NANJING UNIVERSITY

# Evolution of Jovian planets in a self-gravitating planetesimal disk

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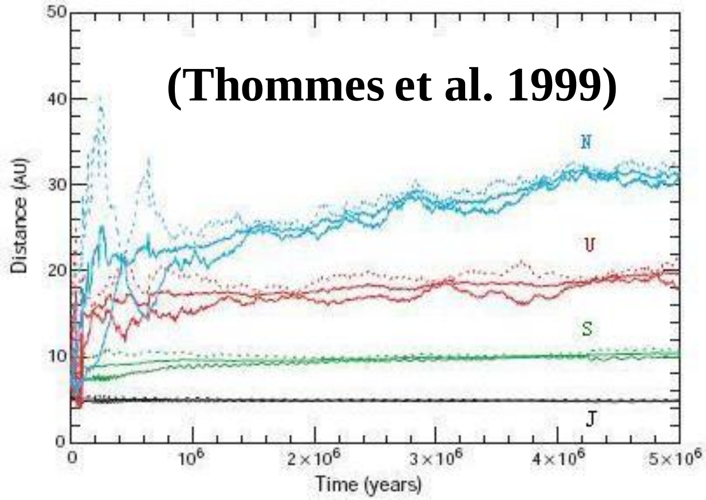
# Outline

- Indications of the Jovian planets migration
- A analytic insight in the migration process
- Numerical simulations
- Summary and open questions

# Formation of Uranus and Neptune

**In situ formation? Not likely.**

**(Levison and Stewart 2001)**



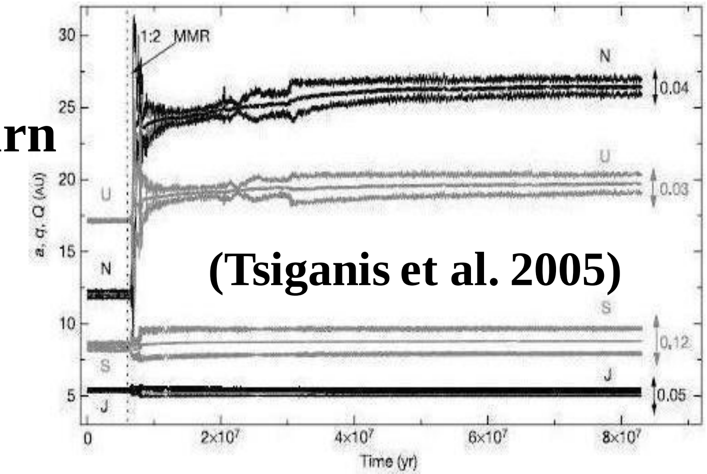

**A possible solution:**

**1) Grow up much closer to the Sun**

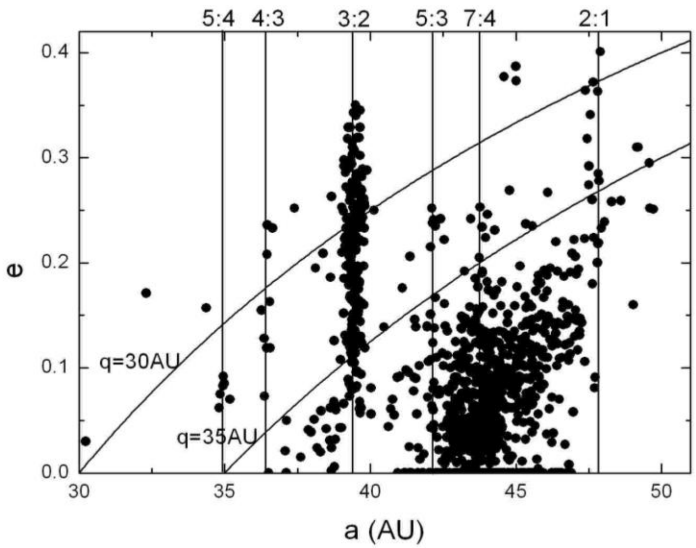
**2) Be scattered outwards by Jupiter/Saturn**

