Obstacle race for the invasion of air within the hydraulic network of biomimetic leaves

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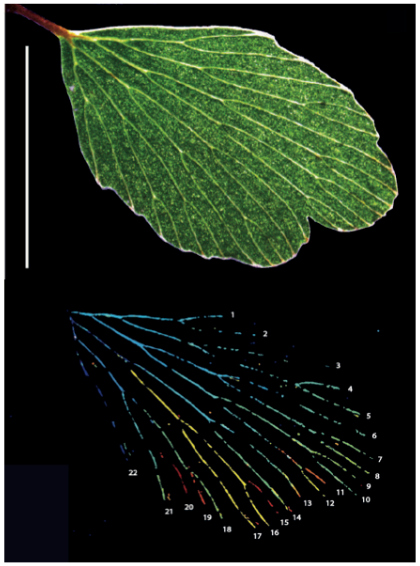

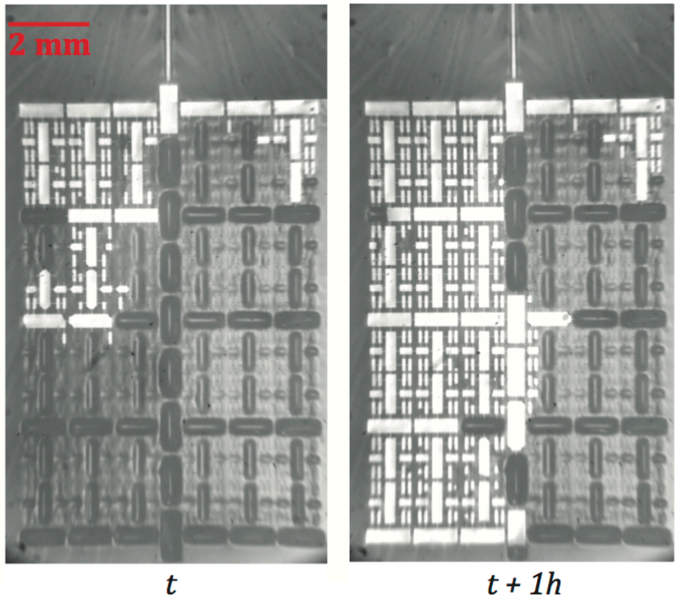

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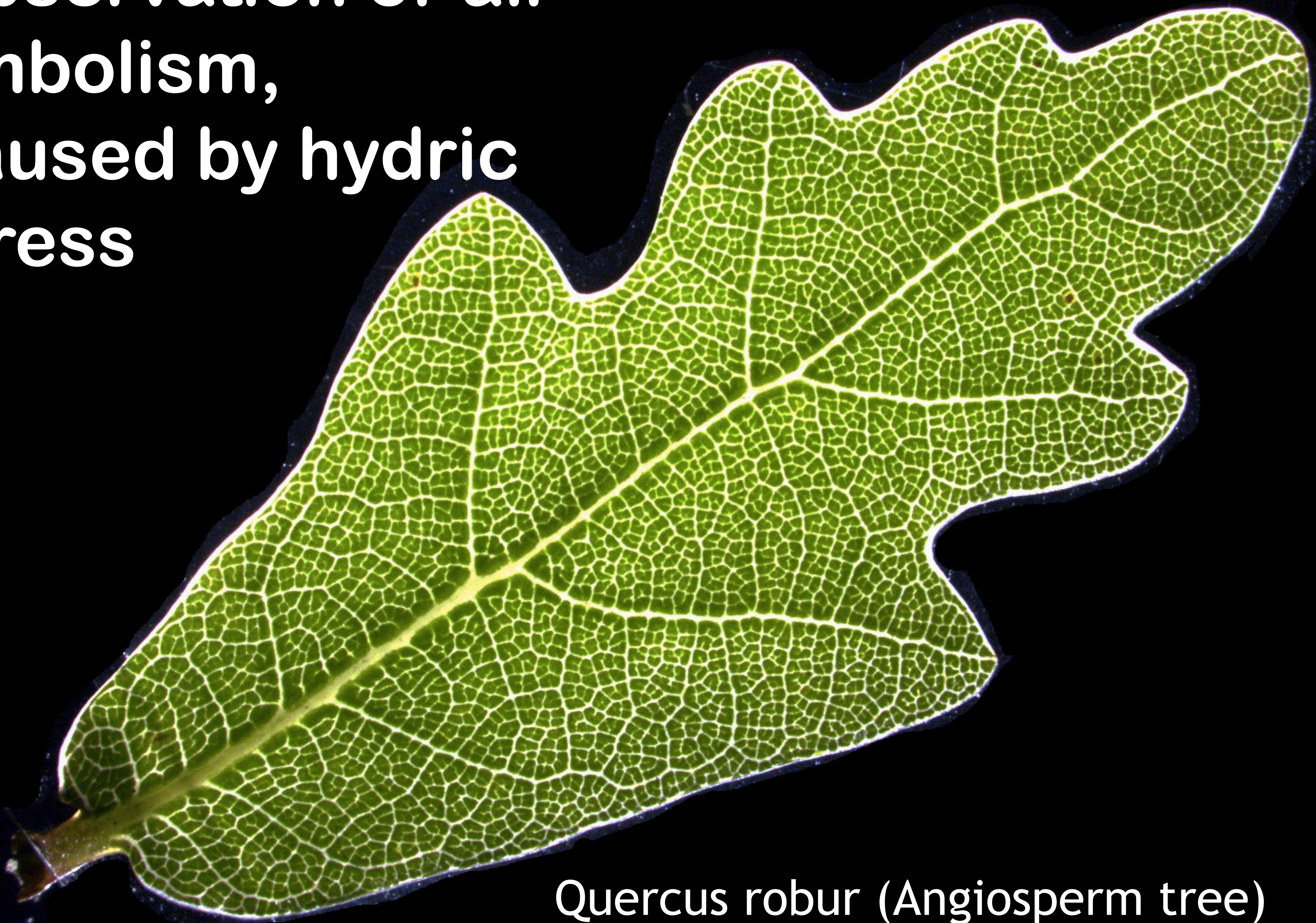
Observation of air embolism, caused by hydric stress



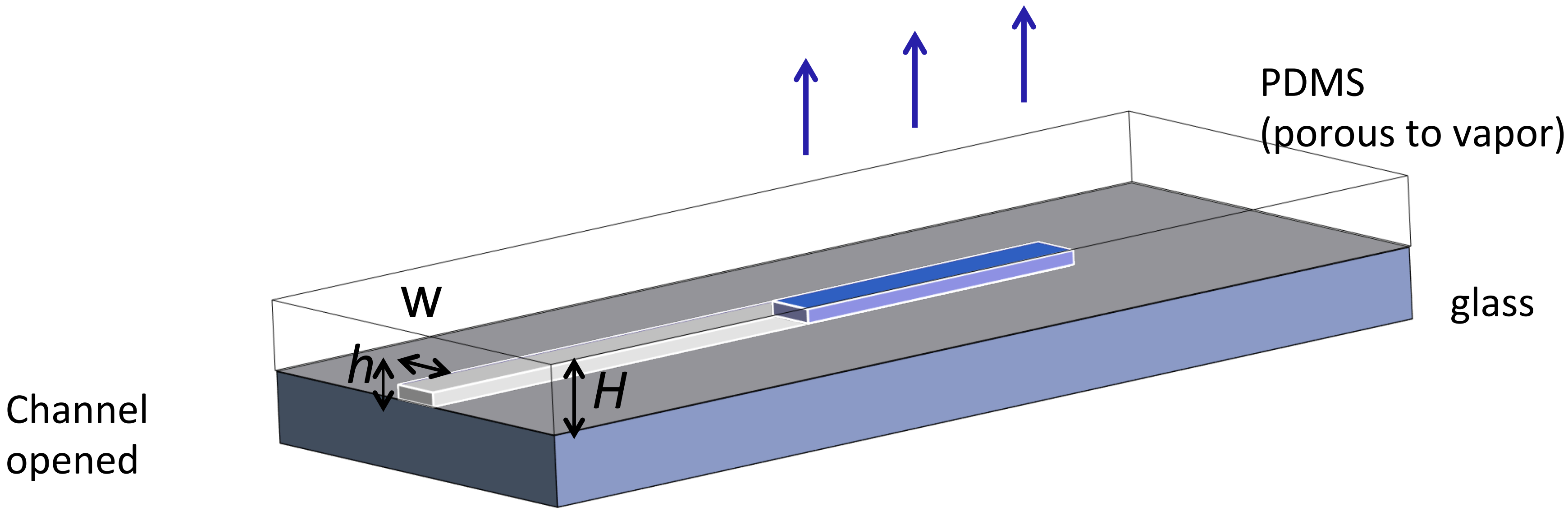
Quercus robur (Angiosperm tree)

