Orbital Structure and Dynamical Evolution of TNOs

Patryk Sofia Lykawka (パトリック ソフィア リカフィカ) patryksan@gmail.com
近畿大学 総合社会学部 天文学分野

Outline

I: Introduction and motivation

II: Dynamical stability and planet migration

III: Stable TNO populations and general implications

IV: Scenarios for the origin and evolution of TNOs

V: Main conclusions

I – Introduction and motivation

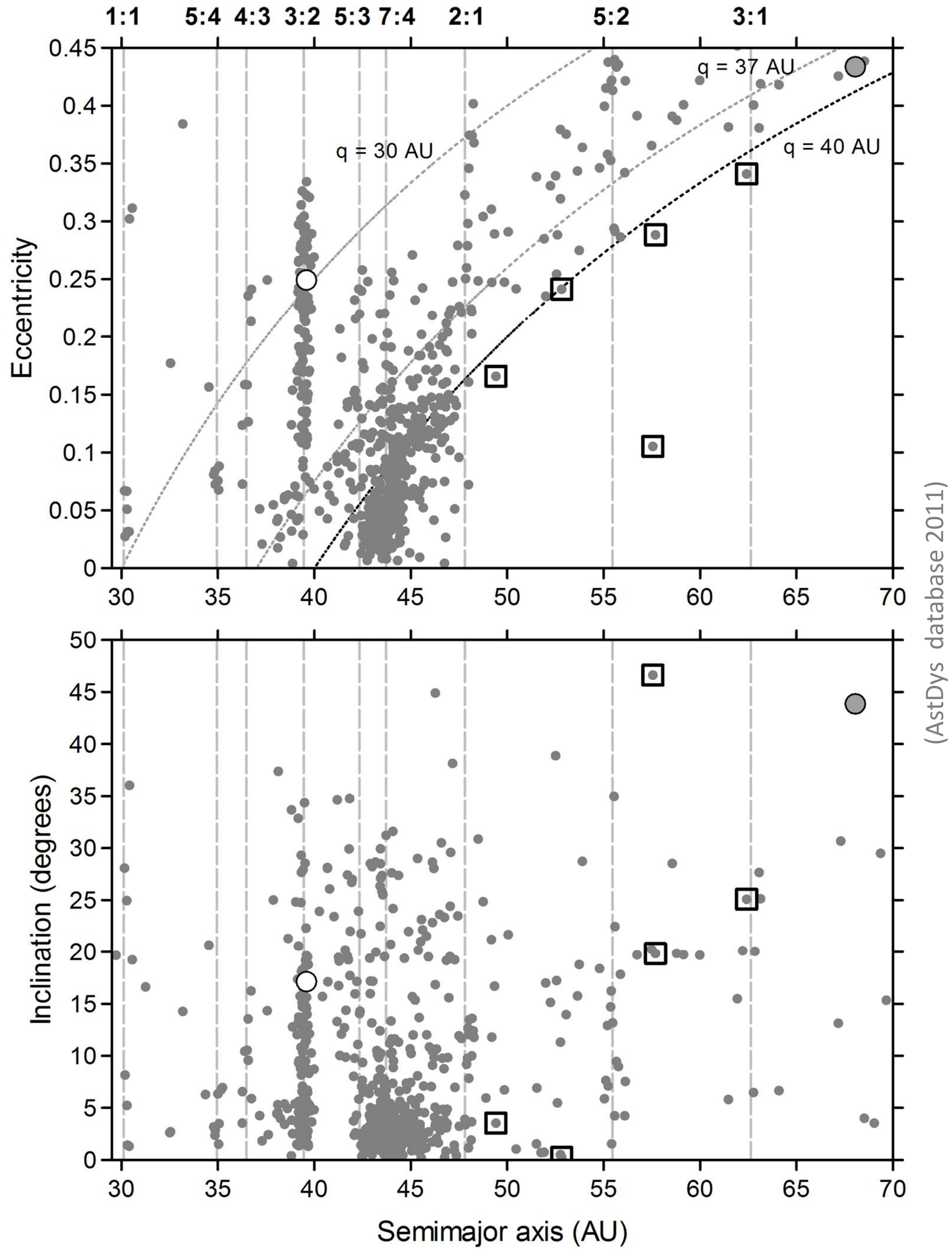
Trans-Neptunian objects (TNOs): icy/rocky bodies orbiting beyond Neptune

TNOs orbital distribution

Main populations: **classical**, **resonant***, **scattered**, and **detached** TNOs

(Gladman et al. 2002; Morbidelli & Brown 2004; Elliot et al. 2005; Delsanti & Jewitt 2006; Lykawka & Mukai 2007b; Gladman et al. 2008)

* Associated with mean motion resonances (MMRs) with Neptune



Evolutionary processes: planet migration, collisional evolution and gravitational sculpting by the planets

(Malhotra 1995; Hahn & Malhotra 1999; Kenyon & Luu 1998, 1999; Kenyon & Bromley 2004; Morbidelli 2006; Chiang et al. 2006; Kuiper Belt Book 2008; Lykawka 2012)

The scattered disk (> 50 AU)

(Torbett 1989; Holman & Wisdom 1993; Duncan & Levison 1997; Morbidelli *et al.* 2004)

q < 40 AU:

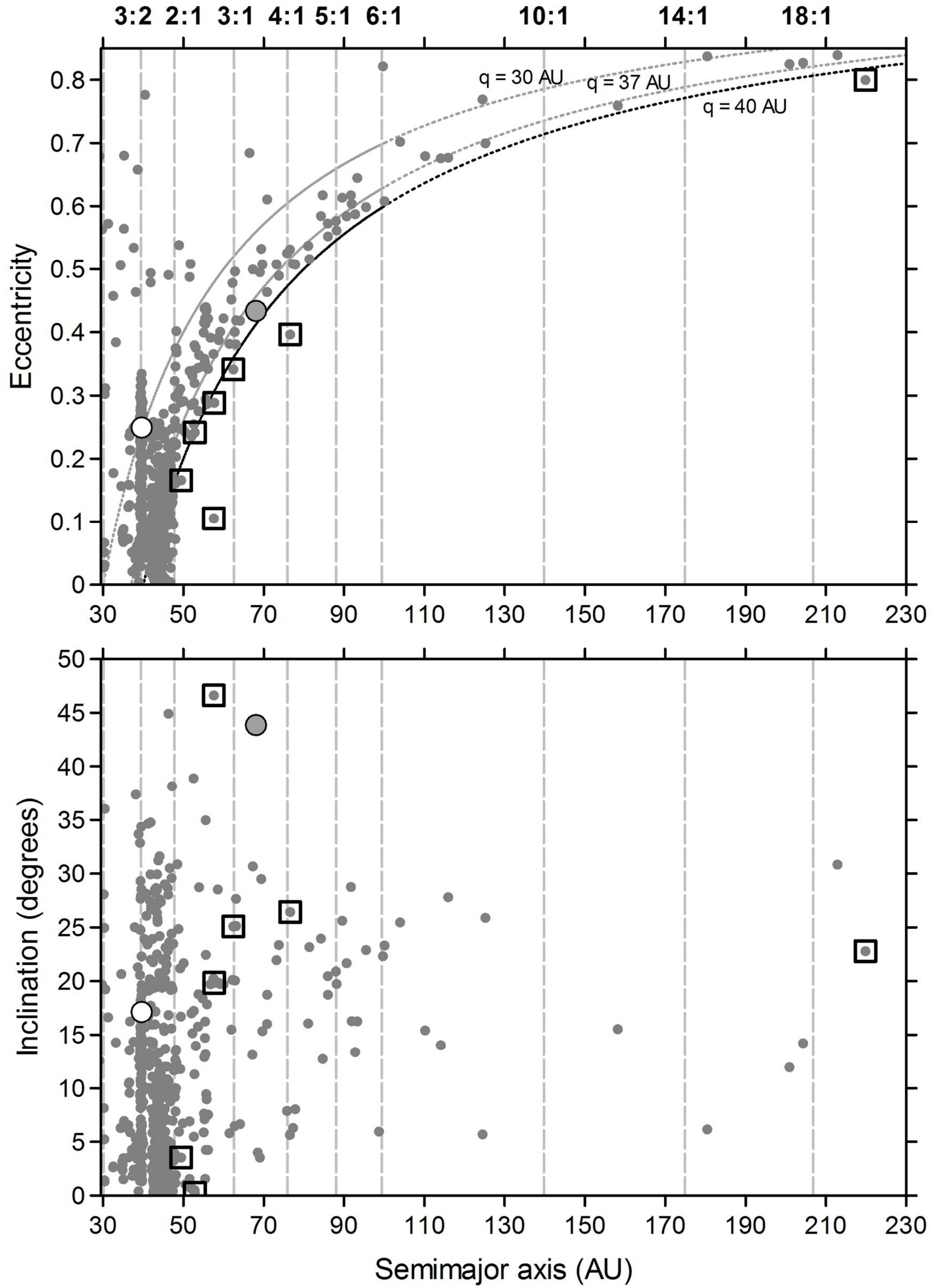
Dynamics dominated by Neptune's gravitational scattering + MMR sticking

Likely the main source of Centaurs and their daughter short-period comets

(Ip & Fernandez 1991; Duncan & Levison 1997; Volk & Malhotra 2008)

q > 40 AU:

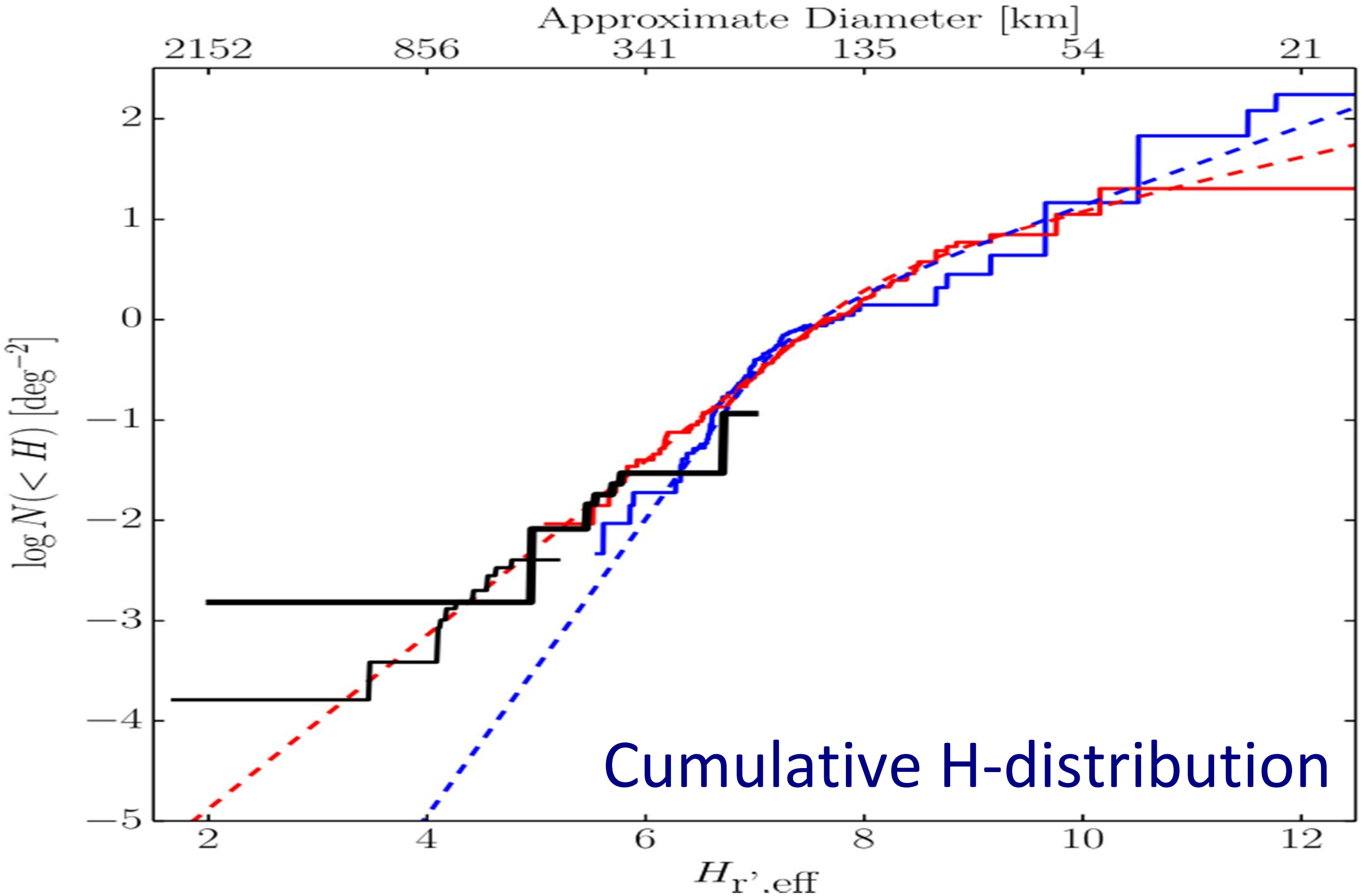
Dynamically quasi-static



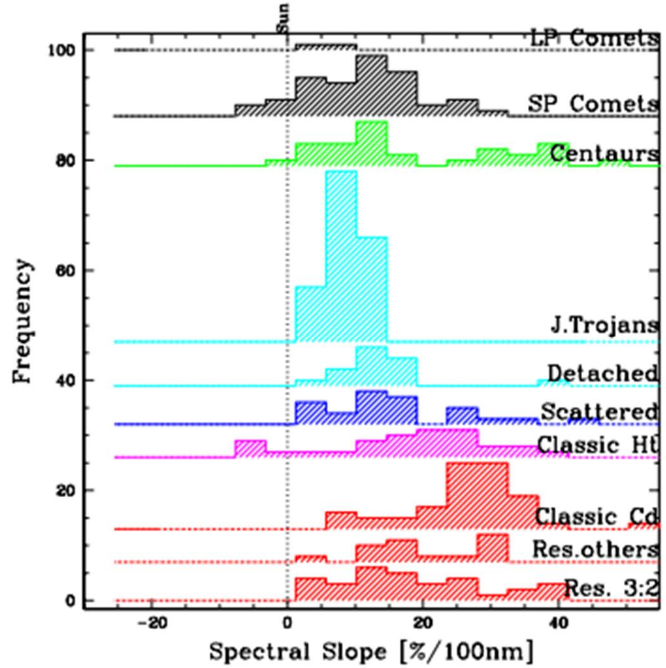
(Kuiper Belt book 2008; Petit et al. 2011; Fraser and collaborators 2008-2014: Brown and collaborators 2005-2014)

Main physical properties

(Fraser et al. 2014)



Surface colors



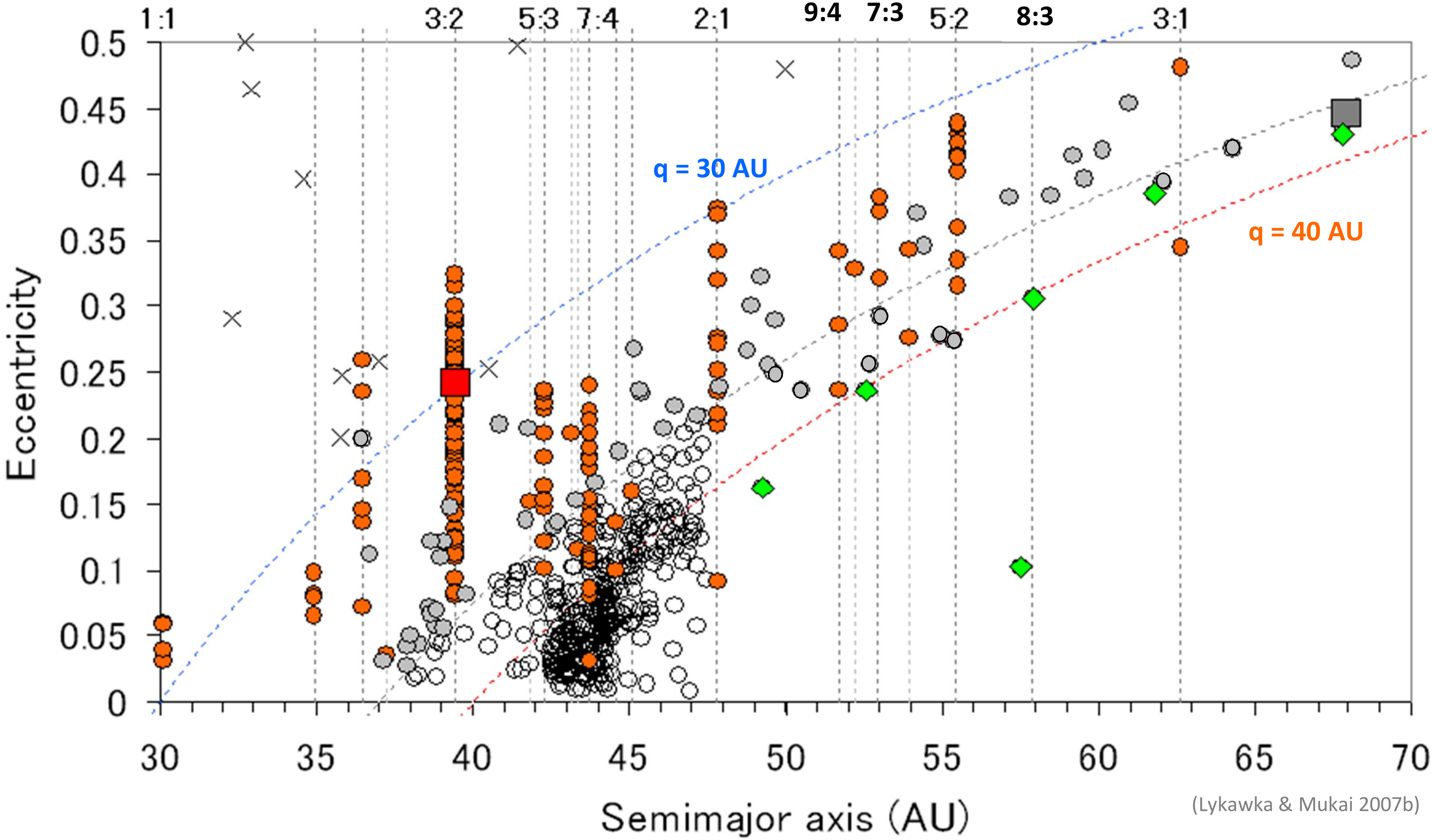
(Hainaut et al. 2012)

