Did our Solar System Lose a Giant Planet?

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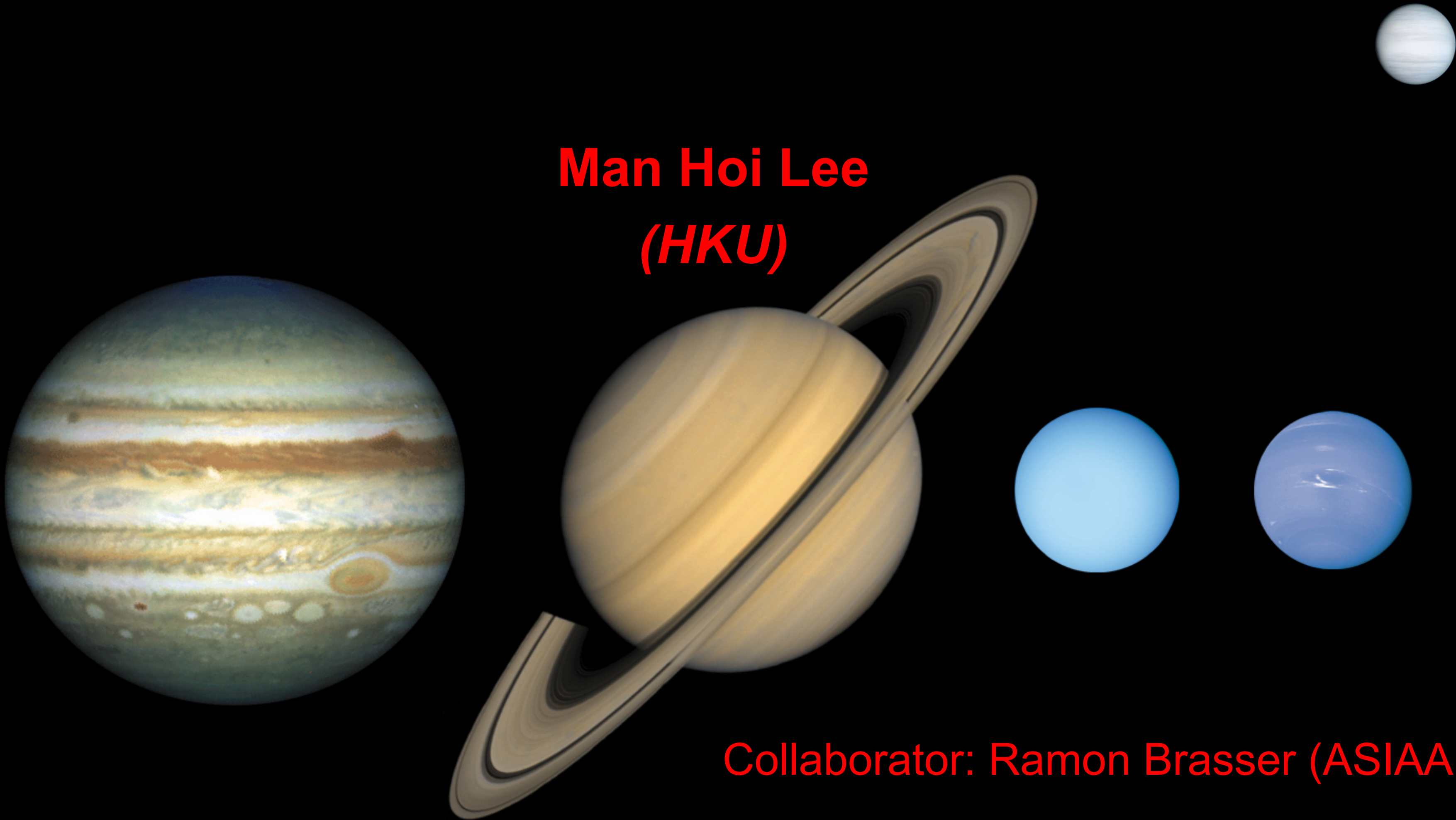


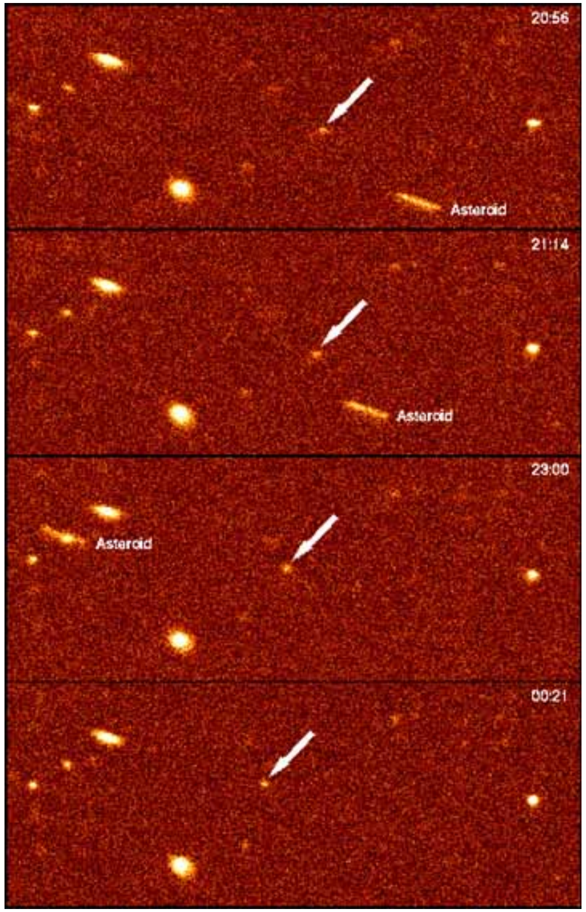
Collaborator: Ramon Brasser (ASIAA)

Outline

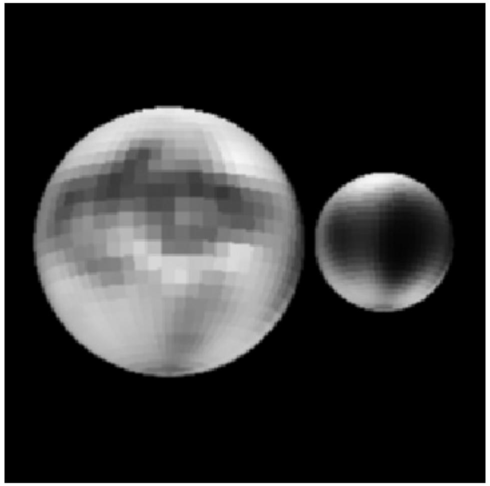
- Evidence for migration of giant planets in our Solar System.
- Migration models.
- Orbital and obliquity (spin axis tilt) constraints: what's the connection between planet migration and obliquities?
- Simulation results.

Kuiper Belt Objects

- Large population of small bodies orbiting the Sun beyond Neptune's orbit.
- Pluto discovered in 1930.
- Many more discovered since 1992.
- Debris (planetesimals) left over from formation of Solar System.

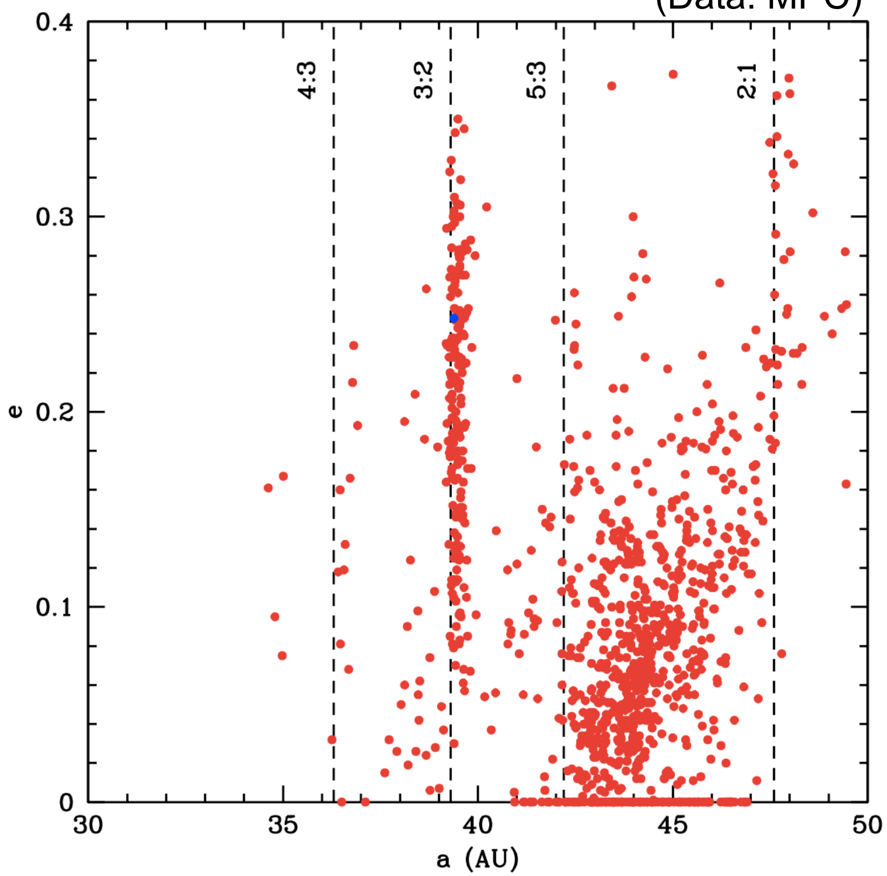


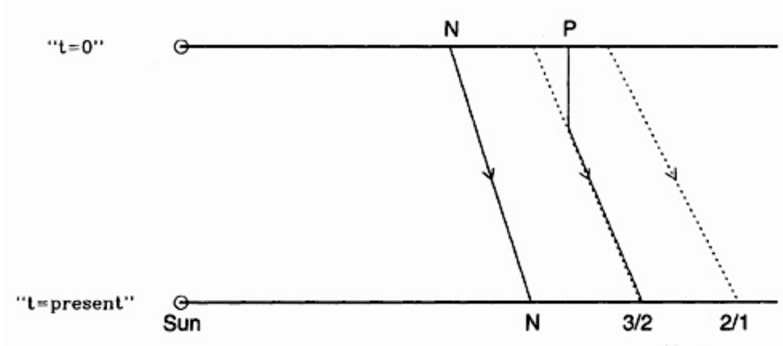
KBO 1992 QB1


Pluto and its satellite Charon

- Many Kuiper belt objects in orbital mean-motion resonance with Neptune: Orbital period is a simple fraction of Neptune’s.
- E.g., Pluto in 3:2.
- Also, 4:3, 3:2, 5:3, 2:1, etc.
- Evidence for outward migration of Neptune driven by planetesimals.
- To pump up Plutino orbital eccentricities to *e* ~ 0.3, Neptune's orbit must have migrated by *Δa* ~ 7 AU (Malhotra 1995; Malhotra & Hahn 1999).

