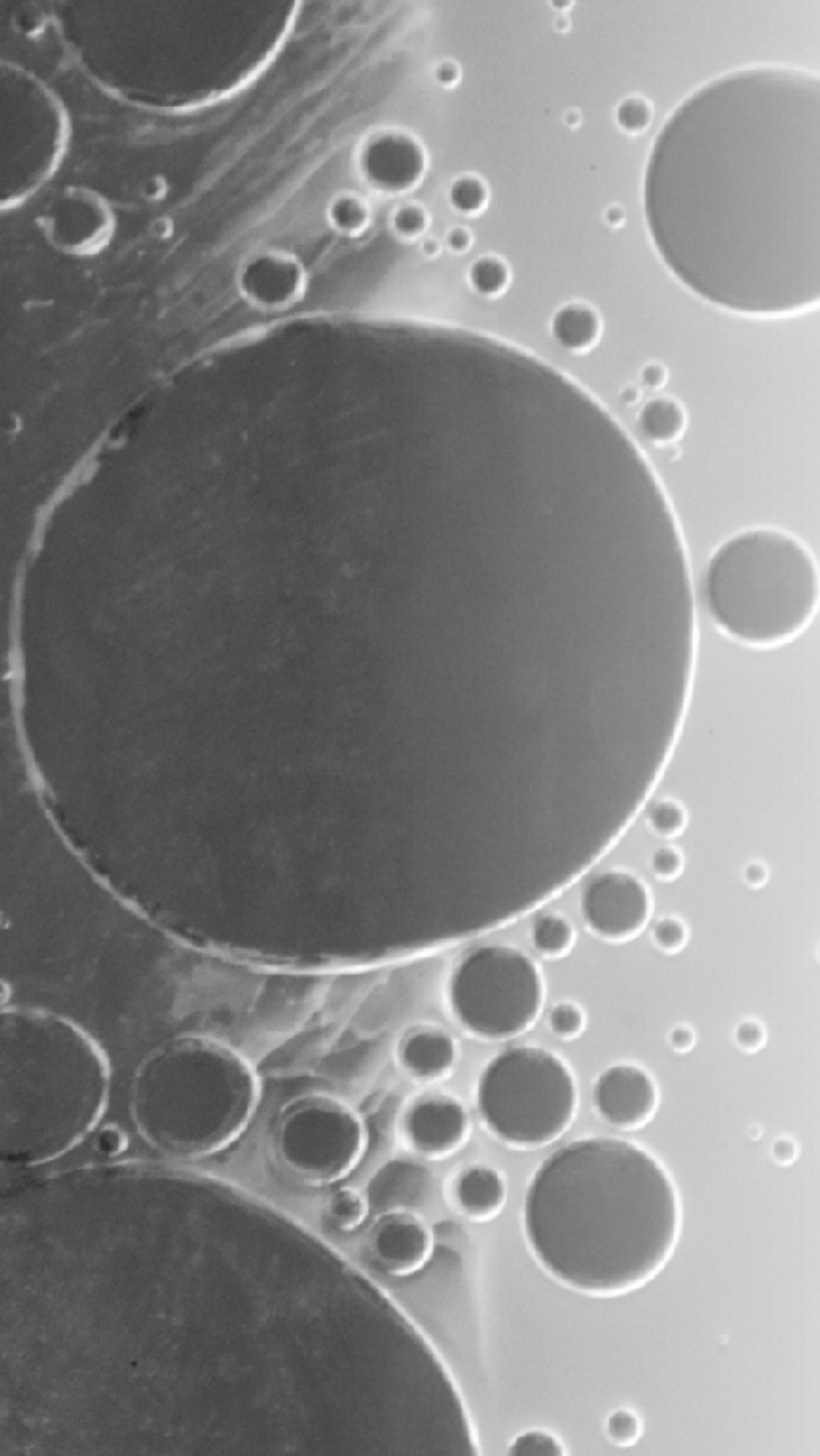

∂'Alembert
Institut Jean le Rond d'Alembert

MSC

cnrs

Freezing dynamics of an aqueous foam

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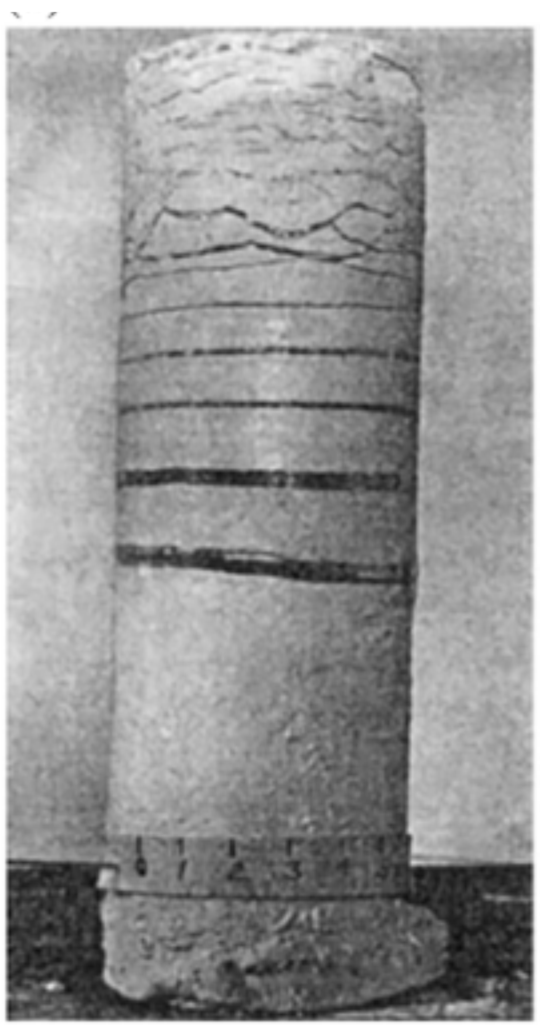
Supervisors
Thomas Séon
Juliette Pierre
Axel Huerre

