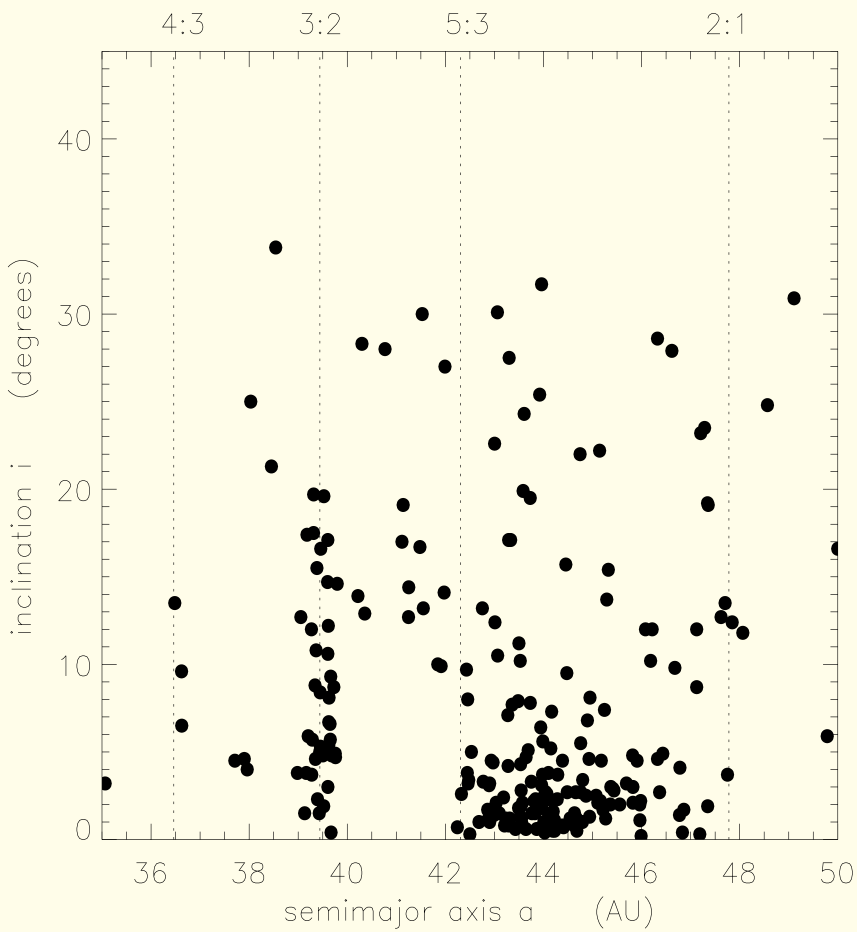
Secular Resonance Sweeping in a Self–Gravitating Kuiper Belt

Joseph M. Hahn (LPI)

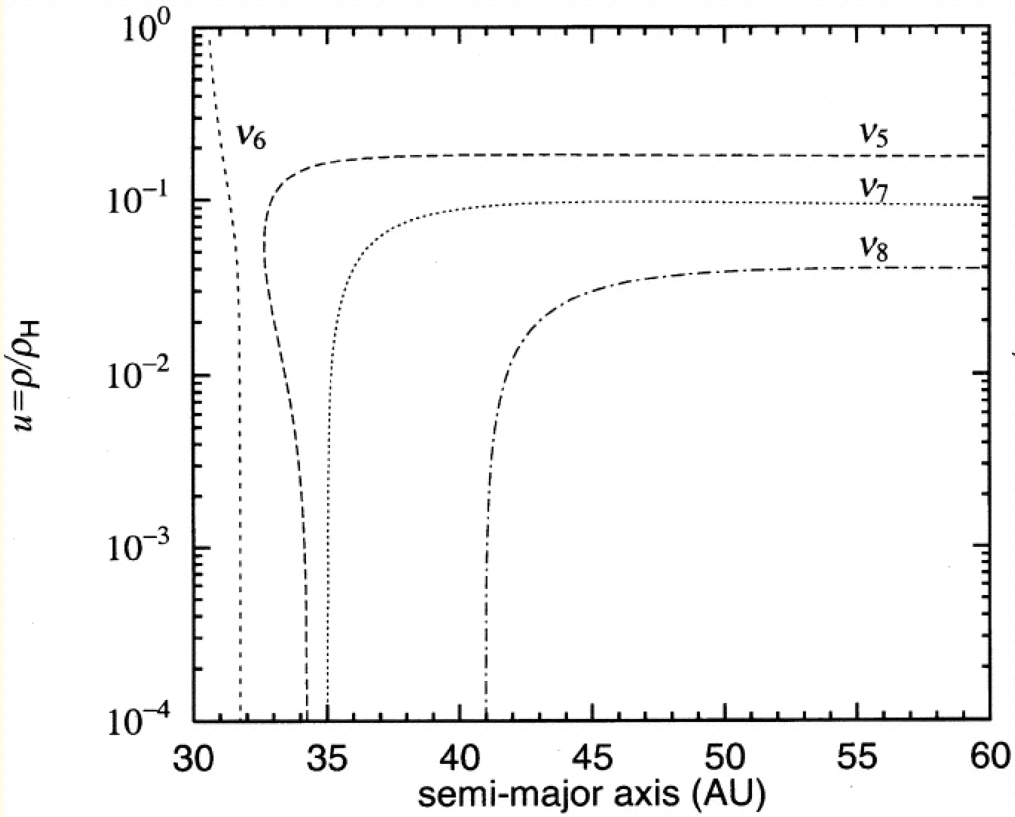
William R. Ward (SWRI)

