# Sculpting the Kuiper Belt via Neptune's Orbital Migration

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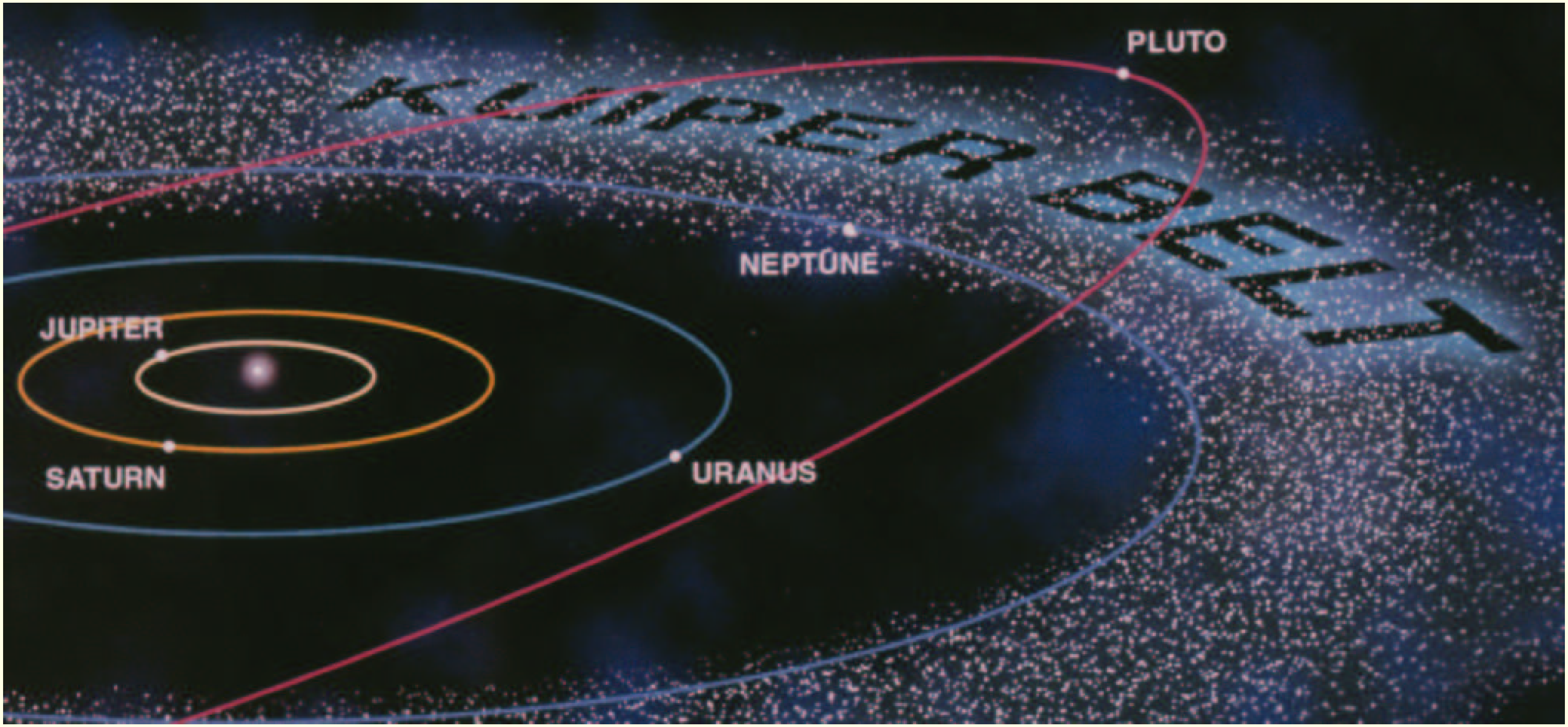
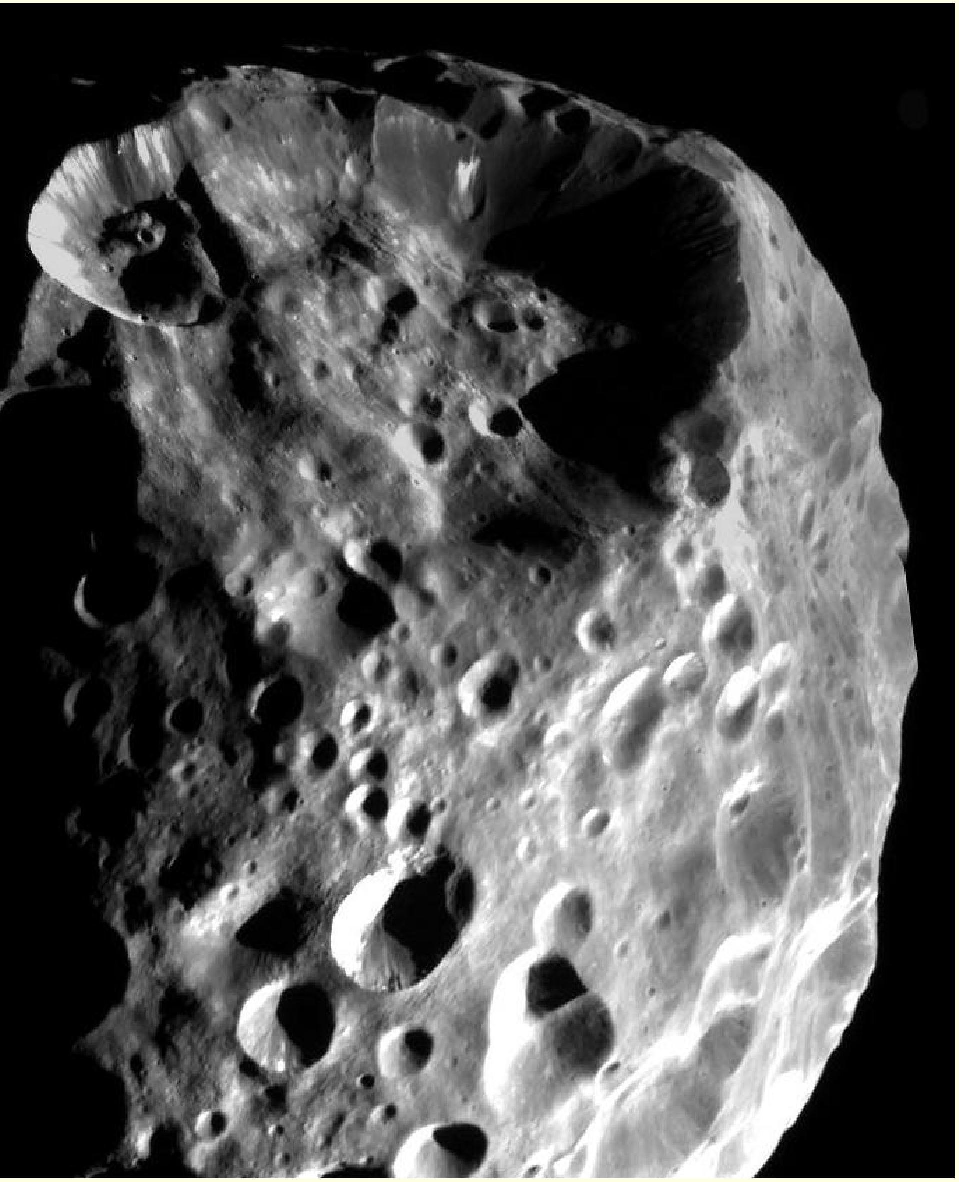


