Dust coagulation with porosity evolution; effects on planetesimal formation and opacity evolution

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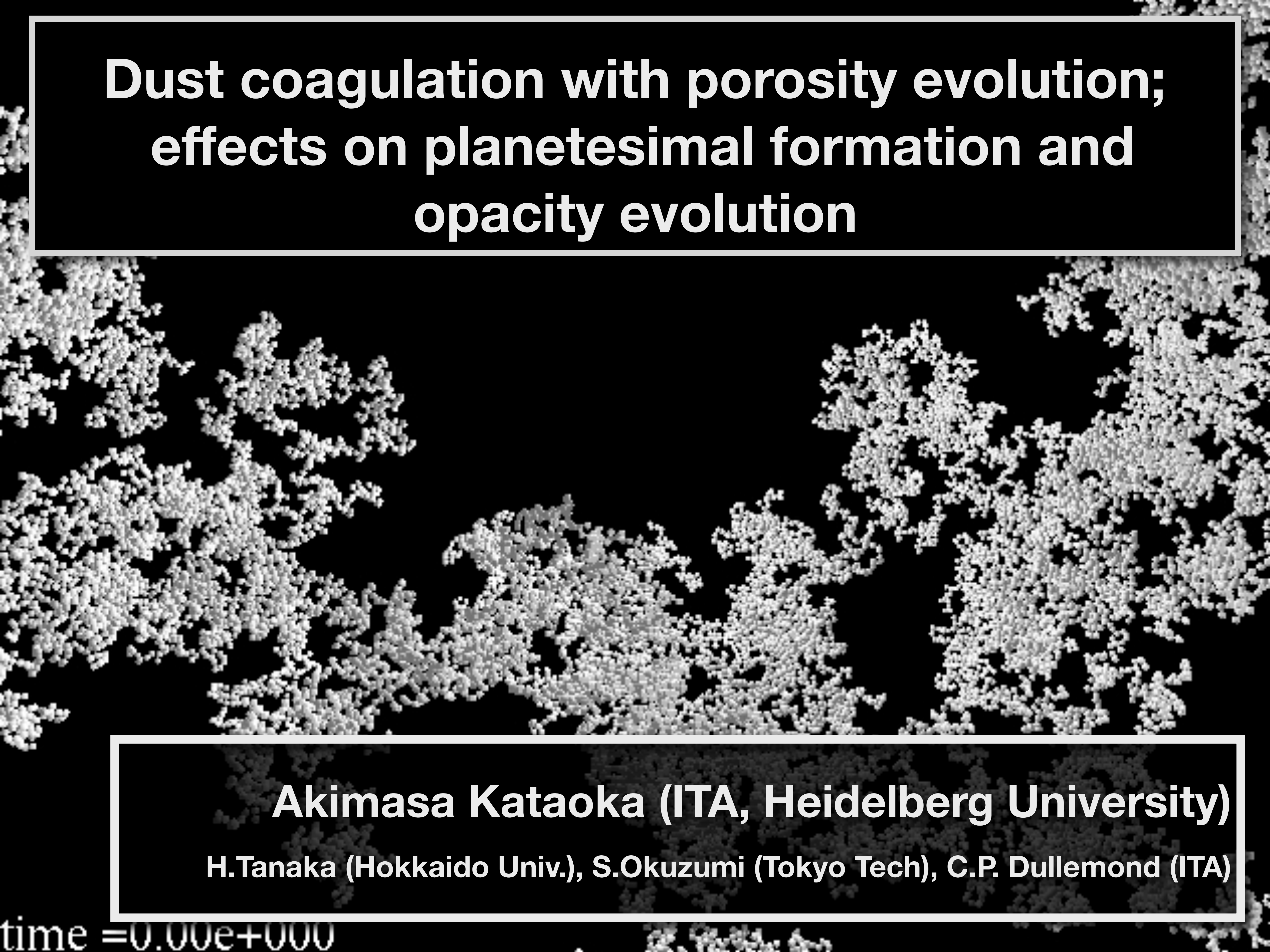
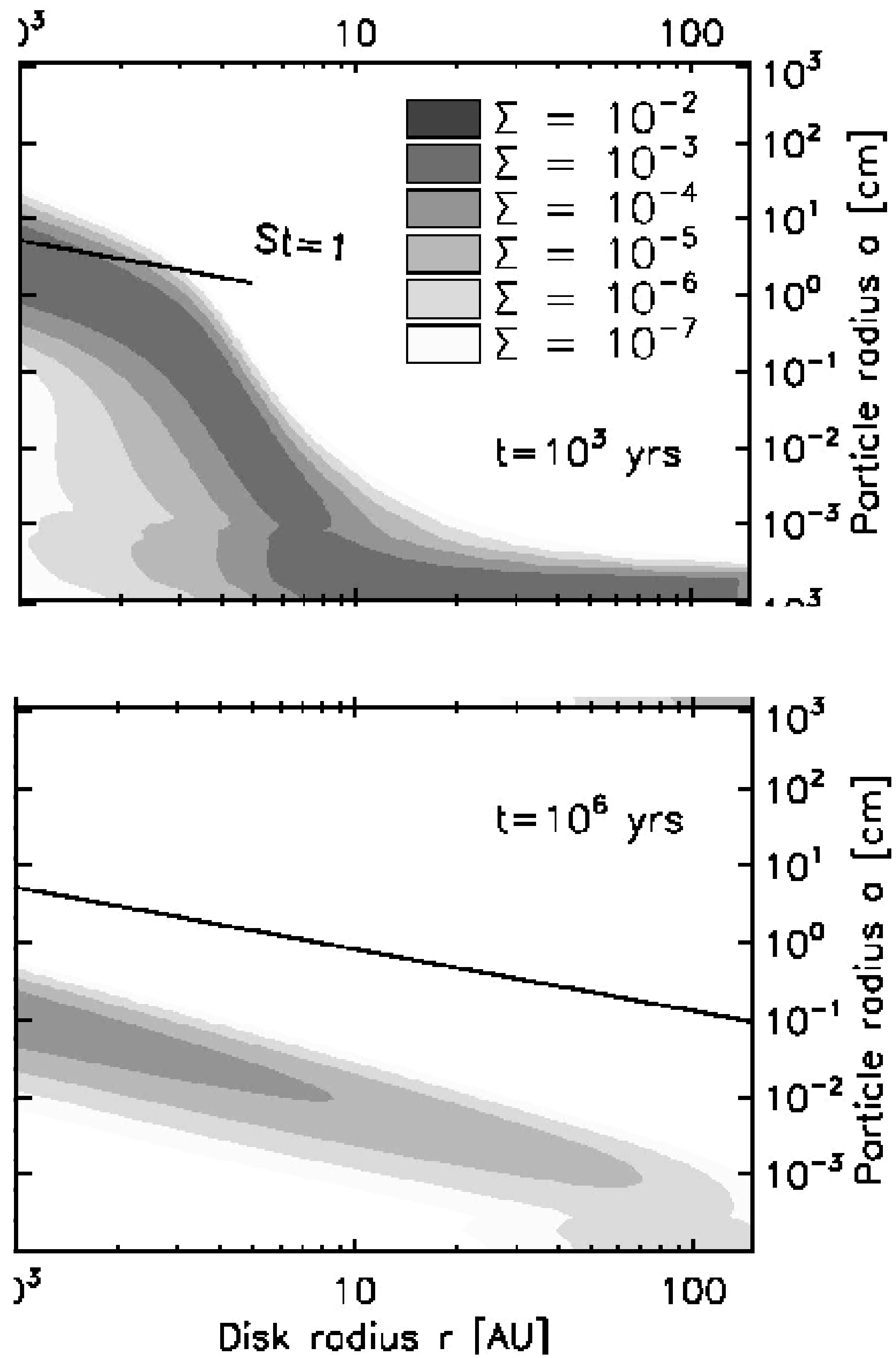


Planet formation in size evolution

Barriers in dust coagulation

- Radial drift barrier for planetesimal formation (e.g., Adachi et al. 1976)
  - Dust grains have to "jump" the barrier
- Radial drift barrier for millimeter-wave observations (e.g., Beckwith & Sargent 1991)
  - Dust grains has to "jump" the barrier and we should "keep" them
- Fragmentation barrier (e.g., Blum & Münch 1993)
  - Dust should overcome high-speed collisions such as ~ 50 m/s
- Bouncing barrier (e.g., Zsom et al. 2010)



Brauer et al. 2008

Possible solution

Porous dust aggregates

- Radial drift barrier for planetesimal formation
  → Rapid coagulation by large cross section (Okuzumi et al. 2012)

- Radial drift barrier for millimeter-wave observations
  → Do they account for millimeter-wave emission? Opacity?

- Fragmentation barrier
  → Ice is more sticky than silicate (Wada et al. 2009)

- Bouncing barrier
  → Highly porous dust aggregates do not bounce (Wada et al. 2011)

Wada et al. 2009

Dust aggregate

radius : a, mass: m

internal density: ρ

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  2009)

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Dust aggregate
radius : a, mass: m
internal density: ρ

Numerical simulations

$$u_{\mathrm{col,crit}} = \begin{cases} 80\,(r/0.1\mu\mathrm{m})^{-5/6} & \text{[m/s] for ice} \\ 8\,(r/0.1\mu\mathrm{m})^{-5/6} & \text{[m/s] for silicate} \end{cases}$$

(Wada et al. 2009, 2013)

Laboratory experiments
Quarz (Colwell et al. 2003), **SiO_2**, **$MgSiO_3$** (Blum and Wurm 2000), **Graphite, Al_2O_3** (Reisshaus et al. 2006), **Ice** (Gundlach and Blum 2015), **CO_2** (Musiolik et al. 2016)