**3) Dynamical friction (*e* damping)**

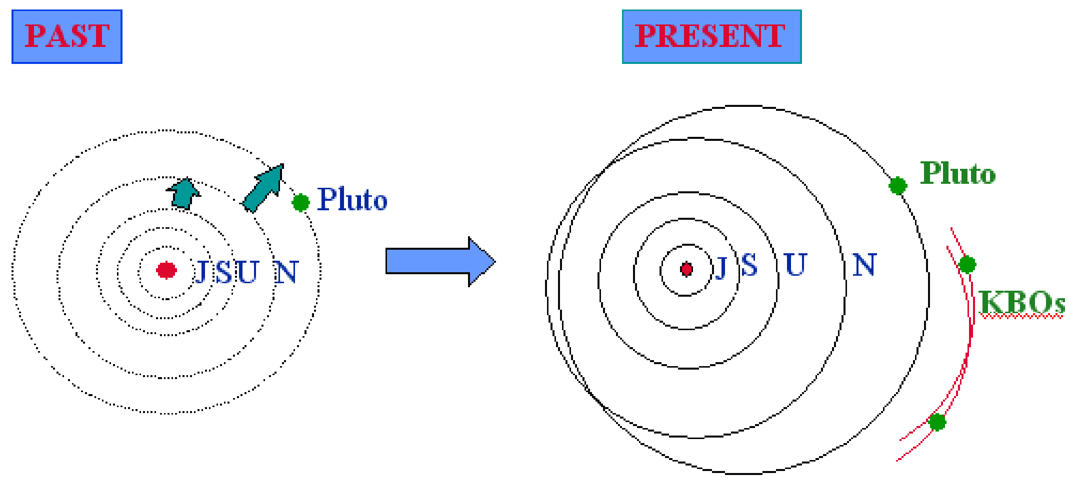
**4) Migrate outwards to present locations**



# Resonant Kuiper Belt Objects



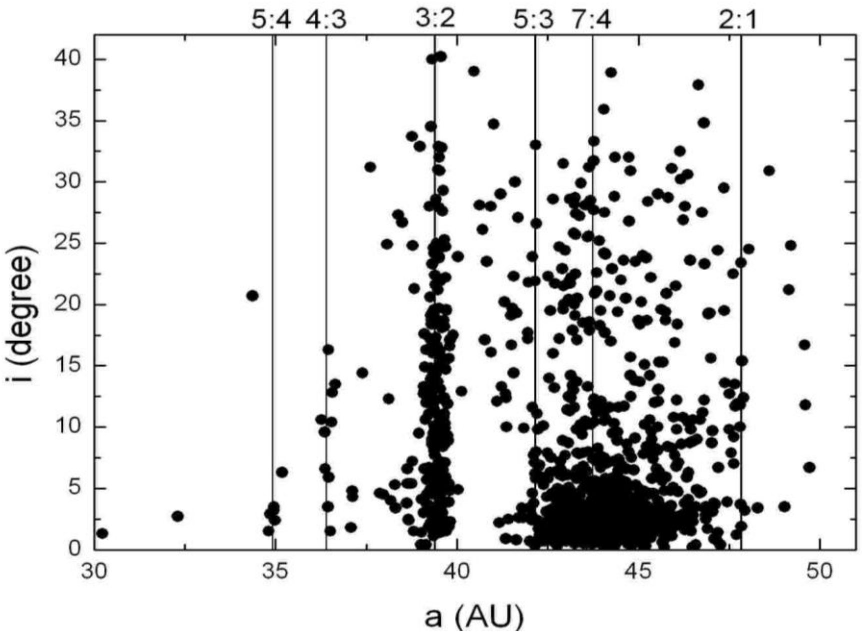

**As Neptune migrated outwards, its mean motion resonances swept through the original Kuiper Belt and many small objects were captured (Malhotra 1995).**




## Eccentricity excitation of the resonant KBOs:

$$\Delta e^2 \approx \frac{k}{j+k} \ln \frac{a_f}{a_i} = \frac{k}{j+k} \ln \frac{a_N}{a_{N,i}}$$

# Classical Kuiper Belt Objects




**Between 40 and 50AU:**

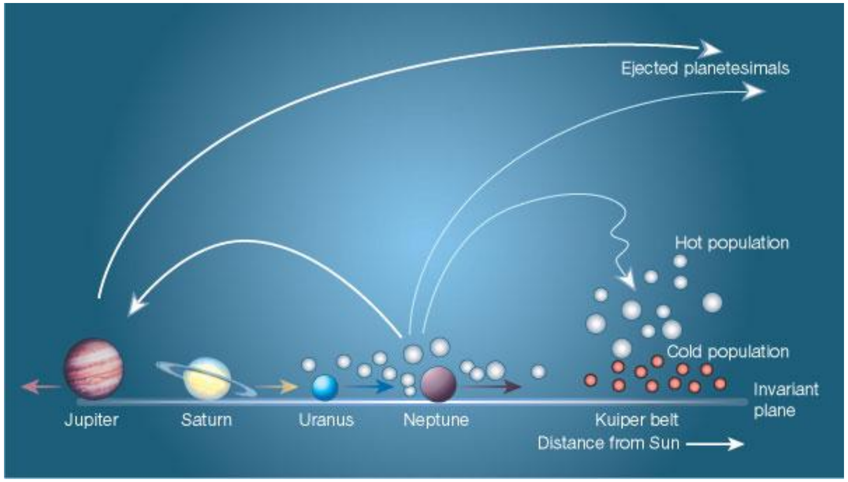
**cold population (i < 5 °): r < 170 km, red**

