Low Temperature Crystallization of Dust

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(Tanaka+2010, ApJ, 717, 586)

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

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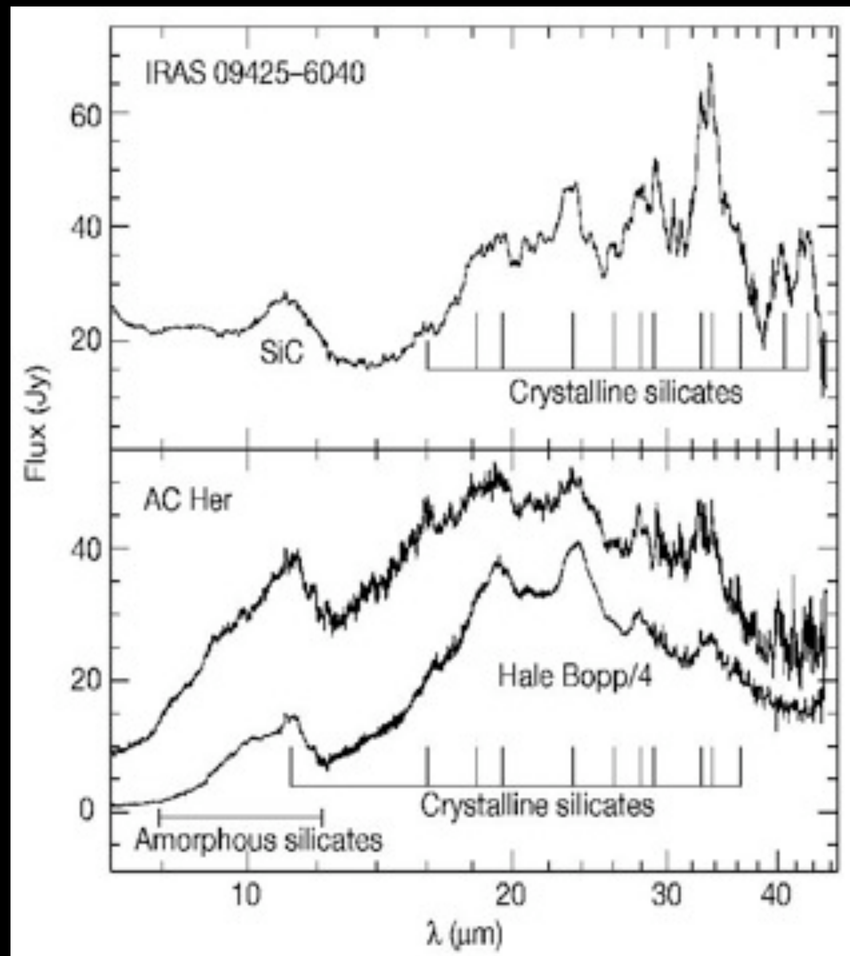
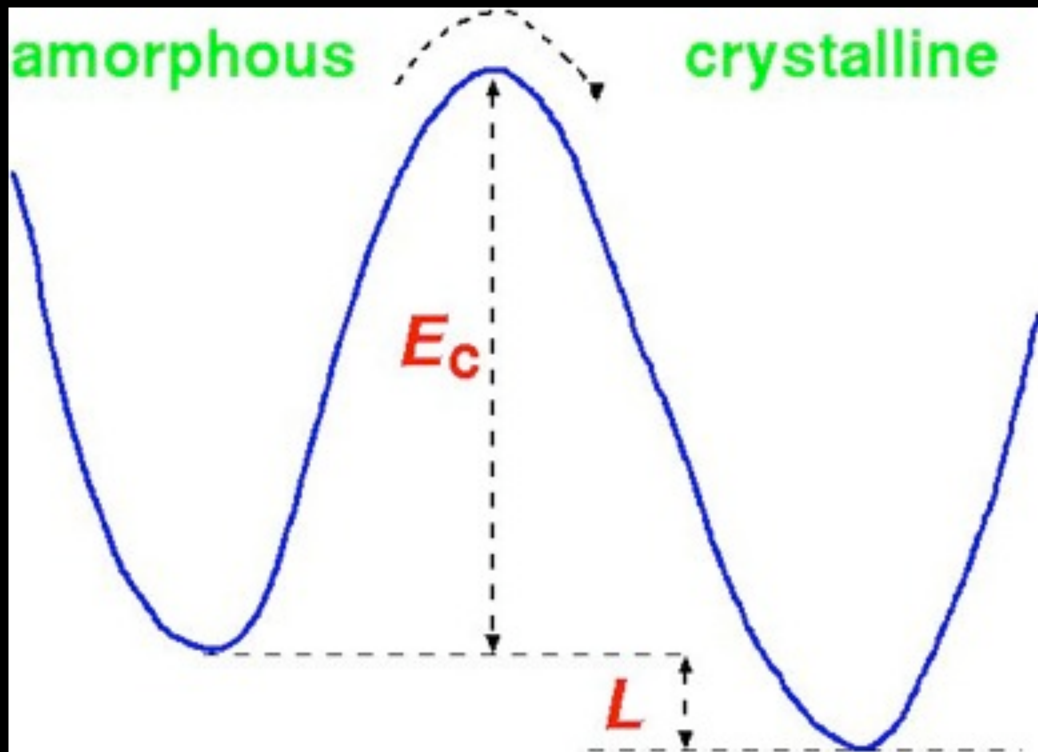
Crystalline silicate in various kinds of objects

- Observed in
  - evolved stars
    - C-rich giant stars, post AGB stars
  - Herbig Ae/Be stars
  - T Tauri stars
  - young MS stars
  - Comets
  - ZL dust
  - IDPs
  - other galaxies (ULIRG)
- Not observed in
  - ISM & molecular clouds
  - Protostars



(Molster et al. 1999)

Crystallization: Transition from amorphous to crystalline state



internal energy : E(crystal) < E(amorphous)

