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Recent Progress of Experimental Studies on Dust Formation Kinetics

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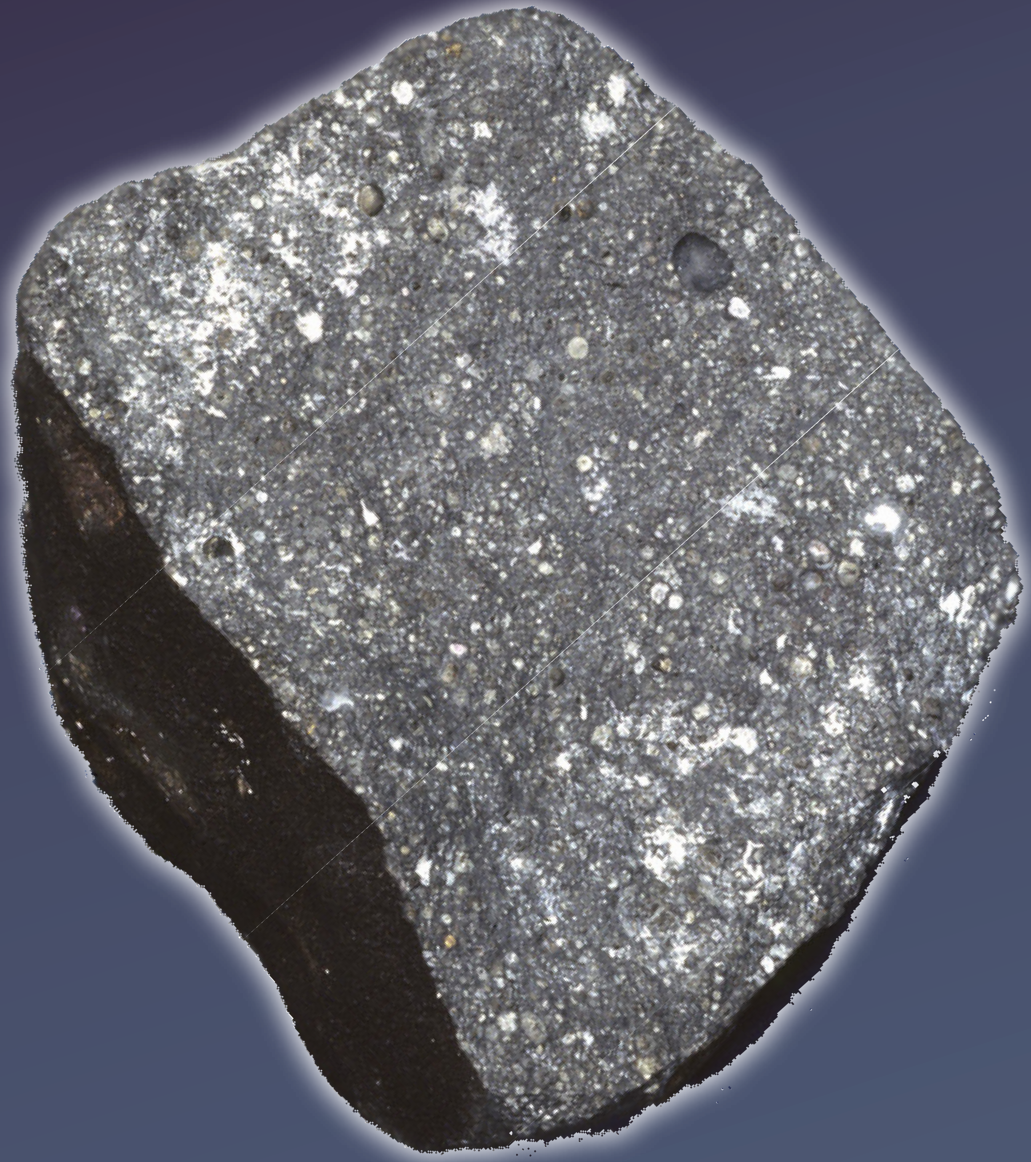
Kaori Kataoka   Kazuhito Ozawa

Outline

1. Importance of **Kinetics**
2. Condensation in the **Fe-S-H** system
3. Condensation in the **Mg-Si-O-H** system

Solids in Protosolar Disk

Primitive meteorites "chondrites"
record the history of the protosolar disk



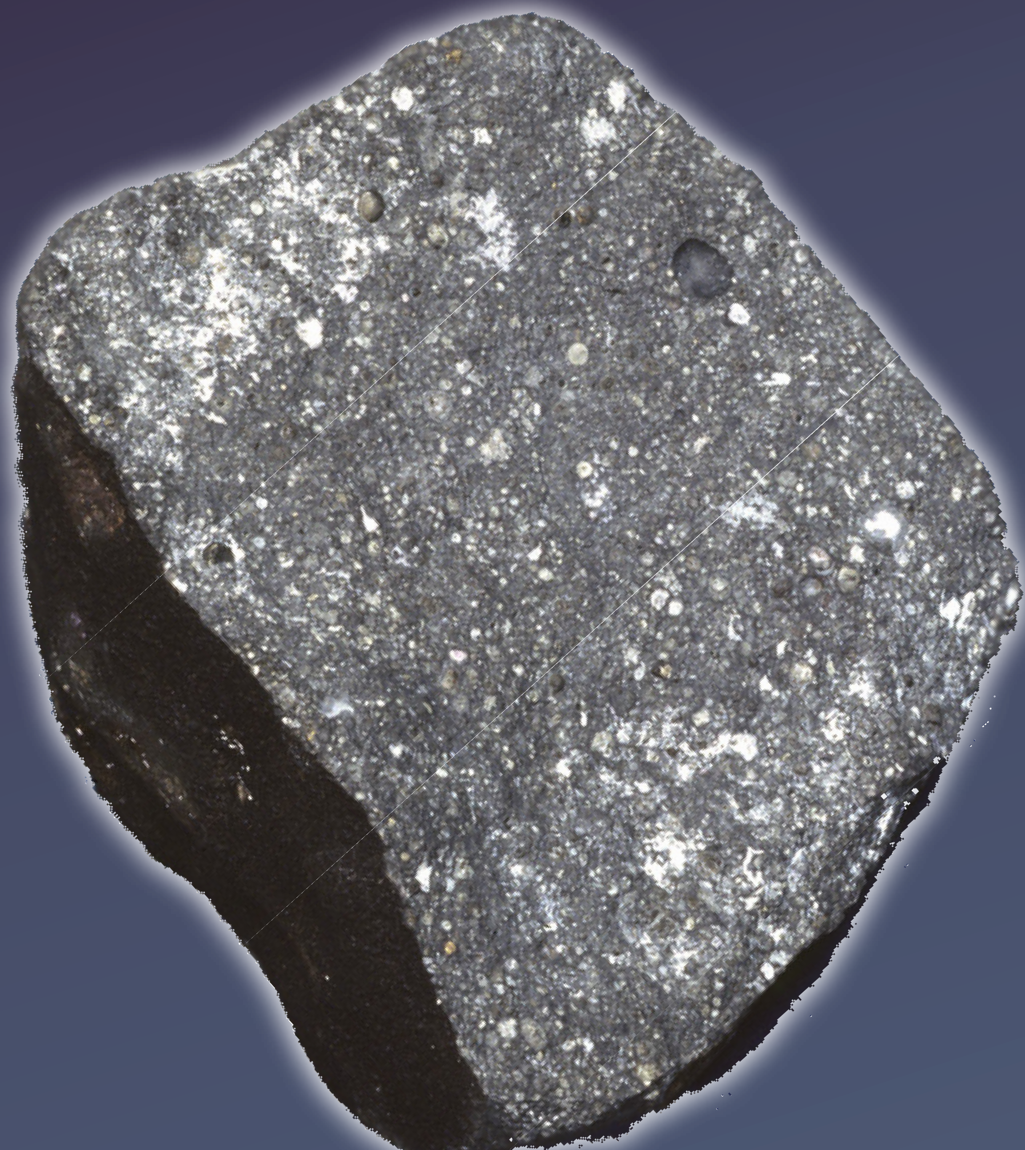
Ca-Al-rich inclusions (CAIs):

Oldest rock (4.567 Ga) formed by high-T process (1500-1600K)

(e.g., Amelin+ 2002)

Solids in Protosolar Disk

Primitive meteorites "chondrites" record the history of the protosolar disk



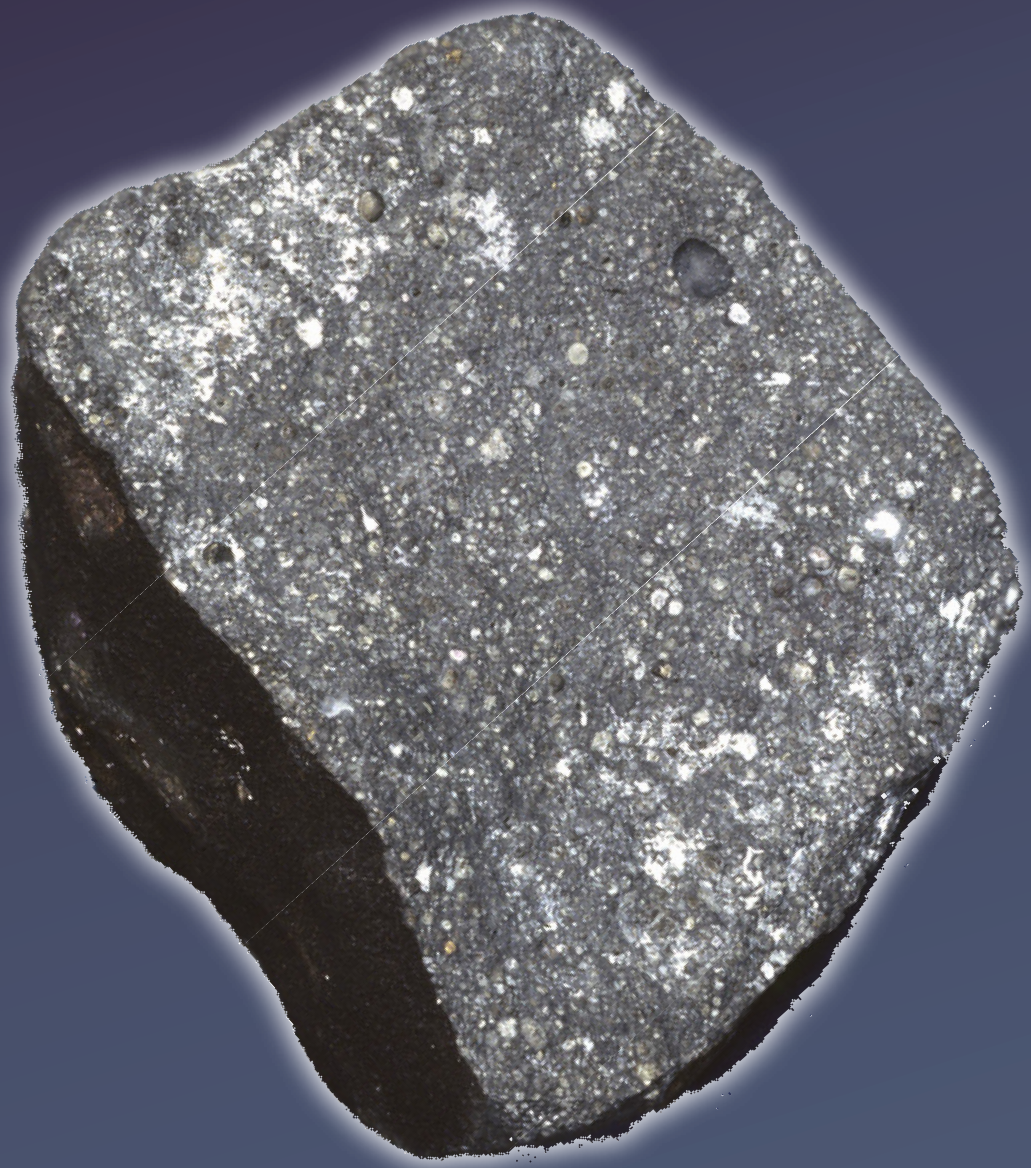
Amoeboid Ol. Aggregates (AOAs):

Aggregates of crystalline forsterite formed 0.5-1 Myr after CAIs

(Itoh+ 2004)

Solids in Protosolar Disk

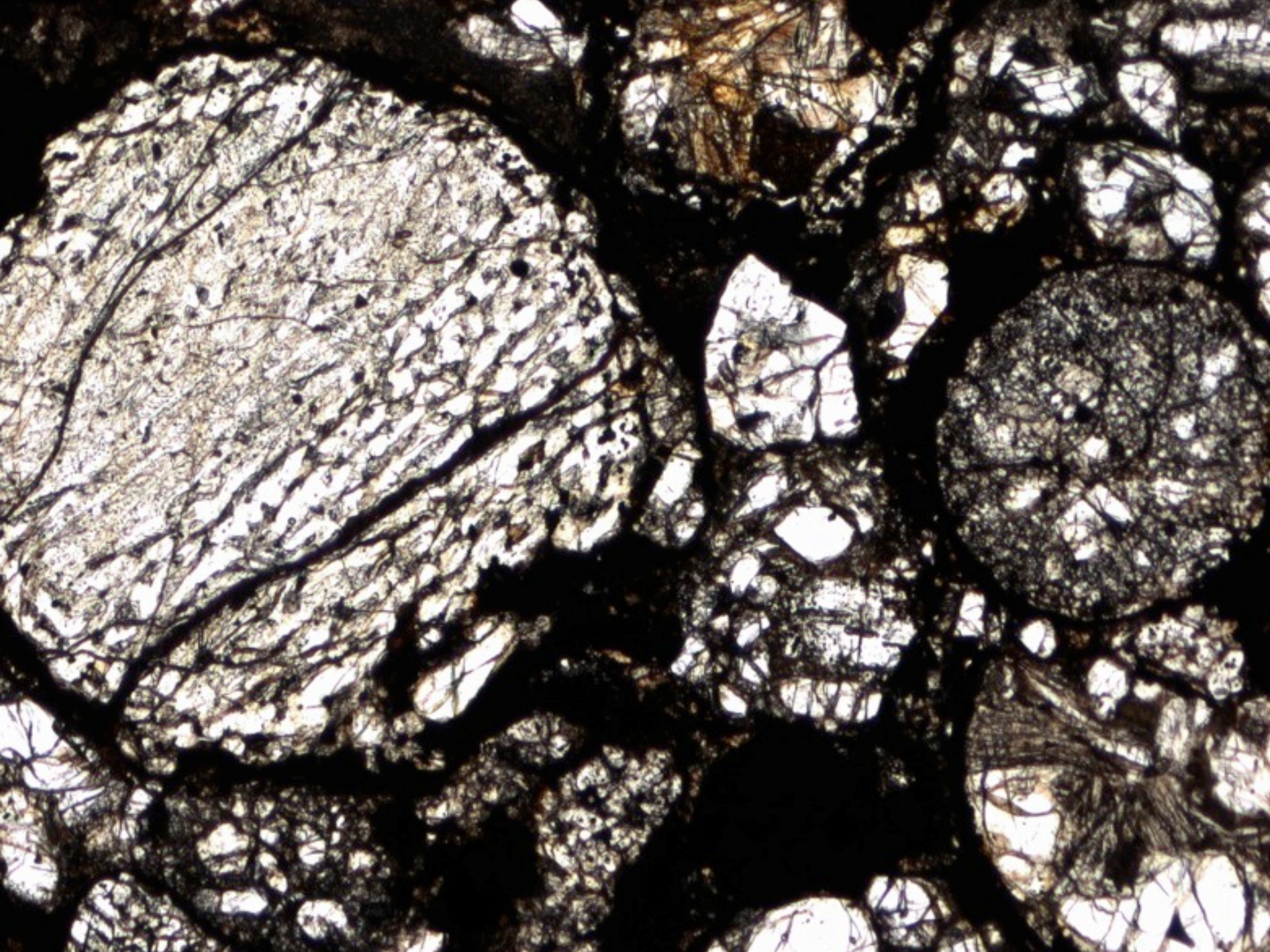
Primitive meteorites "chondrites" record the history of the protosolar disk



Chondrules:

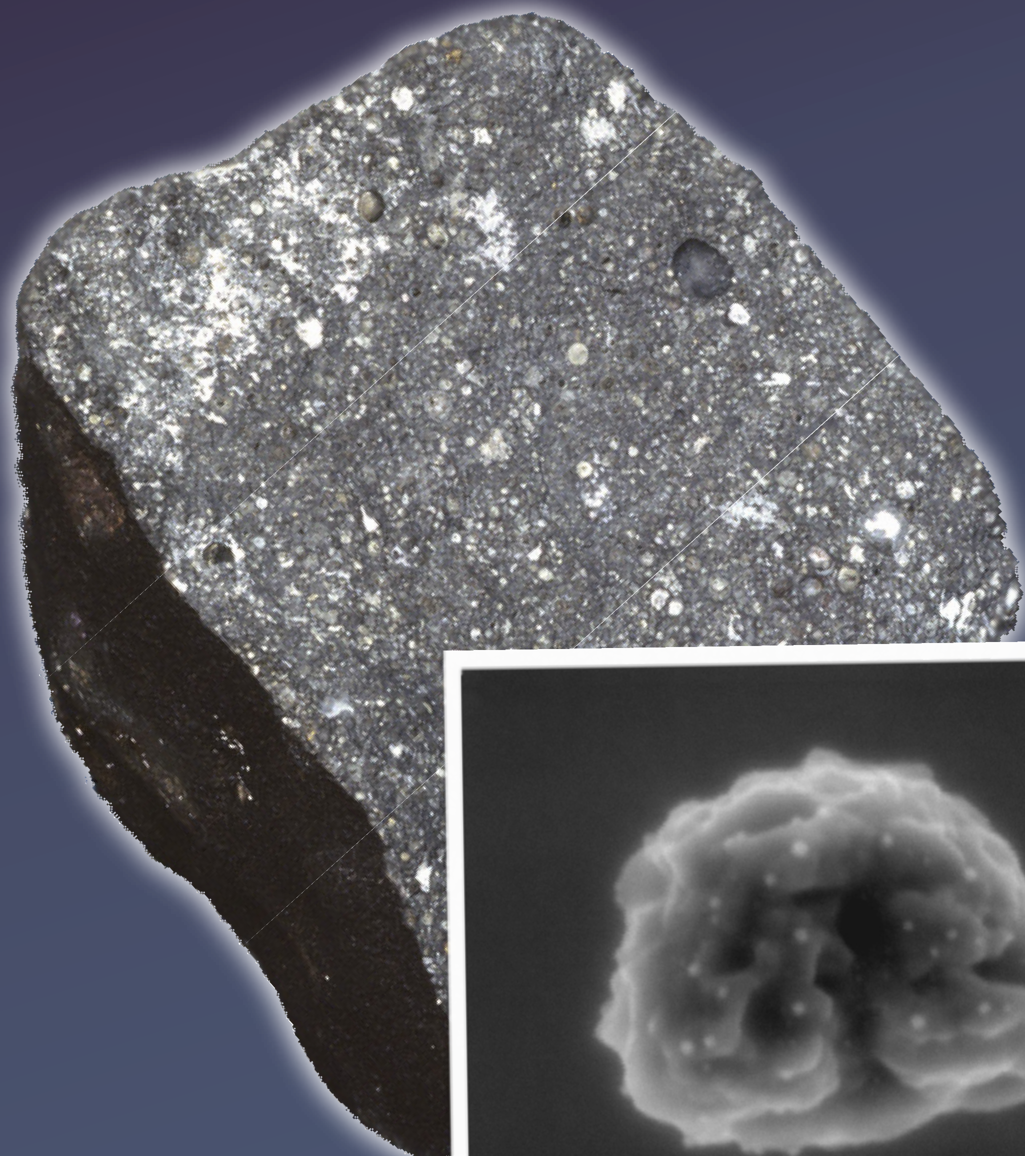
Silicate spherules formed by rapid heating and cooling in the gas- and dust-disk

(e.g., Lauretta+, 2006; Tachibana & Huss, 2005; Alexander+, 2009; Pascucci & Tachibana, 2010)



Solids in Protosolar Disk

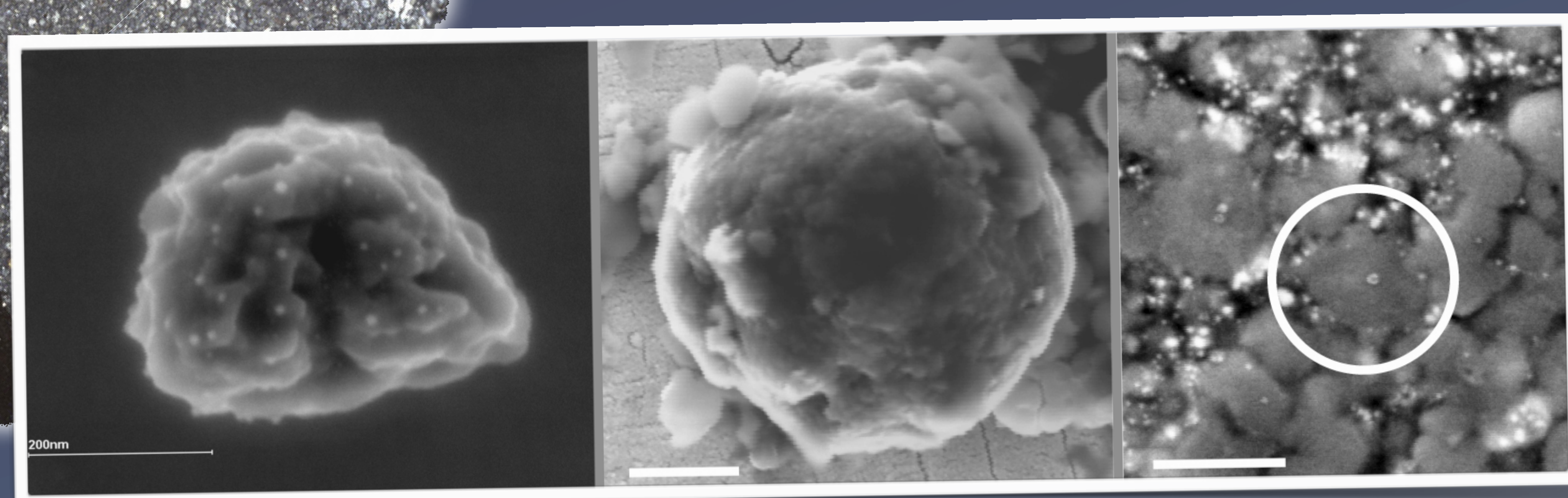
Primitive meteorites "chondrites" record the history of the protosolar disk



Presolar grains:

"Stardust", survived thermal processes in the protosolar disk

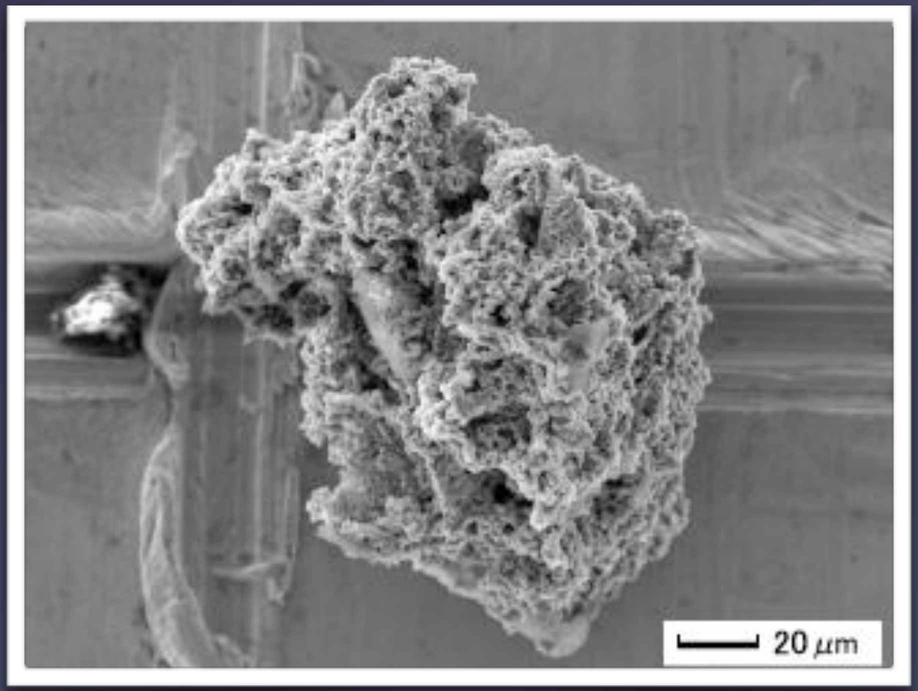
(e.g., Gail & Hoppe, 2010)

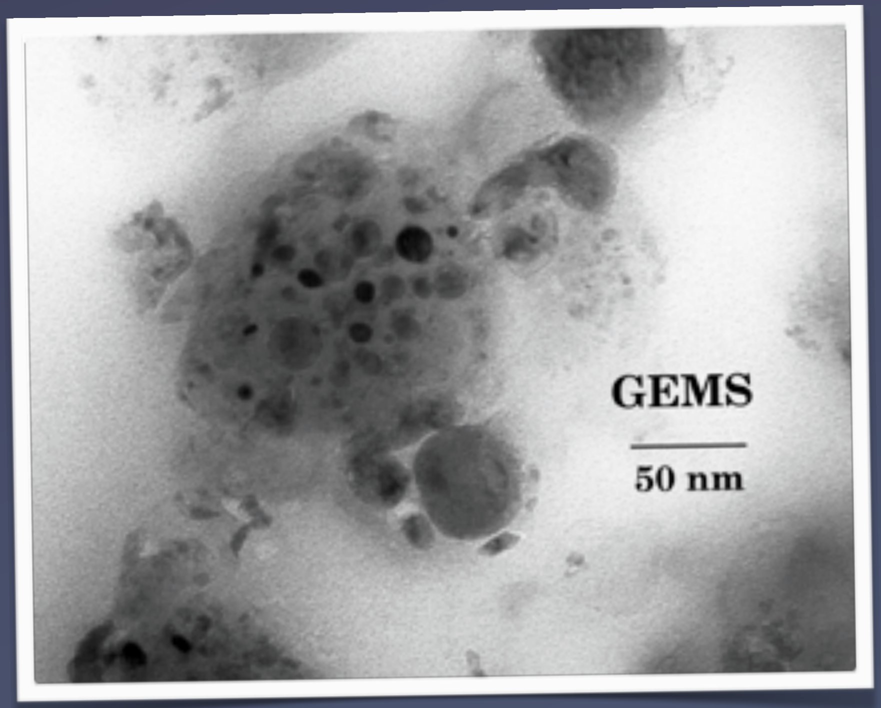


Solids in Protosolar Disk

Interplanetary dusts:

contain GEMS (glass w/ embedded metal and sulfides)





Circumstellar dusts:

amorphous silicates + small amounts of crystalline dust (Talks in this workshop)

Solids in PP Disks – Non-Equilibrium!

Ca-Al-rich inclusions (CAIs):

... formed by **high-T** process

Chondrules:

... **rapid** heating and cooling

Presolar grains:

... **survived** thermal processes

Interplanetary dusts:

contain **GEMS** ...

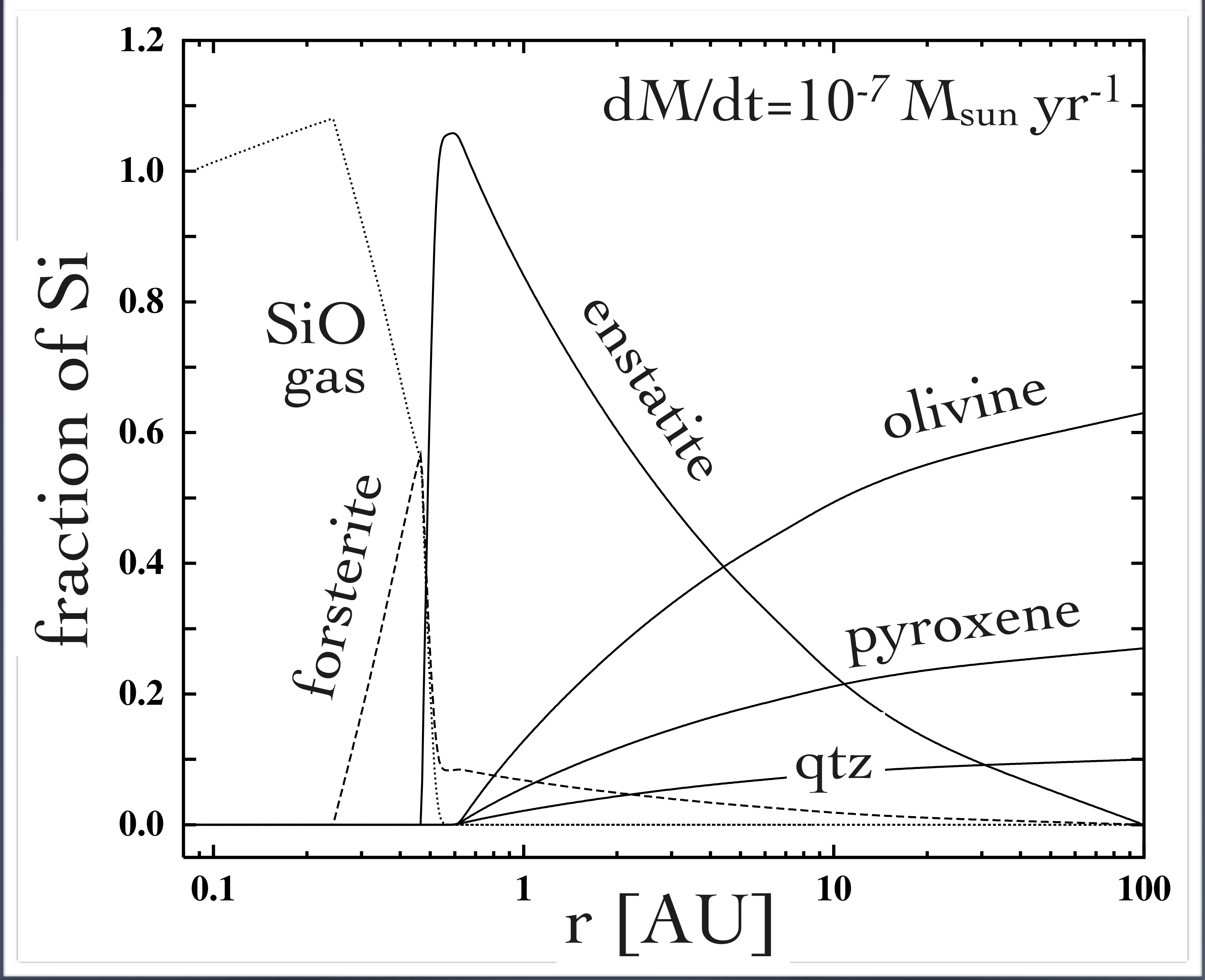
Circumstellar dusts:

amorphous silicates
+ crystalline dust ...

Dust formation – not necessarily occurs in equilibrium in protoplanetary disks

Solids in PP Disks – Non-Equilibrium!

Dust formation – not necessarily occurs in equilibrium in protoplanetary disks



A series of papers by H.-P. Gail

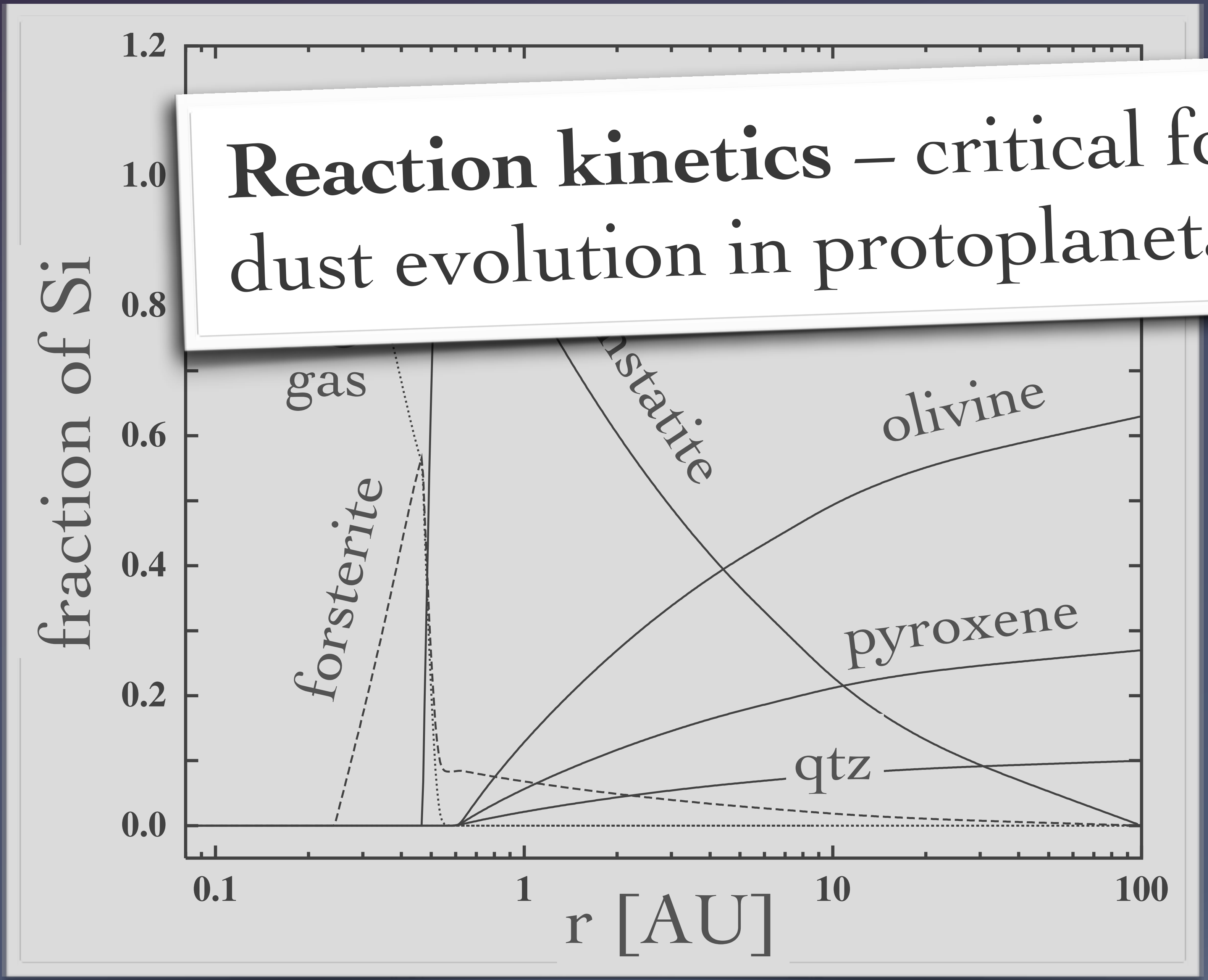
Change of dust properties in accreting disks and in outflows

Kinetics:

Hashimoto (1990); Imae+ (1993); Tsuchiyama & Fujimoto (1995); Nagahara & Ozawa (1996); Lauretta+ (1996); Chakraborty (1997); Tachibana & Tsuchiyama (1998); Tachibana+ (2002)

Solids in PP Disks – Non-Equilibrium!

