Anisotropic Growth of Crystalline Dust Grains in Protoplanetary Disks

*Aki Takigawa

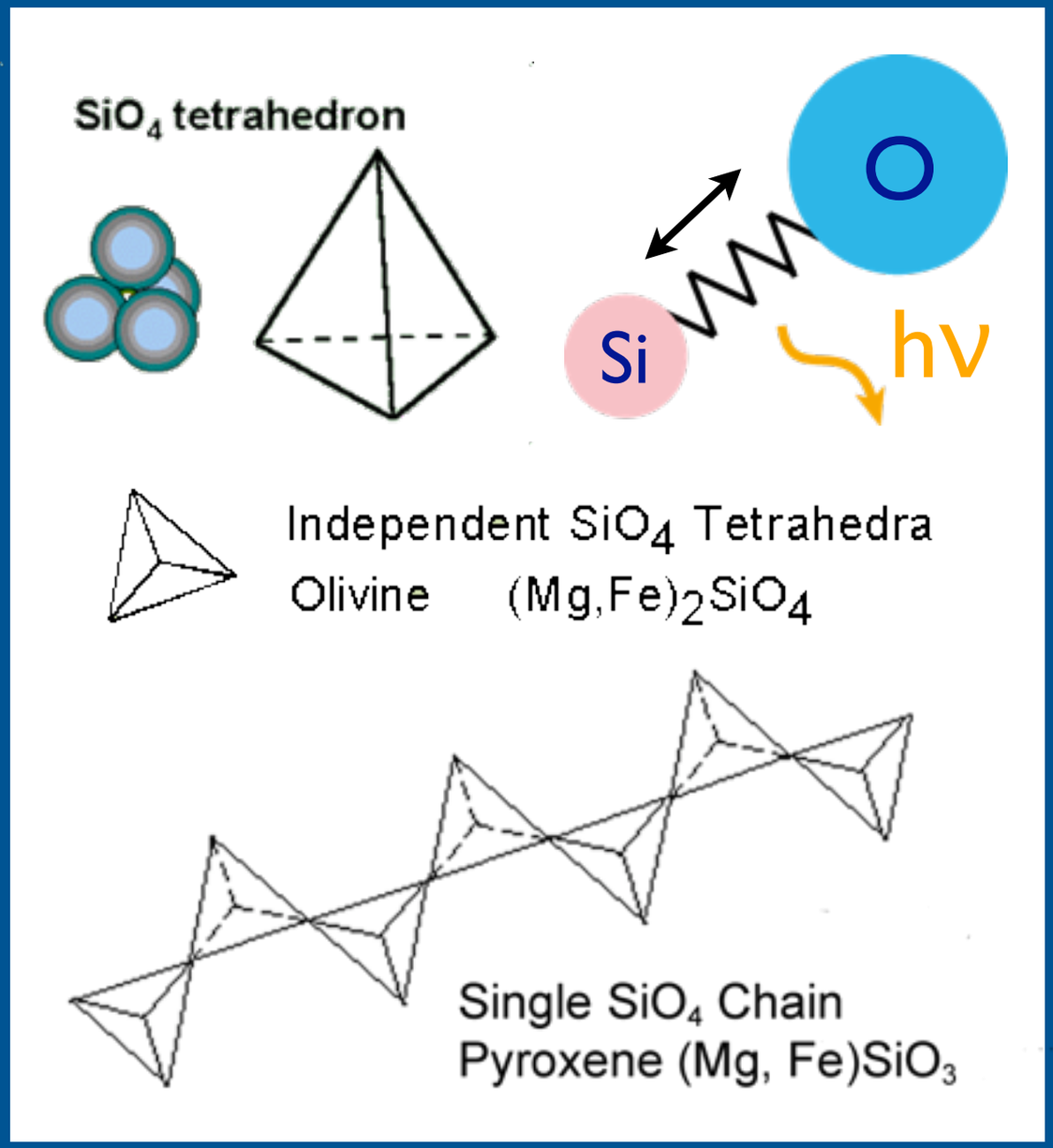
Shogo Tachibana, Hiroko Nagahara, Kazuhito Ozawa

Dept. Earth and Planetary Science, Univ. Tokyo

Harald Mutschke, Akemi Tamanai, Simon Zeidler

Astrophysical Institute and University Observatory
- Friedrich-Schiller University Jena

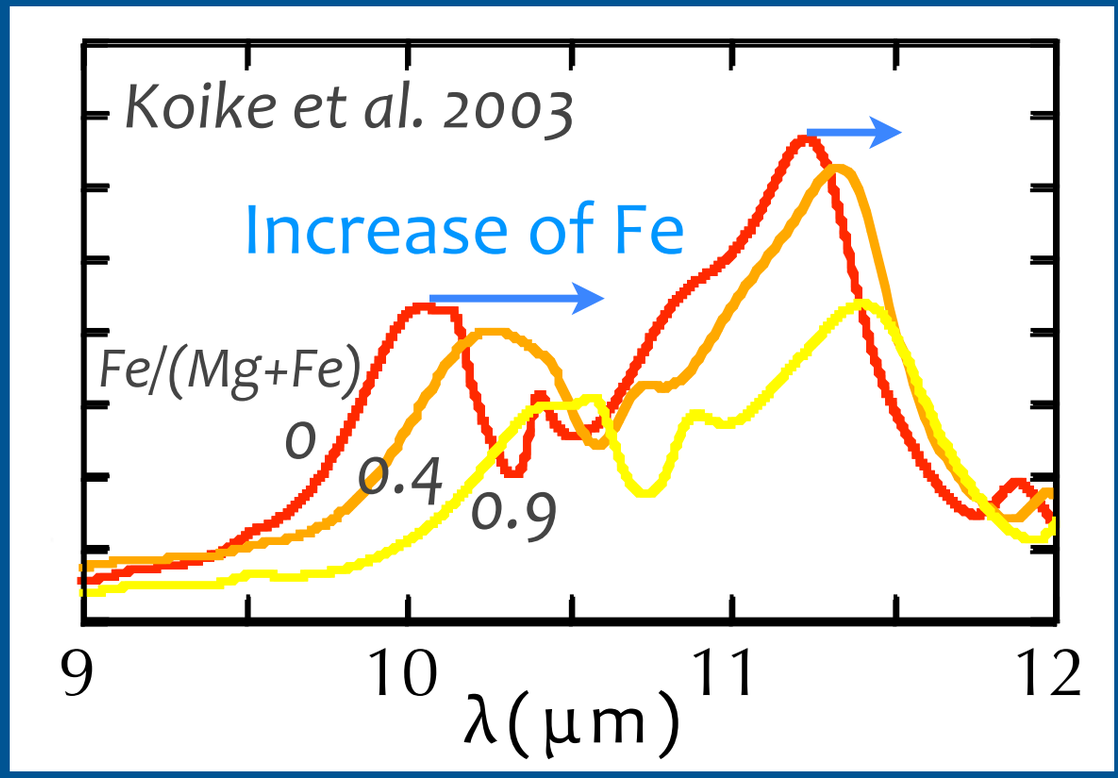
Infrared Spectrum



Spectra of dust grains depend on

- *arrangement of atoms*
- *temperature, composition, size, shape*

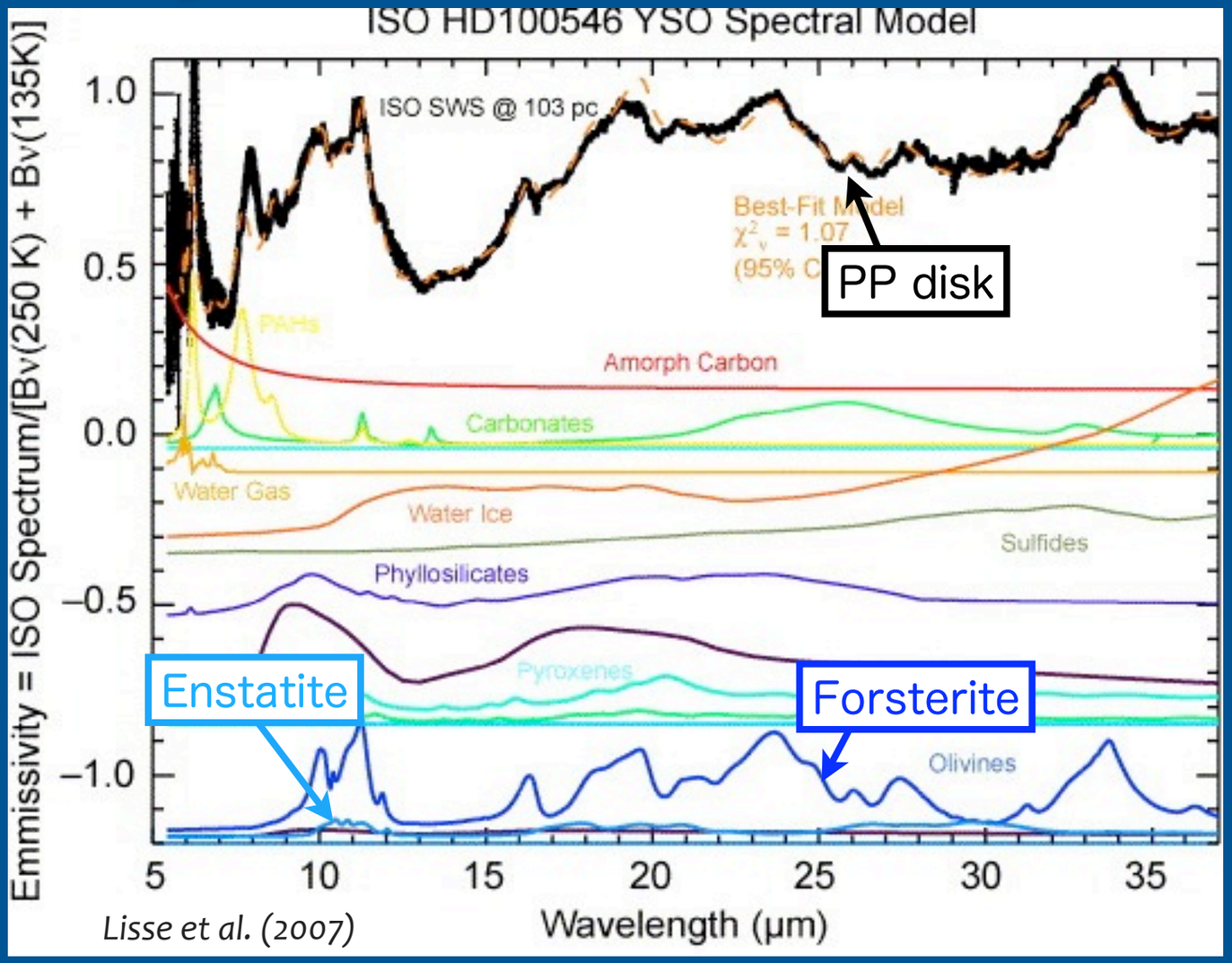
e.g., Fo spectrum depends on Fe content



Koike et al. 1993,1995, 2003, 2006, Fabian et al. 2001, Jäger et al. 1994, 1998, Tamanai et al. 2006, 2009, Murata et al. 2007

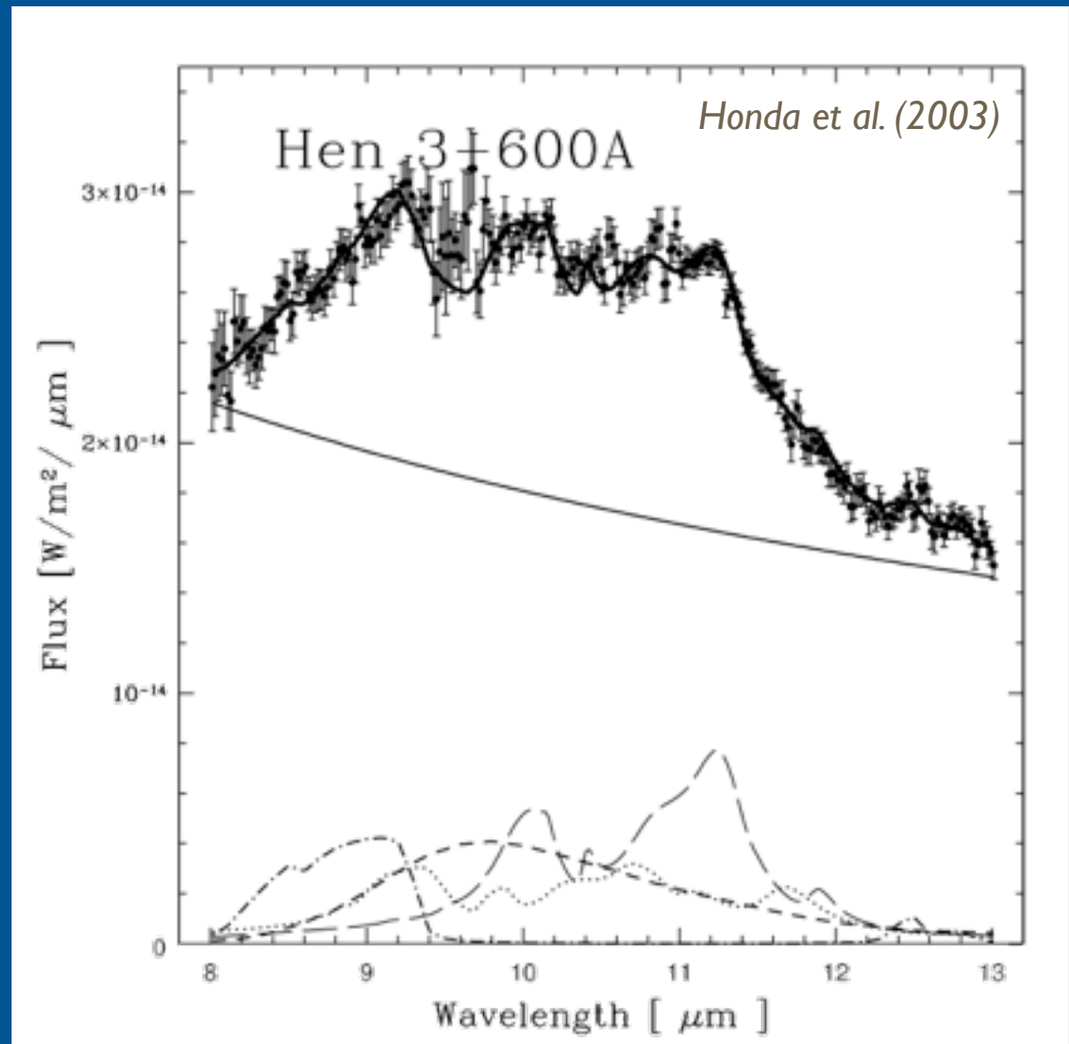
Observation & Laboratory spectra

Herbig AeBe star



Lisse et al. (2007)

T-Tauri star



Dust: Amorphous silicates, Forsterite, Enstatite, Oxides, H_2O ice, ...

--> Crystal / Amorphous, Chemical compositions, Size, ...

Motivation

Understanding of dust formation processes and/or conditions from observed spectra using the relationship between dust properties & formation processes

- *Dust shape and its relation to crystallographic orientation (**crystallographically anisotropic shape**)*

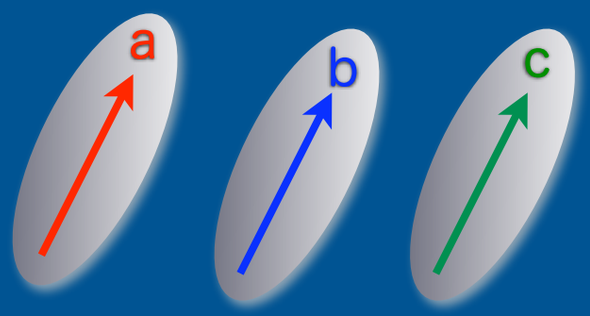
- *Dust spectra formed under circumstellar conditions*

Crystallographically Anisotropic Shape

Specific shape related to a specific crystallographic orientation

- reflects crystal structure, **formation process & condition**

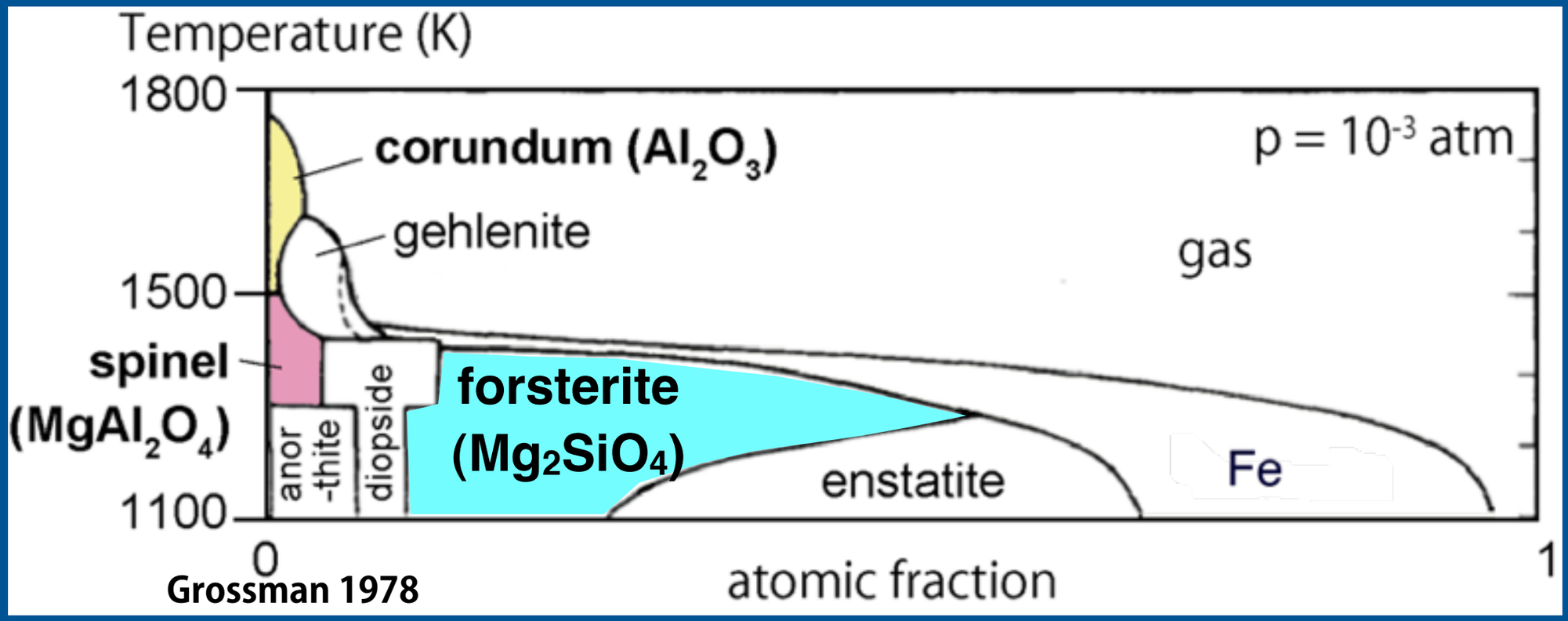
IR spectra depend on crystallo-graphically anisotropic shape



apparently look the same, but different crystallographically anisotoropic shapes

Crystallographically anisotropic shape in circumstellar environments?

