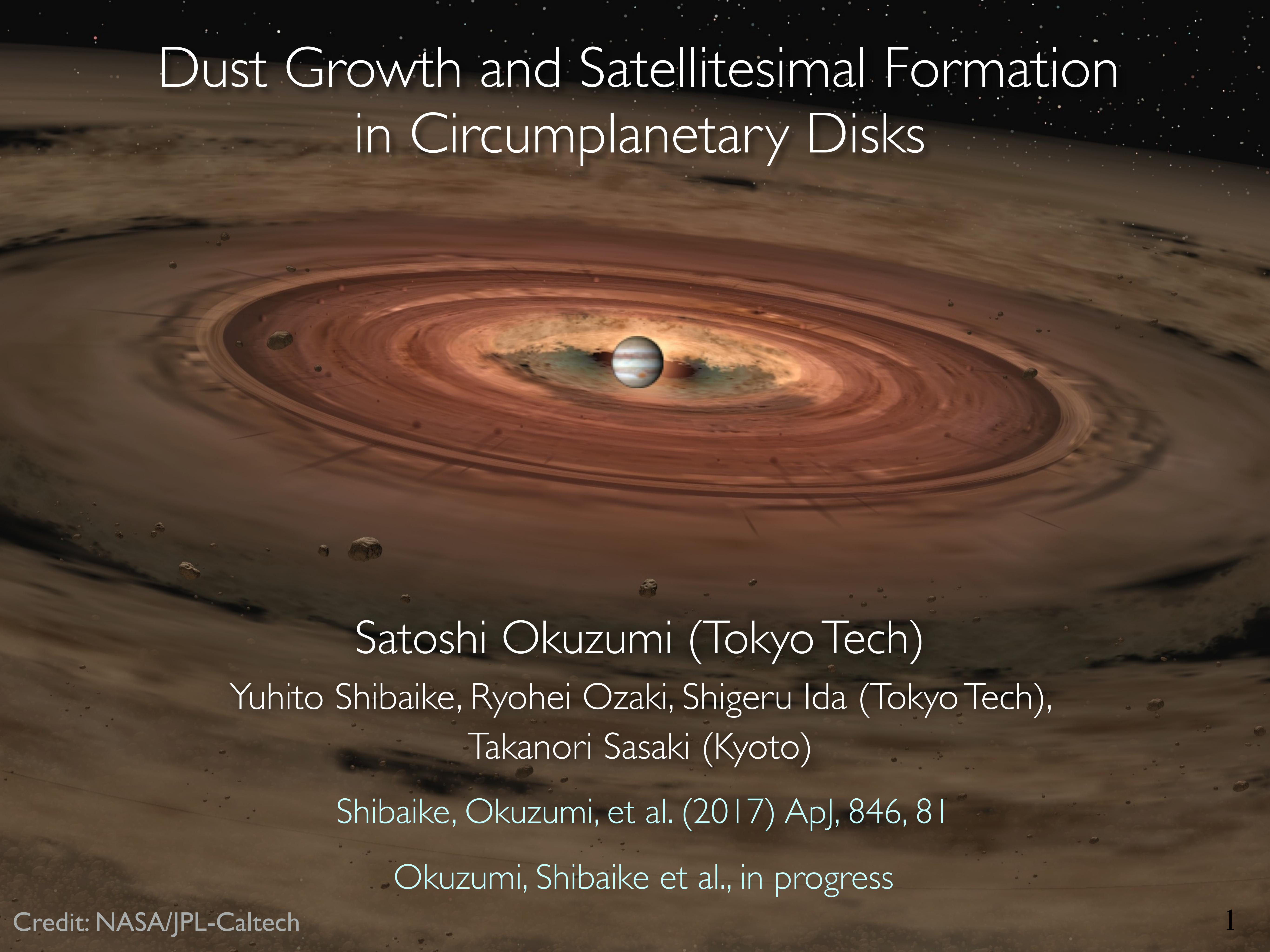
Dust Growth and Satellitesimal Formation in Circumplanetary Disks



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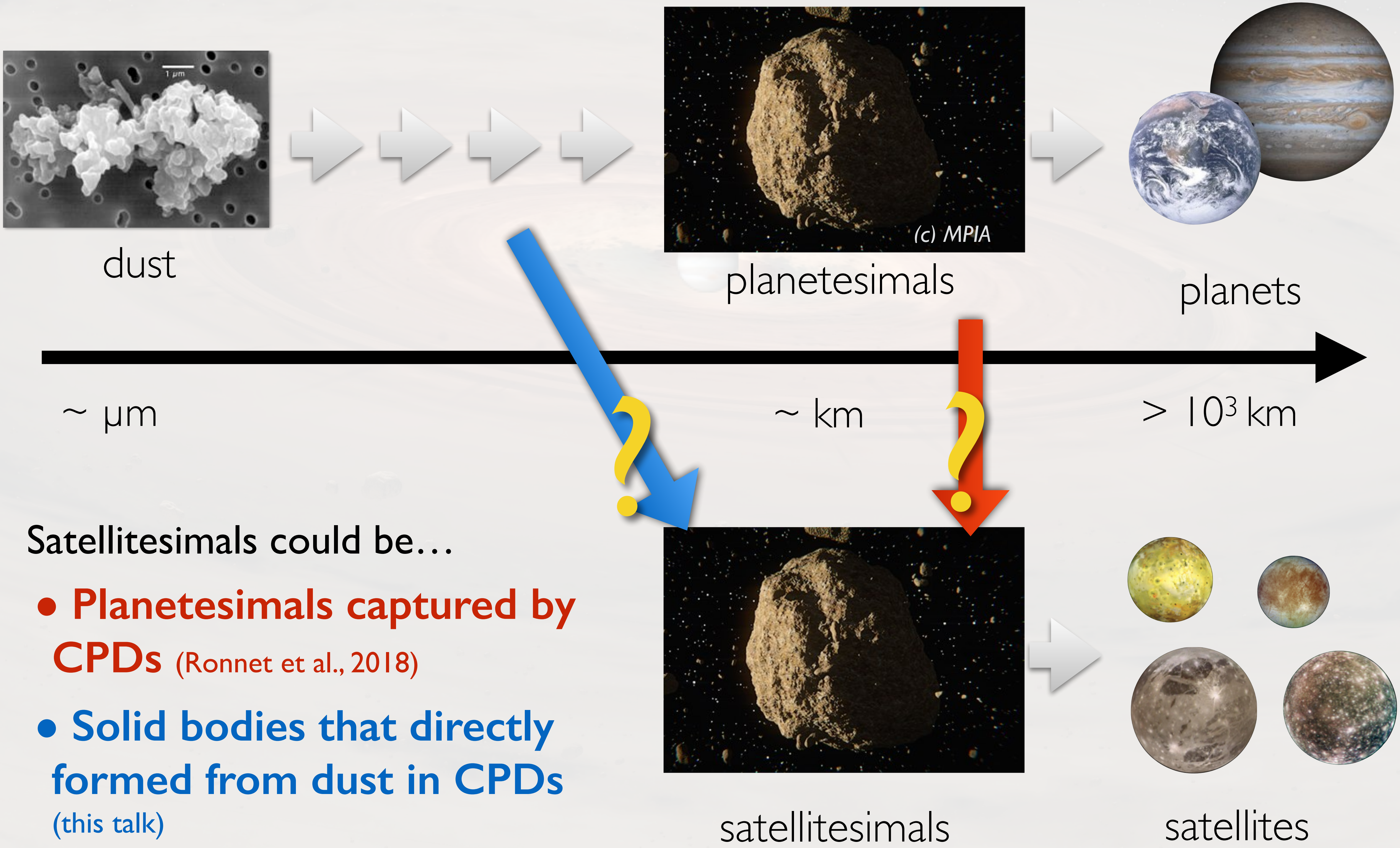
Takanori Sasaki (Kyoto)

Shibaike, Okuzumi, et al. (2017) ApJ, 846, 81

Okuzumi, Shibaike et al., in progress

Credit: NASA/JPL-Caltech

How the Large Satellites Formed in CPDs?



dust

(c) MPIA

planetesimals

planets

~ μm

~ km

> 10^3 km

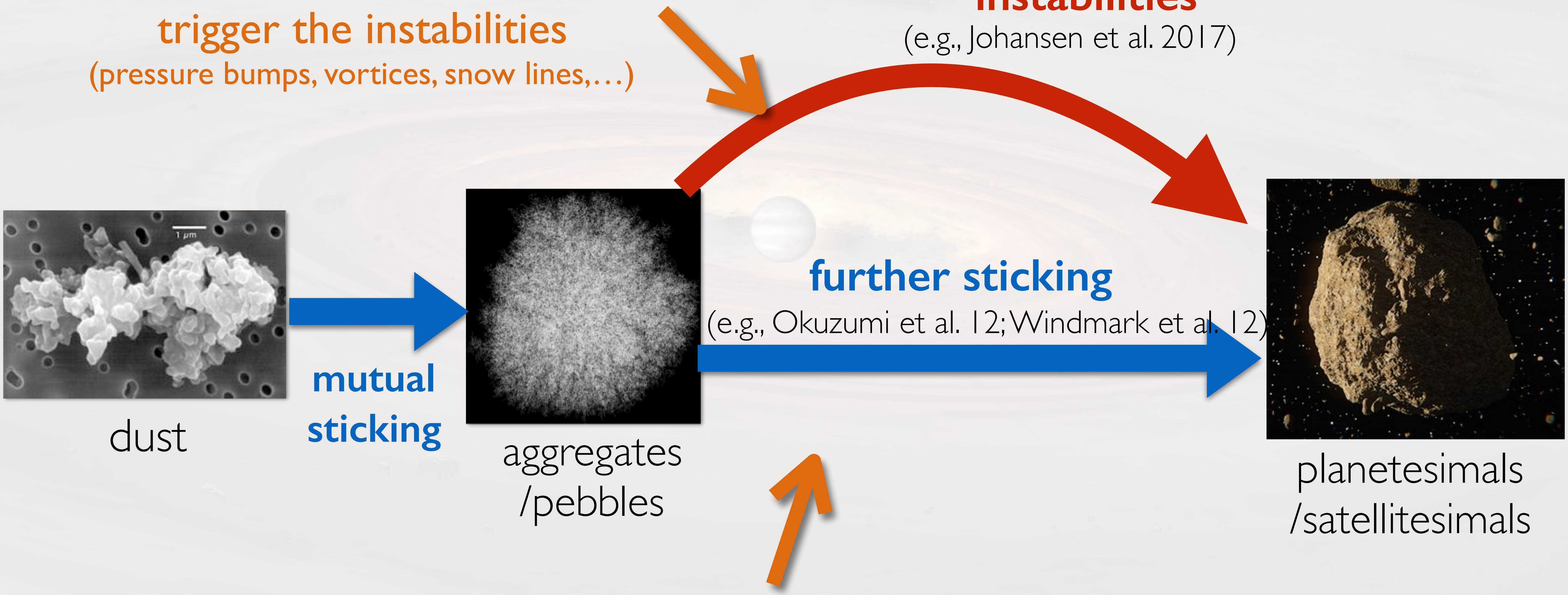
satellitesimals

satellites

Satellitesimals could be…

- **Planetesimals captured by CPDs** (Ronnet et al., 2018)
- **Solid bodies that directly formed from dust in CPDs** (this talk)

How Can Satellitesimals Form in Circumplanetary Disks?



