Origin and Dynamical structure of the Trans -Neptunian Belt: Evidence for an Outer Planet in the Solar System

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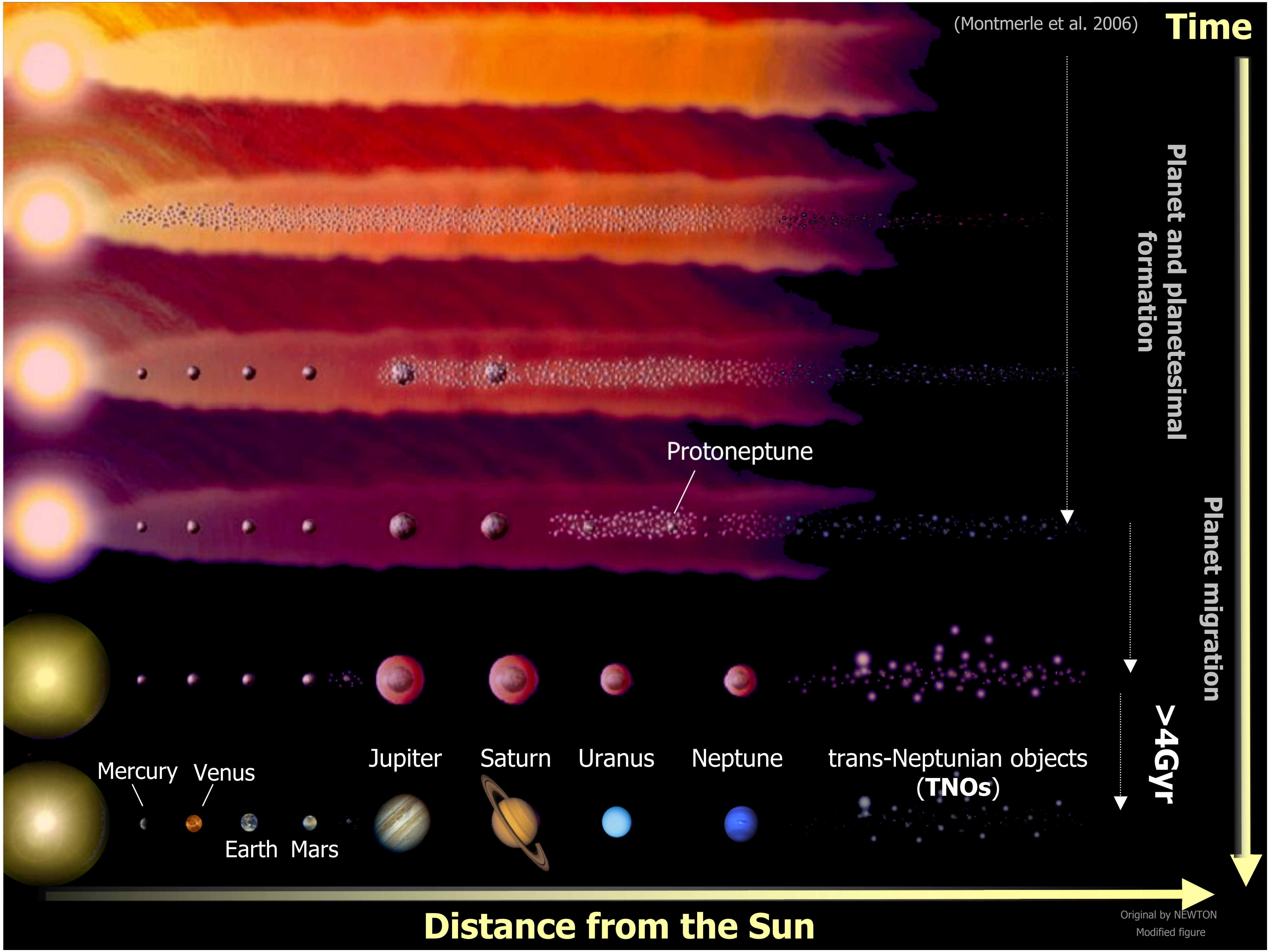
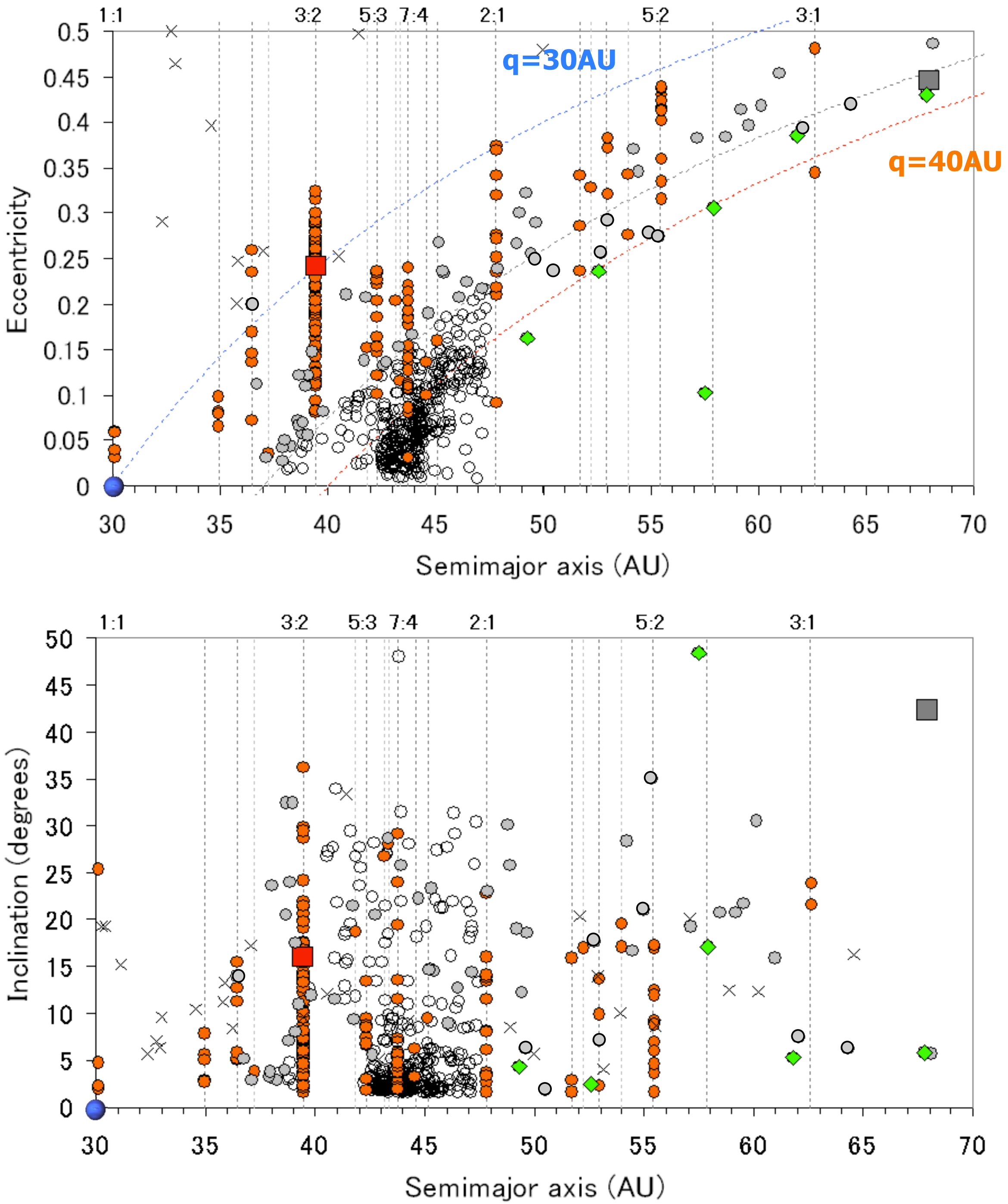

