercury	0.03
Venus	177.36
Earth	23.44
Mars	25.19
Jupiter	3.13
Saturn	26.73
Uranus	97.77
Neptune	28.32

Affect the surface conditions, climate

-- Insolation
-- Atmosphere circulation
-- Milankovich cycles

Reflect the formation/evolution history of the planet

-- Giant impacts/collisions?
-- Secular spin-orbit resonances/overlaps (to be discussed)

Obliquities of Exoplanets

Constraints for distant planetary-mass companions
(Bryan et al.2020,2021)

Future constraints for transiting planets?

Large obliquities can affect atmosphere conditions, transit signatures

Dynamical effects of finite obliquities: Tidal dissipation/heating, orbital evolution

Super-Earths: How to generate obliquities?

Planet Collisions

Likely have occurred for super-Earths in multi-planet systems

-- Many Kepler multi-planet systems are at the edge of dynamical instability (Volk & Gladman 2015; Pu & Wu 2015)

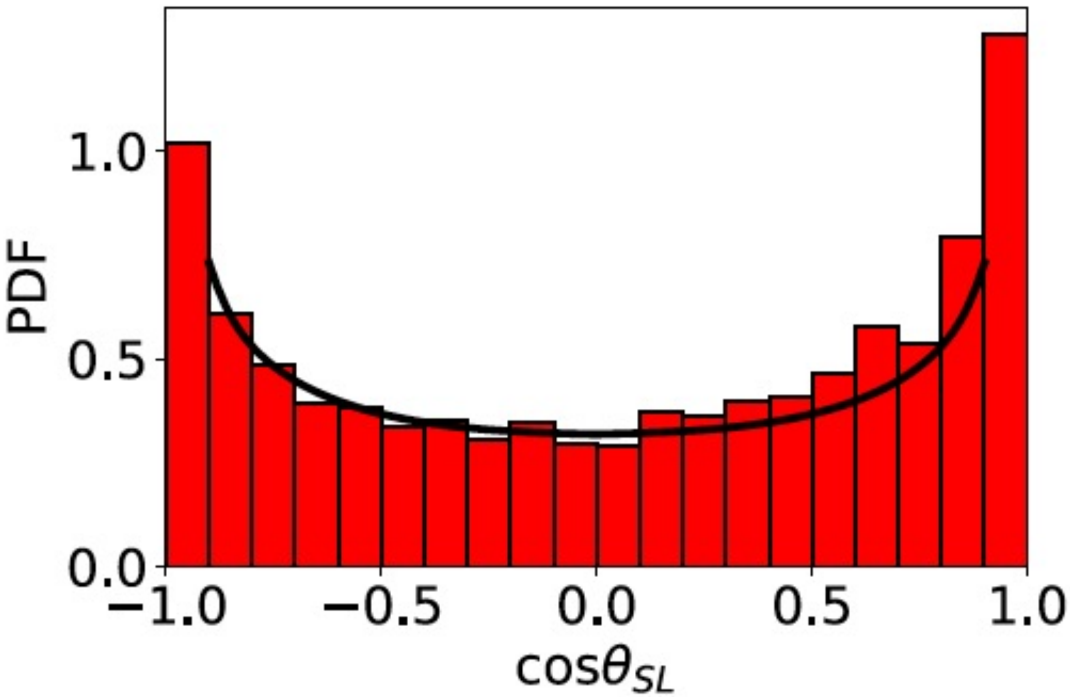
-- Super-Earths form in gas disks:
Migration and eccentricity damping → leading to densely-packed systems;
After the gas disk dissipates, mutual gravitational interaction causes instability;
➔ the system settles down to "metastable" state.

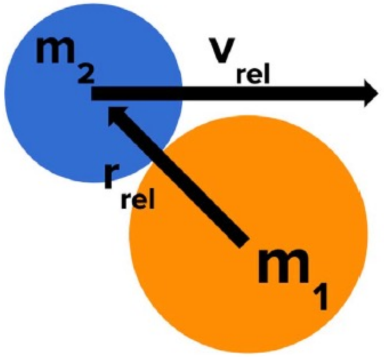
Outcomes of orbital instability of multiple super-Earths:

planet-planet collisions/mergers

Planetary Obliquities from Mergers

As long as initial mutual inclination >> R/a
==> Broad distribution of obliquities





Jiaru Li & Lai 2020

➔ Some super-Earths likely had large primordial obliquities

Tidal dissipation in planet

tends to synchronize/align the spin with orbit

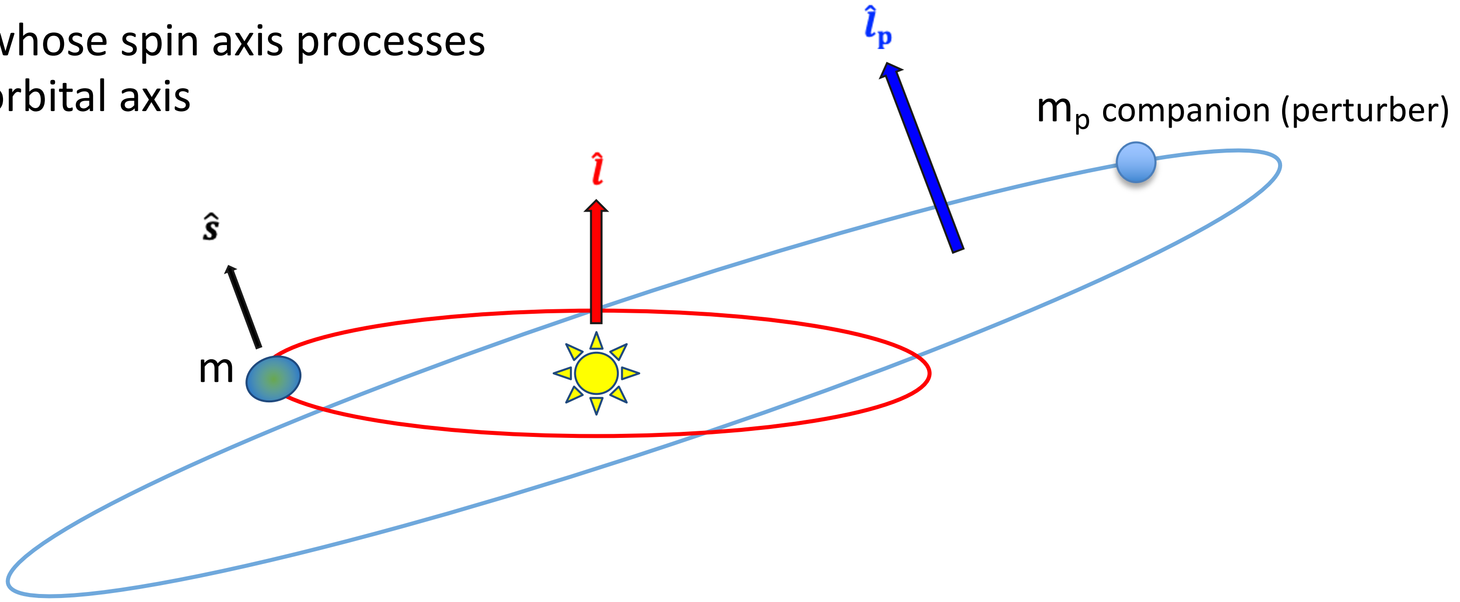
$$t_s \simeq 30 \left(\frac{Q}{10^3}\right) \left(\frac{M_\star}{M_\odot}\right)^{-3/2} \left(\frac{m}{4M_\oplus}\right) \left(\frac{R}{2R_\oplus}\right)^{-3} \left(\frac{a}{0.4\,\mathrm{au}}\right)^{9/2} \mathrm{Myr}$$

➔ Isolated super-Earths will have aligned spin

What about super-Earth with a companion (perturber)?

