

# Accretion of Uranus and Neptune by collisions among planetary embryos

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# Outline

- Intro
- Methods
- Attempts to form Uranus and Neptune
- Conclusions

# Introduction

- Formation of U and N – challenging problem for a long time in planetary science
    - Safronov (1969) – formation took implausibly long time (at their current locations)
    - Levison and Stewart (2001) – confirmed this using numerical simulations
    - Goldreich et al. (2004) – found the possibility to form U and N in-situ – in planetary disk strongly dominated by collisional damping
    - Levison and Morbidelli (2007) – planetary cores open up gaps and stop accreting
- 

- Consolidated view that giant planets were formed closer to each other (all within 12 AU) and they moved to their current orbits after formation



IS NOT necessary to construct model that explain formation of U and N at their current, remote locations

- Forming U and N within 12-15 AU from Sun is (in principle) easier than at 20-30 AU – the density of solids was higher and dynamical timescale was shorter

...BUT...

- **PROBLEM: forming 10-15 Earth mass (EM) cores**

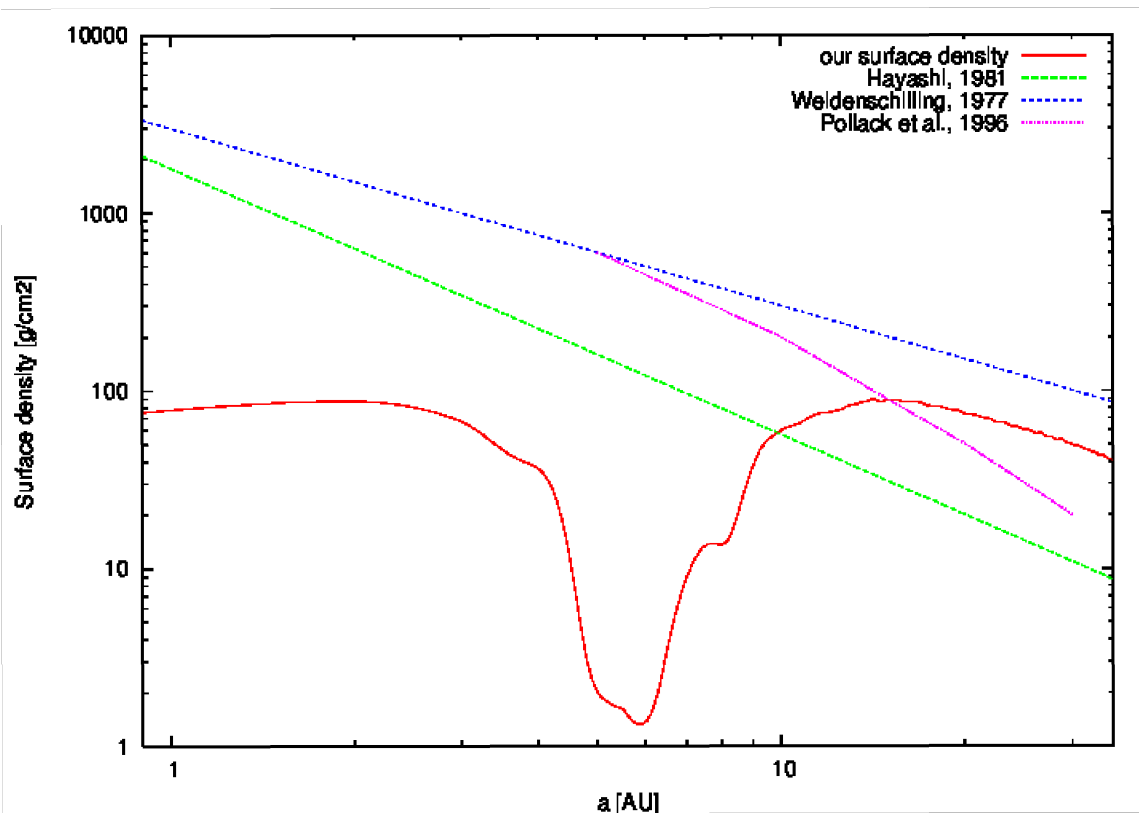
## **at ANY location**

- **Levison et al. (2010) – when planetary embryos achieve a mass of 1-3 EM – tend to scatter rather than accreting remaining planetesimals**
- **OUR SOLUTION:**
  - we envision the possibility that the planetesimal disk could generate a system of planetary embryos of only 1-3 EM
  - we investigate whether these embryos could have collided with each other – they converged at specific orbital radii (their inward radial migration in the gas-disk was stopped by the presence of Jupiter and Saturn)

