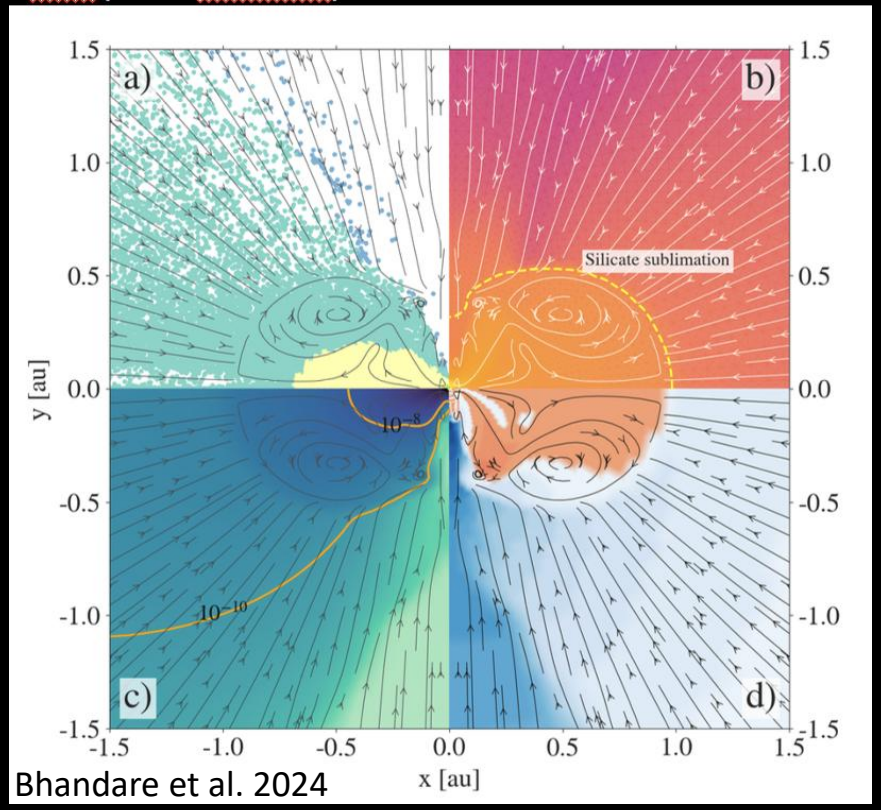
Out of equilibrium condensation processes
In the Solar Nebula: from thermodynamics to MHD simulations



Bhandare et al. 2024

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Primitive meteorites (chondrites) are divided in 3 « broad » classes

Enstatite C.

Ordinary C.

Carbonaceous C.

Iron oxidation level

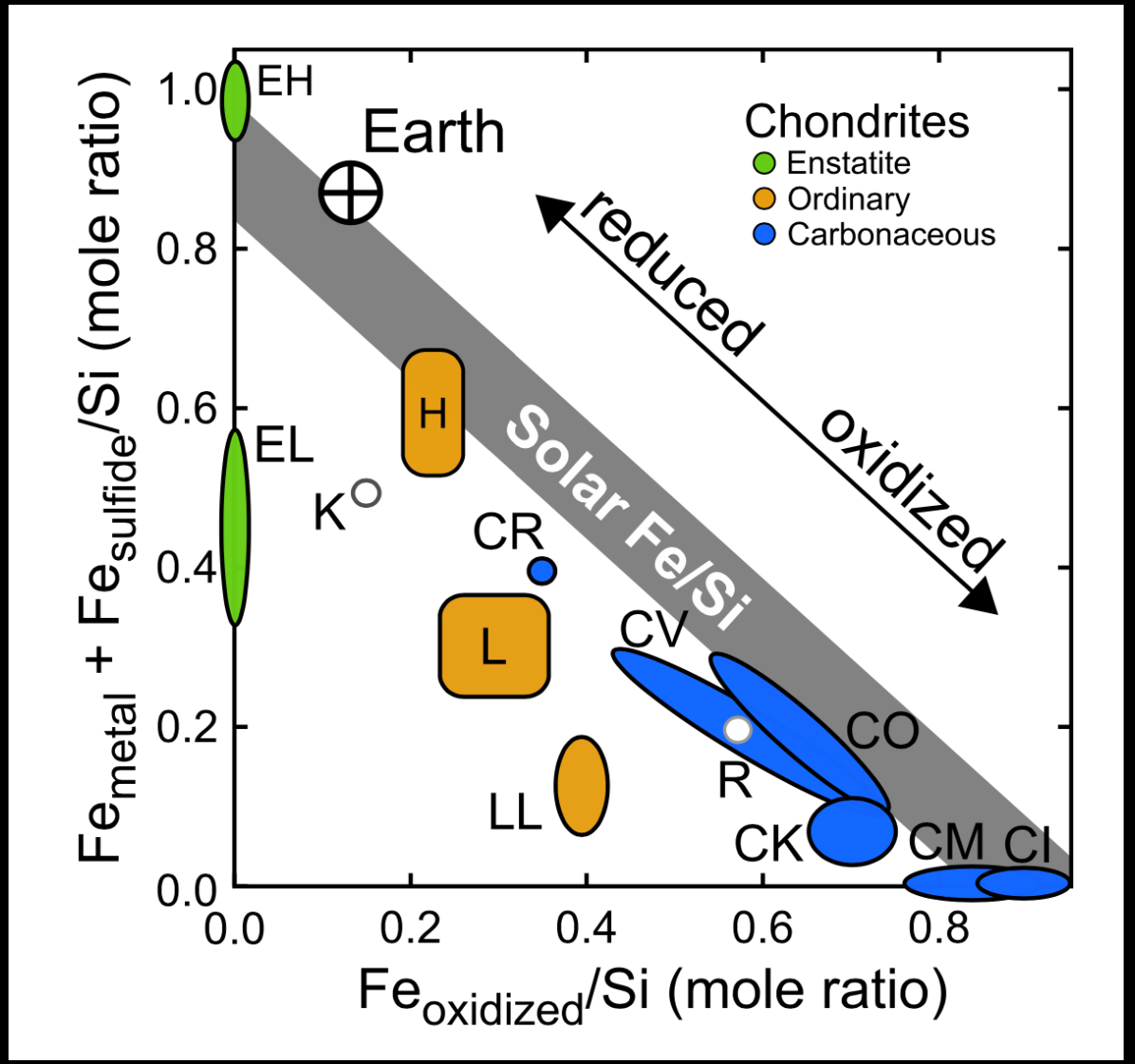
Enstatite

Olivine (Forst., Faya)

Refractory atoms + CAIs

The Urey-Craig Diagram (1953) : a proxy for the oxidation state of chondrites

Fe without O



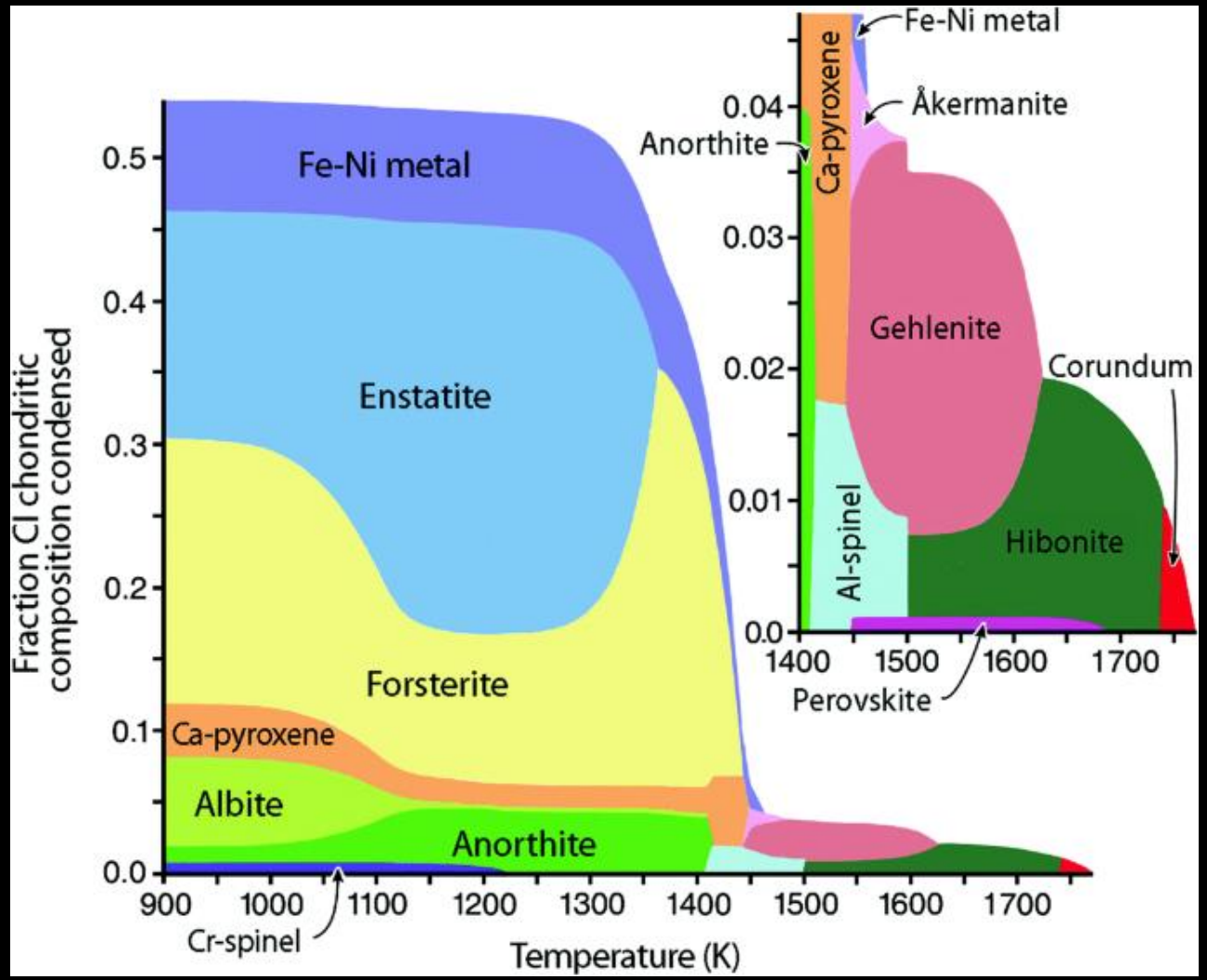
(Urey & Craig, 1953)
adapted from
Yoshizaki et al. (2021)

Fe with O

- Discontinuous mineralogies

The « Equilibrium Condensation Sequence »

Grossman 1972, and many others… Woitke et al., 2016, Ebel et al., 2023



Gas of Solar composition

Minimization of Gibbs free energy =>

Chemical equilibrium=>
« most stable minerals »

⇒ NON –EQUILIBRIUM MUST BE INTRODUCED =>
⇒ Fractionated condensation , isolation factor
⇒ (Work of Petaev)

=> Importance of secondary processes.

Woitke et al., 2017

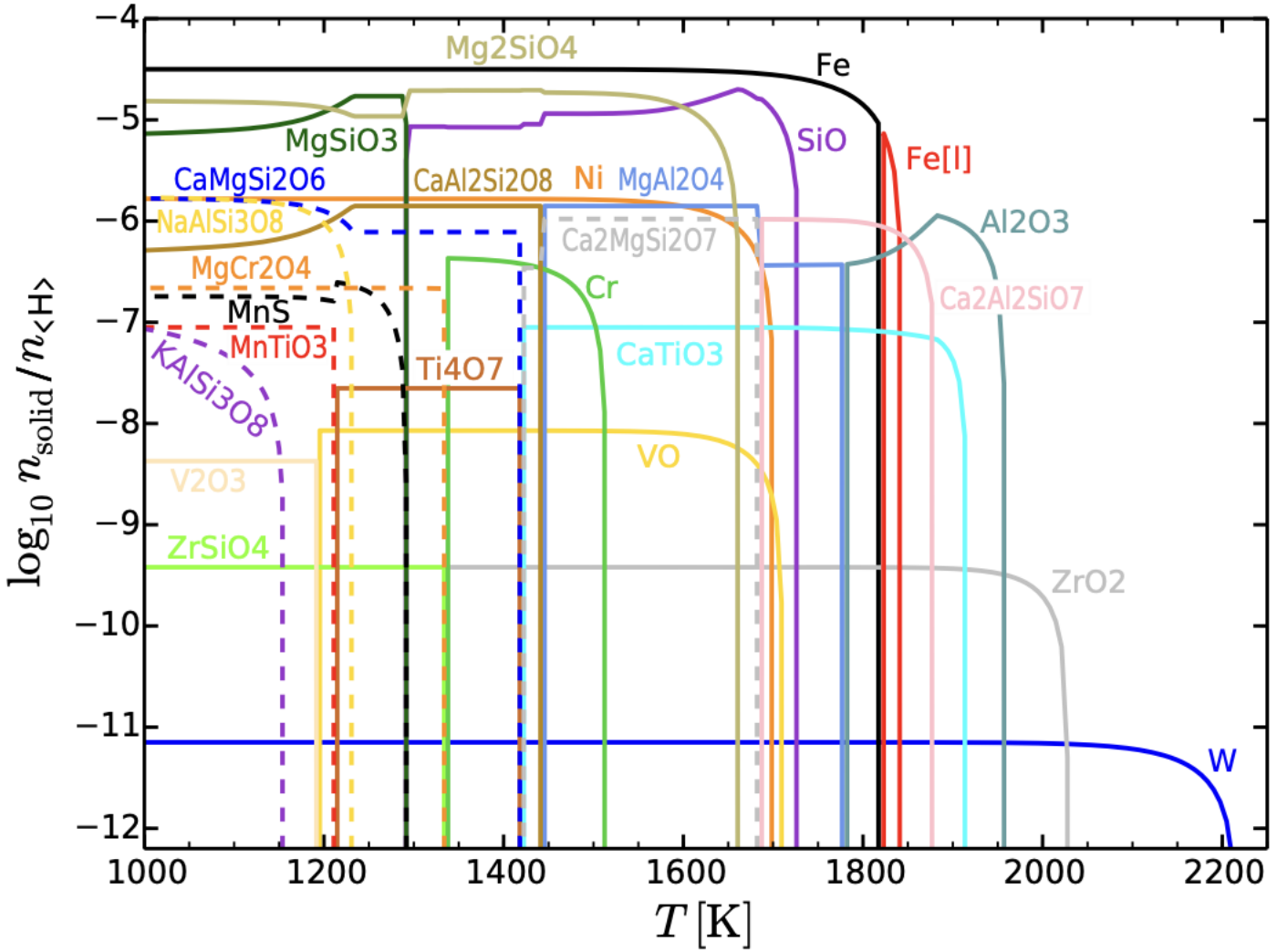
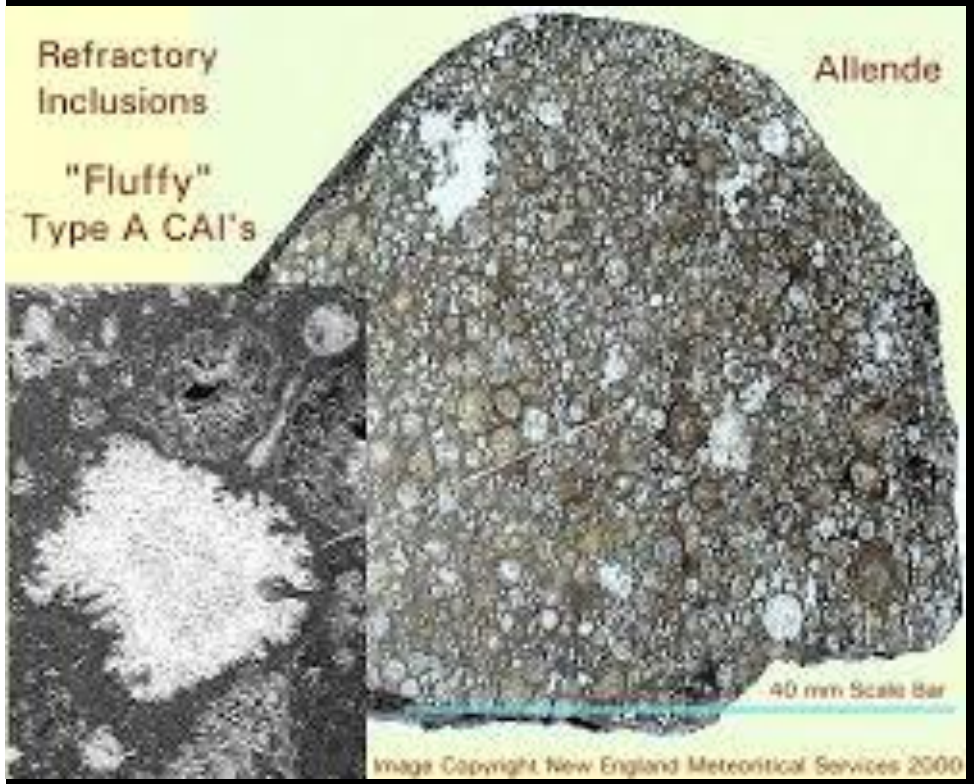
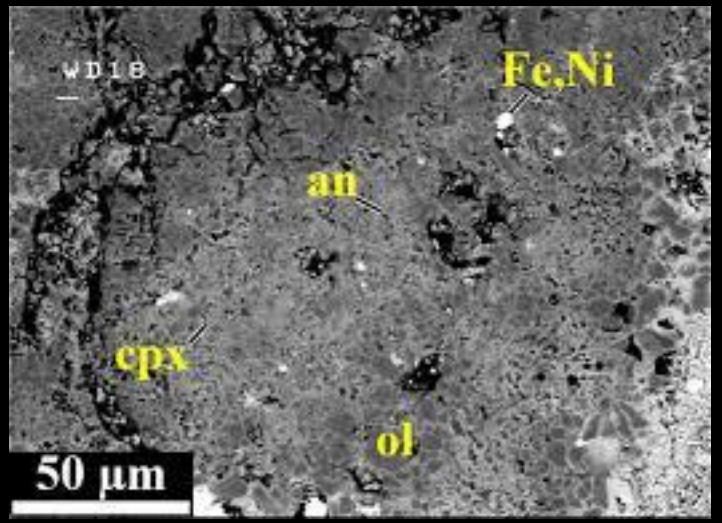


Fig. 6. The onset of condensation at $p = 1$ bar for solar abundances in phase equilibrium. The graph show the concentration of the various condensed species with respect to hydrogen nuclei.

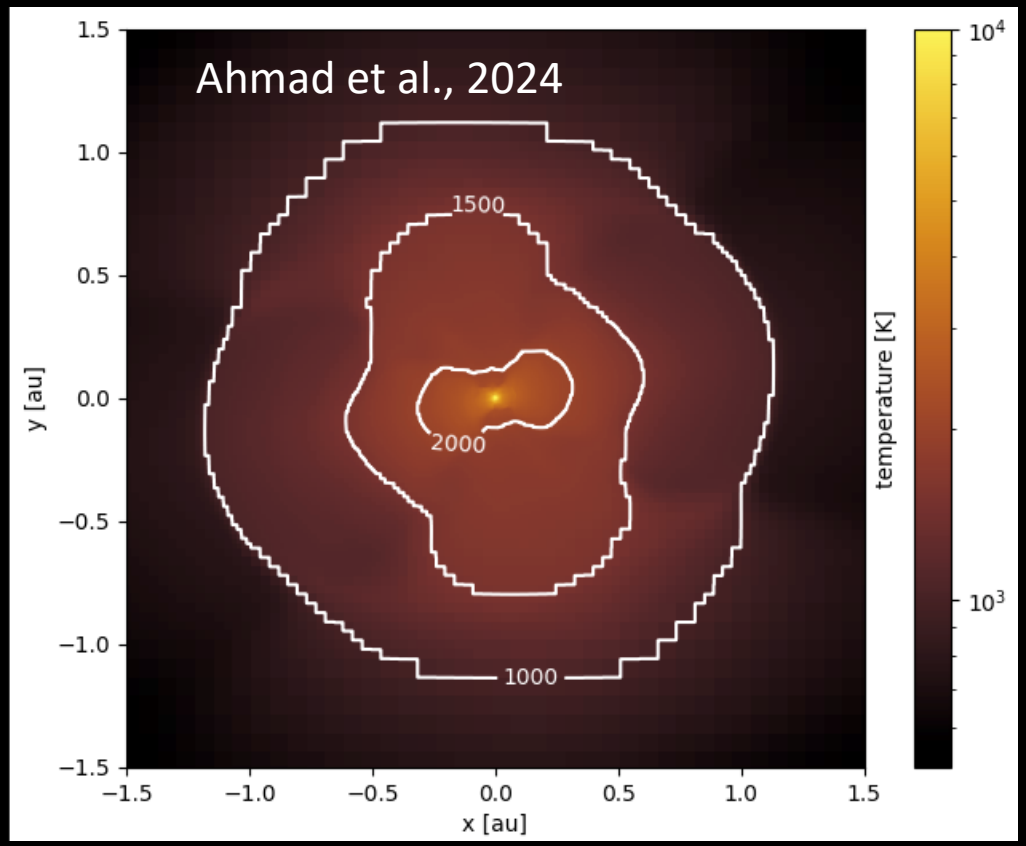


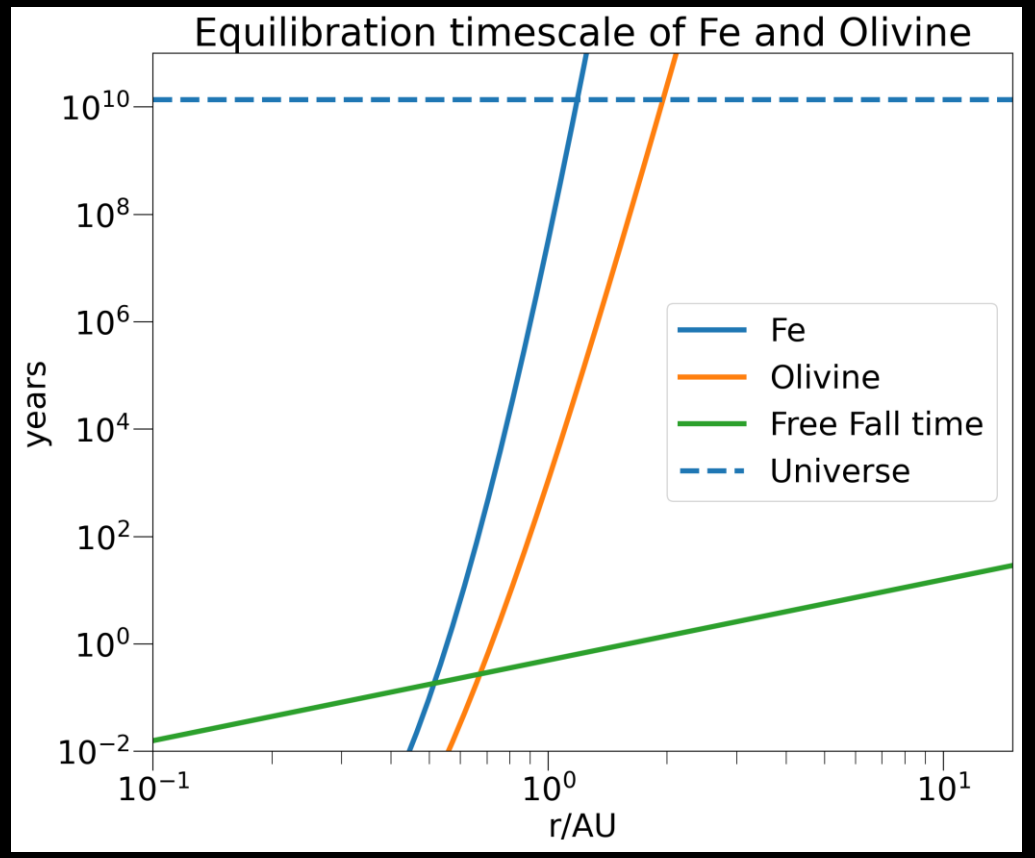


But « equilibrium» is maybe NOT a fully right assumption….

- CAIs disappears at low temperature: =>need ‘isolation factor’ (see Petaev et al.)
- Equil. : Does not tell WHAT reaction leads to equilibrium (=>just lowest Gibbs E.)