(Data: MPC)





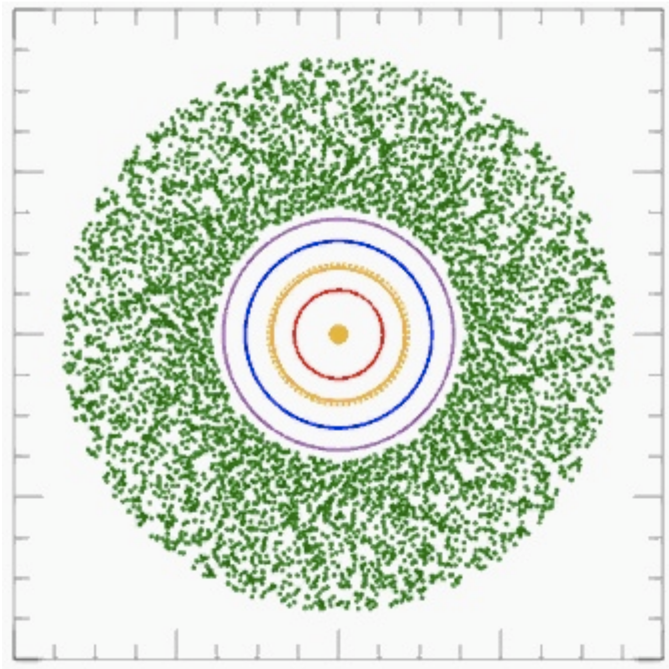
(Malhotra 1995)

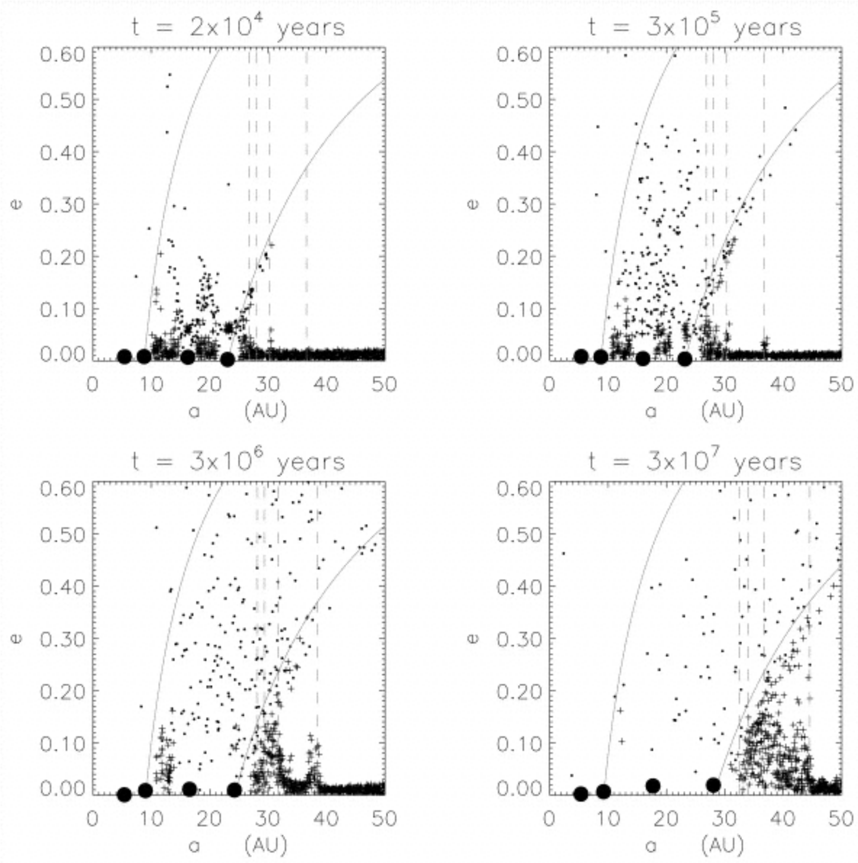
Giant Planet Migration Models

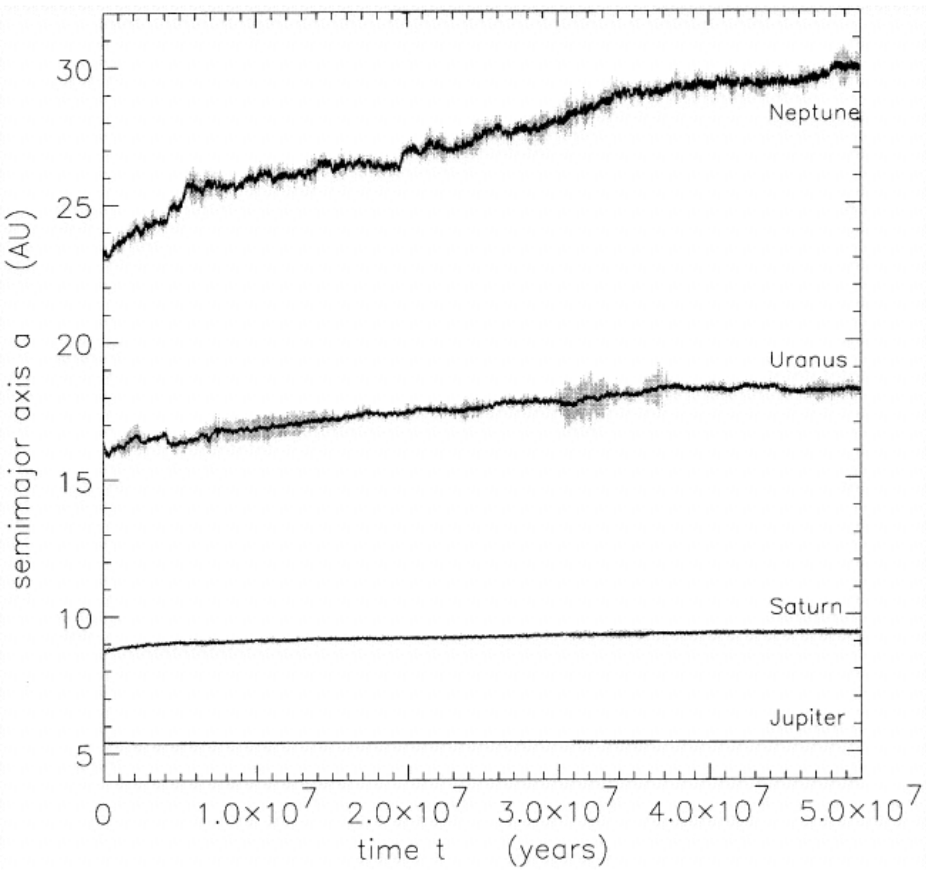
- Smooth Migration Model
- Classic Nice Model
- Resonant Nice Model
- Resonant 5-Planet Model

Model I: Smooth Migration

- Even before Kuiper Belt was discovered, Fernandez & Ip (1984) asked
  - what happened to the orbits of the giant planets when they interacted gravitationally with a disk of leftover planetesimals?







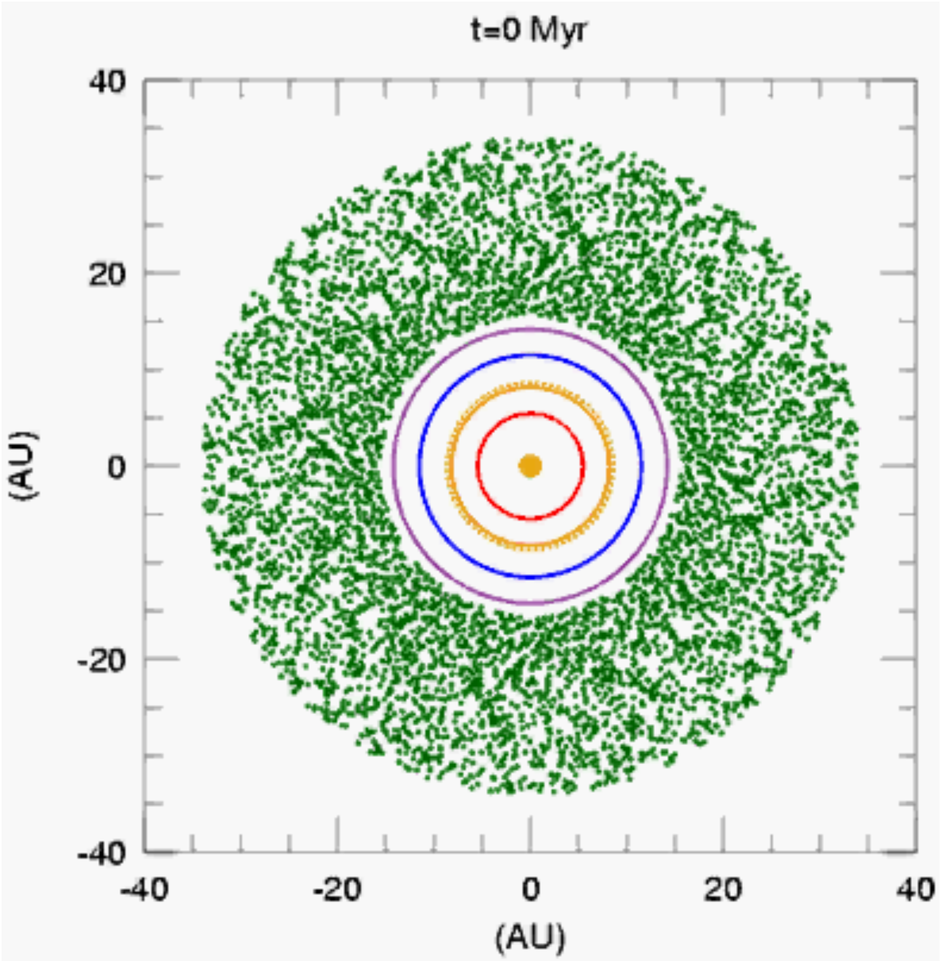
(Hahn & Malhotra 1999)