★ **A few (?) 10^5 TNOs with D > 100 km**

★ **Total mass around 0.1 Earth mass?**

★ **Albedos 0.03-0.30 in general**

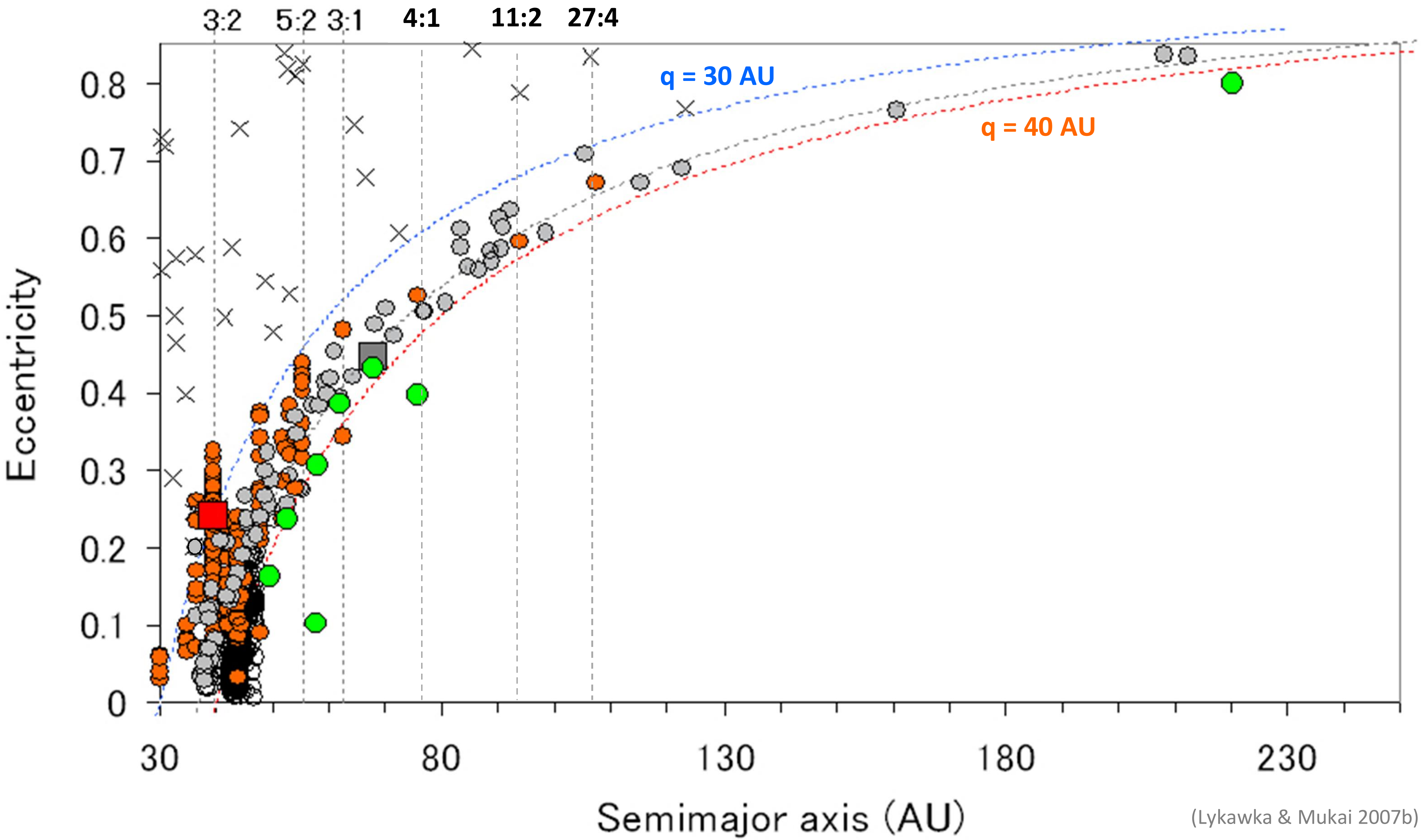
★ **Rock and ice compositions** (H_2O, CO_2, CH_3OH, NH_3, CH_4, CO, N_2など)



Four main classes of TNOs:

① Classical TNOs (q > 37 AU; 37 AU < a < 50 AU) ② Resonant TNOs

③ Scattered TNOs (q < 37 AU) ④ Detached TNOs (q > 40 AU)



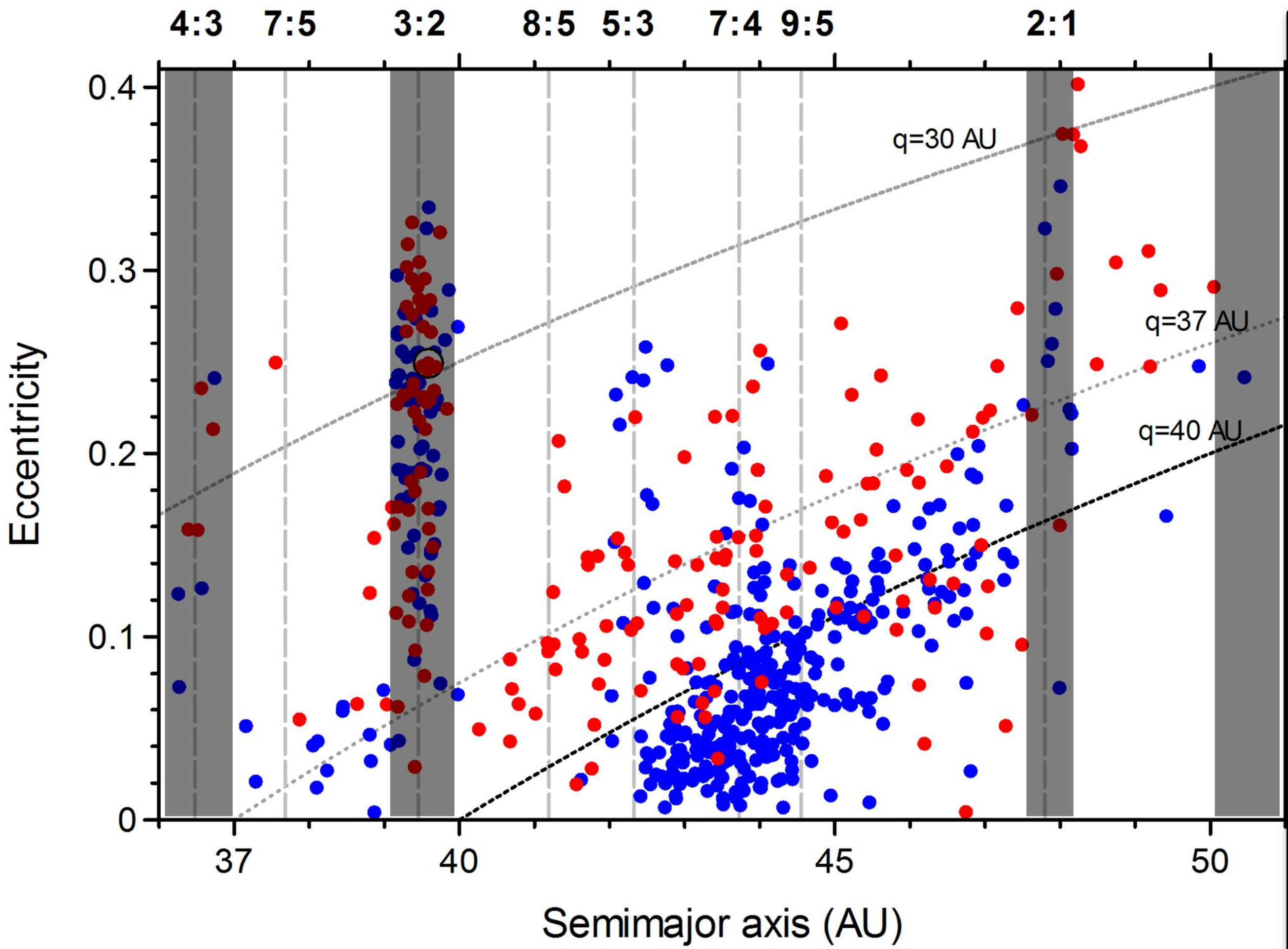
(Petit et al. 2011; Gladman et al. 2012)

Approximate relative fractions (D > 100 km):

① Classical TNOs: 40-60% ② Resonant TNOs: 15-25%

③ Scattered TNOs: 10-20% (?) ④ Detached TNOs: 10-20% (?)

Classical TNOs



(Noll et al. 2008; Peixinho et al. 2008, 2013; Brucker et al. 2009; Petit et al. 2011; Fraser et al. 2010, 2014; Vilenius et al. 2012, 2014)

Cold population

- i < 5-10 deg (R=38-48 AU)
- 3~10·10^{-4} Earth masses
- Predominantly red colors
- Lack of large objects (>500km)
- Higher albedos (med. ~0.14)
- Higher fraction of binaries

Hot population

- i > 5-10 deg (R=32-57+ AU)
- 10~30 times more massive than the cold population
- Mix of various colors
- Shallower slope at large sizes
- Lower albedos (med. ~0.085)

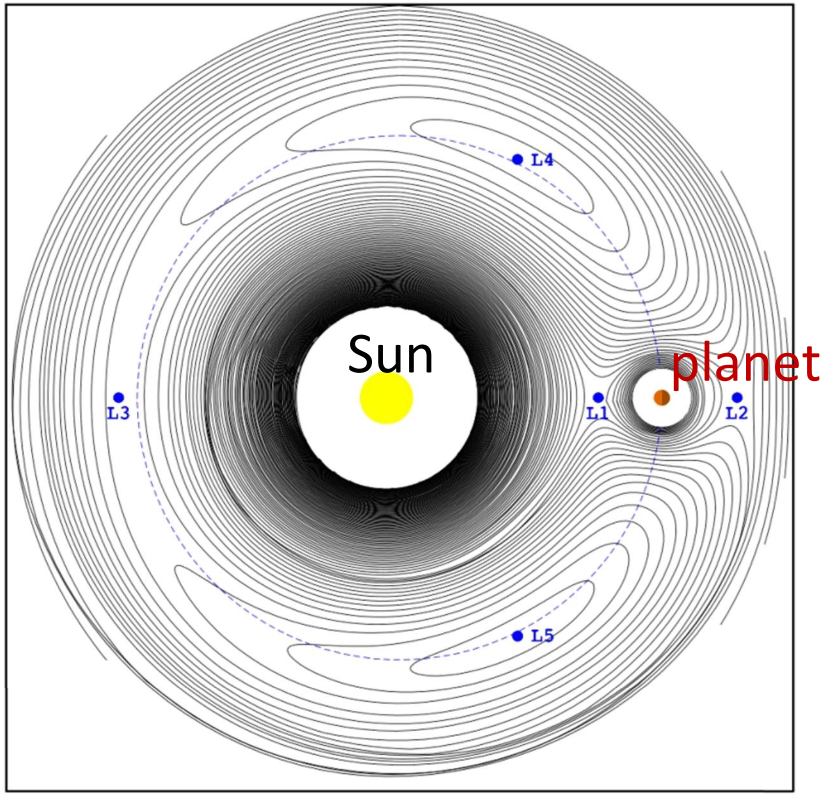
★ **Distinct inclination, radial, color, size and albedo distributions!**

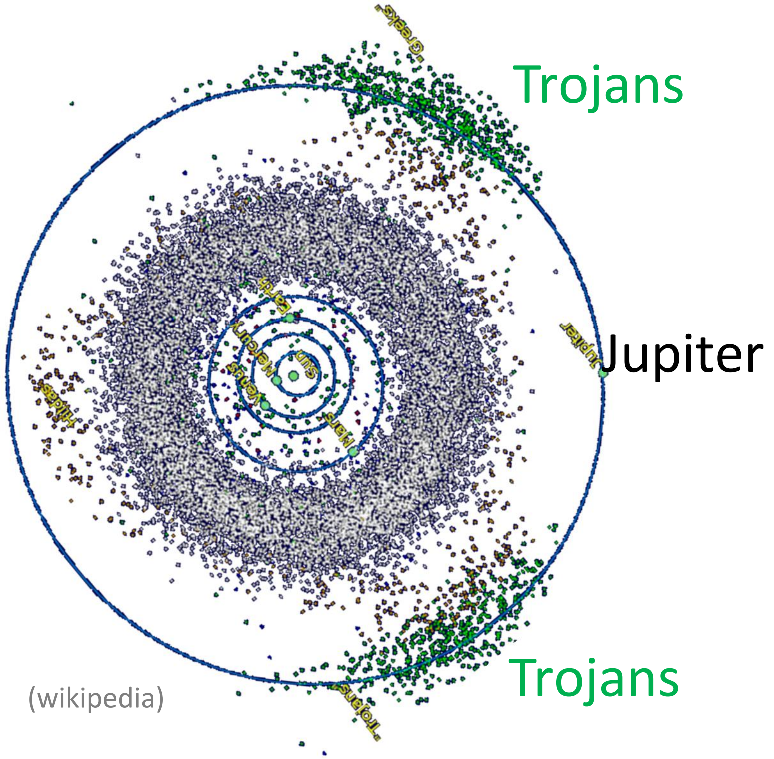
★ **Surprisingly high orbital excitation and fine structure**

(Kuiper Belt book 2008)

(Dawson & Murray-Clay 2012)

→ **What are the main mechanisms responsible for this structure?**





(wikipedia)

(Horner & Lykawka 2011)

Trojans

Objects orbiting about the Lagrangian L4 and L5 points in their 1:1 MMR

Typically lie ~60 deg ahead of or behind the position of the planet

Jupiter Trojans： More than 3000 objects

★ Intrinsic population may exceed the population of asteroids within the same size range!

(Sheppard & Trujillo 2006)