MHD collapse simulations show complex inflow structure & short timescales





Complex inflow structure

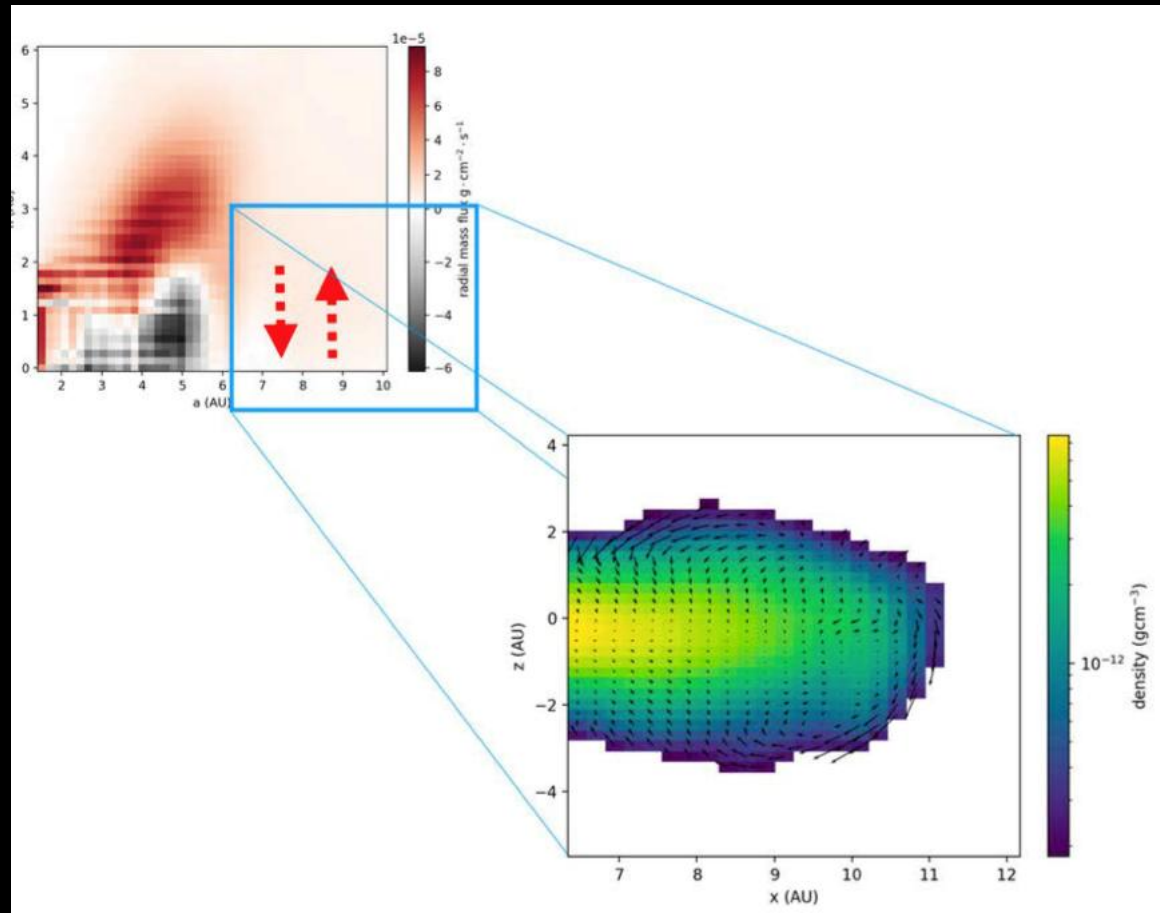


Fig. 13. Dynamics of gas as the envelope accretes onto the disk. It is obtained from the simulations described in Commerçon et al. (2024), after averaging over the elliptic motion of the gas streamlines around the star. The main plot shows the net radial flux, which is directed toward the star at the surface of the disk (red color) and outward near the midplane (gray color), whereas there is no net radial component beyond ~6 au, where instead the motion of the gas is vertical. The latter is illustrated by black arrows in the inlet, where the color depicts the density of gas.

Commerçon et al., 2024

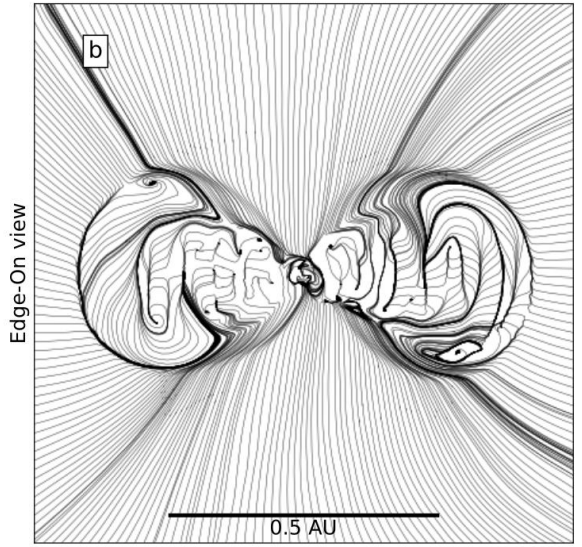
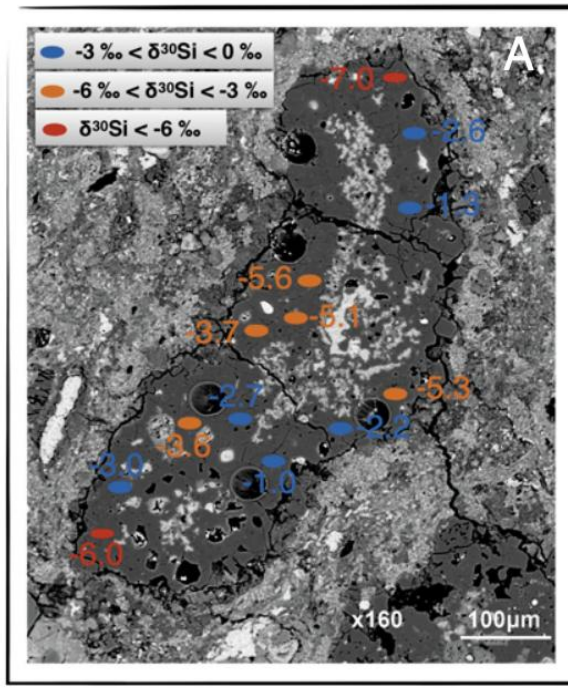


Fig. 5: Unbroken velocity vector field streamlines of run G1 at $t \approx 322$ days after the birth of the inner disk, illustrating the dynamics of accretion onto the disk and protostar in a top-down (panel a) and edge-on (panel b) view. The scale bar in panel (b) applies to panel (a) as well. An animated version of these streamlines, made using windmap, is available in the online journal.

Ahmad et al., 2024

Rapid condensation of fine grained amoeboid olivine aggregates (Marrocchi et al., 2019)



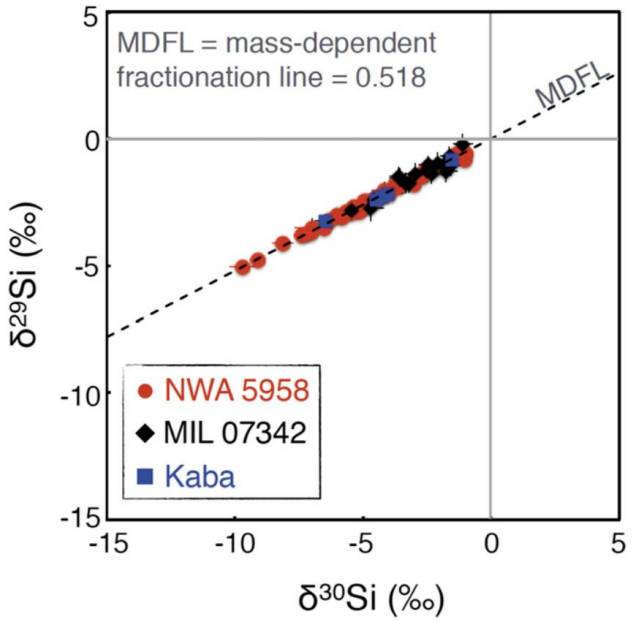


Fig. 2. Silicon 3-isotope plot showing the large range of mass-dependent isotopically light values measured in all analyzed AOAs in NWA 5958 (red), MIL 07342 (black), and Kaba (blue).

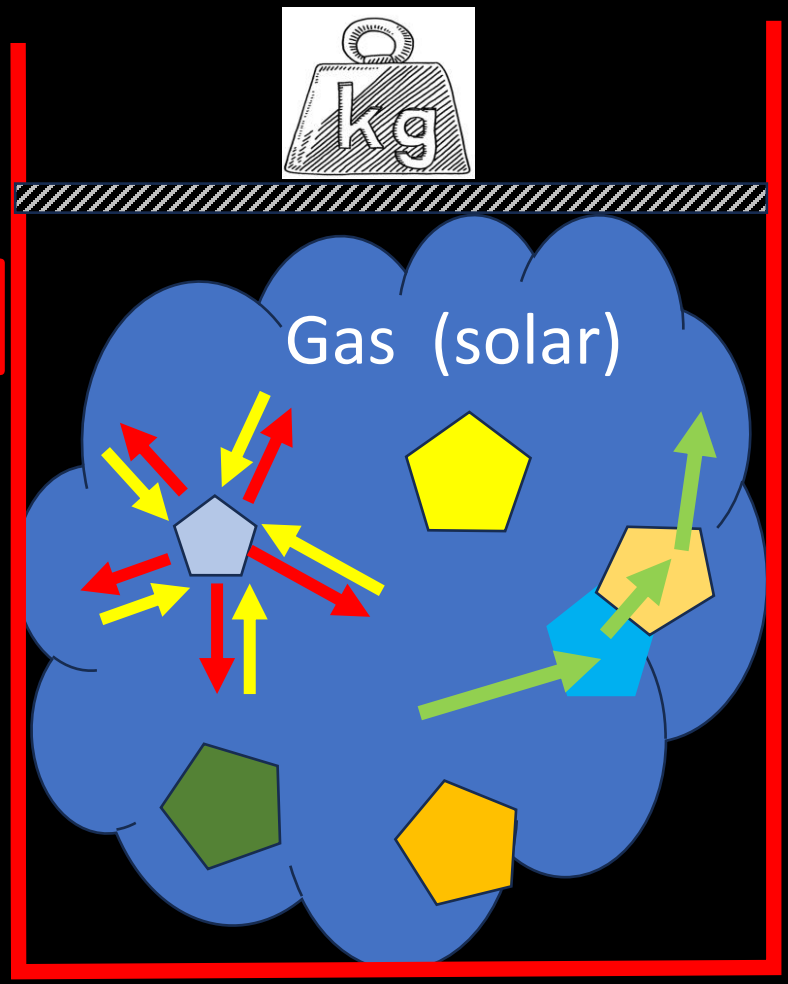
Fig. 1. A representative AOA and the Si isotopic compositions of its olivines. (*A*) Back-scattered electron image of AOA N1-8 from the CM-related chondrite NWA 5958 (30, 31). SIMS measurements are indicated by colored ellipses and the Si isotopic compositions associated with each analysis point. The color of the ellipses indicates the variability of the Si isotopic compositions by the range of the δ^{30}Si value: blue, $-3‰ < \delta^{30}Si < 0‰$, orange, $-6‰ < \delta^{30}Si < -3‰$, and red, $\delta^{30}Si < -6‰$. (*B*) $\delta^{29}Si - \delta^{30}Si$ diagram showing the mass-dependent variation observed in N1-8; MDFL, mass-dependent fractionation line.

Large mass dependant Si fractionation, light isotopes dominate=> condensation process

Condensation time : 10^5 seconds only (1-2 days !!!)

Kinetic condensation sequence ? How to calculate ?

Write **all possible reactions**…(well.. most important..)



Condensation / Evaporation

HERTZ-KNUDSEN Formalism

Following :
Tsuchiyama et al. (1988)
Richter et al. (2002)
39 minerals

Nebular reactions

Mineral 1 + Gas 1+Gas 2 => Mineral 2

Following :
Fegley (1988, 2000)
Lauretta et al. (2006)
38 reactions

Condensation evaporation in **Hydrogen** : Hertz Knudsen law

Condensation Evaporation

$$\frac{dN_{min}}{dt} = \gamma S \sum_{i,gas} \frac{P_{g,i}}{\sqrt{2\pi m_i kT}} - \gamma S \sum_{i,sat} \frac{P_{sat,i}}{\sqrt{2\pi m_i kT}}$$

Richter et al. (2002, 2004, 2007) Fedkin et al. (2013)

$P_{g,i}$ **: partilal pressures in the gas surrounding the mineral**

$P_{sat,i}$ **for every species. : saturating vapor pressure for every mineral**

These value depend on the local chemistry of te gas, and in the abundance of H

One big unknown the « sticking coefficient » : The gamma term in the HZ equation

Our approach : We pre-compute evaporative flux (look-up tables)

we compute in real time condesation fluxes

→ $P_{isat,i}$ **for every species. : Pre-Calculated by compurting mineral-H2 equlibrium**

We use a chemical code (CEA/NASA) with mineral condensation to pré-calculate the $P_{ij,sat}$ for 38 minerals, in the presence of H

→ $P_{g,i}$ **: partial pressures in the gas surrouding the mineral computed for the instantaneous composition of the gas**

We assume local thermodynamical equlibrium of GAS

We use a chemical code (CEA/NASA) to compute the gas molecular species assuming

For all atoms in gas (H, O,C, Fe, Ni, Ca, Mg, Si, K, Cr..)

ASSUMPTIONS/SIMPLIFICATIONS:

(1) gas is at thermodynamic Equilibrium

(2) minerals contact surface is constant (no nucleation model)

Tabulated evaporation rate in H2

Comparison with experiment (Tsuchiyama et al., 1998)

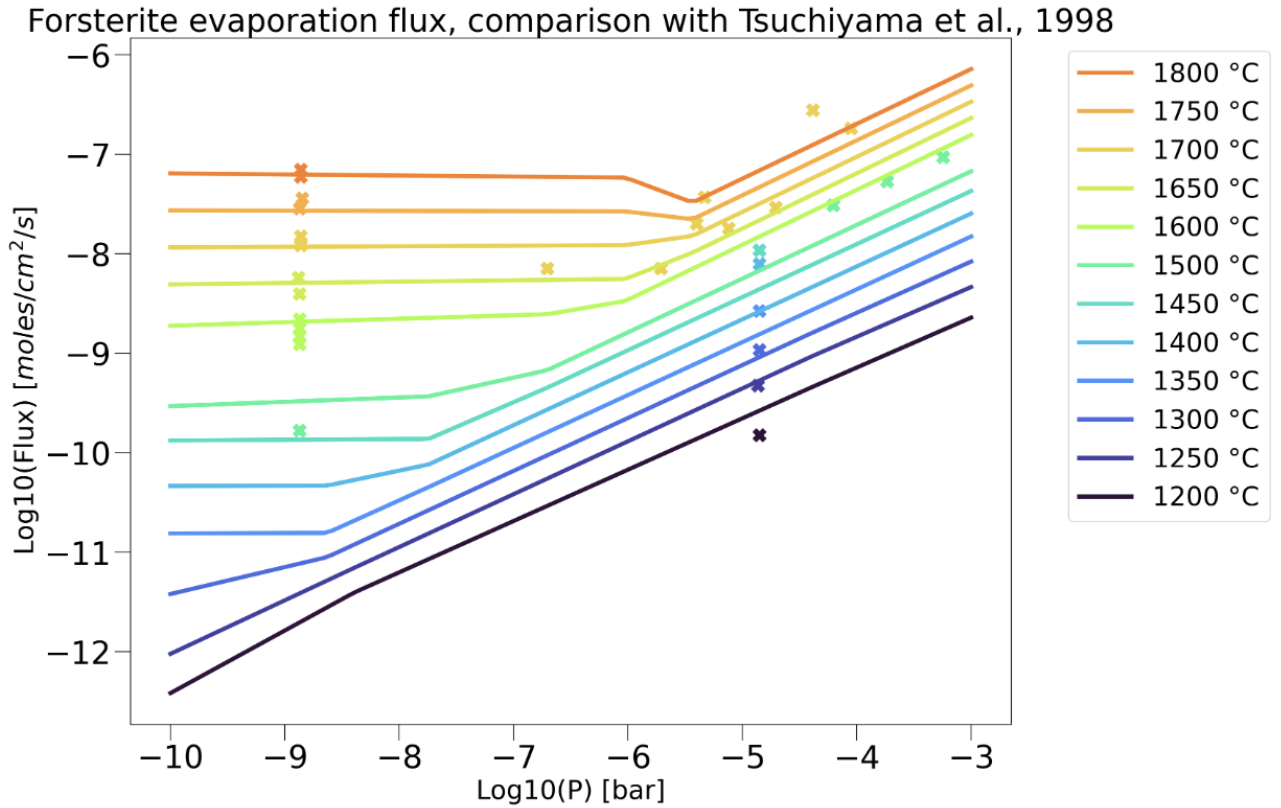
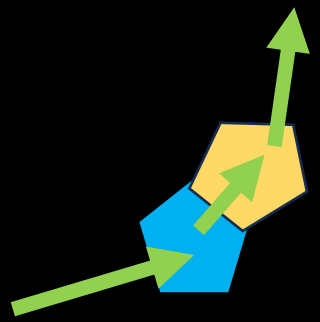


Fig. 1 Comparison of the Mg_2SiO_4 evaporation flux tabulated in `KineCond` (solid lines) and measured flux in laboratory experiments [3] (crosses). P is the total pressure of hydrogen species in the gas. At low hydrogen pressure, the vaccuum evaporation flux is revovered, whereas at high hydrogen pressure, the effect of hydrogen increases the evaporative flux. Good match between the model and experimental data is observed.

Charnoz et al., 2024

Gas-mineral interactions : « nebular reactions »
One pre-existing mineral (M1) is transformed into another one (M2)



Many reactions… Simplest form :

Mineral 1 + Gas => Mineral 2

The kinetics of these rections depend on details of surface physics:

They depends on an activation energy

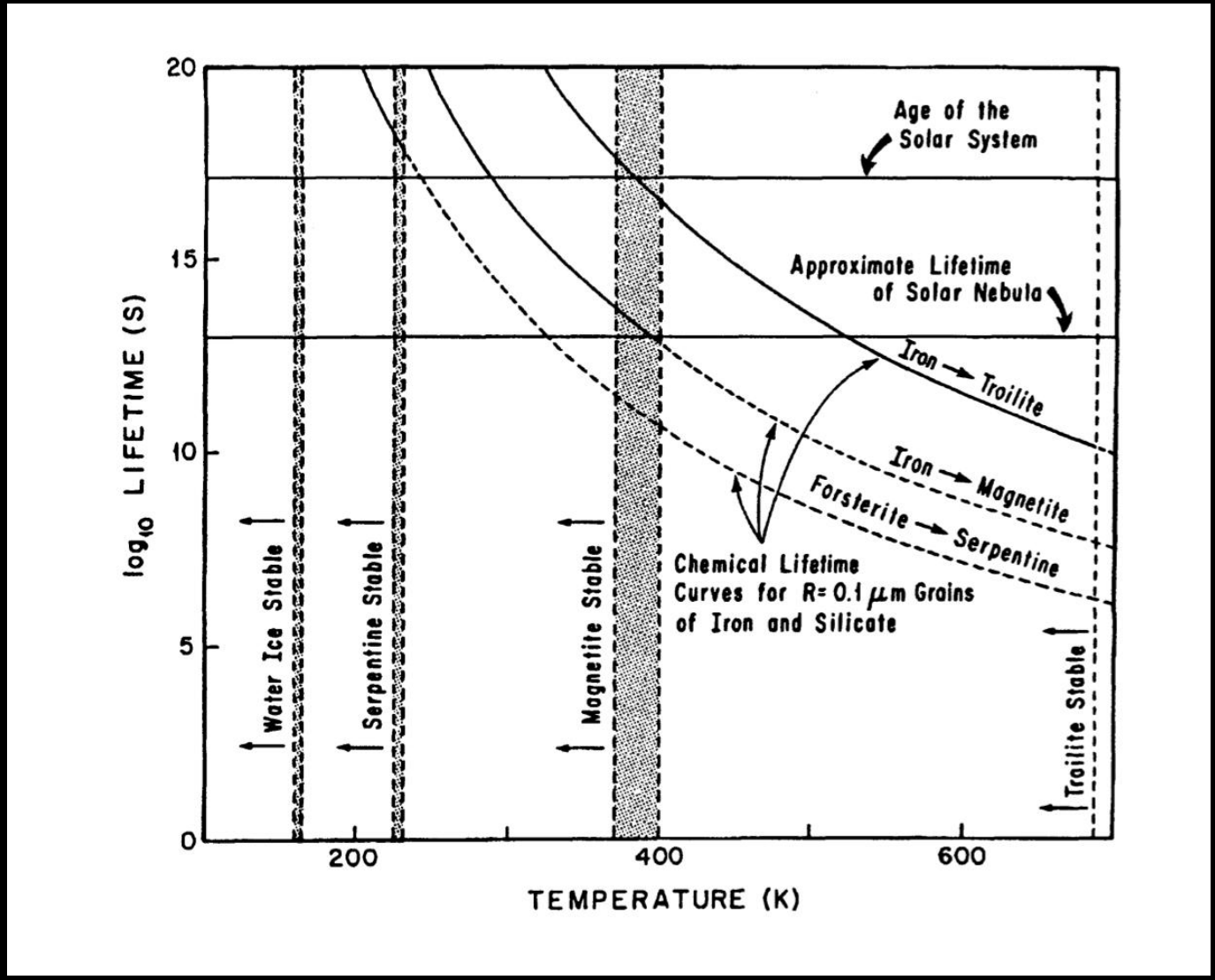
The most simplest case : The Simple Kinetic Theory (Fegley et al., 1999)

Mineral 1 + gas => Mineral 2

$$\frac{dN_2}{dt} = Flux(gas) * surface * e^{-Ea/RT}$$

$Ea \sim 100\ Kj/mol$ for Fe+S => FeS (Fegley et al., 1993)
$\Rightarrow$ Iron can be sulfidized into FeS during Solar nebula life
Fegley et al., 1993 (at T=700K)

$Ea \sim 70\ Kj/mol$ for phyllosilicates or magnetite formation from
But T < 400K



Fegley et al. 1993

But this is a simple representation of gas-grains reactions.

Surface reactions are important and they are present in 2 regimes :
Linear and parabolic

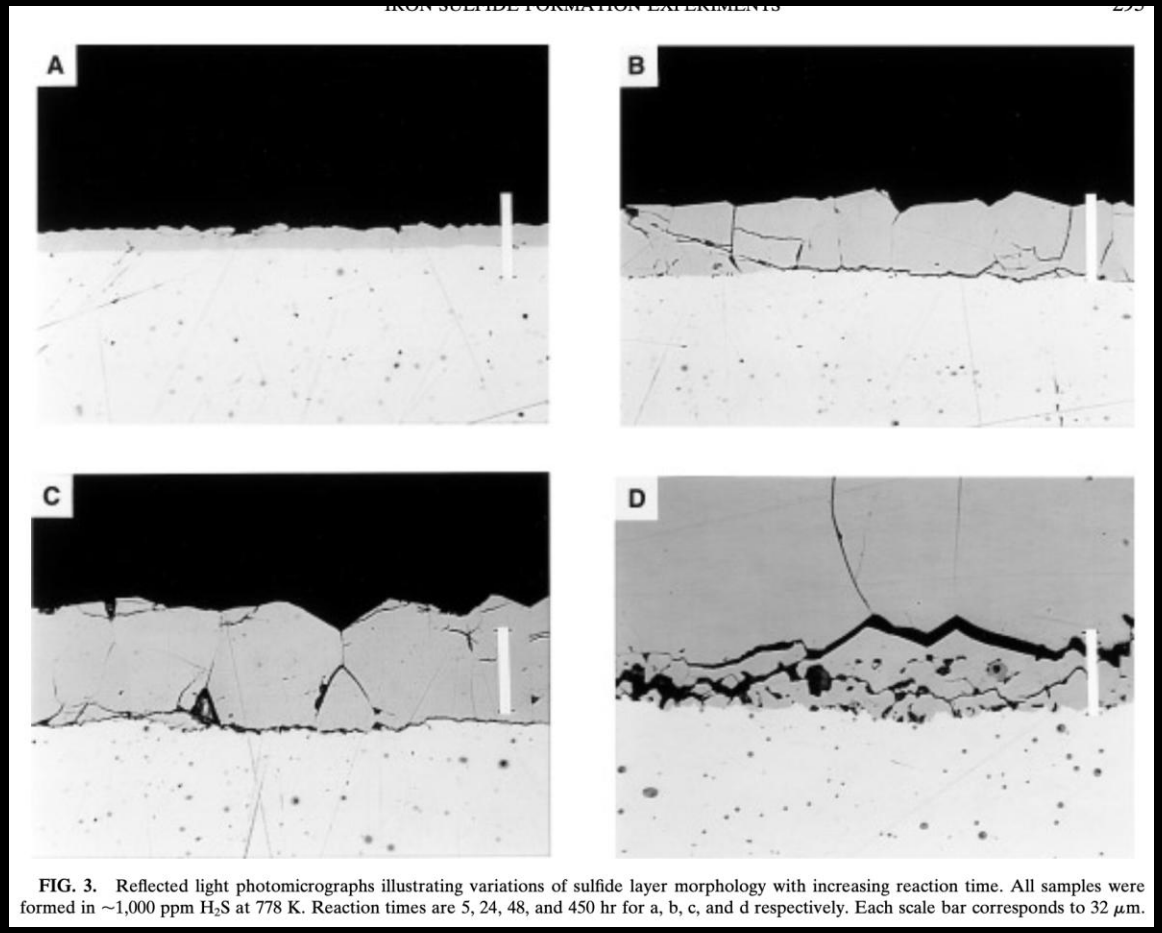


FIG. 3. Reflected light photomicrographs illustrating variations of sulfide layer morphology with increasing reaction time. All samples were formed in ~1,000 ppm H_2S at 778 K. Reaction times are 5, 24, 48, and 450 hr for a, b, c, and d respectively. Each scale bar corresponds to 32 μm.

