A few points on the dynamical evolution of the young solar system

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- Kuiper belt & asteroid belt ⇒ extent, timescale of Jupiter-Neptune migration

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  - appears to be nearly incompatible with stability of terrestrial planets

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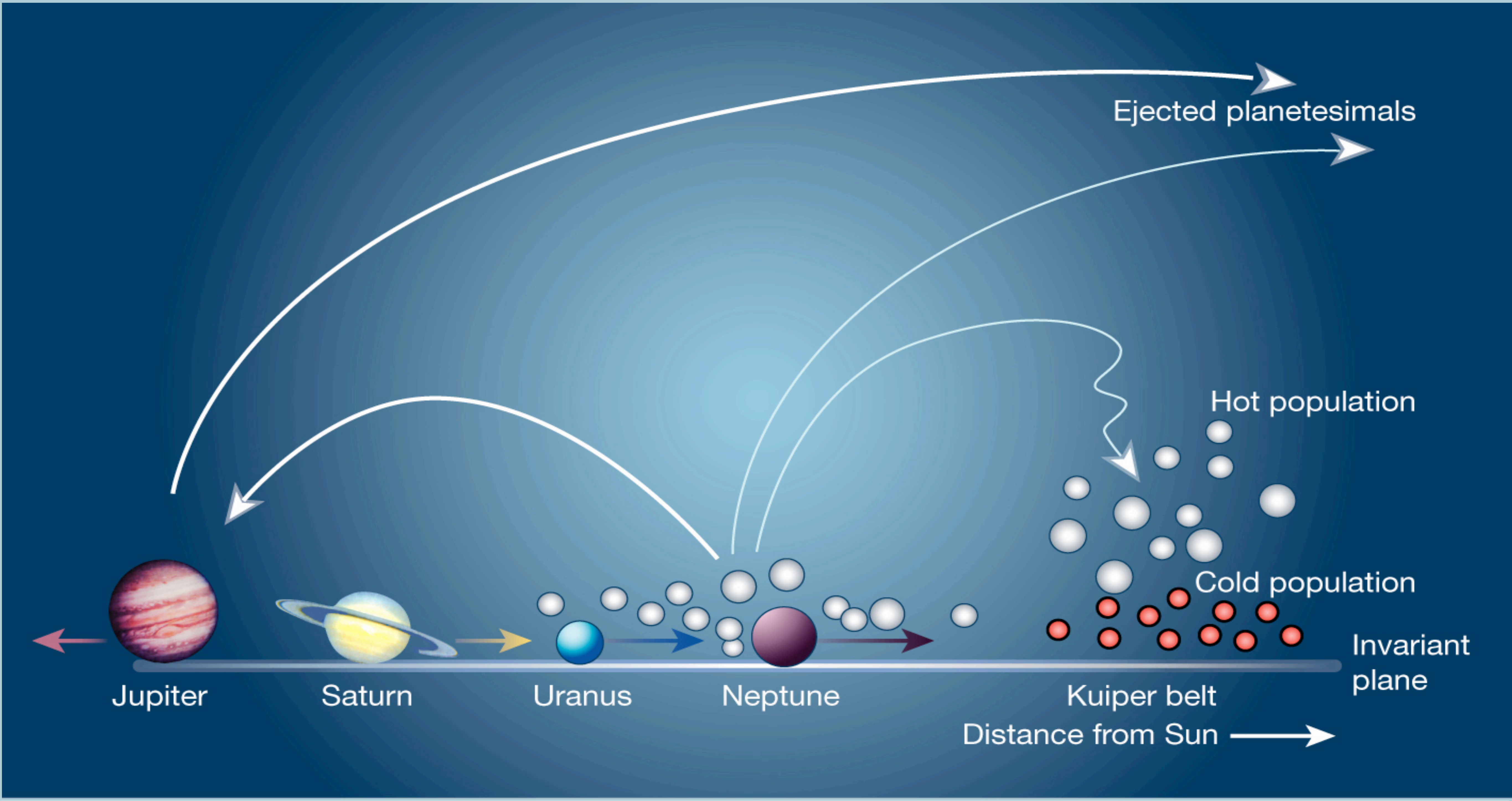
- ✦ Late stages of planet formation - planetesimal-driven migration
- ✦ Kuiper belt & asteroid belt ⇒ extent, timescale of Jupiter-Neptune migration
  - appears to be nearly incompatible with stability of terrestrial planets
  - how to save Earth ?

Jupiter,….,Neptune + trillions of leftover planetesimals ⇒ Jupiter migrates inward, Neptune migrates outward

Fernandez & Ip 1984



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The origin of Pluto's peculiar orbit

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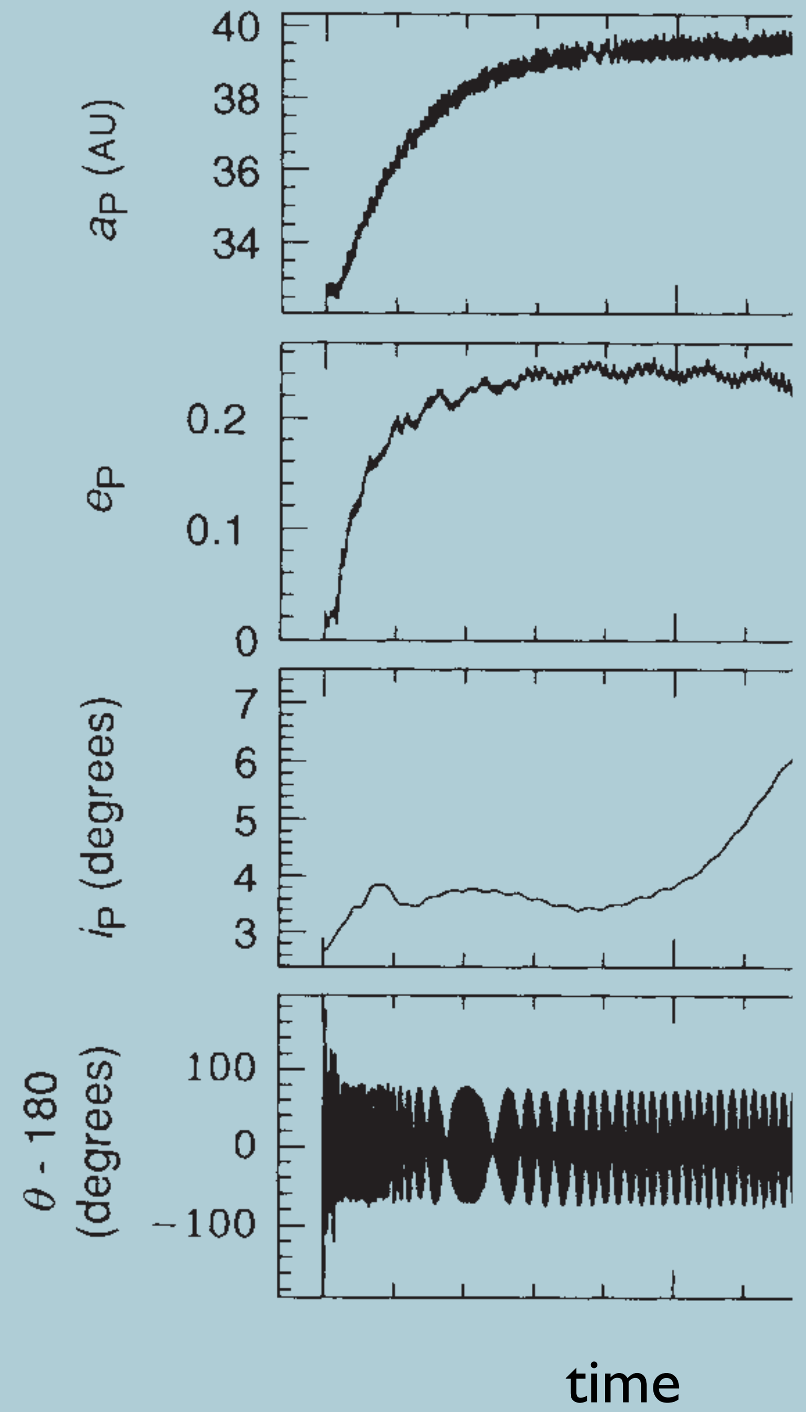
$$e^2_{\mathrm{P,final}} - e^2_{\mathrm{P,initial}} \approx \frac{1}{j+1} \ln\left(\frac{a_{\mathrm{N,final}}}{a_{\mathrm{N,initial}}}\right)$$

