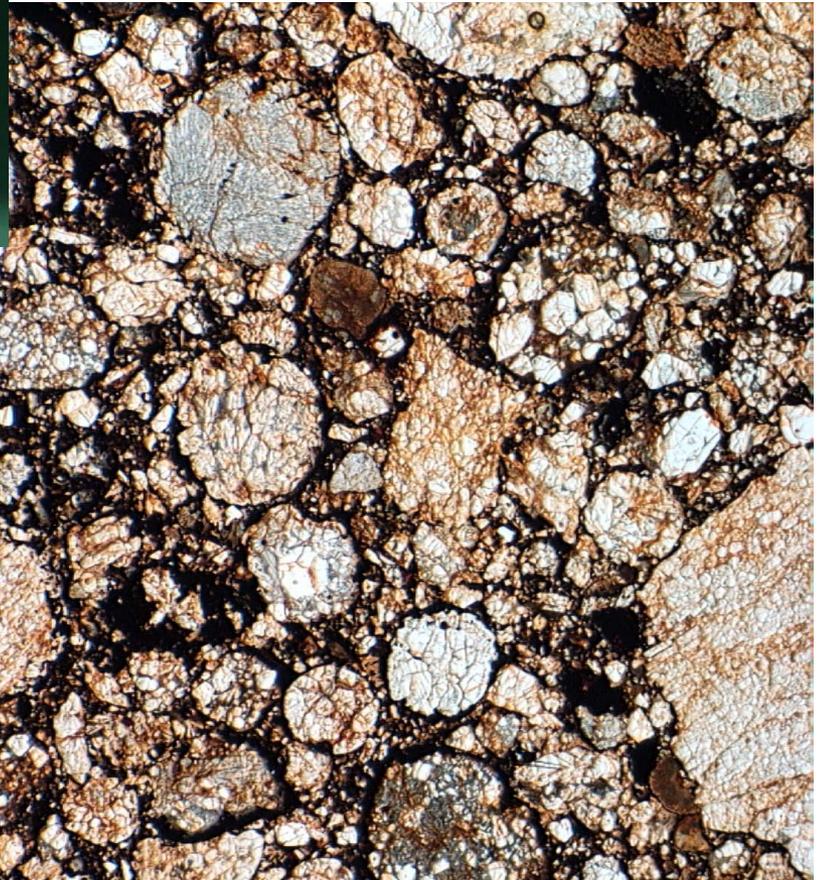


Chondrule and Planetesimal Formation

中本泰史 (東工大)

1. コンドリュールとは
2. コンドリュール形成モデル
3. 微惑星形成との関係
4. 惑星系形成の理解

隕石



1. コンドリユールとは

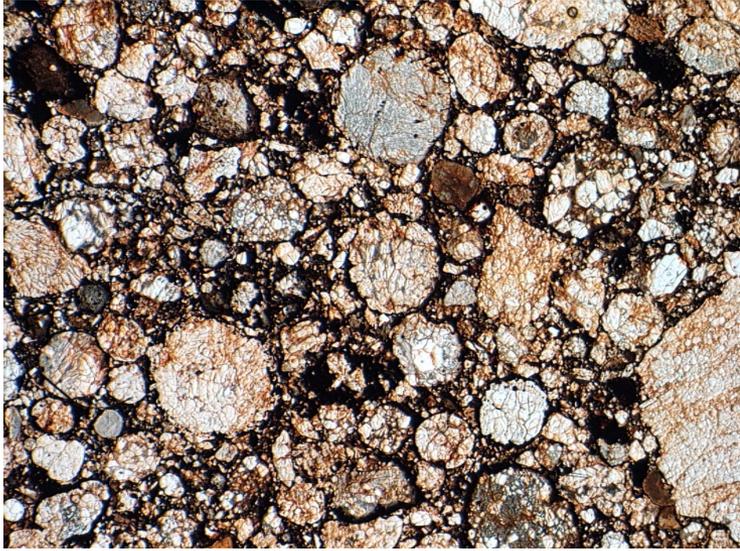


1mm

隕石

鉄隕石	5%
石鉄隕石	1%
石質隕石	
{ エイコンドライト	8%
{ コンドライト	86%
{ 普通コンドライト	90%
{ 炭素質コンドライト	4%
{ エンスタタイトコンドライト	2%
{ 他	4%

コンドリュール



↔
1mm

“Flash Heating”による形成

- T タウリ型星期

時期 ~ 0 - 3 Myr after CAI

期間 ~ 2-3 Myr

- 熔融 & 固化

前駆体 < 650 K

温度上昇 > 10^4 K/hr

最高温度 ~ 1600 - 2000 K

液体状態

継続時間 ~ 数分

冷却 ~ 1 - 1000 K/hr

- サイズ

0.1 - 1 mm

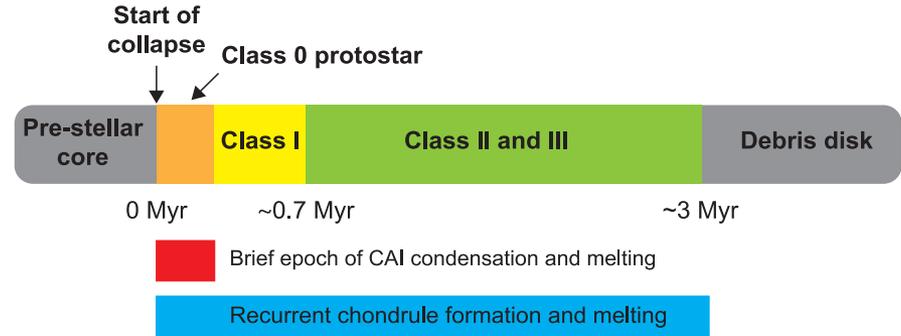
- 大量に存在 (up to 80%)

- 複数回加熱を受けている

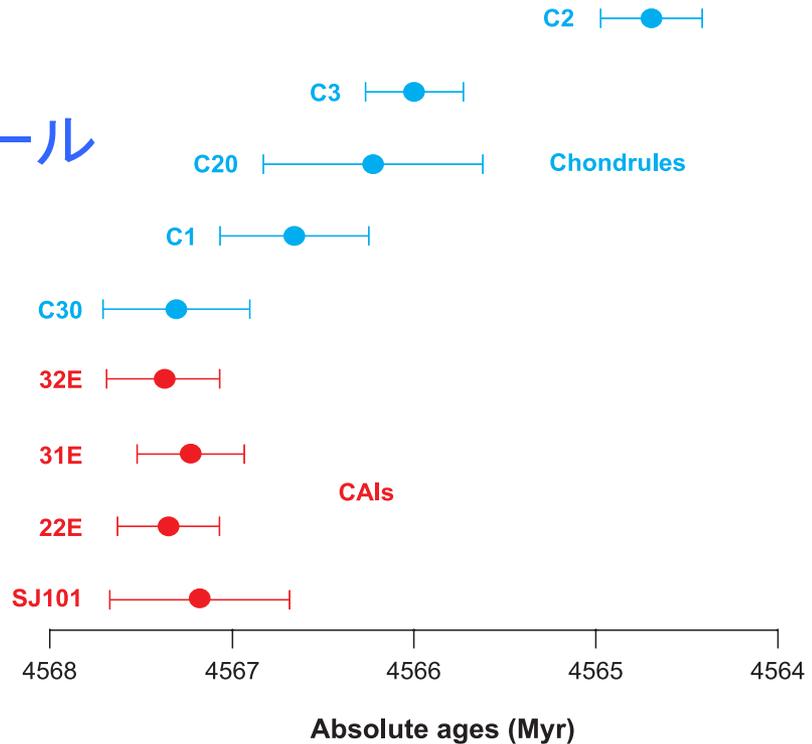
太陽系初期の年代(再測定)

Connelly et al. 2012

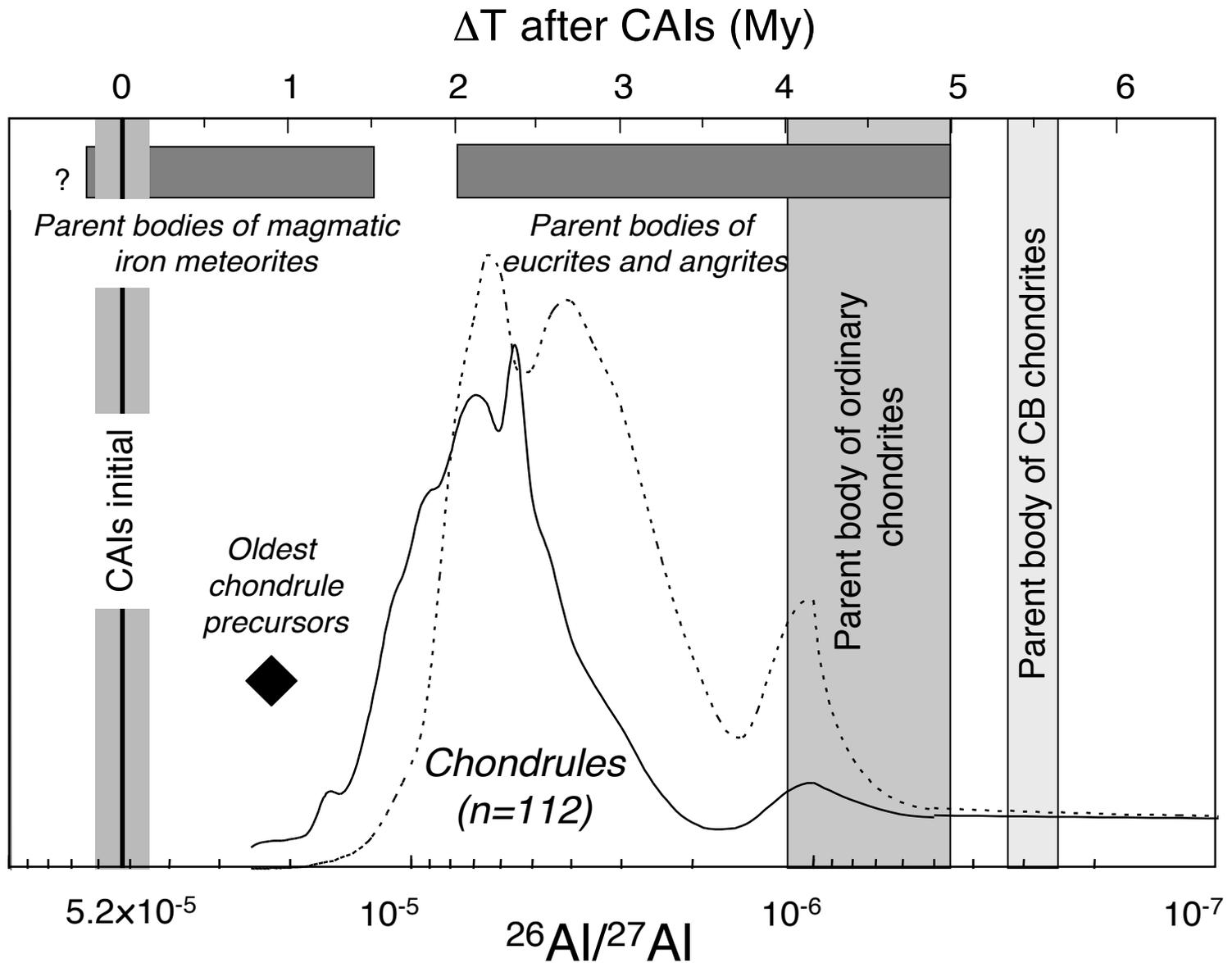
$^{238}\text{U}/^{235}\text{U}$ が非一様であることを考慮



コンドリュール



CAI



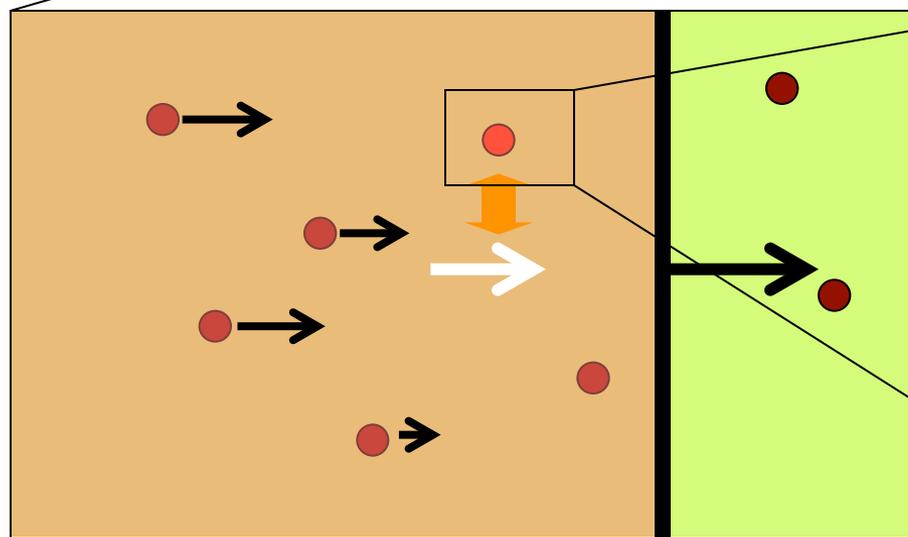
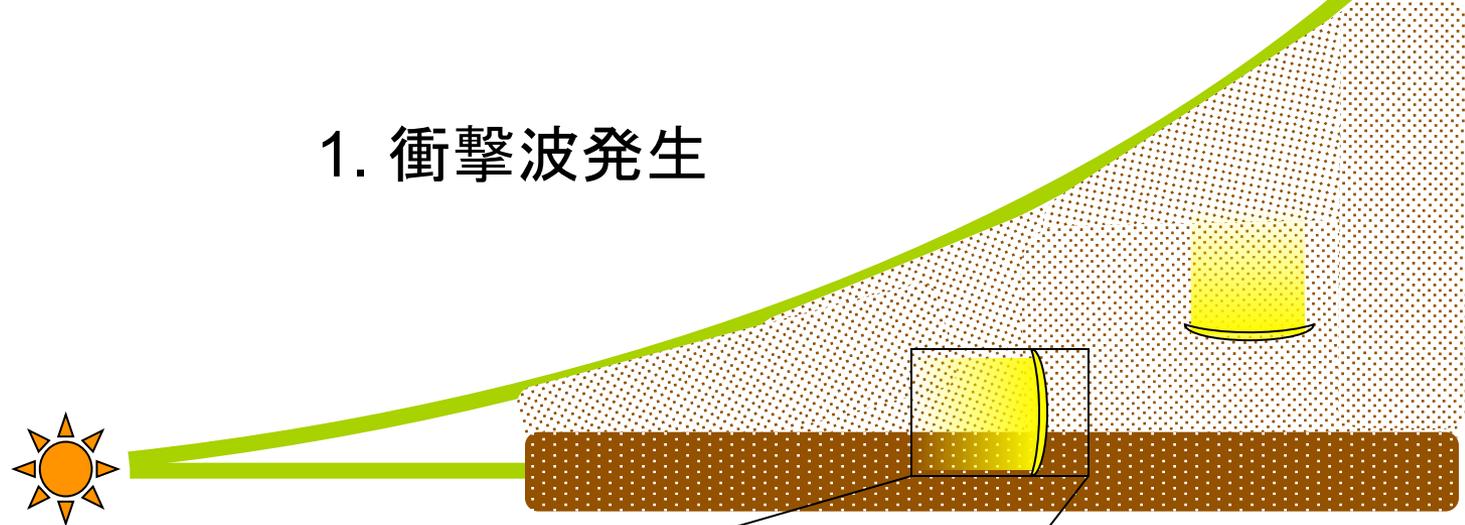
2. コンドリユール形成モデル

- 衝撃波加熱
- 雷加熱
- X-Windモデル
- ...

