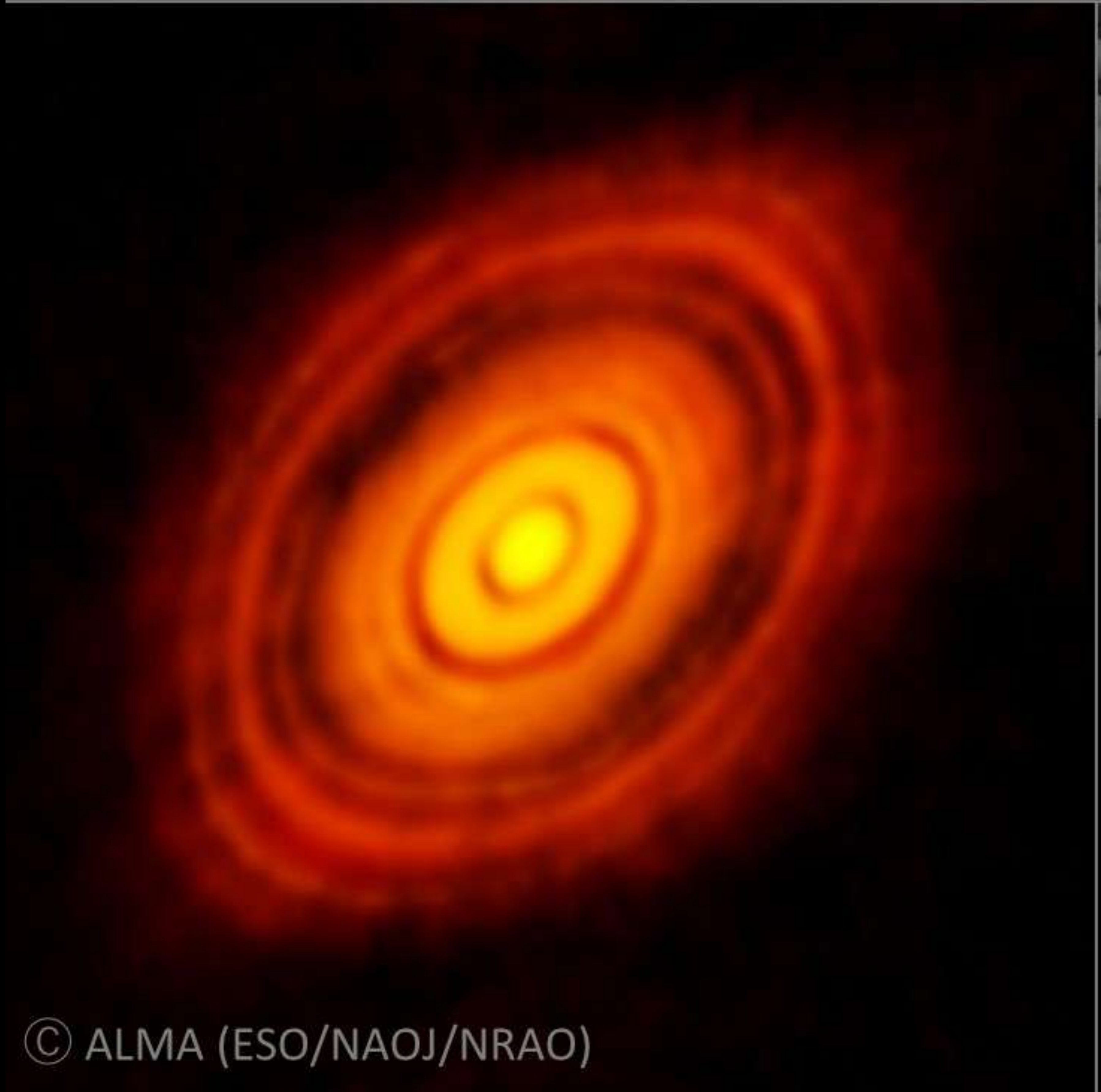
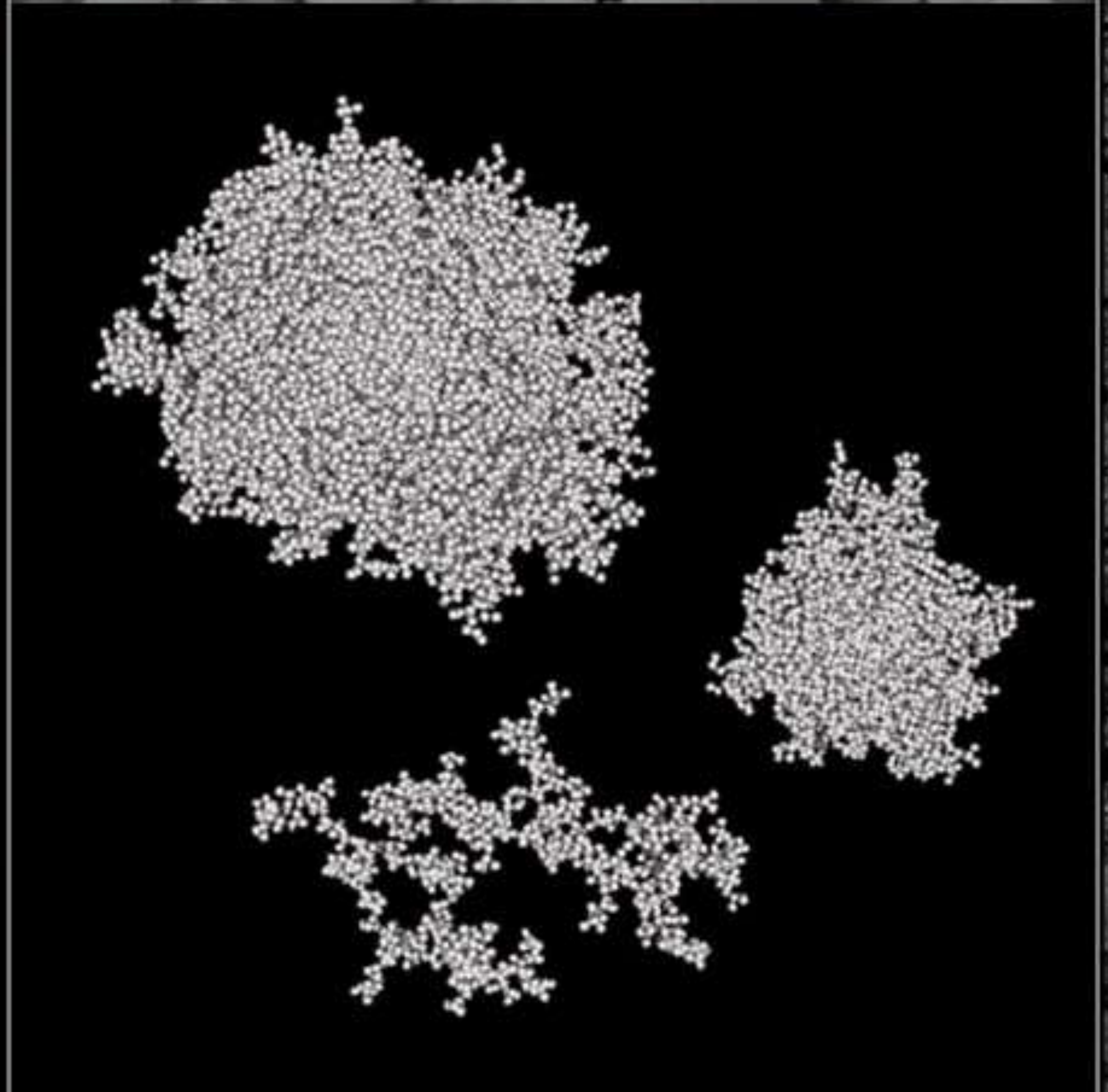
Pebbles in Planet Formation

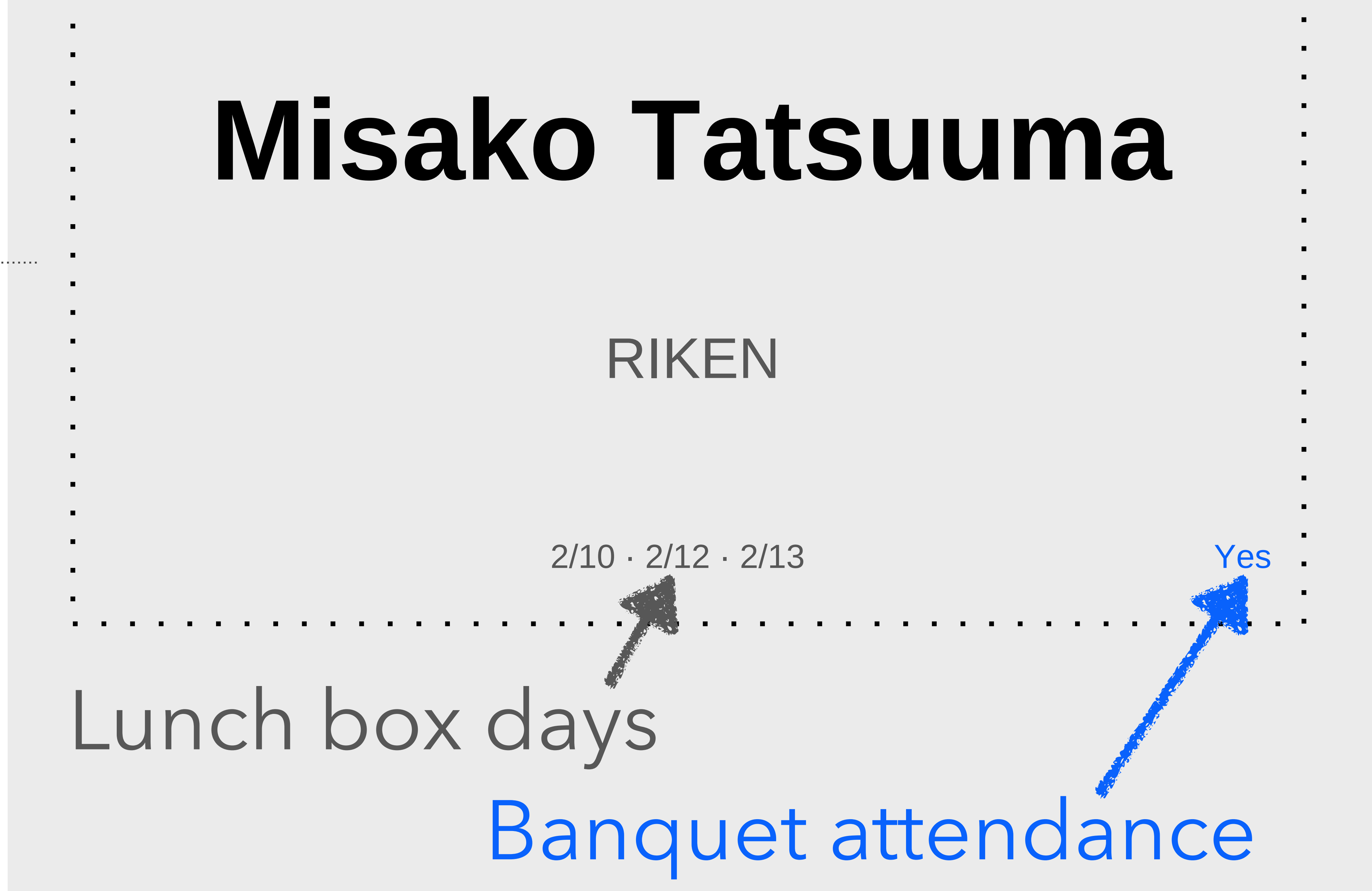
Opening Remark

Misako Tatsuuma (RIKEN iTHEMS)





Local information



- **Wi-Fi**:
  - SSID: **naoj-open**
  - Password: Please check the posted notice.
- **Talks**:
  - **Keynote: 45 min.** = transition time + talk (≈ 35 min.) + discussion (< 10 min.)
  - **Contributed: 15 min.** = transition time + talk (≈ 12 min.) + discussion (< 3 min.)
  - Presenters should **share their screens directly via Zoom**.
    (The shared screen will also be displayed on the big screen in the seminar room.)
  - **On-site attendees should not connect to Zoom**.
  - If you have a question, please line up at the microphone.
- **Lunch**: Please pay in **cash** at the registration desk.

Sponsor & Organizers

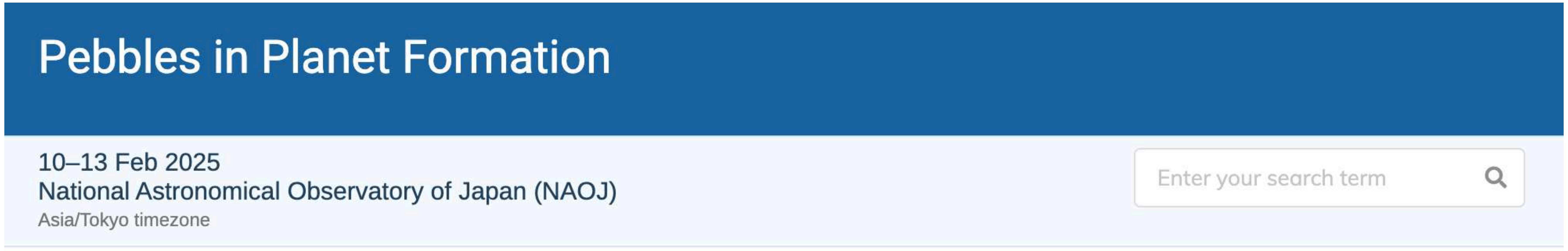
- **Sponsor**: iTHEMS RIKEN Interdisciplinary Theoretical and Mathematical Sciences Program
  - **RIKEN I**nterdisciplinary **The**oretical and **M**athematical **S**ciences Program **(iTHEMS)**
  - The program facilitates close collaborations among researchers from different disciplines in theoretical, mathematical, and computational sciences.

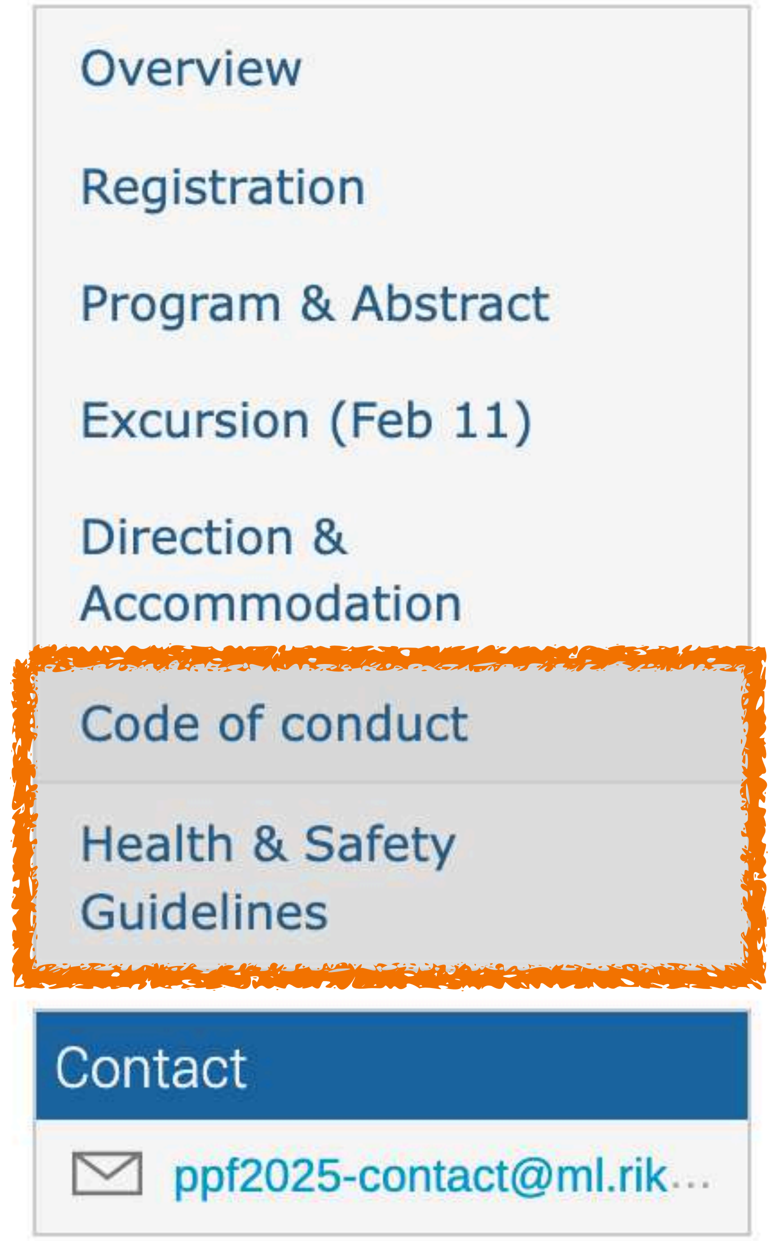
- **Organizers**:
  Misako Tatsuuma (RIKEN iTHEMS), Akimasa Kataoka (NAOJ), Yuhito Shibaike (NAOJ), Tomomi Omura (Osaka Sangyo Univ.), Ryosuke Tominaga (Institute of Science Tokyo), Kiyoaki Doi (MIPA), Naoya Kitade (NAOJ)

- **Participants**: 63 in-person, 70 online

Code of conduct & Health guidelines

- Take a look at the webpage:





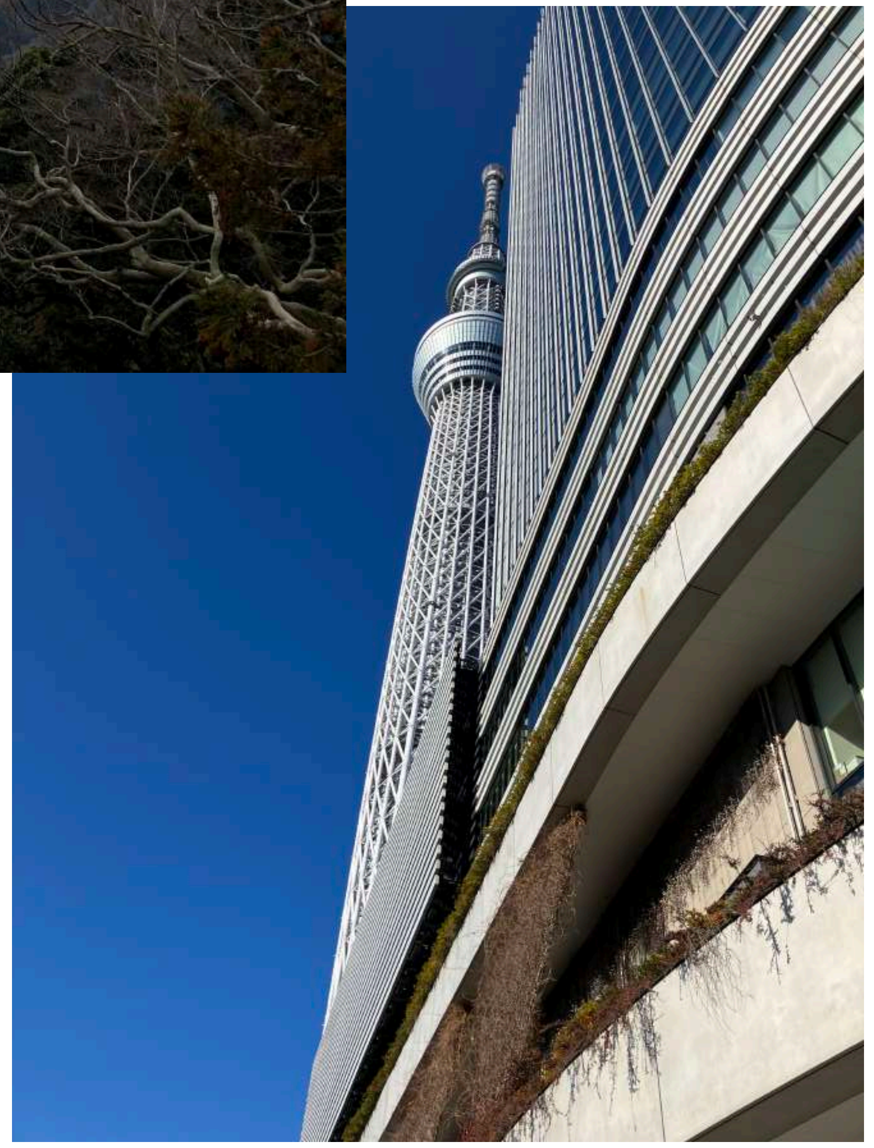
- **Code of conduct**
  - Contact points: Misako Tatsuuma (she/her), Akimasa Kataoka (he/him), Tomomi Omura (she/her), Ryosuke Tominaga (he/him)
- **Health guidelines**
  - If you feel unwell, please consider attending online instead of in person.
  - Oral presenters may switch to remote presentations via Zoom.

Slack & Excursion

- **Slack**
  - Join Slack to upload your slides and engage in discussions with online participants.

- **Excursion (Tomorrow)**
  1. Mount Takao Course
  2. Tokyo City Course (Tokyo Skytree)
  - **How to Join**
    - Join the Slack channel for your chosen course.
    - All updates and communication will be on Slack.

