Staub in Planetensystemen/惑星系の「うちゅうじん」

Sep. 27 - Oct. 1, 2010, Jena, Germany

Formation of cosmic crystals by eccentric planetesimals

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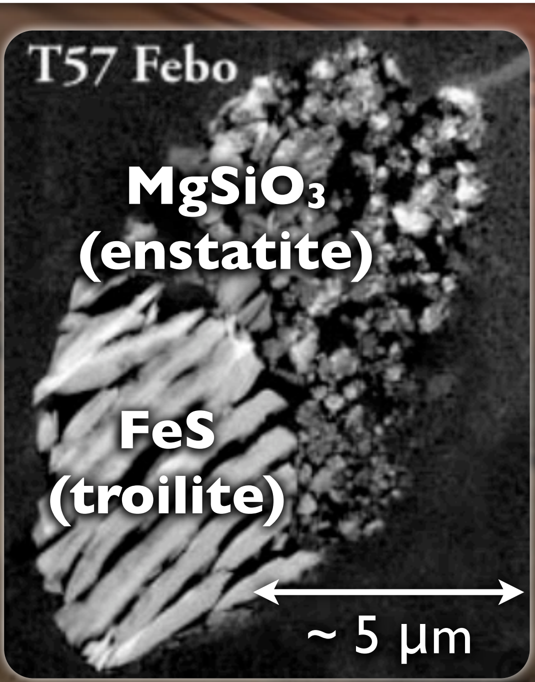
This study has been already published. (Miura+2010, ApJ 719, 642-654)

TOHOKU UNIVERSITY

Global Education and Research Center for Earth and Planetary Dynamics

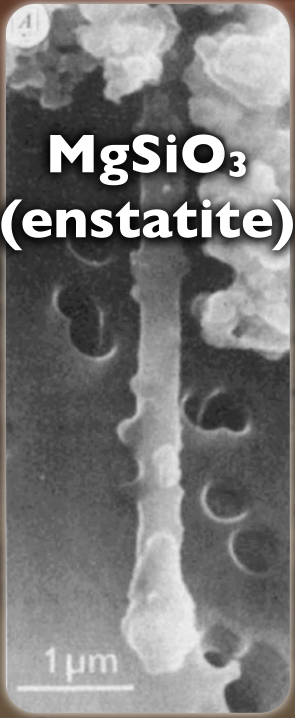
COSMIC CRYSTALS

Fine dust from comet



Stardust mission
(e.g., Brownlee+2006,
Science 314, 1711)

IDPs



(Bradley+1983,
Nature 301, 473)

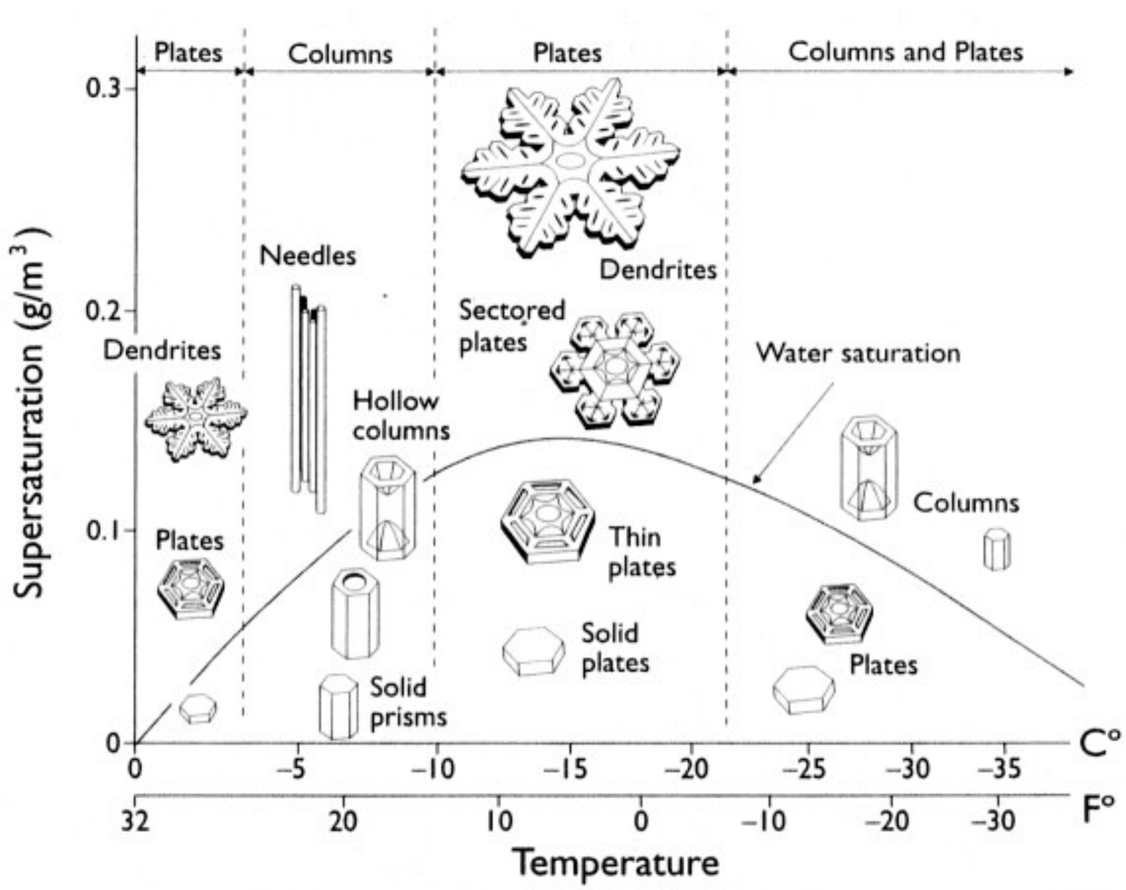
Primitive meteorite

(Nozawa+2009,
Icarus 204, 681)

NASA / JPL-Caltech

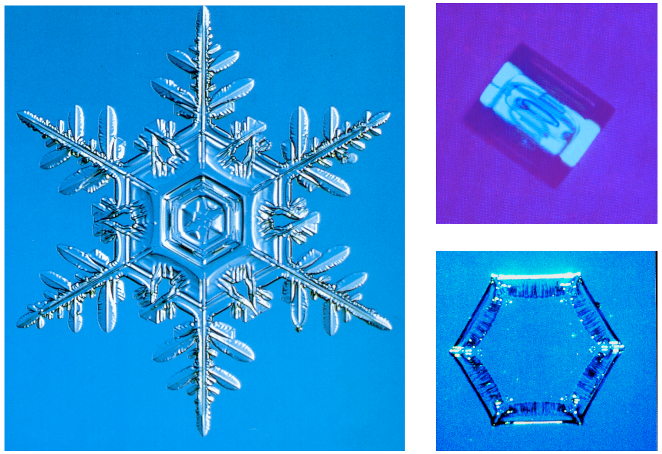
Introduction:

Morphodrom (snowflake)



Snowfrake changes its shape depending on temperature (undercooling) and supersaturation (density of water vapor)

(Nakaya diagram)



From Prof. Furukawa, Hokkaido Univ.

http://www.lowtem.hokudai.ac.jp/ptdice/

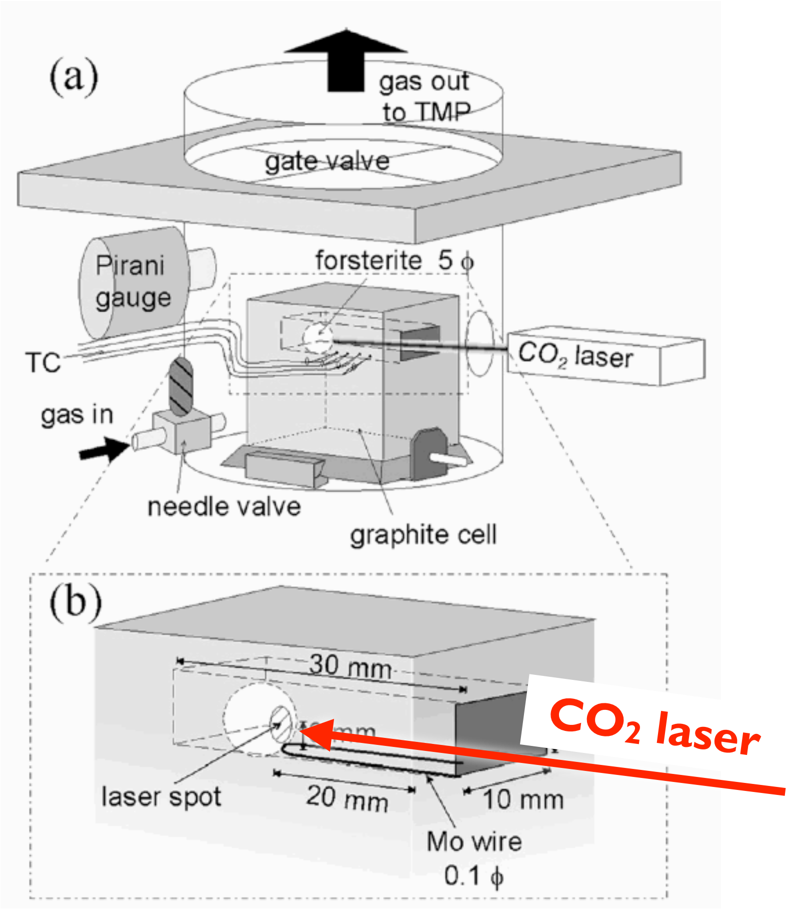
Morphologies of crystals reflect their formation condition

relationship
morphologies v.s.
formation condition
↓
"morphodrom"

