Divining the Orbital History of the Outer Solar System From Models and Observations of the Kuiper Belt

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Outline

- Review the current planet–formation paradigm via a sequence of cartoons.

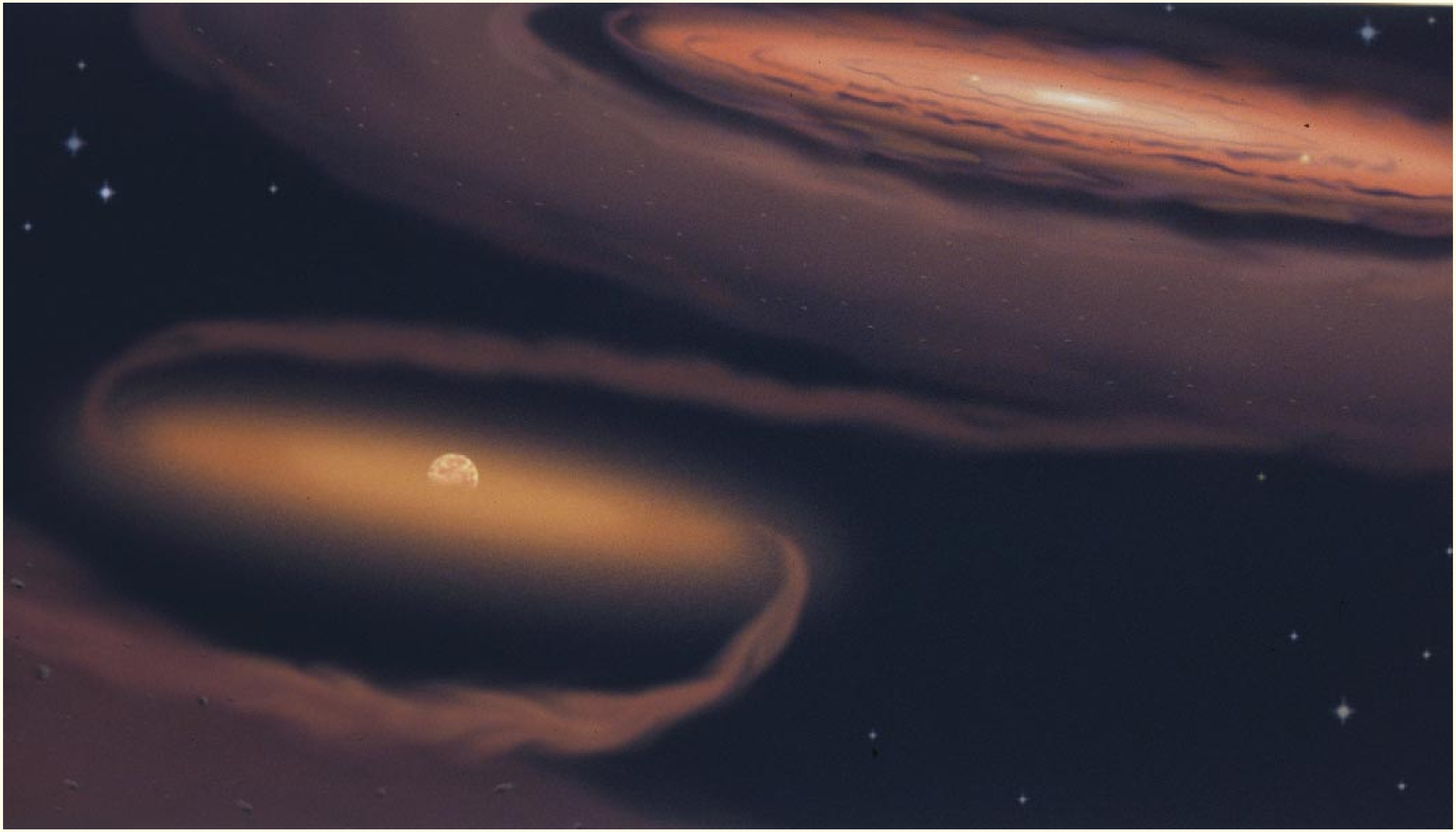
- Examine the Kuiper Belt:
  - the observations that preserve evidence of an early epoch of planet–migration
  - focus on the effects of sweeping mean–motion & secular resonances, and how this may have sculpted the Kuiper Belt

- Summarize what the Kuiper Belt is telling us about events that may have occurred in the early history of the outer Solar System.

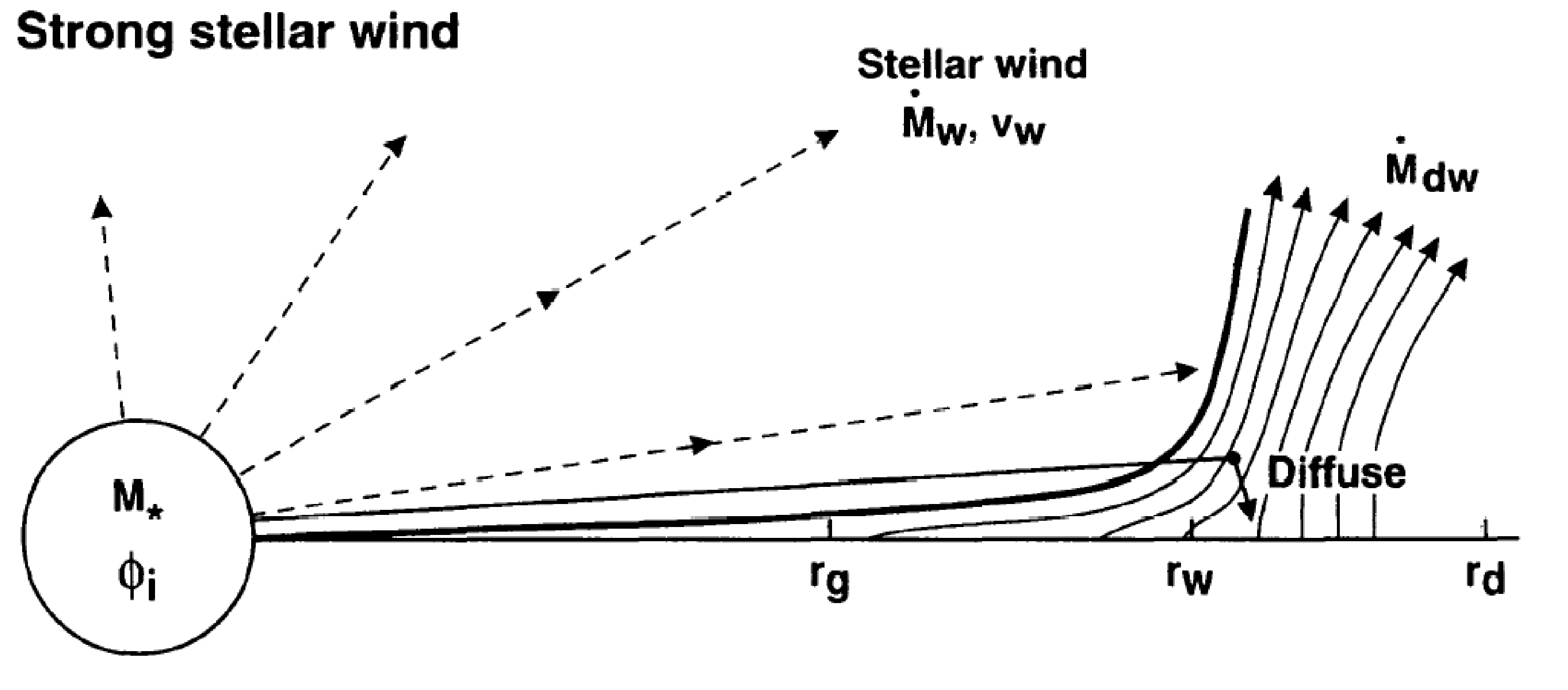
1. Molecular cloud collapses and forms Sun + disk of gas & dust in $\sim 10^5$ years.

2. Dust settles at the disk midplane where accretion produces planetesimals → protoplanets → cores of the giant planets by time $t \sim 10^{6 \text{ or } 7}$ years.

3. Giant planet cores accrete their H and He atmospheres directly from the disk by time $t \sim 10^{6 \text{ or } 7}$ years.

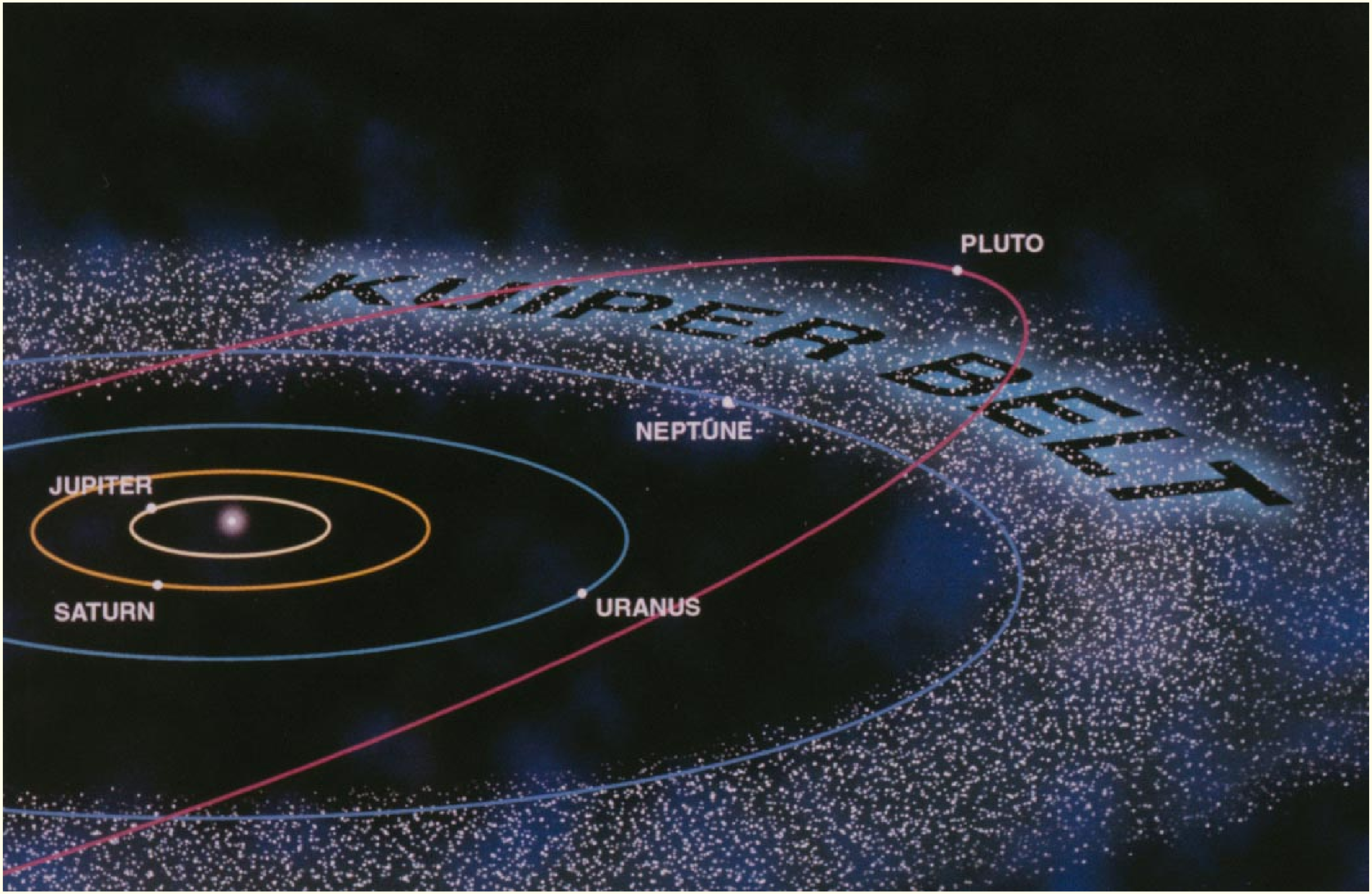


4. The disk’s gas content is dispersed after $t \sim 10^{6 \text{ or } 7}$ years, possibly due to photoevaporation by solar UV photons.