- L : latent heat of crystallization
- must overcome energy barrier Ec for crystallization

Energy source to overcome Ec

Annealing induced by fluctuation of thermal energy

(Hallenbeck et al. 1998, Fabian et al. 2000, Kamitsuji et al. 2005, and many others)

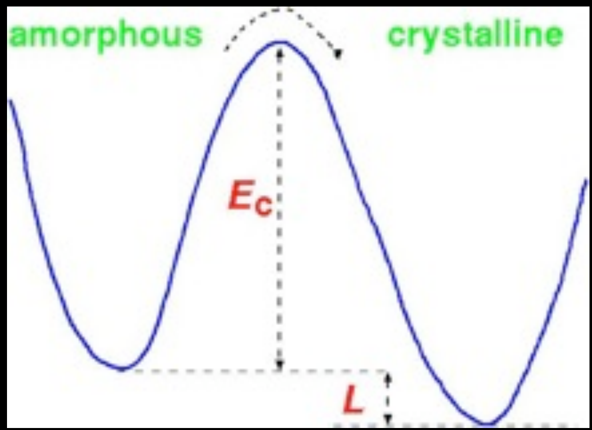
But other energy sources:

- irradiation of electrons or high energy particles

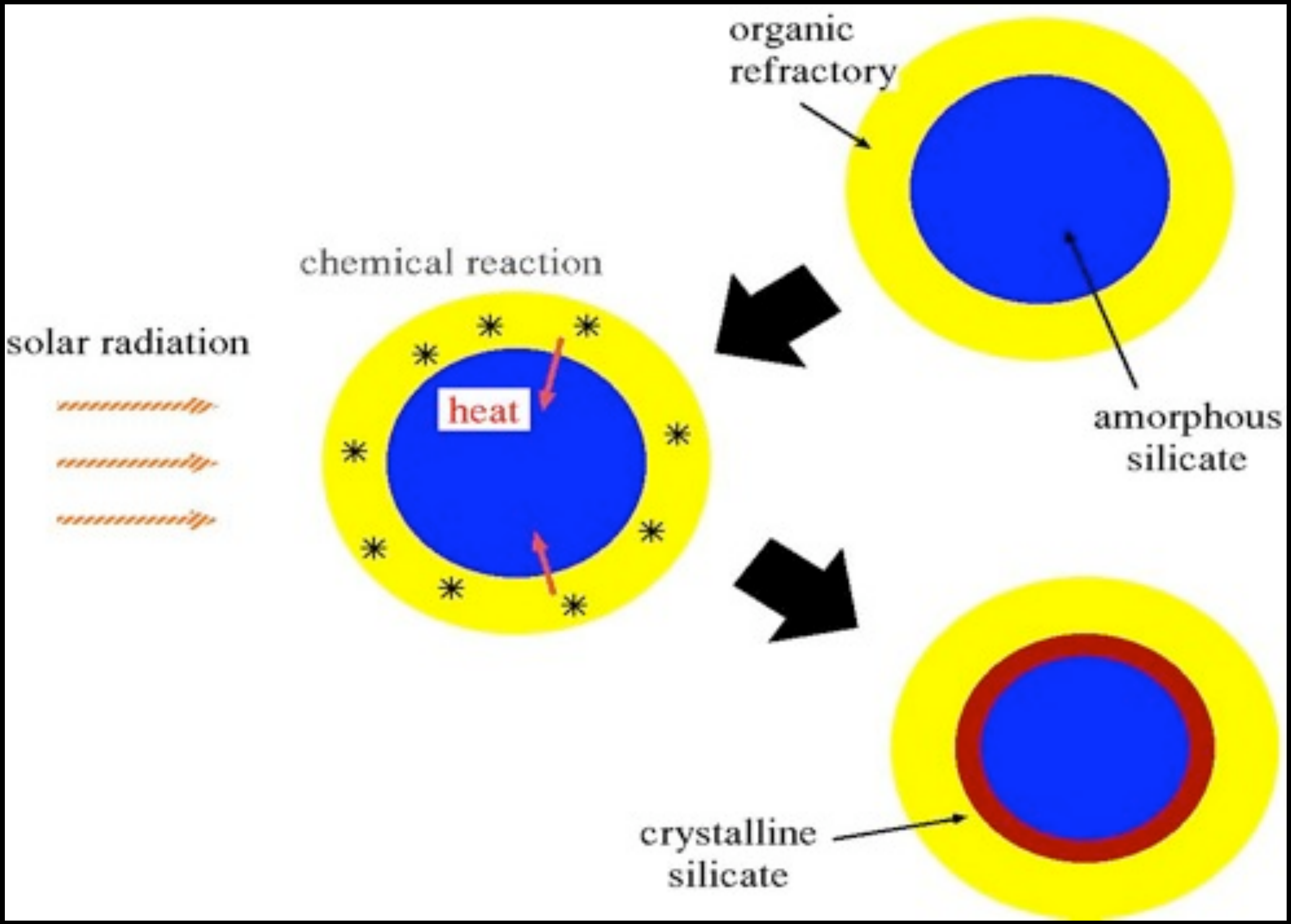
  (Carrez et al. 2002, Y. Kimura et al. 2008)

- heat of chemical reactions

  (Yamamoto & Chigai 2005, Yamamoto+2010)



