

# Spiral structures of the Moon-forming disk

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# Overview

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## Background:

In the moon-forming simulations, it has been reported that spiral structures which are not in lower-resolution simulation appear when increasing the numerical resolution.

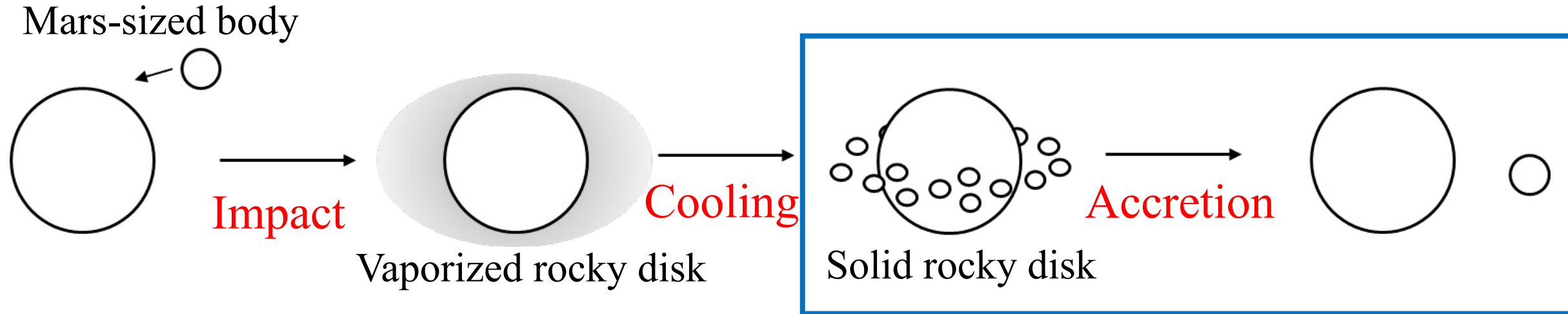
## Approach:

We performed high-resolution simulation to investigate the spiral structures.

## Results:

1. Loose leading spirals develop in the outer region of the disk, while tight leading spirals develop in the inner region.
2. Gravitational instability increases within the leading spirals.
3. Azimuthal structures develop within the leading spirals due to gravitational instability.

# 1. Background: Giant impact hypothesis



**Accretion process:** Gravitational accretion of rocky disk ( $N$ -body simulations)

- A single large Moon can form within approximately 1 month.
- The mass of the Moon depend on the initial disk mass.
- The timescale of the Moon formation depend on the angular momentum transport. (e.g., Ida et al. 1997; Kokubo et al. 2000)
- **Accretion process depends on the numerical resolution.**

(Sasaki & Hosono 2018)

# 1. Background: Numerical resolution

Gravitational  $N$ -body simulation of Moon-forming disk. (Sasaki & Hosono 2018)

$N = 10^5$

$N = 10^7$

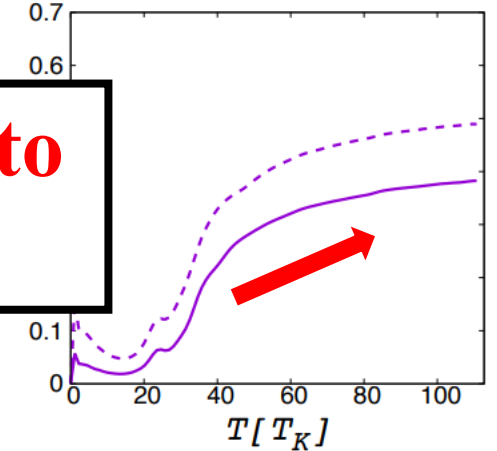
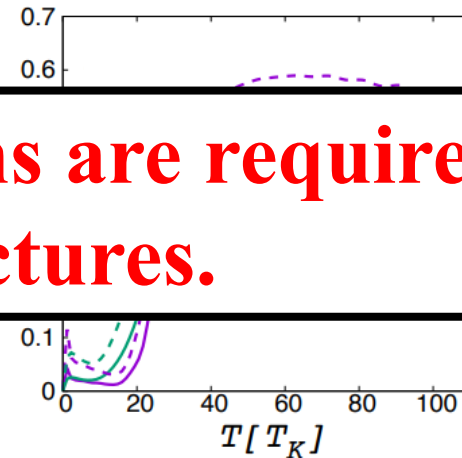
**Mass evolution**

Solid line: The largest mass

Dashed line: Total of 3 largest masses

$N = 10^5$

$N = 10^7$



**high-resolution simulations are required to investigate the spiral structures.**

In the case of  $N = 10^7$  compared to  $N = 10^5$ , the spirals are interconnected, resulting in a more complex structure.