(Montmerle et al. 2006)
Time
Planet and planetesimal formation
Protoneptune
Planet migration
>4Gyr
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
trans-Neptunian objects (TNOs)
Distance from the Sun
Original by NEWTON
Modified figure



Trans-Neptunian objects (TNOs) are icy bodies orbiting beyond Neptune...

Four main classes of TNOs:

- Resonant
- Classical
- Scattered
- Detached

(e.g., Lykawka & Mukai, 2007b)

Outstanding questions

→ What caused the primordial excitation of the Kuiper belt? (excitation of e and i around 40-50AU)

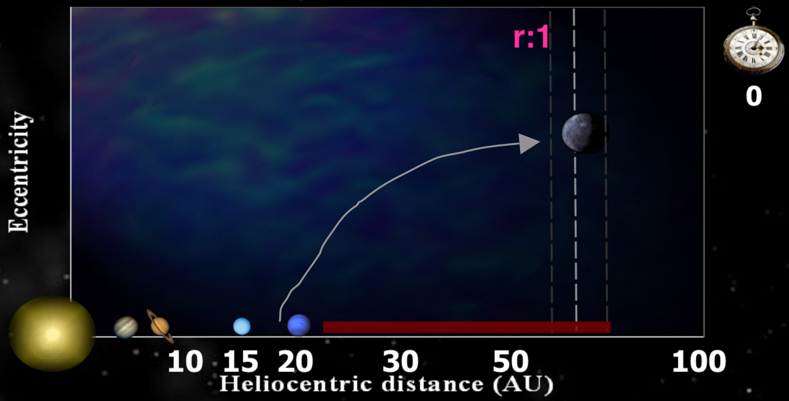
→ How to explain the four main classes of TNOs?

→ What is the nature of the Kuiper belt outer edge at about 48AU?

Kuiper Belt Origin and Evolution

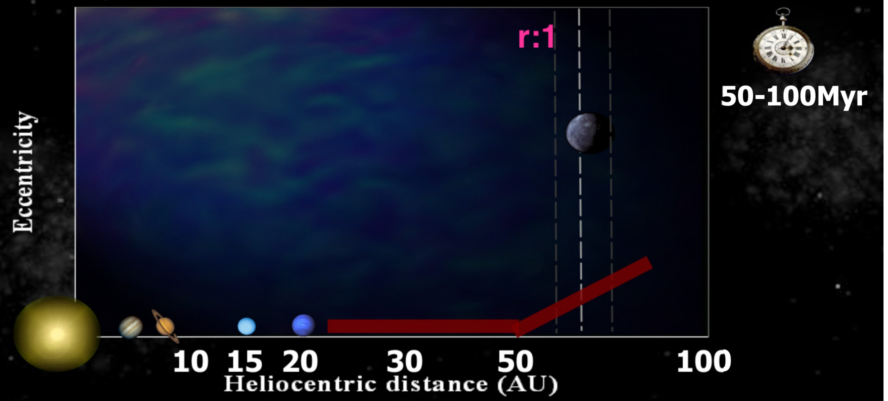
1 Formation stage

A large planetesimal (the outer planet) with tenths of $M_{\oplus}$ is scattered by a giant planet