Dynamics of Colombo's Top

A rotating planet whose spin axis processes around a varying orbital axis

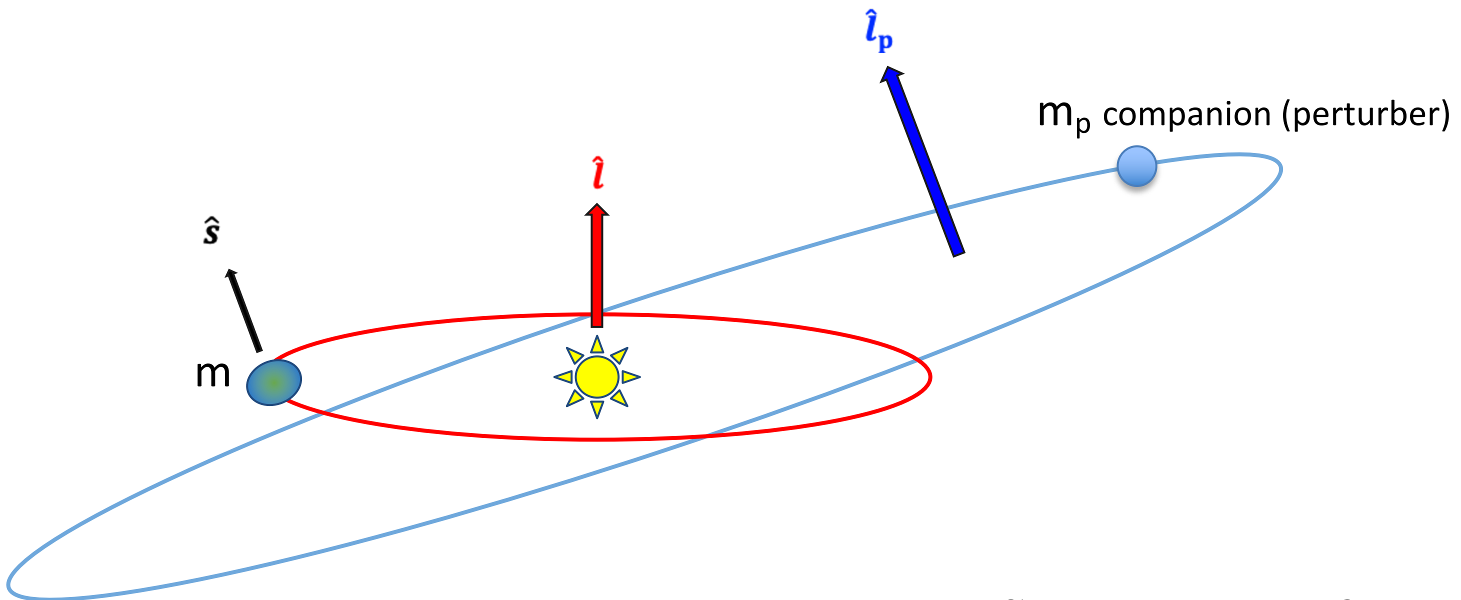


Colombo 66; Peale 69; Ward 75; Henrard & Murigande 87…

Su & Lai 2021, ApJ
2022, MNRAS
2022, arXiv

Yubo Su (Ph.D.22)

Dynamics of Colombo's Top



$$L_p \gg L \gg S \quad \Longrightarrow \mathbf{L}_p \text{ is fixed}$$

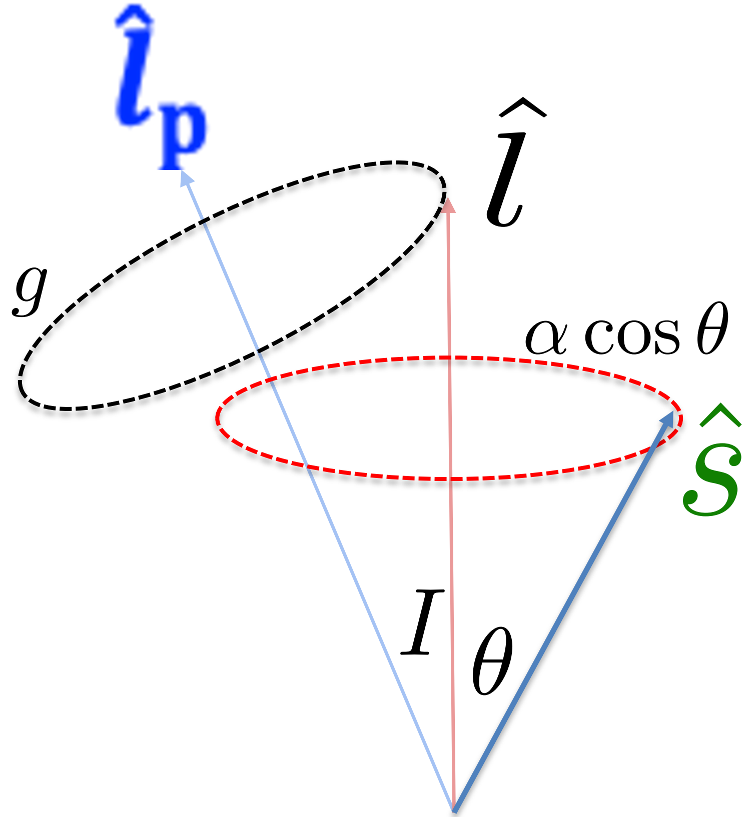
$$\frac{\mathrm{d}\hat{\mathbf{l}}}{\mathrm{d}t} = \omega_{\mathrm{lp}} \left(\hat{\mathbf{l}} \cdot \hat{\mathbf{l}}_{\mathrm{p}}\right) \left(\hat{\mathbf{l}} \times \hat{\mathbf{l}}_{\mathrm{p}}\right) \equiv -g \left(\hat{\mathbf{l}} \times \hat{\mathbf{l}}_{\mathrm{p}}\right), \qquad \text{(Orbit precession)}$$

$$\omega_{\mathrm{lp}} \equiv -\frac{g}{\cos I} = \frac{3m_{\mathrm{p}}}{4M_\star} \left(\frac{a}{a_{\mathrm{p}}}\right)^3 n$$

$$\frac{\mathrm{d}\hat{\mathbf{s}}}{\mathrm{d}t} = \omega_{\mathrm{sl}} \left(\hat{\mathbf{s}} \cdot \hat{\mathbf{l}}\right) \left(\hat{\mathbf{s}} \times \hat{\mathbf{l}}\right) \equiv \alpha \left(\hat{\mathbf{s}} \cdot \hat{\mathbf{l}}\right) \left(\hat{\mathbf{s}} \times \hat{\mathbf{l}}\right), \qquad \text{(Spin precession)}$$

$$\omega_{\mathrm{sl}} \equiv \alpha = \frac{3GJ_2 m R^2 M_\star}{2a^3 I \Omega_{\mathrm{s}}} = \frac{3k_q}{2k} \frac{M_\star}{m} \left(\frac{R}{a}\right)^3 \Omega_{\mathrm{s}}$$

In general, the obliquity varies in time…

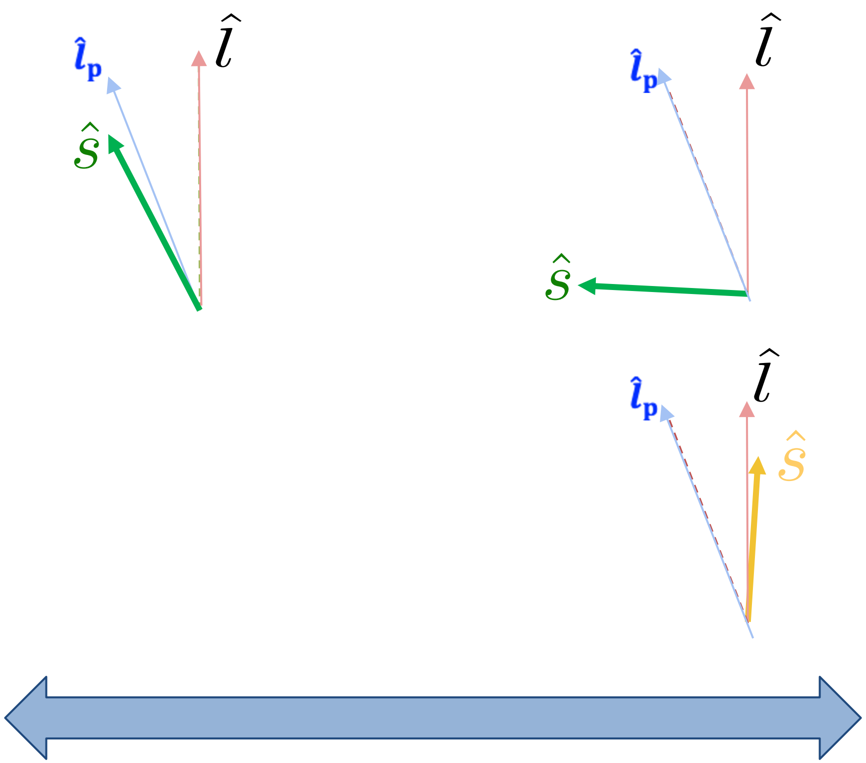


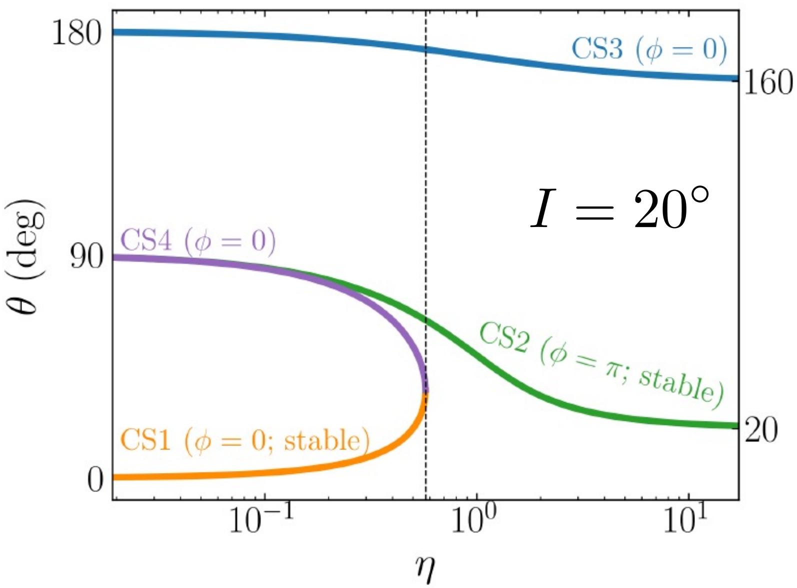
In general, the obliquity varies in time… Is there equilibrium?

