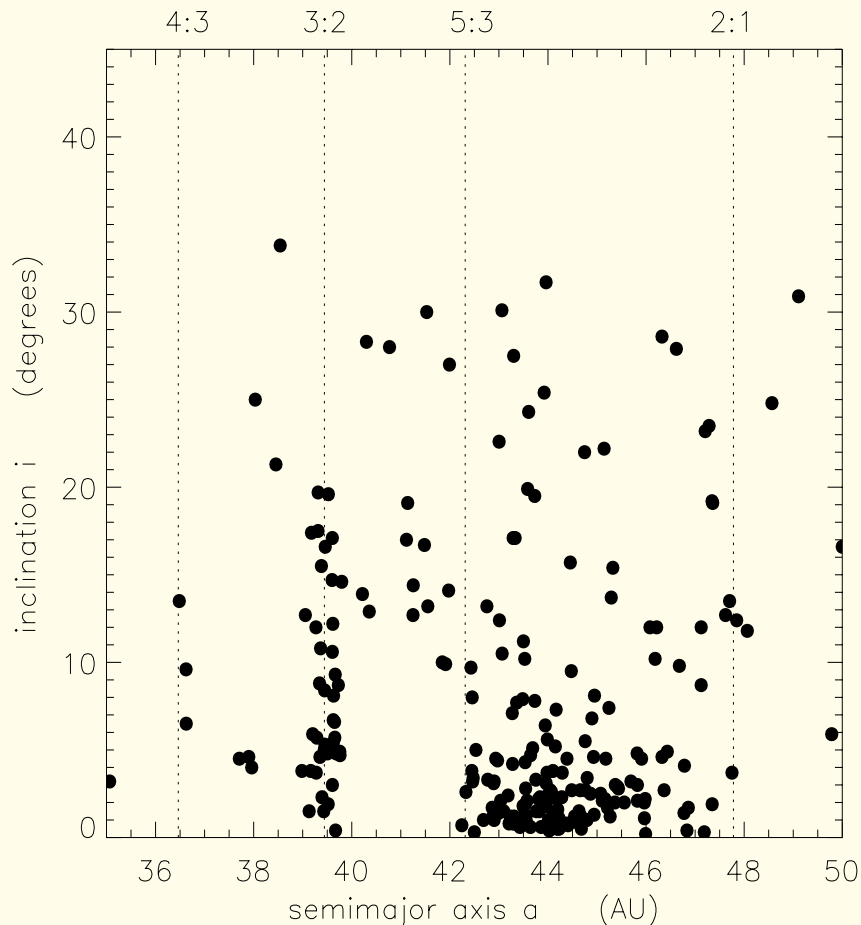


# Secular Resonance Sweeping in a Self-Gravitating Kuiper Belt

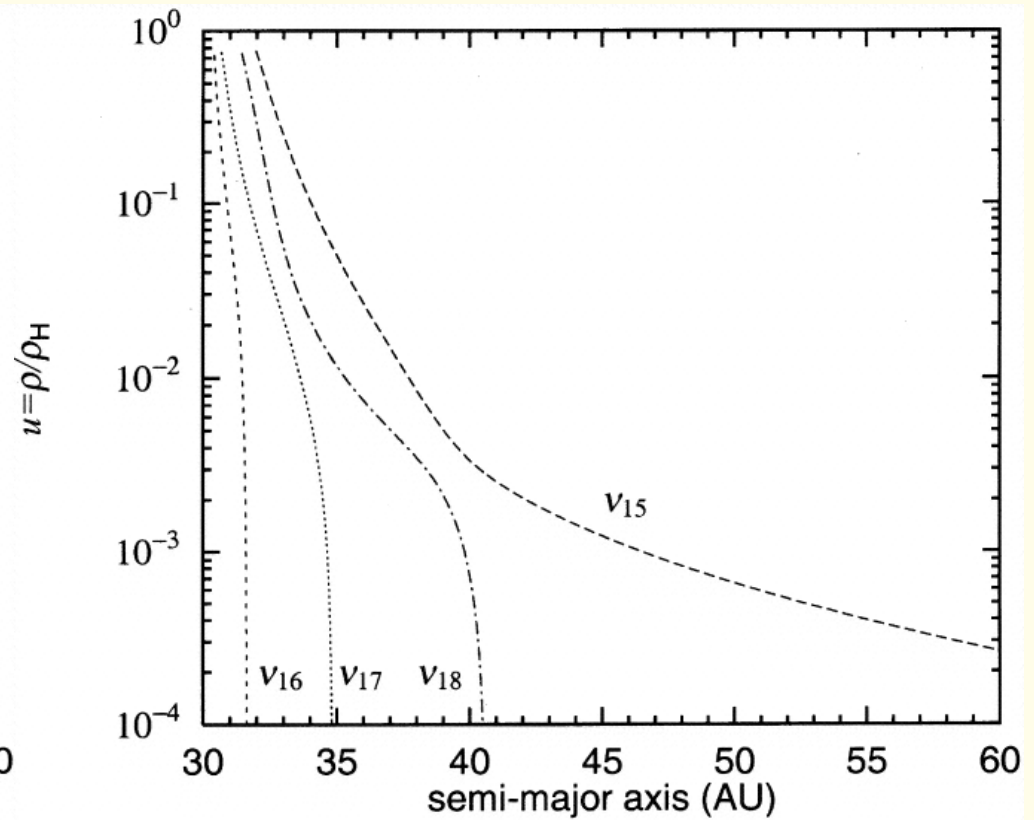
