# High-Resolution Global N-body Simulation of Planetary Formation: Outward Migration of a Protoplanet

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# Overview

Carried out N-body simulations starting from the planetesimal disk ranging from the inner region to the outer region which includes the ice line.

1) Introduction
2) Model and Simulation method
3) Results (gravity between the planetesimals are essential for migration)
    (1) runaway bodies form in the inner edge of the disk and right behind the ice line
    (2) the runaway bodies scatter the surrounding planetesimals and start to migrate
    (3) the migration sustains while the planetesimals with small random velocity remains in the region close to the runaway body.
4) Discussion

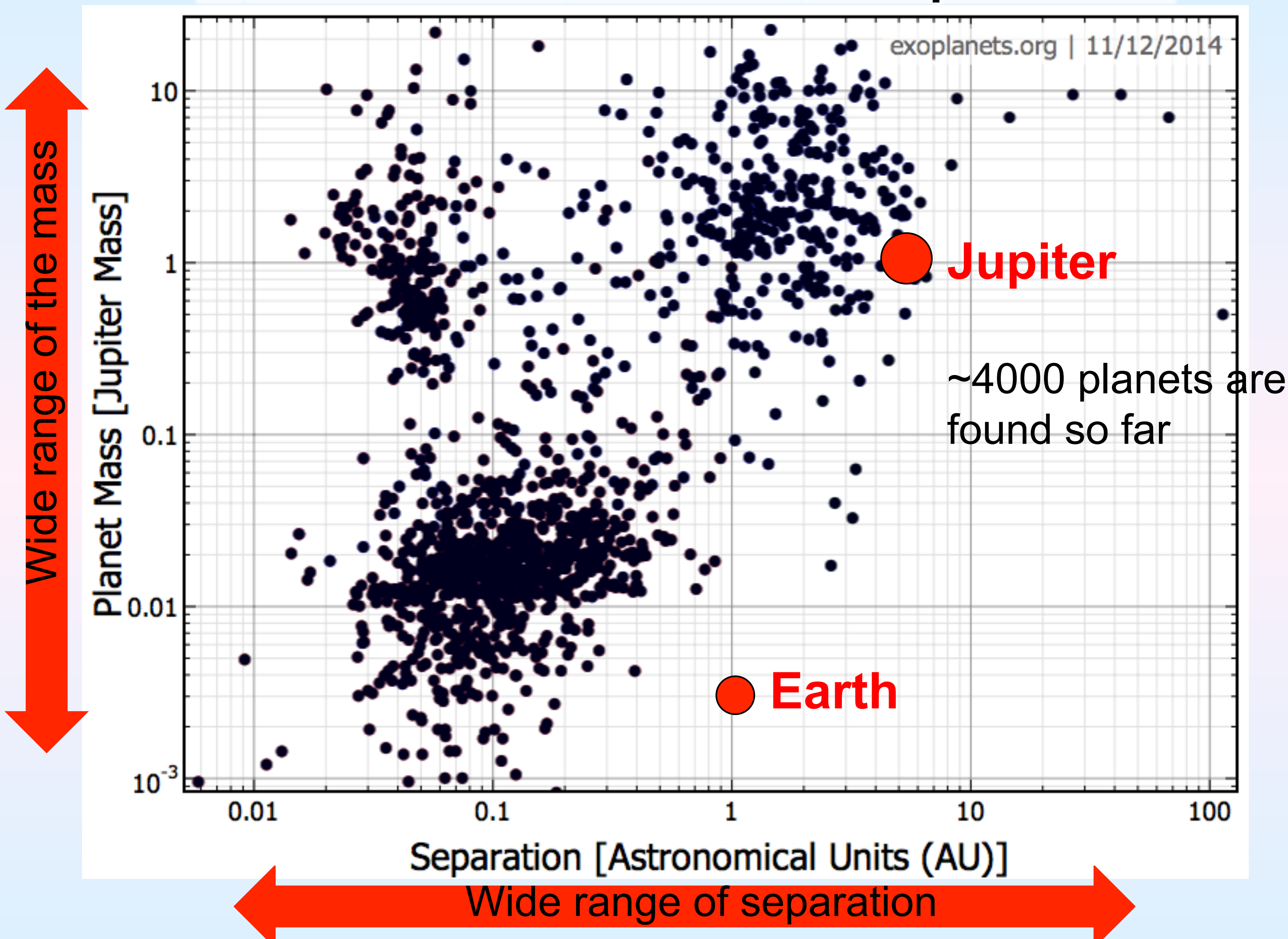
   Protoplanet which migrates outward：

   →can be the core of the giant planet

   Protoplanet which migrates inward：

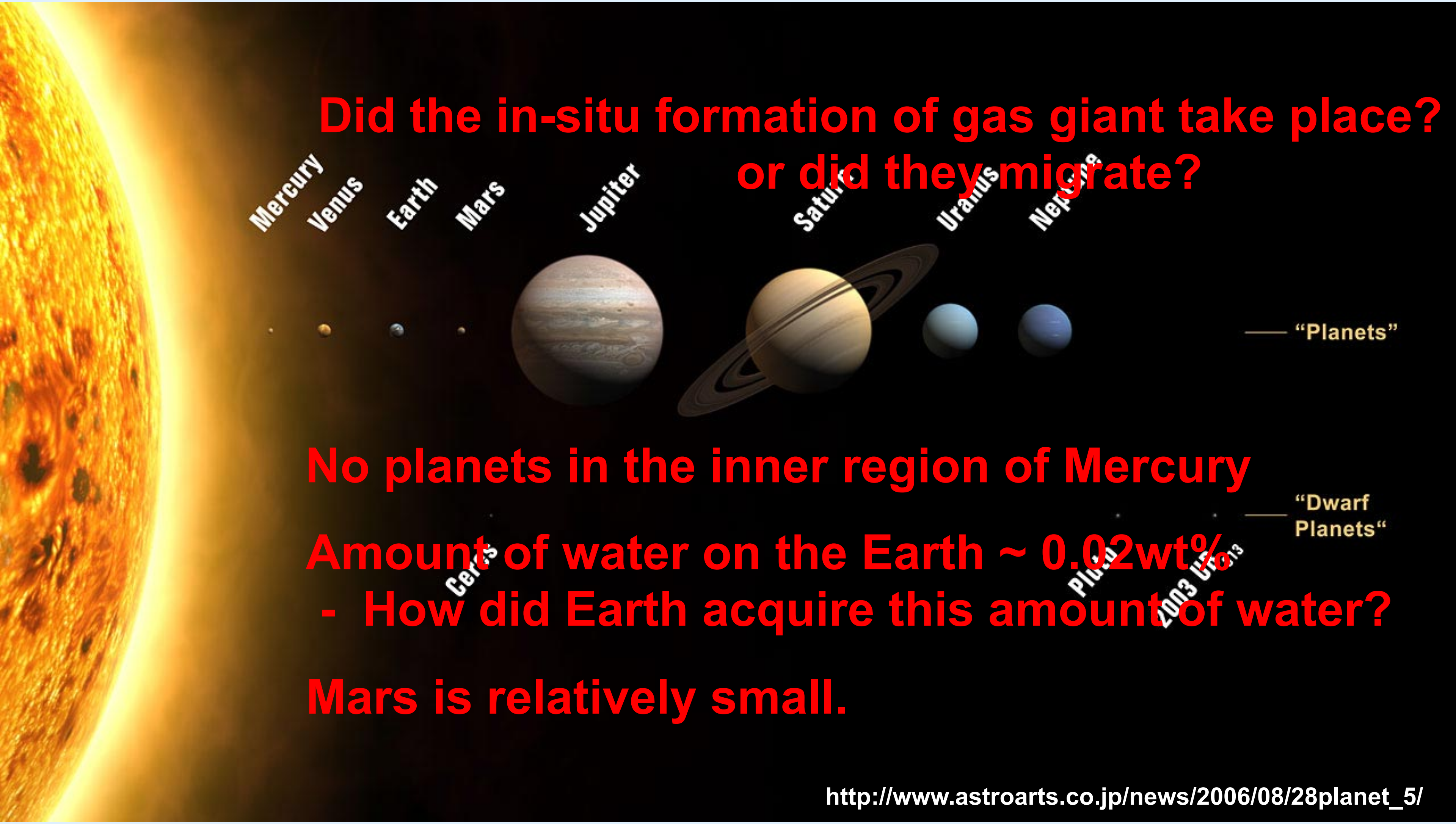
   →can carry water to the terrestrial planet

# Distribution of the Exoplanets




Systems unlike the Solar systems are found.
"Generalized formation theory" has not been established.

# Our Solar System




Did the in-situ formation of gas giant take place?
or did they migrate?