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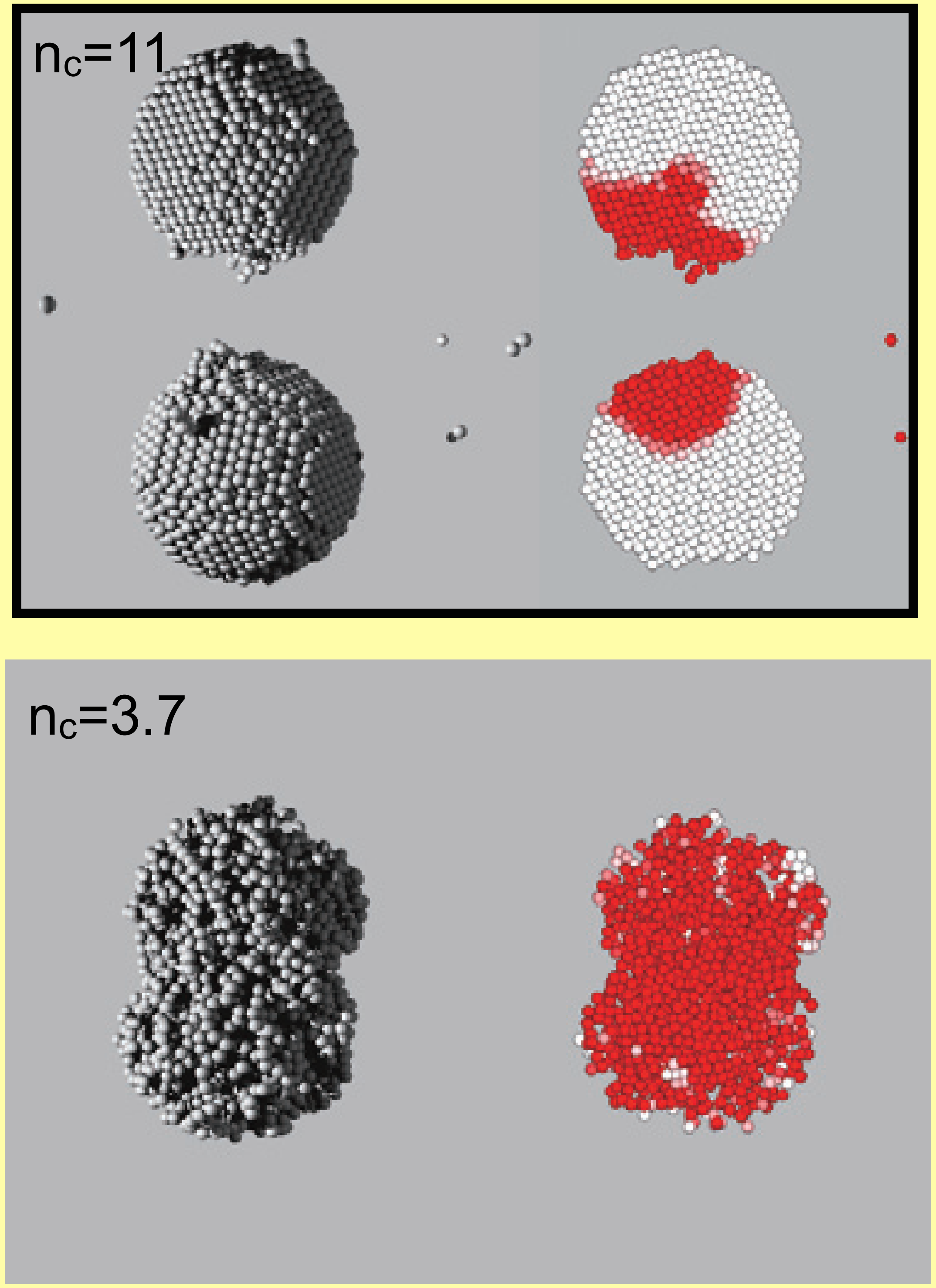
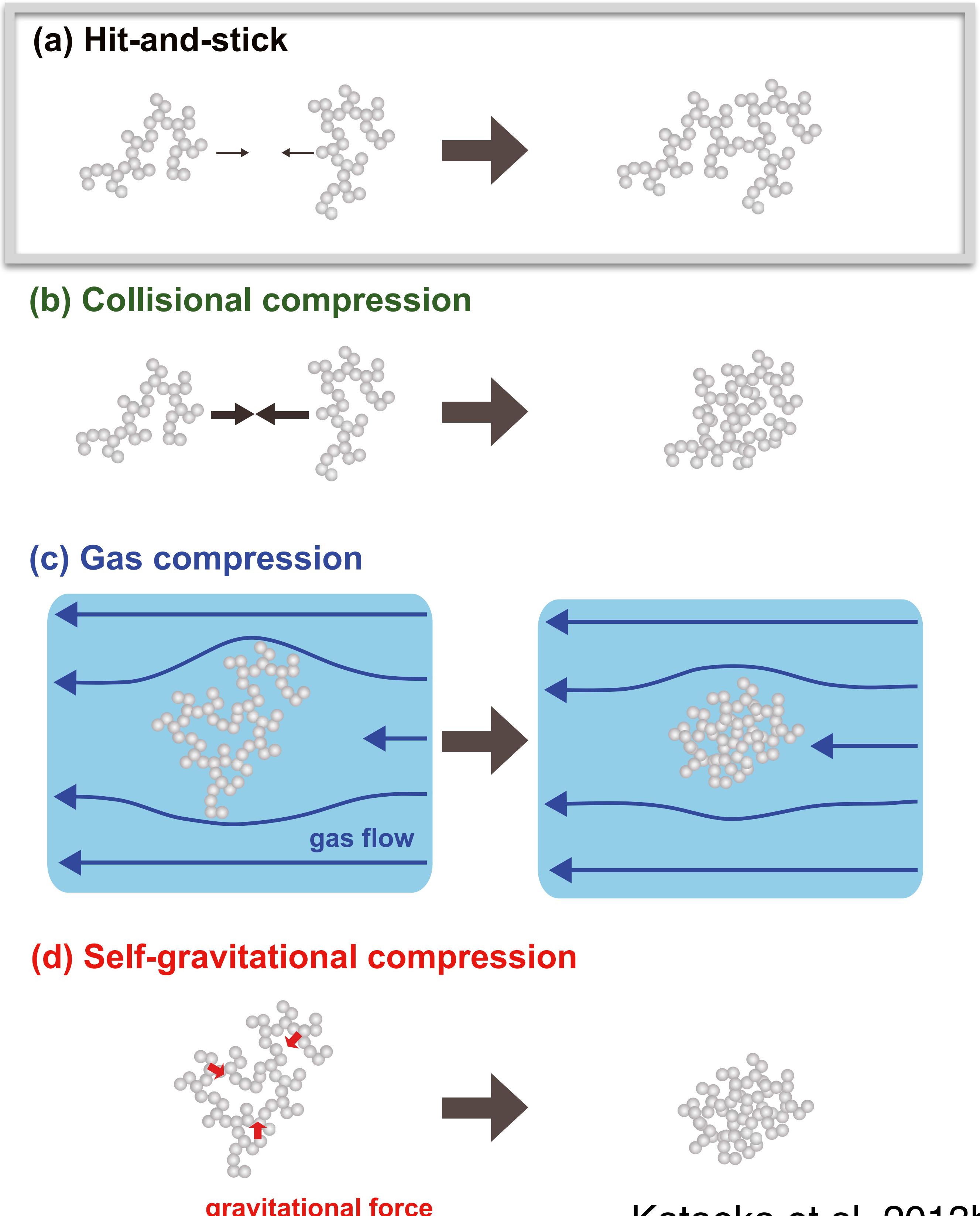
Coordination number : n_c



Wada et al. 2011

Structure evolution of dust aggregates

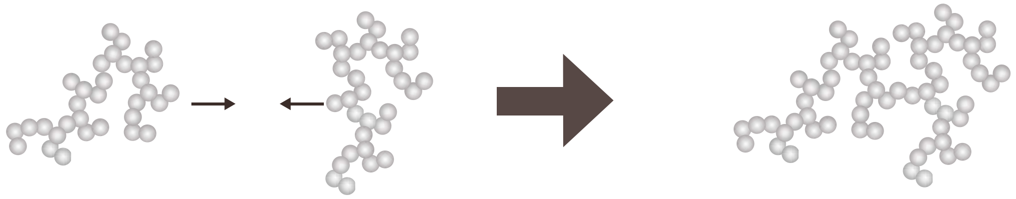


Kataoka et al. 2013b

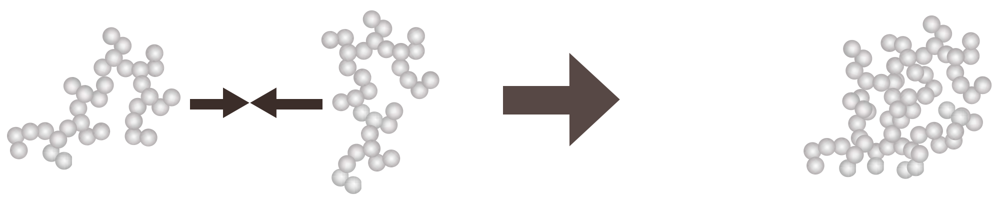
→ Growth with fractal dimension of ~2 due to low-velocity collisions

