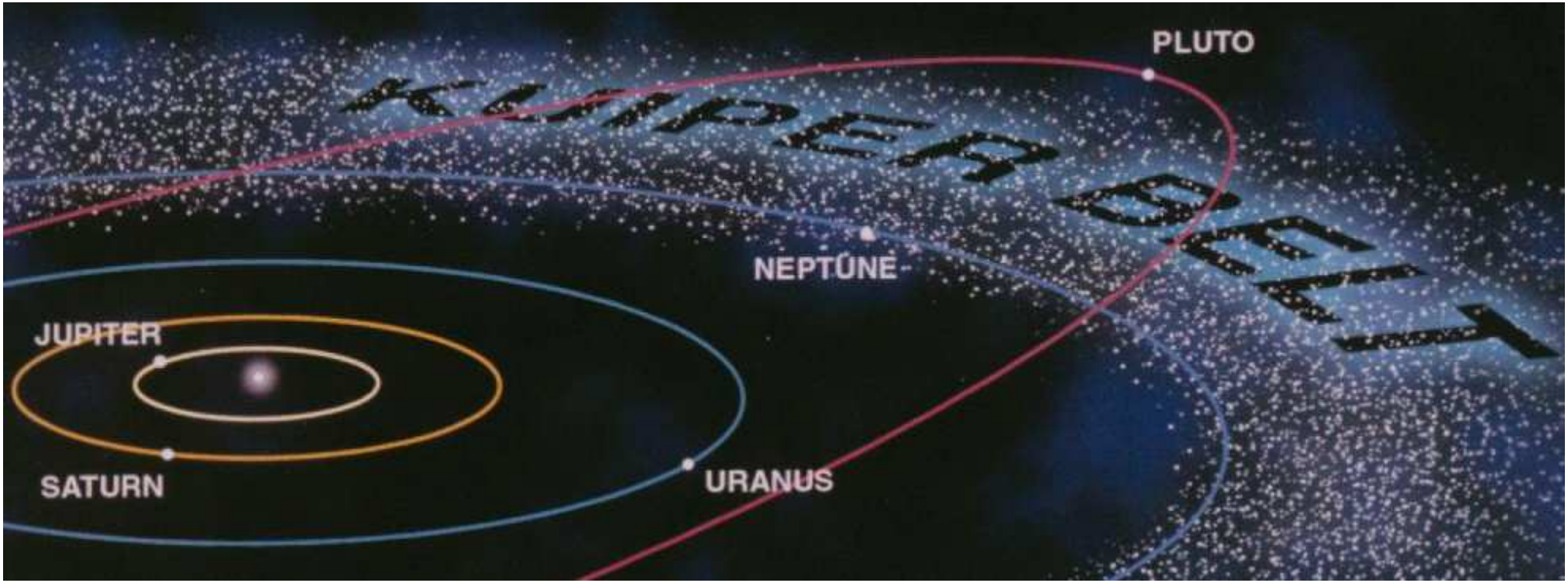
A Detailed Comparison of Simulations of Neptune's Migration to Observations of the Kuiper Belt