Dust formation – not necessarily occurs in equilibrium in protoplanetary disks



Reaction kinetics – critical for understanding dust evolution in protoplanetary disks

properties in accreting disks and in outflows

Kinetics:

Hashimoto (1990); Imae+ (1993); Tsuchiyama & Fujimoto (1995); Nagahara & Ozawa (1996); Lauretta+ (1996); Chakraborty (1997); Tachibana & Tsuchiyama (1998); Tachibana+ (2002)

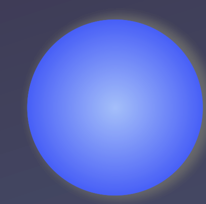
Kinetics of Gas-Solid (-Liquid) Reactions

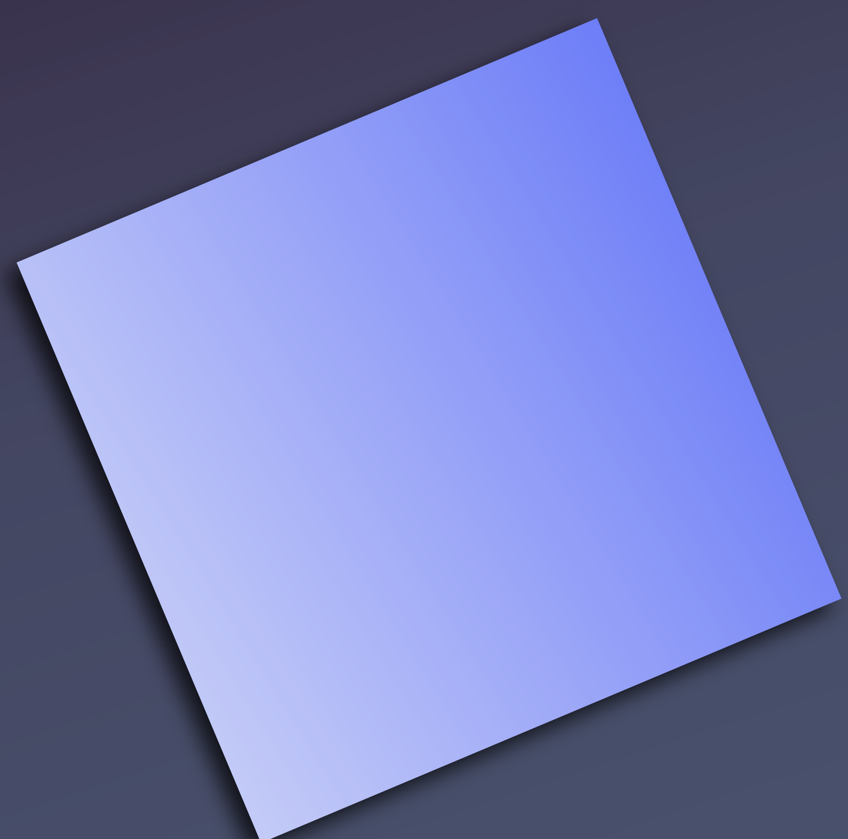
Adsorption

Surface diffusion

Desorption
Incorporation into structure

What We Need is ...