- NOTE: this growth mode by giant collisions would explain the large obliquities of U and N in a natural way
- our scenario is based on the consideration that Jupiter and Saturn presumably got caught in their 2:3 mean motion resonance (MMR), which prevented them from migrating further toward the Sun

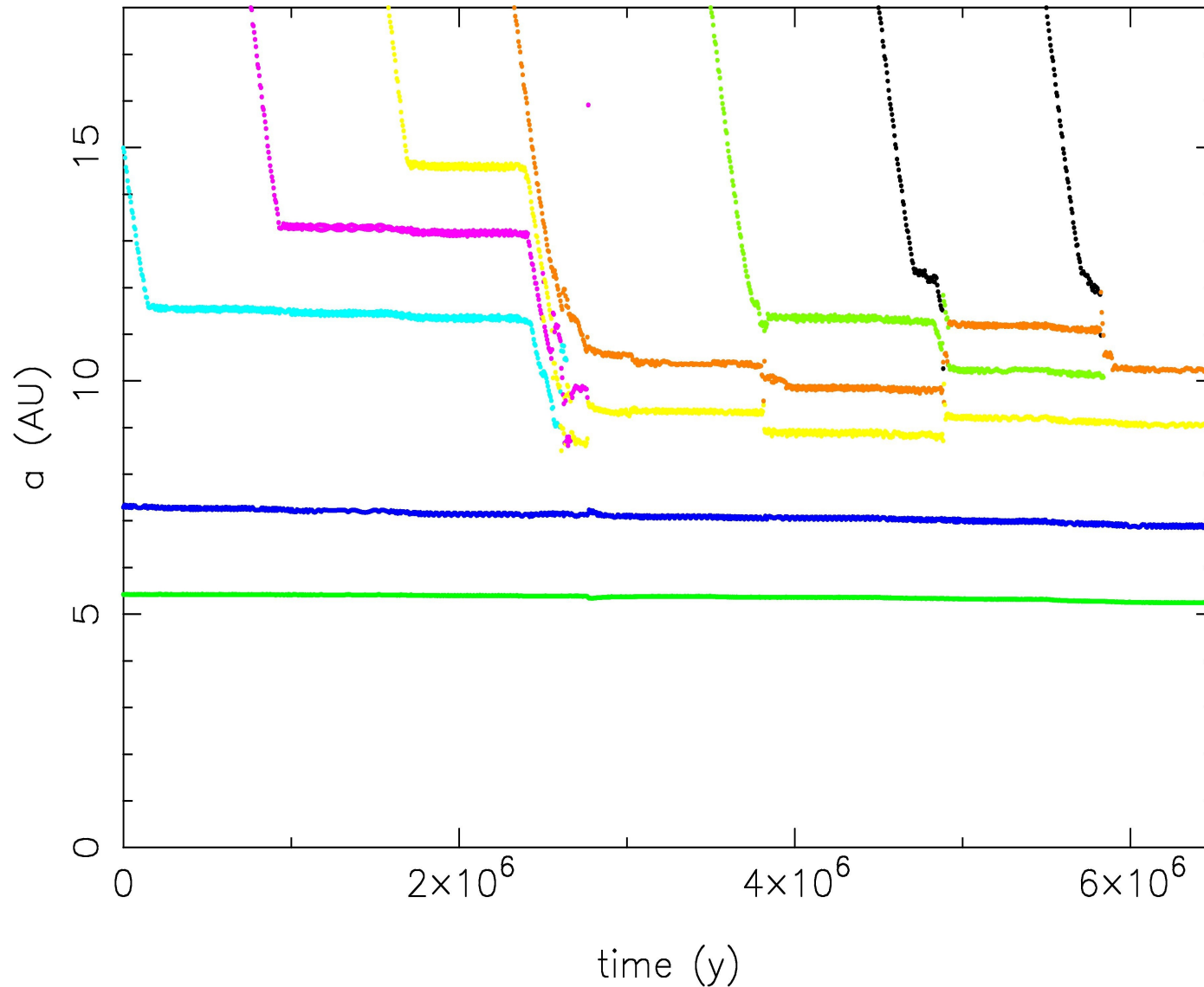
# Methods

- we used the integration software Symba modified to take into account the planet-gas gravitational interactions
- gas density profile that we considered was taken from the hydro-dynamical simulations of Morbidelli & Crida (2007)



