Early Solar System dynamical instability triggered by dispersal of Sun's gaseous disk

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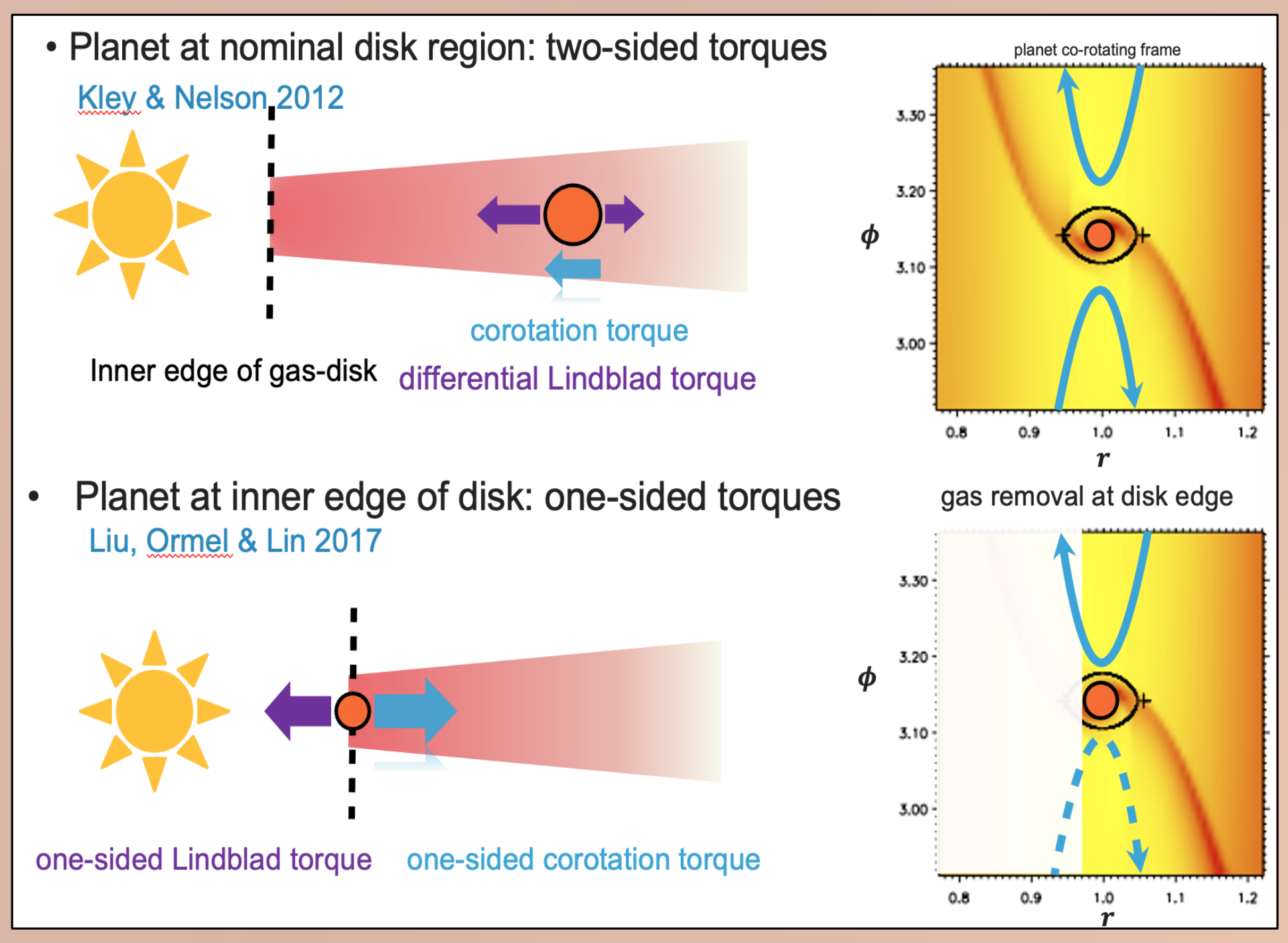
1. Abstract

The Solar System's orbital structure is thought to have been sculpted by an episode of dynamical instability among the giant planets[1-2]. However, the instability trigger and timing have not been clearly established. Hydrodynamical modeling has shown that while the Sun's gaseous protoplanetary disk was present the giant planets migrated into a compact orbital configuration in a chain of resonances[3]. Here we use dynamical simulations to show that the giant planets' instability was likely triggered by the dispersal of the gaseous disk. As the disk evaporated from the inside-out, its inner edge swept successively across and dynamically perturbed each planet's orbit in turn. The associated orbital shift caused a dynamical com- pression of the exterior part of the system, ultimately triggering instability. The final orbits of our simulated systems match those of the Solar System for a viable range of astrophysical parameters. The giant planet instability therefore took place as the gaseous disk dissipated, constrained by astronomical observations to be a few to ten million years after the birth of the Solar System[4]. Terrestrial planet formation would not complete until after such an early giant planet instability; the growing terrestrial planets may even have been sculpted by its perturbations, explaining the small mass of Mars relative to Earth[5].

