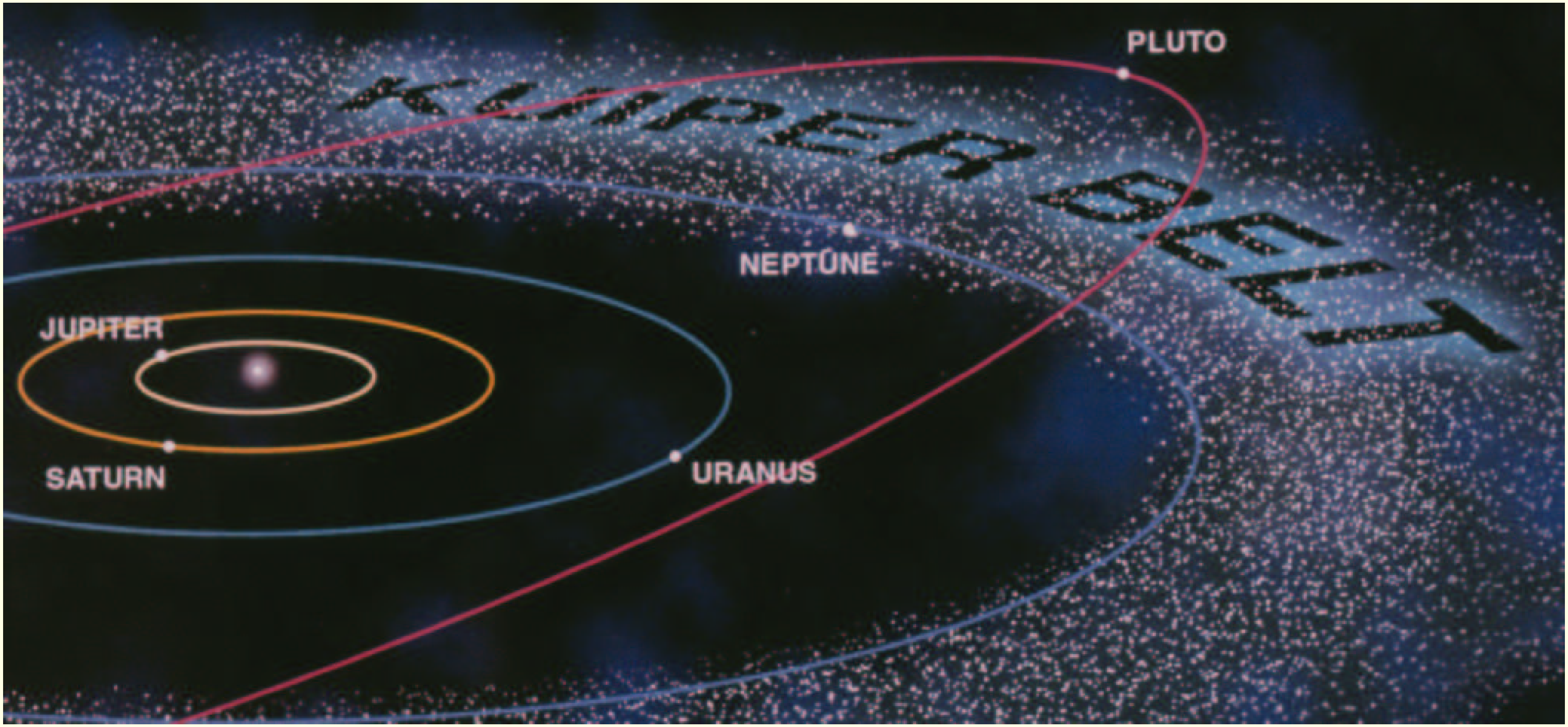
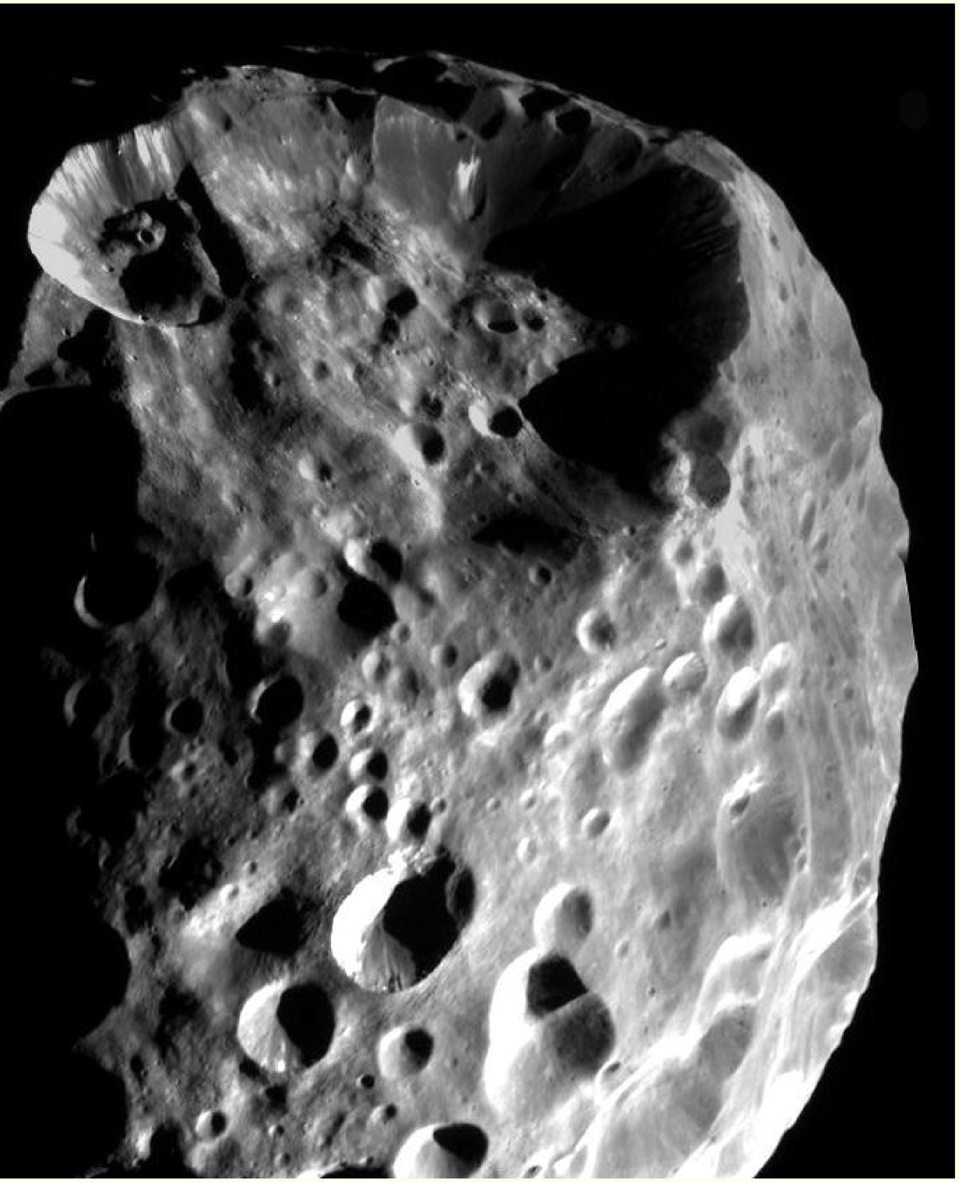
Sculpting the Kuiper Belt via Neptune's Orbital Migration

Joseph M. Hahn
Saint Mary's University
Institute for Computational Astrophysics

with
Renu Malhotra
University of Arizona



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,
  ⇐perhaps like Phoebe

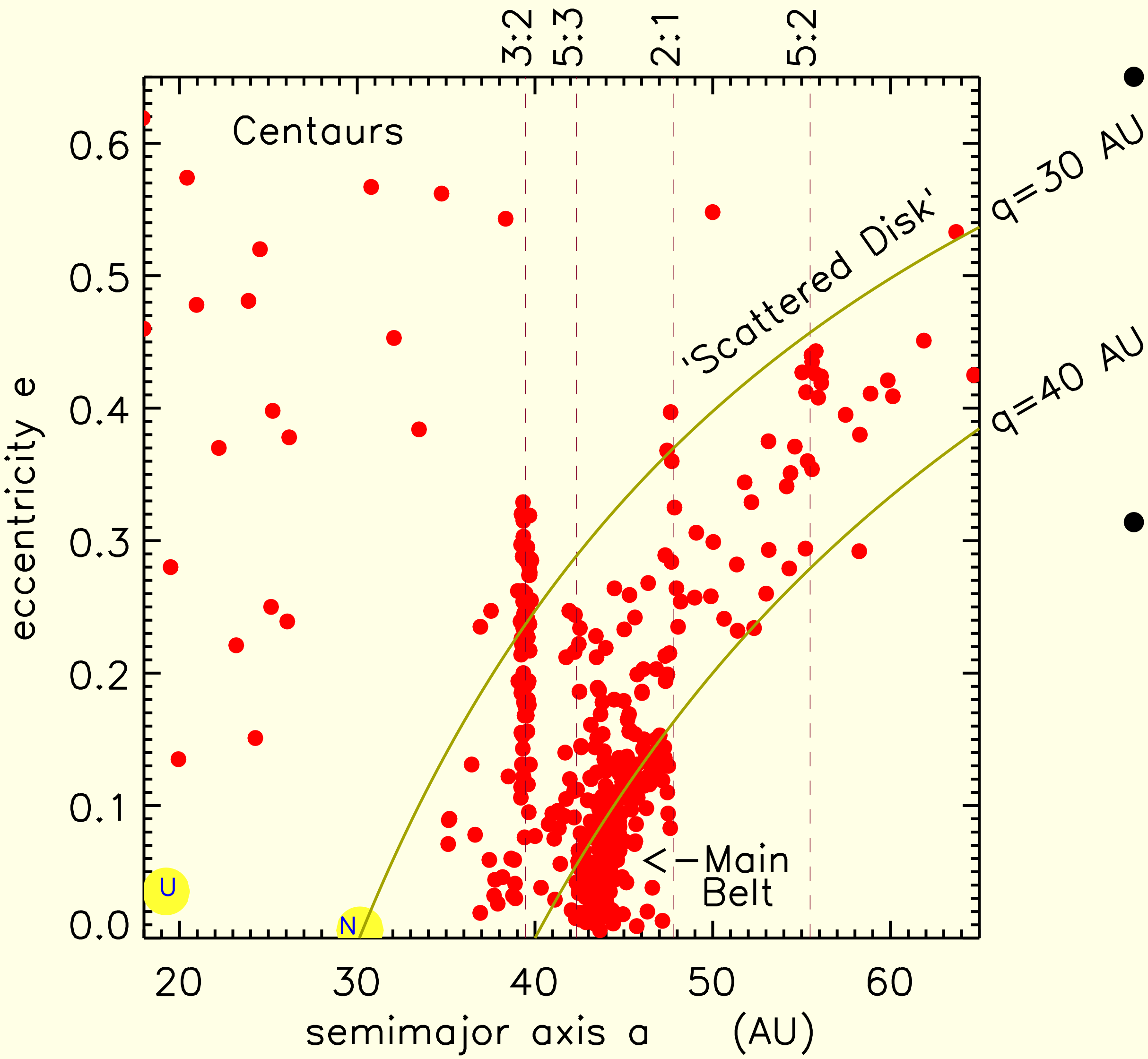
- Phoebe is in a very wide, retrograde orbit about Saturn—was probably captured from *heliocentric* orbit

  - some suggest that Phoebe *originated* in the Kuiper Belt (maybe...)