Lauretta et al., 1996
Sulfidation of iron :`
Fe_solid+S_gas => FeS (solid)

Transition from linear to Kinetic reactions

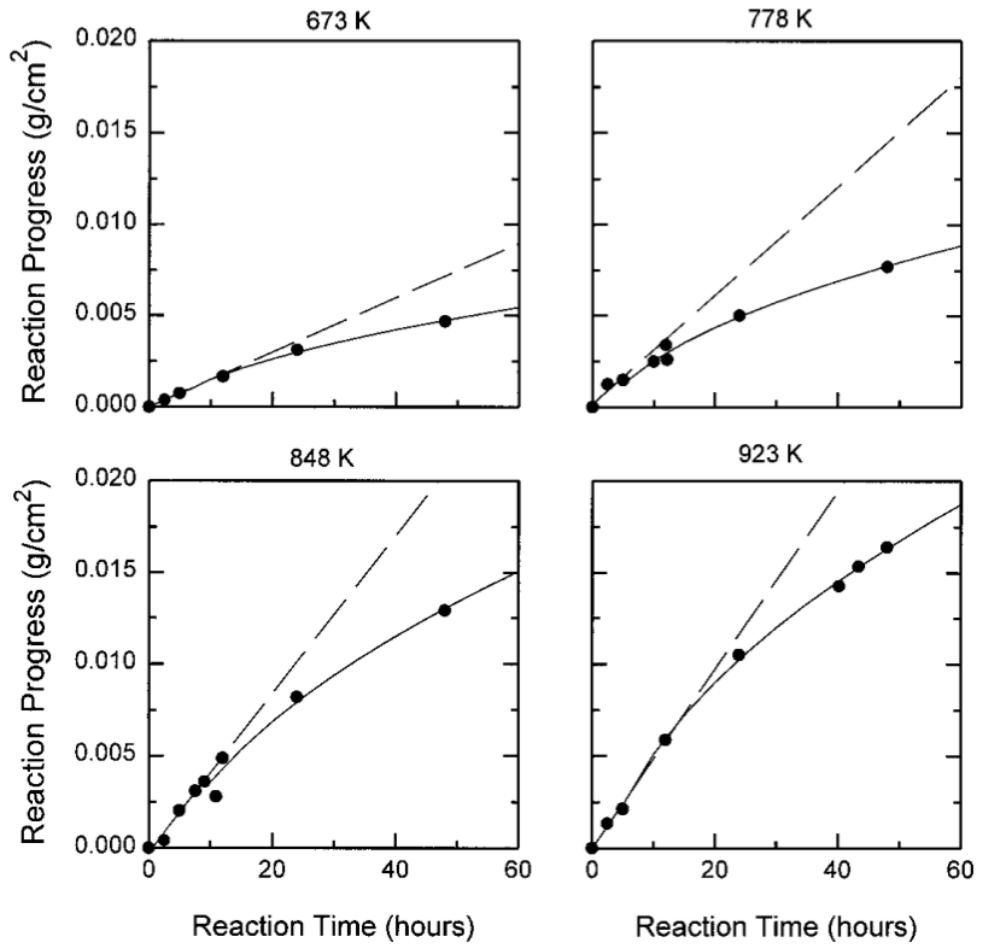


FIG. 15. Plots of reaction progress versus time along four isotherms (673, 778, 848, and 923 K) for samples formed in ~1,000 ppm H_2S. The dashed lines are linear least-squares fits to data points for experiments ≤10 hr. The solid curves are parabolic fits to longer reaction time experiments. Experiments at all temperatures show a transition from linear to parabolic kinetic behavior.

$$H \propto e^{-\frac{Ea_l}{RT}} \times t$$

The reaction rate is proportional to the flux of H2S

$$H \propto e^{-\frac{Ea_p}{RT}} \times t^{\frac{1}{2}}$$

The reaction rate is controlled by the Diffusion of S inside the reaction layer

Comparison with experiments

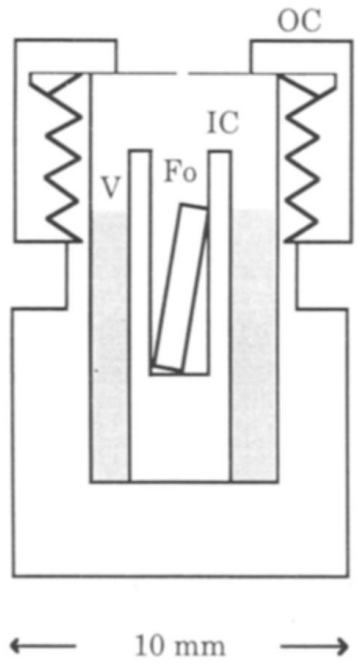


Fig. 1. Cross section of the double capsule. Outer capsule, with an orifice of 0.1 mm, acts as a Knudsen cell. *OC* = outer capsule (Mo); *IC* = inner capsule (Mo); *Fo* = single forsterite crystal (1×1.25×5 mm); *V* = cristobalite powder.

Imae 1993

An experimental study of enstatite formation reaction between forsterite and Si-rich gas

Naoya Imae [a], Akira Tsuchiyama [b] and Masao Kitamura [a]

[a] *Department of Geology and Mineralogy, Faculty of Science, Kyoto University, Kyoto 606, Japan*
[b] *Institute of Earth and Planetary Sciences, College of Education, Osaka University, Toyonaka 560, Japan*

Received October 13, 1992; revision accepted April 26, 1993

$$Mg_2SiO_4 + Si + 2O \Rightarrow 2\,MgSiO_3$$

$$\mathrm{P} \sim 10^{-7}\ bar$$

They found an activation energy in parabolic Regime : $\sim 500\ Kj/mol$

Comparison with experiments (Imae et al, 1993)
Growth of enstatite at the surface of a forsterite mineral

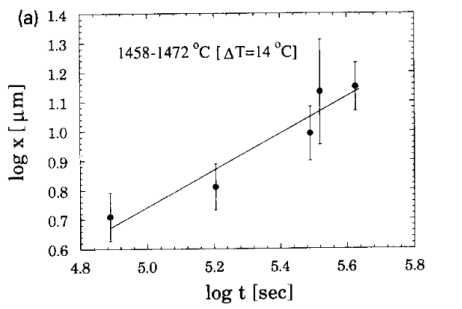


Fig. 4. Logarithm of enstatite width plotted against logarithm of time in nearly constant temperature ranges. (a) 1458–1472°C. (b) 1484–1498°C. (c) 1514–1522°C.

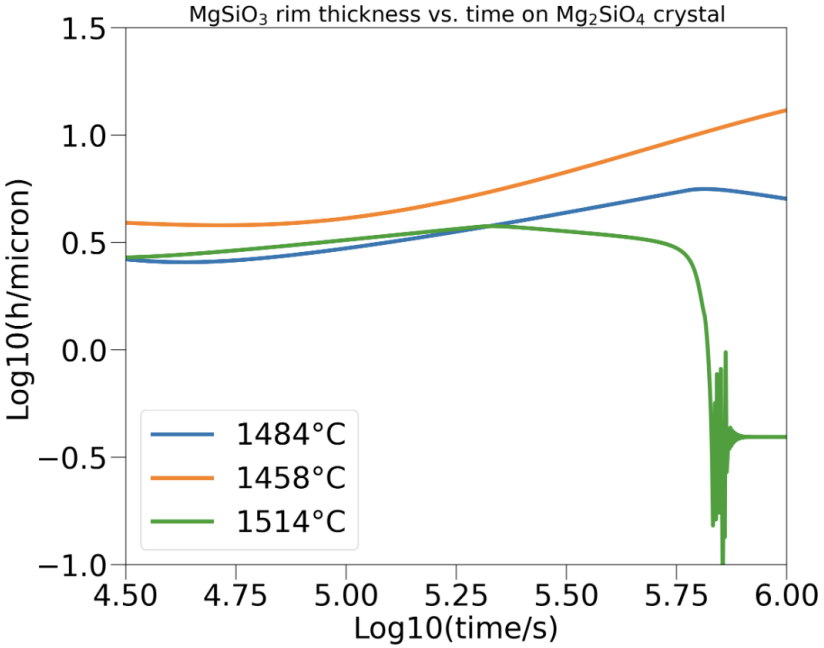


Fig. 2 Enstatite growth over a forsterite crystal in a SiO rich atmosphere, simulated with the `KineCond` code. Here the active rim thickness is plotted as a function of time for different temperatures. Compare with Figure 4 of [23]

Our simulation
(using Ea experimentally measured)

Only very few data exist for the activation energy of nebular reactions
In our code we will treat different en members

We consider 3 cases

- Fast nebular reaction : (end member) $E_a^l = 0$ and $E_p^l = 0KJ/mol$
- Moderate nebular reaction : $E_a^l = 20Kj/ml$ and $E_p^l = 20KJ/mol$
- Slow nebular reactions : $E_a^l = 80Kj/mol$ and $E_a^p = 500KJ/mol$

Our choice of 38 (among about 50) REDUCED nebular reactions with the simpl

Mineral 1 + Gas 1 + Gas 2 => Mineral 2

1	$Fe(s) + S \rightarrow FeS(s)$
2	$Fe(s) + O \rightarrow FeO(s)$
3	$3\ FeO(s) + O \rightarrow Fe_3O_4(s)$
4	$2\ FeO(s) + Si + 2\ O \rightarrow Fe_2SiO_4(s)$
5	$Al_2O_3(s) + 2\ Na + O \rightarrow 2\ NaAlO_2(s)$
6	$NaAlO_2(s) + 3\ Si + 6\ O \rightarrow NaAlSi_3O_8(s)$
7	$NaAlO_2(s) + 2\ Si + 4\ O \rightarrow NaAlSi_2O_6(s)$
8	$Na_2O(s) + 2\ Al + 3\ O \rightarrow 2\ NaAlO_2(s)$
9	$CaAl_{12}O_{19}(s) + 2\ Ca + 2\ O \rightarrow 3\ CaAl_4O_7(s)$
10	$2\ Al_2O_3(s) + O + Ca \rightarrow CaAl_4O_7(s)$
11	$Al_2O3(s) + O + Ca \rightarrow CaAl_2O_4(s)$
12	$Al_2O3(s) + O + Mg \rightarrow MgAl_2O_4(s)$
13	$CaAl_2O_4(s) + 2\ Al + 3\ O \rightarrow 1\ CaAl_4O_7(s)$
14	$CaAl_4O_7(s) + 8\ Al + 12\ O \rightarrow CaAl_{12}O_{19}(s)$
15	$6\ Al_2O_3(s) + O + Ca \rightarrow CaAl_{12}O_{19}(s)$
16	$Mg_2SiO_4(s) + Si + 2\ O \rightarrow 2\ MgSiO_3(s)$
x 17	$MgSiO_3(s) + Mg + O \rightarrow Mg_2SiO_4(s)$
18	$SiO_2(s) + 2\ Mg + 2\ O \rightarrow Mg_2SiO_4(s)$
19	$SiO_2(s) + 1\ Mg + O \rightarrow MgSiO_3(s)$
20	$2\ SiO_2(s) + 2\ K + O \rightarrow K_2Si_2O_5(s)$
21	$SiO_2(s) + Ca + O \rightarrow CaSiO_3(s)$
22	$SiO_2(s) + 2\ Fe + 2\ O \rightarrow Fe_2SiO_4(s)$
23	$SiO_2(s) + 2\ Ca + 2\ O \rightarrow Ca_2SiO_4(s)$
24	$CaAl_4O_7(s) + Ca + O \rightarrow 2\ CaAl_2O_4(s)$
25	$CaAl_4O_7(s) + 8\ Al + 12\ O \rightarrow CaAl_{12}O_{19}(s)$
26	$CaAl_2O_4(s) + 2\ Al + 3\ O \rightarrow CaAl_4O_7(s)$
27	$CaAl_2O_4(s) + 2\ Si + 4\ O \rightarrow CaAl_2Si_2O_8(s)$
28	$CaAl_2O_4(s) + 10\ Al + 15\ O \rightarrow CaAl_12O_19(s)$
29	$Ca_2SiO_4(s) + 2\ Al + 3\ O \rightarrow Ca_2Al_2SiO_7(s)$
30	$Ca_2SiO_4(s) + Si + 2\ O \rightarrow 2\ CaSiO_3(s)$
31	$Mg_2SiO_4(s) + 2\ Ca + 3\ Si + 8\ O \rightarrow 2\ CaMgSi_2O_6(s)$
32	$Mg_2SiO_4(s) + 4\ Ca + 3\ Si + 10\ O \rightarrow 2\ Ca_2MgSi_2O_7(s)$
33	$Al_2O_3(s) + Mg + O \rightarrow MgAl_2O_4(s)$
34	$MgSiO_3(s) + Ca + Si + 3\ O \rightarrow CaMgSi_2O_6(s)$
35	$CaSiO_3(s) + Mg + Si + 3\ O \rightarrow CaMgSi_2O_6(s)$
36	$Ca_2MgSi_2O_7(s) + Mg + 2\ Si + 5\ O \rightarrow 2\ CaMgSi_2O_6(s)$
37	$NaAlO_2(s) + Si + 2\ O \rightarrow 1\ NaAlSiO_4(s)$
38	$3\ Fe(s) + 4\ O \rightarrow Fe_3O_4(s)$

Each reaction
Stands for
Many reaction
With same
Gas-grain exchanges.

Charnoz et al., 2024

Results

1) Close-to equilibrium condensation (high pressure, long cooling time)

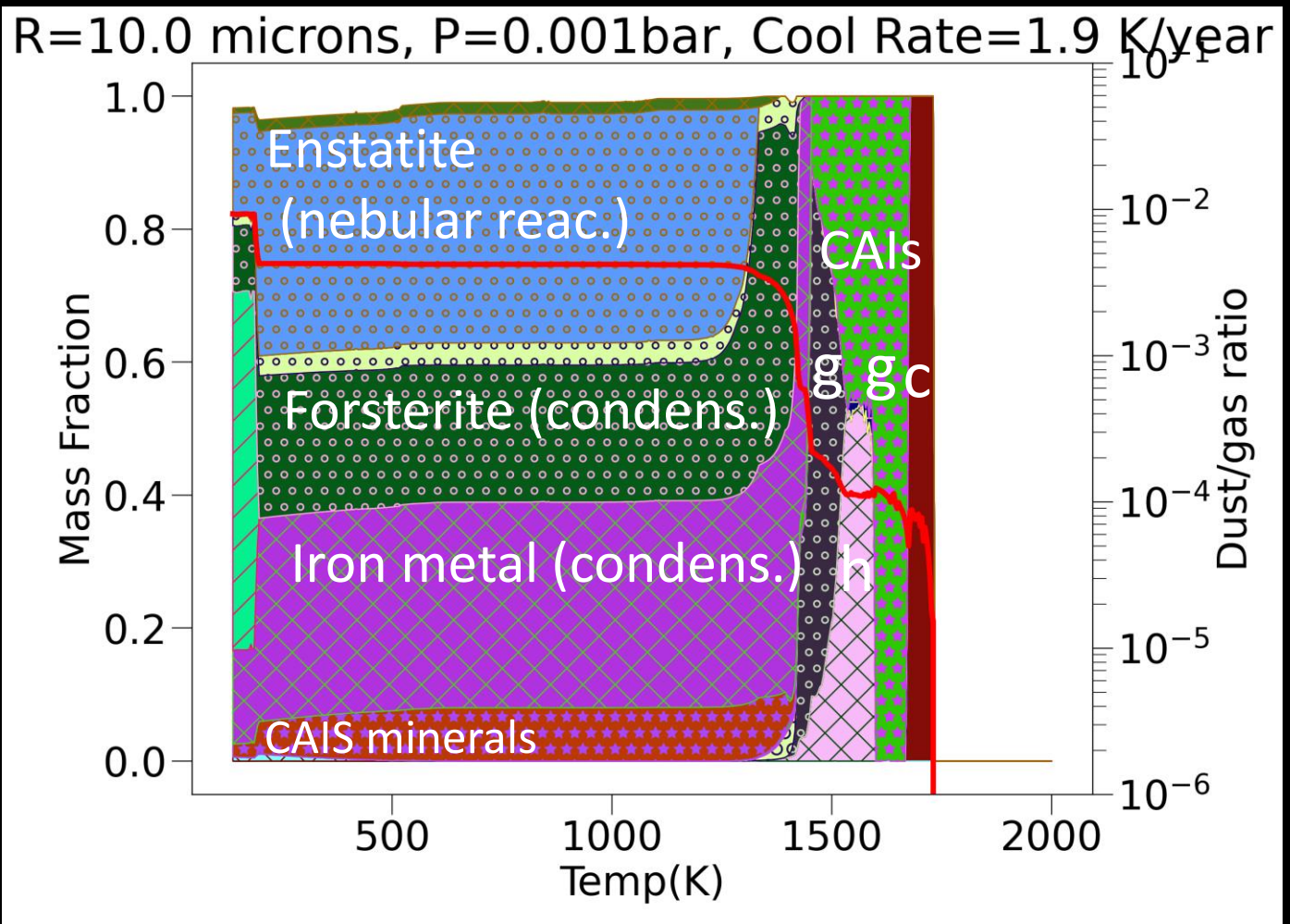
1) out-of-equilibrium condensation (low pressure, short cooling time)

Condensing slowly (1000 yrs) and at high pressure (10^{-3} bar)

Do we recover « equilibrium » condensation sequence on long time ?

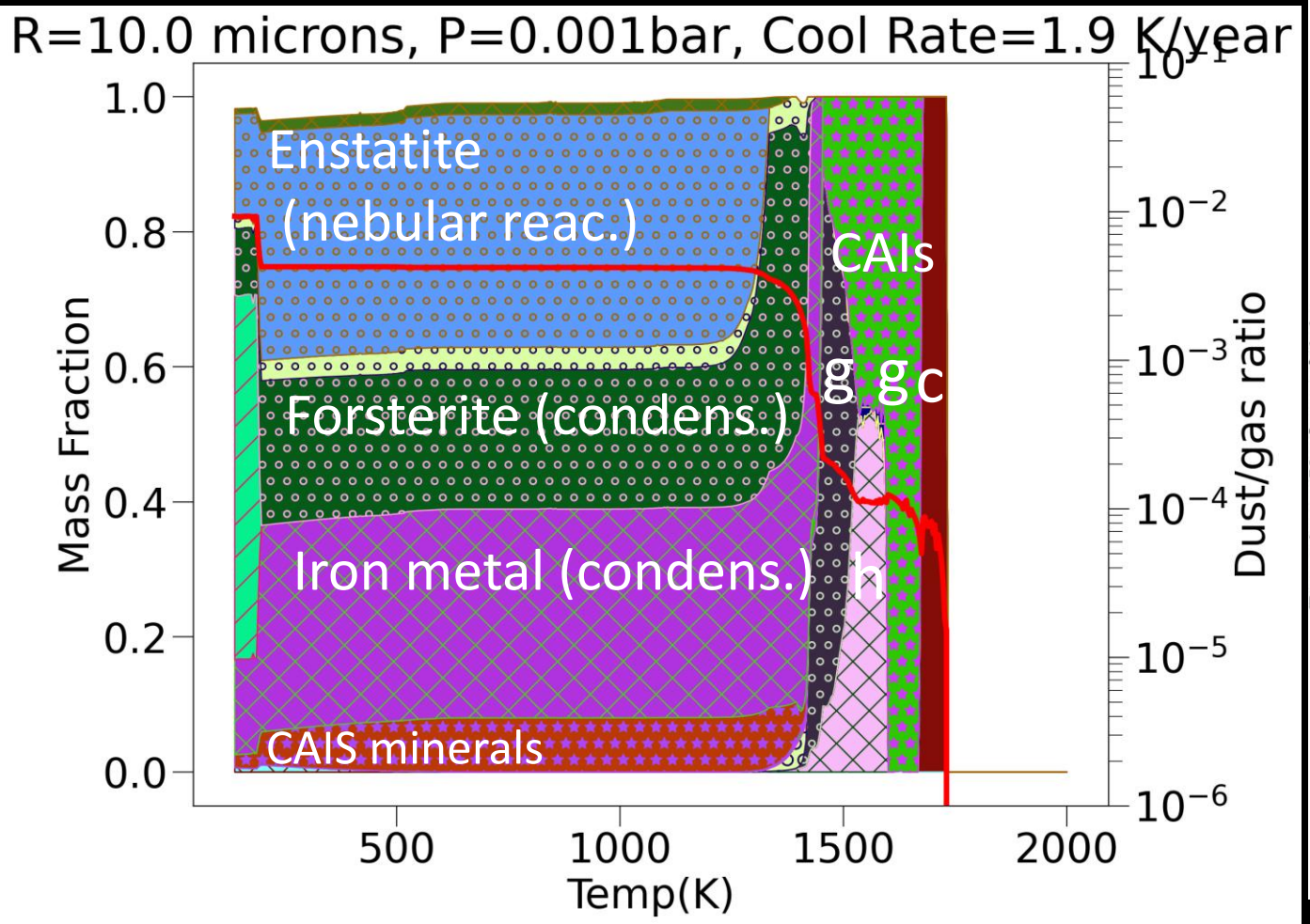
Yes + we preserve CAIs at low temperature

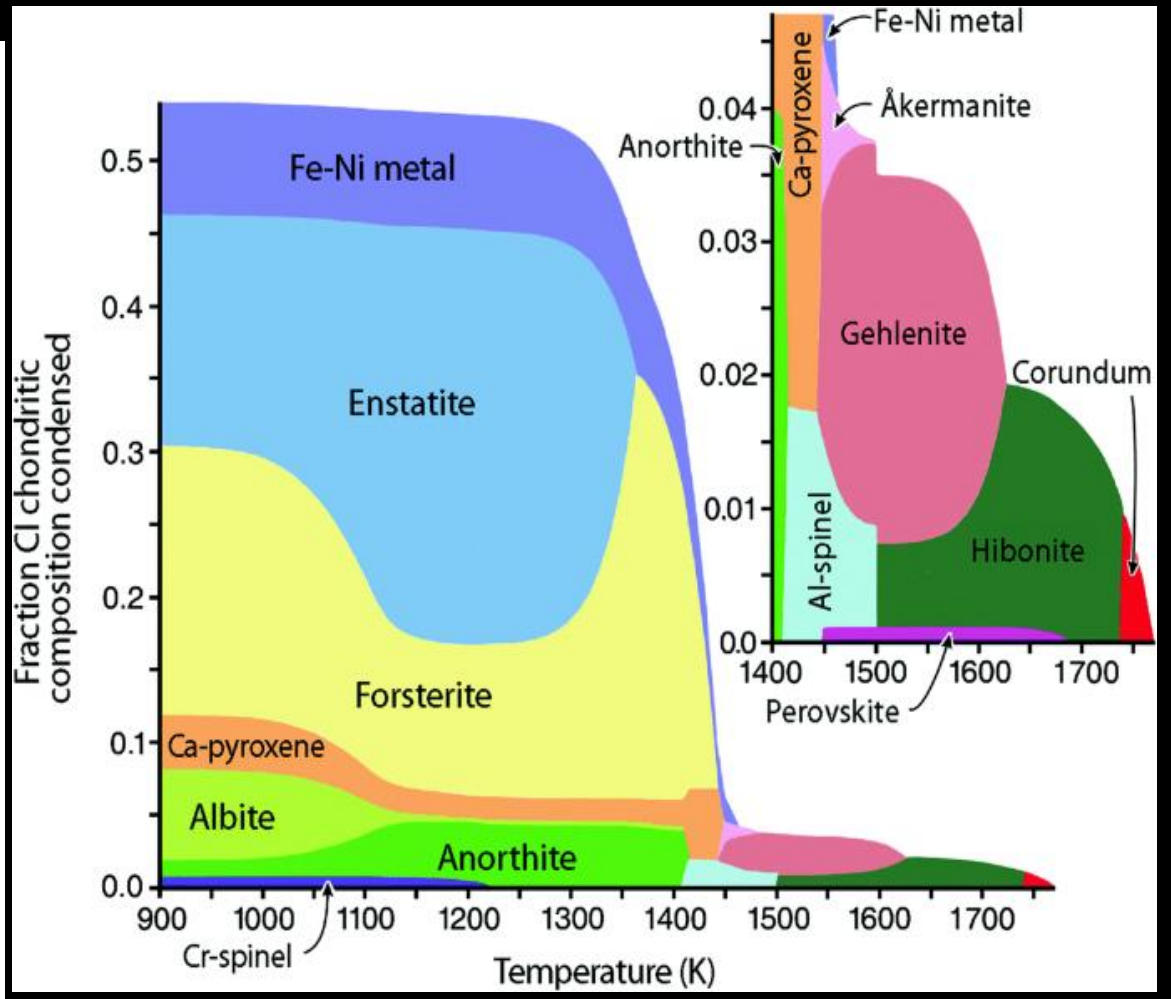
Kinetic (fast nebular interactions)



