CPS seminar 3/6/2013

原始惑星系円盤でのマグネシウムケイ酸塩気相成長と蒸発

Vapor growth/evaporation of Mg-silicate under protoplanetary disk conditions: Experimental study

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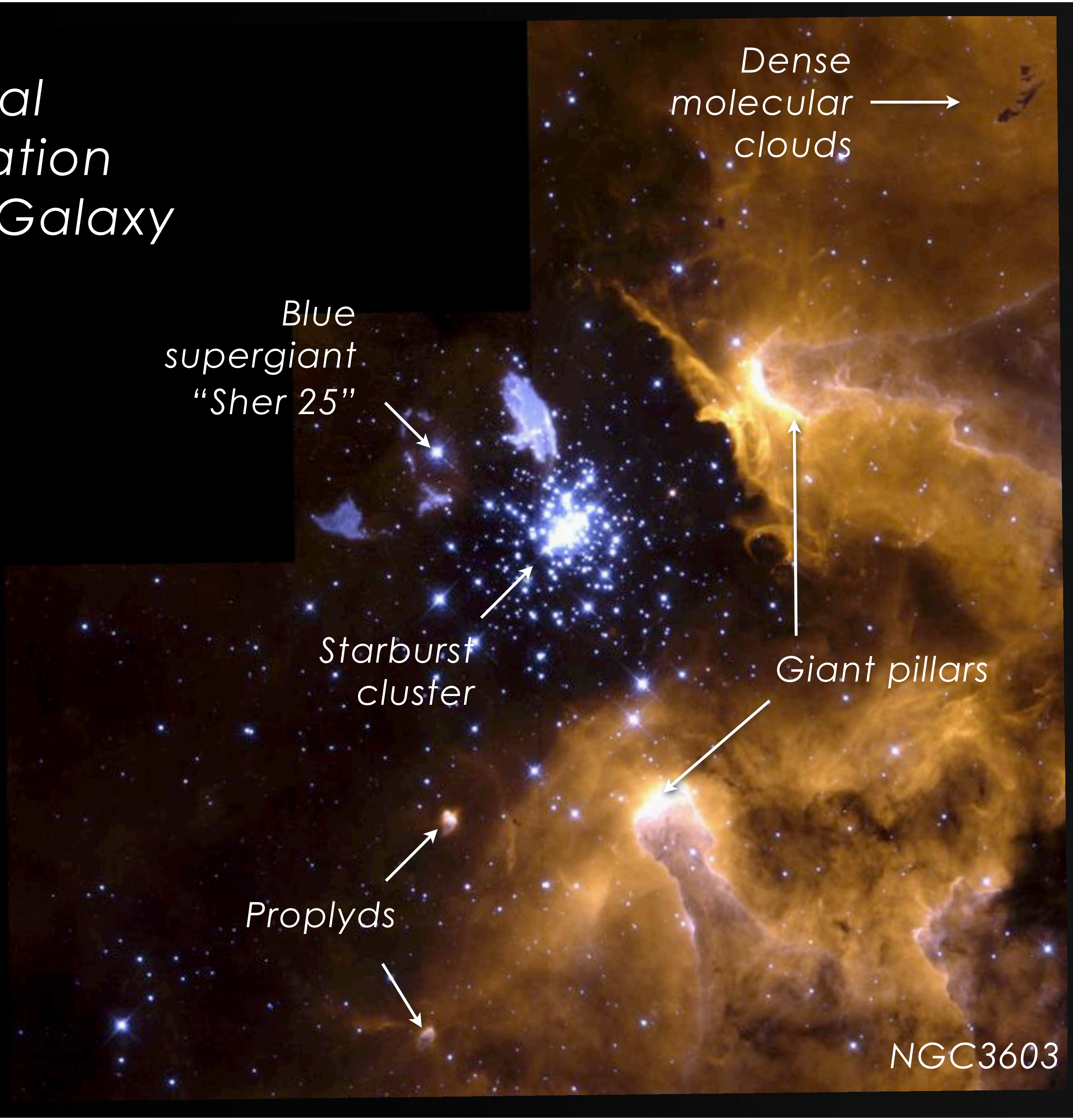
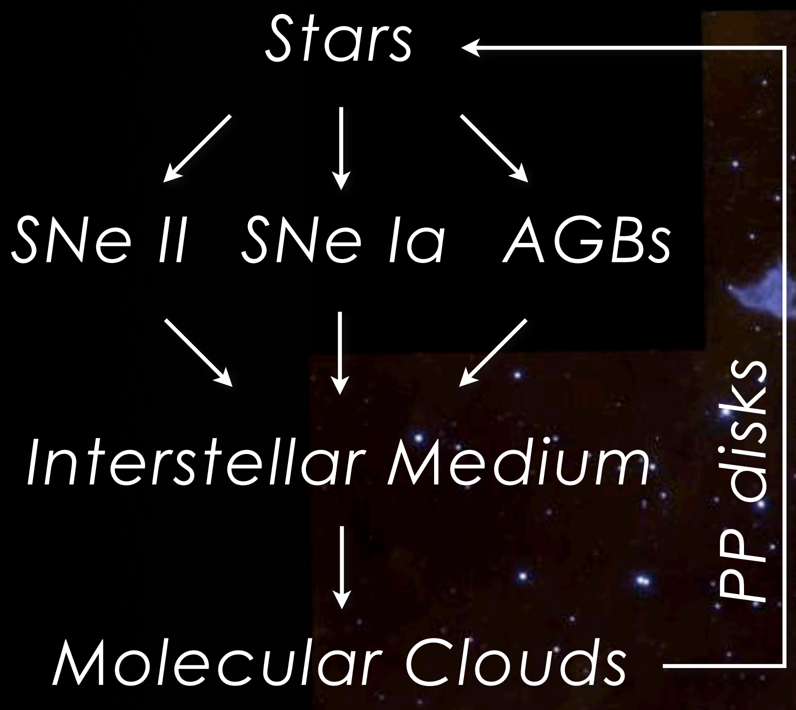
HOKKAIDO UNIVERSITY

Material Circulation in the Galaxy



Material Circulation in the Galaxy



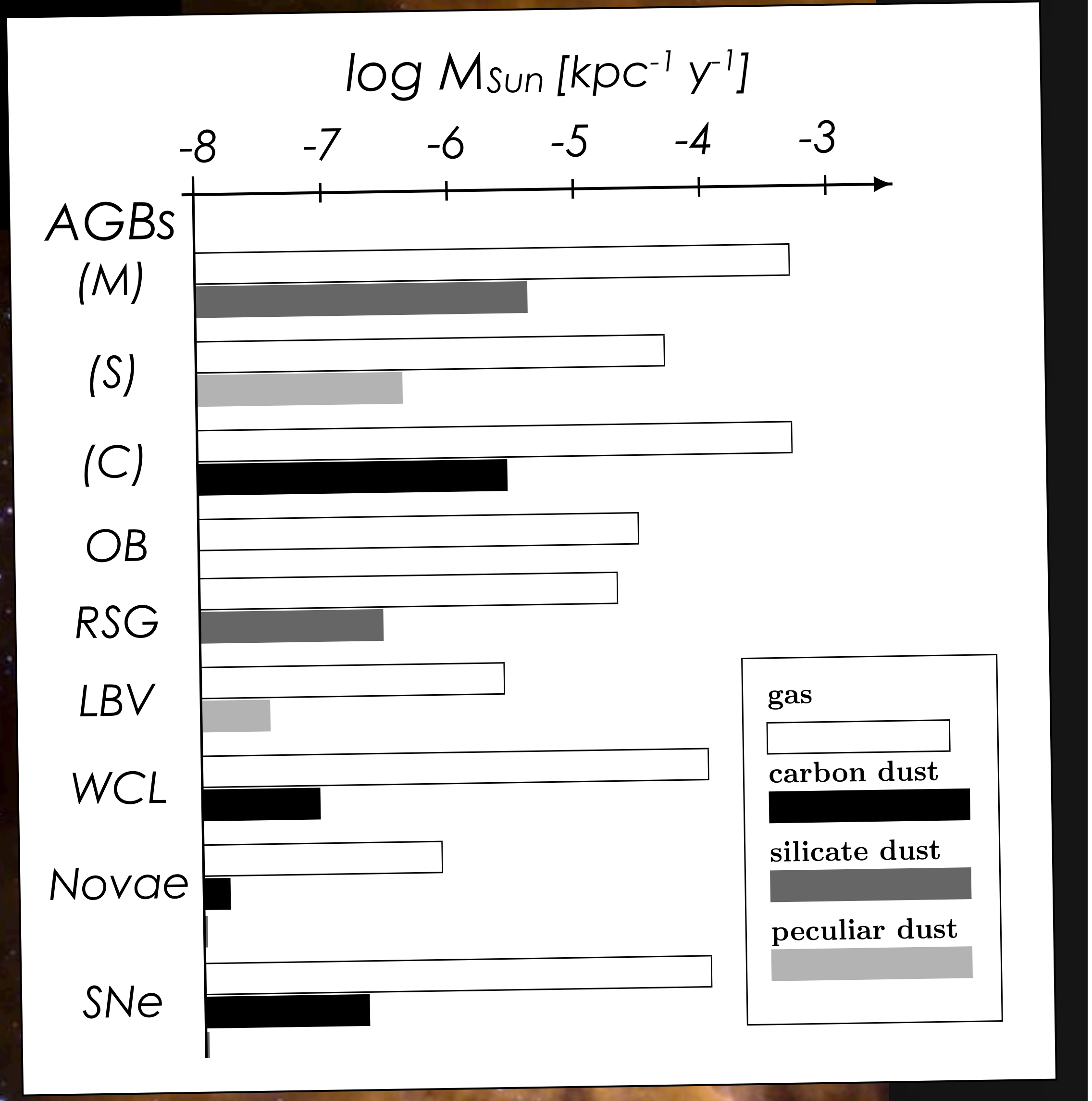
Stars

SNe II SNe Ia AGBs

Interstellar Medium

Molecular Clouds

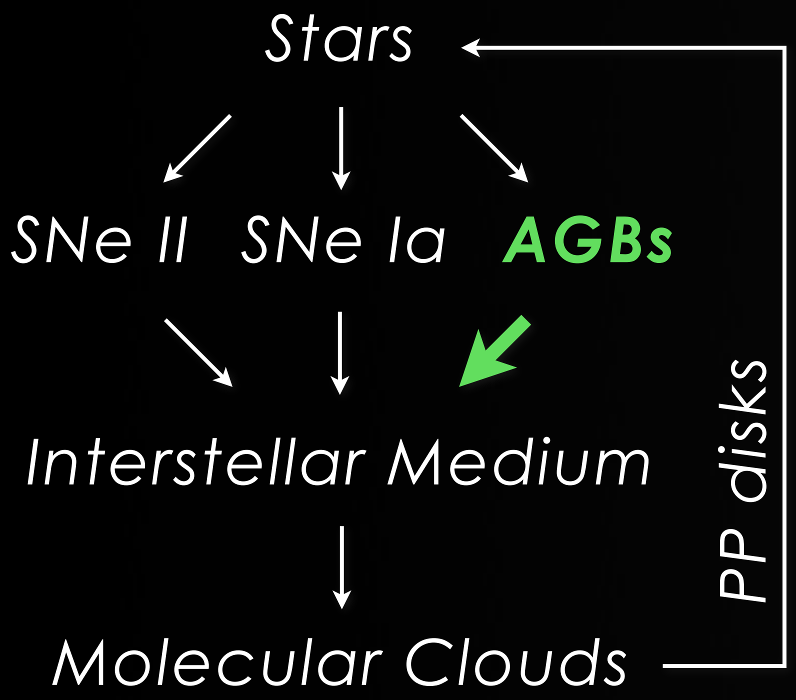
PP disks



Gail & Hoppe (2010)

Journey of Dust

Material Circulation in the Galaxy



Stars

SNe II SNe Ia **AGBs**

Interstellar Medium

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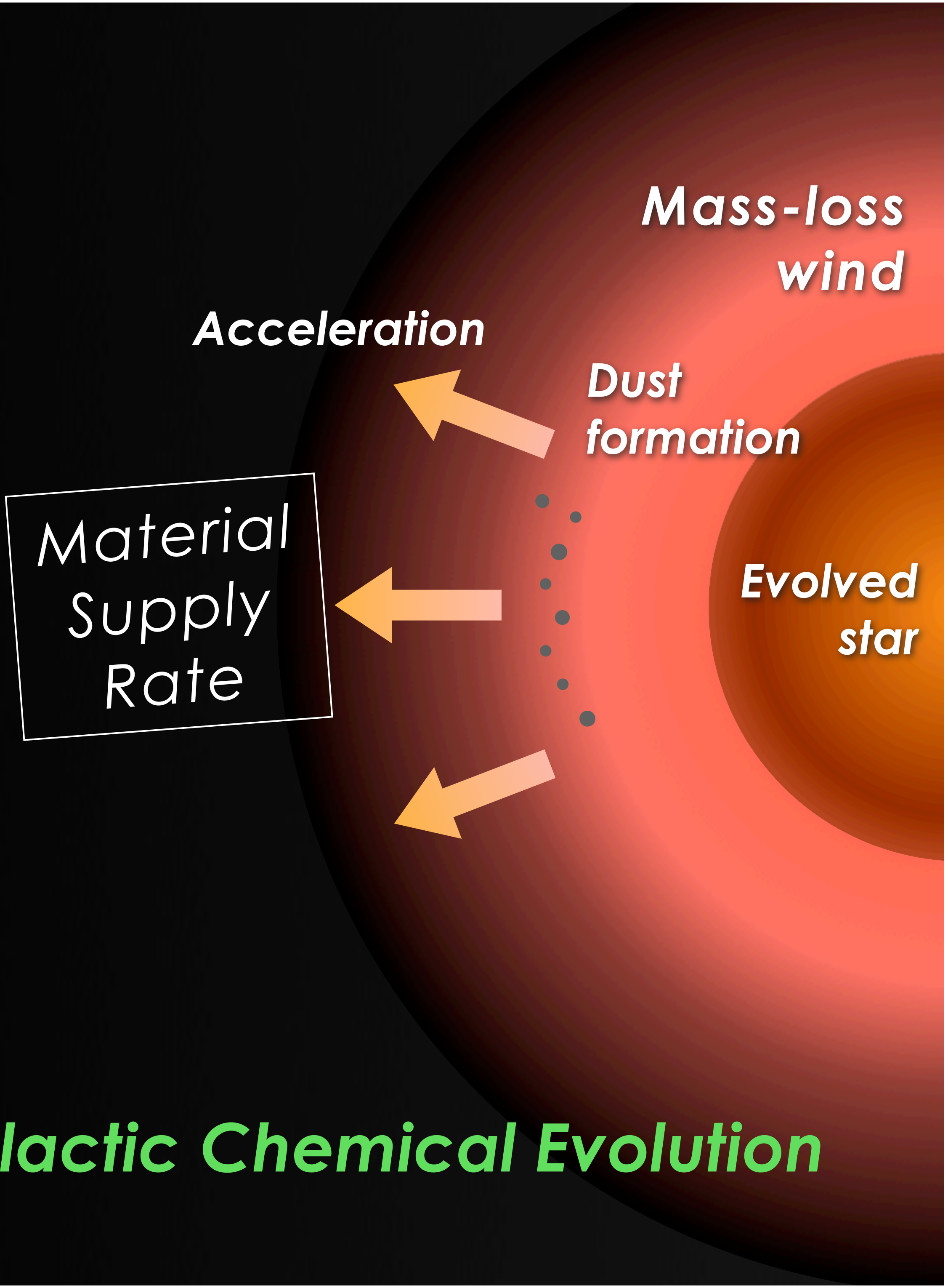