- the surface density profile of the gas is used to compute the migration and damping forces acting on the embryos

# Basic dynamical mechanisms in the migration of embryos and giant planets

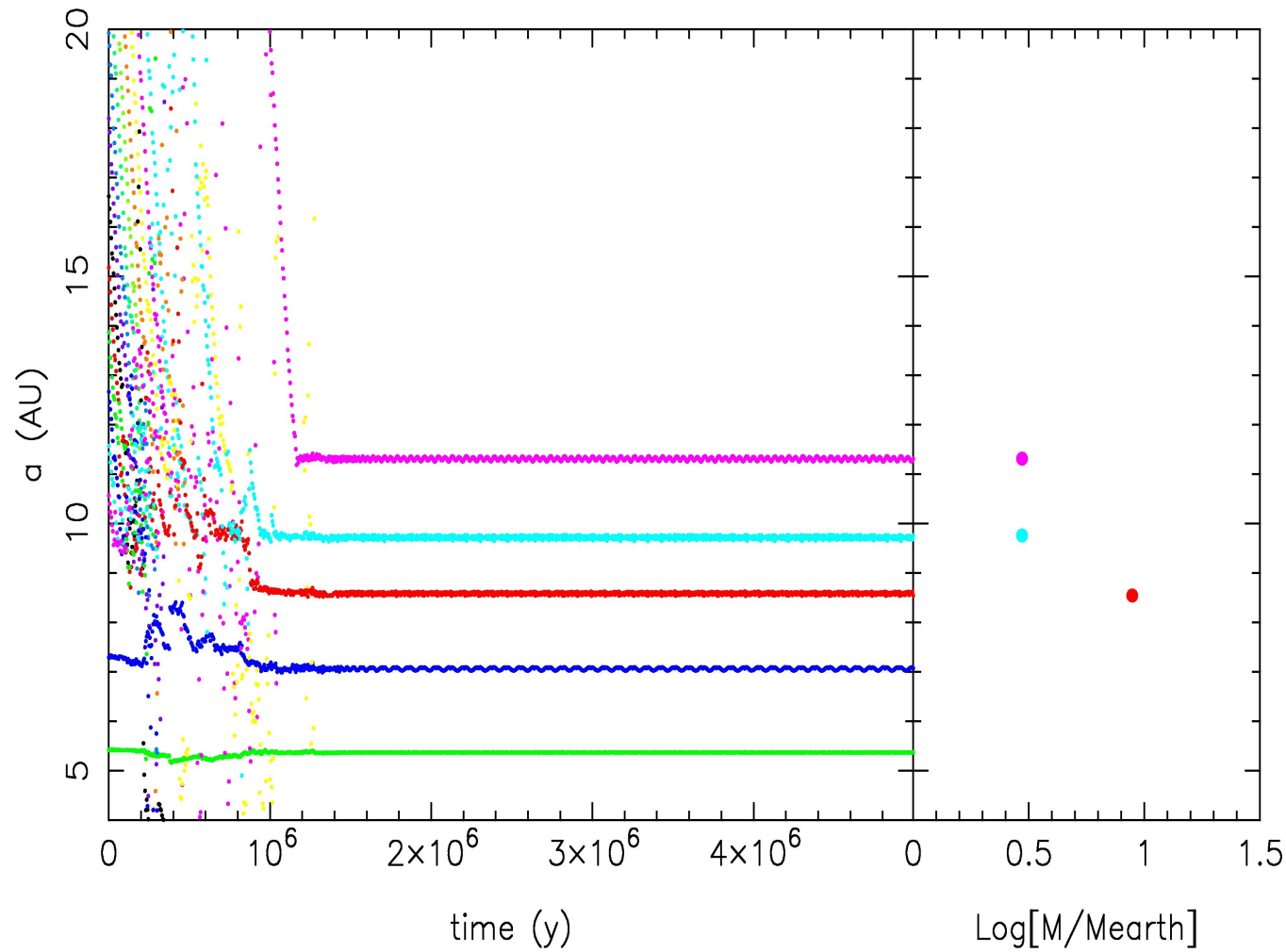


interplay  
between  
migration,  
resonance  
trapping  
and  
mutual  
scattering