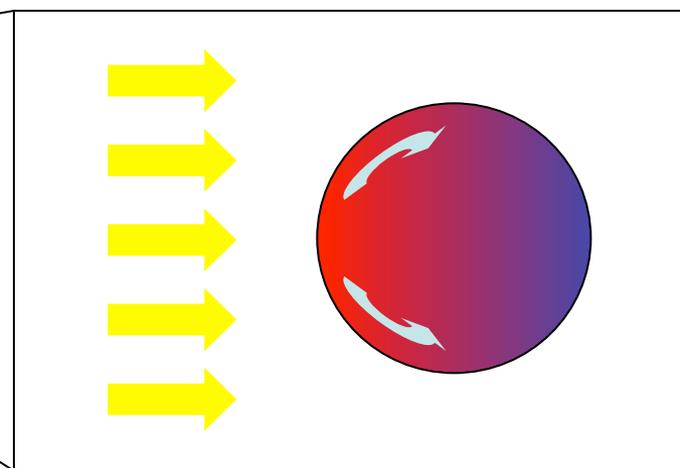
衝撃波加熱

1. 衝撃波の発生
2. 衝撃波内部での加熱機構
3. ダスト粒子内部の現象

1. 衝撃波発生

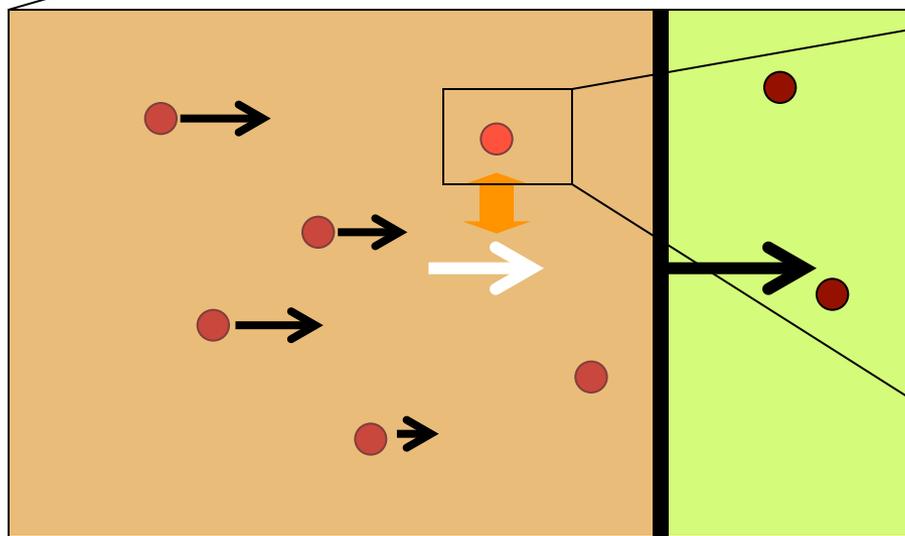
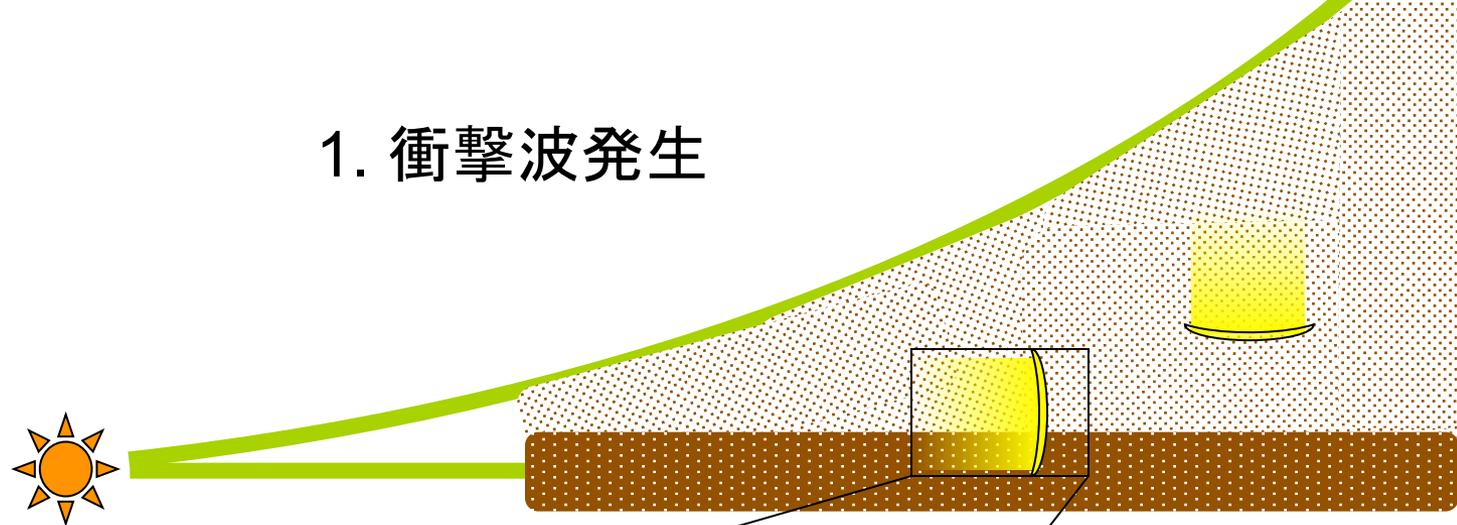


2. 衝撃波内部

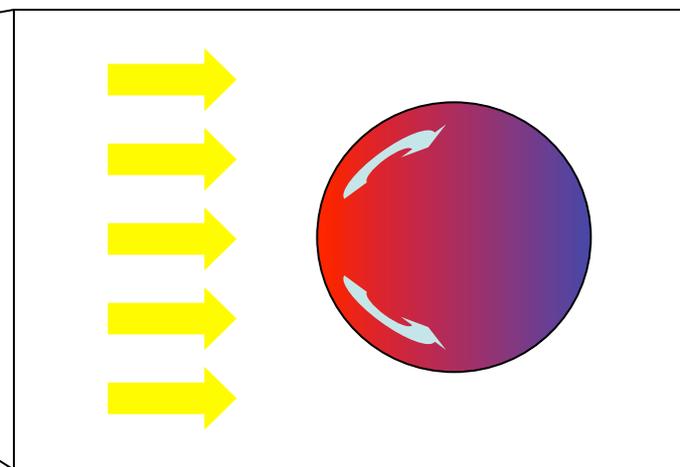


3. ダスト粒子内部

1. 衝撃波発生

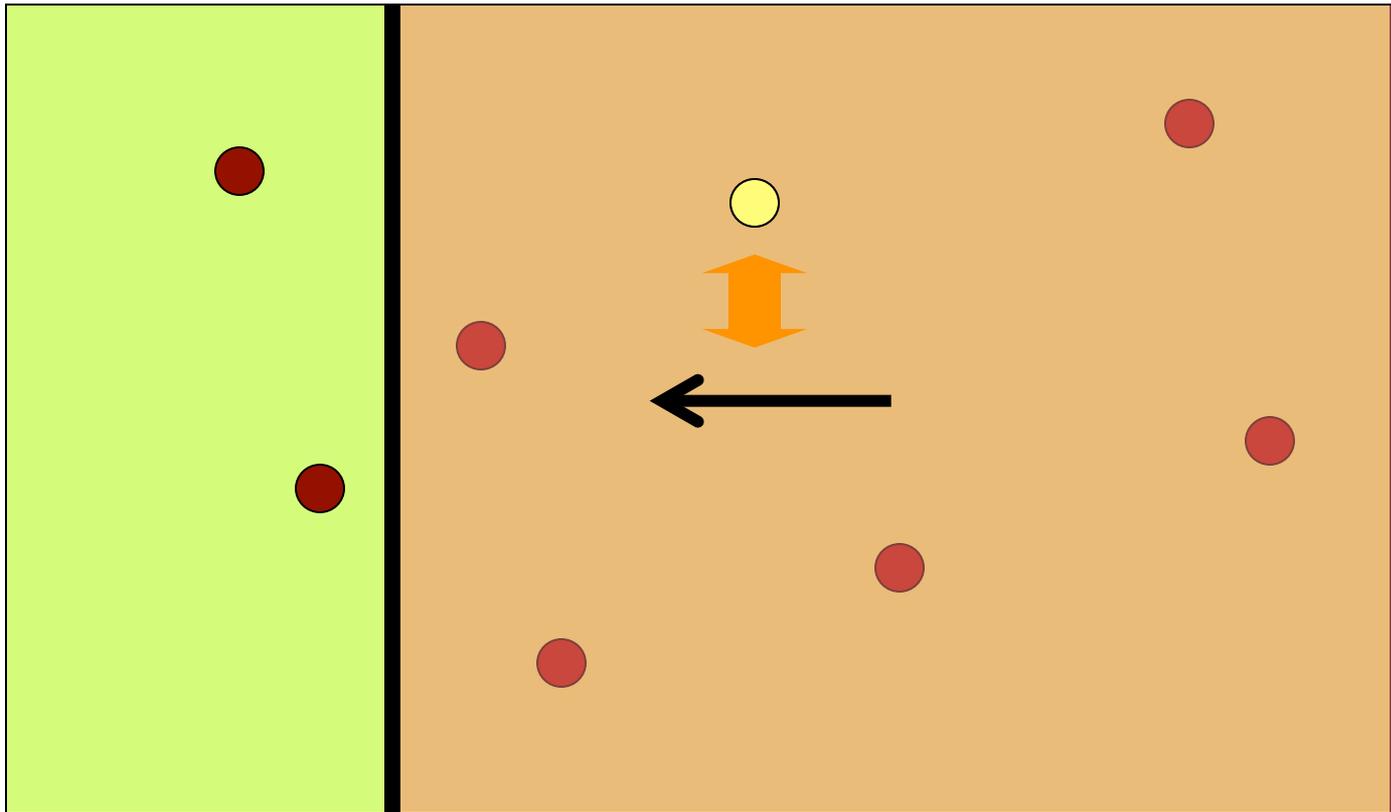


2. 衝撃波内部

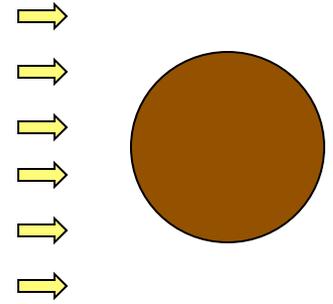


3. ダスト粒子内部

衝擊波加熱機構



簡単な見積もり



$$m_{\text{gr}} C_{\text{gr}} \frac{dT_{\text{gr}}}{dt} = \pi a^2 \frac{1}{2} \rho_{\text{gas}} V^3 - 4\pi a^2 \sigma T_{\text{gr}}^4$$

最高温度到達時: $\frac{dT_{\text{gr}}}{dt} = 0$

$$\begin{aligned} \Rightarrow T_{\text{max}} &= \left[\frac{1}{2\sigma} \rho_{\text{gas}} V^3 \right]^{1/4} \\ &= 1700 \left(\frac{n_{\text{gas}}}{10^{15} \text{ cm}^{-3}} \right)^{1/4} \left(\frac{V}{10 \text{ km s}^{-1}} \right)^{3/4} \text{ K} \end{aligned}$$

Basic Equations for Dust Particles:

$$m_{\text{gr}} \frac{dv_{\text{gr}}}{dt} = -\pi a_{\text{gr}}^2 \frac{C_D}{2} \rho v_{\text{rel}}^2$$

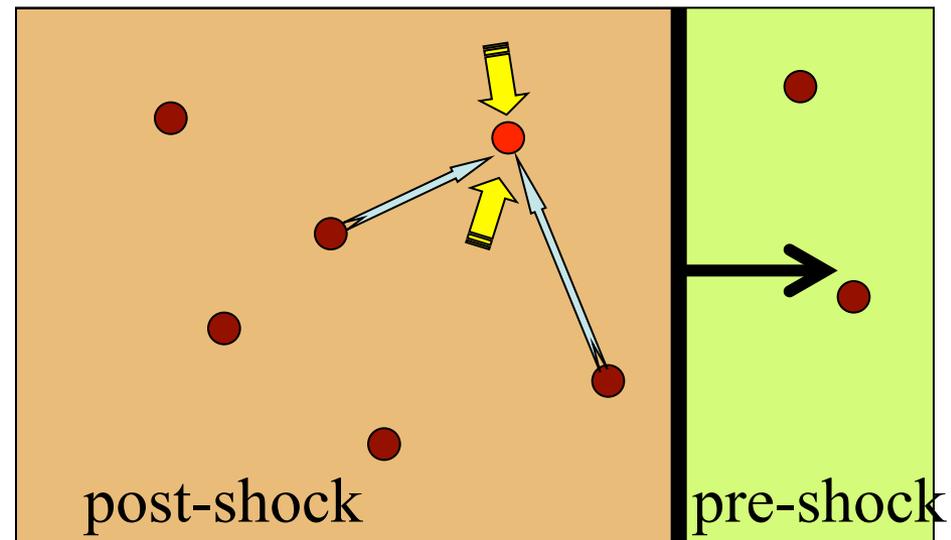
$$m_{\text{gr}} C_{\text{gr}} \frac{dT_{\text{gr}}}{dt} = -\Lambda_{\text{rad}} - \Lambda_{\text{evap}} \quad \boxed{+\Gamma_{\text{drag}}} \quad \boxed{+\Gamma_{\text{rad,gas}}} \quad \boxed{+\Gamma_{\text{rad,dust}}}$$

$$\rho_{\text{gr}} \left(\frac{da_{\text{gr}}}{dt} \right)_{\text{evap}} = -J_{\text{evap}}$$

radius a_{gr} : 0.01 μm – 1 cm

emissivity : size dependent

evaporation rate : pure forsterite



Basic Equations for Gas

$$\frac{\partial}{\partial x}(\rho v) = 0$$

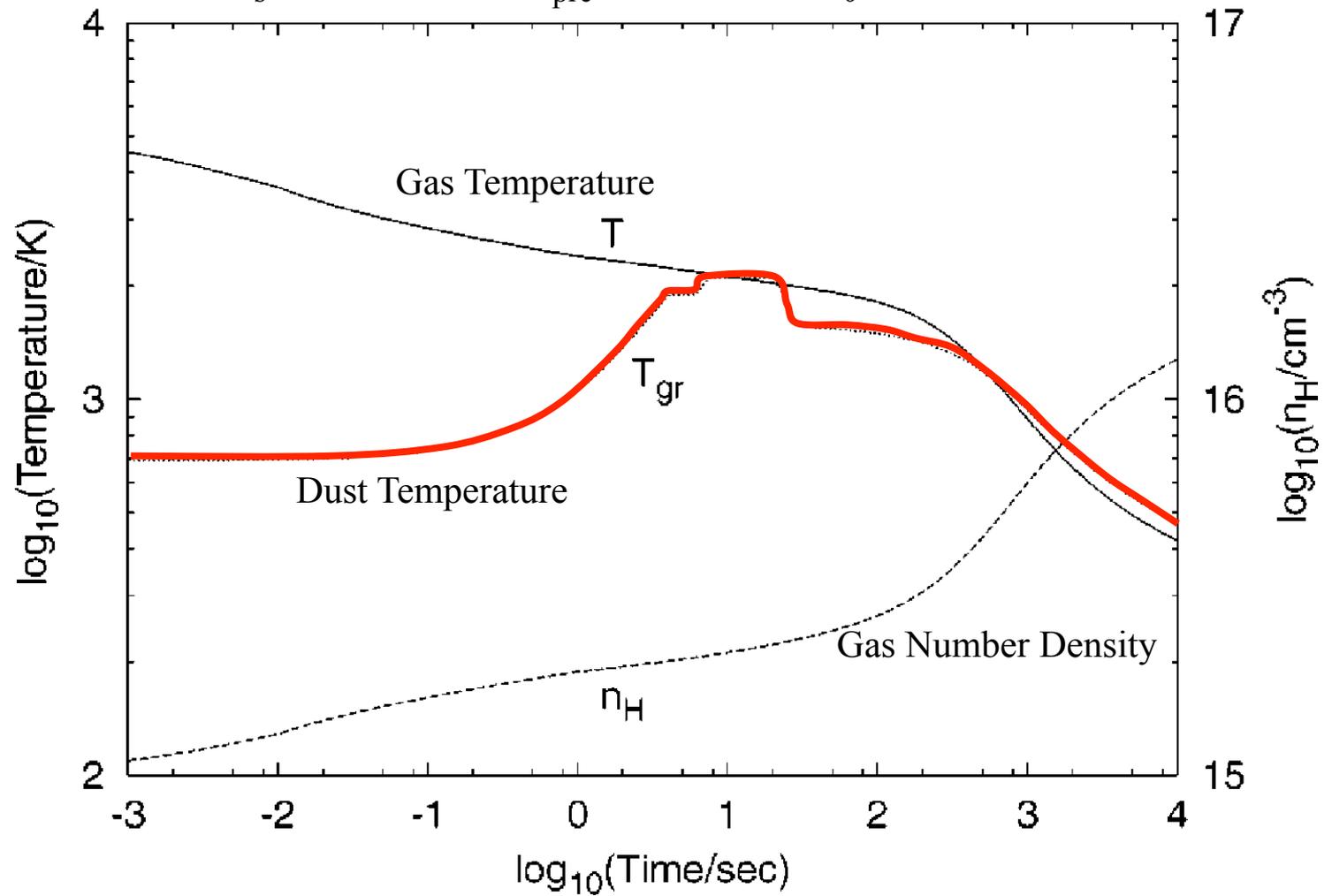
$$\frac{\partial}{\partial x}(\rho v^2 + p) = 0$$

$$\begin{aligned} & \frac{\partial}{\partial x} \left[\left(\frac{1}{2} r v^2 + E + P \right) v \right] \\ &= \Gamma_{\text{H}_2\text{form}} - \Lambda_{\text{Ly}\alpha} - \Lambda_{\text{H}_2\text{diss}} - \Lambda_{\text{H}_2\text{O(V)}} - \Lambda_{\text{H}_2\text{O(R)}} \\ & \quad - \Lambda_{\text{CO(V)}} - \Lambda_{\text{CO(R)}} - \Lambda_{\text{OH(R)}} - \Lambda_{\text{grain}} \end{aligned}$$