Hollenback *et al.* (1994)

5. The giant planets then eject or accrete the remaining planetesimal debris over the next $\sim 10^7$ years.



How does one find KBOs?

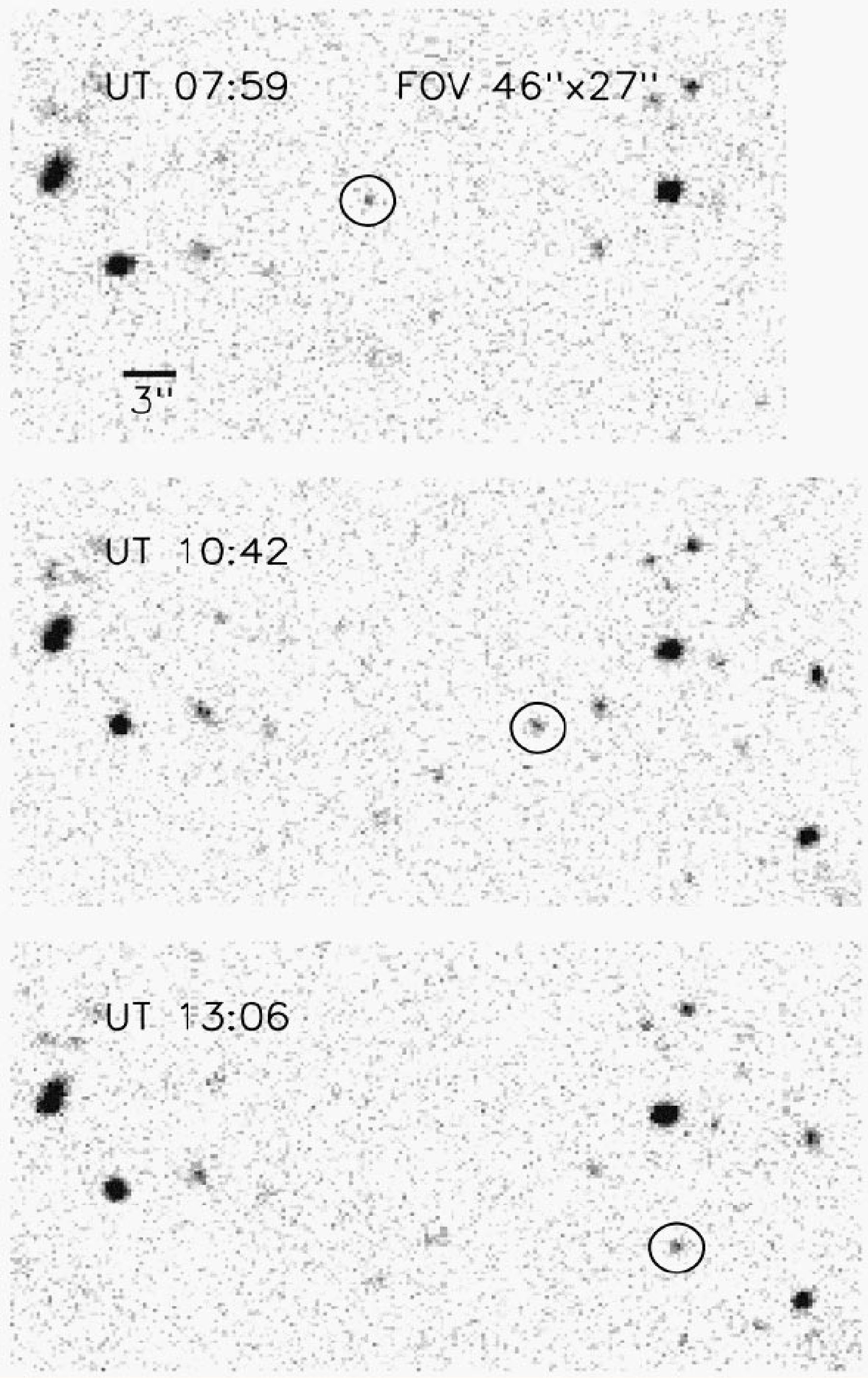
Stare at a tiny patch of sky and look for faint, slow–moving objects.

KBOs Statistics:

$N \sim 10^5$ KBOs with $R > 50$ km
and total mass $M \sim 0.1$ $\mathrm{M}_\oplus$.
(Luu and Jewitt 1998).

Compare to the Asteroid Belt:

$N \sim 10^3$ asteroids with $R > 50$ km
and total mass $M \sim 0.001$ $\mathrm{M}_\oplus$.



Chiang and Brown (1999)

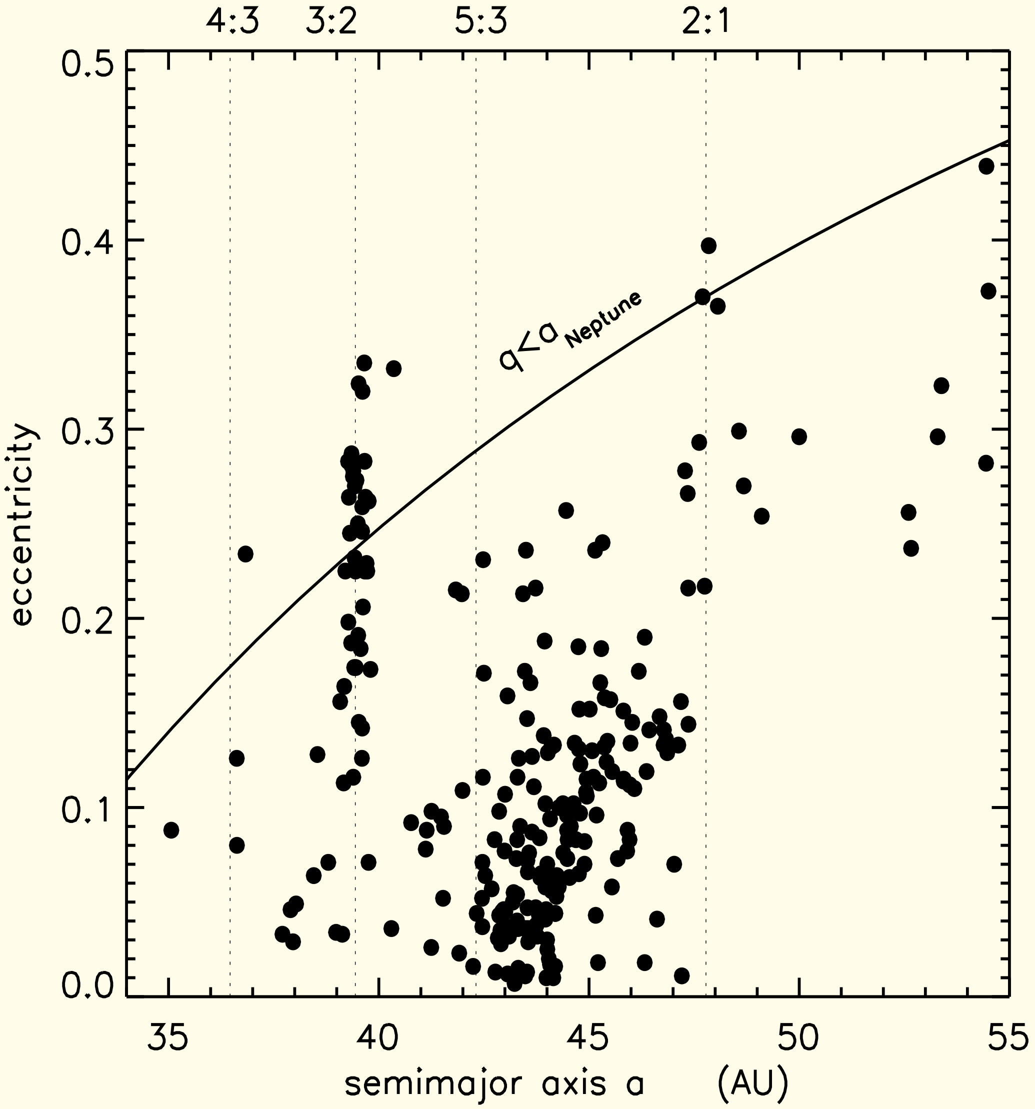
Main features of KB orbits

- the KB has 3 dynamical classes:

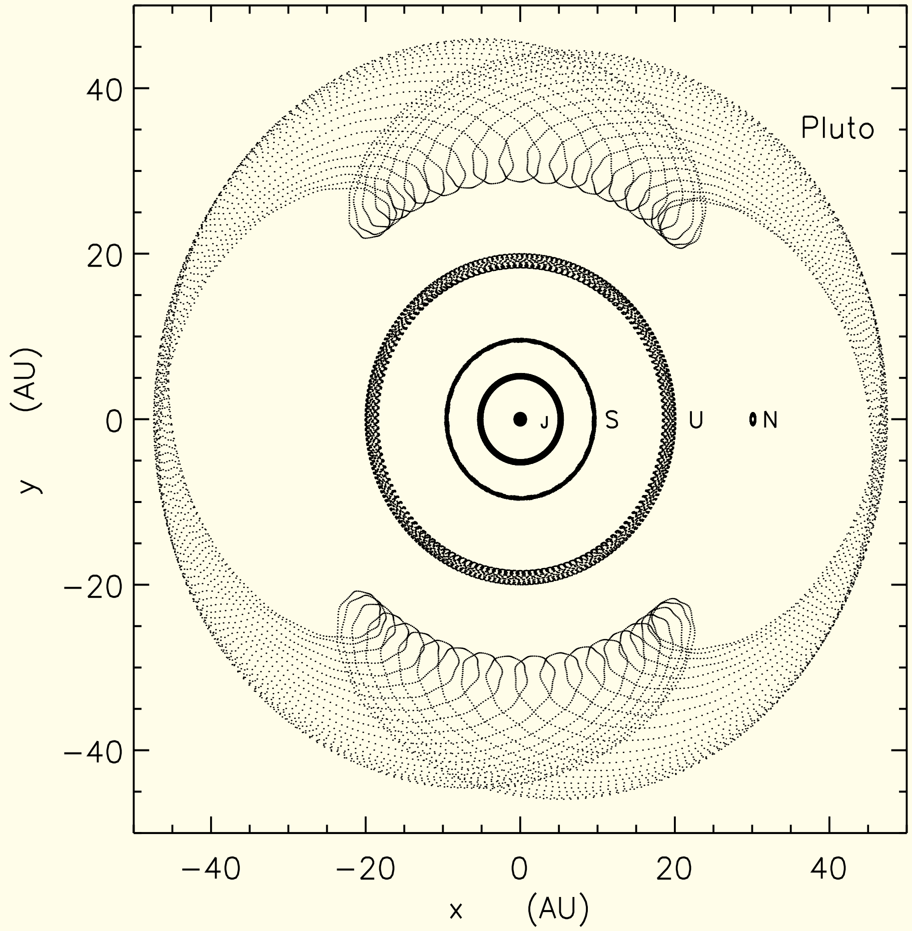
$\sim 1/4$ are resonant KBOs;
the resonance protects KBOs & Pluto from encounters with Neptune (Cohen and Hubbard 1965).