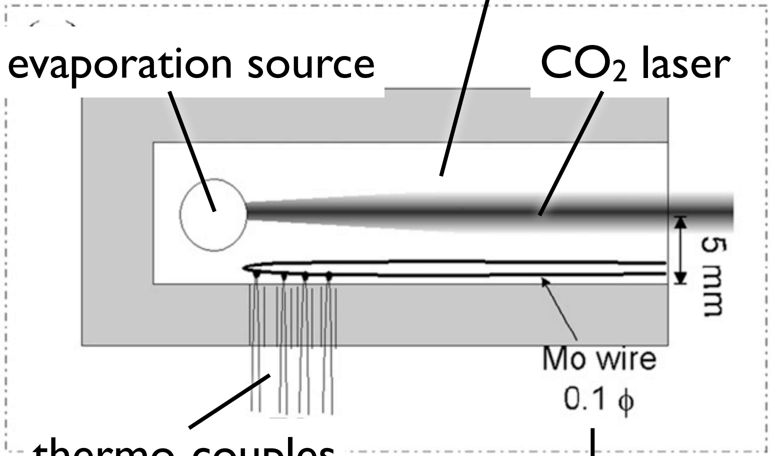
Introduction:

Evaporation + condensation experiments

flash heating by
CO_2 laser irradiation
(Kobatake+2008, Icarus 198, 208)



top view of graphite cell



Ar atmosphere ~ 10^{-3} - 10^{-2} atm

evaporation source

CO_2 laser

thermo-couples

↓

temperature measurement

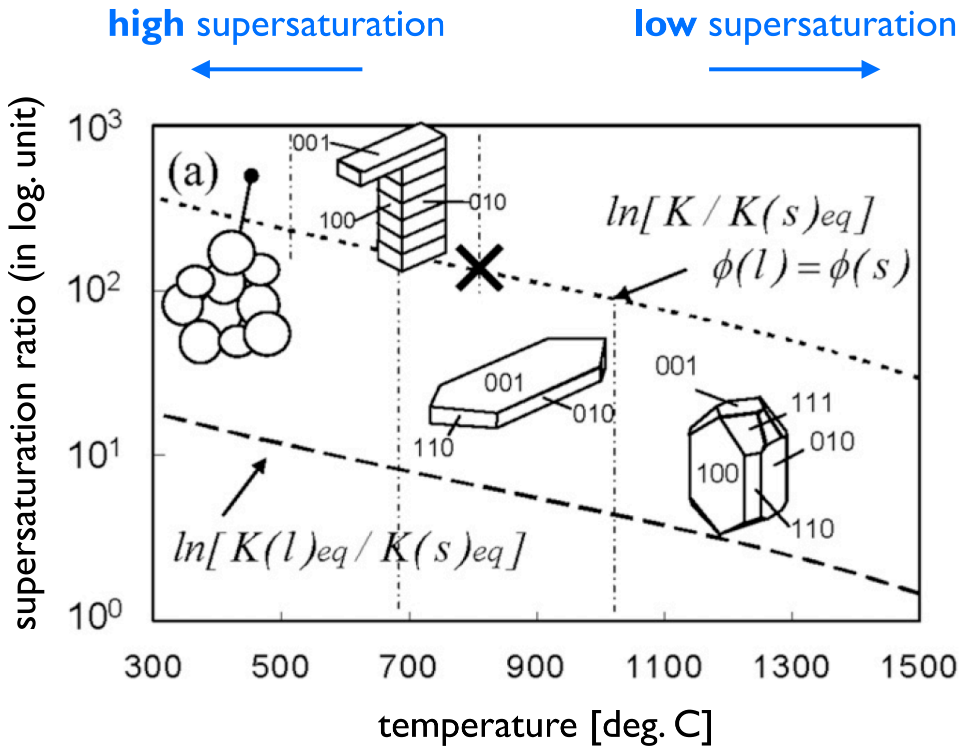
sample correction

↓

- chemical composition (EDS)
- morphology (FE-SEM)
- identification (TEM)

Introduction:

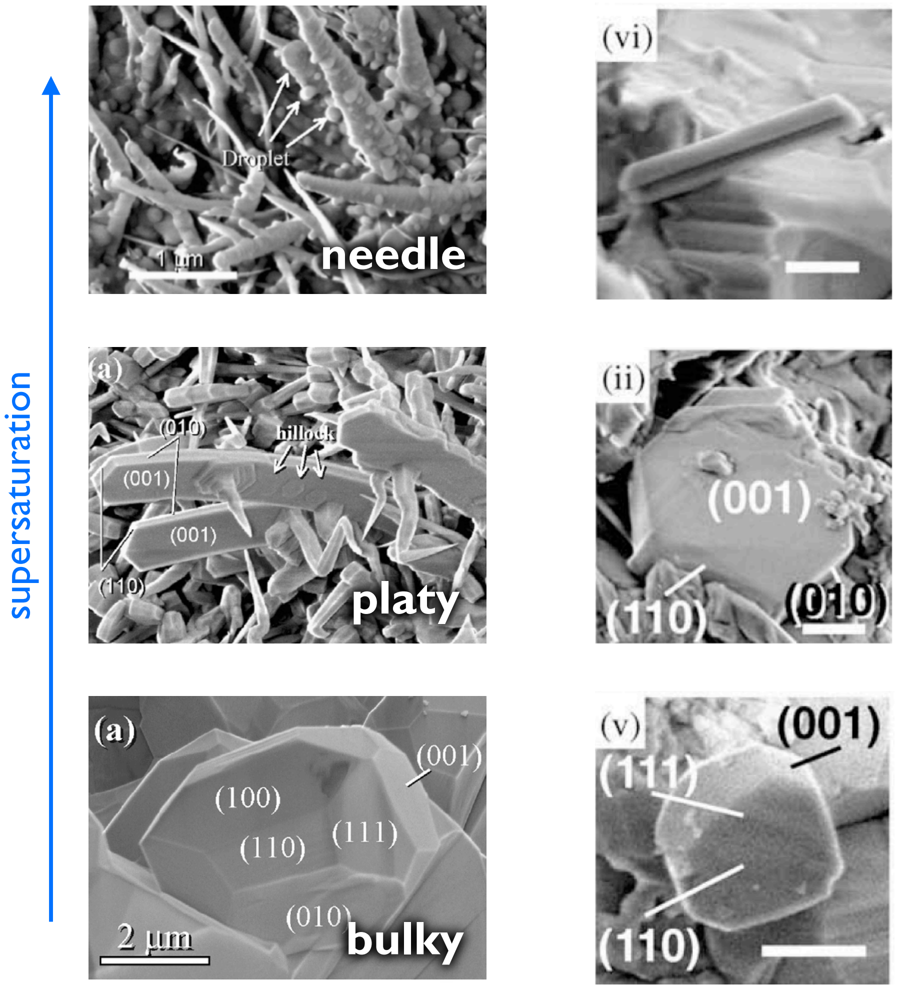
Morphodrom (forsterite)