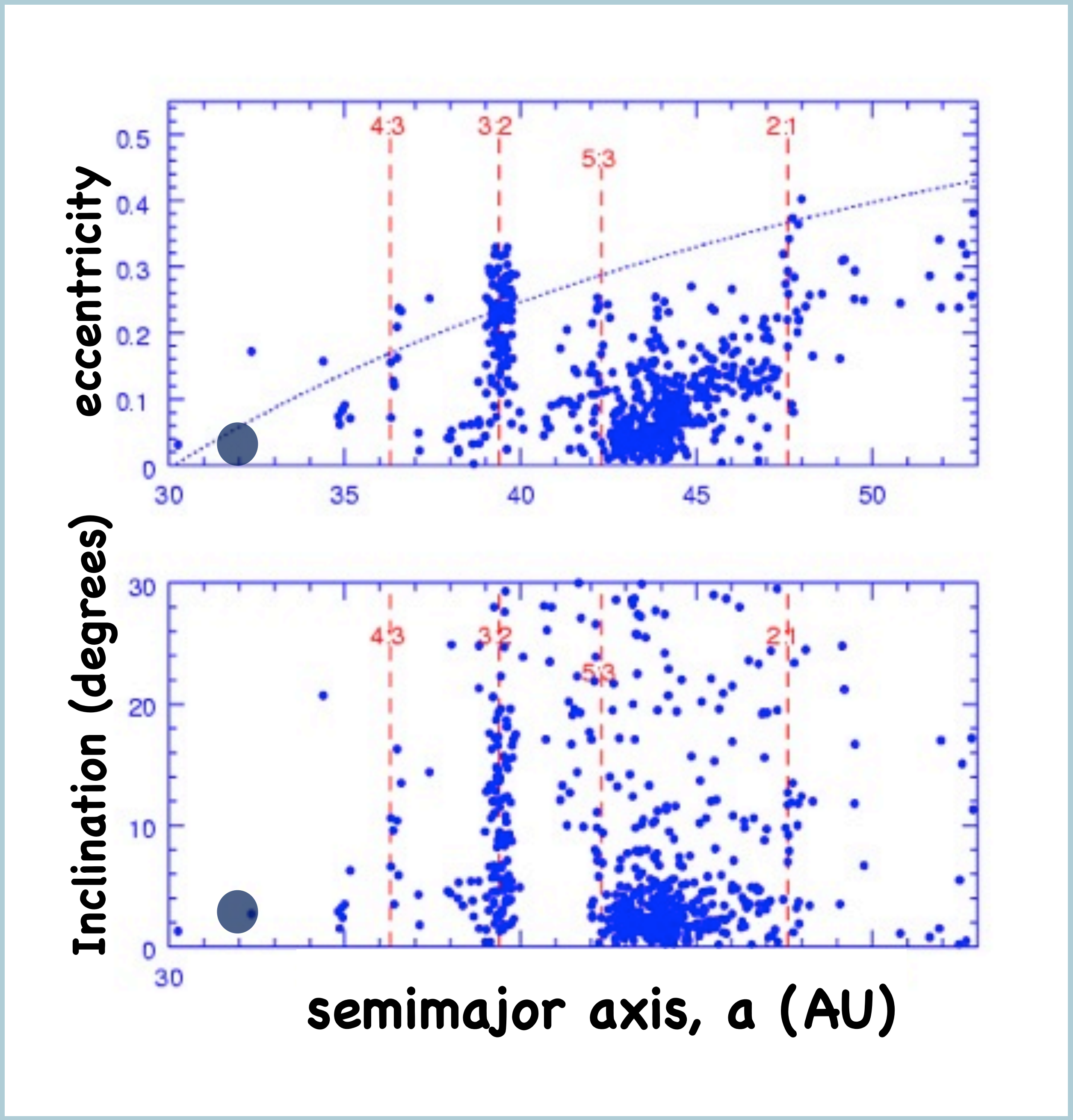
Pluto's resonance and eccentricity

Neptune's migration



$$e_p = 0.25 \Rightarrow \Delta a_N \gtrsim 5 \text{ AU}$$

More observational evidence in Kuiper Belt dynamical structure



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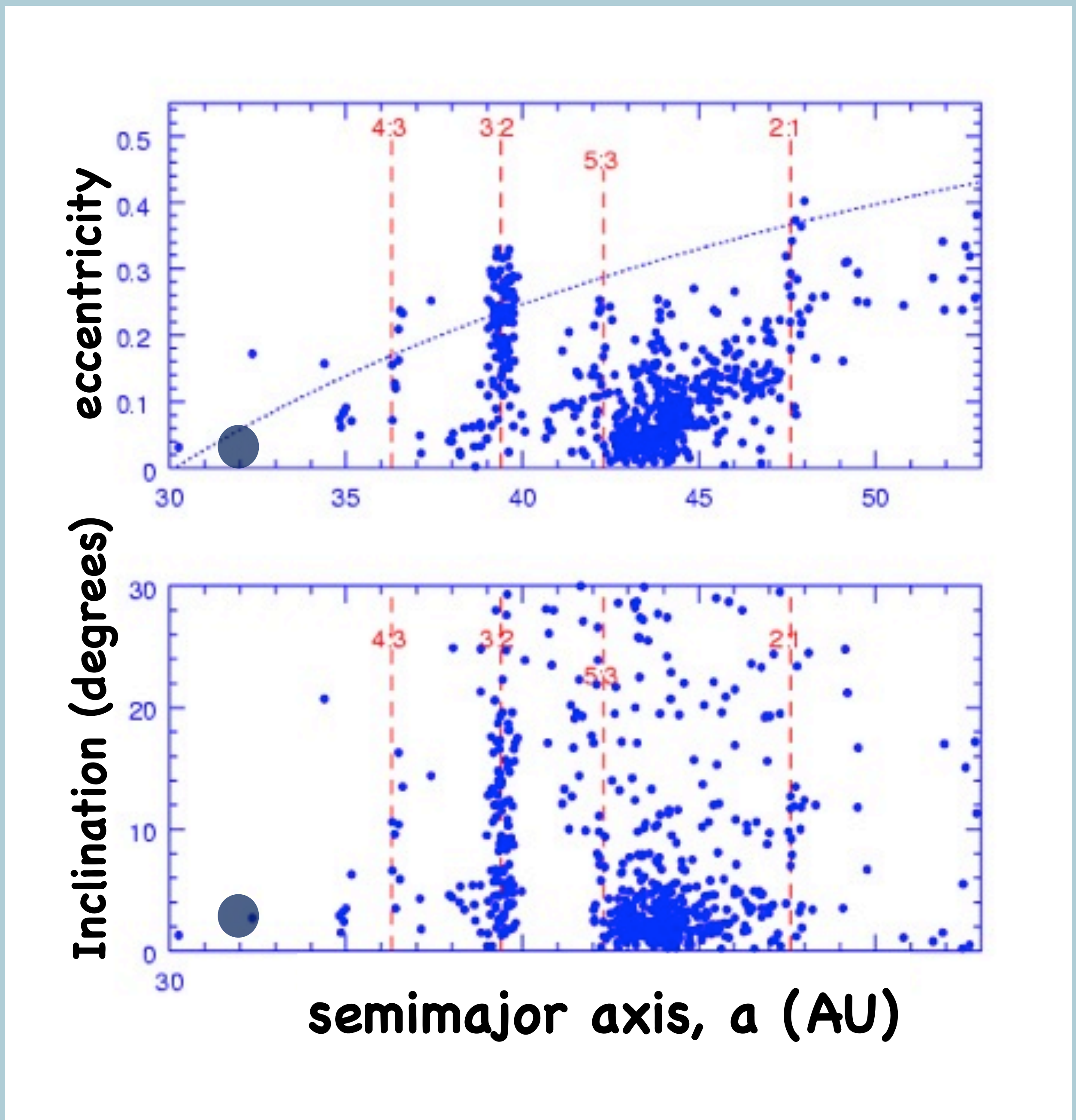
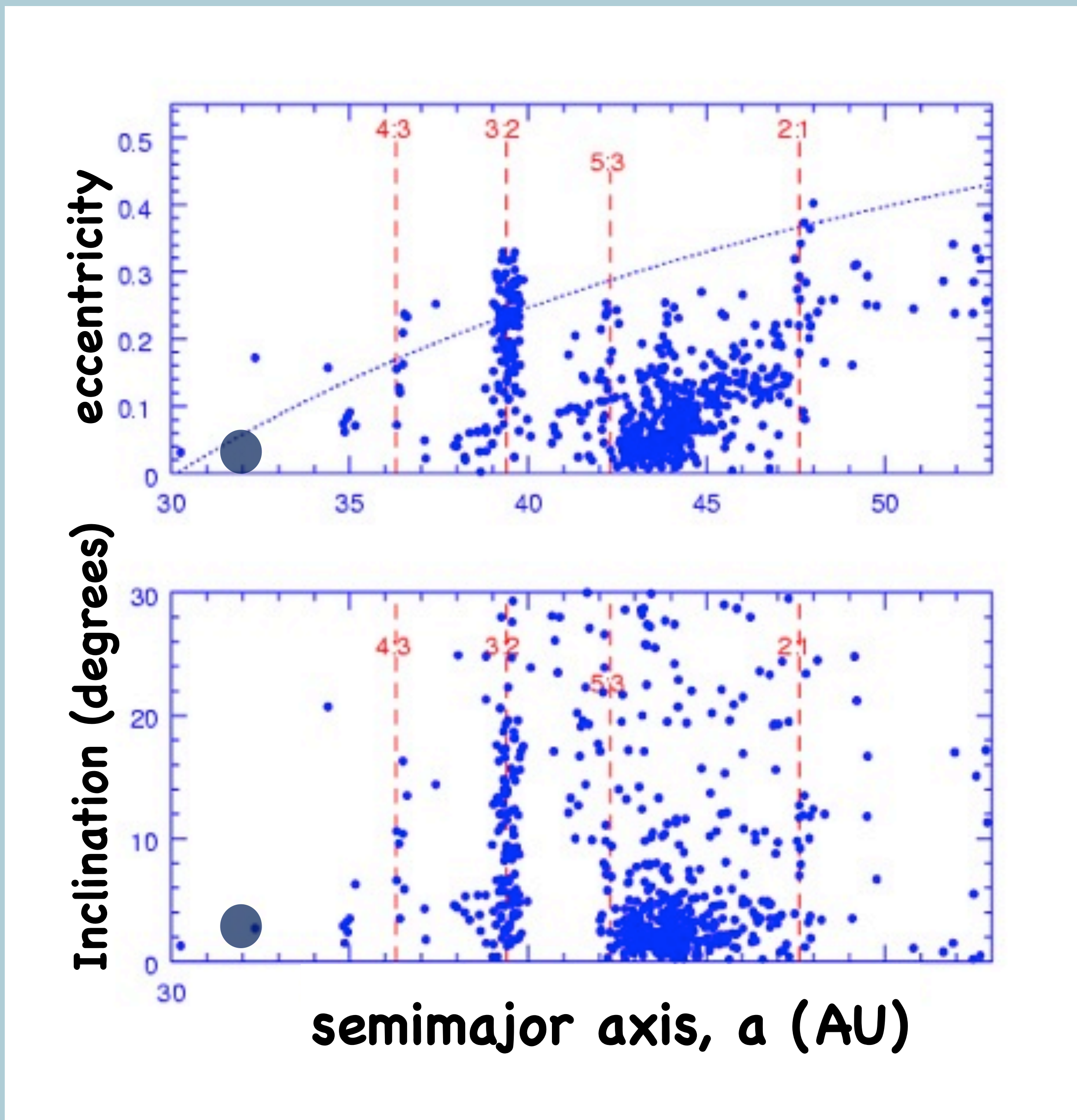


- resonances
- eccentricities
- inclinations

More observational evidence in Kuiper Belt dynamical structure



"Resonance sweeping" during outward migration of Neptune

- smooth migration
  - adiabatic invariant (3:2 MMR): $a^{1/2}[2-3(1-e^2)^{1/2}\cos i]$
  - Neptune migrated out ≳10AU

