Reticulated pattern formation during folding instabilities in thin films: what does it teach us about venation?

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PRINCETON UNIVERSITY

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Howard A. Stone

Instabilities in compression

Instabilities limit loading of layered materials: delamination

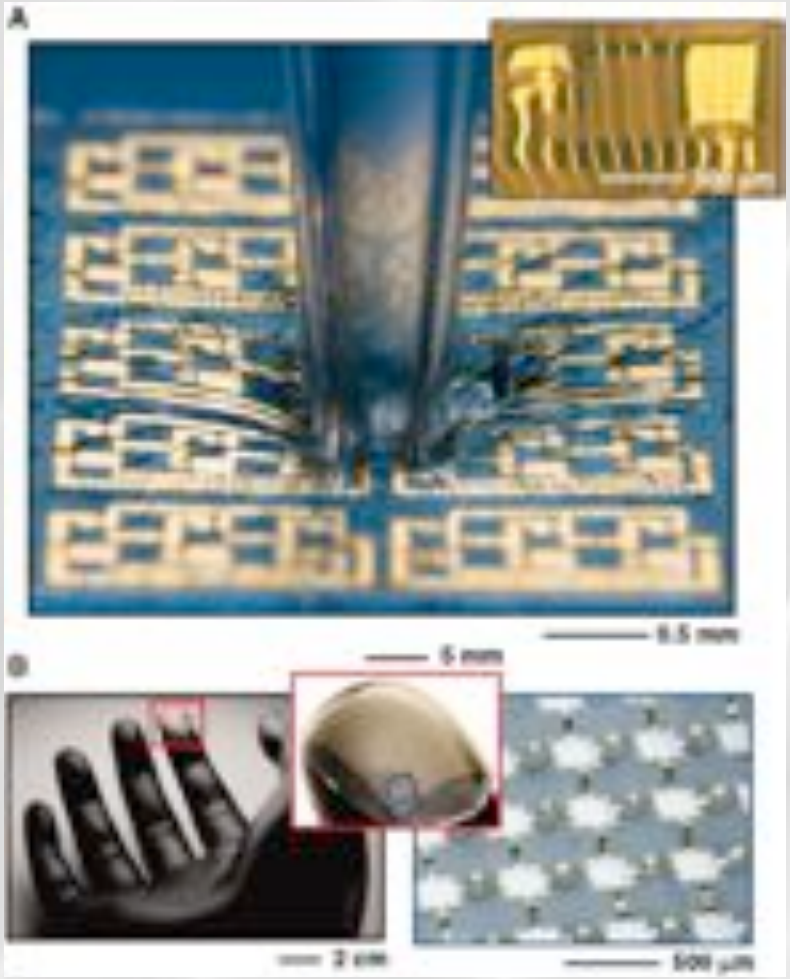
Wear resistant coating

Optical coating

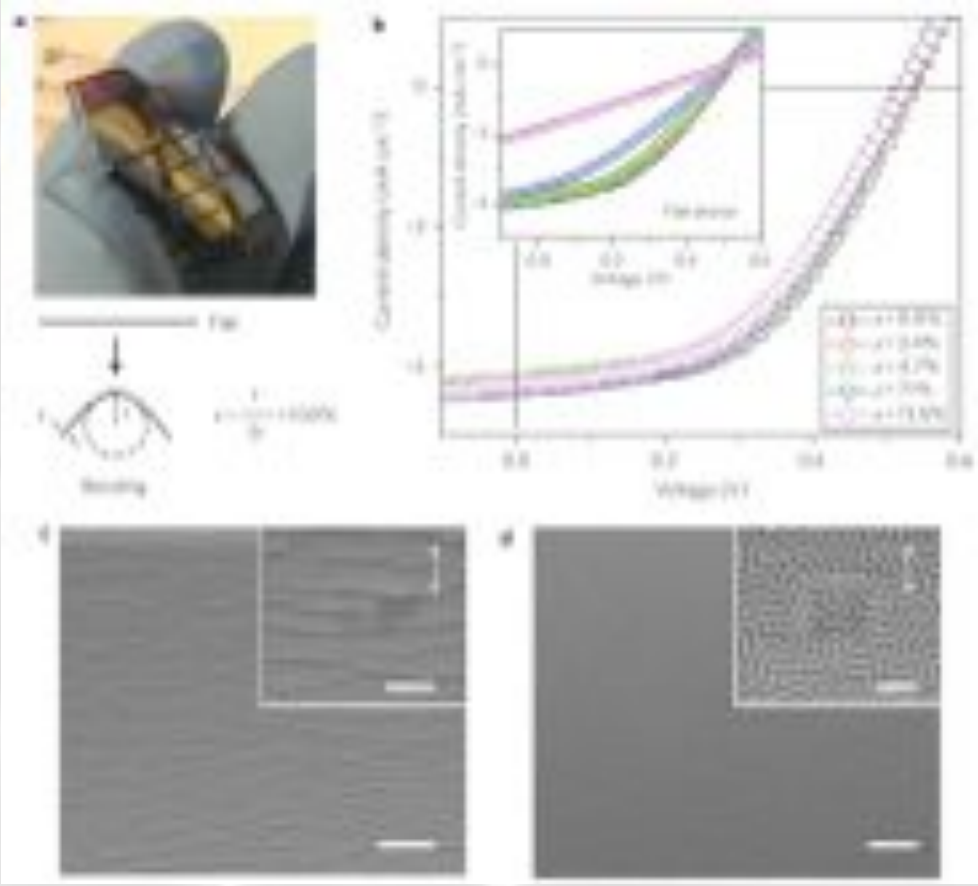
Instabilities in compression

Whose understanding and control finds original applications :

Flexible electronic devices



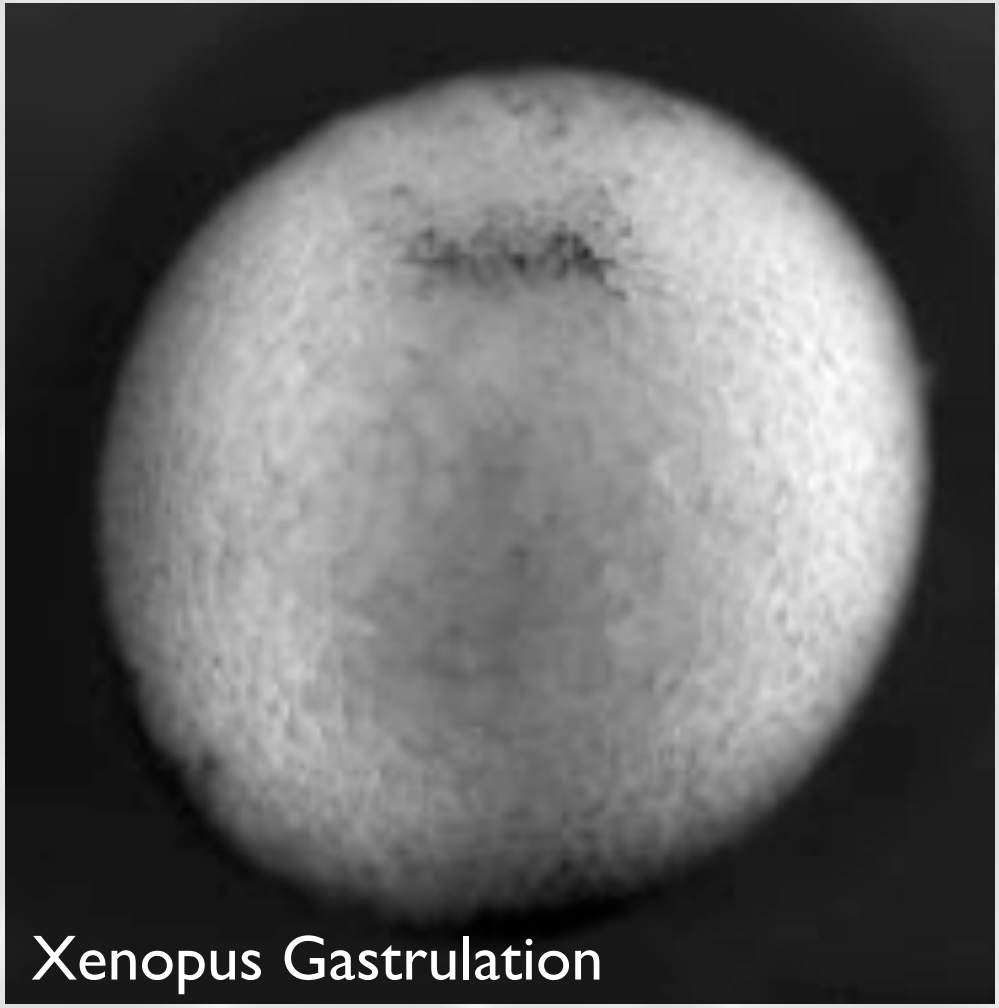
Resilient Light harvesting films



Kim et al. Nature Photonics,

Instabilities in compression

And may be understand some aspects of morphogenesis ?



Folding ?

Creasing ?

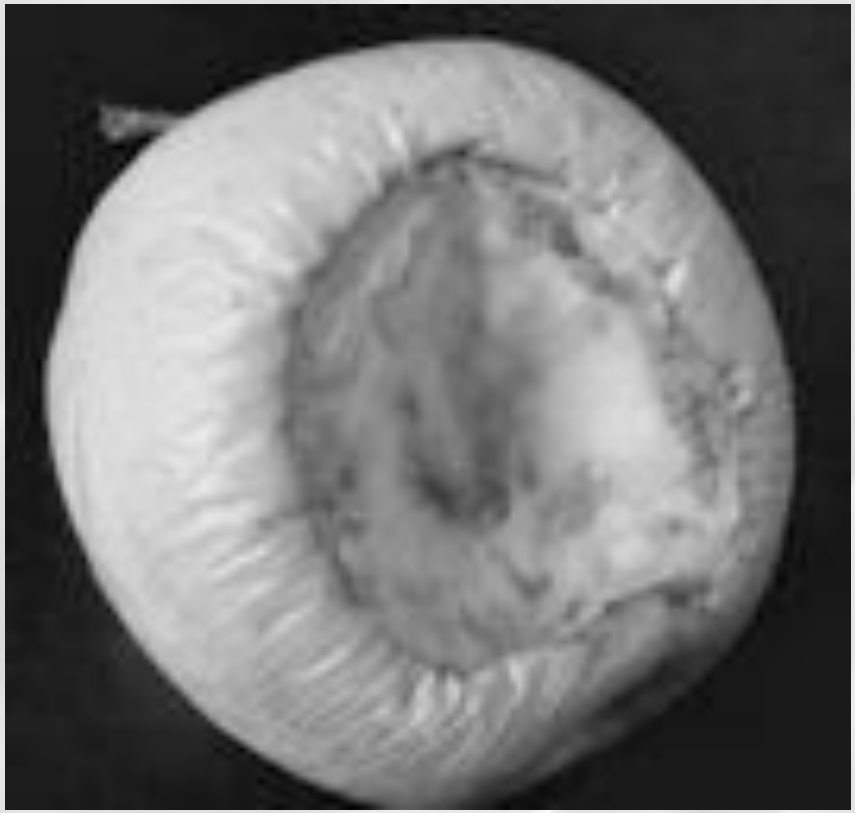
Crumpling ?

... ????

http//www.gastrulation.org

Instabilities in compression

Drying fruits ?



Aging Skin ?

Euler Buckling of a free-standing film

$$E = h^3 \times (\text{bending}) + h \times (\text{stretching})$$

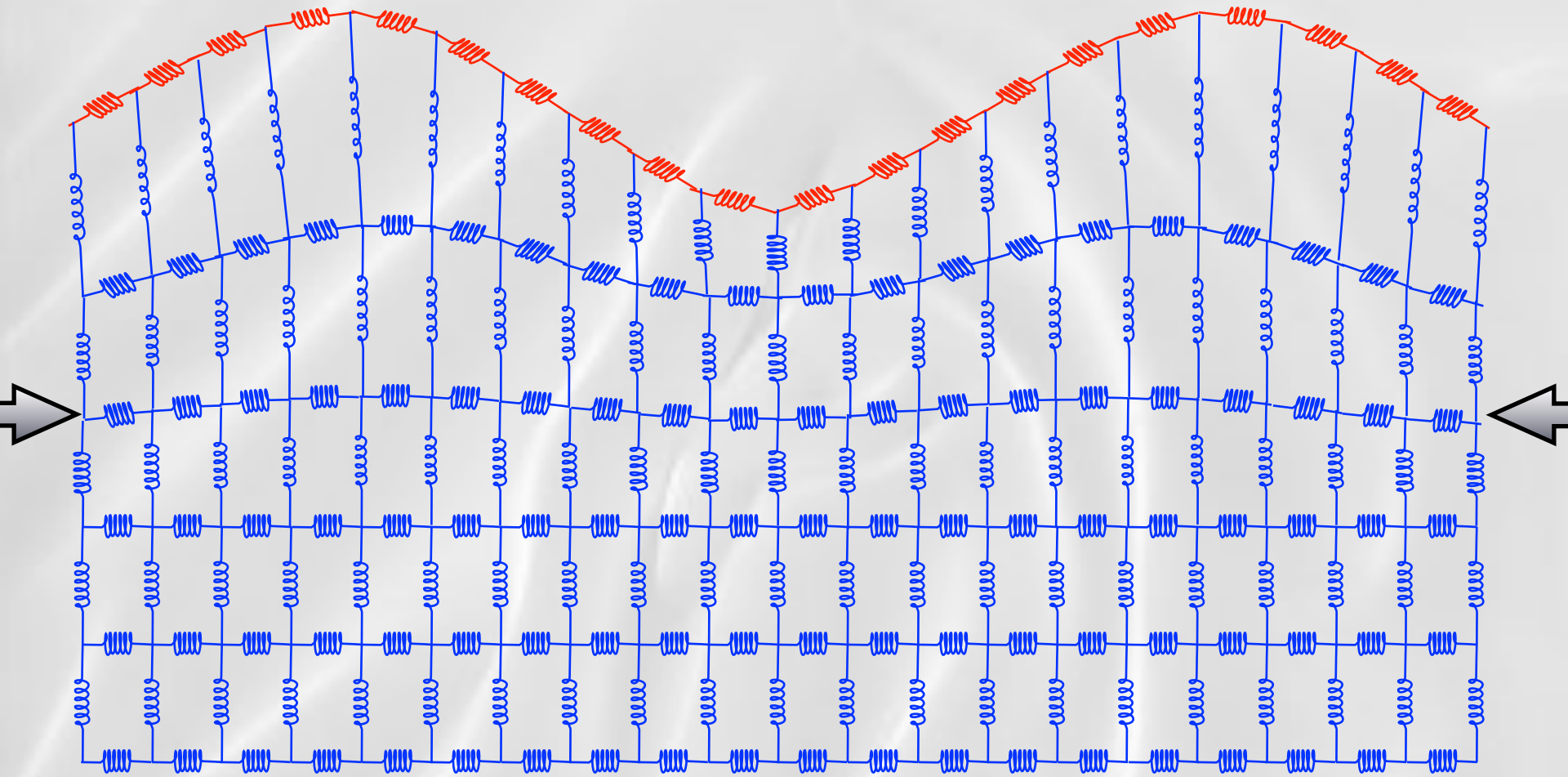
h => 0 , bending is preferred by the stripe

Presence of a foundation

$$E = B \times (\text{film bending}) + K \times (\text{substrate stretching})$$

B: bending stiffness

K: 'effective' stiffness



Presence of a foundation

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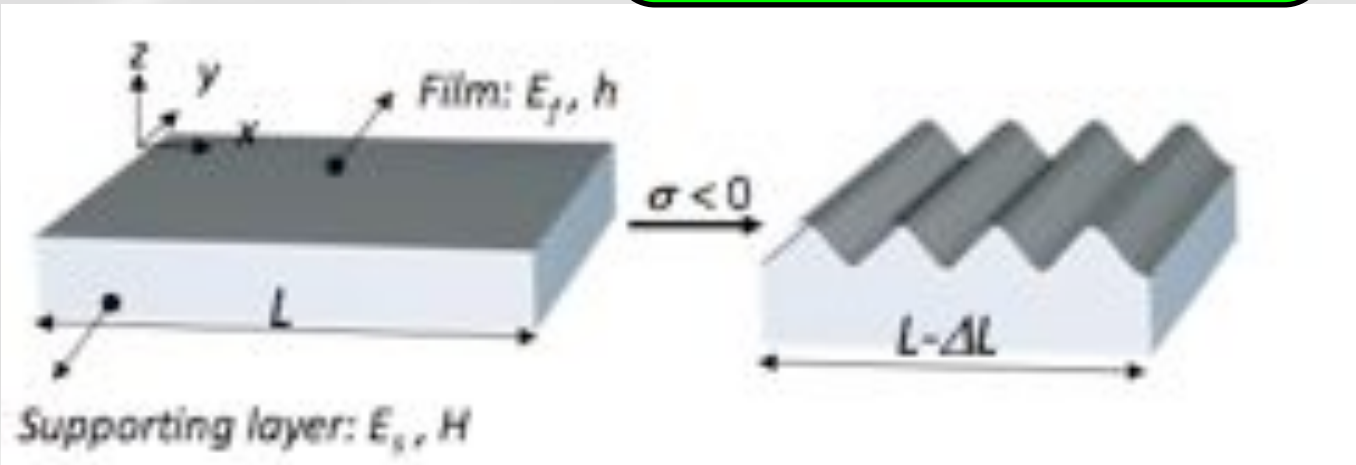


$h \ll H$ Elastic foundation $K = K(E_s, \sigma) \approx E_s/\lambda$

$B \sim E_f \times h^3$ Liquid foundation $K \approx \rho g$

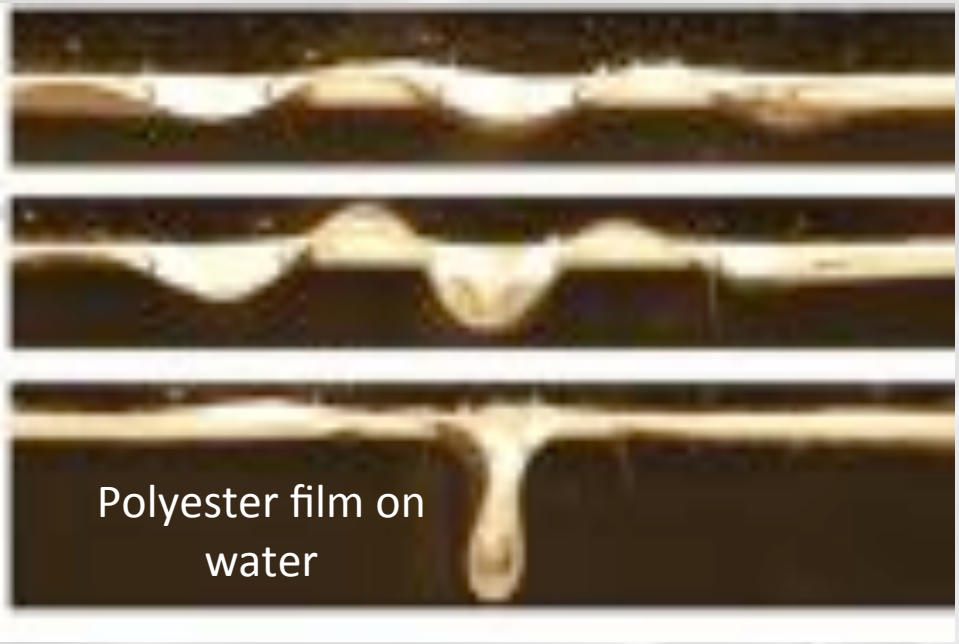
Evans et al, *Nature* 1998
Cerda et al, *PRL* 2003

$$\varepsilon_{c,w} \sim \left(\frac{E_s}{E_f}\right)^{2/3}, \quad \lambda \sim \left(\frac{B}{K}\right)^{1/4}, \quad A \sim \varepsilon^{1/2}\lambda$$

Wrinkles are unstable

Uniaxial stress: on Liquid foundation

Pocivavsek *et al*, *Science* (2008)



Leahy *et al*, *PRL* (2010)

Gold nanoparticles film

Wrinkles are unstable

Uniaxial stress: On elastic substrate

Brau et al. Nature Physics, 2010

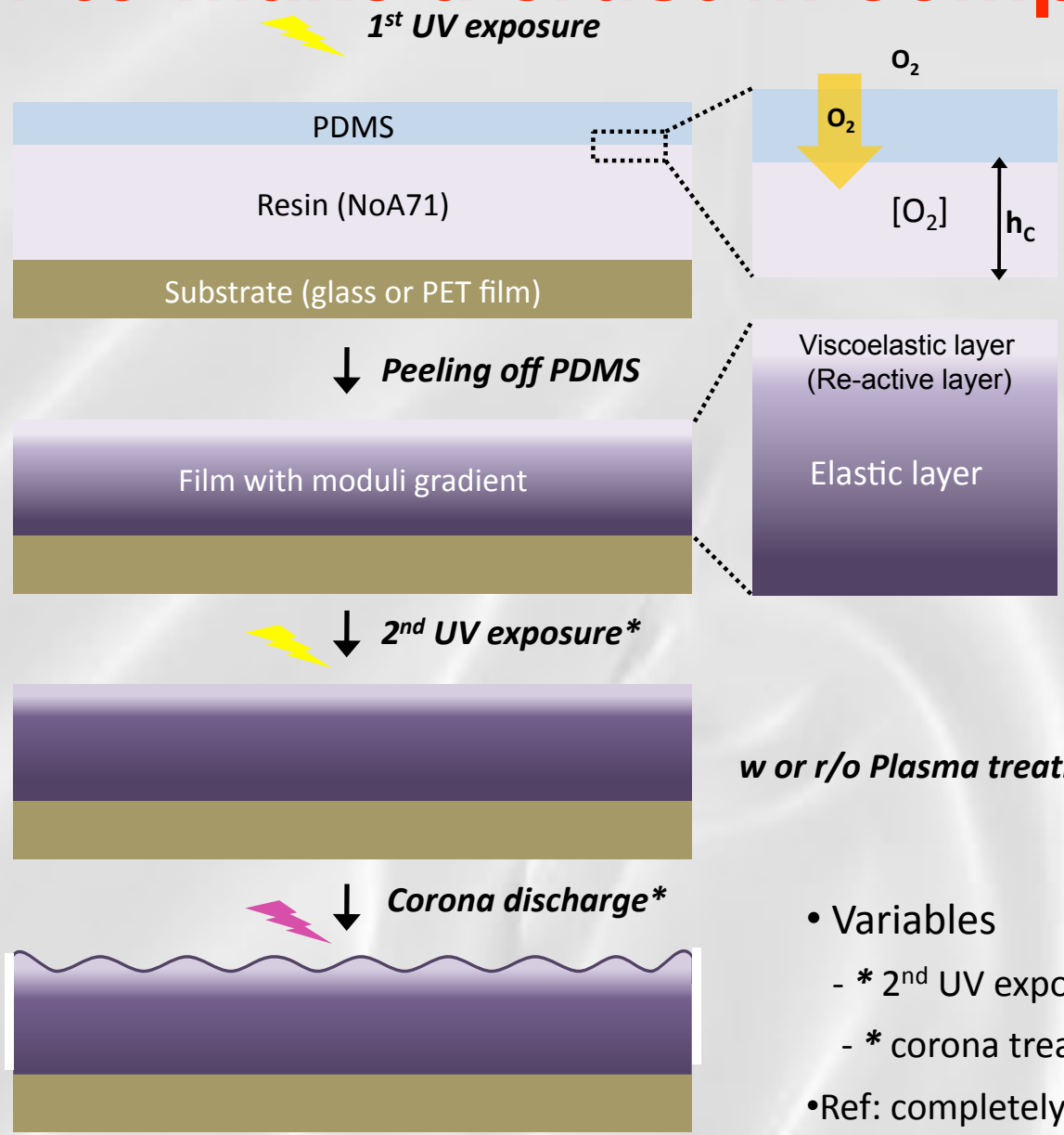
Biaxial case: our questions

What happens in the more general biaxial case ?

