

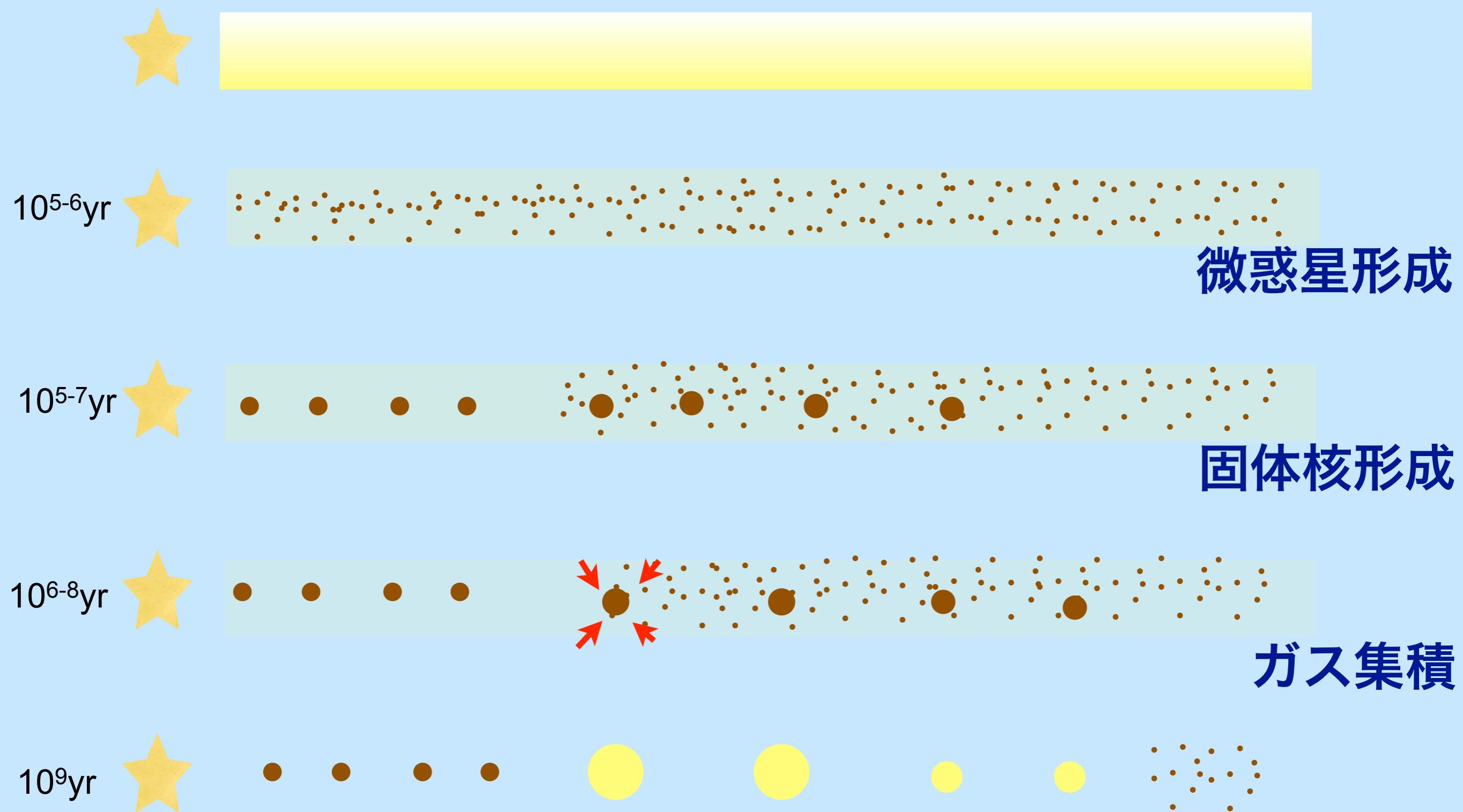
# 巨大ガス惑星の形成

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## 内容

- ・惑星系生成標準モデル
- ・微惑星形成
- ・ガス惑星の固体核の形成
- ・ガス集積
- ・その他

# 惑星系形成標準モデル



# 林モデル円盤

ガス面密度

$$\Sigma_g = 1.7 \times 10^3 \left( \frac{r}{1 \text{AU}} \right)^{-3/2} \text{g/cm}^2$$

固体面密度

$$\Sigma_s = \begin{cases} 7.1 \left( \frac{r}{1 \text{AU}} \right)^{-3/2} \text{g/cm}^2 & (r < 2.7 \text{AU}) \\ 30 \left( \frac{r}{1 \text{AU}} \right)^{-3/2} \text{g/cm}^2 & (r > 2.7 \text{AU}) \end{cases}$$