Mass-loss wind

Acceleration

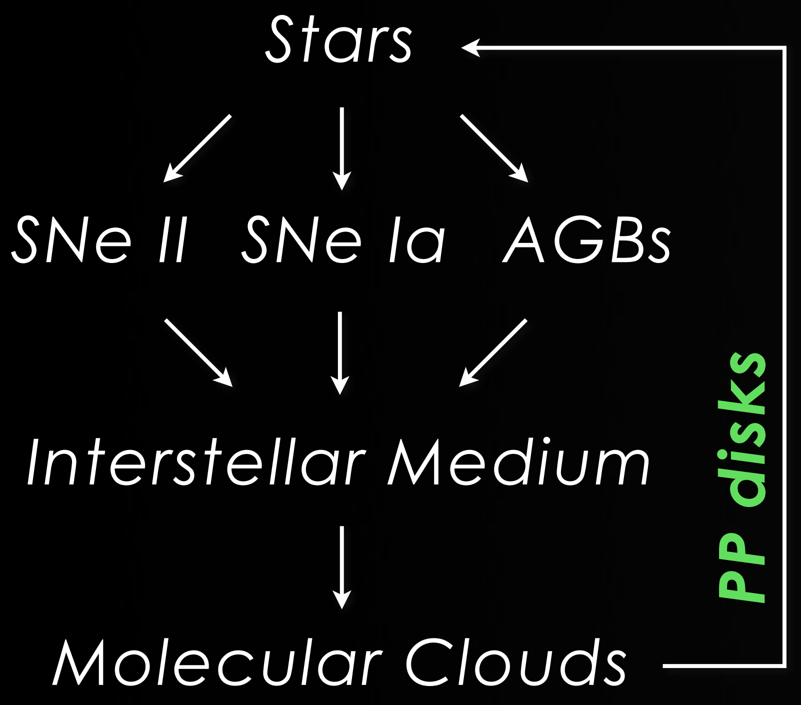
Dust formation

Material Supply Rate

Evolved star

Dust: Key for the Galactic Chemical Evolution

Material Circulation in the Galaxy



Stars

SNe II SNe Ia AGBs

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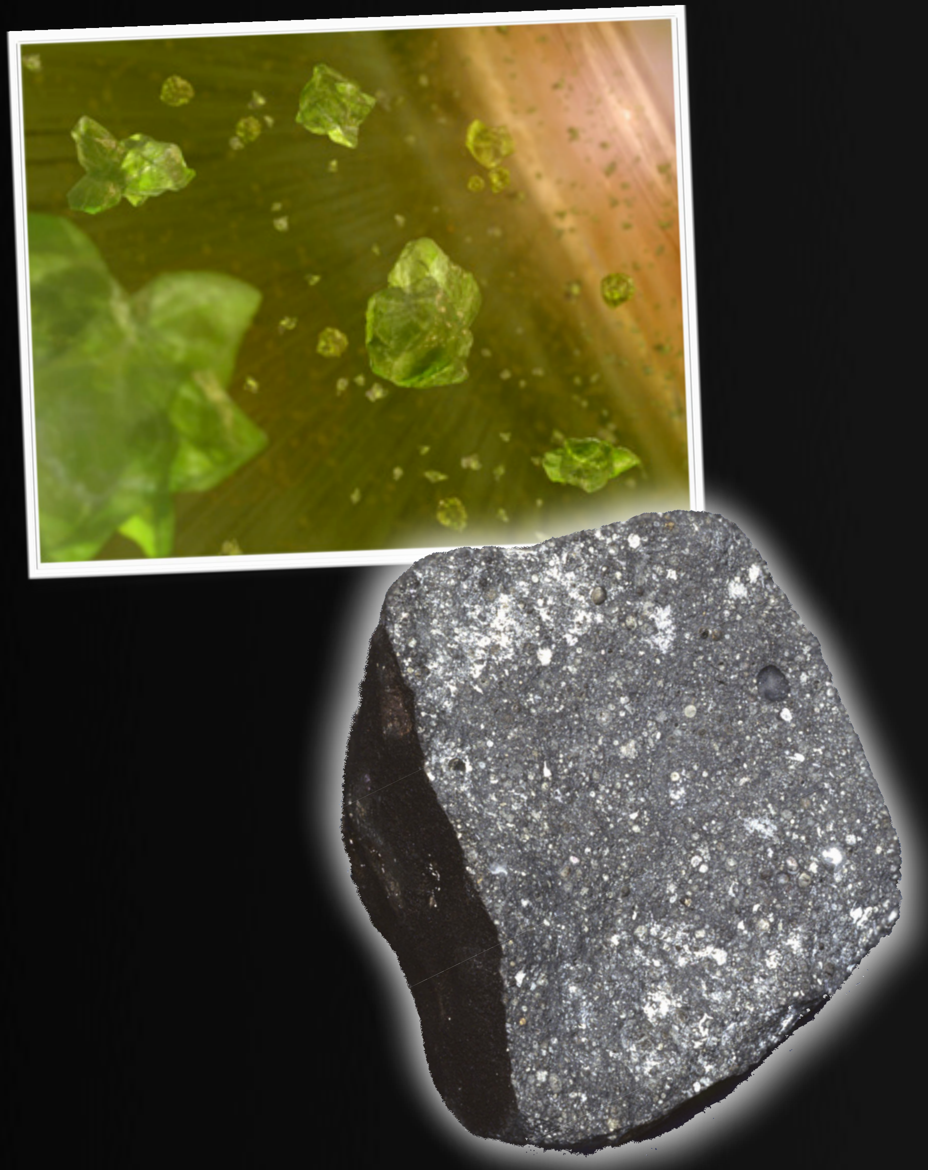
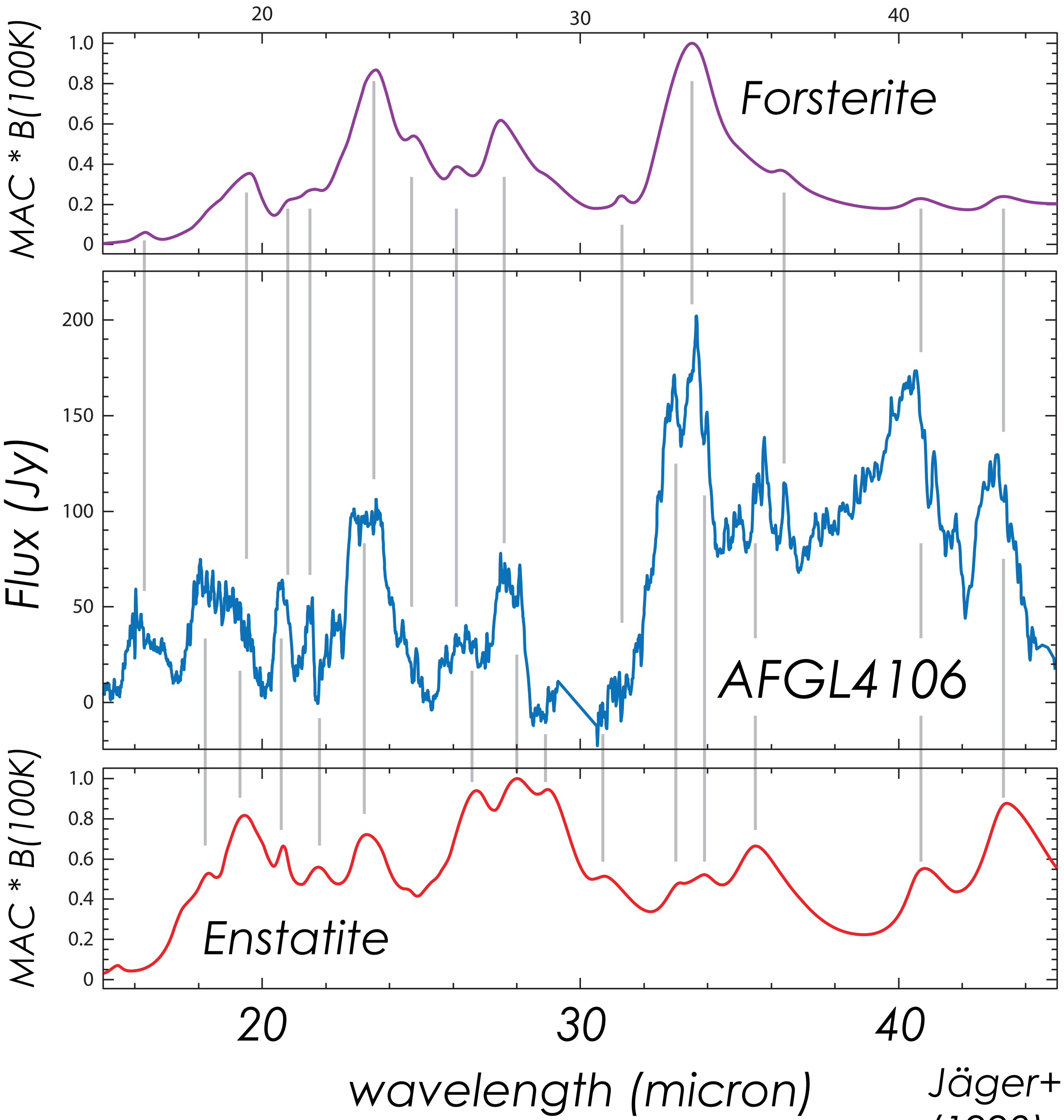


Dust: Building block of planets

Infrared Spectroscopy

Presence of crystalline Mg-silicates

Astromineralogy

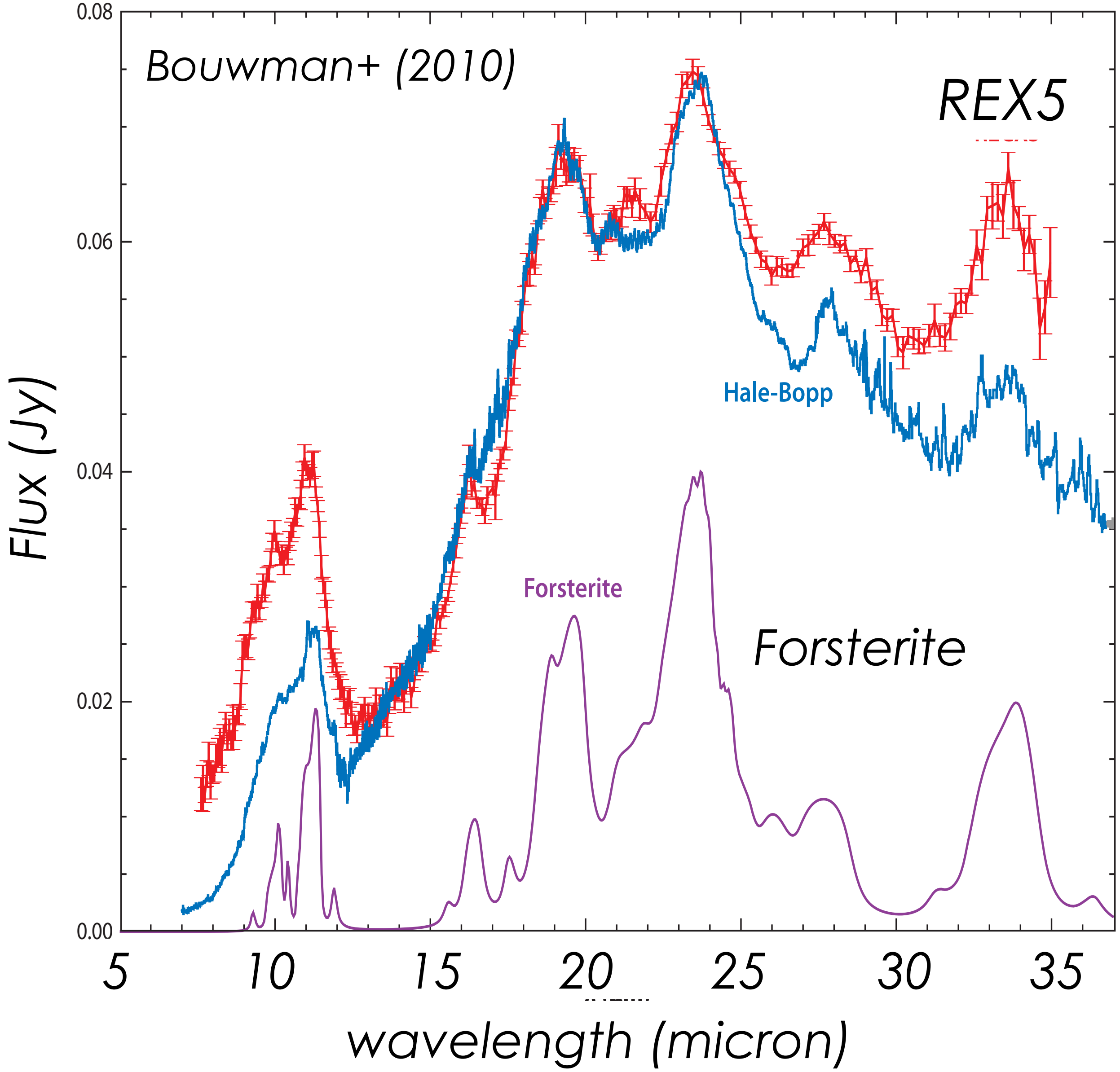


Jäger+ (1998)