Canonical example of the paper ball

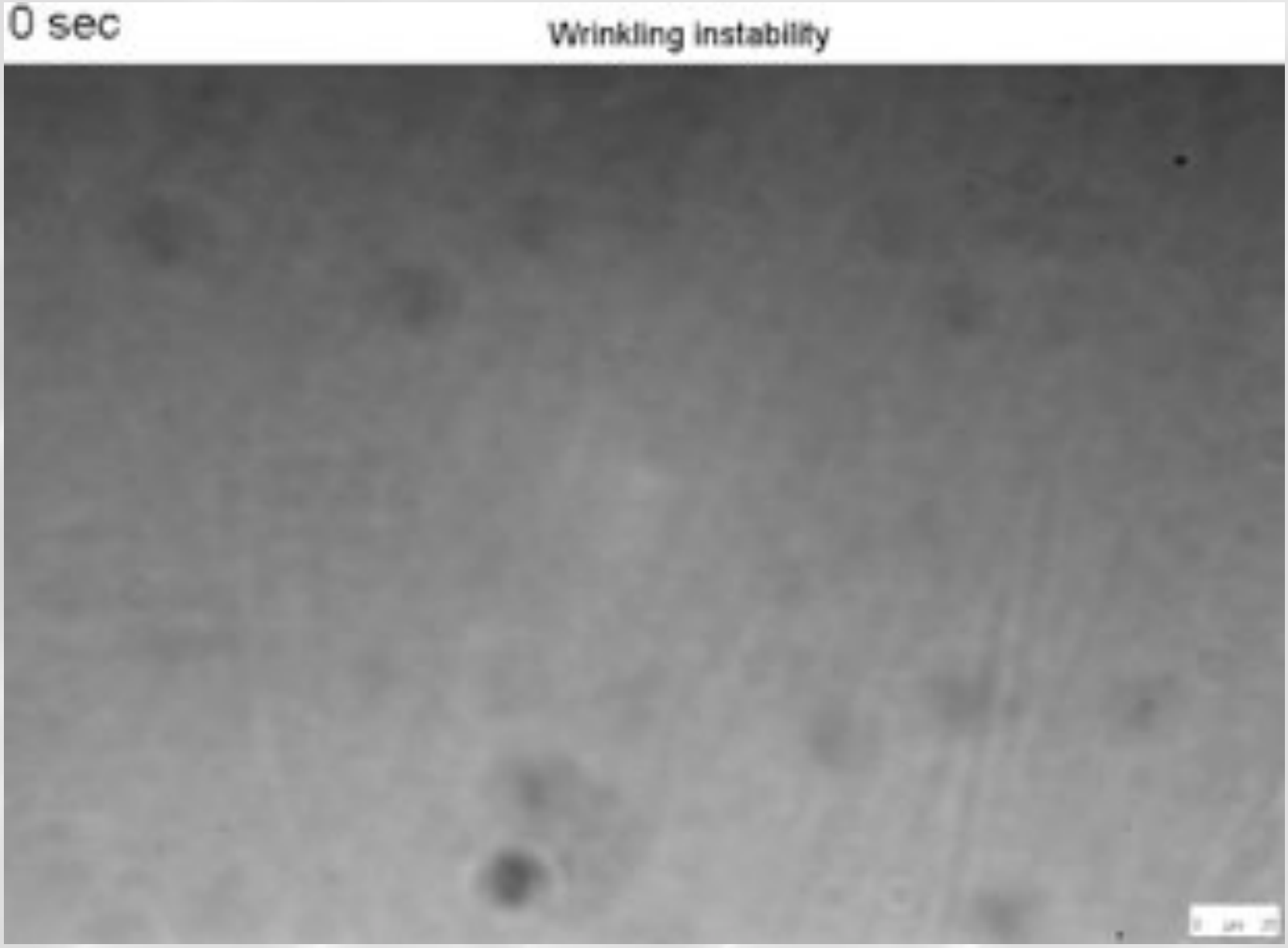
What is the dynamics of proliferation of these localizations ?

How to make a crust in compression ?



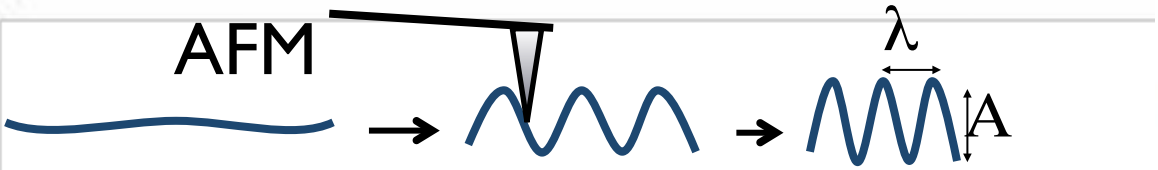
- Variables
  - * 2nd UV exposure : control of E_s/E_f
  - * corona treatment: increasing strain
- Ref: completely cured NoA ~ 400 MPa

Wrinkling instability

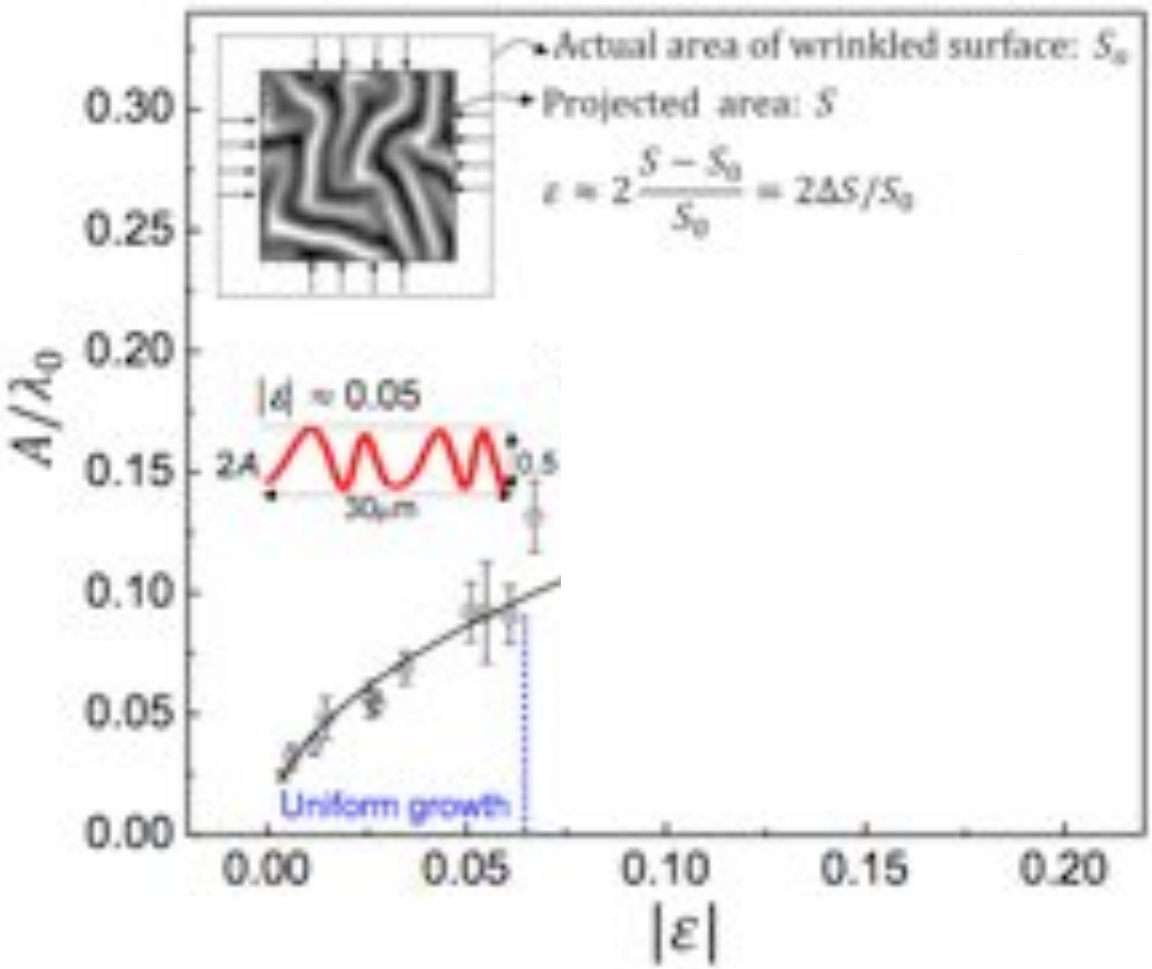


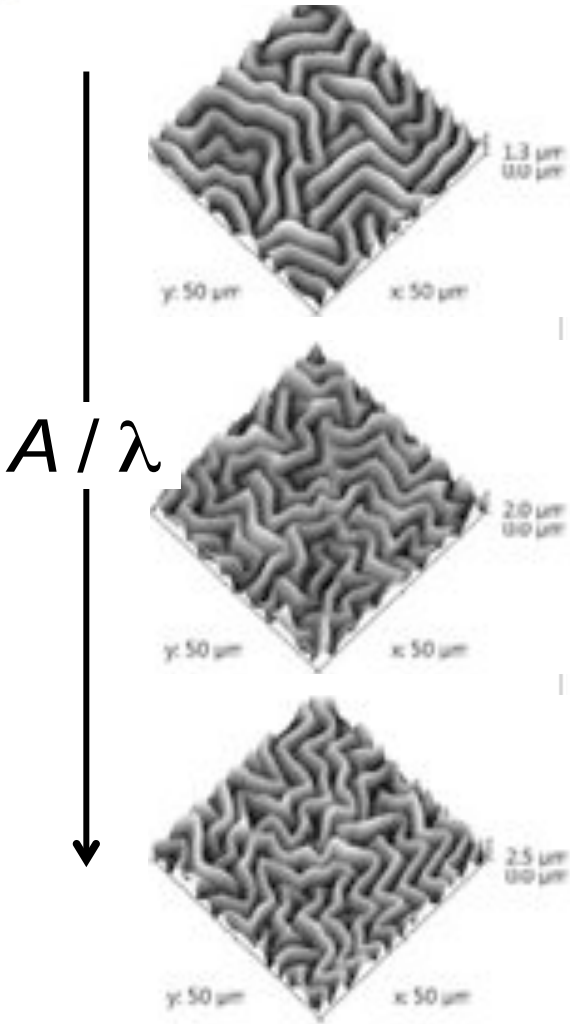
Wrinkling instability

Chen, X. and J. Hutchinson, J. Appl. Mech.-T Asme, 2004

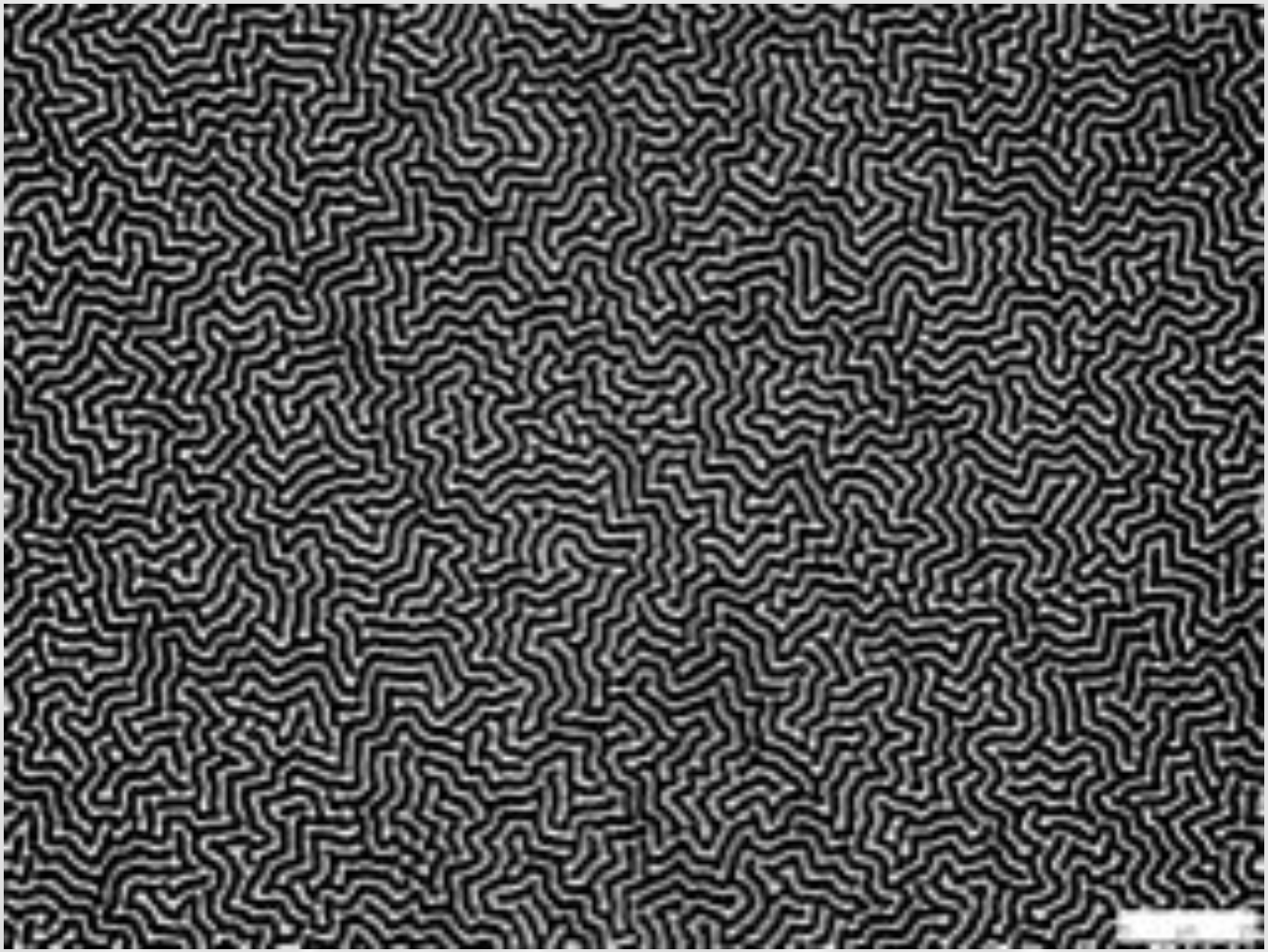


$$\frac{A}{\lambda_o} \approx \frac{\sqrt{1+\nu}}{\pi}\sqrt{|\varepsilon| - \varepsilon_c}$$