Moon in the run with  $N = 10^5$  grows rapidly.  
Moon in the run with  $N = 10^7$  grows slowly.

**Spiral structures and growth rate depend on the numerical resolution.**

## 2. Objective

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1. Sasaki & Hosono (2018) revealed that spiral structures depend on the numerical resolution.
2. Differences in disk structure influence angular momentum transport.
3. Changes in angular momentum transport alter the growth rate.

We investigate the evolution and the dynamics of the spiral structure in the inner disk.

### 3. Method: Numerical setup

Global  $N$ -body + Rubble pile model + Soft sphere: Self-gravitational simulation

Planetary ring system simulation code (nbody-with-center by Makino)

( <https://github.com/jmakino/nbody-with-center> )

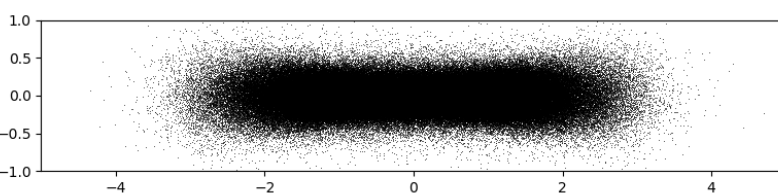
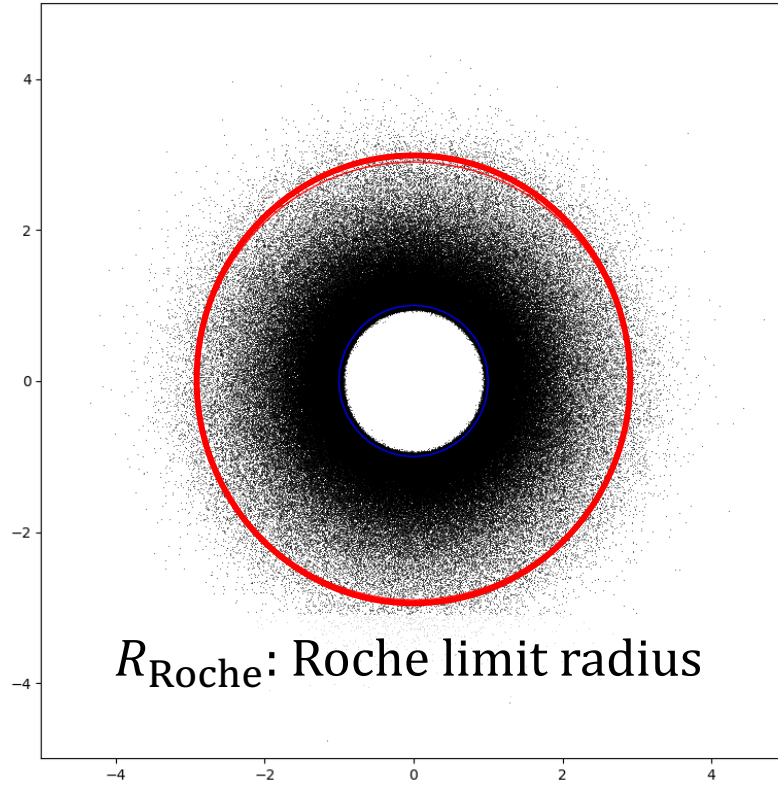
Equation of motion

$$\frac{d\mathbf{v}_i}{dt} = \underbrace{-GM_{\oplus} \frac{\mathbf{x}_i}{x_i^3}}_{\text{Gravity from Earth}} - \underbrace{\sum_{j \neq i}^N \frac{\mathbf{F}_{G,ij}}{m_i}}_{\text{Gravity from another particle}} - \underbrace{\sum_{j \neq i, x_{ij} \leq r_{coll}}^N \frac{\mathbf{F}_{D,ij}}{m_i}}_{\text{Damping term}}$$

Super-computer: XD2000 (CfCA/NAOJ)

