MODELLING GROWTH: HYDRAULICS AND MECHANICS

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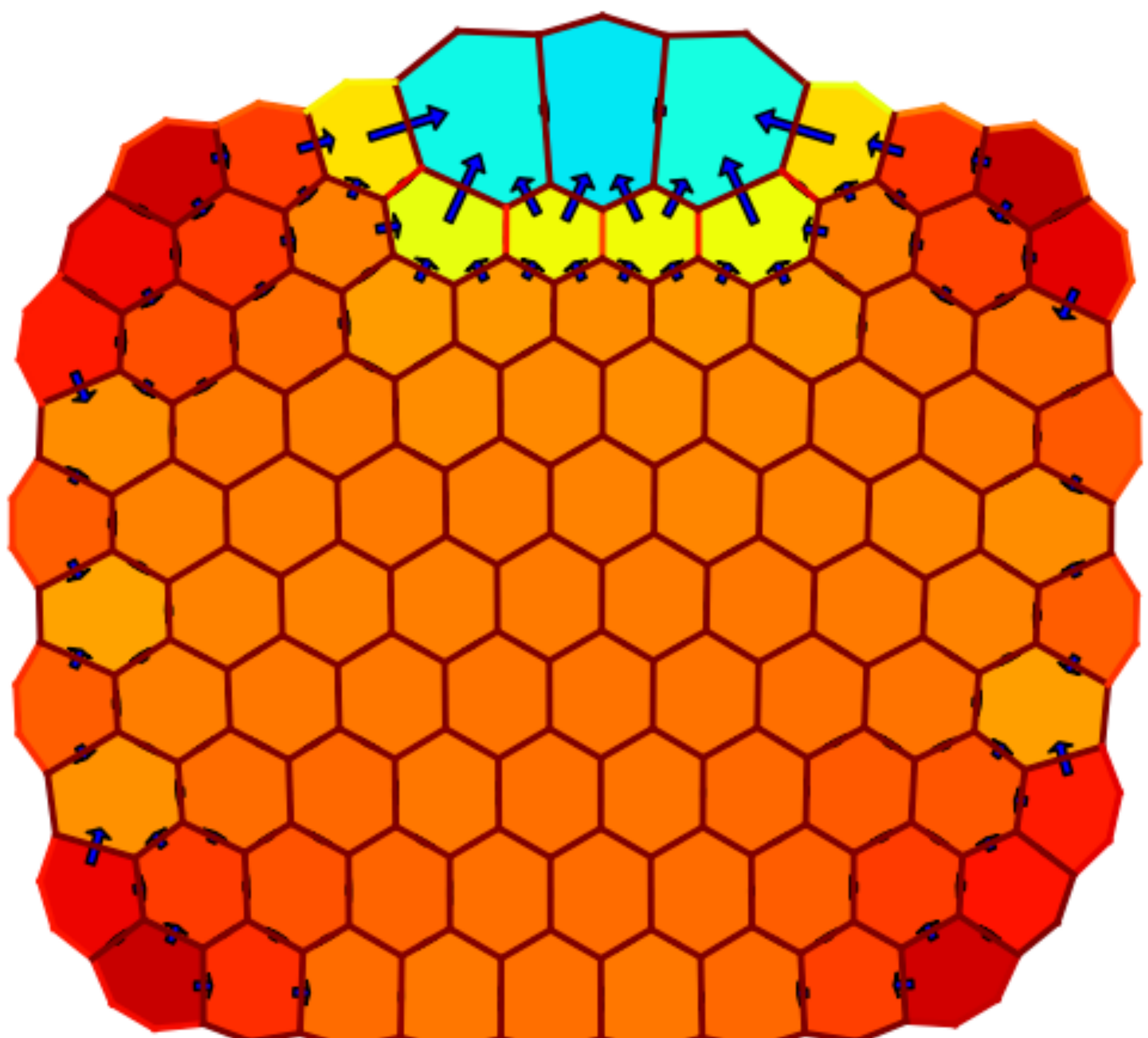
HORTIMODEL 2016

