An outer planet beyond Pluto and the origin of Kuiper belt architecture

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INTRODUCTION

Trans-Neptunian objects (TNOs) in the Kuiper belt are the remnants of the protoplanetary disk, thus they carry important clues on the origin and evolution of the solar system [1]. In contrast to results predicted using accretion theory, TNOs exhibit surprisingly large eccentricities, *e*, and inclinations, *i*, which can be grouped into distinct dynamical classes: classical (37AU<*a*<48AU), resonant[a], scattered (*q*<37AU), and detached TNOs (*q*>40AU) [2] (Fig. 1). TNOs also exhibit diverse surface colors, albedos and compositions (e.g., H_2O, CH_4, N_2, etc.)[1,3]. Several models have addressed the origin and orbital evolution of TNOs, but none has reproduced detailed observations or provided insightful predictions.

[a] TNOs trapped in r:s external mean motion resonances with Neptune. The ratio of the orbital period of a resonant TNO to that of Neptune is given by r/s.

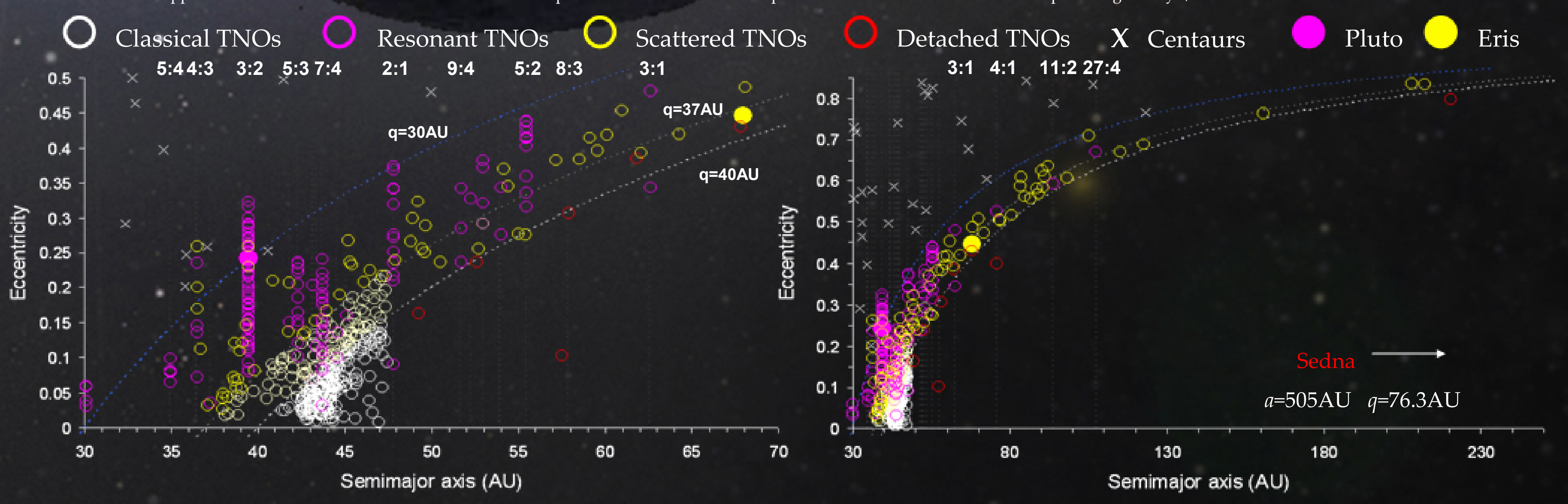


FIGURE 1: TNOs with orbital elements averaged over the last 10Myr. Observational data were taken from the Lowell Observatory database. Dynamical classification is from [2].

Finally, the current orbital structure and physical properties of TNOs strongly suggest the action of planetary migration, collisional evolution, long-term dynamical sculpting by the planets [1,4]. To better understand the Kuiper belt architecture, we try to answer the following motivating questions...

What is the origin of the Kuiper belt orbital excitation and the dynamical classes?

Does the Kuiper belt outer edge at *a*~48AU reflect the original planetesimal disk size?

How the dynamical evolution of TNOs could affect their physical properties?

