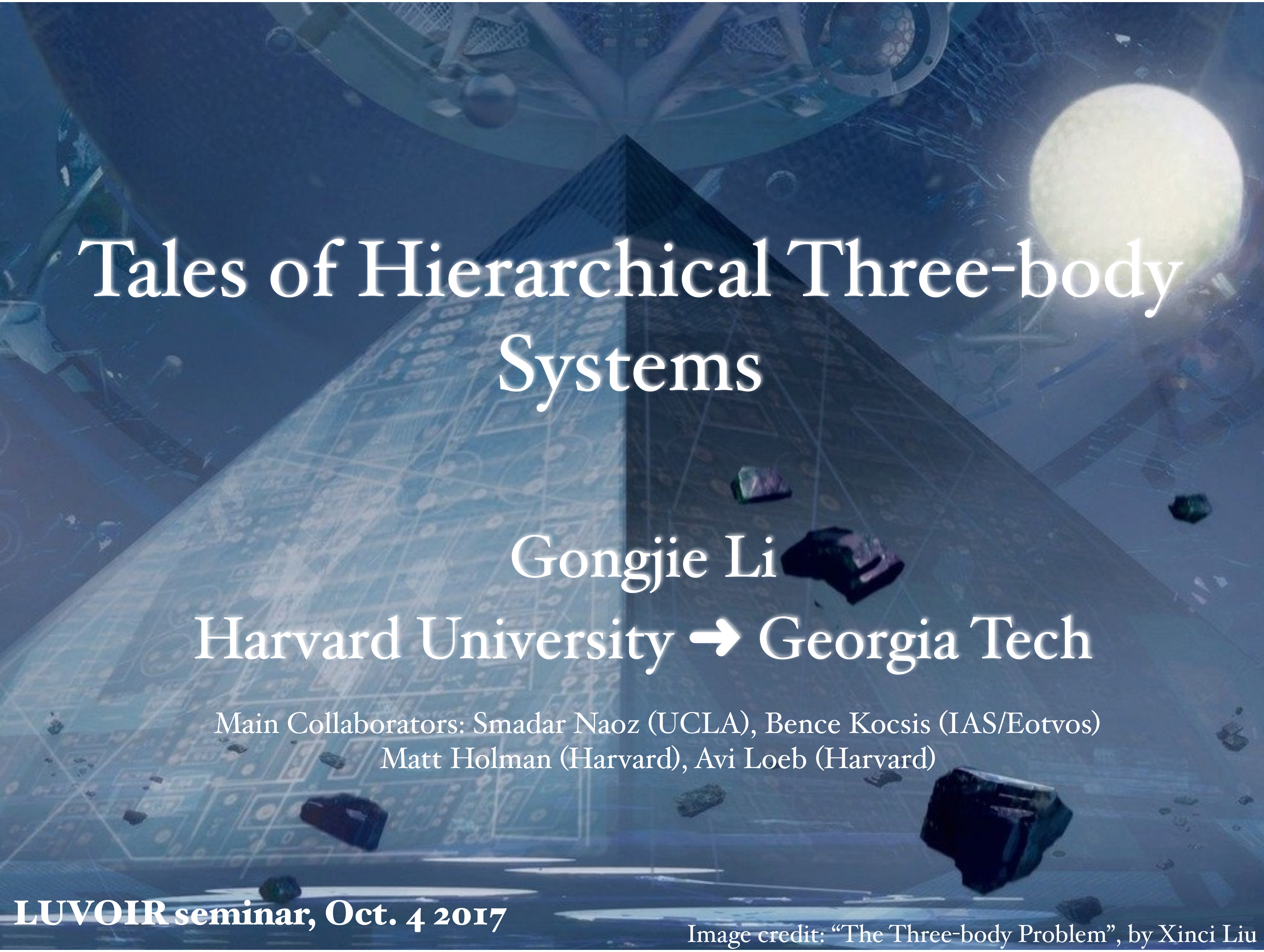


Tales of Hierarchical Three-body Systems

Gongjie Li
Harvard University ➜ Georgia Tech

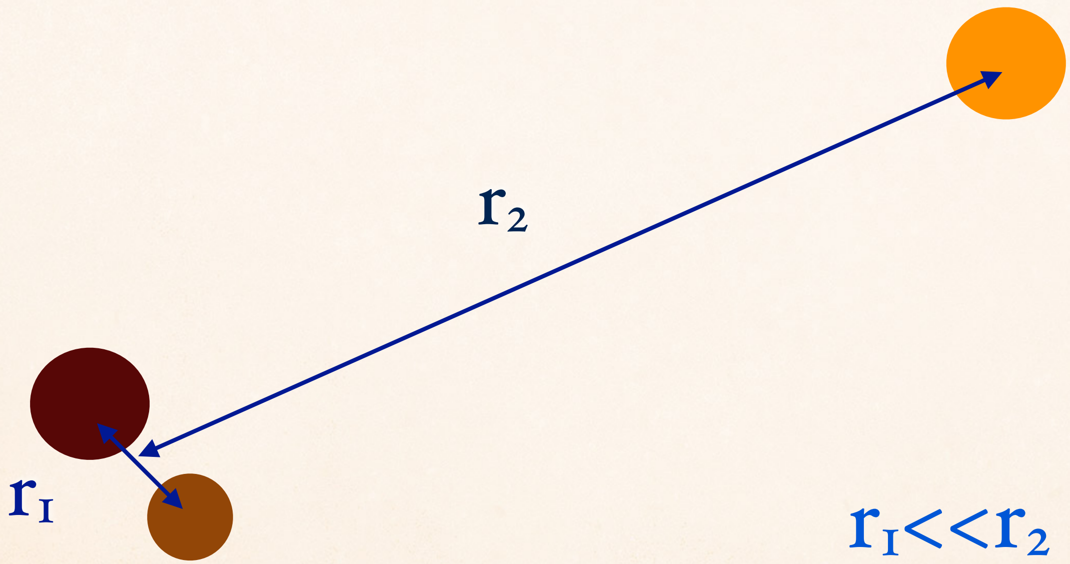
Main Collaborators: Smadar Naoz (UCLA), Bence Kocsis (IAS/Eotvos)
Matt Holman (Harvard), Avi Loeb (Harvard)

LUVOIR seminar, Oct. 4 2017

Image credit: "The Three-body Problem", by Xinci Liu

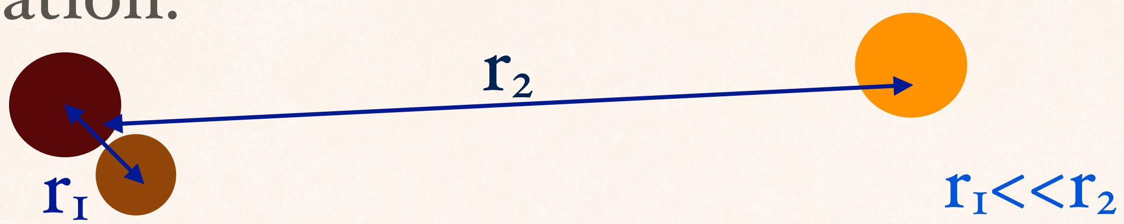
HIERARCHICAL THREE-BODY SYSTEMS

- Configuration:



HIERARCHICAL THREE-BODY SYSTEMS

- Configuration:



- Hierarchical configurations are COMMON:

- For binaries with period < 3 days, ≥96% are in systems with multiplicity ≥3. (*Tokovinin et al. 2006*)
- 282 of the 299 triple systems (~ 94.3%) are hierarchical. (*Eggleton et al. 2007*)

- Hierarchical 3-body dynamics gives insight for hierarchical multiple systems formation/evolution.

OUTLINE

- Dynamical properties:
  - Flips of inner binary
  - Eccentricity excitation of the inner binary

- Examples:
  - Formation of misaligned hot Jupiters
  - Enhancement of tidal disruption rates for stars in galactic nuclei

CONFIGURATION OF HIERARCHICAL 3-BODY SYSTEM

System is stable and can be thought of as interaction between two orbital wires (secular approximation):

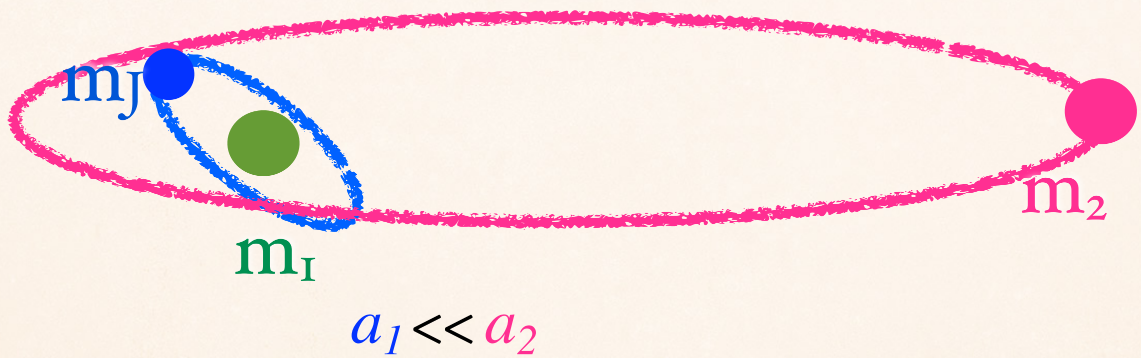
CONFIGURATION OF HIERARCHICAL 3-BODY SYSTEM

System is stable and can be thought of as interaction between two orbital wires (secular approximation):

- Inner wires (1): formed by m_1 and m_J.
- Outer wires (2): m_2 orbits the center mass of m_1 and m_J.

CONFIGURATION OF HIERARCHICAL 3-BODY SYSTEM

System is stable and can be thought of as interaction between two orbital wires (secular approximation):



- Inner wires (1): formed by m_1 and m_J.
- Outer wires (2): m_2 orbits the center mass of m_1 and m_J.
- a_1/a_2 small, expand H in a_1/a_2 and apply perturbative analysis

LIDOV-KOZAI MECHANISM

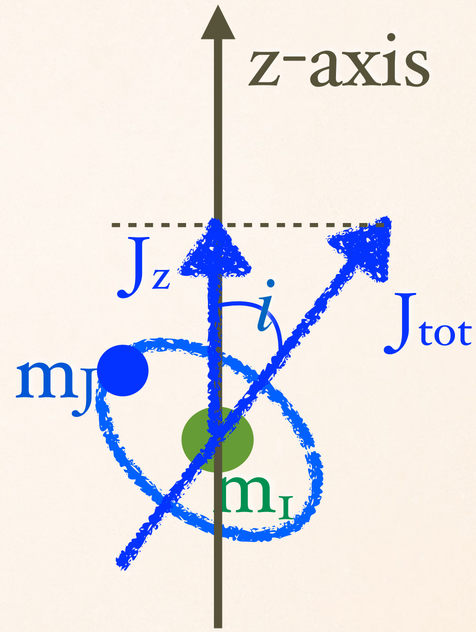
Lidov-Kozai Mechanism

($e_2 = 0$, $m_J \rightarrow 0$)

(*Kozai 1962; Lidov 1962: Solar system objects*)

- Octupole level $O((a_1/a_2)^3)$ is zero.
- Quadrupole level $O((a_1/a_2)^2)$:

=> $Jz = \sqrt{1-e_1^2}\cos i_1$ conserved (axi-symmetric potential).



LIDOV-KOZAI MECHANISM

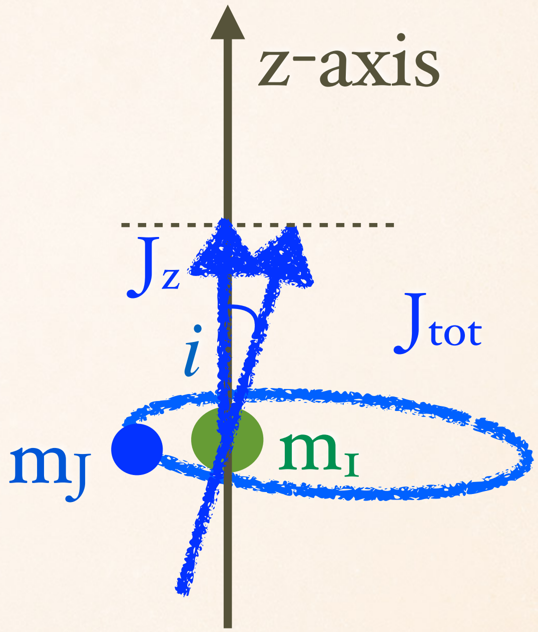
Lidov-Kozai Mechanism

($e_2 = 0$, $m_J \rightarrow 0$)

(*Kozai 1962; Lidov 1962: Solar system objects*)

- Octupole level $O((a_1/a_2)^3)$ is zero.
- Quadrupole level $O((a_1/a_2)^2)$:

=> $Jz = \sqrt{1 - e_1^2} \cos i_1$ conserved (axi-symmetric potential).



$e\uparrow, \; i\downarrow$

LIDOV-KOZAI MECHANISM

Lidov-Kozai Mechanism

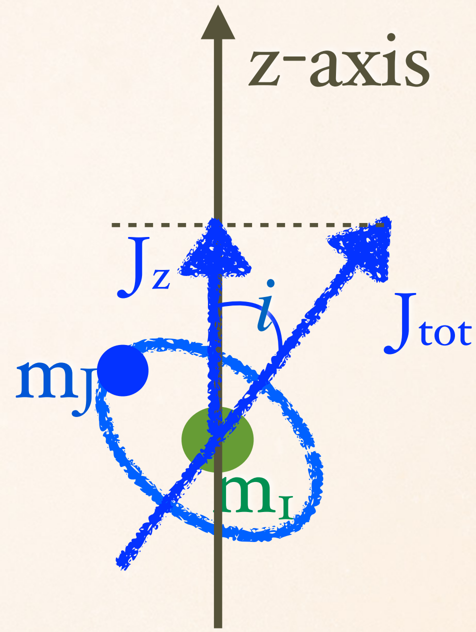
(e_2 = 0, $m_J \rightarrow 0$)

(*Kozai 1962; Lidov 1962:*

Solar system objects)

- Octupole level $O((a_1/a_2)^3)$ is zero.
- Quadrupole level $O((a_1/a_2)^2)$:

=> $Jz = \sqrt{1-e_1^2}\cos i_1$ conserved (axi-symmetric potential).



$e\uparrow,\ i\downarrow$

LIDOV-KOZAI MECHANISM

Lidov-Kozai Mechanism

(e_2 = 0, $m_J \to 0$)

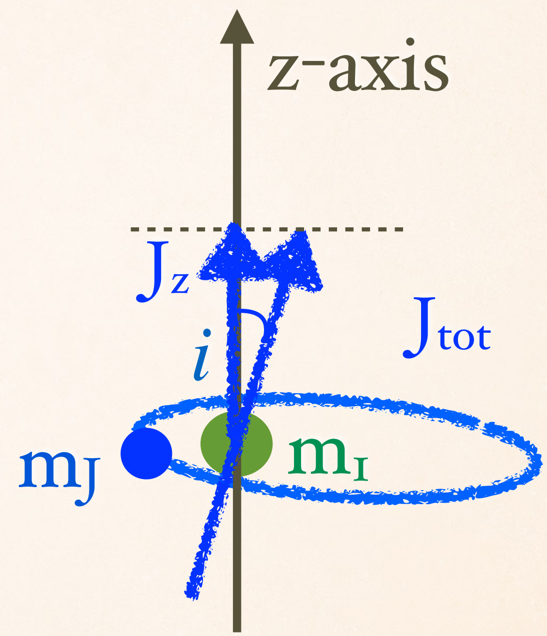
(*Kozai 1962; Lidov 1962:*

Solar system objects)

- Octupole level $O((a_1/a_2)^3)$ is zero.
- Quadrupole level $O((a_1/a_2)^2)$:

=> $Jz = \sqrt{1-e_1^2}\cos i_1$ conserved

(axi-symmetric potential).



$e\uparrow,\ i\downarrow$

i does not cross 90°

LIDOV-KOZAI MECHANISM

Lidov-Kozai Mechanism

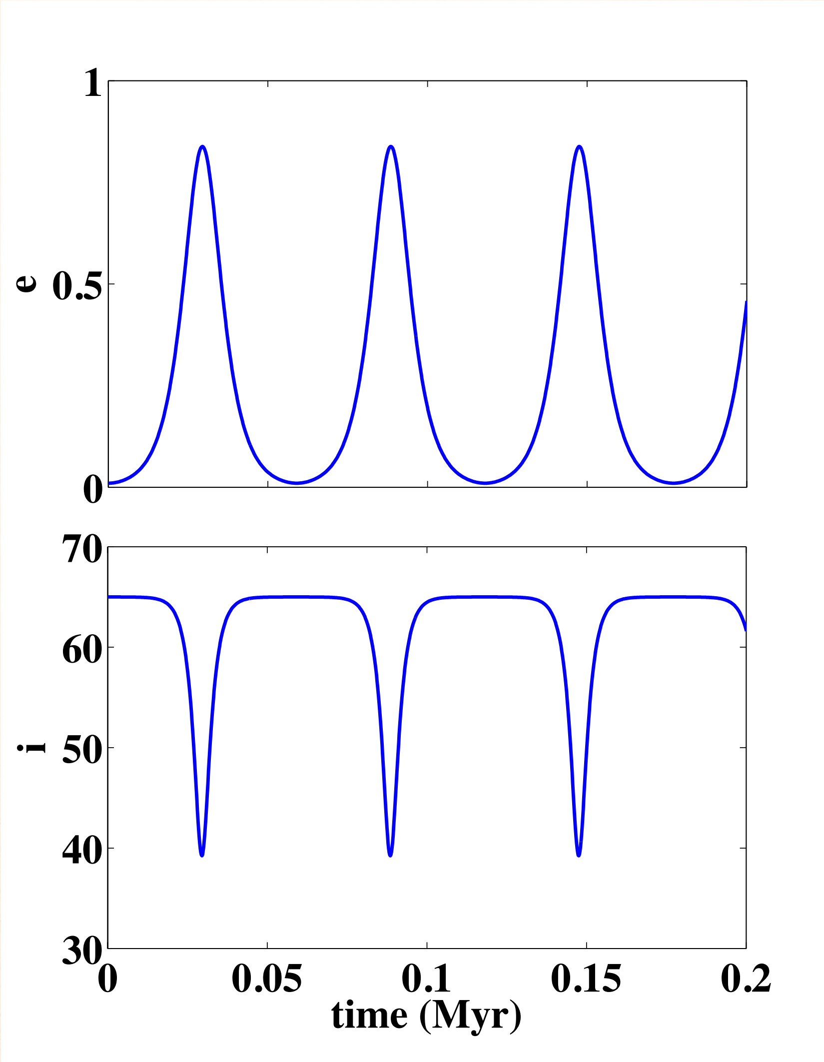
(e_2 = 0, $m_J \to 0$)

(Kozai 1962; Lidov 1962: Solar system objects)

- Octupole level $O((a_1/a_2)^3)$ is zero.
- Quadrupole level $O((a_1/a_2)^2)$:

=> $Jz = \sqrt{1-e_1^2}\cos i_1$ conserved (axi-symmetric potential).

=> when i>40°, e_1 and i oscillate with large amplitude.



Example of Lidov-Kozai Mechanism.

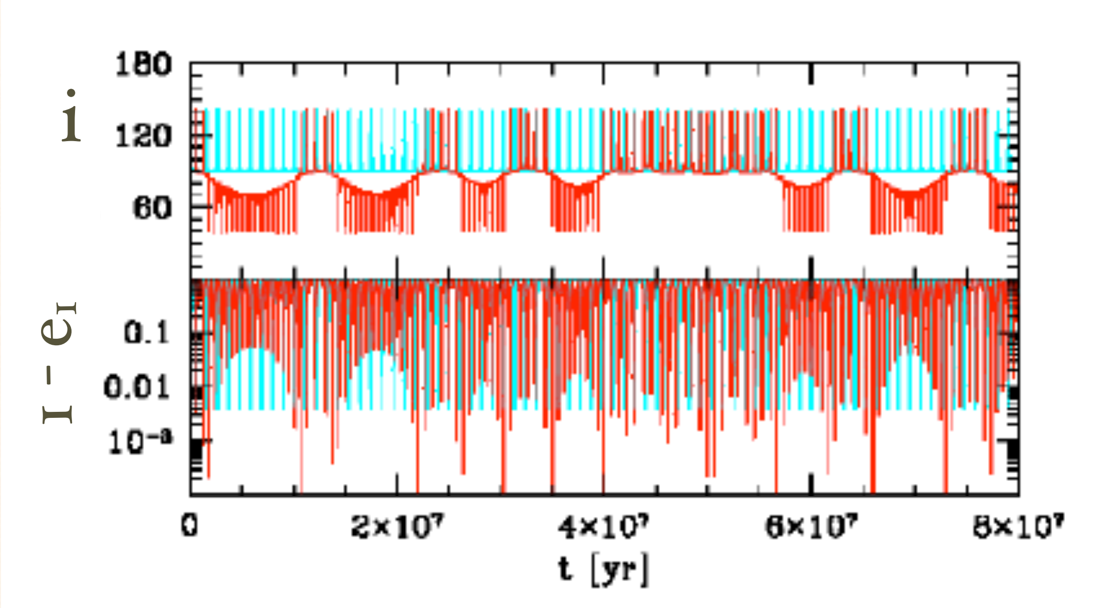
OCTUPOLE LIDOV-KOZAI MECHANISM

$e_2 \neq 0$ (Eccentric Lidov-Kozai Mechanism) or $m_J \neq 0$:

(e.g., *Naoz et al. 2011, 2013, test particle case: Katz et al. 2011, Lithwick & Naoz 2011*):

- Jz NOT constant, octupole ≠ 0.

- when i>40º: $e_1 \rightarrow 1$.
- when i>40º: i crosses 90º



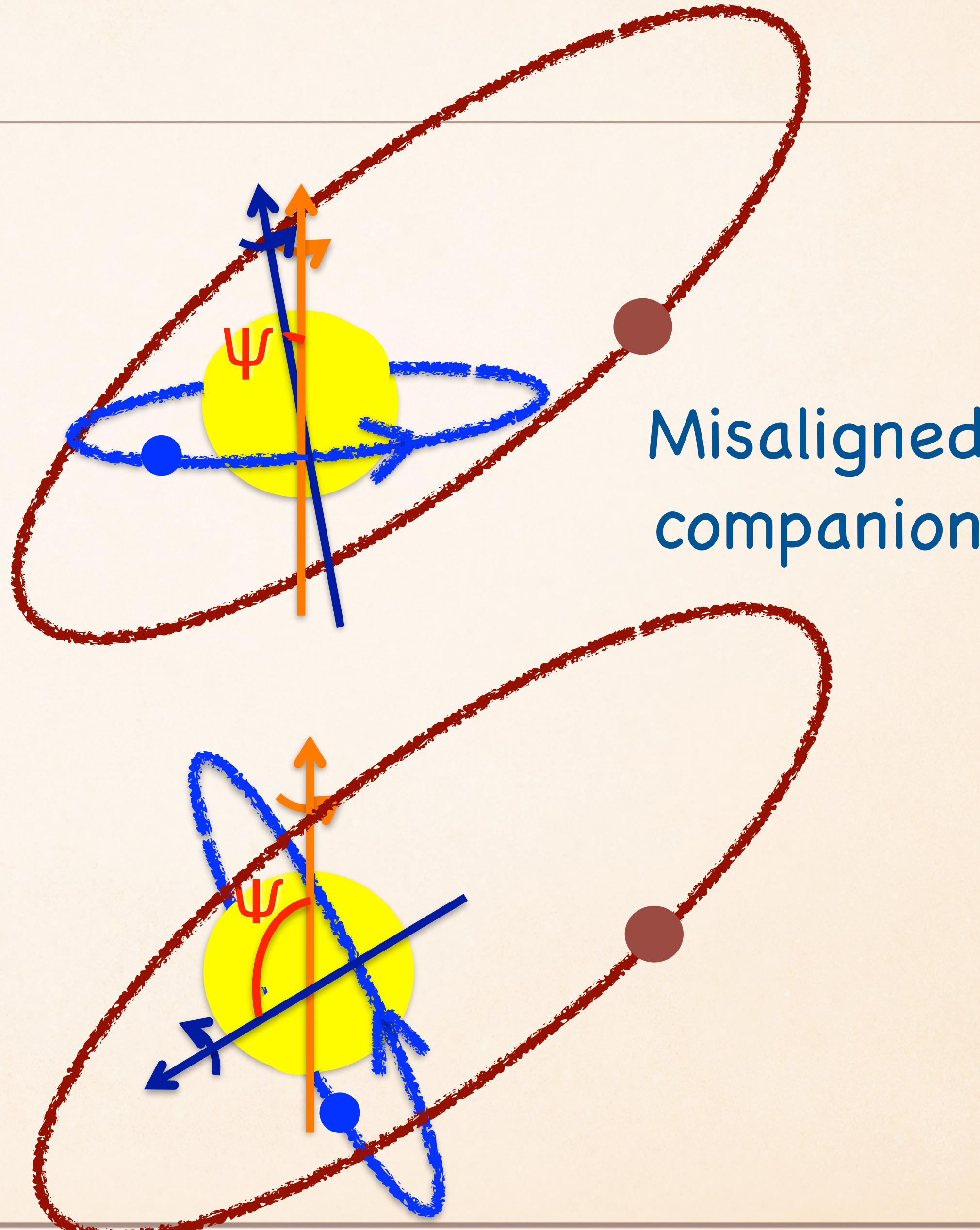
Cyan: quadrupole only.
Red: quadrupole + octupole. Naoz et al 2013

OCTUPOLE LIDOV-KOZAI MECHANISM

$e_2 \neq 0$ (Eccentric Lidov-Kozai Mechanism) or $m_J \neq 0$:

(e.g., *Naoz et al. 2011, 2013, test particle case: Katz et al. 2011, Lithwick & Naoz 2011*):

- Consequence:
  - Produces retrograde hot Jupiters (i>90^o) (e.g., Naoz et al. 2011)

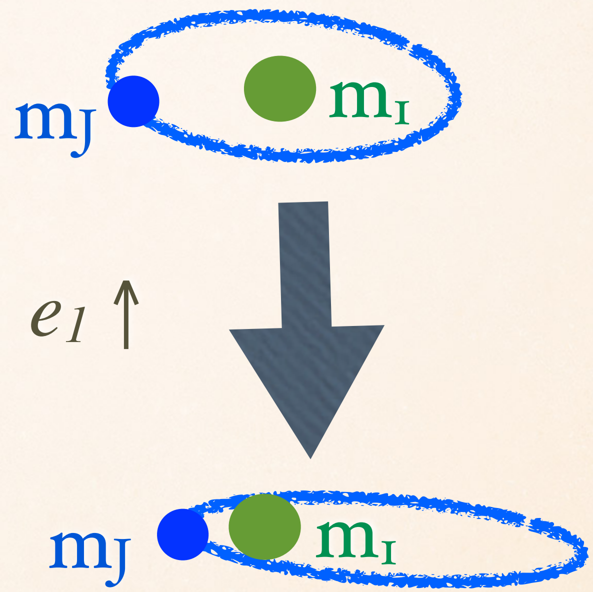


OCTUPOLE LIDOV-KOZAI MECHANISM

$e_2 \neq 0$ (Eccentric Lidov-Kozai Mechanism) or $m_J \neq 0$:

(e.g., *Naoz et al. 2011, 2013, test particle case: Katz et al. 2011, Lithwick & Naoz 2011*):

- Consequence:
  - Tidal disruption rate enhancement ($e_1 \rightarrow 1$)
    (e.g., Chen et al. 2009, Bode & Wegg 2014, Li et al. 2015)

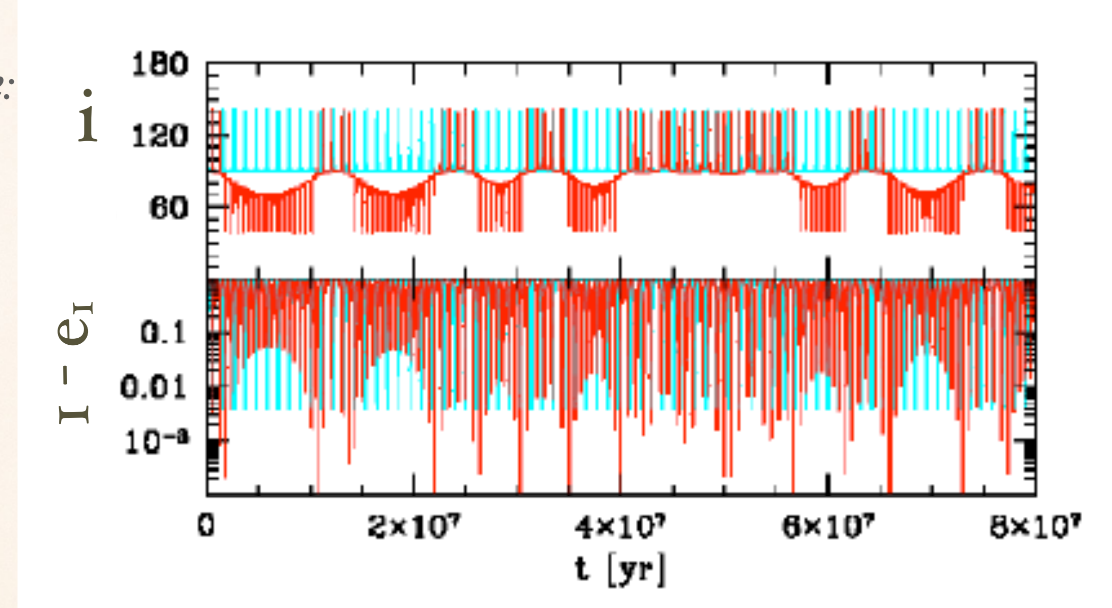


$R_p \propto 1-e_1$

OCTUPOLE LIDOV-KOZAI MECHANISM

$e_2 \neq 0$ (Eccentric Lidov-Kozai Mechanism) or $m_J \neq 0$:

(e.g., *Naoz et al. 2011, 2013, test particle case: Katz et al. 2011, Lithwick & Naoz 2011*):



- Consequence:
  - Produces retrograde hot Jupiters (i>90°) (e.g., Naoz et al. 2011)
  - Tidal disruption rate enhancement ($e_1 \rightarrow 1$) (e.g., Chen et al. 2009, Bode & Wegg 2014, Li et al. 2015)

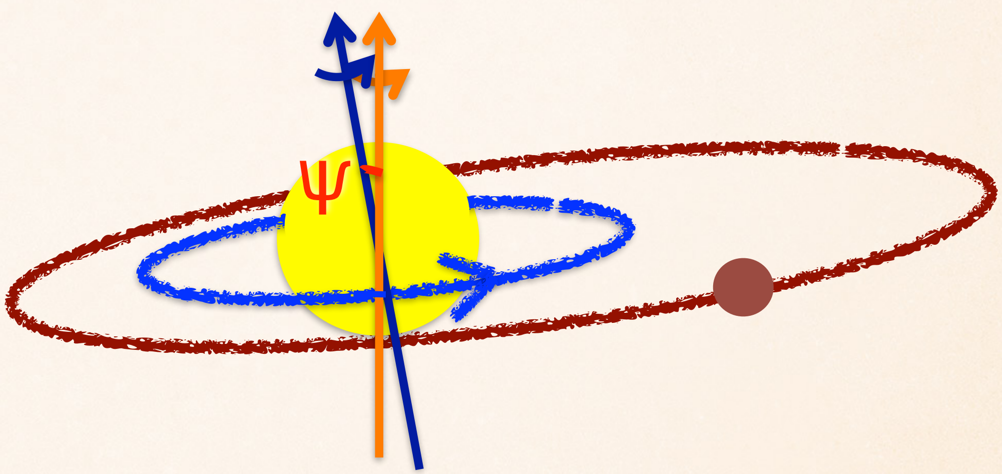
Cyan: quadrupole only.
Red: quadrupole + octupole. Naoz et al 2013

$40^o < i < 140^o$

COPLANAR FLIP

- Starting with $i \approx 0$, $e_1 \geq 0.6$, $e_2 \neq 0$:

  $e_1 \rightarrow 1$, i flips by $\approx 180^o$ (*Li et al. 2014a*).

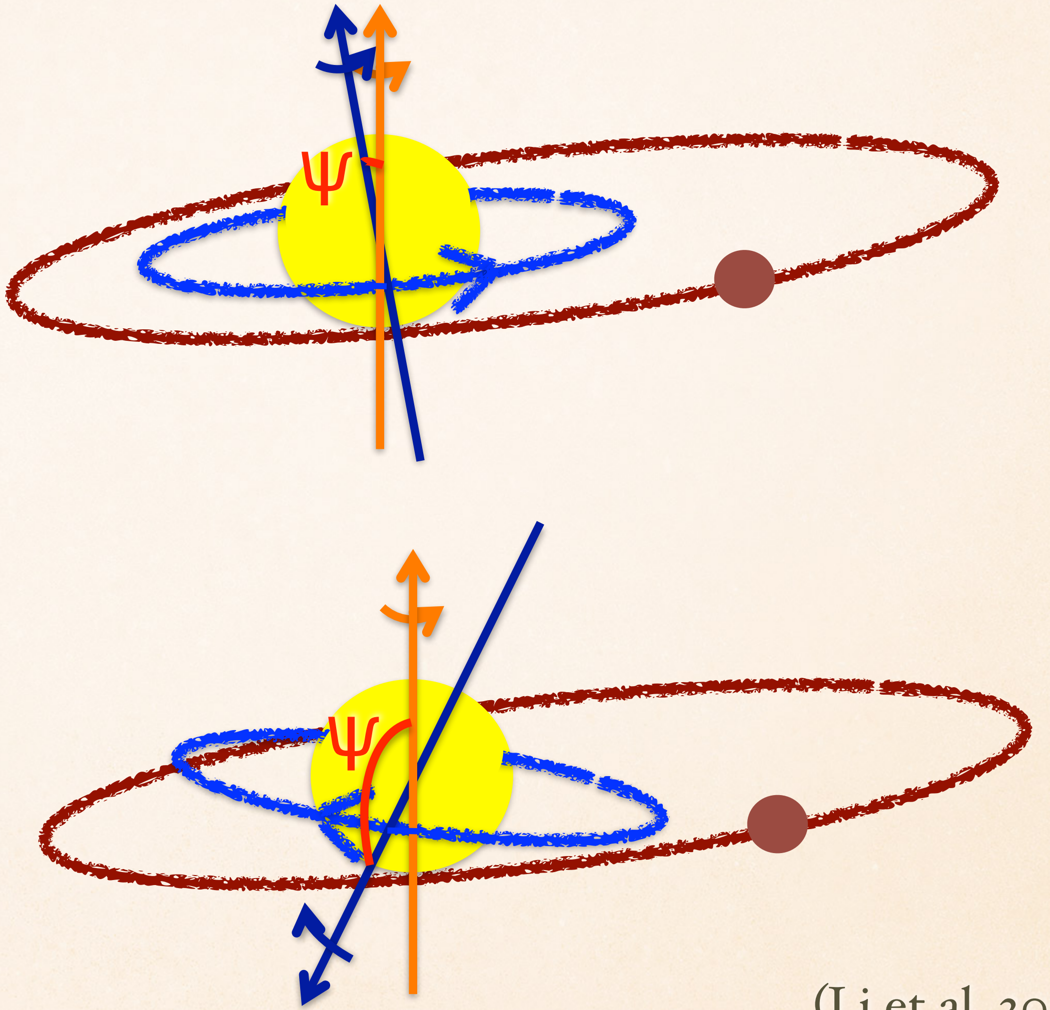


(Li et al. 2014a)

COPLANAR FLIP

- Starting with $i \approx 0$, $e_1 \geq 0.6$, $e_2 \neq 0$:

  $e_1 \rightarrow 1$, i flips by $\approx 180^{\circ}$ (*Li et al. 2014a*).

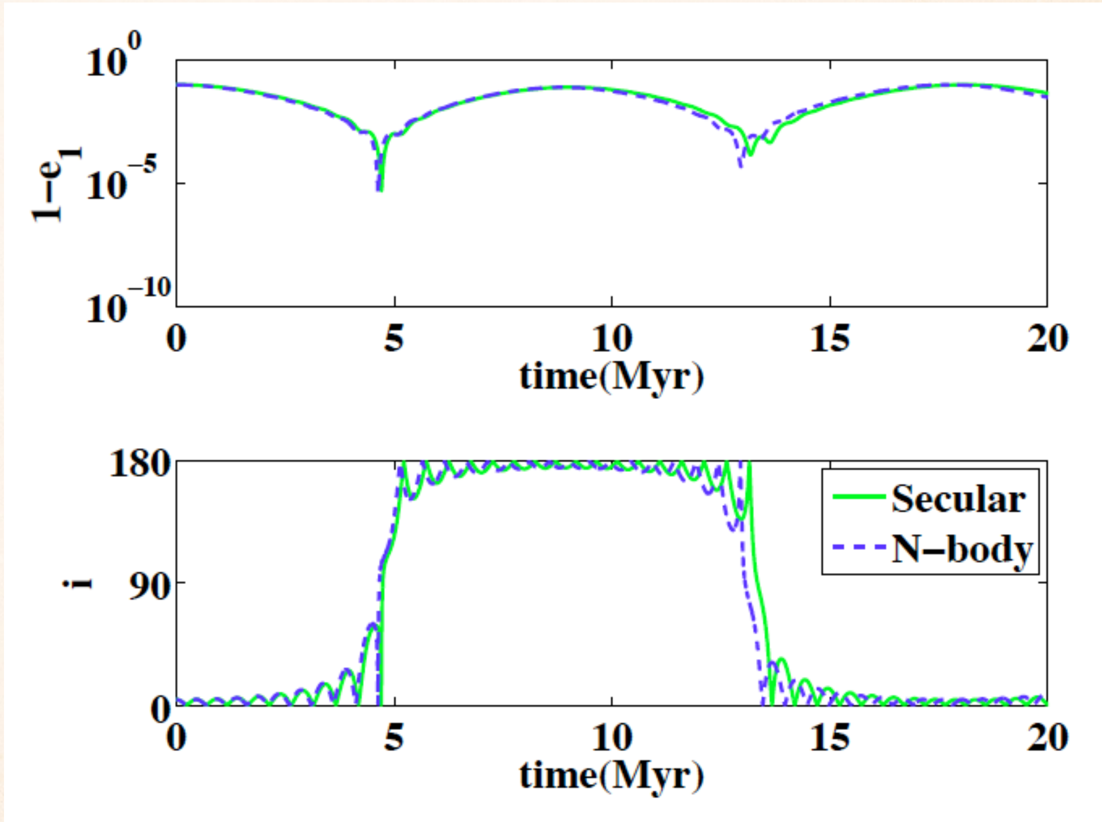


(Li et al. 2014a)

COPLANAR FLIP

- Starting with $i \approx 0$, $e_1 \geq 0.6$, $e_2 \neq 0$:

  $e_1 \rightarrow 1$, i flips by $\approx 180^o$ (*Li et al. 2014a*).



(Li et al. 2014a)

COPLANAR FLIP

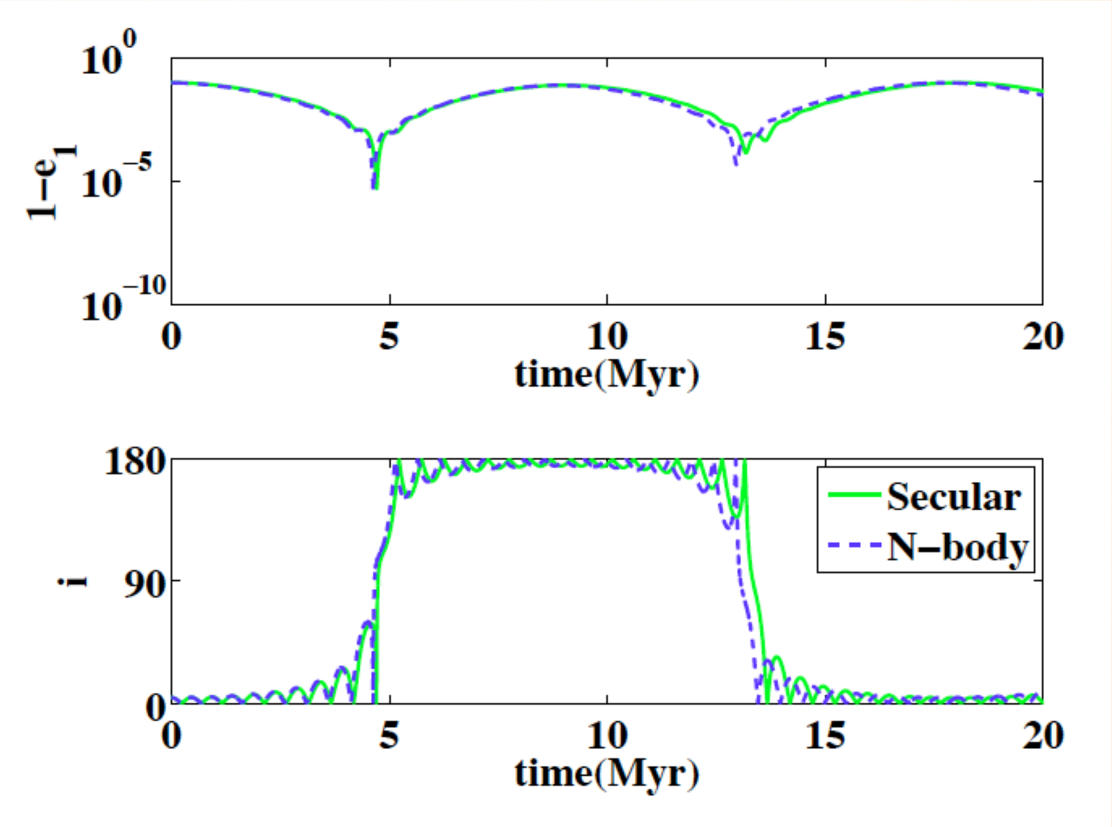
- Starting with $i \approx 0$, $e_1 \geq 0.6$, $e_2 \neq 0$:

  $e_1 \rightarrow 1$, i flips by $\approx 180^o$ (*Li et al. 2014a*).

  => Increase the parameter space of interesting behaviors.

  => Produces counter orbiting hot Jupiters.

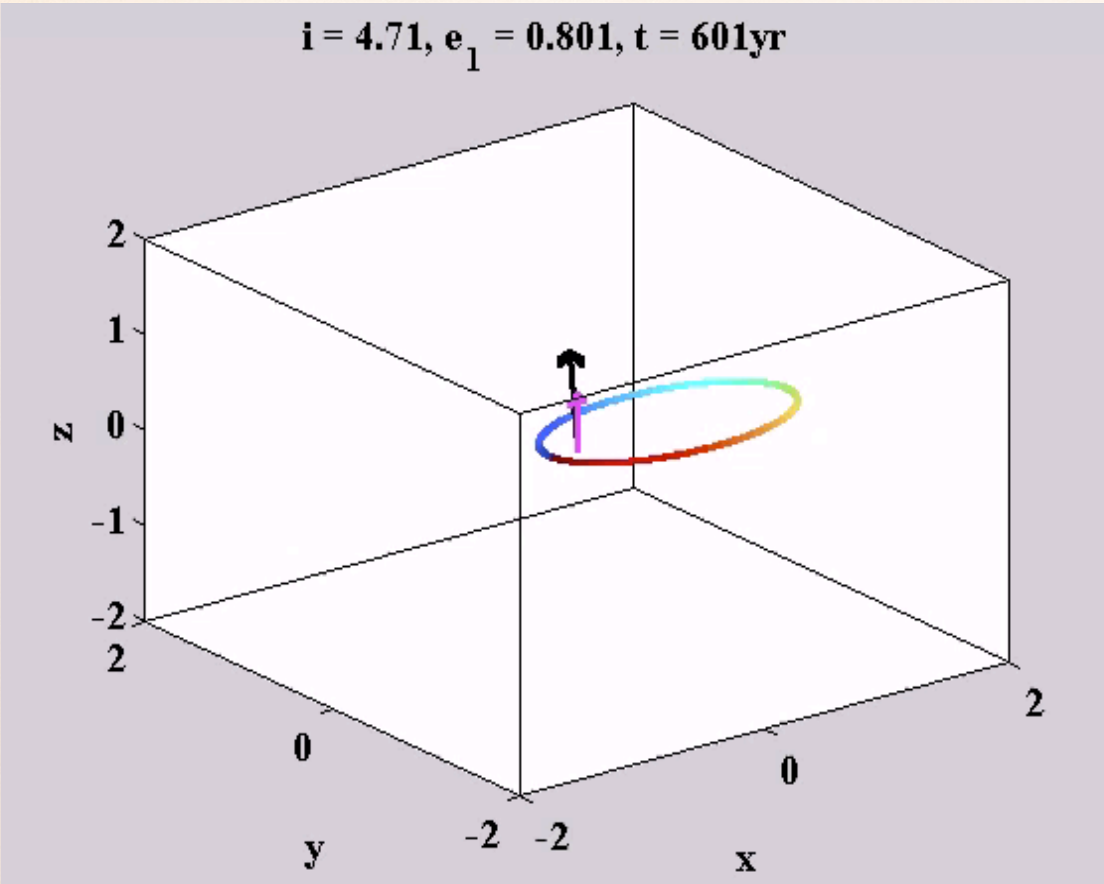
  => Enhance tidal disruption rates.



(Li et al. 2014a)

DIFFERENCES BETWEEN HIGH/LOW I FLIP

- Low inclination flip



- For simplicity:

take $m_j \rightarrow 0$ => outer orbit stationary.