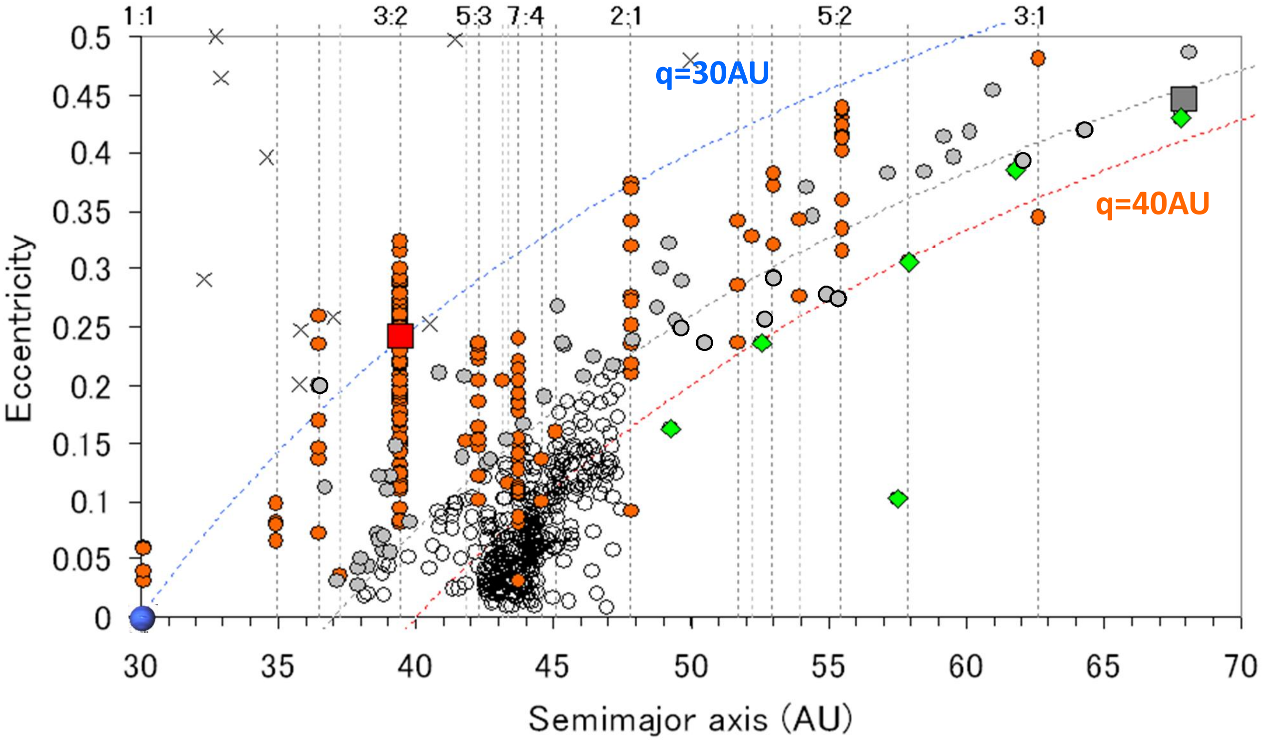
Neptune Trojans： Nine objects

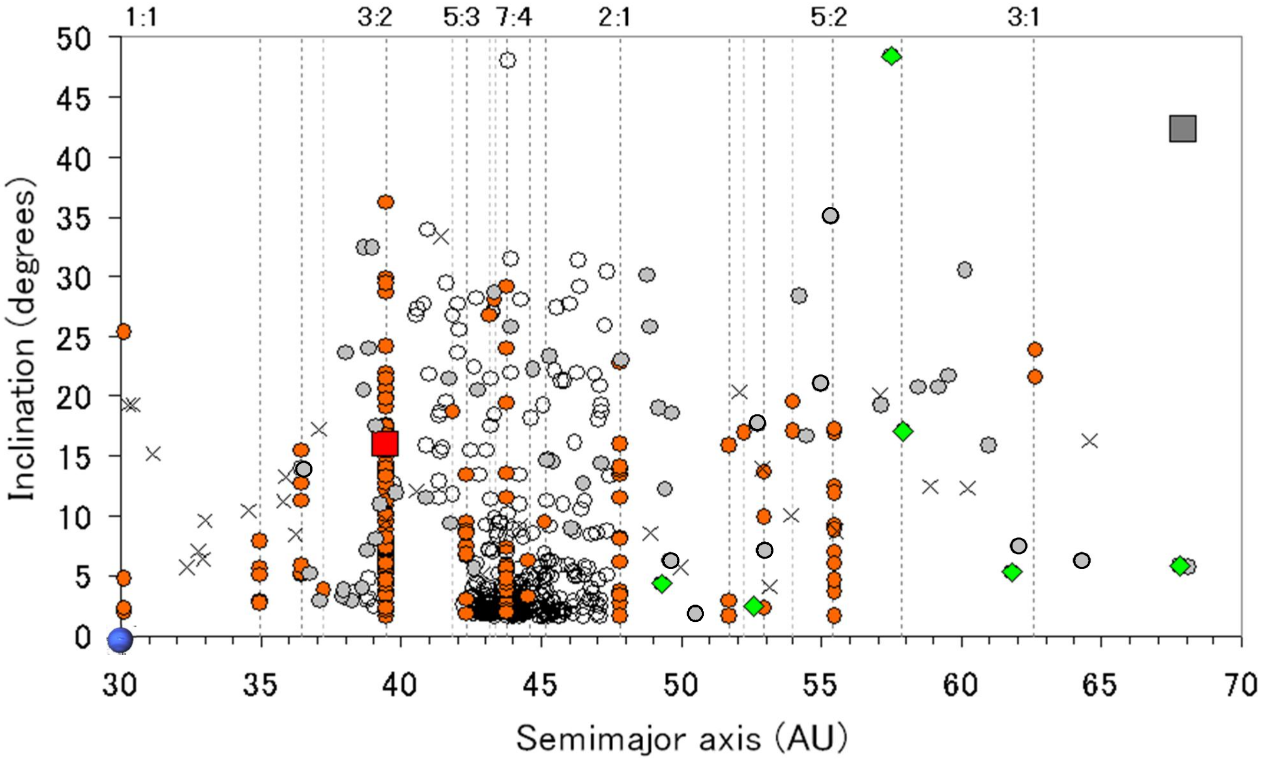
★ Intrinsic population is at least as large as the Jovians (Chiang et al. 2003; Chiang & Lithwick 2005; Lykawka et al. 2009, 2011)

Surprisingly:

e = 0-0.1(5) and i = 0-30(35)deg

→ **How to reconcile this with the KB and planet formation?**





Outstanding questions

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

→ How to explain the four main classes of TNOs?

In particular, the fine structure of **cold and hot classical TNOs** AND **resonant populations**

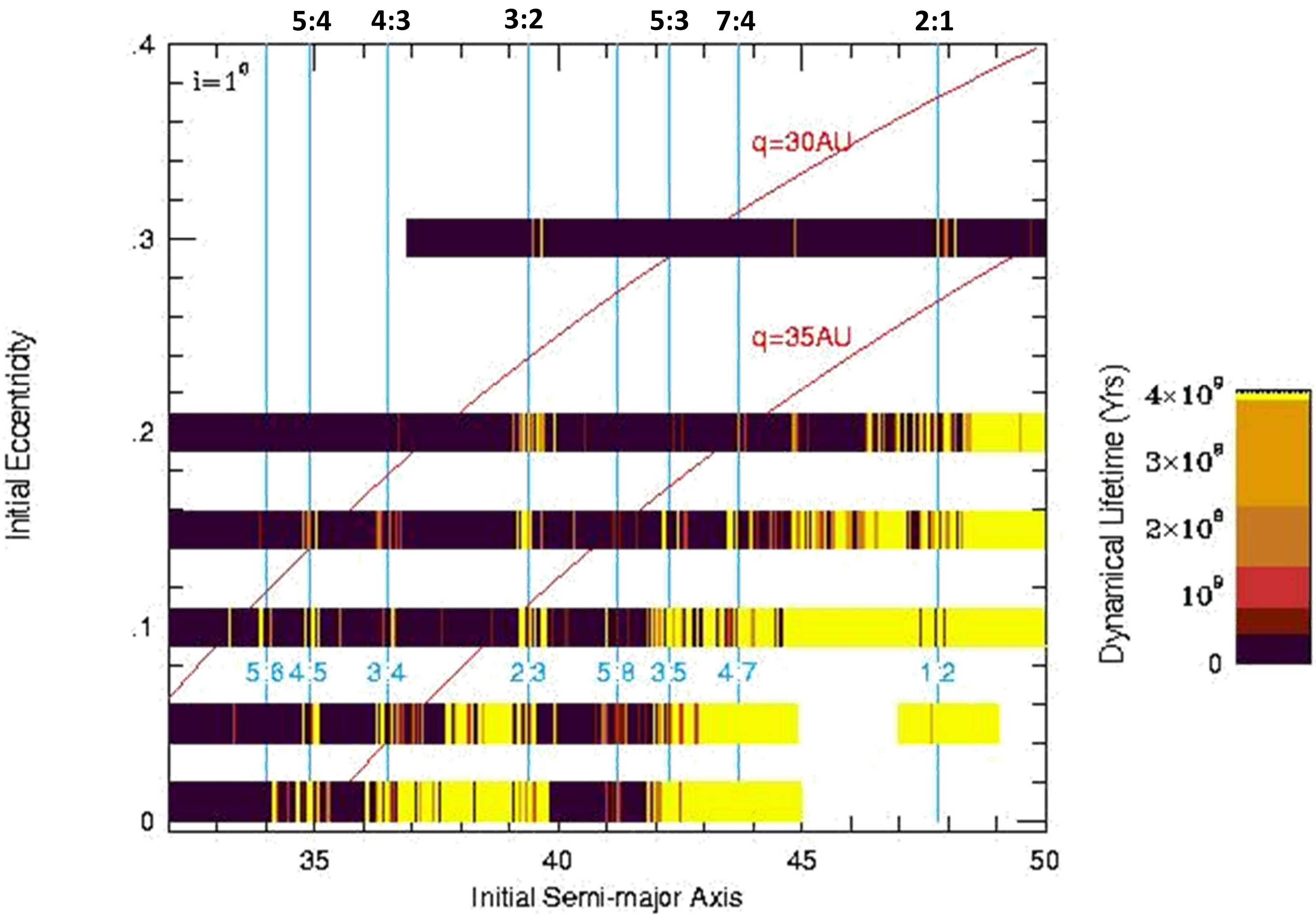
→ How TNOs and other minor body populations are related?

Ex: Centaurs, planetary Trojans, irregular satellites, outer main belt asteroids, etc.

→ How the giant planets (and extra planets) evolved to produce the current KB?

II – Dynamical stability and planet migration

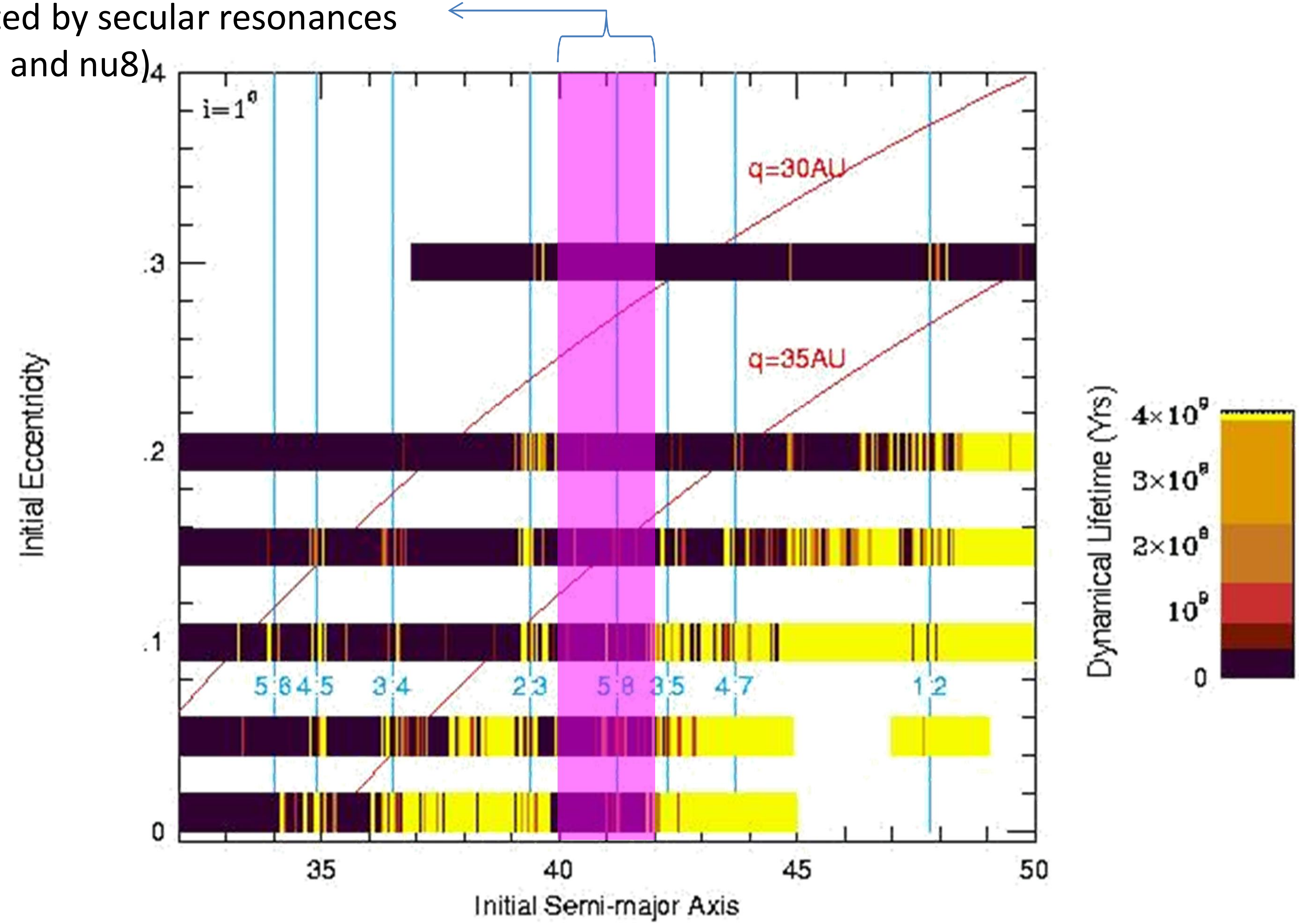
Stability maps of TNOs (i = 0)



(Duncan et al. 1995)

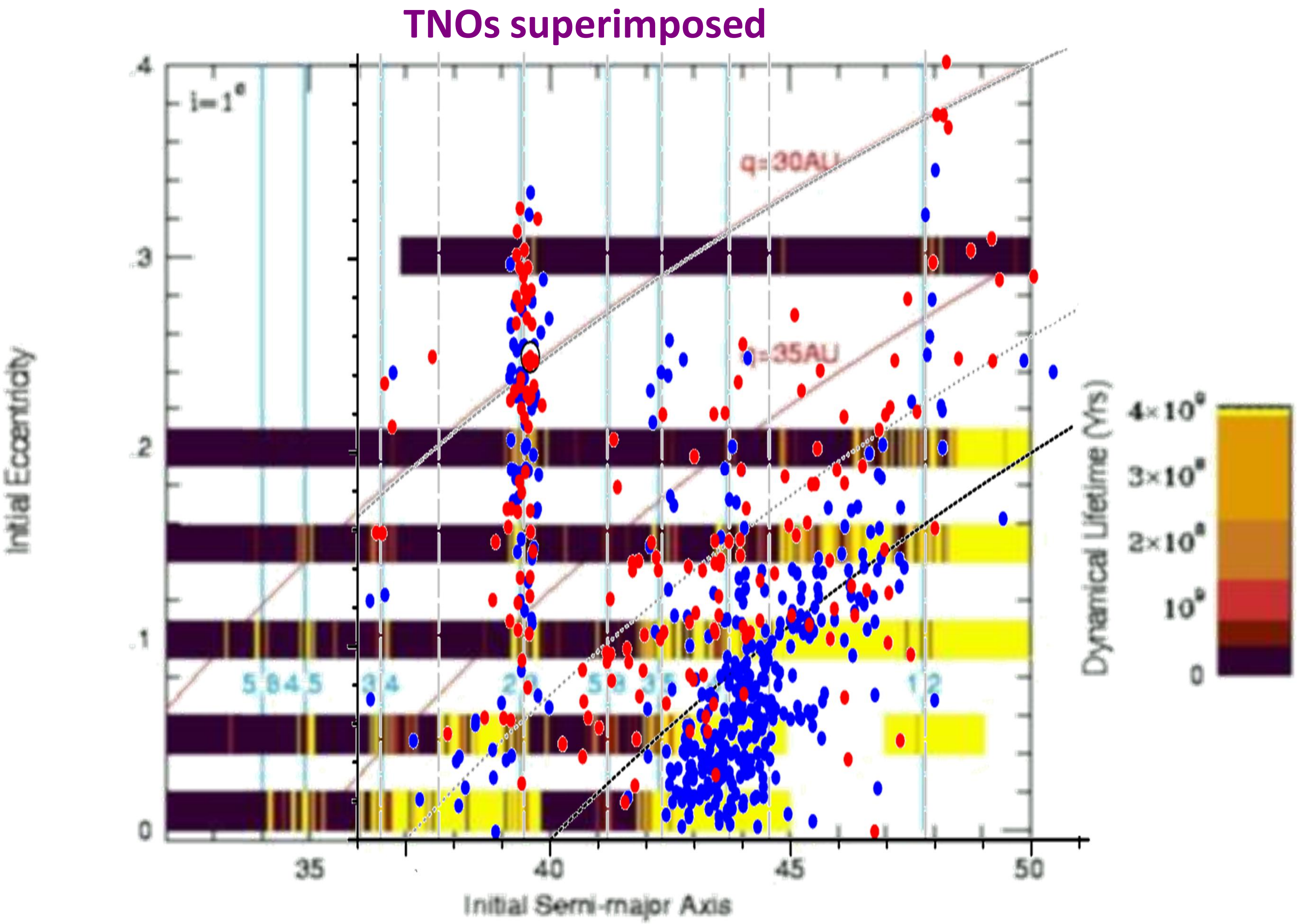
Stability maps of TNOs (i = 0)

Affected by secular resonances
(nu18 and nu8)



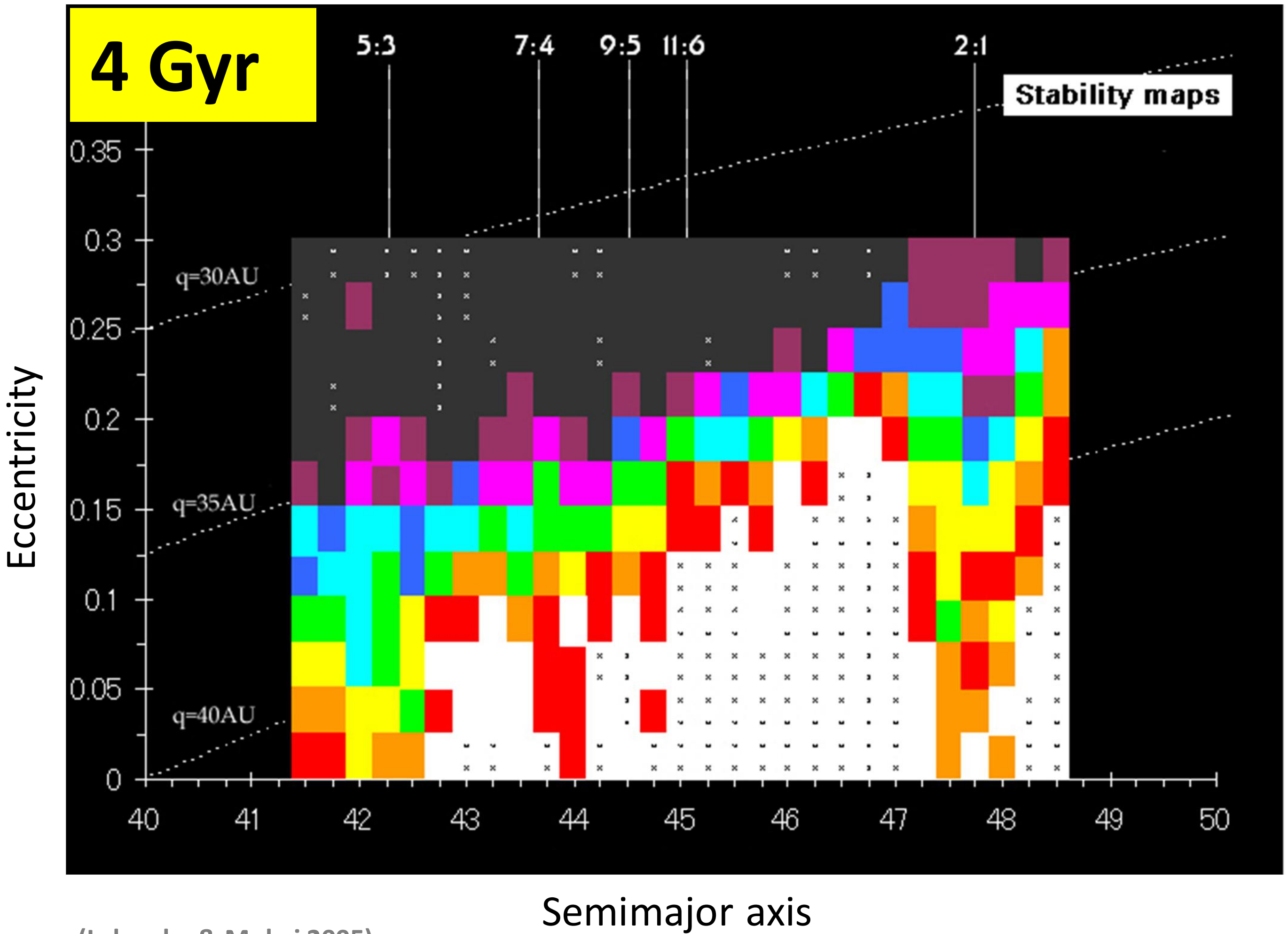
(Duncan et al. 1995)