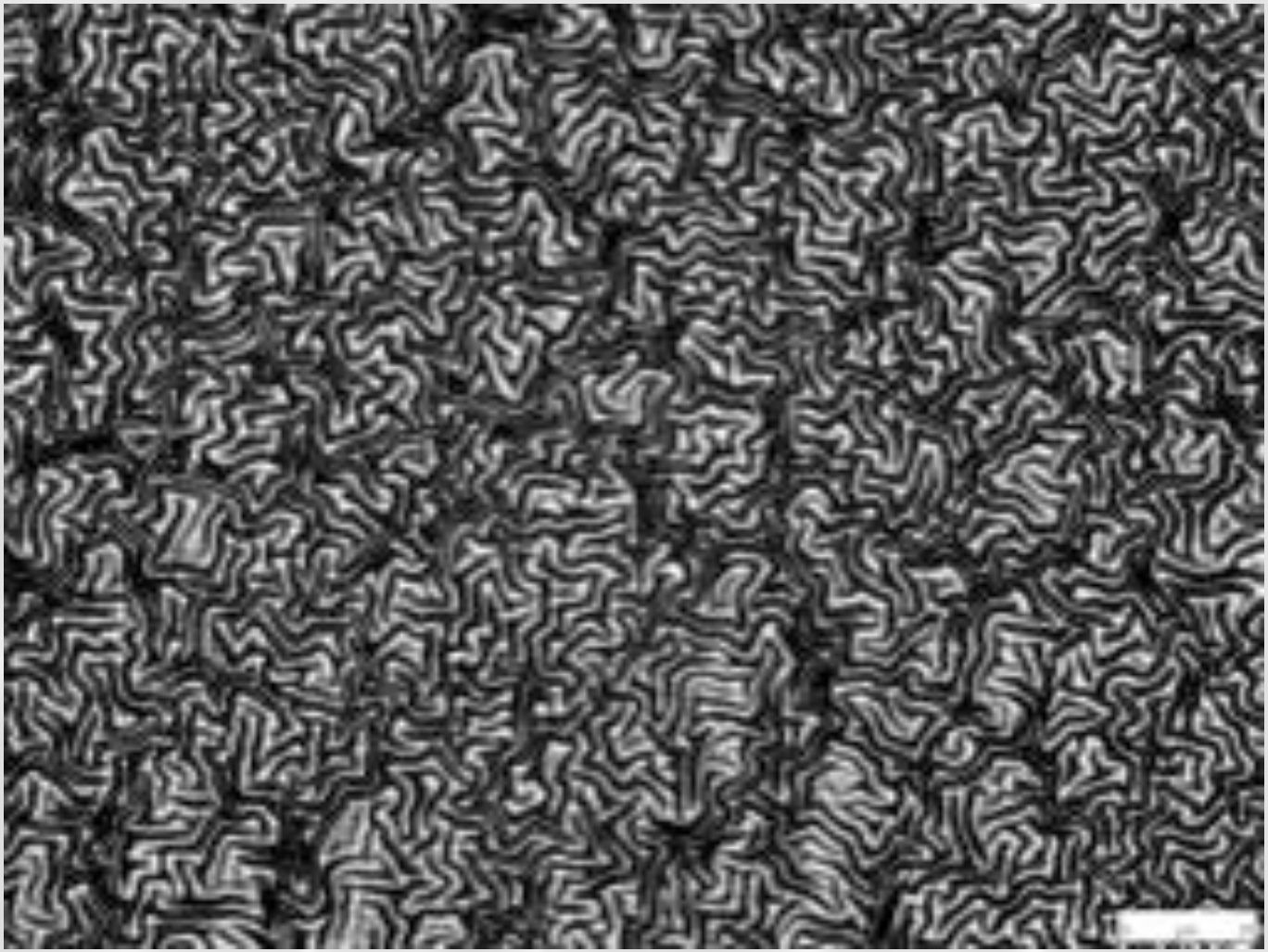




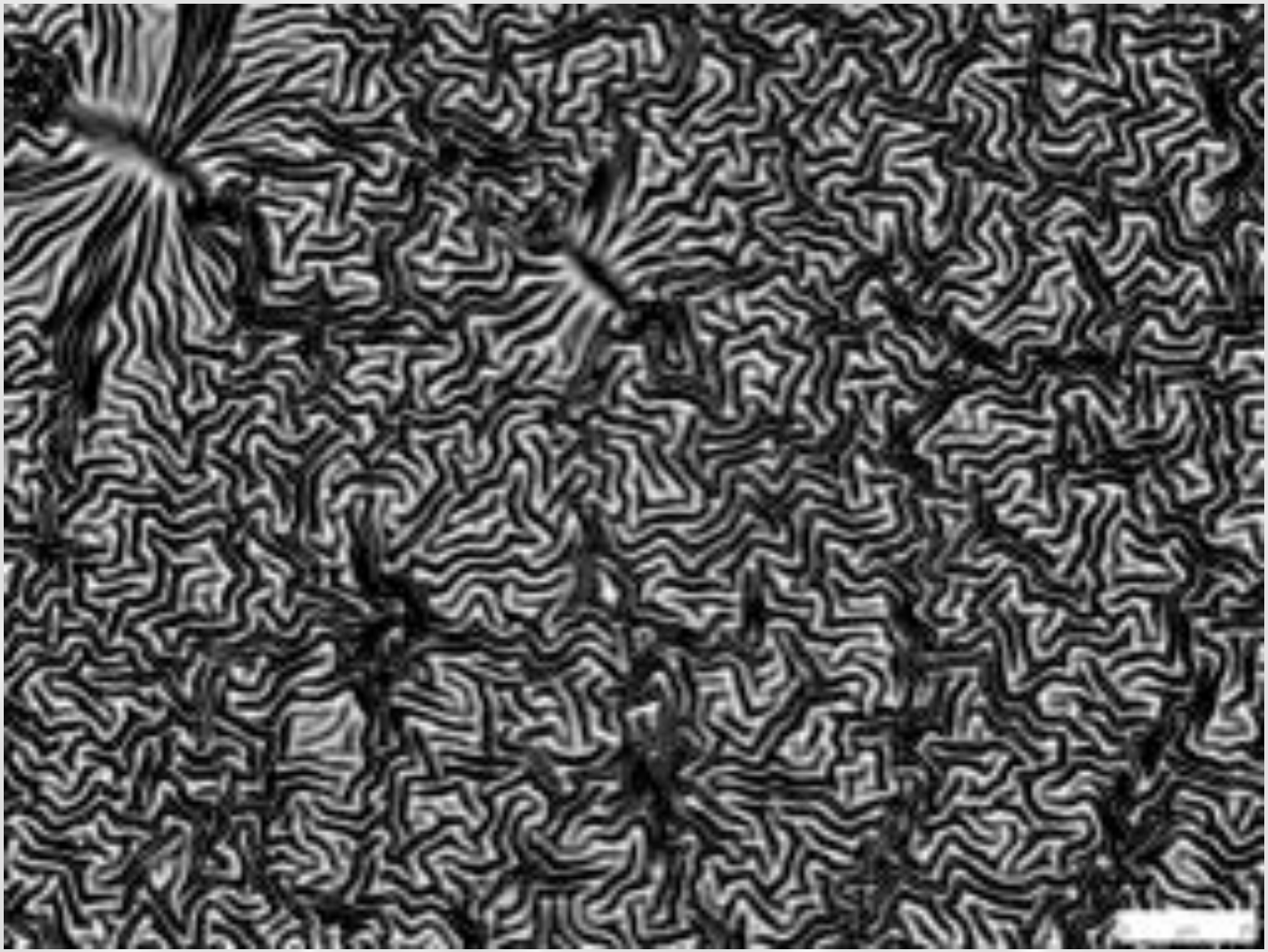
Fold nucleation



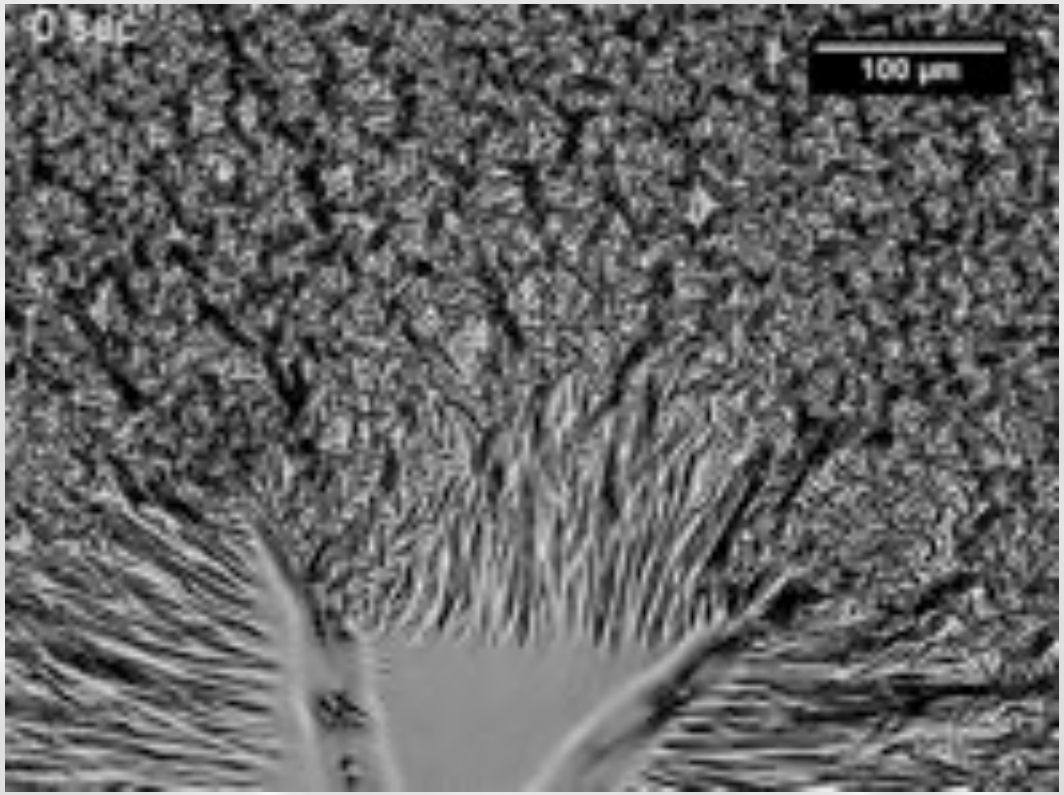
Fold nucleation

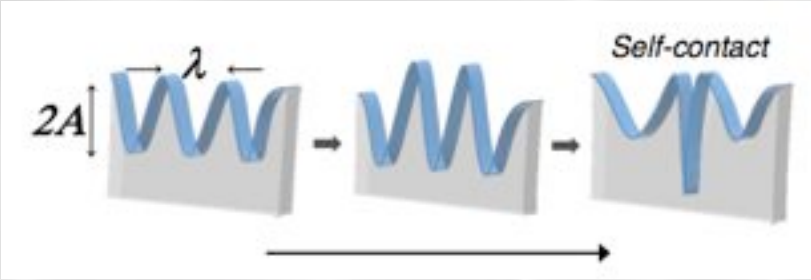


Fold nucleation



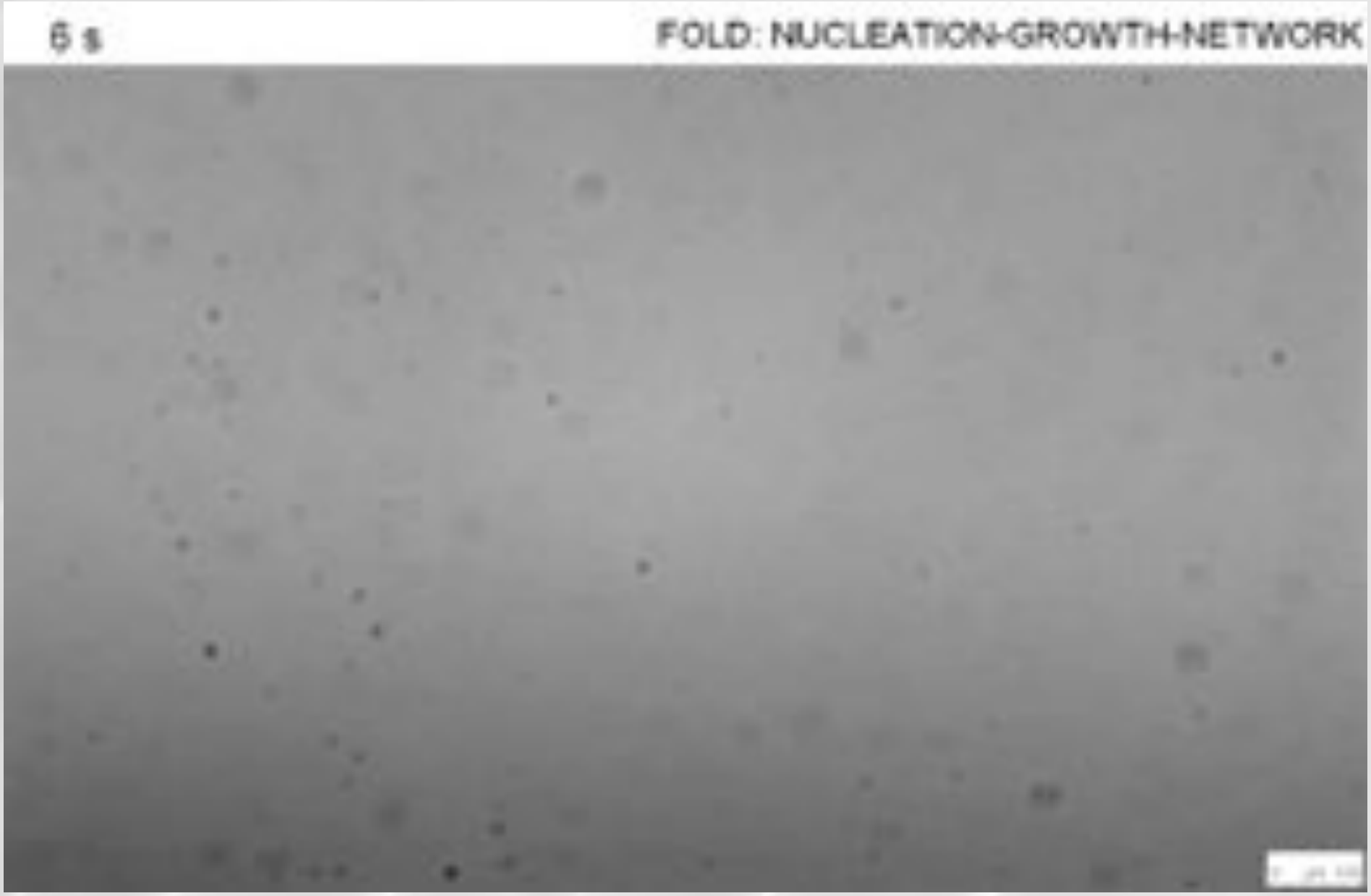
Nonlinear transition: Wrinkle-to-Fold





SEM of a fold cross section

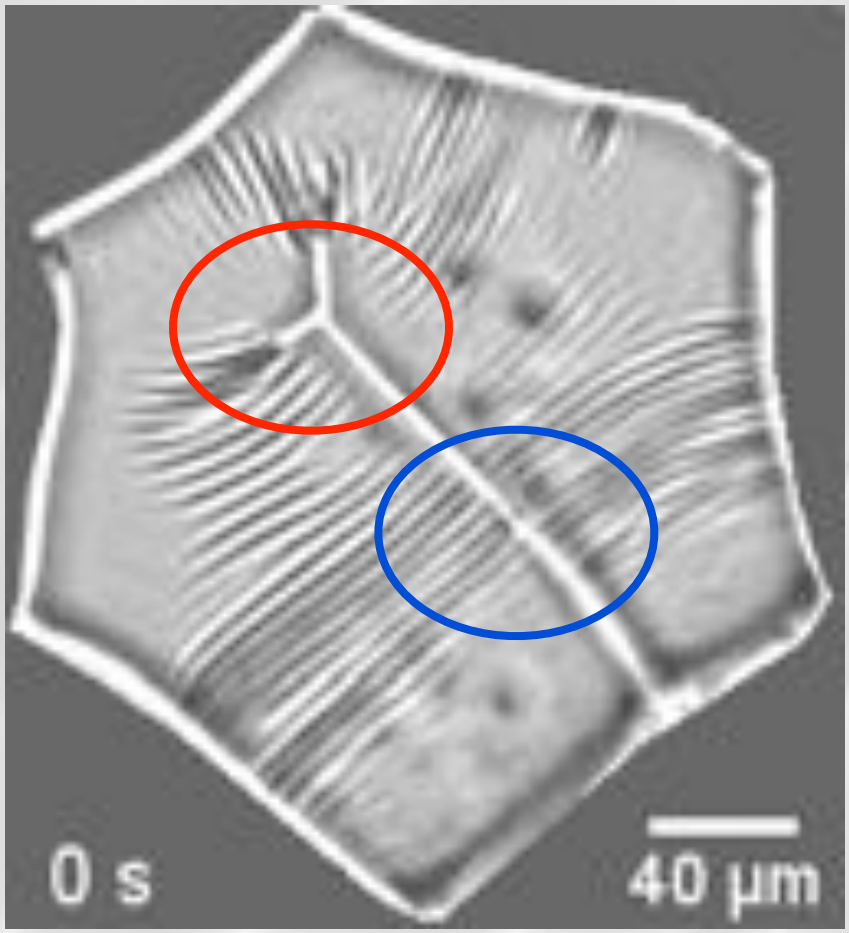
Reticulated network formation



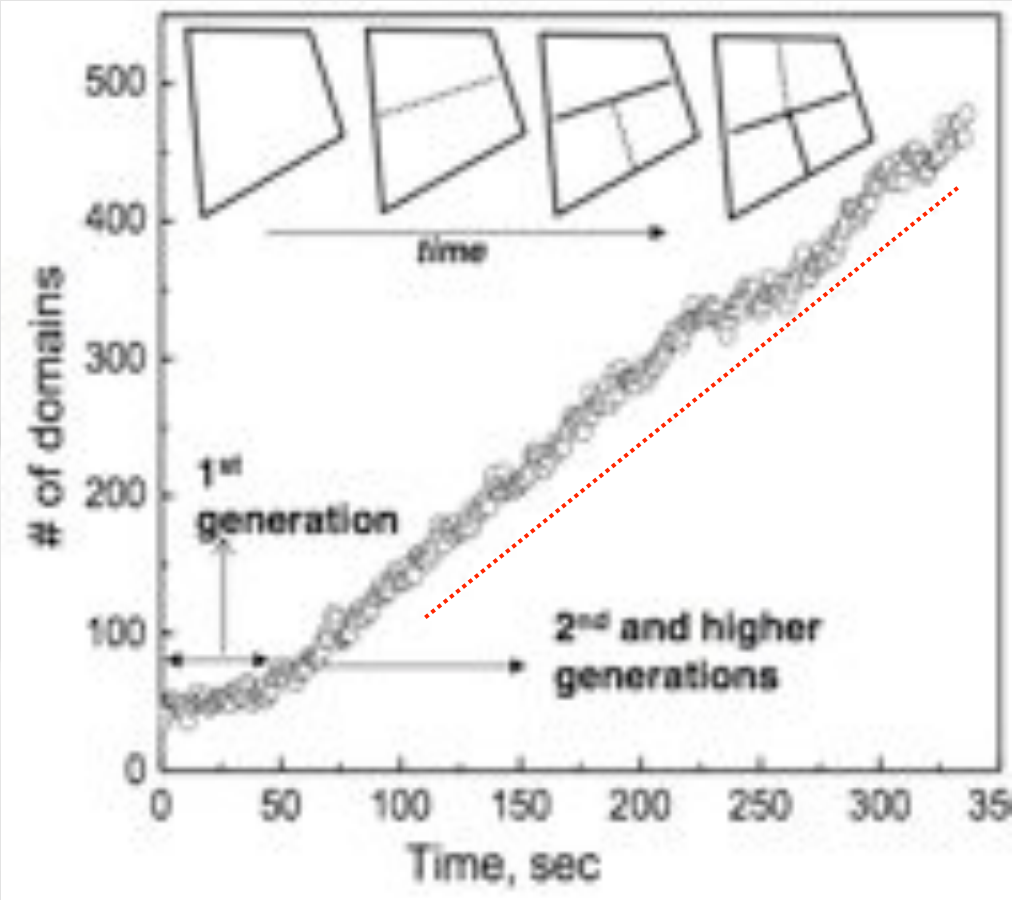
Pilnam, Abkarian* and Stone, Nature Materials 2011*