**hot population (*i* > 5 °): larger size, blue**

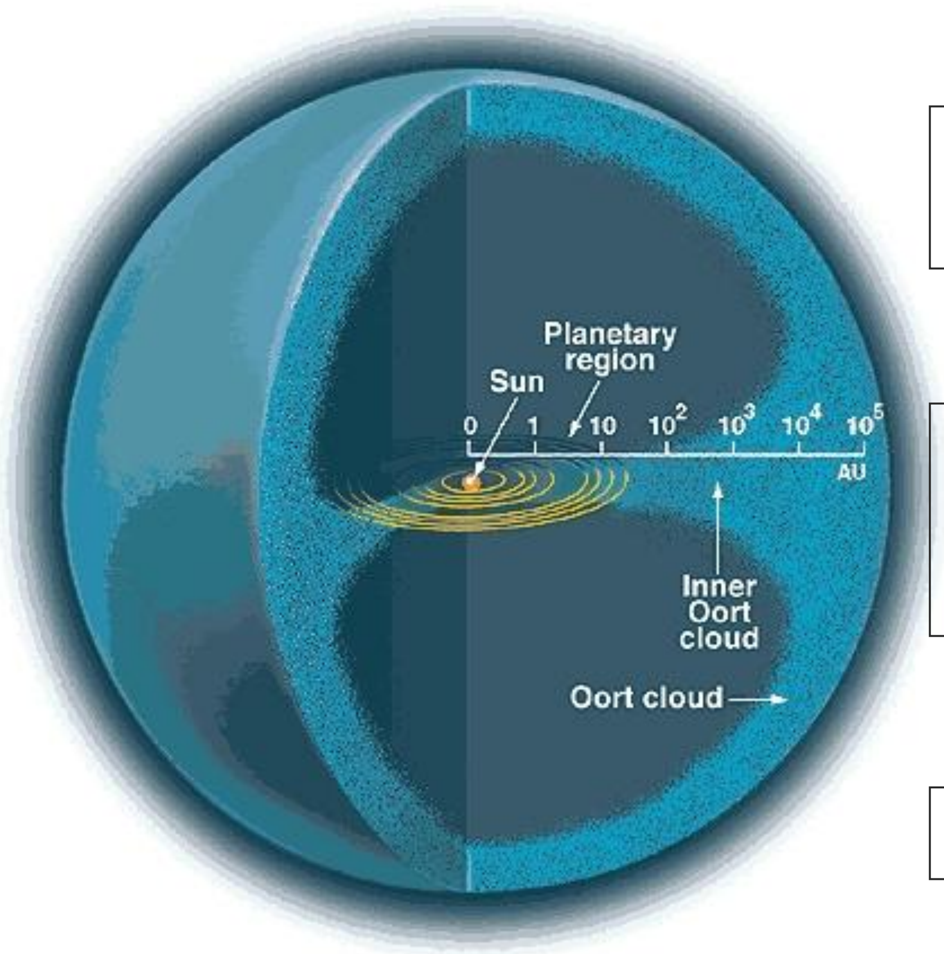
**Different origins (Gomes 2003)**

**cold objects: in situ**

**hot objects: closer to the Sun**



# The Oort Cloud




**Planetesimals were scattered outwards by migrating planets**

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**Galactic tides and passing stars decouple particles from the planetary system**

⇩

**Planetesimals archived Oort cloud**

# Other indications

- The main asteroid belt
- Trojan asteroids of Jupiter and Neptune
- Irregular satellite
- The Late Heavy Bombardment period of the terrestrial planets
- Origin of the obliquities of the Jovian planets

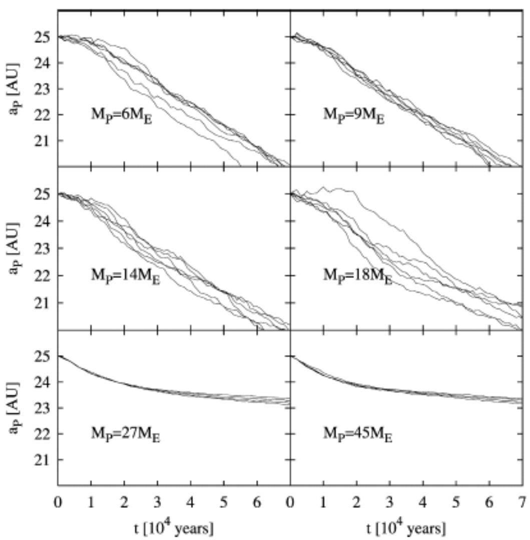
**Migration of Jovian Planets plays an important role in the formation of our Solar system !!!**