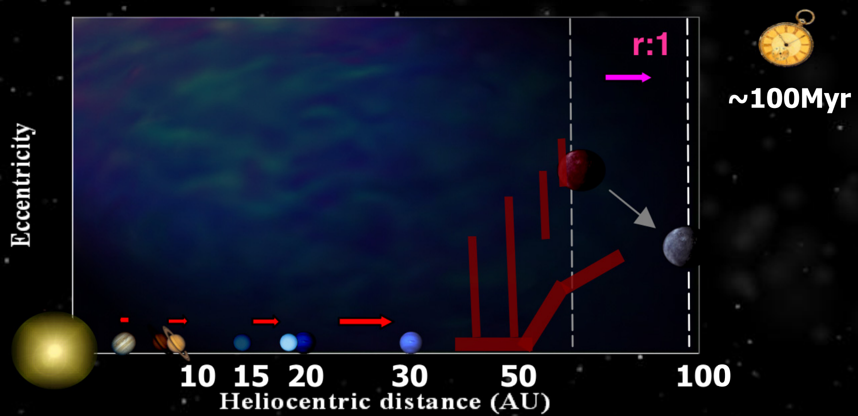
2 Pre-migration stage

The planetoid excites the planetesimal disk for several tens of Myr, before planet migration



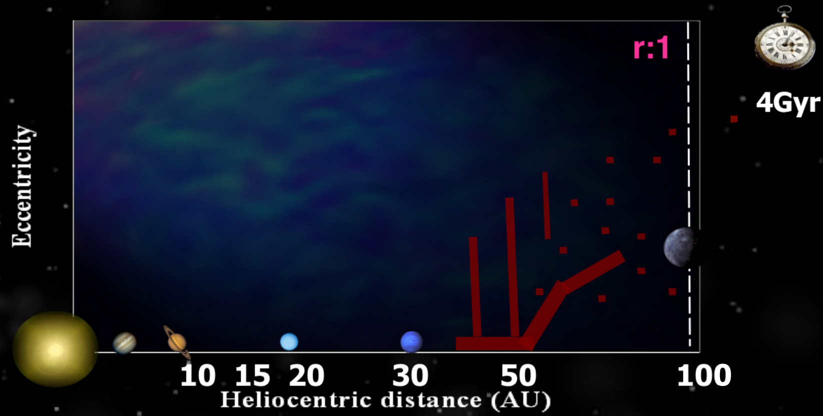
3 Migration stage

The planetoid is captured by a strong Neptunian resonance of the type r:1, which then transports it to ≥100AU