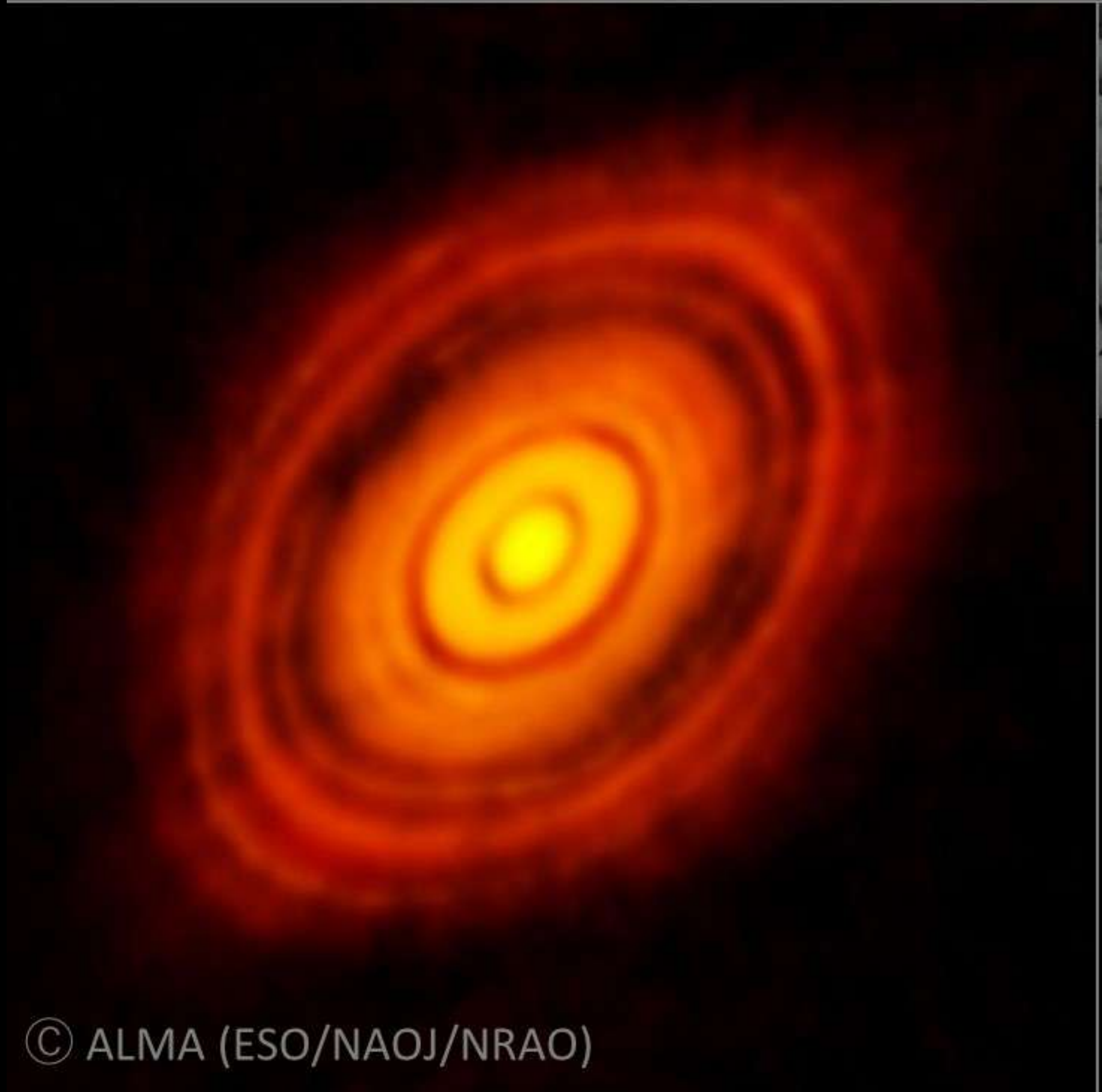
excursion-mt-takao
excursion-tokyo-city

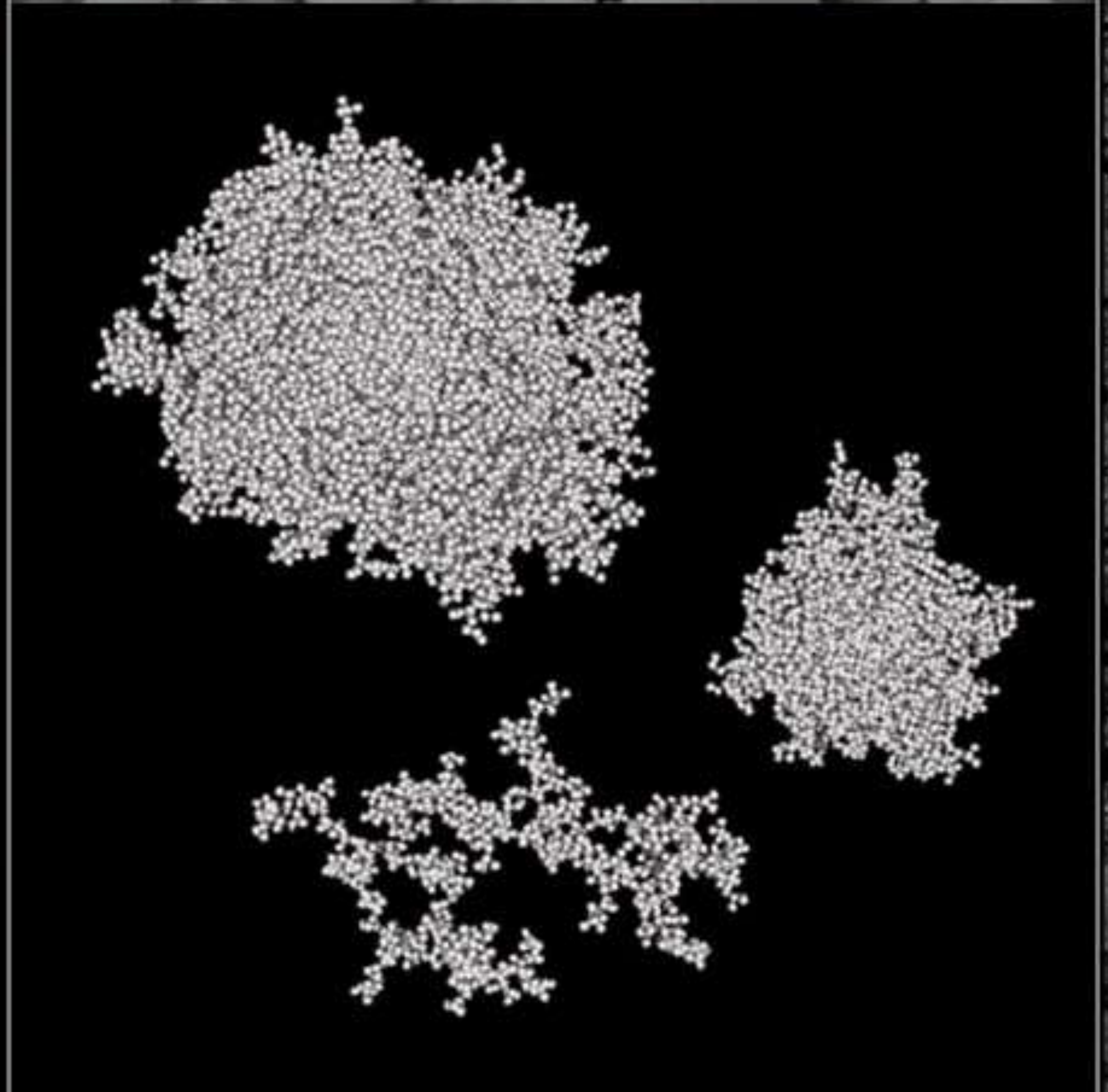


Motivation: What do we discuss?

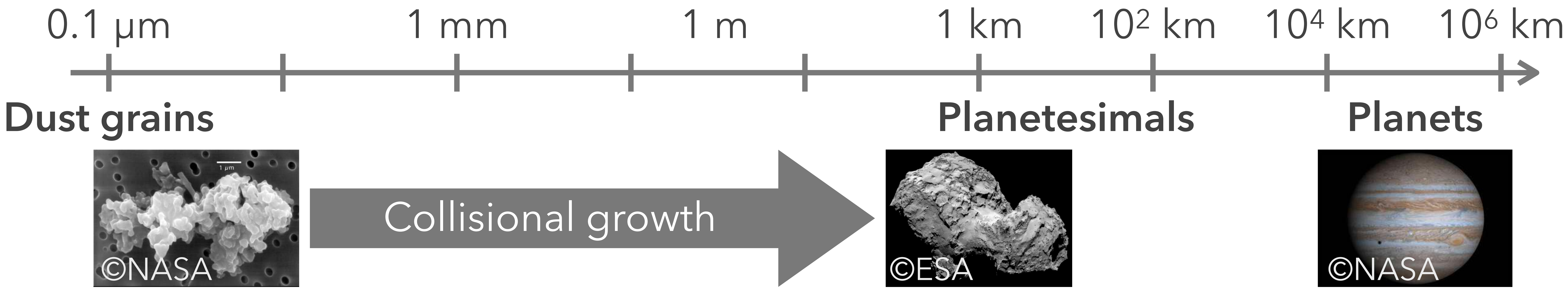
Understanding grain growth

in the context of planet formation





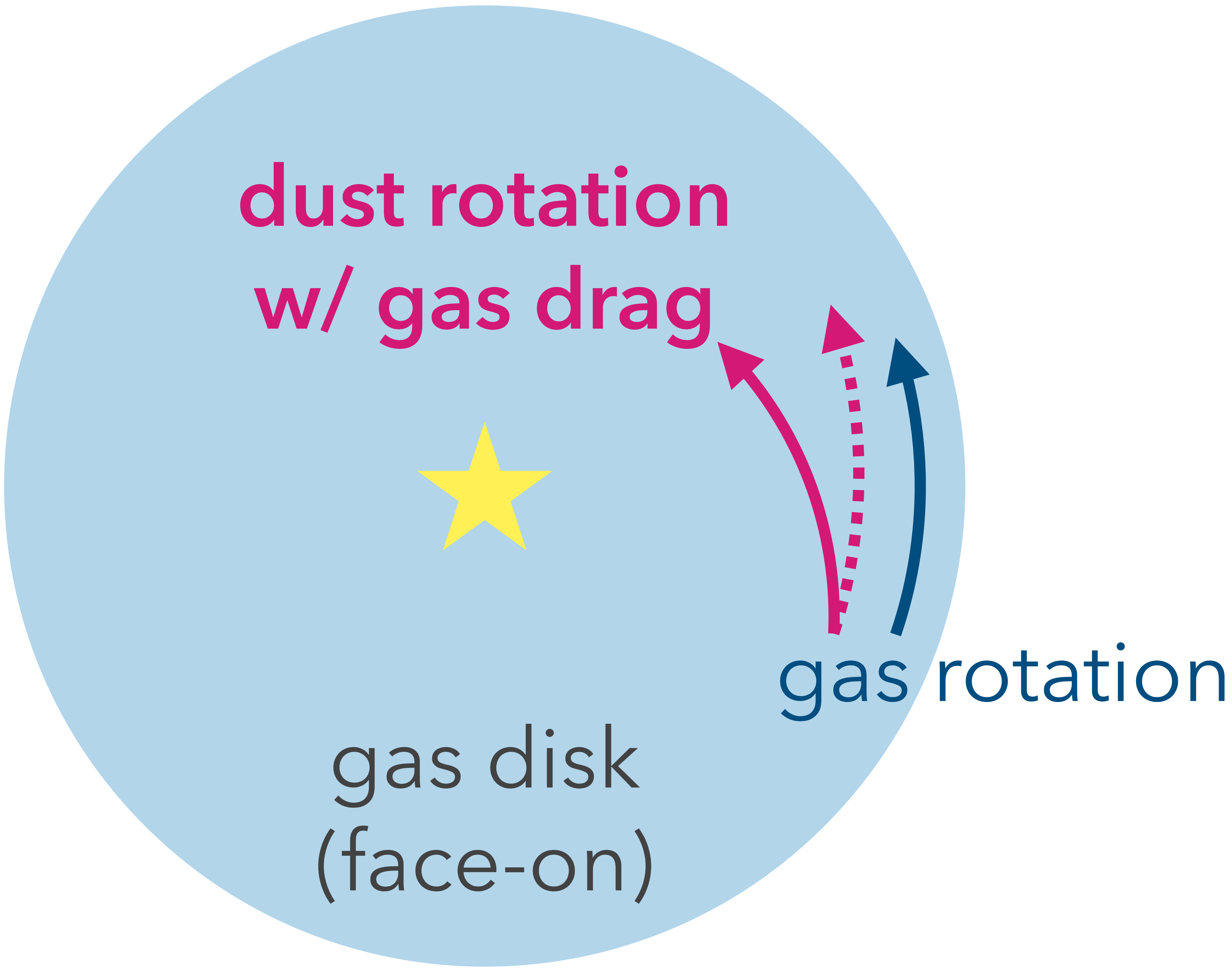
Grain growth in the context of planet formation



→ **However, there are barriers to overcome...**

Barriers against grain growth

Radial drift barrier



$St_{max} \sim 0.1$ for compact dust

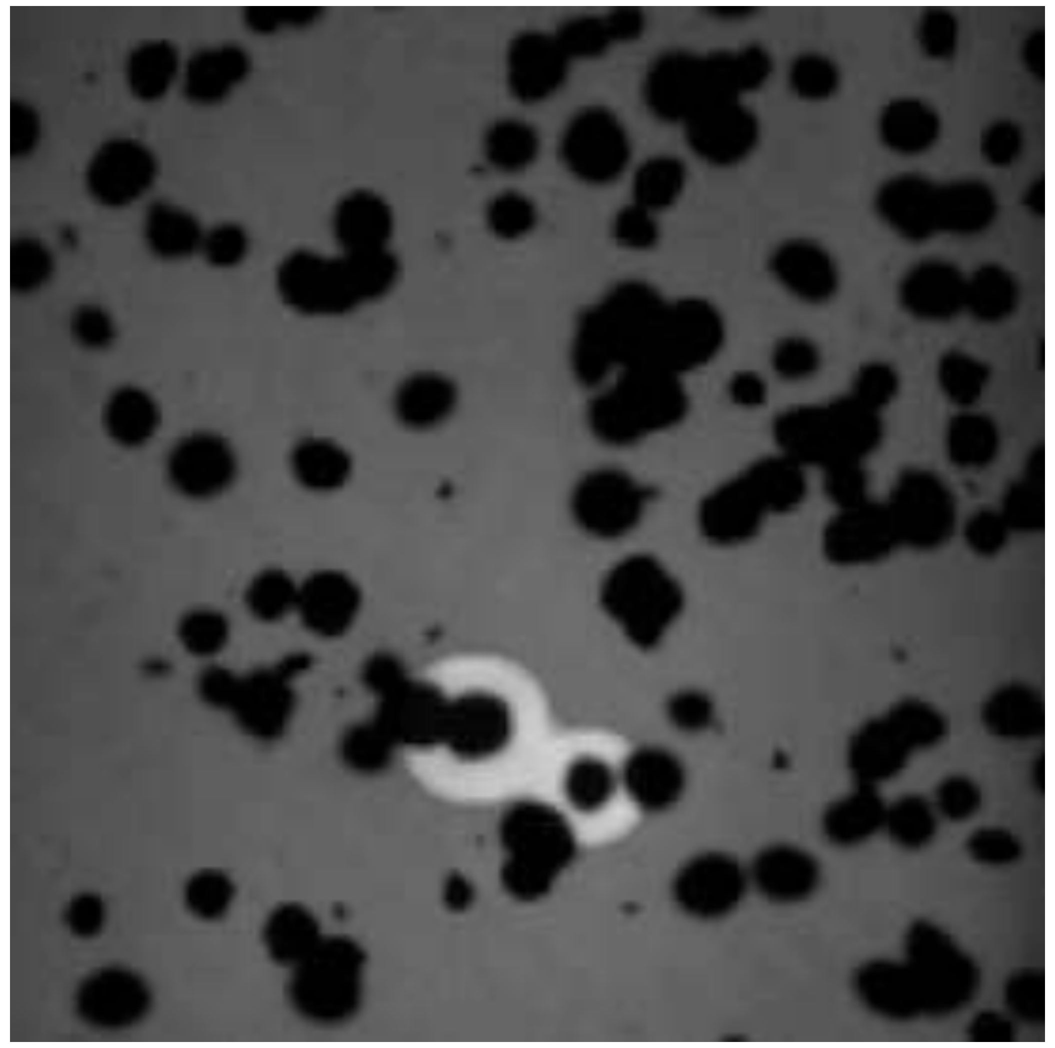
(e.g., Okuzumi et al. 2012)

- $St = t_{fric}\Omega_K$: Stokes number
- t_{fric}: friction time for a dust grain
- Ω_K: Keplerian angular velocity

Fragmentation barrier

©NAOJ 4D2U Wada et al. (2018)

Bouncing barrier



Weidling et al. (2012)

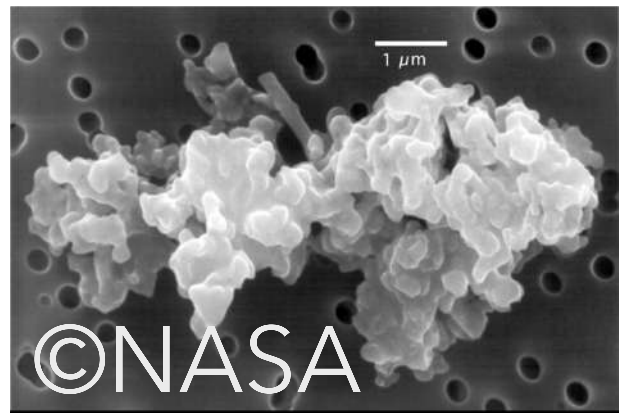
→ The keys to overcoming these barriers are dust porosity and instabilities.

+ Charge barrier (e.g., Okuzumi 2009),
Rotational disruption (e.g., Tatsuuma & Kataoka 2021), etc.

Formation process of planetesimals and planets

0.1 μm — 1 mm — 1 m — 1 km — 10^2 km — 10^4 km — 10^6 km

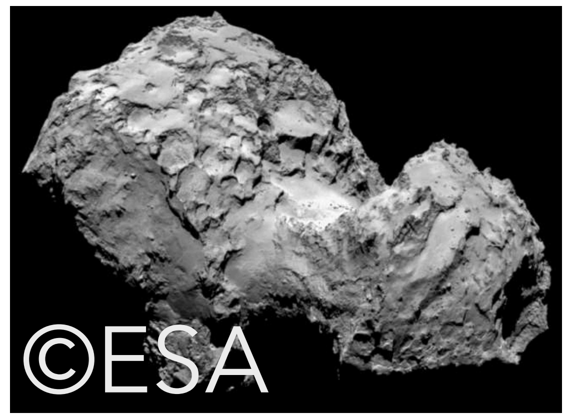
Dust grains



Collisional growth

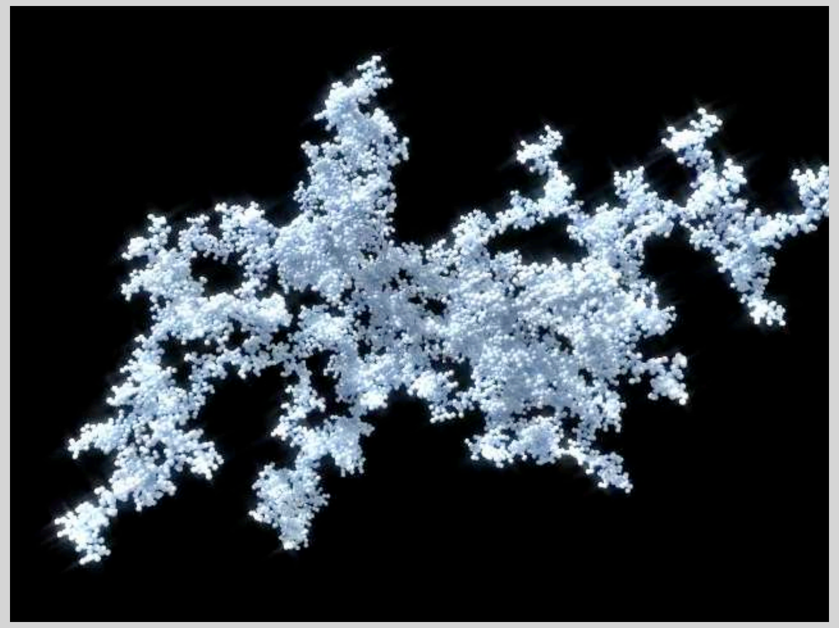
?

Planetesimals



Planets

Porous dust aggregates



Suyama et al. (2008)

Streaming instability

(e.g., Youdin & Goodman 2005)

+ Gravitational collapse of dust clumps

(e.g., Johansen et al. 2007)

etc.