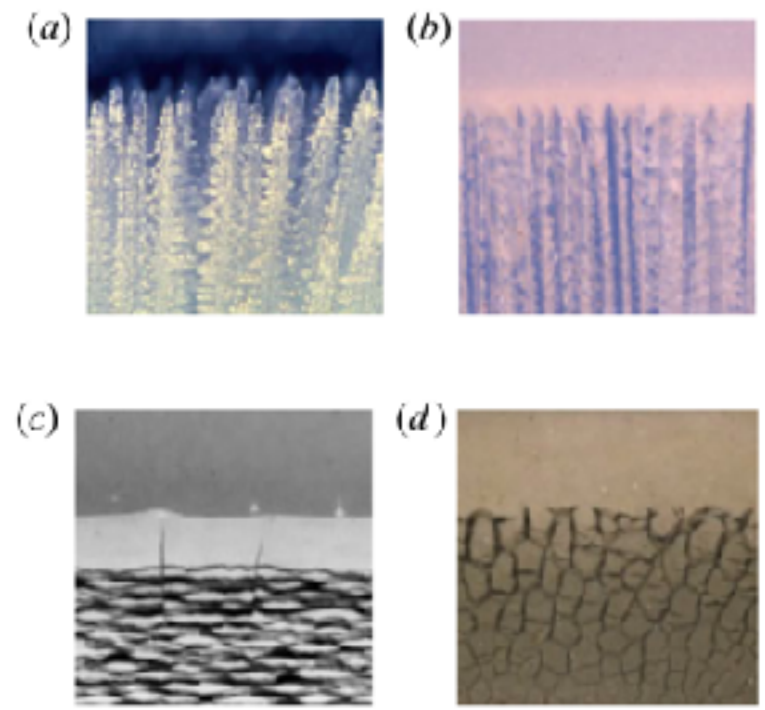
GDR Transinter Aussois 2022

Context

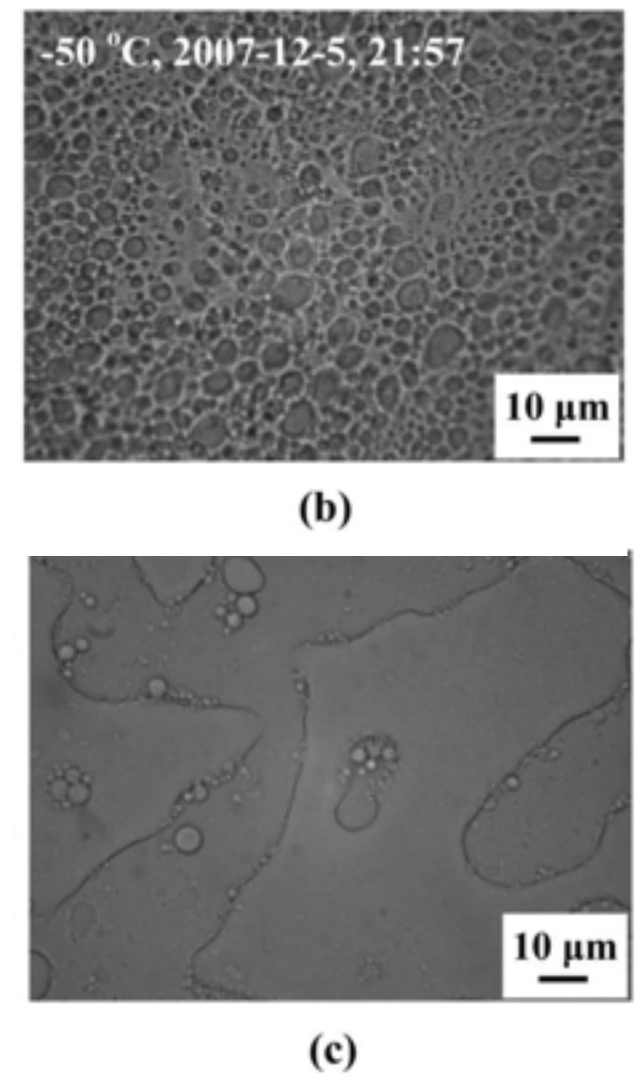
Solidification of disordered media



Taber 1930



Worster et al. 2021



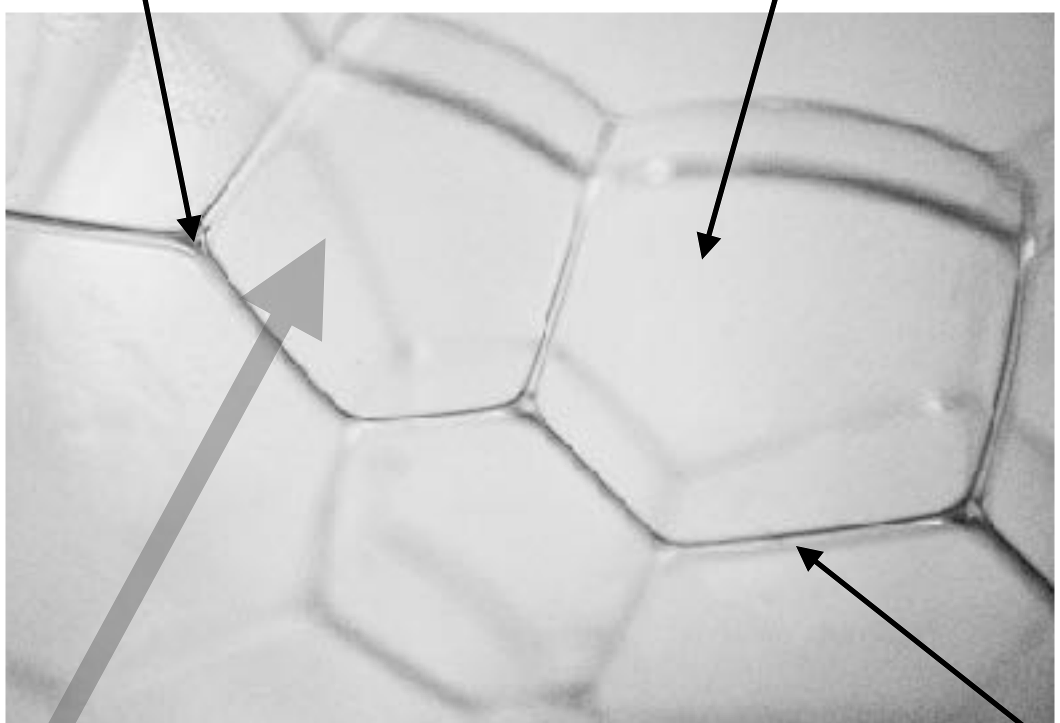
Lin et al. 2008

Context

Liquid foam as a complex disordered medium

Vertex

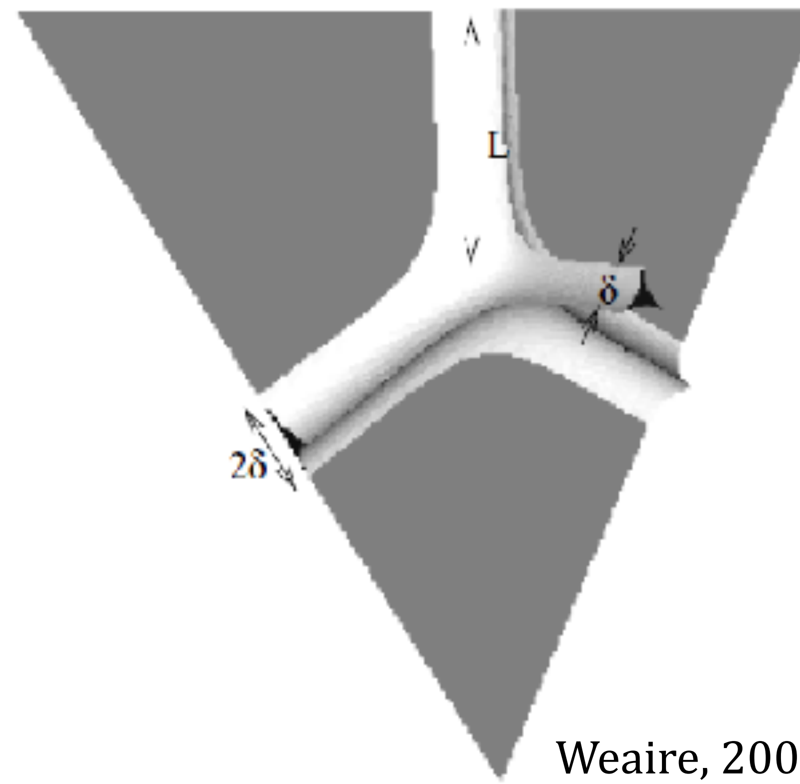
Soap film



The structure of a liquid foam as seen by photographer-artist me

Plateau border

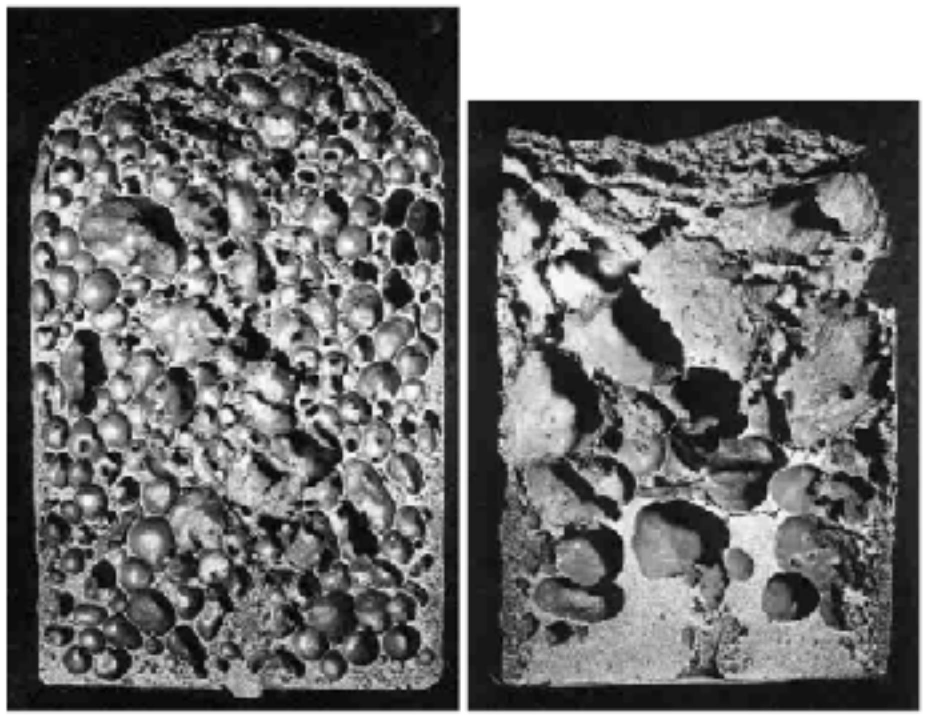
Gas phase



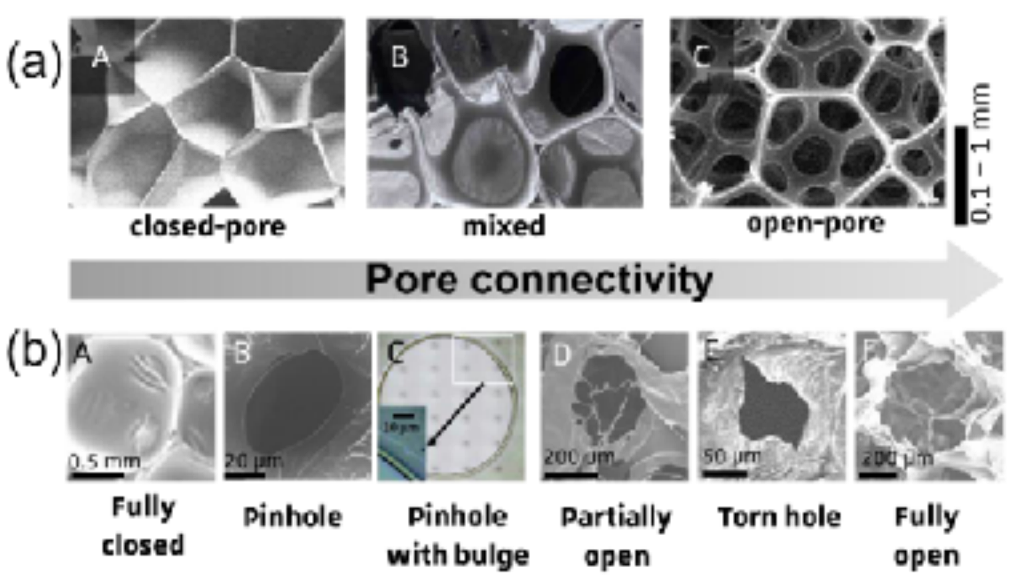
Weaire, 2002

Context

Solidification of foam



Cox et al. 2001



Andrieux et al. 2022

Does an aqueous foam freeze?

How fast does it freeze?

Is it still the same foam?