温度

$$T = 280 \left( \frac{r}{1 \text{AU}} \right)^{-1/2} \text{K}$$

スケールハイト

$$h = 4.7 \times 10^{-2} \left( \frac{r}{1 \text{AU}} \right)^{5/4} \text{AU}$$

# 微惑星形成

# ガスの公転速度

- ・ 動径方向の力の釣り合い

$$r\Omega_g^2 = r\Omega_K^2 + \frac{1}{\rho} \frac{dP}{dr}$$

- ・ 公転速度差

$$\Omega_g = \Omega_K(1 - 2\eta)^{1/2} \simeq \Omega_K(1 - \eta)$$

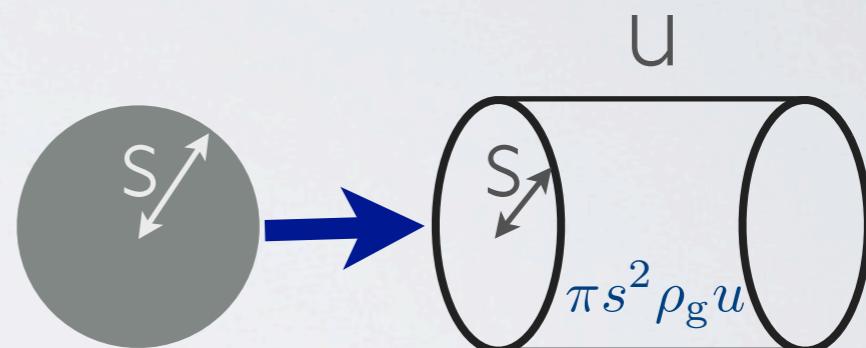
$$\eta = -\frac{1}{2} \left( \frac{c_s}{r\Omega_K} \right)^2 \frac{d \ln P}{d \ln r}$$

# ガス抵抗

(Adachi et al. 1976; Weidenschilling 1977)

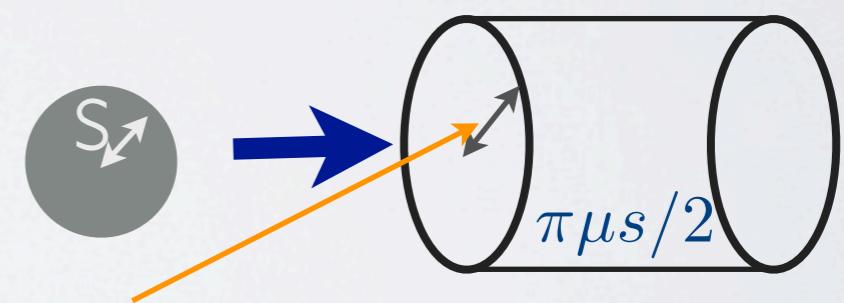
- レイノルズ数が高い場合( $Re = 2 \rho_g u s / \mu > 10^3$ )

$$f_D = 0.25\pi s^2 \rho_g u^2$$



- ストークス則(クヌーセン数  $K = l / s < 1$ かつ  $Re < 10$ )

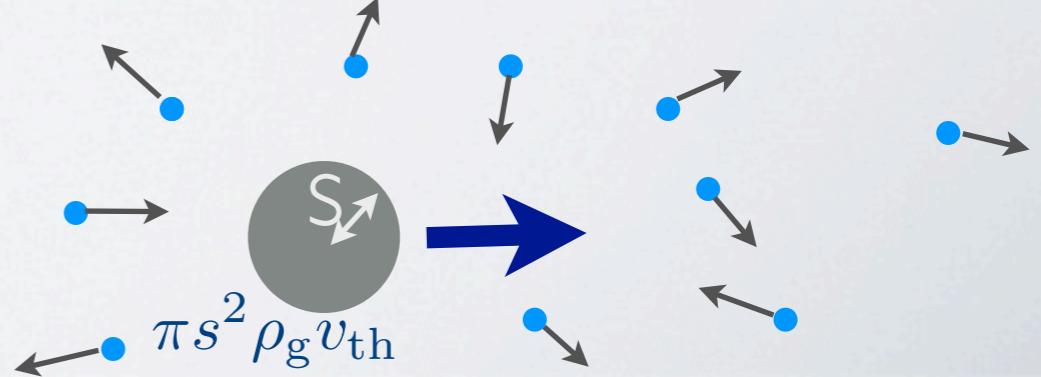
$$f_D = 6\pi\mu s u$$



- エプシュタイン則 ( $K > 1$ )