Stability maps of TNOs (i = 0)

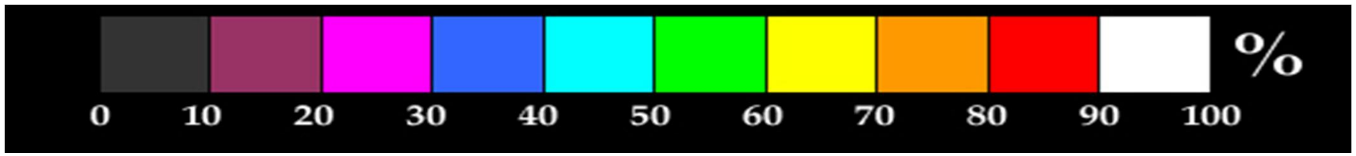


(Duncan et al. 1995)

Stability map of TNOs (all i)



(Lykawka & Mukai 2005)



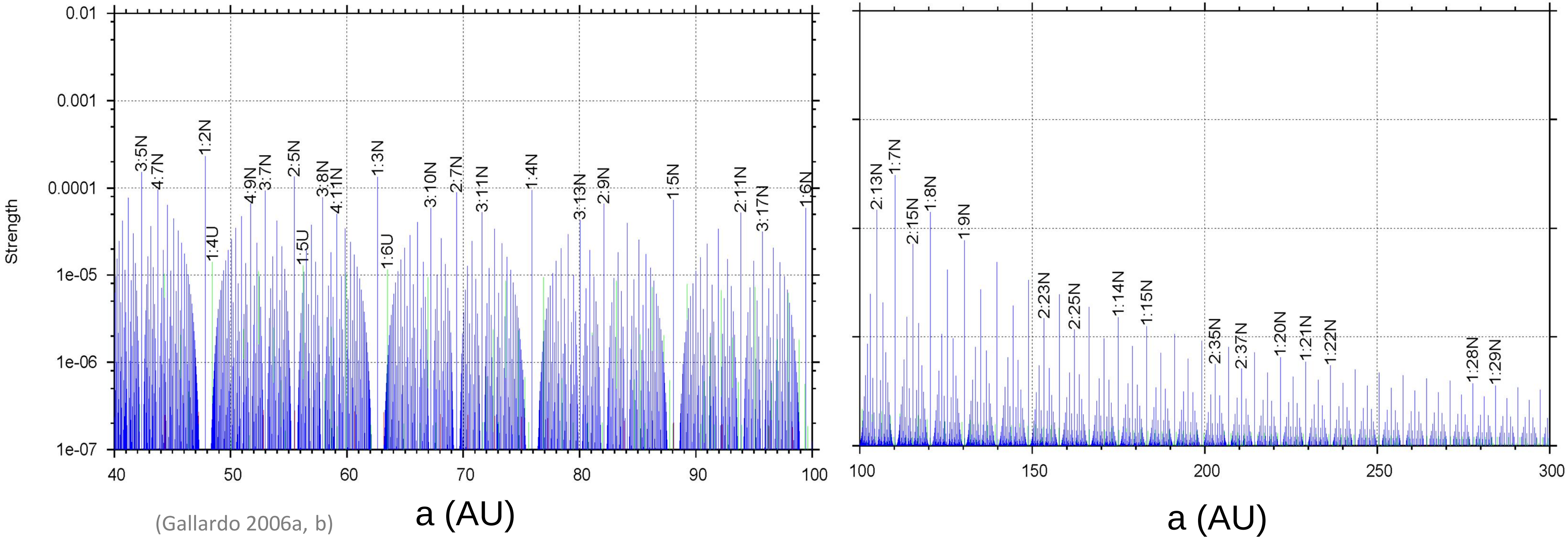
Strong perturbations at q < 35 AU

Perturbations also seen near 42 AU and around the 5:3, 7:4 and 2:1 resonances

★ **Long-term sculpting of "weaker" MMRs plays an important role in the region**

★ **Missing stable objects in the outer region…**

Strength of MMRs beyond Neptune



(Gallardo 2006a, b)

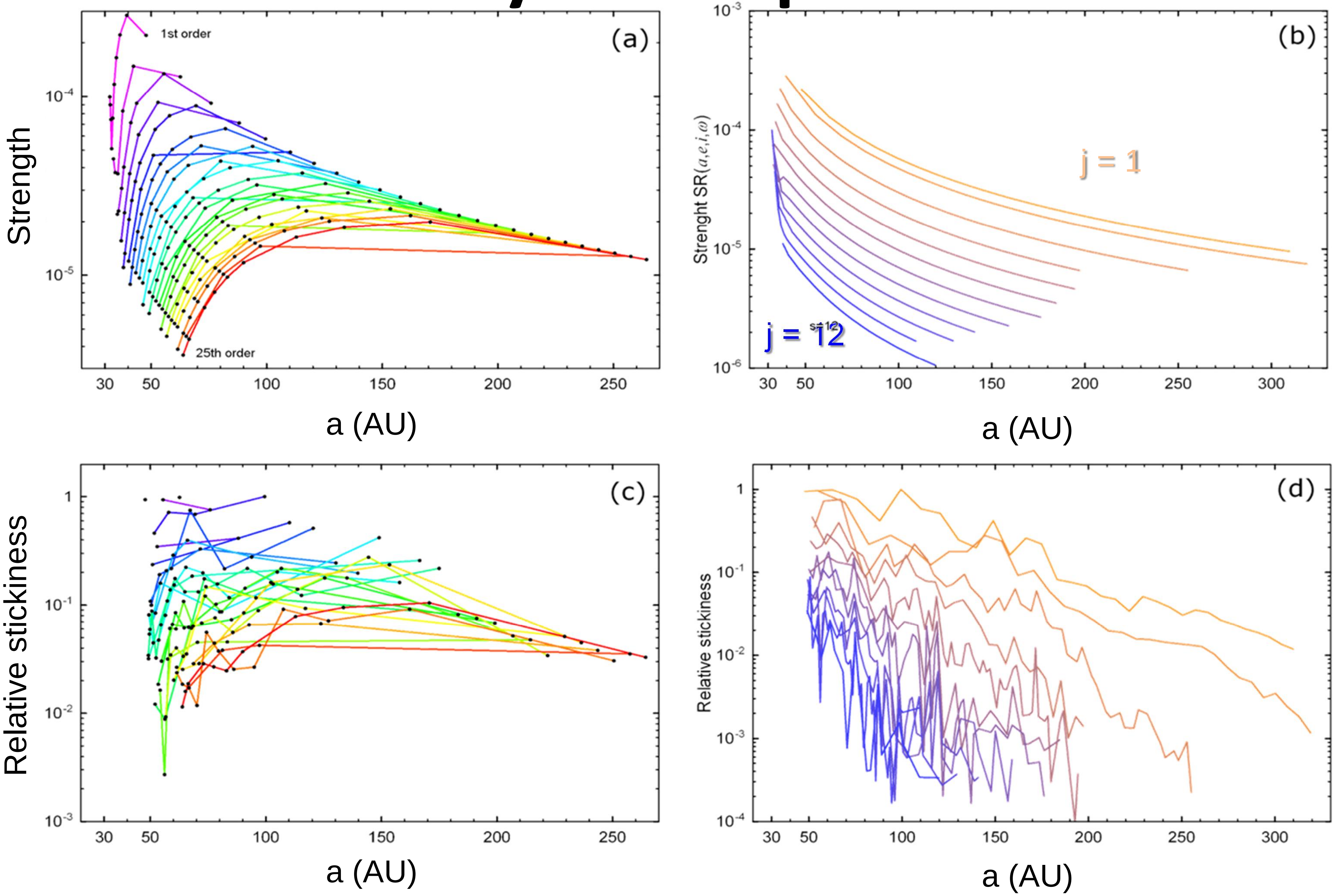
$$\boxed{SR(a,e,i,\omega) = <R> - R_{min}}$$

$$R(\sigma) = \frac{1}{2\pi|p|}\int_0^{2\pi|p|} \mathbb{R}(\lambda_P, \lambda(\lambda_P,\sigma))d\lambda_P \qquad \sigma = (p+q)\lambda_P - p\lambda - q\varpi$$

$$\mathbb{R} = k^2 m_P\Big(\frac{1}{|\ \mathbf{r}_P - \mathbf{r}\ |} - \frac{\mathbf{r}\cdot\mathbf{r}_P}{r_P^3}\Big)$$

Strength/stickiness of MMRs beyond Neptune

(Lykawka & Mukai 2007c)



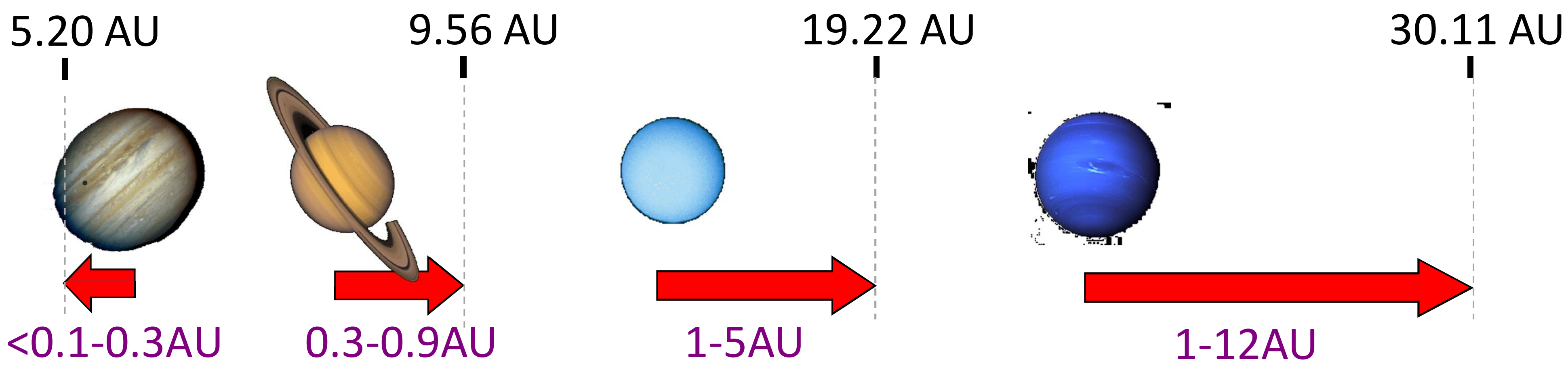
Planet migration in the solar system

Stage ①: Driven by interactions of the (giant) planets with the nebular gas over the first few Myr (Morbidelli et al. 2007; Pierens & Raymond 2011; Kley & Nelson 2012; D`Angelo & Marzari 2012)

Stage ②: Planet-planet or planet-embryo gravitational scattering can yield very rapid or chaotic radial displacements for any planet in the system (Brasser et al. 2009; Morbidelli et al. 2009; Agnor & Lin 2012; Nesvorny & Morbidelli 2012)

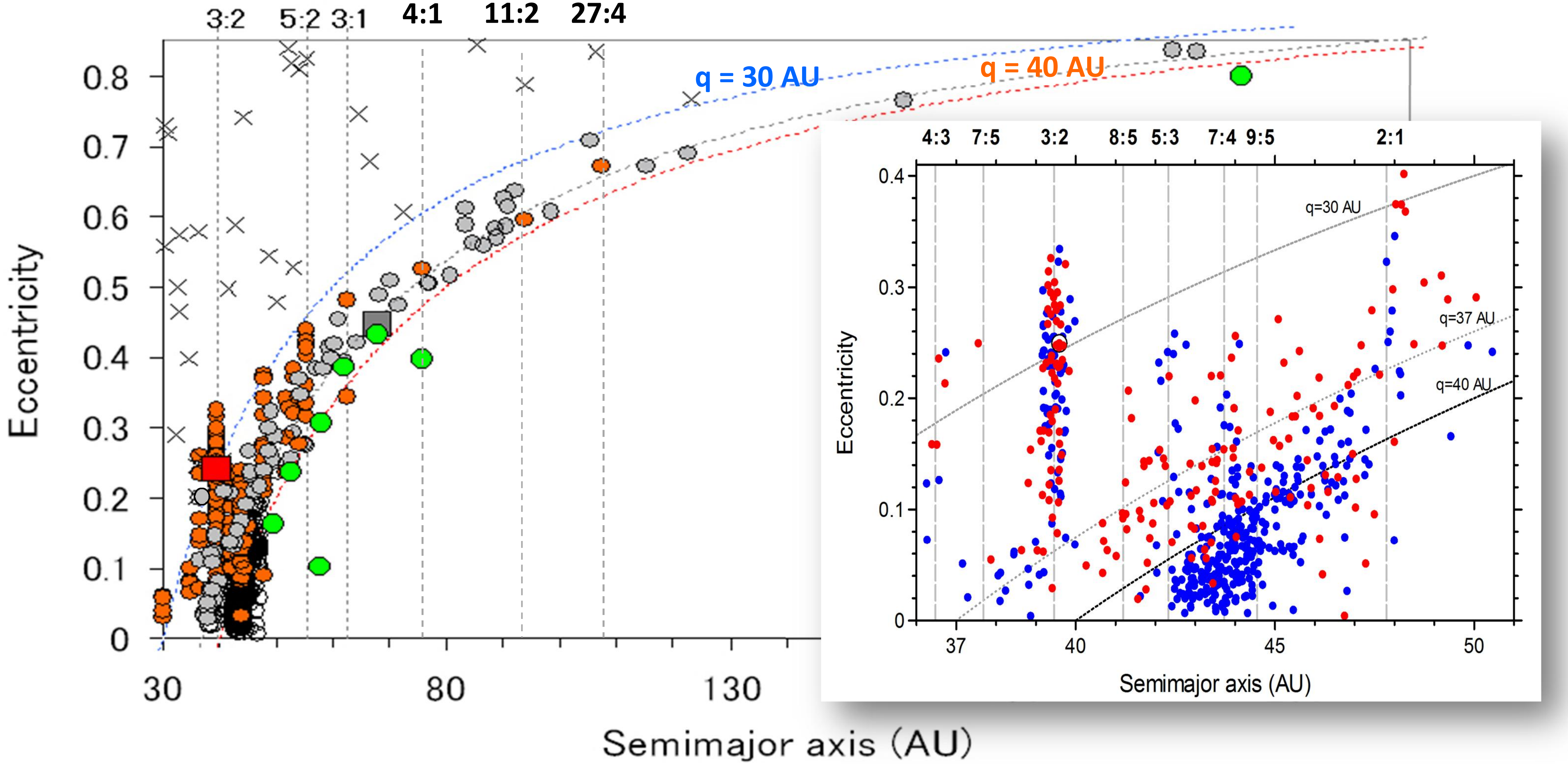
Stage ③: Driven by interactions of the planets with the remaining disk planetesimals (in between and beyond)

(Fernandez & Ip 1984; Malhotra 1995; Hahn & Malhotra 1999; Chiang & Jordan 2002; Hahn & Malhotra 2005; Levison et al. 2007; Kirsh et al. 2009)