5 mm
x40

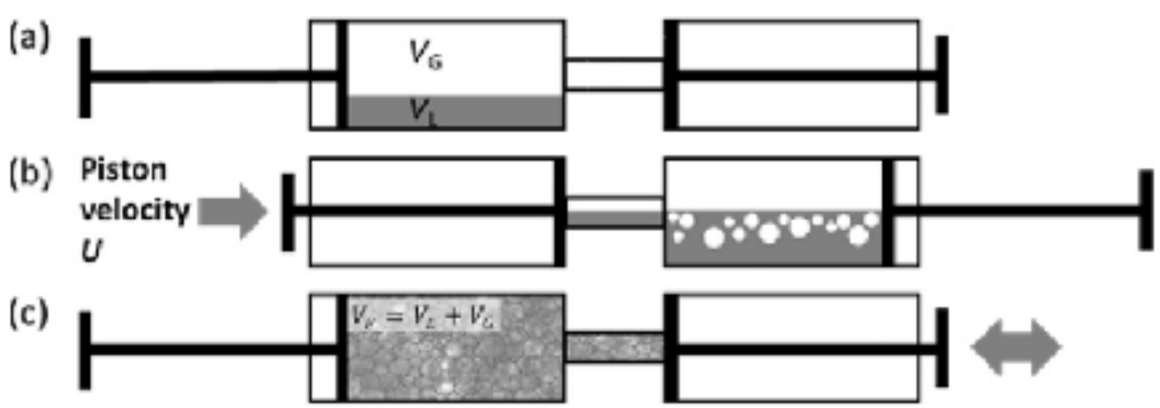
Experiment

1D solidification of a 3D foam

Water
10 g/L SDS
(5CMC)
0.5 g/L
Fluorescein

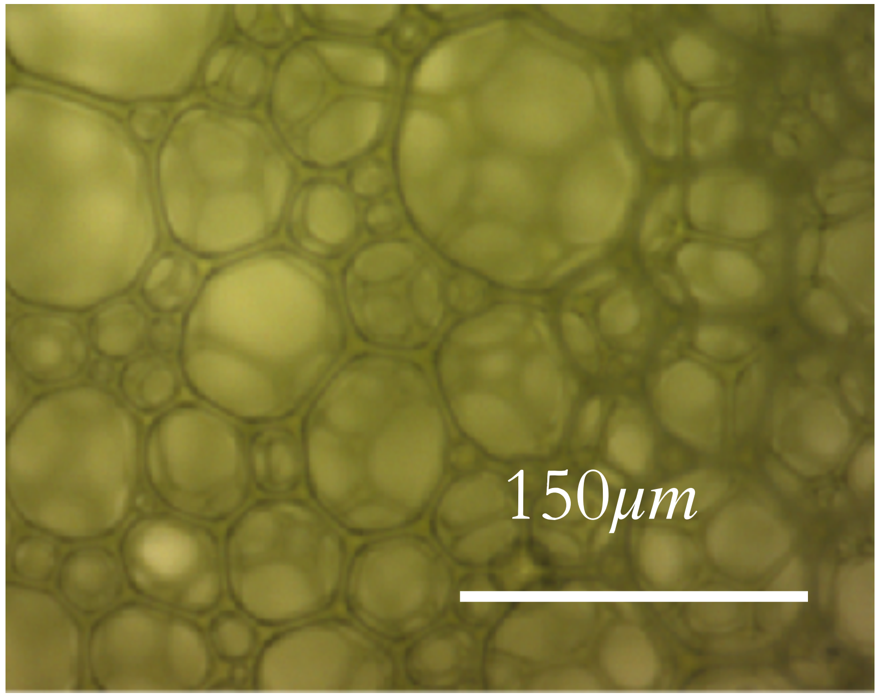
+

C_6F_{14}-saturated
air



$$\phi = \frac{V_l}{V_l + V_g}$$

Gaillard, 2017



$R \approx 25\ \mu m$
polydispersity 30%

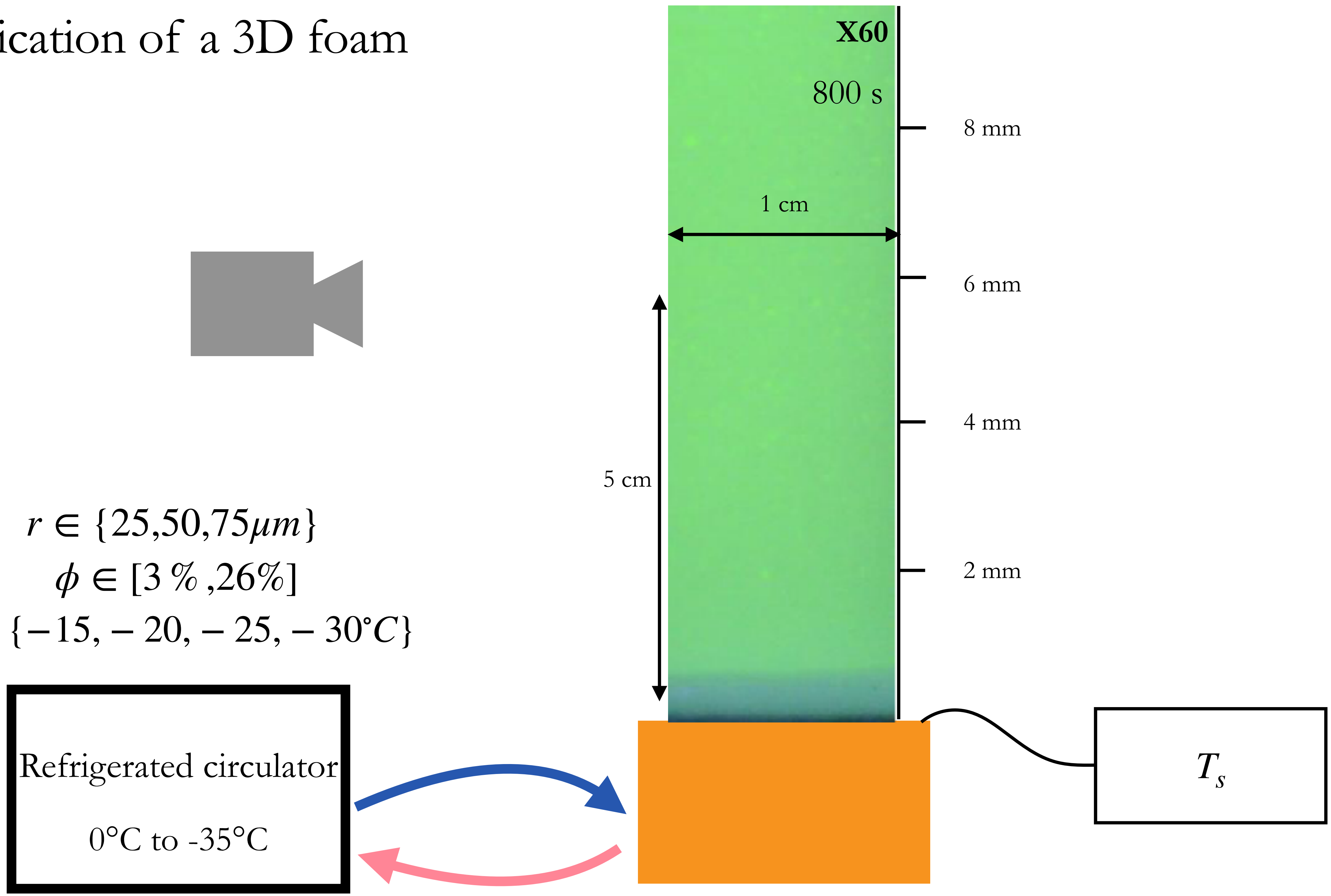
Experiment

1D solidification of a 3D foam

$r \in \{25, 50, 75 \mu m\}$

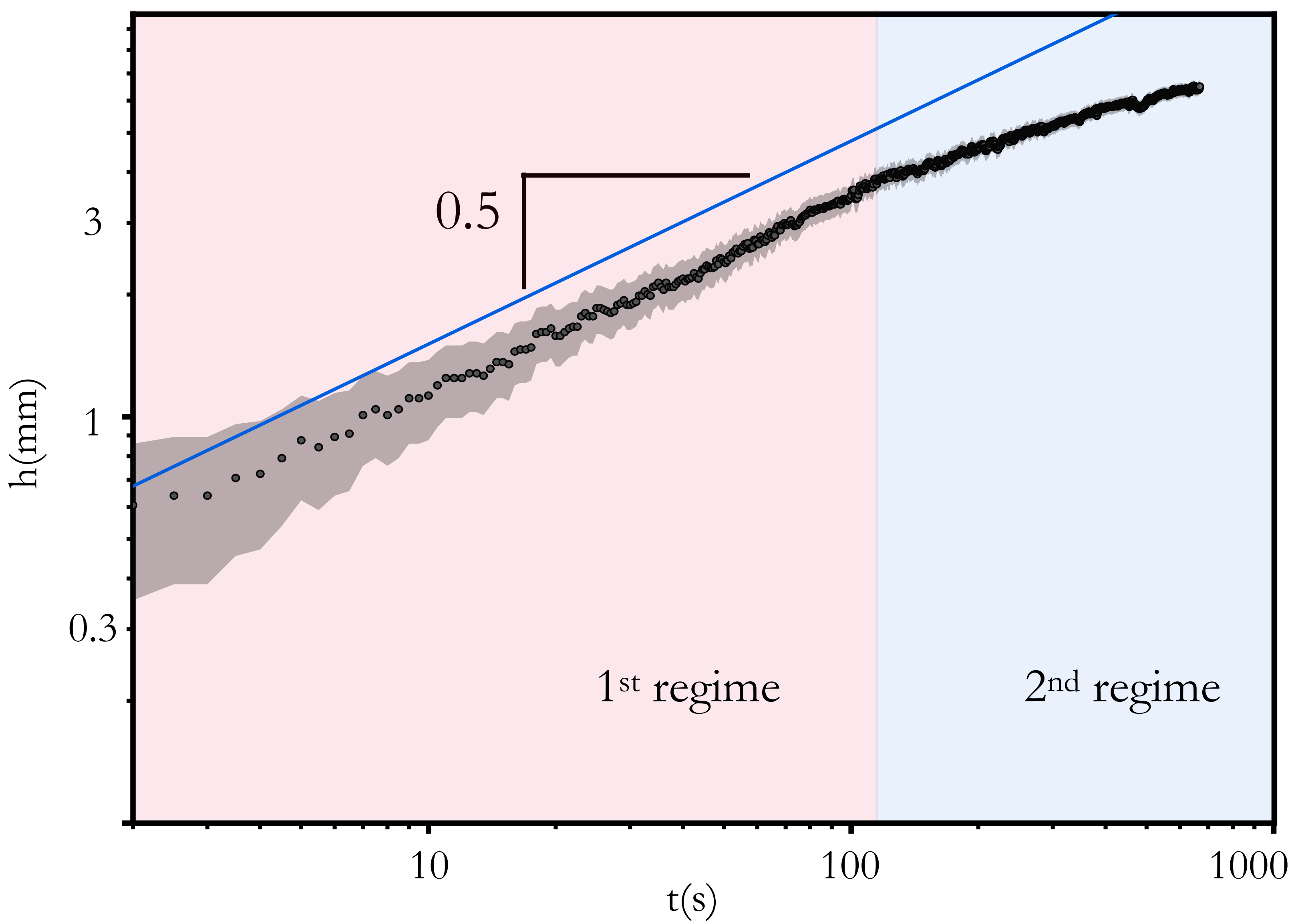
$\phi \in [3\,\%, 26\%]$

$T_s \in \{-15, -20, -25, -30^{\circ}C\}$



Experiment

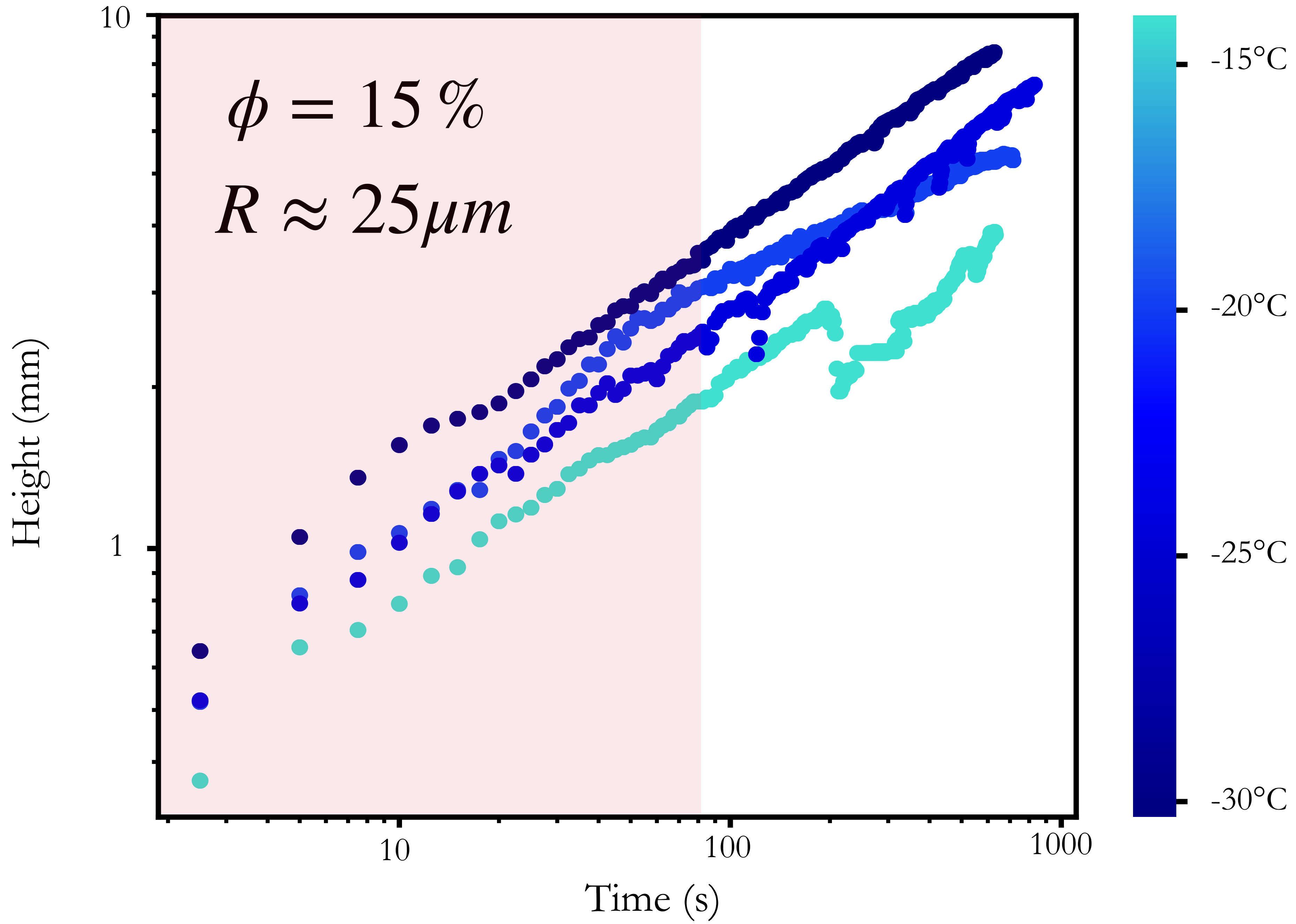
1D solidification of a 3D foam



Square root regime, and second slower regime after $\approx 100s$

Experiment

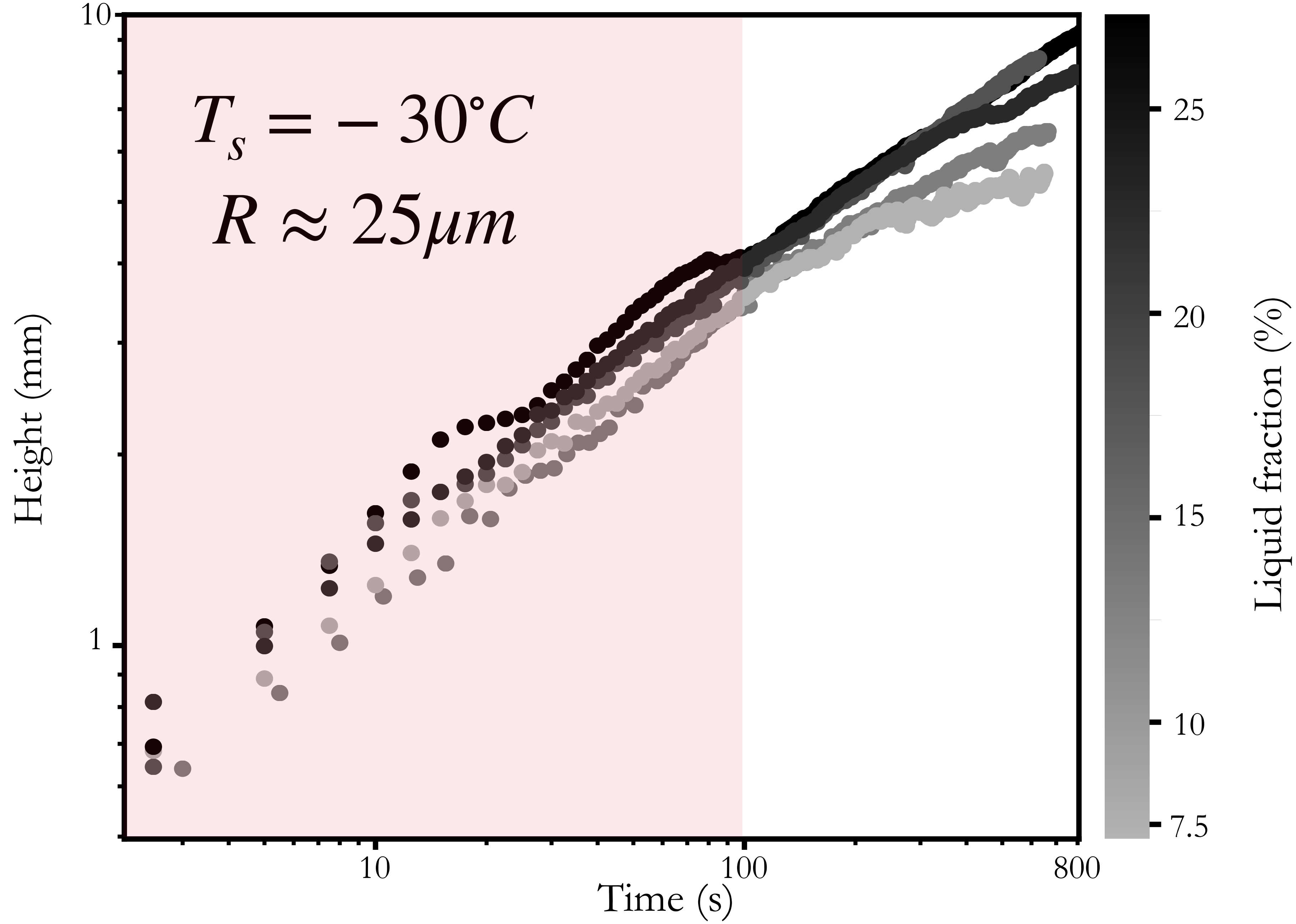
Changing the substrate temperature



The foam freezes faster on a colder substrate

Experiment

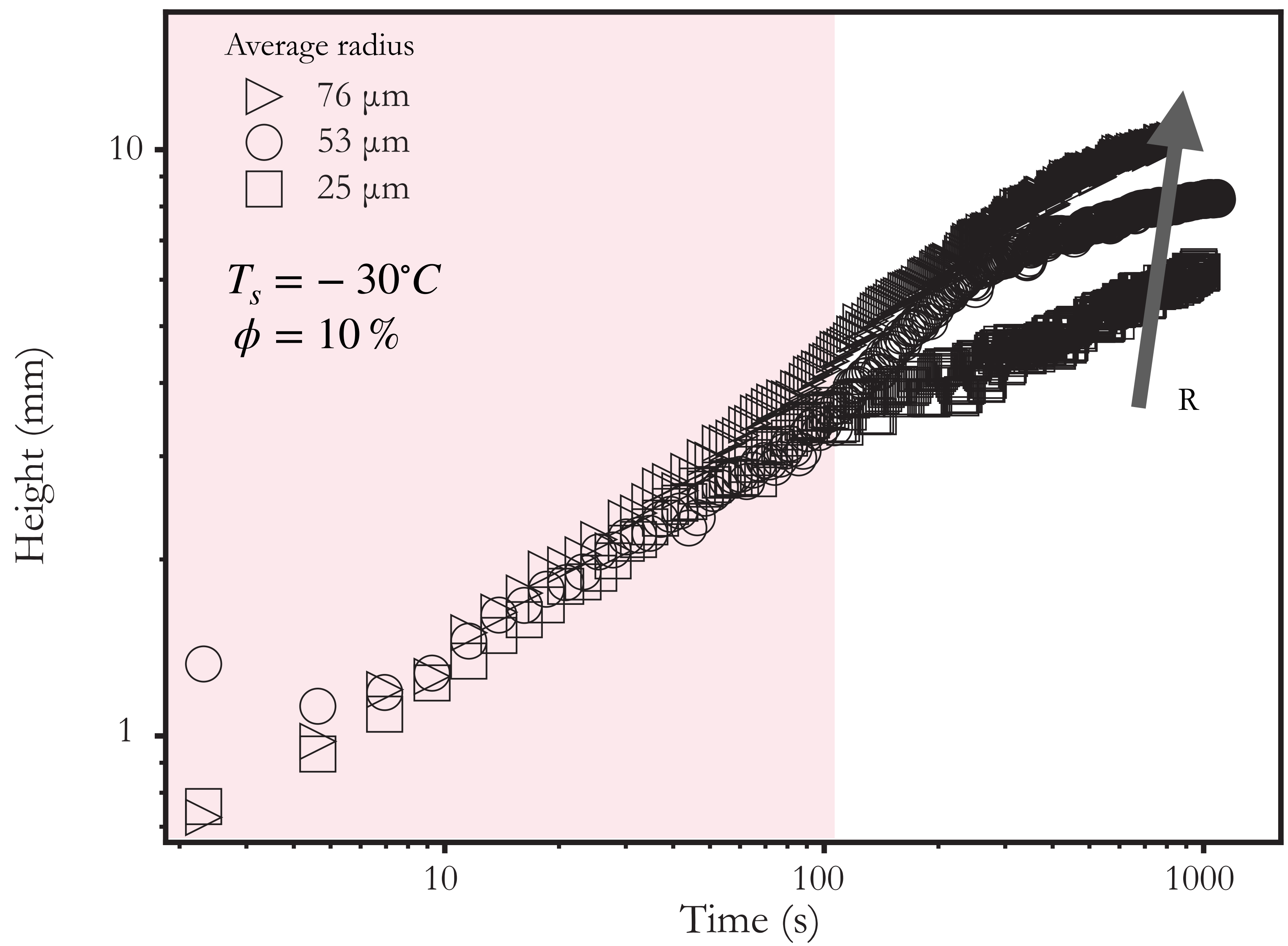