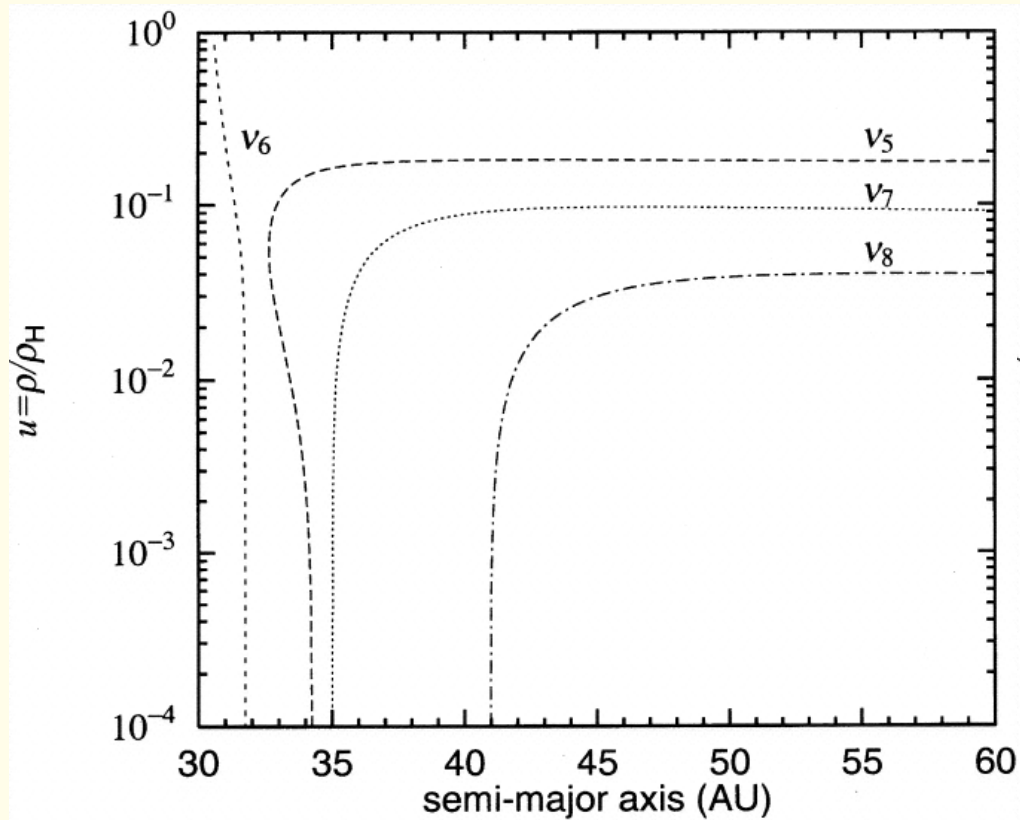
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April 16, 2002