Equilibria: Cassini States

(θ =const, or $\hat{s}$ =const in rotating frame)

$$\left(\frac{\mathrm{d}\hat{\mathbf{s}}}{\mathrm{d}t}\right)_{\mathrm{rot}} = \alpha\left(\hat{\mathbf{s}}\cdot\hat{\mathbf{l}}\right)\left(\hat{\mathbf{s}}\times\hat{\mathbf{l}}\right) + g\left(\hat{\mathbf{s}}\times\hat{\mathbf{l}}_{\mathrm{p}}\right) = 0$$



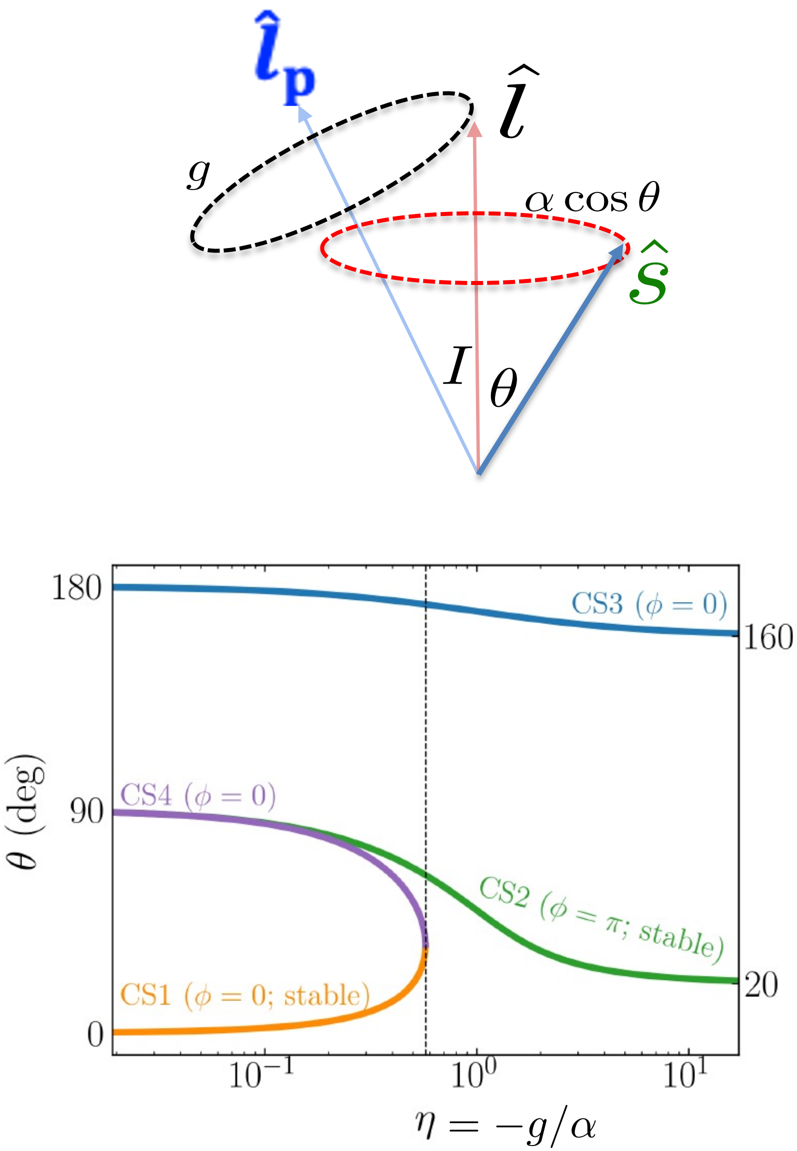


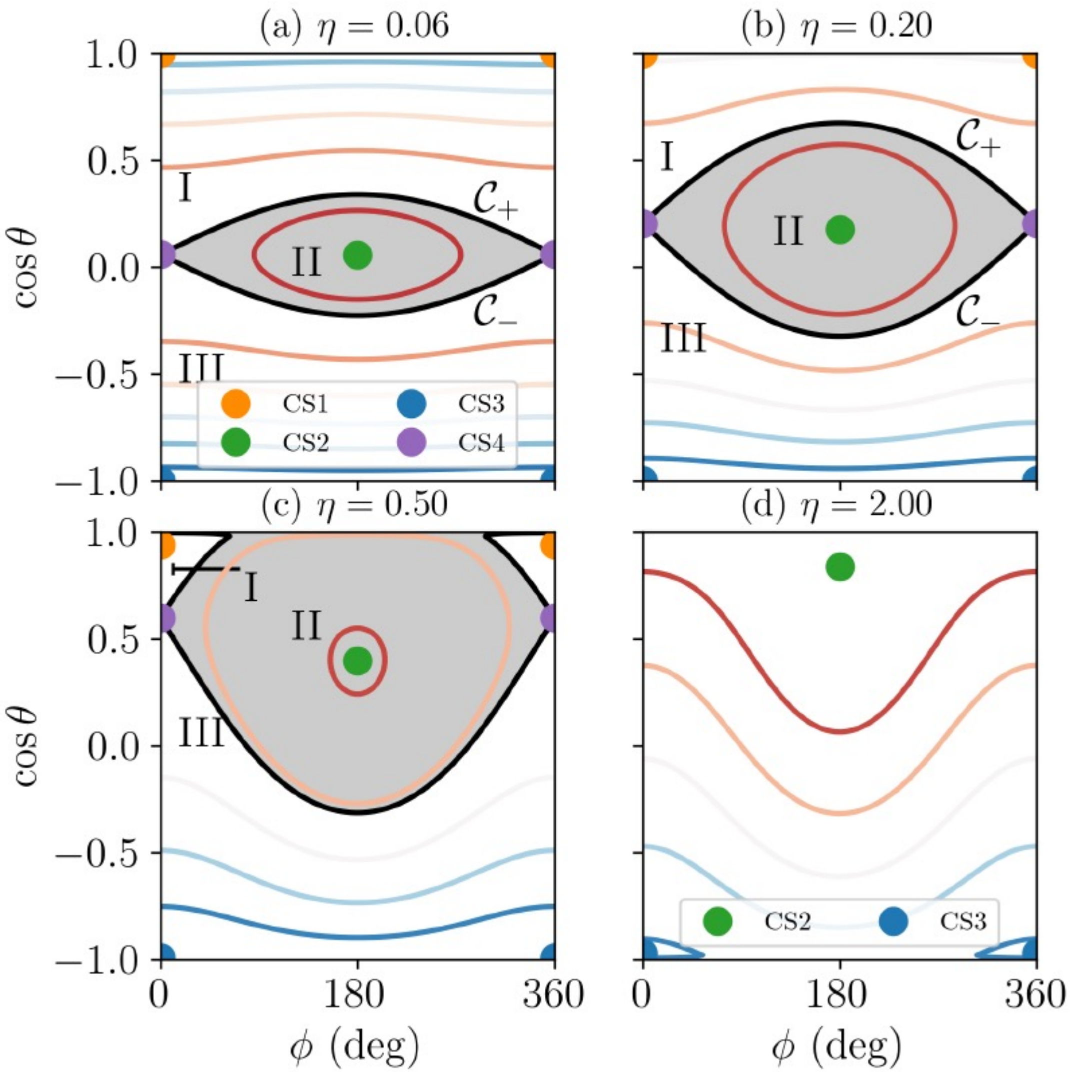
$$\eta \equiv -\frac{g}{\alpha}$$

$\eta \gg 1$
(fast orbital precession)

$\eta \ll 1$
(fast spin precession)