- nonetheless, this pic' of Phoebe might be a representative of a typical KBO

What is the Kuiper Belt?

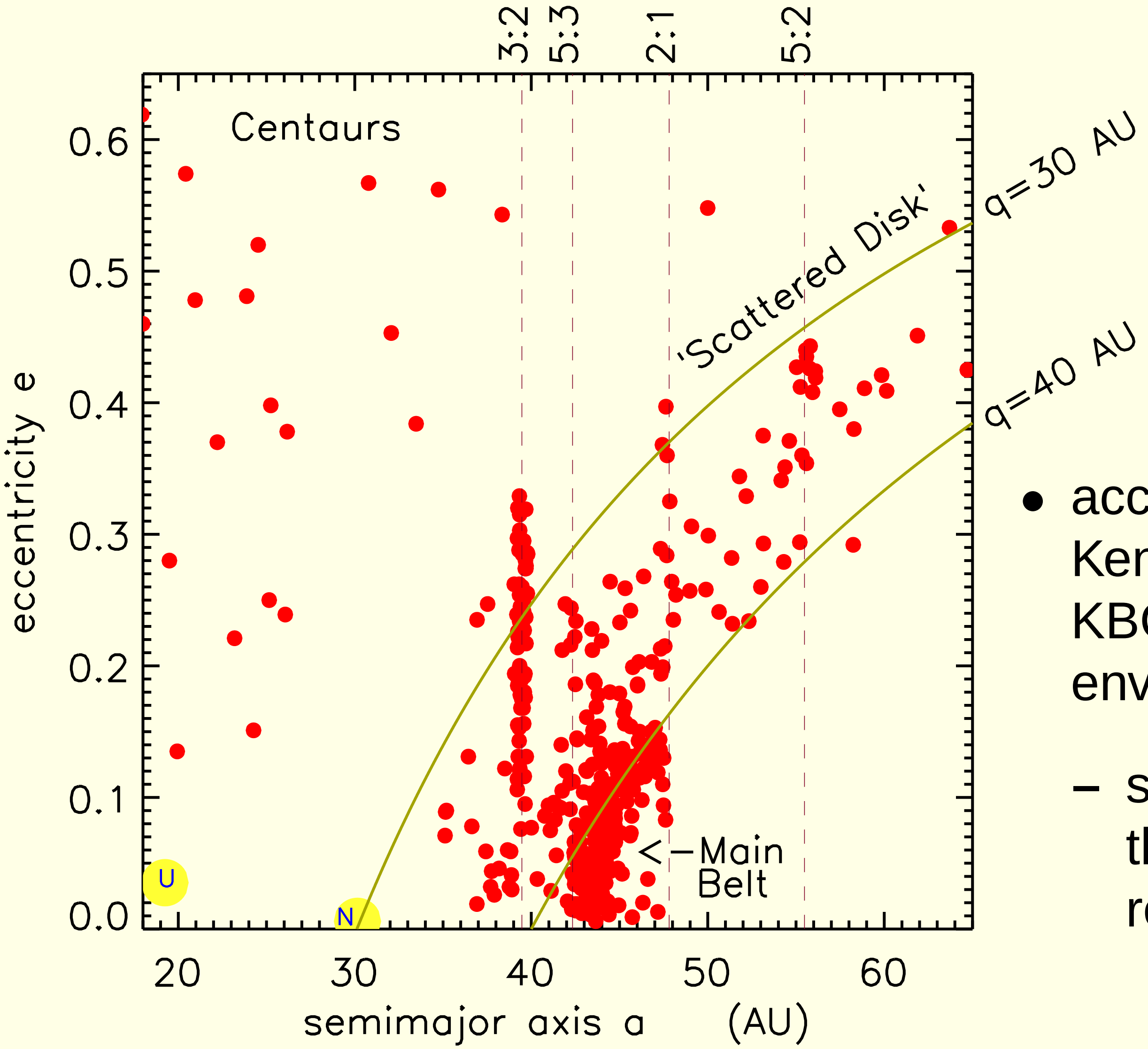
- a vast swarm of giant comets orbiting just beyond Neptune



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 ($\mathbf{a > 50}$ AU & $\mathbf{30 < q < 40}$ AU)
  - Centaurs ($\mathbf{a < a_{Neptune}}$)

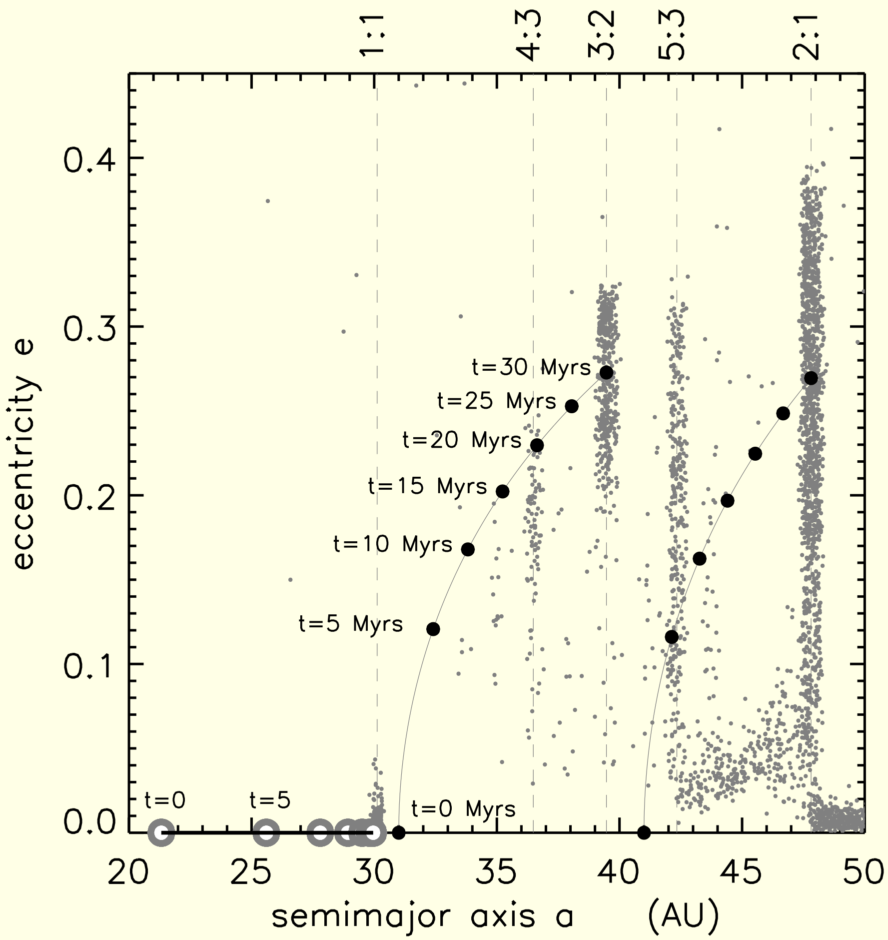


orbits from Minor Plant Center.

- accretion models (Stern 1995, Kenyon & Luu 1999) show that KBOs can only form in a quiescent environment, ie, $\mathbf{e_{initial} \lesssim 0.001}$
  - some process has disturbed the Kuiper Belt & pumped up resonant KBOs' $\mathbf{e}$'s (and $\mathbf{i}$'s)

- these eccentric KBOs orbiting at Neptune's MMRs are generally interpreted as evidence for Neptune's orbit having migrating outwards by $\mathbf{\Delta a_{Nep} \simeq 9}$ AU

3:2 $\Rightarrow$ evidence for planet migration

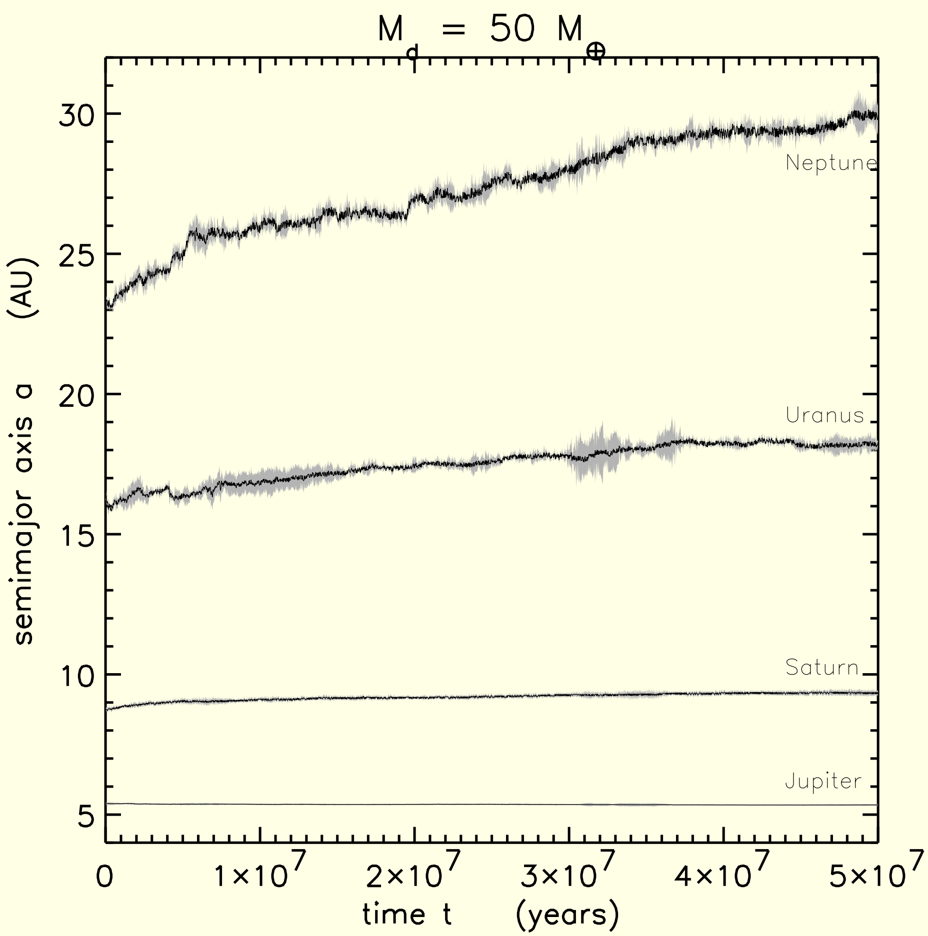


- outward migration causes Neptune's mean motion resonances (MMR's) to sweep out across the Kuiper Belt
- ex: the 3:2 is where a KBO orbits 2 times for every 3 orbits of Neptune
- Malhotra (1993) showed that KBOs get trapped at sweeping MMR's, are dragged outwards, and have $\mathbf{e}$ pumped up
  - this mechanism accounts for Pluto, with $\mathbf{e = 0.25}$ at 3:2
  - the $\mathbf{e}$–pumping depends only on Neptune's displacement, $\mathbf{e = f(\Delta a)}$

- KBOs at Neptune's 3:2 have $\mathbf{e = 0.33}$, so $\mathbf{e = f(\Delta a) = 0.33 \Rightarrow \Delta a = 12}$ AU, so they were dragged outwards from $\mathbf{a = 28 \rightarrow 40}$ AU

- since Neptune's 3:2 resonance expanded by 12 AU, its semimajor axis evidently expanded by $\mathbf{\Delta a_{Nep} = 9}$ AU

Why would the giant planets migrate?