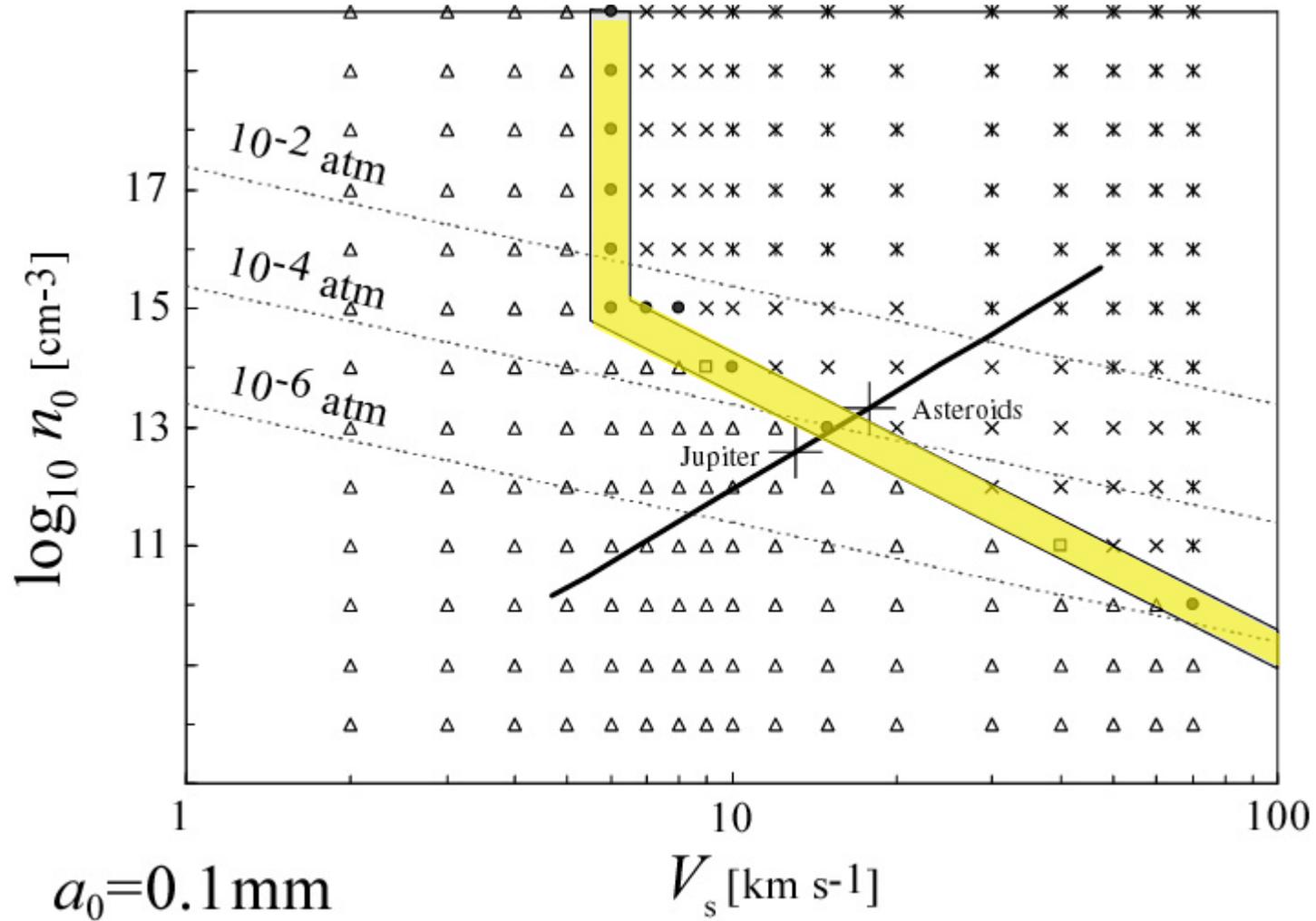
$$\frac{dy_i}{dt} = n_H \sum_{j=1}^{32} \sum_{k=1}^{32} k_{jk} y_j y_k + n_H^2 \sum_{l=1}^{32} \sum_{m=1}^{32} \sum_{n=1}^{32} k_{lmn} y_l y_m y_n$$

Chemical Reactions : 32 species, 167 reactions

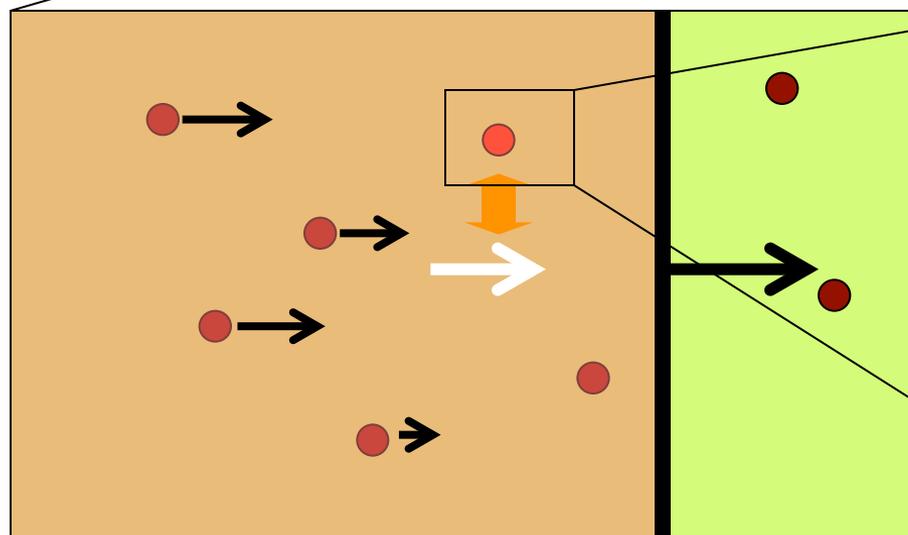
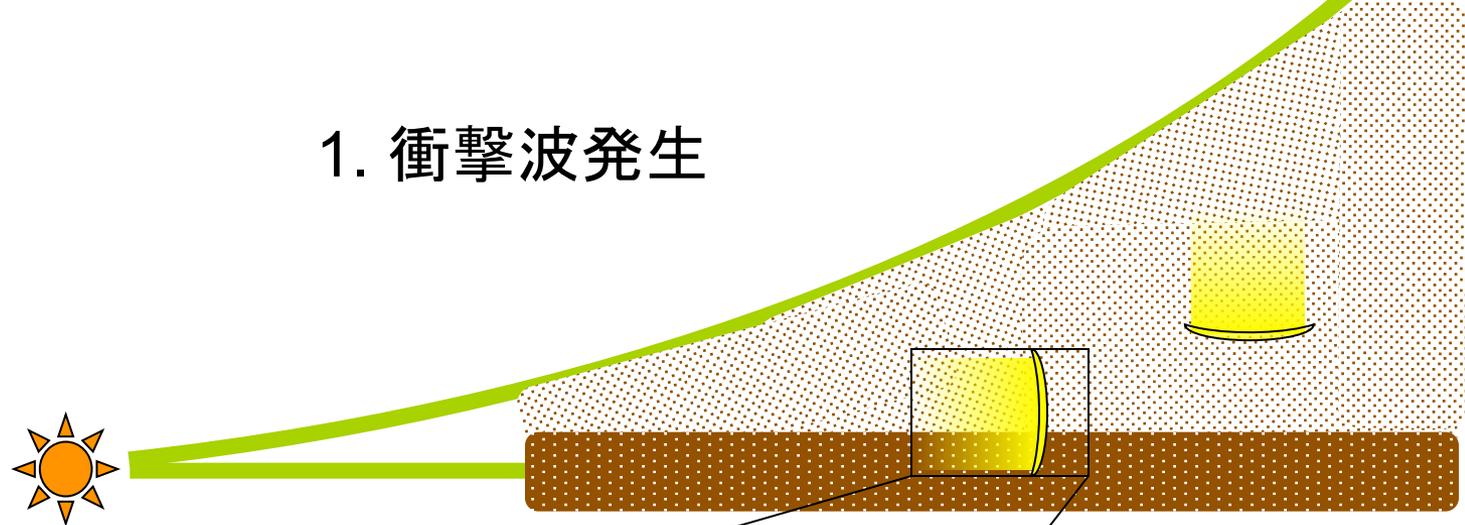
$$V_s = 10 \text{ km s}^{-1}, n_{\text{pre}} = 10^{14} \text{ cm}^{-3}, a_0 = 0.1 \text{ mm}$$



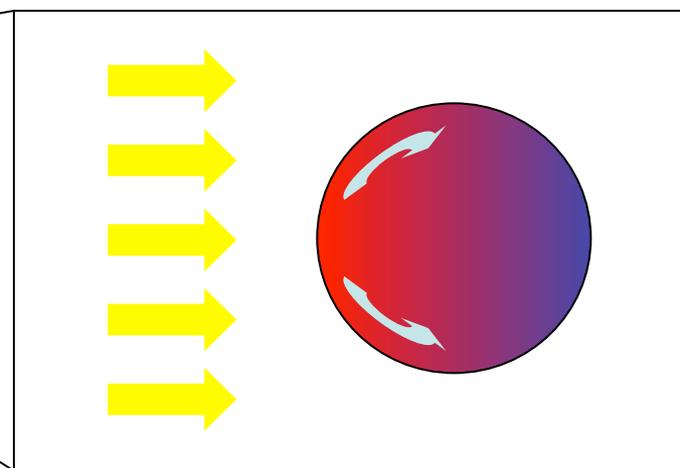
Chondrule Forming Shock Waves: Peak Temperature



1. 衝撃波発生



2. 衝撃波内部



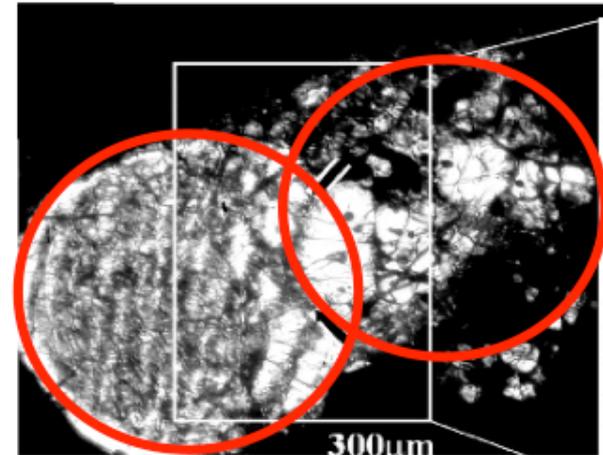
3. ダスト粒子内部

複合コンドリュール

- ▶ 二個以上のコンドリュールが付着
- ▶ コンドリュール全体の**数%**存在

Akaki and Nakamura 2004

二つのコンドリュールが
溶融状態を経験中に衝突



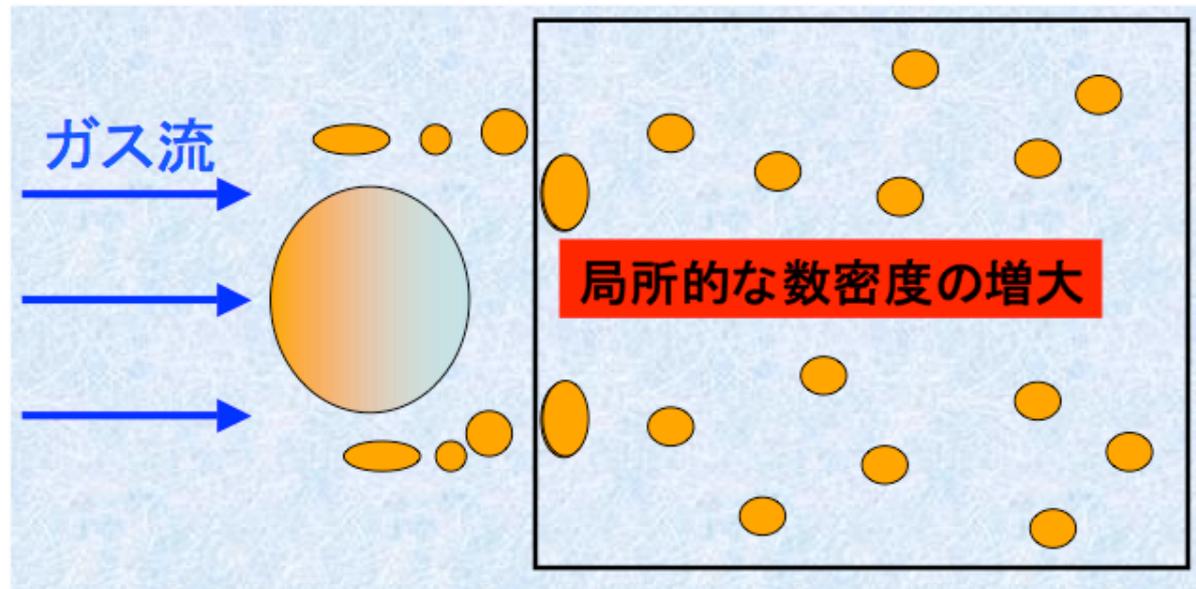
原始太陽系星雲中のダストの直接衝突は低頻度

(Sekiya and Nakamura 1996, Wasson et al. 1995, Gooding and Keil 1981)

分裂—衝突モデル

～複合コンドリュール形成の1モデル～

(Miura, Yasuda, and Nakamoto 2007)