Planetesimal accretion

Pebble accretion

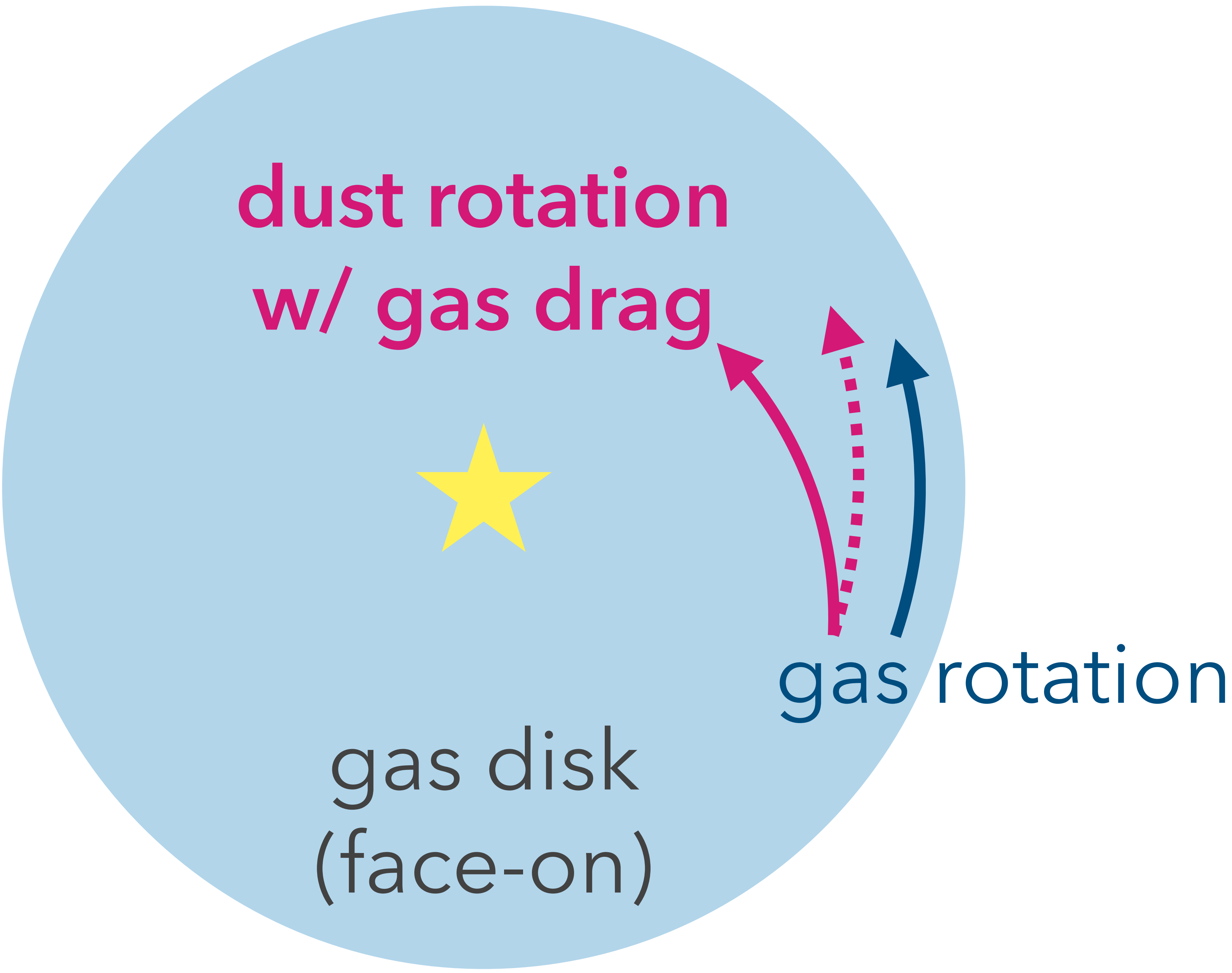
(e.g., Ormel & Klahr 2010)

Gas accretion

→ "Pebbles"?

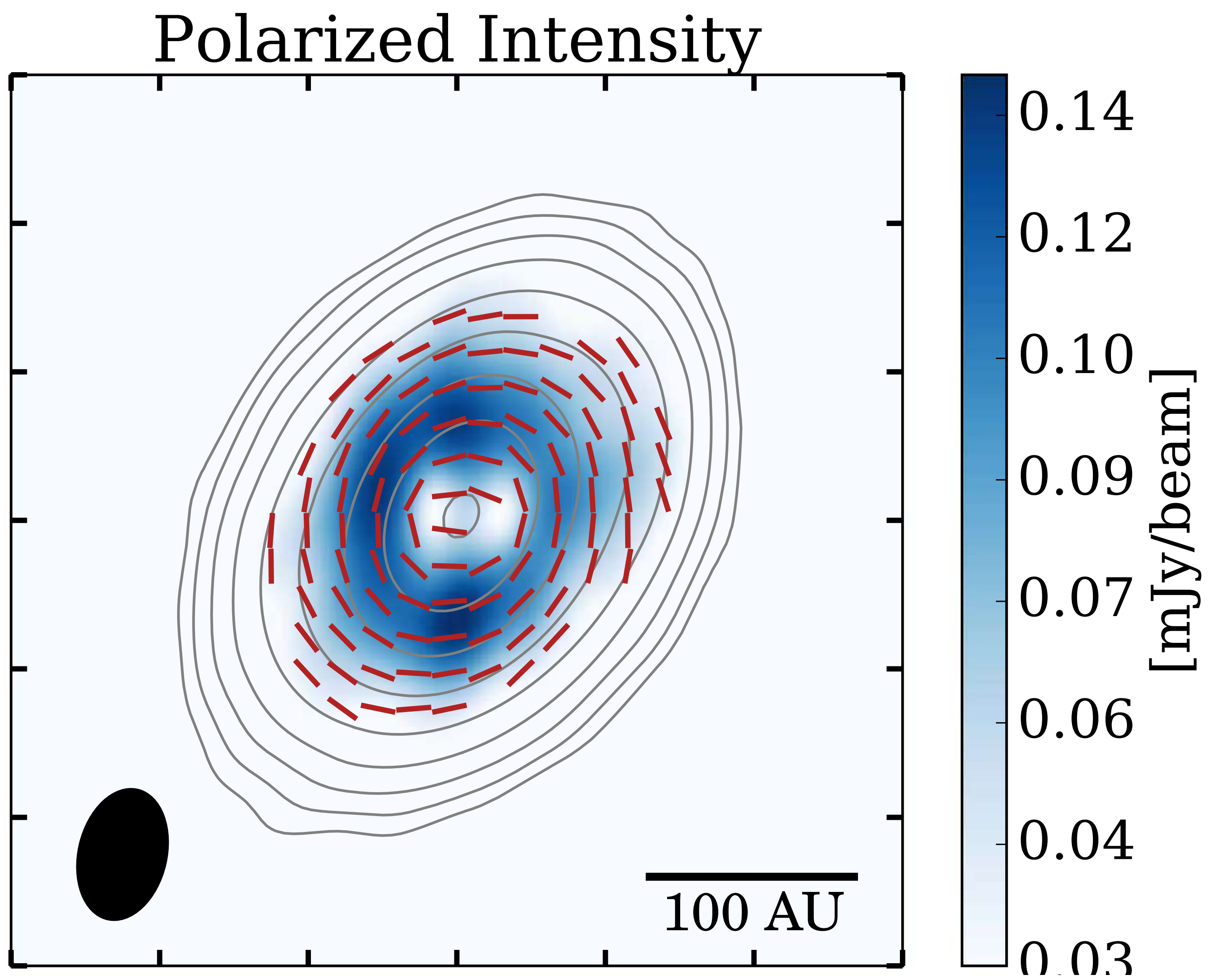
Pebbles? How do we define them?

Radial drift barrier



St ~ 0.1?

Protoplanetary disk observations

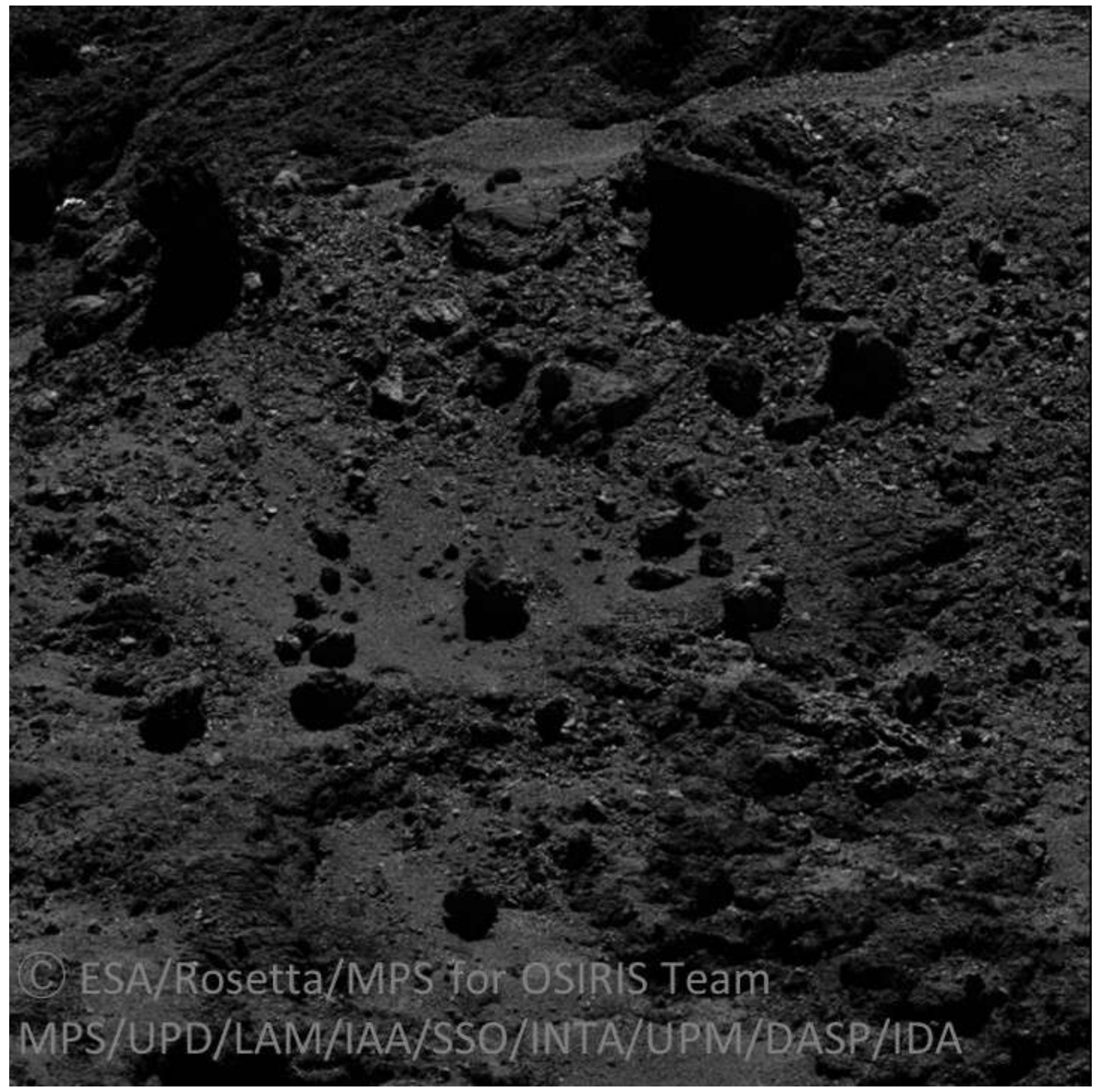


~ 100 μm–mm?

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

→ Talk by Takahiro Ueda

Small solar system body explorations & observations



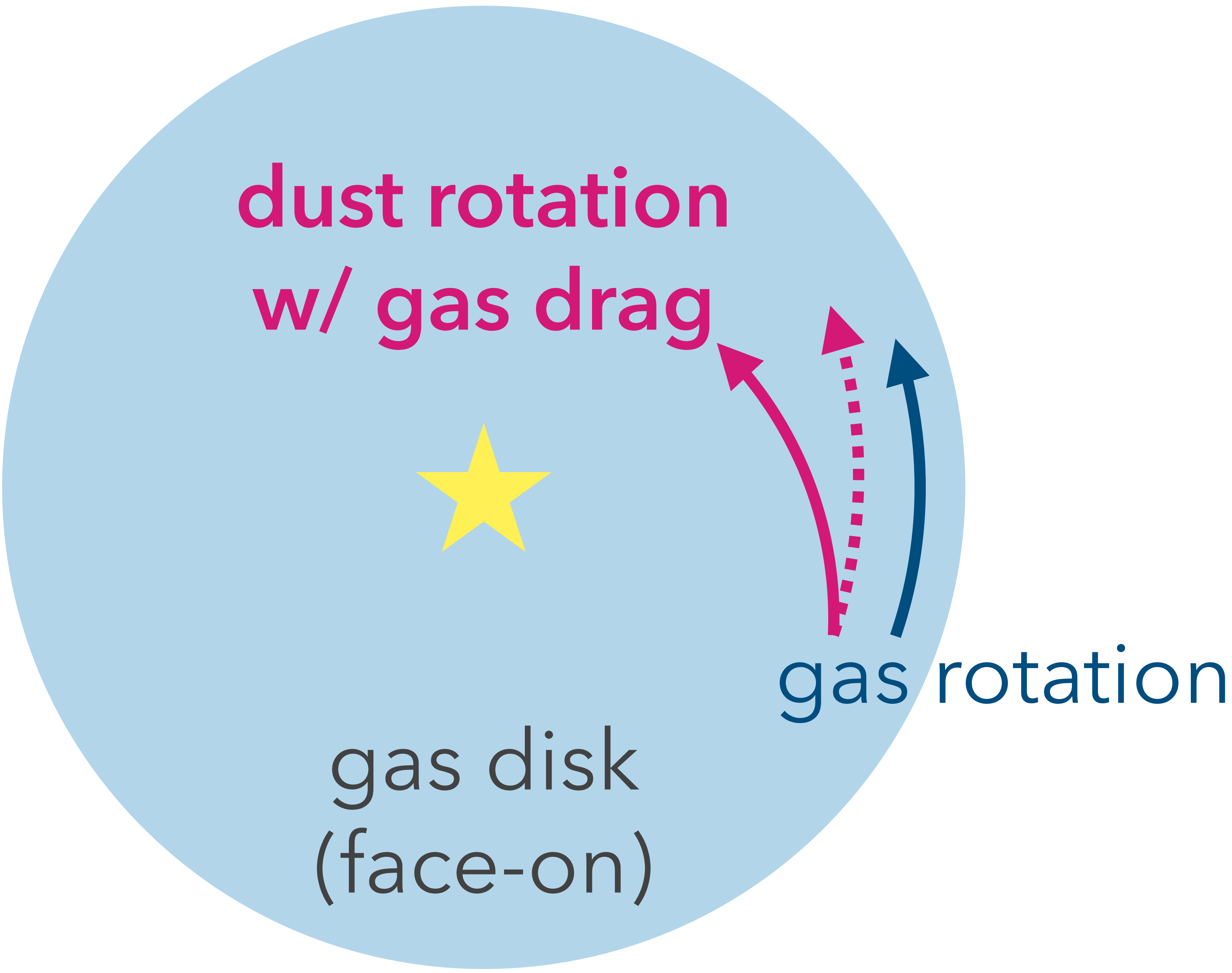
~ mm–cm?

(e.g., Okada et al. 2020)

→ Talks by Carsten Güttler and Ryota Fukai

Size of pebbles with St of 0.1

Radial drift barrier



St ~ 0.1?

Stokes number in the Epstein drag regime

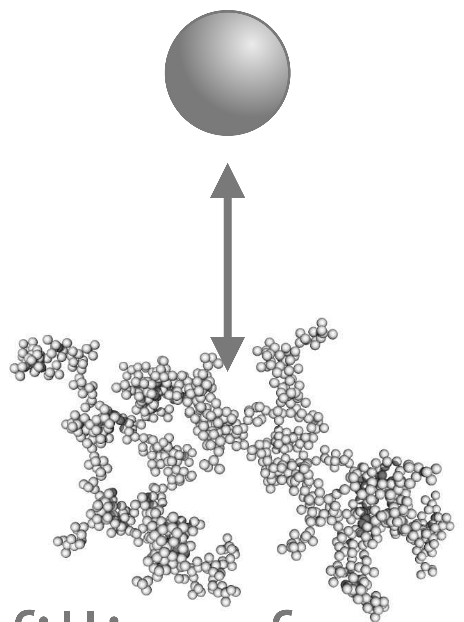
$$\mathrm{St} \equiv \Omega_{\rm K} t_{\rm fric} = \Omega_{\rm K} \frac{\rho_{\rm int} a}{\rho_{\rm gas} v_{\rm th}} = \Omega_{\rm K} \frac{\rho_{\rm int} a \sqrt{2\pi} c_{\rm s}}{\Sigma_{\rm gas} \Omega_{\rm K} \sqrt{8/\pi} c_{\rm s}} = \frac{\pi \rho_{\rm int} a}{2 \Sigma_{\rm gas}}$$

- $\rho_{\rm int}$: internal density of pebbles, a: pebble radius,
- $\rho_{\rm gas}$: gas density, $\Sigma_{\rm gas}$: gas surface density,
- $v_{\rm th}$: thermal velocity, $c_{\rm s}$: sound velocity

For $\Sigma_{\rm gas}$ = 54 g cm^{-2} (MMSN model @ 10 au) and $\rho_{\rm int} = \phi \times 1$ g cm^{-3},

volume filling factor and size of pebbles with St = 0.1:

- $\phi = 1 \rightarrow a$ = 3.4 cm (compact)
- $\phi = 0.1 \rightarrow a$ = 34 cm (moderate porous)
- $\phi = 0.01 \rightarrow a$ = 3.4 m (extremely porous)



(porosity = 1 – volume filling factor)

Size and porosity of pebbles observed in disks

Size

- Dust continuum spectral index: ~ mm

  (e.g., Pérez et al. 2012, 2015; Testi et al. 2014; Tazzari et al. 2016; Carrasco-González et al. 2019)

- Linear polarization observations of mm wavelengths: ~ 100 μm (for compact pebbles)

  (e.g., Kataoka et al. 2016a,b, 2017; Bacciotti et al. 2018; Liu 2019; Miotello et al. 2023; Drążkowska et al. 2023)

Volume filling factor (= 1 – porosity)

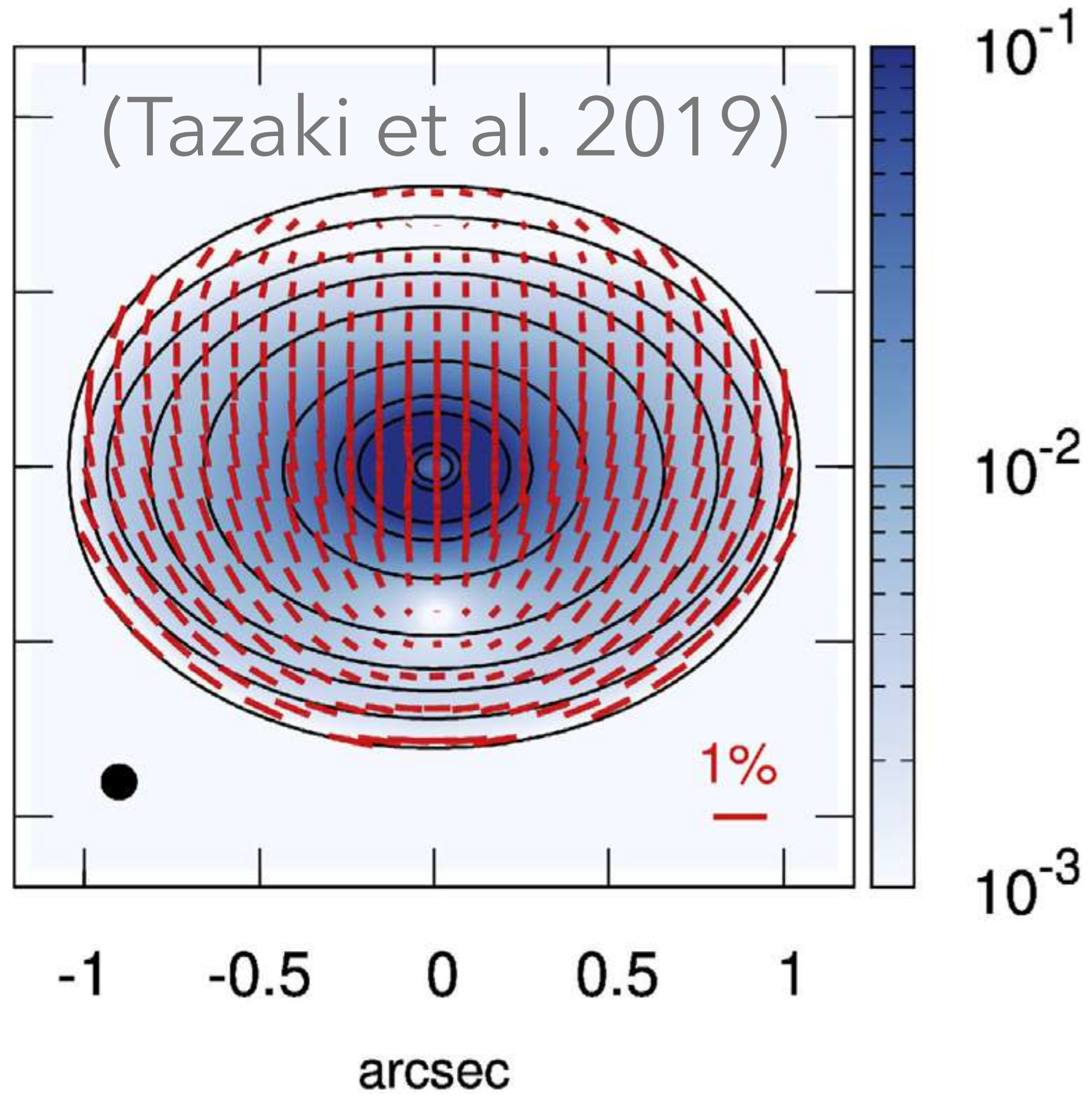
- Linear polarization observations of mm wavelengths: $\phi \approx 0.03$–0.3

