# Capillary waves on glass surfaces: from float glass to photonic crystal fibres

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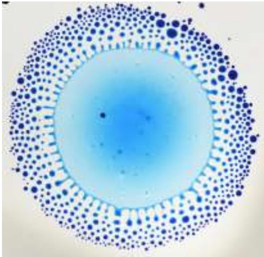
Ecole Verre et Optique,
Presqu'île de Giens, 5-10 octobre 2025

# Soft matter vs hard glasses



Emulsification of Binary Mixtures on a Liquid Layer

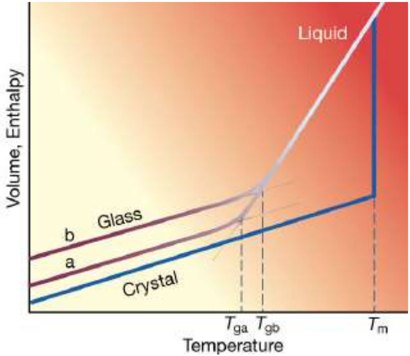
Glass ribbon produced with the float glass process

Keyser et al. PRL 2017

# Credits

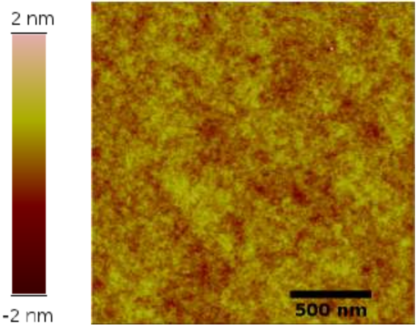
- Coralie Brun, Xavier Buet PMMH, CNRS/ESPCI Paris
- Bruno Bresson, Matteo Ciccotti SIMM, CNRS/ESPCI Paris
- Gilles Tessier, Neurophotonics Lab. Univ. Paris Descartes
- Marco Petrovich, Francesco Poletti, David Richardson, Optoelectronics Research Center, Univ. Southampton
- Thomas Sarlat, Anne Lelarge, Elin Sondergard, CNRS/Saint-Gobain

# Basics of glasses

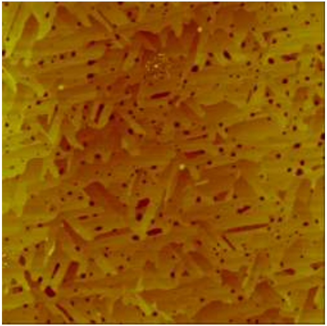



- Glass transition at $T_G$ such that viscosity $\eta \approx 10^{12}\mathrm{Pa.s}$
- Bulk structure $\approx$ snapshot of liquid at $T_G$

# Amorphous vs Crystalline Silica Surface: AFM



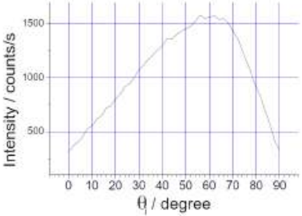

Amorphous silica



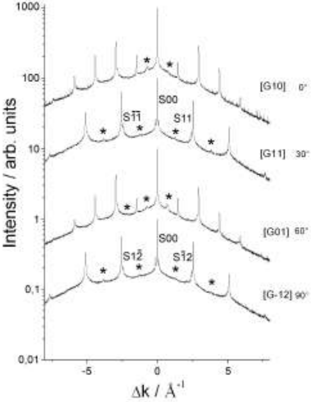
$\alpha$-$SiO_2$(0001) quartz

# Amorphous vs Crystalline Silica Surface: He scattering

Amorphous silica



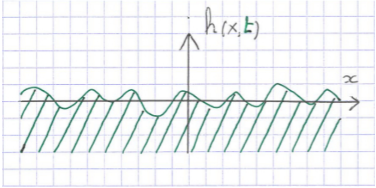

$\alpha$-$SiO_2(0001)$ quartz



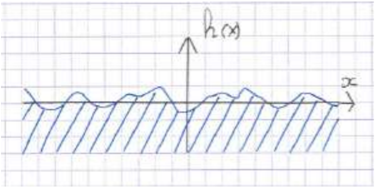

Steurer et al. Surface Sci. (2007)

# What is a glass surface ?

Naive answer: a liquid surface that crossed glass transition




Liquid interface

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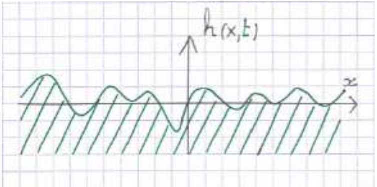
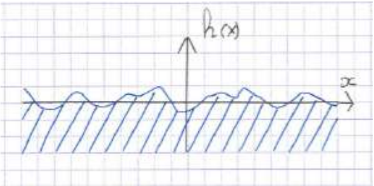



Liquid interface




Glass interface

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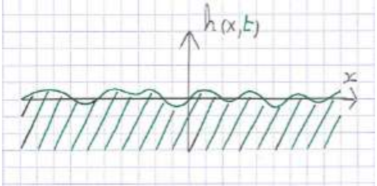
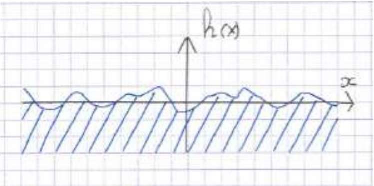



Liquid interface




Glass interface

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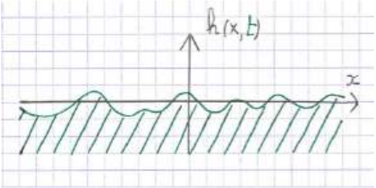
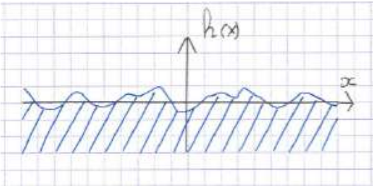


Liquid interface

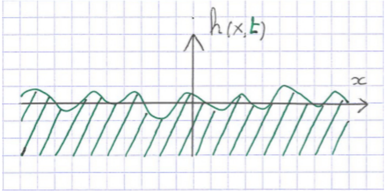


Glass interface

# Liquid surface: spectrum of capillary waves

Thermal noise $kT$ vs interface tension $\gamma$: capillary waves

Interface width $w = \sqrt{\frac{kT}{\gamma}}$, capillary length $\ell_c = \sqrt{\frac{\gamma}{\Delta\rho.g}}$




$$\tilde{h}_{\mathbf{q}} = \int_{\mathcal{S}} d\mathbf{r}\, h(d\mathbf{r}) e^{-i\mathbf{q}.\mathbf{r}}$$
$$h(\mathbf{r}) = \frac{1}{S_0} \sum_{\mathbf{q}} \tilde{h}_{\mathbf{q}} e^{i\mathbf{q}.\mathbf{r}}$$

2D static structure factor: $S_0(\mathbf{q}) \approx S_0 \frac{kT}{\gamma q^2}$ , $\quad q \gg \frac{2\pi}{\ell_c}$

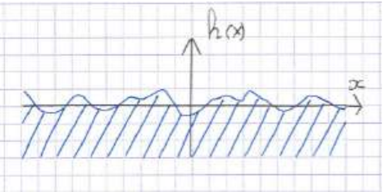
1D height power spectrum: $P(f) \approx \frac{kT}{2\pi\gamma f}$ , $\quad f \gg \frac{1}{\ell_c}$

Spatial correlation: $\langle |\Delta h(\Delta r)|^2 \rangle_r \approx \frac{kT}{\pi\gamma} \log\left(\frac{\Delta r}{\ell_{min}}\right)$ , $\Delta r \ll \ell_c$

# Glass surface: spectrum of frozen capillary waves?

Thermal noise $kT$ vs interface tension $\gamma$: capillary waves

Interface width $w = \sqrt{\frac{kT_G}{\gamma}}$, capillary length $\ell_c = \sqrt{\frac{\gamma}{\Delta\rho.g}}$

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Spatial correlation: $\langle|\Delta h(\Delta r)|^2\rangle_r \approx \frac{kT_G}{\pi\gamma} \log\left(\frac{\Delta r}{\ell_{min}}\right)$ , $\Delta r \ll \ell_c$

# Can we observe capillary waves ?

| | water | molten glass |
|---|---|---|
| $\gamma$ | 0.07 J.m$^{-2}$ | 0.3-0.5 J.m$^{-2}$ |
| $\eta$ | $10^{-3}$ Pa.s | $10^3 - 10^{13}$ Pa.s |
| T | 300 K | $900 - 1500$ K |
| $\ell_c$ | 3 mm | $3 - 5$ mm |
| $\tau_c$ | $10^{-4}$s | $10^1 - 10^{10}$s |
| $w$ | 0.25 nm | $0.2 - 0.3$ nm |

A difficult task: interface fluctuations are sub-nanometer!

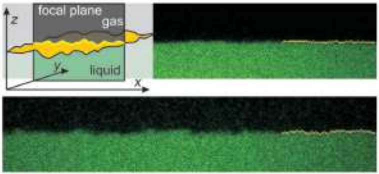
# Direct observation in near-critical mixtures

| | water | colloidal liquid | molten glass |
|---|---|---|---|
| $\gamma$ | $0.07$ J.m$^{-2}$ | $10^{-9} - 10^{-6}$ J.m$^{-2}$ | 0.3-0.5 J.m$^{-2}$ |
| $\eta$ | $10^{-3}$ Pa.s | $10^{-3}$ Pa.s | $10^{3} - 10^{13}$ Pa.s |
| T | 300 K | 300 K | $900 - 1500$ K |
| $\ell_c$ | 3 mm | $10^{-3} - 10^{-2}$ mm | $3 - 5$ mm |
| $\tau_c$ | $10^{-4}$s | $1 - 10$s | $10^{1} - 10^{10}$s |
| $w$ | 0.25 nm | $0.05 - 2$ $\mu$m | $0.2 - 0.3$ nm |

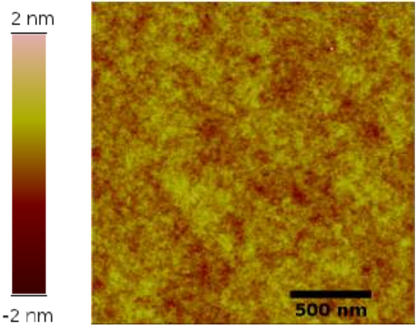
**Direct Visual Observation of Thermal Capillary Waves**

Dirk G. A. L. Aarts,[1*] Matthias Schmidt,[2†] Henk N. W. Lekkerkerker[1]

www.sciencemag.org SCIENCE VOL 304 7 MAY 2004



# AFM measurements on an amorphous silica surface

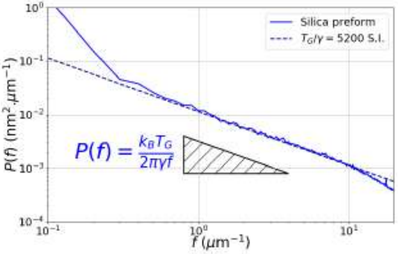



- $T_G \approx 1500$ K
- $\gamma \approx 0.3\ \mathrm{J.m^{-2}}$
- molecular length $\ell_{\min} \approx 0.3$ nm
- capillary length $\ell_c \approx 4$ mm

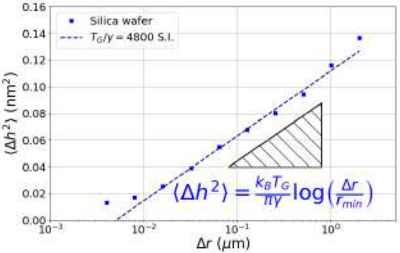
AFM measurements consistent with the expected roughness:

$$w_G = \frac{kT_G}{2\pi\gamma} \log \frac{\ell_c}{\ell_{\min}} \approx 0.4\mathrm{nm}$$

1D power spectrum




Spatial correlations

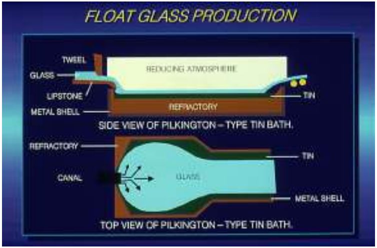



$T_G \approx 1500K$, $\gamma \approx 0.3 J.m^{-1}$, $T_G/\gamma \approx 5000$S.I.

Glass surface roughness achieves a lower bound:
a thermodynamical noise frozen at $T_G$!

T. Sarlat, A. Lelarge, E. Sondergard, DV, EPJB, **54**, 121 (2006)

# An industrial test case: the float process



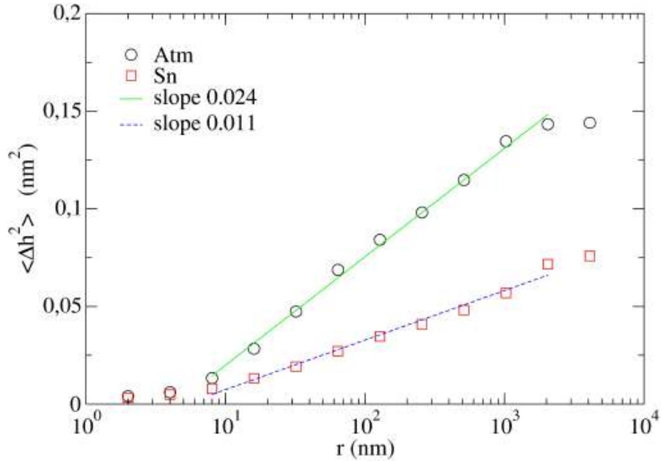

The ribbon of molten glass is cooled down on a liquid tin bath

Two contrasting interfaces:

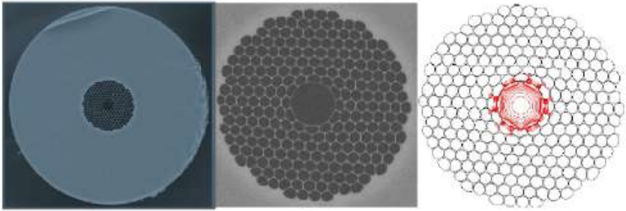
Glass/Gas: $\gamma \approx 0.3$ J.m$^{-2}$

Glass/Tin: $\gamma \approx 0.5$ J.m$^{-2}$

# Frozen capillary waves on a float glass surface



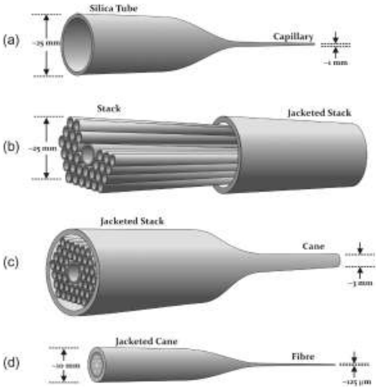
# Photonic band-gap fibres

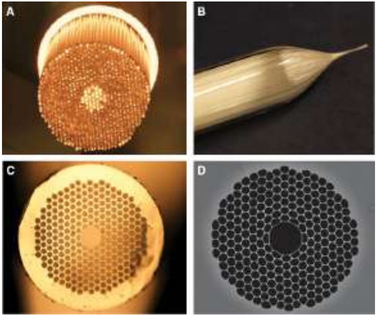


(a) (b) (c)

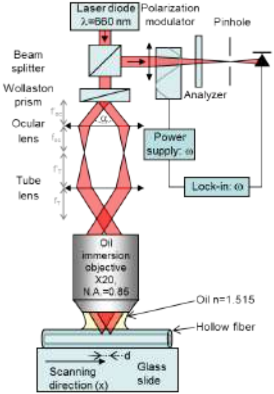
Micro-structured optical fibre : photonic crystal + hollow core
Propagation of light through air instead of glass

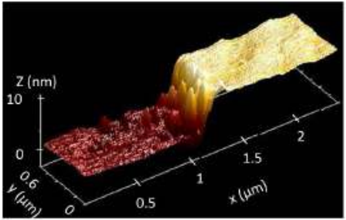
# Stack and draw process

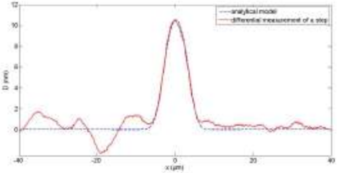


# Picometer-scale roughness Measurements by differential optical profilometry

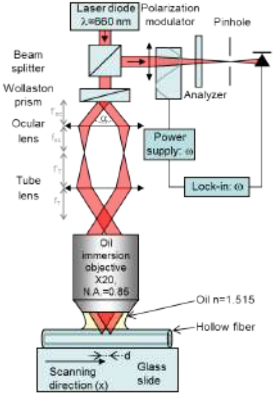


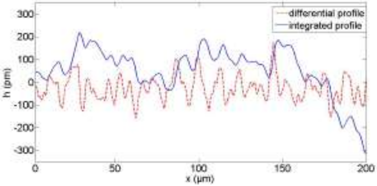



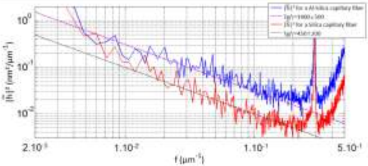



C. Brun et al., Optics Exp. **22** 29554 (2014)

# Roughness Measurements of inner surface of silica tubes

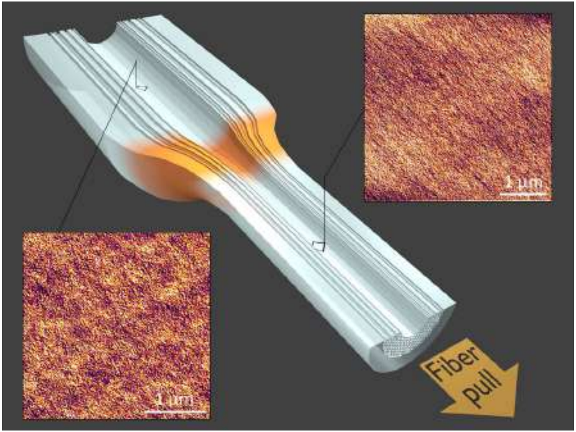


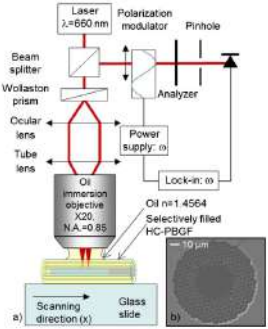

C. Brun et al., Optics Exp. **22** 29554 (2014)

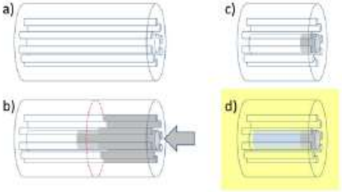
# Roughness Measurements within Photonic fibres




B. Bresson et al, Phys. Rev. Lett. **119** 235501, (2017)

# Roughness Measurements within Photonic fibres

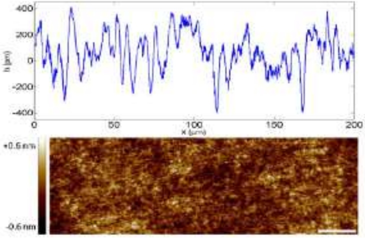


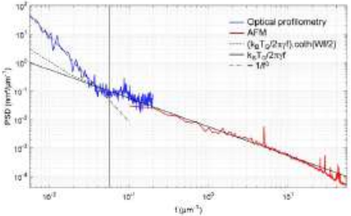




Differential profilometry + selective filling: picometer resolution

C. Brun et al. Opt. Express **22** 29554, (2014) ; X. Buet et al, Opt. Lett. **41** 5089, (2016)

# Roughness Measurements within Photonic fibres

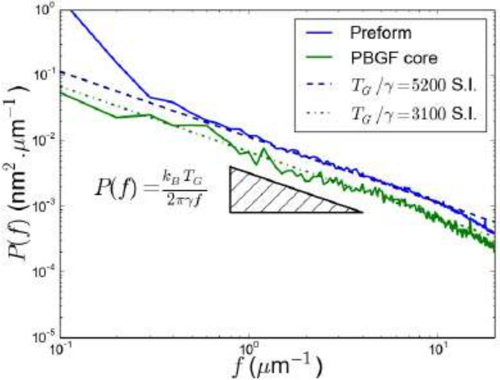



Capillary waves on the inner core surface of micro-structured photonic fibres

C. Brun et al. Opt. Express **22** 29554, (2014) ; X. Buet et al, Opt. Lett. **41** 5089, (2016)

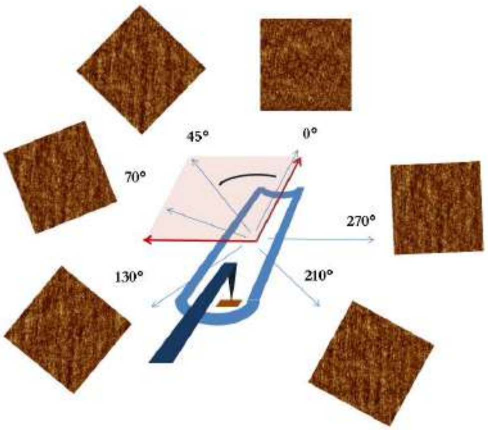
# AFM Measurement within Photonic fibres



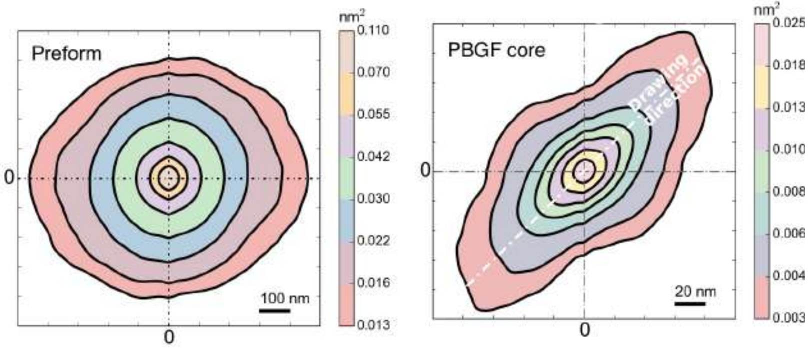

Amorphous silica: $T_G \approx 1500$K, $\gamma \approx 0.3$J.m$^{-2}$ $\Rightarrow$ $T_G/\gamma \approx 5000$, recovered before drawing.

