

Phase Transformations

K.G. Field^{1,a},

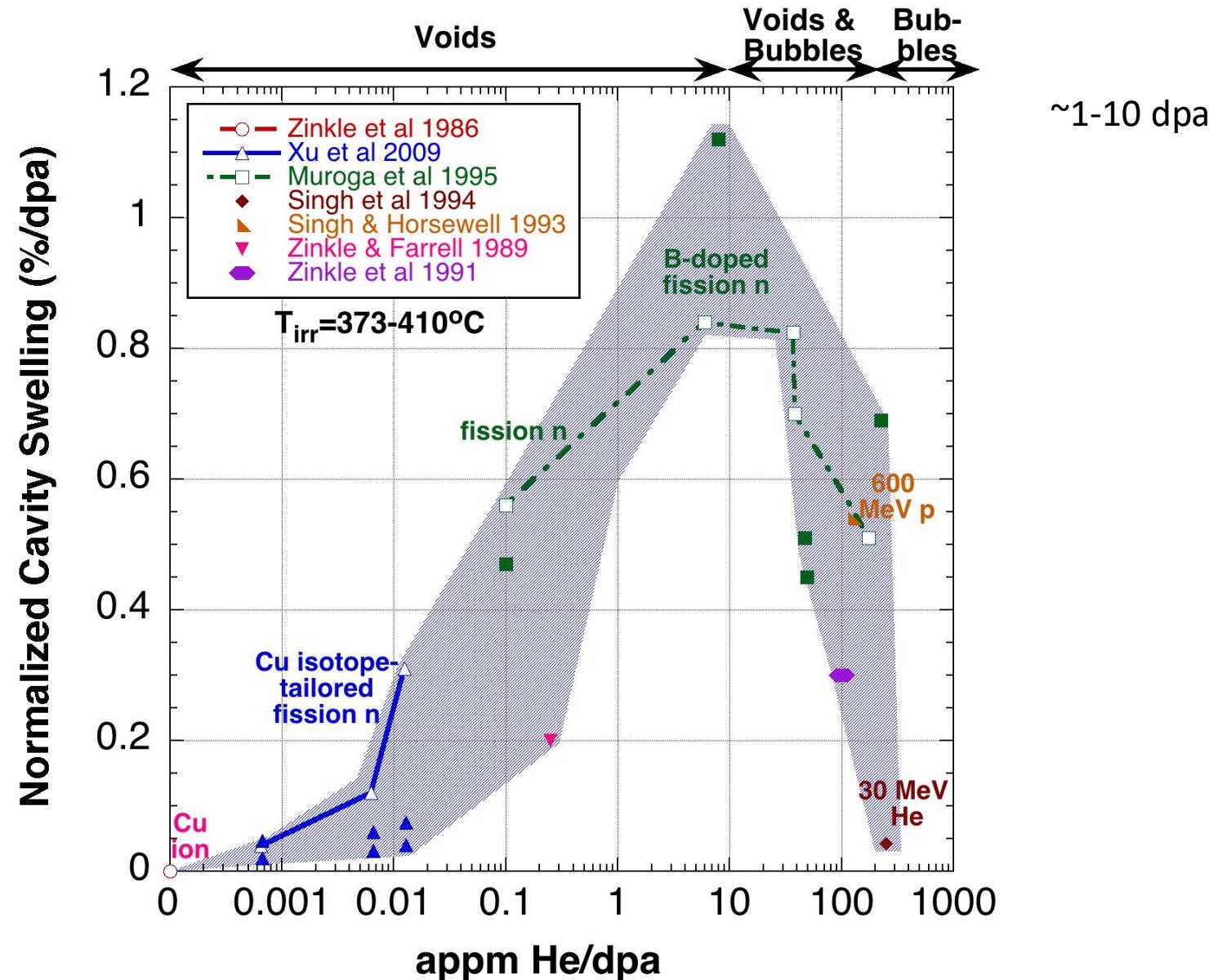
^a kgfield@umich.edu

¹University of Michigan

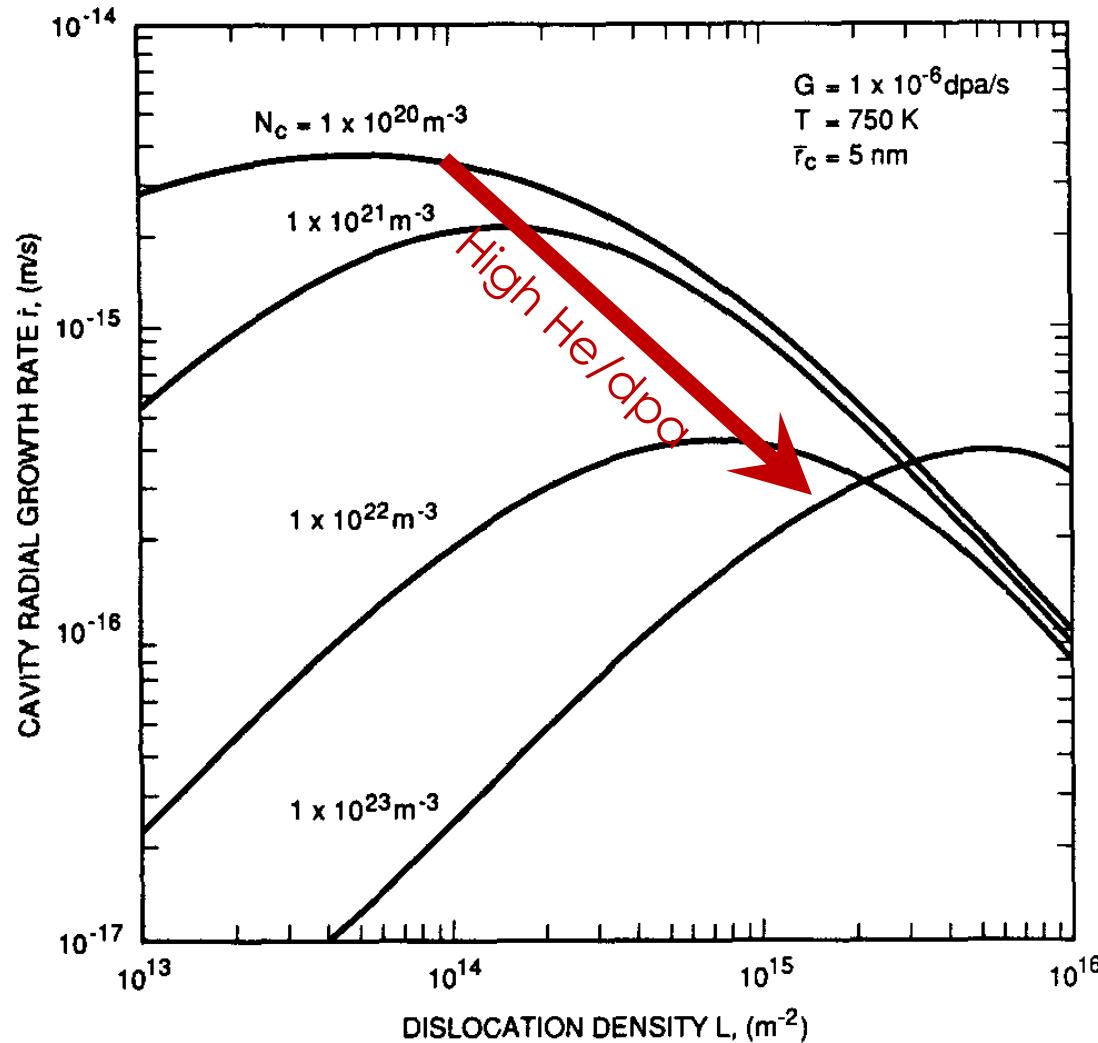


NUCLEAR ENGINEERING &
RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN

Cavity swelling vs. He/dpa ratio in irradiated copper

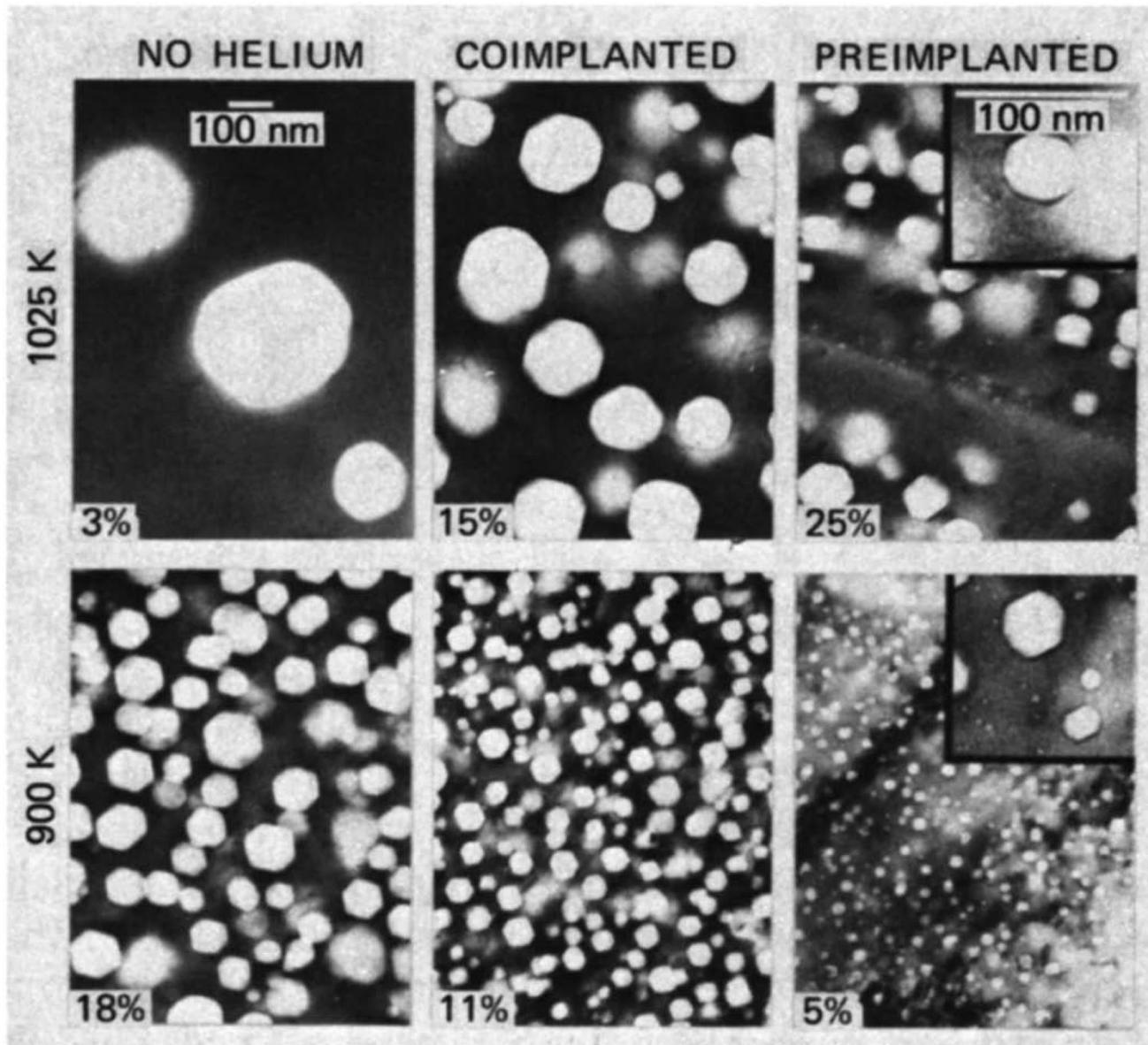


Calculated void growth rate is typically reduced for high cavity and dislocation sink strengths



Over nucleation of cavities
due to too high He/dpa
can suppress void swelling

Effect of He in ion irradiations



Implantation method of He can drastically effect swelling in ion irradiated materials

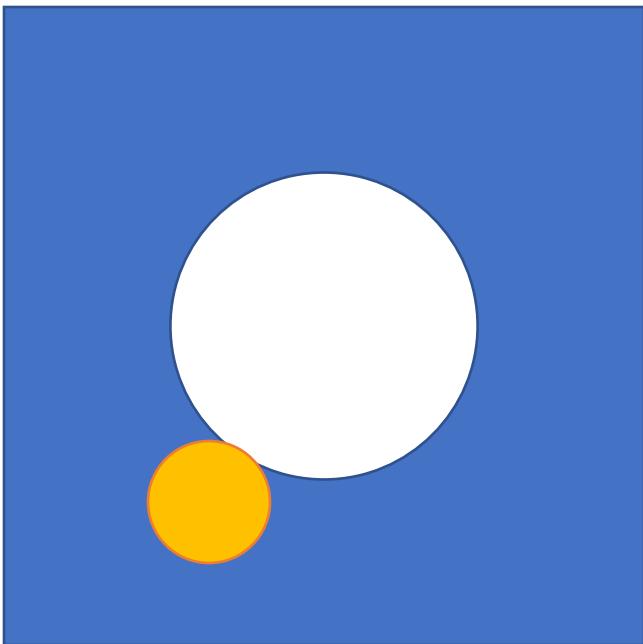
Image of
Fe-17Cr-16.7Ni-2.5Mo

Packan & Farrell, NT-Fusion, 1983

Why are we interested in phase transformations under irradiation?