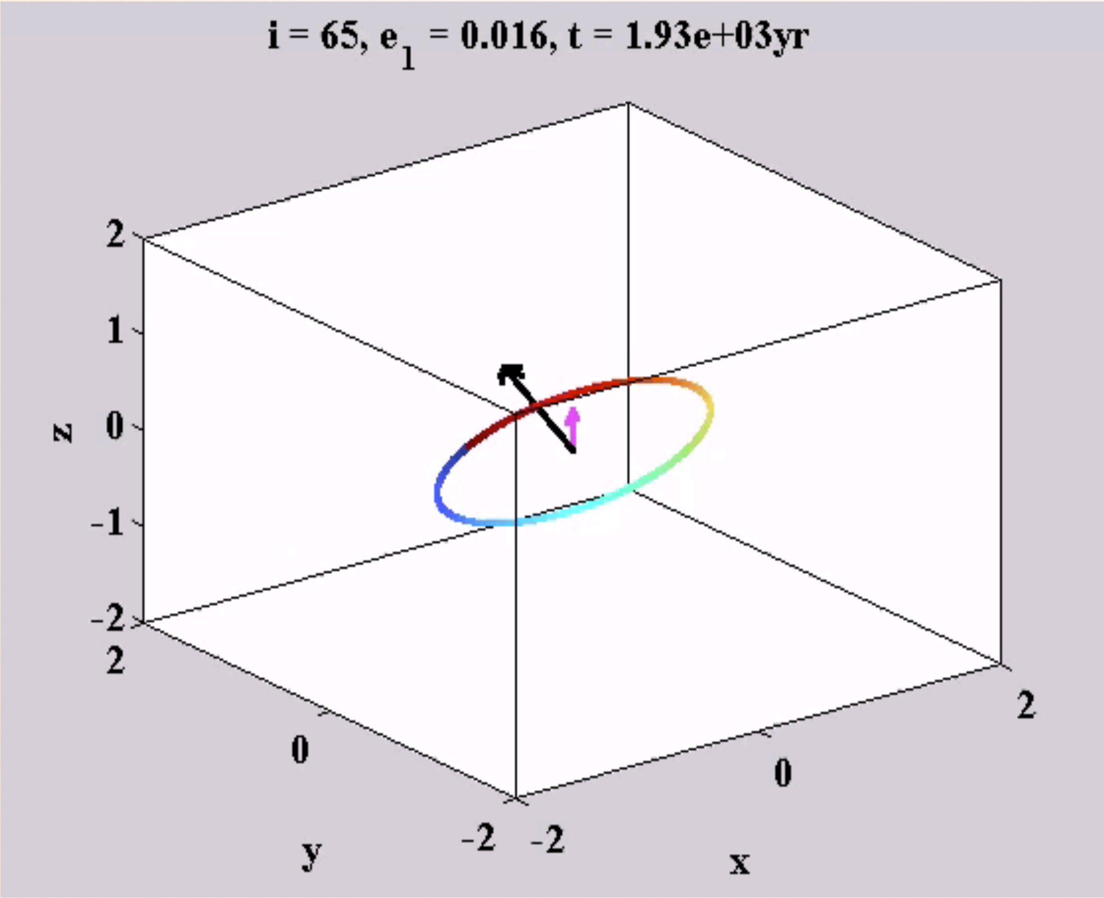
- z direction: angular momentum of the outer orbit.

- ⬆: direction of J_1.
- ⬆: Jz_1 => indicates flip.
- Colored ring: inner orbit. Color: mean anomaly.

Li et al. 2014a

DIFFERENCES BETWEEN HIGH/LOW I FLIP

- High inclination flip



- For simplicity:

take $m_j \to 0$ => outer orbit stationary.

- z direction: angular momentum of the outer orbit.

- ⬆: direction of J_1.
- ⬆: Jz_1 => indicates flip.
- Colored ring: inner orbit. Color: mean anomaly.

Li et al. 2014a

ANALYTICAL OVERVIEW

- Hamiltonian has two degrees of freedom in test particle limit:

  $(J = \sqrt{1-e_1^2},\ Jz = \sqrt{1-e_1^2}\cos i_1,\ \omega,\ \Omega\,)$

  2 conjugate pairs: J & ω, Jz & Ω

- The Hamiltonian up to the Octupole order:

$$H = F_{quad}(J, Jz, \omega) + \epsilon F_{oct}(J, Jz, \omega, \Omega)$$

Quadrupole order: Independent of Ω => Jz constant

ϵ : hierarchical parameter: $\epsilon = \frac{a_1}{a_2}\frac{e_2}{1-e_2^2}$

Octupole order: Depend on both Ω & ω => J and Jz not constant

CO-PLANAR FLIP CRITERION

- Hamiltonian (at O(i)):
  - Evolution of e_1 only due to octupole terms:

    => e_1 does not oscillate before flip
  - Depend on only J_1 and $\varpi_1 = \omega_1 + \Omega_1$

    => System is integrable.

    => $e_1(t)$ can be solved.

    => The flip timescale can be derived.

    => The flip criterion can be derived.

$$\varepsilon > \frac{8}{5} \frac{1 - e_1^{\,2}}{7 - e_1\left(4 + 3e_1^{\,2}\right)\cos\left(\omega_1 + \Omega_1\right)}$$

Li et al. 2014a

CO-PLANAR FLIP CRITERION

- Hamiltonian (at O(i)):
  - Evolution of e_1 only due to octupole terms:

    => e_1 does not oscillate before flip

  - Depend on only J_1 and $\varpi_1=\omega_1+\Omega_1$

    => System is integrable.

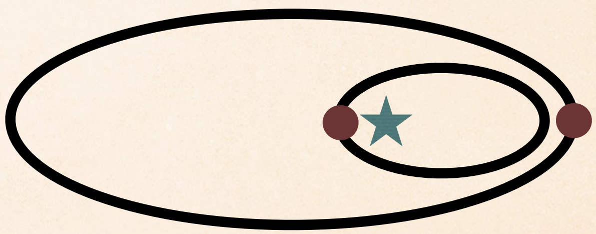
    => e_1(t) can be solved.

    => The flip timescale can be derived.

    => The flip criterion can be derived.

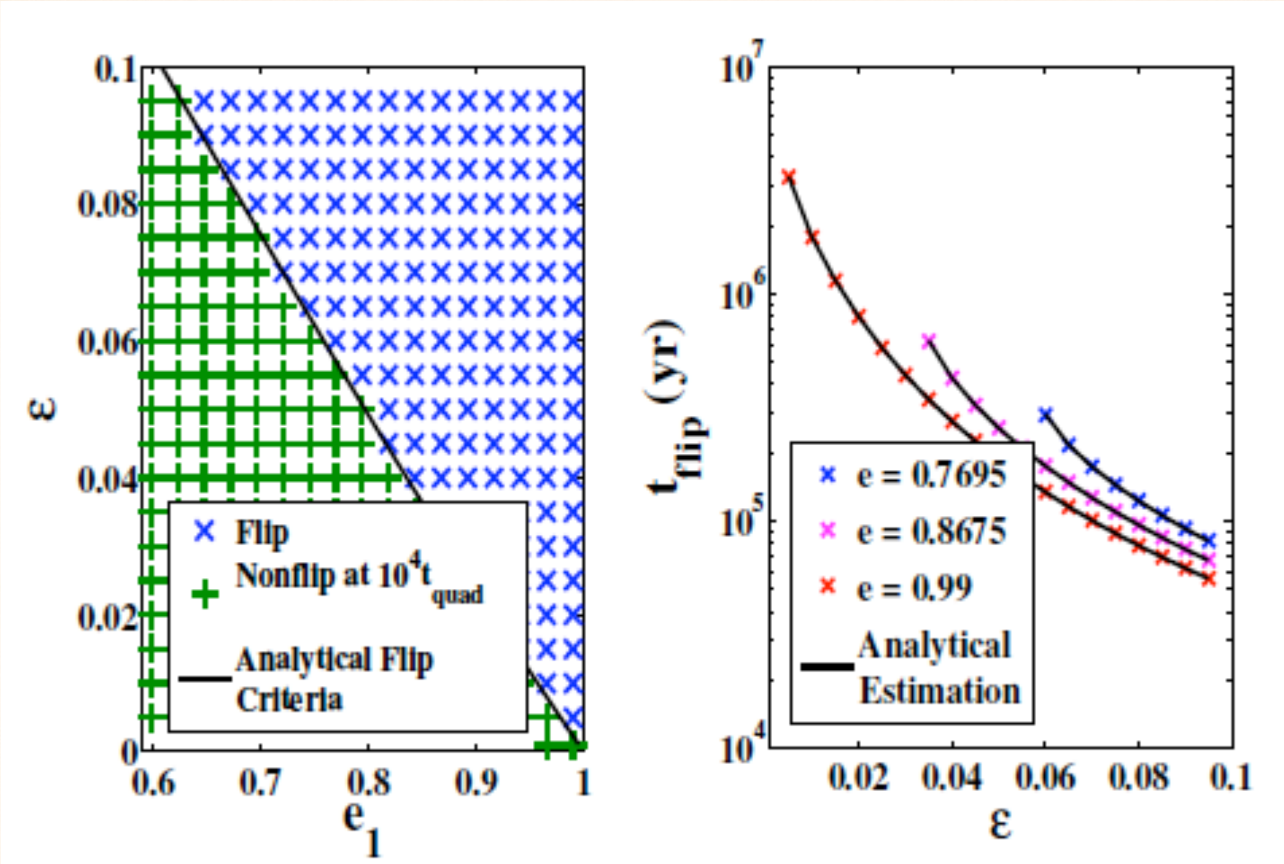
Easier to flip:

* e_1 larger
* $\varpi_1=\omega_1+\Omega_1 \sim 180^o$



Li et al. 2014a

ANALYTICAL RESULTS V.S. NUMERICAL RESULTS



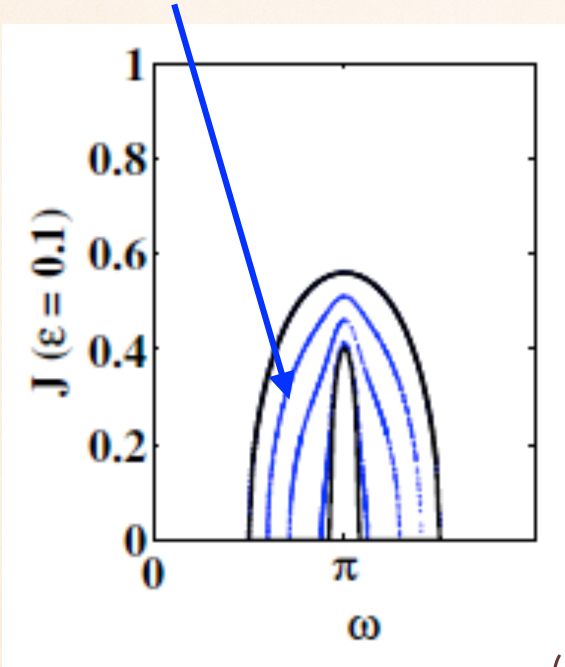
IC: i=5°.

- The flip criterion and the flip timescale from secular integration are consistent with the analytical results.

Li et al. 2014a

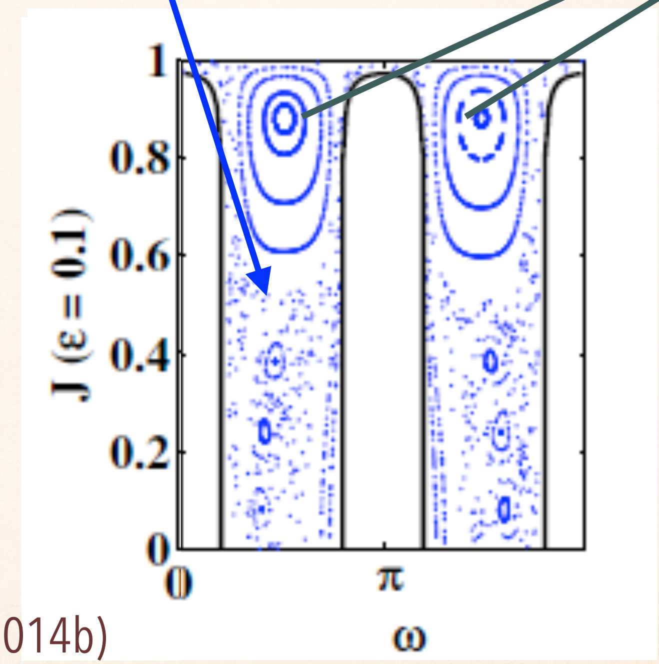
SURFACE OF SECTIONS

Coplanar Flip:



High inclination Flip:

Quadrupole resonances
(e.g., Kozai 1962)

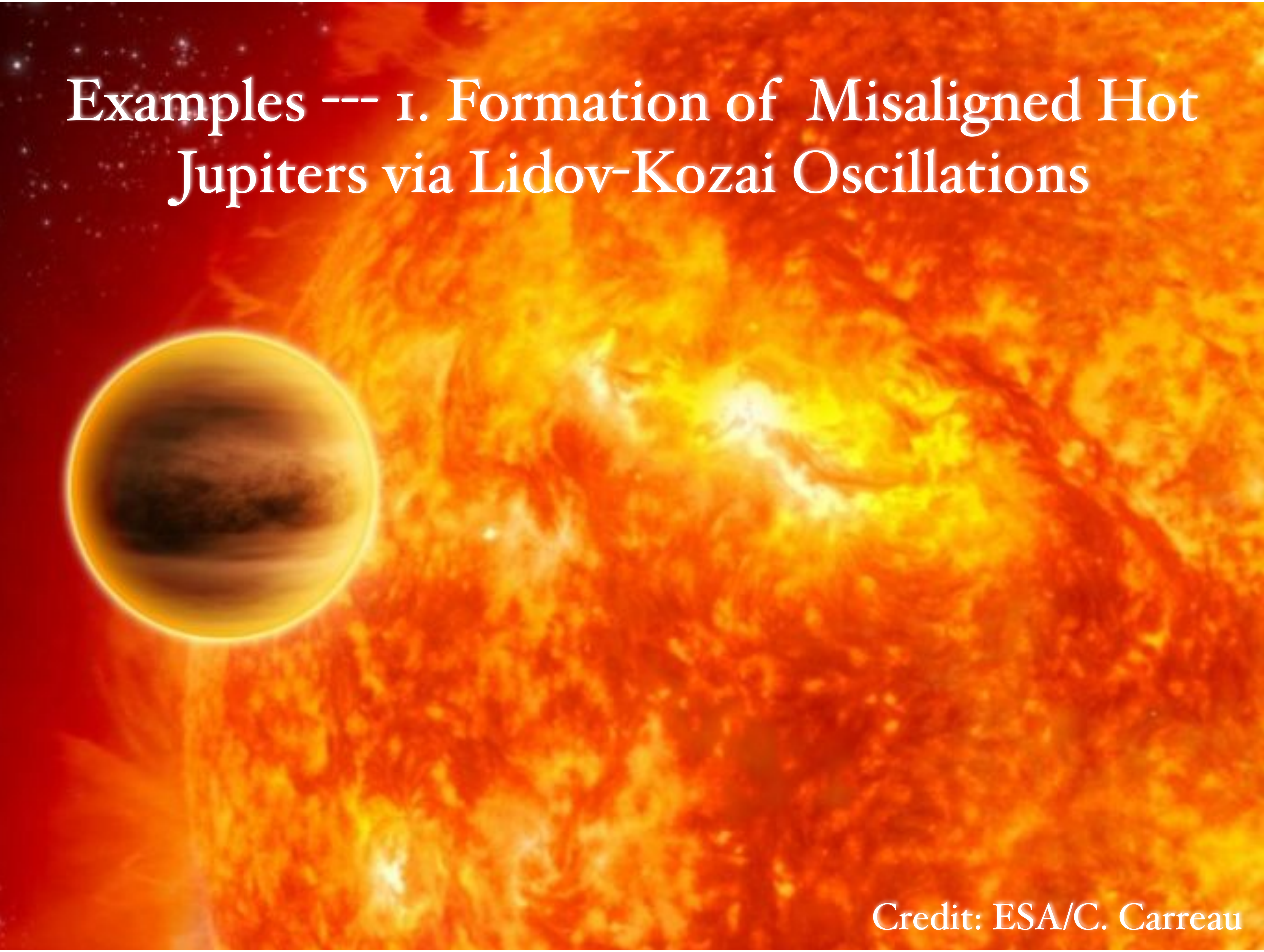


(**Gongjie Li** et al. 2014b)

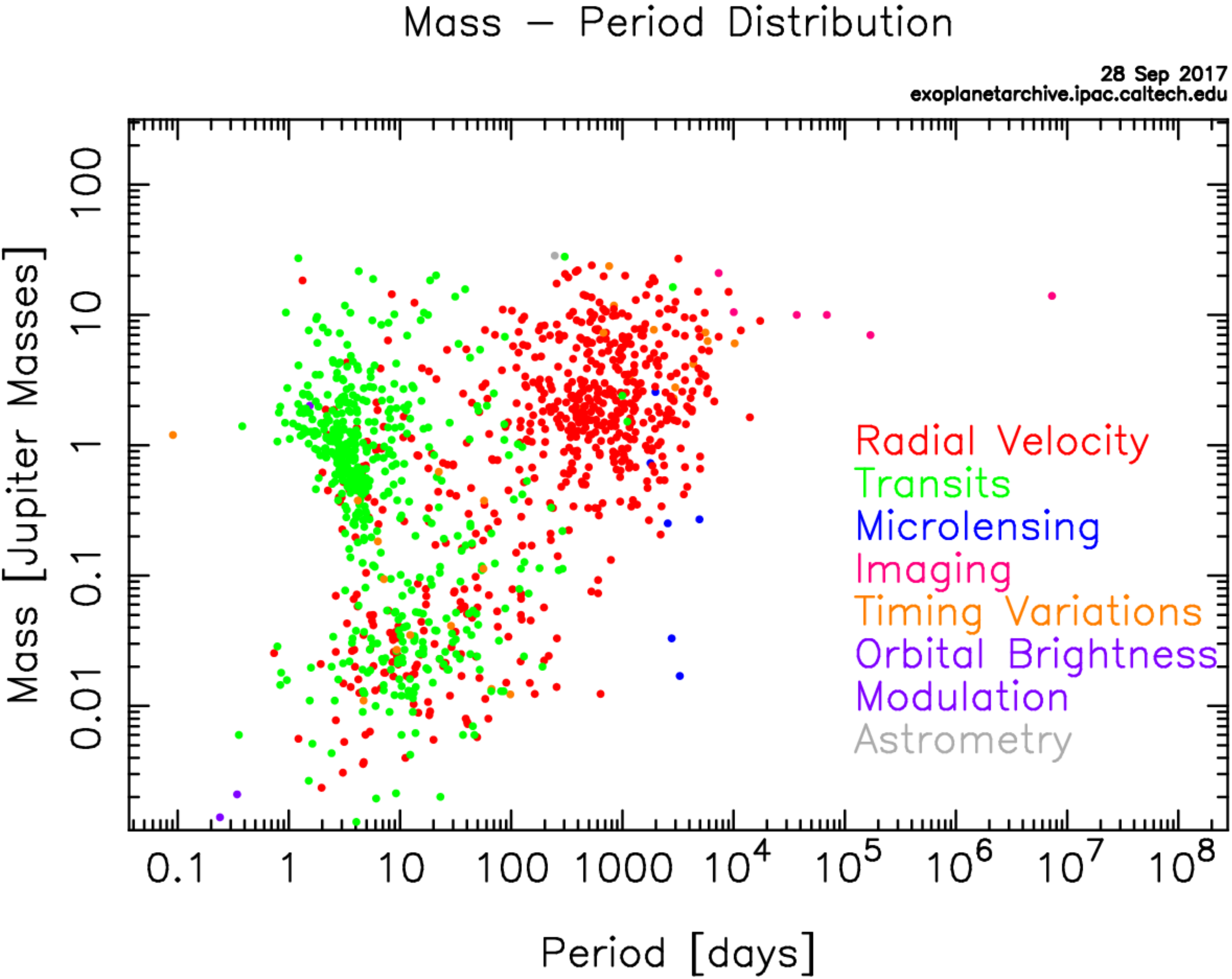
Caused by the octupole resonance, Regular (ϖ librates around π)

Caused by the overlap of quadrupole and octupole resonances, Chaotic: $t_L \sim 6t_K$

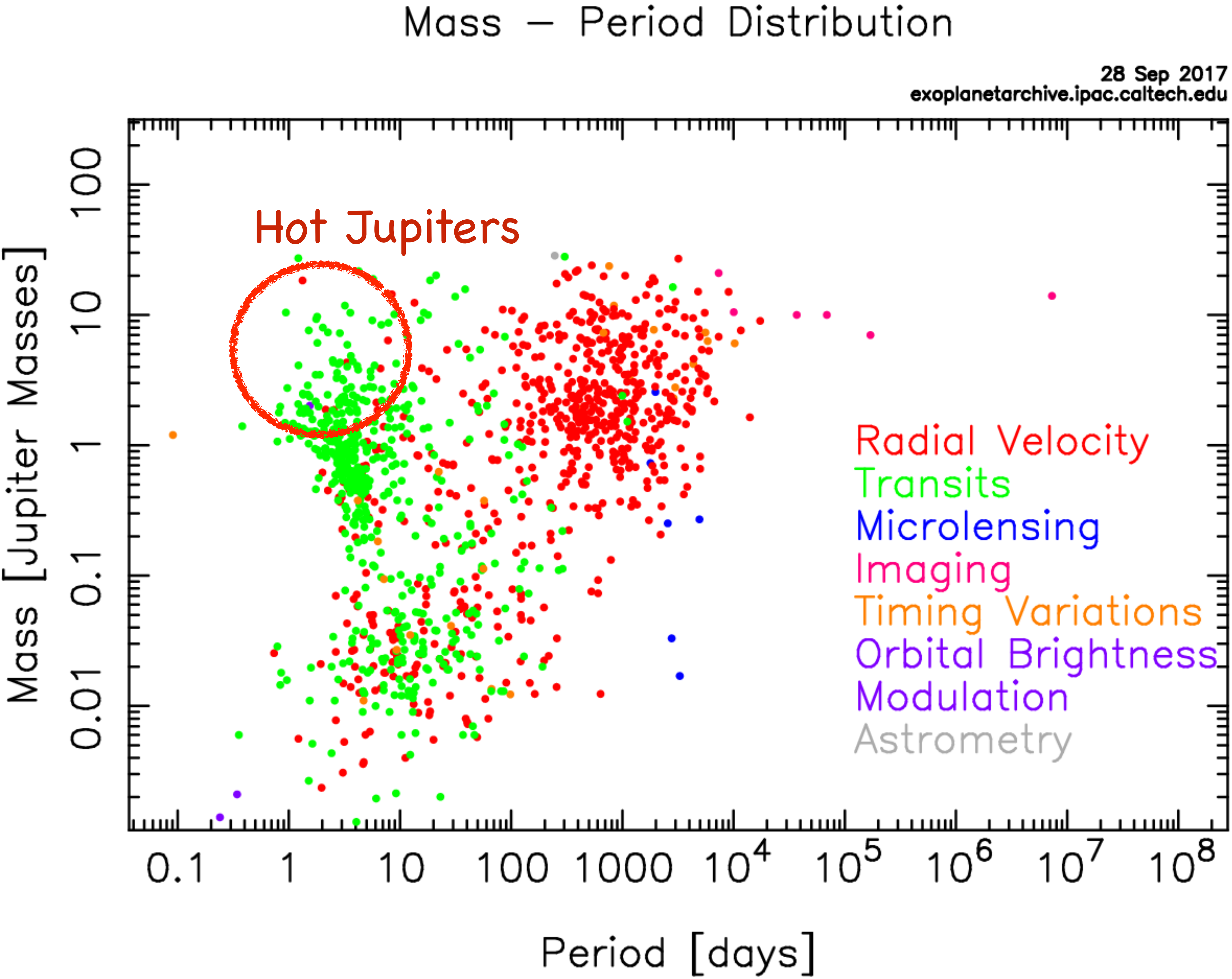
Examples --- 1. Formation of Misaligned Hot Jupiters via Lidov-Kozai Oscillations



Credit: ESA/C. Carreau

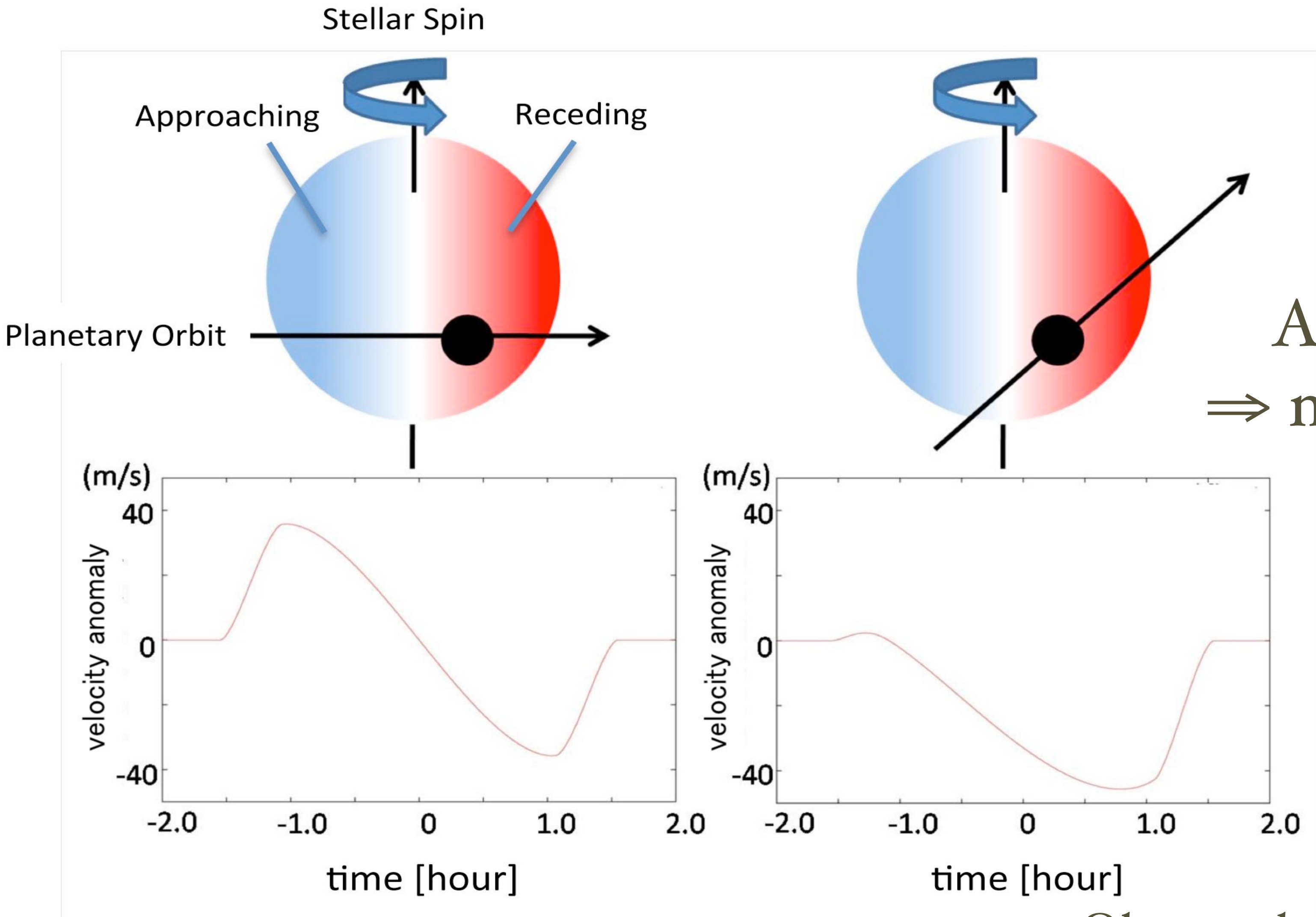


Mass – Period Distribution
28 Sep 2017
exoplanetarchive.ipac.caltech.edu
Mass [Jupiter Masses]
100
10
1
0.1
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
10^7
10^8
Period [days]
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
Astrometry



Mass – Period Distribution
28 Sep 2017
exoplanetarchive.ipac.caltech.edu
Hot Jupiters
Mass [Jupiter Masses]
100
10
1
0.1
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
10^7
10^8
Period [days]
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
Astrometry

SPIN-ORBIT MISALIGNMENT (ROSSITER-MCLAUGHLIN METHOD)

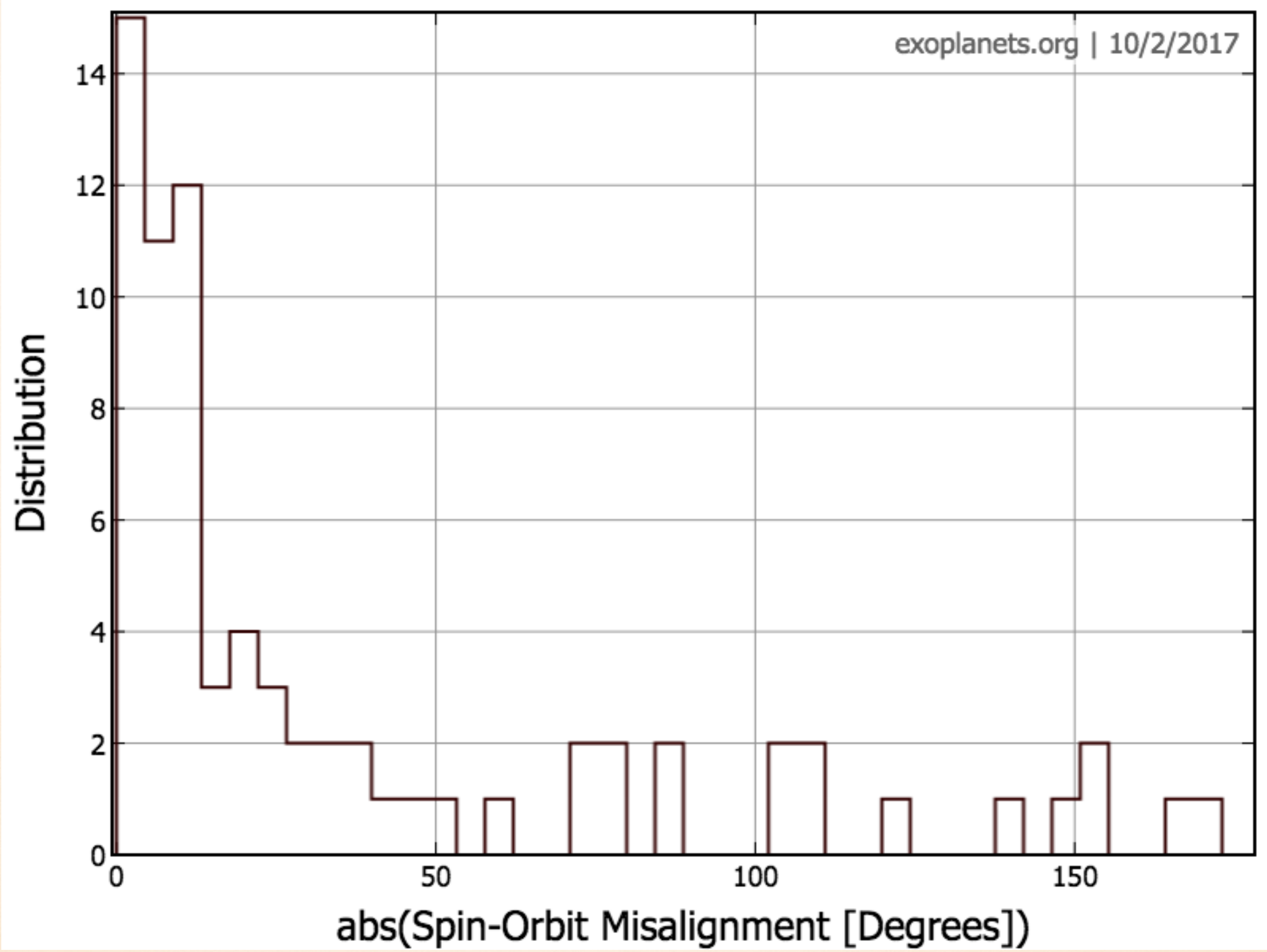


Asymmetry
$\Rightarrow$ misalignment

e.g., Ohta et al. 2005, Winn 2006

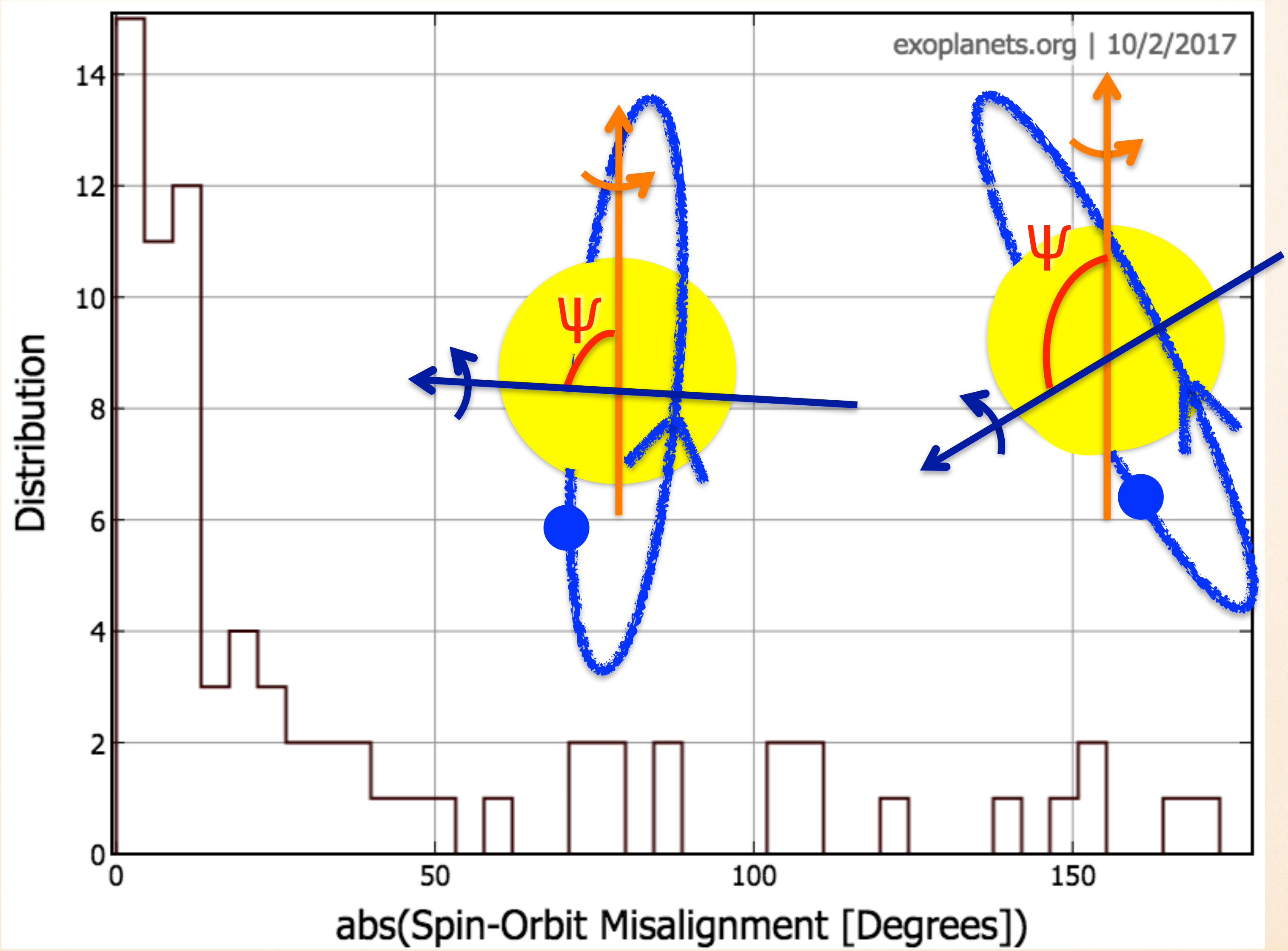
OBSERVED SPIN-ORBIT MISALIGNMENT

Solar System: misalignment $\Psi \lesssim 7^o$

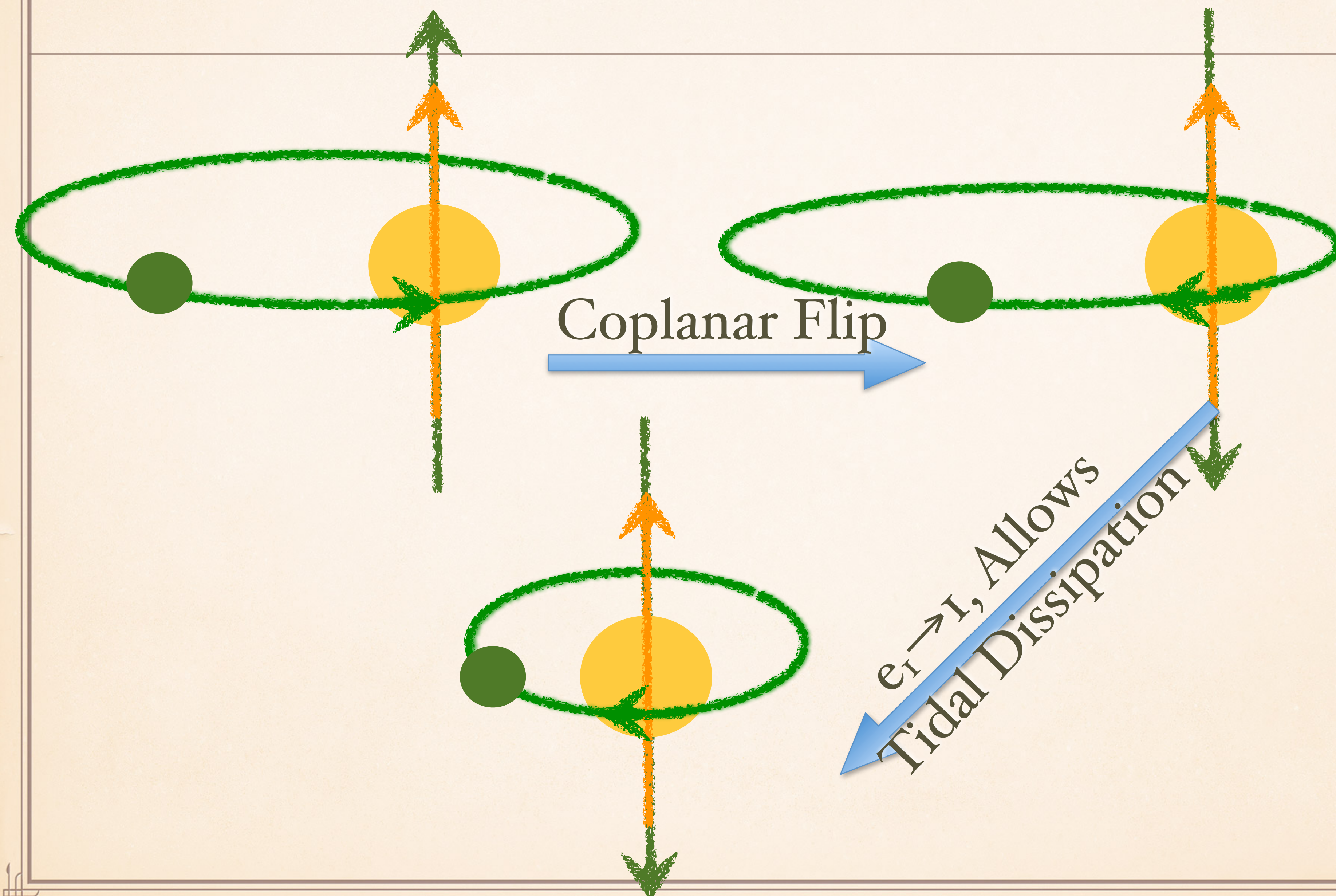


OBSERVED SPIN-ORBIT MISALIGNMENT

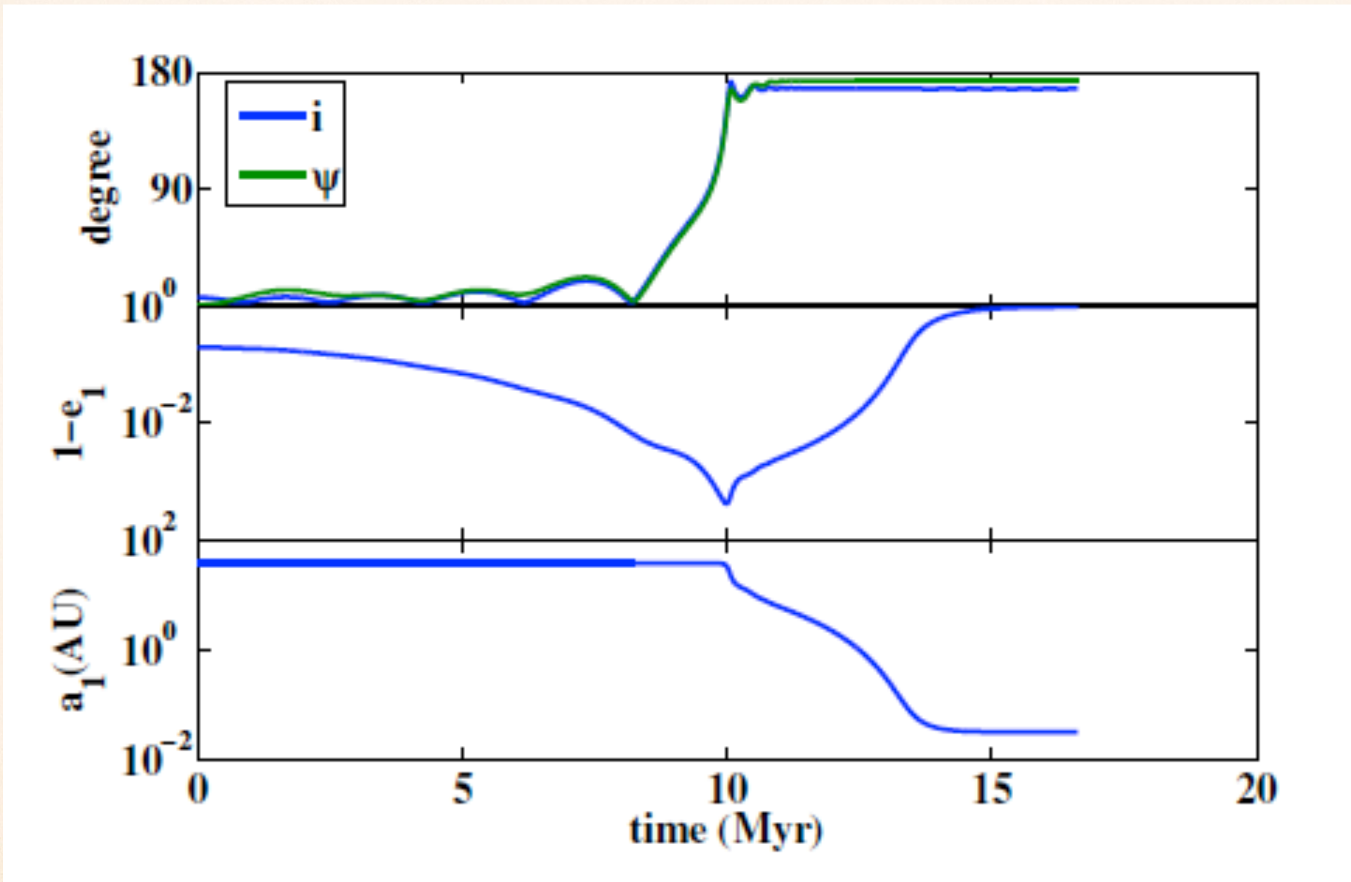
Solar System: misalignment $\Psi \lesssim 7^o$



FORMATION OF COUNTER ORBITING HOT JUPITERS (LK + TIDE)



FORMATION OF COUNTER ORBITING HOT JUPITERS (LK + TIDE)



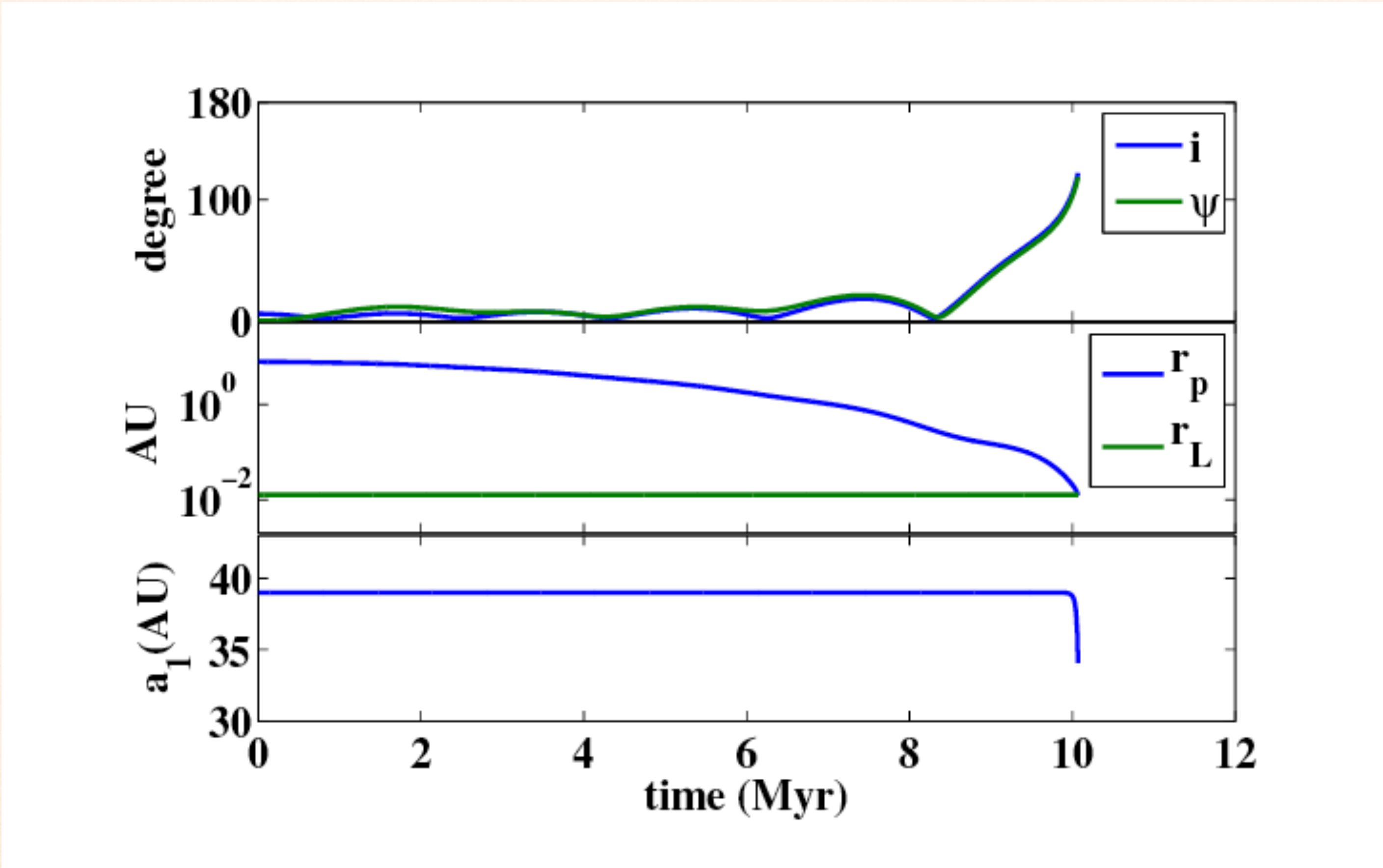
$e_1 \rightarrow 1$ during the flip

=> $r_p\downarrow$, tide dominates.

=> $e_1 \rightarrow 0$, $a_1\downarrow$, i, $\psi \approx 180^o$.