[Brodribb, Bienaimé, Marmottant PNAS 2016]

Oak leaf drying in 8h

Biomimetic system
Step 1: linear channel

- simplify the problem to understand the physics

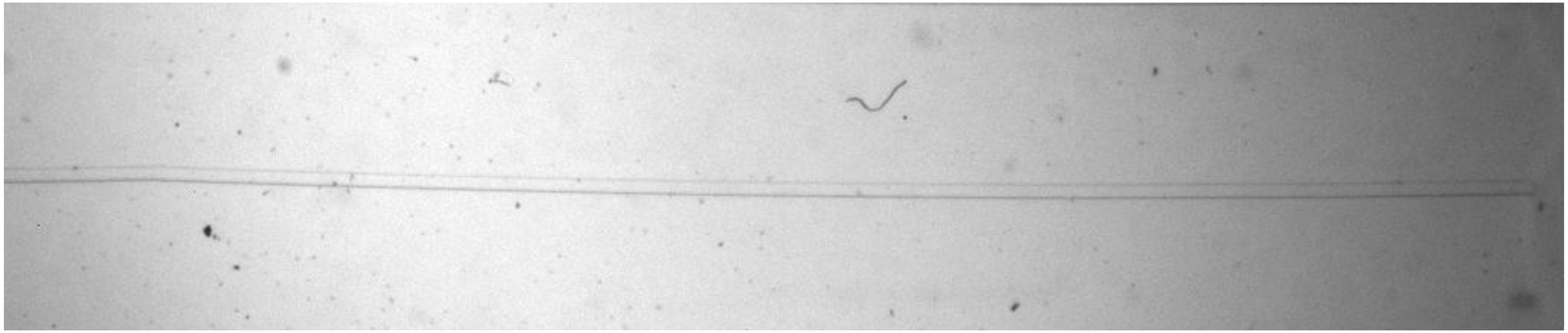


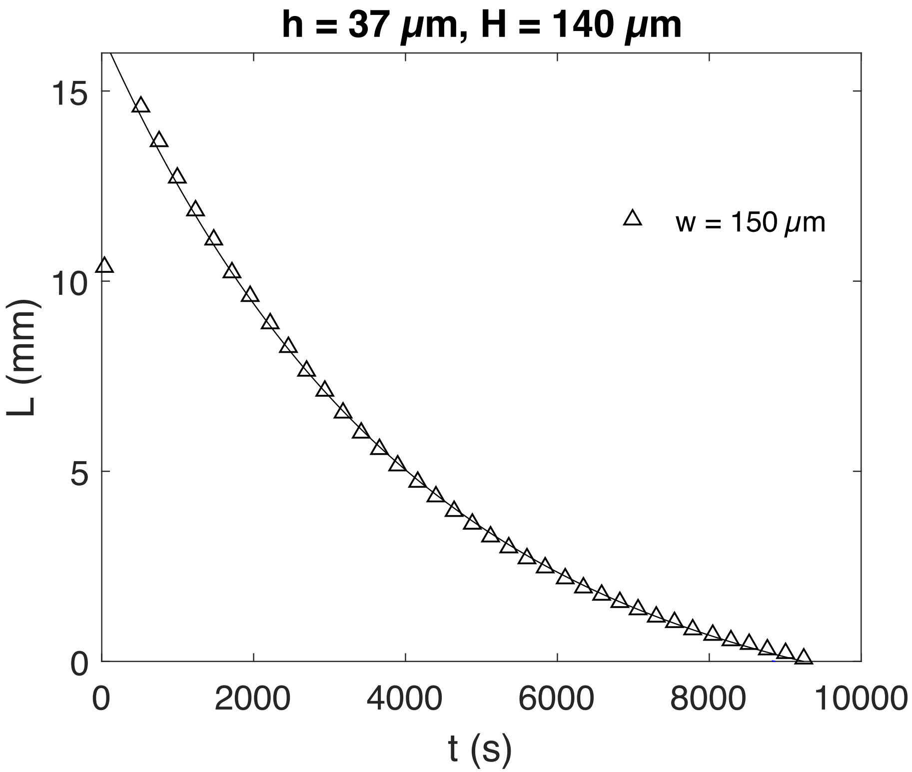
PDMS thickness H=140 µm (spin-coating)
inspired by idea of [X. Noblin PNAS 2008]

- channels initially water filled, then placed under dry air

- channels dry over time, mainly through the solid
(unlike usual granular media)