No planets in the inner region of Mercury

Amount of water on the Earth ~ 0.02wt%
- How did Earth acquire this amount of water?

Mars is relatively small.

**There are a lot of issues that have not been clarified.**
**We still do not know how our Solar system formed.**

# The reasons why planet formation has not been clarified yet, while a lot of N-body simulations have been performed

- Simulations with wide planetesimal disks are required

  past simulations were restricted to small range planetesimal disks

- Initial planetesimal mass was large

  large body may form density structure in the planetesimal disk, and the structure may affect the planet's orbit.

- Perfect accretion is assumed

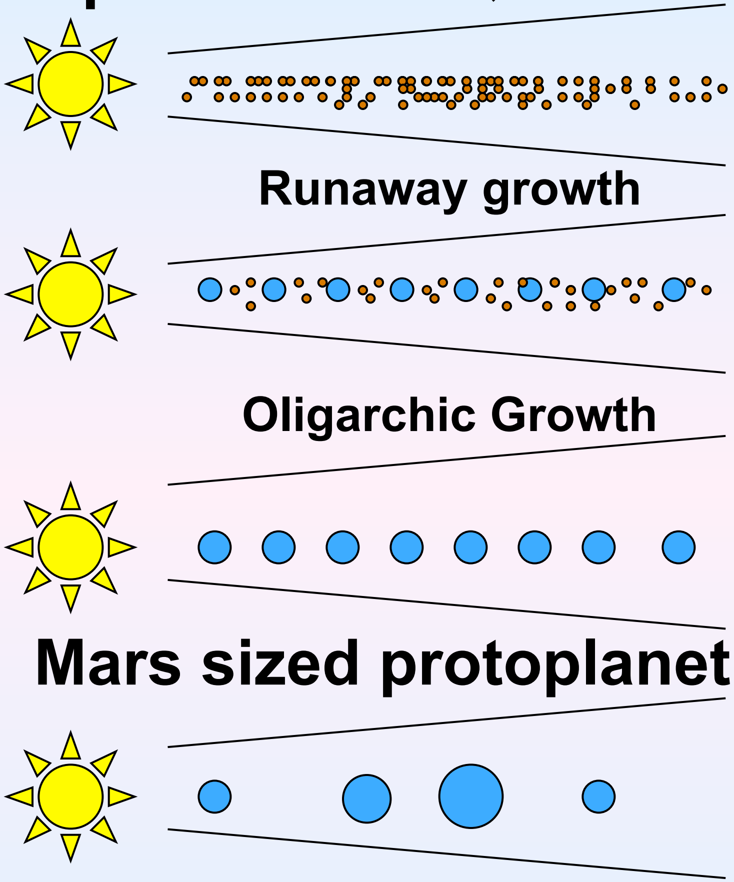
  Fragments may affect the planets' orbits as well.

# Widely Accepted “Classical” Formation Theory

# Terrestrial Planet Formation

**planetesimal**（~km size）

(Greenberg et al. 1978,
Wetherill and Stewart 1989, 1993,
Kokubo and Ida 1996,
Inaba et al. 2001)




(Makino et al. 1998
Kokubo and Ida 1998)

(Weidenschilling et al. 1997
Kokubo and Ida 1998,2000,2002)

**Isolation mass**

**Giant impact stage**

**Terrestrial Planet**

This scenario has been investigated with N-body simulations of several thousand particles.