Basic idea of crystallization by heat of reactions



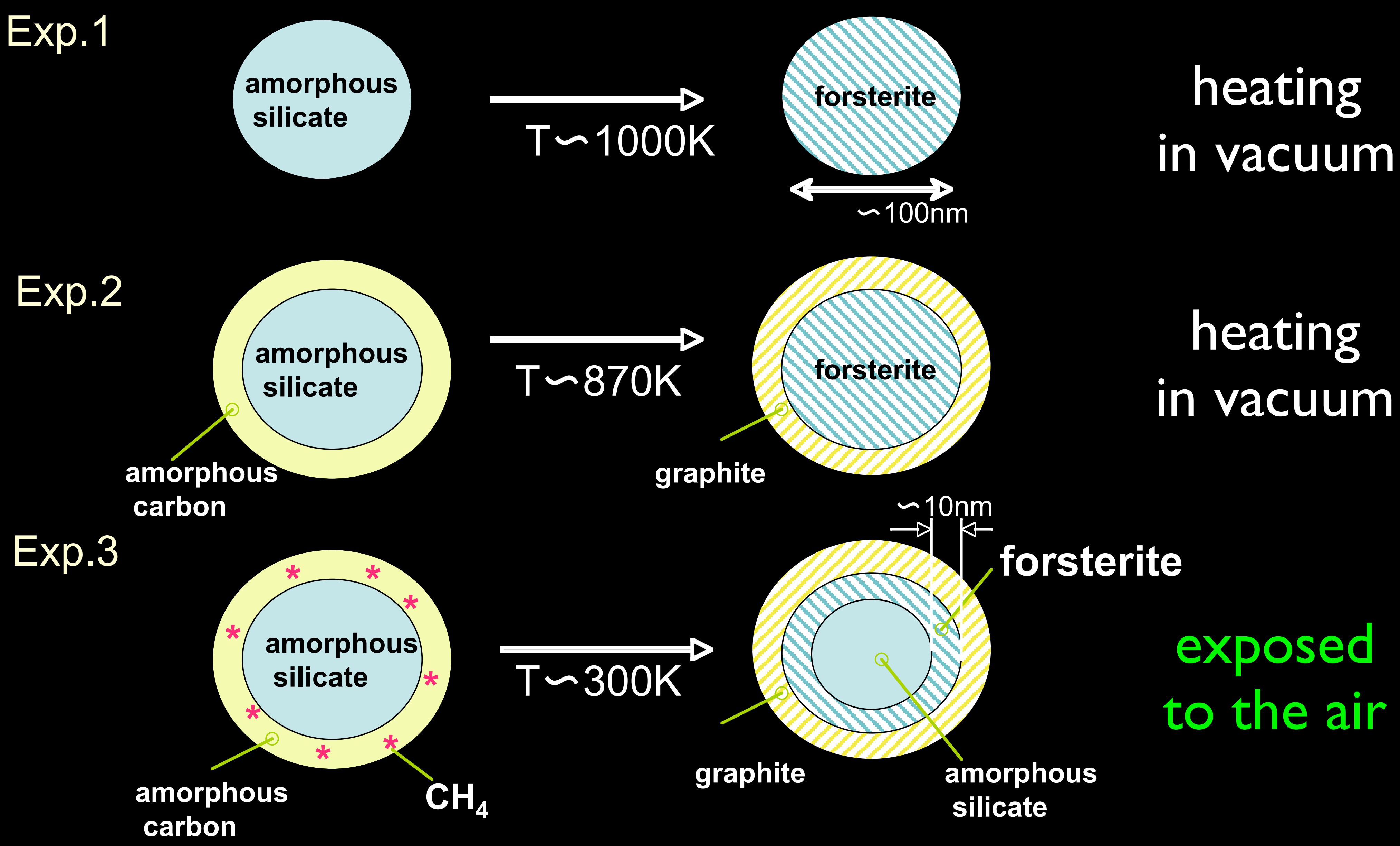
0) Suppose a silicate grain coated with a mantle including chemically reactive molecules (radicals).

1) Moderate heating induces chemical reactions in the mantle

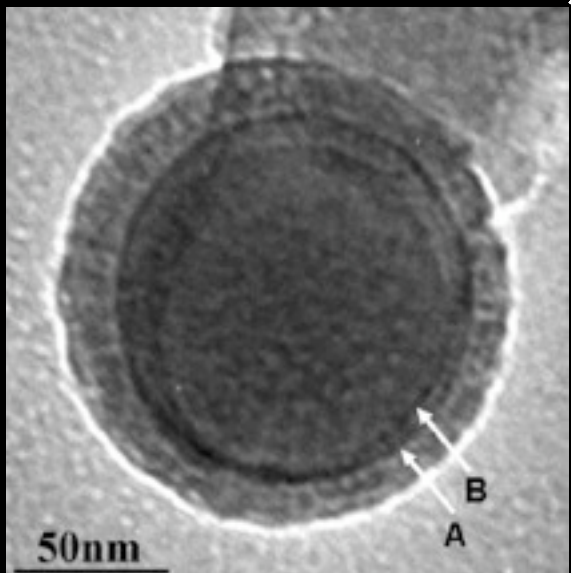
2) heat of reactions leads to crystallization