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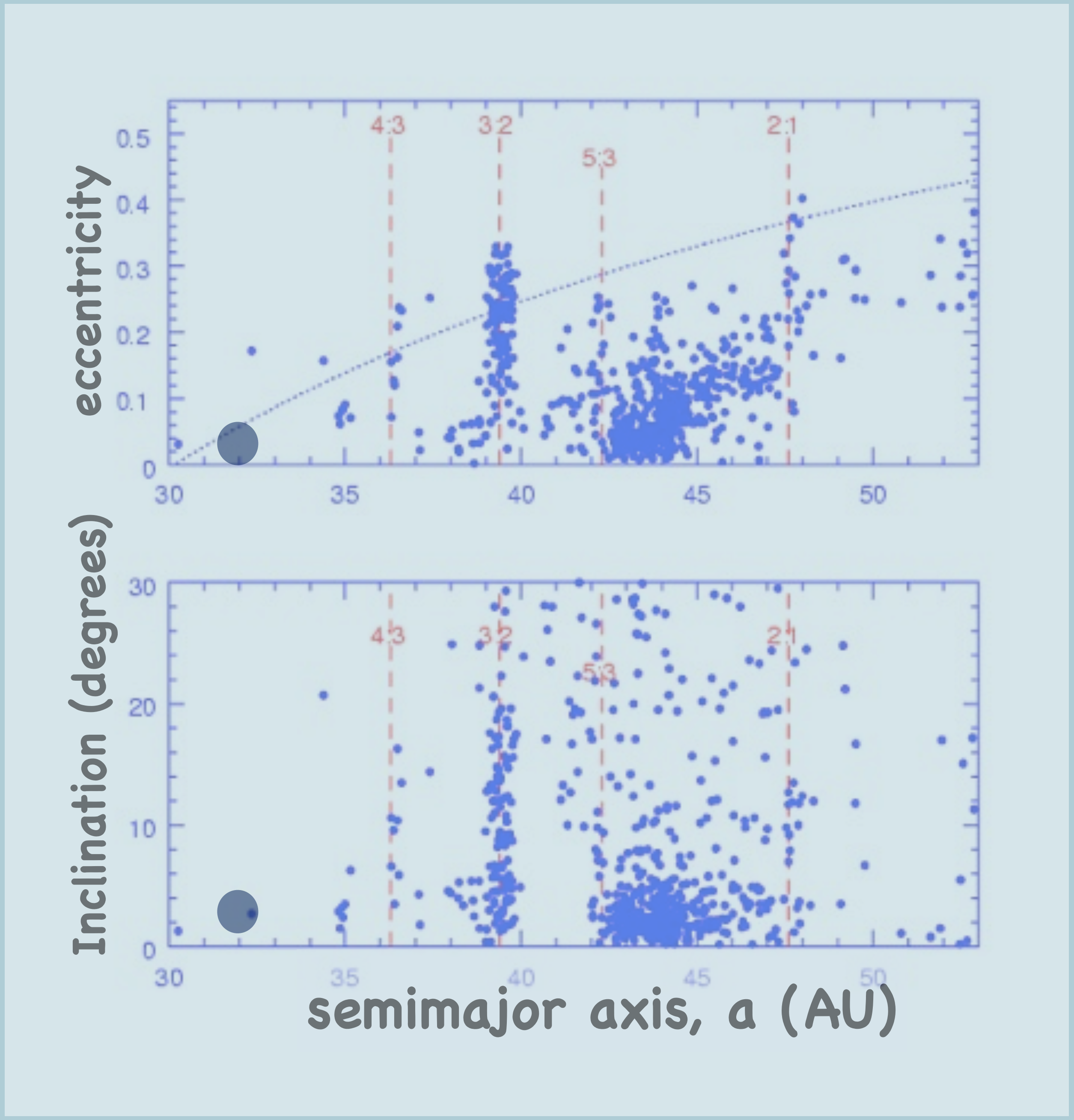

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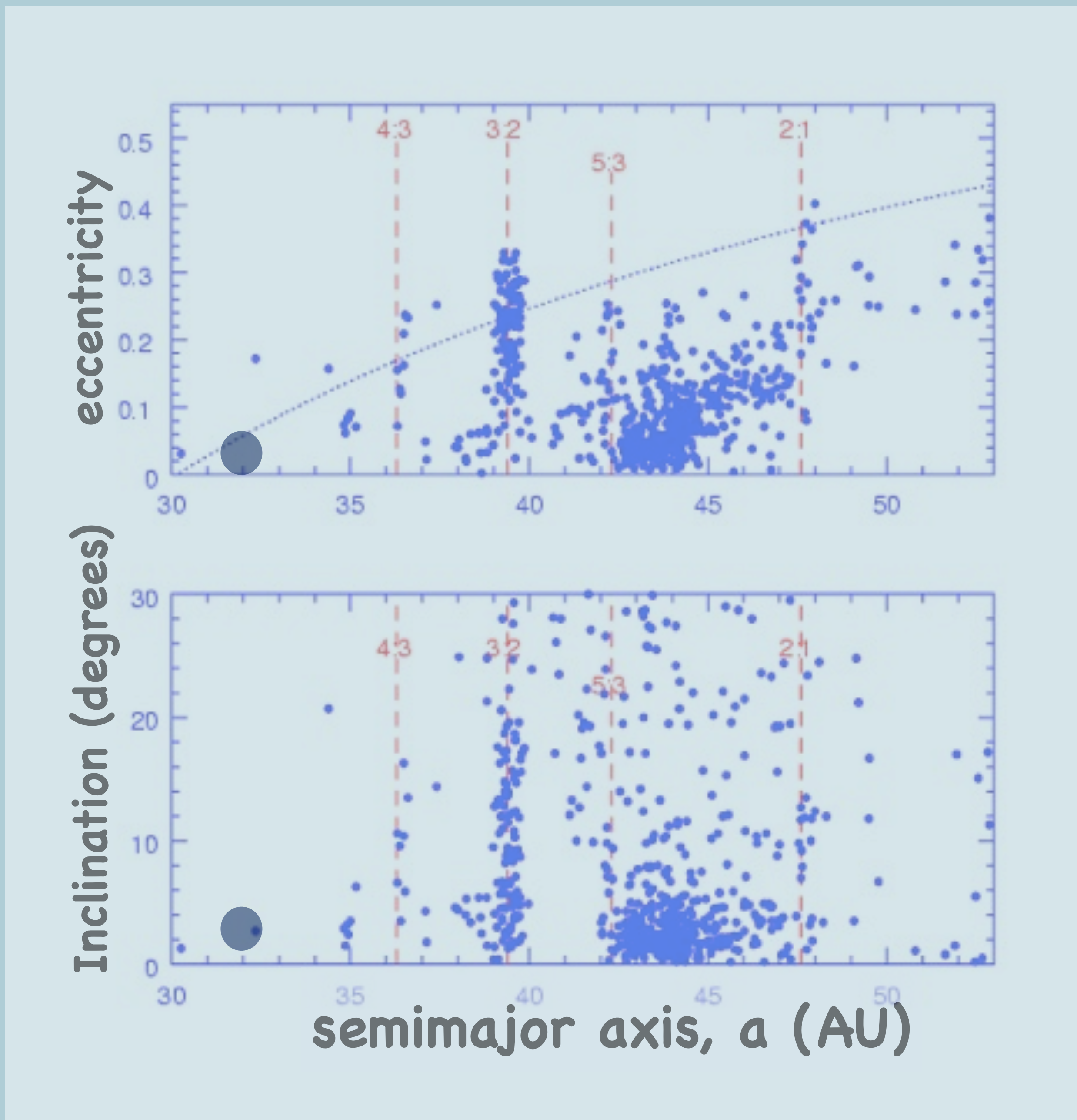


<u>Planetesimal-driven migration</u>

Angular momentum conservation:

$\sum(m_{pl}\sqrt{a}) \approx \Delta(m_N\sqrt{a_N})$

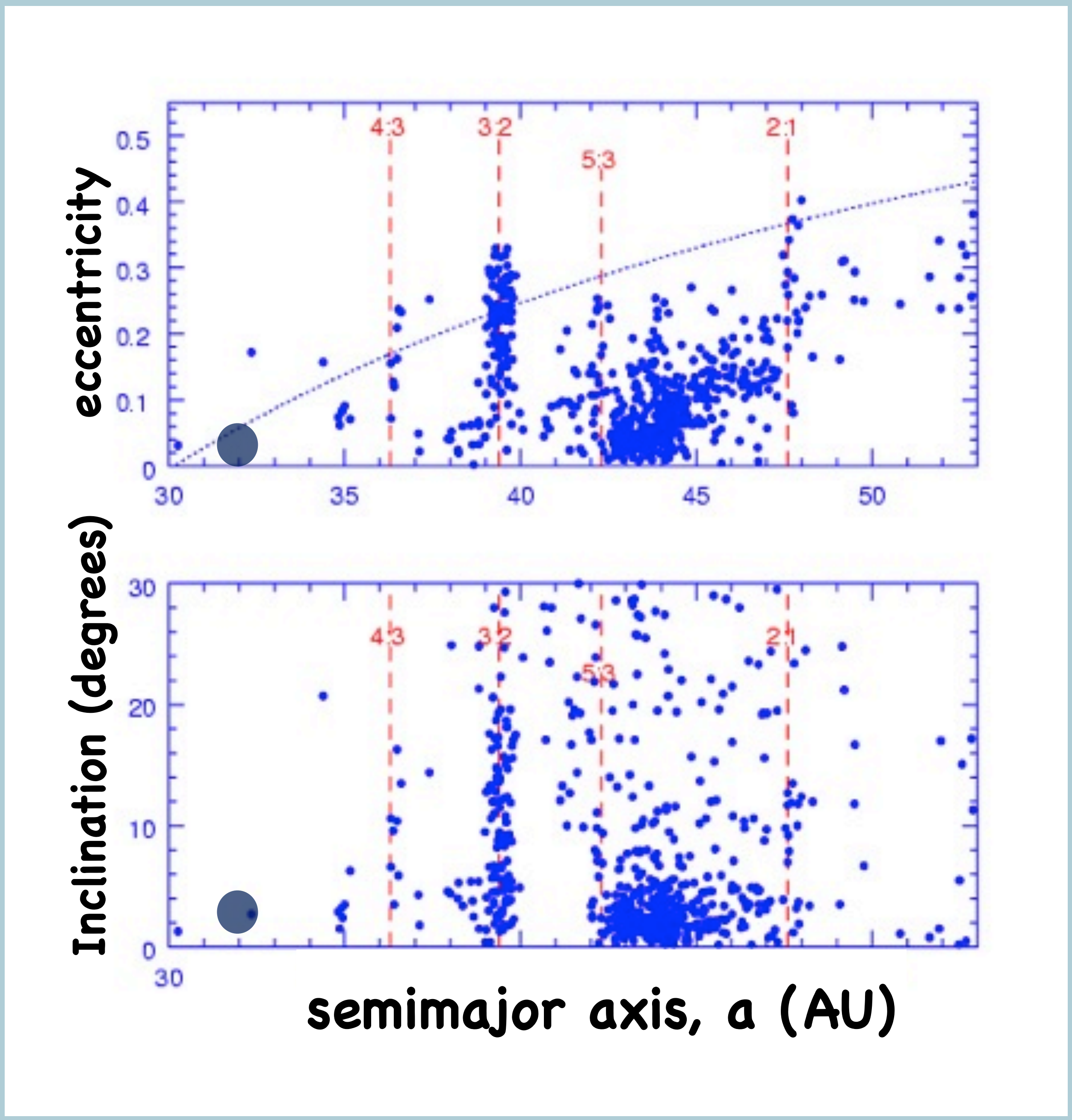
$\Rightarrow \sum m_{pl} \approx 30\ m_\oplus$ planetesimal disk fueled Neptune's ~10 AU migration