Needs solid accumulation to trigger the instabilities

(pressure bumps, vortices, snow lines,…)

streaming/gravitational instabilities

(e.g., Johansen et al. 2017)

dust

mutual sticking

aggregates /pebbles

further sticking

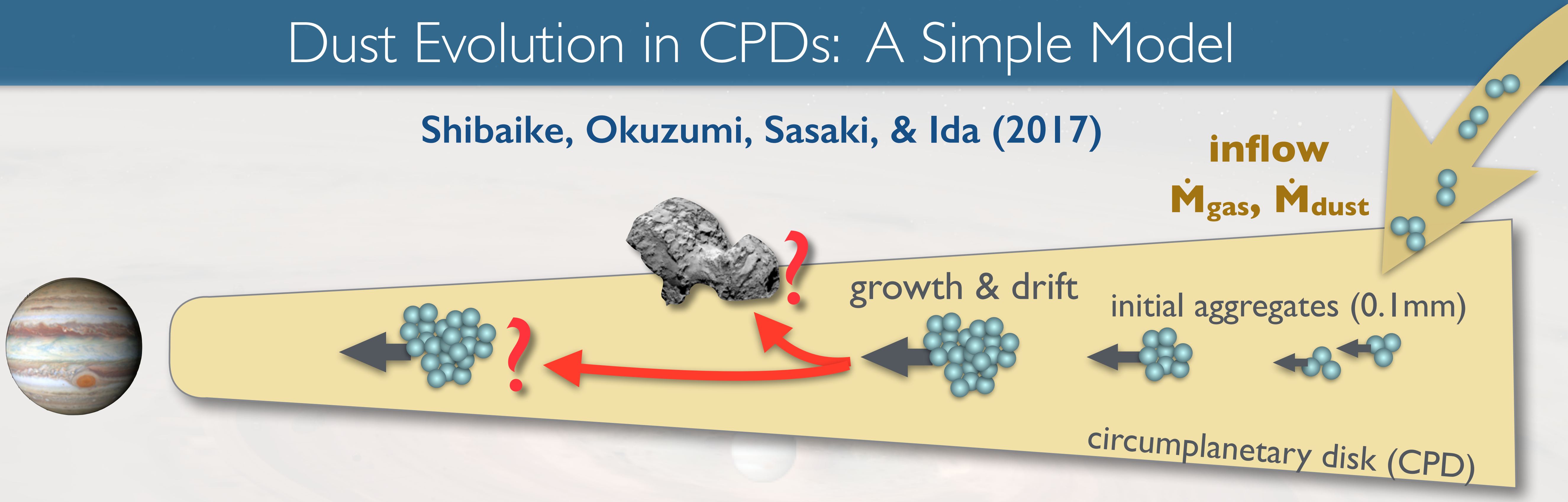
(e.g., Okuzumi et al. 12; Windmark et al. 12)

planetesimals /satellitesimals

- Growth must be faster than drift
- Sticky grains (e.g., subμm ice grains) needed to avoid fragmentation
- Because of particle filtration at gas gap, only small grains can arrive in CPDs

Dust Evolution in CPDs: A Simple Model

Shibaike, Okuzumi, Sasaki, & Ida (2017)

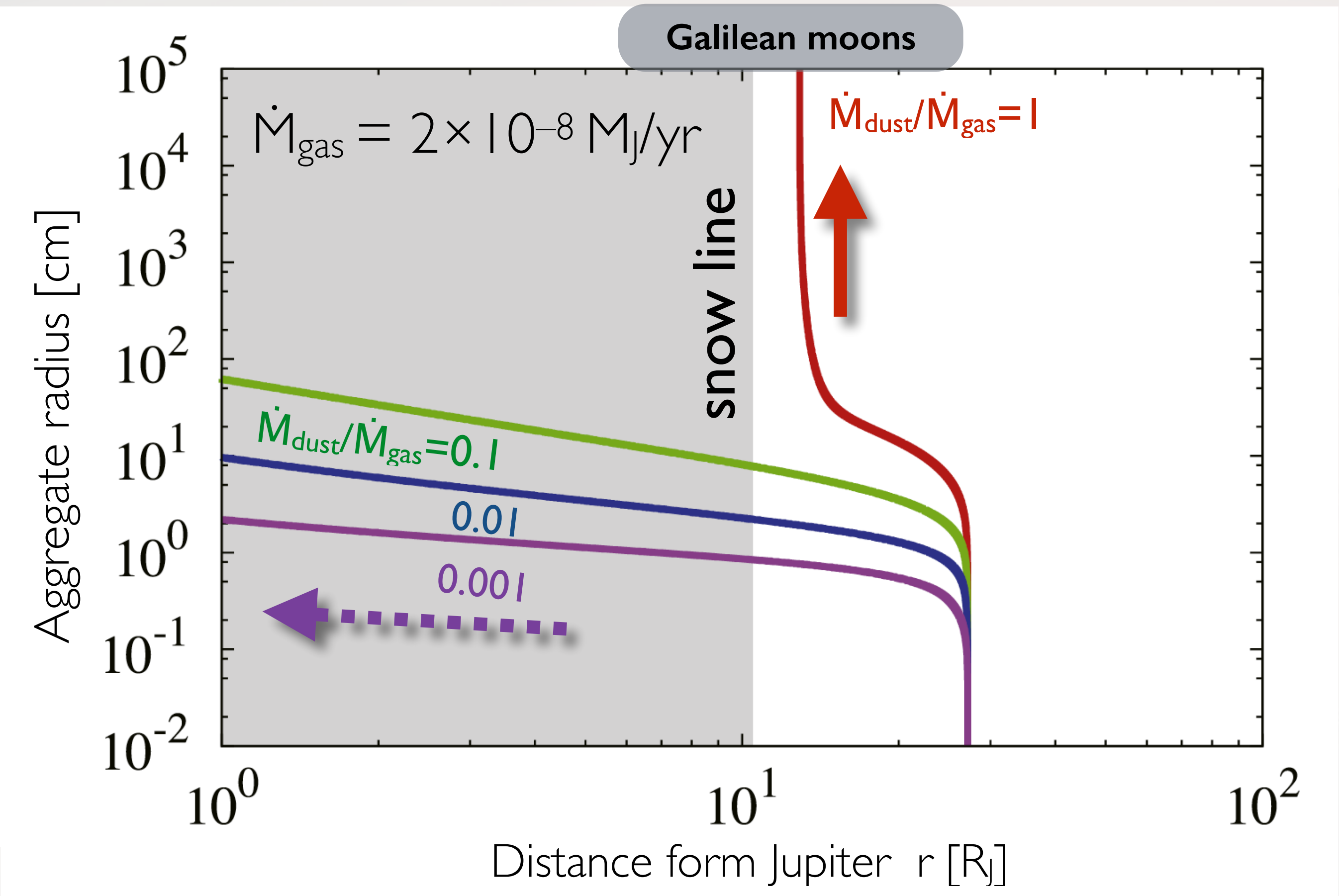


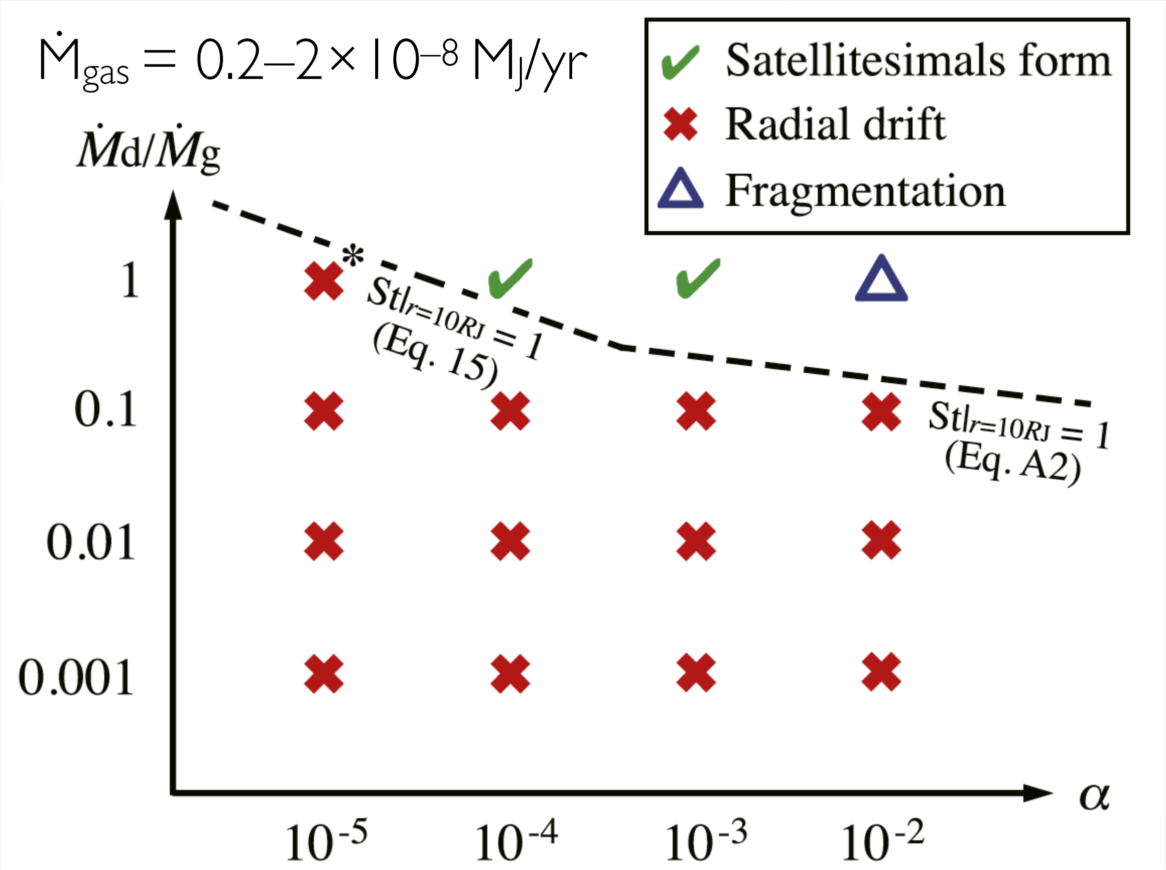
✳ Compute the typical size of dust particles by considering the balance between collisional growth and radial drift.