Comparison with classical equilibrium condensation sequence Obtained by Gibbs Energy minisation (P=10^-3 bar)

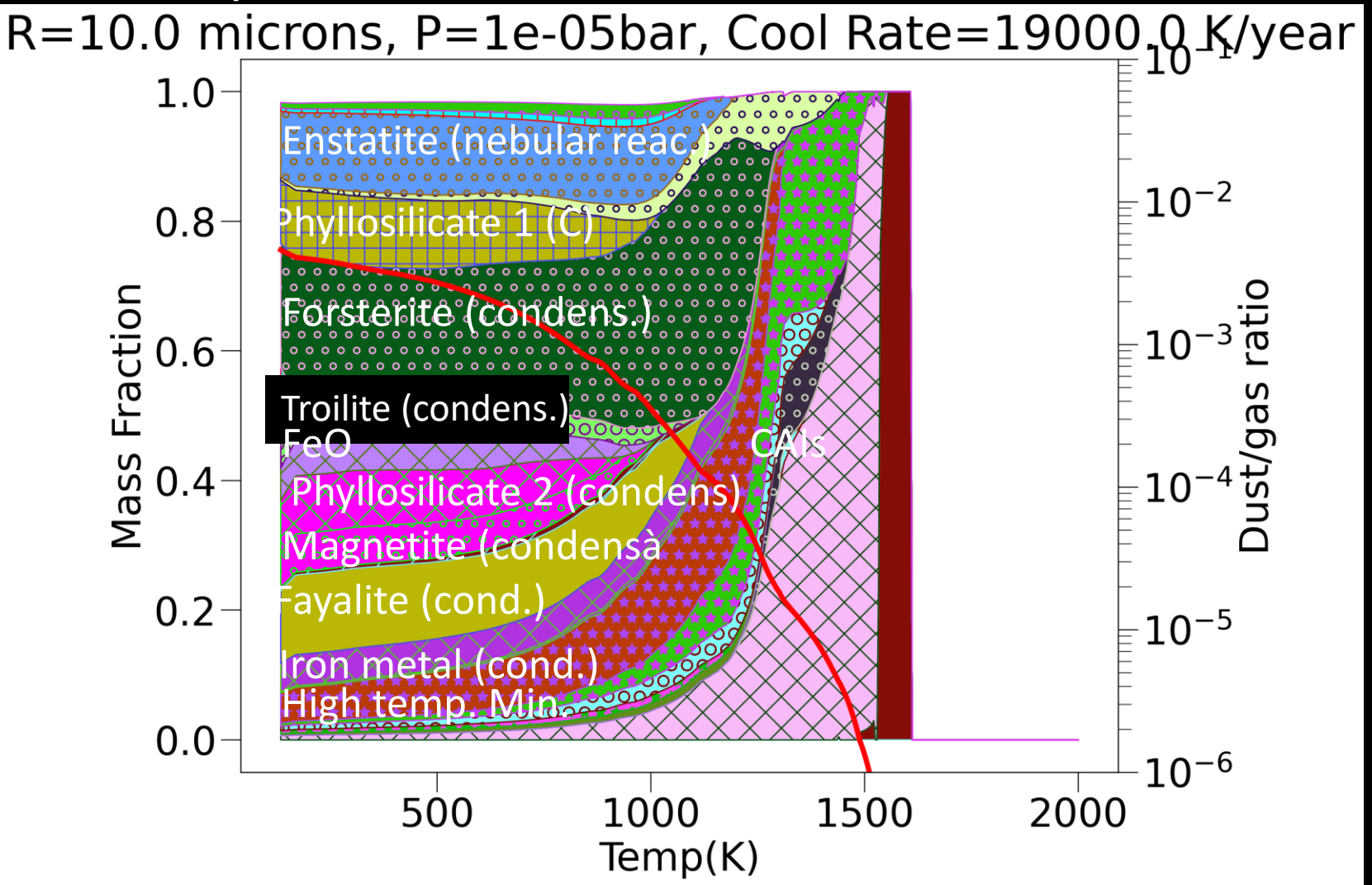
Yoneda & Grossman 1972





Condensing rapidly (10yrs) and at low pressure(10^{-7} bar) : surprises !

Either rapid or slow nebular reactions=>



rich diversity of minerals

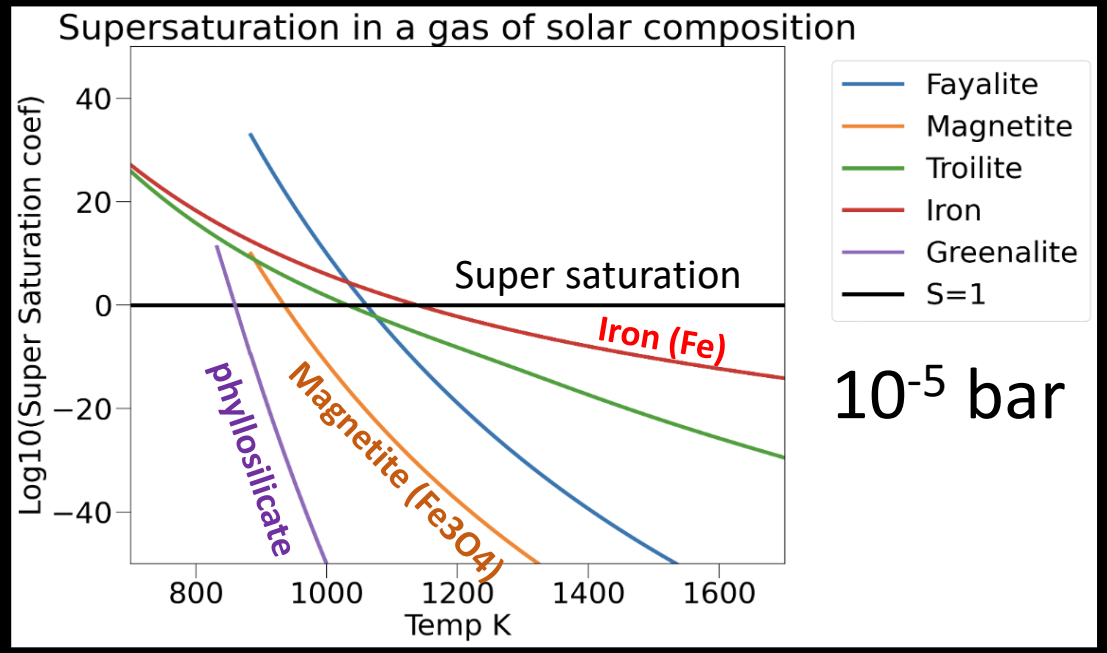
Formation of oxidized phases : Fayalite, phyllosilicates, magnetite etc..

Final mineralogy « apparently » oxidized… without more water nor O_2 !

What happens in low pressure/fast cooling ?

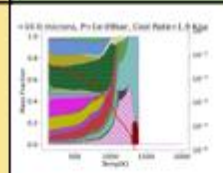
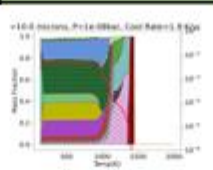
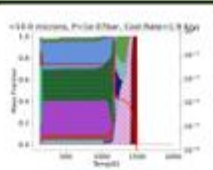
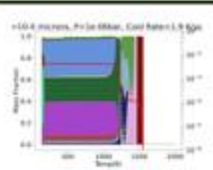
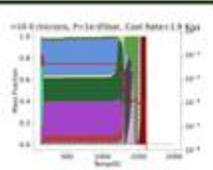
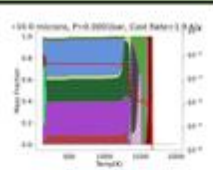
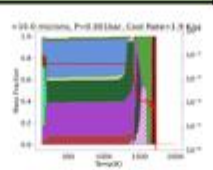
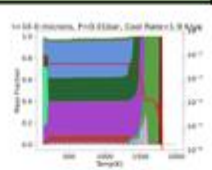
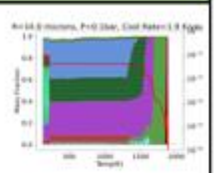
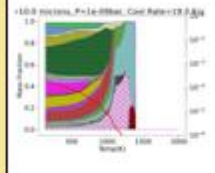
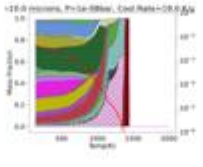
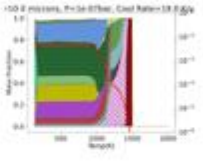
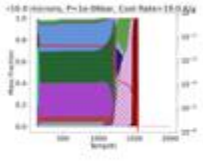
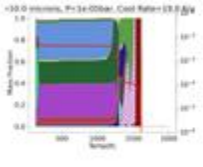
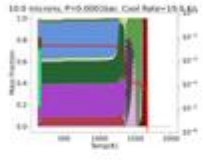
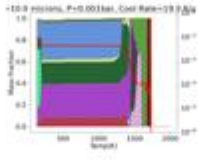
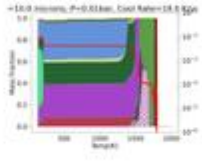
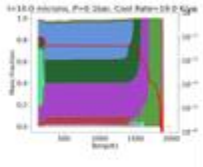
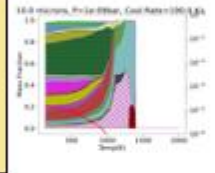
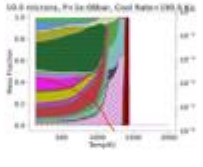
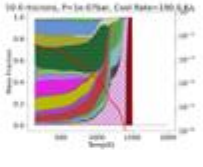
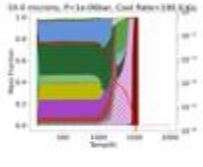
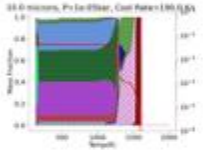
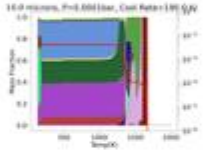
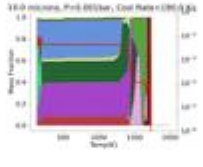
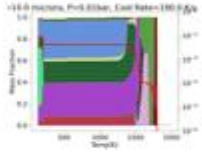
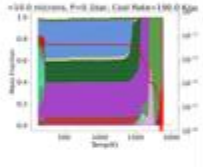
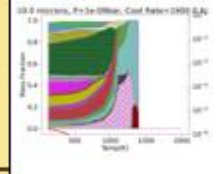
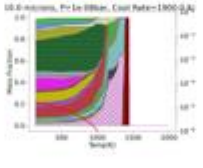
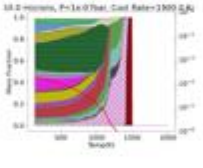
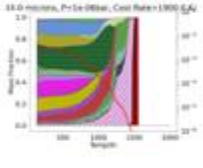
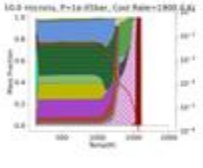
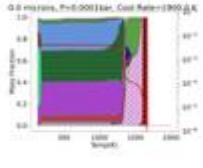
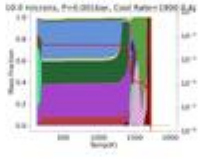
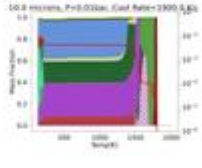
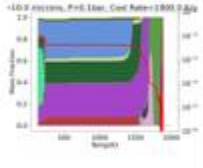
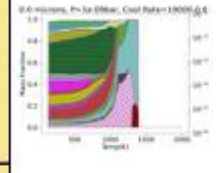
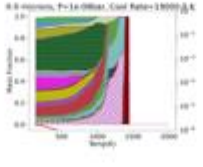
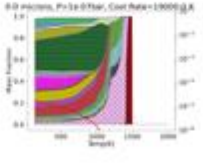
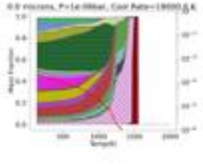
Major elements in the gas (Si, Al, Fe..) have no time to condense in fast cooling at high temp.

They become available to react at low temperature where oxides become super-saturated

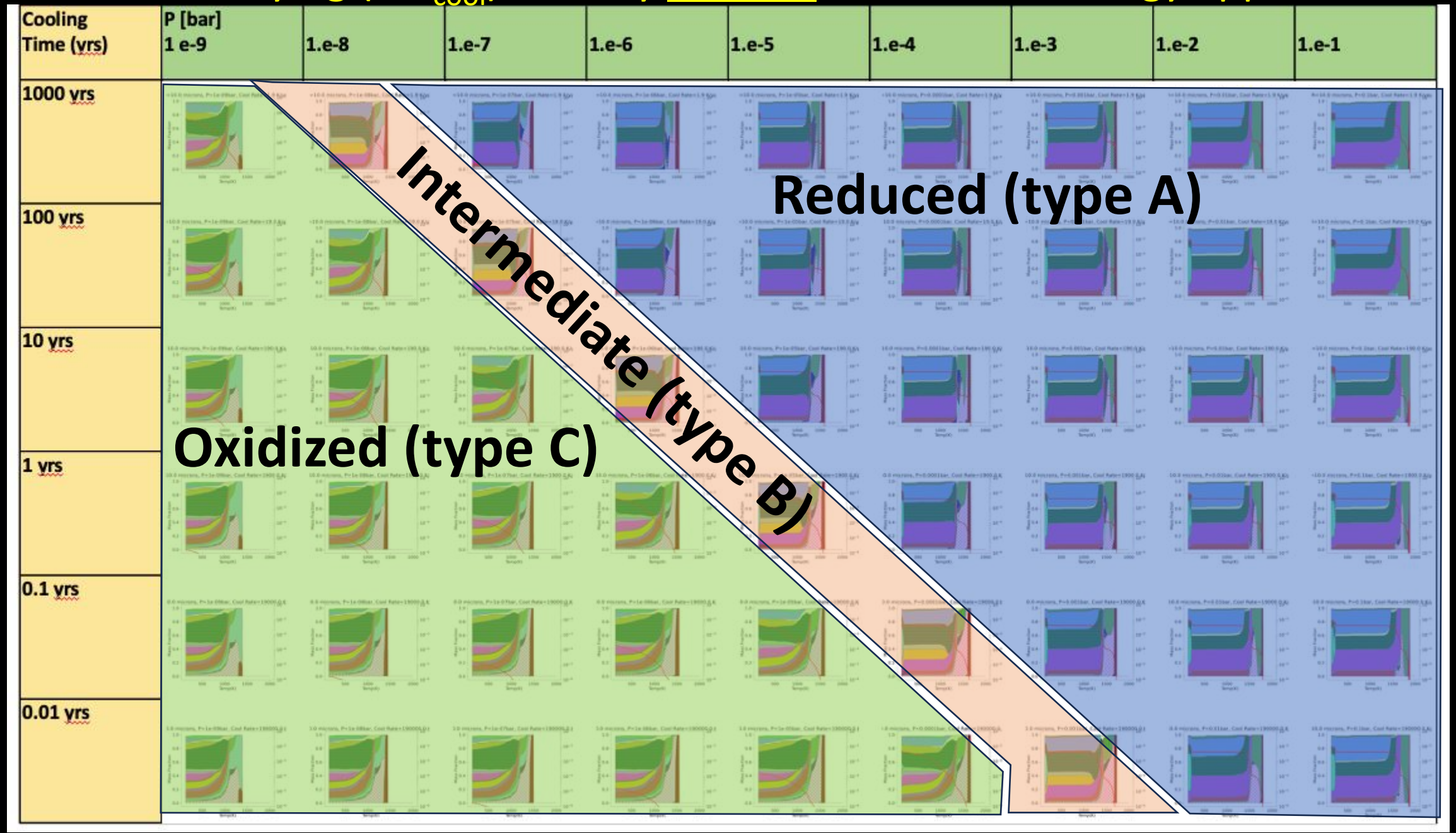


Systematic exploration of P and Tc : cooling time

when varying (P, T_{cool}) => Only 3 types of dust mineralogy appear

Cooling Time (yrs)	P [bar] 1 e-9	1.e-8	1.e-7	1.e-6	1.e-5	1.e-4	1.e-3	1.e-2	1.e-1
1000 yrs									
100 yrs									
10 yrs									
1 yrs									
0.1 yrs									
0.01 yrs									

when varying (P, T_{cool}) => Only 3 types of dust mineralogy appear

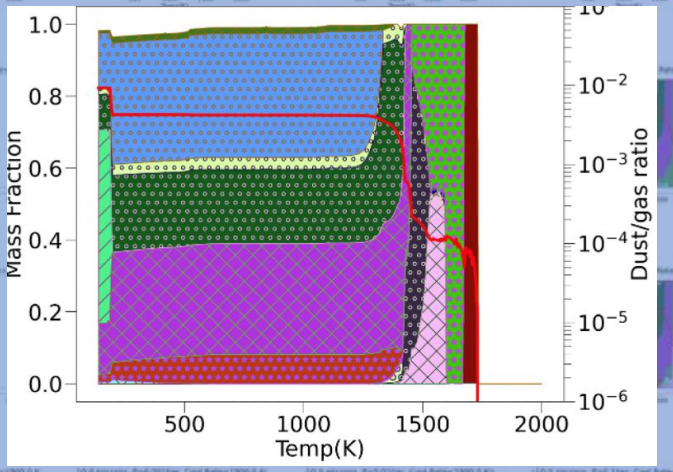


Only 3 types of dust mineralogy appear (when varying (P, T_{cool}))

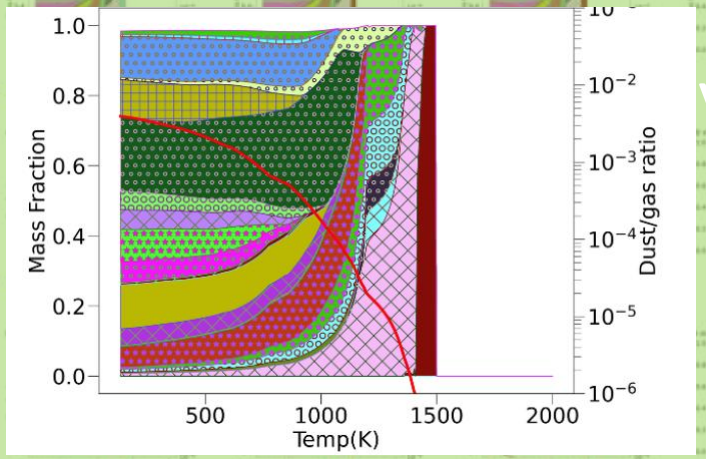
Cooling Time (yrs)	P [bar] 1 e-9	1.e-8	1.e-7	1.e-6	1.e-5	1.e-4	1.e-3	1.e-2	1.e-1
1000 yrs									
100 yrs									
10 yrs									
1 yrs									
0.1 yrs									
0.01 yrs									

Intermediate (type B)

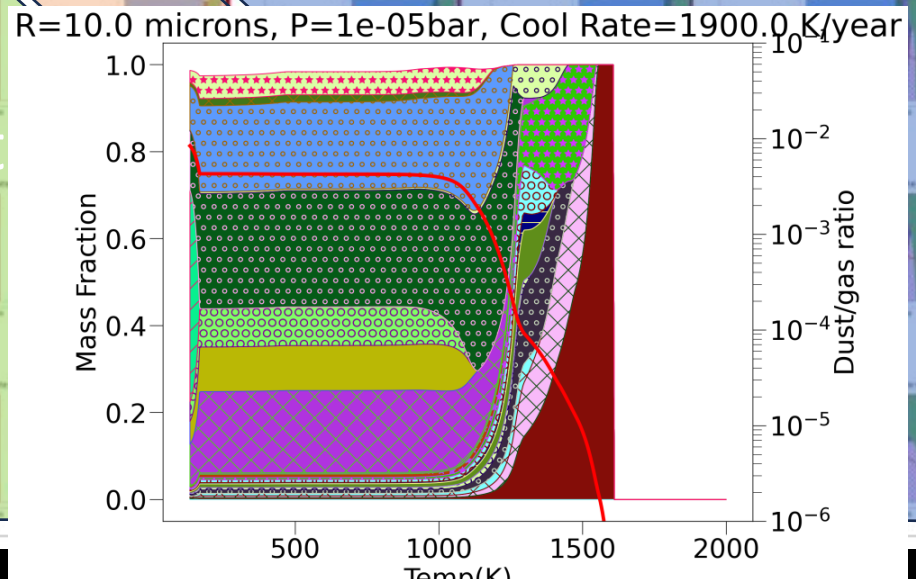
Reduced (type A)



Oxidized (type C)



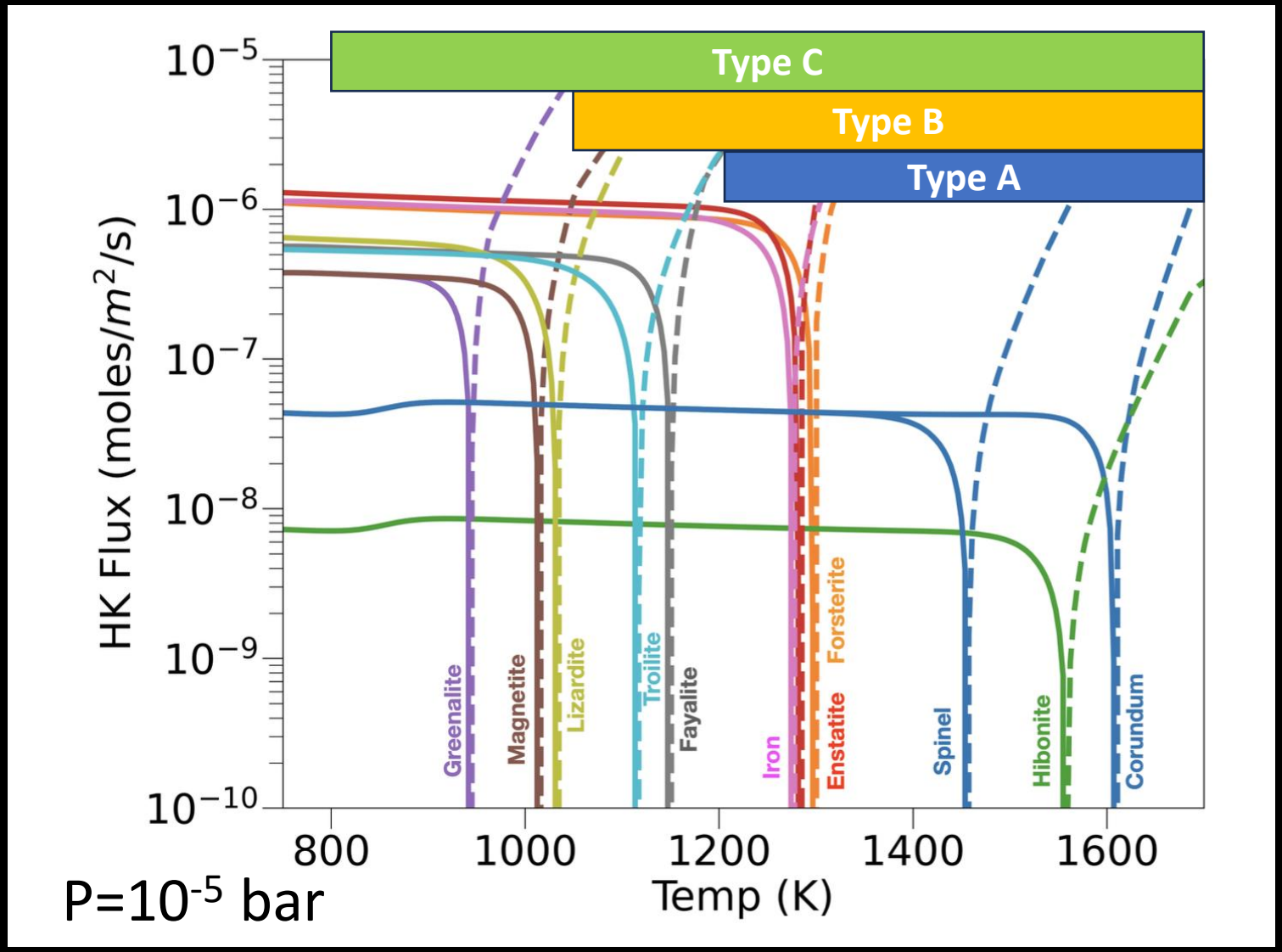
yalit



Why 3 discontinuous classes of mineralogies ?