  (e.g., Kirchschlager et al. 2019; Tazaki et al. 2019; Zhang et al. 2023; Ueda et al. 2024)

→ **mm-sized and moderately porous** ($\phi \approx 0.03$–0.3)**?**

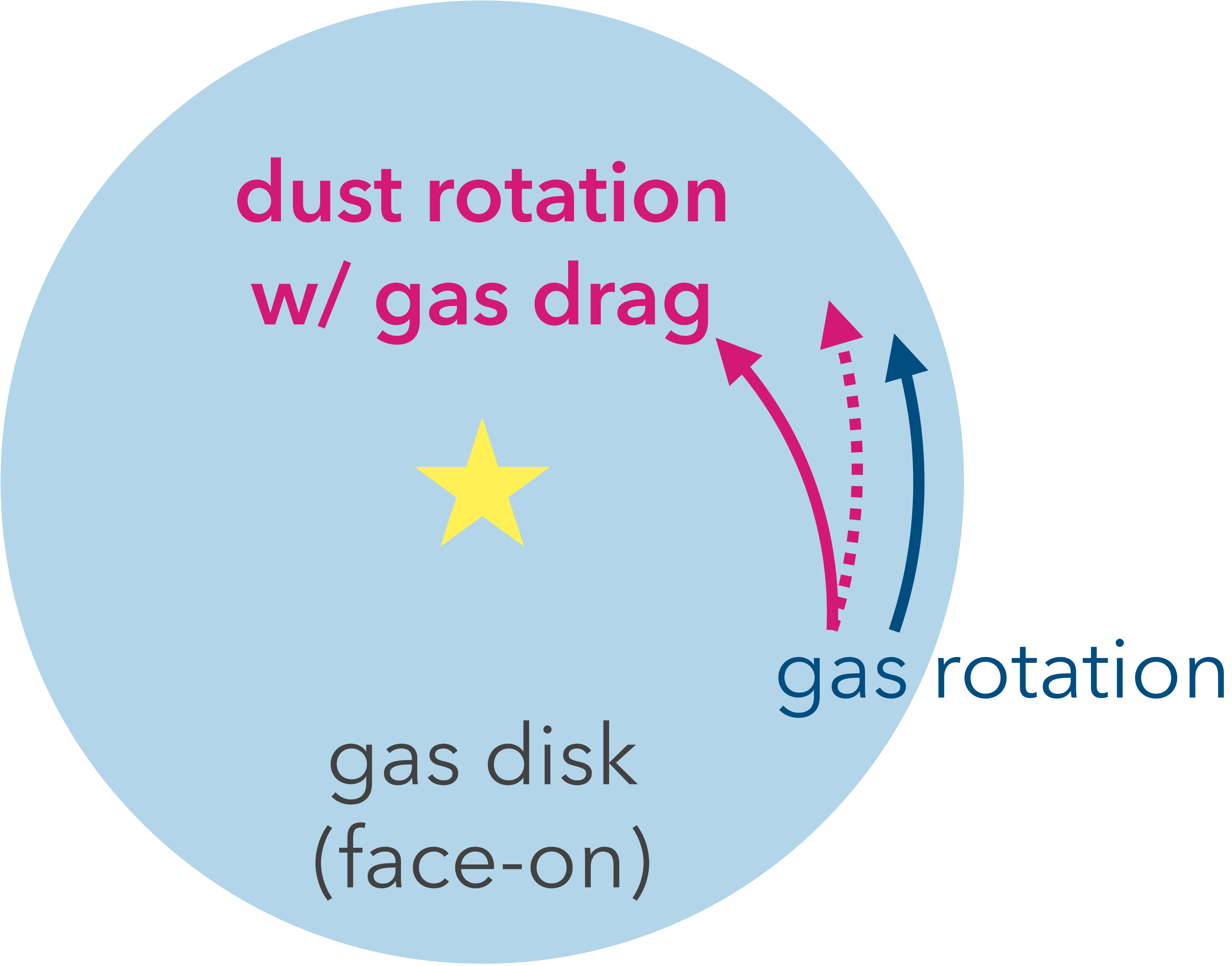
→ **Talk by Takahiro Ueda**

$\phi = 0.1,\ a_{\max} = 1.6$ mm

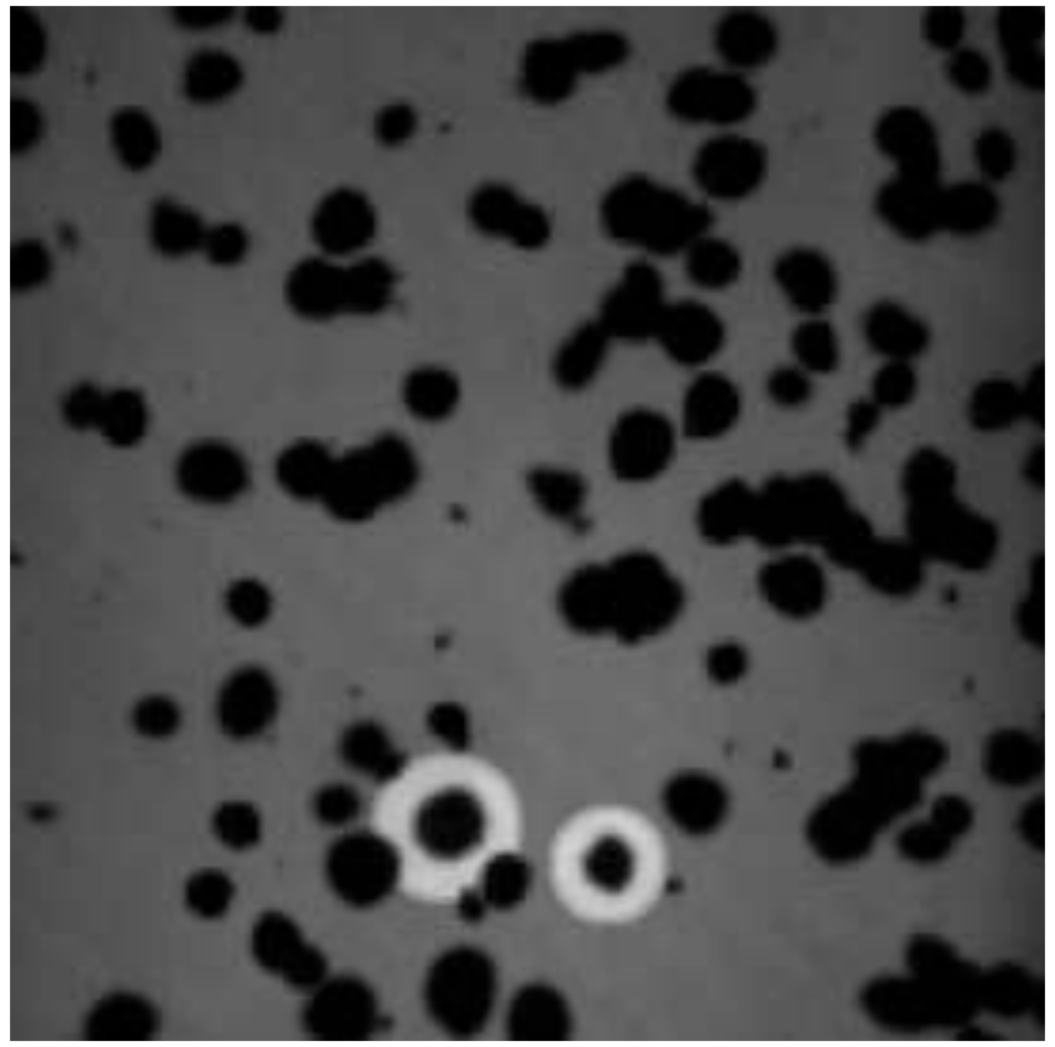


Key questions about pebbles

- How, when, and where do pebbles form?
  - Radial drift, fragmentation, bouncing, or other processes?
- Are pebbles sufficient for forming planets?



©NAOJ 4D2U Wada et al. (2018)



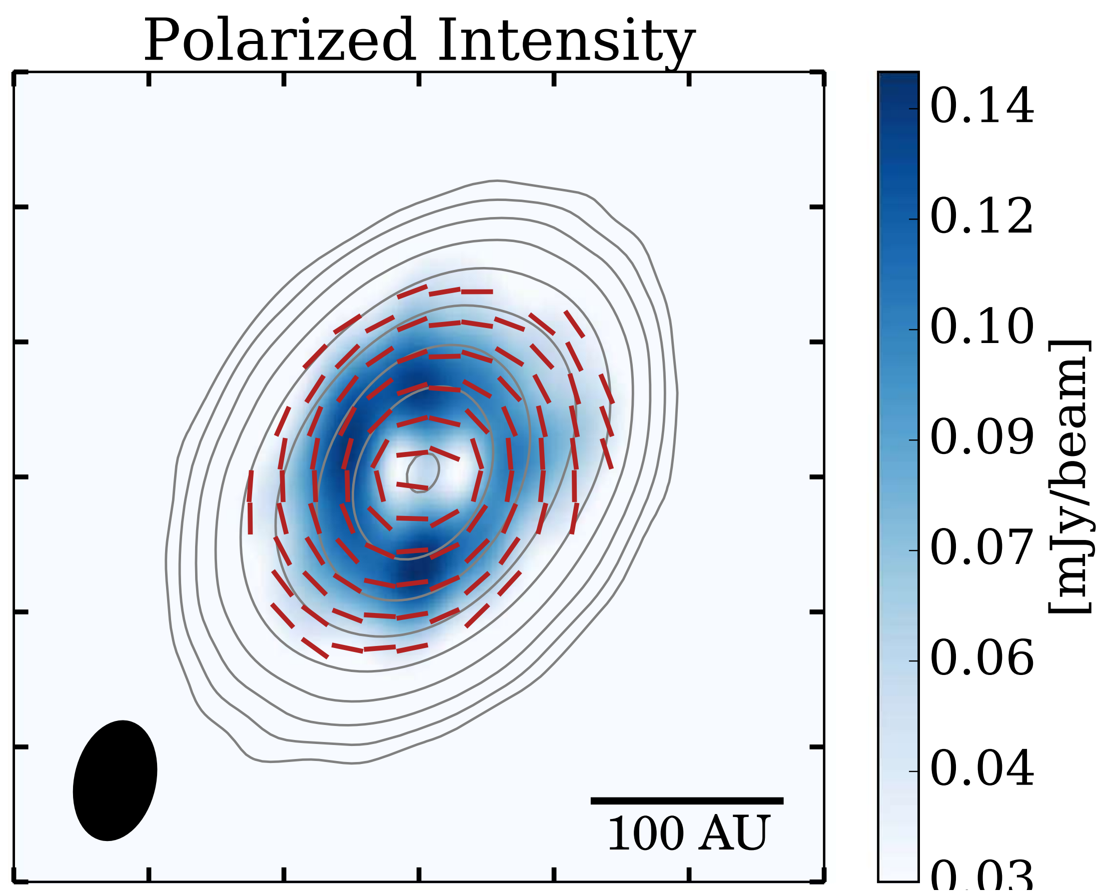
Weidling et al. (2012)

Questions about protoplanetary disk observations

- What are the properties of pebbles in protoplanetary disks?
  - Size, porosity, spatial distribution, etc.
- Which physical processes determine these properties?
  - Radial drift, fragmentation, bouncing, or others?

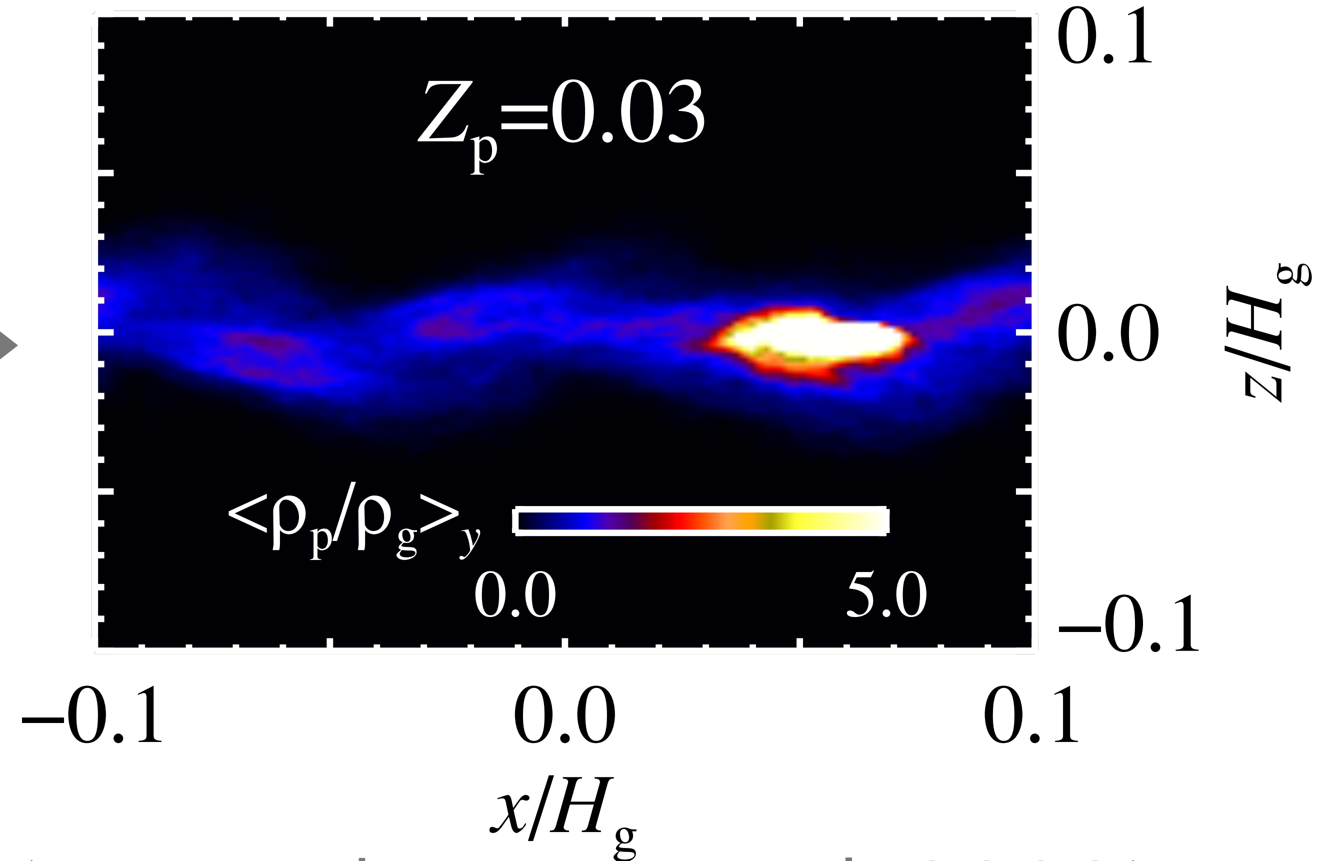
→ Talk by Takahiro Ueda

- Is the mass of pebbles sufficient for planetesimal formation?
  - Can the instabilities form planetesimals from those pebbles? **→ Talk by Min-Kai Lin**



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

?



(e.g., Johansen et al. 2009)

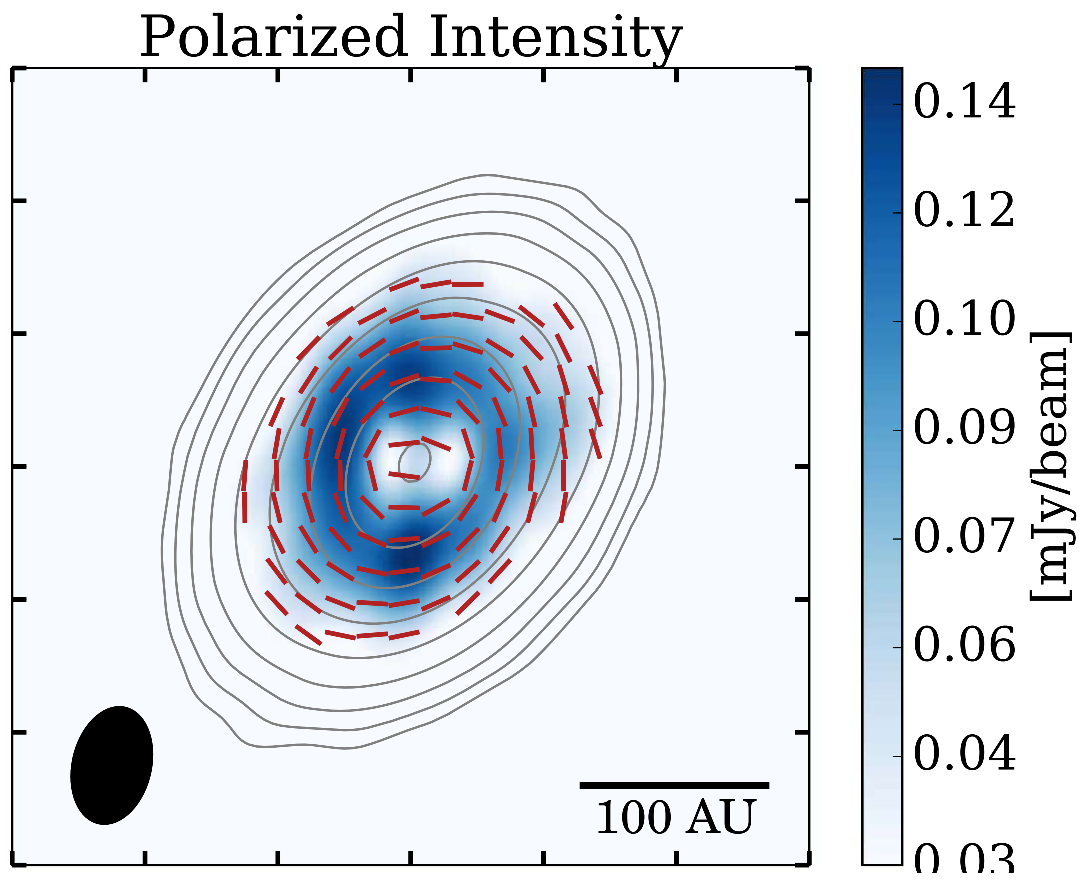
Questions about solar system studies

- What are the properties of pebbles in the solar system?
  - Size, porosity, formation time, etc.