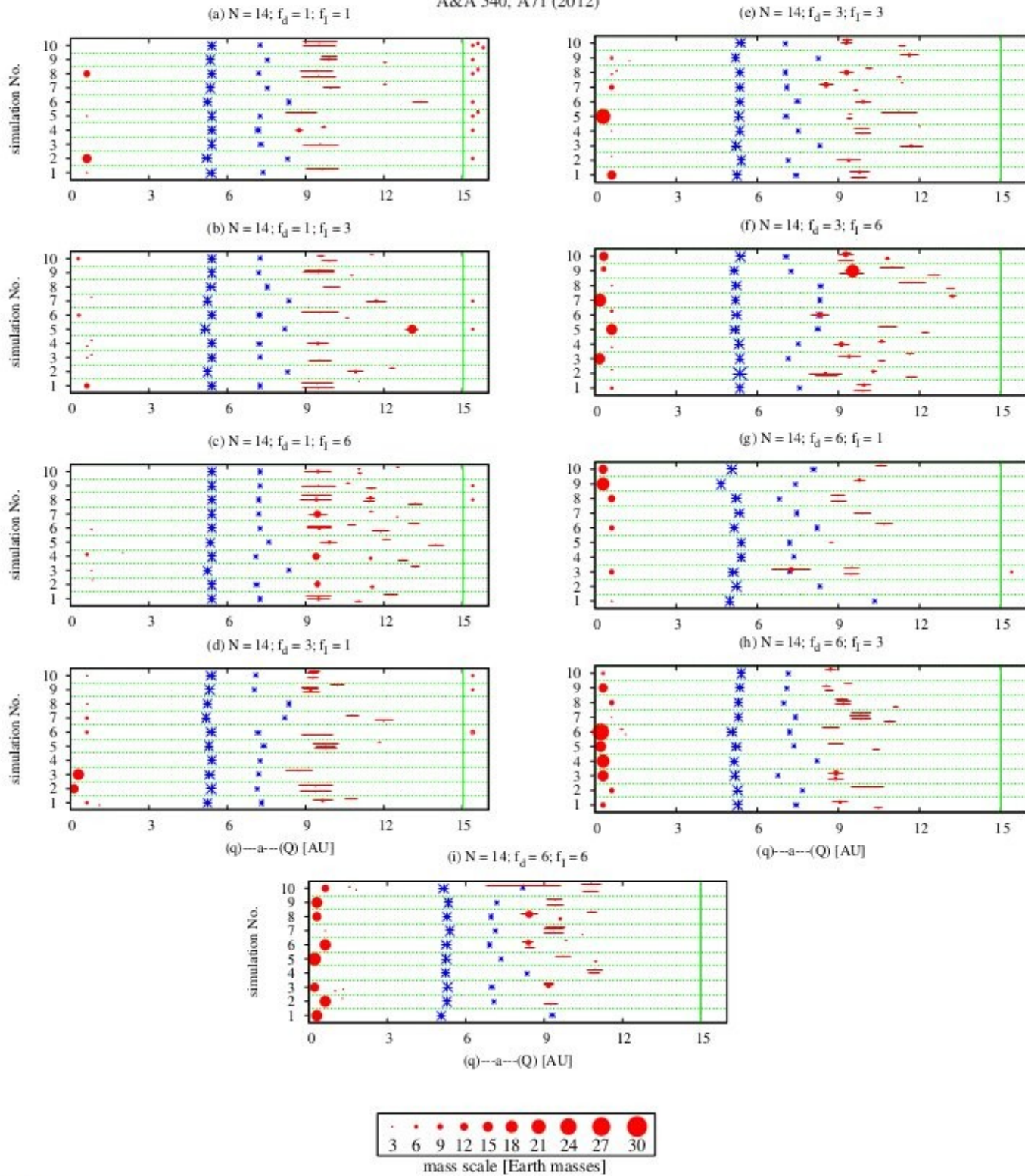


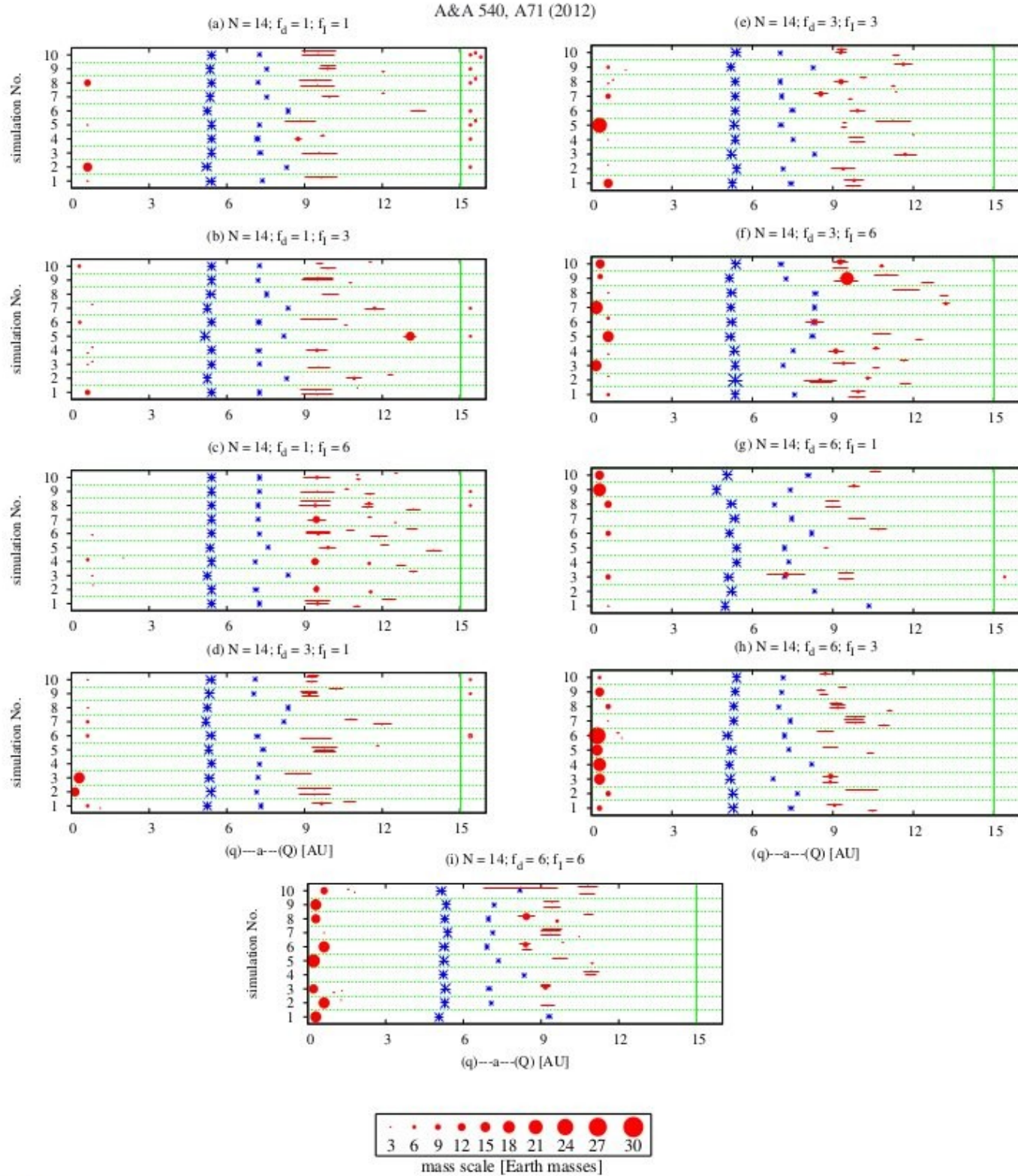
# Attempts to form Uranus and Neptune

- we assume:
  - Jupiter and Saturn are fully formed – still unresolved problem
  - Uranus and Neptune formed after Jupiter and Saturn – did not accrete as much gas
- $f_d$  (factor - gas surface density / MULTIPLY)
- $f_i$  (type-I migration factor / DIVIDE)
- 10 simulations per each combination of  $(f_d, f_i)$ 
  - $f_d = (1, 3, 6)$
  - $f_i = (1, 3, 6)$



- 14 embryos (3 EM) originally distributed in semi-major axis from 10 to 35 AU with  $e \sim 10^{-2}$  and  $i \sim 10^{-2}$  rad





