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

（微惑星の大領域集積計算：ガス円盤内での惑星の外側への移動）

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ABSTRACT

By means of fully self-consistent N-body simulations, we investigated whether the outward Planetesimal Driven Migration (PDM) takes place when the self gravity of the planetesimals and the effect of the gas disk are included. We first performed N-body simulations of wide planetesimal disks (0.7 – 4.0AU) which range over the ice line. Runaway accretion takes place at the inner edge of the disk and at the region right outside the ice line. In the next simulation, in order to investigate the orbital evolution of the runaway bodies formed in the region just outside the ice line, we replaced the runaway bodies by the protoplanet with about the isolation mass. We conclude that even when the self gravity of the planetesimals is included, under specific circumstances, outward migration of the protoplanets takes place. Cases with gas drag and type-I migration were performed as well. Here we show that inward type-I migration can be overcome by outward PDM. Our results suggest that formation of large bodies in the inner region of the disk and making them migrate outward is possible.

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Outline and Conclusion

Introduction

- Solar System
- Classical planet formation theory
- Two problems

Motivation and Model

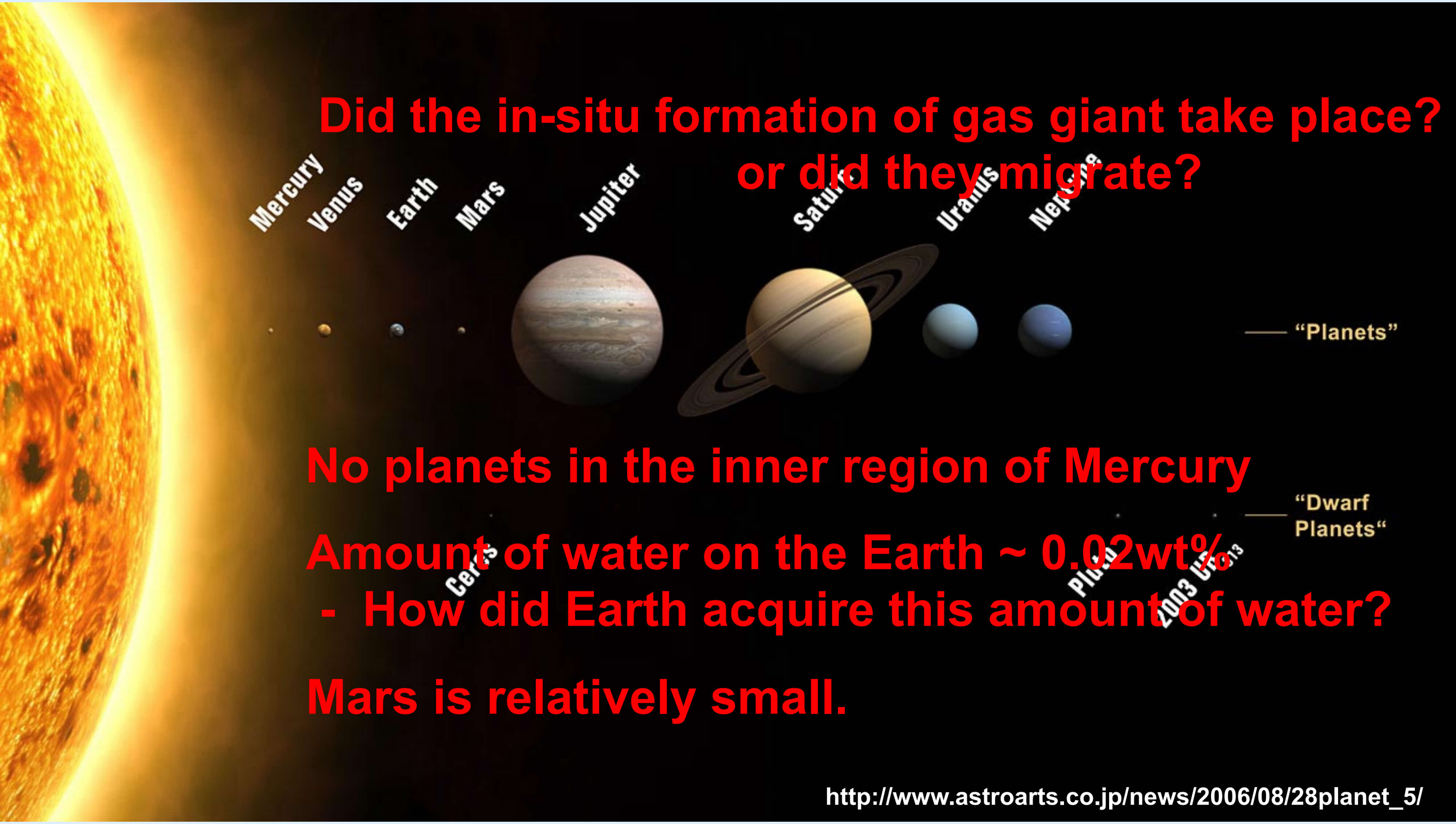
- Wide range of disk including the ice line

Results and Discussion

- Outward migration of the protoplanet within the gas disk

Planet migrating outward can be the core of giant planets
May be a breakthrough of planet formation theory

Our Solar System



http://www.astroarts.co.jp/news/2006/08/28planet_5/

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?**

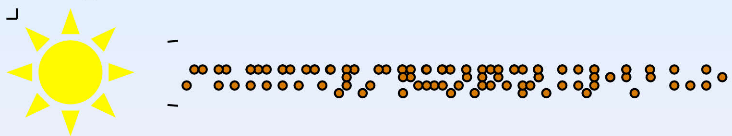
Mars is relatively small.

There are a lot of issues that have not been clarified. We haven't fully understood how our Solar system was formed.