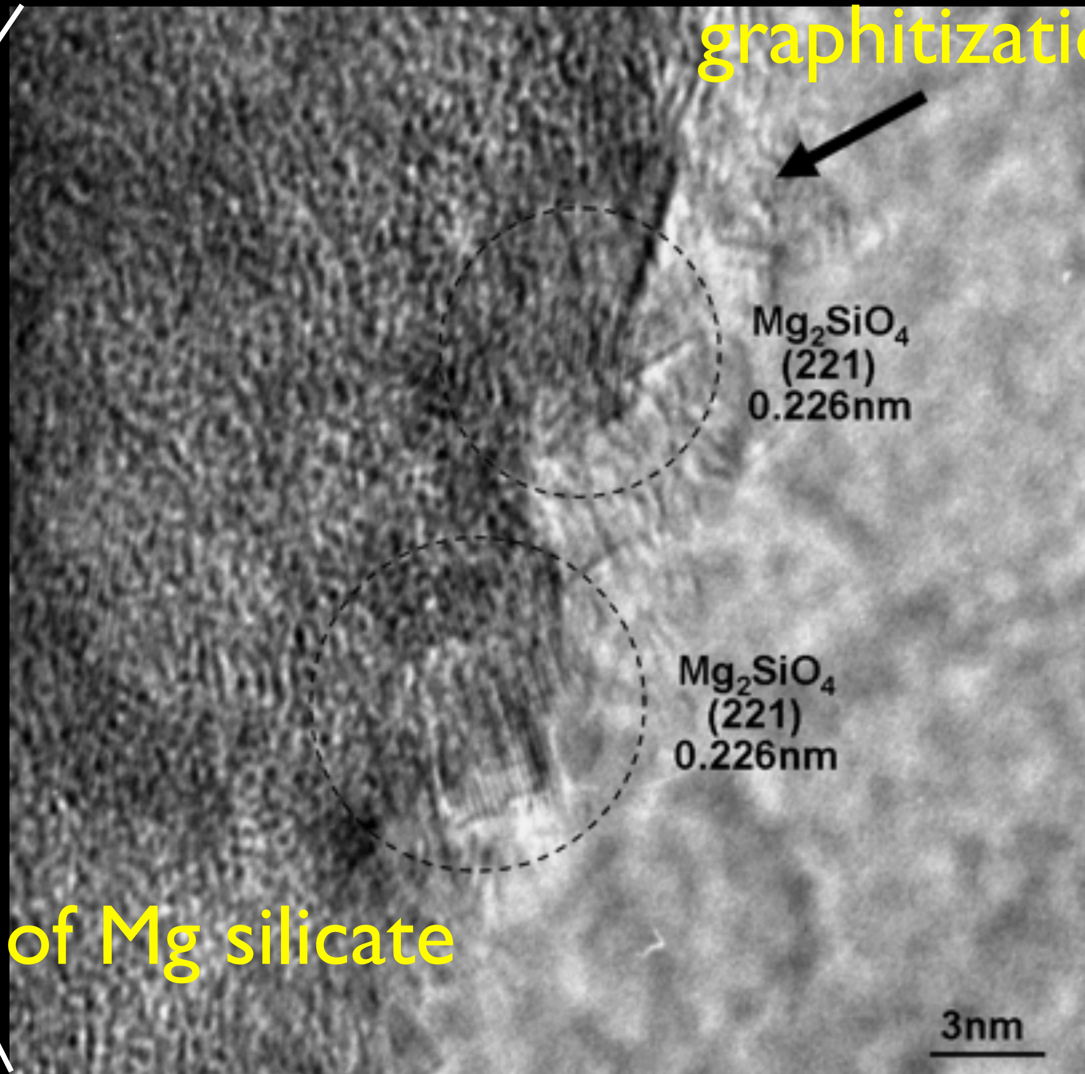
(Yamamoto & Chigai 2005, Yamamoto+2010)

Series of experiments by Kaito et al.
(Kamitsuji et al. 2005; Kaito et al. 2007a,b)



HREM image of the sample and its magnification of the interface region

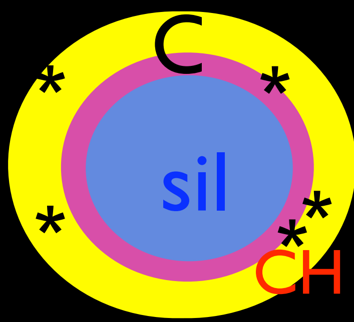




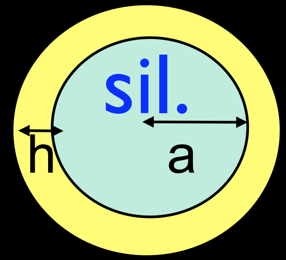
Kaito et al. 2007b

Picture of crystallization in Exp. 3 by Kaito et al. (2007b)

1. Release of heat of chemical reactions (oxidation of CH_4) in C mantle
2. Induce graphitization in the C mantle
3. Latent heat deposited by graphitization leads further temperature elevation
4. Induce crystallization of silicate from the interface of C mantle and silicate core
5. Cessation of crystallization due to cooling



Modelling of Exp. 3



Time variation of temperature of the particle

$$\frac{4}{3}\pi a^3 \rho c \frac{dT}{dt} = \frac{4}{3}\pi[(a+h)^3 - a^3]\dot{\varepsilon} - \Lambda_{\rm air} - \Lambda_{\rm rad} + H_{\rm si} + H_{\rm c}$$

Rate of generation of heat of reactions in mantle

$$\dot{\varepsilon} = -\frac{dn_{\rm rad}}{dt} E_{\rm r} \qquad \frac{dn_{\rm rad}}{dt} = -\nu_{\rm r} e^{-E_{\rm ar}/kT} n_{\rm rad}$$