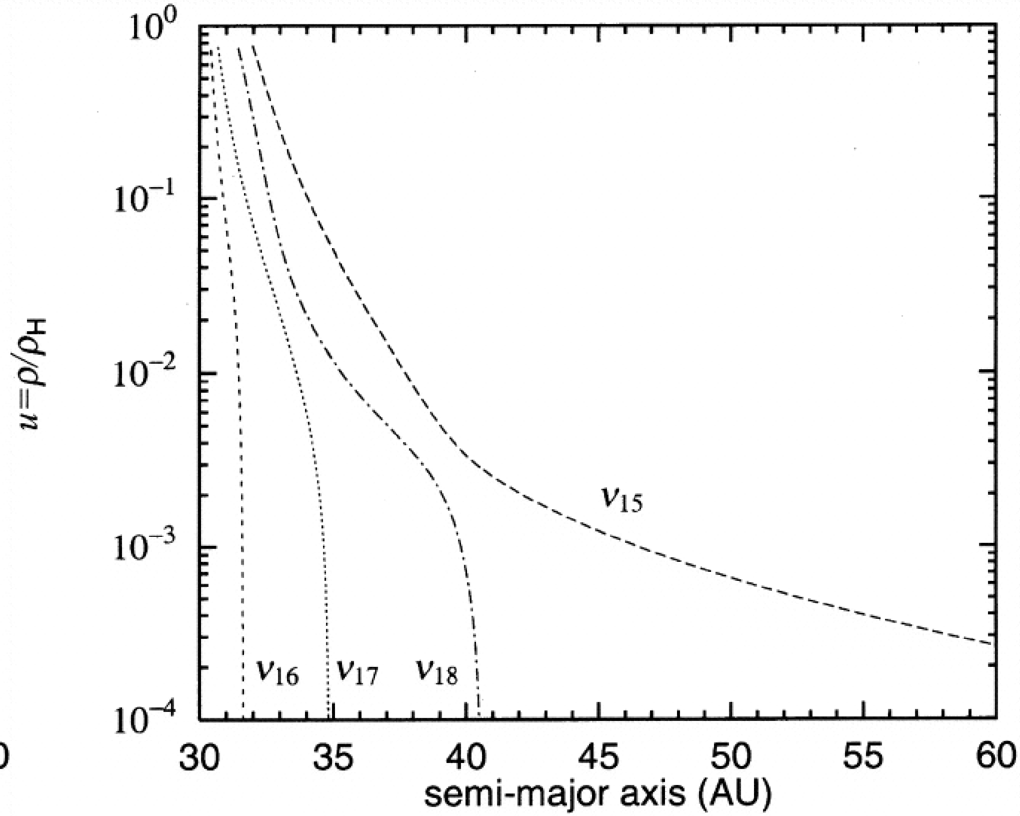
April 16, 2002

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.*, $i \sim 2°$ and $i \sim 17°$ (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).