Terrestrial Planet Formation

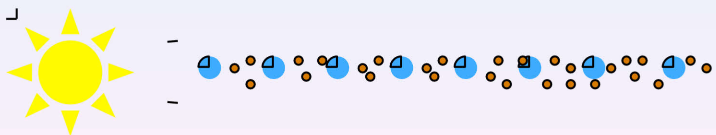
planetesimal（~km size）

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



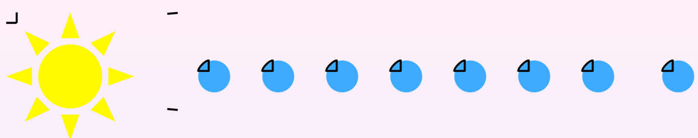
Runaway growth

(Makino et al. 1998
Kokubo and Ida 1998)



Oligarchic Growth

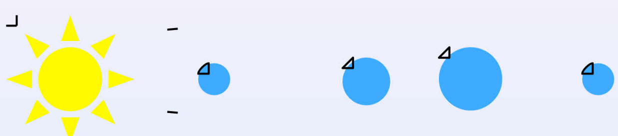
(Weidenschilling et al. 1997
Kokubo and Ida 1998,2000,2002)



Isolation mass

Mars sized protoplanet

Giant impact stage



Terrestrial Planet

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

Runaway growth and Oligarchic growth

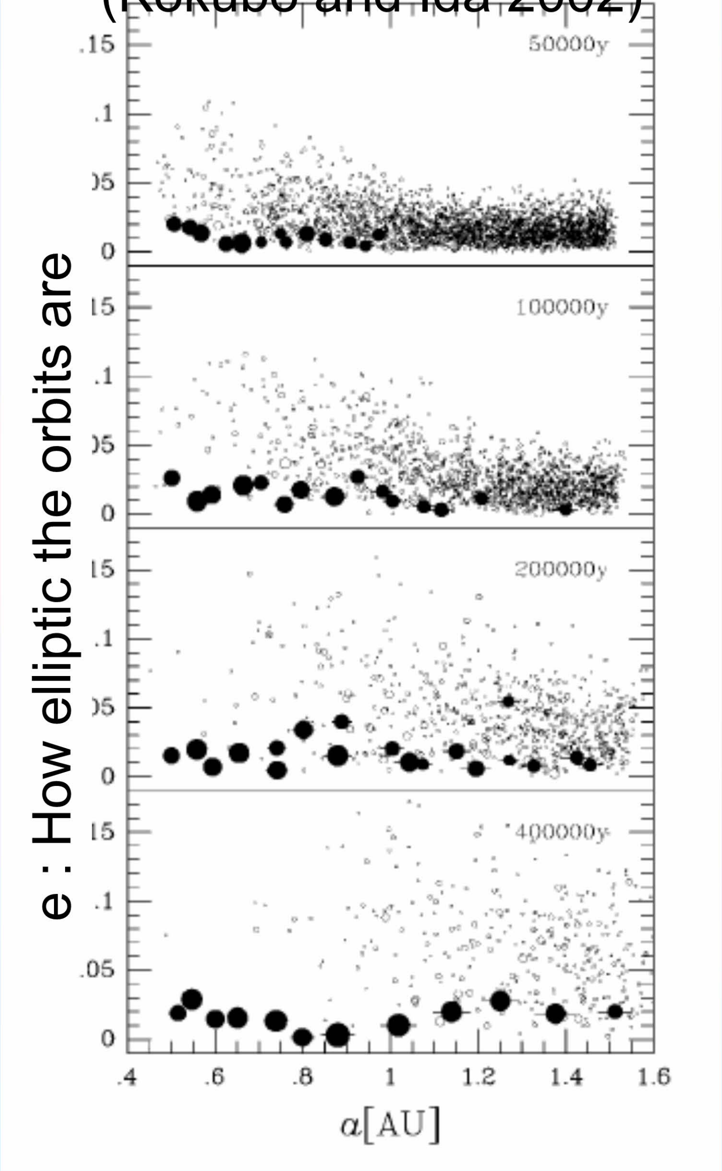
Accretion proceeds from the inner region.

Large bodies tend to grow faster.

The protoplanets line up with almost equal separation.

It is assumed that this can be extrapolated to outer region

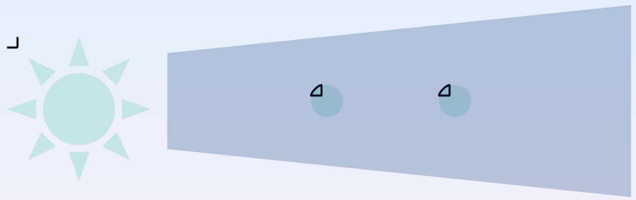
(Kokubo and Ida 2002)



Problems of Existing Model

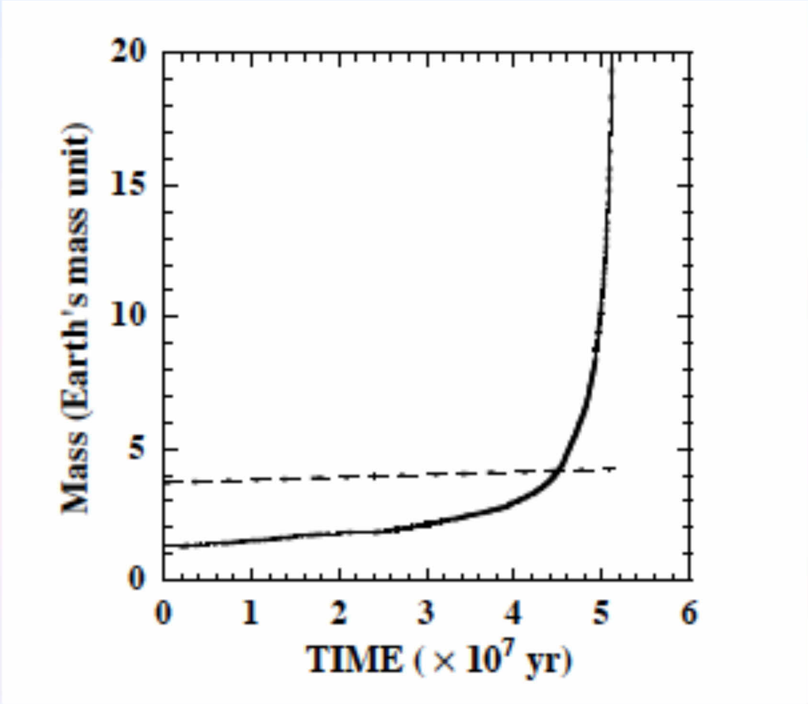
- Formation timescale
- Effect of gas disk

Gas Giant Formation



When the protoplanet's mass reaches to ~several Earth mass,

they start to accrete gas.