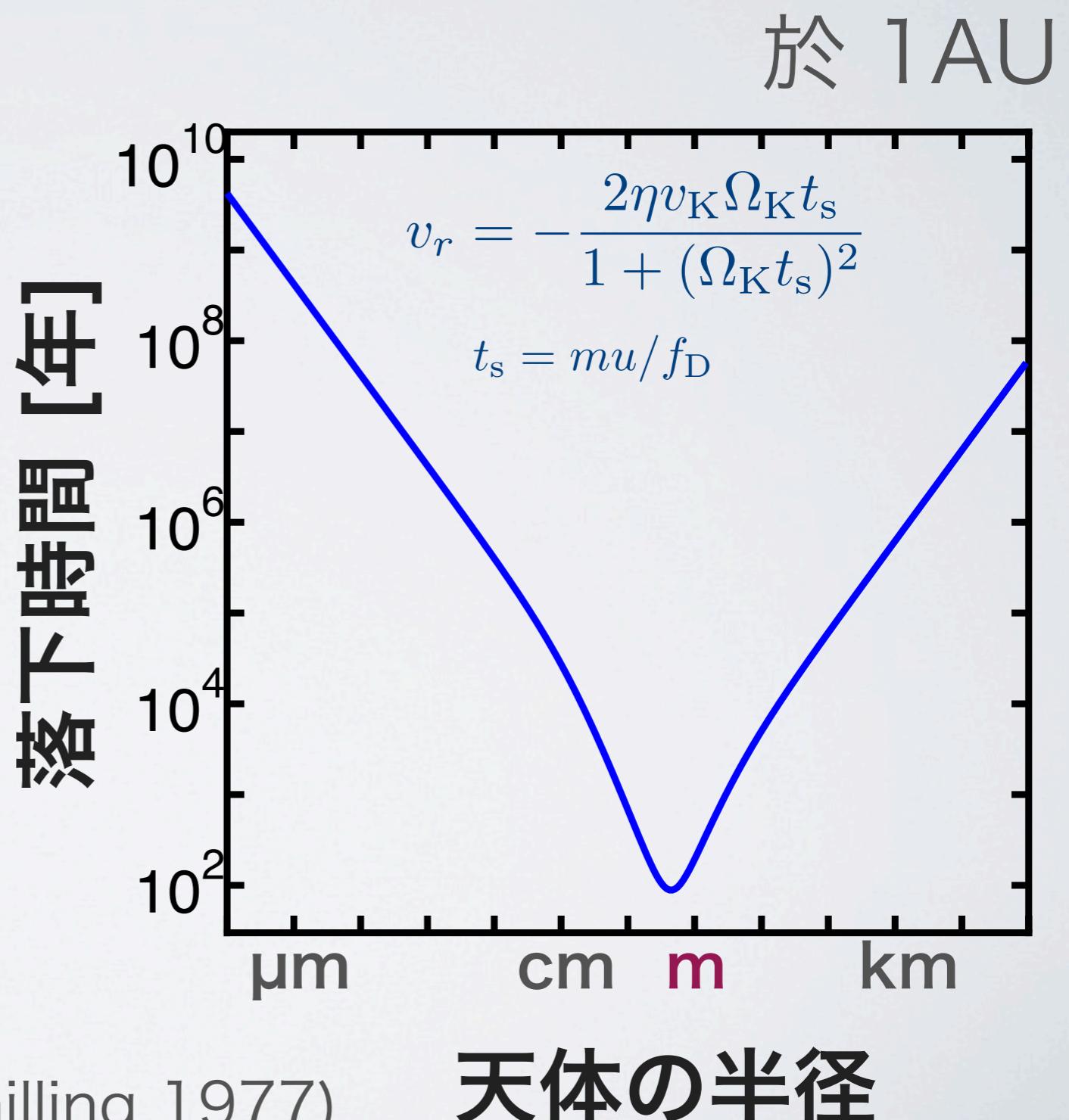
$$f_D = (4\pi/3)s^2 \rho_g v_{th} u$$

粘性境界層の厚さ  $\sim s/Re^{1/2} = (\mu s / 2 \rho_g u)^{1/2}$



# 落下時間

- 原始惑星系円盤中ではガス成分は圧力勾配のためケプラー速度よりも遅く公転している。
- 天体はガスの向かい風を受けて角運動量を失い落下する。
- 1 m程度の天体は100年程度で中心星に落下する。



# 成長時間と落下時間

成長率

$$\frac{dm}{dt} = \frac{\Sigma_s}{2h_d} \pi s^2 \delta v$$

ダストスケールハイト

$$h_d = h_g \left( 1 + \frac{\Omega_K t_s}{\alpha} \frac{1 + 2\Omega_K t_s}{1 + \Omega_K t_s} \right)^{-1/2}$$

成長時間

$$t_g = \frac{m}{\dot{m}} = \frac{4\pi\rho_s s}{3\Sigma_s} \frac{2h_d}{\delta v}$$

