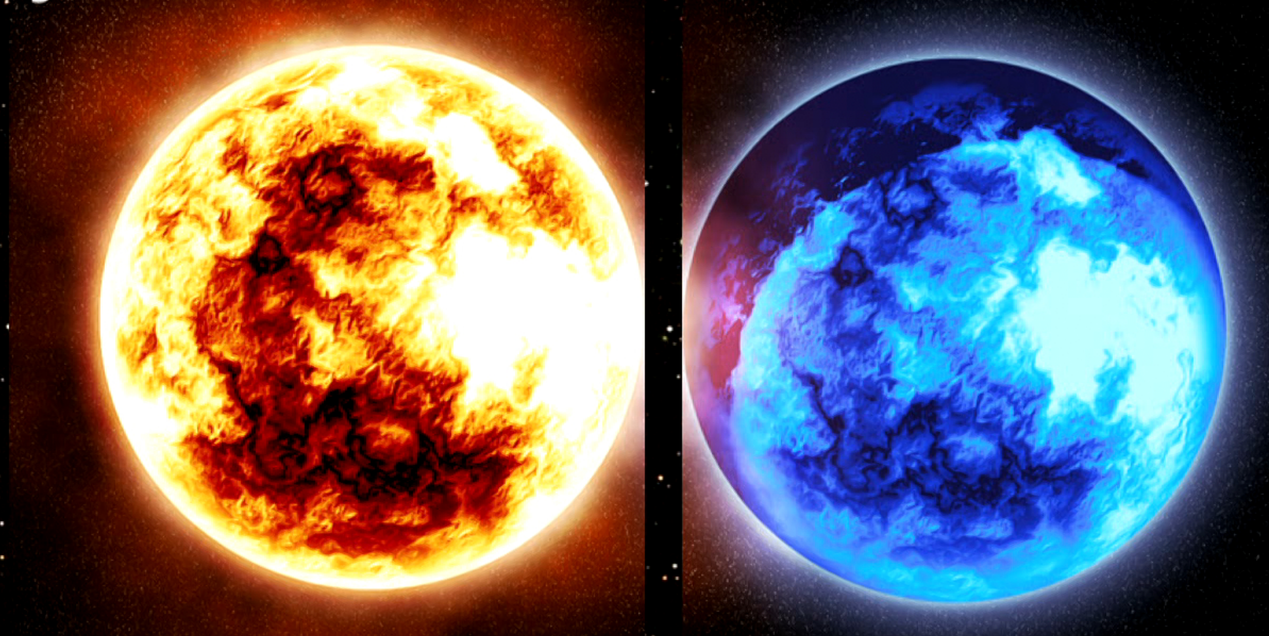
Title: A Song of Ice and Fire --- Dynamics of Planets Hot and Cold

Date: Oct 18, 2018 01:00 PM

URL: http://pirsa.org/18100083

Abstract: <p>The unexpected diversity of planetary systems has posed challenges to our classical understanding of planetary formation. For instance, Jupiter sized planets have been detected with short orbital periods of a few days in misaligned orbits with respect to the spin-axis of their host stars. I will first describe the statistical implication of detecting misaligned hot Jupiters and will suggest how dynamical interactions between an outer perturber and the inner planet, can naturally lead to the formation of such misaligned hot Jupiters. Next, I will discuss a similar dynamical process in the outer Solar System, far away from our Sun, which could cause the observed clustering of extreme trans-Neptunian objects. This can constrain properties of a possible outer planet, Planet Nine, in our own Solar System. </p>

A Song of Ice and Fire ---
Dynamics of Planets Hot and Cold



Gongjie Li (Georgia Tech)

Strong Gravity Seminar, Oct. 2018

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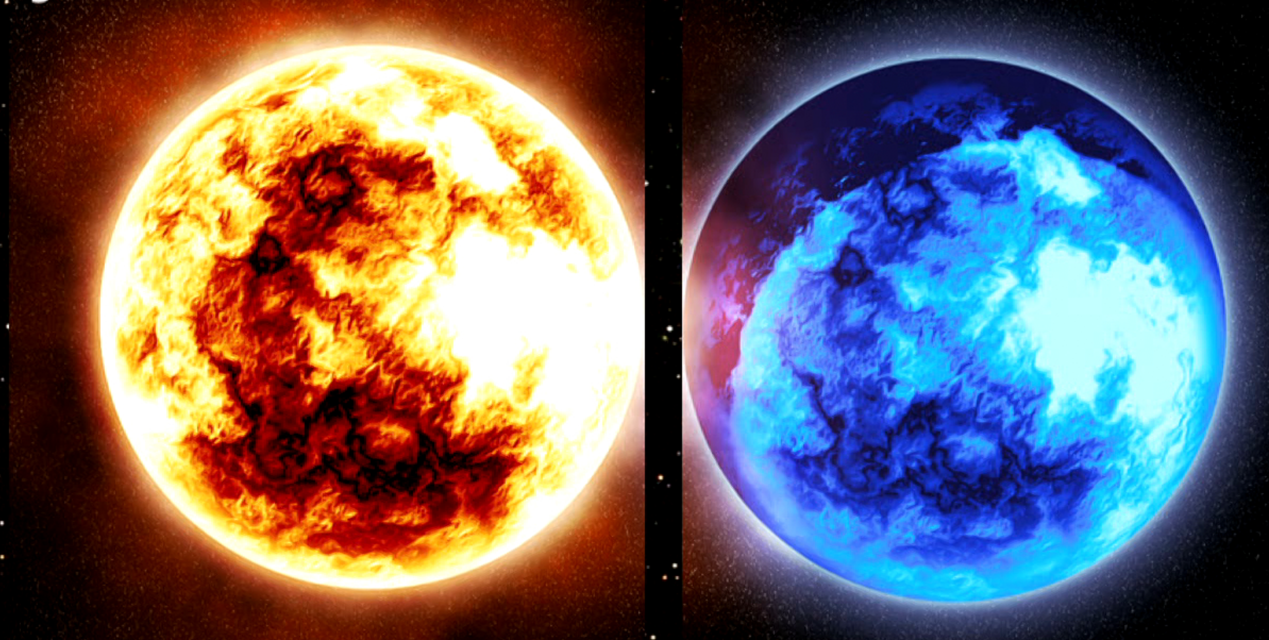

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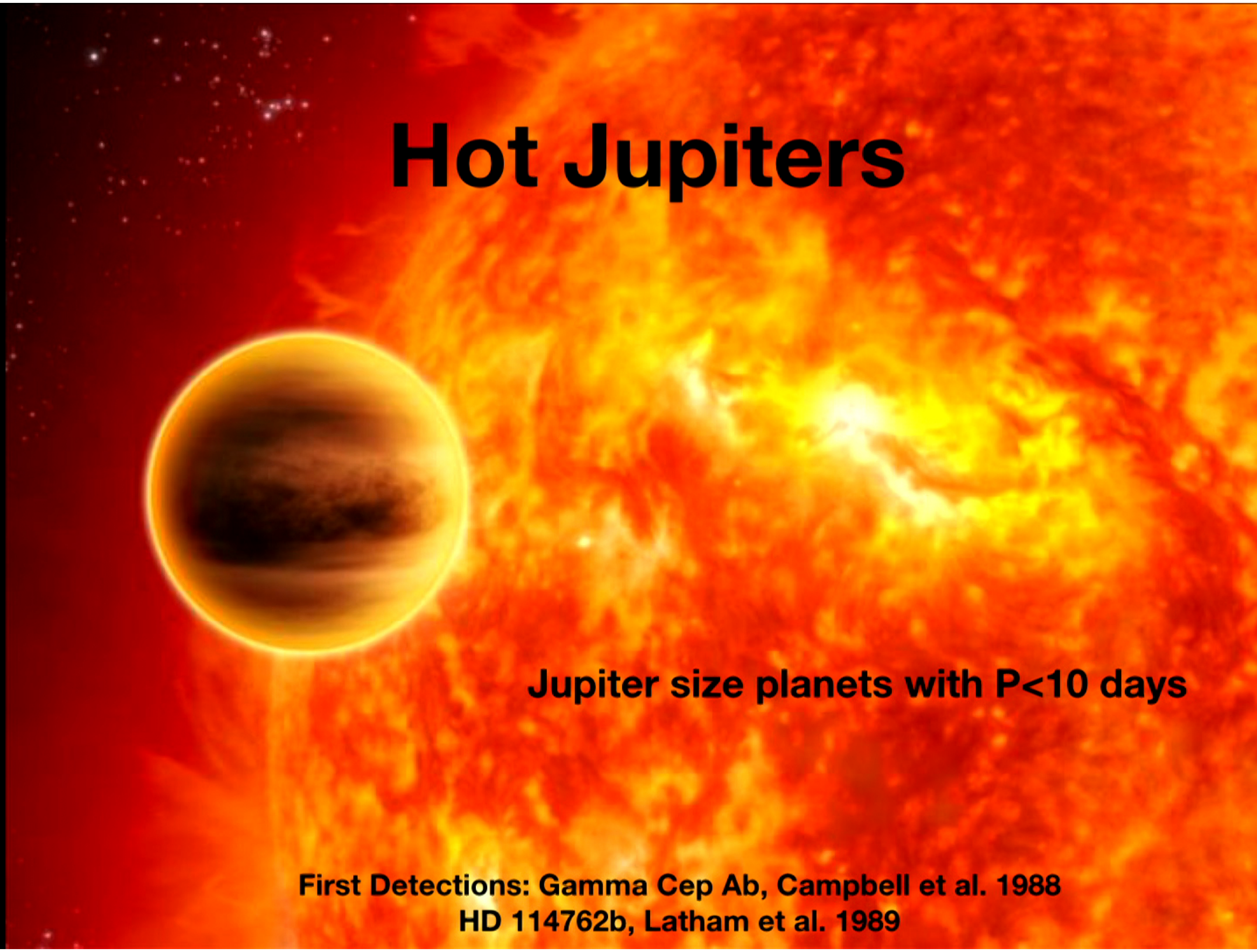
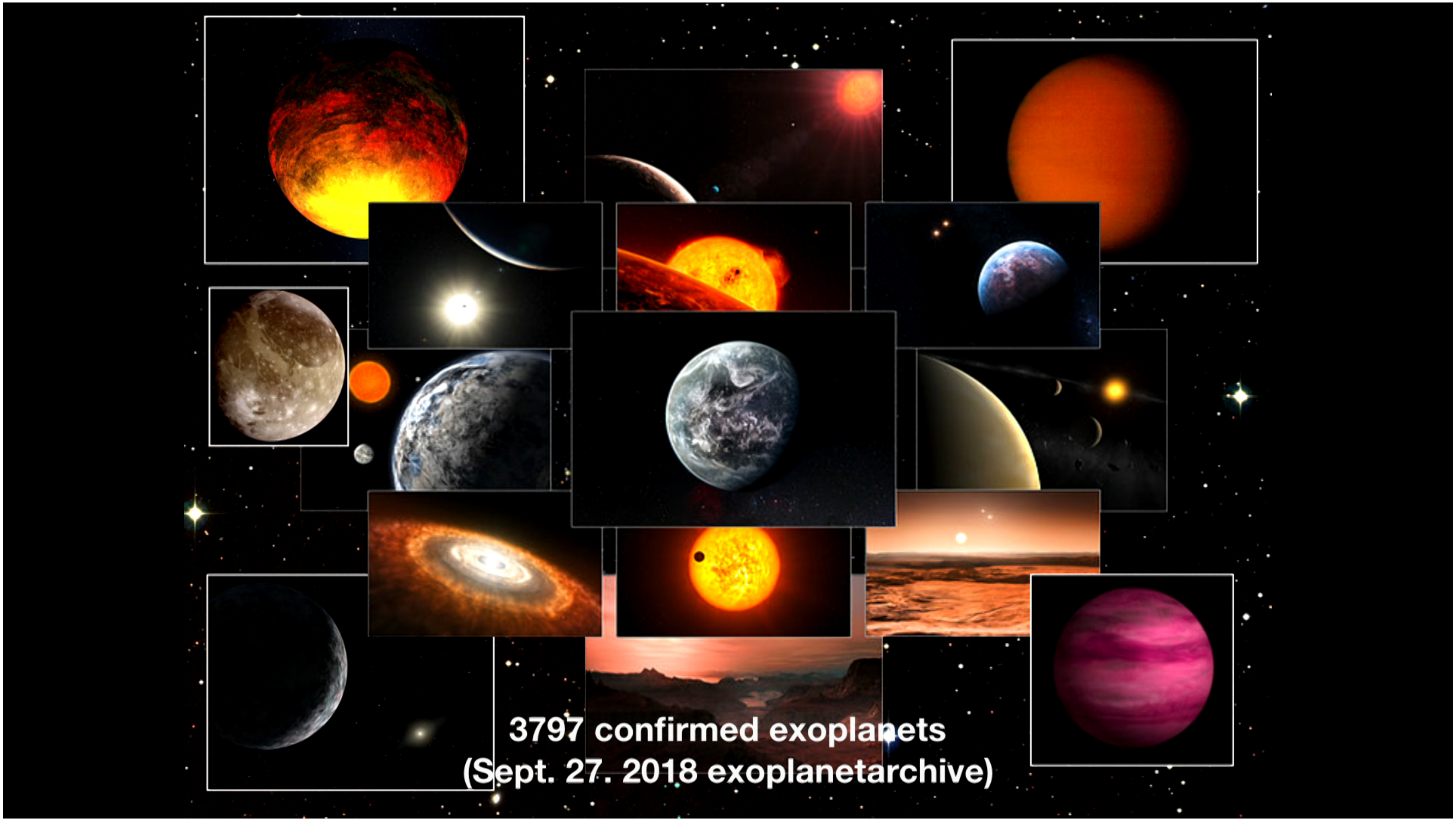
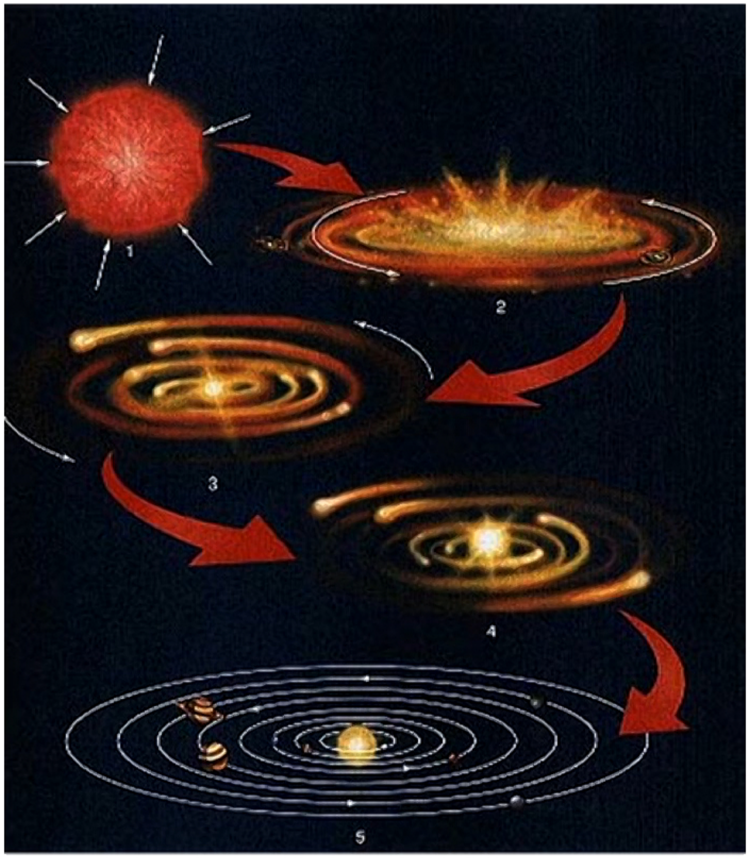

Hot Jupiters
Jupiter size planets with P<10 days
First Detections: Gamma Cep Ab, Campbell et al. 1988
HD 114762b, Latham et al. 1989


3797 confirmed exoplanets
(Sept. 27. 2018 exoplanetarchive)

Architecture of the Solar System

Classical Formation Theories of Planetary Systems

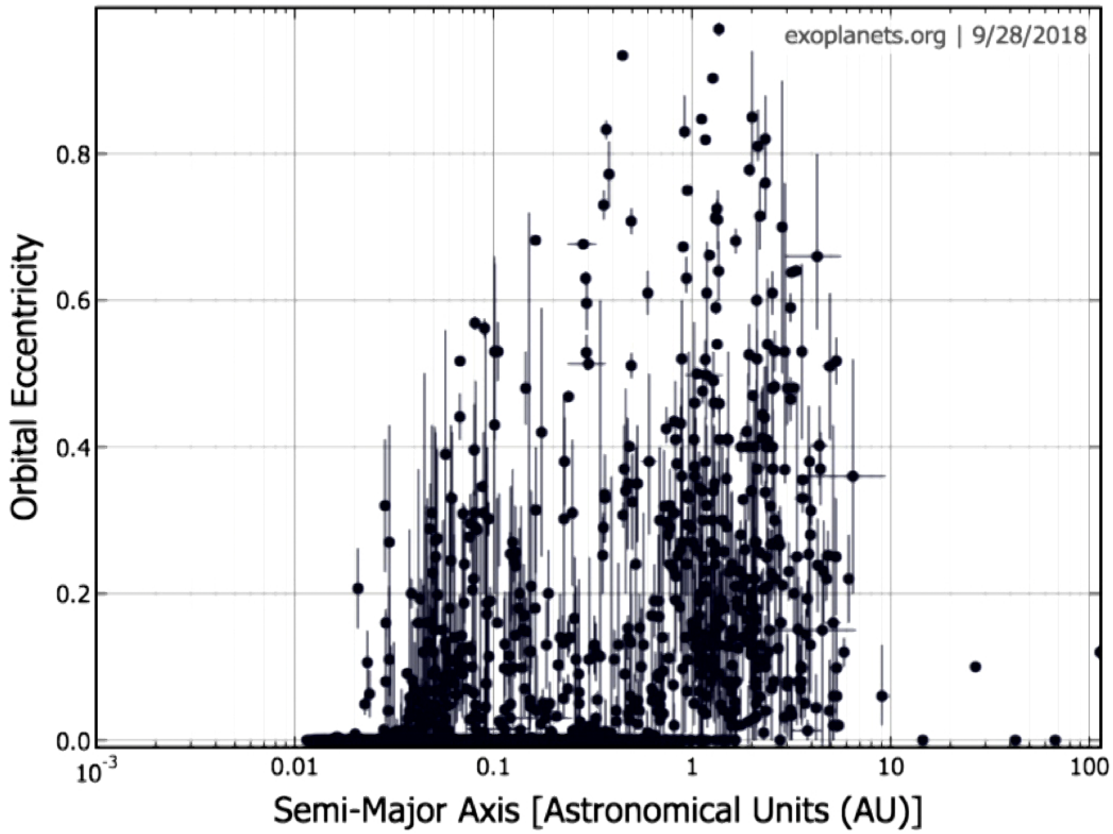


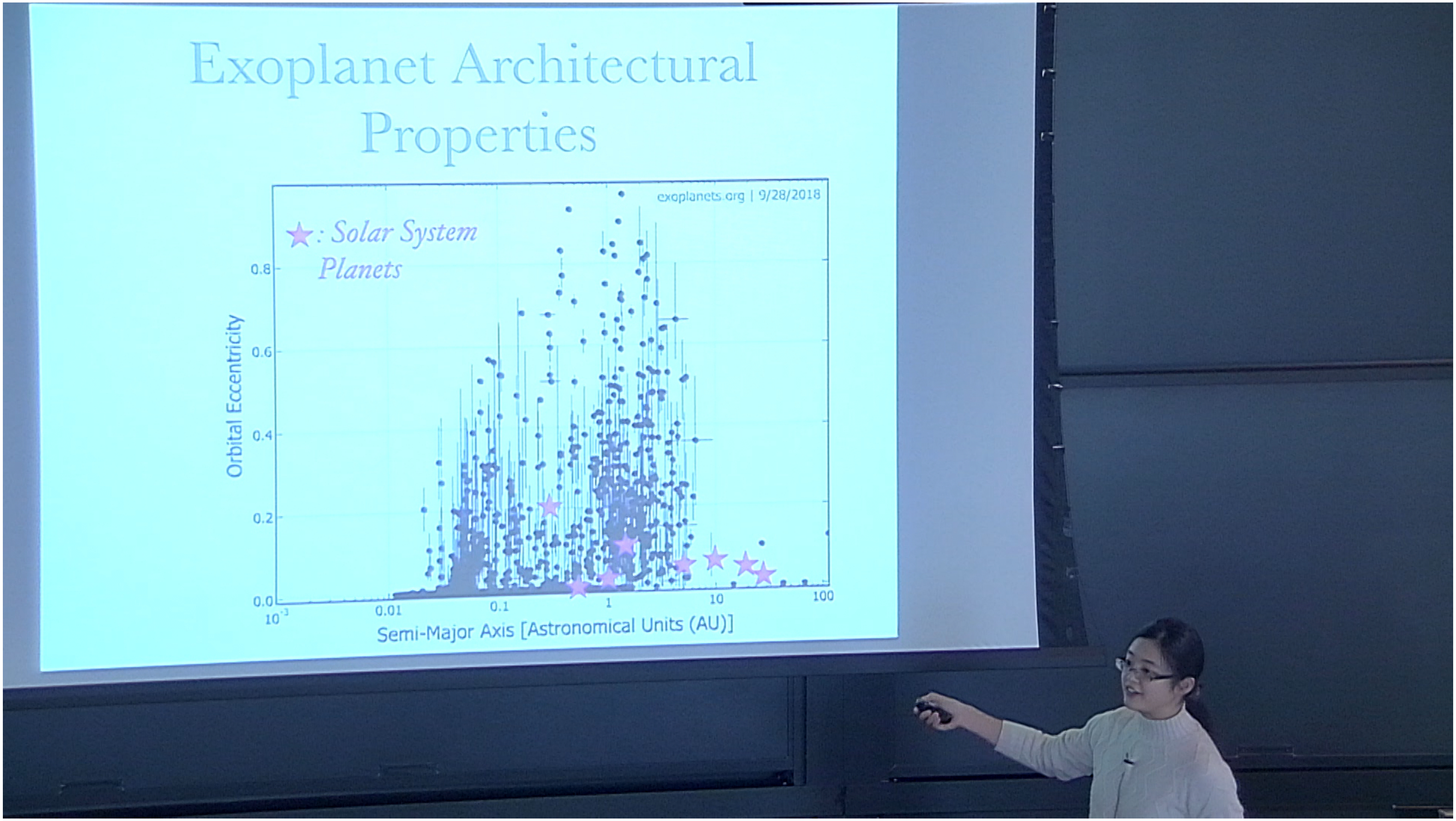
Star and planets form in a molecular cloud

$\Rightarrow$

- circular planetary orbit
- no inclination excitation
- orbital orientation aligned with stellar spin axis.