After drawing: effective interface tension 70% larger, height fluctuations 30% lower than thermal fluctuations !

# Roughness anisotropy induced by fiber drawing



# Anisotropic spatial correlations



# Attenuation of capillary waves under shear

PRL 97, 038301 (2006) PHYSICAL REVIEW LETTERS week ending 21 JULY 2006

**Suppression of Thermally Excited Capillary Waves by Shear Flow**

Didi Derks,[1] Dirk G. A. L. Aarts,[2,3] Daniel Bonn,[3,4] Henk N. W. Lekkerkerker,[2] and Arnout Imhof[1]

[1]*Soft Condensed Matter, Debye Institute, Utrecht University, Princetonplein 5, 3584 CC Utrecht, The Netherlands*
[2]*Van 't Hoff Laboratory, Debye Institute, Utrecht University, Padualaan 8, 3584 CH Utrecht, The Netherlands*
[3]*Laboratoire de Physique Statistique, Ecole Normale Supérieure, 24 Rue Lhomond, F-75231 Paris Cedex 05, France*
[4]*van der Waals-Zeeman Institute, University of Amsterdam, Valckenierstraat 65, 1018 XE Amsterdam, The Netherlands*

(Received 31 March 2006; published 18 July 2006)

PHYSICAL REVIEW E **81**, 031602 (2010)

**Nonequilibrium fluctuations of an interface under shear**

Marine Thiébaud and Thomas Bickel*

*CPMOH, Université de Bordeaux and CNRS (UMR 5798), 351 Cours de la Libération, 33405 Talence, France*

(Received 28 August 2009; published 22 March 2010)

The steady-state properties of an interface in a stationary Couette flow are addressed within the framework of fluctuating hydrodynamics. Our study reveals that thermal fluctuations are driven out of equilibrium by an effective shear rate that differs from the applied one. In agreement with experiments, we find that the mean-square displacement of the interface is reduced by the flow. We also show that nonequilibrium fluctuations present a certain degree of universality in the sense that all features of the fluids can be factorized into a single control parameter. Finally, the results are discussed in the light of recent experimental and numerical studies.

$$S(\mathbf{q},\sigma_{vis}) \approx S_0(q)\left[1 - A\alpha^2|\cos\theta_q|^2\right],\; S_{eq}(\mathbf{q}) = \frac{kT}{\gamma|(\mathbf{q}|^2},\; \alpha = \frac{w\sigma_{vis}}{\gamma}$$

# Drawing hollow fibres at different temperatures

- keep same geometry
- different velocities
- different viscosities, hence stress

Control parameter = adimensioned drawing stress:

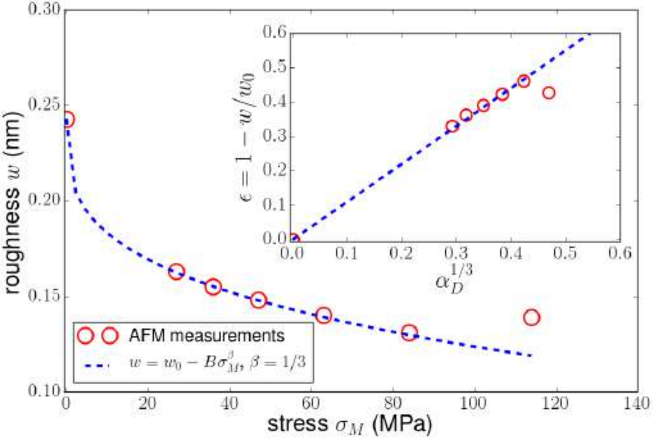
$$\alpha_D = \frac{w\sigma_M}{\gamma}$$

Range of furnace temperature $T_D \in [2000^\circ\mathrm{C} - 2100^\circ\mathrm{C}]$,

Range of drawing stress $\sigma_M \in [20\mathrm{MPa} - 120\mathrm{MPa}]$

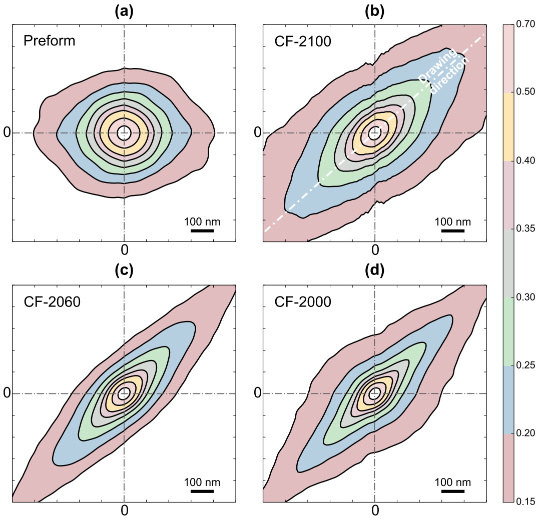
Range of control parameter $\alpha_D \in [0.02 - 0.12]$

# Surface roughness attenuation under drawing

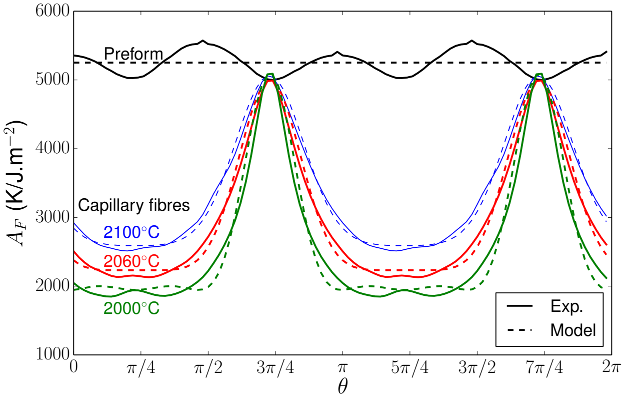



The larger the stress, the lower the roughness: $\frac{w_0 - w(\alpha_D)}{w_0} \approx B\alpha_D^{1/3}$

# Stress dependent anisotropy of glass surfaces



# Non-linear attenuation of the capillary modes




$$S(\mathbf{q}) = \frac{k_B A_F(\theta_q)}{|\mathbf{q}|^2} \approx \frac{k_B T_G}{\gamma |\mathbf{q}|^2} \left(1 - a\cos^2[\theta_q + b\sin(\theta_q)]\right)$$

# Conclusion: the long memory of glass surfaces

- Glass surfaces keep the memory of their liquid state
- Height fluctuations: frozen capillary waves at $T_G$
- Under flow: ultra-low roughness, below equilibrium thermodynamics expectation
- Strongly anisotropic correlations
- Non-linear attenuation of the capillary modes under flow

B. Bresson et al, Phys. Rev. Lett. **119** 235501, (2017) J. Osorio et al, Nat. Comm. **14** 1146, (2023)

# A stochastic hydrodynamics approach

$$\frac{\partial h_{\mathbf{k}}}{\partial t} + i\dot{\gamma} k_x \left[h^2\right]_{\mathbf{k}} = -\frac{\sigma|k|}{\eta} h_{\mathbf{k}} + \eta_{\mathbf{k}}$$

$$\begin{aligned} S(\mathbf{q}, \sigma_{vis}) &\approx S_0(q)\left[1 - A\alpha^2 |\cos\theta_q|^2\right] \ , \quad \alpha = \frac{w}{\ell_c}\dot{\varepsilon}\tau_c \ ; \\ C(\mathbf{r}, \sigma_{vis}) &\approx C_0(r)\left[1 - \frac{A}{2}\alpha^2\right] + \frac{A}{8\pi}\alpha^2 w_0^2 \cos 2\theta \ . \end{aligned}$$

# Spectrum of (frozen) capillary waves

$$\langle|\tilde{h}_{\mathbf{q}}|^2\rangle = S_0 \frac{kT}{\gamma q^2} \frac{1}{1+(q\ell_c)^{-2}} \; , \quad \tau_q = \frac{4\eta}{\gamma q} \frac{1}{1+(q\ell_c)^{-2}}$$

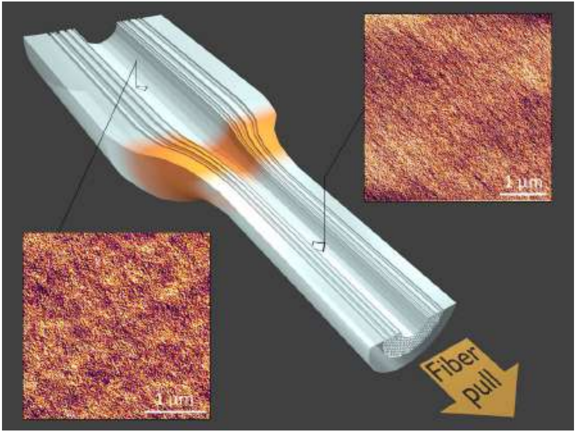
Height correlations:

$$\langle|h(r)h(0)|\rangle = \frac{kT}{2\pi\gamma} K_0(\frac{r}{\ell_c}) \approx \frac{kT}{2\pi\gamma} \log\left(\frac{r}{\ell_c}\right) \quad \text{for } r \ll \ell_c$$

$$\langle h(\mathbf{r},t)h(\mathbf{r},0)\rangle = \frac{kT}{2\pi\gamma} K_0(\frac{t}{\tau_c}) \approx \frac{kT}{2\pi\gamma} \log\left(\frac{t}{\tau_c}\right) \quad t \ll \tau_c = \frac{\eta\ell_c}{\gamma}$$

Glass roughness : static correlations of capillary waves at $T_G$ ?

# Drawing hollow fibres at different temperatures




B. Bresson et al, PRL 2017

# Roughness of fibres drawn at different temperatures

| Sample | $T_{\text{Furnace}}$ (°C) | $\sigma_M$ (MPa) | $\alpha_D$ | RMS (nm) |
|---|---|---|---|---|
| Preform | N.A. | 0 | 0 | 0.243 |
| Capillary Fibres | 2100 | 27 | 0.024 | 0.163 |
| | 2080 | 36 | 0.031 | 0.155 |
| | 2060 | 47 | 0.041 | 0.148 |
| | 2040 | 63 | 0.055 | 0.140 |
| | 2020 | 84 | 0.074 | 0.131 |
| | 2000 | 114 | 0.101 | 0.139 |

The larger the stress, the lower the height fluctuations

B. Bresson et al, PRL 2017

# Morphologie et rugosité des surfaces de verres

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Sorbonne Université, Université de Paris France
Laboratoire SVI, CNRS/Saint-Gobain