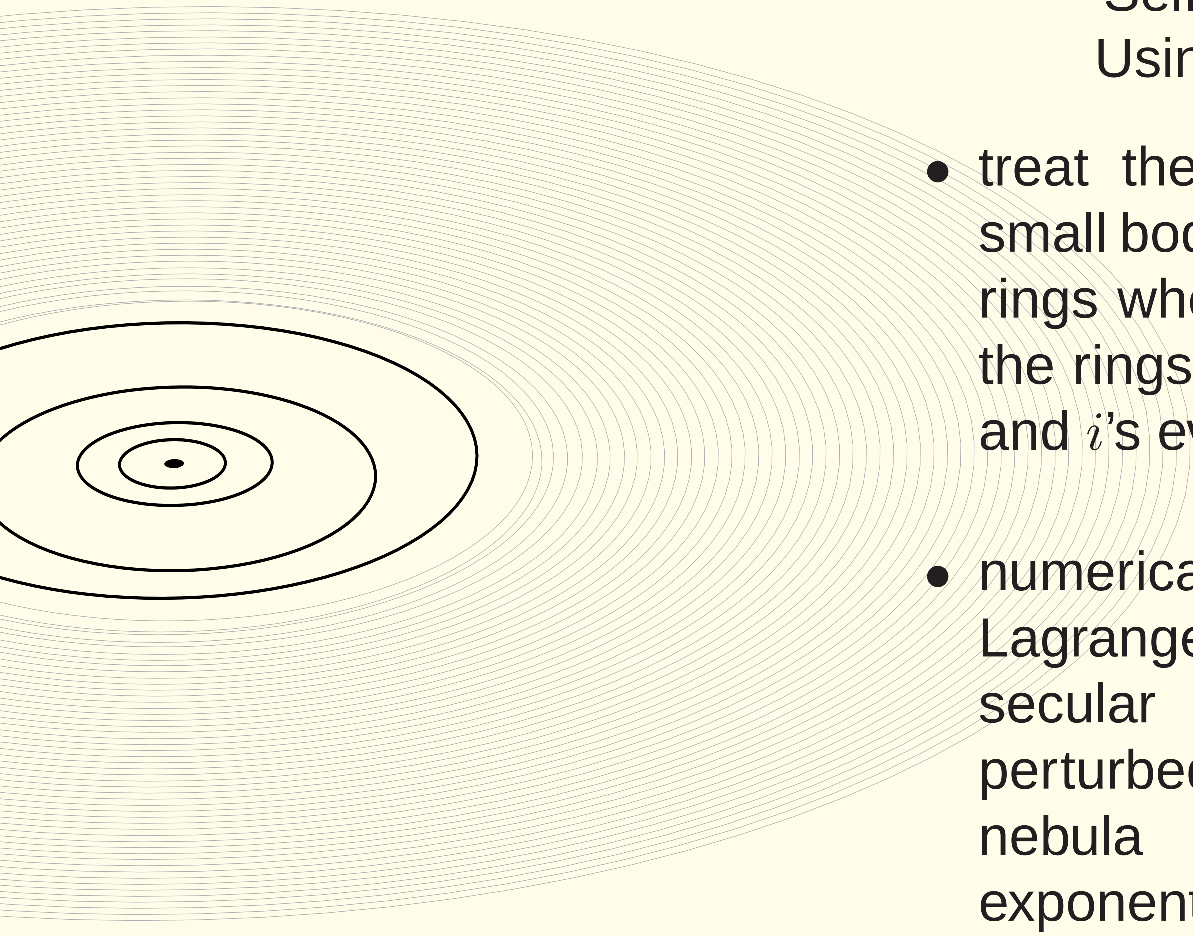




Secular resonances are sites where a small body's orbital precession rates matches one of the solar system's natural eigenfrequencies. Large e's are excited at the ν_j resonances (left figure) and large i's are excited at the ν_{1j} (right). Fig's from Nagasawa and Ida (2000) for a *massless* Kuiper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

As the solar nebula gas is depleted, the ν_5, ν_7, and the ν_8 resonances sweep inwards across the KB and excite eccentricities.