# What is a Kuiper Belt Object (KBO)?



from CICLOPS: Cassini Imaging page.

- KBOs are distant, ice–rich debris that were left over from when Solar System first formed

- likely heavily cratered
  due to impacts w/other KBOs,
  $\Leftarrow$perhaps like Phoebe

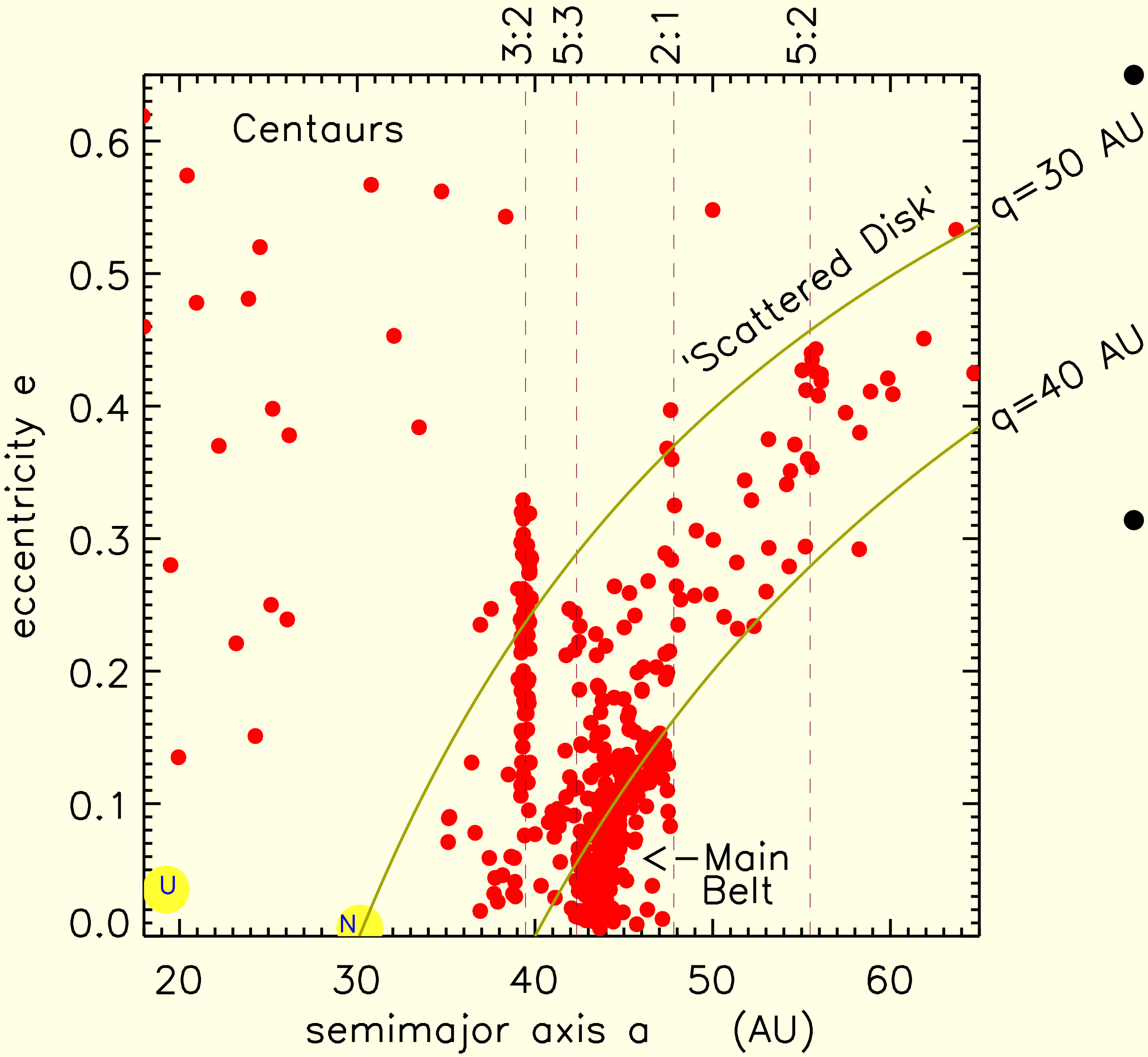
- Phoebe is in a very wide, retrograde orbit about Saturn

  – some suggest that Phoebe originated in the Kuiper Belt

    ∗ retrograde satellites are probably captured from heliocentric orbits

    ∗ Phoebe could have been a *Centaur* that wandered inwards from the KB & was captured by Saturn