Outline



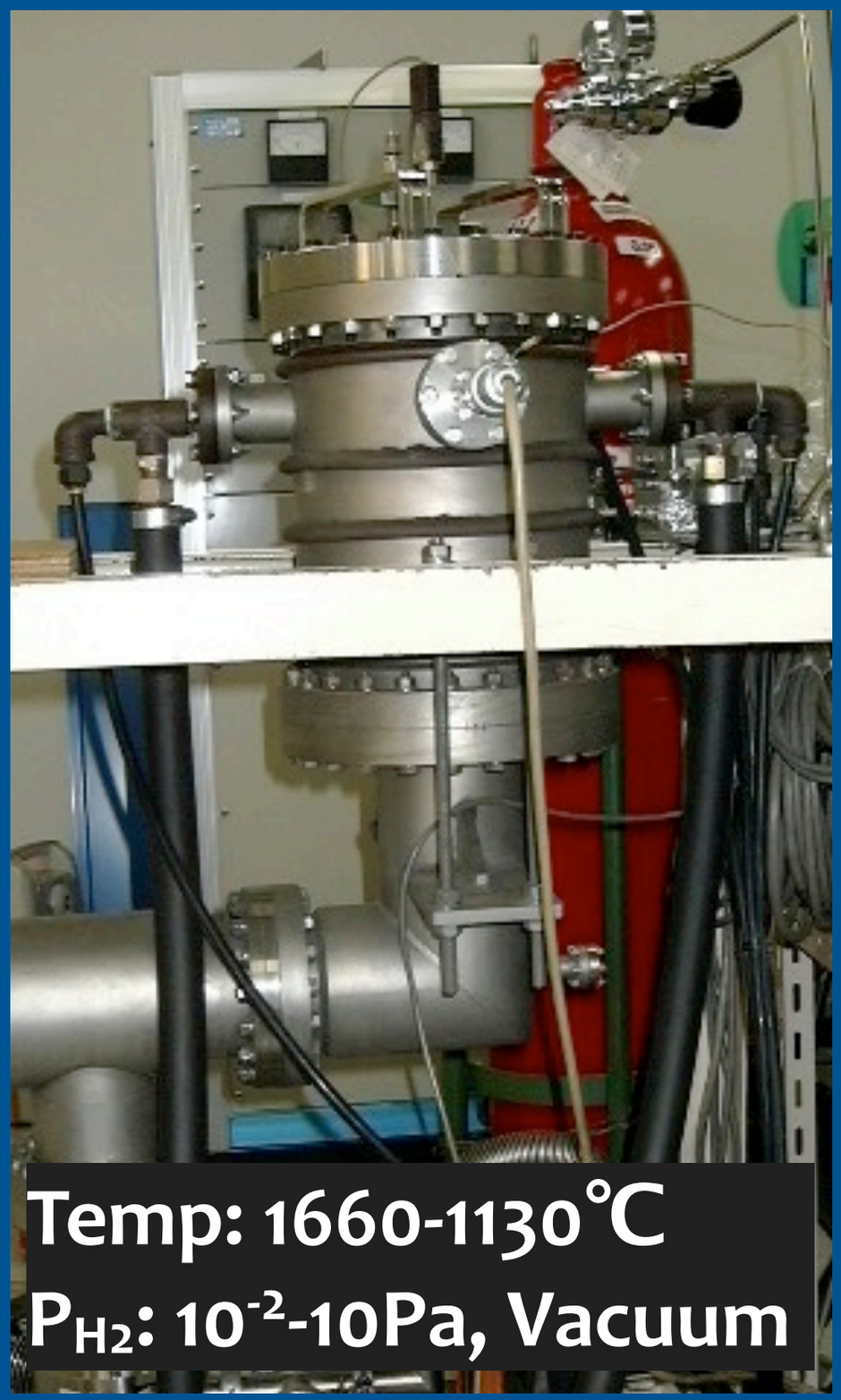
Grossman 1978

1. Processes to change crystallographically anisotropic shapes

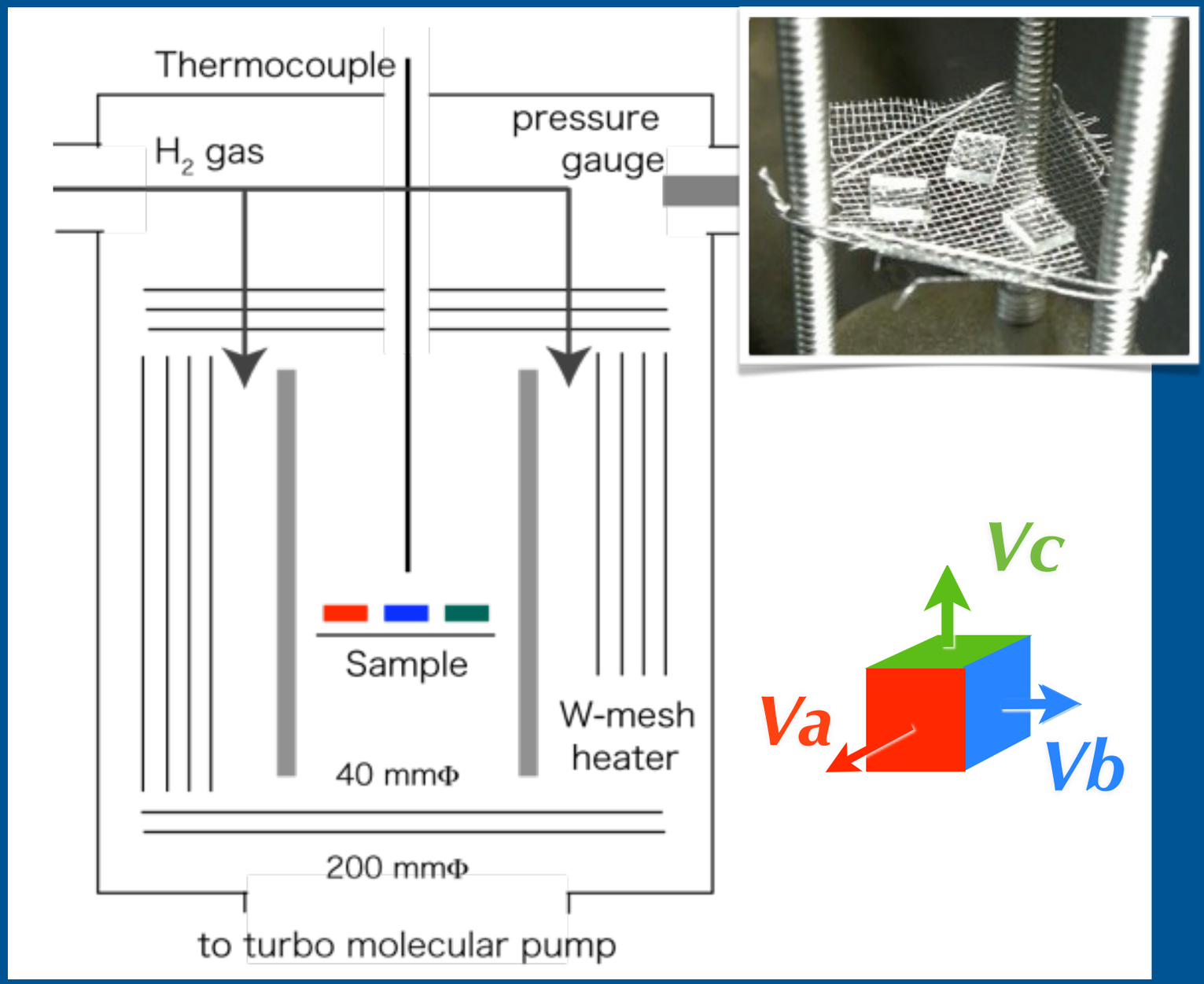
- Evaporation experiments of forsterite in H_2 gas
- Condensation experiments of corundum
- Spectra of different crystallographically anisotropic shapes

2. IR spectra of spinel formed under circumstellar conditions

Evaporation experiments of forsterite

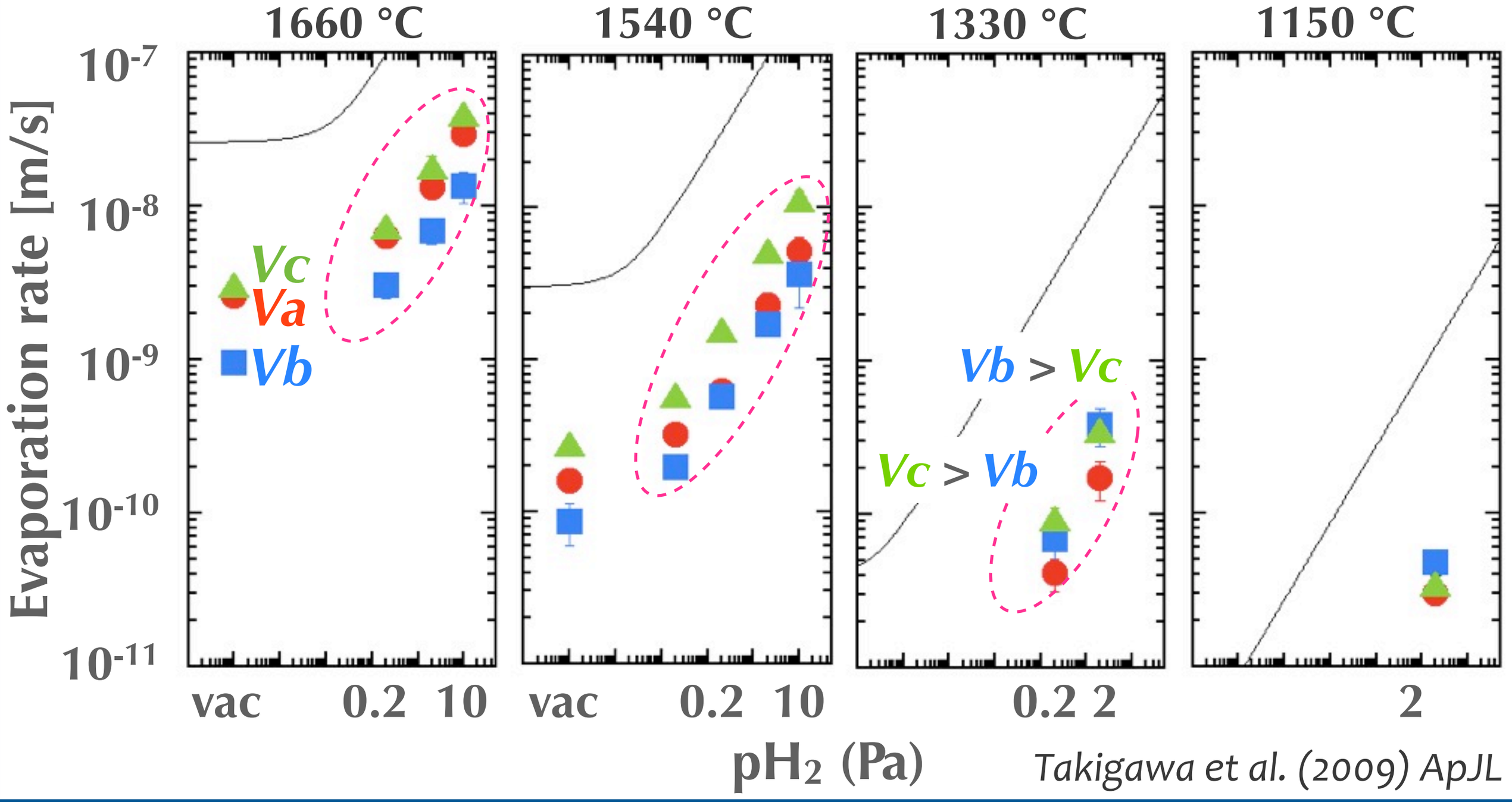


Temp: 1660-1130℃
P_{H2}: 10^{-2}-10Pa, Vacuum



Anisotropic evaporation rates along different crystallographic axes

Anisotropy in evaporation rates of forsterite

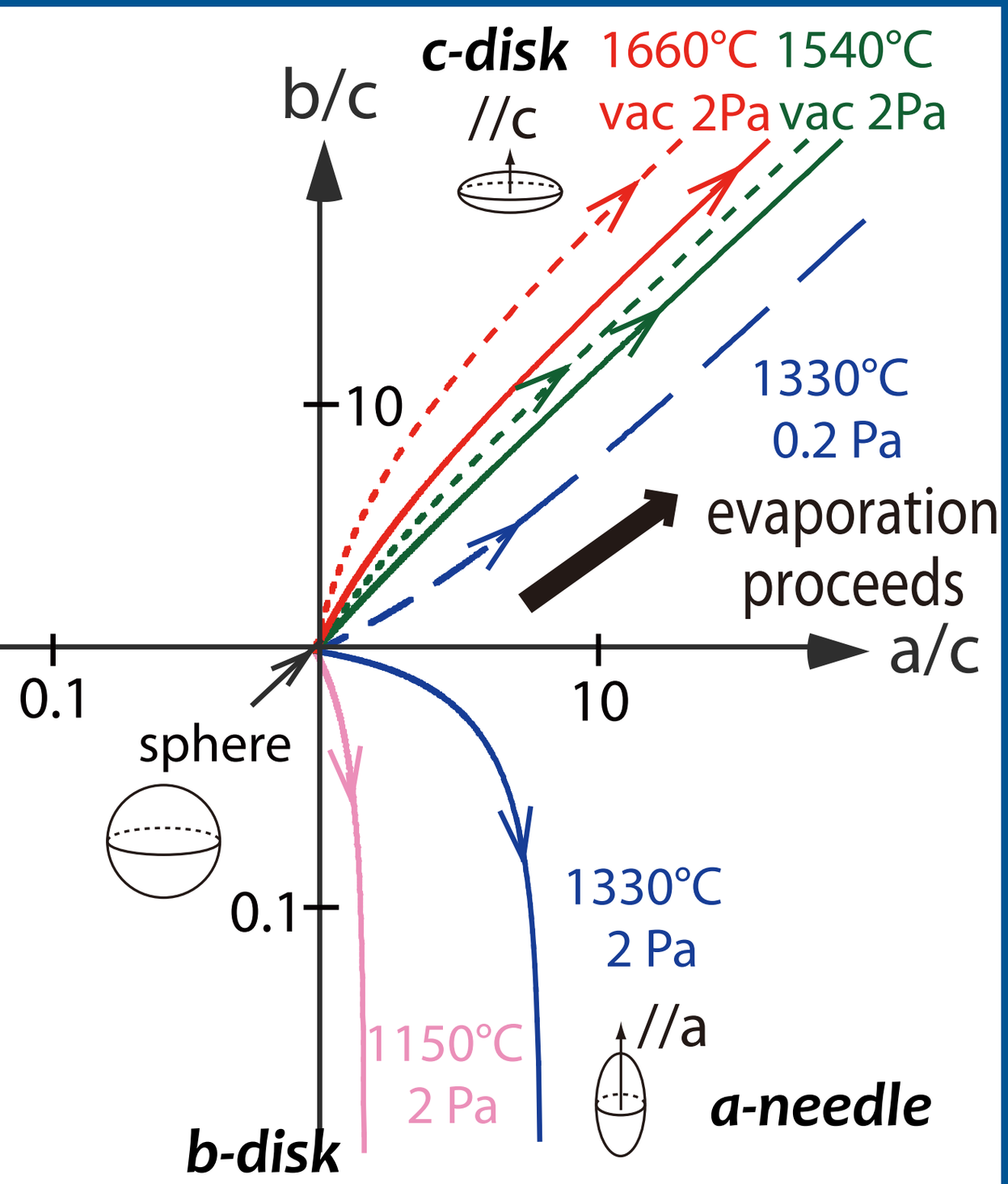


Takigawa et al. (2009) ApJL

Anisotropy in evaporation rates changes with T and pH_2

Shape change due to anisotropic evaporation

Evaporation from a sphere



At higher T., fastest evaporation along the c-axis

- disk flattened along the c-axis

At lower T., fastest evaporation along the b-axis

- needle elongating along the a-axis
- disk flattened along the b-axis

Evaporation makes shapes only with a/c ≥ 1

Spectral change of forsterite

shapes formed by evap.

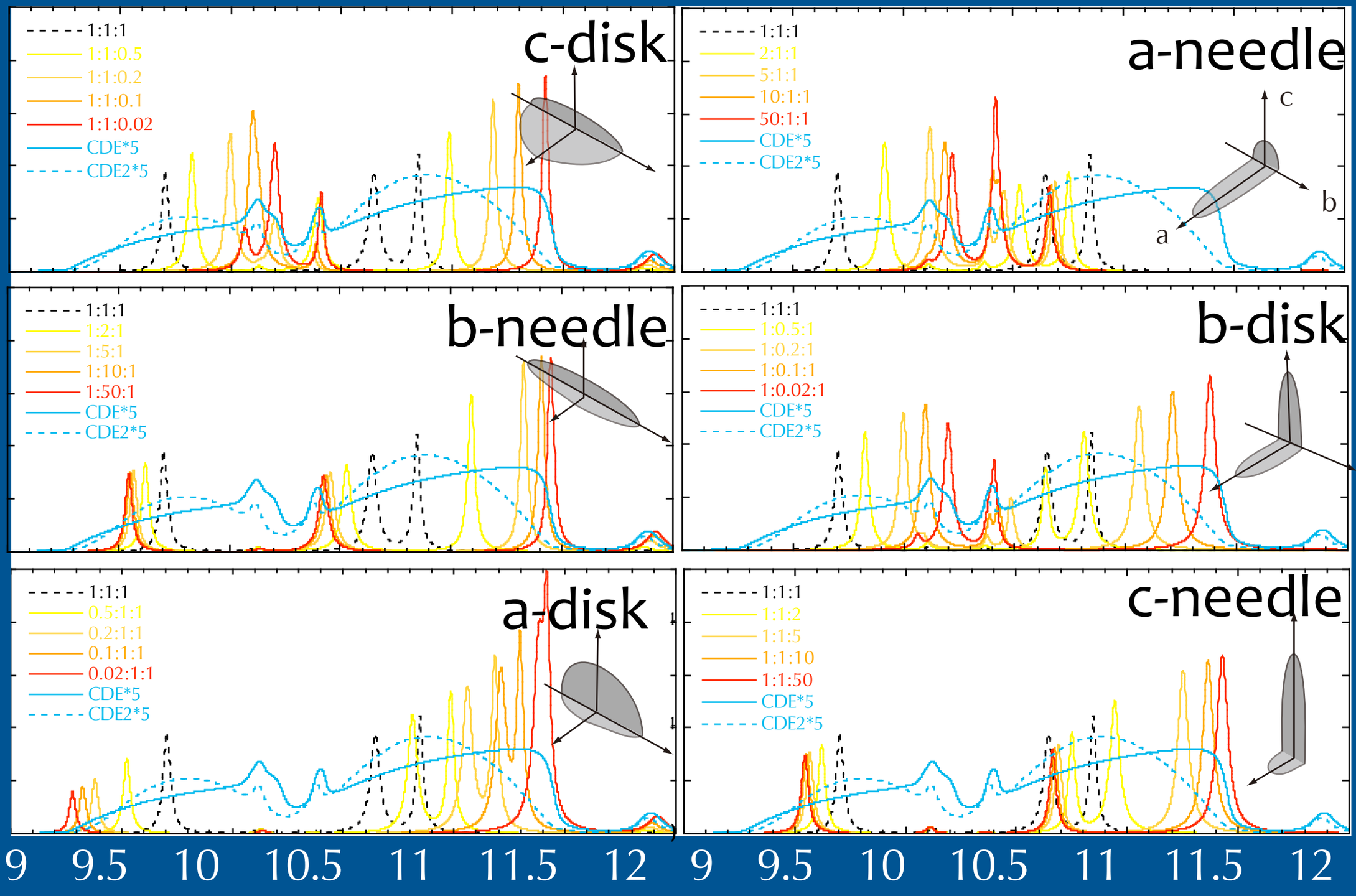
b/c>1

b/c<1

a/c>1

a/c=1

a/c<1



Takigawa et al. in prep.