Hierarchical partitioning of the surface

Terminal and segmental branches

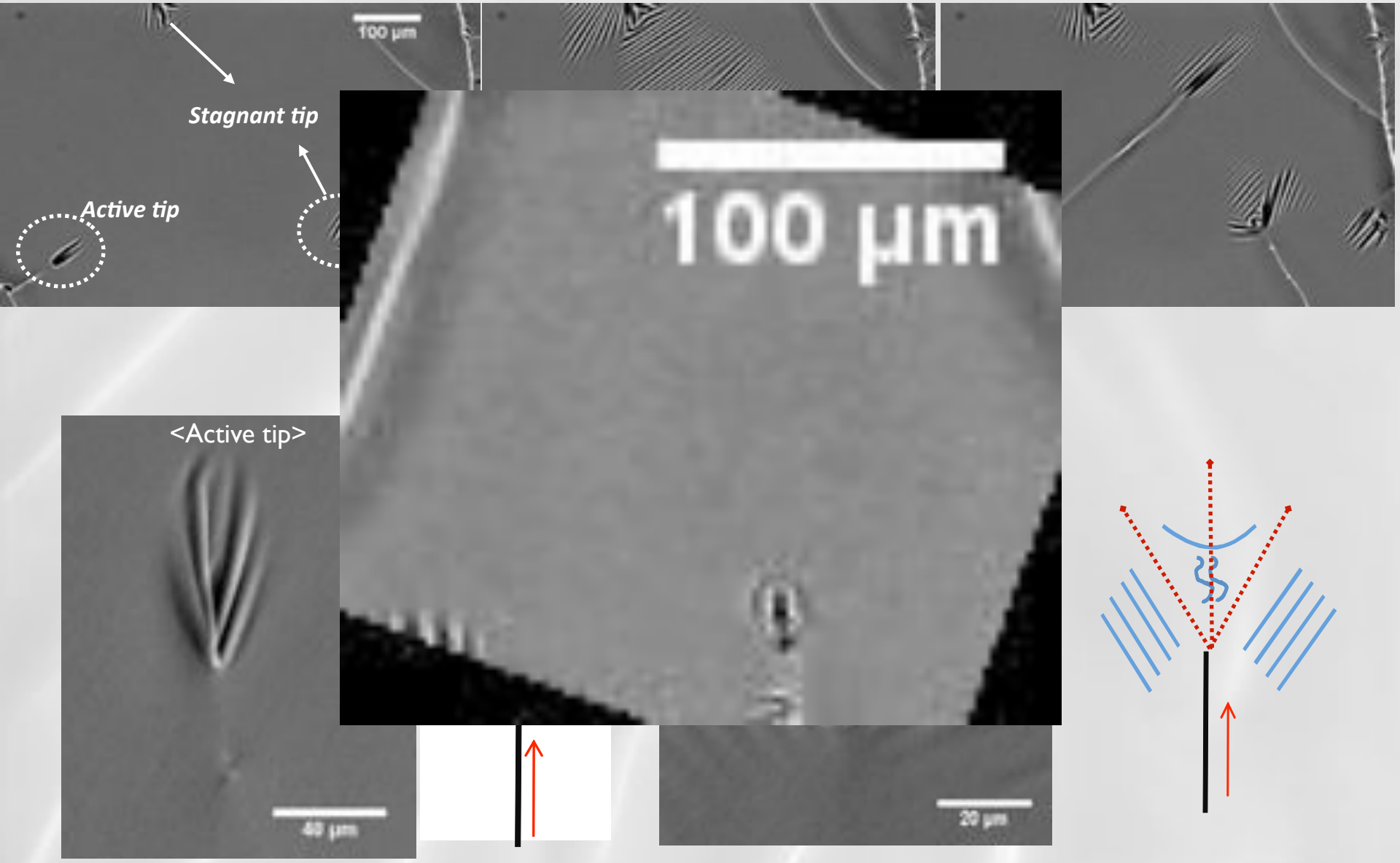


Linear growth rate due to the self-regulation



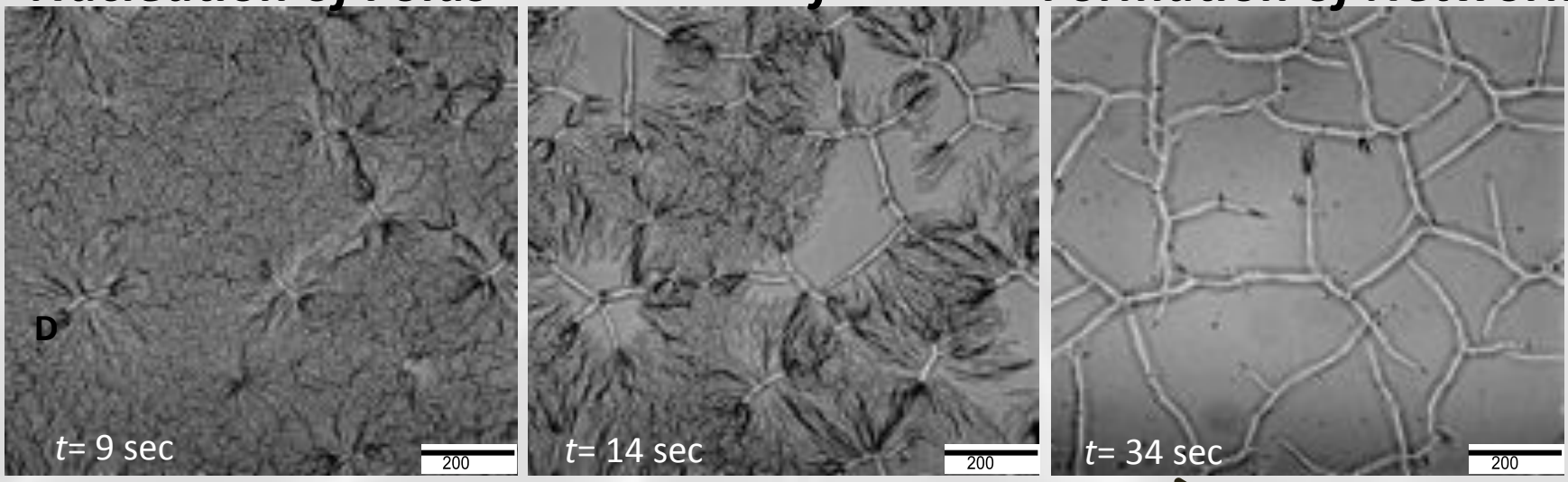
Self-regulation process

Δt =5 sec



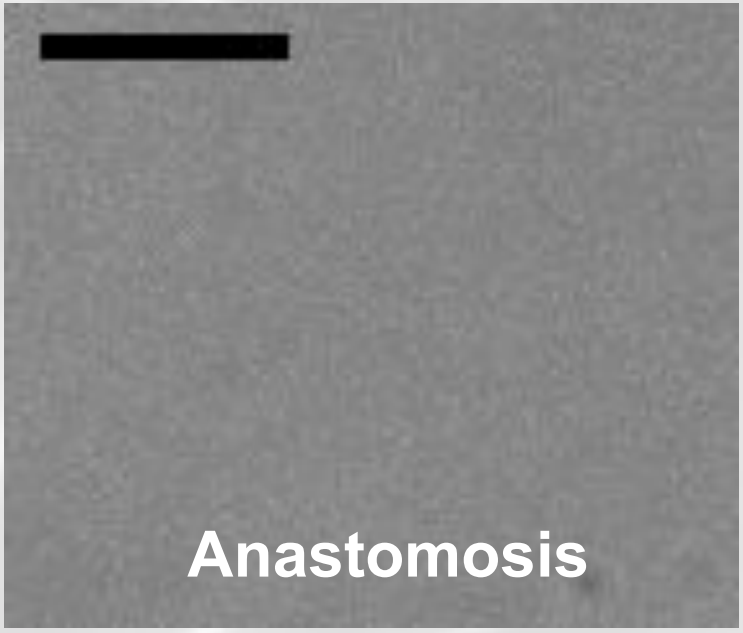
Communication and networking

Nucleation of Folds ***Growth of Folds*** ***Formation of Network***

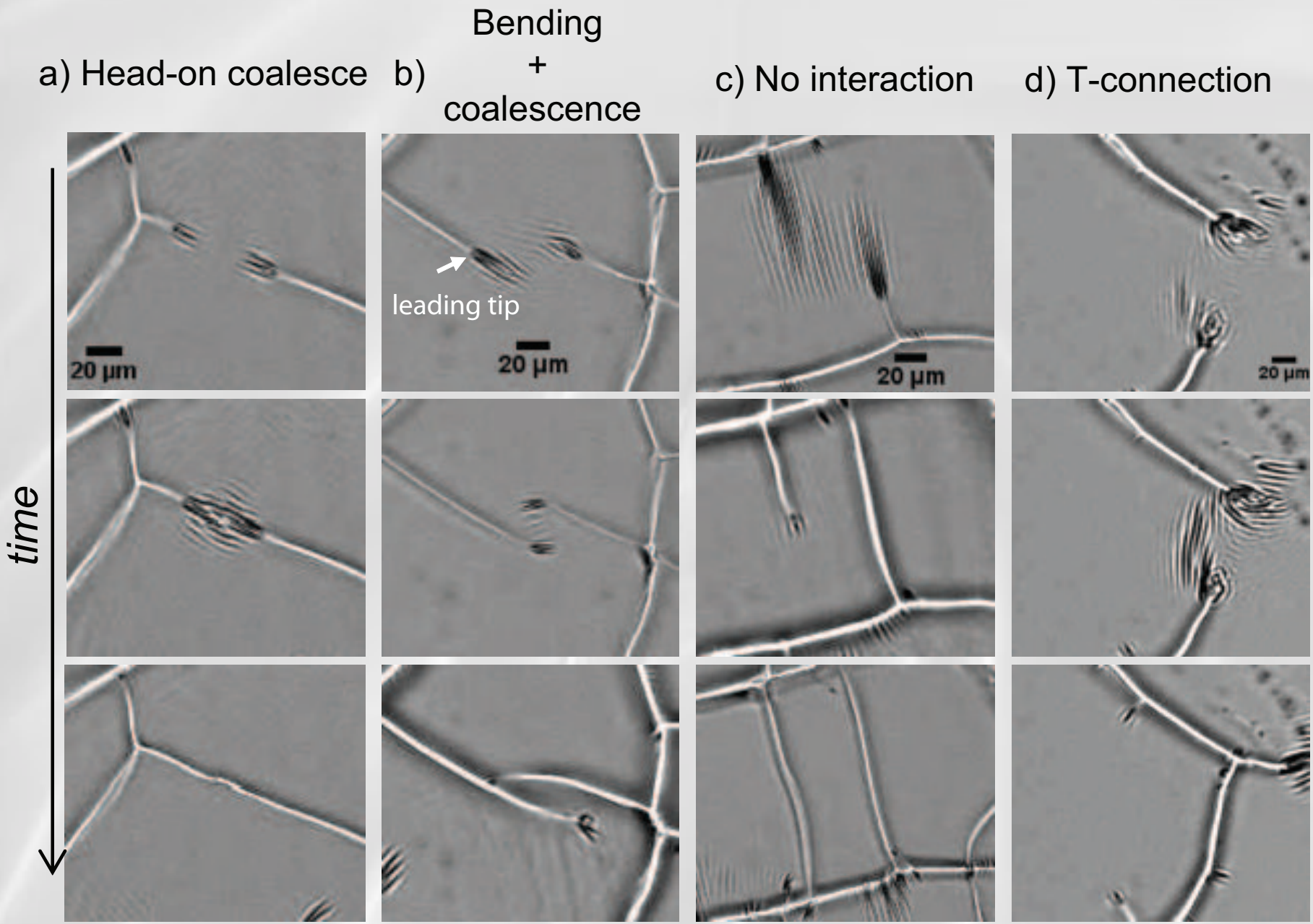


Time

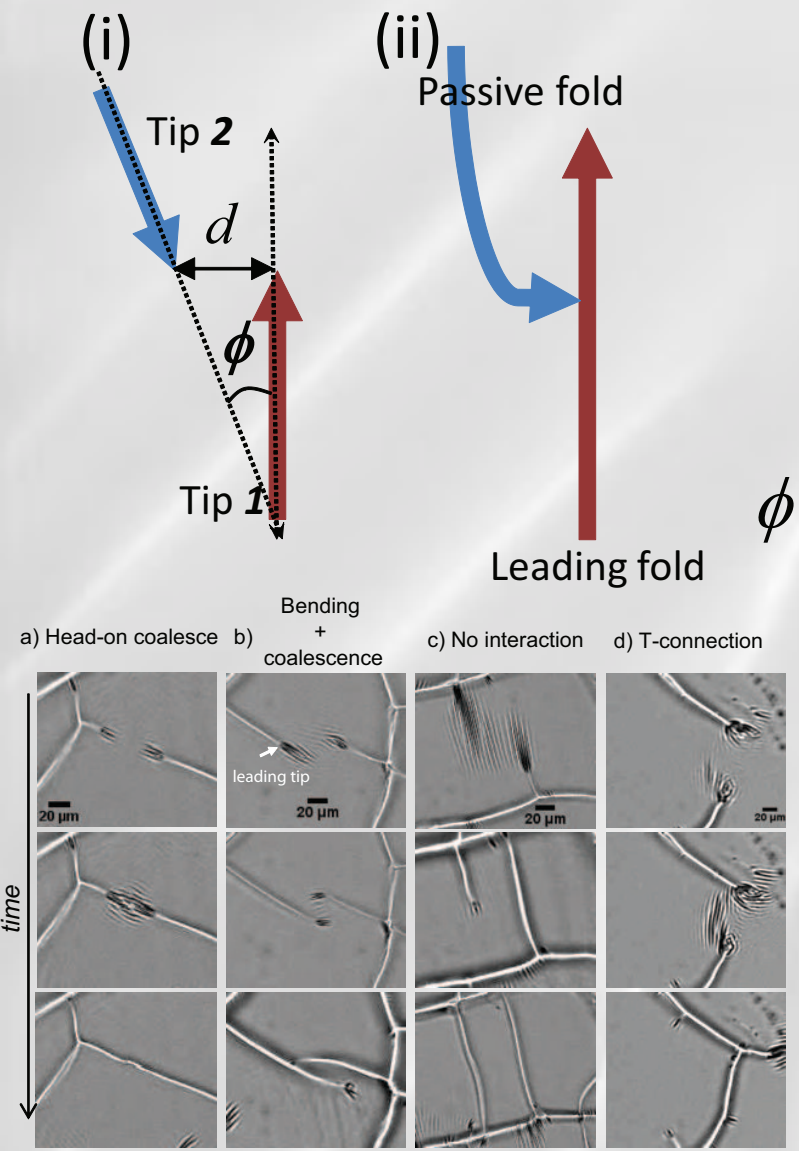
➢ ***How does it form closed domains?***

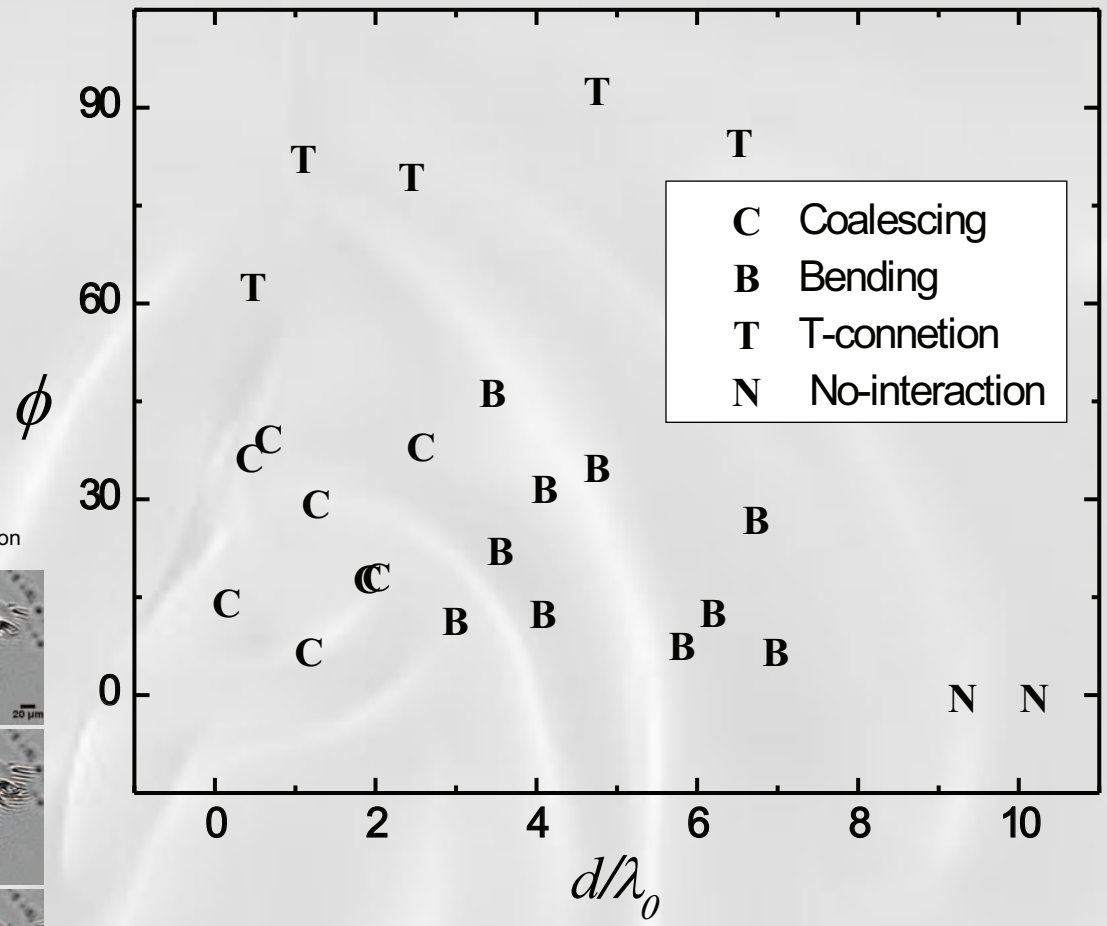


Self-regulation process: fold-fold interaction

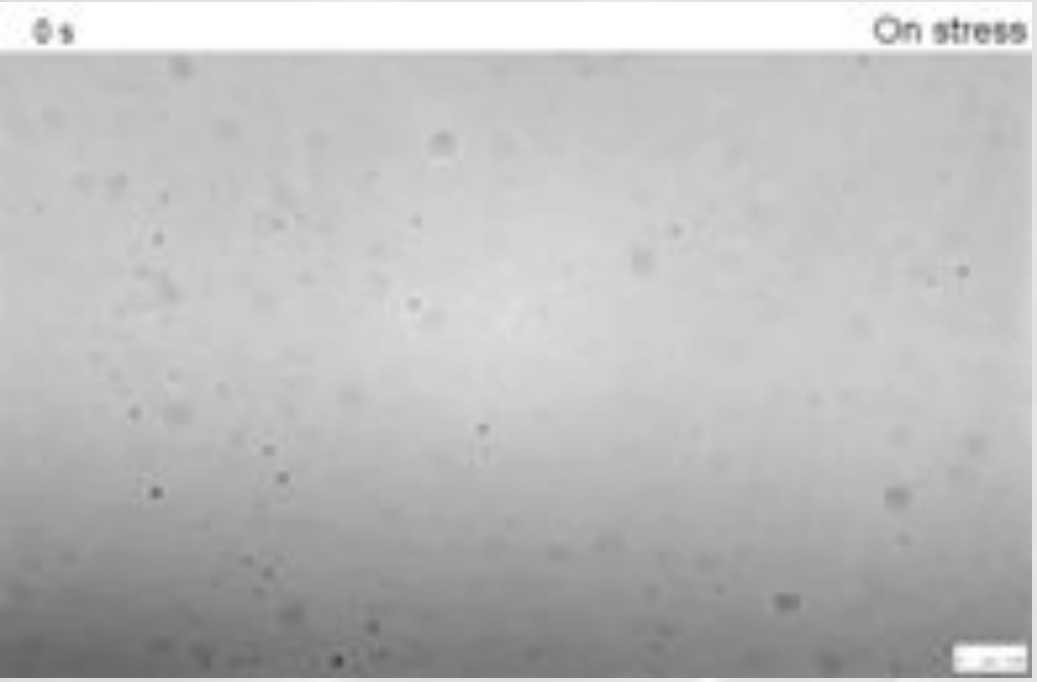


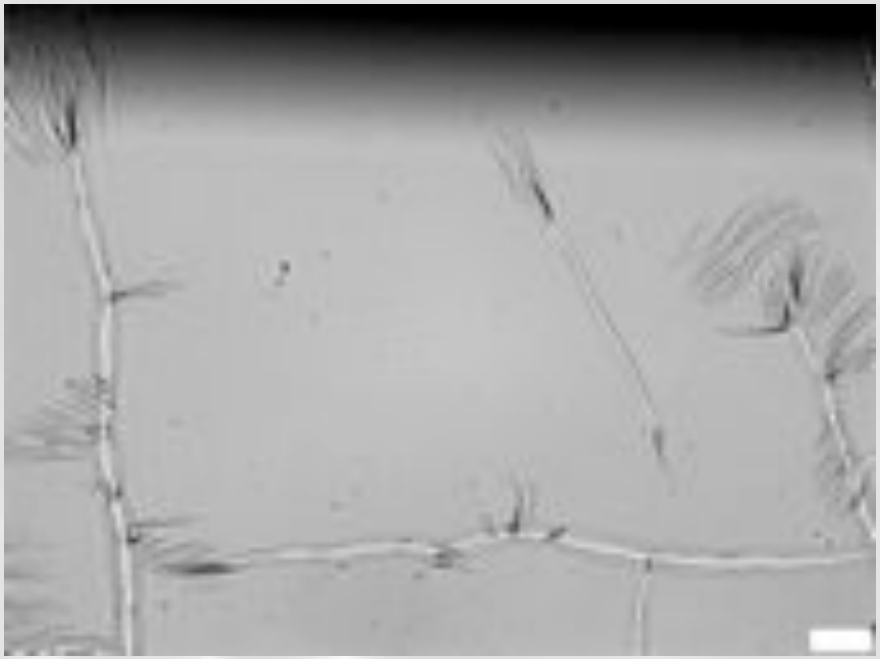
Self-regulation process: fold-fold interaction





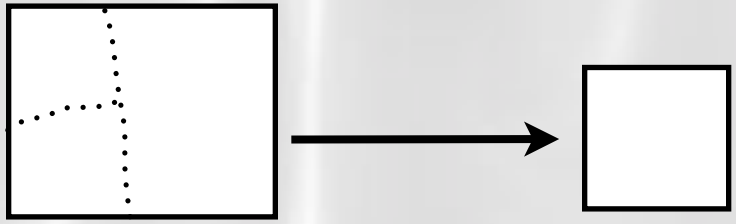
Boundary Effect and defects density





Isotrope

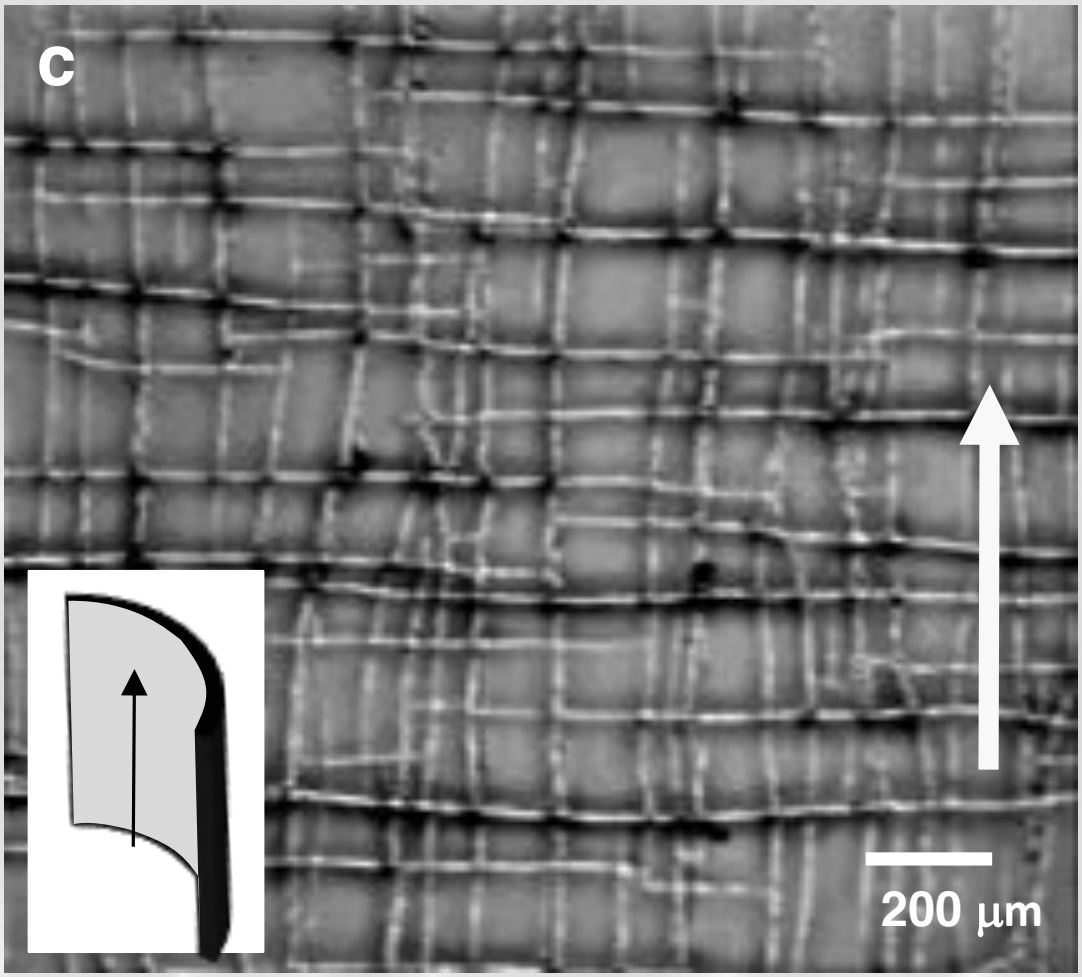
With parallel folds



analogous to cracks

Bohn et al., 2005

Other features: playing with geometry



Conclusion

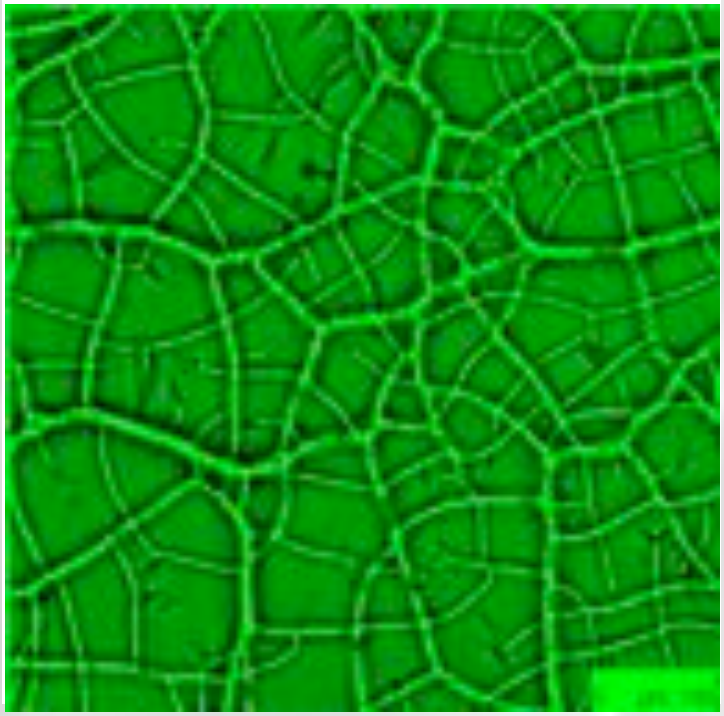
Formation of a **network** under a 2D compressive stress in multilayers

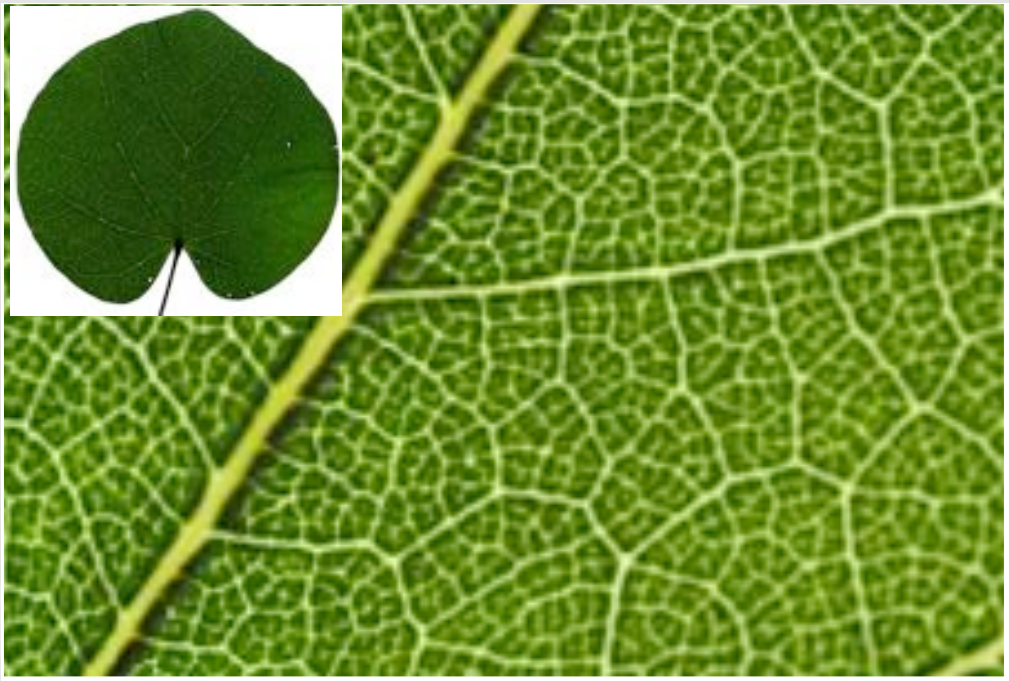
Result of **repetitive wrinkle-to-fold transitions**:
Folds propagate, frequently branch and intersect with each other in a **self-regulated manner**.

The **hierarchical division of space** is fundamentally linked to the **tensorial nature of the stress field** and t**he local and anisotropic release of stress via fold localization**

Can we say something about venation ?