Li et al. 2014a

FORMATION OF COUNTER ORBITING HOT JUPITERS (LK + TIDE)

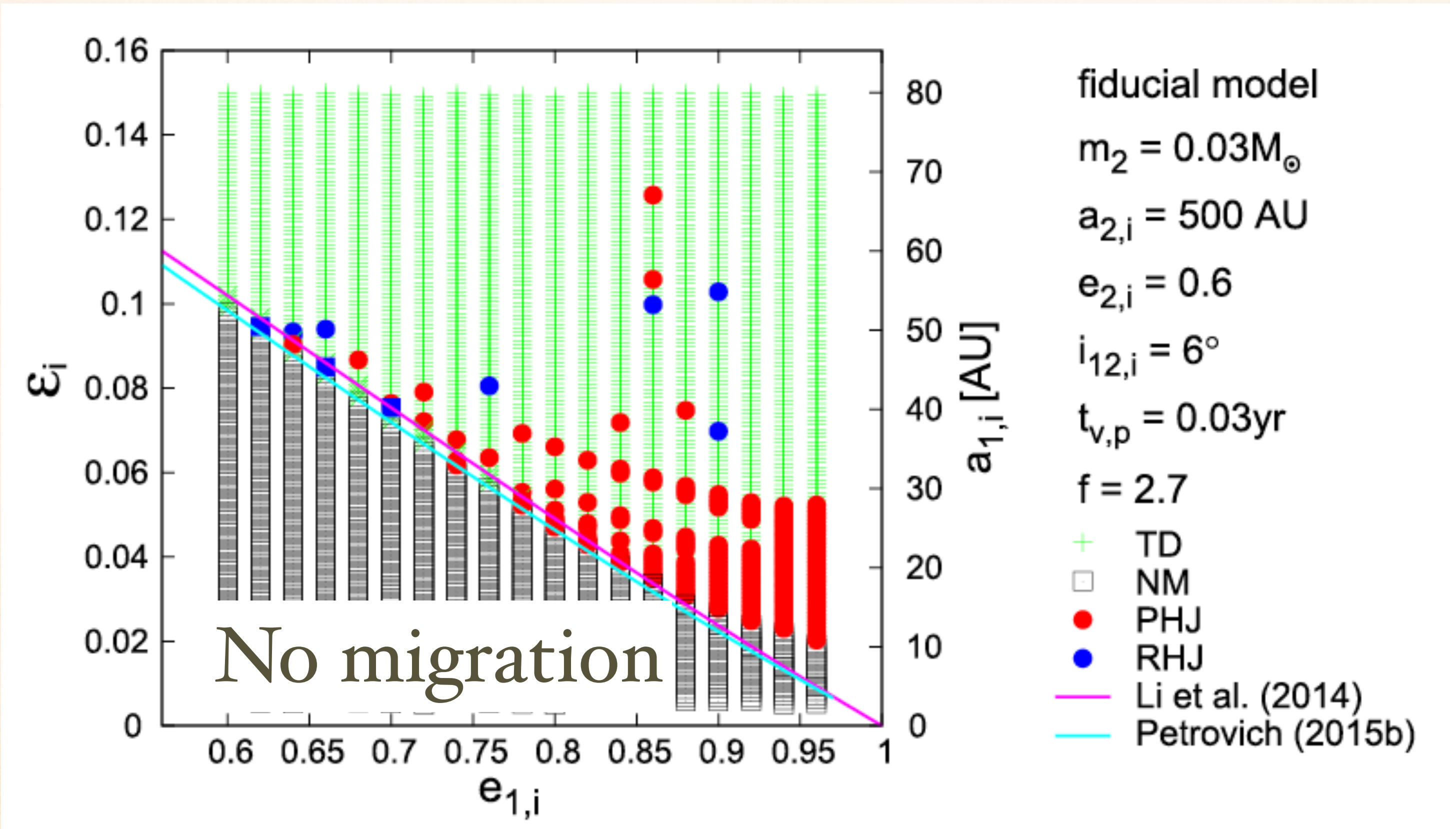


May produce tidal disruption events

Li et al. 2014a

DIFFICULTY IN THE FORMATION OF COUNTER-ORBITING HOT JUPITERS

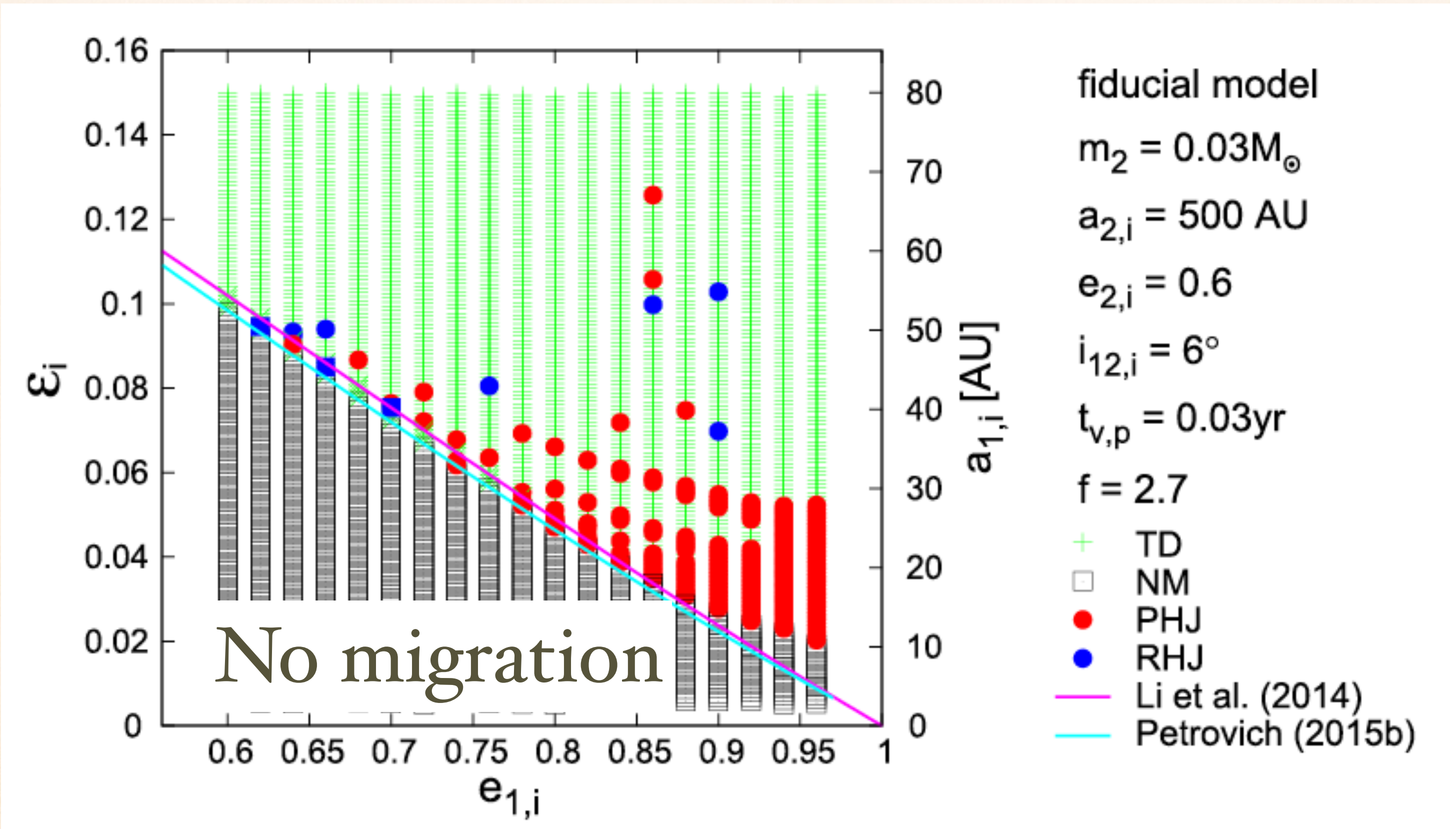
Including short range forces, a small fraction survive and produce retrograde planets



Xue & Suto 2016, Xue et al. 2017

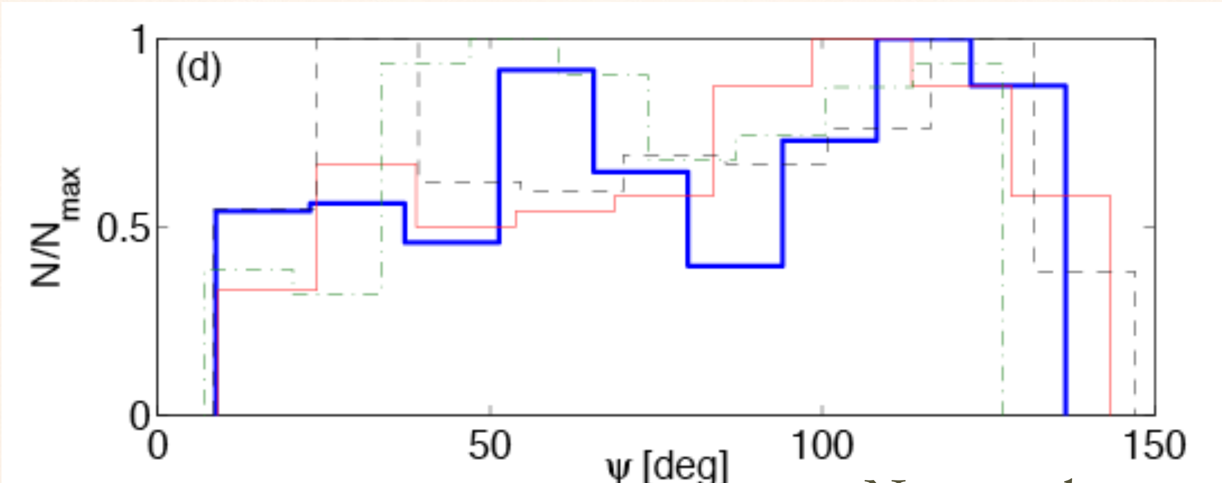
DIFFICULTY IN THE FORMATION OF COUNTER-ORBITING HOT JUPITERS

Flip condition (with no short range forces) is also a good approximation for migration condition



Xue & Suto 2016, Xue et al. 2017

FORMATION OF MISALIGNED HOT JUPITERS (LK + TIDE) BY POPULATION SYNTHESIS

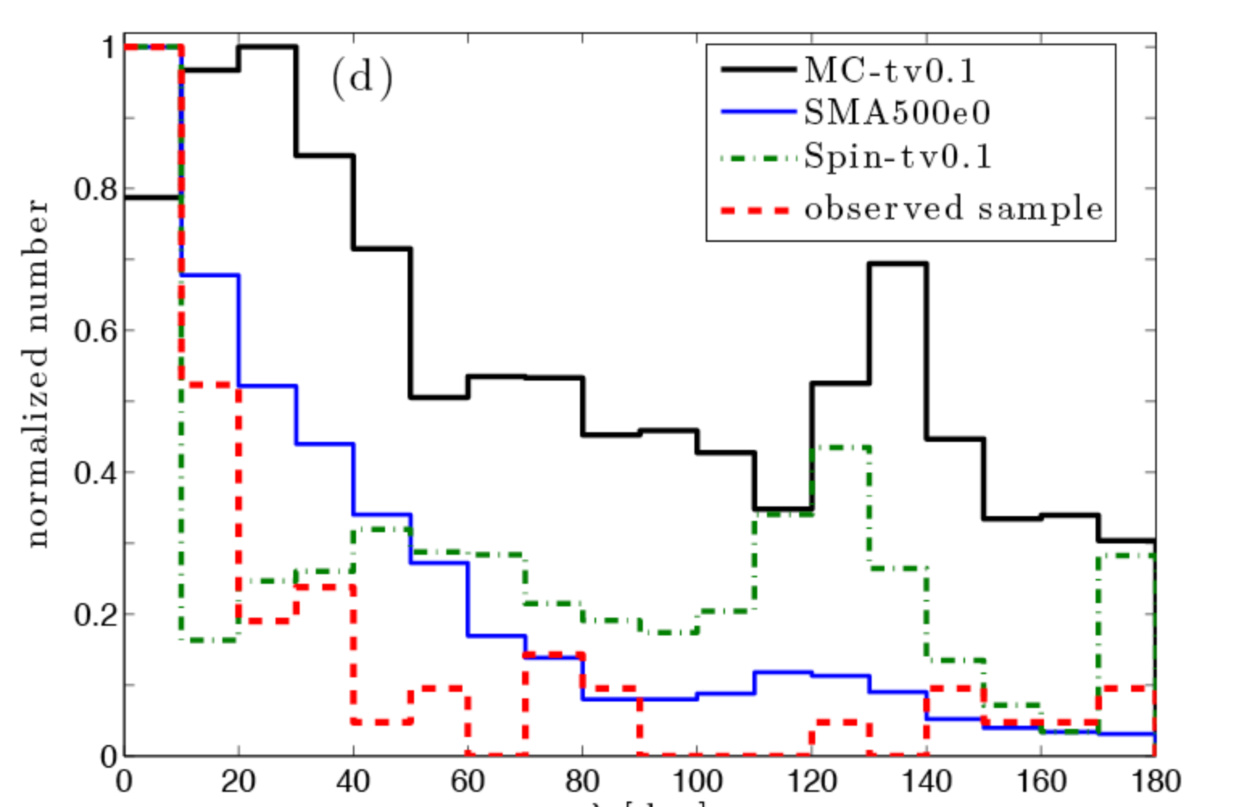


Naoz et al. 2011

- 15% of systems produce hot Jupiters
- ELK may account for about 30% of hot Jupiters

(Naoz et al. 2011)

FORMATION OF MISALIGNED HOT JUPITERS (LK + TIDE) BY POPULATION SYNTHESIS

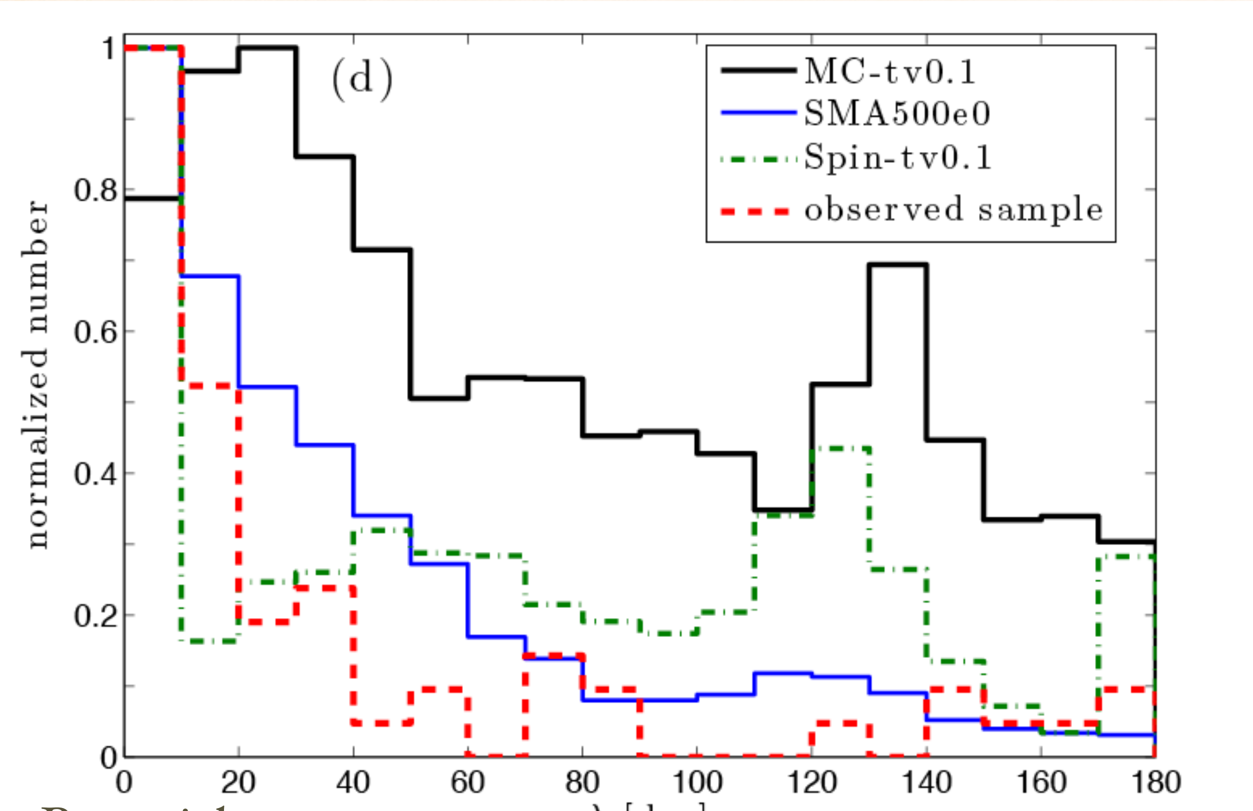


Petrovich 2015

Population synthesis study of interaction of two giant planets.

=> a different mechanism is needed (Petrovich 2015)

FORMATION OF MISALIGNED HOT JUPITERS (LK + TIDE) BY POPULATION SYNTHESIS



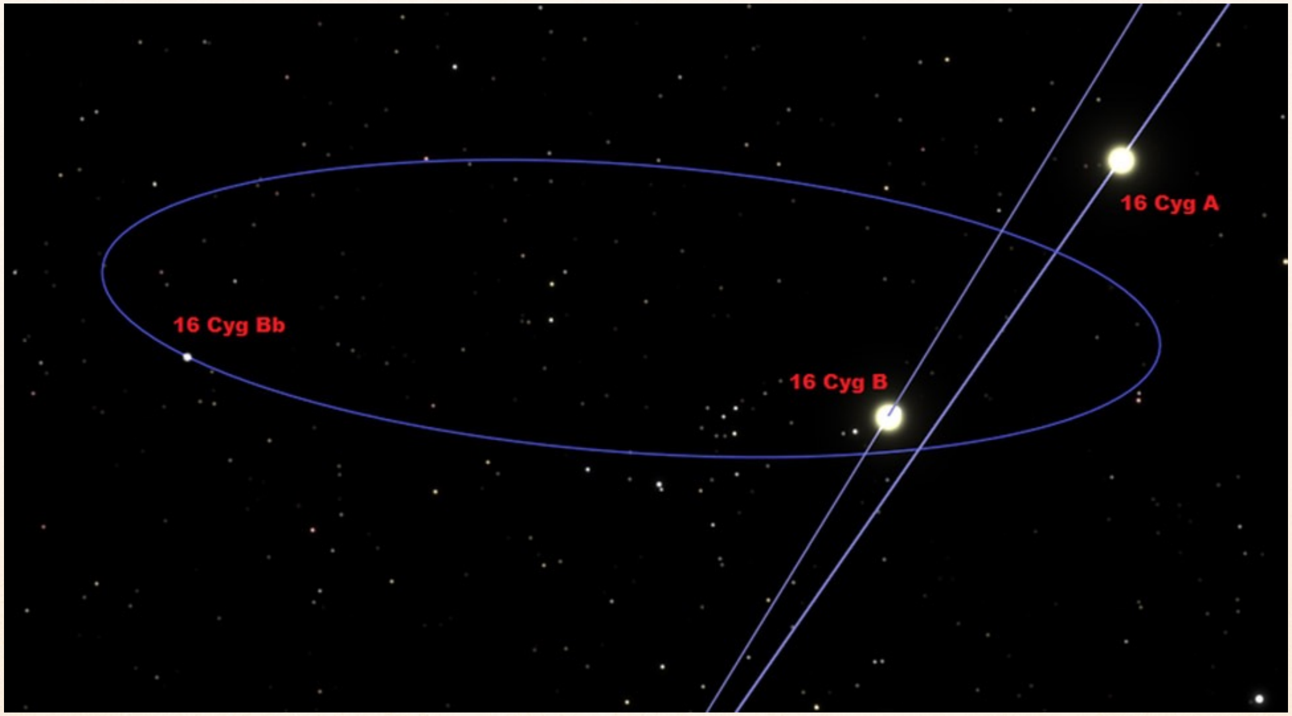
Petrovich 2015

Population synthesis study of interaction of two giant planets.

=> a different mechanism is needed (Petrovich 2015)

LK produces ~ 20% of the observed HJs

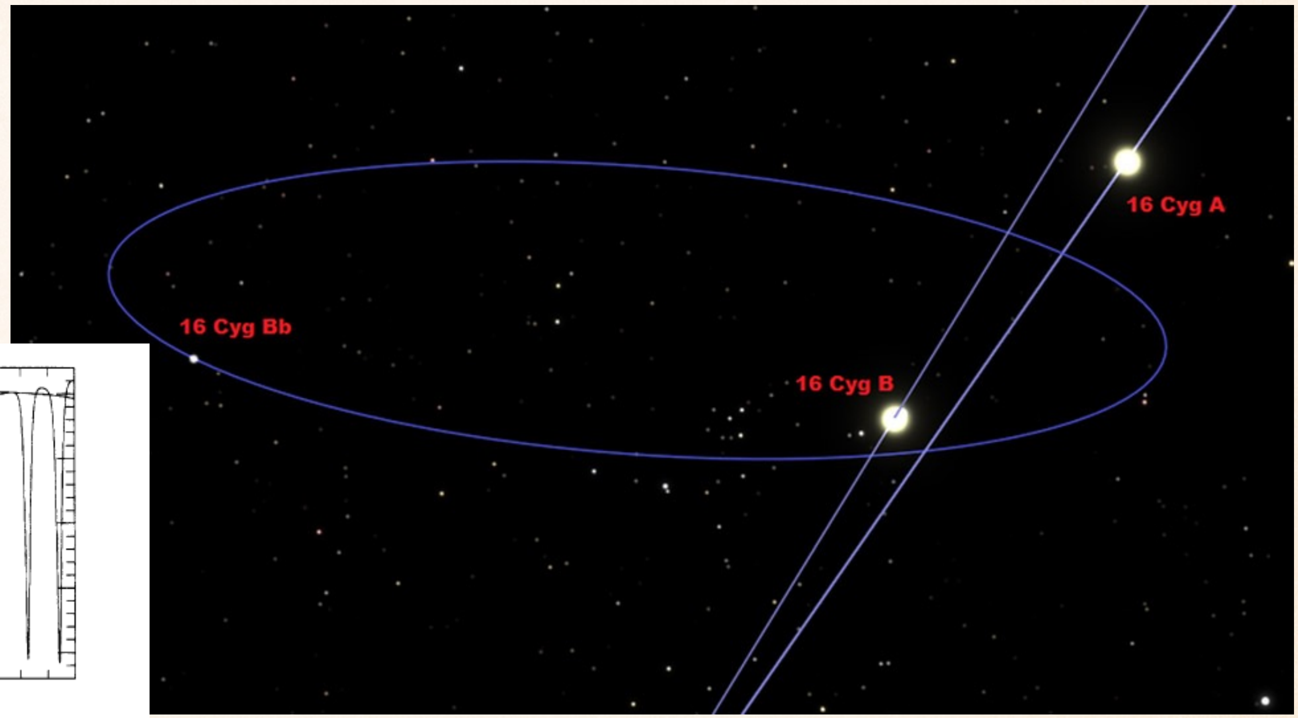
FORMATION OF HOT JUPITERS — OBSERVATIONAL EVIDENCES

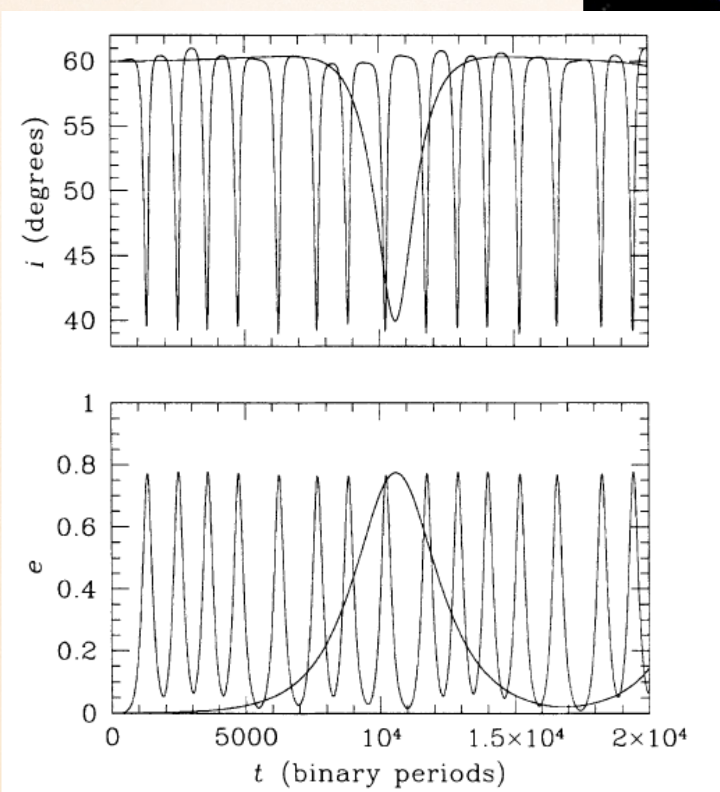


16 Cygni Bb: e = 0.67

Cochran et al. 1996

FORMATION OF HOT JUPITERS

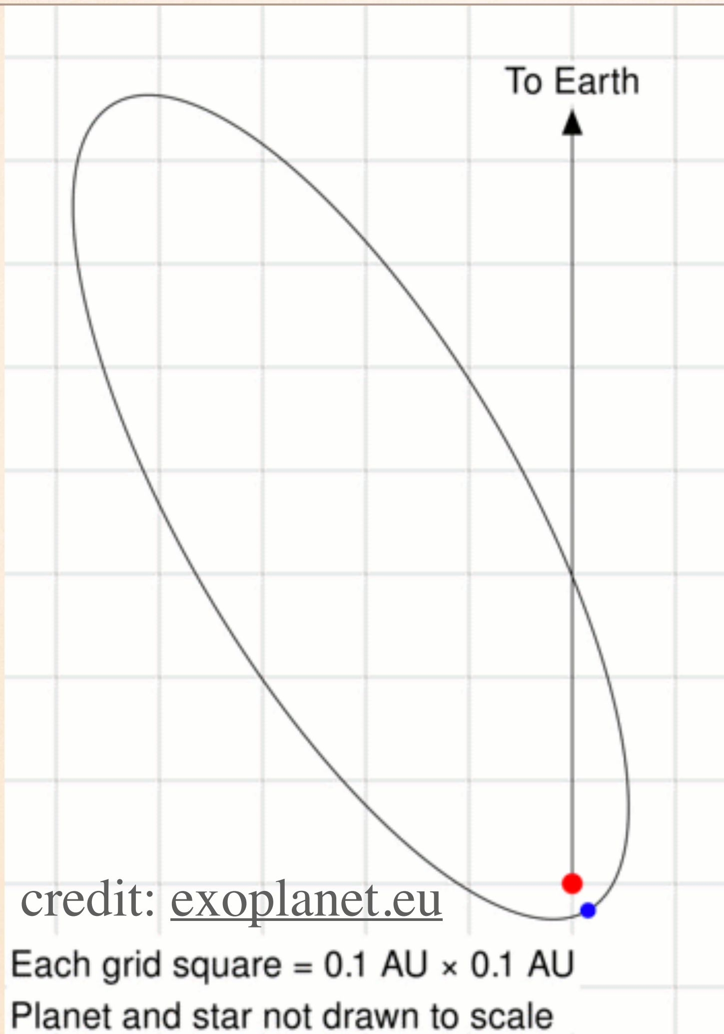




16 Cygni Bb: e = 0.67, can be produced by Lidov-Kozai mechanism

Holman et al. 1997

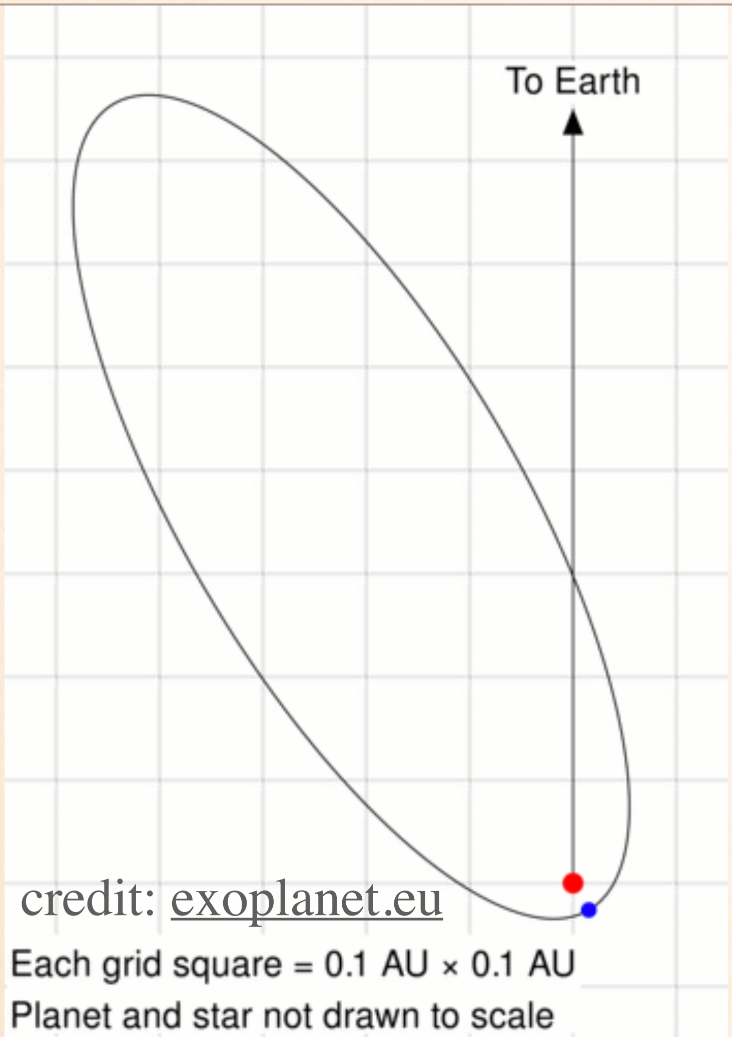
FORMATION OF HOT JUPITERS



credit: exoplanet.eu

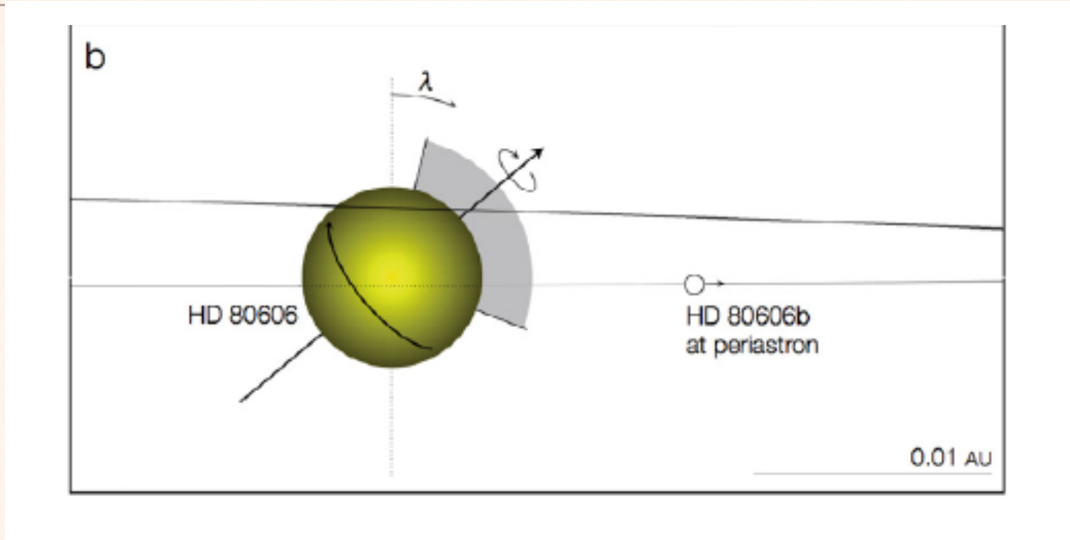
Naef et al. 2001

FORMATION OF HOT JUPITERS



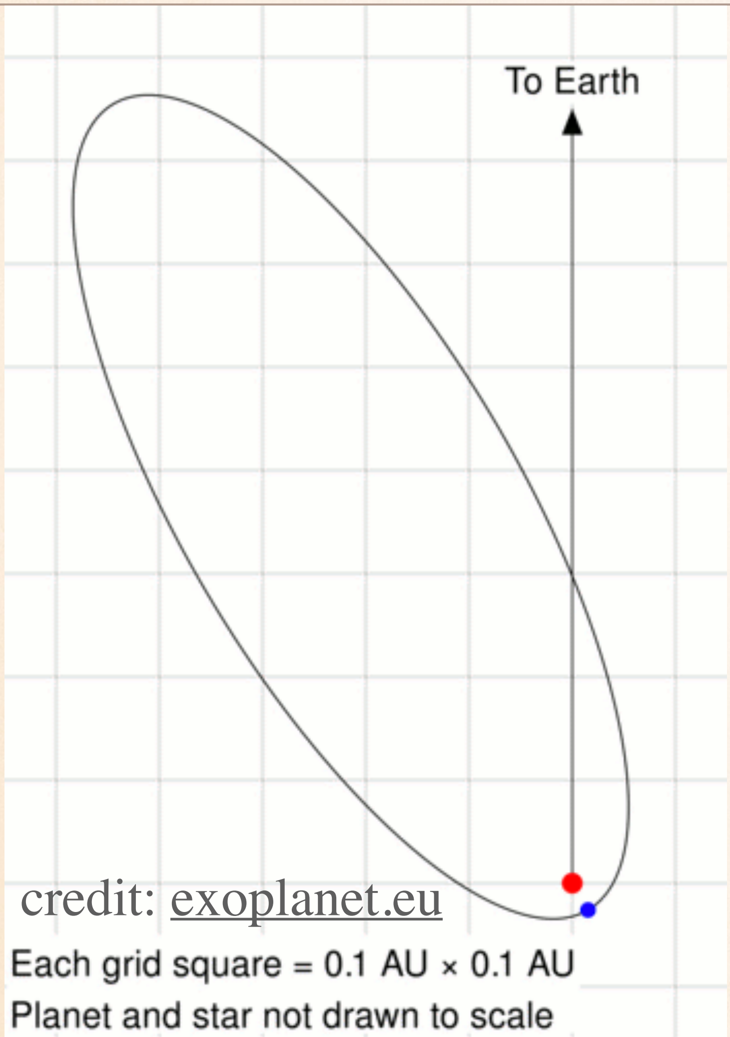
credit: exoplanet.eu

Naef et al. 2001



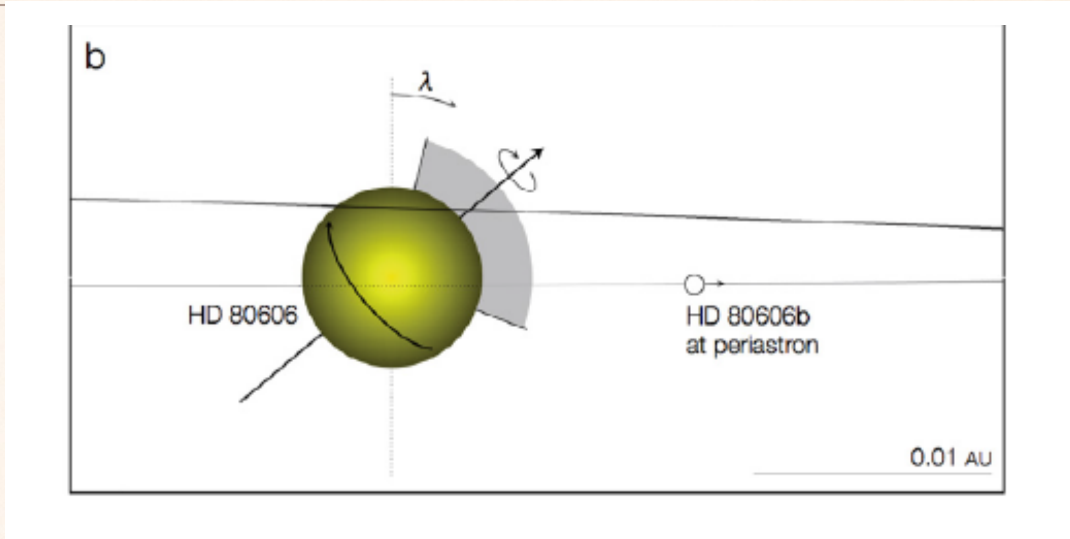
Pont et al. 2009

FORMATION OF HOT JUPITERS



credit: exoplanet.eu

Naef et al. 2001



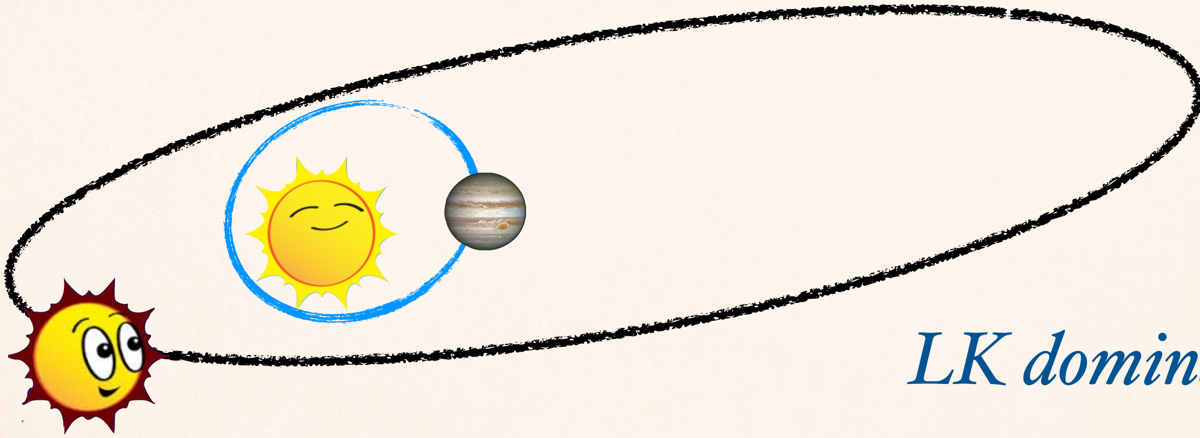
Pont et al. 2009

HD80606b: e = 0.93, can be produced by Lidov-Kozai mechanism

Wu & Murray 2003

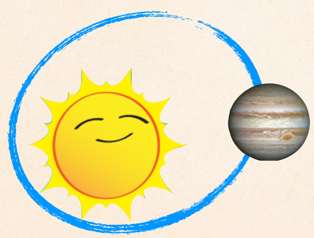
FRIENDS OF HOT JUPITERS

Existence an outer companion?



LK dominate

or



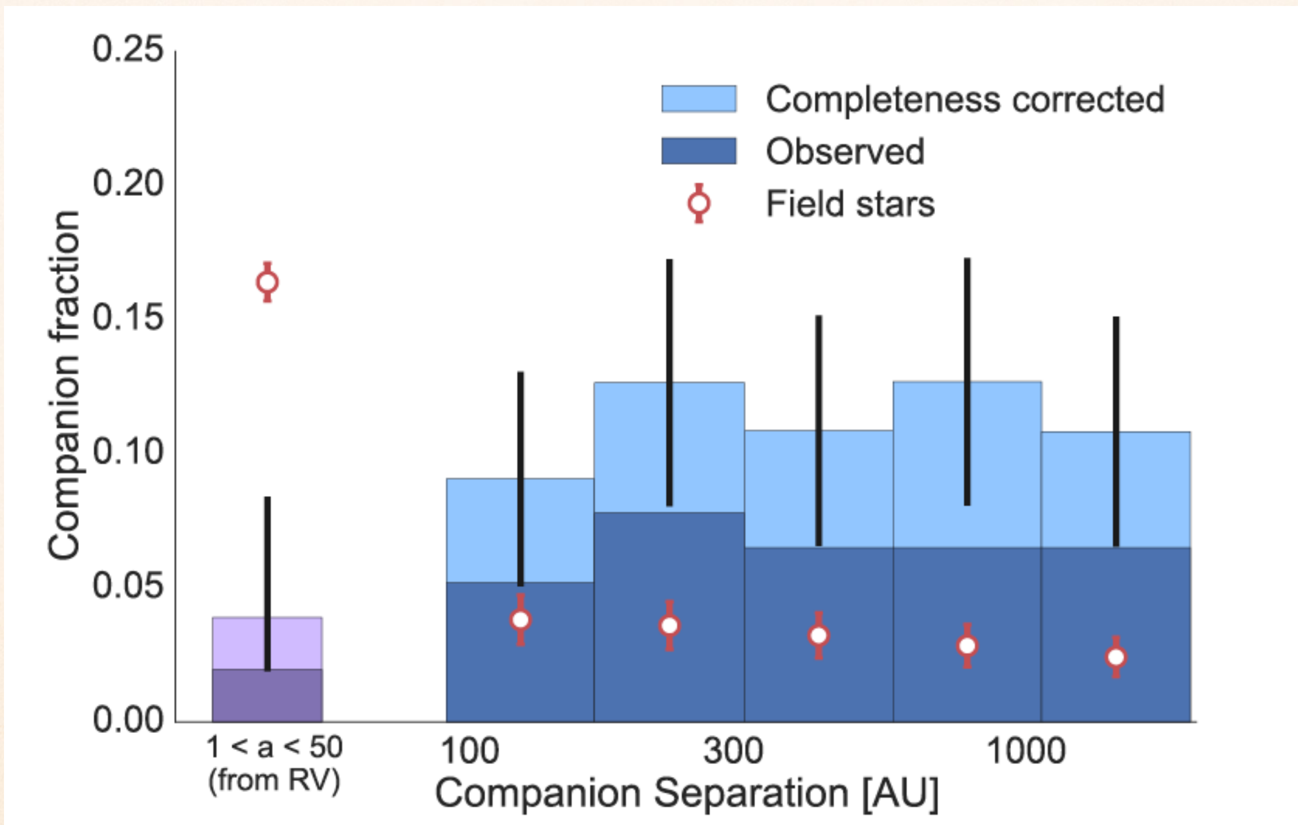
LK not dominate

Knutson et al. 2014

FRIENDS OF HOT JUPITERS

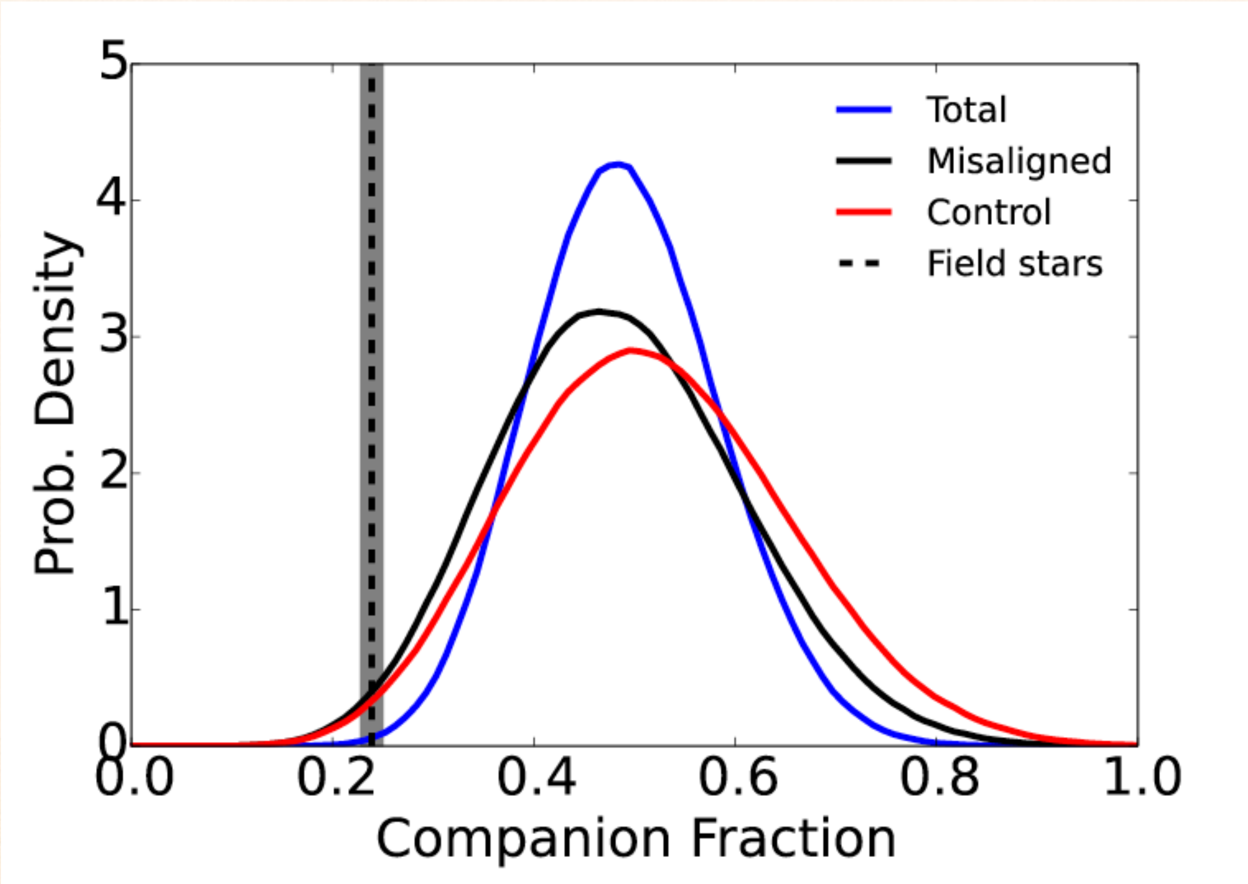
47%±7% of hot Jupiter have stellar companions with *a* b.t. 50-2000 AU based on 77 transiting hot Jupiters

Ngo et al. 2016



< 16%±5% systems formed via Lidov-Kozai oscillations

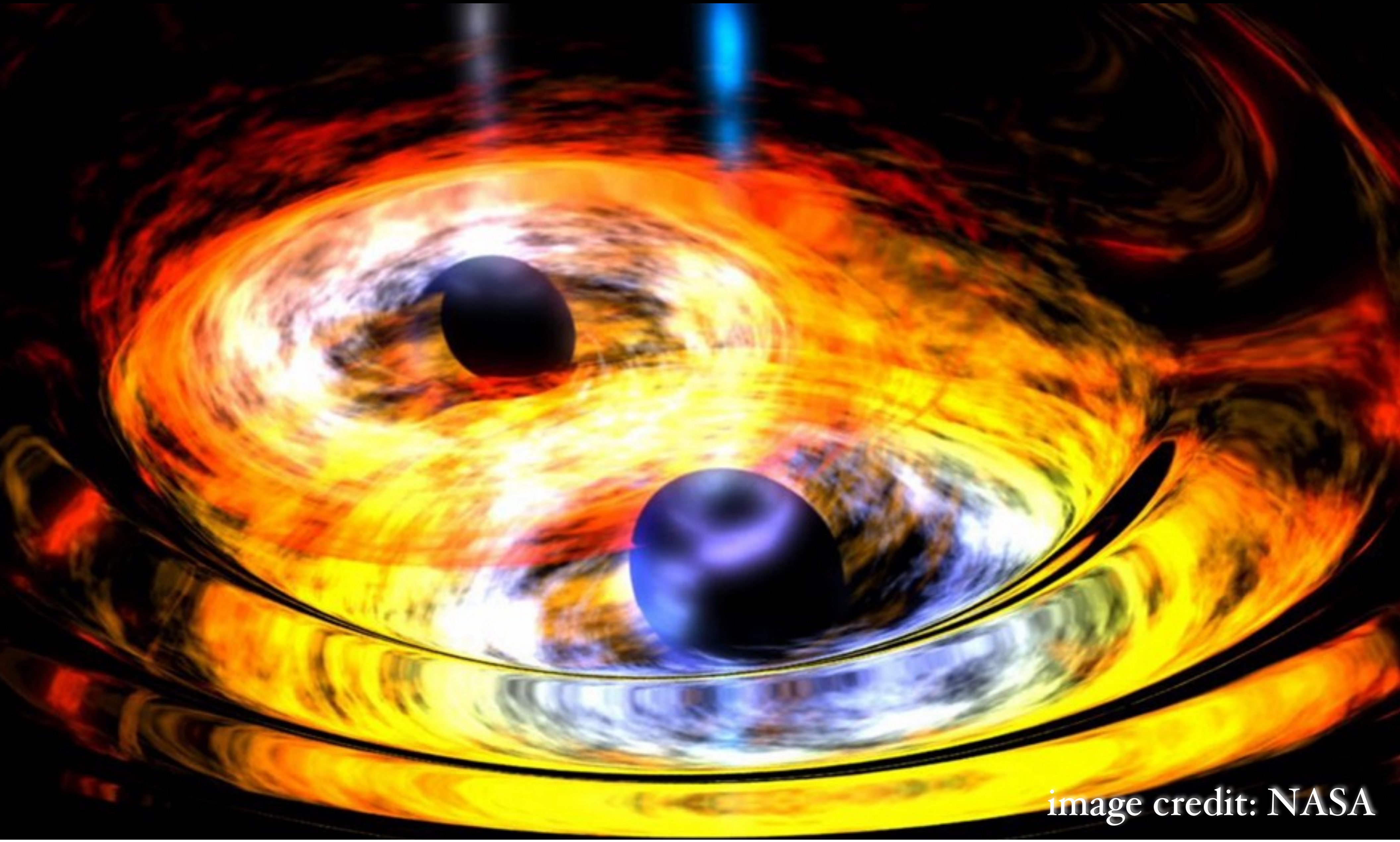
FRIENDS OF HOT JUPITERS



No correlation between misaligned/eccentric hot Jupiter systems and the incidence of stellar companions based on 27 misaligned/eccentric HJs

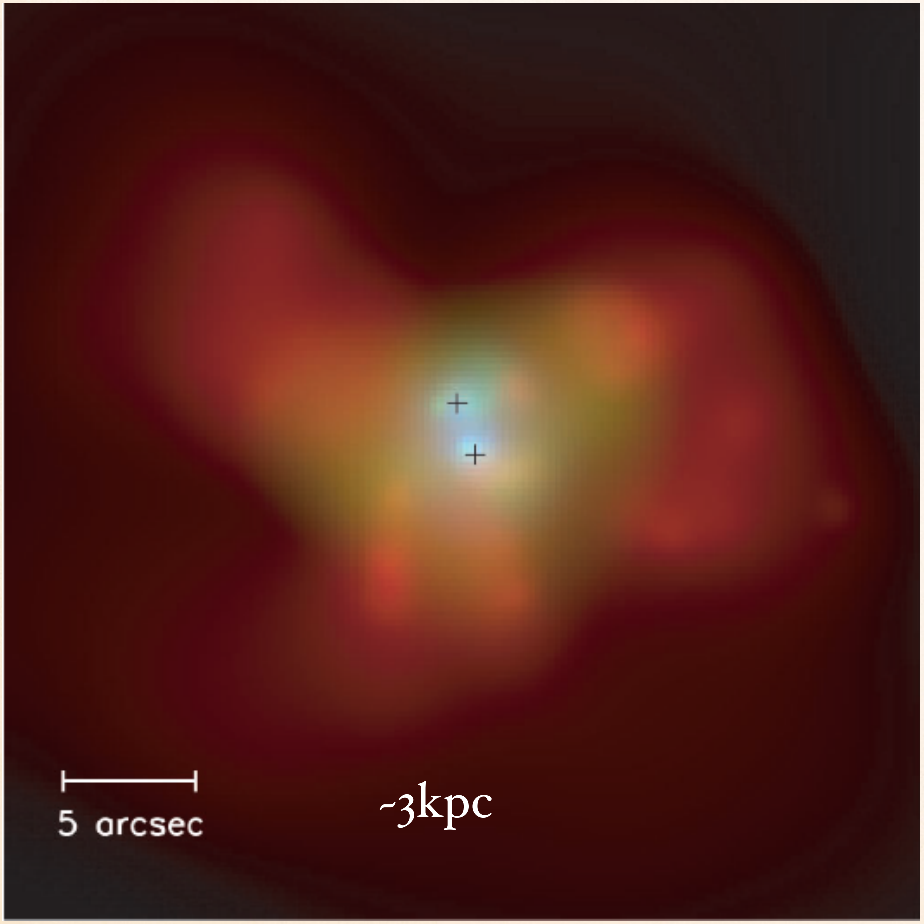
Ngo et al. 2015

EXAMPLES --- 2. EFFECTS ON STARS SURROUNDING SMBHB



EXAMPLES --- 2. EFFECTS ON STARS SURROUNDING SMBHB

- SMBHBs originate from mergers between galaxies.