# 3. Method: Initial disk conditions

$T = 0.0007 T_K$



Surface density:  $\Sigma \propto a^{-3}$

Semi-major axis:  $[R_{\oplus}, R_{\text{Roche}})$

Integration time of  $90T_K$  orbital periods ( $\sim 26$  days)

$1T_K$ : Kepler period at  $R_{\text{Roche}}$

$$R_{\text{Roche}} = 2.456 \left( \frac{\rho_p}{\rho_{\oplus}} \right)^{-1/3} R_{\oplus} \\ \simeq 2.9R_{\oplus}$$

Earth mass:  $5.972 \times 10^{24}$  kg

Earth radius [ $R_{\oplus}$ ]: 6371 km

Earth density [ $\rho_{\oplus}$ ]:  $5.5 \times 10^3$  kg/m<sup>3</sup>

Moon mass [ $M_L$ ]:  $7.349 \times 10^{22}$  kg

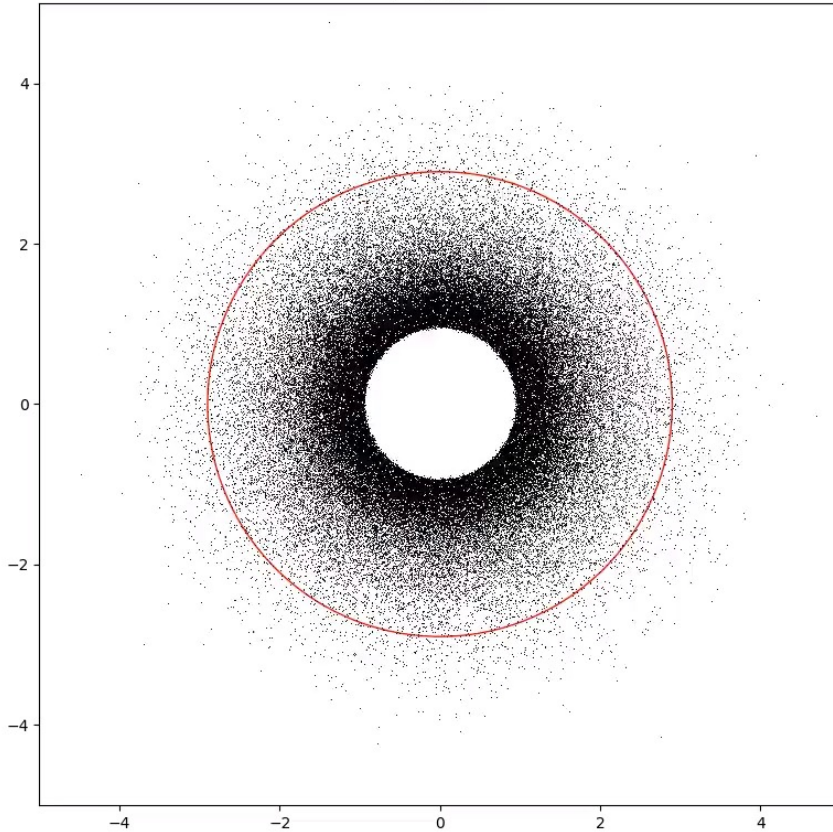
Particle density [ $\rho_p$ ]:  $3.3 \times 10^3$  kg/m<sup>3</sup>

	Disk mass [ $M_L$ ]	# of particles	Particle mass [kg]	Particle radius [km]
<b>Set1</b>	4.0	$10^5$	$2.94 \times 10^{18}$	<b>59.69</b>
<b>Set2</b>	4.0	$10^6$	$2.94 \times 10^{17}$	<b>27.71</b>
<b>Set3</b>	4.0	$10^7$	$2.94 \times 10^{16}$	<b>12.86</b>