# What Stirred Up the Kuiper Belt?



- Pluto and  $R \sim 100$  km KBOs only form when initially in nearly circular orbits, *i.e.*,  $e_0 \sim \sin i < 0.01$  (Kenyon and Luu 1999).
- However Main Belt KBOs ( $40 \lesssim a \lesssim 50$  AU) are bimodal, *i.e.*,  $i \sim 2^\circ$  and  $i \sim 17^\circ$  (Brown 2001).
- Possible explanations:
  - scattering by giant planets (Levison and Stern 2001),
  - scattering by long-gone protoplanets (Petit *et al* 1999),
  - perturbations from a passing star (Ida *et al* 2000),
  - $i$ -pumping by secular resonances that sweep across the solar system as the solar nebula gas dissipates (Nagasawa and Ida 2000).

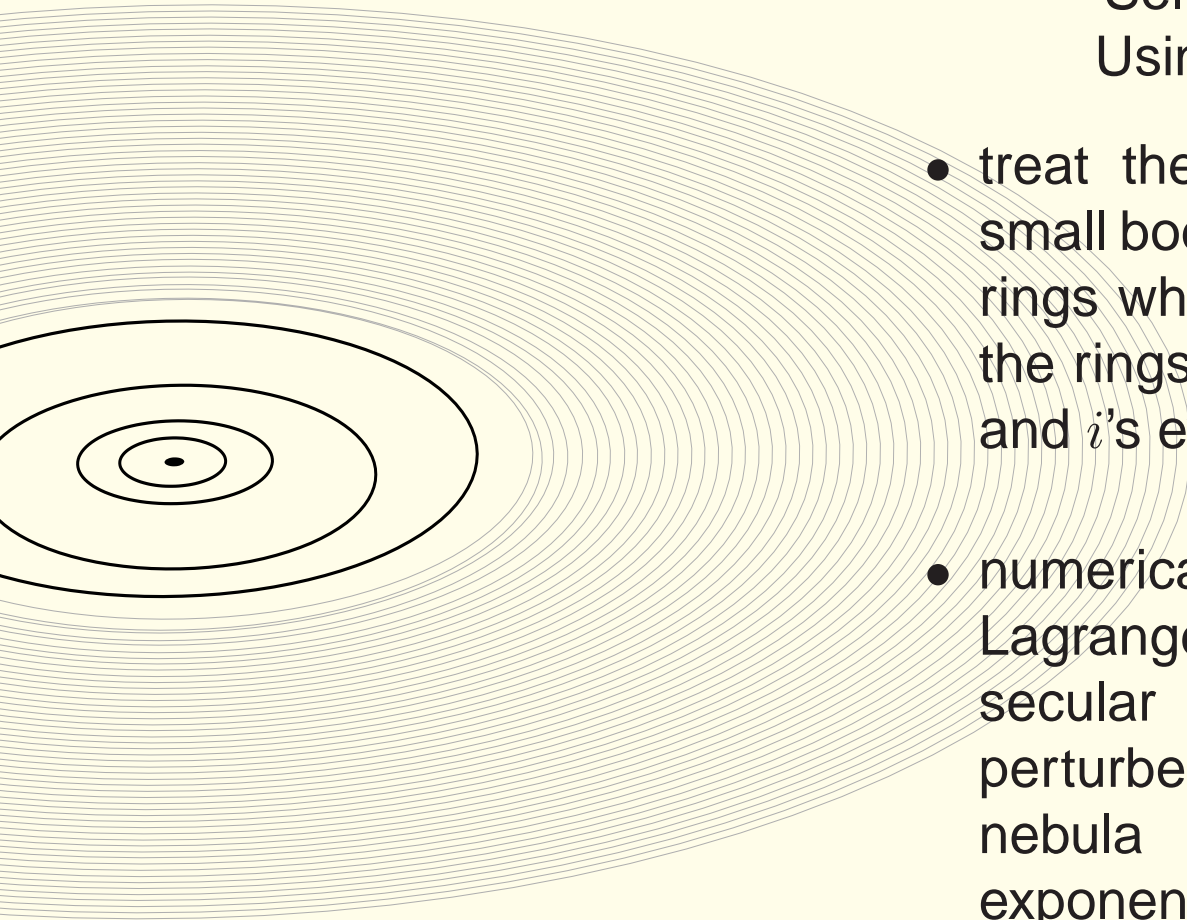


Secular resonances are sites where a small body's orbital precession rates matches one of the solar system's natural eigenfrequencies. Large  $e$ 's are excited at the  $\nu_j$  resonances (left figure) and large  $i$ 's are excited at the  $\nu_{1j}$  (right). Fig's from Nagasawa and Ida (2000) for a *massless* Kuiper Belt.