Infrared Spectroscopy

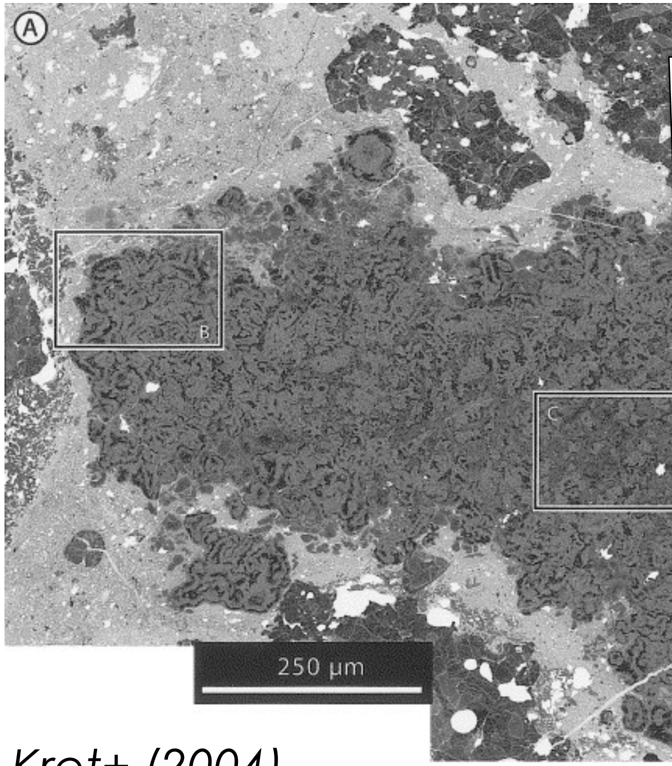
Presence of crystalline Mg-silicates

Astromineralogy

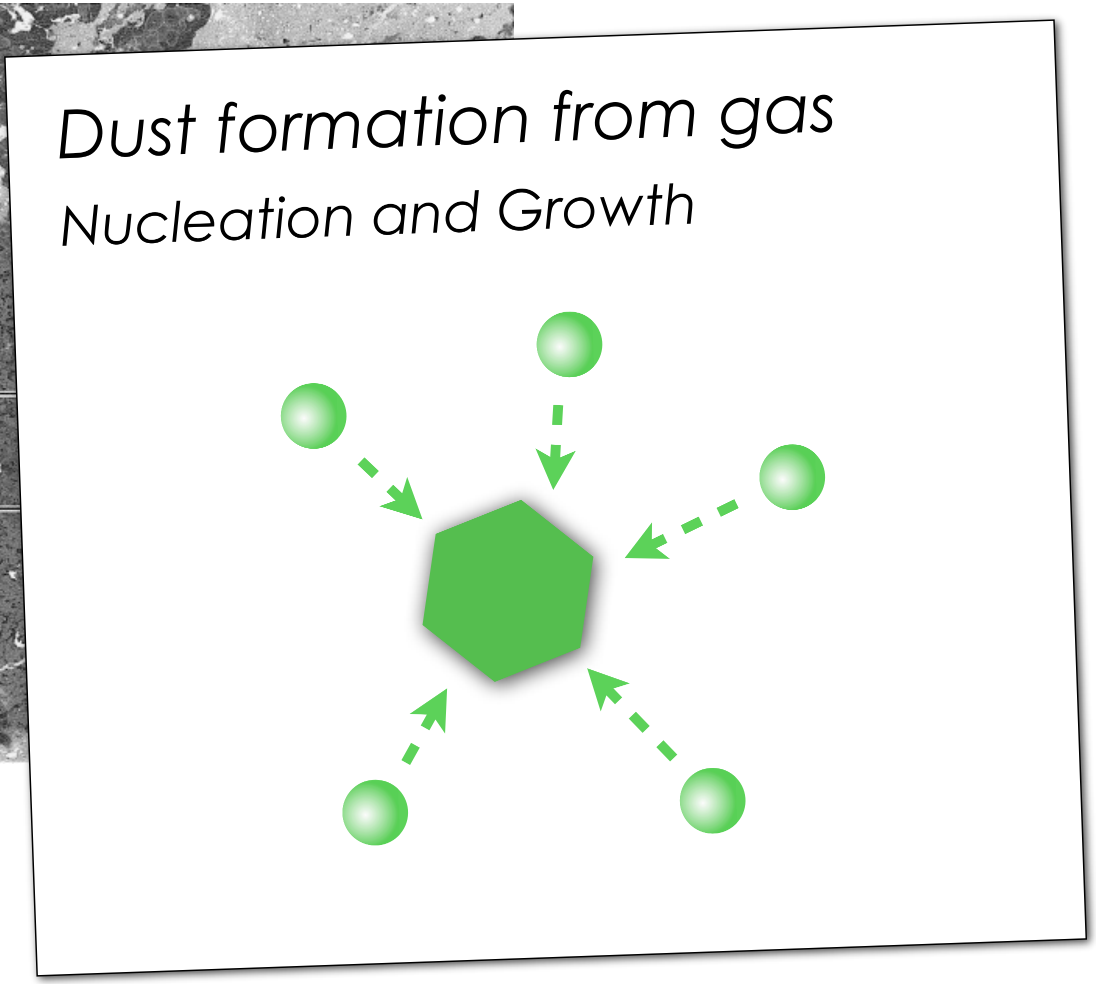


How did dust particles form in space?

Grain size, number density, mineral assemblages



Krot+ (2004)

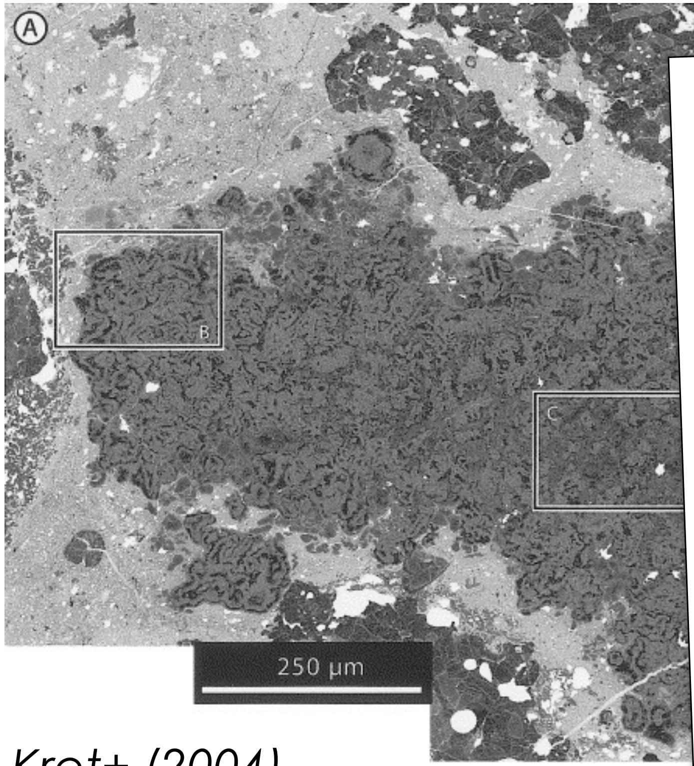


Dust formation from gas

Nucleation and Growth

How did dust particles form in space?

Grain size, number density, mineral assemblages

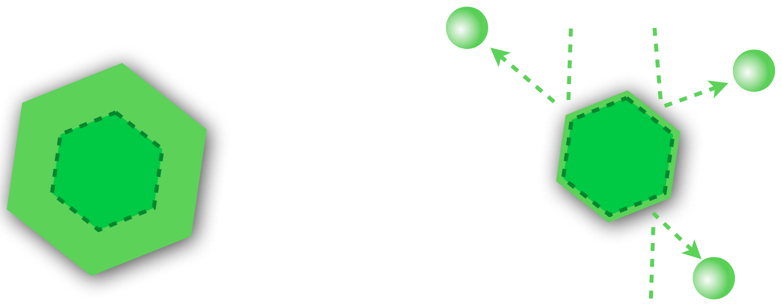


Krot+ (2004)

Dust formation from gas

If all the colliding gas condense,

If only a fraction of gas condense,



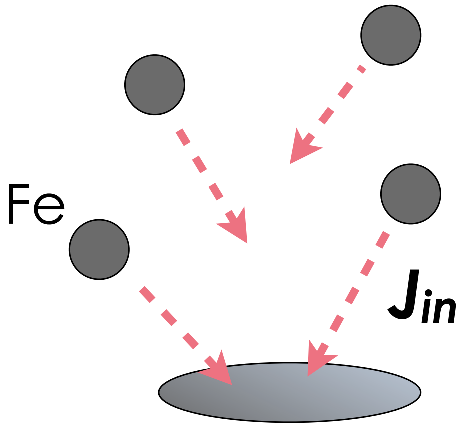
slower *growth*

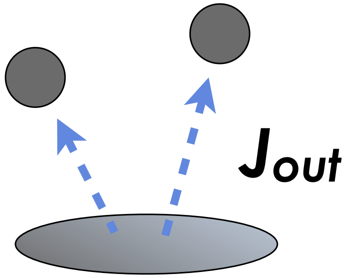
less amount *of dust*

diversity *of dust species*

Growth kinetics of dust from vapor

$Fe(g) \rightarrow Fe(s)$





$$J_{net} = J_{in} - J_{out}$$

$$\boxed{J_{net} = \frac{\alpha_c\, p_{Fe} - \alpha_e\, p_{Fe}(eq)}{\sqrt{2\pi\, m_{Fe} kT}}}$$

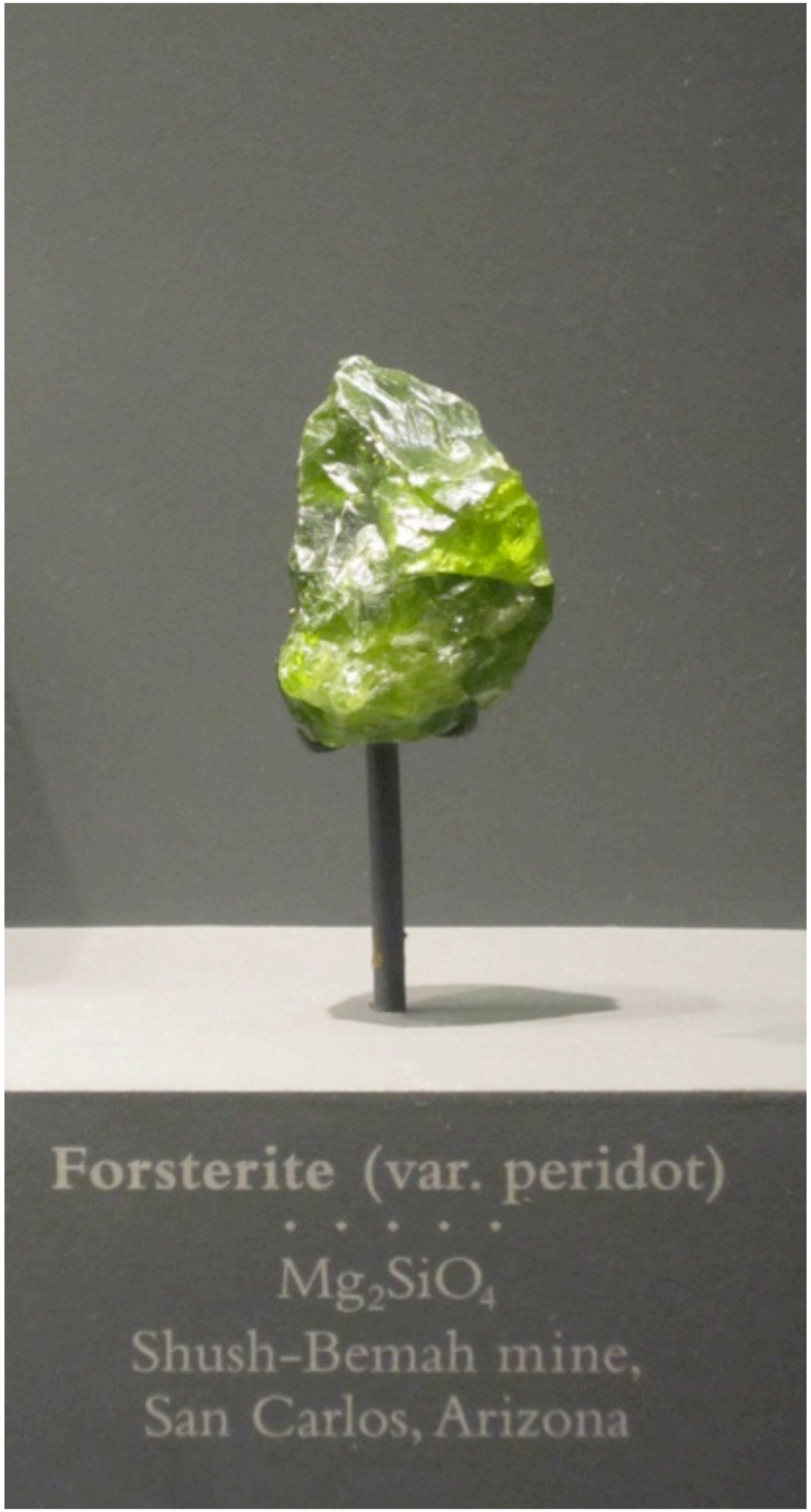
α_c : **Condensation coefficient**

(Sticking probability of impinging atoms/molecules)

α_e : **Evaporation coefficient**

Laboratory Studies !