衝突頻度

$$P_{\text{coll}} = n_e \sigma \Delta v t$$

~0.36

>>

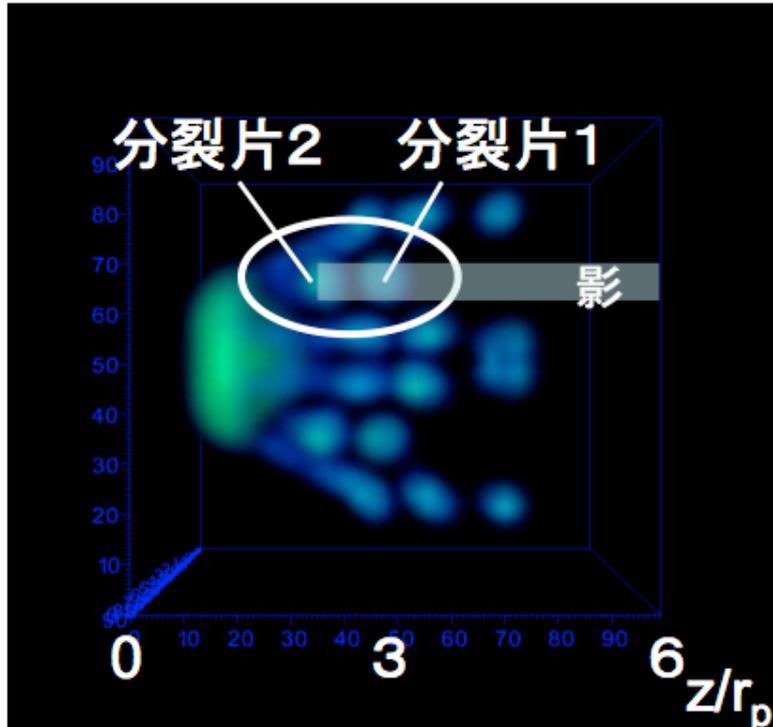
存在割合

$$\frac{\text{複合コンドリュールの数}}{\text{コンドリュールの数}}$$

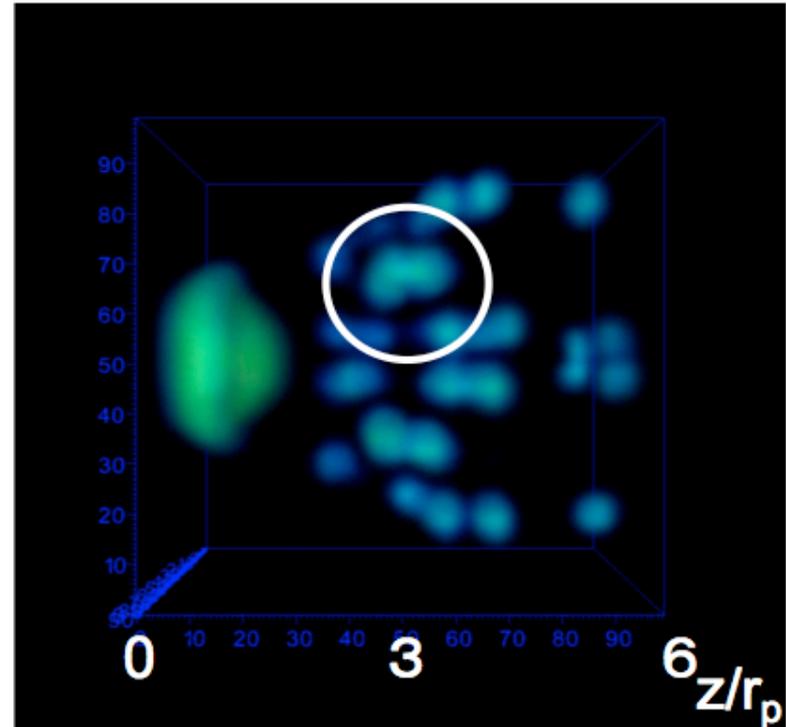
~0.05

分裂片同士の衝突

t = 0.0109sec



t = 0.0136sec



分裂片同士は確かに衝突する！

Miura, Yasuda, & Nakamoto (2008)

衝突付着条件

分裂片2 ($r_{e1} = 1.1\text{mm}$) 分裂片1 ($r_{e2} = 0.98\text{mm}$)



相对速度 ($\Delta v = 97\text{cm/s}$)

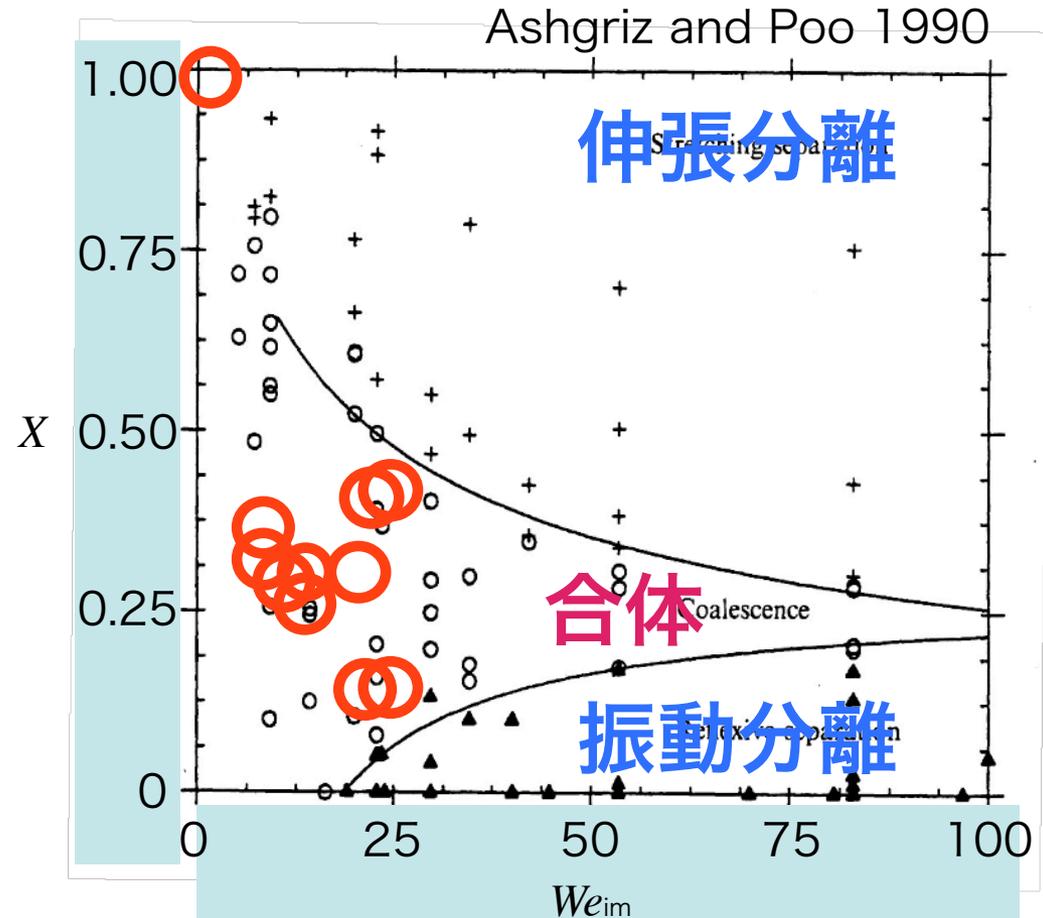
● Impact parameter

$$X \equiv \frac{D}{r_{e1} + r_{e2}} = \underline{0.29}$$

● Weber number

$$We_{im} = \frac{2r_{e2}\rho_{mat}\Delta v^2}{\gamma_s} = \underline{14.1}$$

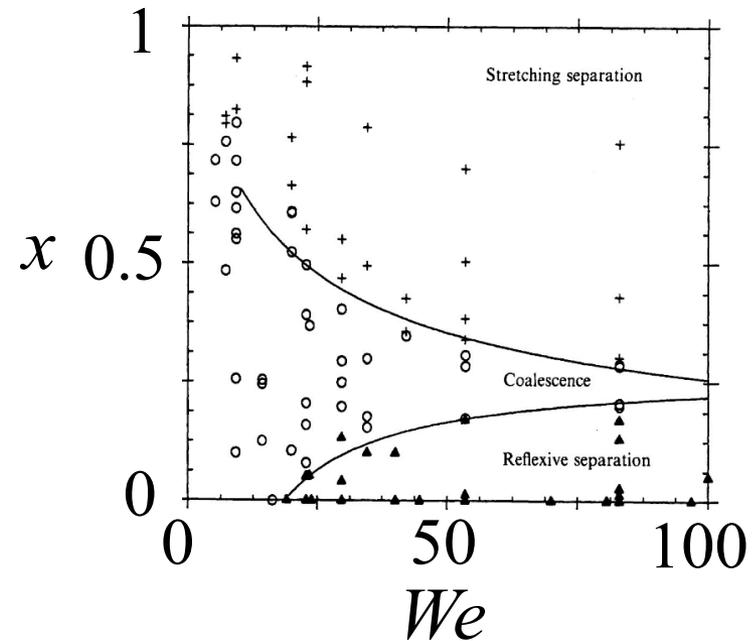
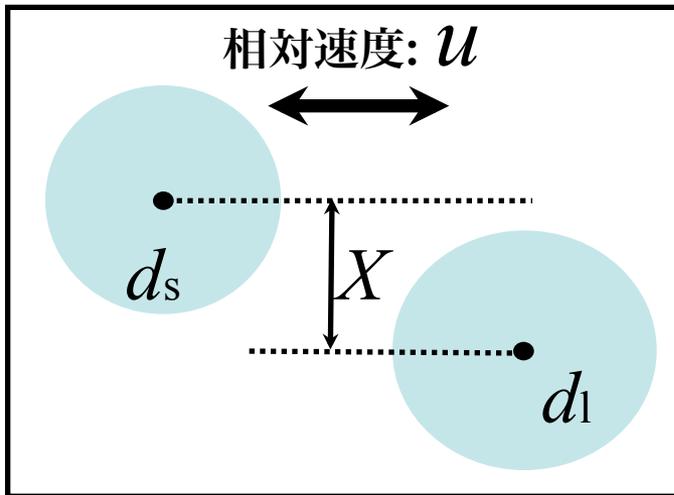
ρ_{mat} : 分裂片の質量密度
($= 3\text{g/cm}^3$)



分裂片同士は
ほとんど付着

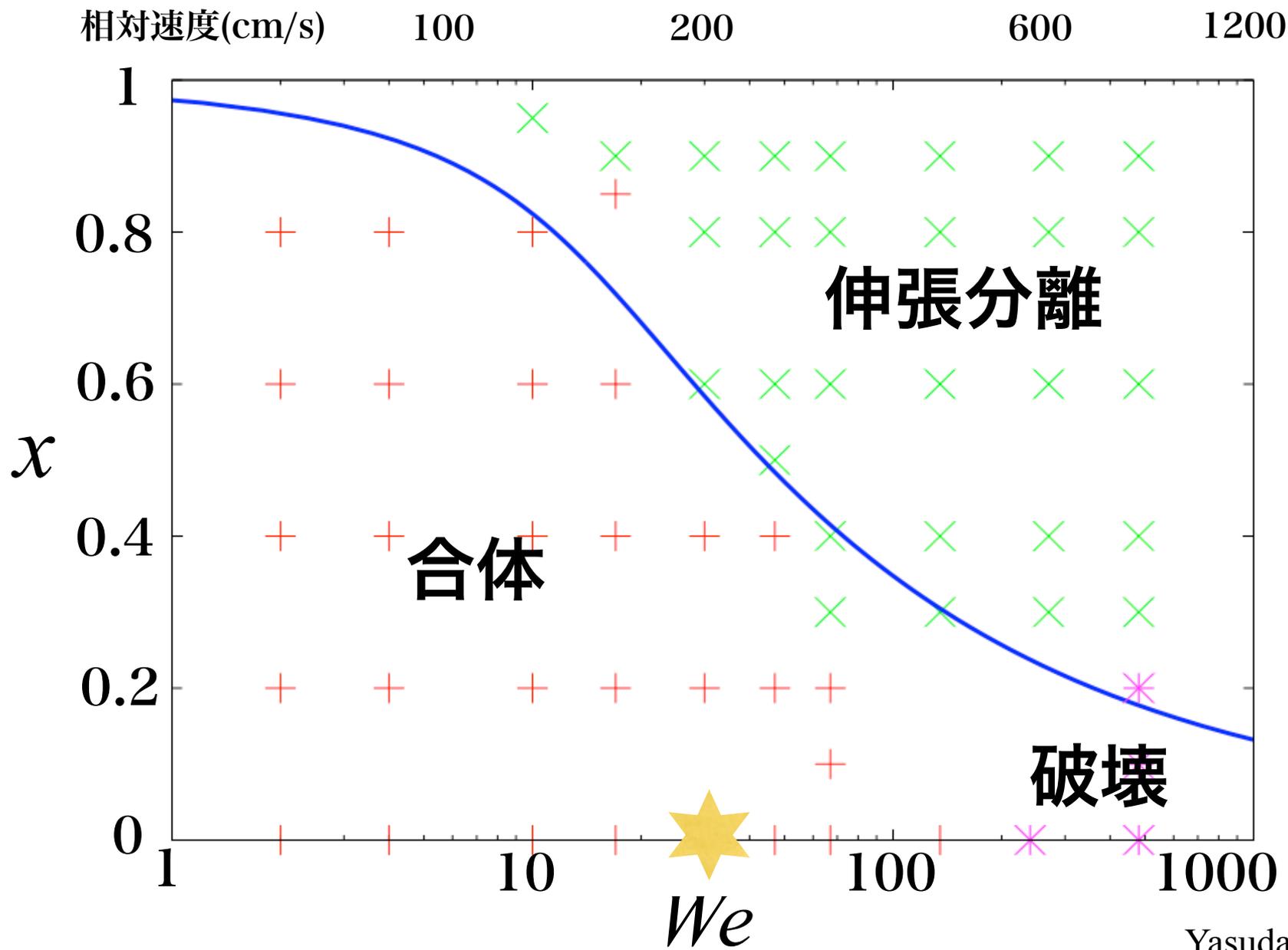
パラメータ

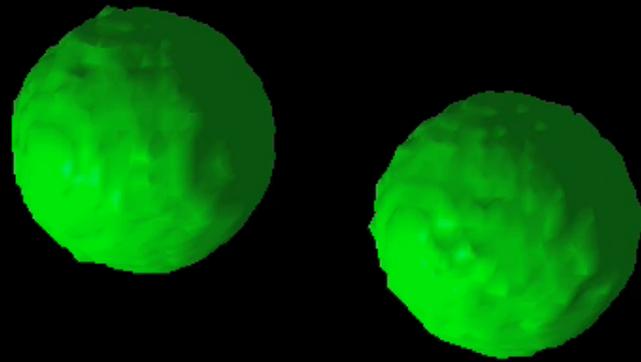
液滴の衝突実験 (水)
(Ashgriz and Poo 1990)