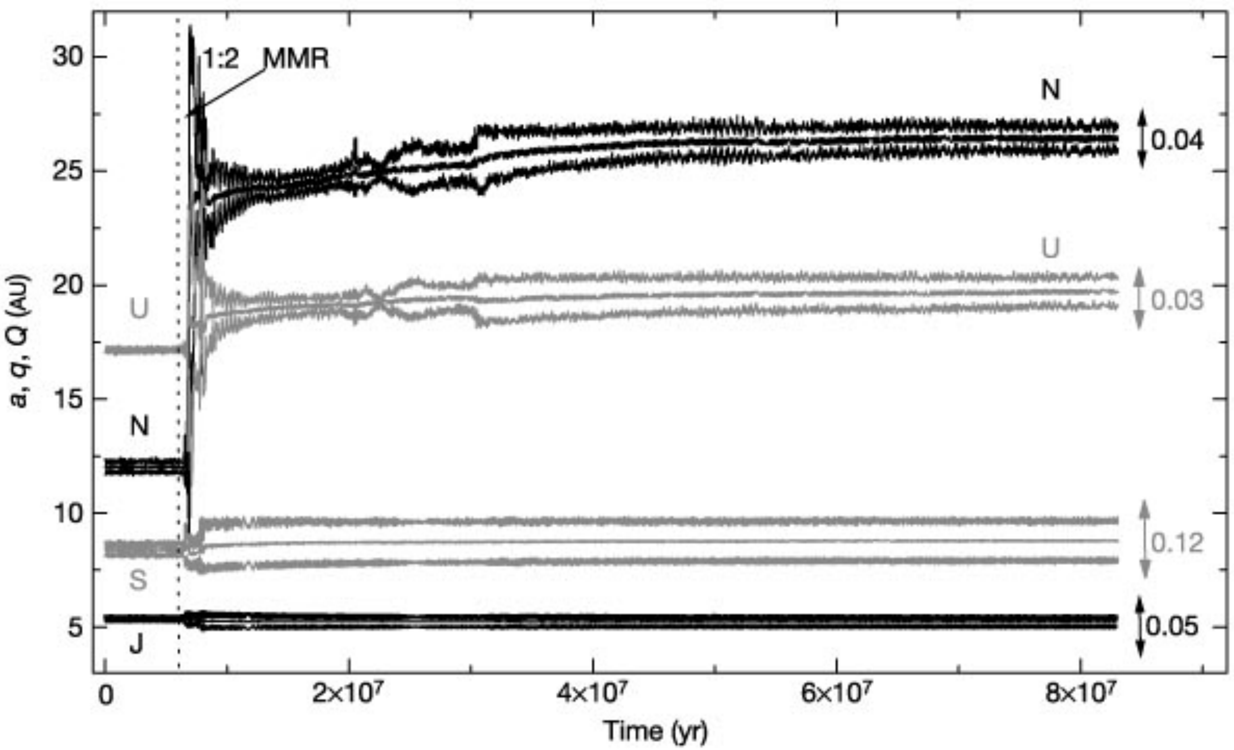
- Saturn, Uranus, and Neptune evolve radially outward as they scatter planetesimals, while Jupiter's orbit shrinks as it ejects planetesimals.
- Outer Solar System initially more compact (but Saturn outside 2:1 mean-motion resonance with Jupiter).
- Disk mass ~ 50 $M_{\oplus}$ is required to expand Neptune’s orbit by Δa ~ 7 AU (Malhotra 1995; Malhotra & Hahn 1999).

Model II: Classic Nice

Tsiganis et al. (2005)

- Saturn closer than 2:1 mean-motion resonance with Jupiter.
- Ice giants within ~ 18 AU.

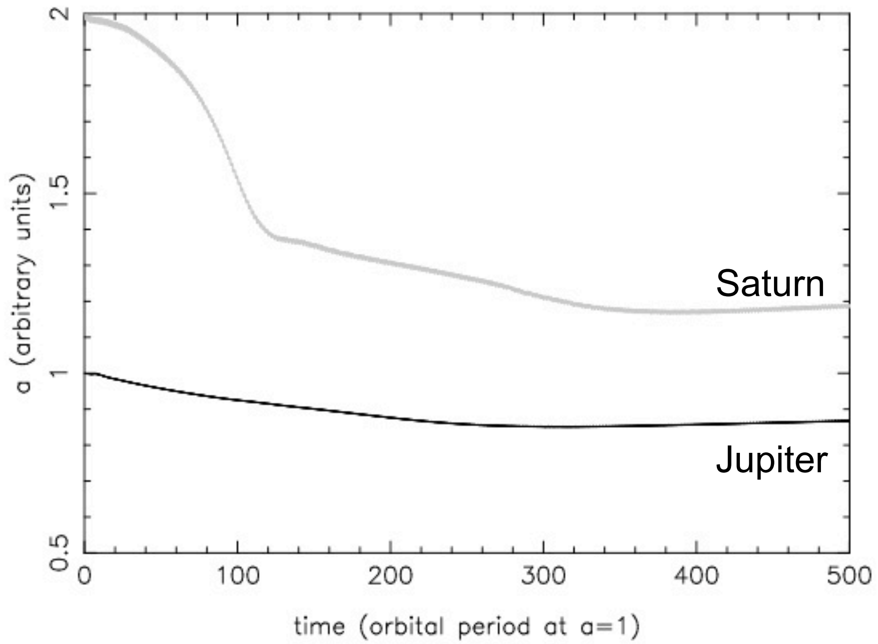




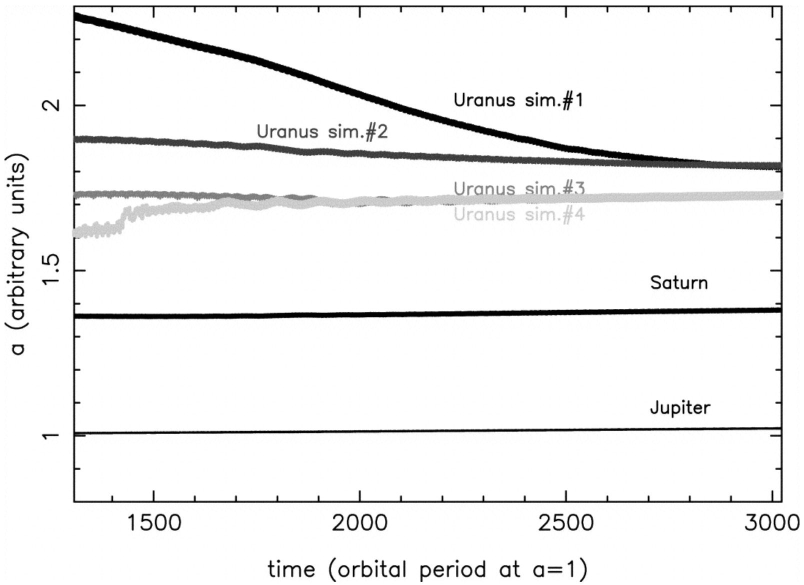
- Jupiter and Saturn crossed 2:1 orbital resonance by divergent migration.
- Close encounters among giant planets scattered Uranus and Neptune out.
- Eccentricities and inclinations damped to present values by interactions with planetesimals.

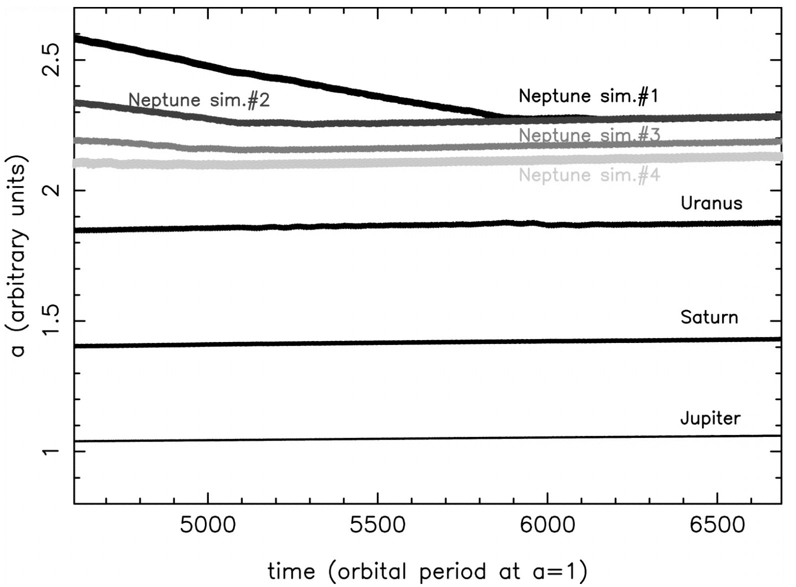
Model III: Resonant Nice

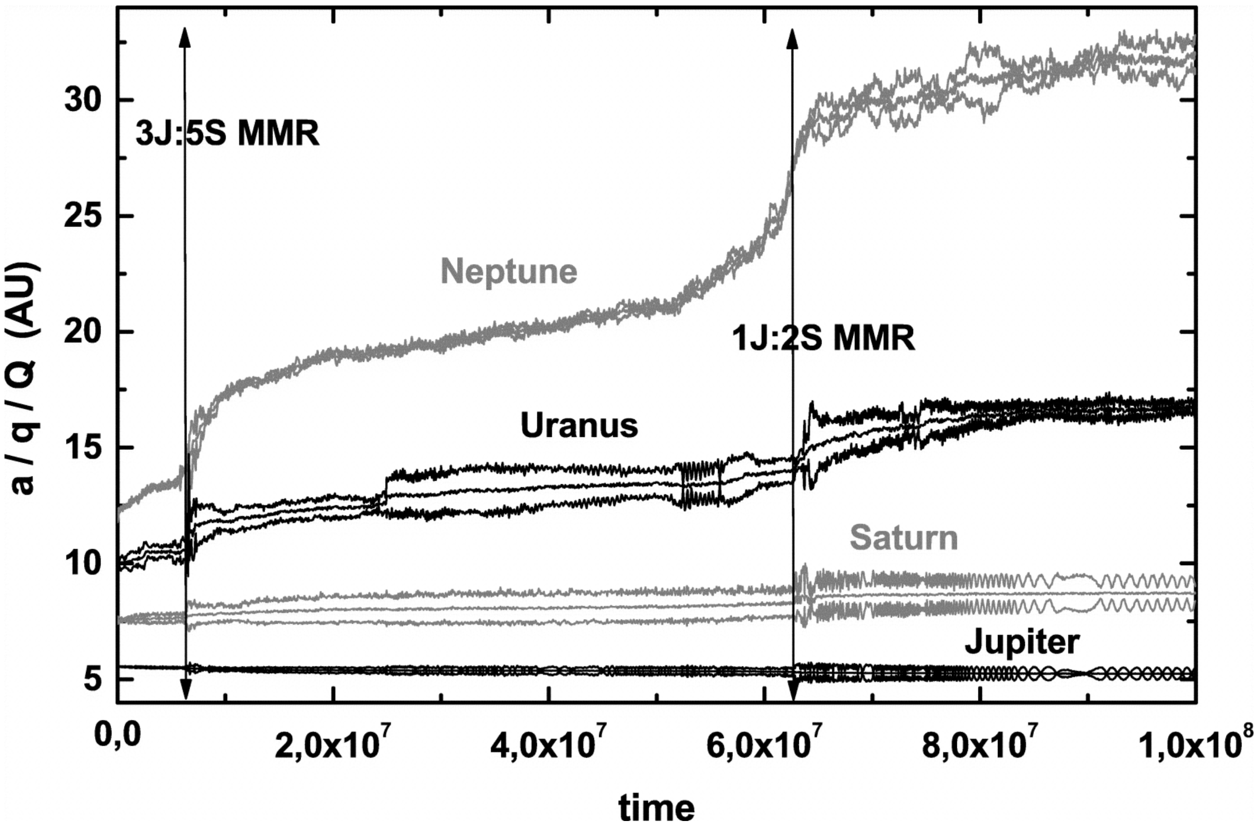
- Before the protoplanetary gas disk dispersed
  - Interactions with the gas disk can cause inward migration of Jupiter and Saturn.
  - Capture of Jupiter and Saturn into 3:2 mean-motion resonance can stop migration (Masset & Snellgrove 2001; Morbidelli & Crida 2007).