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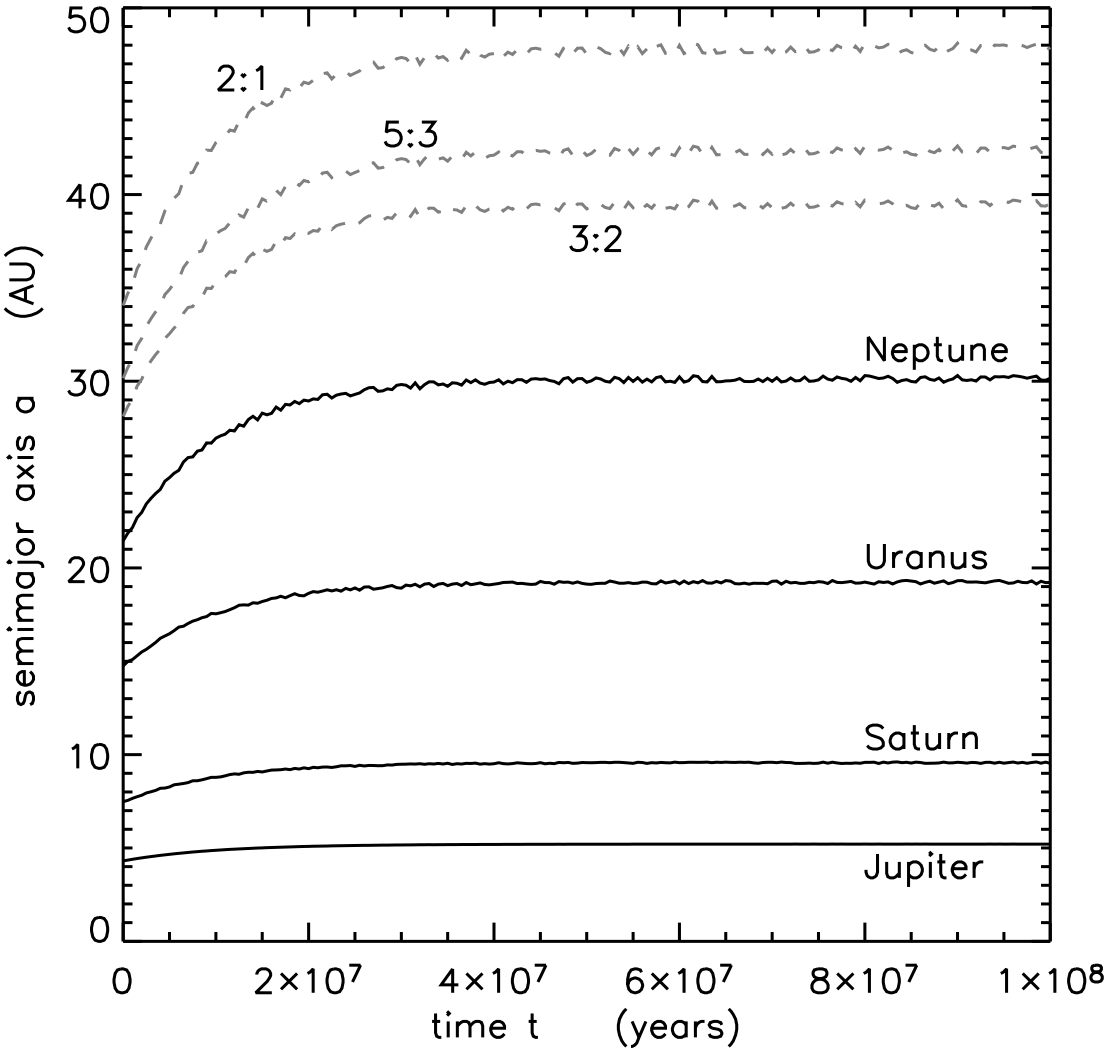
Examine the consequences of ‘conventional’ planet migration

- use Mercury integrator (Chambers 1999) to evolve 4 giant planets + 10^4 massless particles over Solar Age