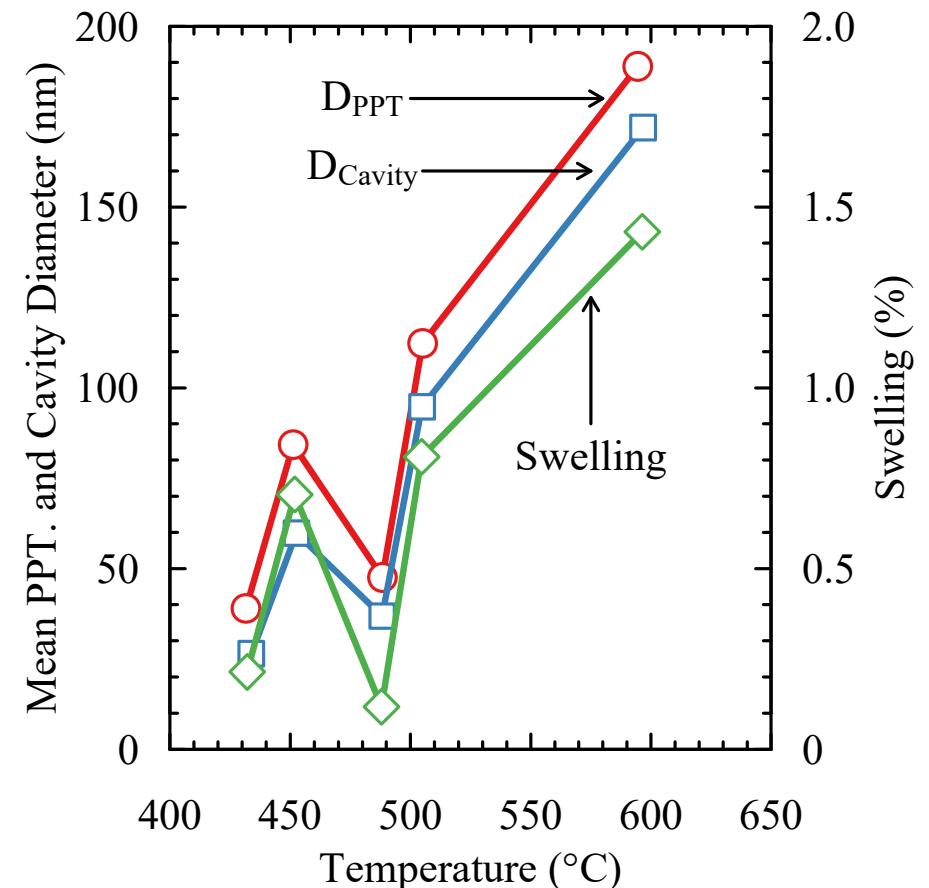


Influence of phase stability and cavity growth

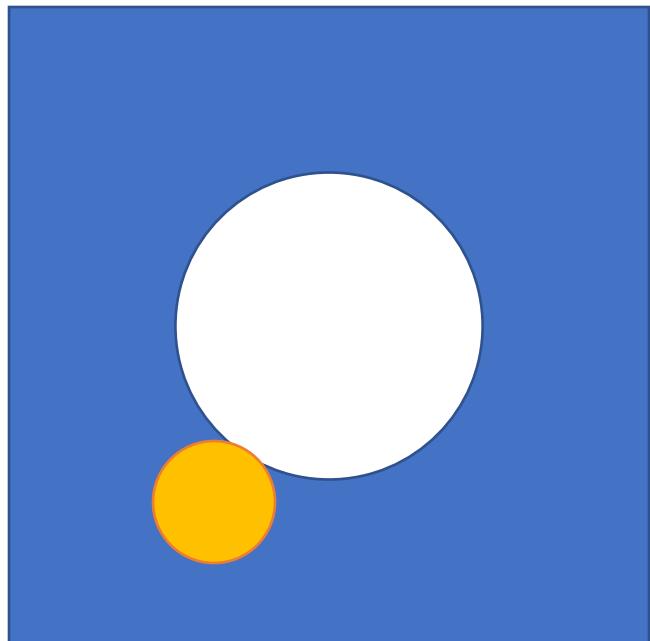


If we account for cavity growth on a precipitate-matrix interface, then we can relate the cavity growth to precipitate size by:

$$\frac{dr_{cp}}{dr_c} = \frac{(r_{cp}^2 + r_p^2)^{1/2}}{r_{cp}^2} r_c$$



Influence of phase stability and cavity growth



If we account for cavity growth on a precipitate-matrix interface, then we can relate the cavity growth to precipitate size by:

$$\frac{dr_{cp}}{dr_c} = \frac{(r_{cp}^2 + r_p^2)^{1/2}}{r_{cp}^2} r_c$$

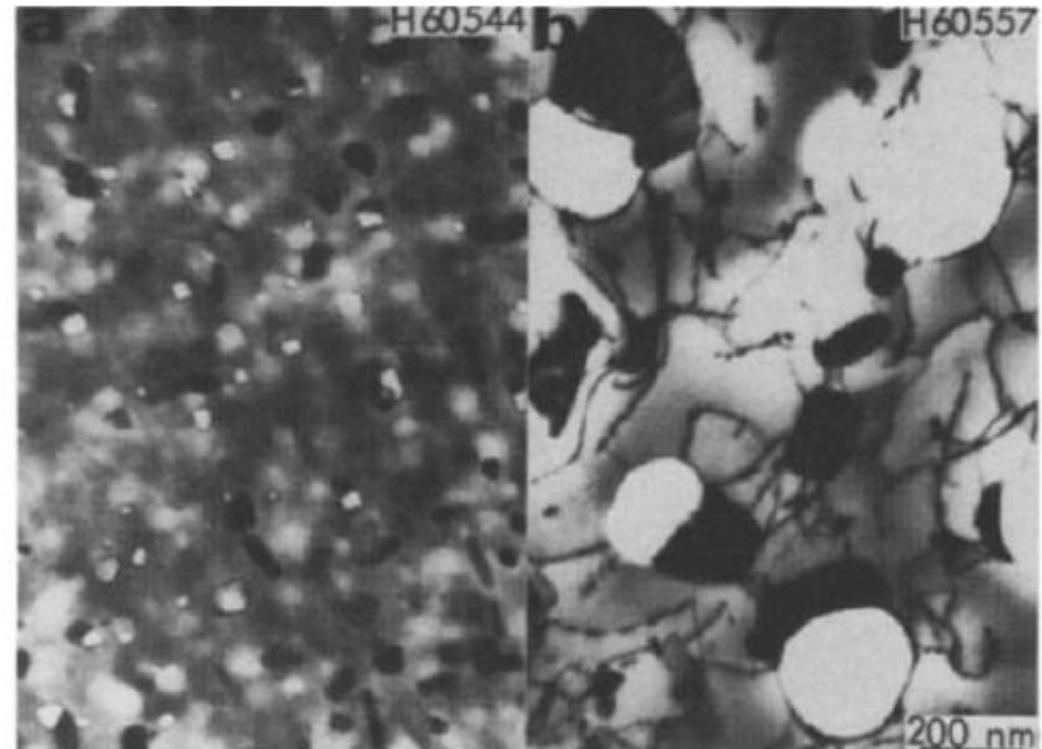


Fig. 2. Cavity-particle association in LS1C irradiated to ~35 dpa in EBR-II at (a) 425°C, (b) 600°C.

Two primary irradiation induced phase transformation types:

1. Requires compositional changes

1. Induced precipitation from solid solution

2. Dissolution of precipitates

2. Constant composition

- Allotropic or Polymorphic

- Allotropic: change in the crystal structure of a single element

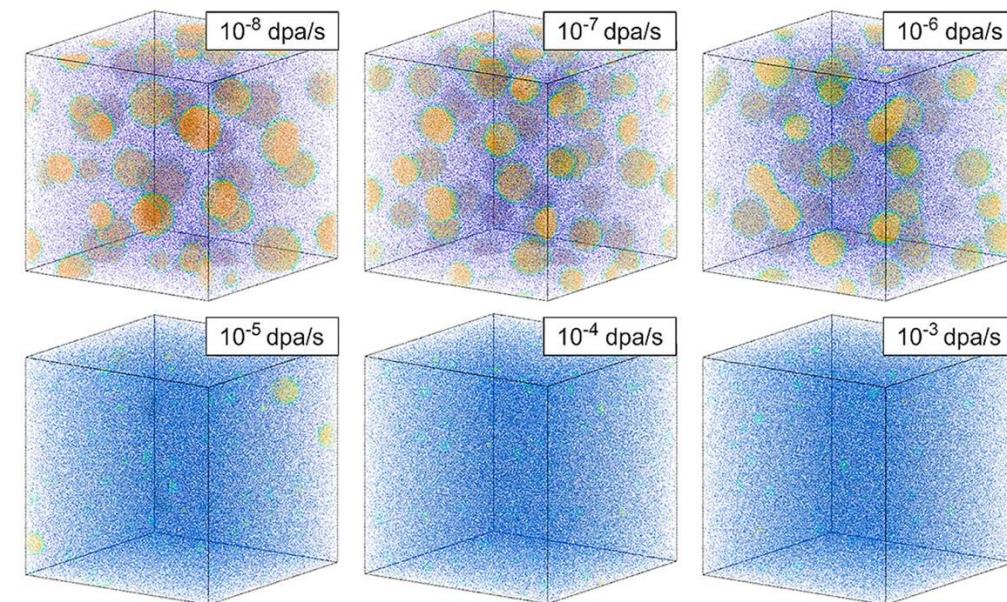
- Polymorphic: change in the structure of an alloy or compound