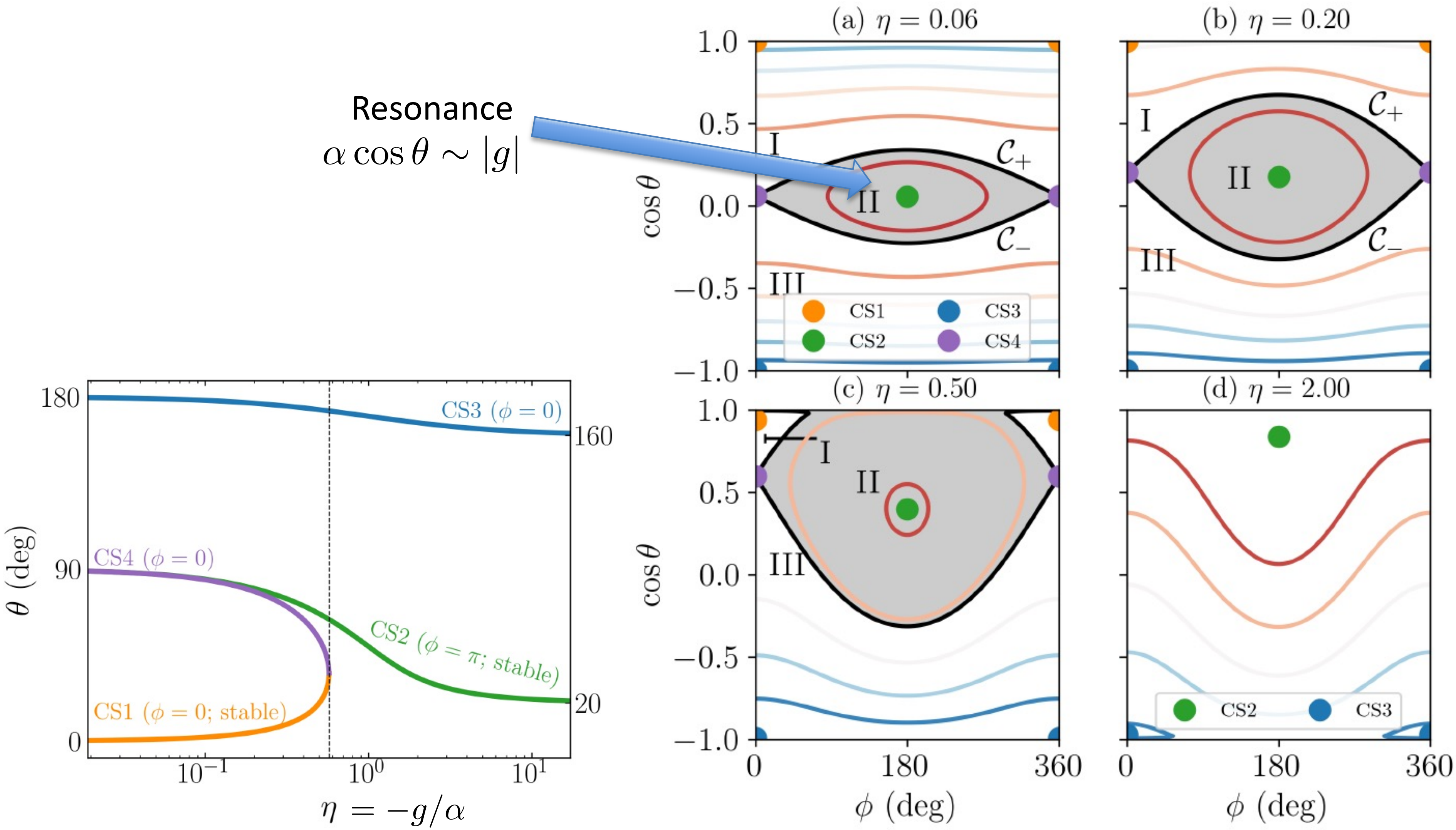
Phase portrait and Spin-Orbit Resonance





Phase portrait and Spin-Orbit Resonance

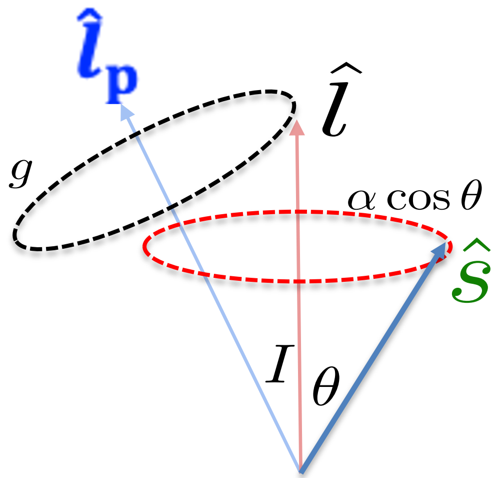
Resonance
$\alpha \cos\theta \sim |g|$



Add tidal torque...

Tidal torque tries to push $\hat{s}$ toward $\hat{l}$, but $\hat{l}$ is changing...

$\hat{S}$ evolves toward one of the equilibria (Cassini states)



$$\omega_{\rm sl} \equiv \alpha = \frac{3GJ_2 m R^2 M_\star}{2a^3 I \Omega_{\rm s}} = \frac{3k_q}{2k}\frac{M_\star}{m}\left(\frac{R}{a}\right)^3 \Omega_{\rm s}$$

Spin precession

$$\omega_{\rm lp} \equiv -\frac{g}{\cos I} = \frac{3m_{\rm p}}{4M_\star}\left(\frac{a}{a_{\rm p}}\right)^3 n.$$

Orbital precession

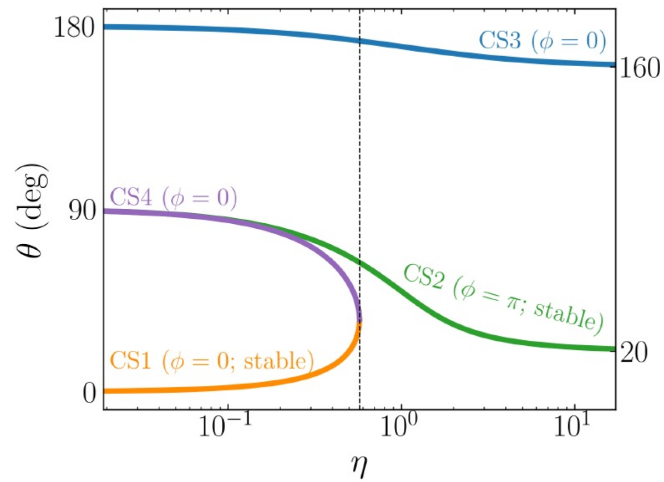
$$\eta \equiv -\frac{g}{\alpha} \sim 0.06\left(\frac{a}{0.04\,\mathrm{au}}\right)^3 \left(\frac{m_p}{10M_\oplus}\right)\left(\frac{1.3a}{a_p}\right)^3$$

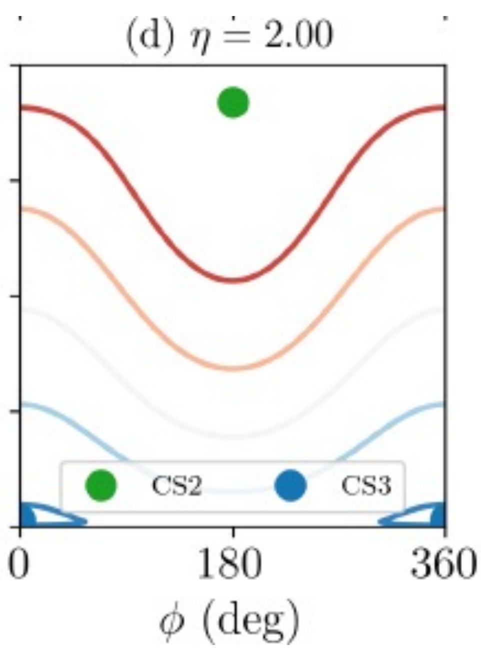
Add tidal torque...

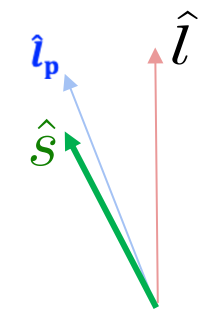
$$\eta \equiv -\frac{g}{\alpha} \sim 0.06 \left(\frac{a}{0.04\,\mathrm{au}}\right)^3 \left(\frac{m_p}{10M_\oplus}\right) \left(\frac{1.3a}{a_p}\right)^3$$

For $\eta \gtrsim 1$ (fast orbital precession, strong perturber)

All initial $\hat{S}$ evolves towards CS2





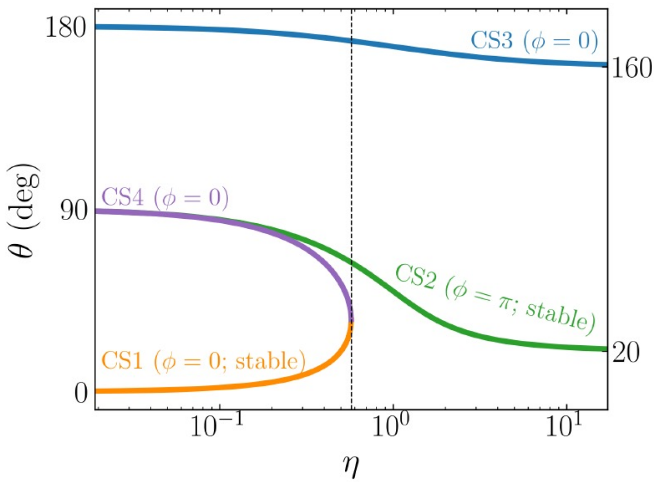


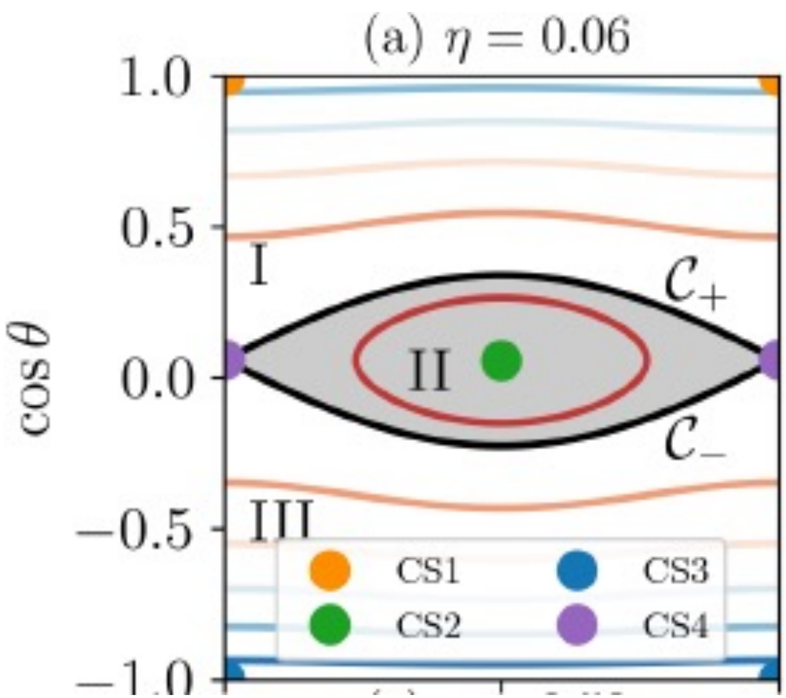
Add tidal torque…

$$\eta \equiv -\frac{g}{\alpha} \sim 0.06 \left(\frac{a}{0.04\,\mathrm{au}}\right)^3 \left(\frac{m_p}{10M_\oplus}\right) \left(\frac{1.3a}{a_p}\right)^3$$

For $\eta \lesssim 1$ (fast spin precession, weak perturber):