similarity in morphology
↓
vapor growth
at high supersaturation

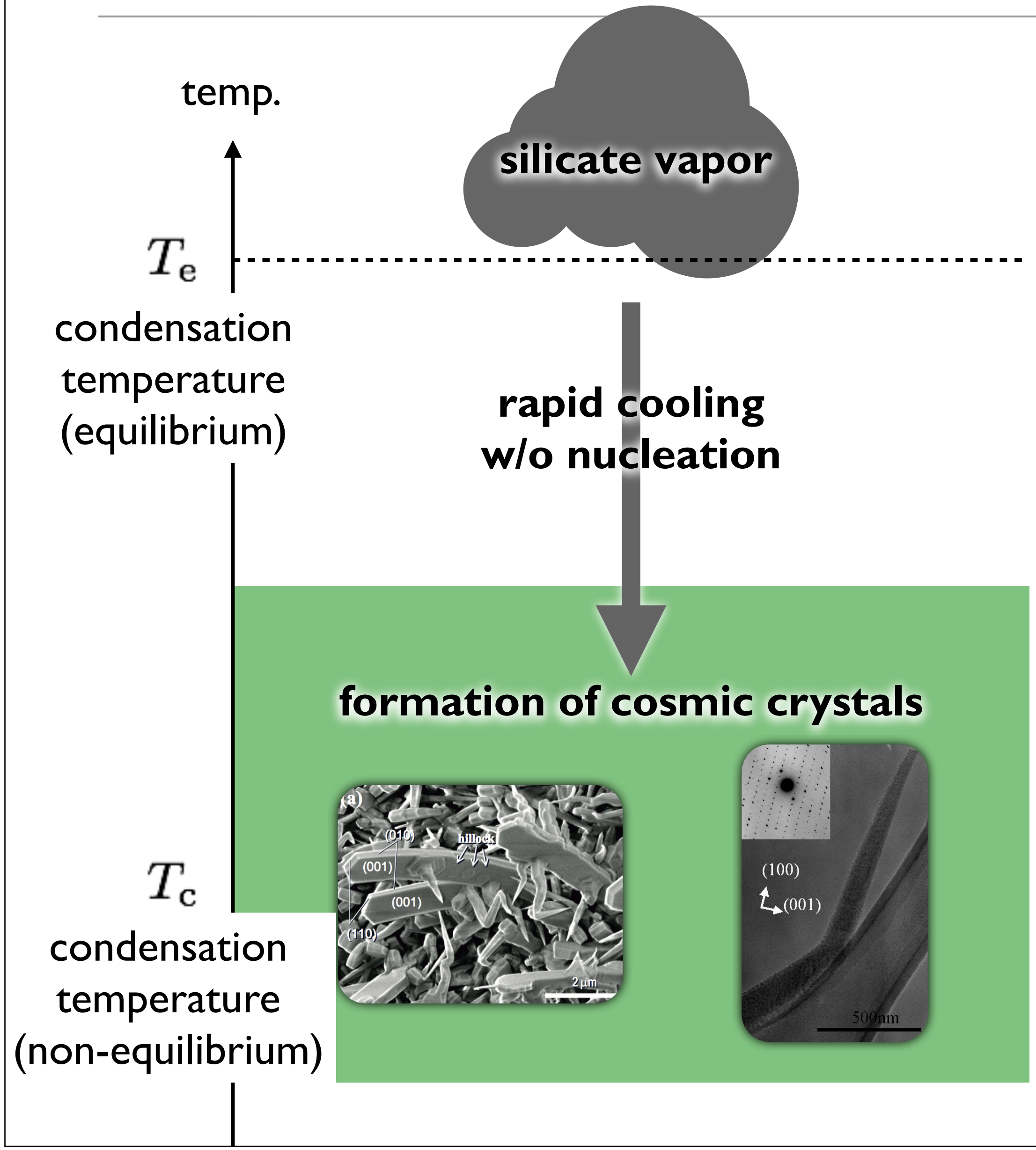
synthesized
(Kobatake+2008, Icarus 198, 208)

in matrix of Allende
(Nozawa+2009, Icarus 204, 681)



Introduction:

Condensation in non-equilibrium



condensation (equilibrium)

~ **1400 K** for forsterite (Mg_2SiO_4)

at 10^{-3} atm (Grossman 1972, GCA 36, 597)

supercooling of ~ 200 - 700 K

condensation (non-equilibrium)

~ **700 - 1200 K** for forsterite (Mg_2SiO_4)

at ~ 10^{-3} atm (Kobatake et al. 2008, Icarus 198, 208)

requirement:

- **vapor generation**
- **rapid cooling of the vapor**

Introduction:

Candidate of cosmic crystal formation

eccentric planetesimals:

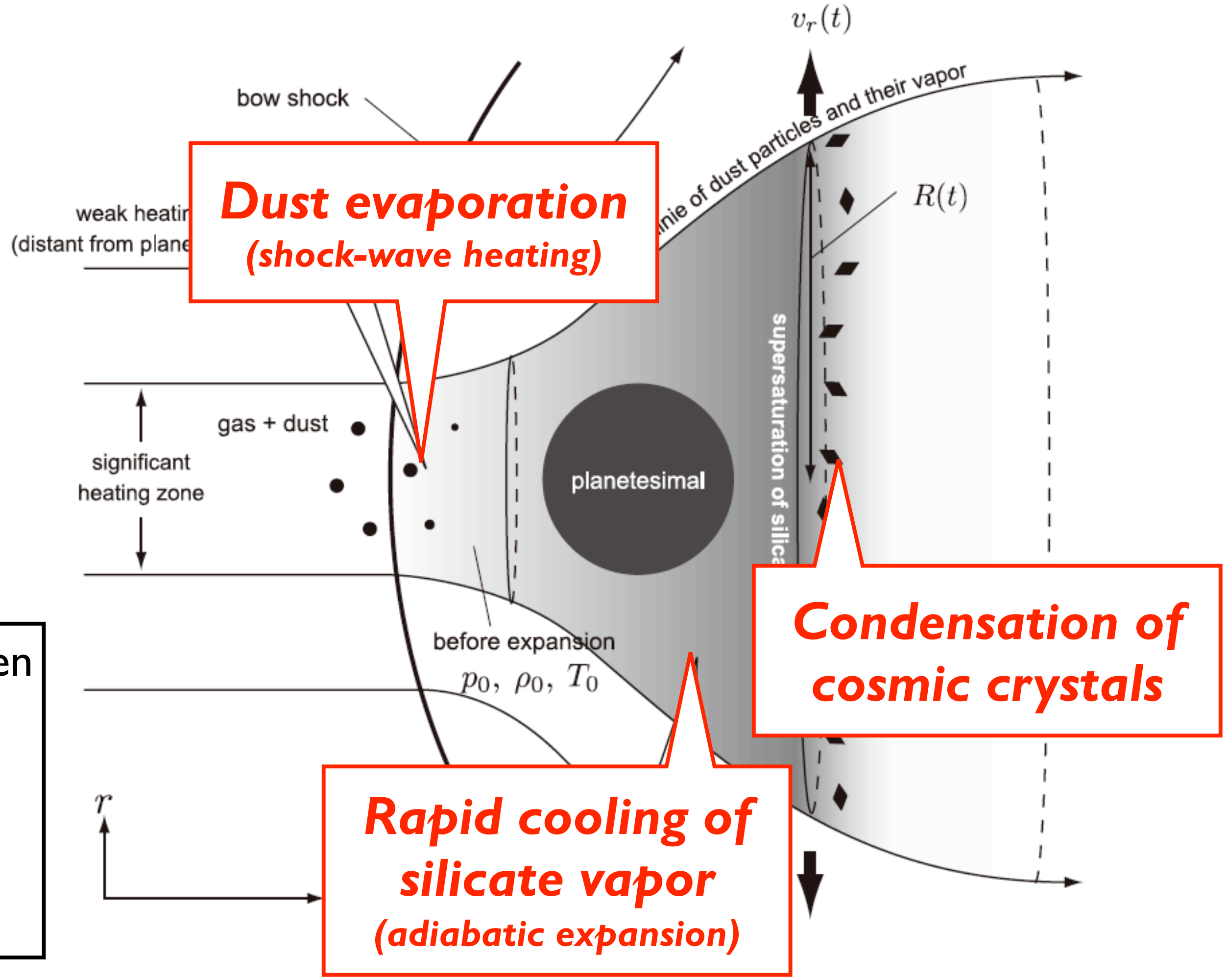
During planet formation, planetesimals take eccentric orbits because of gravitational interaction between themselves.

- **Jovian resonances**
  (Weidenschilling+1998, Science 279, 681)
- **Dynamical shake-up**
  (Nagasawa+2005, ApJ 635, 578)

relative velocity (supersonic) between
- nebular gas (e ~ 0)
- planetesimals (e > 0)

↓

"bow shock"