Ikoma et al. (1998)

Once they reach the critical mass, gas giant forms (Ikoma et al. 1998)

The protoplanets have to grow to the critical mass before the gas dissipates.

In-situ Formation Timescale of Gas Giant Cores

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

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

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

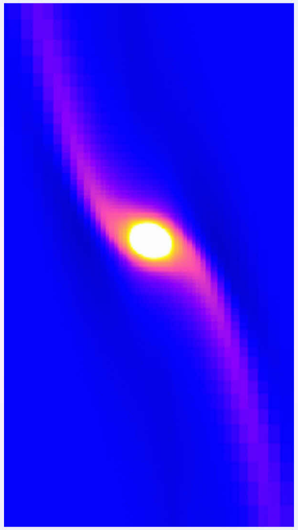
$$t_{\mathrm{gas.disk}} \sim 10^{6}\mathrm{year} < t_{\mathrm{formation}}$$

In-situ formation can not explain
the Solar system structure

Effect from the Gas Disk

(1) gas drag：damps *a,e,i*
(Adachi et al. 1976, Tanaka & Ida 1999)

(2) Tidal interaction with the gas disk：damps *a,e,i*
(e.g. Ward 1986, Tanaka et al. 2002, Tanaka and Ward 2004)



Planet triggers a wave structure

↓

The structure exerts a torque on the planet

↓

Results in angular momentum decrease

(Morohoshi and Tanaka 2003)

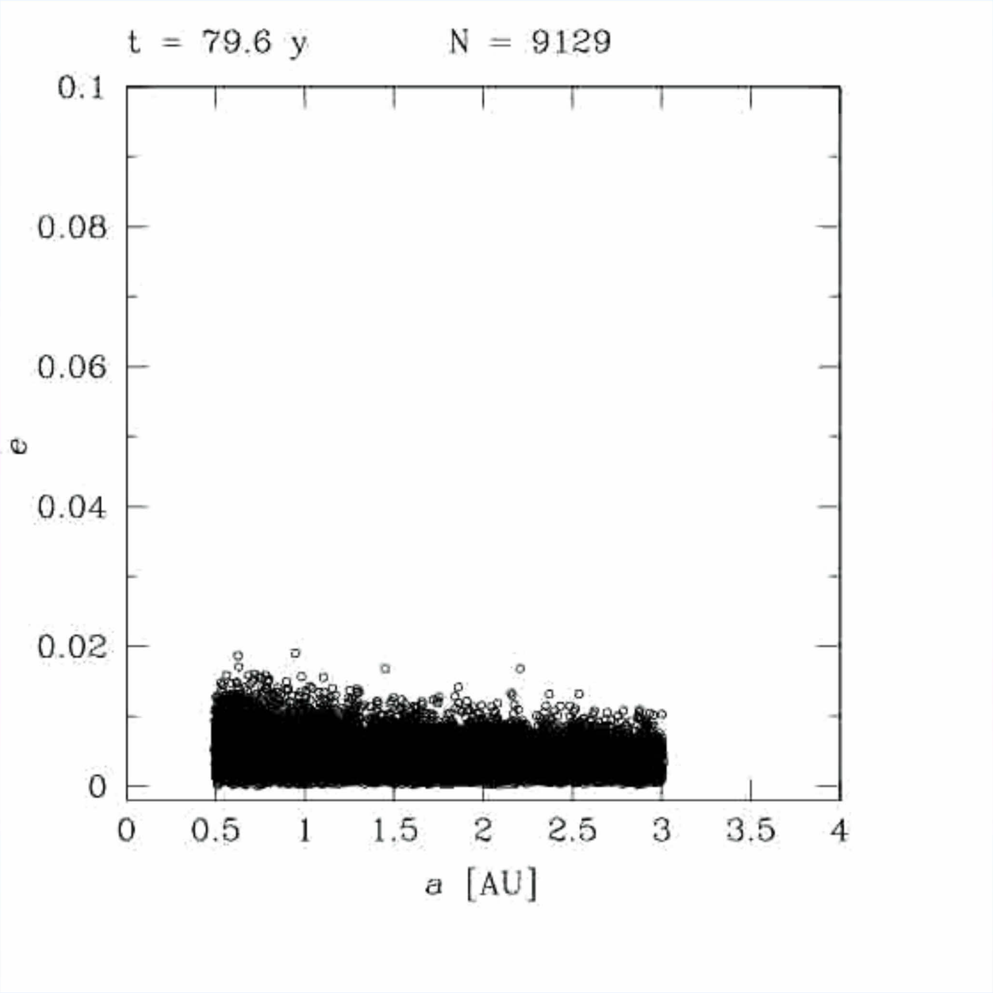
Planet's inward Type-I migration

(1) Gas drag $\rightarrow \tau_{\mathrm{gas}} \propto m^{1/3}$

(2) Tidal interaction with the gas disk $\rightarrow \tau_{\mathrm{grav}} \propto m^{-1}$

When $m > m_{\mathrm{moon}}$, type-I migration effect drags the planet toward the Sun

Planets Falling into the Sun



You can see that planets are moving inward, falling into the Sun.