$\sim 1/4$ are Scattered KBOs;
these objects likely formed near the giant planets and were scattered outwards (Duncan and Levison 1997).

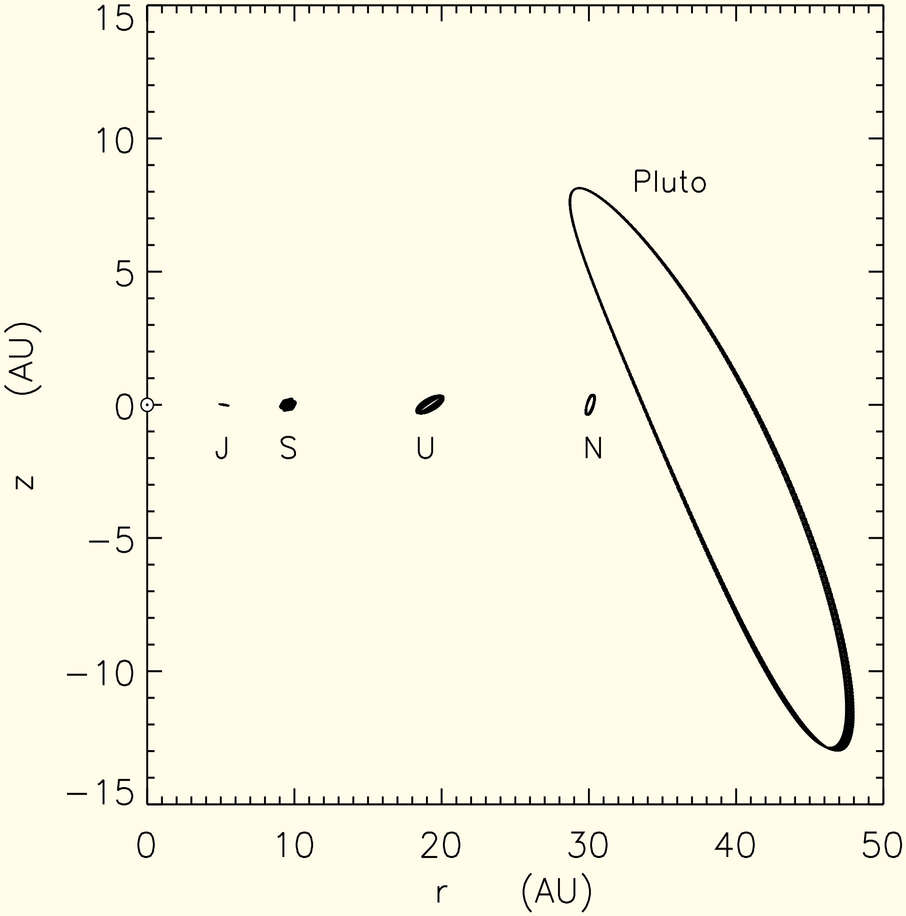
$\sim 1/2$ are Main Belt KBOs;
native KBOs?



Pluto’s Orbit



3:2 resonance provides ‘radial’ protection.



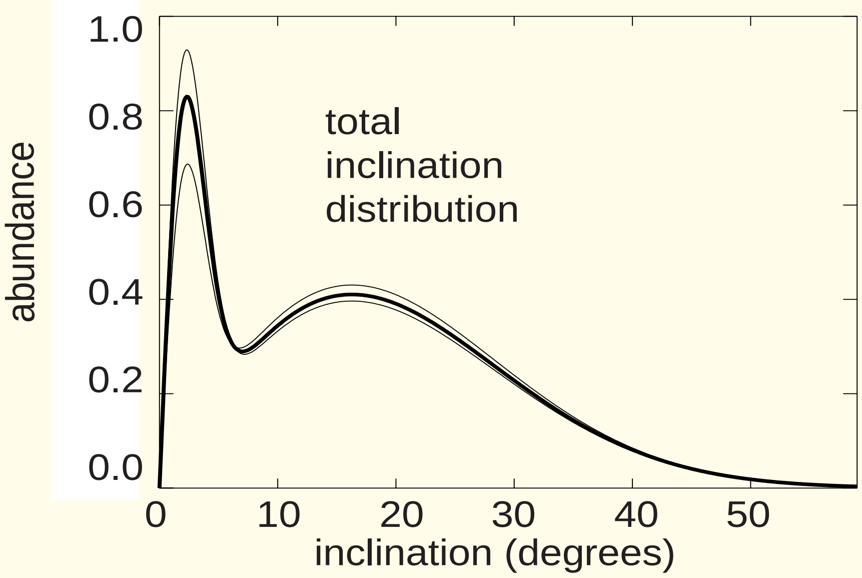
ω resonance provides ‘vertical’ protection.

The KB inclination distribution

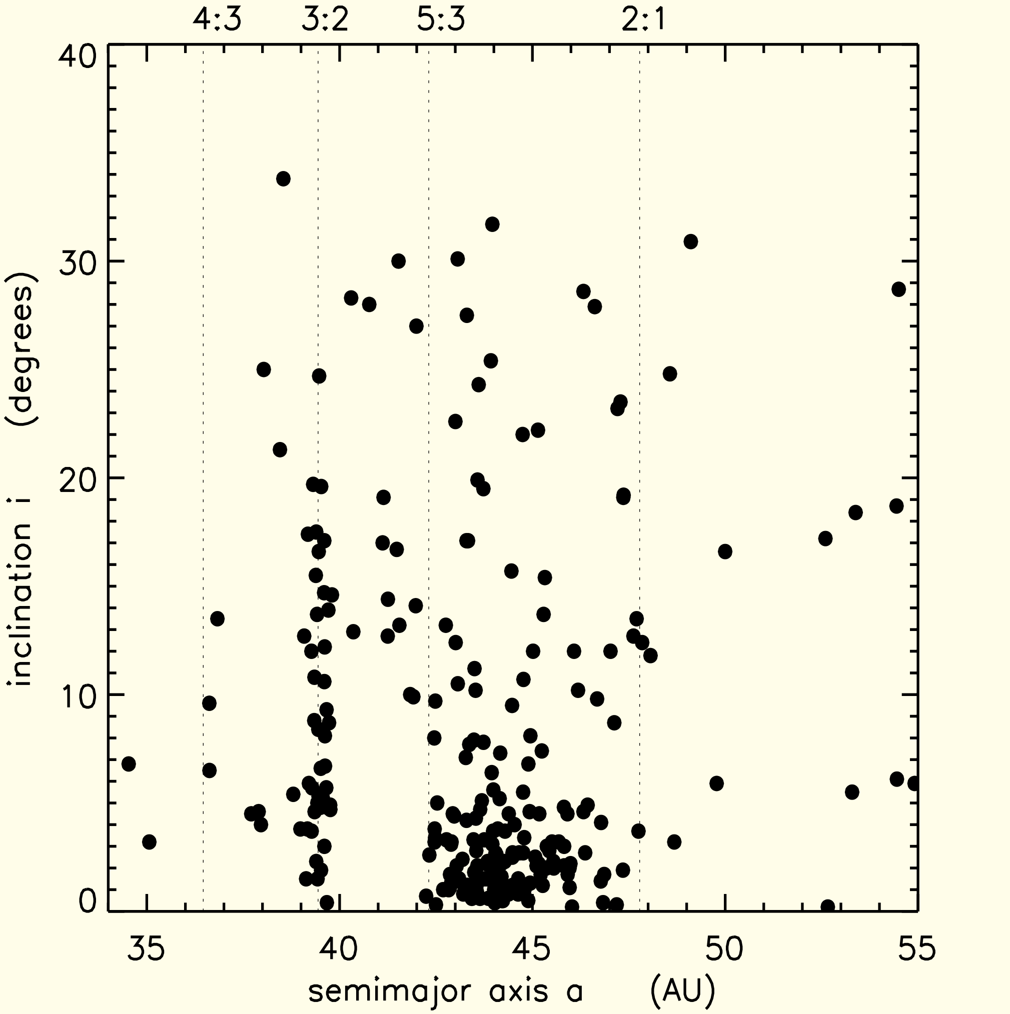
- the KB has a bimodal inclination distribution:

Dynamically cold population having $i \sim 2^\circ$.

Stirred–up population with $i \sim 17^\circ$.

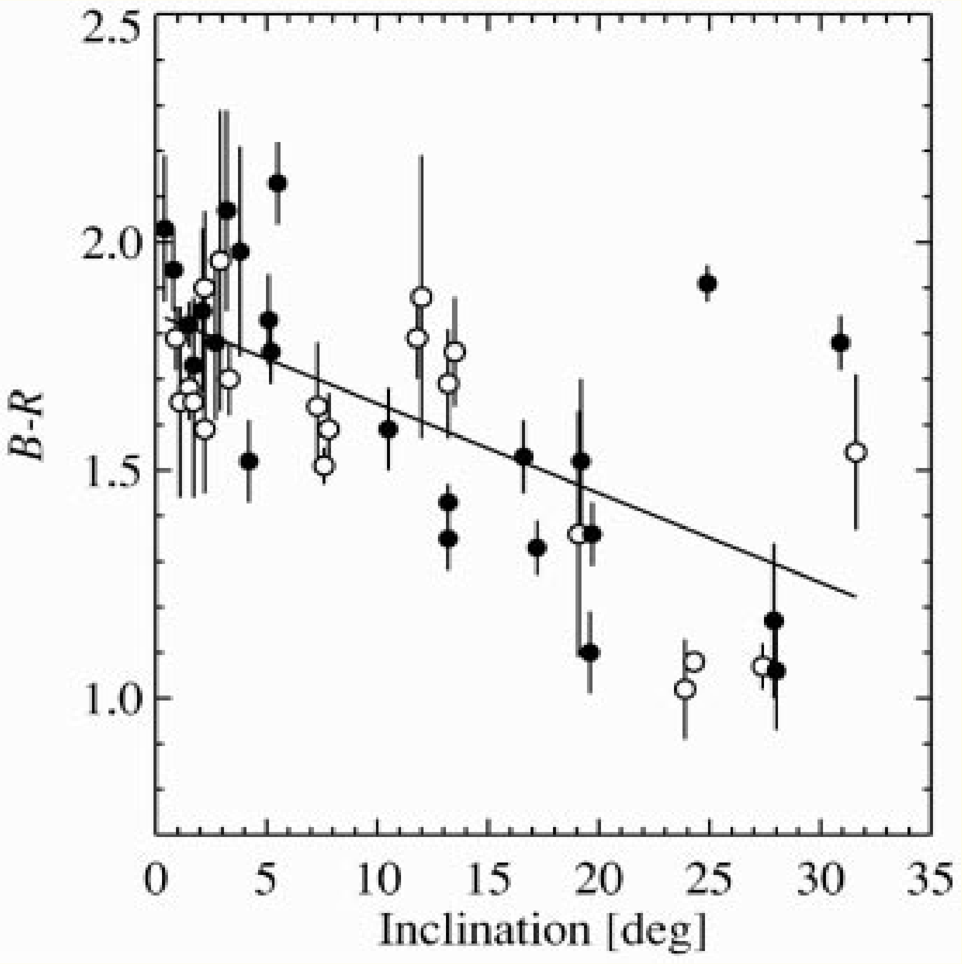


Brown (2001)



KB Color Trends

- low i KBOs tend to be redder than high i KBOs.