19-22 september, Avignon

INRA SCIENCE & IMPACT
PSH

Inria INVENTEURS DU MONDE NUMÉRIQUE
Virtual Plants



agropolis fondation
Supporting agricultural research for sustainable development

PLANTS ARE **UNDER PRESSURE** THANKS TO **WATER FLUXES**

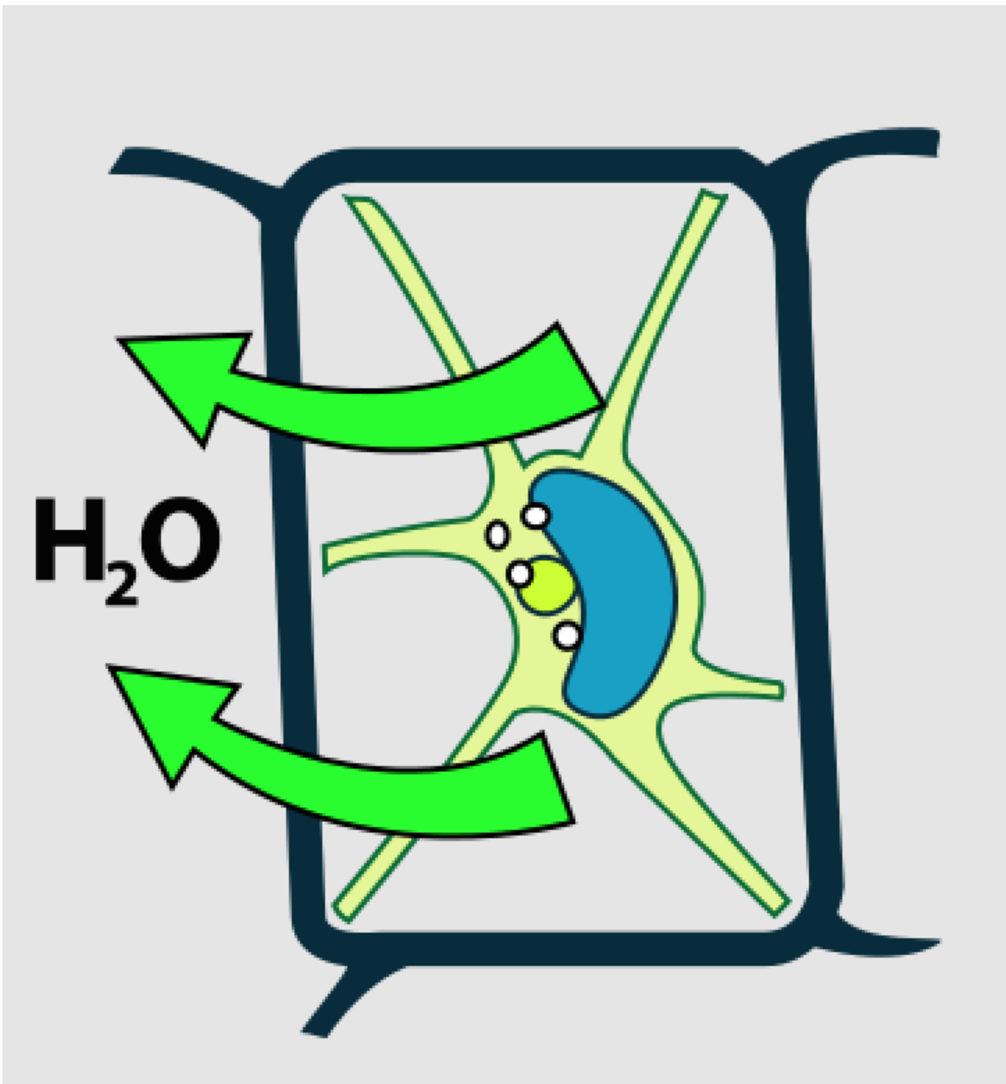
Water stress

After a few hours

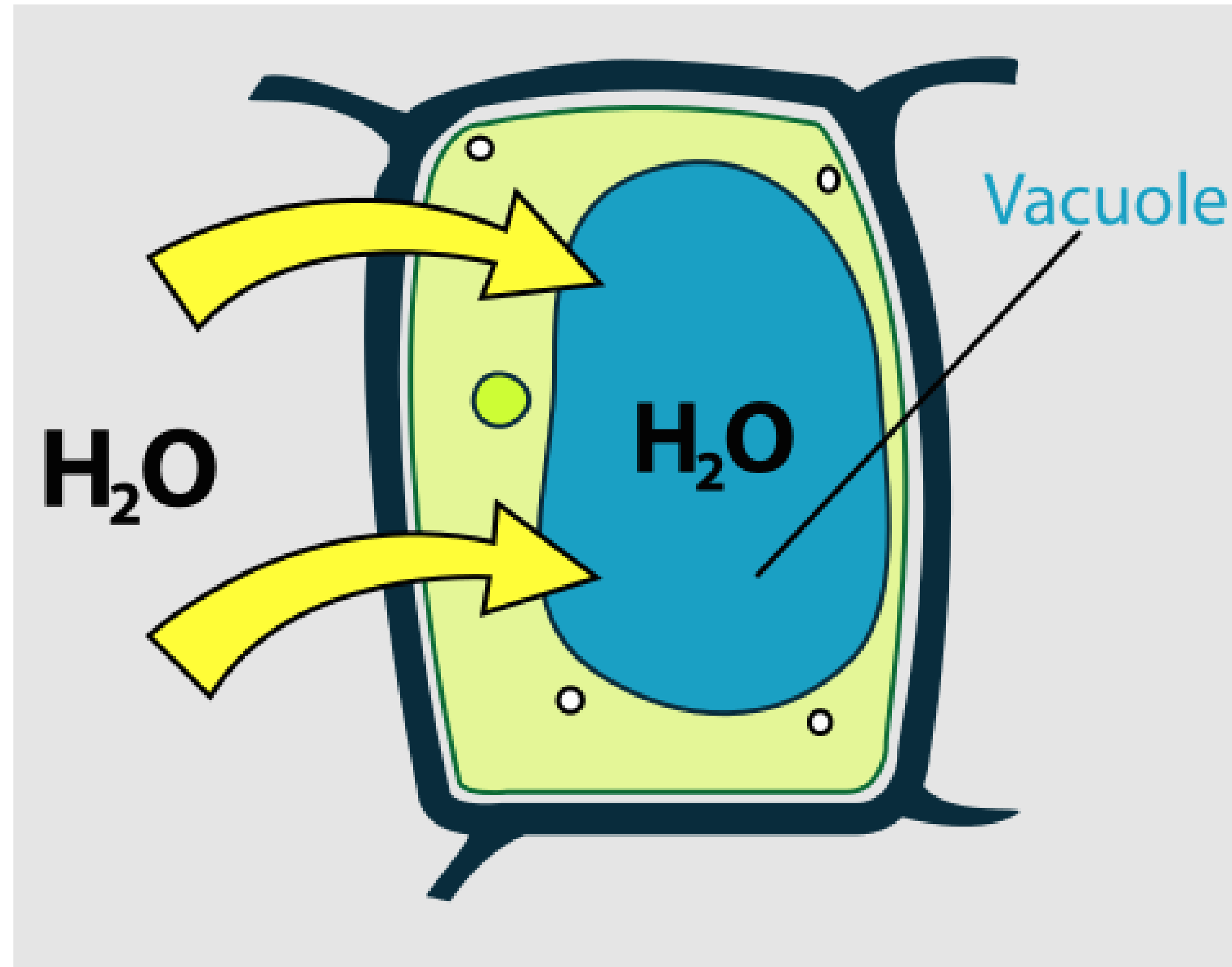
Water fluxes $\longleftrightarrow$ **Turgor**

PLANTS ARE **UNDER PRESSURE** THANKS TO **WATER FLUXES**

Cell scale:



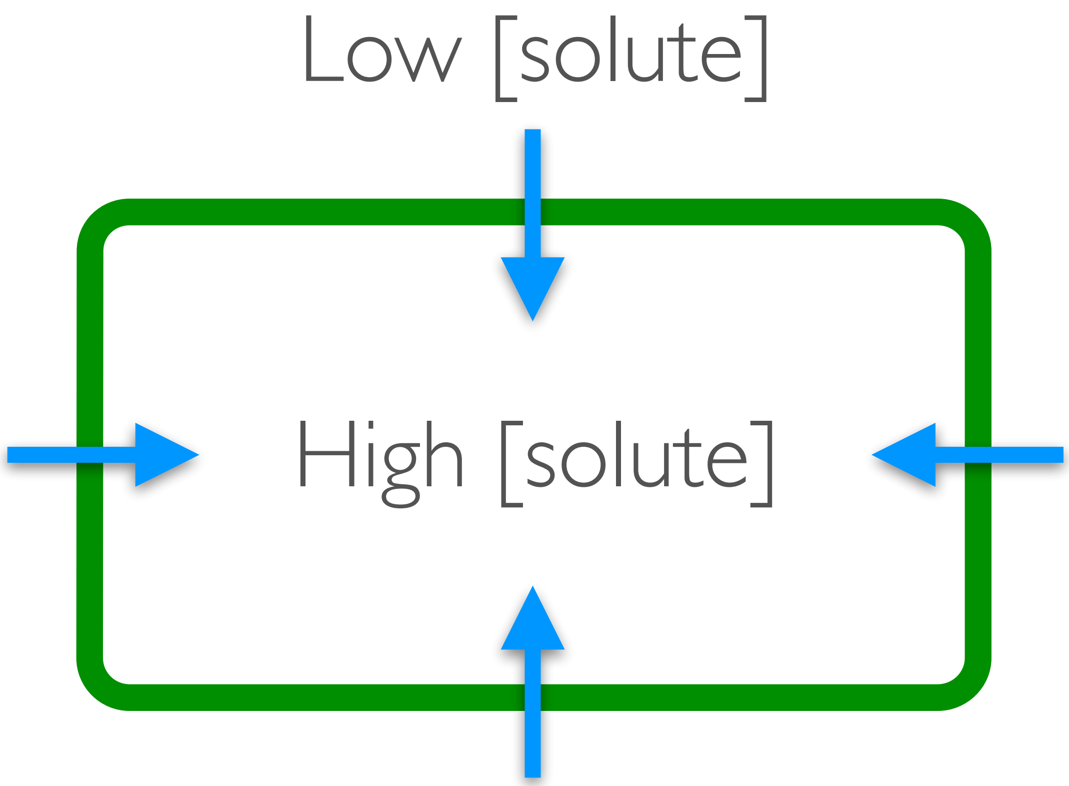
Plasmolyzed



Turgid

Water fluxes $\longleftrightarrow$ **Turgor**

OSMOSIS, TURGOR, AND GROWTH



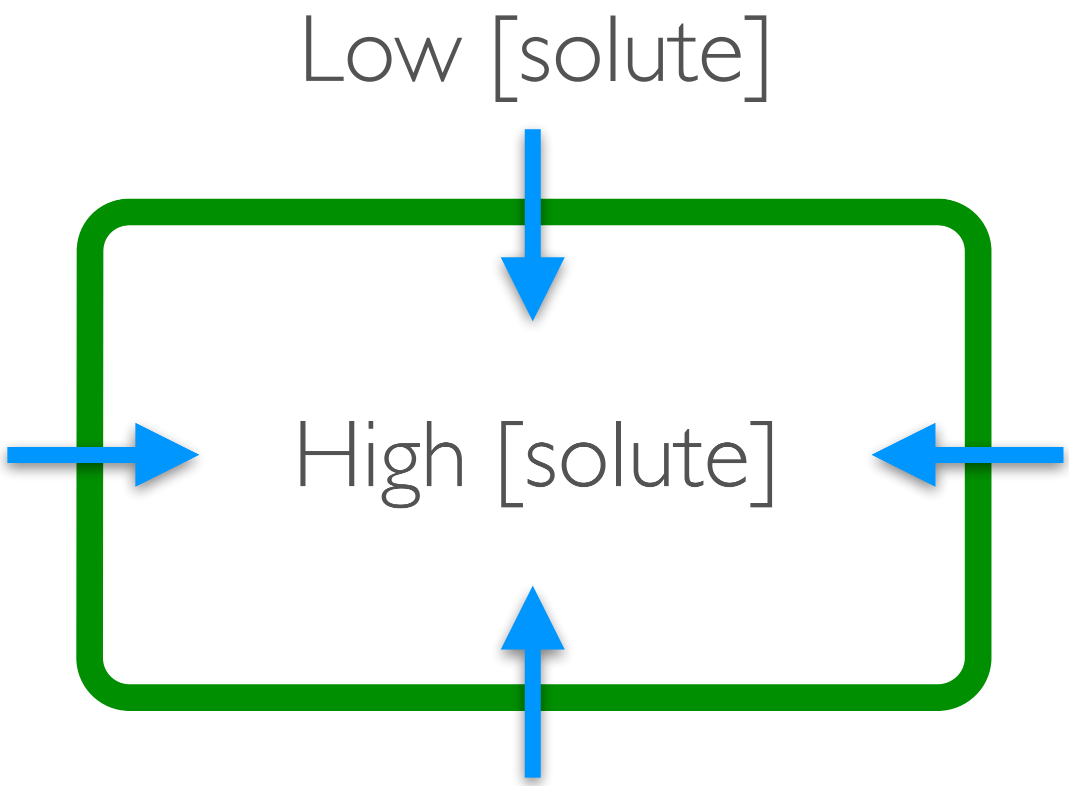
Osmosis = **motor** for **fluxes**

vs

Walls = **resistance** to growth

⇒ **Turgor**

OSMOSIS, TURGOR, AND GROWTH



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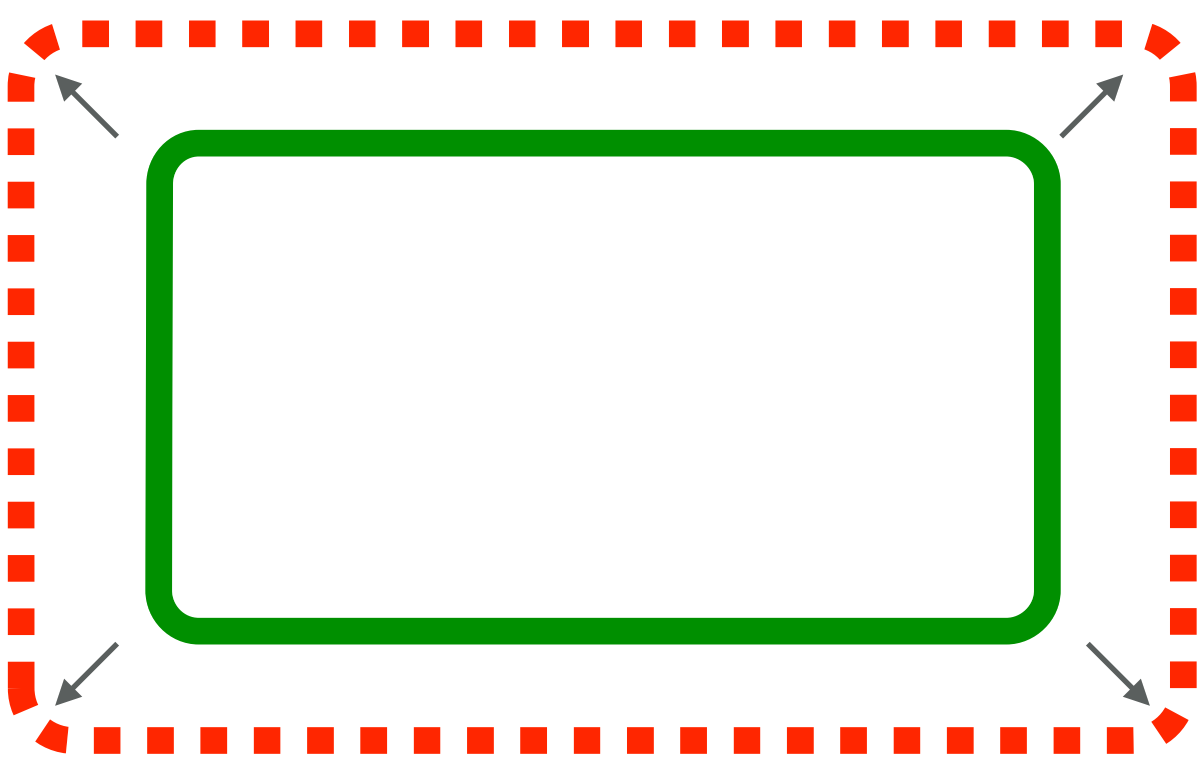