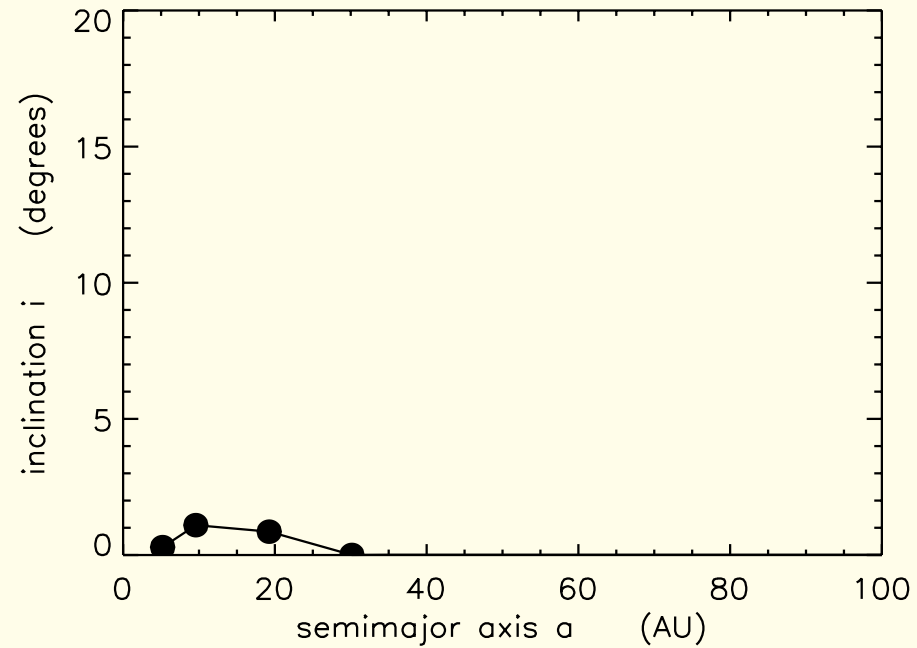
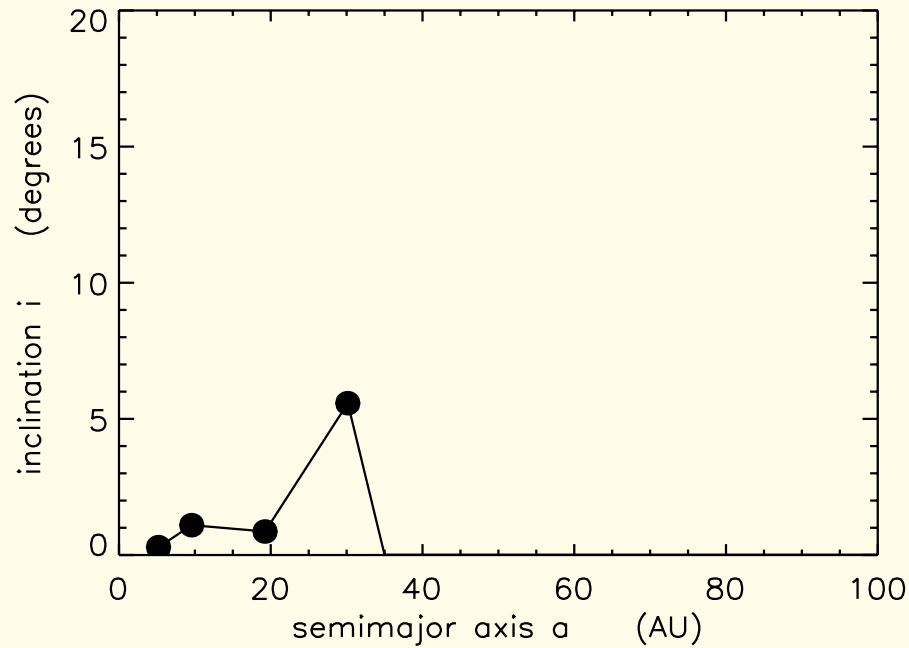
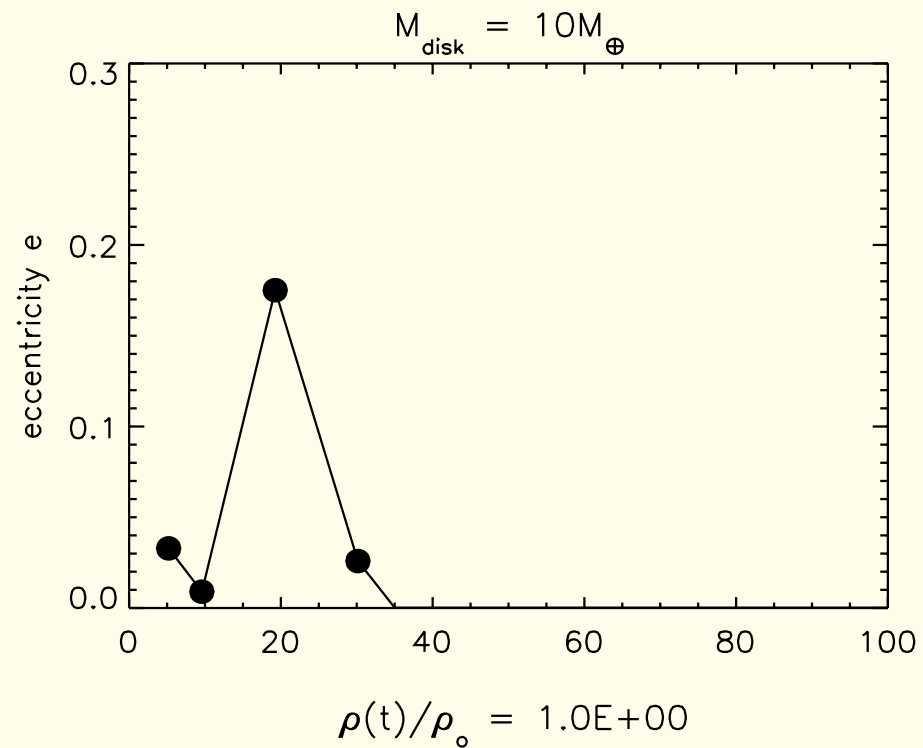
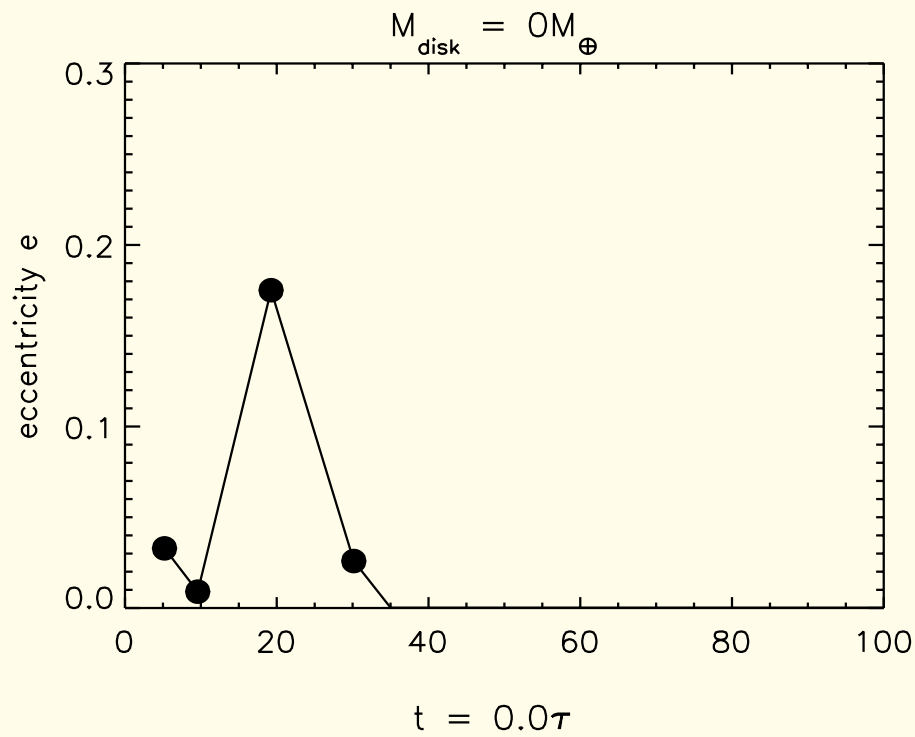
As the solar nebula gas is depleted, the  $\nu_5$ ,  $\nu_7$ , and the  $\nu_8$  resonances sweep inwards across the KB and excite eccentricities.