- SMBHBs with mostly ~kpc separation have been observed with direct imagine.

  (e.g., Woo et al. 2014; Komossa et al. 2013, Fabbiano et al. 2011, Green et al. 2010, Civano et al. 2010, Rodriguez et al. 2006, Komossa et al. 2003, Hutchings & Neff 1989)

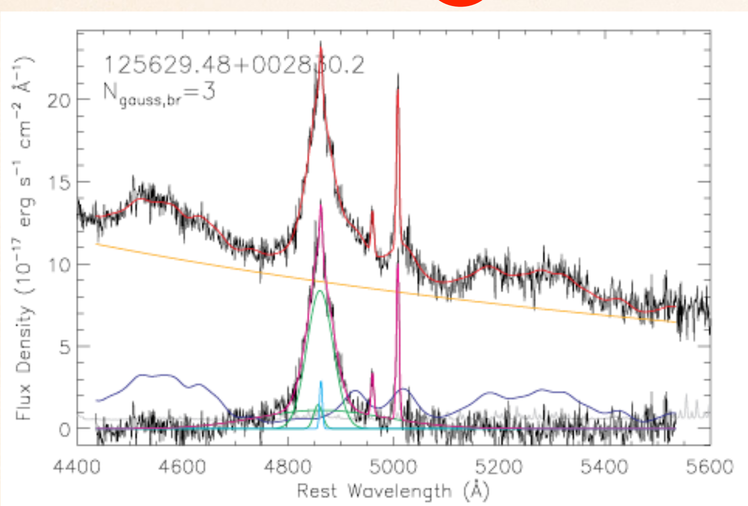
Multicolor image of NGC 6240. Red p soft (0.5–1.5 keV), green p medium (1.5–5 keV), and blue p hard (5–8 keV) X-ray band. (Komossa et al. 2003)

STARS SURROUNDING SMBHB

- At ~1pc separation it is more difficult to identify SMBHBs. SMBHBs can be observed with photometric and spectral features.

  (e.g., Shen et al. 2013, Boroson & Lauer 2009, Valtonen et al. 2008, Loeb 2007)

Example of multi-epoch spectroscopy (Shen et al. 2013):



active BH dominates the BL features, multi-epoch BL features => binary orbital parameters

STARS SURROUNDING SMBHB

- At ~1pc separation it is more difficult to identify SMBHBs. SMBHBs can be observed with photometric and spectral features.

  (e.g., Shen et al. 2013, Boroson & Lauer 2009, Valtonen et al. 2008, Loeb 2007)

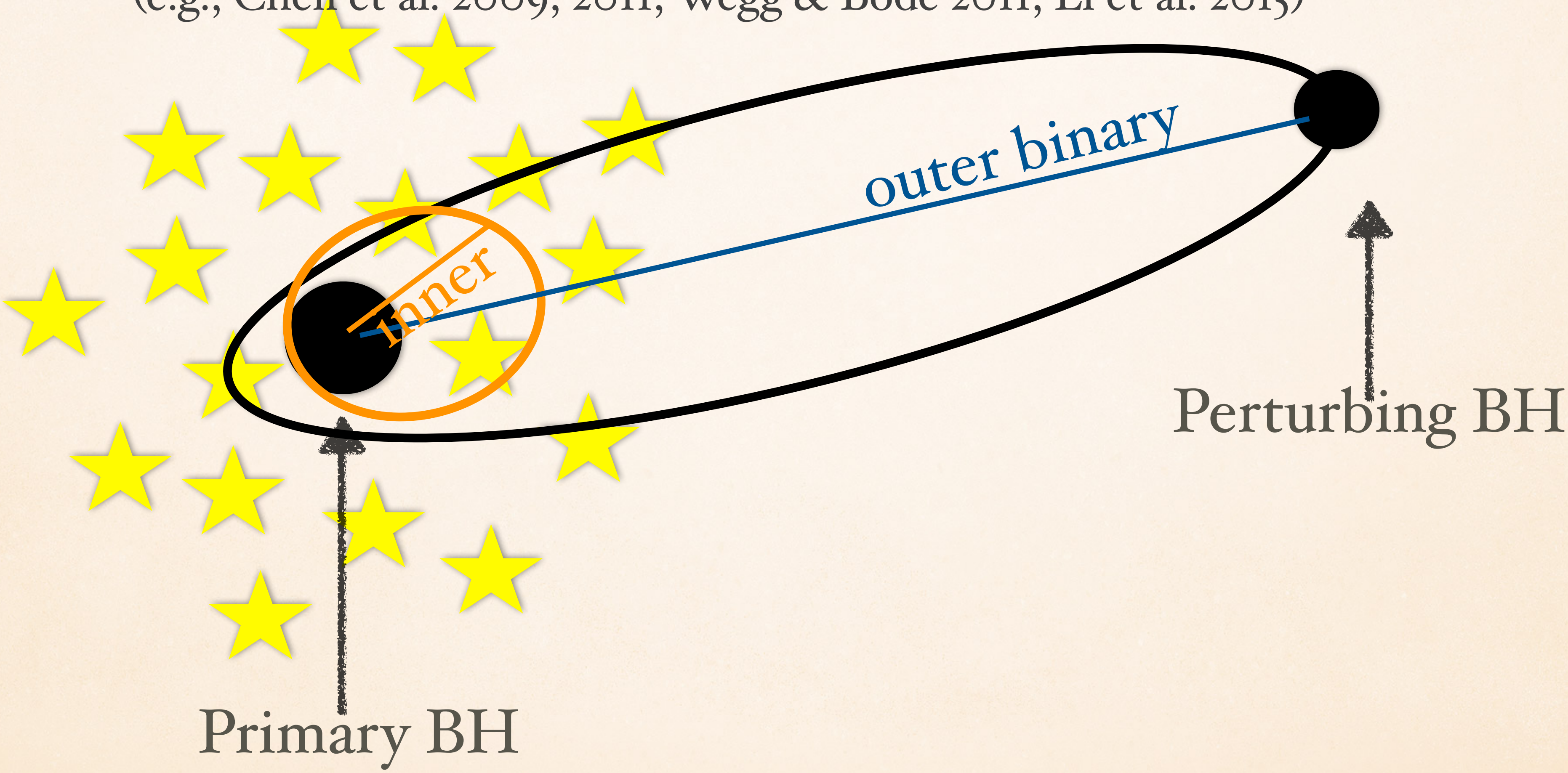
- Identify SMBHB at ~1 pc separation by stellar features due to interactions with SMBHB.

  (e.g., Chen et al. 2009, 2011, Wegg & Bode 2011, Li et al. 2015)

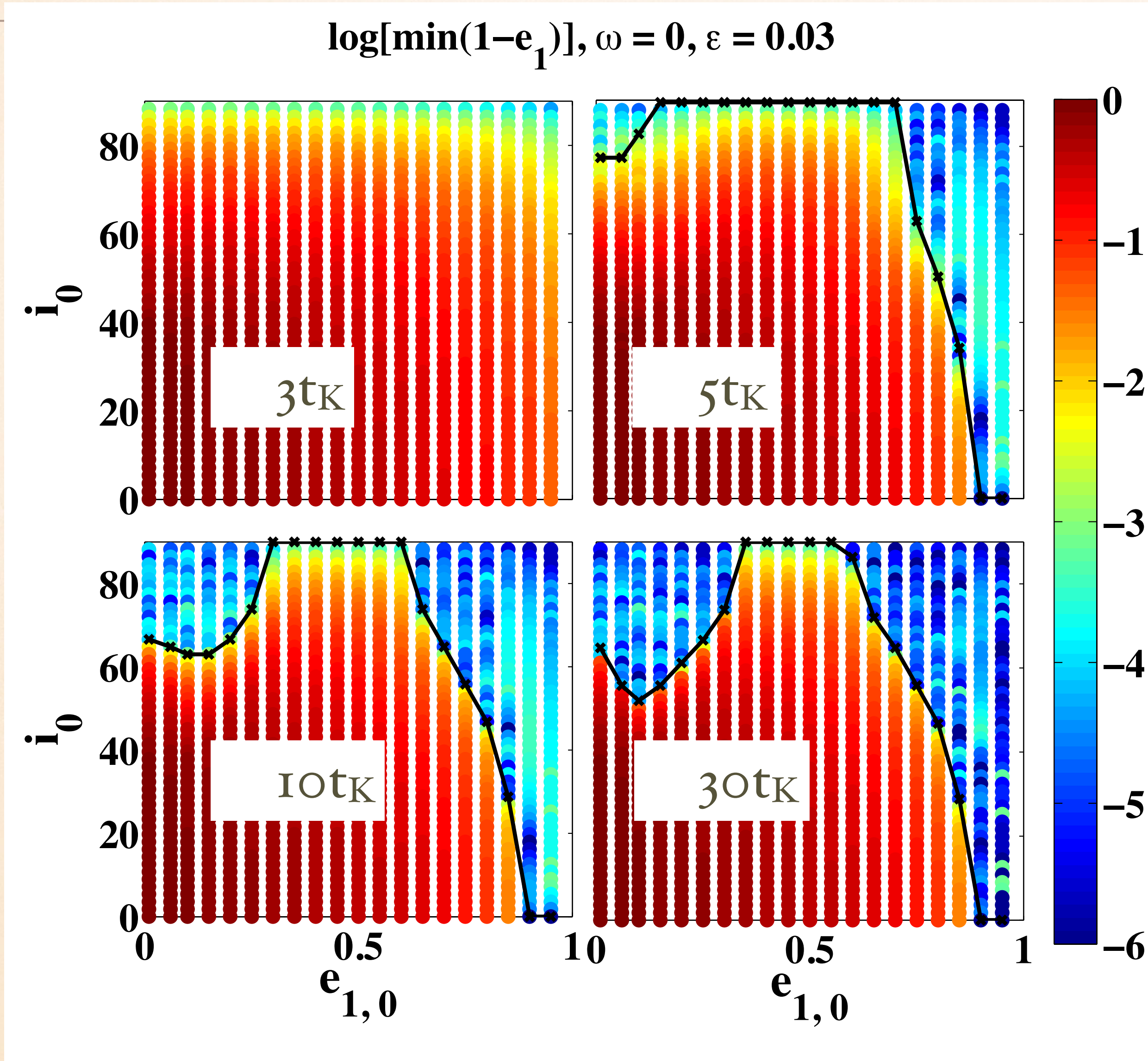
PERTURBATIONS ON STARS SURROUNDING SMBHB

- Identify SMBHB at ~1 pc separation by stellar features due to interactions with SMBHB.

(e.g., Chen et al. 2009, 2011, Wegg & Bode 2011, Li et al. 2015)



ENHANCEMENT OF TIDAL DISRUPTION RATES



$e_{1,\,max}$ determines the closest distance:

$r_p \propto (1\text{-}e_1)$

$$t_K = \frac{8}{3} P_{in} \frac{m_1}{m_2} \left(\frac{a_2}{a_1}\right)^3 (1 - e_2^2)^{3/2}$$

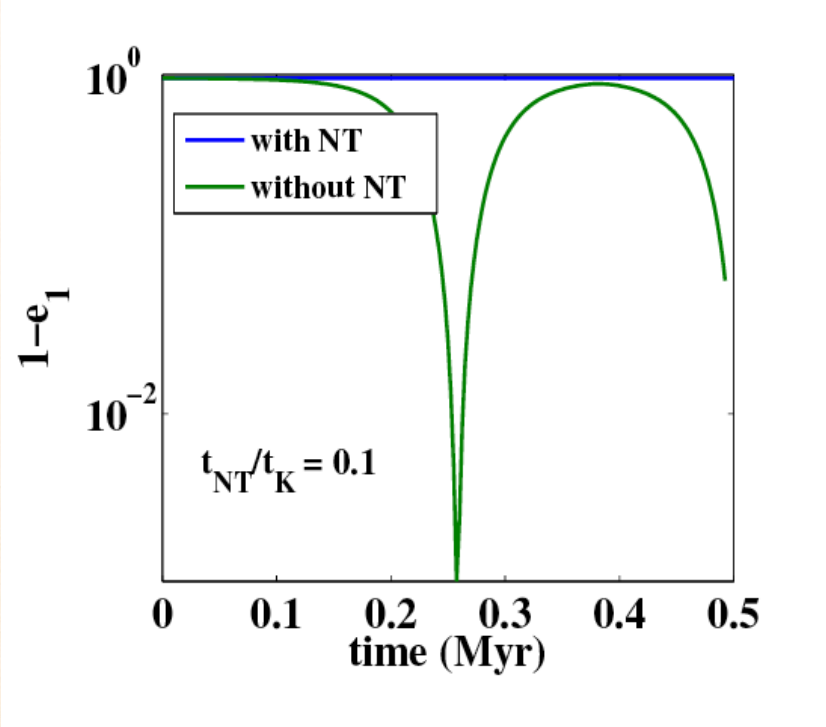
e_{max} reaches $1\text{-}10^{-6}$ over ~$30t_K$ (~Myrs)

Starting at a~$10^6 R_t$, it's still possible to be disrupted in ~$30t_K$!

Li et al. 2014a

SUPPRESSION OF ELK

- Eccentricity excitation suppressed when precession timescale < Kozai timescale.

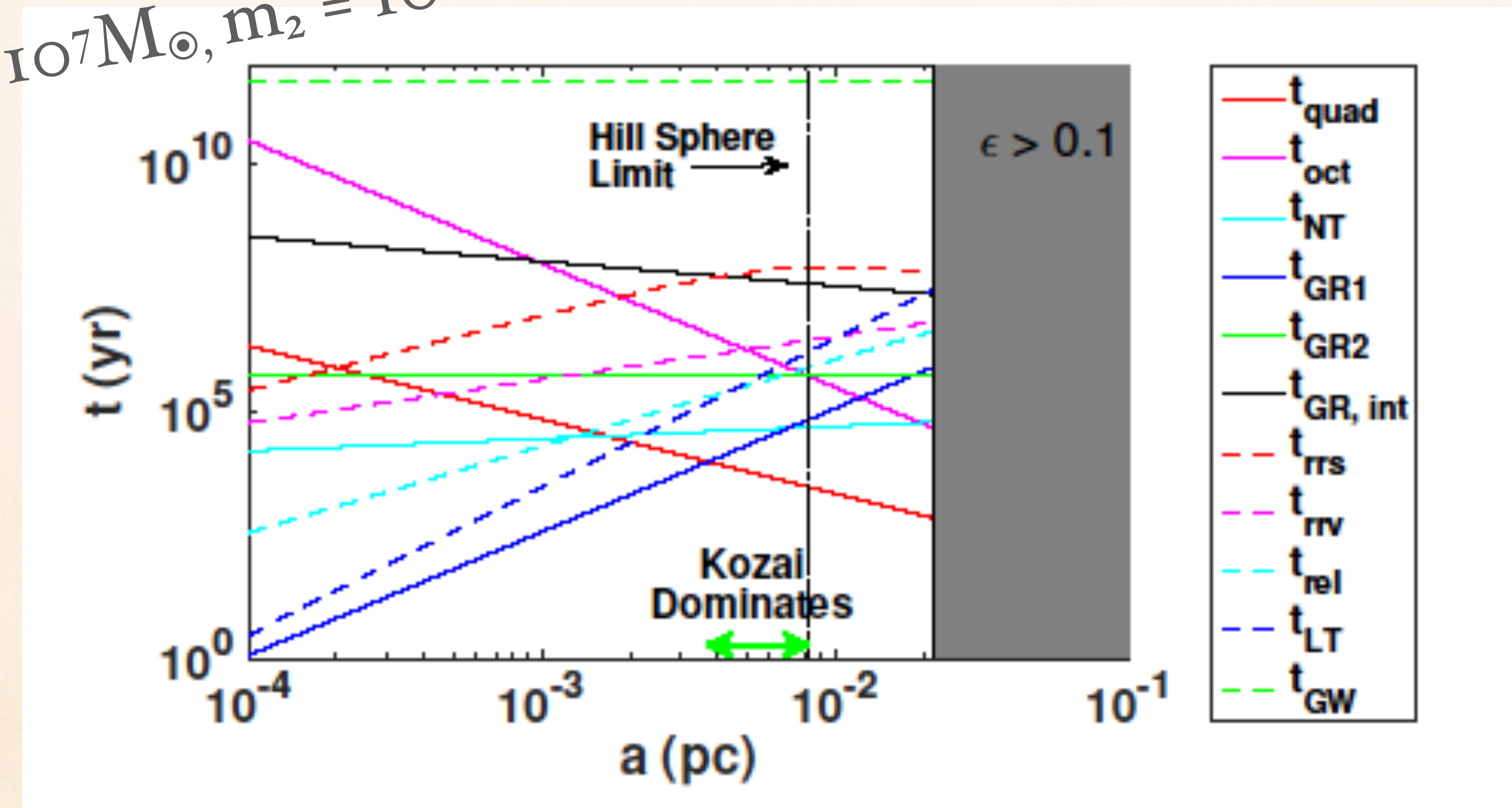


$m_0 = 10^7 M_\odot$, $m_2 = 10^9 M_\odot$, $e_1 = 2/3$, $a_2 = 0.3$ pc, $m_1 = 1 M_\odot$, $e_2 = 0.7$. (Li et al. 2015)

SUPPRESSION OF ELK

- Eccentricity excitation suppressed when precession timescale < Kozai timescale.

$m_0 = 10^7 M_\odot$, $m_2 = 10^9 M_\odot$

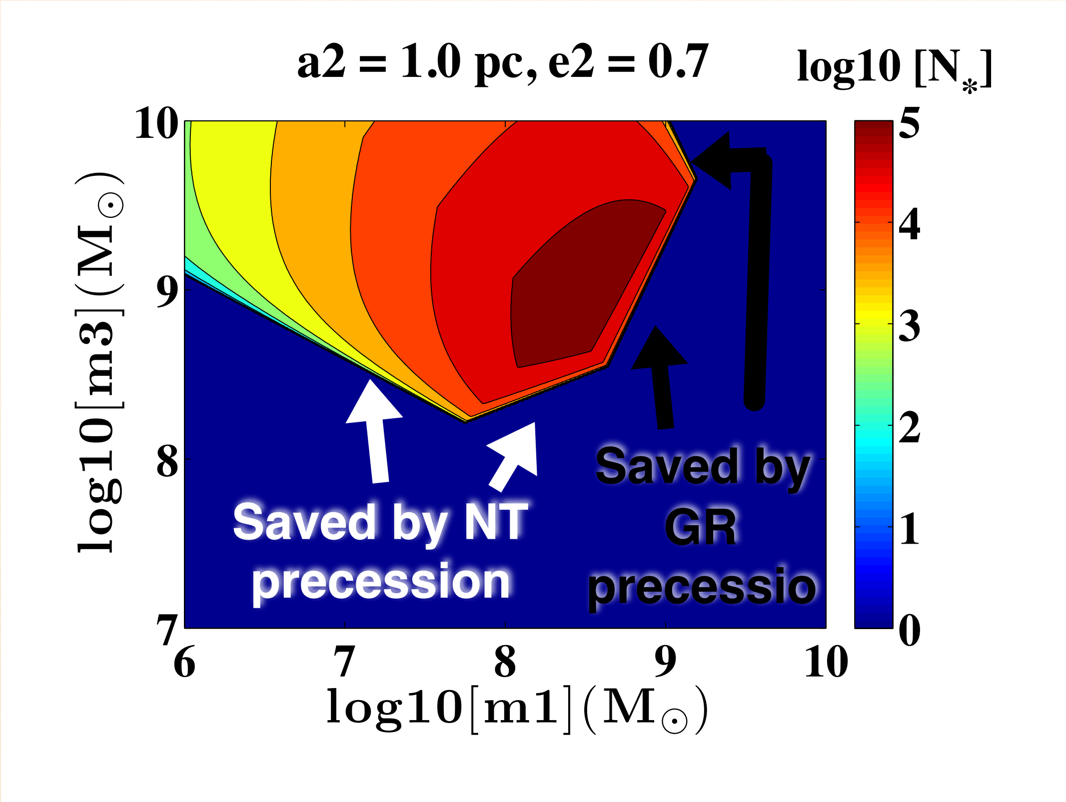


$e_1 = 2/3$, $a_2 = 0.3$ pc, $m_1 = 1 M_\odot$, $e_2 = 0.7$.

(Li et al. 2015)

EXAMPLES --- 2. EFFECTS ON STARS SURROUNDING SMBHB

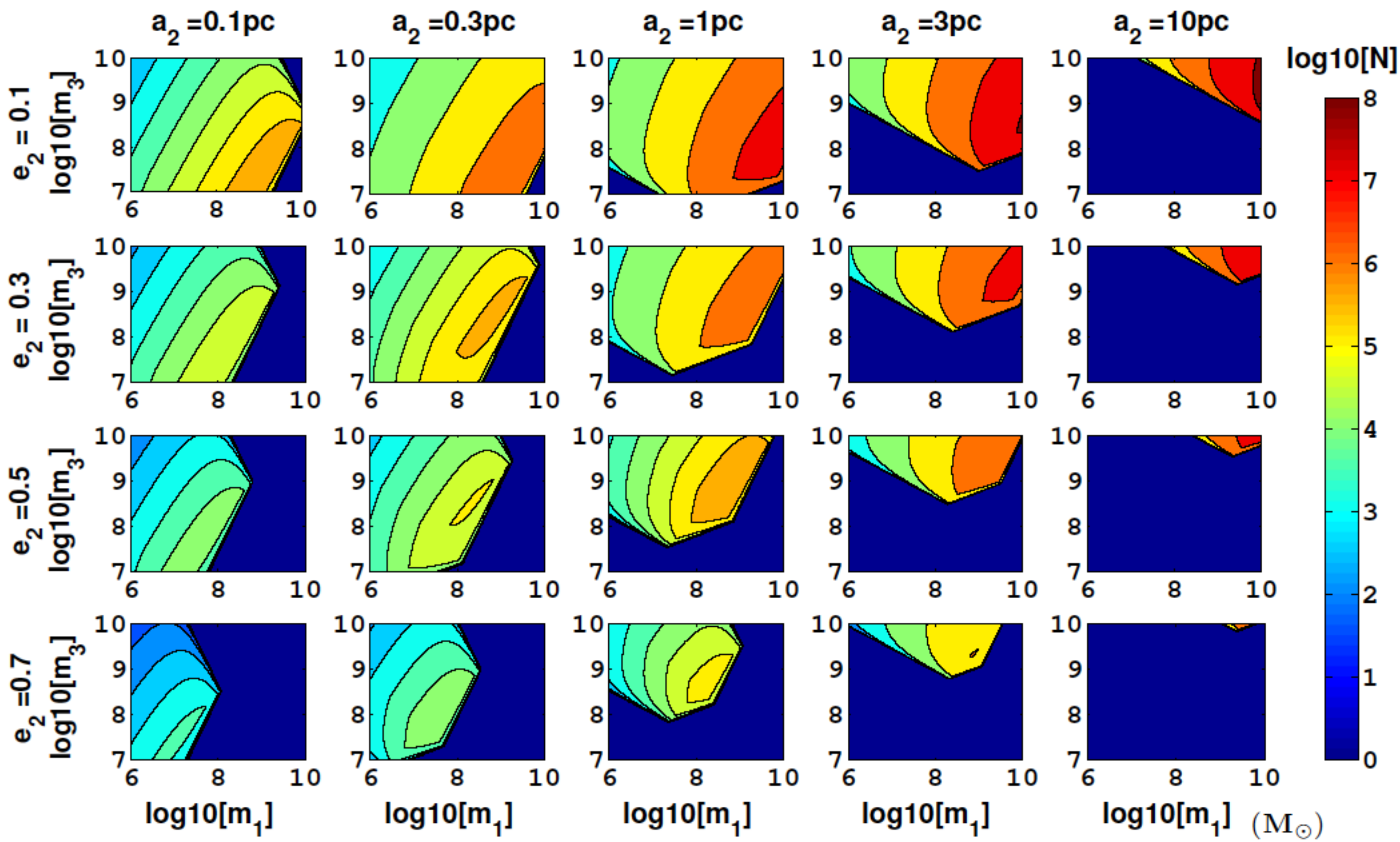
- Eccentricity excitation suppressed when precession timescale < Kozai timescale.



- Kozai affects more stars when perturbing more massive SMBH.

(Li et al. 2015)

SUPPRESSION OF ELK

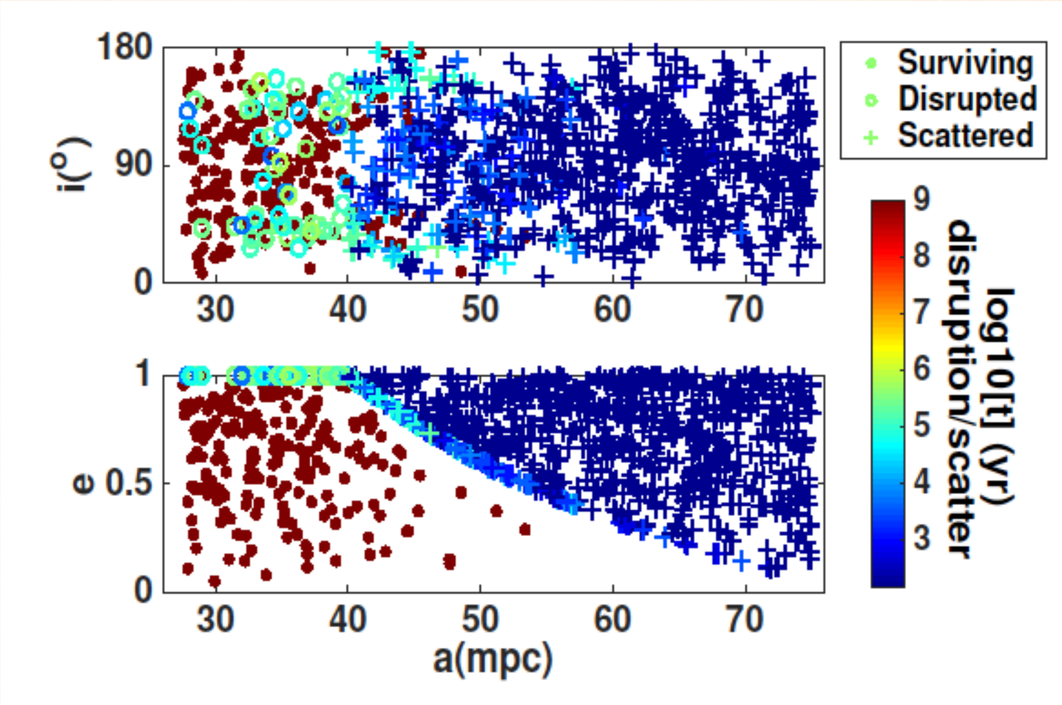


(Li et al. 2015)

EXAMPLES --- 2. EFFECTS ON STARS SURROUNDING SMBHB

- 57/1000 disrupted; 726/1000 scattered.

=> Scattered stars may change the stellar density profile around the SMBH to the shape of a donut.



- Example: $m_1 = 10^7 M_\odot$, $m_2 = 10^8 M_\odot$, $a_2 = 0.5$pc, $e_2 = 0.5$, Run time: 1Gyr.

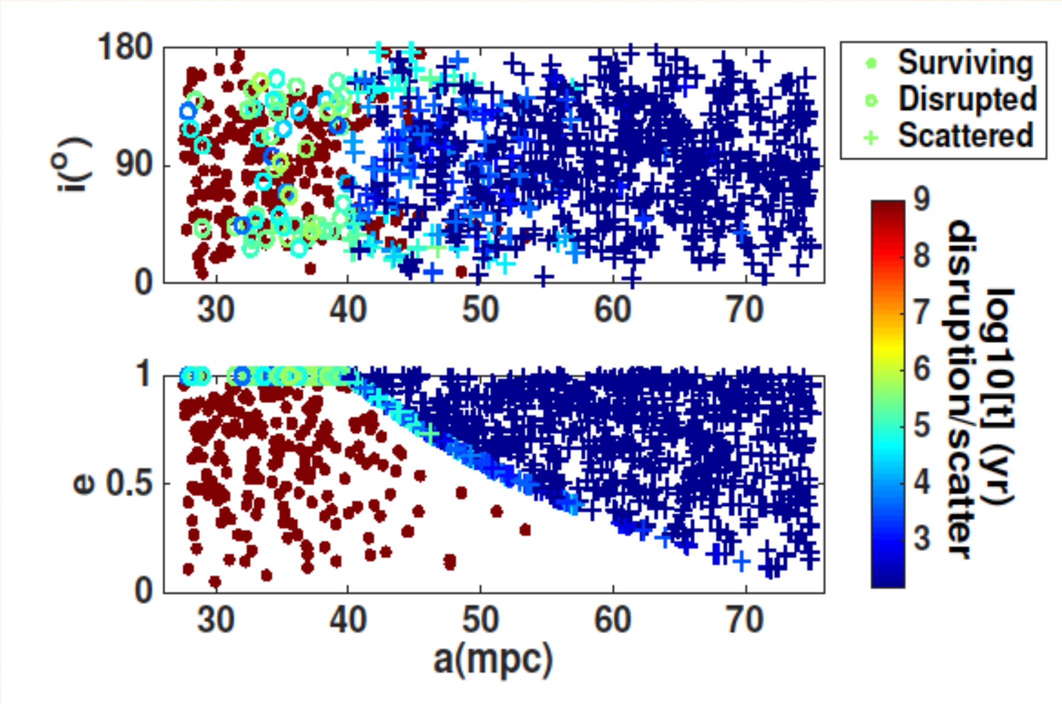
(Li et al. 2015)

EXAMPLES --- 2. EFFECTS ON STARS SURROUNDING SMBHB

- 57/1000 disrupted; 726/1000 scattered.

=> Scattered stars may change stellar density profile around the SMBH.

=> Disruption rate can reach $\sim 10^{-3}$/yr.



- Example: $m_1 = 10^7 M_\odot$, $m_2 = 10^8 M_\odot$, $a_2 = 0.5$pc, $e_2 = 0.5$, Run time: 1Gyr.

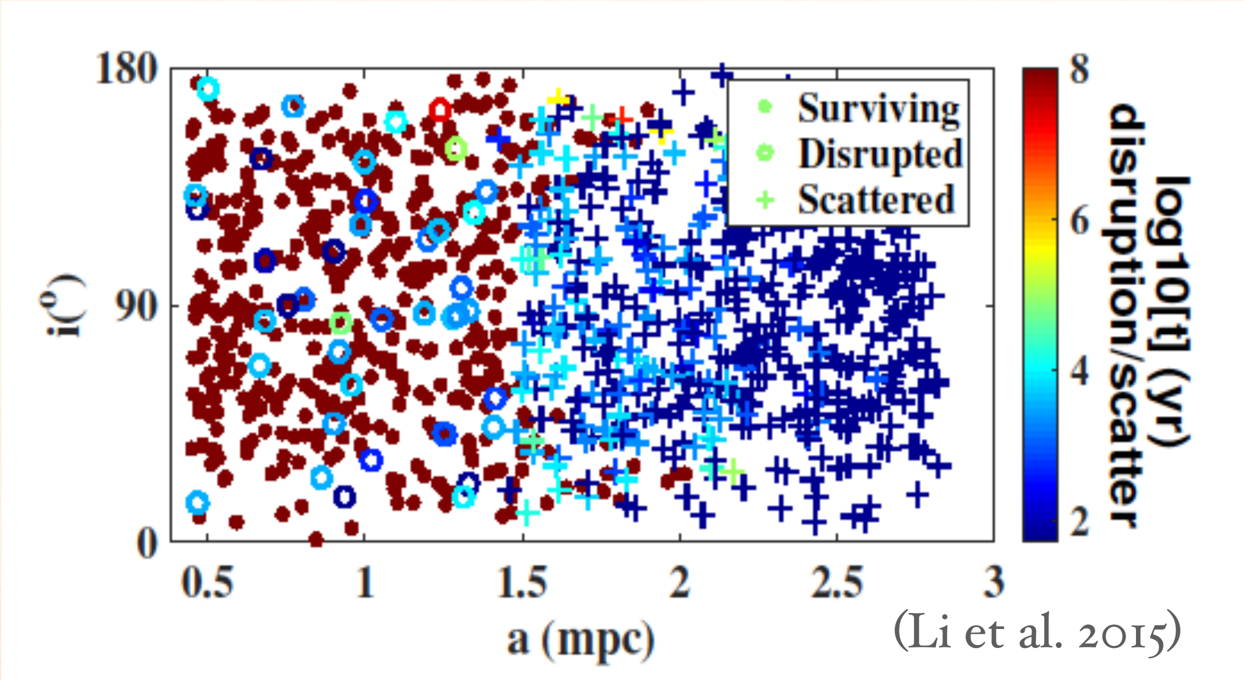
(Li et al. 2015)

EFFECTS ON STARS SURROUNDING AN IMBH IN GC

- Example: $m_1 = 10^4\,M_\odot$, $m_2 = 4\times10^6 M_\odot$, $a_2 = 0.1$pc, $e_2 = 0.7$ (Run time: 100 Myr)

EFFECTS ON STARS SURROUNDING AN IMBH IN GC

- Example: $m_1 = 10^4 M_\odot$, $m_2 = 4\times10^6 M_\odot$, $a_2 = 0.1$pc, $e_2 = 0.7$ (Run time: 100 Myr)



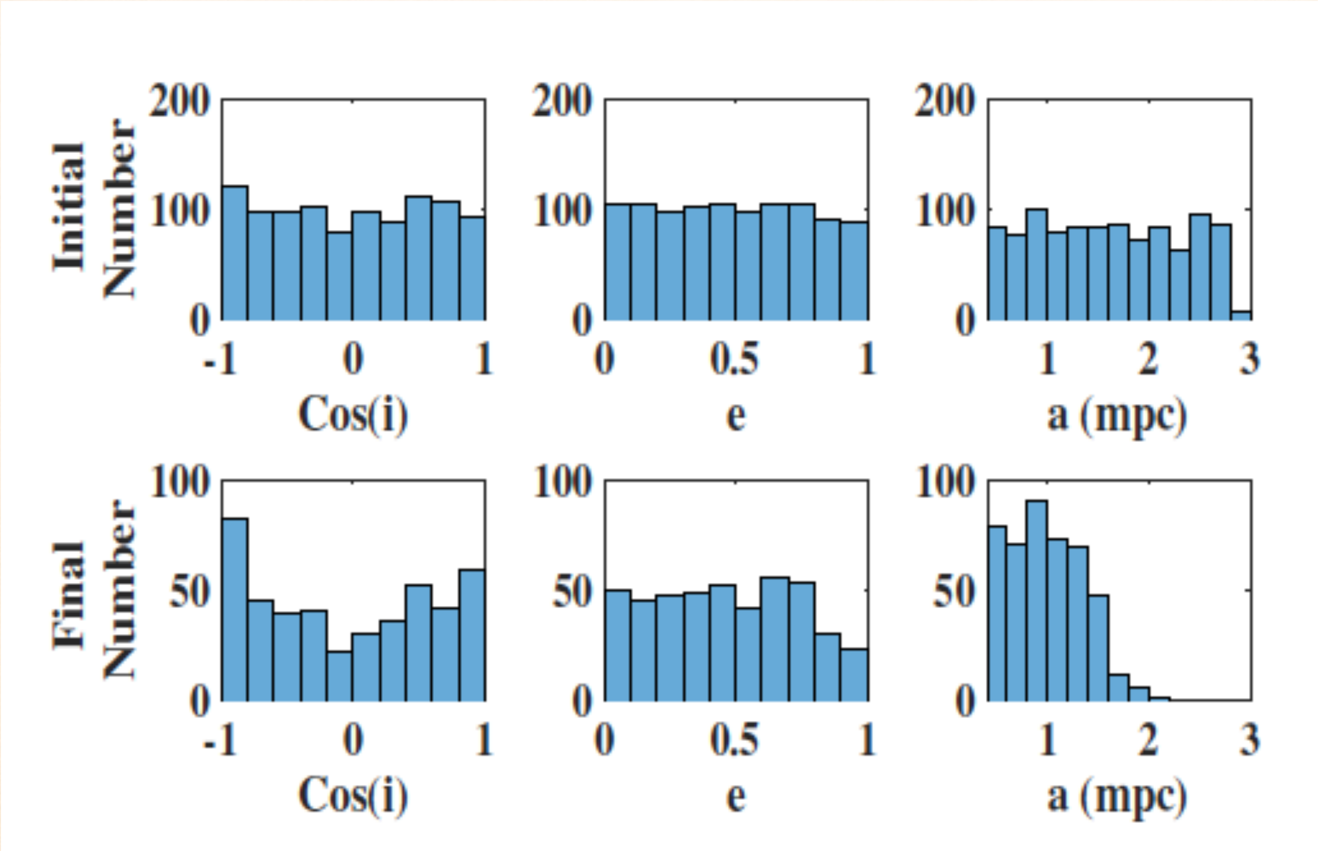
- 40/1000 disrupted; 500/1000 scattered.

=> ~50% stars survived.

=> Disruption rate can reach ~10^{-4}/yr.

EFFECTS ON STARS SURROUNDING AN IMBH IN GC

- Example: $m_1 = 10^4 M_\odot$, $m_2 = 4\times10^6 M_\odot$, $a_2 = 0.1$pc, $e_2 = 0.7$, $\alpha = 1.75$ (Run time: 100Myr)



(Li et al. 2015)

CONCLUSION

- Perturbation of the outer object can produce flips of the inner orbit and excite inner orbit eccentricity
- Under tidal dissipation, the perturbation of a farther companion can produce misaligned hot Jupiters
- Perturbation of a SMBH may enhance the tidal disruption rate of stars.

THANK YOU!

Systematic Study of the Parameter Space

- Identify the resonances and the chaotic region.

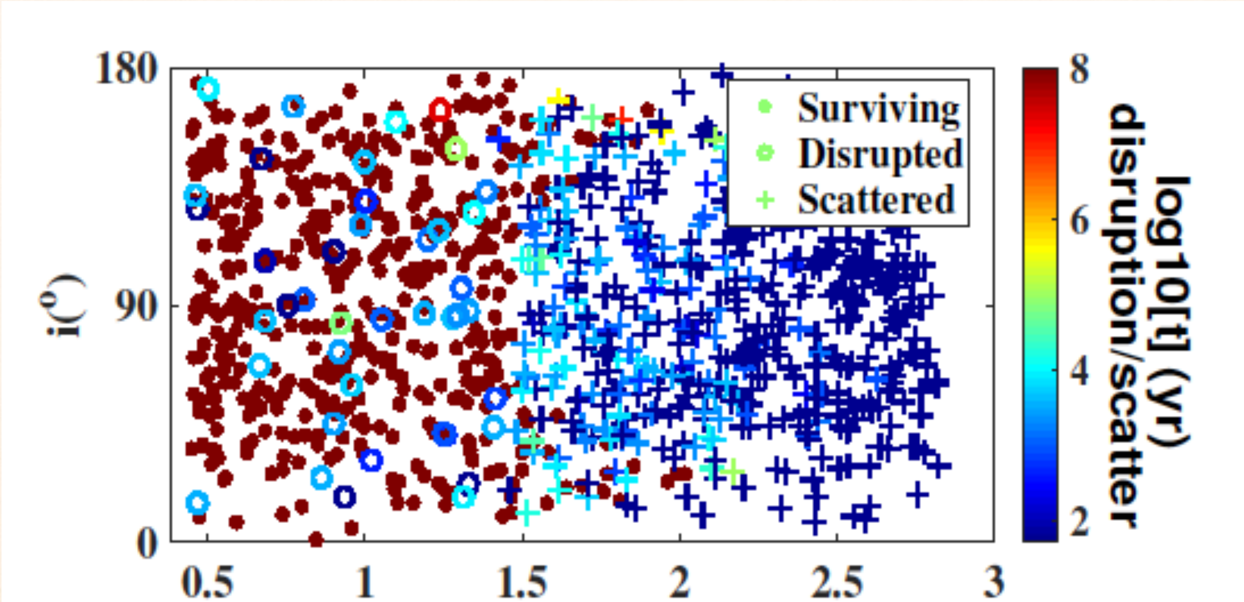
- Characterize the parameter space that give rise to the interesting behaviors --- eccentricity excitation and orbital flips.

EFFECTS ON STARS SURROUNDING AN IMBH IN GC

- Example: $m_1 = 10^4\,M_\odot$, $m_2 = 4{\times}10^6 M_\odot$, $a_2 = 0.1$pc, $e_2 = 0.7$ (Run time: 100 Myr)

EFFECTS ON STARS SURROUNDING AN IMBH IN GC

- Example: $m_1 = 10^4$ M$_\odot$, $m_2 = 4\times10^6$M$_\odot$, $a_2 = 0.1$pc, $e_2 = 0.7$ (Run time: 100 Myr)



(Li et al. 2015)

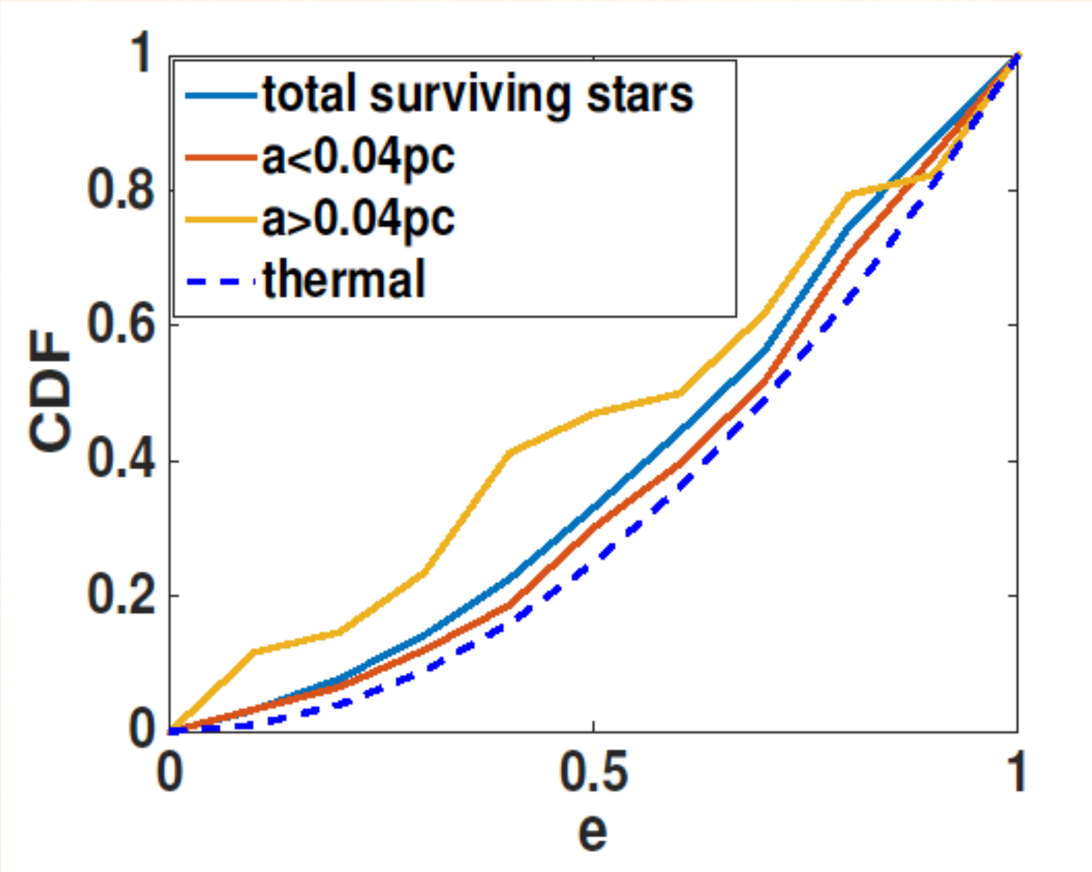
- 40/1000 disrupted; 500/1000 scattered.