# KBO Abundances & Orbits

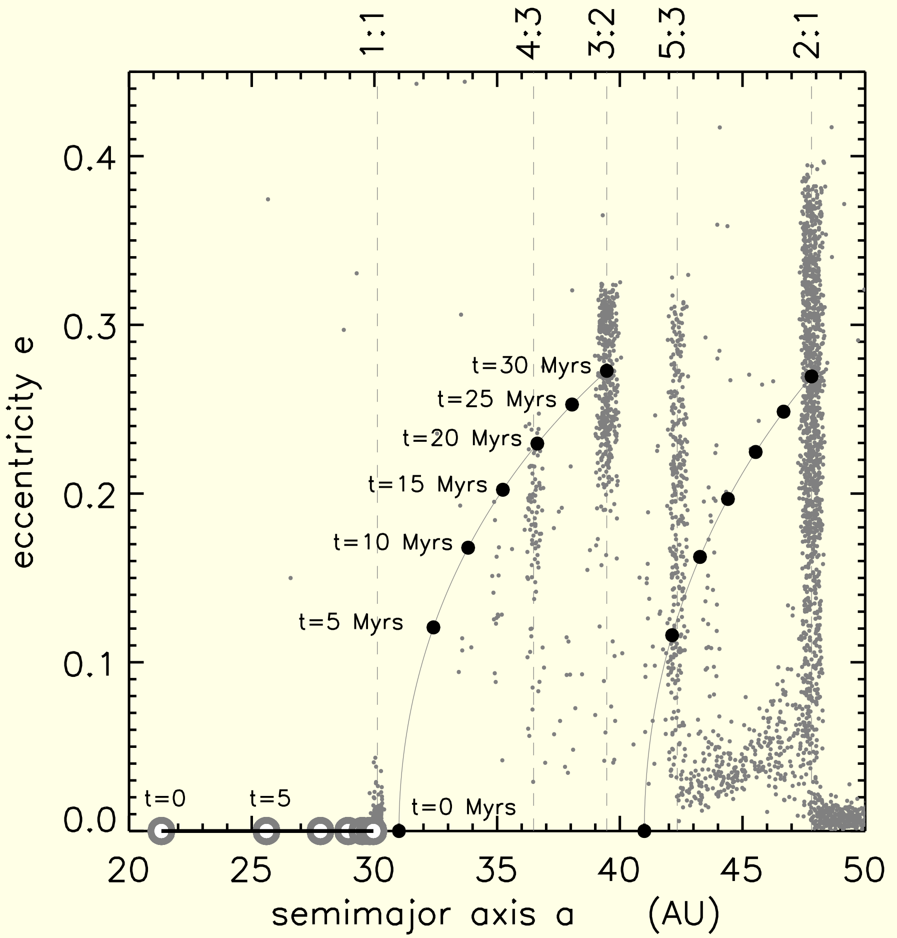



orbits from Minor Plant Center.

- observed KBOs have radii $10 \lesssim R \lesssim 1000$ km
  - $N(R > 50$ km$) \sim 10^5$
  - $mass(R > 50$ km$) \sim 0.1$ $M_\oplus$
  - $\sim 100\times$ asteroid belt

- several dynamical subclasses
  - resonant populations (e.g., 3:2, 2:1, 5:2)
  - Main Belt ($40 \lesssim a \lesssim 50$ AU, ie, between 3:2 and 2:1)
  - Scattered Disk ($a > 50$ AU & $30 < q < 40$ AU)
  - Centaurs ($a < a_{Neptune}$)

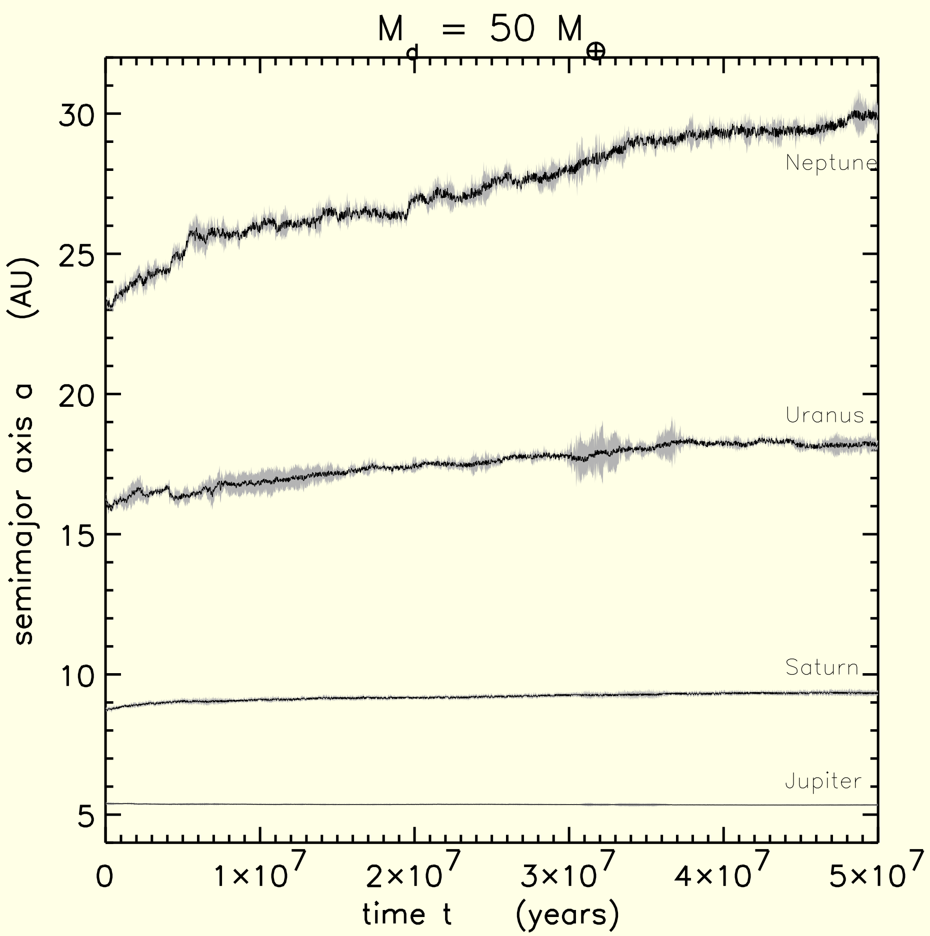
# 3:2 $\Rightarrow$ evidence for planet migration




- outward migration causes Neptune's mean motion resonances (MMR's) to sweep out across the Kuiper Belt
- KBOs get trapped at MMR's, are dragged outwards, and have $\mathbf{e}$ pumped up
- Malhotra (1993) showed this mechanism can account for Pluto's orbit (in 3:2 with $\mathbf{e} = \mathbf{0.25}$)
- this $\mathbf{e}$–pumping depends on Neptune's $\mathbf{\Delta a}$