=> Fast temperature drop allows to condense lower temperature minerals (if condensation is incomplete)

Hertz Knudsen Fluxes



Reduced (A):
All atoms condensed above 1200K
(slow coolng)

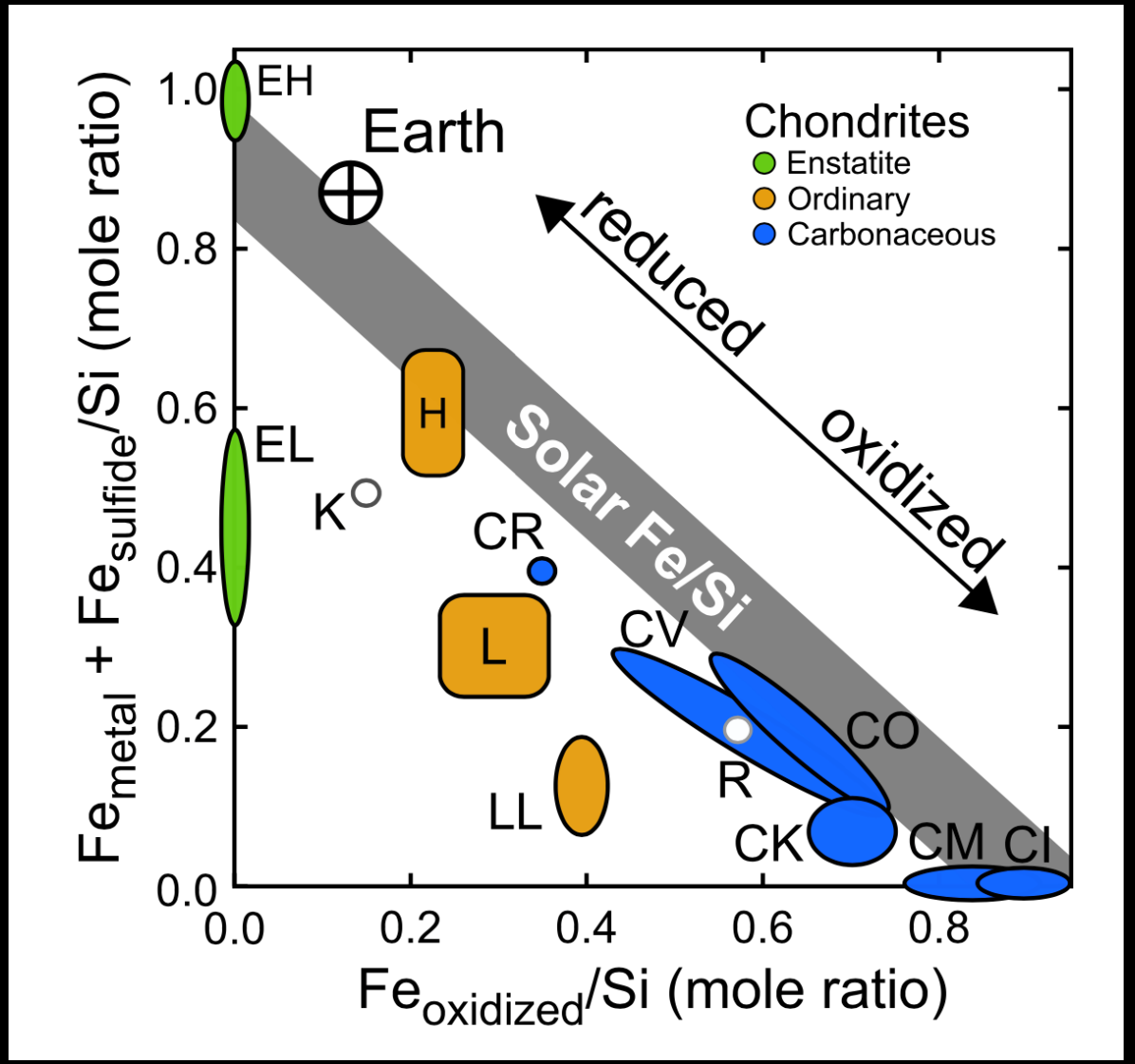
slightly oxid. (B):
All atoms condensed above 1100K
Contains **Fayalite + Fe metal**
(quite fast cooling)

Very oxidized(C):
Most atoms condensed below 800K
Contains Fayalite, phyllos., magnet.,etc.
(very fast cooling)

Computing oxydation level and Evolution in the Urey-Craig Diagram Oxidation diagram

The Urey-Craig Diagram (1953) : a proxy for the oxidation state of chondrites

Fe without O



(Urey & Craig, 1953)
adapted from
Yoshizaki et al. (2021)

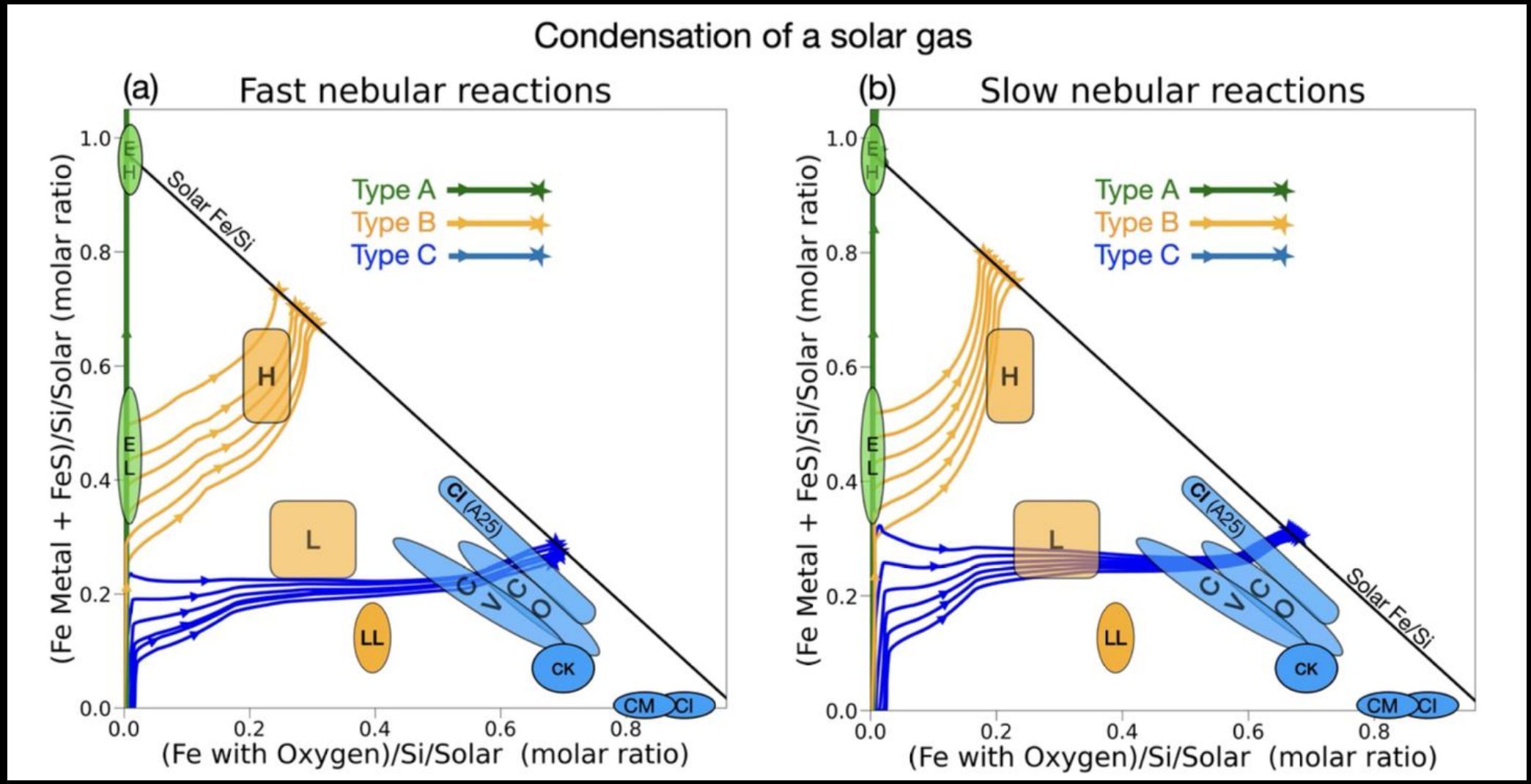
Fe with O

- Discontinuous mineralogies

Recovering the « classical » Iron Oxidation Diagram (Urey Craig)

Rapid nebular reactions

Slow nebular reactions



Discontinuous mineralogies : nothing between the 3 classes

For Fast cooling => kinetic of nebular reactions play a minor role=> Condensation dominates

Computing Equivalent FO2

What would be the apparent fO2 of the
Mineral assembage we calculated ?

Re-equilibrating our mineralogies with FACTSAGE

Apparent fo2 of mineral assemblage

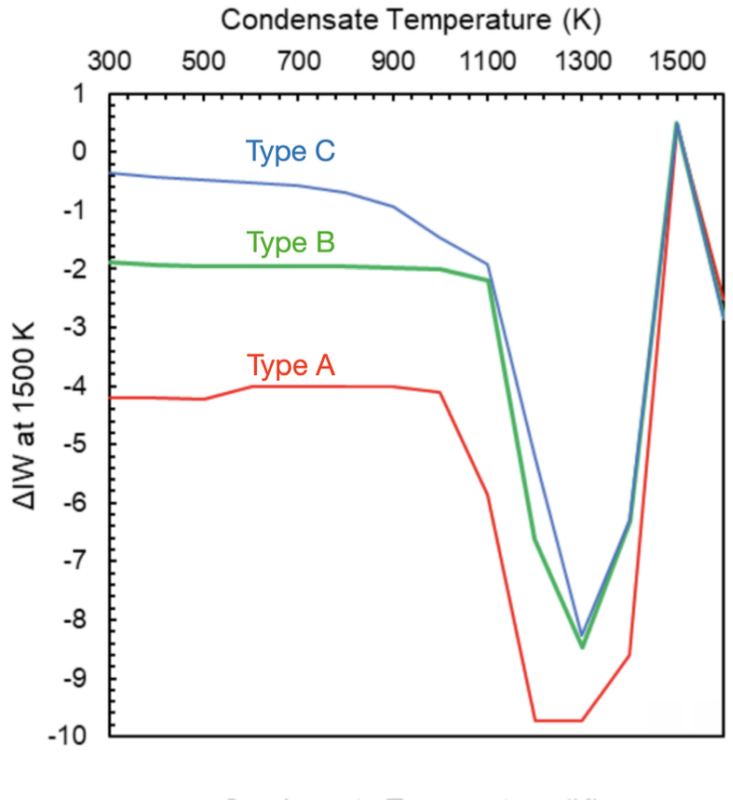
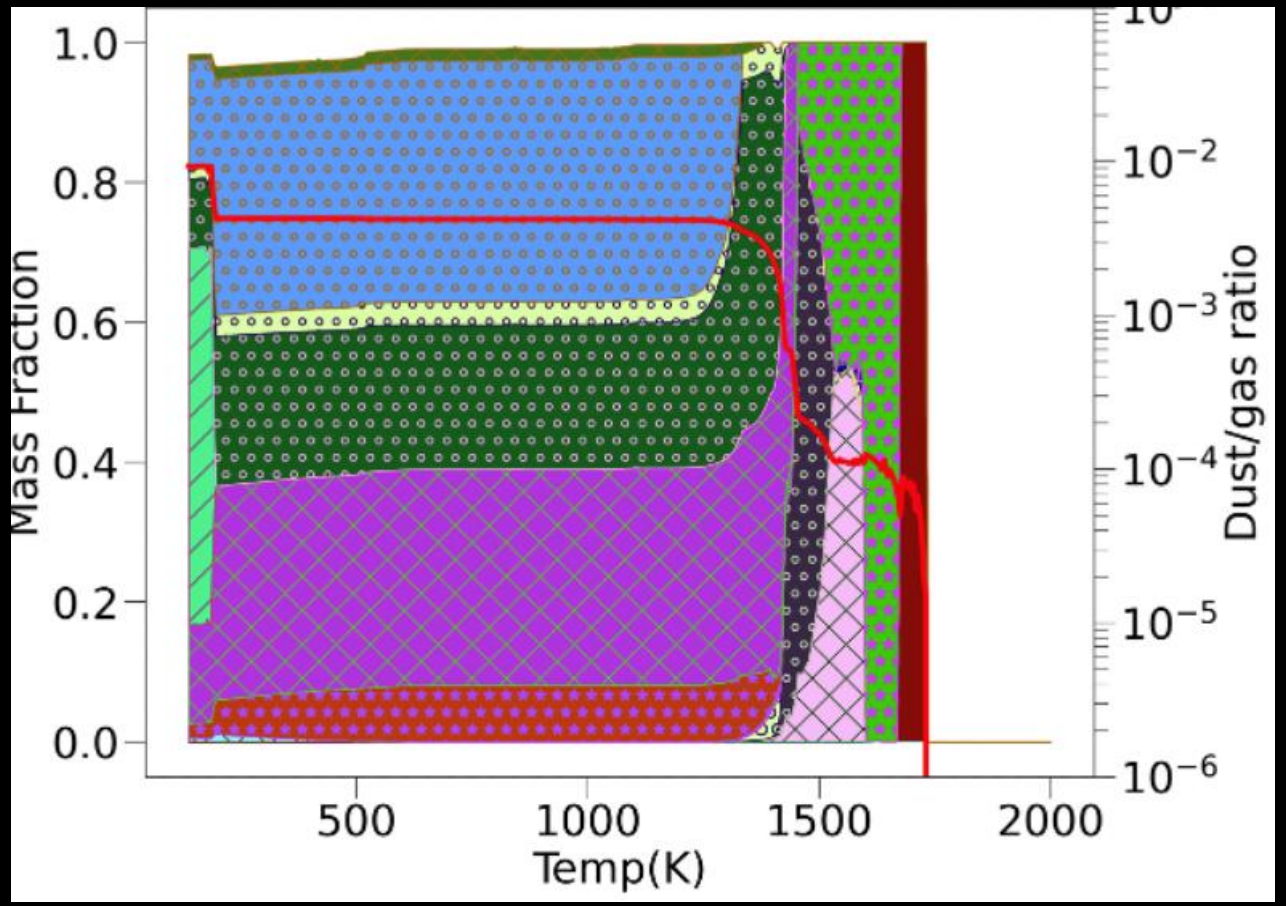


Fig. 14 Equivalent fo2 of re-equilbrated mineralogies for the three types A,B and C. The X axis stands for the temperature at which condensates are considered, while the Y axis gives the equivalent fo2 (with respect to the iron-wustite buffer). Here the types A,B,C are computed using the fast nebular reaction case.

Type A



Re-equilibrating our mineralogies with FACTSAGE

Apparent fo2 of mineral assemblage

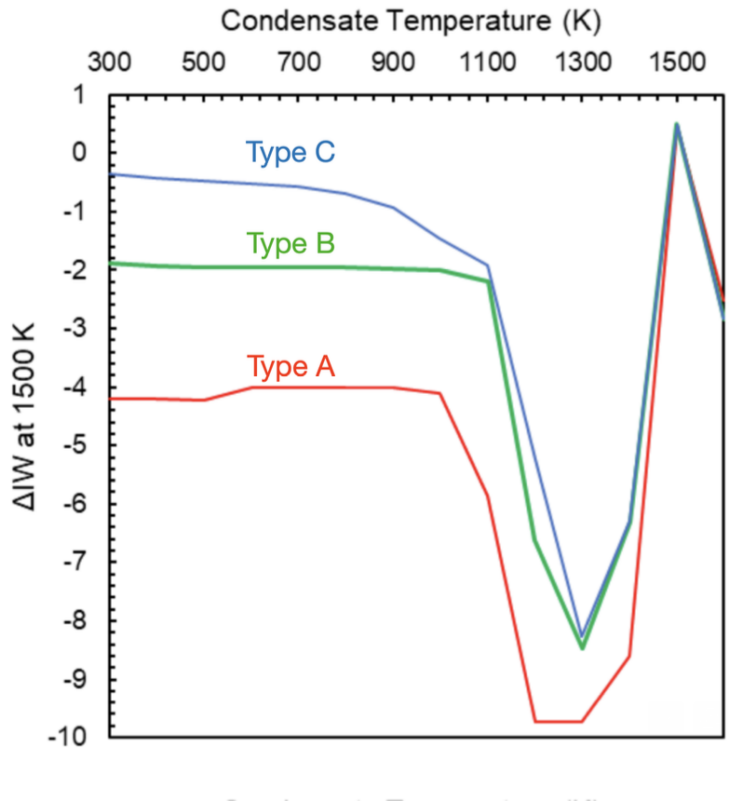
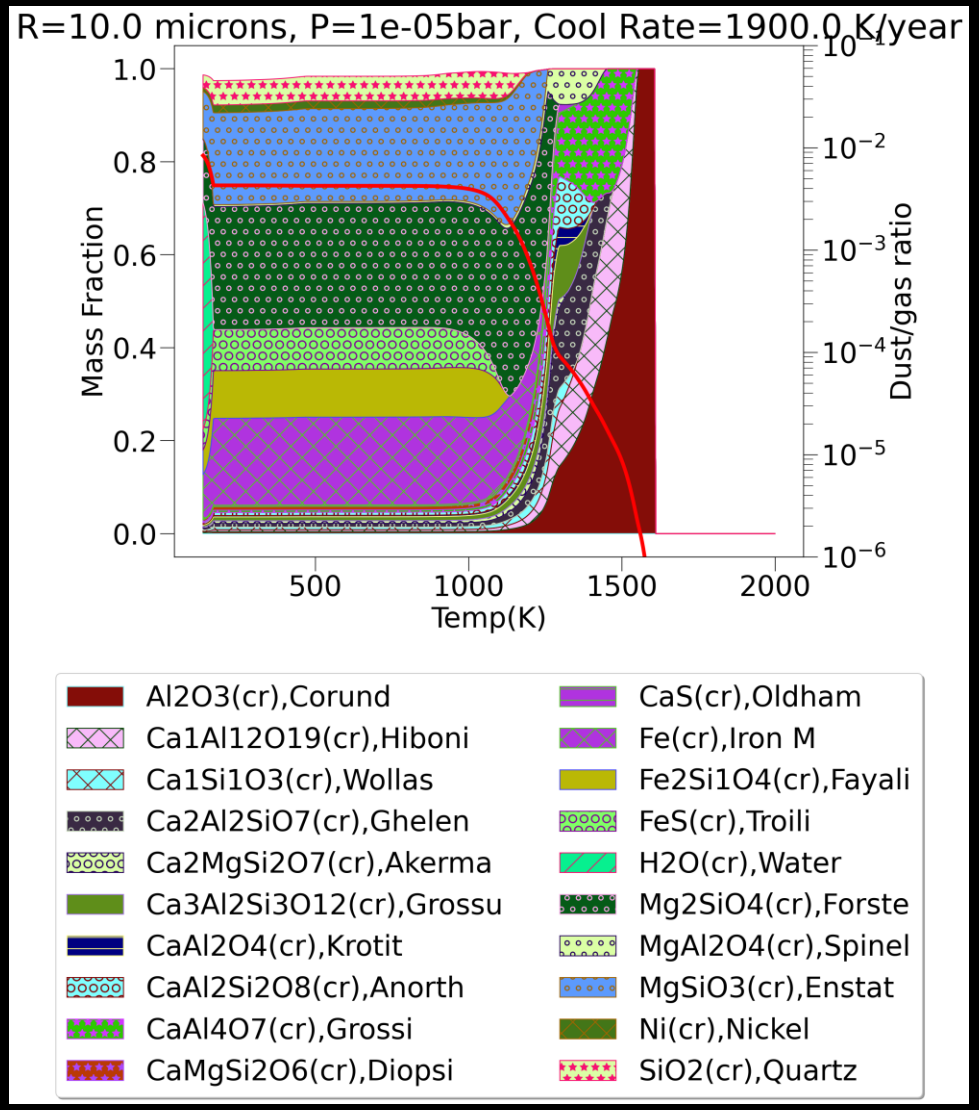


Fig. 14 Equivalent fo2 of re-equilbrated mineralogies for the three types A,B and C. The X axis stands for the temperature at which condensates are considered, while the Y axis gives the equivalent fo2 (with respect to the iron-wustite buffer). Here the types A,B,C are computed using the fast nebular reaction case.

Type B



Re-equilibrating our mineralogies with FACTSAGE

Apparent fo2 of mineral assemblage

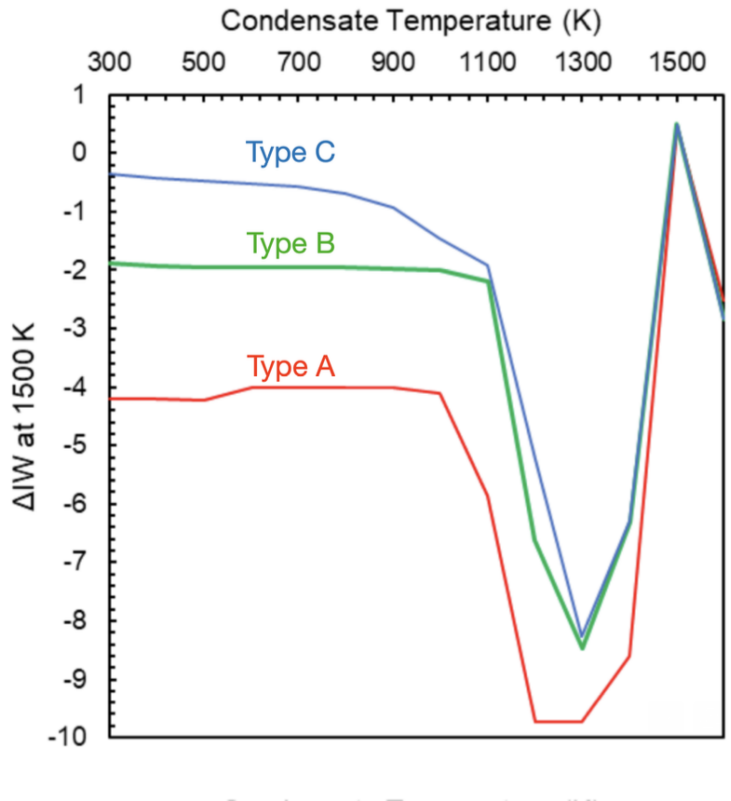
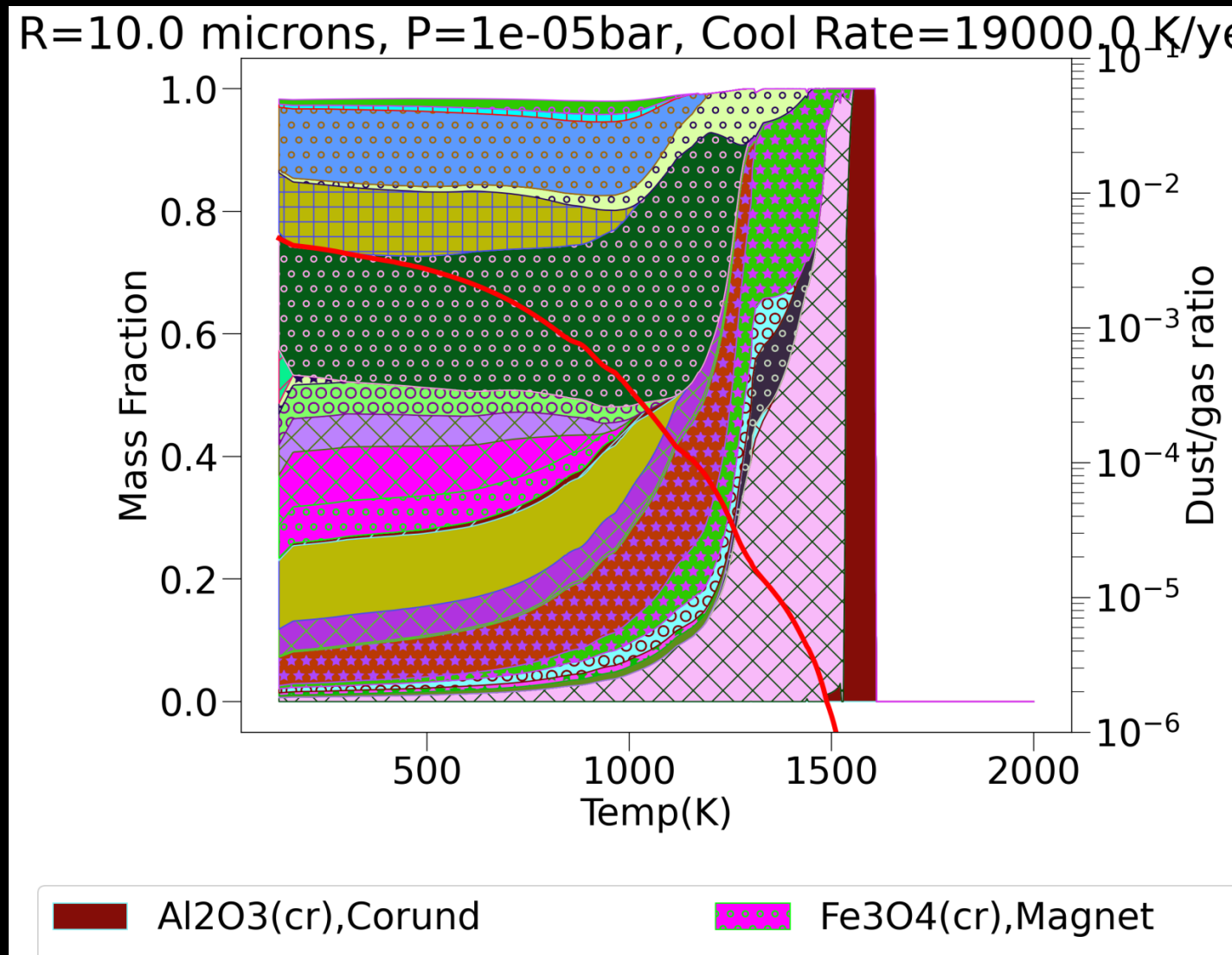
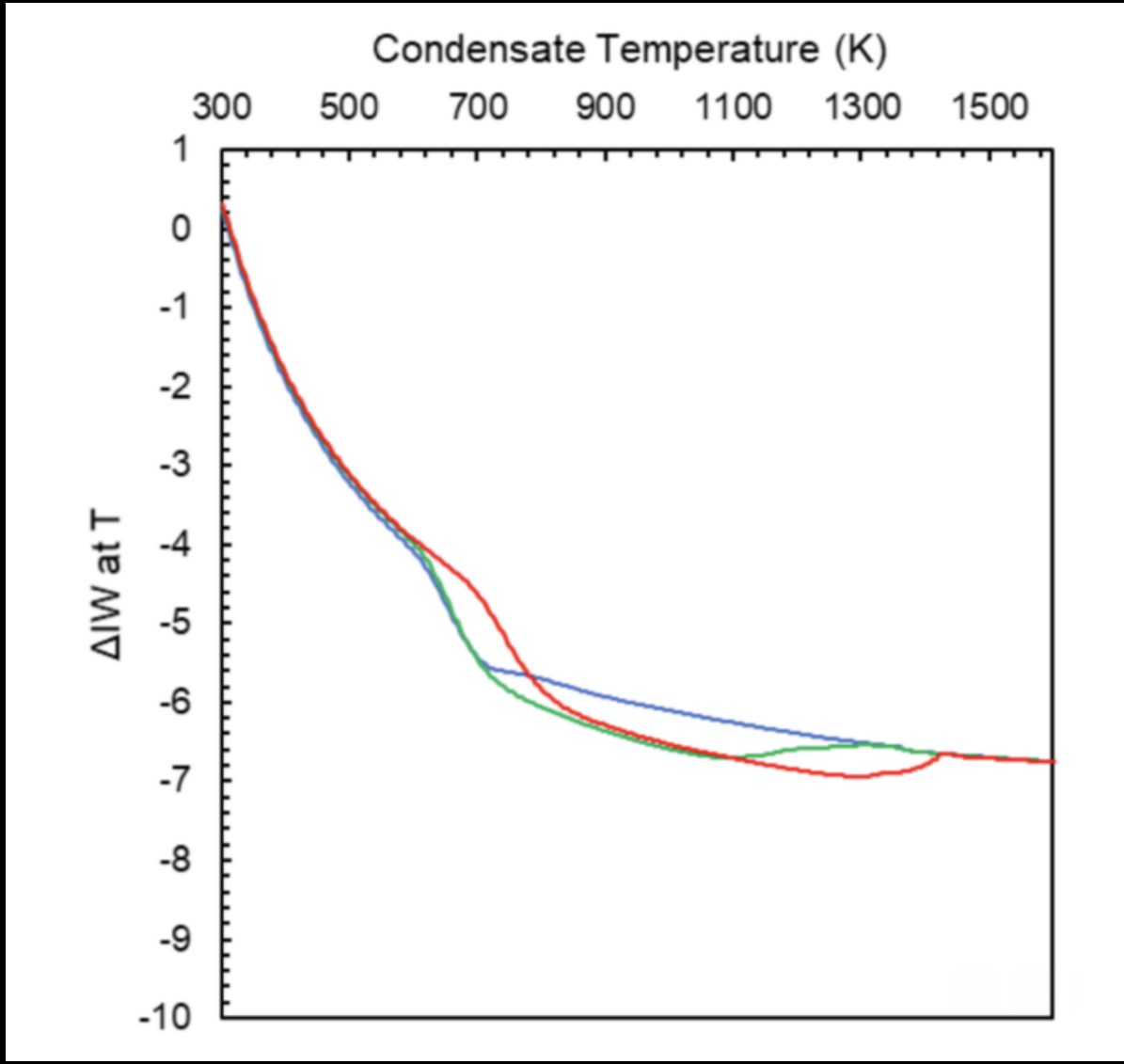