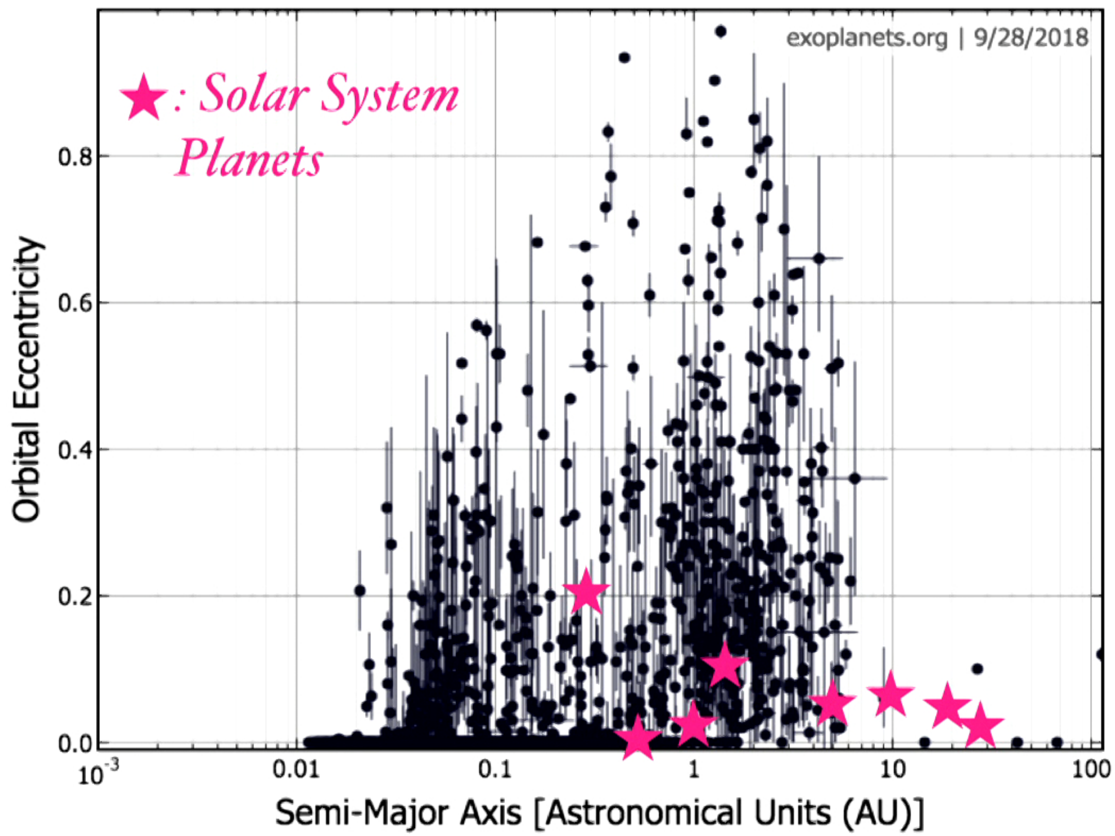
Exoplanet Architectural Properties



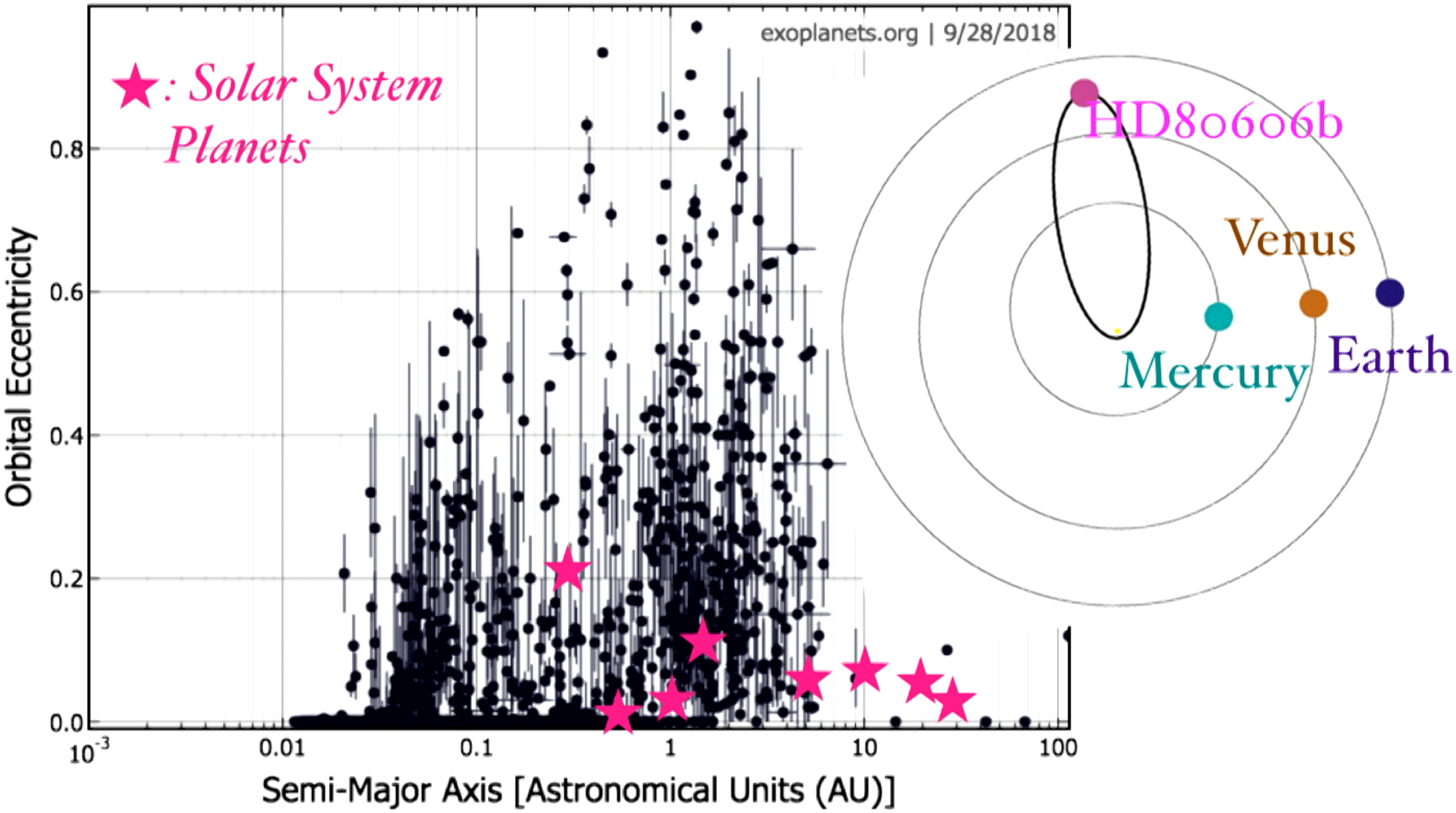


Exoplanet Architectural Properties
exoplanets.org | 9/28/2018
★: Solar System Planets
Orbital Eccentricity
0.0
0.2
0.4
0.6
0.8
10^{-3}
0.01
0.1
1
10
100
Semi-Major Axis [Astronomical Units (AU)]

Exoplanet Architectural Properties



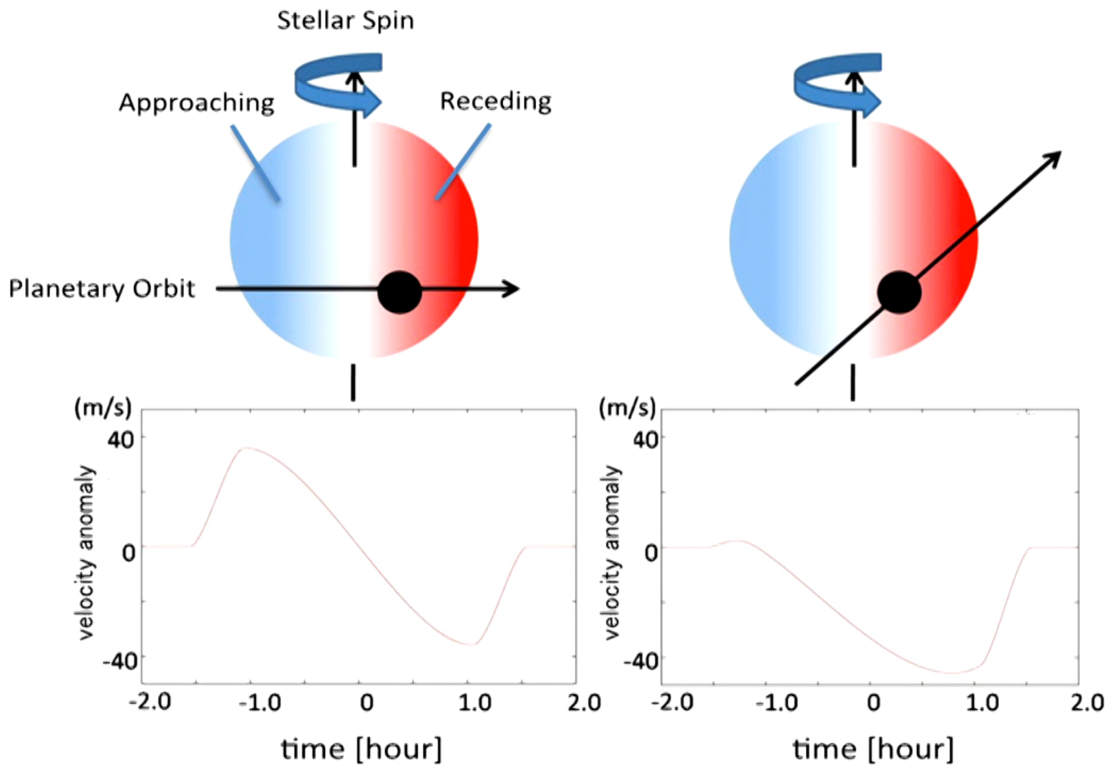
Exoplanet Architectural Properties



Stellar Spin-Planetary Orbit Misalignment

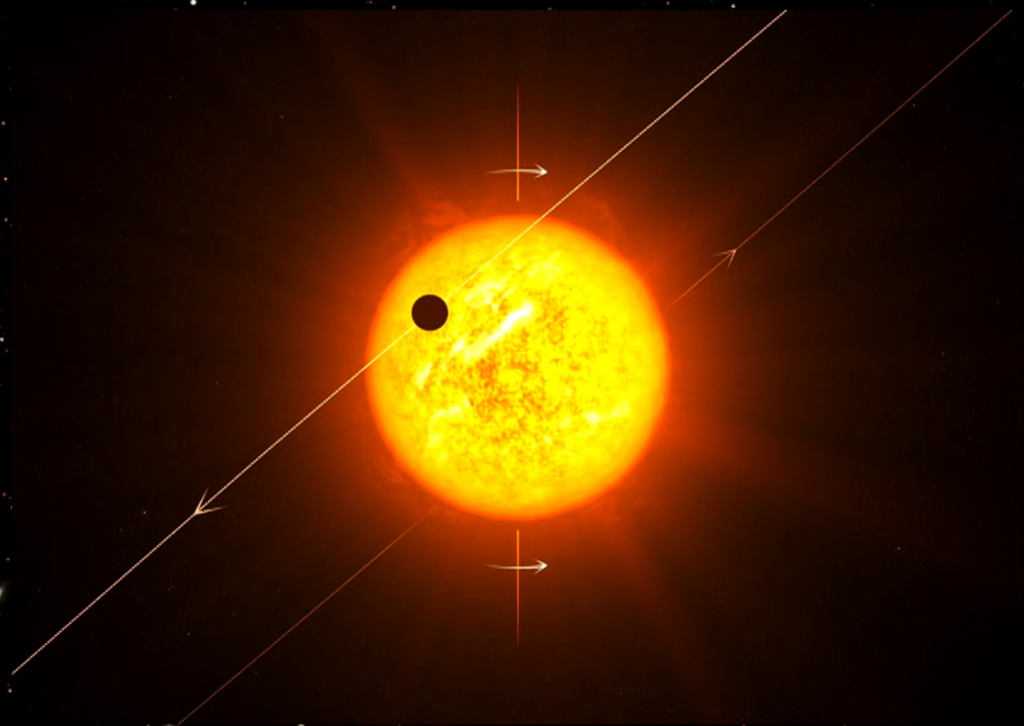
illustration of spin-orbit misalignment

Spin-orbit Misalignment (Rossiter-McLaughlin Method)

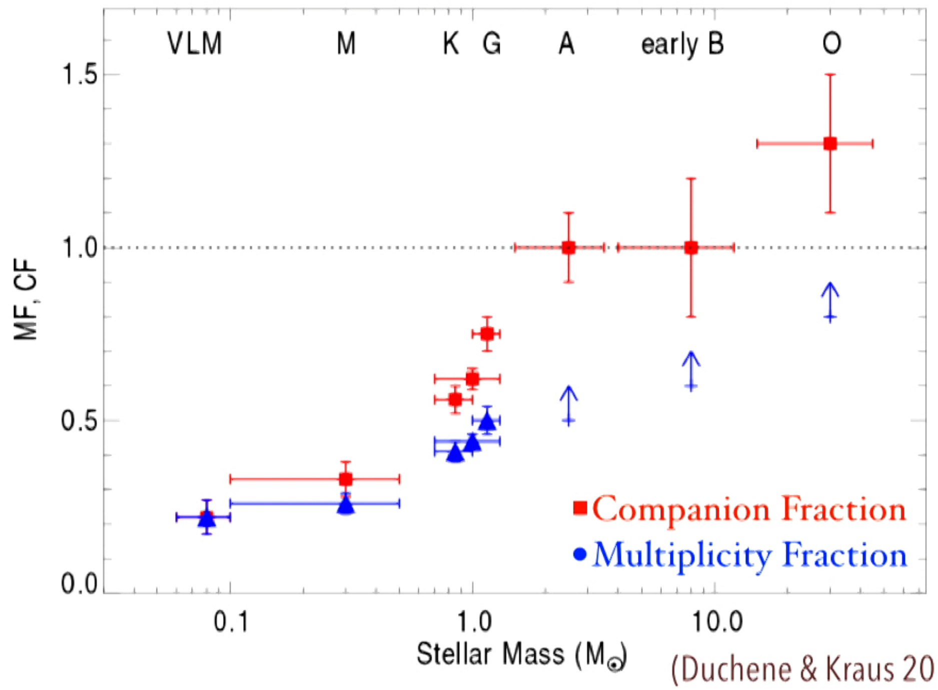


e.g., Ohta et al. 2005, Winn 2006

What leads to the highly misaligned hot Jupiters?



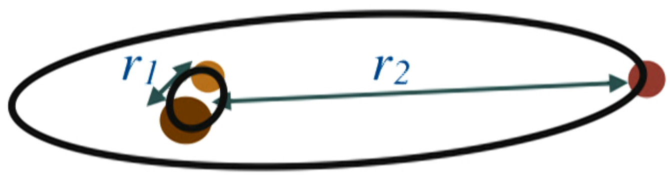
Stellar Multiplicity



(Duchene & Kraus 2013)

~ 30% are binary systems for bright stellar systems
(Eggleton et al. 2007)

Effects of Stellar Binaries



$r_1 \ll r_2$

Hierarchical 3-body System

Secular effects (long term effects):

Eccentricity excitation of inner binary

Inclination variation of inner binary

Lidov-Kozai Mechanism

Lidov-Kozai Mechanism

($e_2 = 0$, test particle limit)

(Kozai 1962, Lidov 1962)

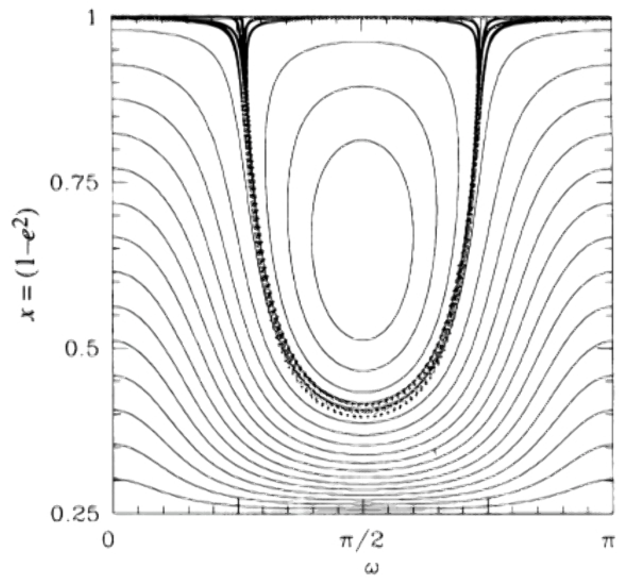
Lidov-Kozai Mechanism

Lidov-Kozai Mechanism

(e_2 = 0, test particle limit)

(Kozai 1962, Lidov 1962)

- $Jz = \sqrt{1-e_1^2}\cos i$ conserved
- i>40°, e_1 and i oscillate with large amplitude.



Holman et al. 1997

Lidov-Kozai Mechanism

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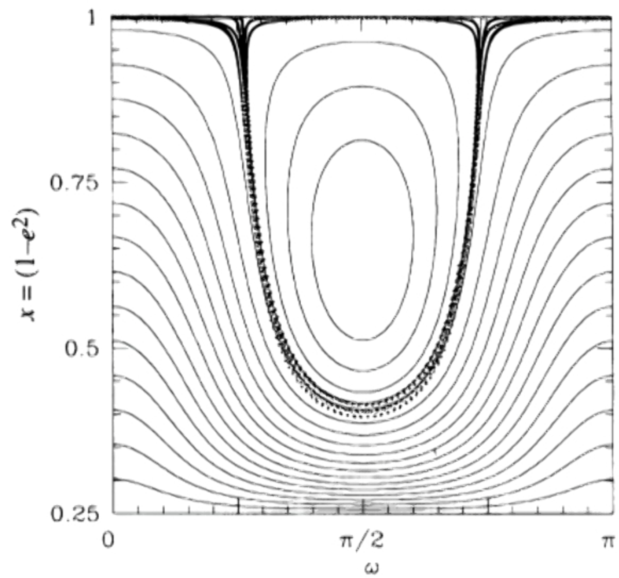

Holman et al. 1997

Eccentric Lidov-Kozai Mechanism

($e_2 \neq 0$) (e.g., Naoz et al. 2011, 2013, Katz et al. 2011)

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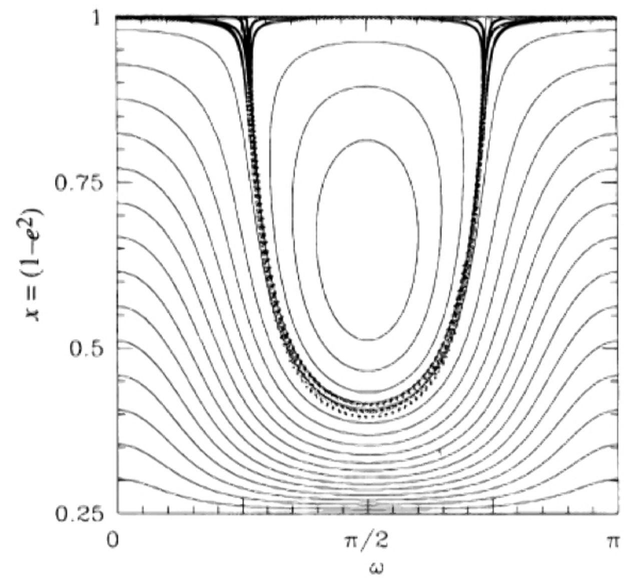

Holman et al. 1997

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- i>40°: i crosses 90°

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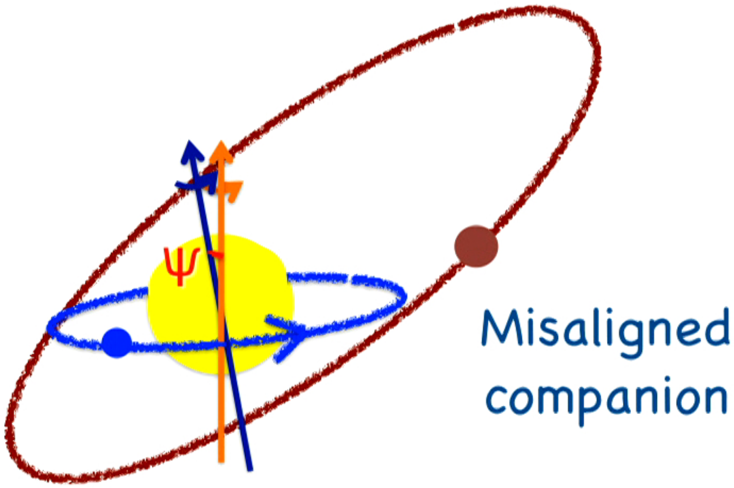

