Moon formation via Streaming Instability

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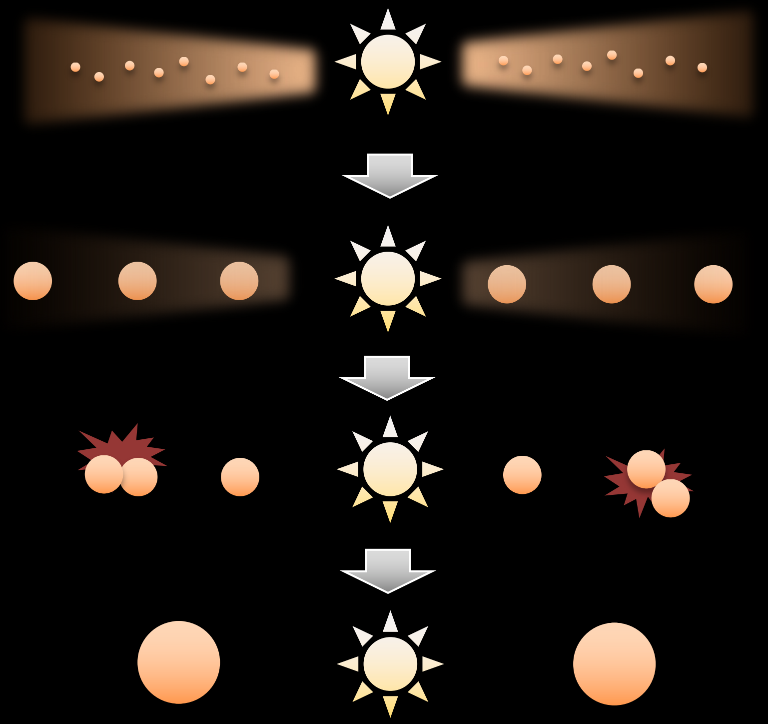
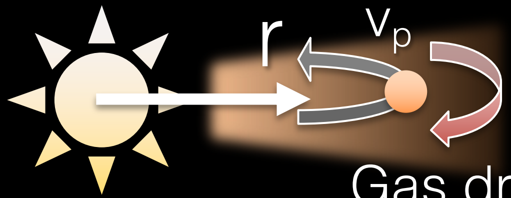
Classical planet formation scenario

Planetesimals grow to Mars-sized embryos (protoplanets)

The embryos experience large impacts to reach the final planetary masses
(e.g., Weidenschilling, 1977, Kokubo and Ida, 1998)



Classical “meter barrier” problem



Particle velocity

$$\frac{v_p^2}{r} = \frac{GM}{r^2}$$

Gas velocity

$$\frac{v_g^2}{r} = \frac{GM}{r^2} + \frac{1}{\rho}\frac{\partial p}{\partial r}$$

< 0

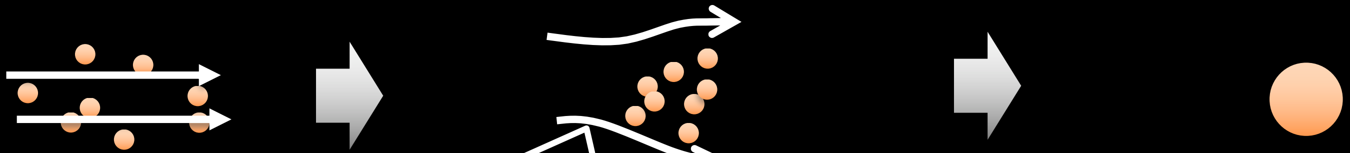
$\Rightarrow$ $$v_p > v_g$$

Particles feel gas drag and fall towards the central star

~ 1 m particle at 1 AU falls to the Sun in 80 years
(e.g., Adachi et al., 1976, Weidenschilling, 1977)