Energy conservation

$\Rightarrow$ Jupiter: $\Delta(m_J/a_J) \approx \sum(m_{pl}/a)$

$\Delta a_J \simeq -0.2AU$

More observational evidence in Kuiper Belt dynamical structure



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  - Neptune migrated out ≳10AU
  - Δm(planetesimals) ≈ 30 $M_\oplus$
  - Jupiter migrated inward ~ 0.2 AU

BUT: This constraint fails if planets encounter MMRs

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The origin of Pluto's peculiar orbit

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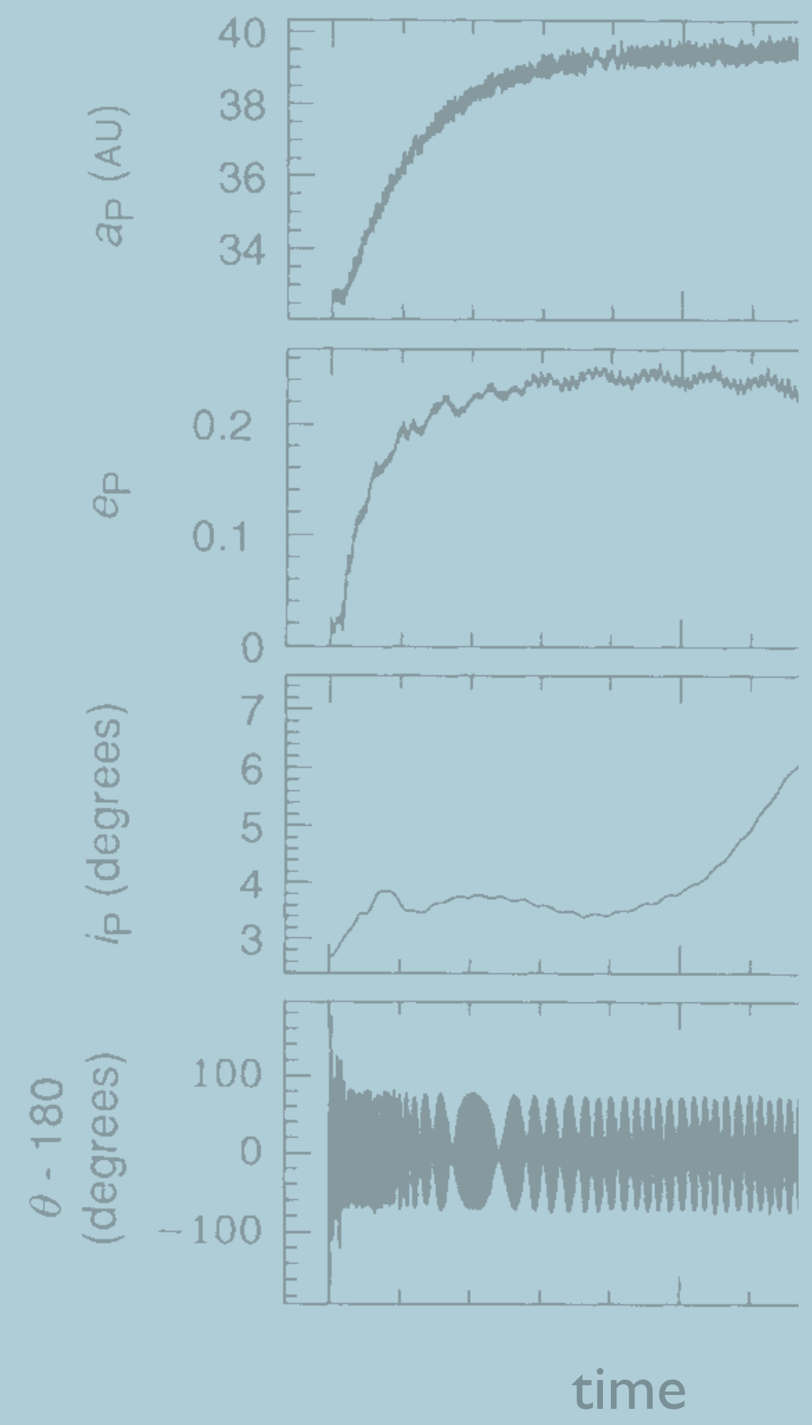

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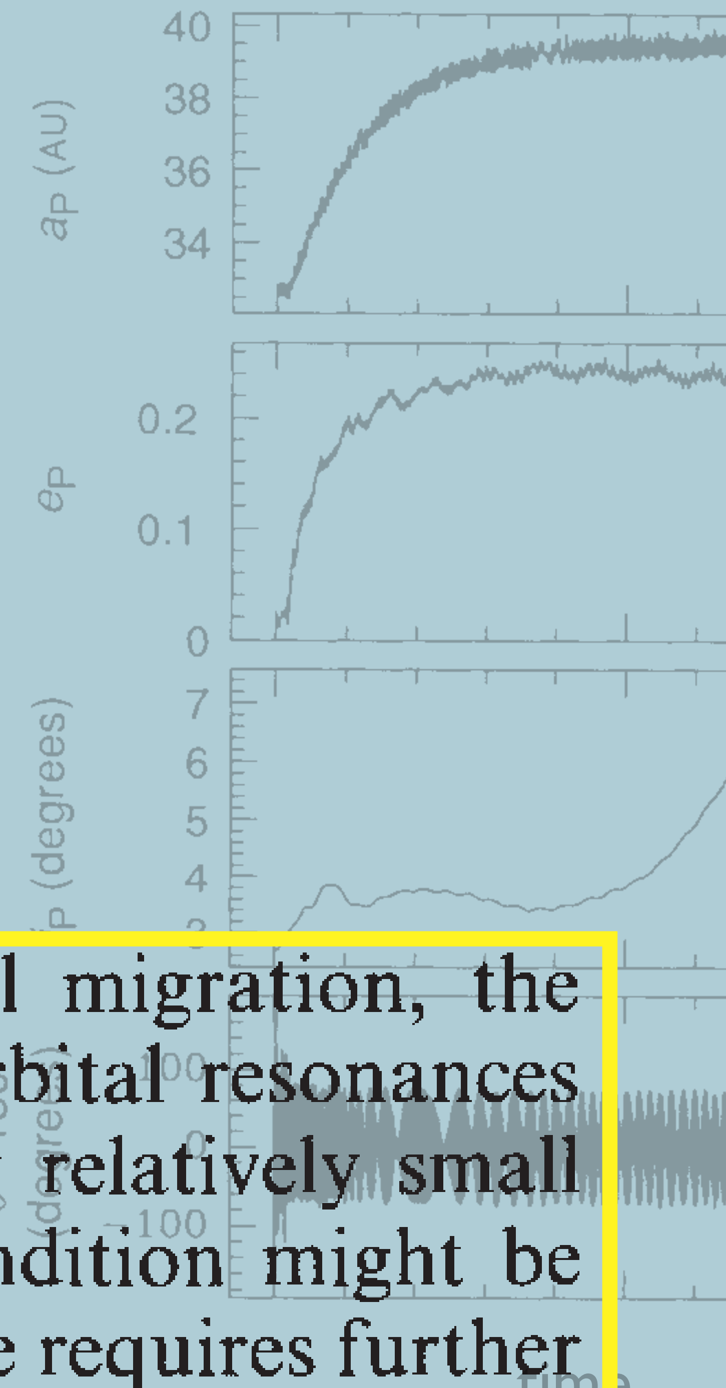

The initial conditions were carefully chosen to...

ensure that during their radial migration, the jovian planets do not encounter any strong orbital resonances amongst themselves, and therefore suffer only relatively small mutual perturbations. How restrictive this condition might be on the entire dynamical evolution described here requires further study. (4) Finally, the role of possible planetesimal collisions with Pluto during its evolution in the 3:2 Neptune resonance also needs to be evaluated. This may have an important bearing on the origin and properties of the Pluto–Charon binary.

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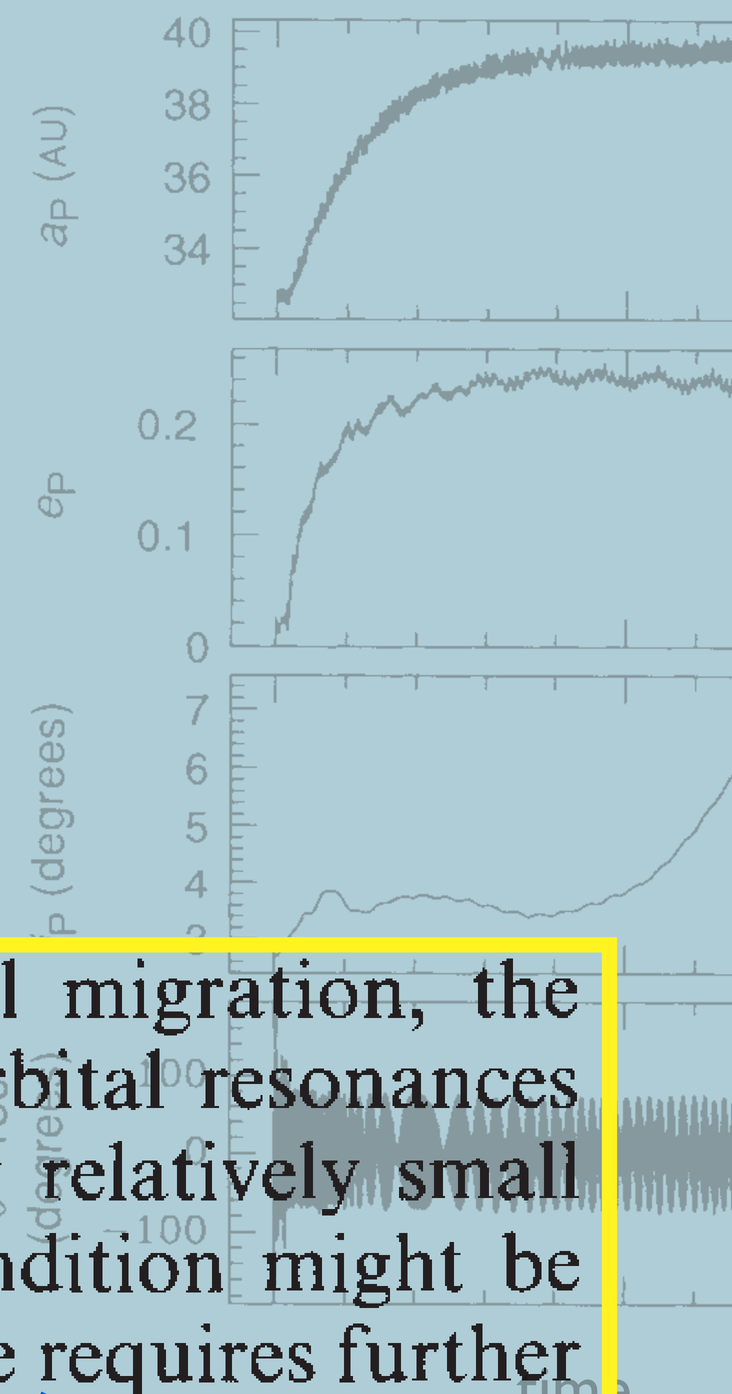