Spectral change of forsterite

shapes formed by evap.

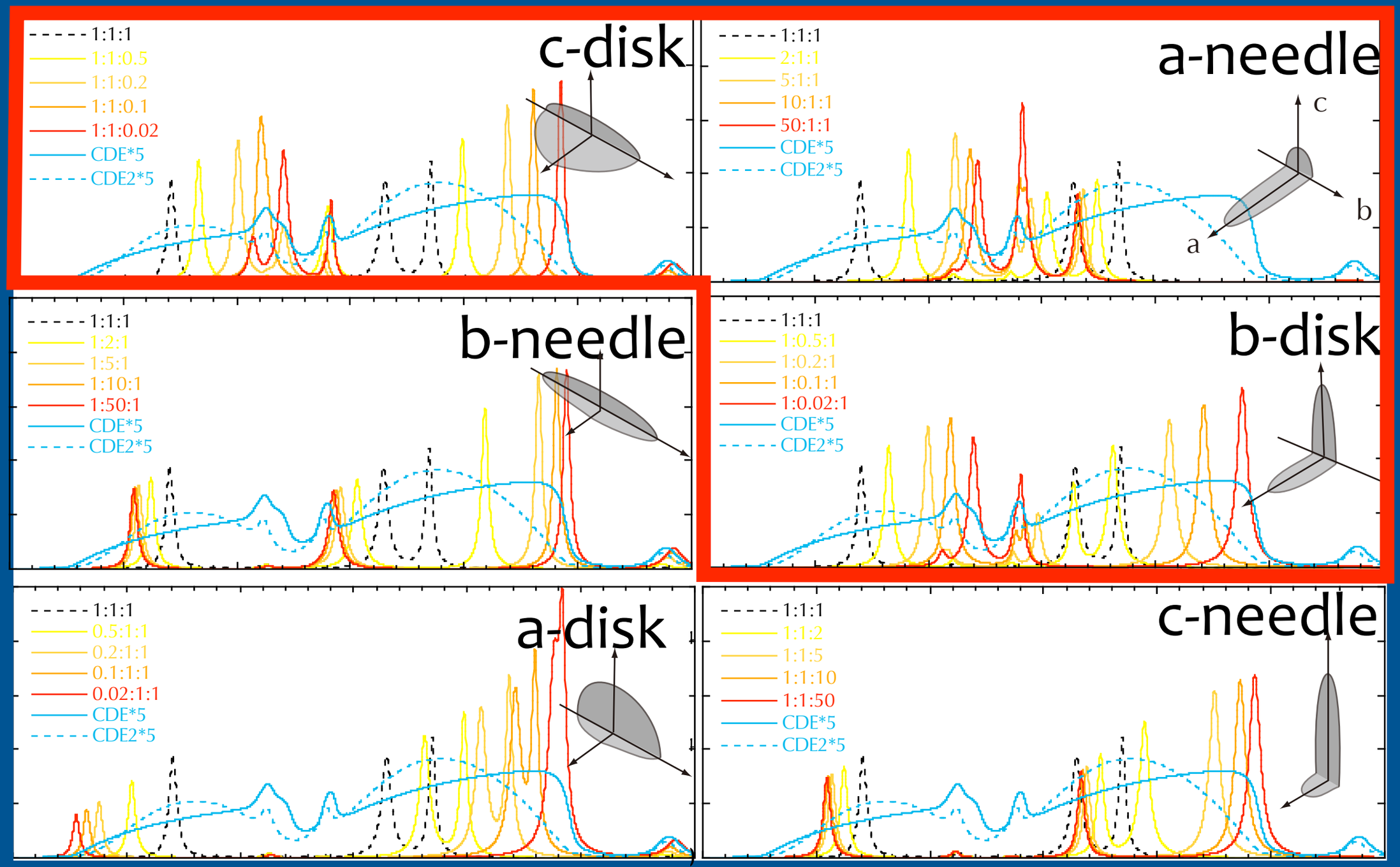
b/c>1

b/c<1

a/c>1

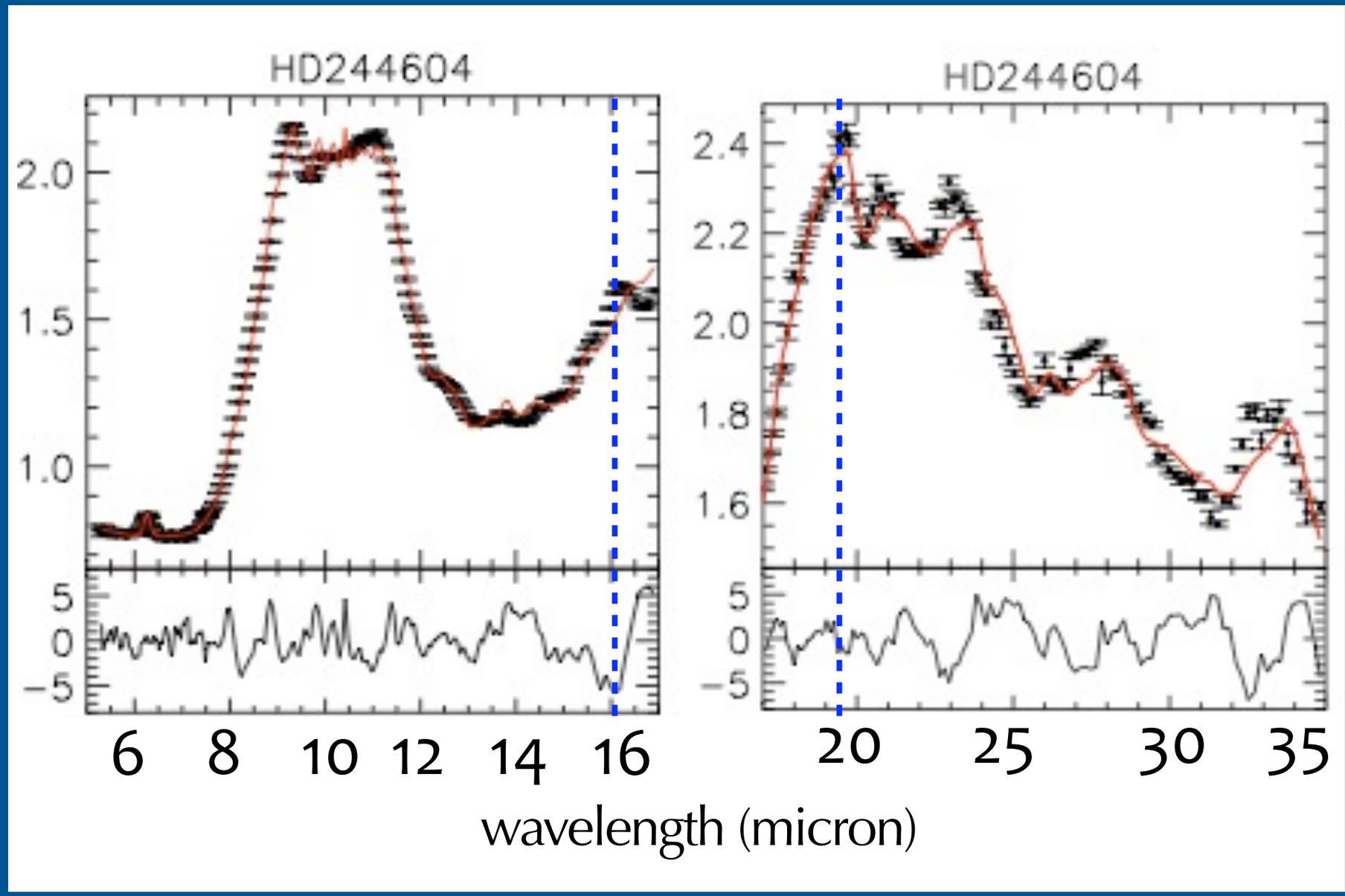
a/c=1

a/c<1



Takigawa et al. in prep.

16 & 19.5 micron features



Juhász et al. 2010

16 & 19.5 micron features

shapes formed by evap.

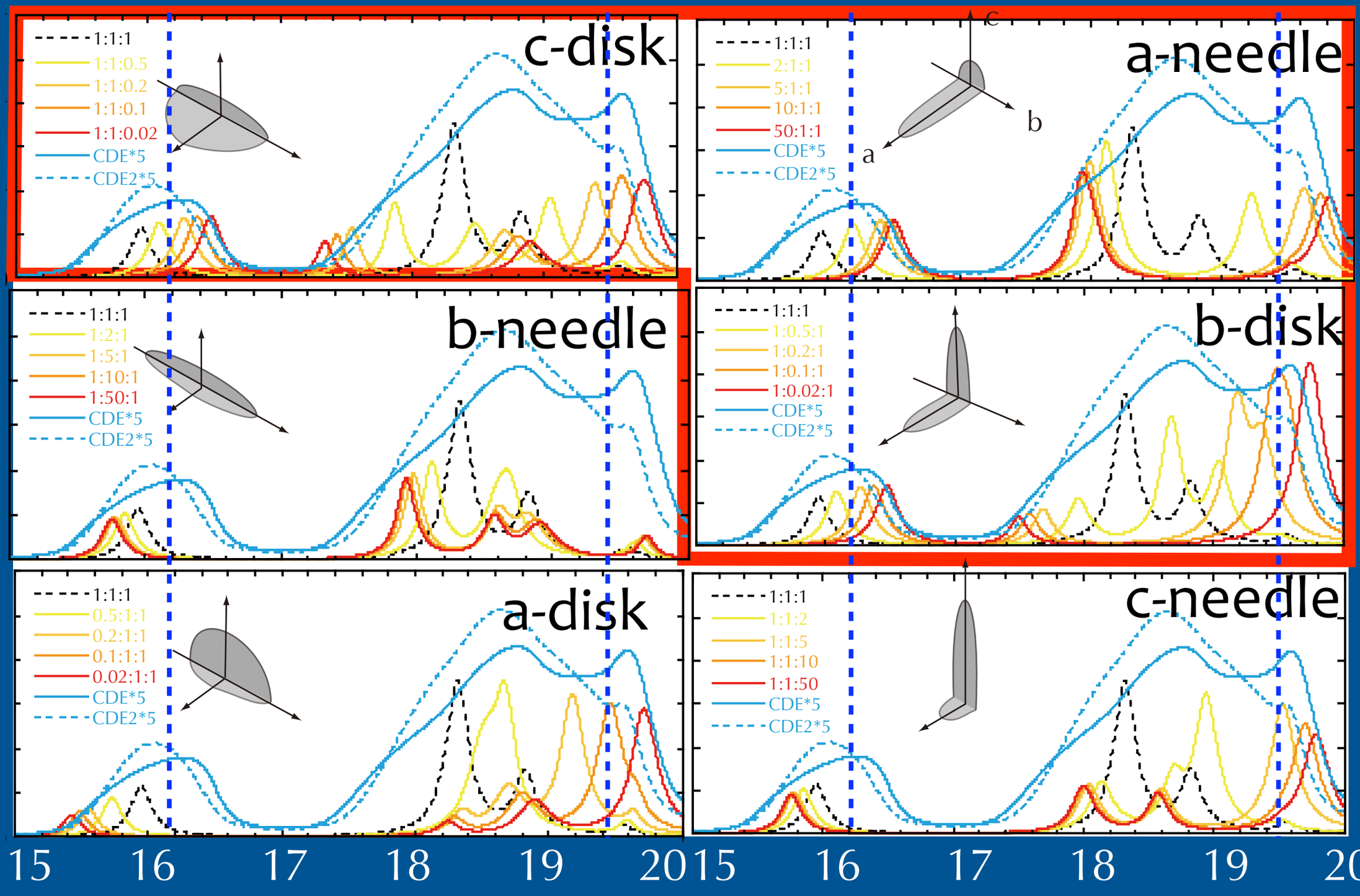
b/c>1

b/c<1

a/c>1

a/c=1

a/c<1



wavelength (micron)

Takigawa et al. in prep.

69-micron feature

shapes formed by evap.

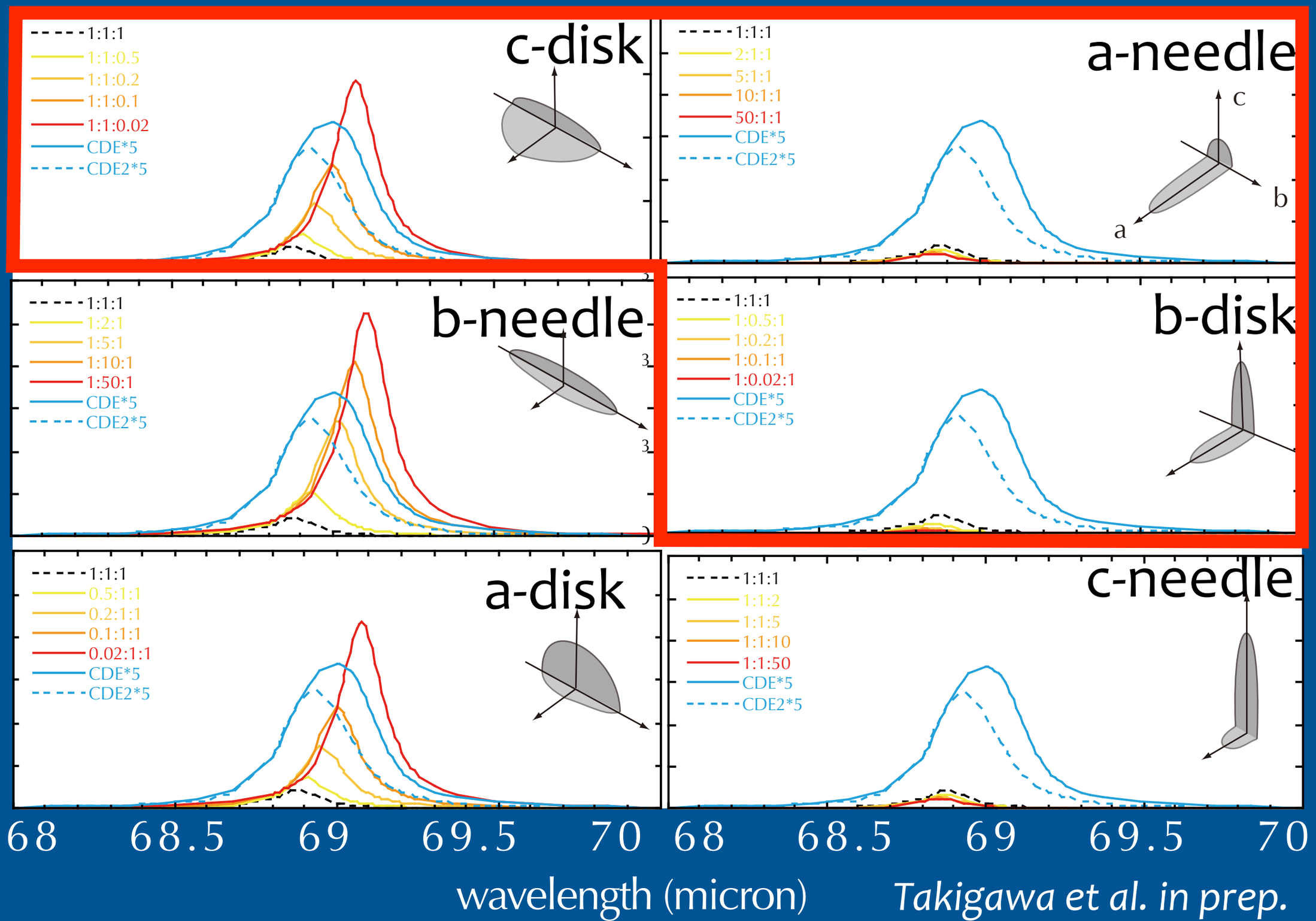
b/c>1

b/c<1

a/c>1

a/c=1

a/c<1



Takigawa et al. in prep.

69-micron feature

shapes formed by evap.