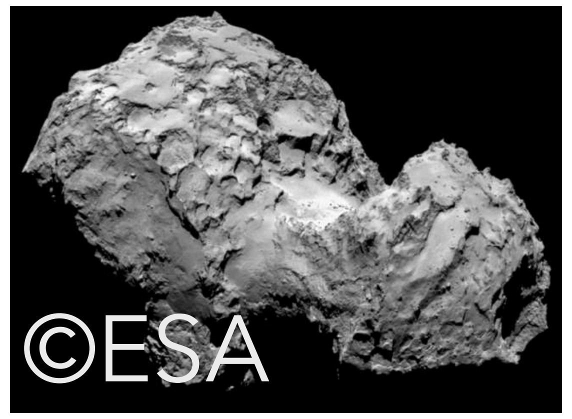
→ **Talks by Carsten Güttler and Ryota Fukai**

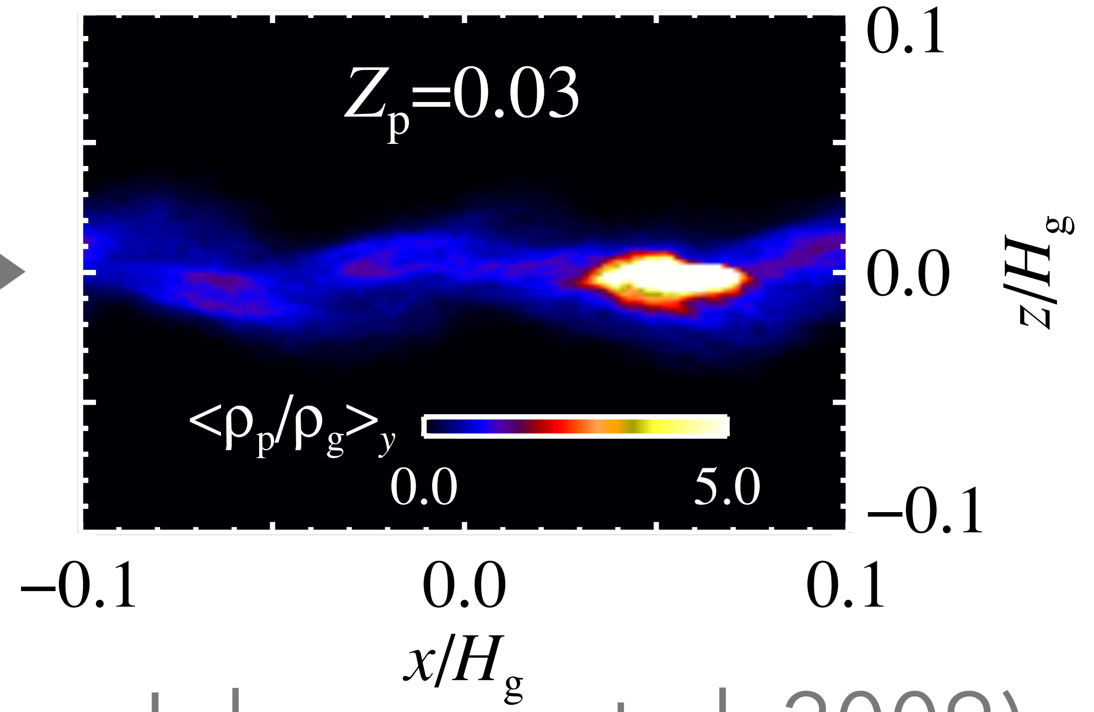
- Can we regard them as the same as pebbles in protoplanetary disks?
- Are small bodies the same as planetesimals formed via the instabilities?

→ **Talk by Min-Kai Lin**



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



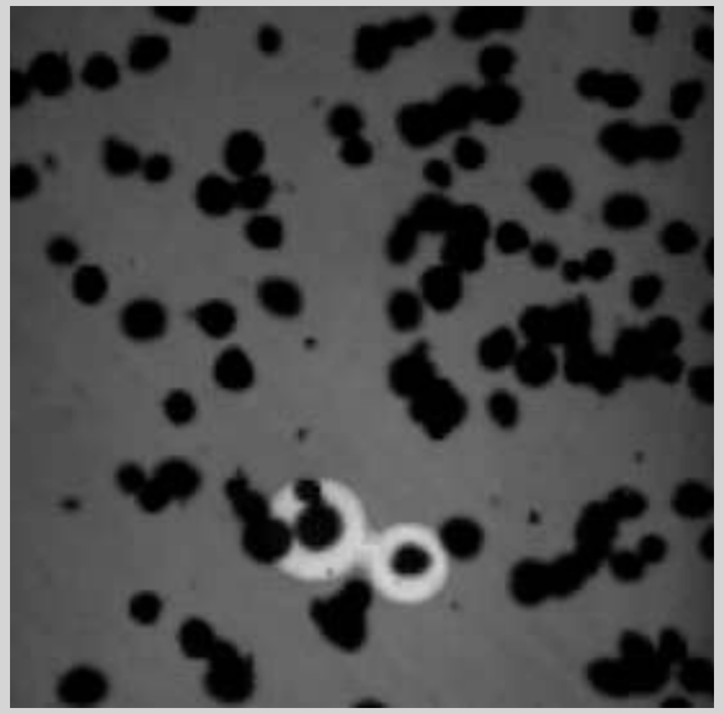


(e.g., Johansen et al. 2009)

Questions about dust growth

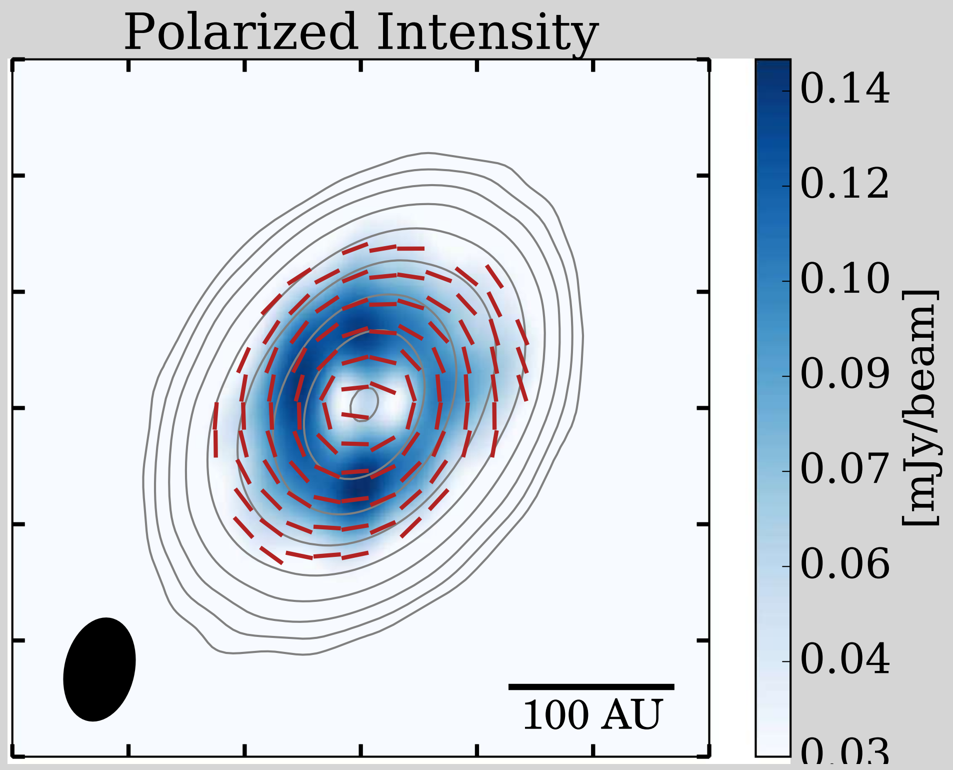
- Are laboratory experiments consistent with dust *N*-body simulations?
- Can we test the dust growth theory through protoplanetary disk observations and solar system studies?

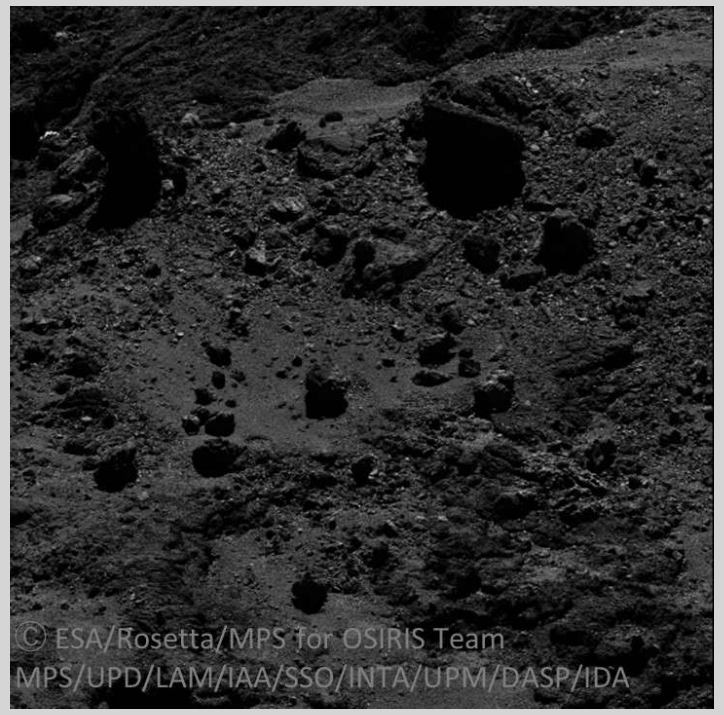
→ Talks by me and Bastian Gundlach



Weidling et al. (2012)

Suyama et al. (2008)



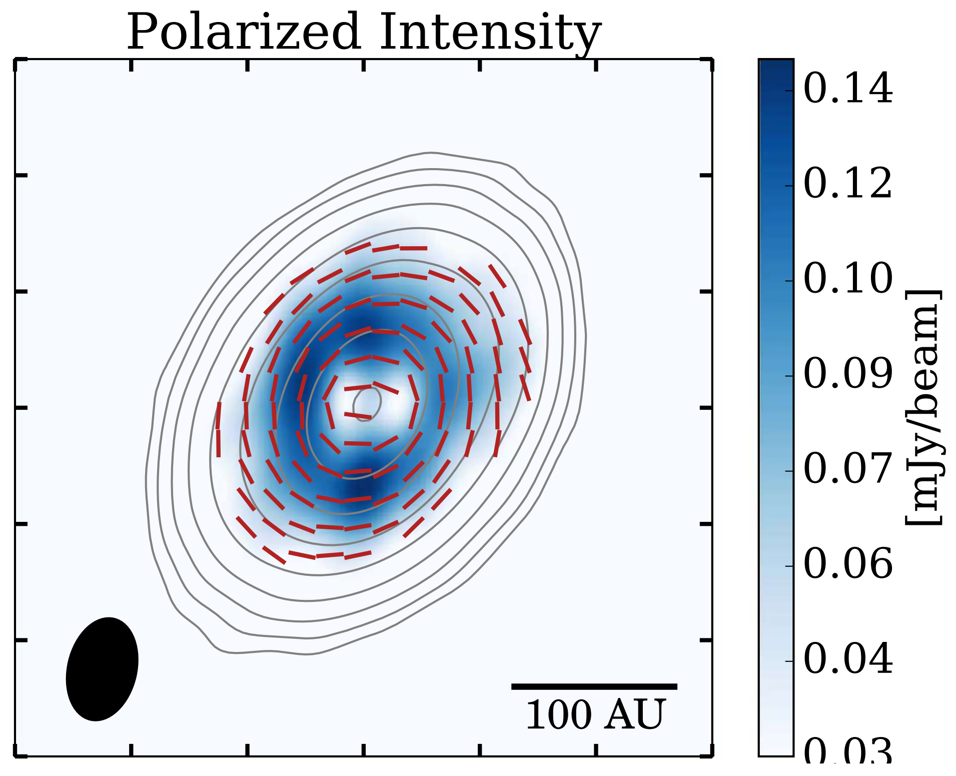


(e.g., Kataoka et al. 2017)

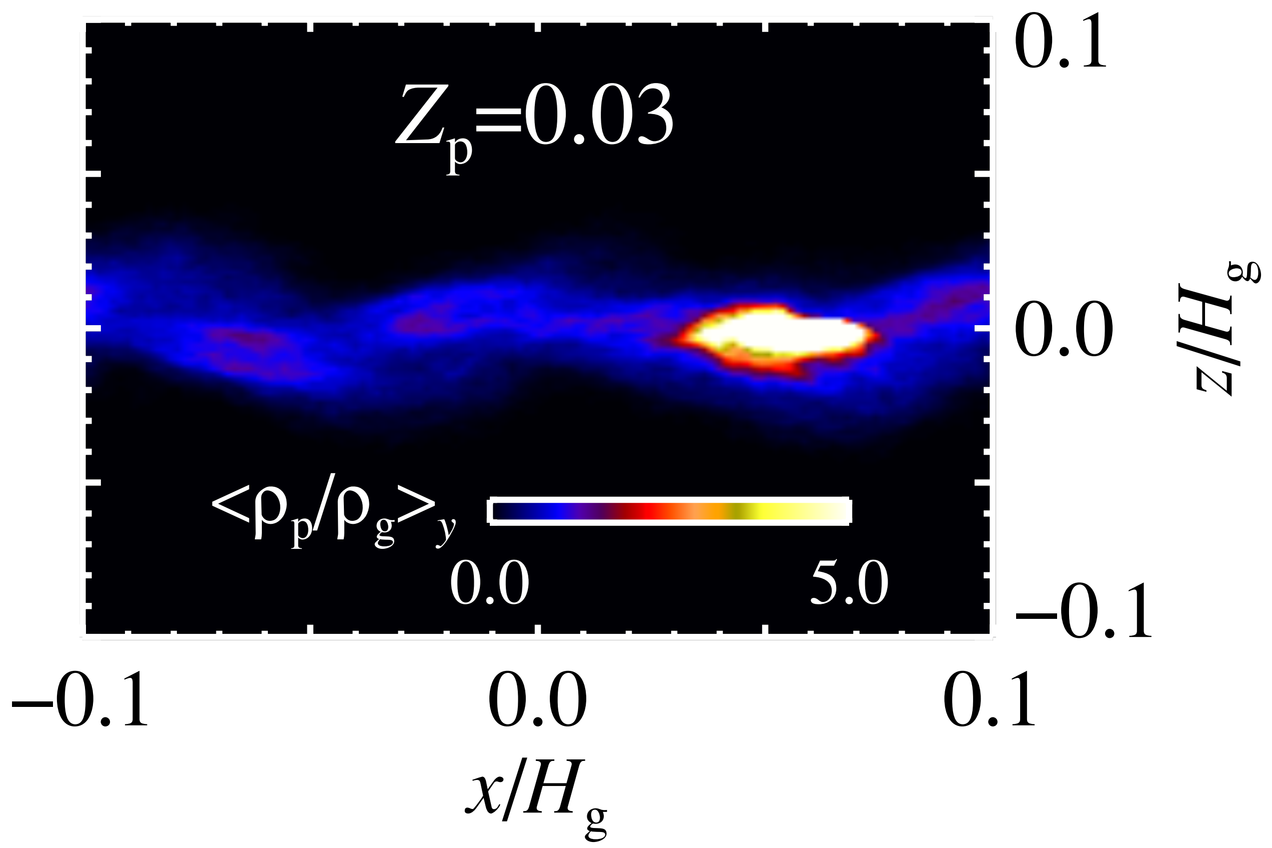
Questions about planetesimal formation

- Have all barriers to planetesimal formation been solved?
- What are the necessary conditions for planetesimal formation via the instabilities?
- Is the planetesimal formation process consistent with protoplanetary disk observations and solar system studies?

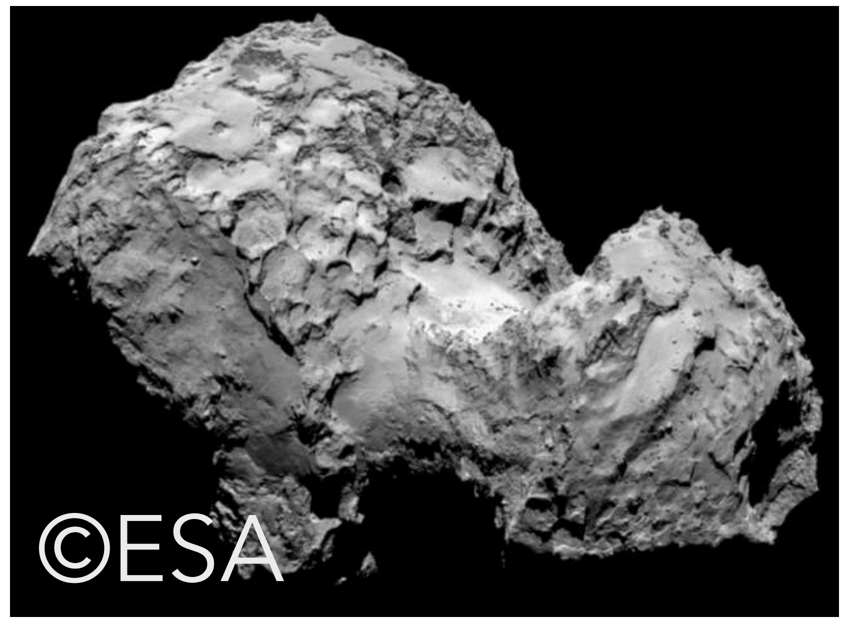
→ Talk by Min-Kai Lin



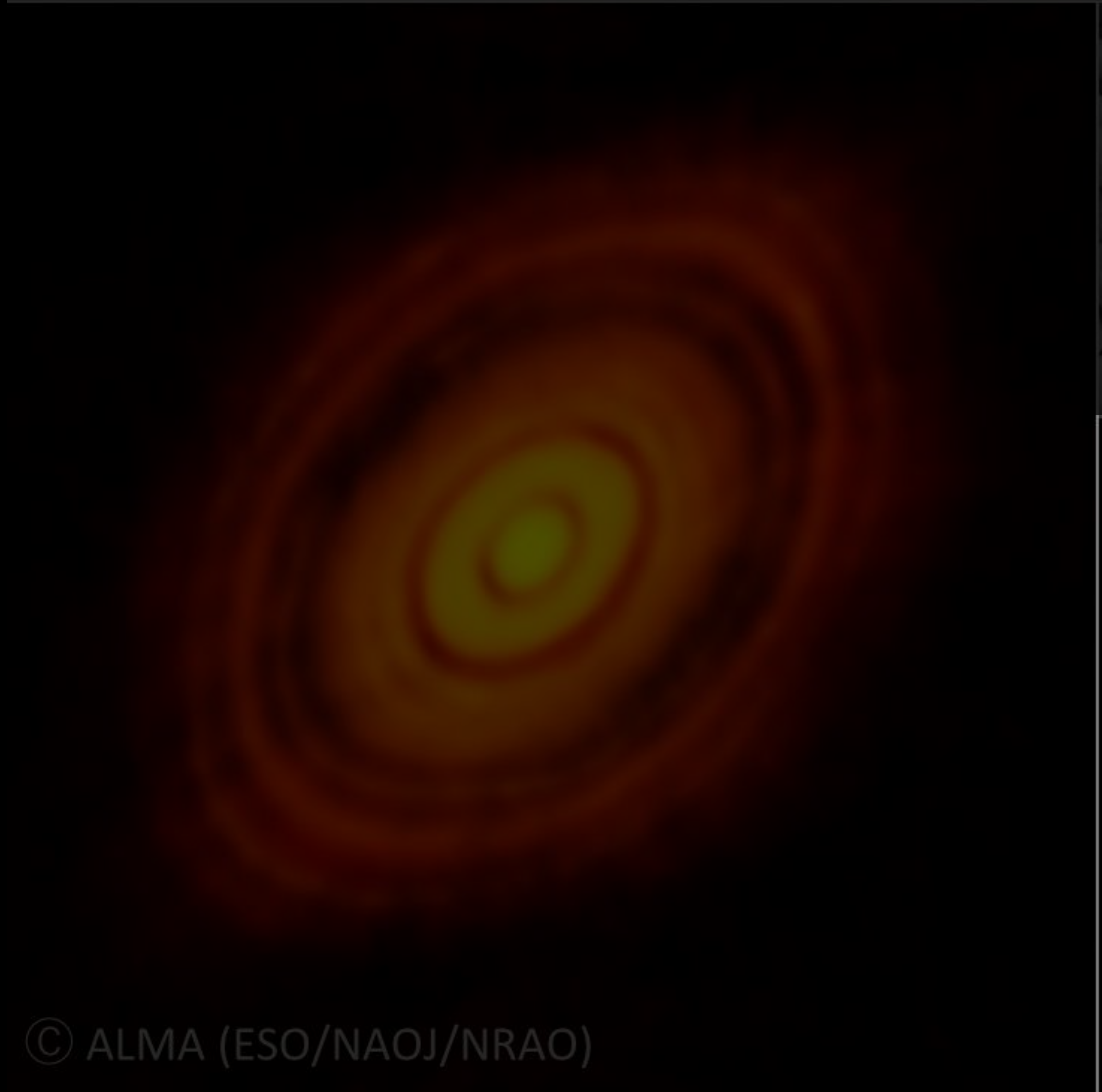
(e.g., Kataoka et al. 2017)