Ecole Verre et Optique, Presqu’île de Giens 05-10 octobre 2025





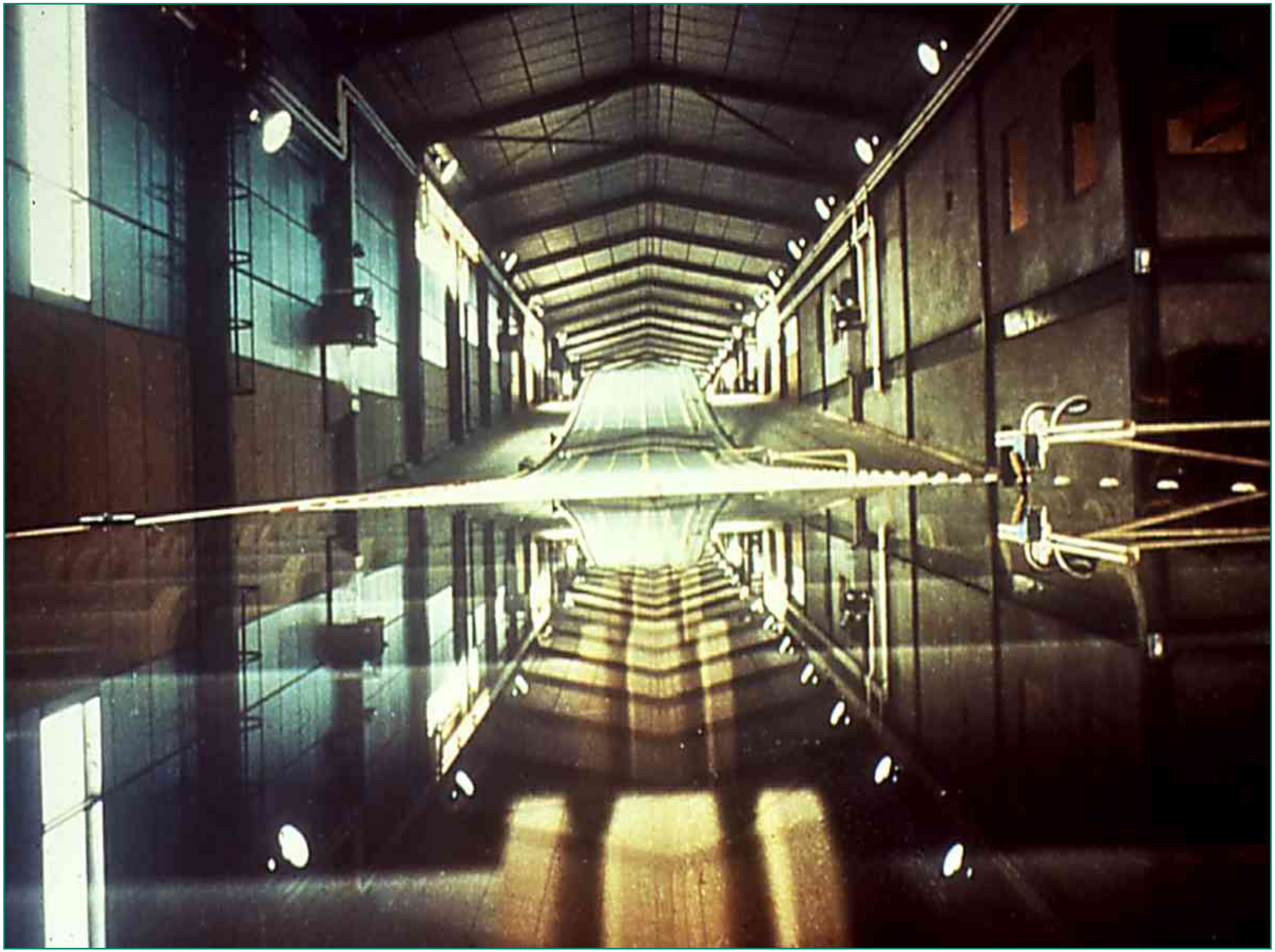









# Float glass process



# Verres imprimés

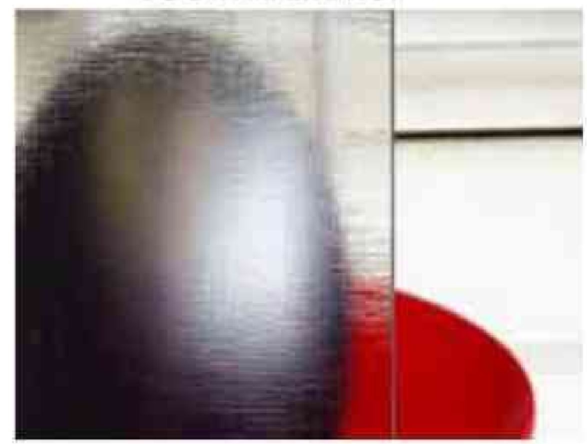
SGG PIXARENA

SGG LISTRAL M

SGG WATERDROP

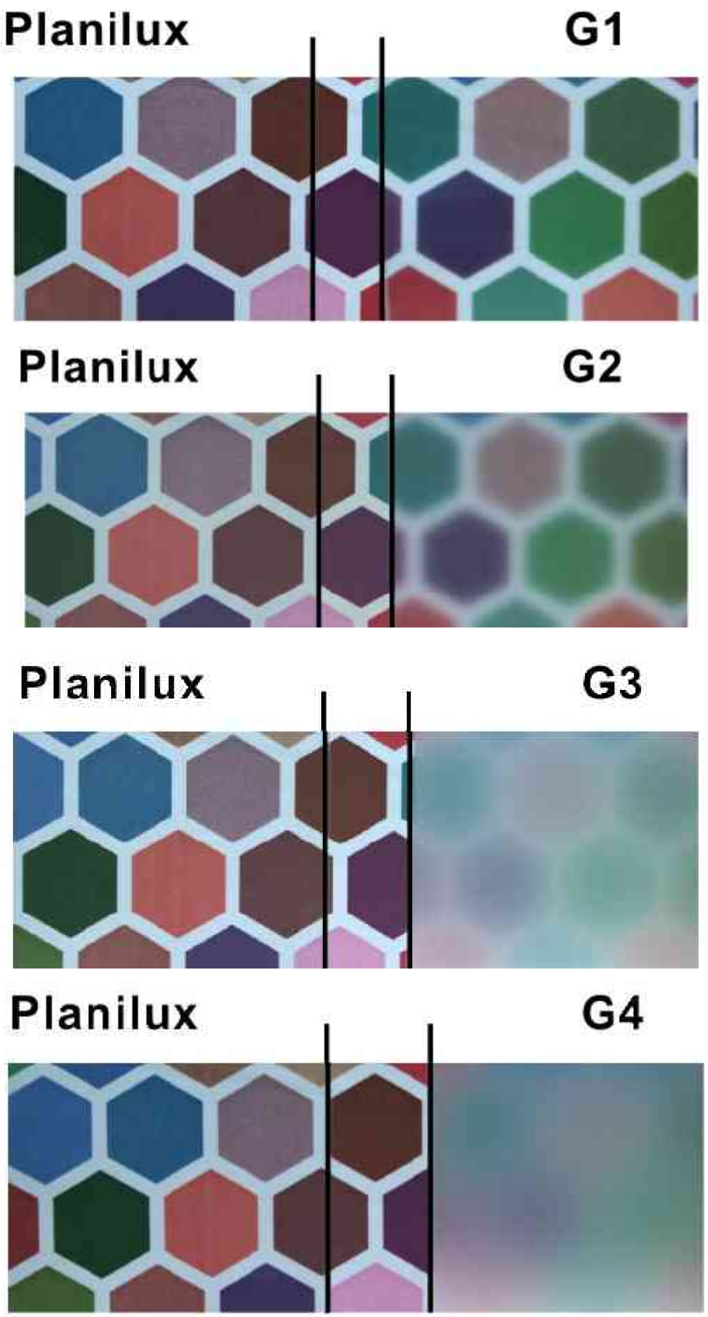
SGG ENTRELAZADO

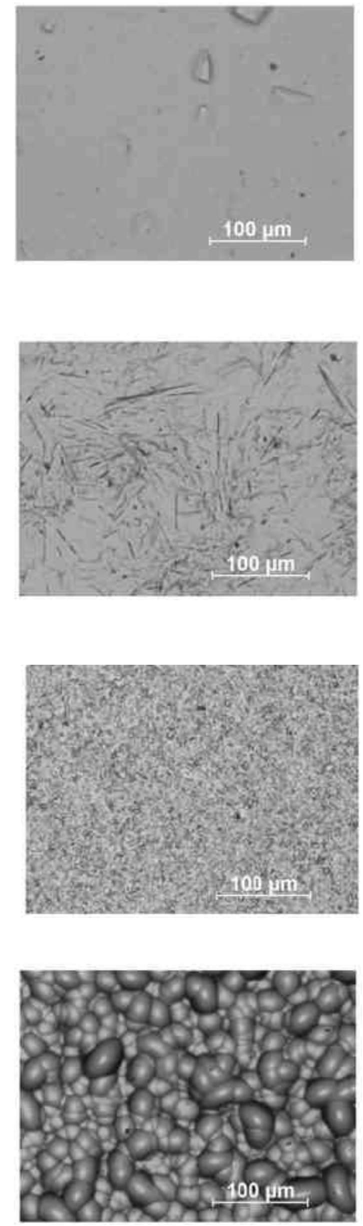
SGG MARIS



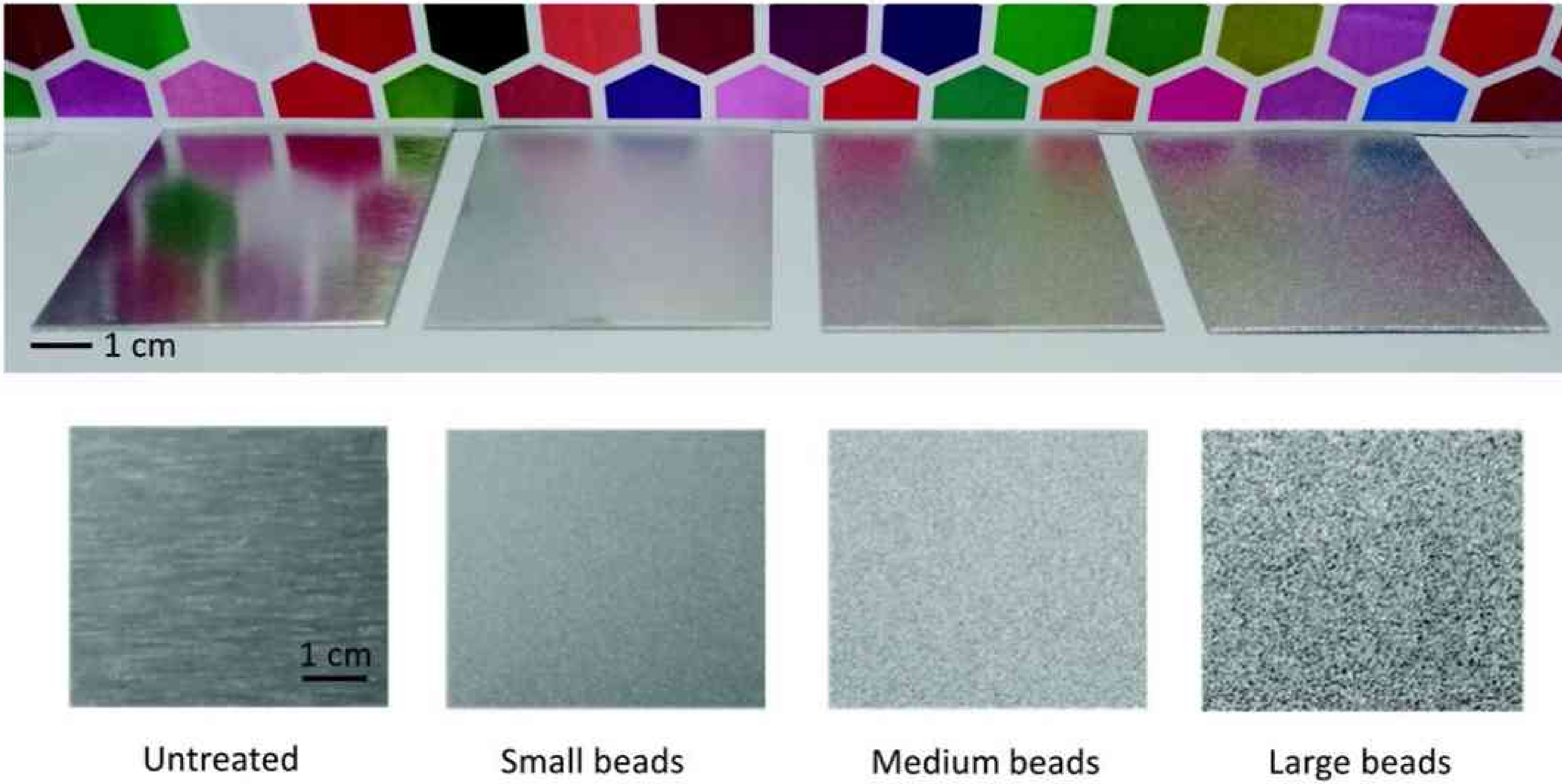
SGG THELA

# Verres dépolis

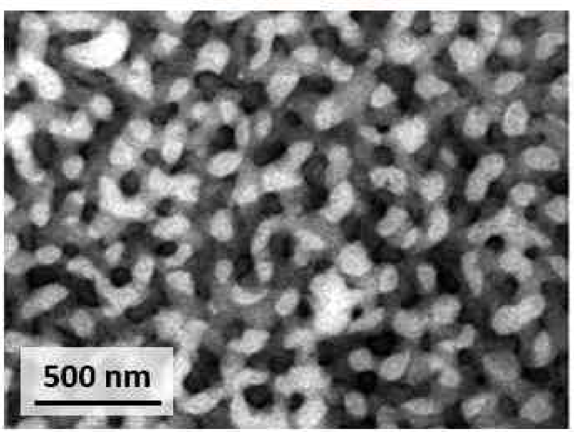


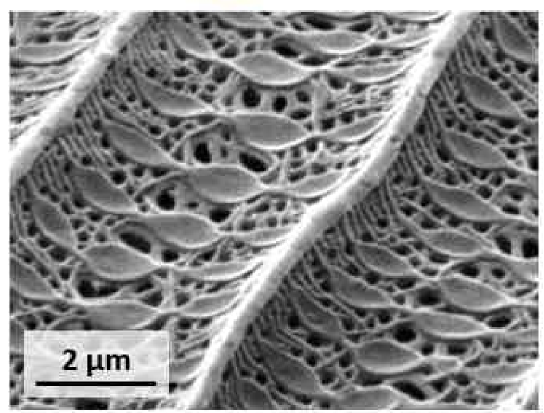



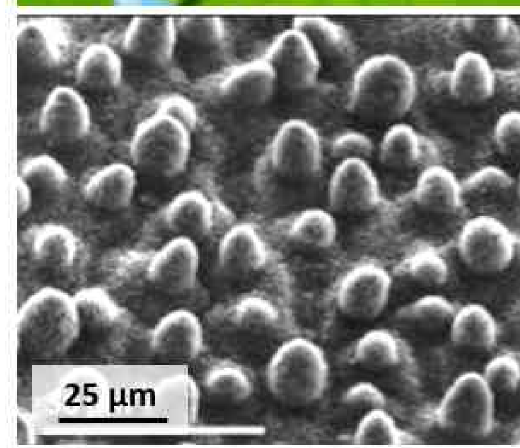
# Surfaces métalliques sablées



# Surfaces texturées : bio-inspiration

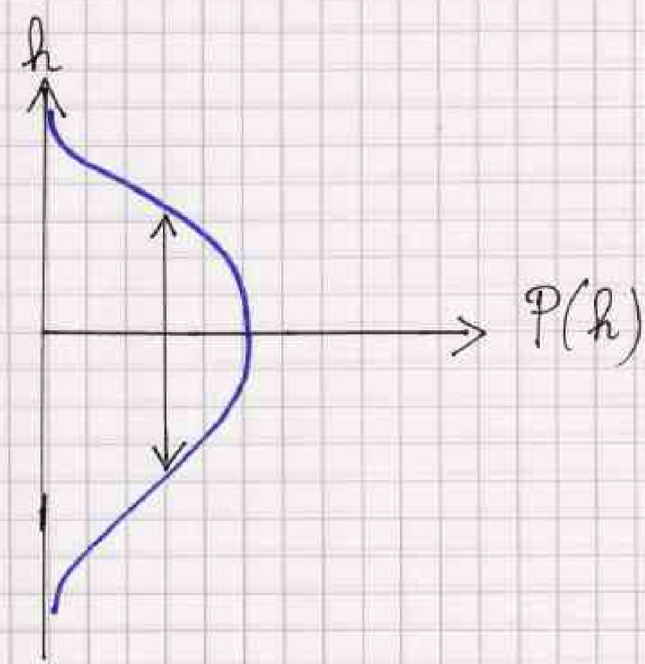


# Interfaces rugueuses

# Rugosité : distribution des hauteurs


- Approche probabiliste
- Un paramètre essentiel : la LARGEUR de la distribution
  - plusieurs estimateurs pour une même quantité

$$R_q = RMS = \text{écart-type de la distribution} = \left(\frac{\sum h_i^2}{N}\right)^{\frac{1}{2}} = \left(\int h^2 P(h)\,dh\right)^{\frac{1}{2}}$$

$$R_a = \frac{1}{N}\sum_i |h_i| = \int |h|\,P(h)\,dh$$

# Rugosité : variance, skewness, kurtosis

- De façon générale la distribution des hauteurs est caractérisée par la donnée de l'ensemble de ses moments

$$M_n = \int h^n P(h)\, dh$$

$M_1$ = moyenne $= 0$

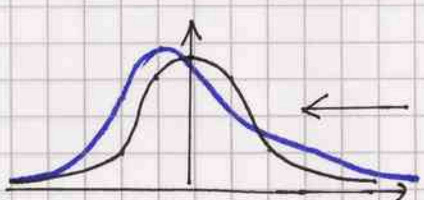
$M_2$ = variance = $RMS^2$ $\longrightarrow$ largeur de la distribution

$M_3$ = skewnes $s$ $\longrightarrow$ symétrie de la distribution

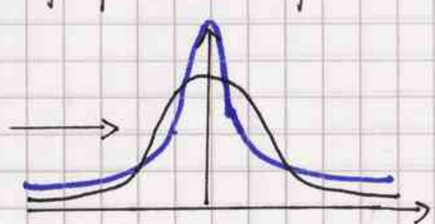
$M_4$ = kurtosis $\kappa$ $\longrightarrow$ forme "piquée" ou aplatie de la distribution

asymétrie

$|s| > 0$



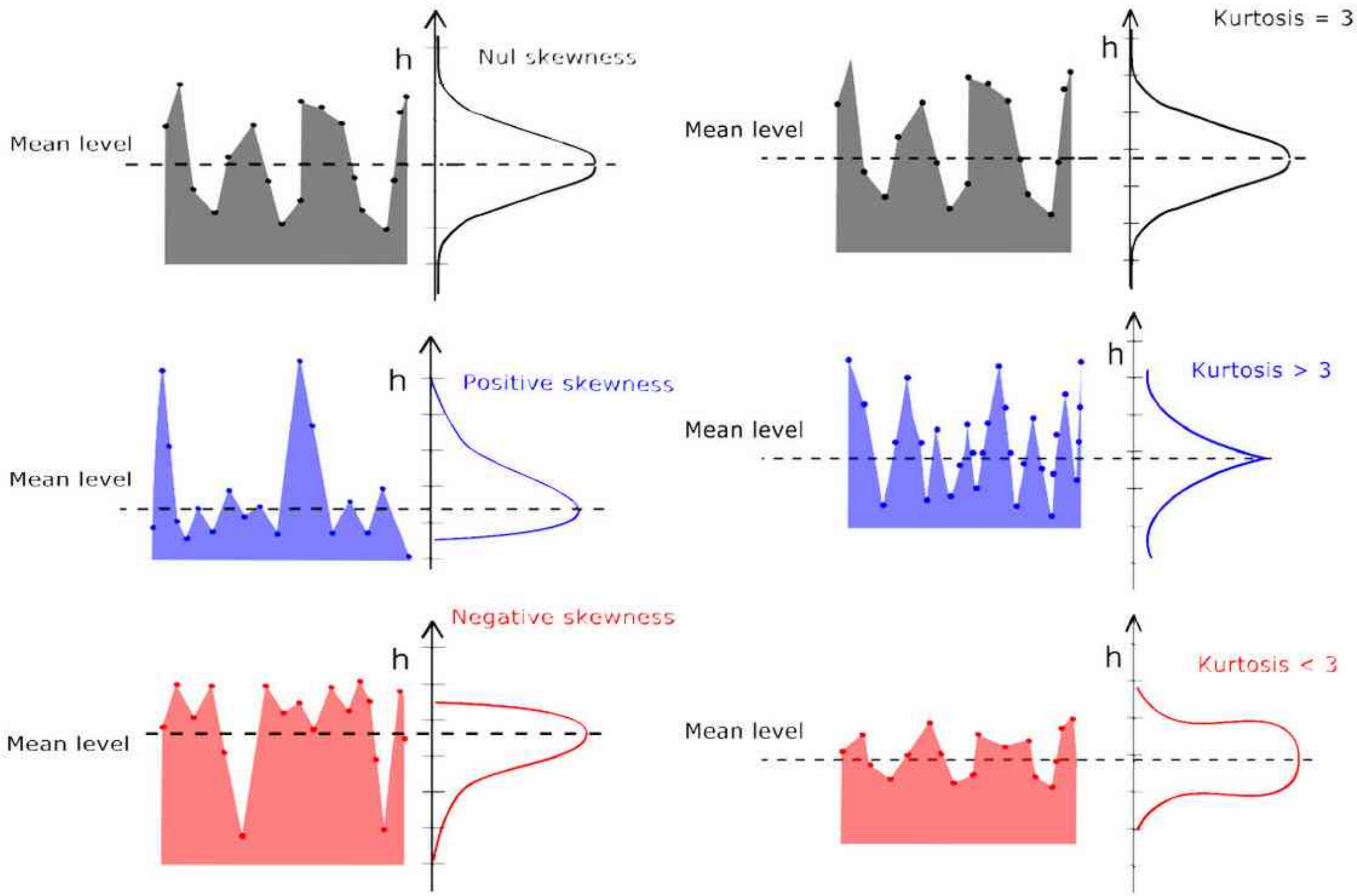
$\longleftarrow$ Gaussienne $\longrightarrow$



écart à la Gaussienne

$K - 3 \neq 0$

# Skewness et Kurtosis



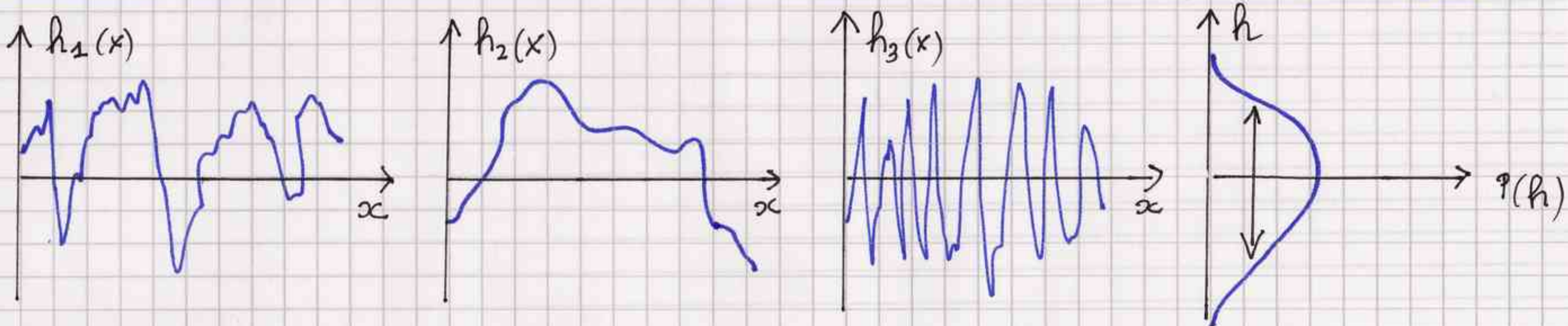

Skewness et kurtosis: utiles, mais délicats à estimer,
Sensibles aux valeurs extrêmes (défauts/erreurs de mesure)

# Rugosité: fluctuations verticales vs horizontales

- En pratique, lorsque la surface est Gaussienne, la RMS suffit à caractériser la distribution

$$P(h) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{h^2}{2\sigma^2}\right) \qquad \sigma = \text{RMS}$$

- <u>RMS et a fortiori distribution des hauteurs = **essentielle mais pas suffisante**</u>



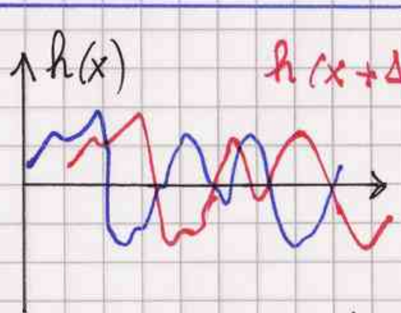

La distribution des hauteurs fournit une information sur les fluctuations **verticales**. Une même RMS, une même distribution peut correspondre à des surfaces très différentes

# Corrélations spatiales

☐ Dans les cas les plus simples la fonction d'auto-corrélation $C(\Delta x)$ est très rapidement décroissante, exponentielle, Gaussienne

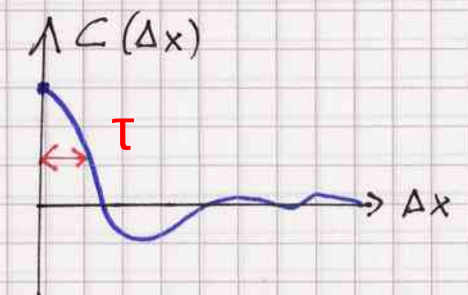
⟶ définition d'1 longueur de corrélation

☐ Corrélation des hauteurs ⟶ information sur les motifs horizontaux




$$C(\Delta x) = \langle h(x)\, h(x+\Delta x) \rangle$$

fonction d'auto-corrélation




Un paramètre essentiel : la LONGUEUR de CORRÉLATION ~ taille motifs $h^{aux}$

# Longueur de corrélation

□ Dans les cas les plus simples la fonction d'auto-corrélation $C(\Delta x)$ est <u>très rapidement décroissante</u>, exponentielle, Gaussienne