2. Migration is different at inner disk edge

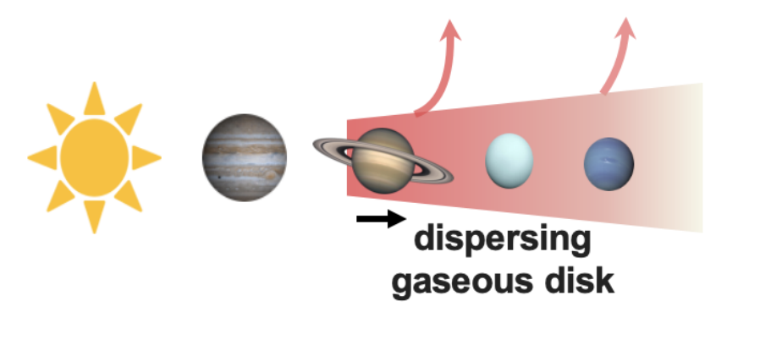
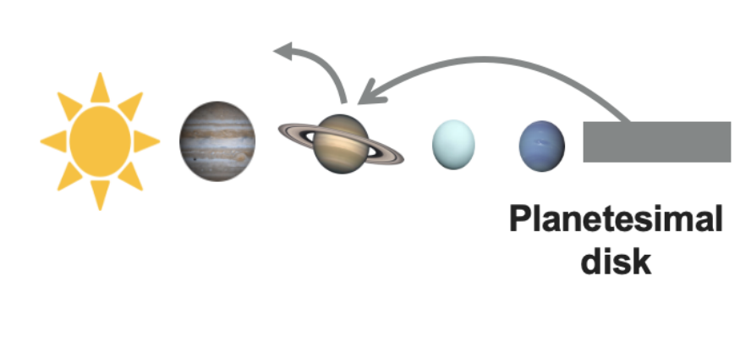


1) When the planet is far from the inner disk edge, it experiences torques from the disk gas on both sides, known as differential Lindblad and corotation torques.
2) As the planet reaches the disk edge, the inner Lindblad torque diminishes. Due to the rapid removal of gas at the front edge, the gas parcel's horseshoe orbit becomes axisymmetric. The gas during the upper U-turn imparts more angular momentum to the planet than it receives from the planet during the lower U-turn, resulting in a positive corotation torque. A planet with certain planet-mass and disk conditions could undergo outward migration (termed as rebound [6]).

4. Method

We perform N-body numerical simulations using the publicly available code HERMIT4. The giant planets are initially placed in resonance orbits during the dispersing phase of gaseous disks. The code incorporates planet-gas disk interaction by implementing Liu et al.'s (2017) torque recipes. We vary the initial number of giant planets (4, 5, and 6), resonance states (2:1, 3:2, and a hybrid of 2:1 and 3:2), and gas disk parameters. Over 14,000 simulations have been conducted by Monte Carlo sampling these initial conditions.

6. Model comparison

Metrics	Rebound model	Nice model
schematic		
trigger	planet-**gas** disk interaction	planet-**plt** disk interaction
time after solar system birth	**early** $t \sim 10$ Myr	$t \sim 500 \longrightarrow 100$ Myr

References

scan above for presentations

Our results are published in "**Early Solar System instability triggered by dispersal of the gaseous disk**",Liu, Raymond,Jacobson, Nature 604, 643 (, 2022).
For further information, contact beibei at bbliu@zju.edu.cn