Structure evolution of dust aggregates

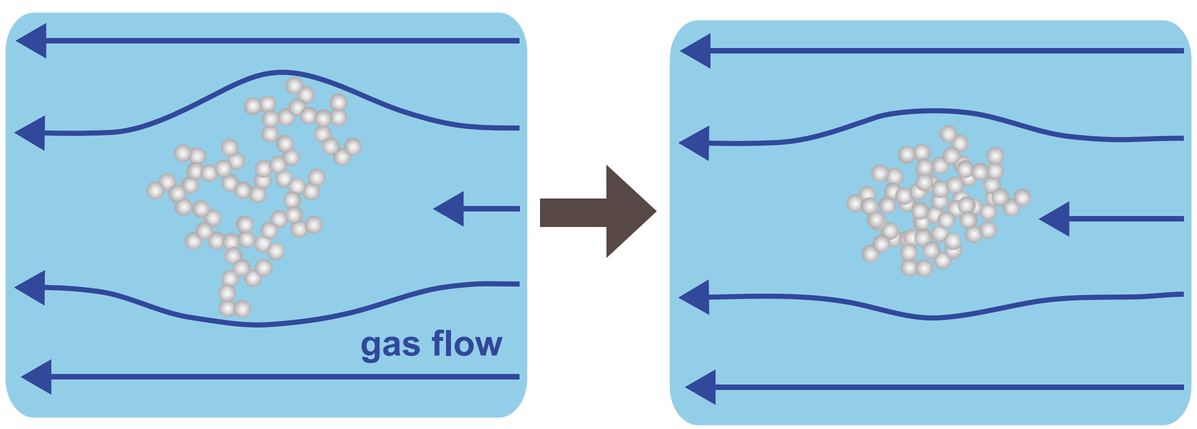
(a) Hit-and-stick



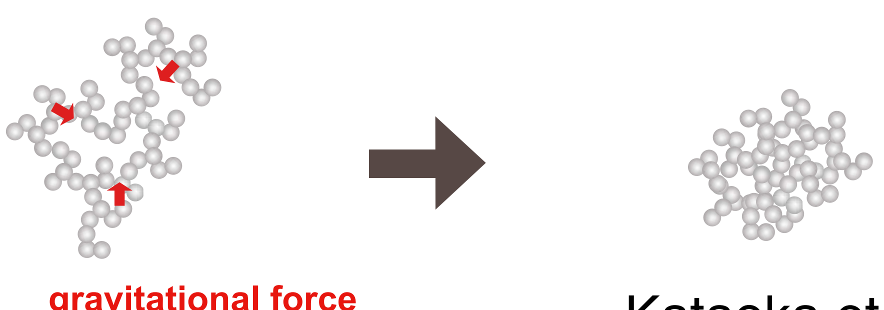
(b) Collisional compression



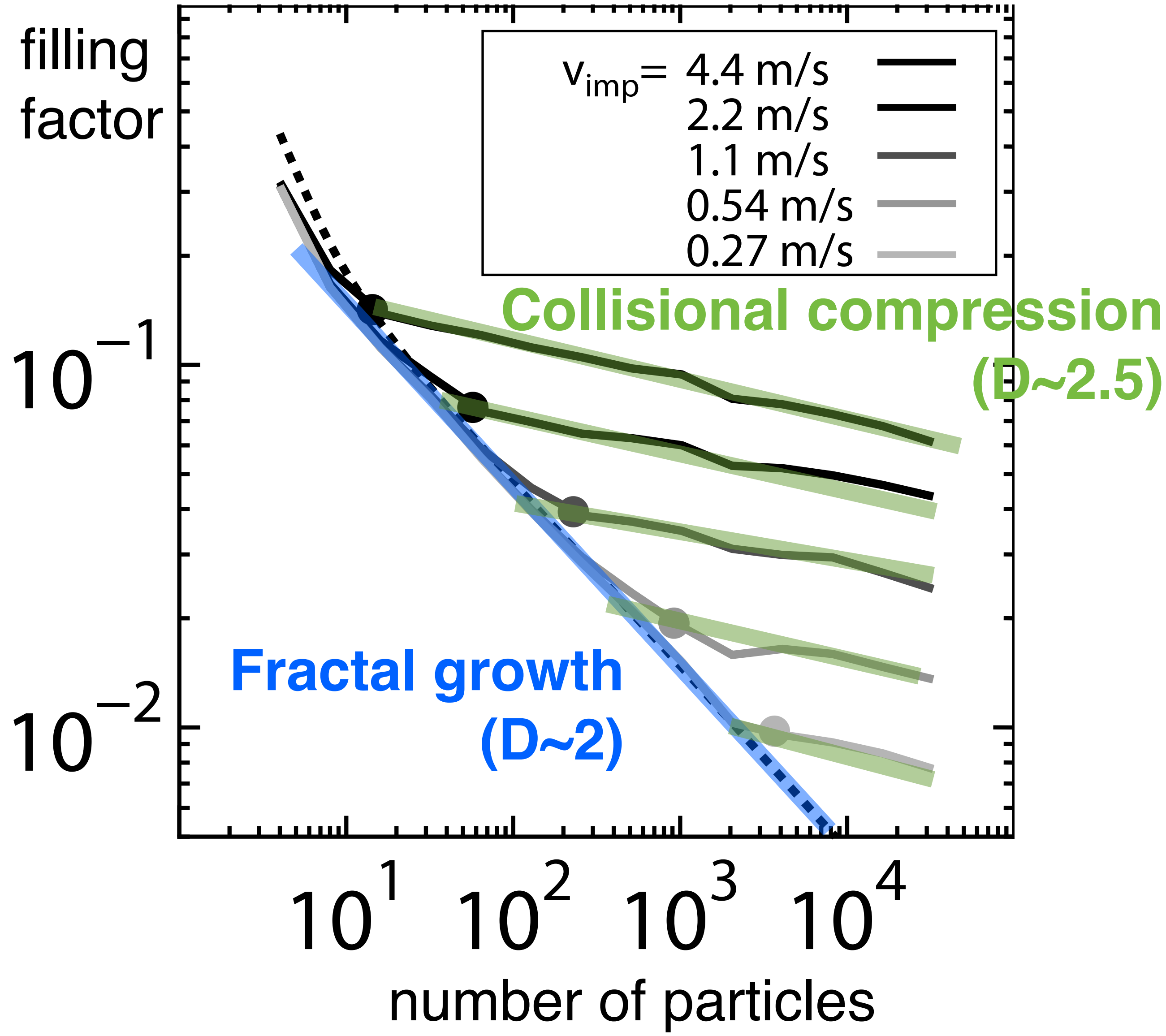
(c) Gas compression



(d) Self-gravitational compression



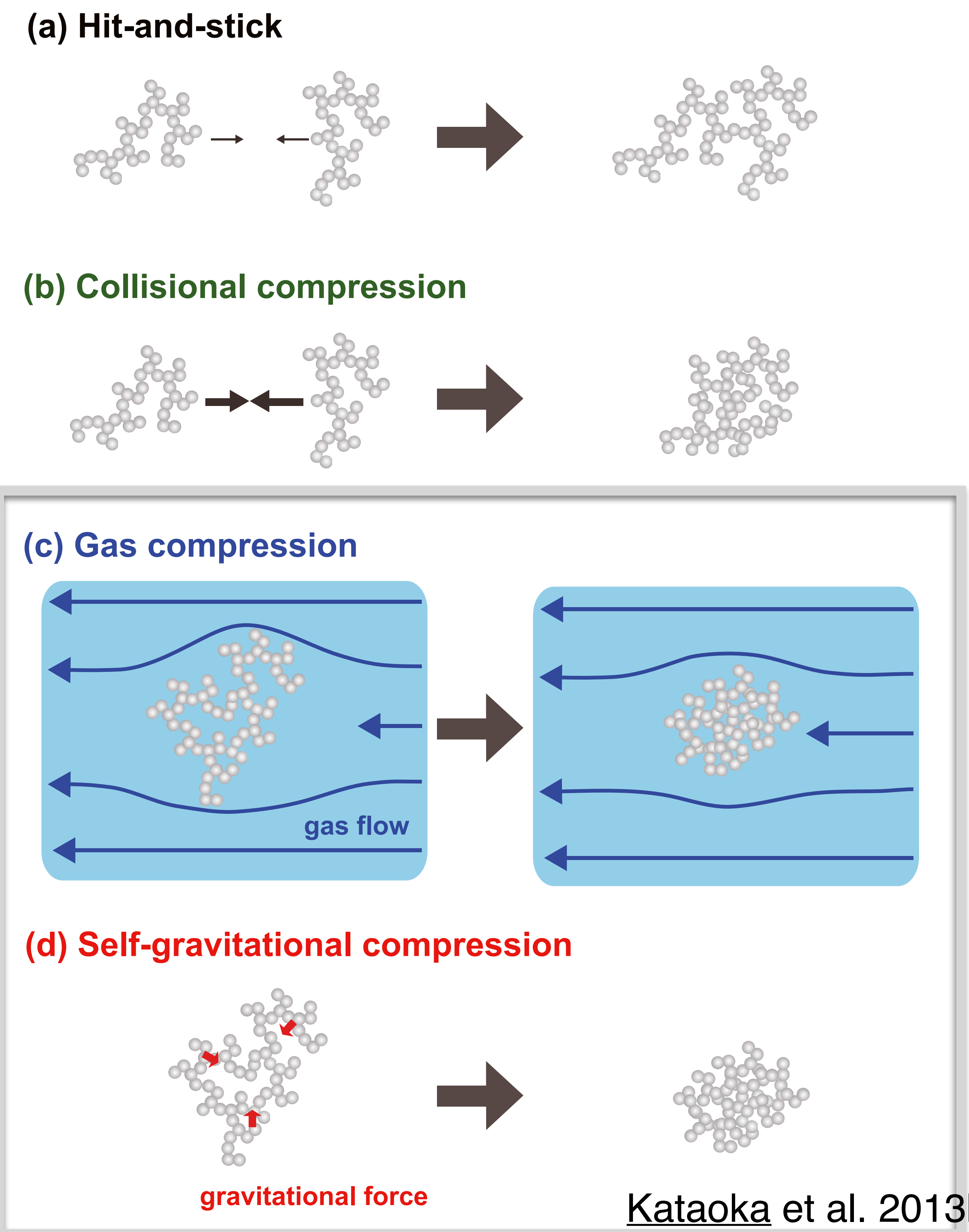
Kataoka et al. 2013b



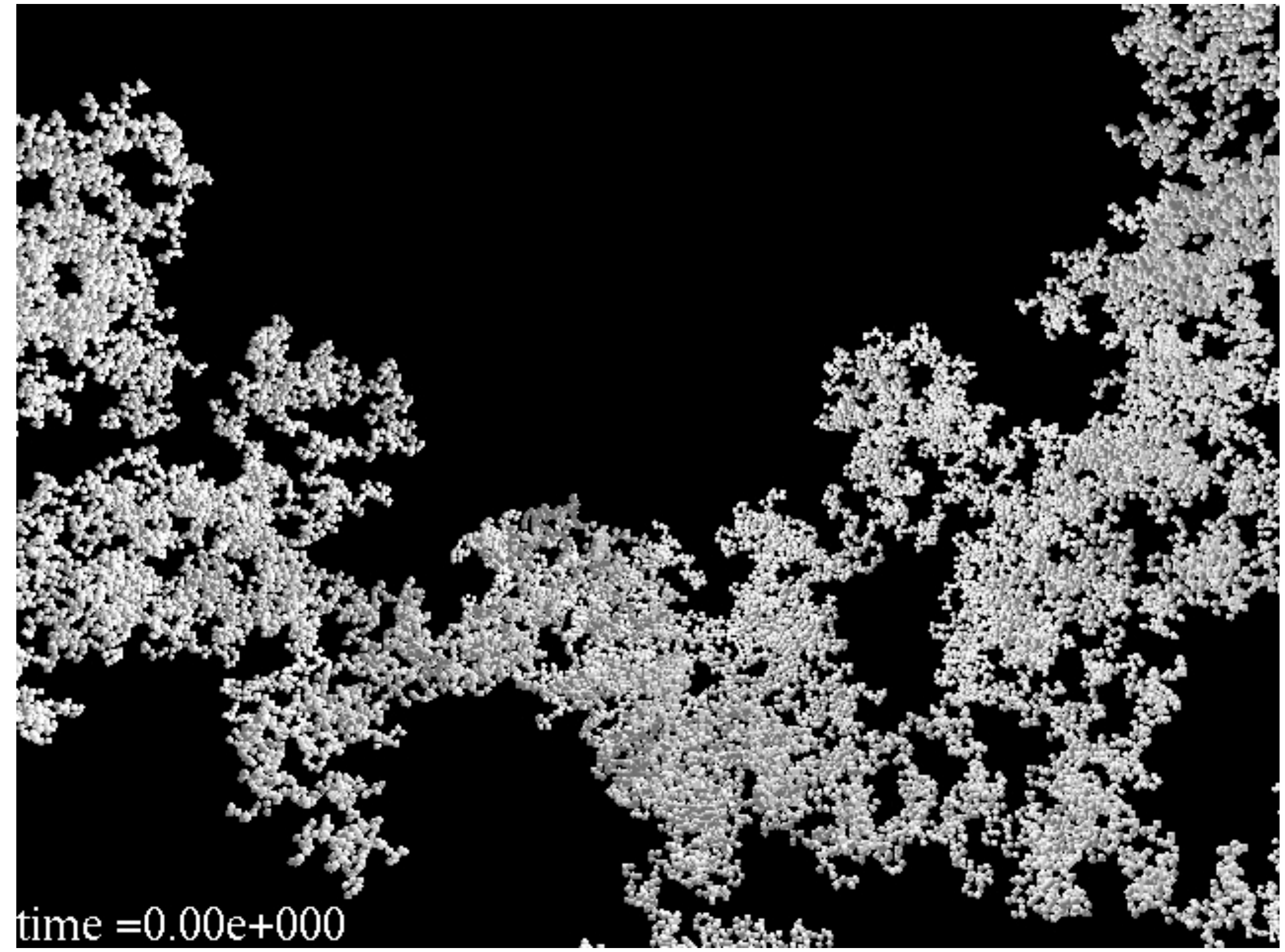
Suyama et al. 2008

Collisional compression : ineffective to make aggregates compact

Structure evolution of dust aggregates



Kataoka et al. 2013b



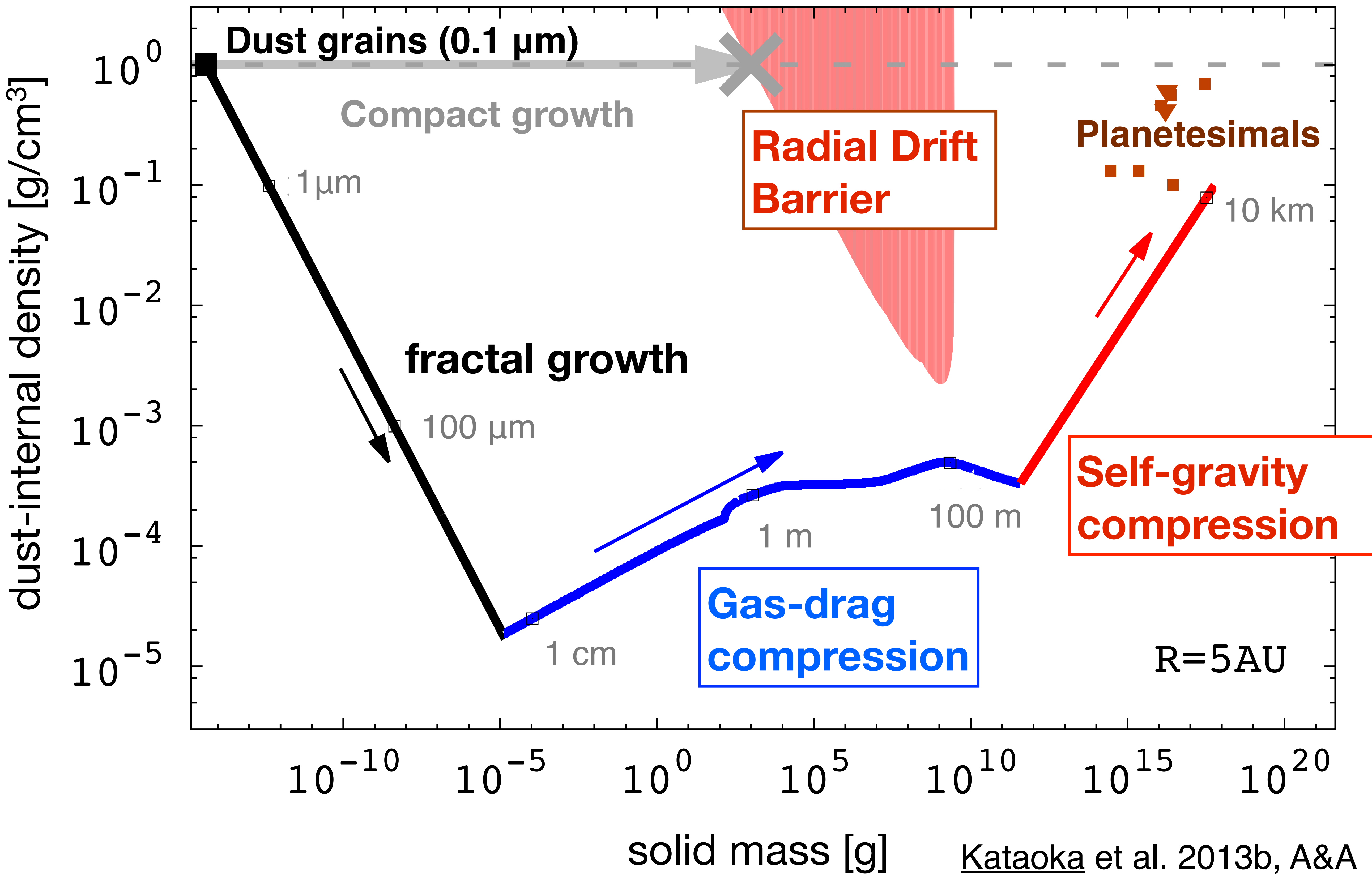
- compressive strength

$$P = \frac{E_{\rm roll}}{r_0^3}\phi^3$$

(Kataoka et al. 2013a, A&A)

- external pressure
  - ram pressure of the gas
  - self-gravity

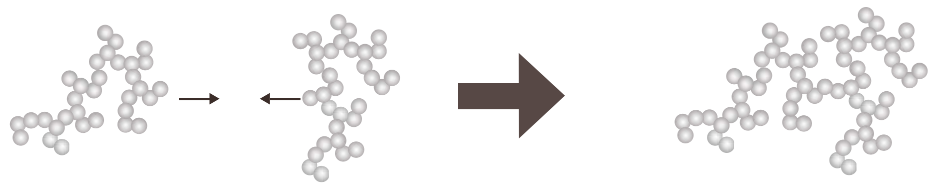
Planetesimal formation via fluffy aggregates



