標準降着円盤からの検討に基づくペブル集積と衝突破壊を考慮した惑星形成*N*体シミュレーション

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Summary

Aims.

We investigated the planet formation process in a protoplanetary disk with a radial structure using *N*-body simulations with collisional fragmentation.

数値シミュレーションの立場から, リング状構造を持つ原始惑星系円盤内で惑星がどのように形成され, 進化するかを解明する.

Results.

[1] Protoplanets grow efficiently in dust rings in terrestrial planet-forming regions.
地球型惑星形成領域に存在する**ダストリング内で微惑星は効率的に成長.**

[2] The growth processes of the planets are similar for the fragmentation and the perfect accretion model.
惑星の成長プロセスは, **衝突破壊モデルと完全合体モデルで類似している.**

[3] The prolonged sweep-up of collision fragments makes about a factor of two difference in the largest planet mass at the end of the simulation.
衝突破片の掃き集めが長引くことで, **最大惑星質量に約2倍の差が生じる.**

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  - Thesis Statement
- Methods
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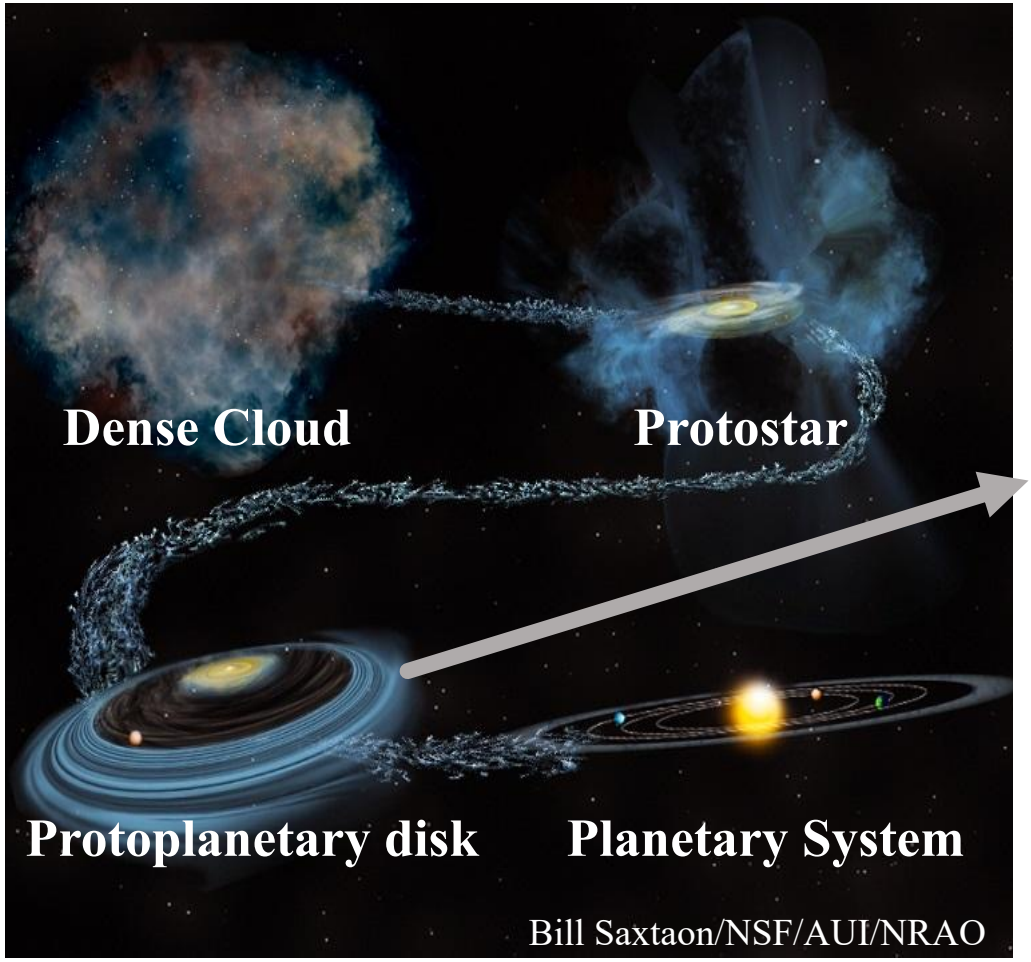
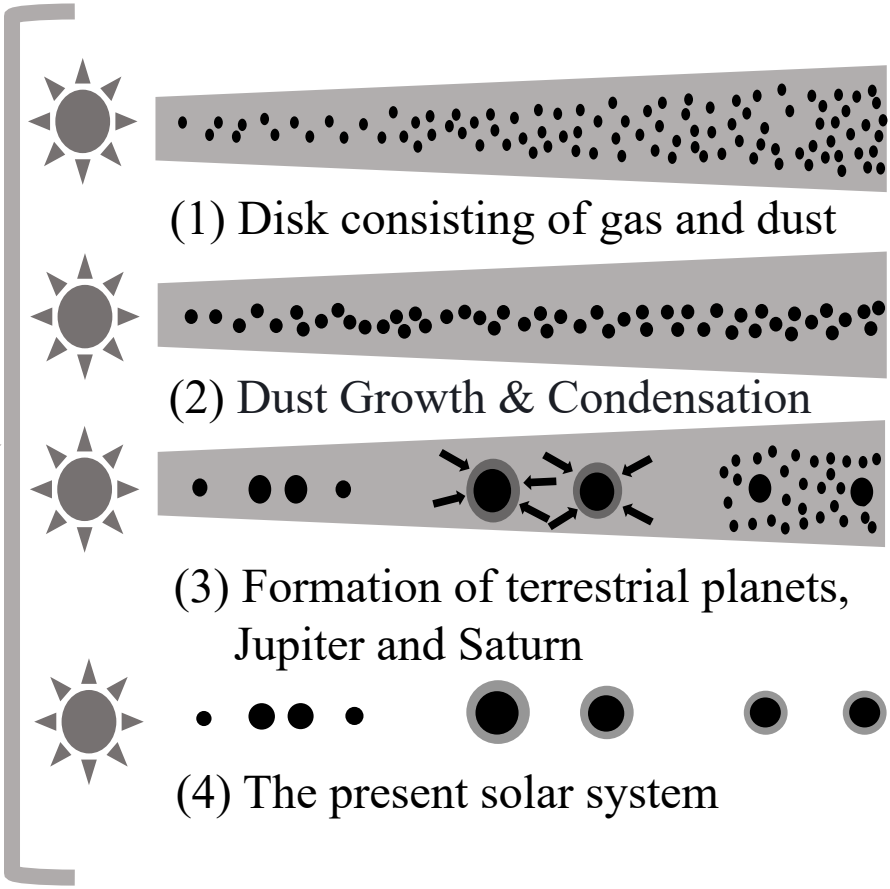
  - Fragmentation model
- Results
  - Animations, The effect of fragmentation
- Discussion
  - Velocity dispersion, Cumulative mass distribution
- Summary and Conclusion