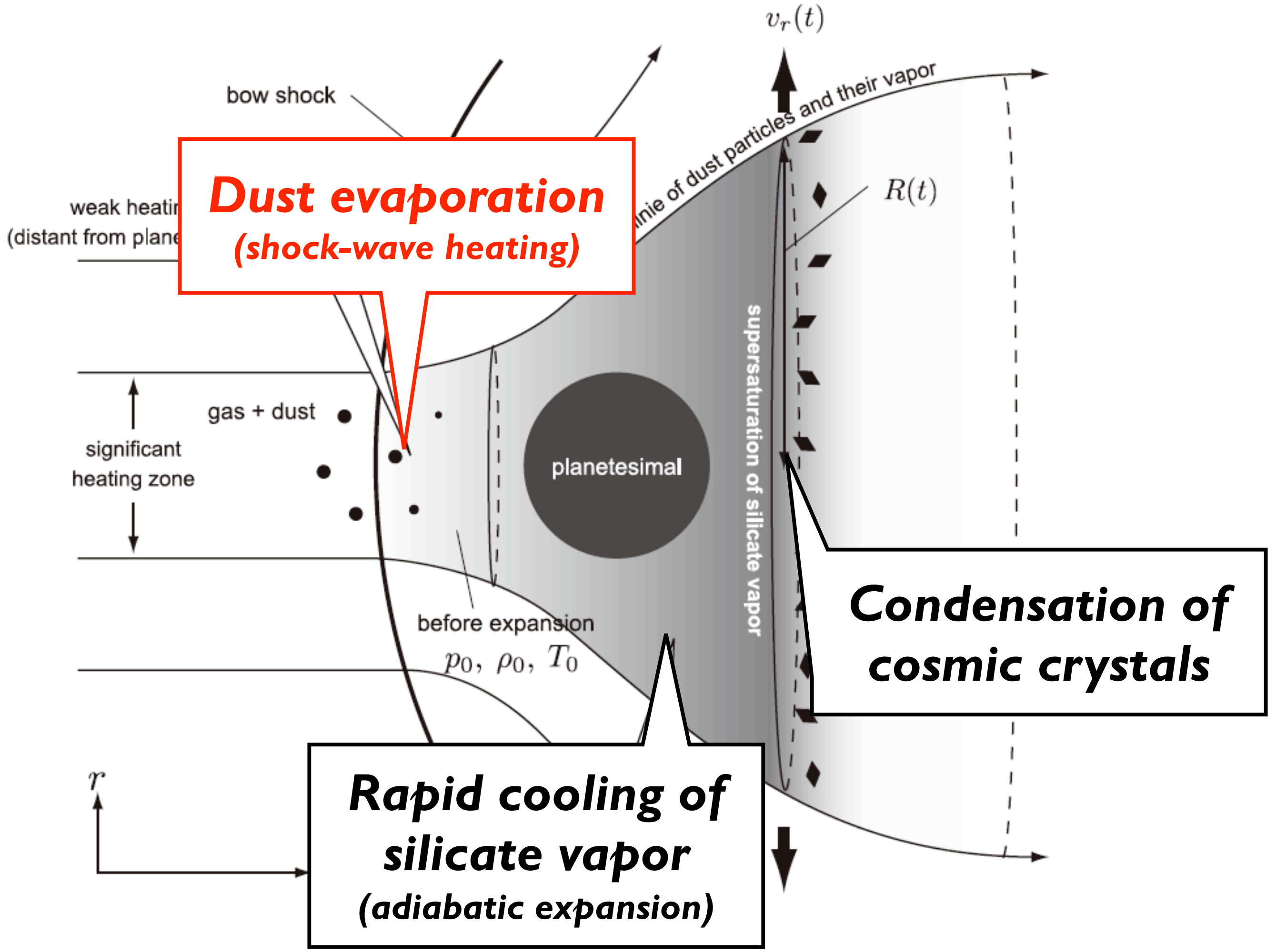
Dust evaporation
(shock-wave heating)

Condensation of cosmic crystals

Rapid cooling of silicate vapor
(adiabatic expansion)

Fig. schematic of planetesimal bow shock
(Miura+2010, ApJ 719, 642)

1. Dust evaporation



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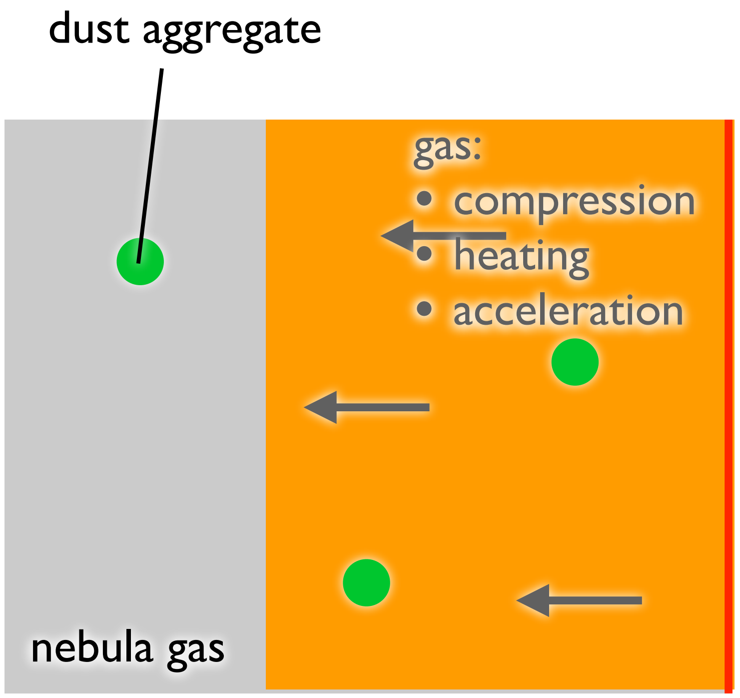
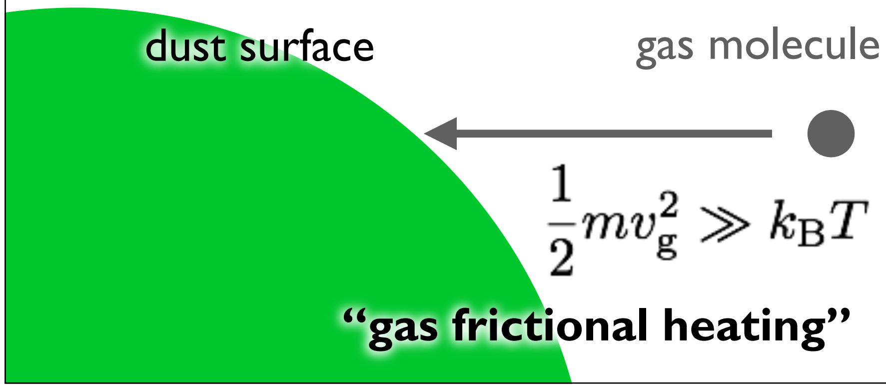
1. Dust evaporation

Shock-wave heating

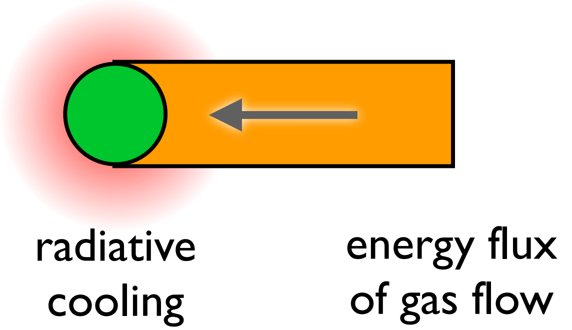




$$\frac{1}{2}mv_{\rm g}^2 \gg k_{\rm B}T$$

"gas frictional heating"

How strong is the gas frictional heating?



$$4\pi a_{\rm d}^2 \epsilon \sigma_{\rm SB} T^4 = \pi a_{\rm d}^2 n m v_{\rm g}^3$$

(Iida+2001, Icarus 153, 430)

For v_g = 10 km s^{-1} and n = 10^{15} cm^{-3}, we obtain

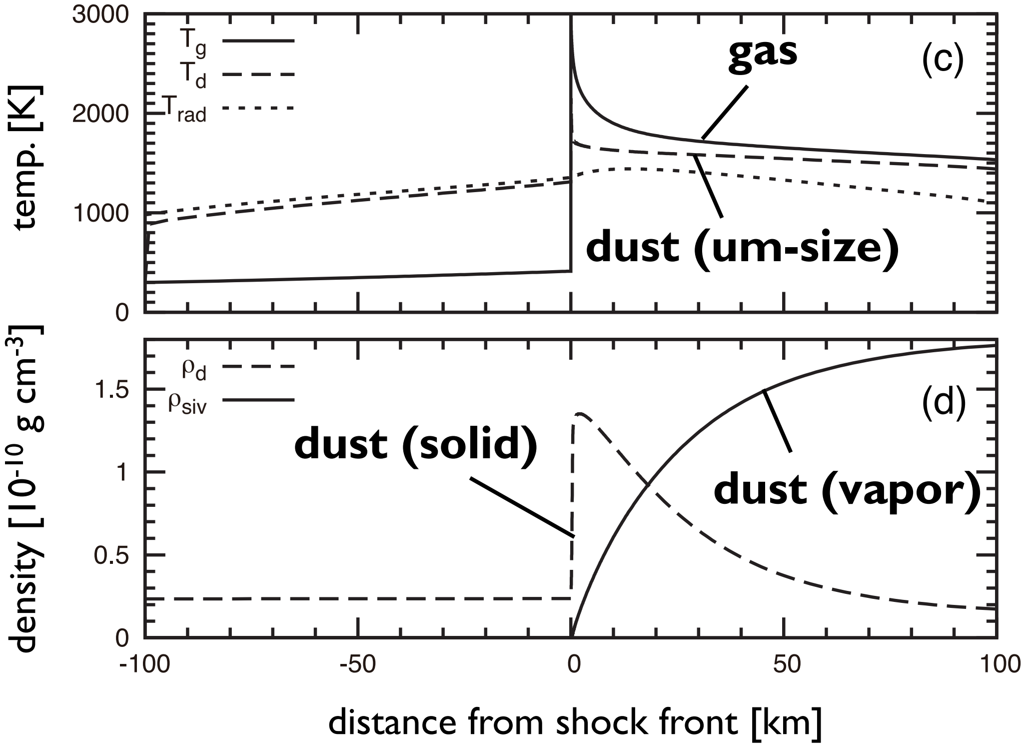
T_{peak} ~ 1720 K

- melting of silicate dust aggregates (chondrule formation)
  (Wood 1984, EPSL 70, 11 and others)
- evaporation of um-sized particles
  (Miura+2005, Icarus 175, 289)