Trujillo and Brown (2002)

A Working Dynamical Model of the Outer Solar System Should Explain the Observed KB Structure:

- the causes for the KB’s 3 dynamical classes
  - resonant KBOs
  - main–belt KBOs
  - scattered KBOs

- the KB’s bimodal inclination distribution
  - dynamically cold population with $i \sim 2^\circ$
  - excited population with $i \sim 17^\circ$

- the i–color trend:
  low–i KBOs tend to be redder than high–i KBOs.

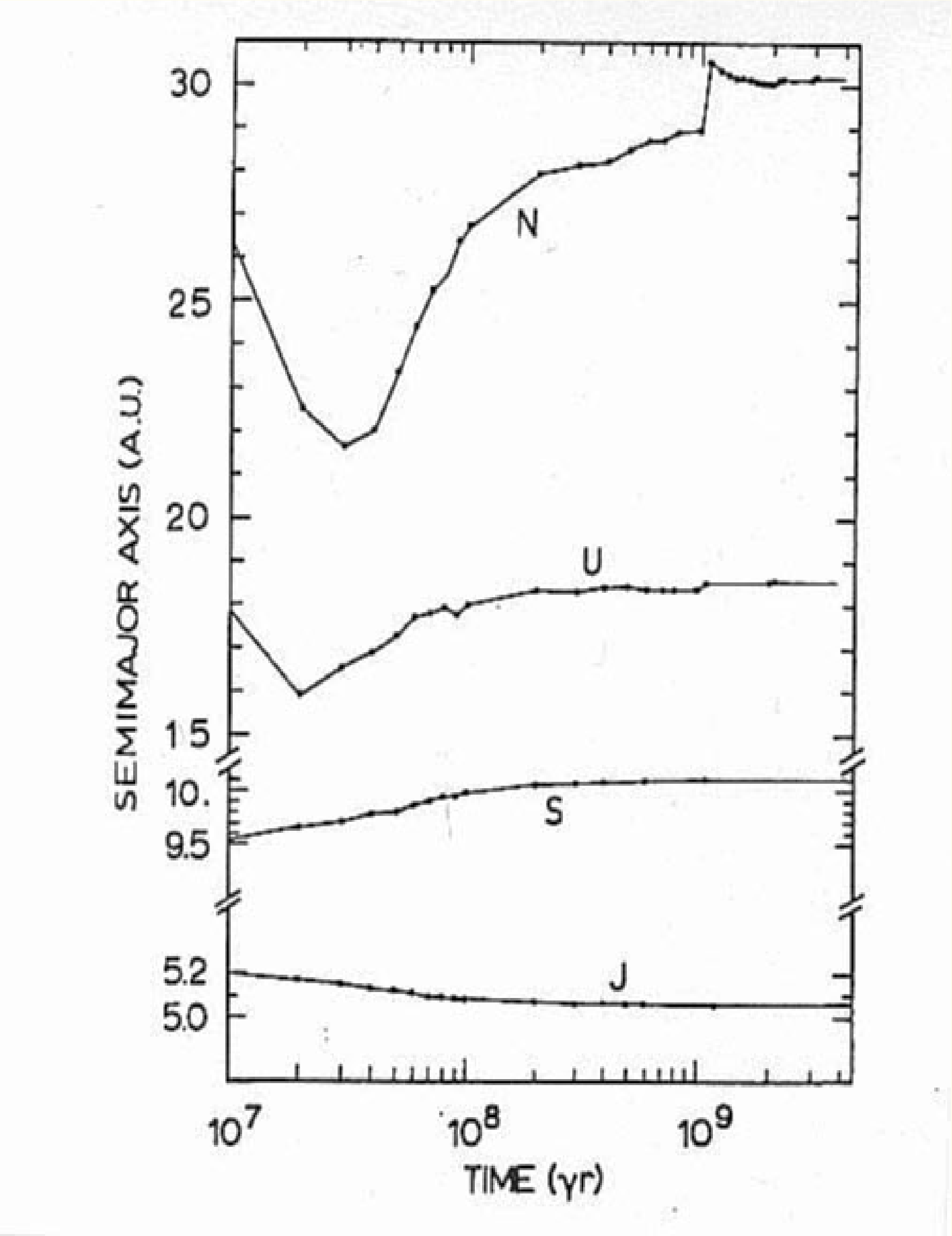
Possible Explanations for the Observed KB Structure:

- gravitational scattering by large planetesimals (Morbidelli and Valsecchi 1997).
- perturbations from a passing star (Ida *et al.* 2000).
- the gravitational scattering of Uranus & Neptune outwards into their present orbits by Jupiter & Saturn (Thommes *et al.* 1999).
- secular resonance sweeping that occurs as the nebula's gas is dispersed (Nagasawa *et al.* 2000).
- outward migration of Neptune's orbit (Malhotra 1993).

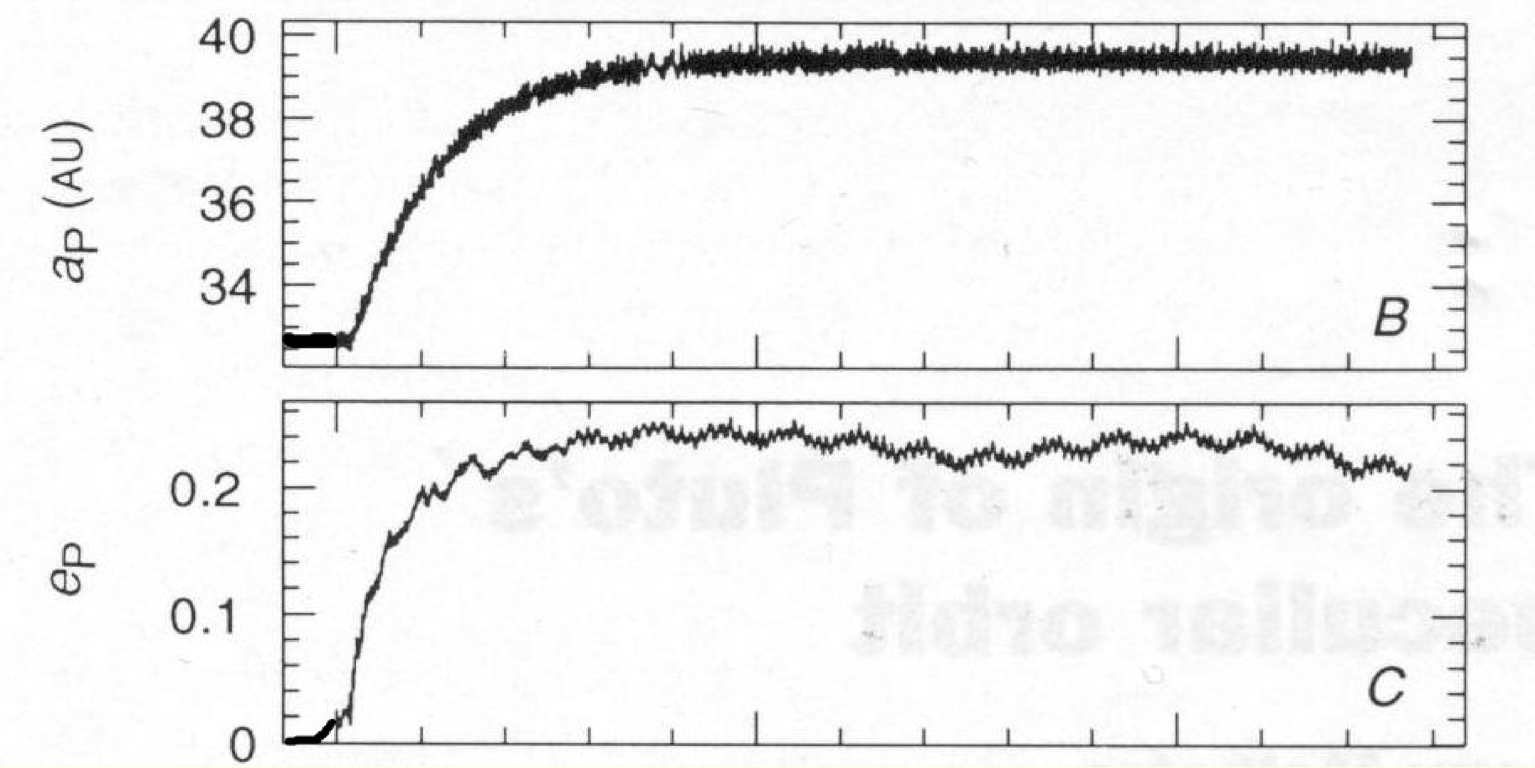
Planet Migration Driven by a Planetesimal Disk

- Fernández and Ip (1984) used an Öpik integrator to model the accretion of Uranus & Neptune while embedded in a $M_d \simeq 100$ M$_\oplus$ disk.

- Uranus & Neptune acquire **L** (and migrate outwards) as they scatter bodies to smaller perihelia, while Jupiter's orbit shrinks slightly as it ejects that mass.



Pluto’s Peculiar Orbit: Evidence of Planet Migration?



- Malhotra (1993) recognized that this early episode of migration could explain Pluto’s unusual orbit having $e = 0.25$ at 3:2 resonance with Neptune.

- Had Neptune’s orbit expanded by $\Delta a_N \geq 5$ AU, Pluto can get trapped in the advancing 3:2 resonance and have its e pumped up to 0.25.

- Planet migration & resonant trapping can also explain the swarm of KBOs orbit at Neptune’s 3:2 resonance.