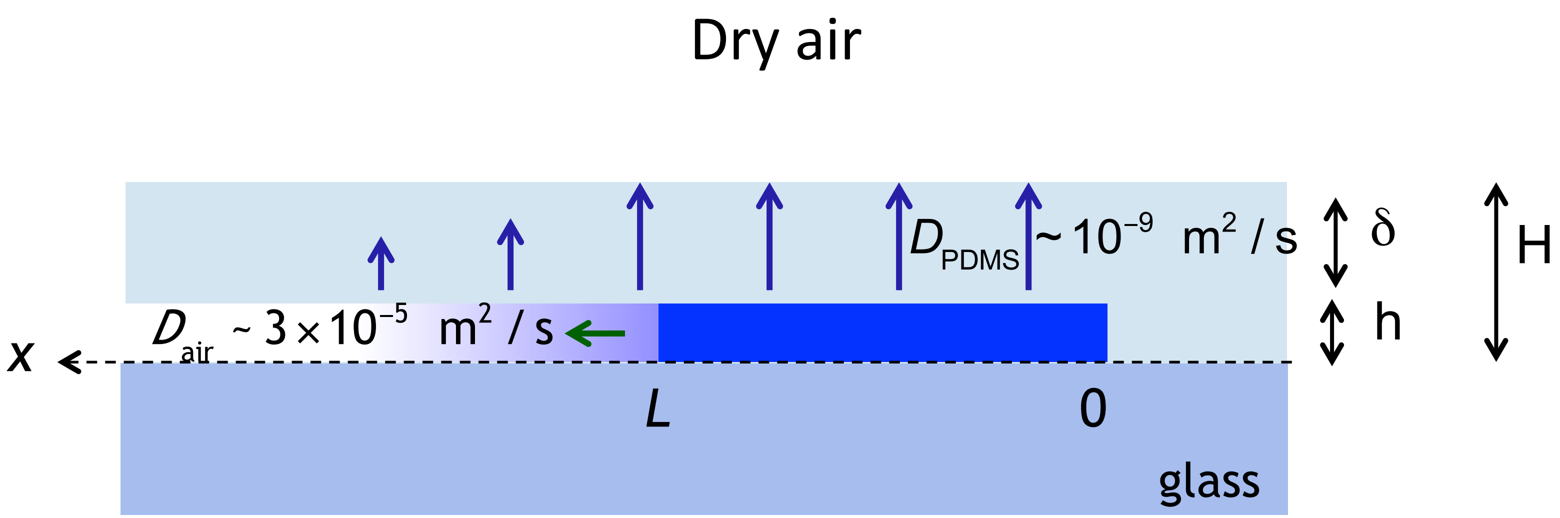
Top view





Length of remaining water

Side view: diffusion and evaporation of water

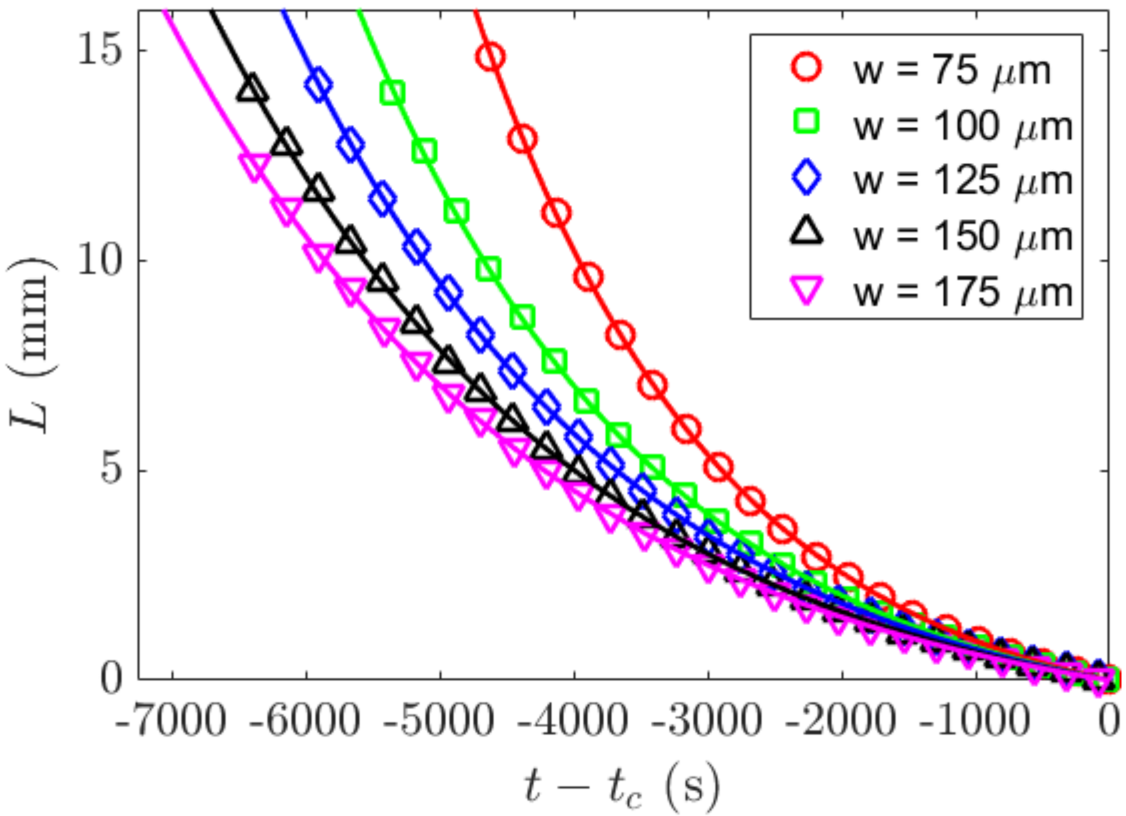


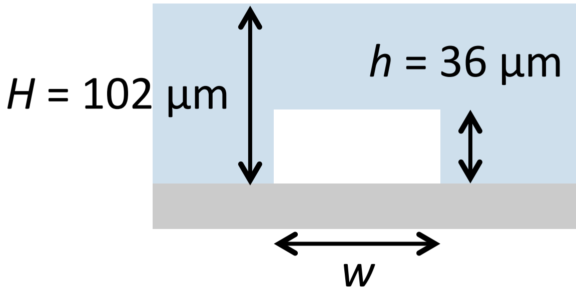
Model: $Q = Q_g + Q_l$

$$\dot{L} = -\frac{L + L_0}{\tau}$$

[Dollet et al., *J. R. Soc. Interface* (2019)]

Results





• solution of $\dot{L} = -\frac{L + L_0}{\tau}$:

$L(t) = -L_0 + L_1 e^{-t/\tau}$

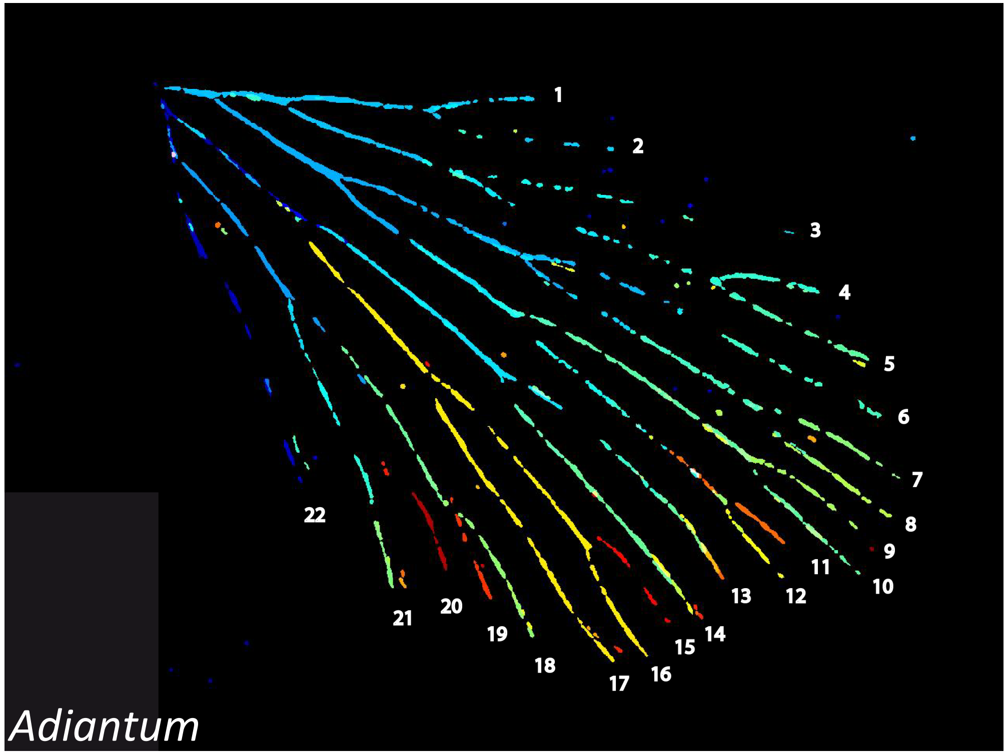
• excellent fit of the data

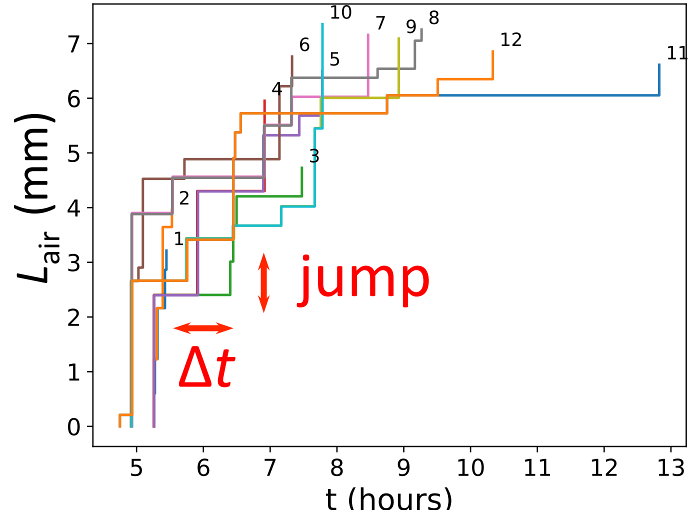
• prediction of the parameters τ and L_0 as function of the geometrical and physico-chemical parameters: done and validated

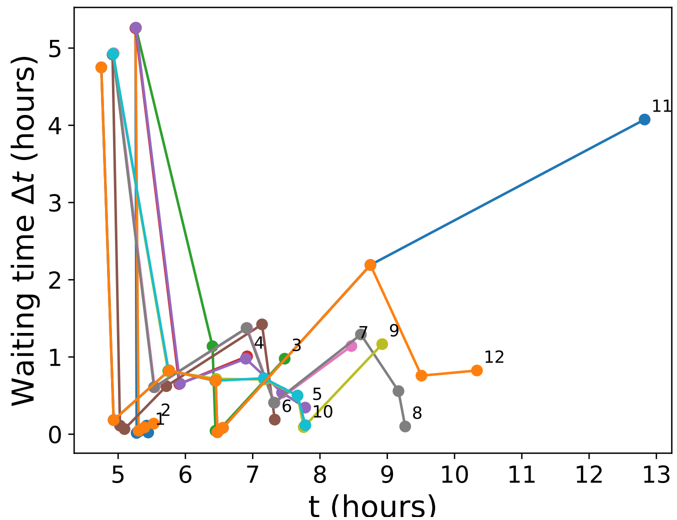
[Dollet et al., *J. R. Soc. Interface* (2019)]

Back to biology

- in real leaves, drying dynamics is more complex, showing stops and jumps!