✳ Assumptions/simplifications (some of them will be relaxed later):

- ✦ Particle size distribution neglected (Sato et al. 2016)
- ✦ Perfect sticking assumed (therefore limited to icy particles)
- ✦ Aggregates = compact spheres (aggregate density = 1.4 g/cm^3)
- ✦ (gas viscosity) = (dust diffusivity) = $\alpha c_s H$ (α: free parameter)
- ✦ Steady gas & dust inflow at $\dot{M}_{\rm gas}$, $\dot{M}_{\rm dust}$ (free parameters)

Conditions for Satellitesimal Formation from the Toy Model





Conclusion:

Within this simple modeling, satellitesimal formation demands *extremely* high dust/gas flux ratio, $\dot{M}_{dust}/\dot{M}_{gas}$ ~ 1…

A Comprehensive Model for Dust Growth in CPDs

Work in progress, Okuzumi, Shibaike et al.

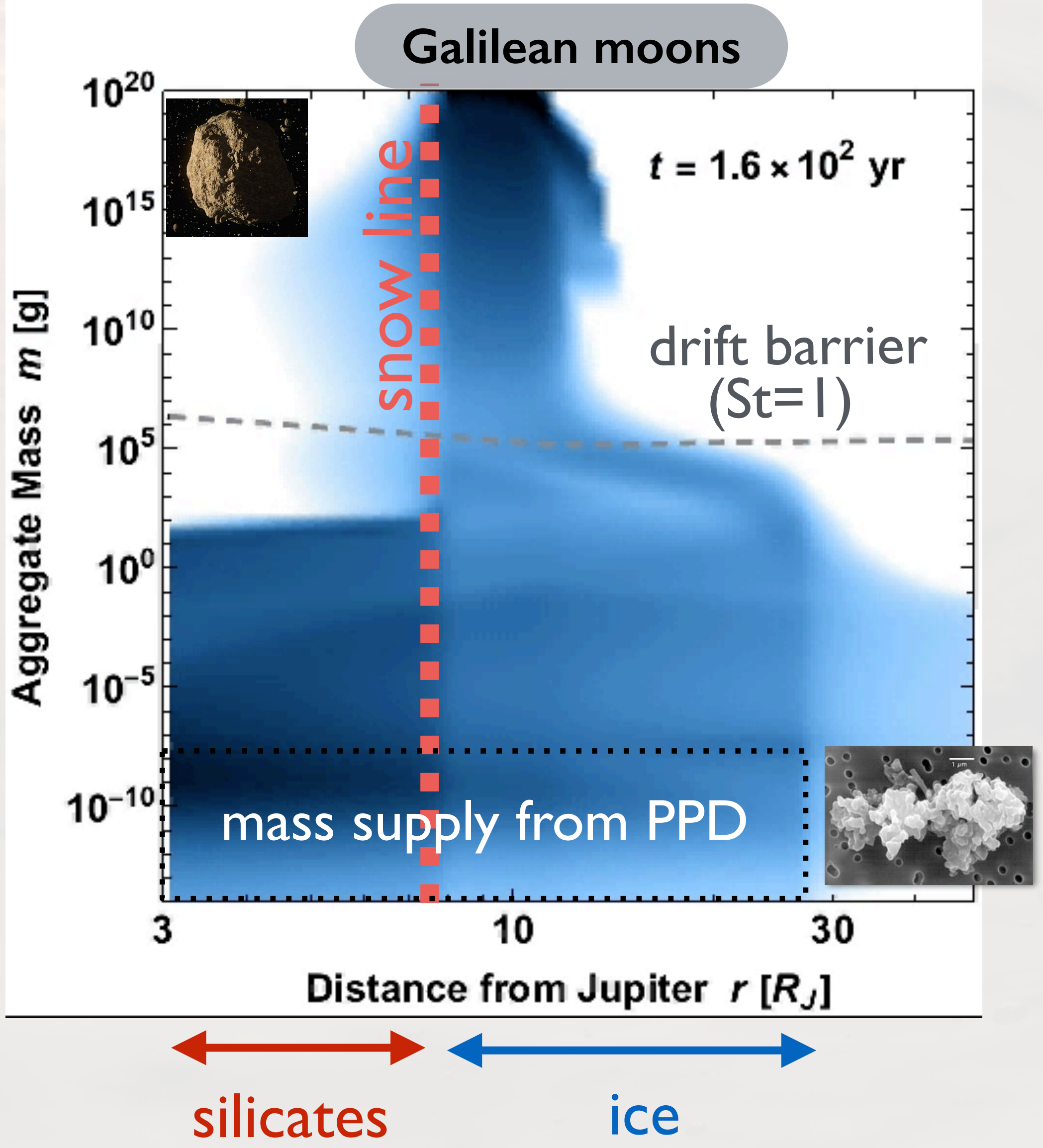
- ✳ Full particle size distribution resolved
- ✳ Fragmentation included, with the sticking threshold v_{frag} taken to be temperature-dependent:
  - ✦ v_{frag} = 8 m/s for T>200 K (silicates)
  - ✦ v_{frag} = 80 m/s for T<200 K (H_2O ice)

  (aggregates of 0.1 μm grains assumed; see Wada et al. 2013)
- ✳ Porosity of aggregates included
- ✳ Different parametrization for gas viscosity and dust diffusivity (discussed later).
- ✳ Vapor transport, ice re-condensation, temperature evolution to be included

$\dot{M}_{gas} = 2\times10^{-8}$ M_J/yr, $\dot{M}_{dust}/\dot{M}_{gas} = 0.1$

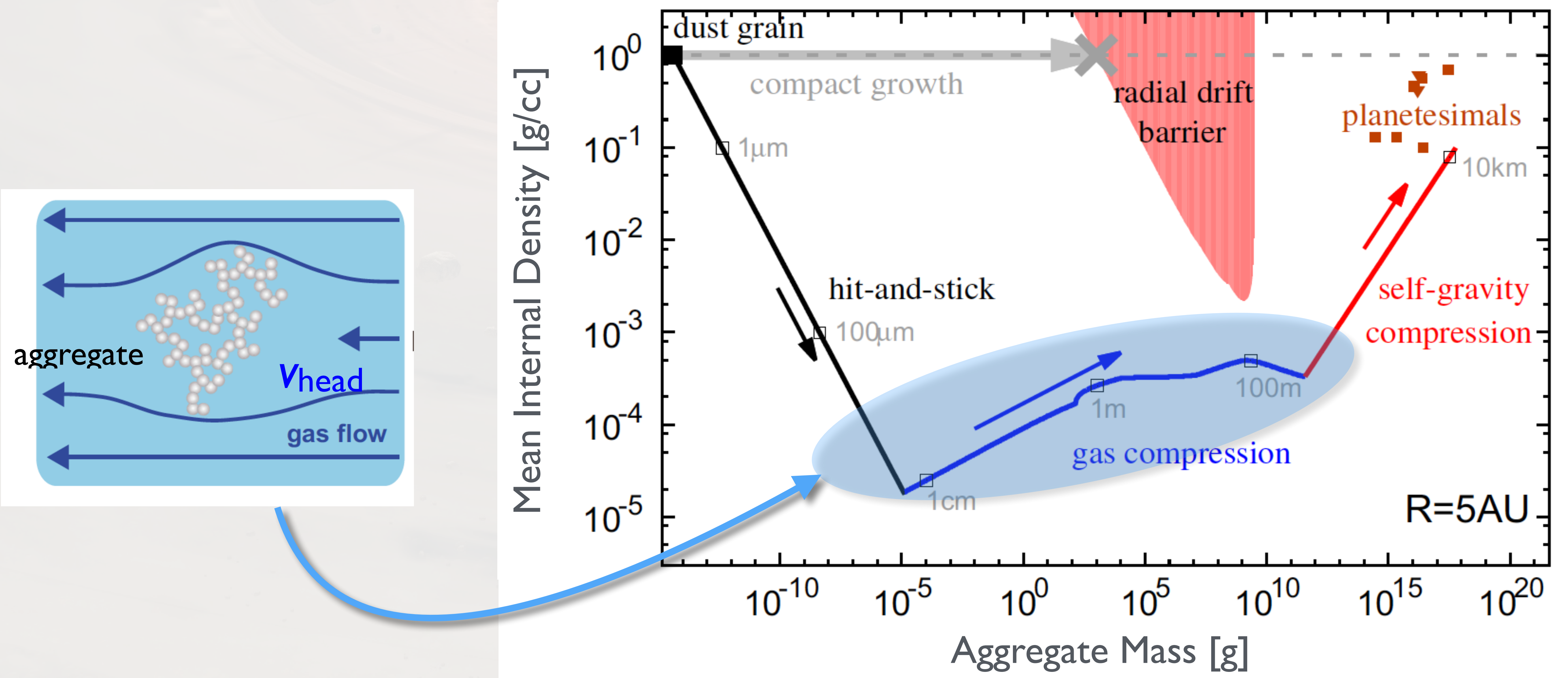
$\rho_{int} = 10^{-2}$ g/cm^3,

$\alpha_{acc} = 10^{-2}$, $\alpha_{diff} = 10^{-4}$



Key Effect (1): Porosity Evolution

- Aggregates obtain high porosity (i.e., low density) as they grow through low-velocity collisions (Meakin 1991; Suyama et al. 2008).
- Larger aggregates are compressed by ambient gas flow, but can still have a very low density of ~ 10^{-4} g cm^{-3} ! (Kataoka et al. 2013a,b)



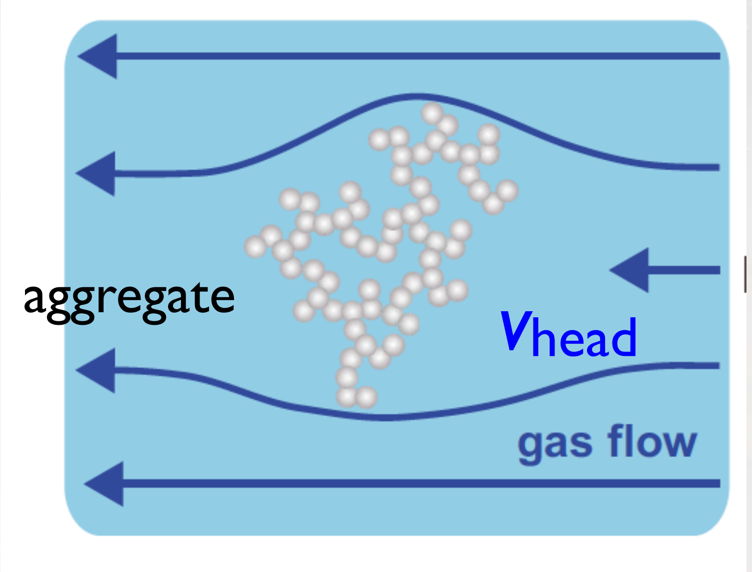
Kataoka, Tanaka, SO, & Wada (2013b)

How Fluffy Can Aggregates be in CPDs?