=> ~50% stars survived.

=> Disruption rate can reach ~10^{-4}/yr.

EFFECTS OF EKM ON STARS SURROUNDING BBH

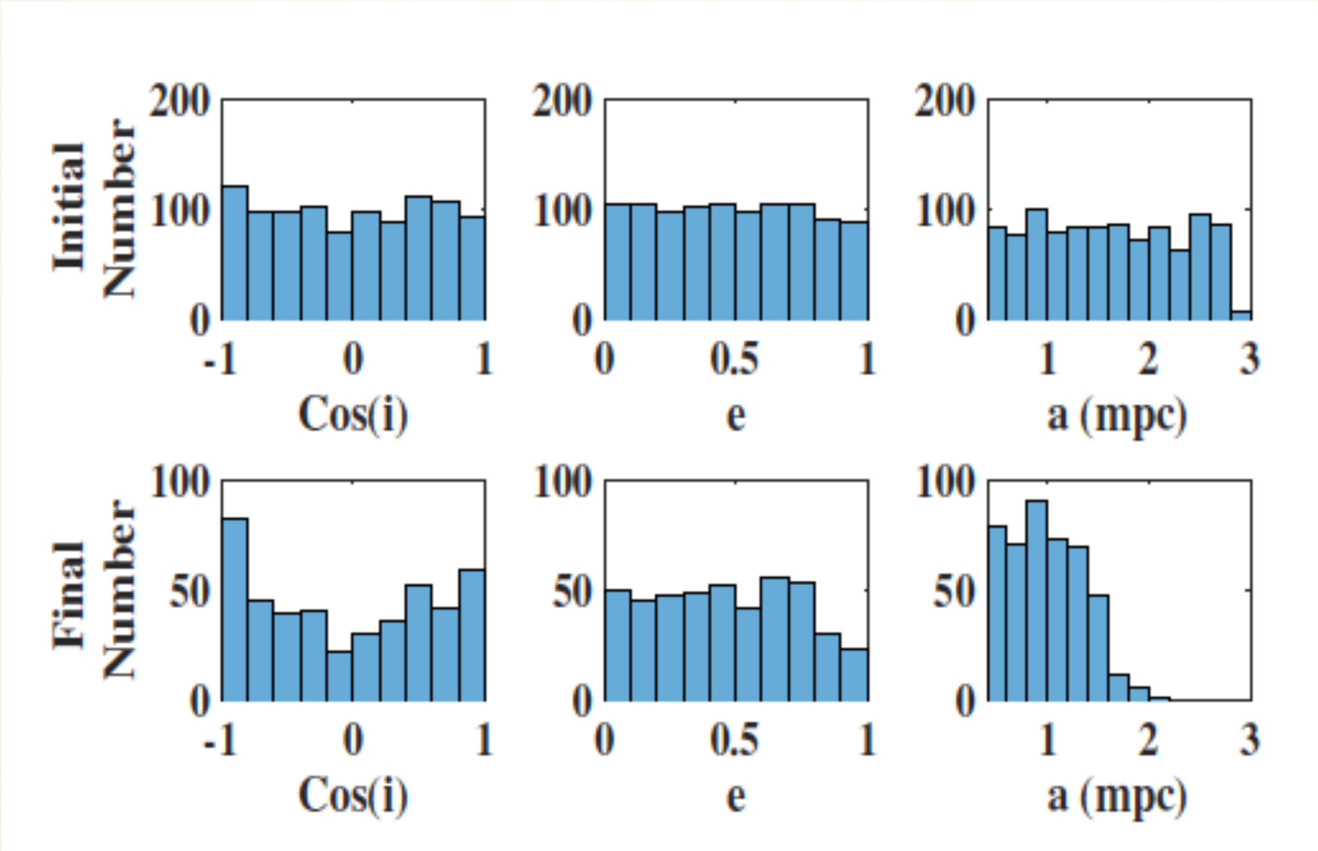
- Example: $m_1 = 10^7 M_\odot$, $m_2 = 10^8 M_\odot$, $a_2 = 0.5$pc, $e_2 = 0.5$, $\alpha = 1.75$. Run time: 1Gyr.



(Li et al. 2015)

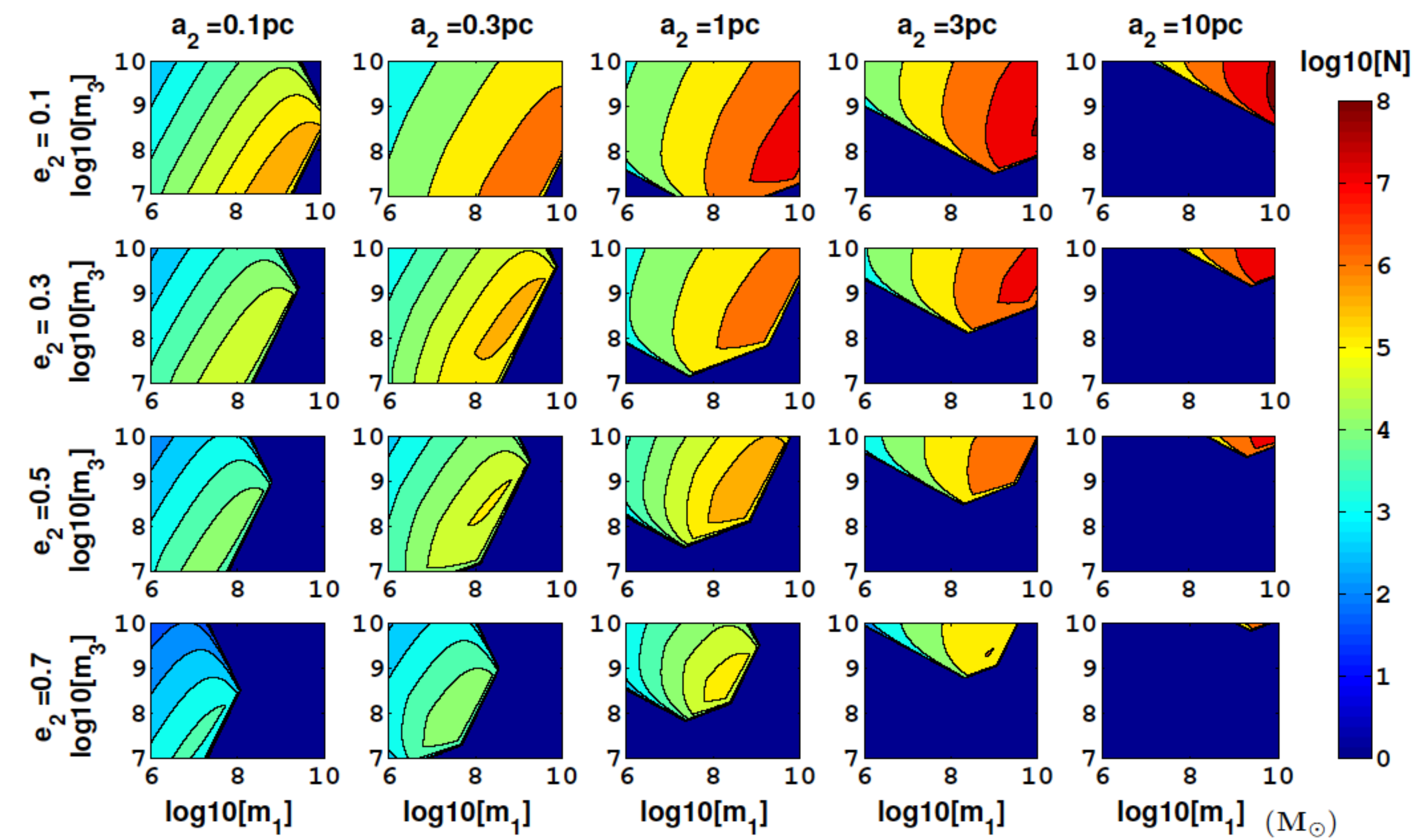
EFFECTS ON STARS SURROUNDING AN IMBH IN GC

- Example: $m_1 = 10^4$ M$_\odot$, $m_2 = 4\times10^6$M$_\odot$, $a_2 = 0.1$pc, $e_2 = 0.7$, $\alpha = 1.75$ (Run time: 100Myr)



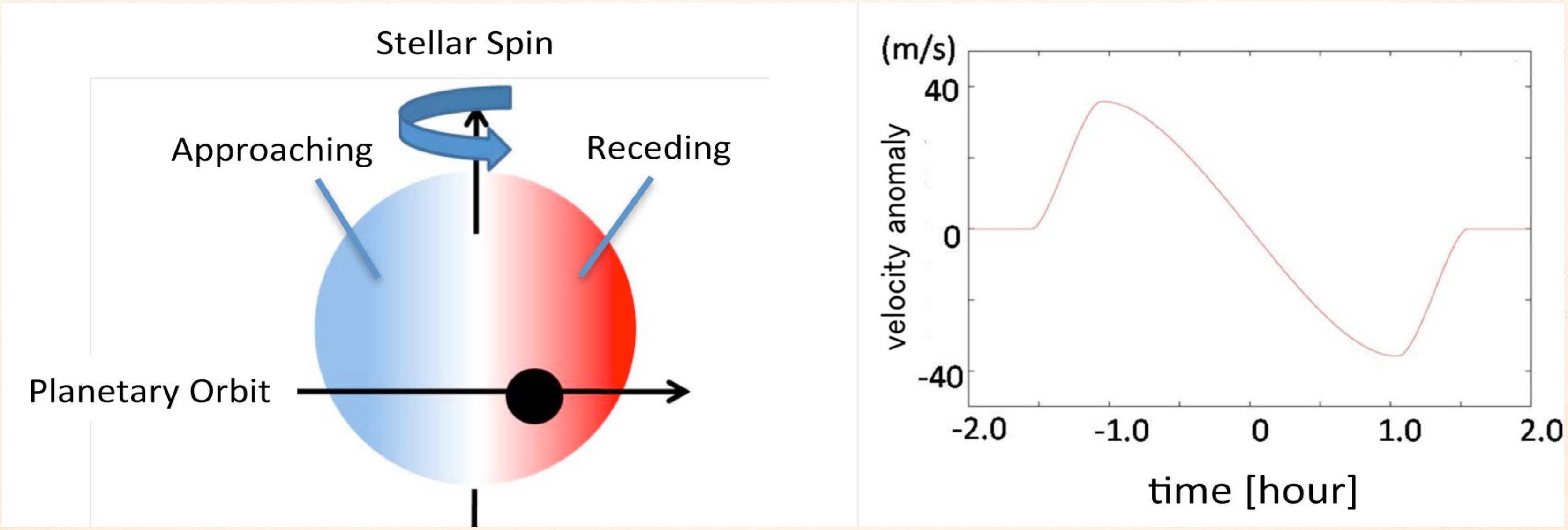
(Li et al. 2015)

SUPPRESSION OF ELK



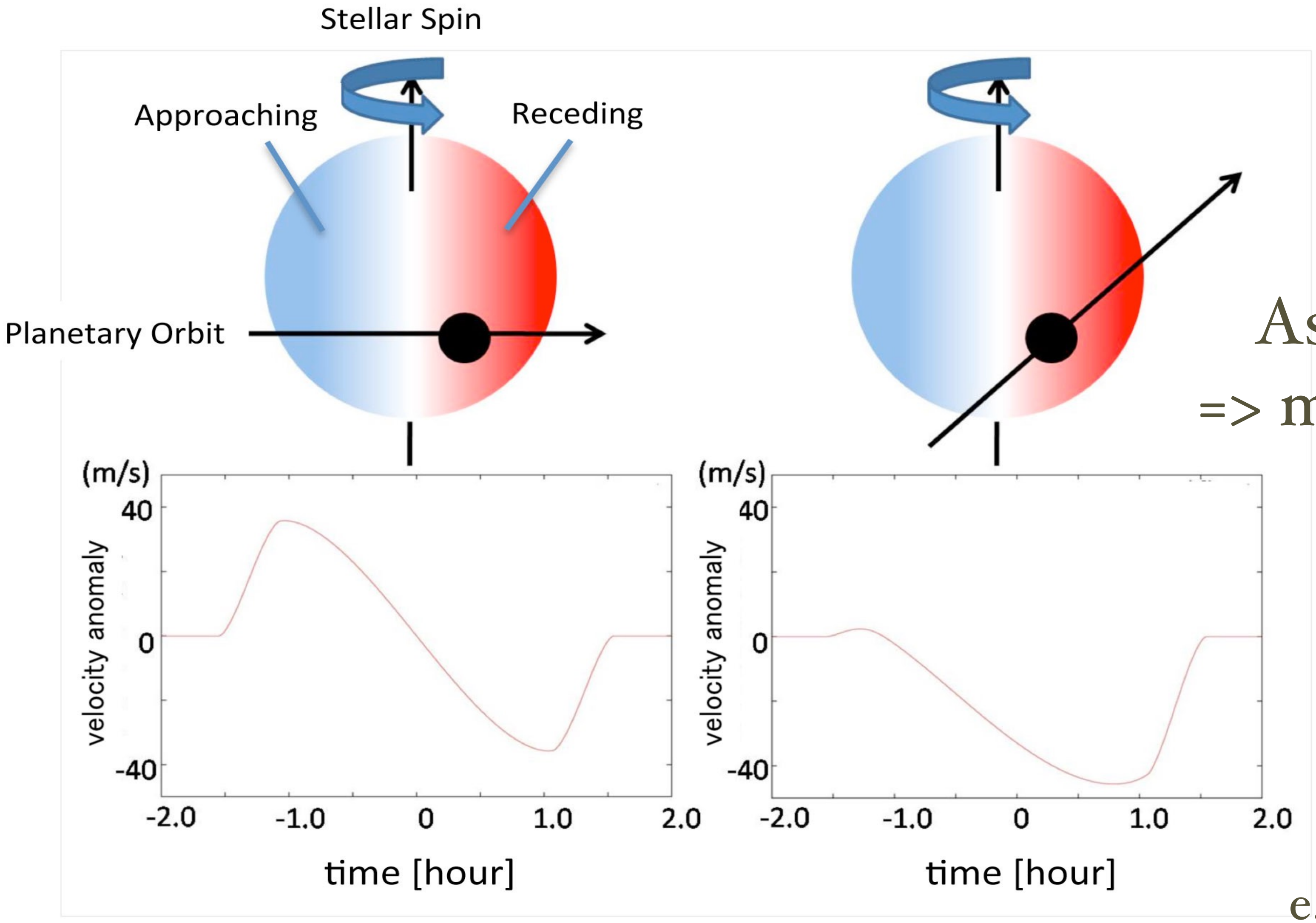
(Li et al. 2015)

ROSSITER-MCLAUGHLIN METHOD (SPIN-ORBIT MISALIGNMENT)



e.g., Winn 2006

ROSSITER-MCLAUGHLIN METHOD (SPIN-ORBIT MISALIGNMENT)

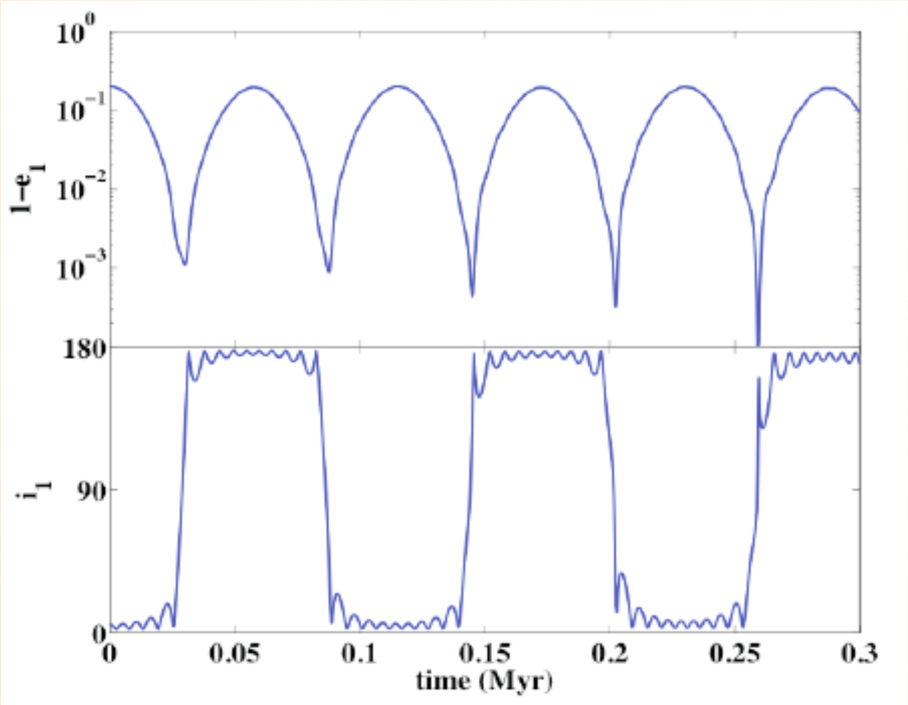


Asymmetric => misalignment

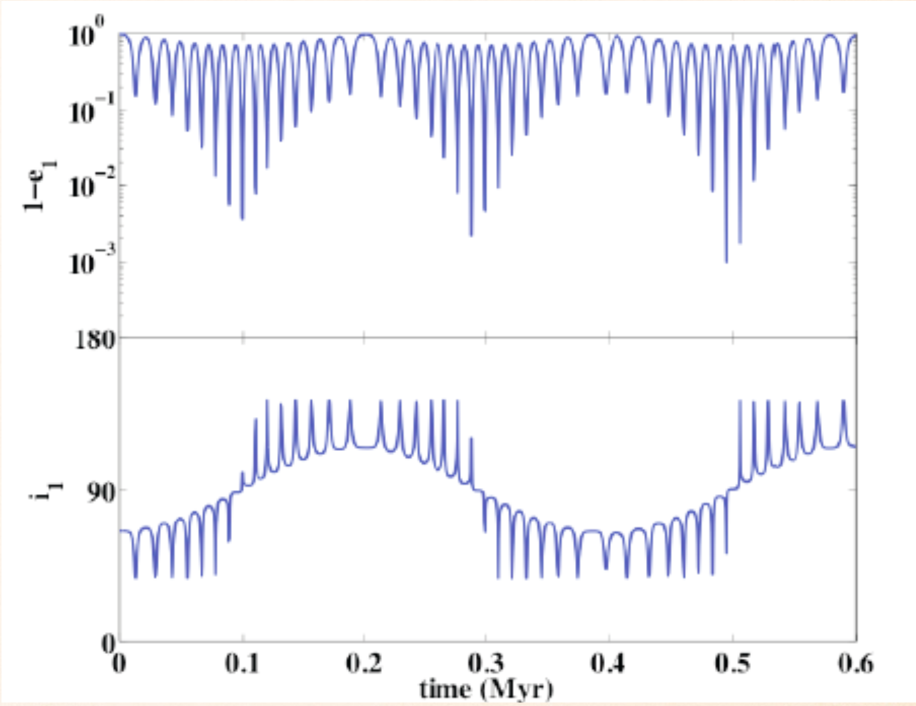
e.g., Winn 2006

DIFFERENCES BETWEEN HIGH/LOW I FLIP

Low inclination flip



High inclination flip



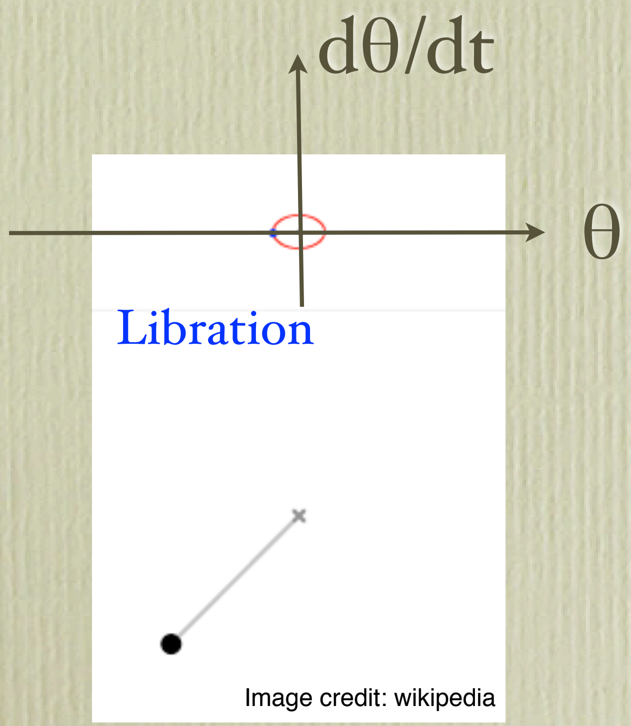
Low inclination flips:

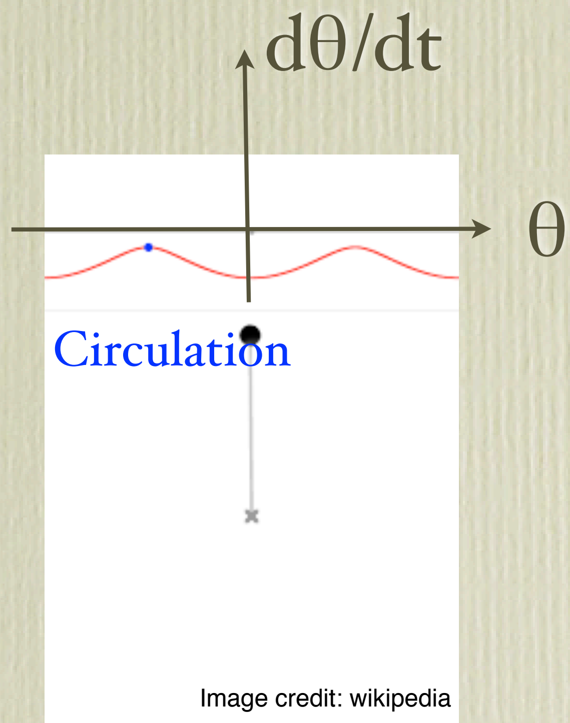
- e_1 ↑ monotonically, inclination stays low before flip.
- Flip occurs faster.

(Li et al. 2014a)

Resonances and Chaotic Regions

- The Hamiltonian H_{res} takes form of a pendulum.
- Two dynamical regions: libration region and circulation region.

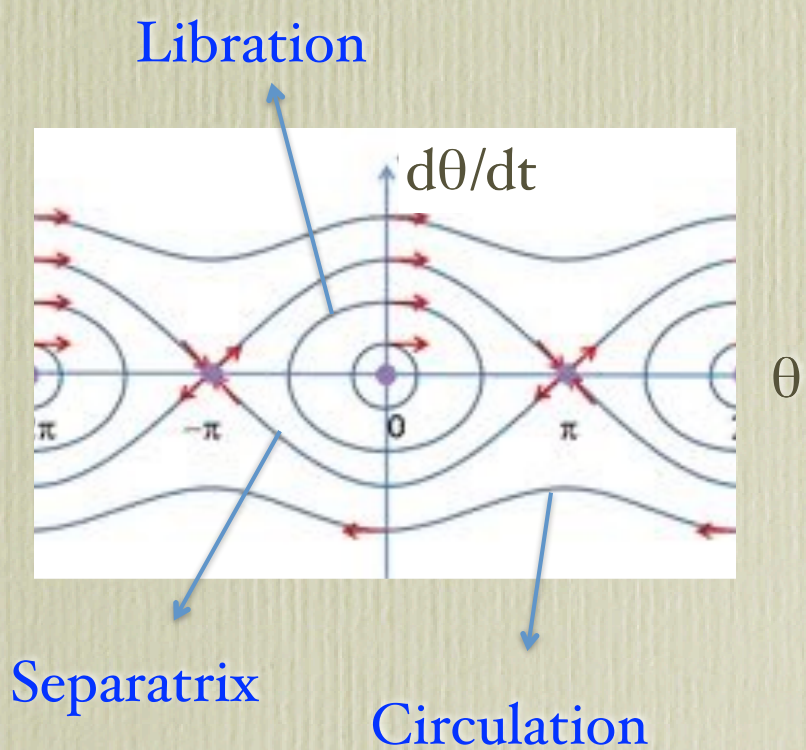




Resonances and Chaotic Regions

- The Hamiltonian H_{res} takes form of a pendulum.
- Two dynamical regions: libration region and circulation region, separated by separatrix.

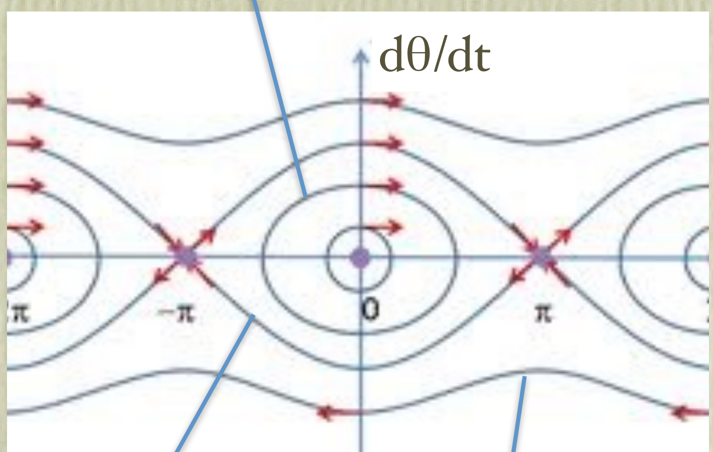
Phase Diagram:



Resonances and Chaotic Regions

- The Hamiltonian H_{res} takes form of a pendulum.
- Two dynamical regions: libration region and circulation region, separated by separatrix.

Libration

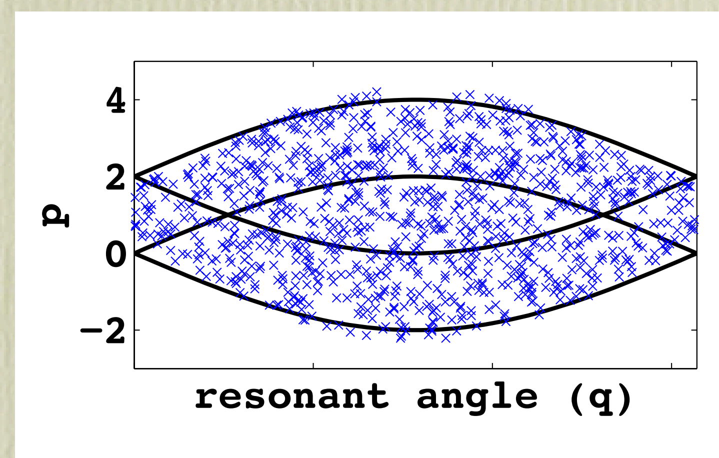


θ

Separatrix

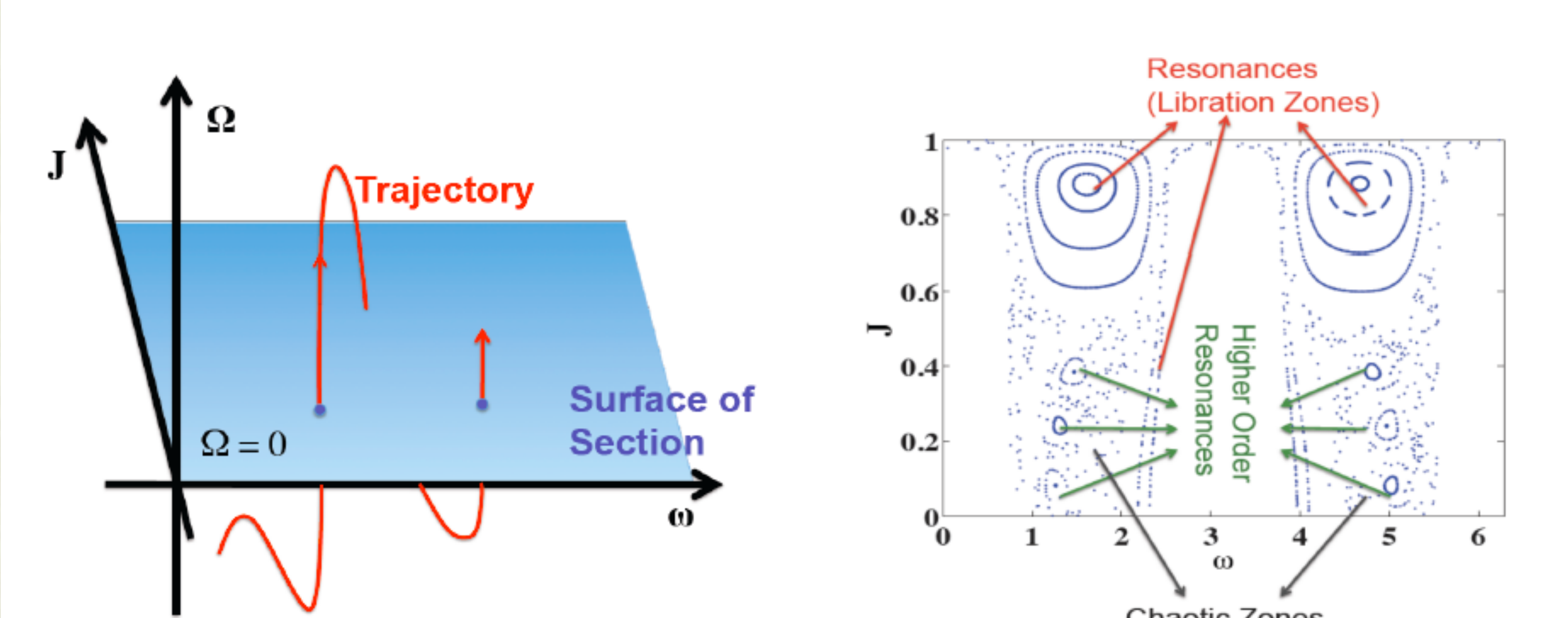
Circulation

Overlap of resonances can cause chaos



Surface of Section

Example of a 2-degree freedom H (J, ω, Jz, Ω)



(Li et al. 2014b)

- Resonant zones: points fill 1-D lines.
  trajectories are quasi-periodic.
- Chaotic zones: points fill a higher dimension.

Surface of Section

- Surface of section of hierarchical three-body problem in the test particle limit in the J − ω Plane.
- $J = \sqrt{1 - e_1^2}$ (specific angular momentum);

ω: argument of periapsis

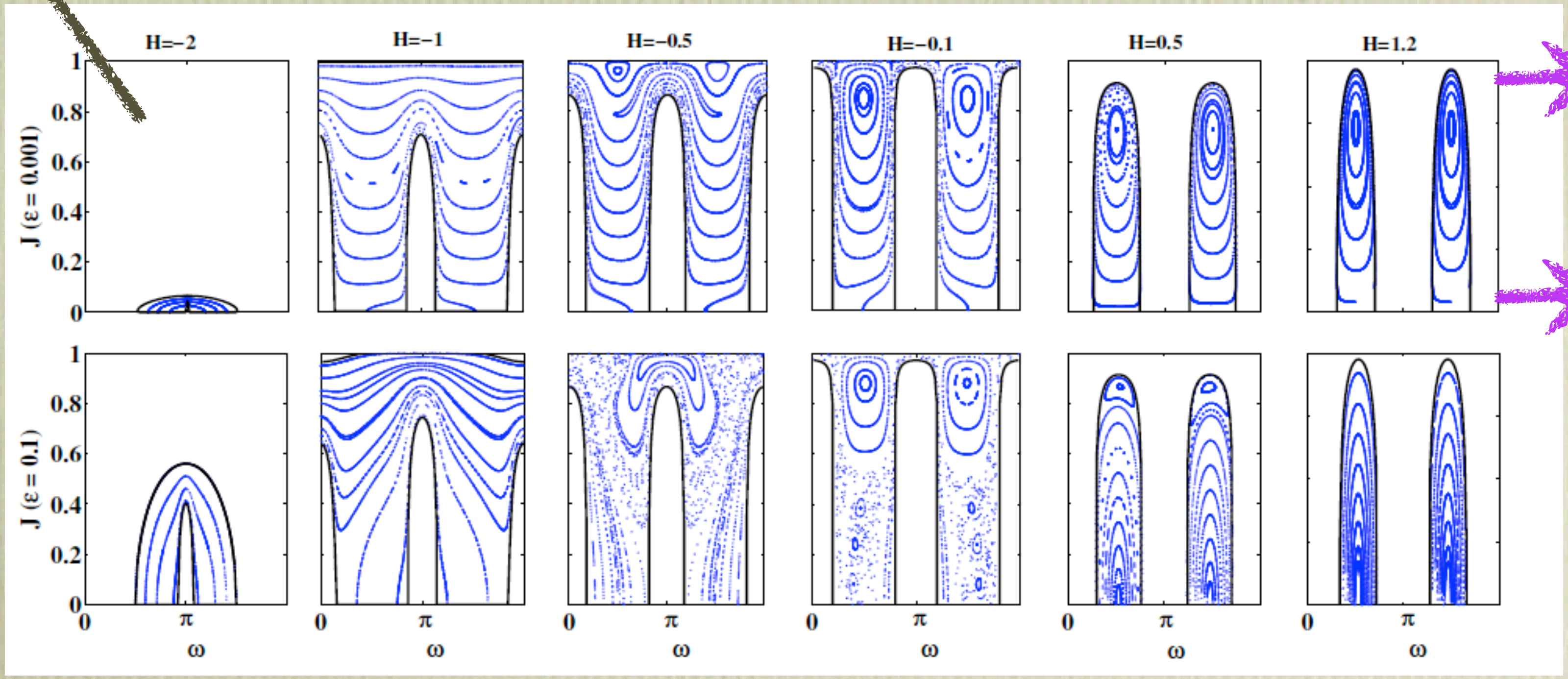
Low i ⟷ High i (40-60°) ⟷ i~90°

Low H ⟷ High H

No physical solution

Quadrupole order dominates

Octupole order stronger



low e

high e

Li et al. 2014b

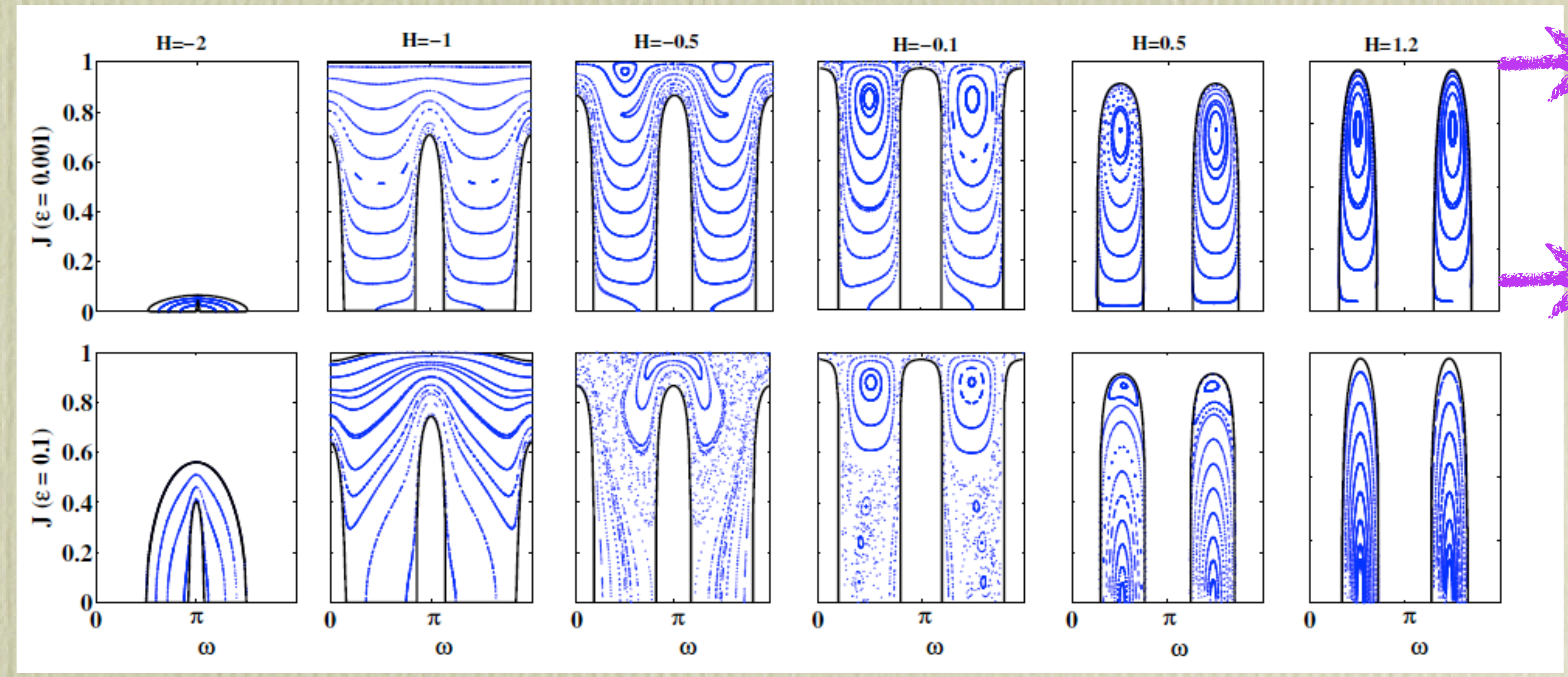
Surface of Section

Resonances exist for all surfaces:

Low i ⟷ High i (40-60°) ⟷ i~90°

Quadrupole order dominates

Octupole order stronger



low e

high e

Quadrupole resonances:

centers at low e_1, $\omega=\pi/2$ and $3\pi/2$ (*e.g. Kozai 1962*)

Octupole resonances:

centers at high e_1, $\omega=\pi$ or $\pi/2$ and $3\pi/2$

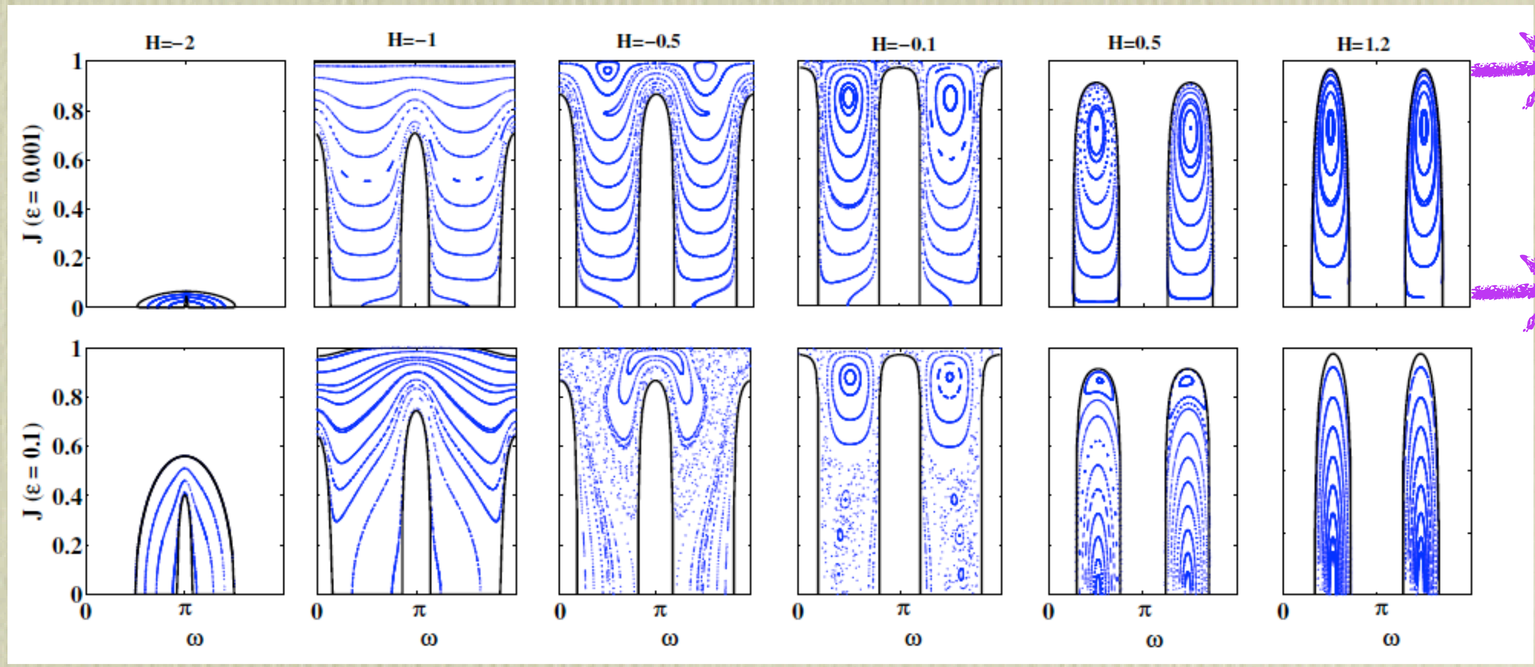
Li et al. 2014b

Surface of Section

Low i ⟷ High i (40-60°) ⟷ i~90°

Quadrupole order dominates

Octupole order stronger



- e_1 excitation (J→0) are caused by octupole resonances.
- Near coplanar flip due to octupole resonances alone.
- High inclination flip due to both quadrupole and octupole order resonances.

Li et al. 2014b

Summary

- Hierarchical Three Body Dynamics:
    - Starting with near coplanar configuration, the inner orbit of a hierarchical 3-body system can flip by ~180°, and $e_1 \rightarrow 1$.
    - This mechanism is regular, and the flip criterion and timescale can be expressed analytically.
    - This mechanism can produce counter orbiting hot exoplanets, and can enhance collision/tidal disruption rate.

- Underlying resonances:
    - Flips and e_1 excitations are caused by octupole resonances.
    - High inclination flips are chaotic, with Lyapunov timescale ~ $6t_K$.

Summary

- Coplanar flip:
  - Starting with near coplanar configuration, the inner orbit of a hierarchical 3-body system can flip by ~180°, and $e_1 \rightarrow 1$.
  - This mechanism is regular, and the flip criterion and timescale can be expressed analytically.
  - This mechanism can produce counter orbiting hot exoplanets, and can enhance collision/tidal disruption rate.

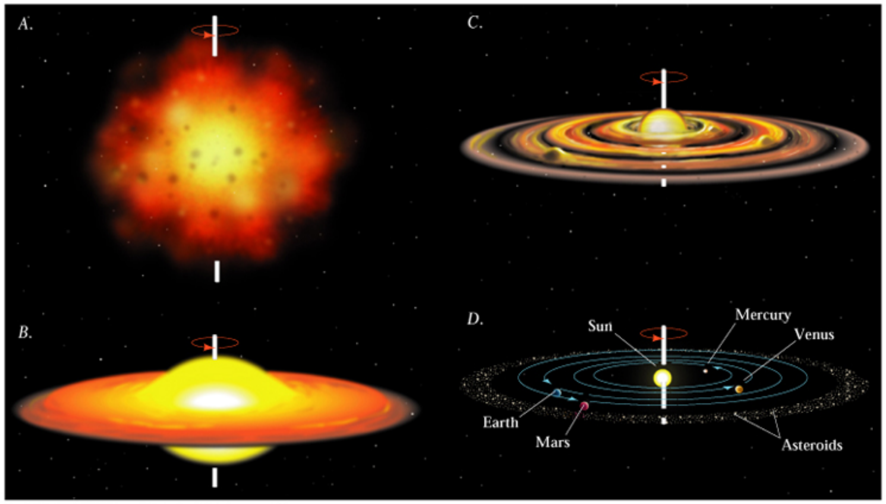
- Characterization of parameter space:
  - Near coplanar flip and e_1 excitations are caused by octupole resonances.
  - High inclination flips are chaotic, with Lyapunov timescale ~ $6t_K$.

Potential Applications

- Captured stars in BBH systems may affect stellar distribution around the BHs (e.g., Ann-Marie Madigan, Smadar Naoz, Ryan O'Leary).
- Tidal disruption and collision events for planetary systems (e.g., Eugene Chiang, Bekki Dawson, Smadar Naoz).
- Production of supernova (e.g., Rodrigo Fernandez, Boaz Katz, Todd Thompson).
- Other aspects:
  - Involving more bodies (e.g., Smadar Naoz, Todd Thompson).
  - Obliquity variation of planets.