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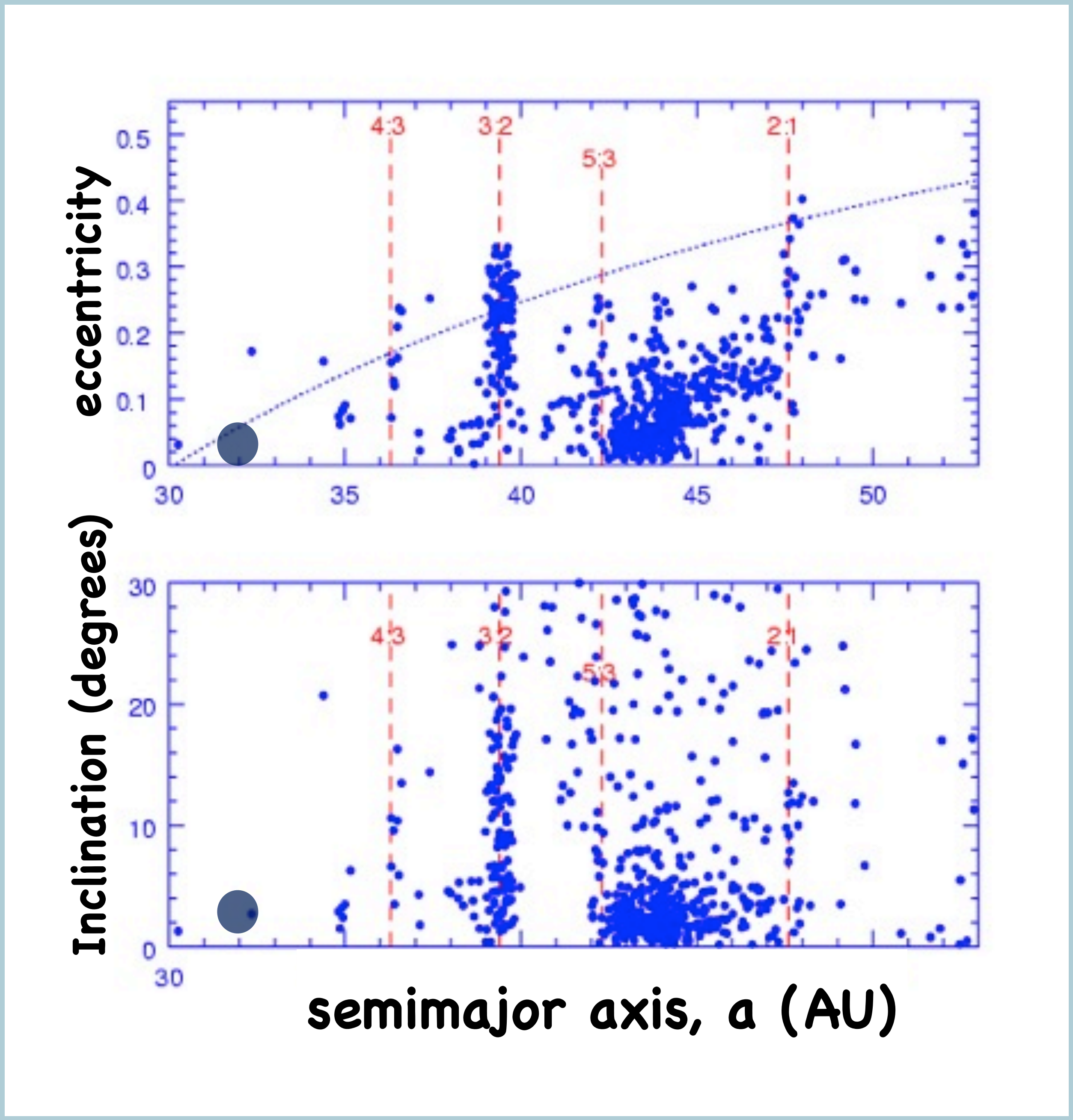
Nice Model
(2005)

More observational evidence in Kuiper Belt dynamical structure



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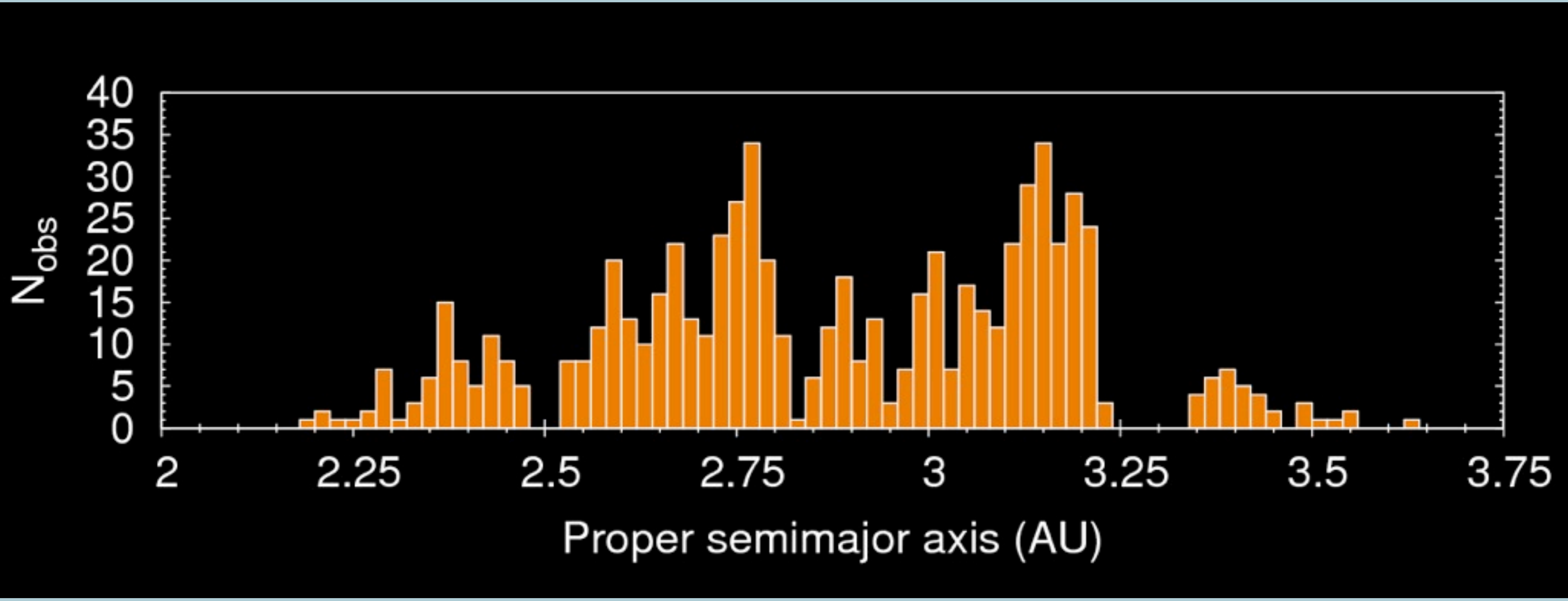
- smooth migration
  - adiabatic invariant (3:2 MMR): $a^{1/2}[2-3(1-e^2)^{1/2}\cos i]$
  - Neptune migrated out $\gtrsim$ 10 AU
  - Δm(planetesimals) $\approx$ 30 $M_\oplus$
  - Jupiter migrated inward ~ 0.2 AU

BUT: This constraint fails if planets encounter MMRs.

Does that mean we have NO constraints on Neptune/Jupiter migration ?

Distribution of asteroids observationally complete primordial set: H<9.7 (D>50 km), N~950

Minton & Malhotra, 2009



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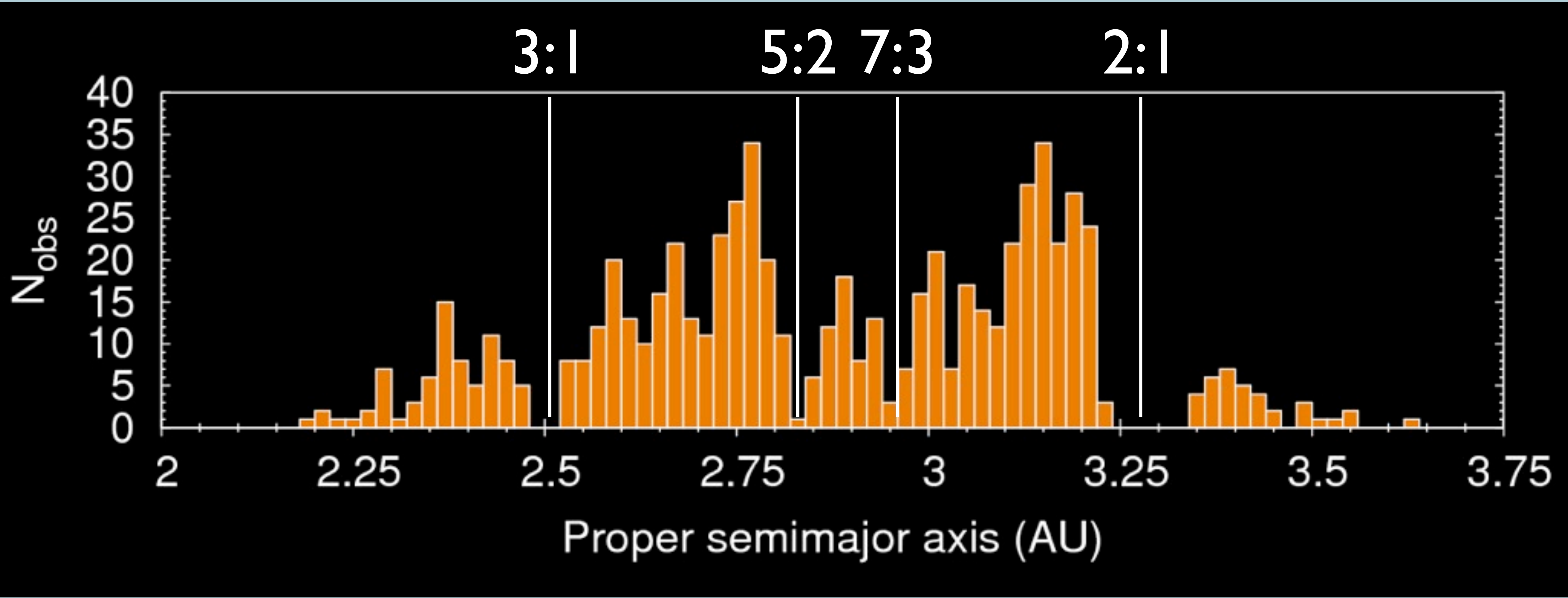