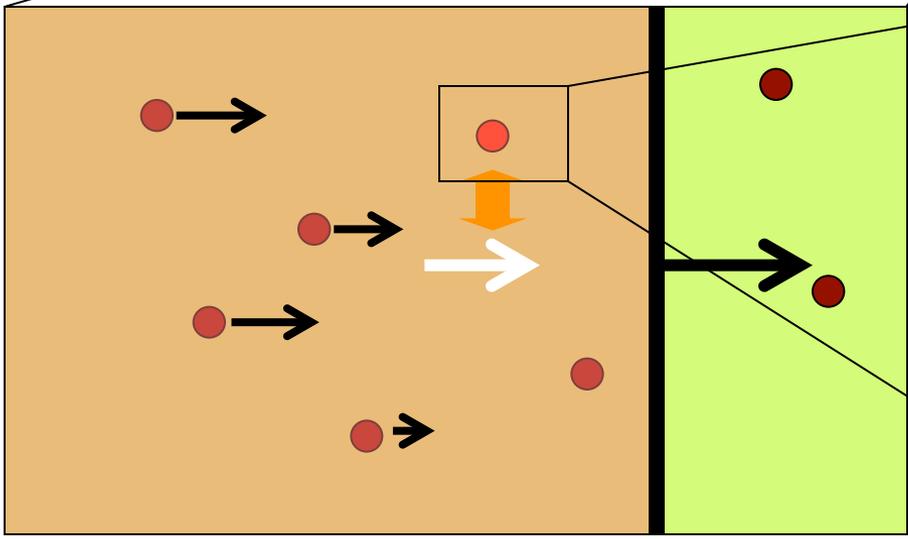
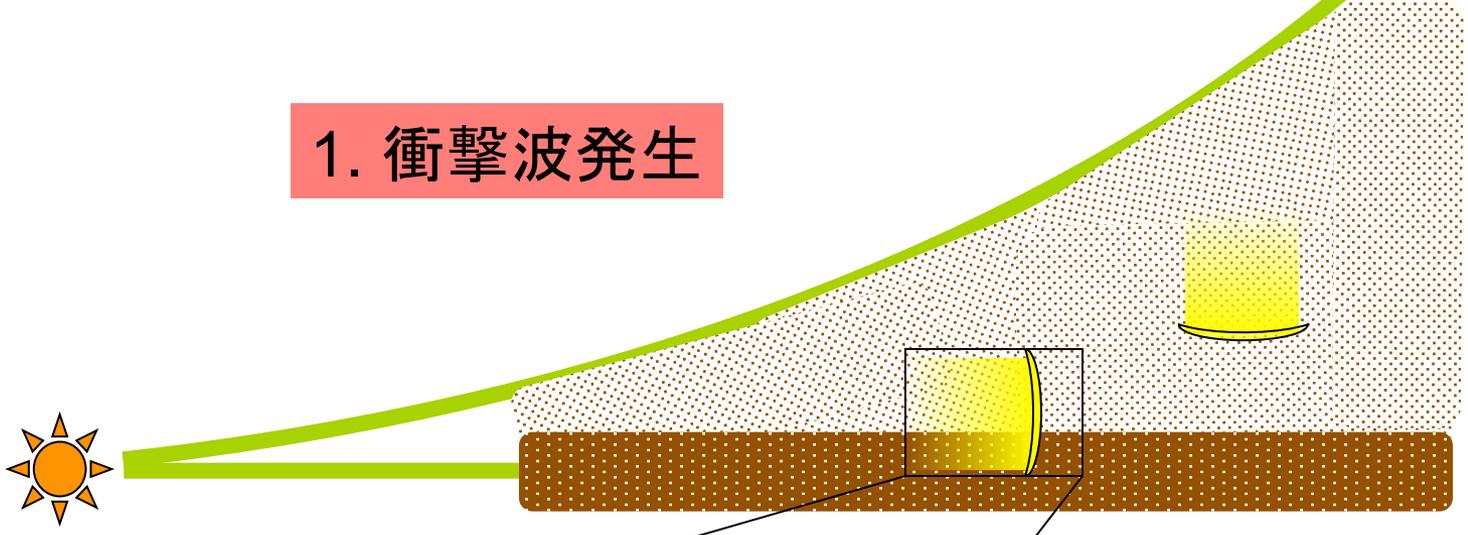
$$We = \frac{\rho v^2}{\gamma / R} = \frac{\text{動圧}}{\text{表面張力}}$$

計算結果(ns1-n11)

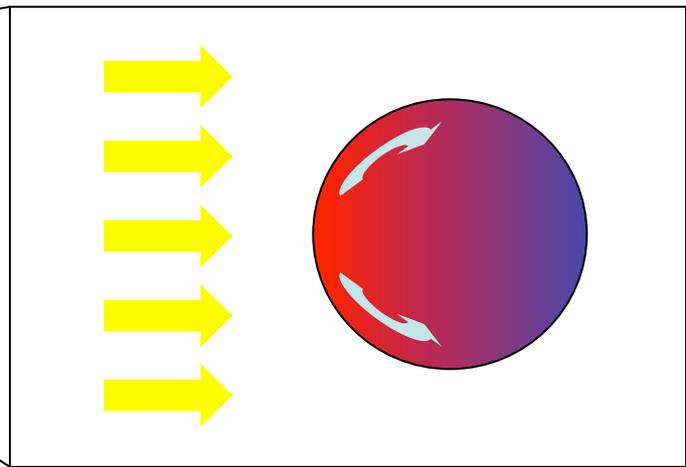




1. 衝撃波発生



2. 衝撃波内部



3. ダスト粒子内部

衝撃波の起源は何か？

- ・ 降着衝撃波

分子雲コアからの降着流による衝撃波

- ・ 自己重力円盤内密度波

自己重力不安定なガス円盤内の密度波

- ・ 微惑星前面のバウショック

木星により大きなランダム運動を獲得した
微惑星前面に発生するバウショック

- ・ 星風による円盤上層衝撃波

X線フレアによる星風とそれによる衝撃波

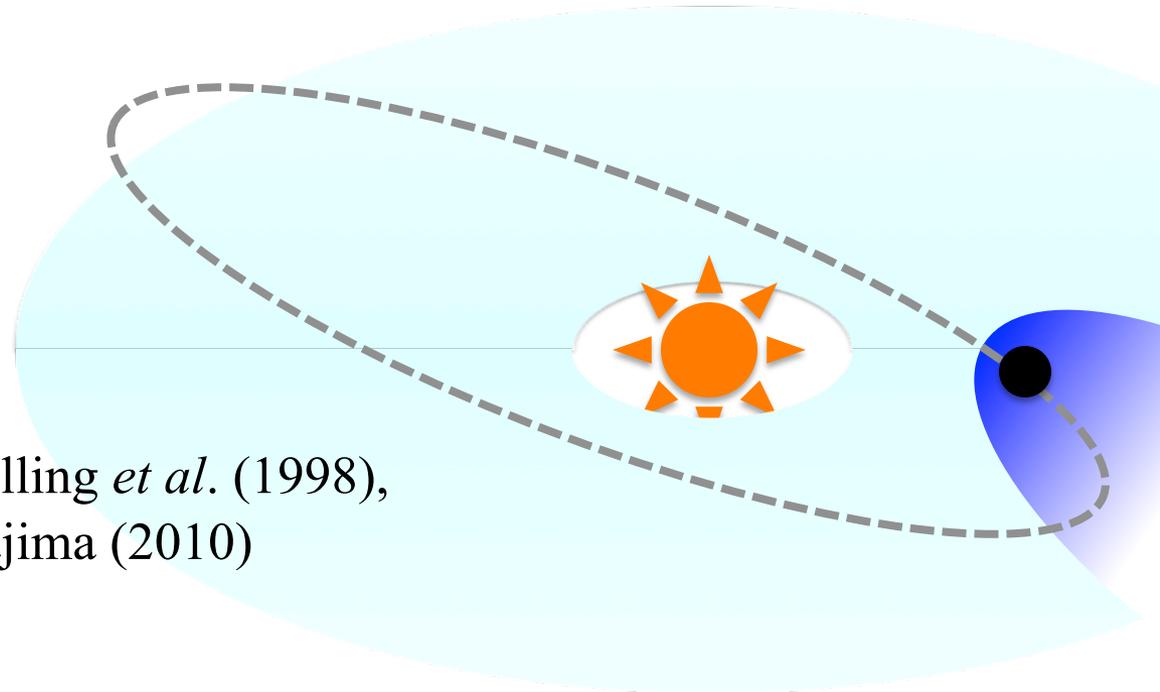
ショック源は何か

- コンドリュール前駆体を融かせるほど強い
- 数百万年にわたって起こる



微惑星まわりの
バウショック

Hood (1998), Weidenschilling *et al.* (1998),
Ciesla *et al.* (2004), Nakajima (2010)



木星による高速 微惑星形成と 微惑星前面の バウショック形成

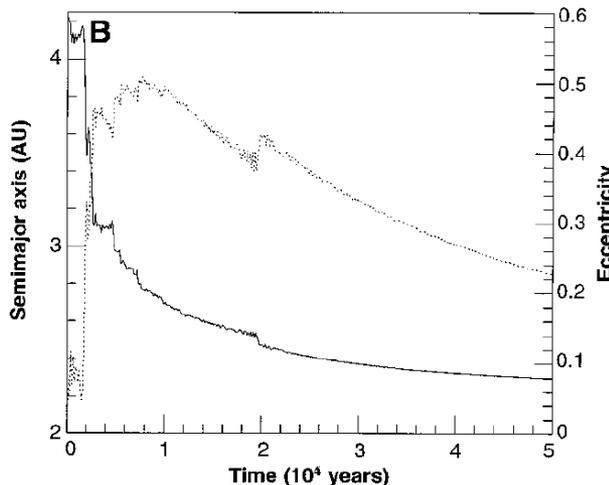
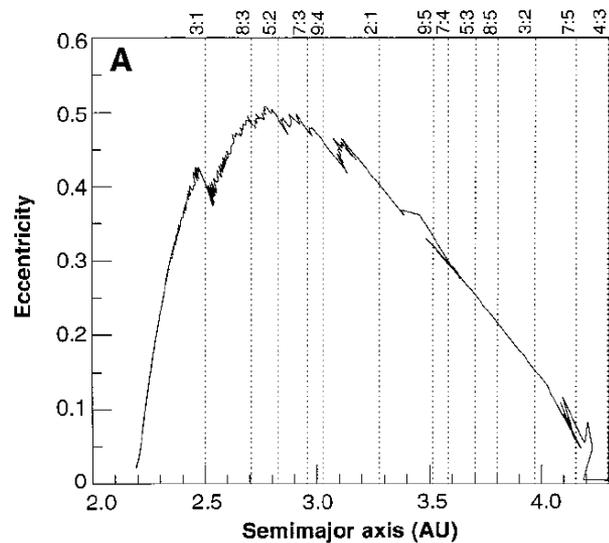
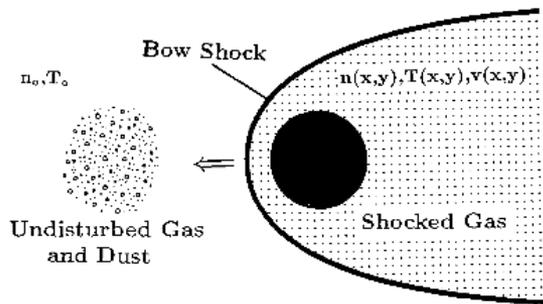


Fig. 1. (A) Eccentricity versus semimajor axis for a 100-km-diameter planetesimal started at 4.2 AU. Dashed lines mark the centers of major commensurability resonances, which overlap at eccentricities above 0.2 to 0.3 (27). (B) Semimajor axis (solid line) and eccentricity (dotted line) versus time for the planetesimal in (A). There is 3×10^5 years of slow orbital decay before encountering the resonance. Eccentricity

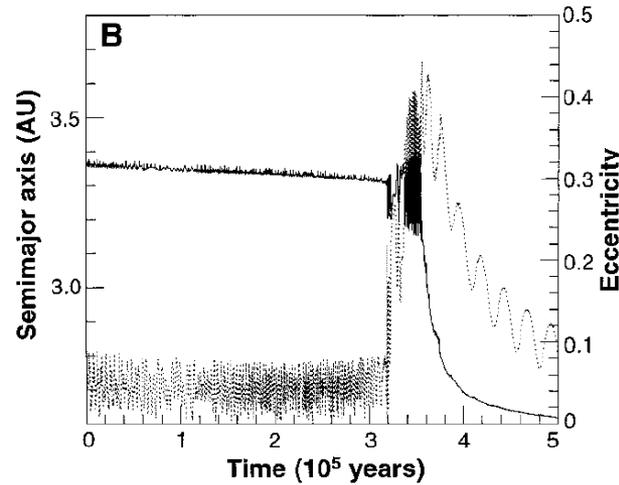
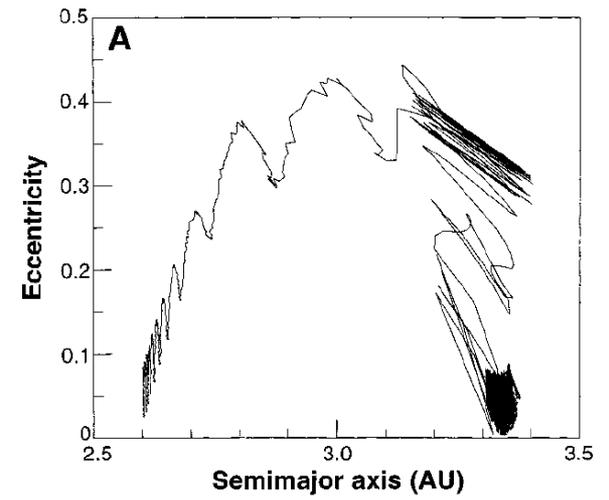
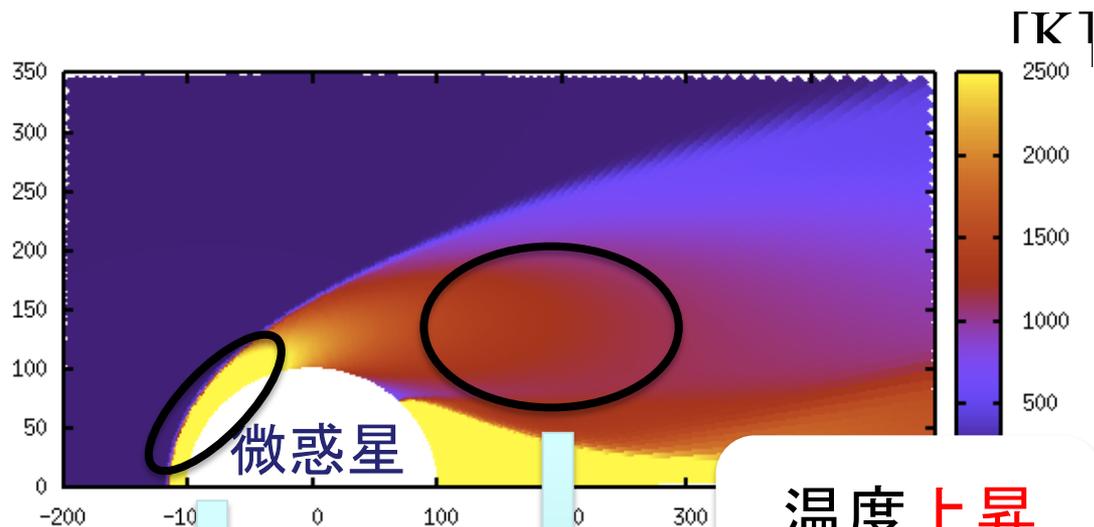


Fig. 2. (A) Eccentricity versus semimajor axis for a 100-km-diameter planetesimal started outside the 2:1 resonance. Jupiter is assumed to have its present eccentricity of 0.048. The planetesimal becomes trapped in the resonance until its eccentricity exceeds 0.3, then it escapes and is damped by drag. (B) Semimajor axis (solid line) and eccentricity (dotted line) versus time for the planetesimal in (A). There is 3×10^5 years of slow orbital decay before encountering the resonance. Eccentricity