Standard Theory of Planetary System Formation

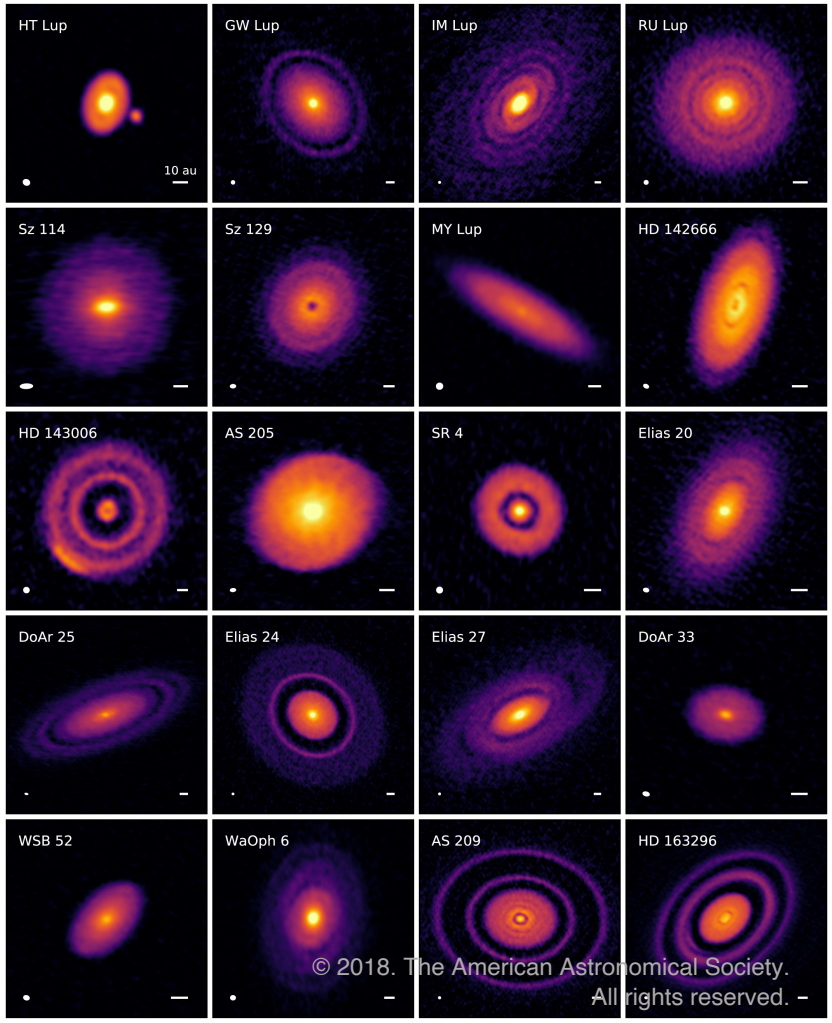




Problems with the Standard Theory

Differences between standard theory and observations

“PPDs are axisymmetric and have a smooth structure in the radial direction”



Strong azimuthal asymmetry in the dust emission (Muto et al., 2015)

Multiple ring-shaped structure of disks (Andrews et al., 2018)

Protoplanetary disks are full of diversity!