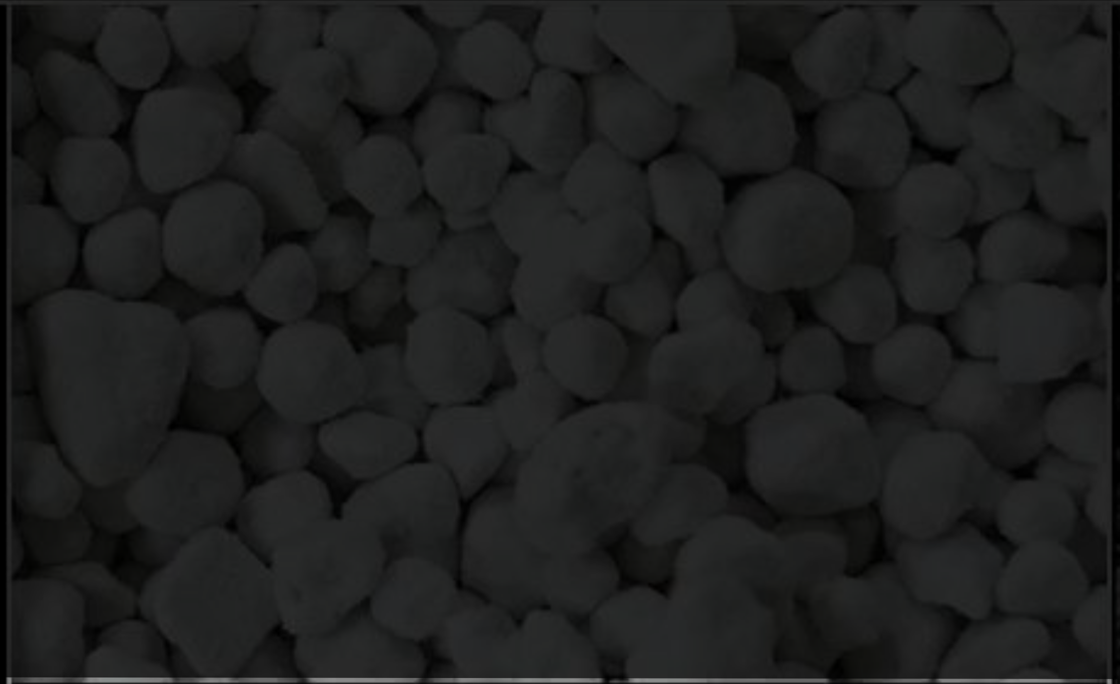


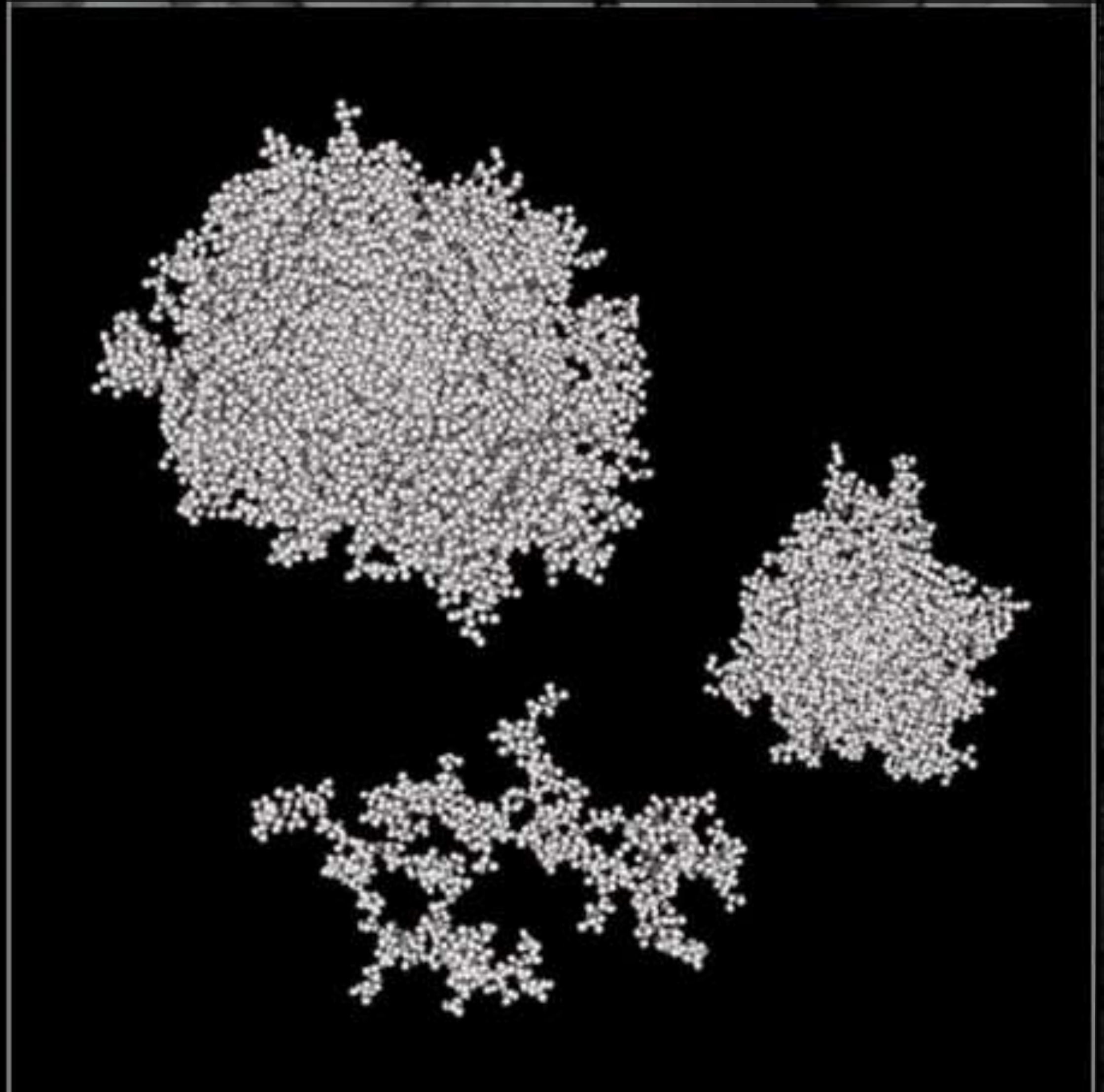
(e.g., Johansen et al. 2009)



From Dust to Planetesimals: A Theoretical Review of Dust Aggregation and Pebble Formation in Planet Formation

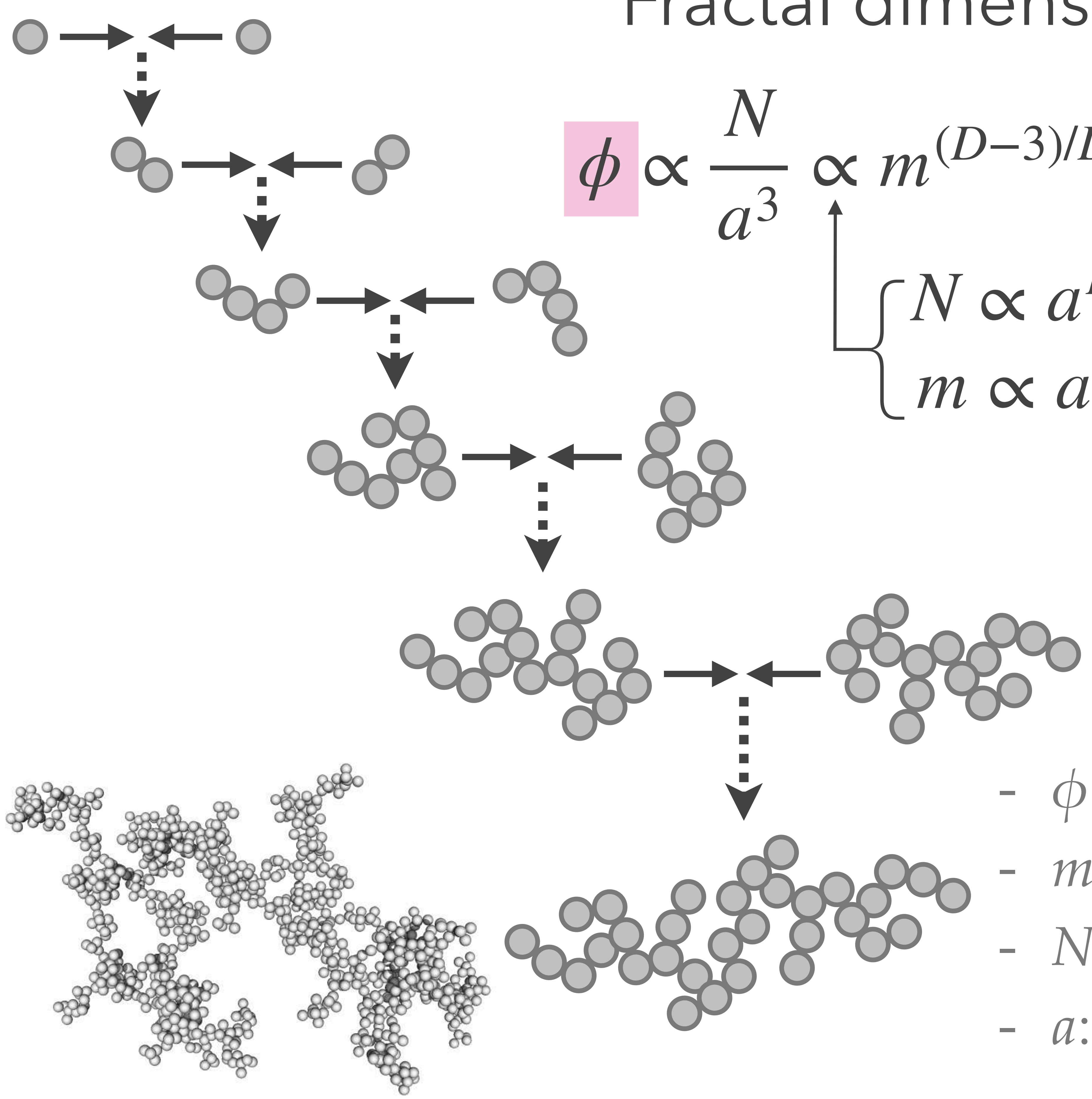






Early stages of dust growth: dust aggregation

BCCA
(Ballistic Cluster-Cluster Aggregation)



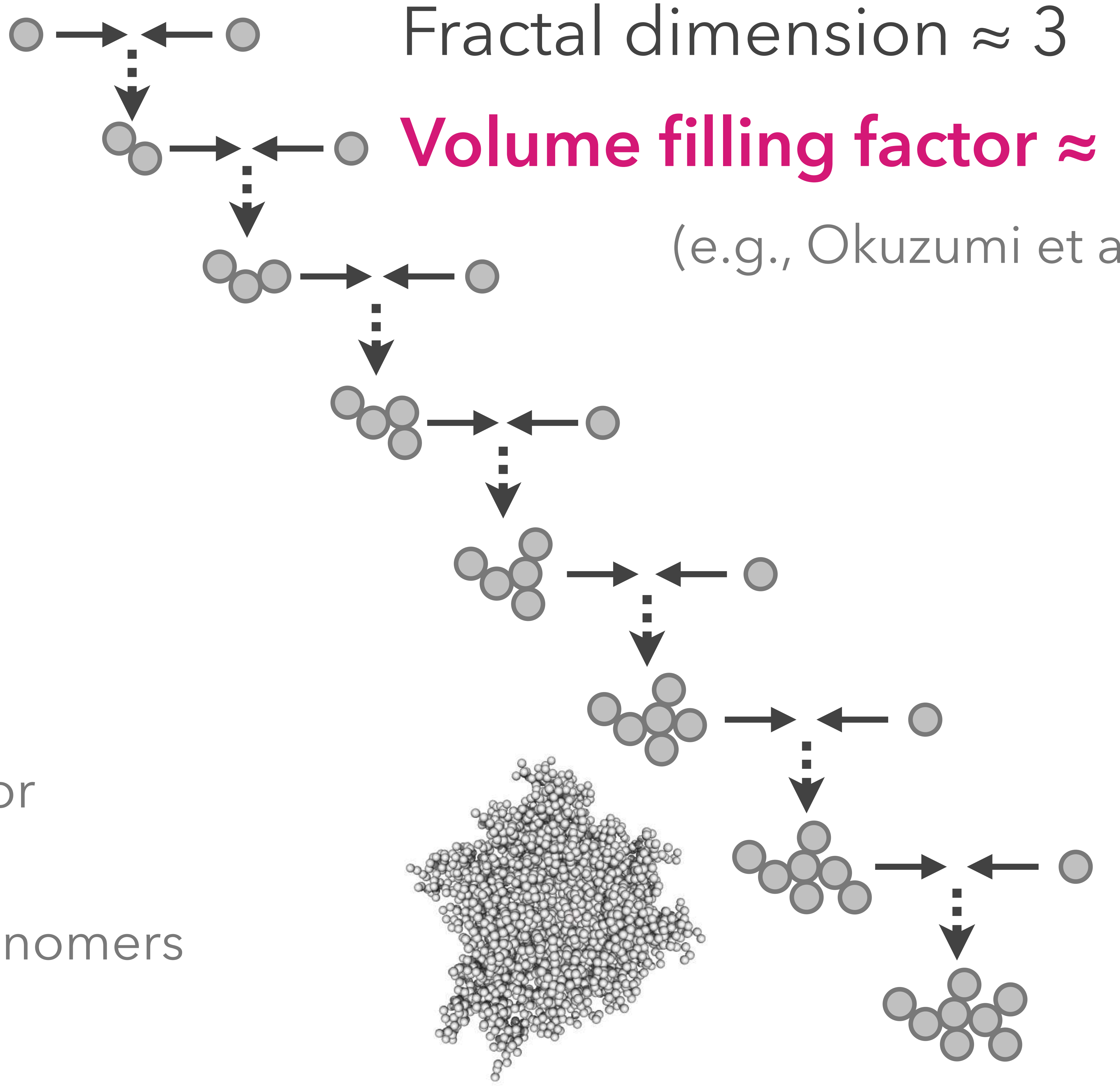
Fractal dimension ≈ 2

$$\phi \propto \frac{N}{a^3} \propto m^{(D-3)/D} = m^{-1/2}$$

$$\begin{cases} N \propto a^D \\ m \propto a^3 \phi \end{cases}$$

- ϕ: volume filling factor
- m: pebble mass
- N: the number of monomers
- a: pebble radius

BPCA
(Ballistic Particle-Cluster Aggregation)



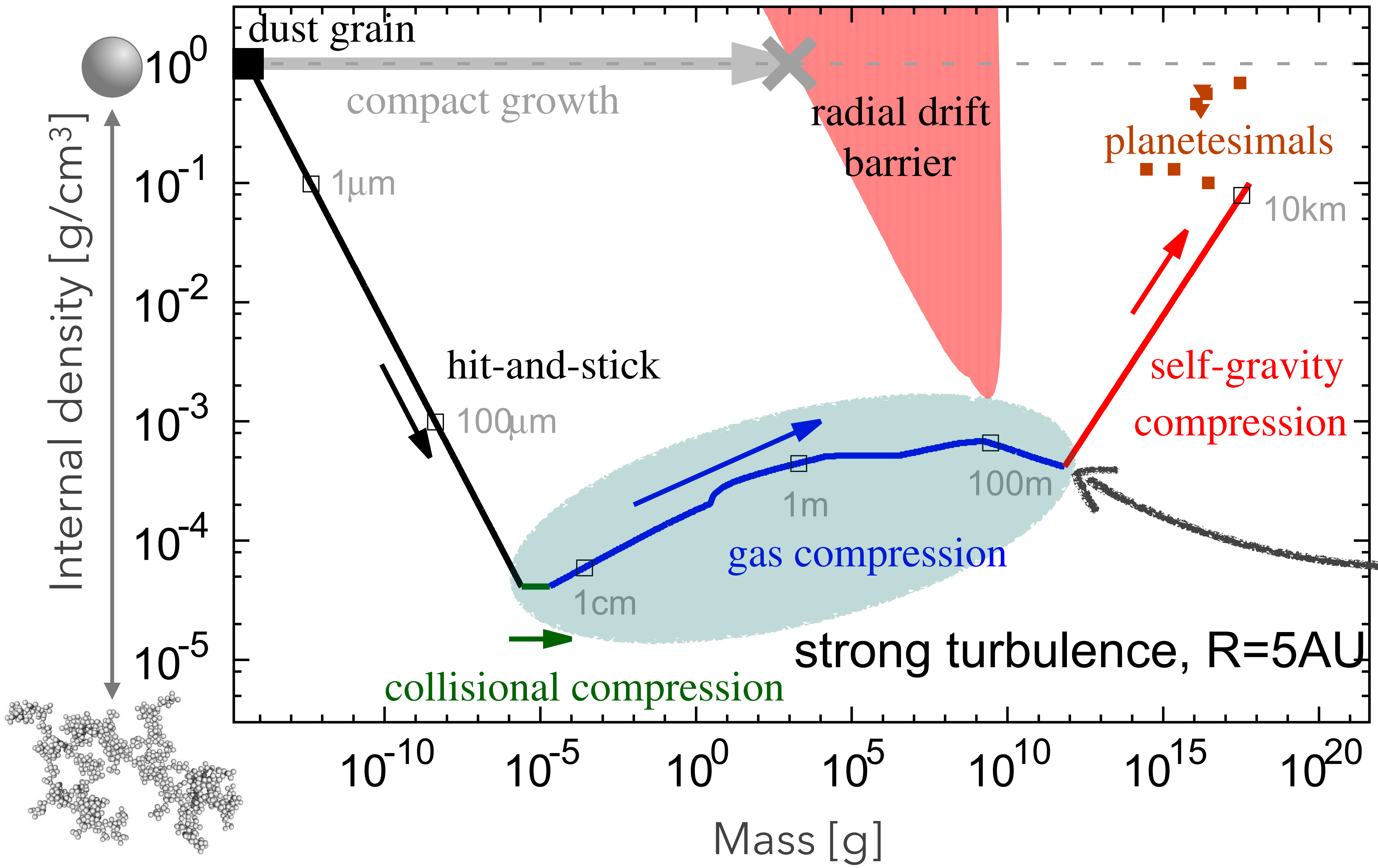
Fractal dimension ≈ 3

Volume filling factor ≈ 0.126

(e.g., Okuzumi et al. 2009)

Porosity evolution of dust aggregates

BCCA and further compression (Kataoka et al. 2013a, b)

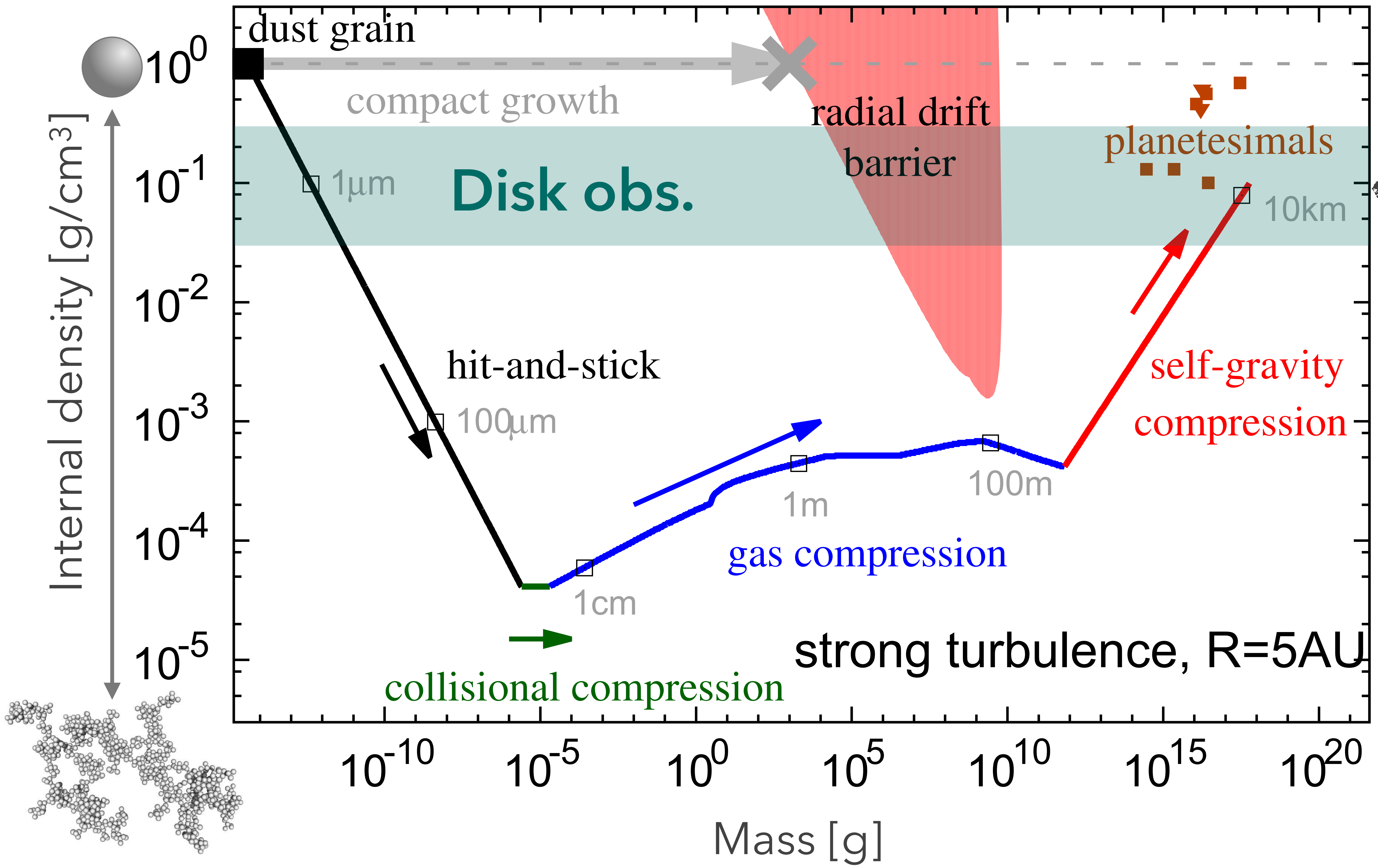


- Dust aggregates can become **extremely porous** (ϕ ~ 10^{-4})!
- The BCCA model represents **the lower limit** of the volume filling factor.
- Collisional and gas compression, as well as the radial drift barrier, depend on the disk model.