解離入り計算

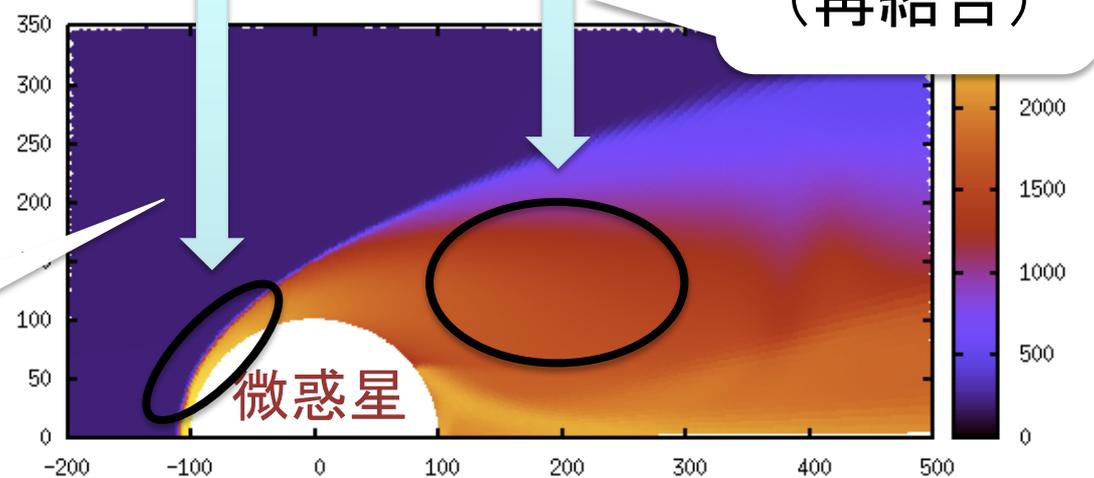
$\rho=10^{-8} \text{ g/cm}^3, v=12\text{km/s}$ の場合

解離・再結合
なし

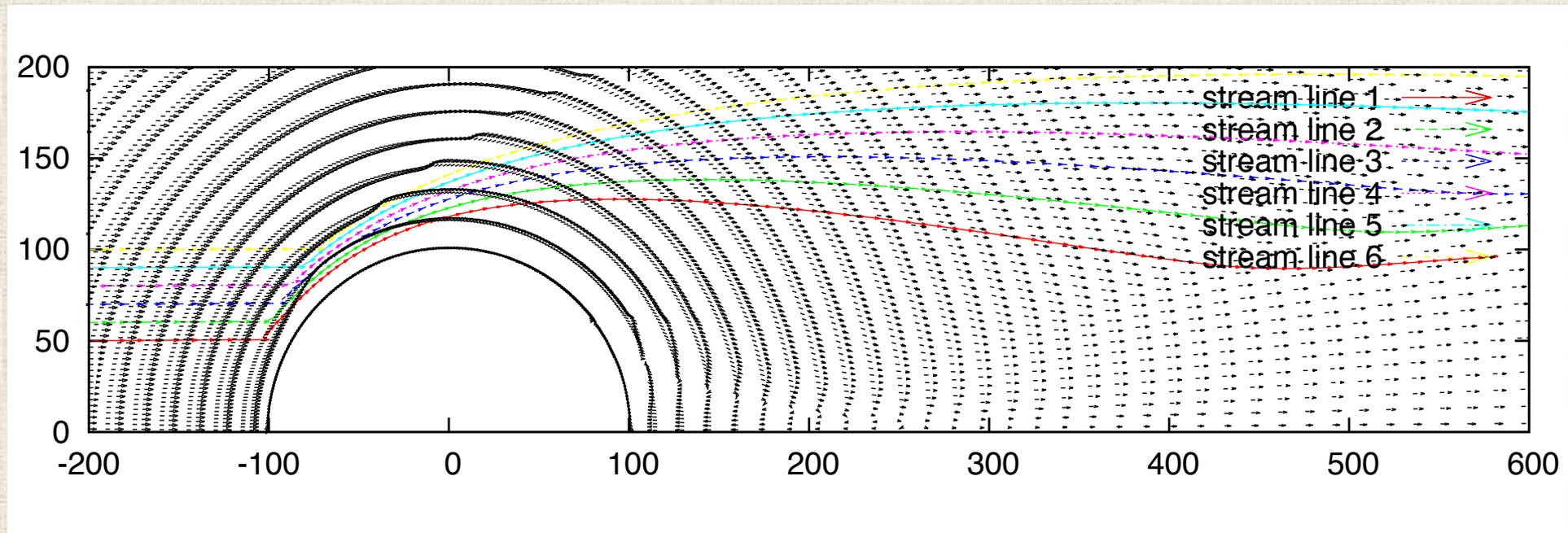


解離・再結合
あり

低下
密度上昇
(解離)



ガスの流線



バウショックに突入した粒子の熱履歴

- パラメータ

- $x_{\text{imp}} = 80 - 400 \text{ km}$

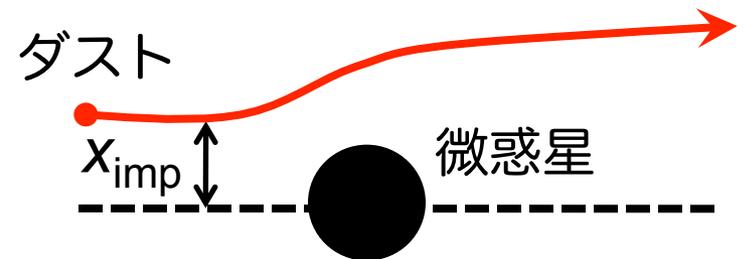
- $a = 0.1, 1, 10 \text{ mm}$

- 粒子に働く力

- ガス摩擦

- 粒子の加熱と冷却

- ガス摩擦加熱、放射冷却



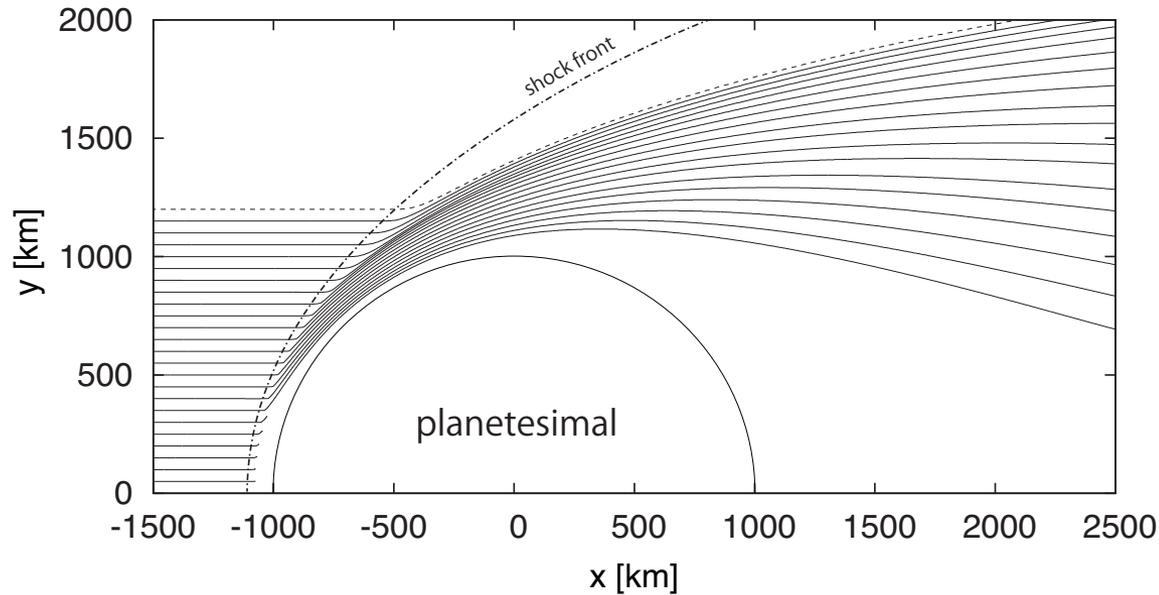
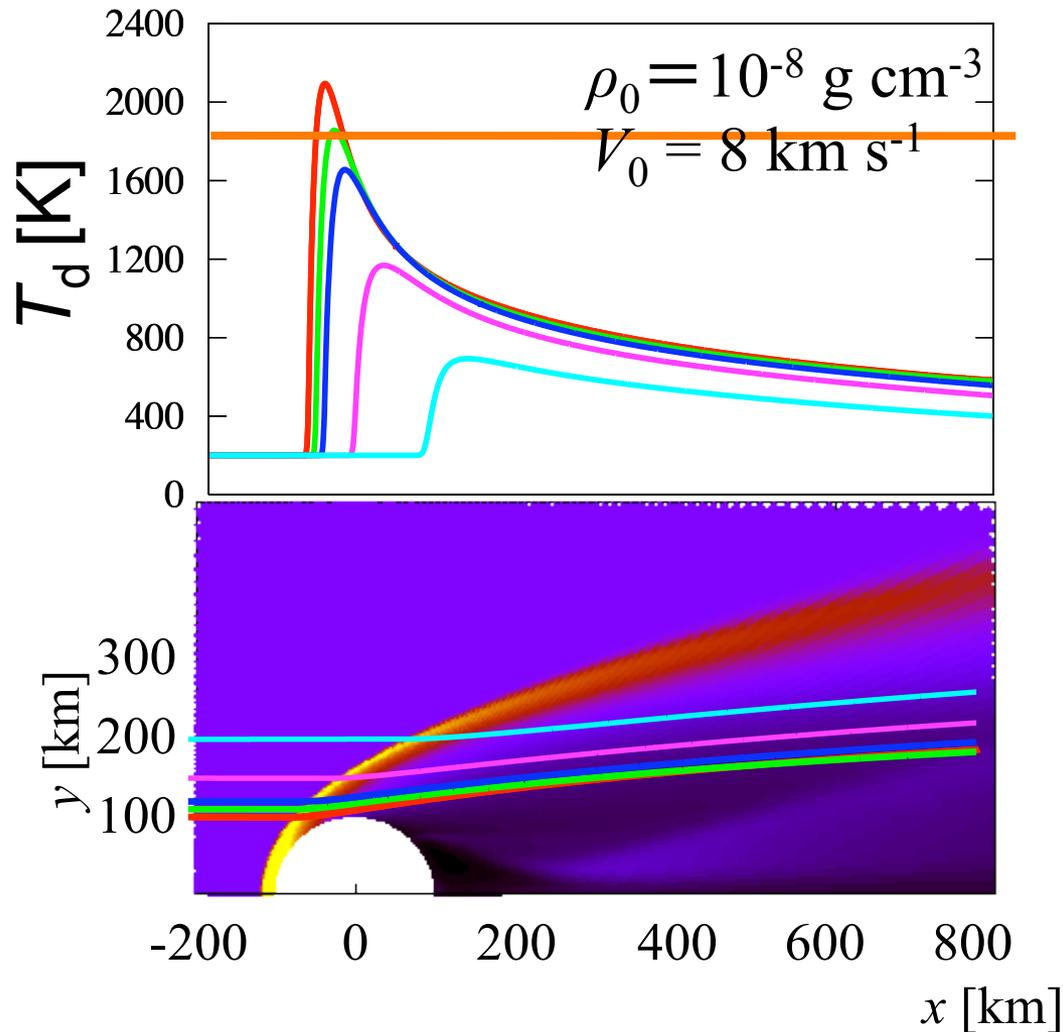
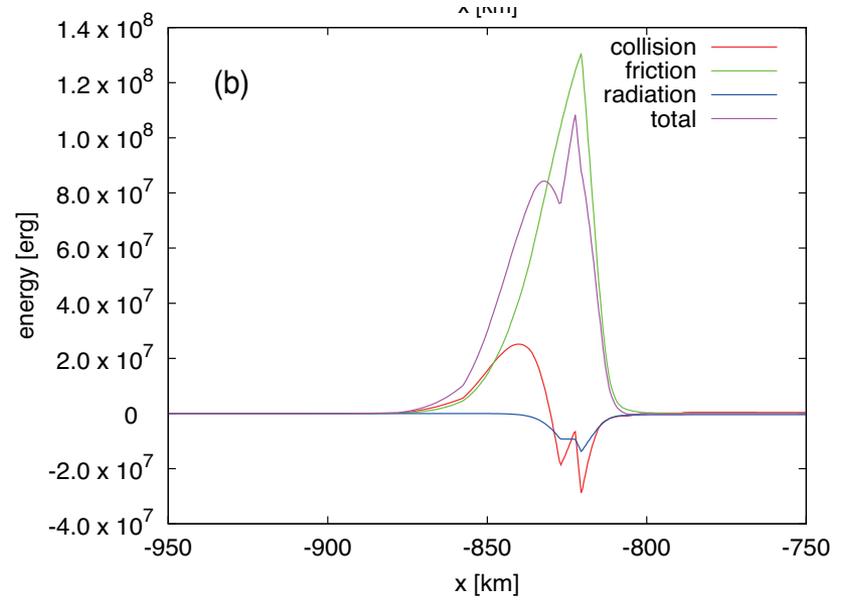
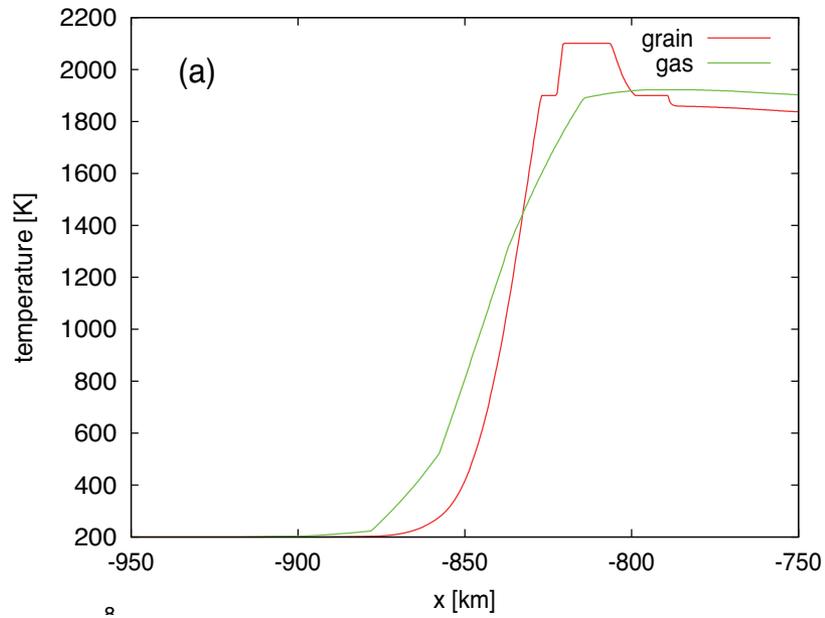


Figure 5.5: Trajectories of dust grains in the flow around the planetesimal with $R_{\text{pl}} = 1000$ km, $\rho_{\text{g},0} = 10^{-8}$ g cm $^{-3}$, $\mathbf{v}_{\text{g},0} = 10$ km s $^{-1}$ and $a = 1$ mm. The background gas is calculated with H $_2$ dissociation and the trajectories are calculated with melting and evaporation. Dashed line represents a trajectory of a dust particle whose peak temperature does not reach T_{melt} .