1. Dust evaporation

Dust in hot gas

1D plane-parallel steady model
(Miura+2010, ApJ 719, 642)



input parameters:

planetesimal radius	$R_\mathrm{p} = 100\ \mathrm{km}$
gas number density (pre-shock)	$n_0 = 10^{15}\ \mathrm{cm}^{-3}$
shock velocity	$v_\mathrm{s} = 8\ \mathrm{km\ s}^{-1}$
gas/dust mass ratio	$\xi = 0.01$
dust radius	$a_\mathrm{d} = 1\ \mu\mathrm{m}$

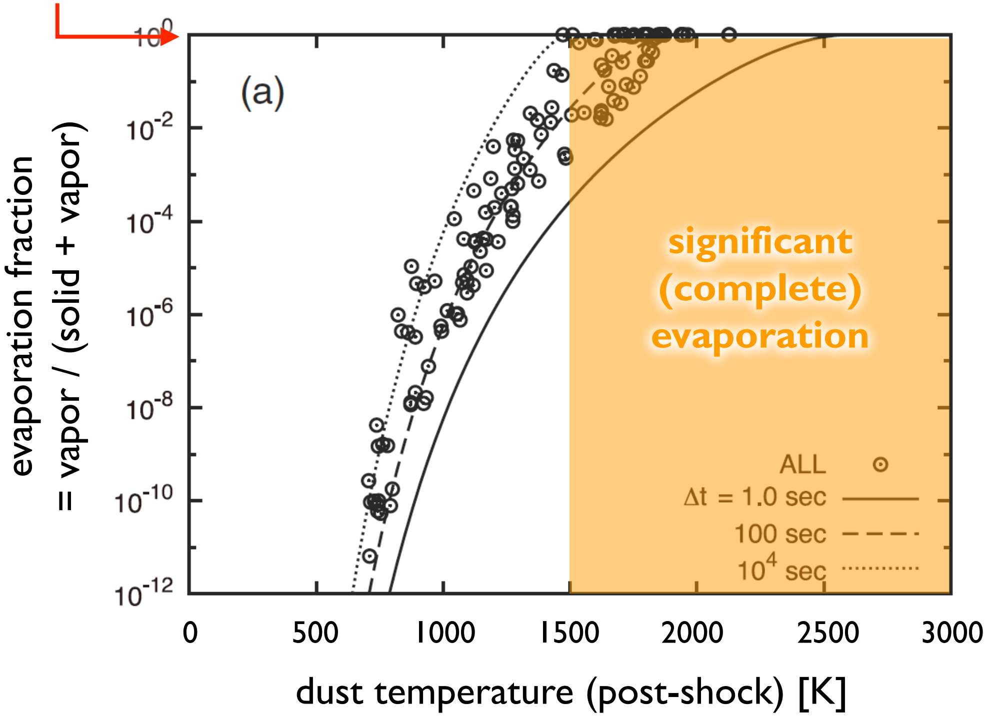
post-shock gas (far from shock front):

- temp. ~ 1700 K
- density ~ 4×10^{-8} g cm^{-3}
- no relative velocity to dust

- dust temperature > 1500 K
- evaporate significantly (90% in mass evaporates away, in this case)

1. Dust evaporation

Evaporation fraction



complete evaporation (fraction = 1)

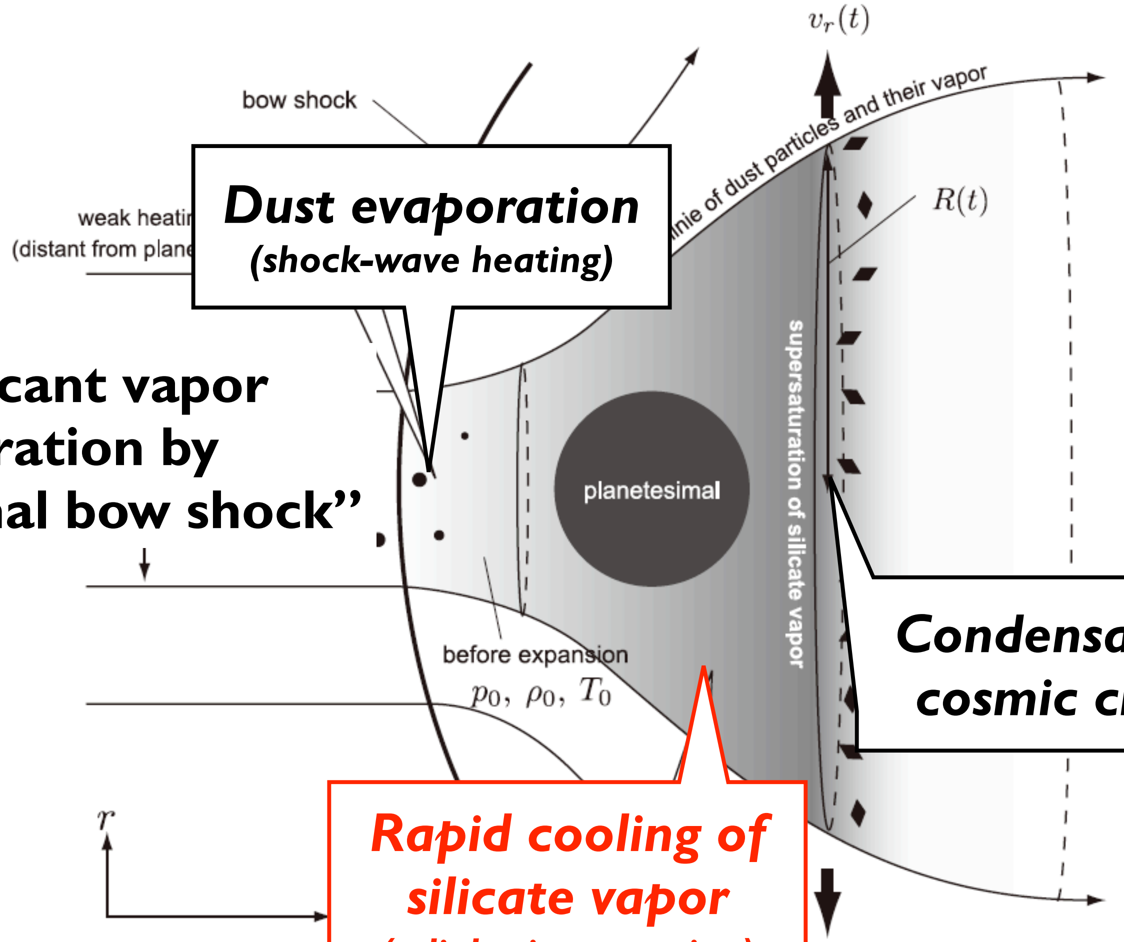
input parameters:

planetesimal radius	$R_\mathrm{p} = 1 - 1000$ km
gas number density (pre-shock)	$n_0 = 10^{13} - 10^{15}\ \mathrm{cm}^{-3}$
shock velocity	$v_\mathrm{s} = 5 - 60\ \mathrm{km\ s}^{-1}$
gas/dust mass ratio	$\eta = 0.01 - 0.1$
dust radius	$a_\mathrm{d} = 1\ \mu\mathrm{m}$

“significant vapor generation by planetesimal bow shock”

2. *Rapid cooling of silicate vapor*

"significant vapor generation by planetesimal bow shock"



Dust evaporation
(shock-wave heating)

Condensation of cosmic crystals

Rapid cooling of silicate vapor
(adiabatic expansion)

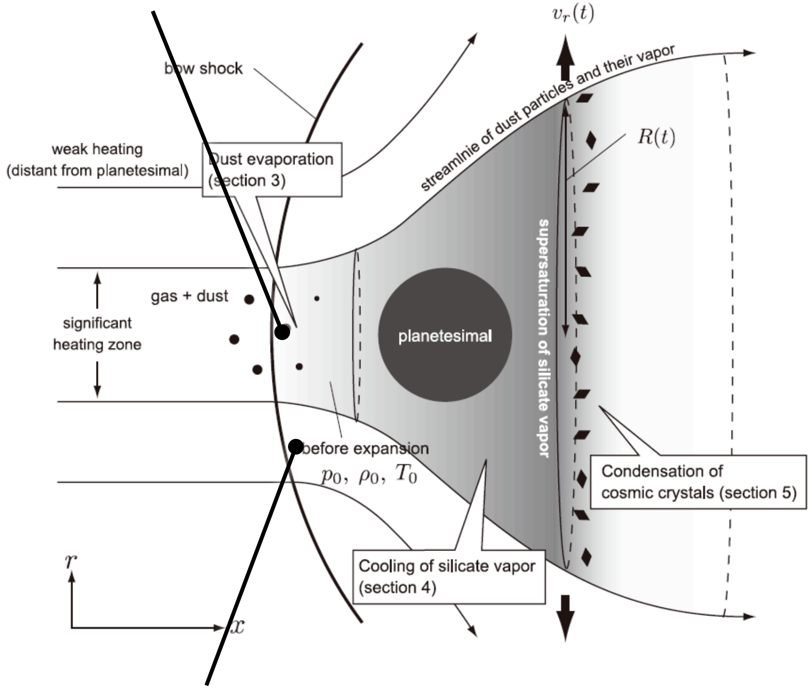
Fig. schematic of planetesimal bow shock
(Miura+2010, ApJ 719, 642)