III – Stable TNO populations and general implications

Resonant TNO populations

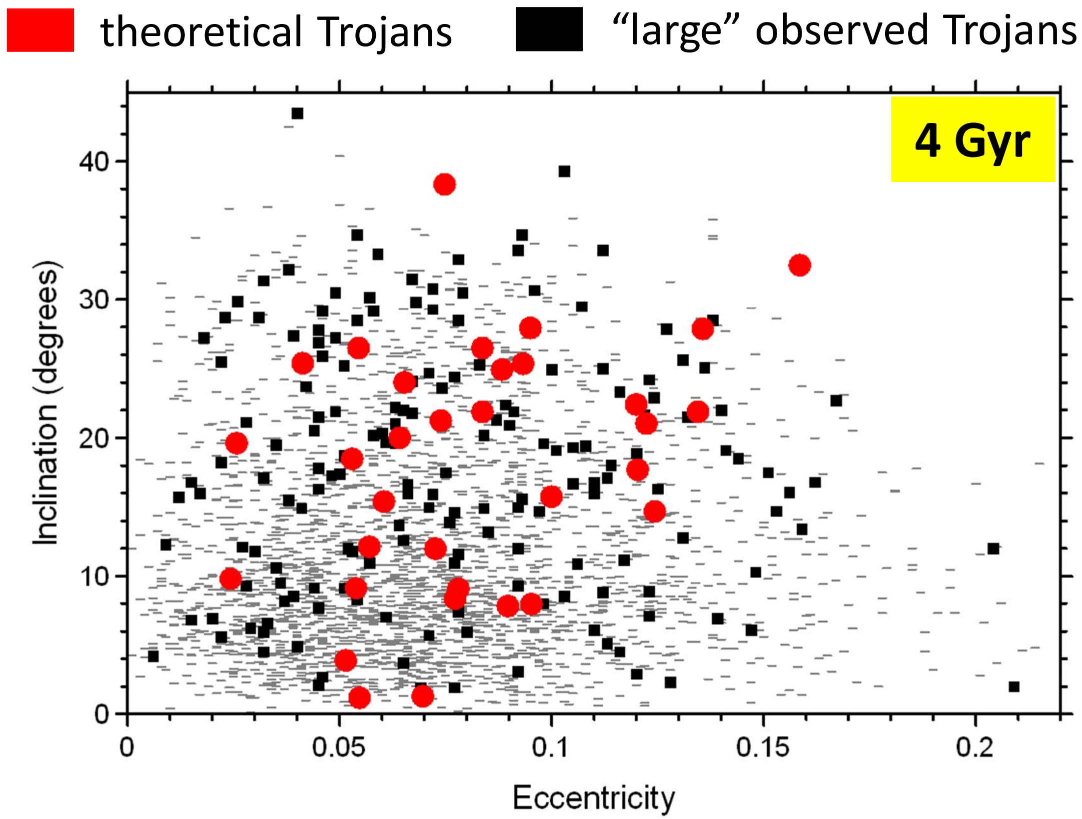


★ **Members from 1:1 to 27:4. Stable populations likely represent slowly decaying captured populations formed ~4 Gyr ago** (Lykawka & Mukai 2007b) (Gladman et al. 2008)

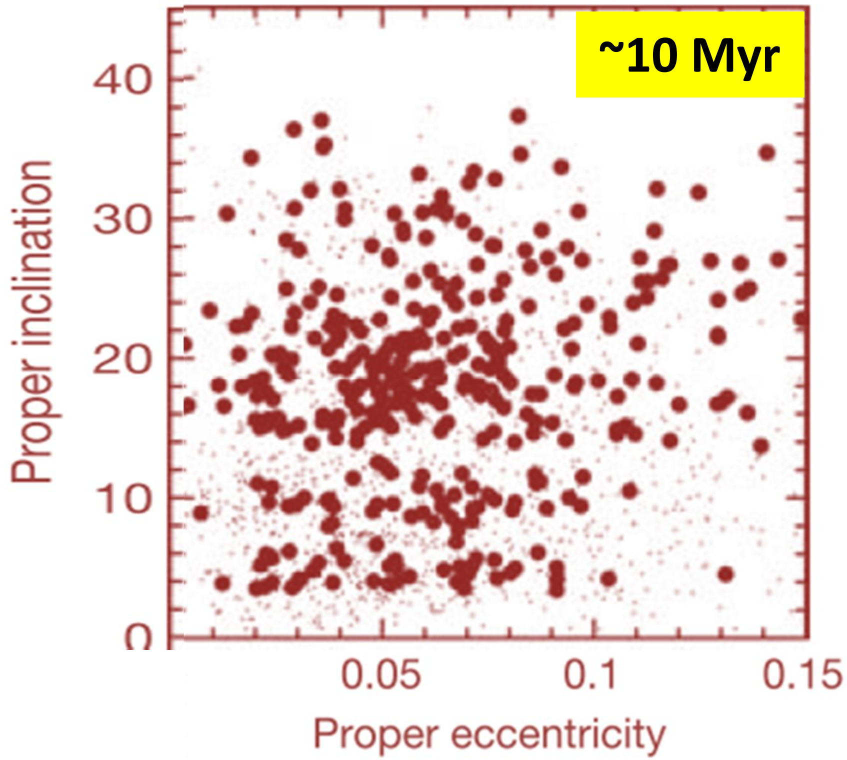
★ **About 15-25% of the entire TNO population** (Petit et al. 2011; Gladman et al. 2012)

★ **3:2 and 5:2 are the most populous!**

1:1 MMRs (Jupiter Trojans)



(Lykawka & Horner 2010)

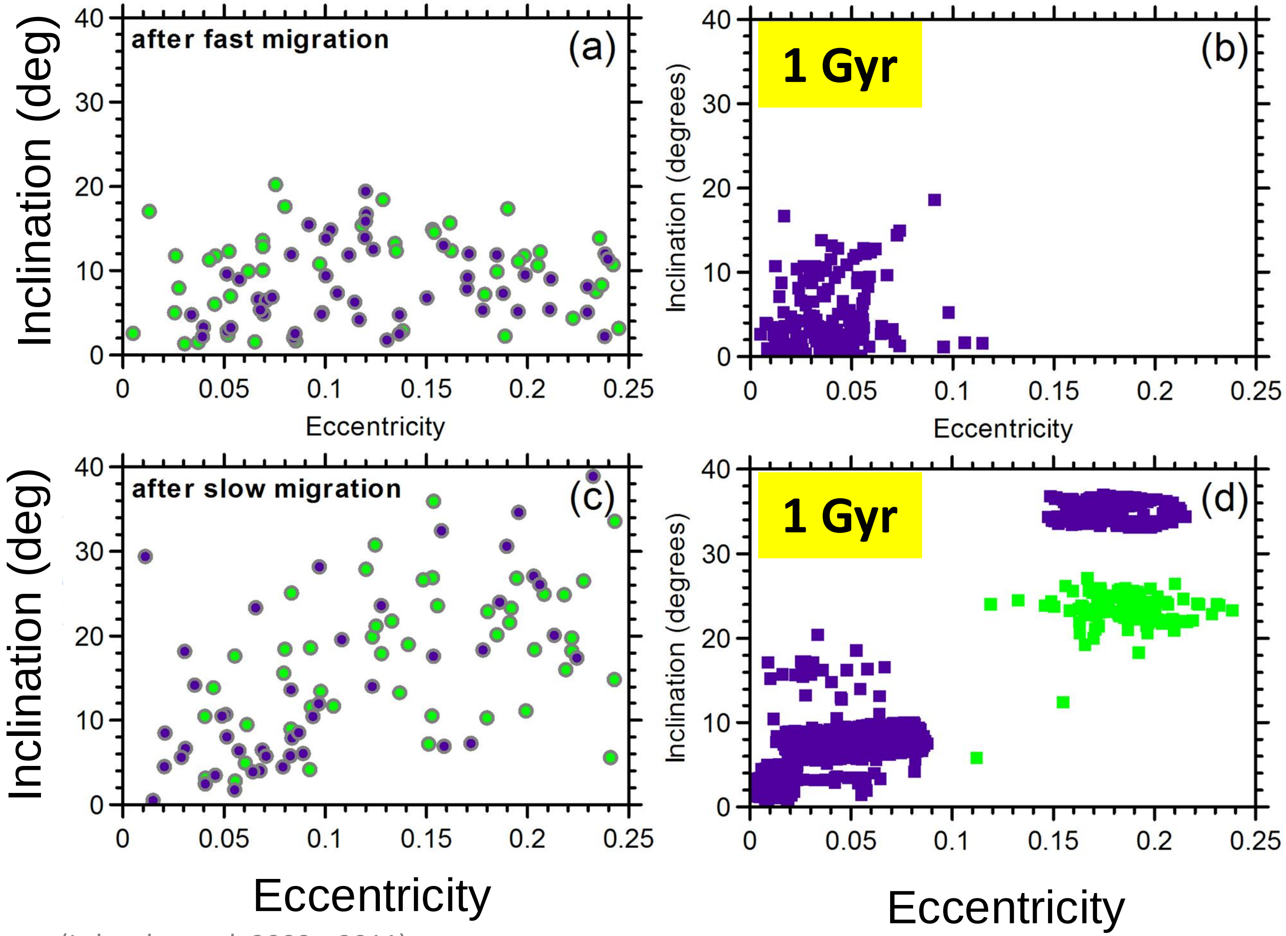


(adapted from Morbidelli et al. 2005
Similar results also in Nesvorny et al. 2013)

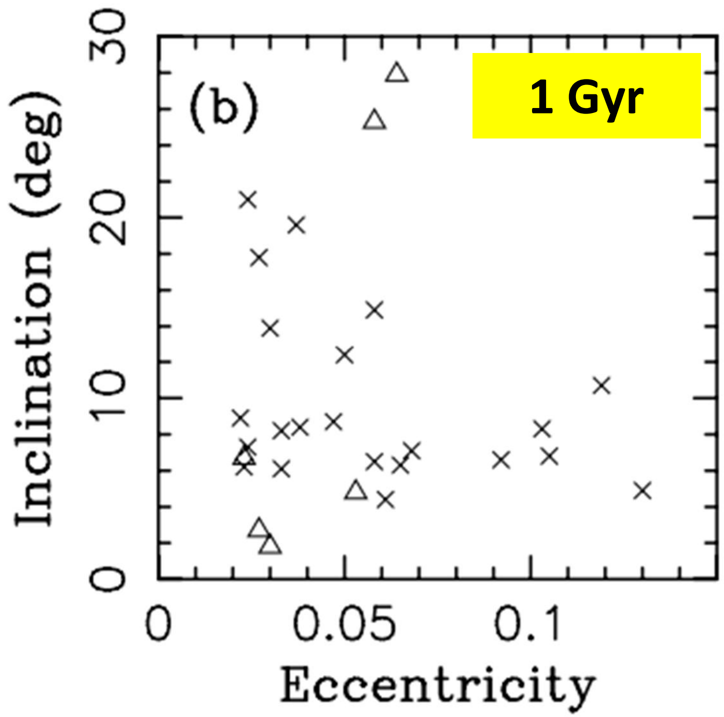
★ **Approximately 25% of captured Jupiter Trojans survived 4 Gyr**

Links Jupiter (Trojans) science with the primordial Kuiper belt

1:1 MMRs (Neptune Trojans)



(Lykawka et al. 2009 - 2011)



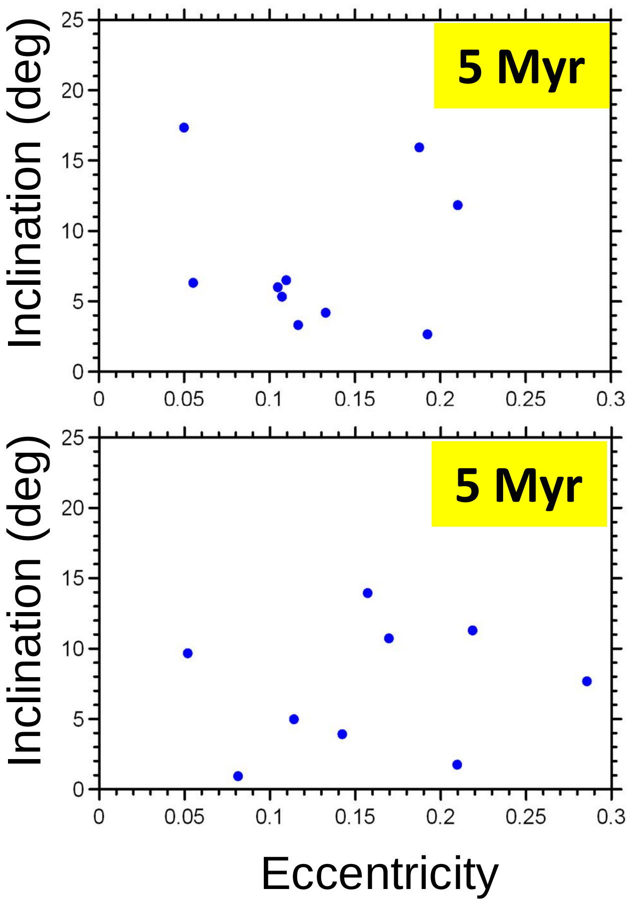
(Nesvorny & Vokrouhlicky 2009)

★ **Approximately 1-5% of captured Neptune Trojans survived 4 Gyr**

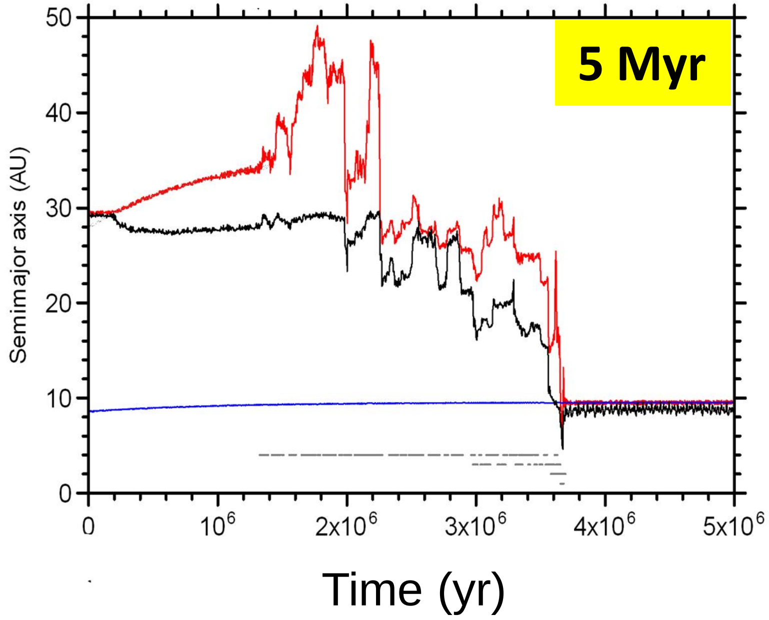
Links Neptune (Trojans) science with the primordial Kuiper belt

1:1 MMRs (Saturn and Uranus Trojans)

Captured Uranus Trojans

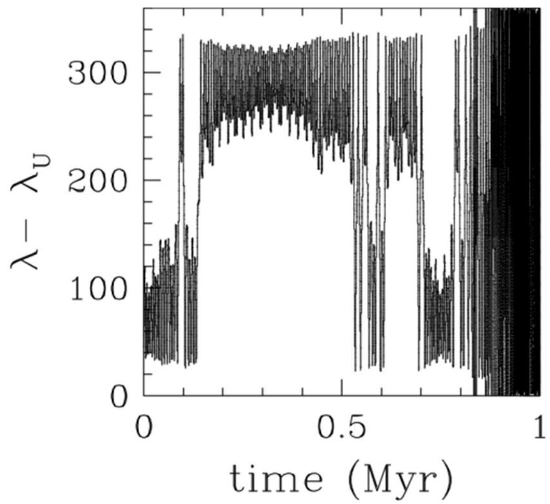


Captured Saturn Trojan



Lykawka & Horner (2010)

First Uranian Trojan



(Alexandersen et al. 2013)

★ **Saturn and Uranus were able to capture a significant population of Trojan objects after planet migration**

What happened to captured Trojans of the four giant planets?

Table 2. Capture of Trojans by the giant planets at the end of planetary migration.

Planet	$\varepsilon_{\min}$[a]	$\varepsilon_{\max}$[a]	$M_{\min}$ $(M_{\oplus})$[b]	$M_{\max}$ $(M_{\oplus})$[b]
Jupiter	$5 \cdot 10^{-6}$	$5 \cdot 10^{-5}$	$3 \cdot 10^{-5}$	$2 \cdot 10^{-4}$
Saturn	$<10^{-6}$	10^{-5}	$<8 \cdot 10^{-6}$	$6 \cdot 10^{-5}$
Uranus	$5 \cdot 10^{-5}$	$5 \cdot 10^{-4}$	$6 \cdot 10^{-4}$	$7 \cdot 10^{-3}$
Neptune	$3 \cdot 10^{-4}$	10^{-3}	$4 \cdot 10^{-3}$	$2 \cdot 10^{-2}$

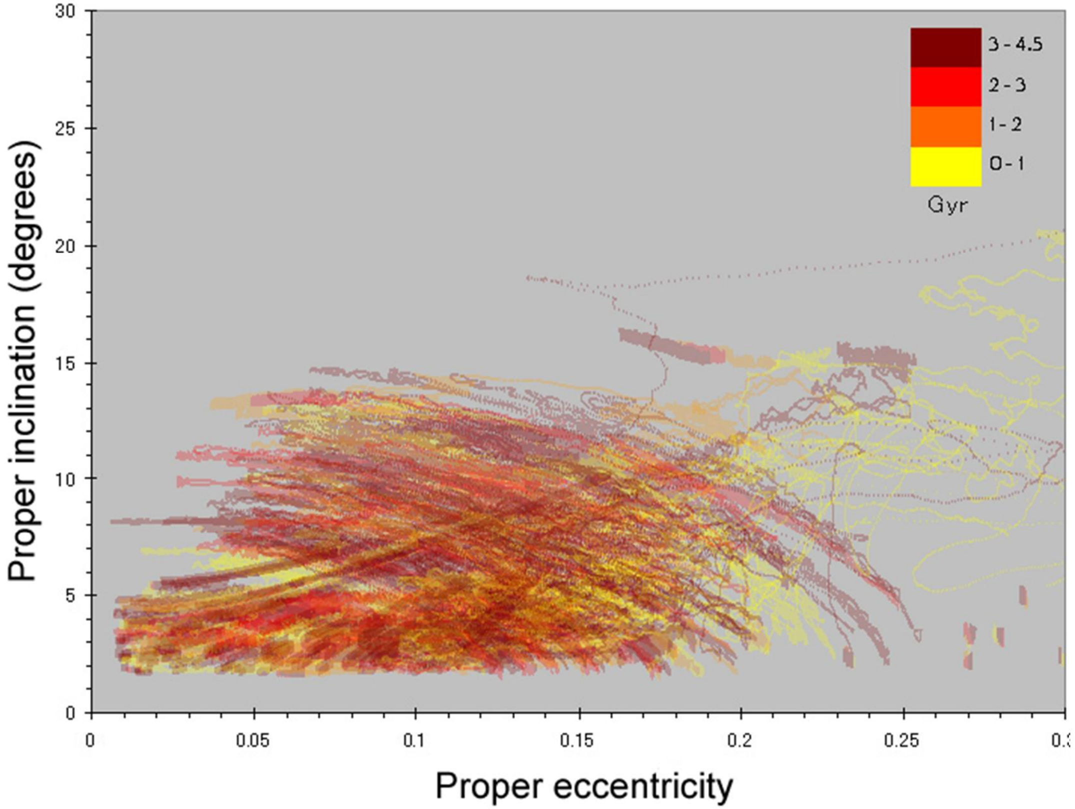
[a]Minimum and maximum capture efficiencies ($\varepsilon_{\min}$, $\varepsilon_{\max}$). These calculations assume that a mass of between 13 and 25 $M_{\oplus}$ of material was initially present in the planetesimal disk through which the giant planets migrated (based on Lykawka and Horner, 2010).