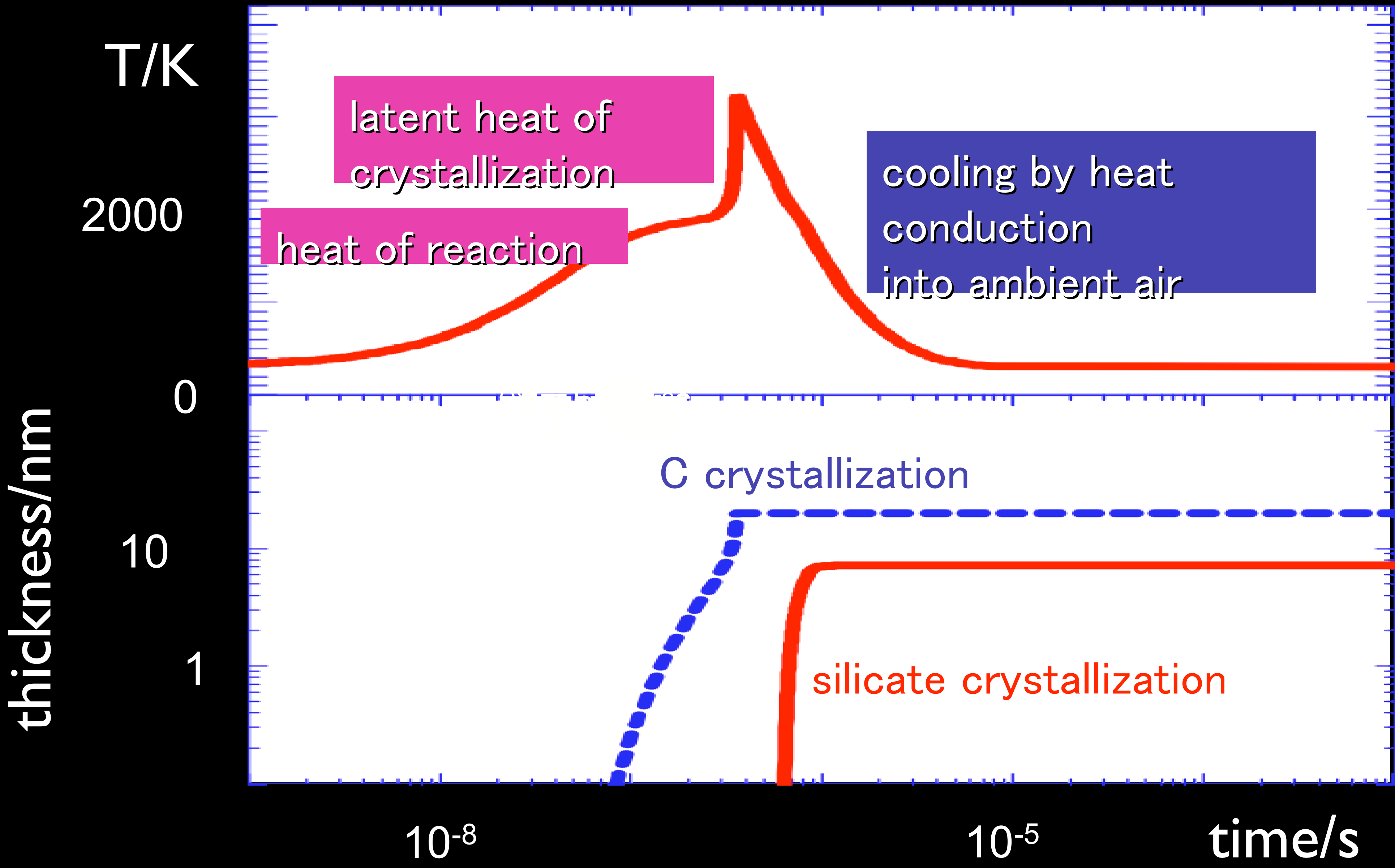
Crystal growth

$$\frac{da_{\rm sil}}{dt} = a_0 \nu e^{-E_{\rm sil}/kT}(1 - e^{-q_{\rm sil}(T_{\rm m}-T)/kT})$$

Key physical quantities

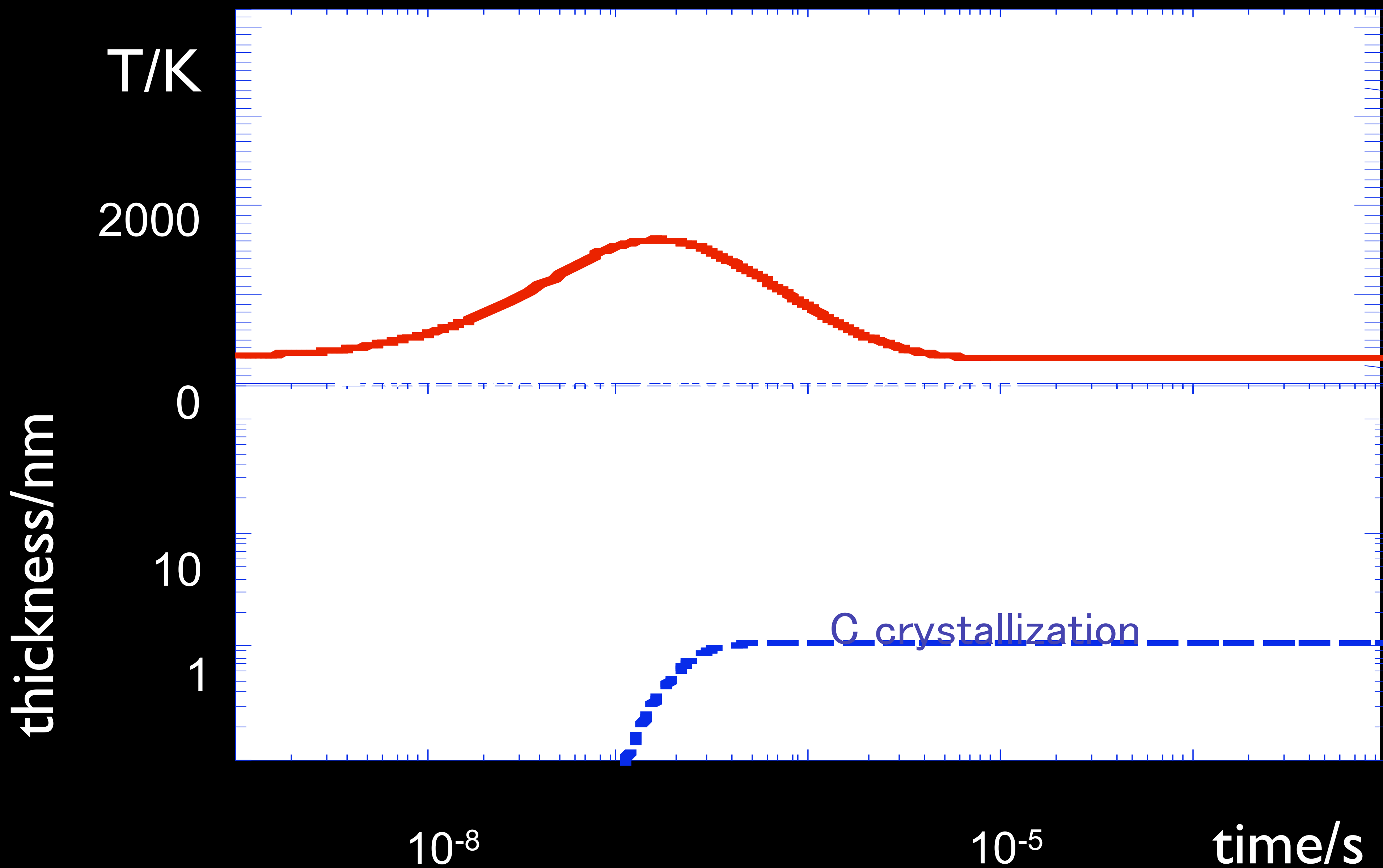
- Stored nergy densiy : $Q = n_{rad}(0)\ E_r$
- Time scale of the reactions : τ
- Ambient gas pressure