* Density [g/cm^3] = 1 g/cm^3 (ice) × ϕ

Problems with the extremely porous evolution model

BCCA and further compression (Kataoka et al. 2013a, b)

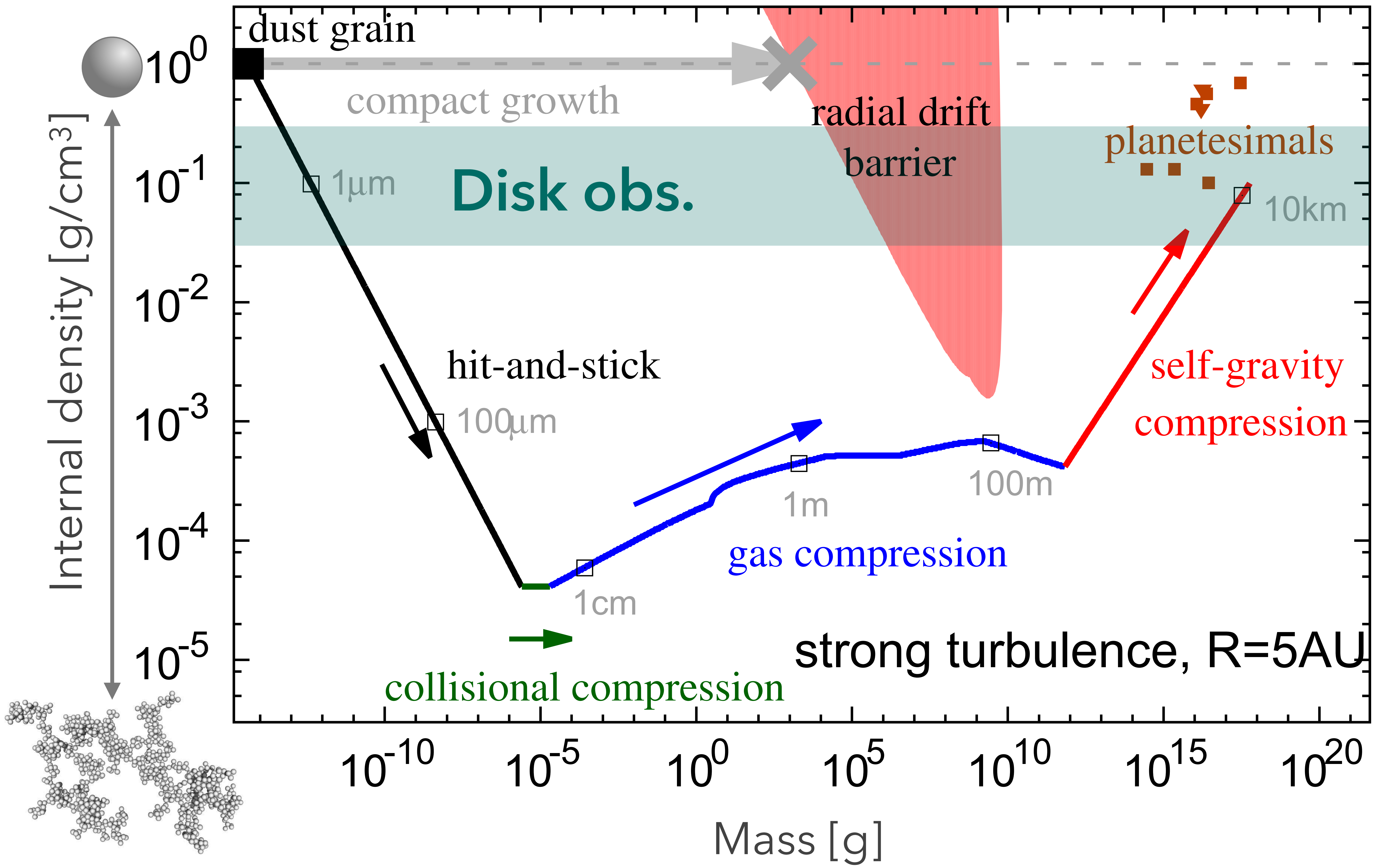


- The extremely porous evolution model can overcome growth barriers!
- However, **it fails to explain the volume filling factor of pebbles observed in disks** ($\phi \approx$ 0.03–0.3).

* Density [g/cm³] = 1 g/cm³ (ice) × ϕ

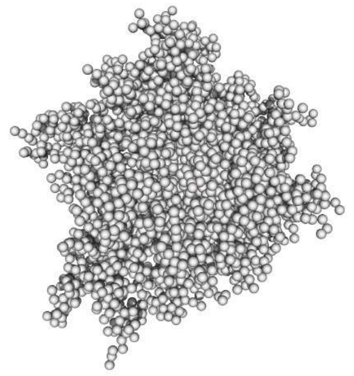
How to explain pebbles observed in disks?

BCCA and further compression (Kataoka et al. 2013a, b)



* Density [g/cm³] = 1 g/cm³ (ice) × ϕ

- **BPCA-like evolution** ($\phi \approx 0.1$)

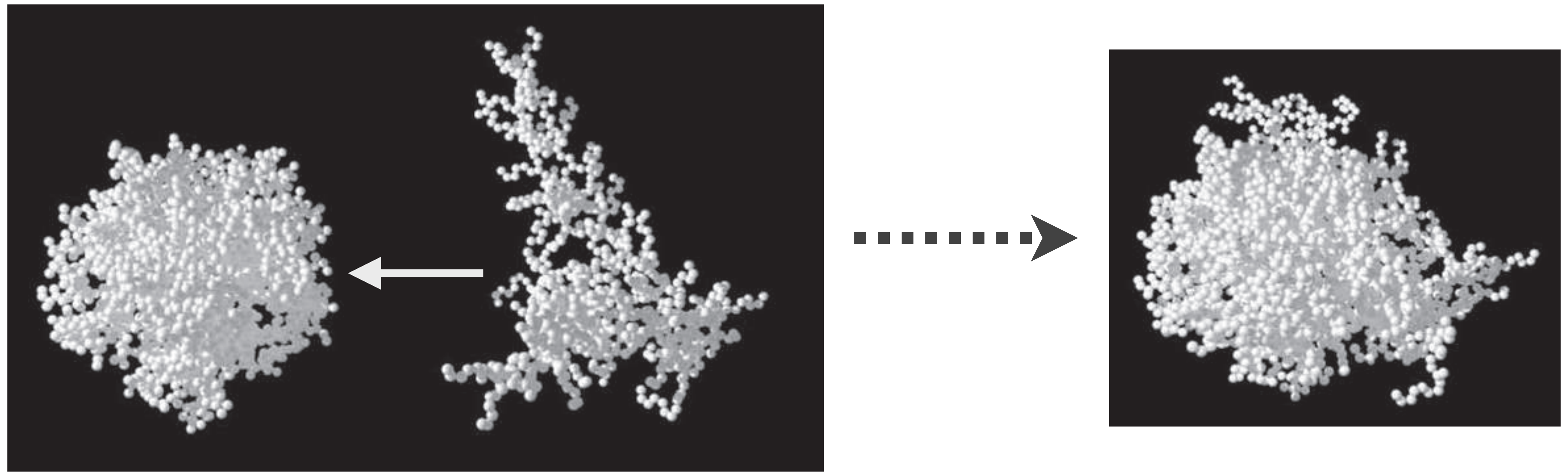


- **Collisional compression**: Although aggregate growth is dominated by similar-sized collisions (Okuzumi et al. 2012), **high-mass ratio collisions** can effectively compress aggregates ($\phi \approx 0.06$–0.2). (Tanaka et al. 2023)
- **Self-gravity compression**

Collisional compression of dust aggregates

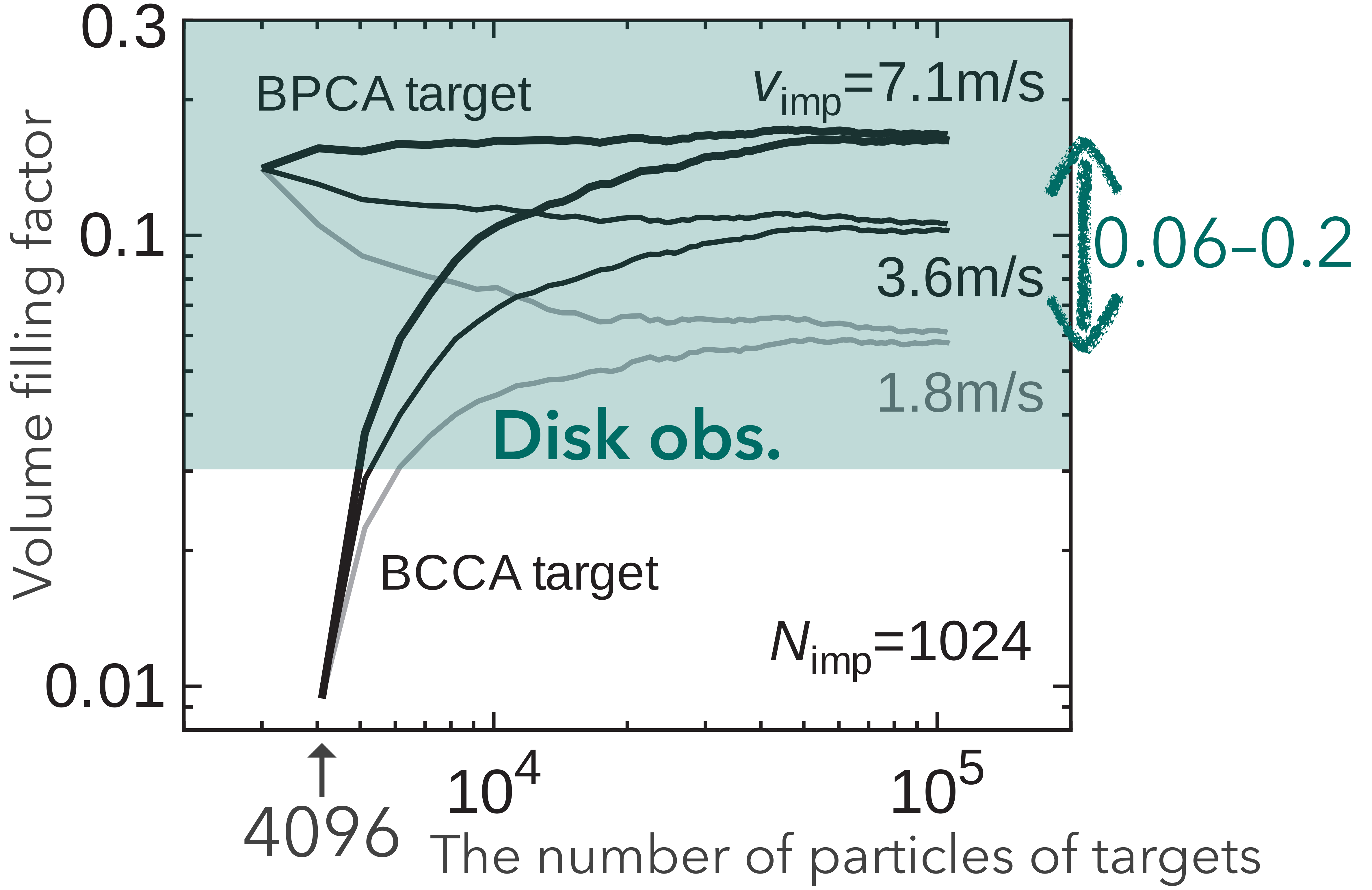
Sequential head-on collisions with high mass ratios (Tanaka et al. 2023)

Target (BPCA, BCCA) Outcome



Impactor (BCCA)

* Identical for each sequential collision

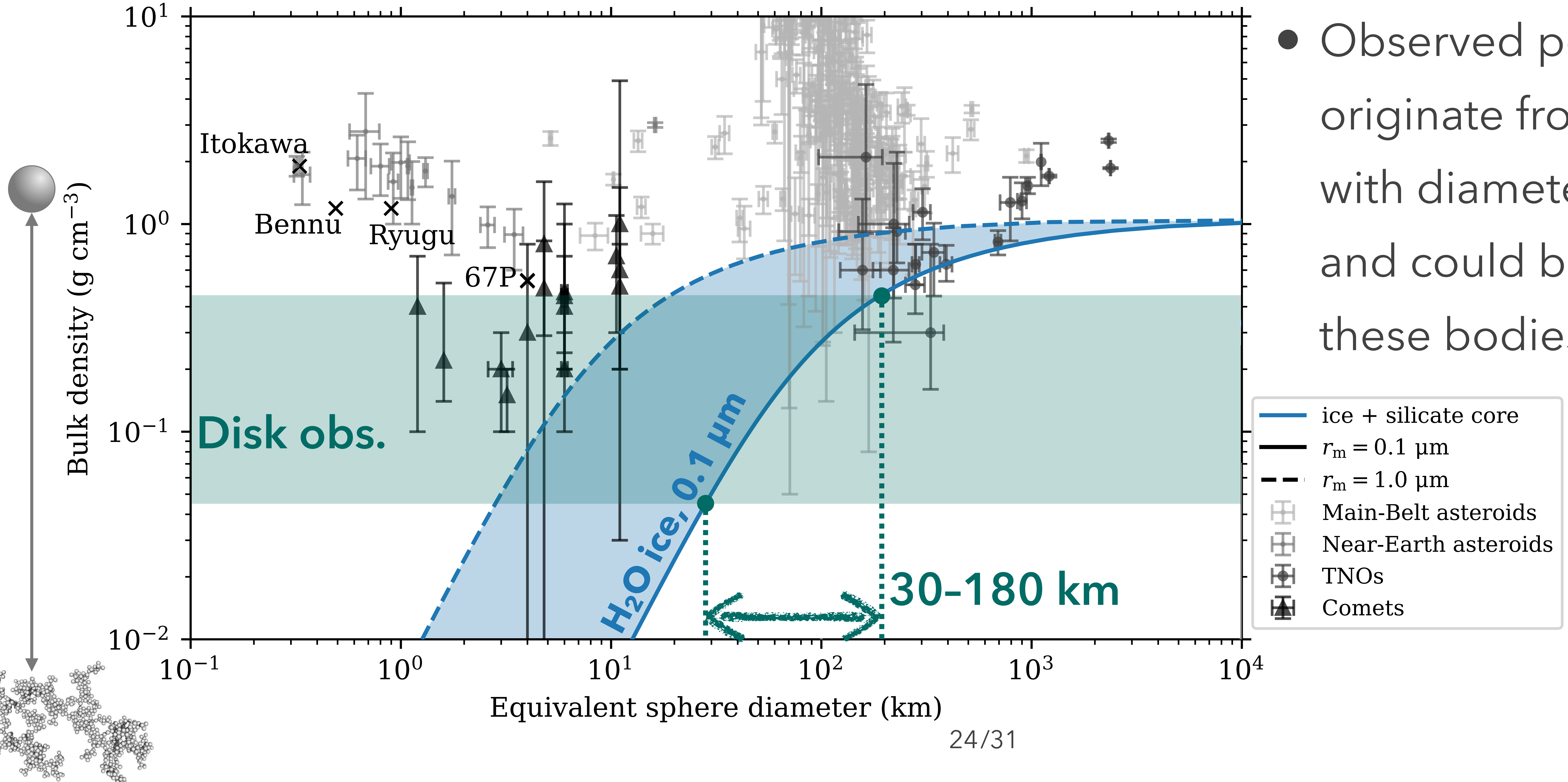


Although aggregate growth is dominated by similar-sized collisions (Okuzumi et al. 2012), **high-mass ratio collisions** can effectively compress aggregates ($\phi \approx$ 0.06–0.2).

Pebbles in disks as fragments of planetesimals?

Self-gravity compression of BCCAs based on their compressive strength

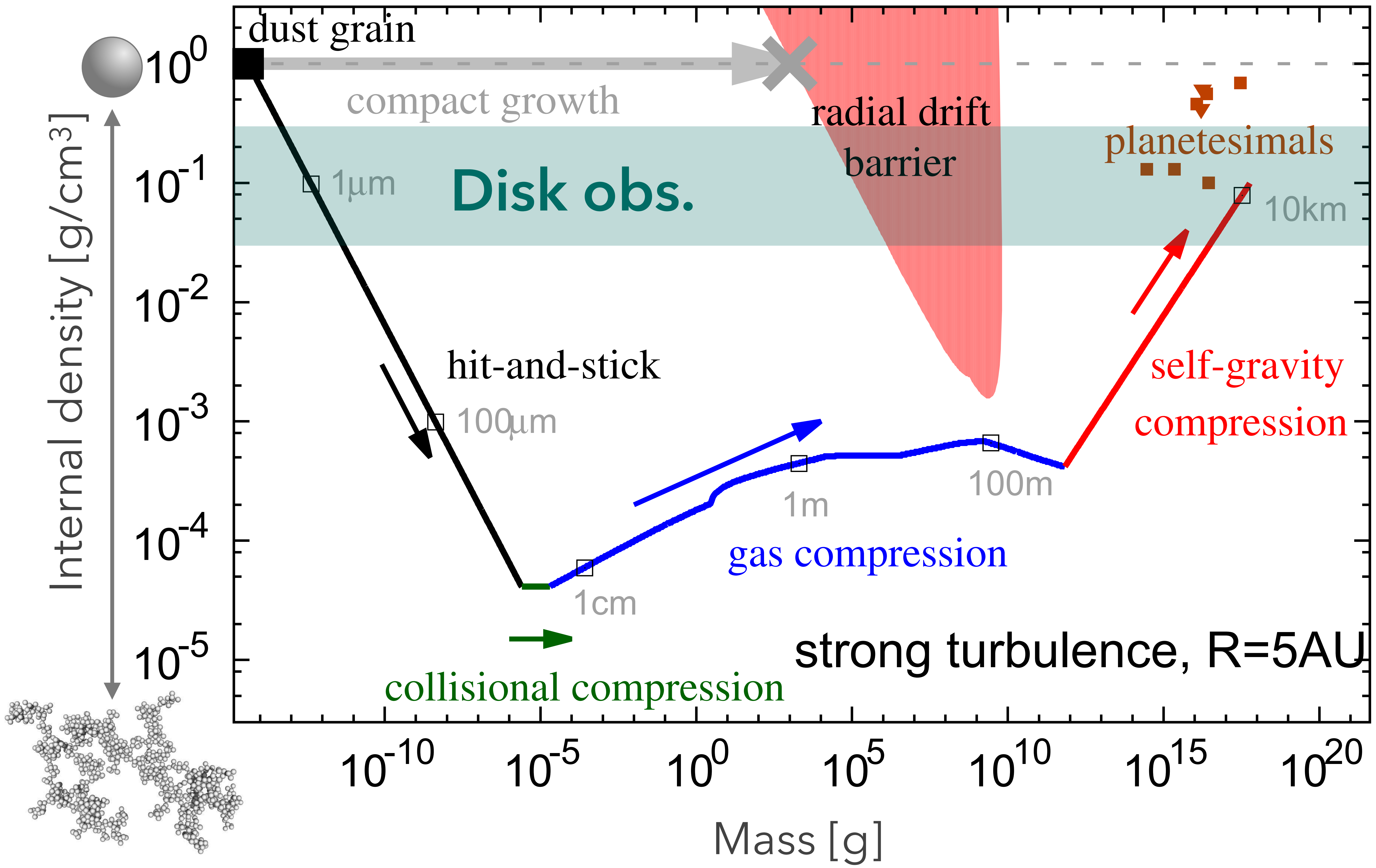
(Tatsuuma et al. 2023, 2024)



- Observed pebbles may originate from parent bodies with diameters of 30–180 km and could be fragments of these bodies.

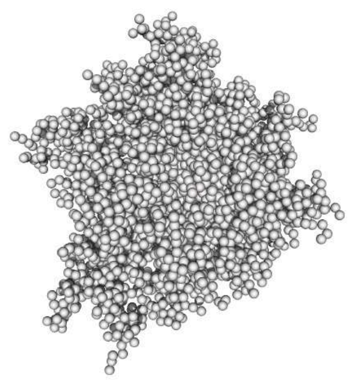
How to explain pebbles observed in disks?