The  $\nu_{15}$  and  $\nu_{18}$  also sweep across the KB and excite inclinations.

# Revisit Sweeping Secular Resonances in a Self-Gravitating Kuiper Belt Using an 'N-Ring' Integrator



- treat the 4 giant planets + numerous small bodies at a set of nested gravitating rings whose mutual perturbations cause the rings to flex and tilt, causing their  $e$ 's and  $i$ 's evolve over time.
- numerically solve the linearized Laplace–Lagrange eqn's of motion for the rings' secular evolution while they are also perturbed by a minimum–mass solar nebula whose gas content decays exponentially over a timescale  $\tau$ .



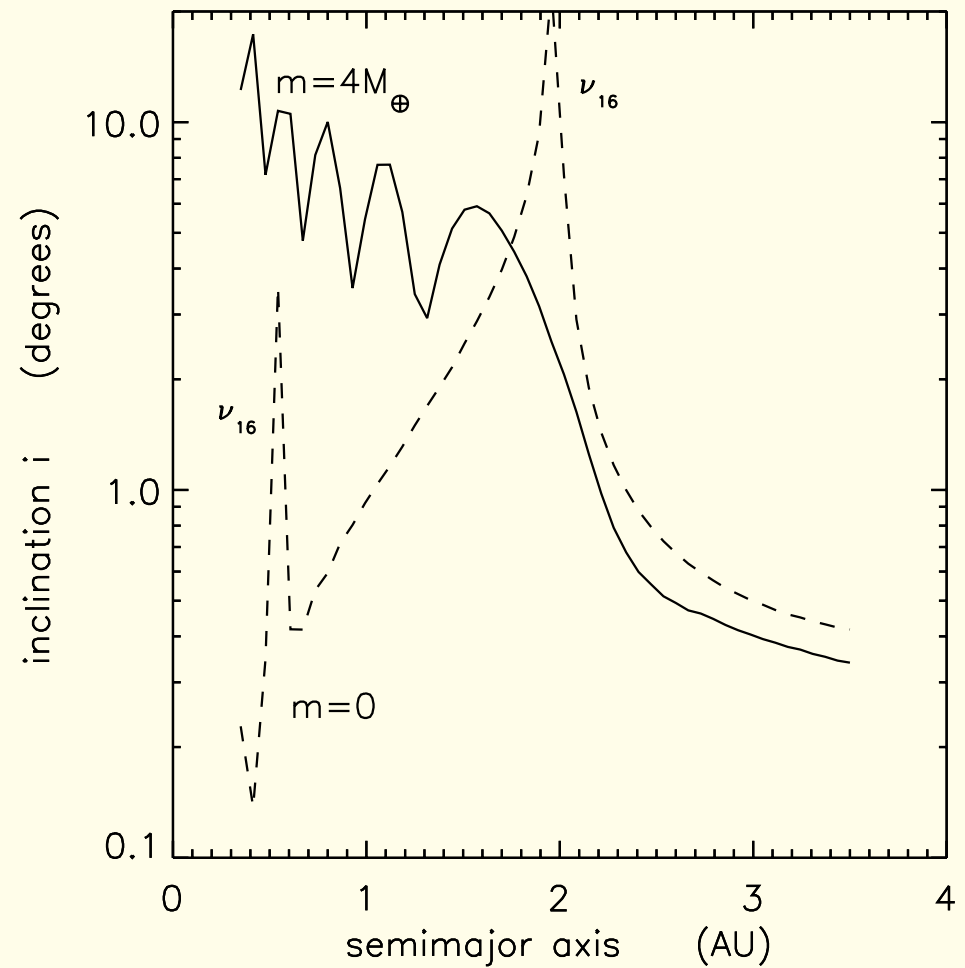
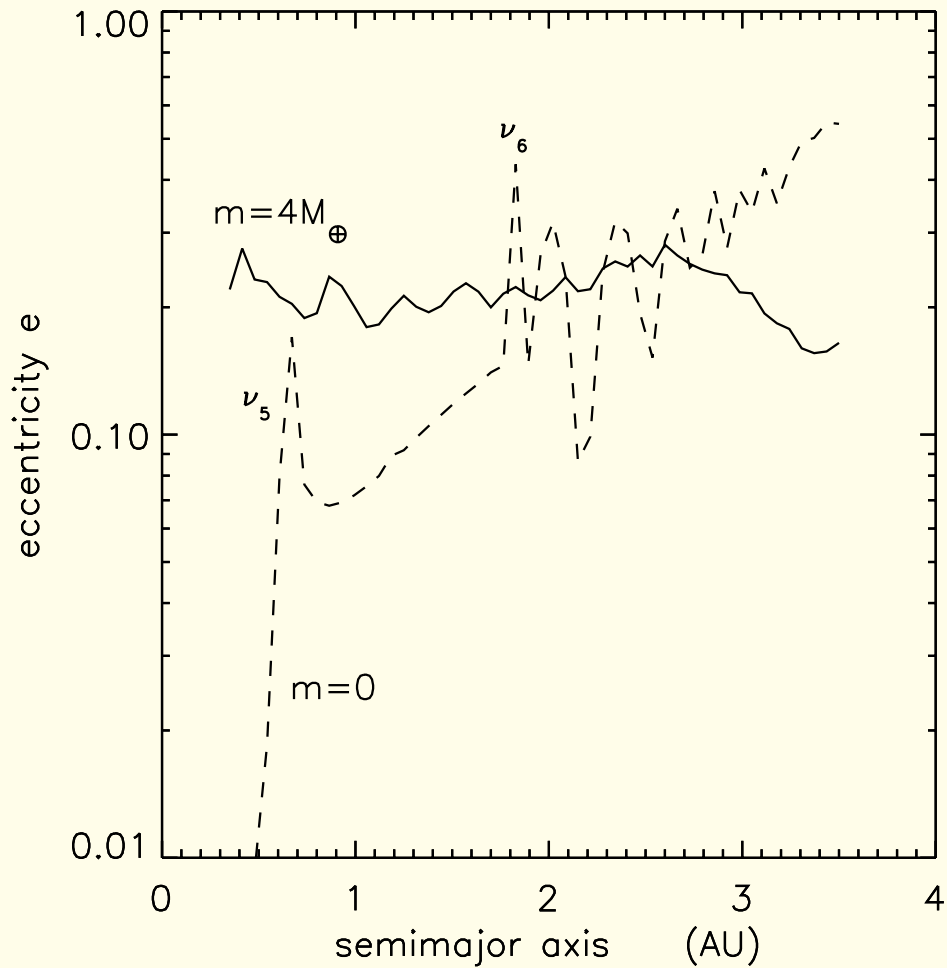
## Results for a Massless Kuiper Belt $M_{disk} = 0$