Inferring Neptune's Migration from the KB

Brouwer (1963) showed that object orbiting at an $m+1:m$ resonance obeys the integral

$$\beta \equiv a(t)[(m+1)\sqrt{1-e(t)^2}-m]^2.$$

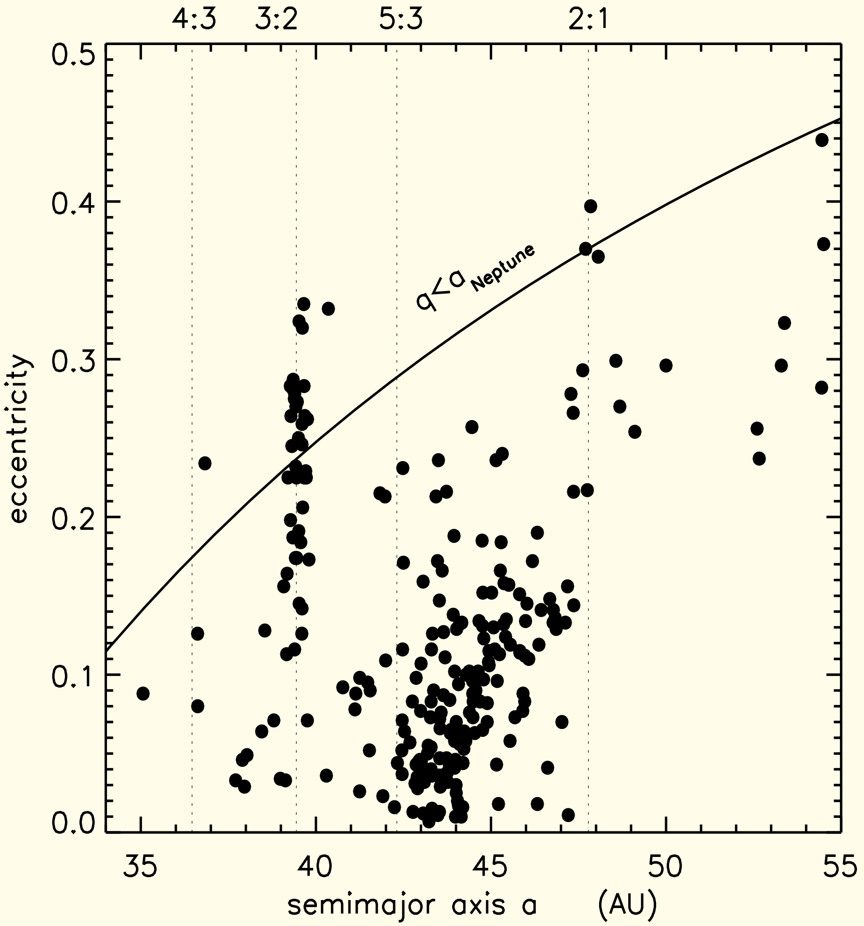
This is preserved even when shepherded outwards a distance Δa by a migrating planet (Yu and Tremaine 1999):

$$\frac{\Delta a}{a_f} = 1 - \left[(m+1)\sqrt{1-e_f^2}-m\right]^2 .$$

For $m=2$, $a_f = 39.5$ AU, $e_f = 0.3$,

$$\begin{aligned} \Rightarrow \Delta a &= 10 \text{ AU and} \\ \Delta a_N &= (1+1/m)^{-2/3}\Delta a = 8 \text{ AU} \end{aligned}$$

The early planetary system expanded $\sim 35\%$.



How Much Mass Will Drive Planet Migration?

N–body simulations show that giant–planets do indeed migrate when embedded in a sufficiently massive planetesimal disk.

Driving Neptune $\Delta a_N \sim 8$ AU requires an initial KB mass of $M_d \sim 50$ M$_\oplus$ distributed over $10 < r < 50$ AU.

Caution: this N–body planetesimal disk is poorly resolved with $N = 10^3$ bodies having masses $m = 0.05$ M$_\oplus$. This makes Neptune's migration too ragged to capture KBOs at resonance. This low–resolution simulation also ignores:

- collective effects (e.g., waves)
- dynamical friction

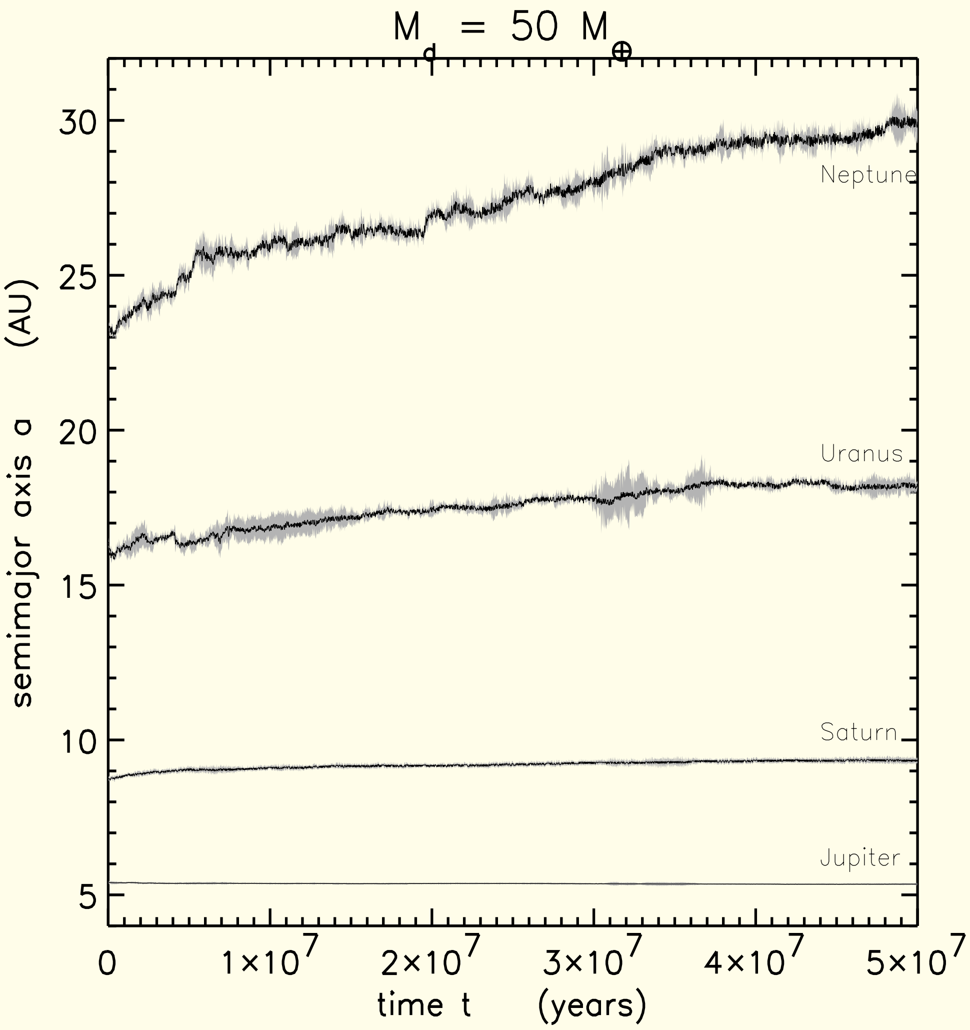


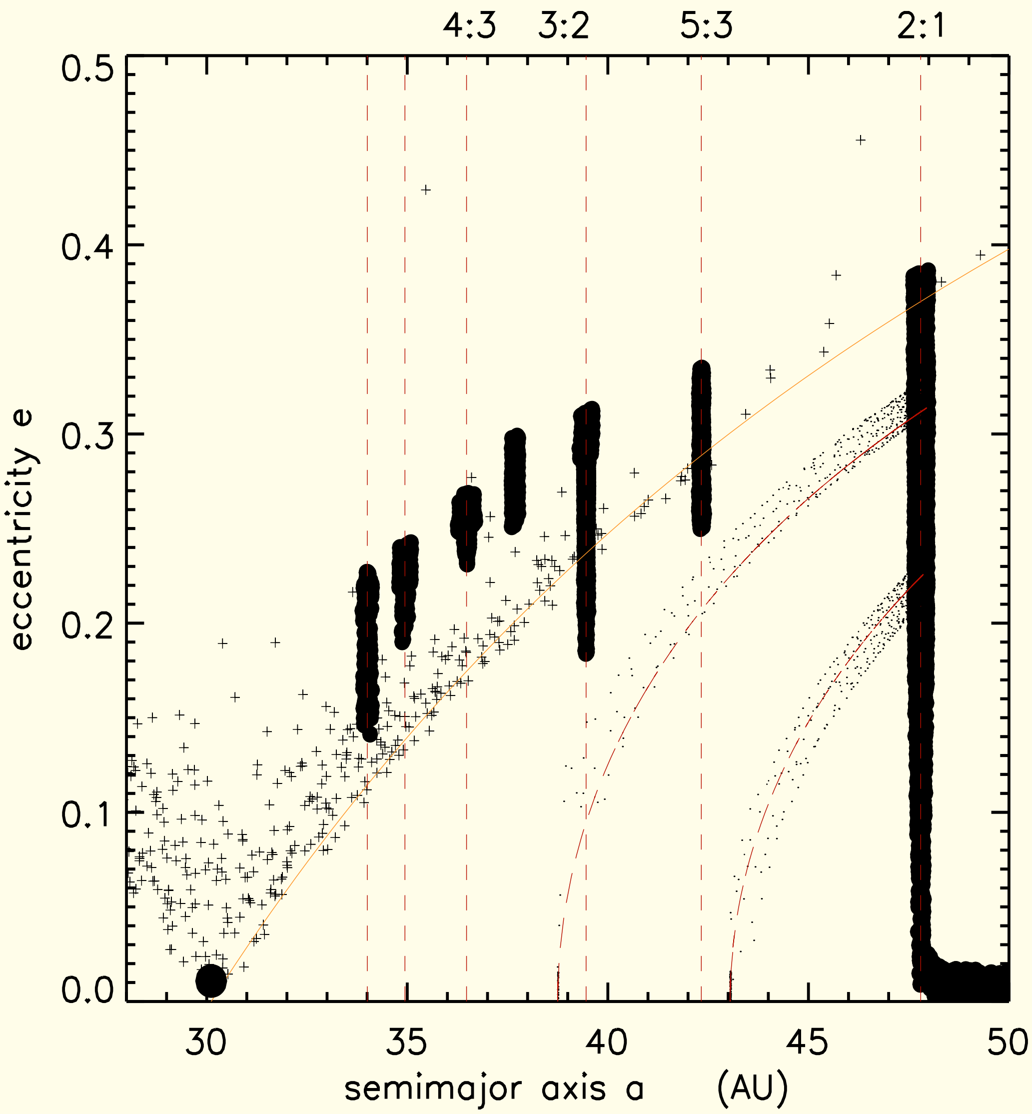
figure from Hahn and Malhotra (1999)

Adiabatic (Smooth) Planet Migration

- Adiabatically expand Neptune's orbit from $a_N = 23 \rightarrow 30$ AU by applying a smooth torque $\mathbf{T}_o$ over an exponential timescale $\tau = 3 \times 10^7$ years.

- Adiabatic migration results in very efficient trapping of KBOs at Neptune's resonances, which precludes the formation of the Main Kuiper Belt.