Changing the liquid fraction



The liquid fraction ϕ seems to play a role

Experiment

Effect of the bubble size



The radius does not influence the dynamics during the first regime

Experiment

Recap

$$\text{Square root regime : } \sqrt{D_{eff}(T_s, \phi, \cancel{R}, \ldots)\,.\,t}$$

$T_s \searrow \quad D_{eff} \nearrow$

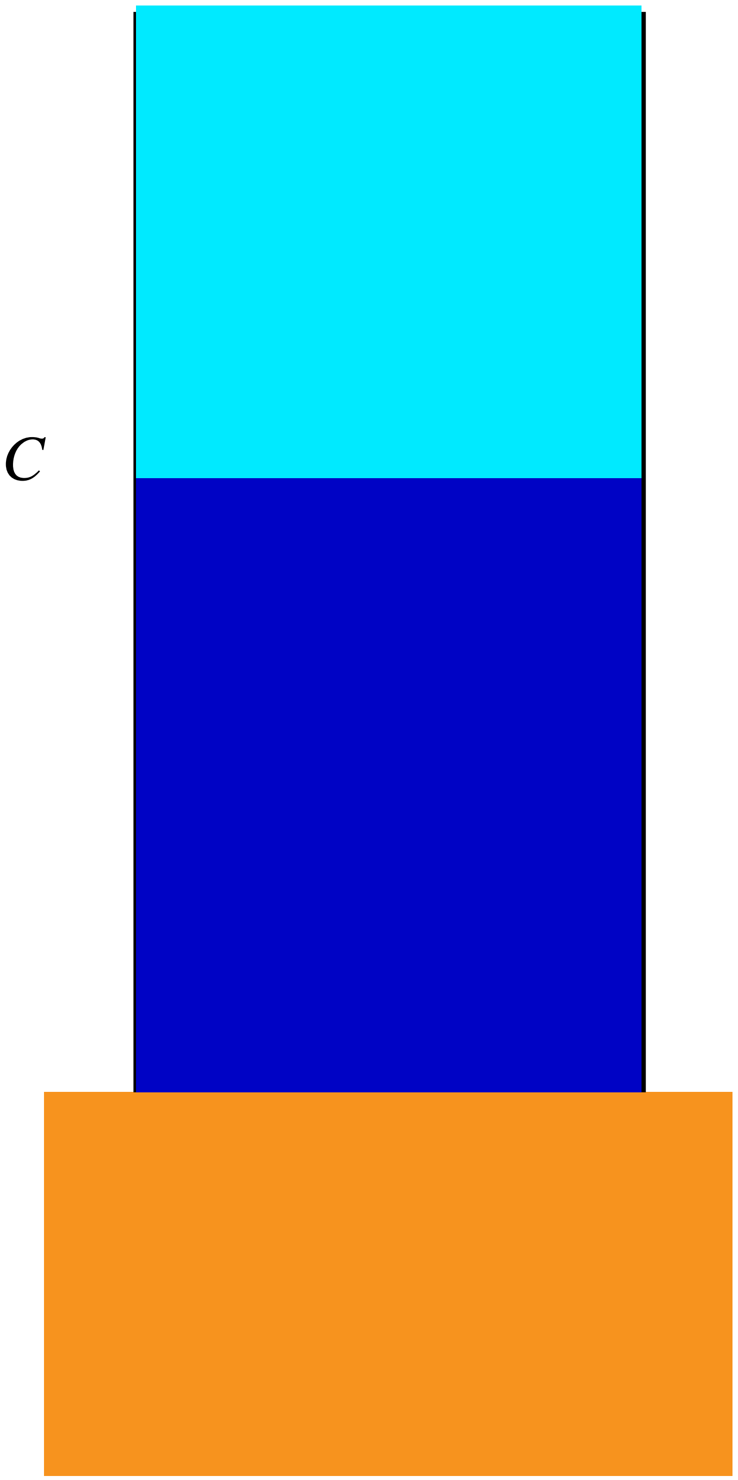
$\phi \nearrow \quad D_{eff} \nearrow$

Effective medium model

Related Stefan problem

$$\rho_l C_{p_l} \frac{\partial T}{\partial t} = \lambda_i \frac{\partial^2 T}{\partial z^2}$$

$$T(h) = 0°C$$



$$\rho_i L \frac{\mathrm{d}h}{\mathrm{d}t} = \lambda_i \frac{\partial T}{\partial z}(h^-) - \lambda_l \frac{\partial T}{\partial z}(h^+)$$

$$\rho_i C_{p_i} \frac{\partial T}{\partial t} = \lambda_i \frac{\partial^2 T}{\partial z^2}$$

$$(\rho C_p)_s \frac{\partial T}{\partial t} = \lambda_s \frac{\partial^2 T}{\partial z^2}$$