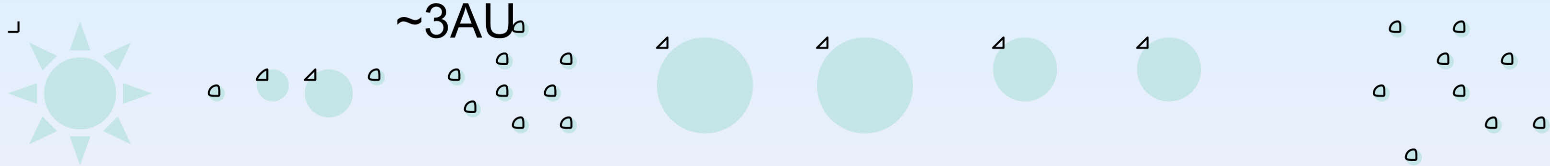
We can not make Jupiter this way.

In order to form giant planets…

1: Form a planet in the inner region of the disk

2: Make the planet migrate outward

The Ice Line



The line that the water becomes ice(150-170K)

Assuming that the disk is optically thin,
by equating radiation from the central star($\pi d^2 L_* / 4\pi r^2$, *d* is dust size)
and the black body radiation of the particles in the disk($4\pi d^2 \sigma T^4$),

$$T \simeq 2.8 \times 10^2 \left(\frac{r}{1\mathrm{AU}} \right)^{-1/2} \left(\frac{L_*}{L_\odot} \right)^{1/4}$$

In our Solar system right now, it is at 2.7 AU

However, in the past, it may have been at different places due to the viscous accretion rate of the disk and/or the evolution of the central star (Oka et al. 2011)

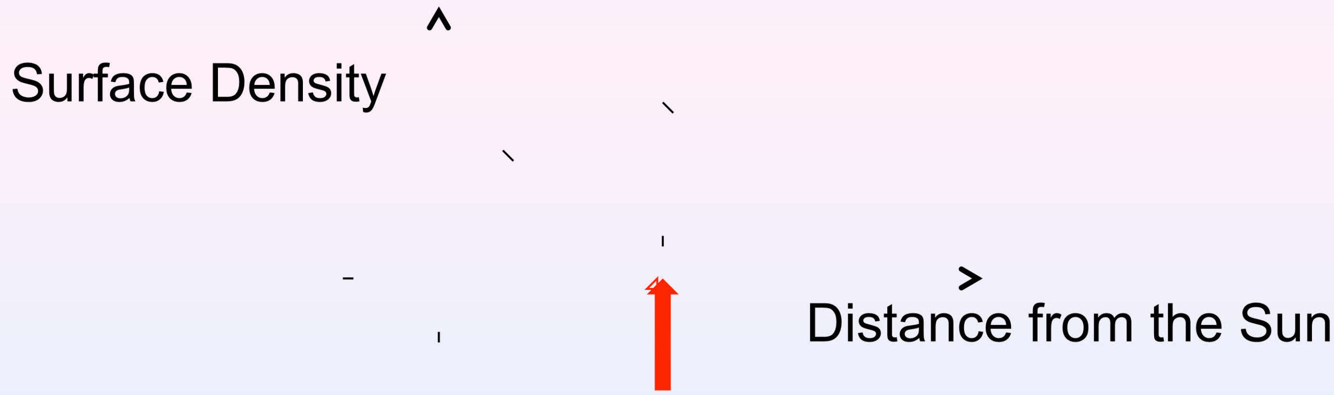
Surface Density Increase at the Ice Line

Solid surface density in the Standard disk
(The amount of solid that reproduces the Solar system)

$$\sigma_{\rm dust} = 7.1 \times \left(\frac{r}{1\rm AU}\right)^{-3/2} [\rm g\ cm^{-2}] \quad \text{for } 0.35\text{AU} < a < 2.7\text{AU},$$

$$\sigma_{\rm dust} = 30 \times \left(\frac{r}{1\rm AU}\right)^{-3/2} [\rm g\ cm^{-2}] \quad \text{for } 2.7\text{AU} < a < 36\text{AU},$$

(Hayashi et al. 1985)



Ice line (2.7AU)
Water becomes ice and the surface density increases

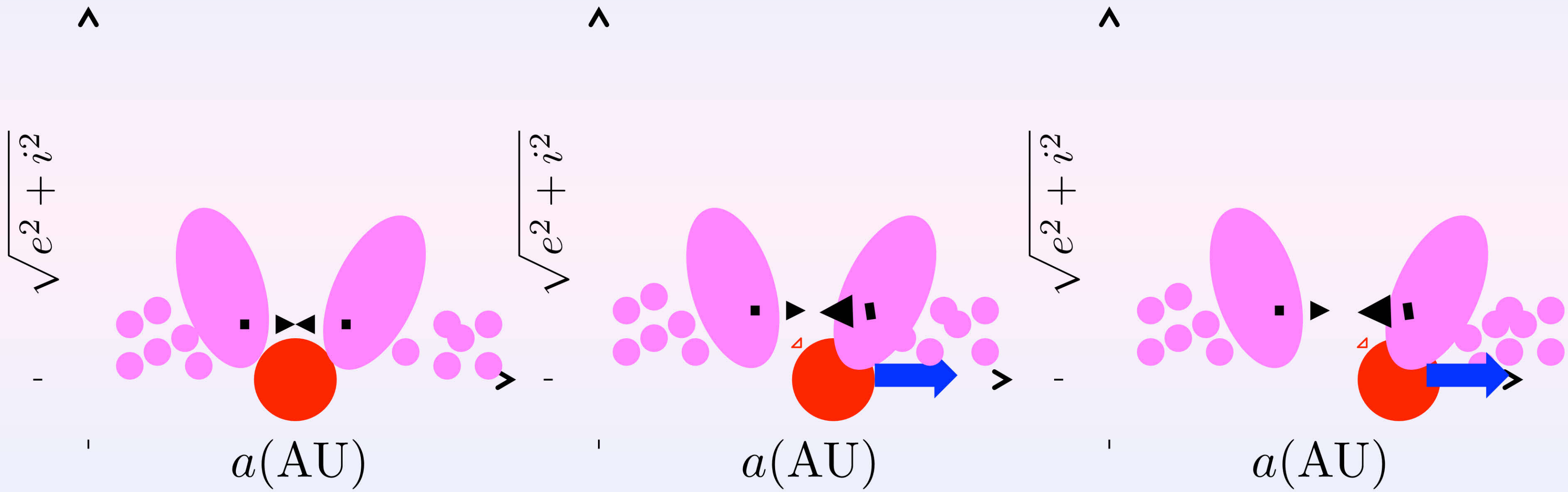
When the surface density is large, it is easier to form large bodies. Possible giant planet's core formation region is right outside the ice line and the inner edge of the disk

Planet's Outward Migration

When the Protoplanet/Planetesimal ~ 100

→Planetesimal Driven Migration

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



Protoplanet scatters the planetesimals. Planetesimals have symmetric distribution.