- A particle trapped at a $\mathbf{j+k:j}$ MMR obeys $\mathbf{B = a(\sqrt{1-e^2} - \frac{j}{j+k})^2}$ = constant (Brouwer 1963, Yu & Tremaine 1999) $\Rightarrow \mathbf{e(a)^2 = 1 - \left(\frac{j+k\sqrt{a_{initial}/a}}{j+k}\right)^2}$ if $\mathbf{e_{init} = 0}$
- KBOs at Neptune's 3:2 ($\mathbf{j=2, k=1}$) have $\mathbf{e = 0.33}$, so they were dragged from $\mathbf{a_{initial} = 28}$ to $\mathbf{a = 40}$ AU
  - these KBOs were shepherded $\mathbf{\Delta a_p = 12}$ AU
  - and Neptune migrated $\mathbf{\Delta a_{Nep} = \Delta a_p/(1+k/j)^{2/3} = 9}$ AU

# Why would the giant planets migrate?



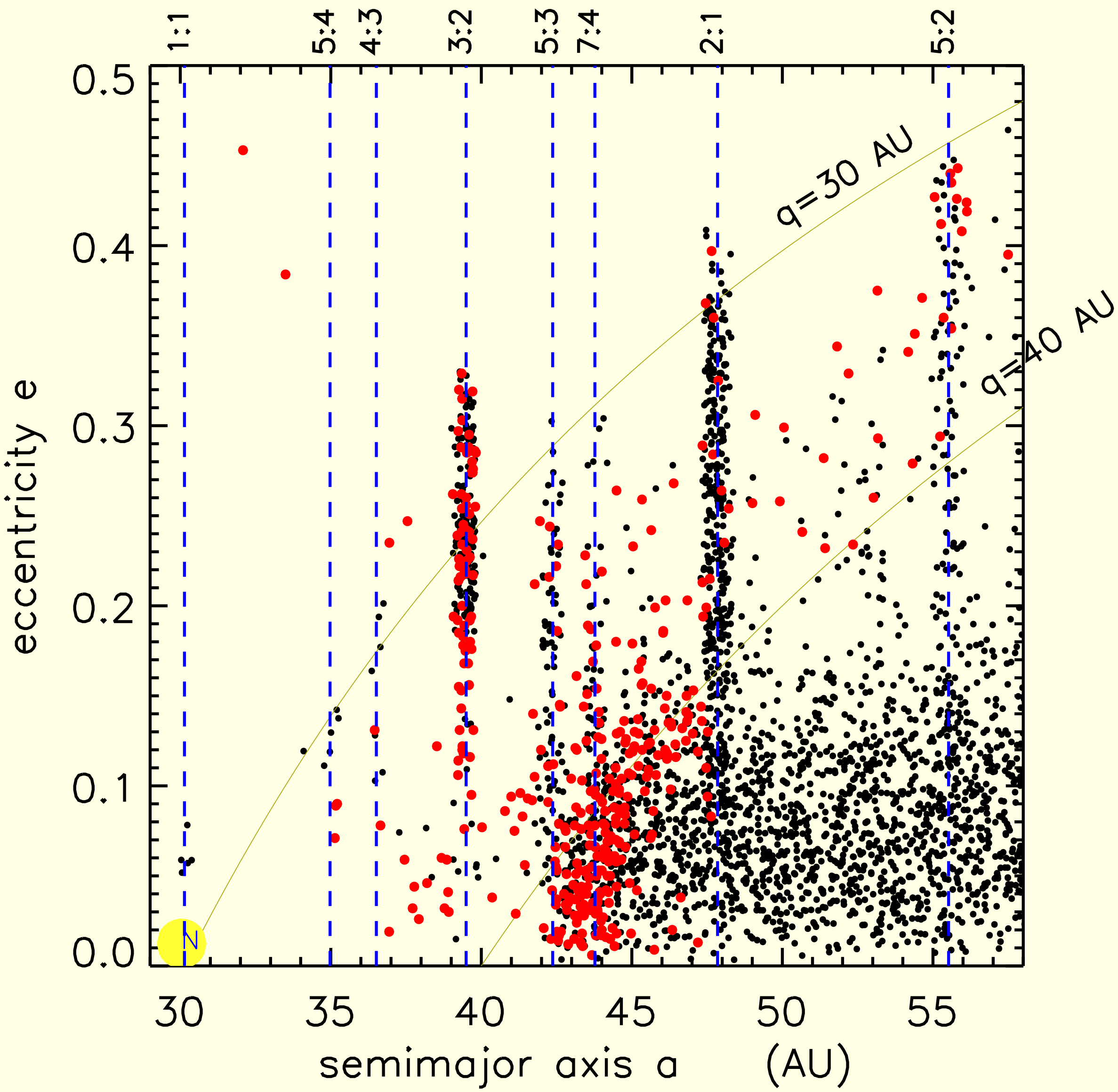

from Hahn & Malhotra (1999)

- cores of giant planets formed within a planetesimal disk
- planet–formation was likely not 100% efficient
  - residual planetesimal debris is left over
- recently–formed planets scatter the planetesimal debris, exchange $\mathbf{L}$ with planetesimal disk
- Nbody simulations (Fernandez & Ip 1984, Hahn & Malhotra 1999, Gomes, Morby, Levison 2004) show planets evolve away from each other, ie, Jupiter inwards, Neptune outwards

- driving Neptune $\Delta \mathbf{a_{Nep}} \simeq \mathbf{9}$ AU requires disk mass $\mathbf{M_D} \sim \mathbf{50}$ $M_\oplus$ over $\mathbf{10 < r < 50}$ AU.

# Simulated & Observed Endstates

- Mercury Nbody integrator (Chambers 1999) is used to simulate Neptune's migration into Kuiper Belt (black dots)
  - 4 planets + $10^4$ massless p's evolved for 4.5 Gyrs,
  - in serial mode on McKenzie & ICA's Pluto cluster
    - $*$ 4 planets + $100$ p's on 100 CPUs, evolved in $\sim 10$ days
  - planet migration is driven by an external torque on planets, $\Delta a_{Nep} = 9$ AU