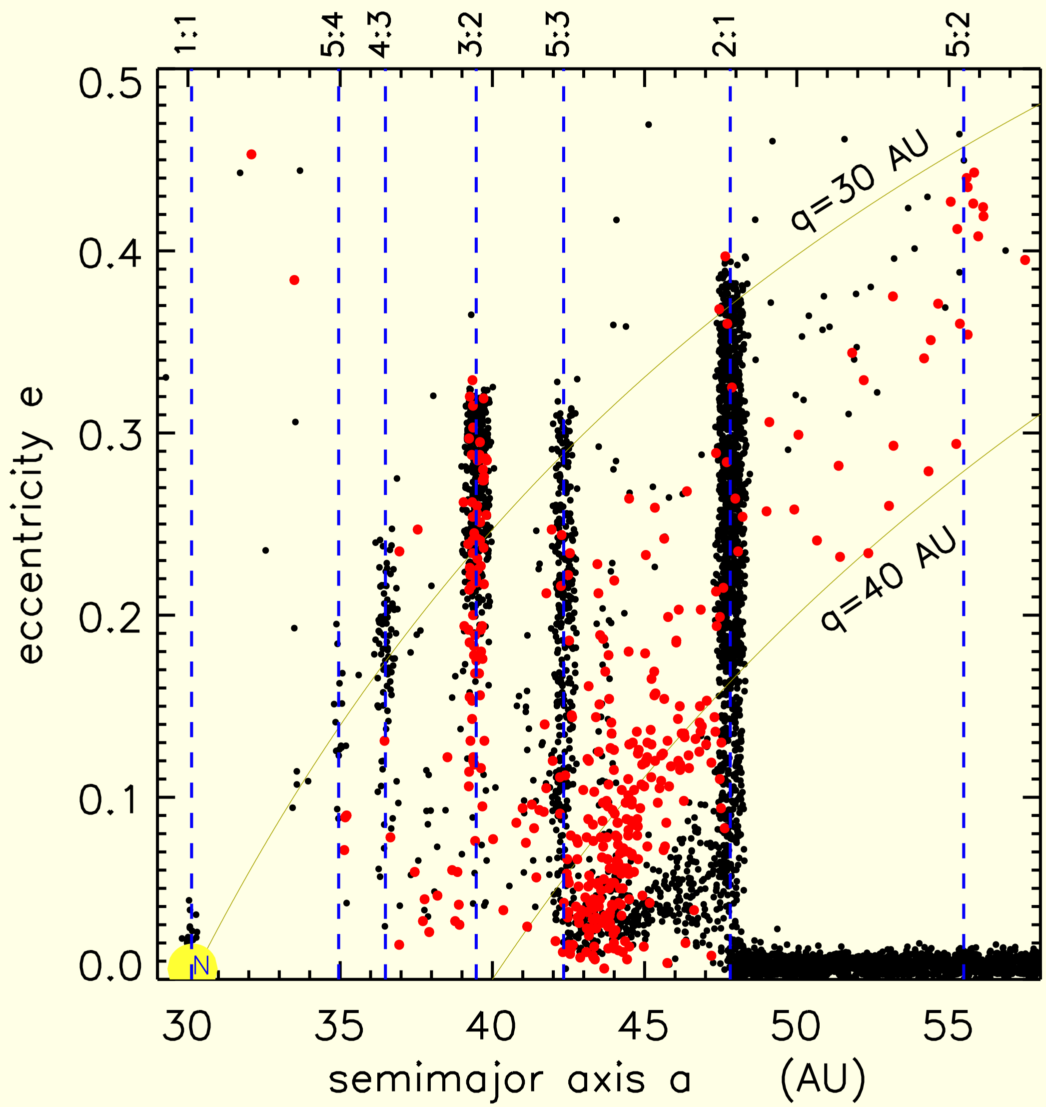
from Hahn & Malhotra (1999)

- 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.

Migration into a dynamically cold Kuiper Belt

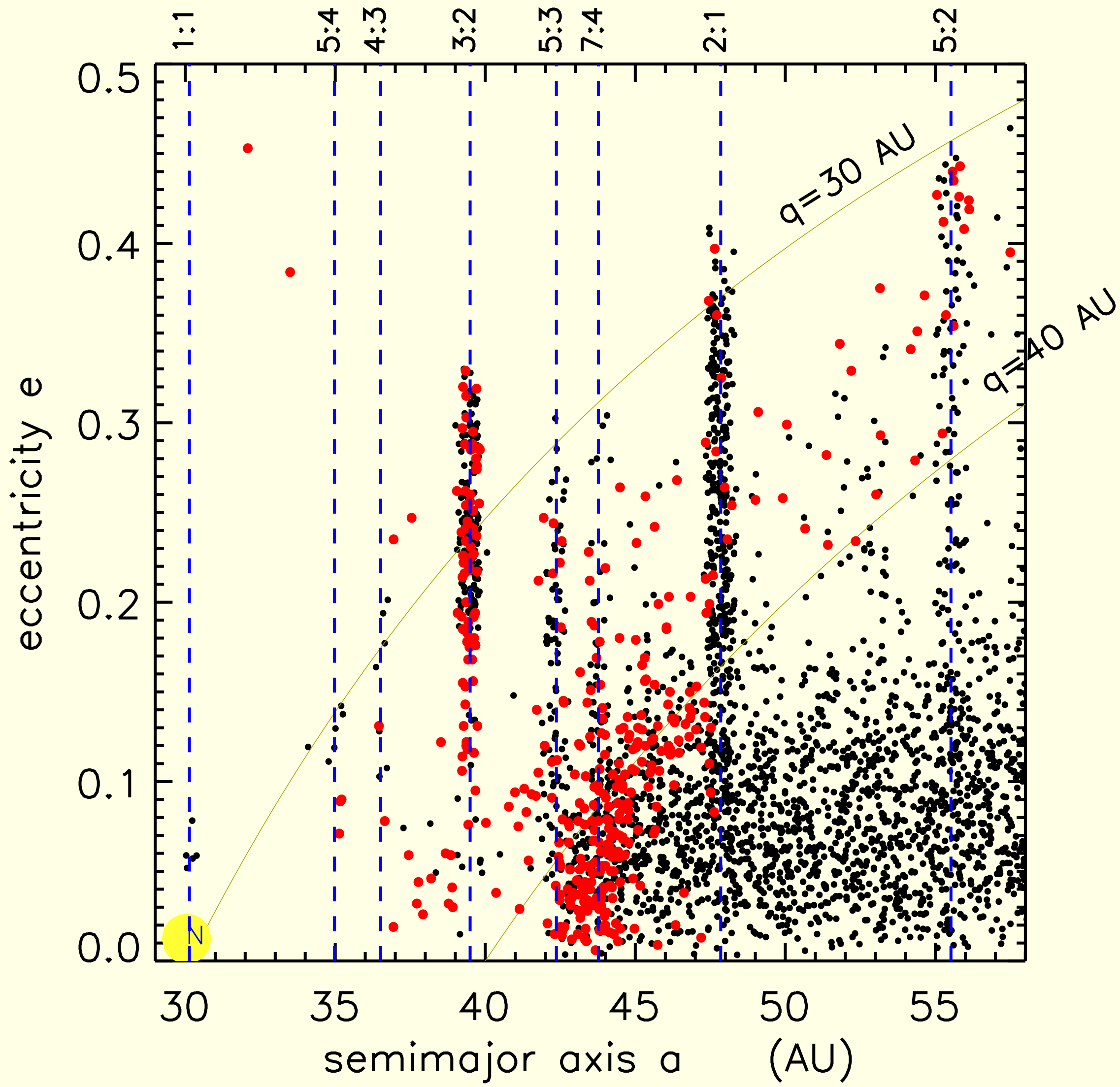
- red dots=observed KBO orbits
- Mercury Nbody integrator (Chambers 1999) is used to simulate Neptune's migration into Kuiper Belt (black dots)
  - 4 planets + 10^4 massless p's evolved for 4.5 Gyrs
  - planet migration is driven by an external torque on planets, $\Delta a_{Nep} = 9$ AU
  - initial KB is dynamically cold (ie $e_{initial} = 0 = i_{initial}$)
- note: observed Main Belt has $e_{obs} \sim 0.1$ while $e_{sim} \sim 0.03$



⇒something has stirred–up the Kuiper Belt, either prior to, or after the onset of planet–migration