Aggregate density can be estimated from the ram pressure of the headwind:

$$\rho_{\rm int} \propto P_{\rm ram}^{1/3} \qquad P_{\rm ram} \sim \rho_{\rm gas} v_{\rm head}^2$$

(Kataoka et al., 2013a,b)

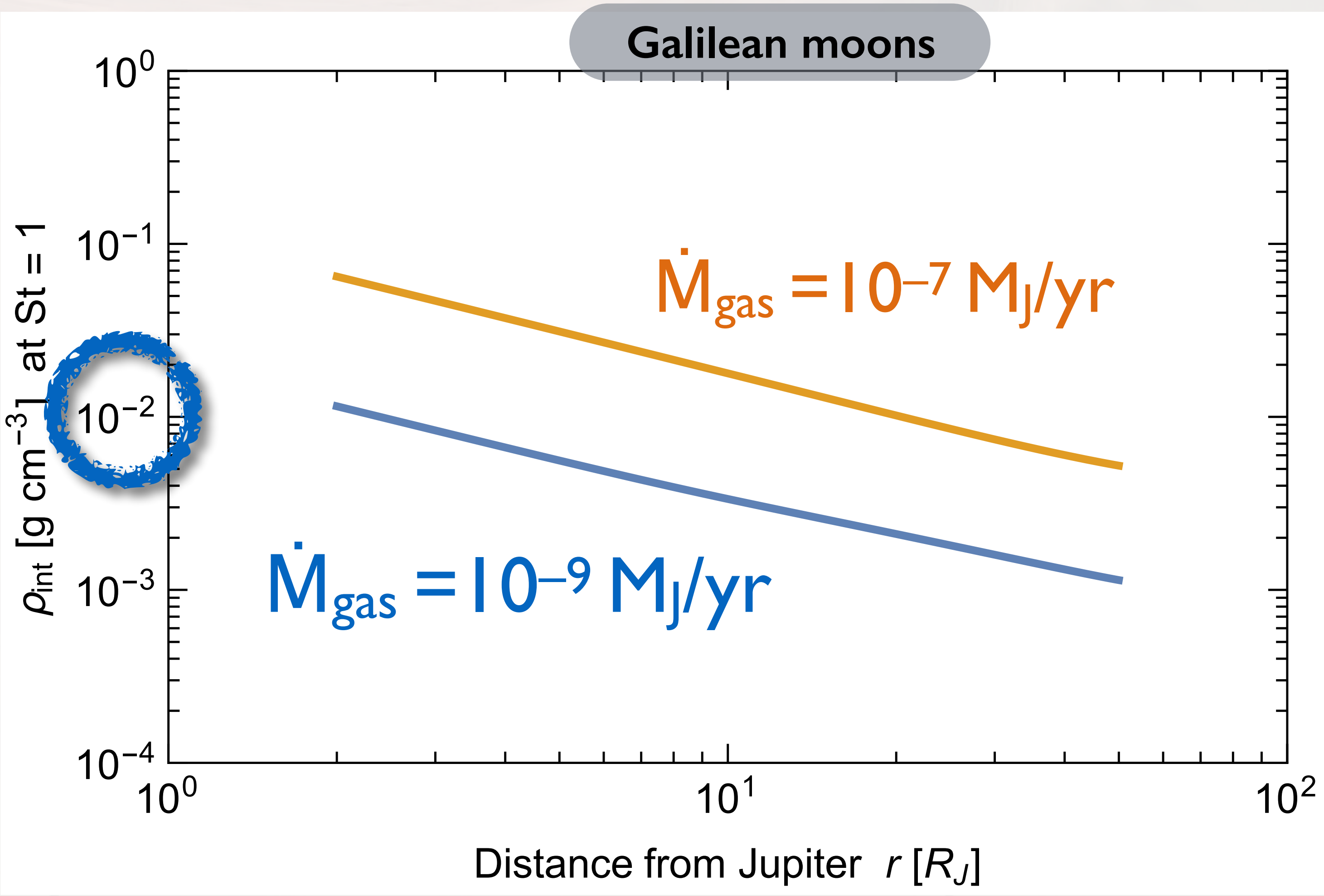


(Kataoka et al., 2013b)

In the circum-Jovian disk,

$\rho_{\rm int} \sim 10^{-2}$ g/cm^3
(⇔ porosity ~ 99%)

for $\dot{M}_{\rm gas} \sim 10^{-7\ldots-9}$ M_J/yr.



Breaking Through the Drift Barrier with Fluffy Aggregates

compact aggregates

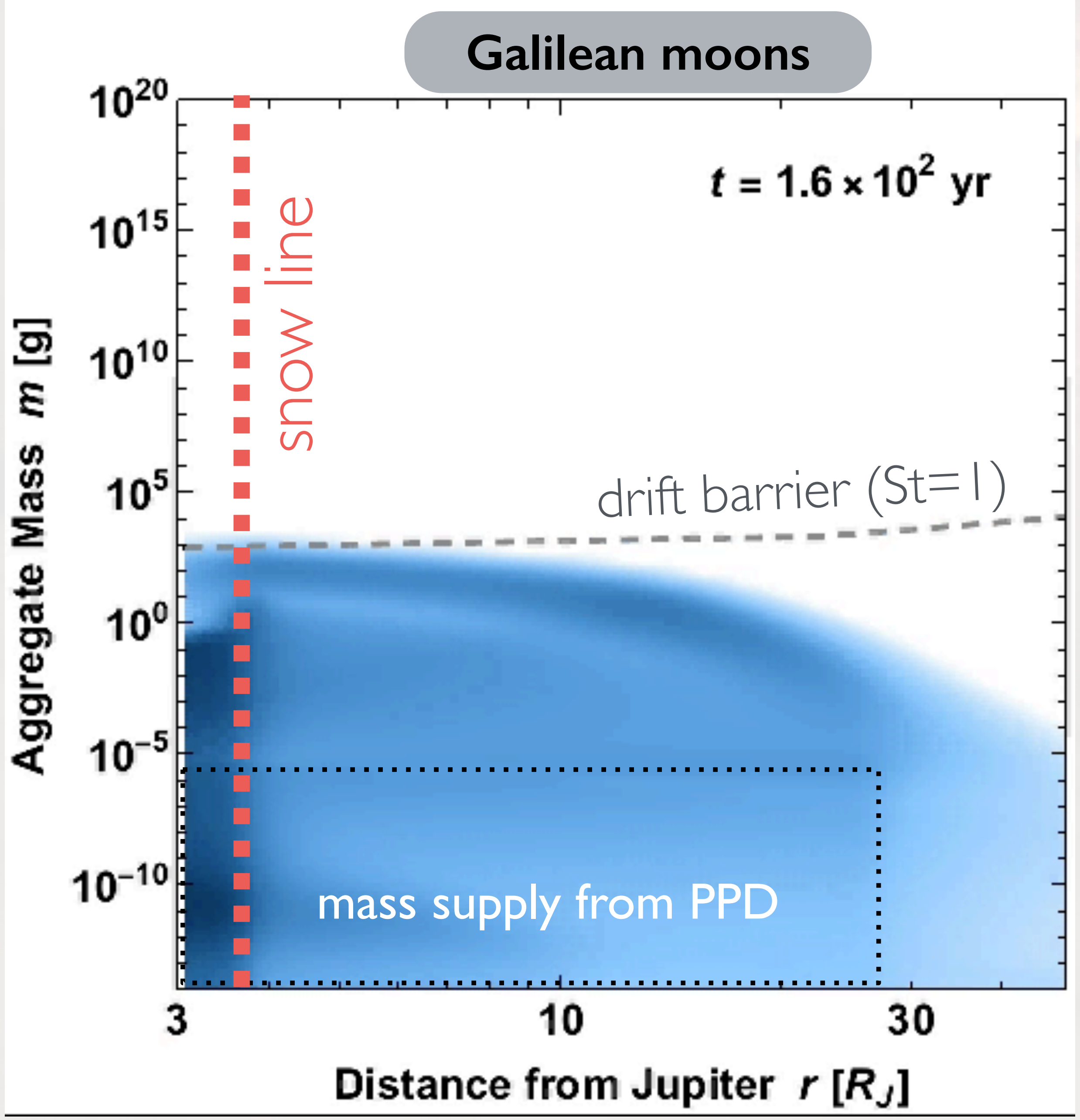
$\dot{M}_{\rm gas} = 2\times10^{-9}\ M_J/{\rm yr},\ \ \dot{M}_{\rm dust}/\dot{M}_{\rm gas} = 0.1$