Feature of crystallization

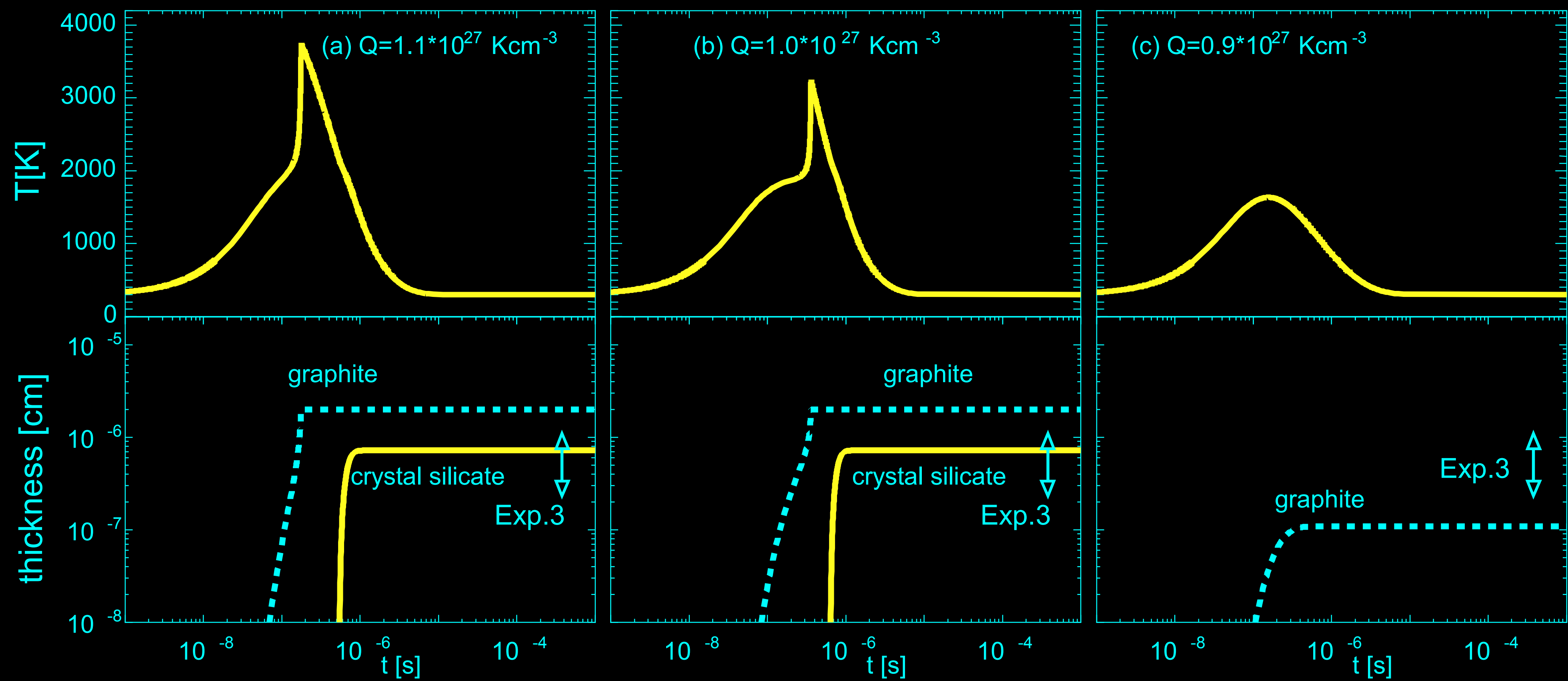


(n_{rad} (0) E_r $=10^{27}$ K cm^{-3} ; tr = 10^{-8} s, gas density = 10^{-3} g cm^{-3} = 1 atm)