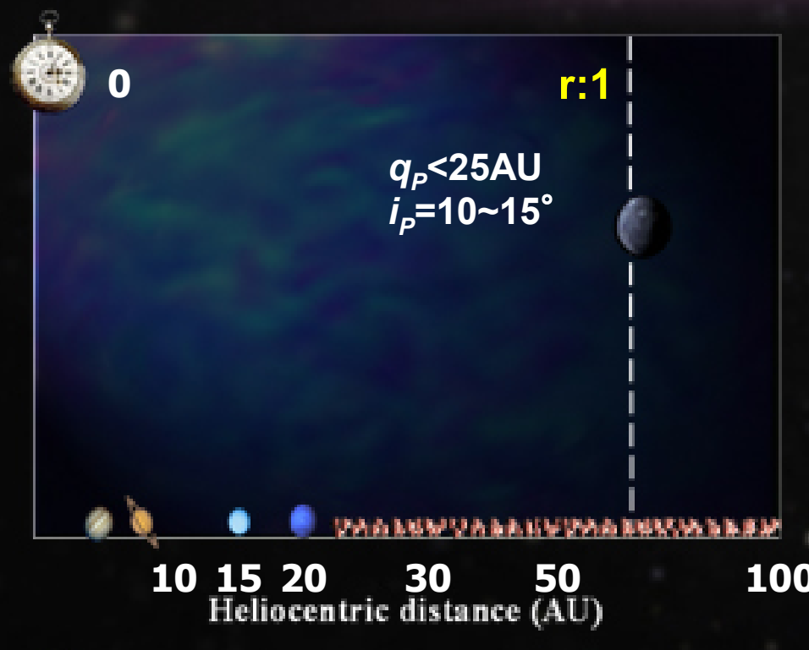
How the Kuiper belt lost ~99% of its original mass?

Does a distant outer planet exist within the solar system?

METHODS

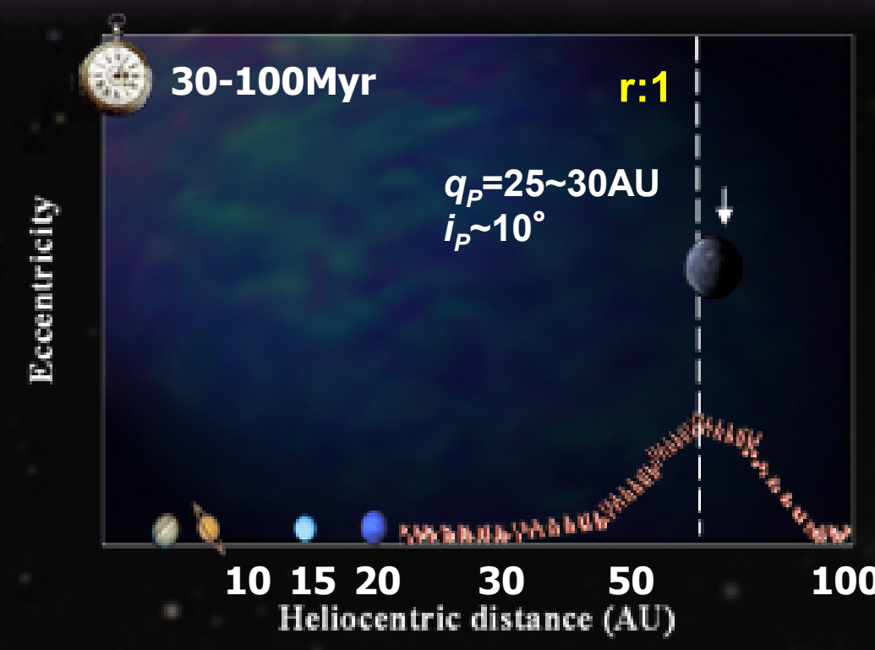
We performed large-scale simulations over the age of the solar system. Integrations were conducted taking into account fully the four giant planets, a massive outer planet, and several tens of thousands of bodies using the EVORB and MERCURY packages [5,6]. The results were compared to up-to-date observations (Fig. 1).

A NEW MIGRATION MODEL



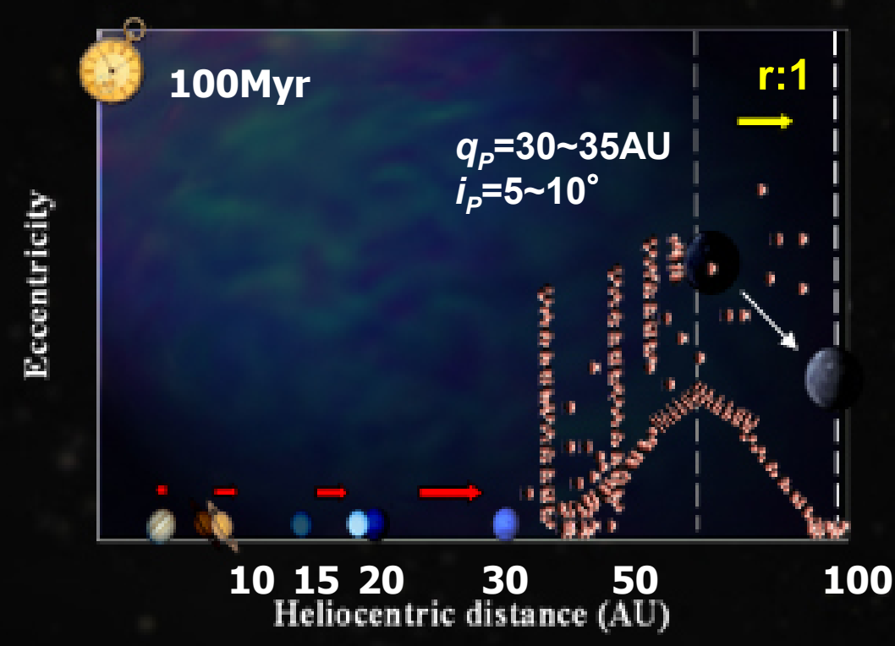
1 Formation stage

- The planets and TNOs are formed in <100Myr
- In few Myr a large planetesimal (0.3~0.5$M_\oplus$) is scattered by a giant planet