2. Rapid cooling of silicate vapor

Expansion of shocked gas

vertical shock

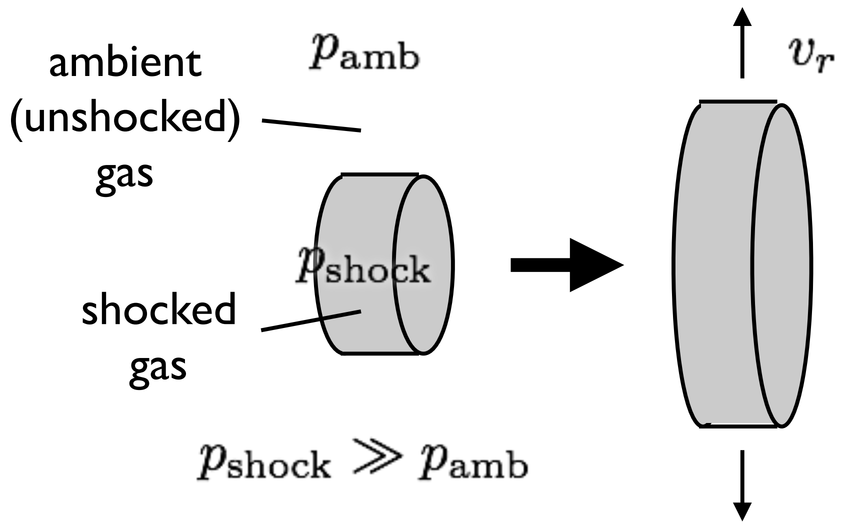
post-shock gas is **strongly** compressed and heated.



oblique shock

Compression and heating are relatively weaker.

adiabatic expansion by pressure gradient (one-zone model):



$$p_{\rm shock} \gg p_{\rm amb}$$

timescale of expansion:

$$t_{\rm s0} \sim R_{\rm p}/c_{\rm s0}$$

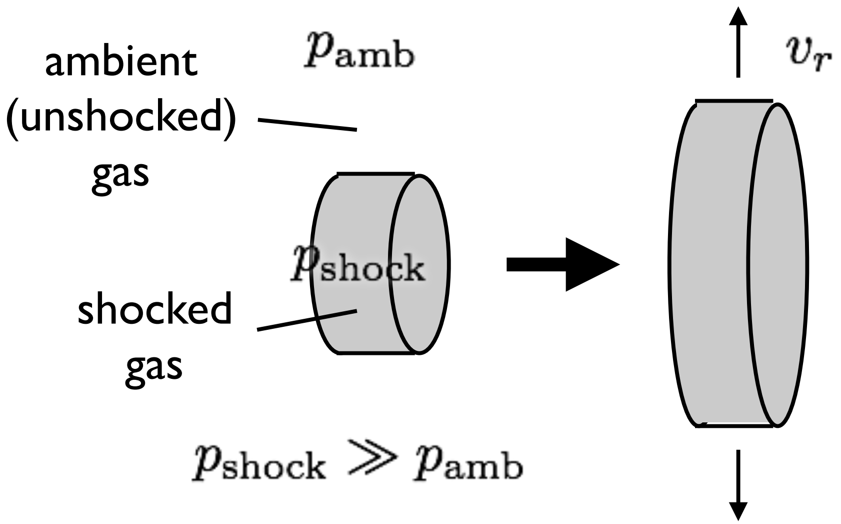
sound speed (~ 4 km s^{-1})

radius of shocked region ~ planetesimal radius (assumption)

Shocked gas expands in sound-crossing time

2. Rapid cooling of silicate vapor

One-zone model



Eq. of motion for vertical direction:

$$\frac{dv_r}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial r},$$

One-zone approximation:

$$v_r \sim \frac{dR}{dt}, \qquad \frac{\partial p}{\partial r} \sim -\frac{p}{R},$$

↓

Eq. of expansion:

$$\frac{d^2\tilde{R}}{d\tilde{t}^2} = \frac{1}{2}\tilde{R}^{-2\gamma+1},$$

with normalization as

- radius: $\tilde{R} = R/R_{\rm p}$
- time: $\tilde{t} = t/t_{\rm s0}$
- velocity: $\tilde{v}_r = v_r/c_{\rm c0}$

solution:

- expansion velocity

$$\tilde{v}_r = \frac{d\tilde{R}}{d\tilde{t}} = \left[\frac{1-\tilde{R}^{-2(\gamma-1)}}{\gamma(\gamma-1)}\right]^{1/2}$$

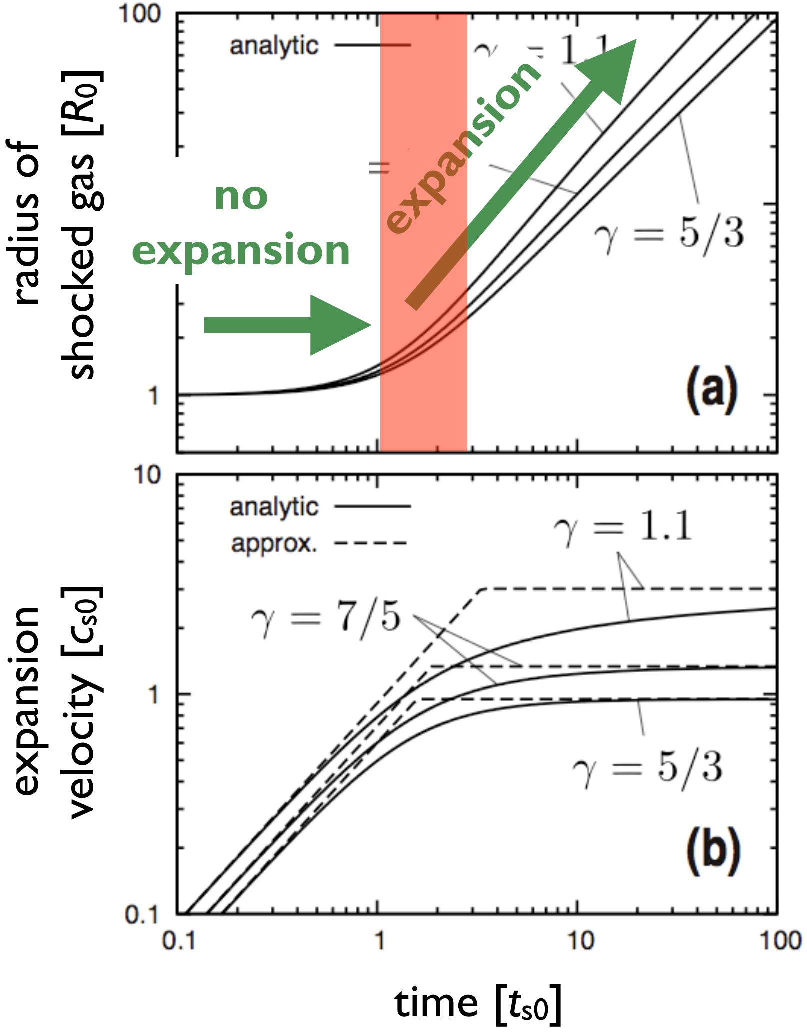
- radius of shocked gas

$$\frac{\tilde{t}}{\sqrt{\gamma(\gamma-1)}} = \int_1^{\tilde{R}} \frac{dy}{\sqrt{1-y^{-2(\gamma-1)}}}$$