Folds



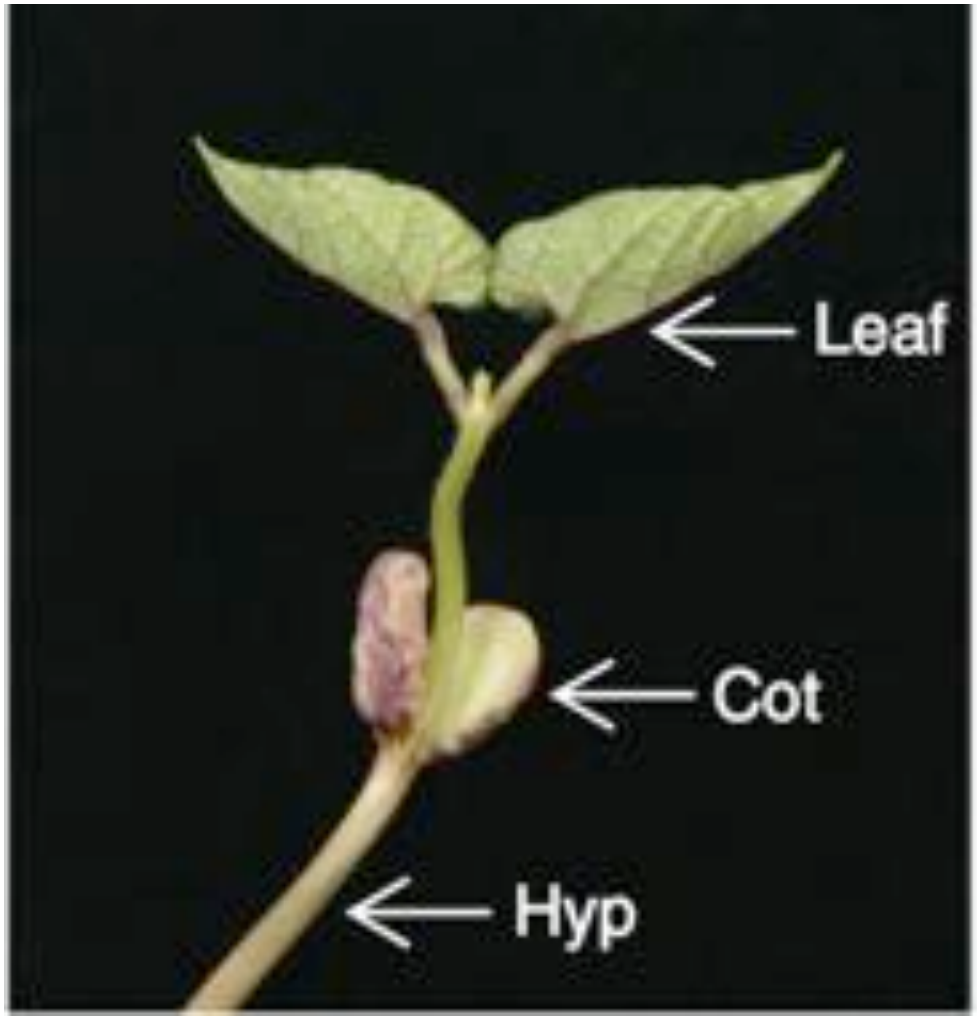


Schizophragma hydrangeoides reticulated

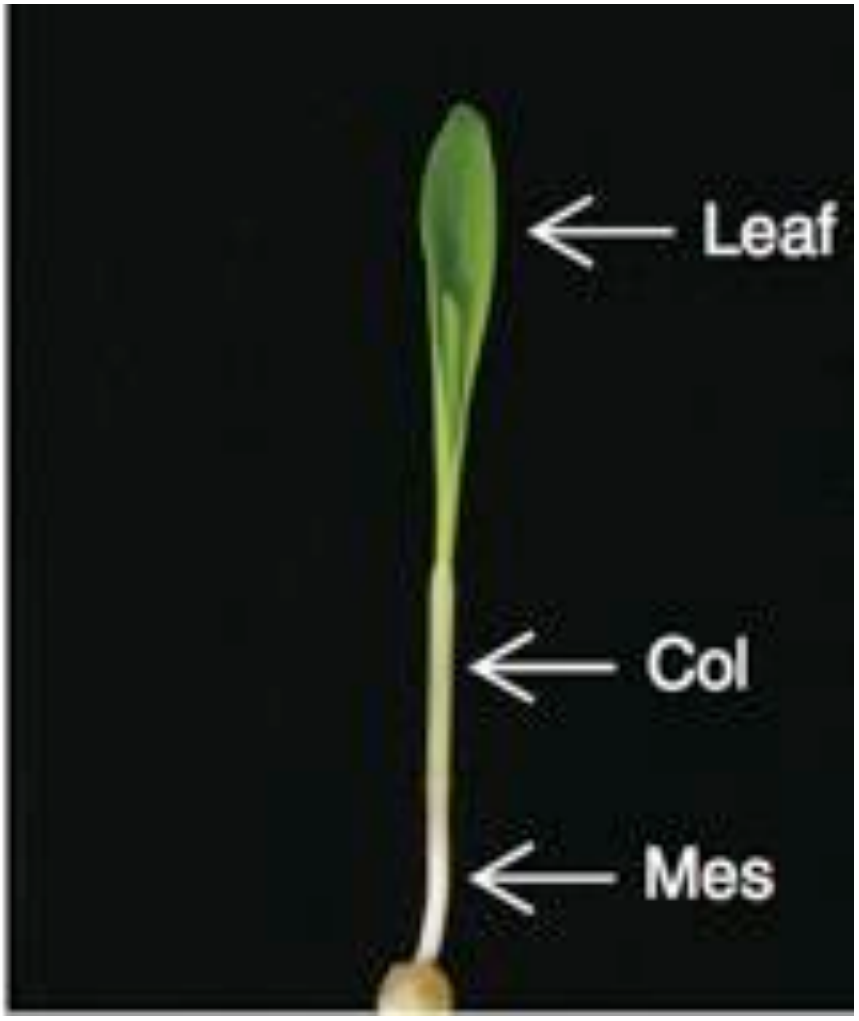
Leaves venation architecture

Two groups of flowering plants

Dicotyledons



Monocotyledons



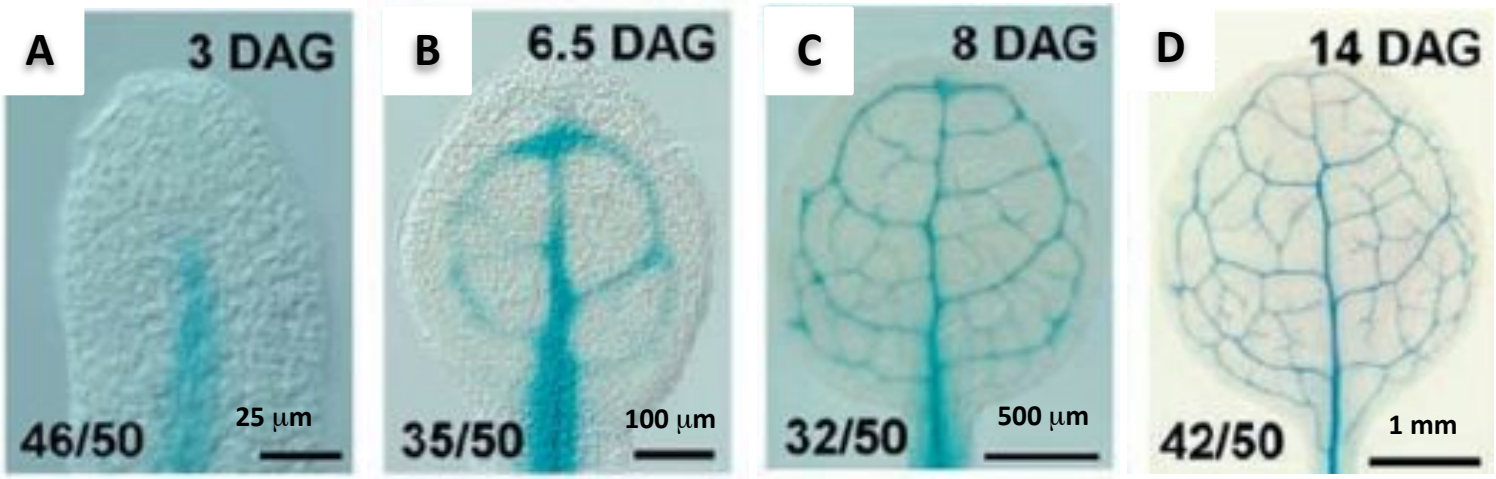
McSteen, 2010

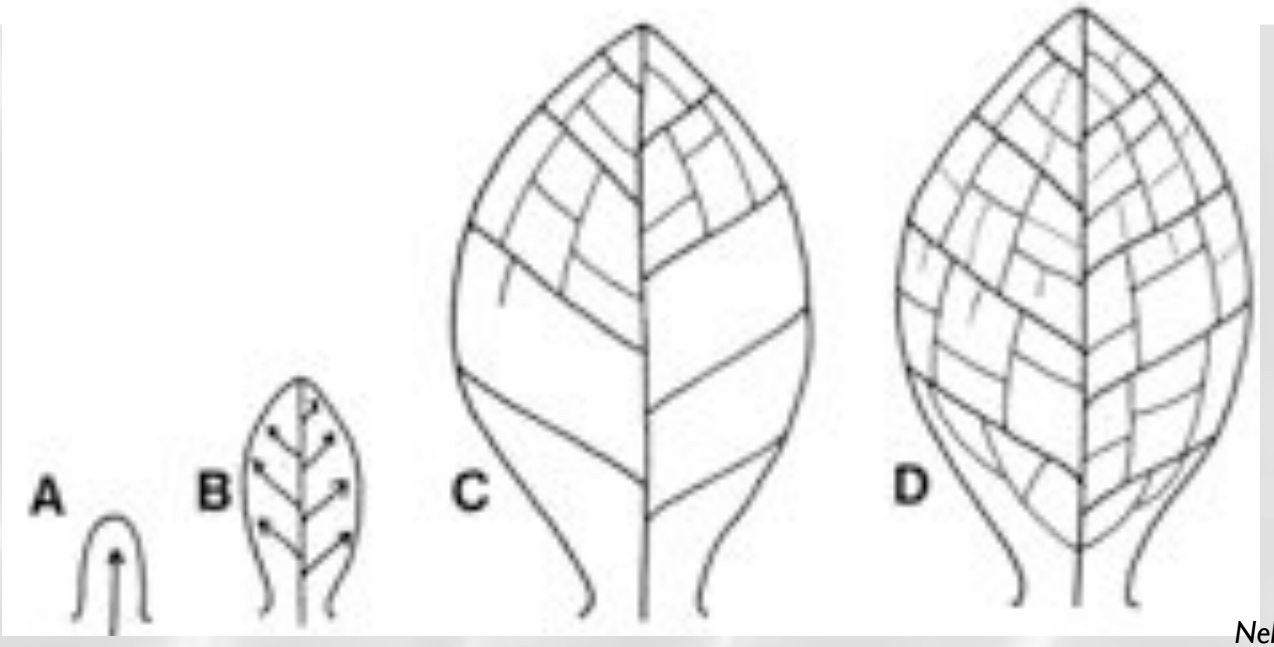
Venation formation and architecture

Hierarchical division of space

Network of veins

Scarpella *et al*, *Development (2004)*

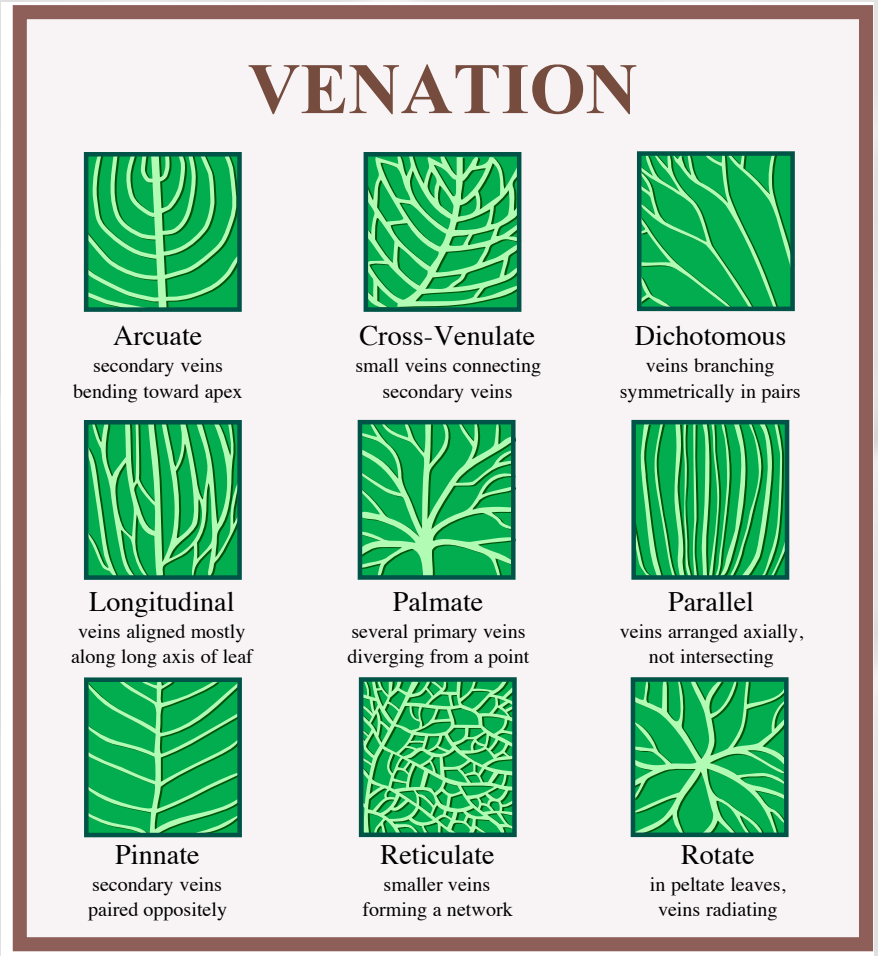




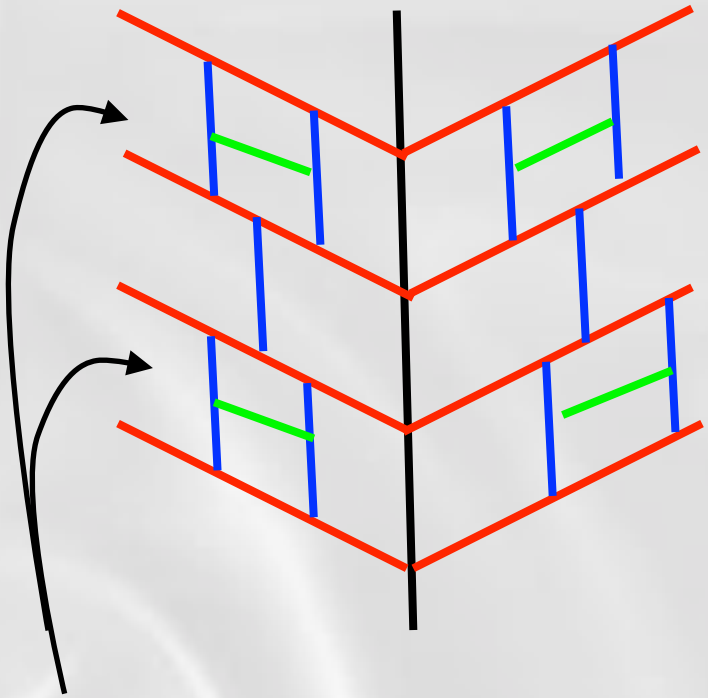
Nelson and Dengler 1997

Leaves venation architecture

1st and 2nd generation conserved in the plant



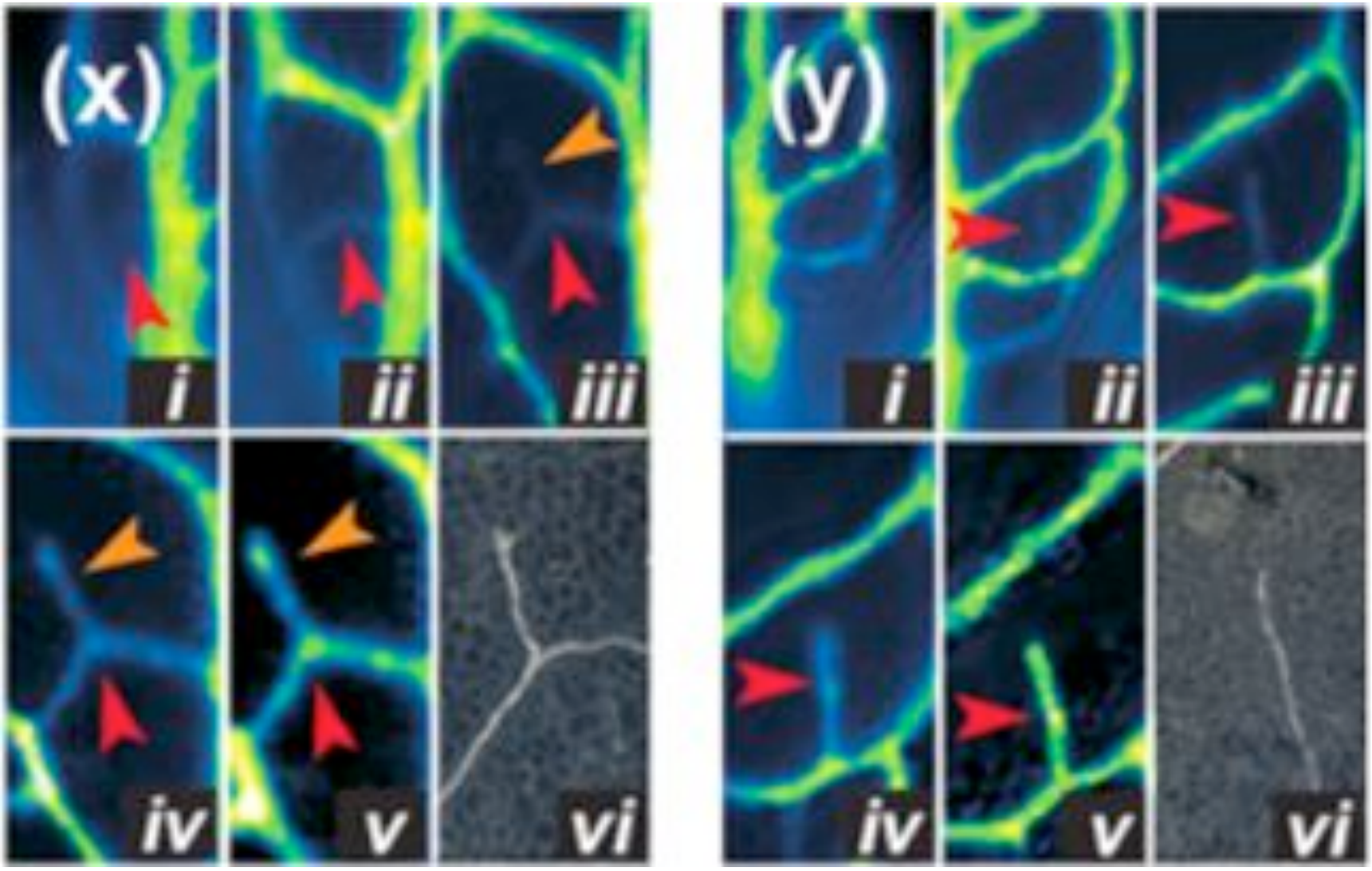
wikipedia



3rd, 4th...generations variable from leaf to leaf

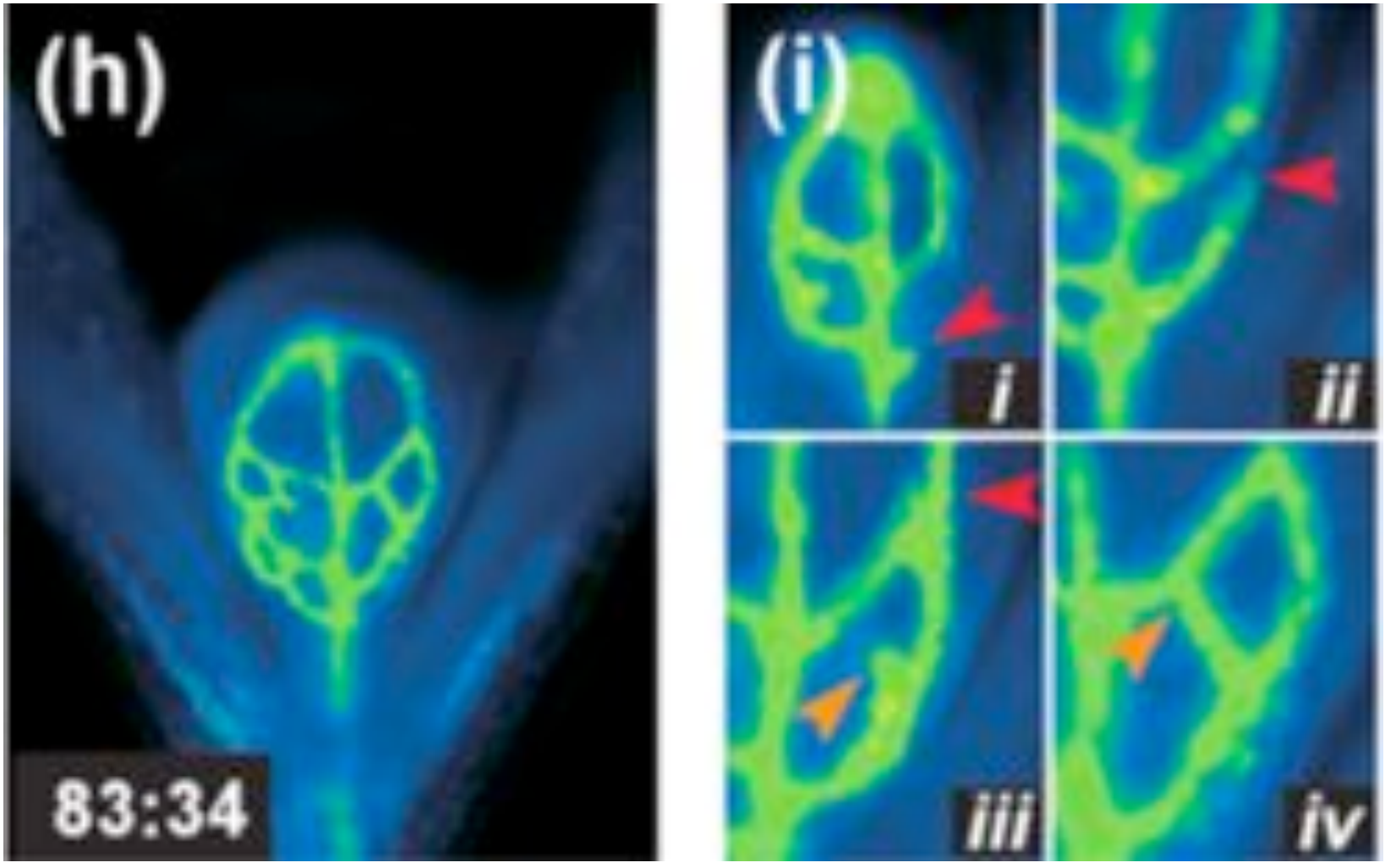
Self-organized process not only genetics ?