It is assumed that this can be extrpolated to outer region

# In-situ Formation Timescale of Gas Giant Cores

Time scale for the protoplanets to grow to the gas accreting mass
Around 30AU

$$t_{\rm formation} \sim 10^{10} \rm years$$

$$t_{\rm solar.system} \sim 10^{9} \rm year < t_{\rm formation}$$

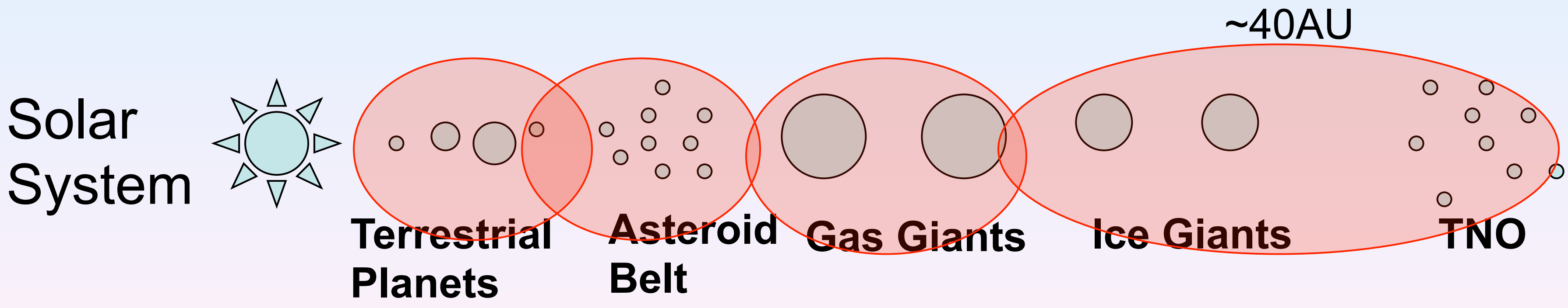
$$t_{\rm gas.disk} \sim 10^{6} \rm year < t_{\rm formation}$$

Form the planets in the inner region and make them migrate outward … such as Nice model has been proposed

How the initial conditions of Nice model are made is not clear yet.

If we carry out large scale simulation…..

# Expected Outcome of Large Scale Simulations




focus

- Planetesimal accretion in the disk including the ice line (Inclusion of the Solid density increase at the ice line)
- Orbital evolution of gas accreting planet (effect of gradual increase of mass. Does it effect the dynamics of the planetesimal disk?)
- Explanation of water abundance on the Earth

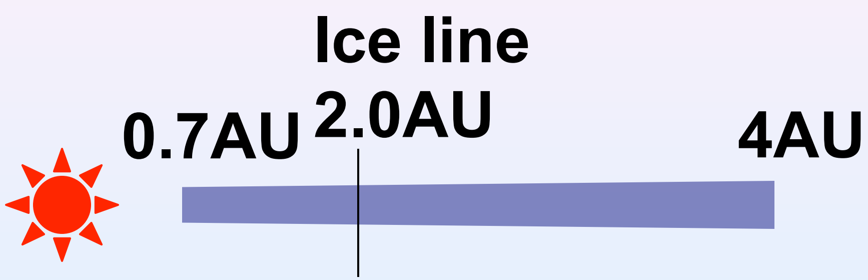
# Method

•Kninja : Parallelized N−body code for planet accretion
（Kominami et al. in prep）

•Machine : K-computer

•Number of nodes used ~1024
•Performance: 30% of the theoretical peak
•Simulation time ~ about a week