2. *Rapid cooling of silicate vapor*

Analytic solution

expansion occurs after ~ 1 - 3 x t_{s0}



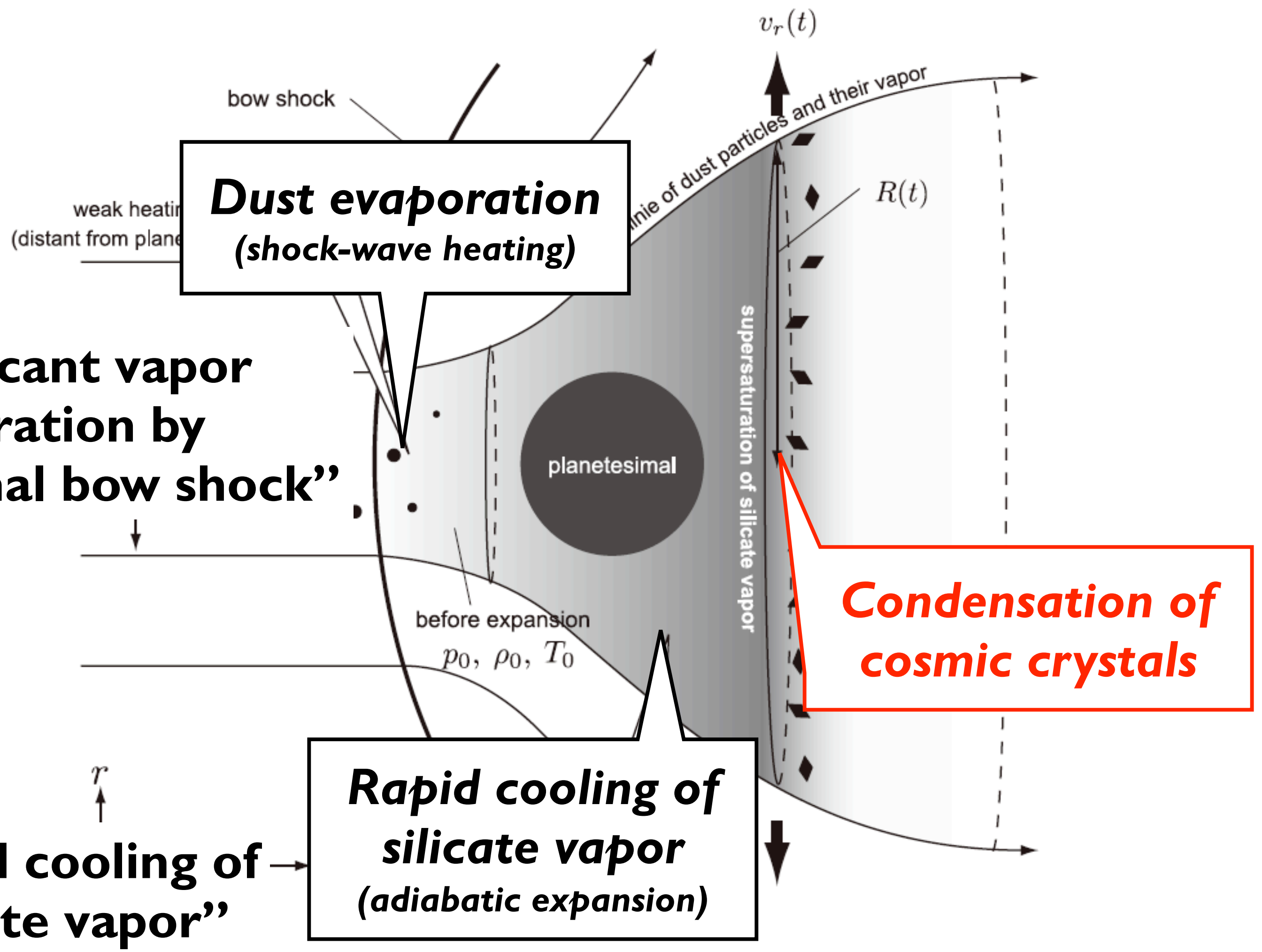
cooling rate of silicate vapor:

$$-\left(\frac{dT}{dt}\right) \simeq (0.25-0.35)\times T_0/t_{s0}$$
$$\simeq 2000\left(\frac{R_\mathrm{p}}{1\ \mathrm{km}}\right)^{-1}\left(\frac{T_0}{2000\ \mathrm{K}}\right)$$
$$\times\left(\frac{c_{s0}}{3.7\ \mathrm{km\ s^{-1}}}\right)\ \mathrm{K\ s^{-1}}$$

- **small** planetesimal → **rapid** cooling
- **large** planetesimal → **slower** cooling

“rapid cooling of silicate vapor”

3. Condensation of cosmic crystals



Dust evaporation
(shock-wave heating)

“significant vapor generation by planetesimal bow shock”

Condensation of cosmic crystals

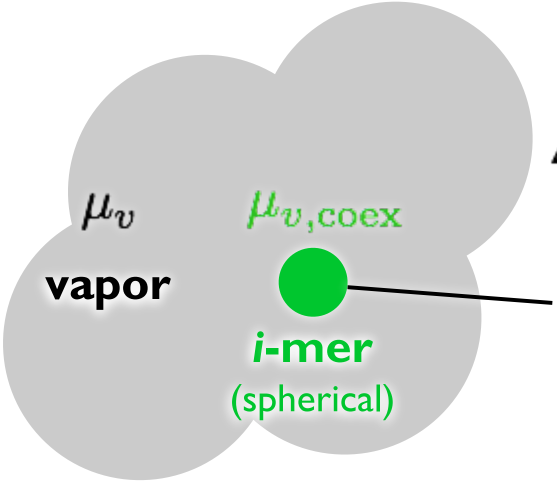
“rapid cooling of silicate vapor”

Rapid cooling of silicate vapor
(adiabatic expansion)

Fig. schematic of planetesimal bow shock
(Miura+2010, ApJ 719, 642)

3. Condensation of cosmic crystals

Homogeneous nucleation



chemical potential
(per molecule)

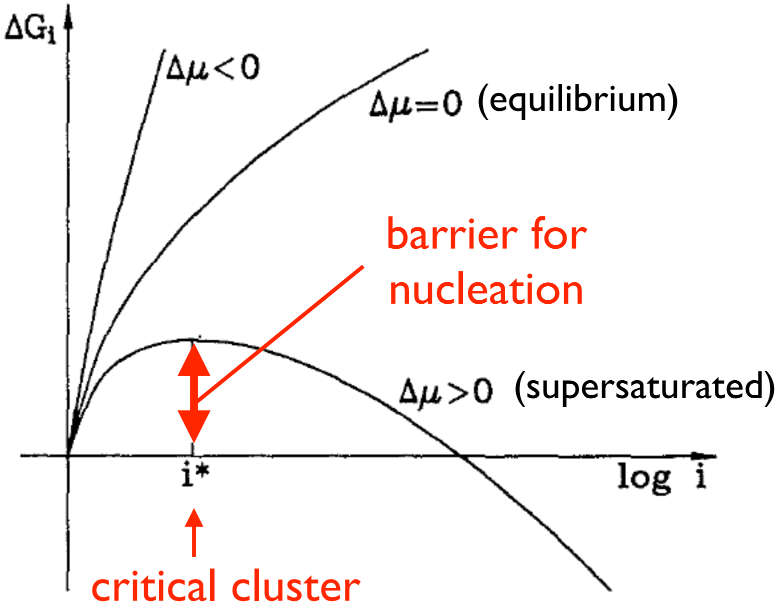
$$\Delta\mu = \mu_v - \mu_{v,\mathrm{coex}}$$

surface free energy

$$a\gamma_{\mathrm{s}} i^{2/3}$$

Gibbs free energy of formation:

$$\Delta G_i = a\gamma_{\mathrm{s}} i^{2/3} - i\Delta\mu$$



barrier for nucleation

critical cluster

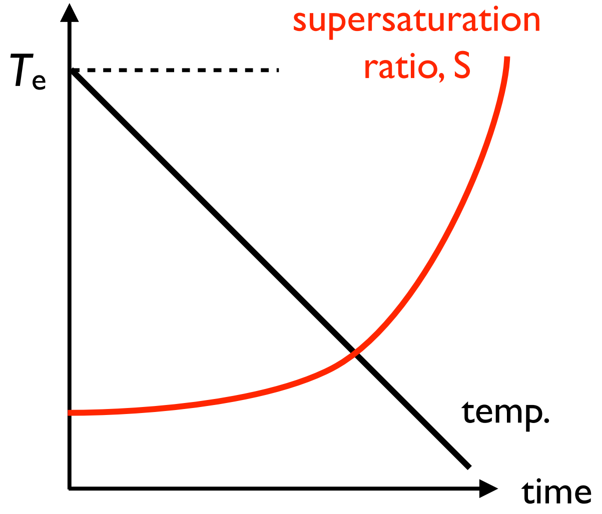
Feder+1996, Adv. Phys. 15, 111
Dillmann and Meier 1991, J. Chem. Phys. 94, 3872

“delay of nucleation by surface free energy”

3. *Condensation of cosmic crystals*

Cooling parameter Λ

nucleation and growth in
monotonically cooling gas
(Yamamoto and Hasegawa 1977, Prog. Theo. Phys. 58, 816)



$$S(t) = \boxed{\frac{c_1(t)}{c_1(0)}} \exp\left(\frac{t}{\tau_{\rm sat}}\right)$$

depletion of gas number density

timescale of cooling (increase of *S*)

Only two non-dimensional parameters determine

- (actual) condensation temperature,
- size distribution of condensed grains.