If a "Kick" is added to the protoplanet, the distribution becomes asymmetric

Number of planaetesimals at the right is larger and this asymmetric distribution continues

Planet's Outward Migration

When the 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.

In order to reproduce this migration, we need to simulate $\sim 10^5$ planetesimals' orbital evolution for at least $\sim 10^5$ orbits

We developed a parallel N-body planet accretion code which enables this simulation

Performed on Super Computer “K”

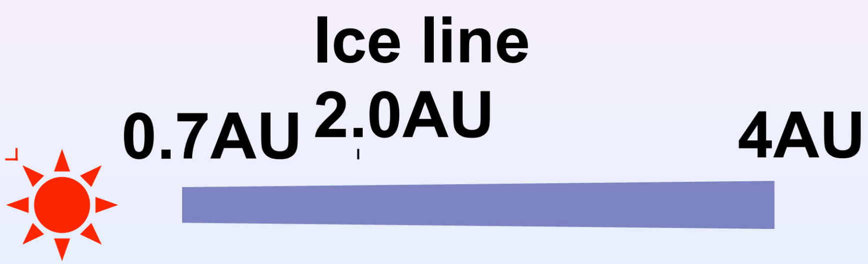
http://www.aics.riken.jp/jp/k/system.html

Method

- Kninja : Parallel N−body code for planet accretion
  （Kominami et al. in prep）
- Machine : K-computer

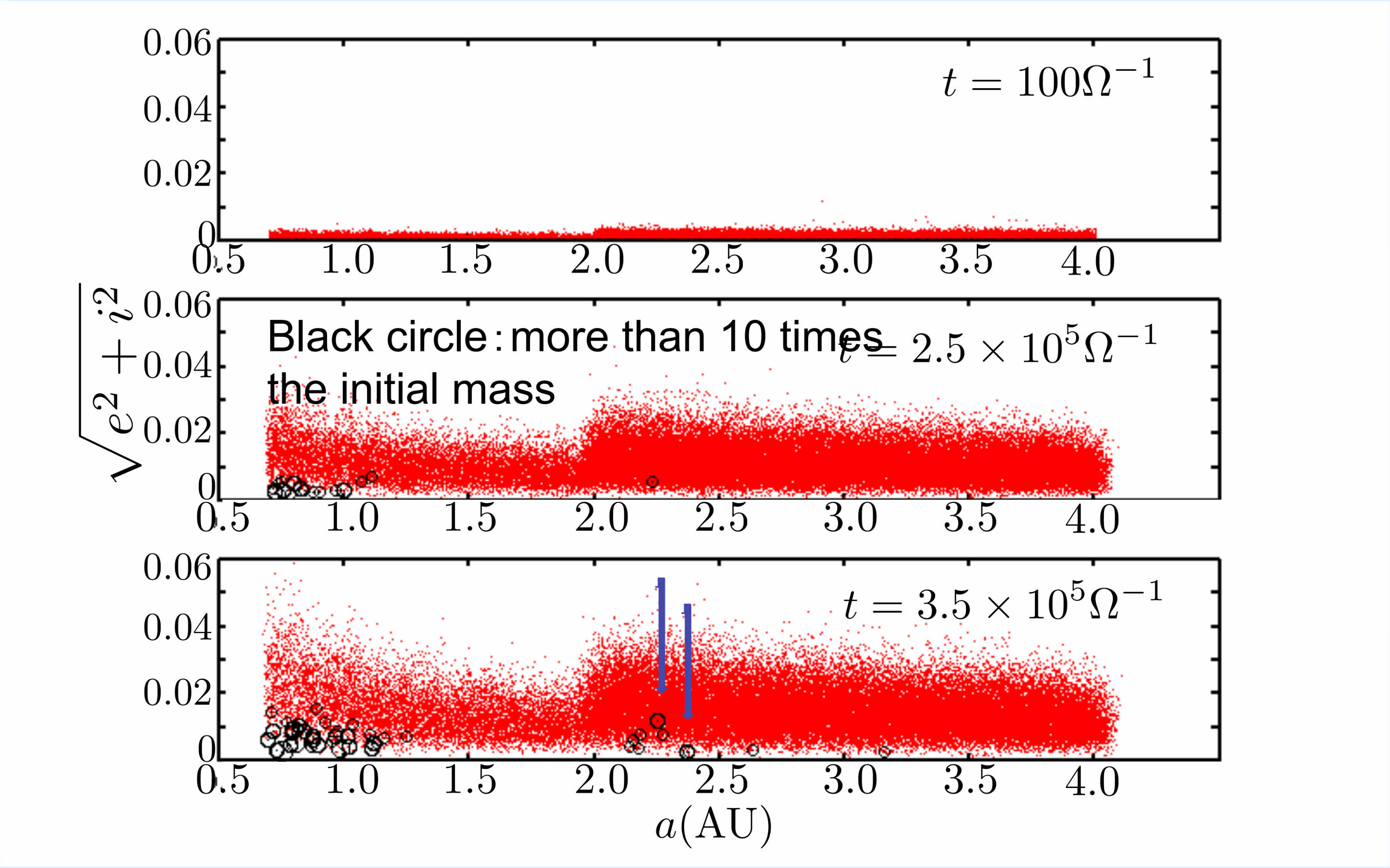
- Number of nodes used ~1024
- Performance: 30% of the theoretical peak
- Simulation time ~ about a week