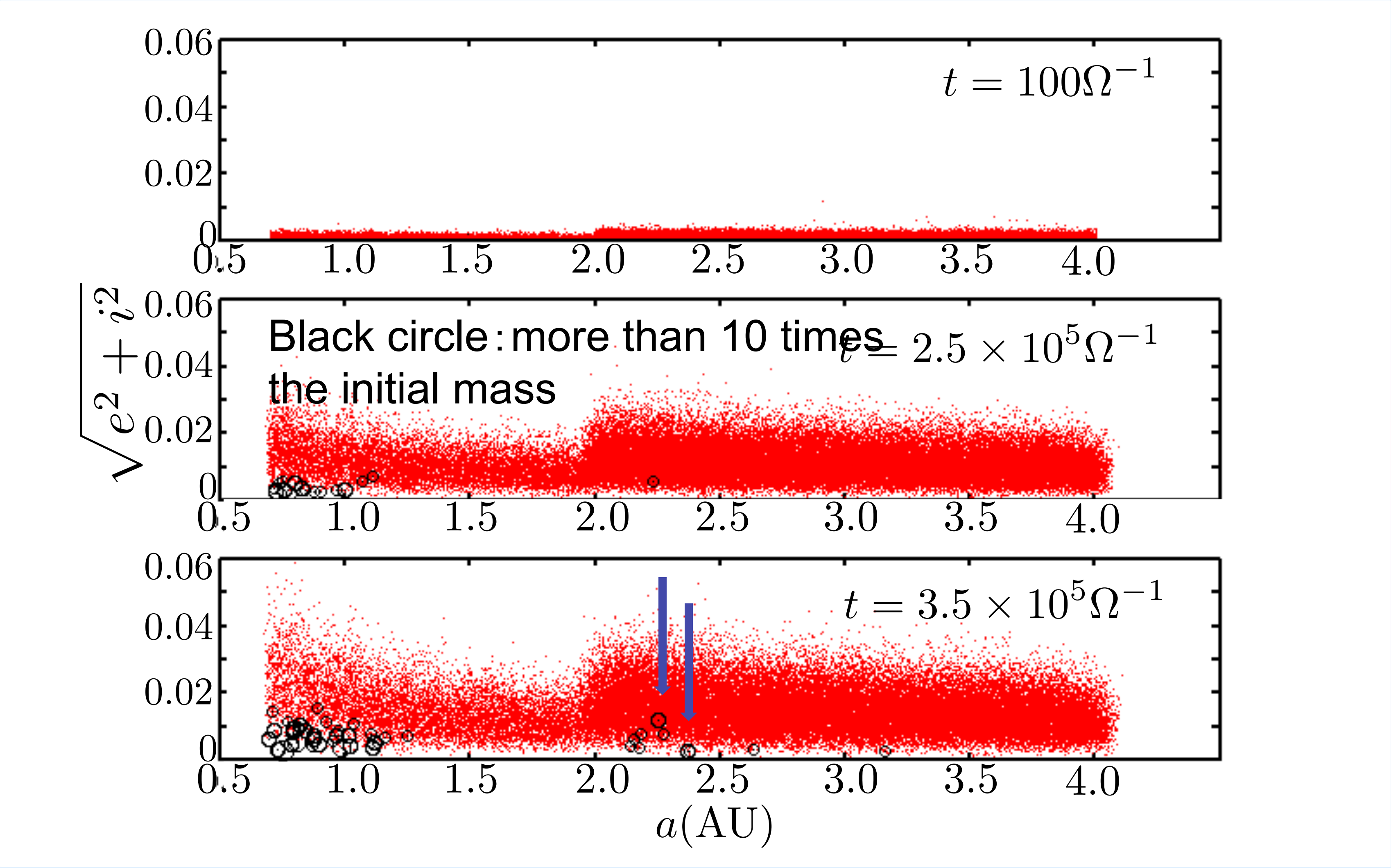
## Simulation 1 ：Initial Condition




・initial planetesimal number ＝ 82362（each planetesimal mass~ $10^{24}$ g）

・Disk surface density = MMSN $< \tilde{e}^2 >^{1/2} = 2 < \tilde{i}^2 >^{1/2} = 4$
(Kokubo and Ida 1998)

# Runaway bodies beyond the ice line

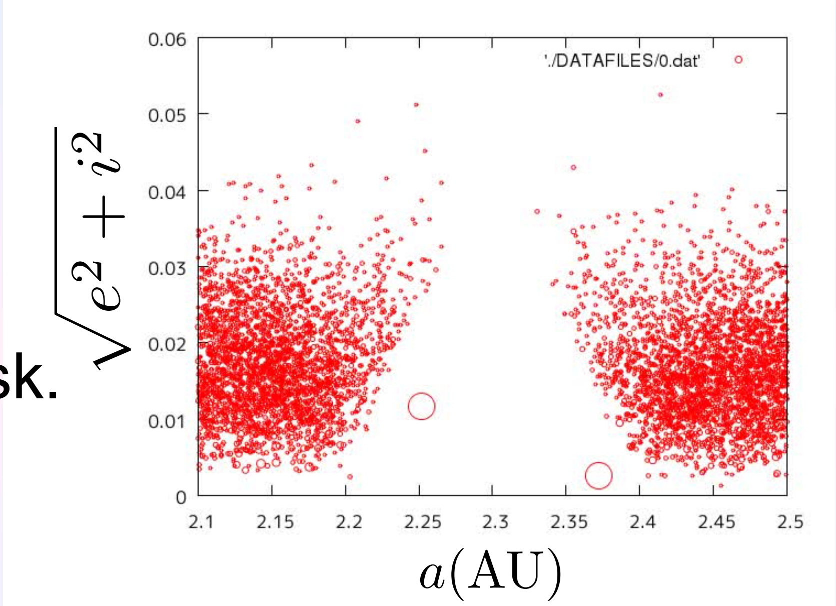



**Runaway bodies form at the inner edge and right behind the ice line**

# Initial Condition of Simulation 2

The protoplanet formed right behind the ice line

- They will eat up the planetesimals within several Hill radius
- They will gradually accrete gas




Assumption:
Increase the mass of the protoplanet to 0.1Earthmass.
Gap forms in the planetesimal disk.