- Repeats Nagasawa and Ida (2000) result for  $\tau = 10^7$  years.
- sizable eccentricities are excited in the KB over  $30 \lesssim a \lesssim 50$  AU.
- very large inclinations of  $> 10^\circ$  are excited by  $\nu_{18}$  at  $a = 41$  AU and by  $\nu_{15} \rightarrow \infty$ .
- NOTE: Nagasawa and Ida put their nebula in the *ecliptic* which is tilted  $\Delta i = 1.6^\circ$  from the invariable plane.
  - repeating this experiment with the nebula midplane in the giant-planets' invariable plane reduces the  $i$  excitation by *orders of magnitude*.

## Results for a Self-Gravitating Kuiper Belt of mass $M_{disk} = 10 M_{\oplus}$

- This particular simulation has  $\sigma_{solids} \simeq \frac{1}{5} \times$  solids in a minimum-mass nebula. Other runs with  $10 \times$  more/less mass have also been performed.
- When  $t \simeq 2.5\tau$  and  $\rho(t) \simeq 0.1\rho_0$ , the giant planets launch a spiral density wave that propagates from the inner to the outer edge of the KB where it reflects multiple times.
- When  $t \simeq 5\tau$  and  $\rho(t) \simeq 0.01\rho_0$ , a spiral bending wave is launched.
- The effect of the giant planets secular perturbation is analogous to tugging on a sheet:
  - When there is no tension in this Kuiper Belt sheet (*i.e.*, no mass or self-gravity), the giant planets perturbations' generate large-amplitude 'wrinkles' in the inner part of this sheet nearest the planets.
  - But when the sheet has tension (e.g.,  $M_{disk} > 0$ ), the planets' pushes and pulls gets transmitted across the length of this sheet in the form of spiral waves. This results in very low-amplitude excitation that spans the entire KB.

# What About the Asteroid Belt?



Endstate for uniform nebula depletion over  $\tau = 10^5$  years.  
Inside-out erosion of the nebula may yield different results.

# Conclusions

- Secular resonance sweeping due to nebula dispersal can excite the KB only if:
  - $M_{disk}(30 < a < 100 \text{ AU}) \lesssim 1 M_{\oplus}$ , or  
if  $\sigma_{solids} \simeq \frac{1}{50} \times$  solids in a minimum-mass nebula.
  - and if the midplane of the solids has a slight tilt relative to the gas midplane. Sustaining this tilt may be a difficulty since the planets and KBOs accreted from dust that sedimented right in the gas midplane...
- But if  $M_{disk} \gtrsim 1 M_{\oplus}$ , then disk self-gravity allows spiral waves to propagate. This smears the giant planets' perturbations clear across the KB. The excitation is no longer localized in the Main Belt, and low-level excitation instead spans the entire Belt.
- Wave action also redistributes any disturbances occurring in the terrestrial zone, but asteroids still achieve  $e \gtrsim 0.2$  when the nebula is depleted uniformly over a  $\tau \gtrsim 10^5$  year timescale. But other nebula-erosion scenarios (e.g., inside-out) still need to be examined over a range of depletion timescales  $\tau$ .