# 4. Results: face-on/edge-on animation

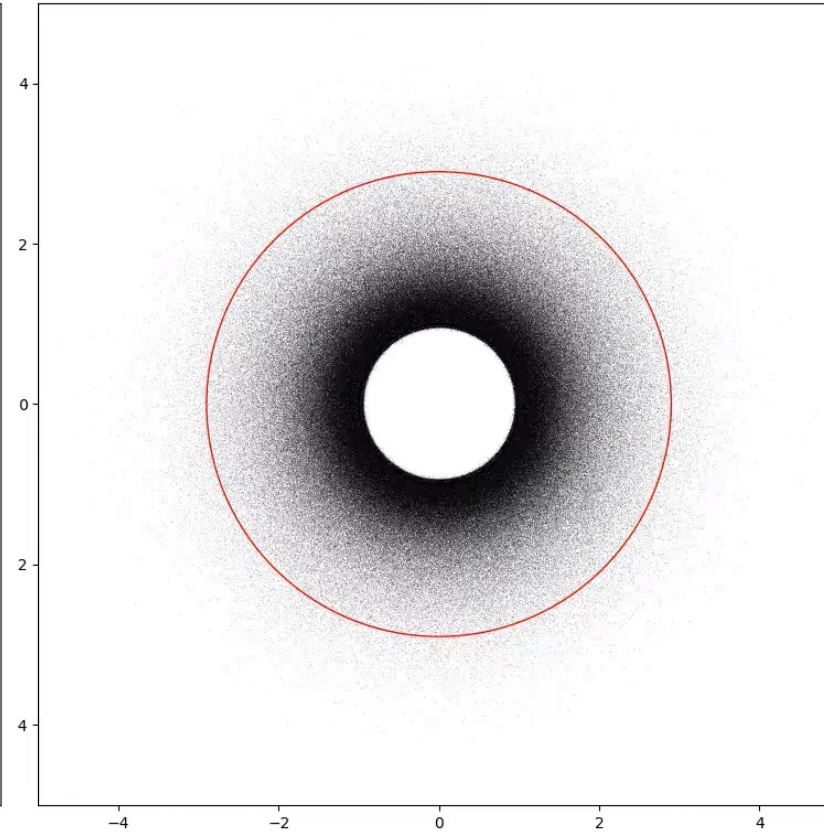
Set1 ( $N = 10^5$ )

$T = 0.00T_K$



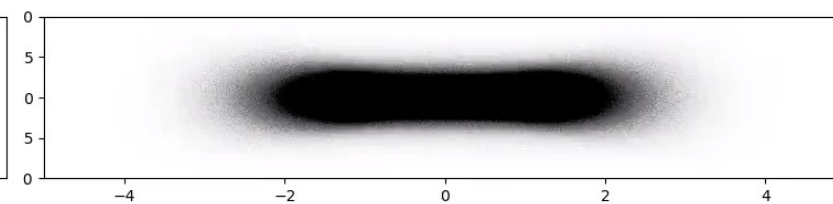