Branching



Sawchuk et al. 2007

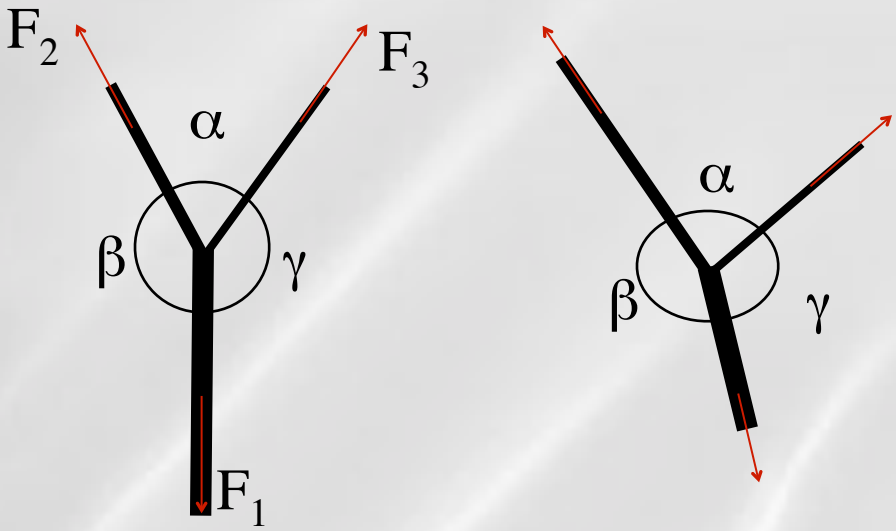
Reorganization



Sawchuk et al. 2007

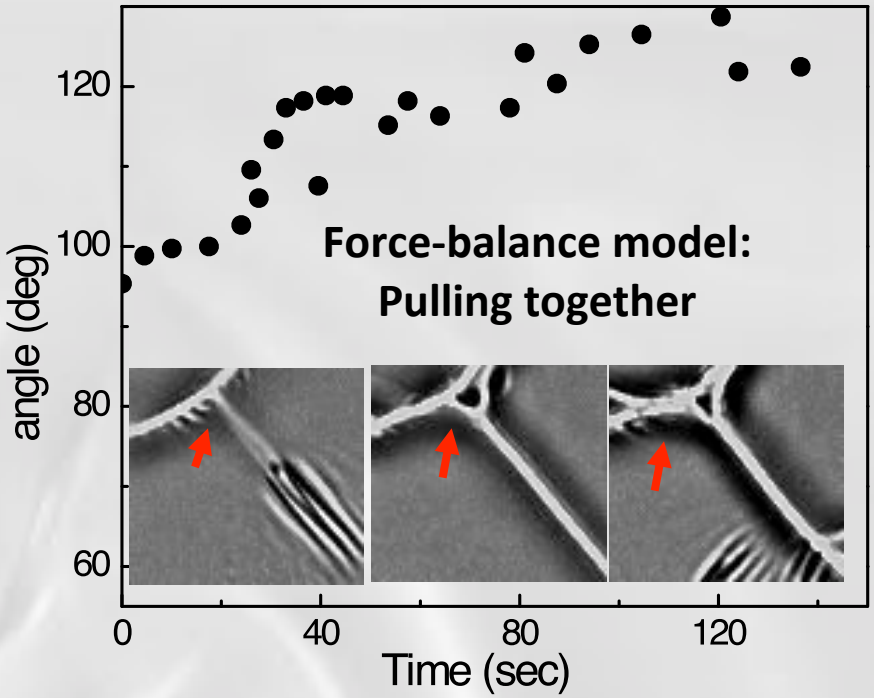
Not only static but also dynamic

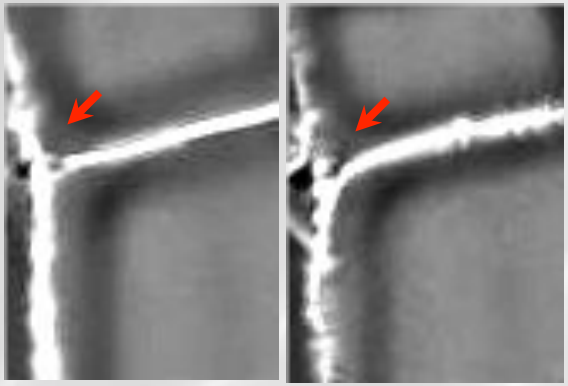
Time-dependent deformation: Remodeling

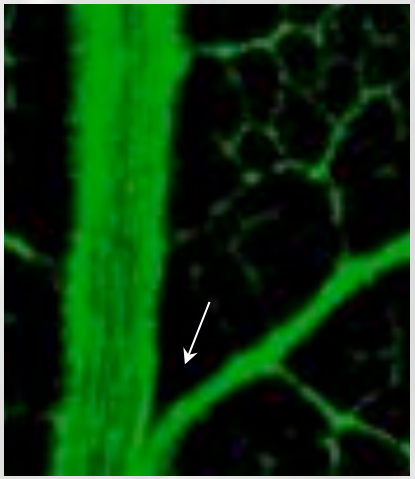


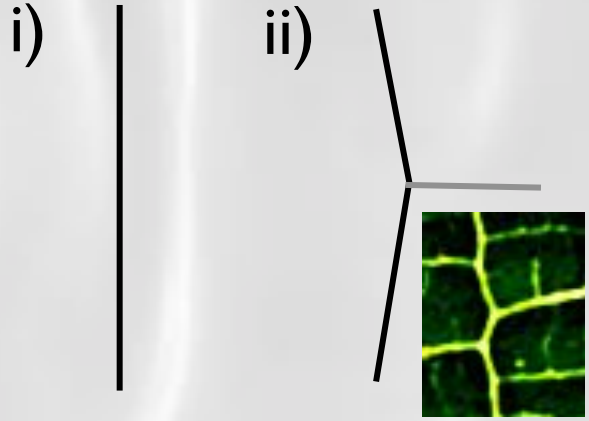
$F_2 > F_1 > F_3$

Bohn et al., 2002



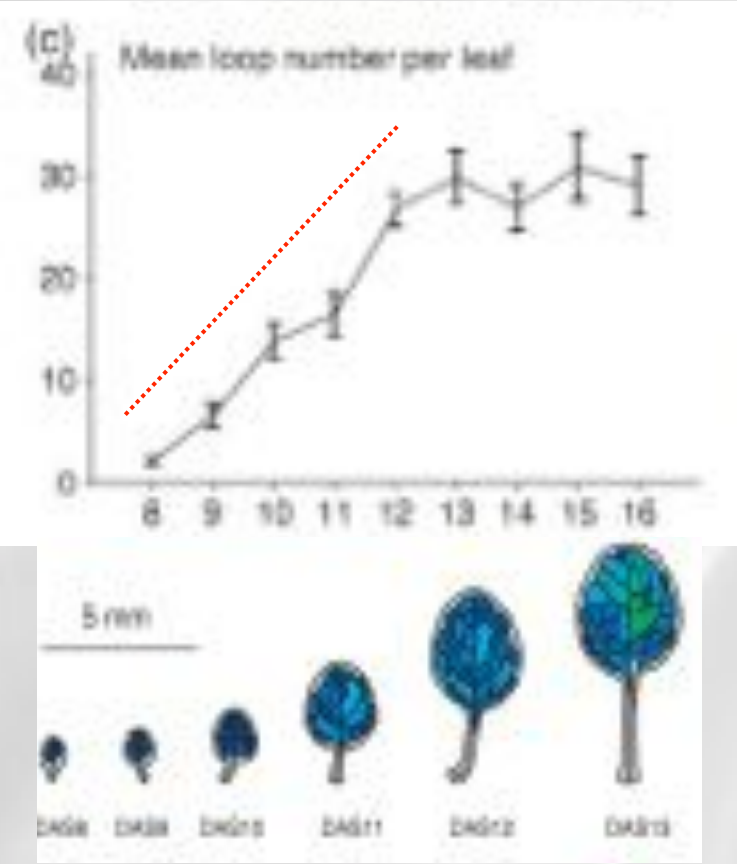




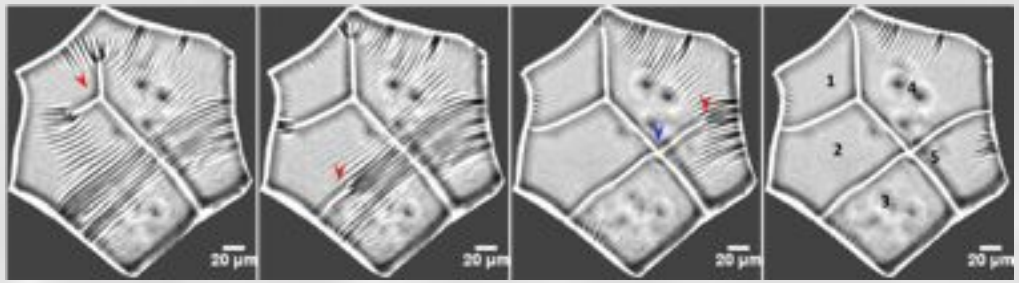


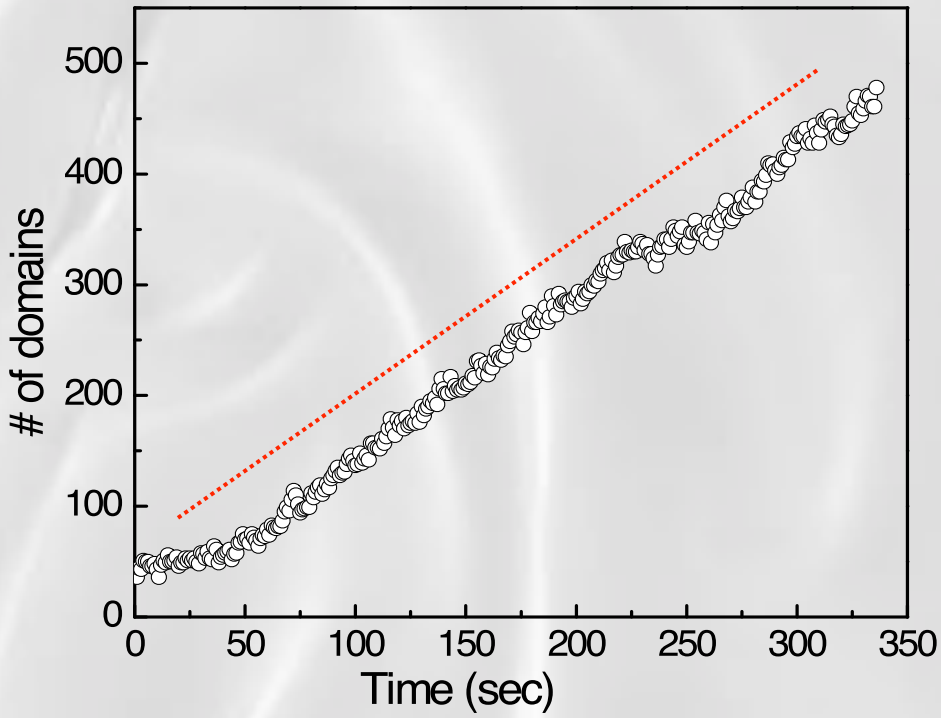
Not only static but also dynamic

Linear growth rate due to the self-regulation



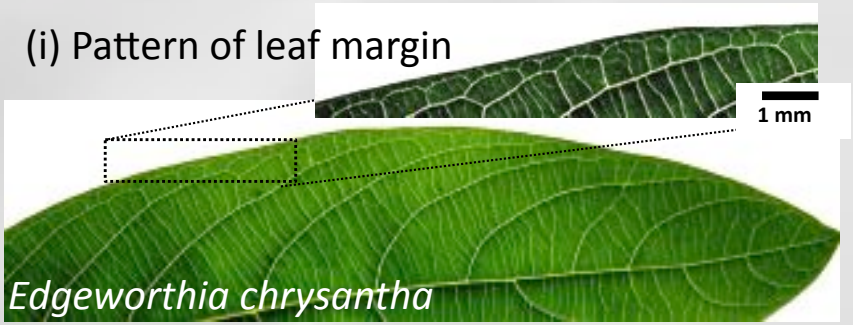
A. Rolland-Lagan , *The Plant Journal* (2009)



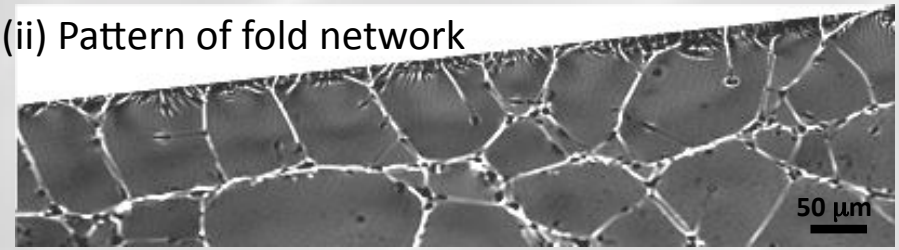


More analogies with venation of leaves

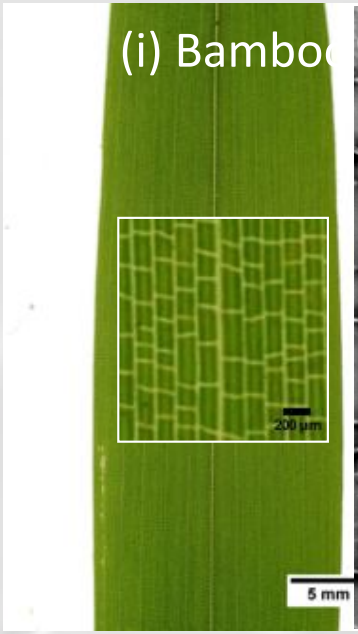
(i) Pattern of leaf margin



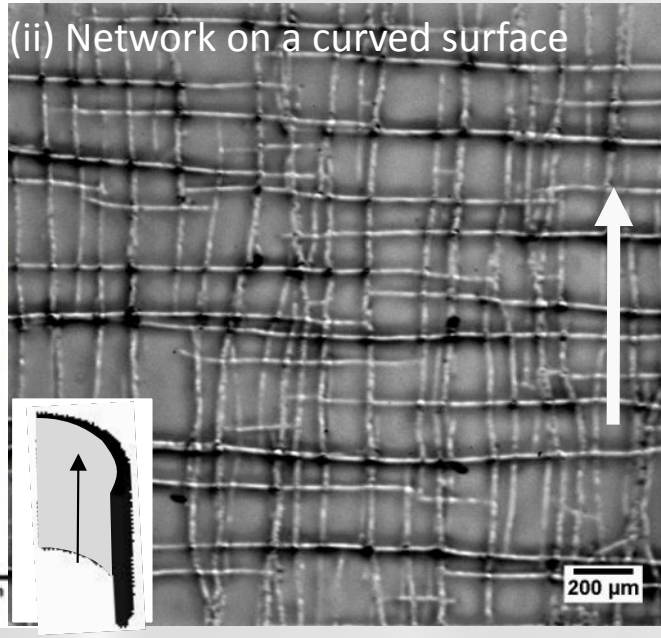
(ii) Pattern of fold network

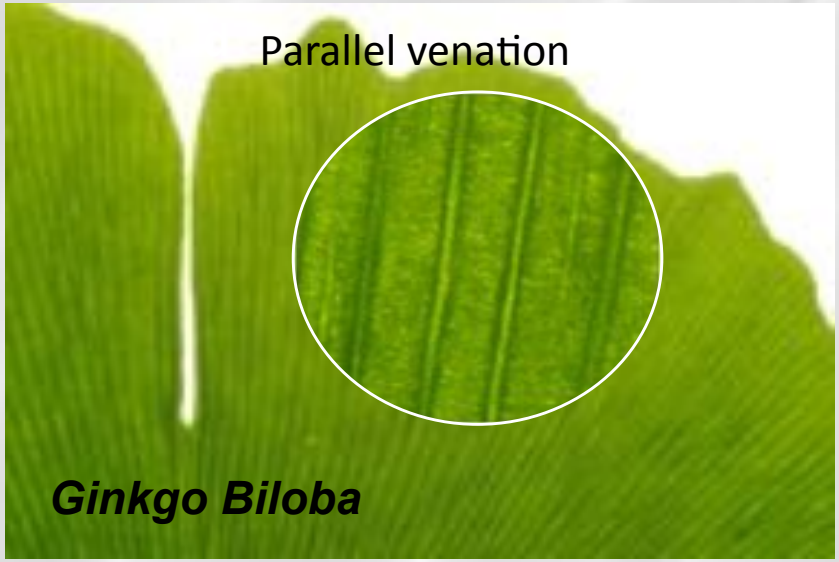


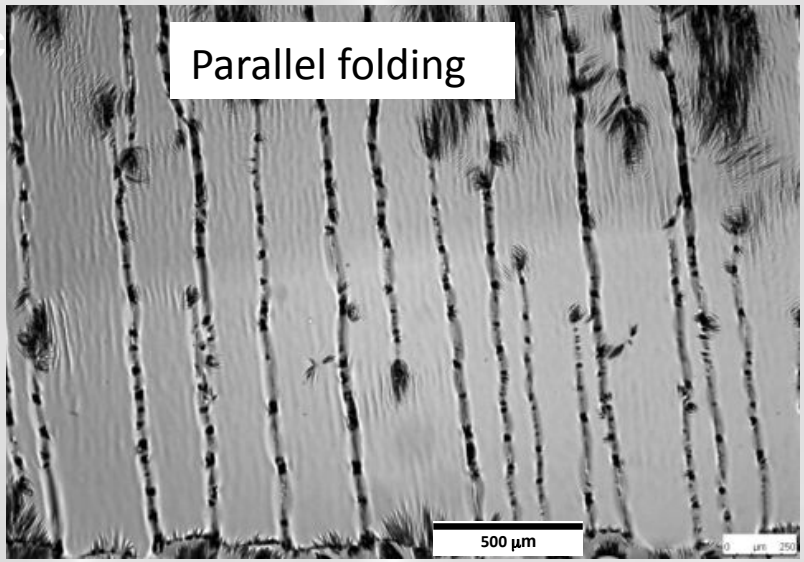
(i) Bambo



(ii) Network on a curved surface

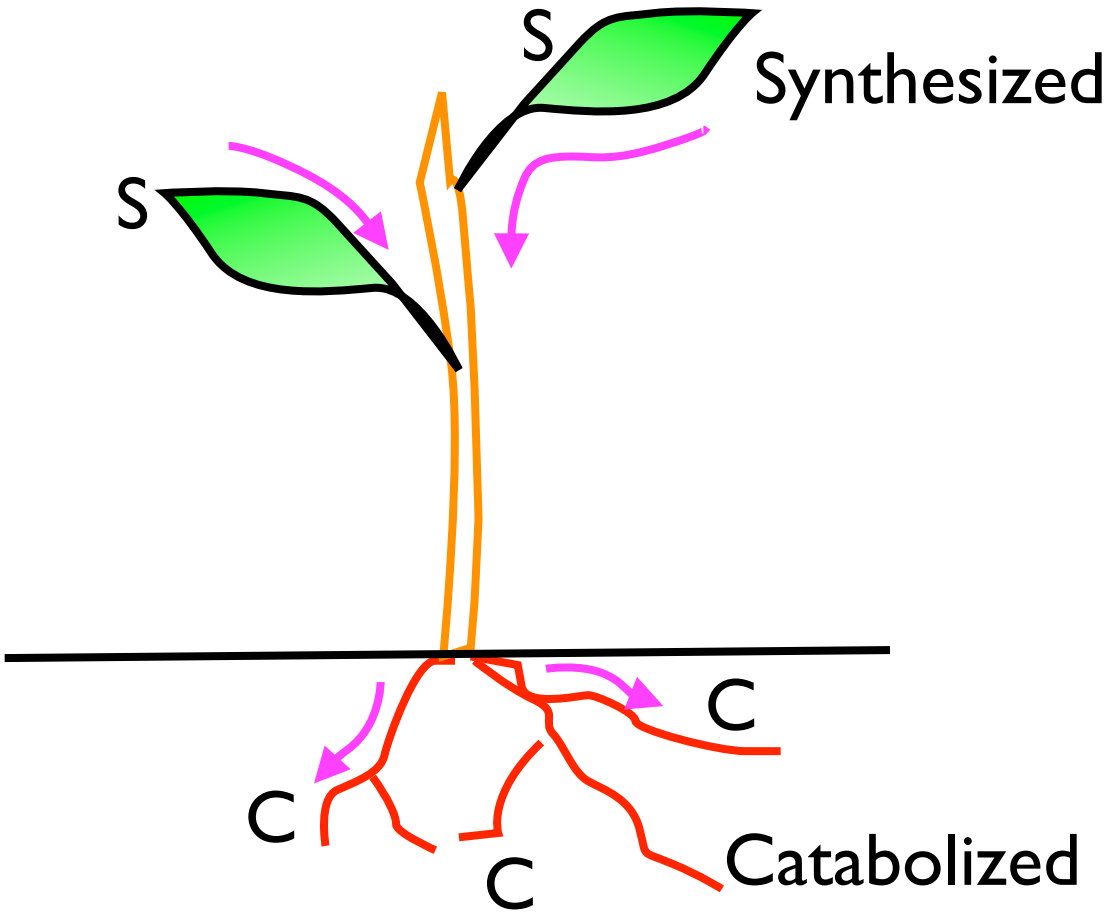


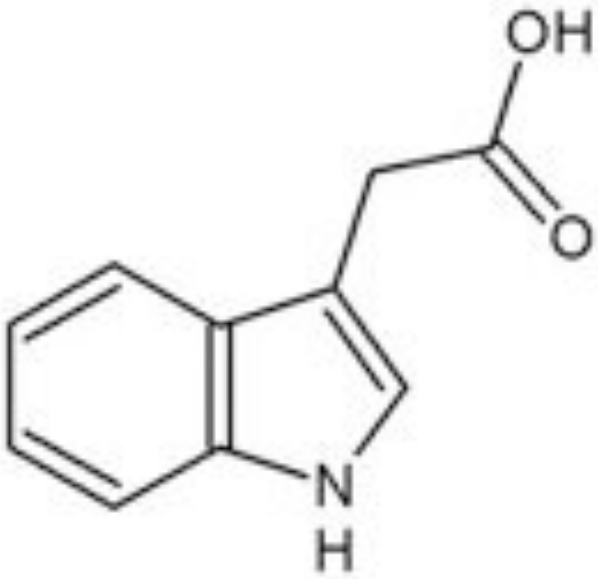




Growth hormone Auxin

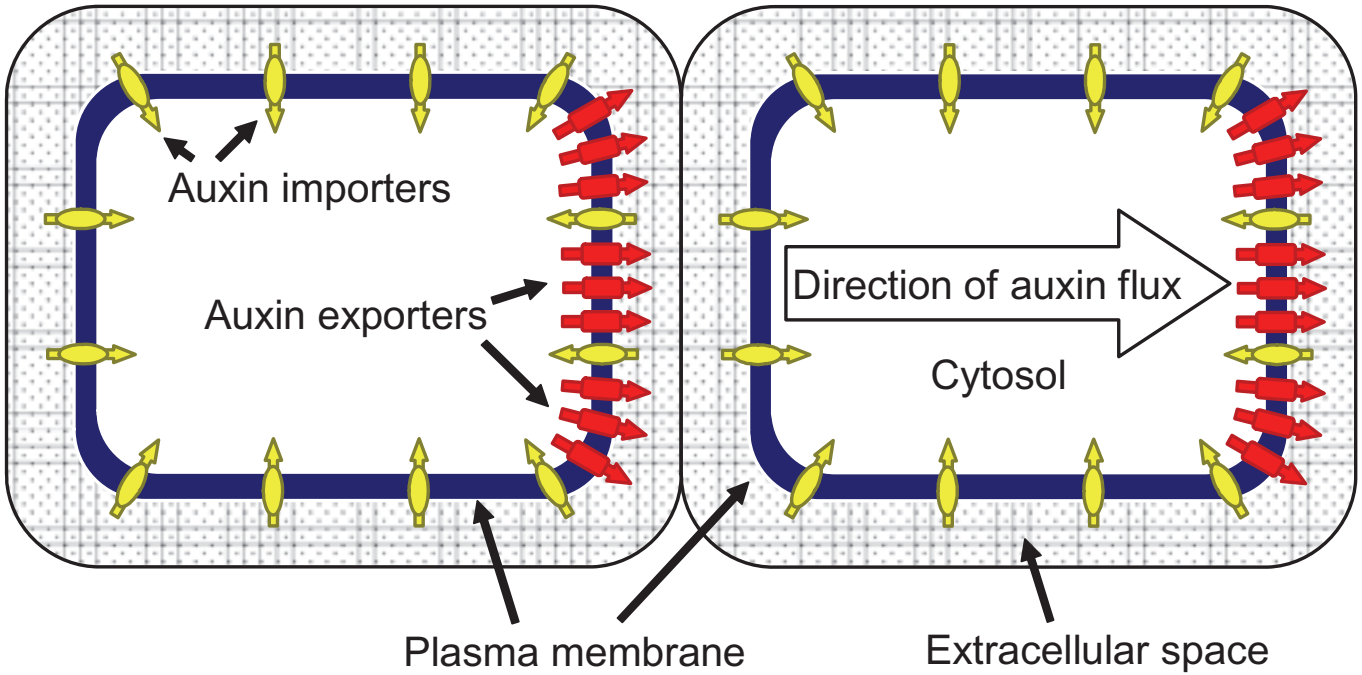
from the greek *auxien* - «to grow»