The fraction of atoms and/or molecules incorporating into structure

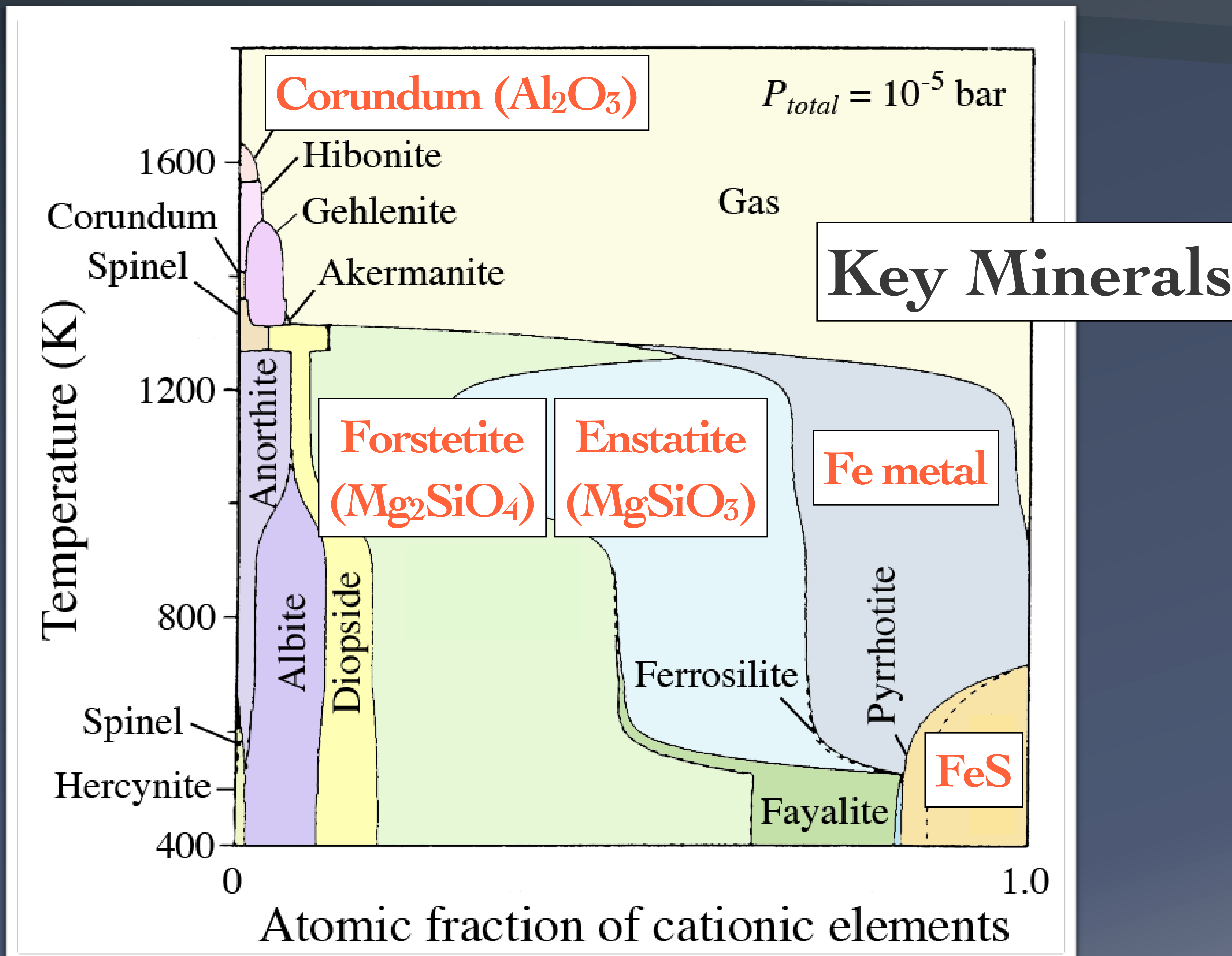
Condensation / Reaction efficiency

Need experiments under realistic conditions

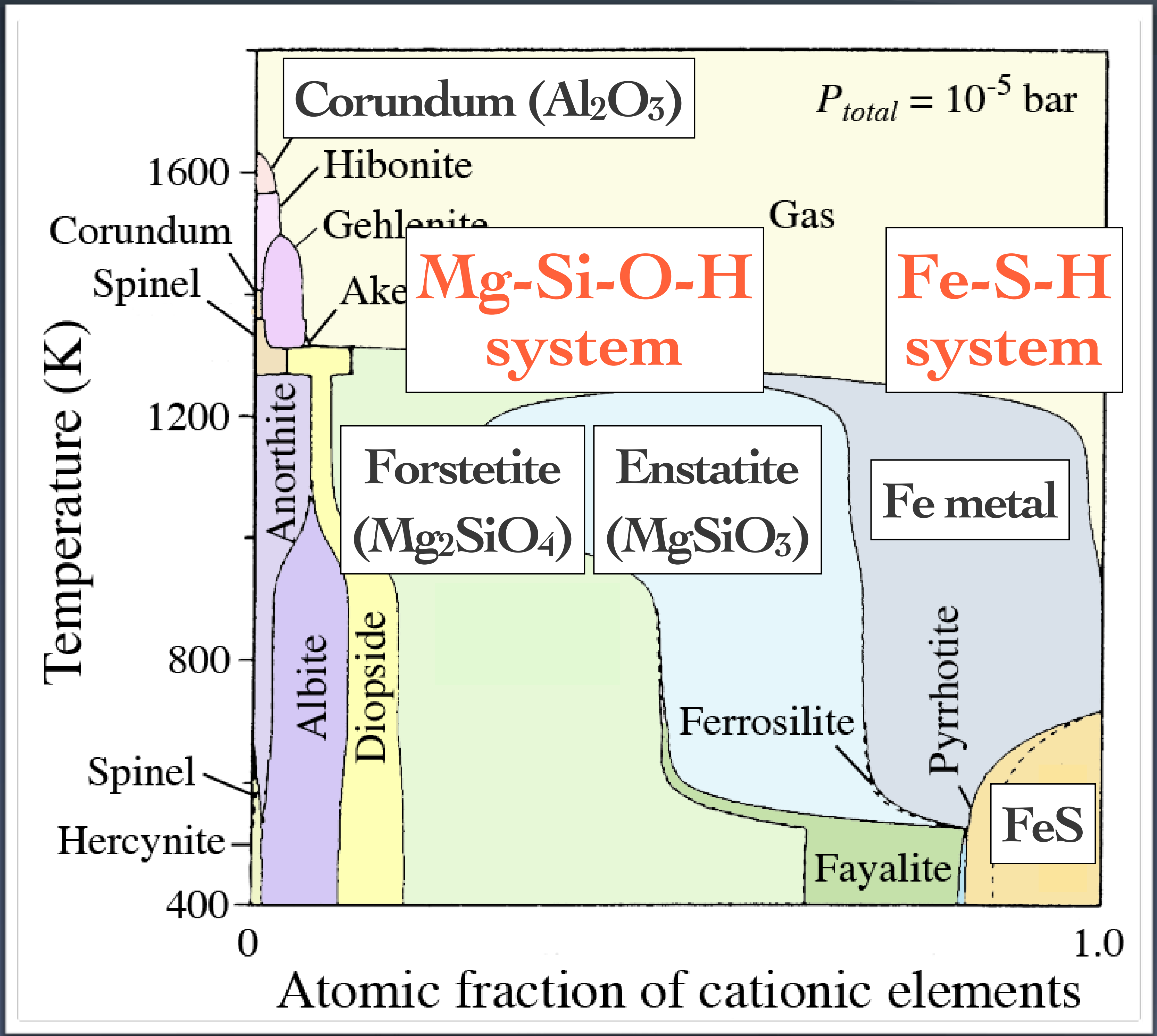
Outline

1. Importance of **Kinetics**
2. Condensation in the **Fe-S-H** system
3. Condensation in the **Mg-Si-O-H** system

Thermodynamical Stability of Minerals

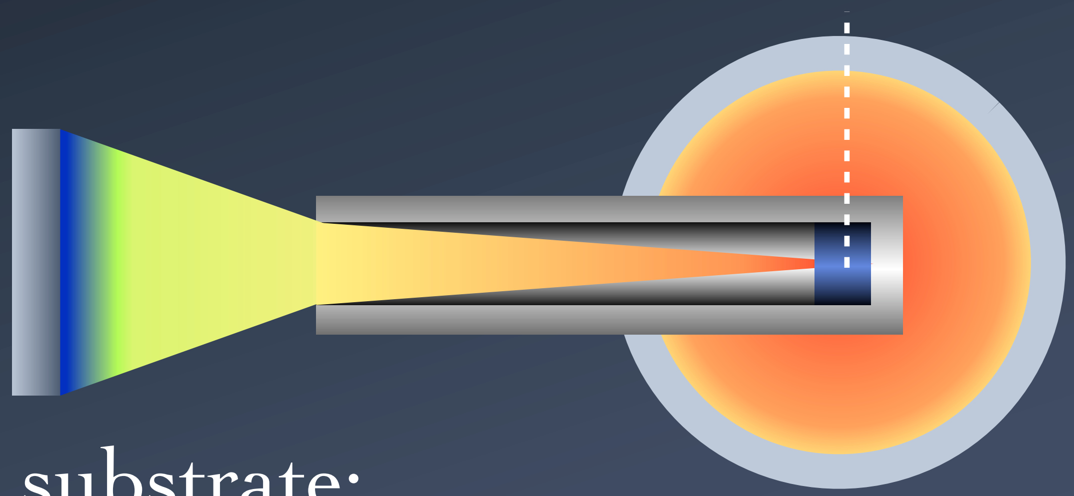


Thermodynamical Stability of Minerals

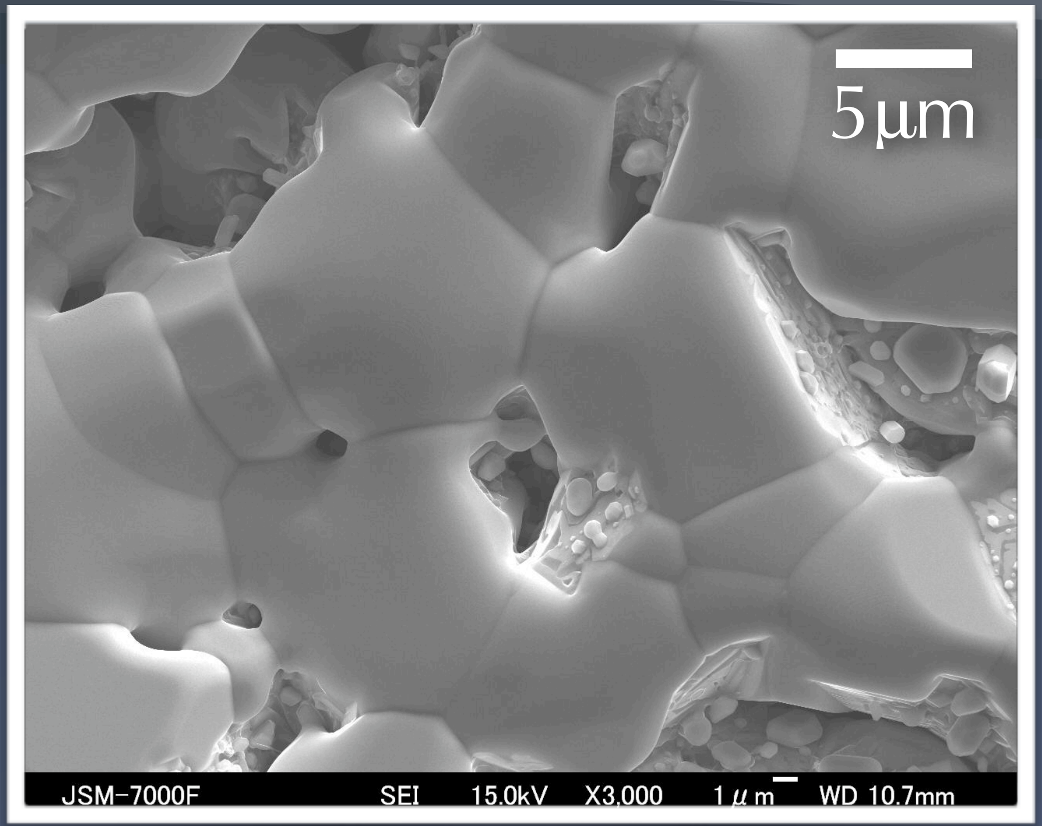


Growth of Metallic Iron

Fe metal @1600~1700K

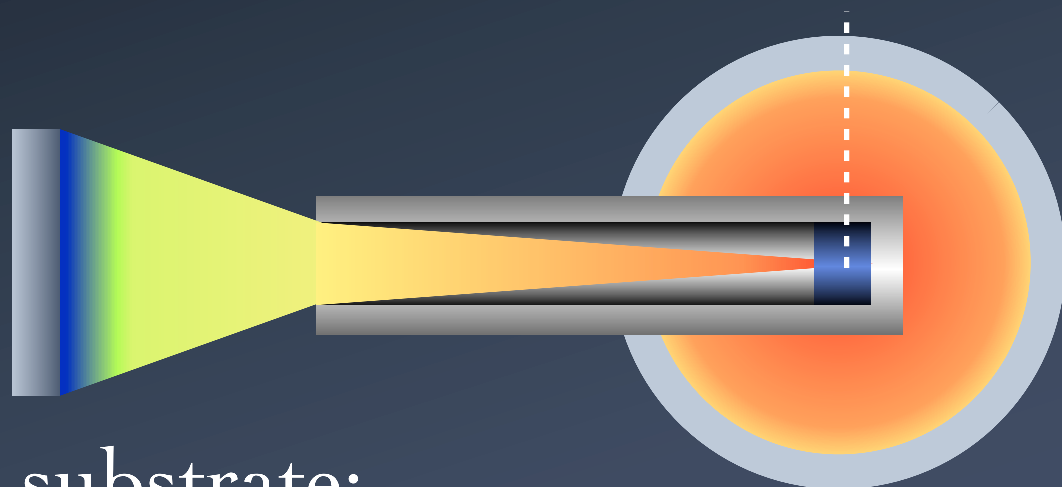


substrate:
Corundum@1215~1335K

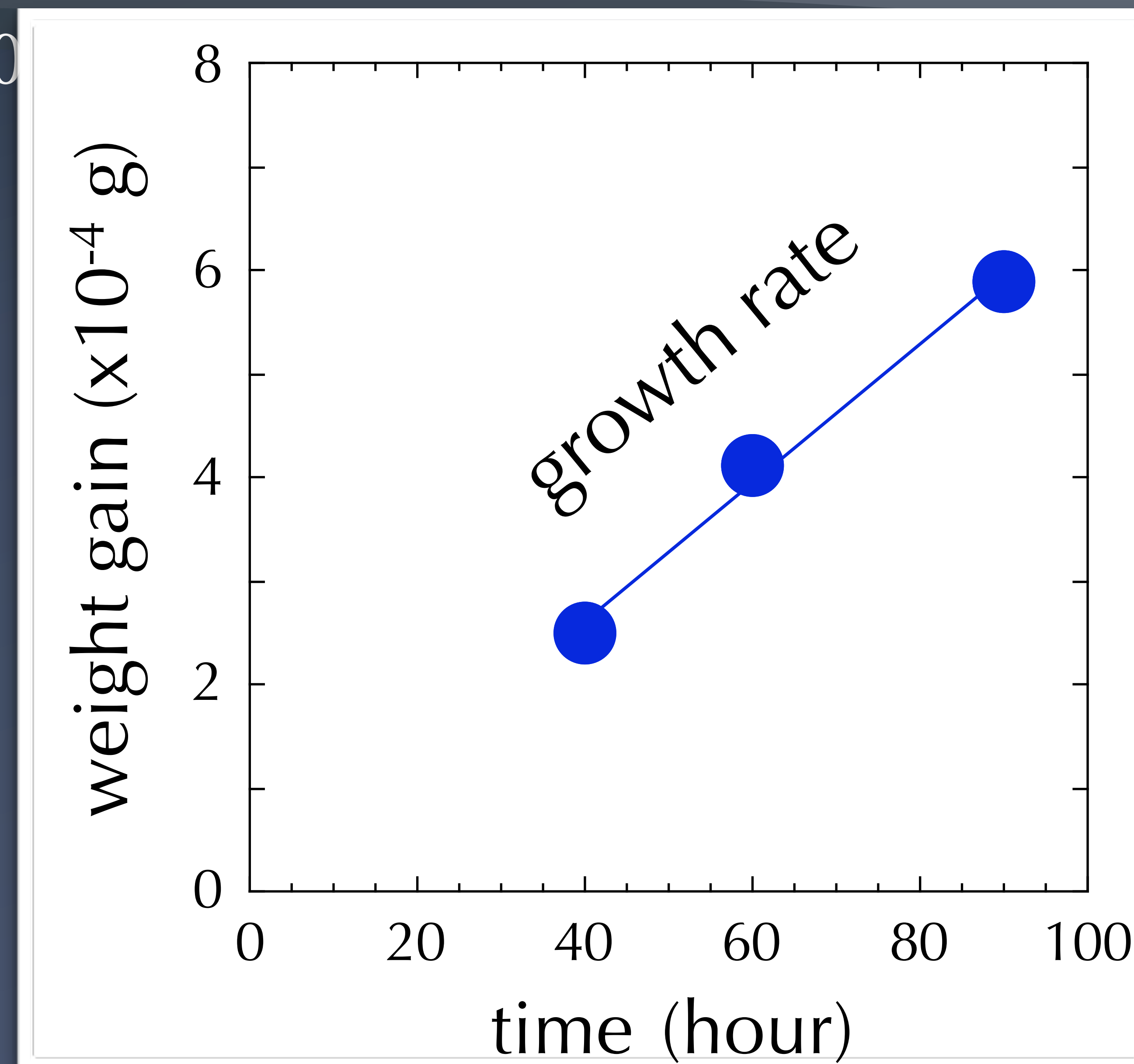


Growth of Metallic Iron

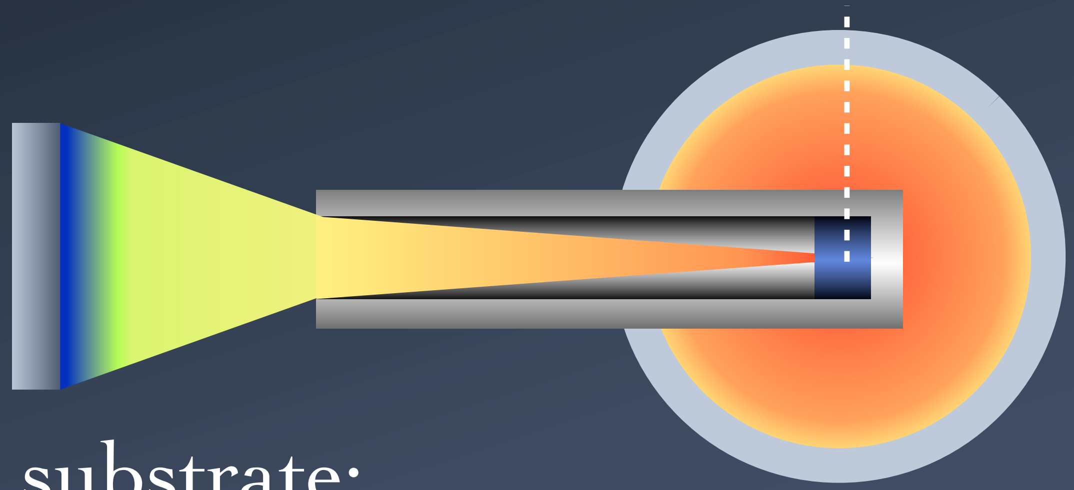
Fe metal @1600~1700

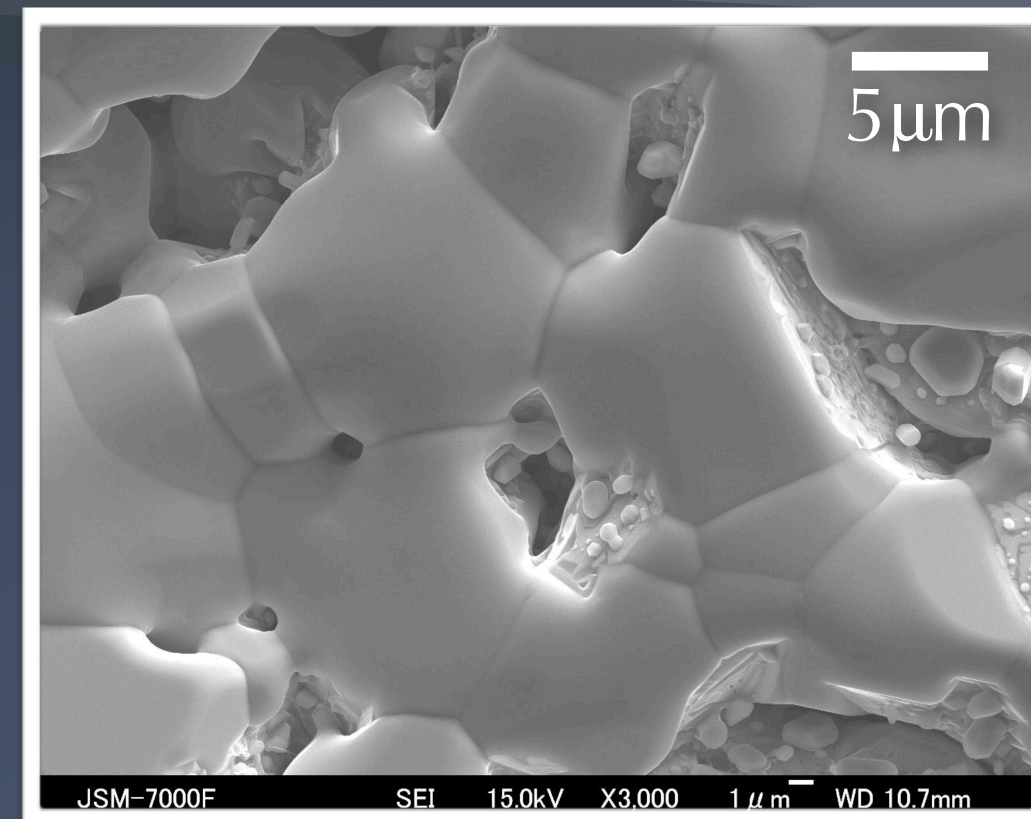


substrate:
Corundum@1235~1425K



Growth of Metallic Iron



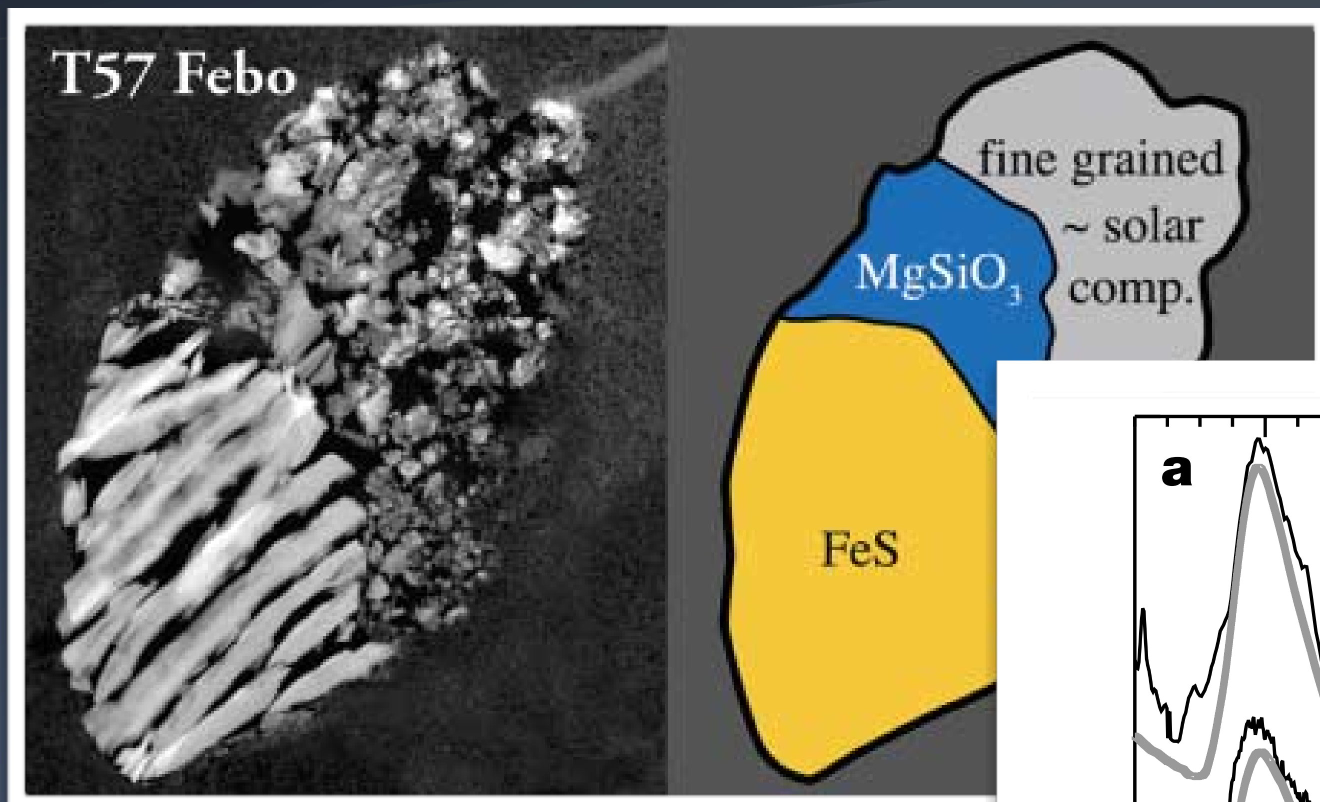


Condensation efficiency of Fe metal at 1235-1425 K:

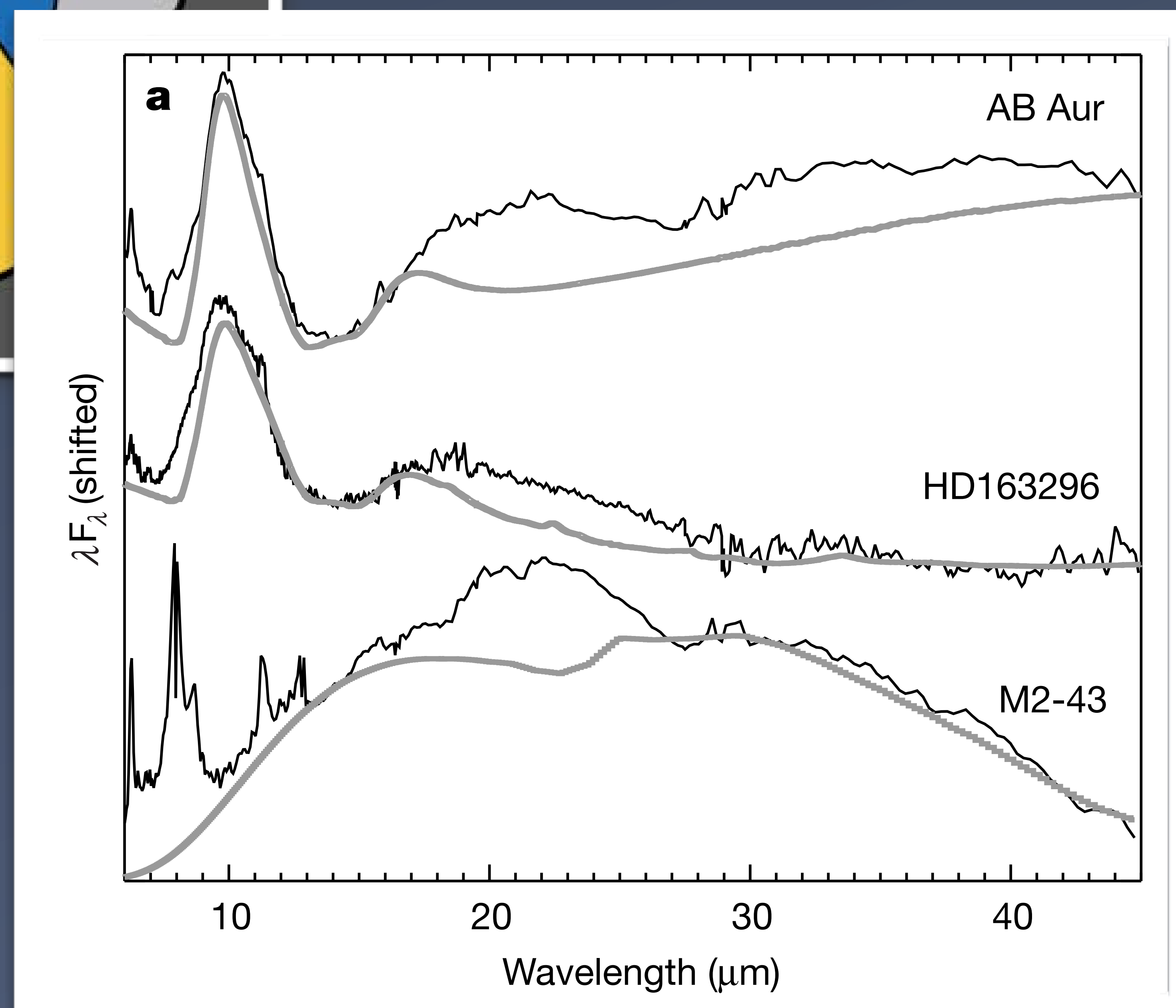
- **1** for highly supersaturated conditions
- **0.5** for supersaturation ratio of <10

Fe metal condenses easily on preexisting silicates/oxides

Formation of Iron Sulfide (FeS)



Cometary iron sulfide
(Brownlee+ 2006)