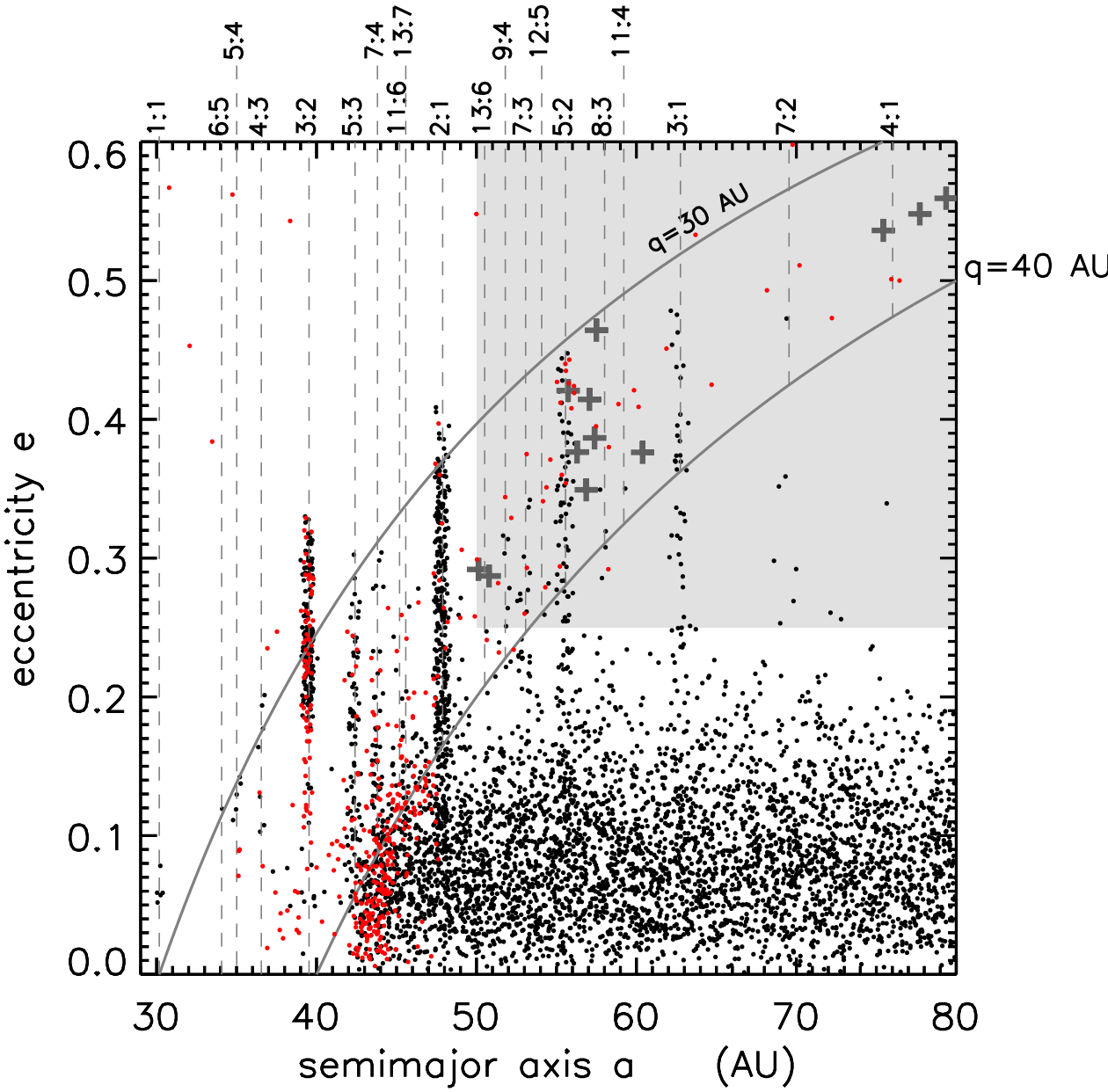
- external torques drive smooth planet migration
  - $\Delta a_{Nep} = 9$ AU
  - over $\tau \sim 10^7$ yr timescale