→Protoplanet/Planetesimal ~ 100

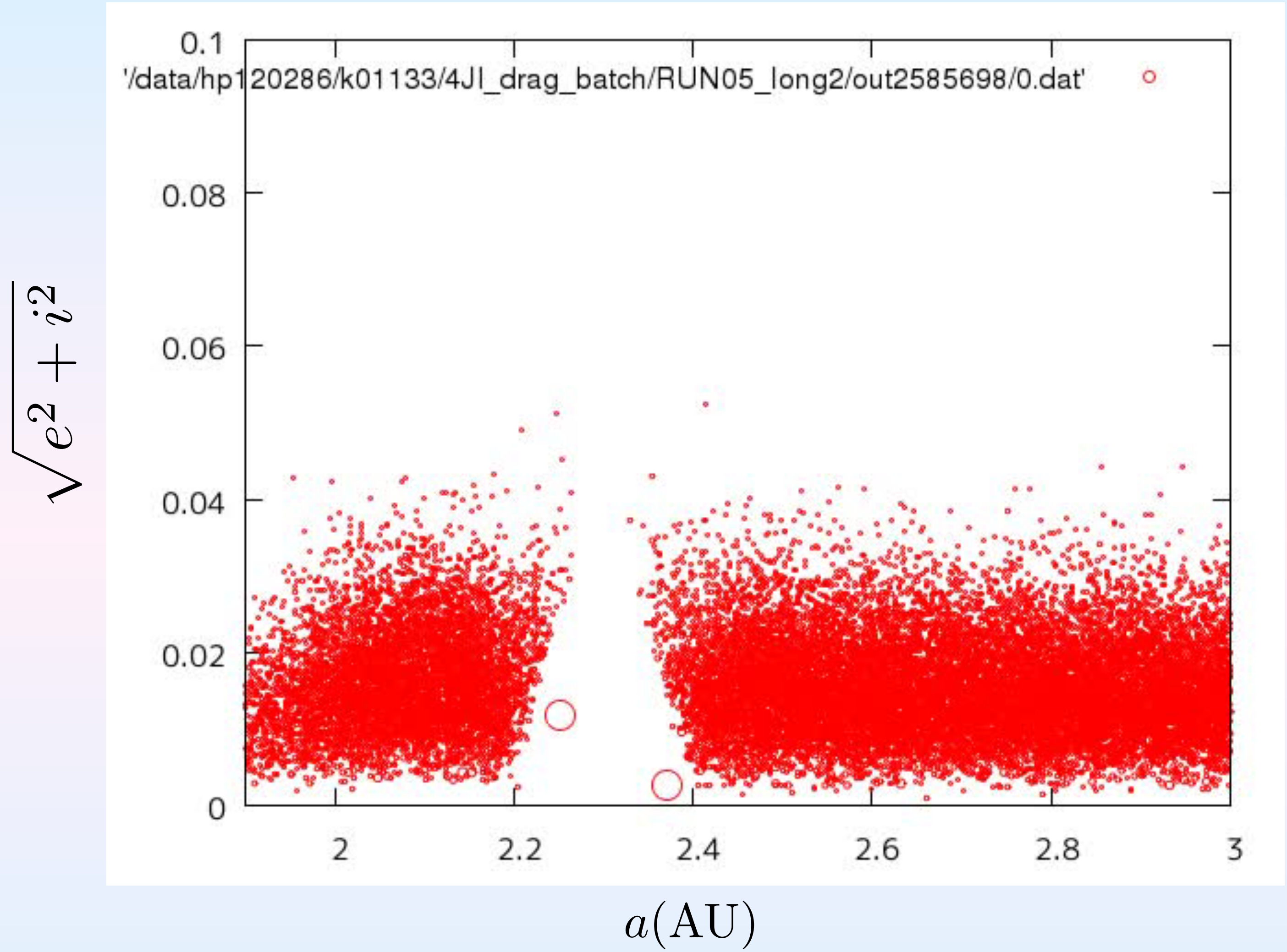
→Planetesimal Driven Migration

(e.g. Ida et al. 2000, Minton & Levison 2014)

Formation of density structure around the protoplanet results in the asymmetric torque. The protoplanet migrates to one direction.