Initial Condition for the 1st Stage Simulation



- 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

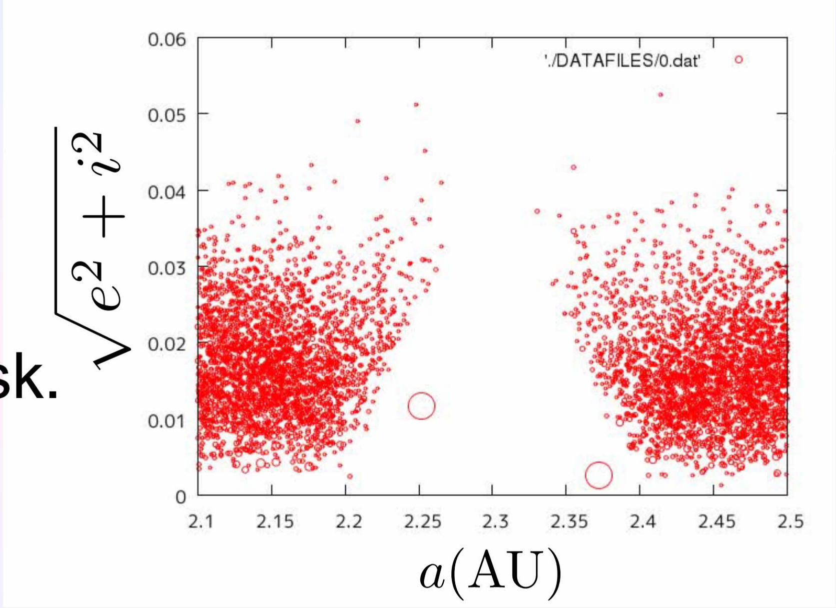


Runaway bodies form at the inner edge and right behind the ice line

Initial Condition of the 2nd Stage Simulation s

The protoplanet formed right behind the ice line

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

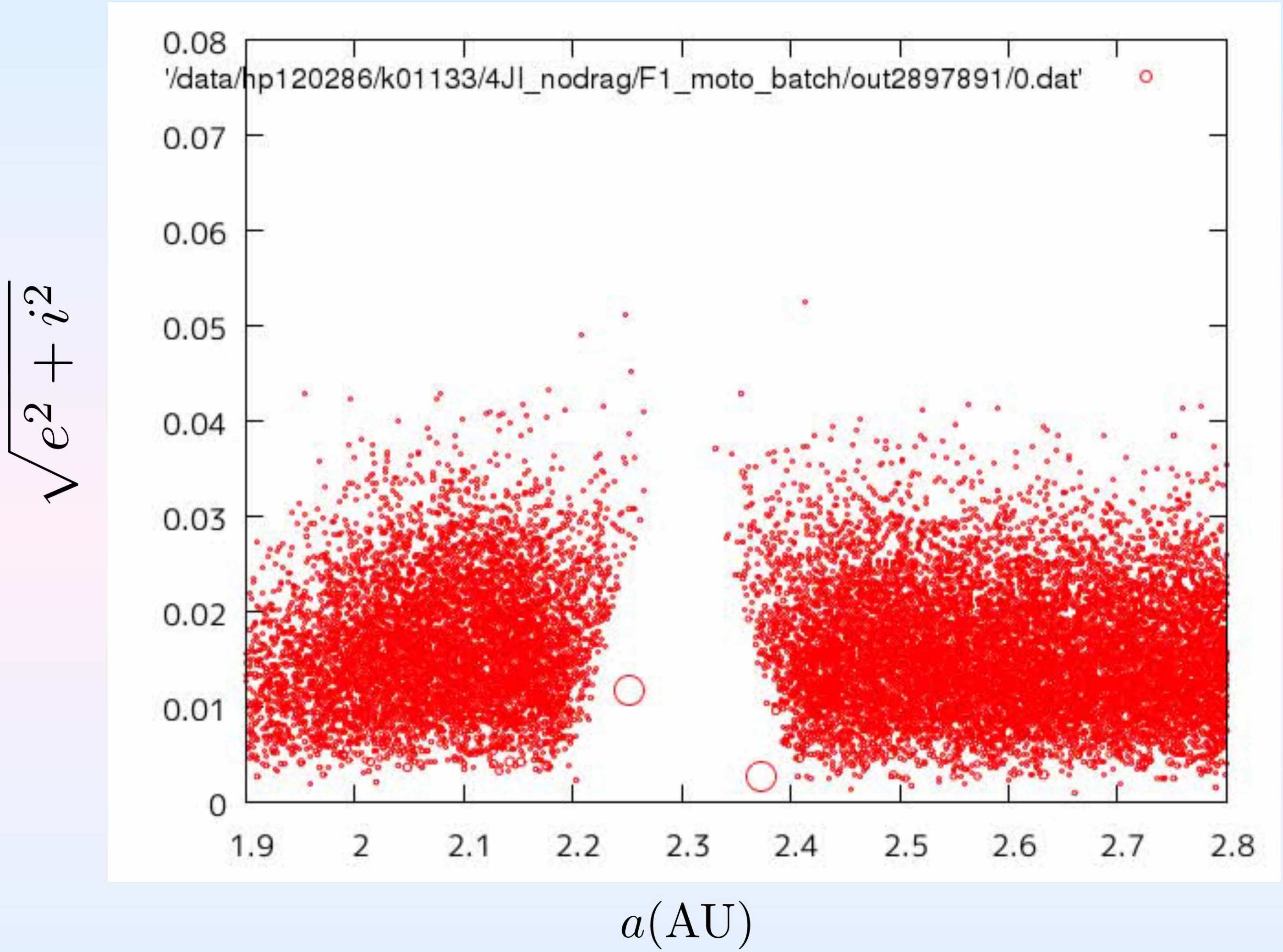


Assumption:
Increase the mass of the protoplanet to 0.1Earthmass.
Gap forms in the planetesimal disk.