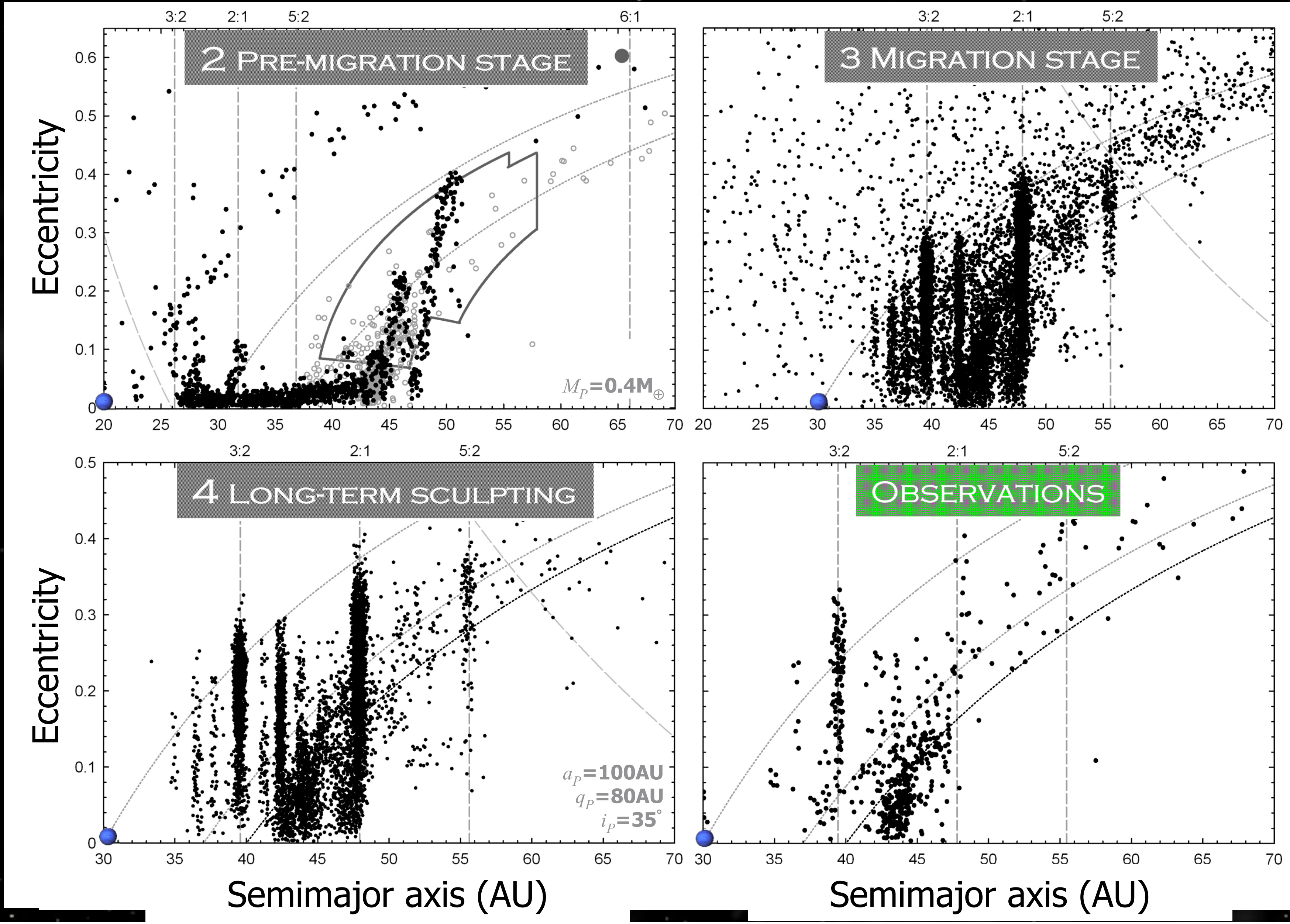


4 Long-term sculpting stage

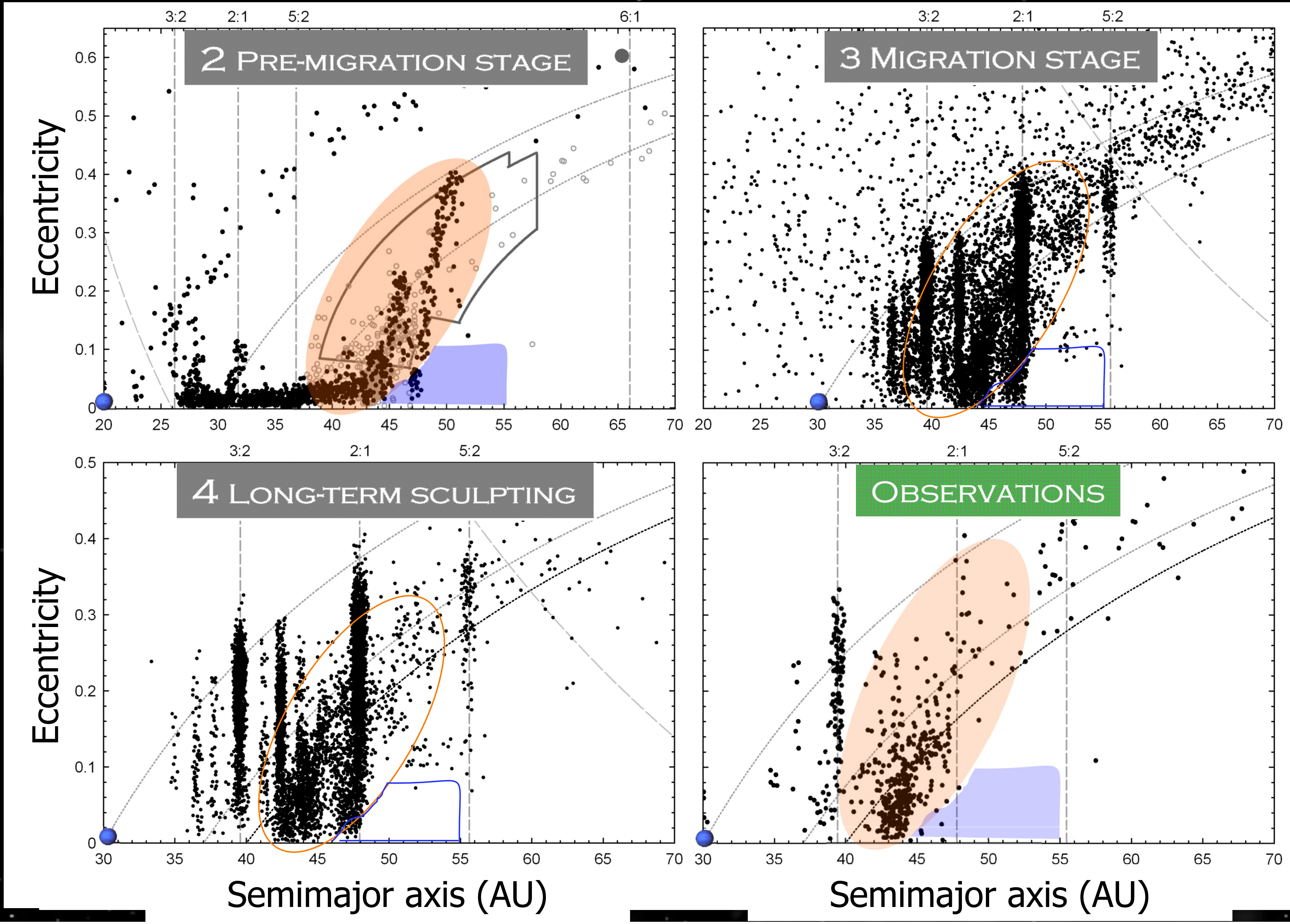
The Kozai resonance (KR) forces the planet's eccentricity to decrease at the expense of increasing its inclination