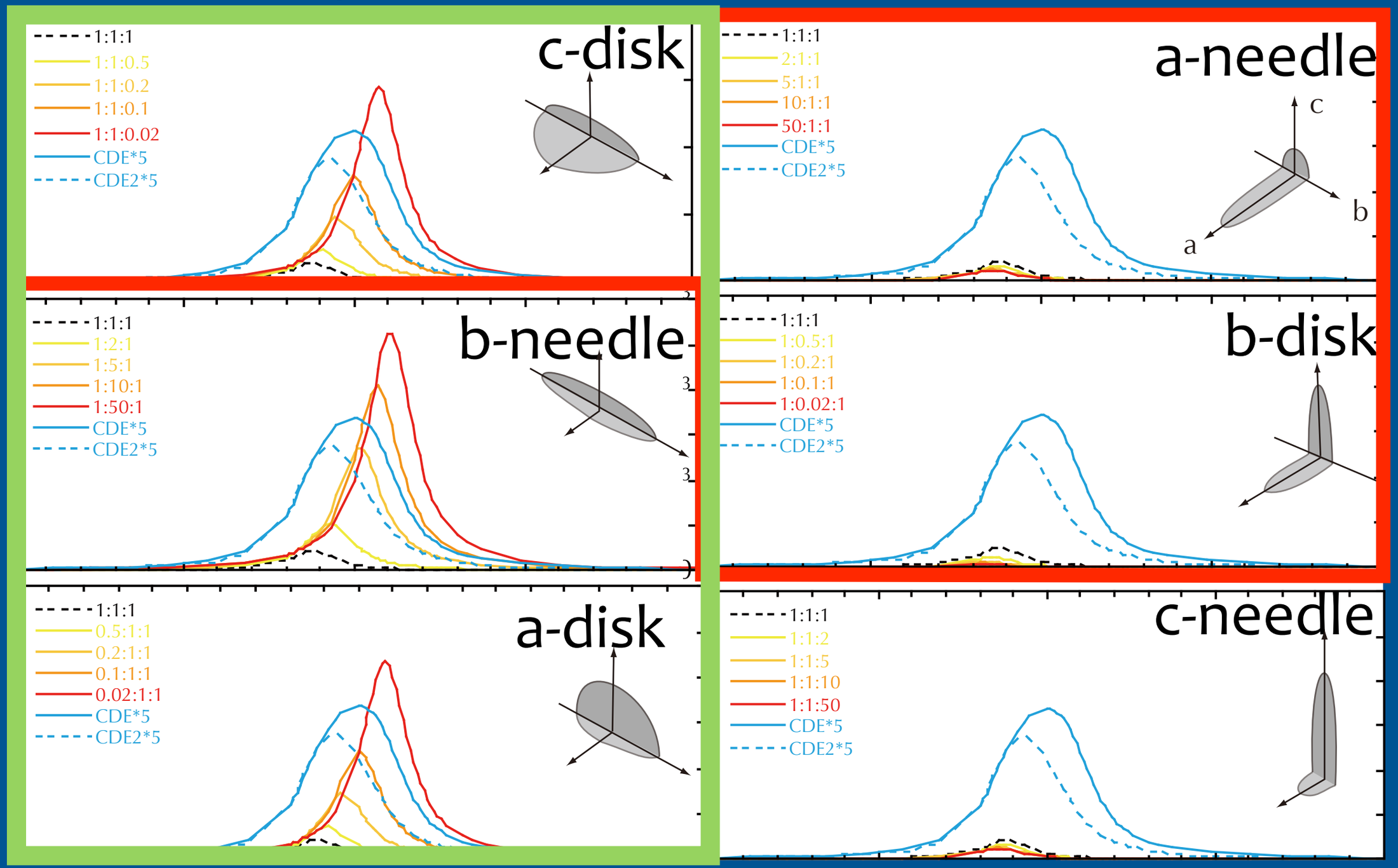
b/c>1

b/c<1

a/c>1

a/c=1

a/c<1



wavelength (micron)

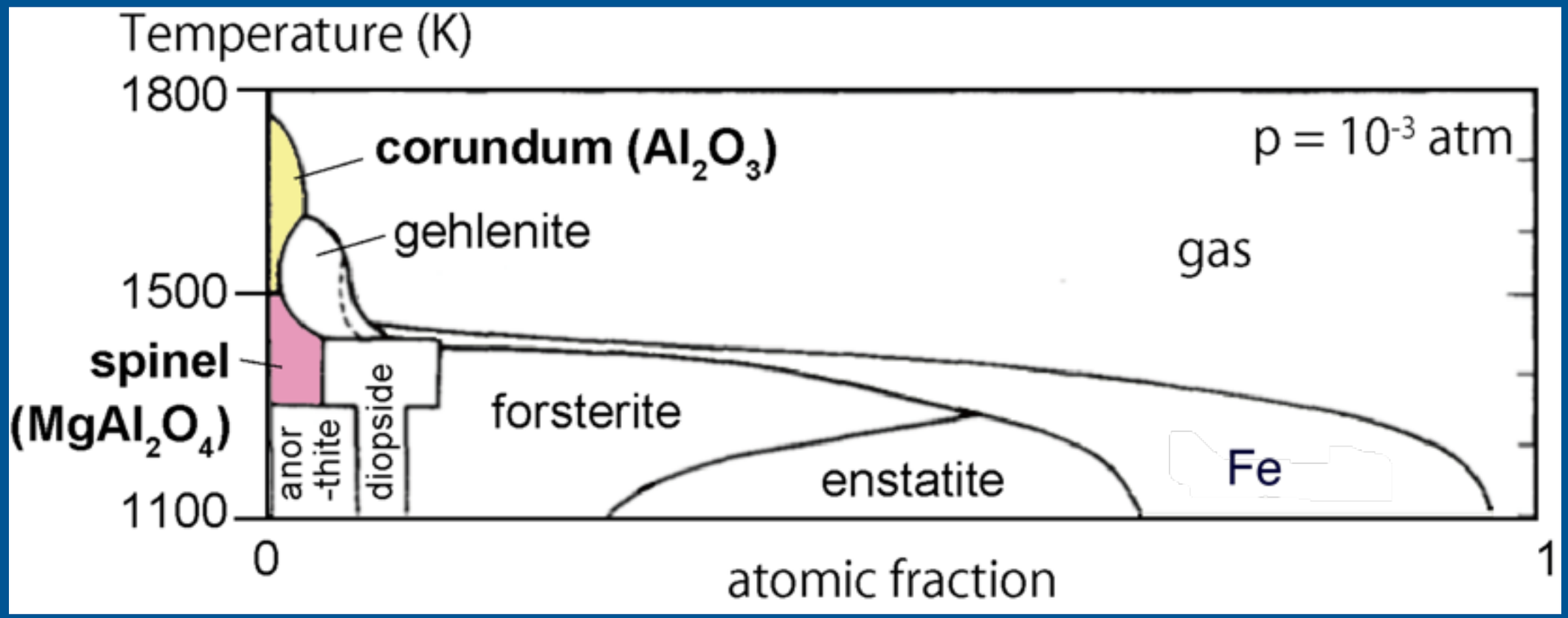
Takigawa et al. in prep.

Evaporation of forsterite

- Anisotropic
- Changes of crystallographically anisotropic shape cause observable changes of IR spectra

Corundum

- First condensate from gas in protoplanetary disks and around O-rich AGB stars



Grossman 1978

Corundum

- Presolar & solar corundum
  - direct evidence of corundum condensation

- Astronomical observation
  - candidate for the 13 um-feature in outflows around O-rich AGB stars (e.g., Posch et al. 1999)

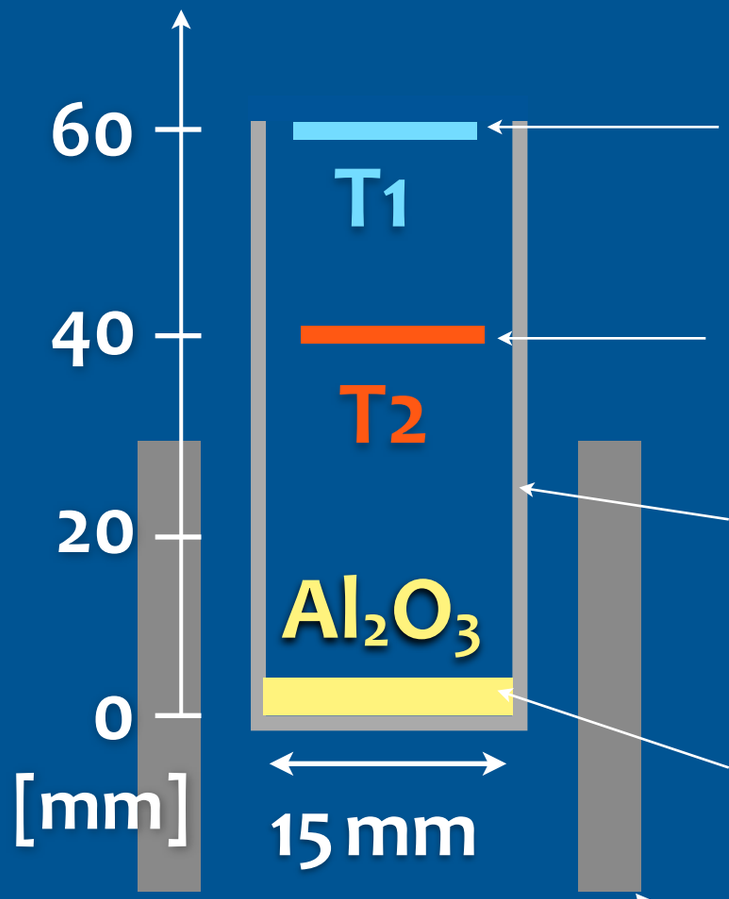
Condensation experiments of corundum

gas source: Al_2O_3 powder (4N+)

substrate: Mo-ribbons

crucible: Ir (>99.9%)

Condensation experiments of corundum



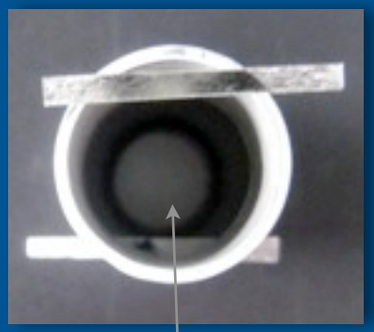
Mo sbst(lowT)

Mo sbst(high T)

Ir crucible
(>99.9%)

Al_2O_3 powder
(>99.99%)

W-mesh Heater

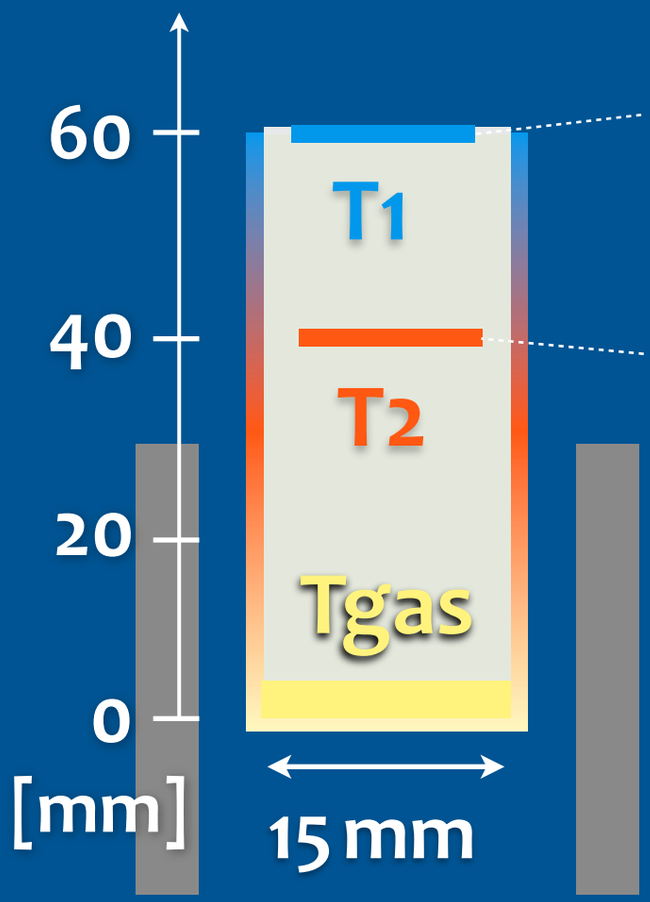


Al_2O_3 powder
(>99.99%)

$p = 5 \times 10^{-5}$ Pa

Condensation experiments of corundum

supersaturation ratio



$$S1 = \frac{f_{in}}{f_{out}(T1)}$$

$$S2 = \frac{f_{in}}{f_{out}(T2)}$$

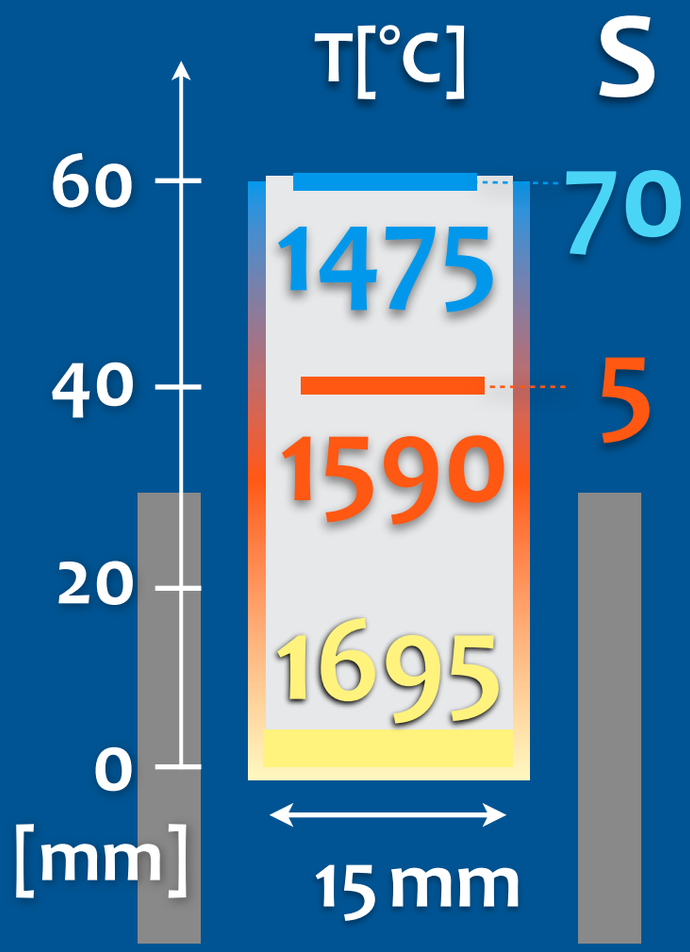
$p = 5x10^{-5}$ Pa

T_{gas}[°C]	T1 [°C]	S1	T2 [°C]	S2	*t* [h]
1695	1590	**5**	1475	**70**	9
1605	1490	**9**	1370	**180**	6,12,18
1535	>1435	**<5**	-	**-**	240
1505	1380	**15**	1260	**330**	120,360