Evaporation experiments of minerals



Evaporation experiments at low pressures

- Forsterite (Mg_2SiO_4):

  Hashimoto, 1990; Nagahara & Ozawa, 1996; Tsuchiyama+, 1999; Wang+, 1999; Kuroda & Hashimoto, 2002; Yamada+, 2006; Takigawa+, 2009; Ozawa+, 2012

- Olivine ($(Mg_{0.9}Fe_{0.1})_2SiO_4$): *Ozawa & Nagahara, 2000*

- Enstatite ($MgSiO_3$): *Tachibana+, 2002*

- Silica (SiO_2): *Young+, 2002*

- Silicate melts: *e.g., Hashimoto, 1983; Nagahara & Ozawa, 1996; Wang+, 2001; Yu+, 2003; Richter+, 2002, 2007*

Evaporation experiments at low pressures

- Forsterite (Mg_2SiO_4):

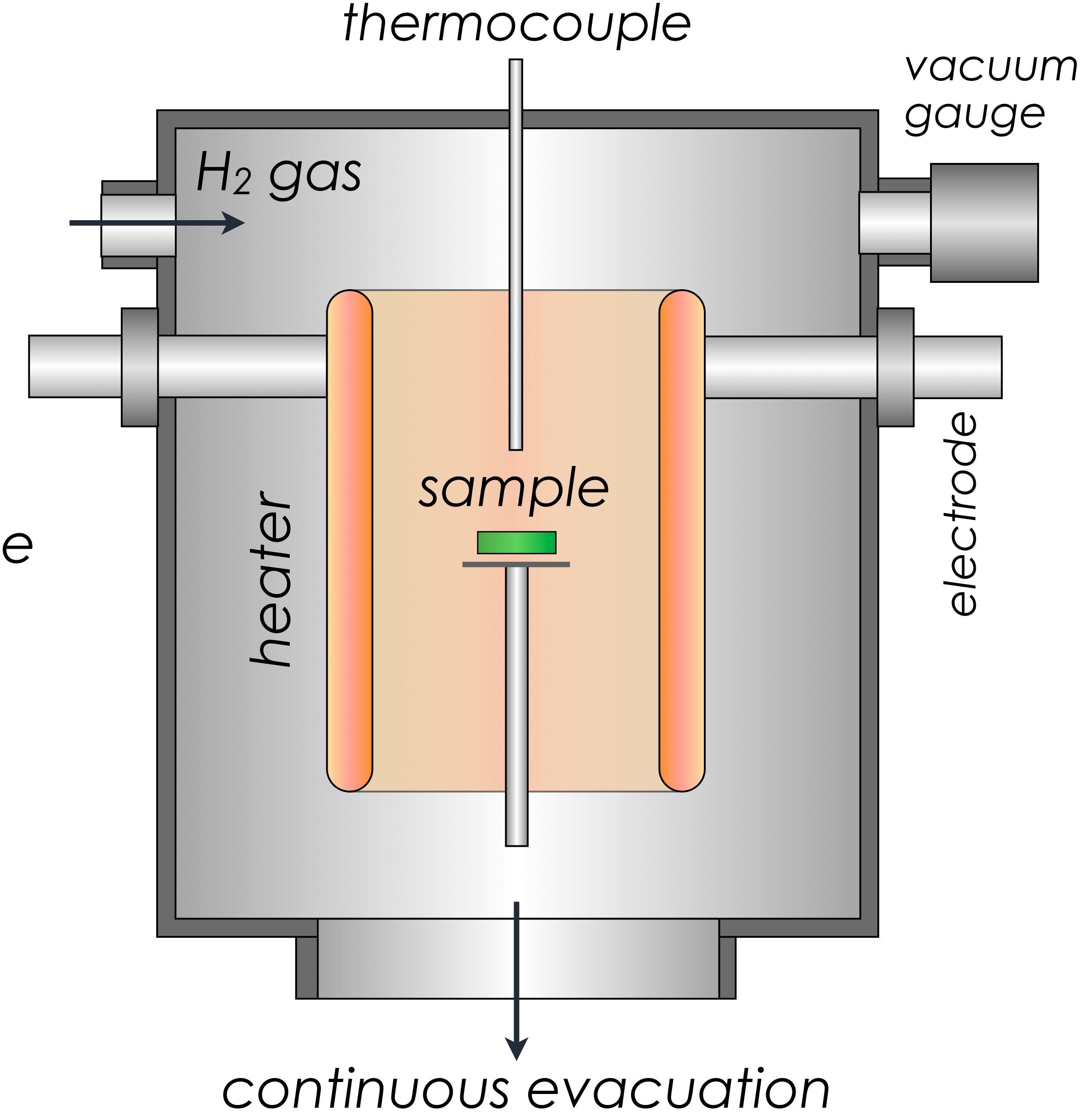
  Hashimoto, 1990; Nagahara & Ozawa, 1996; Tsuchiyama+, 1999; Wang+, 1999; Kuroda & Hashimoto, 2002; Yamada+, 2006; Takigawa+, 2009; Ozawa+, 2012

- Metallic iron : *Tsuchiyama & Fujimoto, 1995; Tachibana+, 2011*

- Troilite (FeS): *Tachibana & Tsuchiyama, 1998*

- Corundum (Al_2O_3): *Takigawa, 2012, Ph.D. thesis*

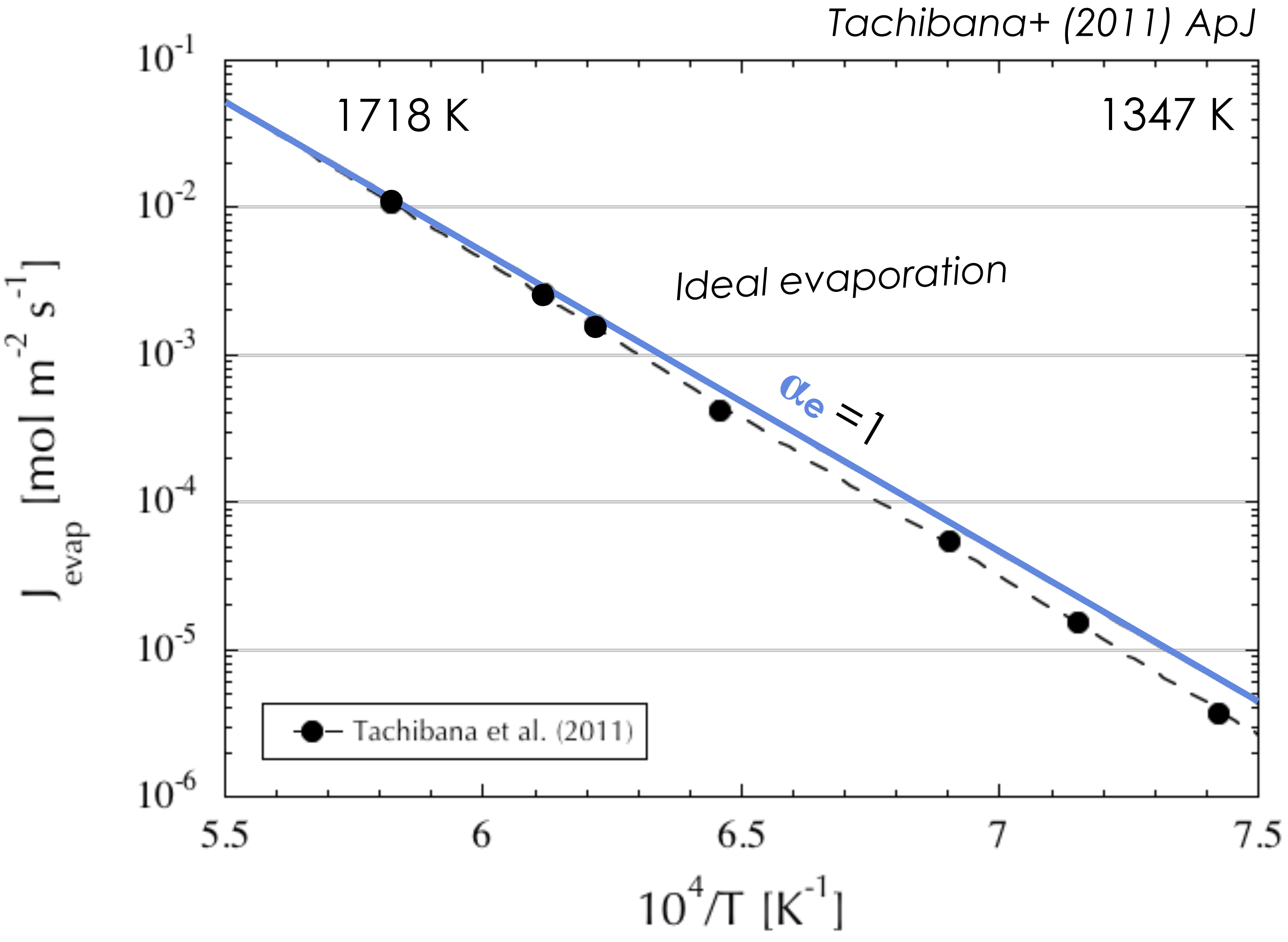
Evaporation experiments at low pressures



Weight loss of sample due to isothermal heating in vacuum or at low hydrogen pressures

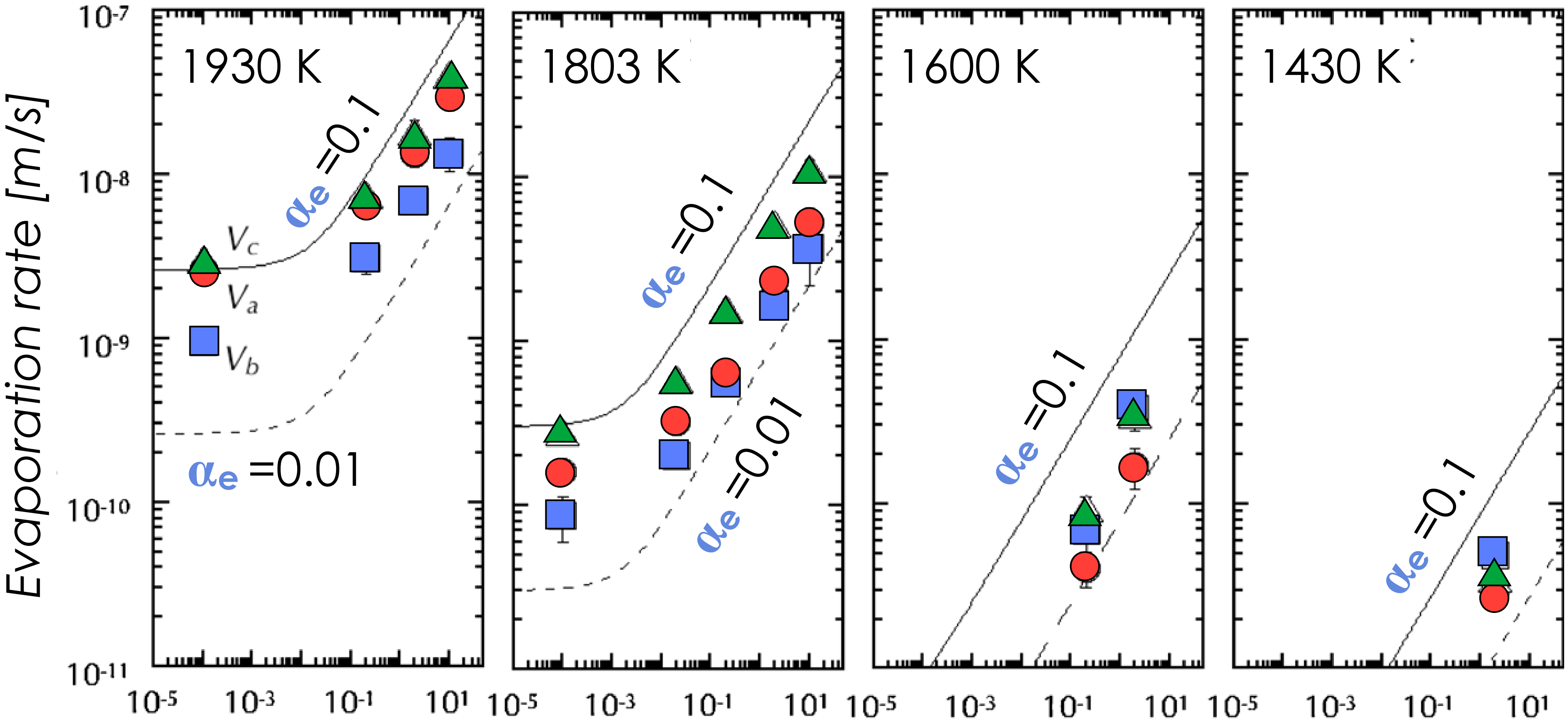
→ Evaporation rate

Evaporation of Fe metal in vacuum



Evaporation of forsterite at low hydrogen pressures

circle: along the a-axis
square: along the b-axis
triangle: along the c-axis



Anisotropic evaporation w/ kinetic hindrance

Takigawa+ (2009) ApJL

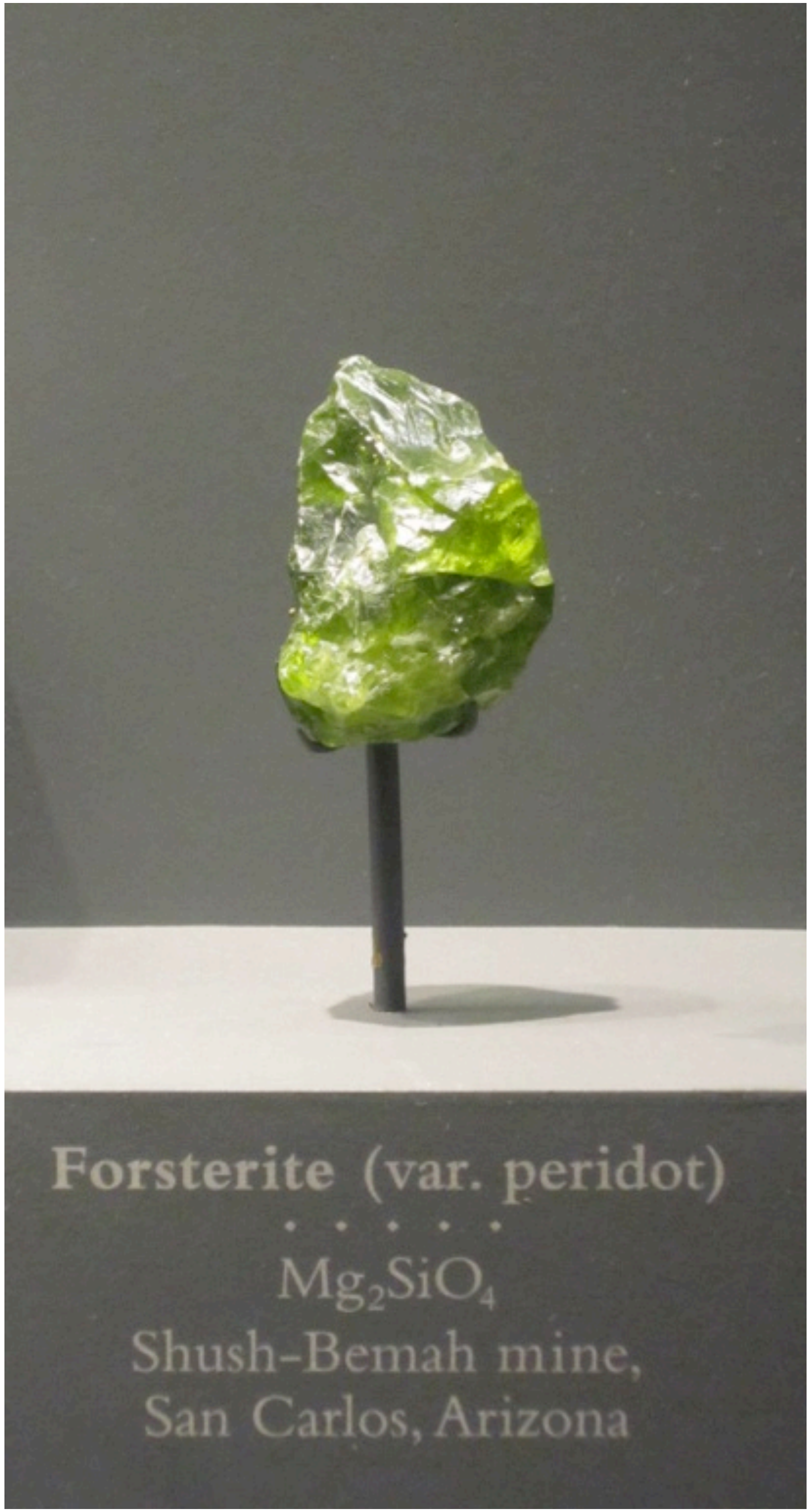
Evaporation coefficients

mineral	α_e	*references*
corundum	0.1-0.01	*Takigawa (2012, PhD thesis)*
forsterite	**0.1–0.01**	*e.g., Tsuchiyama+ (1998); Yamada+ (2006); Takigawa+ (2009)*
enstatite	0.1 (as Fo)	*Tachibana+ (2002)*
Metallic Fe	**1–0.6**	*Tsuchiyama & Fujimoto (1995)* *Tachibana+ (2011)*
troilite	$0.1–10^{-3}$	*Tachibana & Tsuchiyama (1998)*