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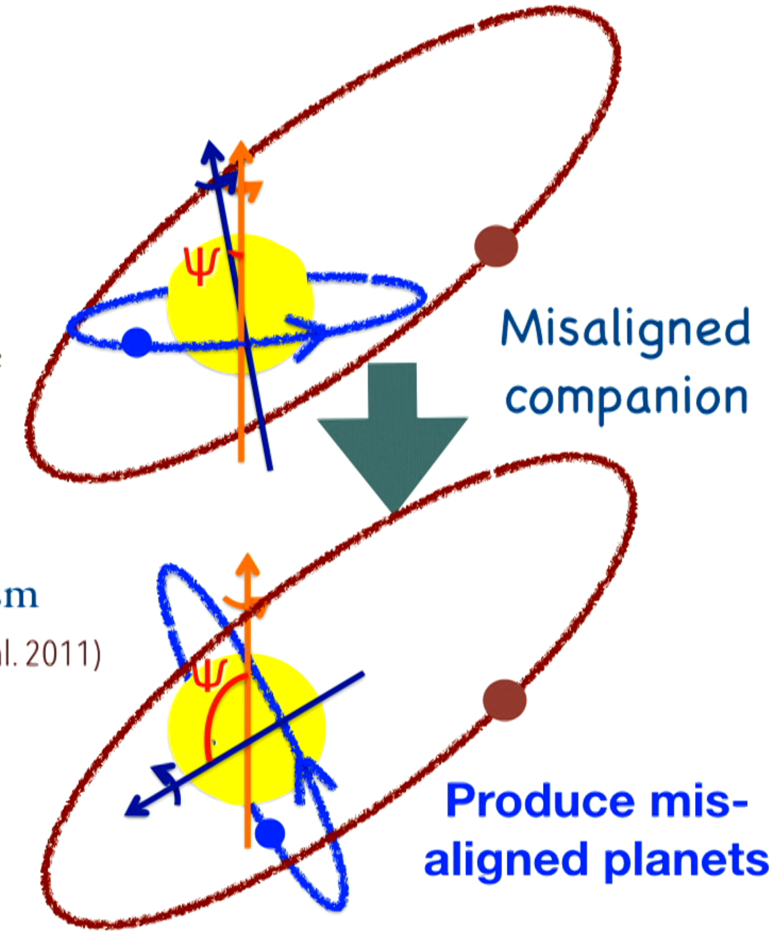

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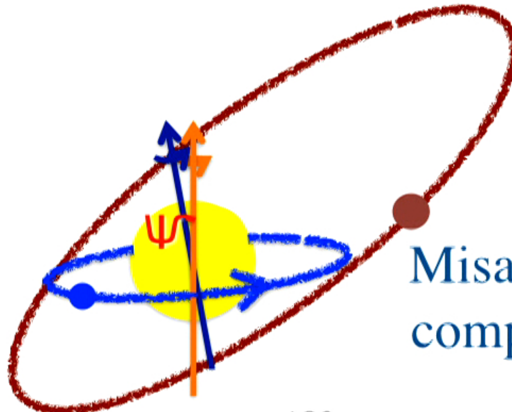

Misaligned companion

Eccentric Lidov-Kozai Mechanism

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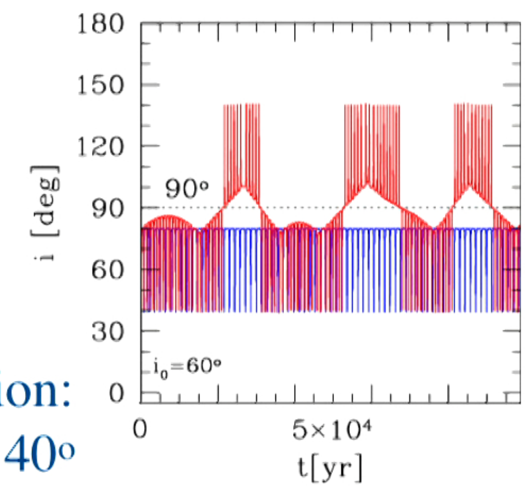
Limitation:
40°<i<140°

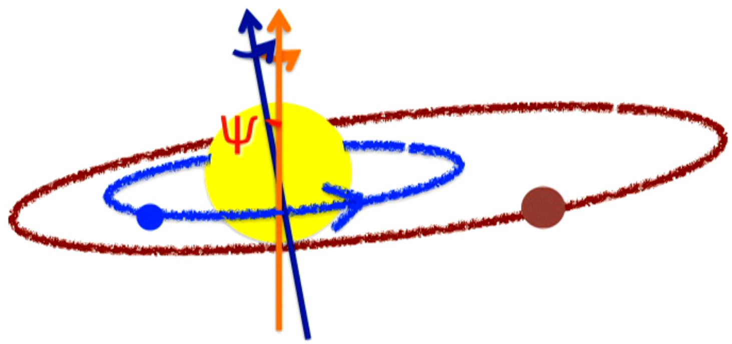


Lidov-Kozai Mechanism

- 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)



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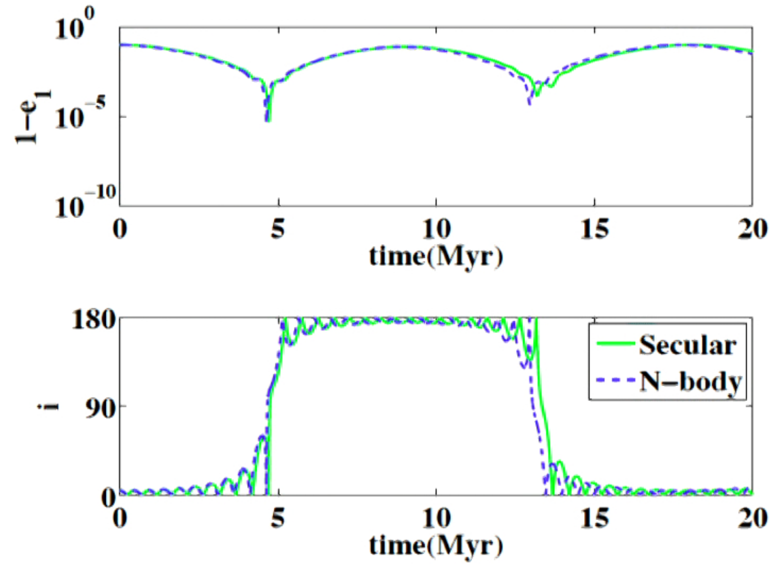

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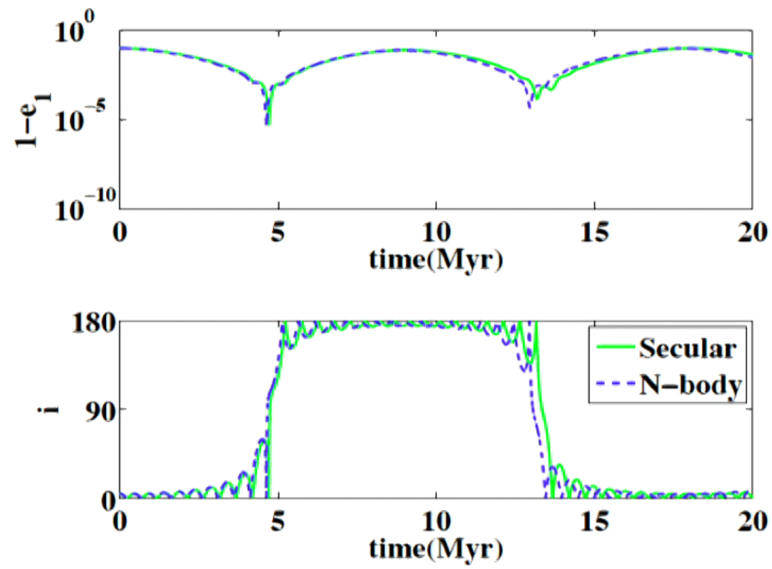
$\Rightarrow r_p = a(1-e_1) \ll a$

help with migration (with tidal dissipation)

⇒ Produces counter orbiting planets



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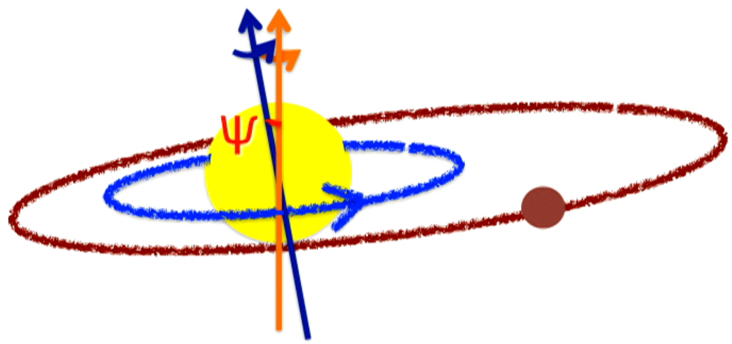

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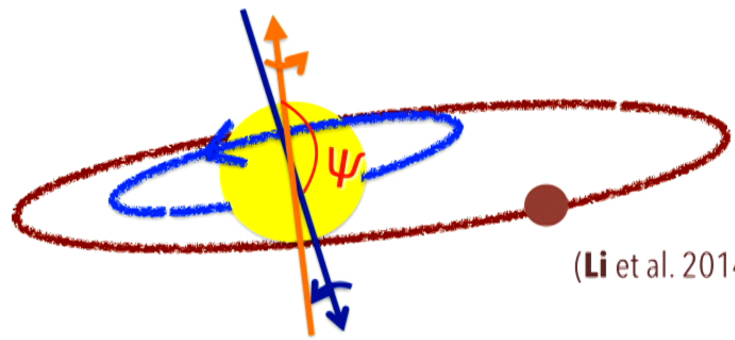

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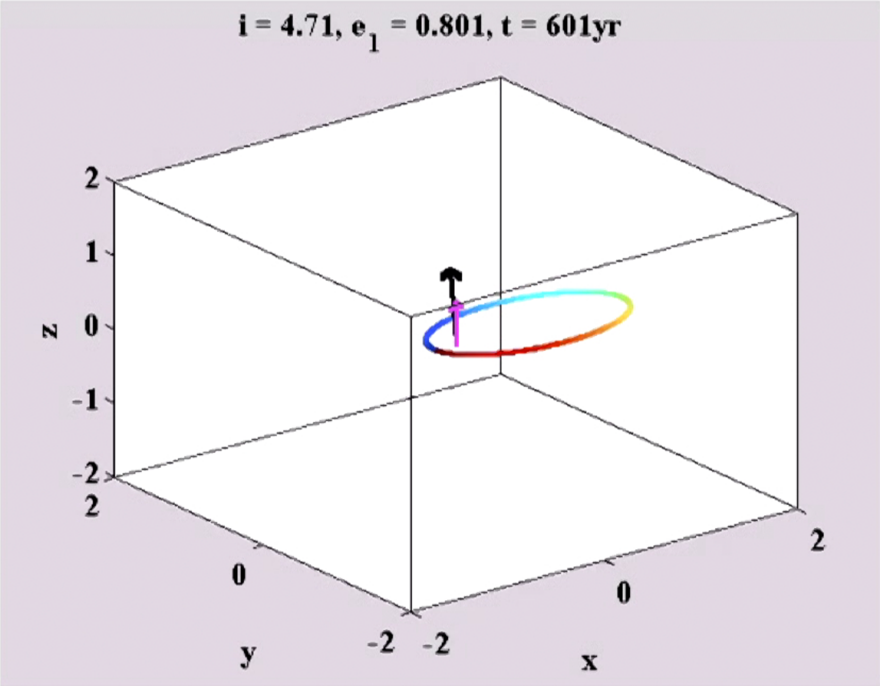
Differences between High/Low i Flip

- Low inclination flip



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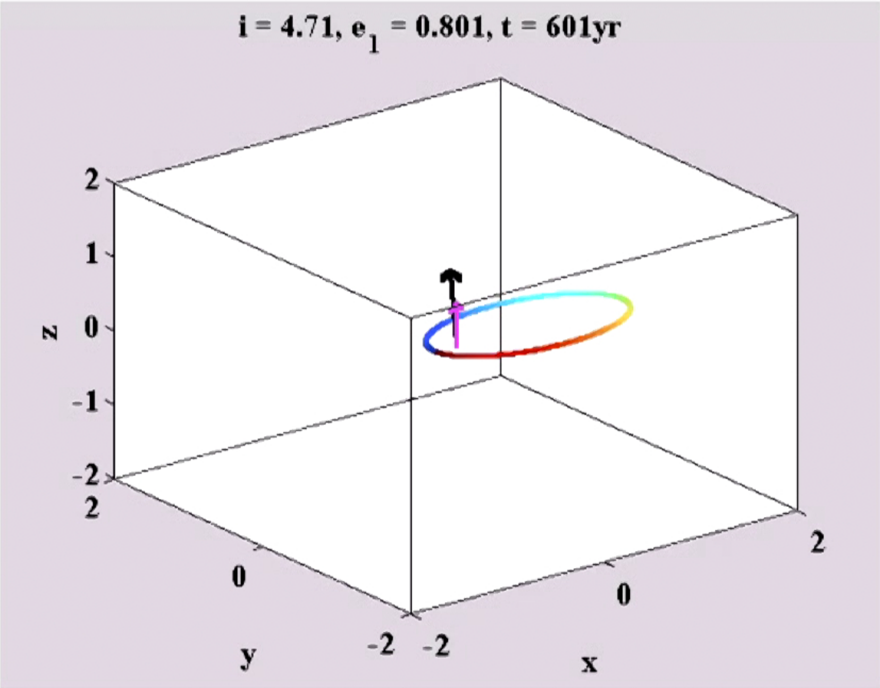

- Inner orbit:
  colored ring
- Outer orbit:
  lie in x-y plane, stationary (test-particle limit)
- ⬆ : direction of $J_{I.}$
- ⬆ : z component

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

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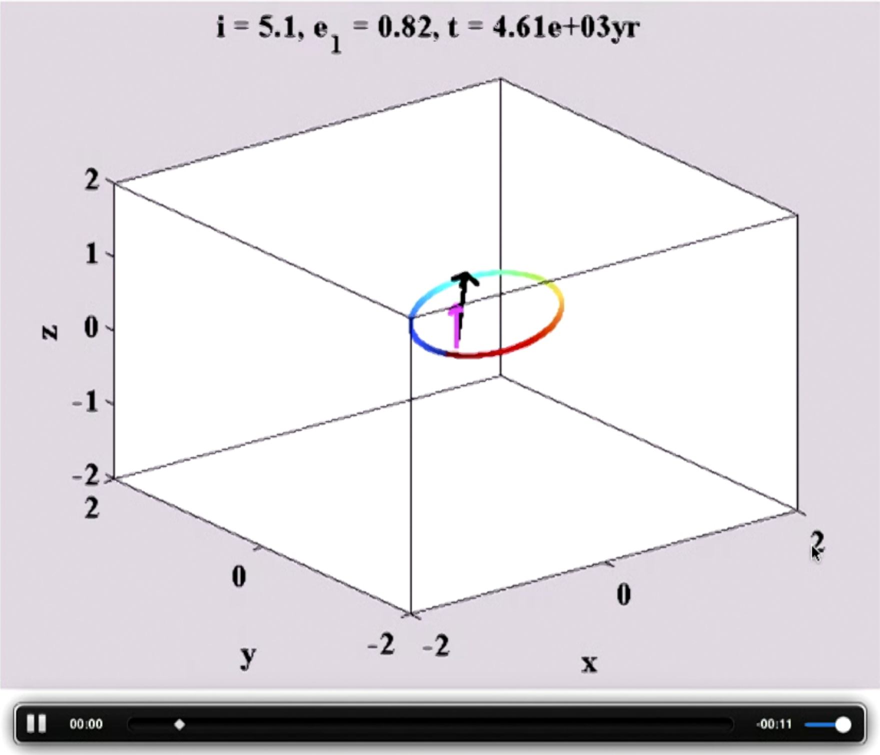

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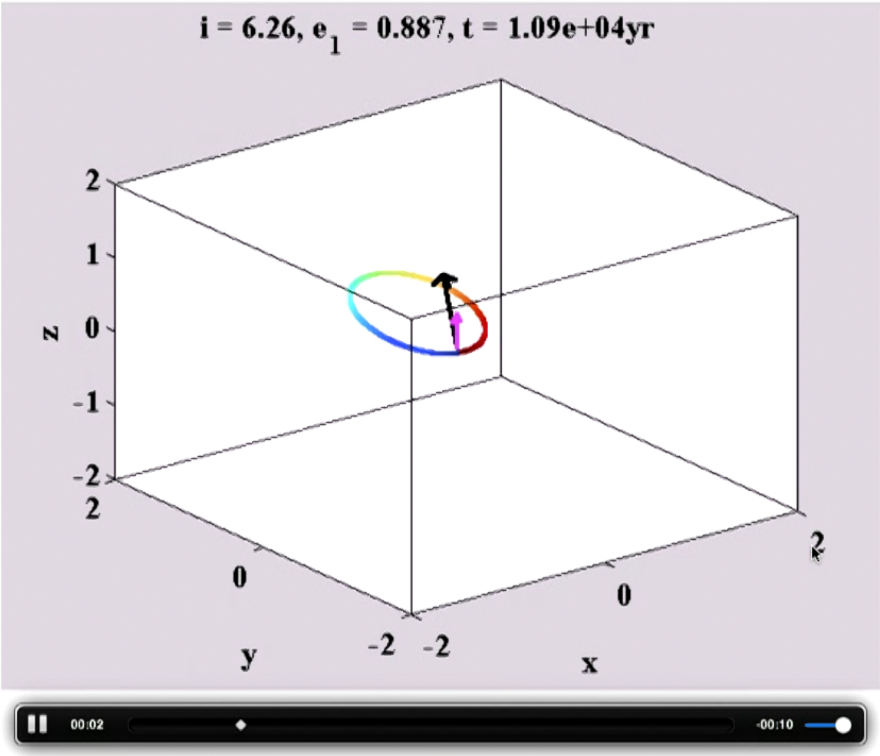

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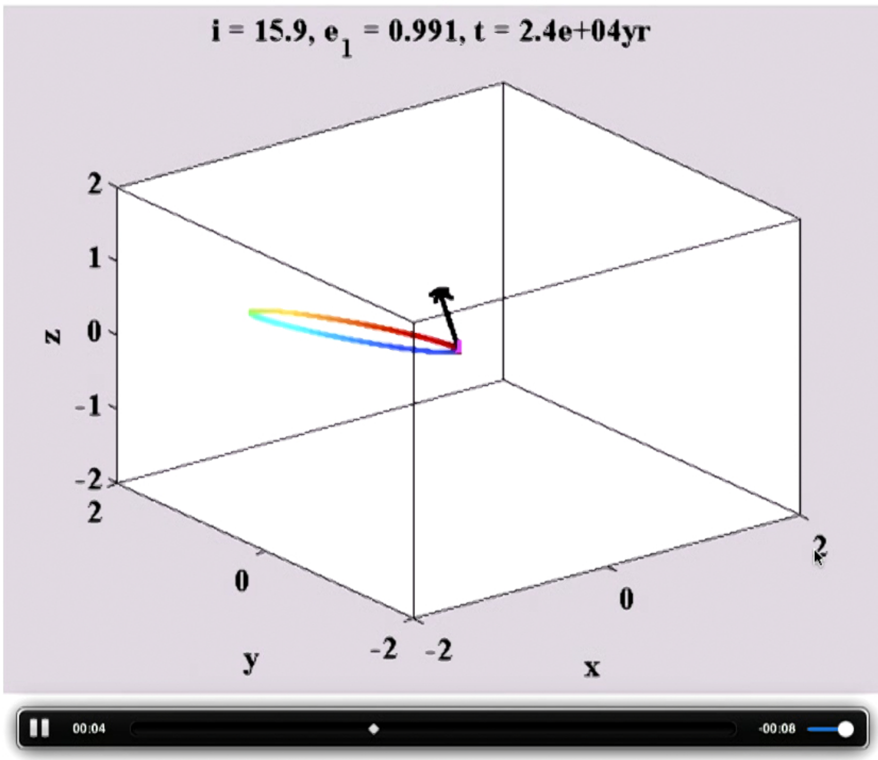

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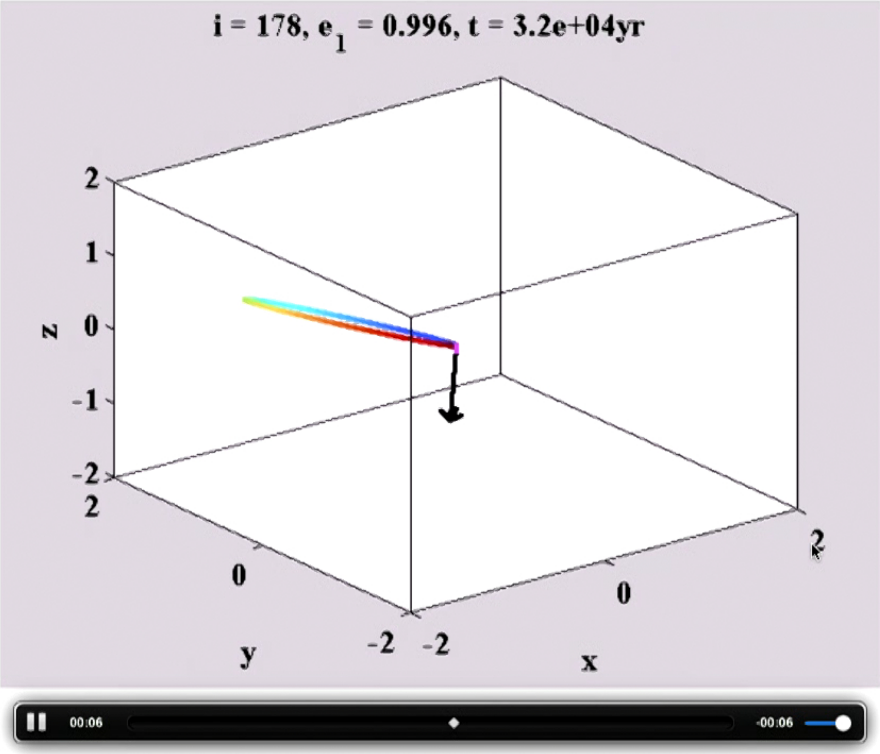