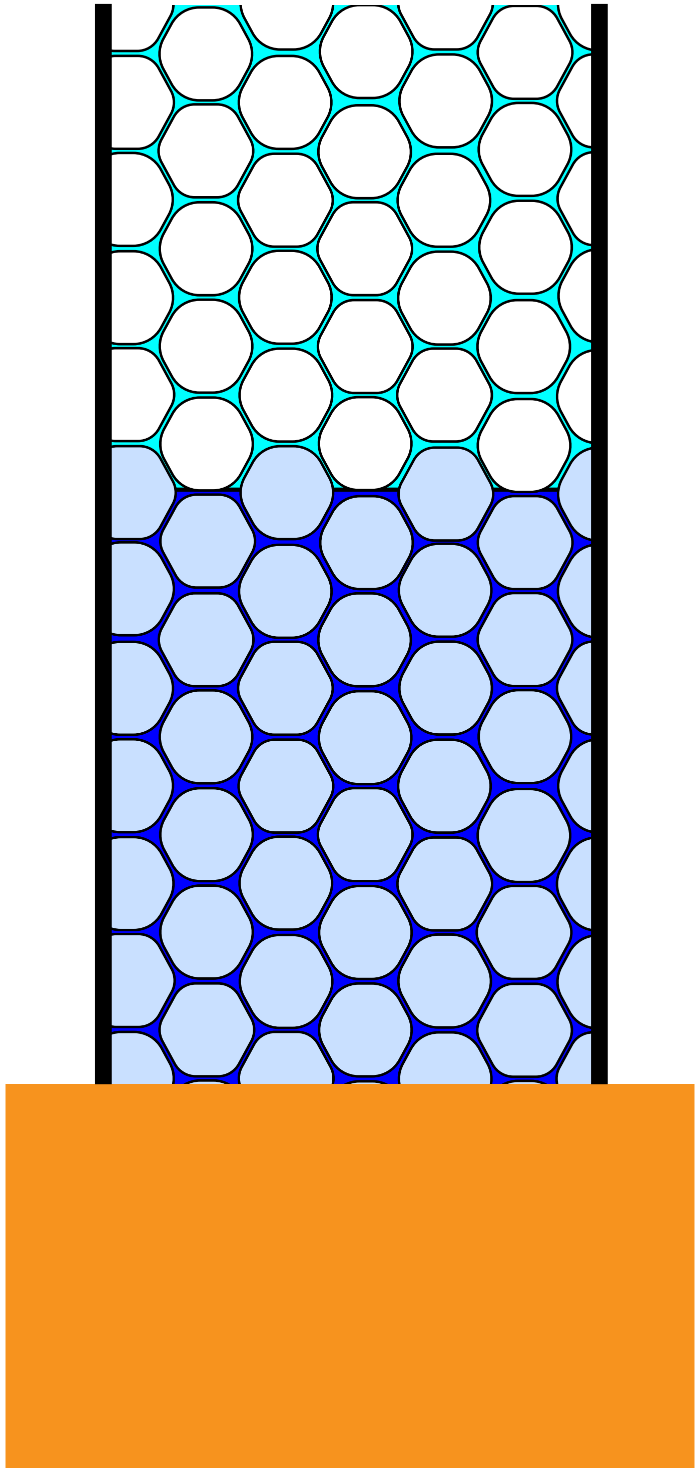
$$\boxed{h(t) = \sqrt{D_{eff}(T_s, \ldots) \, . \, t}}$$

Thievenaz 2019, Kant 2021

Effective medium model

Related Stefan problem

$$(\rho C_p)_{fl}\frac{\partial T}{\partial t} = \lambda_{fl}\frac{\partial^2 T}{\partial z^2}$$



$$\phi\rho_l L\frac{\mathrm{d}h}{\mathrm{d}t} = \lambda_{fi}\frac{\partial T}{\partial z}(h^-) - \lambda_{fl}\frac{\partial T}{\partial z}(h^+)$$

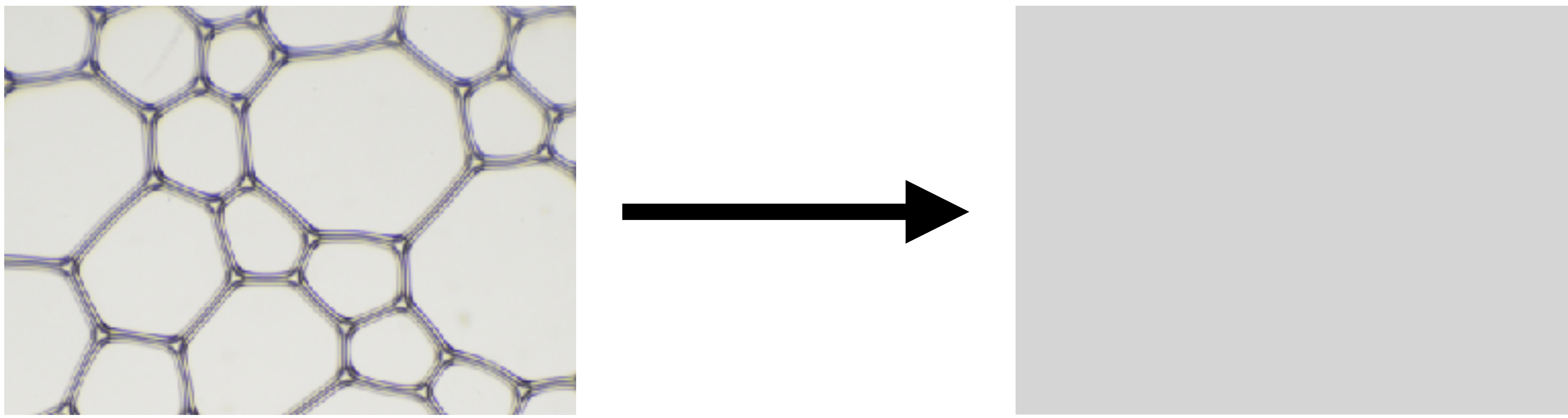
$$(\rho C_p)_{fi}\frac{\partial T}{\partial t} = \lambda_{fi}\frac{\partial^2 T}{\partial z^2}$$

$$(\rho C_p)_{s}\frac{\partial T}{\partial t} = \lambda_{s}\frac{\partial^2 T}{\partial z^2}$$

$$h(t) = \sqrt{D_{eff}(T_s, \phi \ldots) \,.\, t}$$

Effective medium model

$$(\rho C_p)\frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial z^2}$$



$\rho_l, \rho_g, C_{p_l}, C_{p_g}, \lambda_l, \lambda_g$

Microstructure
information
$\rho(\mathbf{x}), \lambda(\mathbf{x}), C_p(\mathbf{x})$

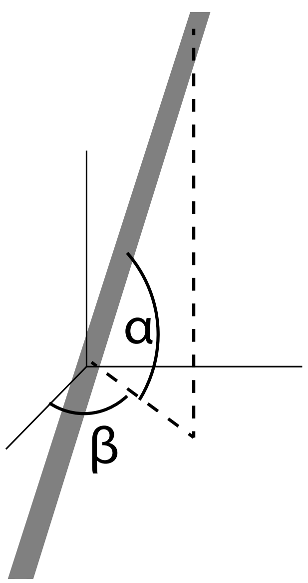
$$(\rho C_p)_f = \phi \rho_l C_{p_l} + (1 - \phi)\rho_g C_{p_g}$$

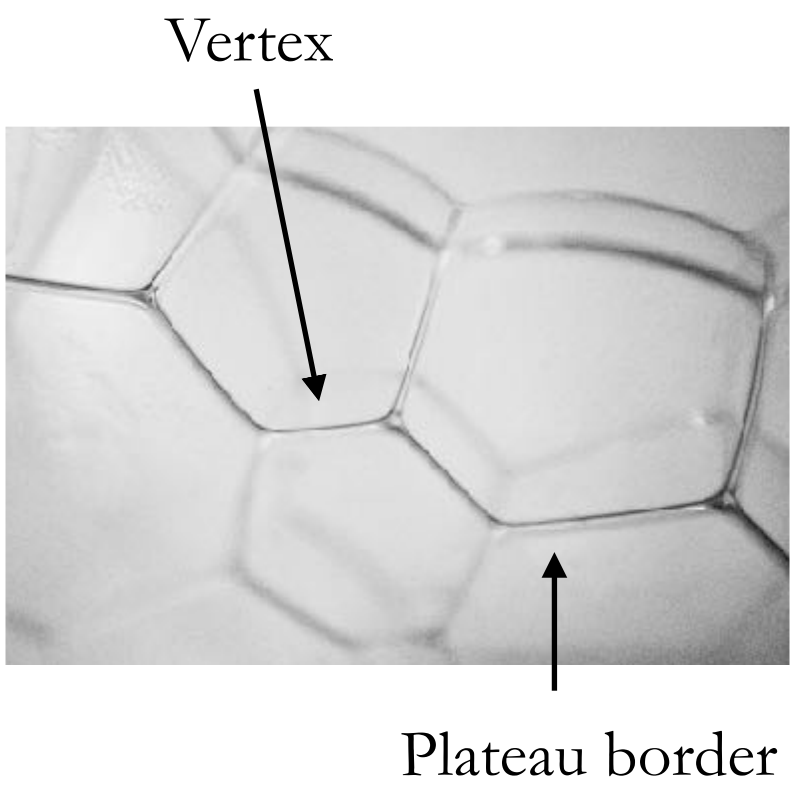
$$\lambda_f$$

Effective medium model

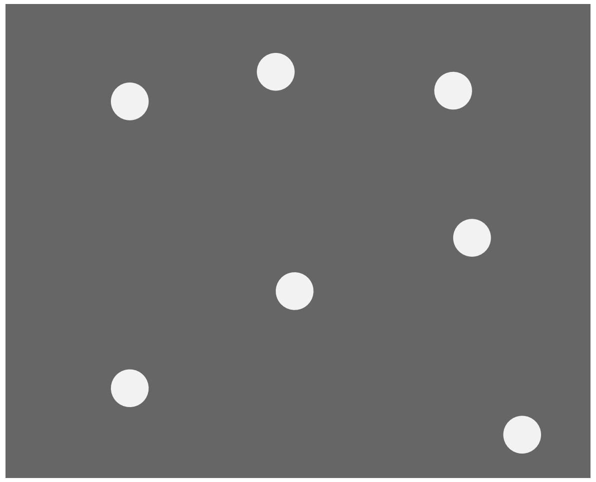
Electrical conductivity

Lemlich (1978)





Maxwell (1892)



0 % → $\phi_c = 36\,\%$

$$\frac{1}{3}\phi\sigma_l$$

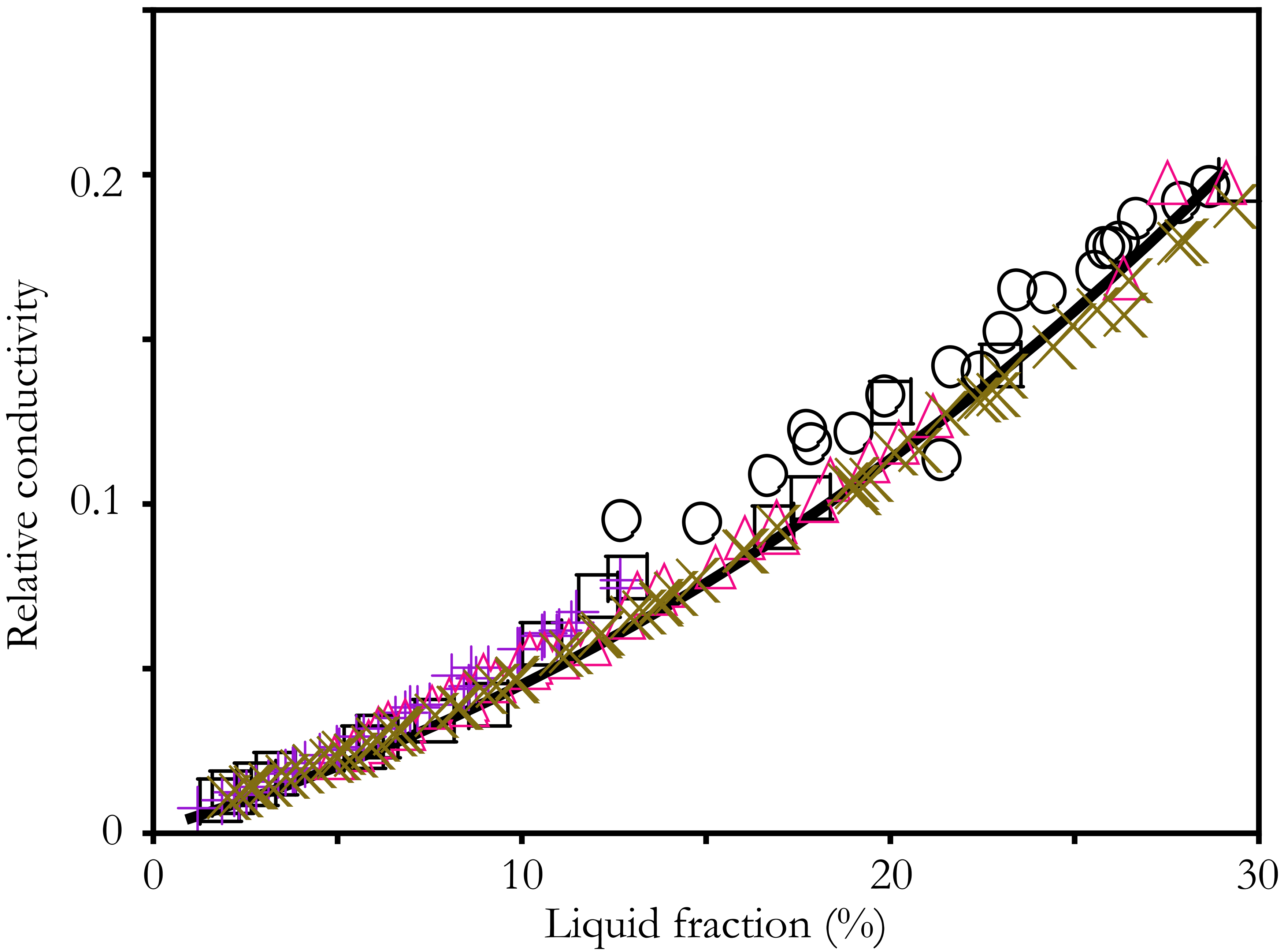
$$f_{PB}(\phi) = 1 - \frac{\phi}{\phi_c}$$

$$\frac{2}{3-\phi}\phi\sigma_l$$

$$\sigma_{foam} = \phi\sigma_l\frac{1}{3}(1 - \frac{\phi}{\phi_c}) + \phi\sigma_l\frac{2}{3-\phi}\frac{\phi}{\phi_c}$$