Condensation experiments of minerals

Growth at low pressures

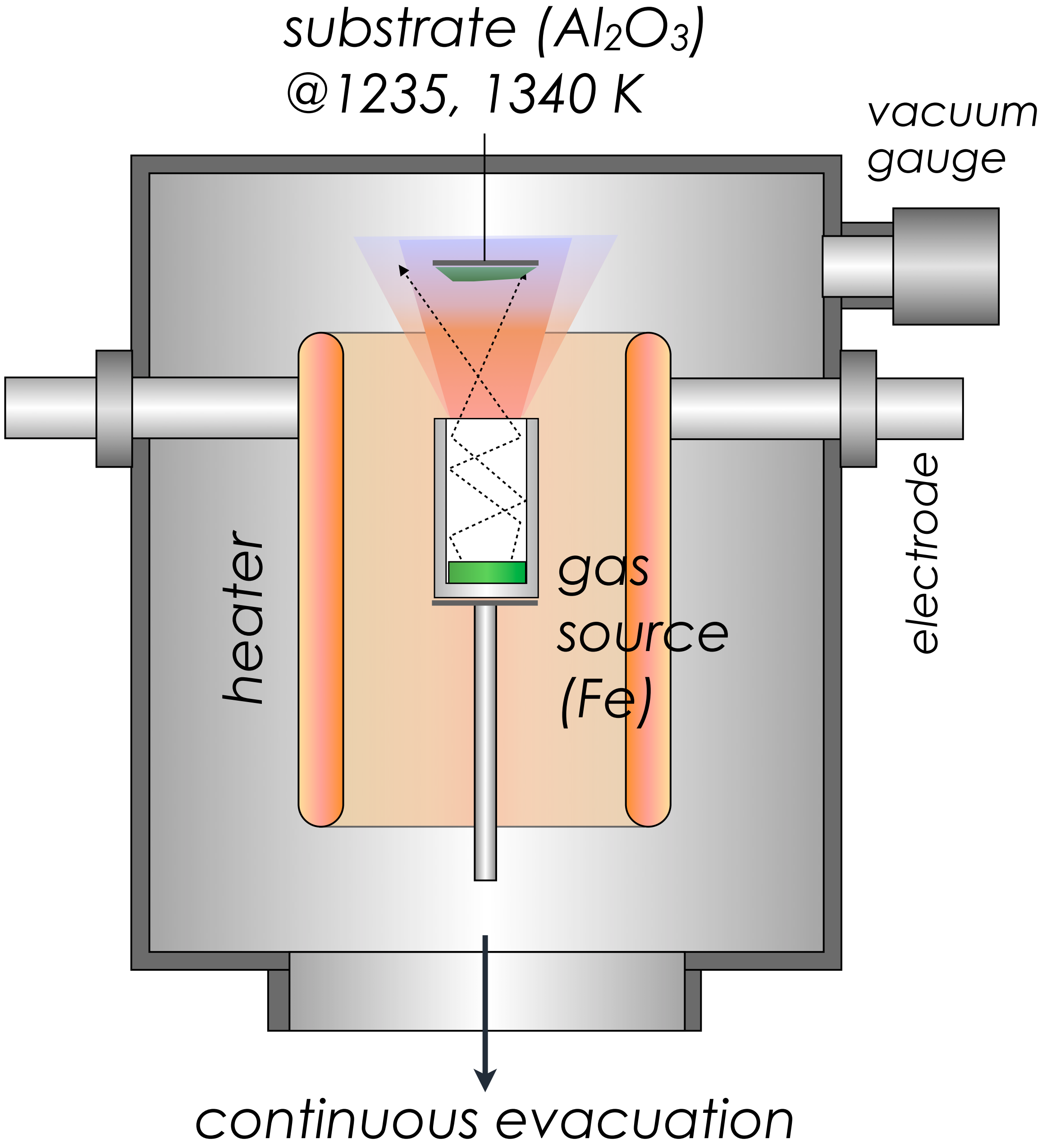
- *good for understanding kinetics if experimental conditions are controlled*



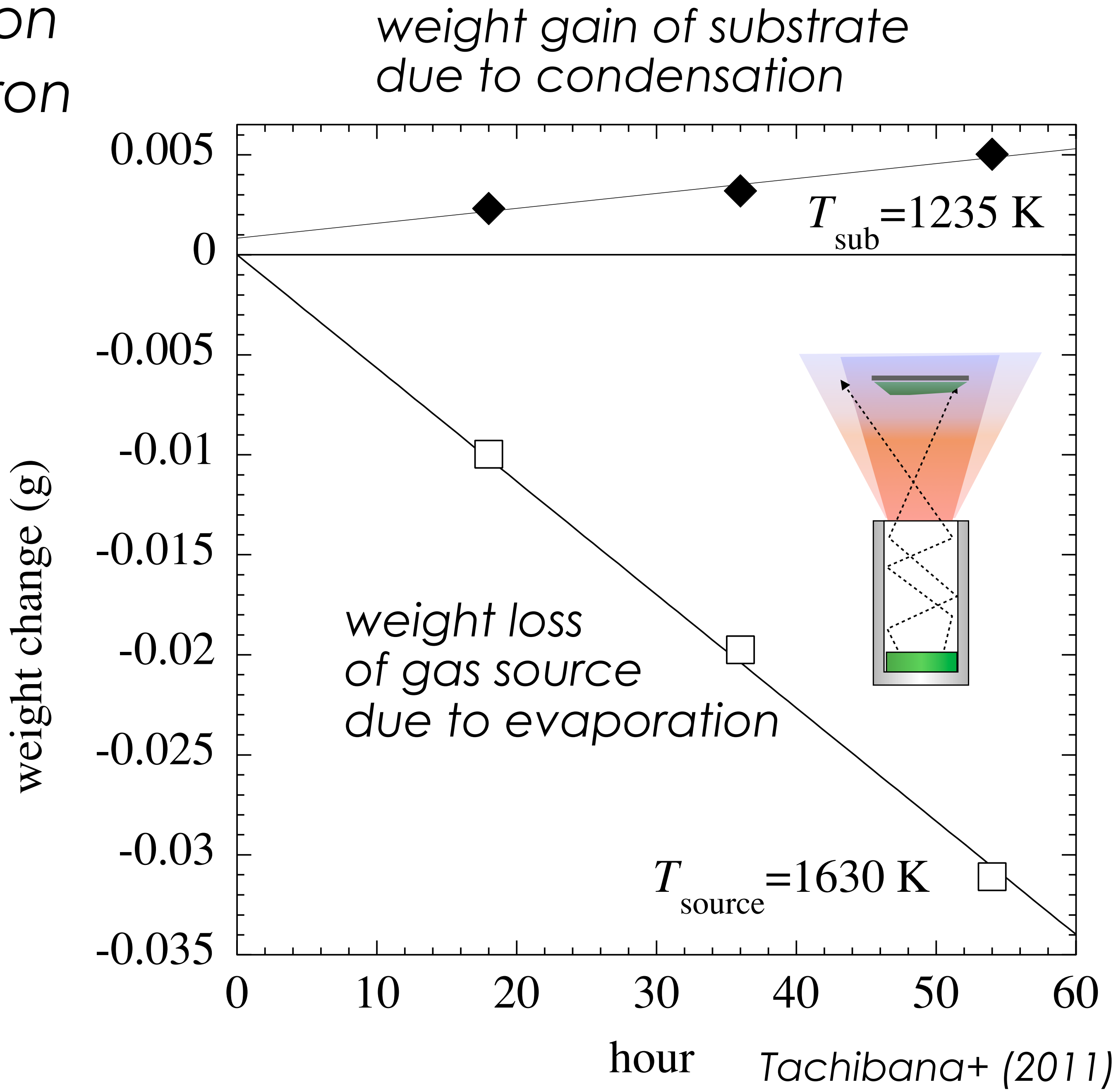
Condensation of metallic iron in vacuum

(Tachibana+, 2011)

Growth of metallic iron at controlled T and P_{Fe}



Condensation of metallic iron in vacuum



Tachibana+ (2011)

Condensates

Tachibana+ (2011)

Photo:

Growth steps on Fe metal condensed from vapor at 1235 K for 48 hr

Condensates

Tachibana+ (2011)

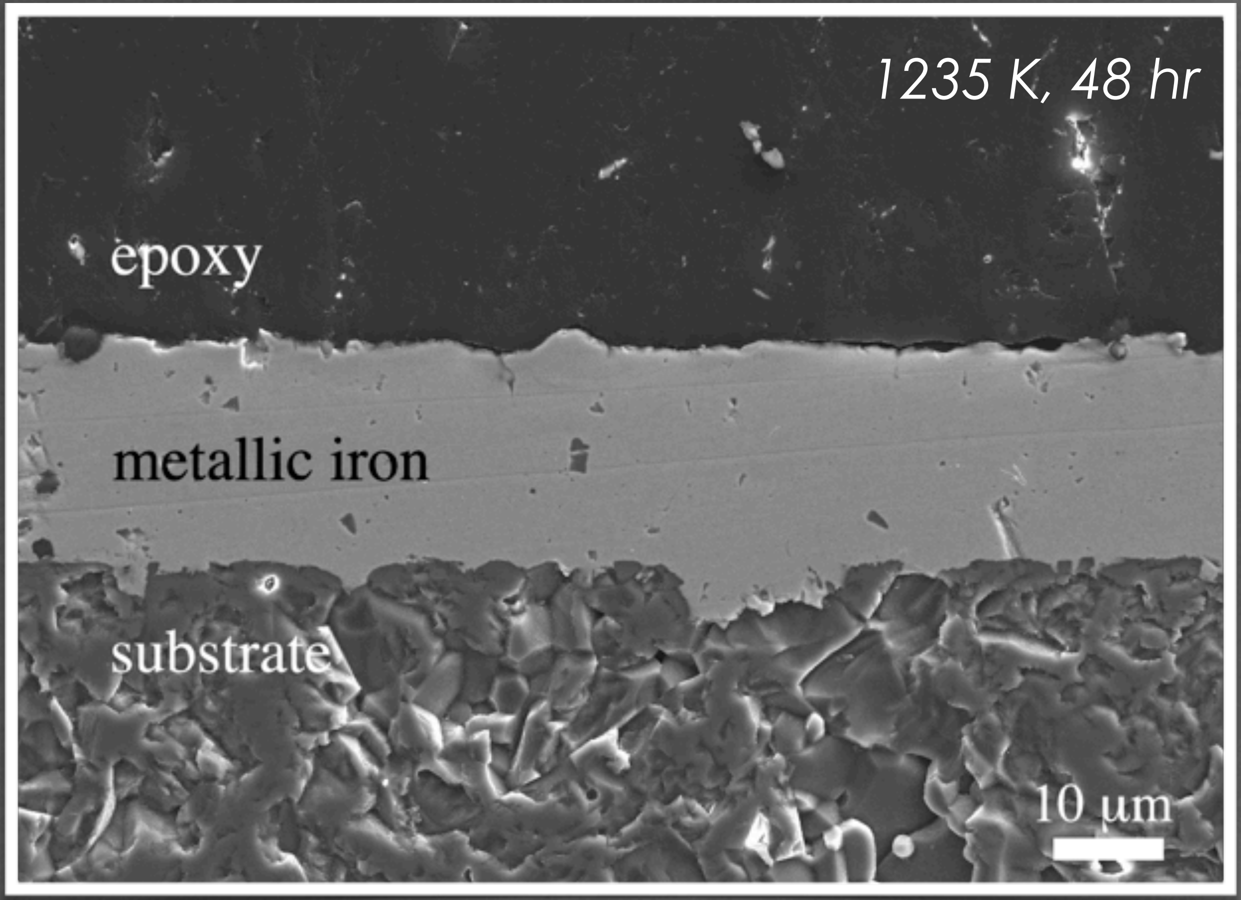
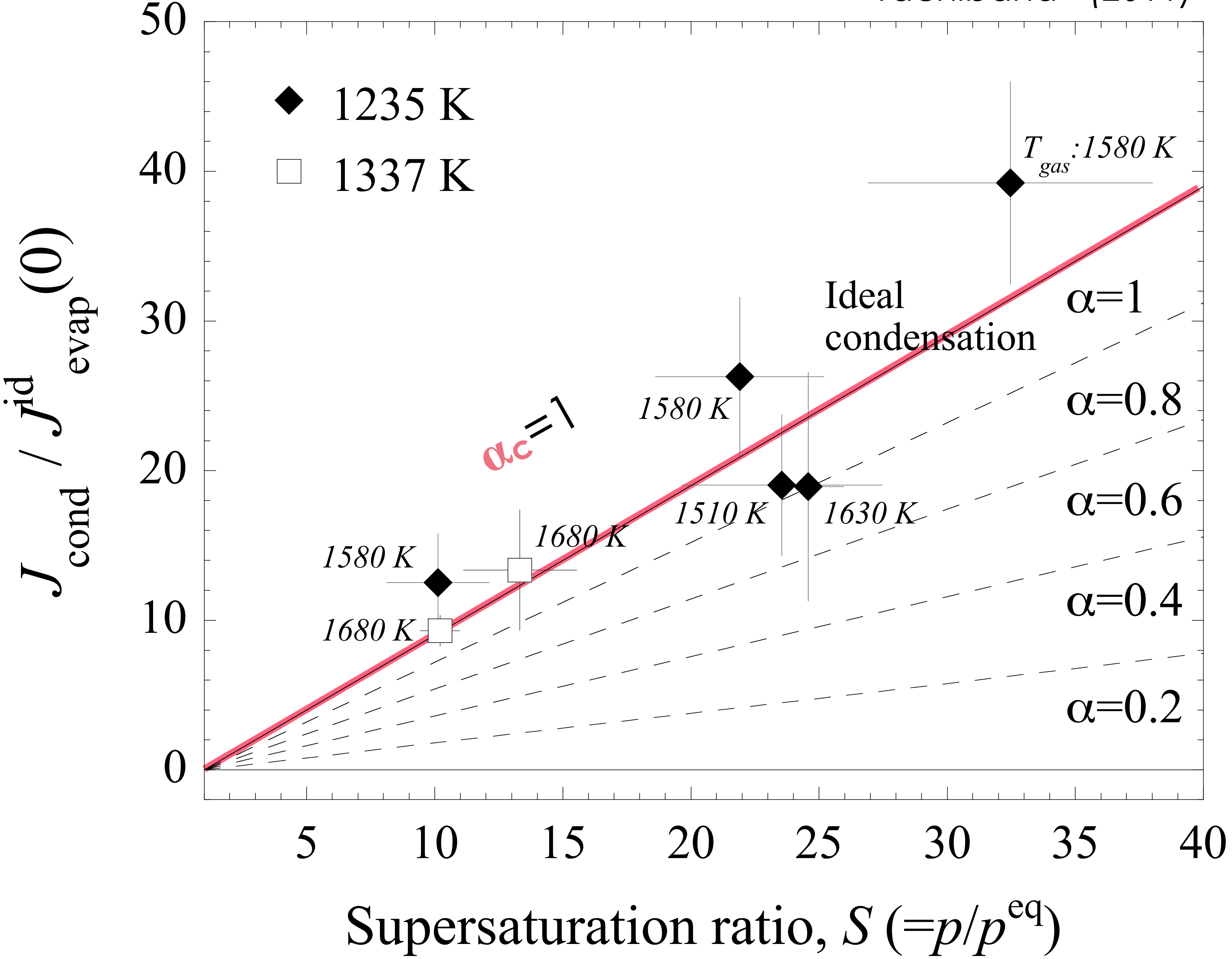