Fig. 14 Equivalent fo2 of re-equilbrated mineralogies for the three types A,B and C. The X axis stands for the temperature at which condensates are considered, while the Y axis gives the equivalent fo2 (with respect to the iron-wustite buffer). Here the types A,B,C are computed using the fast nebular reaction case.

Type C

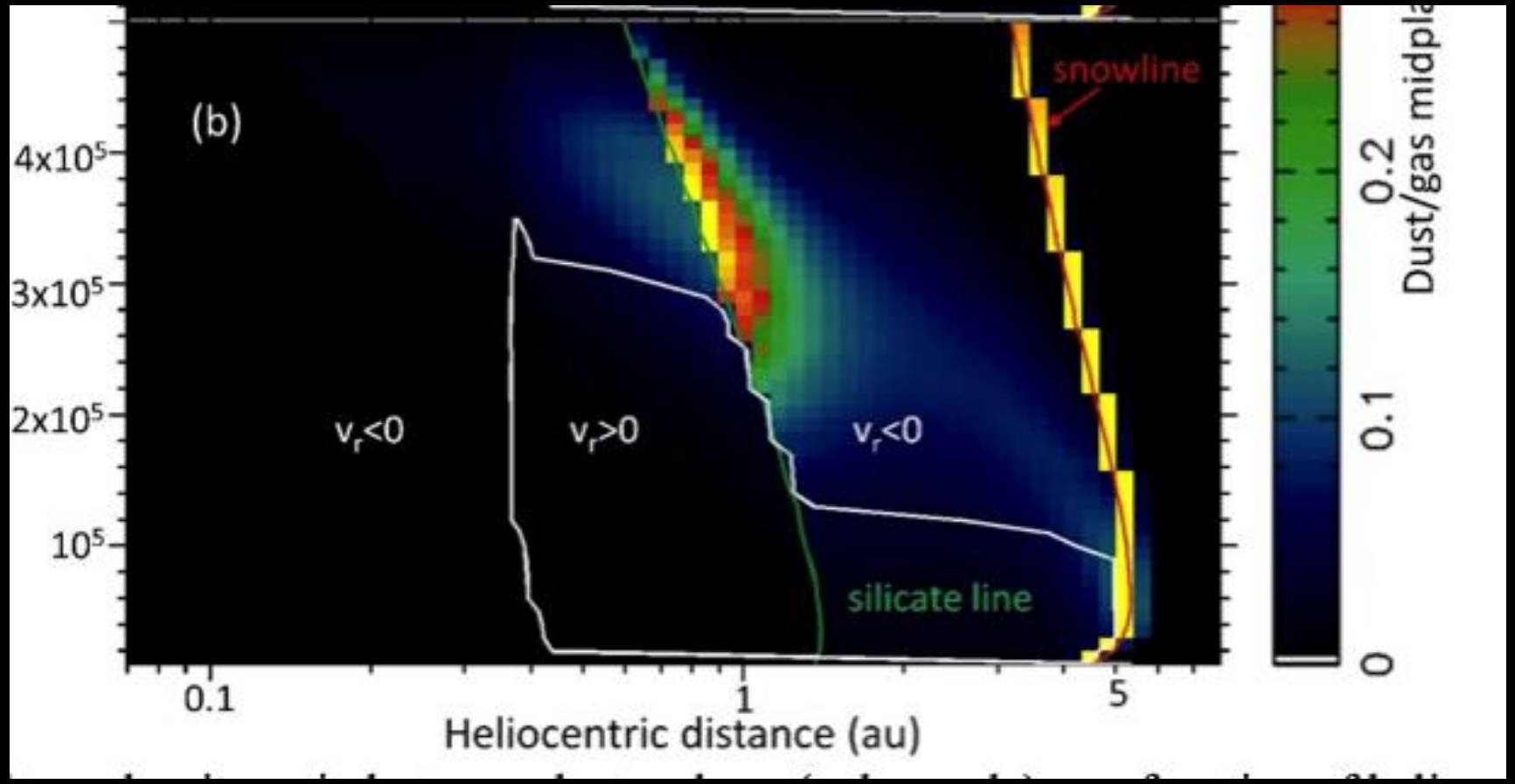


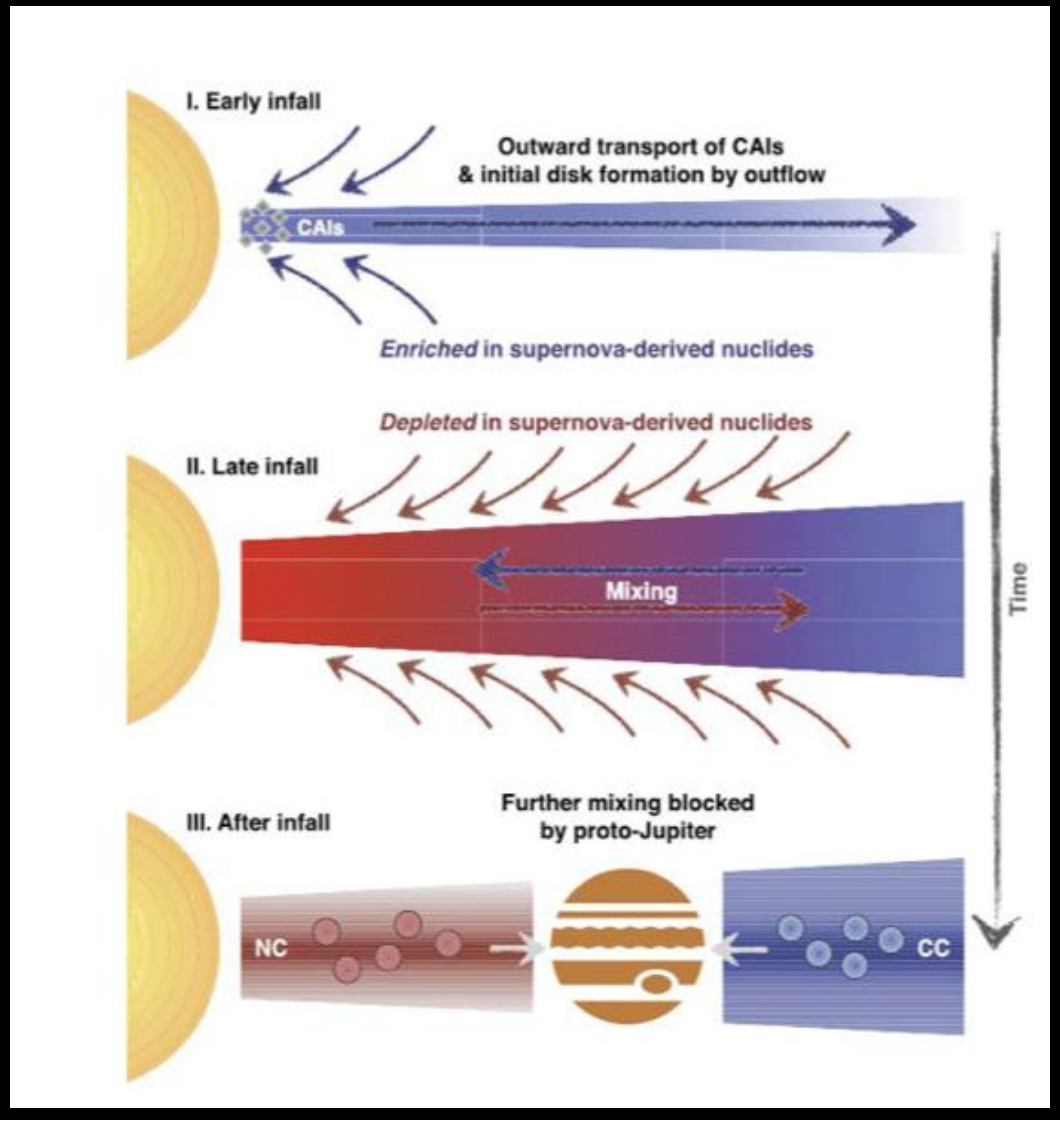
But the TRUE fO2 is :



Very different
From mineral
Assemblages

The model of planetesimals formation in 2 sites (Morbidelli et al., 2022)





⇒ NC planetesimals should form in a water free environement

⇒ NC population should be « oxygen poor » =>reduced

Fig. 10. Origin of the isotopic dichotomy. Left: Scheme of the accretion of material of changing isotopic composition in the inner part of the disk, as the disk is radially spreading, from Nanne et al. (2019). This established an isotopic gradient throughout the disk which is then turned into a dichotomy by the formation of early planetesimals at two distinct sites (Morbidelli et al. 2022) and the establishment of a barrier against radial drift of dust, here symbolized by Jupiter (see Sect. 4.2). Right: Isotopic composition in Δ^{95}Mo of CAIs (Brennecka et al. 2020), showing that the shift from the original isotopic composition toward the NC composition started to occur while condensation of calcium-aluminum inclusions was still ongoing.

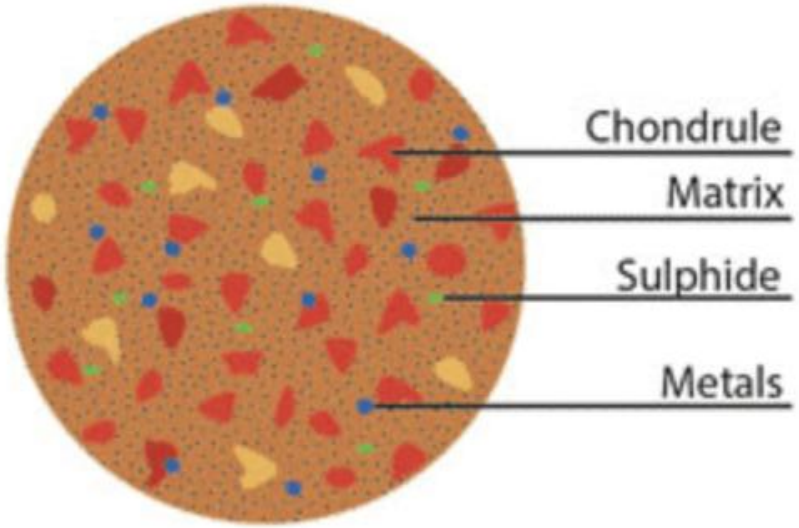
A ‘stone in the shoe ’=> Grewal 2024 paper

⇒ Interested in Iron meteorites

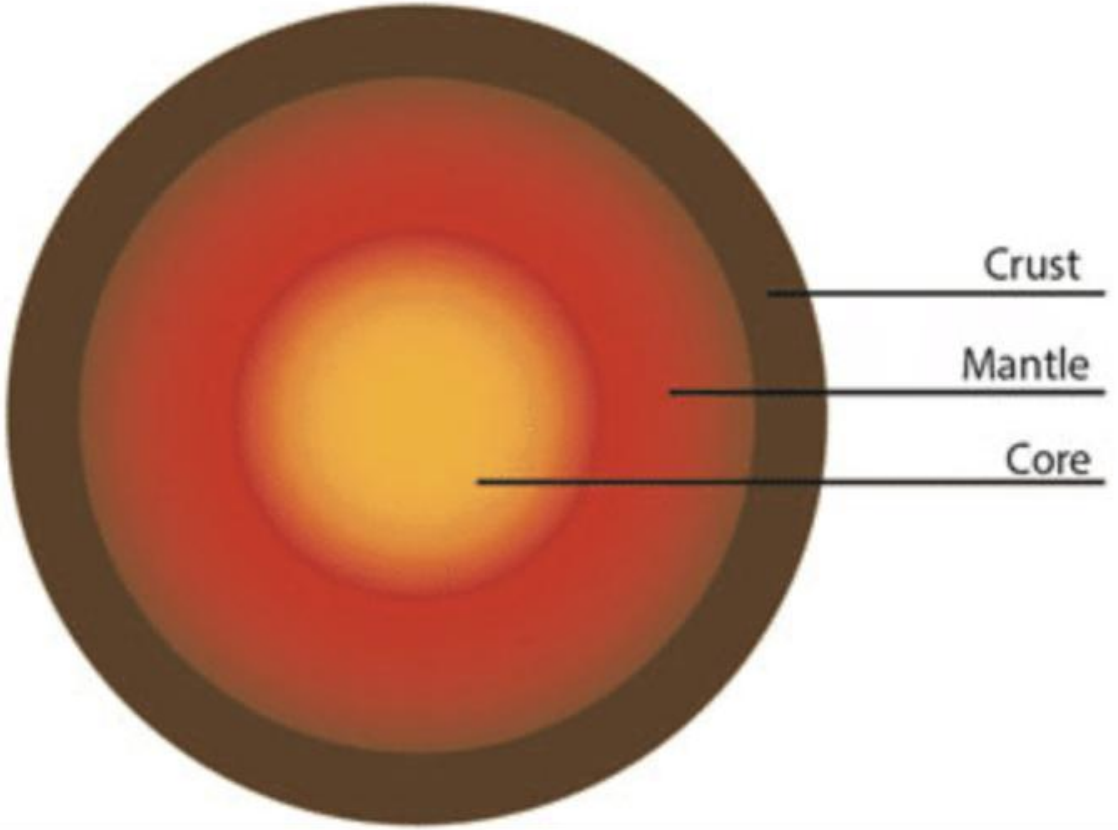
⇒ (cores of an old population of differentiated planetesimals)

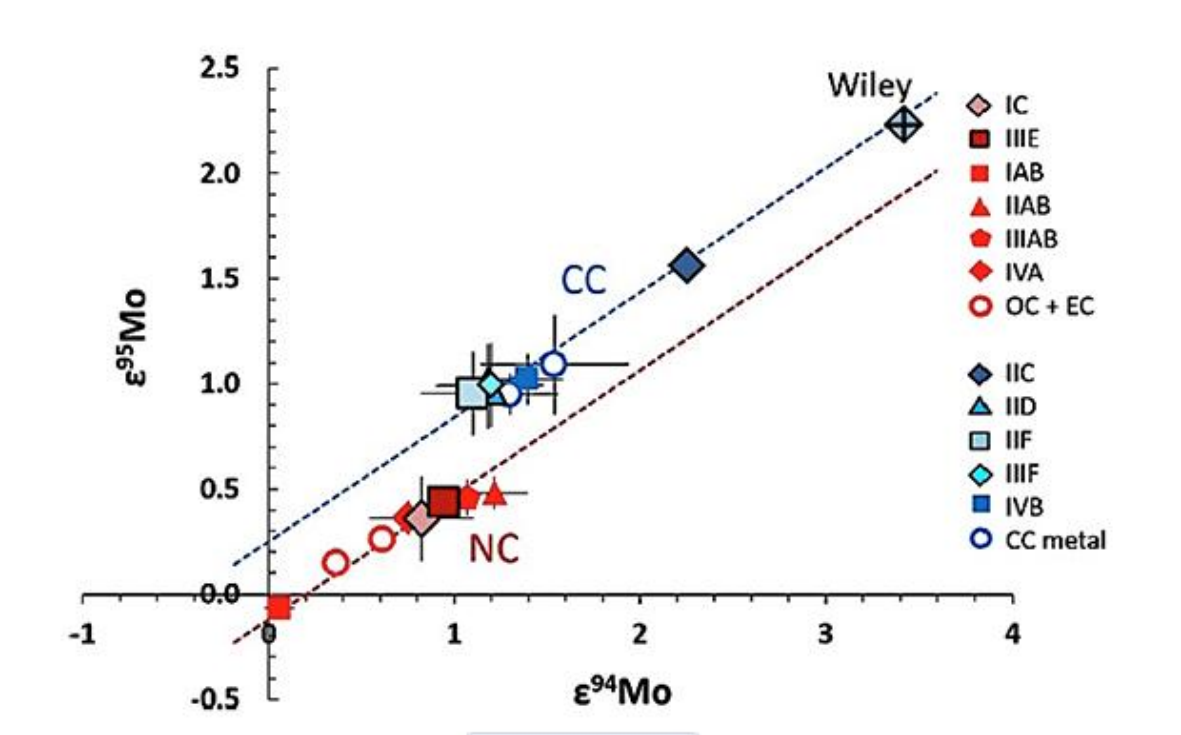
⇒ Very old (comparable to CAIs age)

Undifferentiated asteroids

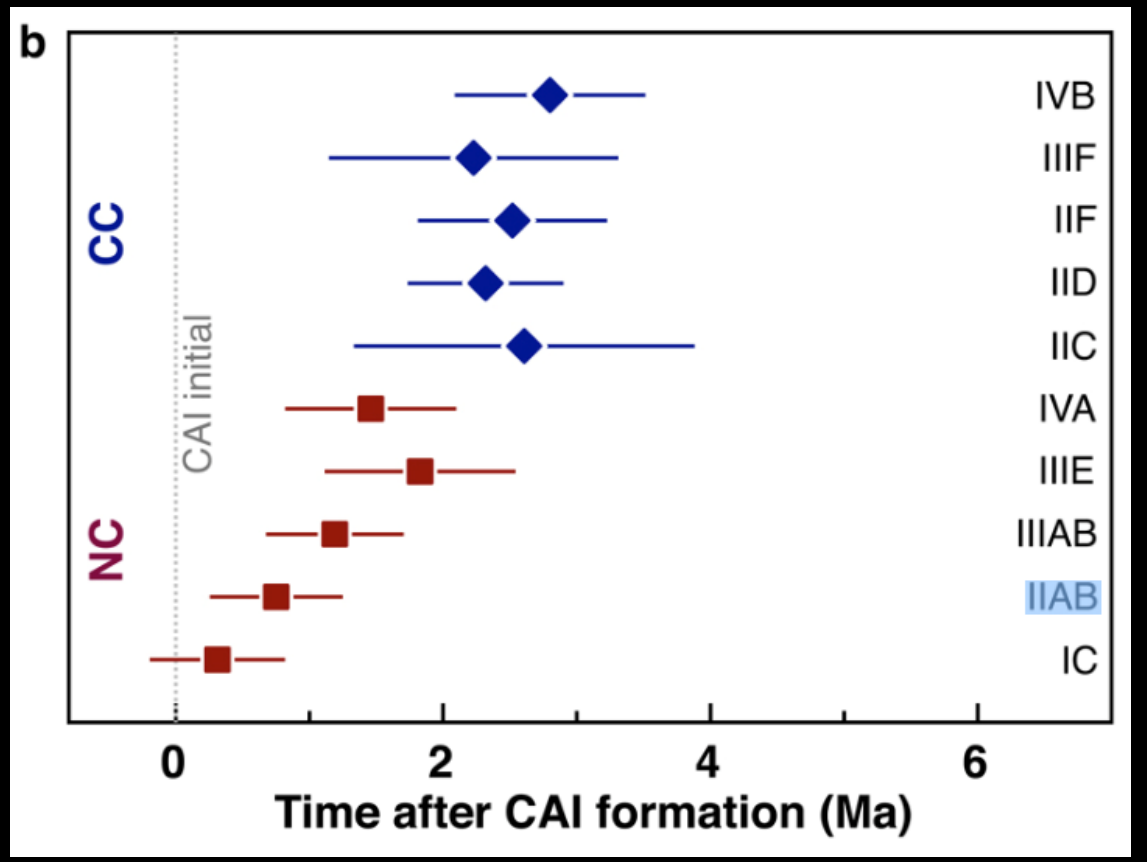


Differentiated asteroids and planets





Scott et al., 2022

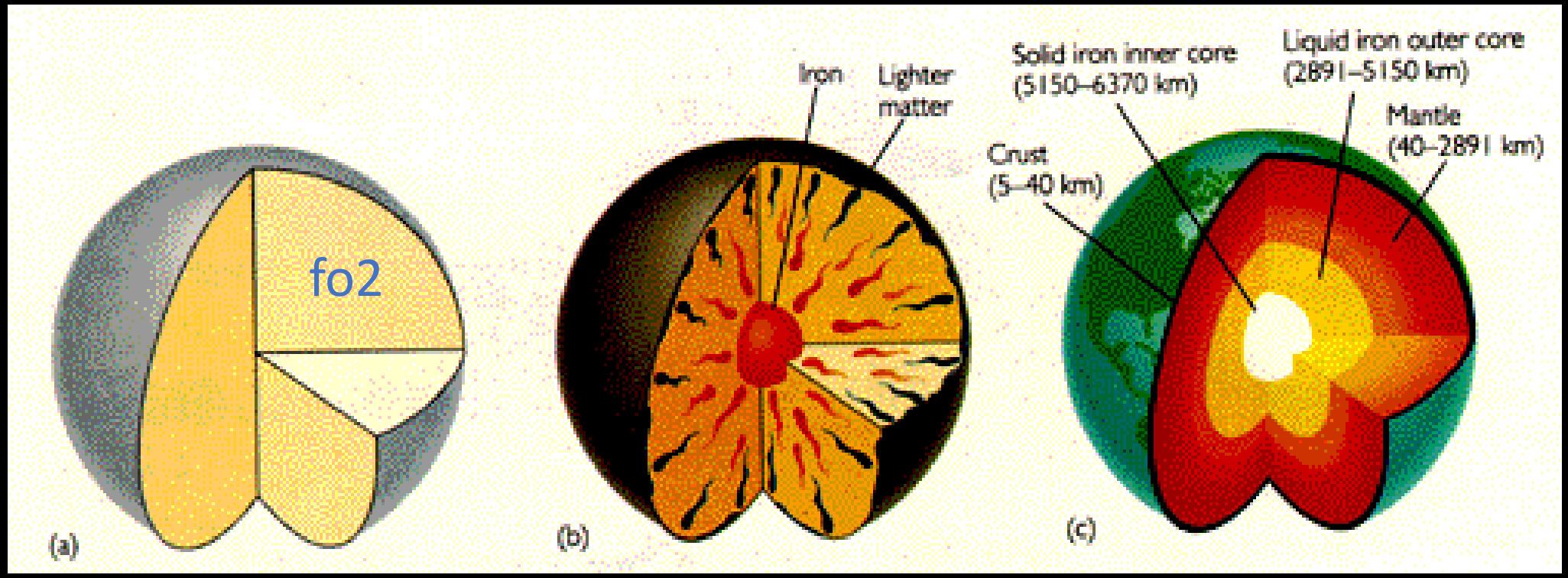


Kruijet 2024, age of differenciation
Of magmatic iron meteorites

The Oxidation state of Iron meteorite :

It is possible to determine the oxidation state of the PARENT BODY of iron meteorites by measure their Iron/Nickel and Cobalt/Nickel ratio

⇒ Their ratio depend on the amount of oxygen during differenciation..