Growth = **simultaneous**
water flux **and** **wall enlargement**

LOCKHART (1965) AND ORTEGA (1985) MODELS

$$\Psi_{ext}$$

$$\boxed{\Psi = P - \pi}$$

Water flux into the cell:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = AL(\Psi_{ext} - \Psi)$$

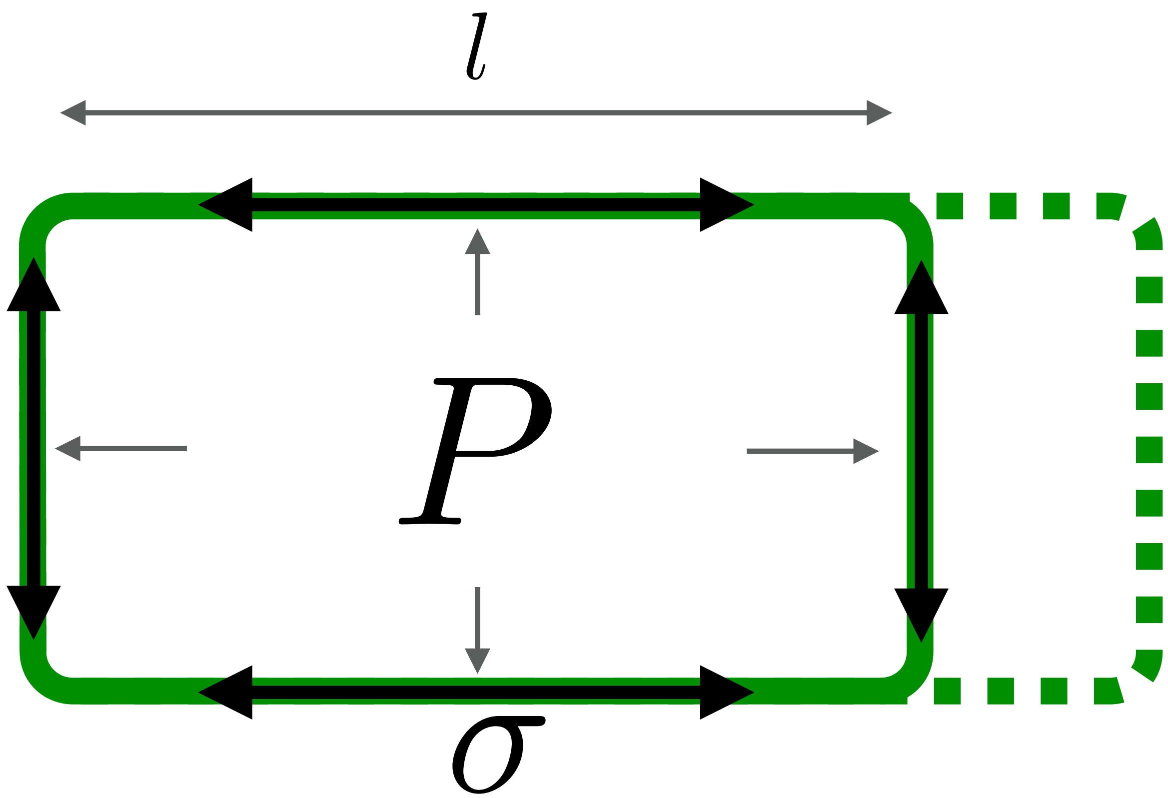
From **high to low water potential**

Ψ: water potential
P: hydrostatic pressure
π: osmotic pressure

A: cell area
L: water conductivity

LOCKHART (1965) AND ORTEGA (1985) MODELS

Growth in one direction



Mechanical equilibrium
between **cell turgor** P
and **wall stress** σ **:**

$$P \propto \sigma$$

Wall enlargement:

$$\frac{1}{l}\frac{\mathrm{d}l}{\mathrm{d}t} = \frac{1}{E}\frac{\mathrm{d}P}{\mathrm{d}t} + \phi(P - P^Y)$$

Elongation rate | **Elastic response** | **Wall synthesis**

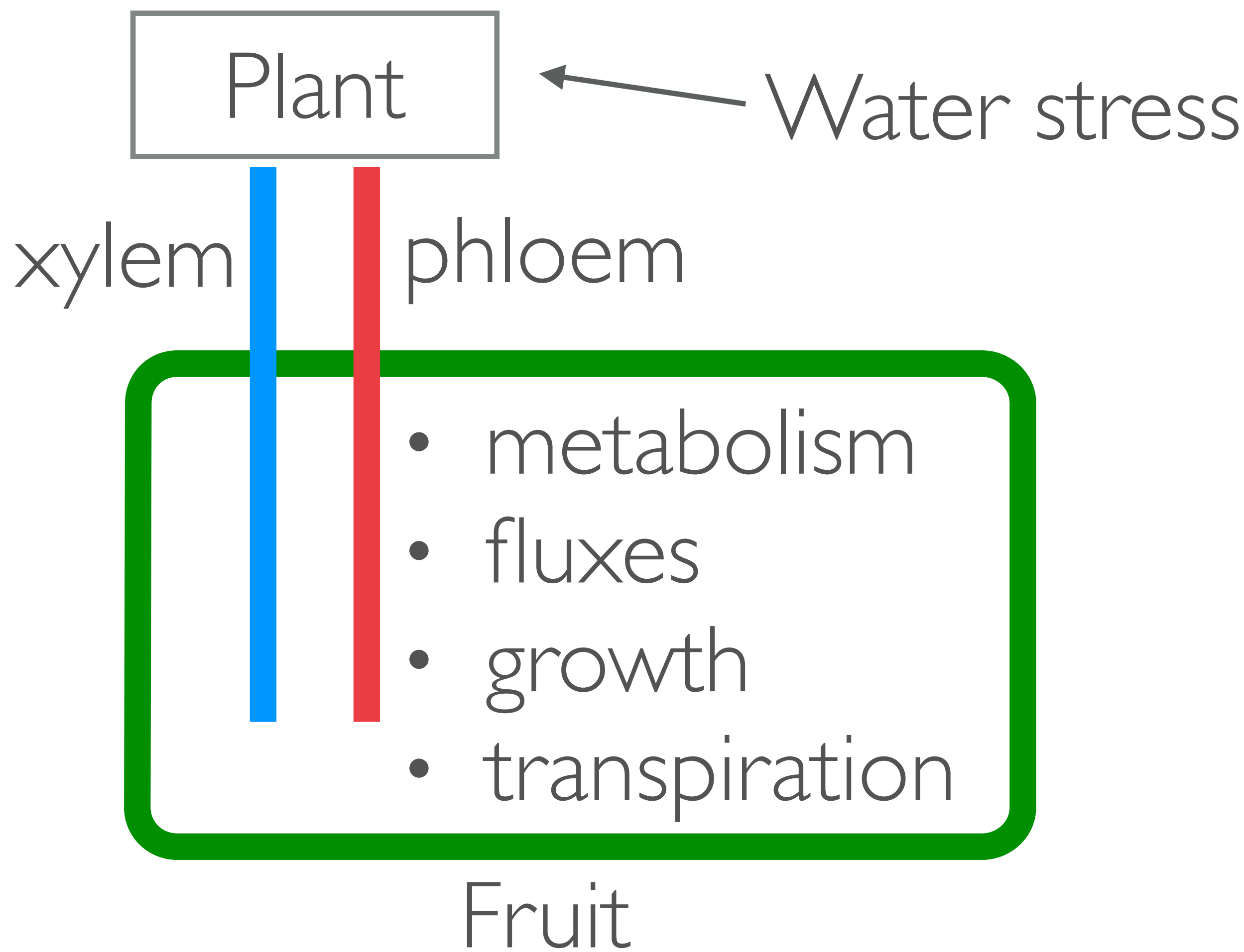
E: elastic modulus
ϕ: extensibility
P^Y: threshold turgor