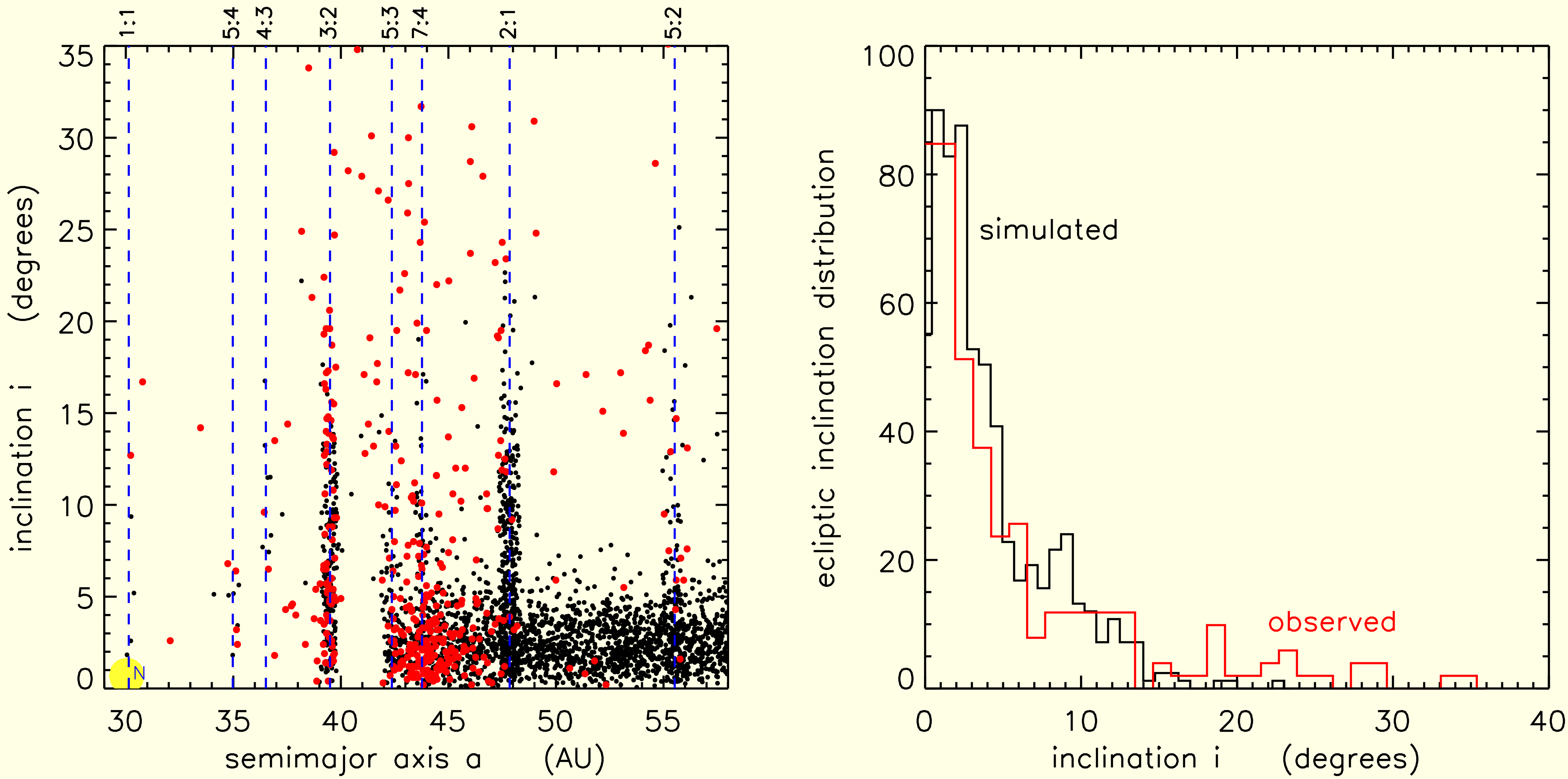
Migration into a dynamically hot Kuiper Belt

- assume KB is stirred–up prior to migration, ie, $\mathbf{e_{initial}} \sim \mathbf{0.1}$
- simulation in better agreement with observed Main Belt
- weaker, higher–order res'nces (eg, 7:4, 5:2) trap particles
  - first noted in migration sim's by Chiang et al (2003)
  - a surprise—the theory of resonance capture theory shows trapping probability $\mathbf{P} \ \alpha \ \mathbf{e}_{\mathbf{initial}}^{-3/2}$ (B&G 1984)...



- other exotic resonances get populated: 11:6, 13:7, 13:6, 9:4, 12:5, 8:3, 11:4
- migration into a previously stirred–up KB having $\mathbf{e_{initial}} \sim \mathbf{0.1}$ can account for:
  - Main Belt $\mathbf{e} \sim \mathbf{0.1}$
  - the 7 KBOs known to librate at the 5:2

Compare simulation & observed inclinations

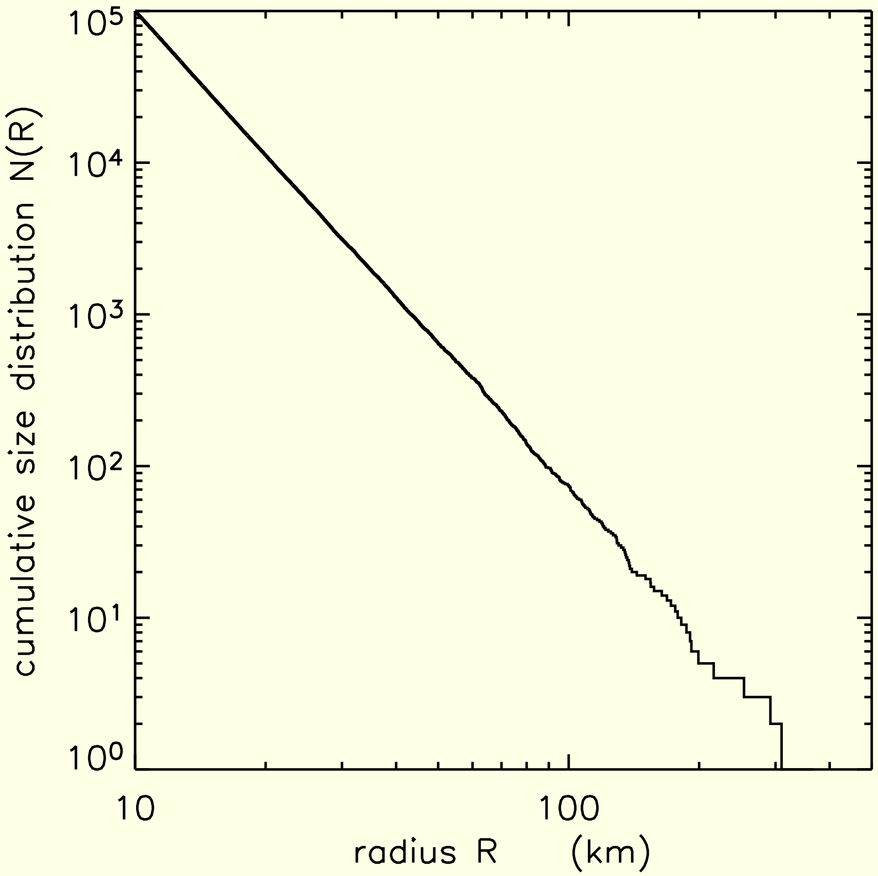


- don't directly simulated $\mathbf{i}$'s to observed KBO $\mathbf{i}$'s $\longleftarrow$ these are biased
- instead, compare *ecliptic* $\mathbf{i}$–*distribution* $\longrightarrow$ $\mathbf{i}$'s of bodies with latitudes $|\beta| < \mathbf{1}^\circ$
  - this model can account for bodies with $\mathbf{i} \lesssim \mathbf{15}^\circ$
  - but it does not account for bodies with higher $\mathbf{i}$'s
- this is problematic since $\sim \mathbf{1/2}$ of all KBOs have $\mathbf{i} > \mathbf{15}^\circ$ (eg, Brown 2001)

Dealing with telescopic selection effects

- telescopes select for larger & brighter KBOs that live nearest the Sun & ecliptic
  - discovery of low $\mathbf{a}$, high $\mathbf{e}$, and low $\mathbf{i}$ KBOs are favored

- use Monte Carlo methods to account for selection effects
  - replicate each Nbody particle $\times\mathbf{10^4}$, & randomize their positions along their orbital ellipses
  - assume a power–law in the bodies' cumulative size distribution $\mathbf{N(R)} \propto \mathbf{R^{-Q}}$
  - assign apparent magnitudes via $\mathbf{m} = \mathbf{m_\odot} - \mathbf{2.5}\log(\mathbf{pR^2}\text{AU}^\mathbf{2}/\mathbf{r^4})$, where $\mathbf{p} =$ albedo



- the size distribution $\mathbf{Q}$ is obtained from the KBO luminosity function:

  $\Sigma(\mathbf{m}) =$ sky–plane number density of KBOs brighter than magnitude $\mathbf{m}$

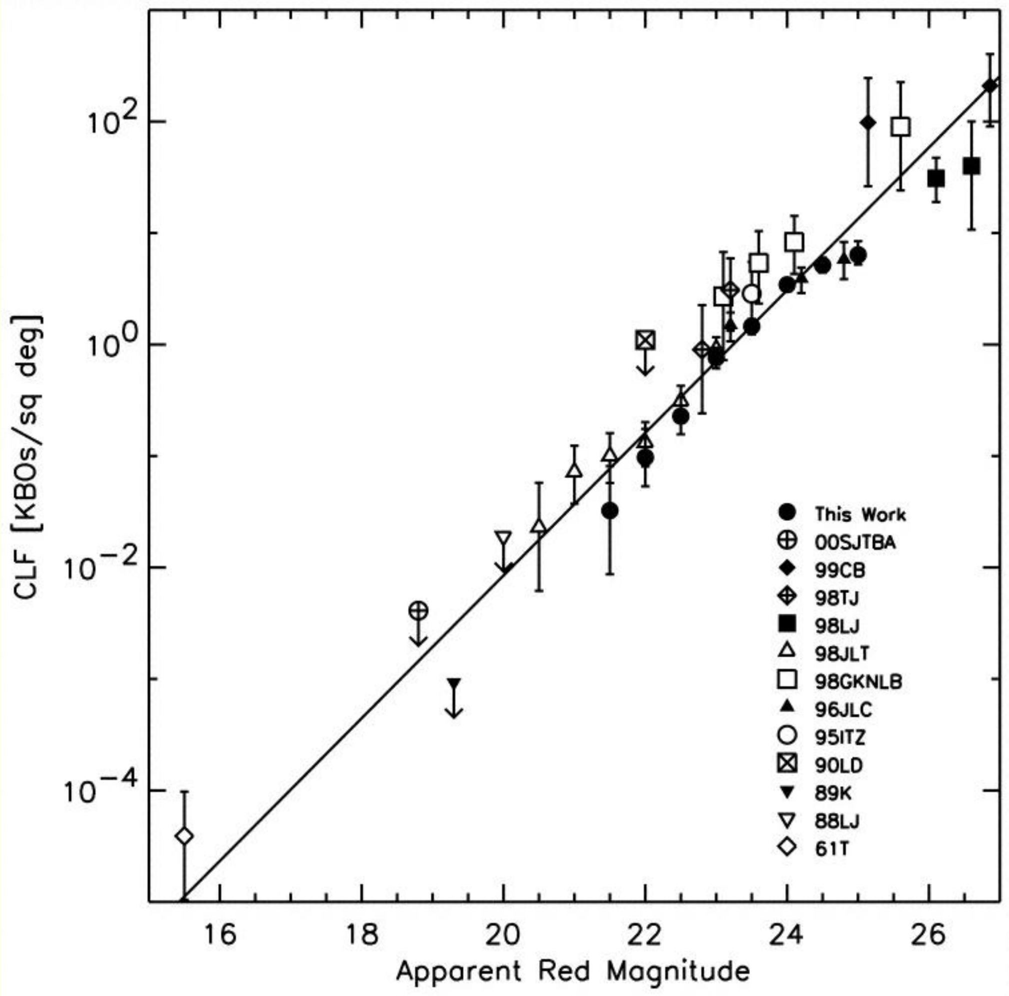
  – $\boldsymbol{\Sigma(m) = \int_m^{-\infty} \frac{dN(R(m))}{dR} dR}$

  $$\sim \mathbf{10^{Qm/5}}$$

  – the HST KBO survey by Bernstein *et al* (2004) shows that the 'bright end' of $\boldsymbol{\Sigma(m < 24)}$ has logarithmic slope $\boldsymbol{\alpha = d \log \Sigma / dm = Q/5 = 0.88}$