- Ordering/disordering

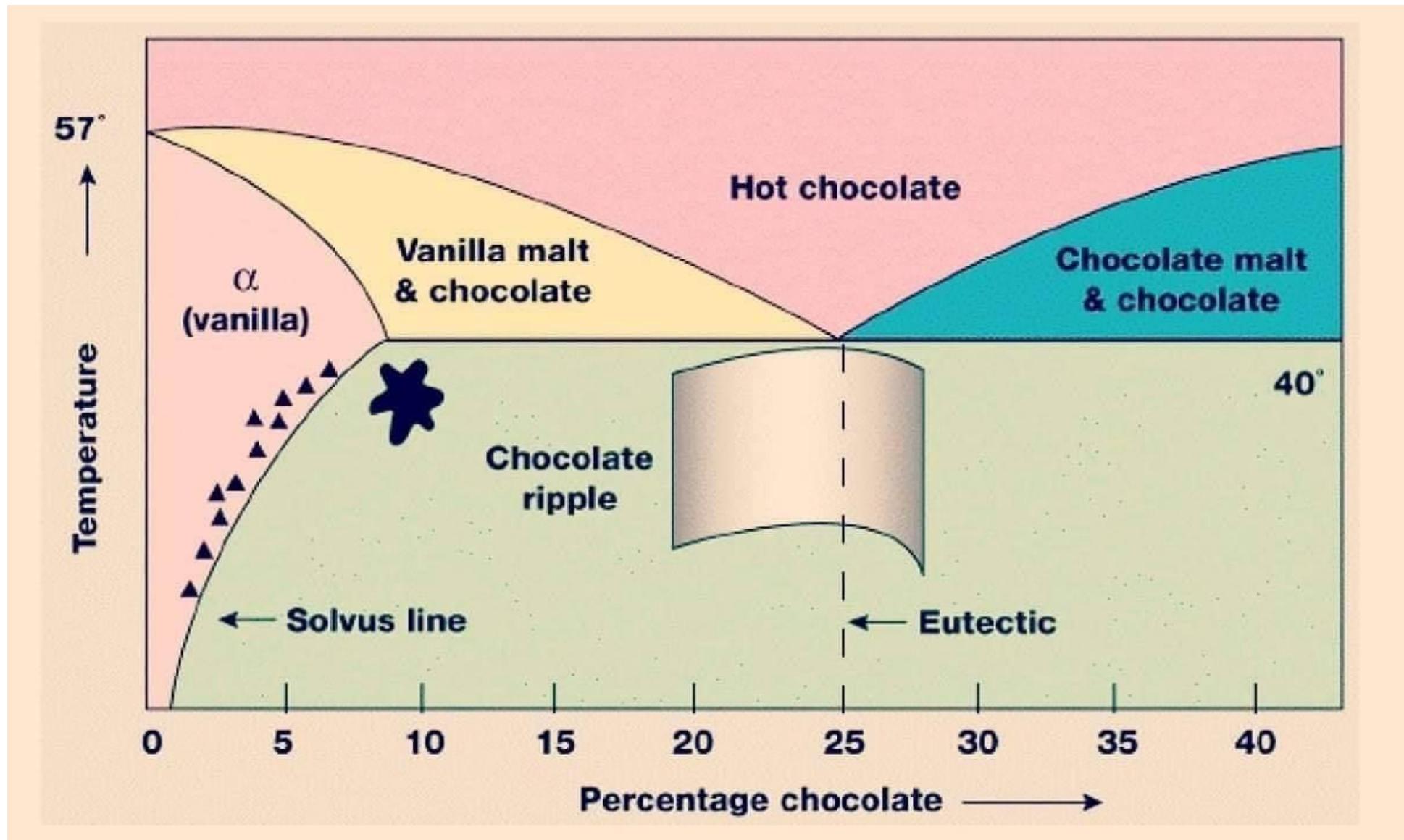
- Loss of chemical order (disordering)

- Loss of crystal structure, e.g. amorphization

Irradiation flux effect on α' precipitation in Fe-Cr



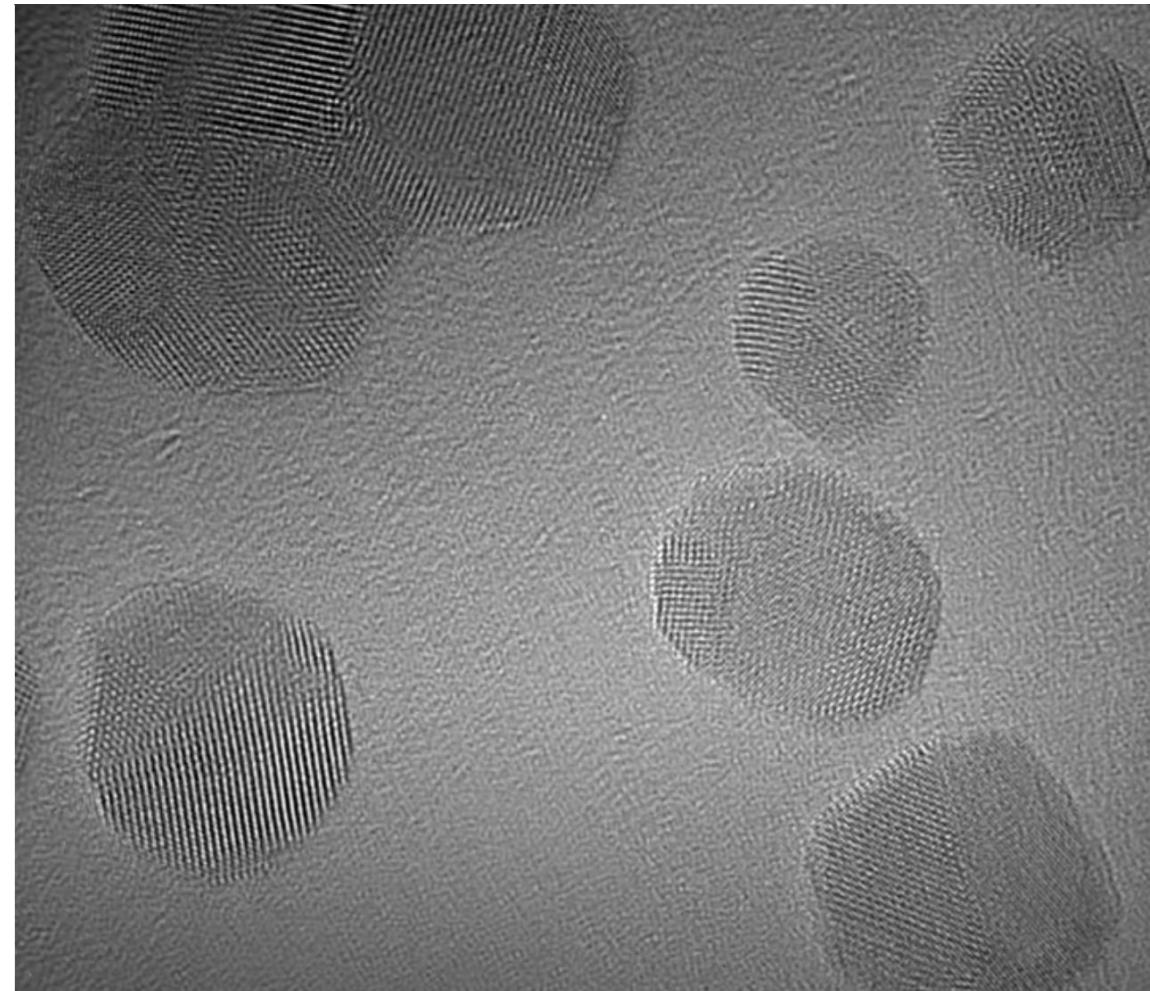
Food for thought



Ostwald Ripening

- Ostwald ripening is the spontaneous process of larger precipitates growing at the expense of small precipitates
- This is because:
 - Large precipitates have lower energy states
 - The formation of small precipitates is kinetically favored (in thermal systems)
 - Small precipitates have a larger surface area to volume ratio

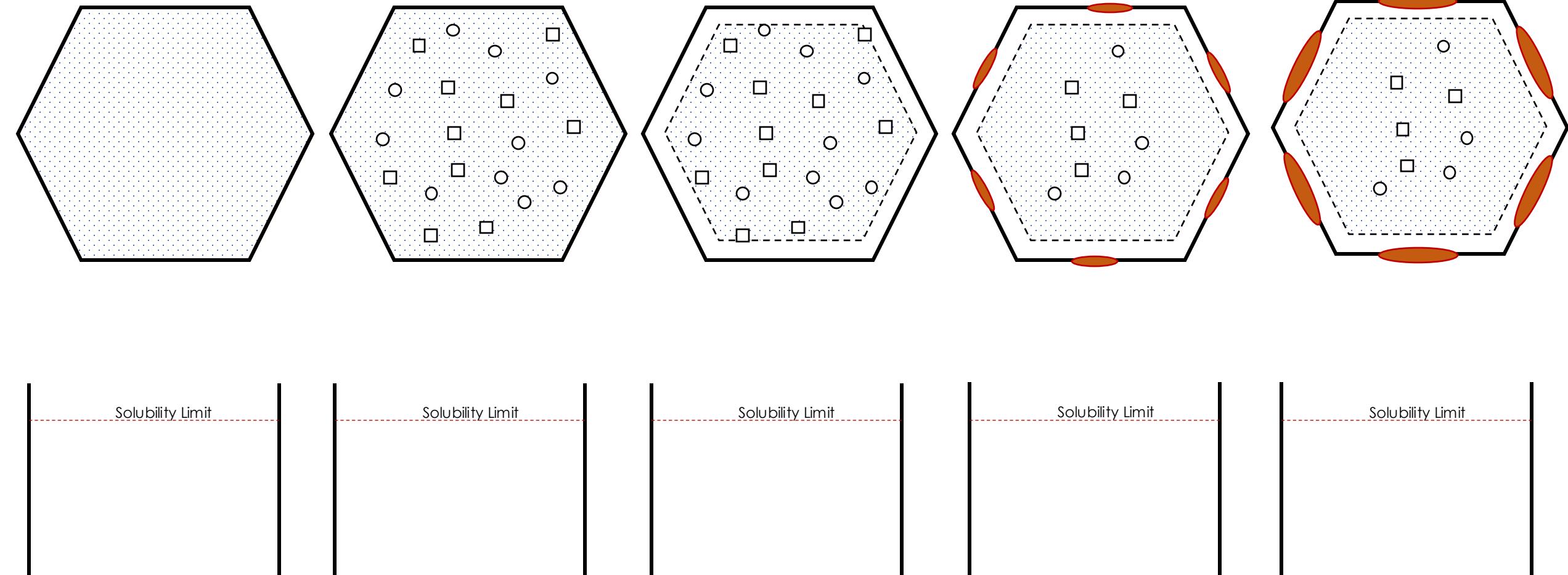
→ **Small precipitates will attain a lower energy by being consumed by larger precipitates**