落下時間

$$t_d = \frac{r}{|v_r|} = \frac{1 + (\Omega_K t_s)^2}{2\eta\Omega_K^2 t_s}$$

$\Omega_K t_s = 1$  のとき

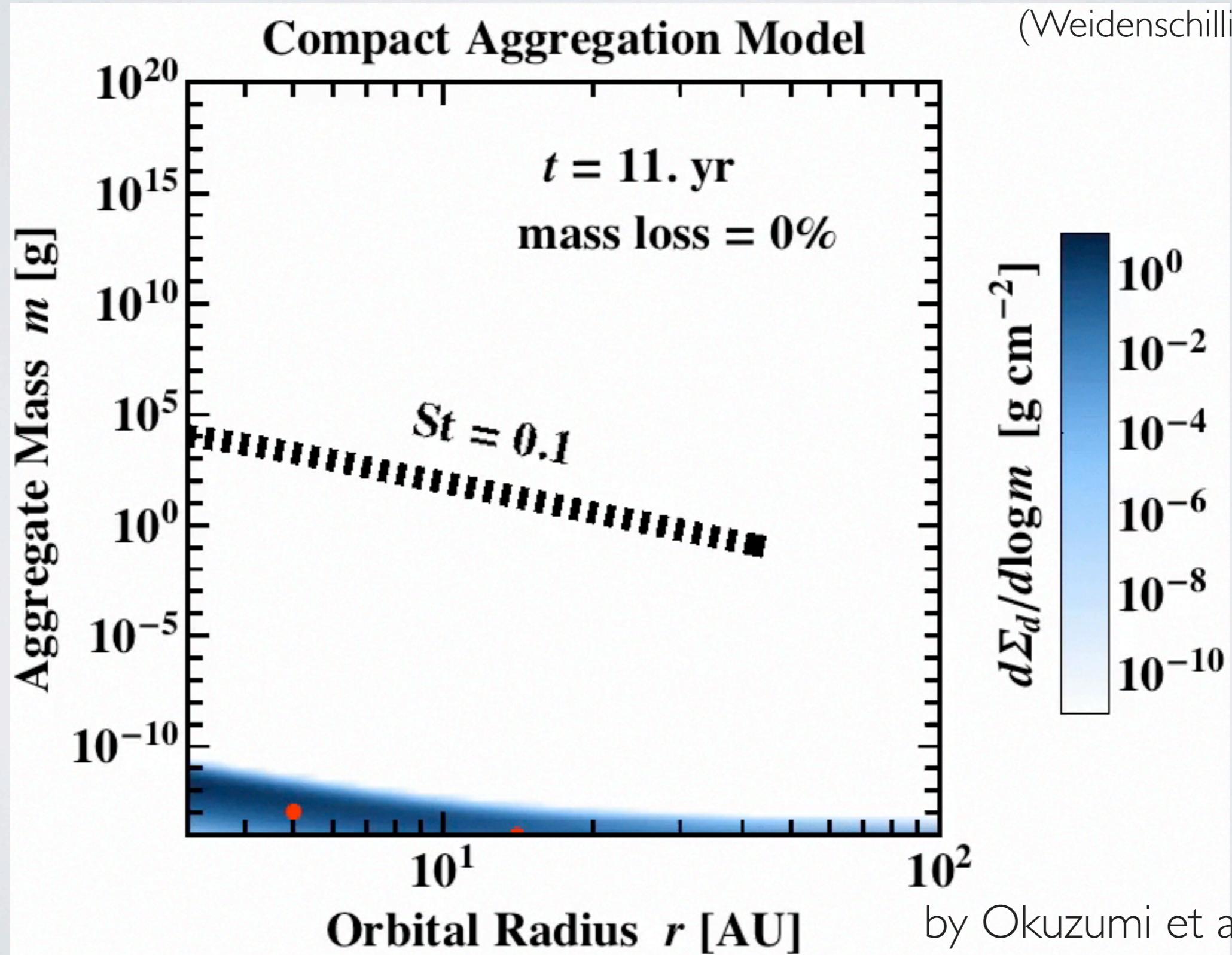
$$\delta v \approx \sqrt{\alpha} c_s \quad h_d \approx \sqrt{\alpha} c_s / \Omega_K$$

$$\frac{t_g}{t_d} \approx \frac{8\pi}{3} \eta \frac{s\rho_s}{\Sigma_s} \approx 0.6 \left( \frac{\Sigma_{s,1\text{AU}}}{7.1\text{g/cm}^2} \right)^{-1} \left( \frac{s\rho_s}{300\text{g/cm}^2} \right) \left( \frac{r}{1\text{AU}} \right)^2$$

# 落下バリア

Compact Aggregation Model

(Weidenschilling 1980)

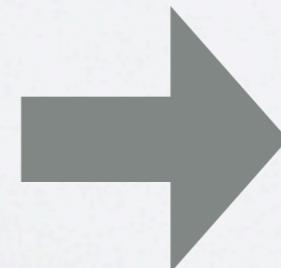


# 相対速度

$$\delta v = \sqrt{v_B^2 + \delta v_r^2 + \delta v_\phi^2 + \delta v_z^2 + v_{\text{turb}}^2}$$

$$v_B = \sqrt{\frac{\pi m_1 m_2}{8(m_1 + m_2) k_B T}}$$

$$\begin{aligned}\frac{dv_r}{dt} - \frac{v_\phi^2}{r} &= -\Omega_K^2 r - \frac{v_r}{t_s} \\ \frac{dv_\phi}{dt} + \frac{v_r v_\phi}{r} &= -\frac{(v_\phi - r\Omega_g)}{t_s} \\ \frac{dv_z}{dt} &= -\Omega_K^2 z - \frac{v_z}{t_s}\end{aligned}$$



(Adachi et al. 1976; Nakagawa et al. 1981)

$$\frac{dv_{\text{turb}}^2}{dt} = \left( \frac{\sqrt{\alpha} c_s}{t_s \Omega_K} \right)^2 \Omega_K$$