Condensates at S=70

$P = 5x10^{-5}$ Pa

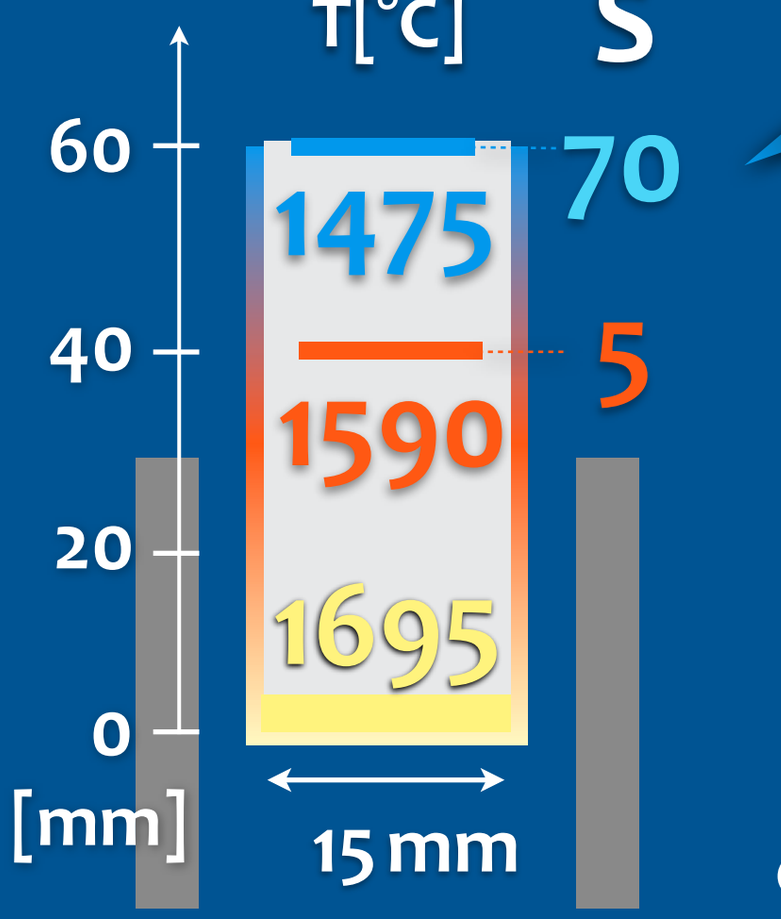
t = 9 hrs

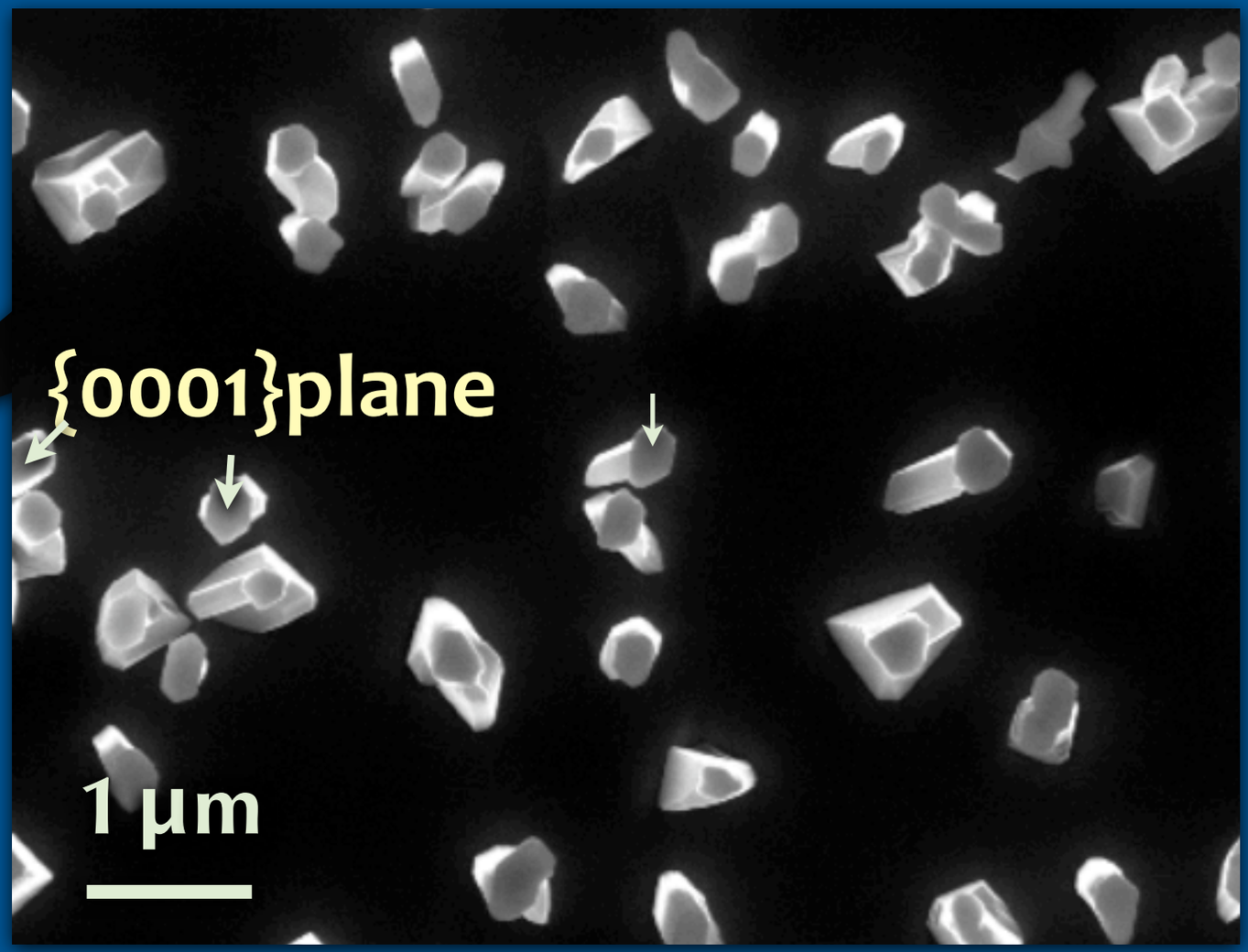


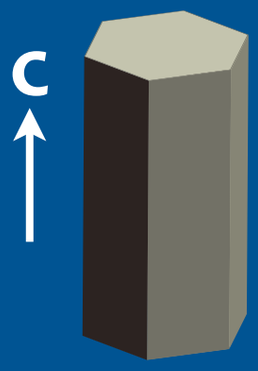
Condensates at S=70

P = 5x10^{-5} Pa

t = 9 hrs







Condensates at S=70

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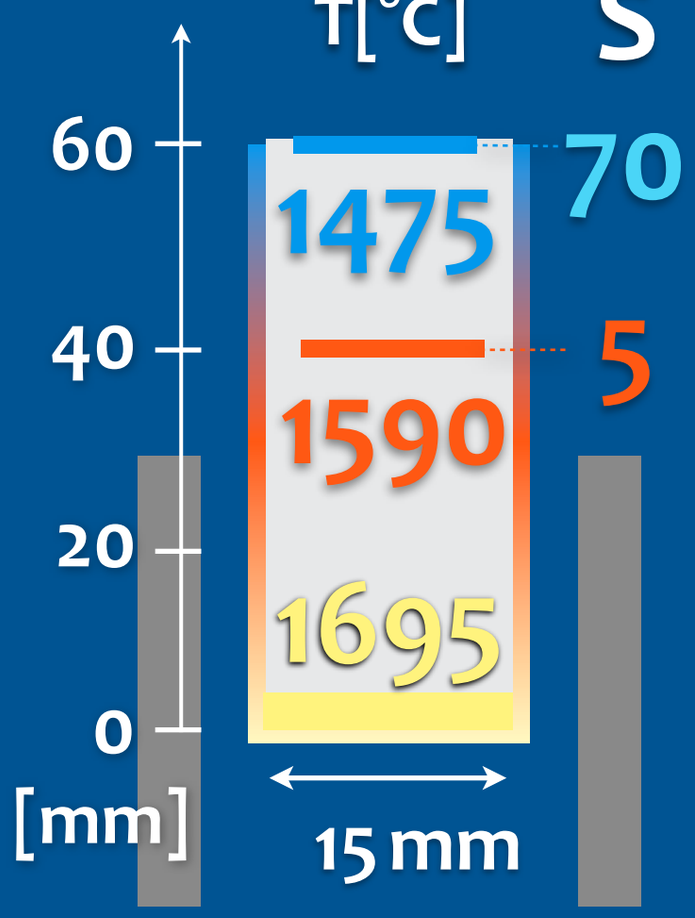
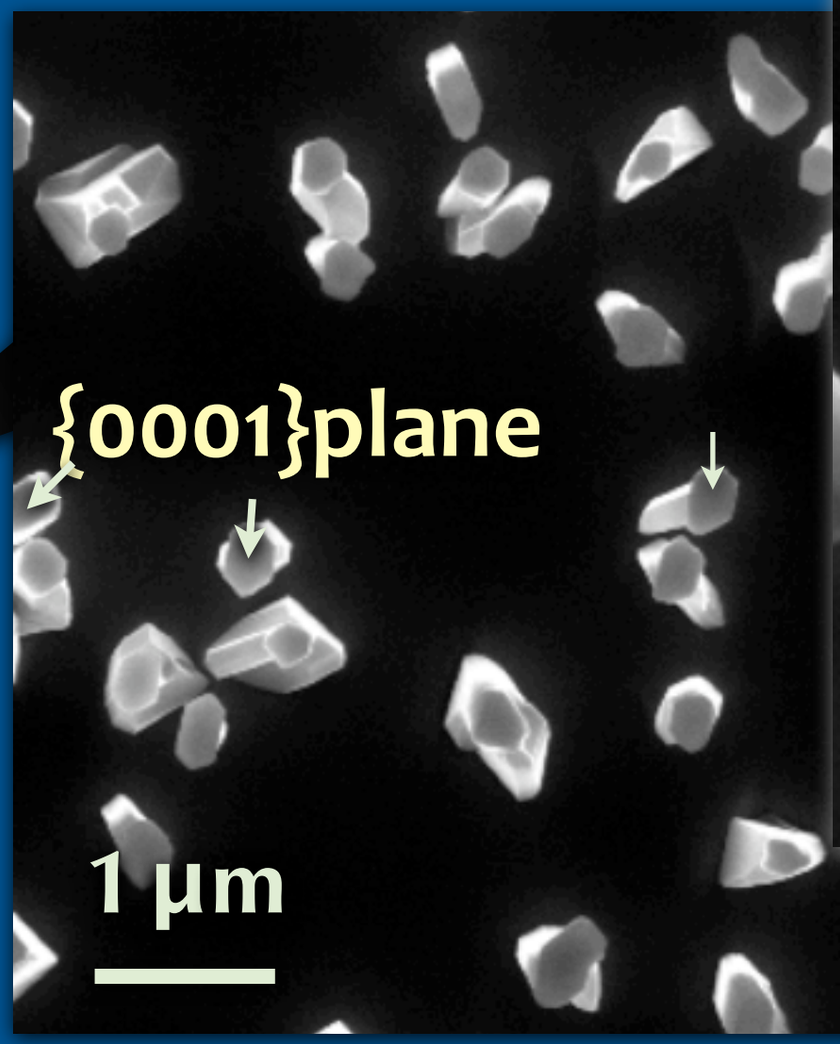
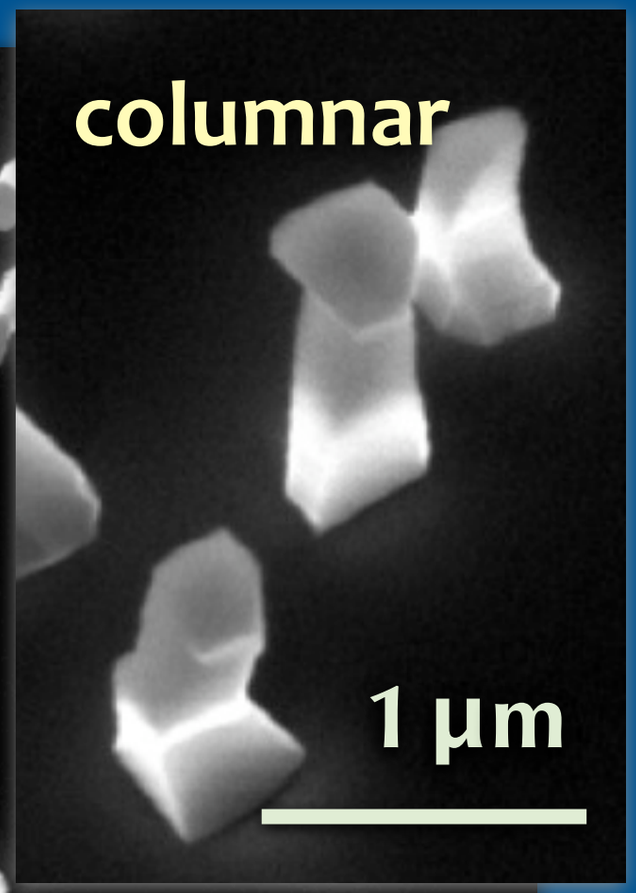
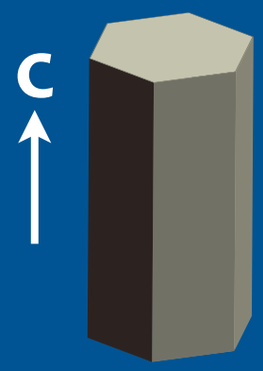






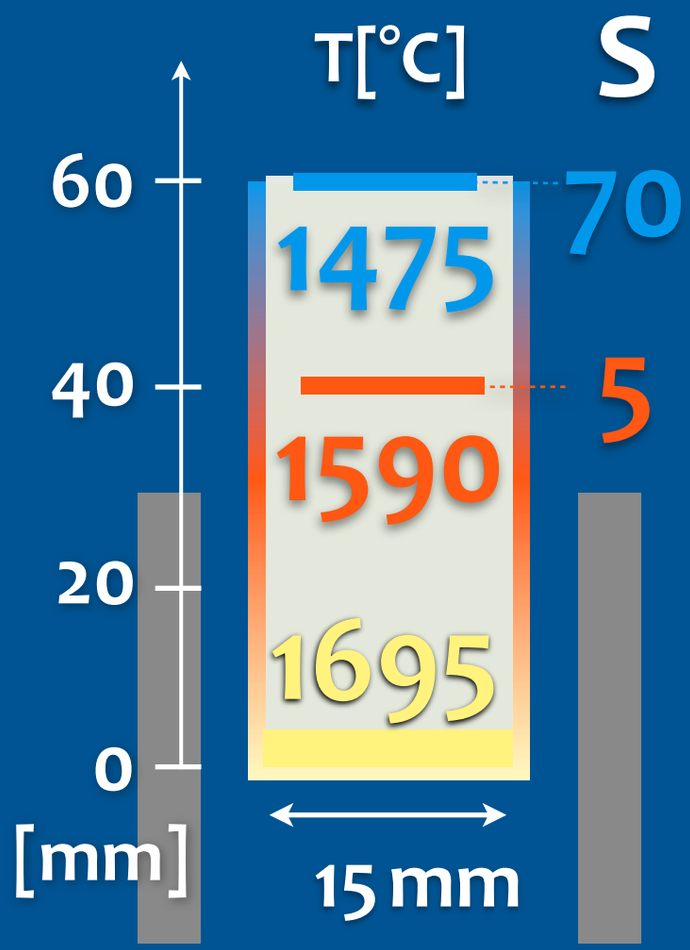


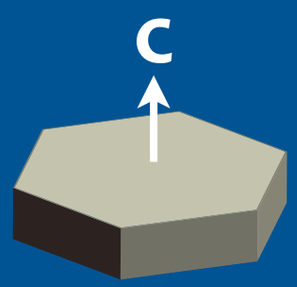
α-corundum elongating along the c-axis (~0.3x2 μm)