- Morbidelli et al. (2007) proposed that earlier migration in gas disk put all four giant planets in mean-motion resonances:
  - Jupiter and Saturn in 3:2.
  - Saturn and inner ice giant in 3:2.
  - Ice giants in 4:3.



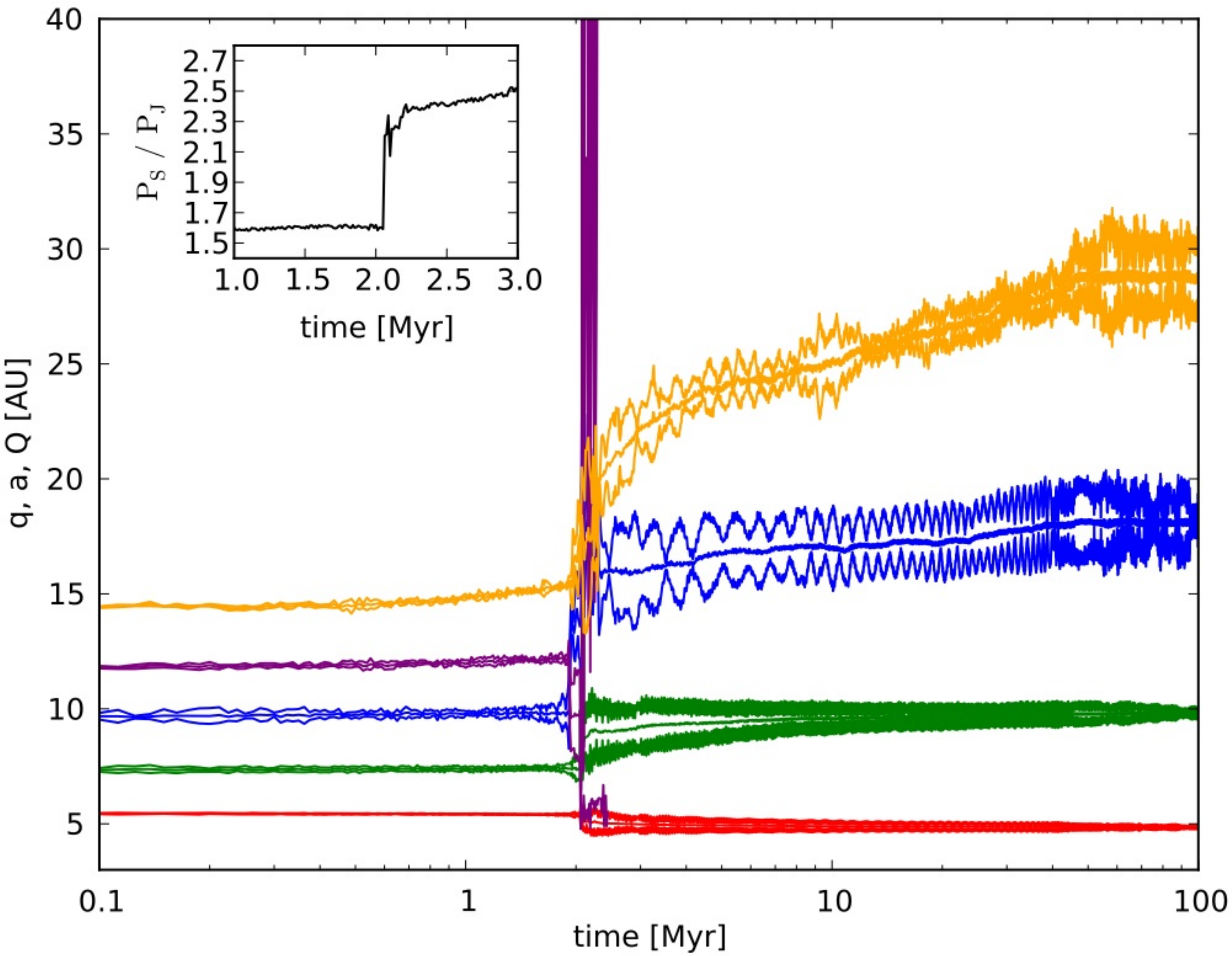




- Subsequent divergent migration driven by planetesimals.
- *N*-body simulations with planetesimals show that
  – Probability that all four giant planets survive is small.
  – It is very difficult to match constraints on orbital history.

Model IV: Resonant 5-Planet

- Since a giant planet is often ejected in the resonant Nice model, what if the Solar System started with an extra ice giant, which was ejected during the encounter phase? (Nesvorný 2011; Batygin et al. 2012)
- We consider two initial resonance configurations:
  - Compact: J and S in 3:2, S and I_1 in 3:2, I_1 and I_2 in 4:3, I_2 and I_3 in 4:3.
  - Loose: 3:2, 3:2, 2:1, 3:2.

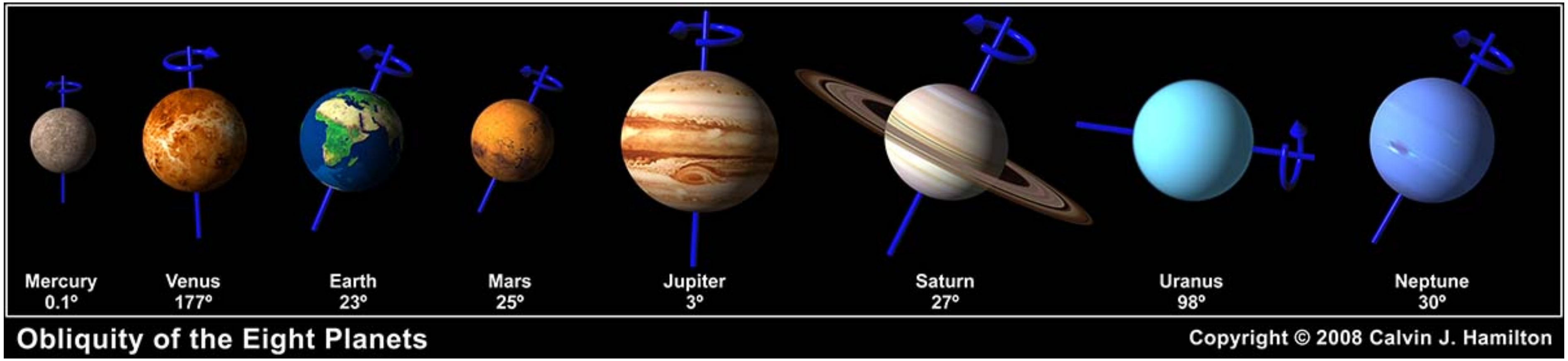


40
35
30
25
20
15
10
5
q, a, Q [AU]
0.1
1
10
100
time [Myr]
2.7
2.5
2.3
2.1
1.9
1.7
1.5
P_S / P_J
1.0
1.5
2.0
2.5
3.0
time [Myr]

Orbital Constraints

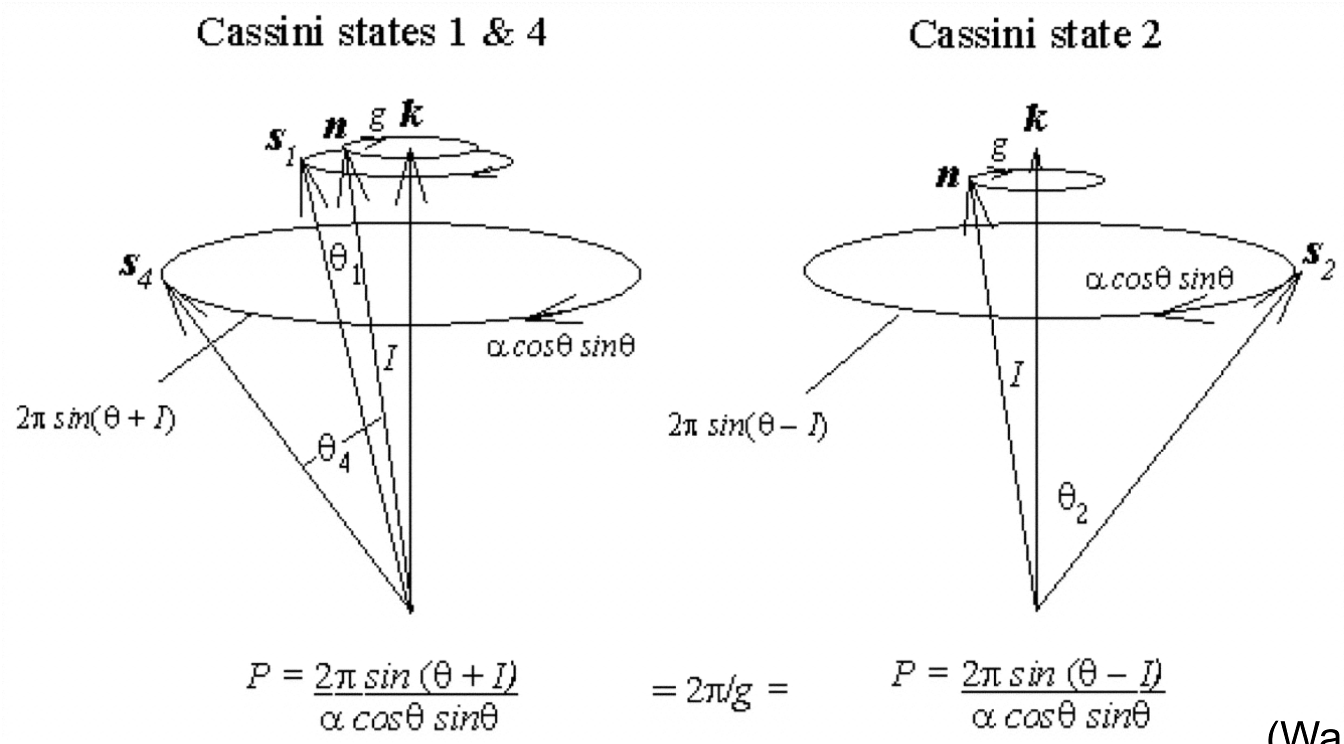
- Four giant planets (Jupiter, Saturn and two ice giants) left at the end of the evolution.
- Planets are within 10% of their current semimajor axes, with $P_S/P_J > 2.35$.
- P_S/P_J must jump from ~ 2.1 to ~ 2.3 in a short time to avoid making terrestrial planet orbits too eccentric and secular resonance sweeping through asteroid belt.
- $\Delta\varpi_{JS} = \varpi_J - \varpi_S$ circulates.