Photo:

Growth steps on Fe metal condensed from vapor at 1235 K for 48 hr

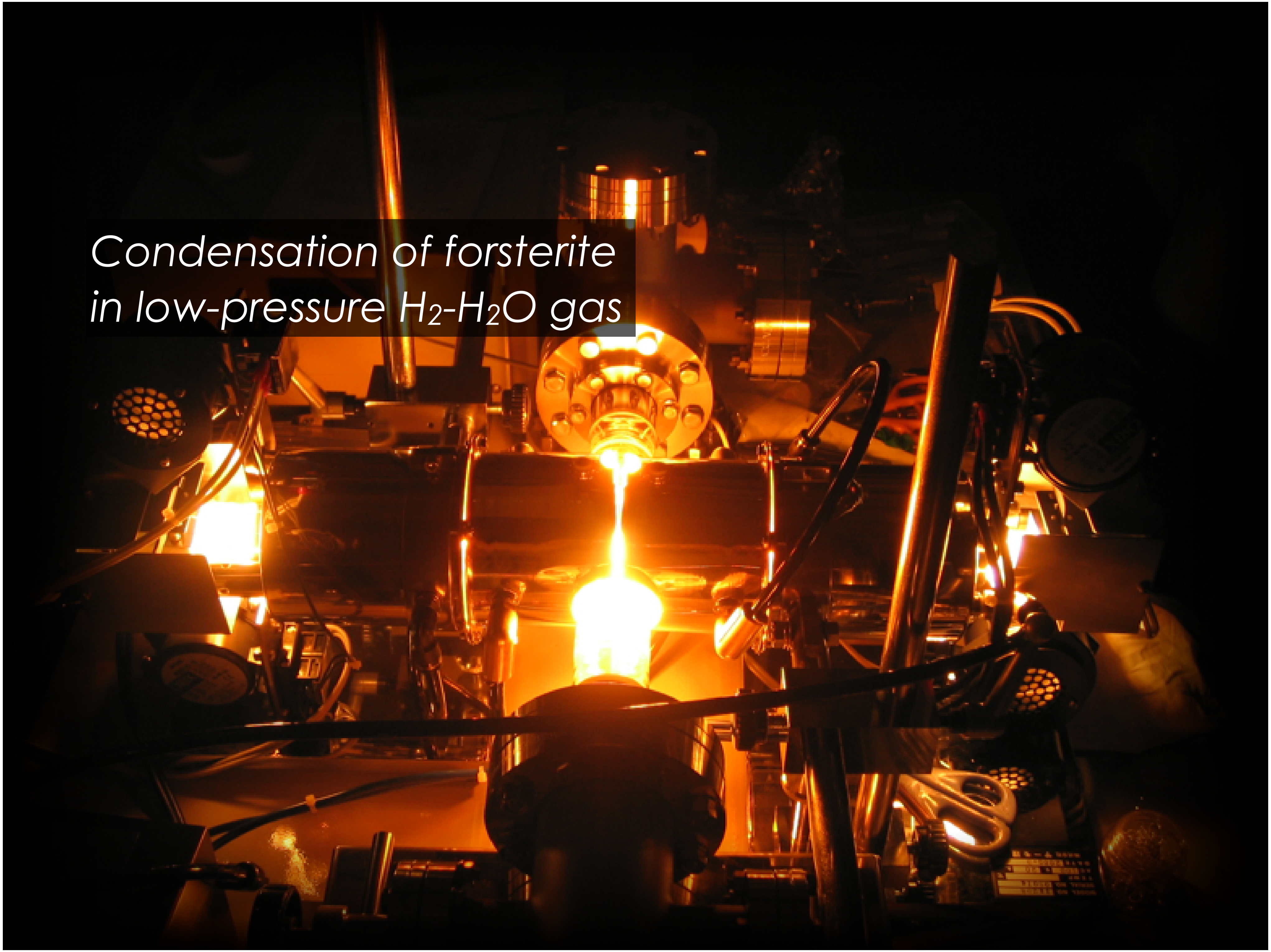
1 micron



Tachibana+ (2011)

Evaporation & Condensation coefficients

mineral	α_e	α_c
corundum	0.1-0.01	~0.05 *(Takigawa, 2012)*
forsterite	0.1–0.01	
enstatite	0.1 (as Fo)	
Metallic Fe	1–0.6	**~1** *(Tachibana+, 2011)*
troilite	$0.1–10^{-3}$	*~0.02*



Condensation of forsterite
in low-pressure H_2-H_2O gas

Evaporation of forsterite

$Mg_2SiO_4(s) = 2Mg(g) + SiO(g) + 3O(g)$

Free evaporation regime (**FED**)

Hashimoto (1990); Wang+ (1999); Yamada+ (2006);
Takigawa+(1999); Ozawa+ (2012)

$Mg_2SiO_4(s) + 3H_2(g) = 2Mg(g) + SiO(g) + 3H_2O(g)$

Hydrogen-reaction dominated regime (**HRD**)

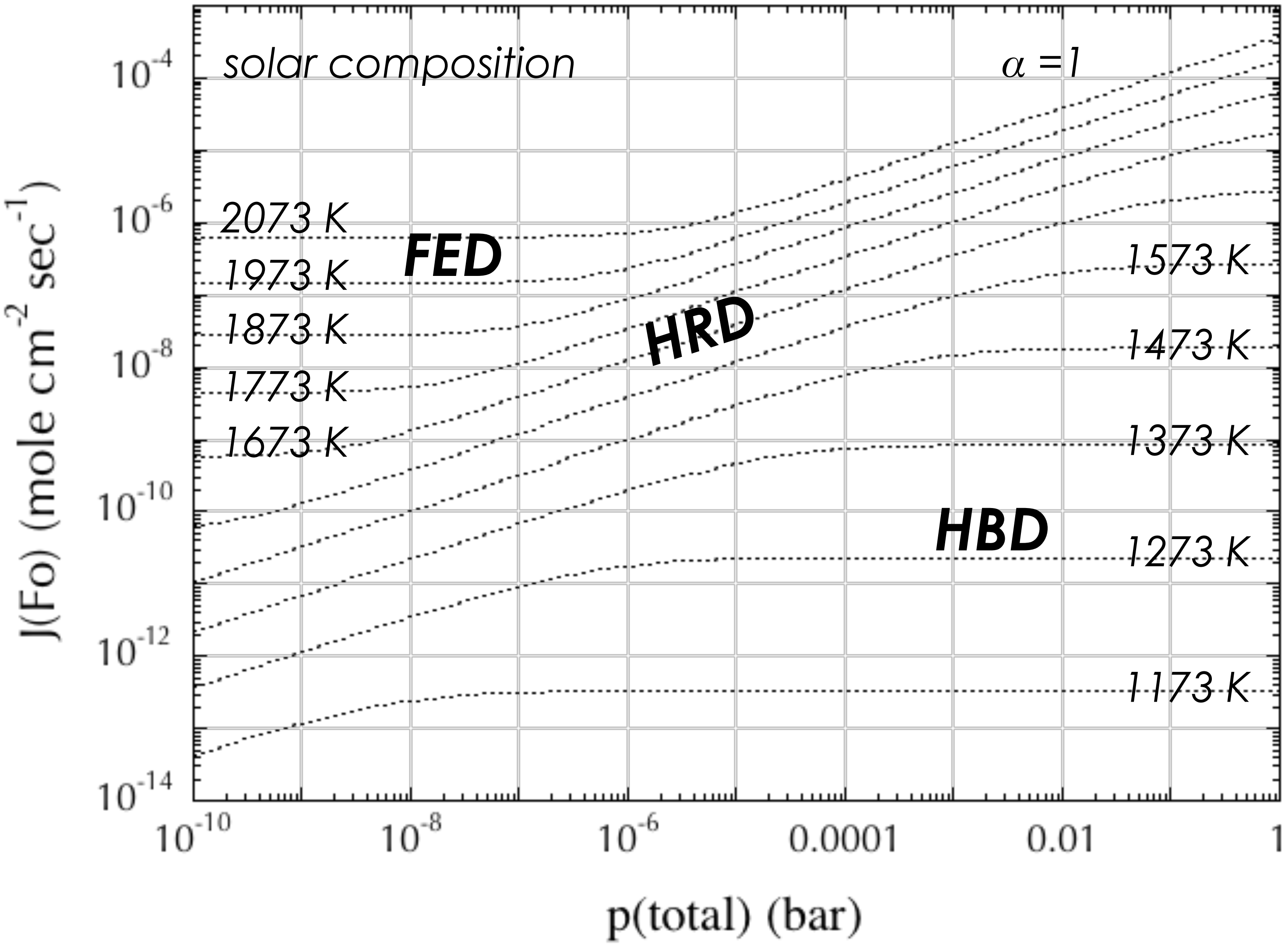
– J_{evap} proportional to $pH_2^{1/2}$

Nagahara & Ozawa (1996); Tsuchiyama+ (1998);
Kuroda & Hashimoto (2002); Takigawa+ (2009)

pH_2O/pH_2-buffer dominated regime (**HBD**)

– J_{evap} proportional to pH_2O/pH_2

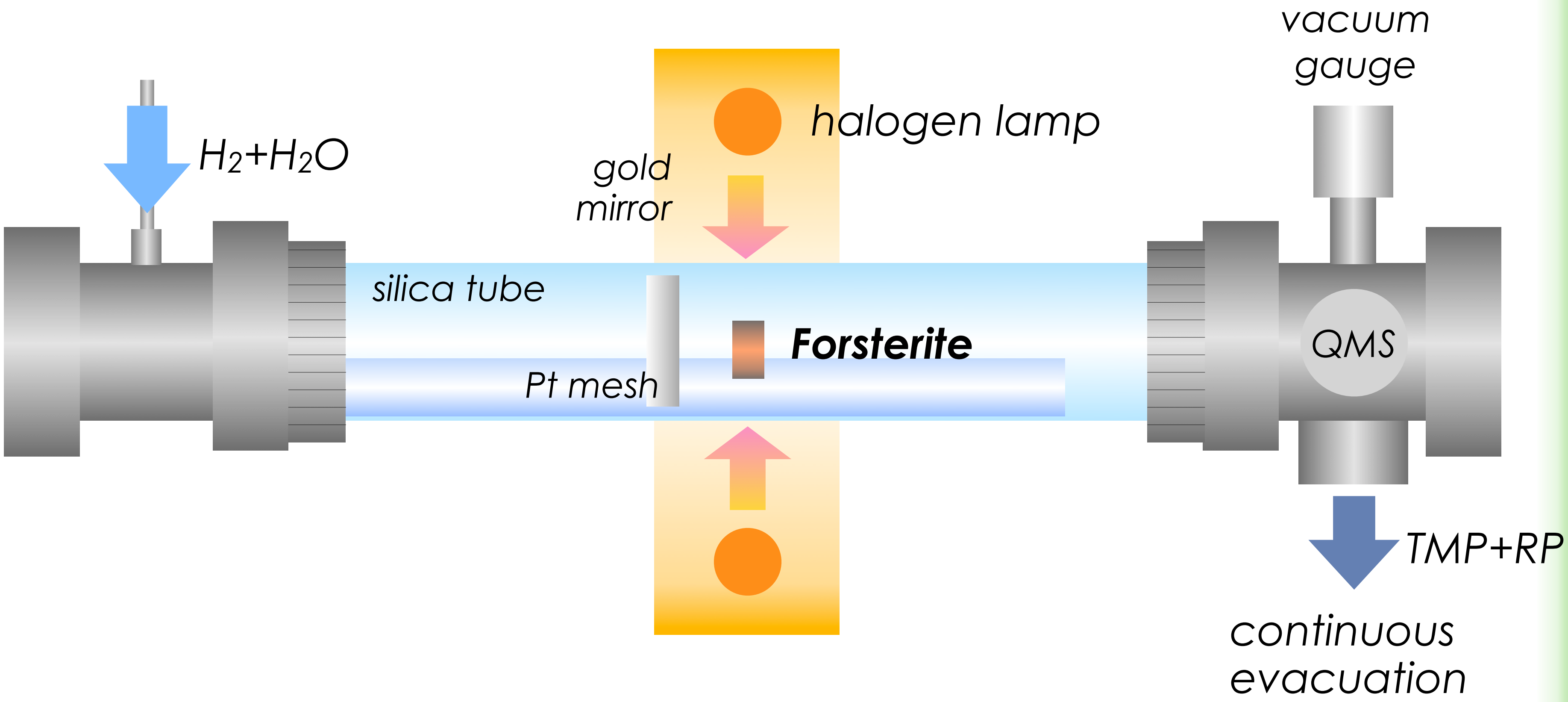
Evaporation of forsterite



Tsuchiyama, Tachibana, Takahashi (1999)