Skipping the barrier by streaming instability

Streaming instability can transform dust particles to a large planetesimal, which is an efficient way to skip the 1 m barrier



cyclists cluster together

Gravitational collapse
~ 100 km sized
planetesimals

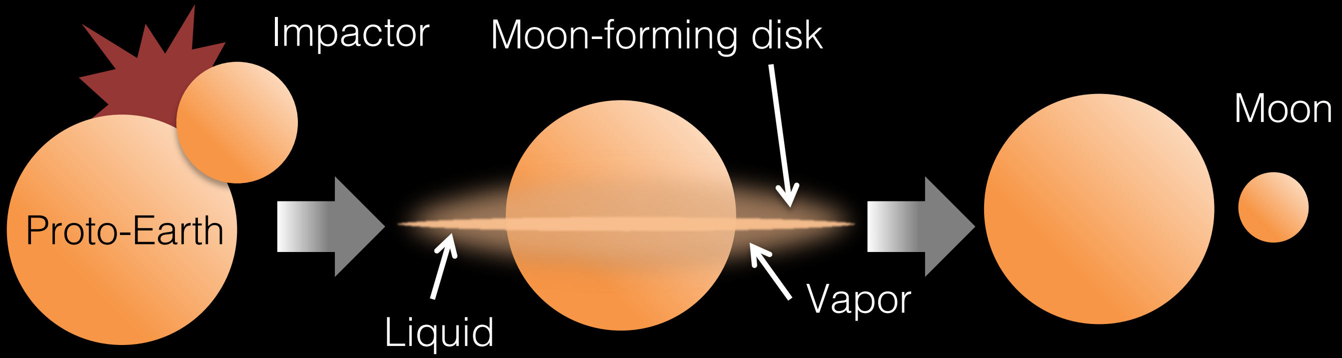
(e.g., Youdin & Goodman ... 7, Johansen et al., 2015, Simon et al., 2016)

Origin of the Moon

The standard giant impact hypothesis

(e.g., Hartmann & Davis 1975, Cameron & Ward 1976, Canup & Asphaug, 2001)

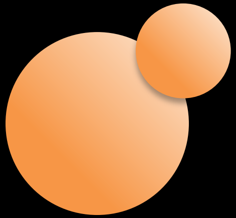
The Moon formed by an impact between the proto-Earth and a Mars-sized object around 4.5 billion years ago



Implication for the Moon-forming disk

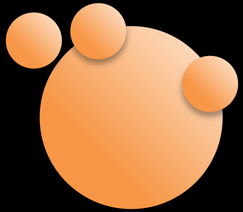
Standard/Hit-and-run collisions

(Hartmann & Davis, 1975,
Cameron & Ward, 1976, Asphaug et al 2021)



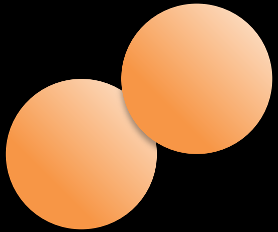
Multiple impact model

(Rufu et al., 2017)



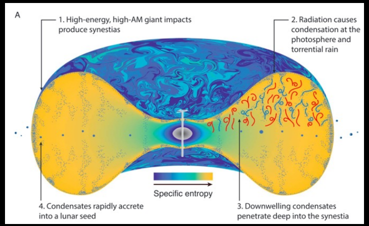
Half-Earths

(Canup, 2012)



Fast-spinning Earth & Synestia

(e.g., Cuk & Stewart, 2012, Lock & Stewart, 2017, Lock et al., 2018)



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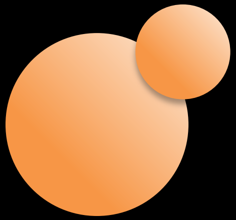

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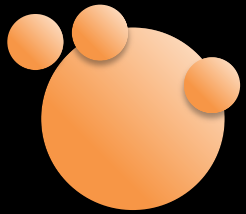