Obliquity Constraints



- Obliquity ε = Angle between spin axis and orbit normal

- Similarity between Saturn’s spin-axis precession rate ($\alpha \cos \varepsilon$) and nodal regression rate of Neptune’s orbit (eigenfrequency $-s_8$) and between 27° obliquity and Cassini state 2 of secular spin-orbit resonance (Ward & Hamilton 2004; Hamilton & Ward 2004):
  - Secular resonant interaction responsible for tilting Saturn.
  - Capture into Cassini state whose obliquity increases with decreasing $|s_8|$.
- Jupiter’s obliquity is only 3°, but its spin precession rate is close to nodal regression rate of Uranus’s orbit (eigenfrequency $-s_7$) (Ward & Canup 2006).

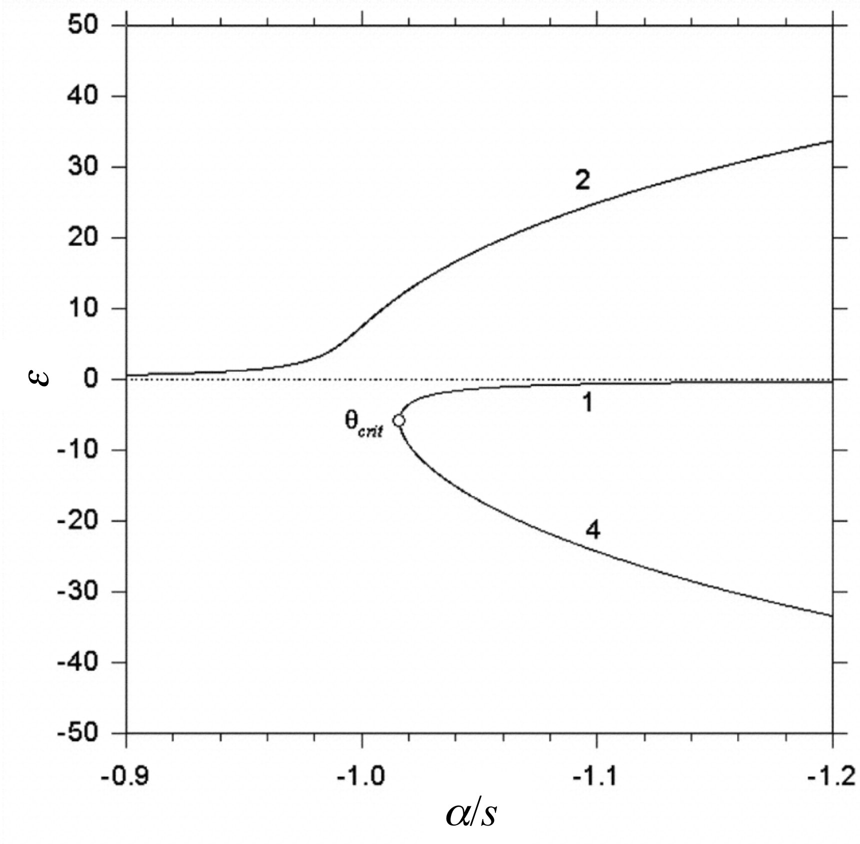


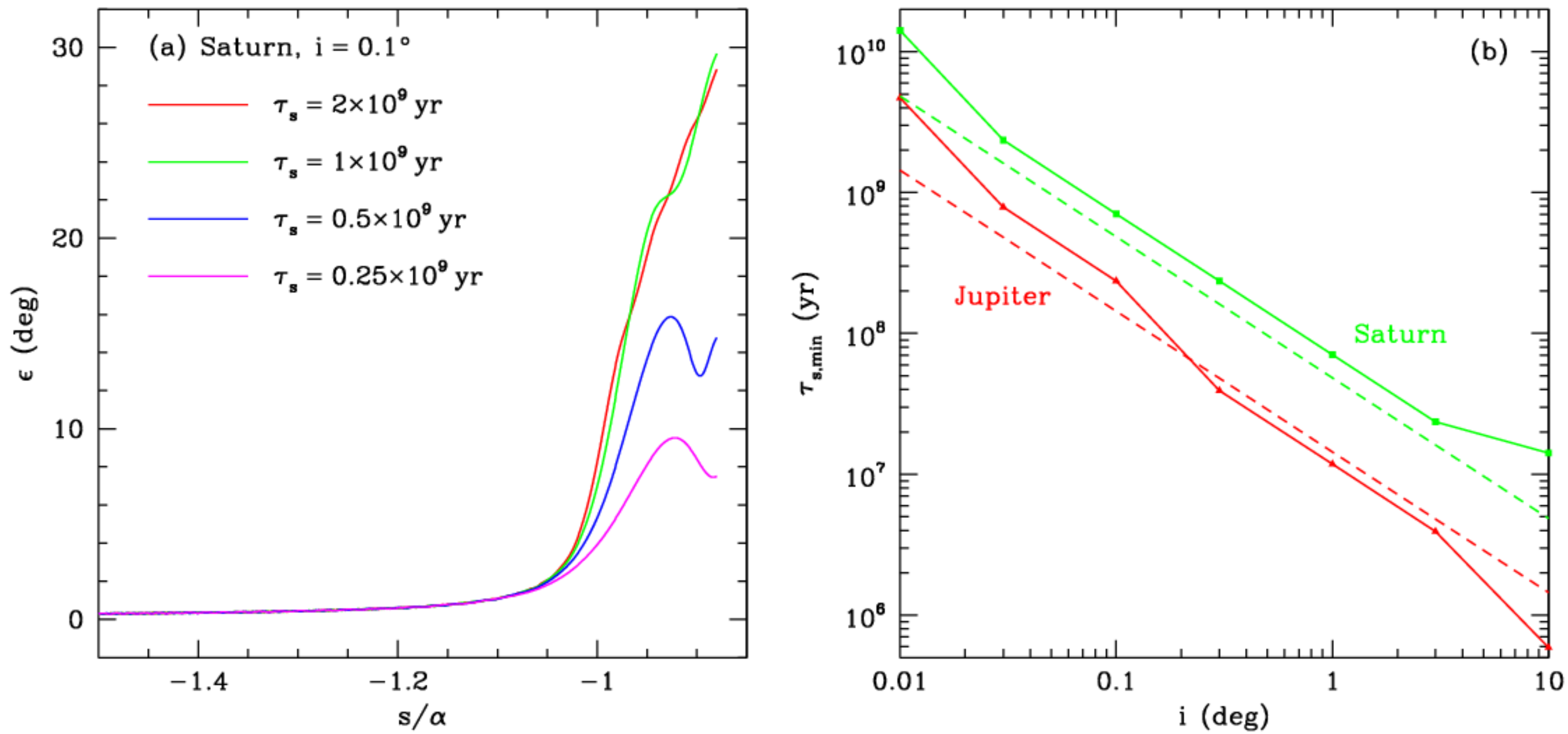
(Ward & Hamilton 2004)

- ***k*** = normal to invariable plane
- ***n*** = orbit normal, precessing about ***k*** at rate *s*
- ***s*** = unit vector of spin direction
- Cassini states: ***s*** coplanar with ***n*** and ***k*,** and ***s*** and ***n*** co-precess at the same rate *s*.

(Ward & Hamilton 2004)

- Resonance capture:
  - If spin axis starts near Cassini state 2 with $|\alpha/s| << 1$ and $|\alpha/s|$ increases, obliquity can become large.
  - Decrease in $|s_8|$ due to depletion of planetesimals and/or outward migration of Neptune.
  - Timescale for change in s_8 must be longer than libration period to stay in resonance.





- For Jupiter and Saturn on inclined orbit precessing at frequency *s* that changes on timescale τ_s, we find $\tau_{s,min} \sim 1/\,i$.

Numerical Methods

Secular Simulations

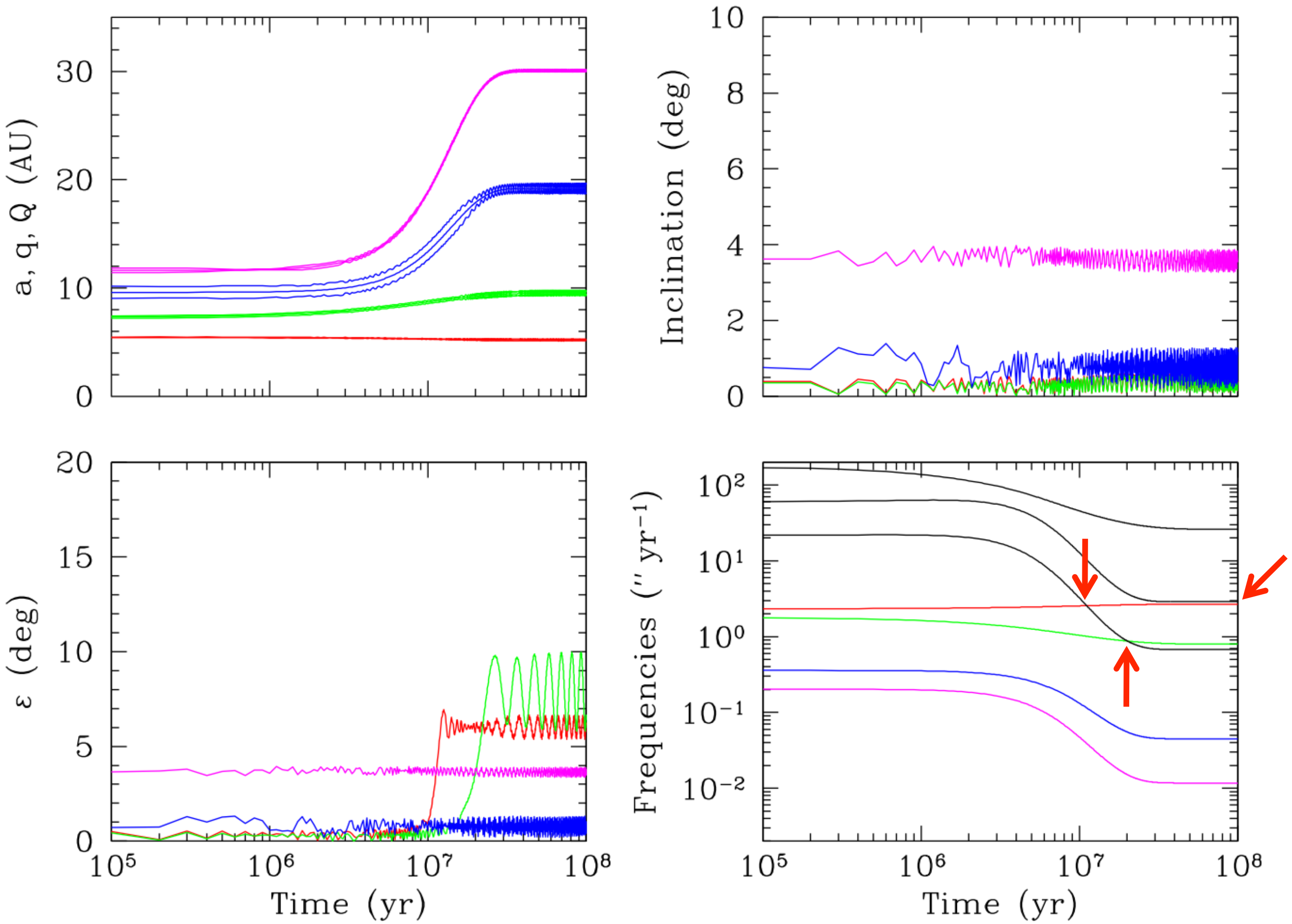
- Imposed migration of planets on timescale τ.
- Planets interact according to secular Laplace-Lagrange equations.
- Spin evolution due to torques from the Sun and mutual planetary interactions.