Thesis Statement

The standard theory does not take into account the diversity of protoplanetary disks represented by dust rings and asymmetric dust distributions.

We investigate how planets are formed by considering pebble accretion at the inner discontinuity boundary (~ 0.6AU) in a radially structured disk using a planet-forming N-body simulation.

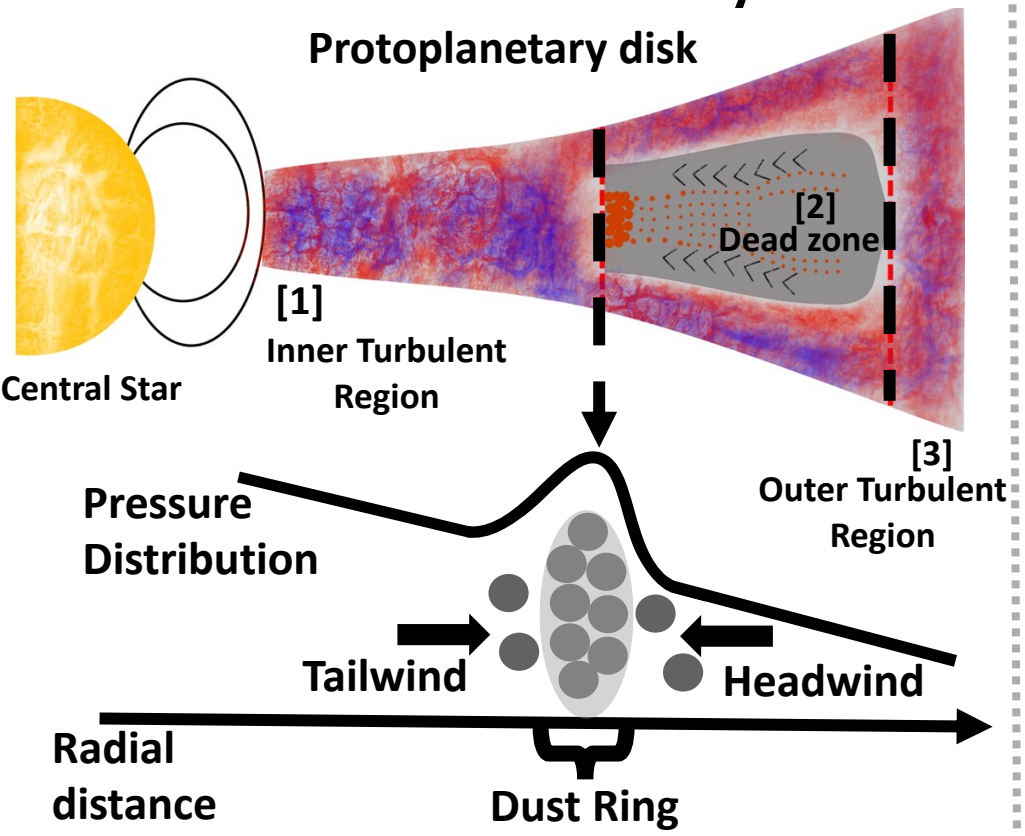
動径方向に構造を持つ円盤内の内側不連続境界(~0.6AU)への

ペブル集積を考慮することで, どのように惑星が形成されるかを

惑星形成*N*体シミュレーションで調べる.

The gas disk & dust evolution models

Disk model:
One-dimensional stationary α model



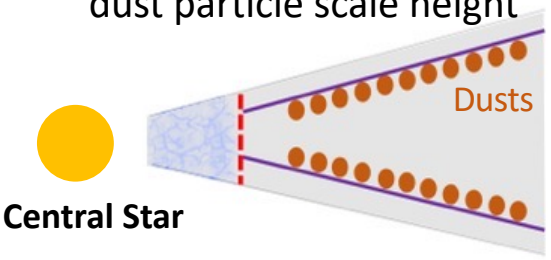
The Planet-forming region exist b/w [1] and [2]