# Planetary migration

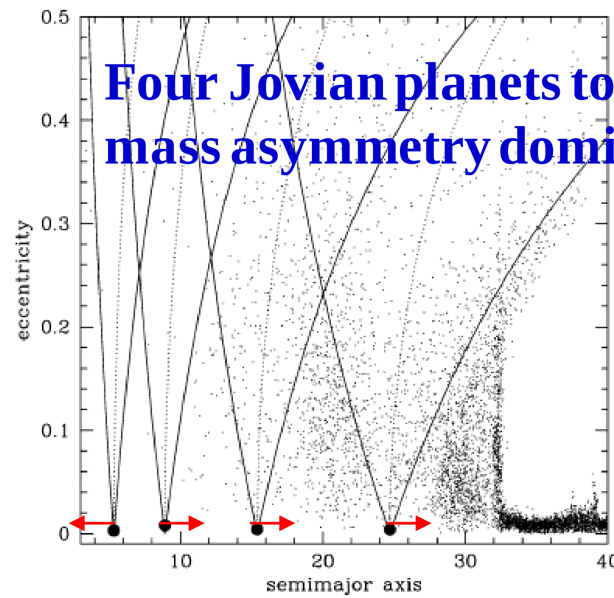
**Direction of migration:** **(Gomes et al. 2004)**

$$H = \sqrt{a(1-e^2)}\cos i, \text{ averaged over planetesimals encountered}$$

- **$H < H_p$ (inner encounter zone) → decelerate planet → inward migration**
- **$H > H_p$ (outer encounter zone) → accelerate planet → outward migration**