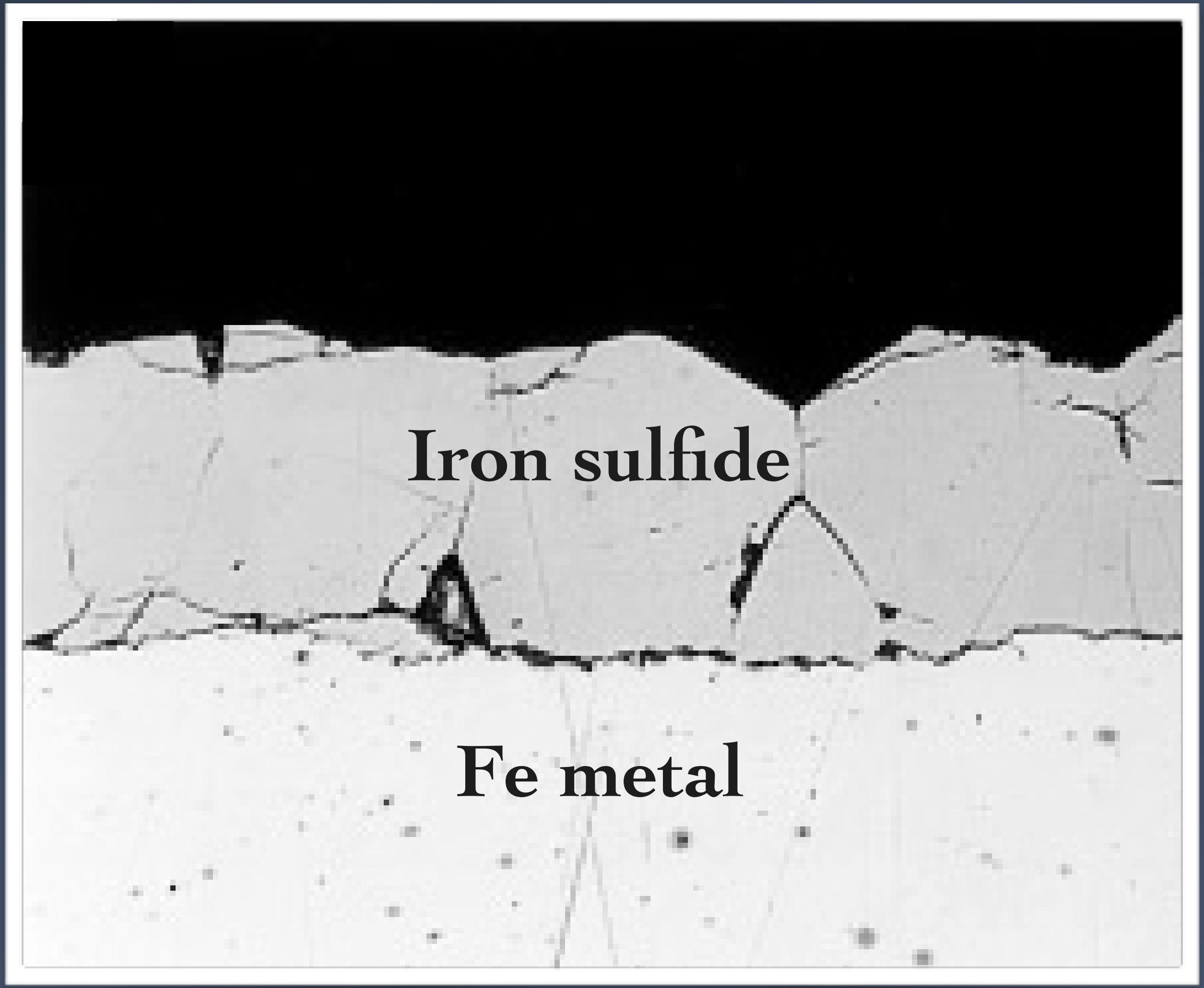


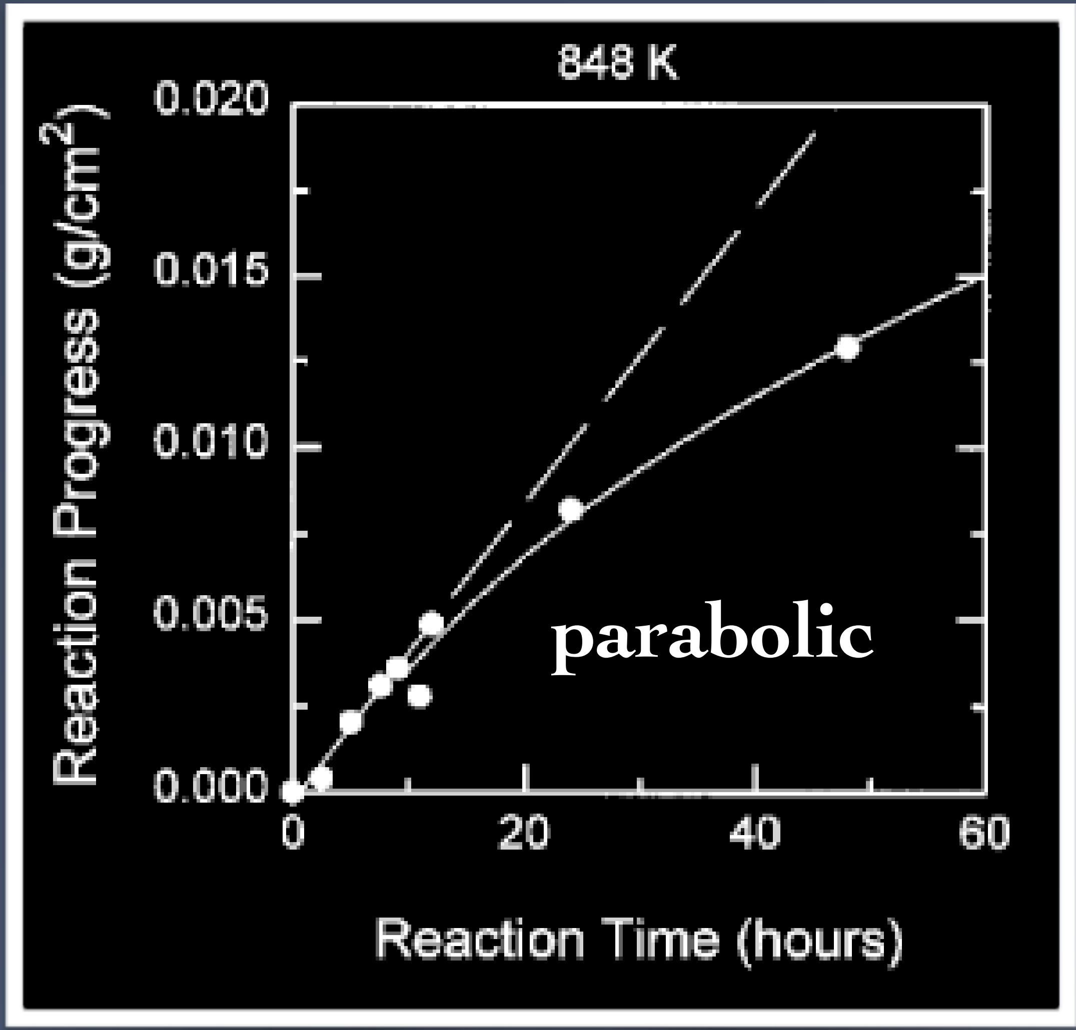
Iron sulfide in PP disk?
(Keller+ 2004)

Formation of Iron Sulfide (FeS)

Sulfidation experiments of metals at 1 atm

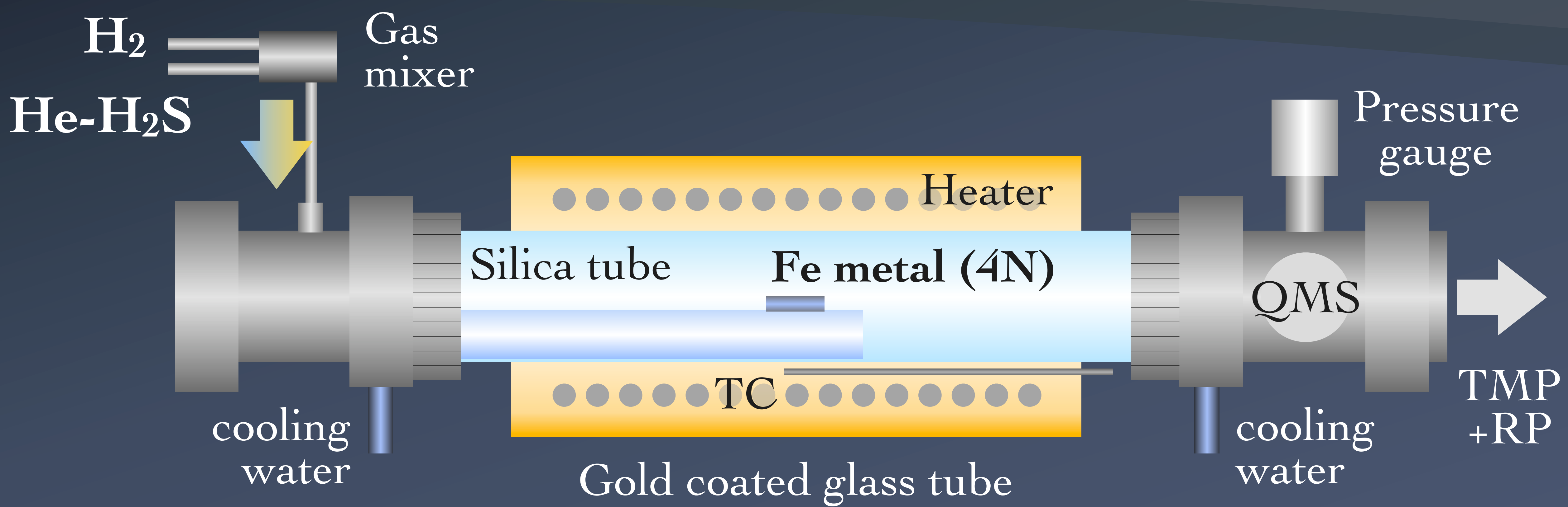
(Lauretta+ 1996; Lauretta 2005; Schrader & Lauretta 2010)



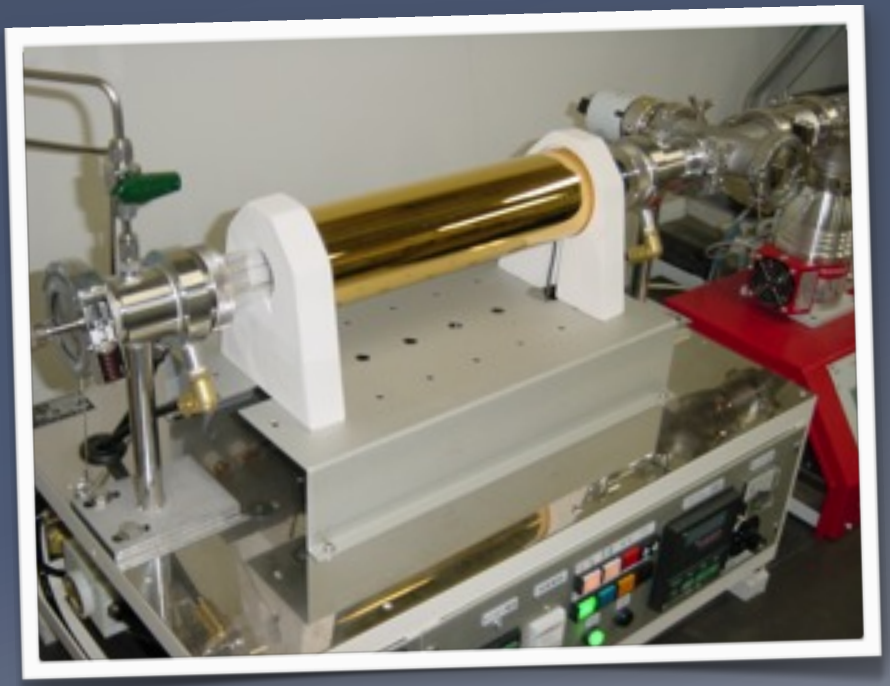


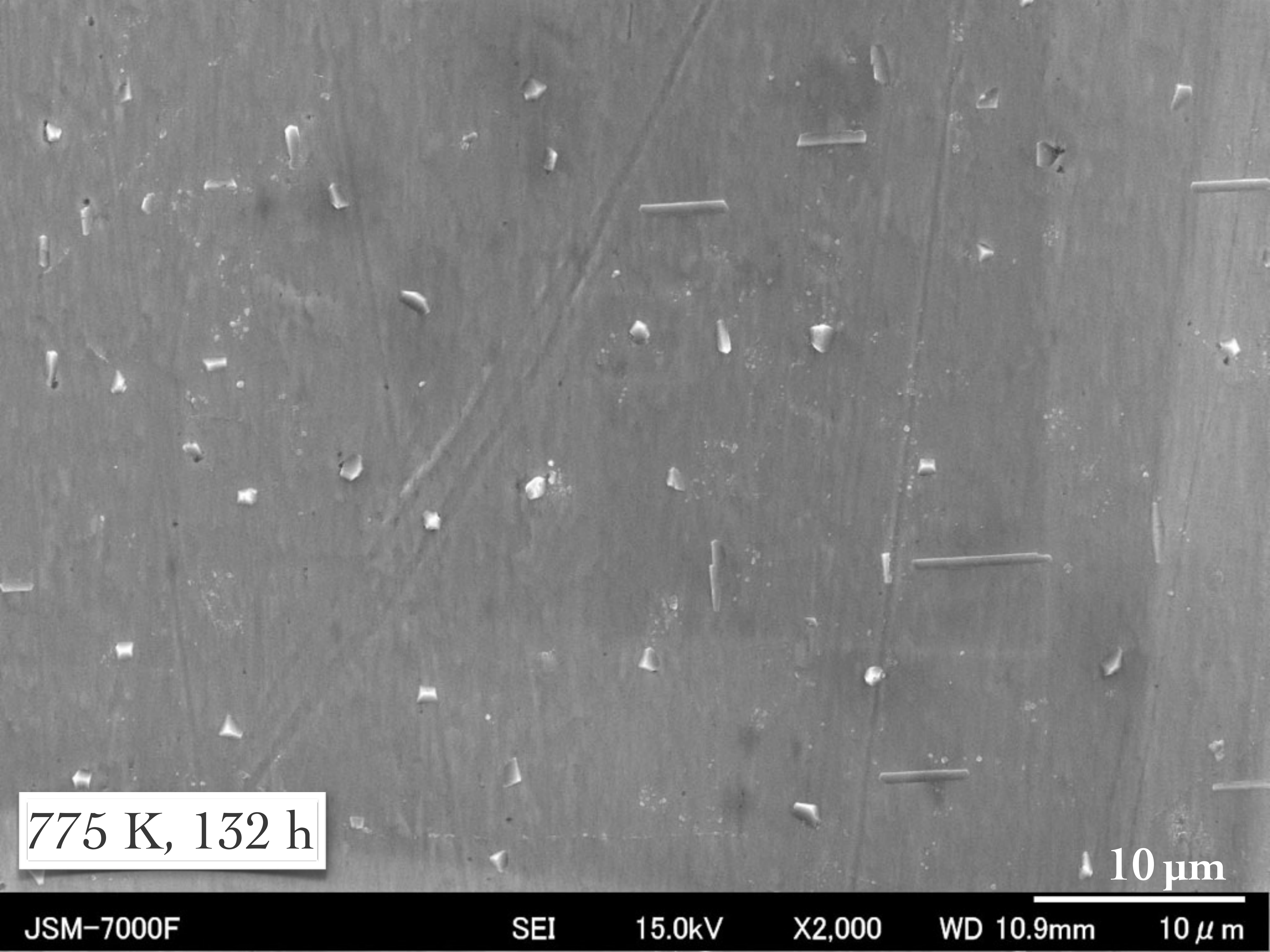
No kinetic data under low pressure conditions

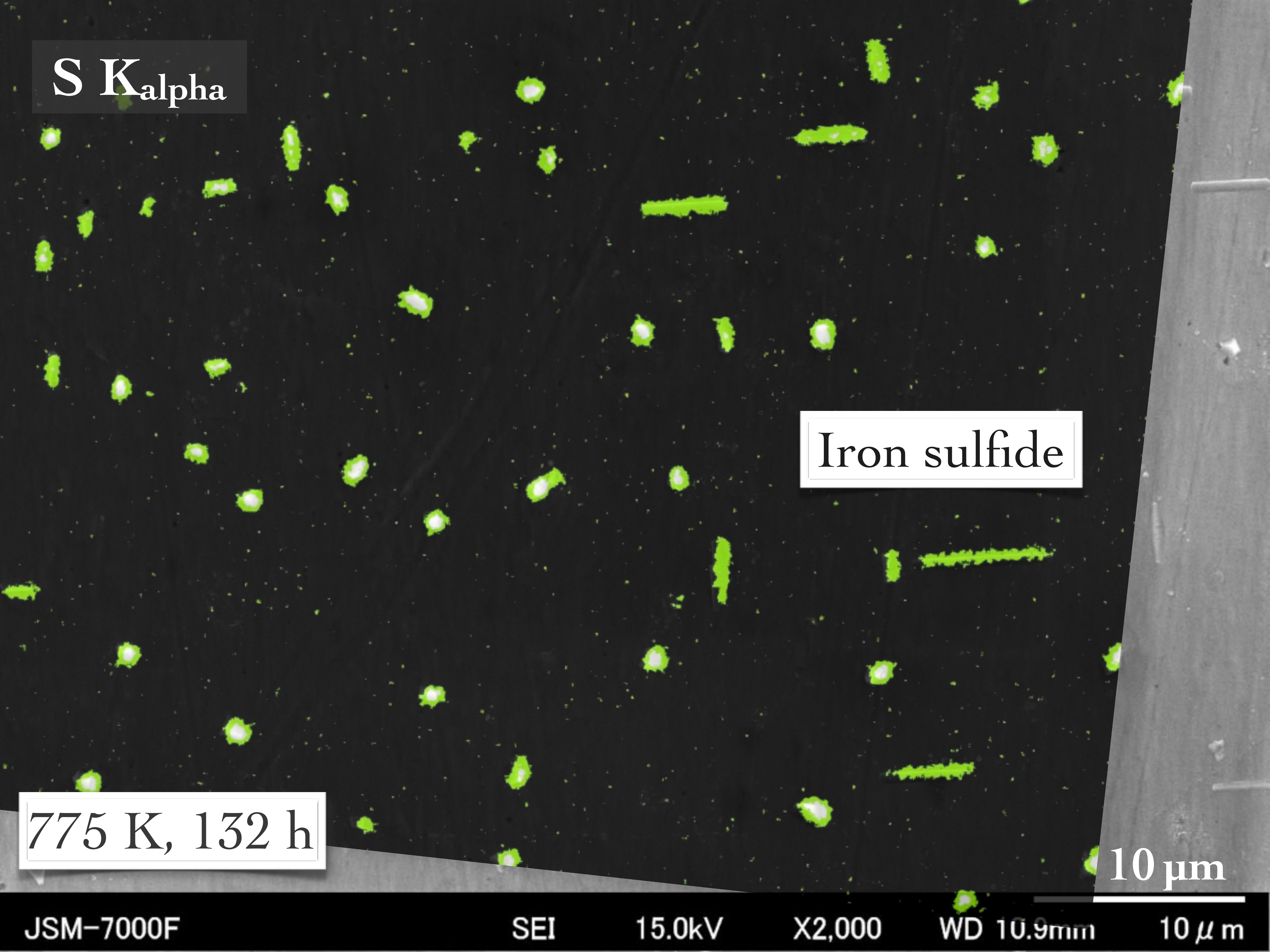
Suflidation Experiments of Metallic Iron