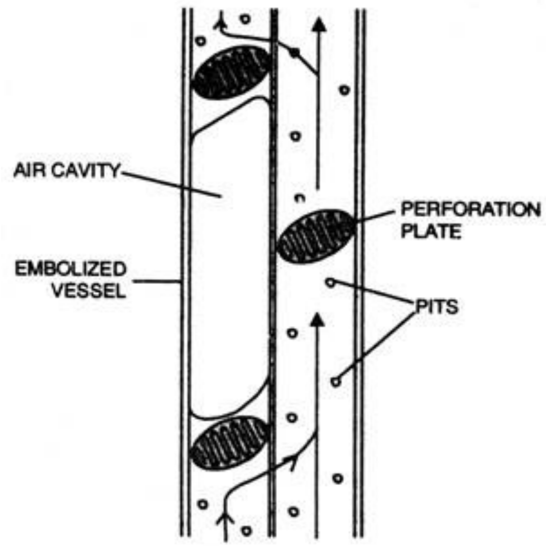


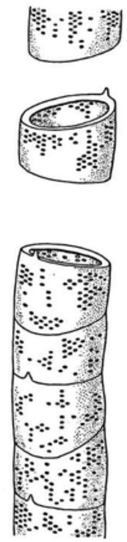


- we need to increase the complexity of our networks

Back to biology

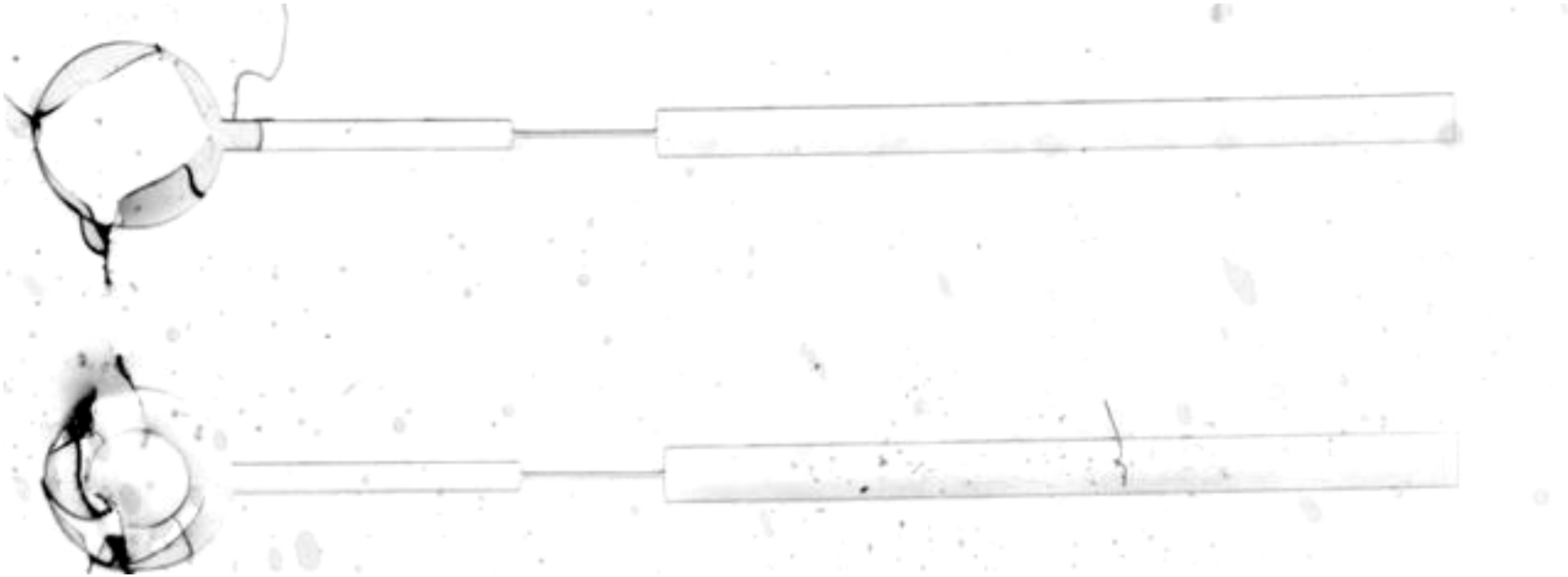
• hypothesis: intermittency linked to the presence of "nanopits", constrictions between sap-conducting cells in leaves and trees





• we test this hypothesis in a model geometry: constriction within channel

Step 2: Constrictions

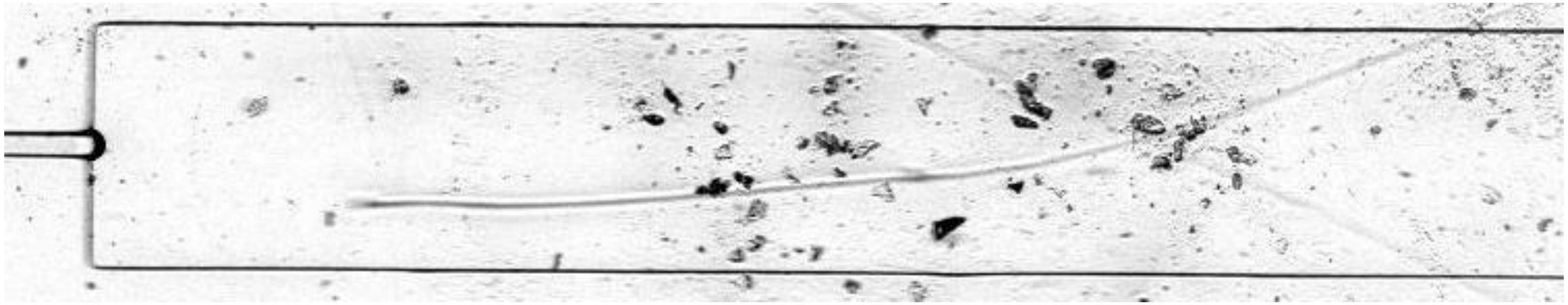


- jumps!

[Keiser, Marmottant & Dollet, *J. Fluid Mech.* (2022)]

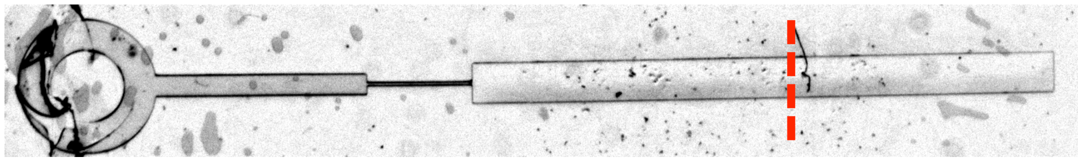
Constrictions

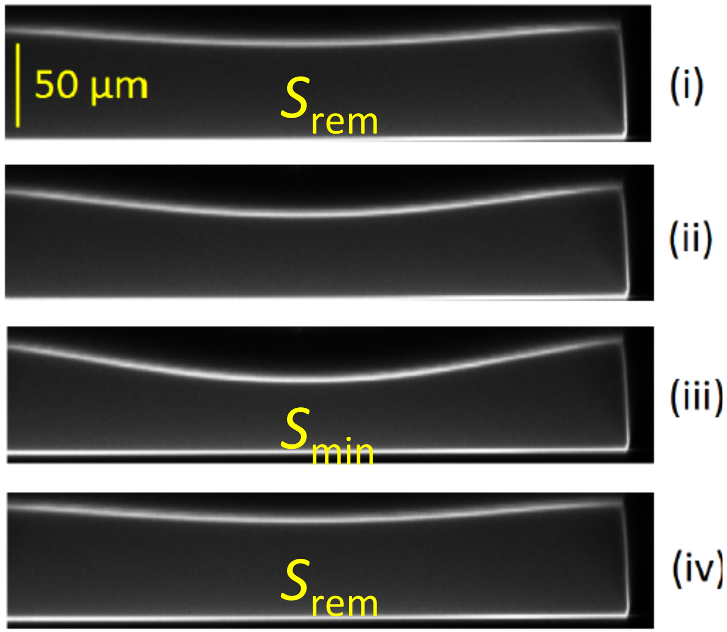
- origin of arrest and jump afterwards: meniscus gets pinned