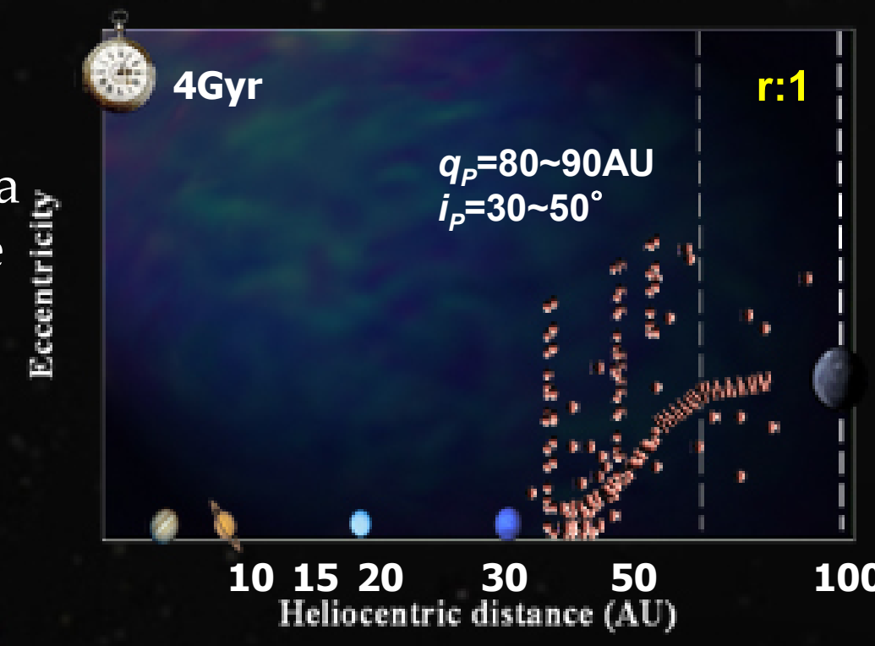
2 Pre-migration stage

- The planet excites the planetesimal disk for several tens of Myr
- The planetesimal disk MUST be excited before planet migration [7]



3 Migration stage

- The planet is captured by a strong Neptunian resonance of the type r:1 [8] and transported to ≥100AU
- Best resonance candidates: 6:1 - 13:1



4 Long-term stage

- The Kozai resonance (KR) forces a decreased planet's eccentricity at the expense of an increased inclination, reaching 30–50° (e.g., Fig. 2)
- Long-term sculpting by the planets

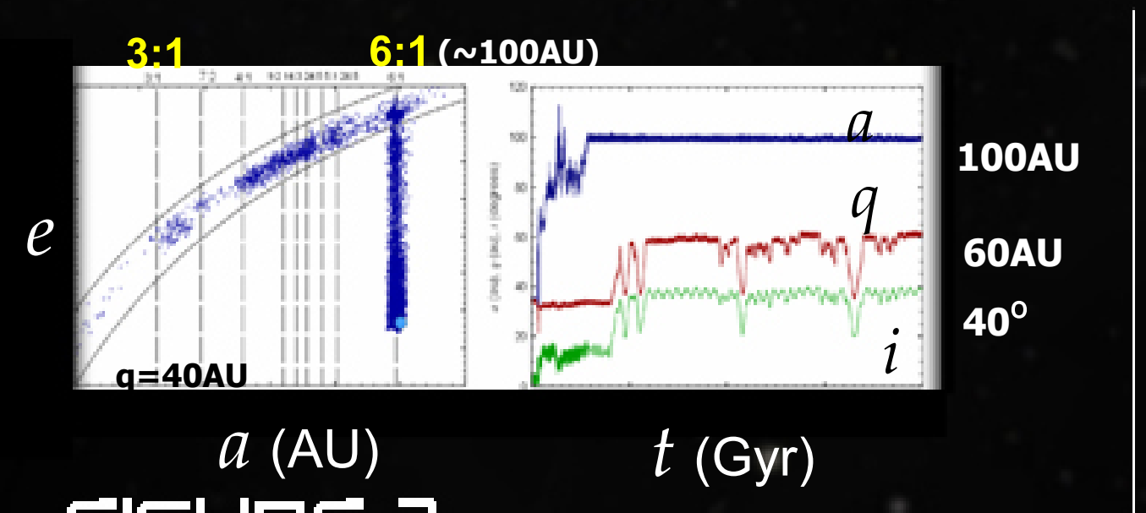


FIGURE 2: Capture in the 6:1 resonance + the onset of the Kozai resonance. From [8].

