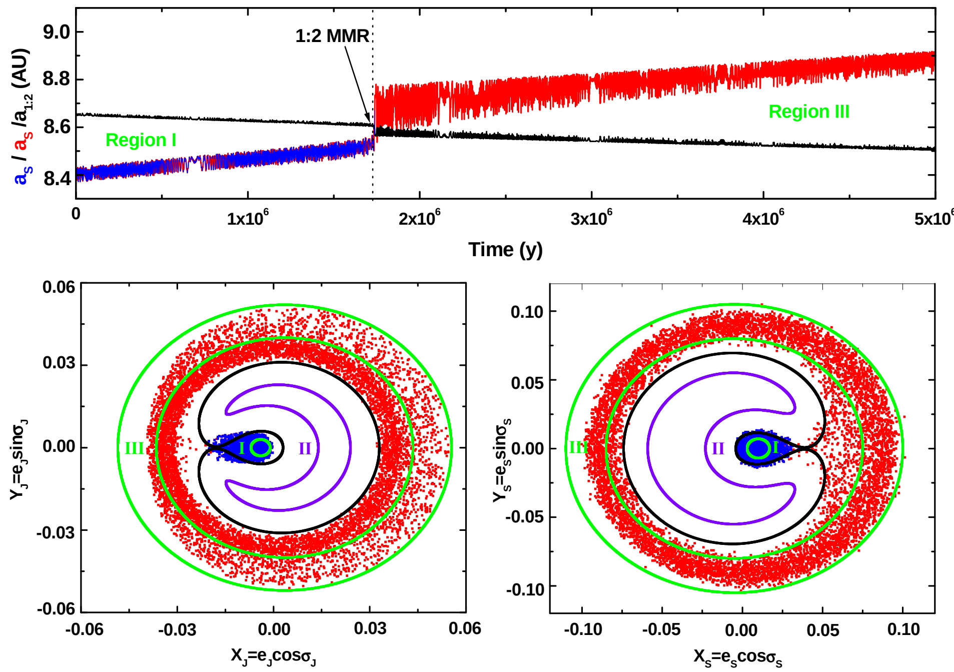
Supplemental Material



A Detailed illustration of the 1:2 MMR crossing of Jupiter and Saturn.

The top panel shows the semi-major axis of Saturn (blue/red curve) and the exact location of the 1:2 MMR with Jupiter (black curve) as functions of time. The dotted vertical line marks the time of resonance crossing at $t = 1.72$ My.

The bottom panels show the dynamical structure of the 1:2 resonance for Jupiter (left) and Saturn (right) respectively. The natural way to represent the resonance dynamics is with polar coordinates, with the eccentricity e as the radius and the so-called critical argument of the resonance σ as the angle. In this case, the critical argument of the resonance felt by Jupiter is $\sigma_J = \lambda_J - 2\lambda_S + \varpi_J$ while that of the resonance felt by Saturn is $\sigma_S = \lambda_J - 2\lambda_S + \varpi_S$, where λ and ϖ are the mean longitude and the longitude of perihelion, respectively, and the index J/S refers to Jupiter/Saturn (see chapter 9 of [S1]). The curves in the bottom panels are free hand illustrations of the dynamics near and inside the resonance. The green curves represent orbits in the non-resonant regions. There are two of such regions. Region I, at small eccentricity, is called the region of 'apocentric libration' or 'inner circulation', while Region III, at large eccentricity ($e \gtrsim 0.05$), is called the region of 'external circulation'. The banana-shaped violet curves represent orbits in the resonant Region II. Along these orbits the critical angle σ librates. The border between all three regions is the black self-crossing curve, called the 'separatrix'. Regions I and III only touch each other at the crossing point (or **X** point) of the separatrix, which is an unstable equilibrium point of the dynamics.

As the planets approach exact resonance during migration, the **X** point moves toward smaller eccentricities, i.e. Region I shrinks and Region III grows. Adiabatic theory [S2-S4] predicts that Jupiter and Saturn should continue to evolve in Region I (blue dots in the bottom panels, which correspond to the temporal evolution in the top panel before $t = 1.72$ My), until Region I shrinks so much that its area becomes smaller than that filled by the planets' evolution. When this occurs, the **X** point touches the region inhabited by the planet. The curves drawn in the bottom panels are intended to represent a snapshot of the dynamics at this exact instant. At this time, the planets must jump from Region I to Region III (red dots), by passing through the 'X' point. This, in turn, causes a jump in eccentricity. Because of the conservation of the actions $2\sqrt{a_J} - \sqrt{a_J(1-e_J^2)}$ and $\sqrt{a_S} - 2\sqrt{a_S(1-e_S^2)}$, the jumps of the eccentricities are correlated with a jump of the semi-major axes a_J, a_S. The jump of a_S is visible in the top panel at the transition from the blue to the red color.

The amplitude of the eccentricity jump can be quantitatively predicted from the shape of the separatrix curve at the moment of resonance crossing, and is a function of the planetary masses. Thus, the eccentricity excitation mechanism advocated in the main text is a deterministic one, which explains why all our simulations gave similar results (the differences being due to the evolution after the resonance crossing, which depends on the interactions of Jupiter and Saturn with the ice giants and the disk particles). We emphasize that this resonance jumping occurs because the planets migrate in divergent directions. If the two planets were approaching each other, adiabatic theory predicts that they could be trapped in resonance (i.e. enter into Region II) (see [S5] for an example).

To illustrate the resonance crossing dynamics in detail and avoid additional ‘noise’, the simulation presented here is not one of the simulations presented in the main text. It has been performed by integrating the equations of motion of the Sun-Jupiter-Saturn system alone (no disk, no ice giants), with an additional drag force acting on the planets, using a now standard technique [S5]. The drag force was designed so to force the two planets to migrate at the same rate as seen in our $N-$body simulations.

References:

[S1] Morbidelli, *Modern Celestial Mechanics: aspects of Solar System dynamics*, in “Advances in Astronomy and Astrophysics”, Taylor & Francis. (2002).

[S2] Henrard, J. Capture into resonance - an extension of the use of adiabatic invariants. Celestial Mechanics 27, 3-22. (1982).

[S3] Henrard, J., Lemaitre, A. A mechanism of formation for the Kirkwood gaps. Icarus 55, 482-494. (1983).

[S4] Neishtadt, A. I. Changes in the adiabatic invariant due to separatrix crossing in systems with two degrees of freedom. Prikladnaia Matematika i Mekhanika 51, 750-757. (1987).

[S5] Malhotra, R. The origin of Pluto’s orbit: implications for the Solar System beyond Neptune. Astron. J. 110, 420-432. (1995).