Simple geometry ⇒ **easy coupling and resolution**

LOCKHART (1965) AND ORTEGA (1985) MODELS

- Theoretical framework to understand plant growth
- Flux ↔ turgor ↔ growth ↔ wall enlargement
- Very useful to interpret experimental data
- Extended to larger scales: organ = 1 compartment

  e.g [Fishman-Génard (1998)]:



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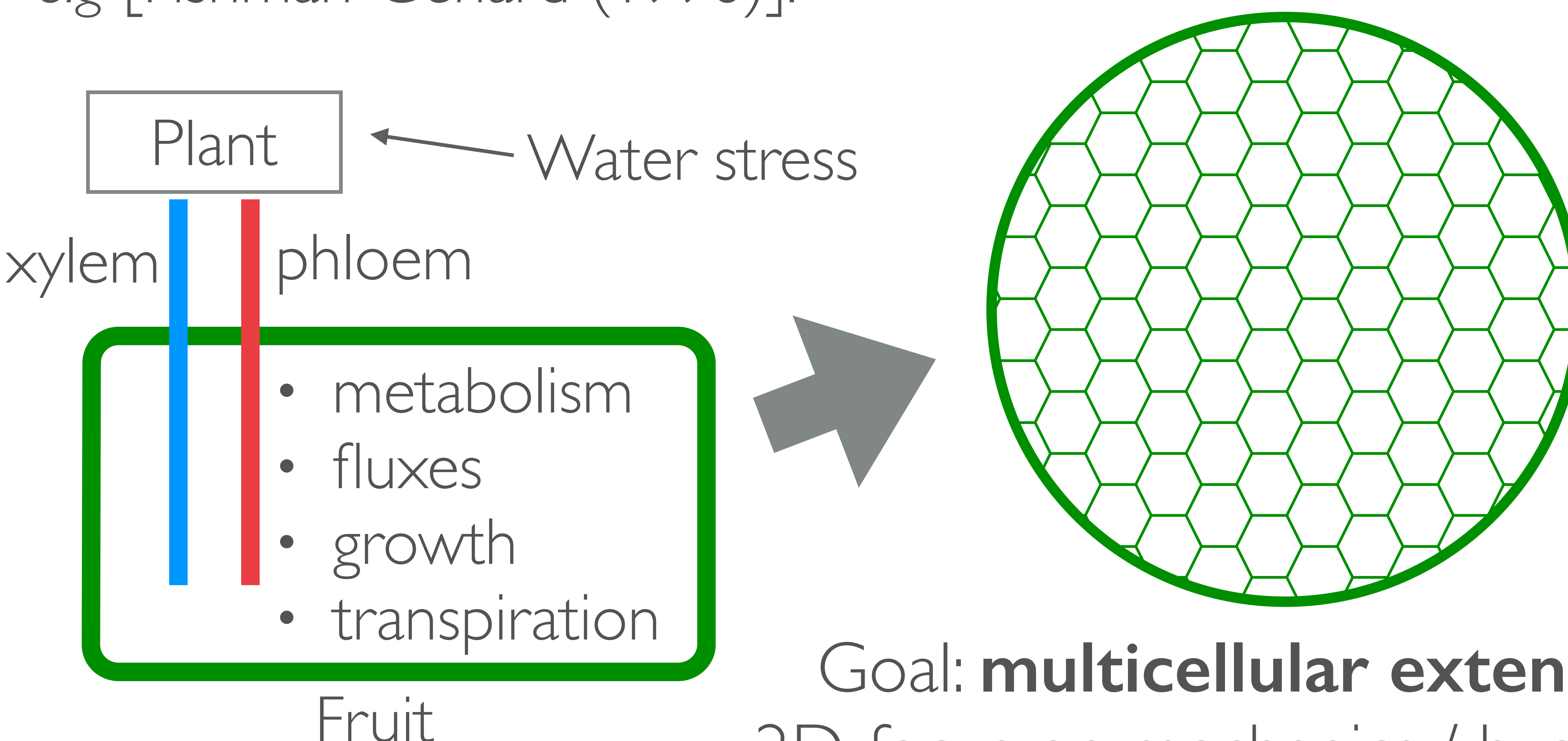
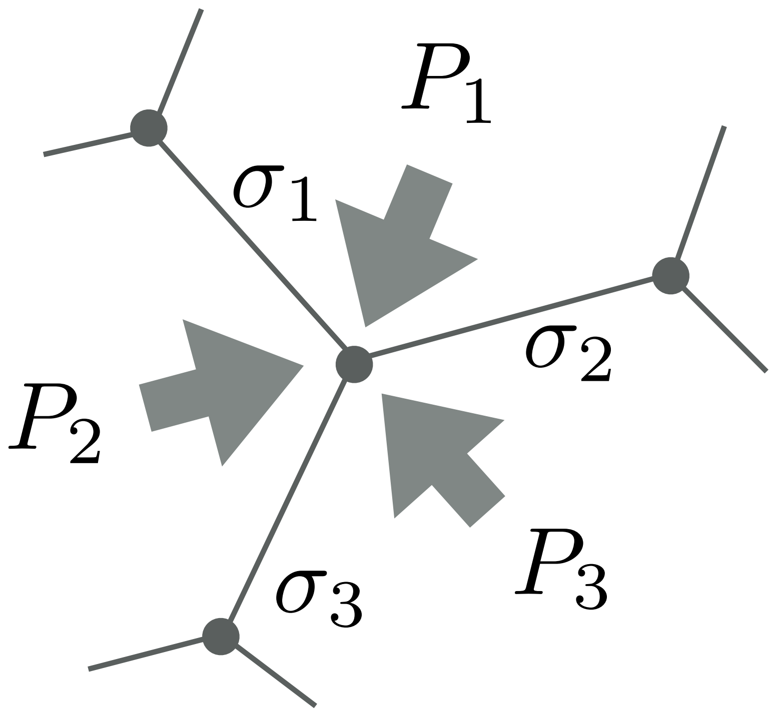