This scenario considers fundamental aspects of the solar system history: scattering of large planetary bodies by the newly formed giant planets, planet migration, and resonance capture. Our initial conditions are shown in Stage 1 above. The three other stages were simulated including smooth 5-planet migration [9] + Kozai resonance.

MAIN RESULTS

Resonant structure

- Stable resonant objects were obtained in the entire Kuiper belt during Stage 3, including in the 9:4, 5:2, and 8:3 resonances (Fig. 4). The orbital distribution and resonant properties of obtained resonant populations are in agreement with observations
- Most resonant objects were distributed between 30–50AU prior to resonance capture

Scattered population

- Scattered objects evolved over 4Gyr acquiring eccentric and inclined orbits (5–50°)
- The scattered population came originally from three distinct regions: ~15–30AU (Neptune's migration path, <10%), 30–40AU (region sculpted by Neptune over 4Gyr, >50%), and 40–50AU (10–40%)

Detached population

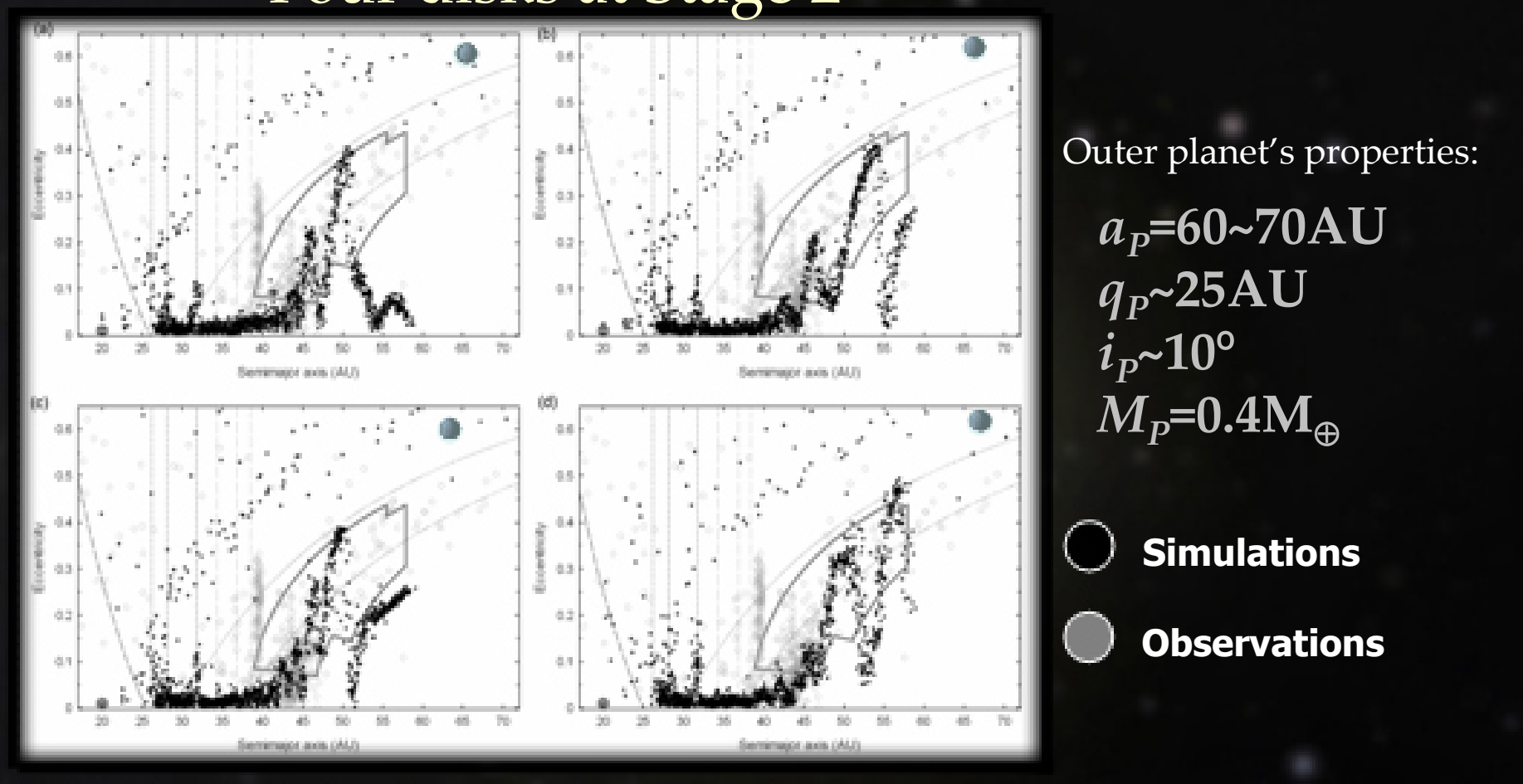
- The outer planet's perturbation on initially Neptune-scattered bodies created most of the detached population over Gyr (Stage 4) (Fig. 5)
- There is no obvious preference for the source region (<50–55AU) of detached objects
- In agreement with observational constraints and unbiased total population estimates [10-12]