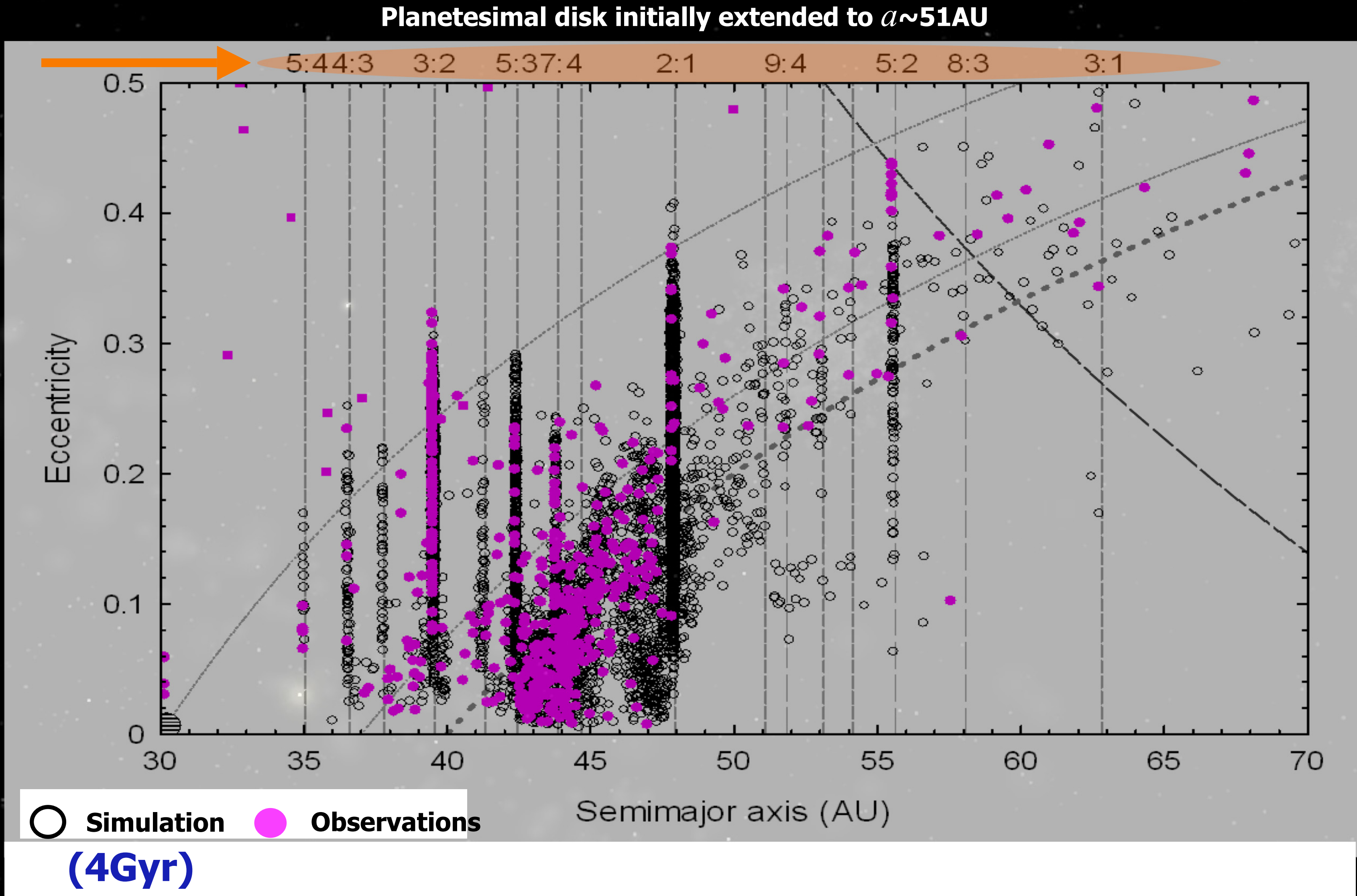
General Results



General Results



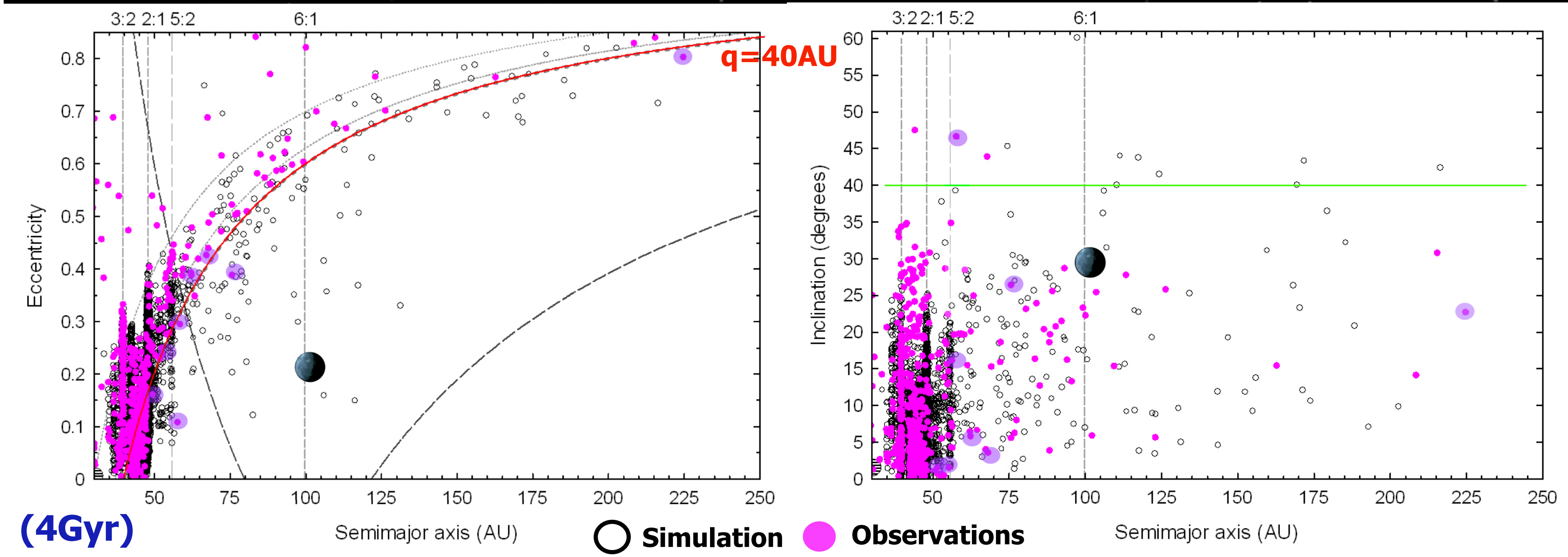
Resonant Populations



Production of resonant TNOs with orbital and resonant properties compatible with observations