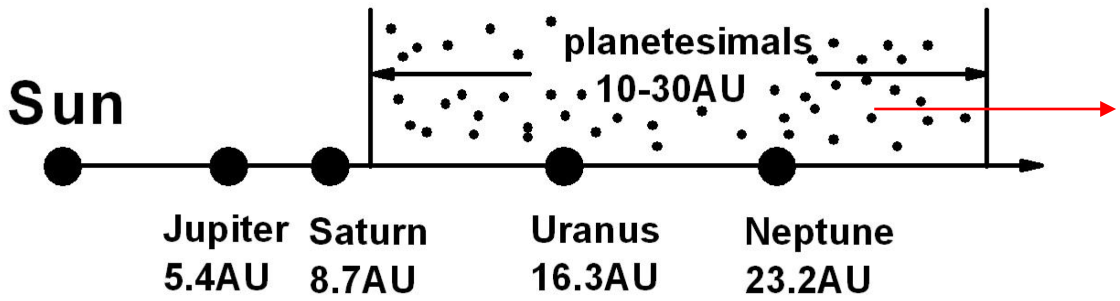



**For a single planet: scattering bias of probabilities of crossing (higher in the inner zone)**
**(Kirsh et al. 2008)**




**Four Jovian planets together: mass asymmetry dominates**

# Regular model




Mass: 30 earth masses

Surface density: $1/r$

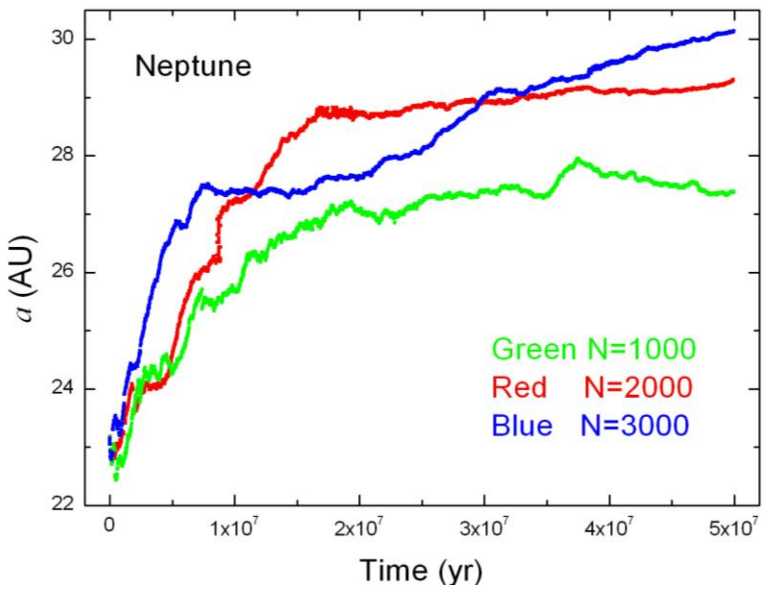
**General concerns:**

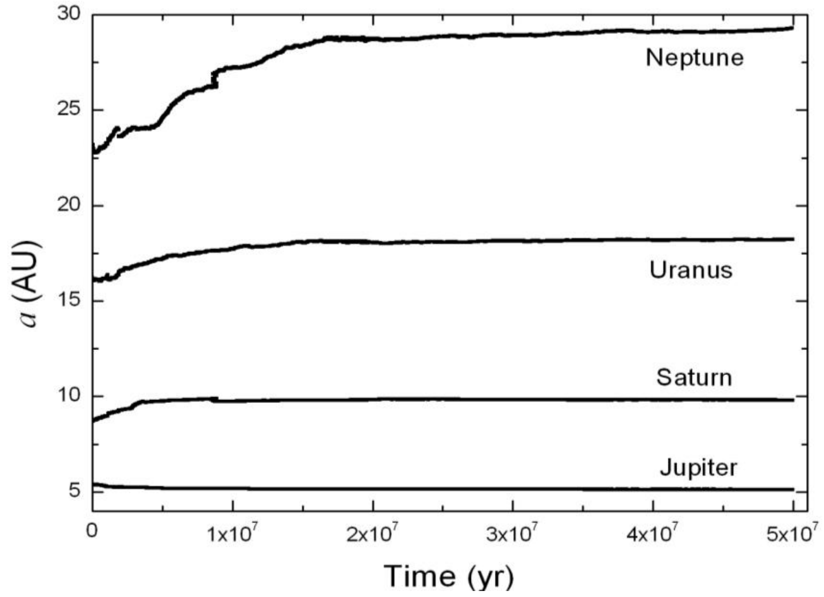
1) Migration timescale
2) The stochastic effect
3) The mass of the disk
4) The distribution of survival planetesimals

Further investigation considered a self-gravitating planetesimal disk

- The macro-accretion process
- The outer edge of the disk

# Variation of semimajor axis



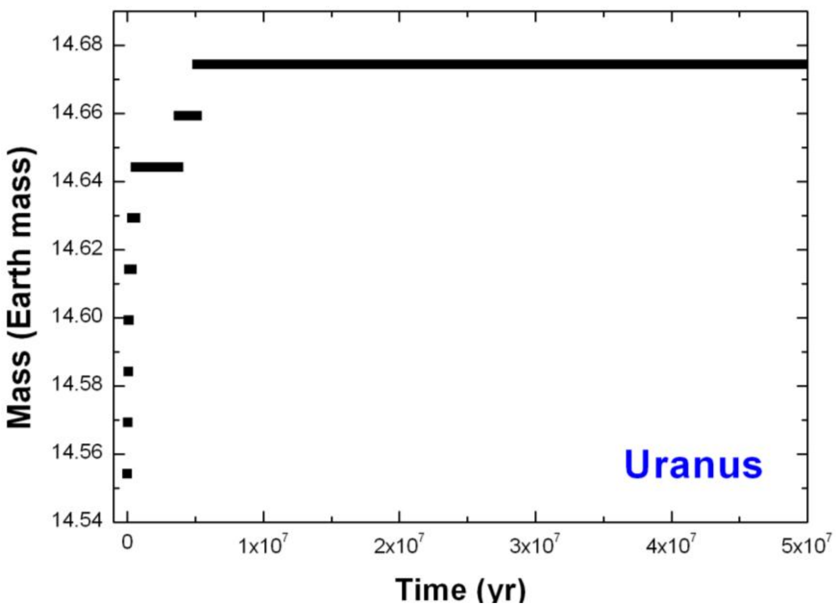

N = { 1000 $a_{Neptune}$≈ 27 AU (unrealistic)
2000 $a_{Neptune}$≈ 30 AU (suitable)
3000 $a_{Neptune}$≈ 30 AU (expensive) }

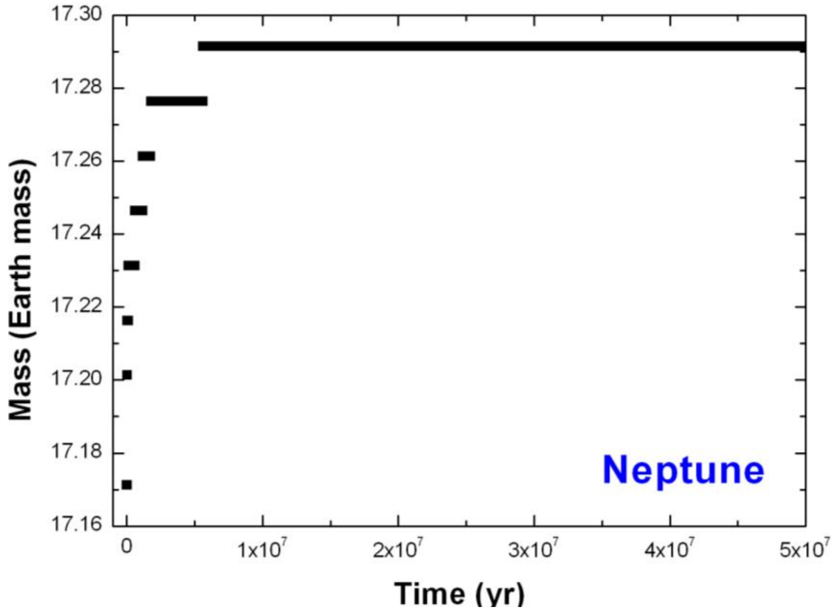
**N increases → stochastic effect decreases**