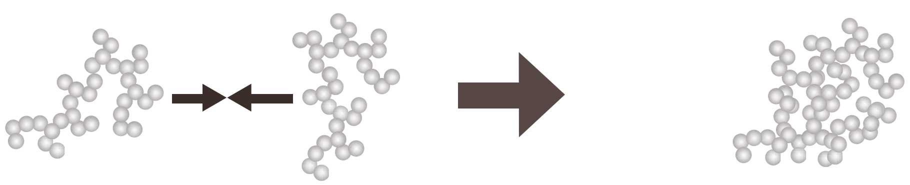
Kataoka et al. 2013b, A&A

Dependence on the orbital radius

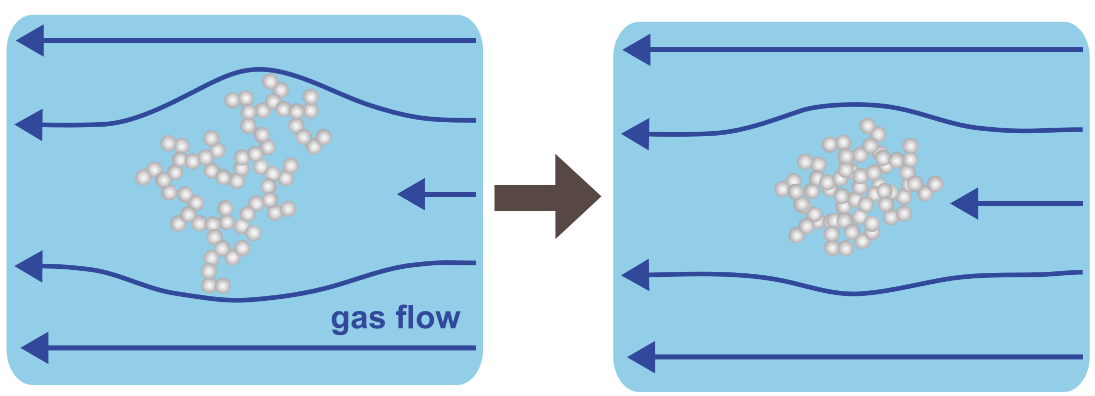
(a) Hit-and-stick



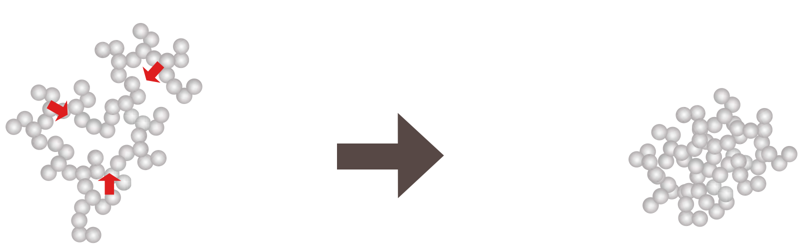
(b) Collisional compression

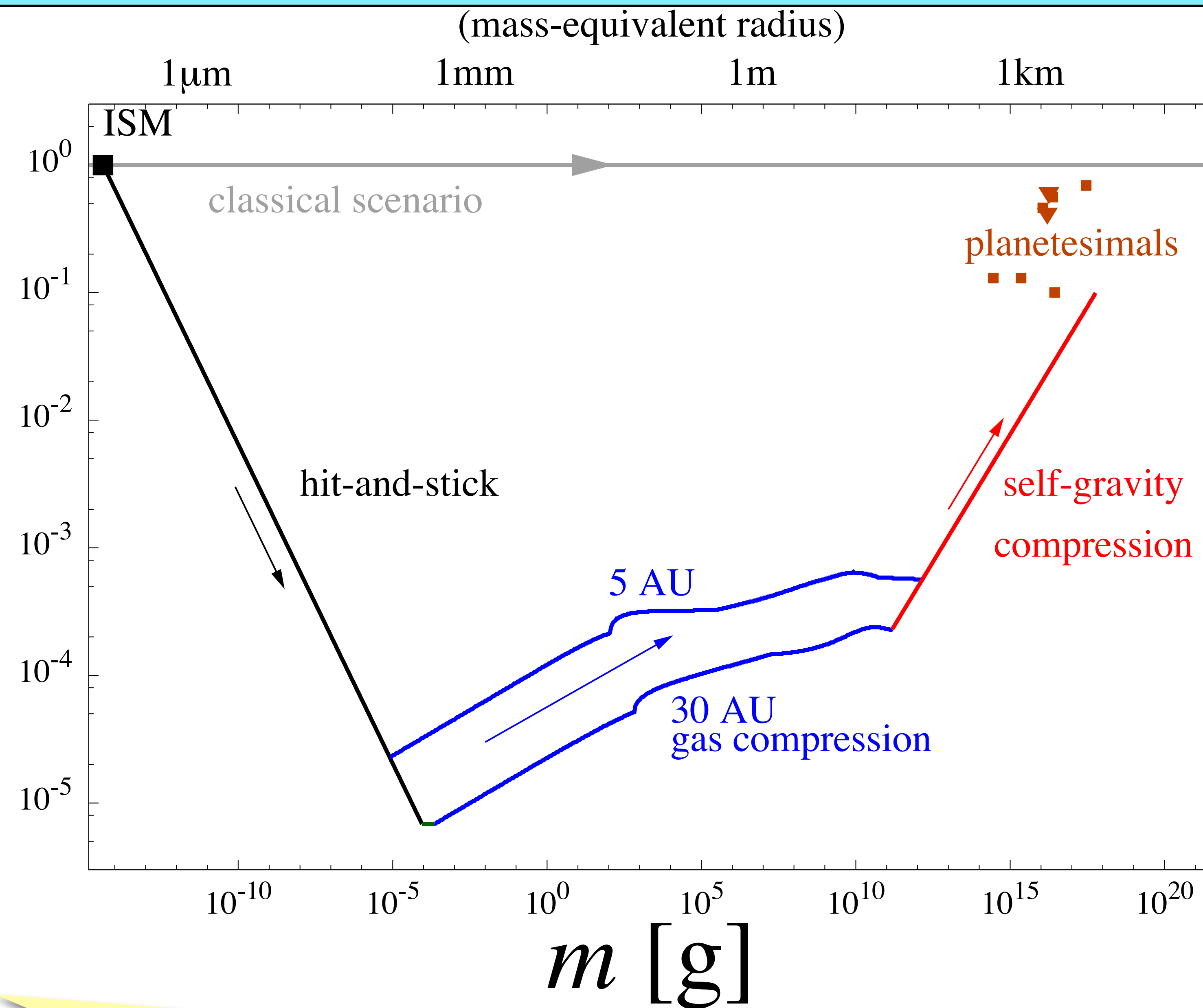


(c) Gas compression



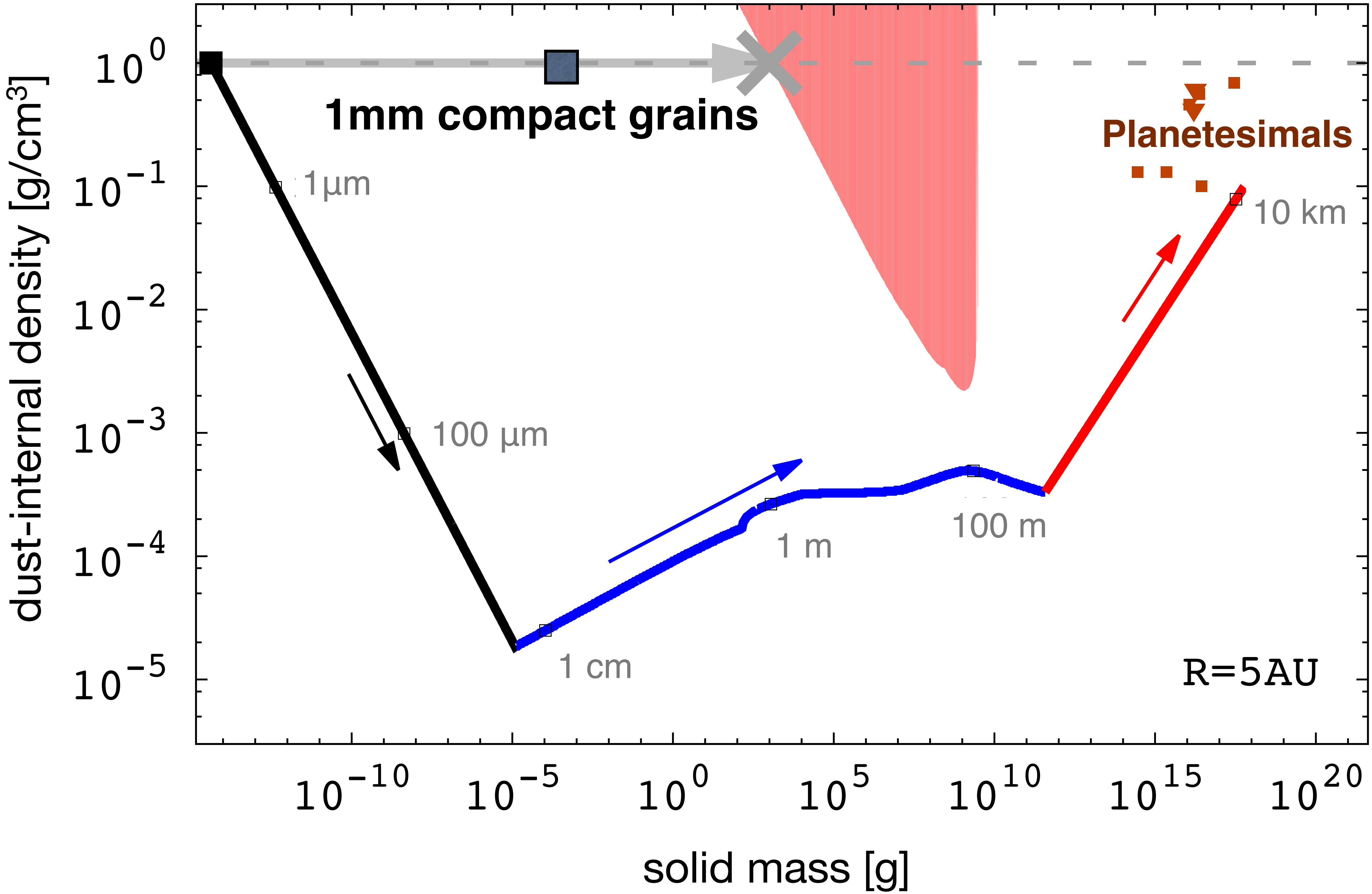
(d) Self-gravitational compression



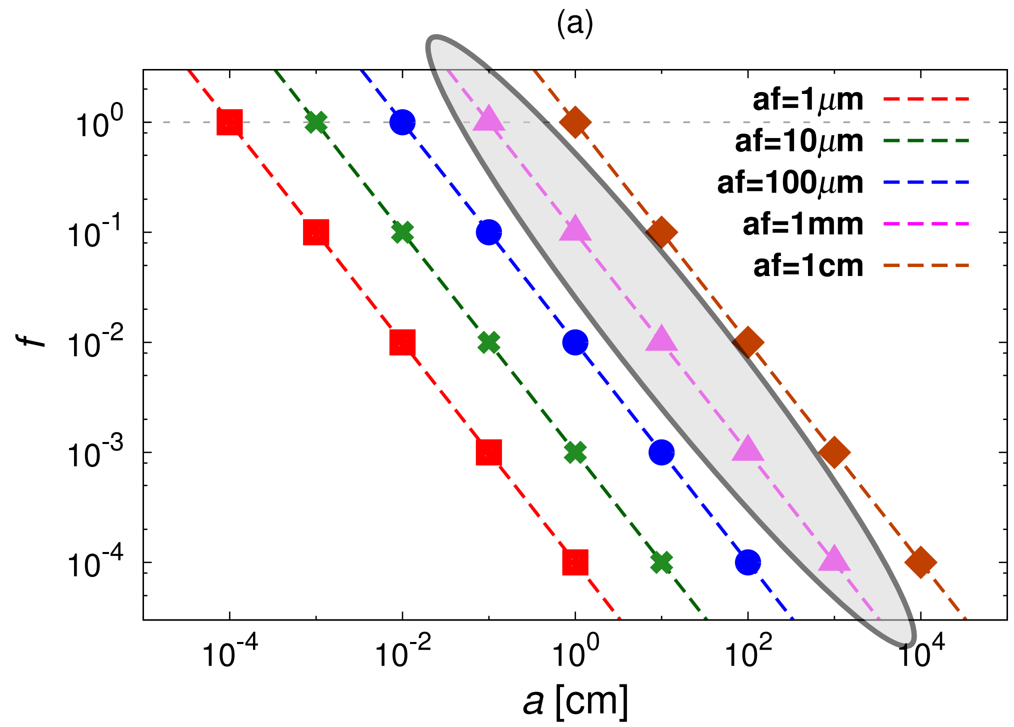


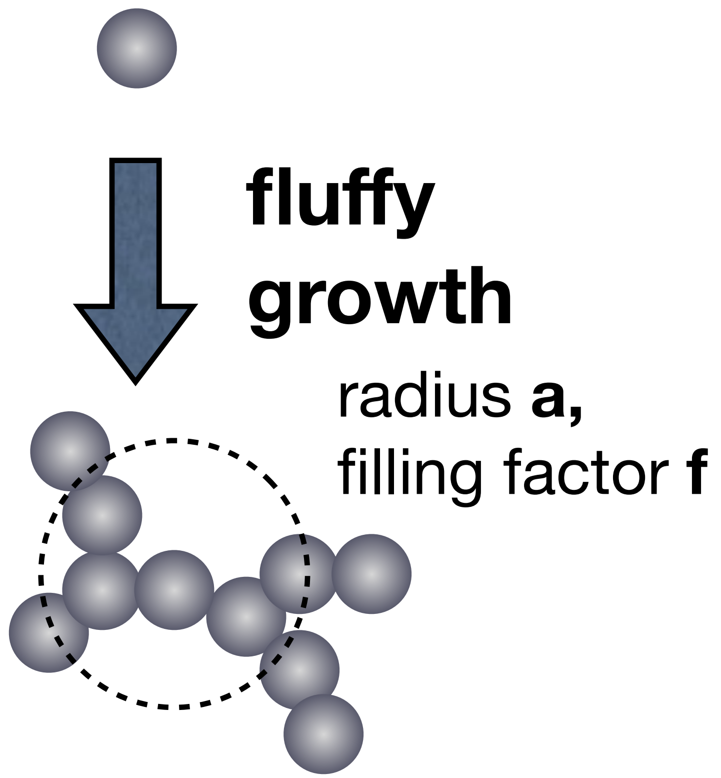
$$\rho_{\rm eq} = \left(\frac{r_0^3}{E_{\rm roll}} P_{\rm gas} \right)^{1/3} \rho_0 .$$