  – observing the Belt 1 magnitude fainter yields $\mathbf{8}\times$ more KBOs

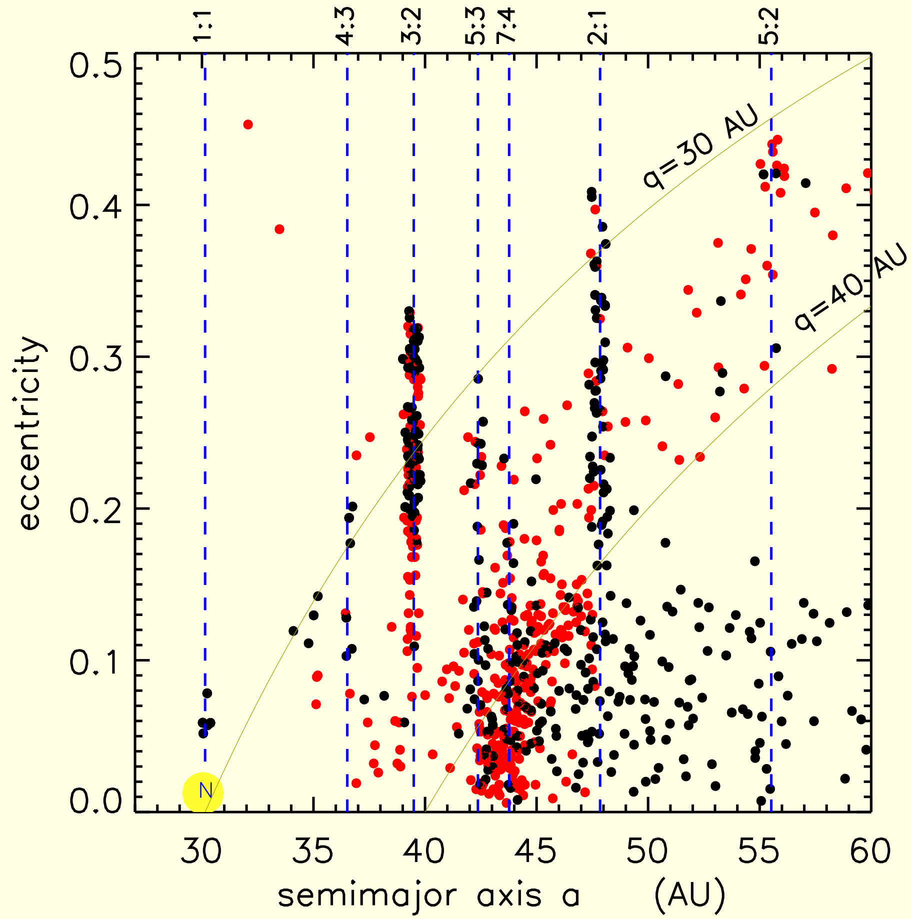
  – $\boldsymbol{\Rightarrow Q = 5\alpha = 4.4}$



from Trujillo, Jewitt, & Luu (2001)

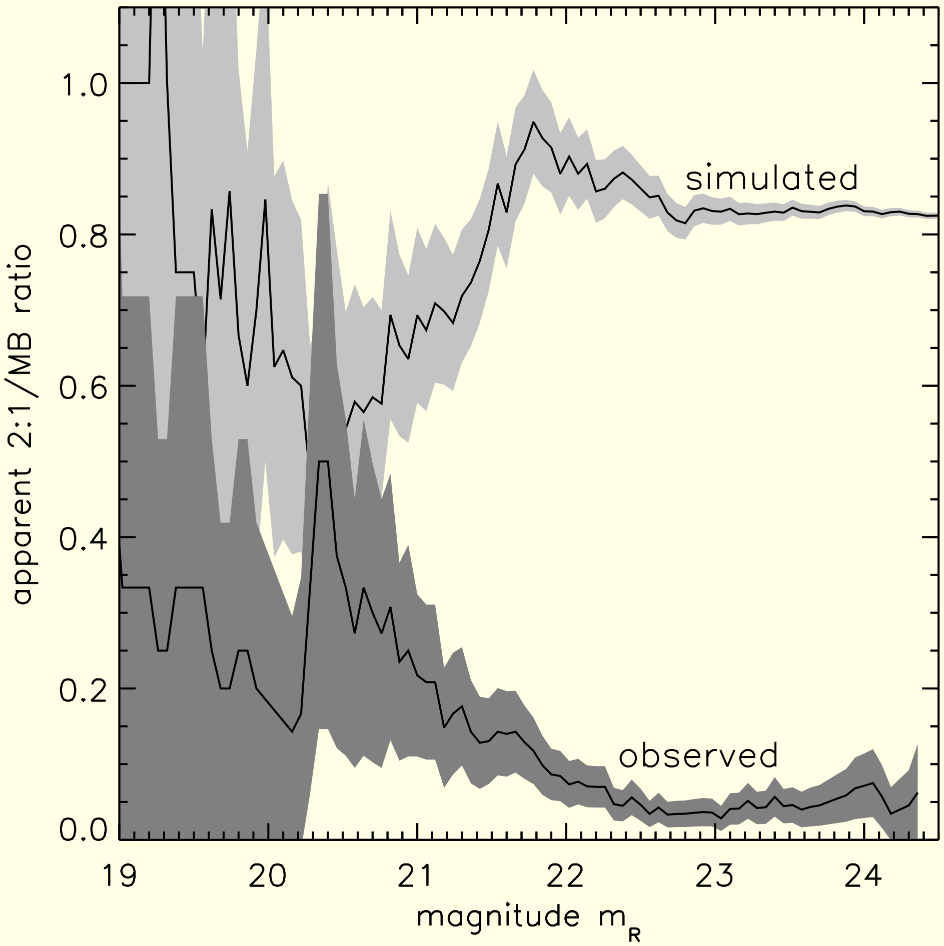
Nbody/Monte Carlo model of the Kuiper Belt

- use Monte Carlo method to assign sizes & magnitudes to Nbody sim'
- $\sim \mathbf{500}$ KBOs with known orbits; all have $\mathbf{m < 24}$
- also shown are 500 random Nbody/MC particles having $\mathbf{m < 24}$
- two notable discrepancies
  - model 2:1 is overdense
  - the model's 'Outer Belt' of $\mathbf{e \sim 0.1}$ particles beyond $\mathbf{a > 50}$ AU is *extremely* overdense
    - $*$ edge of Solar System at $\mathbf{a \simeq 50}$ AU (eg, Trujillo & Brown 2001)?



the apparent 2:1/Main Belt ratio

- plot the ratio of 2:1/Main Belt (MB) KBOs as a function of magnitude $\mathbf{m}$
  - Note: although the number of known KBOs is sensitive to the sky–area surveyed $\mathbf{A(m)}$ surveyed by various astronomers, their ratios are *not* sensitive to survey details



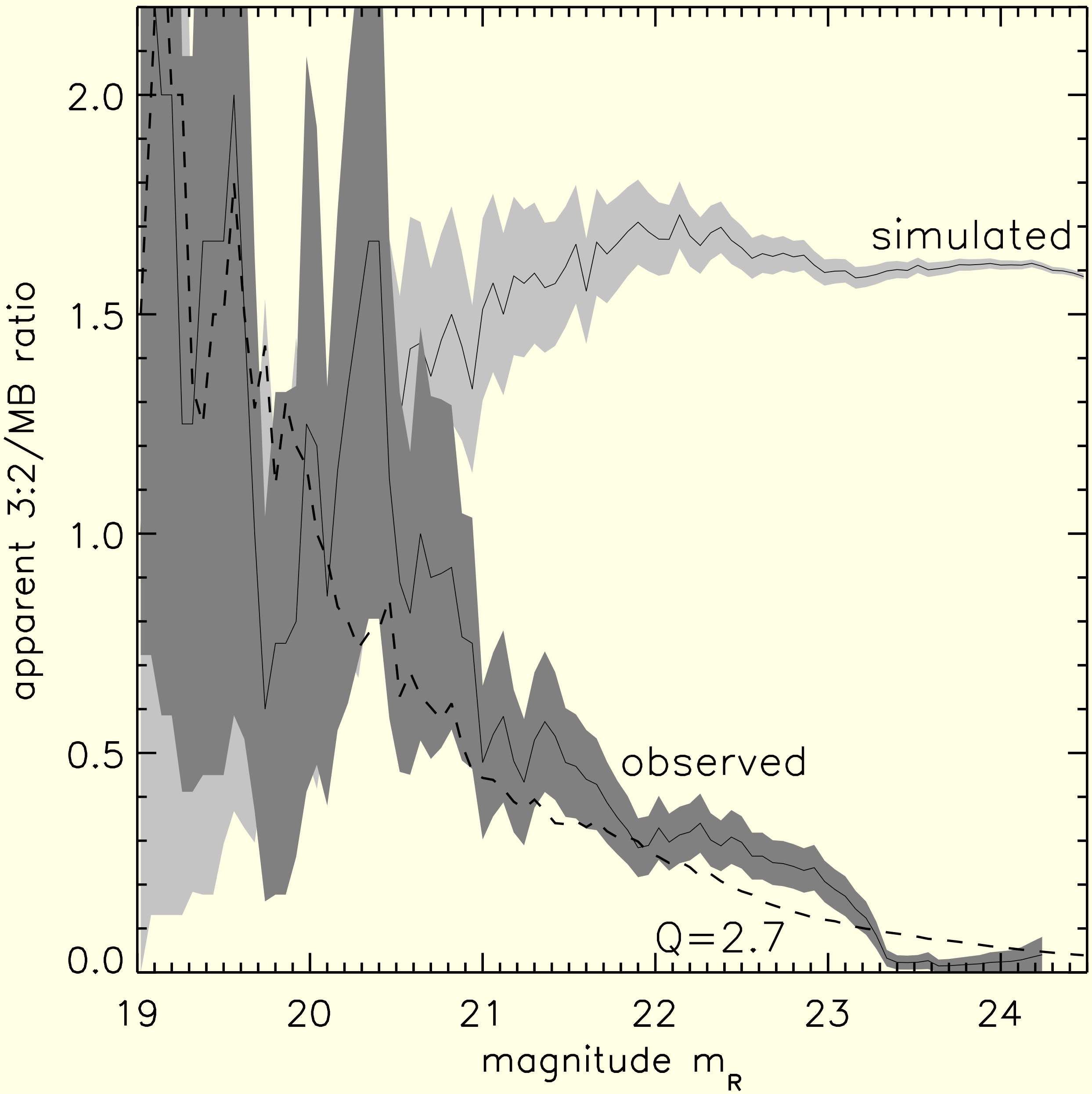
- the model's 2:1/MB ratio $\simeq \mathbf{0.8}$, while observed ratio $\simeq \mathbf{0.04}$
  - the observed 2:1 population is *underabundant* by a factor of $\mathbf{0.8/0.04 \simeq 20}$, relative to model predictions