- pinned meniscus bulges out → depressurisation of water ahead

- measurement of the downstream cross-section by confocal microscopy

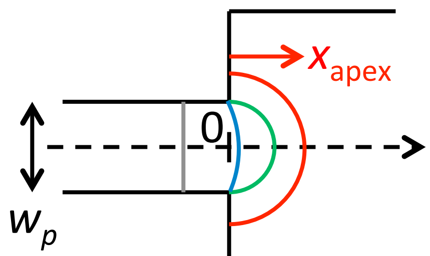




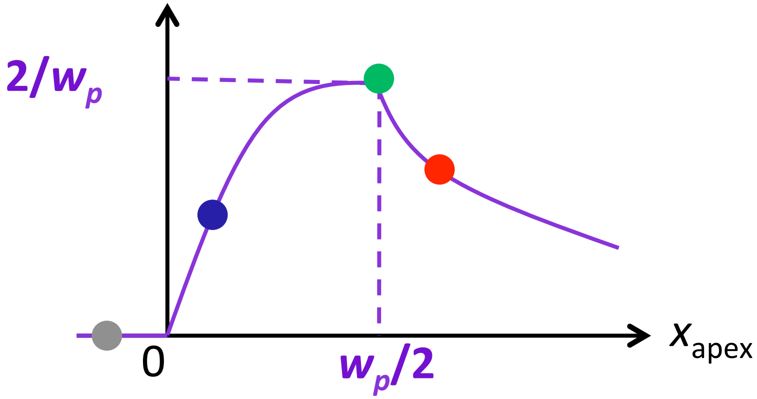
Constrictions

• capillary threshold: maximal curvature allowed by constriction geometry

• illustration with an ideal 2D case: sharp corners, 90° contact angle

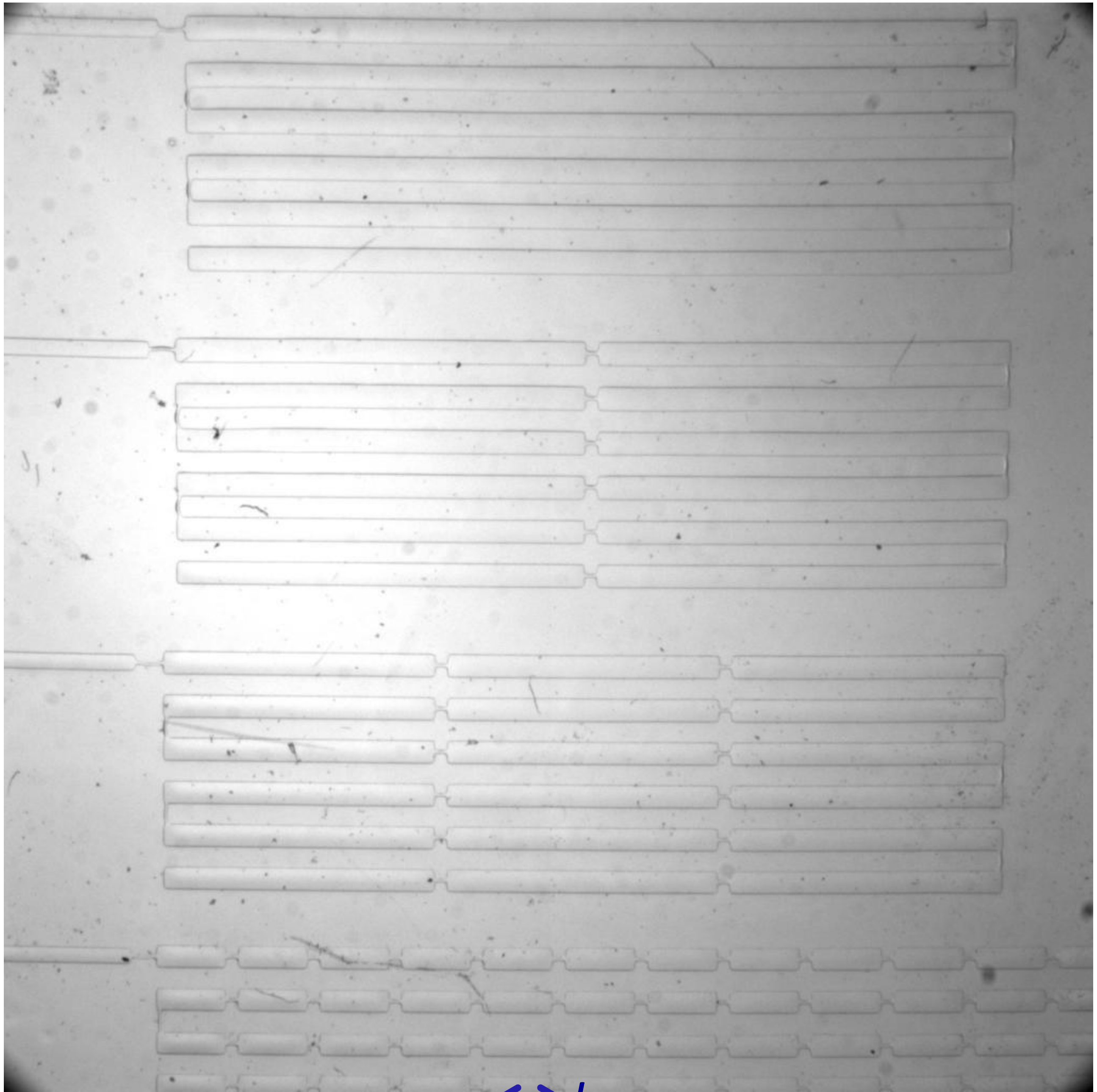


meniscus curvature ∝ Laplace pressure, $\Delta p_c = 2\sigma / w_p$



• intermittency results from channel compliance and meniscus pinning (role of nanopits in plants)