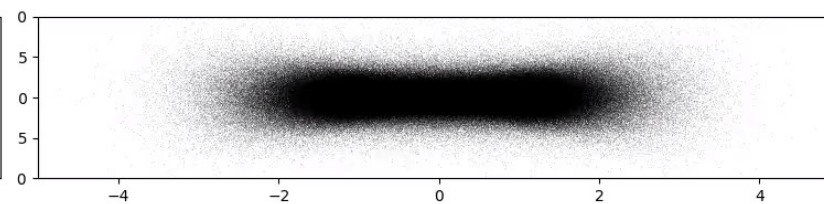
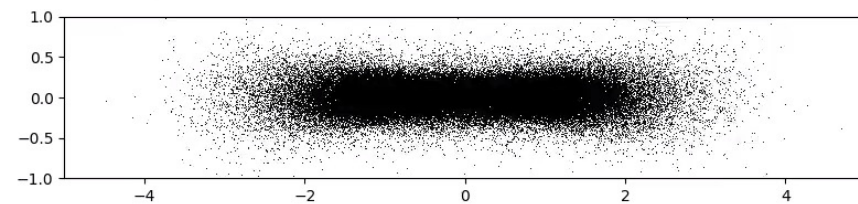
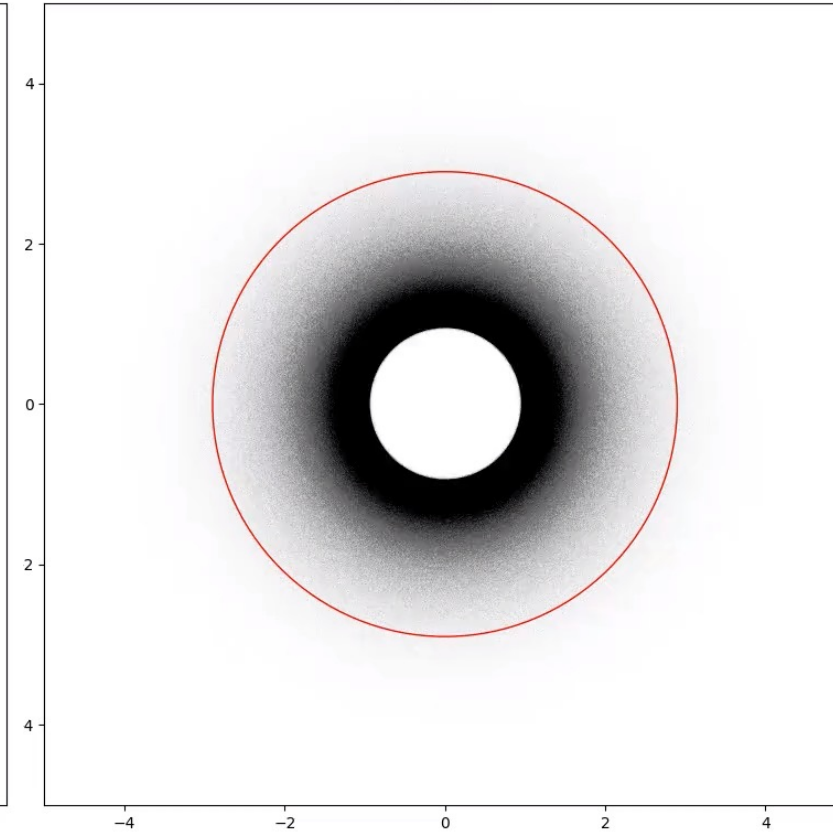
Set2 ( $N = 10^6$ )