- this discrepancy has been known for some time—see previous figure

The 3:2 population

- but we didn't know that the 3:2 is *also* depleted (relative to the MB) by a factor $\sim \mathbf{6–60}$

- note also that the 3:2/MB ratio *decreases* with $\mathbf{m}$



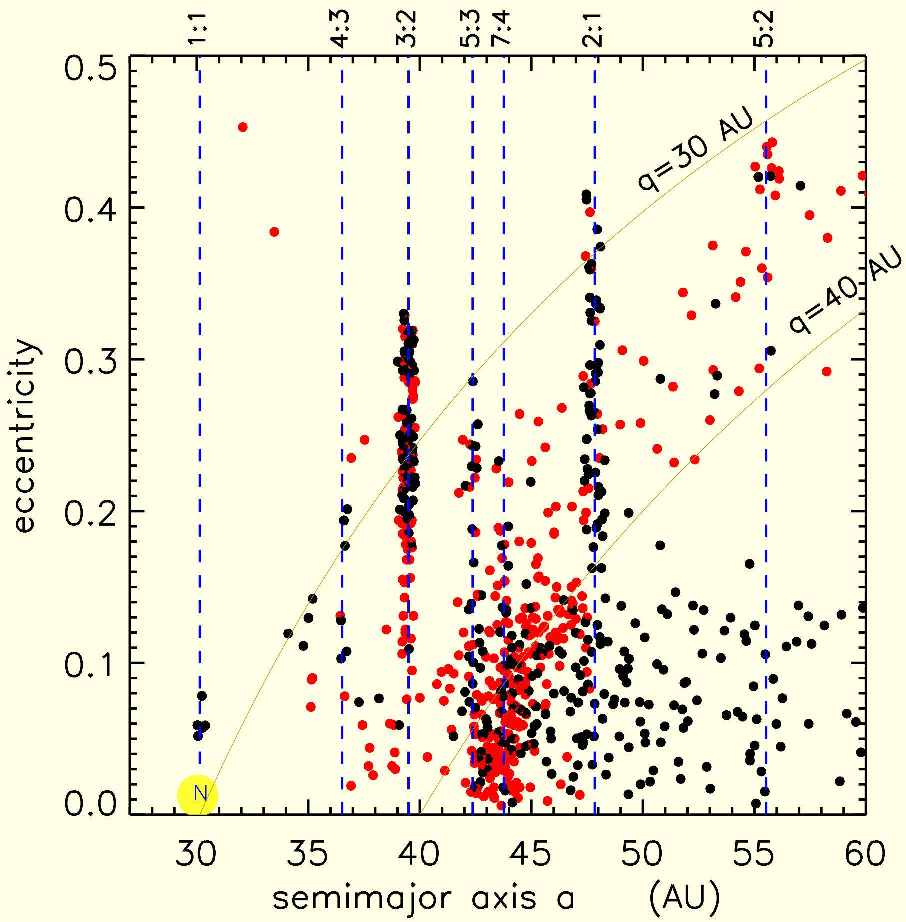
- why?
  - a dearth of fainter objects in 3:2, *not an overabundance of faint MB objects!*
  - can be accounted for if the 3:2 population has *shallower* $\mathbf{Q = 2.7}$ size distribution
  - why might the 3:2 population be so different?
    * Note: asteroid families exhibit $\mathbf{2 \lesssim Q \lesssim 6}$ (Tanga et al 1999)
      · asteroid families result when a parent asteroid collides & breaks up; the physics of collisional breakup determines the fragments' $\mathbf{Q}$
      · might the 3:2 KBO population be debris from the breakup of a large KBO?

Why are the observed resonant populations depleted (relative to model expectations)?

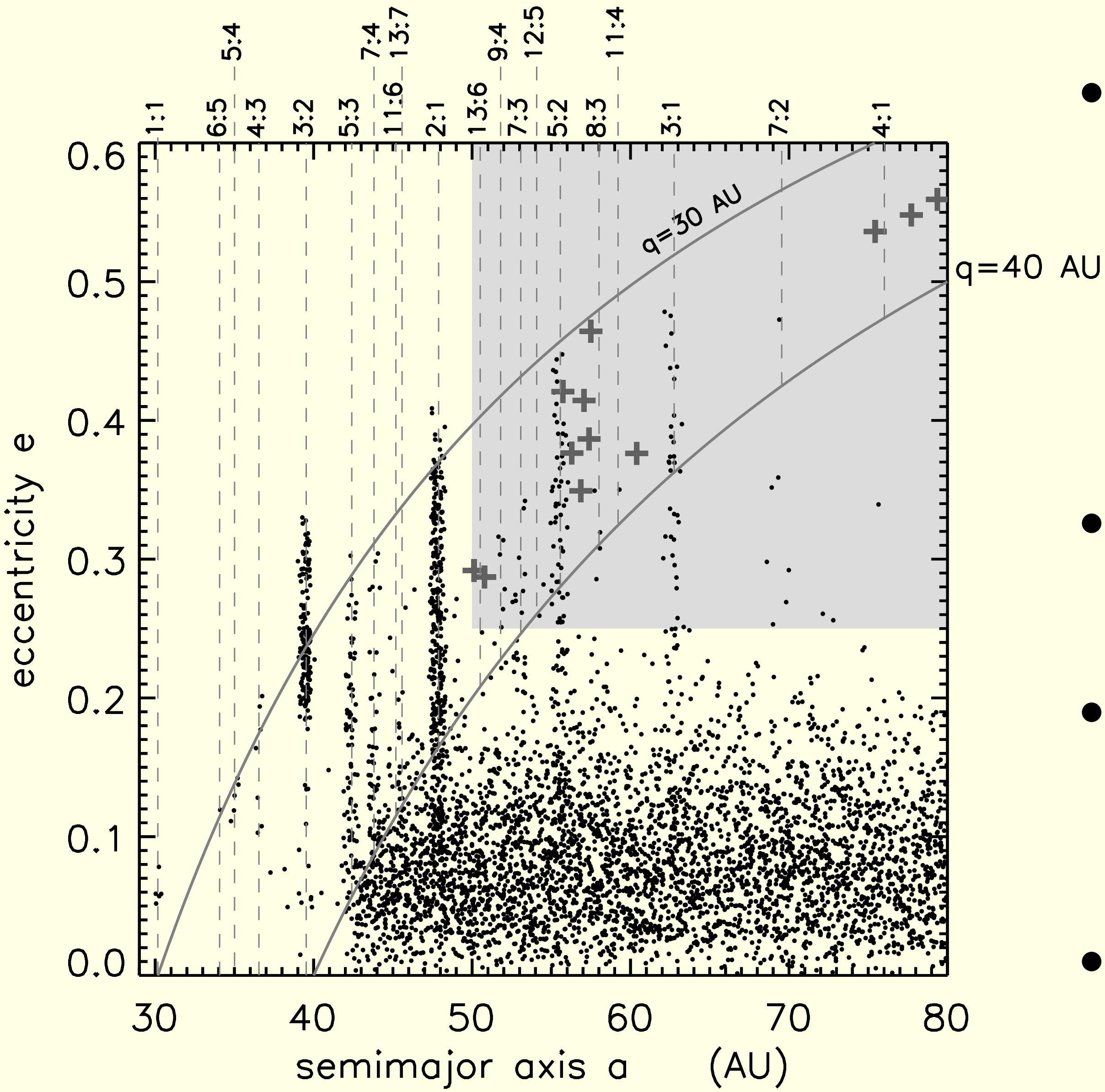
- blame it on other unmodeled effects:
  - planet migration is driven by scattering of planetesimals by planets
  - particularly large or close scatterings at Neptune will cause its orbit (and its resonances) to shudder some
  - likewise for particles at resonances
    - I expect this shaking of the resonance location & particles' orbits reduces the trapping efficiency & depletes the resonant populations

Upper limits on an Outer Belt

- **No** KBOs have been detected in the Outer Belt (OB) beyond $\mathbf{a > 50}$ AU
  - outer edge of the Solar System?
- can infer several distinct upper limits:
  - density of KBOs in OB is smaller than MB density by factor $\mathbf{f > 100}$,
  - **OR** all OB bodies are fainter than the faintest KBO in the MB, $\mathbf{m = 24.5}$
    - ∗ radii $\mathbf{R_{OB} \lesssim 80}$ km (eg, Allen et al 2002)
  - **OR** large bodies in OB are *rare*
    - ∗ the OB size distribution is steep, ie, $\mathbf{Q > 6.0}$