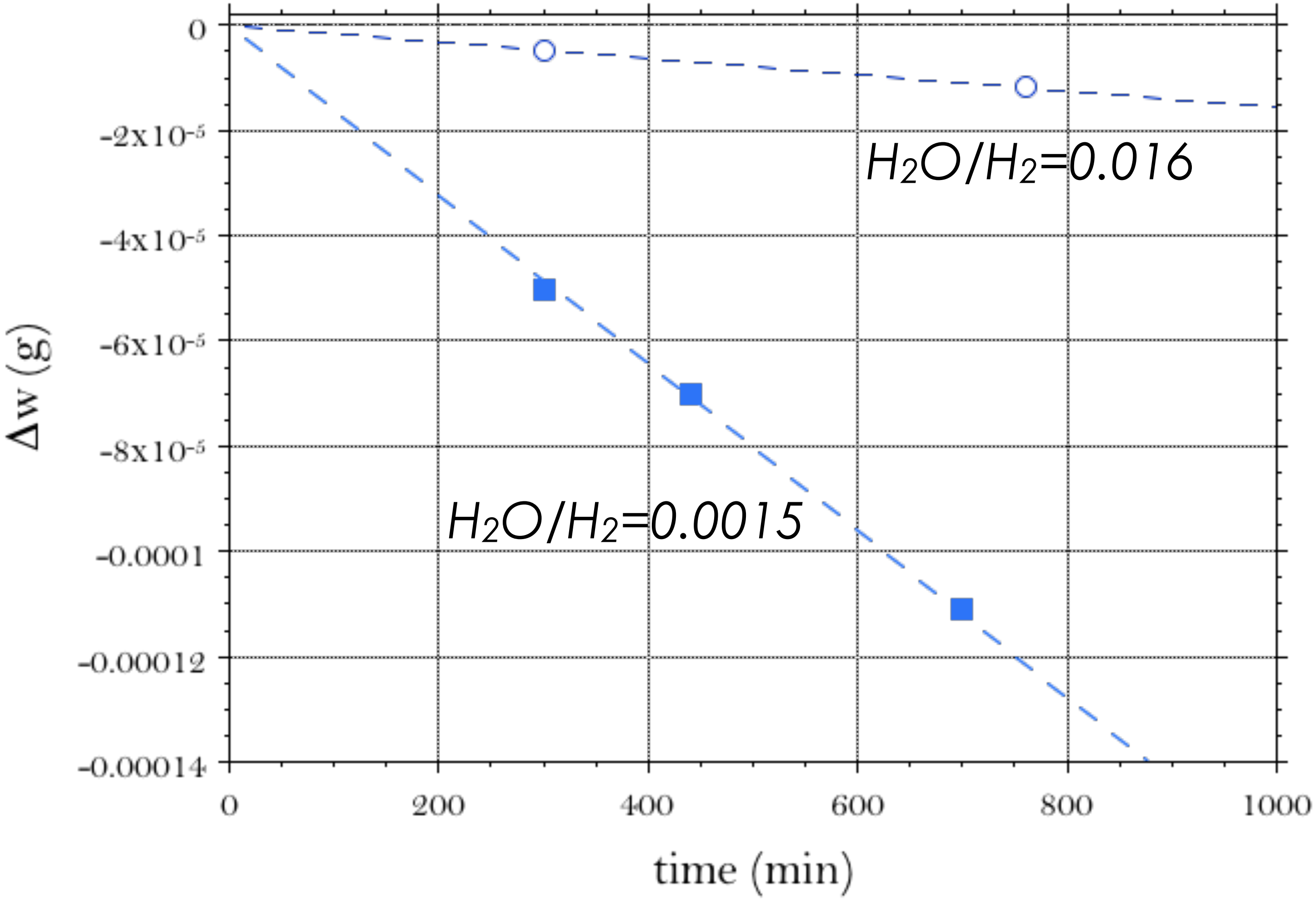
Evaporation of forsterite in low-pressure H_2-H_2O gas

Infrared vacuum furnace



Evaporation of forsterite in low-pressure H_2-H_2O gas

$p_{total}=4\times10^{-5}$ atm, T~1150°C (1423 K)

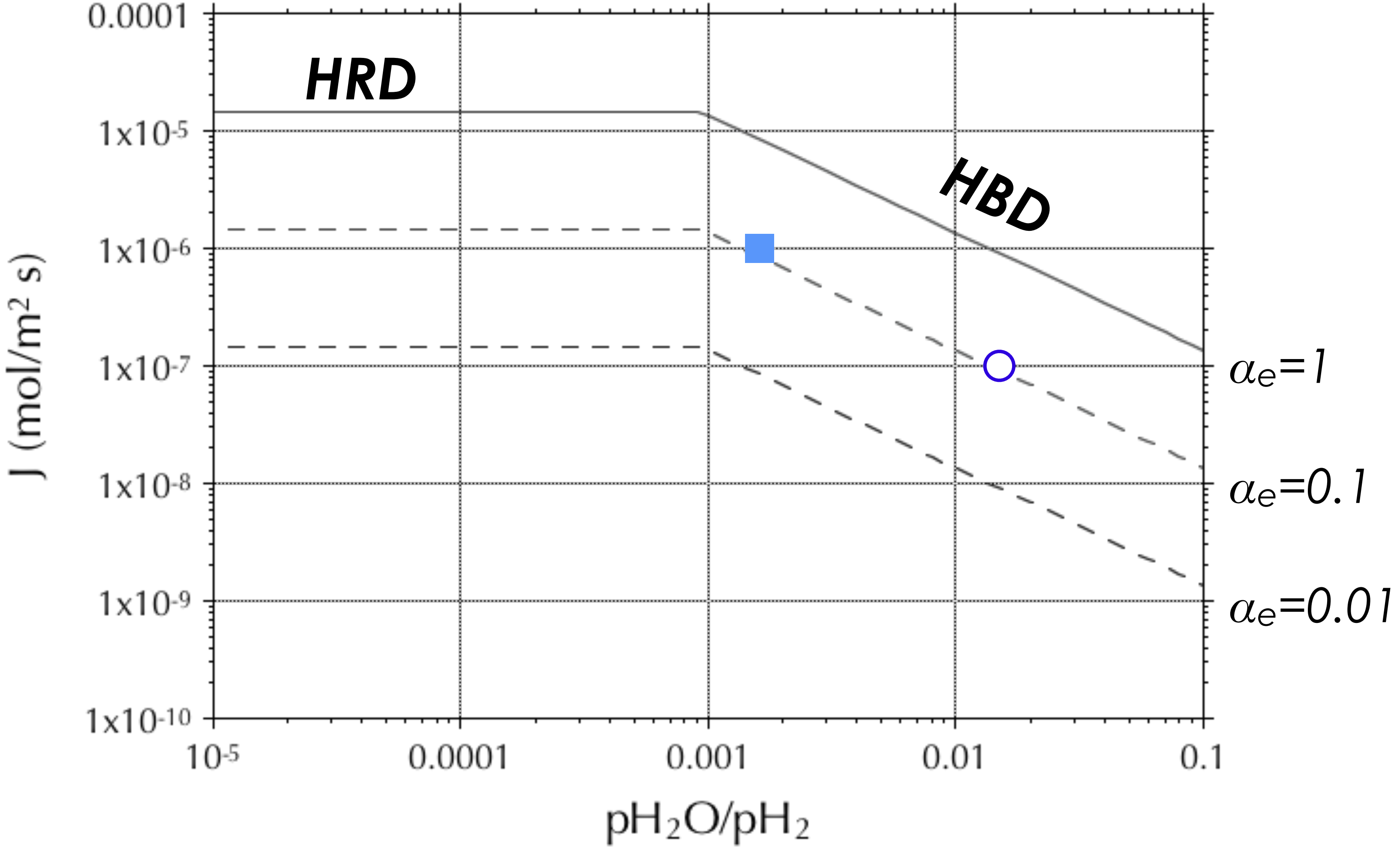


$H_2O/H_2=0.016$

$H_2O/H_2=0.0015$

Evaporation of forsterite in low-pressure H_2-H_2O gas

$p_{total}=4x10^{-5}$ atm, T~1150°C (1423 K)



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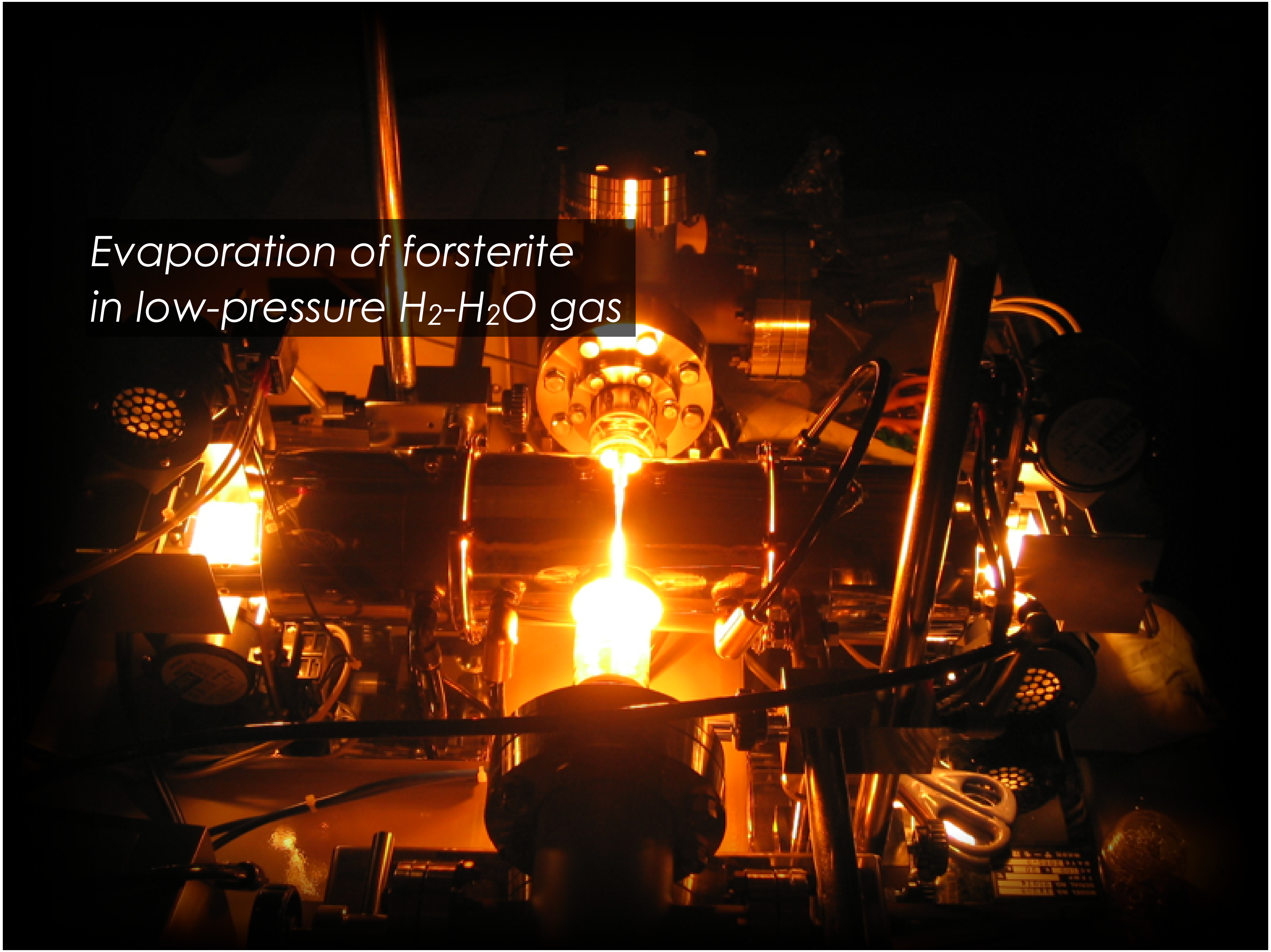
pH_2O/pH_2-buffer dominated regime (**HBD**)

– J_{evap} proportional to pH_2O/pH_2 confirmed for the first time



Evaporation of forsterite
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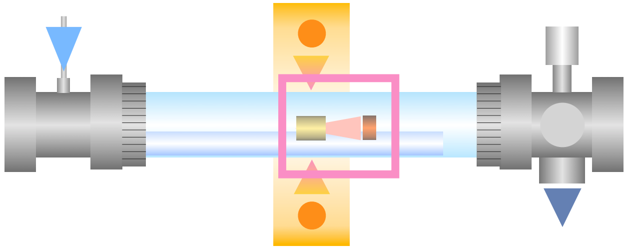
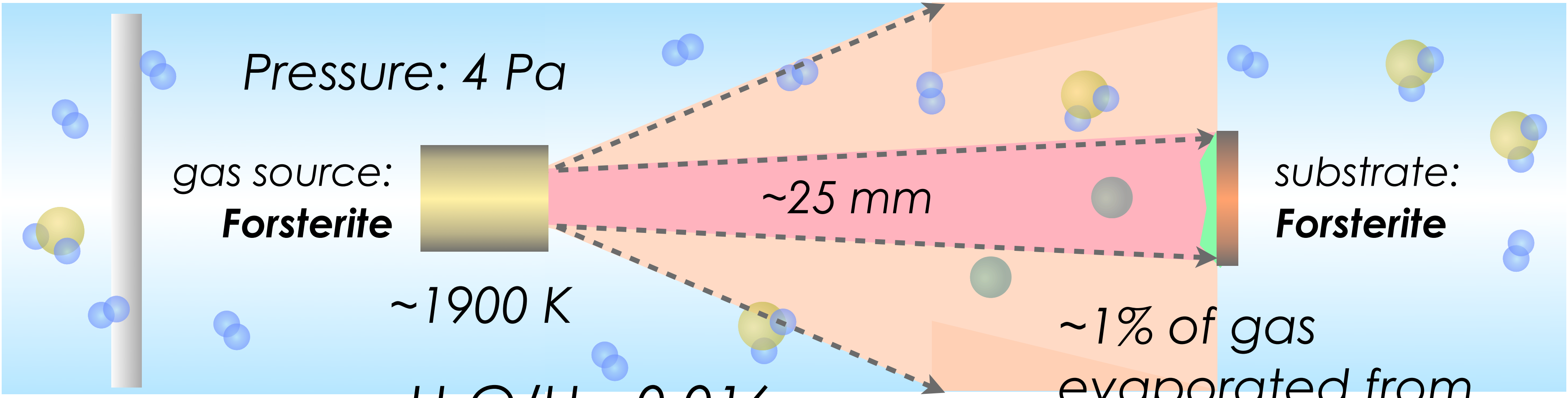
Condensation of forsterite in low-pressure H_2-H_2O gas