Condensates at S=5

$P = 5x10^{-5}$ Pa

t = 9 hrs

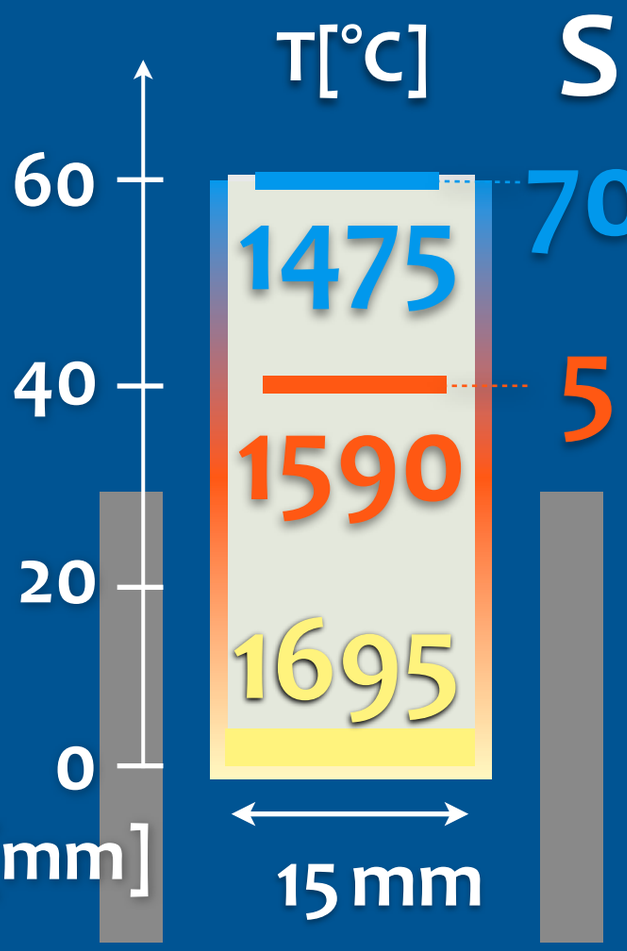


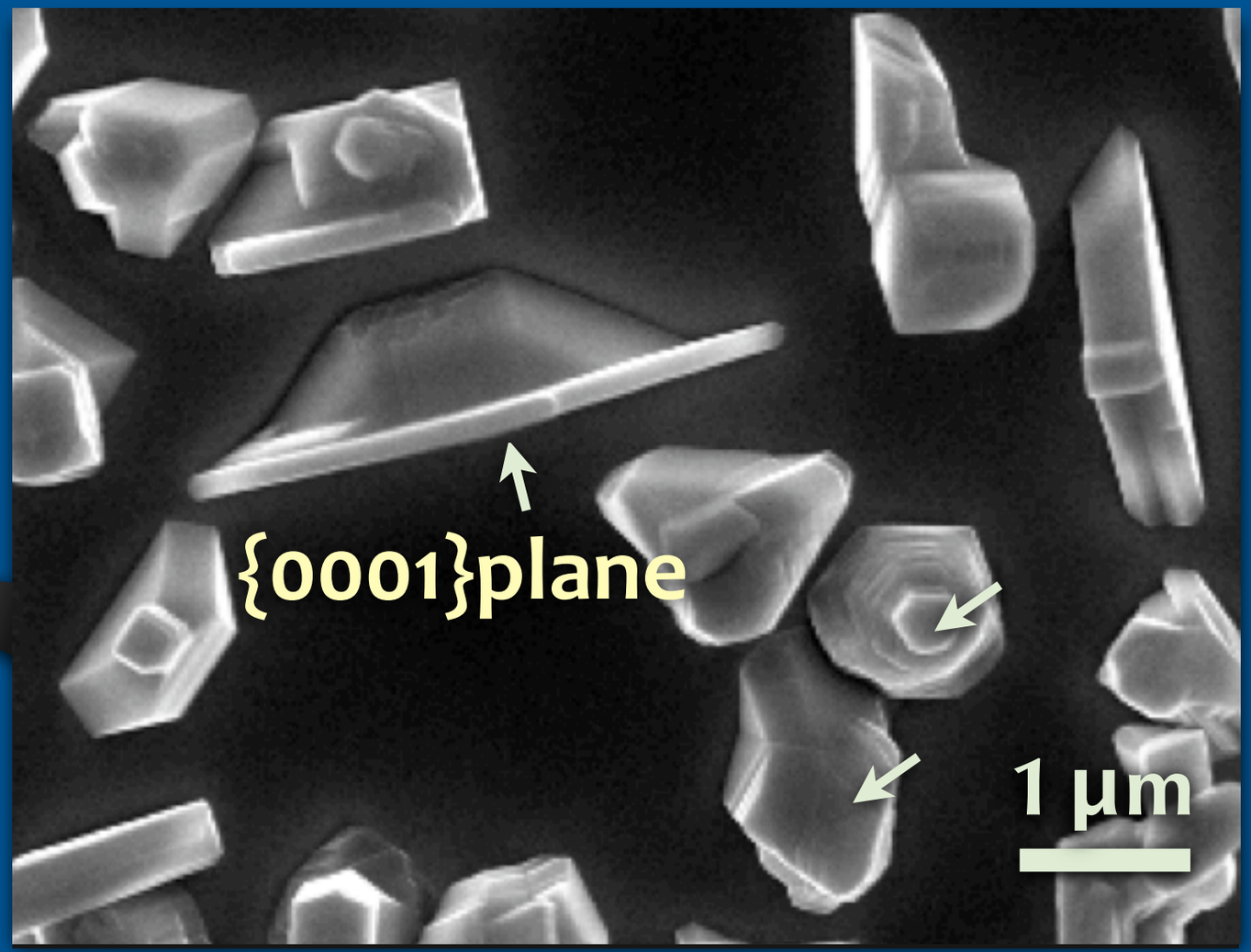


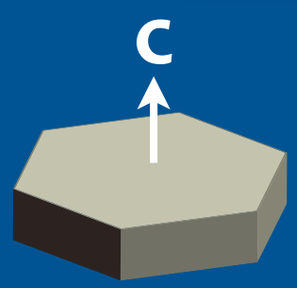
Condensates at *S*=5

$P = 5 \times 10^{-5}$ Pa

t = 9 hrs



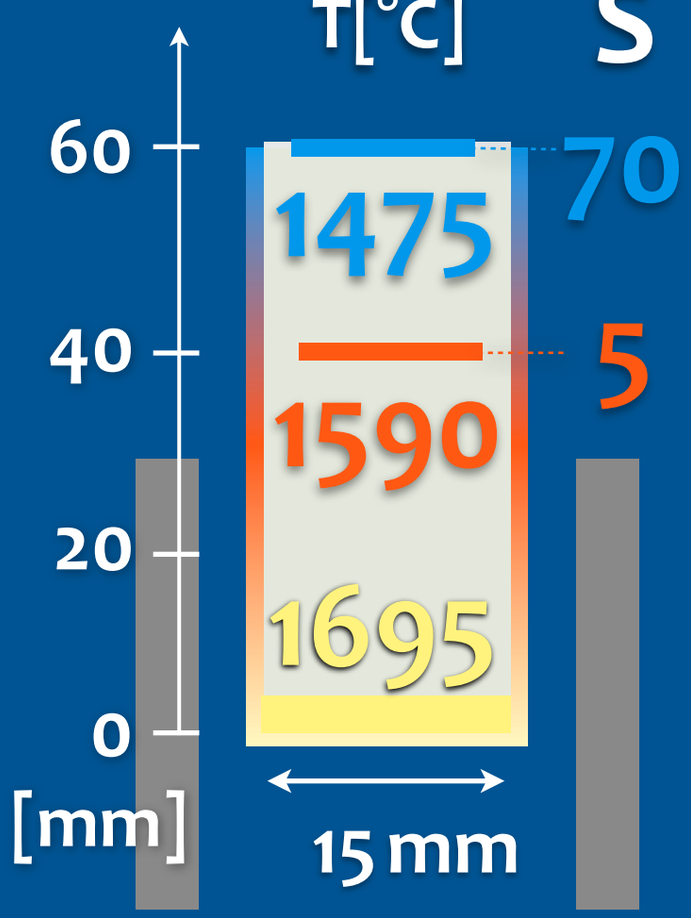


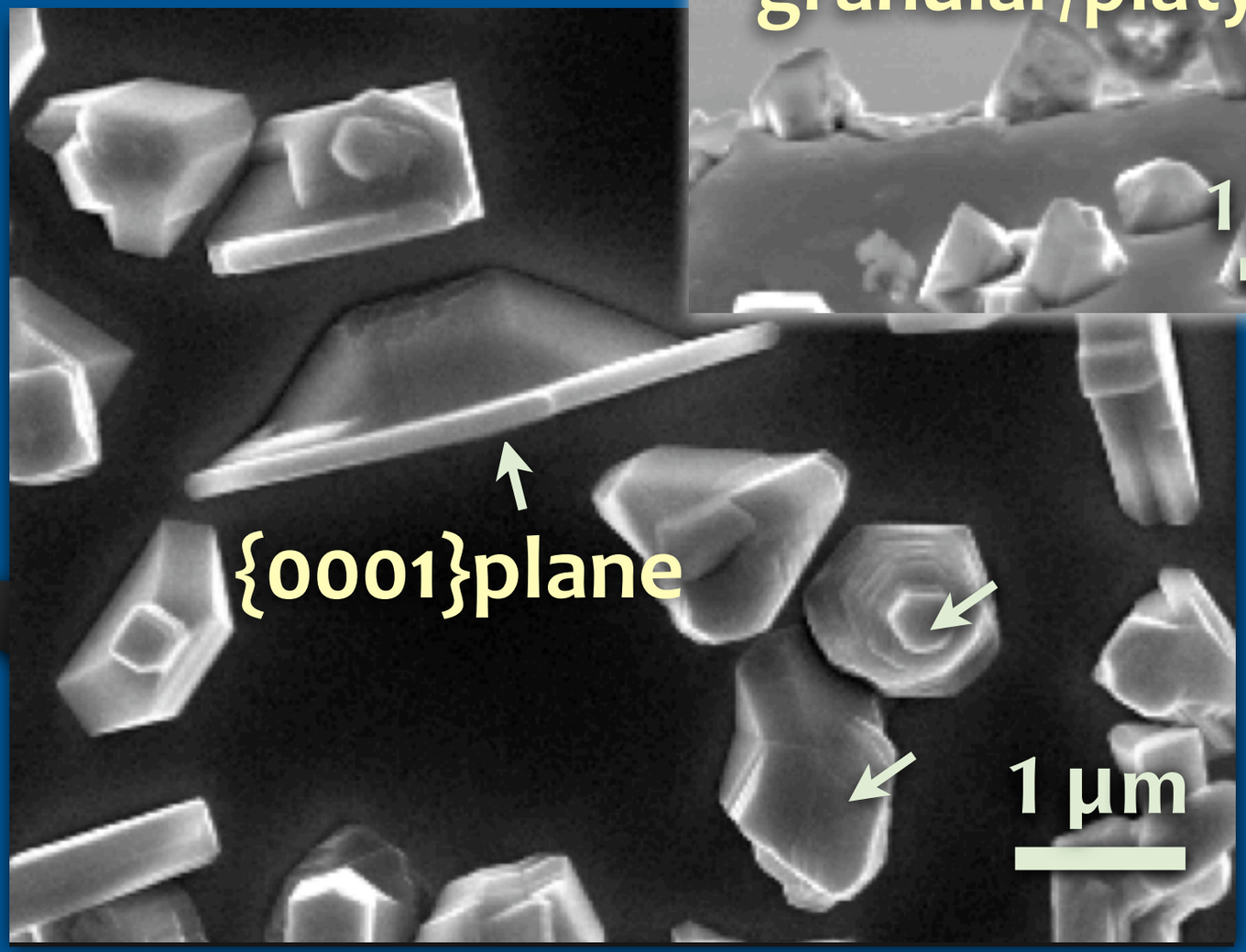


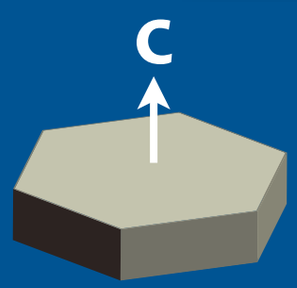
Condensates at *S*=5

P = 5x10^{-5} Pa

t = 9 hrs

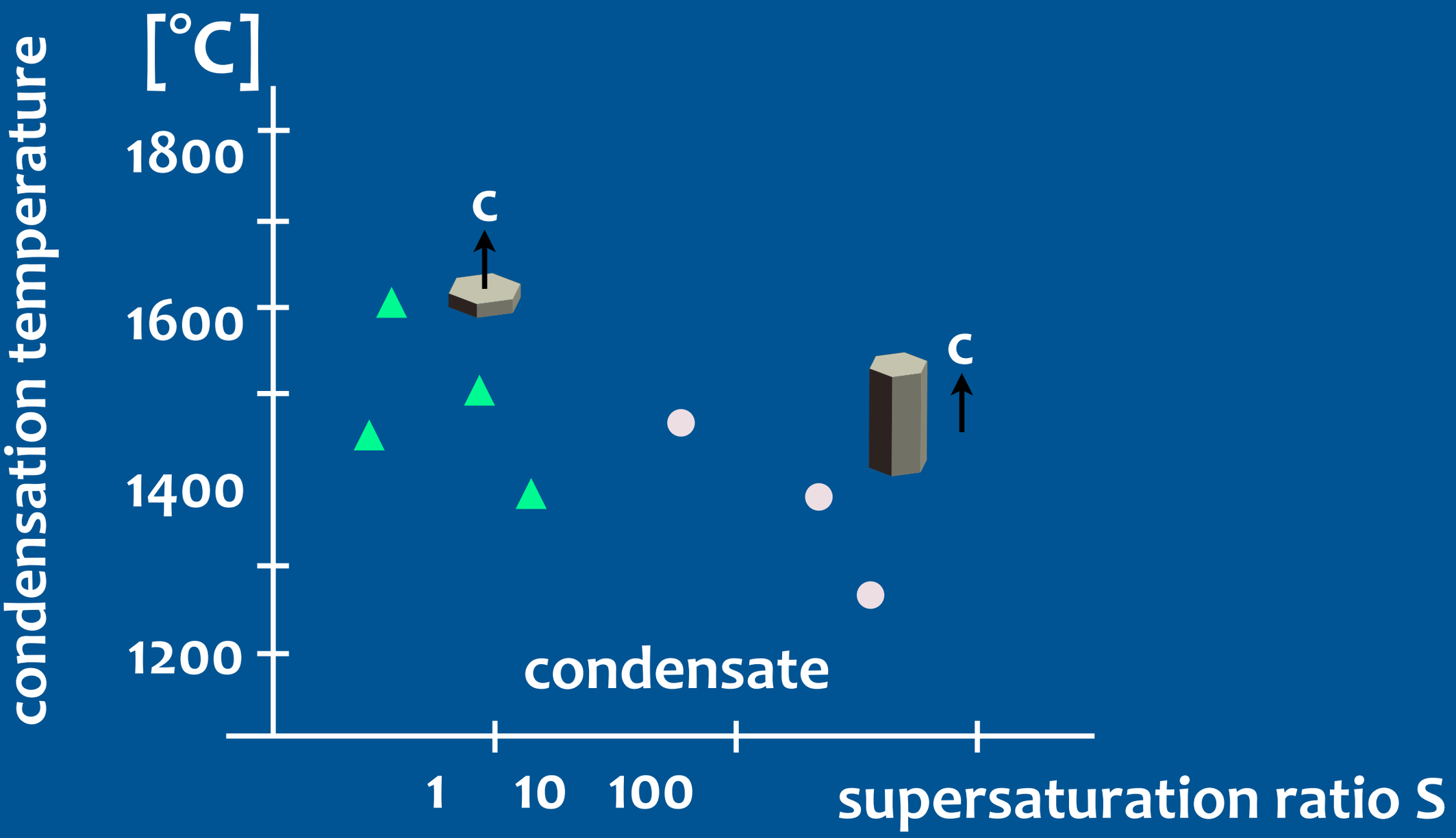






granular to tabular grain
along the c-axis (~1 um)

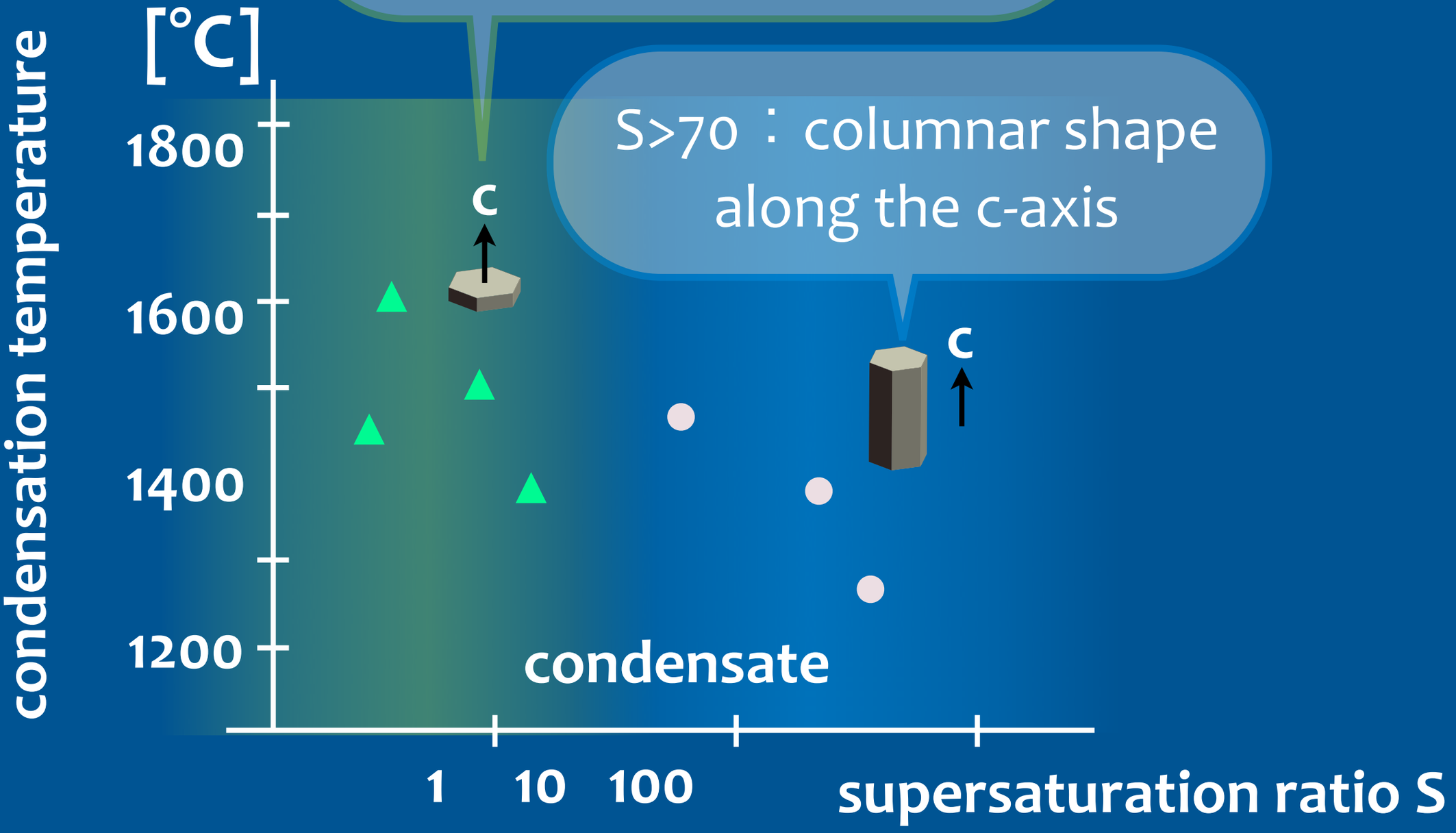
Growth form & condensation condition



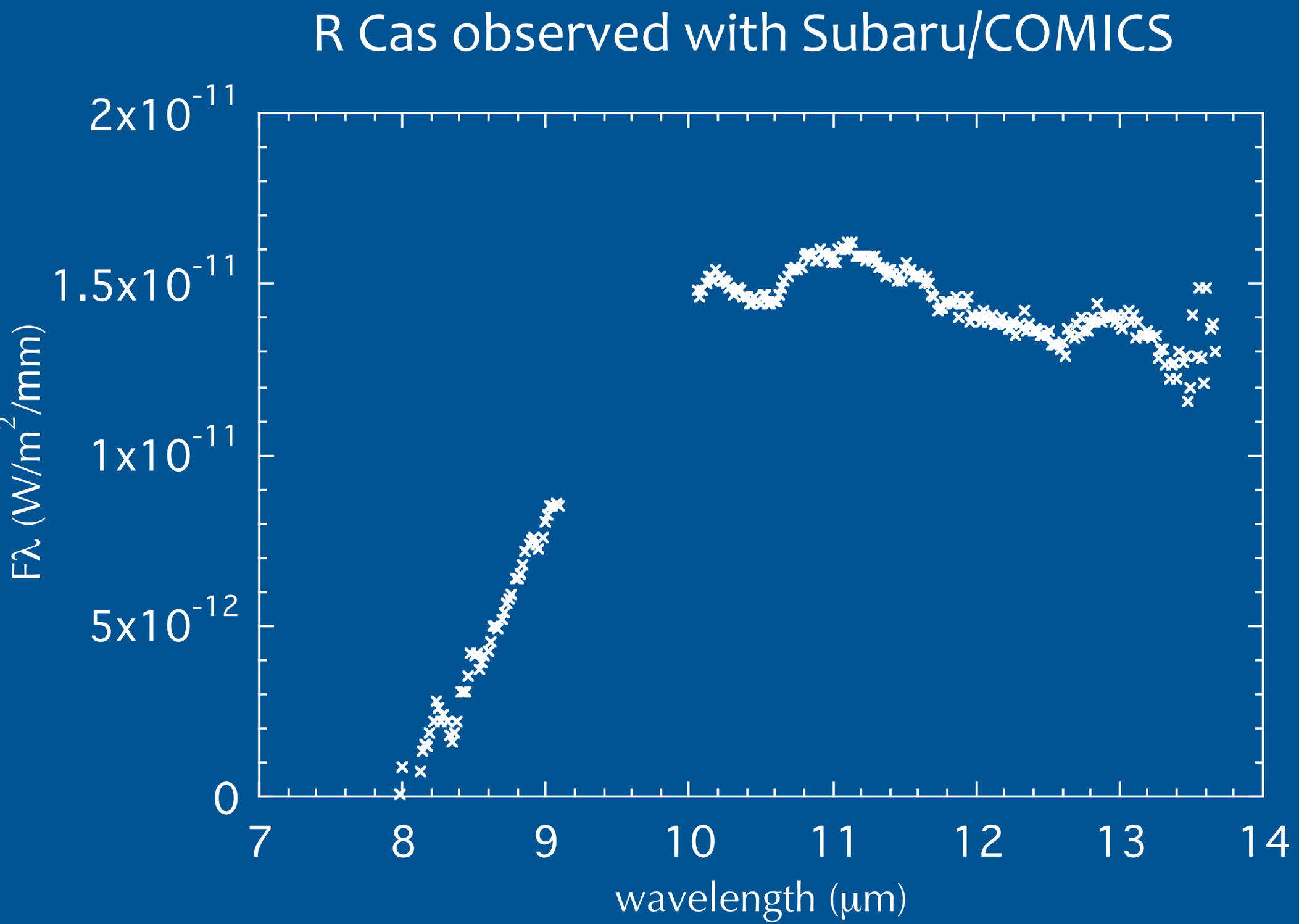
Growth form & condensation condition

S<15 : granular to tabular grain along the c-axis (~1 μm)