N-body Simulations

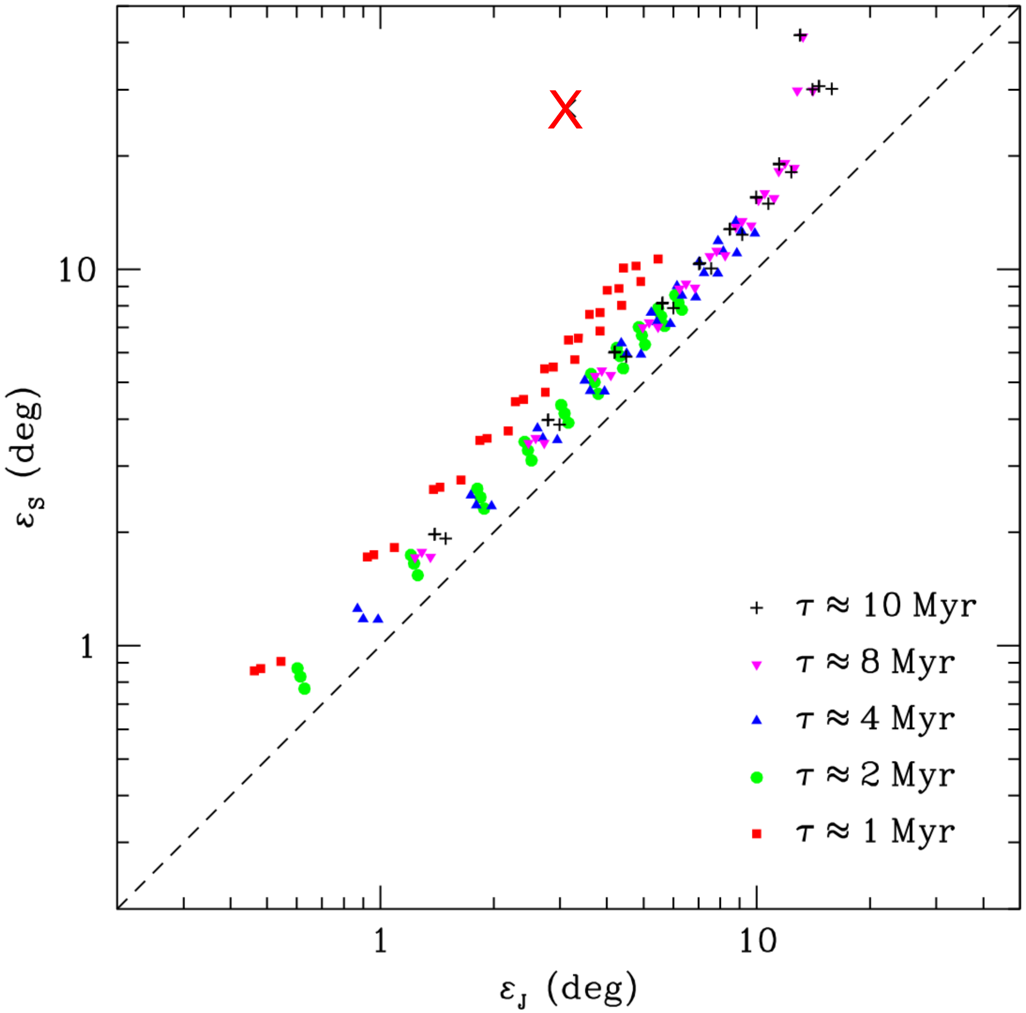
- *N*-body code SyMBA modified to include spin evolution due to torques from the Sun and mutual planetary interactions (Lee et al. 2007).
- Recursively subdivided timestep used by SyMBA to handle close encounters between the planets also implemented for spin evolution due to planetary torques.
- 2000 planetesimals in a disk outside the outermost ice giant.
- 1280 simulations for each migration model.

Secular Simulations of Resonant Nice Model

τ = 10Myr, i_N = 4°



ε_S vs ε_J from simulations with τ = 1-10 Myr and i_N = 1-10°

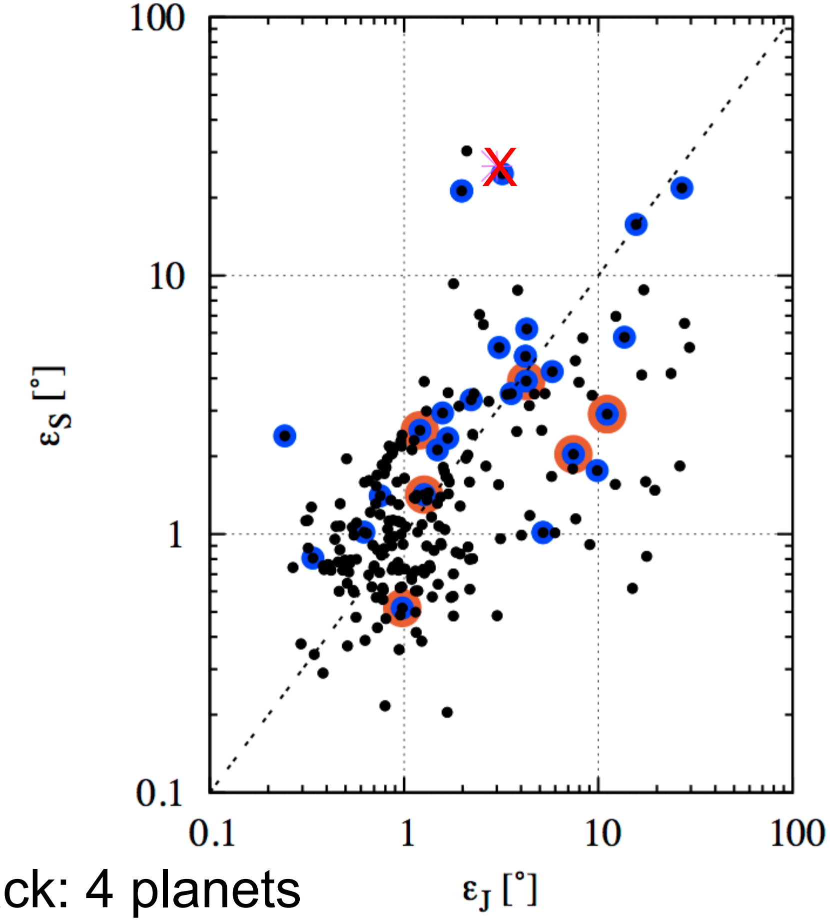


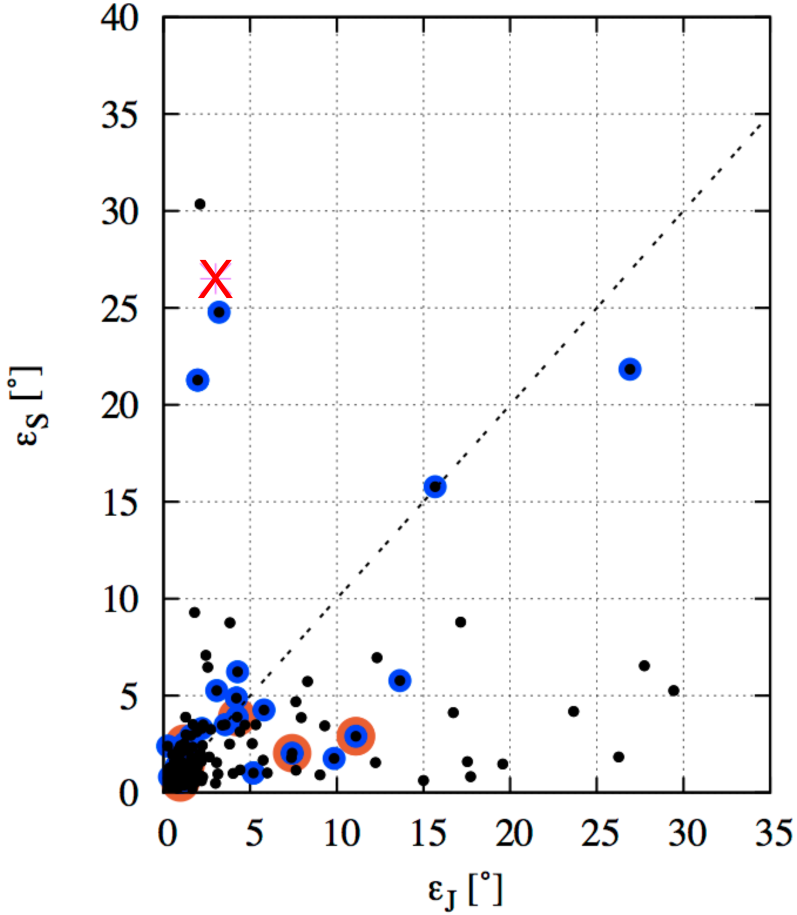
- $|s_8|$ must cross Jupiter's spin precession frequency to reach Saturn's and $\varepsilon_J \sim \varepsilon_S$.