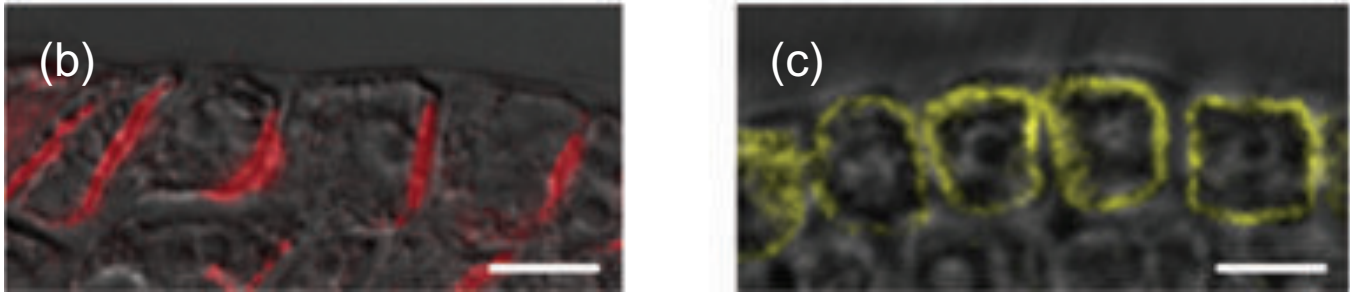




indole-3-acetic acid (IAA)

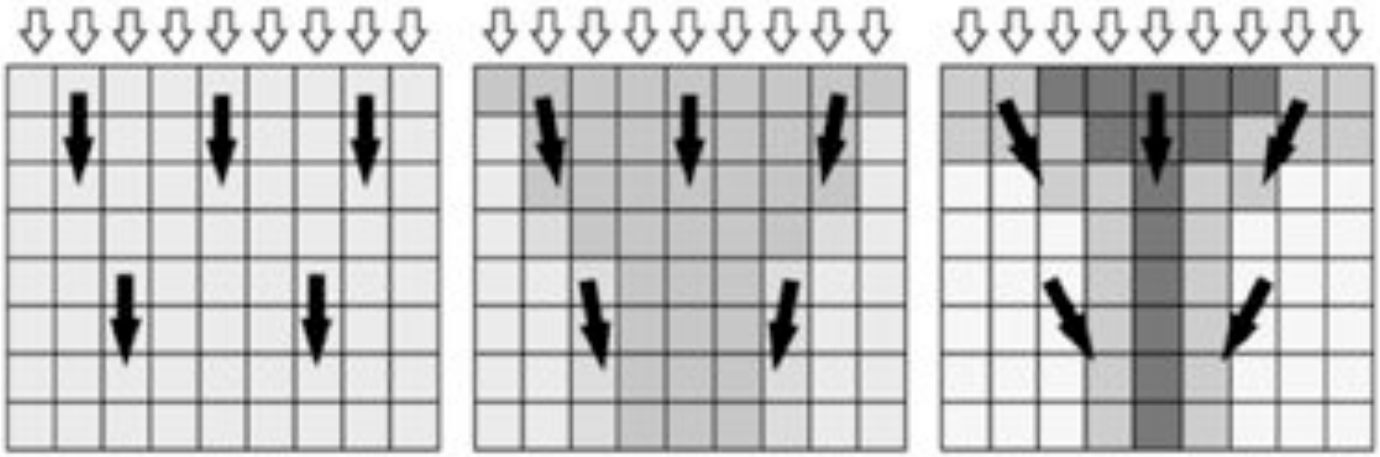
Growth hormone Auxin



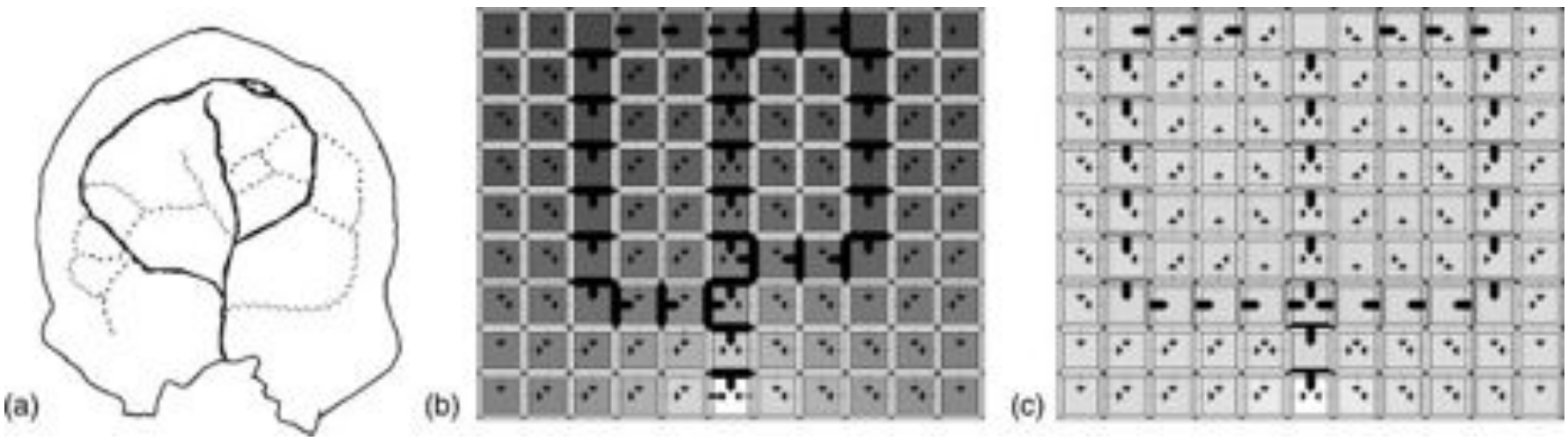


Smith and Bayer, Plant, Cell and Environment (2009)

Sachs Canalization hypothesis



Sachs, 1981



Rolland-Lagan

Symphony of sources and sinks

To model branching and loops: synchronization of sources and sinks

Range of hypothesis on Auxin production and detection of cells with no clear experimental data

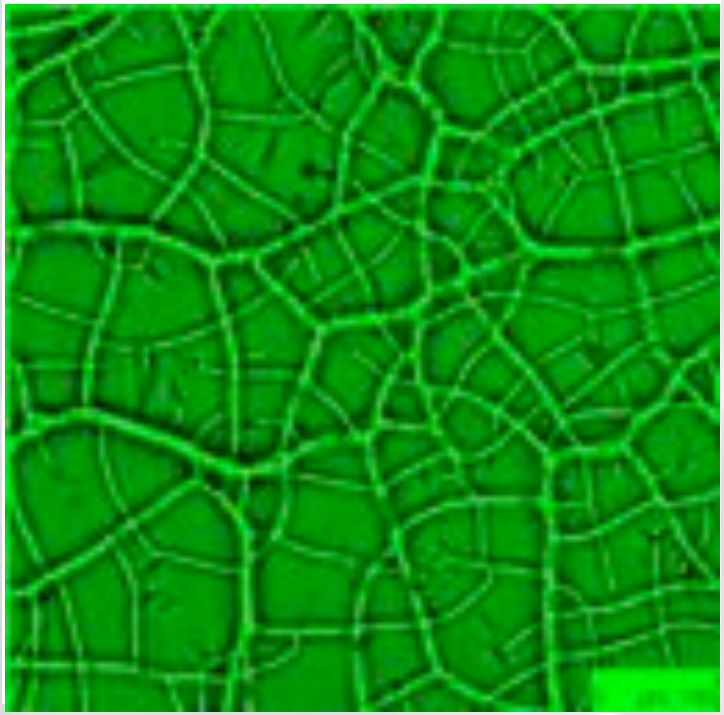
Where and when Auxin is produced by cells ?

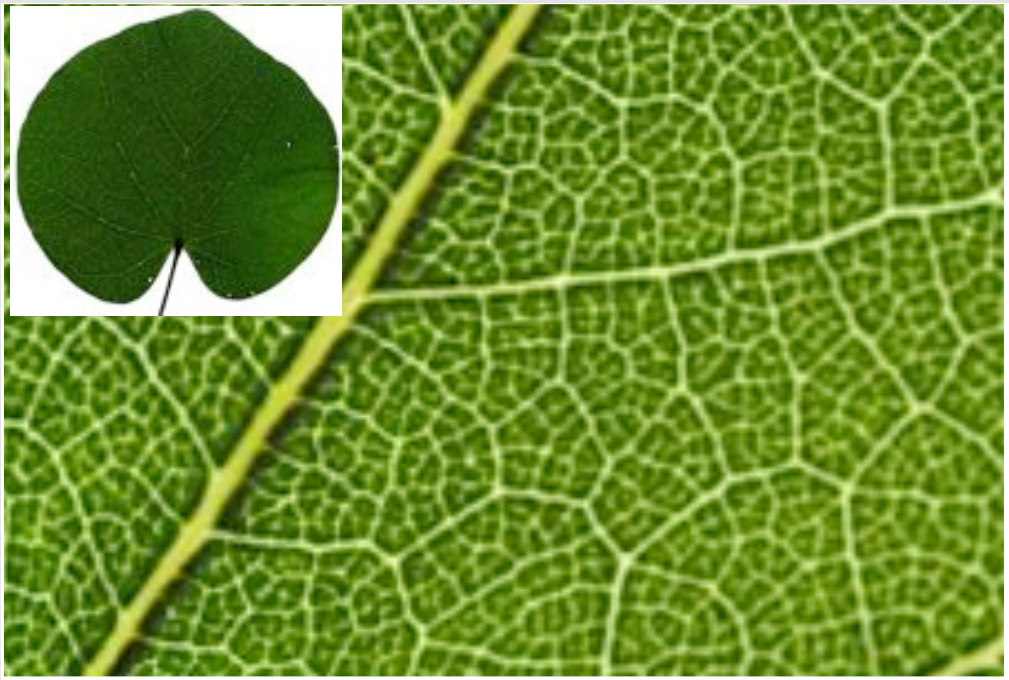
How cells perceive Auxin differences and/or fluxes ?

Santos et al. Plant Biology 2010

What can we say about it ?

Folds

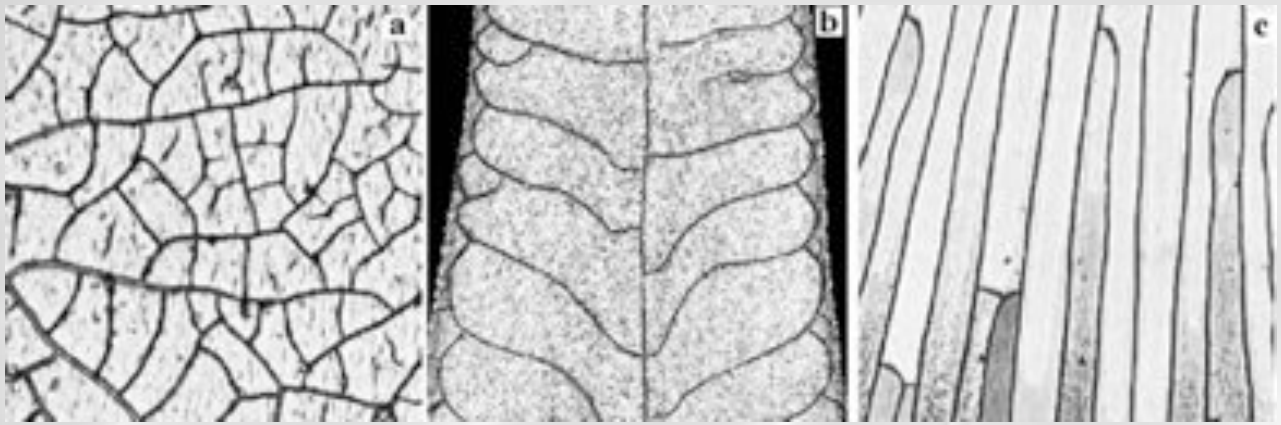




Schizophragma hydrangeoides reticulated

Visual analogy between venation & crack patterns

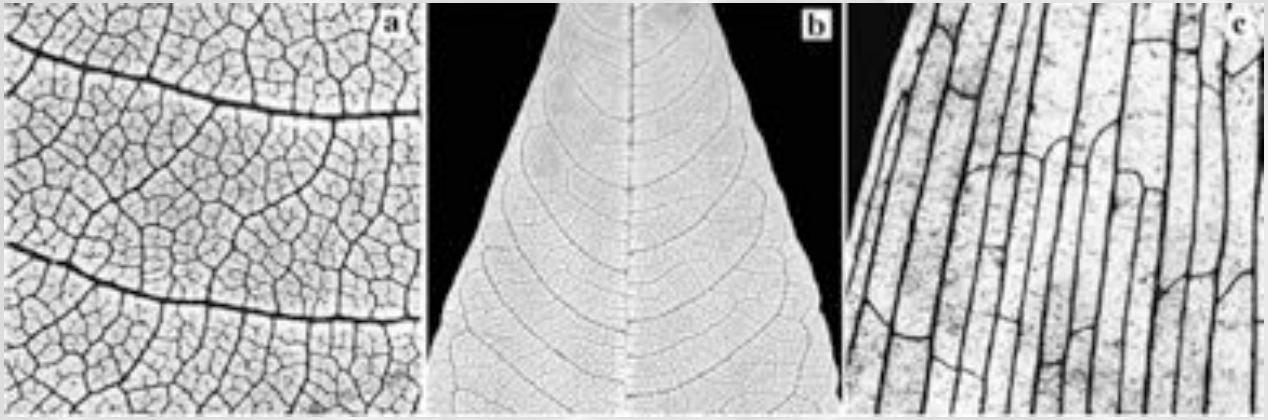
Crack Patterns



Pattern controlled by a tensorial field,

Couder et al., 2002

Venation Patterns

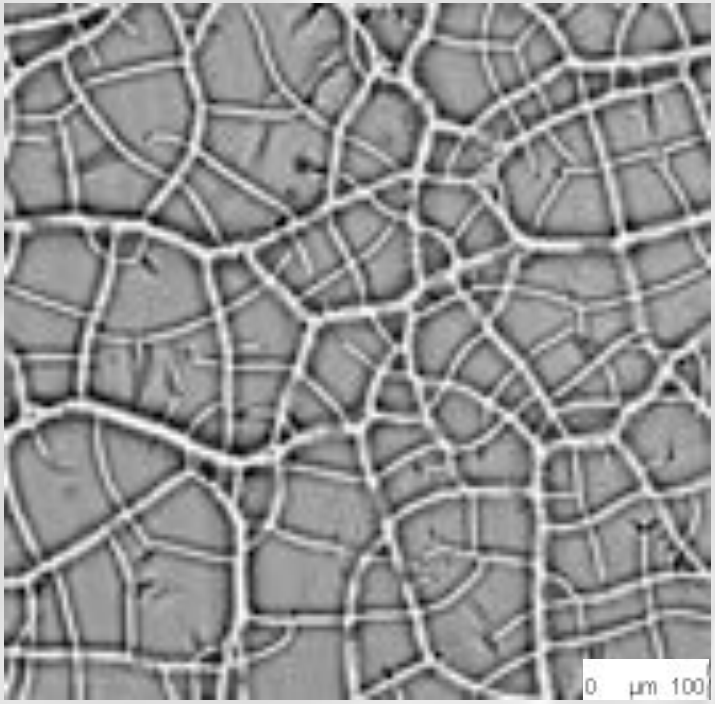


while [Auxin] is a scalar field.

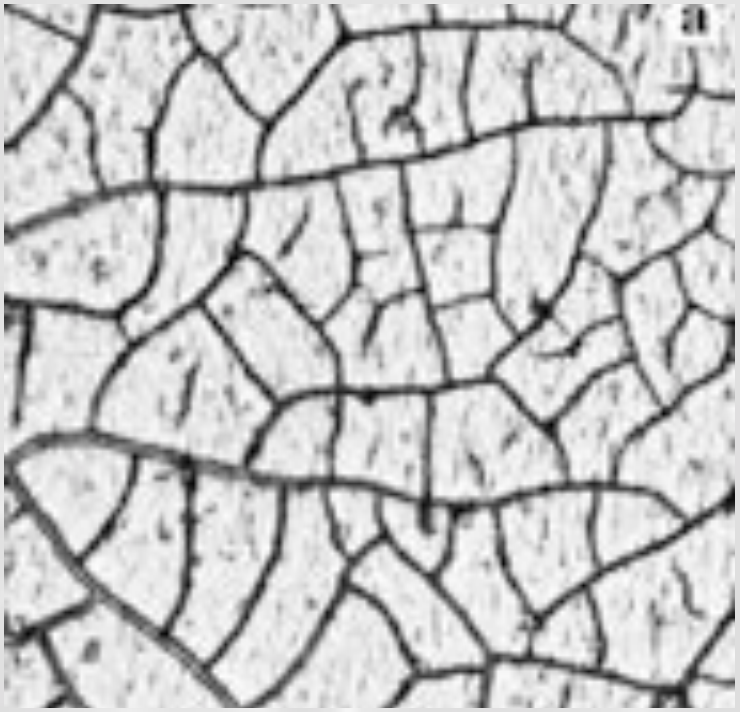
Is this field represented by mechanical stress ?

Visual analogy between Fold & Crack patterns

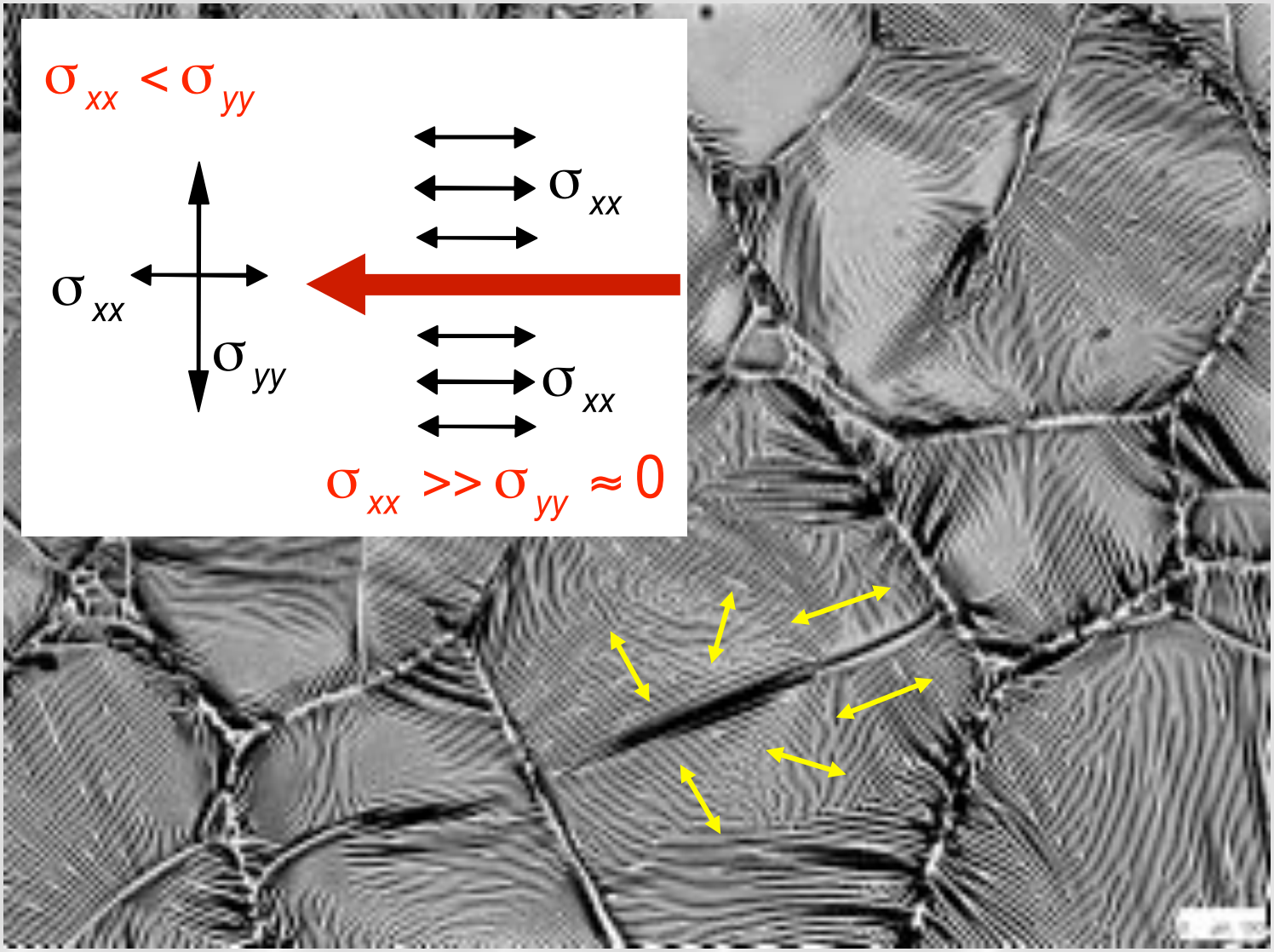
In compression



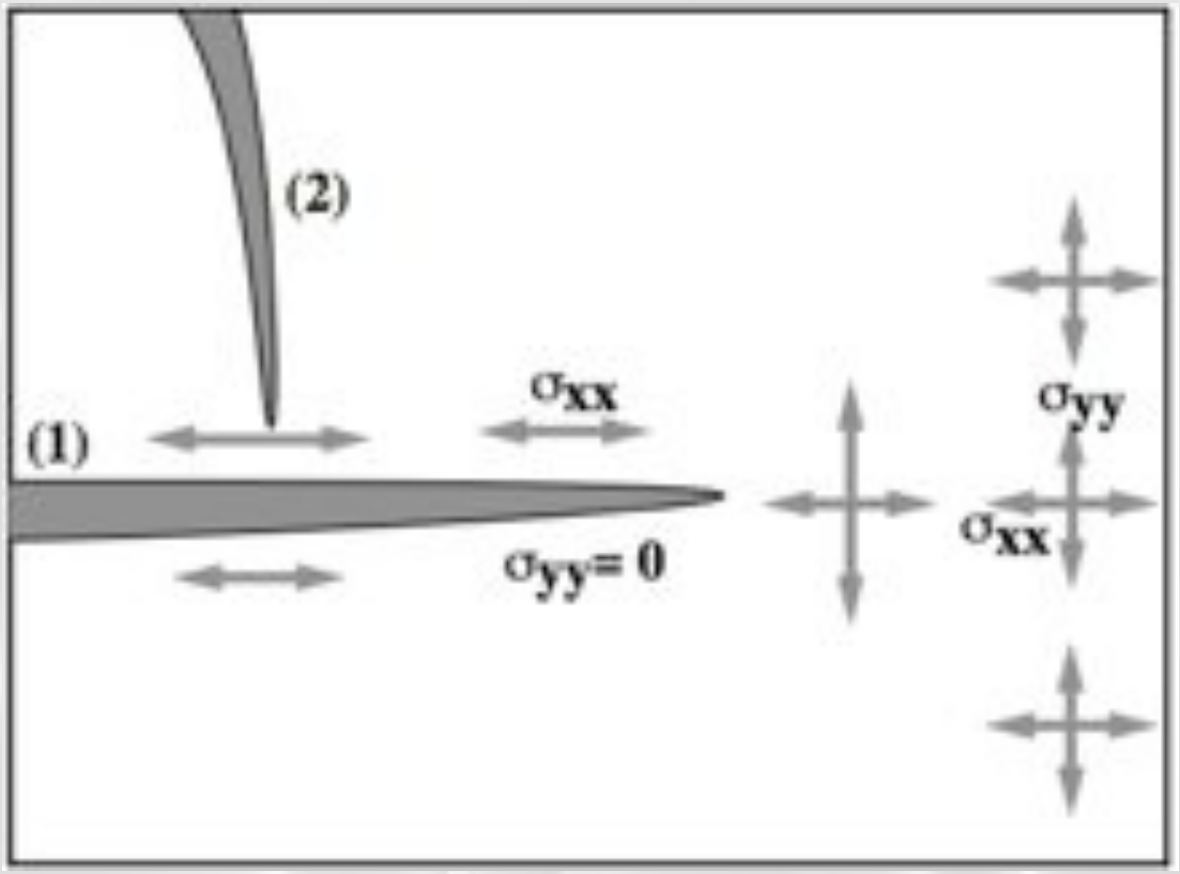
In tension



Reorganization of stress distribution: Visible thanks to the wrinkles !