→Protoplanet/Planetesimal ~ 100
→Planetesimal Driven Migration
(e.g. Ida et al. 2000, Minton & Levison 2014)

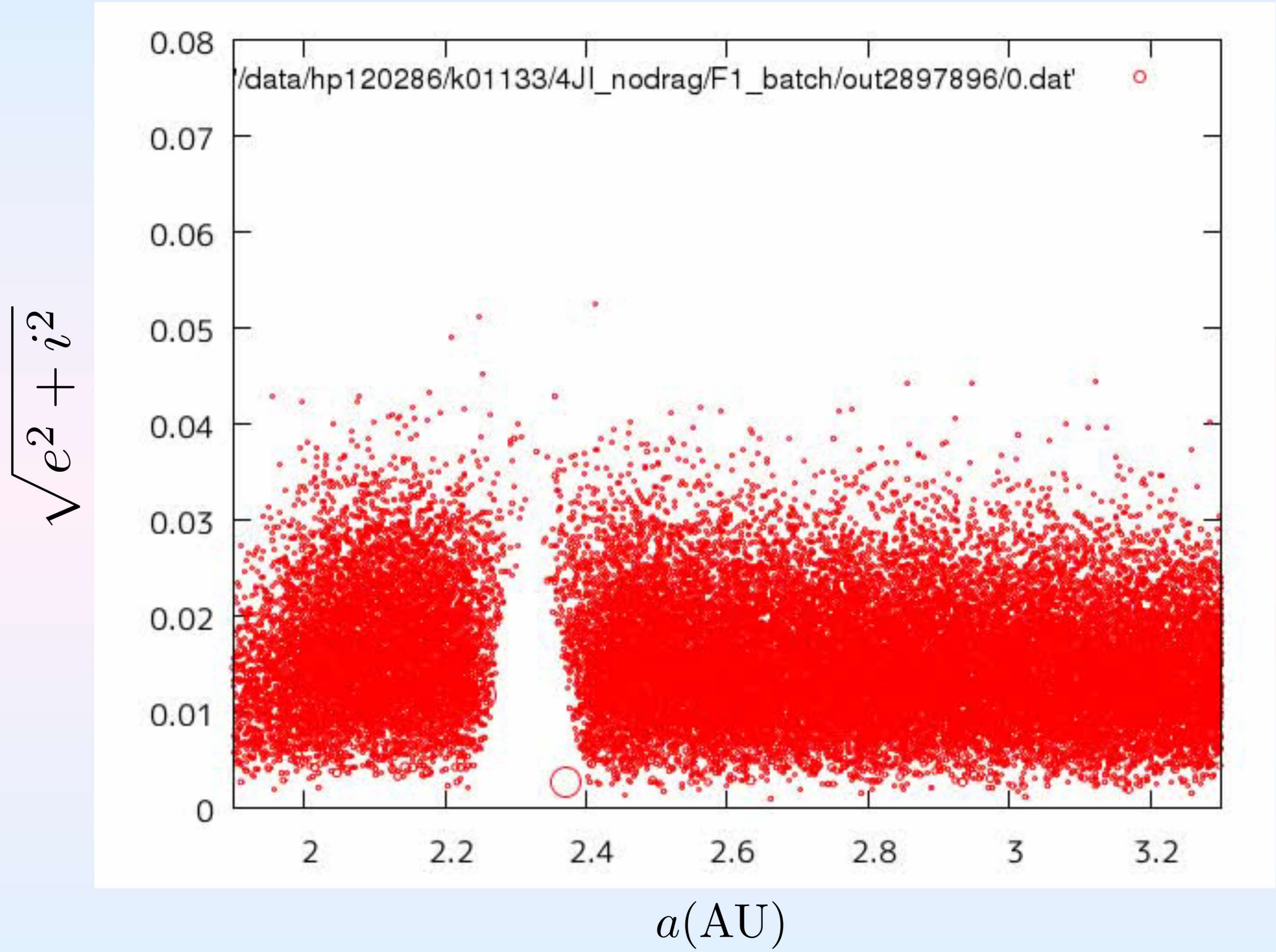
We performed first simulation with full gravity of planetesimals.

Protoplanet Migration



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

Another example of PDM (No Gas)



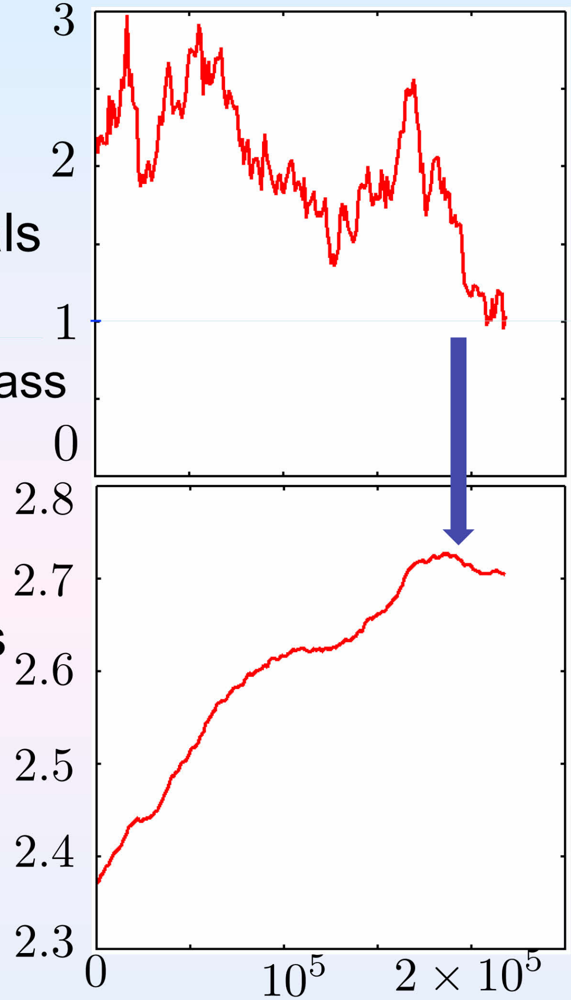
We changed the azimuthal random seed and performed the same simulation. The outside protoplanet moves outward and the inner Protoplanet moves inward.