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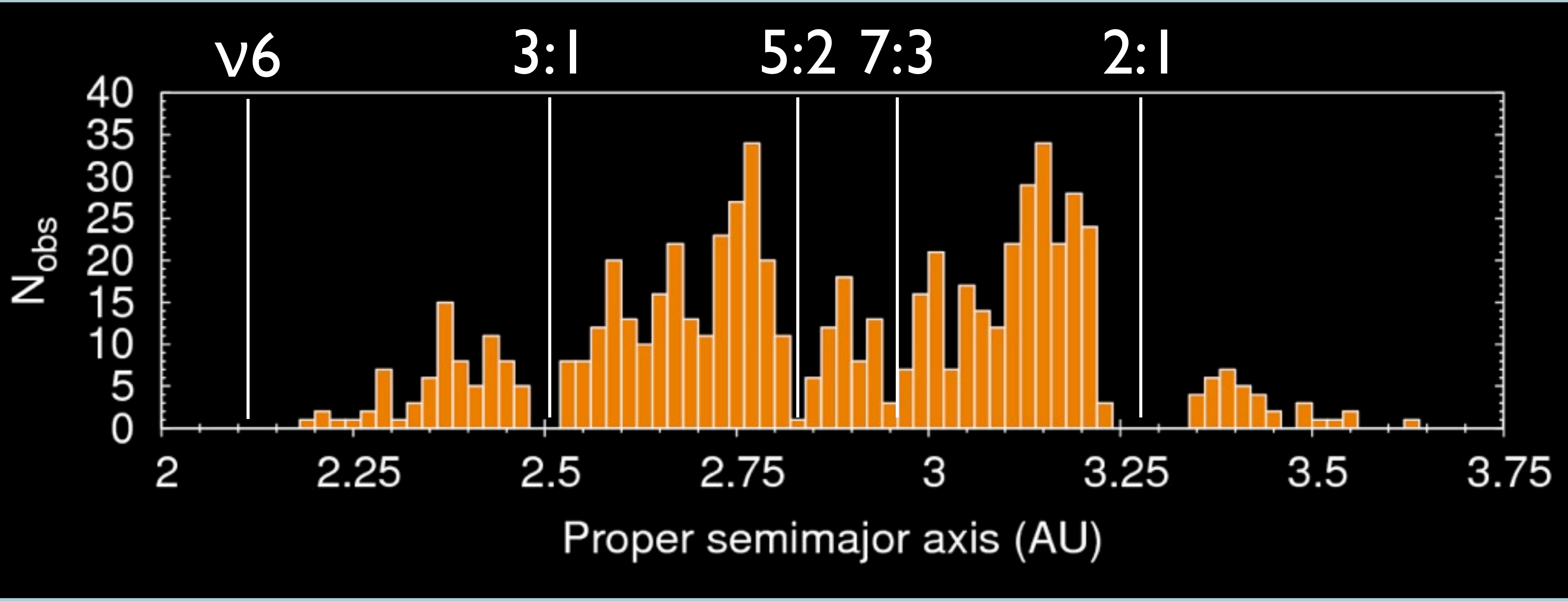

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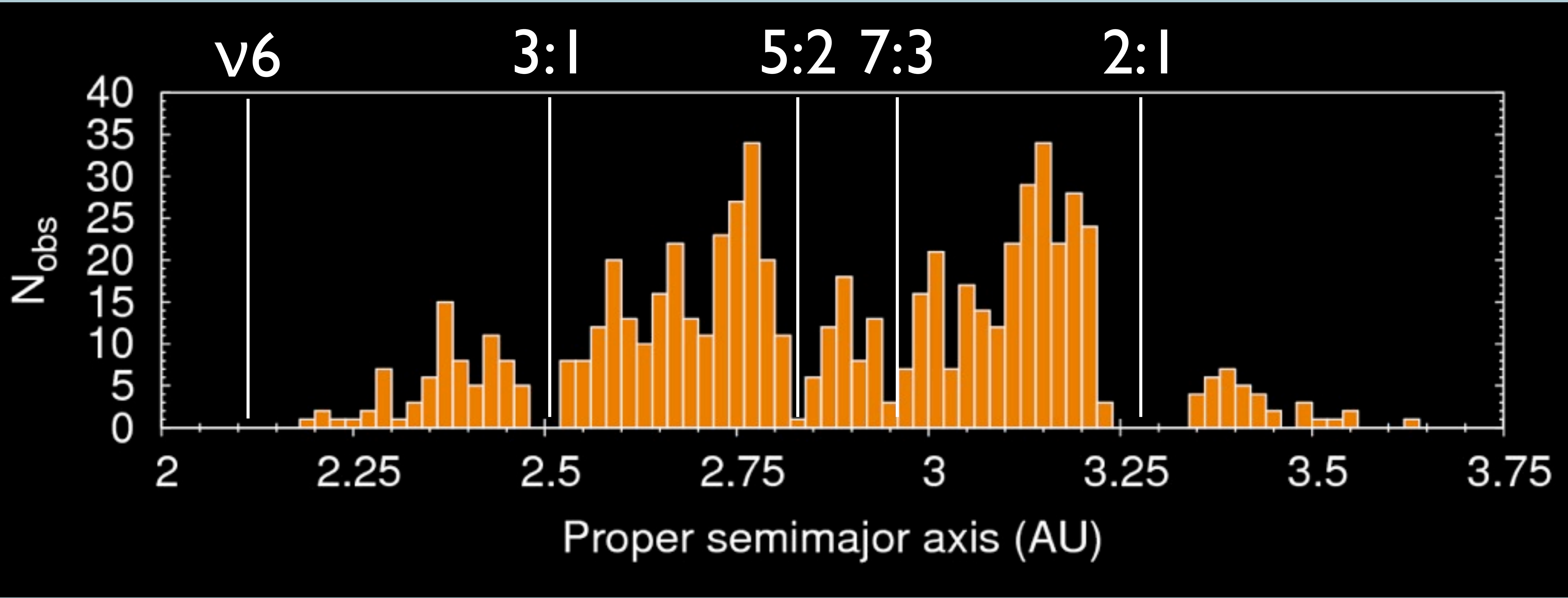


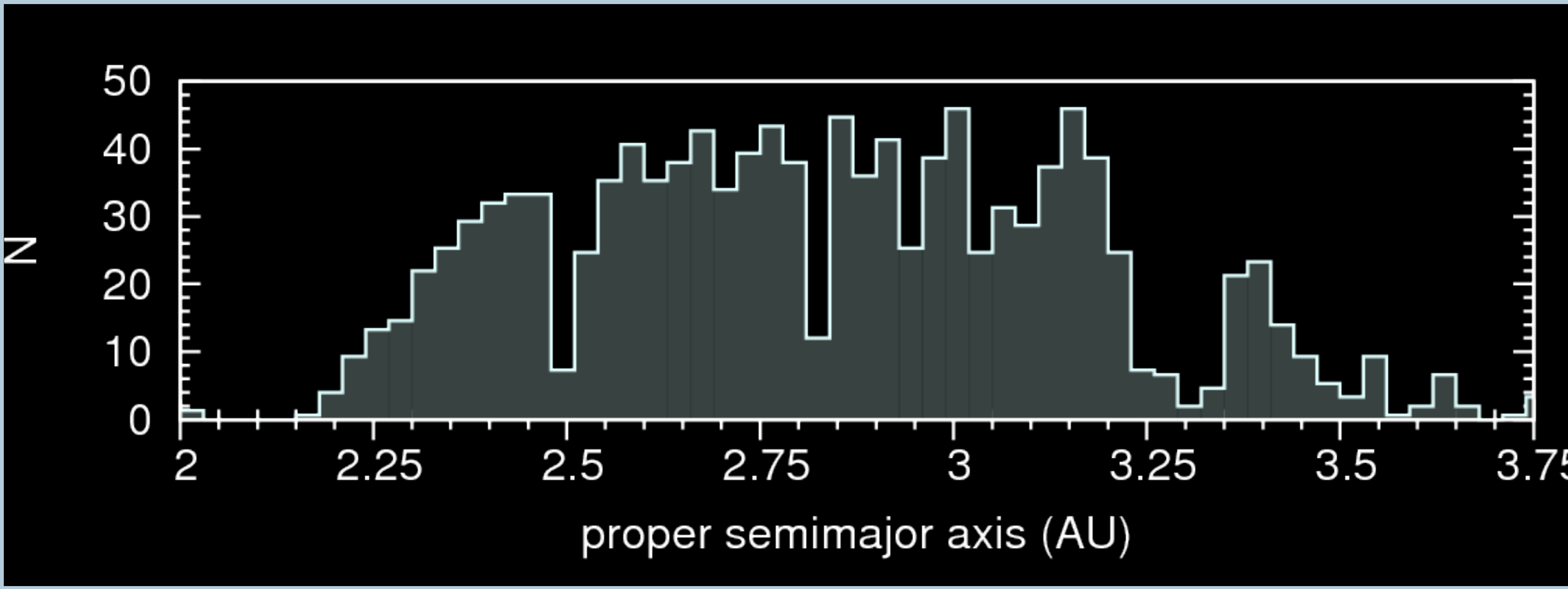
dynamically stable regions are not uniformly filled

distribution reflects "the last major dynamical event"