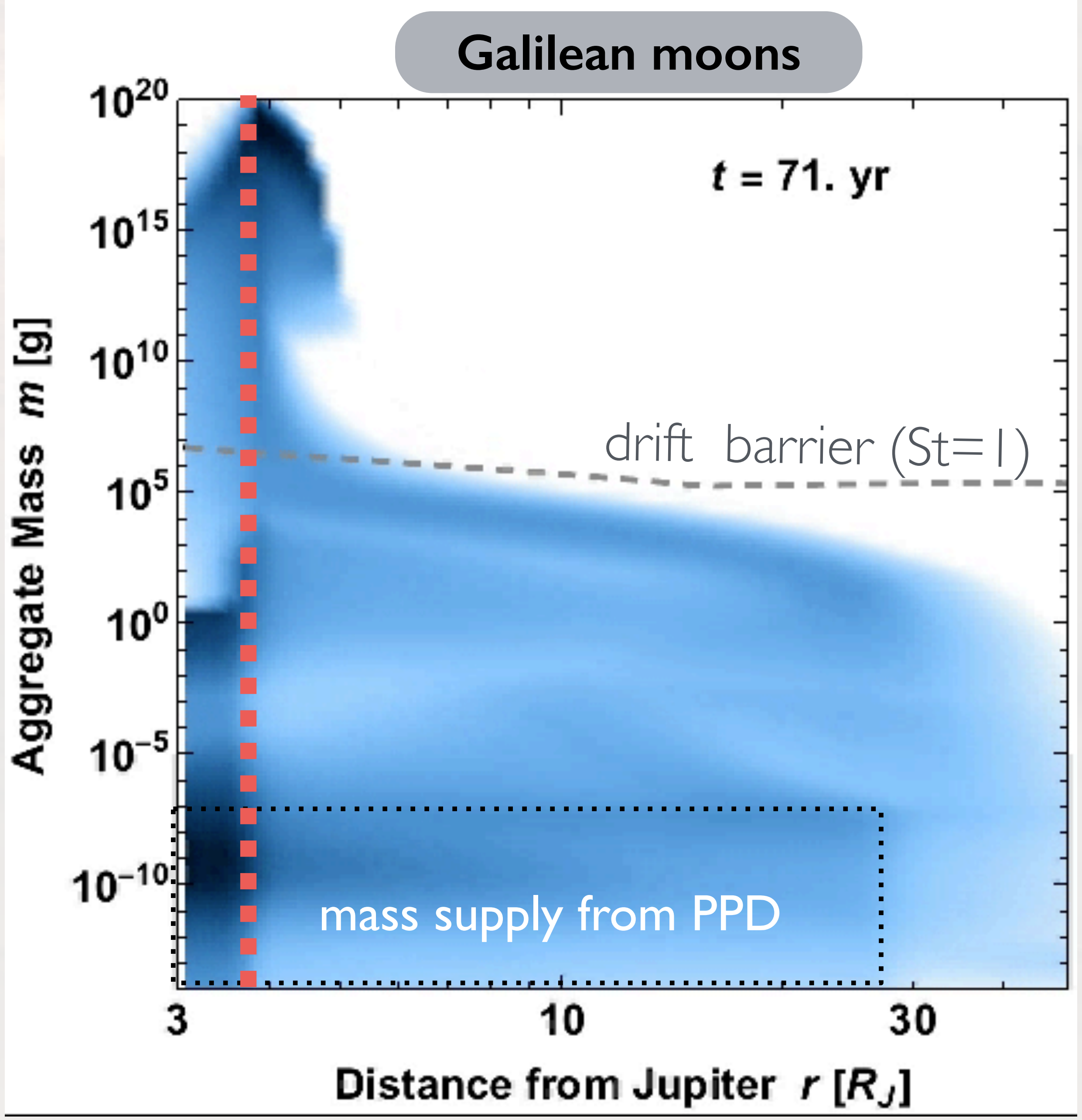
$\rho_{\rm int} = 1\ {\rm g/cm^3},\ \ \alpha_{\rm acc} = \alpha_{\rm diff} = 10^{-3}$

fluffy aggregates

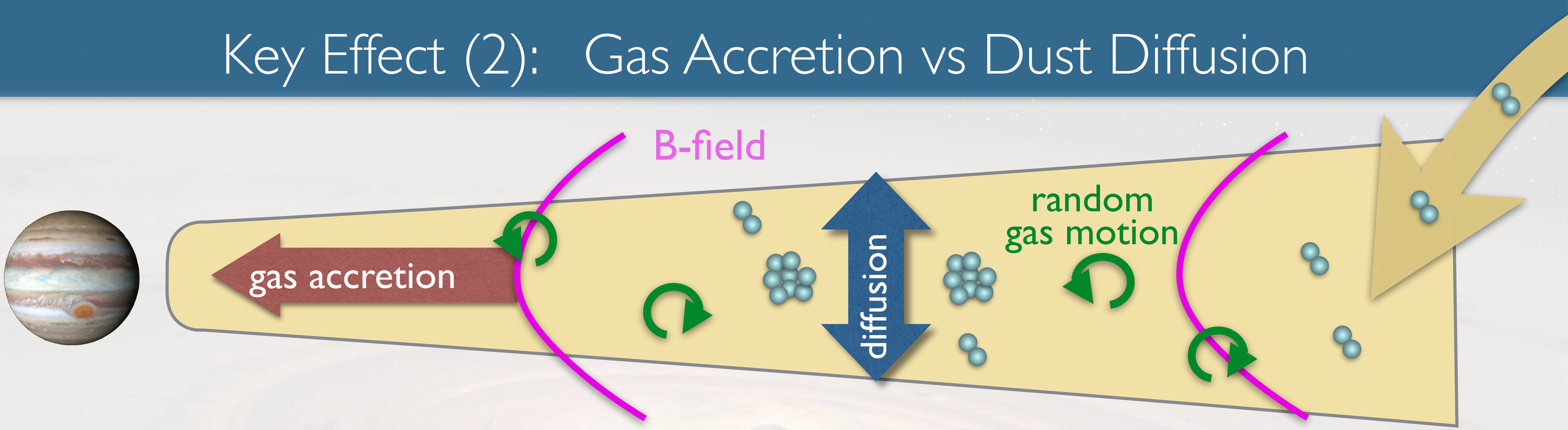
$\dot{M}_{\rm gas} = 2\times10^{-9}\ M_J/{\rm yr},\ \ \dot{M}_{\rm dust}/\dot{M}_{\rm gas} = 0.1$

$\boldsymbol{\rho_{\rm int} = 10^{-2}\ {\rm g/cm^3}},\ \ \alpha_{\rm acc} = \alpha_{\rm diff} = 10^{-3}$





Key Effect (2): Gas Accretion vs Dust Diffusion



There are two important transport mechanisms that affect dust growth:

Gas Accretion (ang. mom. transport)

$$\Sigma_{\rm gas} = \frac{\dot{M}_{\rm gas}}{3\pi \underline{\alpha_{\rm acc}} c_s H}$$

gas motion (horizontal) B-field

$$\underline{\alpha_{\rm acc}} = \frac{2}{3}\frac{\int \langle \rho_{\rm gas}\delta v_{\rm gas,r}\delta v_{\rm gas,\phi} - B_r B_\phi/4\pi\rangle dz}{\Sigma_{\rm gas} c_s^2}$$

Vertical Dust Diffusion

$$\rho_{\rm dust,mid} \propto D_z^{-1/2}$$

$$D_z = \underline{\alpha_{\rm diff}} c_s H$$

gas motion (vertical)

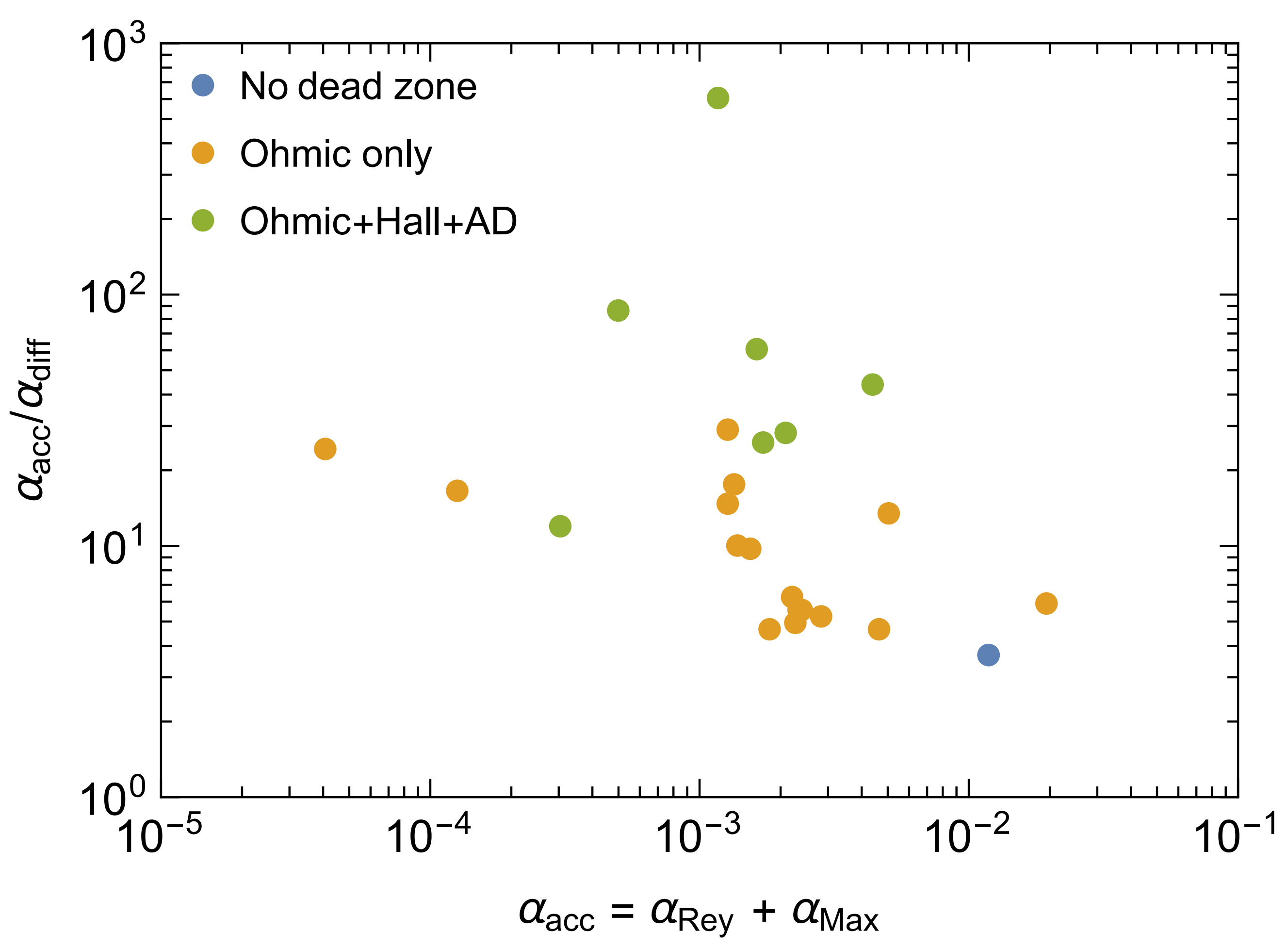
$$\underline{\alpha_{\rm diff}} \approx \langle \delta v_{{\rm gas},z}^2 \rangle / \Omega_{\rm Kep}$$