$\longrightarrow$ définition d'1 longueur de corrélation $\tau$

$$C(\Delta x) = \sigma^2 f(\Delta x/\tau)$$

$\sigma$ = rugosité RMS

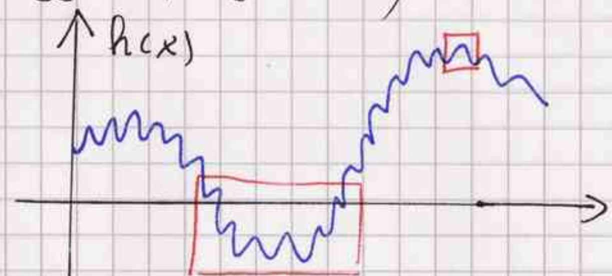
$f(\Delta x/\tau) \rightarrow$ 1 si $\Delta x/\tau \rightarrow 0$

$f(\Delta x/\tau) \rightarrow$ 0 si $\Delta x/\tau \gg 1$

Pente caractéristique $s = \sigma/\tau$

# Longueurs de corrélations

- Parfois la surface est caractérisée par plusieurs longueurs de corrélation, voire par un "continuum" de longueurs de corrélations (surfaces de type "fractal" ou "auto-affines", cf + loin)

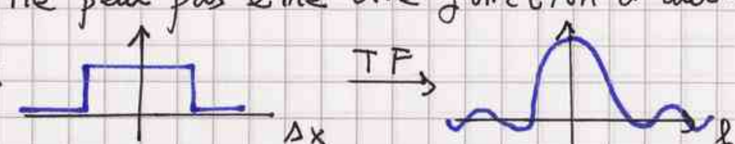



2 motifs caractéristiques à petite et grande échelle

- Sur le plan mathématique, la fonction d'autocorrélation $C(\Delta x)$ est la transformée de Fourier de la densité spectrale de puissance $PSD(f)$

$$PSD(f) = |\hat{h}|^2$$

→ Toute fonction réelle paire ne peut pas être une fonction d'auto-corrélation, sa TF doit être positive ! Ex




≠ fonction autocorrélation

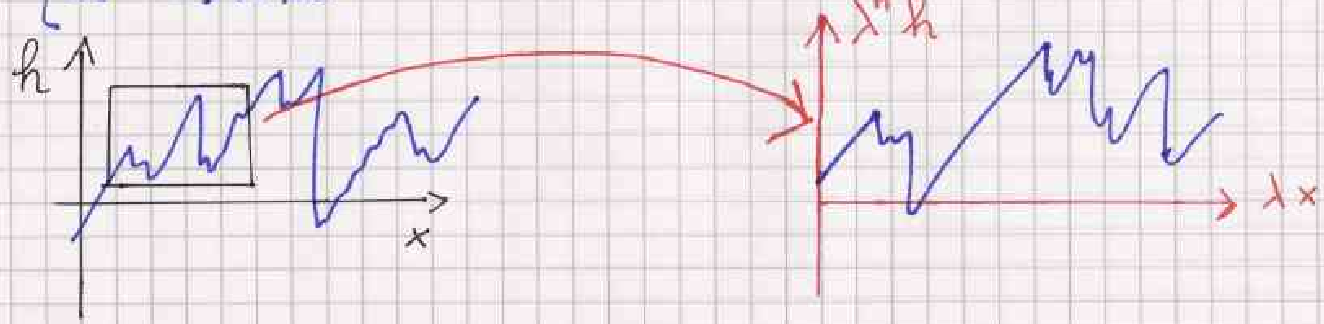
# Echelles de mesure vs longueurs de corrélations

- Dans certains cas la surface n'est pas caractérisée par 1 mais par un continuum de longueurs de corrélation

- Une symétrie particulière : la symétrie auto-affine
  la surface reste statisquement invariante par des "zooms" anisotropes

$$\begin{cases} x \rightarrow \lambda x \\ h \rightarrow \lambda^H h \end{cases}$$

$H$ = exposant de rugosité

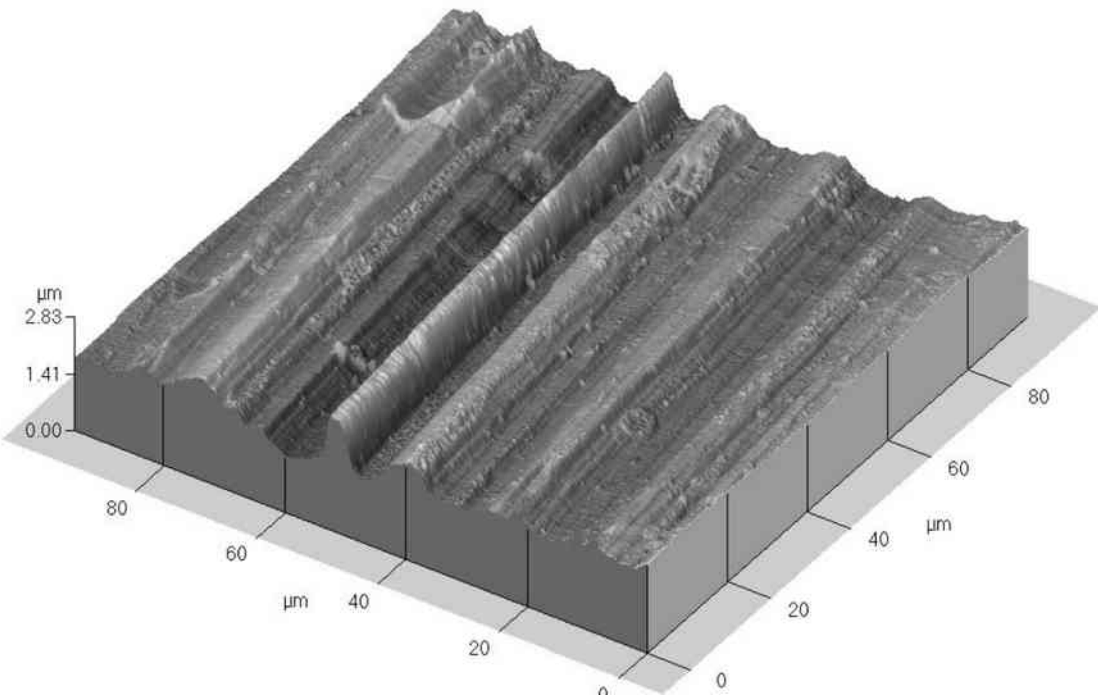


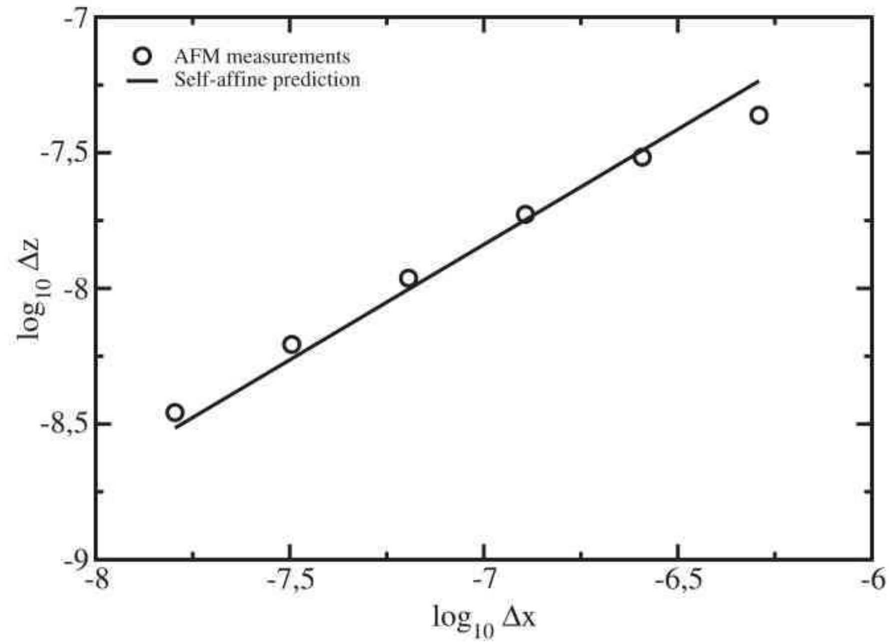

- Sur le plan pratique, cette invariance a une conséquence importante:

  la rugosité RMS dépend de l'échelle sur laquelle on la mesure !

$$\boxed{\sigma(\Delta x) \propto \Delta x^H}$$

# Surface d'une feuille d'aluminium laminée à froid



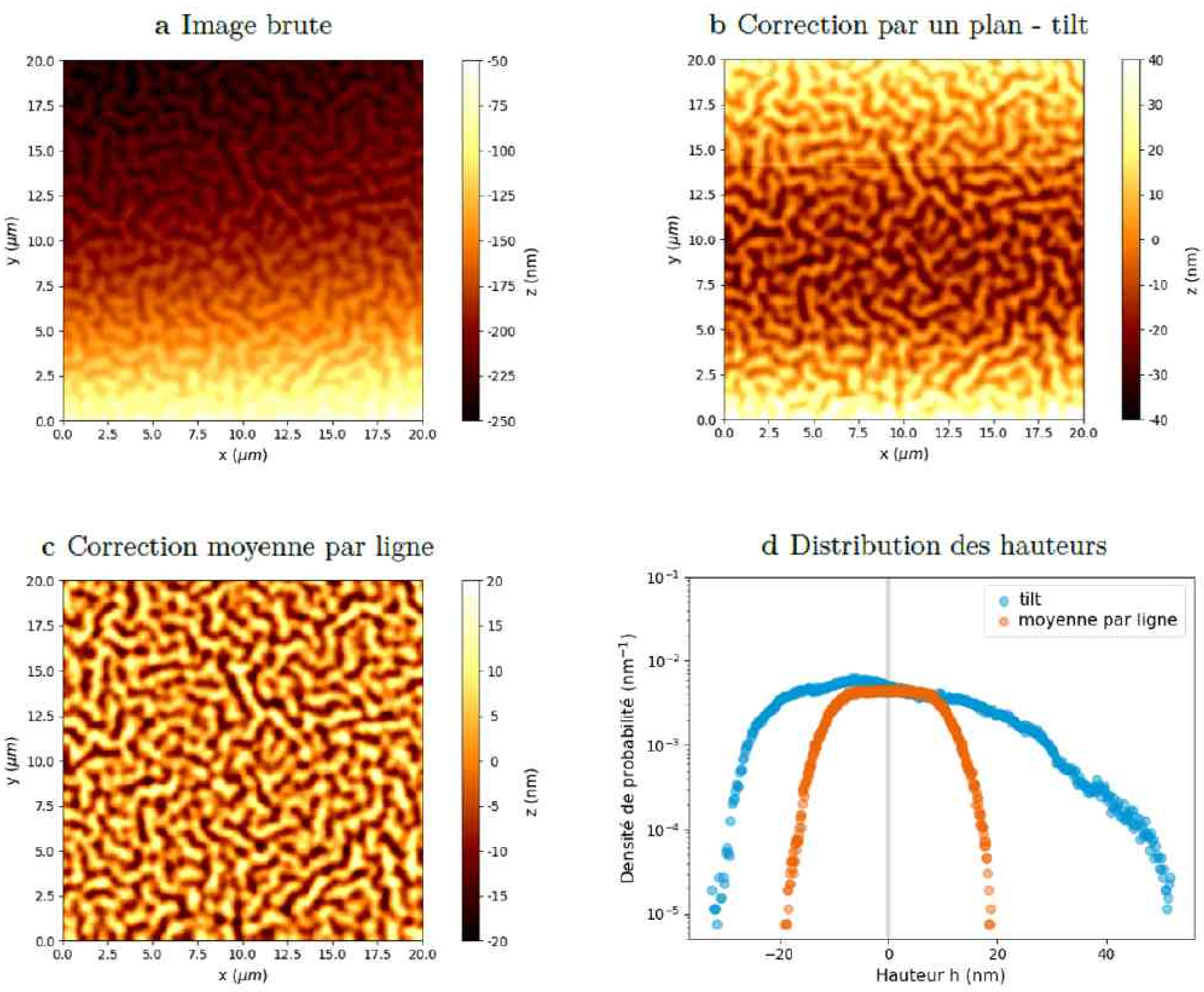

Corrélations autoaffines :

$\sigma_z(\Delta x) \propto (\Delta x)^H$, $H \approx 0.78$

Pente caractéristique :

$S(\lambda) \approx 0.11$ @ $\lambda = 638.2$ nm

# Rugosité : pré-traitement des données



# More about roughness, local slopes and curvatures

IOP Publishing    *Surf. Topogr.: Metrol. Prop.* **11** (2023) 025018    https://doi.org/10.1088/2051-672X/acd469

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**PAPER**

## Statistically representative estimators of multi-scale surface topography: example of aluminum blasted rough samples

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**Keywords:** multi-scale roughness, blasted aluminum, topography, surface slopes, mounded surface

# Diffusion de la lumière par des interfaces rugueuses

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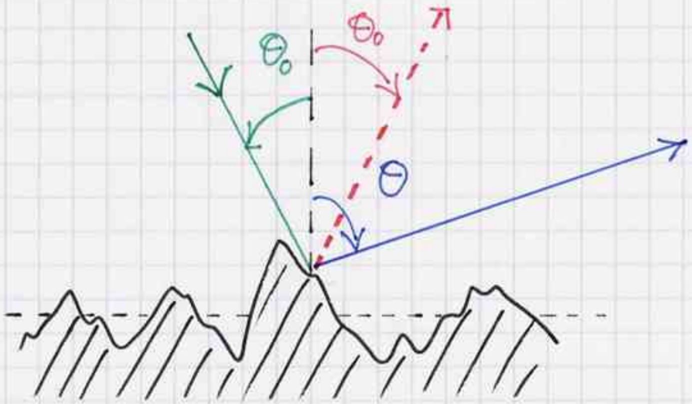



$\theta_0$ : angle incident

$\theta$ : angle de diffusion

$\theta = \theta_0$ : direction spéculaire

Intensité diffusée : $I_d(\theta, \theta_0) = \langle |A|^2 \rangle$

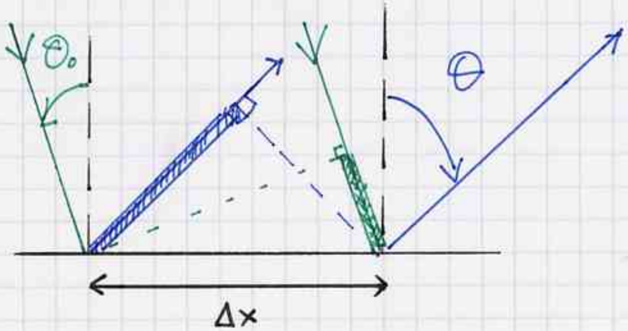
———— cohérente : $I_{coh}(\theta, \theta_0) = |\langle A \rangle|^2$

———— incohérente : $I_{inc}(\theta, \theta_0) = \langle |A|^2 \rangle - |\langle A \rangle|^2$

où $A = A_0 \, e^{i\varphi}$ est l'amplitude de l'onde

# Rugosité et retard de phase

## Décalage horizontal

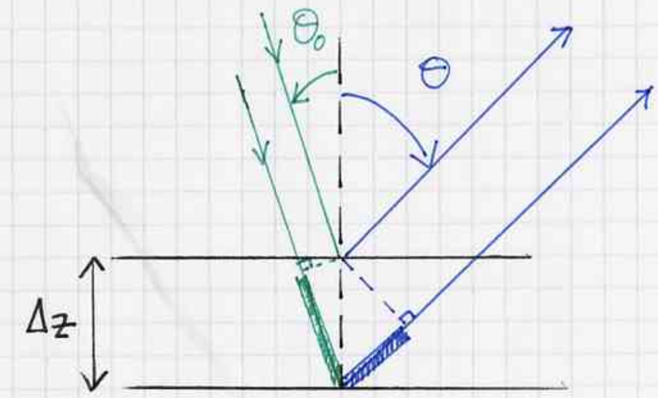



$$\Delta c_h = \Delta x \left( \sin\theta_0 - \sin\theta \right)$$

$$\delta_h \sim \frac{\lambda}{|\sin\theta_0 - \sin\theta|}$$

longueur de cohérence
t.q. $\Delta c \sim \lambda$

## Décalage vertical




$$\Delta c_v = \Delta z \left( \cos\theta + \cos\theta_0 \right)$$

$$\Delta\varphi = \frac{2\pi}{\lambda}\left( \Delta c_h + \Delta c_v \right)$$
$$= \frac{2\pi}{\lambda}\left[ \Delta x \left( \sin\theta_0 - \sin\theta \right) + \Delta z \left( \cos\theta + \cos\theta \right) \right]$$

# Diffusion cohérente et distribution de hauteurs

$$I_{coh}(\theta, \theta_0) \propto \int e^{i\varphi(\theta, \theta_0)}\, dx$$

- $\theta \neq \theta_0 \Rightarrow$

$$\delta_h = \frac{\lambda}{|\sin\theta - \sin\theta_0|} \ll L$$

$\uparrow$ longueur surface

$$I_{coh}(\theta \neq \theta_0) = 0$$

- $\theta = \theta_0$ Réflexion spéculaire

$$I_{coh}(\theta_0) = \int e^{\frac{2i\pi}{\lambda} \Delta z (\cos\theta + \cos\theta_0)}\, dx = \langle e^{i\varphi} \rangle$$

$$= \int e^{2i\pi \Delta z \frac{2\cos\theta_0}{\lambda}}\, P(\Delta z)\, d\Delta z$$

$\downarrow$ TF

$\downarrow$ distribution des hauteurs

$$P(\Delta z) \propto e^{-\Delta z^2/4\sigma^2} \Rightarrow I_{coh}(\theta_0) \propto e^{-\frac{\sigma^2 \cos^2\theta_0}{\lambda^2}}$$

# Diffusion incohérente et corrélations de hauteurs

deux longueurs de cohérence :

$$\delta_h \sim \frac{\lambda}{|\sin\theta - \sin\theta_0|}$$ $\searrow$ quand l'écart angulaire $\nearrow$

$\delta_v$ [Gaussien ou self-affine] $\searrow$ quand la pente locale $\nearrow$

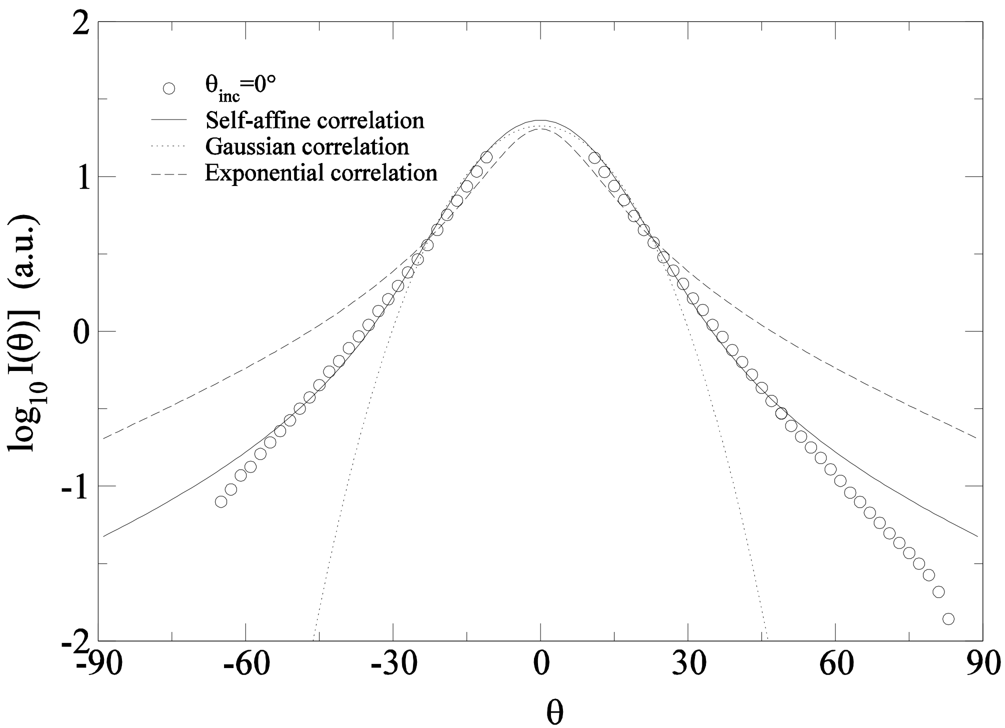
Aux petits angles $|\theta - \theta_0| \ll 1$ : $\delta_v \ll \delta_h$