An excited classical region

- The outer planet excited the 40–50AU region leading to a lack of low-*e* TNOs beyond ~45AU, and the formation of an outer edge at ~48AU during Stage 2 (Fig. 3-4)
- Part of the classical bodies acquired *i* up to ~15°, contributing to the "hot population" [4]

Examples of obtained Kuiper belts

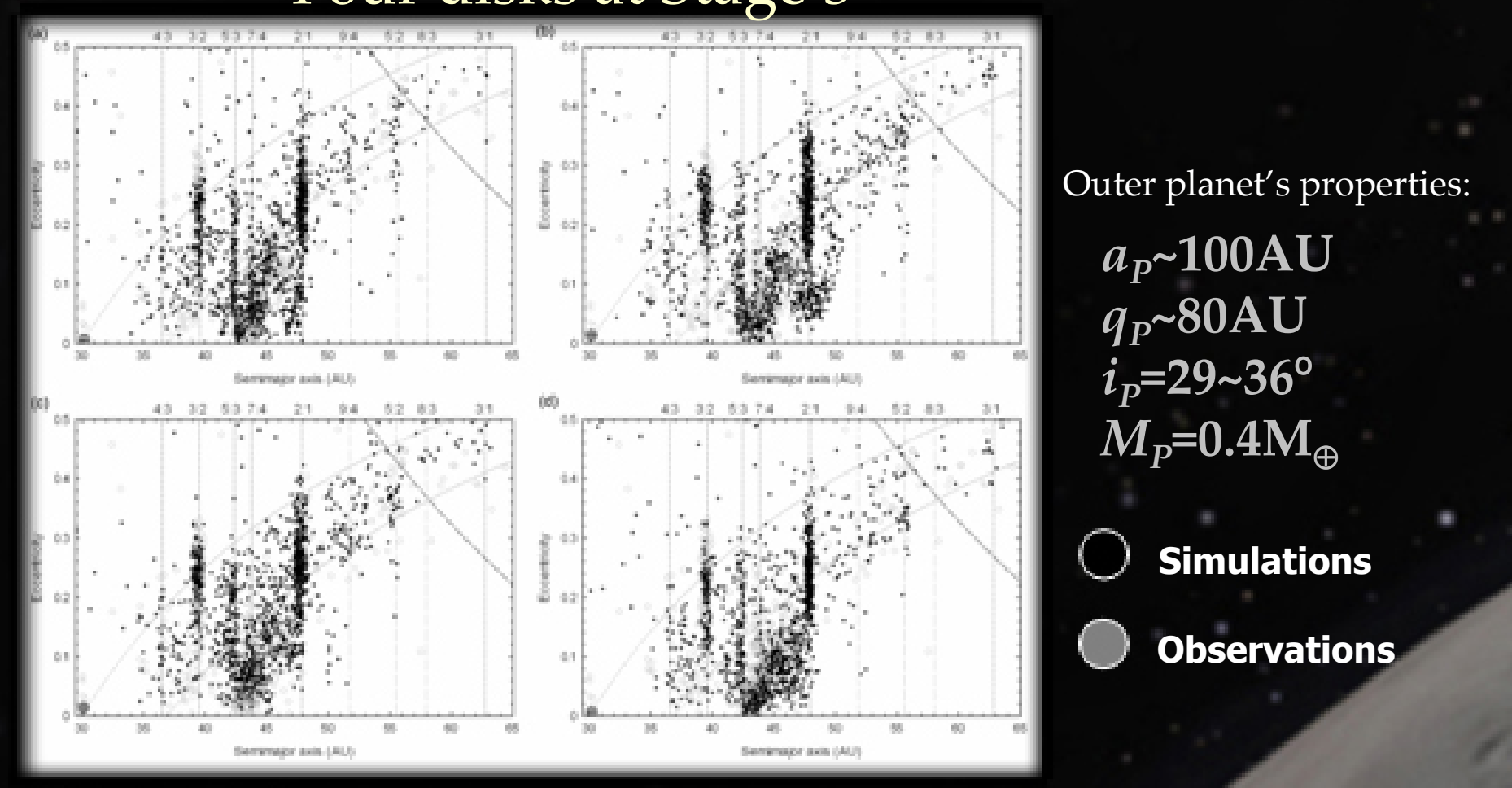
Four disks at Stage 2



Outer planet's properties:
a_P=60~70AU
q_P~25AU
i_P~10°
M_P=0.4$M_\oplus$

FIGURE 3: Examples of the excitation caused by a massive planetesimal (the outer planet) on planetesimal disks in a pre-migration system over 60-80Myr (Stage 2). All disks were ~60AU in radius.