**Similar configuration to the outer Solar system for the case of N=2000.**

**(Migration timescale ～$10^7$ years)**

# Accretion of Uranus and Neptune




**Only by the order of 0.1 earth mass**

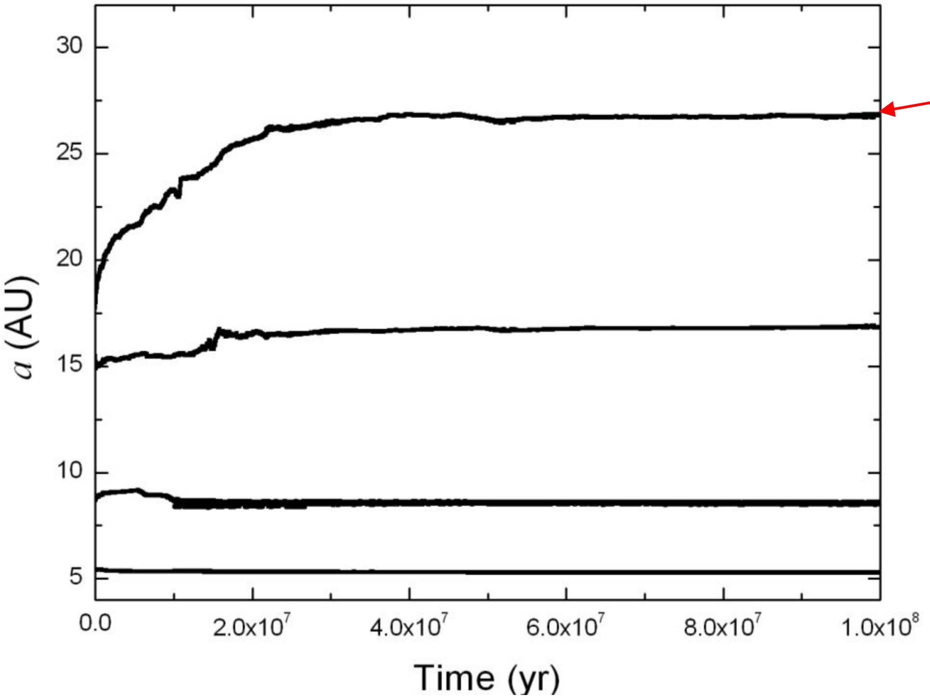
**Also no significant accretion for extra runs starting with proto-Uranus and proto-Neptune with 1/5 of their present masses (Brunini and Melita 2002).**