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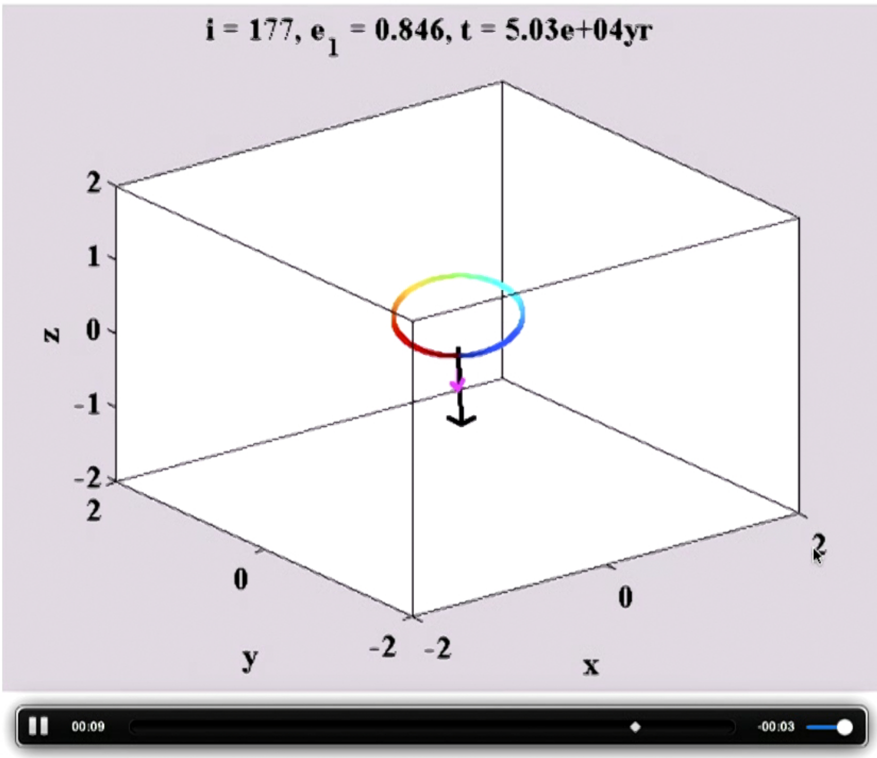

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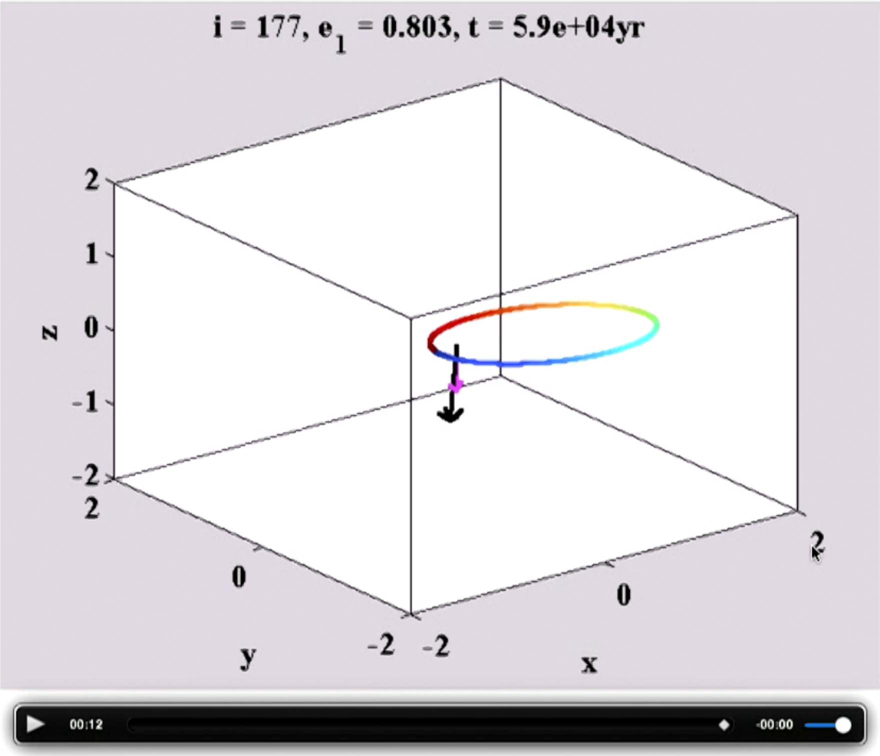

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Differences between High/Low i Flip

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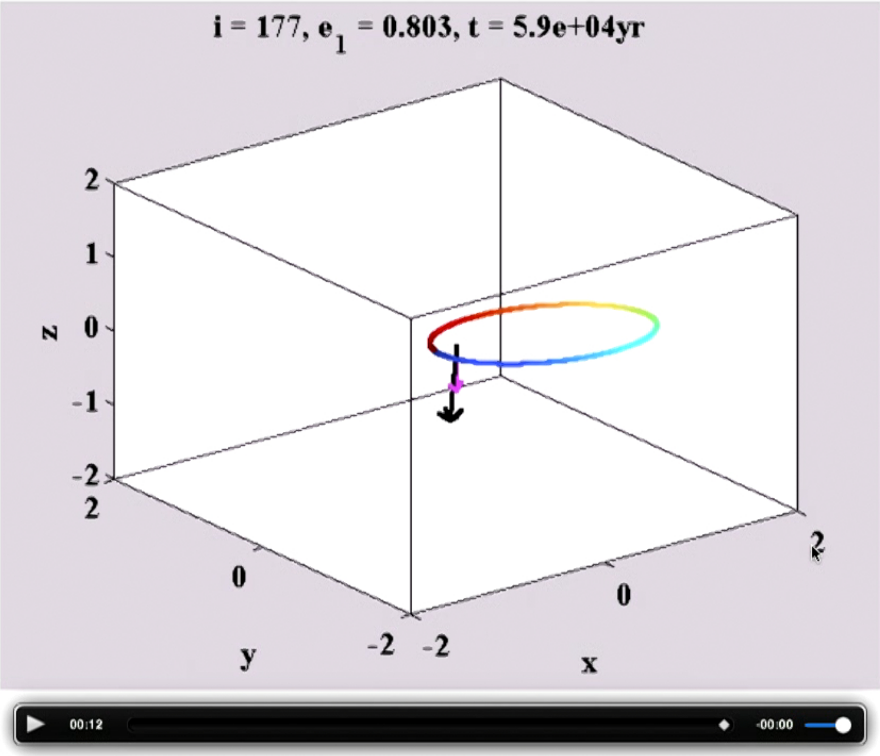

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(**Gongjie Li** et al. 2014a)

Differences between High/Low i Flip

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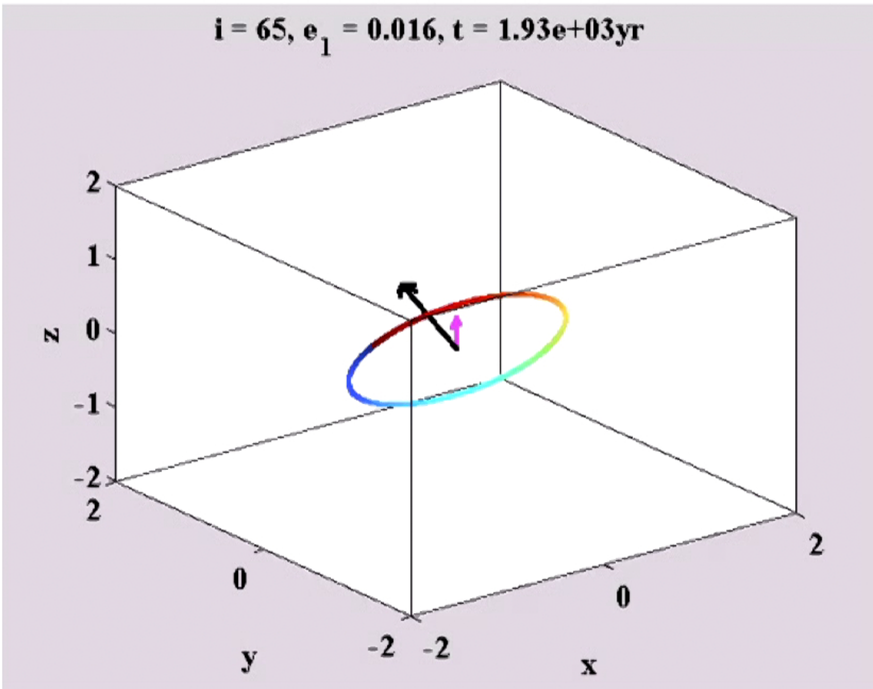

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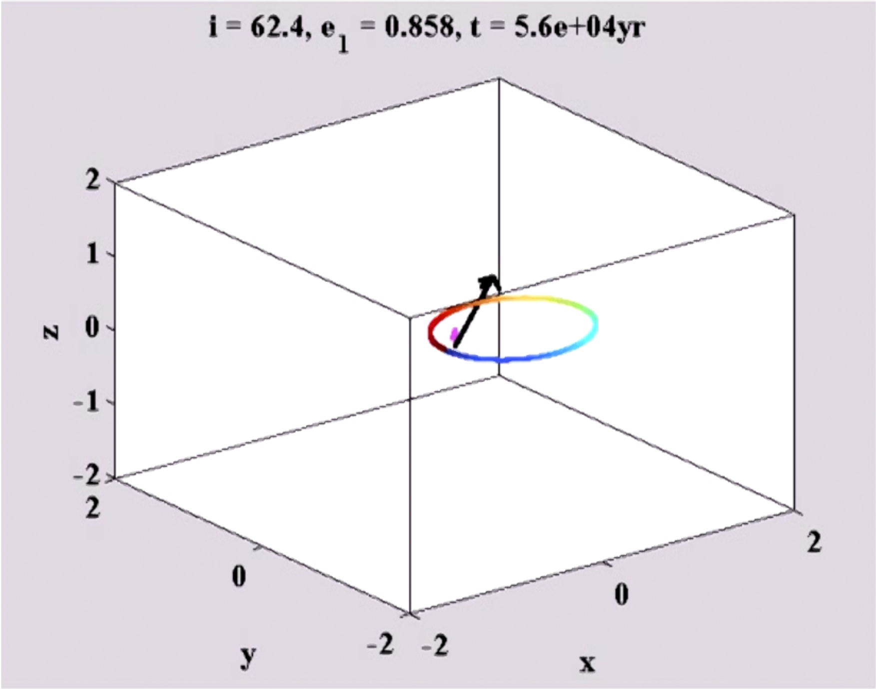

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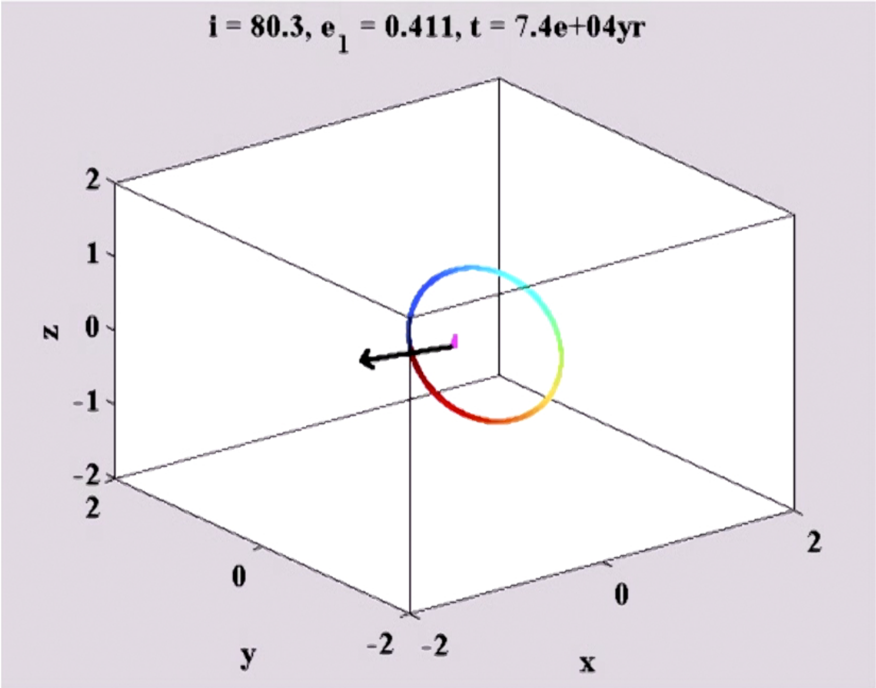

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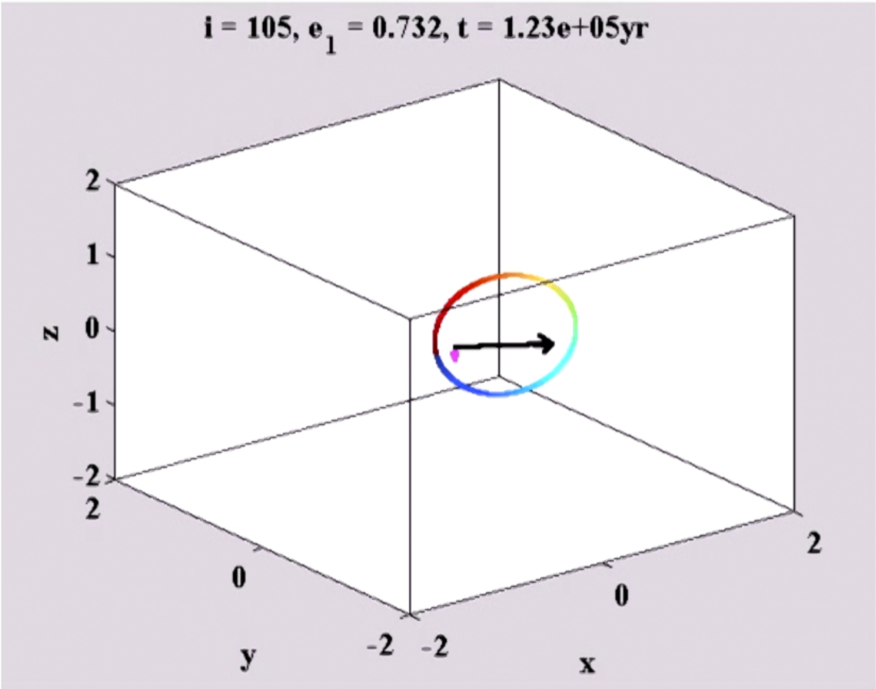

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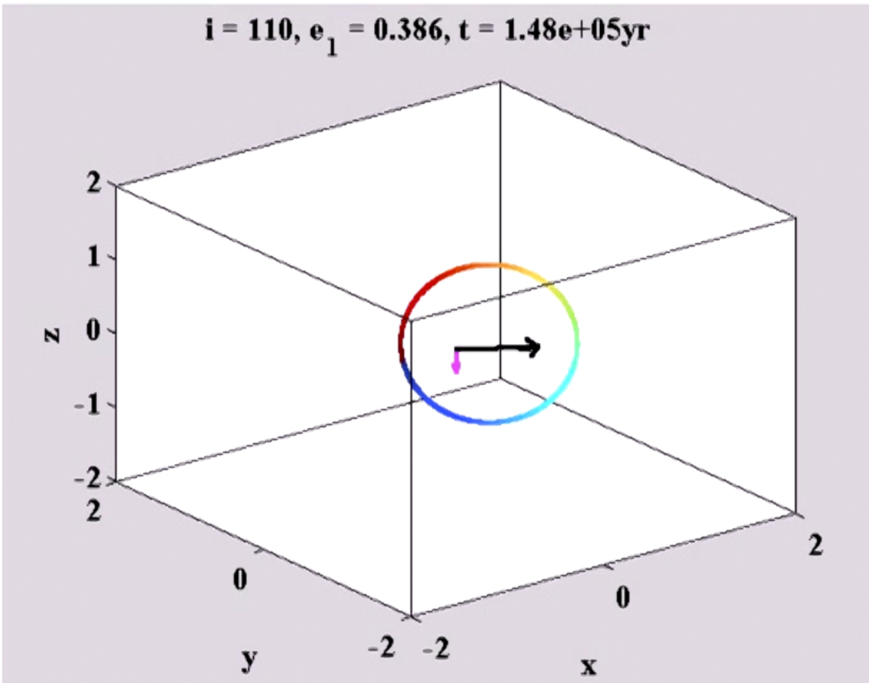

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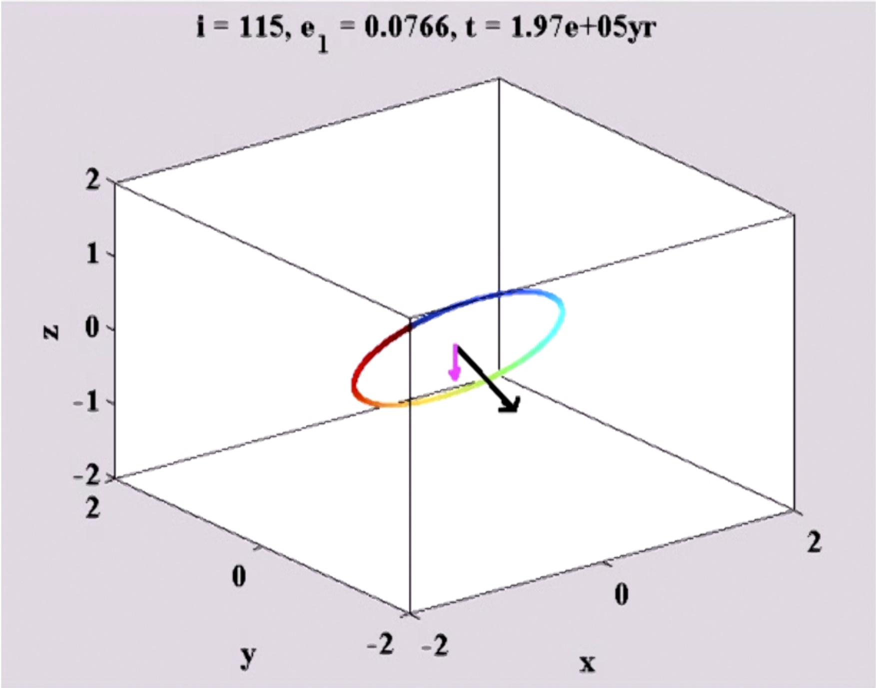

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(**Gongjie Li** et al. 2014a)

Analytical Overview

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

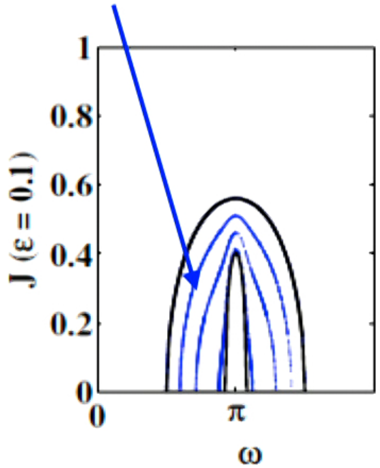
$$
\begin{aligned}
F_{quad} &= -(e_1^2/2) + \theta^2 + 3/2 e_1^2 \theta^2 \\
&\quad + 5/2 e_1^2 (1-\theta^2)\cos(2\omega_1), \\
F_{oct} &= \frac{5}{16}(e_1 + (3e_1^3)/4) \\
&\quad \times ((1 - 11\theta - 5\theta^2 + 15\theta^3)\cos(\omega_1 - \Omega_1) \\
&\quad + (1 + 11\theta - 5\theta^2 - 15\theta^3)\cos(\omega_1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

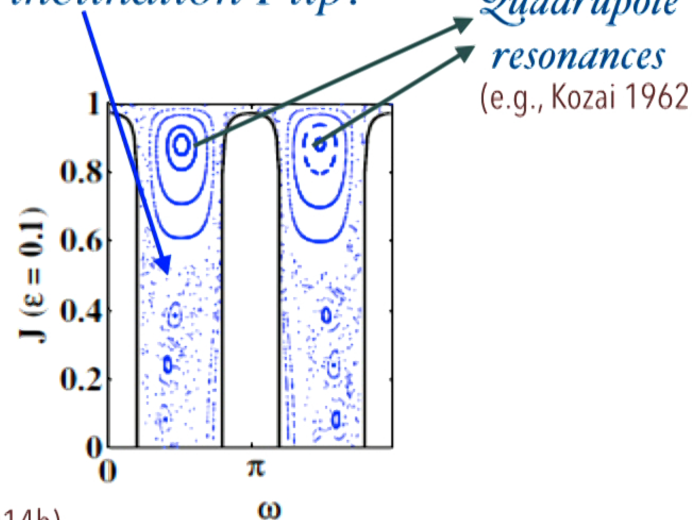
- Independent of Ω_1, J_z const.
- Depend on both ω_1 and Ω_1 ➔ both J and J_z are not const.

Surface of Sections

Coplanar Flip:

High inclination Flip:





(**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~$6t_K$

Analytical Flip criterion

Low inclination approximation (test particle limit):

(**Li** et al. 2014a)

Analytical Flip criterion

Low inclination approximation (test particle limit):

- Hamiltonian can be simplified to 1 d.o.f.
  - ⇒ System is integrable
  - ⇒ *e(t)* depends on octupole terms only
  - ⇒ The flip timescale, and criterion can be derived.