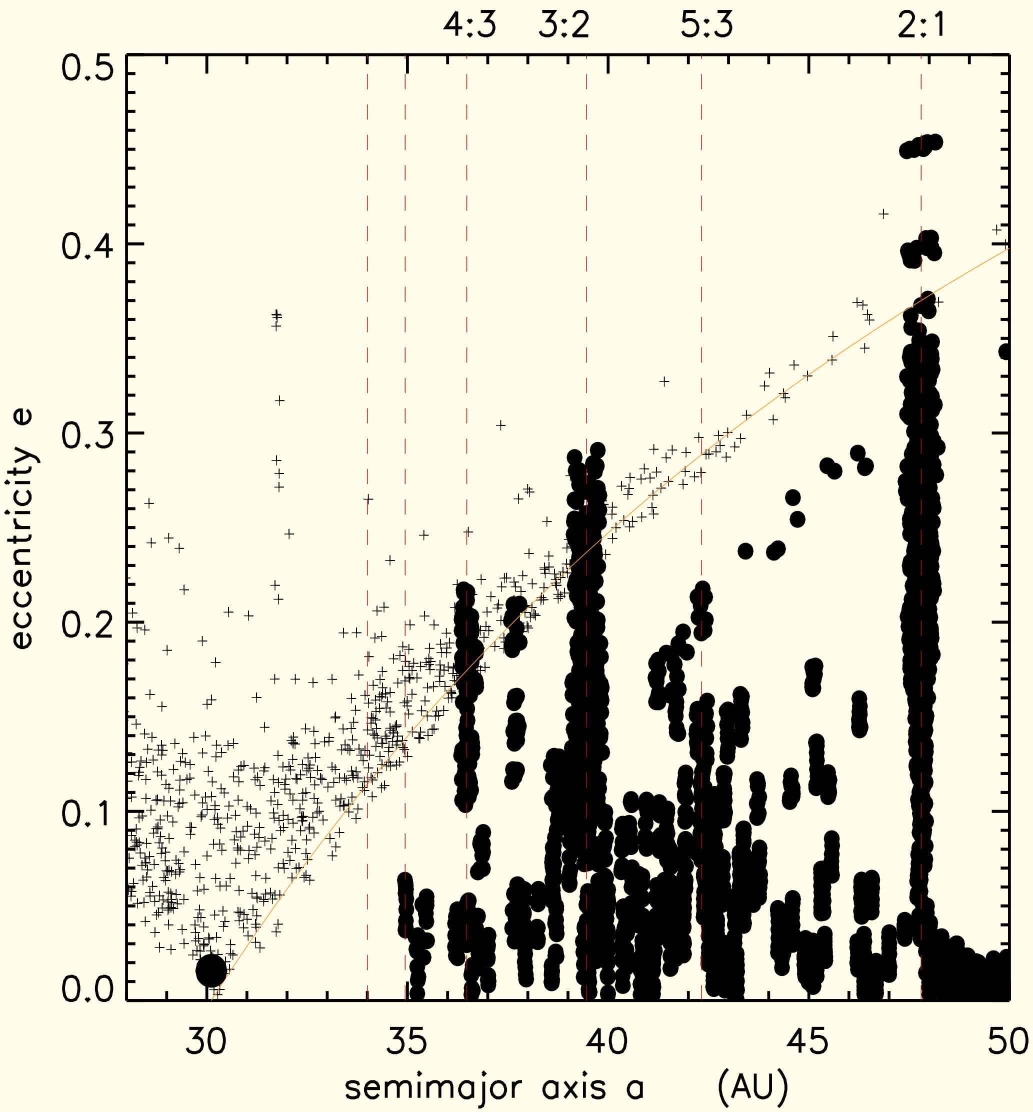
- Adiabatic migration did not occur.



Ragged Planet Migration

- Mimic stochastic scattering events at Neptune by adding some 'jitter' to the planet–migration torque: $\mathbf{T}_o \rightarrow (1+\sigma)\mathbf{T}_o$ where is a random number of order $\sigma \sim \pm 25$.

- Jitter reduces the resonances' trapping efficiency which allows some KBOs to slip through the advancing 2:1 resonance and enter the Main Belt with $e \sim 0.1$.

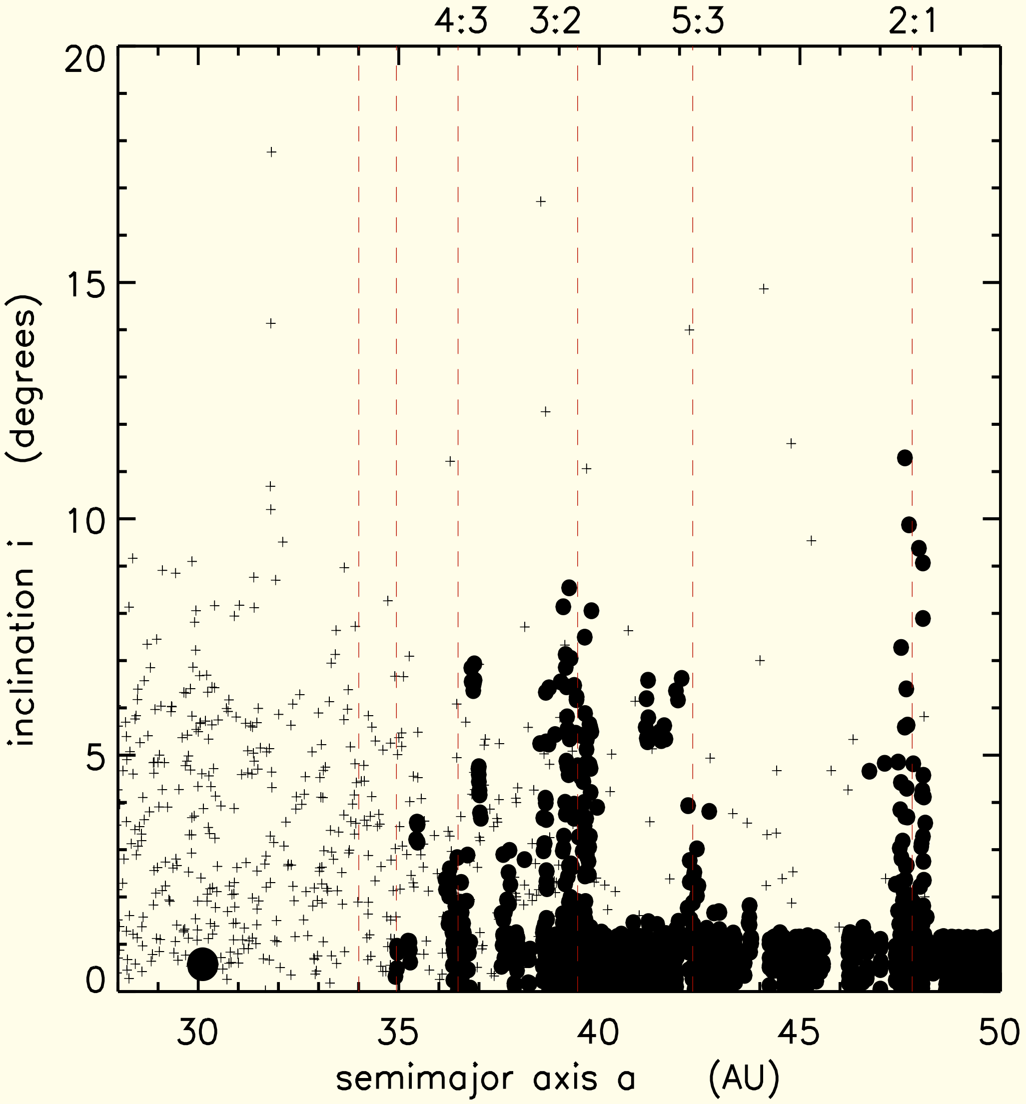


The Pros & Cons of Planet Migration

- Ragged planet migration produces well–populated resonances and a somewhat stirred Main Belt having $e \sim 0.1$.

- But the model predicts inclinations of $i \sim 1°$ in the Main Belt, which cannot account for the excited KBO population having $i \sim 17°$.

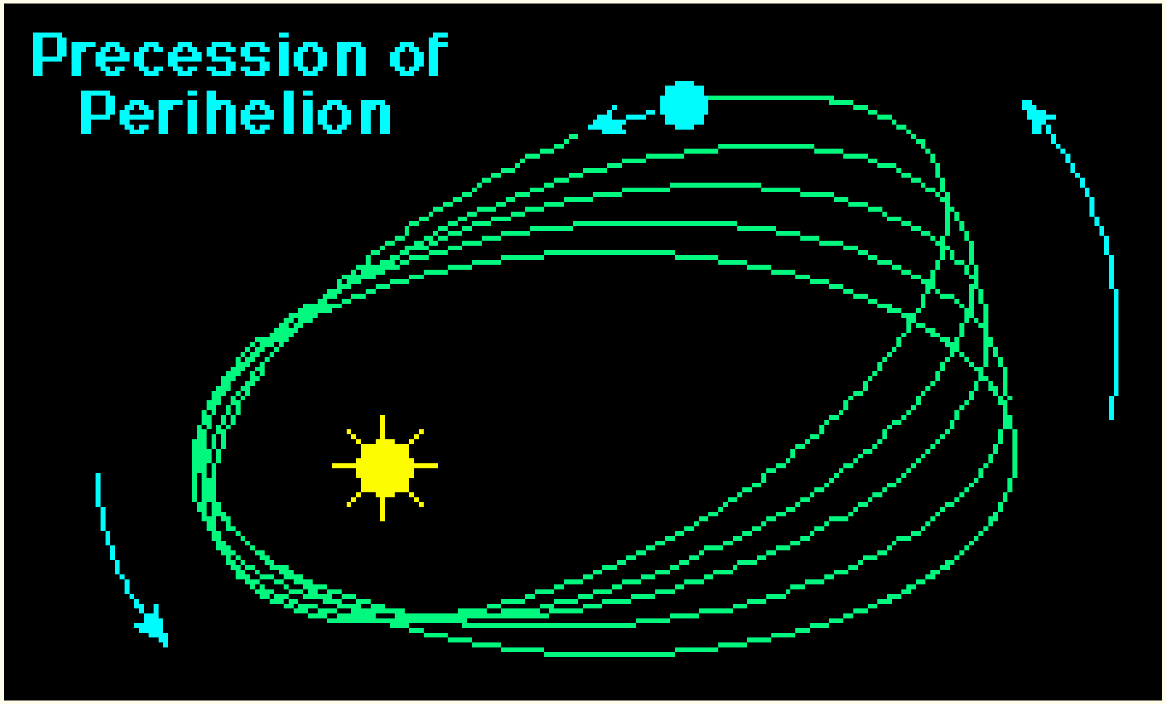
- Either the planet–migration hypothesis is bad, or we are missing some important physics.



Secular Resonance Sweeping ← is this the missing physics?

- A secular resonance is a site where a small body's orbital precession rate matches one of the solar system's natural eigenfrequencies.

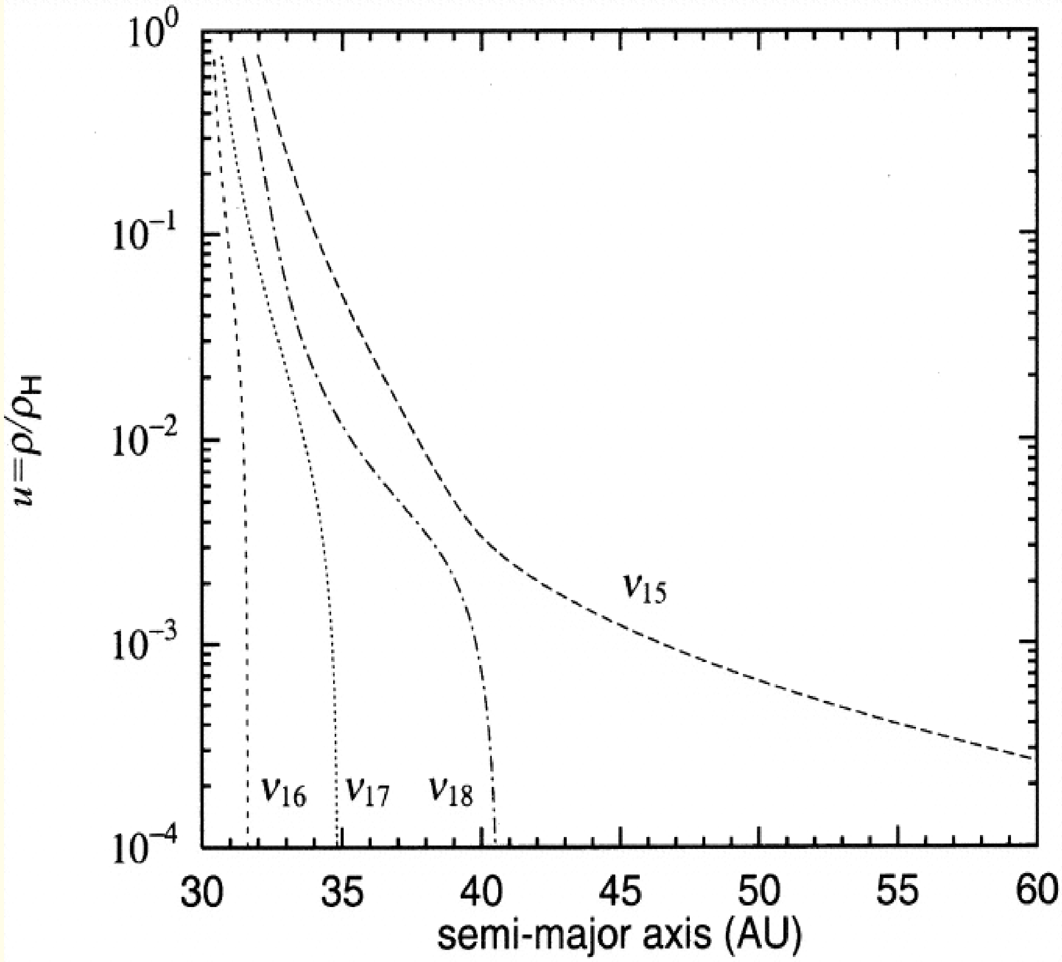
- Roughly, this is where a body's precession rate matches that of another planet.