**Probably they had formed within 20 AU (Levison and Stewart 2001)**

# Compact Model

**Compact model: the same Jupiter, Saturn and disk as before but**

**Uranus 16.3AU → 15.5AU, Neptune 23.2AU → 17.8AU**




**Neptune stops at ～26AU**

**Empty outer encounter zone**

⇩

**The planet runs "out of fuel"**

⇩

**Mode: damped migration (Gomes et al. 2004)**

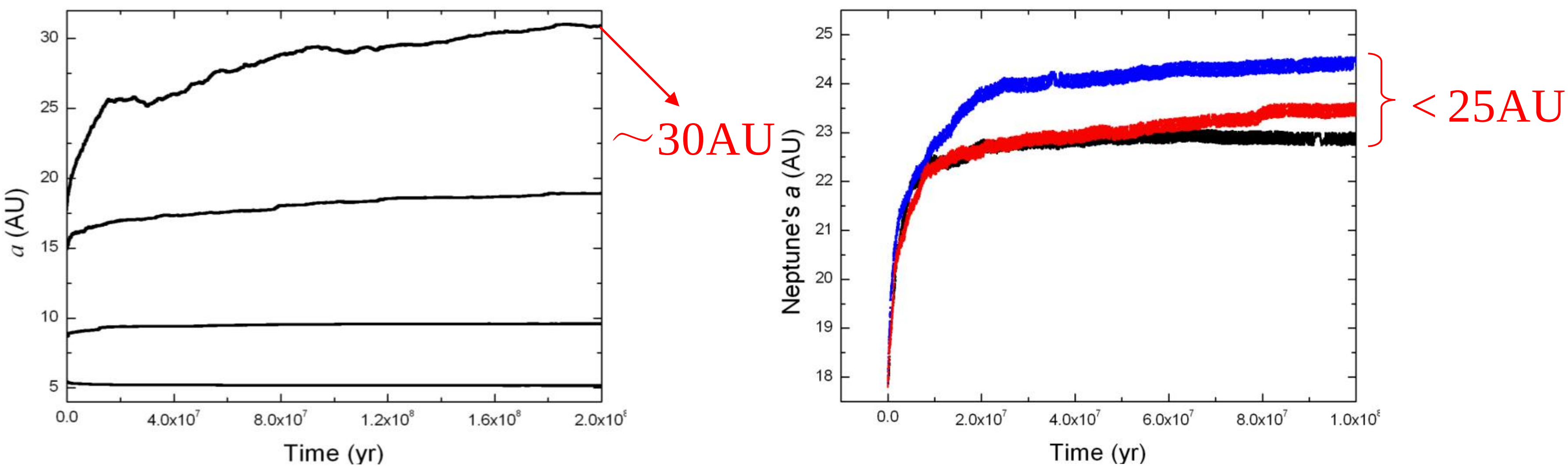
# Compact model

**Problem: How to compensate the outer encounter zone of Neptune?**

**A likely routine: extend the outer edge of the disk**

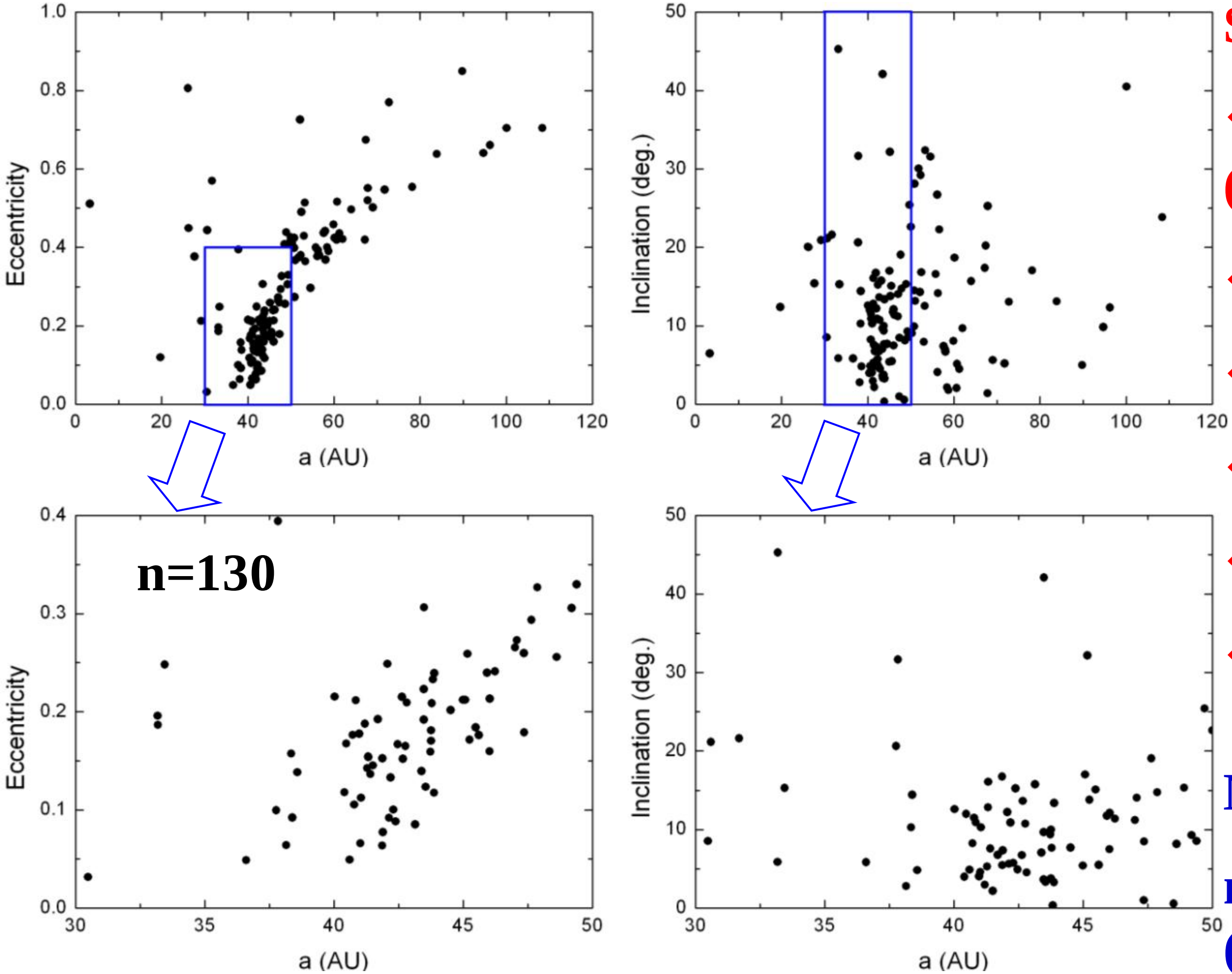
**Cause: particles passing by AND local self –stirring → eccentricity excitation**