Dust growth is faster with **larger $\alpha_{\rm acc}$** and **smaller $\alpha_{\rm diff}$**:

$$t_{\rm grow} \propto \Sigma_{\rm gas}\rho_{\rm dust,mid}^{-1} \propto \alpha_{\rm acc}^{-1}\alpha_{\rm diff}^{1/2}$$

α_{acc} and α_{diff} from MHD Simulations

- ✦ **$\alpha_{acc} \sim 2–20\ \alpha_{diff}$** in MRI turbulence (Johansen & Klahr 2005; Johansen et al. 2006)
- ✦ **$\alpha_{acc} \sim 5–30\ \alpha_{diff}$** when Ohmic diffusion impedes MRI at midplane (Okuzumi & Hirose 2011)
- ✦ No direct measurements of α_{diff} with the Hall effect, but a simple estimate from $\langle \delta v_z^2 \rangle$ suggests **$\alpha_{acc} > 10\ \alpha_{diff}$** (based on data by Bai 2015)



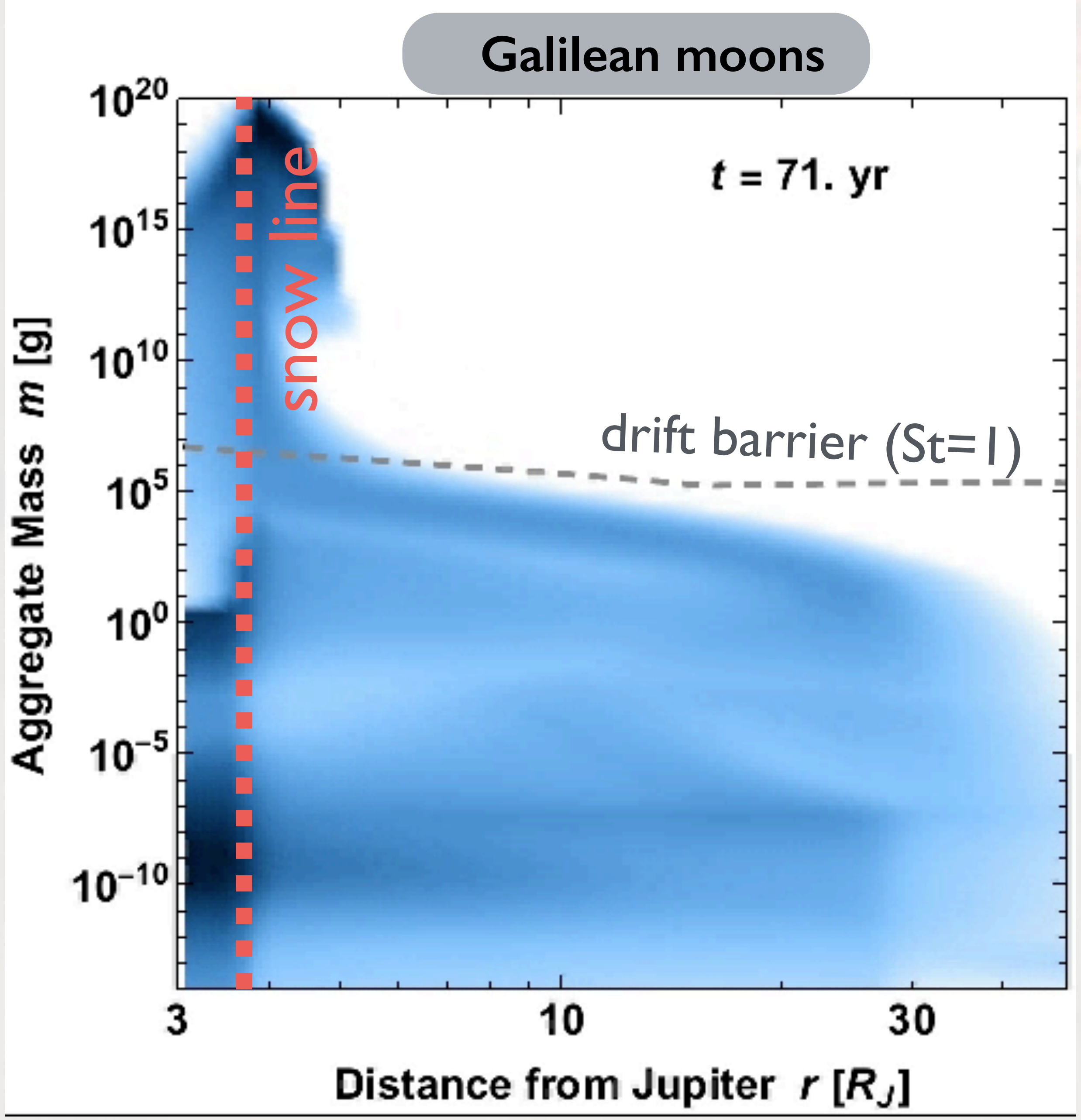
MRI is likely dead in dense part of CPDs
(Turner et al. (2014); Fujii et al. (2014)

➡ Appropriate to assume $\alpha_{acc} > 10\ \alpha_{diff}$?

Caveat: $\alpha_{acc} < \alpha_{diff}$ can happen in low-density regions where ambipolar diffusion dominates (Zhu, Stone, & Bai 2015)

α_{acc} > α_{diff} Facilitates Satellitesimal Formation

$\dot{M}_{gas} = 2\times10^{-9}$ M_J/yr, $\dot{M}_{dust}/\dot{M}_{gas} = 0.1$
$\rho_{int} = 10^{-2}$ g/cm^3,
$\alpha_{acc} = \alpha_{diff} = 10^{-3}$



$\dot{M}_{gas} = 2\times10^{-9}$ M_J/yr, $\dot{M}_{dust}/\dot{M}_{gas} = 0.1$
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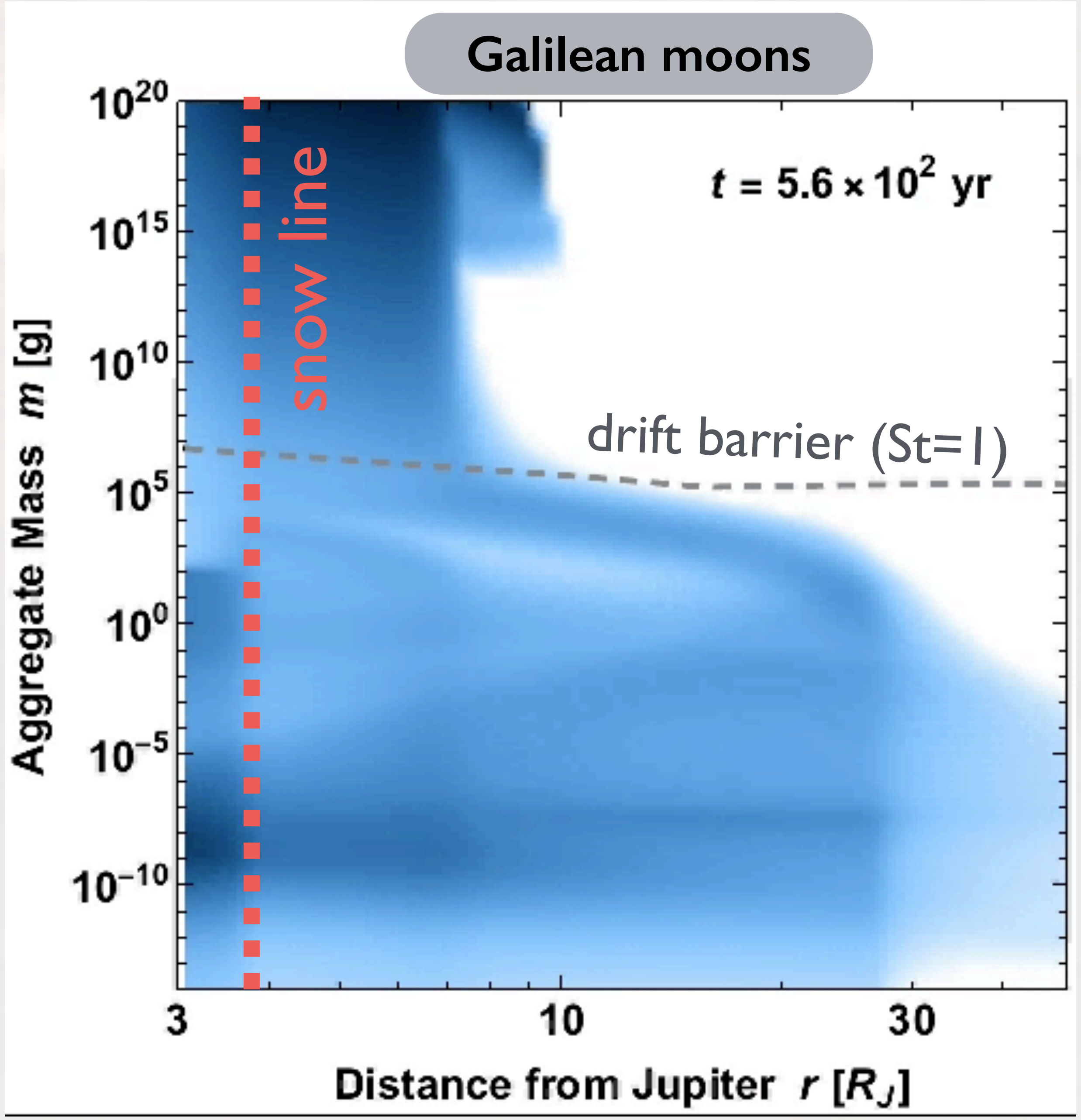
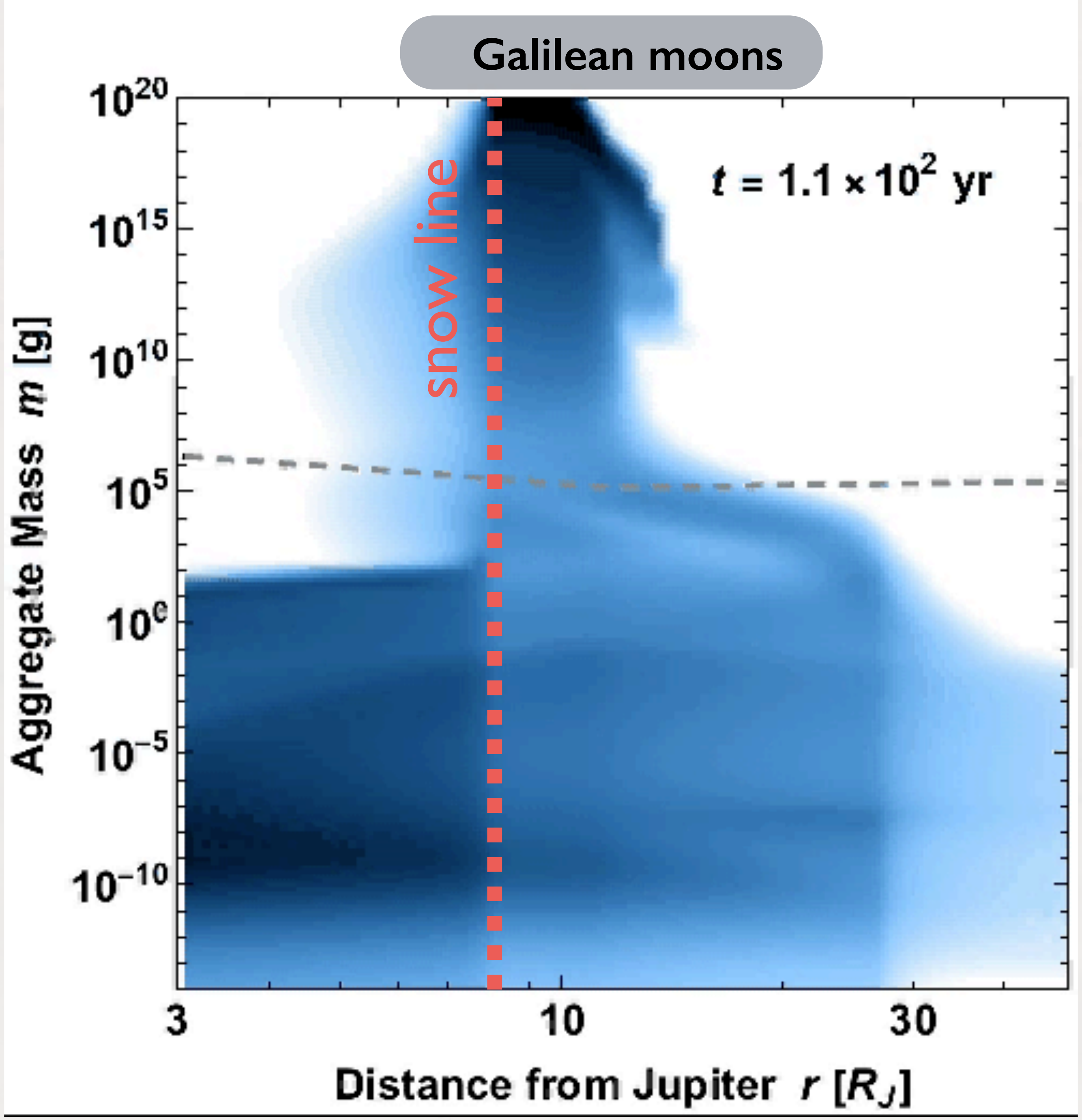