$T = 0.00T_K$



Set3 ( $N = 10^7$ )

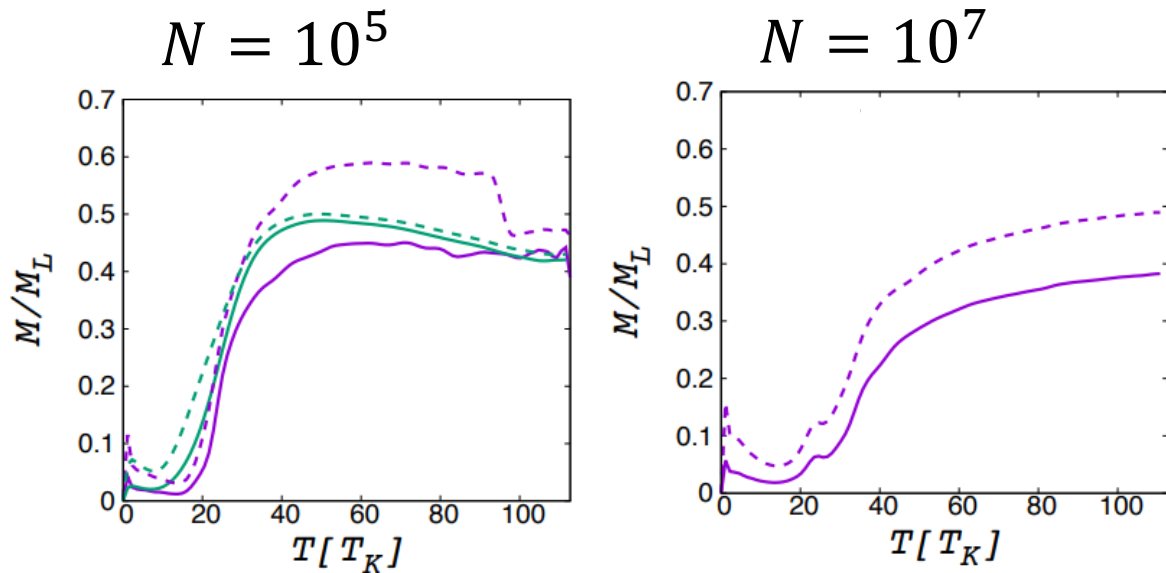
$T = 0.00T_K$



# 4. Results: Mass growth

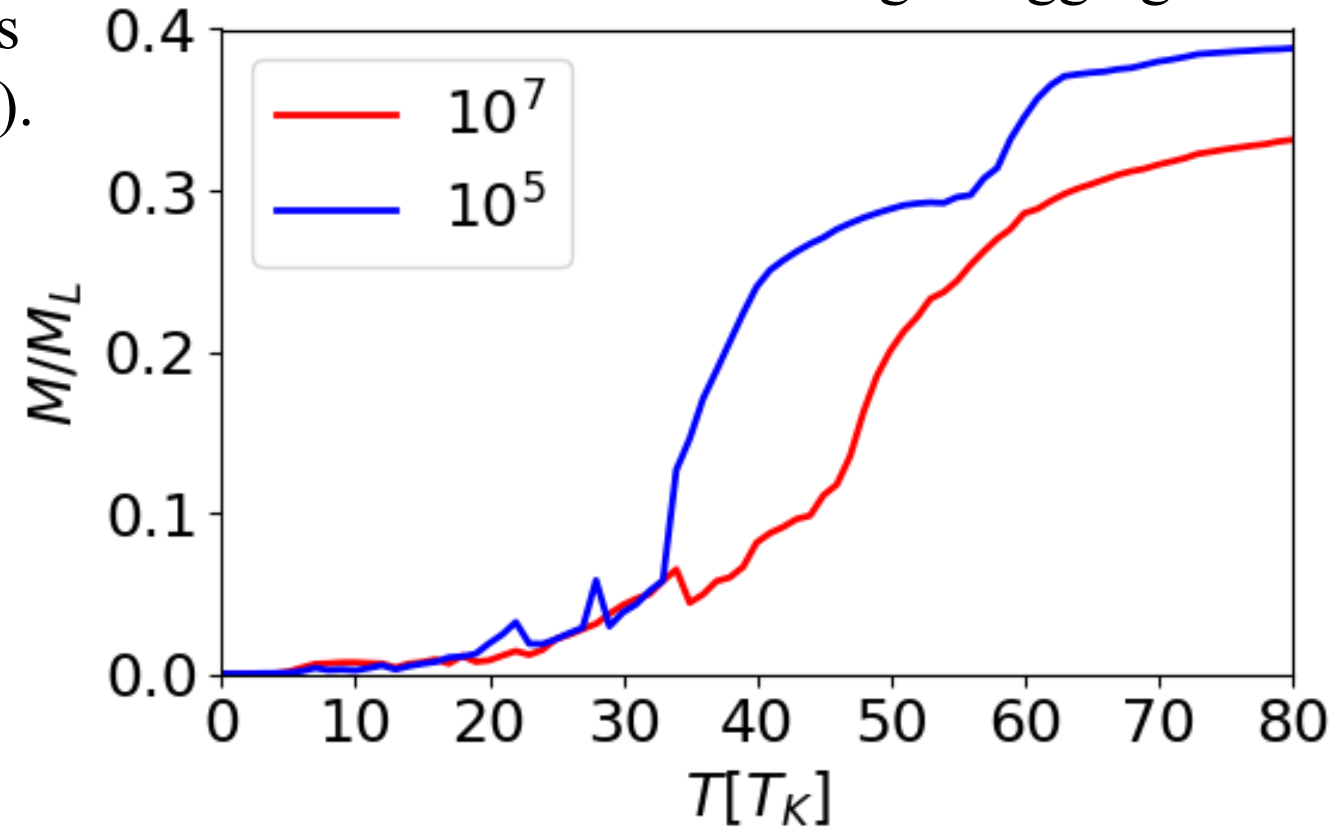
## Mass grows plot:

Simulations with higher resolution results in slower growth of largest aggregate, as consistent with Sasaki & Hosono (2018).



Sasaki & Hosono (2018)