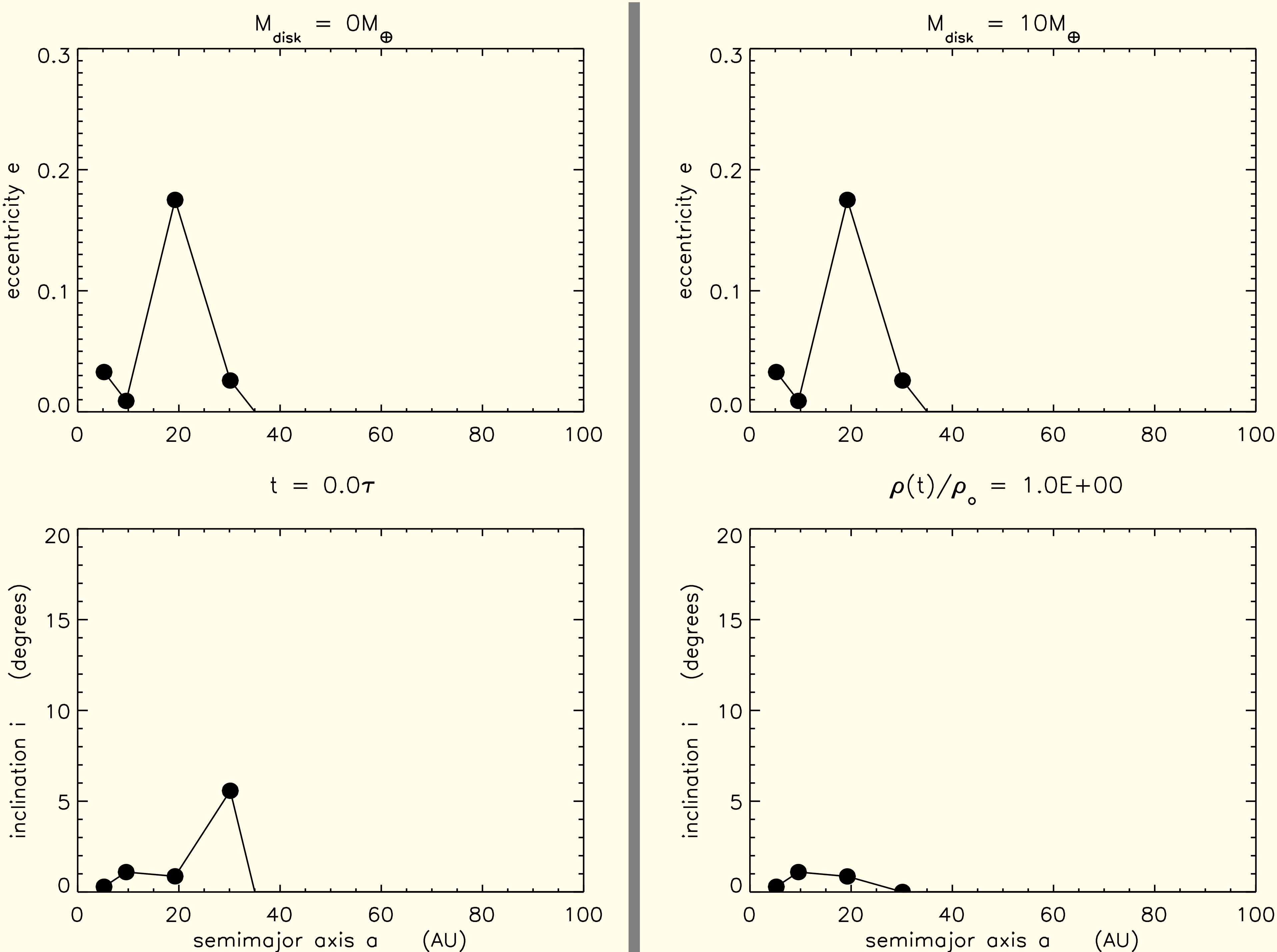
The ν_{15} and ν_{18} also sweep across the KB and excite inclinations.



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 τ.



M_{disk} = 0$M_\oplus$
eccentricity e
0.3
0.2
0.1
0.0
0
20
40
60
80
100
M_{disk} = 10$M_\oplus$
t = 0.0τ
$\rho(t)/\rho_o$ = 1.0E+00
inclination i (degrees)
20
15
10
5
semimajor axis a (AU)

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 ν_{18} at $a = 41$ AU and by $\nu_{15} \to \infty$.