【結果】

- 軌跡に沿った粒子の温度

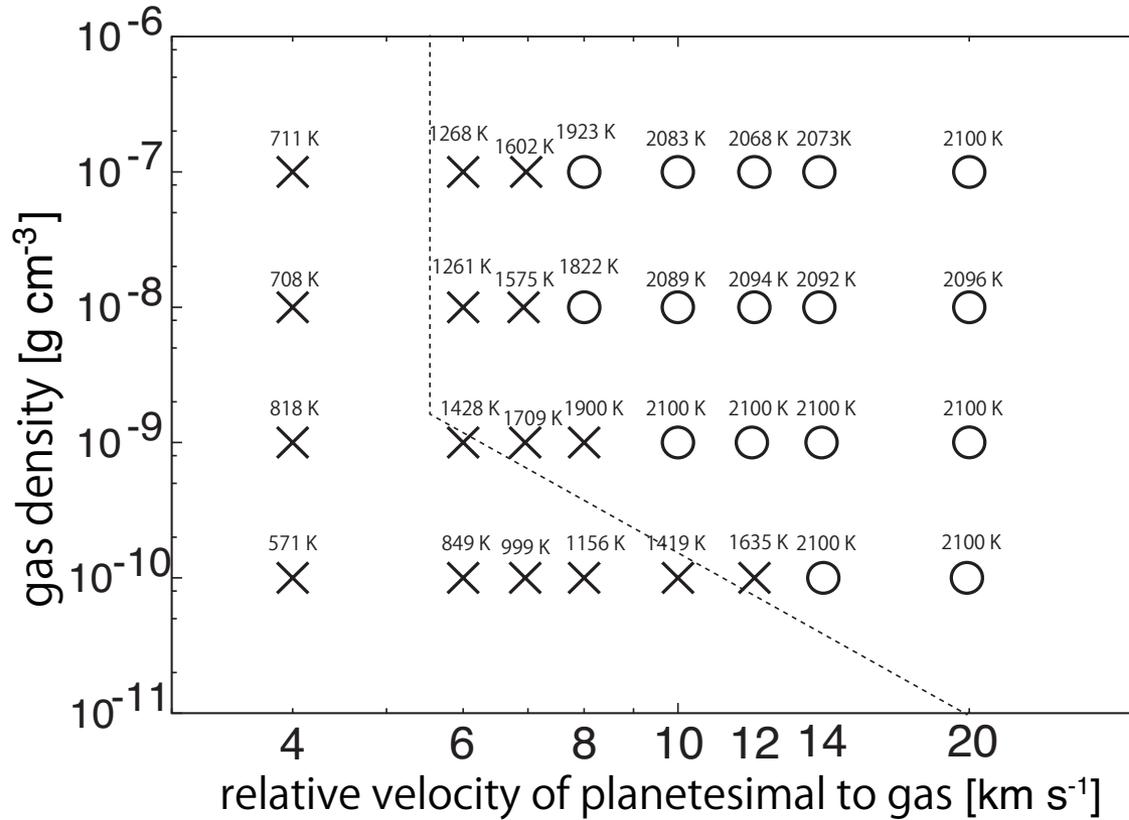




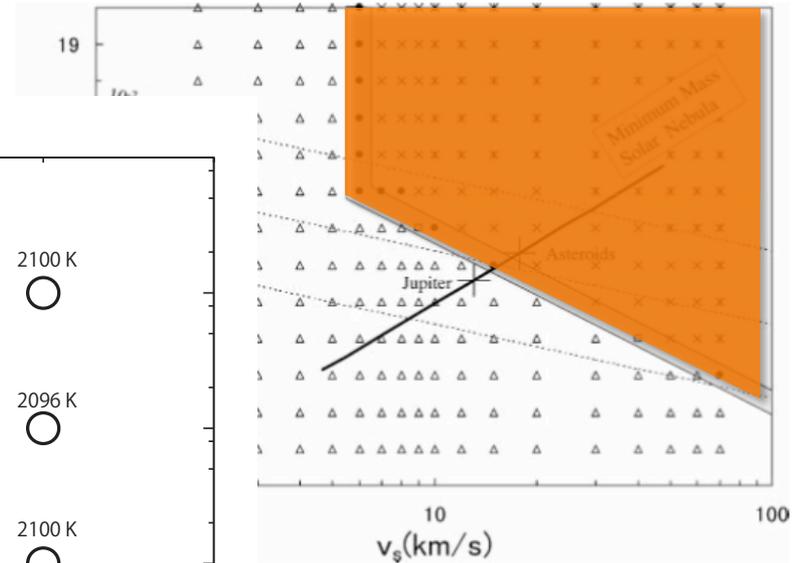
Yamazaki 2013

$$y_{\text{imp}} = 800 \text{ km}$$

Yamazaki 2013



$$R_{pl} = 1000 \text{ km}, a = 0.1 \text{ mm}$$



Iida *et al.* 2001

異なるサイズのダスト粒子の軌跡：複合コンドリュール形成？

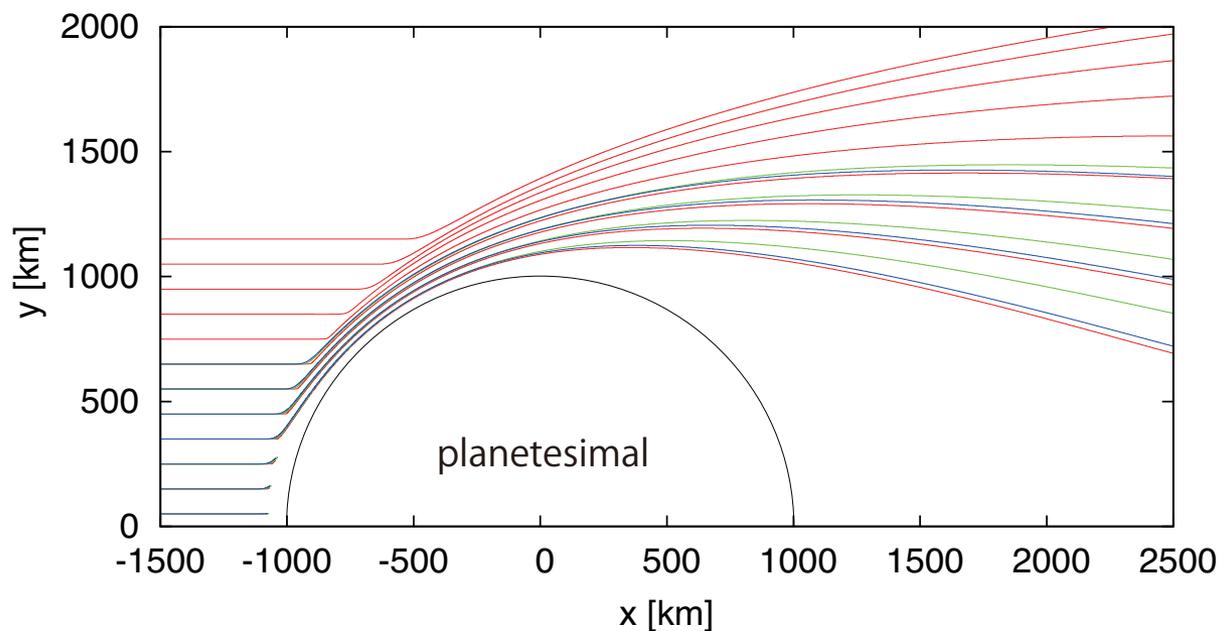


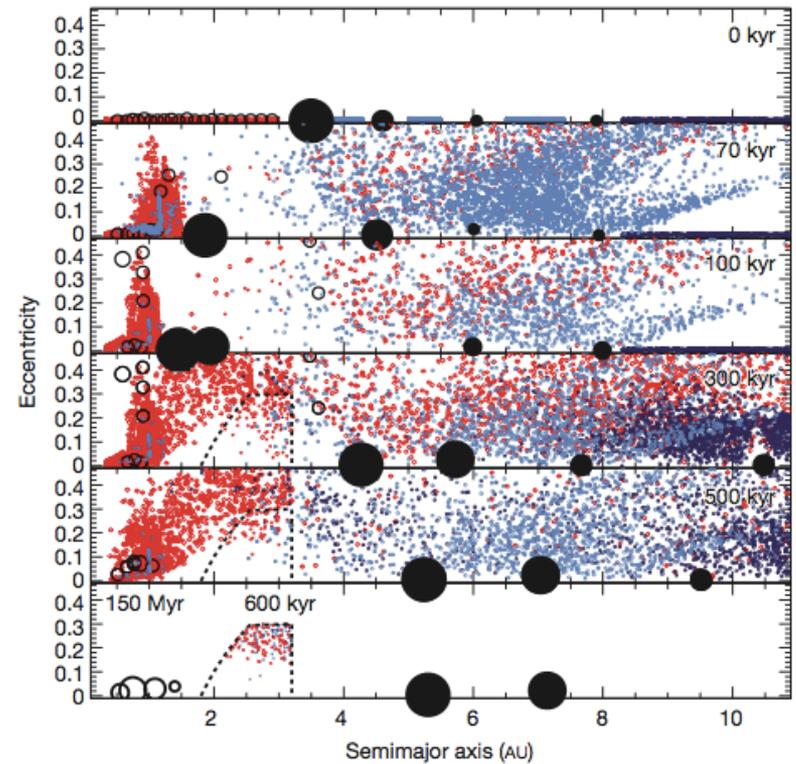
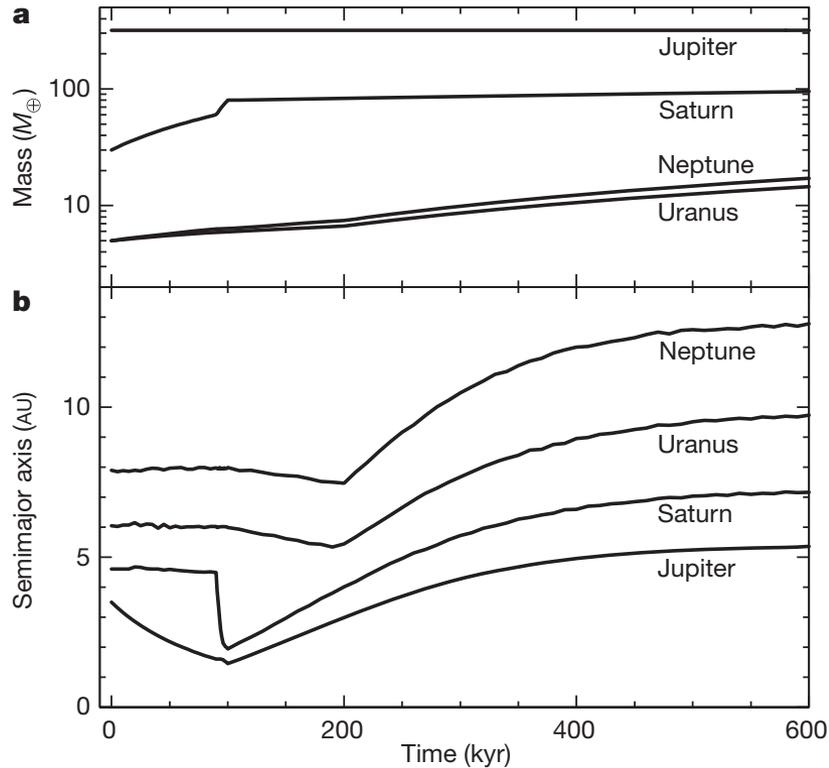
Figure 5.22: Trajectories of dust grains with $a_0 = 1\text{mm}$ (red), 0.1 mm (green), 0.01 mm (blue). The background gas is calculated with $\rho_{g,0} = 10^{-8}\text{ g cm}^{-3}$ and $v_{g,0} = 10\text{ km s}^{-1}$ with H_2 dissociation.

Yamazaki 2013

$$\Delta V = 26\text{ m/s} \quad \dots ?$$

太陽系の形成に特化したモデル:

The Grand Tack Scenario (Morbidelli *et al.* 2012)



Walsh *et al.* 2011

- ガス惑星/氷惑星
- 地球型惑星
- 小惑星
- ...

3. 微惑星形成との関係

- ・連続合体成長モデル
大丈夫？
- ・重力不安定モデル
重力不安定が起こるか？

乱流中でダスト集積 → 重力不安定

★ Streaming Instability

Youdin & Goodman 2005

Nakagawa *et al.* 1986 の定常解は不安定

粒子速度と
方位角方向速度
のゆらぎ

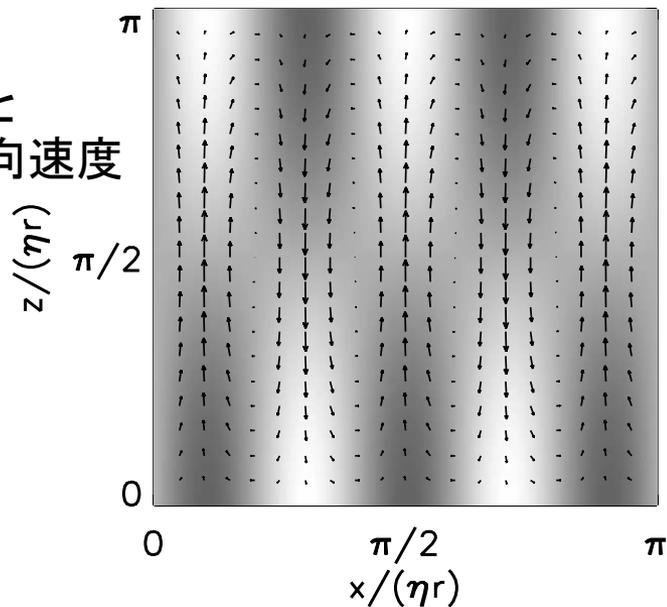


FIG. 5.—Instantaneous (perturbed) particle velocity v_p in the x - z plane with a gray-scale image of azimuthal velocities (white is positive) for a growing mode with $K_x = 5$, $|K_z| = 1$, $\tau_s \approx .044$, and $\rho_p/\rho_g = 0.2$. Gas velocities are very similar because of strong coupling. The density is very nearly in phase with the azimuthal speed, so the vertical flow is channeled to high-density regions. The ratio of azimuthal to vertical velocity amplitudes is $|v_p|/|w_p| \simeq 0.66$. The radial-to-vertical ratio, $|u_p|/|w_p| \simeq K_z/K_x = 0.2$, follows from near incompressibility. This mode has a growth rate $s/\Omega \approx 2.9 \times 10^{-3}$ and a phase speed $\omega_R/k_x = -0.42|\Delta U|$.

ガス速度と
密度の
ゆらぎ

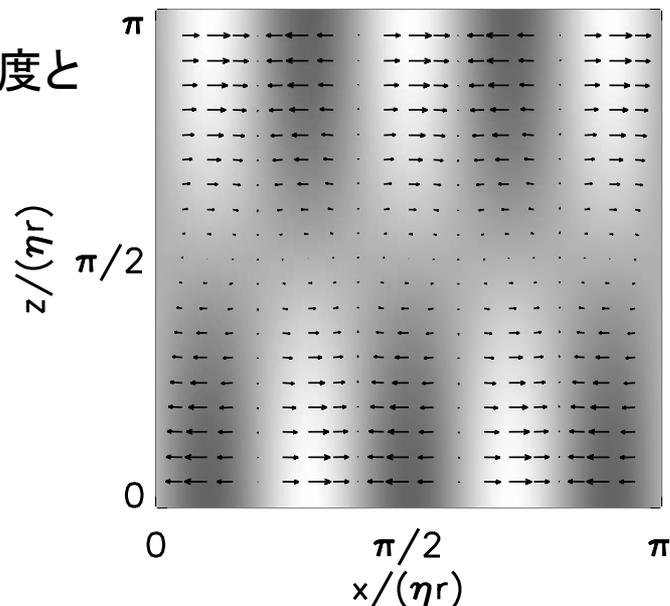
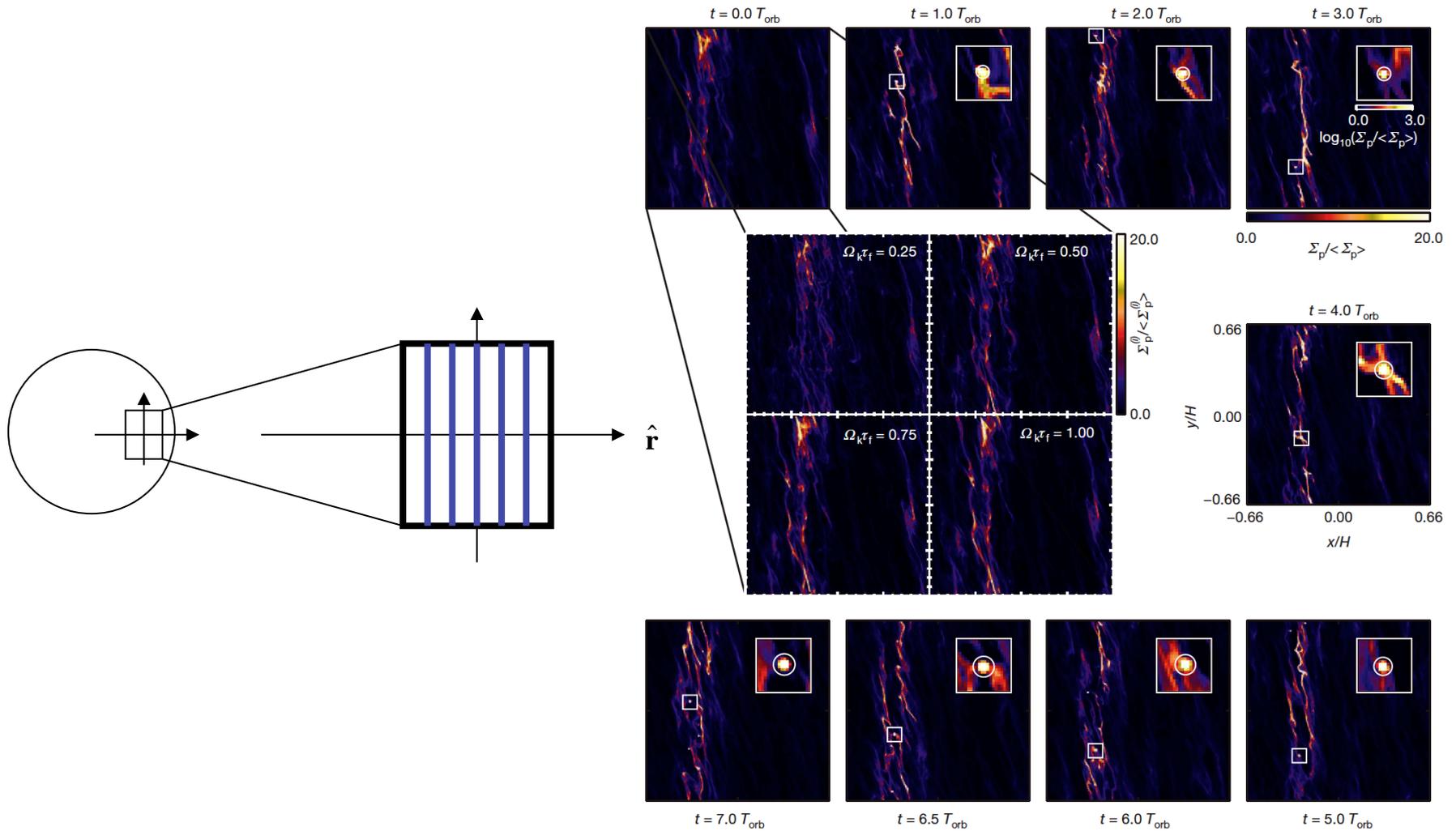