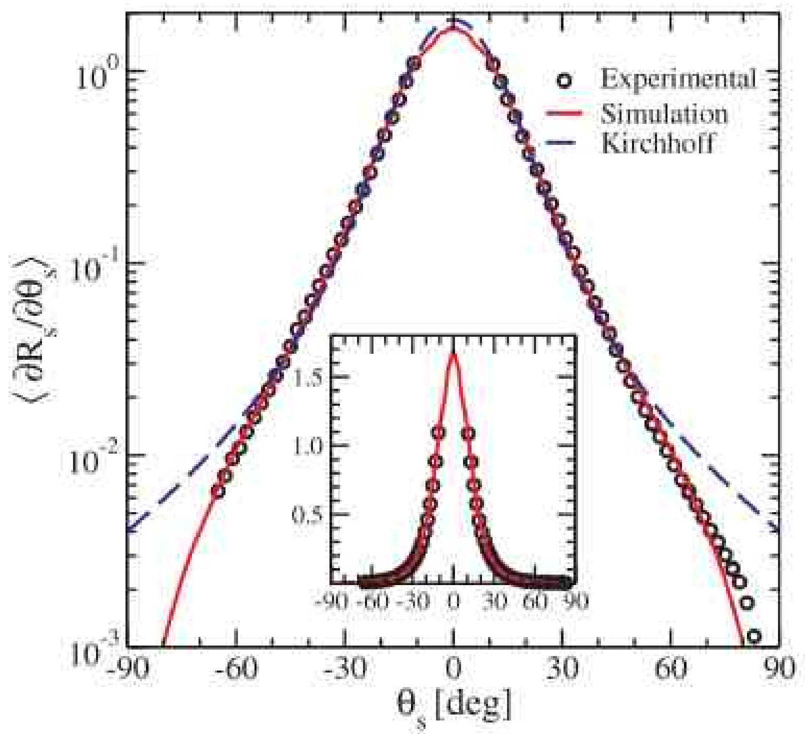
Aux grands angles : $\delta_h \ll \delta_v$

$W$ largeur angulaire du pic de diffusion tq $\delta_v \sim \delta_h$

$$\boxed{W_G \sim 2\frac{\sigma}{\zeta} \quad ; \quad W_{SA} \sim [2s(\lambda)]^{-\frac{1}{H}}}$$

# Diffusion de la lumière par une surface d'aluminium



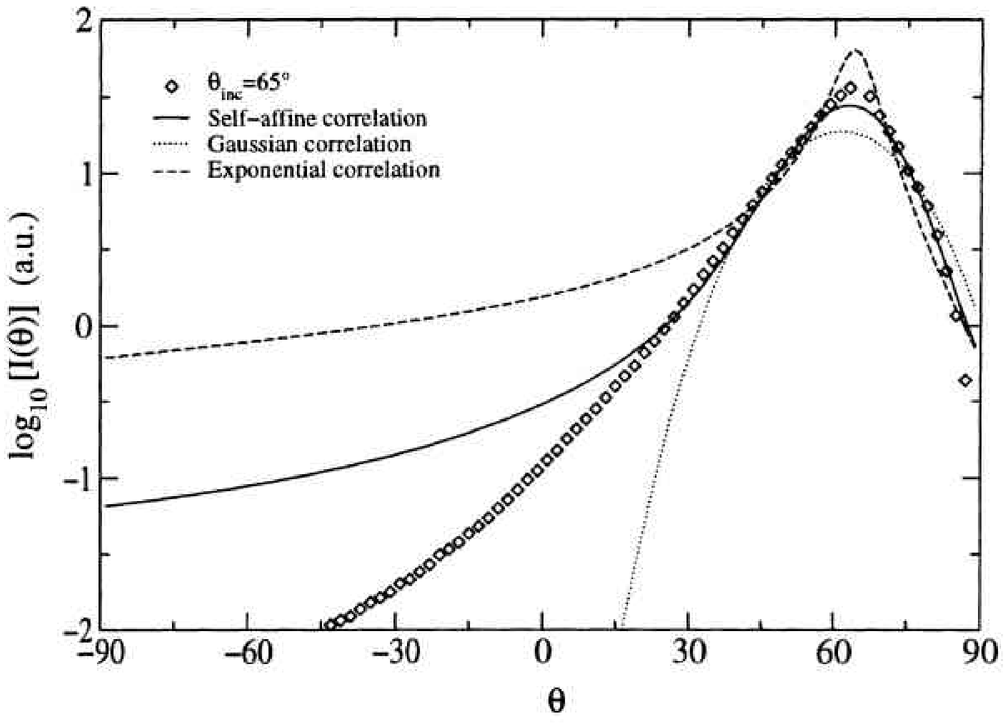

Résultats expérimentaux vs Approximation de Kirchhoff et Simulations avec corrélations Gaussiennes, Exponentielles ou Auto-Affines

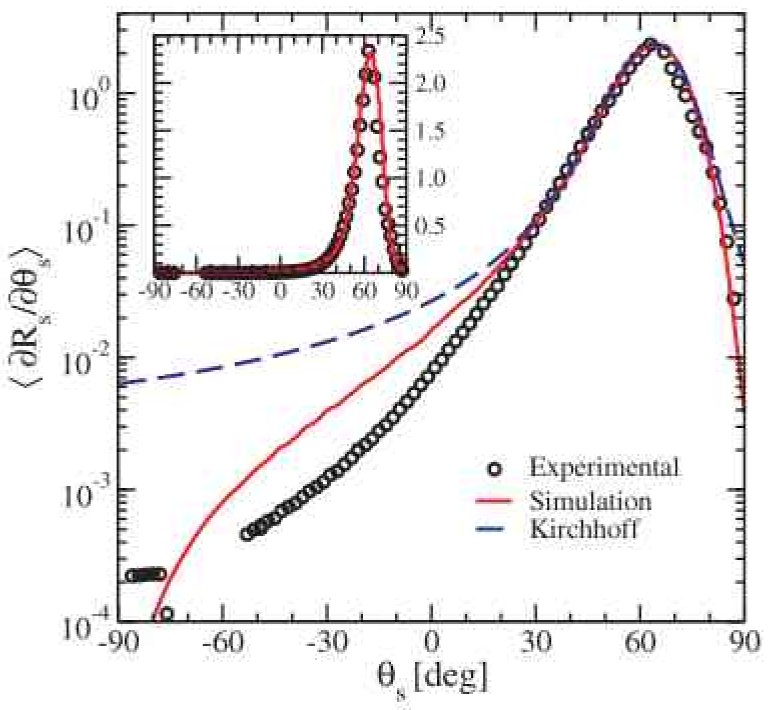
Paramètres expérimentaux rugosité : $\sigma_z(\Delta x) \propto (\Delta x)^H$, $H \approx 0.78$

$s(\lambda) \approx 0.11$ @ $\lambda = 638.2$ nm

Vandembroucq et. al. Optics Comm. (2001), J. Opt. A (2002)

# Diffusion de la lumière par une surface d'aluminium

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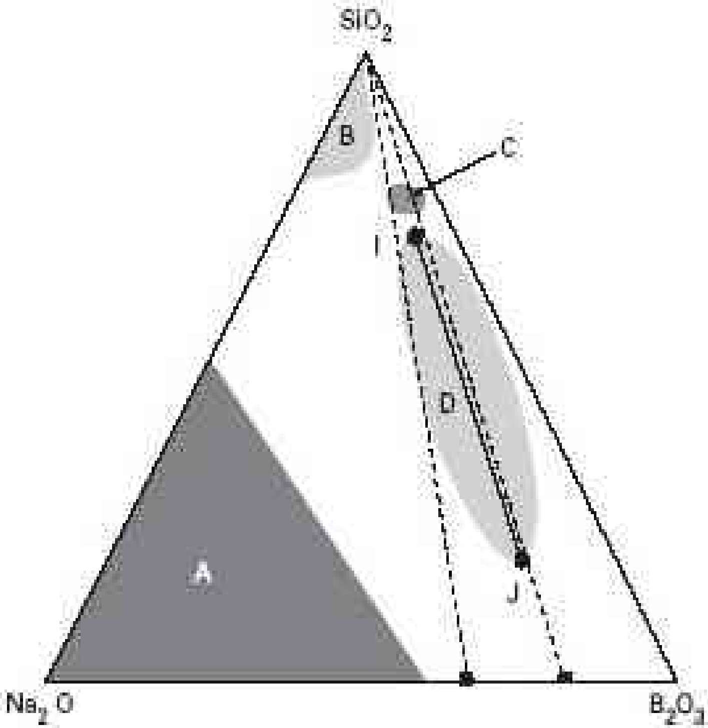
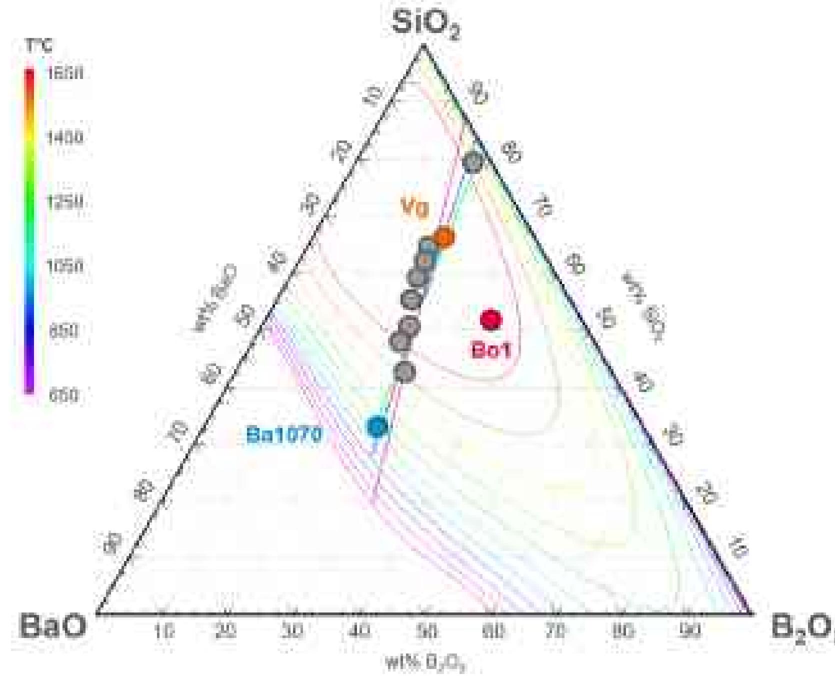
Vandembroucq et. al. Optics Comm. (2001), J. Opt. A (2002)

# Application à l’étude de la séparation de phase dans les verres

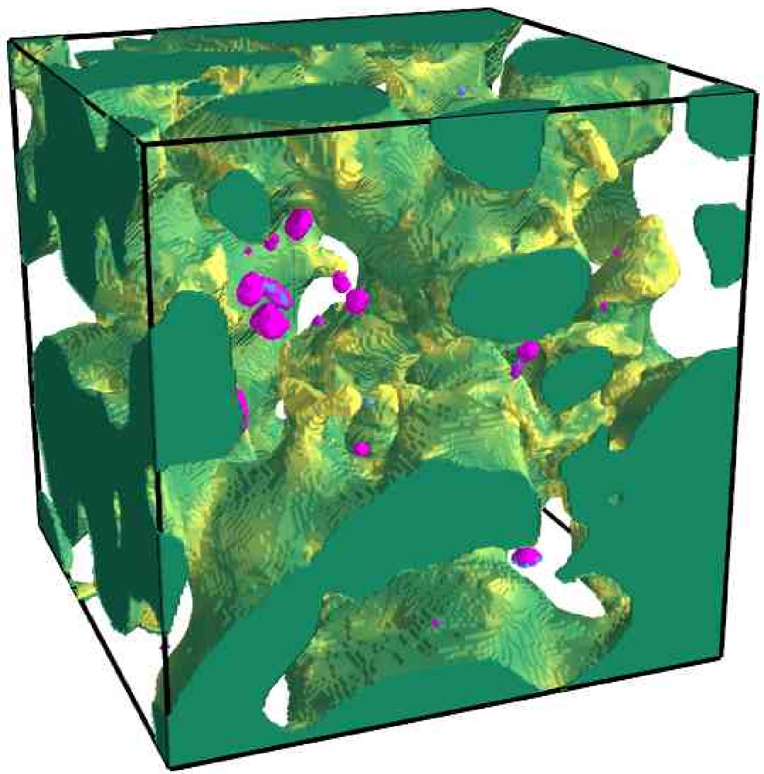
# Verres démixés

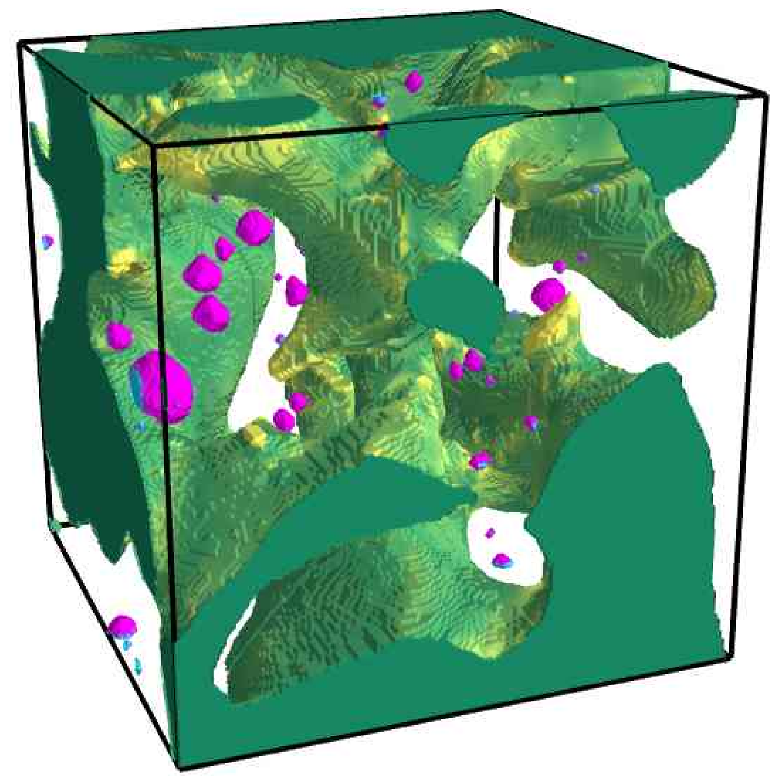



Séparation de phase dans de nombreuses compositions verrières binaires ou ternaires
Différentes tailles de domaines, morphologies variées, mûrissement hydrodynamique ou diffusif. Applications: pyrex, vycor, etc.

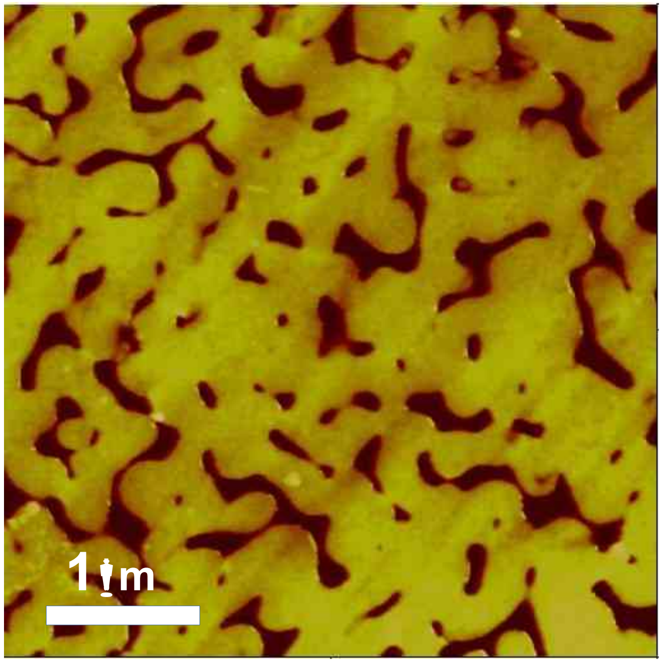
# Suivi temps réel du mûrissement par tomographie X