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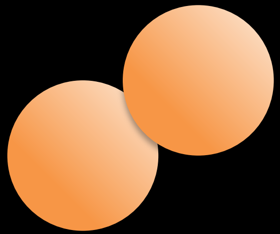

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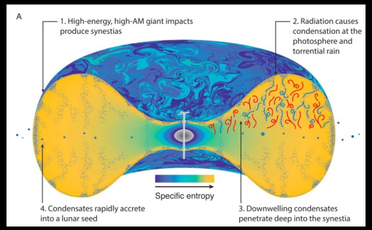
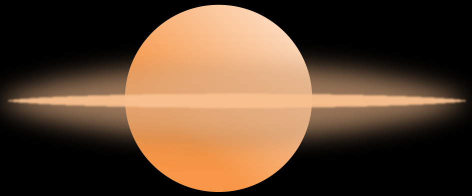


Vapor mass fraction of the disk

~ 20 wt%[1]



80-90 wt%[1] 80-100 wt%[1]

Strong gas drag on silicate particles?

1: Nakajima & Stevenson, 2014

Simple analysis

Radial velocity of a particle

(e.g., Adachi et al., 1975, Widenschilling et al., 1977)

$$v_r = -2\eta v_K \tau_f / (1 + \tau_f^2)$$

$$\eta = -\frac{1}{2}\left(\frac{c_s}{v_k}\right)^2 \frac{\partial \ln P}{\partial \ln r}$$

Pressure gradient parameter

$$\tau_f = \frac{8}{3C_D}\frac{\rho_p}{\rho_g}\frac{R_p}{v}\Omega_K$$

Dimensionless stopping time

c_s: sound speed, P: pressure, r: radial distance from Earth, C_D: gas drag coefficient, ρ_p: particle density, ρ_g: gas density, R_p: Particle radius, v: relatively velocity, Ω_K: angular velocity

Nakajima et al. (2022)

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Radial fall timescale

~ 20 days for R_p= 100 m

~ 1 day for R_p = 2 km *(VERY FAST!)*

~ 1 month for R_p= 100 km

~ 1 year for R_p = 1000 km

Parameter example

ρ_p=3 g/cc, ρ_g=0.04 g/cc,
C_D=0.44, η=0.04, r=3 R_{Earth}

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Radial fall timescale

Problem with forming the Moon

~ 20 days for R_p = 100 m
~ 1 day for R_p = 2 km *(VERY FAST!)*
~ 1 month for R_p = 100 km
~ 1 year for R_p = 1000 km

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Overview

Problem

Growing moonlets likely to face the ``km barrier problem”: km-sized moonlets fall towards Earth on a very short time scale (less than one day!) in a vapor-rich Moon-forming disk

Question

Can streaming instability (SI) solve this problem by making much larger moonlets (>> km) quickly?

We investigate whether streaming instability can help forming the Moon from an initially vapor-rich disk

Model

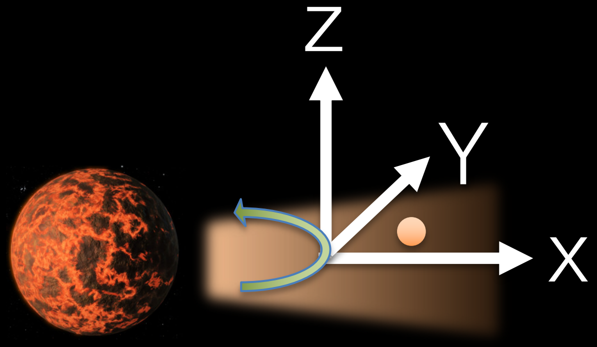
Hydrodynamic simulations using Athena (e.g., Bai & Stone, 2010)