1公転中の乱流によるキック

$$\frac{dv_{\text{turb}}^2}{dt} = -\frac{2v_{\text{turb}}^2}{t_s}$$

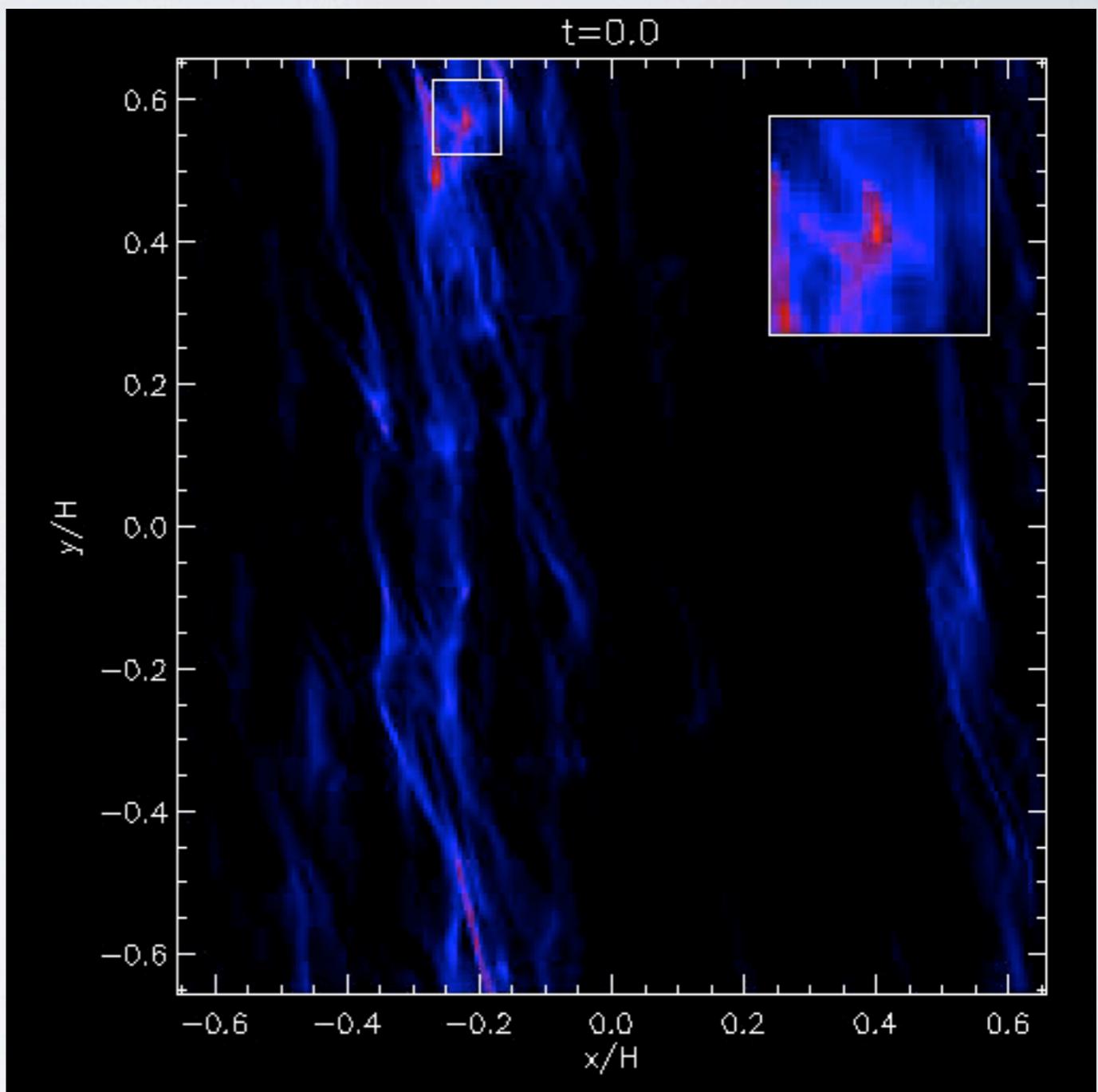
$$v_{\text{turb}}^2 = \frac{1}{2} \frac{\alpha c_s^2}{t_s \Omega_K}$$

(Youdin & Lithwick 2007)

$$\begin{pmatrix} v_r \\ v'_\phi \\ v_z \end{pmatrix} = \begin{pmatrix} -\frac{2\eta v_K \Omega_K t_s}{1+(\Omega_K t_s)^2} \\ -\frac{\eta v_K}{1+(\Omega_K t_s)^2} \\ -\Omega_K^2 t_s z \end{pmatrix}$$