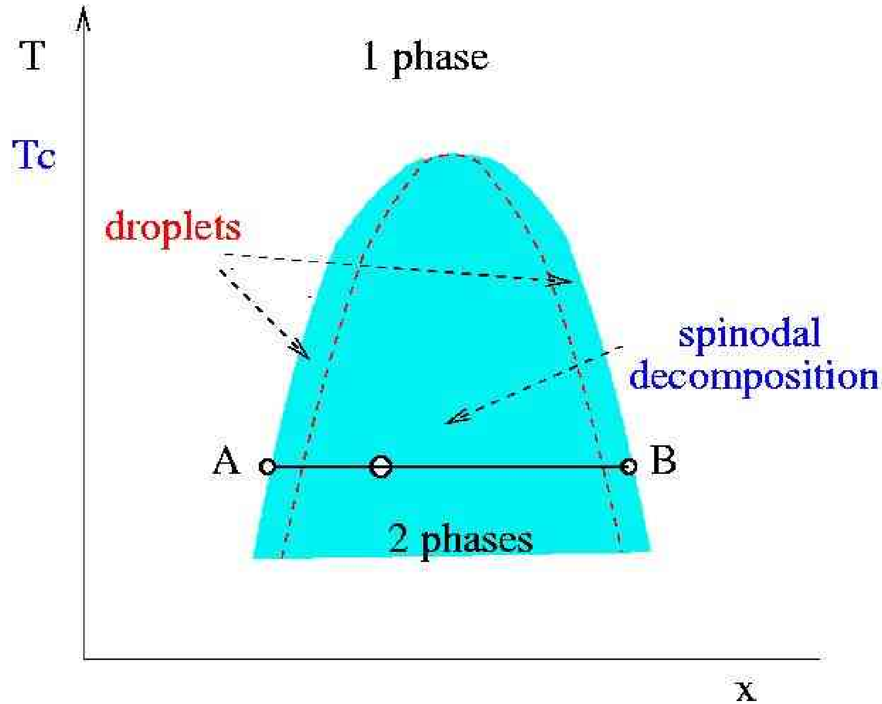




Bouttes et al. PRL 2014, Acta Mater. 2015, PRL 2016

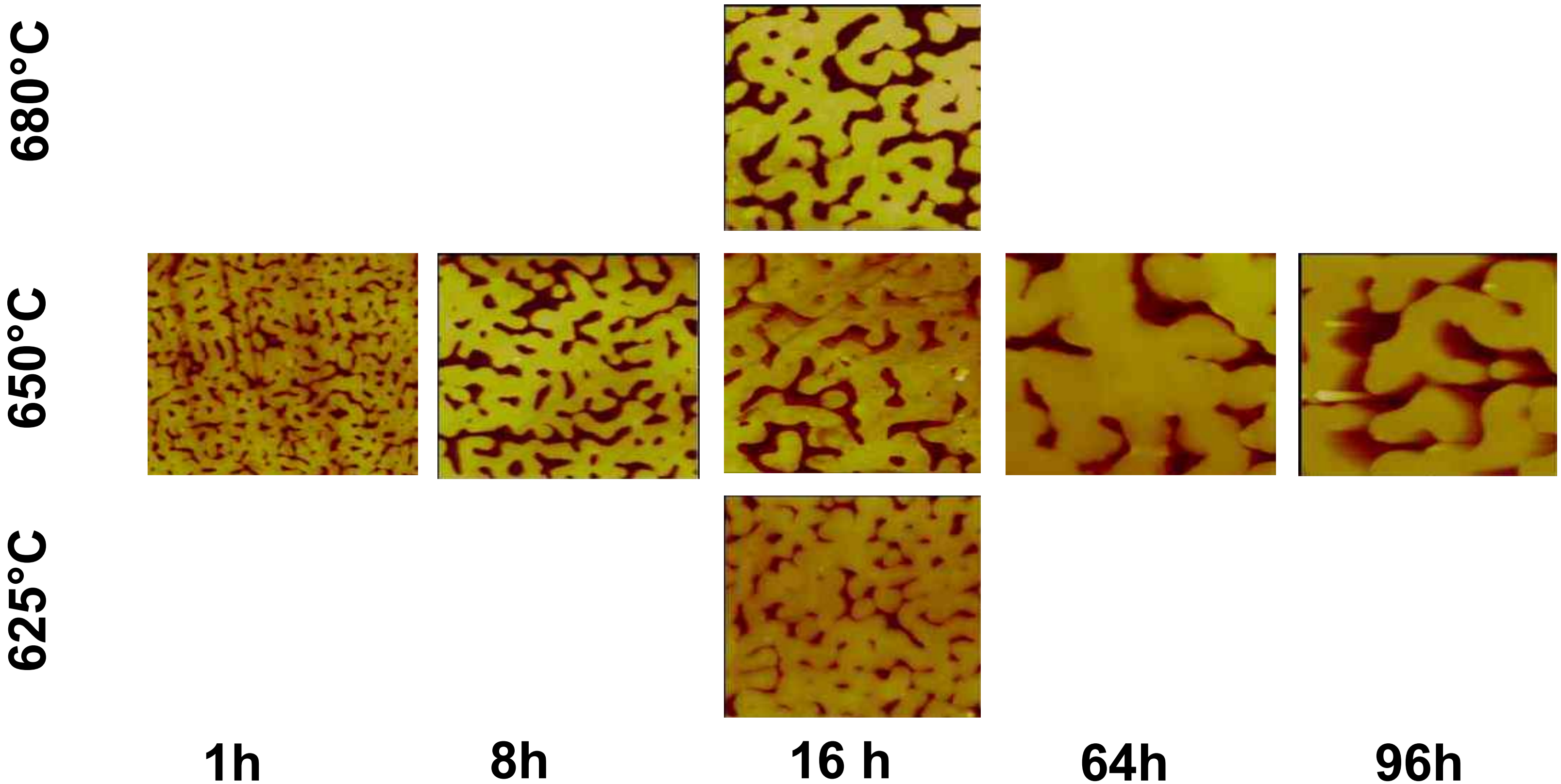
# Séparation de phase dans les verres



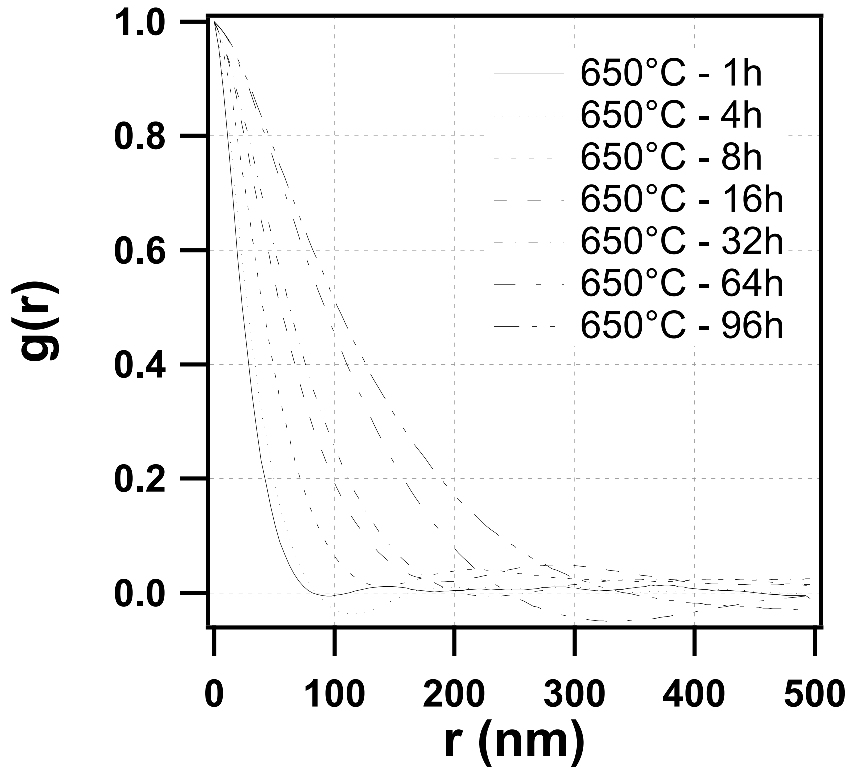

AFM image of a surface of a phase separated alkaline borosilicate glass after selective etching
Lateral size: 4µm, Z-scale: [-100:+100 nm]

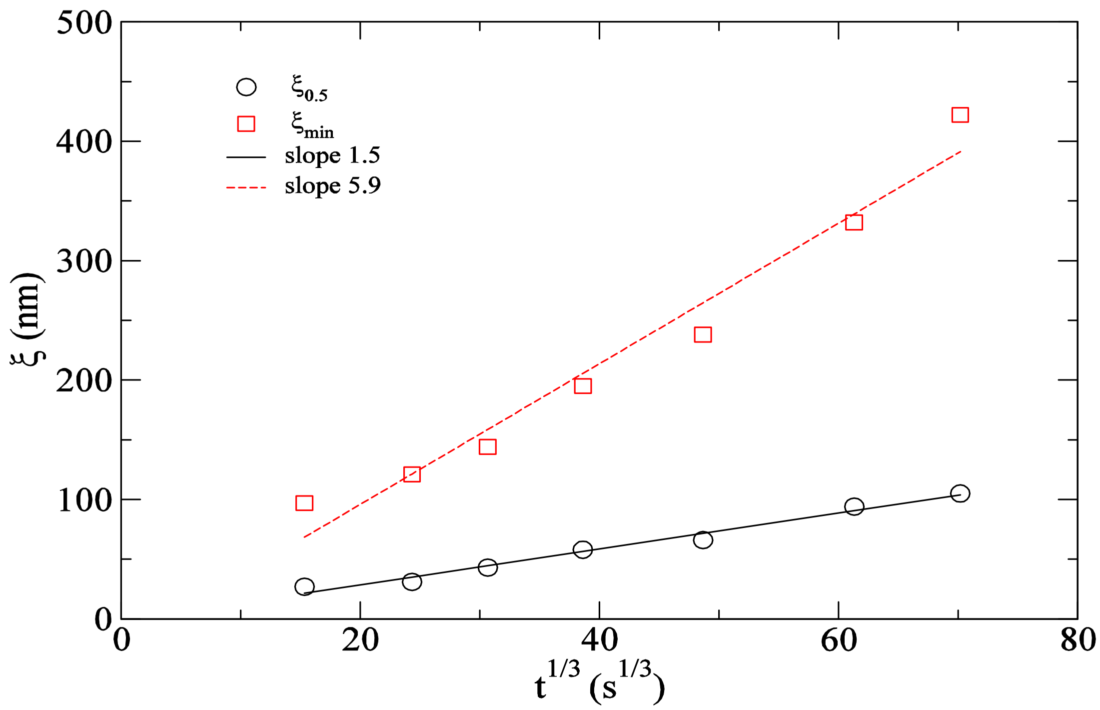
# Cinétique de croissance des domaines




D. Dalmas et al. JNCS 2007

# Loi d'échelle Lifshitz-Slyozhov-Wagner

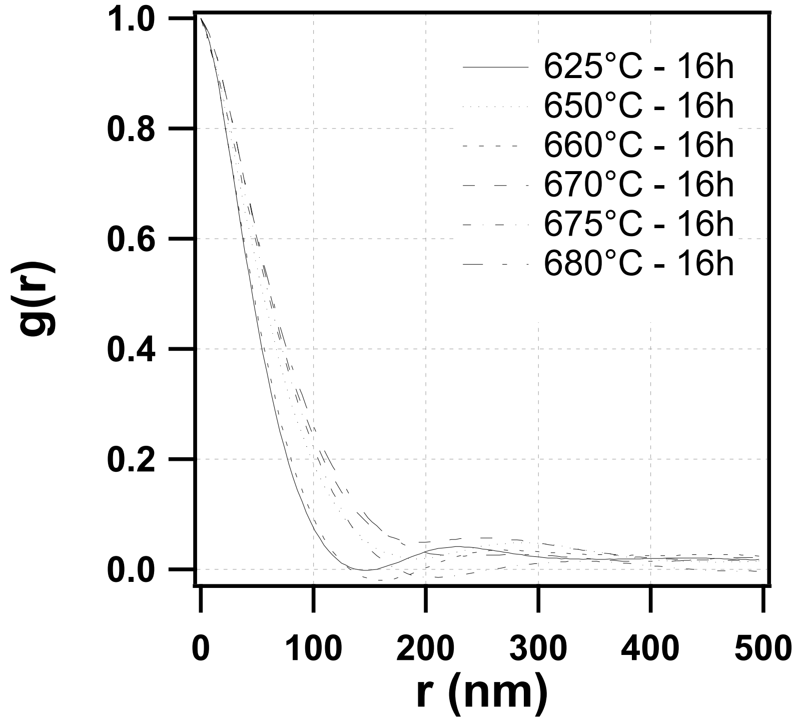


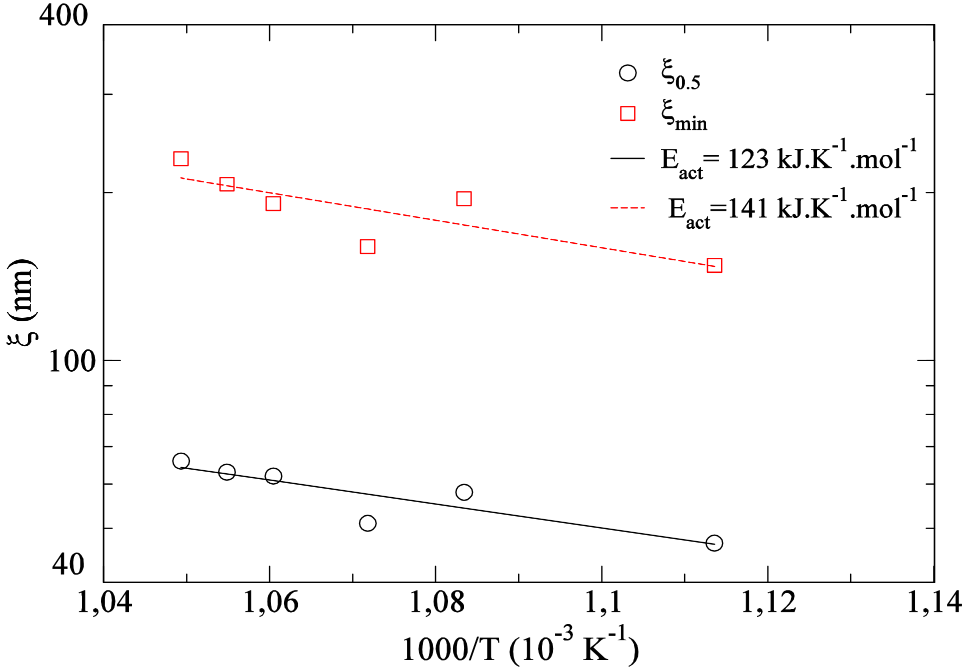




$$R \approx (Kt)^{1/3}, \quad K \approx \frac{\gamma D v}{kT} \qquad D \sim 10^{-16}\,\mathrm{cm\,s^{-1}}$$

D. Dalmas et al. JNCS 2007

# Temperature dependence: Arrhenius behavior

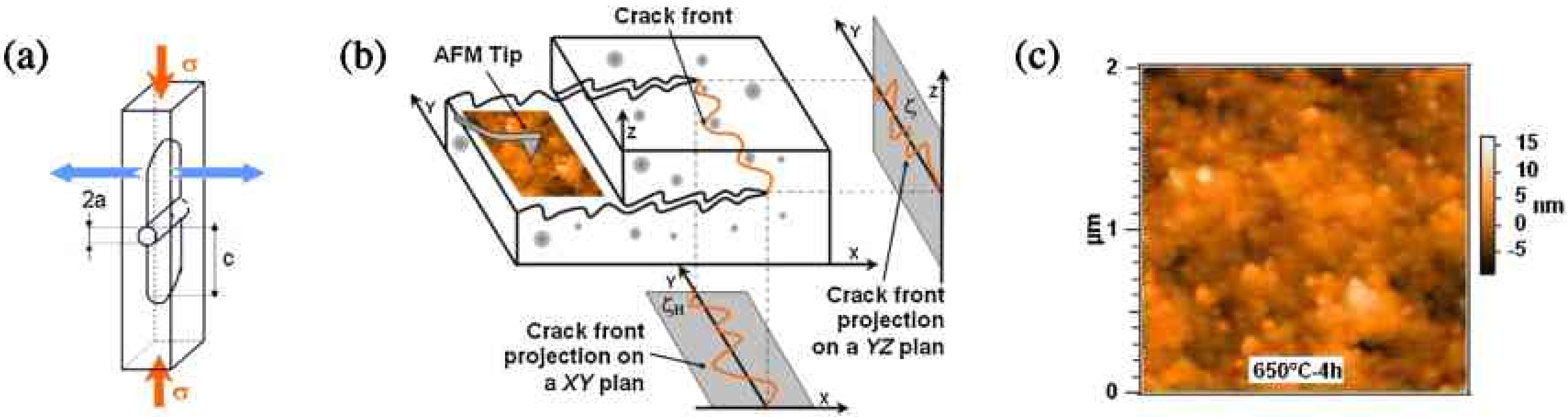


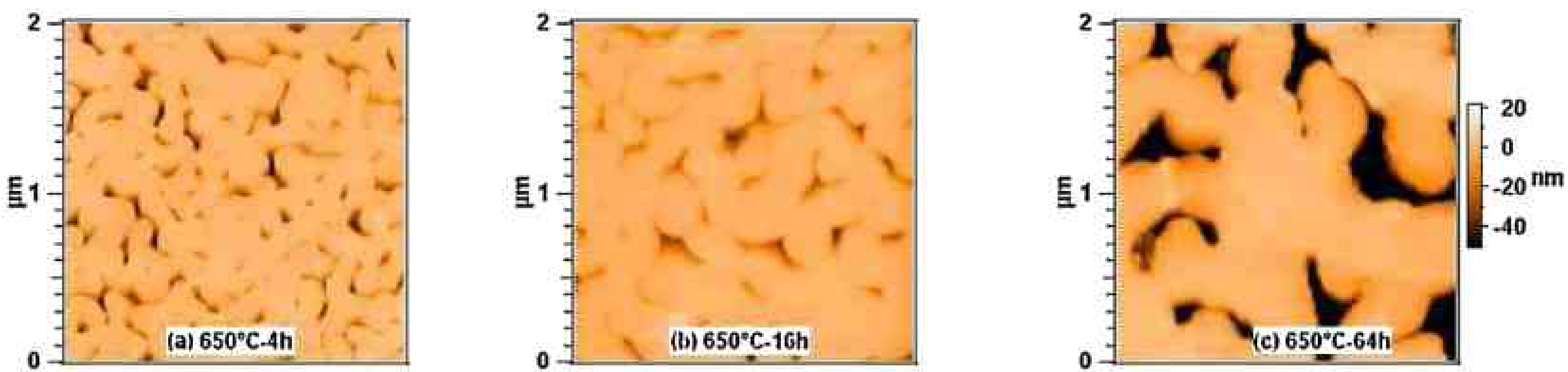




Estimate of activation energy from AFM measurements

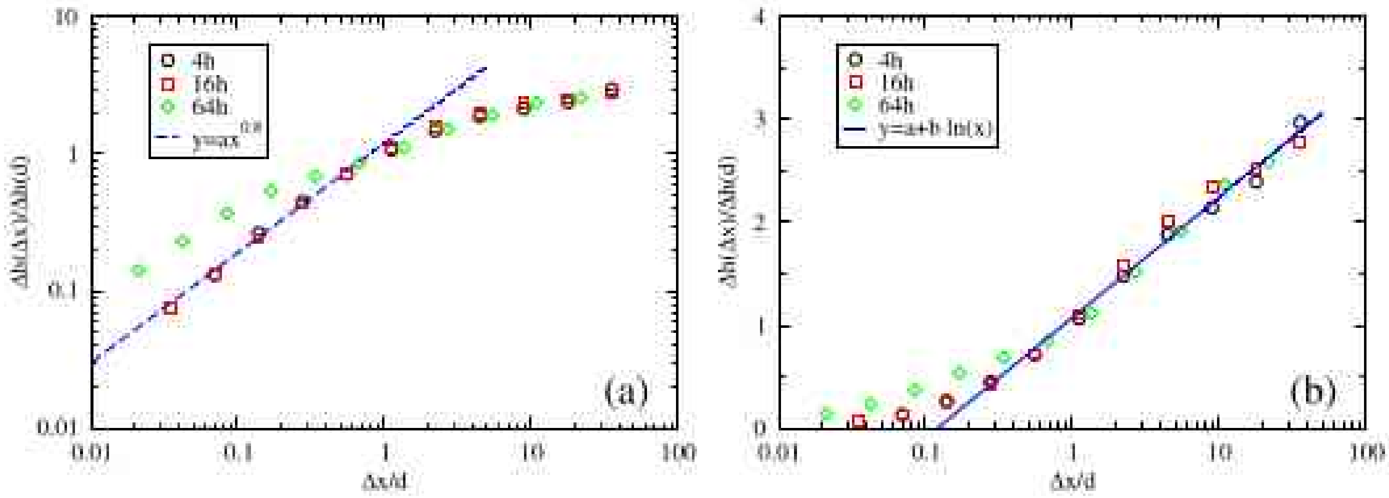
D. Dalmas et al. JNCS 2007

# Surface de fracture de verre démixé



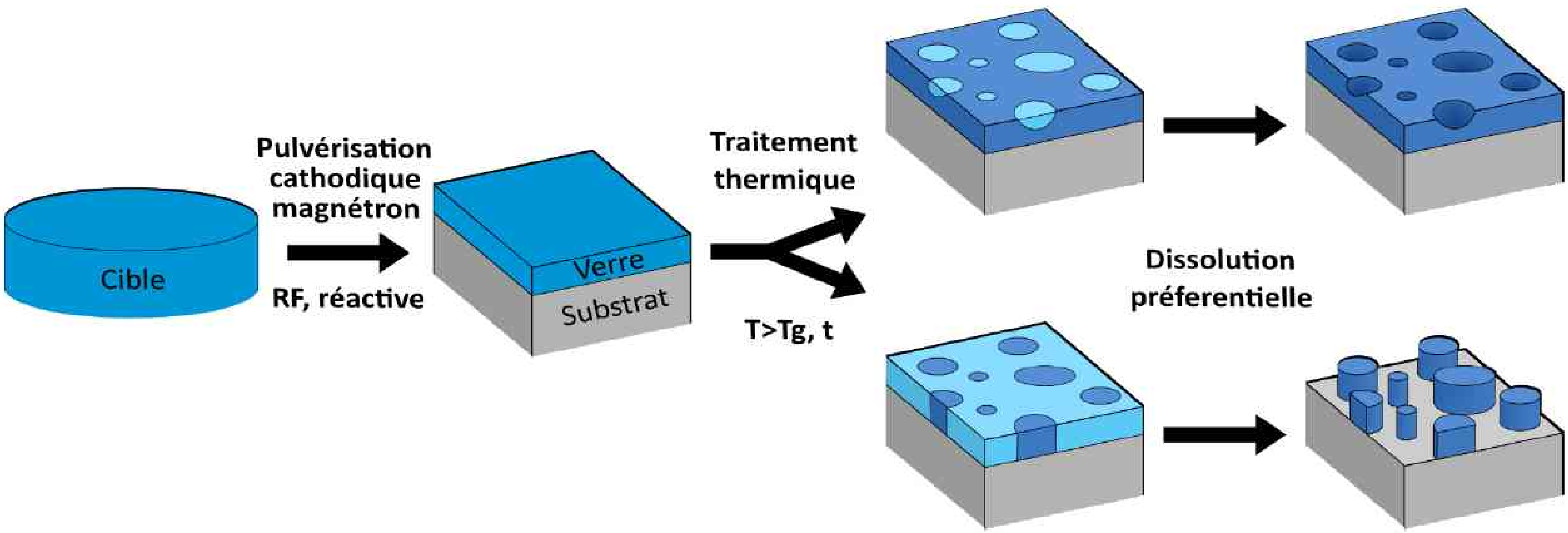
# Rugosité de surface de fracture de verre