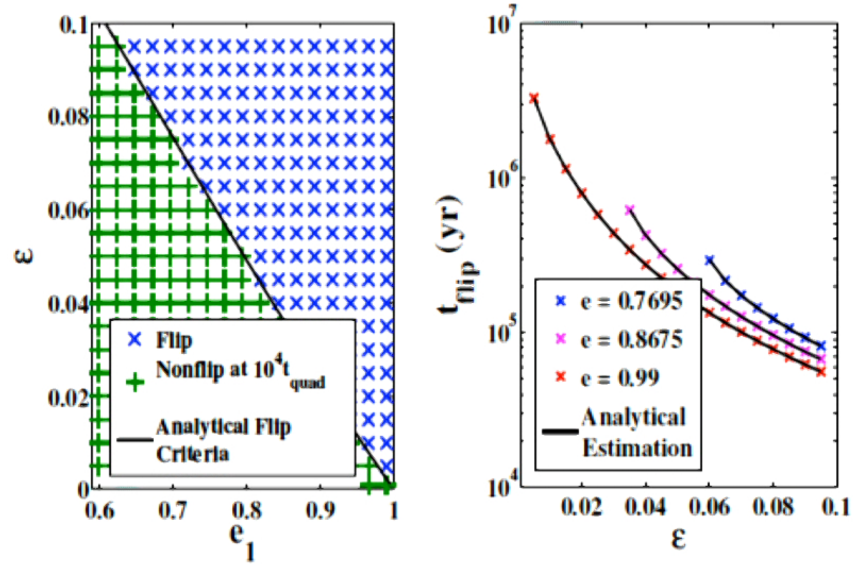
Flip Criterion:

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

(**Li** et al. 2014a)

$$\varepsilon = \frac{a_1}{a_2}\frac{e_2}{1-e_2^2}$$

Analytical vs. Numerical Results

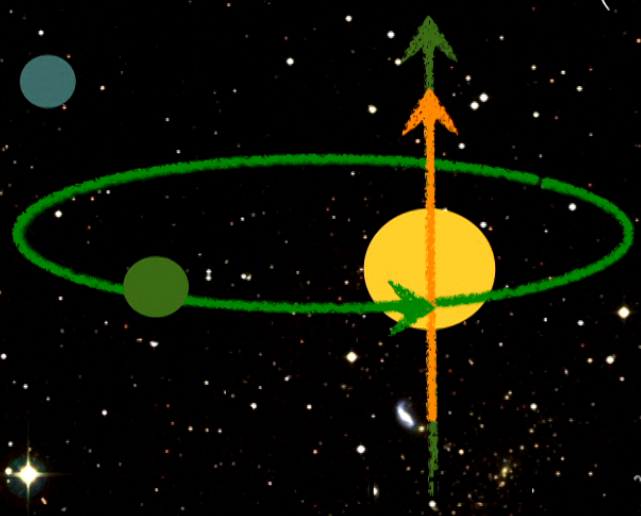


IC: i=5°.

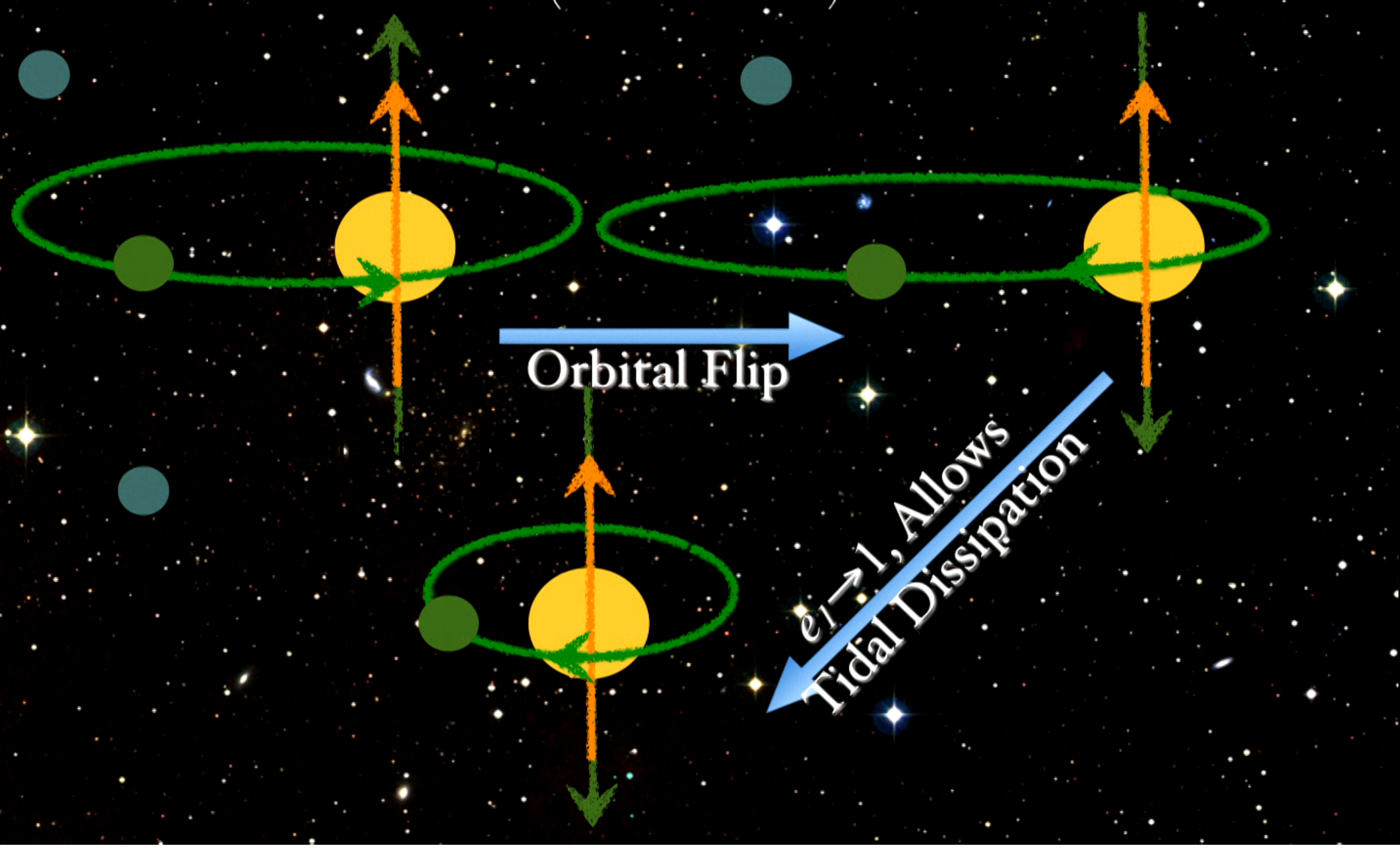
(**Li** et al. 2014a)

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

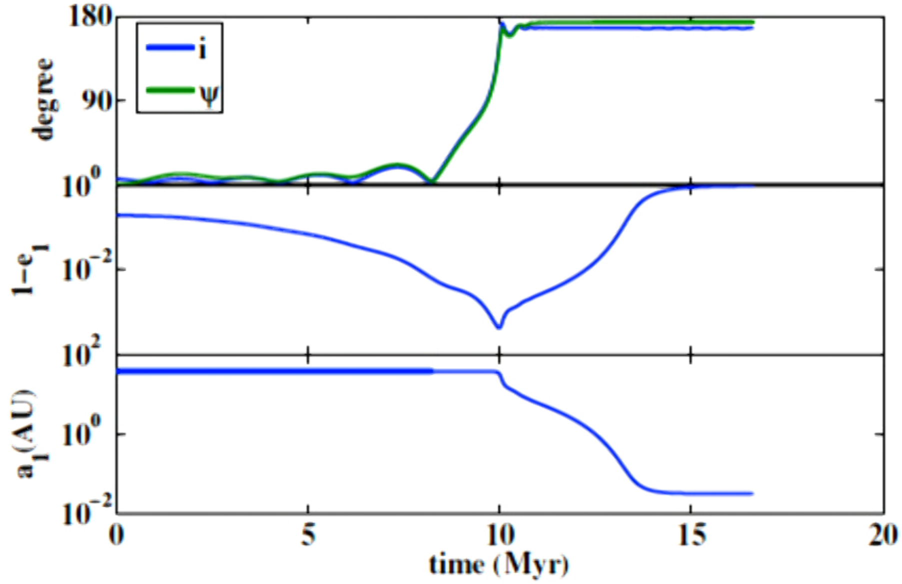
Formation of Misaligned Close-in Planets
(KL + tide)



Formation of Misaligned Close-in Planets
(KL + tide)



Formation of Counter Orbiting Close-in Planets (LK + tide)



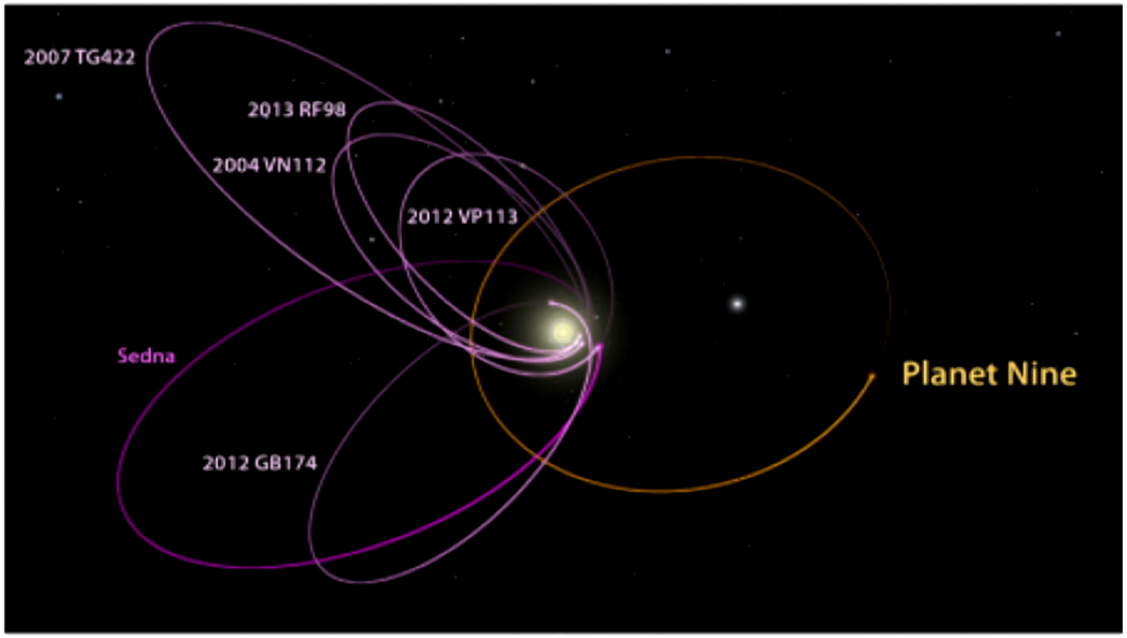
$e_1 \rightarrow 1$ during the flip

$\Rightarrow$ $r_p\downarrow$, tide dominates.

(**Li** et al. 2014a)


Cold Planet: Planet Nine in
Our Own Solar System

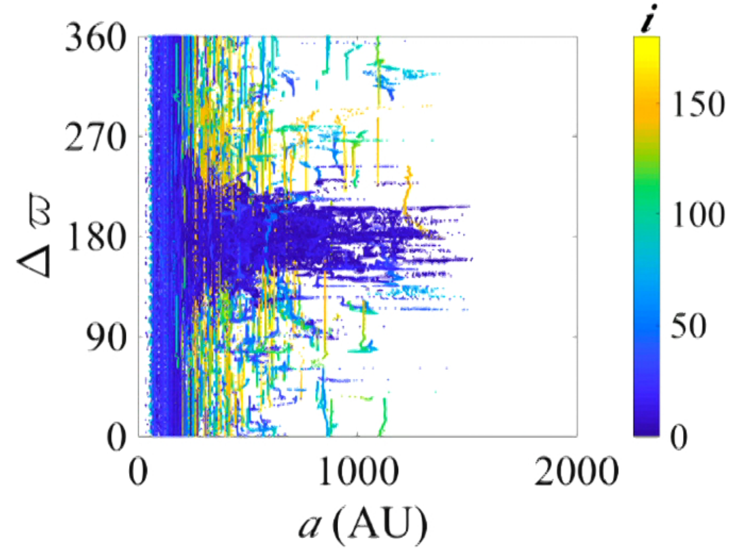
eTNO Orbital Clustering



Clustering of the eTNOs indicates possibilities of an outer planet
(*Trujillo & Sheppard 2014, Batygin & Brown 2016*)

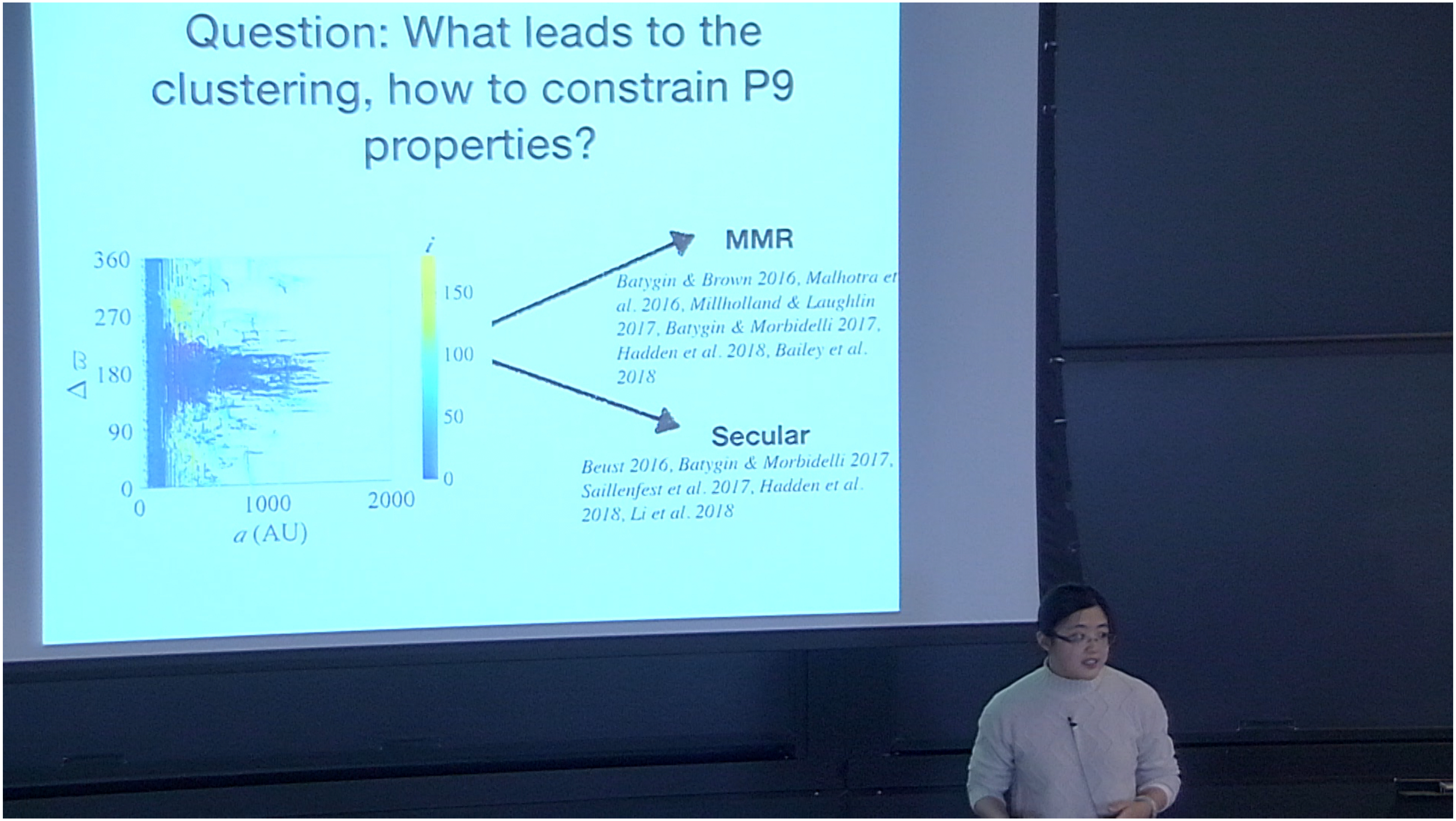
Clustering in Near Coplanar Configuration

Set up:
M9: $10M_\oplus$, $e_9 = 0.6$, $a_9 = 500$ AU near the ecliptic plane ($i_9 \sim 3^o$),
TNOs: $150<a<500$ AU, $30<rp<50$ AU
Neptune + J2 potential from inner three giant planets



After 3Gyr, $\Delta\varpi \sim 180^o$, low inclination TNOs anti-aligned with P9 pericenter (e.g., *Brown & Batygin 2016, Lawler et al.2017; Shankman et al. 2017, Hadden et al. 2018*).

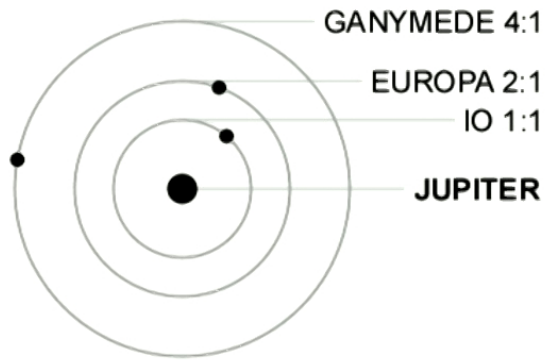
Question: What leads to the clustering, how to constrain P9 properties?



Question: What leads to the clustering, how to constrain P9 properties?
360
270
180
90
0
Δϖ
0
1000
2000
a (AU)
i
150
100
50
0
MMR
Batygin & Brown 2016, Malhotra et al. 2016, Millholland & Laughlin 2017, Batygin & Morbidelli 2017, Hadden et al. 2018, Bailey et al. 2018
Secular
Beust 2016, Batygin & Morbidelli 2017, Saillenfest et al. 2017, Hadden et al. 2018, Li et al. 2018

MMRs

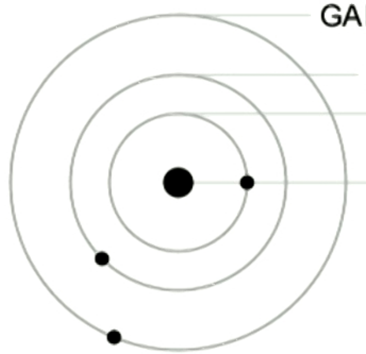
Orbital periods are related by a ratio of small integer ratio



Example: Laplace resonance by three of Jupiter's Galilean moons.

MMRs

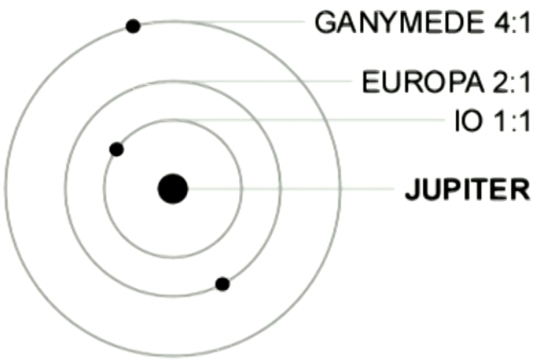
Orbital periods are related by a ratio of small integer ratio



Example: Laplace resonance by three of Jupiter's Galilean moons.

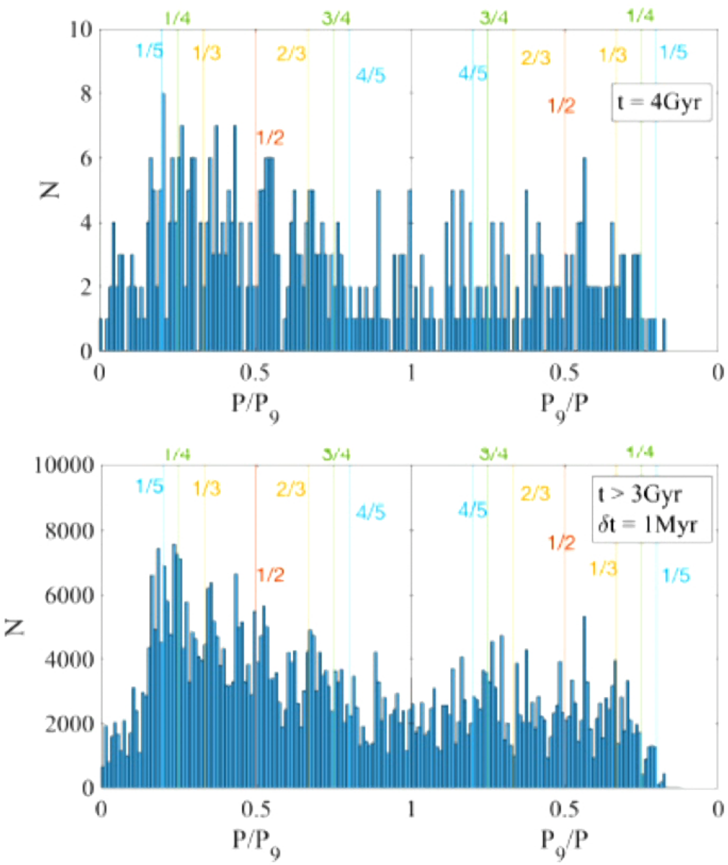
MMRs

Orbital periods are related by a ratio of small integer ratio



Example: Laplace resonance by three of Jupiter's Galilean moons.