- Large e's and i's can get excited at a secular resonance.

Nebula Dispersal Drives Secular Resonance Sweeping

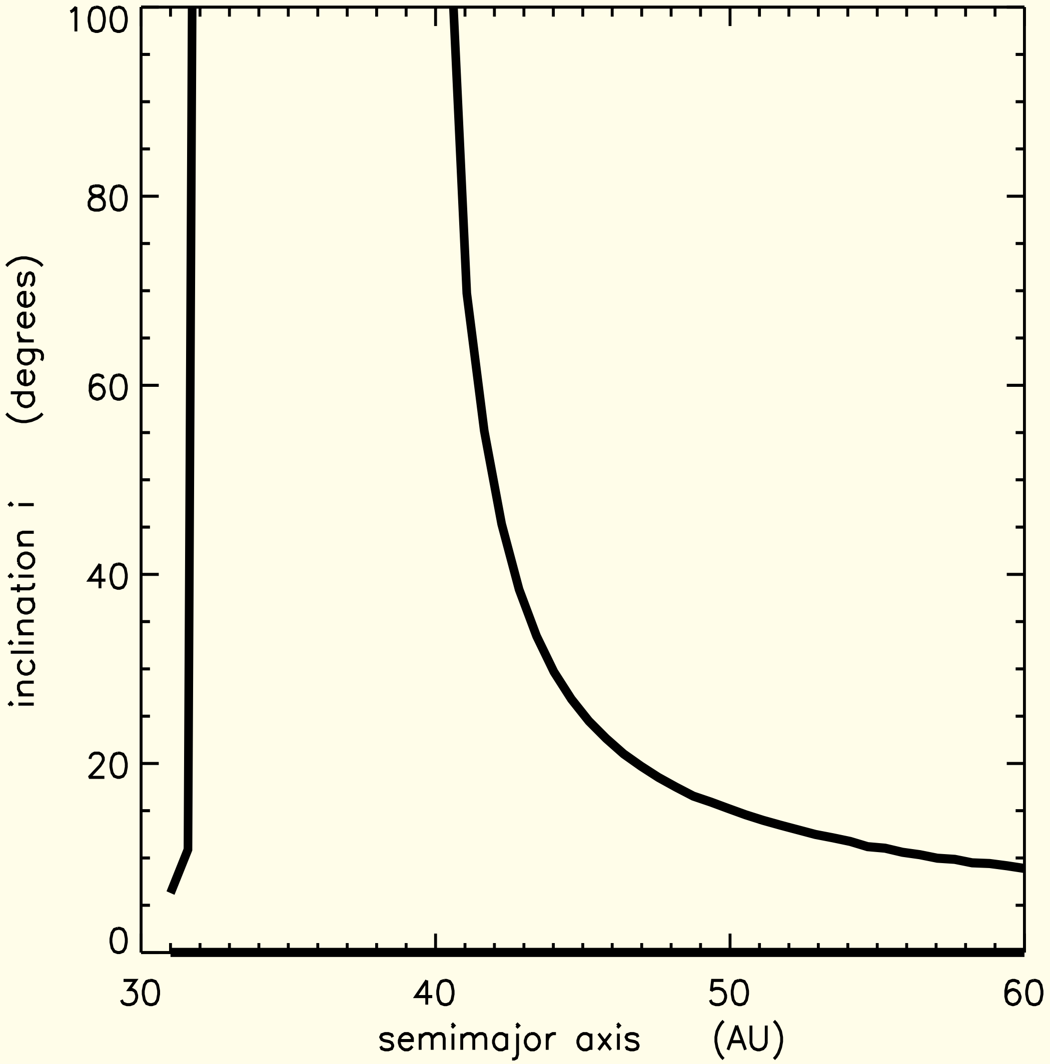
- Planets formed in a gas nebula having an initial mass $M \sim 0.01$ M$_\odot$. The gas disk's gravity causes these planets orbits to rapidly precess.
  - initially, Neptune's periapse rotates every $P_{\tilde{\omega}} \sim 5 \times 10^4$ years and its ascending node cycles every $P_\Omega \sim 3 \times 10^3$ years.
- But this rapid precession slows as the nebula gas is dispersed.
  - Neptune's current precession periods are $P_{\tilde{\omega}} \sim P_\Omega \sim 2 \times 10^6$ years.
- Nebula dispersal thus steadily 'retunes' the solar system which causes secular resonances to sweep across the Kuiper Belt.



Nagasawa and Ida (2000)

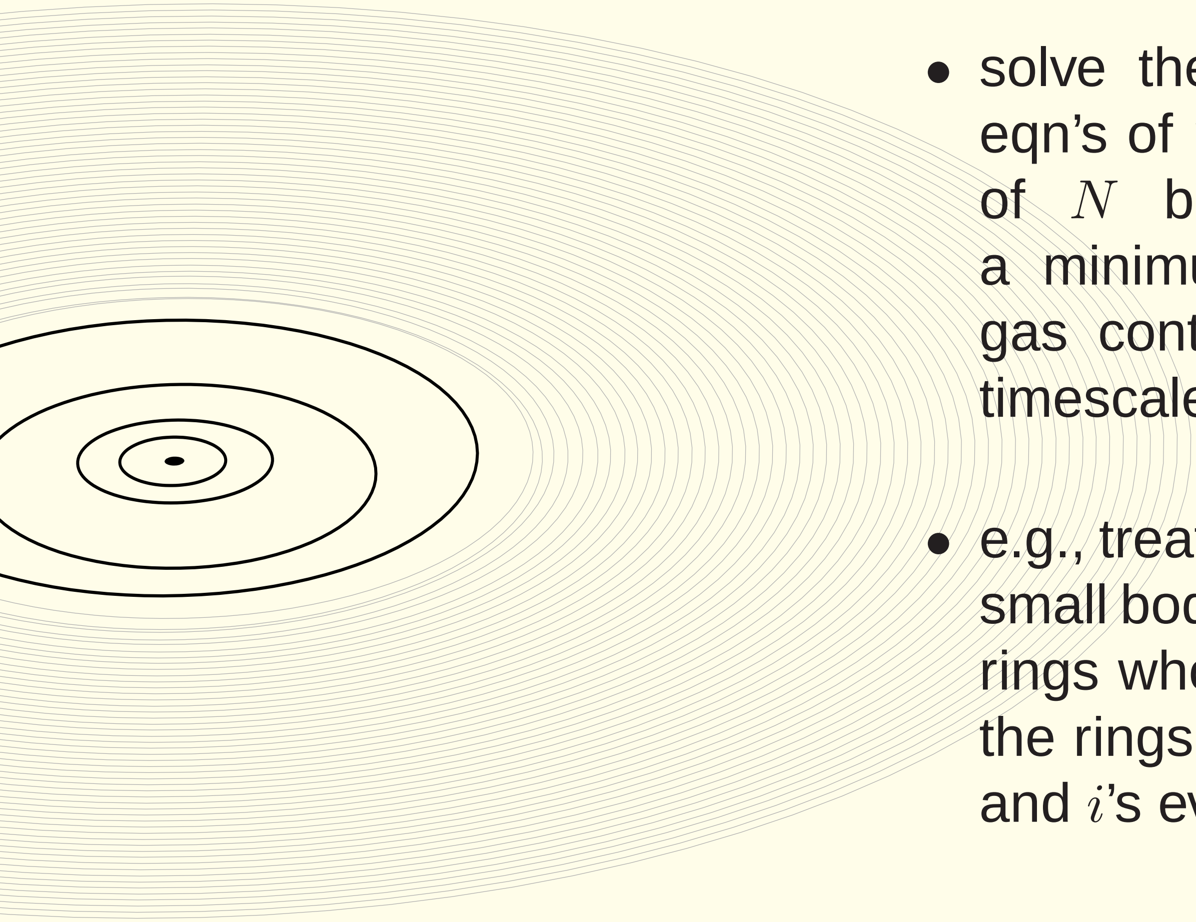
Secular Resonance Sweeping in a Massless Kuiper Belt

- Observed circumstellar disks tend to fade after $\tau \sim 10^{6\text{ to }7}$ years (Strom *et al.* 1993).
- Nagasawa & Ida (2000) find that secular resonance sweeping in a massless Kuiper Belt pumps up Main Belt KBOs to $i \sim 20^\circ$ for $\tau \gtrsim 3 \times 10^6$ years.
- but the initial KB was not massless...