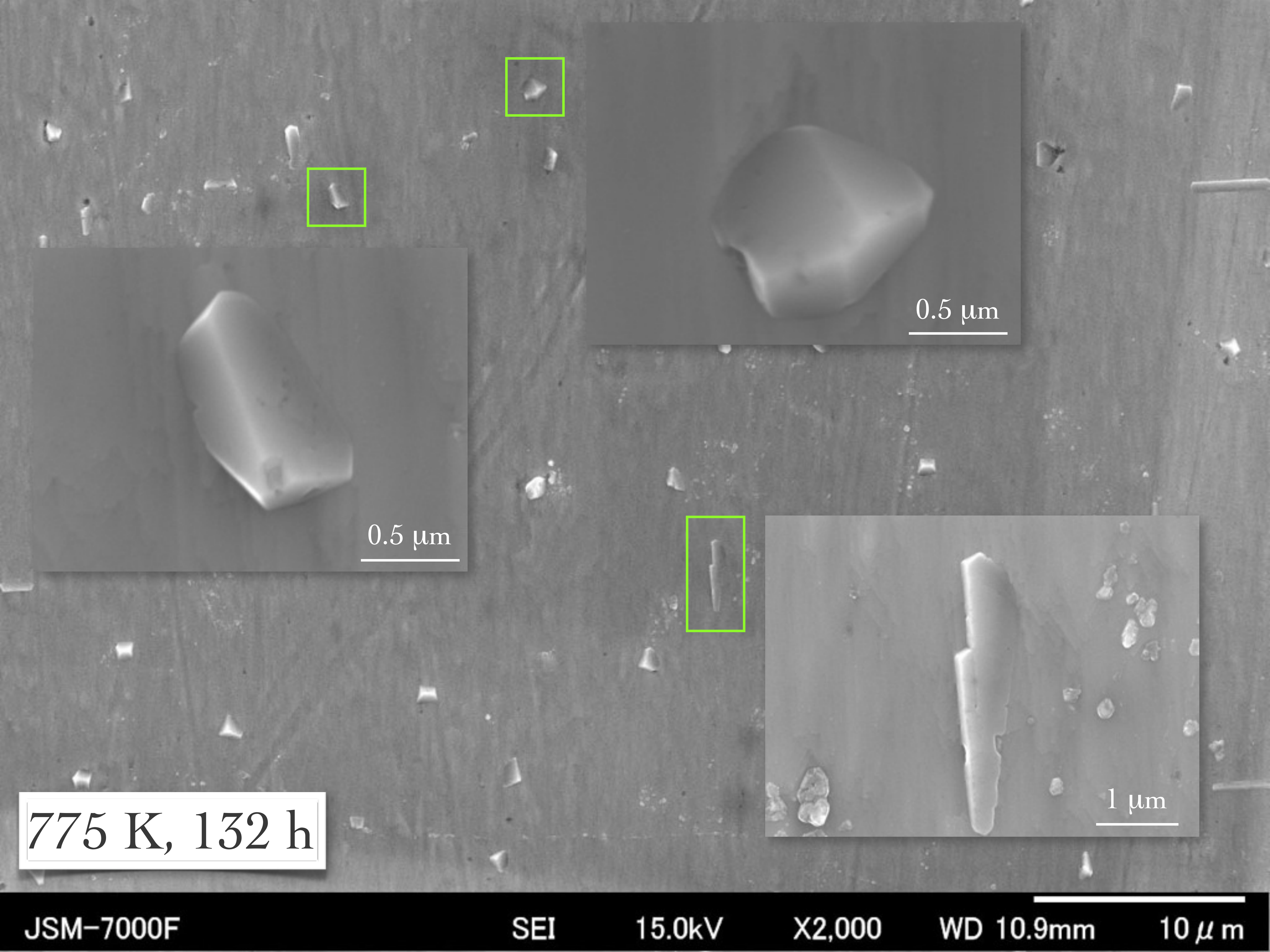
Temp.:	773, 803, 833 K
Pressure:	1 Pa
Gas:	He-H_2S (H_2S=160 ppm)
Duration:	6-132 hours



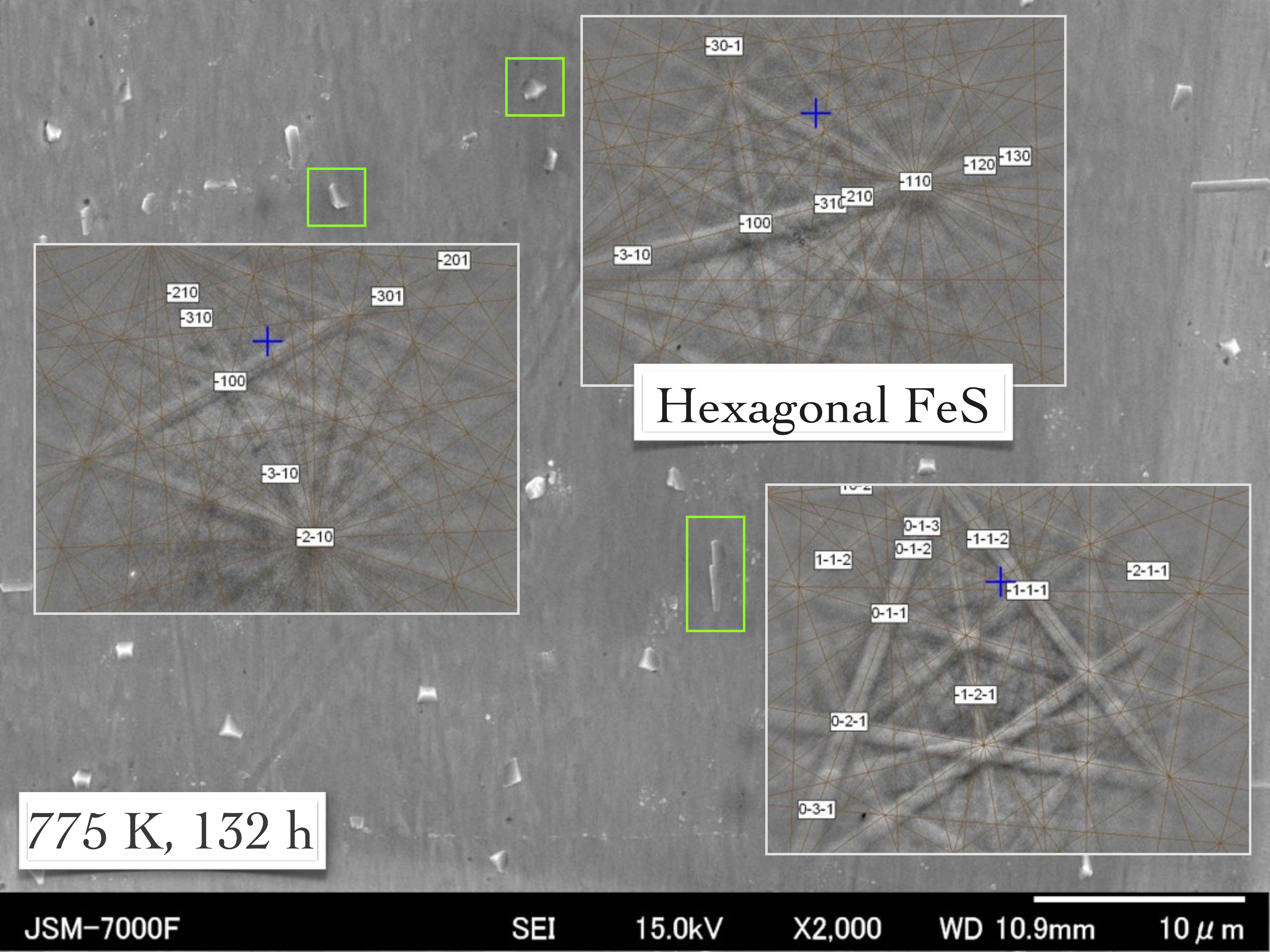

775 K, 132 h
10 μm
JSM-7000F
SEI
15.0kV
X2,000
WD 10.9mm
10 μm



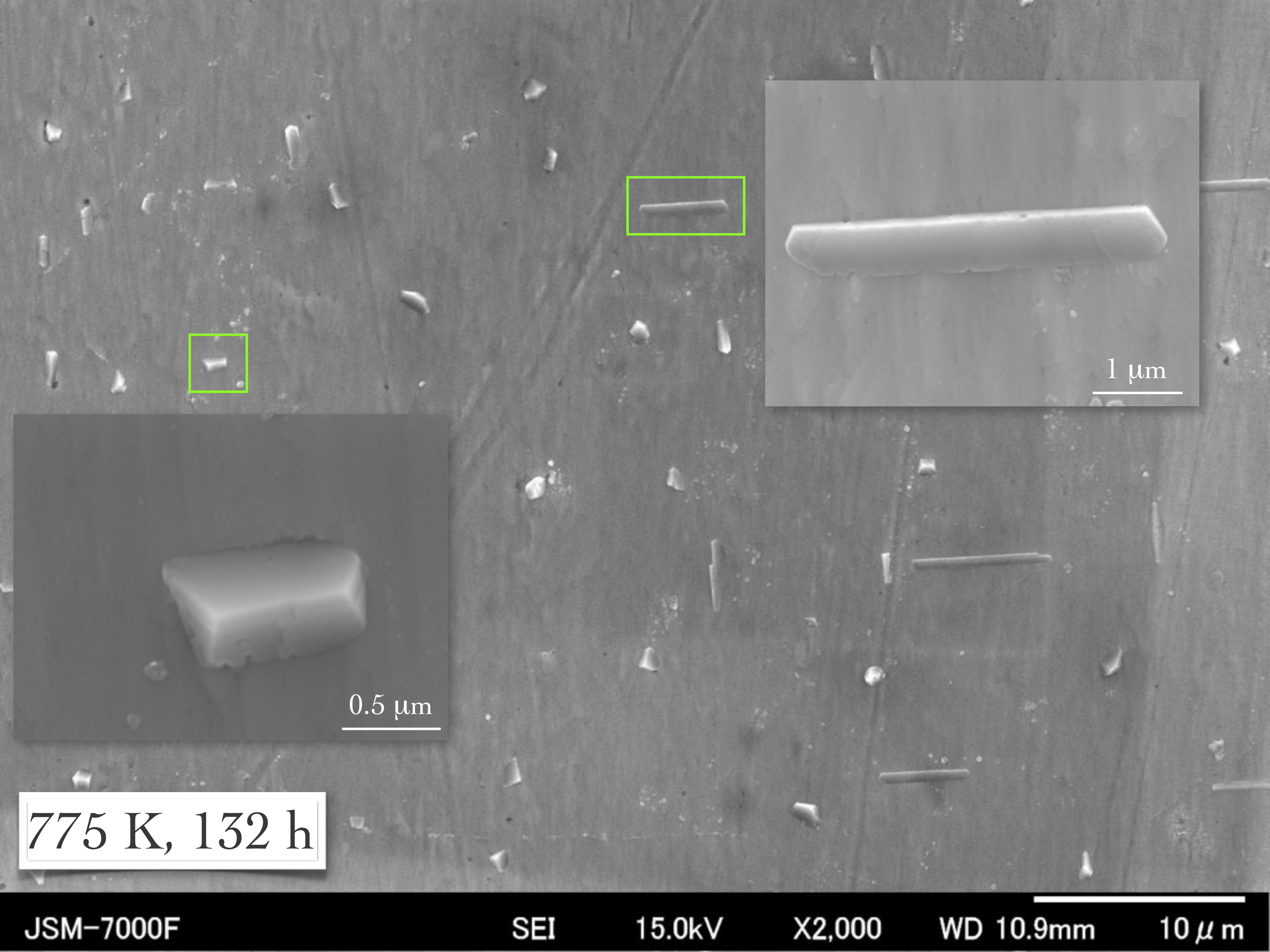
S Kalpha
Iron sulfide
775 K, 132 h
10 µm
JSM-7000F
SEI
15.0kV
X2,000
10 µ m

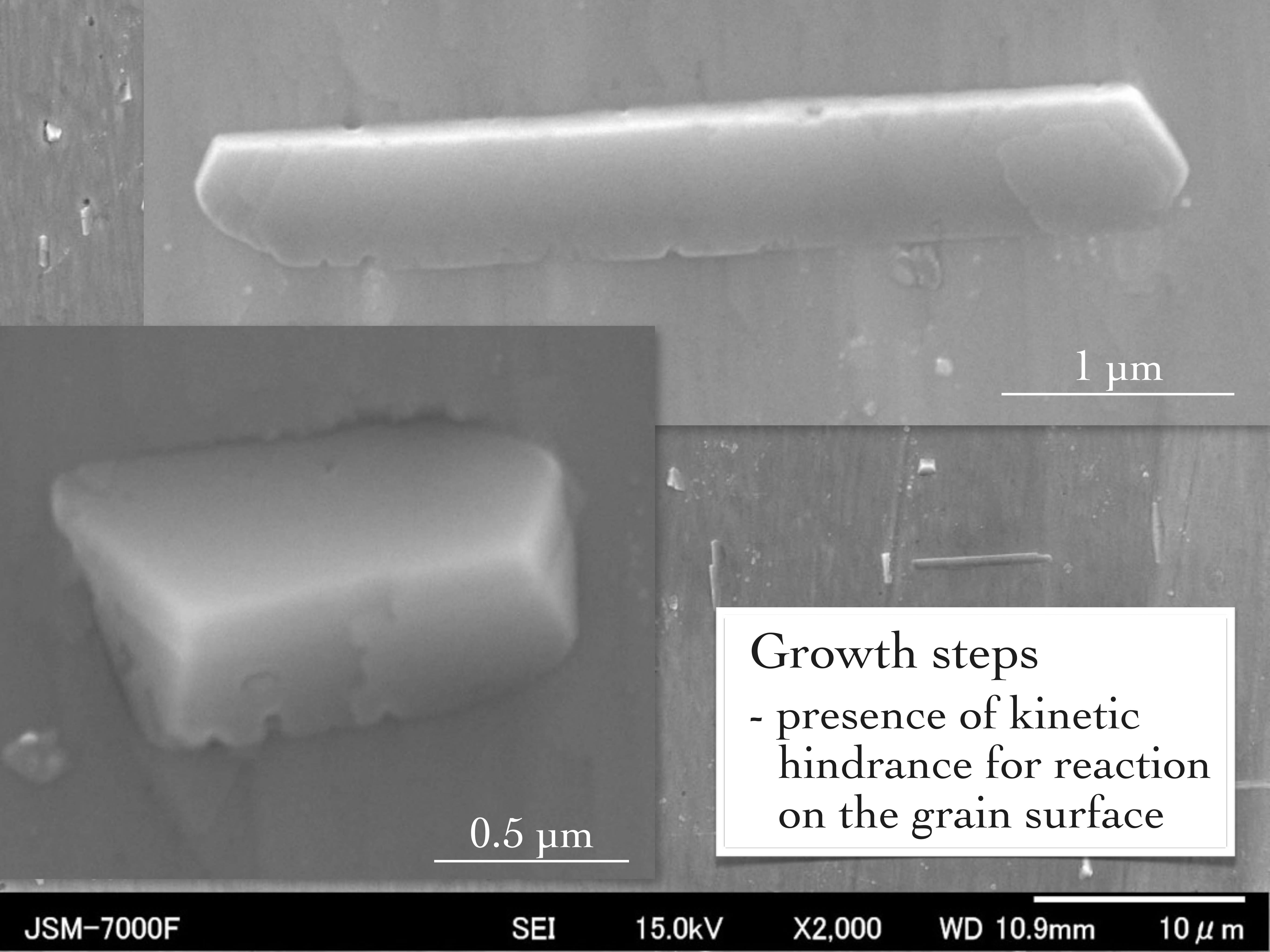


775 K, 132 h
0.5 μm
0.5 μm
1 μm
JSM-7000F
SEI
15.0kV
X2,000
WD 10.9mm
10 μm



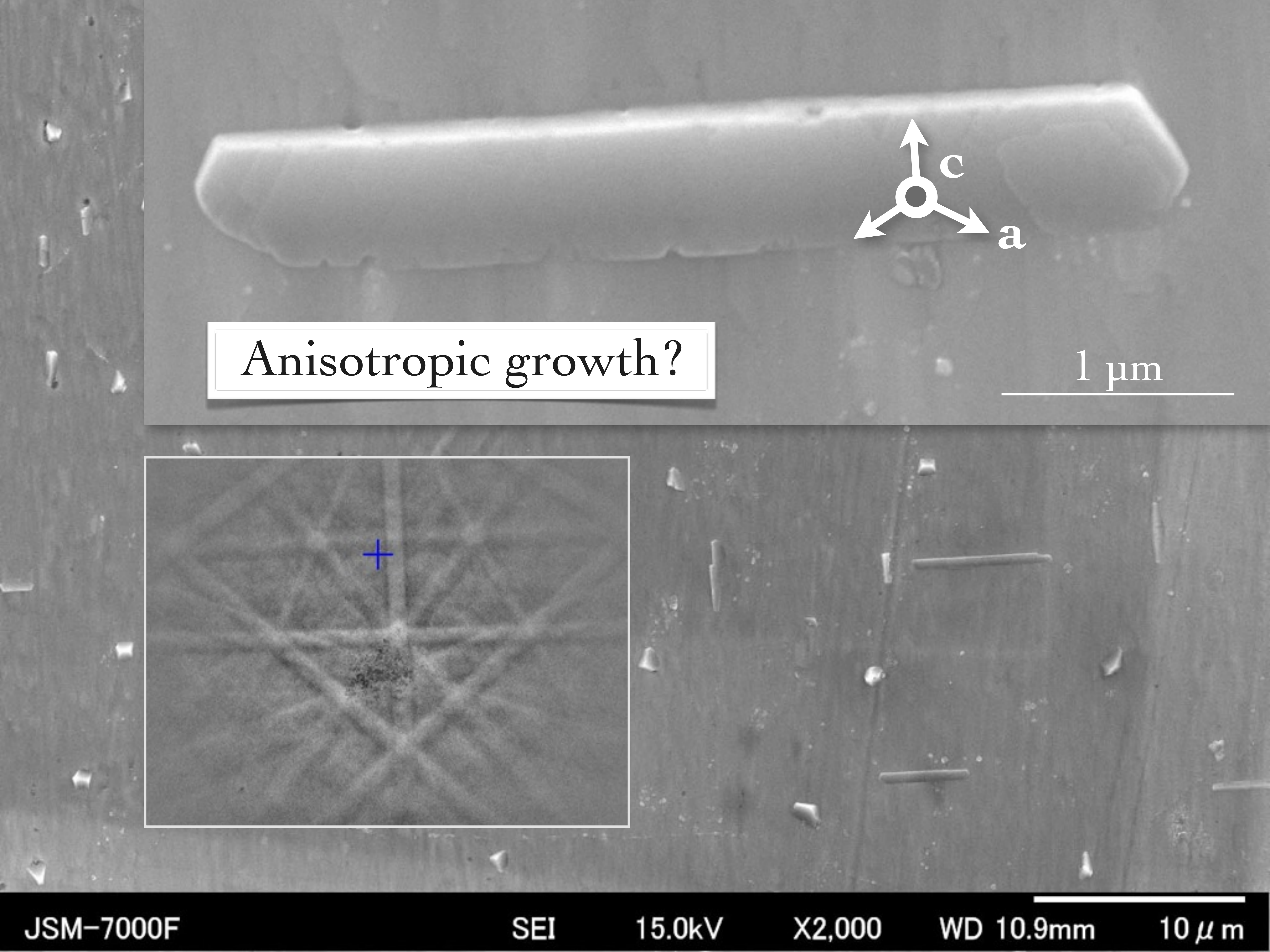
Hexagonal FeS
775 K, 132 h
-30-1
-130
-120
-110
-310
-210
-100
-3-10
-201
-210
-301
-310
-100
-3-10
-2-10
0-1-3
-1-1-2
0-1-2
1-1-2
-2-1-1
-1-1-1
0-1-1
-1-2-1
0-2-1
0-3-1
JSM-7000F
SEI
15.0kV
X2,000
WD 10.9mm
10 μm