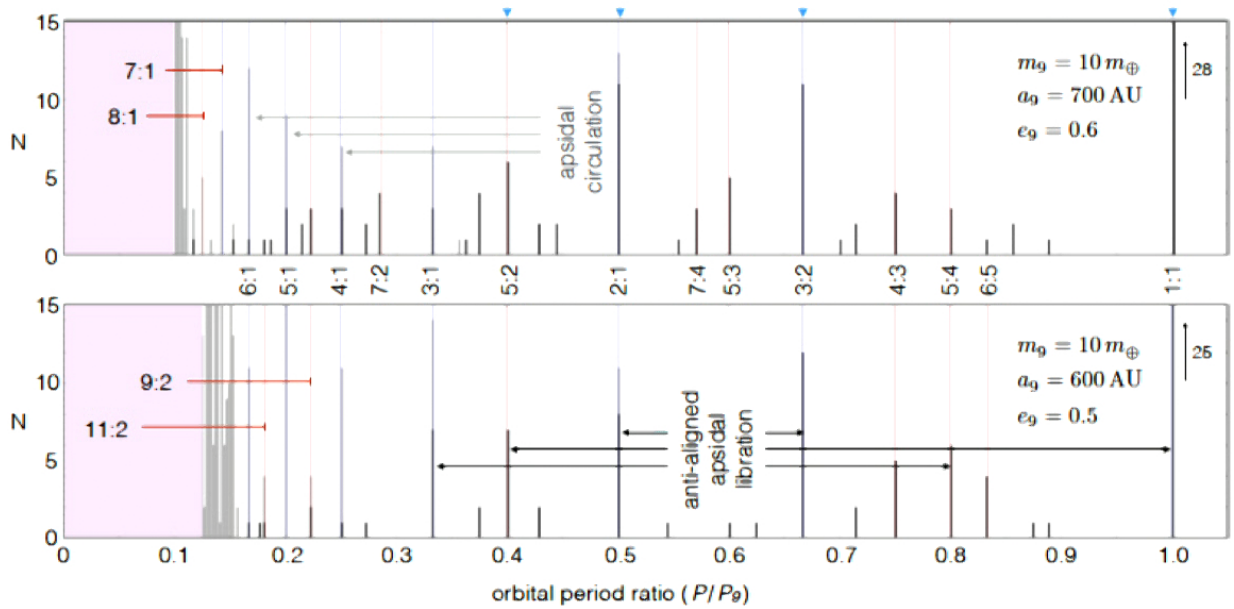
Near coplanar Case: MMR



- With i_9 ~ 3° and Neptune as a massive particle, many TNOs can survive outside MMR
- More than ~80% of the survived TNOs stay outside of MMR for more than 80-90% of time.

Li et al. 2018

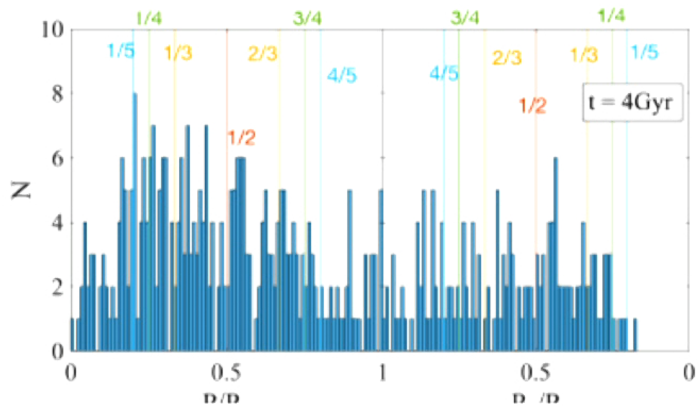
Coplanar Case: MMR



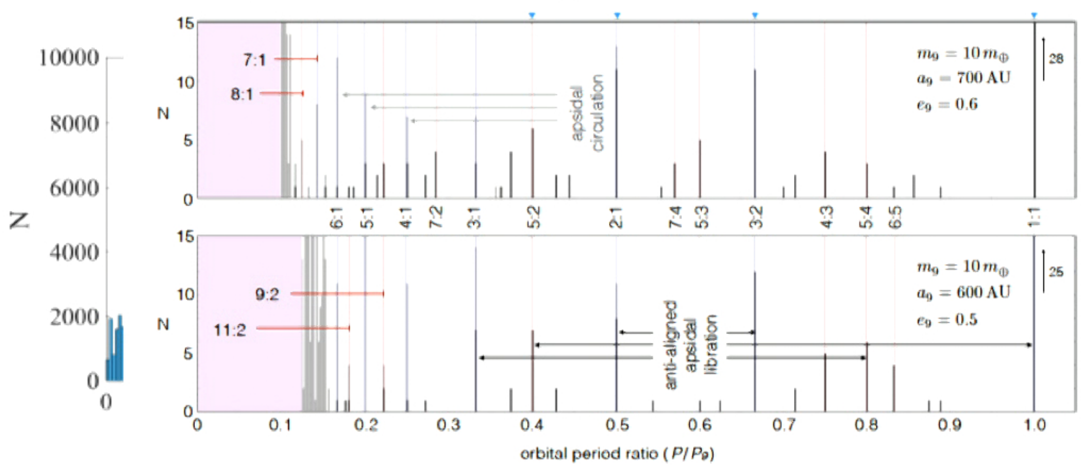
Survived TNOs are mostly in commensurability with P9, dominated by MMR

Batygin & Morbidelli 2017

Near coplanar Case: MMR

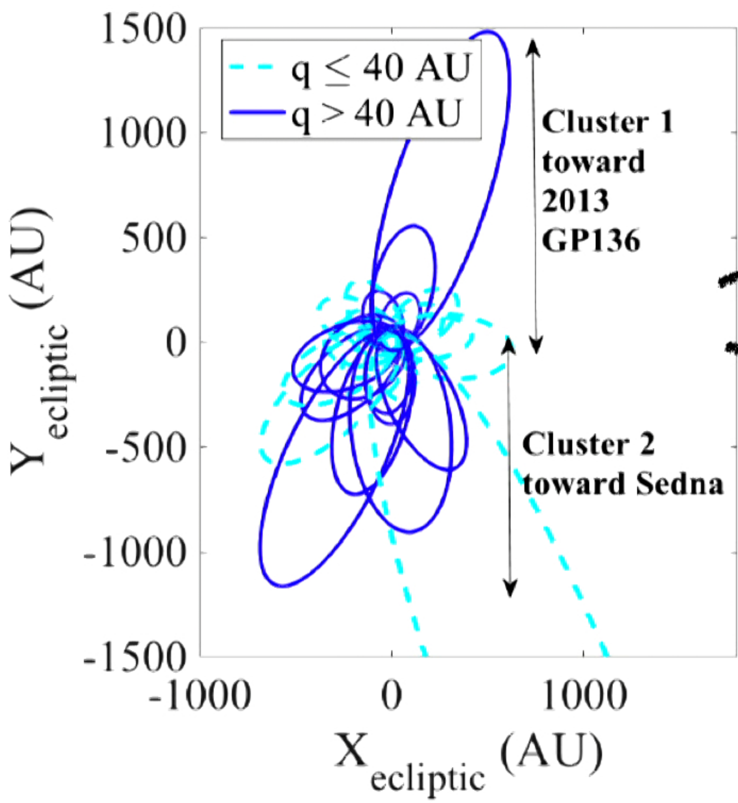


- With $i_9 \sim 3^o$ and Neptune as a massive particle, many TNOs can survive outside MMR



Different from the coplanar case in Batygin & Morbidelli 2017.

Question: What leads to the clustering?



MMR

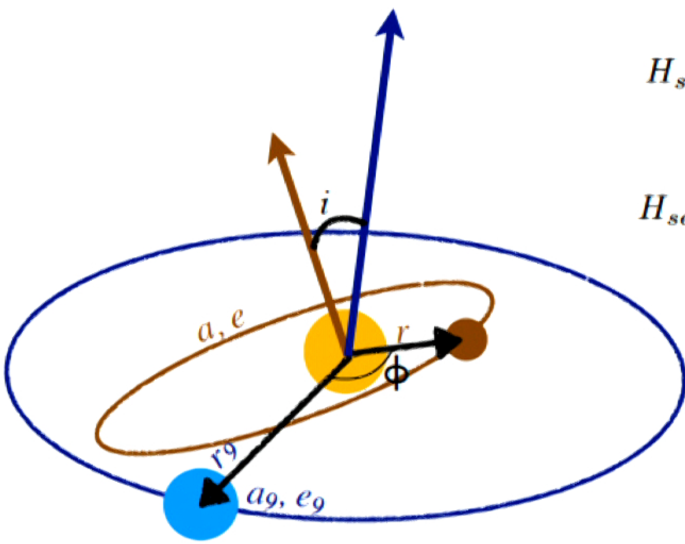
Batygin & Brown 2016, Malhotra et al. 2016, Millholland & Laughlin 2017, Batygin & Morbidelli 2017, Hadden et al. 2018, Bailey et al. 2018

Secular

Beust 2016, Batygin & Morbidelli 2017, Saillenfest et al. 2017, Hadden et al. 2018, Li et al. 2018

Secular Dynamics between TNOs and Planet Nine

Without expansion in a_1/a_2



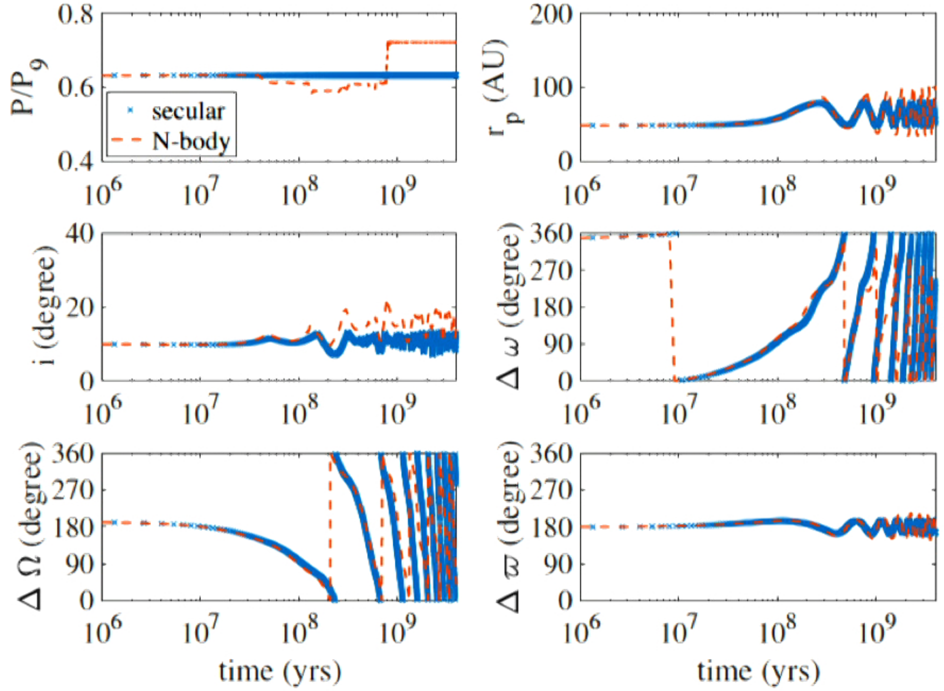
$$H_{sec,0} = -\frac{Gm_9}{4\pi^2}\int_0^{2\pi}\int_0^{2\pi}\left(\frac{1}{|\vec{r}-\vec{r_9}|}-\frac{\vec{r}\cdot\vec{r_9}}{r_9^3}\right) dl\, dl_9$$

$$H_{sec,1} = H_{sec,0} - \frac{1}{8}\frac{GM}{a}\frac{(3\cos^2 i - 1)}{(1-e^2)^{3/2}}\sum_{i=1}^{4}\left(\frac{m_{pi}a_{pi}^2}{Ma^2}\right)$$

J_2 potential from inner four giant planets

Secular Interactions

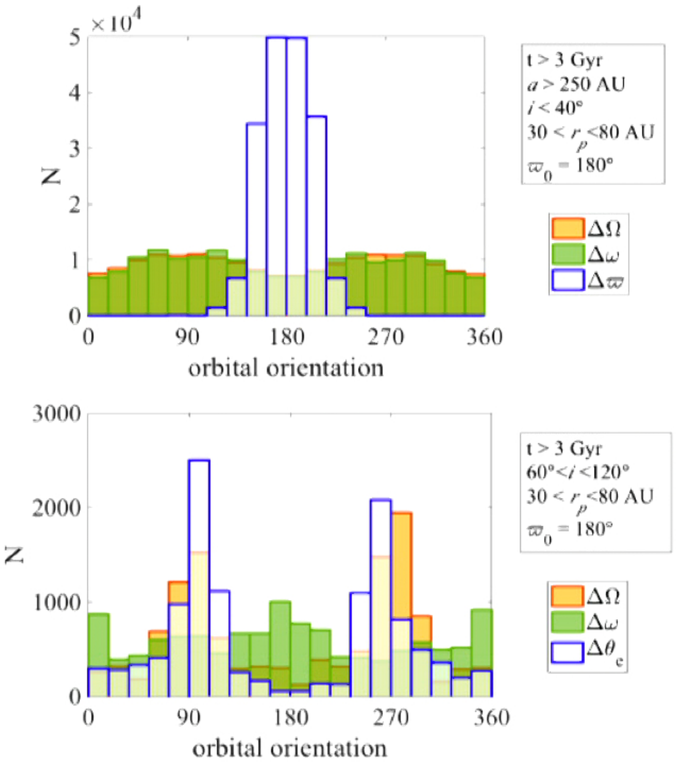
Slightly Inclined Case:



- Secular integrations can reproduce basic dynamical features of N-body results, e.g., the libration of $\Delta\varpi \sim 180^o$

Li et al. 2018

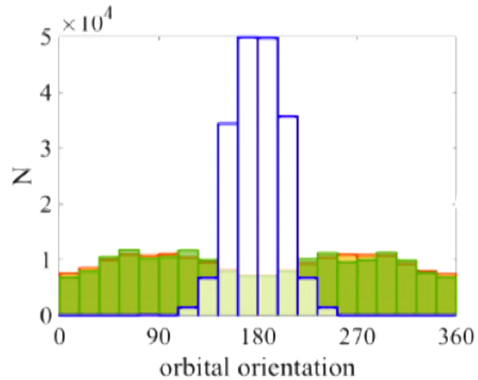
Secular Interactions



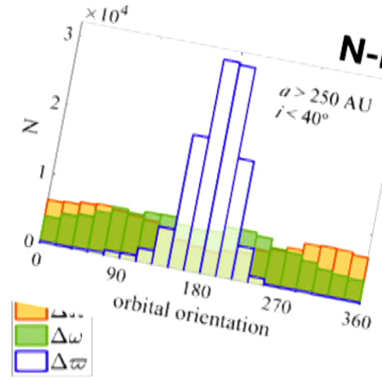
- Starting with $\Delta\varpi_0$~180°, secular interactions can produce similar clustering to the N-body results

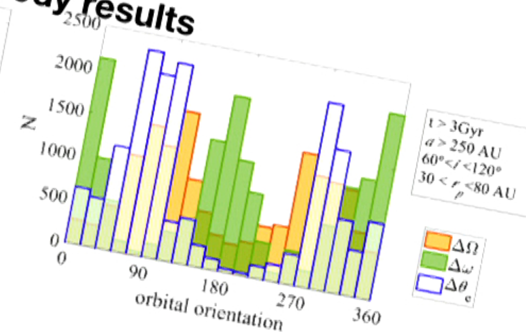
Li et al. 2018

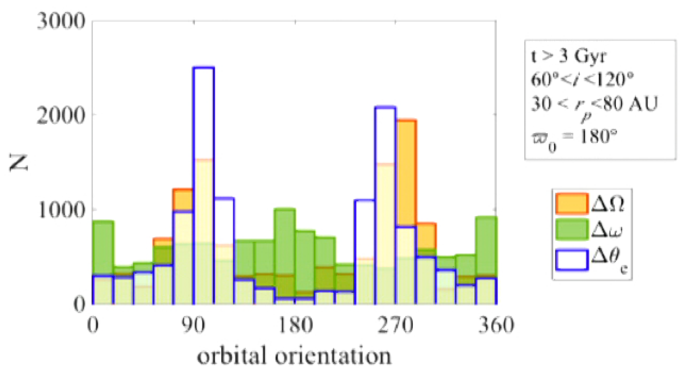
Secular Interactions



N-body results





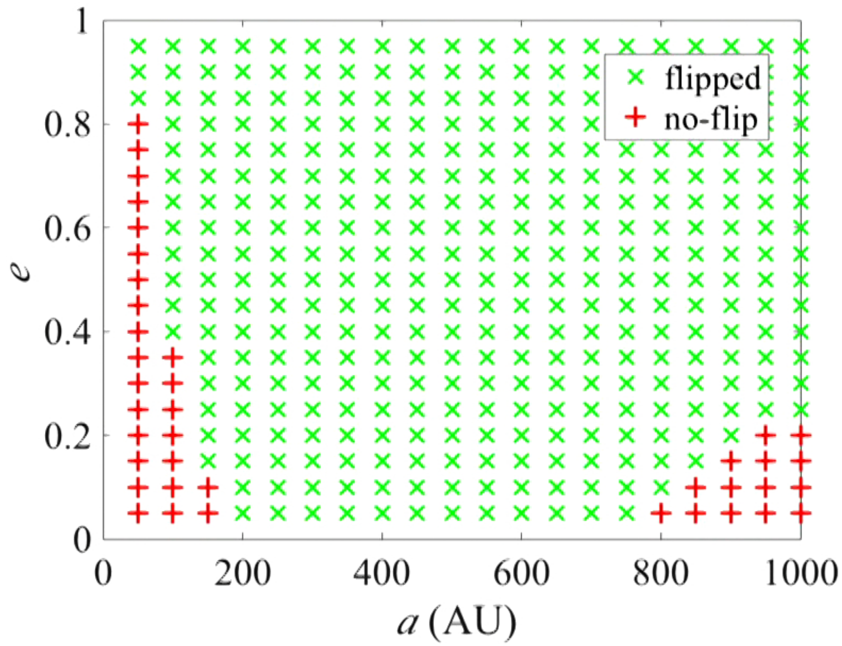


- Starting with $\Delta\varpi_0 \sim 180^o$, secular interactions can reproduce the dominant clustering

Li et al. 2018

Origin of Clustering

Including only three-body interactions, with no J2-precession



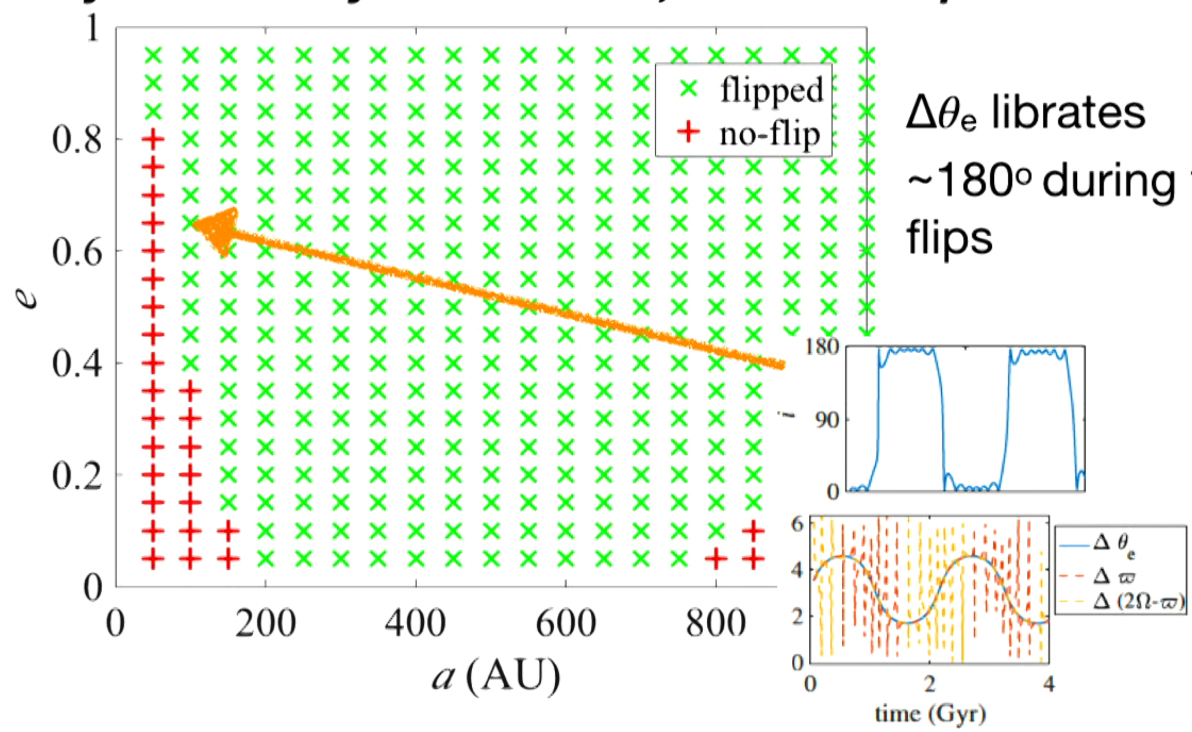
$M_9 = 10\ M_\oplus$, $i = 5^o$
$a_9 = 500$ AU, $e_9 = 0.6$