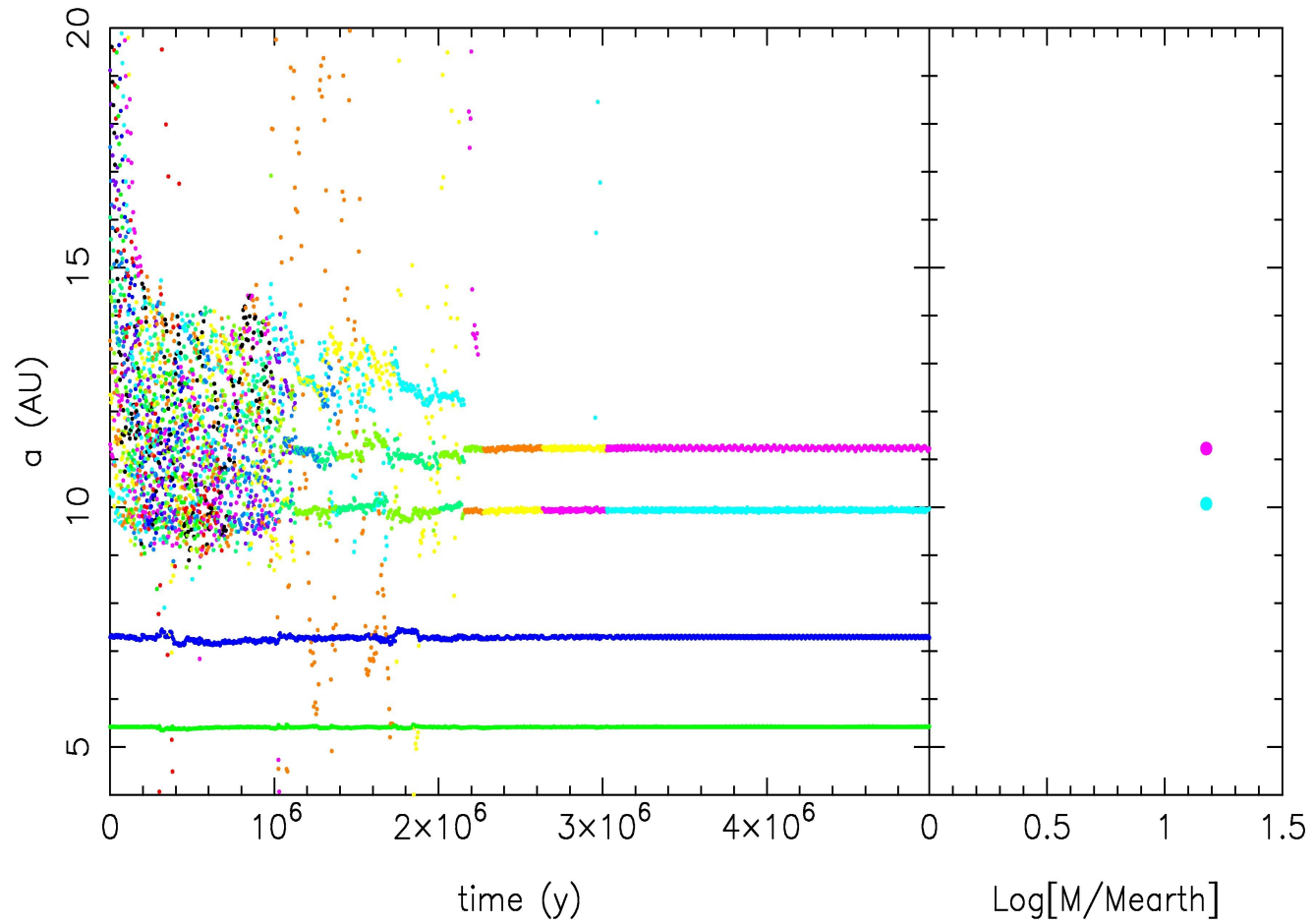
- **MASS LOST!**
  - insufficient total mass?
    - we performed another series of simulations with 28 embryos (each 3EM)

DOES NOT IMPROVE SIGNIFICANTLY!