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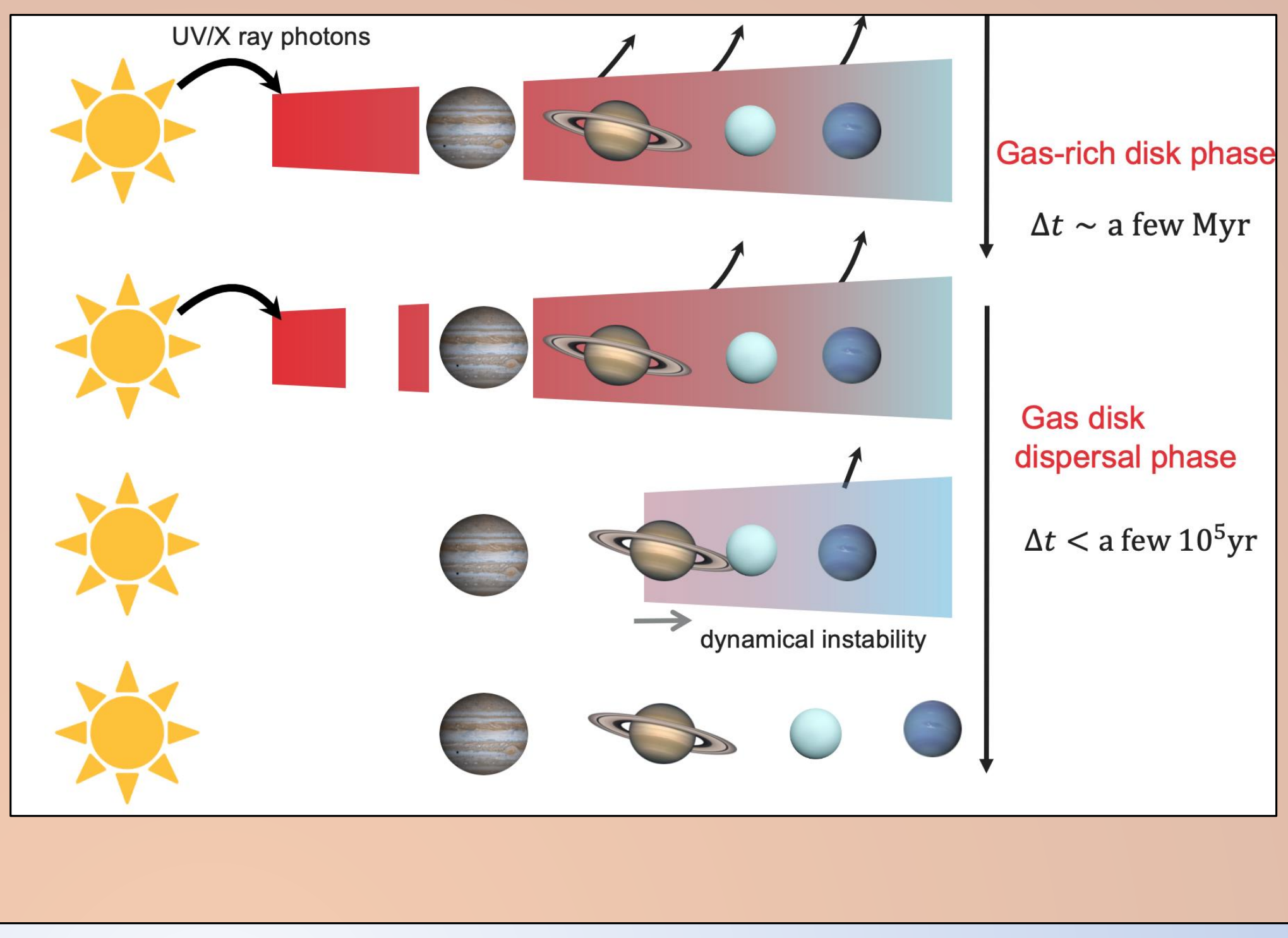
2.Nesvorny, ARAA 56, 137–174 (2018)
3. Morbidelli et al., A&A 134, 1790–1798 (2007)
4.Williams et al., ARAA 49, 67–117 (2011)
5.Clement et al., *Icarus* 311, 340–356 (2018)
6. Liu et al., A&A 601, A15 (2017)
7. Alexander et al., *Protostars and Planets VI*, 475 (2014)

3. Schematic



1 Giants form and migrate into resonant orbits in the gas-rich disk phase.

2. Stellar photoevaporation dominates the later dispersal phase. An inner hole is generated, causing the disk to dissipate from the inside out[7].