[b]Estimated minimum and maximum masses of the captured Trojan populations for each of the giant planets at the end of their migration.

Lykawka & Horner (2010)

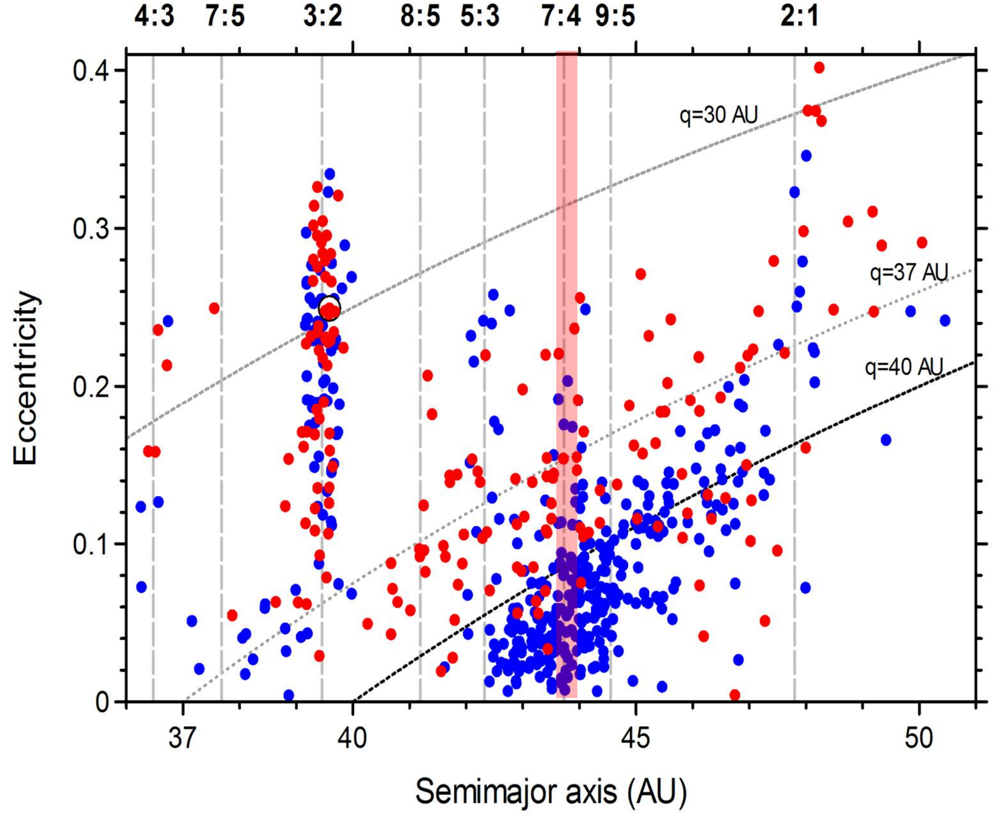
“weak” MMRs: rich dynamical evolutions

7:4 resonant theoretical classical objects



(Lykawka & Mukai 2005)

MMRs in the classical region



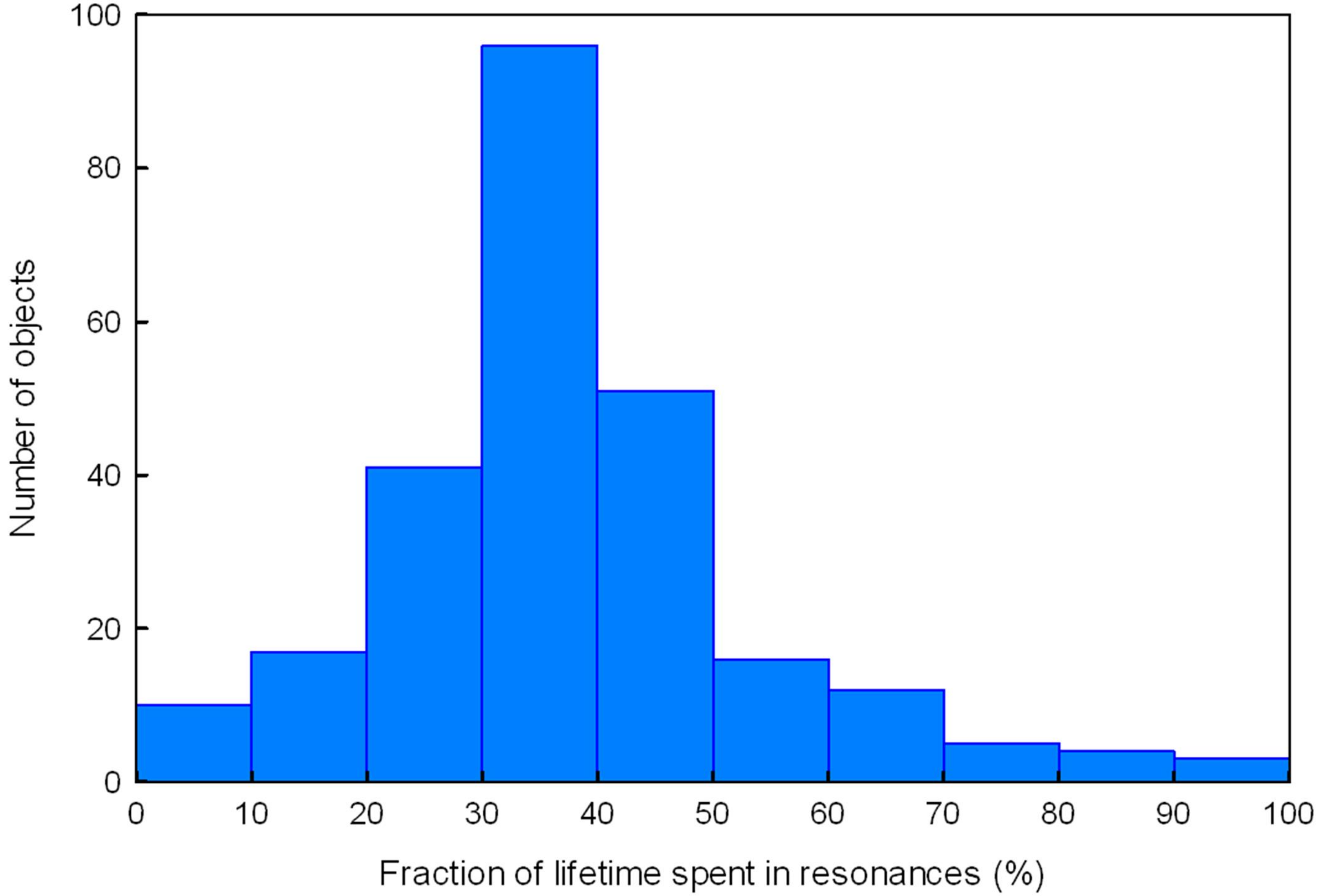
(Volk & Malhotra 2011)

★ **MMRs in the classical region define the fine structure and affect stability in the same region**

e.g., complex evolution of classical objects within the 7:4 MMR

☆ **“weak” MMRs also play an important role!**

"weak" MMRs (2): resonance sticking



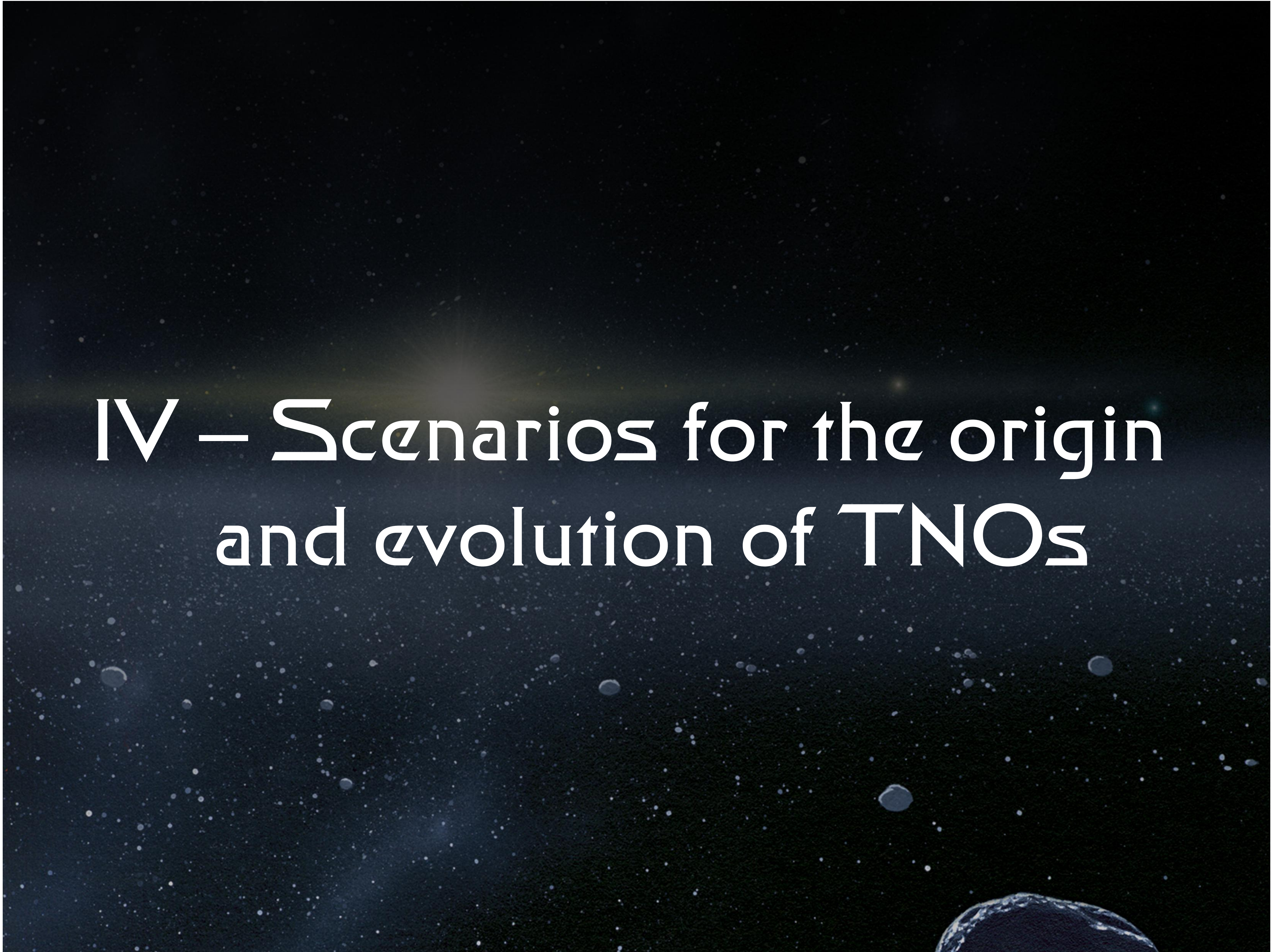
(Lykawka & Mukai 2007c)

★ Scattered objects spend on average 38% of lifetimes locked in MMRs

★ N:1, N:2, and N:3 resonances dominate the dynamics with 100-1000 Myr captures (Kozai mechanism also common) (Fernandez et al. 2004; Gomes 2005; Gallardo 2006a,b; 2012)

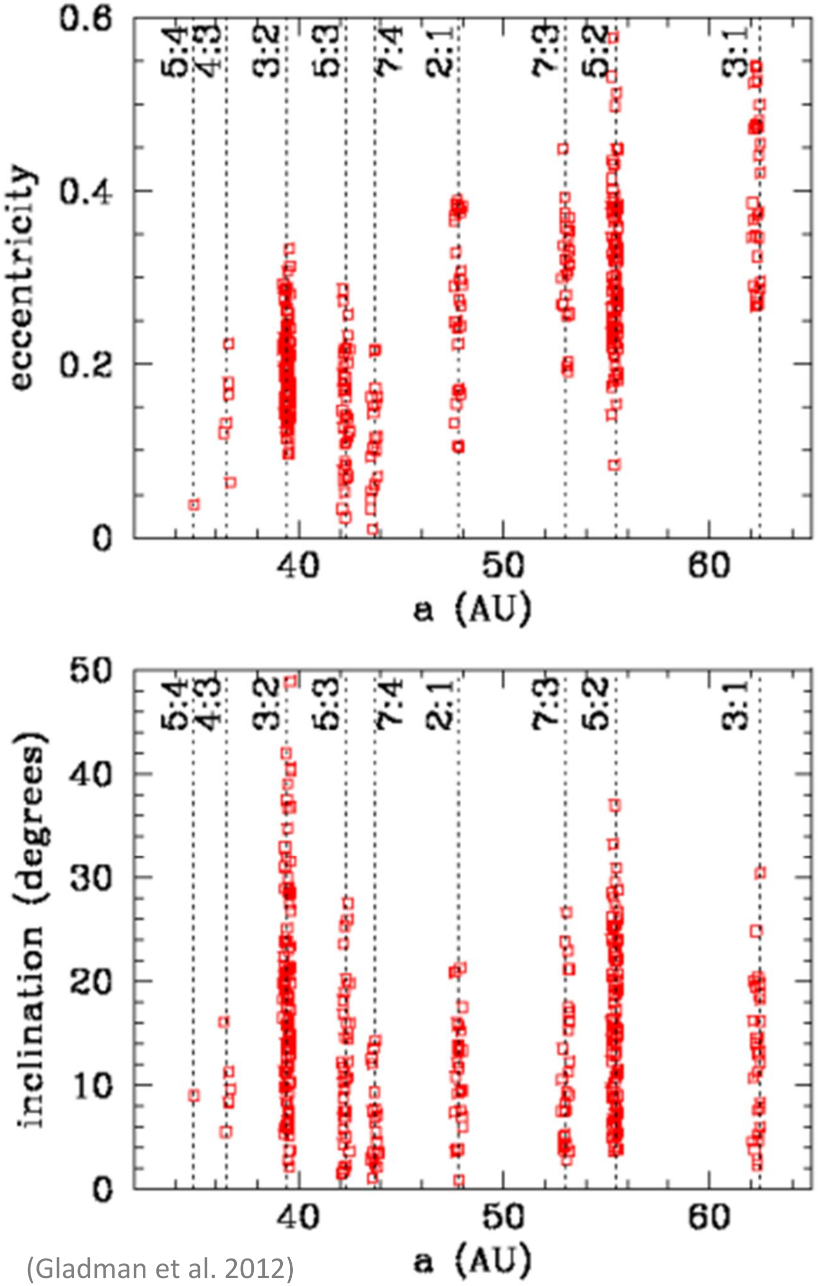
☆ Suggests a SD consisting of scattering(ed) + resonant populations

IV – Scenarios for the origin and evolution of TNOs



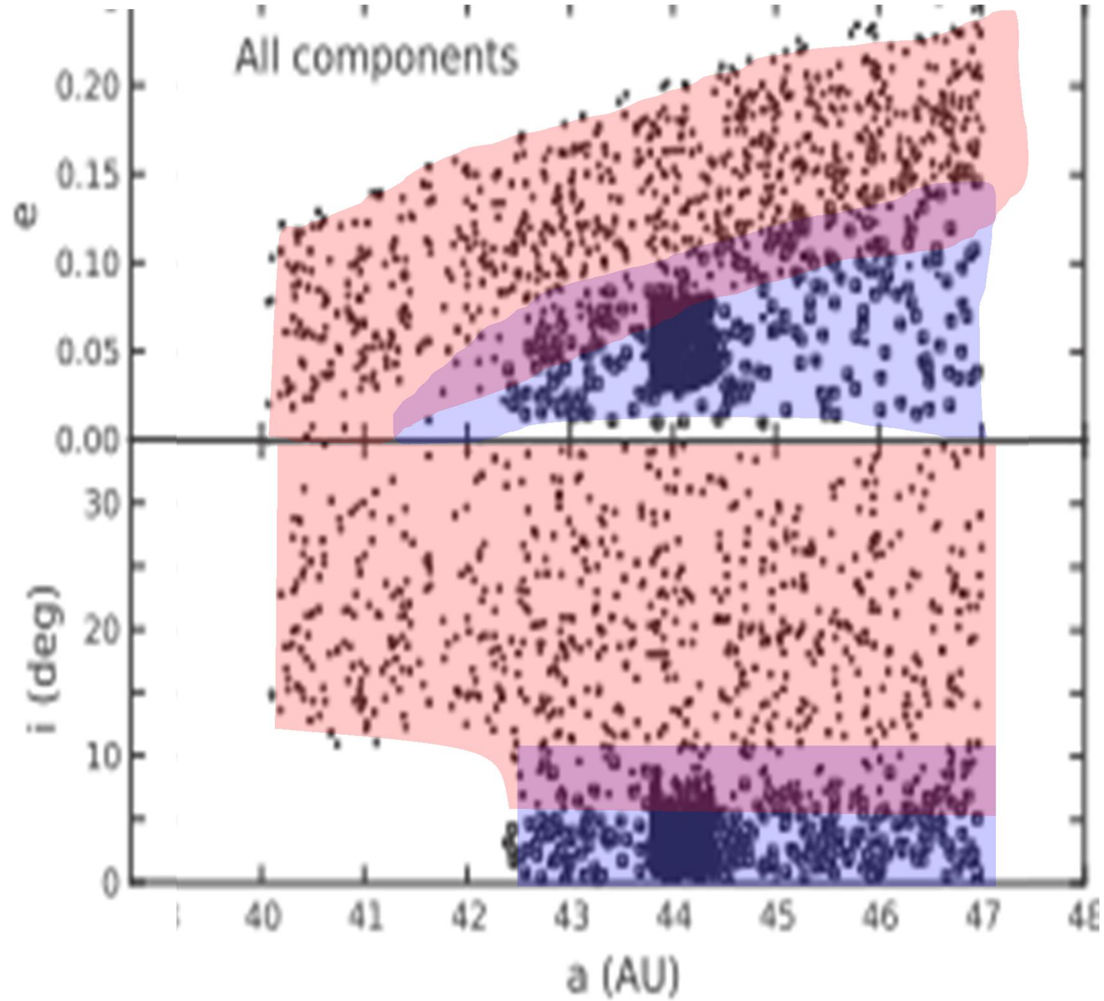
Intrinsic resonant and classical populations