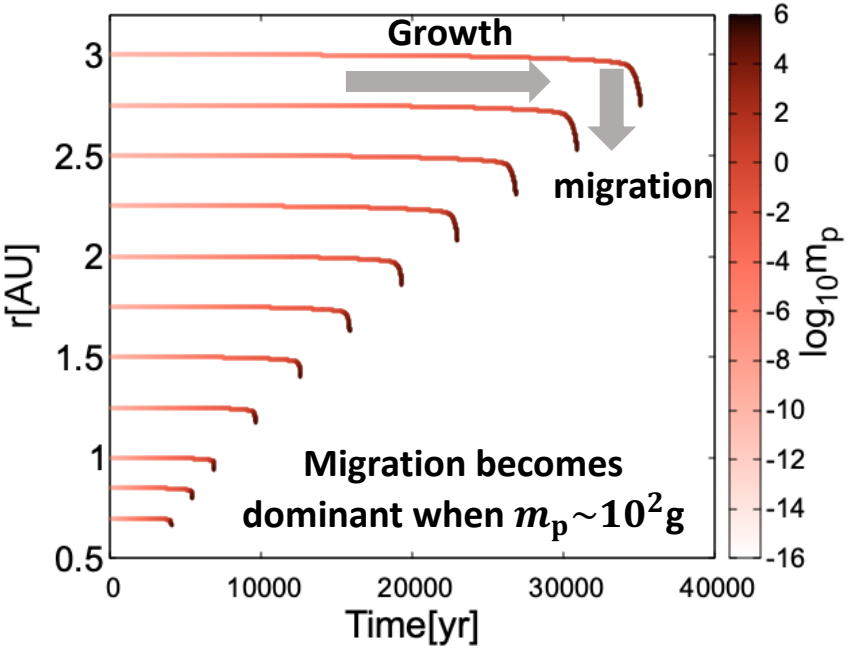
Positive pressure gradient in radial direction on turbulent region → Pebbles drift outward

Dust mass and orbital evolution in a disk model

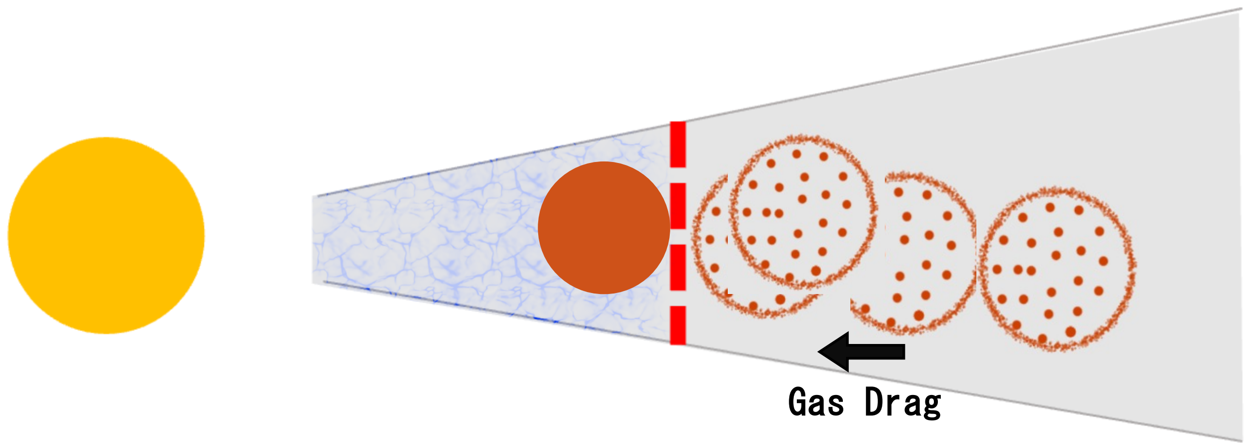
Assumptions

Evaluate dust growth at dust particle scale height





Implementation of *N*-body simulation



[illegible]

accretion onto the inner dead zone boundary.

Assumptions

[1]Perfect dust filtration
(e.g., Jiang & Ormel, 2023)