Phase transformations with changes in composition



RIS and Radiation-induced precipitation



RIS and Radiation-induced precipitation

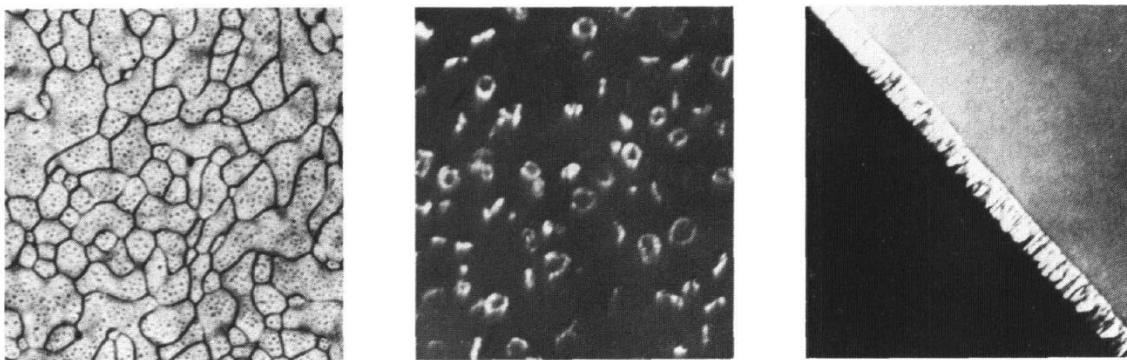
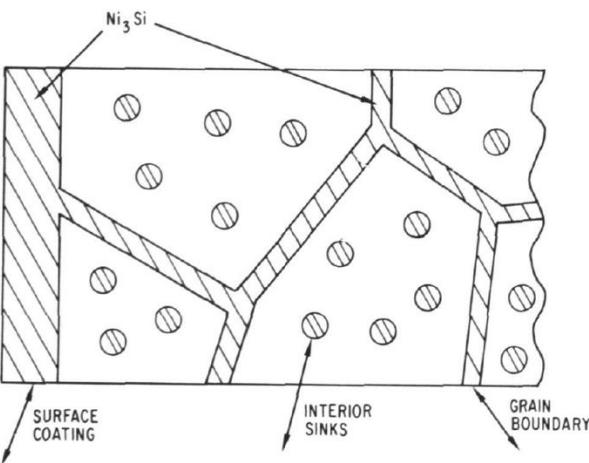
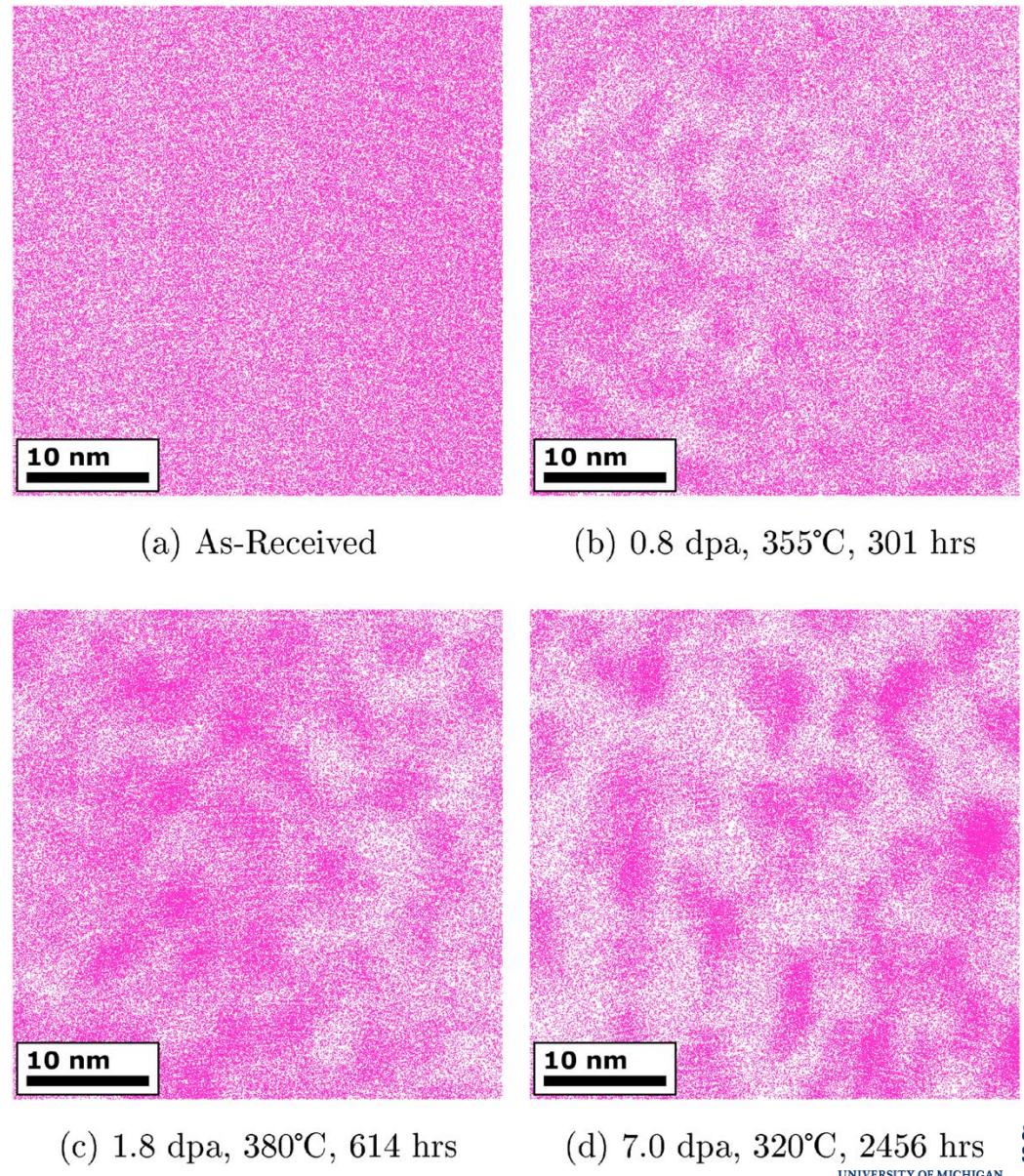
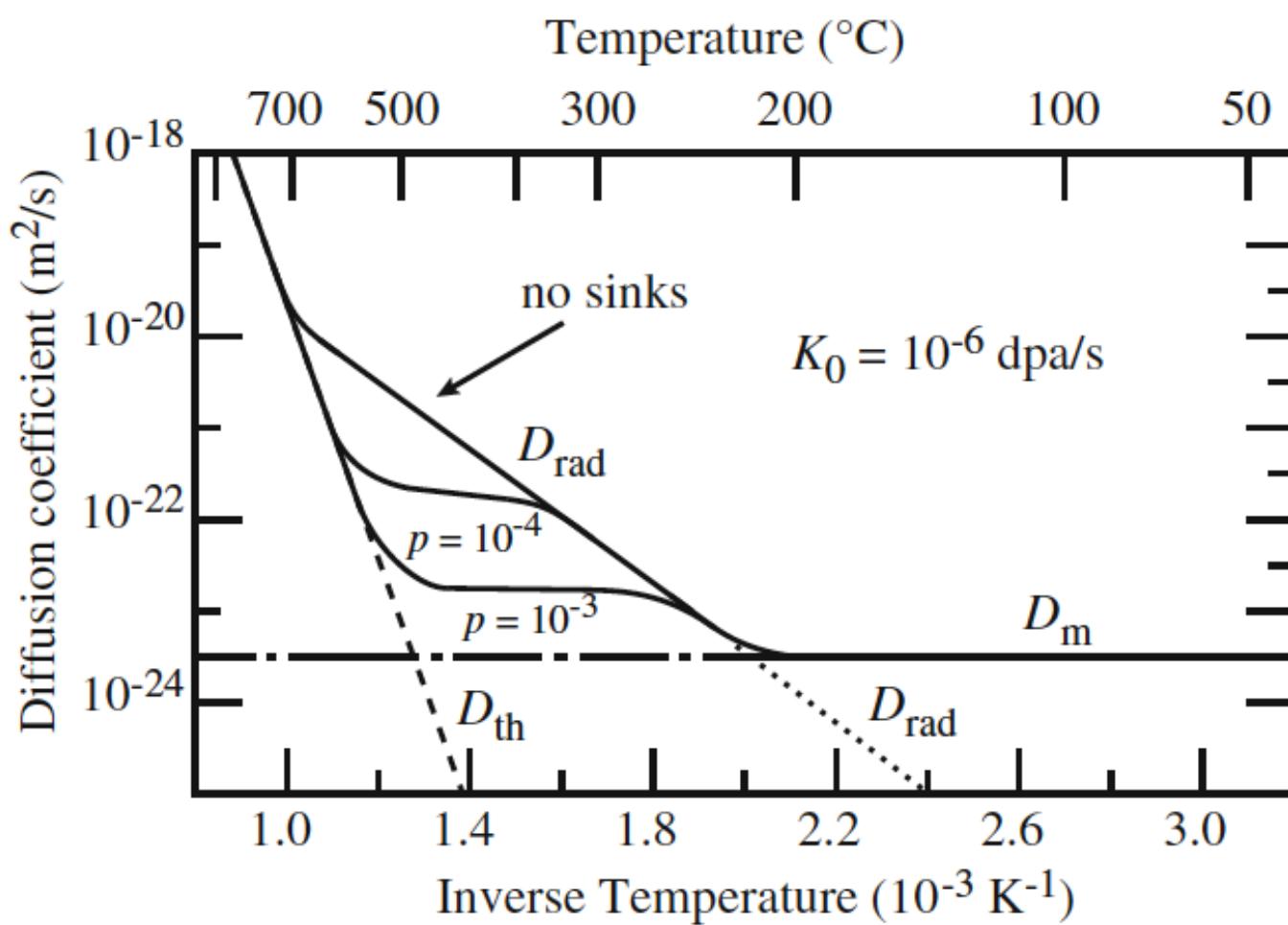


Fig. 1. Formation of γ' -Ni₃Si on defect sinks in a solid solution Ni-Si alloy because of RIS. The dark-field micrographs from the work of K.-H. Robrock and P. R. Okamoto show: (a) the anti-phase domain structure in a contiguous surface coating; (b) toroidal γ' -precipitates on interstitial loops; and (c) a grain boundary coated with γ' .



Radiation-enhanced effects on kinetics



Dimo's Deli in Ann Arbor originally started as an Amy Joy donut chain location in 1973, featuring 54 different varieties of donuts including French curlers and apple fritters. What is the address of this original location?

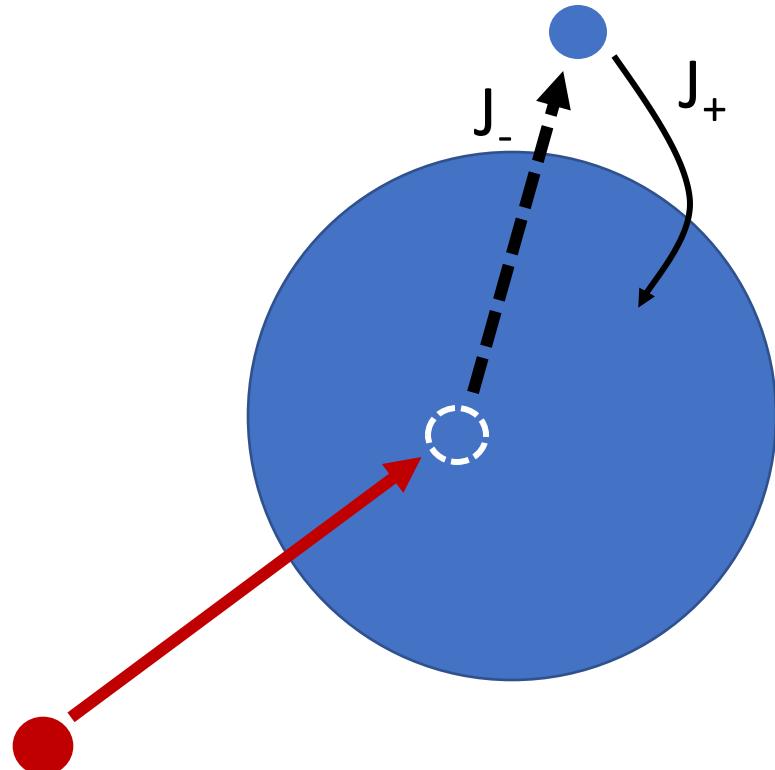


Lecture Break

- Mole (pronounced MOH-lay) is a thick, flavorful sauce used in Mexican cuisine that is composed of five major components: chiles (at least two different types); sour (tomatoes or tomatillos); sweet (dried fruits or sugar); spices; and thickeners (bread, nuts or seeds). Generally speaking, how many different Mole sauces exist in Mexican cuisine?



Radiation-induced precipitate dissolution



Assumptions:

- Binary (simple) alloy
- Overall solute concentration: x_s
- Precipitates are evenly distributed
- Precipitates do not interact

Growth or dissolution of the precipitates will be governed by the solute flux at the precipitate interface:

$$\frac{dn}{dt} = J_+ - J_-$$



Radiation-induced precipitate dissolution

$$r_{eq}^3 = \frac{3}{4\pi N_p} \left(\frac{X_s}{C_p} - \frac{K_0 \mu}{4} [1 - X_s] \frac{r_{eq}}{D_s} \right)$$

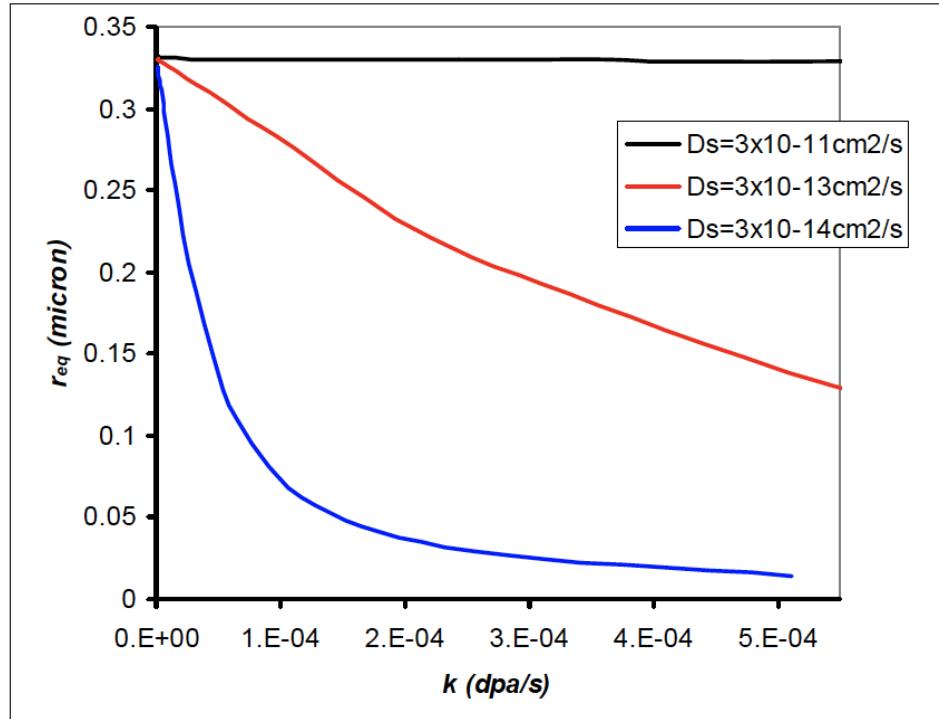


Figure 24.13: Equilibrium radius for a precipitate subjected to recoil dissolution as a function of displacement rate for three values of the solute diffusion coefficient. $x_s=1\%$ and $C_p=66\%$.