- 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 $\mathbf{M}_{disk} = 10\ \mathbf{M}_{\oplus}$

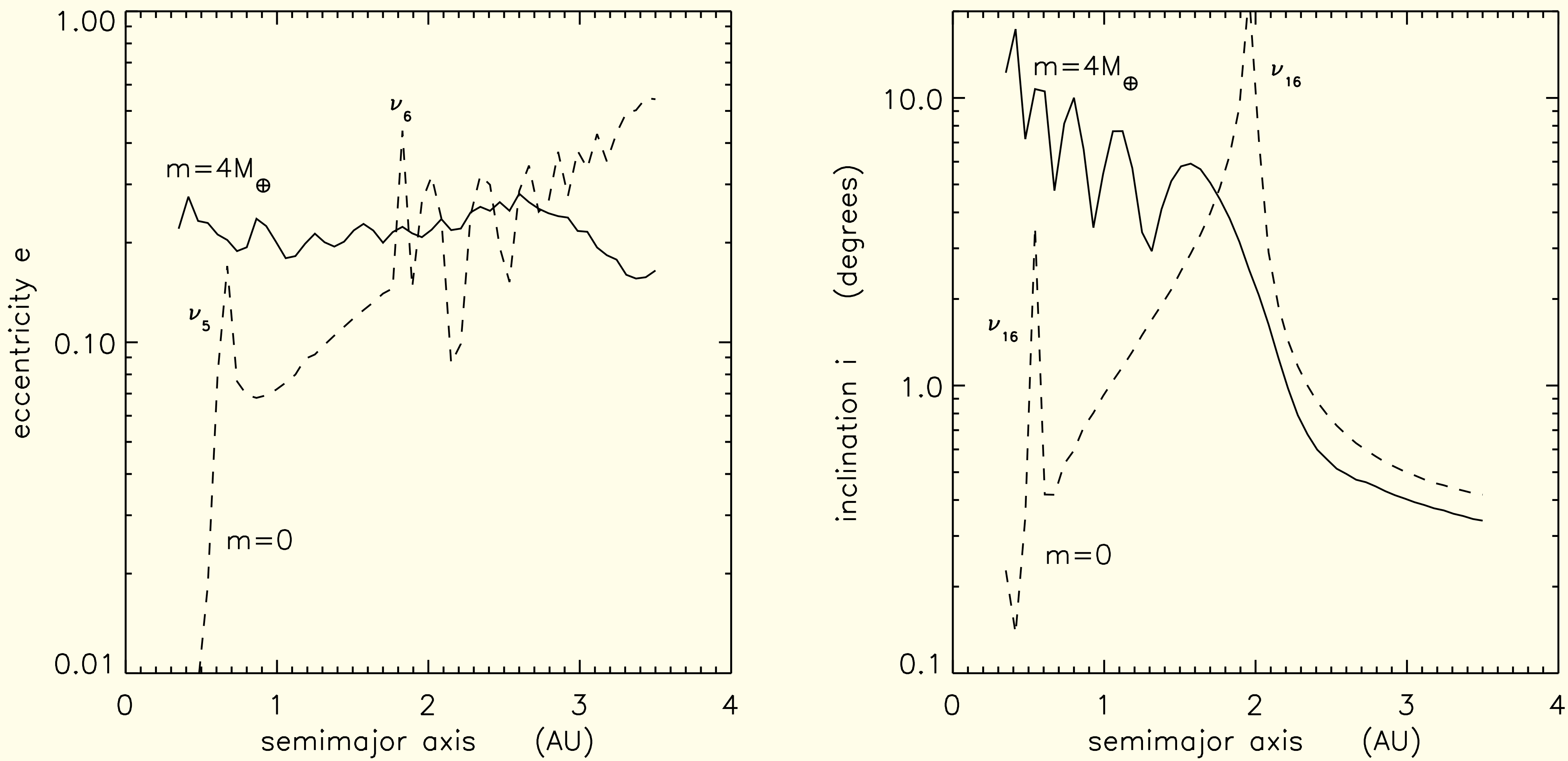
- This particular simulation has $\sigma_{solids} \simeq \frac{1}{5}\times$ solids in a minimum–mass nebula. Other runs with $10\times$ more/less mass have also been performed.

- 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., $\mathrm{M}_{disk} > 0$), 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$_{disk}(30 < a < 100$ 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 τ.