Pressure: 4 Pa

gas source:
Forsterite

~1900 K

~25 mm

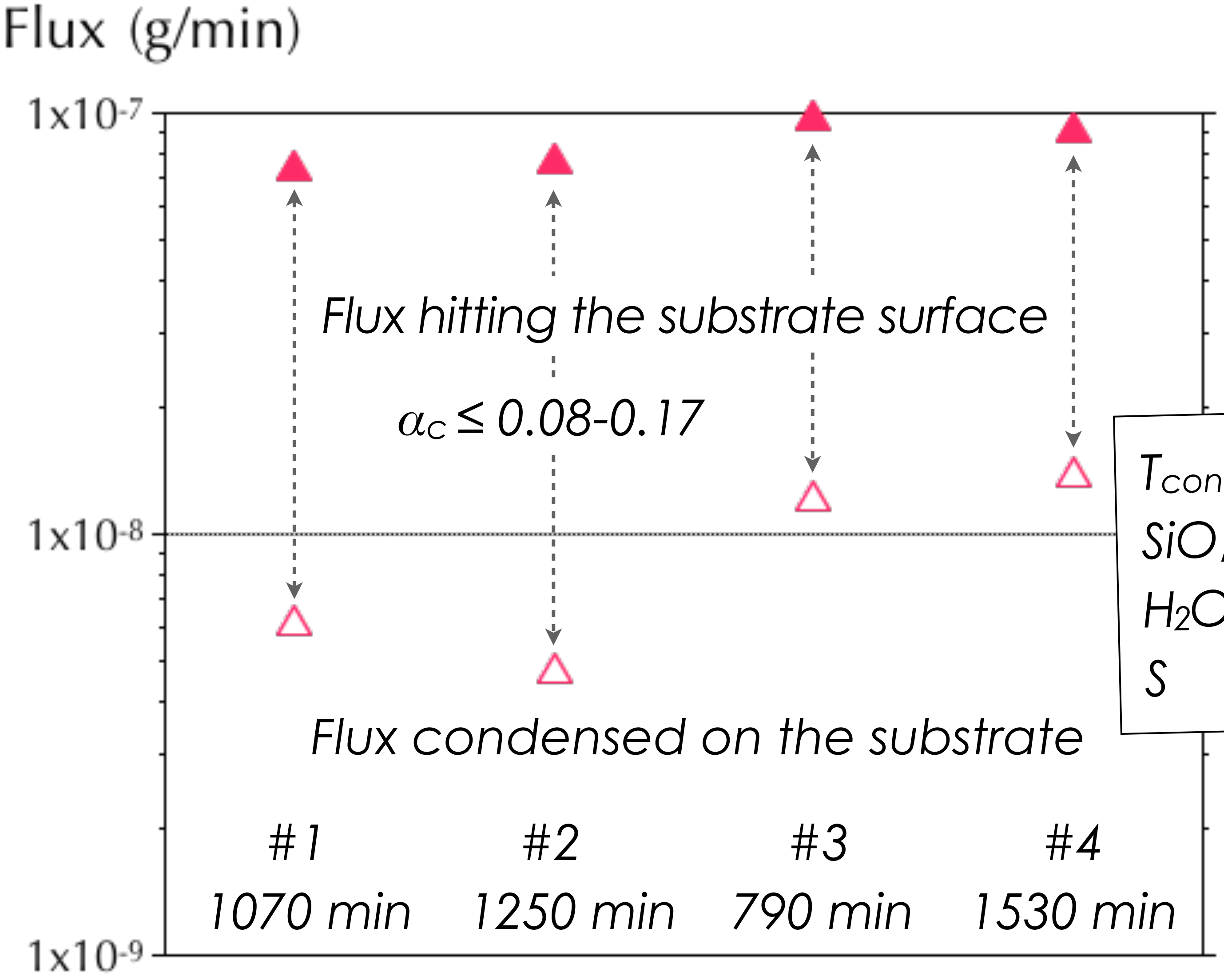
substrate:
Forsterite

Pt mesh

$H_2O/H_2=0.016$

~1% of gas evaporated from the gas source

Condensation coefficient



Flux hitting the substrate surface

$\alpha_C \lesssim 0.08\text{-}0.17$

Flux condensed on the substrate

T_{cond} = ~1350 K
SiO/H_2 = ~0.15 solar
H_2O/H_2 = ~16 solar
S = ~5

Evaporation & Condensation coefficients

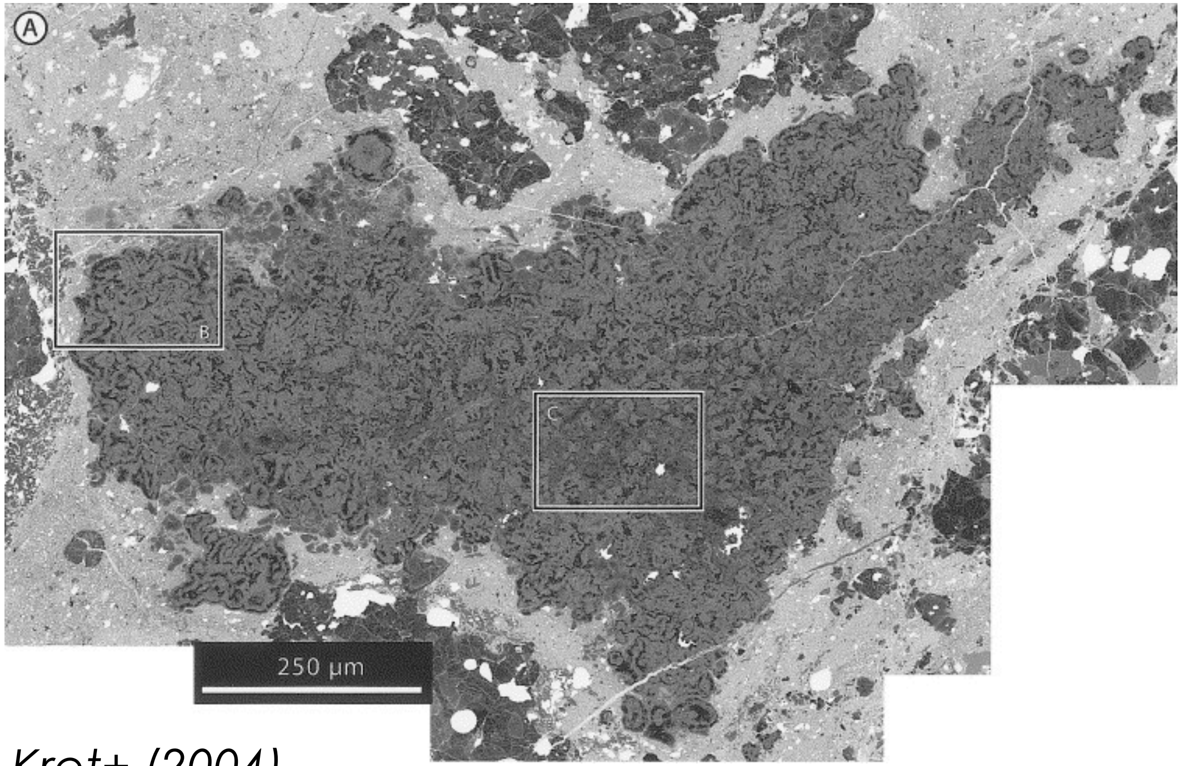
mineral	α_e	α_c
corundum	0.1-0.01	~0.05 *(Takigawa, 2012)*
spinel		*~0.02*
forsterite	**0.1–0.01**	**~0.1?**
enstatite	0.1 (as Fo)	
Metallic Fe	**1–0.6**	**~1** *(Tachibana+, 2011)*
troilite	$0.1–10^{-3}$	

Growth (and evaporation) of forsterite dust occurs less efficiently than Fe metal

Application to cosmochemistry

AOA Formation

Grain size, number density, mineral assemblages



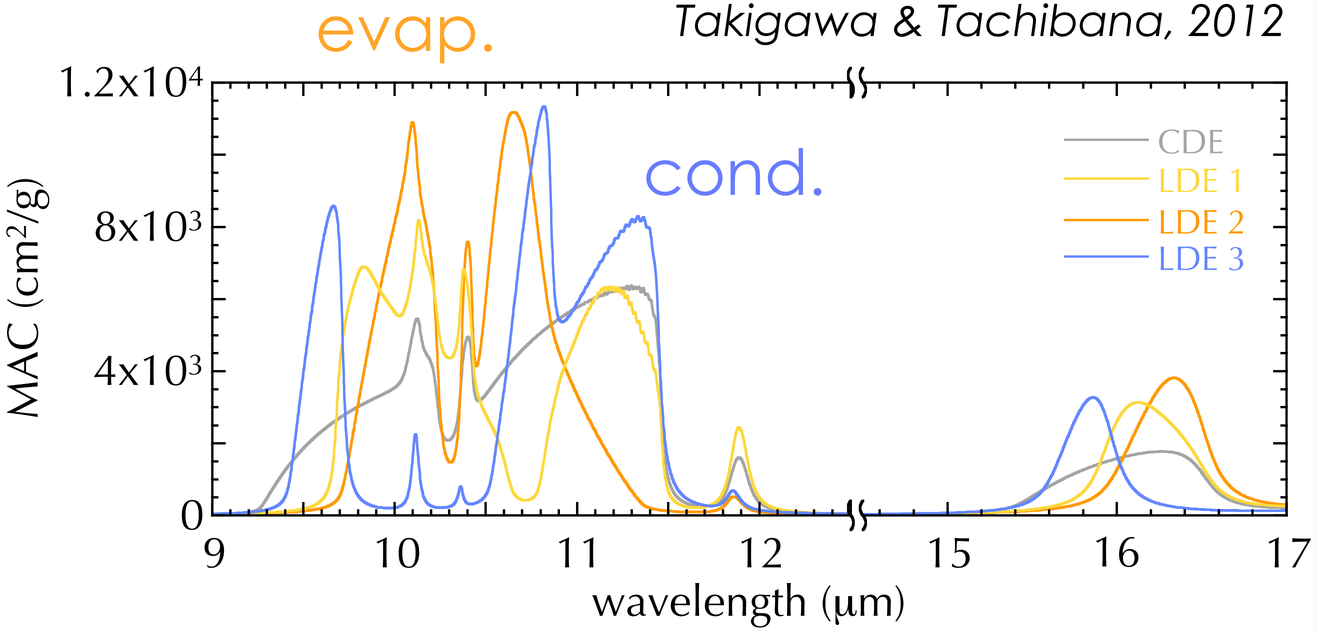
Krot+ (2004)

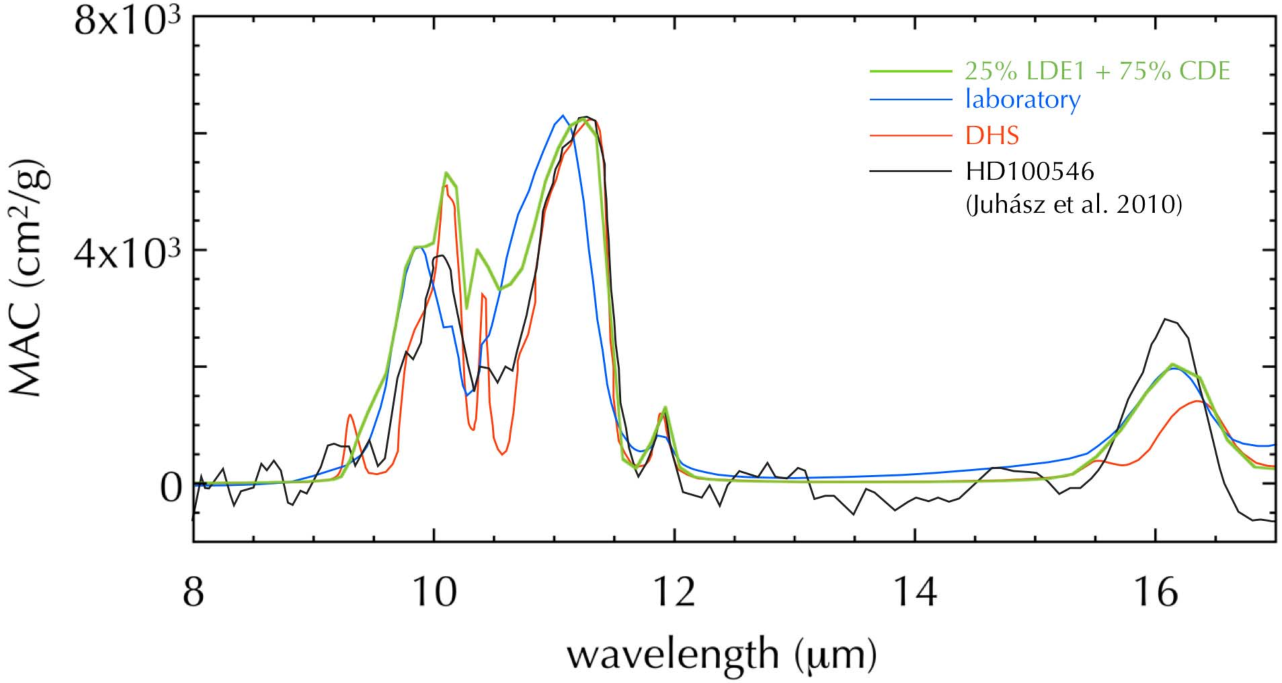
Application to infrared spectroscopy

Anisotropy:

Probe for high-T history of dust

Takigawa & Tachibana, 2012





Summary & Conclusions

Understanding of ***dust formation kinetics*** *is a key to understand dust forming environments*

— *experiments at* ***controlled low-pressure "realistic" conditions*** *combined with observation and modeling*

Evaporation of forsterite controlled by pH_2O/pH_2 *is confirmed; Kinetics is likely to be the same*

Growth experiments of forsterite under controlled protosolar disk-like conditions *are now being made;*
The growth efficiency is not as good as metallic iron