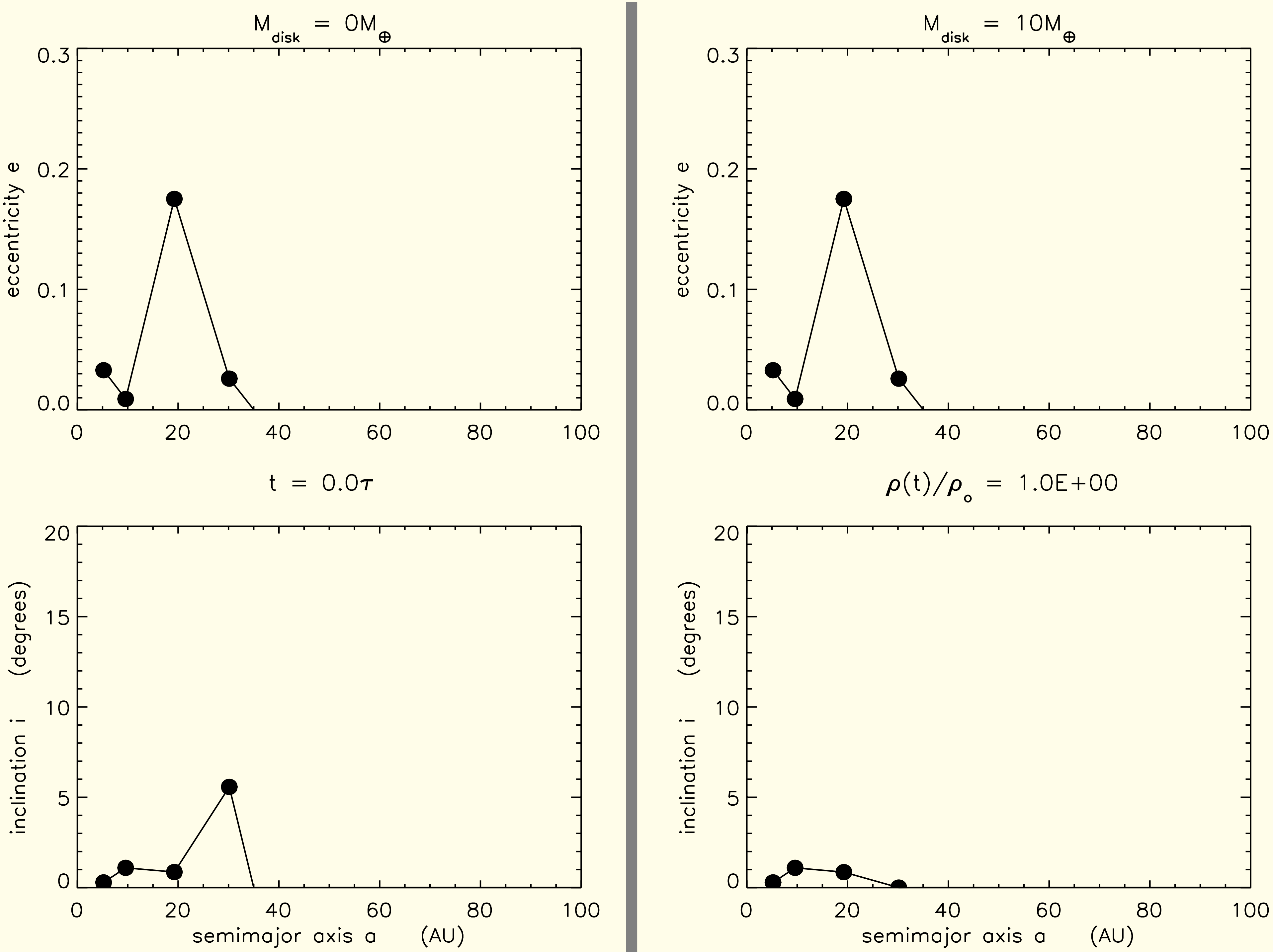
endstate for depletion timescale of $\tau = 10^7$ years.

Re–examine Sweeping Secular Resonances in a Self–Gravitating Kuiper Belt Using an ‘N–Ring’ Integrator



- solve the linearized Laplace–Lagrange eqn’s of motion for the secular evolution of N bodies that are perturbed by a minimum–mass solar nebula whose gas content decays exponentially of a timescale τ.

- e.g., 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.


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

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.

- When $t \simeq 5\tau$ and $\rho(t) \simeq 0.01\rho_0$, a spiral bending wave is launched.

- The effect of the planets secular perturbation is similar 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.

- secular resonance sweeping is unable to stir up the Kuiper Belt due to its self–gravity.

Overview of the Planet–Migration Hypothesis

- Current modeling shows that an outward expansion of Neptune's orbit by $\Delta a_N \sim 8$ AU can account for several (but not all) of the features observed in the Kuiper Belt
  - planet–migration parks lots of KBOs at Neptune's 3:2 resonance.
  - it also stirs up the Main Belt to $e \sim 0.1$, which could be due to jitter associated with stochastic scattering events at Neptune.
  - it also produces a scattered Belt of objects having $q \sim a_N$.

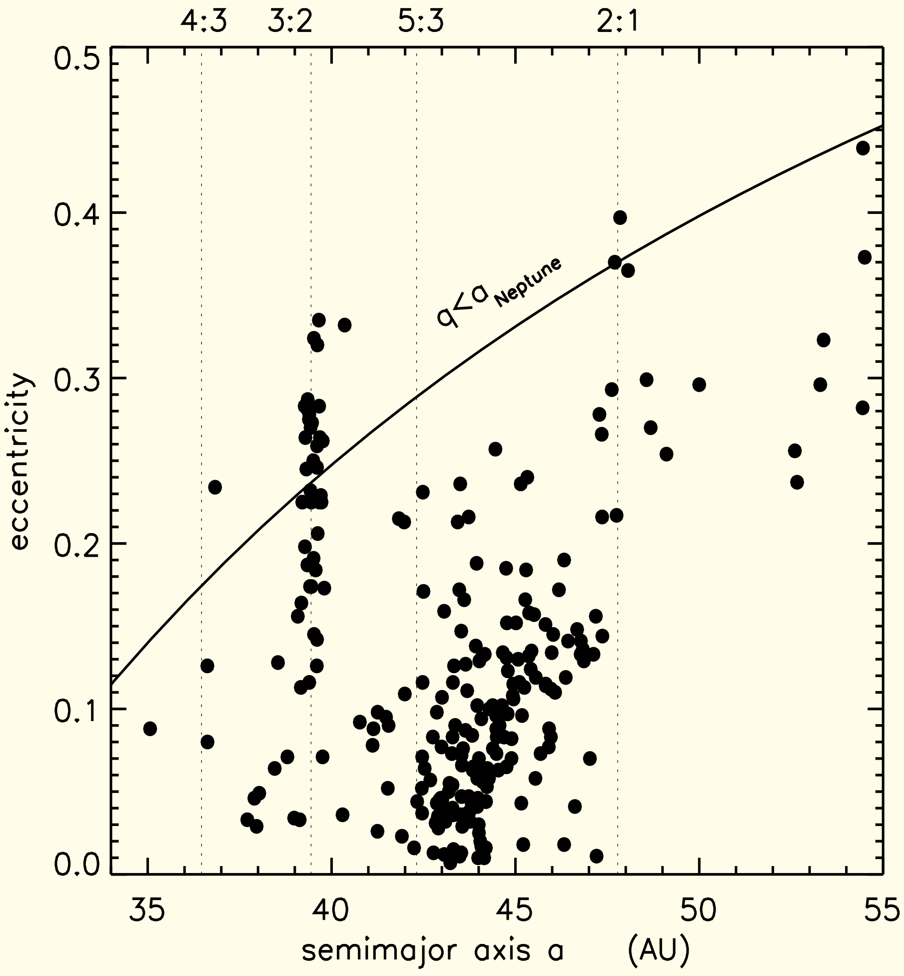
- If the Solar System is larger than 50 AU, there may also be a swarm of undisturbed, dynamically cold KBOs orbiting beyond Neptune's 2:1. We are looking for these objects with the Suburu telescope.

However...

- The observed Scattered Objects are less eccentric than anticipated ($q_{obs} \sim 35$ AU while $q_{model} \sim 30$ AU).

- The observed population at the 2:1 is less abundant than predicted by the model, but this may be due to telescopic selection effects.

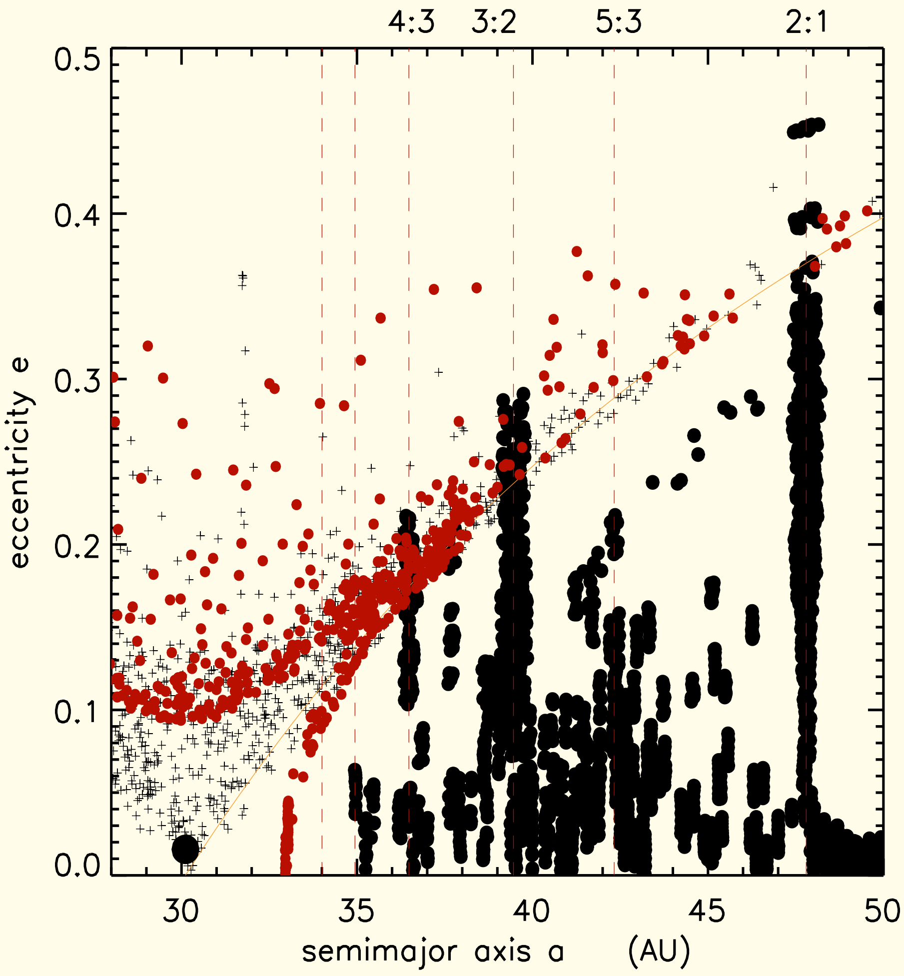
- Although planet–migration does produce low–i KBOs having $i \sim 1^\circ$, it does not produce the observed high i component having $i \sim 17^\circ$.
  - an additional phenomenon is responsible for stirring up the KB.
    - $\ast$ it is not secular resonance sweeping.



A Possible KB Scenario that Might Resolve these Discrepancies

- I suspect that the KB has been ‘invaded’ by eccentric, inclined Scattered KBOs.

- This requires an additional perturbation to cause Scattered KBOs to diffuse into lower–e orbits where they might masquerade as high i Main Belt Objects.
  - its not: nebula gas drag, nebula gravity, or KB gravity.



- Perhaps other protoplanets were once wandering the SD. They might scatter other SD Objects into vacant regions of phase space and seed the Main Belt with high i KBOs. This scenario will be studied in the coming weeks.

Future Activities

- Solve the Kuiper Belt.
  - What excited the KBO i's? Transient protoplanets in the Scattered Disk? Or some other mechanism?
  - Where is the outer edge of the Solar System? Is the 2:1 resonance inhabited? Is there a dynamically cold disk of KBOs beyond the 2:1?

- Apply the Nring model to other environments:
  - re–examine secular resonance sweeping in the asteroid belt (wave–action may resolve some outstanding issues here).
  - examine the long–term secular evolution of Saturn's ring & satellite system, which may be sensitive to the poorly–known mass of Saturn's rings.
  - the warp in the β Pictoris dust disk has been attributed to perturbations from an inclined planet orbiting in an unseen, massless planetesimal disk (Mouillet *et al.* 1997). Might wave–action alter this result if the planesimals have mass?
  - add gas pressure to the code and study secular interactions between circumstellar gas disks & stellar companions (e.g., HD 141569).

KB Orbit Elements