S>70 : columnar shape along the c-axis

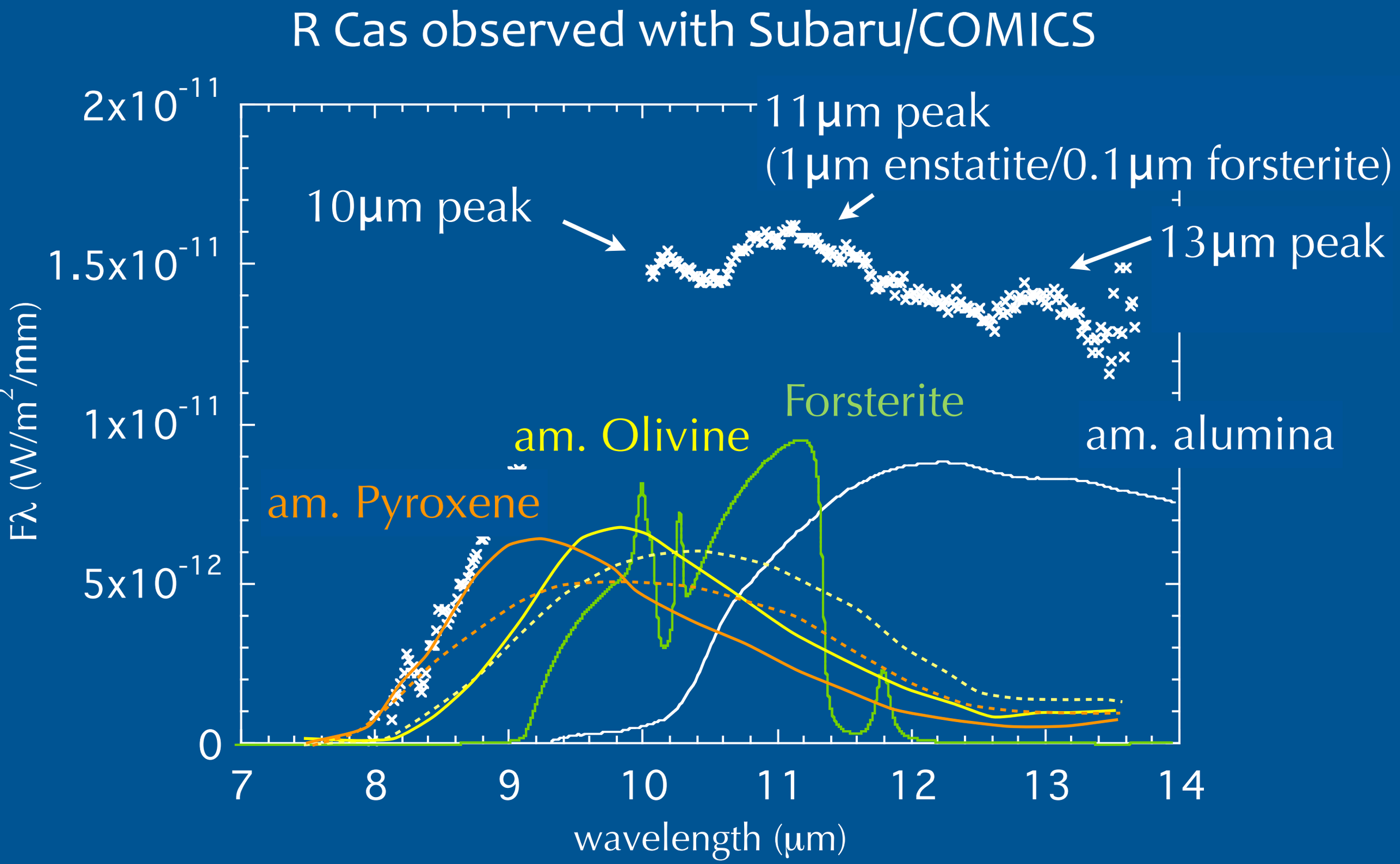


the 13-micron feature of R-Cas



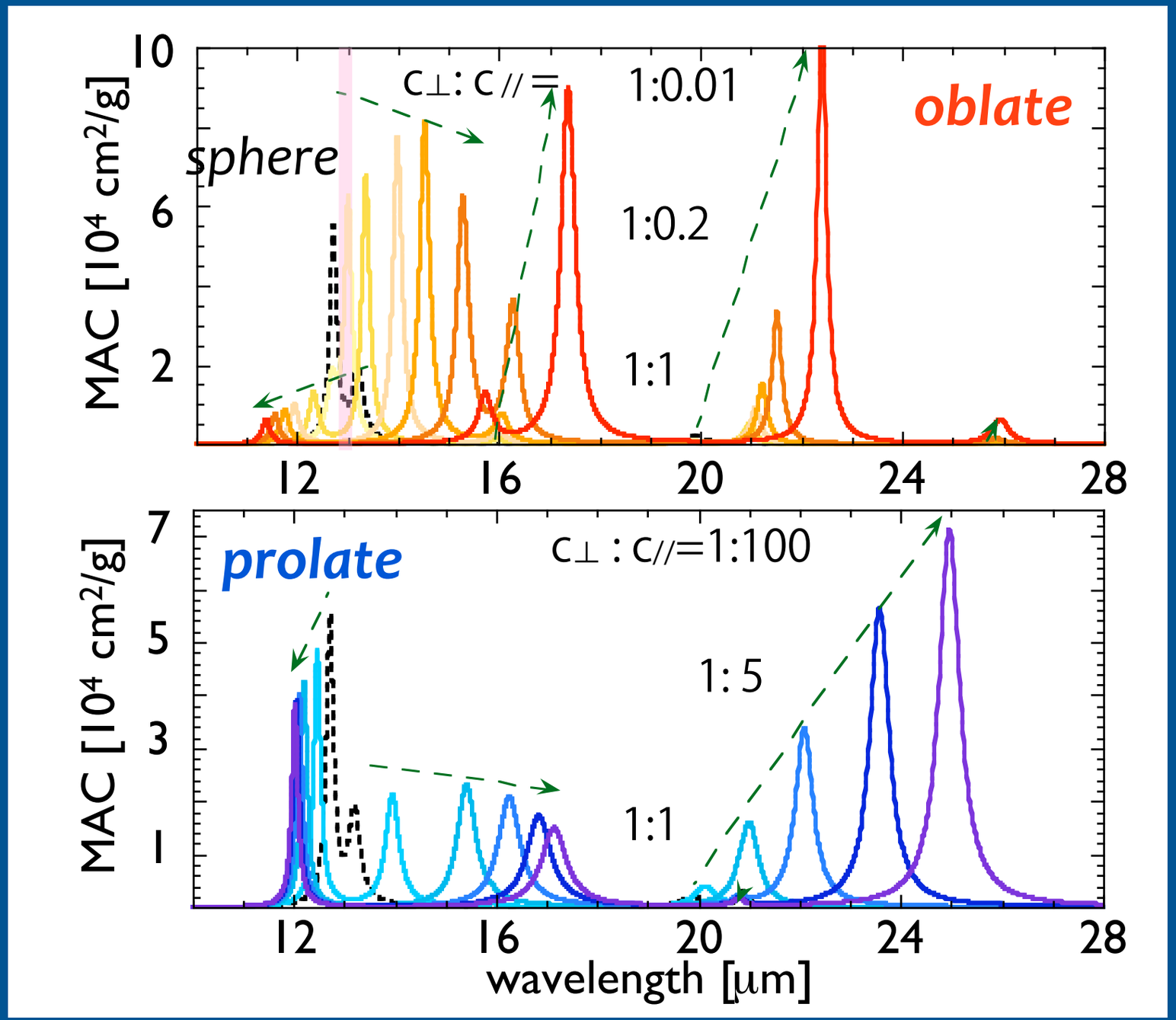
Takigawa et al. unpub. data

the 13-micron feature of R-Cas



Takigawa et al. unpub. data

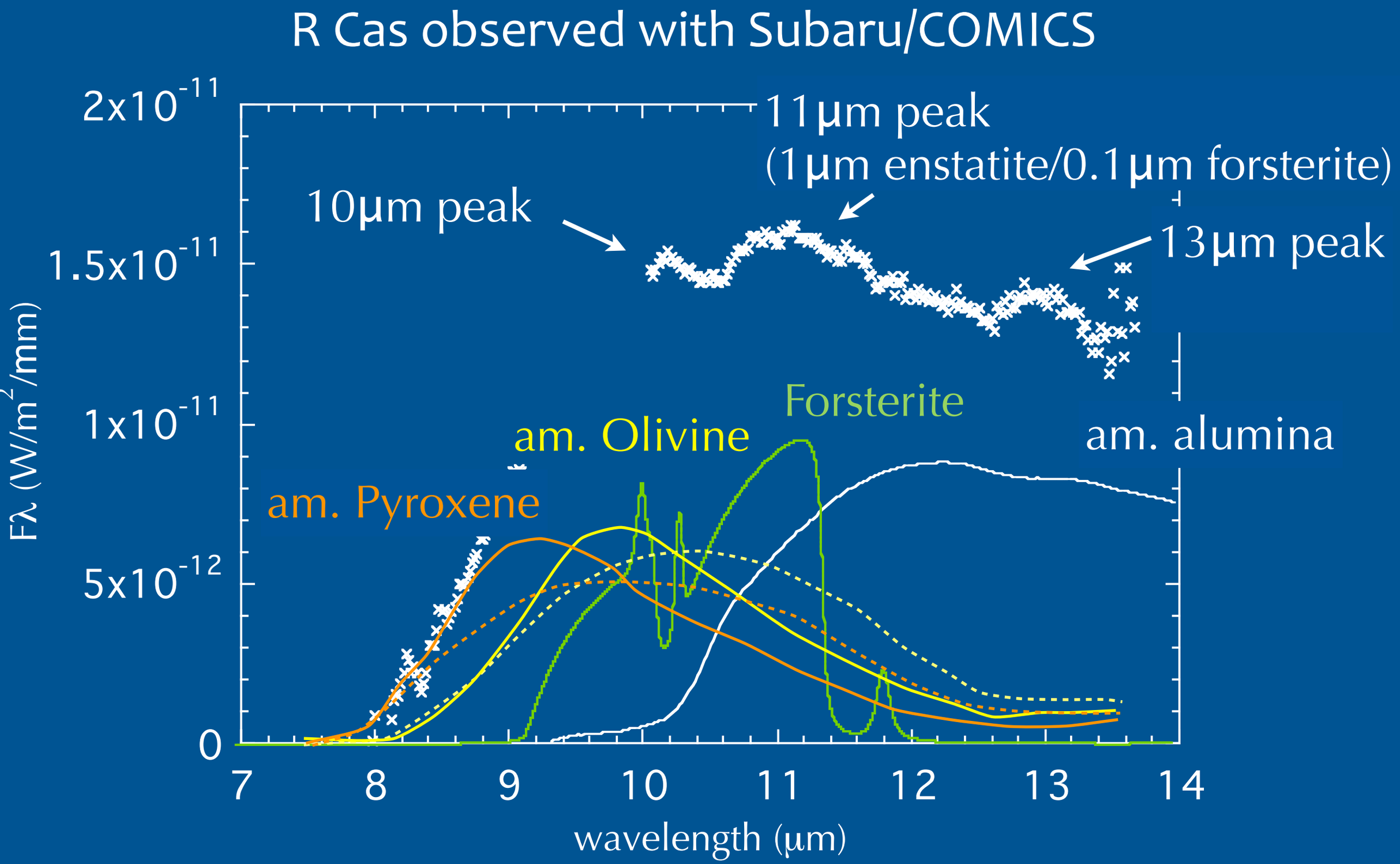
the 13-micron feature of corundum



Disk-shaped corundum grains along the c-axis (c//:c⊥=2:3)

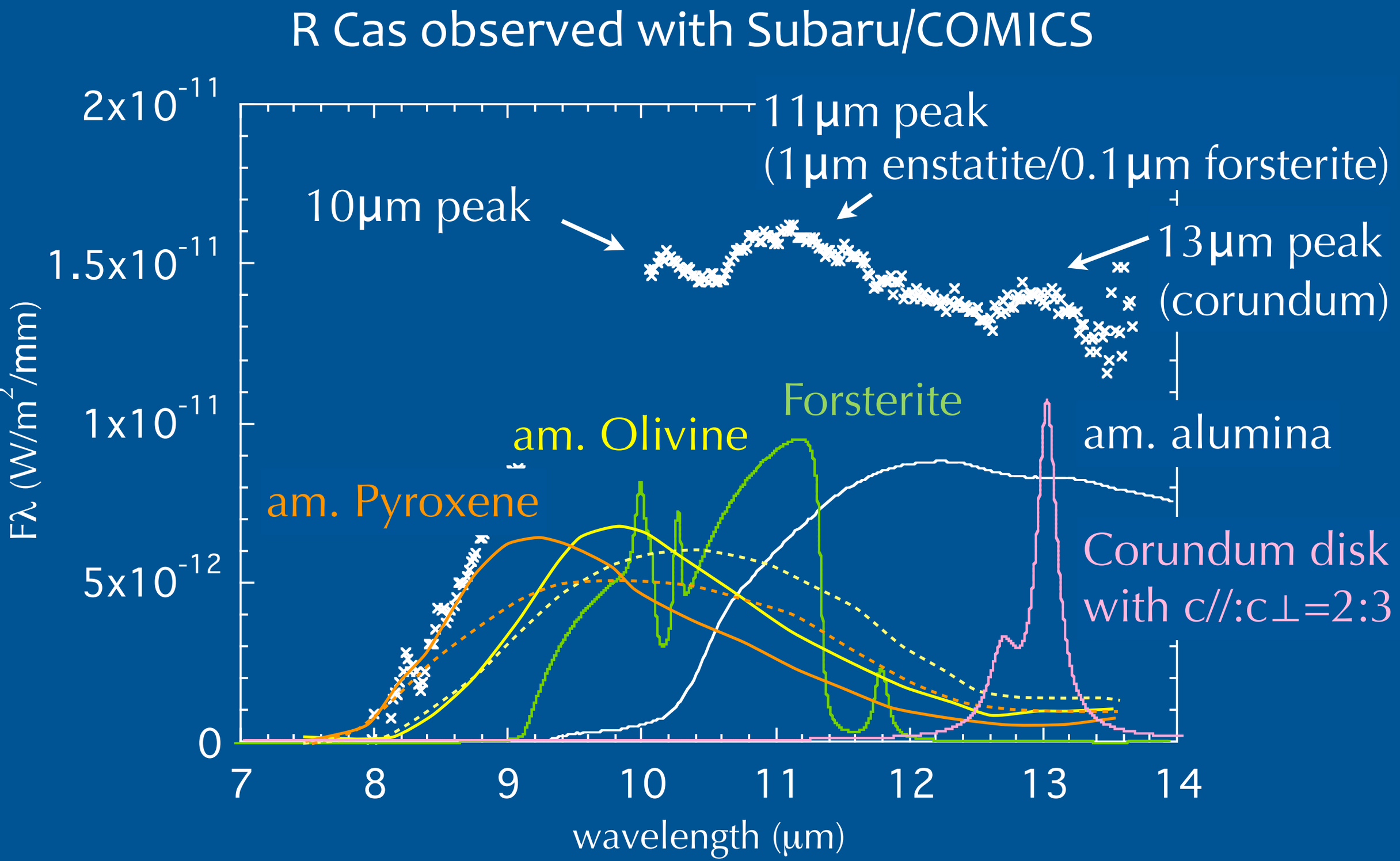
- reproduce the 13-μm feature around O-rich AGB stars

the 13-micron feature of R-Cas



Takigawa et al. unpub. data

the 13-micron feature of R-Cas

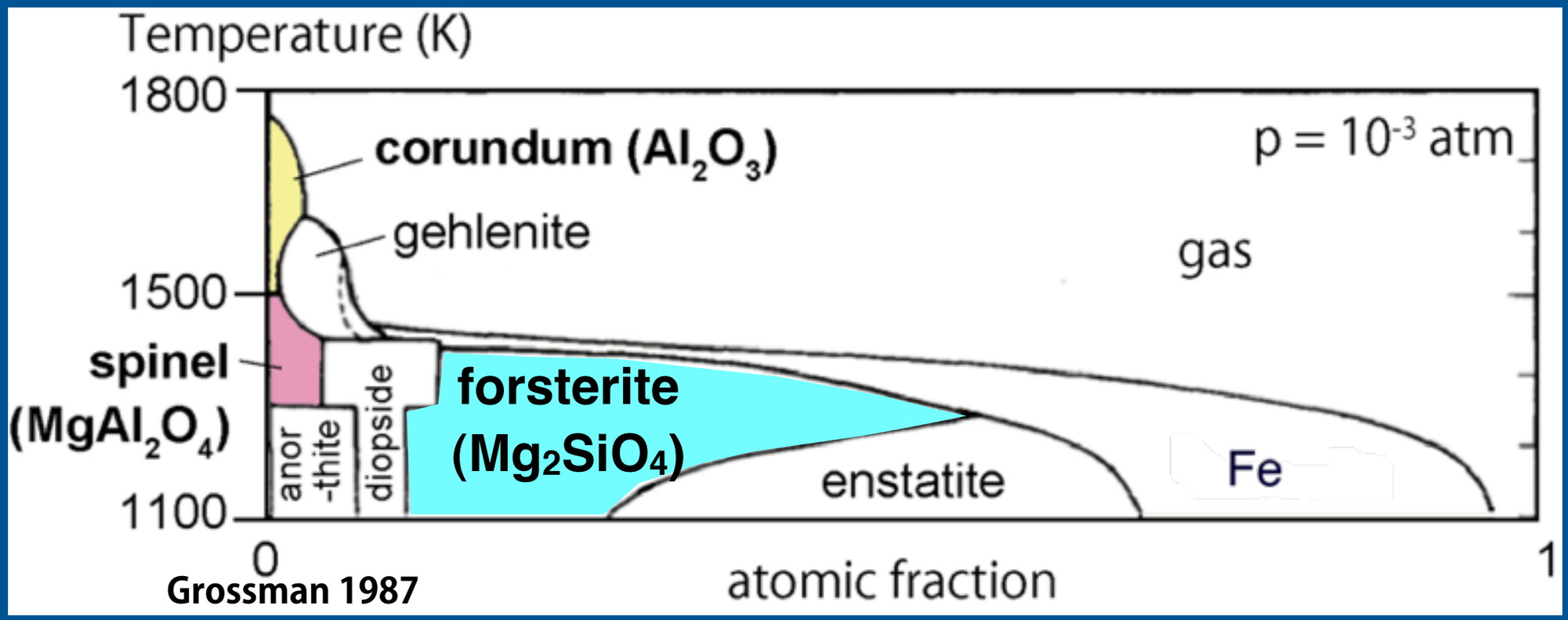


Takigawa et al. unpub. data

Condensation of corundum

- Anisotropic
- Changes of crystallographically anisotropic shape cause observable changes of IR spectra
- Disk-shaped corundum explains the 13-micron feature