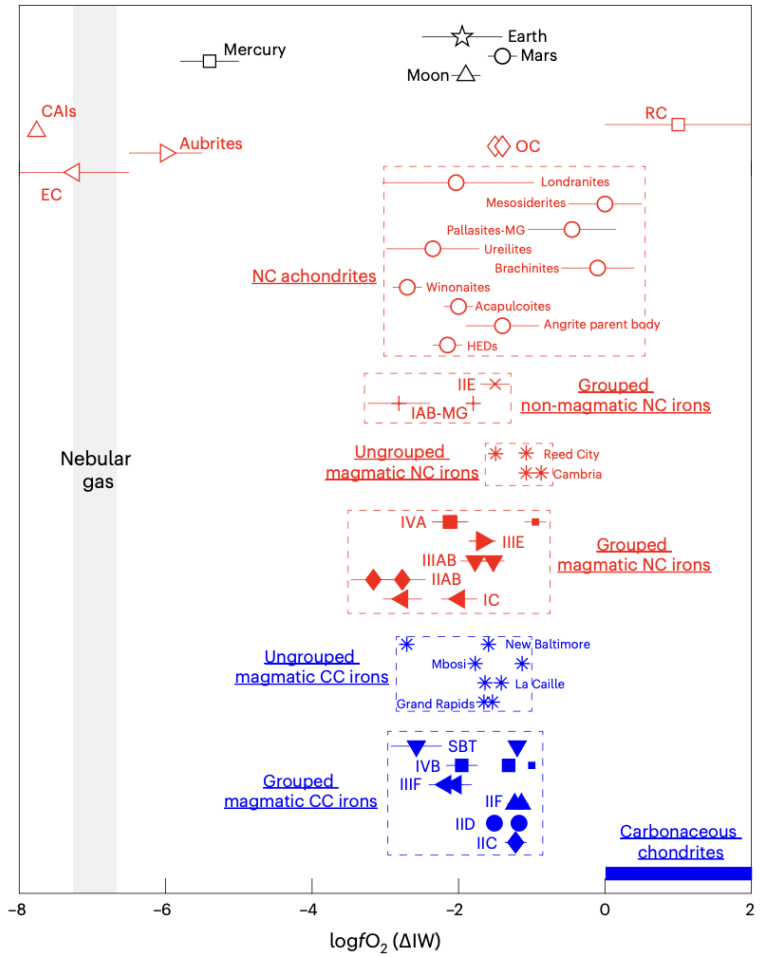


Fig. 3 | Variations in the oxidation states of various Solar System objects and reservoirs. The fO_2 of all rocky bodies in the NC (red) and CC (blue) reservoirs (except for the EC and aubrite parent bodies) are several orders of magnitude higher than the nebular gas and CAIs[47]. Grouped NC IMPBs are not drastically more reduced than their CC counterparts. The fO_2 of grouped NC IMPBs are similar to those of ungrouped IMPBs, non-magmatic irons, OCs and several other groups of achondrites from the NC reservoir. The fO_2 prevailing during core–mantle differentiation of Earth (final event), Mars and the Moon also lie within the range of grouped NC IMPBs and other oxidized NC planetesimals. The two symbols for each grouped and ungrouped magmatic iron represent fO_2 calculated using their Fe/Ni and Fe/Co ratios. The smaller symbols for IVA and IVB groups represent fO_2 estimates from previous studies[18,29]. Error bars for grouped and ungrouped magmatic irons represent 1σ deviation from the mean obtained by the propagation of uncertainty from individual terms in the fO_2 calculation of equation (2). The plotted data are reported in Extended Data Tables 2–4

Oxidation state of Iron NC and CC Meteorites is similar !

⇒ NC Iron meteortie
are not particularly « less oxidized »
Than CC meteorties

⇒ Grewal concludes that NC formed
At the snow line in the presence of
Liquid/solid water

Grewal 2024

Kinetic condensation offers a possible way (?) to reconcile

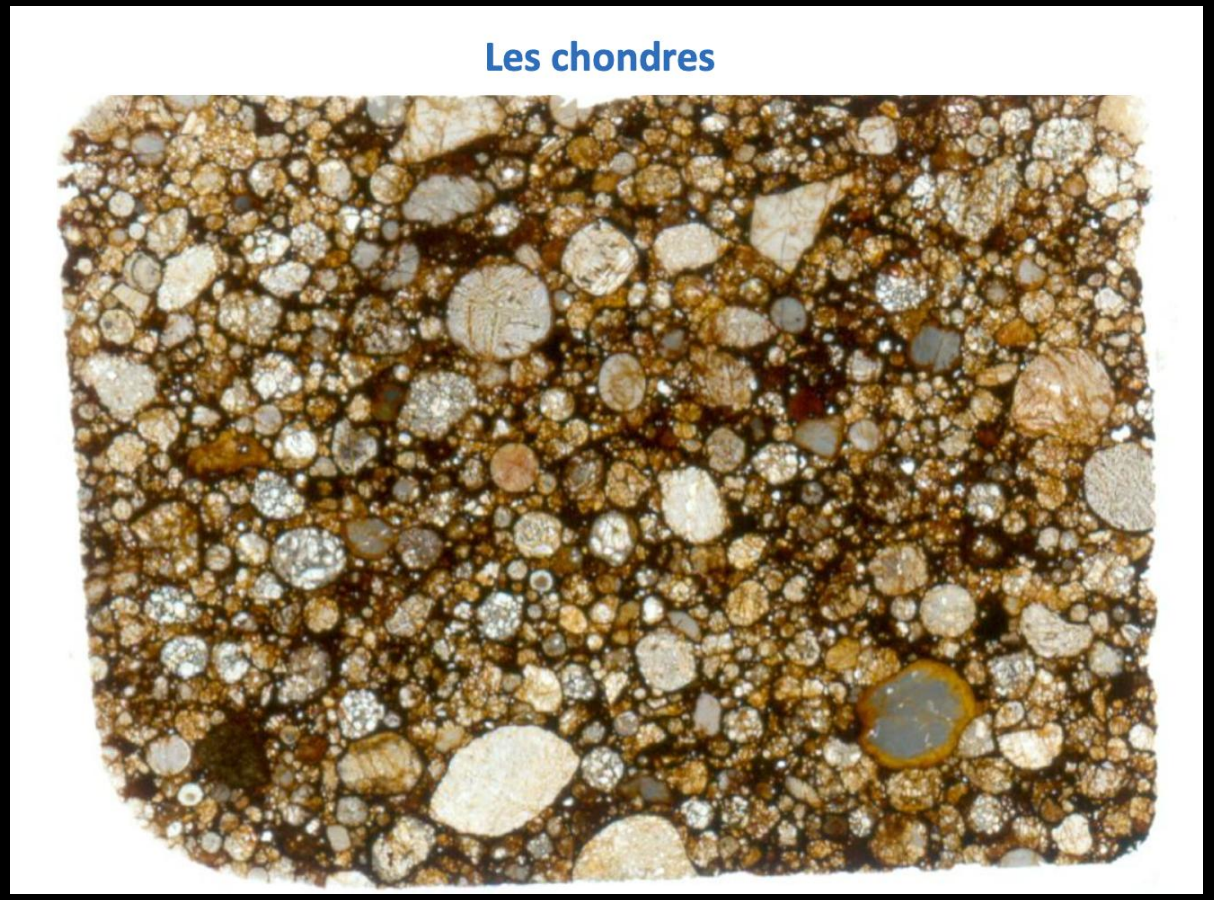
$\Rightarrow$ Kinetic condensations shows that rapid condensation may lead to Oxidized state, if accretion occurs in an hydrogen rich environment

$\Rightarrow$ The Oxidation state is more a sign of the « out of equilibrium » nature Of the condensation process , rather than the Oxygen environement

=> Heat and Cool my open a solution

We know there are heating and cooling processes in the early S.S.

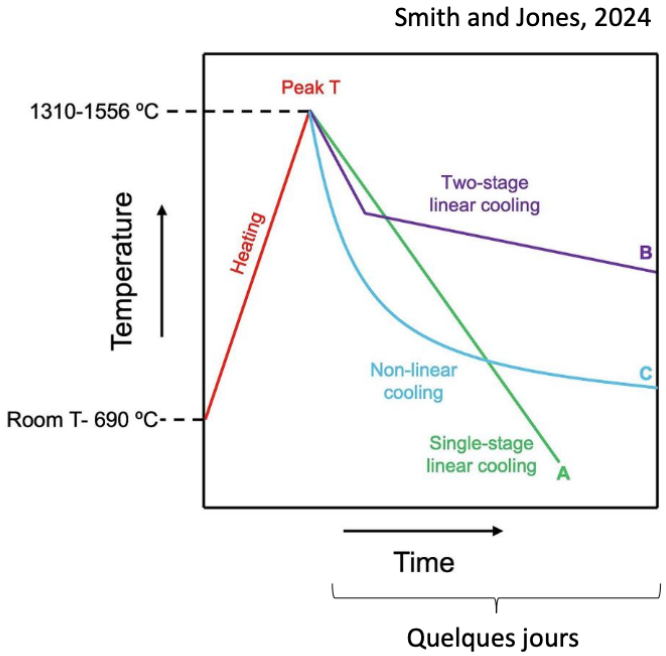
=> Example : chondrules



Molten silicate beads
heated > 1500 K

Histoire thermique des chondres

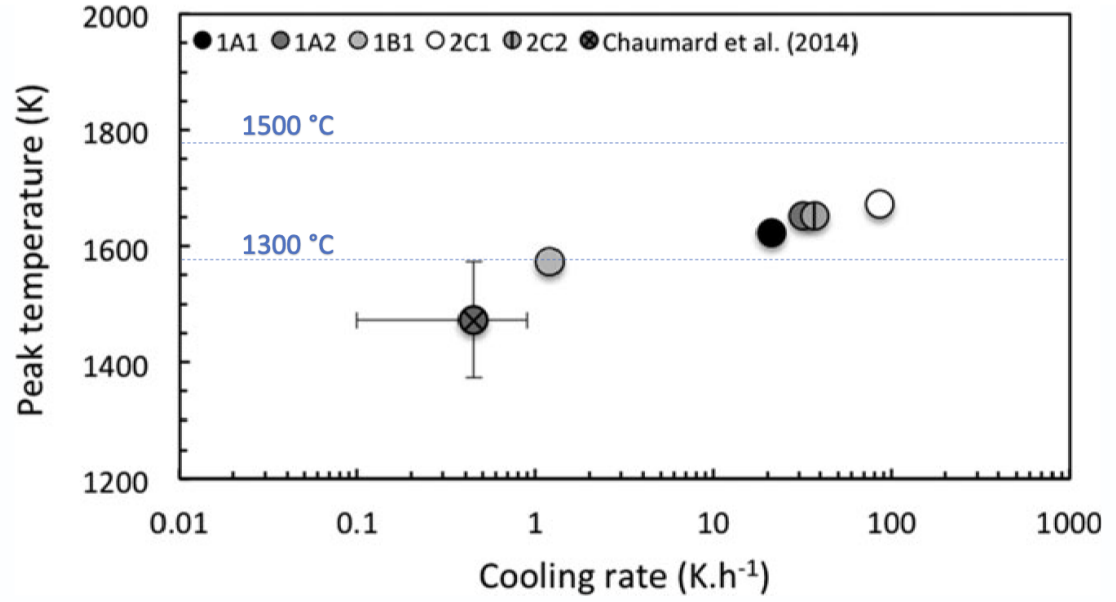
Smith and Jones, 2024



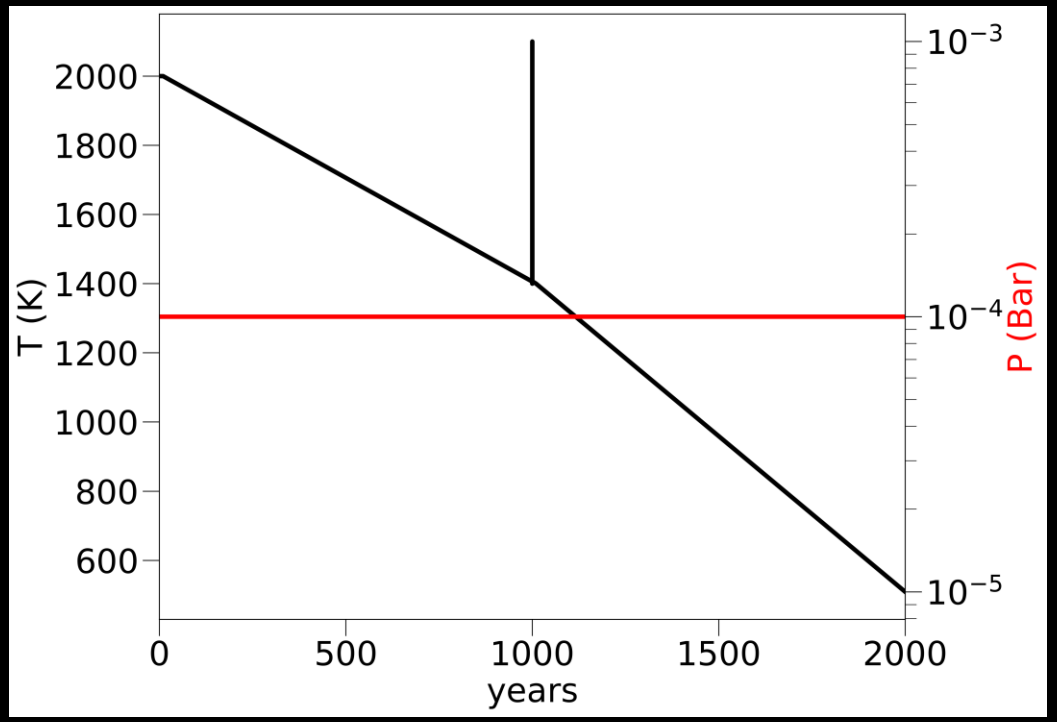
Expériences de laboratoire visant à reproduire la texture, la minéralogie et la chimie des chondres

Taux de refroidissement de
30 and 90 °C/h à 1310–1507 °C,
6 °C/hr à <1200 °C

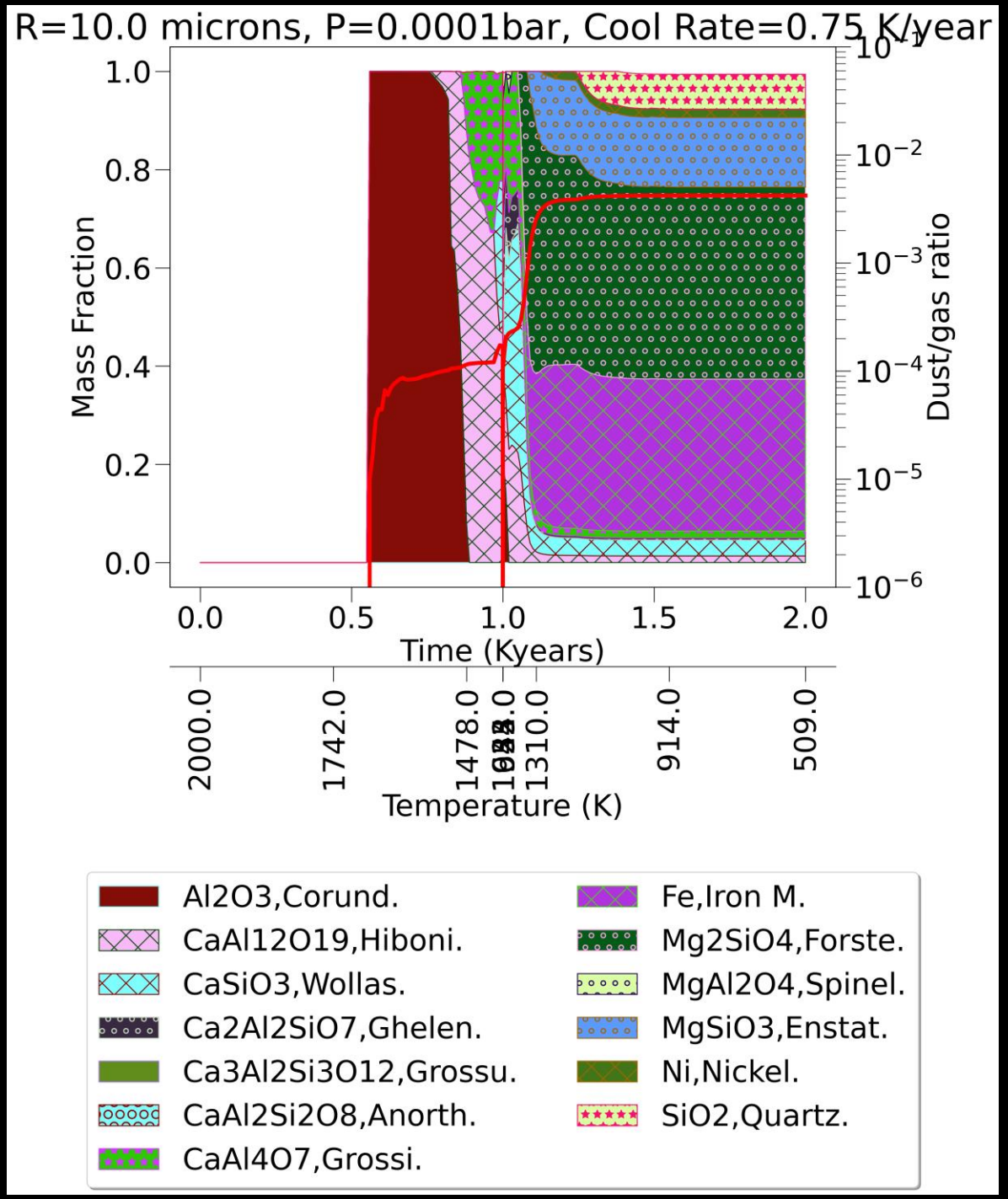
Chaumard et al. (2018): analyse de grains de métal dans ou près des chondres



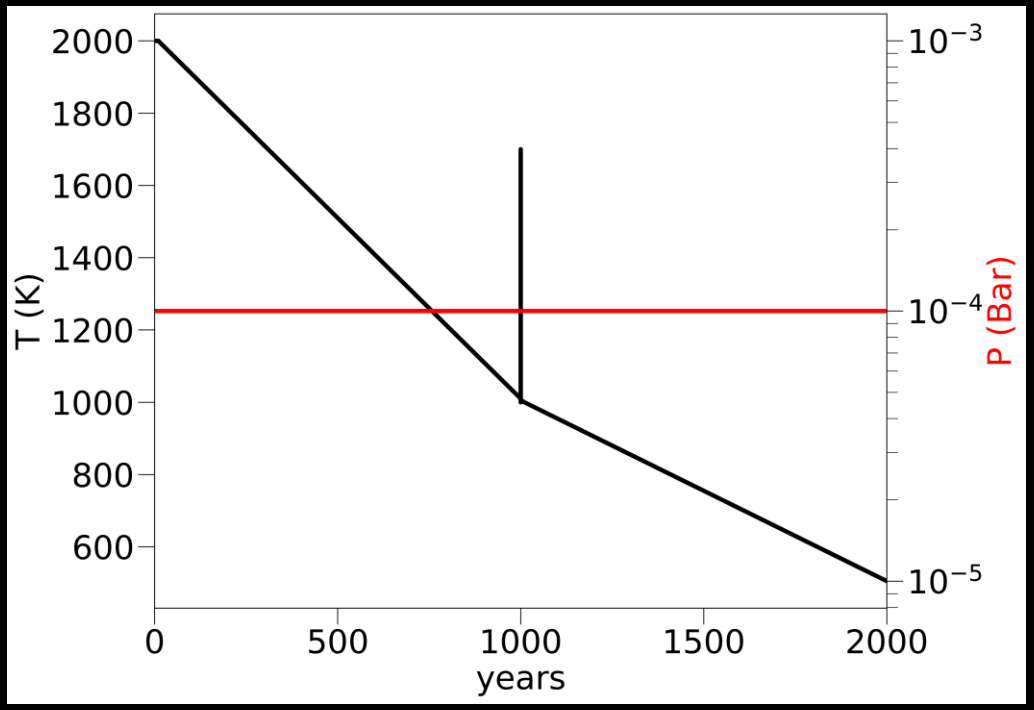
THERMAL PULSE 1: in a hot disk



Reduced mineralogy form
⇒ Close to enstatite.