3. Inner disk edge moves outward, triggering the rebound planet migration.

4. Following the dynamical instability, the remaining four planet orbits expand into the observed non-resonant states.

5. Results

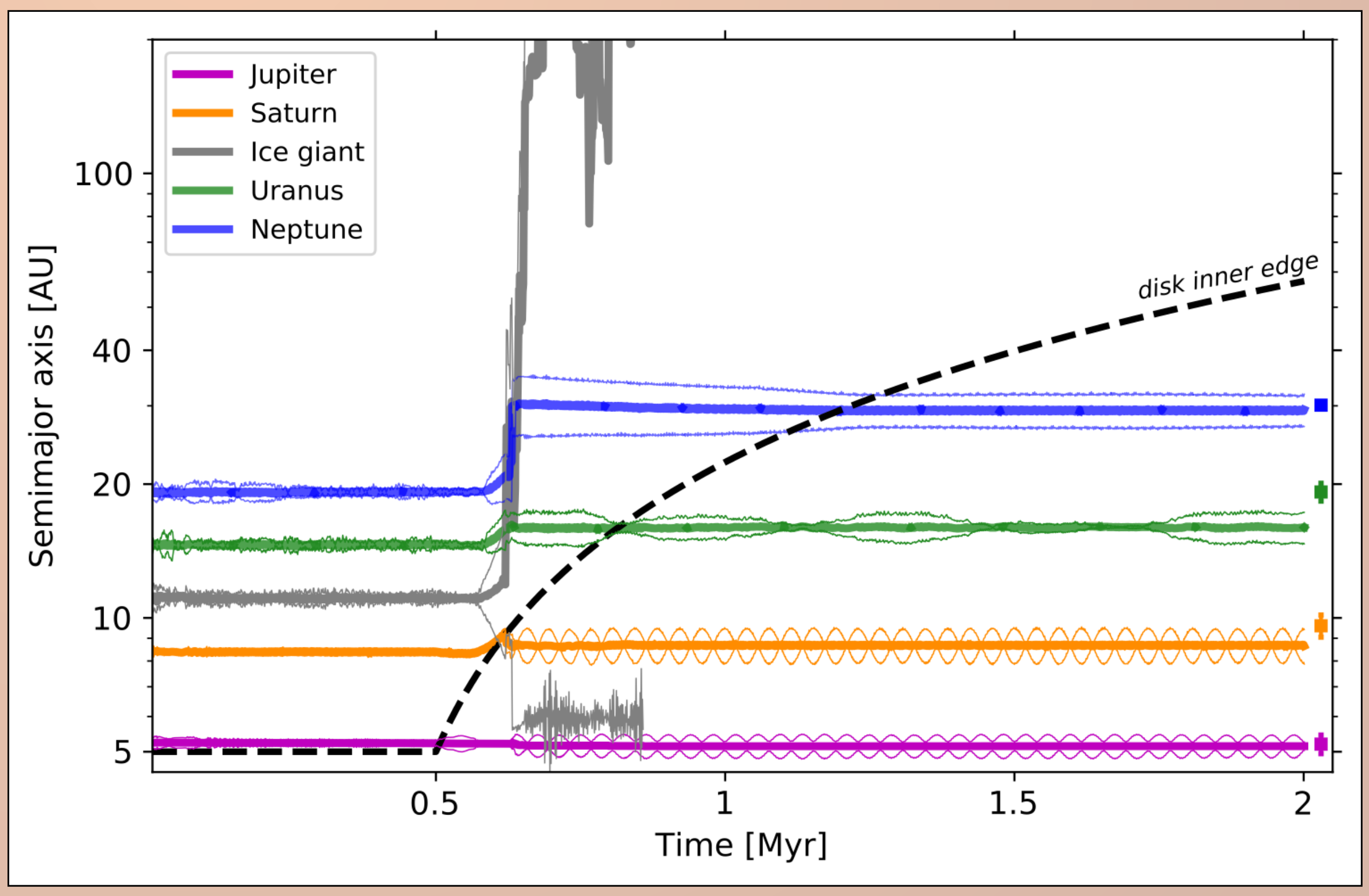
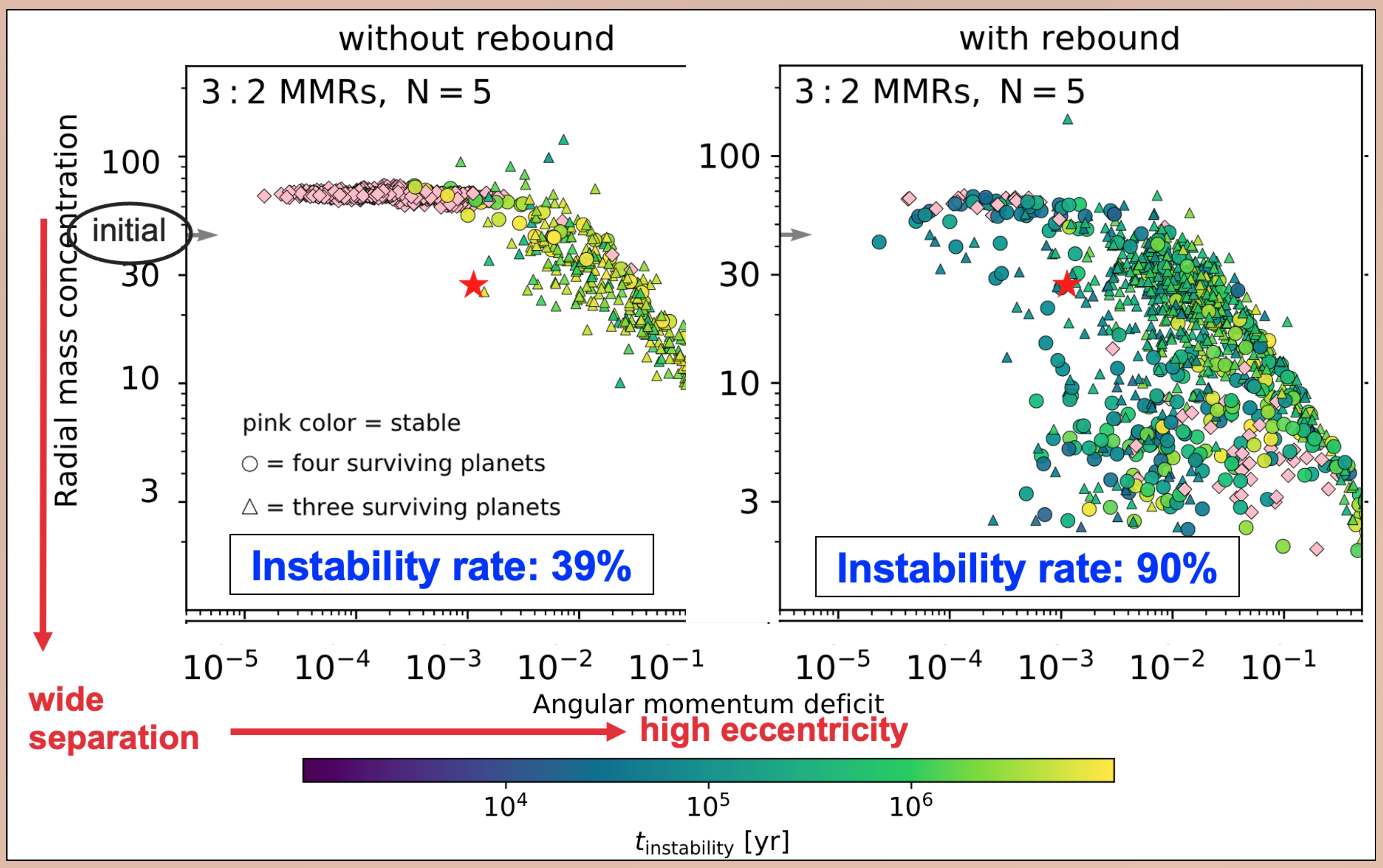


Illustration of early dynamical instability triggered by the dispersal of the Sun's protoplanetary disk.

The initial system consisted of five giant planets: Jupiter, Saturn, and three 15 M_E ice giants, one of which was ejected into interstellar space during the instability. The curves show the orbital evolution of each body including its semimajor axis (thick), perihelion and aphelion (thin). The black dashed line tracks the edge of the disk's expanding inner cavity. We don't follow the early gas-rich disk phase, so the onset of disk dispersal is set arbitrarily to be 0.5 Myr after the start of the simulation.



Metrics for surviving simulated systems in matching the Solar System

The simulations on the left included the rebound effect and those on the right did not. Each simulation started with our four present-day giant planets plus one additional ice giant planet that trapped in 3:2 orbital resonances. Each symbol represents the outcome of a given simulation at t=10 Myr. The color indicates the timing of the instability after the start of gas disk dispersal; pink systems did not undergo an instability (no collision and/or ejection). Diamonds, circles, and triangles correspond to systems with five, four, and three or fewer surviving planets, respectively. The arrow gives the initial radial mass concentration of the system. The Solar System is marked as a red star for comparison. The instability rate gets enhances and the surviving systems better matches the Solar System when rebound is included.