Spinel ($MgAl_2O_4$) formation experiments



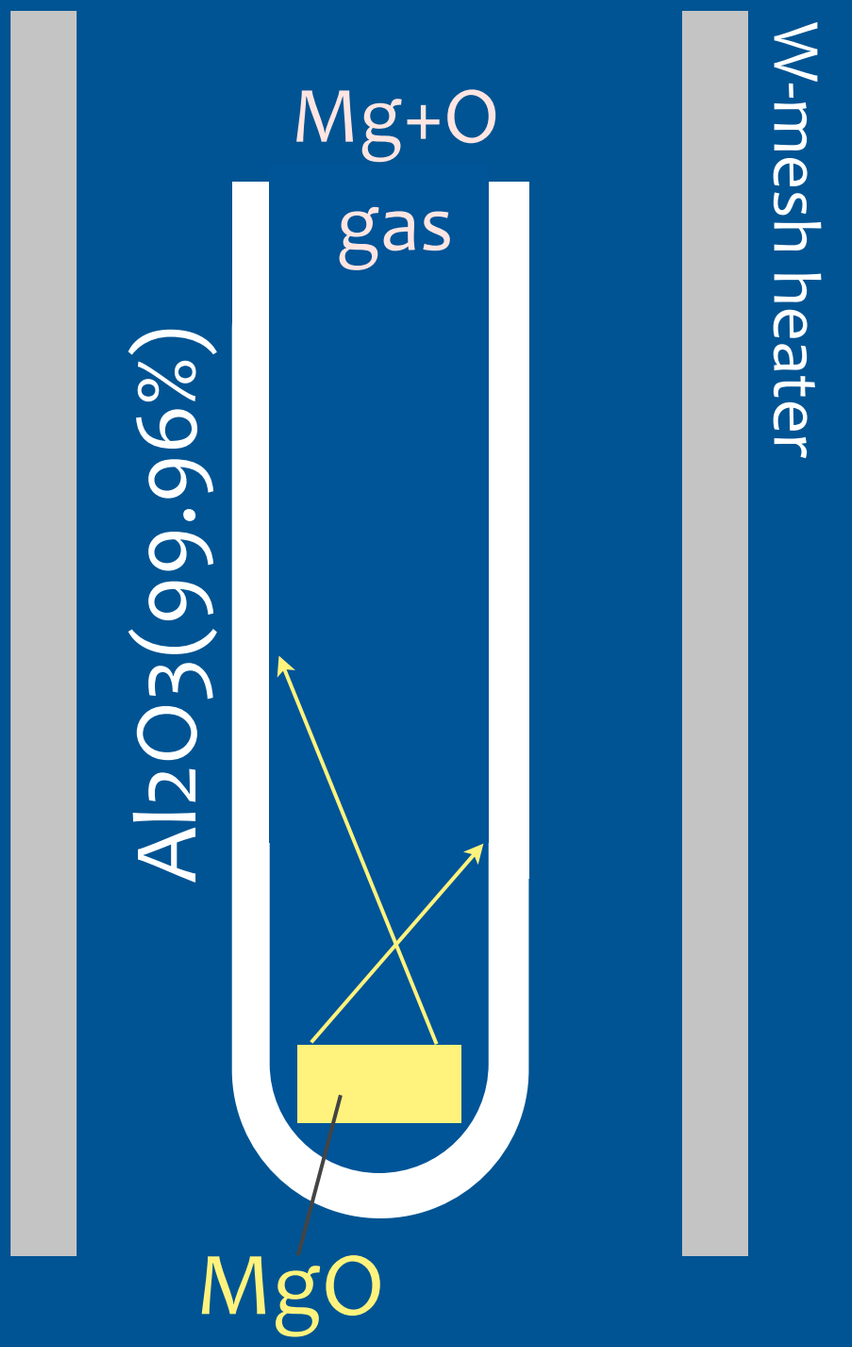
Grossman 1987

Corundum *Spinel*

$$Al_2O_3(s) + Mg(g) + O(g) \rightarrow MgAl_2O_4(s)$$

- Presolar spinel : evidence of spinel formation

Spinel ($MgAl_2O_4$) formation experiments



Reaction

$Al_2O_3(s) + Mg(g) + O(g) \rightarrow MgAl_2O_4(s)$

Condition

T_{gas} = 1650°C

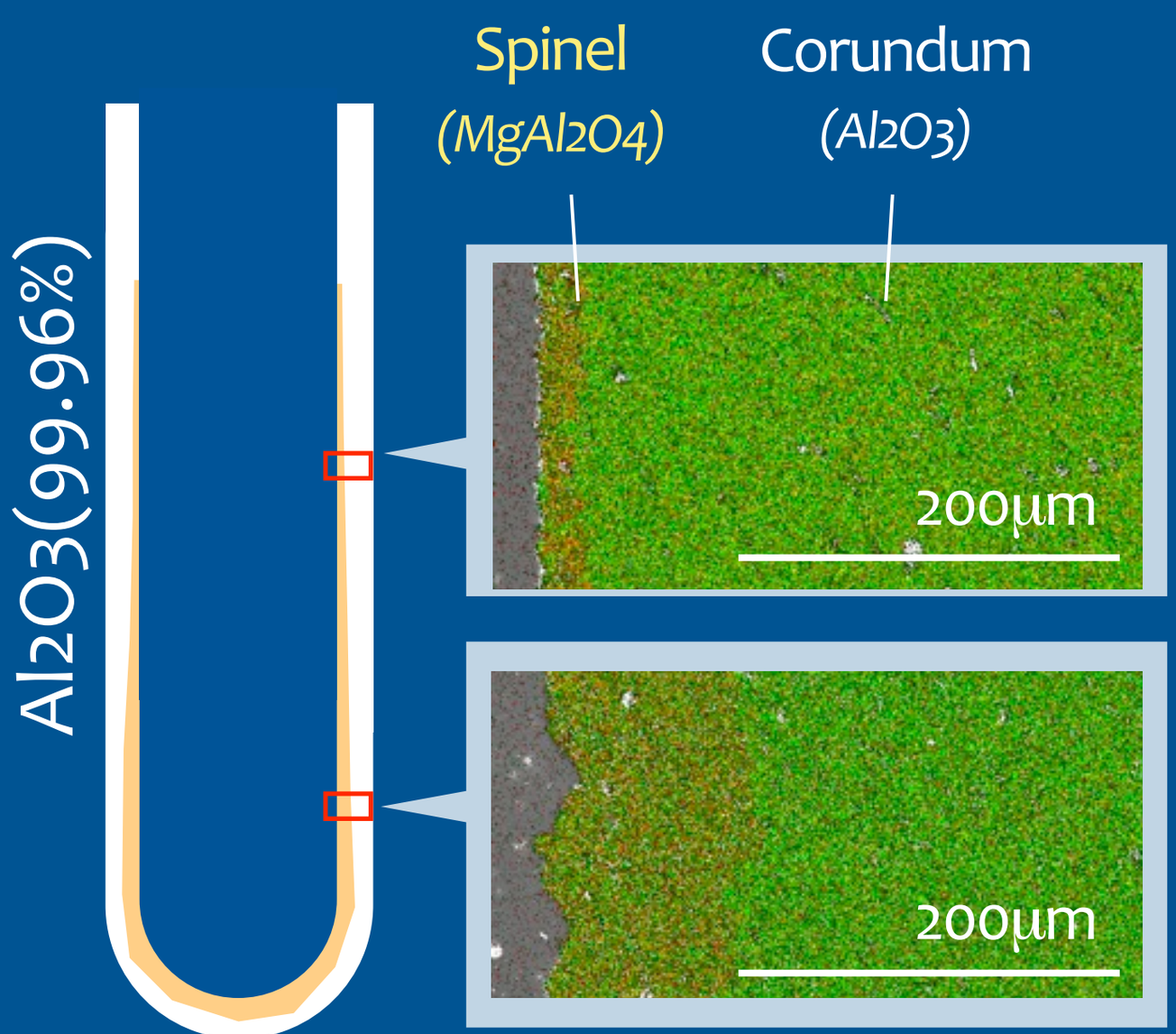
$T_{cond} \approx$ 1550-1650°C

duration = 24, 48, 64, 84, 254 hours

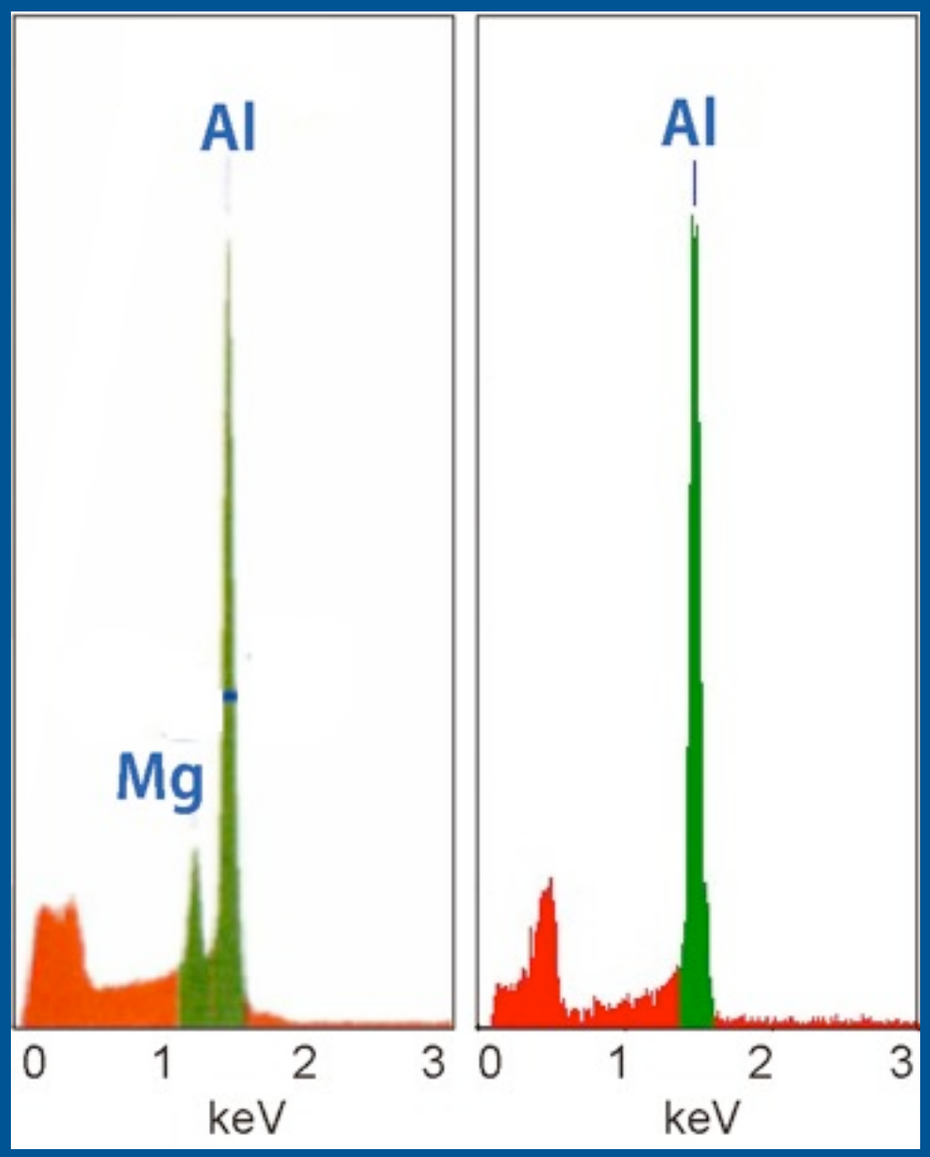
Analysis

SEM, EDS, EPMA, XRD, IR spectroscopy

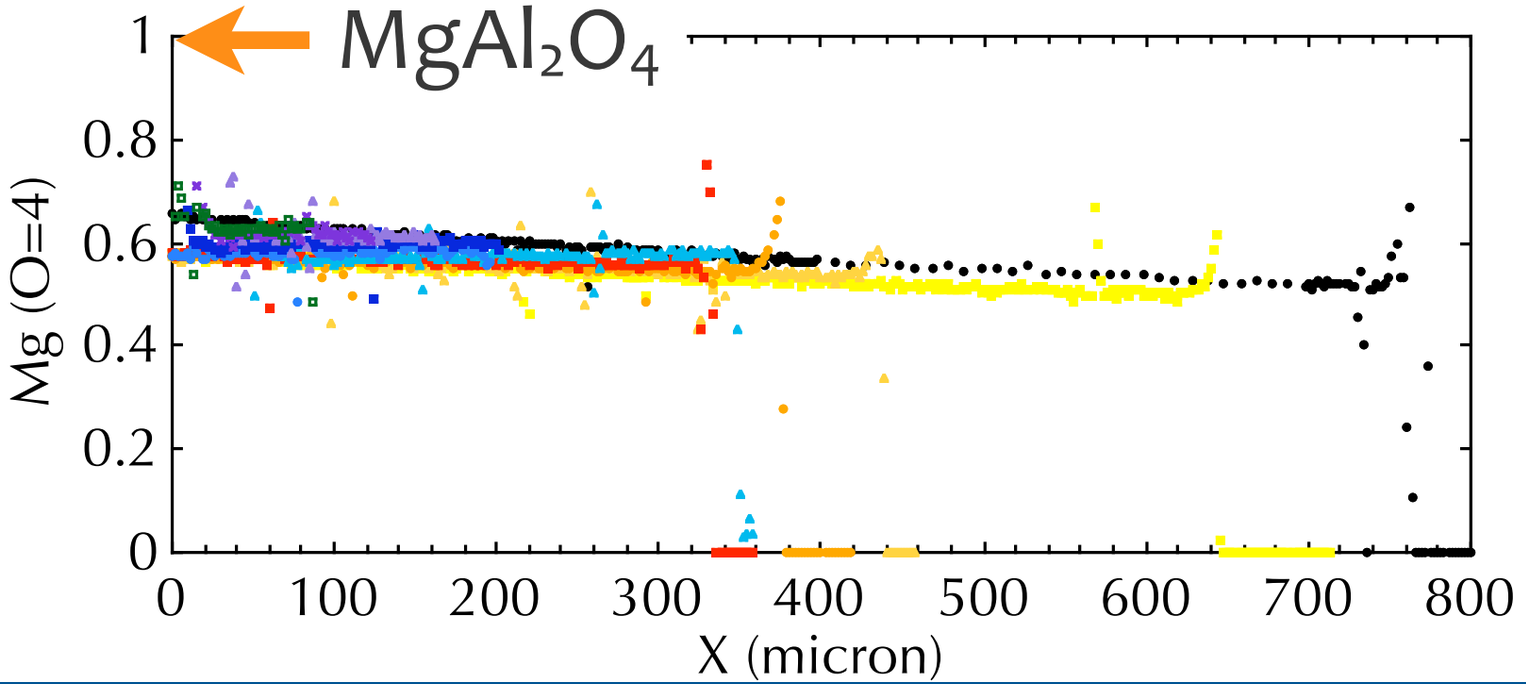
Reaction products



duration = 64 hours



Reaction products

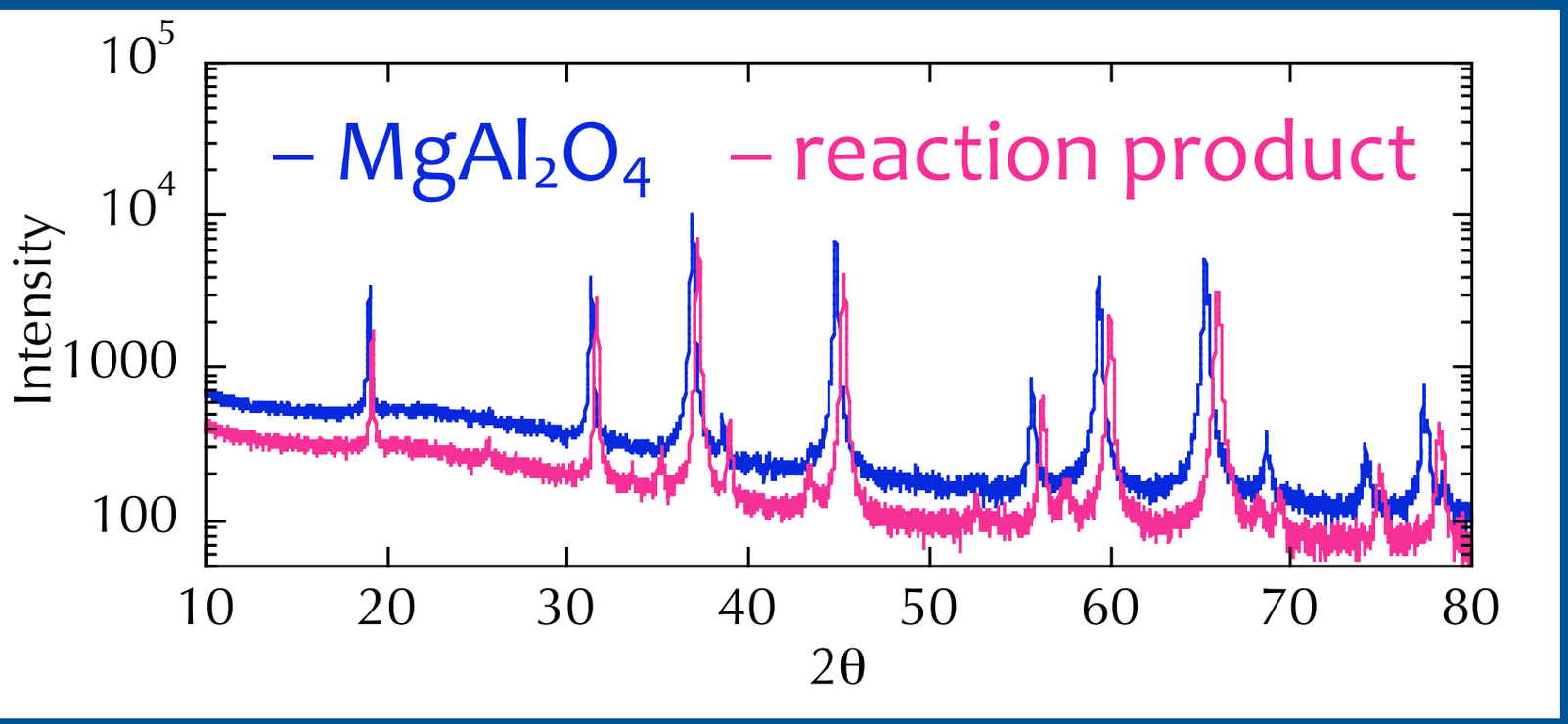


electron microprobe

Mg:Al = 0.6:2.3 (O=4)

non-stoichiometric

$Mg_{0.6}Al_{2.3}O_4$



X-Ray Diffraction

lattice constant is ~1% smaller than that of stoichiometric spinel

IR measurement

IR spectroscopy with KBr method

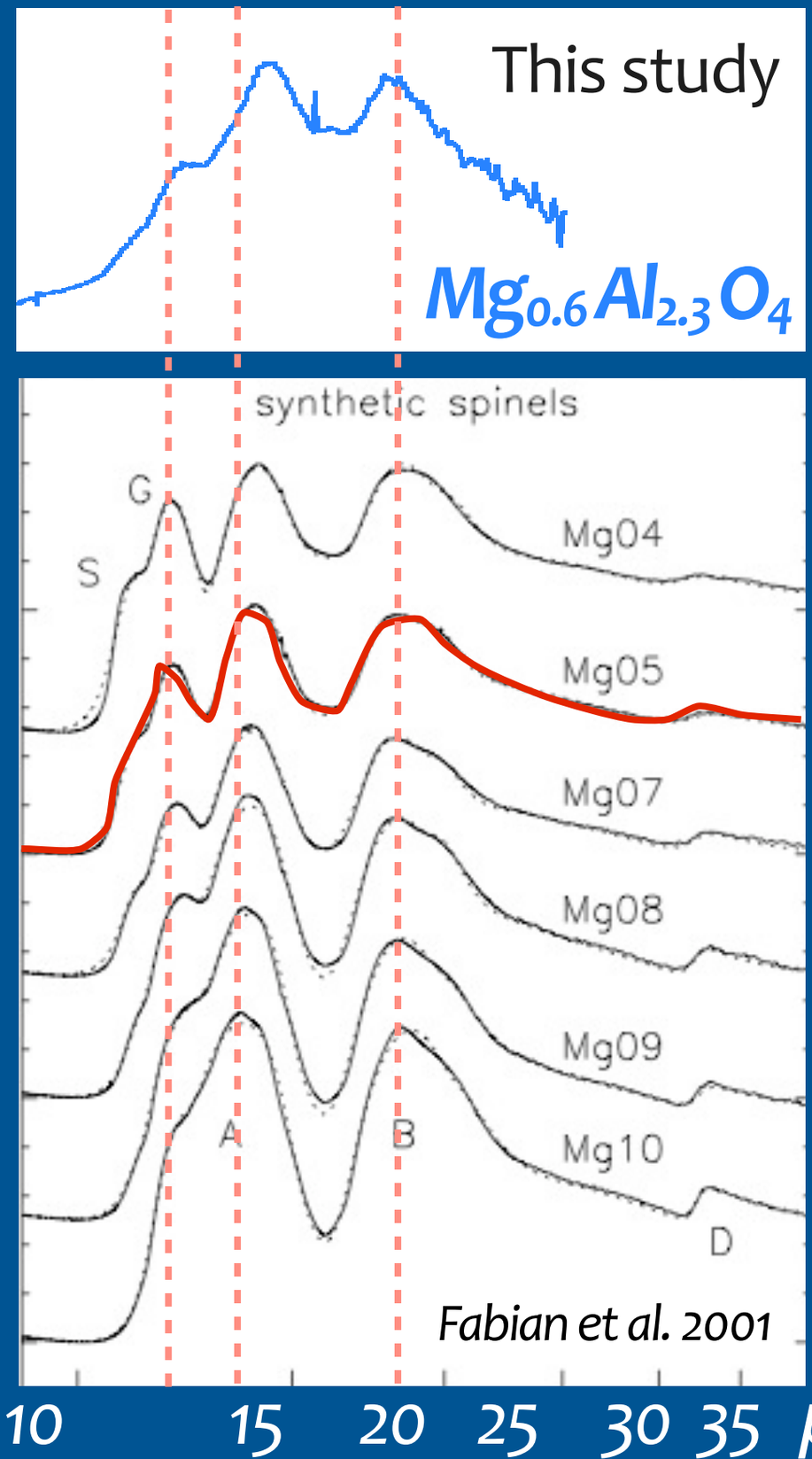
$Mg_{0.6}Al_{2.3}O_4$ formed at
***~1600°C** under low P*

Comparison:
non-stoichiometric spinel synthesized at ***2050-2135°C*** *(Fabian et al., 2001)*

$$Mg_{0.53}Al_{2.31}O_4$$
$$= (Mg_{0.53}Al_{2.31})(Mg_{0.53}Al_{2.31})O_4$$

Different degrees of disordering of cations ?

cf. more disordered at higher T



Conclusions

"Crystallographically anisotropic shape" is a key to link observed dust spectra and their formation conditions

- *Forsterite evaporates anisotropically in H_2 gas depending on temperature and p_{H2}*

- *Corundum condenses anisotropically depending on supersaturation ratio*

- *Crystallographically anisotropic shapes of forsterite and corundum can be deduced from spectral features*

- *IR measurement of non-stoichiometric spinel formed at low pressures is now being in progress*