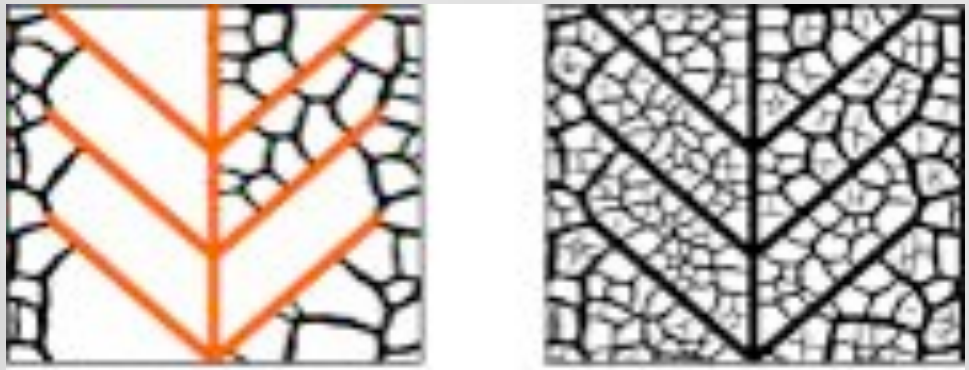
General mechanism to produce a pattern

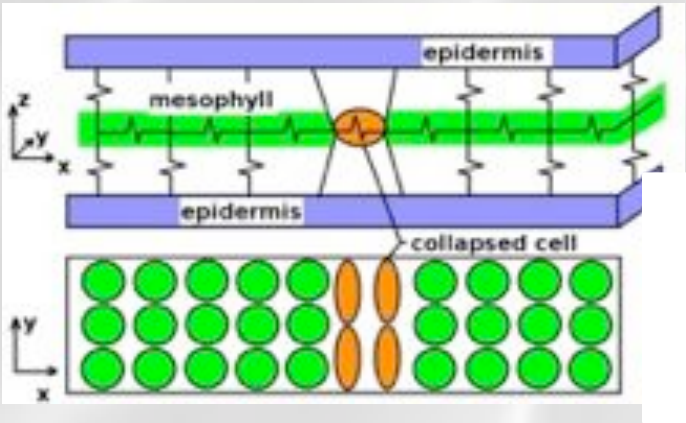


The **hierarchical division of space** is fundamentally linked to the **tensorial nature of the stress field** and t**he local and anisotropic release of stress**

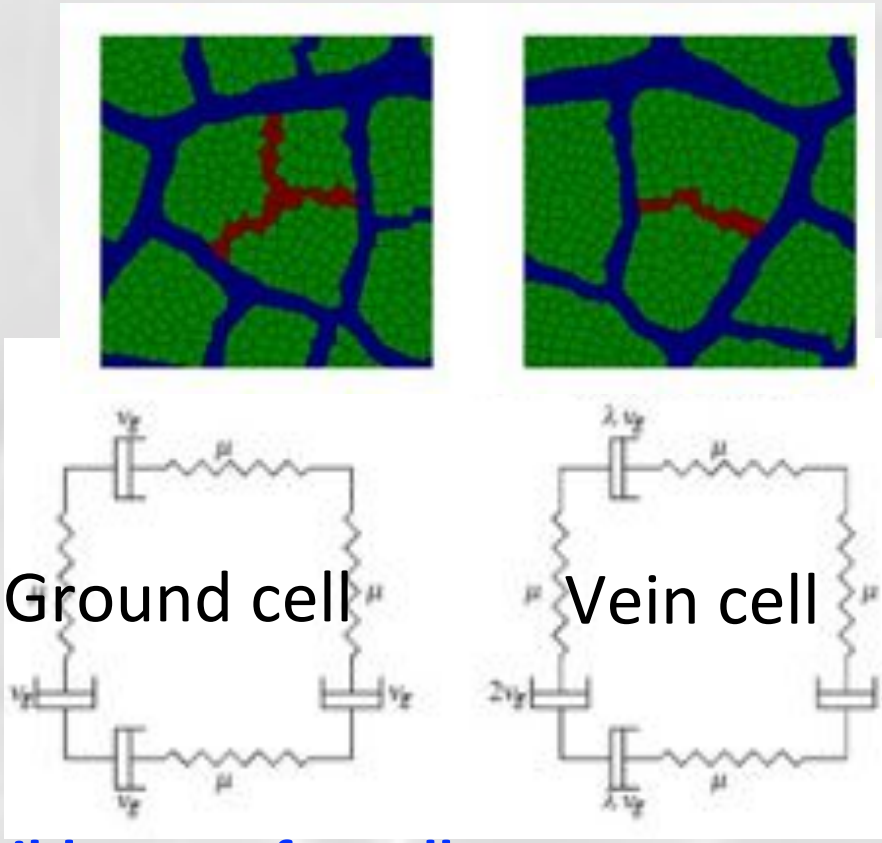
Venation in silico: stress release mechanism

Laguna *et al*, *PLoS Comput. Biol.* (2008)





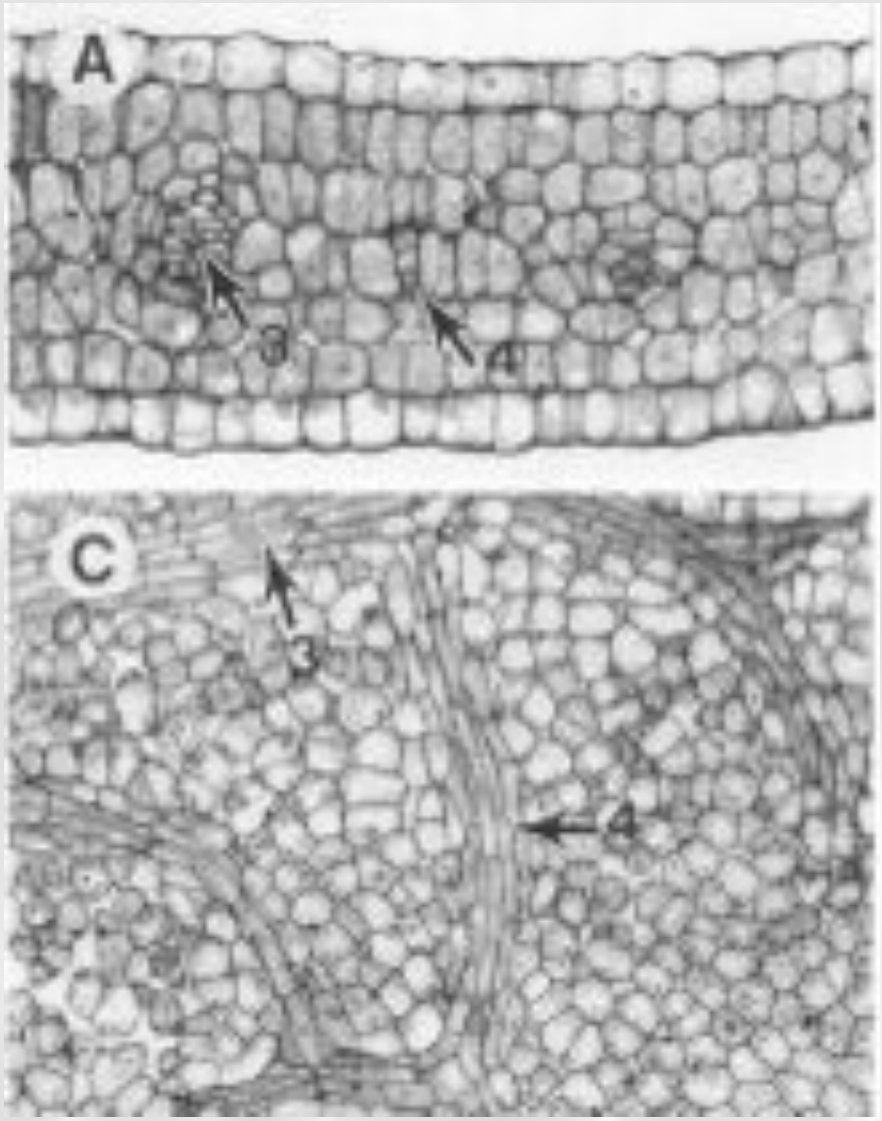
Corson *et al*, *J. Theor Biol* (2009)



- **Irreversible collapsible state for cells**
- **Different mechanical response between veins and ground cells**

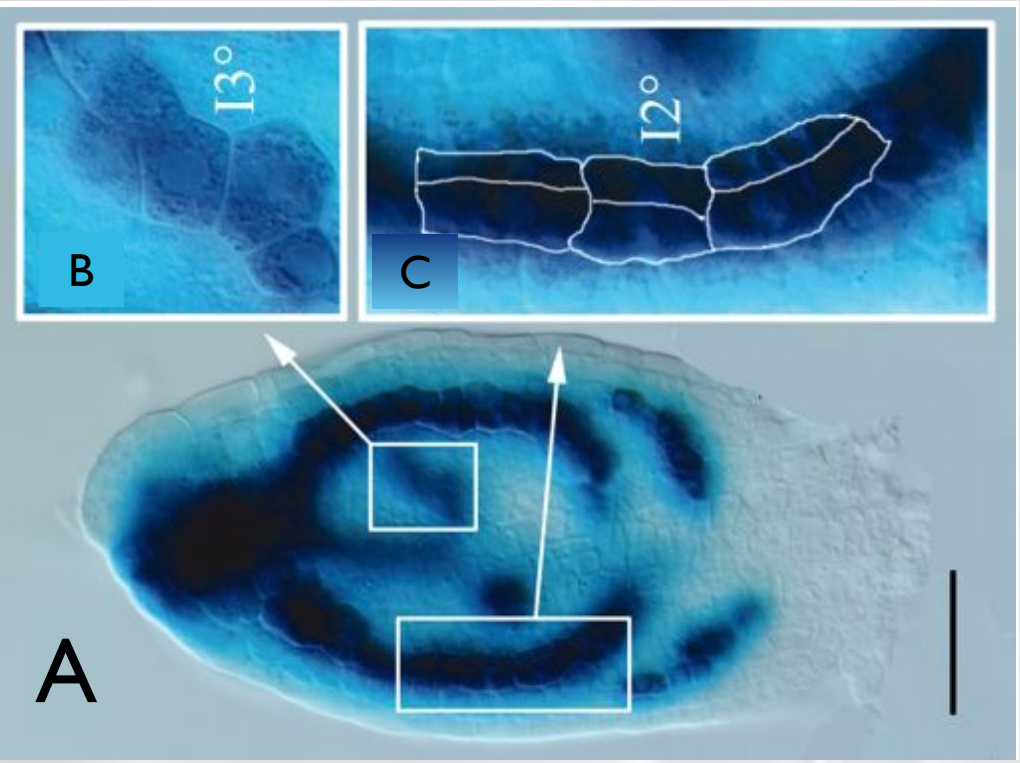
Produce a reticulated pattern. Collapse in leaves ?

Procambial cells are indeed collapsed



Nelson *et al*, *Plant Cell* (1997)

But an analogy is not an homology !

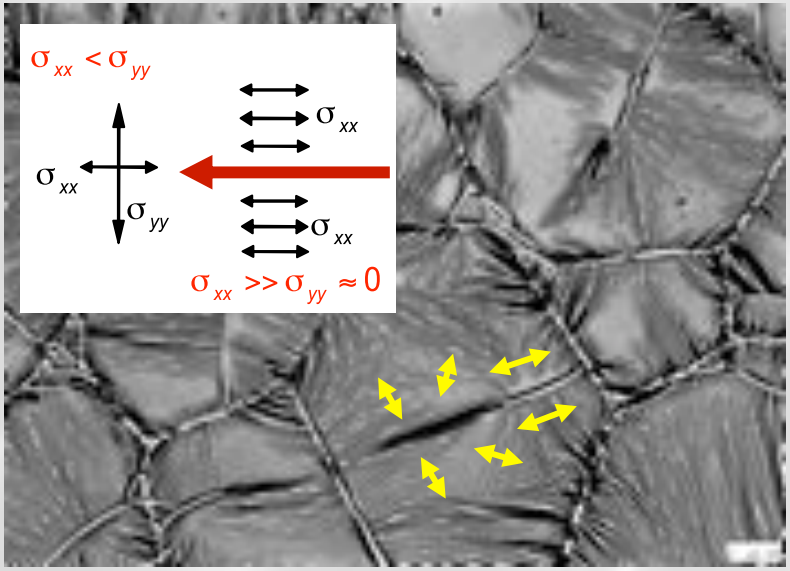


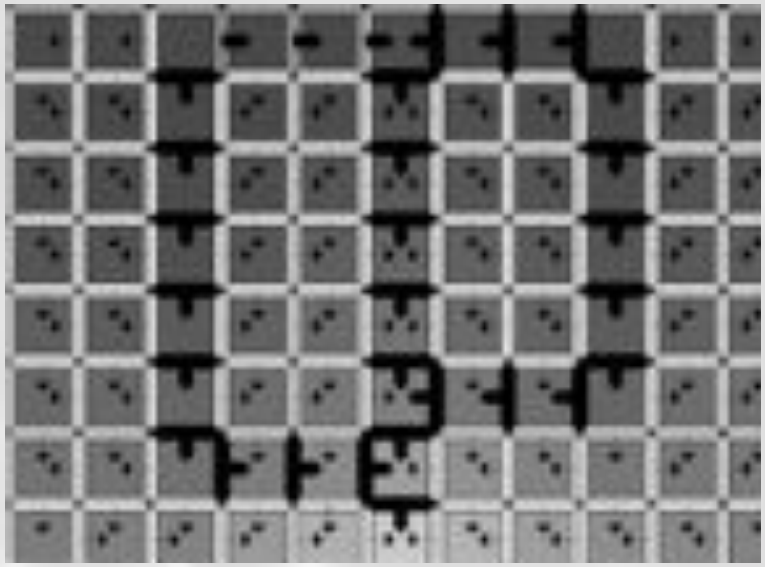
Other fields to take into consideration !

[Auxin] link to elasticity ?

If the stress field is not important
Why such resemblance ?

Stress ? vs Polar transport ?





Equivalent mathematically ?

What tensor ?

stress tensor

$$\sigma_{ij}$$

permeability tensor

$$\kappa_{ij}$$

A vein modifies locally and anisotropically the permability tensor to Auxin

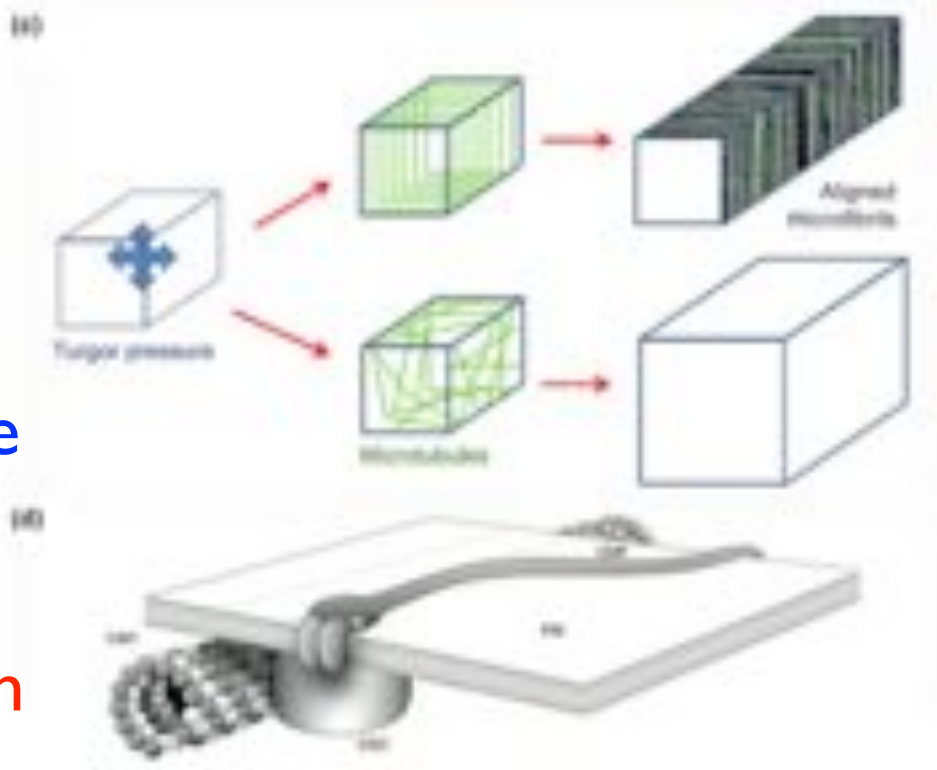
Link between transport and stress ?

Role of Auxin and its transport ?

Auxin controls local growth

Cells have microtubules
They align with stress or before division

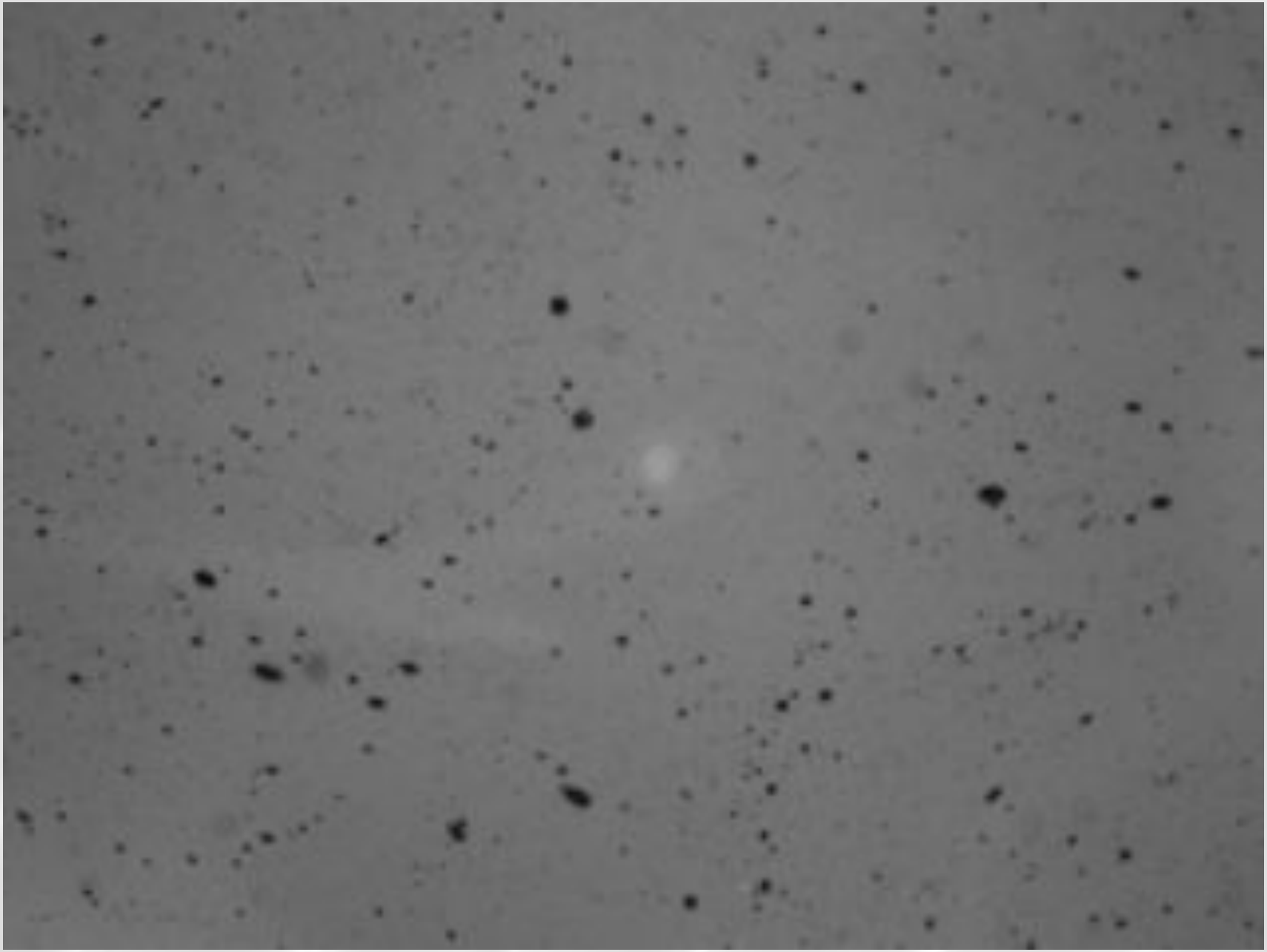
Anisotropic response to growth and to permeability ?



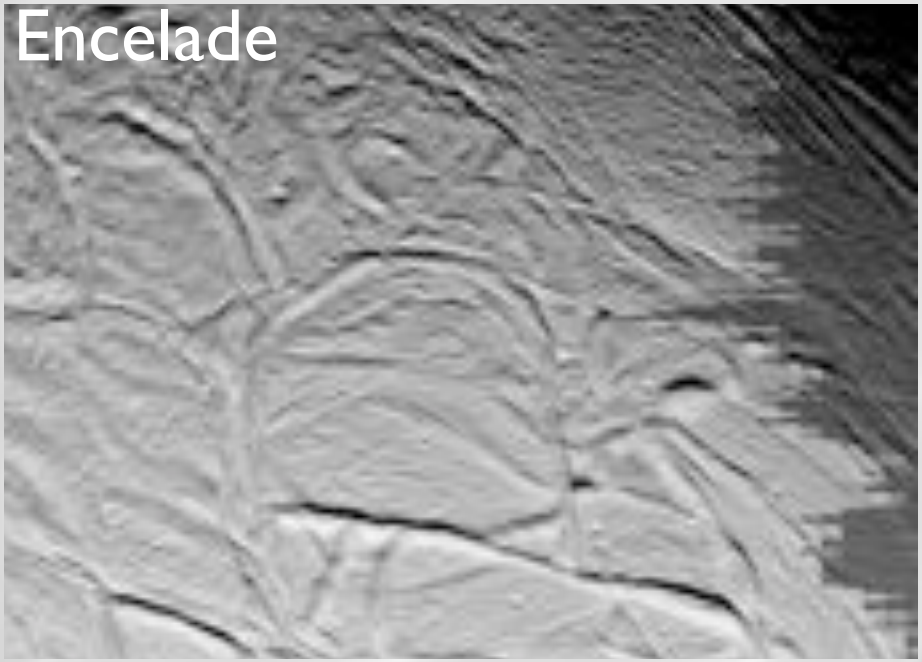
Hamant and Traas, 2010

What do you think ?

Canalization hypothesis realized in a foam ?



Delamination network



Source : NASA/JPL/Space Science Institute