COHJ Contradict with popular Planets' Formation Theory

- Formation Theory:



- Planet systems form from cloud contraction.
- Spin of the star ends up aligned with the orbit of the planets

Analytical Overview --- Test Particle Limit

- Hamiltonian has two degrees of freedom:

isolated 3-body: 6 dof $\xrightarrow{\text{secular}}$ 4 dof $\xrightarrow{\text{test-particle}}$ 2 dof

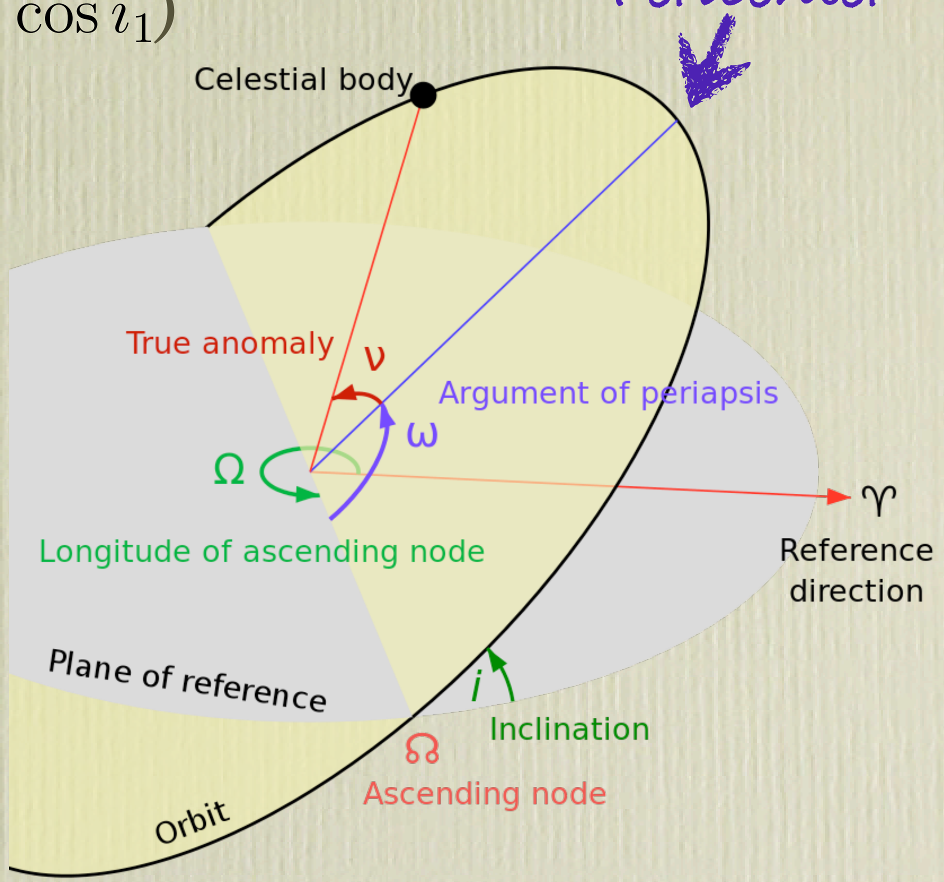
2 conjugate pairs: J & ω, Jz & Ω

$(J = \sqrt{1-e_1^2},\ \ Jz = \sqrt{1-e_1^2}\cos i_1)$

ω: orientation in orbital plane.

Ω: orientation in reference plane.

Pericenter



Analytical Overview

- Hamiltonian (Harrington 1968, 1969; Ford et al., 2000):
  - In the octupole order: $H = -F_{quad} - \varepsilon F_{oct}$, $\varepsilon = (a_1/a_2)e_2/(1-e_2^2)$

$$
\begin{aligned}
F_{quad} &= -(e_1^2/2) + \theta^2 + 3/2 e_1^2 \theta^2 \\
&\quad + 5/2 e_1^2 (1-\theta^2)\cos(2\omega_1), \\
F_{oct} &= \frac{5}{16}(e_1 + (3e_1^3)/4) \\
&\quad \times ((1 - 11\theta - 5\theta^2 + 15\theta^3)\cos(\omega_1 - \Omega_1) \\
&\quad + (1 + 11\theta - 5\theta^2 - 15\theta^3)\cos(\omega_1 + \Omega_1)) \\
&\quad - \frac{175}{64} e_1^3 ((1 - \theta - \theta^2 + \theta^3)\cos(3\omega_1 - \Omega_1) \\
&\quad + (1 + \theta - \theta^2 - \theta^3)\cos(3\omega_1 + \Omega_1)),
\end{aligned}
$$

- Independent of Ω_1, J_z const.
- Depend on both ω_1 and Ω_1 ➔ both J and J_z are not const.

$$t_K = \frac{8}{3} P_{in} \frac{m_1}{m_2} \left(\frac{a_2}{a_1}\right)^3 (1 - e_2^2)^{3/2}$$

Analytical Derivation for Flip Criterion and Timescale

- Hamiltonian (at O(i)):
  - Evolution of e_1 only due to octupole terms:

    => e_1 does not oscillate before flip.
  - Depend on only J_1 and $\varpi_1=\omega_1+\Omega_1$

    => System is integrable.

    => $e_1(t)$ can be solved.
  - Flip at $e_{1,\,max} \sim 1$

    => The flip timescale can be derived.
  - Flip when $\varpi_1=180°$

    => The flip criterion can be derived.

$$\varepsilon > \frac{8}{5}\frac{1-e_1^2}{7-e_1\left(4+3e_1^2\right)\cos\left(\omega_1+\Omega_1\right)}$$

Li et al., 2013

Analytical Overview

- Hamiltonian has two degrees of freedom:

  $$\left(J = \sqrt{1-e_1^2},\ Jz = \sqrt{1-e_1^2}\cos i_1,\ \omega,\ \Omega\right)$$

  2 conjugate pairs: J & ω, Jz & Ω

- Hamiltonian (*Harrington 1968, 1969; Ford et al. 2000*):

  In the octupole order:

  Interaction Energy (H) of two orbital wires:

  $$H = F_{quad}(J, Jz, \omega) + \epsilon F_{oct}(J, Jz, \omega, \Omega)$$

Quadrupole order:
Independent of Ω
=> Jz constant

ϵ: hierarchical
parameter:
$\epsilon = \frac{a_1}{a_2}\frac{e_2}{1-e_2^2}$

Octupole order:
Depend on both
Ω & ω => J and
Jz not constant

Analytical Der … Flip Criterion an … le

put equation in hidden slides

- Hamiltonian (at O(i)) depend on only e_1 and $\varpi_1 = \omega_1 + \Omega_1$:
- Evolution of e_1 only due to octupole terms:

$$\dot{e}_1 = \frac{5}{8} J_1 \left(3J_1^2 - 7\right) \varepsilon \sin(\varpi_1) \qquad \dot{\varpi}_1 = J_1 \left(2 + \frac{5\left(9J_1^2 - 13\right)\varepsilon \cos(\varpi_1)}{\sqrt{1 - J_1^2}} \right)$$

- $e_1(t)$ can be solved =>

The flip criterion and the flip timescale can be derived:

$$\varepsilon > \frac{8}{5} \frac{1 - e_1^2}{7 - e_1\left(4 + 3e_1^2\right)\cos(\omega_1 + \Omega_1)}$$

Li, et al., 2013

FLIP CRITERION

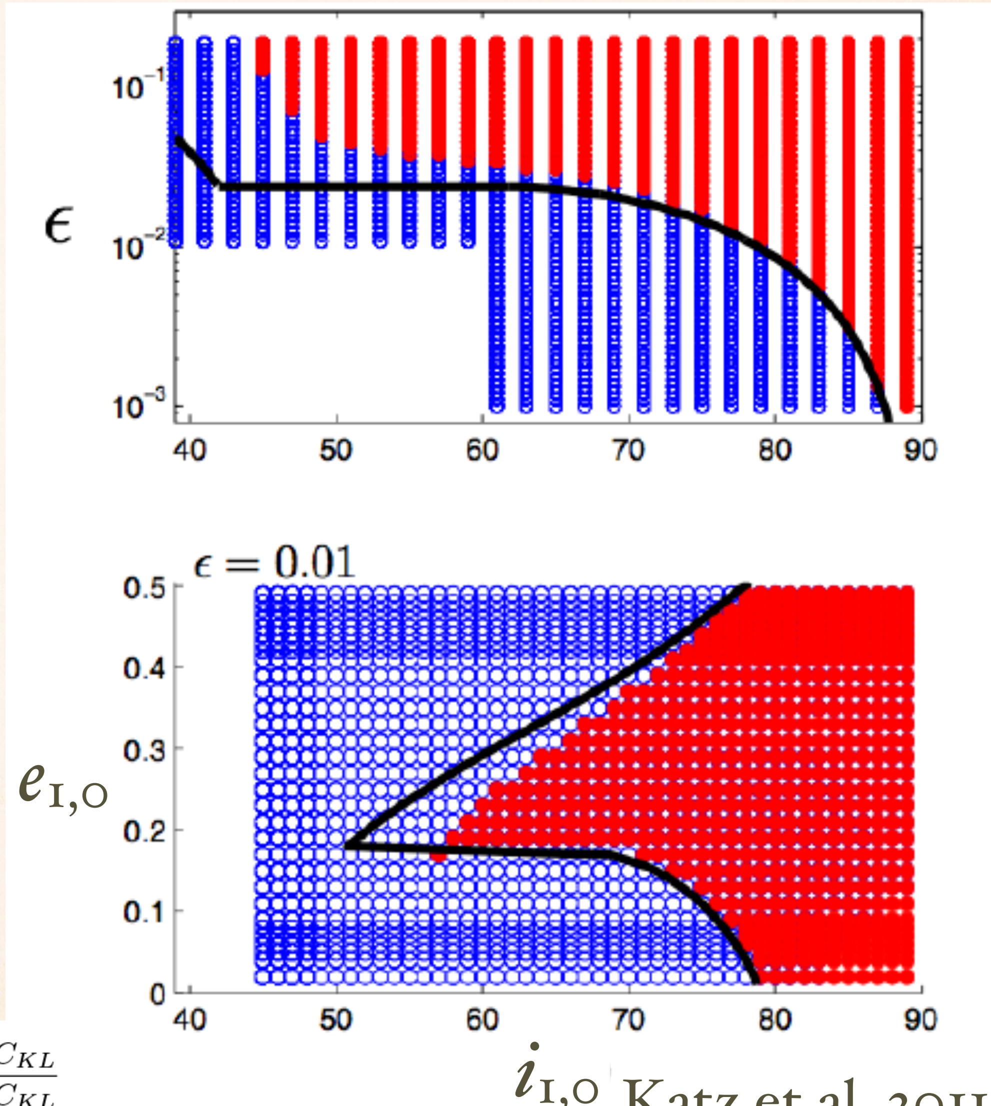
- Averaging the quadrupole oscillations in limit $j_z \sim 0$, Katz et al. 2011 obtain the constant:

$$f(C_{KL}) + \epsilon \frac{\cos i_{tot} \sin \Omega_1 \sin \omega_1 - \cos \omega_1 \cos \Omega_1}{\sqrt{1 - \sin^2 \imath_{tot} \sin^2 \omega_1}}$$

- Requiring $j_z = 0$, during the flip:

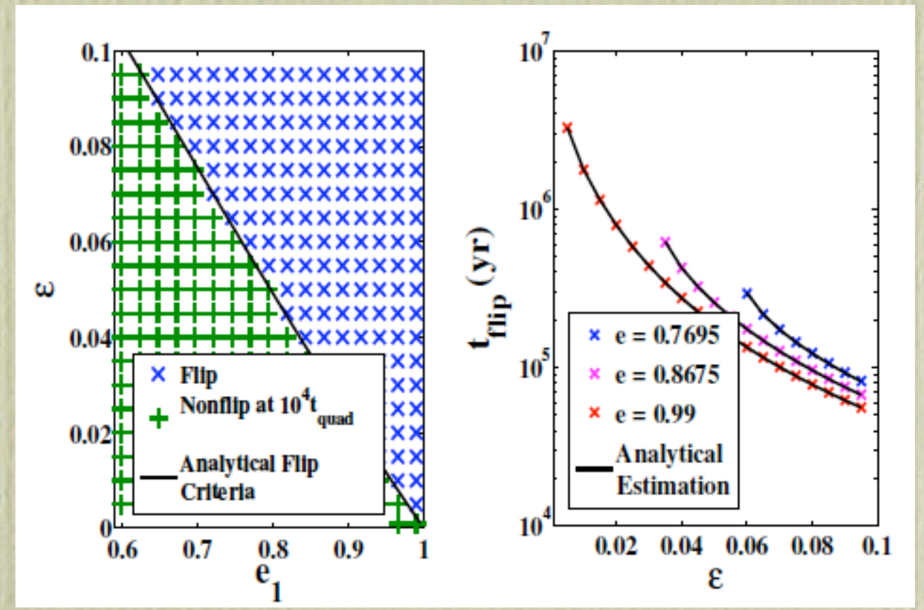
$$\epsilon_c = \frac{1}{2} f\left(\frac{1}{2}\cos^2 i_{tot,0}\right)$$

$$f(C_{KL}) = \frac{32\sqrt{3}}{\pi} \int_{x_{min}}^{1} \frac{K(x) - 2E(x)}{(41x - 21)\sqrt{2x+3}} dx \quad \text{and} \quad x_{min} = \frac{3 - 3C_{KL}}{3 + 2C_{KL}}$$



Katz et al. 2011

Analytical Results v.s. Numerical Results



Why do analytical results with low inclination approximation work?

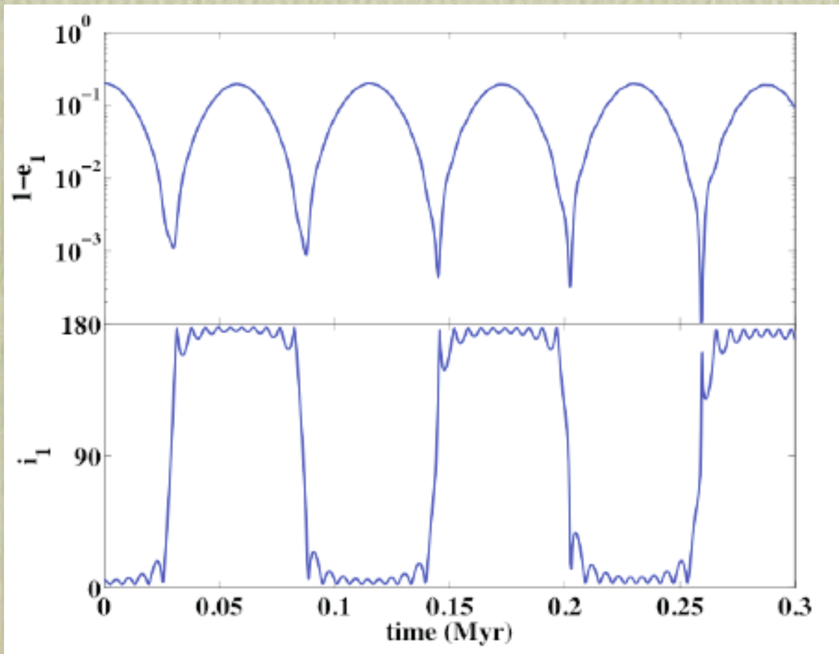
IC: $m_1 = 1M_{\odot}$, $m_2 = 0.1M_{\odot}$, $a_1 = 1AU$, $a_2 = 45.7AU$, $\omega_1 = 0^o$, $\Omega_1 = 180^o$, $i_1 = 5^o$.

Li, et al., 2013

Analytical Results v.s. Numerical Results

Why do analytical results with low inclination approximation work?

Small inclination assumption holds for most of the evolution.



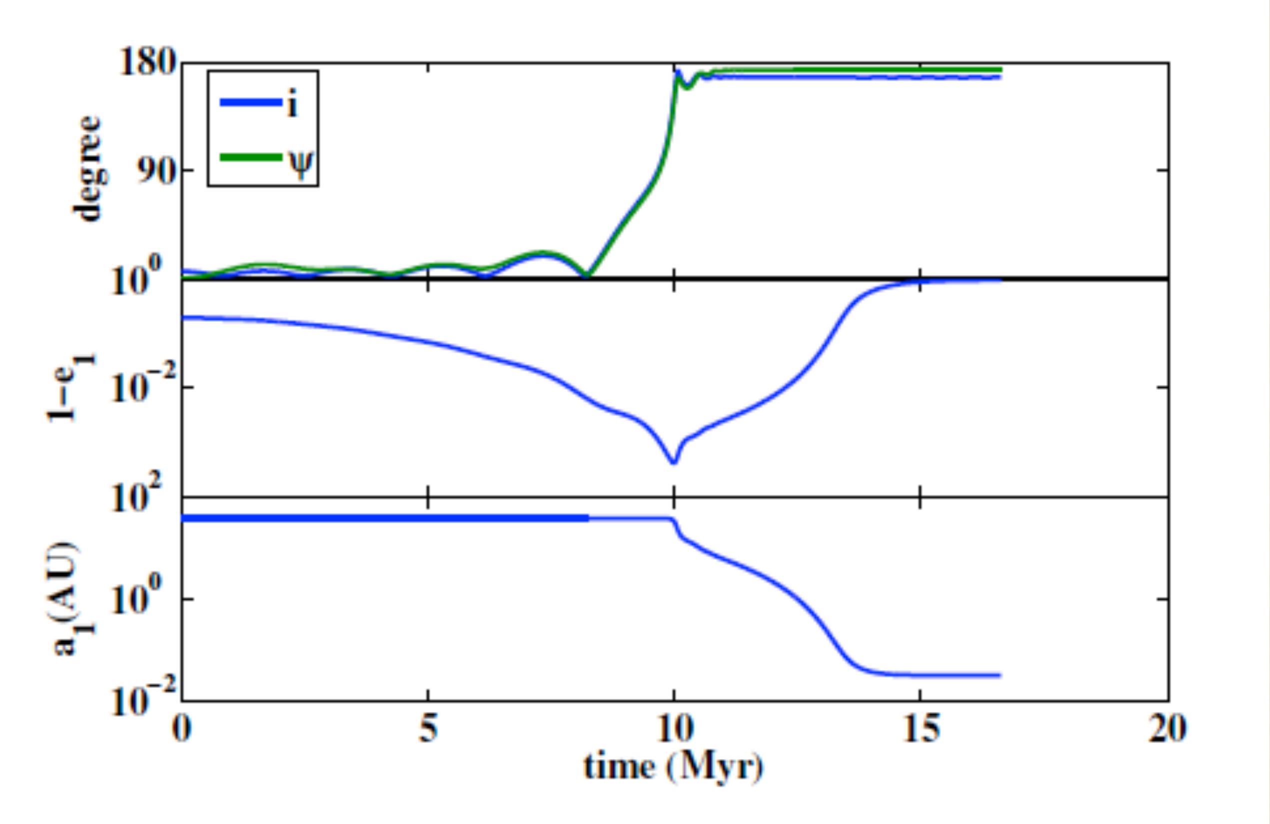
IC: $m_1 = 1\ M_\odot$, $m_J = 1 M_J$, $m_2 = 0.3\ M_\odot$, $\omega_1 = 0^o$, $\Omega_1 = 180^o$, $e_2 = 0.6$, $a_1 = 4\ AU$, $a_2 = 50\ AU$, $e_1 = 0.8$, $i = 5^o$

Li, et al., 2013

Examples --- 1. Produce Counter Orbiting Hot Jupiters (+ tide)

Question:
Does this mechanism produce a peak at $\psi \approx 180°$?

No.

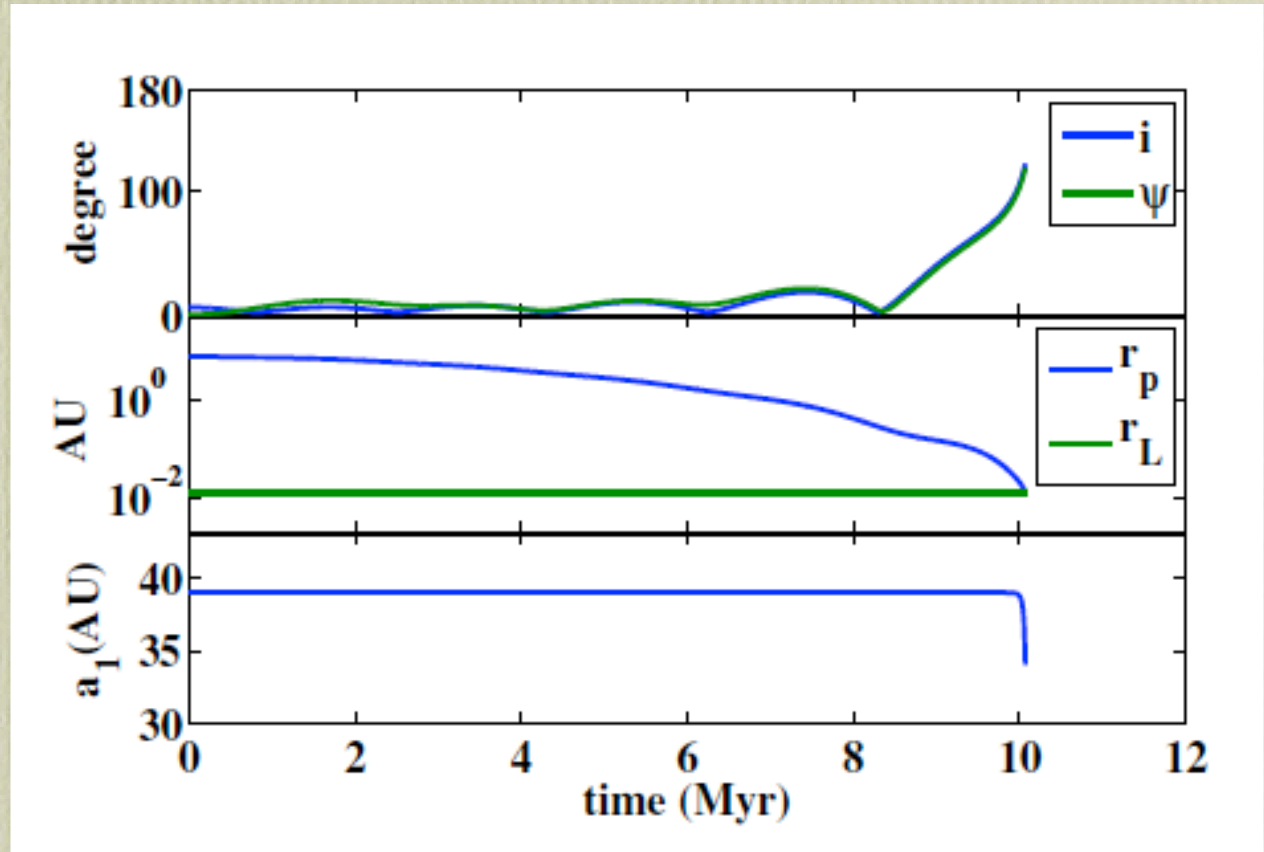


Li et al., 2014a

Examples --- 1. Produce Counter Orbiting Hot Jupiters (+ tide)

Question:
Will planet be tidally disrupted?

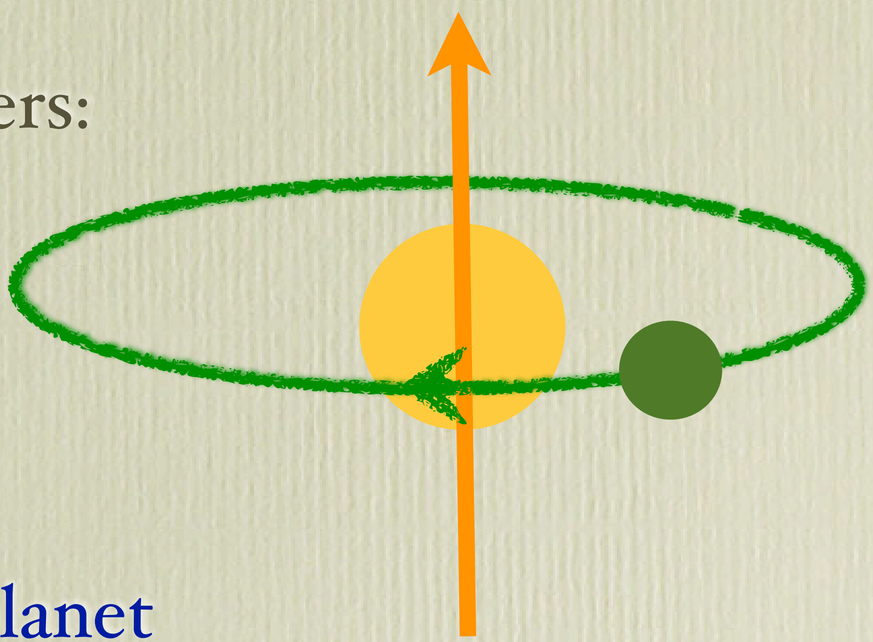
Yes!



Li et al., 2014a

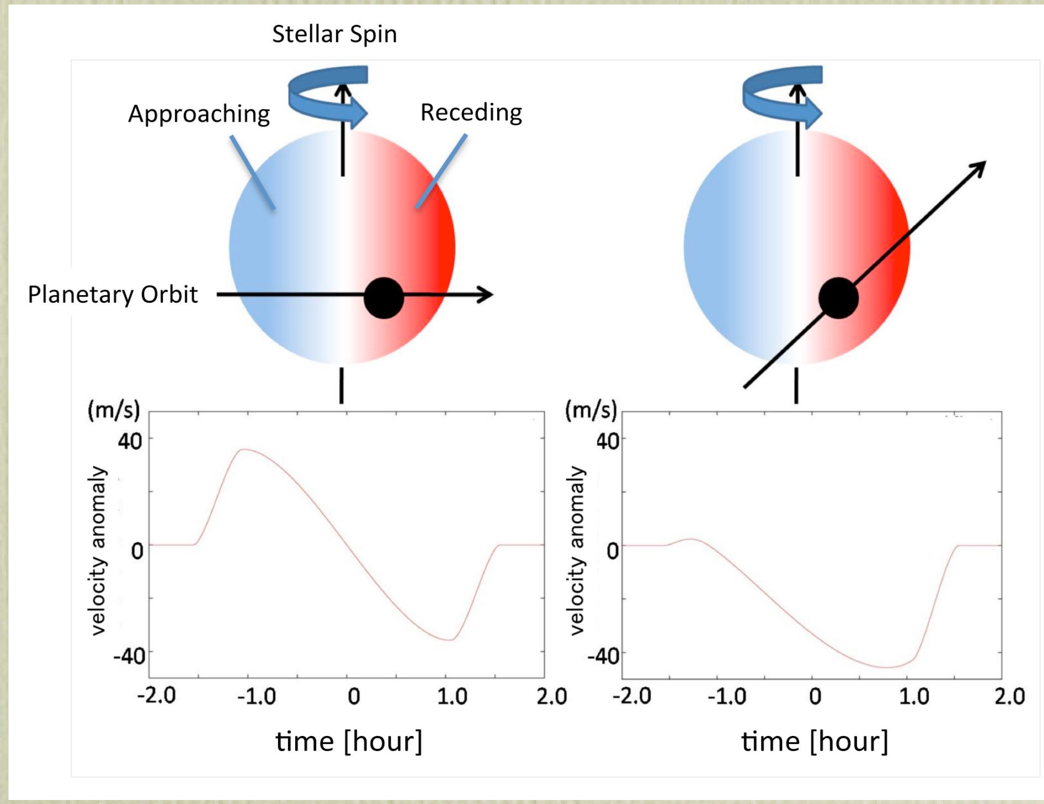
Applications --- 1. Produce Counter Orbiting Hot Jupiters (+ tide)

- Hot Jupiters:
  - massive exoplanets ($m \geq m_J$) with close-in orbits (period: 1-4 day).
- Counter Orbiting Hot Jupiters:
  - Hot Jupiters that orbit in exactly the opposite direction to the spin of their host star.



- Disagree with the classical planet formation theory: the orbit aligns with the stellar spin.

Rossiter-McLaughlin Method



http://www.subarutelescope.org/

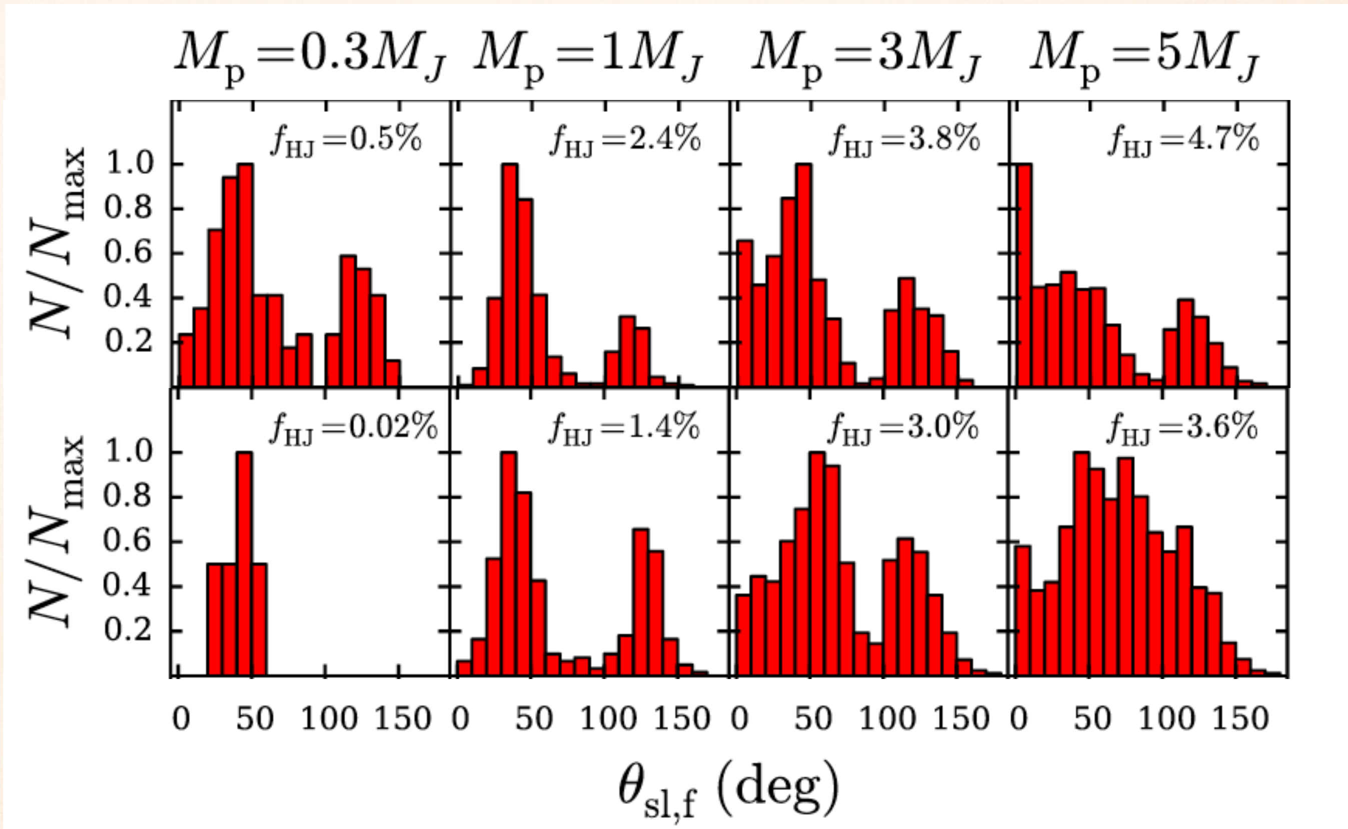
FORMATION OF MISALIGNED HOT JUPITERS (LK + STELLAR OBLATENESS + TIDE)

Anderson et al. 2016:

$M_p < 3\ M_J$
=> bimodal

$M_p \sim 5 M_J$

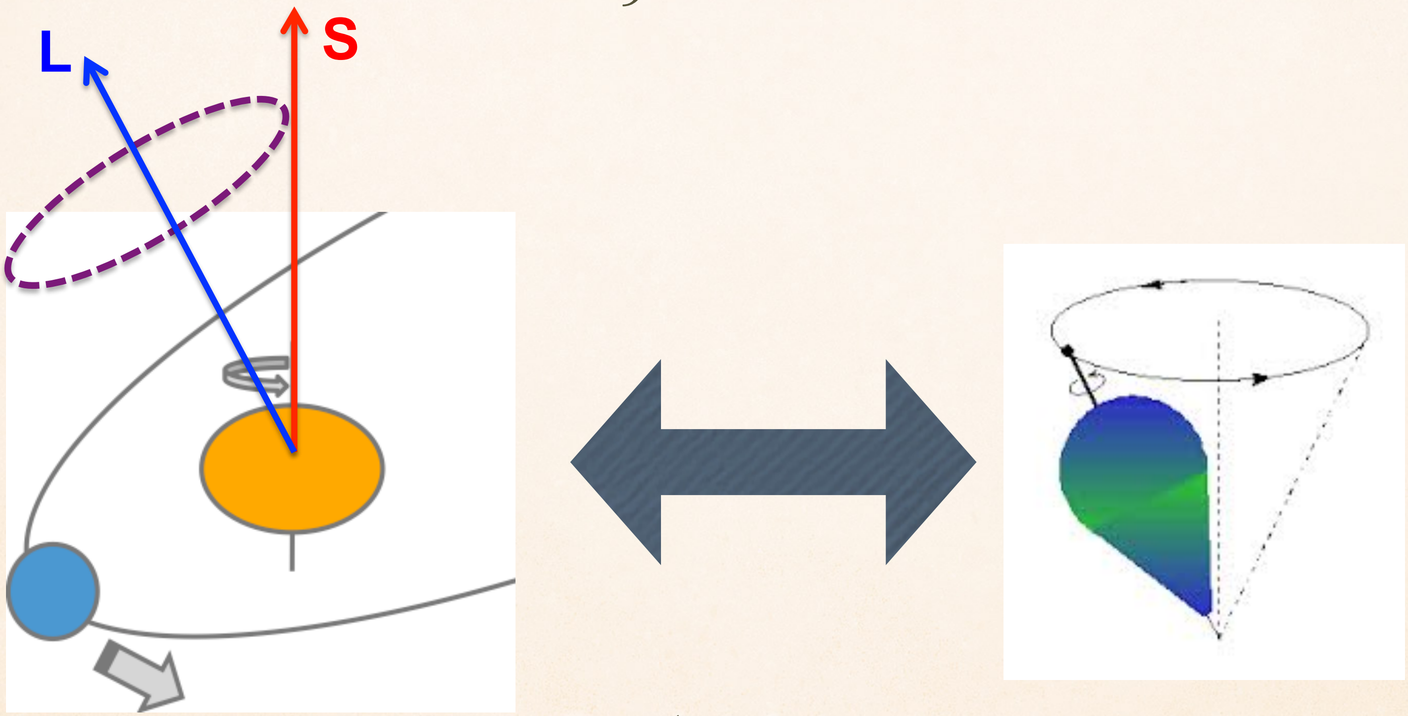
=> low misalignment (solar-type stars)
=> higher misalignment (more massive stars)



Anderson et al. 2016

FORMATION OF MISALIGNED HOT JUPITERS (LK + STELLAR OBLATENESS + TIDE)

If the host star is spinning and oblate, gravity from the planet makes stellar spin precess around L, and can cause chaos under Lidov-Kozai oscillations (Storch & Lai 2015).

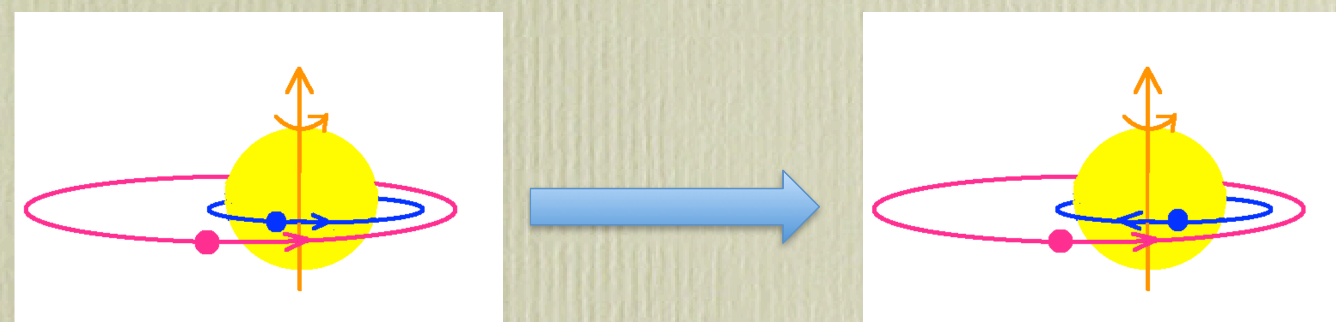


Storch & Lai 2015

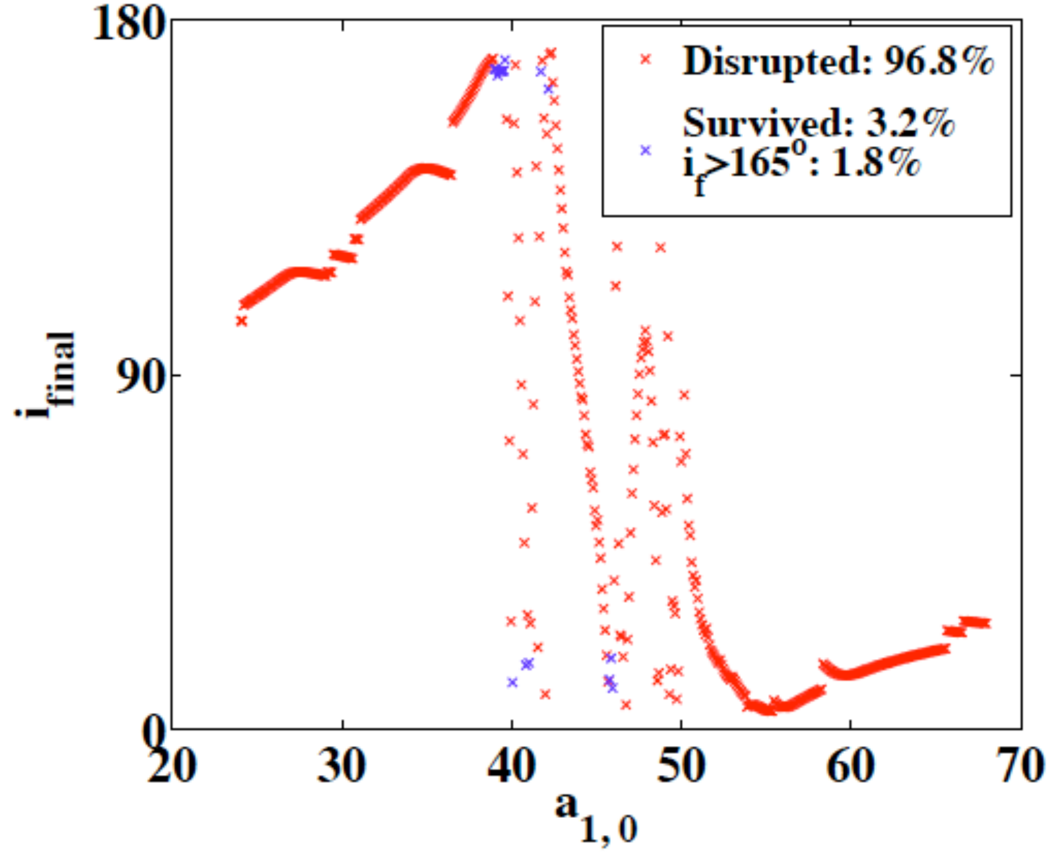
Chaos: precession period ~ Lidov-Kozai oscillation period

Take Home Message

- Eccentric Coplanar Kozai Mechanism can flip an eccentric coplanar inner orbit to produce counter orbiting exoplanets



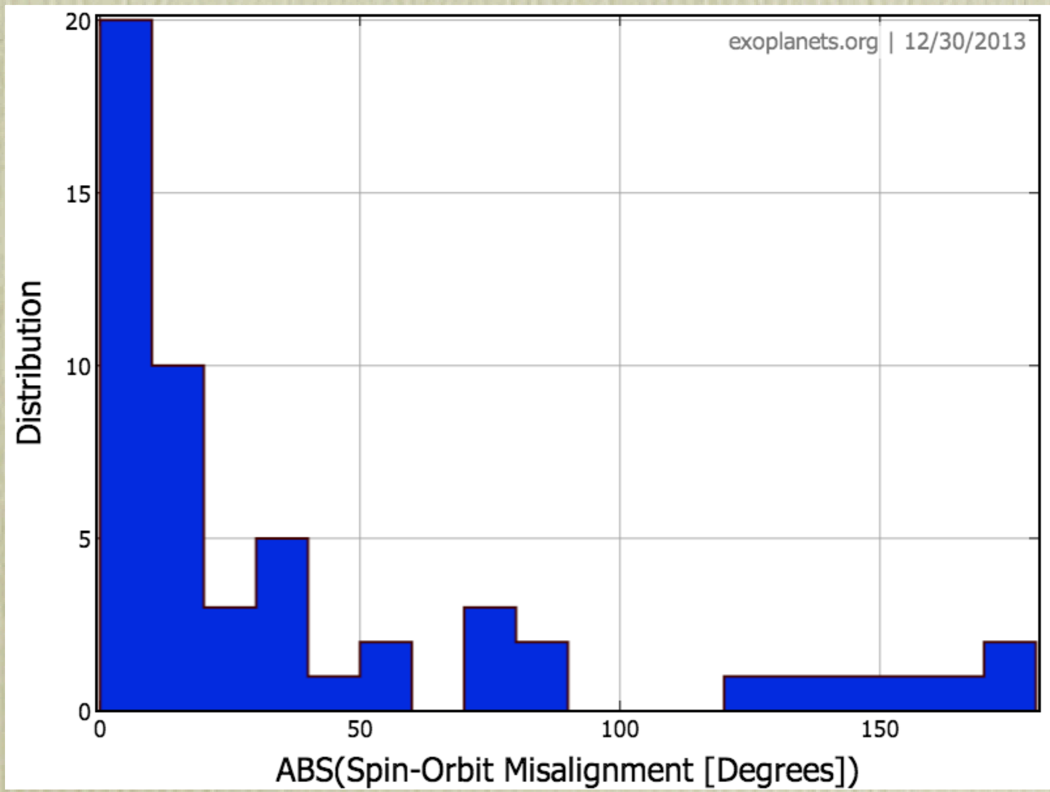
Eccentric inner orbit flips due to eccentric coplanar outer companion

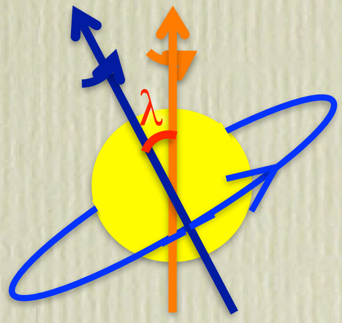


180
90
0
20
30
40
50
60
70
i_{final}
$a_{1,0}$
Disrupted: 96.8%
Survived: 3.2%
i_f>165°: 1.8%

Observational Links to Counter Orbiting Hot Jupiters

- Distribution of sky projected spin-orbit angle (λ) of Hot Jupiters





There are retrograde hot jupiters (λ>90°)

It is possible to have counter orbiting planets.

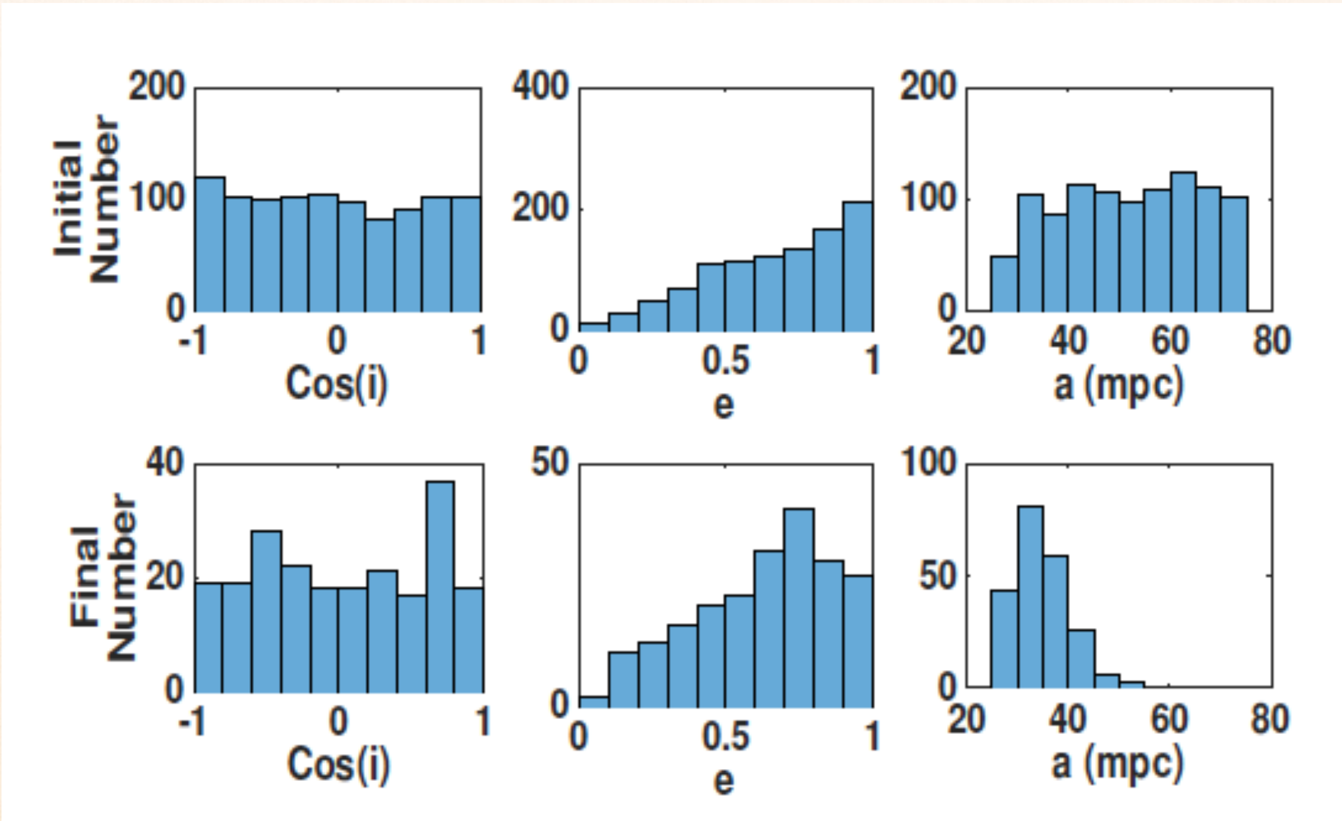
Applications --- 2. Effects of EKM of Stars Surrounding BBH

- Tidal disruption rate is highly uncertain:
  - It is observed to be 10-5--4/galaxy/yr from a very small sample by Gezari et al. 2008.
  - It roughly agrees with theoretical estimates. (e.g. Wang & Merritt 2004)

- The disruption rate may be greatly enhanced:
  - due to non-axial symmetric stellar potential. (Merritt & Poon 2004)
  - due to SMBHB (Ivanov et al. 2005, Wegg & Bode 2011, Chen et al. 2011)
  - due to recoiled SMBHB (Stone & Loeb 2011)

Examples --- 3. Effects of EKM of Stars Surrounding BBH

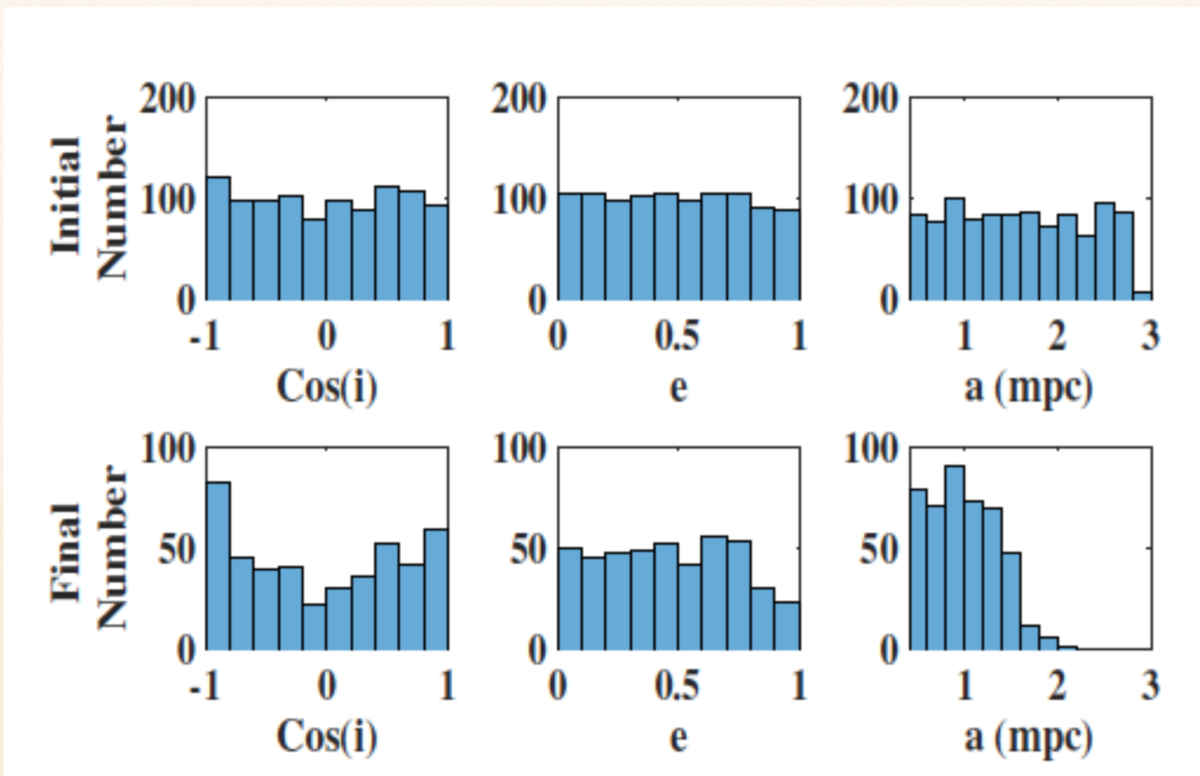
- Example: $m_1 = 10^7 M_\odot$, $m_2 = 10^8 M_\odot$, $a_2 = 0.5$pc, $e_2 = 0.5$, $\alpha = 1.75$ (stellar distribution), normalized by M-σ relation. Run time: 1Gyr.