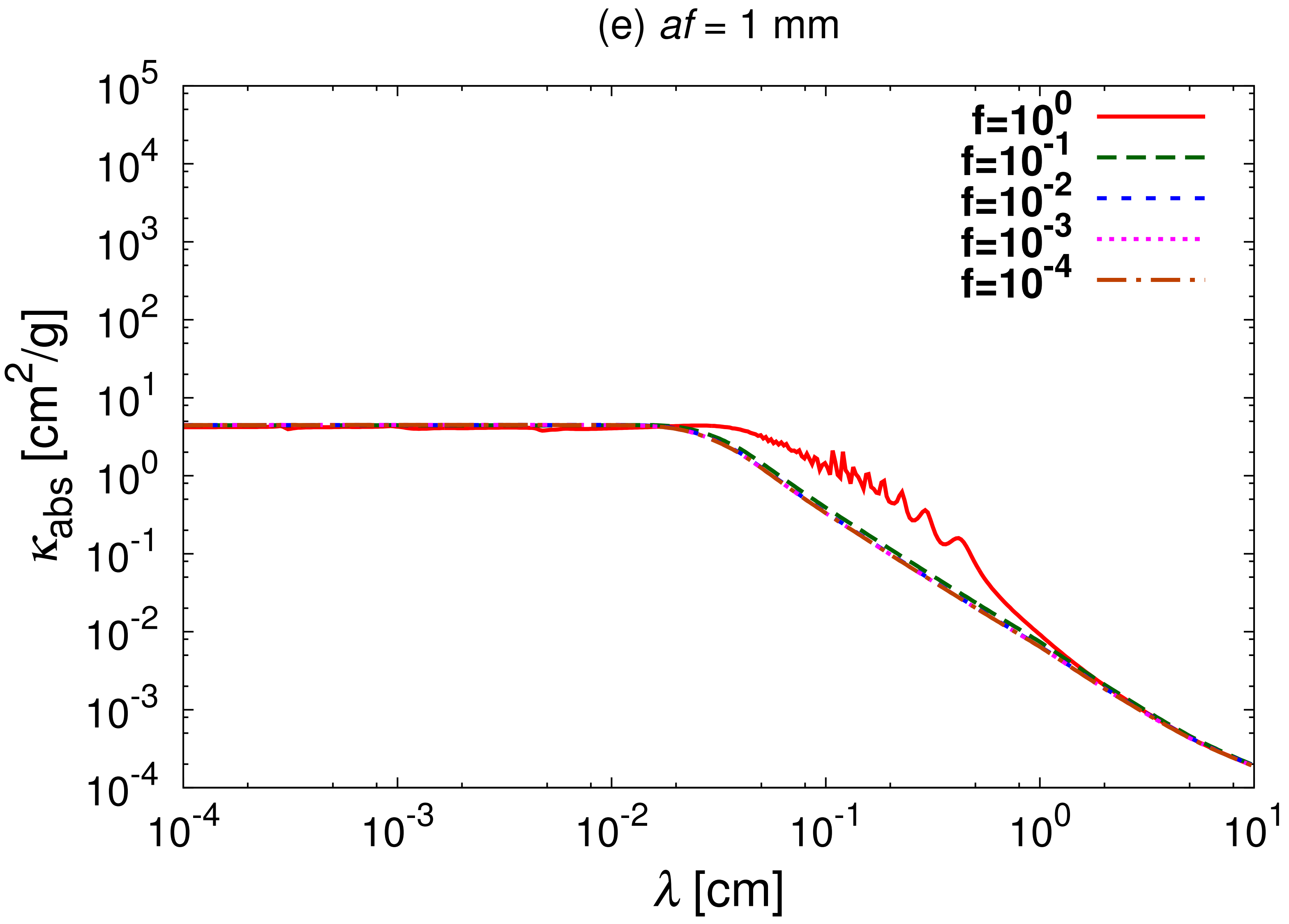
What is the observed "mm-sized grains"?



Opacity evolution







How can we understand porosity?

Stokes number

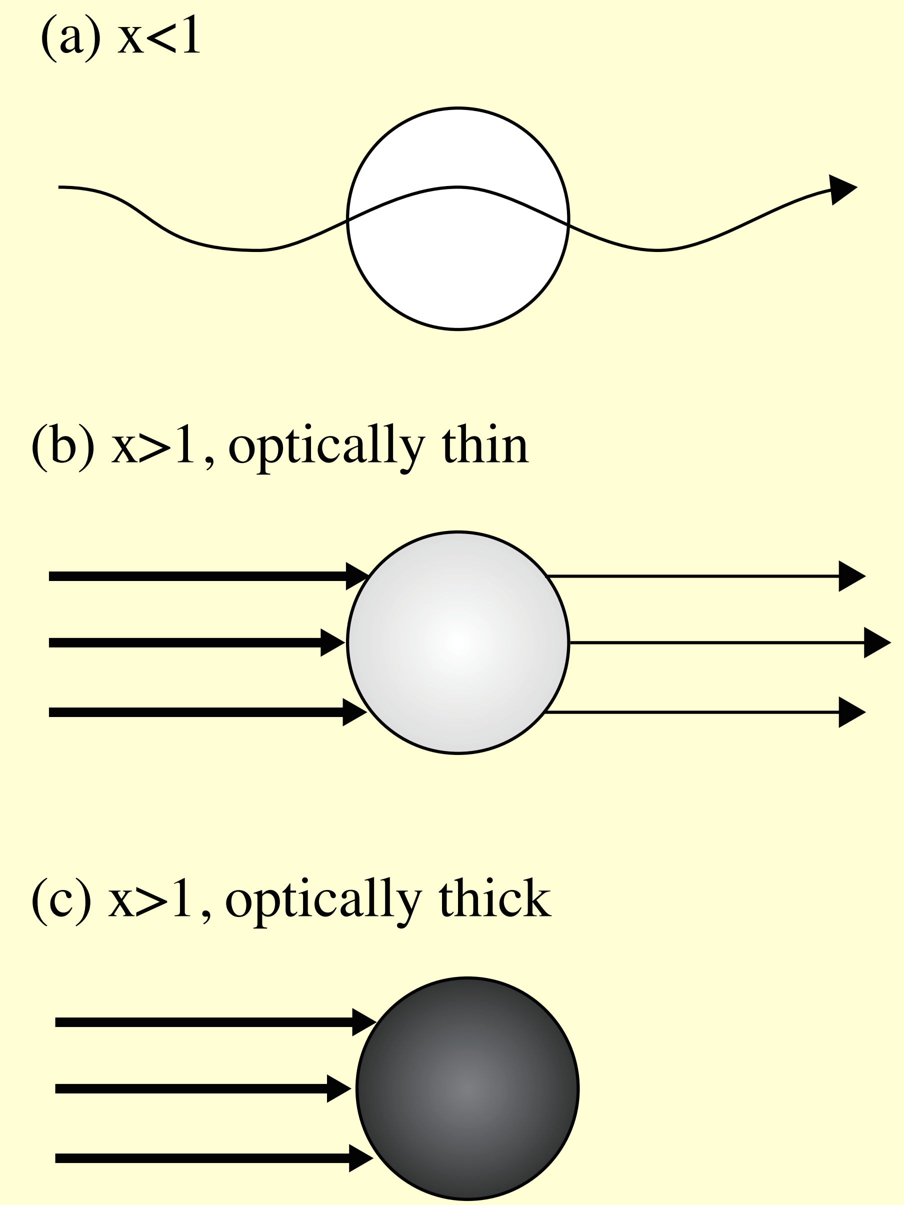
$$\mathrm{St} = \frac{3\Omega}{4\rho_{\mathrm{g}} v_{\mathrm{th}}} \frac{m}{\pi a^2} \quad \text{(Epstein regime)}$$

Opacity

$$\kappa_{\mathrm{abs}} = \frac{\pi a^2}{m} Q_{\mathrm{abs}} = f(m/\pi a^2)$$

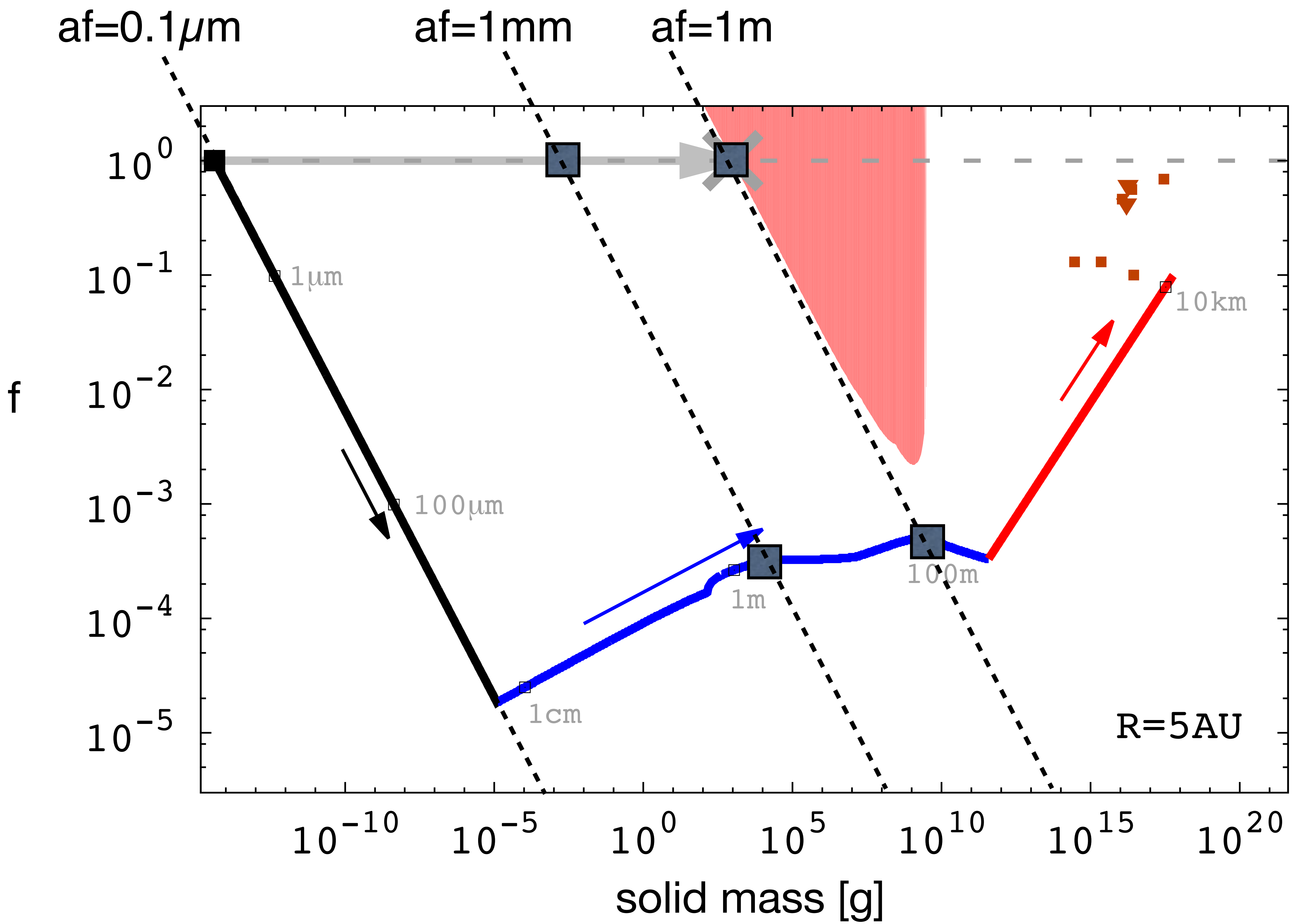
$$\frac{(\mathrm{mass})}{(\mathrm{area})} \sim \frac{a^3 f}{a^2} \sim af$$