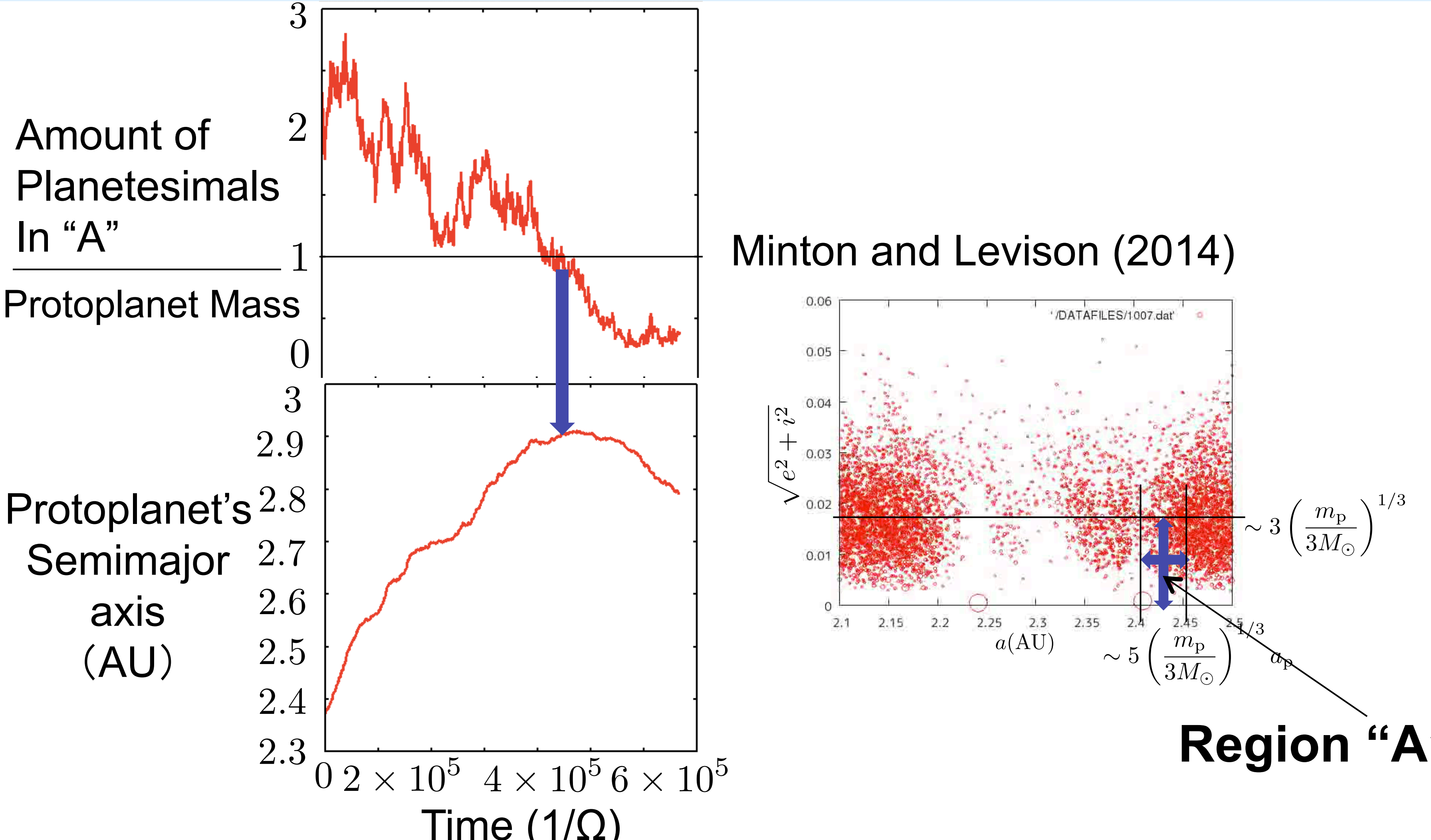
We performed first simulation with full gravity of planetesimals.

# Protoplanet Migration




The protoplanet scatters the planetesimals with low random velocity. The outside protoplanet moves outward and the inner protoplanet Moves inward.

# Protoplanet Migration and the Scattered Planetesimals




Scattering of the planetesimals with low random velocity within several Hill radius of the protoplanet triggers the migration.