Solves particle-gas interaction (2D, 3D)

$$\frac{d\boldsymbol{v}_i}{dt} = 2\boldsymbol{v}_i \times \boldsymbol{\Omega} + 2q\Omega^2 x\hat{\boldsymbol{x}} - \Omega^2 z\hat{\boldsymbol{z}} - \frac{\boldsymbol{v}_i - \boldsymbol{u}}{t_{\rm stop}},$$

$$\frac{\partial \rho_g}{\partial t} + \nabla \cdot (\rho_g \boldsymbol{u}) = 0,$$

$$\frac{\partial \rho_g \boldsymbol{u}}{\partial t} + \nabla \cdot (\rho_g \boldsymbol{u}\boldsymbol{u} + P_g \boldsymbol{I}) = \rho_g \left[2\boldsymbol{u} \times \boldsymbol{\Omega} + 2q\Omega^2 x\hat{\boldsymbol{x}} - \Omega^2 z\hat{\boldsymbol{z}} + \epsilon \frac{\overline{\boldsymbol{v}} - \boldsymbol{u}}{t_{\rm stop}} \right].$$



Parameter space

Normalized pressure gradient parameter $\Delta = \eta \frac{v_K}{c_s}$: 0.1 ~ 0.5

Dimensionless stopping time τ_f : 10^{-3} ~ 10^{1}

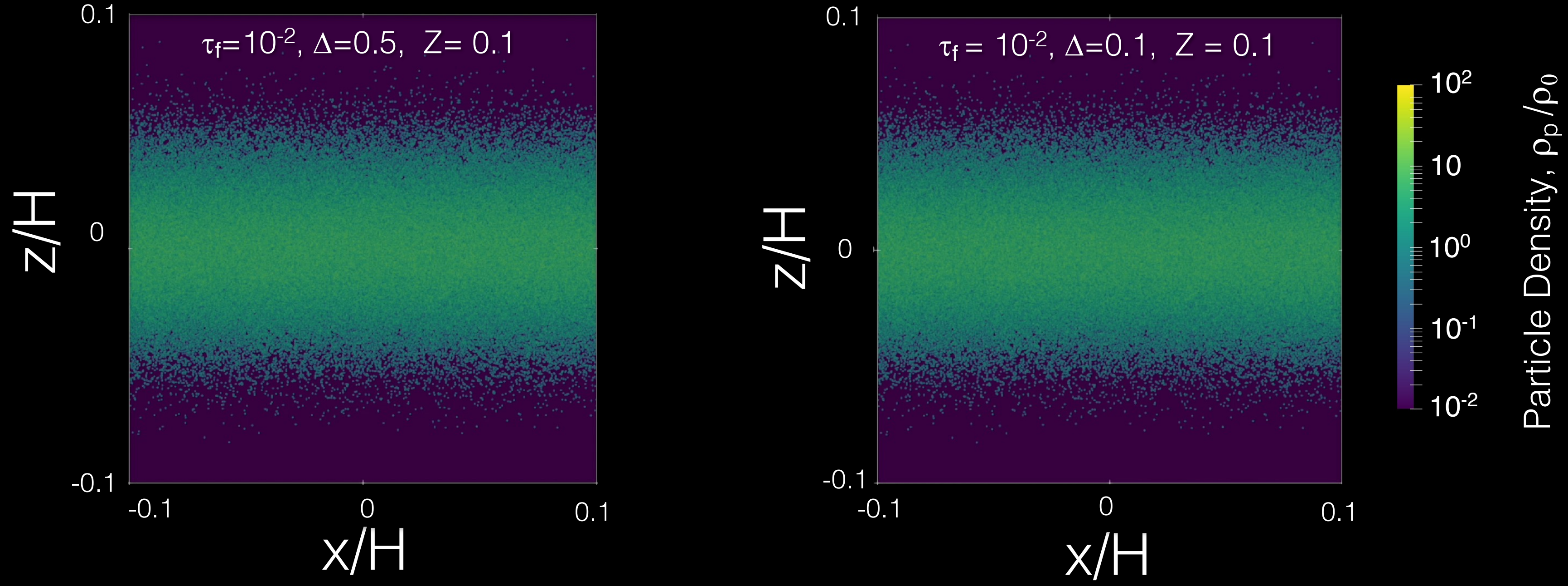
(i.e. R_p : ~ 2 m - 20 km)