$\hat{S}$ evolves towards CS1 or CS2

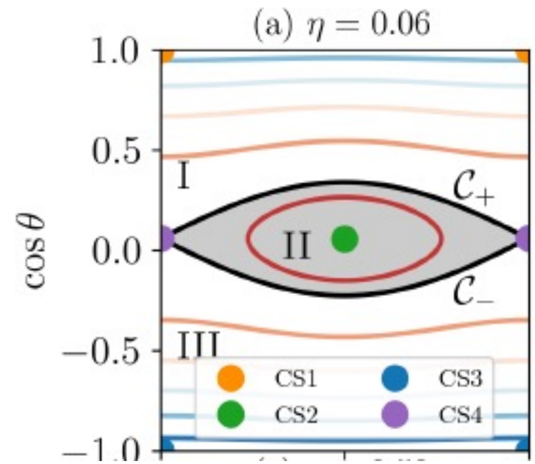


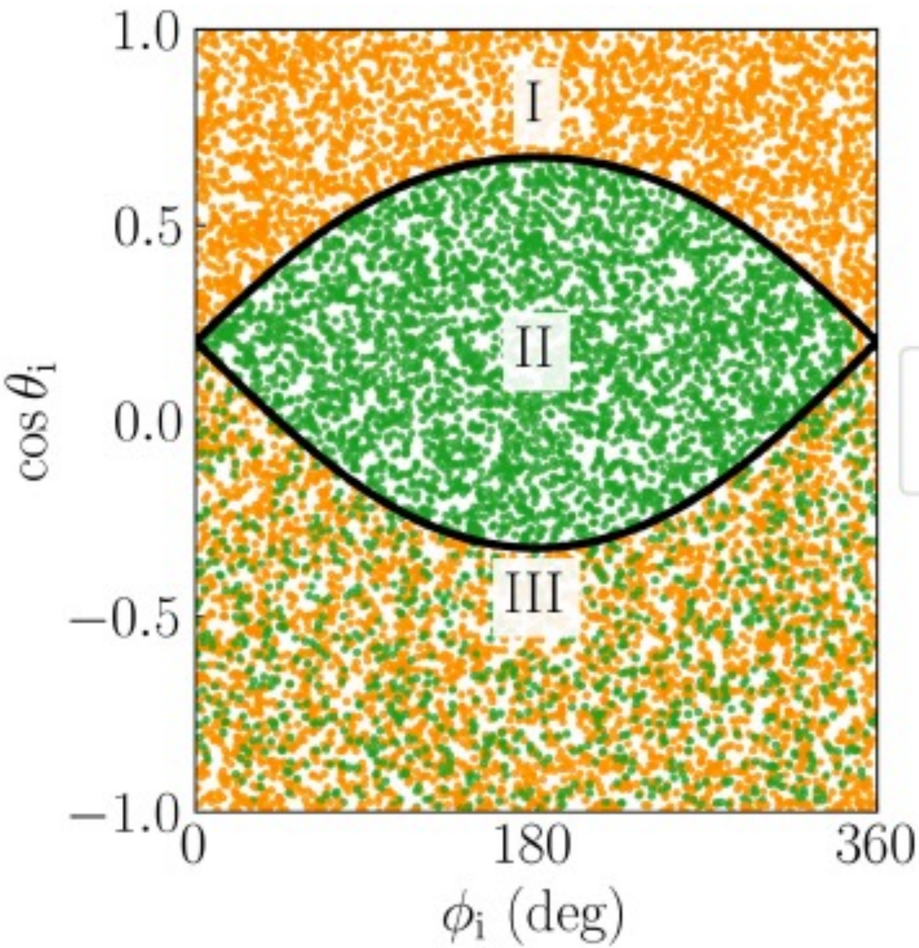


Final Outcomes with tidal alignment torque

For $\eta \lesssim 1$ (fast spin precession, weak perturber):

$\hat{S}$ evolves towards CS1 or CS2



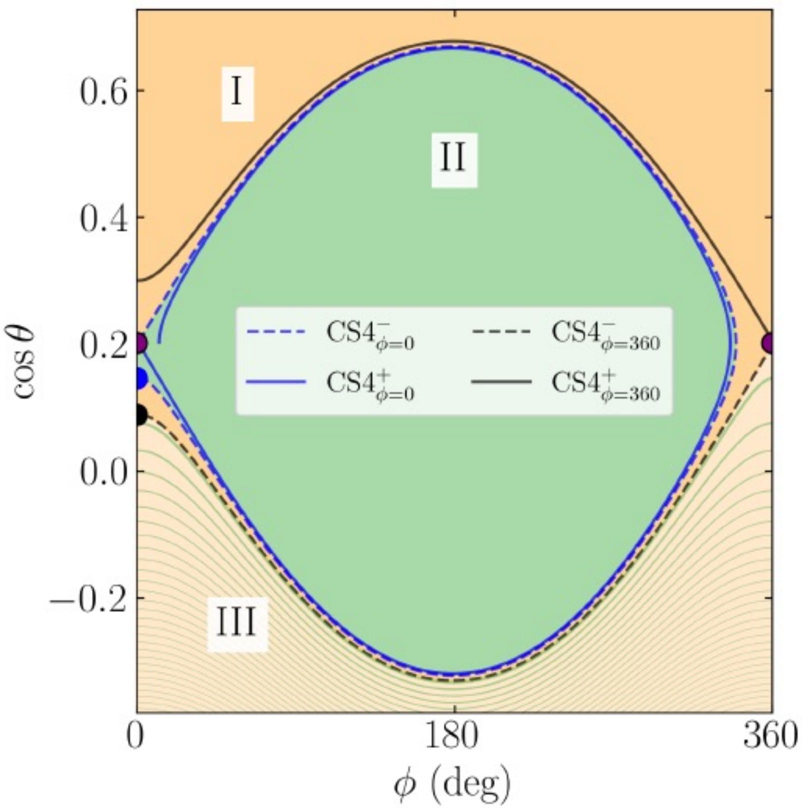


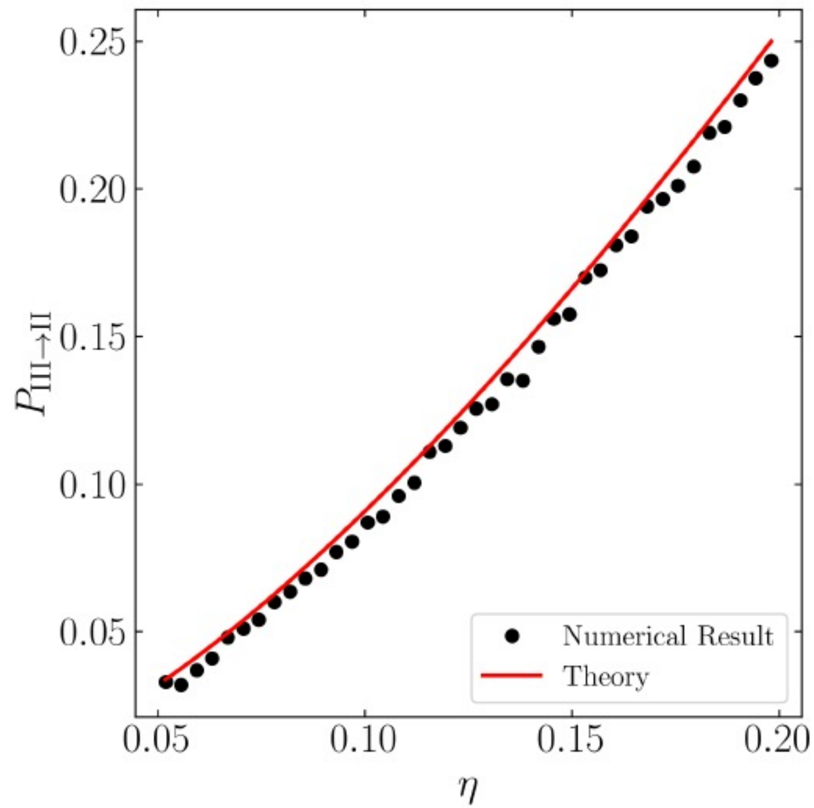
Zone I → CS1 (low obliquity)

Zone II → CS2 (high obliquity)