(Li, et al. submitted 2015)

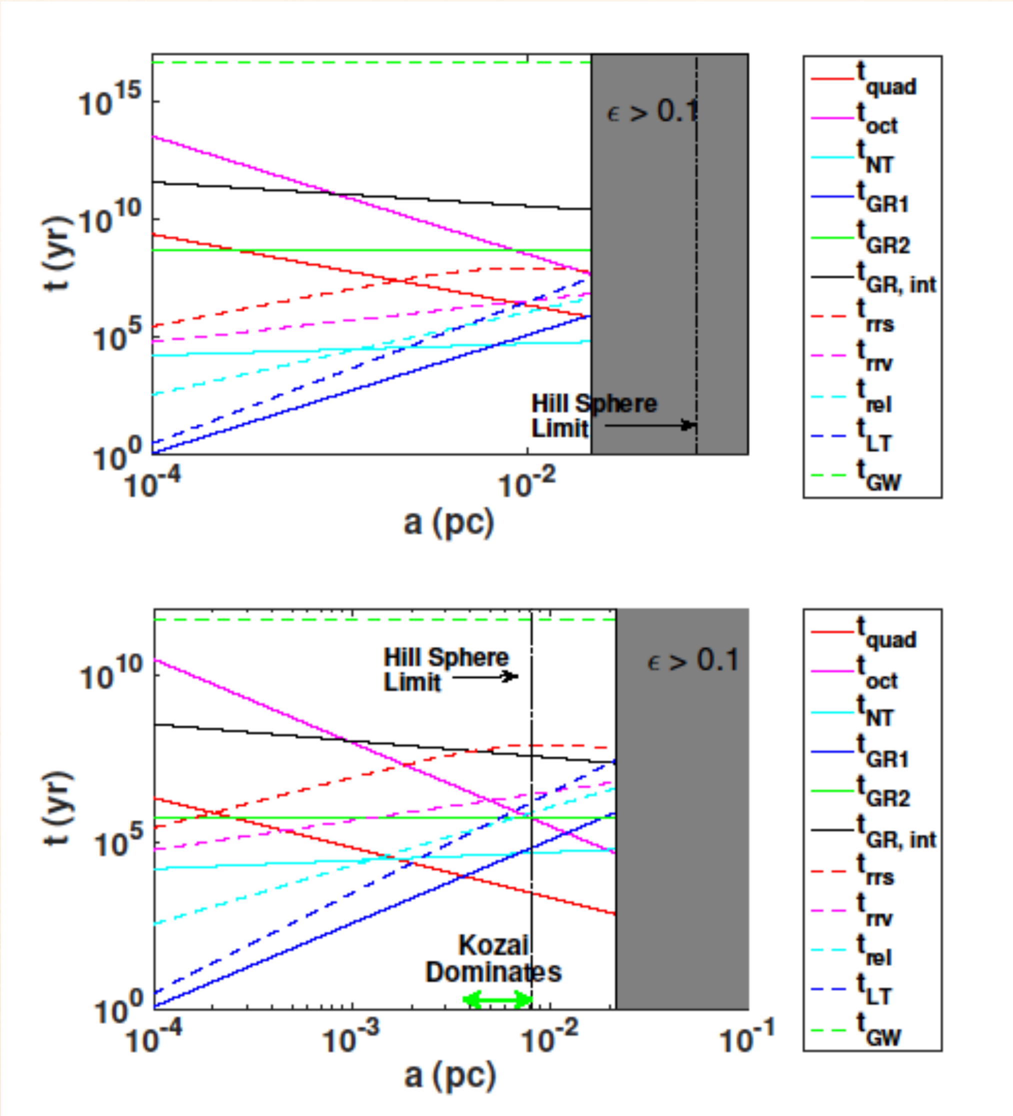
Examples --- 3. Effects of EKM of Stars Surrounding BBH

- Example: $m_1 = 10^4 M_\odot$, $m_2 = 4\times10^6 M_\odot$, $a_2 = 0.1$pc, $e_2 = 0.7$, $\alpha = 1.75$ (stellar distribution), normalized by M-σ relation. Run time: 100Myr.



(Li, et al. submitted 2015)

COMPARISON OF TIMESCALES

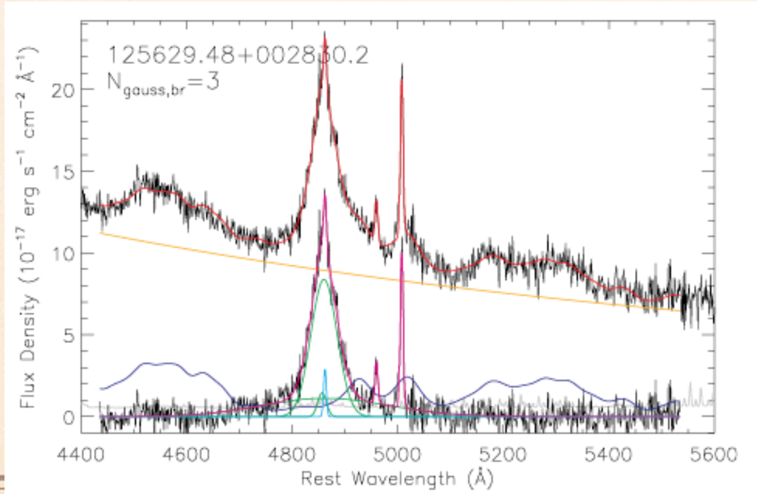


STARS SURROUNDING SMBHB

- At ~1pc separation it is more difficult to identify SMBHBs. SMBHBs can be observed with spectral features.

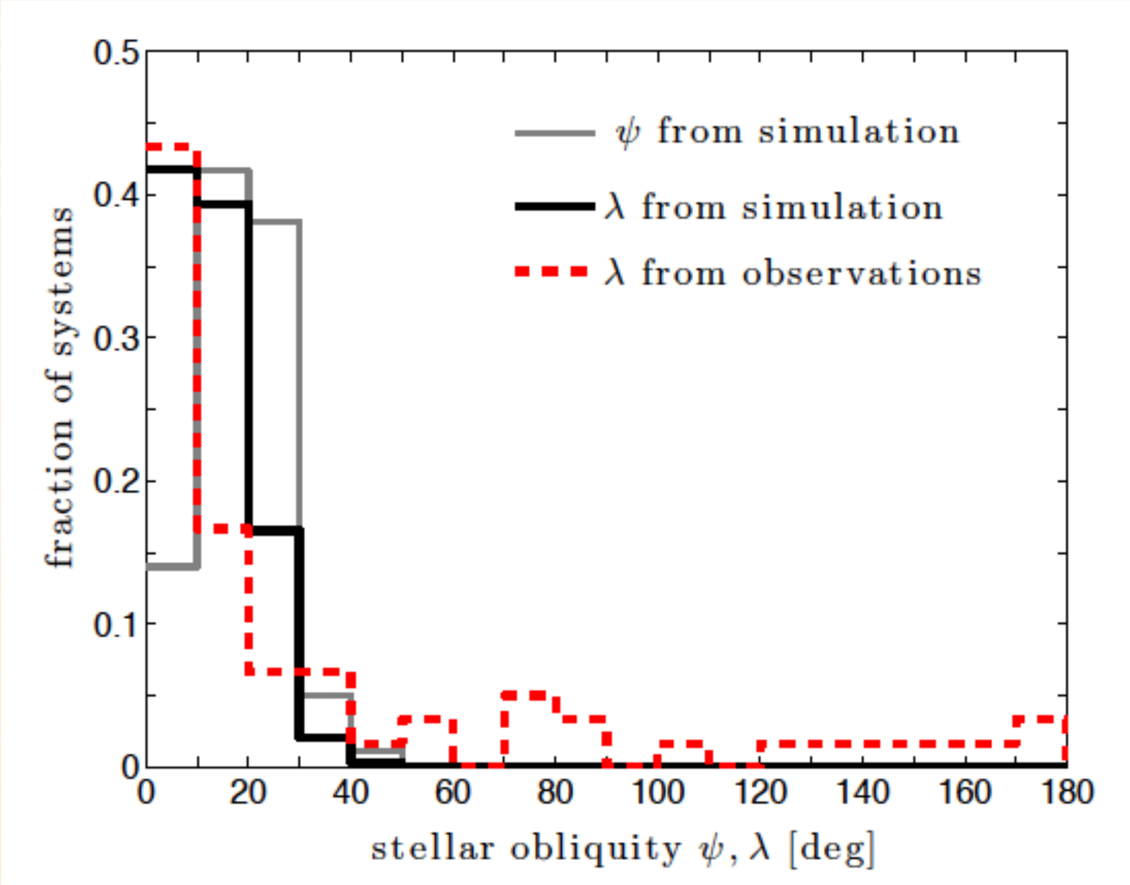
    (e.g., Shen et al. 2013, Boroson & Lauer 2009, Valtonen et al. 2008, Loeb 2007)

Example of multi-epoch spectroscopy (Shen et al. 2013):



active BH dominates the BL features, multi-epoch BL features => binary orbital parameters

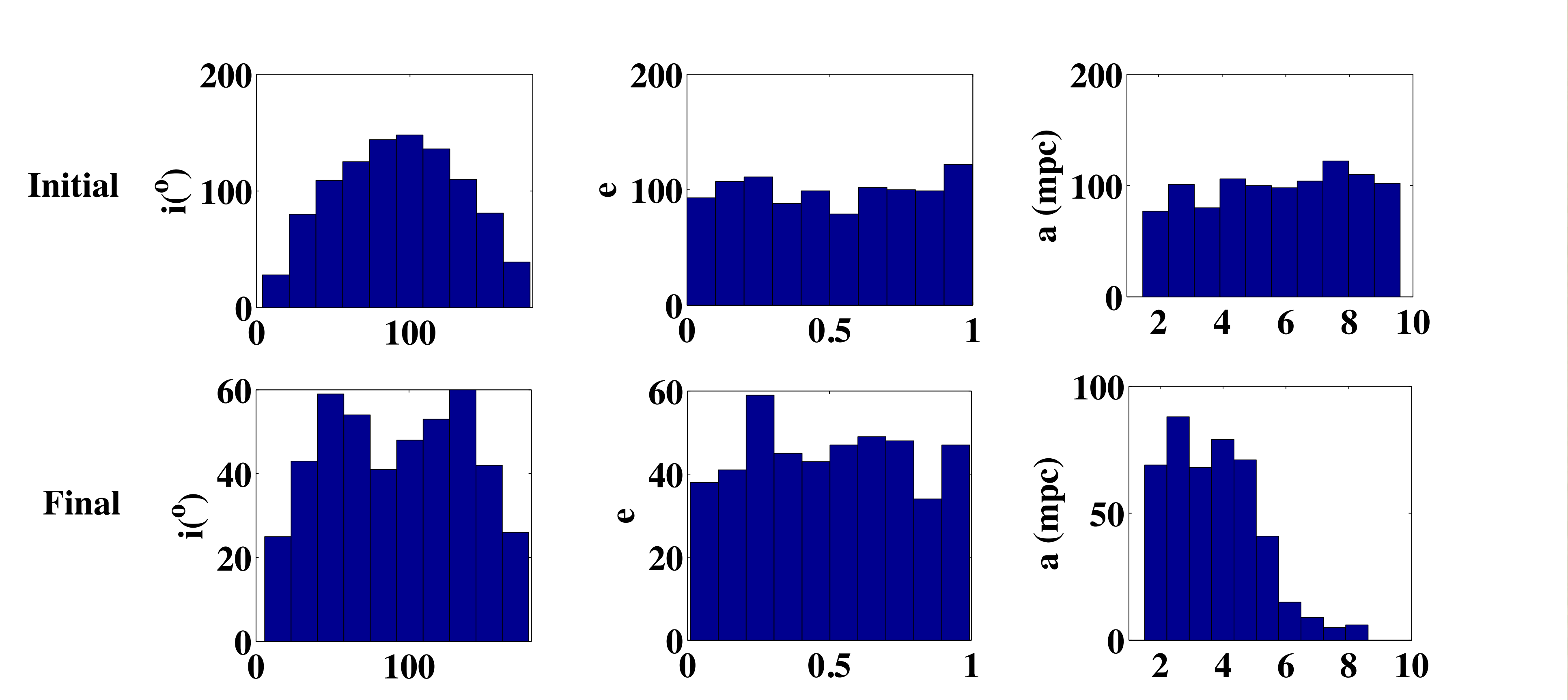
COPLANAR HIGH ECCENTRICITY MIGRATION



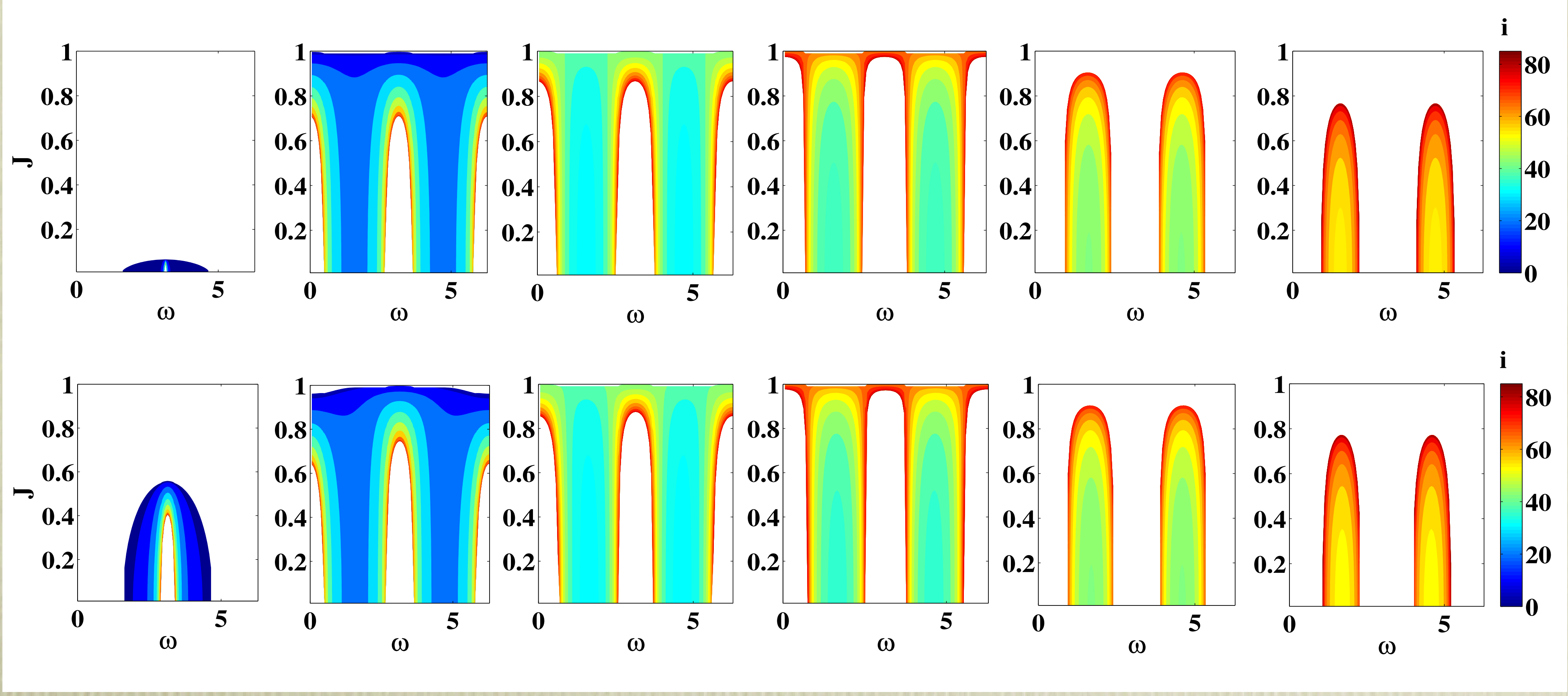
Population synthesis study.
tv=0.1yr

Initial v.s. Final Distribution

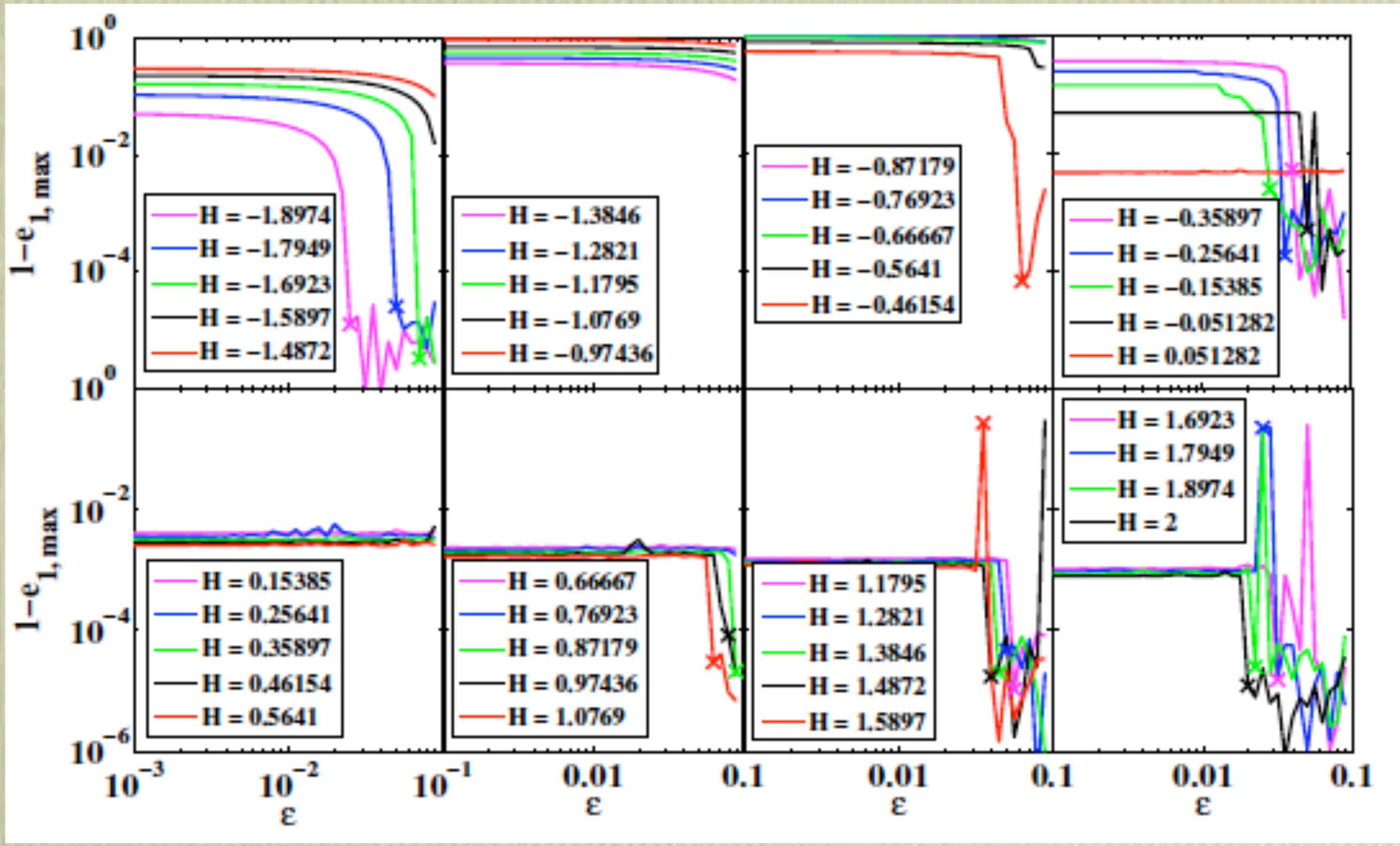
- Example: $m_1 = 10^6 M_\odot$, $m_2 = 10^{10} M_\odot$, $a_2 = 1$pc, $e_2 = 0.7$, $\alpha = 1.75$ (stellar distribution), normalized by M-σ relation. Run time: 1Gyr.



Initial Condition in i

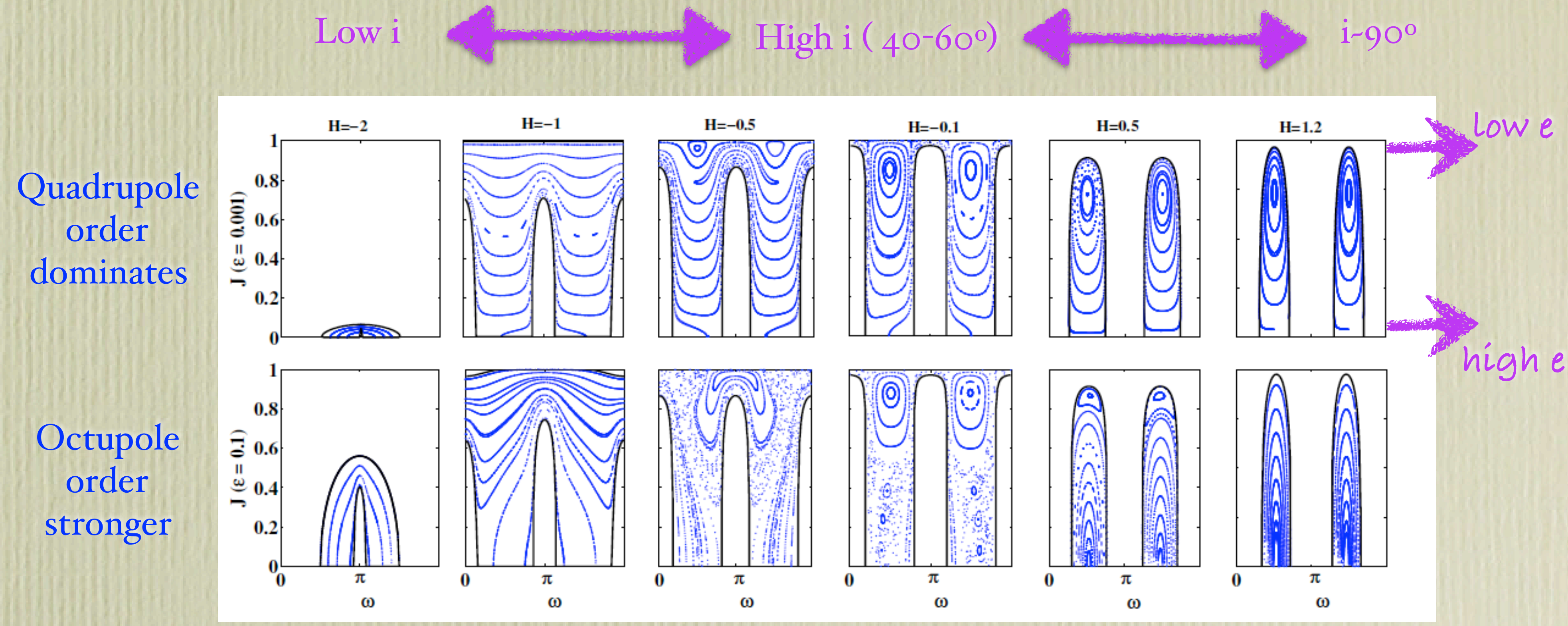


Maximum e_1 for different H and ϵ



Maximum e_1 for low i, high e_1 case, and high i cases

Surface of Section



- Trajectories chaotic only for H=-0.5, -0.1 at high ε .
- High inclination flips are chaotic.
- Overall evolution of the trajectories: evolution sensitive on the initial angles.

Li et al. 2014b

Surface of Section

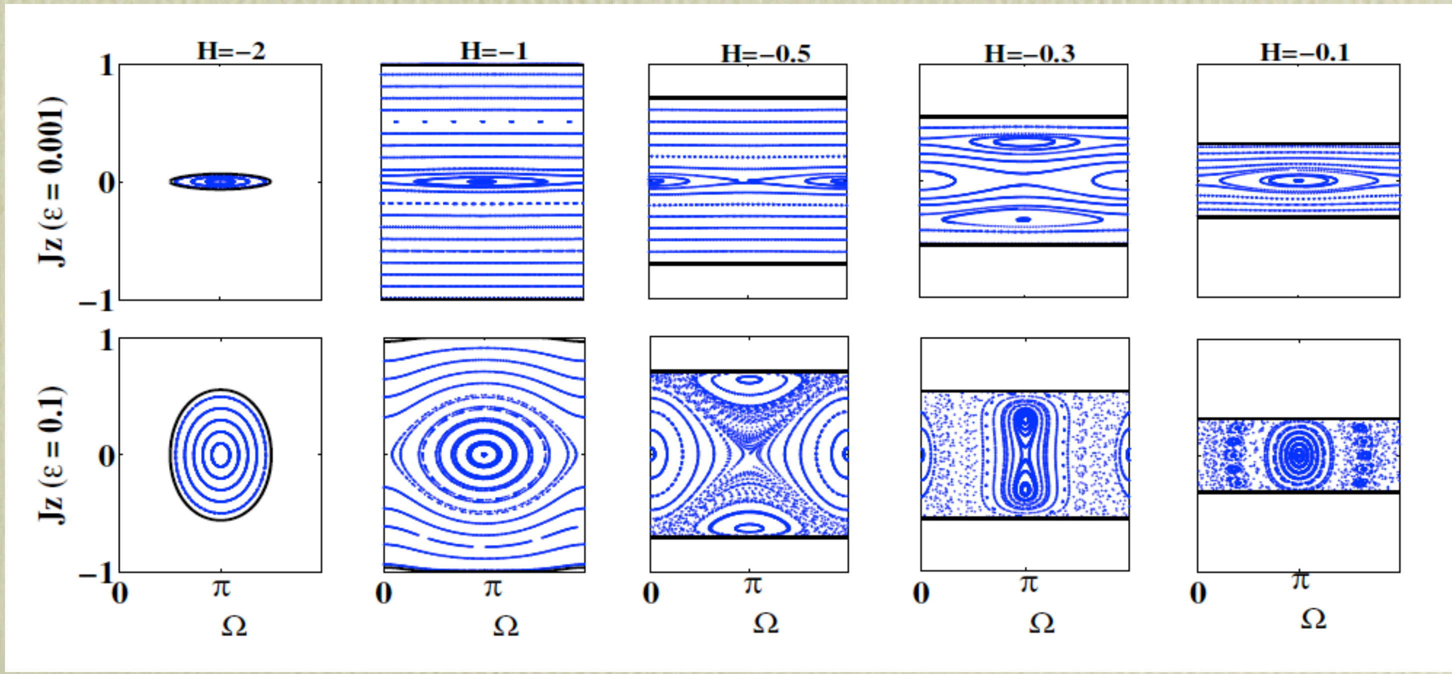
- Surface of section in the Jz − Ω plane

$Jz = \sqrt{1-e_1^2}\cos i_1$ Ω: longitude of node

Low i, high e_1 → High i, low e_1

Quadrupole order dominates

Octupole order dominates

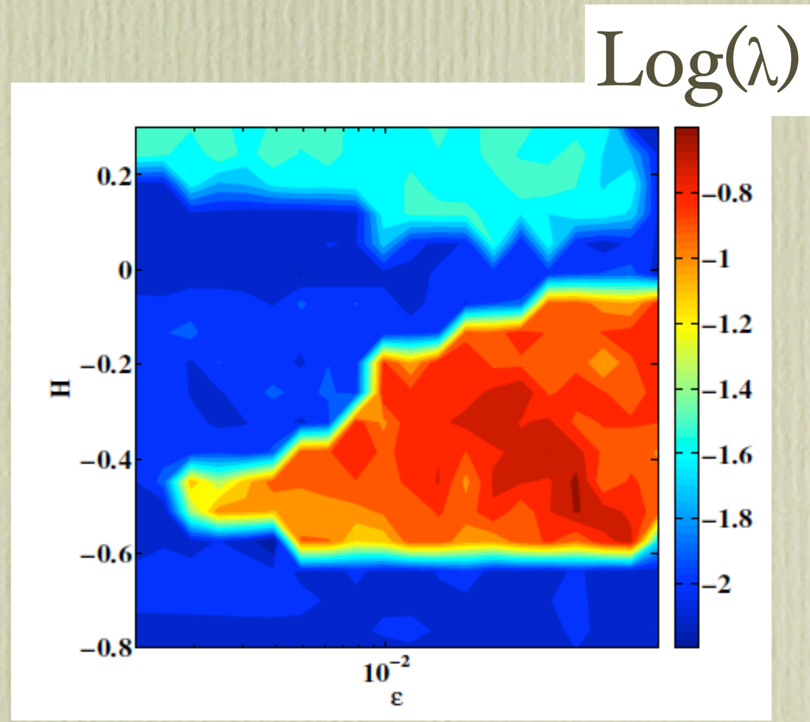


- All features are due to octupole effects.
- Trajectories are chaotic only possible when H=-0.5, -0.3, -0.1, for high ϵ.

Li et al. 2014b

Characterization of Chaos

- Lyapunov exponents (λ): λ↑, more chaotic.



- Chaotic when H≤0 (correspond to high i cases).
- In chaotic region, Lyapunov timescale t_L=(1/λ) ≈ 6t_K.

(t_K corresponds to the oscillation timescale of e_1 and i)

$$t_K = \frac{8}{3} P_{in} \frac{m_1}{m_2} \left(\frac{a_2}{a_1}\right)^3 (1-e_2^2)^{3/2}$$

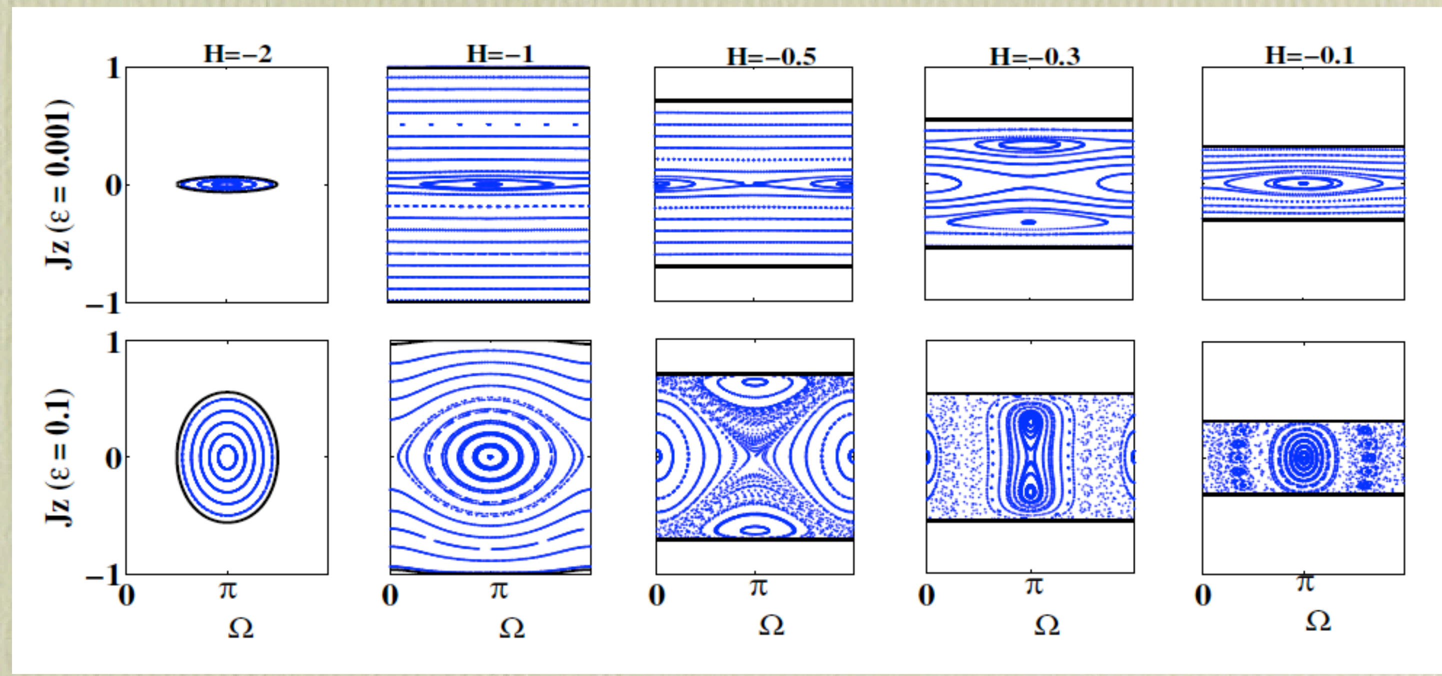
Li et al. 2014b

Surface of Section

Low i, high e_1 → High i, low e_1

Quadrupole order dominates

Octupole order dominates



- All features are due to octupole effects.
- Trajectories are chaotic only when H≤0.
- Flips are due to octupole resonances.

(Li, et al., 2014 in prep)

Applications --- 2. Tidal Disruption of Stars Surrounding BBH

- SMBHBs originate from mergers between galaxies. Following the merger, the distance of the SMBHB decreases.

  (Complete numerical simulations: e.g. Khan et al. 2012)

- SMBHBs with ~kpc separation have been observed with direct imagine.

  (e.g. Fabbiano et al. 2011, Green et al. 2010, Civano et al. 2010, Komossa et al. 2003, Hutchings & Neff 1989)

- At ~1pc separation it is more difficult to identify SMBHBs. SMBHBs have been observed with optical spectra, light variability and radio lines.

  (e.g. Boroson & Lauer 2009, Valtonen et al. 2008, Rodriguez et al. 2006)

- Motivation of tidal disruption of stars by ~1pc SMBHB:

  Identify SMBHB at ~1 pc separation with tidal disruption rate

Effects on Stars Surrounding BBH

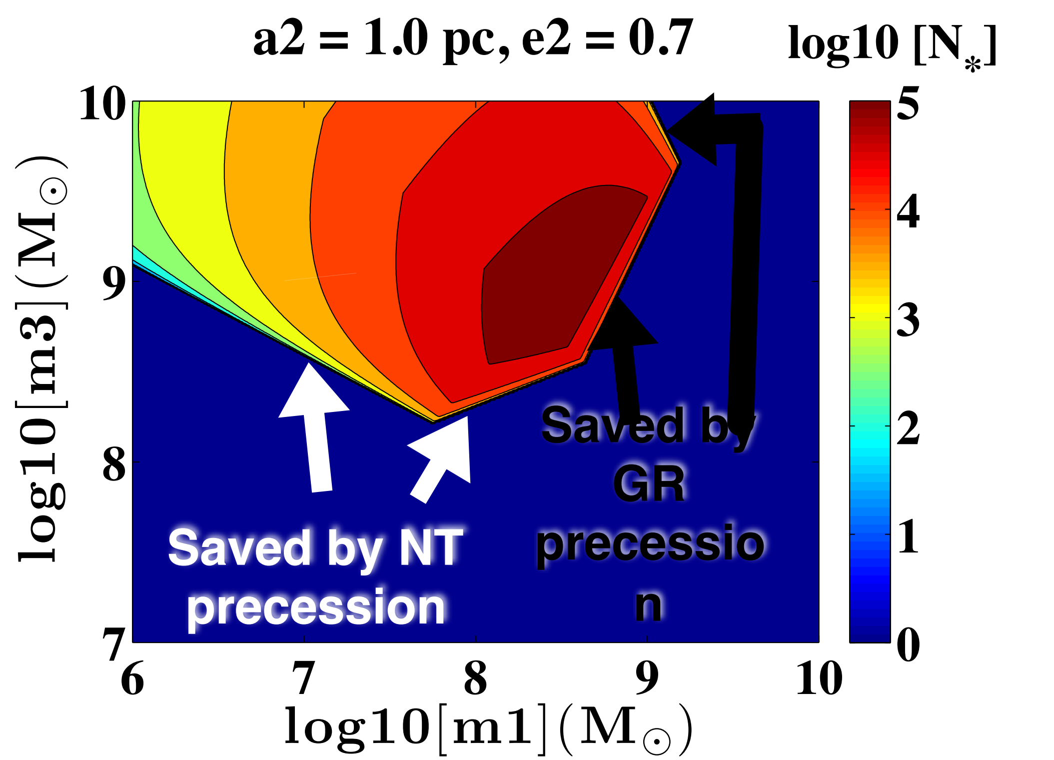
- Dynamics of stars around BH or BBH:
  - Secular dynamics introduce instability in eccentric stellar disks around a single BH (e.g. *Madigan, Levin & Hopman 2009*)
  - Tidal disruption event rate can be enhanced due to BBH and the recoil of BBH (*Ivanov et al. 2005, Wegg & Bode 2011, Chen et al. 2011, Stone & Loeb 2011*)
  - Relic stellar clusters of recoiled BH may uncover MW formation history (e.g. *O'Leary & Loeb 2009*).
- Here we study the effect of EKM to stars surrounding BBH

Effects of EKM on Stars Surrounding BBH

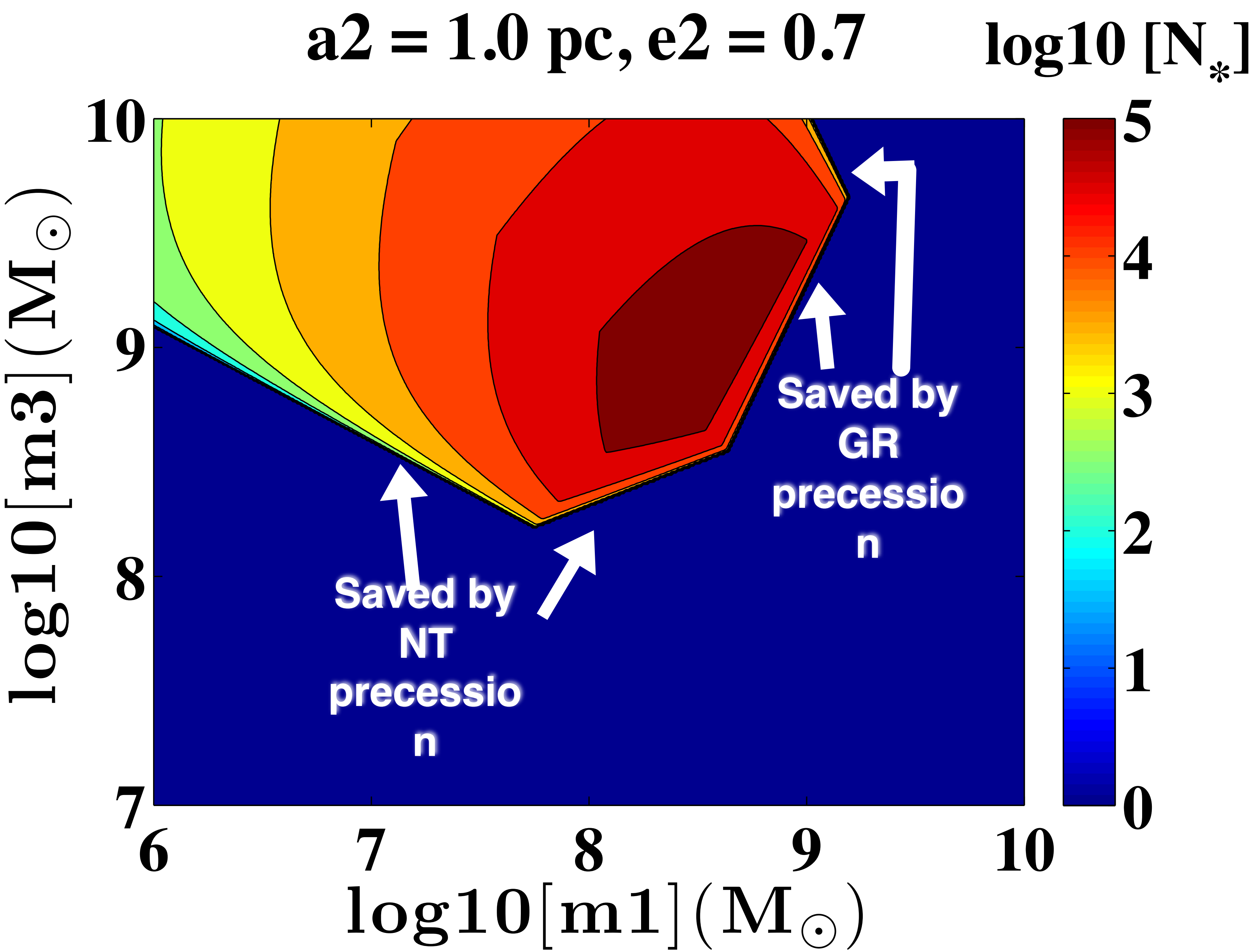
- Study the role of **eccentric ($e_2 \neq 0$) Kozai mechanism** in the presence of **general relativistic (GR) precession** and **Newtonian (NT) precession** for stars surrounding SMBHB.

- Set the separation of the BBH at $a_2 = 1pc$, $e_2 = 0.7$ and assuming $\rho_* \propto a^{-1.75}$, normalized by M-σ relation.

- N_* is the number of stars affected by the eccentric Kozai Mechanism. (Requirement: $t_{GR} < t_{Kozai}$, $t_{NT} < t_{Kozai}$, $\varepsilon < 0.1$, $a_1 < r_{RL}$).



(Li, et al., in prep)



a2 = 1.0 pc, e2 = 0.7
log10 [N*]
log10[m3](M⊙)
log10[m1](M⊙)
Saved by GR precessio n
Saved by NT precessio n
10
9
8
7
6
7
8
9
10
0
1
2
3
4
5

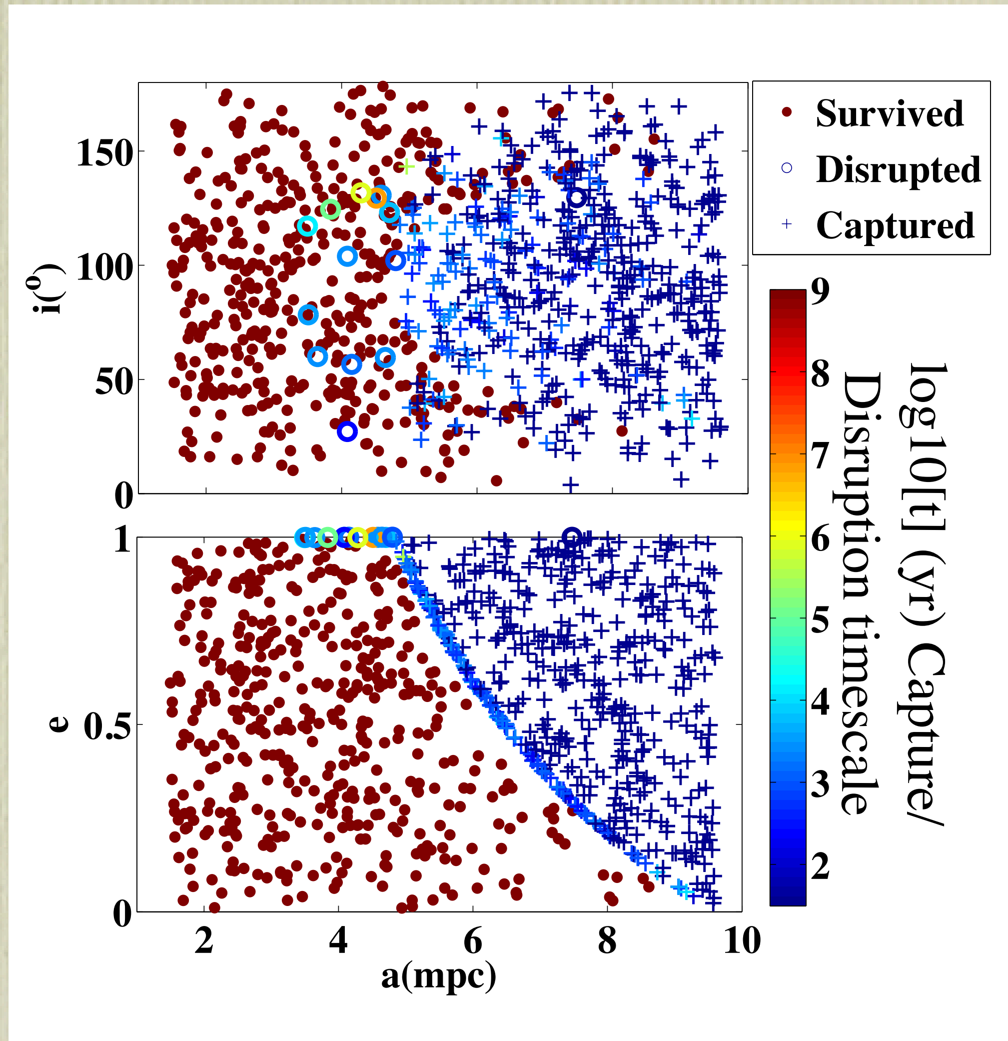
Effects of EKM on Stars Surrounding BBH

- Example: $m_1 = 10^6 M_\odot$, $m_2 = 10^{10} M_\odot$, $a_2 = 1$pc, $e_2 = 0.7$, Run time: 1Gyr.

- 14/1000 disrupted; 535/1000 captured. Disruption/capture timescales are short.