Effective medium model

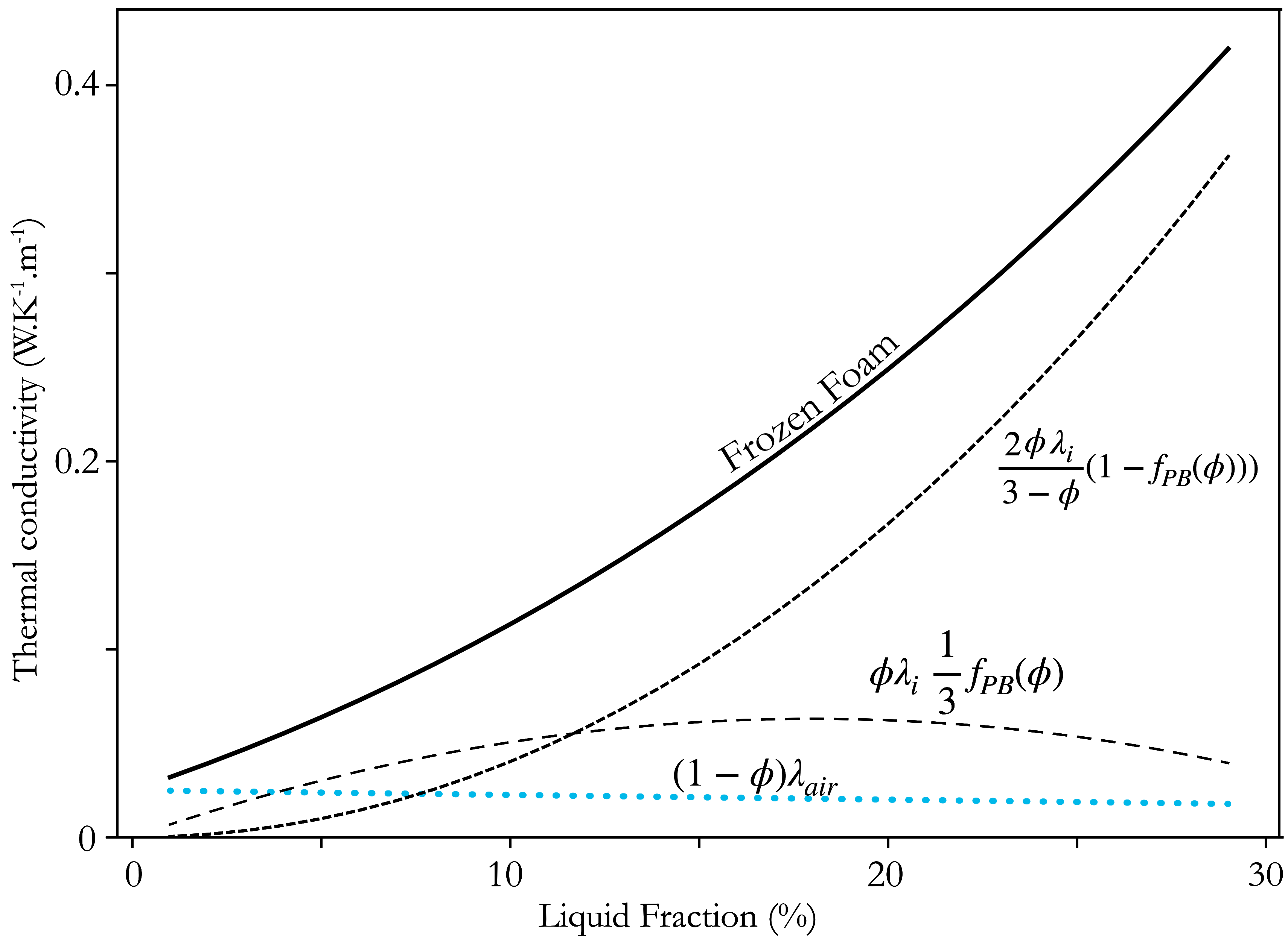
Electrical conductivity



data : Feitosa et al. 2005

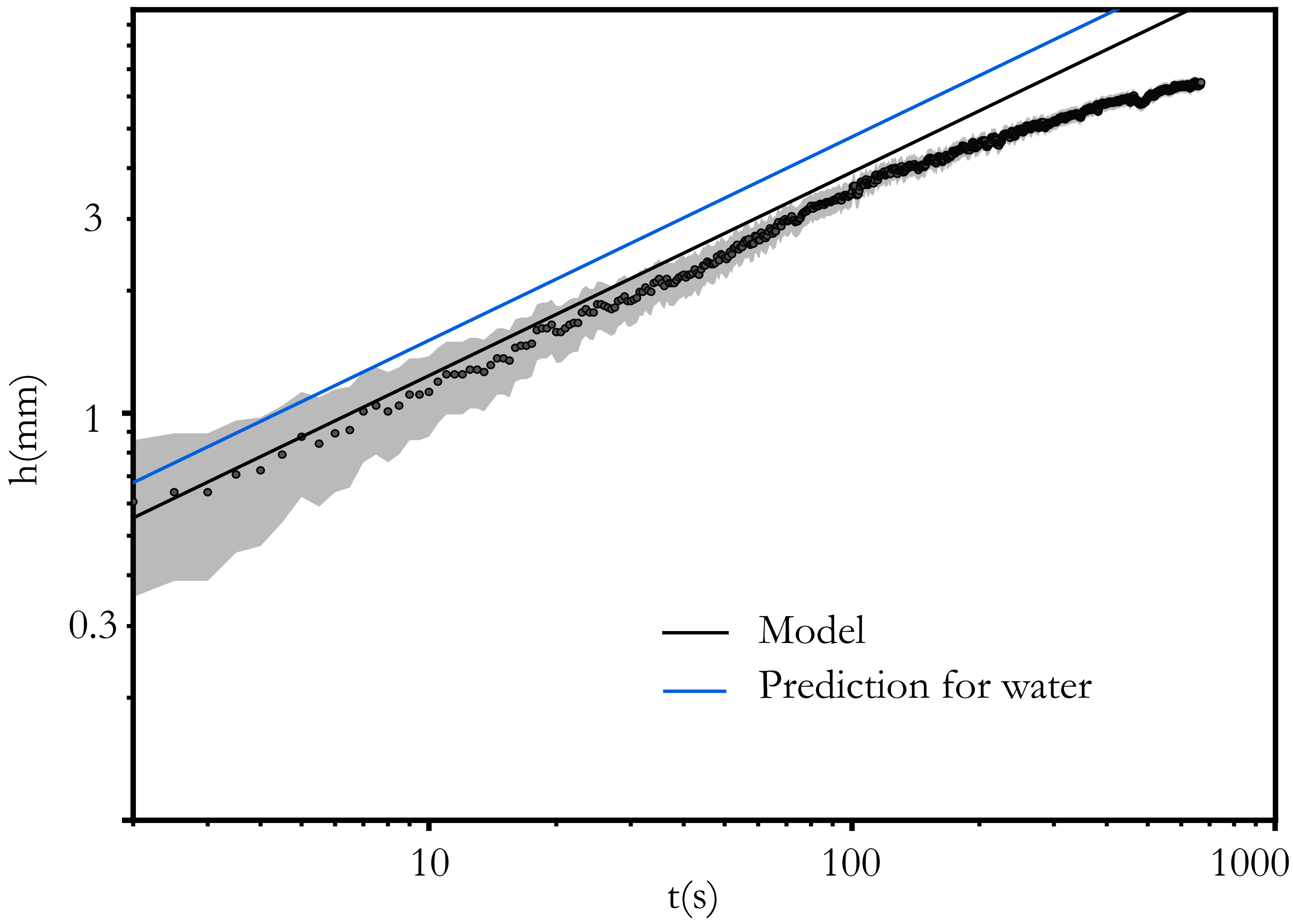
Effective medium model

$$\lambda_{foam} = (1-\phi)\lambda_{air} + \phi\lambda_l\left(\frac{1}{3}f_{PB}(\phi) + \frac{2}{3-\phi}(1-f_{PB}(\phi))\right)$$