Debiased resonant and classical structures (CFEPS)



(Gladman et al. 2012)

COLD and HOT



(Petit et al. 2011;
Gladman et al. 2012)

Planet migration

(Fernandez & Ip 1984; Malhotra 1995; Hahn & Malhotra 1999; Hahn & Malhotra 2005; Levison et al. 2007; Kirsh et al. 2009; Campobianco et al. 2011)

Chaotic orbital evolution during Stage ②:

Much faster timescales than smooth-residual migration

Possible "instantaneous" capture of planetesimals in resonances

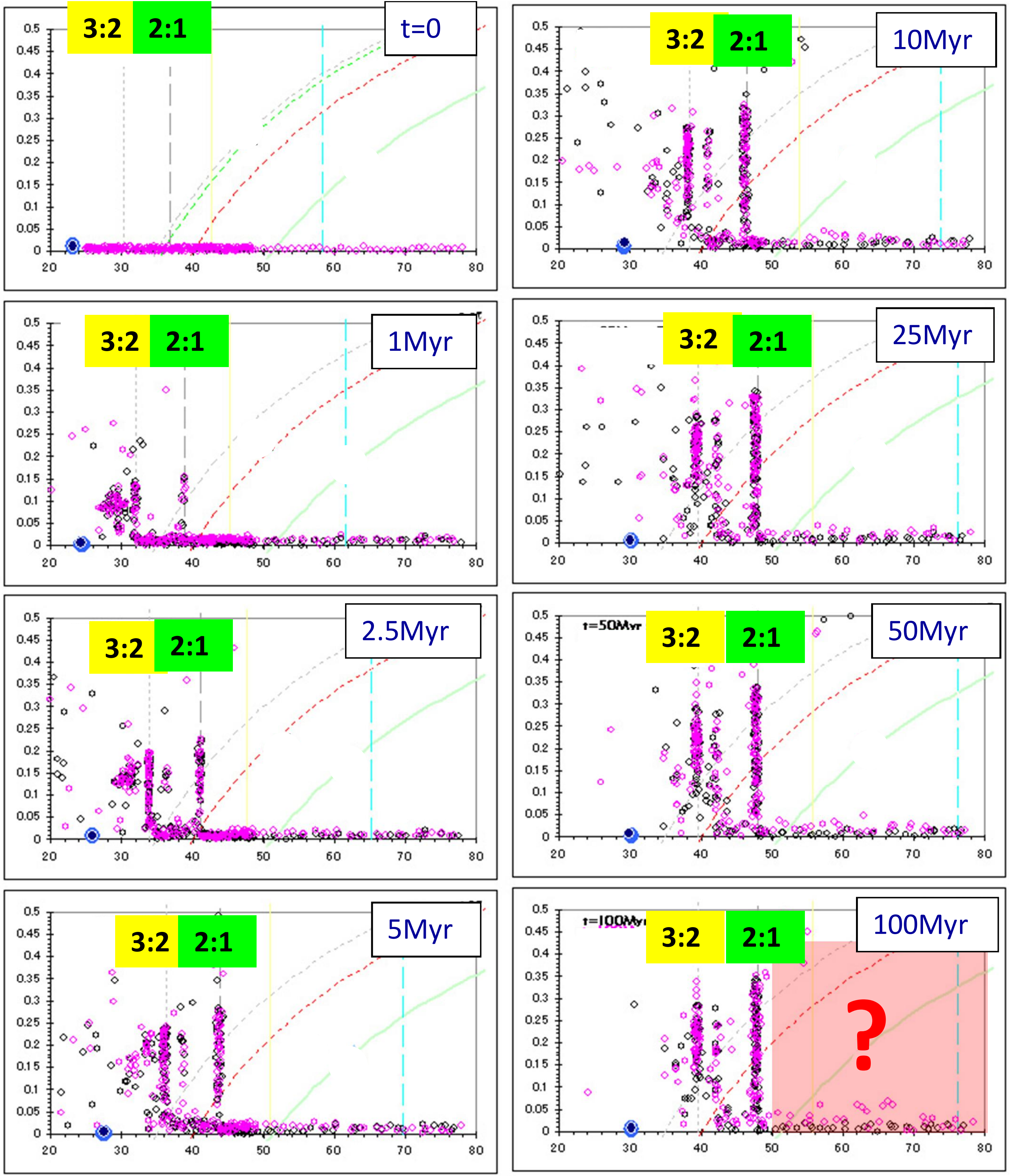
Smooth (residual) migration during Stage ③:

Often modeled as an exponential migration

$$\boxed{a_P(t) = a_i - \Delta a_P \cdot \exp(-t/\tau)}$$

$$a_{res} = a_N \left(\frac{j+k}{j} \right)^{\frac{2}{3}}$$

Neptunian sweeping resonances can capture planetesimals



Planet migration

Migration over a dynamically cold disk

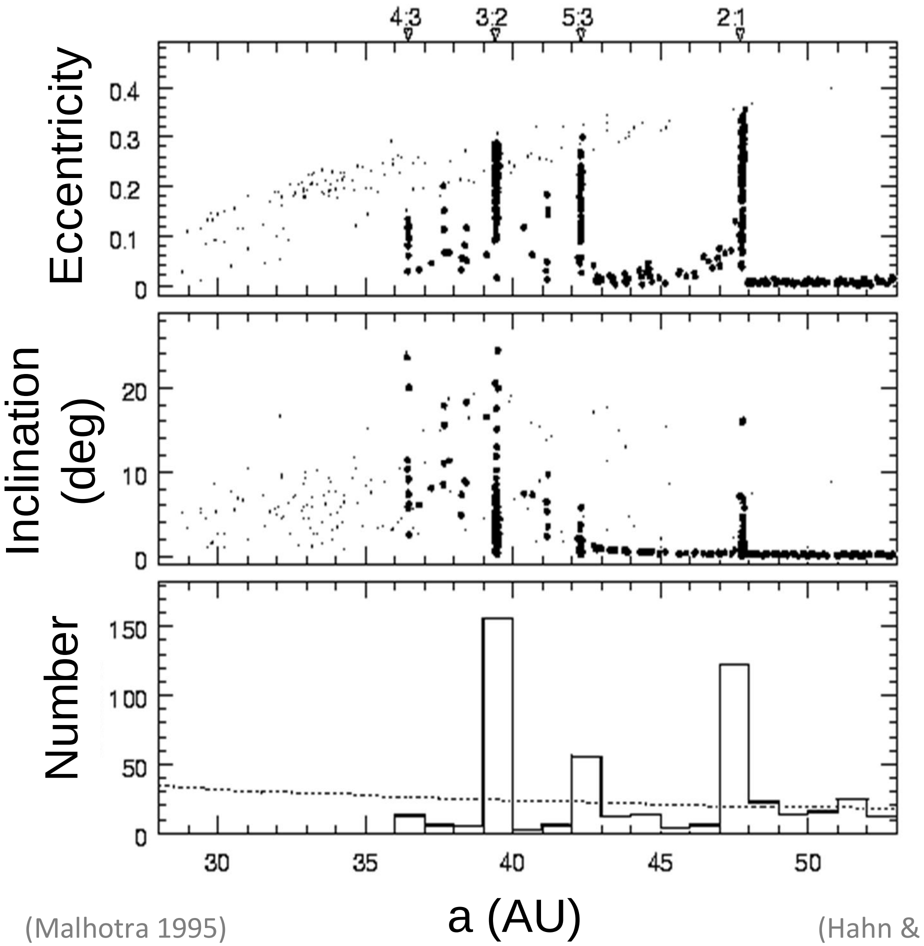
(Malhotra 1995; Hahn & Malhotra 1999; Chiang & Jordan 2002)

★ In low-order resonances (3:2, 2:1, 5:3, etc), capture probability is high for planetesimals on initially low-e orbits

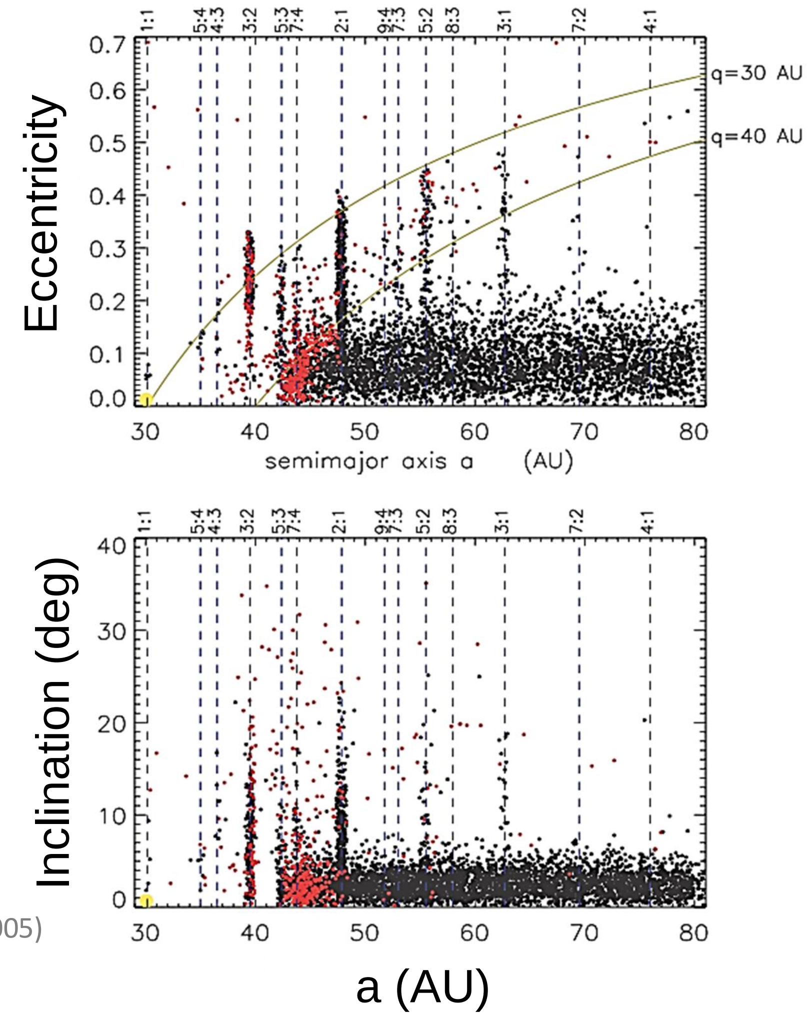
Origin of resonant TNOs: planet migration

Initially cold disk

Initially hot disk



(Malhotra 1995)

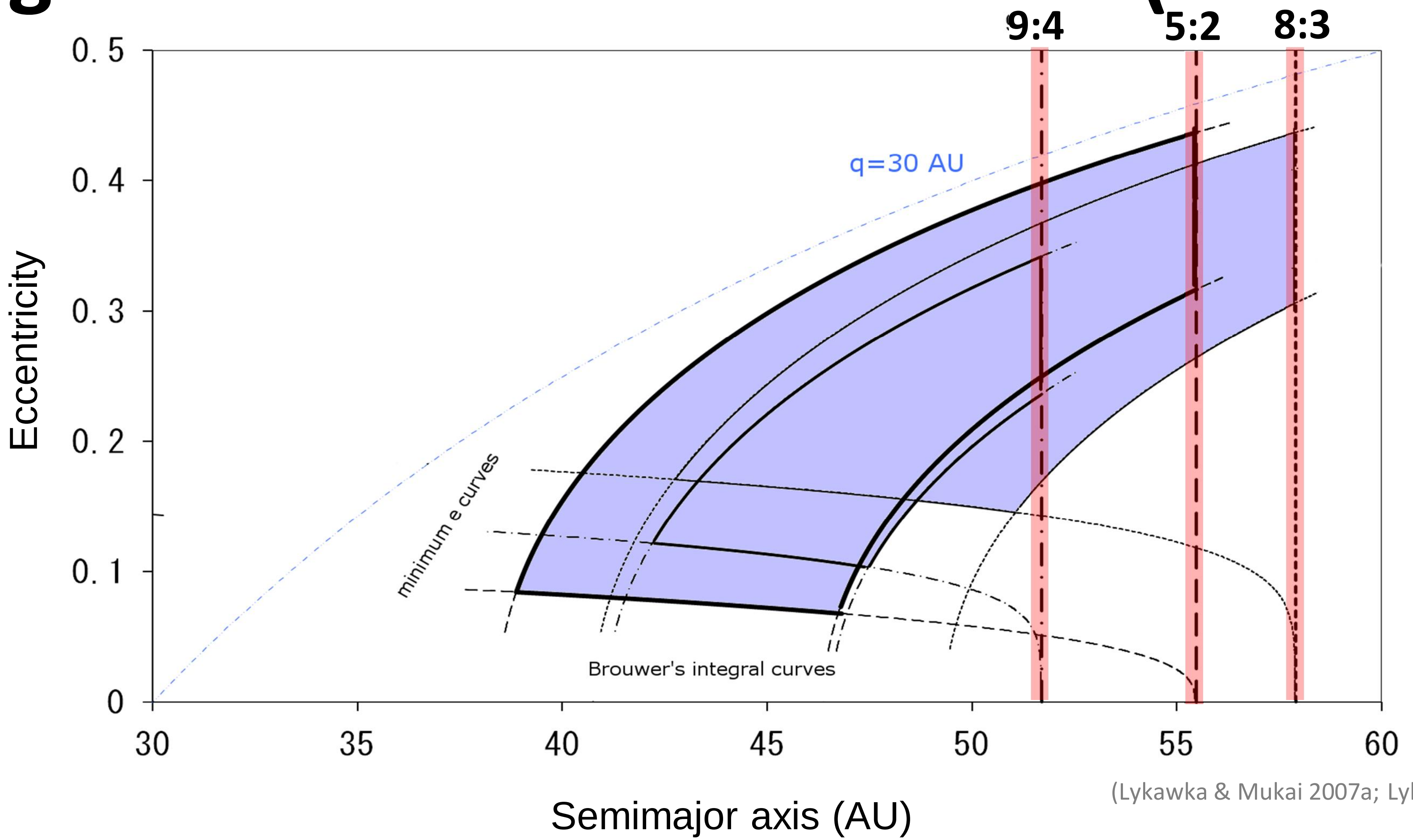


(Hahn & Malhotra 2005)

★ **Resonant TNOs partially reproduced, even beyond 50 AU (for an initially hot disk)**

(Chiang et al. 2003)

Origin of distant resonant TNOs (a > 50 AU)