Particle to gas ratio Z : 0.01, 0.05, 0.1

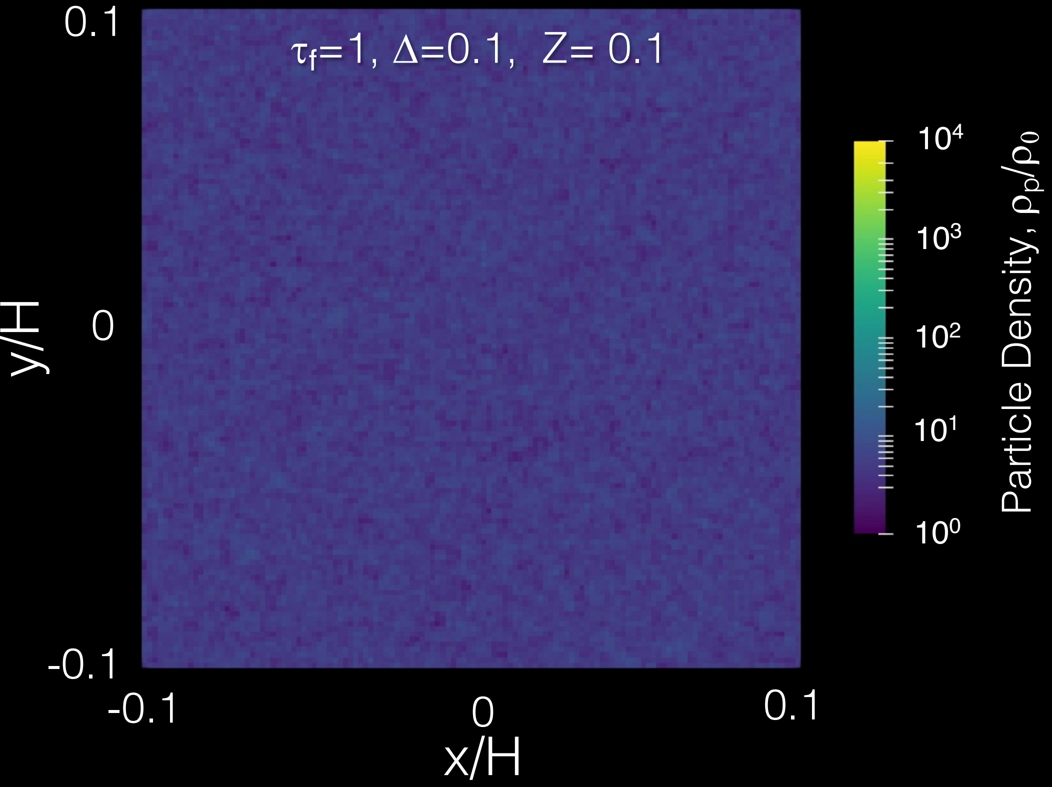
(i.e. vapor mass fraction: ~90-99 wt%)

2D simulations: Clumping *can occur* in the Moon-forming disk

Nakajima, Atkins, Simon, & Quillen, in prep.