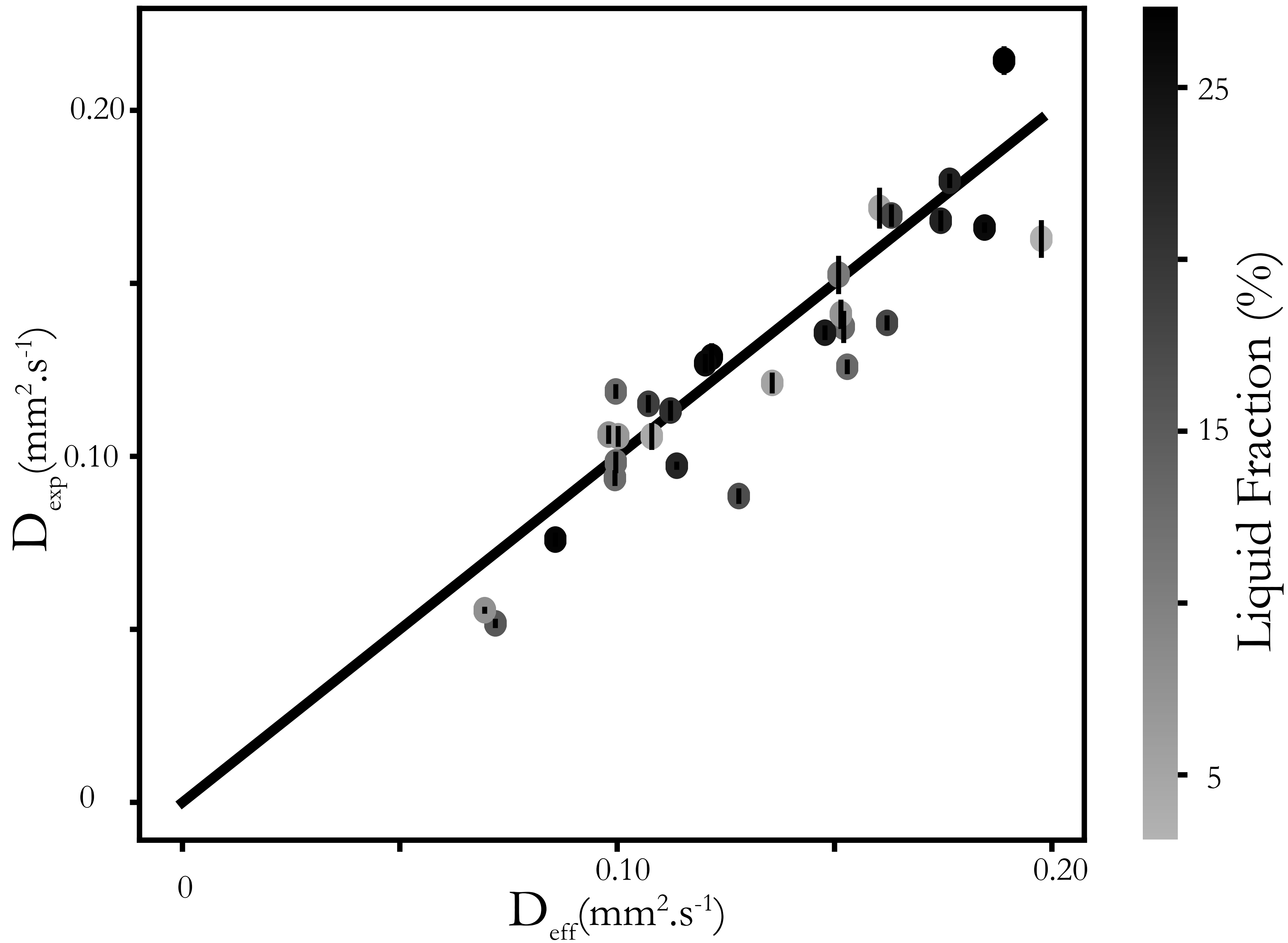
Experiment

1D solidification of a 3D foam



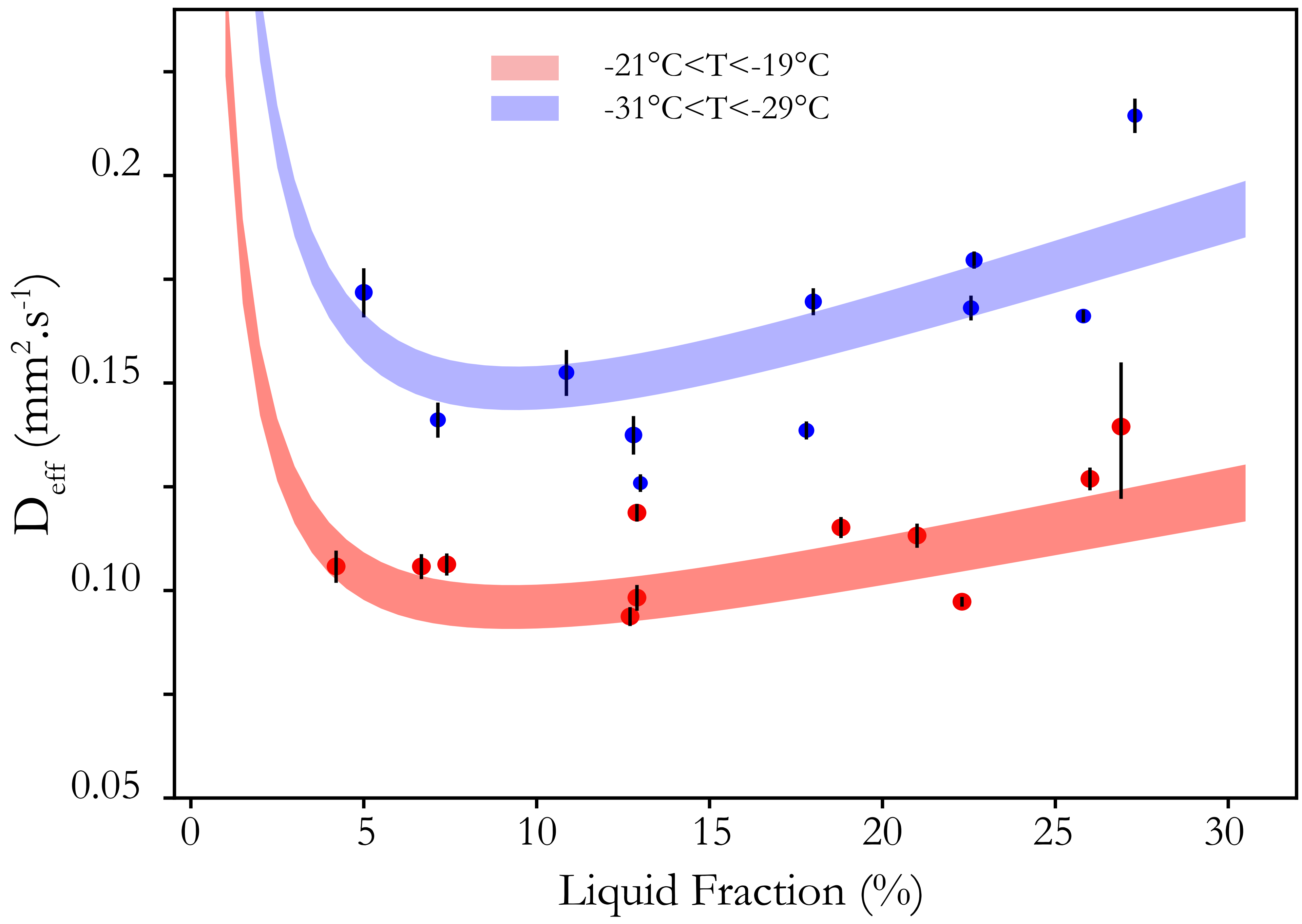
Experiment

1D solidification of a 3D foam



Model

1D solidification of a 3D foam

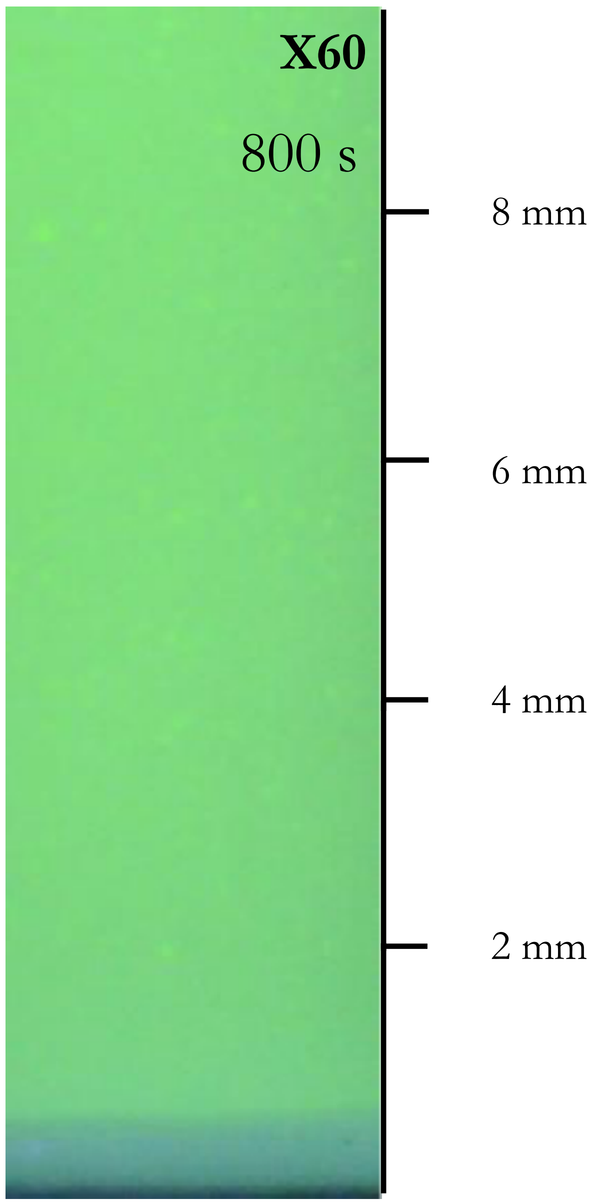


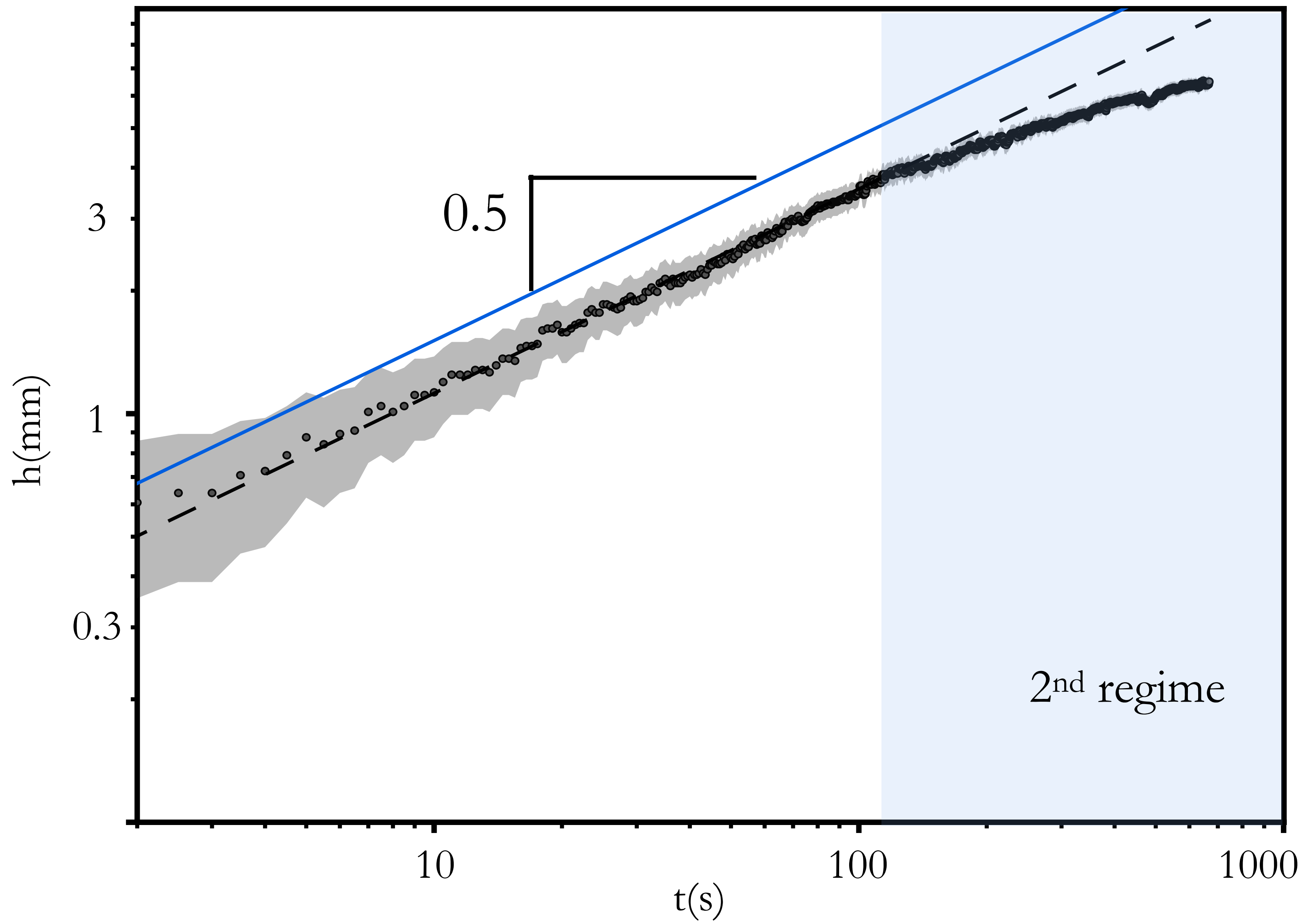
Perspective

Leaving the square root

Leaving the square root

1D solidification of a 3D foam

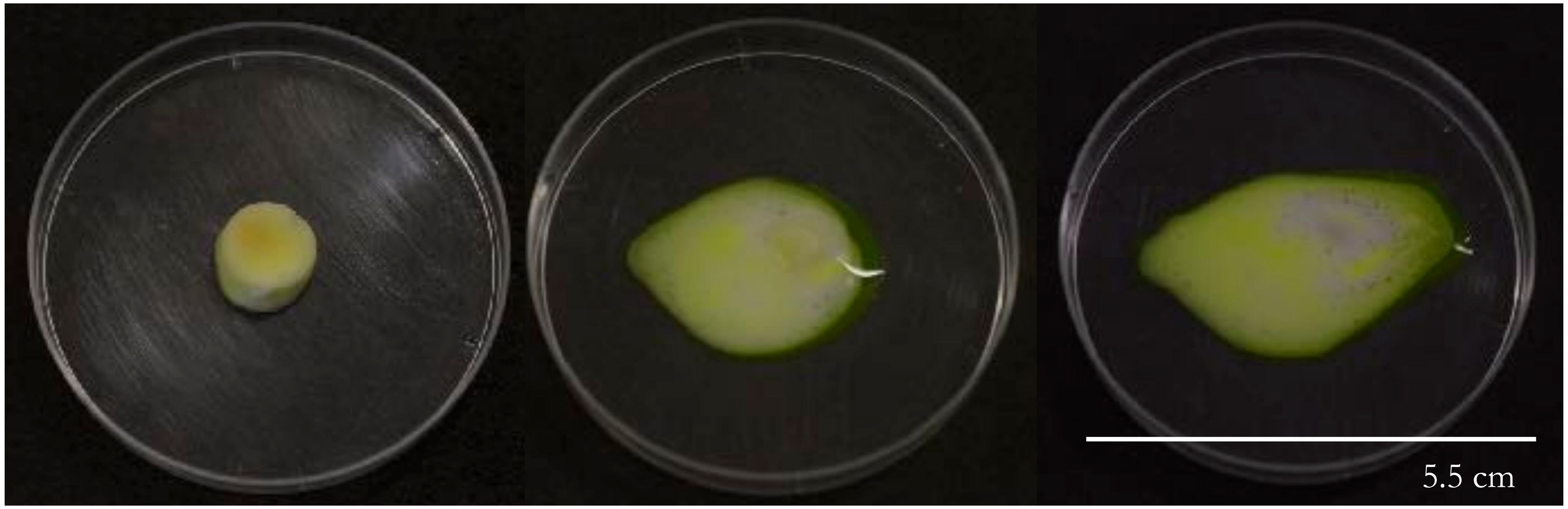




$\phi = 13\,\%\,, T = -\,30.2^{\circ}C$

Leaving the square root

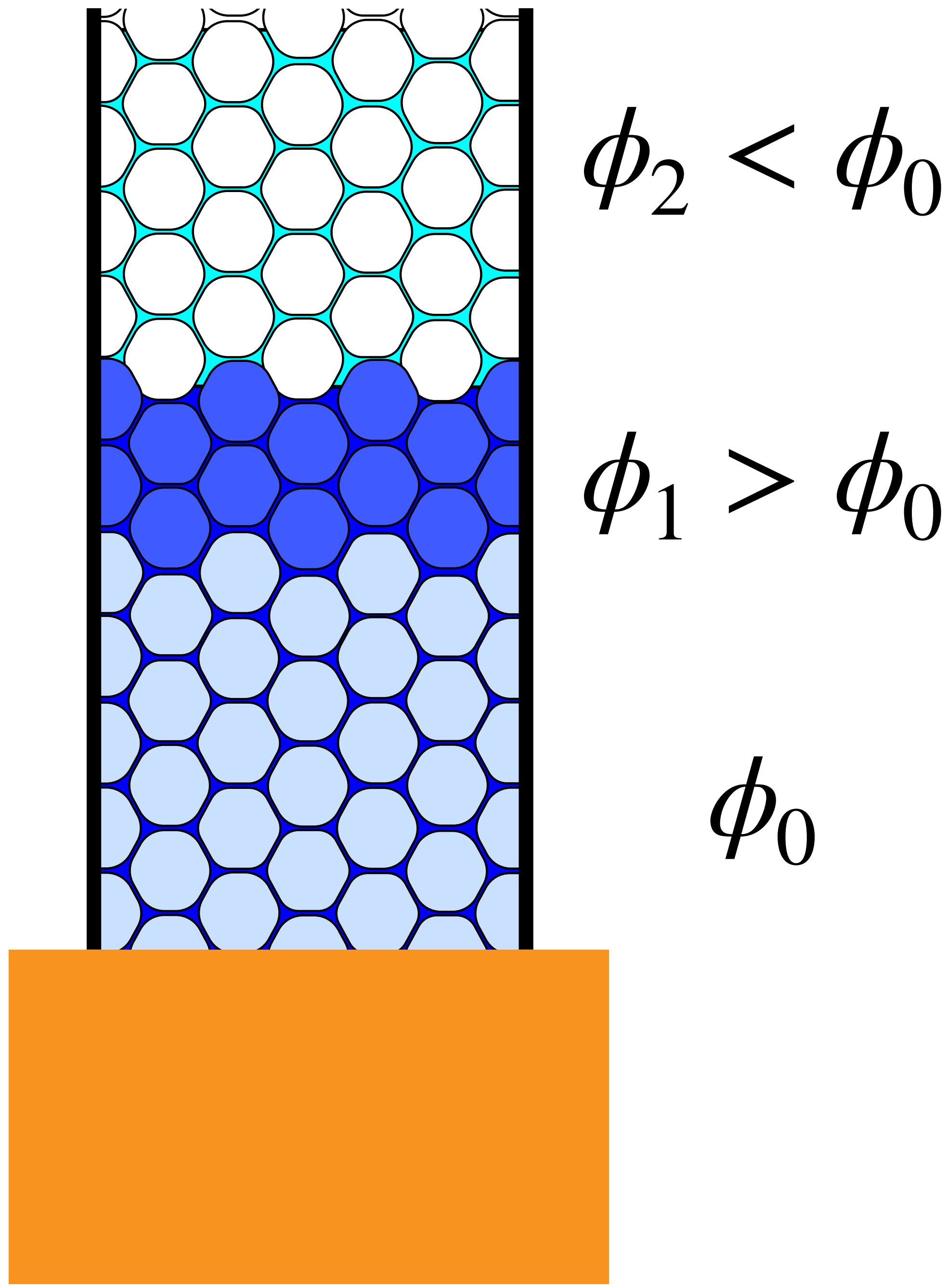
Composition of the frozen foam



0.8 ml of thawed foam
initial liquid fraction = 13%
liquid fraction after freezing = 32%

Leaving the square root

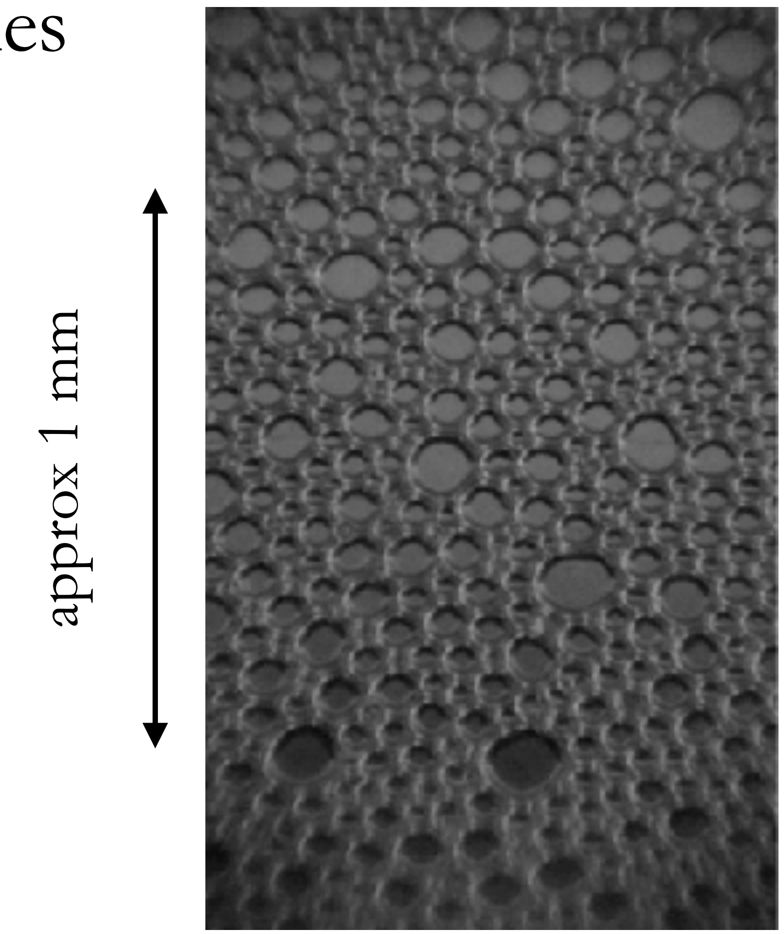