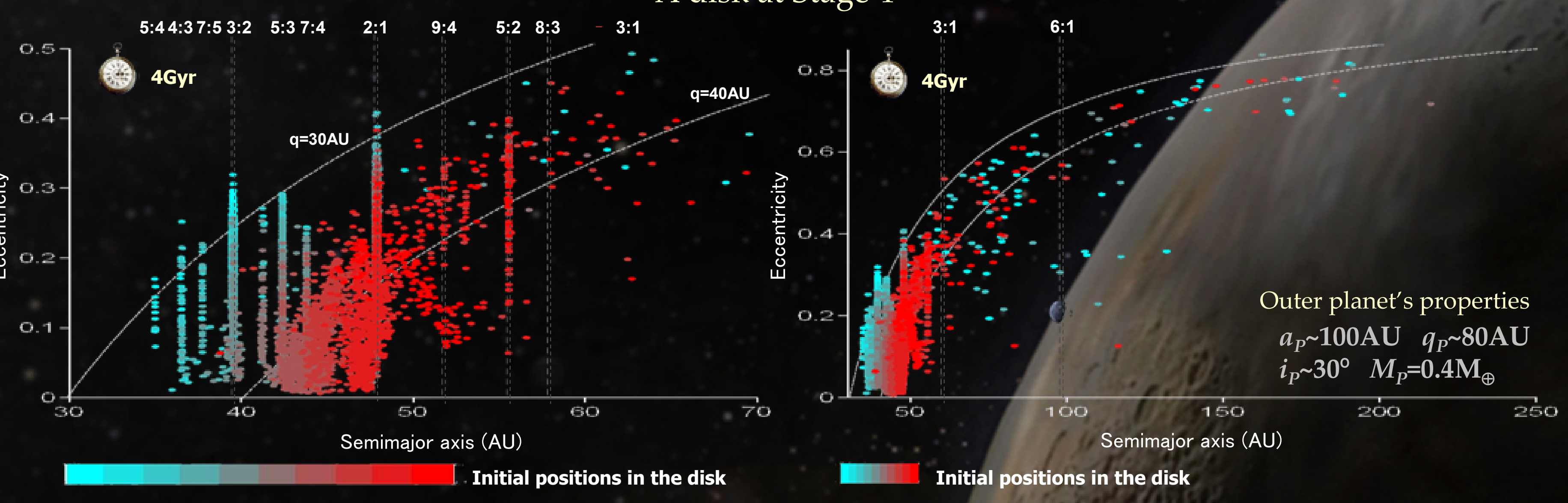
Four disks at Stage 3



Outer planet's properties:
a_P~100AU
q_P~80AU
i_P=29~36°
M_P=0.4$M_\oplus$

FIGURE 4: Examples of Kuiper belts obtained after the migration of the giant planets and the outer planet over 100Myr (Stage 3). The initial conditions were taken from the end states of Stage 2 for the same disks in Fig. 3 up to ~54AU.