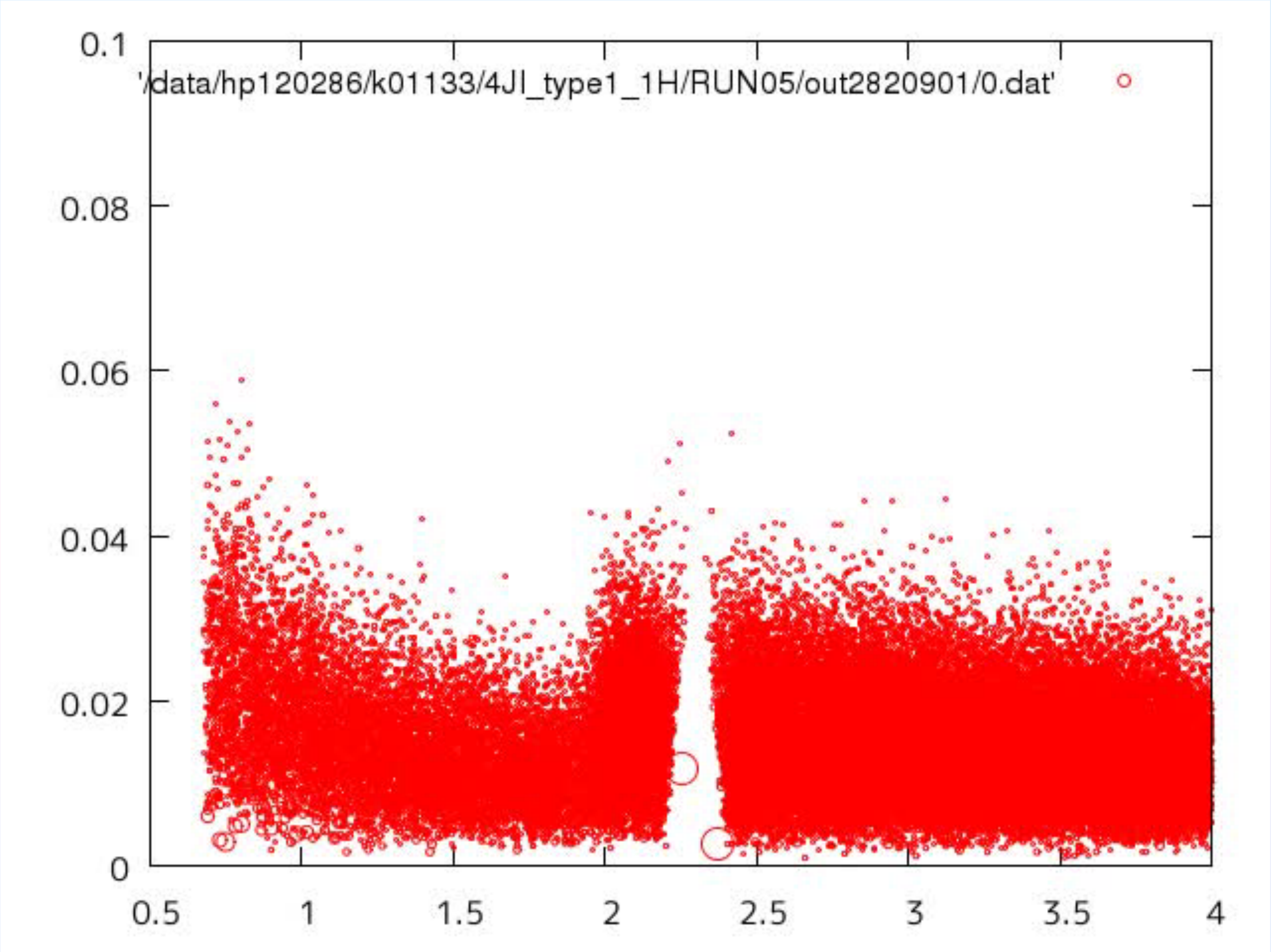
Increase of planetesimals’ random velocity stops the migration.

The increase is due to
the viscous stirring of the planetesimals

Can be damped by gas drag

We included the effect of the gas disk
gas drag & type-I migration

# Protoplanet Migration with Gas Drag and Type-I Migration




$\sqrt{e^2 + i^2}$

$a(\mathrm{AU})$

The outward migration continues while it stops 2.9AU without gas.
The inner protoplanet does not stop migrating at the ice line.

# Summary and Discussion

We performed N-body simulations, starting with the planetesimal disks including increase of the solid surface density at the ice line.

→ resulted in protoplanets' inward and outward migraiton

(1) Runaway accretion at the inner edge and behind the ice line
(2) Runaway bodies scatter the planetesimals and migrate.
(3) Migration continues while the planetesimals with low random velocity stays within several Hill radius of the protoplanet

→Increase of random velocity works as a "break" of the migraiton

→Gas drag can control the migration

Protoplanets moved outward :

→can be the core of the giant planets

Protoplanets moved inward:

→can carry water to the terrestrial planet region

**Possible breakthrough of planet formation theory**