1D solidification of a 3D foam

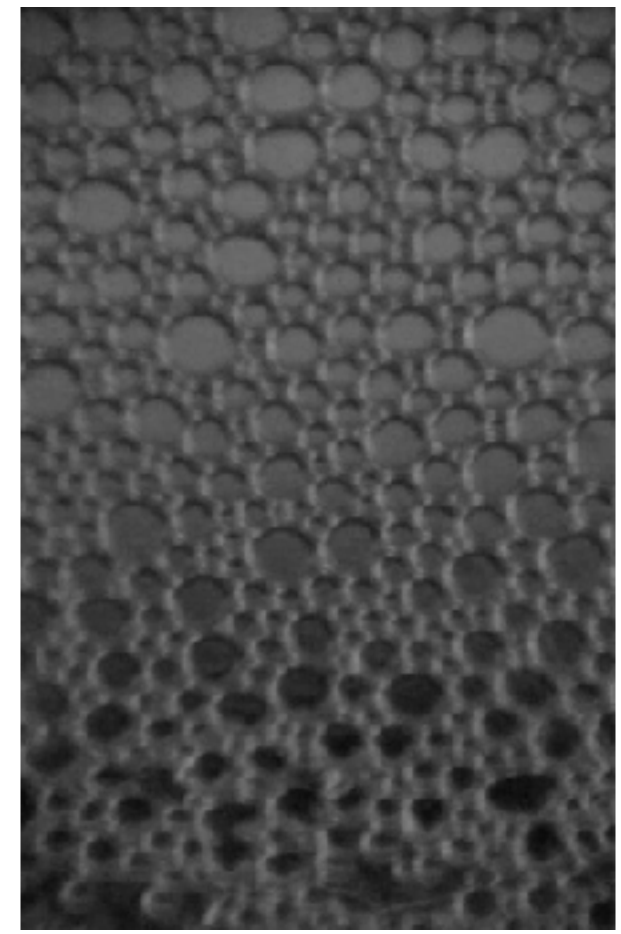


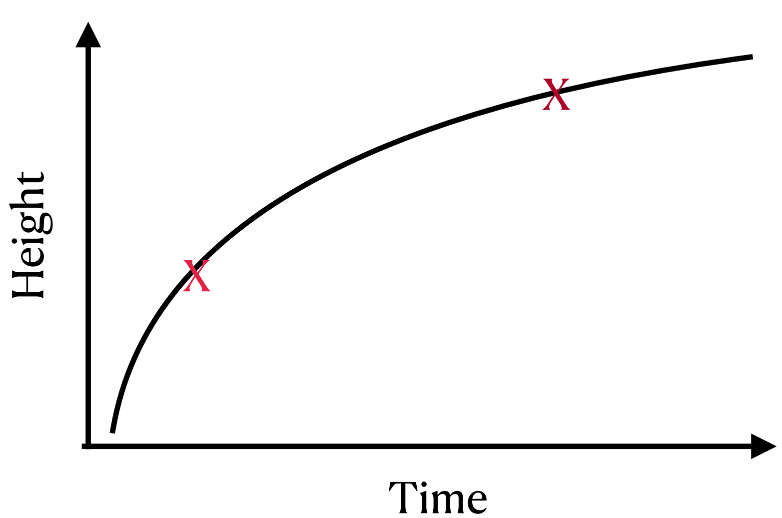
- A change in the liquid fraction of the overall frozen foam
- For some samples, the solid layer easily separates into a softer/lighter part and a harder/denser part
- The liquid foam becomes dimmer, as it gets dryer

Close look in 2D

Different regimes







Conclusion

- Thermal conductivity of foam

- Predict the freezing dynamics of the foam for the first regime

- Conduction through air becomes important at low liquid fractions

- Second regime cause by forced drainage

Next : imbibition mechanism and imbibition stopping criterium, influence of surface properties, 2D/ 3D effects