Scattered and Detached Populations

Planetesimal disk initially extended to a~51AU

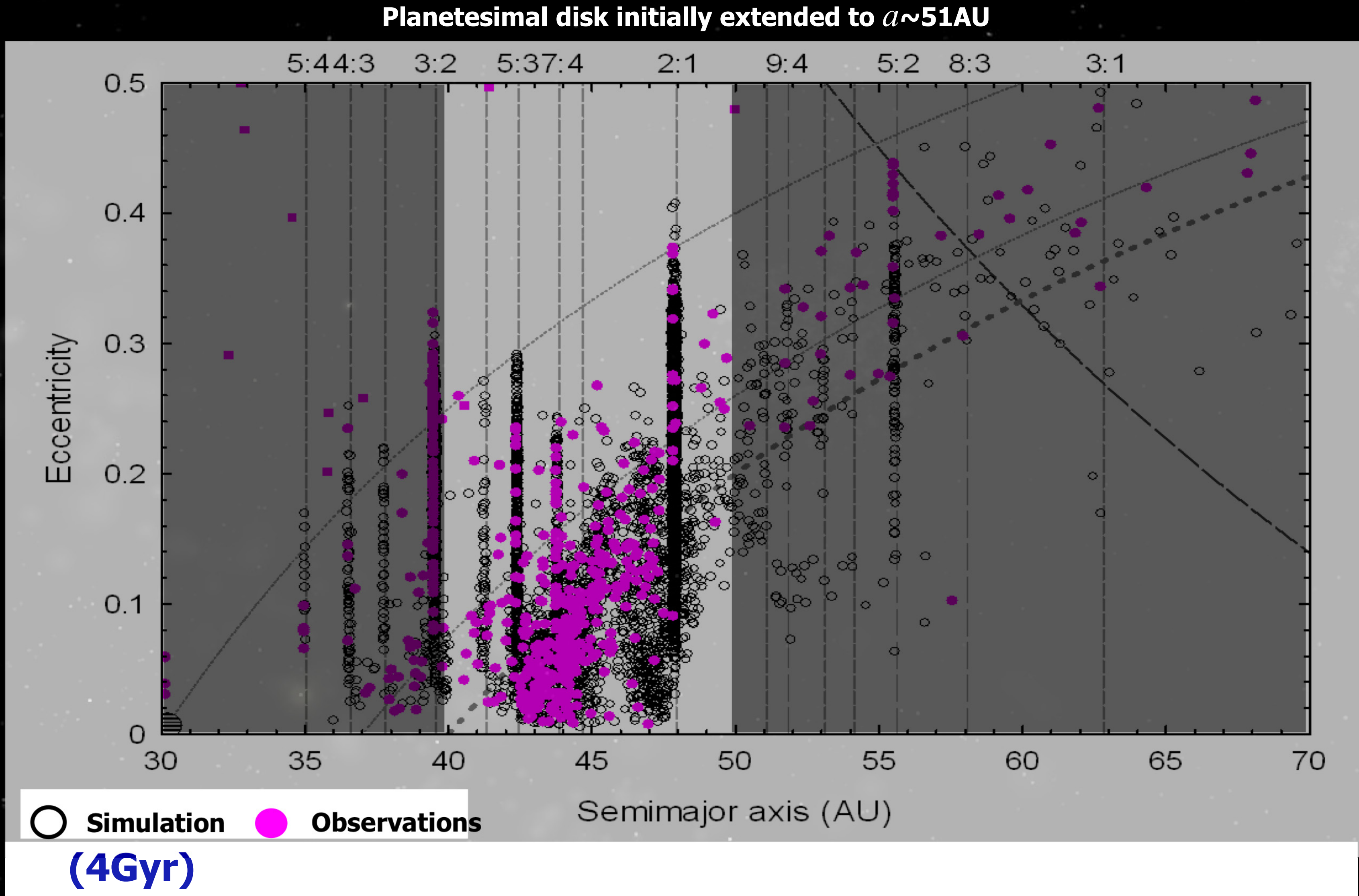


Production of scattered and detached TNOs

(30AU<q<40AU; 0<i<50˚) **(40AU<q<60AU; 0<i<60˚)**