FIG. 6.—Perturbed relative motion of solids and gas, Δv , for the same mode as Fig. 5. The gray-scale image shows density perturbations (white is positive). The radial relative motion dominates the azimuthal, $|\Delta v|/|\Delta u| \approx 0.15$, and vertical, $|\Delta w|/|\Delta u| \approx 0.11$, speeds. Density perturbations correlate with relative motion.

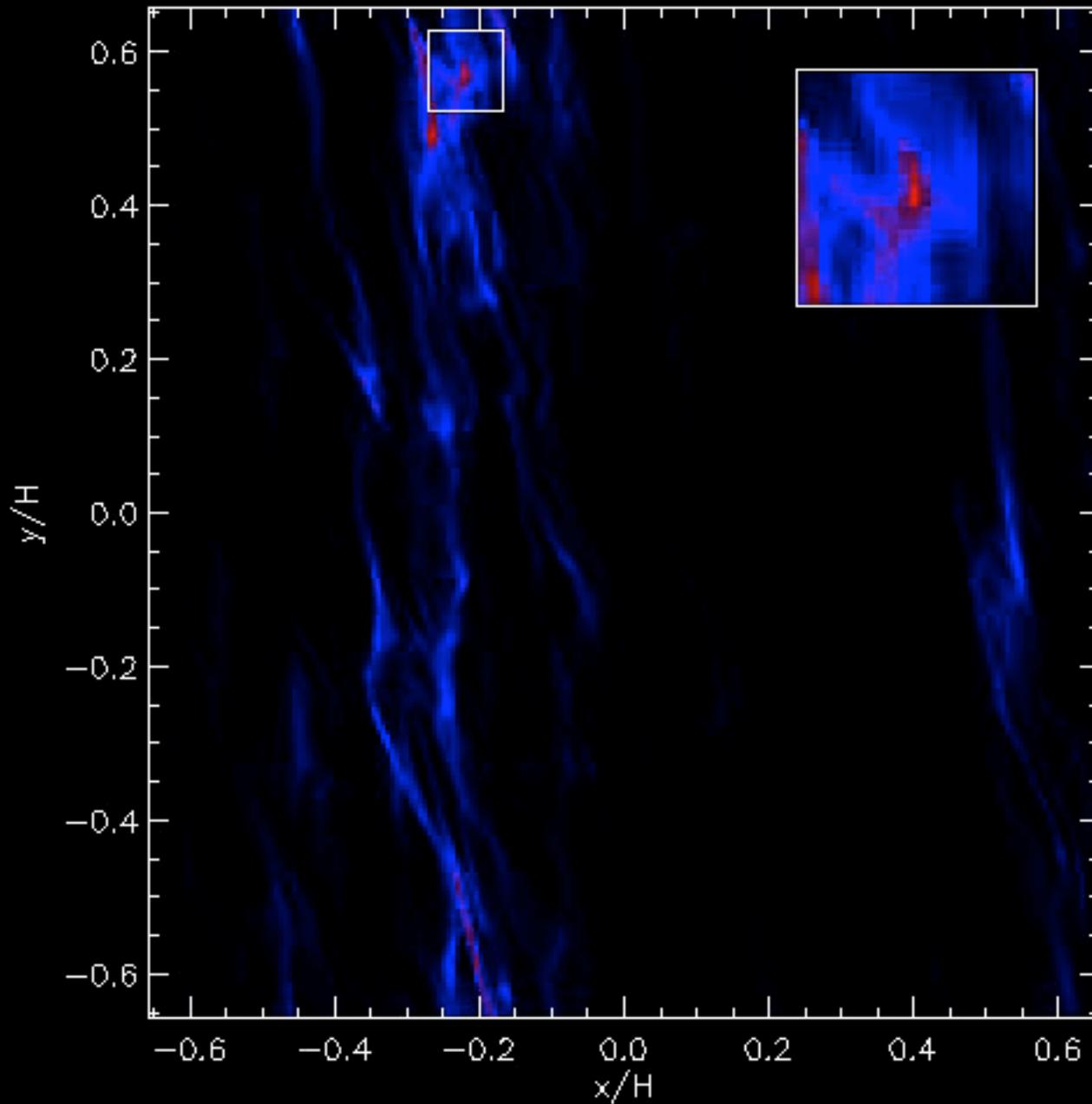
SI + GI による微惑星形成

Johansen *et al.* 2007



t=0.0

Johansen *et al.* 2007



~1000km
の微惑星

加熱の後に集積？

Equations of motion

$$\rho_g \frac{dv_g}{dt} = -\frac{\partial p_g}{\partial x} - \frac{\rho_g(v_g - v_d)}{\tau_{g,s}} \quad : \text{Gas}$$

$$\rho_d \frac{dv_d}{dt} = \frac{\rho_d(v_g - v_d)}{\tau_{d,s}} \quad : \text{Dust}$$

Equations of energy

$$c_g \rho_g T_g \frac{dT_g}{dt} - c_s^2 \frac{d\rho_g}{dt} = -\frac{c_g \rho_g (T_g - T_d)}{\tau_{g,t}} \quad : \text{Gas}$$

$$c_d \rho_d T_d \frac{dT_d}{dt} = \frac{c_d \rho_d (T_g - T_d)}{\tau_{d,t}} - 4\pi r_d^2 \epsilon \sigma_{SB} T_d^4 \frac{\rho_d}{m_d} \quad : \text{Dust}$$

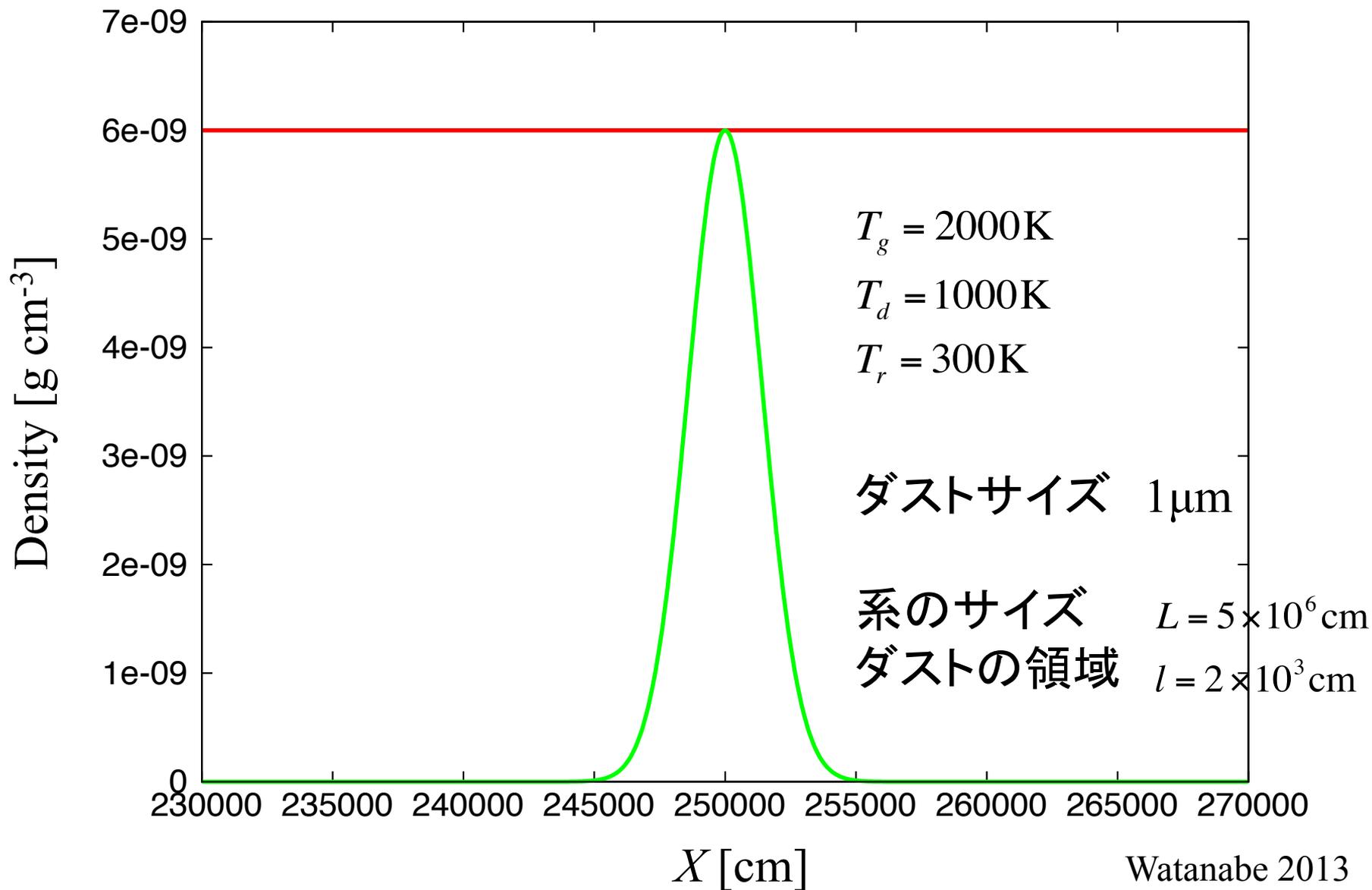
Ideal fluid

$$p_g = c_s^2 \rho_g$$

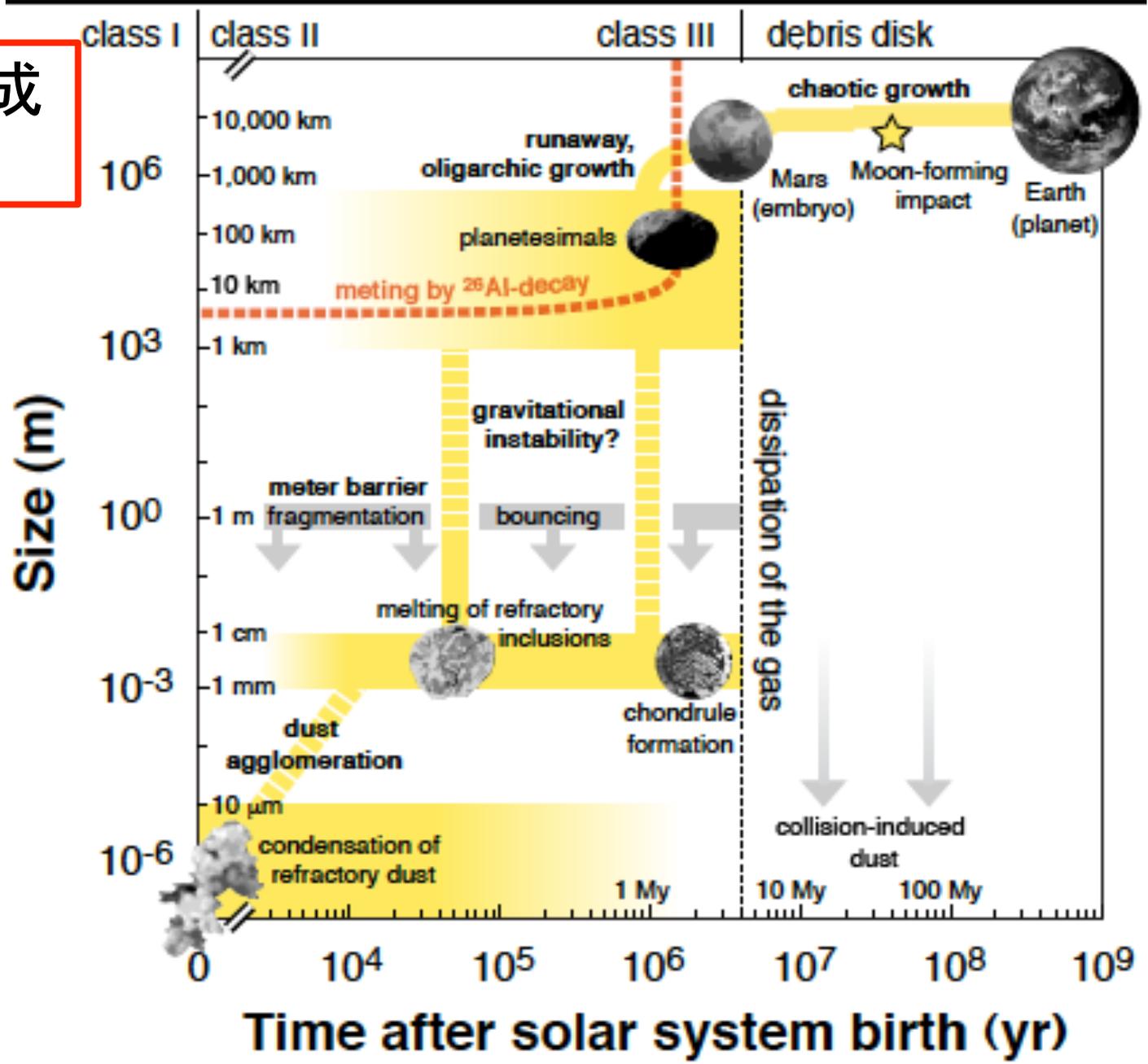
Time scales

$$\tau_{g,s}, \tau_{g,t} \sim \frac{r_d \rho_{\text{int}}}{c_s \rho_d}, \quad \tau_{d,s} = \frac{\rho_d}{\rho_g} \tau_{g,s}, \quad \tau_{d,t} = \frac{c_d \rho_d}{c_g \rho_g} \tau_{g,t}$$

ガス・ダスト初期密度分布



4. 惑星系形成 の理解



太陽系初期

(中本 私見 2013年1月)