## Mass evolution of the largest aggregate

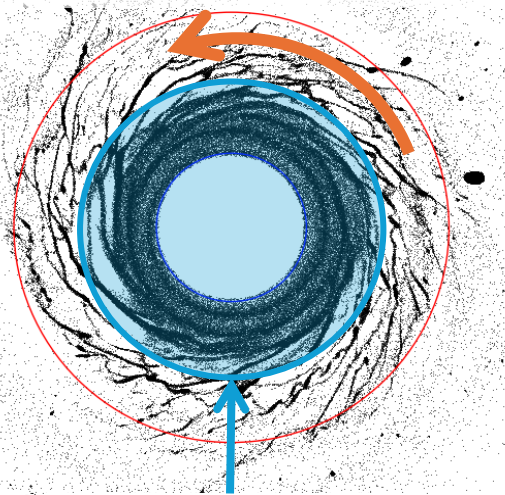


$1 T_K = 7 \text{ h}$

# 4. Results: Evolution of spiral structures

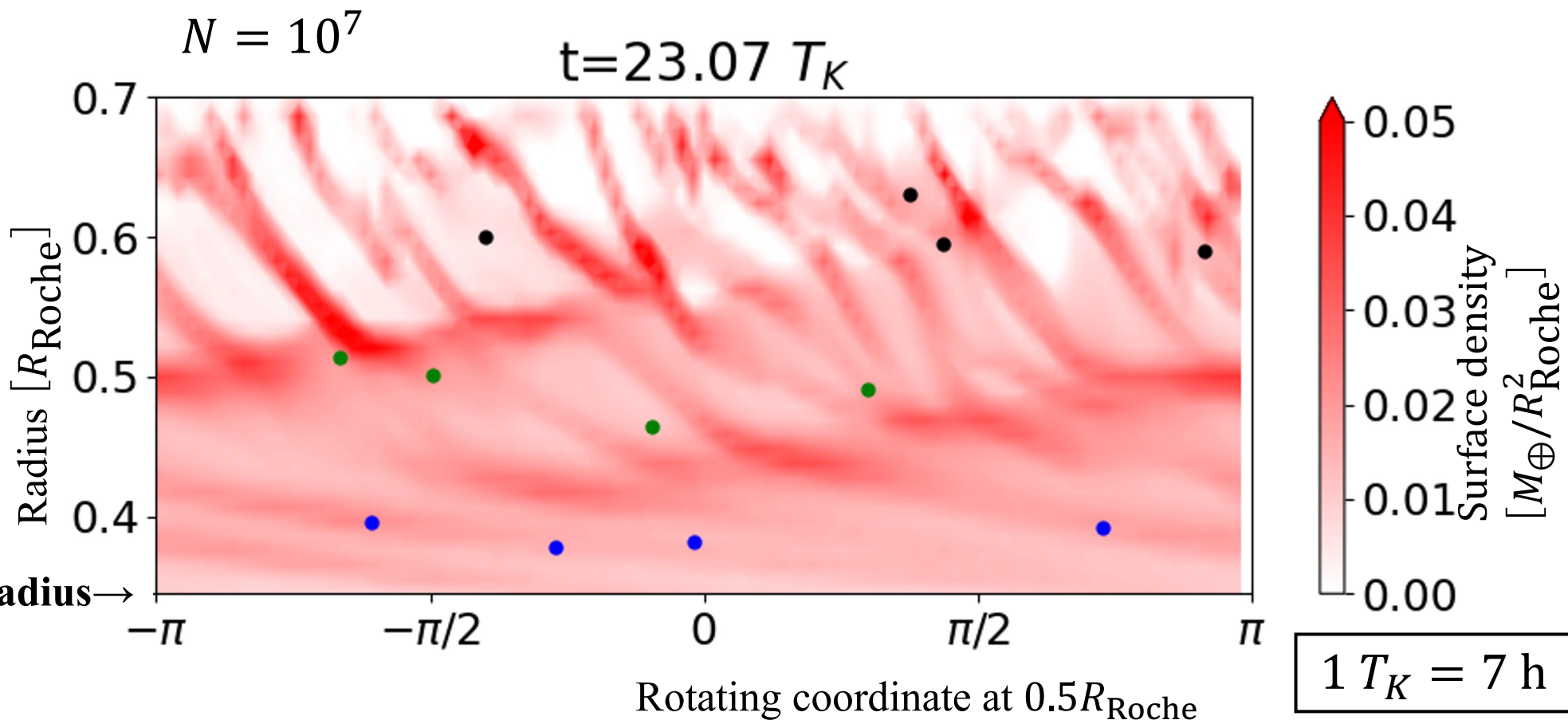
1. Leading spiral appears in the inner region of the Moon-forming disk.
2. Azimuthal instability develops within the leading spiral.