(including analogs of Eris, 2004 XR_{190}, 2000 CR_{105} and Sedna)

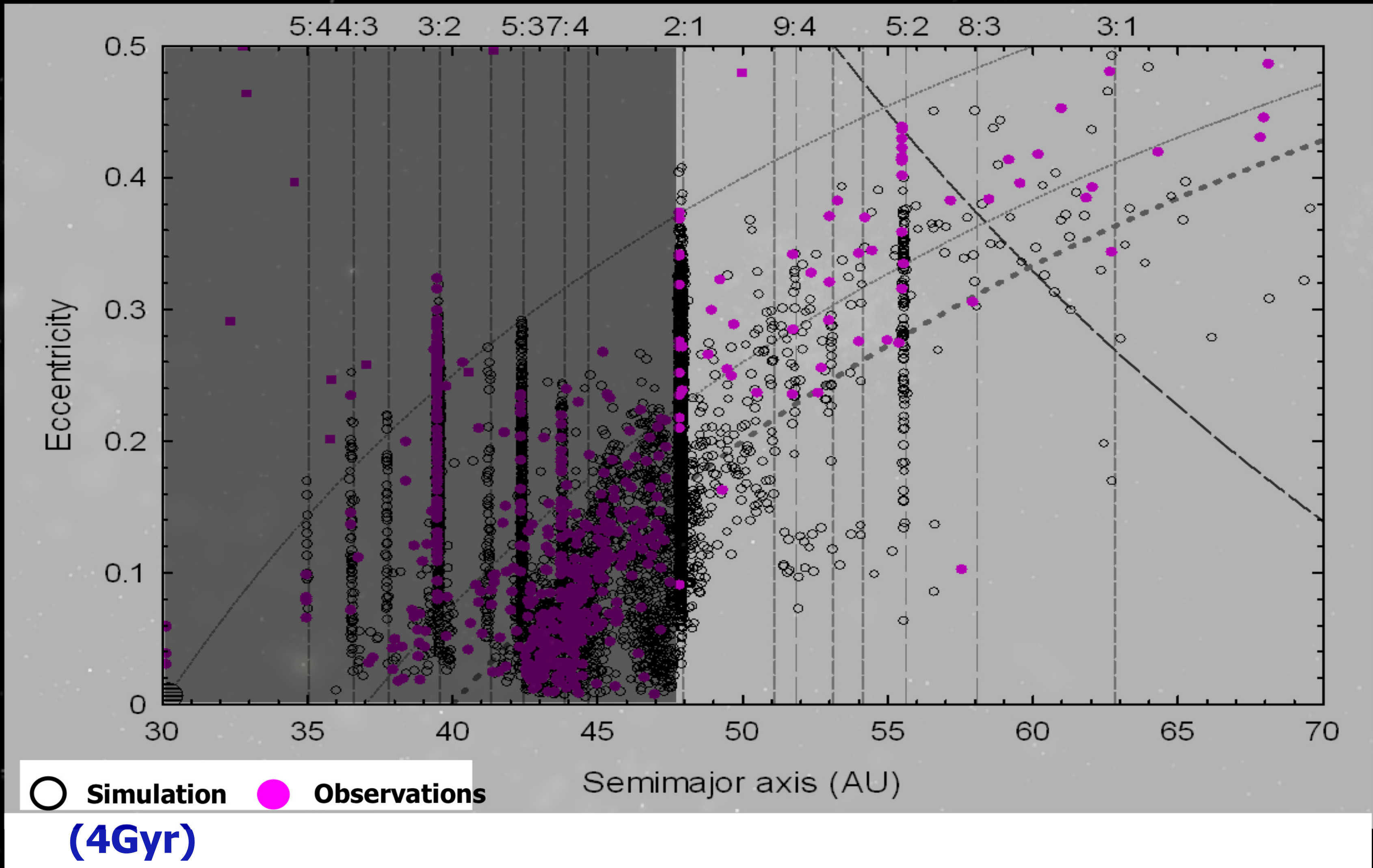
Classical Population



Production of classical TNOs with orbital excitation in excellent agreement with observations