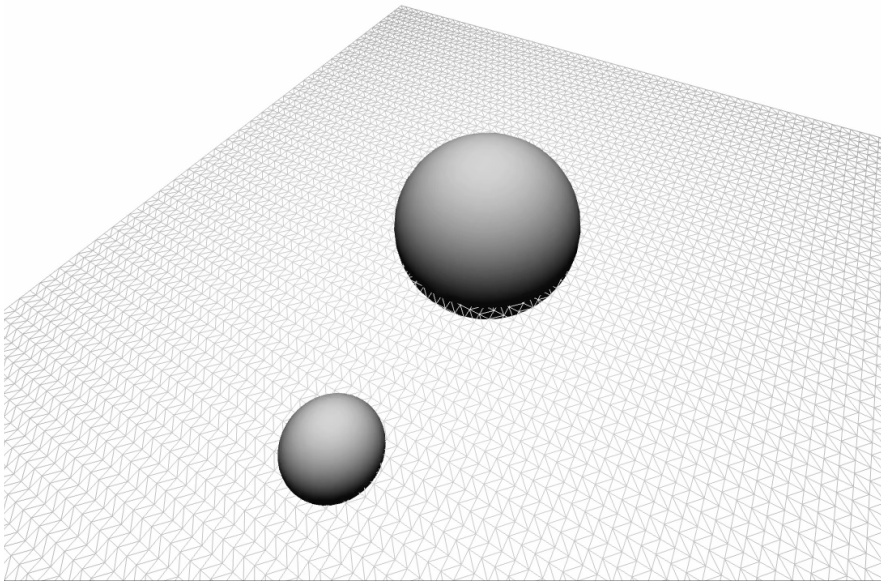
[2]Drifting particles
=super particles

Fragmentation Model：Kominami model

A brief overview of the model

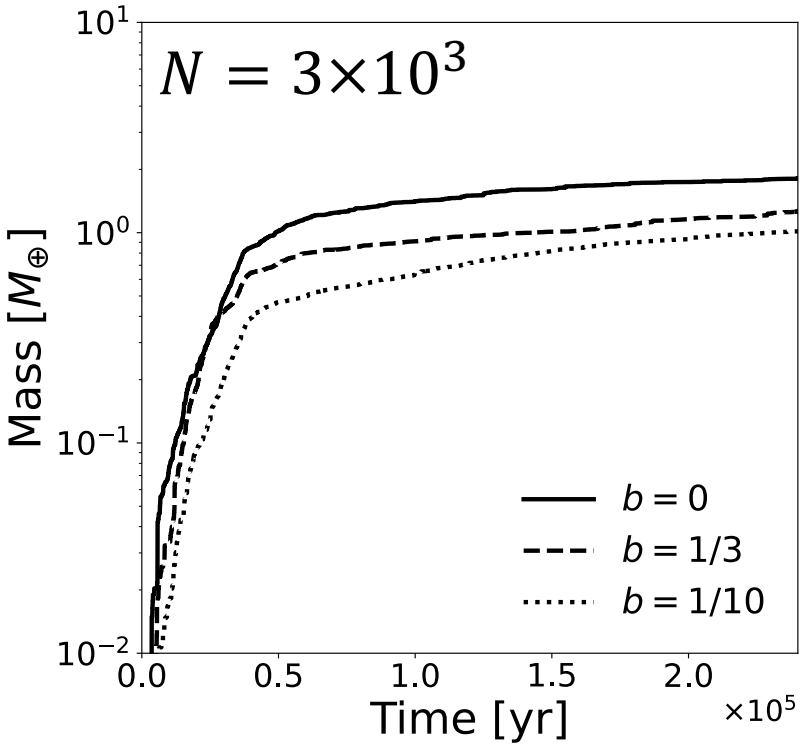
(1). Velocity of the fragments are set to be 1.05 times the escape velocity of the combined mass of impactor and target ($m_{\mathrm{imp}} + m_{\mathrm{tar}}$).

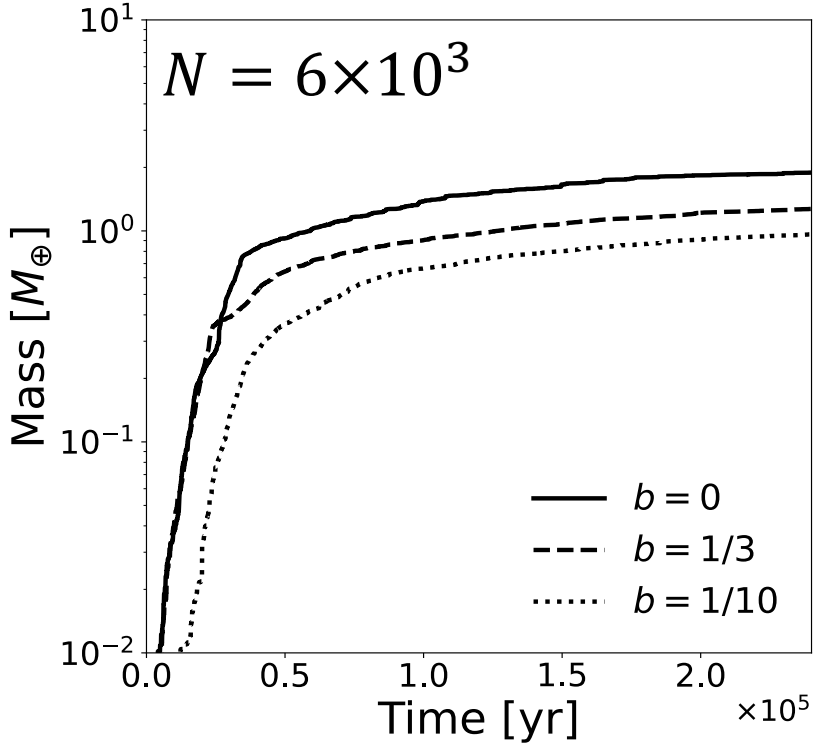
(2). The fragments are distributed on a plane spanned by relative position vector and relative velocity vector of impactor and target.



1. Set the minimum mass of the fragments: $m_{\mathrm{min}} = b \cdot m_{\mathrm{init}}$
2. Large mass forms at the center of mass: $m_{\mathrm{k}} = (1 - a_{\mathrm{frag}})m_{\mathrm{imp}} + m_{\mathrm{tar}}$
3. Fragments form from: $a_{\mathrm{frag}} m_{\mathrm{imp}}$
   (* a_{frag}: Ratio of total fragments mass to impactor mass)
4. # of fragments: $\mathrm{n_f} = \frac{a m_{\mathrm{imp}}}{m_{\mathrm{min}}}$
5. If $\mathrm{n_f}$ = 0 or 1, perfect accretion is assumed.