A disk at Stage 4

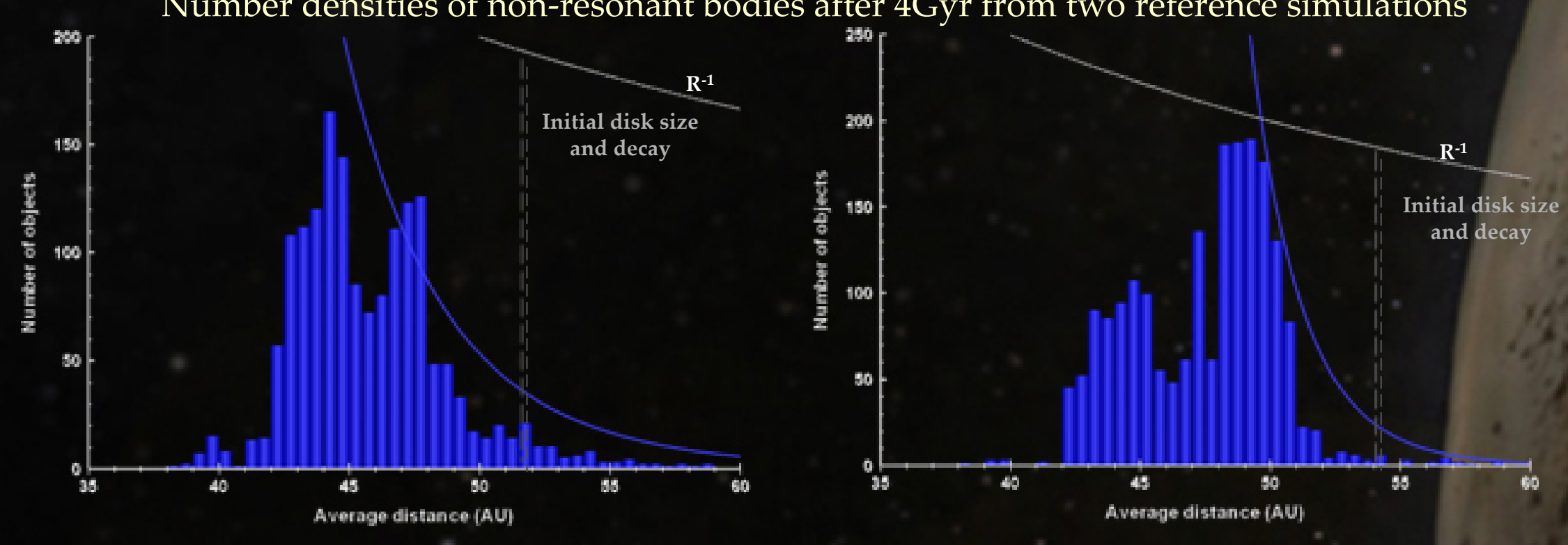


Outer planet's properties
a_P~100AU q_P~80AU
i_P~30° M_P=0.4$M_\oplus$

FIGURE 5: Outcome from one of the main simulations at 4Gyr according to initial positions in a planetesimal disk of ~52AU radius.

The Kuiper belt outer edge

Number densities of non-resonant bodies after 4Gyr from two reference simulations



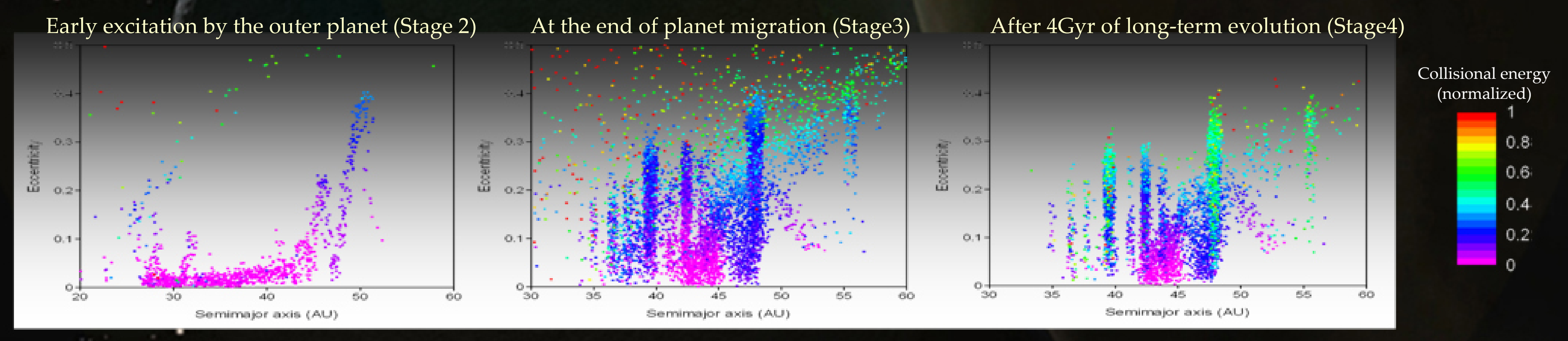
- The planetoid is very effective in creating the outer edge (Fig. 3-4 and left)
- The planetesimal disk extended to at least ~51AU in order to satisfy the existence of observed 8:3 resonant objects and detached TNOs located around 48–51AU

Losing ~99% of the total mass

- Enhanced collisional grinding (high collisional velocities): a substantial population acquired *e*>0.05 and varied *i*, thus entering an erosive regime during the first Myr of solar system history $v_{coll}=\sqrt{v_K^2\left(e^2+i^2\right)+v_{esc}^2}$ Where the Keplerian velocity is given by v_K=29.8kms^{-1}·$a^{-1/2}$, and v_{esc} is the escape velocity
- Combining the dynamical depletion with collisional grinding results of [13], the total loss could reach 1-(0.25~0.4)·(0.03~0.08)=96~99% (a lower limit!)

Collisional evolution and possible effects on the surfaces of TNOs

- Energy associated with collisional velocities during different stages in our model:



- The effects of collisions, space weathering and possible compositional gradients in the protoplanetary disk may explain the color diversity of TNOs

Prospects for the existence of a trans-Plutonian planet

- Figure 6 illustrates that the outer planet would be quite bright, hence rare in the sky, so only wide area surveys could find it [14]
- High-*i* objects (30–50°), such as the planetoid, spend only ~1–2% of their orbits near the ecliptic (β=0–10°) [14]
- The majority of wide area surveys are sensible at most to apparent sky motions of ~1.5 arcsec/h and have probed sky regions near the ecliptic only [15]
- A massive trans-Plutonian planet has probably escaped detection because it is currently either far from the Sun (with sky motion below survey sensibility) or away from the nodal crossing point with the ecliptic