**Consequence: plantesimals beyond 30AU enter the outer encouter zone**




**Orbital evolution of planets embedded in a planetesimal disk extended to 35AU.**
**Left: disk with self-gravity; Right: no self-gravity (slightly different initial conditions)**

# The survival planetesimals



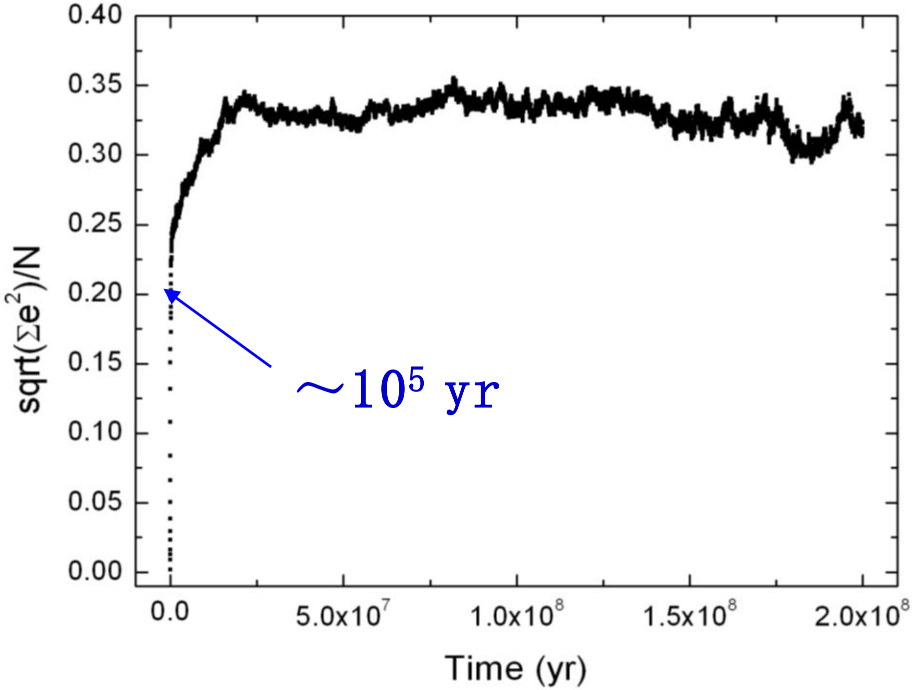

**Similar to the Kuiper Belt**

- **survival ratio ~ 3%**
  **(40-50 region: ~ 0.2 $M_{earth}$ )**
- **empty 30-36AU**
- **particles with *e*<0.1**
- **"cold" and "hot" objects**
- **outer edge near 48AU**
- **scattered disk objects**

**Major discrepancy:**

**non resonant KBOs**
**(DUE to large plantesimals)**

# Disk self-gravity and density waves




**When Neptune launches density waves at an exterior (j+1) : j MMR, the disk exerts the torque $T_j$ on the planet:**

$$T_j \approx -\frac{64\pi j^3}{75(j+1)} m_p^2 m_{disk} M_{Sun} (a_p n_p)^2$$

**which could inhibit Neptune's outward migration**

**The disk becomes too stirred-up to sustain density waves!**

# SUMMARY

◆ Planetary migration timescale ～$10^7$yr

◆ The stochastic effect in the migration process is small

◆ The distribution of survival planetesimals is analogous to the classical Kuiper Belt objects

◆ No significant accretion of Uranus and Neptune during the migration, indicating that they have fully formed before this phase

◆ The disk's outer edge is near 35 AU

◆ Disk self-gravity would contribute more "fuel" for the migration of Neptune and drive it further away

# Open questions

◆ The birth region of Uranus and Neptune

◆ The intensity of disk's self-stirring

◆ The role of spiral density waves

◆ The effect of planets scattered planetesimals on the excitation of the primordial cold KBOs between 40 and 50 AU, IF THEY DID EXIST.

# Thank you !