1 μm
0.5 μm
775 K, 132 h
JSM-7000F
SEI
15.0kV
X2,000
WD 10.9mm
10 μm



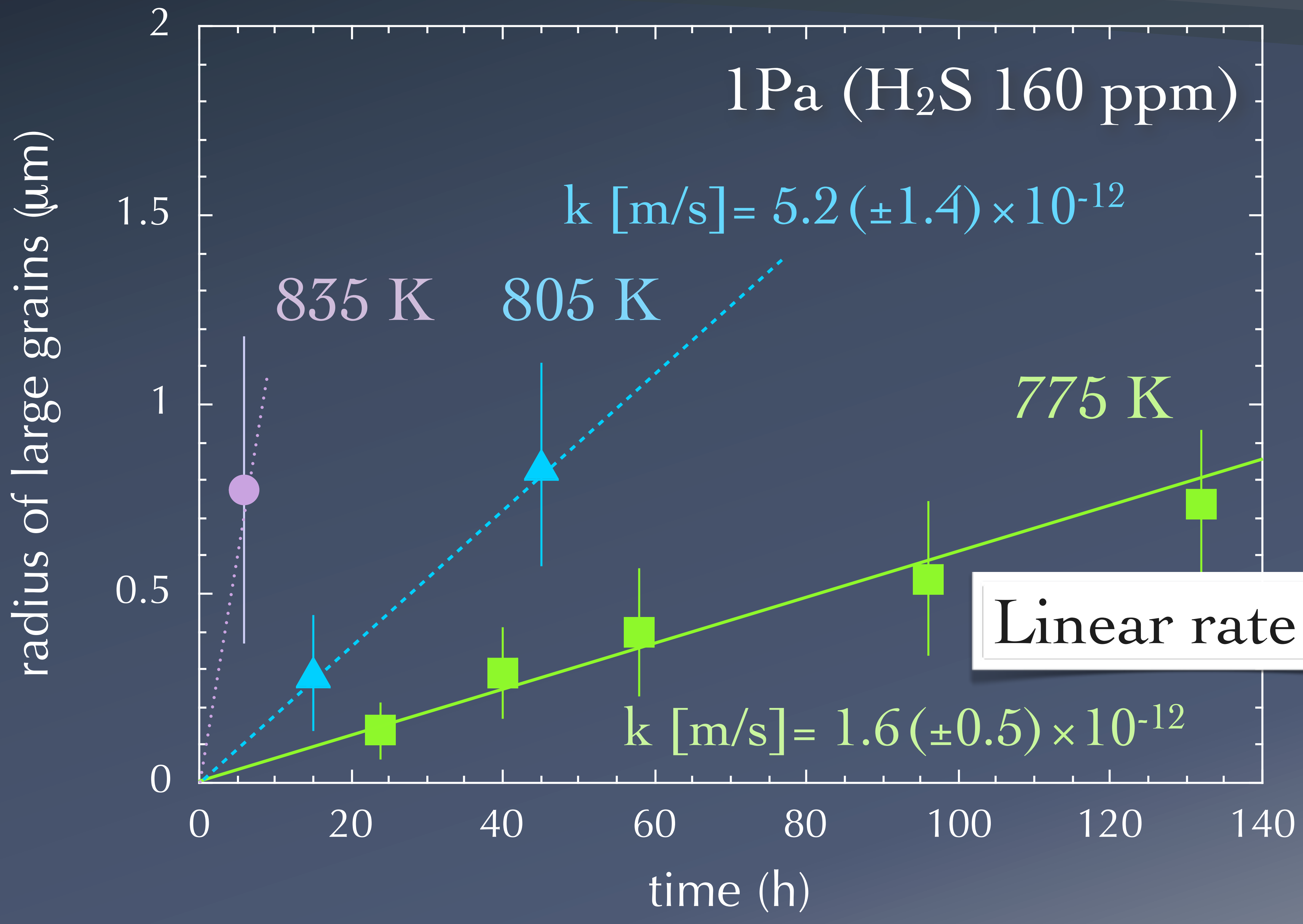
Growth steps

- presence of kinetic hindrance for reaction on the grain surface



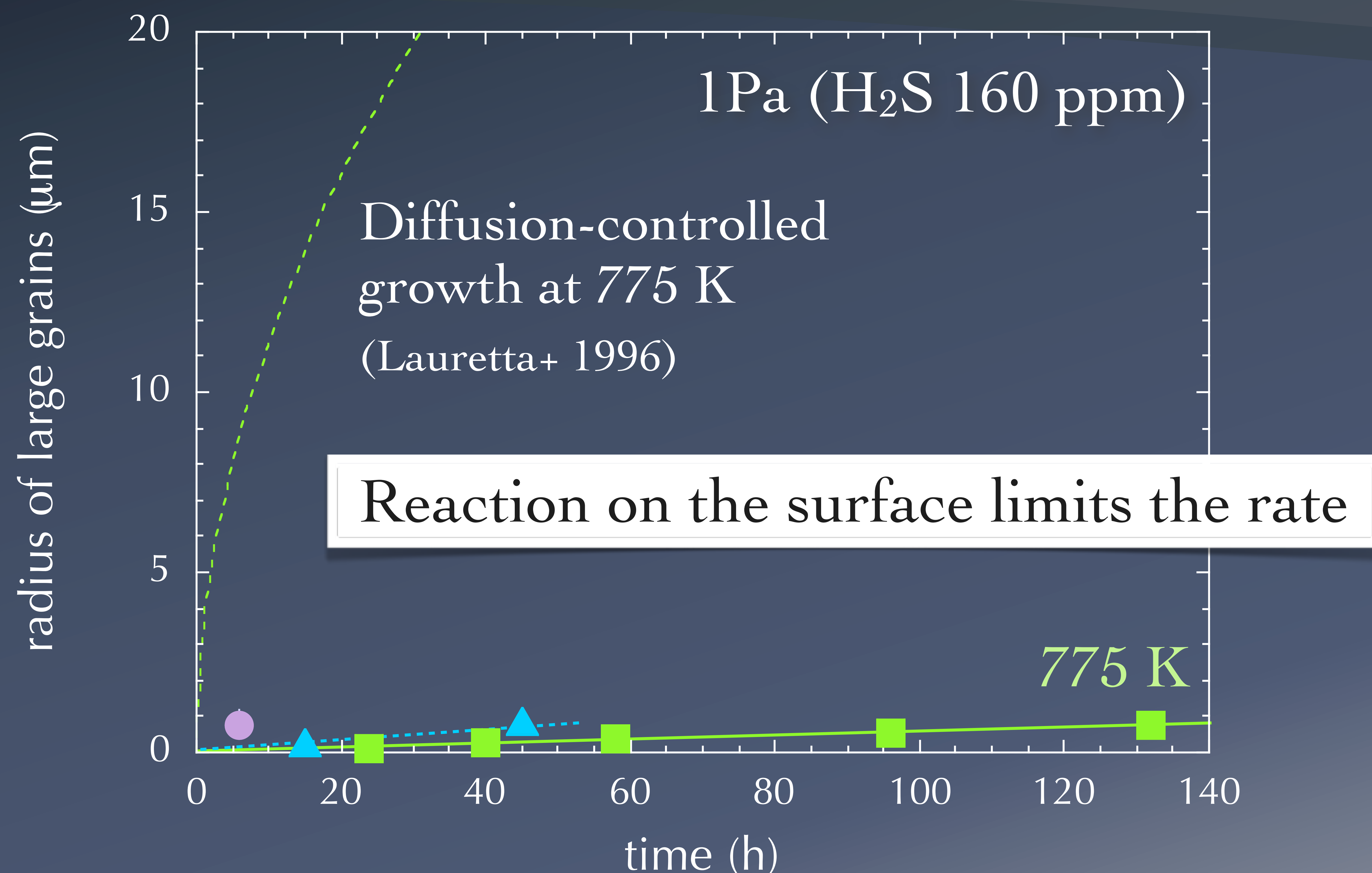
c
a
Anisotropic growth?
1 μm
JSM-7000F
SEI
15.0kV
X2,000
WD 10.9mm
10 μm

Change of Grain Size



Linear rate law

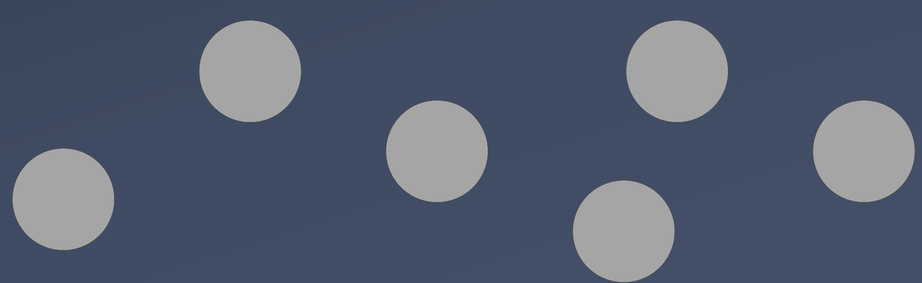
Comparison w/ Diffusion-controlled Rate



Nucleation vs. Growth

Nucleation rate “**>**” Growth rate

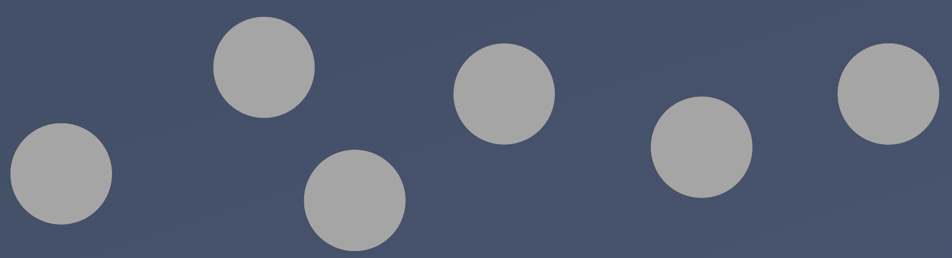
- Nucleation of FeS occurs on **all** grains



Uniform degree of sulfidation

Nucleation rate “**<**” Growth rate

- Nucleation of FeS occurs on **limited** grains



Various degree of sulfidation

Nucleation rate is also important!
($\sim 6 \times 10^{-7}$ [grains μm^{-2} s^{-1}] at 775K)

Outline

1. Importance of **Kinetics**
2. Condensation in the **Fe-S-H** system
3. Condensation in the **Mg-Si-O-H** system

Condensation in the System of Mg-Si-O-H

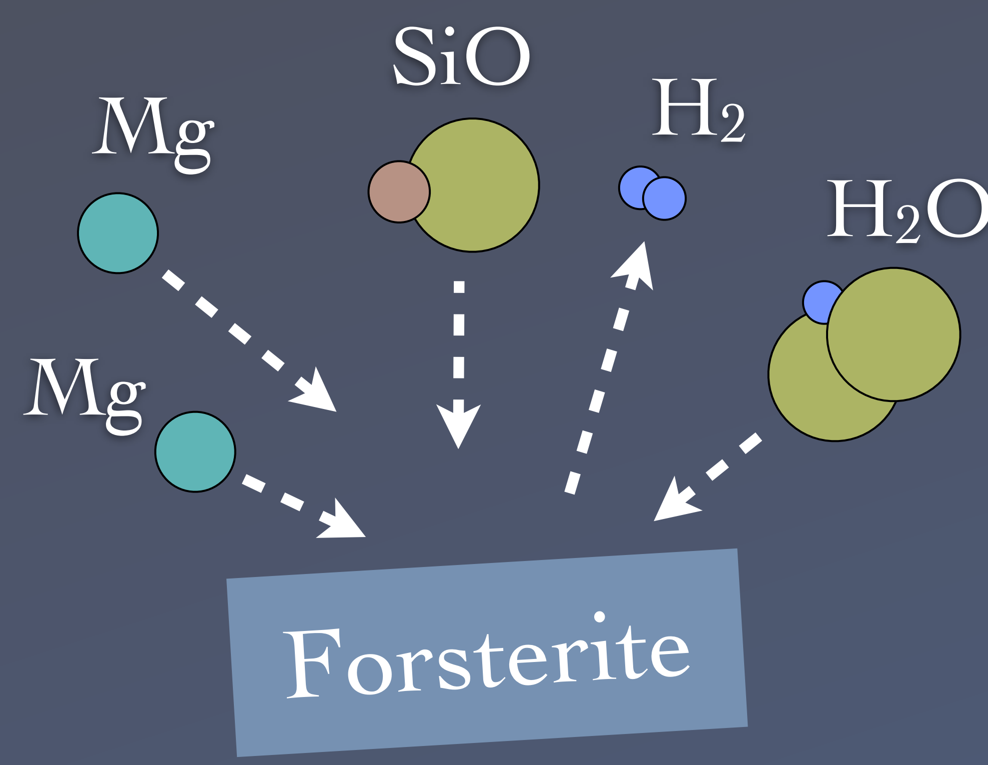
Smoke experiments:

various kinds of non-equilibrium condensates form

e.g., Day, 1979, 1981; Kato, 1976; Day & Donn, 1978; Nuth & Donn, 1982, 1983; Rietmeijer+, 1986, 1999, 2008; Nuth+, 1986, 2000, 2002; Colangeli+, 2002; Kaito+, 2003; Kamitsuji+, 2005; Sato+ 2006a, 2006b; Toppani+ 2006; Jäger+, Kaito+, Kumamoto+, this WS

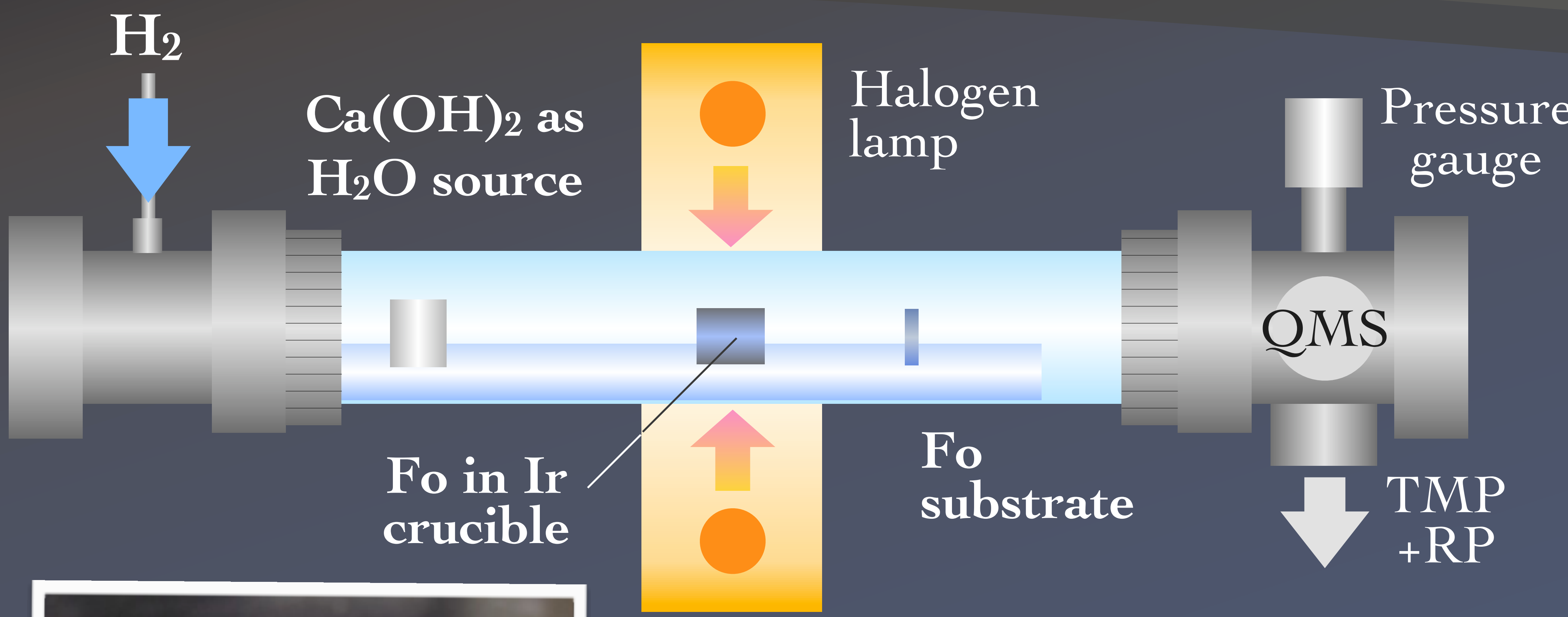
Important, but difficult to obtain kinetic data