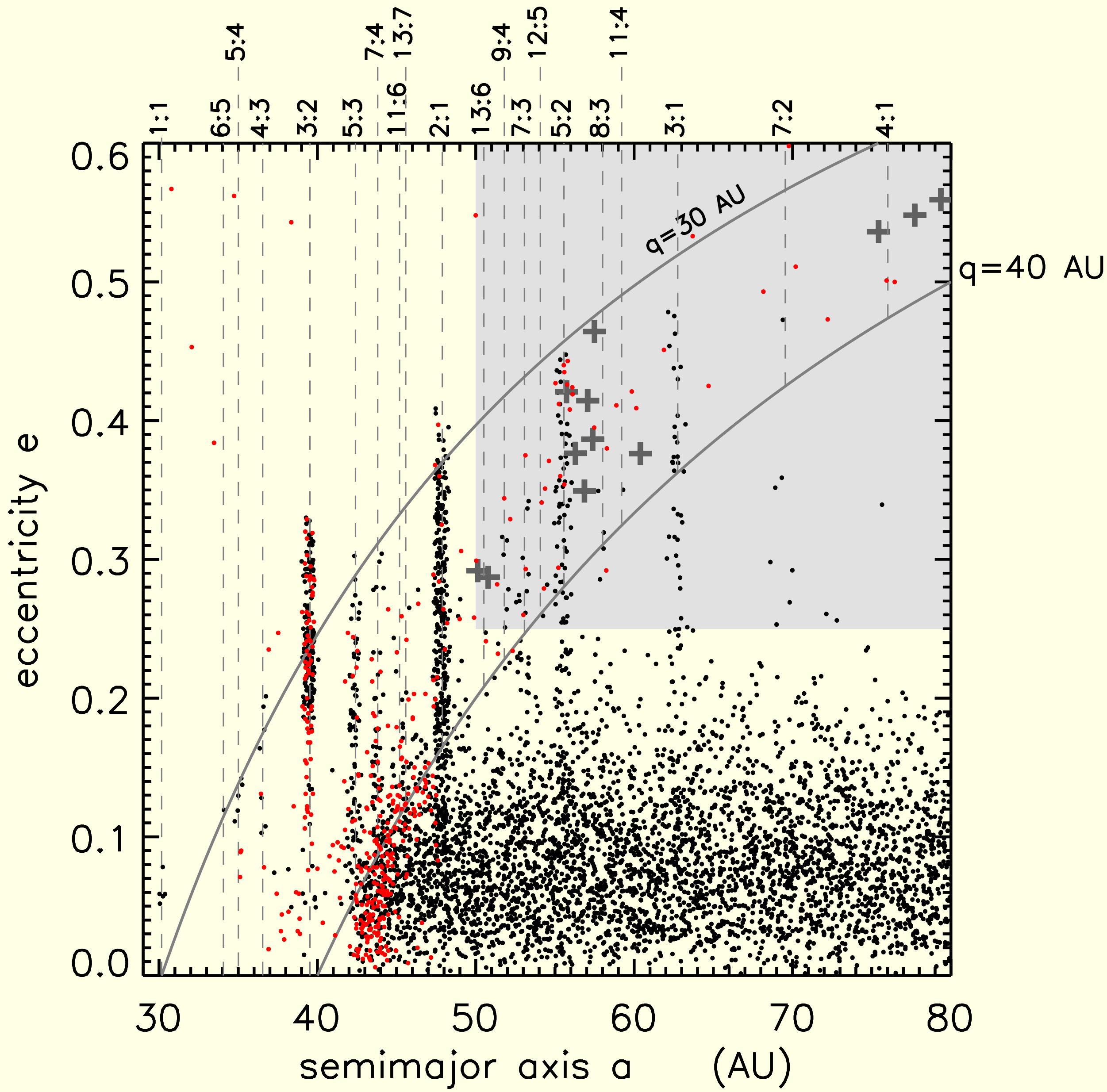

- Neptune's advancing resonances then traps numerous particles (black dots)
- note dearth of low–$e$ KBOs observed beyond $a \gtrsim 50$ AU $\Rightarrow$ the SS's outer edge?

# The Scattered Disk—perhaps not so scattered?

- sim' shows that trapping @ 9:4, 7:3, 5:2, 3:1 promotes particles into Scattered Disk $30 \lesssim q \lesssim 40$ AU.

- suggests the real Scattered Disk might also contains trapped particles

- inspect particles in gray box:
  - 90% of survivors are *res' trapped particles*
  - only 10% of survivors were *scattered* by Neptune