Zone III → Either CS1 or CS2, probabilistic

Separatrix Crossing: Transition Probability

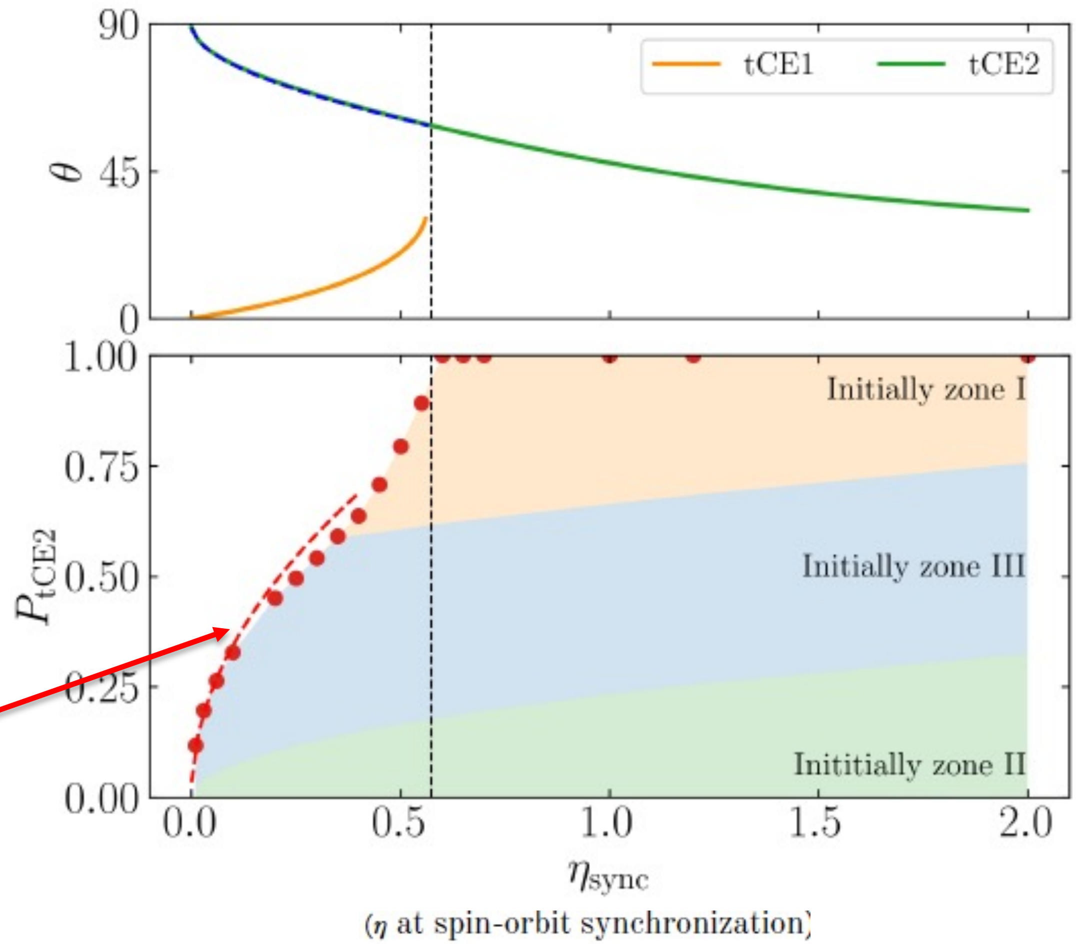




Recap:

In the presence of companion, tidal torque does not erase obliquity;
Instead, it drives the spin axis towards a "tidal-Cassini" equilibrium, tCS1 or tCS2, which can have appreciable obliquity

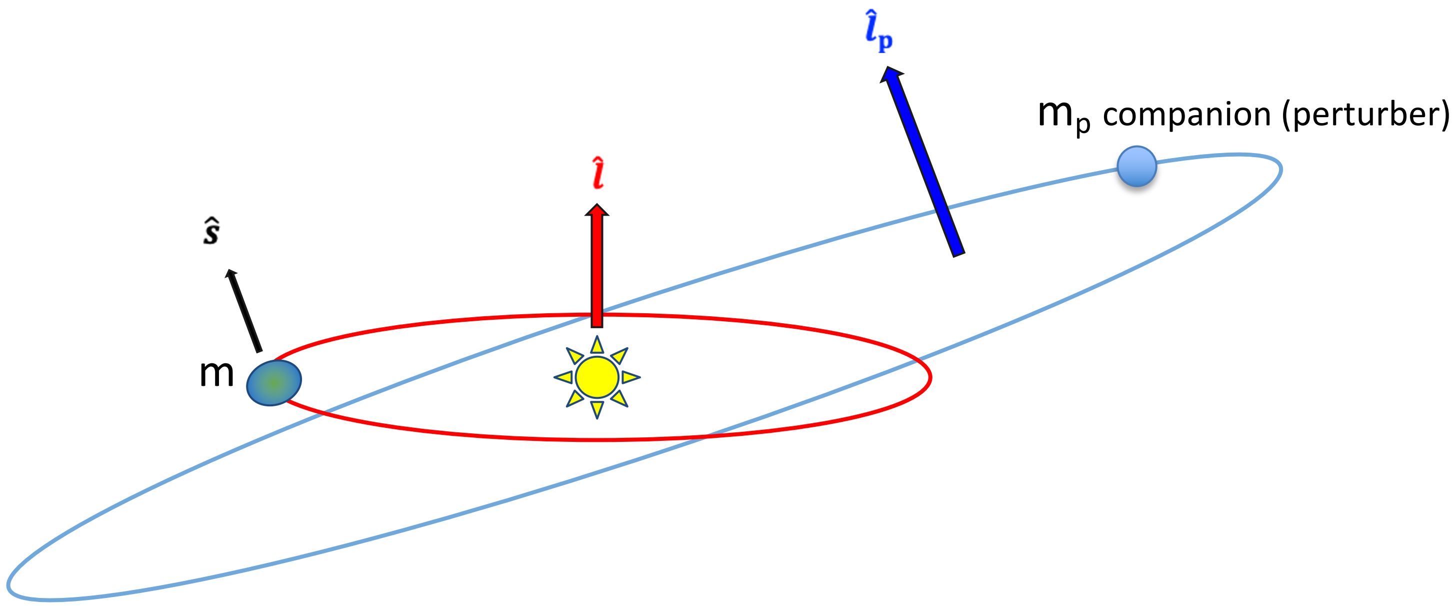
Starting from isotropic spin orientations:



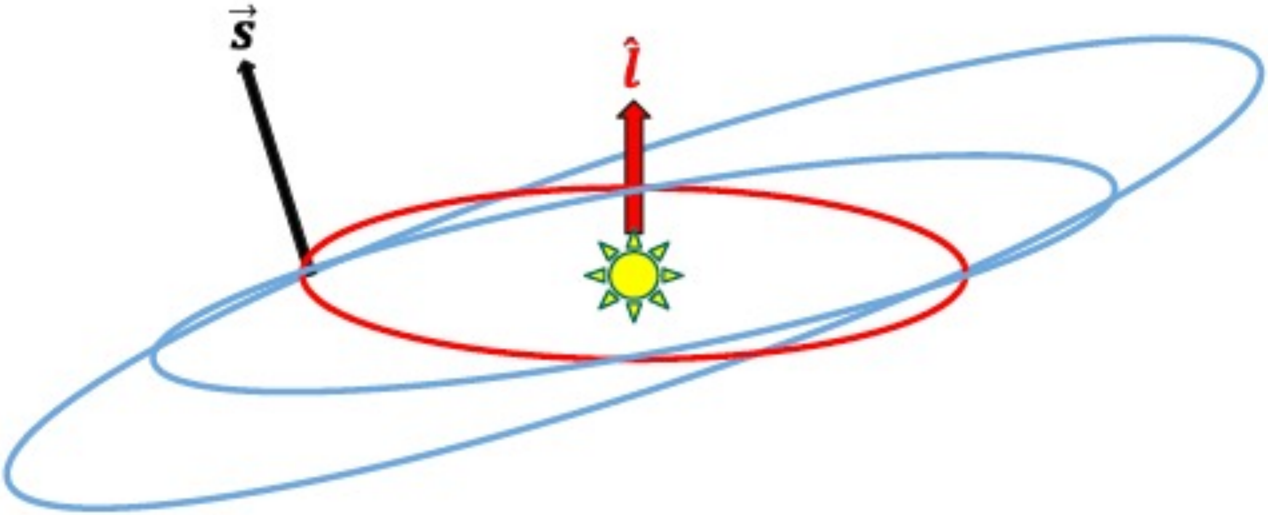
Probability of evolving
Into tCE2

$$P_{\mathrm{tCE2}} \simeq \frac{4\sqrt{\eta_{\mathrm{sync}}}\sin I}{\pi}\left[\sqrt{n/\Omega_{\mathrm{s,i}}} + \frac{3}{2\left(1+\sqrt{n/\Omega_{\mathrm{s,i}}}\right)}\right]$$

So far…



What happens if the super-Earth has 2 (or more) companions?

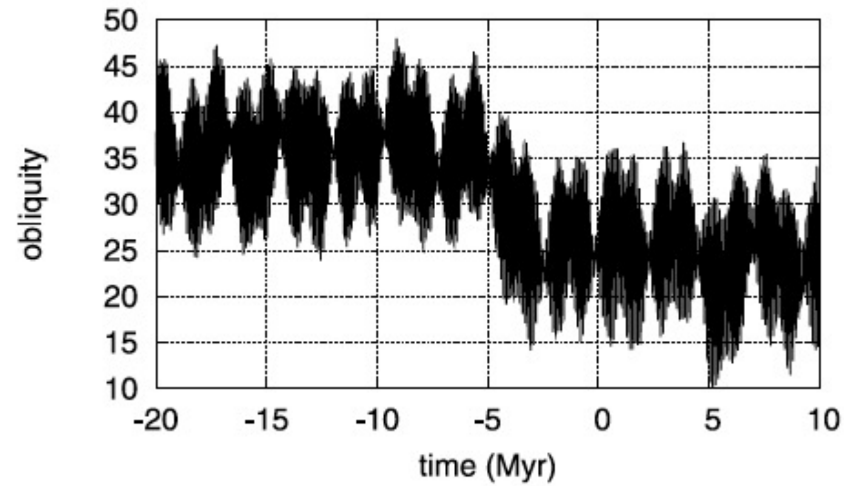


$$\frac{d\hat{\mathbf{s}}}{dt} = \alpha\left(\hat{\mathbf{s}}\cdot\hat{\mathbf{l}}\right)\left(\hat{\mathbf{s}}\times\hat{\mathbf{l}}\right)$$