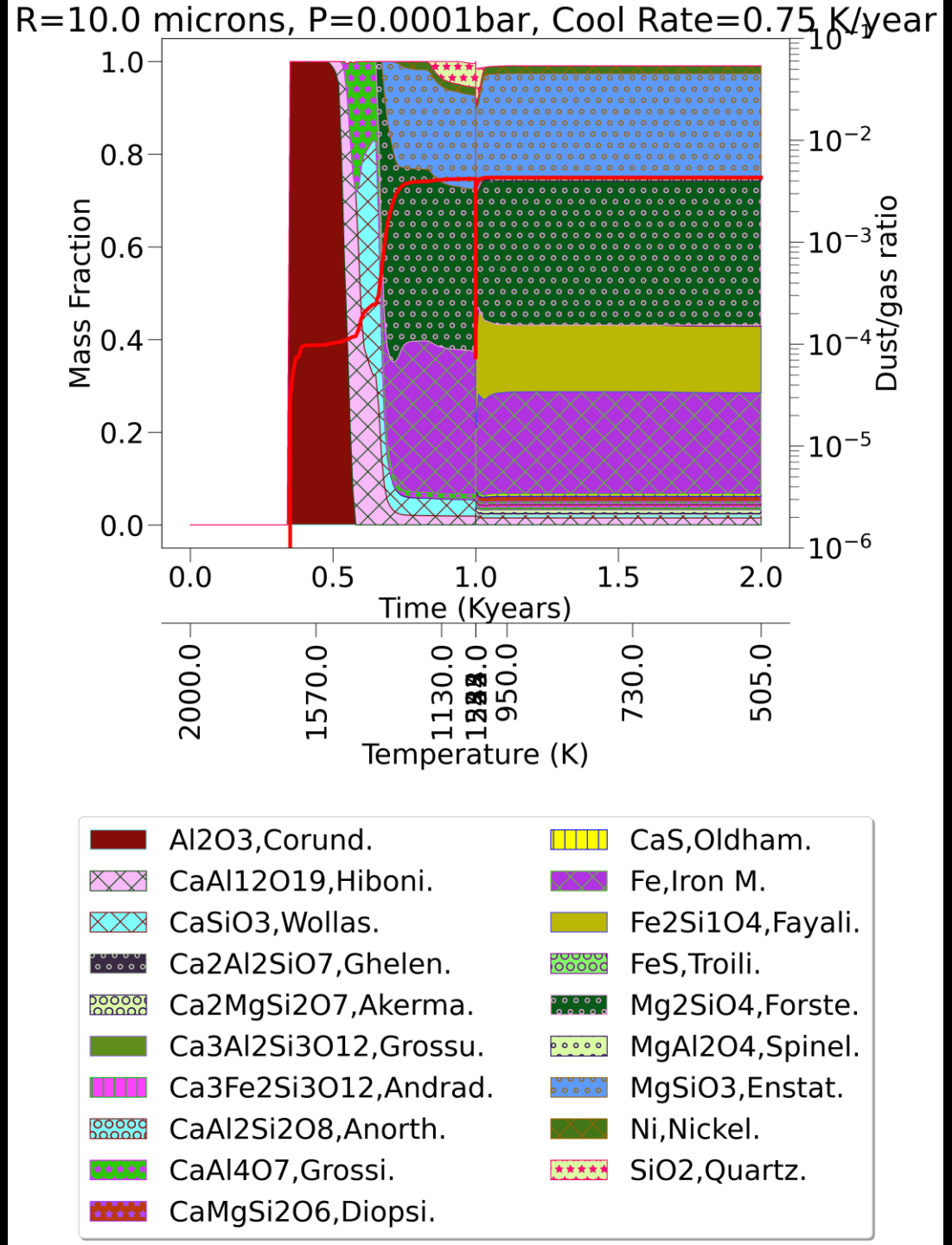


THERMAL PULSE 2 : in a warm disk

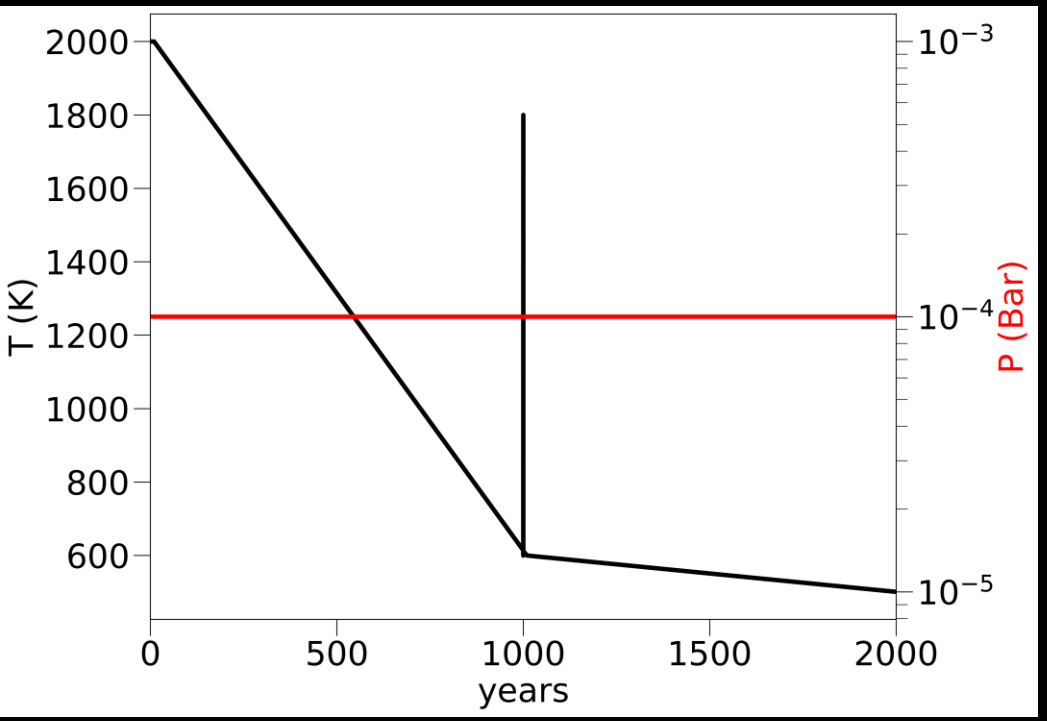


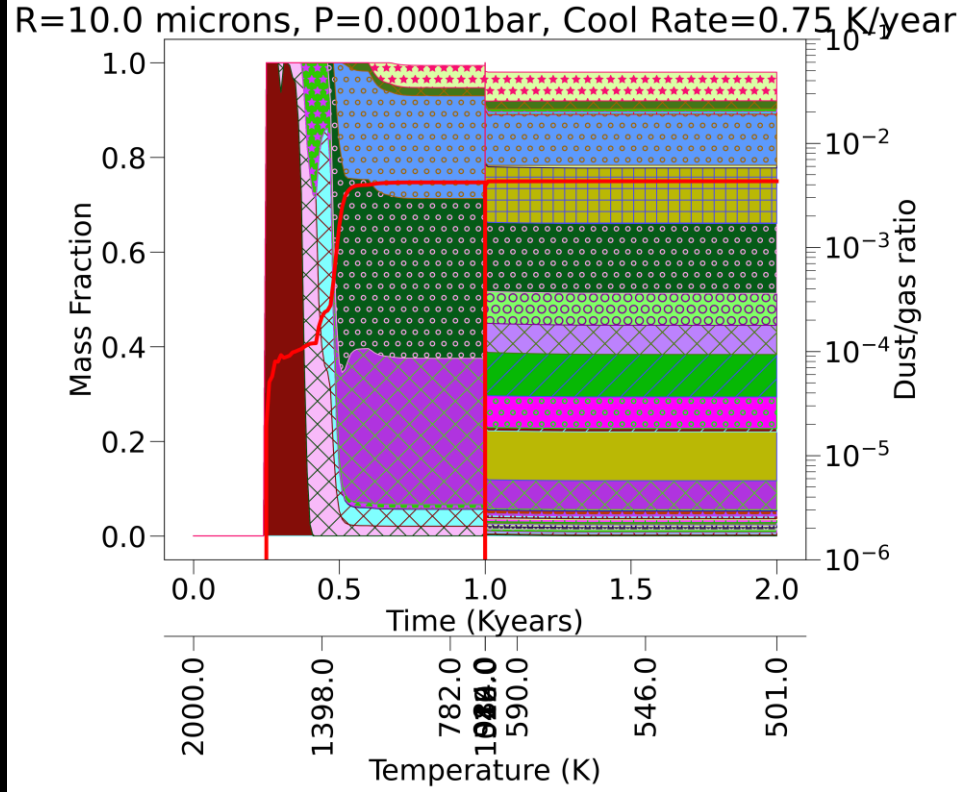
Produce a mineralogy close to ordinary chrondrites :

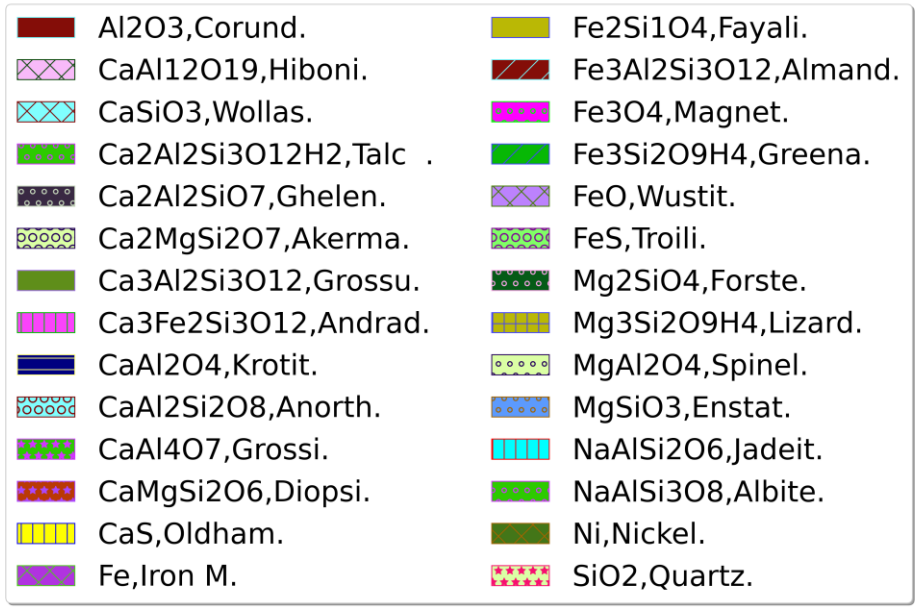
Presence of Fayalite + interestingly we have a little bit of sulfure trapped



THERMAL PULSE 3: in a cold disk







Produce a very rich and diverse mineralogy

And OXIDIZED mineralogy. :
Phyllosilicates :
Lizardite, greenalite, and a little bit of Talc
Very oxidized : Magnetite also

what would be the cause of these thermal pulses ?

How to change the oxidation state of the precursors ?

$\Rightarrow$ Problem somewhat similar to chondrules formatio…
but different epoch..

Impacts/collisions ?

Shockwaves in the disk ?

Electric discharge ?

Other ?

=> A problem of timescale and volume of material to processs

Early planetesimals shocks

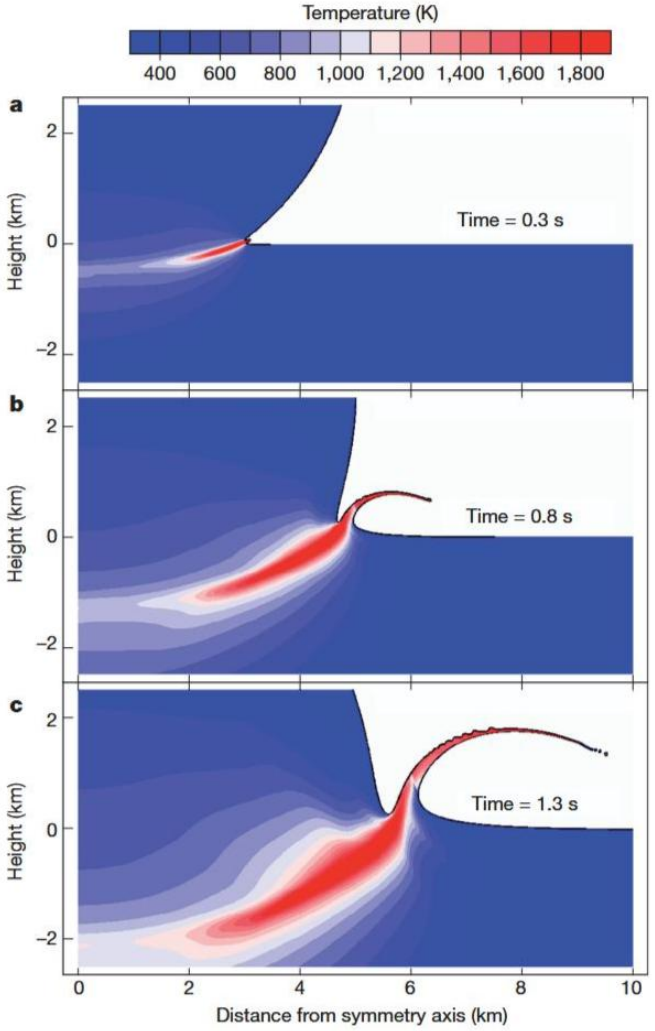
Impacts à haute vitesse entre corps plus ou moins grands peuvent fondre et éjecter dans l'espace une partie de la matière qui ensuite refroidit et cristallise rapidement.

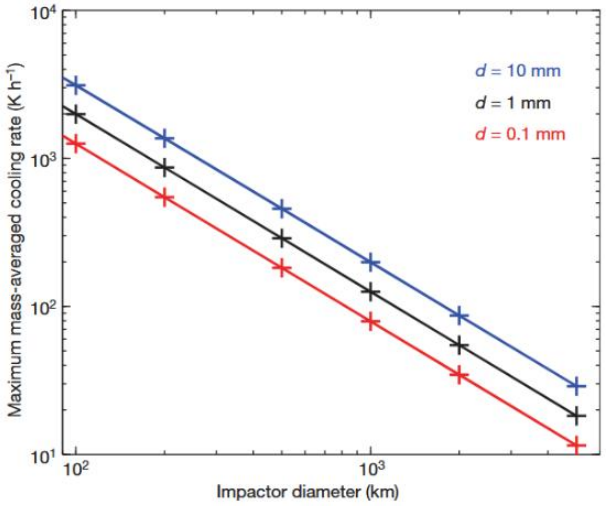
Peut expliquer:

- Début retardé de formation des chondres
- Haute densité de matière pour limiter la dévolatilisation

Mais:

- Les premiers corps auraient dû être différenciés (voir cours #5), mais les chondres n'ont pas un grand déficit en Fe
- Grains précurseurs de chondres (voir séminaire)



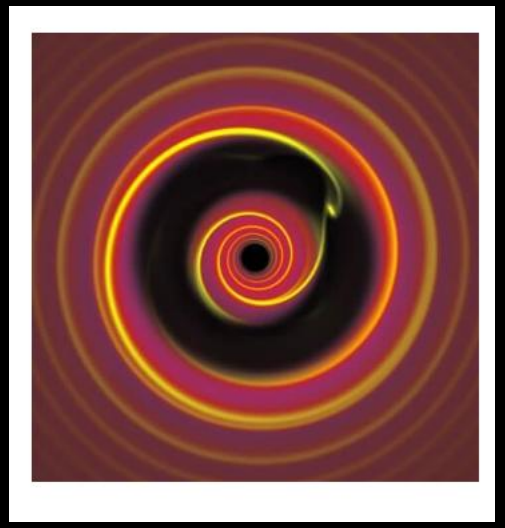


Impact d'un objet de 10km à 3km/s sur objet de taille Lunaire
Johnson et al., 2015

Voir aussi:
Asphaug et al., 2011
Dullemond et al., 2014, 2016

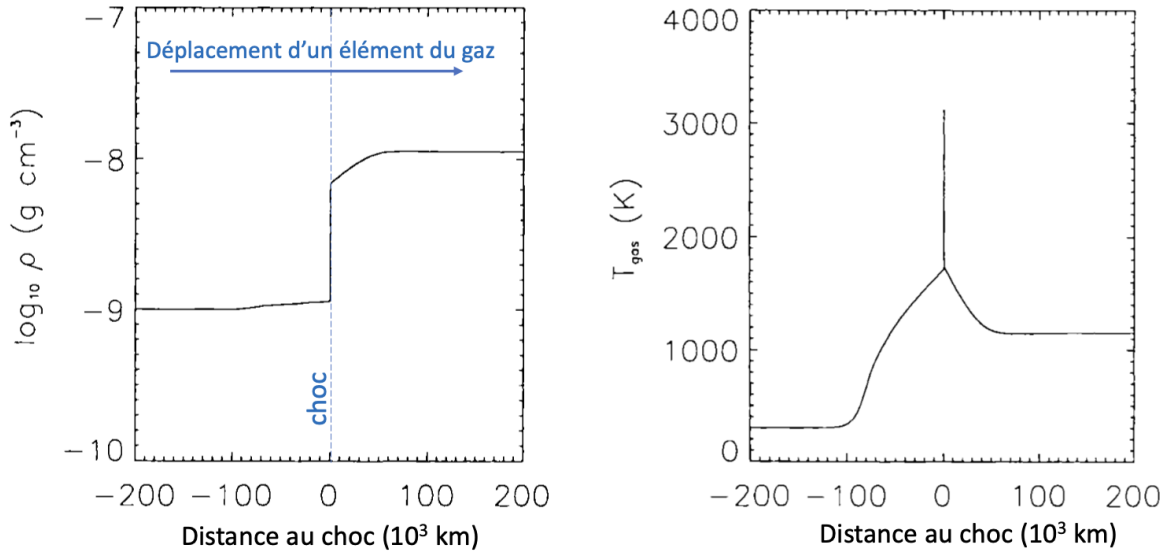
Need early big bodies to collide … and vaporise… then recondense..
=> high velocity ? Not easy

Shockwave in the wake of planetary bodies

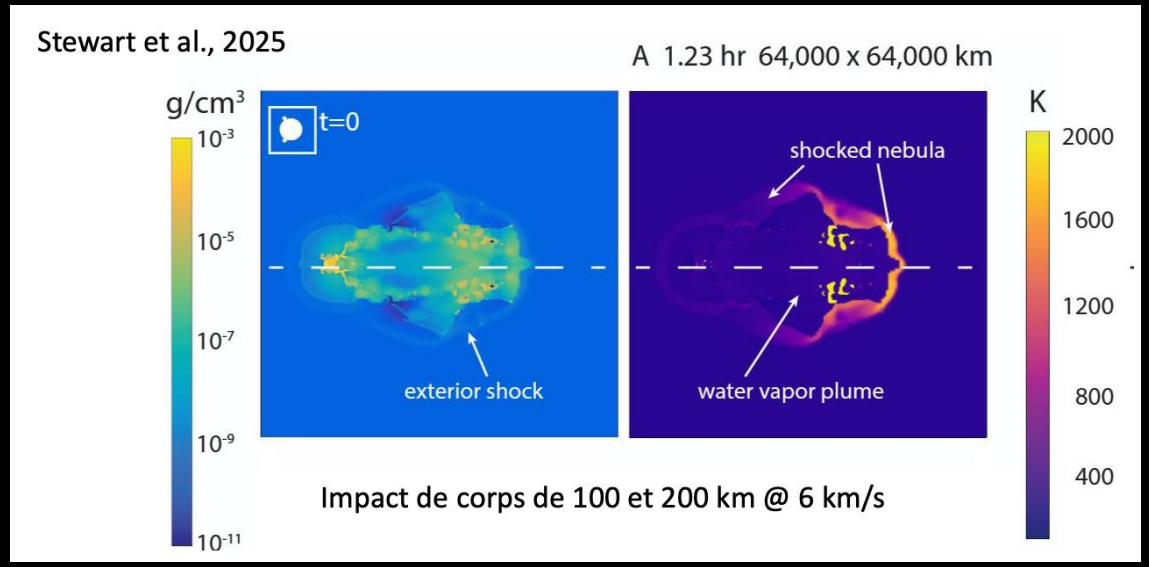


Masset et al., 2000

Choc: *perturbation supersonique de la vitesse du gaz par rapport au mouvement orbital circulaire*



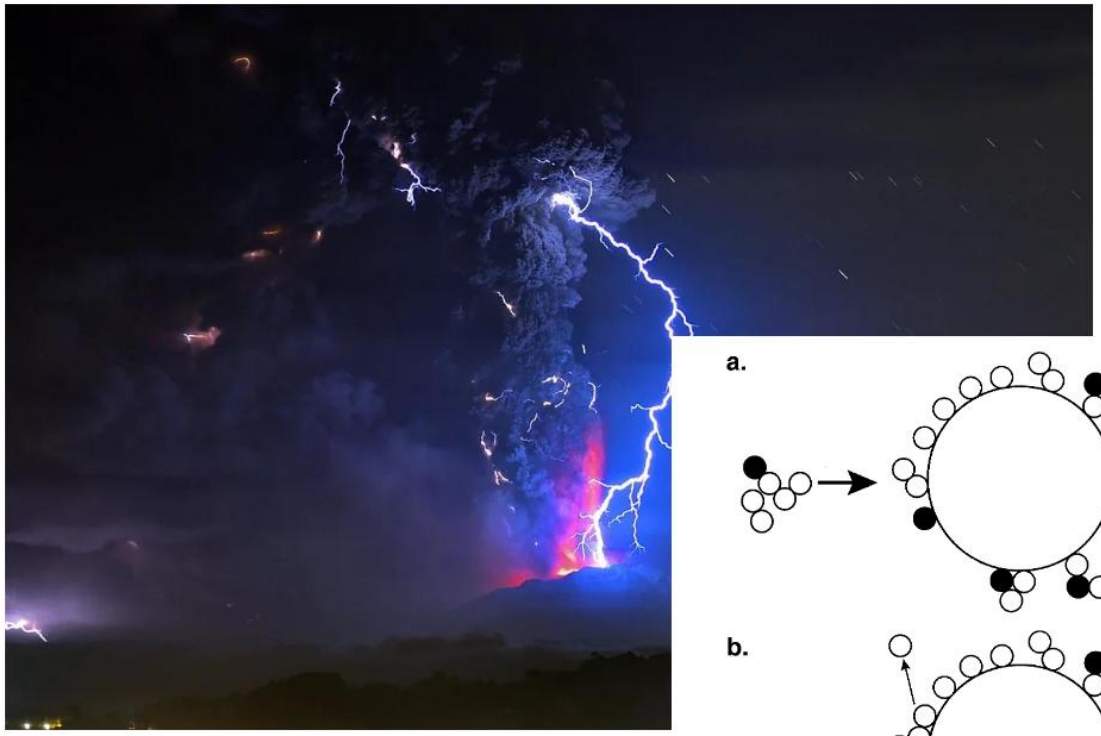
Desch and Connolly, 2002



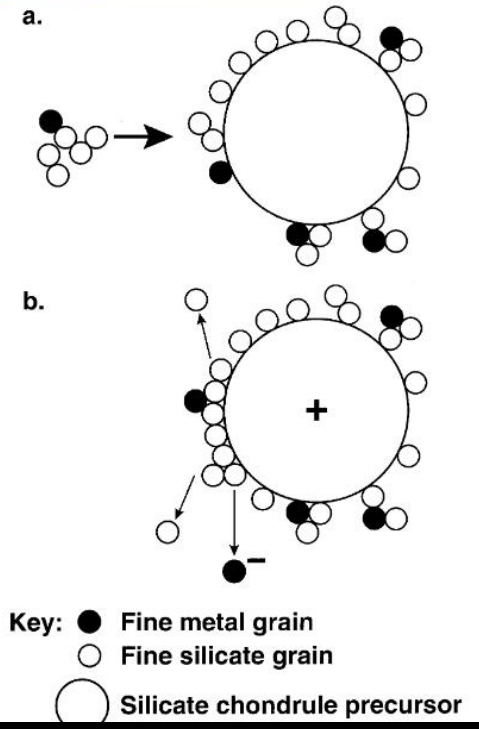
Steam shock

Electric discharge

Desch et Cuzzi, 2000:
Analogie avec ce qu'il se passe lors des éruptions volcaniques: les collisions chargent électriquement les grains.
S'il y a ségrégation des charges, la différence de potentiel peut devenir suffisamment grande pour déclencher une foudre



Compatible avec haute densité de poussières.
Mais processus inefficace car la section d'une foudre est très petite (~100 km)
Pourquoi un délai?



Pb : how to process big quantities of material…

How to heat and cool material rapidly AND early
An unclear situation

Most of heating cooling processes invoque a shock with a fully grown Planetary body…

⇒ Only the surface is affected and melted

⇒ Big planetary bodies appear late

➢ Difficult to process vast quantities of material early in the disk

➢ electric disharge is appealing : may happen any time .. BUT

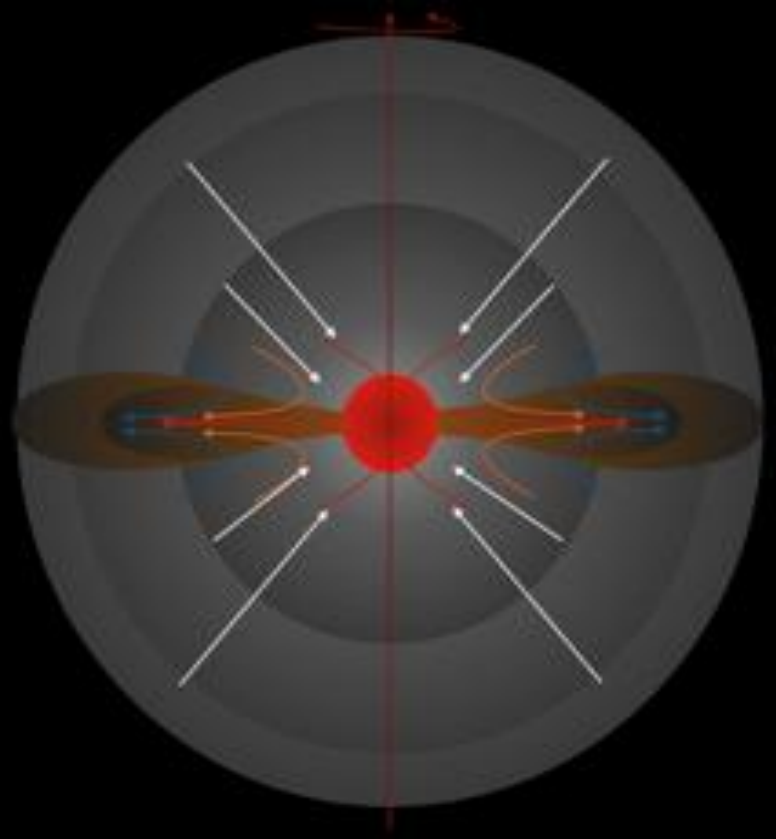
➢ problem to process big quantities of material..

..=> This is still an open question

Condensation above the midplane in outflow..??? New speculative idea..
Needs exploration..

CONCLUSIONS

IMPORTANCE OF NON EQUILBRIUM CONDENSATION
LOW PRESSURE / FAST COOLING
⇒ Equilibrium condensation give a very incomplete view
⇒ Origin of the 3 chondrites families



Oxidation state may reflect
out of equilibrum condensation processes rather than presence of water… a new idea that must be explored

=>
Potential implication for the oxidation state of NC chondrites
And accrection of CC chondrites
=>
Open questions