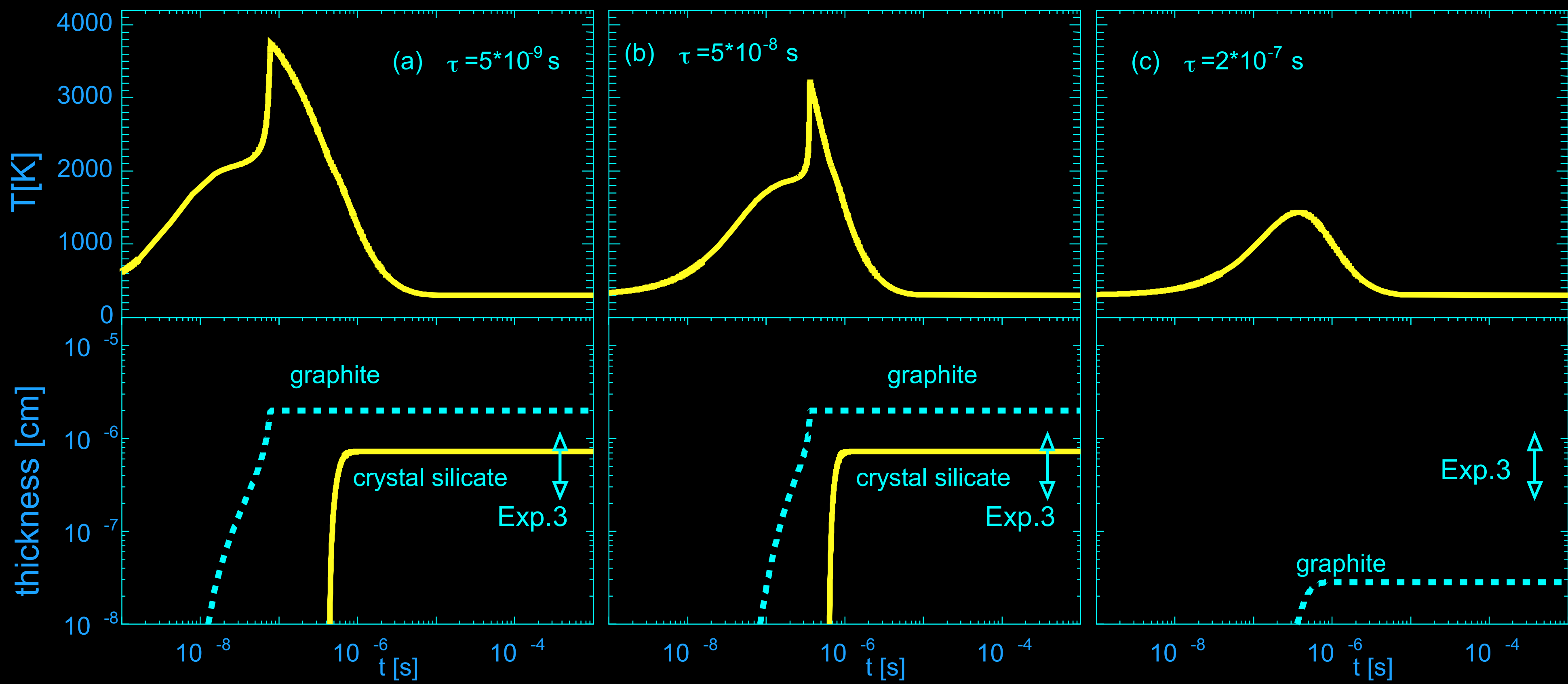
Feature of crystallization (2)
small deposition of heat of reaction



(n_{rad} (0) E_r = 0.9 ×10^{27} K cm^{-3} ; tr = 10^{-8} s, gas density = 10^{-3} g cm^{-3} = 1 atm)

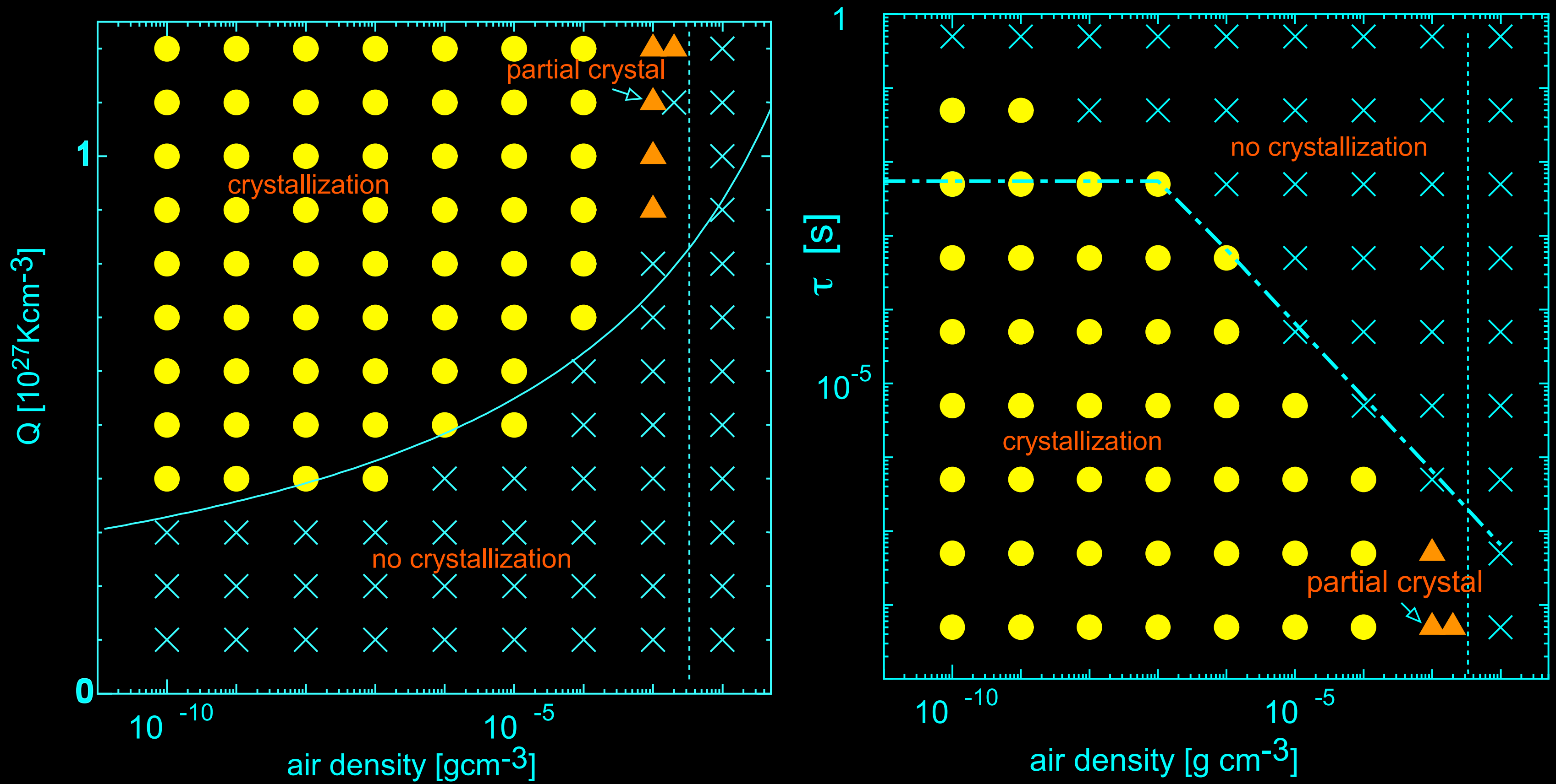

(a) Q=1.1*10^27 Kcm^-3
(b) Q=1.0*10^27 Kcm^-3
(c) Q=0.9*10^27 Kcm^-3
T[K]
4000
3000
2000
1000
0
thickness [cm]
10^-5
10^-6
10^-7
10^-8
graphite
crystal silicate
Exp.3
10^-8
10^-6
10^-4
t [s]