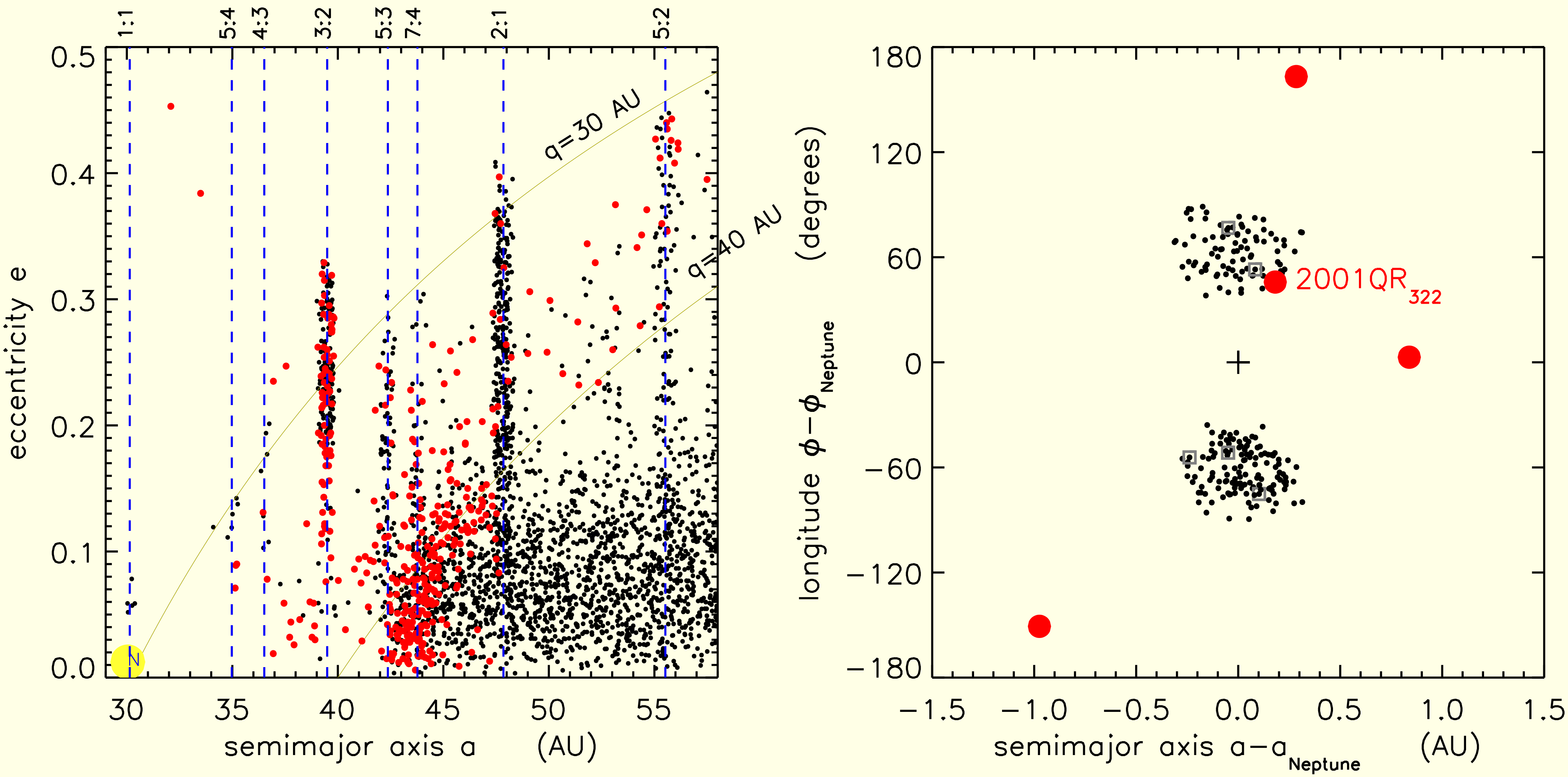
The Scattered Disk of KBOs



- Nbody integrations show that grav' scattering by Neptune produces a swarm of bodies in wide, eccentric orbits at $\mathbf{a} \gtrsim \mathbf{50}$ AU having perihelia $\mathbf{30} \lesssim \mathbf{q} \lesssim \mathbf{40}$ AU (Duncan & Levison 1997)
- but in this sim', very few scattered bodies persist over a Solar age
- rather, $\mathbf{90\%}$ of survivors in gray zone are trapped at various exotic resonances, eg, 9:4, 11:4, 7:2, etc
- only $\mathbf{10\%}$ are truly scattered, indicated by crosses

- KBOs in so–called Scattered Disk might not have had close approach to Neptune
  - rather, they were placed there via resonance trapping

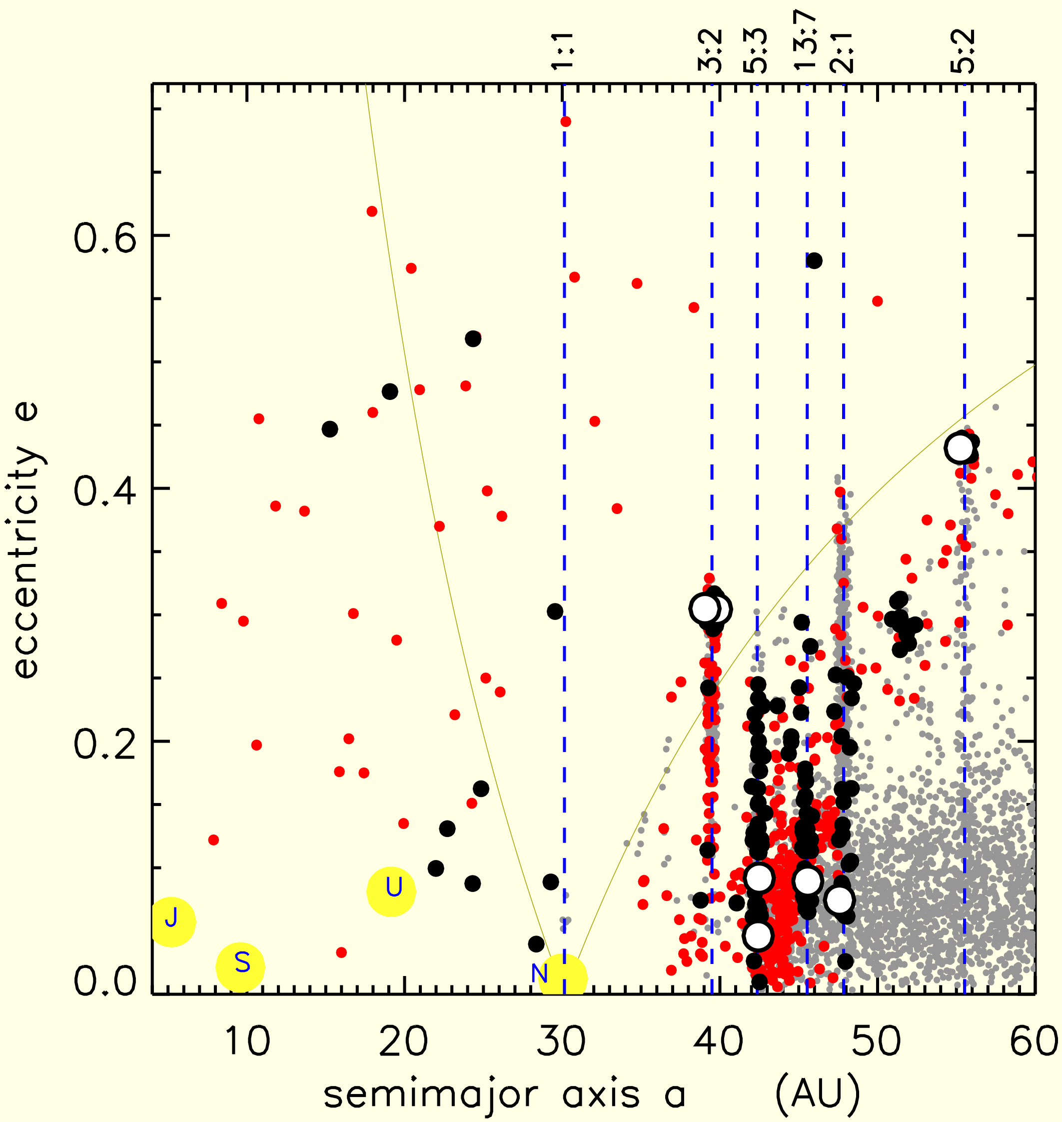
Neptune's Trojans



- 5 Trojans survived at Neptune's triangular Lagrange points for $\mathbf{4.5 \times 10^9}$ years

- the simulation's Trojan/MB ratio is $\mathbf{r_{T/MB} \sim 0.01}$

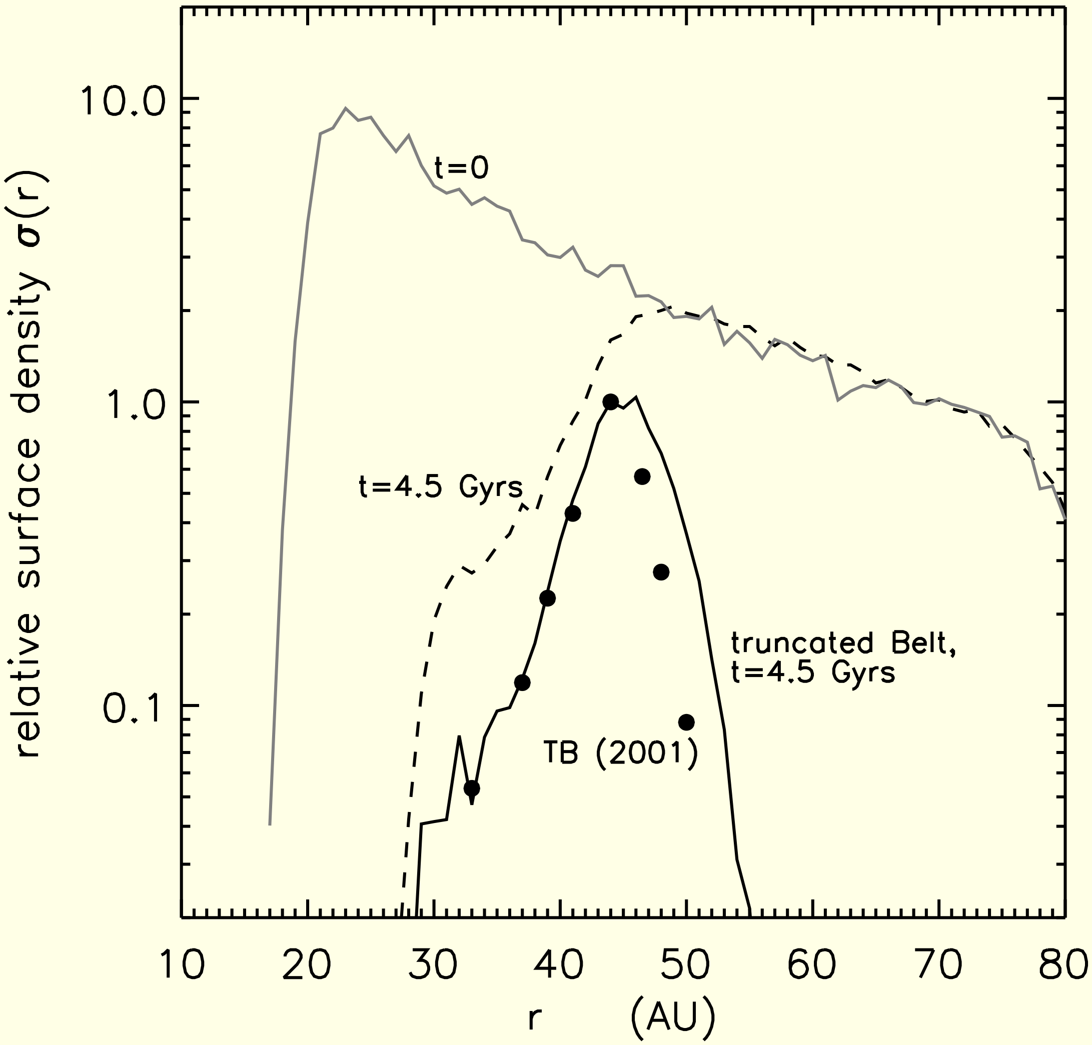
Centaurs



- Centaurs have $\mathbf{a} < \mathbf{a}_{\mathbf{Neptune}}$
- only 7 spotted during simulation's final 2 Gyrs
- simulated Centaurs are rare:
  - due to short dynamical lifetime $\sim \mathbf{10^7}$ yrs
  - and sparse time sampling, $\mathbf{\Delta T = 100}$ Myrs
- observed Centaurs are prominent, due to proximity to Sun