Goal: **multicellular extension**

2D, focus on mechanics / hydraulics

CELL WALL MECHANICS

- **Mechanical equilibrium** on vertices



P_i : pressures of the **cells**
σ_k : elastic stresses of the **walls**

Balance for each vertex:

$$\frac{1}{2}\sum_i P_i l_i \vec{n}_i + \sum_k \sigma_k w \vec{e}_k = \vec{0}$$

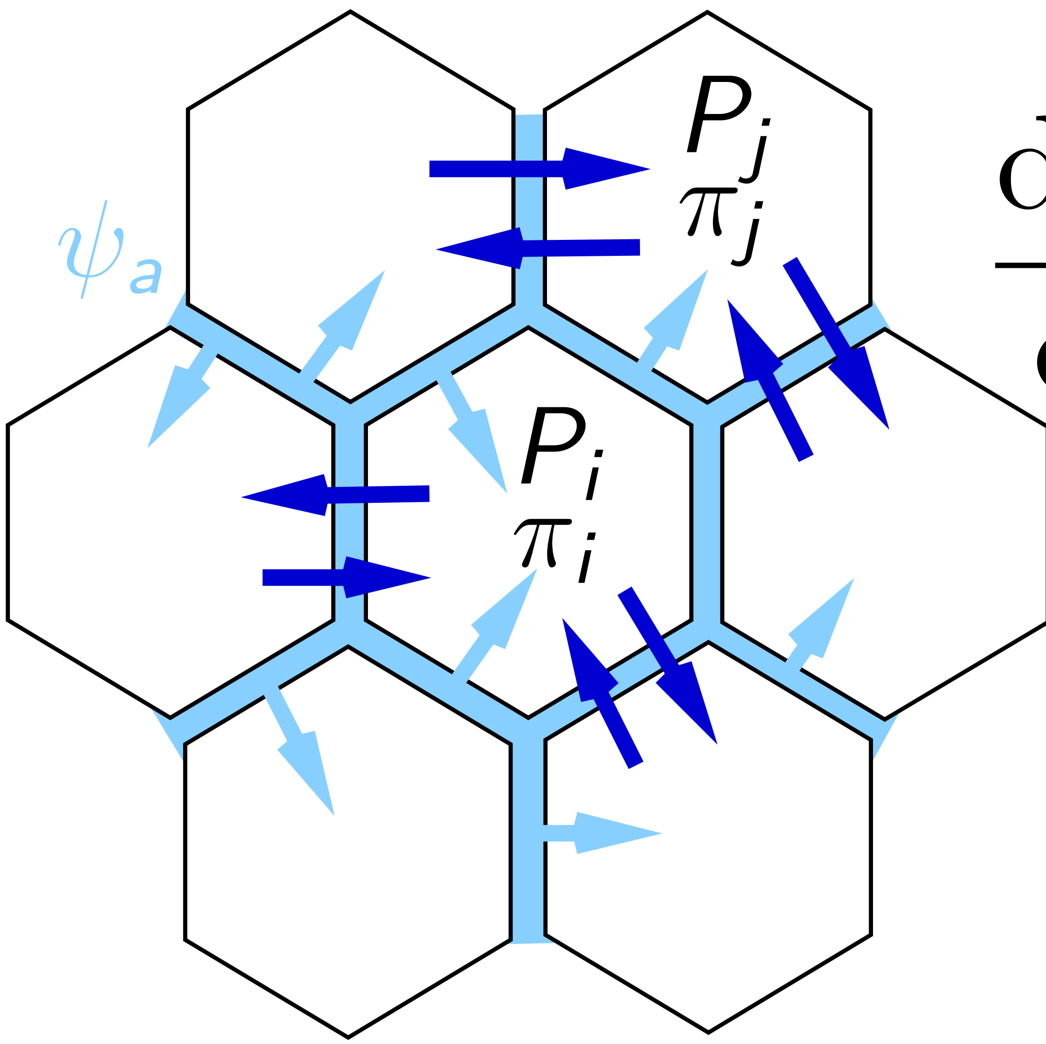
$\vec{e}_k, \vec{n}_i$: tangential and normal vectors
l_i, w : length and width of the walls

- **Wall enlargement**

$$\frac{1}{l_k}\frac{\mathrm{d}l_k}{\mathrm{d}t} = \frac{1}{E_k}\frac{\mathrm{d}\sigma_k}{\mathrm{d}t} + \phi_k(\sigma_k - \sigma_k^Y)$$

Elongation rate — **Elastic** response — Wall **synthesis** — Yield stress

APOPLASMIC AND **SYMPLASMIC** FLUXES



$$\frac{\mathrm{d}V_i}{\mathrm{d}t} = A_i L^a(\psi^a - (P_i - \pi_i)) + \sum_j A_{ij} L^s (P_j - P_i)$$