- Most TNOs can flip due to perturbations of P9

Li et al. 2018

Origin of Clustering

Including only three-body interactions, with no J2-precession

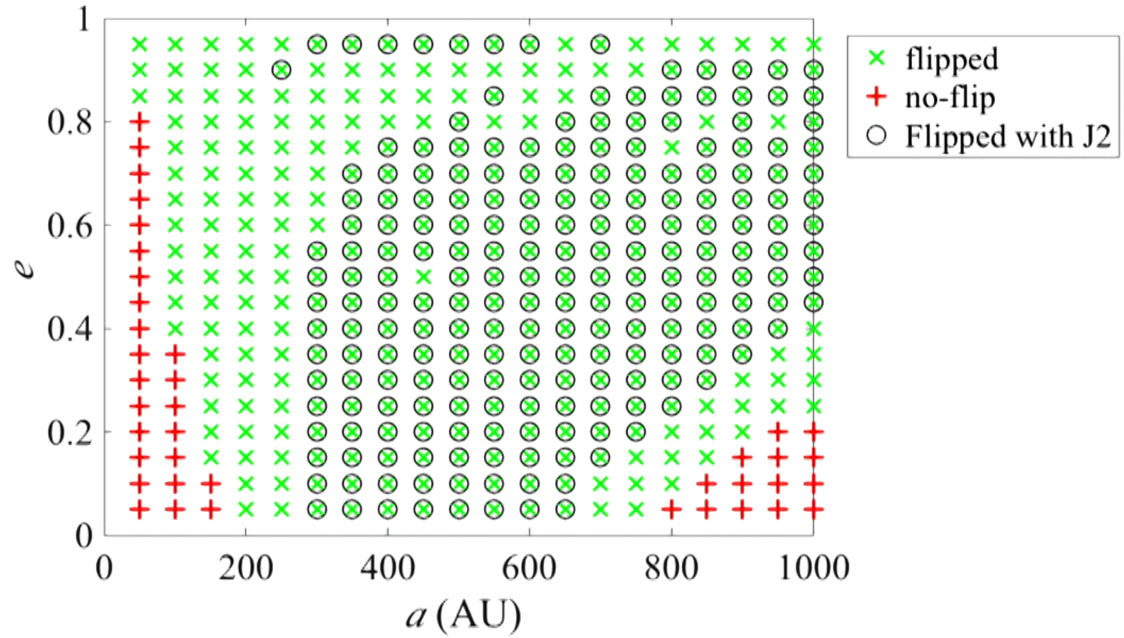


$\Delta\theta_e$ librates ~180° during the flips

Li et al. 2018

Origin of Clustering

Adding J2-precession

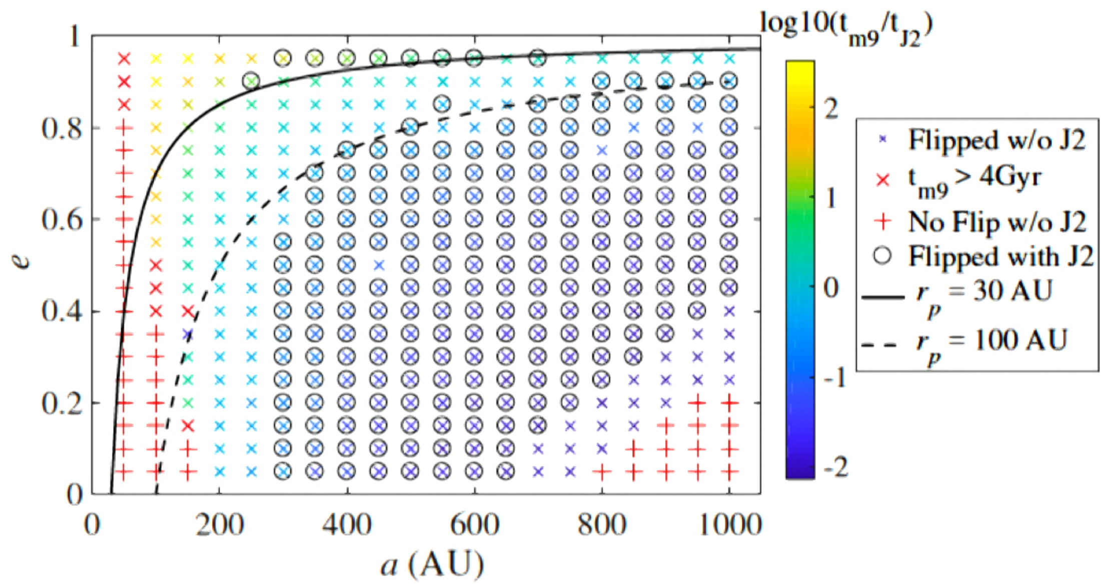


- J2-precession suppresses flips

Li et al. 2018

Origin of Clustering

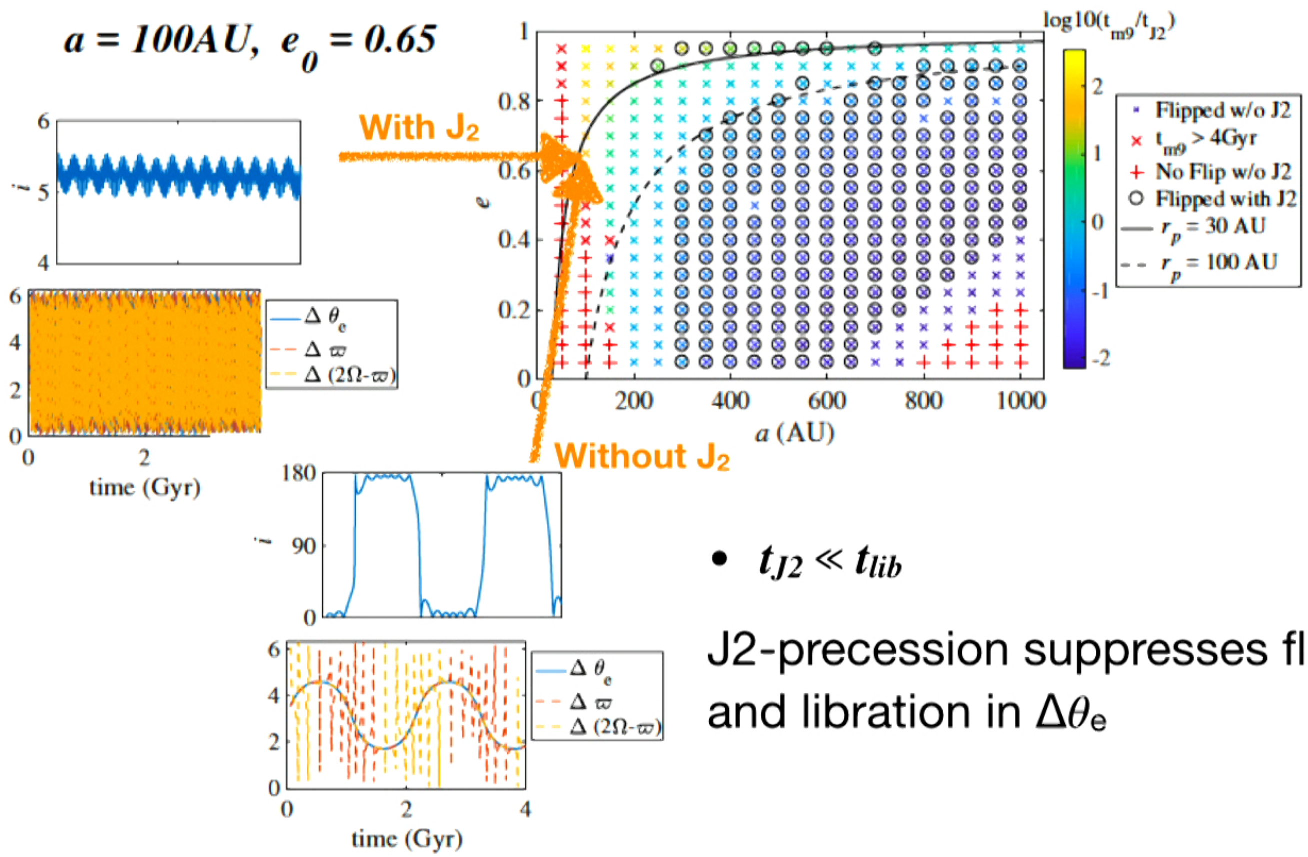
Comparing timescales



- J2-precession suppresses flips when $t_{J2}<t_{lib}$

Li et al. 2018

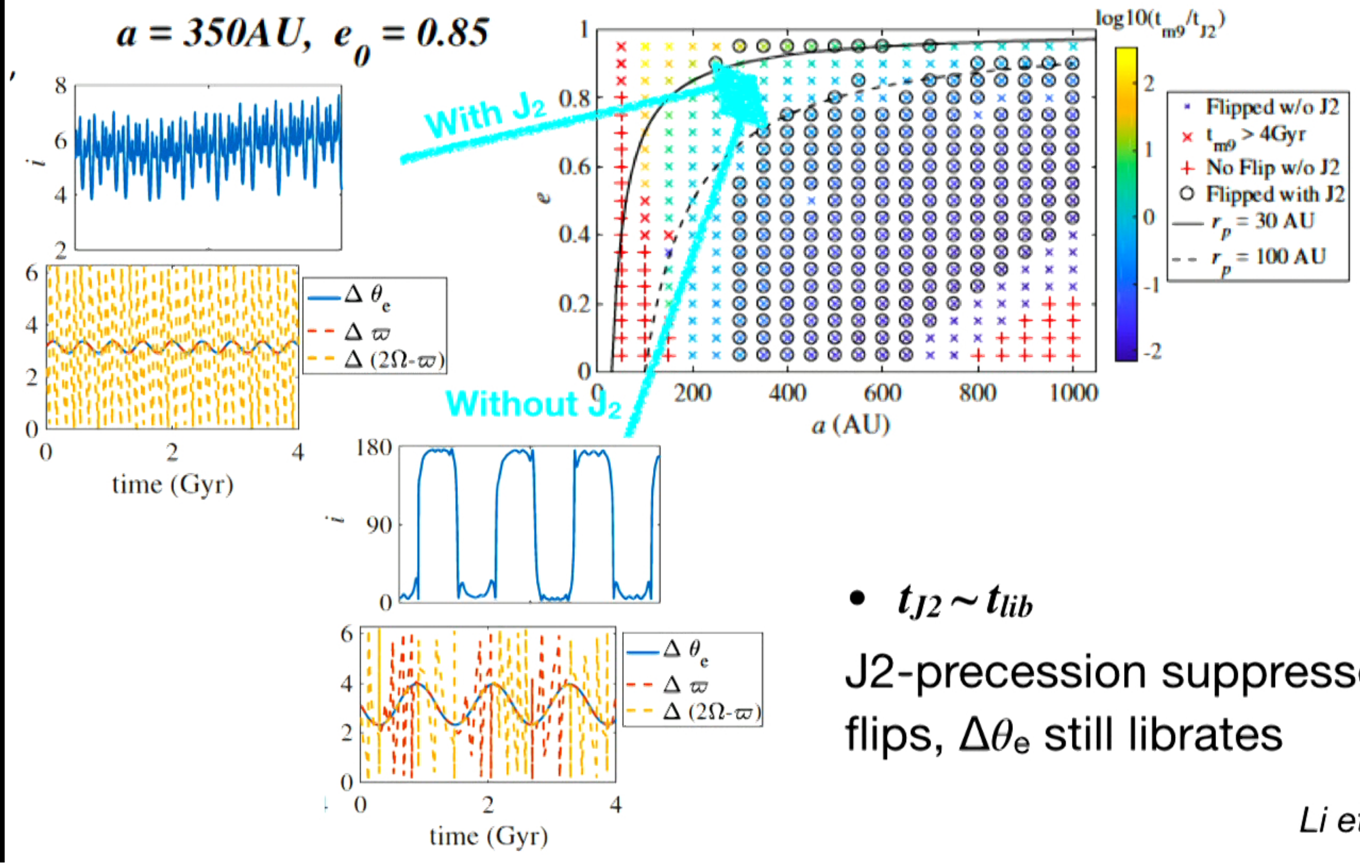
Origin of Clustering



- $t_{J2} \ll t_{lib}$

J2-precession suppresses flips and libration in $\Delta\theta_e$

Origin of Clustering

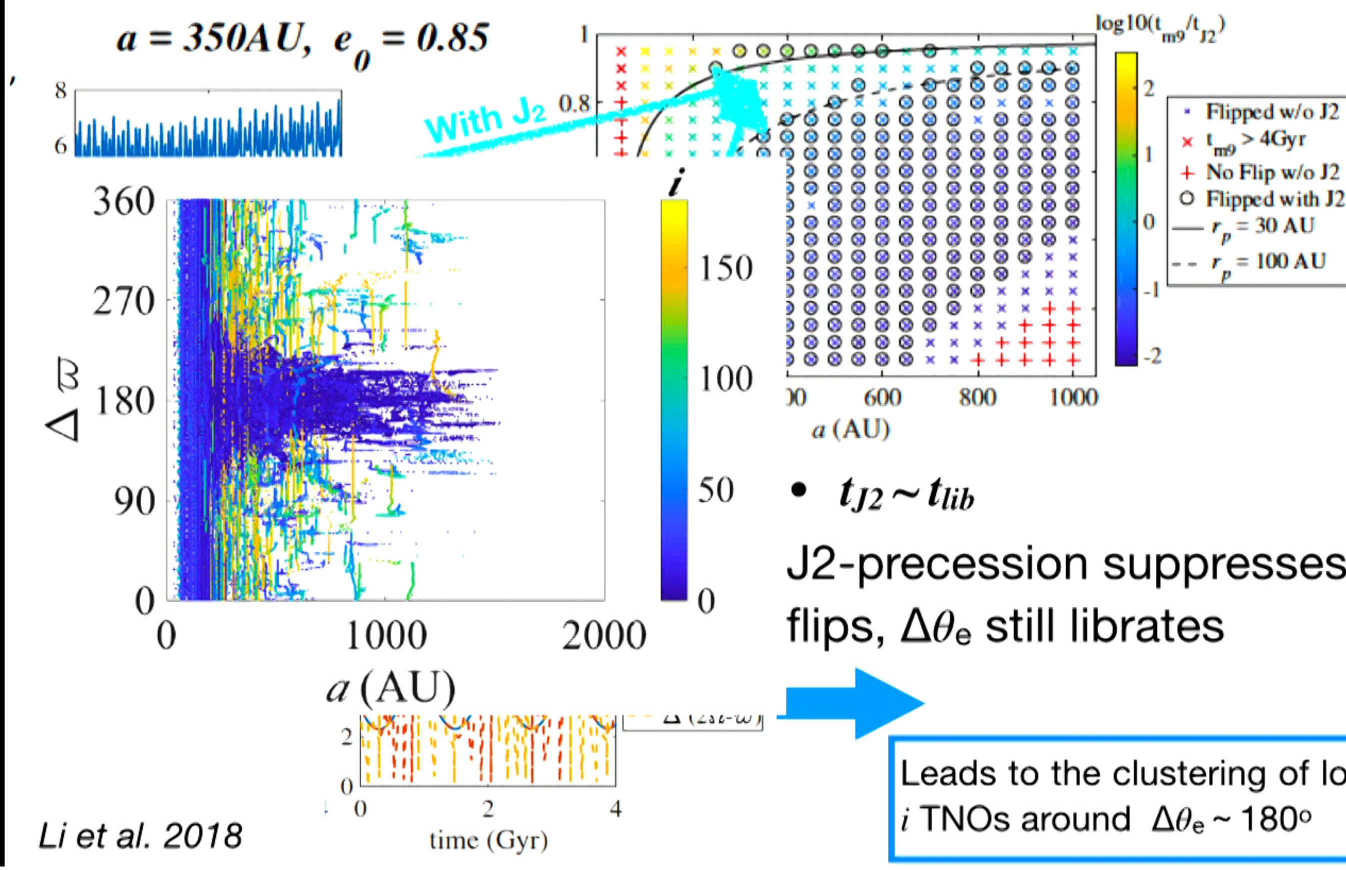


- $t_{J2} \sim t_{lib}$

J2-precession suppresses flips, $\Delta\theta_e$ still librates

Li et al. 2018

Origin of Clustering



- $t_{J2} \sim t_{lib}$

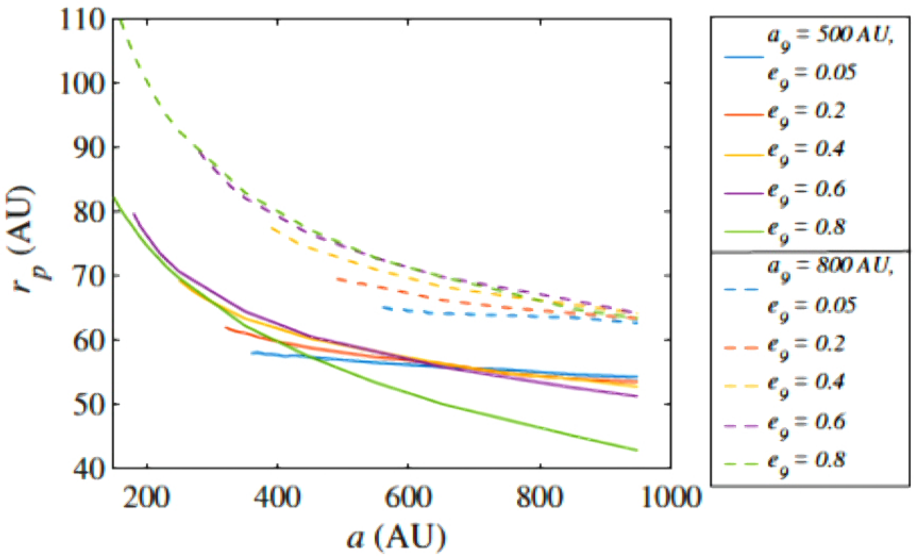
J2-precession suppresses flips, $\Delta\theta_e$ still librates

Leads to the clustering of low i TNOs around $\Delta\theta_e \sim 180°$

Li et al. 2018

Dependence on P9

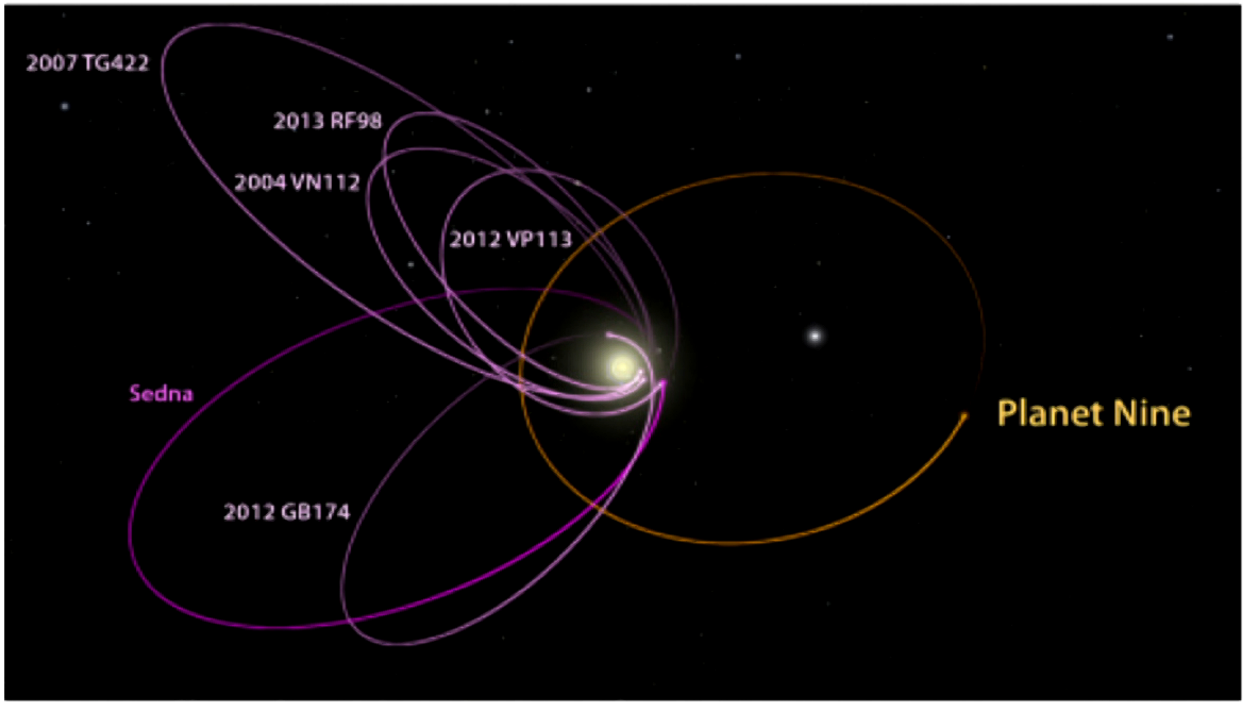
r_p of fixed points at ϖ~180°



- $a_{fix} \downarrow e_9 \uparrow$
- Clustering appears for eccentric and wide P9 orbits (a~500 AU, e>~0.4)

Li et al. 2018

Formation of Planet Nine



Formation of Planet Nine

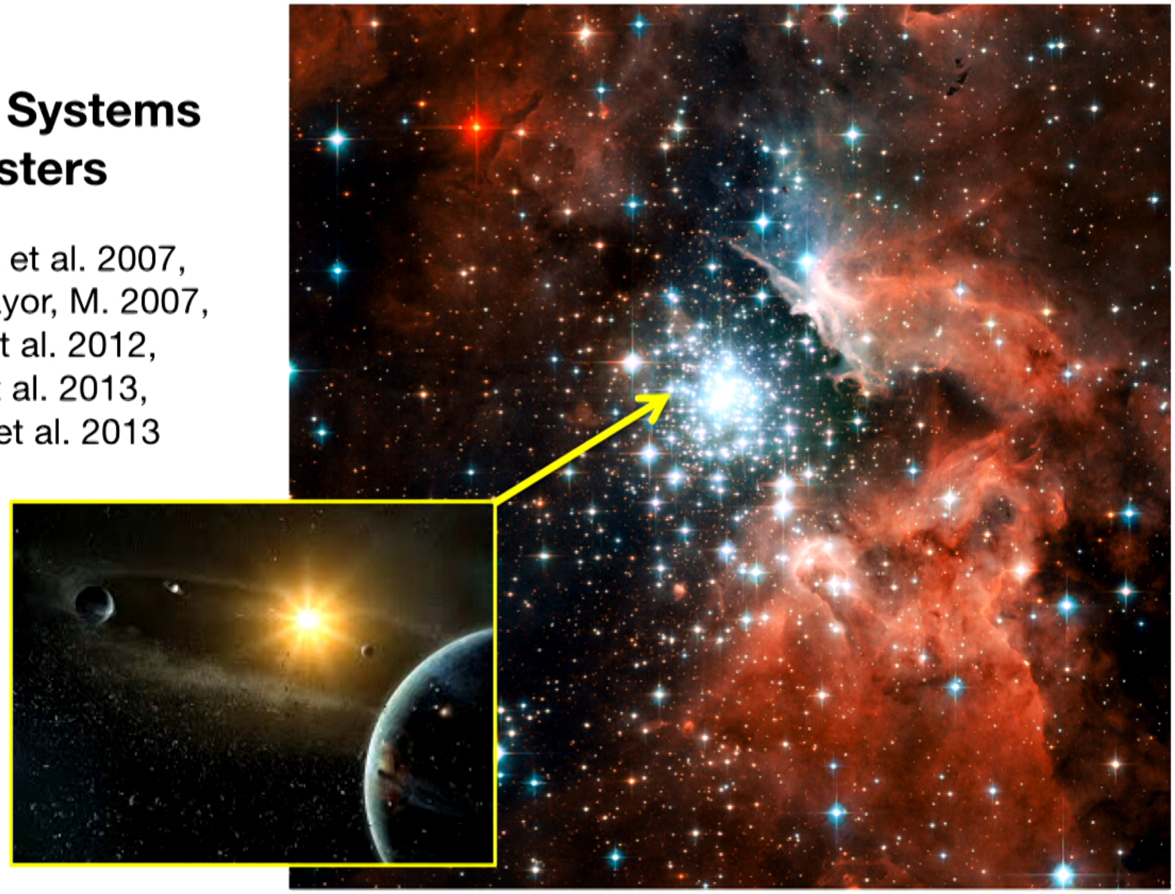
Most stars form in clusters (Carpenter, 2000, Lada & Lada 2003, Porris et al. 2003).

e.g., Catalog of NIR surveys of young (<~Myr) stellar groups and clusters within 1 kpc from the Sun shows ~80% of the stars are in clusters with at least 100 members (Porris et al., 2003).