- Secular model leaves out many relevant dynamical effects.
- Could it be that migration during the encounter phase was fast enough to avoid tilting Jupiter while a late very slow migration of Neptune to its final location tilted Saturn?

N-body Simulations

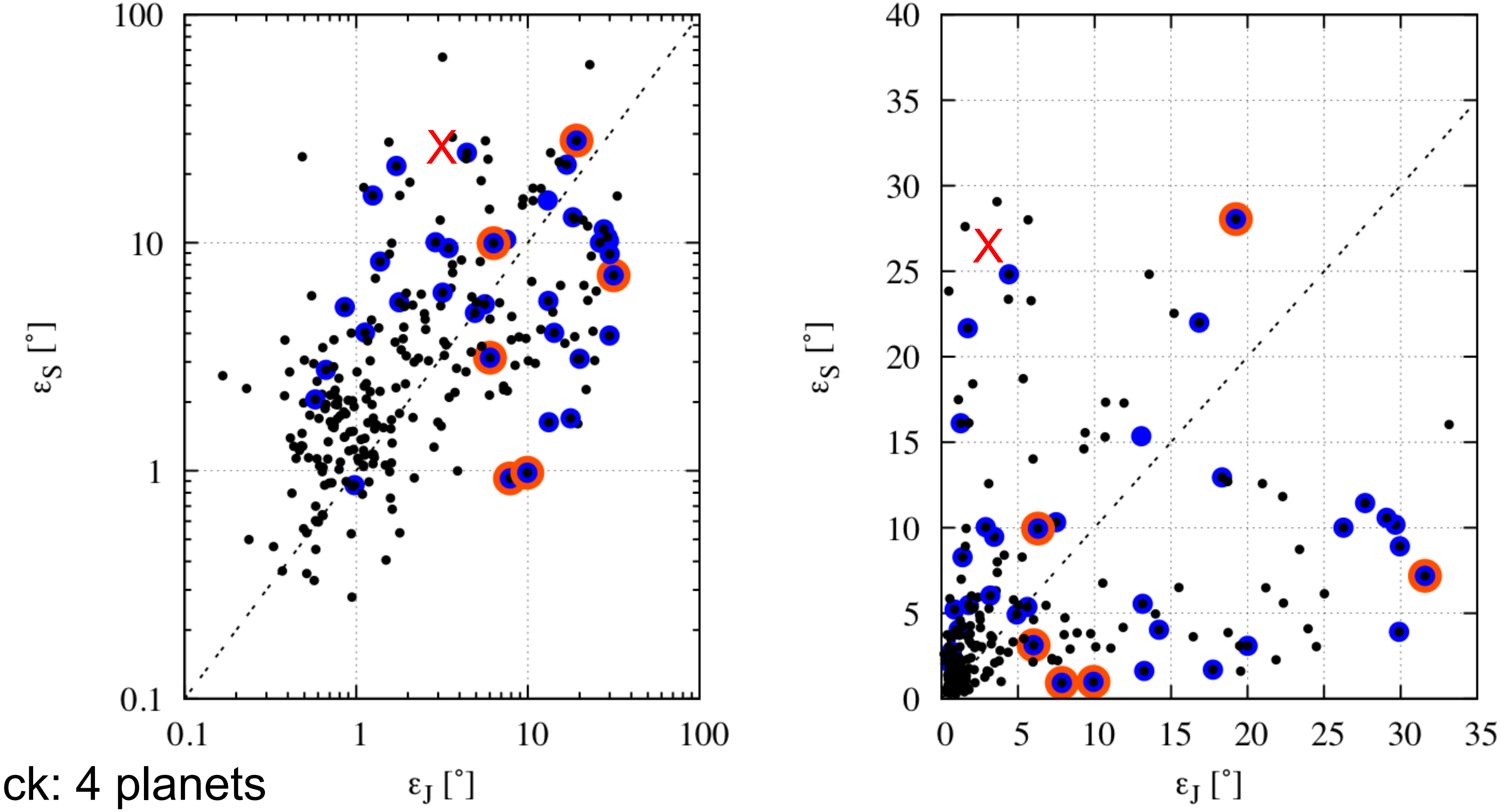
Resonant Nice Model with 50 $M_\oplus$ Disk





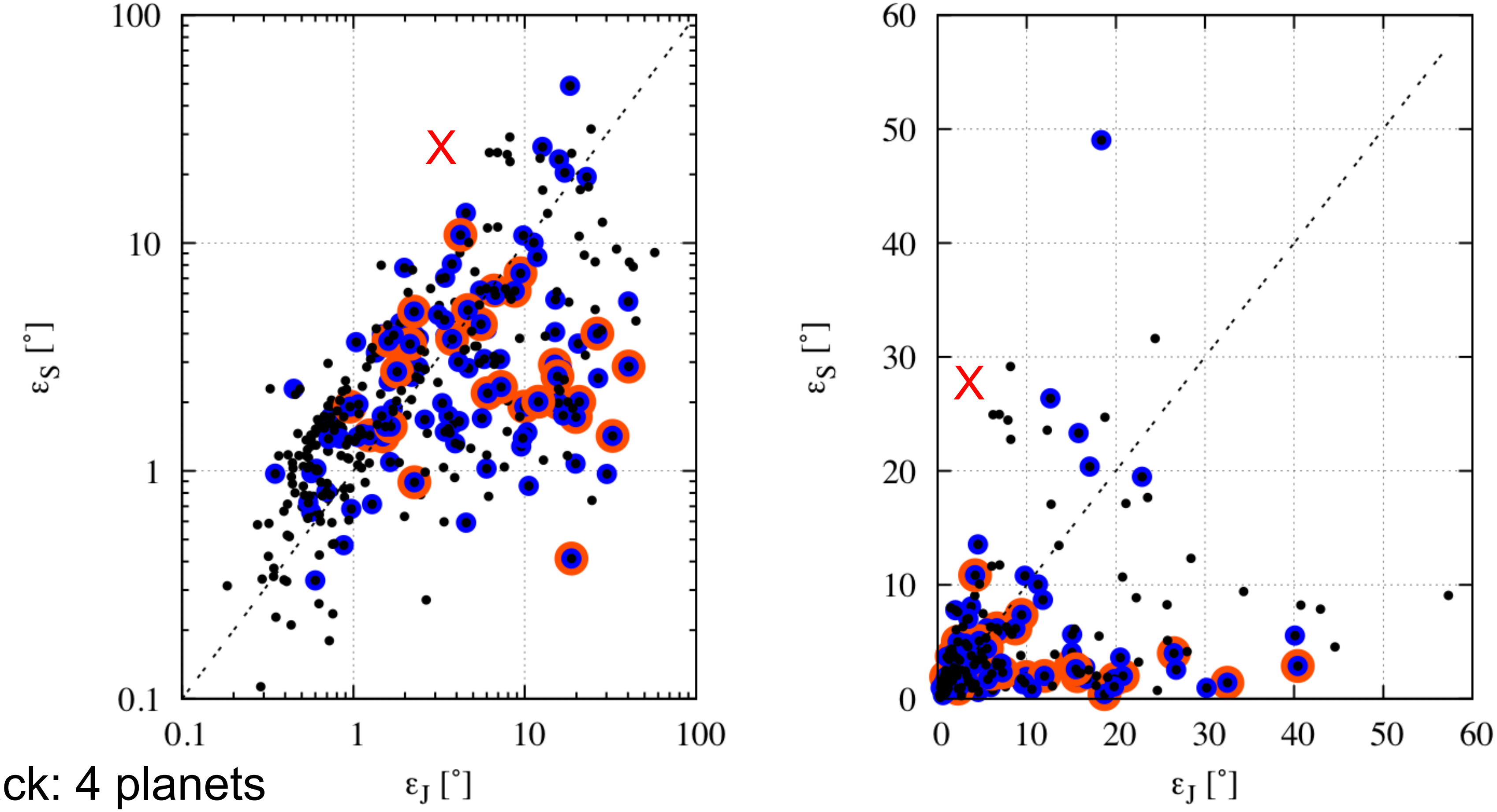
- Black: 4 planets
- Blue: *a* within 10%
- Red: All orbital constraints

Compact 5-Planet Model with 35 $M_\oplus$ Disk



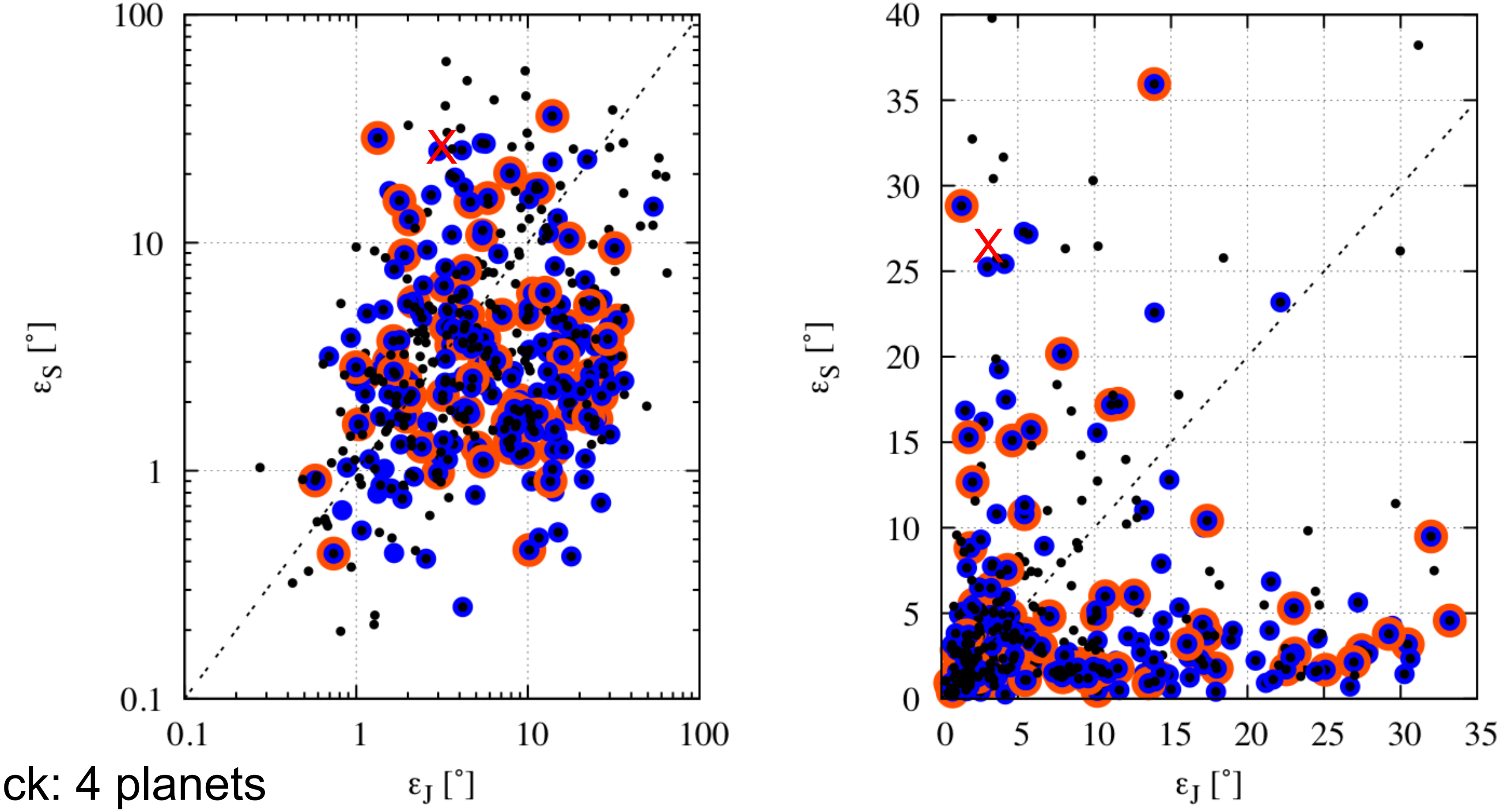
- Black: 4 planets
- Blue: *a* within 10%
- Red: All orbital constraints