- resonances sweep outwards & capture KBOs in eccentric orbits



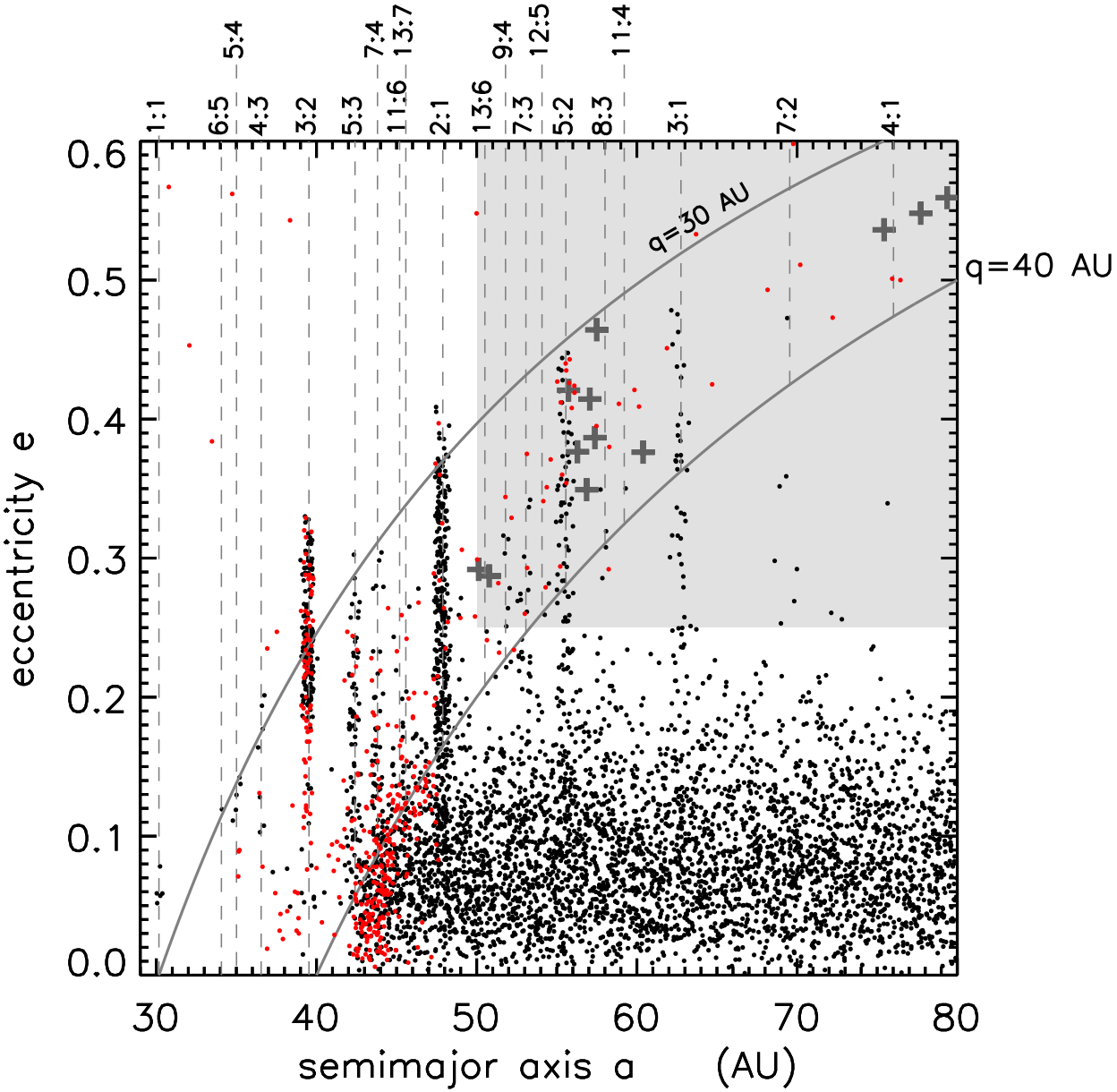
Simulated & Observed Endstates

- Neptune's advancing res's traps particles (black dots) at resonances
- Note: observed Main Belt KBOs (red dots) have $\mathbf{e \sim 0.1}$
  - sim' adopts initial $\mathbf{e_0 \sim 0.1}$
- allows trapping at exotic res's: 13:7, 9:4, 5:2, 3:1, 7:2, ...
  - Chiang et al. (2003): could account for KBOs @ 5:2



The Scattered Disk—perhaps not so scattered?