Step 3: Series of N_p contrictions



N_p=6

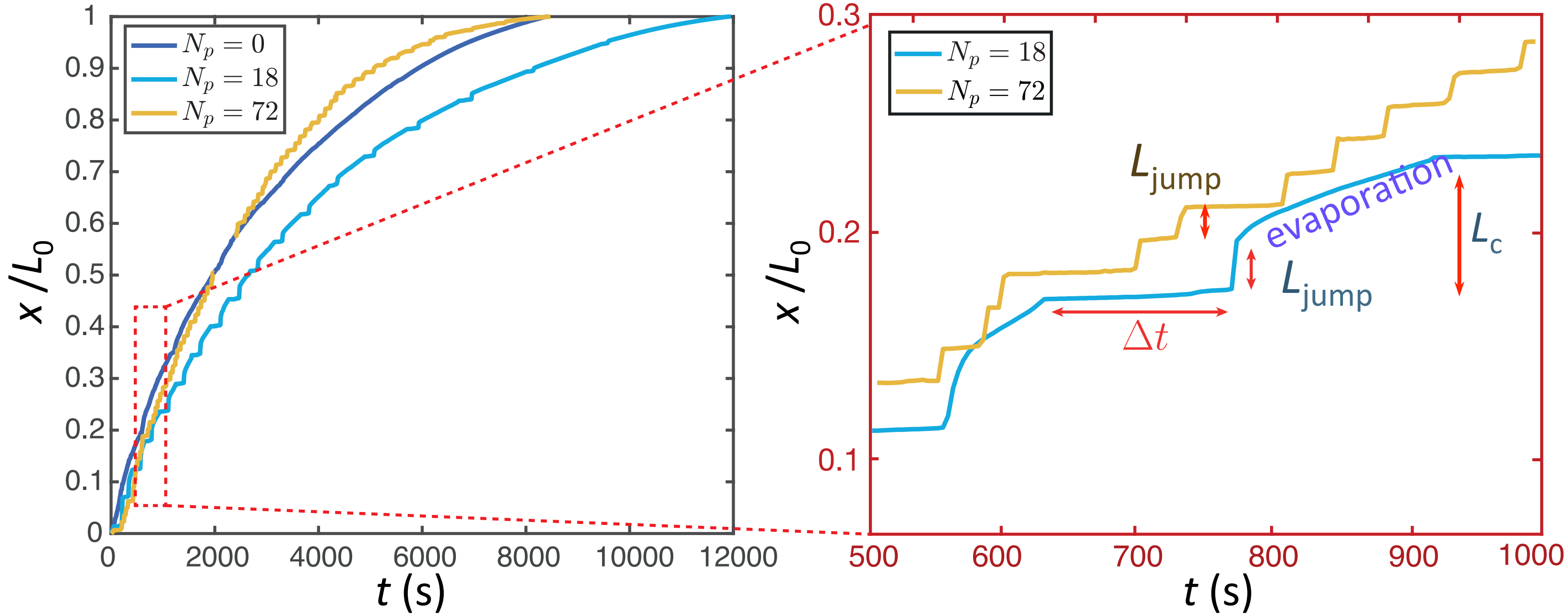
N_p=12

N_p=18

N_p=72

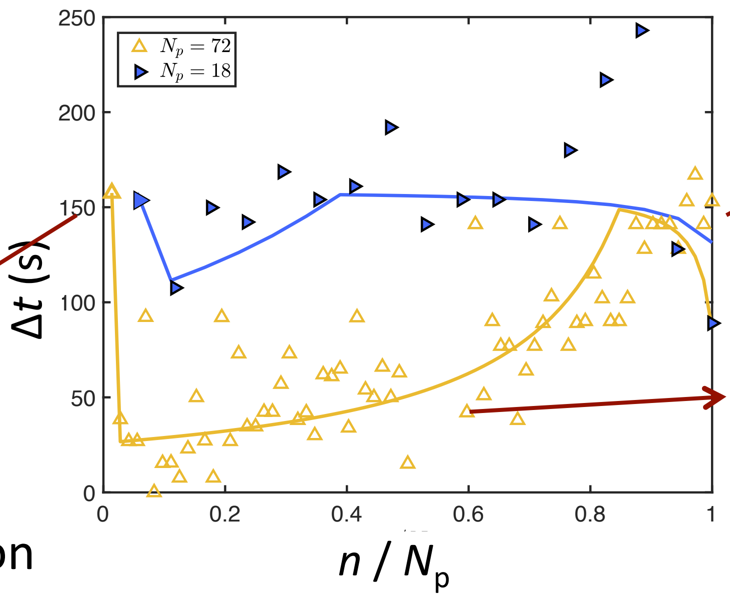
L_c

- Meniscus position along the total path L_0



- Waiting time Δt

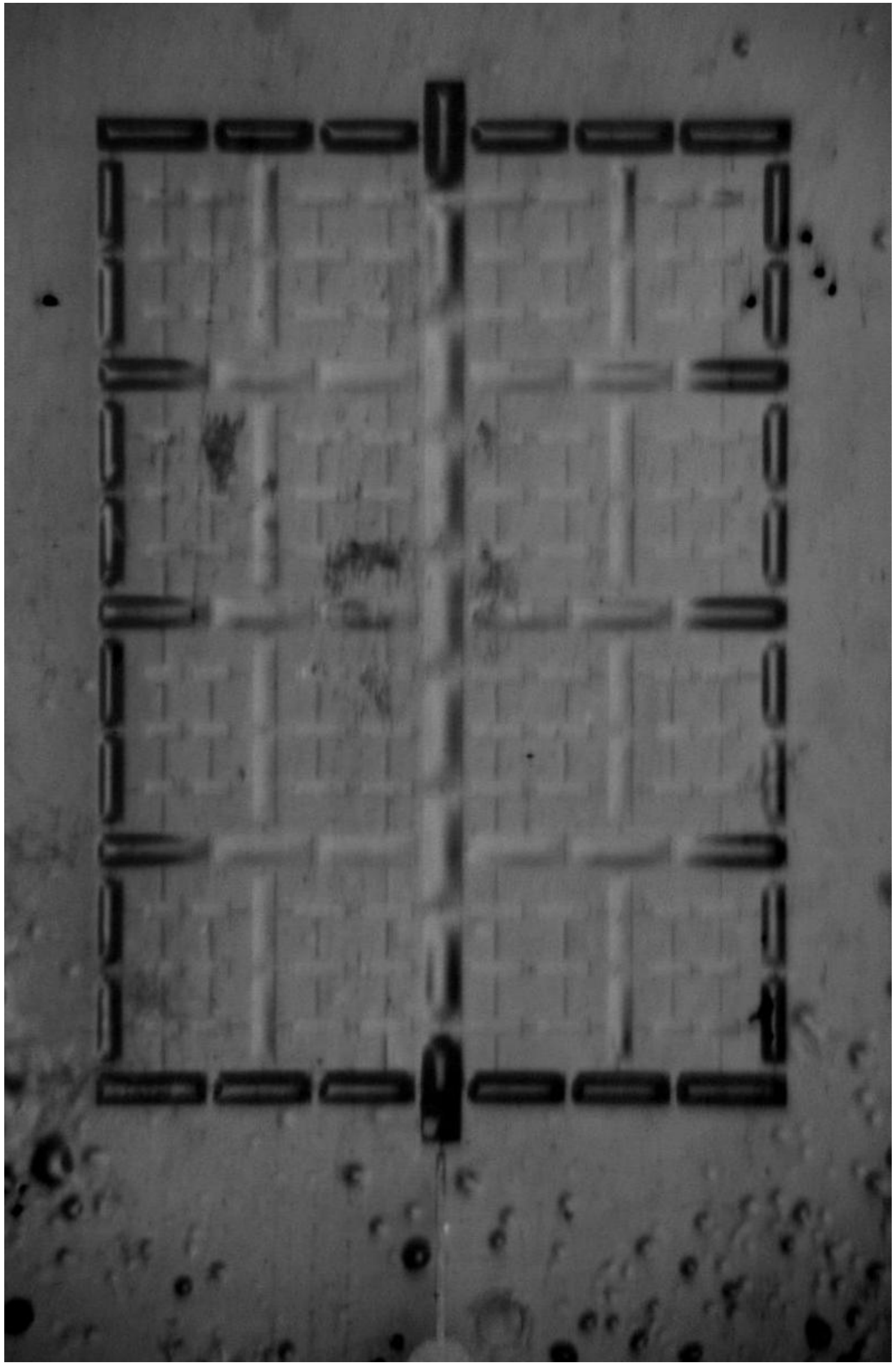
Model: steady evaporation, jump when elastic deformation overcomes critical value



$L_{jump} < L_c$

$L_{jump} = L_c$
incomplete relaxation,
depressurisation
remains,
next jumps is closer

First jump,
time to build depressurisation



Step 4: 2D networks

- Sharp front, non diffusive
- no hierachy of channels sizes

Conclusions

- Constrictions delay embolism invasion
- Jumps: caused by the flexibility of downstream channels

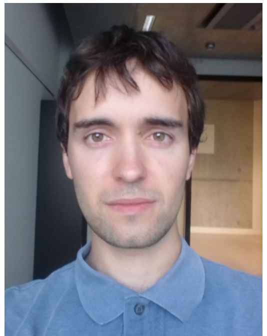
Perspectives

- Understand the hierachy of embolism
- Studying the reverse process: refilling of embolised channels

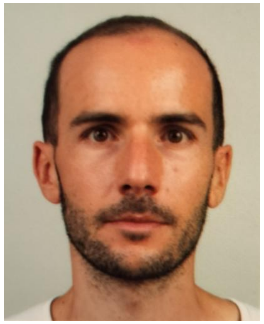
Acknowledgments

Grenoble

B. Dollet



Ludovic Keiser
(LIPhy-> INPHYNI)



F.-X. Gauci

X. Noblin

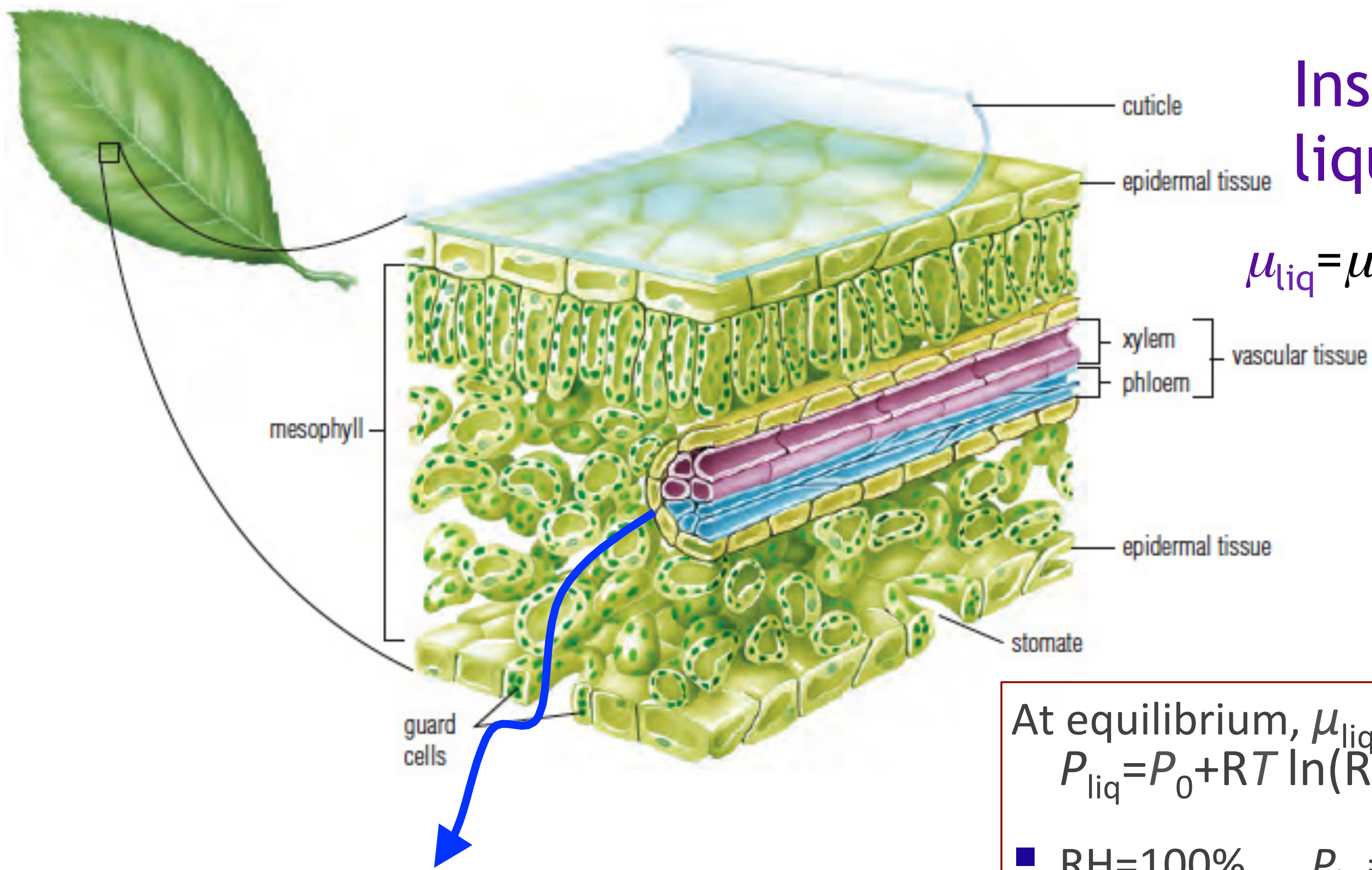
C. Cohen

Nice

Clermont
-Ferrand

ANR PHYSAP
(Physics of Sap)