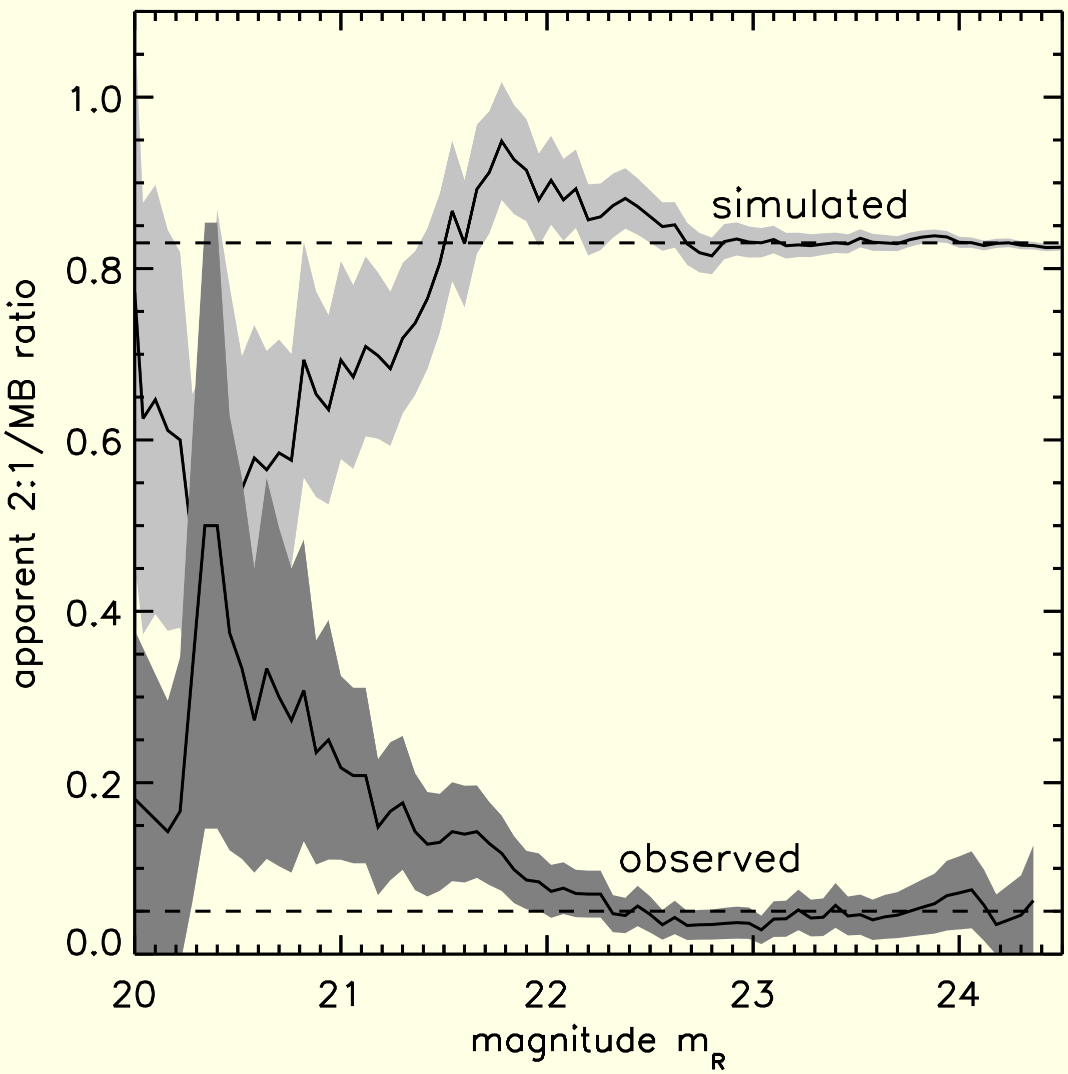

⇒this suggests that the so–called Scattered Disk might be composed mostly of *resonantly trapped particles* that never came close to Neptune

# Use Monte Carlo methods to infer the abundance of KBOs

- replicate each Nbody survivor $10^4$ times

- assign radii $R$ according to 'bright end' ($mag < 24$) of KBO size distribution from Bernstein et al (2004)
  - cumulative size distribution $N(R) \propto R^{-Q}$
  - $Q = 4.4$ or $\alpha = Q/5 = 0.88$

- Note: plot of *relative* KBO abundances are insensitive telescopic selection effects

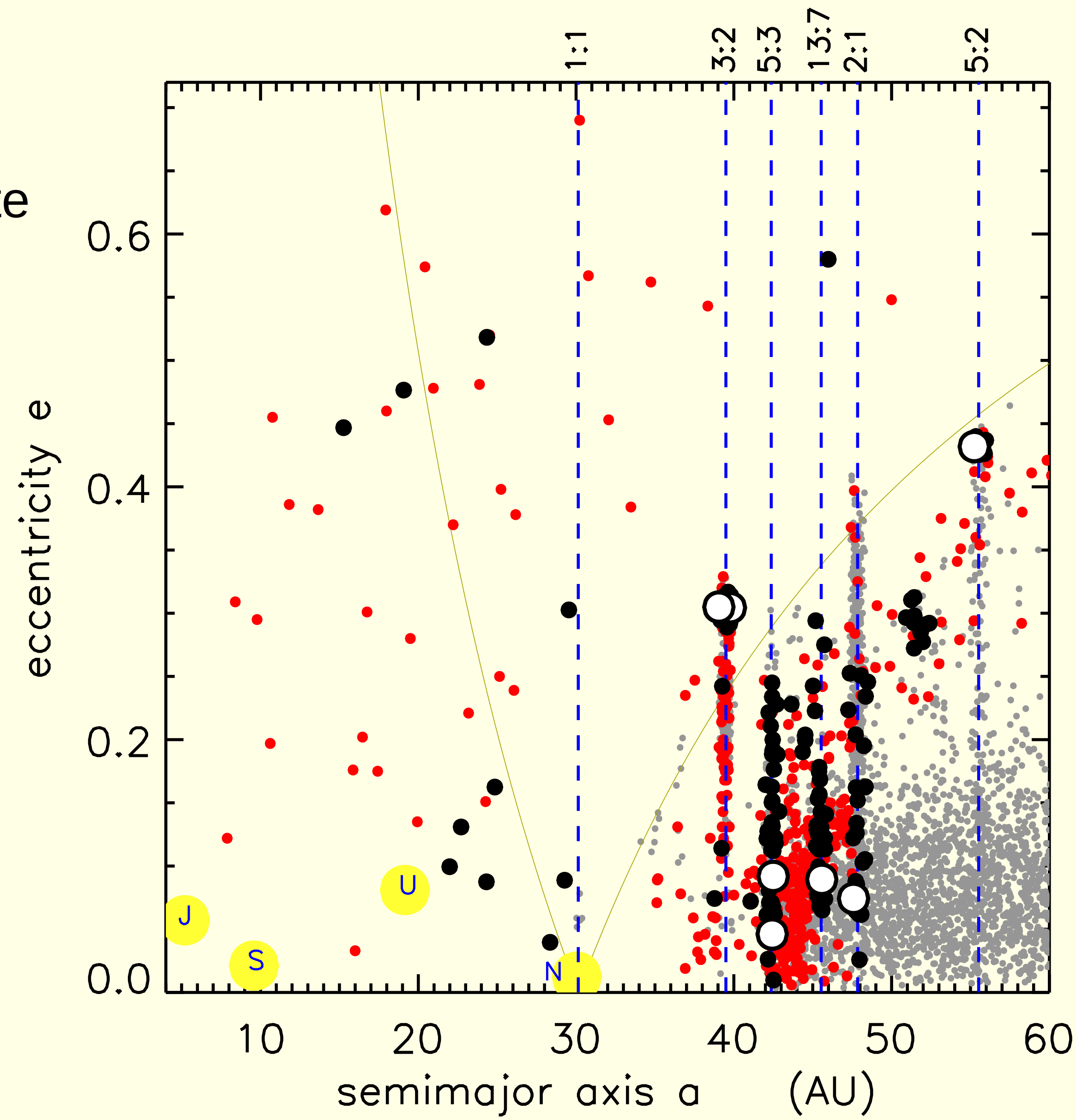



2:1/MB ratios $\Rightarrow$ the observed 2:1 is depleted by factor $\sim 20$ relative to model