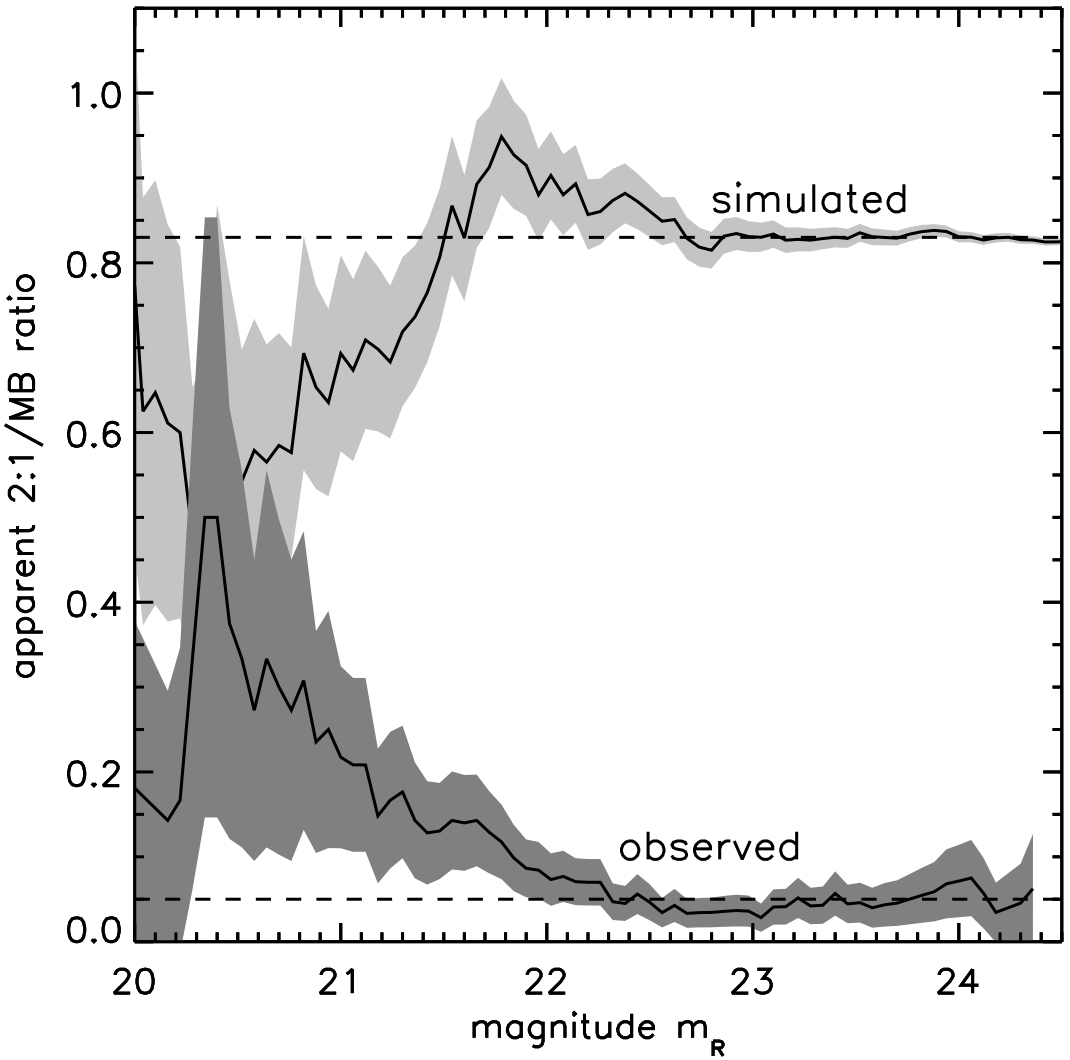
- sim' shows that trapping @ 9:4, 7:3, 5:2, 3:1 promotes particles into Scattered Disk $30 \lesssim q \lesssim 40$ AU.
- suggests the real Scattered Disk might also contains trapped particles
- inspect particles in gray box:
  - 90% of survivors are *res' trapped particles*
  - only 10% of survivors 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 $\mathbf{R}$ according to 'bright end' ($\mathbf{mag < 24}$) of KBO size distribution from Bernstein et al (2004)
  - cumulative size distribution $\mathbf{N(R) \propto R^{-Q}}$
  - $\mathbf{Q = 4.4}$ or $\alpha = \mathbf{Q/5 = 0.88}$
- Note: plot of *relative* KBO abundances are insensitive telescopic selection effects



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

Ditto for 3:2!

- same MC method yields relative abundance of other KBO sub–populations (eg, SD, Centaurs, Neptune Trojans, etc)

- fitting the model's luminosity function to observed yields *total* KBO population:
  - $\mathbf{N} \sim \mathbf{1.7 \times 10^5}$ KBOs having radii $\mathbf{R > 50}$ km
  - mass $\mathbf{M} \sim \mathbf{0.08}$ $M_\oplus$ assuming albedo=0.04, or $\mathbf{M} \sim \mathbf{0.02}$ $M_\oplus$ if albedo=0.1