Démixion = 1 longueur de corrélation associée au mûrissement
Fracture : Corrélation de hauteurs logarithmiques aux grandes longueurs

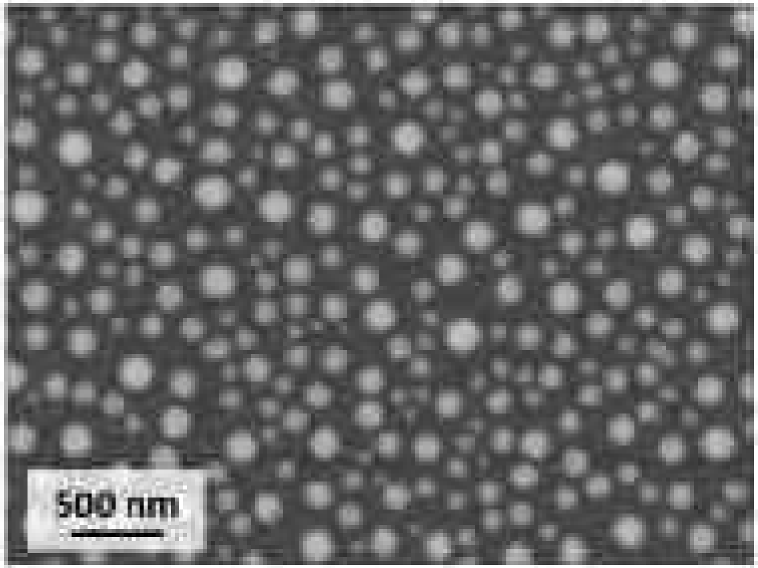
Dalmas et al, Phys. Rev. (2008)

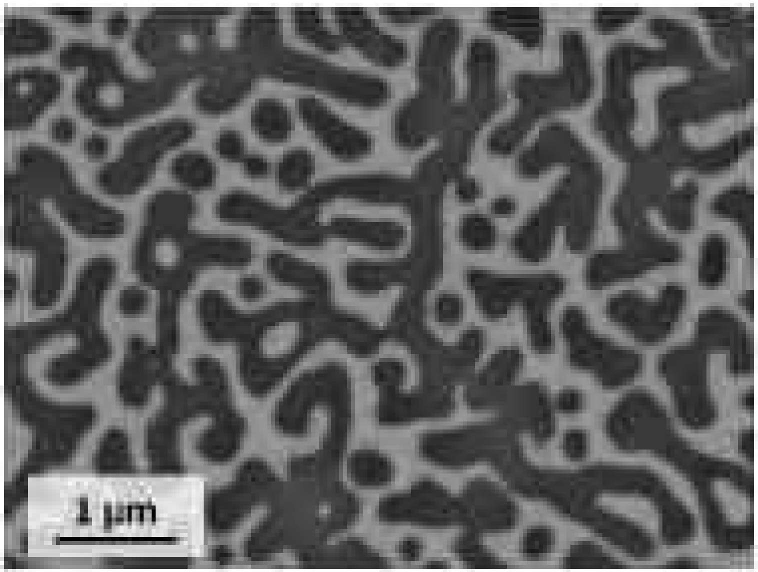
# Texturation de surface par séparation de phase en couche mince

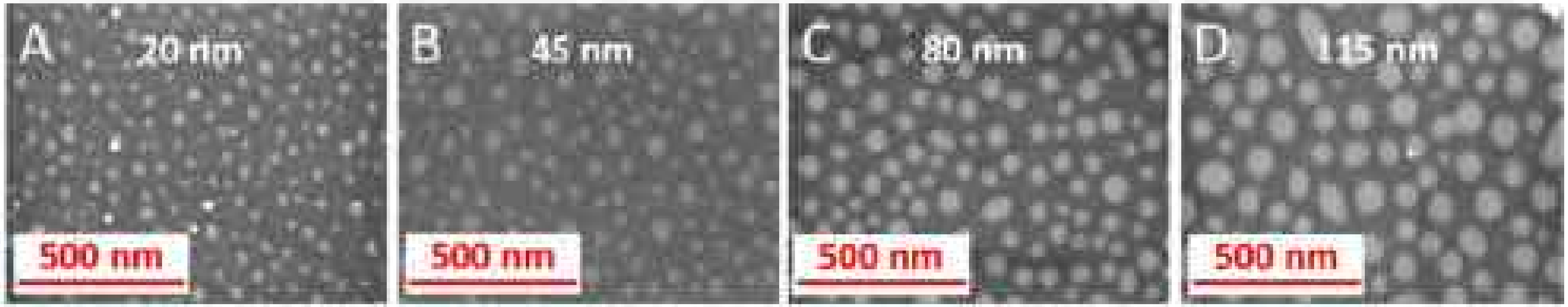



J.-T. Fonné Ph.D 2017, B. Bouteille Ph.D. 2020

# Variétés de tailles et de morphologie des domaines

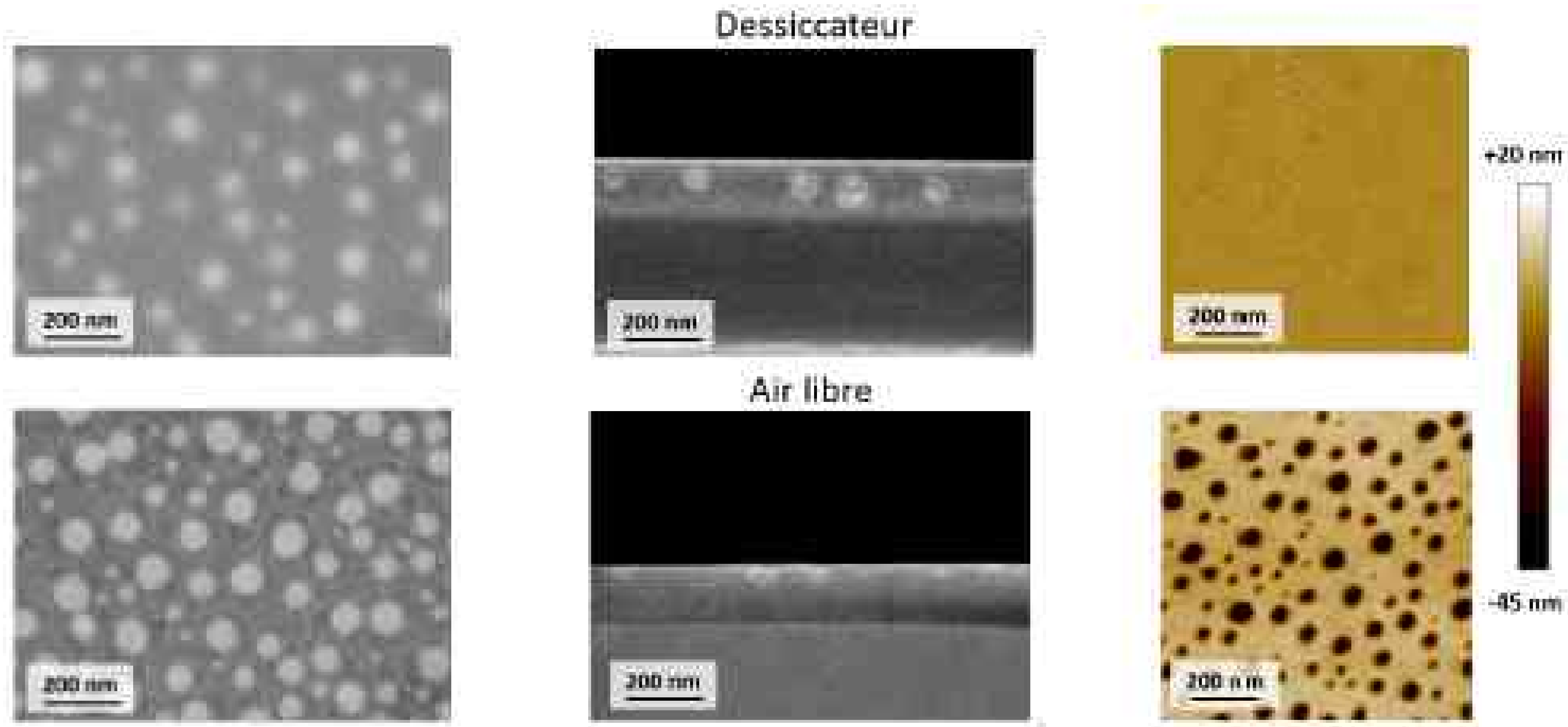


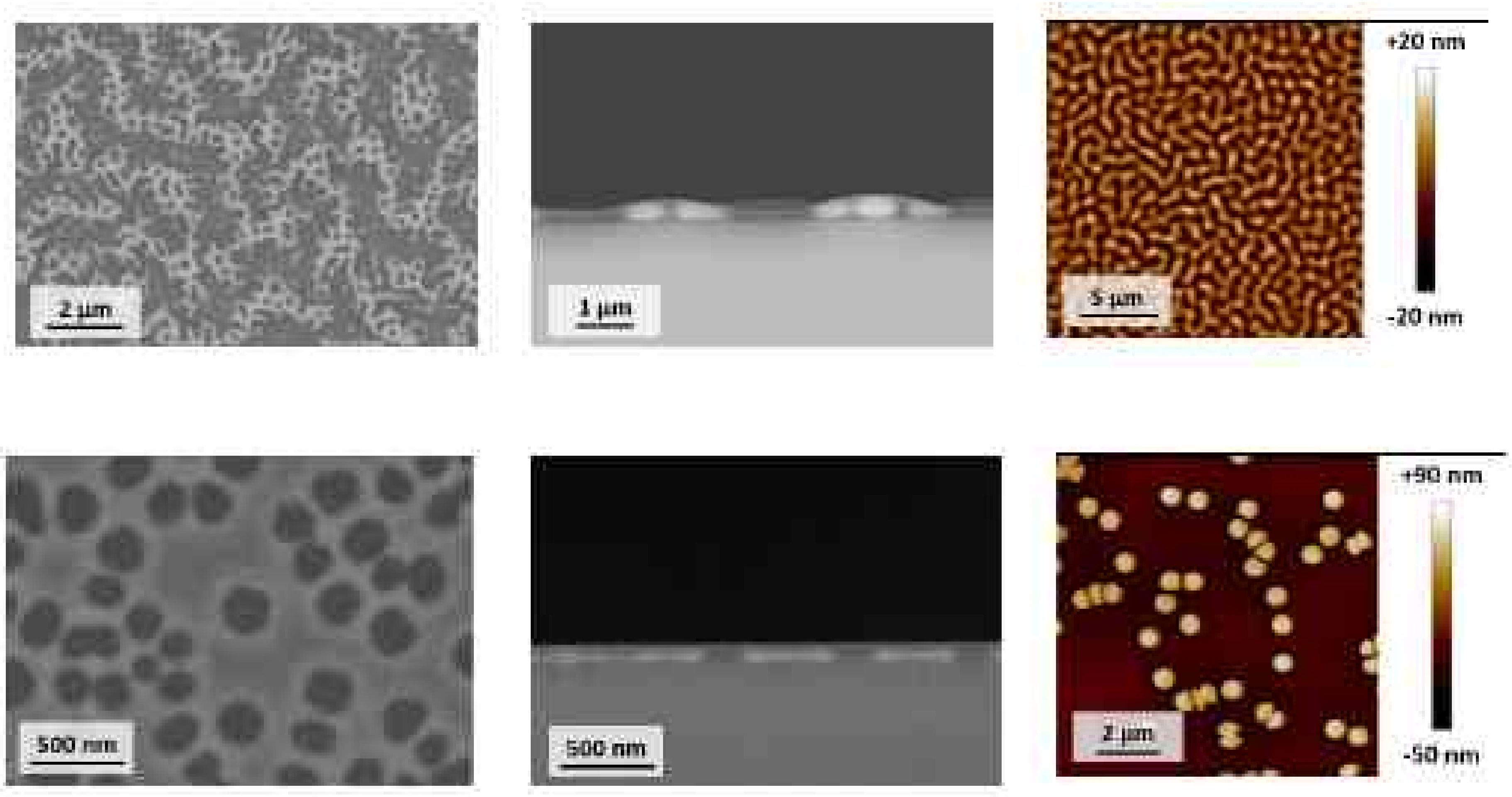

J.-T. Fonné Ph.D 2017, B. Bouteille Ph.D. 2020

# MEB vs AFM

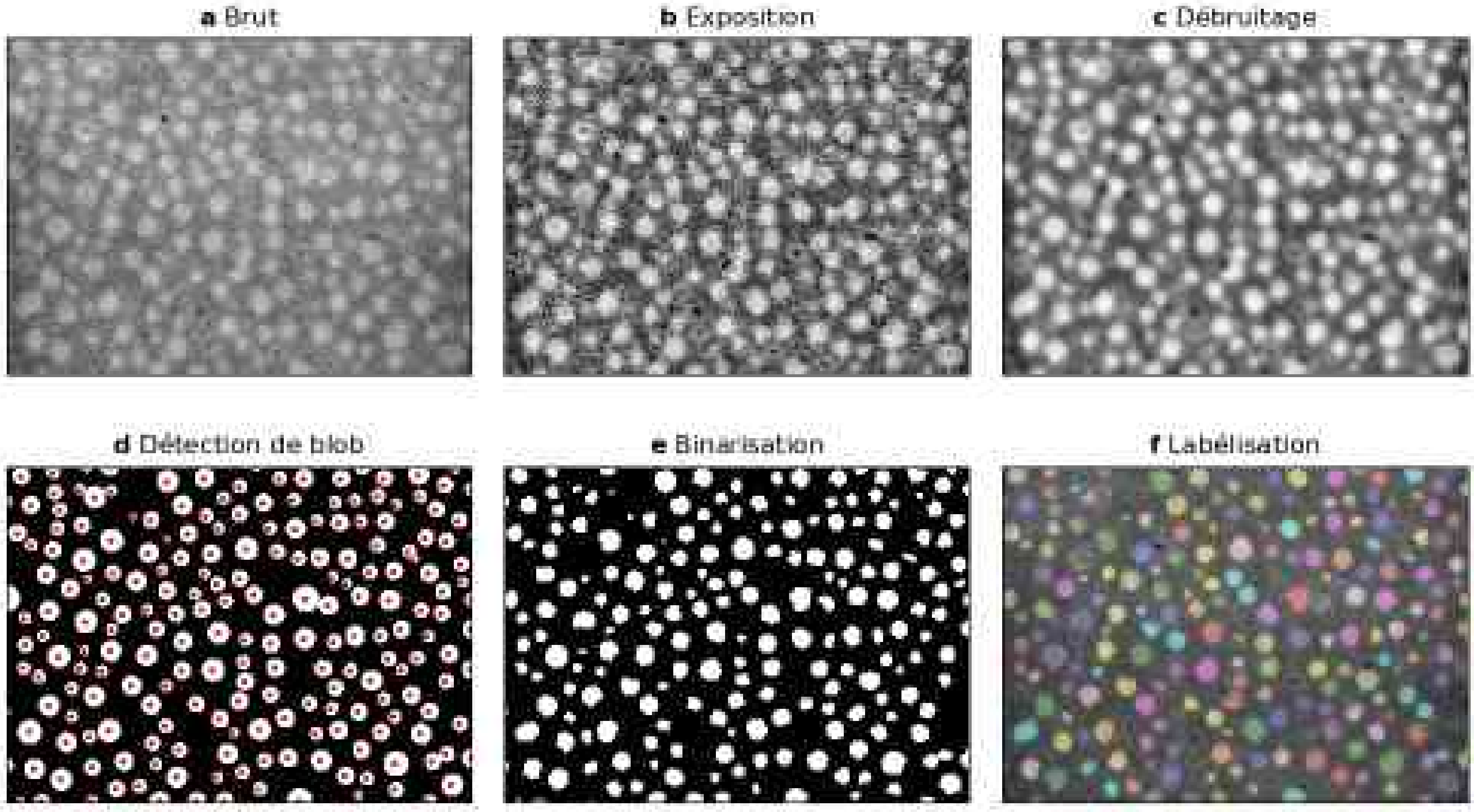



B. Bouteille Ph.D. 2017

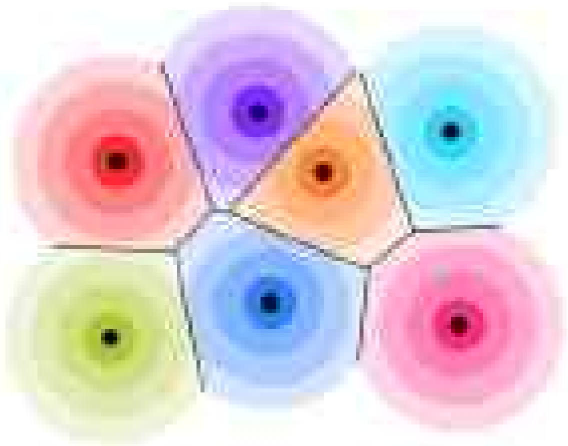
# Différentes compositions, différentes texturations