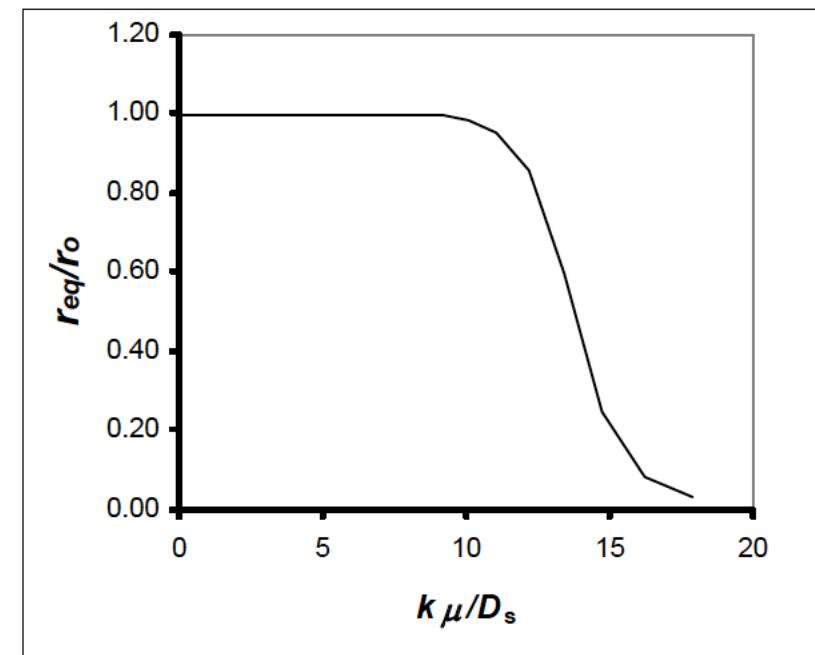
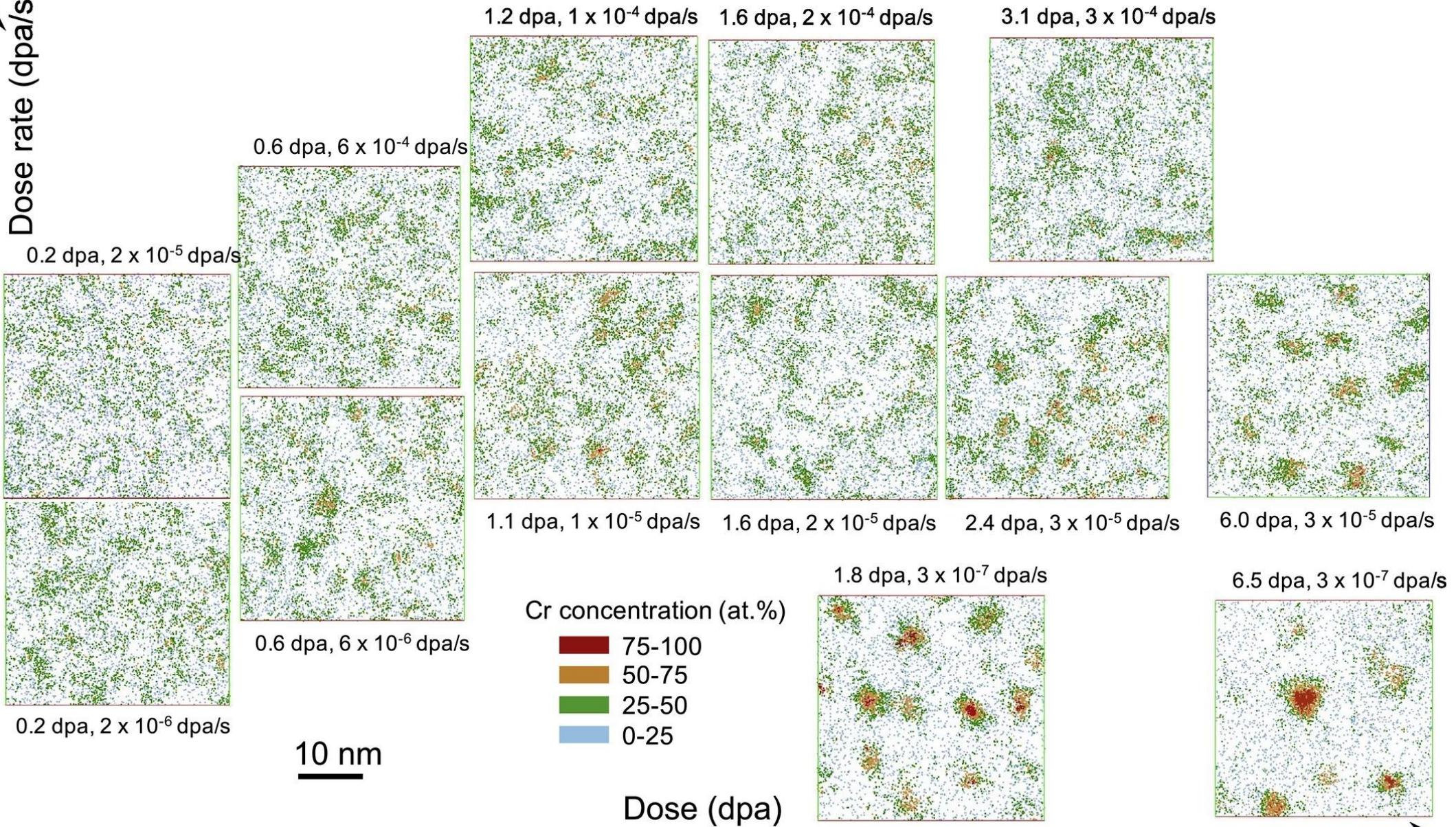


Figure 24.14: Ratio of equilibrium precipitate radius to radius in the absence of recoil dissolution, versus parameter $\frac{k \mu}{D_s}$.

Dose rate (dpa/s)