Protoplanet Migration and the Scattered Planetesimals

Amount of Planetesimals In “A”

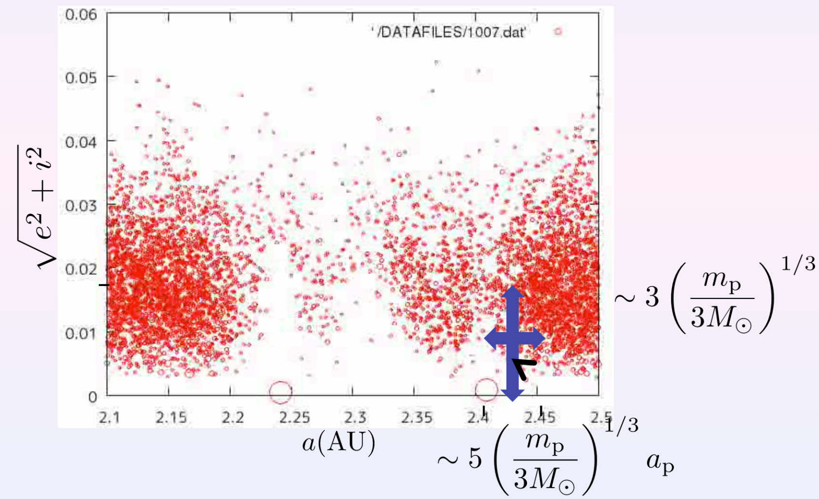
Protoplanet Mass

Protoplanet’s Semimajor axis (AU)



Viscous stirring of the planetesimals

← as it falls below the critical value
Minton and Levison (2014)



Region “A”

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

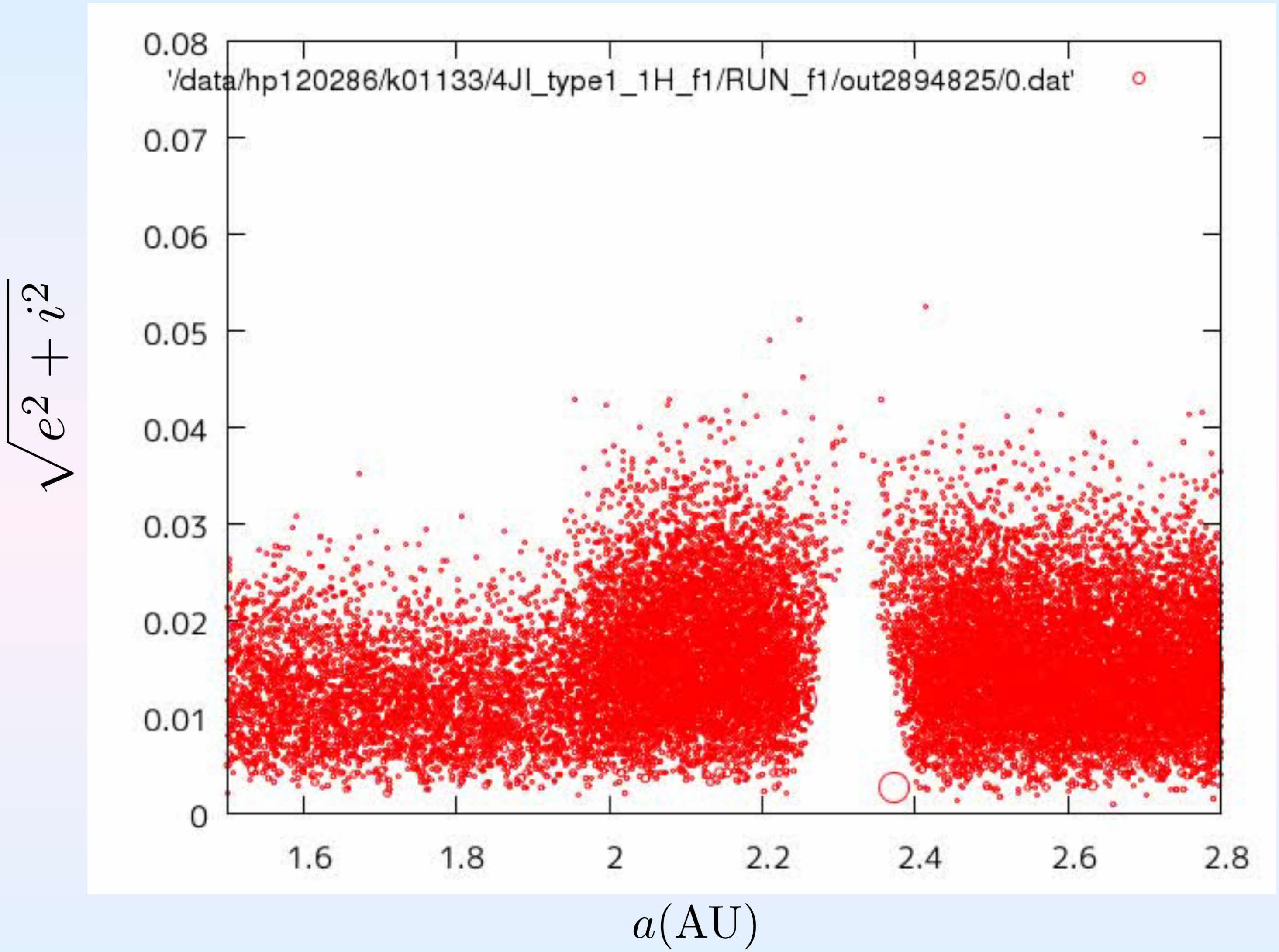
Increase of planetesimals’ random velocity may stops the migration.

This outward migration should take place in the disk when gas is abundant

Type-I pulls the protoplanet inward (decreases the effect of PDM)

We included the effect of the gas disk
gas drag & type-I migration
and saw which effect wins

Protoplanet Migration with Gas Drag and Type-I Migration



The outward migration continues overcoming type-I migration.
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