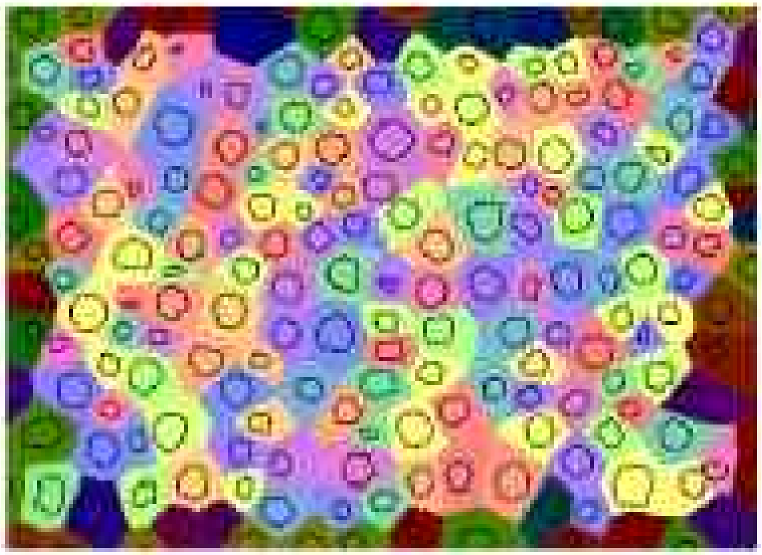
# Traitement d'image



# Cellules de Voronoi

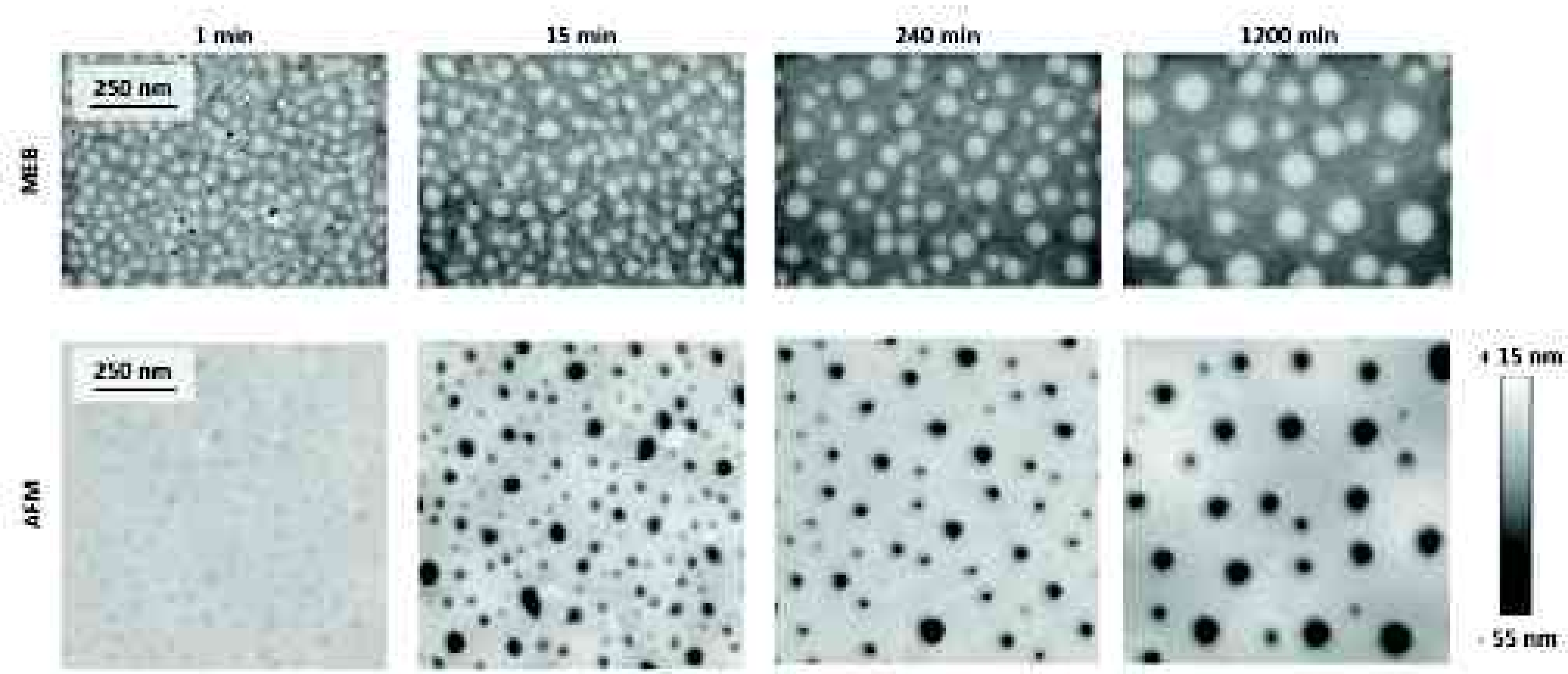


a Diagramme de Voronoï de centre à centre

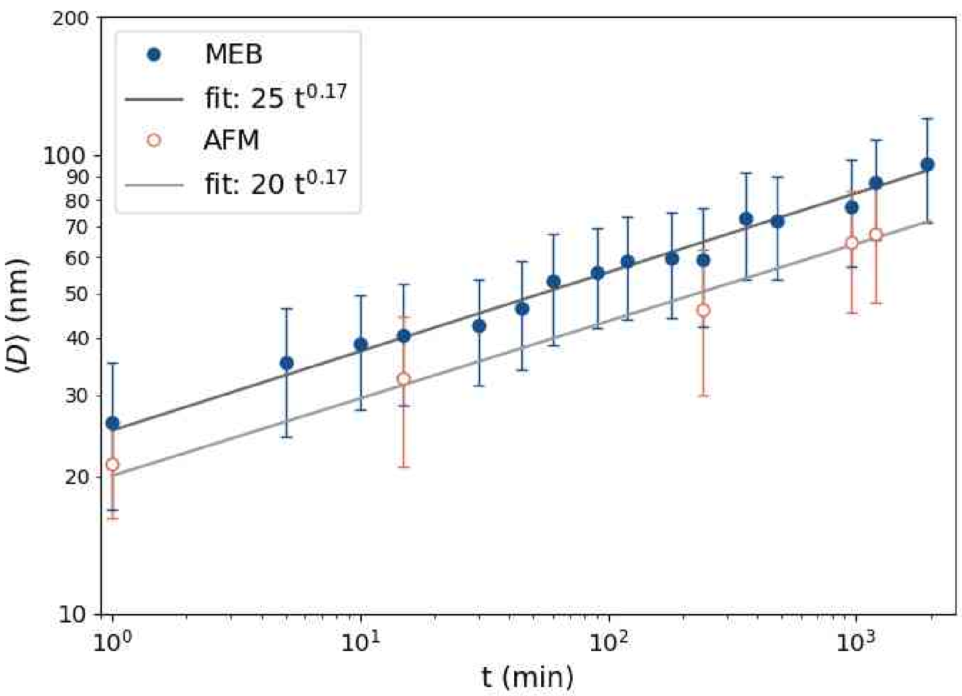


b Diagramme de Voronoï de bords à bords

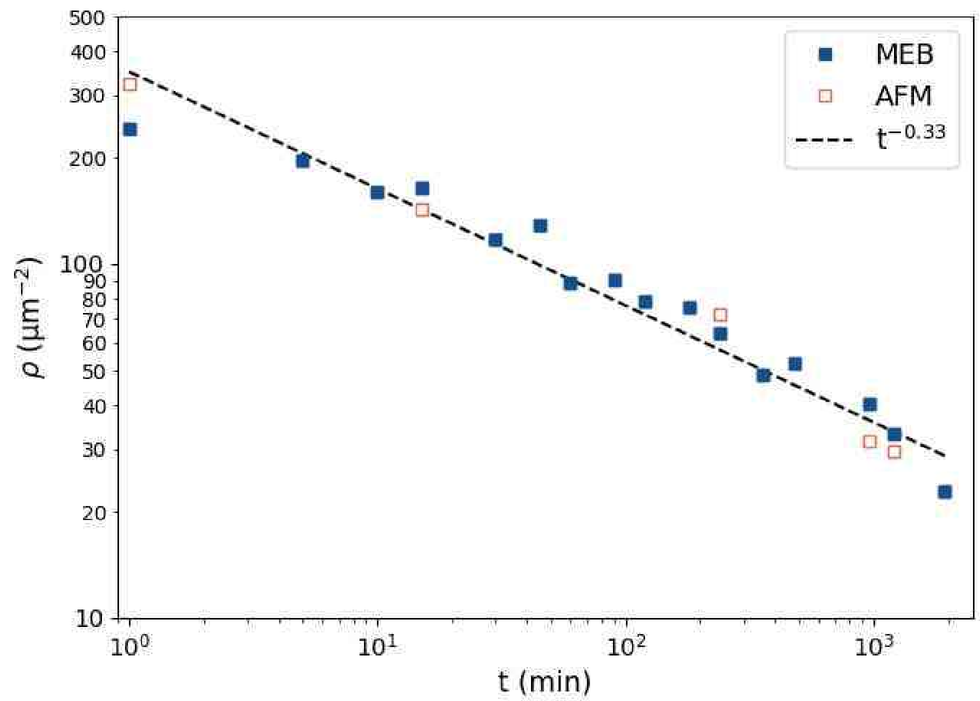
# Croissance de domaines en couche mince



# Cinétique (lente) de croissance



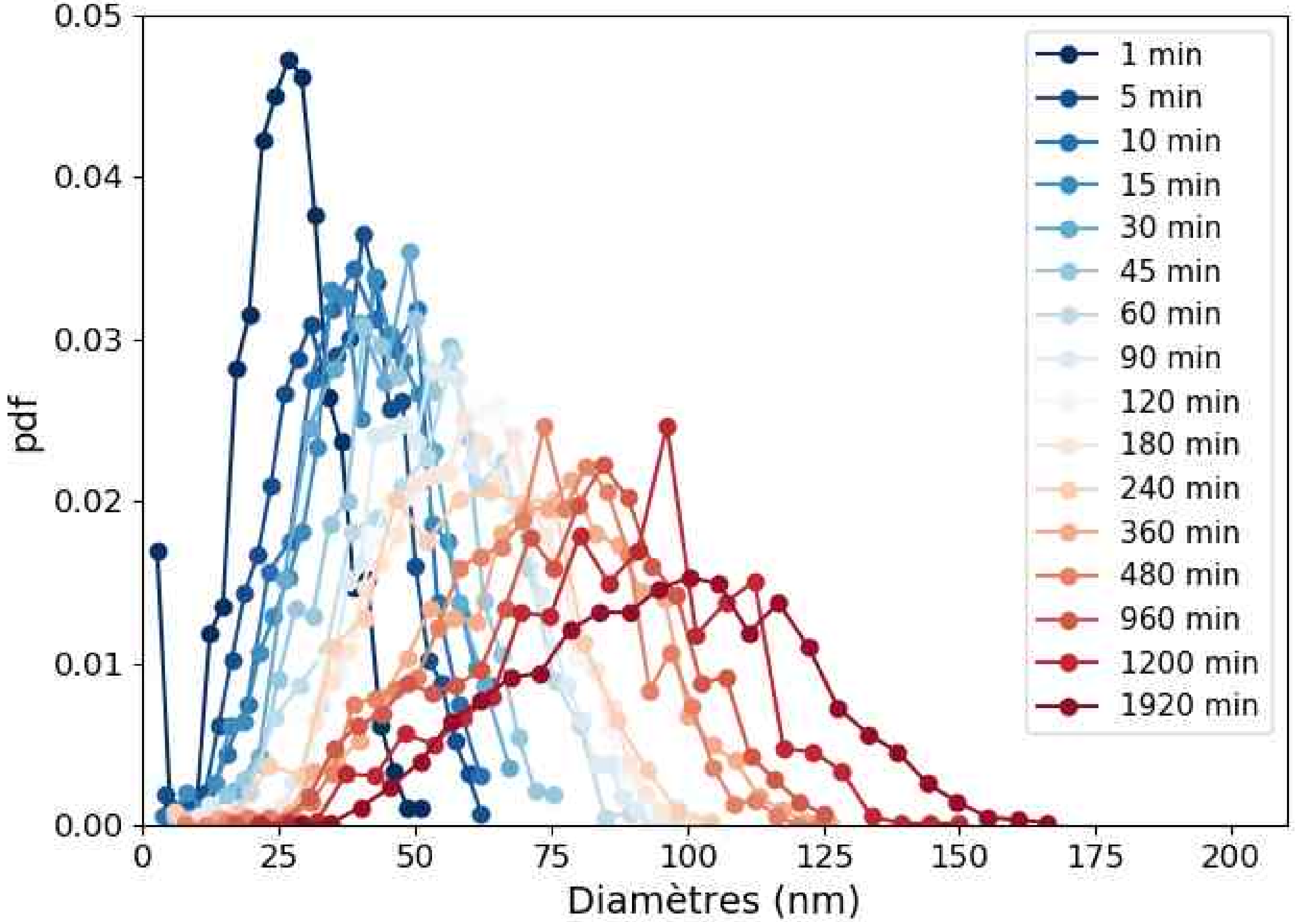

Diamètre Goutelettes



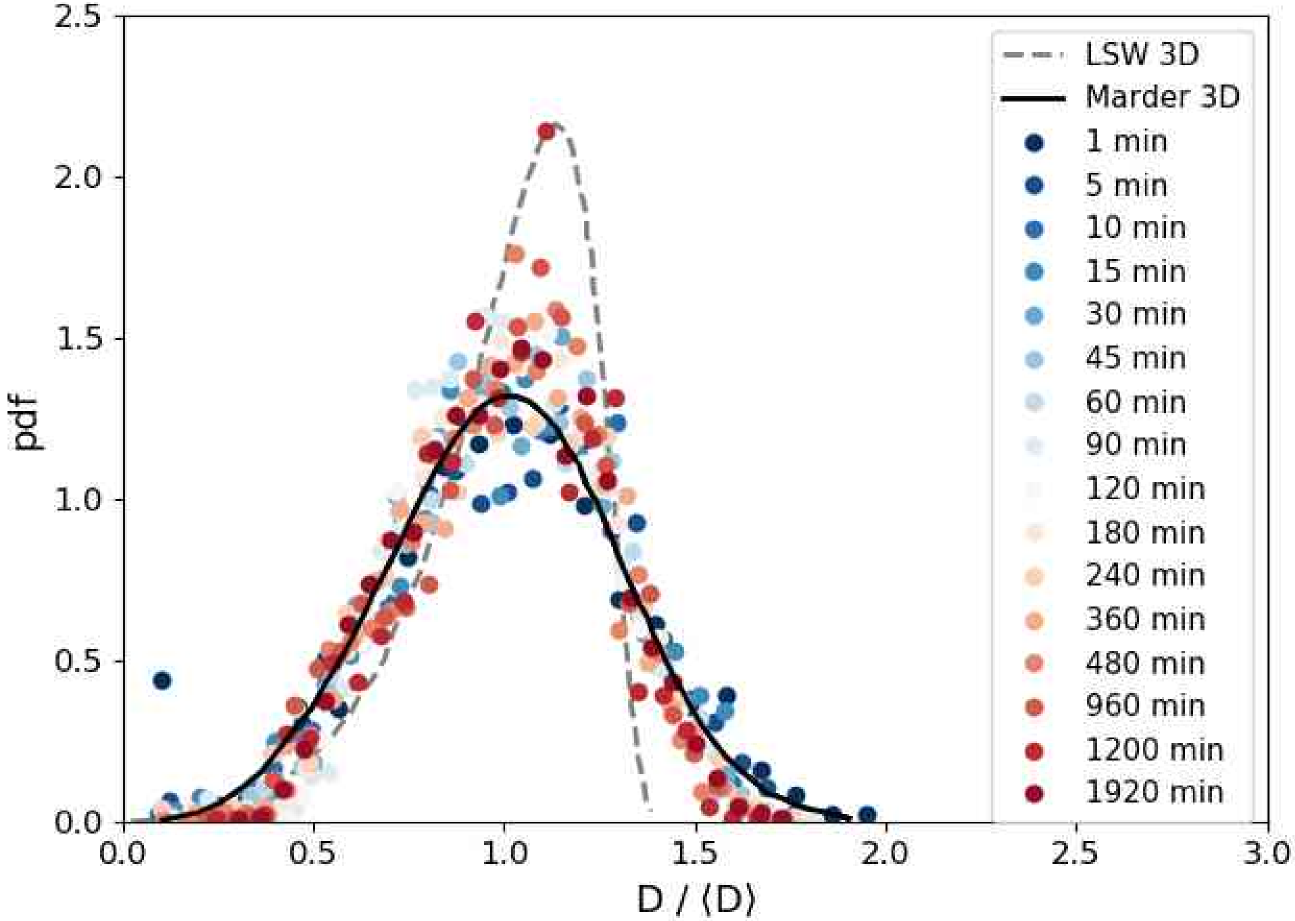

Densité Goutelettes

B. Bouteille et al. APL 2022

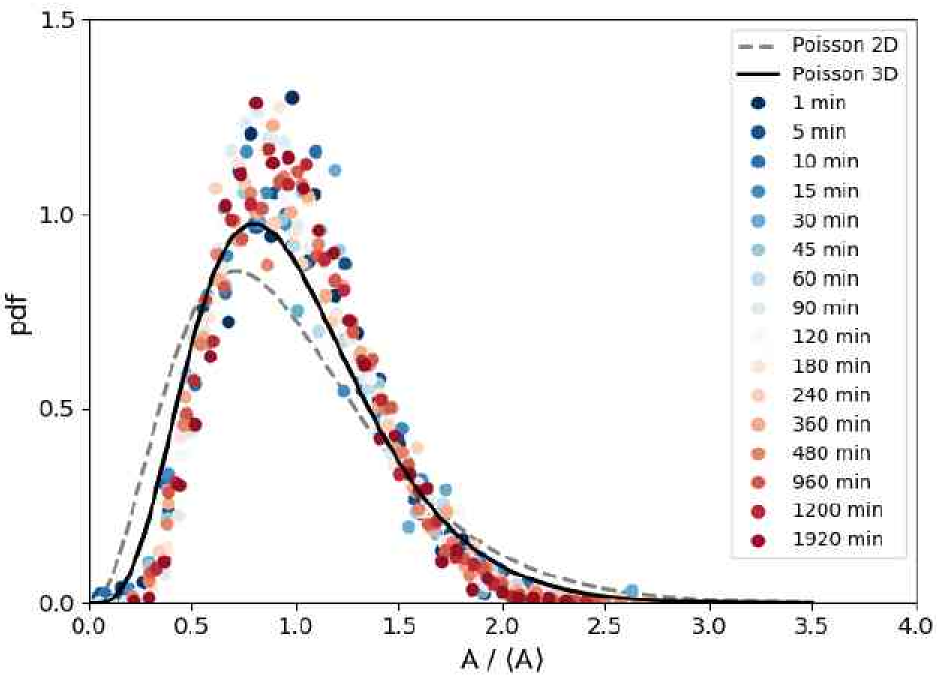
# Evolution de la distribution de taille



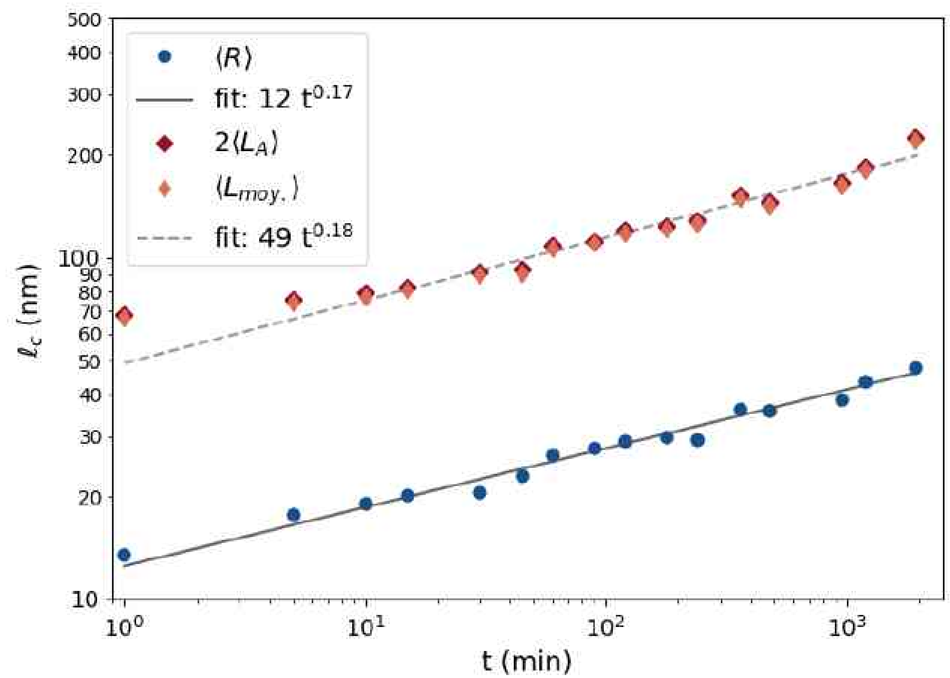
# Distributions de tailles renormalisées



# Cellules de Voronoi




Distribution renormalisée de l'aire des cellules de Voronoi




Evolution temporelle du rayon et de la distance inter-gouttelettes