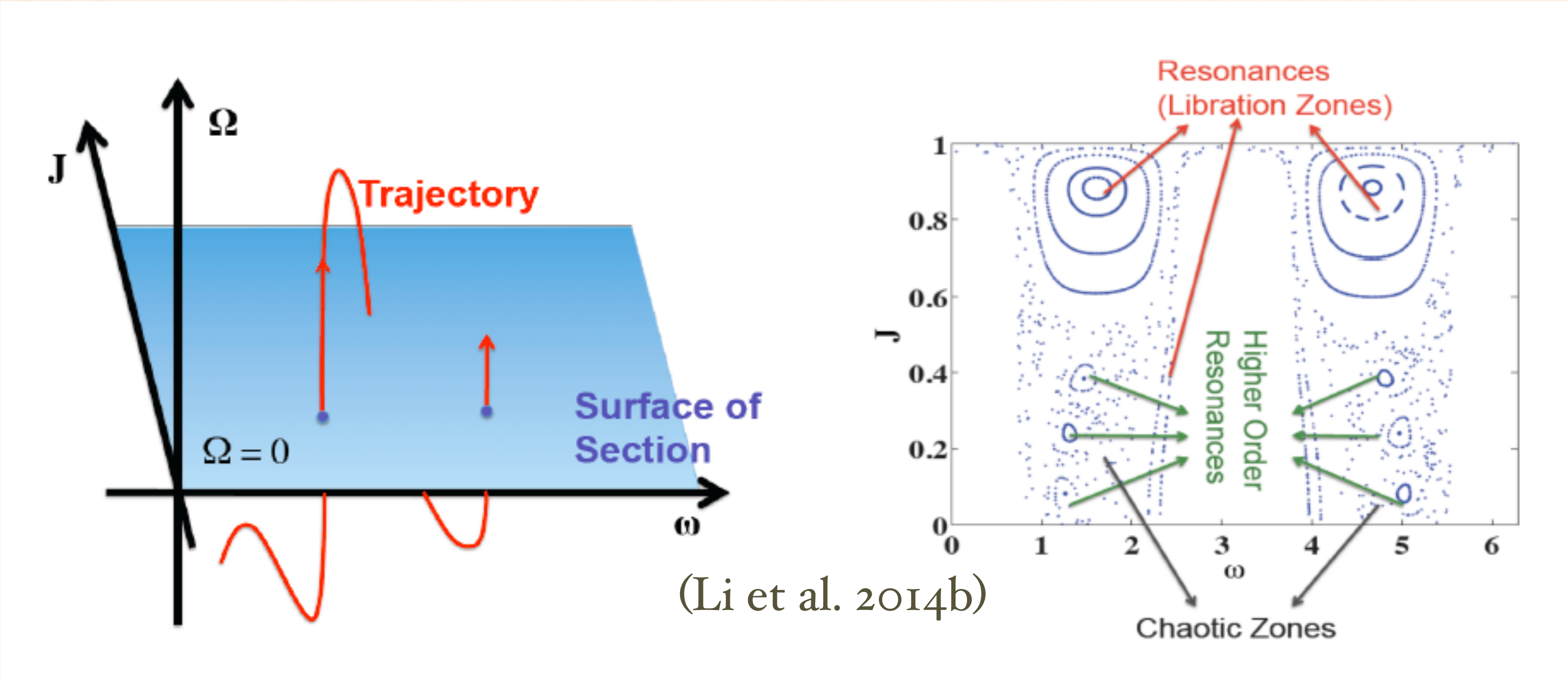
=> Captured stars may change stellar density profile of the other BH

=> With rapid diffusion, disruption rate ~10^{-3}/yr.



(Li, et al., in prep)

SURFACE OF SECTION



(Li et al. 2014b)

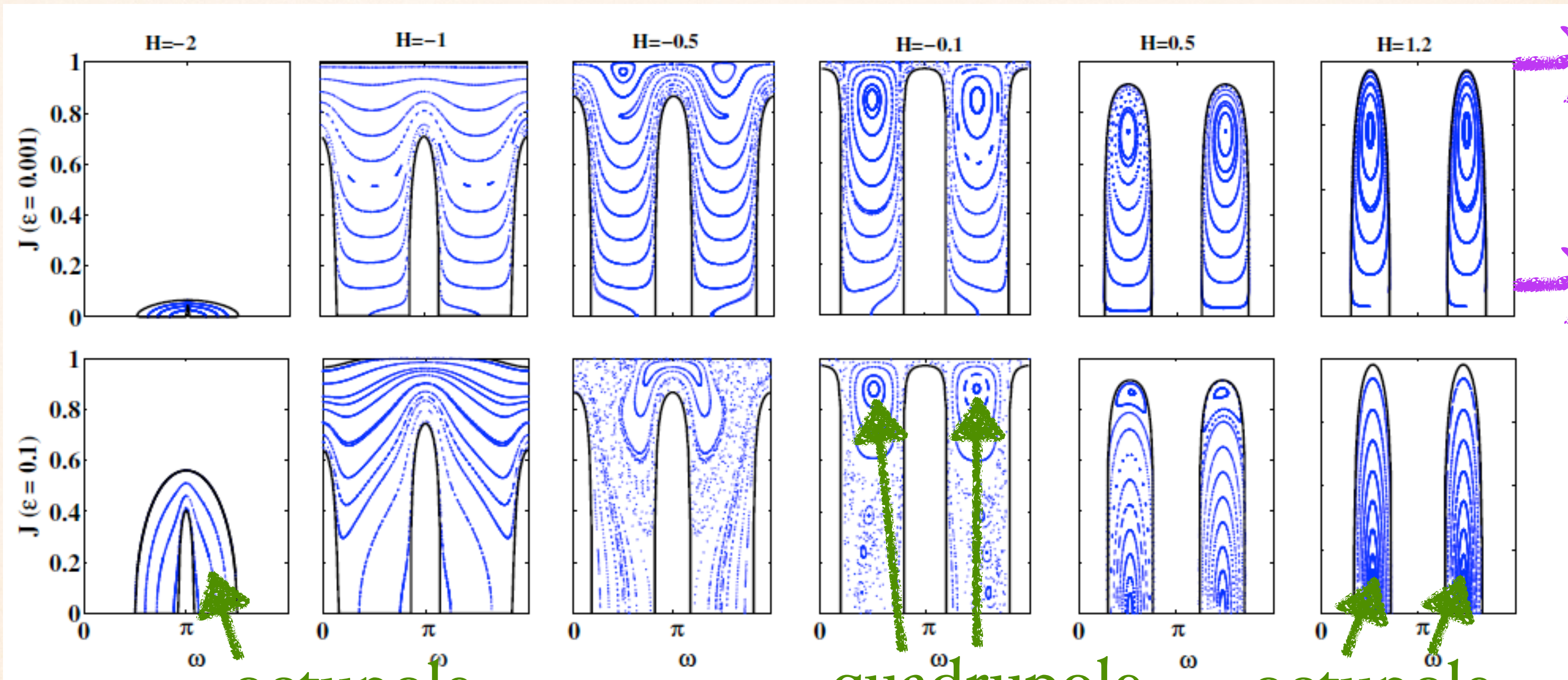
- Resonant zones: points fill 1-D lines.
  trajectories are quasi-periodic.
- Chaotic zones: points fill a higher dimension.
  trajectories are chaotic.

SURFACE OF SECTION

Low i ⟷ High i (40-60°) ⟷ i~90°

Quadrupole order dominates

Octupole order stronger



low e

high e

octupole resonances

quadrupole resonances

octupole resonances

Quadrupole resonances:

centers at low e_1, $\omega=\pi/2$ and $3\pi/2$ (*e.g., Kozai 1962*)

Octupole resonances:

centers at high e_1, $\omega=\pi$ or $\pi/2$ and $3\pi/2$

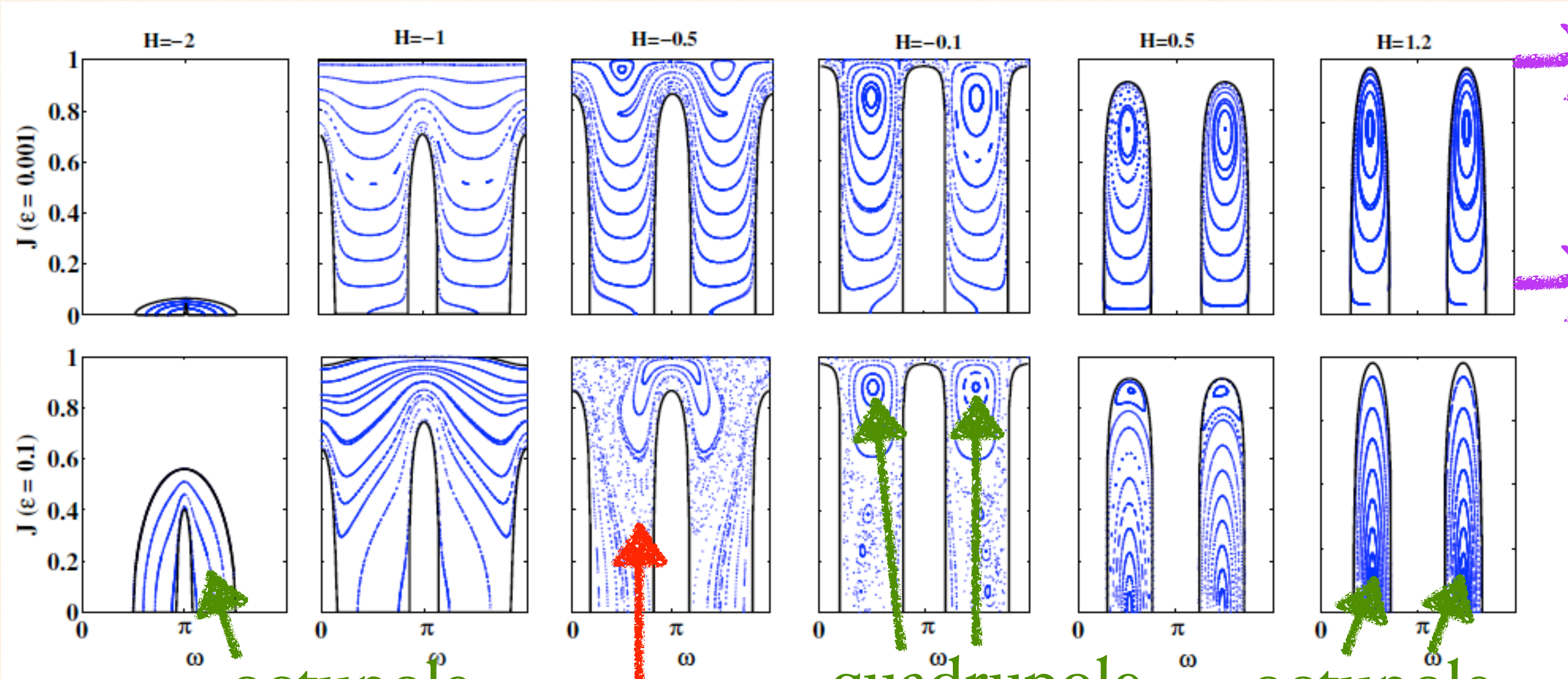
Li et al. 2014b

SURFACE OF SECTION

Low i ⟷ High i (40-60°) ⟷ i~90°

Quadrupole order dominates

Octupole order stronger



low e

high e

octupole resonances

chaos

quadrupole resonances

octupole resonances

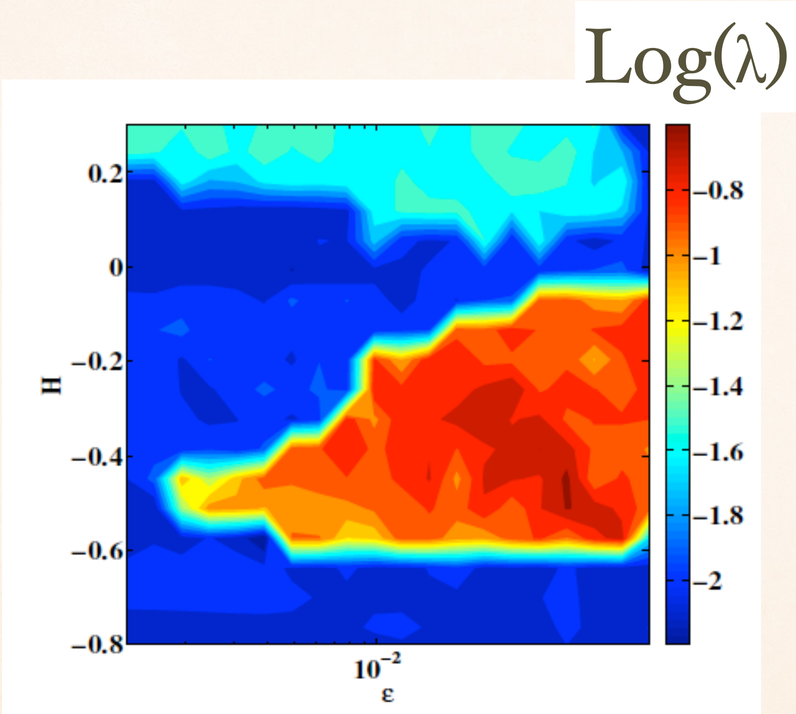
Octupole resonances: responsible for e →1

Chaos: overlap of quadrupole and octupole resonances
high inclination flips

Li et al. 2014b

CHARACTERIZATION OF CHAOS

- Chaotic when H≤0 (correspond to high i cases).



$\Omega_0=0$,
$\omega_0=\pi/2$,
$e_0=0$

- In chaotic region, Lyapunov timescale $t_L=(1/\lambda) \approx 6t_K$.

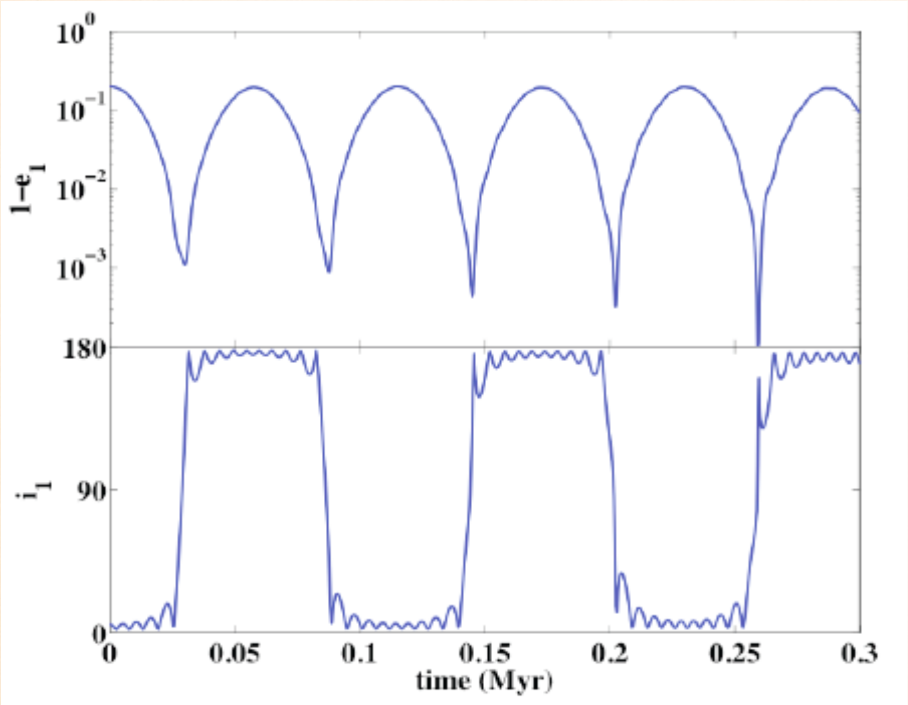
(t$_K$ corresponds to the oscillation timescale of e_1 and i)

$$t_K = \frac{8}{3} P_{in} \frac{m_1}{m_2} \left(\frac{a_2}{a_1}\right)^3 (1-e_2^2)^{3/2}$$

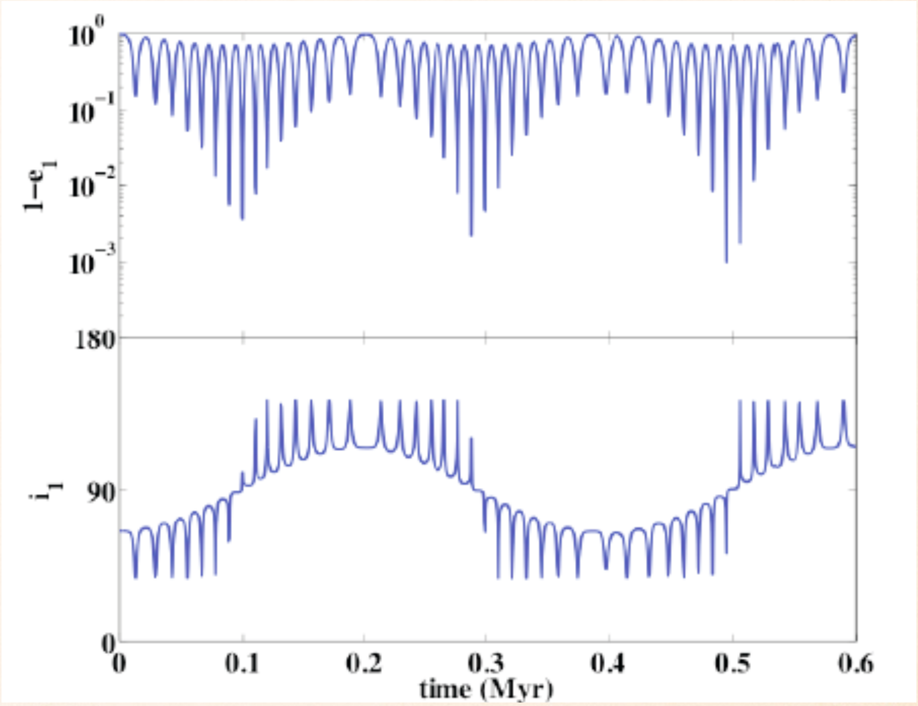
Li et al. 2014b

DIFFERENCES BETWEEN HIGH/LOW I FLIP

Low inclination flip



High inclination flip



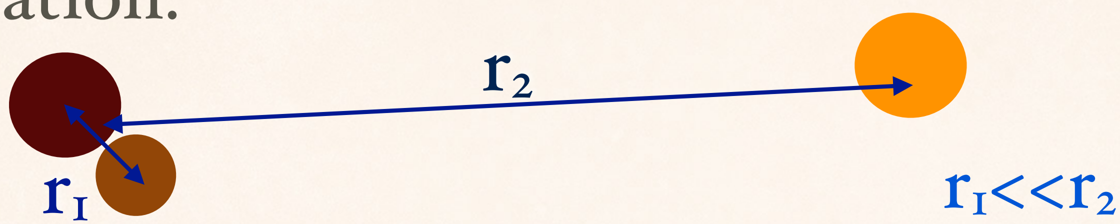
Low inclination flips:

- e_1 ↑ monotonically, inclination stays low before flip.
- i stays low before flip.

(Li et al. 2014a)

HIERARCHICAL THREE-BODY SYSTEMS

- Configuration:



- Hierarchical configurations are COMMON:

- For binaries with periods shorter than 10 days, >40% of them are in systems with multiplicity ≥ 3. (*Tokovinin 1997*)
- For binaries with period < 3 days, ≥96% are in systems with multiplicity ≥3. (*Tokovinin et al. 2006*)
- 282 of the 299 triple systems (~ 94.3%) are hierarchical. (*Eggleton et al. 2007*)

- Hierarchical 3-body dynamics gives insight for hierarchical multiple systems.

EXAMPLES OF HIERARCHICAL 3-BODY DYNAMICS

- For stellar systems:

Short Period Binaries

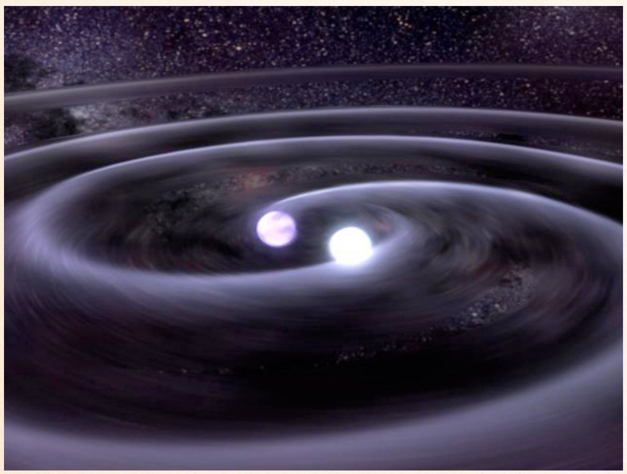


Image credit: NASA/Tod Strohmayer/Dana Berry

e.g., Harrington 1969; Mazeh & Shaham 1979; Ford et al. 2000; Eggleton & Kiseleva-Eggleton 2001; Fabrycky & Tremaine 2007; Shappee & Thompson 2013

Blue Stragglers

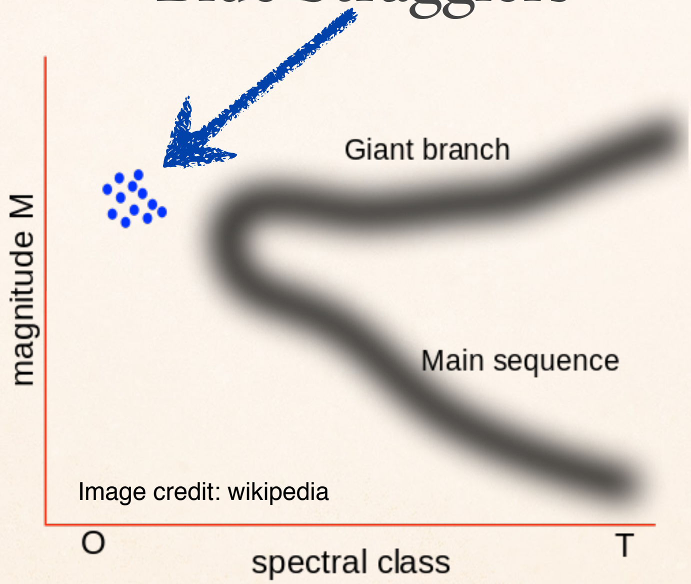
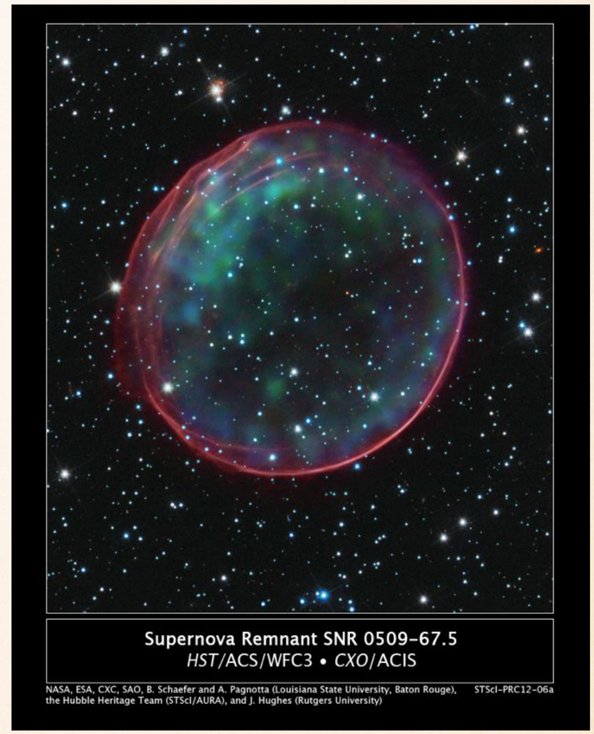


Image credit: wikipedia

e.g., Perets & Fabrycky 2009; Naoz & Fabrycky 2014

Type Ia Supernova

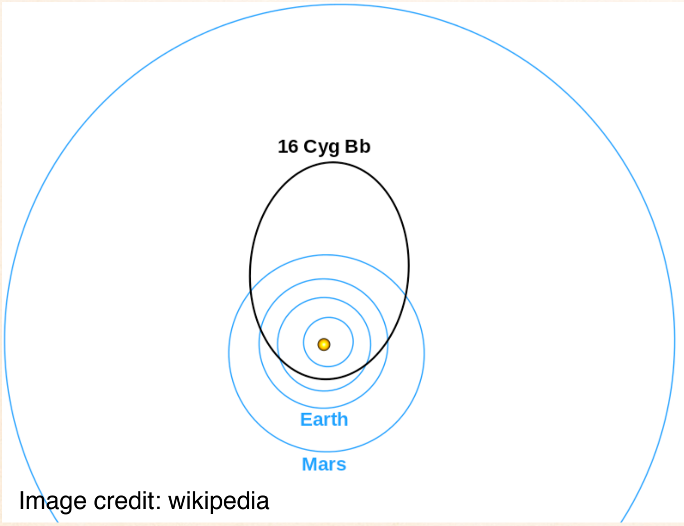


e.g., Katz & Dong 2012; Kushnir et al. 2013

EXAMPLES OF HIERARCHICAL 3-BODY DYNAMICS

- Exoplanetary systems:

Eccentric Orbits



e.g., Holman et al. 1997; Ford et al. 2000; Wu & Murray 2003;

Exoplanets with large spin-orbit misalignment

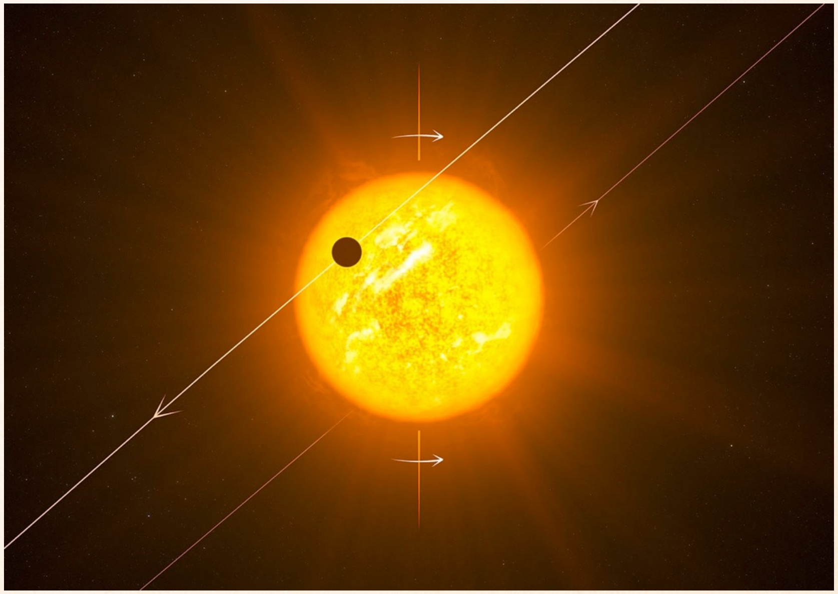


Image credit: ESO/A. C. Cameron

e.g., Fabrycky & Tremaine 2007; Naoz et al. 2011, 2012; Petrovich 2015; Storch et al. 2014; Anderson et al. 2016

EXAMPLES OF HIERARCHICAL 3-BODY DYNAMICS

- Black hole systems:

Merger of short period black hole binaries

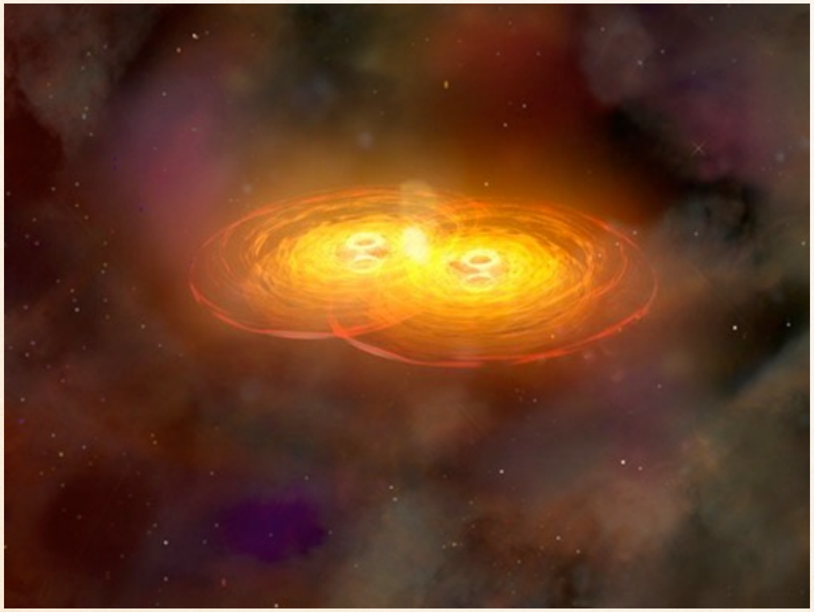


Image credit: NASA / CXC / A. Hobart

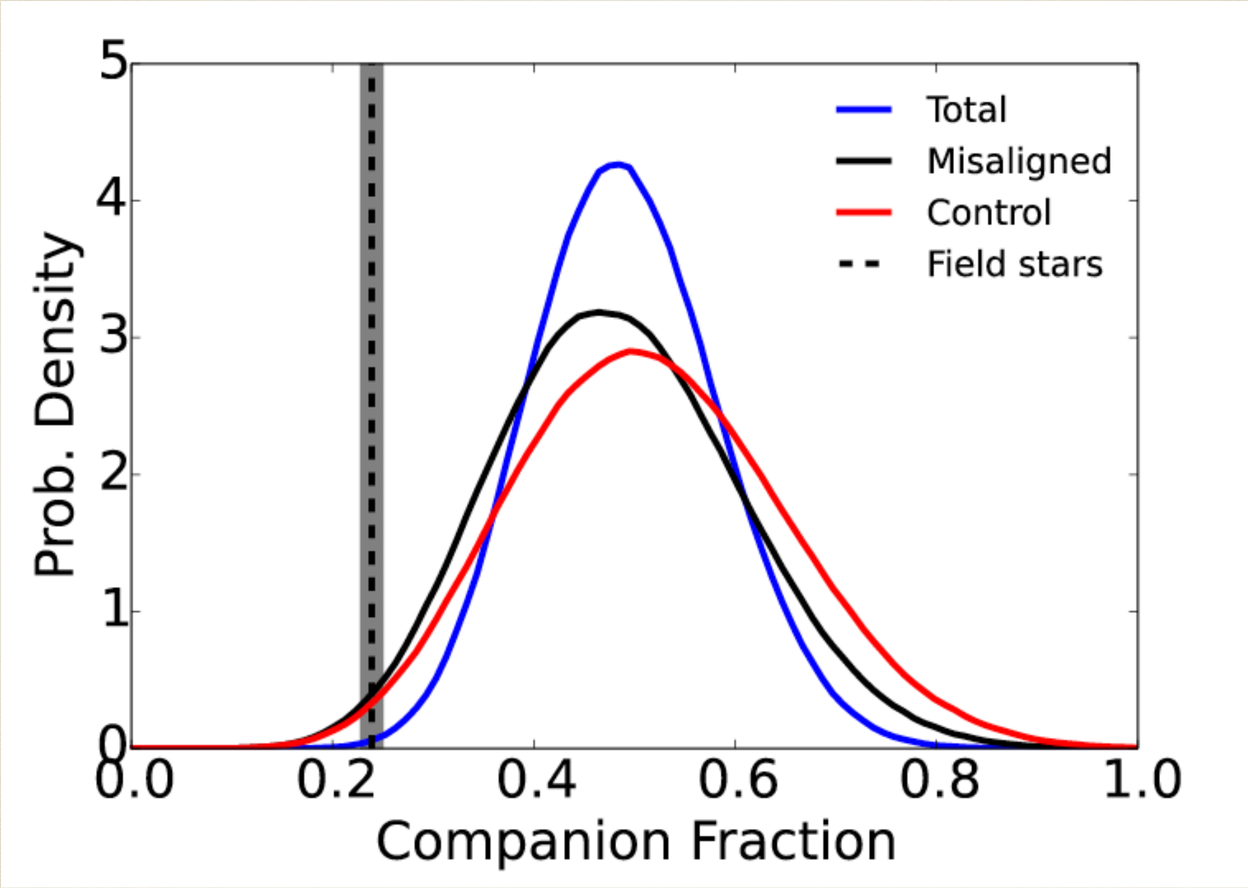
e.g., Blaes et al. 2002; Miller & Hamilton 2002; Wen 2003; Bode & Wegg 2014;

Tidal disruption events

Image credit: NASA/CXC/M.Weiss

e.g., Chen et al. 2009, 2011; Wegg & Bode 2011; Li et al. 2015

Spin-orbit Misalignment

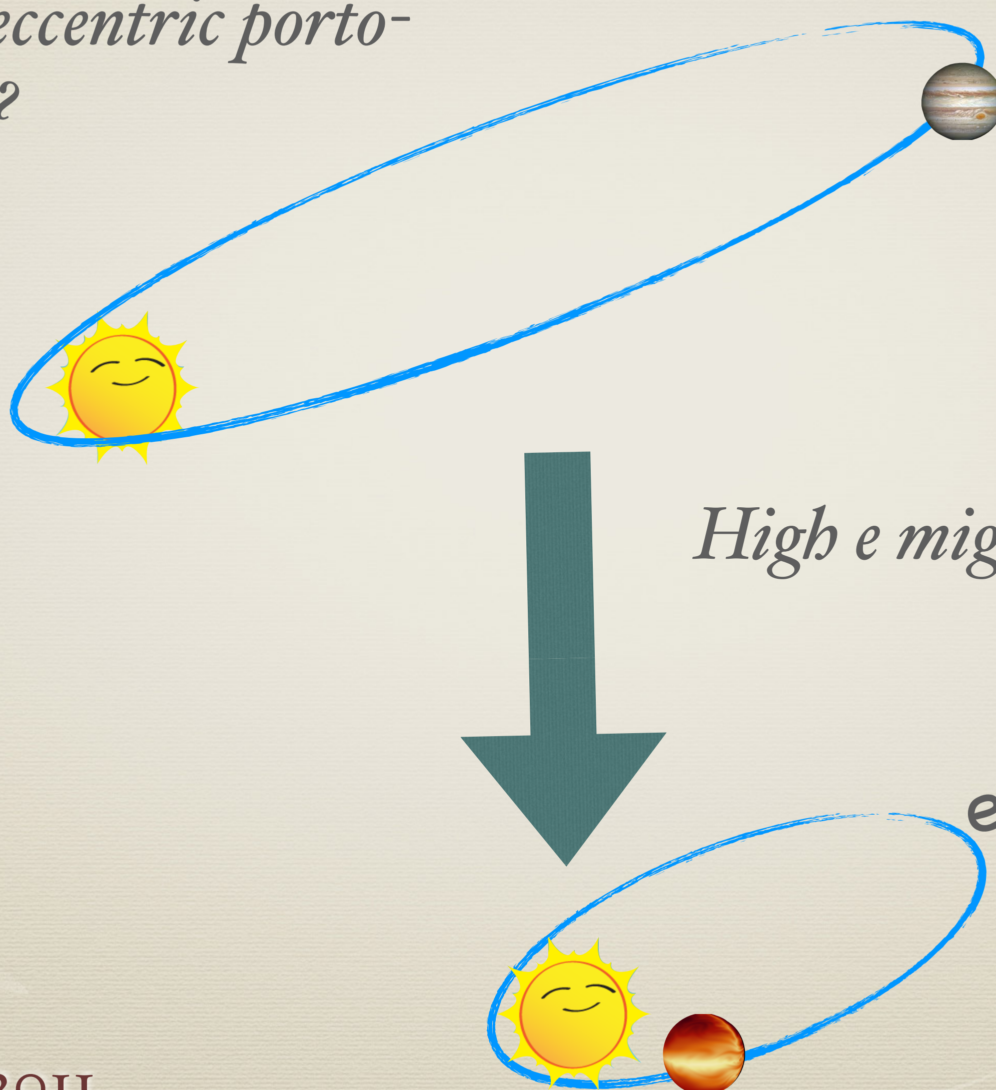


* No correlation between misaligned/eccentric hot Jupiter systems and the incidence of stellar companions

Ngo et al. 2015

Eccentric Proto-Hot Jupiters

Existence of eccentric porto-Hot Jupiters?



High e migration

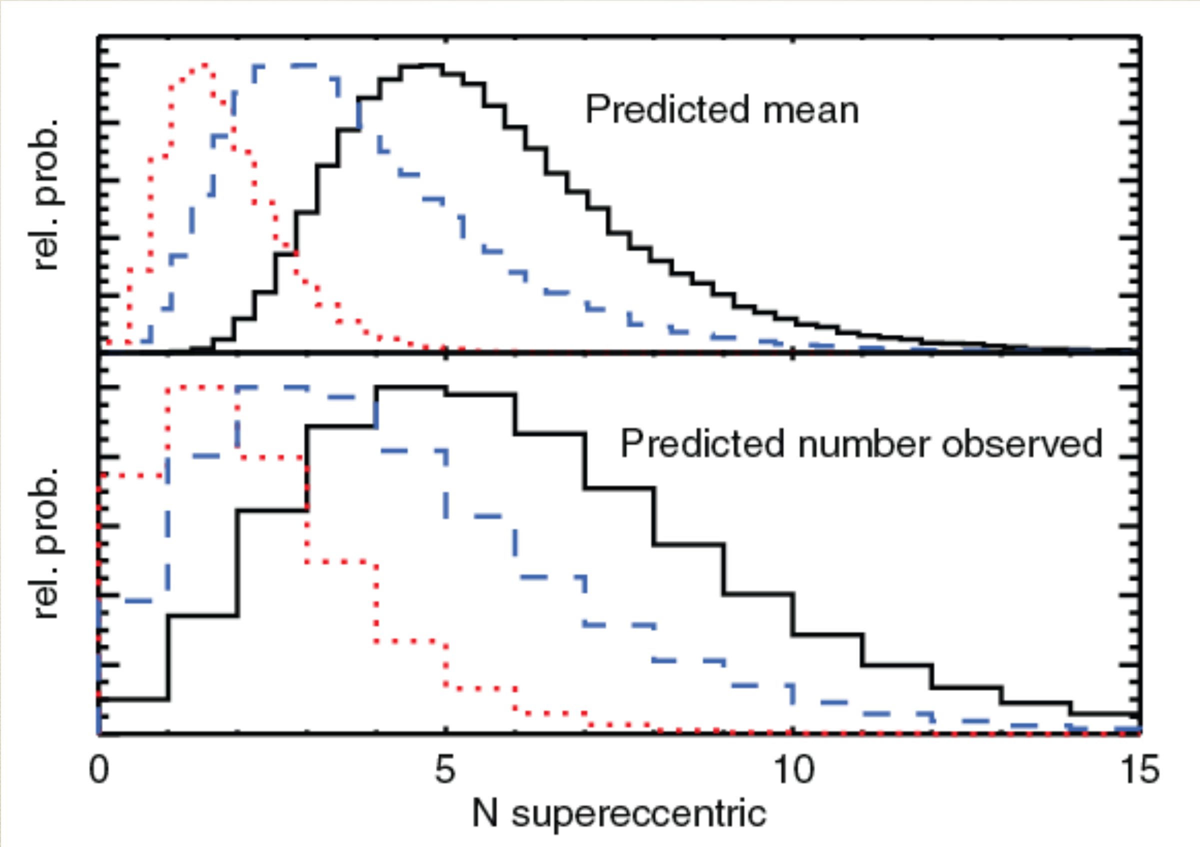
eccentric proto-HJs

Socrates et al. 2011

LK dominate

Proto-Hot Jupiters

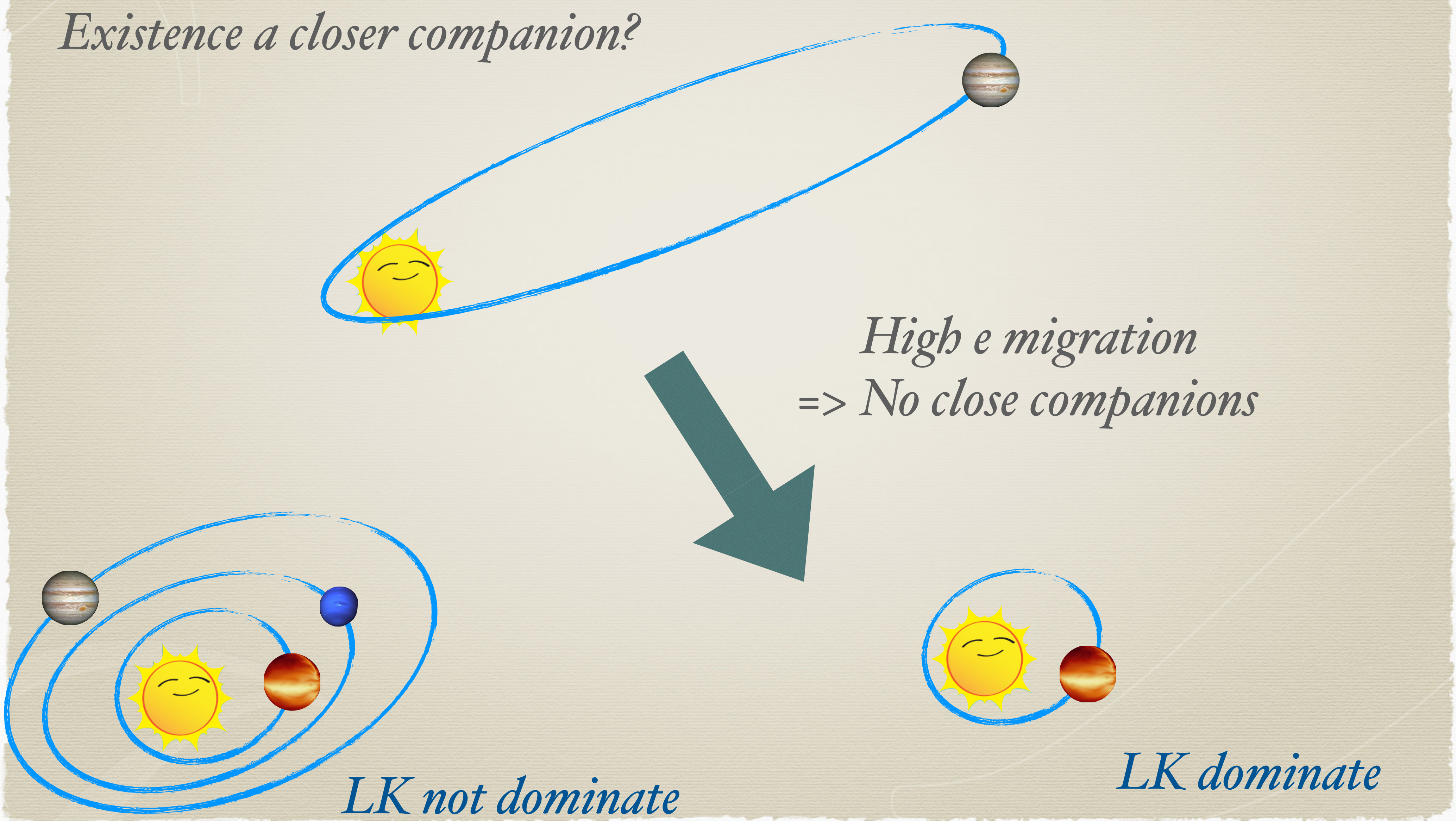
* A paucity of proto-hot Jupiters on super-eccentric orbits



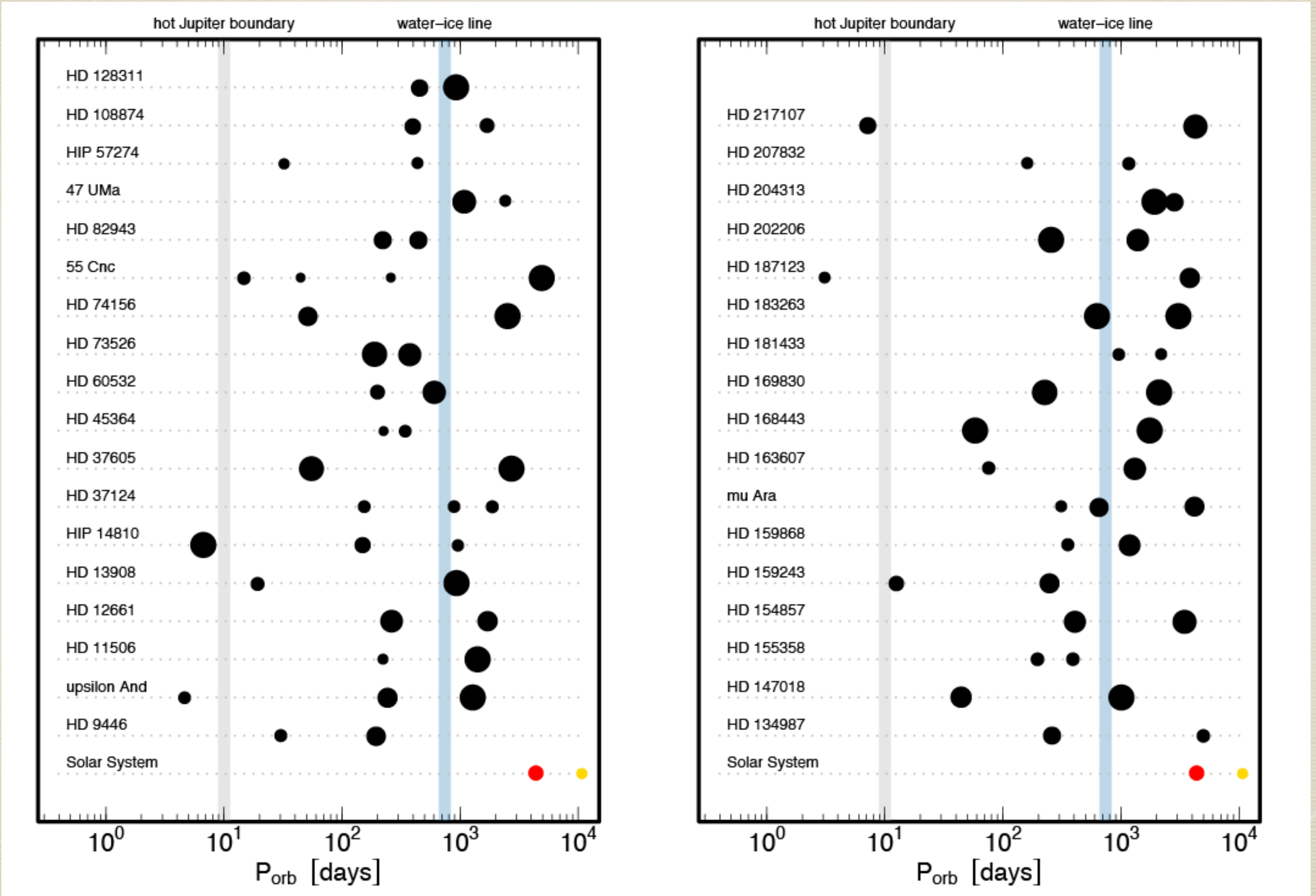
* <44% formed via LK mechanism

Dawson et al. 2015

Closer Companions of Hot Jupiters



Closer Companions of Hot Jupiters



Hot Jupiters (< 10 days) are no more or less likely to have exterior companions than giant planets (>10 days)

=> high e migration does not dominate

Schlaufman & Winn 2016