π_i are assumed **constant**

P_i, P_j : turgor pressures

π_i: osmotic pressure

A_i : area of cell *i*

A_{ij} : area between cells *i* and *j*

L^a : apoplasmic conductivity

L^s : symplasmic conductivity

ψ^a : water potential of the apoplasm

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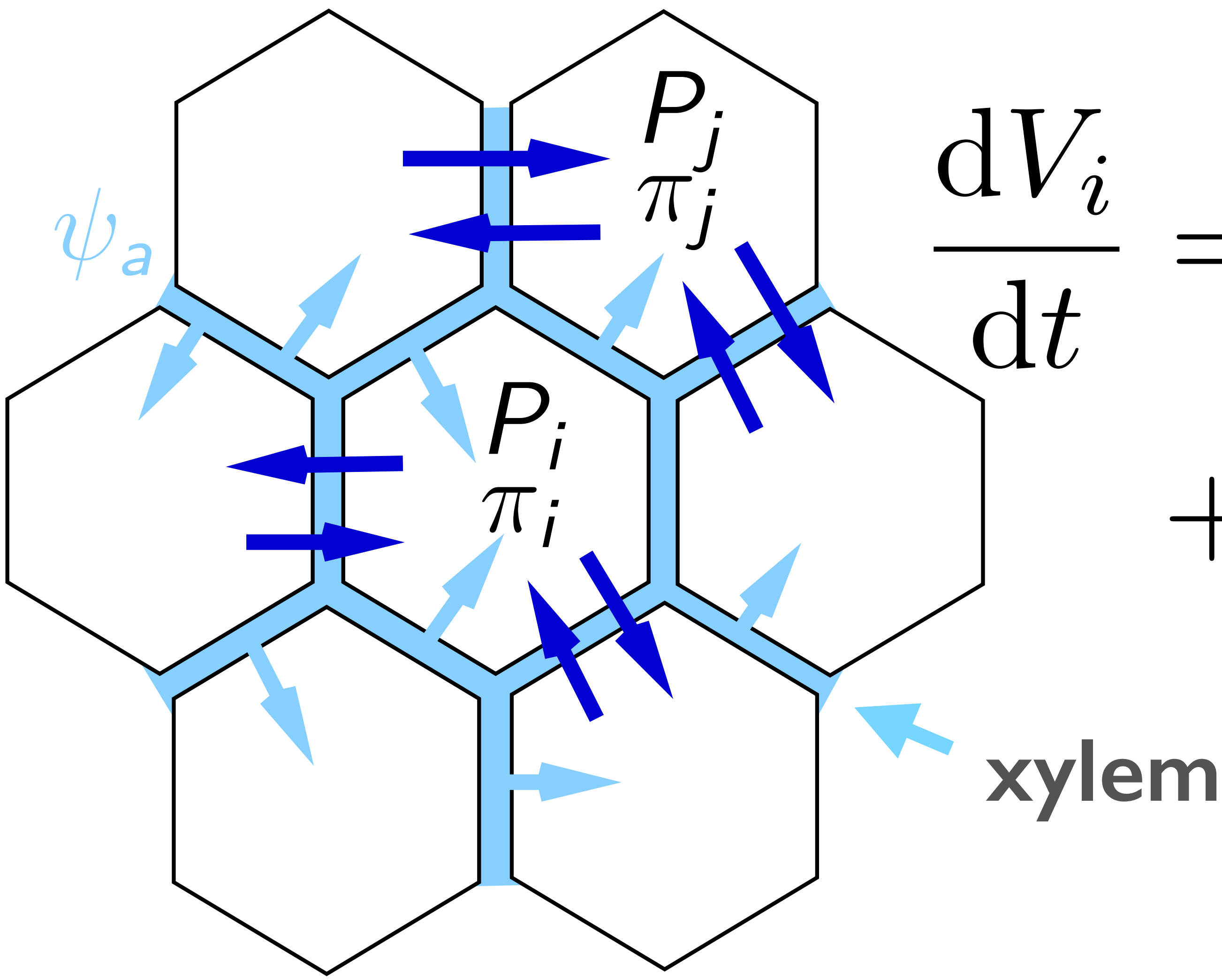

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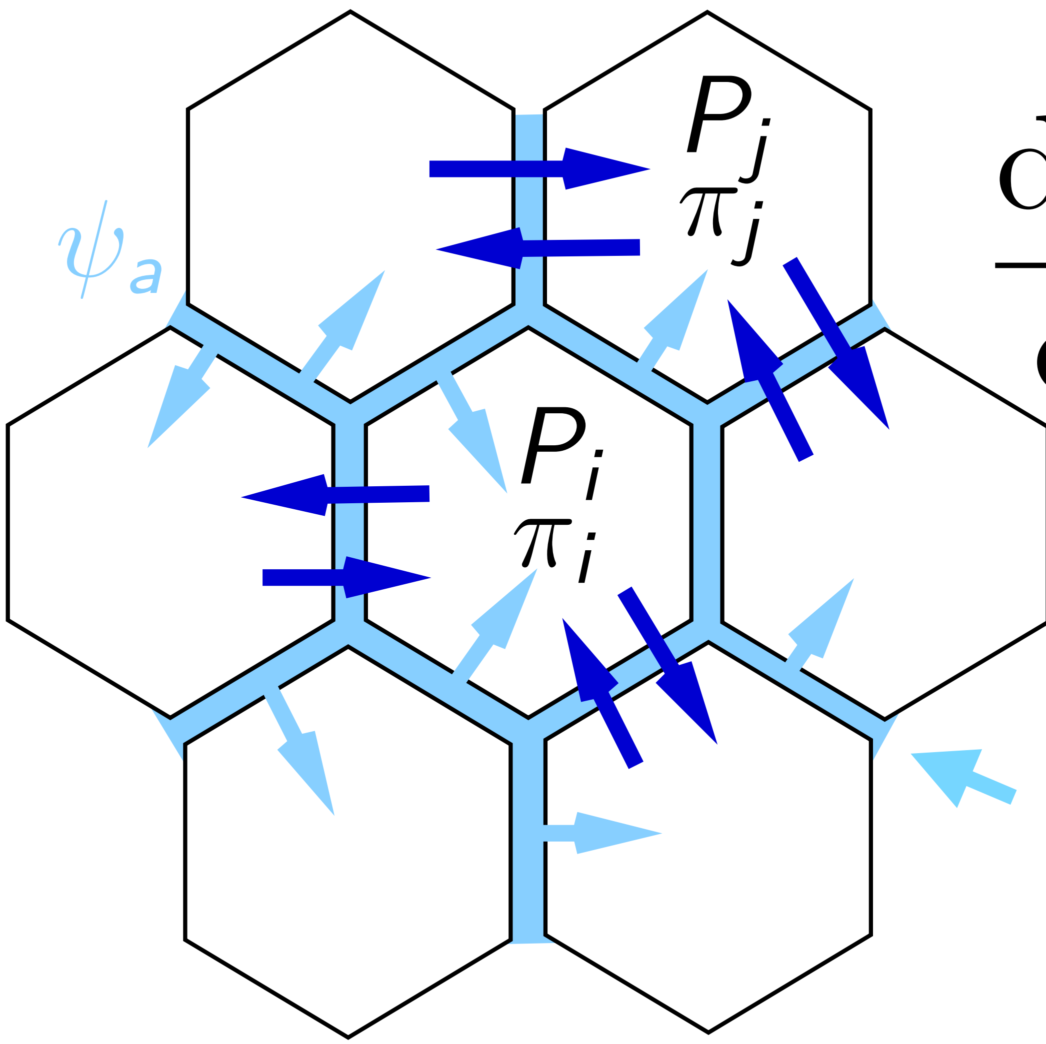