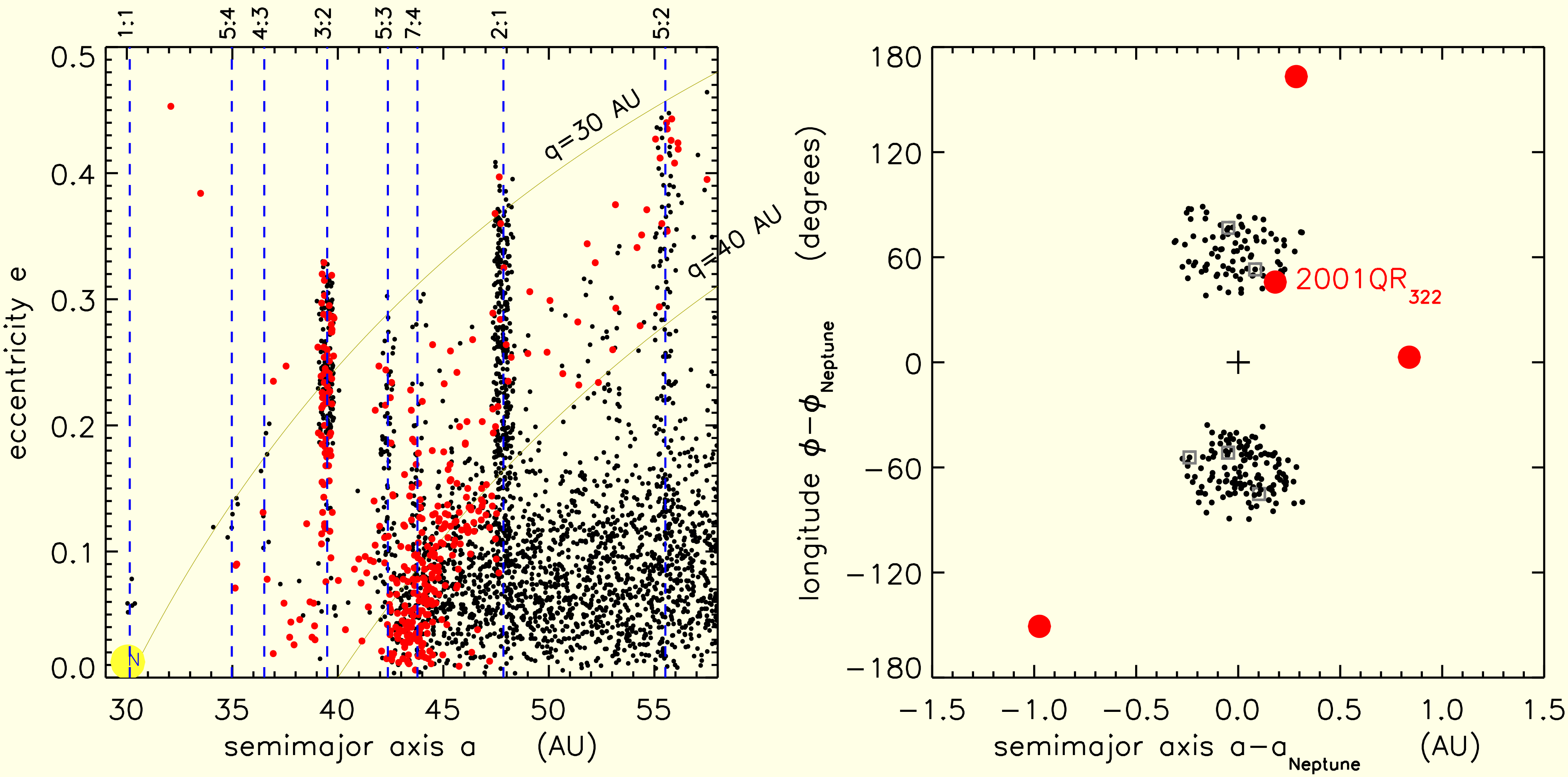
*Ditto for 3:2! $\Rightarrow$ due to unmodeled effects, like grav' scattering?*

# The Origin of Centaurs

- simulation produced only 7 Centaurs during final 2 Gyrs
- gray dots = simulated KB endstate
- red dots = observed endstate
- open circles = future Centaurs at time $t = 10^8$ years
  - sites where migrating Neptune first *parked* these Centaurs
  - all 7 Centaurs originate at Neptune's 3:2, 5:3, 13:7, & 5:2
- model prediction: are $N_C \sim 130$ Centaurs of radius $R > 50$ km, similar to Sheppard et al (2000)