Radiation-induced precipitate dissolution

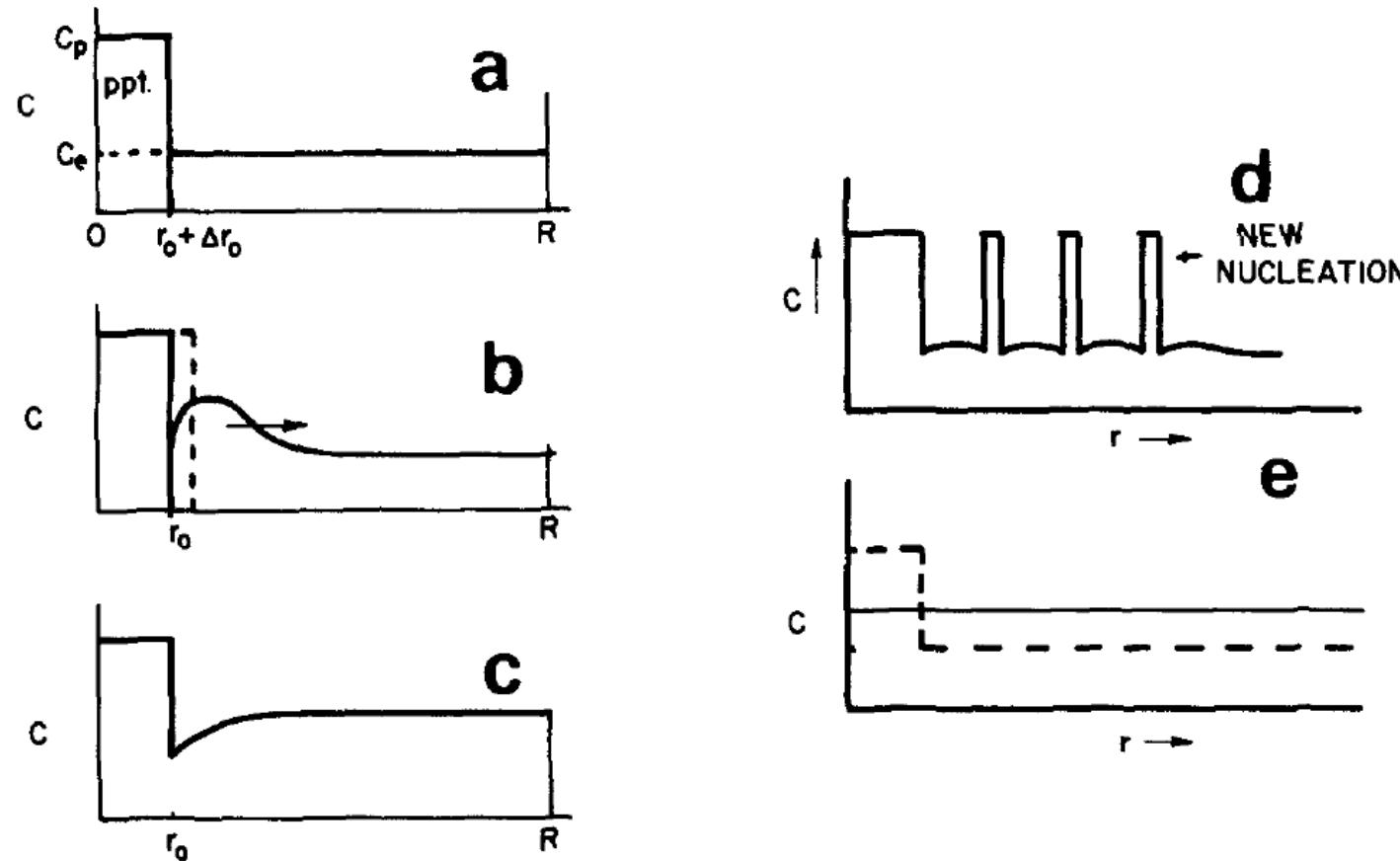


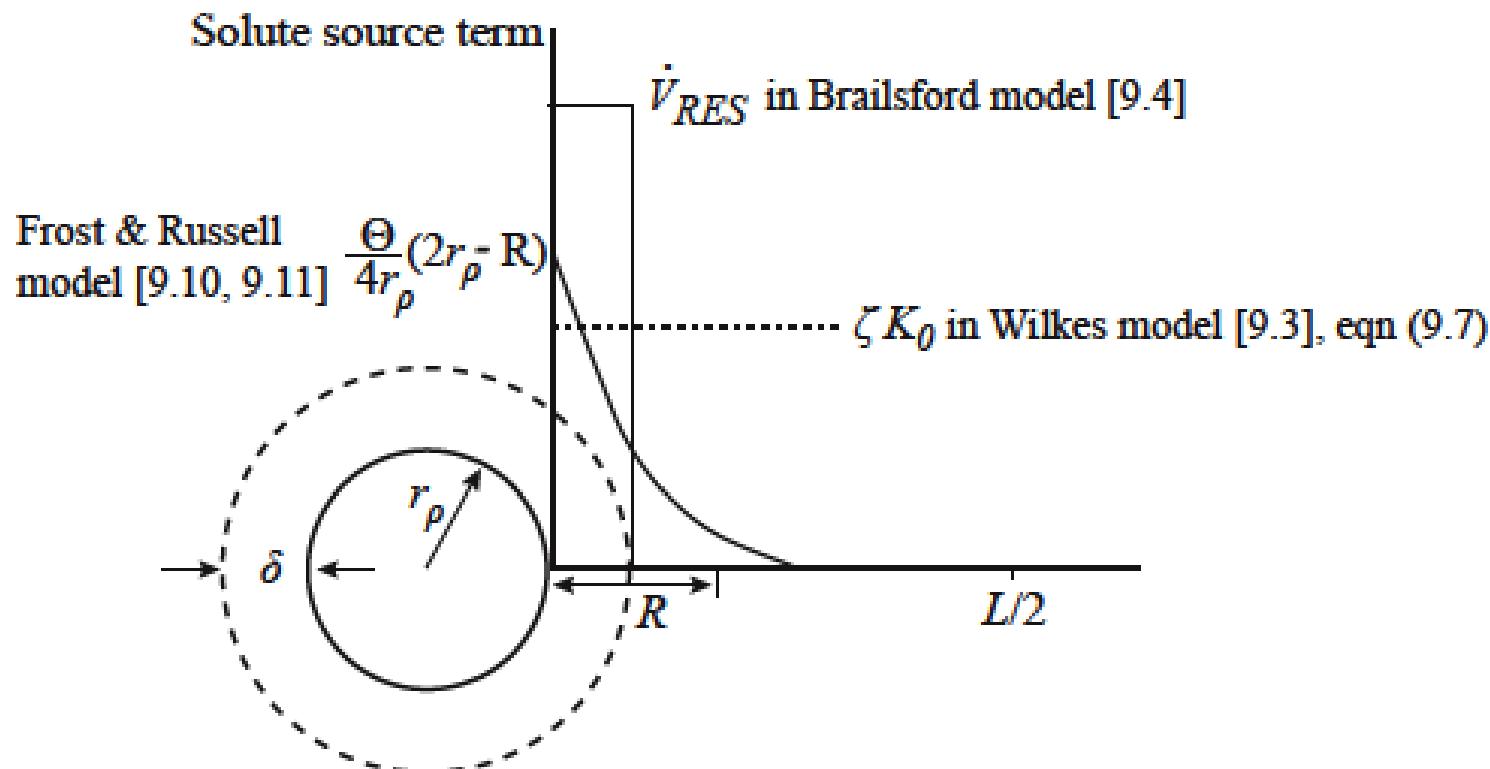
Fig. 3. A schematic diagram of concentration variations in a precipitate cell: (a) before irradiation with a precipitate of radius $r_0 + \Delta r_0$ in equilibrium with a uniform matrix concentration c_e ; (b) when irradiation begins surface dissolution causes a local solute supersaturation some of which diffuses outwards down the gradient; (c) at steady-state, the matrix is now uniformly supersaturated and the precipitate dissolution is matched by the back diffusion into the precipitate; (d) if the local supersaturation around the precipitate exceeds that required for nucleation, new precipitates may nucleate; (e) if the precipitates are widely spaced, the matrix may not reach the steady-state value and all precipitates will then dissolve.



Radiation-induced precipitate dissolution

In reality, modeling recoil distribution is inherently complex. Models that try to take this into account:

- Nelson model (NHM) – pg. 488-489 in Was
- Wilkes model – pg. 489-492 in Was
- Frost and Russell – pg. 492-493 in Was



Phase transformations without changes in composition

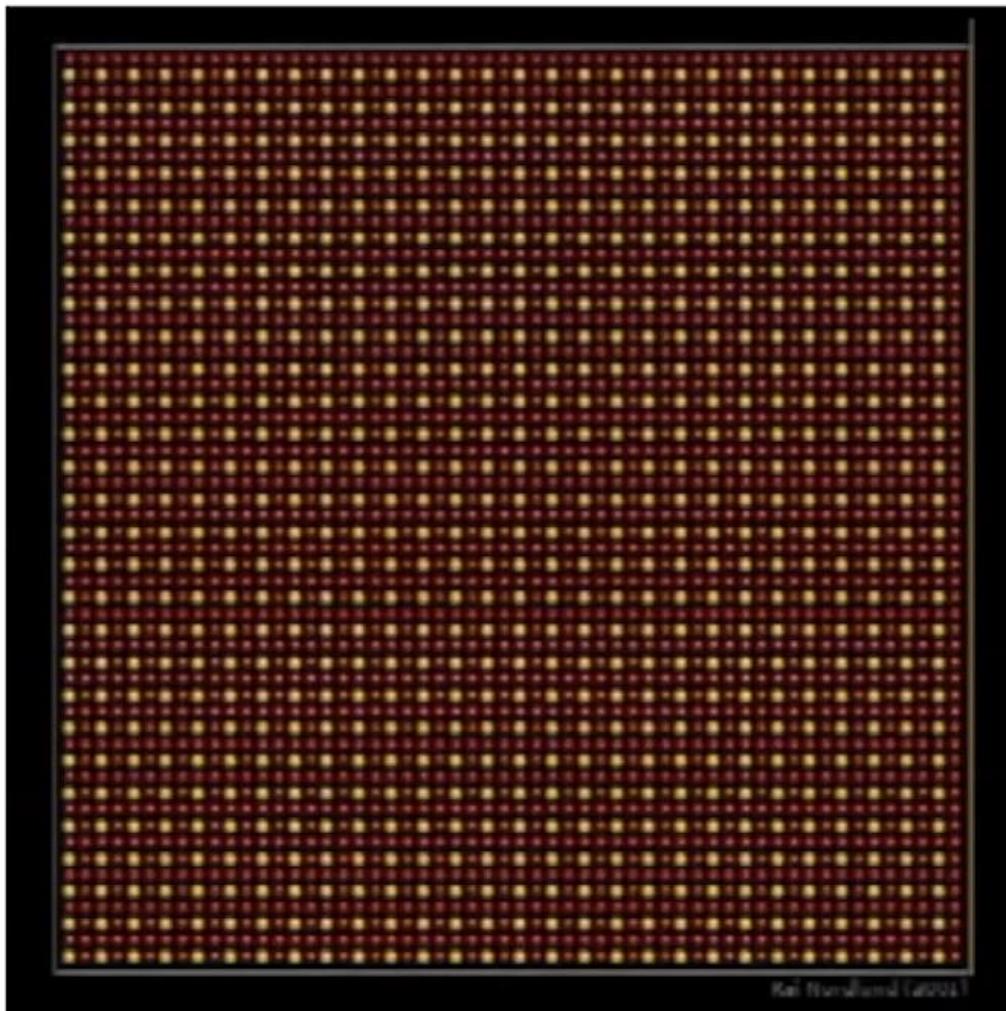


Radiation Disordering

9.1 Irradiation-induced disordering.

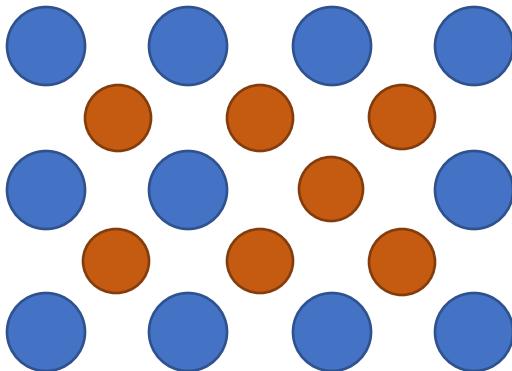
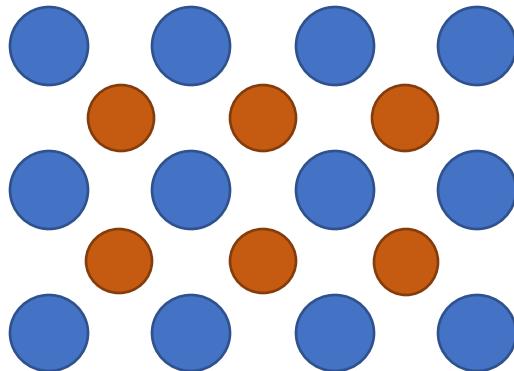
Disordering of Cu₃Au (L1₂ structure)
by bombardment with 10 keV Au ions.
(courtesy K. Nordlund, University of Helsinki)

Radiation disordering:
Loss of long-range
order



Radiation Disordering

- Antisite defects:
 - Occur in an ordered alloy or compound when atoms of different type exchange position



- We now need to consider random recombination so:



Radiation Disordering

- The steady state solution then becomes:

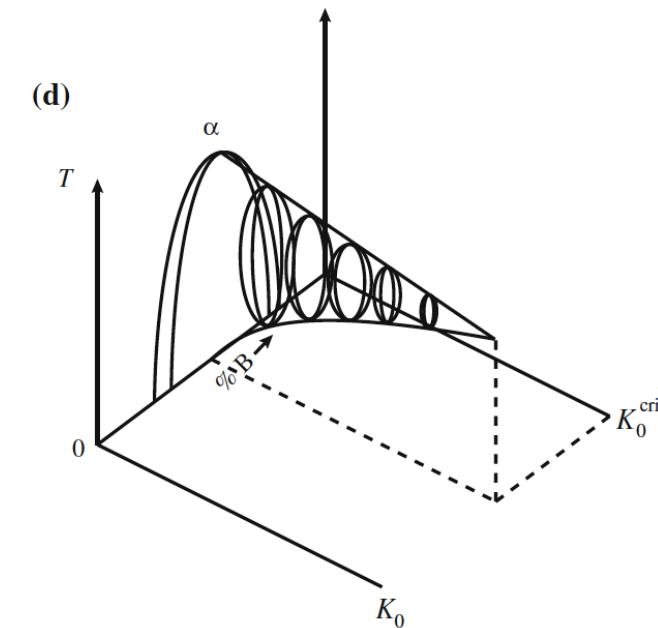
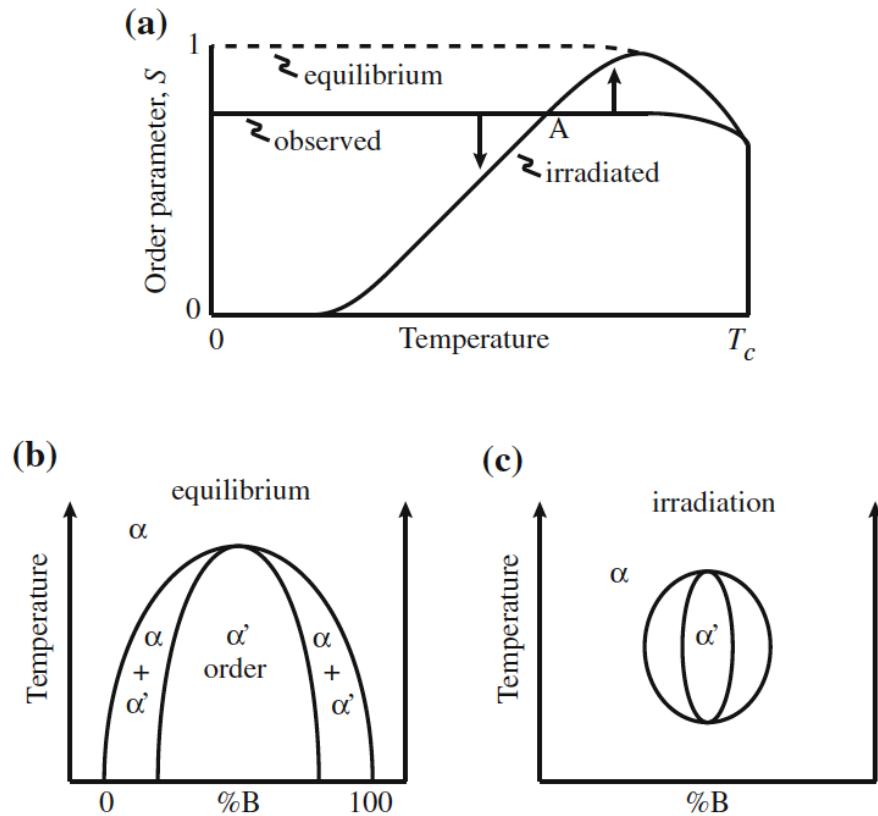
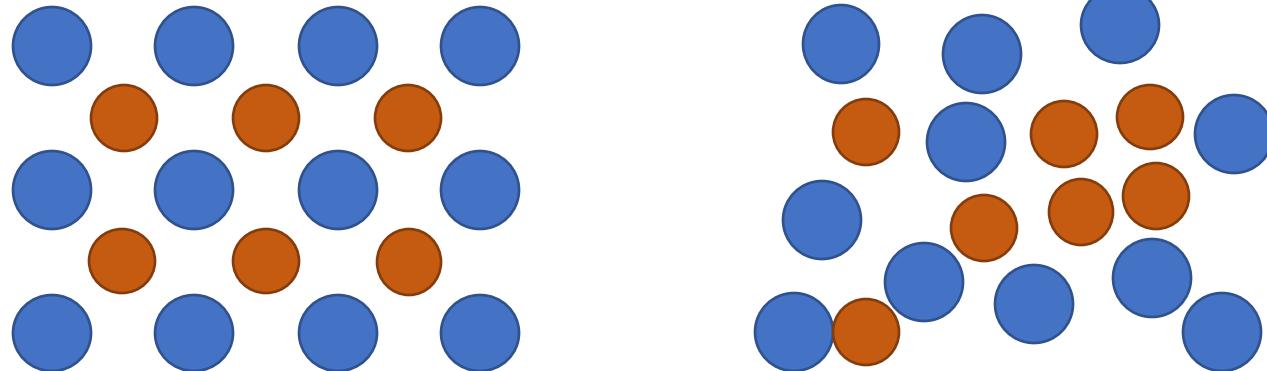