Origin of negative pressure of water in leaves: evaporation



Inside:
liquid water

$\mu_{liq}=\mu_0+(P_{liq}-P_0)V_{mol}$

Air: water vapour

$\mu_{vap}=\mu_0+RT\ln(\underbrace{p_{vap}/p_{vap}^{sat}}_{RH})$

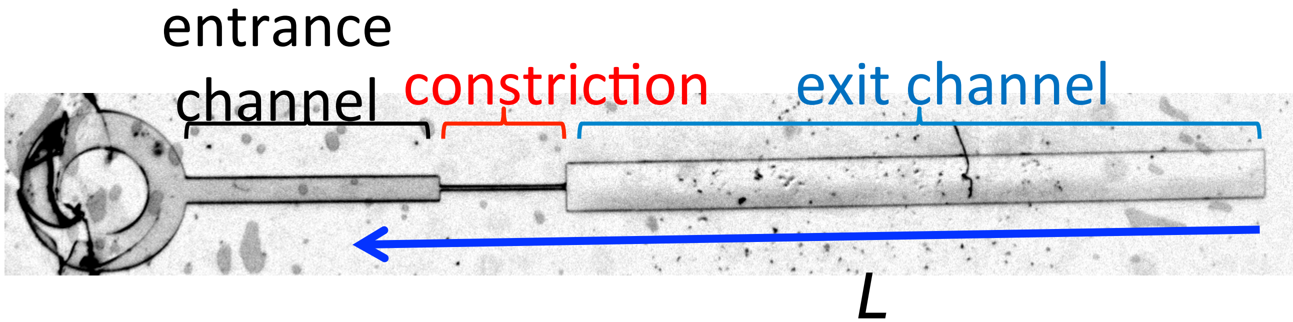
At equilibrium, $\mu_{liq}=\mu_{vap}$,
$P_{liq}=P_0+RT\ln(RH)/V_{mol}$

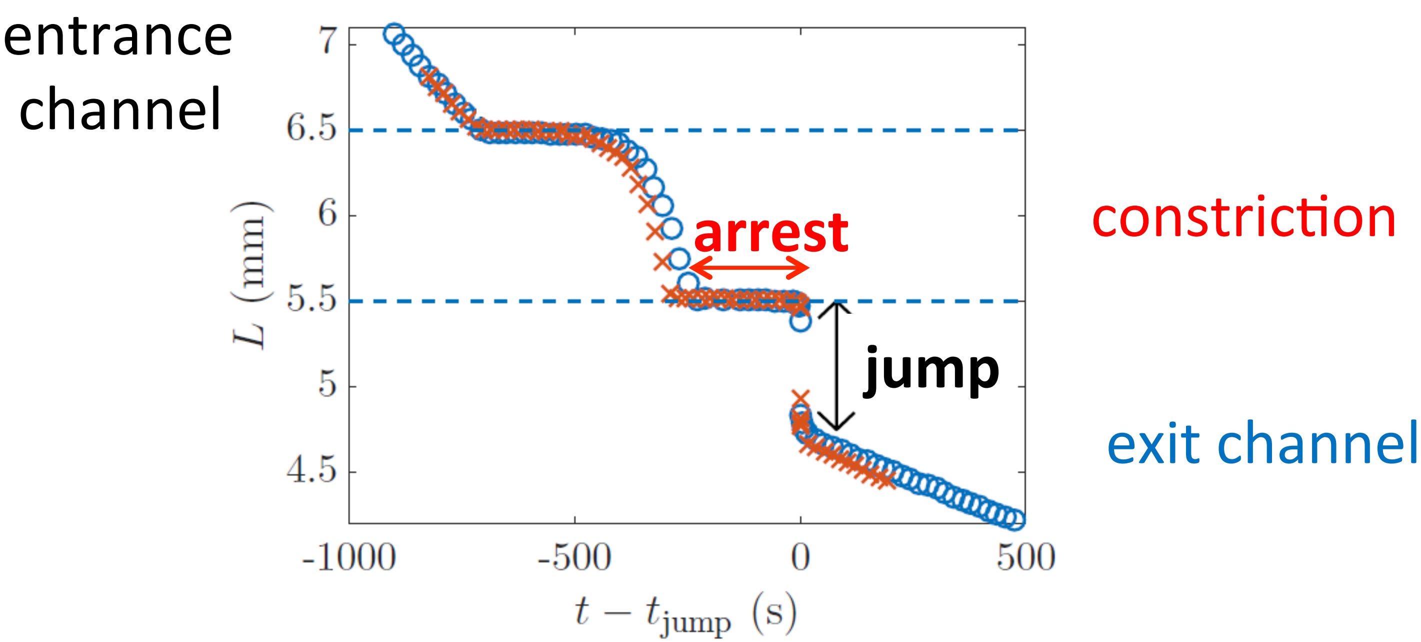
- RH=100% $P_{liq}=$ 1 bar
- RH=99.93% $P_{liq}=$ 0 bar
- RH=95% $P_{liq}=$-70 bar!

Risk of cavitation: entry of air embolism in the network

Constrictions

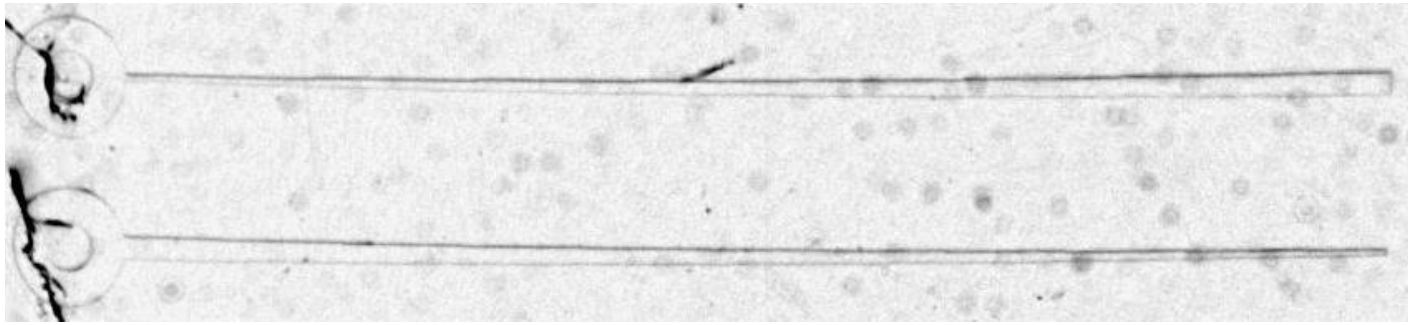
- arrest in the constriction, jump at the constriction exit:



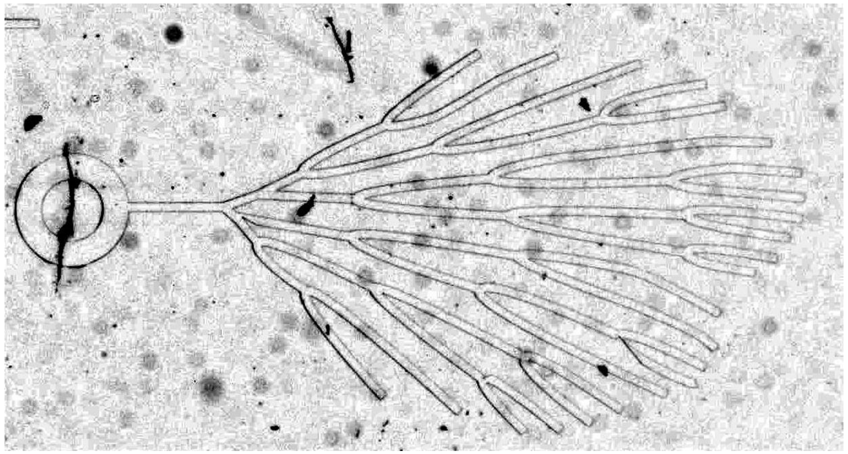


More steps to complexity

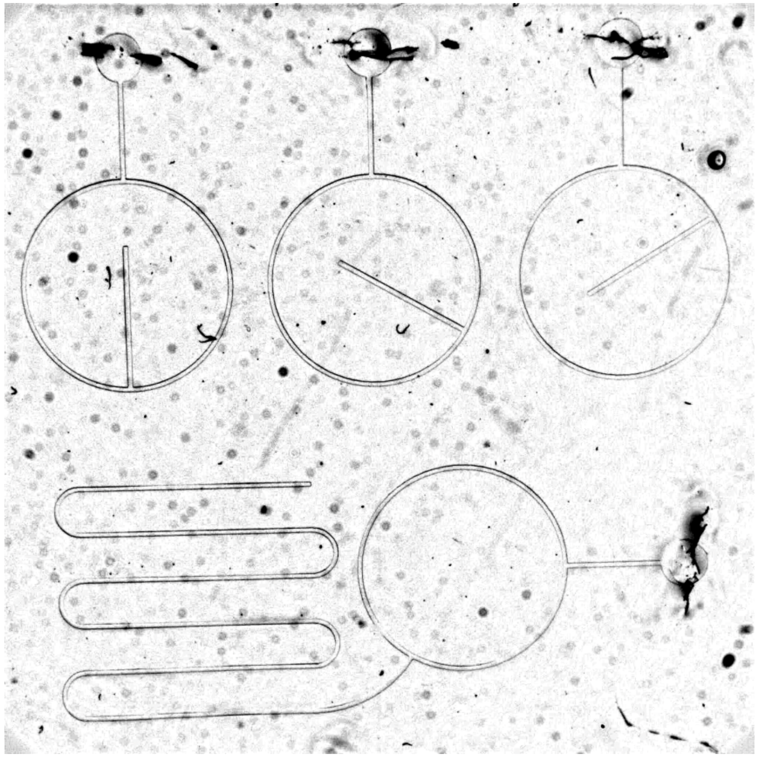
- **Step 2**: single channels of variable width
  [Chagua Encarnación, Dollet & Marmottant, *Microfluid. Nanofluid.* (2021)]