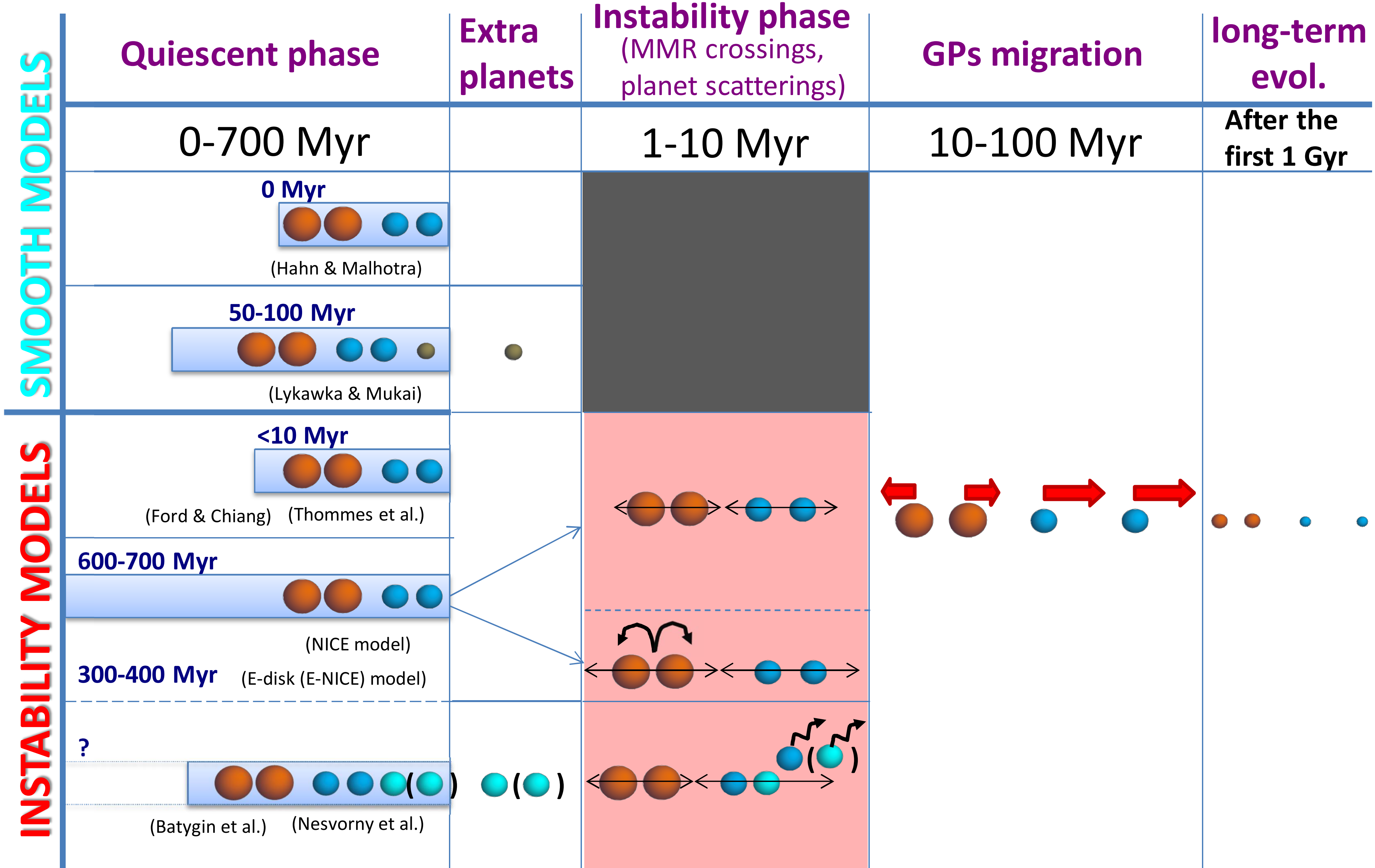
(Lykawka & Mukai 2007a; Lykawka 2012)

★ **Resonance sticking cannot explain all stable populations, but capture during planet migration can. However, populous 5:2 MMR and possibly the 5:1 MMR represent outstanding challenges**

(Lykawka & Mukai 2007a; Dawson & Murray-Clay 2012; Gladman et al. 2012)

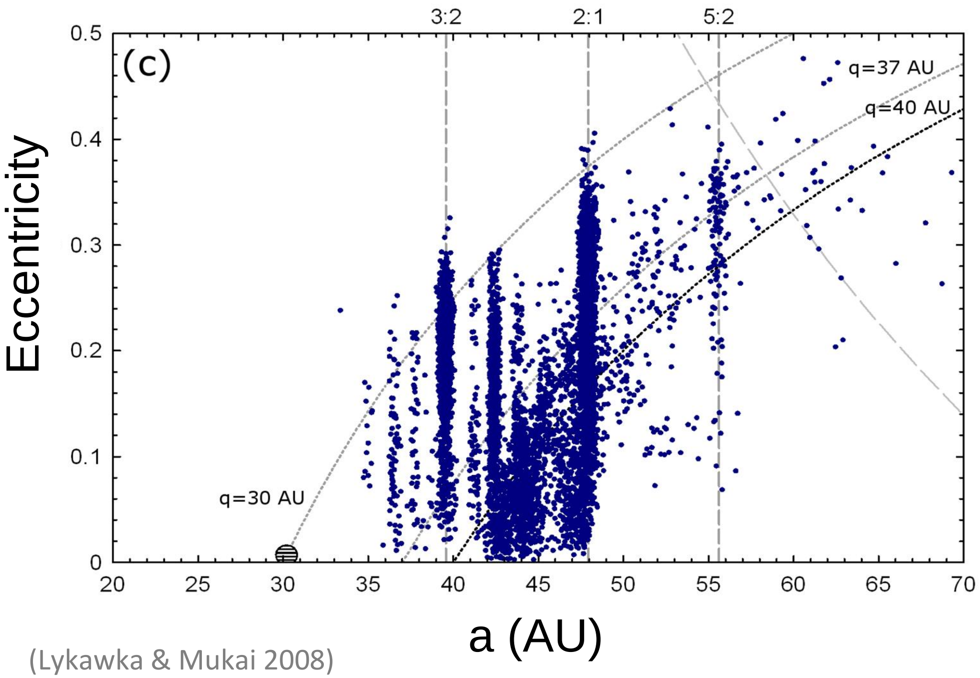
☆ **Pre-excited Kuiper belt likely required**

Summary of main models proposed



Smooth models (4GPs + 1EP)

(Lykawka & Mukai 2008)



(Lykawka & Mukai 2008)

★ Cold population and partial hot population insitu; remaining hot classicals deposited from inner regions of the planetesimal disk (< 30 AU)

★ Trojan populations partially ok

★ Detached objects ok

❓ Cold population too massive

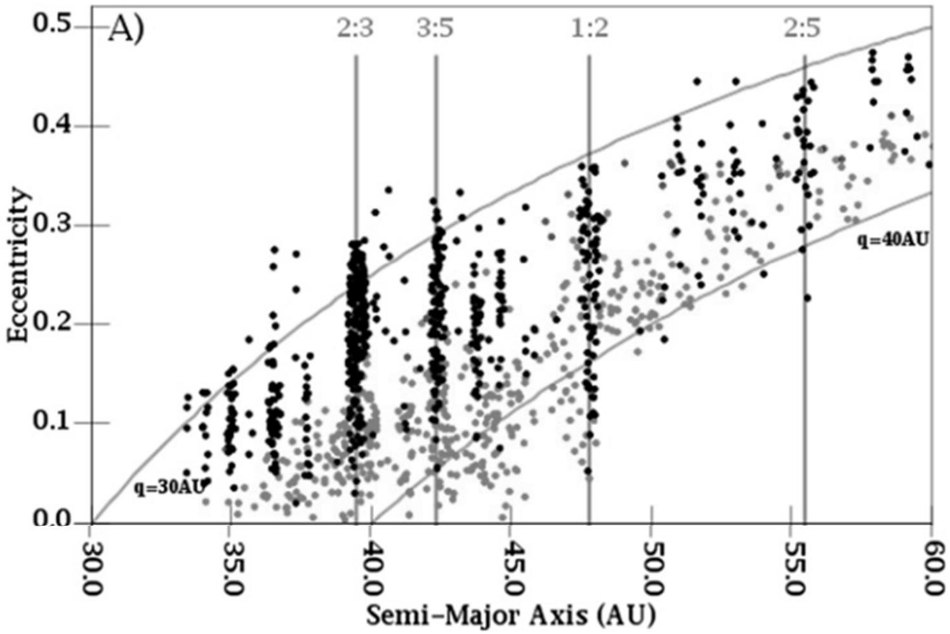
❓ Lack of high-i classicals and high-i Trojans

❓ More distant resonant population (>60 AU) unclear

❓ Difficult to reconcile with giant planet formation/evolution

Instability models: Nice model

(Tsiganis *et al.* 2005; Morbidelli *et al.* 2005; Gomes *et al.* 2005
Morbidelli et al. 2007, 2010; Levison et al. 2008)



(Levison et al. 2008)

★ Both cold population and hot populations deposited from inner regions of the planetesimal disk (< 30 AU)

★ Trojan populations partially ok

❓ Severe lack of cold classicals

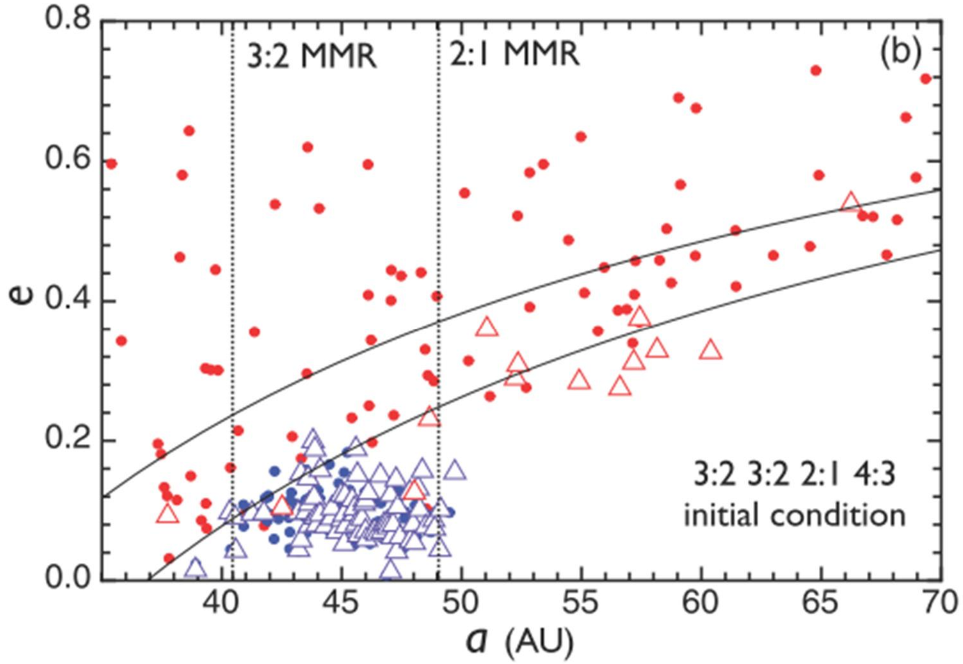
❓ Lack of high-i classicals and high-i Trojans

❓ Distant resonant population unclear

❓ Detached objects unclear

Instability models: multiplanet

(Nesvorny 2011; Batygin et al. 2012; Nesvorny & Morbidelli 2012)



(Batygin et al. 2012)

★ Cold population insitu and hot populations deposited from inner regions of the planetesimal disk (< 30 AU)

★ Classicals apparently ok

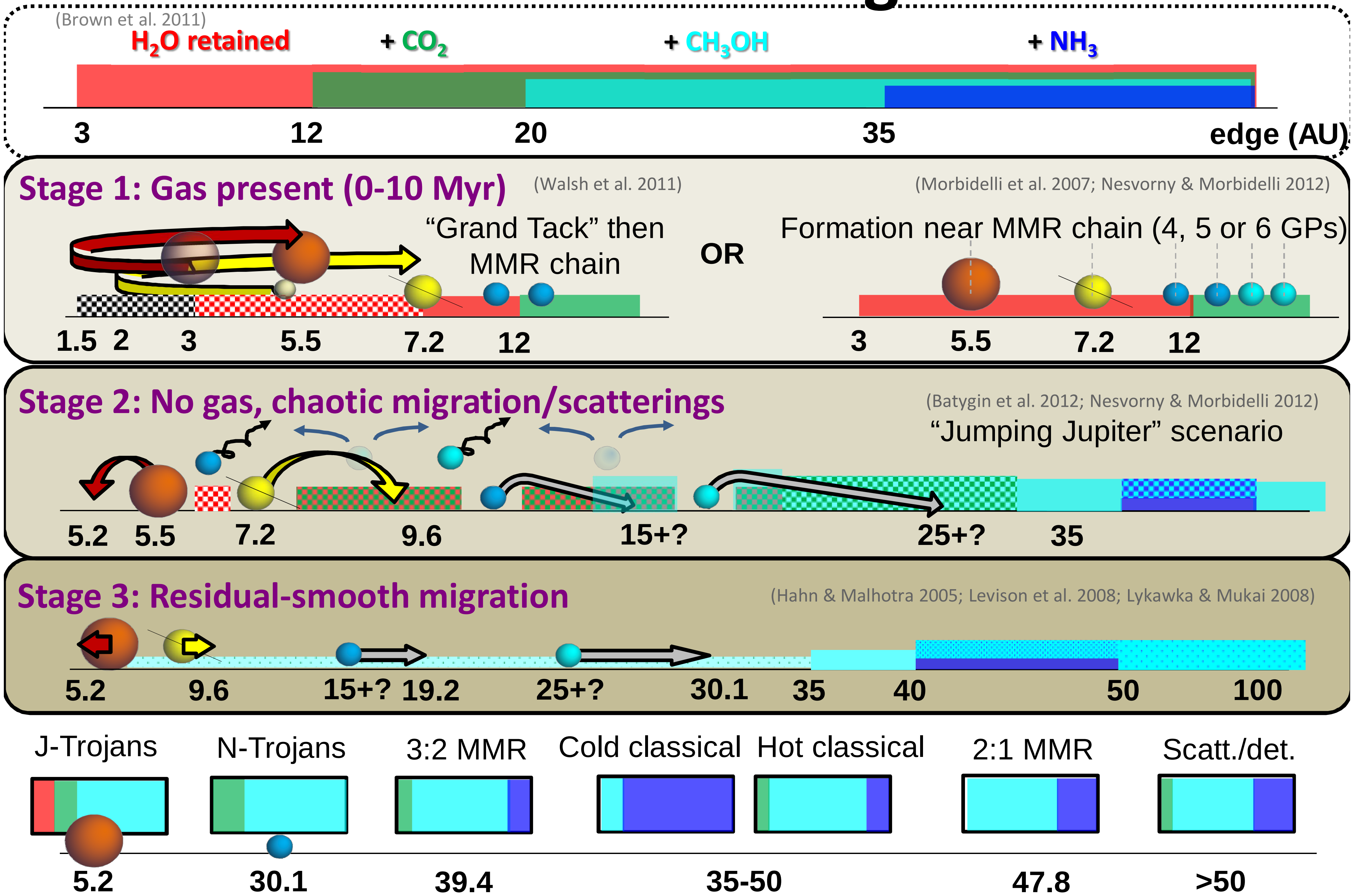
❓ Lack of high-i classicals

❓ Cold population structure unclear

❓ Resonant population may emerge if Neptune jumped to *a* = 24-27 AU and circularized quickly (< 1 Myr)

❓ Detached objects unclear

Models and the source regions of TNOs



V – Main conclusions

Summary

- **A complex orbital structure to be explained:** Classical (cold/hot/kernel), resonant (Trojans, KB and distant), scattering(ed), detached, peculiar TNOs and groupings

- **Resonant population extended to at least ~108 AU**
  - Stable niches strongly point to Neptune's migration over a dynamically pre-excited Kuiper belt
  - Resonance sticking and weak MMRs play an important role
  - Trojan populations and relative fractions of resonant TNOs likely to resolve migration behavior of Uranus and Neptune

- Some **new mechanism** is needed in modeling to account for Trojans and TNOs on high-i orbits (> 20 deg). Also, the dual nature of cold and hot classical TNOs with their fine orbital structure

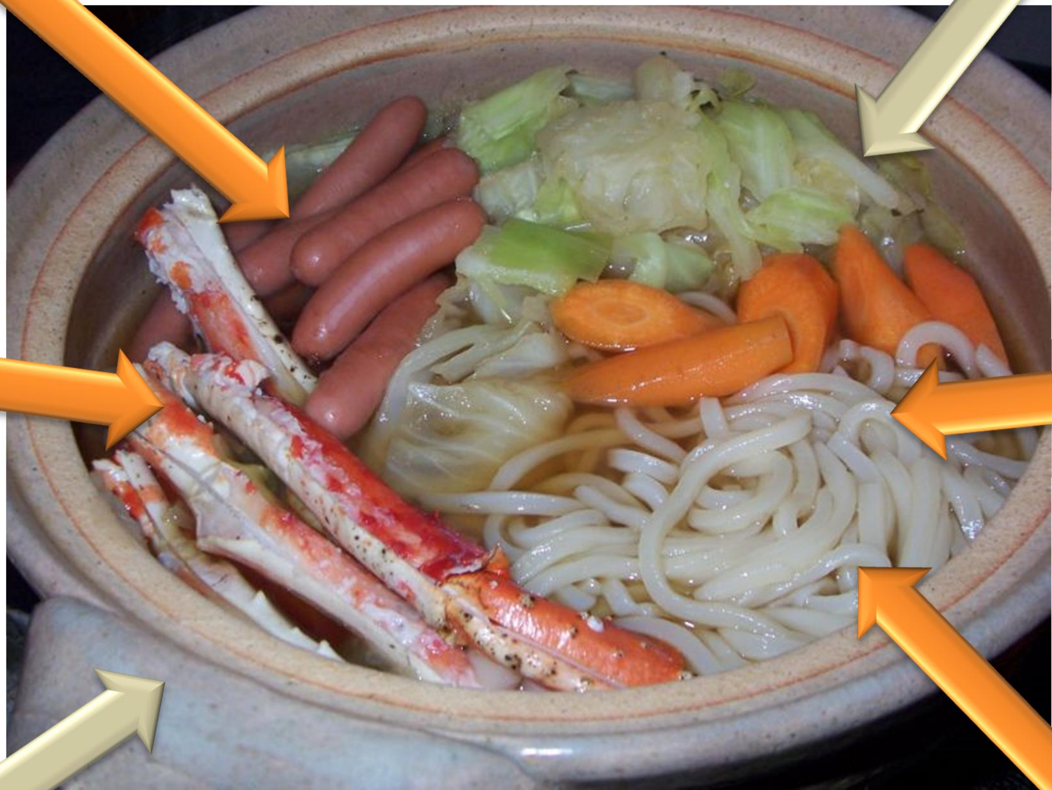
Future: instability-multiplanet models?

extra planets

10-100's of large planetesimals

4 giant planets

planet migration



The Outer Solar System NABE

collisions?

MMR crossings/
Planet-planet scatterings

FIM

皆さん、有難うございました!

E-mail: patryksan@gmail.com

Web: sites.google.com/site/patryksofialykawka/