The effect of fragmentation：Mass evolution

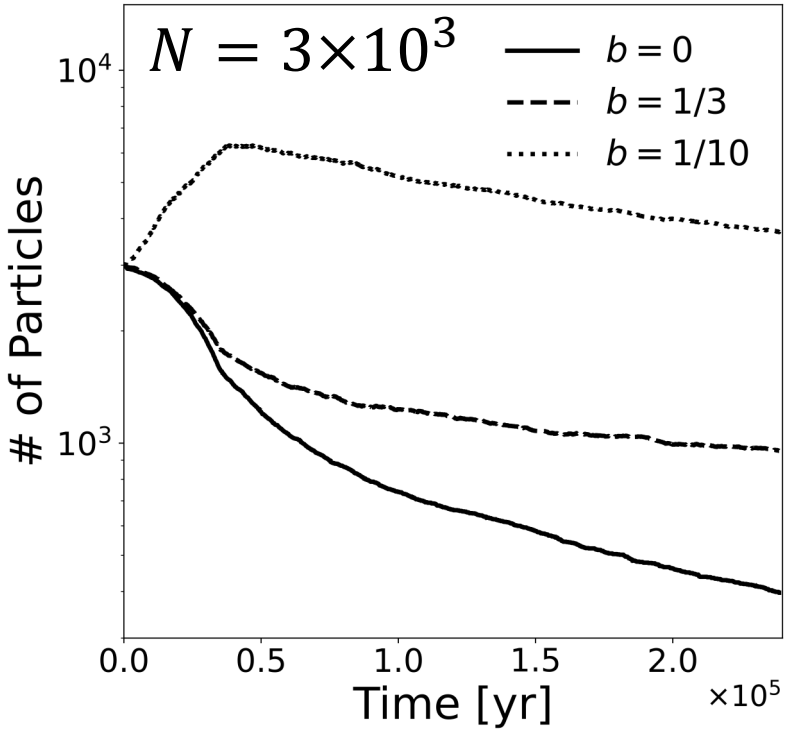


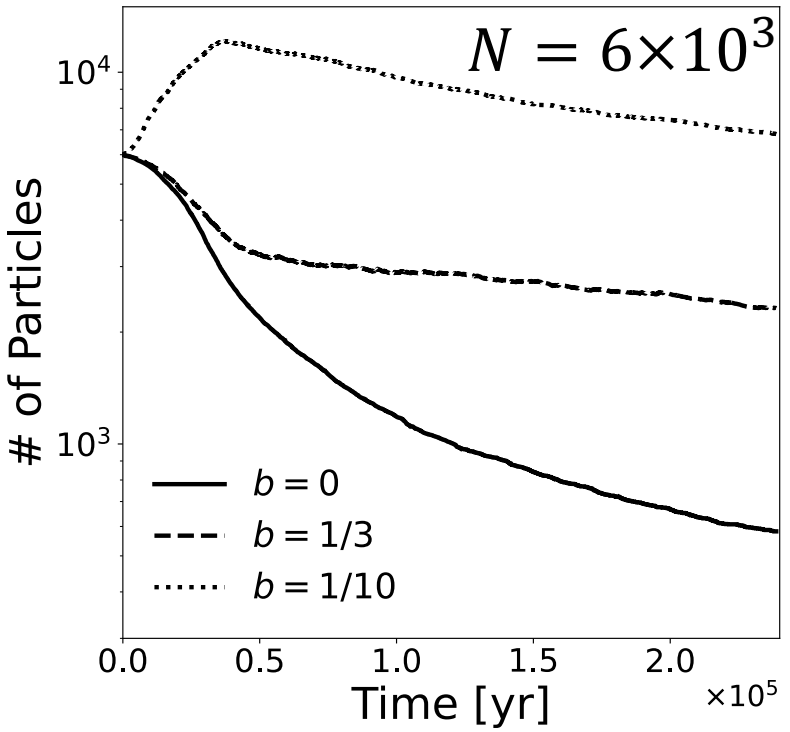


[1] The growth process of the largest planet is independent on the fragmentation effect.

[2] The final masses of the planets differ by a factor of about two, thus depending on the fragmentation effect.