Sculpting of the Asteroid Belt

simulated 4 gyr of planetary perturbations

Minton & Malhotra, 2009



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compared to observed belt

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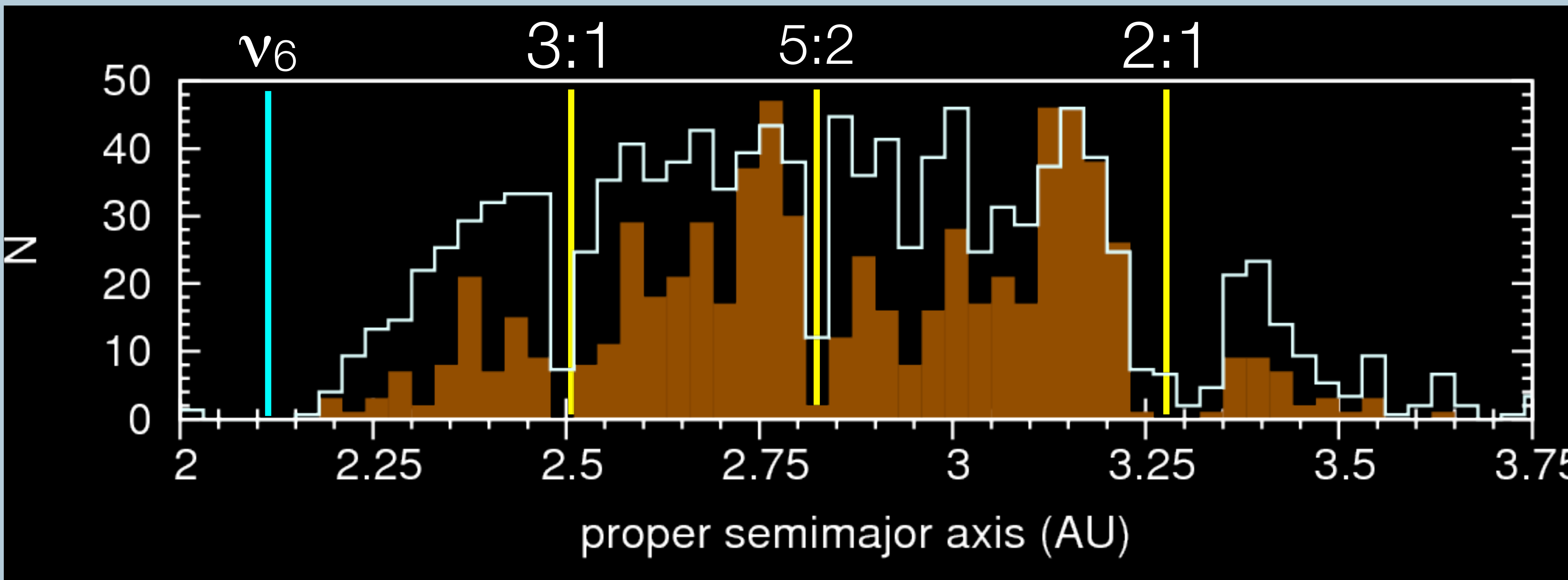

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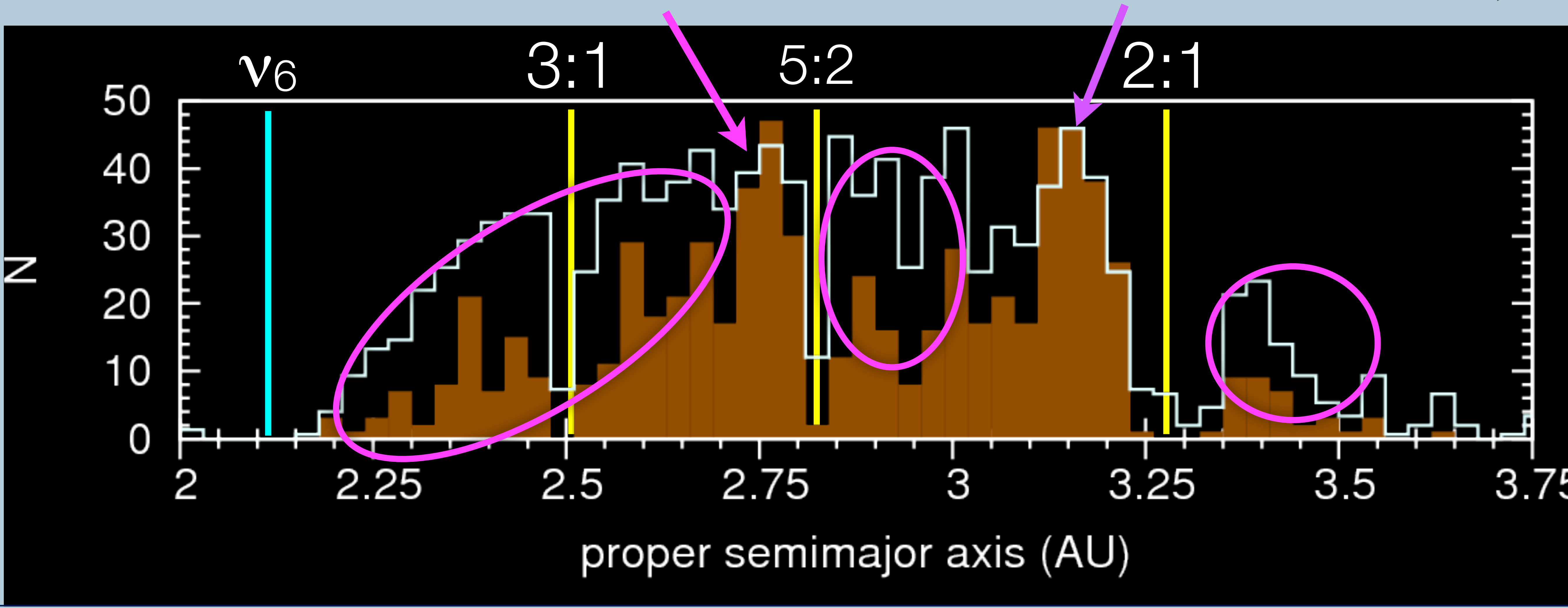


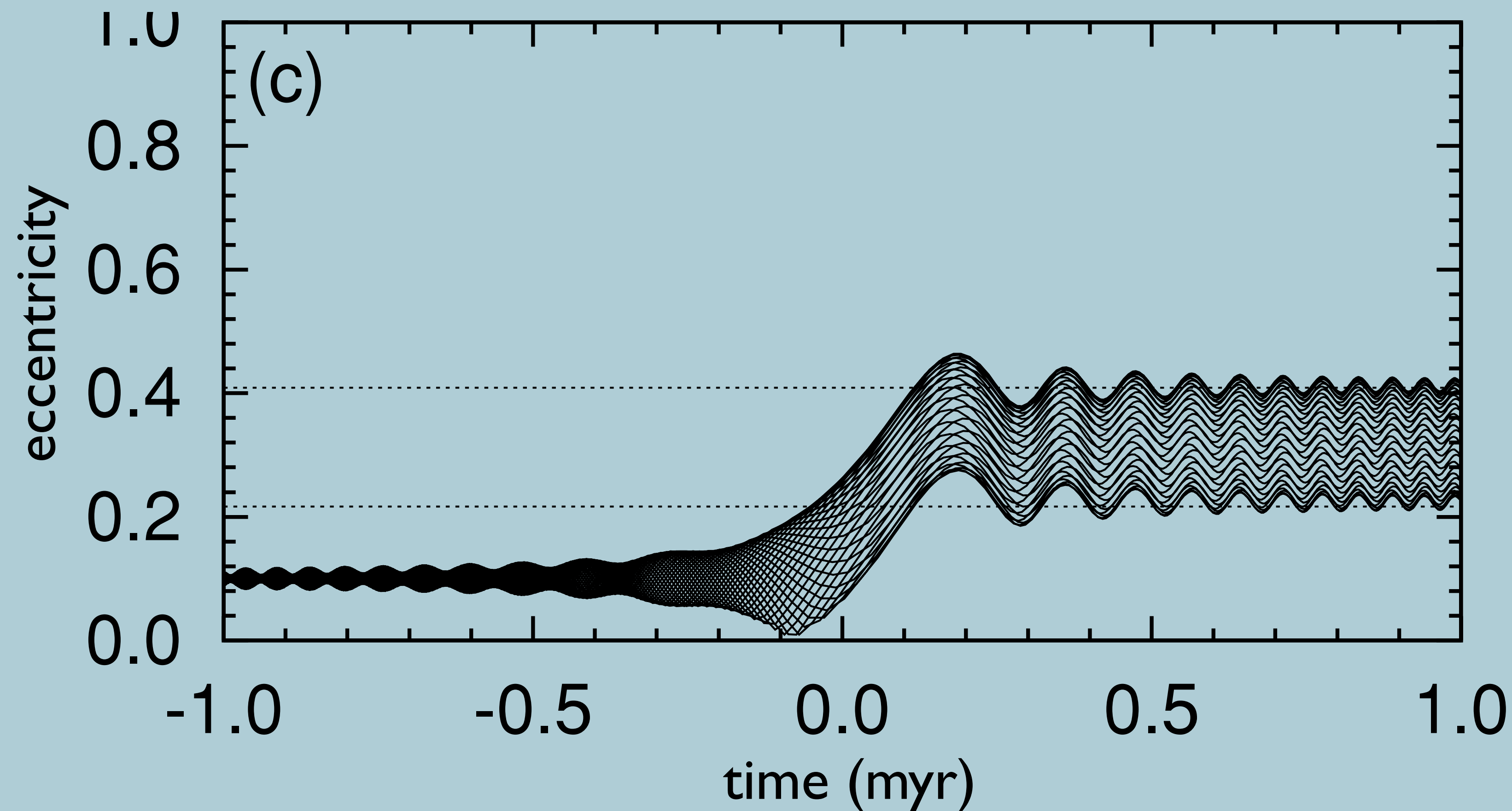
Missing asteroids: explained by effects of Jupiter-Saturn migration

$\Delta a_{Jupiter} \simeq -0.2$AU, $\Delta a_{Saturn} \simeq +1.0$AU

migration timescale $\simeq$ a few megayears

Saturn's migration ⇒ ν_6 secular resonance sweeping excites asteroid eccentricities