KBO Census according to Nbody/MC model

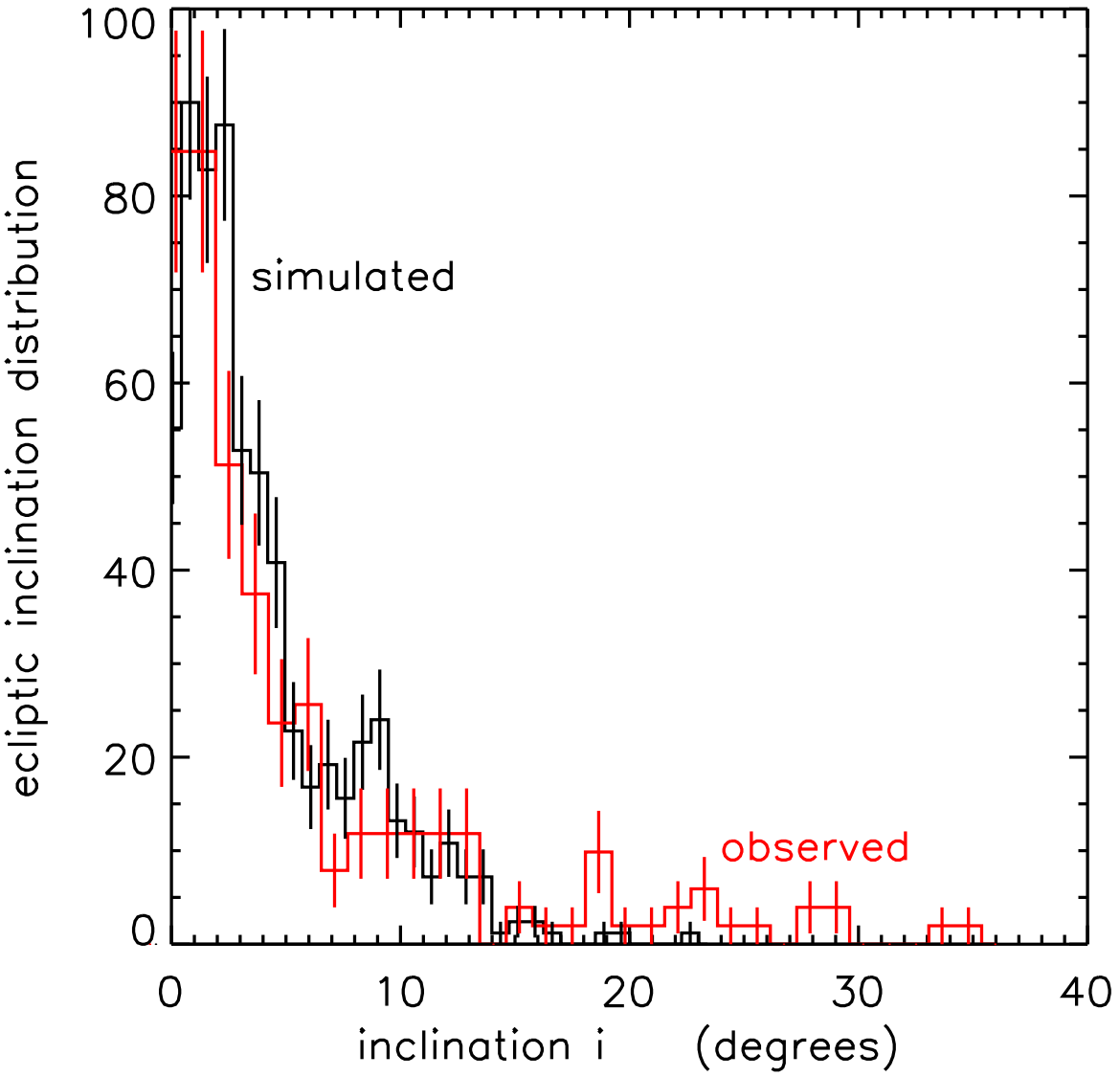
Population	$\mathbf{N(R > 50}$ km$\mathbf{)}$	$\mathbf{mass(R > 50}$ km$\mathbf{)}$ ($M_\oplus$)
Centaurs	$\mathbf{130}$	$\mathbf{7 \times 10^{-5}}$
Trojans	$\mathbf{< 1 \times 10^3}$	$\mathbf{< 5 \times 10^{-4}}$
3:2	$\mathbf{3 \times 10^3}$	$\mathbf{3 \times 10^{-3}}$
Main Belt	$\mathbf{1.3 \times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

...but what about the KBO inclinations?

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 the is the main deficiency of this model**



...but what about the Centaurs?

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)