Rotation direction of  
the rotating coordinate



Animation area

Earth radius →



# 4. Results: Gravitational instability

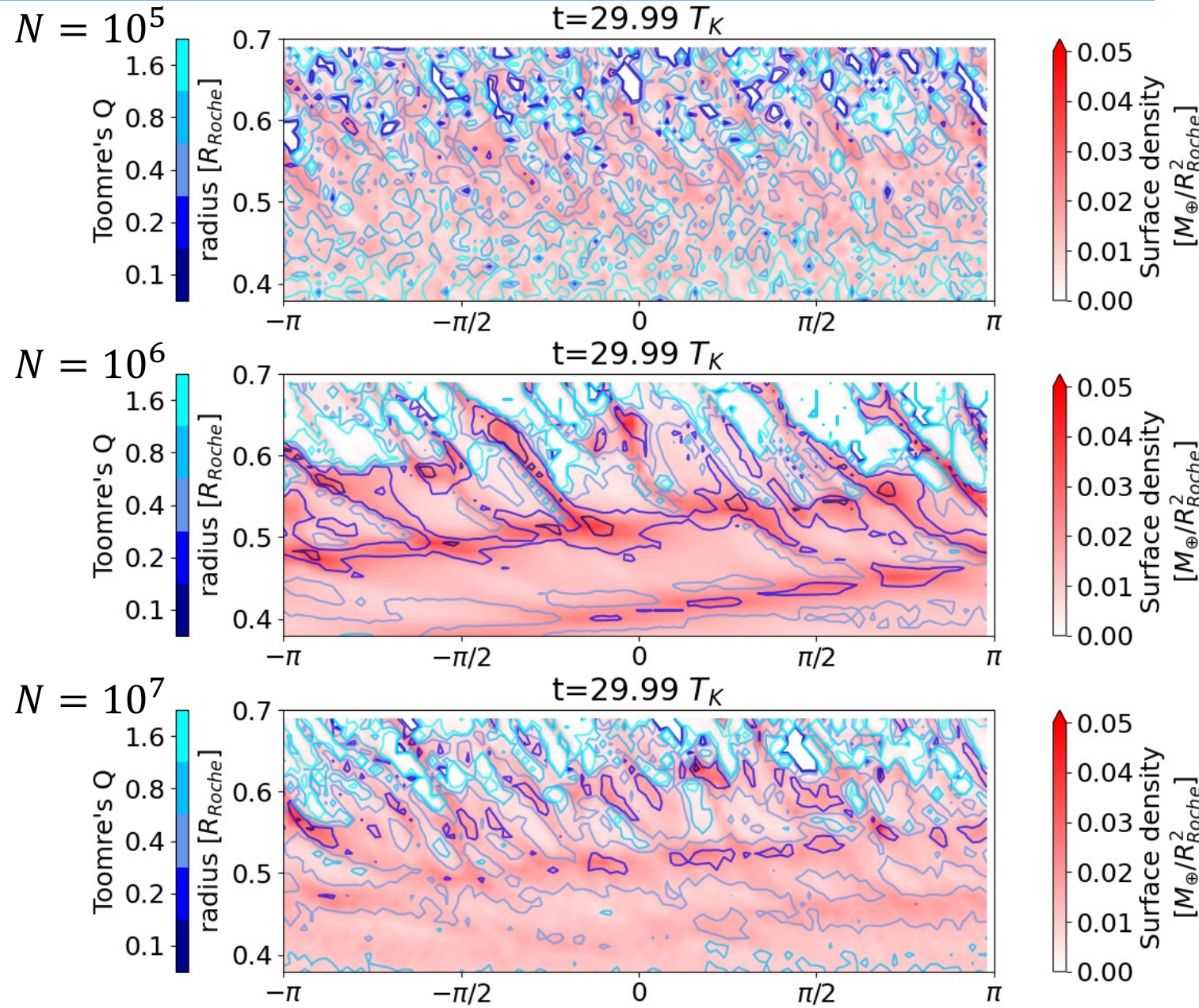
Toomre's  $Q$  value  
(particle system):

$$Q = \frac{\sigma_r \kappa}{3.36 G \Sigma}$$

The disk is stable for  $Q > 1$   
and unstable for  $Q < 1$ .

In simulations with  $10^6$  or more particles, high-density regions are formed by leading spirals.

Areas with low  $Q$  values extend along these leading spirals.



# 5. Summary

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We performed high-resolution simulation to investigate the spiral structures.

## **Results:**

1. Gravitational instability increases within the leading spirals.
2. Azimuthal structures develop within the leading spirals due to gravitational instability.

## **Future work:**

- Run higher-resolution simulations ( $N \sim 10^8, 10^9$ ).
- Investigating the dependence of spiral structures on the initial disk conditions through high-resolution simulations.