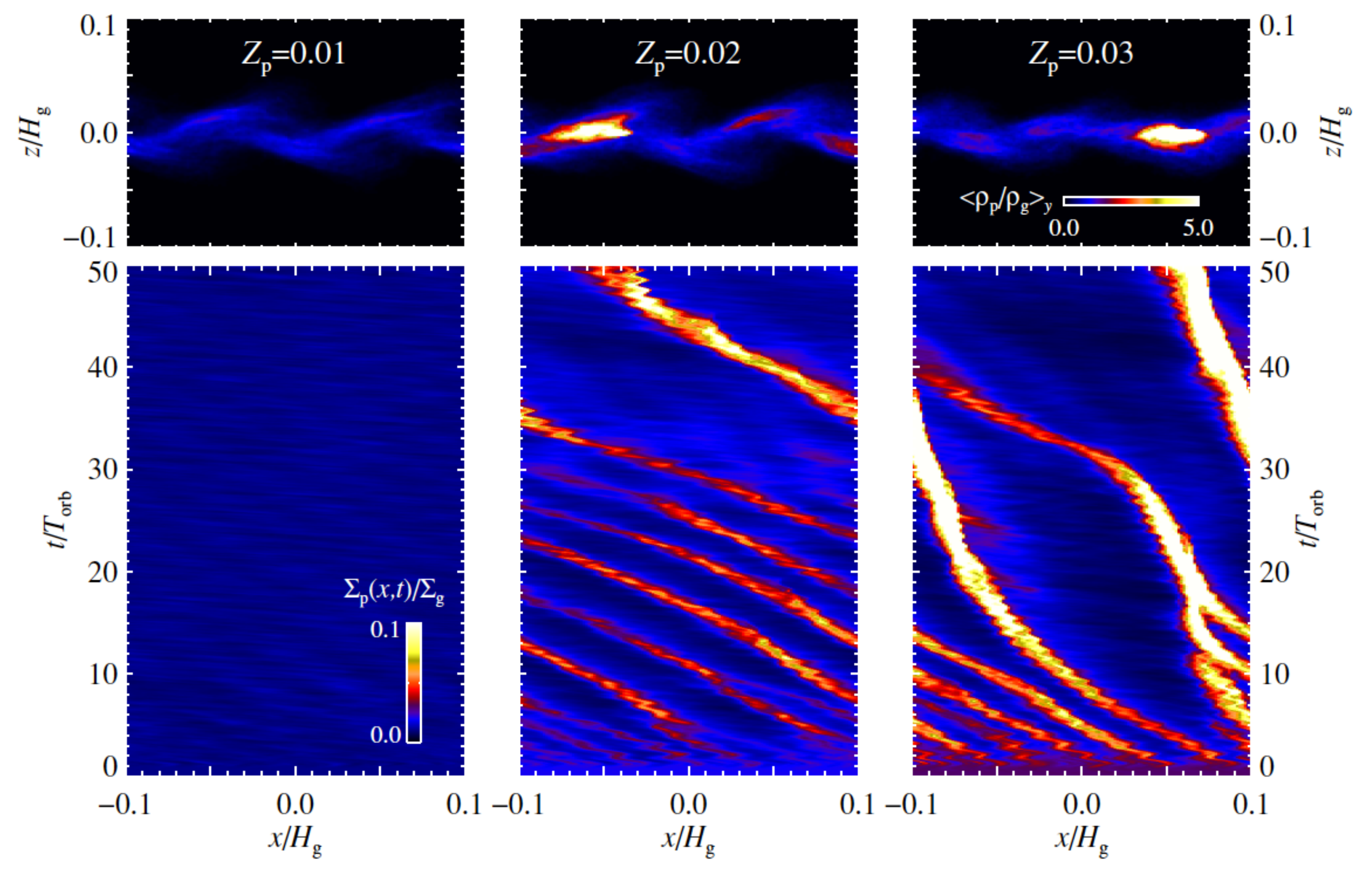
Best Model at This Moment

$\dot{M}_{gas} = 2\times10^{-8}\ M_J/yr$, $\dot{M}_{dust}/\dot{M}_{gas} = 0.1$ $\Rightarrow$ $M_{dust} = 2\times10^{-3}\ M_J$ for 1Myr

$\rho_{int} = 10^{-2}\ g/cm^3$, **$\alpha_{acc} = 10^{-2}$, $\alpha_{diff} = 10^{-4}$**



Planetesimal Formation via the Streaming Instability



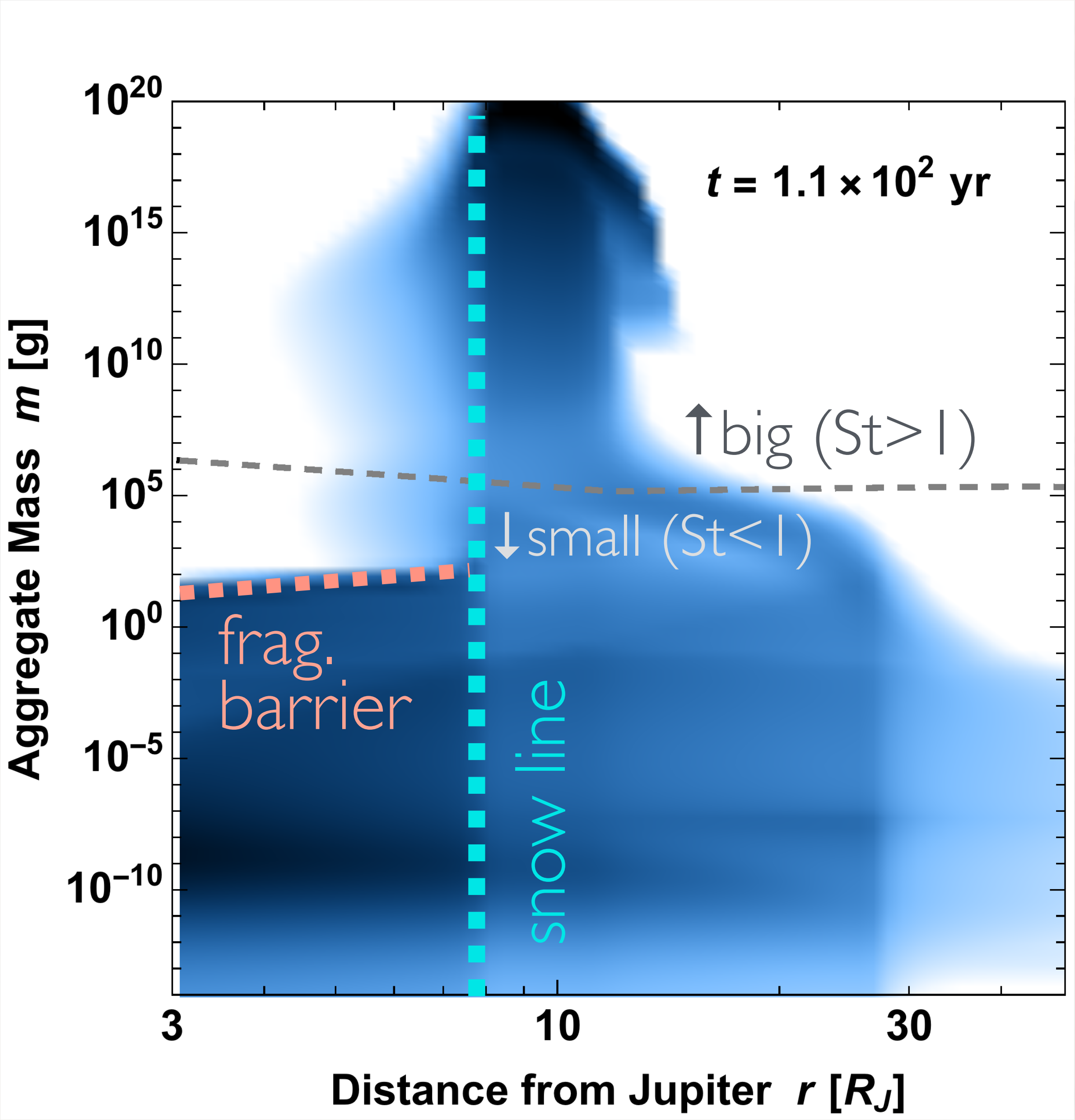
Johansen et al. (2008)