Minton & Malhotra, 2011



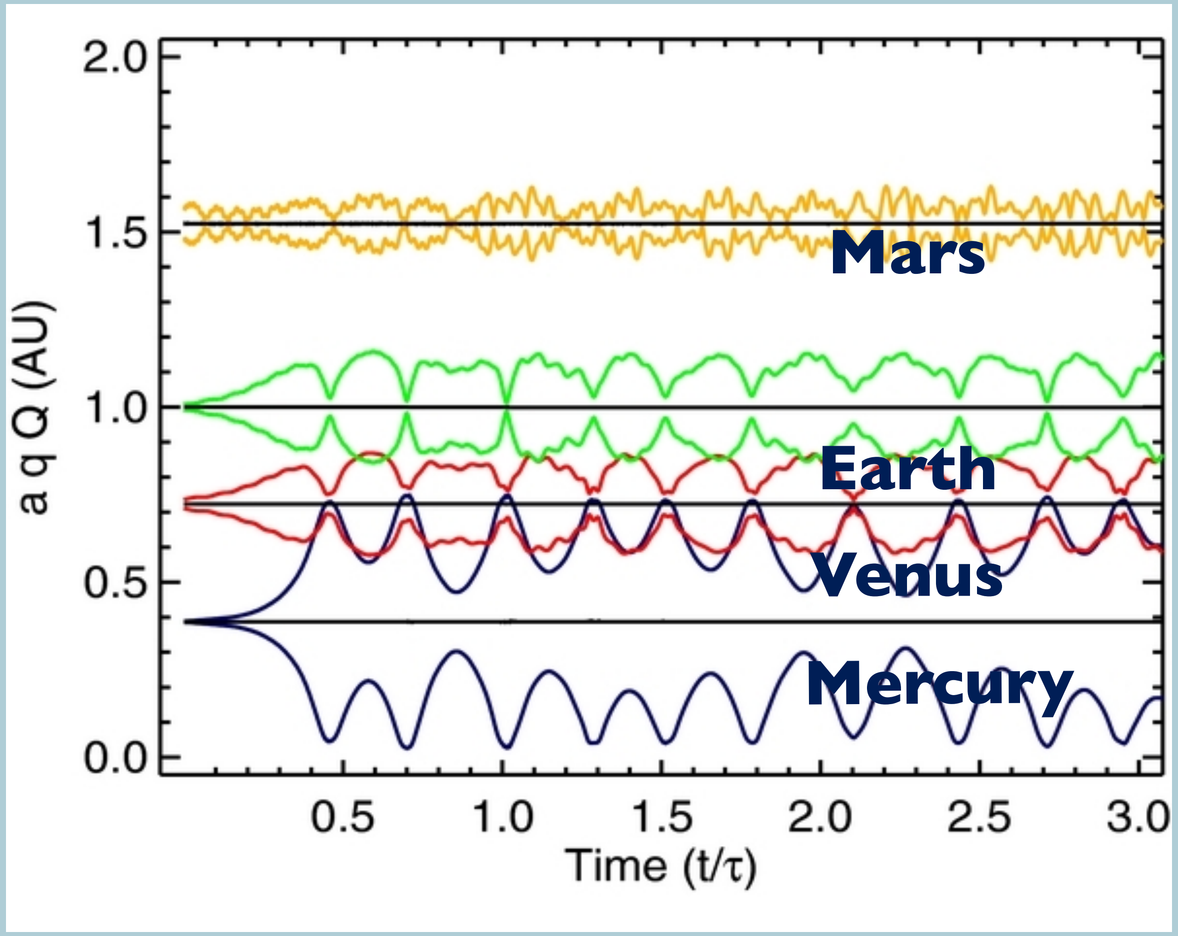
eccentricity vector:
$e_f = e_i + \delta e$

$|\delta e|$: controlled by $e_6\sqrt{da_6/dt}$

Saturn: $\Delta a \approx 1$ AU, $da/dt \gtrsim 0.15\ (e_6/e_{6c})^2$ AU/myr

Effects of Jupiter-Saturn migration on terrestrial planets

Agnor & Lin, 2012
Brasser et al., 2012
Brasser et al., 2013



ν_5 secular resonance

- excite eccentricities
- multiple crossings
- low probability of cancellation
- low probability of "successful" outcomes in numerical sims, even with very fast migration, "jumping Jupiter" style

This is disturbing!

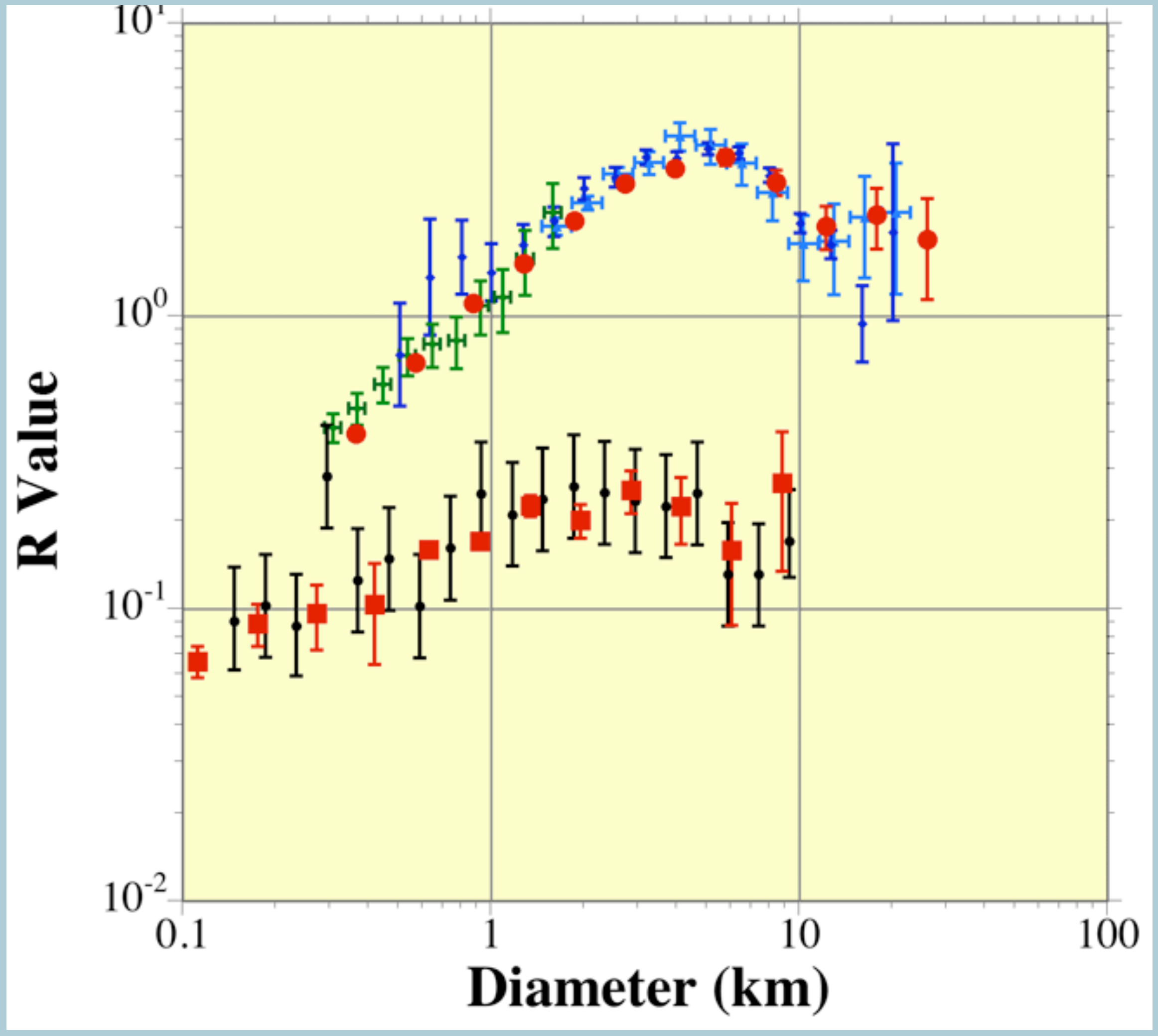
How to save the terrestrial planets?

Options?

Agnor & Lin suggest that the terrestrial planets formed **<u>after</u>** giant planet migration was completed

- But "missing asteroids" left their imprint in the crater record
    - LHB @ ~ 3.9 Ga

Strom et al., 2005



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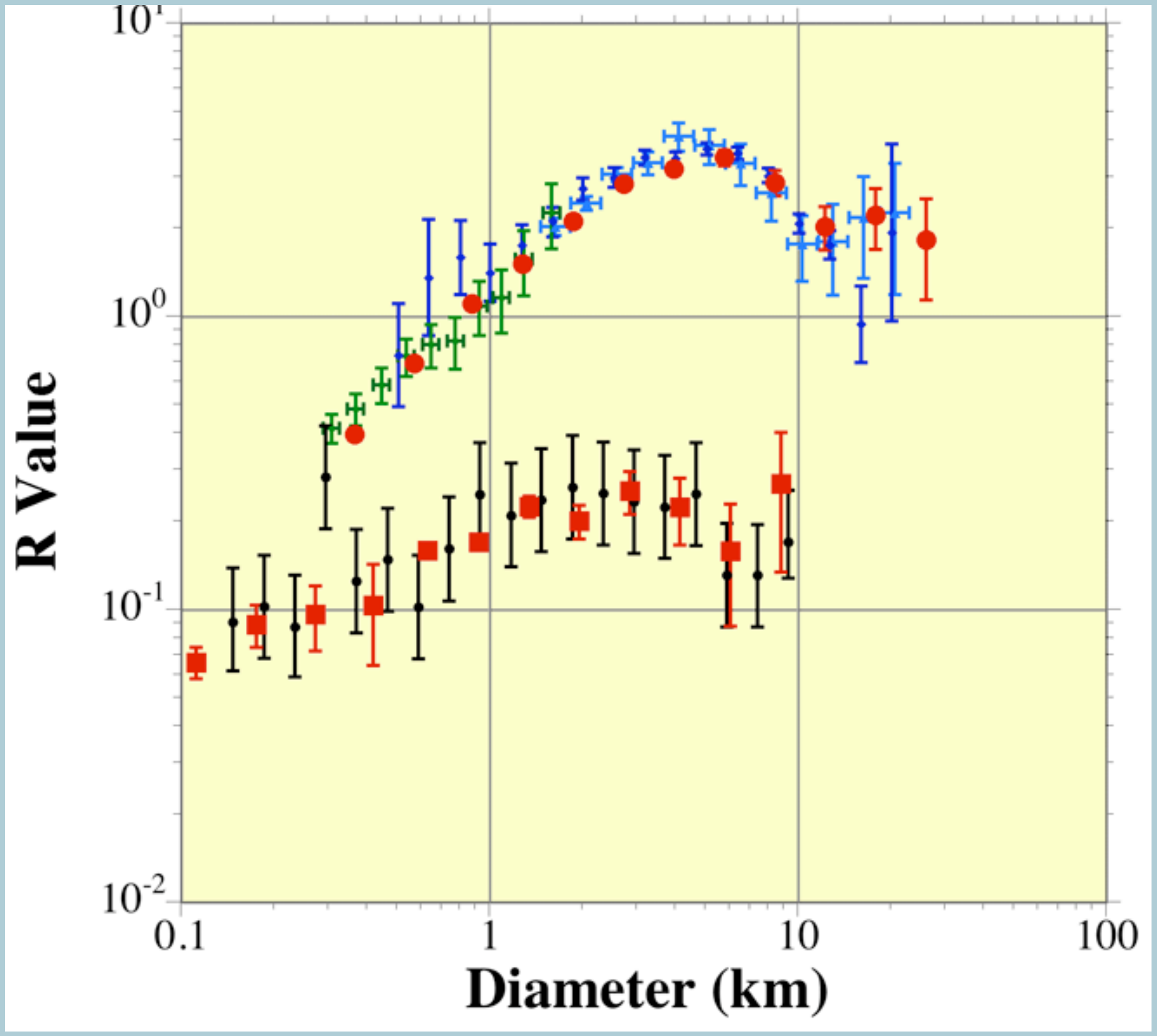
- Size distribution of impactors
    - same as Main belt asteroids
      but different than younger impactors

Strom et al., 2005



How to save the terrestrial planets?

Options?

- other missing mass to kill ν_5 ?
  - different arrangement of terrestrial planets?
  - 5th terrestrial planet?
  - massive leftover planetesimal population in the inner solar system?