Cooling timescale:

$$\Lambda = \tau_{\rm sat}/\tau_{\rm coll}$$

collision interval of vapor molecules

Surface energy of a vapor molecule:

monomer radius

$$\Gamma = \frac{4\pi a_0^2 \gamma_{\rm s}}{k_{\rm B} T_{\rm e}}$$

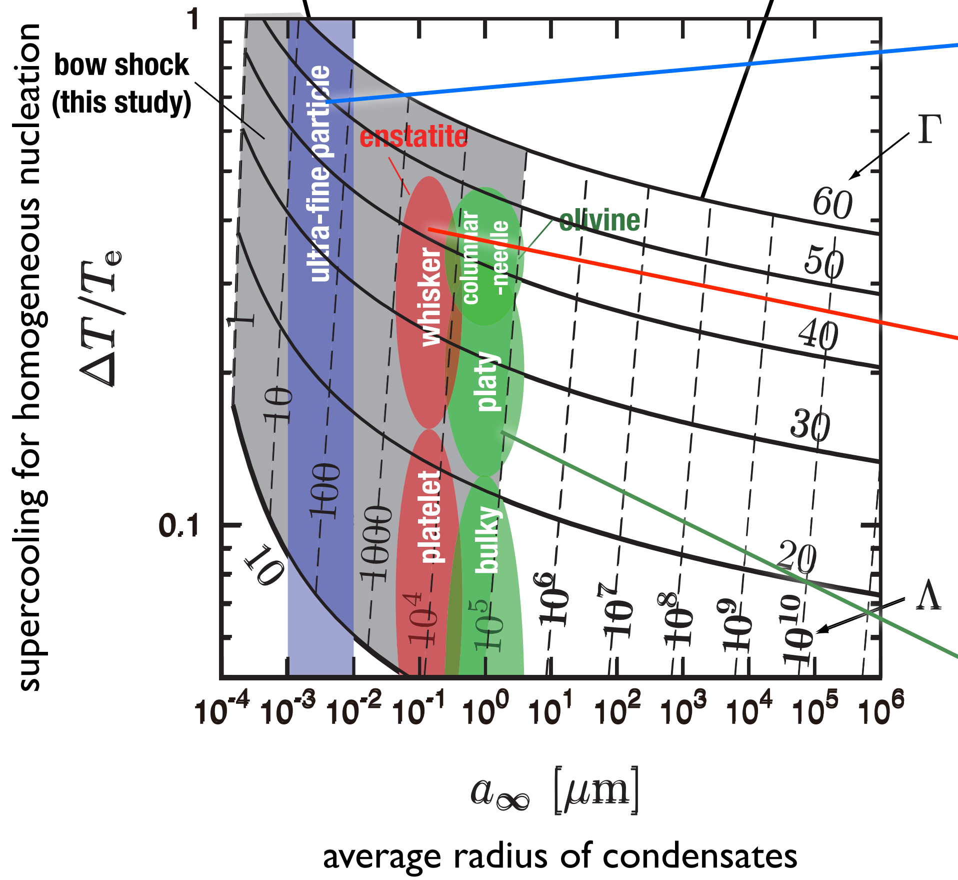
condensation temp. in equilibrium

3. Condensation of cosmic crystals

Diagram of condensed particles

expected from
planetesimal bow shock
(this study)

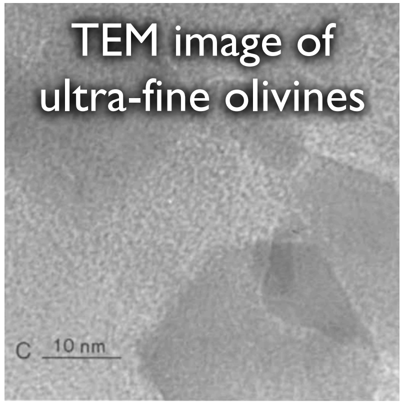
homogeneous nucleation and growth
(Yamamoto and Hasegawa 1977, Prog. Theo. Phys. 58, 816)

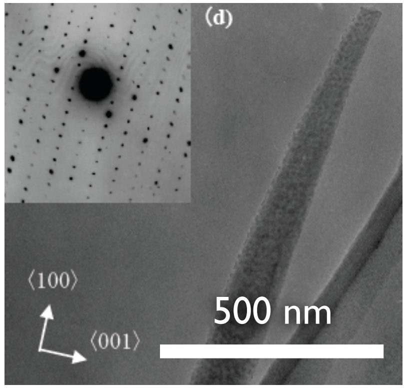


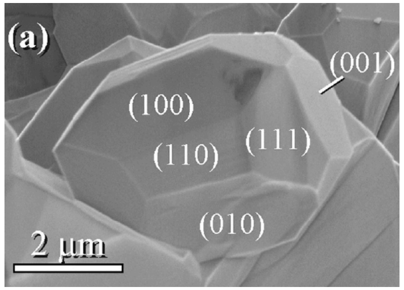
ultra-fine particles
~ a few nm
(Toriumi 1989, EPSL 92, 265)

enstatite particles
~ 100 nm
(Yamada+, unpublished)

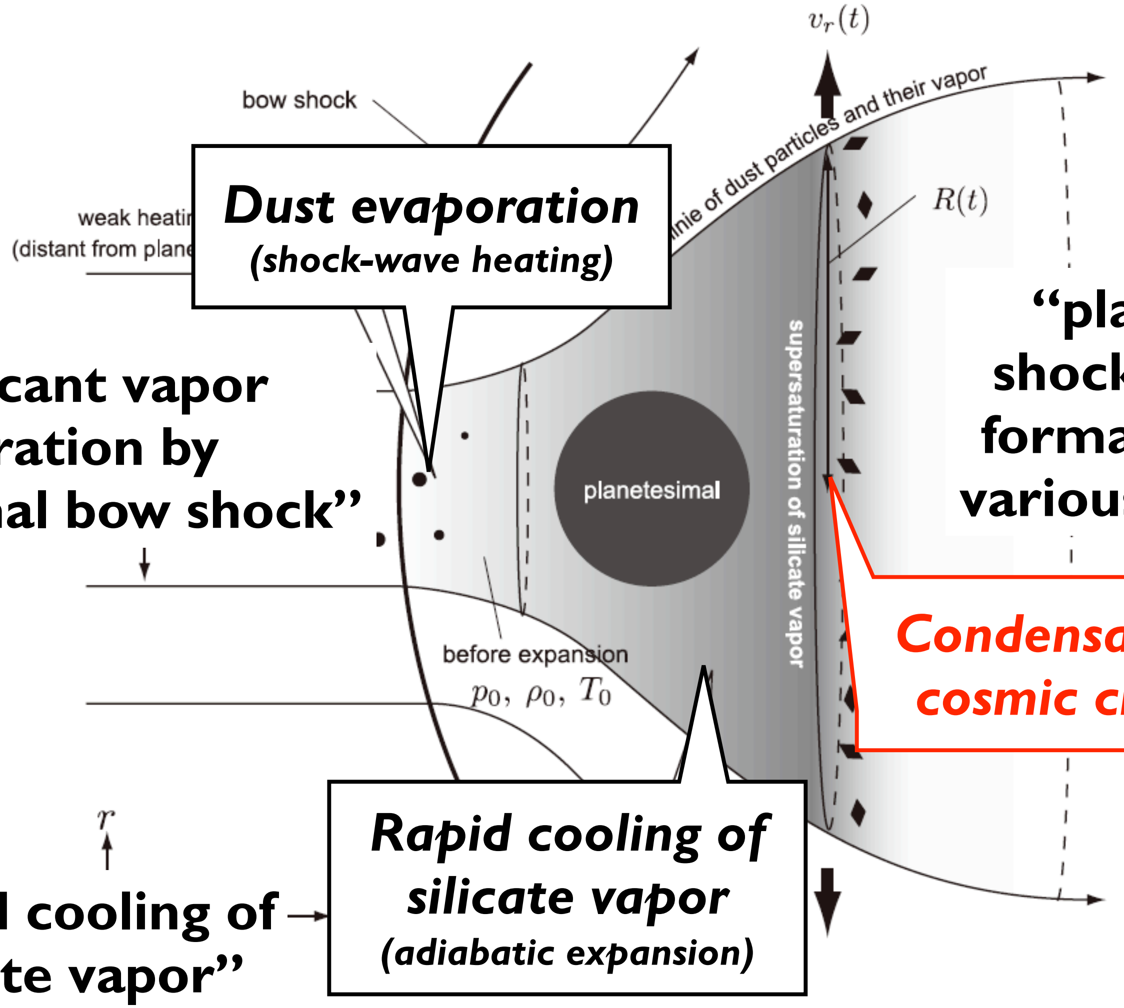
olivine particles
~ 1 um
(Kobatake+2008, Icarus 198, 208)


TEM image of
ultra-fine olivines





3. Condensation of cosmic crystals



Dust evaporation
(shock-wave heating)

"significant vapor generation by planetesimal bow shock"

"planetesimal bow shock scenario covers formation condition of various cosmic crystals"

Condensation of cosmic crystals

Rapid cooling of silicate vapor
(adiabatic expansion)

"rapid cooling of silicate vapor" →

Fig. schematic of planetesimal bow shock
(Miura+2010, ApJ 719, 642)

Conclusions

- Dust evaporation and condensation experiments showed that cosmic crystals with various morphologies were formed from highly-supercooled (supersaturated) silicate vapor. The morphology depends on temperature and supercooling (morphodrom).
- Planetesimal bow shock is one of the candidates for the cosmic crystal formation. It evaporates um-sized fine silicate particles behind the shock front. The silicate vapor cools rapidly due to the adiabatic expansion.
- Depending on the shock conditions (planetesimal radius, shock velocity, gas number density, and dust-to-gas mass ratio), variety of cosmic crystals in sizes (nm-size to um-size) and morphology (bulky, platy, whisker, and so forth) was produced.