# 重力不安定

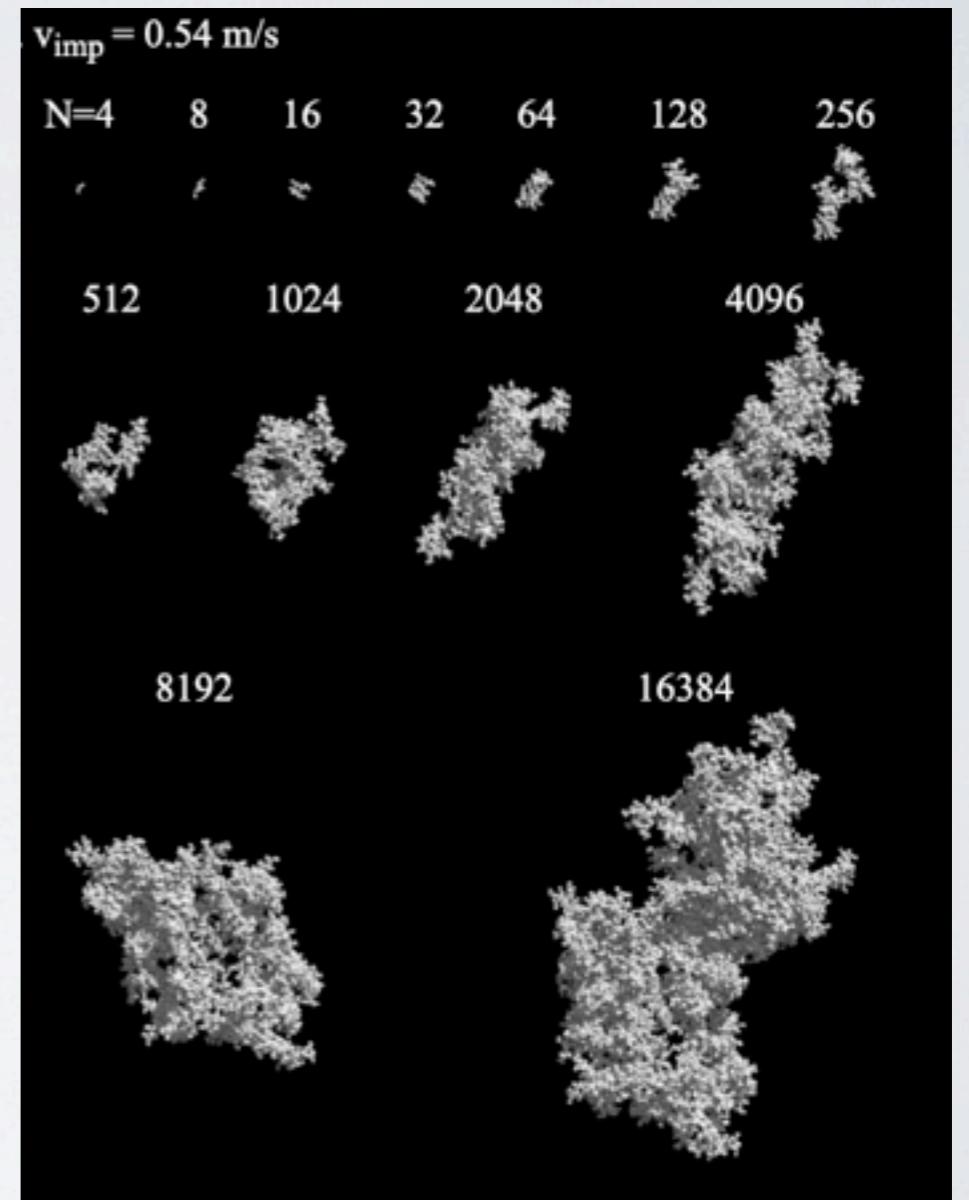
- ・円盤赤道面にダストが集まり、重力不安定 (Goldreich & Ward 1973)。
- ・ダスト層とガス層の速度差により、密集が妨げられる (Weidenschilling 1980)。
- ・永年重力不安定 (Michikoshi et al. 2010, Takeuchi & Ida 2012)。
- ・ストリーミング不安定 (Johansen 2007)。



比較的大きなcm-mサイズの小石形成が必要

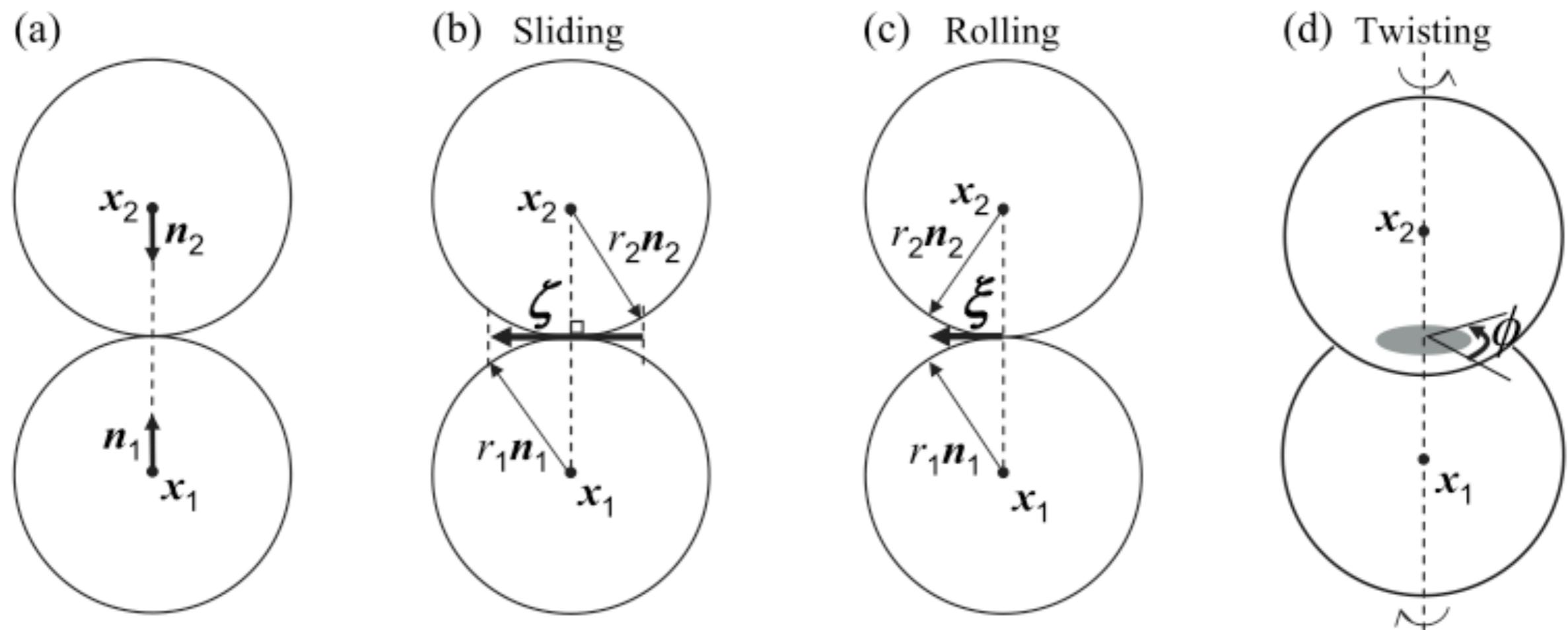
# ダストの直接合体成長

- ・高速衝突 (~50m/s) で衝突・合体できるのか？
- ・ダストの内部は、コンパクトではなく、多孔質(Wada+2007; Suyama+2009).
- ・空隙が多いダストは合体可能 (Wada+2011).