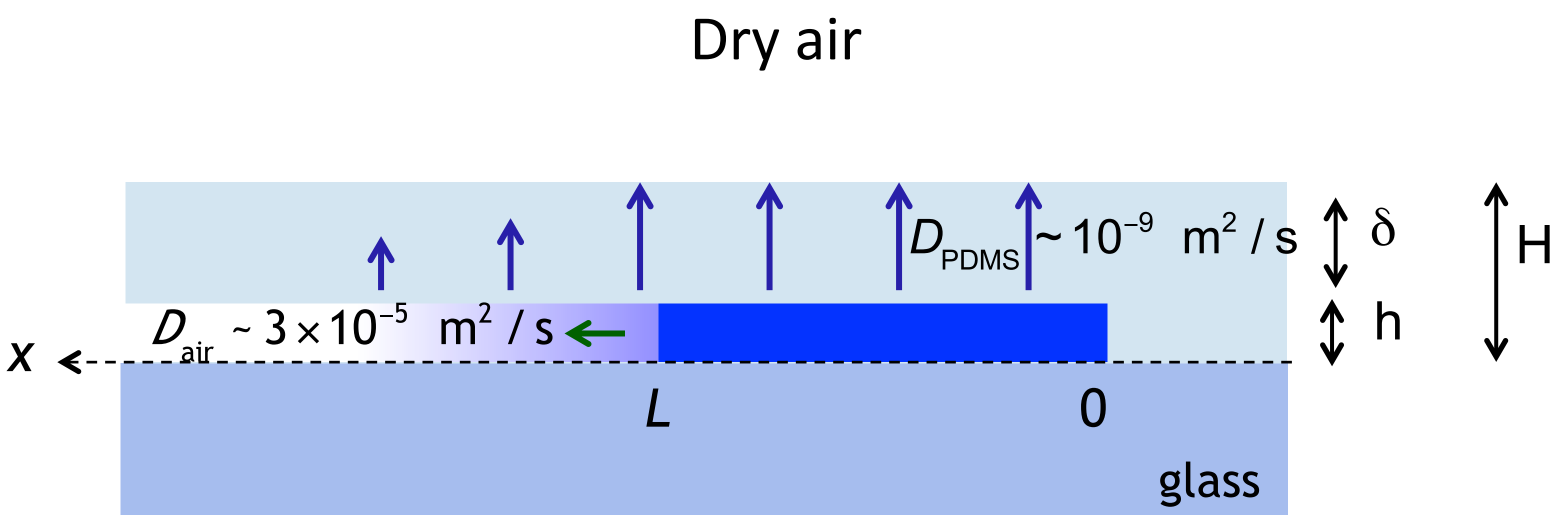
- **Step 3**: branches and loops
  [Dollet et al., *J. Fluid Mech.* (2021)]



Adiantum fern network



Side view: diffusion and evaporation of water



Model: $Q = Q_g + Q_l$

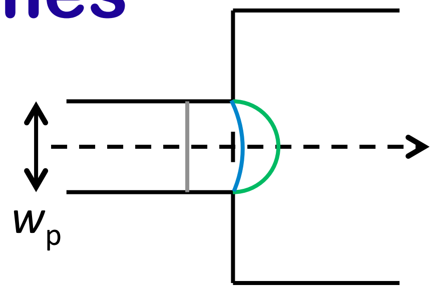
$$\dot{L} = -\frac{L + L_0}{\tau}$$

$$L_0 = \sqrt{\frac{h \delta D_{air}}{D_{PDMS}}}$$

$$\tau \sim \frac{h \delta \rho_{water}}{D_{PDMS}\left(\rho_{sat} - \rho_{dry}\right)}$$

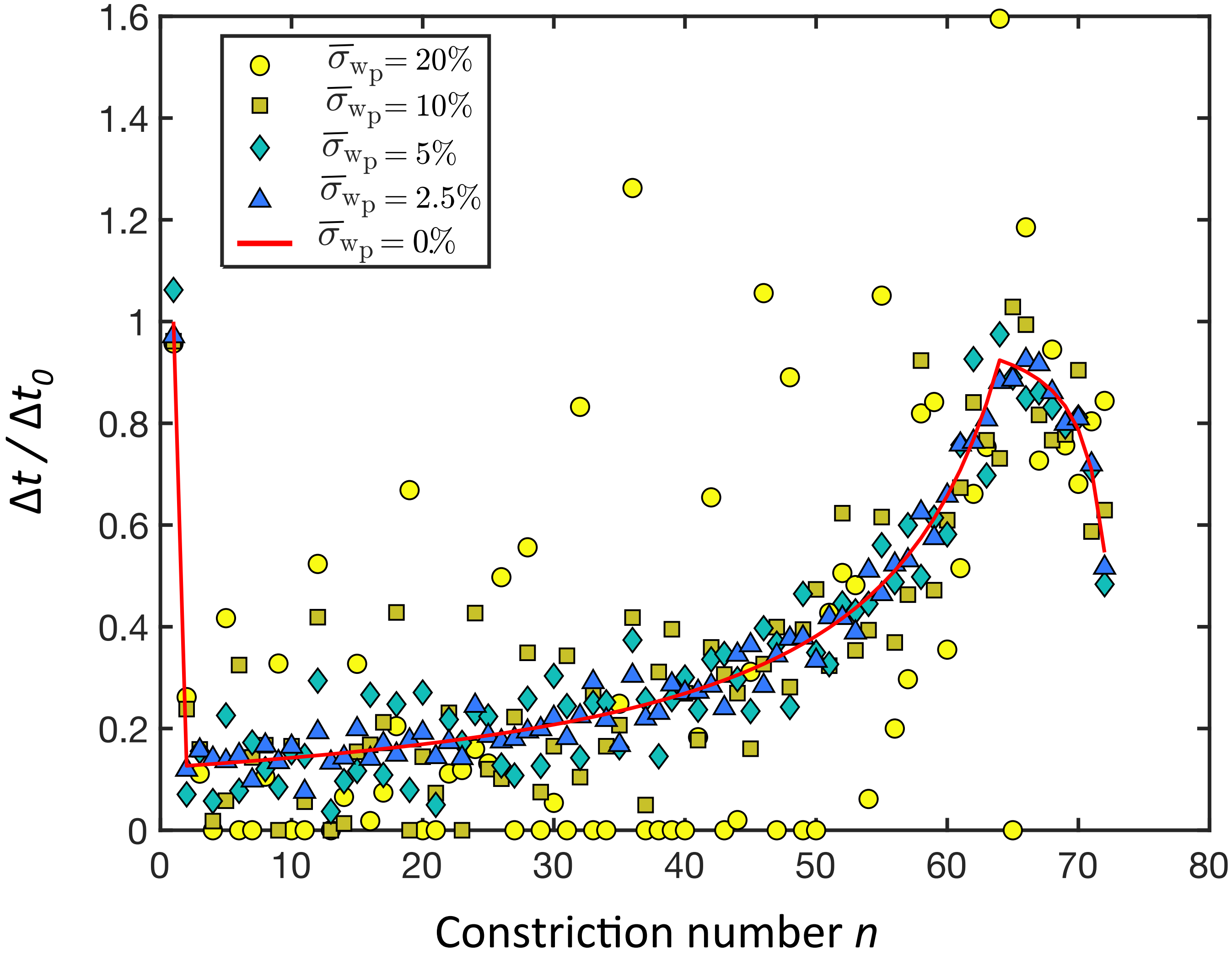
[Dollet et al., *J. R. Soc. Interface* (2019)]

Model for the variability the waiting times



Normal distribution of the constriction width w_p

-> variability of critical capillary pressure $\Delta p_c = 2\sigma / w_p$ and critical elastic deformation for a jump



[Brodribb, Bienaimé, Marmottant PNAS 2016]