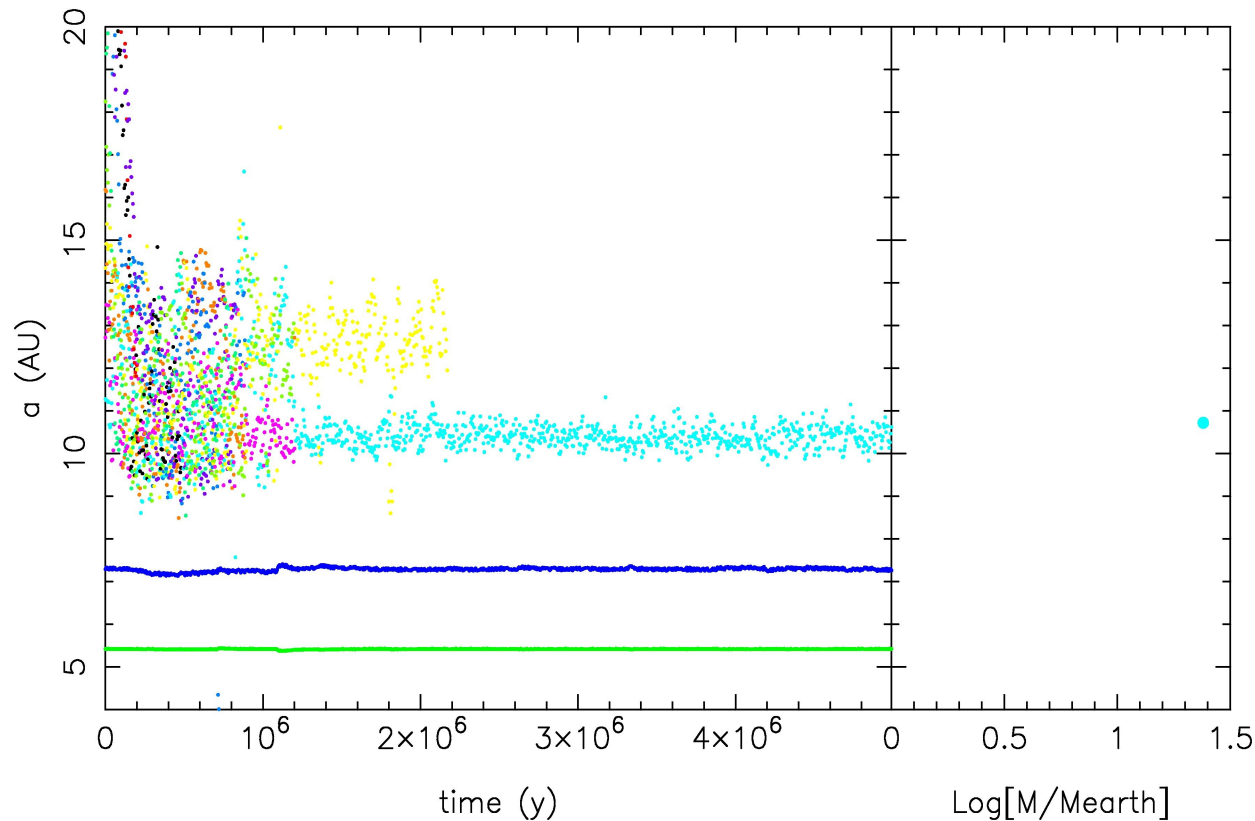
## A “planet trap” at the edge of Saturn’s gap

- previous problems – large part of the initial embryos was lost due to migration into the Jupiter-Saturn region (ejection or injection to inner SS)
- planet trap – prevent the embryos from coming too close to J and S
- our experiments show that the planet trap is very effective in reducing the loss of mass during the embryo’s evolution
- only one major core grows and the rest of the mass remains stranded in too many embryos in stable resonant configuration
- one simulation whose result is about perfect with regard to the SS structure, with only two cores surviving beyond Saturn, each with a mass of 15 EM

# Successful simulation - ONLY ONE!!!



# The effect of the turbulence of the disk



- torques are strong enough - dislodging from resonances - allowing close encounters and collisions

- cores protected from collisions by resonances
- 
- some level of turbulence in the disk might promote accretion
  - turbulence provides stochastic torques on the bodies - random walk of their semimajor axes

**Result from our tests: turbulence is helpful to break the isolation of planets BUT typically only one massive core is produced**



# Conclusions

- our simulations typically do not successfully reproduce the structure of the outer solar system - due to the stochasticity of the accretion process
- **only one** simulation is successful, with two cores of 15 EM produced and surviving beyond Saturn and no rogue embryos
- 2 major problems:
  - typically a large difference in mass between the first- and second-most massive cores – incompatible with U and N (compared masses)
  - final planetary system typically has many more than two embryos/cores
- the origin of Uranus and Neptune is **STILL NOT SOLVED BUT** we point out non-trivial problems that cannot be ignored!

# Thank you for attention...



more details: Jakubik et al. A&A 540, A71 (2012)