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

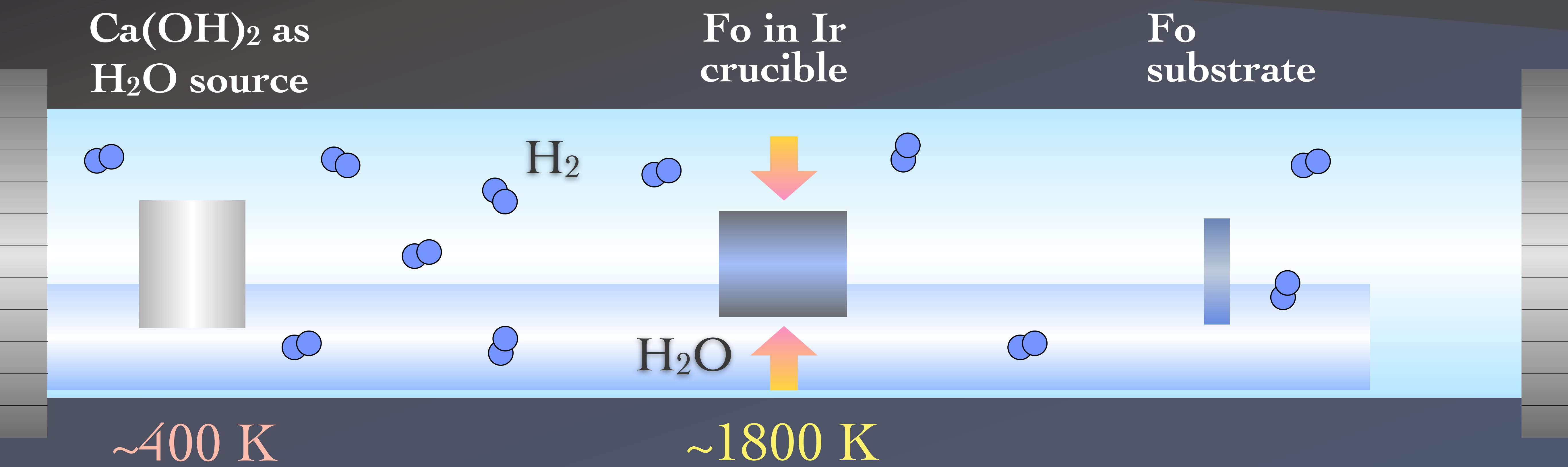


- Realistic conditions: pressure and gas chemistry
- Kinetic data

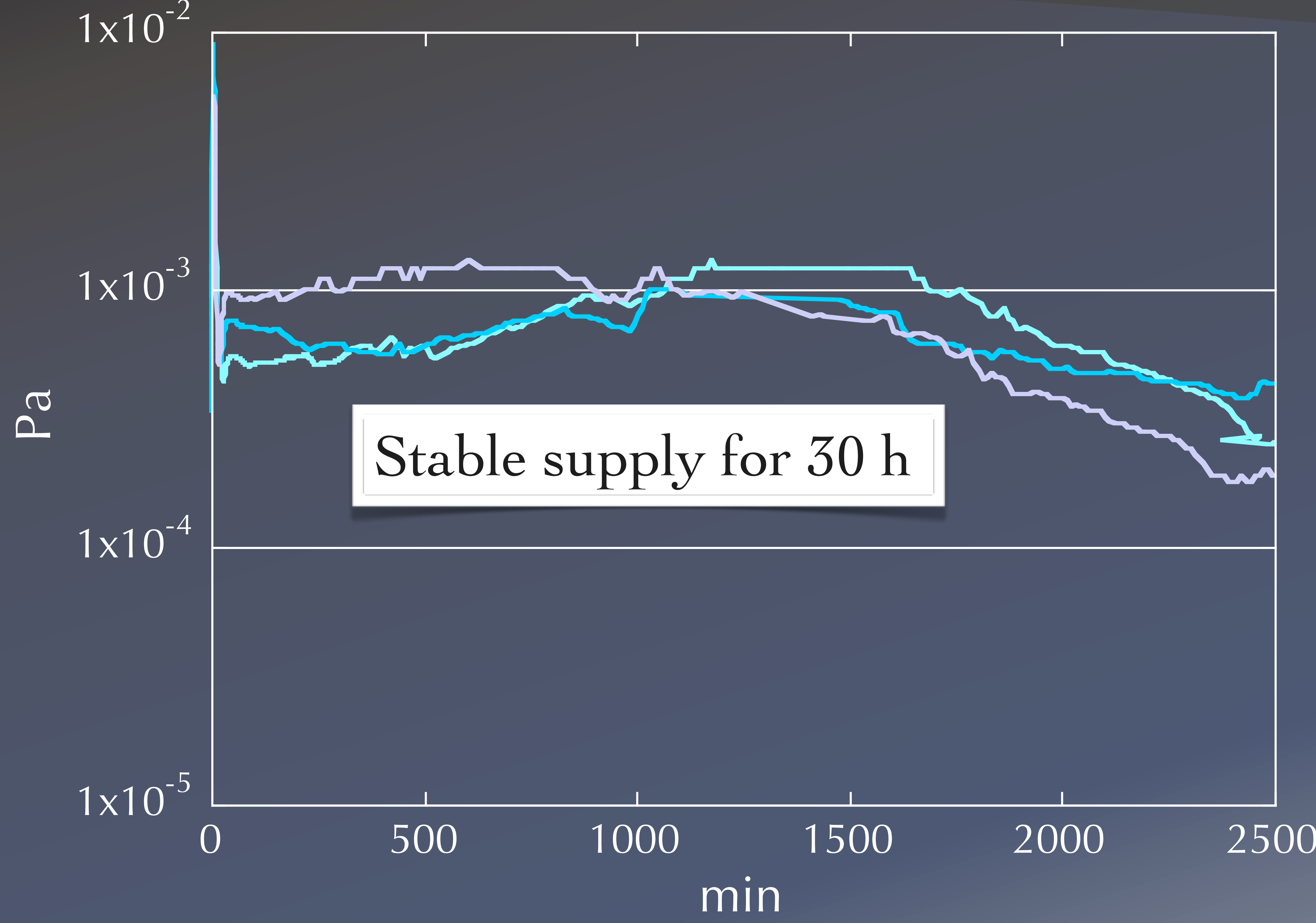
Condensation in the System of Mg-Si-O-H



Condensation in H_2-H_2O vapor



Supply of H_2O by Decomposition of $Ca(OH)_2$



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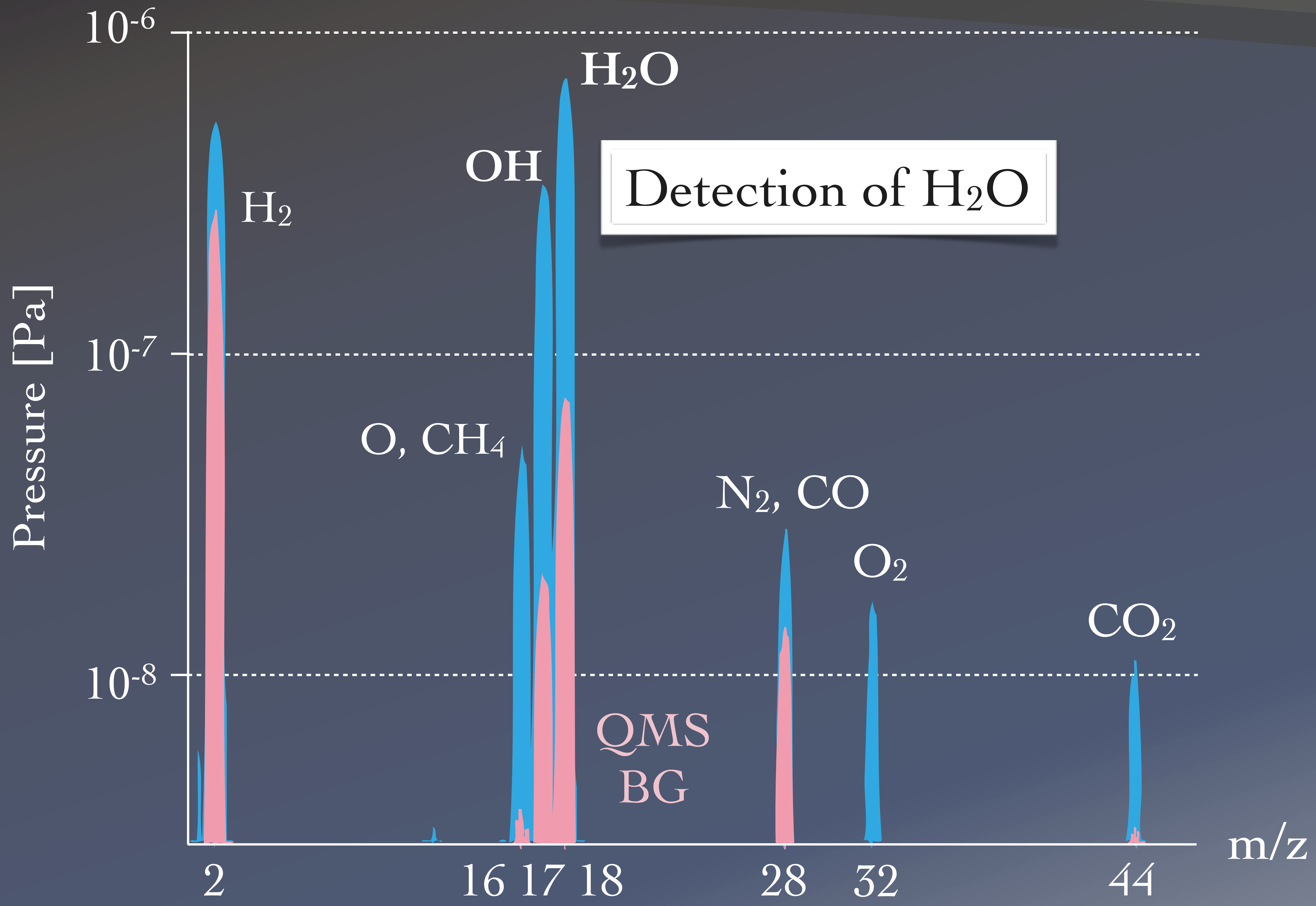


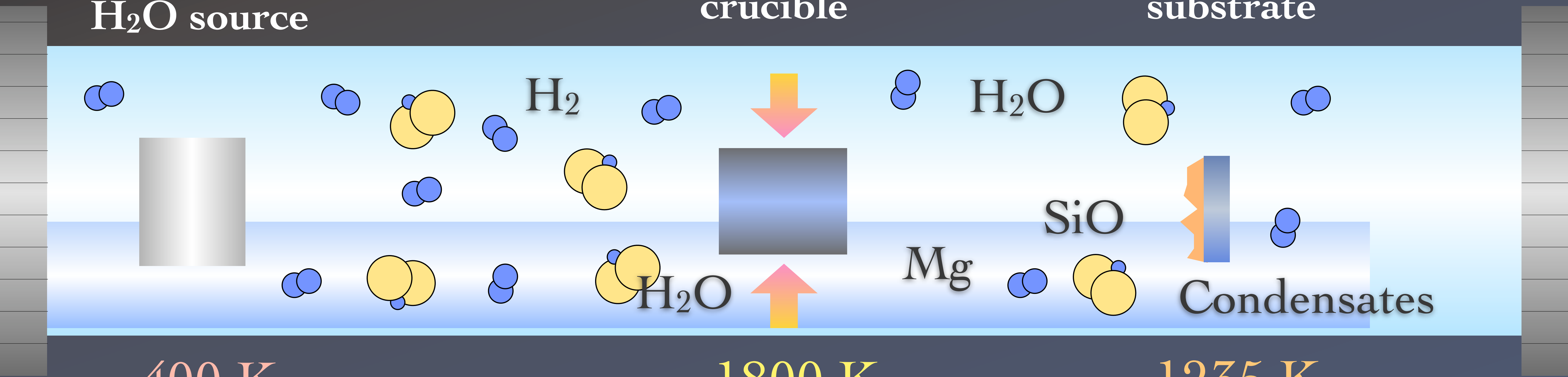
Detection of H_2O

Condensation in H_2-H_2O vapor

$Ca(OH)_2$ as H_2O source

Fo in Ir crucible

Fo substrate

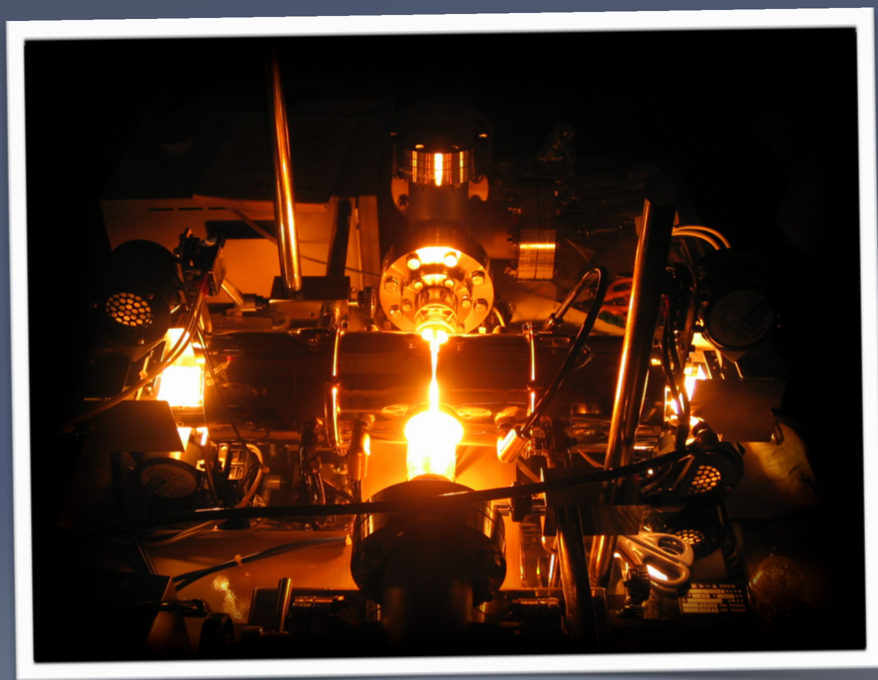


~400 K

~1800 K

1235 K

Pressure:	1 Pa
Gas:	H_2-H_2O (H_2O~0.003 Pa)
Duration:	12 hours



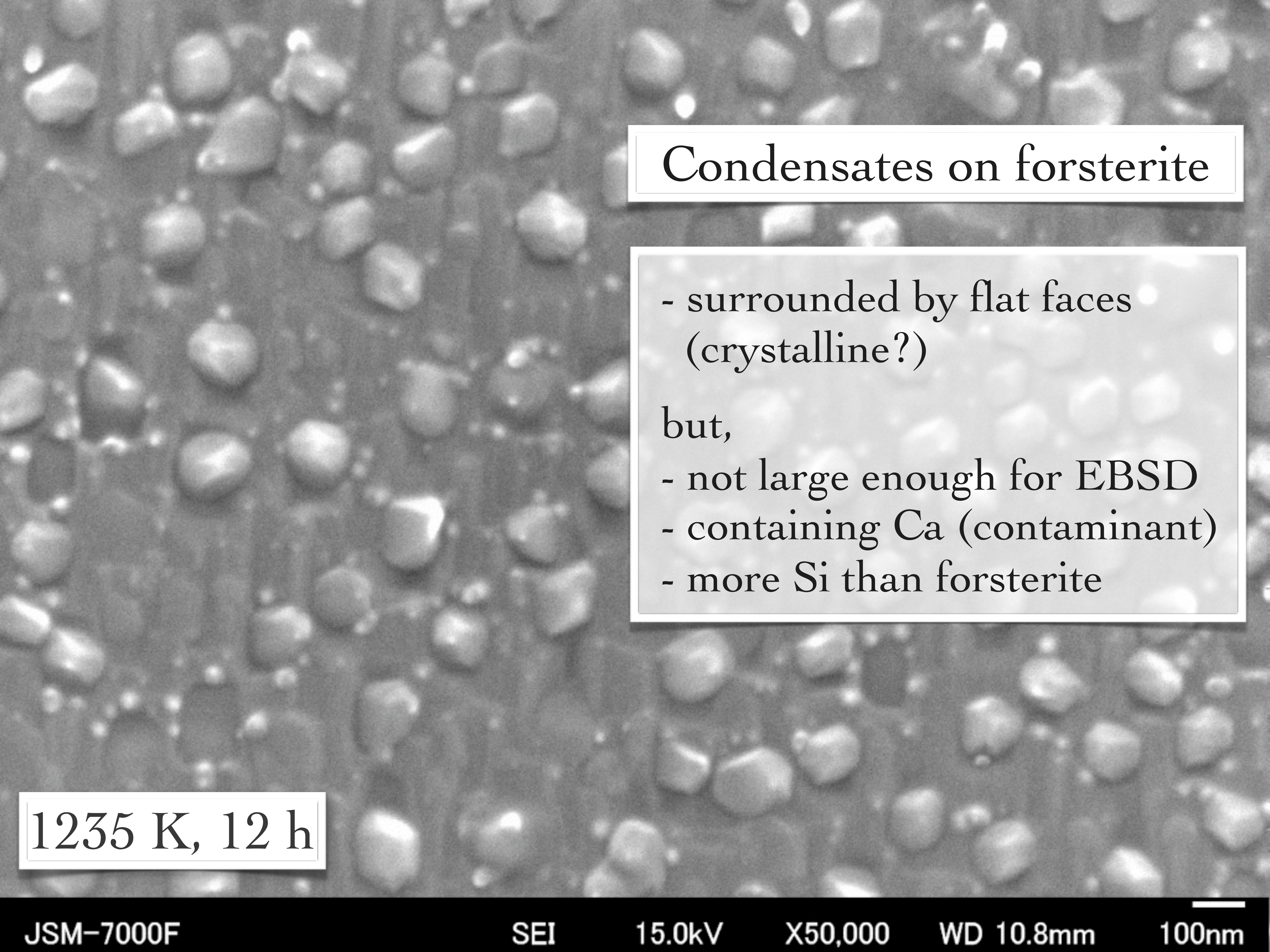
Condensates on forsterite

- surrounded by flat faces (crystalline?)

but,

- not large enough for EBSD
- containing Ca (contaminant)
- more Si than forsterite

1235 K, 12 h



Summary

1. **Kinetics** of dust formation
   – Crucial for understanding of dust evolution

2. Condensation in the **Fe-S-H** system
   – FeS formation under low pressure conditions
   – Surface-reaction controlled rate

3. Condensation in the **Mg-Si-O-H** system
   – Development of experimental setup for condensation in H_2-H_2O gas
   – Experiments are now being in progress