(Suyama+2009)

# 構成粒子間の相互作用モデル



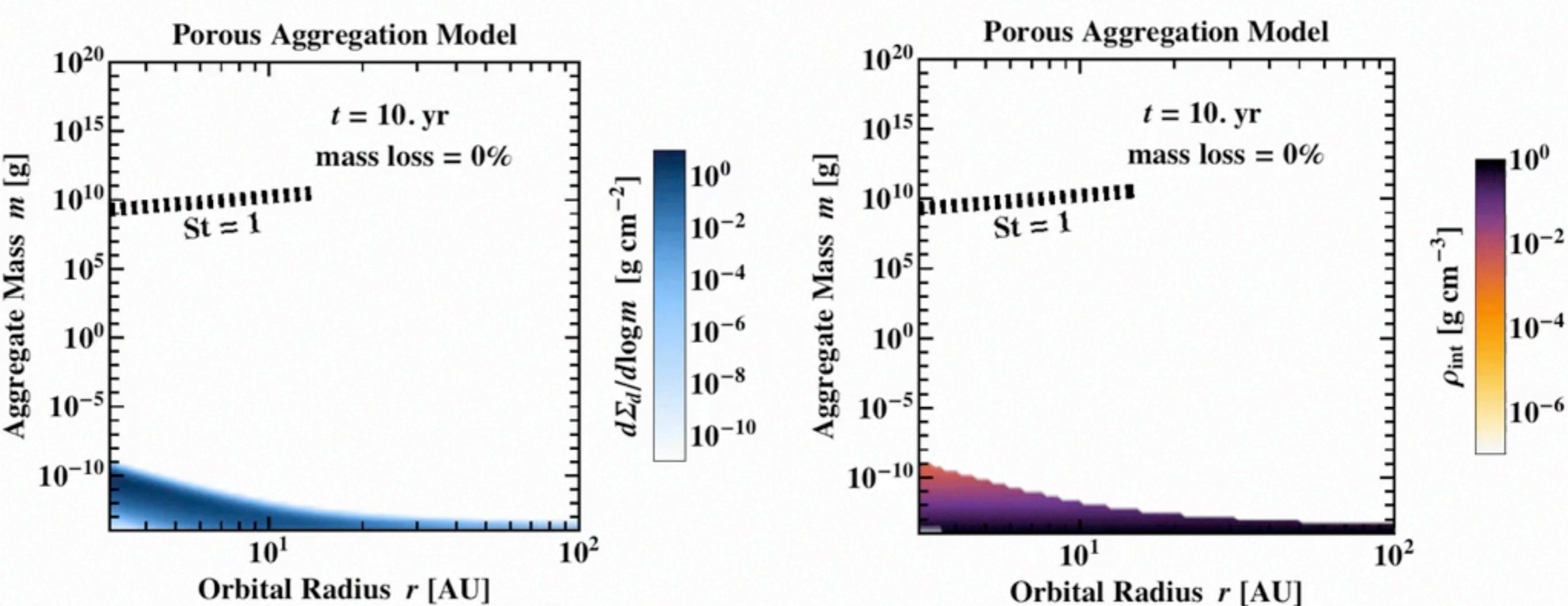
(Dominik & Tielens 1997; Wada et al. 2007)

# 衝突による密度進化



(Suyama et al. 2008; 2012)  
(see also Wada et al. 2007; 2008; 2009; 2011)