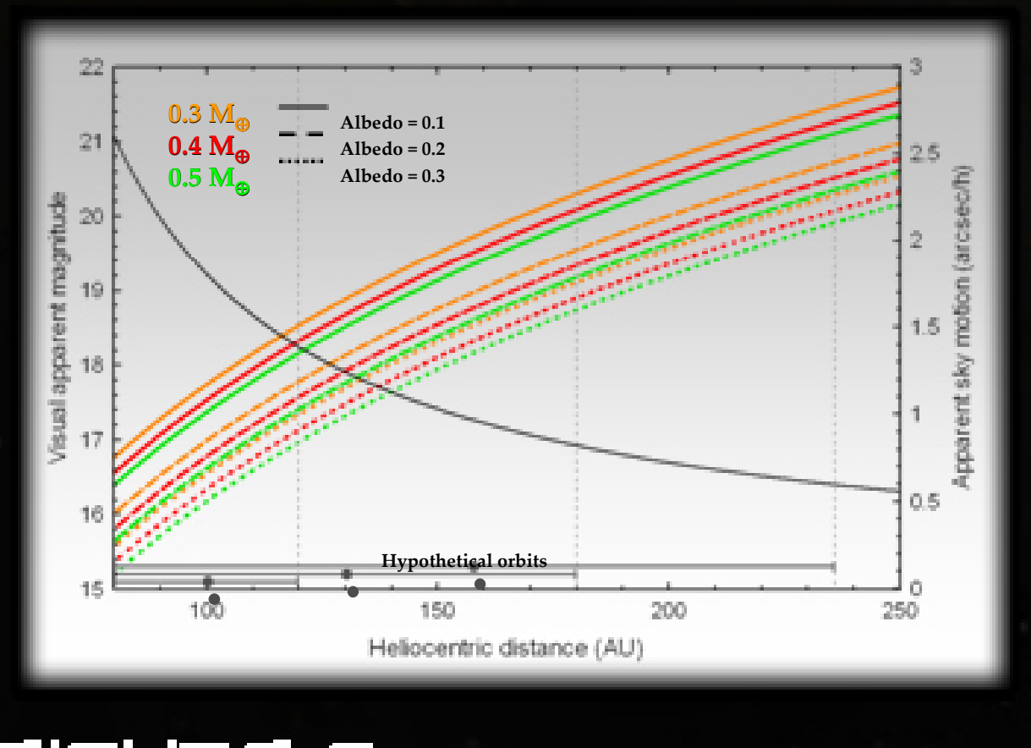


FIGURE 6: Apparent magnitudes and apparent sky motions of an outer planet in distant orbits

SUMMARY

This model consistently describes the Kuiper belt structure with an unprecedented level of details. It satisfies several observational constraints, namely the excitation of the ancient Kuiper belt, the dynamical classes of TNOs and peculiar objects (e.g., Pluto, Eris, 2004 XR_{190}, 2000 CR_{105}, Sedna, etc.), the belt's outer edge at *a*~48AU, the loss of ~99% of the belt's initial mass, Neptune's orbit at 30.1AU, and several others.

SOME PREDICTIONS

- A distant massive planet. Dynamical and physical properties: a_P=100–170AU, q_P>80AU, i_P=30–50°, and probably evolving near an r:1 resonance (6:1 – 13:1). M_P=0.3–0.5$M_\oplus$, ρ=2–3gcm^{-3}, albedo[b]=0.1–0.3, and *m*=15–17mag at perihelion
- Long-term resonant TNOs in the 5:4, 4:3, 7:5, 3:2, 8:5, 5:3, 7:4, 9:5, 2:1, 11:5, 9:4, 7:3, 12:5, 5:2, 8:3, and 3:1 resonances
- Scattered and detached TNOs with similar physical properties (similar source regions)
- Detached bulk population with *q*=40–60AU and *i*=0–50°
- Cold and hot classical populations concentrated at *i*<5° and *i*>10–15°, respectively
- Collisionally evolved TNOs concentrated in the main resonances and beyond 50AU

[b] Assuming an ice-rich inactive/space weathered surface composed of CH_4, N_2, or CO. The best analog is Sedna, whose albedo ~0.1-0.3 [16]

[1] Luu & Jewitt 2002 [2] Lykawka & Mukai 2007b [3] Delsanti & Jewitt 2006 [4] Morbidelli & Brown 2004 [5] Brunini & Melita 2002 [6] Chambers 1999 [7] Lykawka & Mukai 2007a [8] Lykawka & Mukai 2007c [9] Hahn & Malhotra 2005 [10] Morbidelli & Levison 2004 [11] Gladman et al. 2002 [12] Chiang et al. 2006 [13] Kenyon & Bromley 2004 [14] Trujillo et al. 2001 [15] Trujillo & Brown 2003 [16] Emery et al. 2007