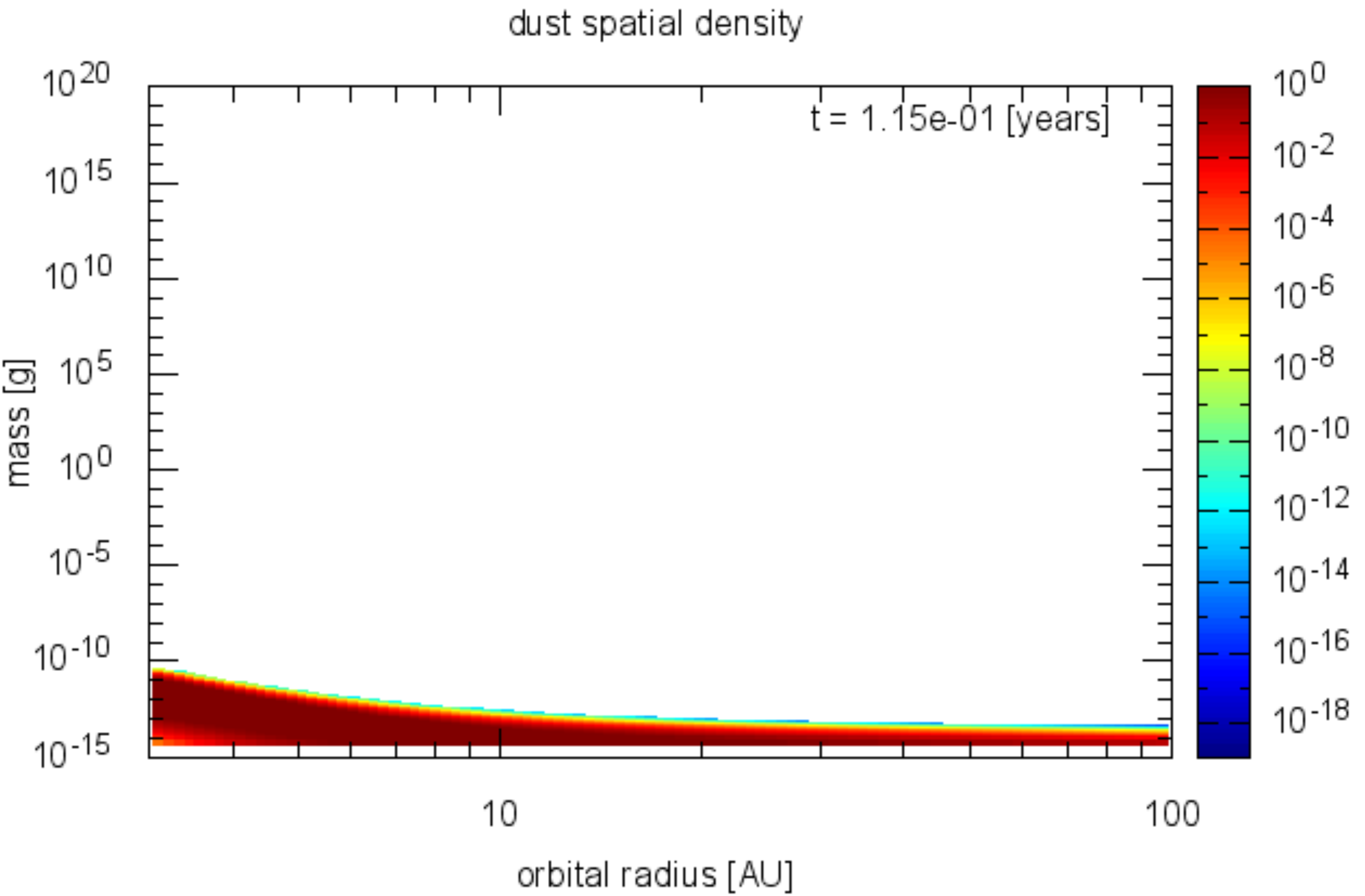
af = const ⇔ mass-to-area ratio = const



(Kataoka et al. 2014)

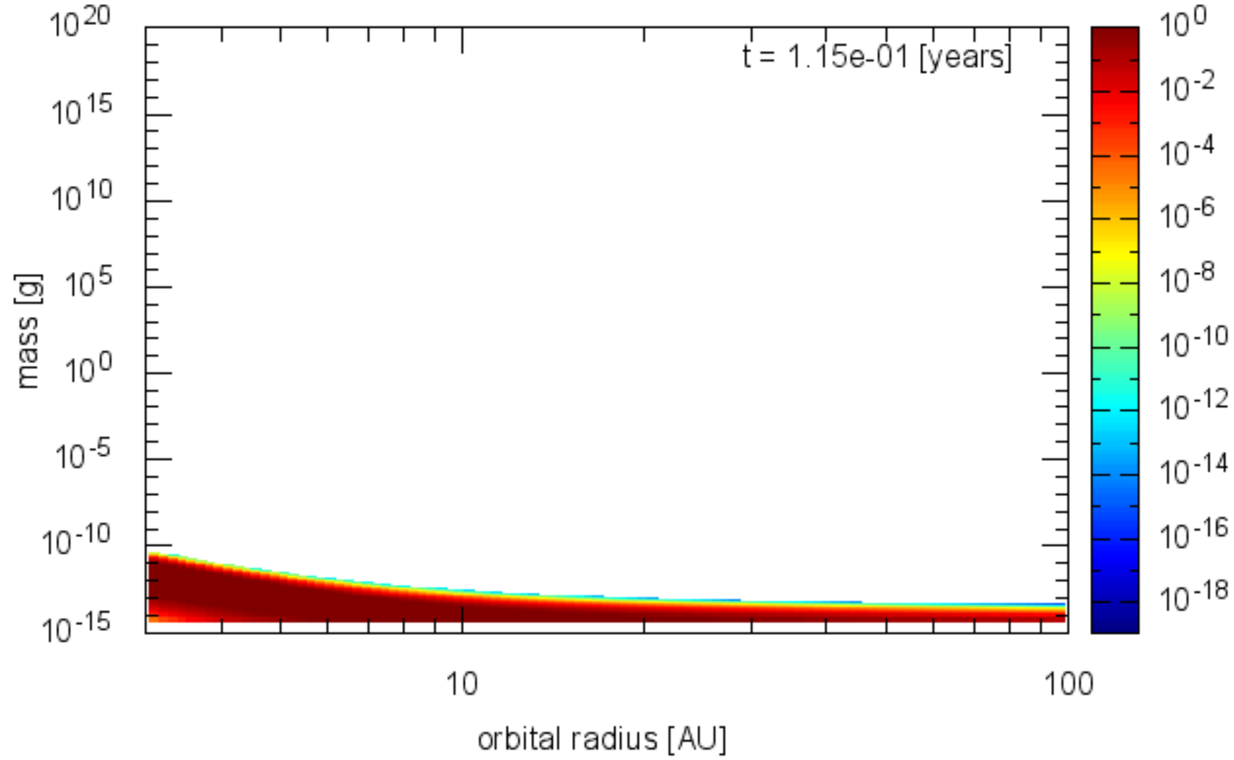
What are "mm-sized grains"?



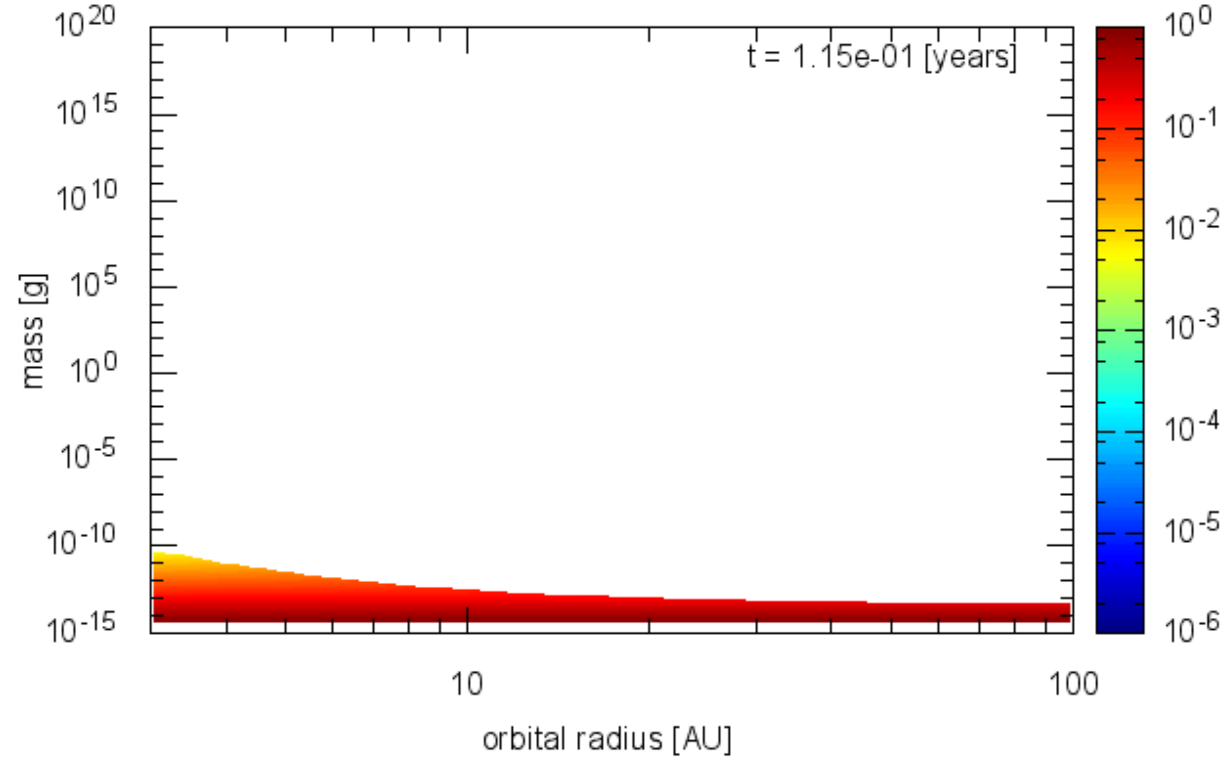


dust spatial density
t = 1.15e-01 [years]
mass [g]
orbital radius [AU]
10
100
10^{20}
10^{15}
10^{10}
10^{5}
10^{0}
10^{-5}
10^{-10}
10^{-15}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}