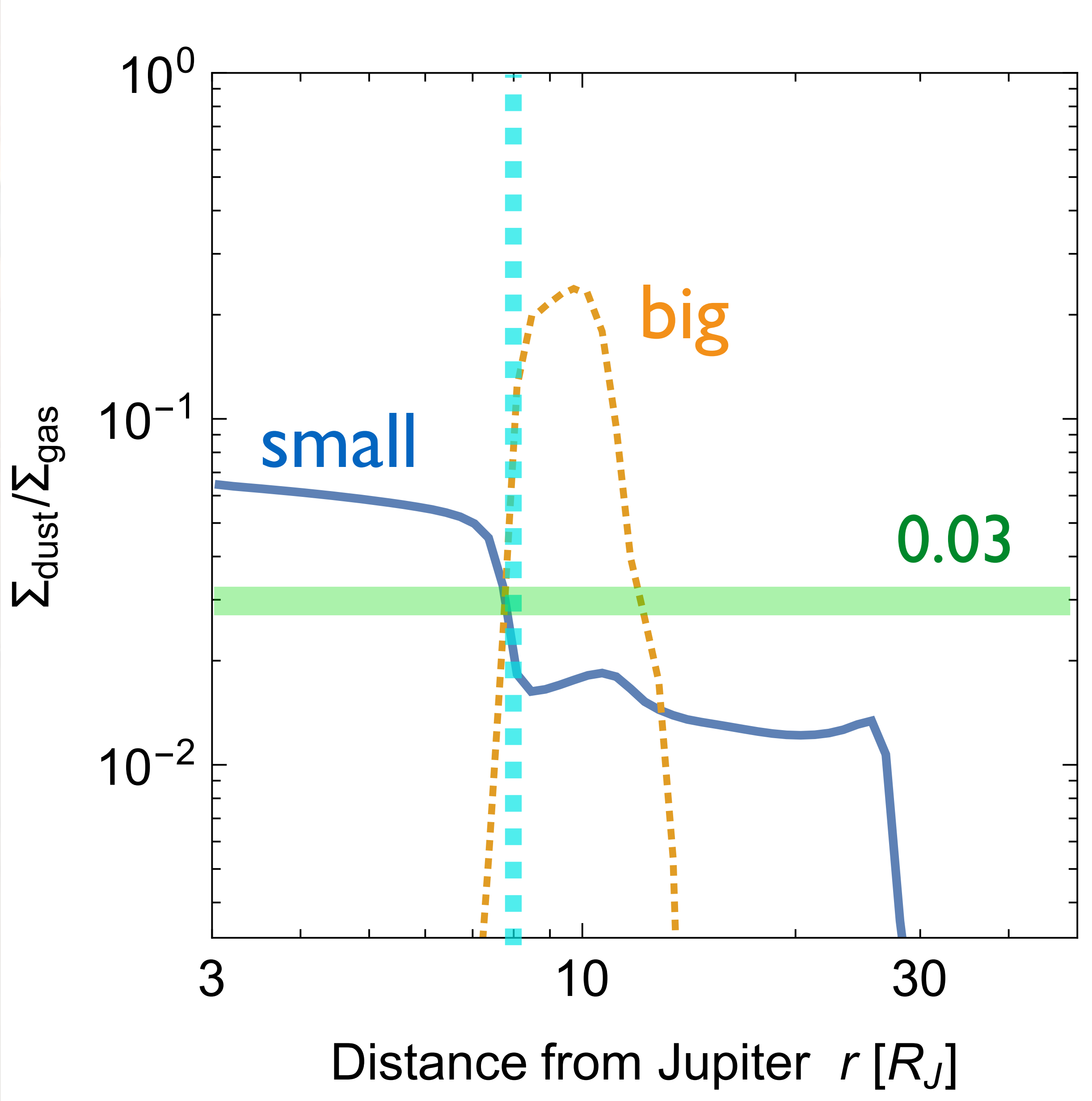
- Strong clumping when $\Sigma_{\rm dust}/\Sigma_{\rm gas} \gtrsim 0.03$
  (Johansen et al. 2008; Bai & Stone 2010; Carrera et al. 2015; Yang et al. 2017)
- Gravitational collapse if $\rho_{\rm clump}$ exceeds the Roche density ~ $M_{\rm center}/r^3$

Streaming Instability Inside the Snow Line?

$\dot{M}_{\rm gas} = 2\times10^{-8}\ M_J/{\rm yr},\ \ \dot{M}_{\rm dust}/\dot{M}_{\rm gas} = 0.1$

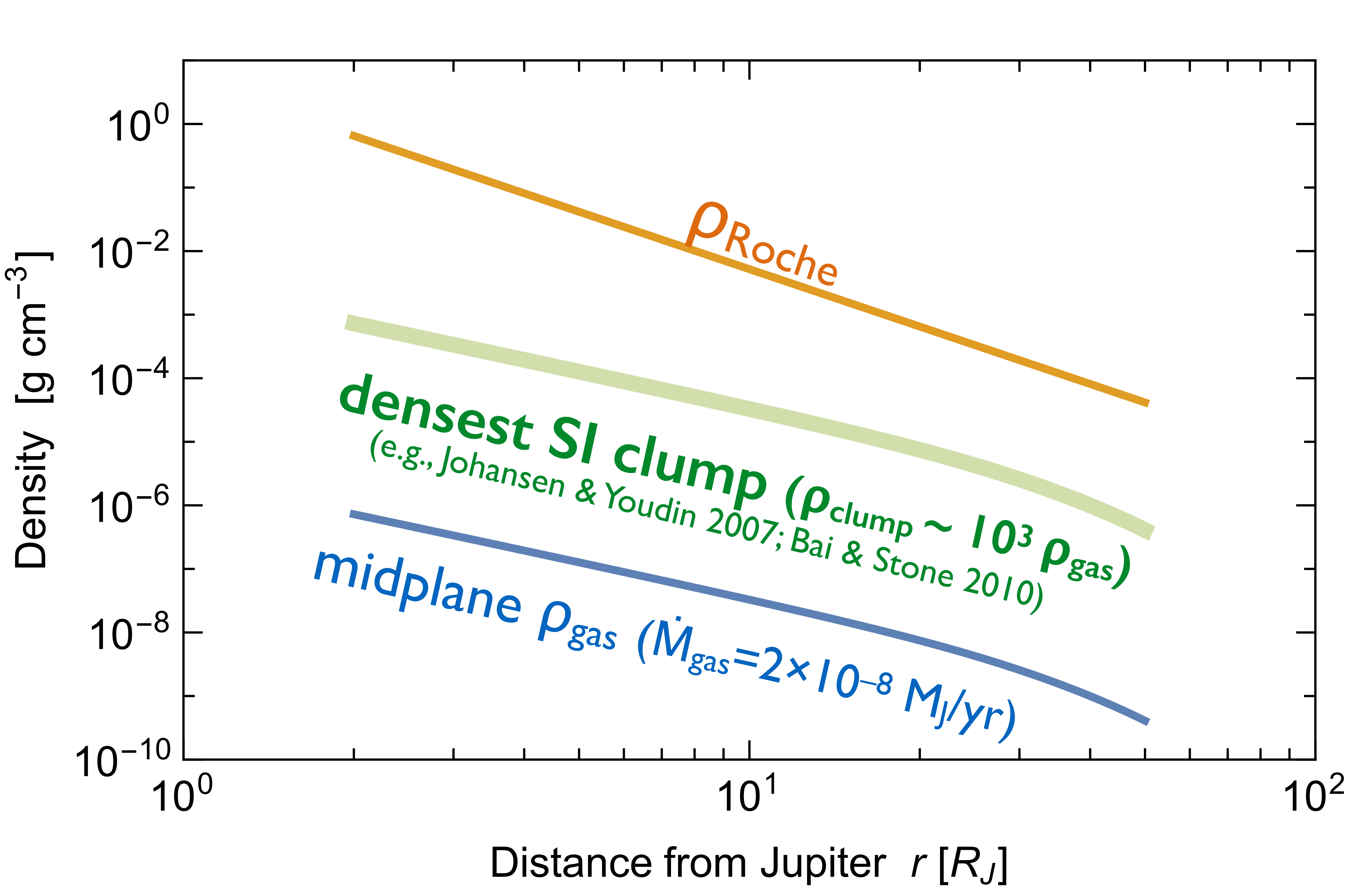
$\rho_{\rm int} = 10^{-2}\ {\rm g/cm^3},\ \ \alpha_{\rm acc} = 10^{-2},\ \ \alpha_{\rm diff} = 10^{-4}$





Streaming Instability without Gravitational Collapse?

Problem: The Roche density in CPDs is too high to achieve with SI!



Dust growth through low-velocity collisions within the dense clumps (Johansen et al. 2009; Carrera et al. 2017) seems to be more important.

Summary

- Overall, satellitesimal formation in CPDs demands high $\dot{M}_{\rm dust}/\dot{M}_{\rm gas}$.

- Icy particles can grow into icy satellitesimals for $\dot{M}_{\rm dust}/\dot{M}_{\rm gas} \gtrsim 0.1$ if porosity evolution and low level of dust diffusion (compared to viscosity) are considered.

- Silicate dust inside the snow line could experience the streaming instability, but the clumps may not undergo gravitational collapse! Sticking through gentle collisions within the clumps could instead be important for rocky satellitesimal formation.