# Neptune's Trojans

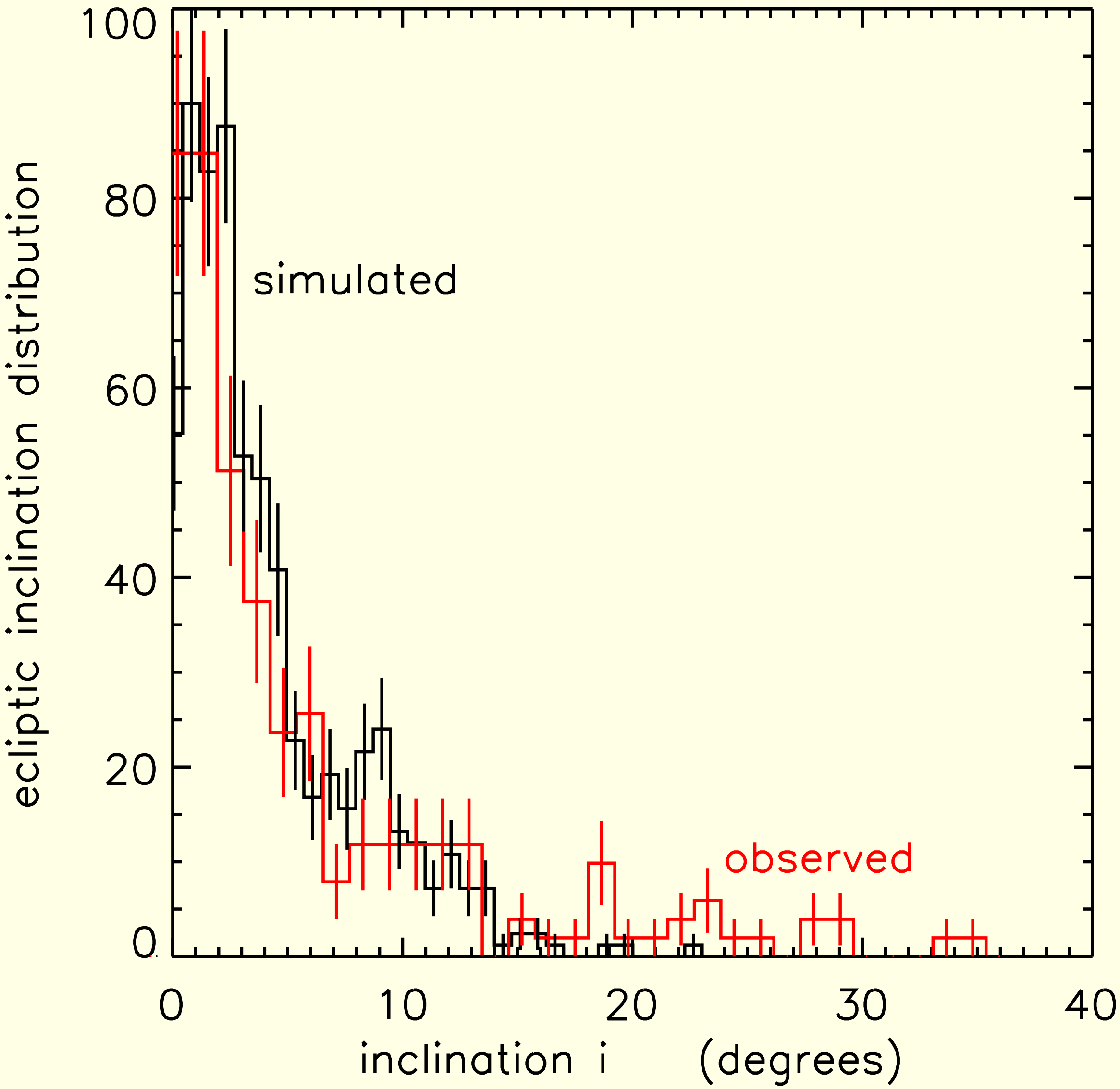



- 5 Trojans survived at Neptune's triangular Lagrange points for $\mathbf{4.5 \times 10^9}$ years
- the simulation's Trojan/MB ratio is $\mathbf{r_{T/MB} \sim 0.01}$

# KBO Inclinations

- KBO astronomers observed near ecliptic, which selects for low–$i$ KBOs
- Brown (2001): avoid $i$–bias by comparing *ecliptic* inclination distributions
- model easily accounts for KBOs having $\mathbf{i < 15^\circ}$
- it does not account for $\mathbf{i > 15^\circ}$

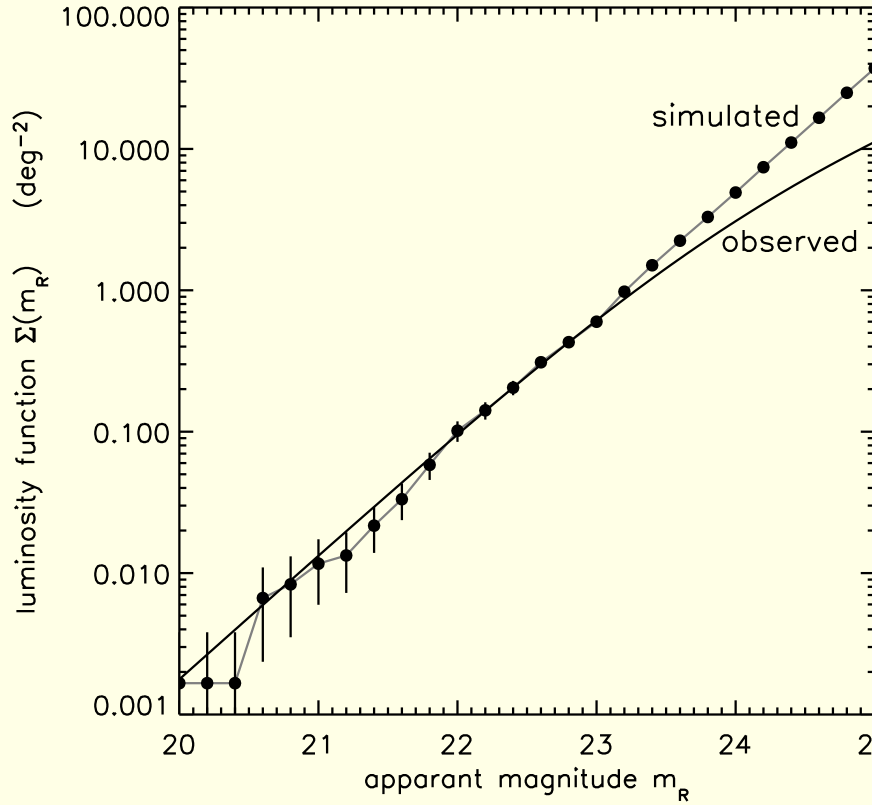
$\Rightarrow$**this is the main deficiency of this model**



# A Kuiper Belt Census

- the Nbody/Monte Carlo model yields the *relative* KBO abundances: MB, SD, Centaurs, Neptune Trojans, etc

- to get the KBO's absolute abundance, fit the model's luminosity function $\Sigma(\mathbf{m})$ (the sky–plane number density of KBOs brighter than $m$) to the observed $\Sigma(\mathbf{m})$:
  - $\mathbf{N \sim 1.7 \times 10^5}$ KBOs having radii $\mathbf{R > 50}$ km
  - mass $\mathbf{M \sim 0.08}$ $M_\oplus$ assuming albedo=0.04, or $\mathbf{M \sim 0.02}$ $M_\oplus$ if albedo=0.1



# KBO Census according to Nbody/MC model

| Population | $\mathbf{N(R > 50}$ km$)$ | $\mathbf{mass(R > 50}$ km$)$ ($M_\oplus$) |
|---|---|---|
| Centaurs | $\mathbf{130}$ | $\mathbf{7 \times 10^{-5}}$ |
| Trojans | $\mathbf{< 1 \times 10^{3}}$ | $\mathbf{< 5 \times 10^{-4}}$ |
| 3:2 | $\mathbf{3 \times 10^{3}}$ | $\mathbf{3 \times 10^{-3}}$ |
| Main Belt | $\mathbf{1.3 \times 10^{5}}$ | $\mathbf{0.06}$ |
| 2:1 | $\mathbf{5 \times 10^{3}}$ | $\mathbf{2 \times 10^{-3}}$ |
| Scattered(?) Disk | $\mathbf{3 \times 10^{4}}$ | $\mathbf{0.01}$ |
| Total | $\mathbf{1.7 \times 10^{5}}$ KBOs | $\mathbf{0.08}$ $M_\oplus$ |

# Acknowledgments


- these simulations used the Mercury integrator (Chambers 1999) on
  - CITA's McKenzie cluster (funded by CFI and OIT)
  - and on the ICA's Pluto cluster (funded by CFI)
- with support from the NSERC Discovery program