Formation of Planet Nine

Planetary Systems in clusters

e.g., Sato, B. et al. 2007,
Lovis, C. & Mayor, M. 2007,
Quinn, S. et al. 2012,
Meibom et al. 2013,
Brucalassi et al. 2013



Formation of Planet Nine

Solar Systems Birth Cluster

Evidences:

- Short lived radioactive isotopes species inferred from meteoritic measurements suggests a SN exploded during Solar System formation (e.g., Wasserburg 1985, Cameron 1993, Goswami & Vanhala 2000)

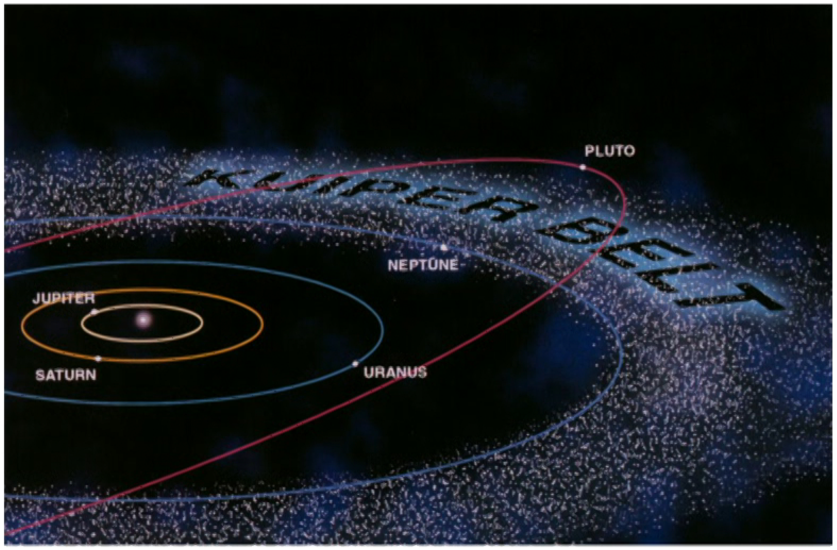
Nuclear species	Daughter	Reference	Half-life (Myr)	Mass fraction
^{7}Be	^{7}Li	^{9}Be	53 days	(8×10^{-13})
^{10}Be	^{10}B	^{9}Be	1.5	$(\sim 10^{-13})$
^{26}Al	^{26}Mg	^{27}Al	0.72	3.8×10^{-9}
^{36}Cl	^{36}Ar	^{35}Cl	0.30	8.8×10^{-10}
^{41}Ca	^{41}K	^{40}Ca	0.10	1.1×10^{-12}
^{53}Mn	^{53}Cr	^{55}Mn	3.7	4.0×10^{-10}
^{60}Fe	^{60}Ni	^{56}Fe	1.5	1.1×10^{-9}
^{107}Pd	^{107}Ag	^{108}Pd	6.5	9.0×10^{-14}
^{182}Hf	^{182}W	^{180}Hf	8.9	1.0×10^{-13}

Formation of Planet Nine

Solar Systems Birth Cluster

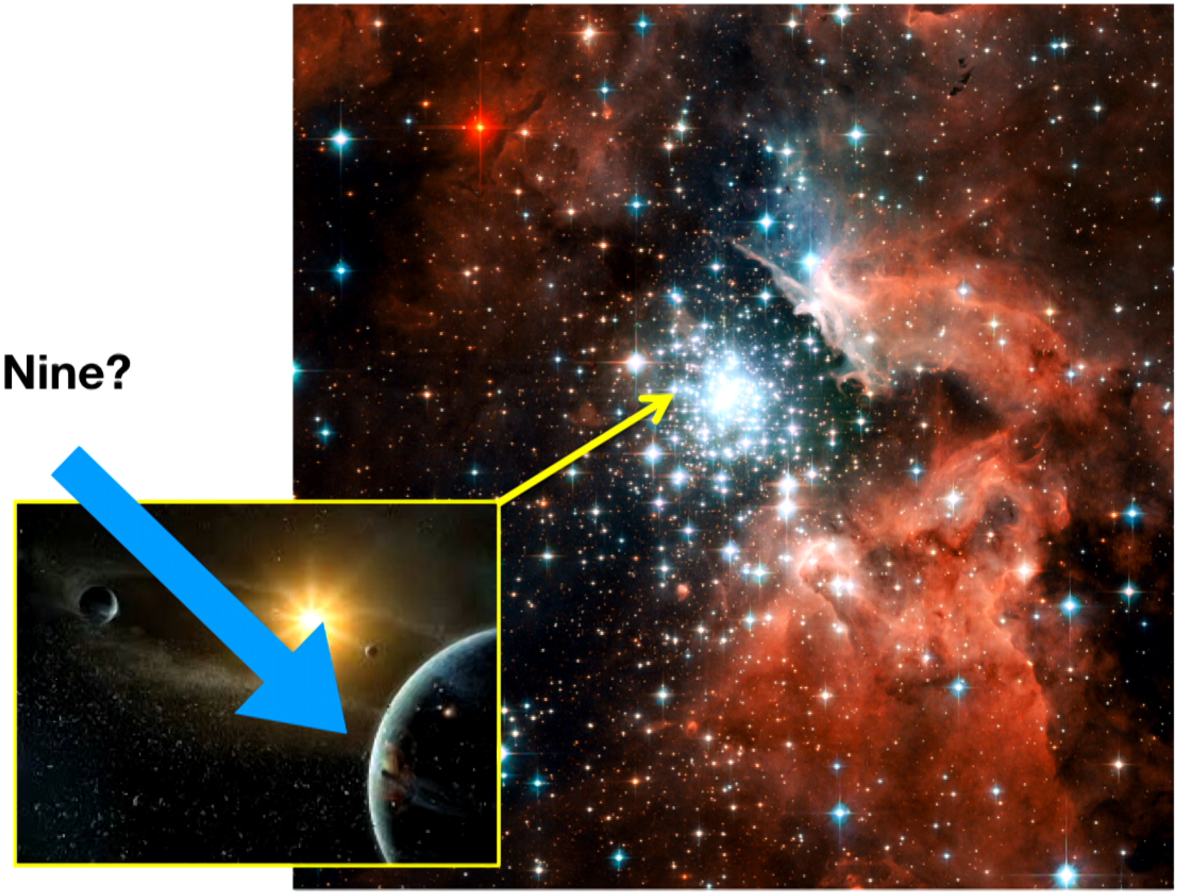
Evidences:

- The edge of Kuiper belt at ~ 50 AU (Allen et al. 2001)

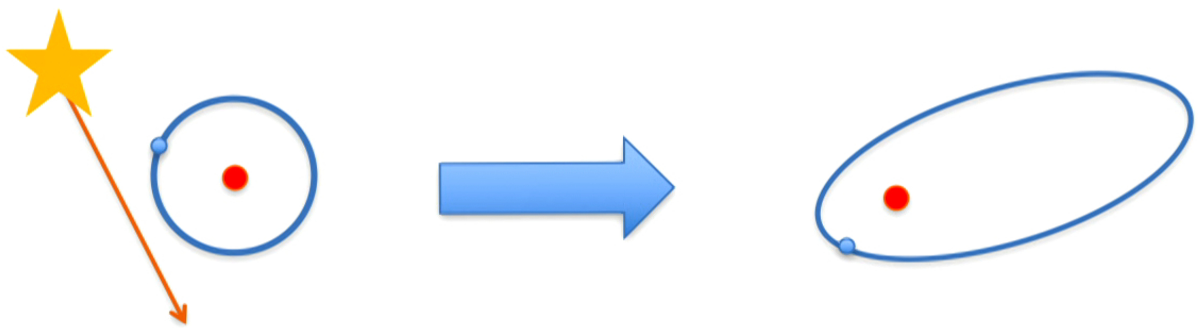


Formation of Planet Nine

Planet Nine?



Scatter Planet Nine Outward?



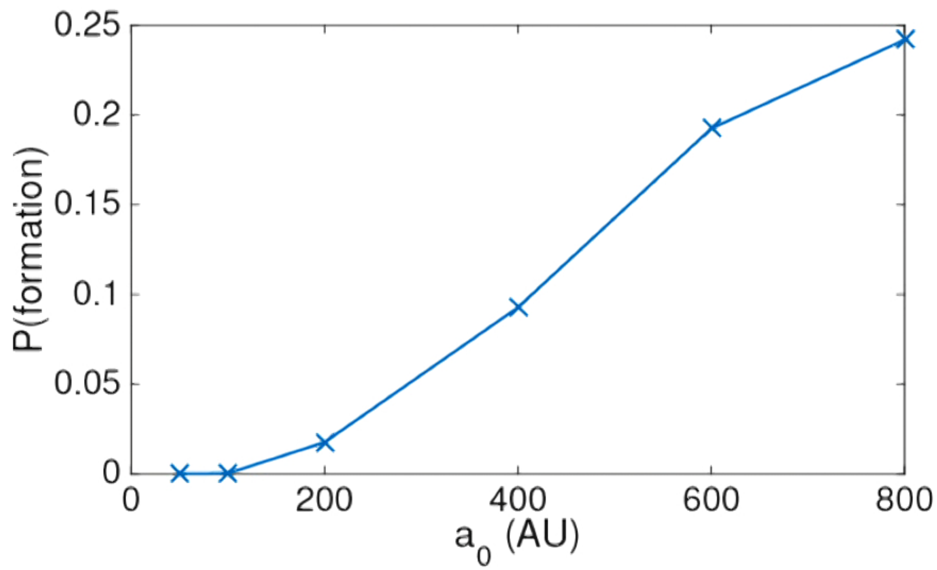
Scatter Planet Nine Outward?

Cluster environment:

$n = 100/pc^3$
(Lada & Lada 2003
Proszkow & Adams 2009)

$\sigma_{rel} = 1km/s$

t = 100 Myr



Formation probability lower if starting with eccentric orbits

Li & Adams 2016

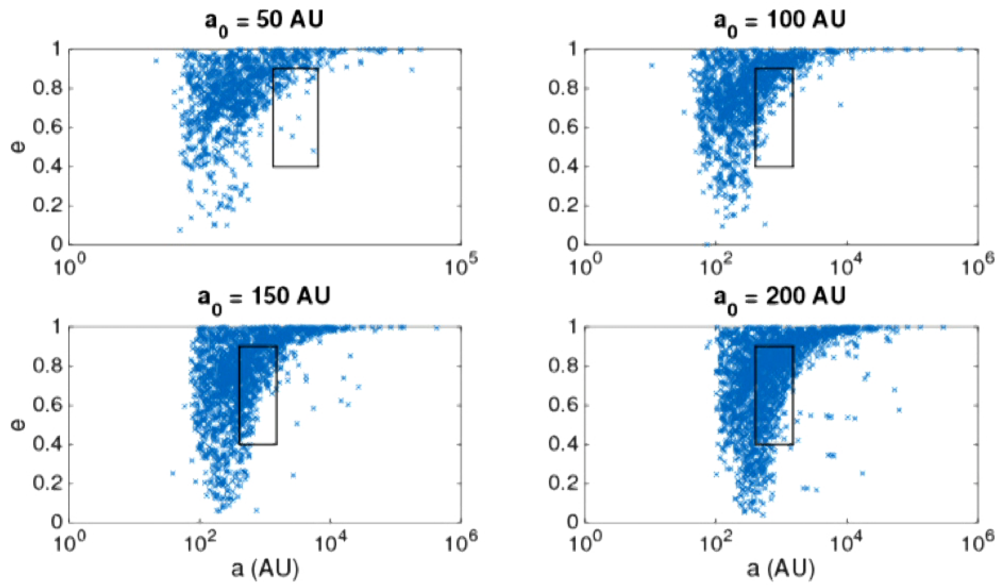
Captured Exoplanet?

- Capture of Planet Nine from other planetary systems

Li & Adams 2016

Captured Exoplanet?

- Capture of Planet Nine from other planetary systems (~2%)

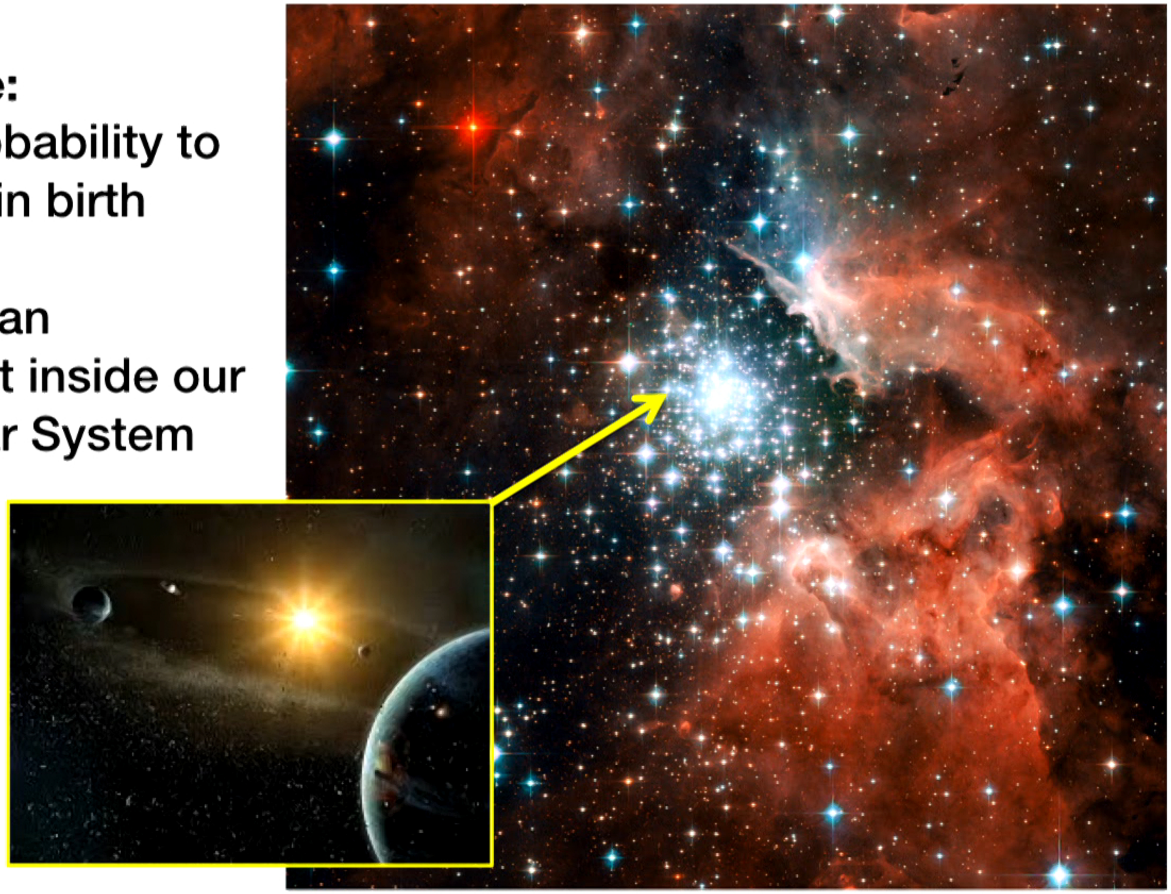


Li & Adams 2016

Formation of Planet Nine

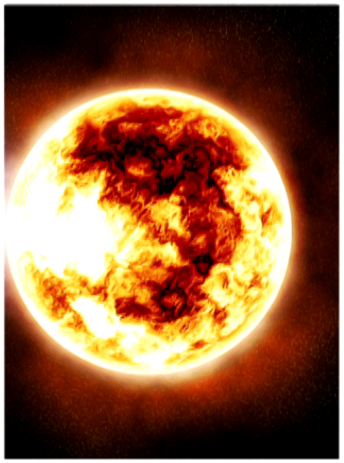
Planet Nine:

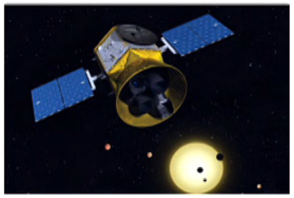
- 1-2% probability to produce in birth cluster
- Possibly an exoplanet inside our own Solar System



Summaries

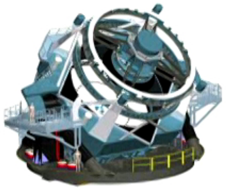
- Misaligned hot Jupiters can be produced due to perturbations of farther companion





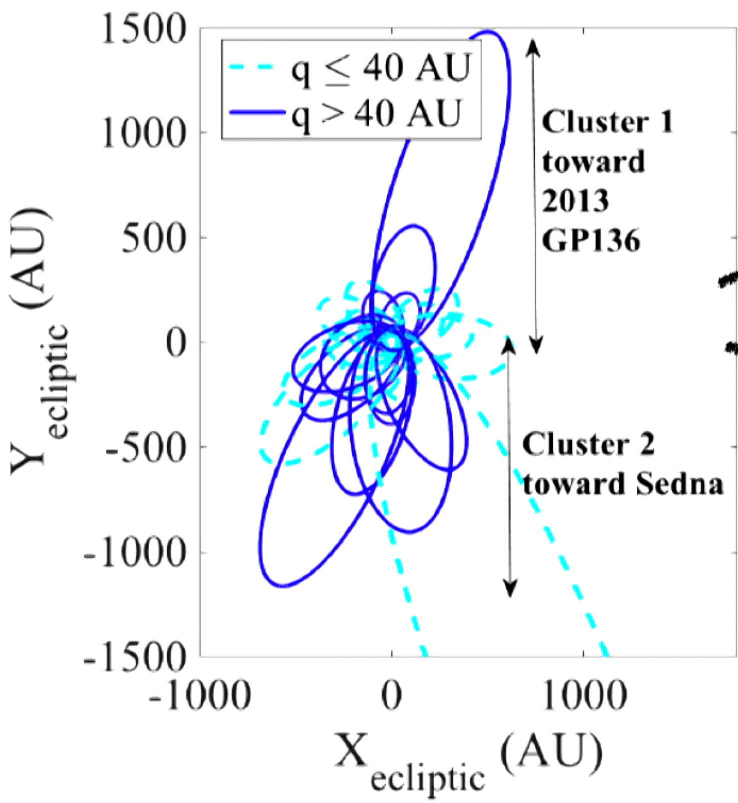
  - Future observations (e.g., TESS) can provide more clues on the formation of Hot Jupiters

- Anti-aligned TNOs can be produced due to perturbations of a farther planet companion (Planet Nine).
- ~2% probability to produce P9 in Solar System birth cluster
  - Detections of TNOs by (e.g., LSST) can further constrain possibilities of planet in the outer Solar System




Summaries
Misaligned hot Jupiters can be produced due to perturbations of farther companion
Future observations (e.g., TESS) can provide more clues on the formation of Hot Jupiters
Anti-aligned TNOs can be produced due to perturbations of a farther planet companion (Planet Nine)
~2% probability to produce P9 in Solar System birth cluster
Detections of TNOs by (e.g., LSST) can further constrain possibilities of planet in the outer Solar System

Question: What leads to the clustering?



MMR

Batygin & Brown 2016, Malhotra et al. 2016, Millholland & Laughlin 2017, Batygin & Morbidelli 2017, Hadden et al. 2018, Bailey et al. 2018

Secular

Beust 2016, Batygin & Morbidelli 2017, Saillenfest et al. 2017, Hadden et al. 2018, Li et al. 2018