# アグリゲイト成長



- ・落下バリアを克服できる(Okuzumi, Tanaka, Kobayashi, Wada 2012)。

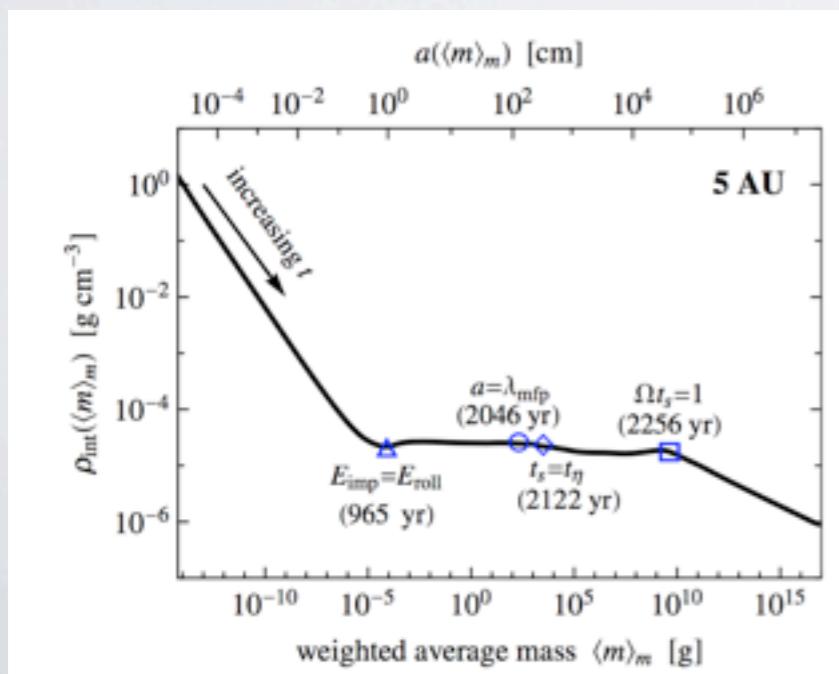
# なぜ成長できたのか？

成長率 v.s. 落下時間

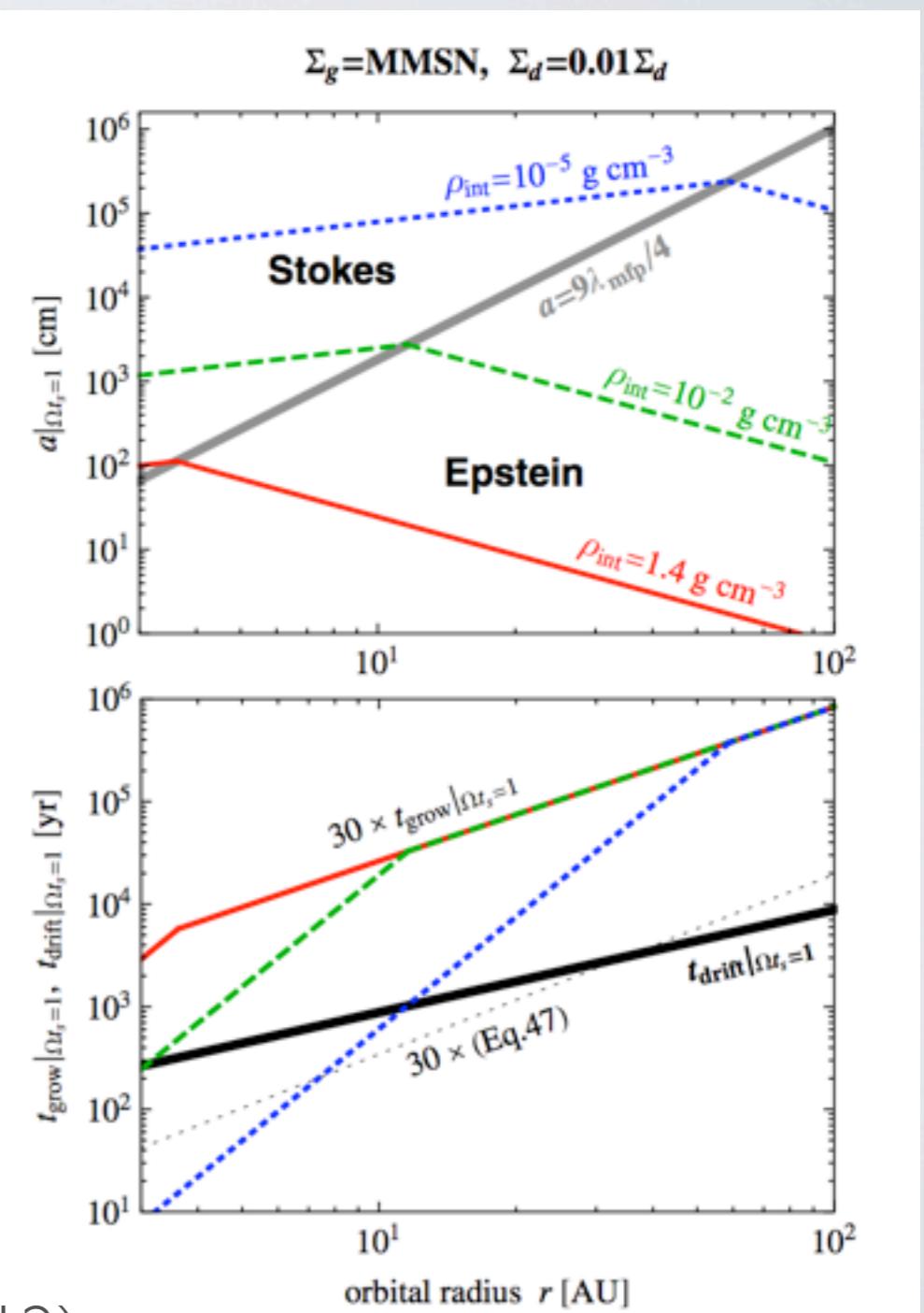
( $\Omega_K t_s = 1$  のとき)

$$\frac{t_g}{t_d} \approx \frac{8\pi}{3} \eta \frac{s\rho_s}{\Sigma_s}$$

$$\approx 0.6 \left( \frac{\Sigma_{s,1AU}}{7.1g/cm^2} \right)^{-1} \left( \frac{s\rho_s}{300g/cm^2} \right) \left( \frac{r}{1AU} \right)^2$$



(Okuzumi et al. 2012)



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