The effect of fragmentation：# of particles

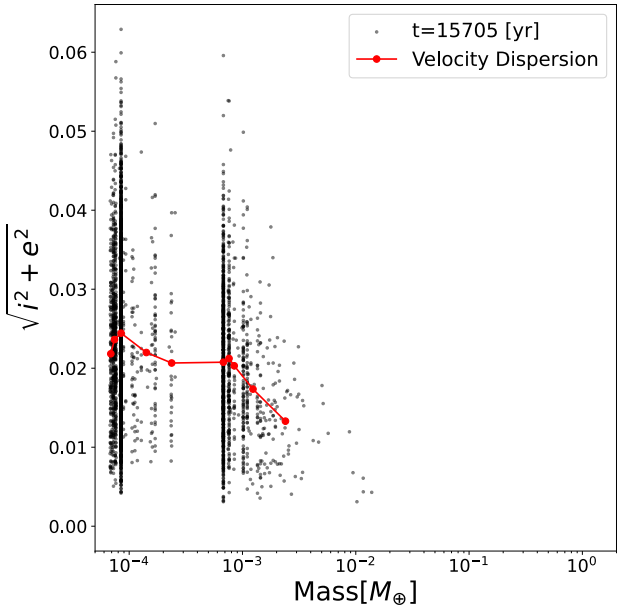


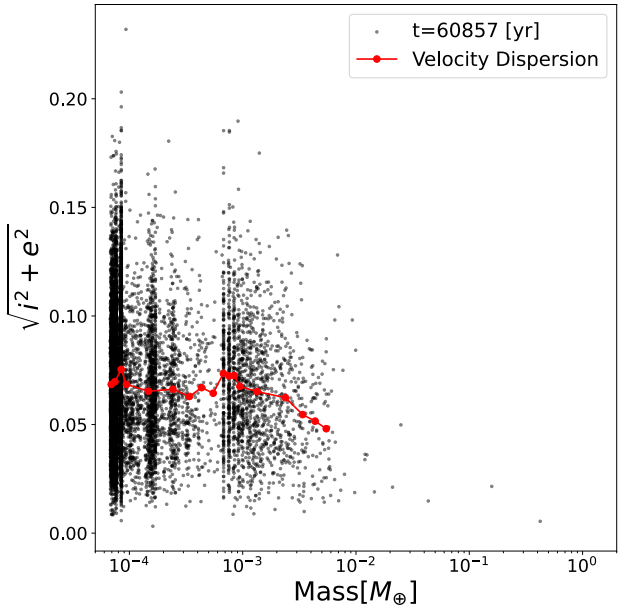


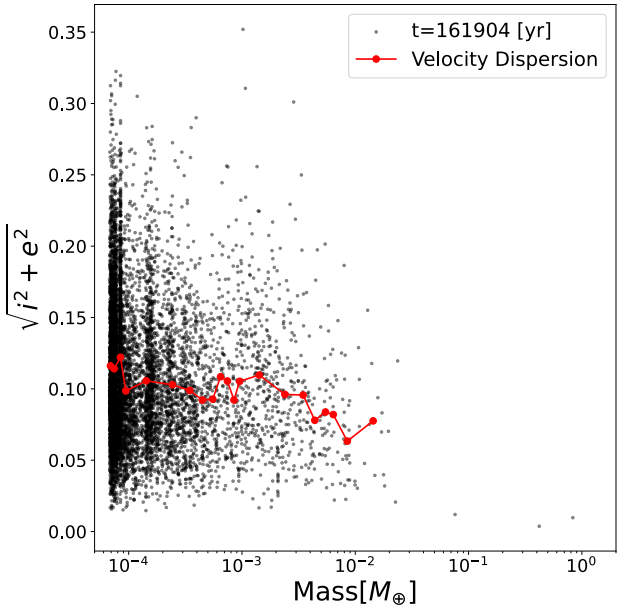
[1] # of particles increased by a factor of 2 when $b = 1/10$.

[2] For $b = 1/3$, the initial change in # of particles is not much different from $b = 0$, but the rate of decrease in # of particles gradually decreases.