- open circles show that all 7 simulated Centaurs emerged from MMRs
- simulation's Centaur/MB ratio is $\mathbf{r_{T/MB} \sim 6 \times 10^{-4}}$

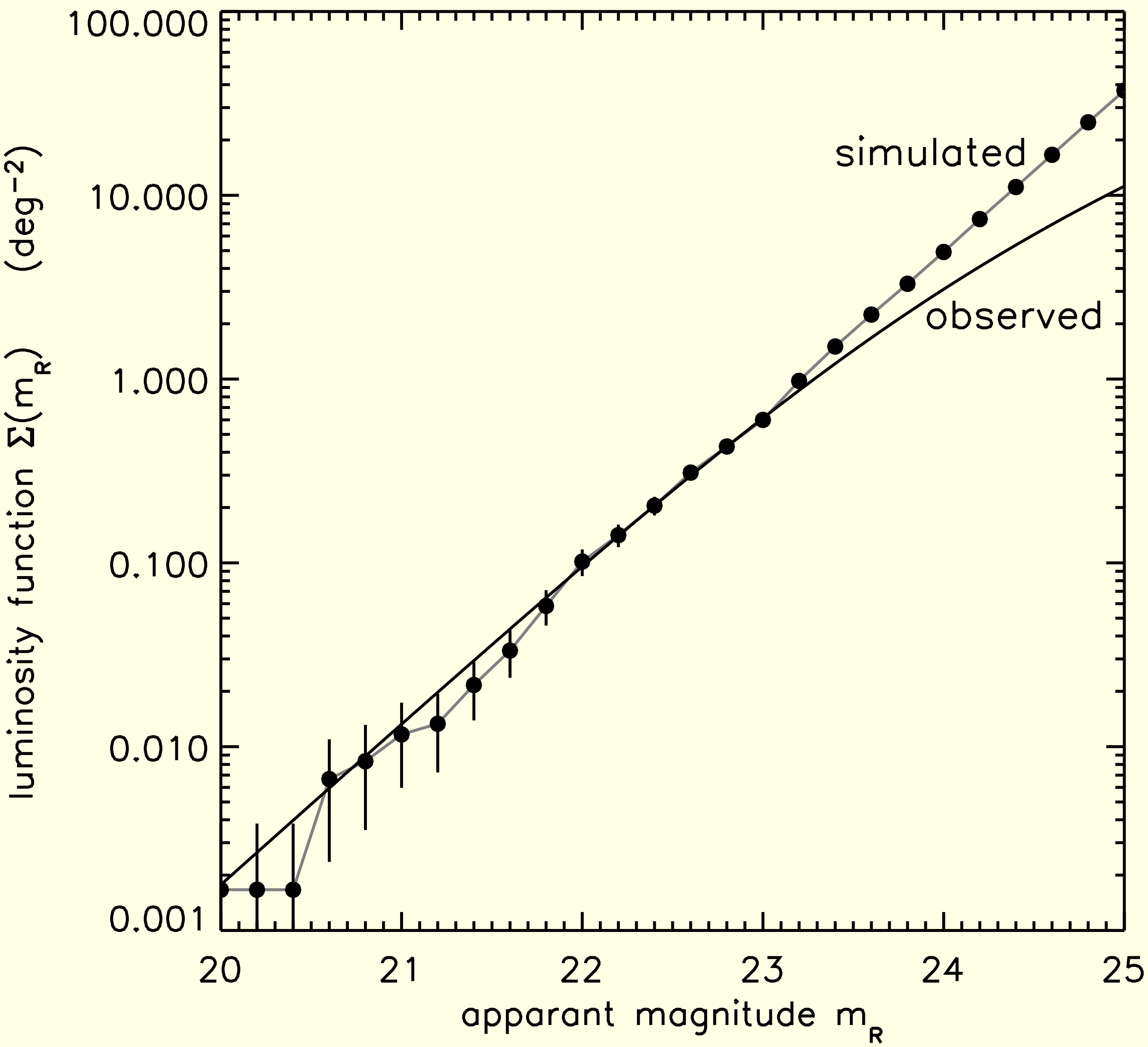
The surface density of the Kuiper Belt



- curves show how Neptune has dynamically eroded the inner KB
  - Note: model does not include *collisional* erosion, another important and unmodeled effect
- however 2:1 & 3:2 are very depleted, and the Outer Belt ($\mathbf{a > 50}$ AU) is absent or unseen
  - form a *truncated* Belt that ignores depleted populations

- surface density of simulated truncated Belt agrees quite well with the KBOs' observed $\sigma(\mathbf{r})$ from Trujillo & Brown (2001)

Calibrate the Kuiper Belt model



- to estimate the total KBO population $\mathbf{N}$, note the Belt's luminosity function $\Sigma(\mathbf{m}) \propto \mathbf{N}$
- estimate $\mathbf{N}$ by fitting the simulation's $\Sigma_{\mathbf{sim}}$ to the observed $\Sigma_{\mathbf{obs}}$ of Bernstein et al (2004):
- recall that the simulation's $\mathbf{i}$'s are too low, ie, my Belt is too *thin*
  - median $\mathbf{i_{sim}} \simeq \mathbf{3}^\circ$, while median $\mathbf{i_{obs}} \simeq \mathbf{15}^\circ$ (from Brown 2001)
  - simulated $\Sigma_{\mathbf{sim}}$ is overdense by factor $\mathbf{f_i} \sim \mathbf{i_{obs}}/\mathbf{i_{sim}} \sim \mathbf{5}$

- to compensate, first divide $\Sigma_{\mathbf{sim}}$ by $\mathbf{f_i}$ and then fit $\Sigma_{\mathbf{sim}}$ to $\Sigma_{\mathbf{obs}}$
- the final tally: there are $\mathbf{N}(\mathbf{R} > \mathbf{50}\ \text{km}) \sim \mathbf{2} \times \mathbf{10^5}$ KBOs larger than 50 km

Census of the Kuiper Belt

- assumptions:
  - albedo $\mathbf{p = 0.04}$ (eg, comet Halley's albedo)
  - body density $\rho = \mathbf{1}$ gm/cm^3
  - $\mathbf{Q = 4.4}$ size distribution, except 3:2 population has $\mathbf{Q = 2.7}$

Subclass	$\mathbf{r_{x/MB}}$	$\mathbf{N(R > 50}$ **km**$)$	**mass ($\mathbf{M_\oplus}$)**
Centaurs	0.001	100	7×10^{-5}
Trojans	0.008	1,000	5×10^{-4}
3:2	0.02	3,000	0.003
2:1	0.04	5,000	0.002
Scattered Disk	0.2	25,000	0.01
Main Belt	1.0	130,000	0.06
Total		160,000	0.08

- these results are all within factors of ~ 2 of other estimates that generally adopt rather simple models of the KB:
  - TJL (2001): $\mathbf{N(R > 50}$ km$) \sim \mathbf{70,000}$ and mass $\sim \mathbf{0.06}$ $M_{\oplus}$
  - extrapolate Bernstein et al (2004) over *entire* Belt: $\mathbf{N(R > 50}$ km$) \sim \mathbf{170,000}$ and mass $\sim \mathbf{0.08}$ $M_{\oplus}$
  - Sheppard et al (2000): $\mathbf{N_{Centaurs}(R > 50}$ km$) \sim \mathbf{100}$

- but recent HST observations of KBO binaries reveal albedos of $\boldsymbol{p} \simeq \mathbf{0.1}$ (ie, $\mathbf{2.5}\times$ larger than previously assumed)
  - so KBO sizes are probably overestimated by $\sqrt{\mathbf{2.5}}$ or $\mathbf{60}\%$
  - and masses overestimated by $\mathbf{2.5^{3/2}} \simeq \mathbf{4} \Rightarrow \mathbf{M_{KB}} \sim \mathbf{0.02}$ $M_{\oplus}$

Summary of Findings

- Neptune's migration into a dynamically cold Kuiper Belt (KB) cannot account for the $\mathbf{e \sim 0.1}$ that are observed in the Main Belt
  - some other unknown mechanism was also responsible for stirring up the KB
- migration into a hot KB does account for the Main Belt $\mathbf{e}$'s, as well as the KBOs trapped at Neptune's 5:2 (first noted by Chiang et al 2003)
  - trapping also occurs at many other exotic resonances: 11:6, 13:7, 13:6, 9:4, 12:5, 8:3, 11:4
  - this mechanism also parks particles in eccentric orbits in the Scattered Disk
    - $*$ most of the simulation's particles inhabiting the so–called Scattered Disk at $\mathbf{a \lesssim 80}$ AU were never scattered...

- a comparison of the model to observations of the KB reveals:
  - the model Belt is 'too thin' by a factor of $\mathbf{f_i \sim i_{obs}/i_{sim} \sim 5}$; this is the main deficiency of the model
  - also reveals that the observed resonant populations are depleted relative to model predictions (for example, 2:1 & 3:2 are depleted by $\times\mathbf{20}$)
    * could be due to (unmodeled) scatterings at Neptune, or among particles
  - if a hypothetical Outer Belt beyond $\mathbf{a > 50}$ AU exists, it must
    * be underdense by a factor $\mathbf{f \gtrsim 100}$ relative to Main Belt
    * or be composed of small bodies, $\mathbf{R \lesssim 80}$ km
    * or be composed of bodies having a steep size distribution, $\mathbf{Q > 6.0}$

- a census of the Kuiper Belt reveals $\mathbf{N(R > 50}$ km$\mathbf{)} \sim \mathbf{160,000}$ having a mass $\sim \mathbf{0.02–0.08}$ $M_\oplus$

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