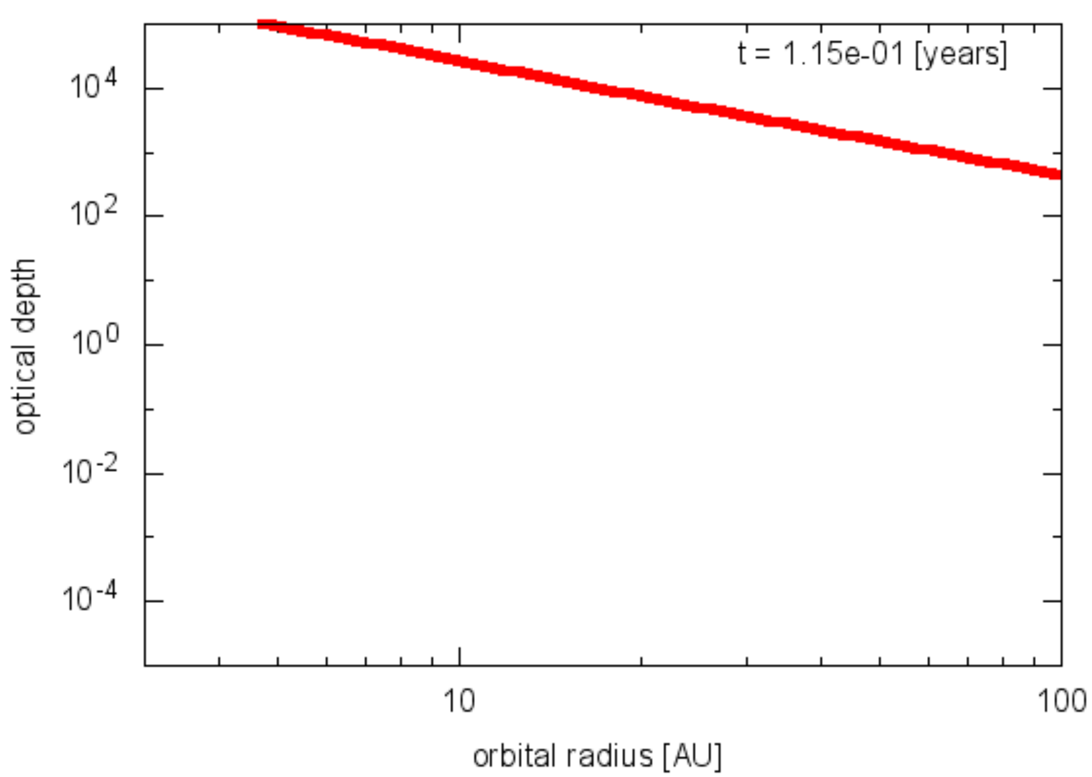
Dust density



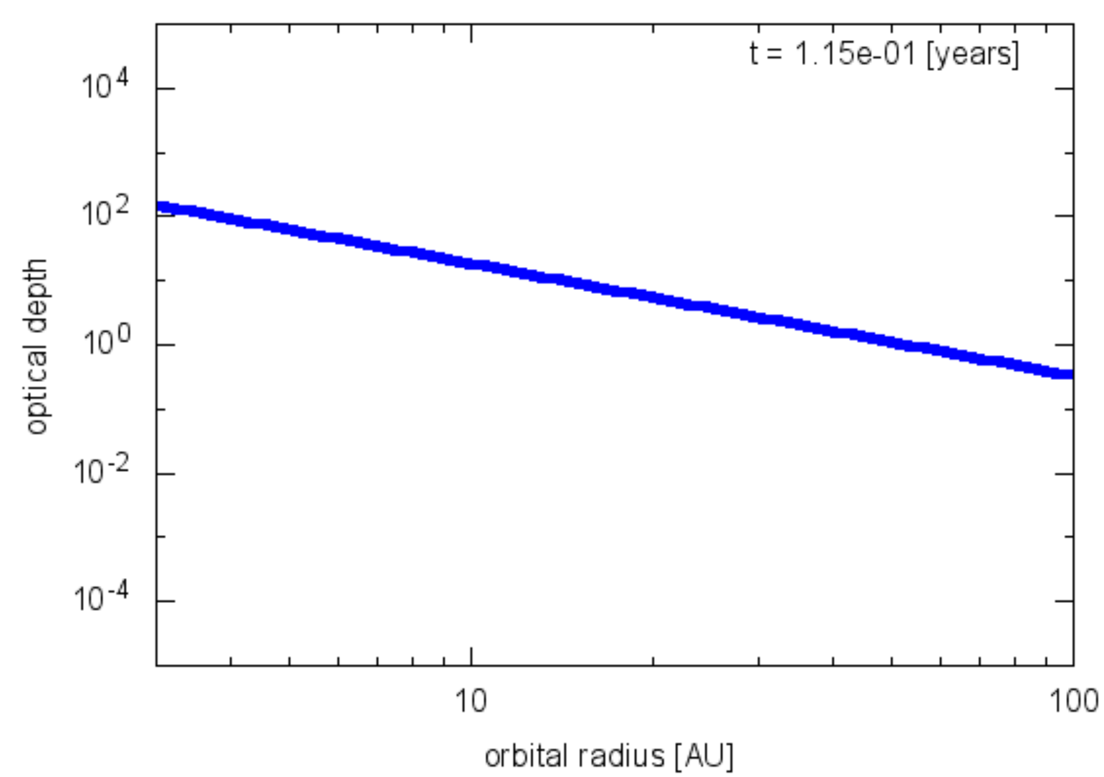
filling factor

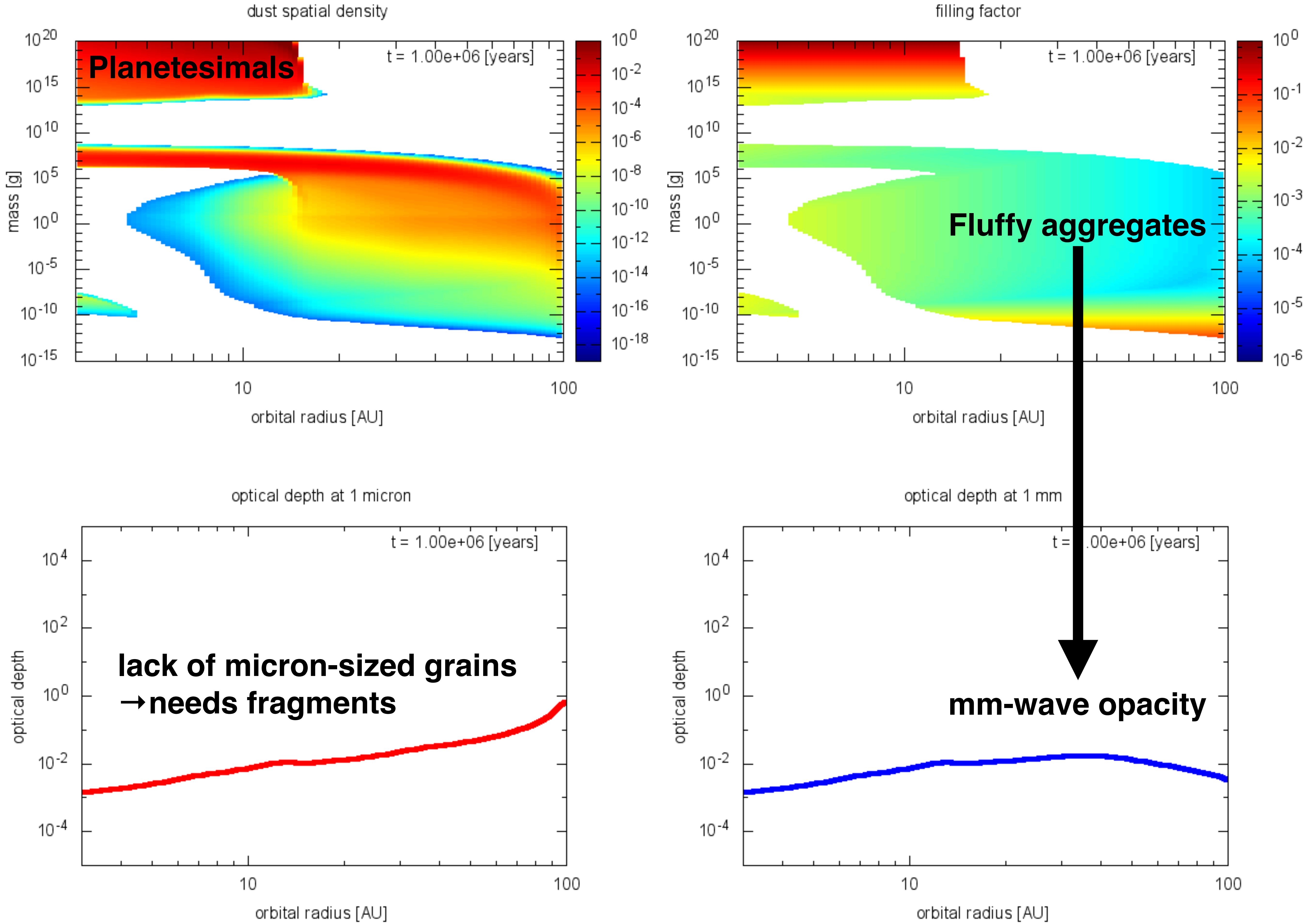


Optical depth at 1 micron



Optical depth at 1 mm




dust spatial density
filling factor
t = 1.00e+06 [years]
Planetesimals
Fluffy aggregates
mass [g]
orbital radius [AU]
optical depth at 1 micron
optical depth at 1 mm
optical depth
lack of micron-sized grains
→needs fragments
mm-wave opacity

Conclusions

- We investigate the the static compressive strength of highly porous aggregates (f<0.1)
  - we reveal the overall porosity evolution
  - the path avoids the three barriers: radial drift, fragmentation, and bouncing barriers

(Kataoka et al. 2013a, A&A, 554, A4, Kataoka et al. 2013b, A&A, 557, L4)

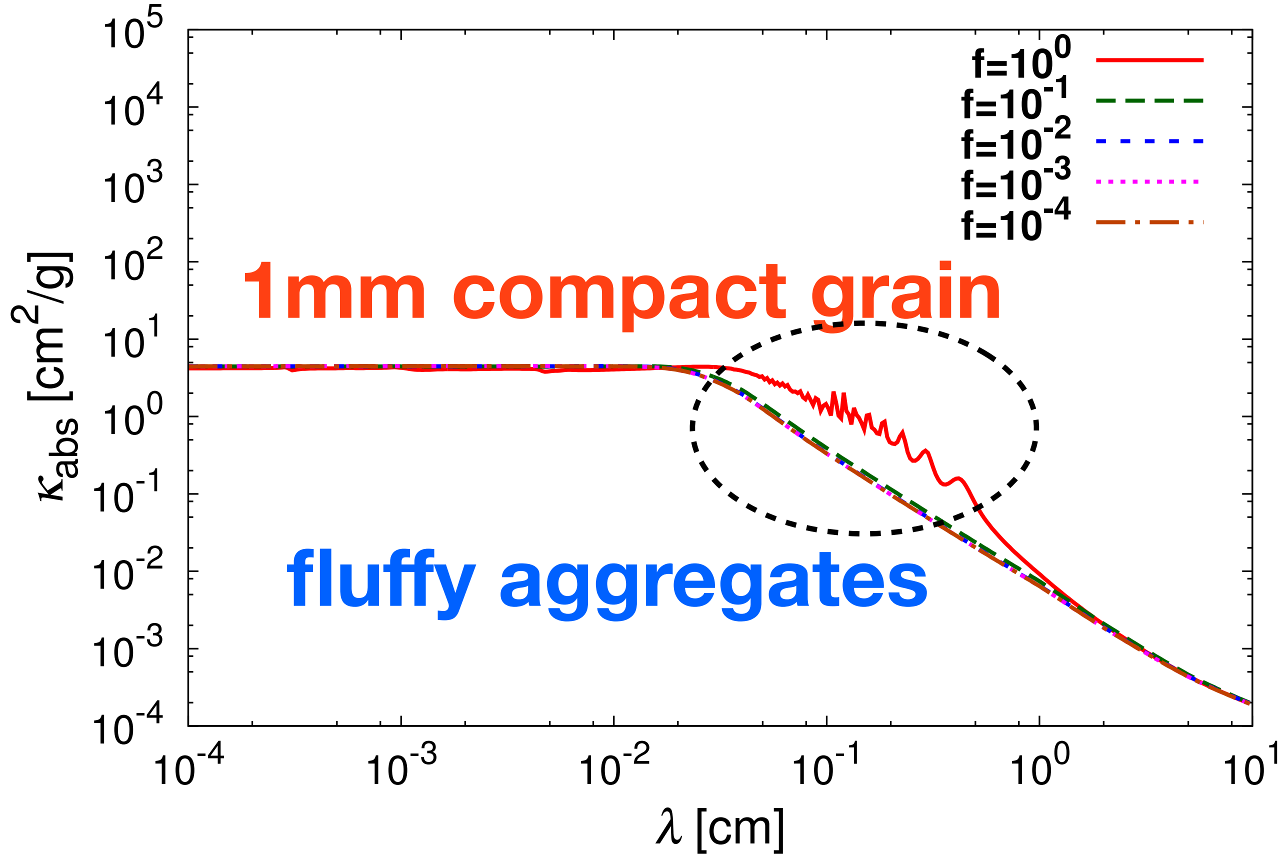
- Opacities are characterized by *af*

(Kataoka et al., 2014, A&A, 568, A42)

- Planetesimals are formed inside ~ 10 AU
- Fluffiness does not help for the radial drift barrier in outer disk.

How to observe fluffy aggregates?