BCCA and further compression (Kataoka et al. 2013a, b)



* Density [g/cm³] = 1 g/cm³ (ice) × ϕ

- **BPCA-like evolution** ($\phi \approx 0.1$)



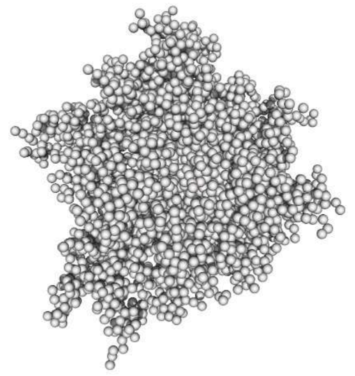
- **Collisional compression**
  (Tanaka et al. 2023)
- **Self-gravity compression**
  (Tatsuuma et al. 2024)

→ **How to stop dust growth?**

- **Fragmentation**
- **Bouncing**

How to stop the dust growth: fragmentation

Fragmentation velocity of BPCAs (Wada et al. 2009)



$$v_{\rm frag} \simeq 50\ {\rm m\ s^{-1}} \left(\frac{\gamma}{100\ {\rm mJ\ m^{-2}}}\right)^{5/6} \left(\frac{r_{\rm mon}}{0.1\ \mu{\rm m}}\right)^{-5/6} \left(\frac{Y_*}{3.7\ {\rm GPa}}\right)^{-1/3} \left(\frac{\rho_{\rm mat}}{1\ {\rm g\ cm^{-3}}}\right)^{-1/2}$$

Surface energy | **Radius of individual grains (monomer radius)** | Young's modulus | Material density

* H_2O ice (e.g., Israelachvili 1992)

Fragmentation velocity of pebbles observed in protoplanetary disks (e.g., Ueda et al. 2024)

$$v_{\rm frag} \lesssim 1\ {\rm m\ s^{-1}}$$

- If $\gamma \to 0.1\gamma$ (surface energy)
- If $r_{\rm mon} \to 10 r_{\rm mon}$ (monomer radius)

➡ $v_{\rm frag} \to 0.15 v_{\rm frag}$ (fragmentation velocity)

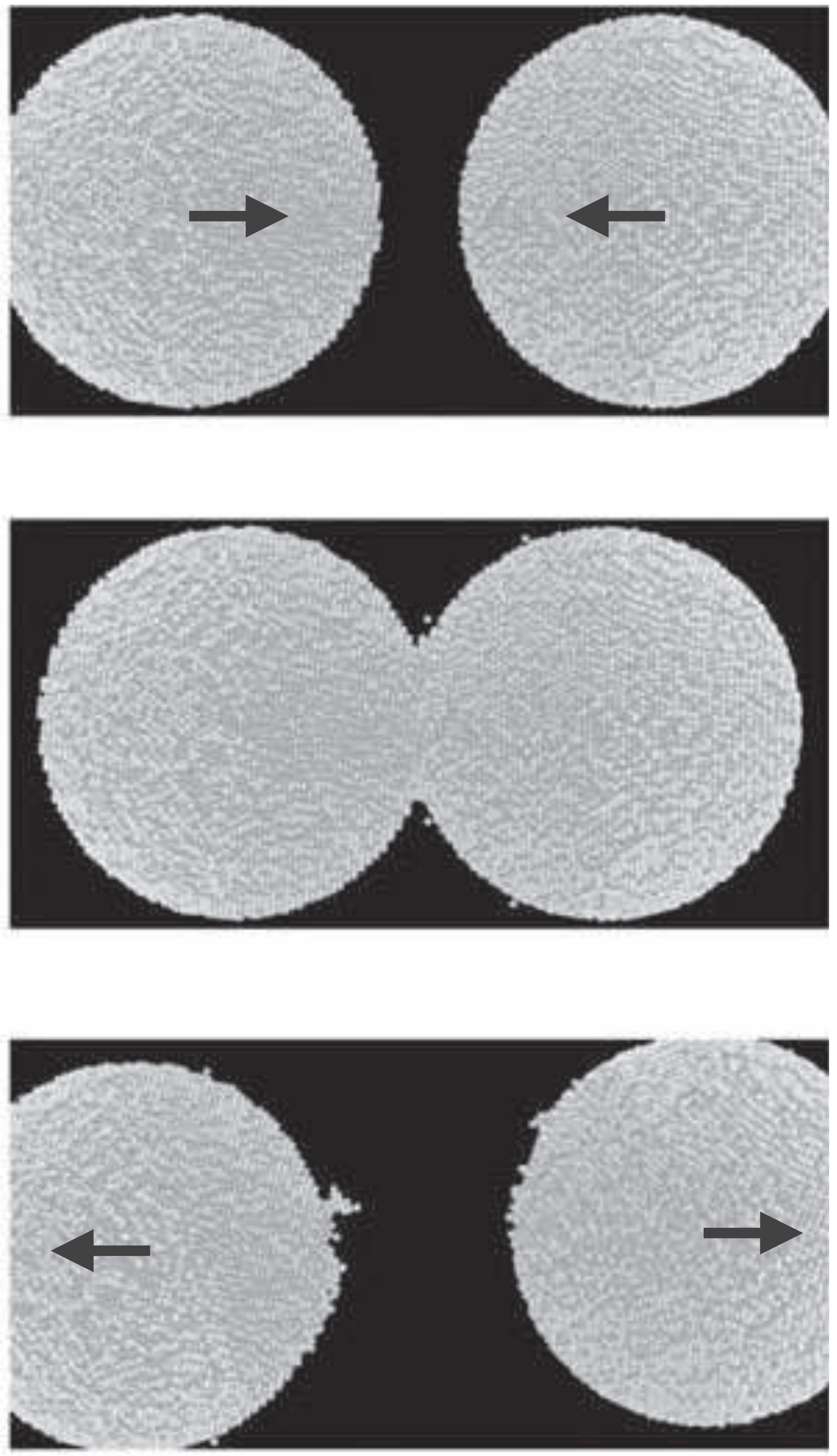
→ Less sticky? Larger individual grains?

How to stop the dust growth: bouncing

Bouncing barrier in simulations (Arakawa et al. 2023; Oshiro et al. submitted)

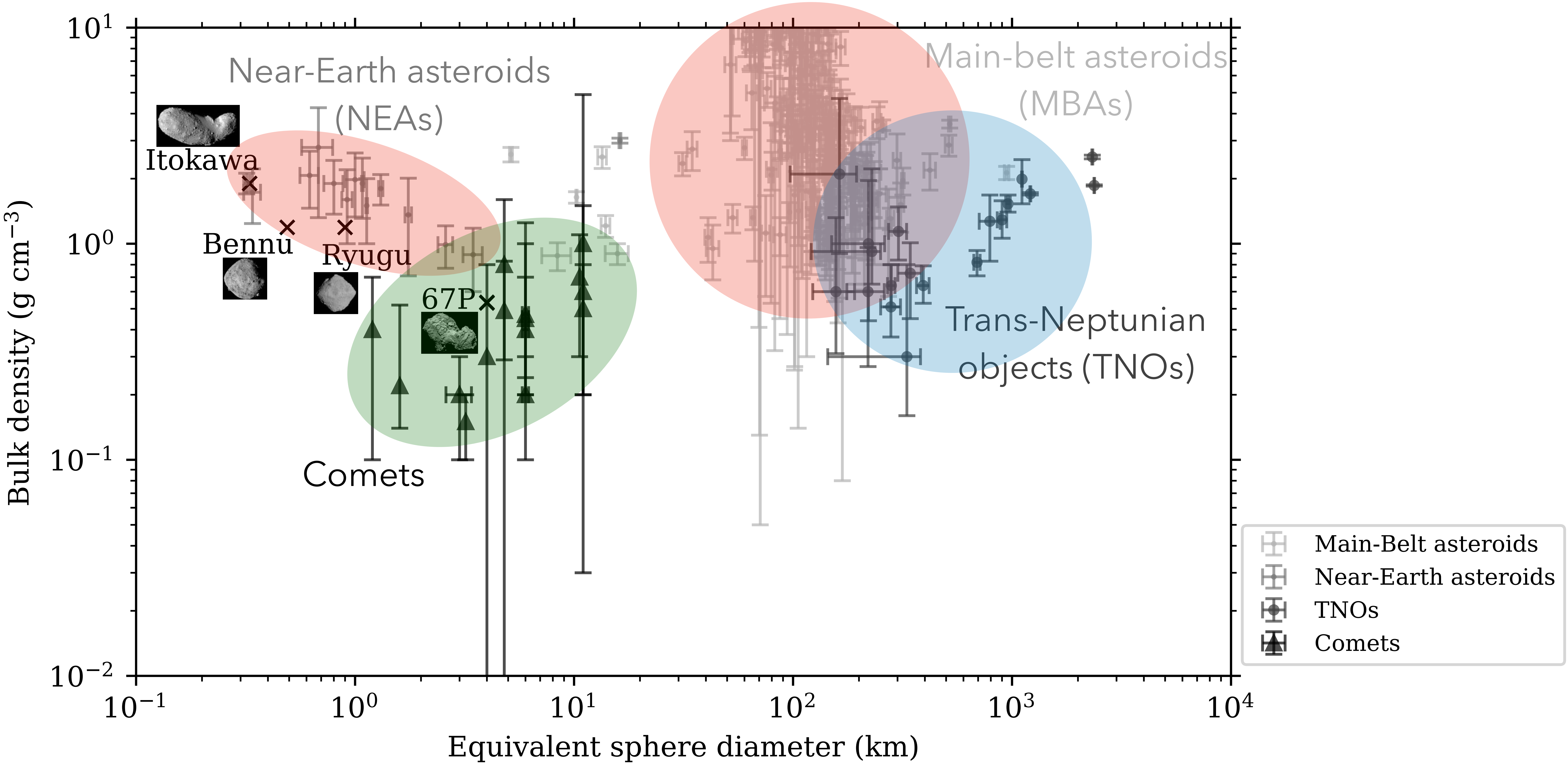
Larger, less porous dust aggregates tend to bounce at intermediate velocities (≤ 10 m/s).

→ **Talk by Haruto Oshiro**



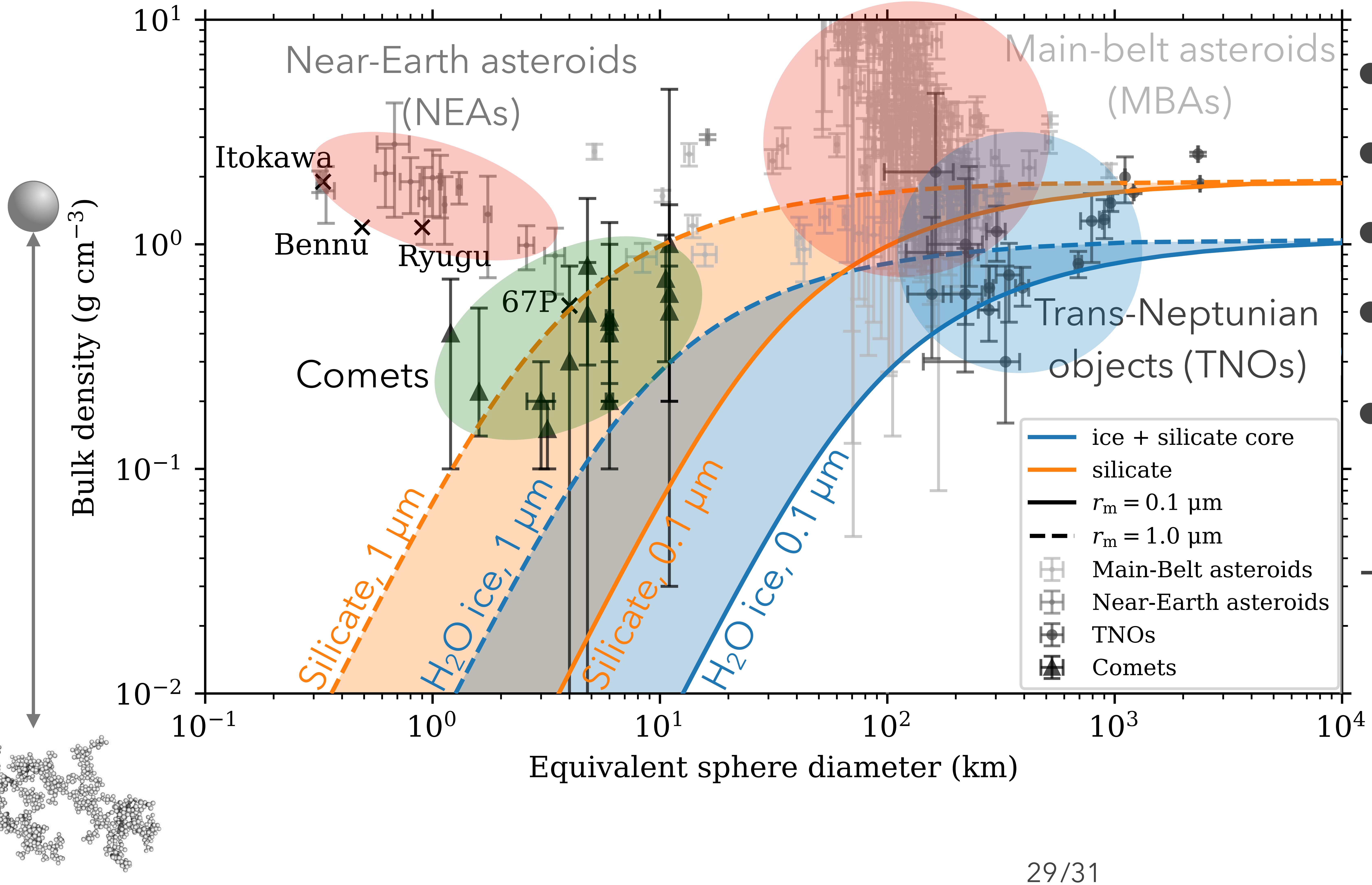
Can we test dust growth through solar system studies?

Relation between diameter and bulk density of small bodies in the solar system



Can we test dust growth through solar system studies?

Self-gravity compression of BCCAs based on their compressive strength: (Tatsuuma et al. 2024)



- can explain low-density TNOs.
- **cannot** explain comets.
- can explain MBAs.
- **cannot** explain NEAs.
- Comets and NEAs are **too dense**.

→ They can be fragments or rubble piles of larger bodies.

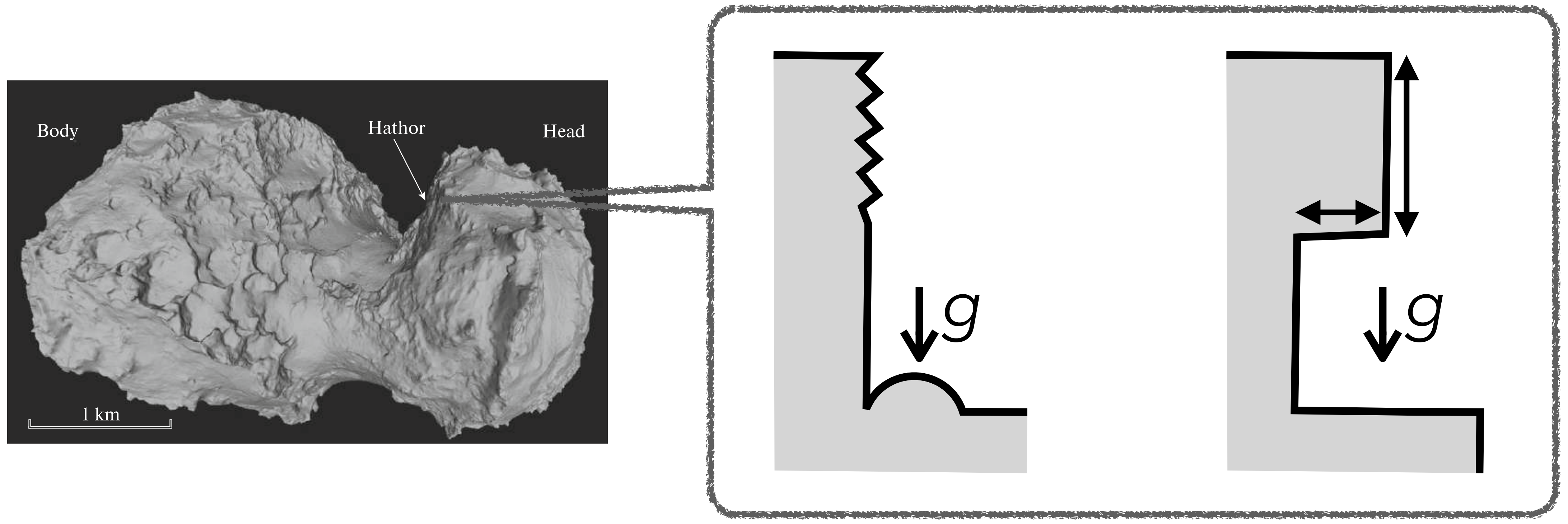
Can we test dust growth through solar system studies?

Tensile strength of dust aggregates (Tatsuuma et al. 2019)

$$\simeq 6 \times 10^5 \ \mathrm{Pa} \left(\frac{\gamma}{100 \ \mathrm{mJ \ m^{-2}}} \right) \left(\frac{r_{\mathrm{mon}}}{0.1 \ \mu\mathrm{m}} \right)^{-1} \phi^{1.8}$$

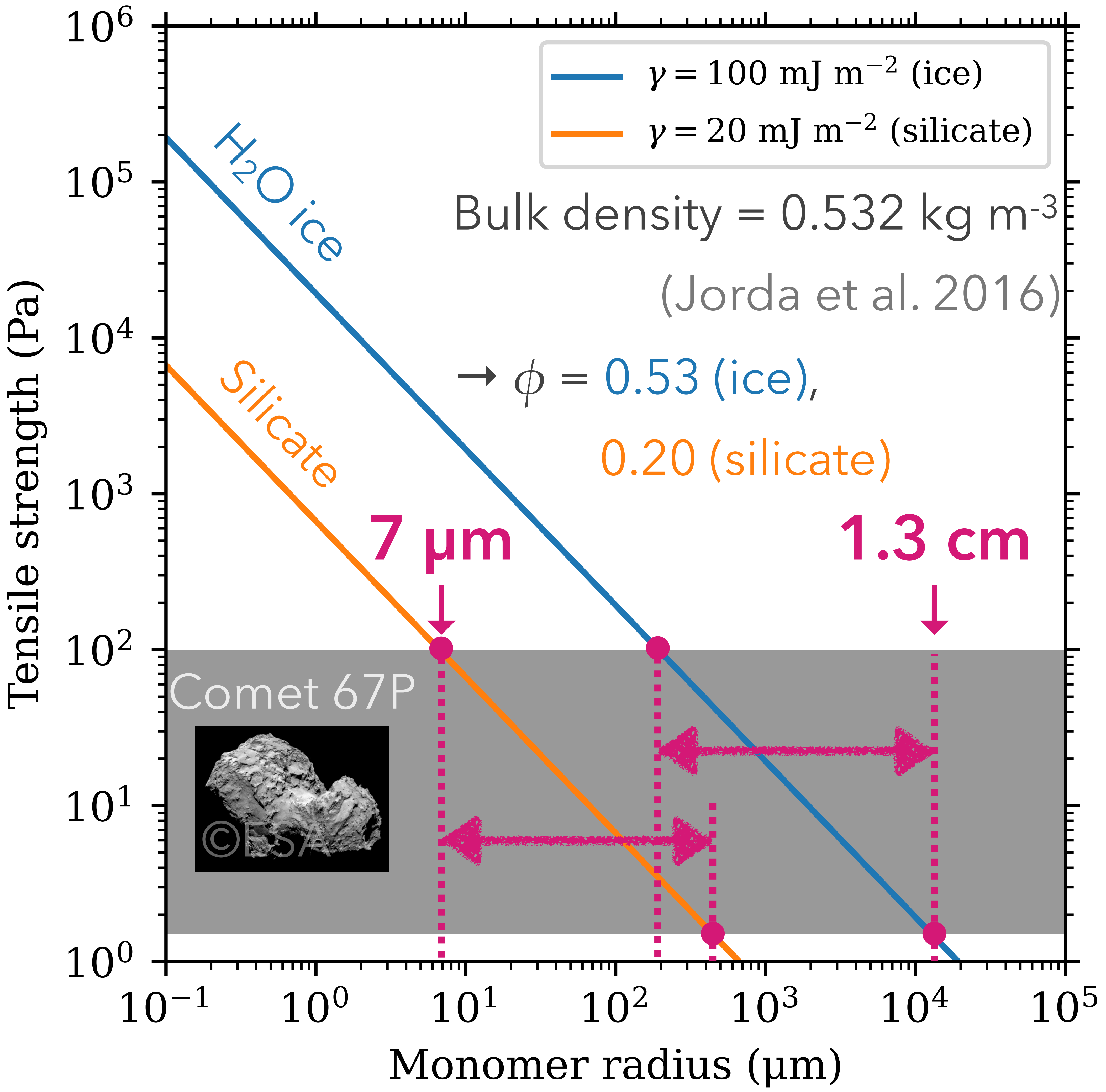
Surface energy Monomer radius

Comet 67P: ~ 1.5–100 Pa (Basilevsky et al. 2016)



→ Monomer radius should be 7 μm–1.3 cm

→ Are monomers the same as pebbles?



Summary

- The extremely porous evolution model, based on BCCA and further compression, can overcome growth barriers, such as radial drift, fragmentation, bouncing. However, it fails to explain the porosity of pebbles observed in protoplanetary disks.
- BPCA-like evolution, collisional compression, and self-gravity compression can explain the observed pebbles, but further studies are needed.
- Once we can explain the porosity of observed pebbles, it becomes necessary to address how dust growth is halted.
  - Fragmentation can stop dust growth, but this requires assuming that the individual grains are either less sticky, larger, or both.
  - Recent simulations show that larger, less porous dust aggregates tend to bounce rather than stick.