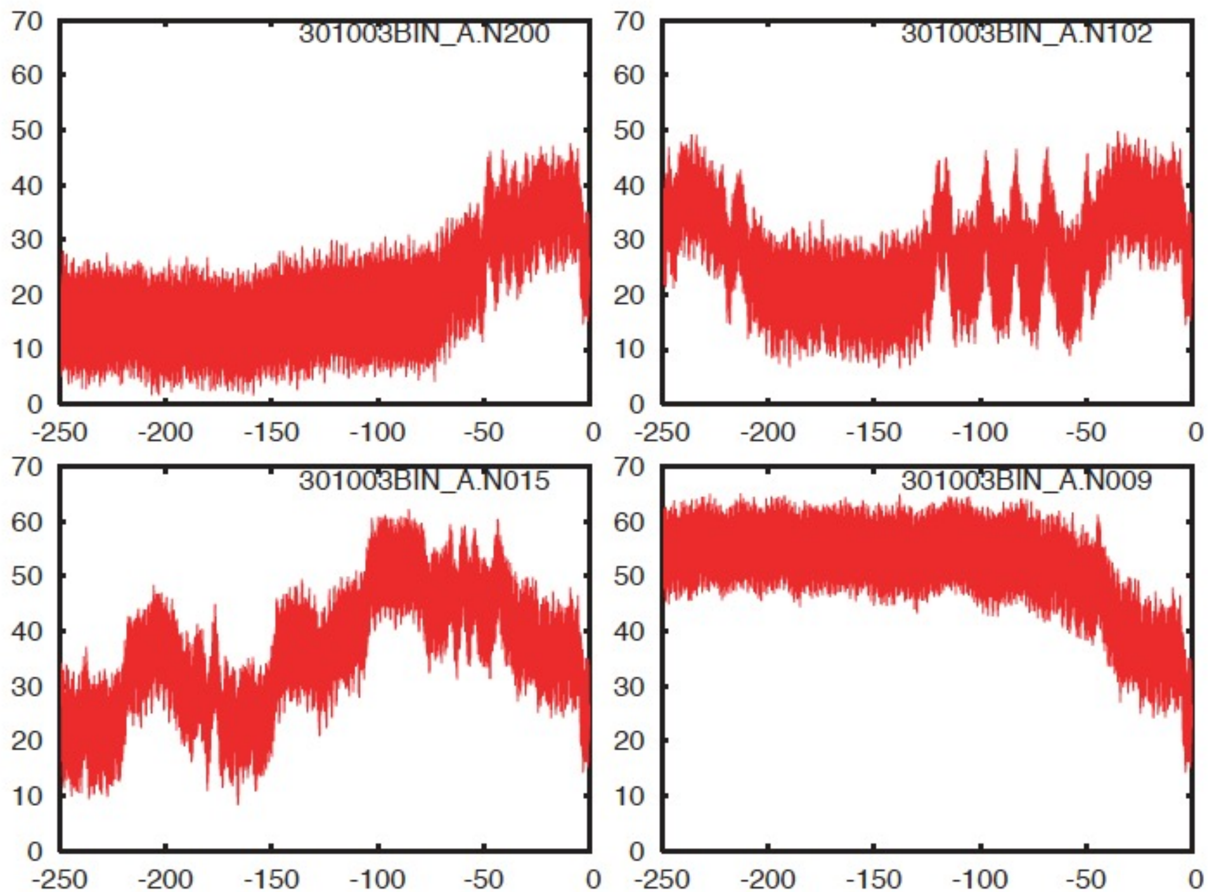
$\hat{\mathbf{l}}$ precesses/wobbles with 2 (or more) frequencies

Mars' obliquity evolution

Chaotic, due to overlapping resonances

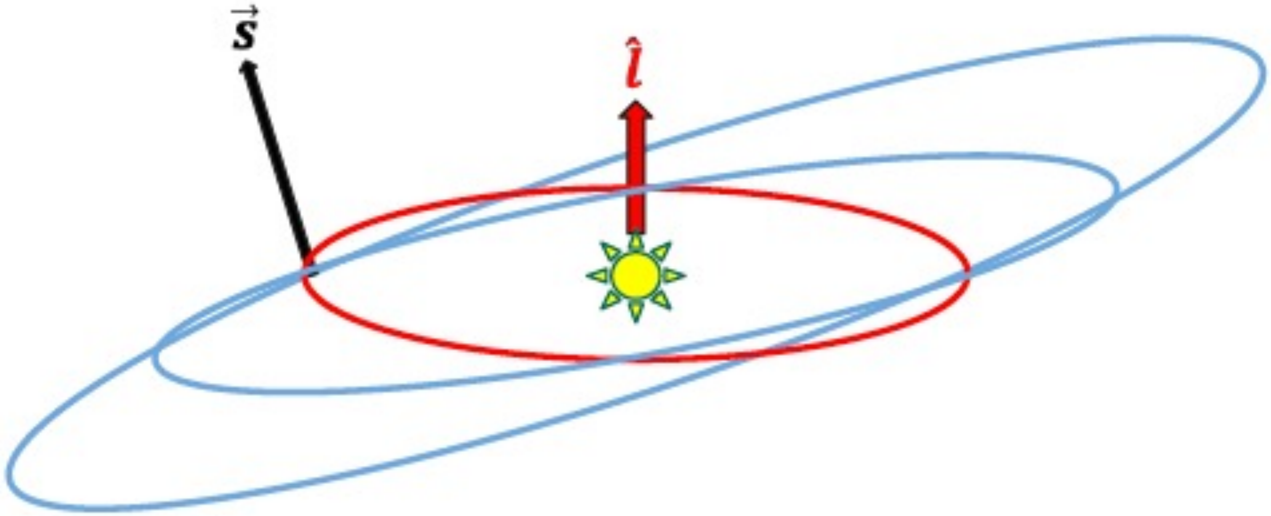


Possible realizations of Mars' obliquity evolution over the last 200 Myrs.



Laskar et al. 2004

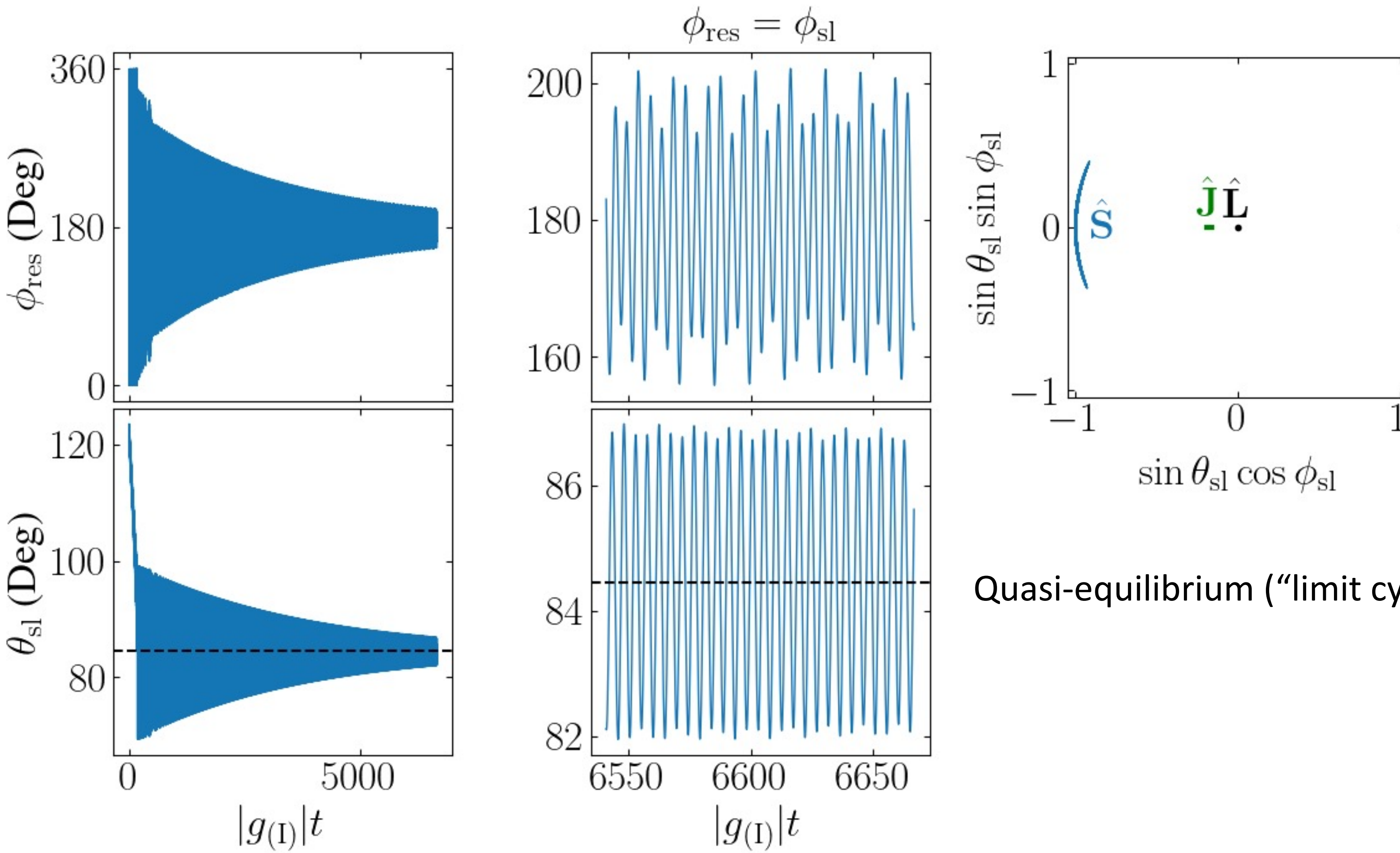
Super-Earth with 2 companions, including tidal alignment torque



$$\frac{d\hat{\mathbf{s}}}{dt} = \alpha \left(\hat{\mathbf{s}} \cdot \hat{\mathbf{l}}\right) \left(\hat{\mathbf{s}} \times \hat{\mathbf{l}}\right)$$ + tidal torque