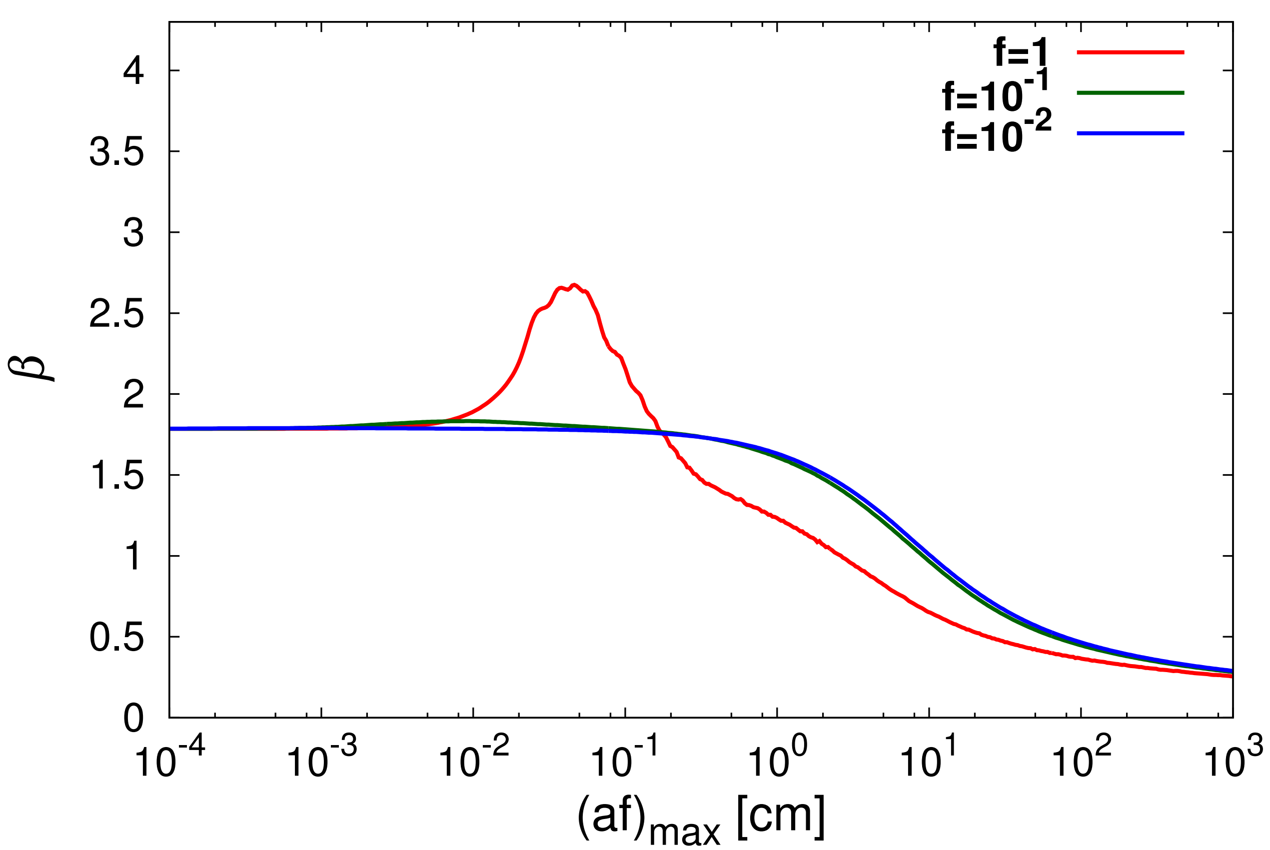
a×f = 1mm



a: radius

f: filling factor

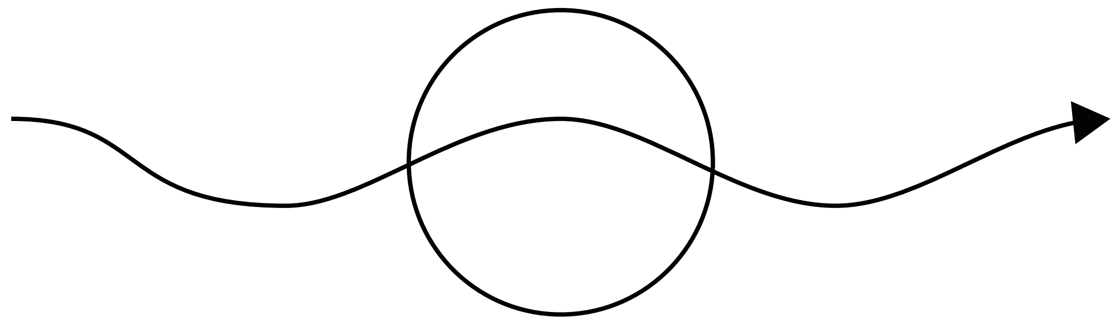
Opacity index β



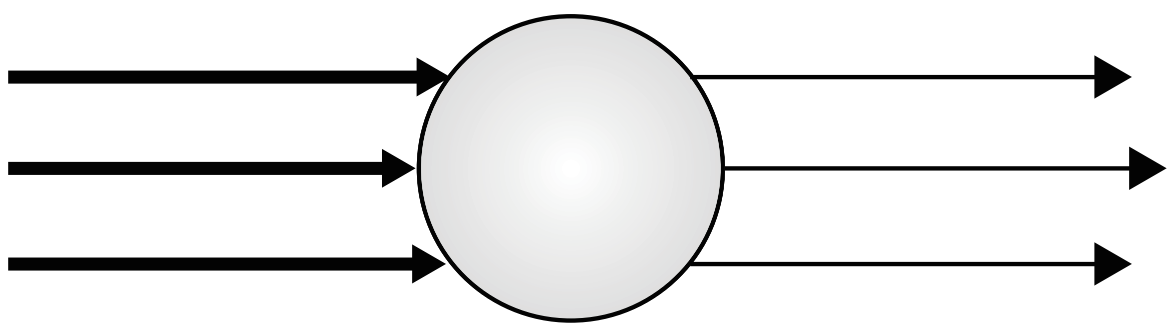
β>1.7 only when grains are compact

Understanding opacity

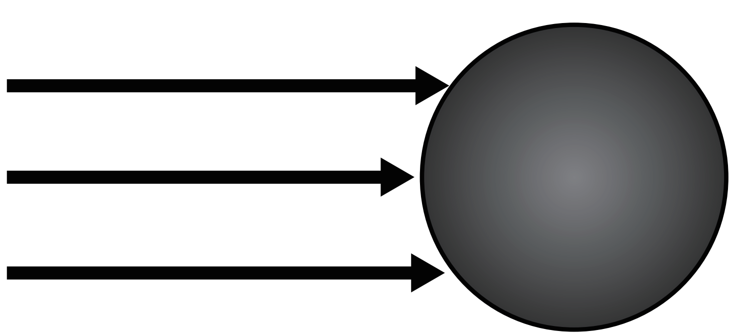
(a) x<1



(b) x>1, optically thin



(c) x>1, optically thick



absorption/scattering opacity

$$\kappa_{\rm abs} = \frac{\pi a^2}{m} Q_{\rm abs},$$

$$\kappa_{\rm sca} = \frac{\pi a^2}{m} Q_{\rm sca}.$$

(m : grain mass)

→Q_{abs}, Q_{sca} is calculated with Mie theory

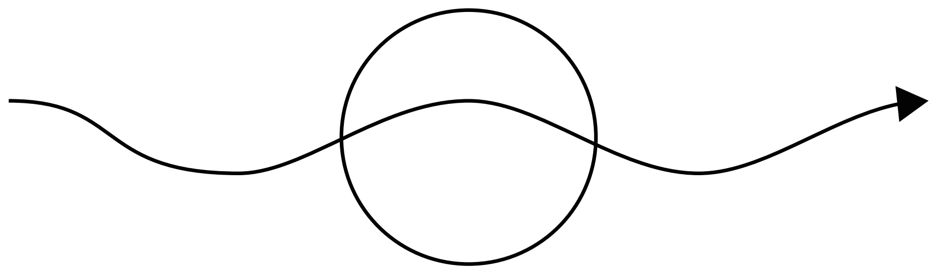
Useful parameters

- size parameter $x \equiv \frac{2\pi a}{\lambda}$
- optical depth kx

-> derive the approximated equations

Understanding opacity : absorption

(a) x<1



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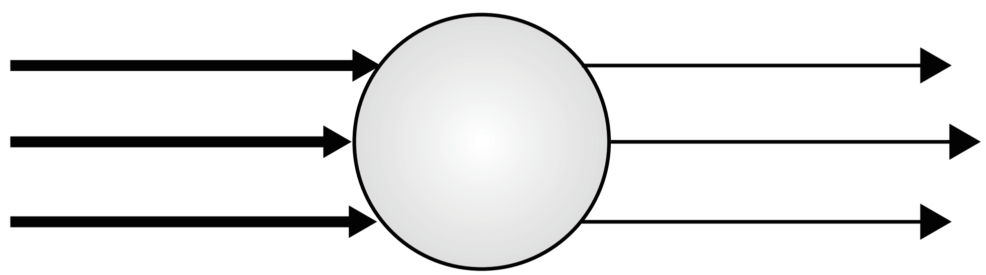

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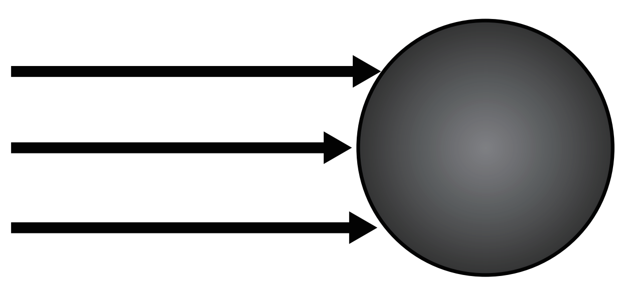


(a) $x \ll 1$ →Rayleigh regime

if $n-1 \ll 1$, $k \ll 1$

$$Q_{\rm abs} \simeq Q_{\rm abs,1} \equiv \frac{24nkx}{(n^2+2)^2}.$$

if $f \ll 1$, $n-1 \propto f$, $k \propto f$, thus

$$Q_{\rm abs,1} \propto af \ \text{ for f} \ll 1$$

(b) $x \gg 1$ & $kx \ll 1$

$$Q_{\rm abs} \simeq Q_{\rm abs,2} \equiv \frac{8kx}{3n}\left(n^3 - (n^2-1)^{3/2}\right)$$

$$Q_{\rm abs,2} \propto af \ \text{ for f} \ll 1$$

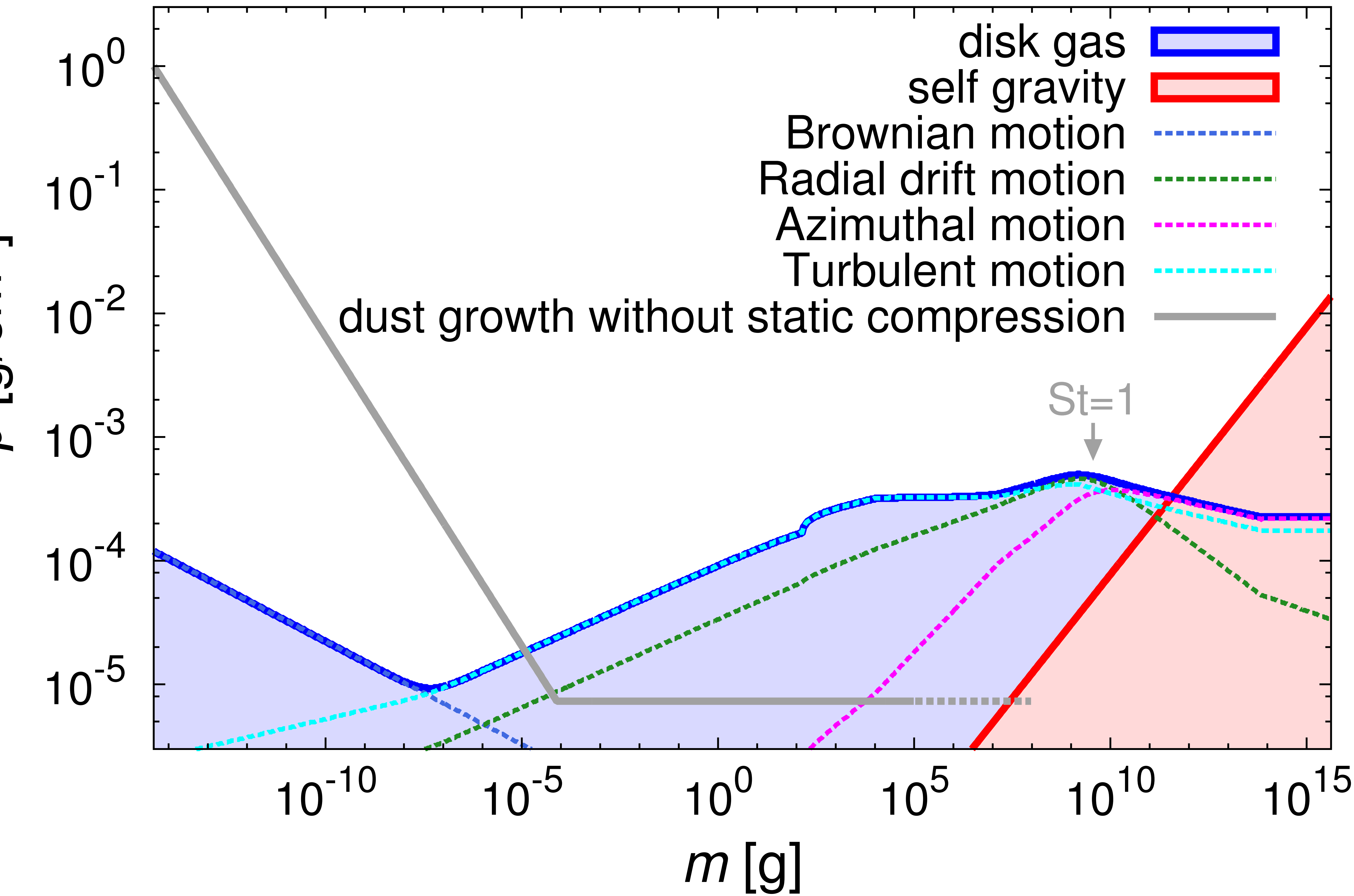
(c) $x \gg 1$ & $kx \gg 1$ → geometric regime

$$Q_{\rm abs} \simeq Q_{\rm abs,3} \equiv \int_0^{\pi/2} (1 - R(\theta_i)) \sin 2\theta_i d\theta_i,$$

$$\approx 1 \ \text{ for f} \ll 1$$

1. $\kappa_{\rm abs}$ is proportional to af

2. we derive the piecewise formula of abs. opacity


disk gas
self gravity
Brownian motion
Radial drift motion
Azimuthal motion
Turbulent motion
dust growth without static compression
St=1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-10}
10^{-5}
10^0
10^5
10^{10}
10^{15}
m [g]