The Belt 's Outer Edge

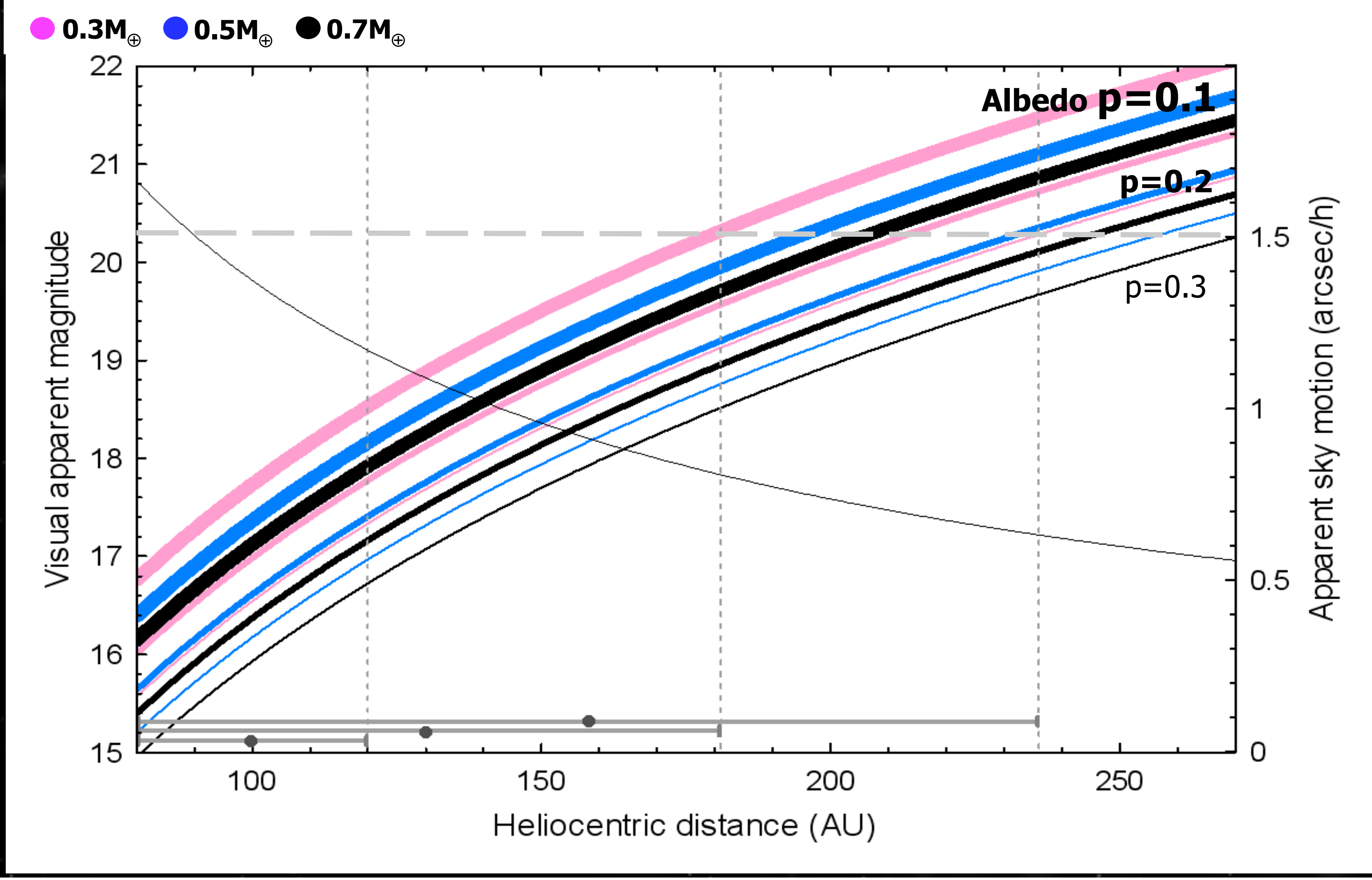
Planetesimal disk initially extended to a~51AU



Effective production of an outer edge at a~48AU:
absence of low-e objects AND abrupt number density decrease

Observational Constraints for the Trans-Plutonian planet

Best orbital elements for the planetoid: a_P=100-175AU, q_P≥80AU, i_P=20-40°



Summary

Our model with a trans-Plutonian planet can explain **consistently** the:

1) excitation of the Kuiper belt
2) the belt's outer edge at ~48AU
3) origin of the four main populations of TNOs
4) loss of ~99% of the Kuiper belt initial mass
5) Neptune's current orbit at 30.1AU

Conclusions

- A massive body (outer planet) was scattered by one of the giant planets during late stages of planet formation
- It then stirred the primordial planetesimal disk to the levels observed at 40-50AU and truncated it at ~48AU, before planet migration (fossilized signatures)
- Later, the outer planet acquired an inclined stable orbit because of a resonant interaction with Neptune
- Long-term signatures of the planetoid's perturbation are the detached and very high-i populations (>40 degrees)

Ongoing/Future Work

1. **Systematic exploration of compact systems of giant planets + embedded planetoids in massive disks**
2. **Influence of more massive outer planets ($\geq 1M_{\oplus}$) with lifetimes <1Gyr to produce more "Sednas" and explain the Late Heavy Bombardment**
3. **Origin and long-term dynamical evolution of Neptune Trojans and collisional families in the Kuiper belt**
4. **Implementation of collisional fragmentation in MERCURY (a N-body code)**
5. **Implementation of effects of stochasticity in planet migration**
6. **Detailed analysis of the dynamics of Centaurs, scattered disk objects and other unstable TNOs**

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有難うございました