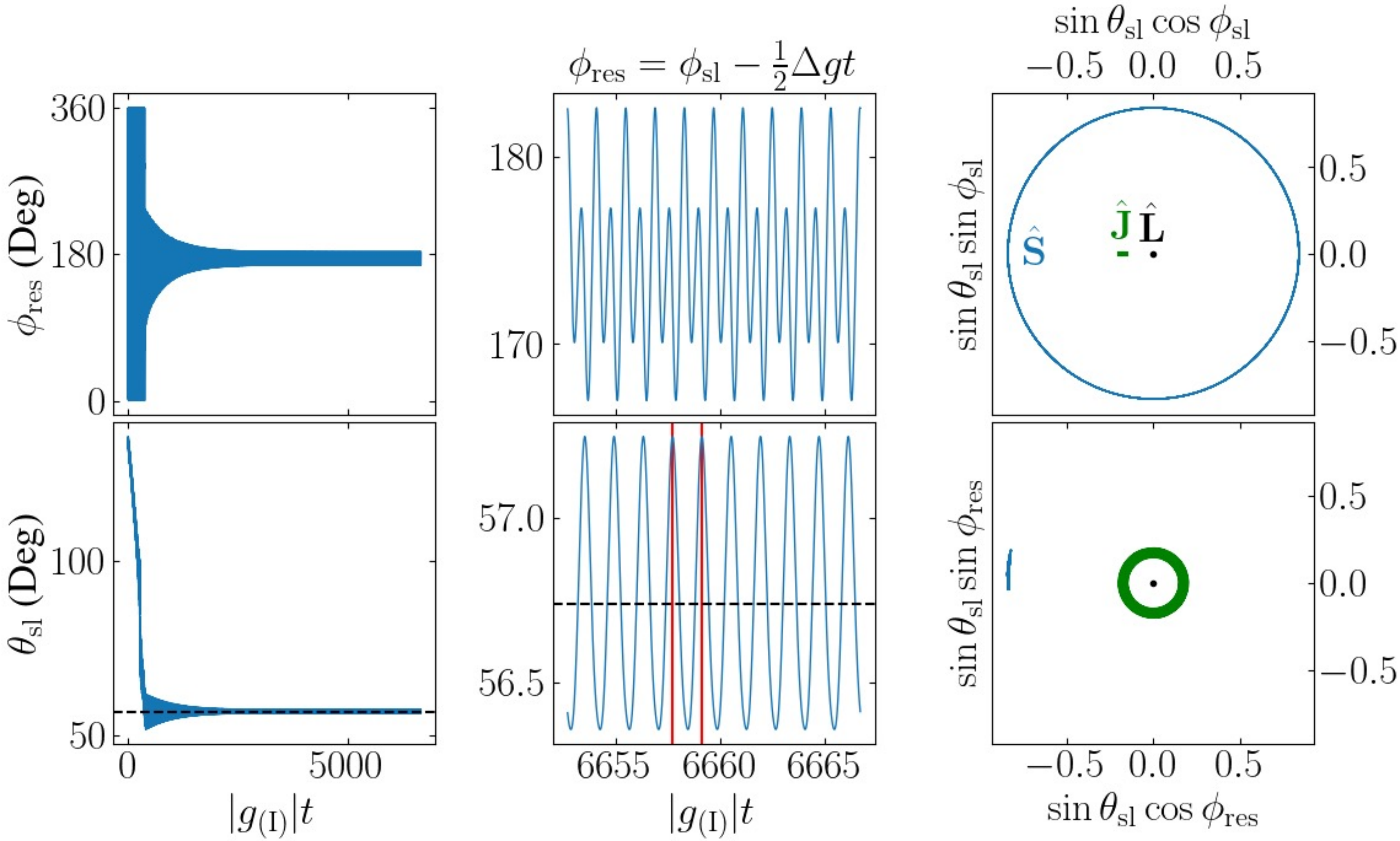
$\hat{\mathbf{l}}$ precesses/wobbles with 2 frequencies

Spin axis evolution of a super-Earth with 2 companions, including tidal torque



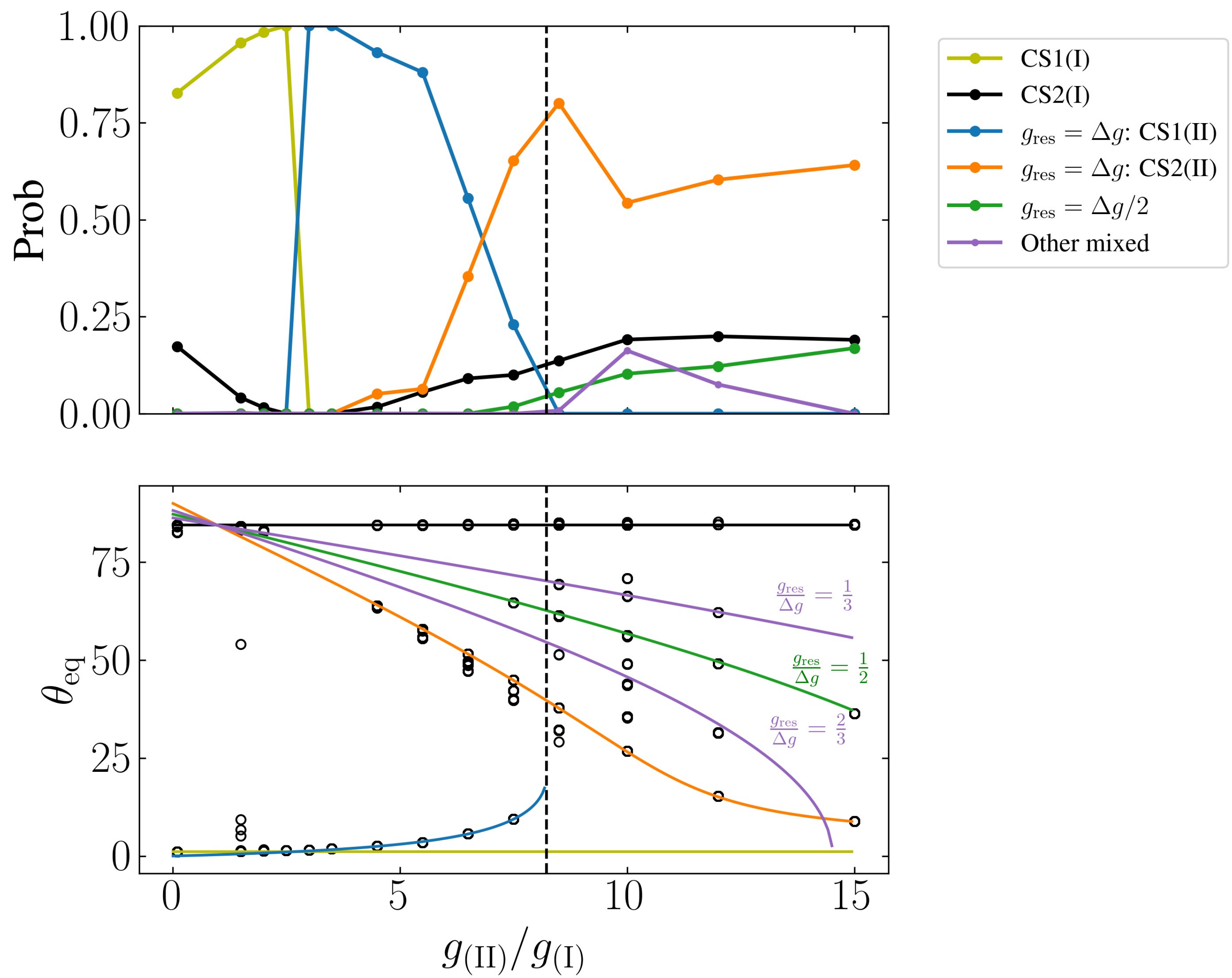
Quasi-equilibrium ("limit cycle")

Spin axis evolution of a super-Earth with 2 companions, including tidal torque



Mixed-mode “equilibrium”

Spin axis evolution of a super-Earth with 2 companions, including tidal torque



Recap:

In the presence of companion(s), tidal torque does not erase obliquity;
Instead, it drives the spin axis towards one of the "tidal-Cassini equilibria",
maintaining a permanent obliquity

Dynamical roles of super-Earth obliquities:

-- Tidal heating
-- Orbital decay
e.g. formation of ultra-short period planets (?)

See Millholland & Spalding 2020
Su & Lai 2021 (Paper II)

Summary

Hot Jupiters:

Formation/migration mechanisms?

High-eccentricity migration via Lidov-Kozai driven by external companion is promising

Spin-orbit misalignment (i.e. stellar obliquity): spin-orbit dynamics important, chaos

Super-Earths:

Likely have experienced collisions

➔broad distribution of primordial planet obliquities

With tidal alignment torque, spin axis evolves towards one of the "tidal-Cassini" equilibria, with non-trivial obliquity

➔ Super-earths may/likely have appreciable obliquities