Fig. 9.11 (a) Effect of irradiation on the temperature dependence of the order parameter for a phase structure that is not at the equilibrium order, S_e . (b) Equilibrium phase diagram showing a first-order phase transformation of the disordered α phase to the ordered α' -phase. (c) Modification of the phase diagram by irradiation reflecting the change in order as given in (a). (d) Dependence on the irradiation-modified phase diagram with dose rate (after [3])



Temperature dependence of amorphization

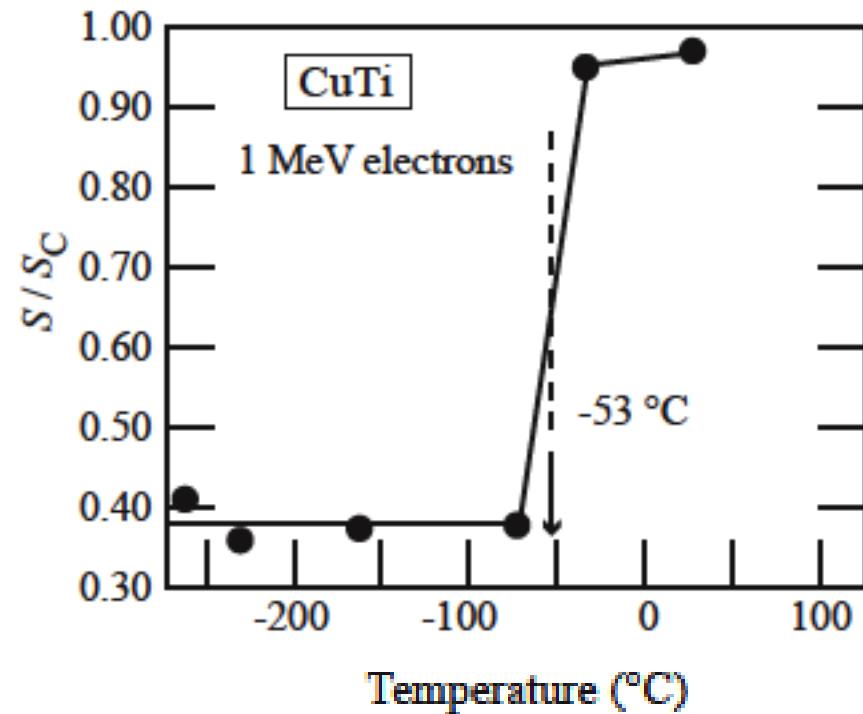
- Amorphization by particle irradiation refers to the complete loss of long-range crystalline structure



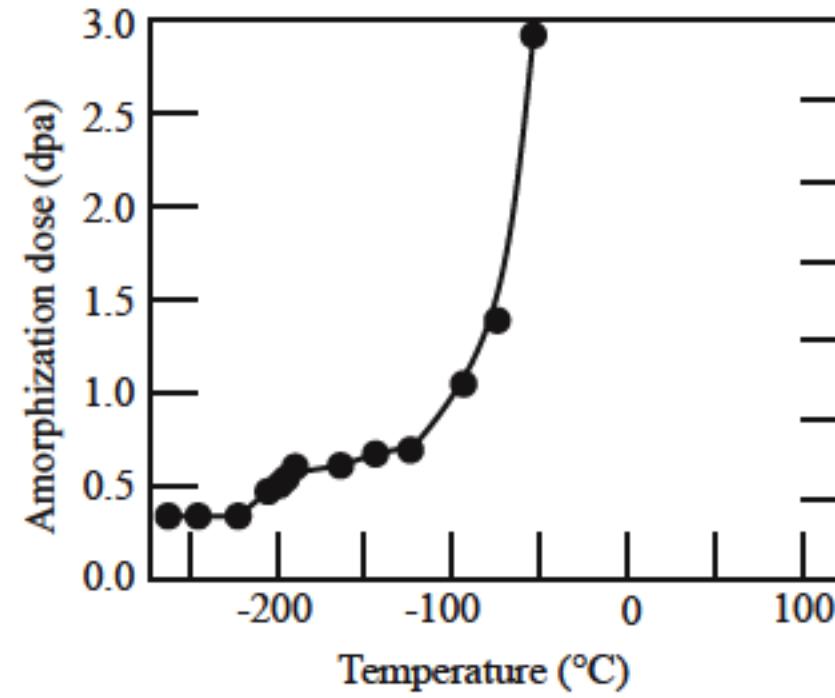
- Irradiation induced amorphization is difficult to describe (model) in a general basis
- Let's consider just describing the critical temperature and dose of amorphization for a simple system based on disordering



Temperature dependence of amorphization



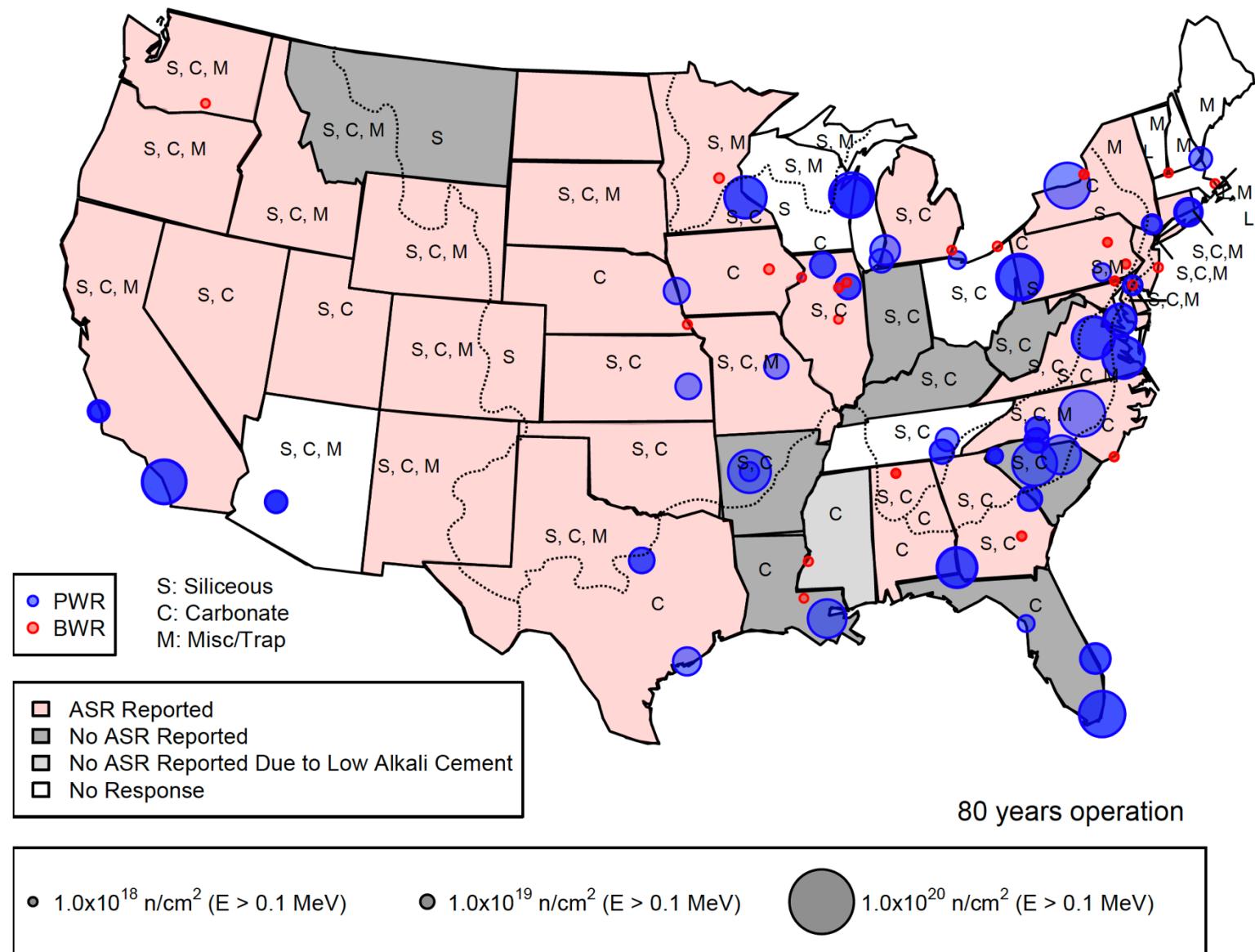
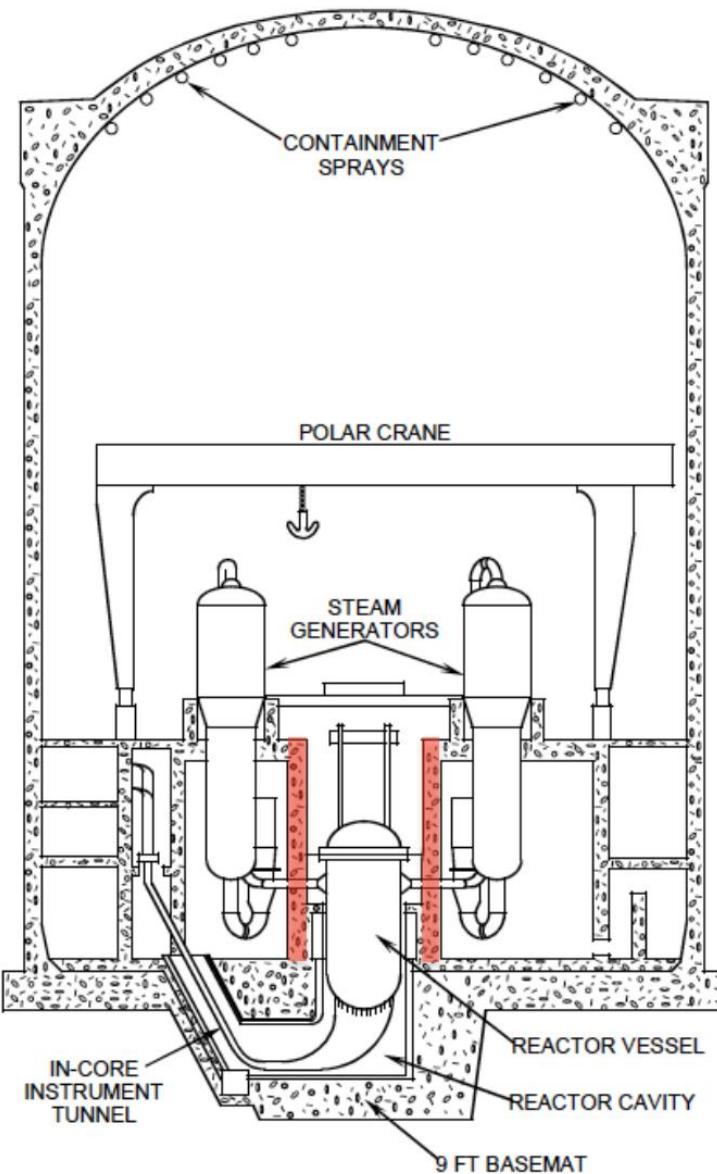
a