Loose 5-Planet Model with 35 $M_\oplus$ Disk



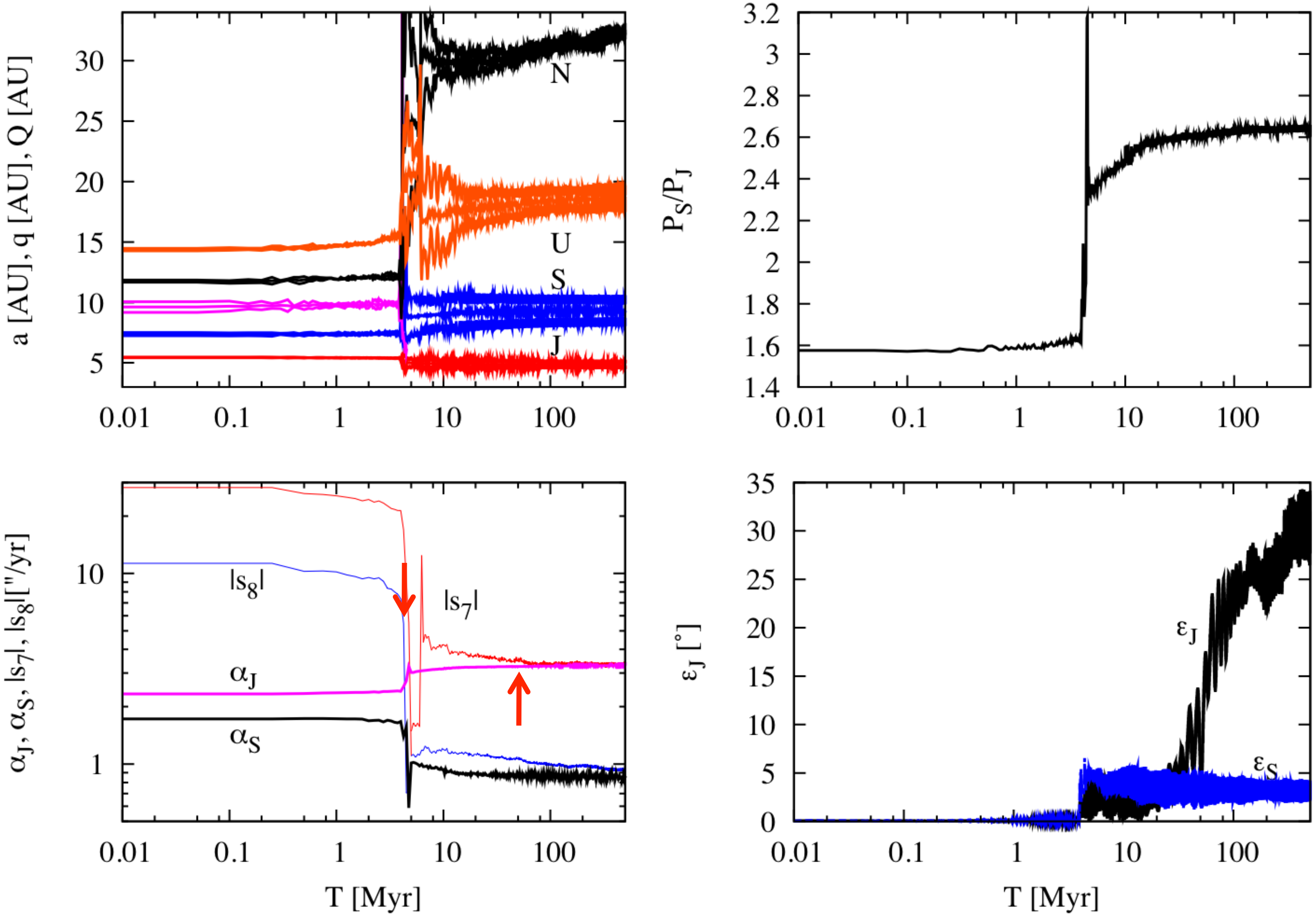
- Black: 4 planets
- Blue: *a* within 10%
- Red: All orbital constraints

Compact 5-Planet Model with 50 $M_\oplus$ Disk



- Black: 4 planets
- Blue: *a* within 10%
- Red: All orbital constraints

- Unsuccessful Example:



- Successful Example:

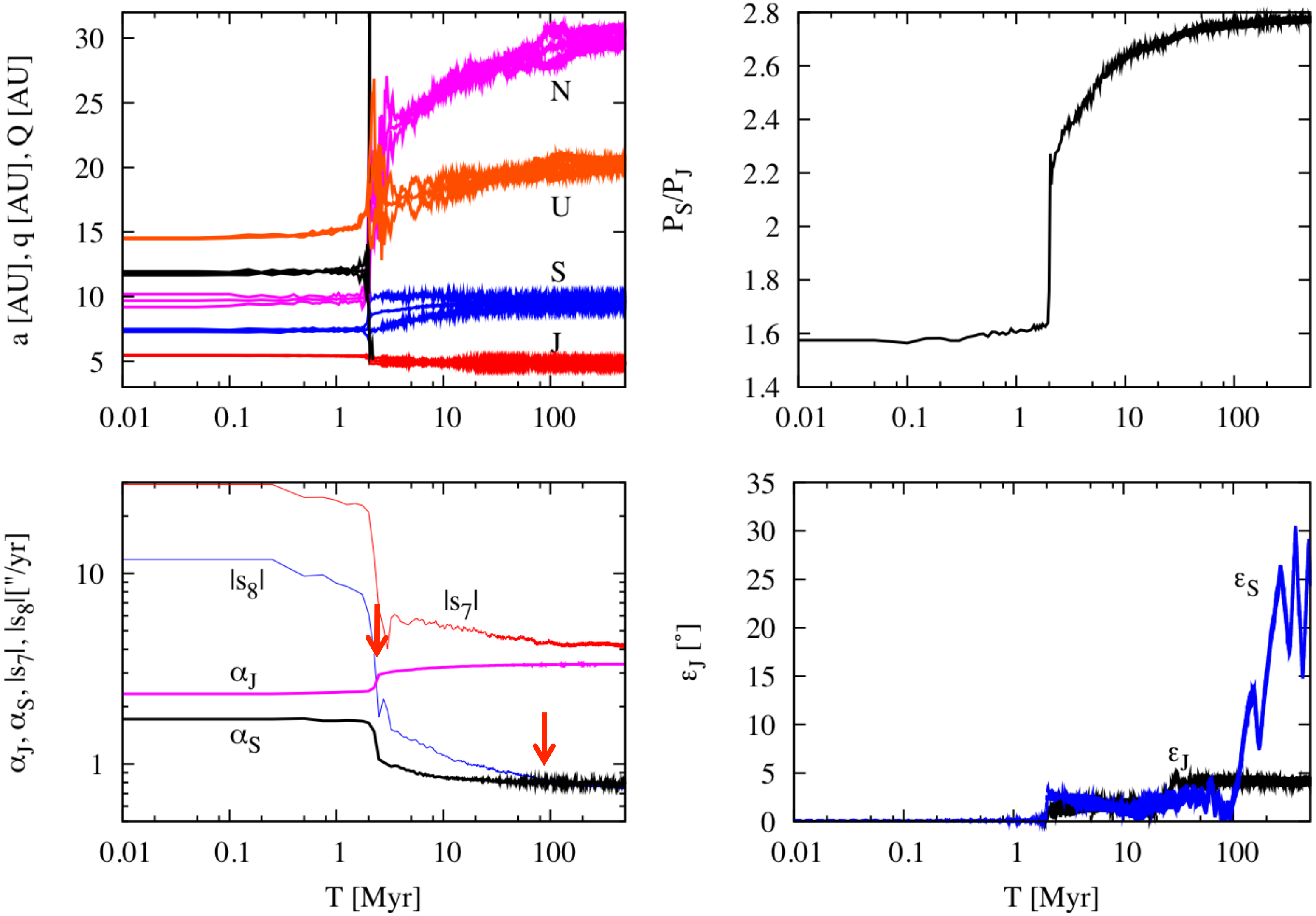


Table 1: Statistics of N-body Simulation Results

Model	M_{d}	a_{N}	f_4	f_a	f_{ϖ}	f_{ε}
3:2 3:2 4:3	50 $M_{\oplus}$	11.6 AU	34%	2.3%	0.5%	<0.08%
3:2 3:2 4:3 4:3	35 $M_{\oplus}$	14.2 AU	33%	2.8%	0.46%	<0.08%
3:2 3:2 2:1 3:2	20 $M_{\oplus}$	22.2 AU	25%	8.3%	2.3%	<0.08%
3:2 3:2 4:3 4:3	50 $M_{\oplus}$	14.2 AU	33%	17%	6.6%	0.4%

Summary

- The high probability of ejecting an ice giant in the Nice model has led to the resonant 5-planet model.
- The obliquities of Jupiter and Saturn provide constraints on the migration and encounter history of the giant planets.
- Both the resonant Nice and nominal 5-planet models fail to simultaneously reproduce the orbital and spin properties of the giant planets.
- Only a compact 5-planet model with a heavier disk has a low probability of matching both constraints, but it is still more likely to produce a Jovian obliquity that is too large.