(P = 1 atm)


(a) τ =5*10^-9 s
(b) τ =5*10^-8 s
(c) τ =2*10^-7 s
T[K]
4000
3000
2000
1000
0
thickness [cm]
graphite
crystal silicate
Exp.3
t [s]

(P = 1 atm)

Crystallization conditions



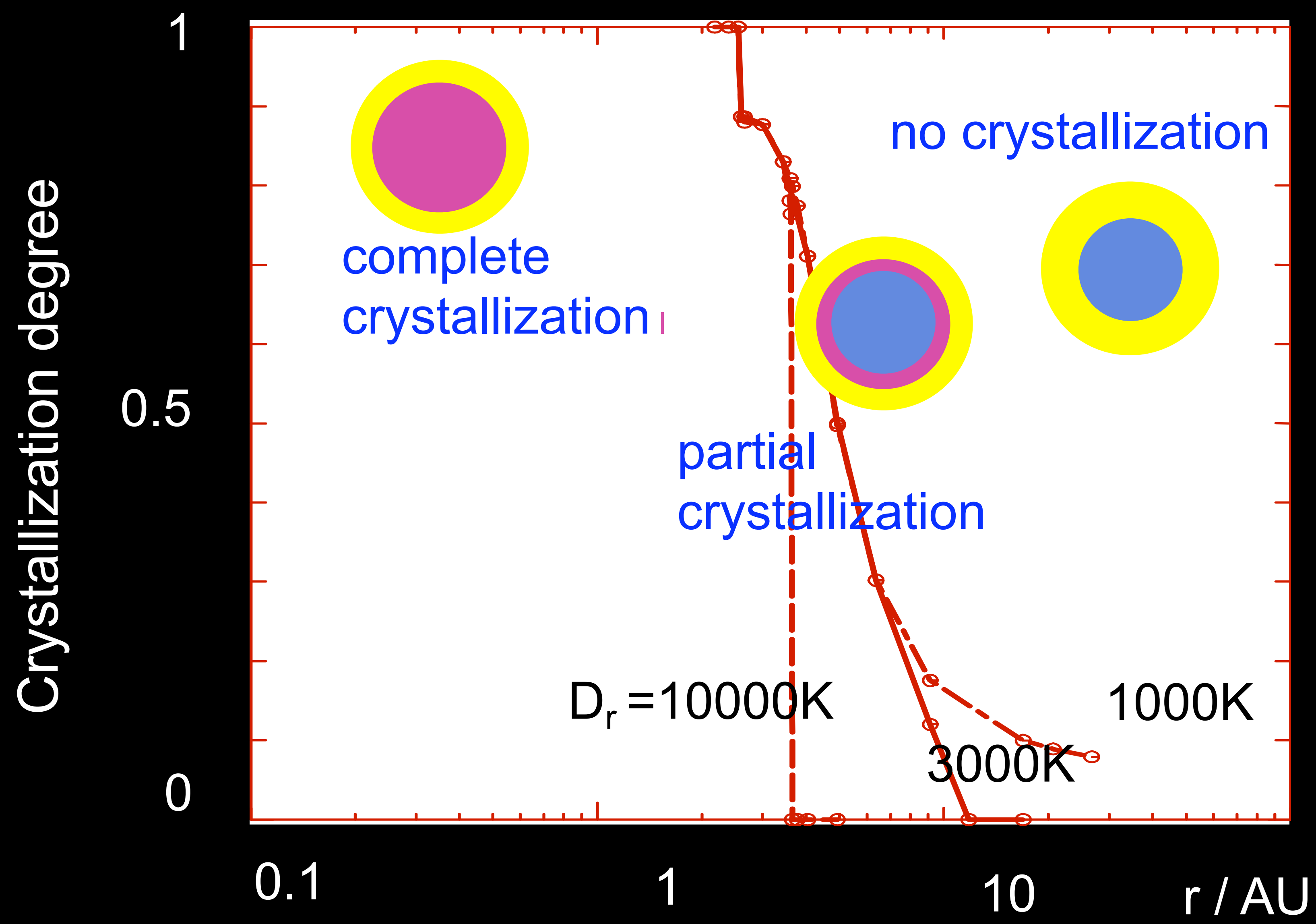
Low gas density, large energy deposition, fast reactions

→ easy crystallization

Radical concentration >1 - 10 % leads to substantial crystallization

Crystallization degree in steady accretion disks

$(Q = n_{rad}(0)\ E_r = 10^{27}\ K\ cm^{-3})$



Crystalline region is much extended than by annealing.

Concluding remarks (1/3)

- Crystallization triggered by chemical reactions may explain ubiquity of crystalline silicate in various objects
  - Similar phenomenon
    - Wigner energy release known in nuclear reactor engineering
    - Sudden release of energy stored in graphite moderator irradiated by neutrons upon moderate heating (Spontaneous energy release)

Concluding remarks (2/3)

- The present mechanism does not depend on the details of the chemistry but depends only on the amount of reactive molecules times heat of reactions, $Q = n_{rad}(0)\ E_r$, and reaction timescale τ.

Concluding remarks (3/3)

- Similarity of ice compositions in molecular clouds and comets:
  - Present mechanism can explain the coexistence of crystalline silicate and ice of IS composition in comets without mixing.
- Search for crystalline silicate at low temperature environments is encouraged by future high resolution observations of disks.