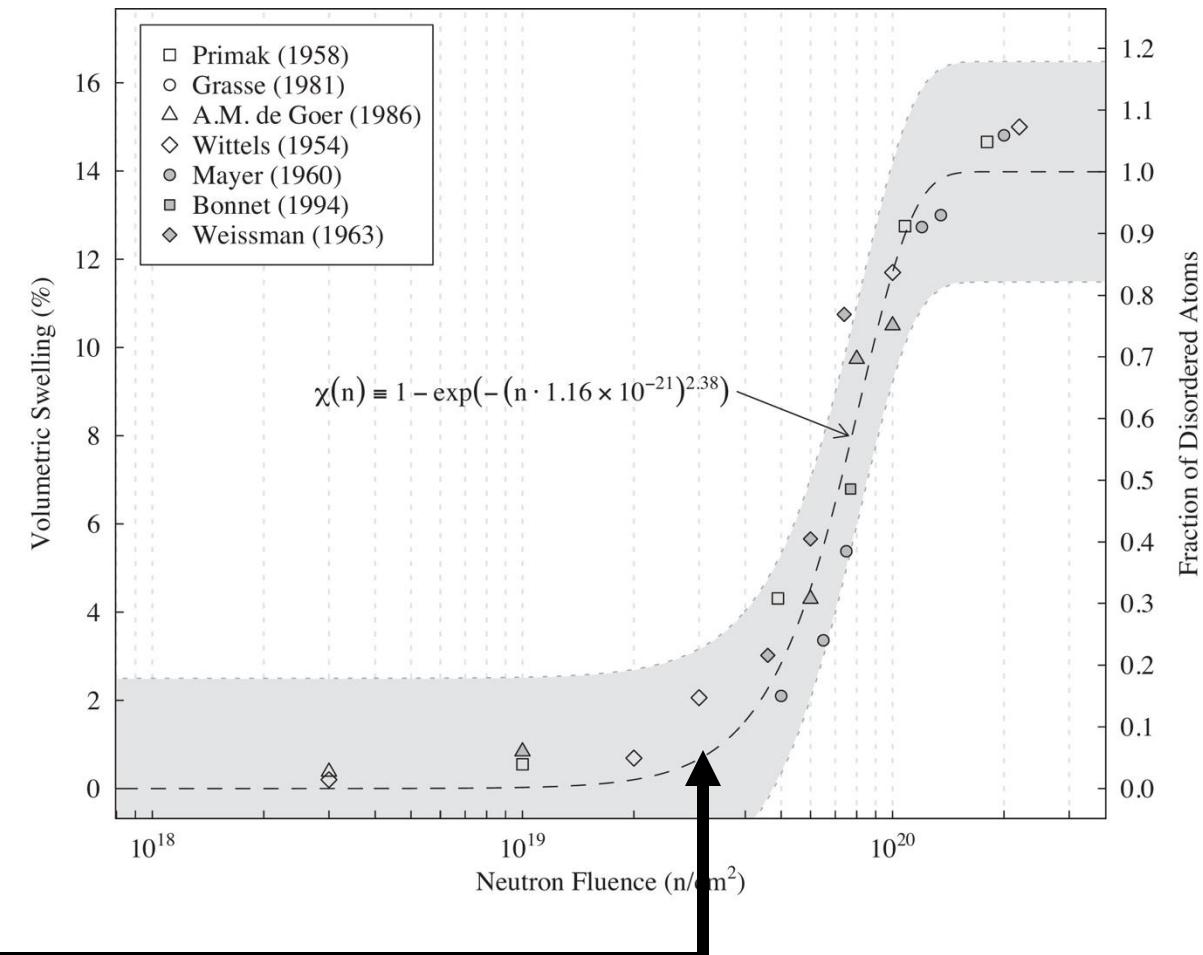
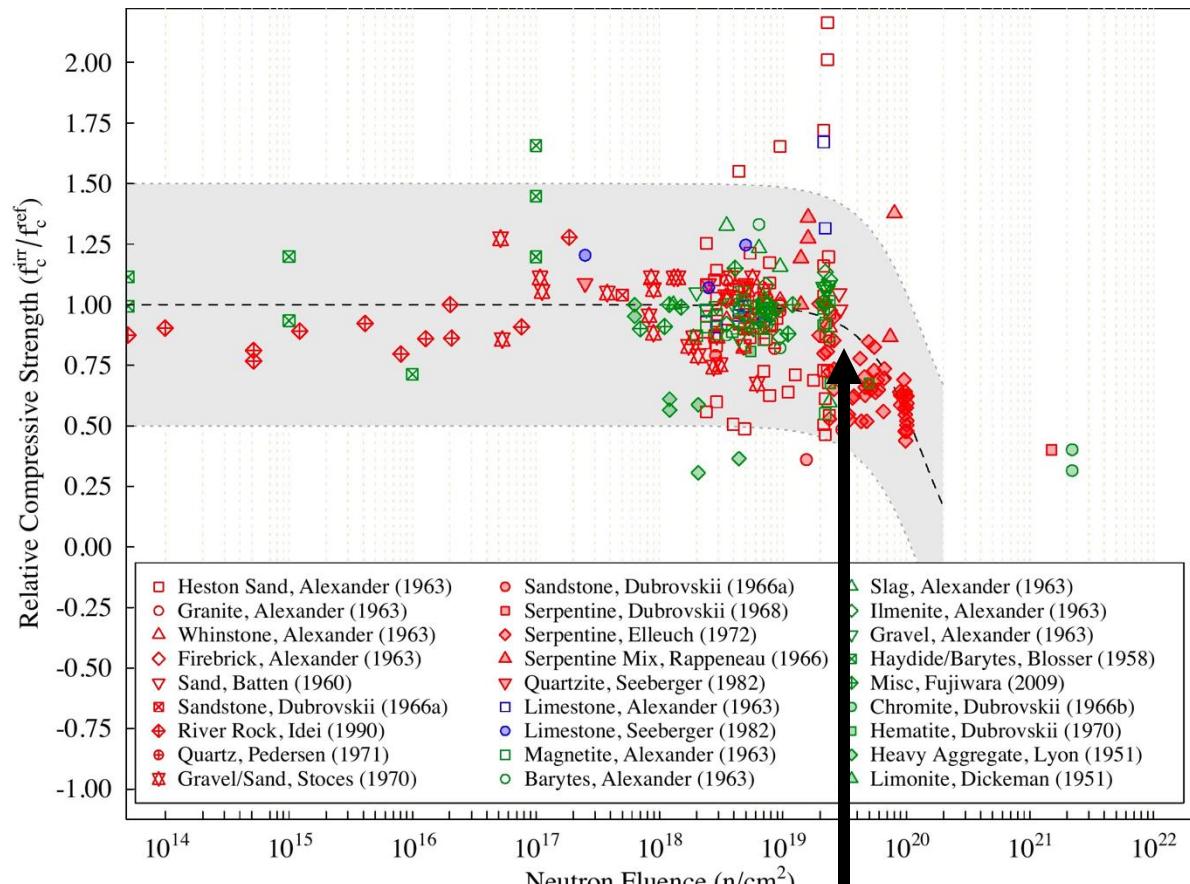
b

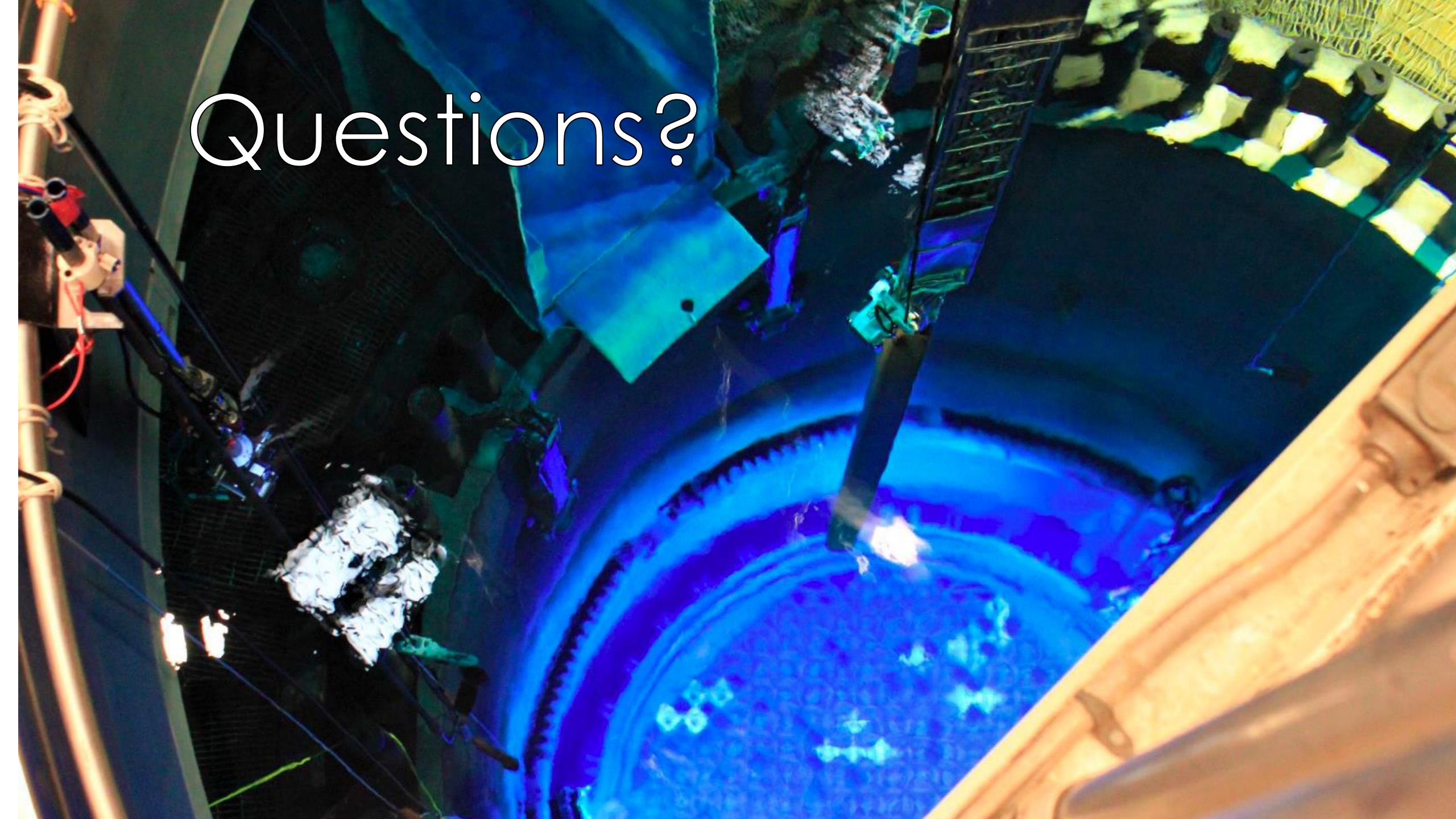
Temperature dependence of a) the long-range order parameter S/S_C , and b) the critical amorphization dose for CuTi, irradiated with 1 MeV electrons

Irradiation-induced amorphization



Irradiation-induced amorphization





Questions?