3D simulation: SI-induced moonlets are too small to avoid gas drag

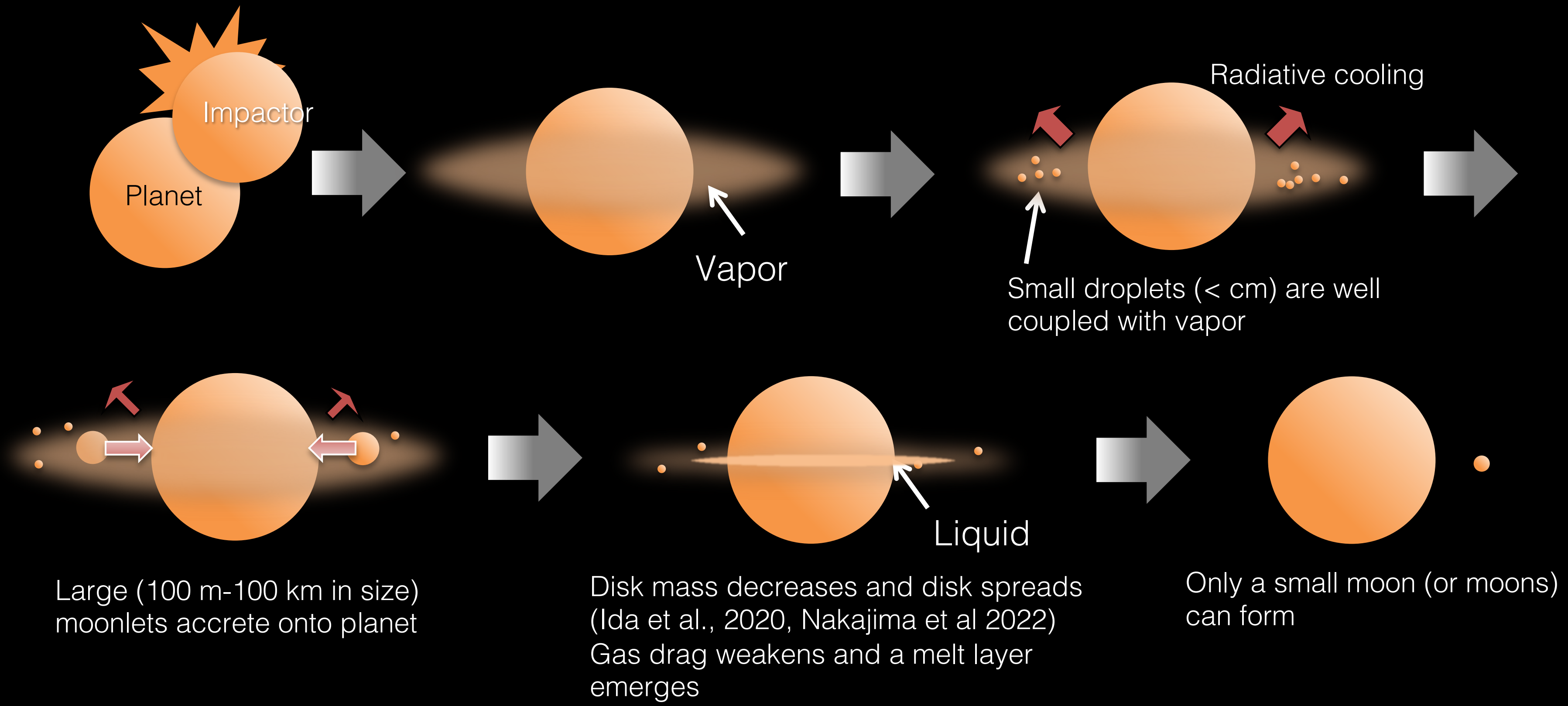


The maximum moonlet size is ~ 50 km

These moonlets still fall onto Earth quickly (~ 2 weeks)

SI-induced moonlets are not large enough to avoid the strong gas drag

Initially vapor-rich disk may not form a large moon



Summary & Discussion

We find that streaming instability can form moonlets in a vapor-rich Moon-forming disk, but the maximum moonlet size is ~ 50 km (Nakajima et al. in prep.)

An initially vapor-rich Moon-forming disk may not be able to form the large Moon because growing moonlets of 100 m-100 km in size fall onto Earth on a short timescale, failing to grow further (Nakajima et al. 2022)

Our model supports the Moon formation model that produces a vapor-poor disk (e.g., standard model)

Disk evolution needs to be modeled in detail