The velocity dispersion





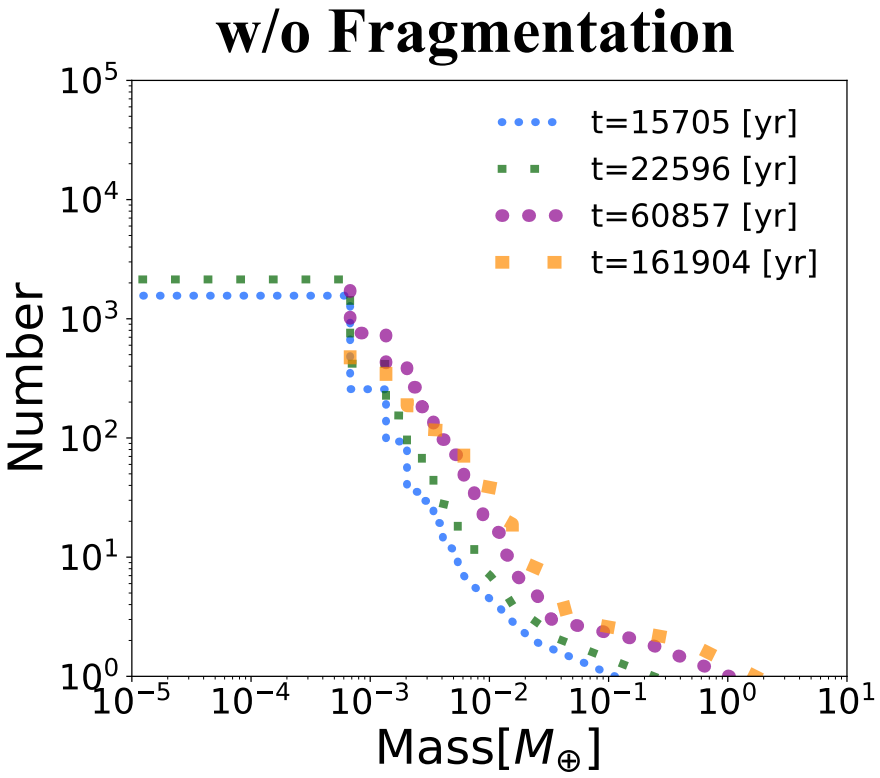


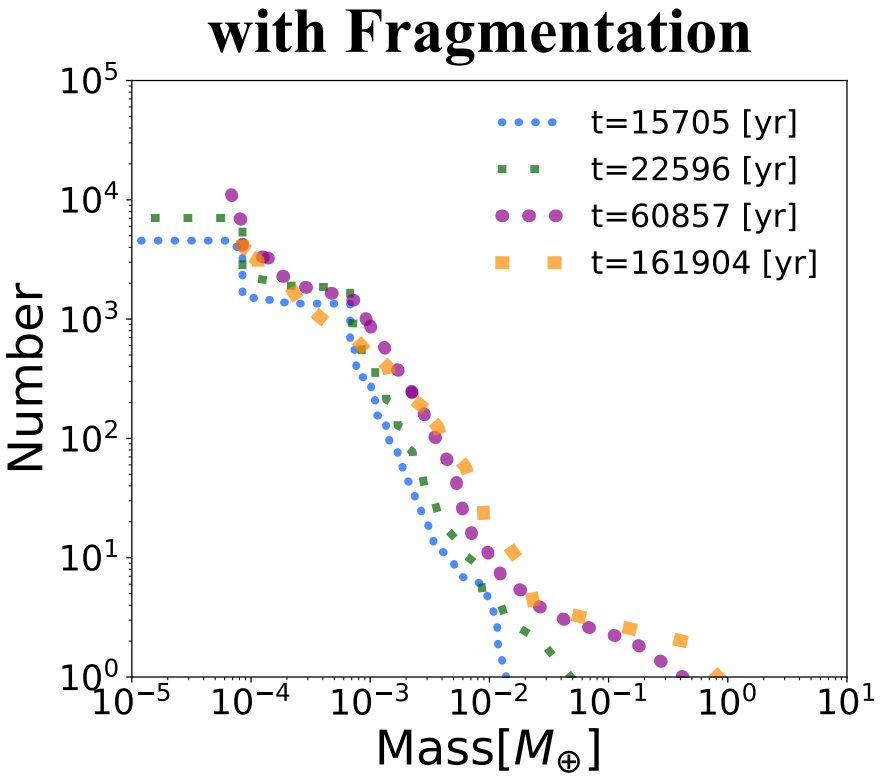
[1] v_{disp} of the system increases on average with time due to the effect of gravitational scattering (viscous stirring) between particles.

[2] The system is polarized into two groups: the large-mass protoplanets on the right side in figures and the other is the numerous small-mass planetesimals distributed on the left side.

→ v_{disp} of small planetesimals is determined by gravitational scattering by the large protoplanets, rather than by the effect of energy equipartition among small planetesimals with different masses due to dynamical friction.

The cumulative mass distribution





[1] In the early stages of the simulation, the slope of the cumulative mass distribution becomes shallower the smaller the number of fragments.

[2] When the fragments are formed by collisions, the mass of the largest-sized planet formed in the simulation decreases.

Summary and Conclusion

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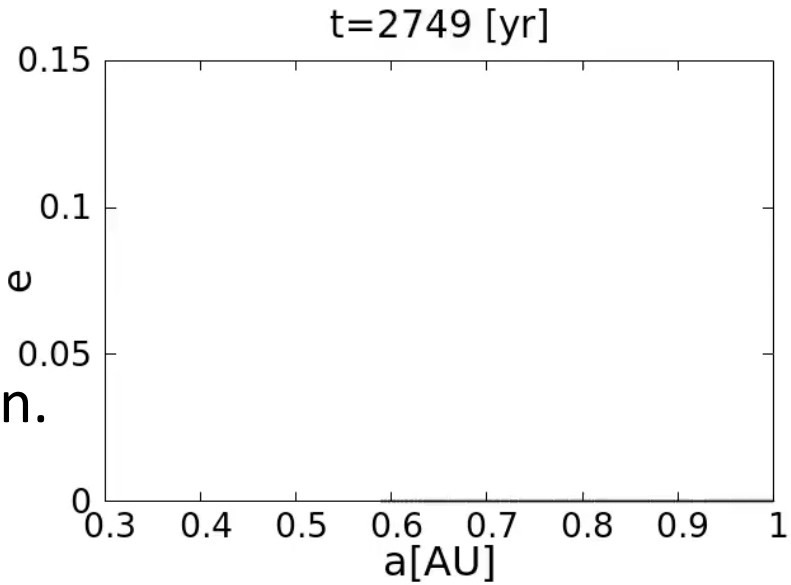
We investigated the planet formation process in a protoplanetary disk with a radial structure using *N*-body simulations with collisional fragmentation.



Main Findings are:

[1] Protoplanets grow efficiently in dust rings in terrestrial planet-forming regions.
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