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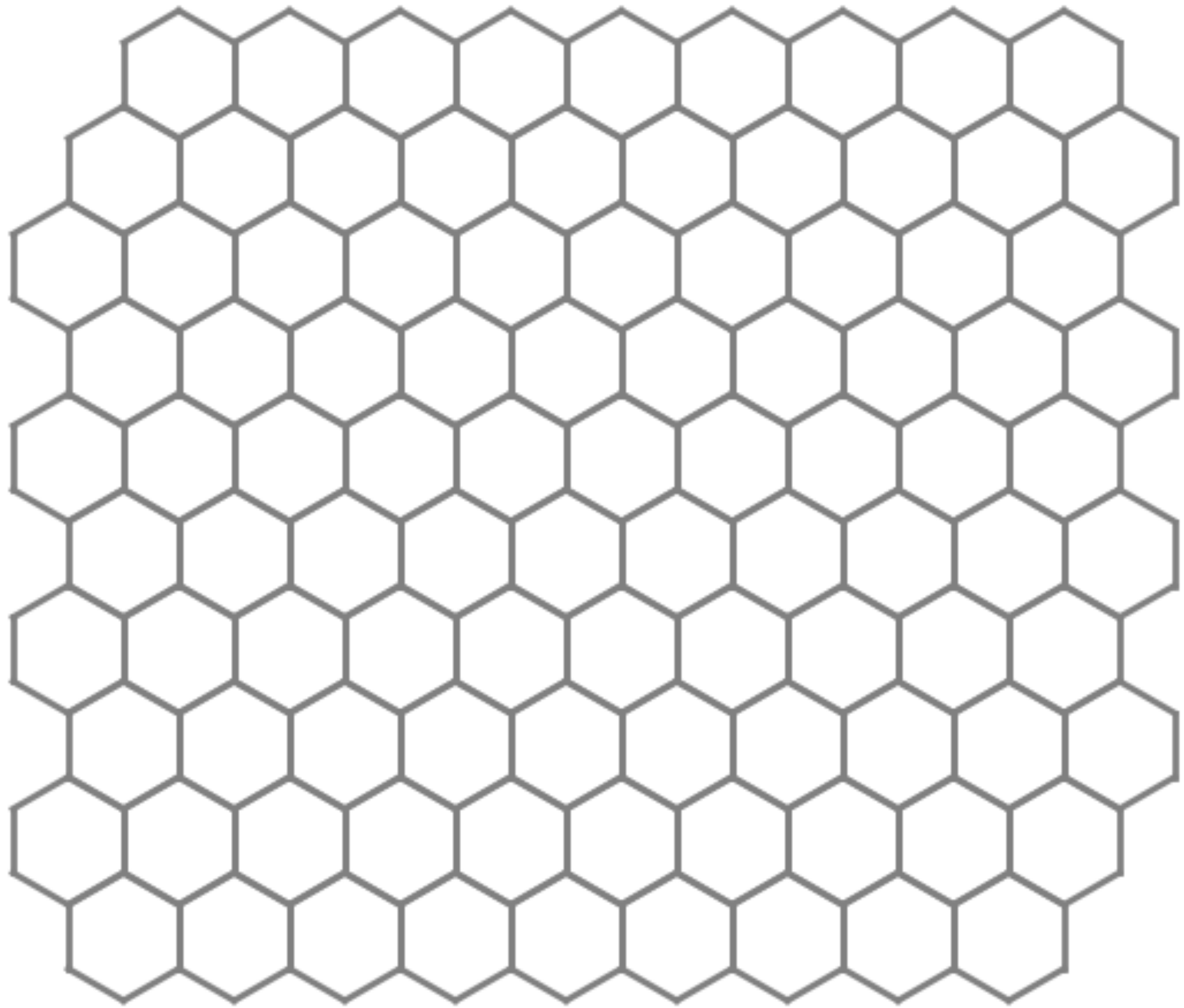
Numerical resolution!

FIRST EXAMPLE



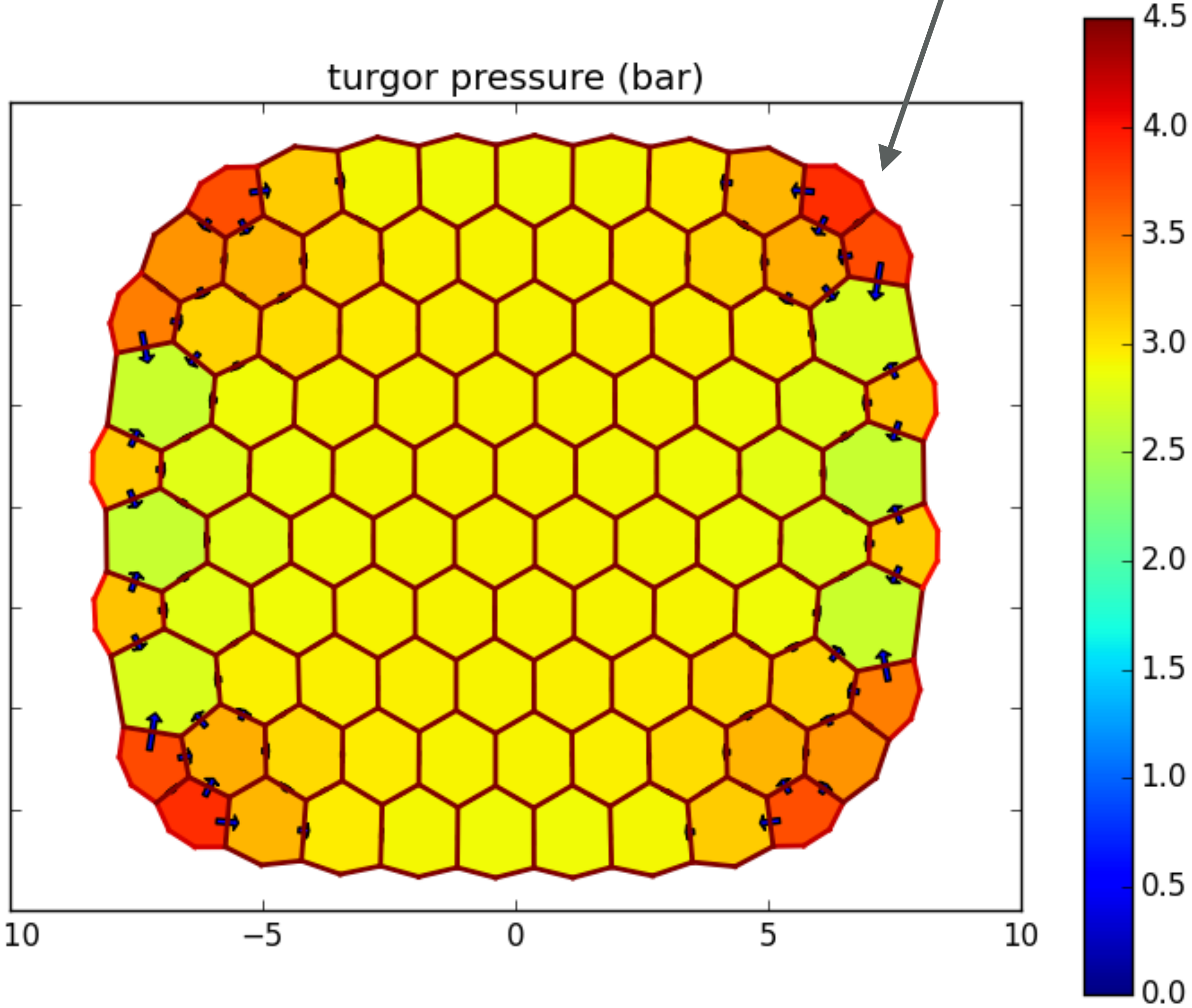
- Homogeneous parameters
- Realistic values
- Global growth rate ~ 2% per hour

FIRST EXAMPLE

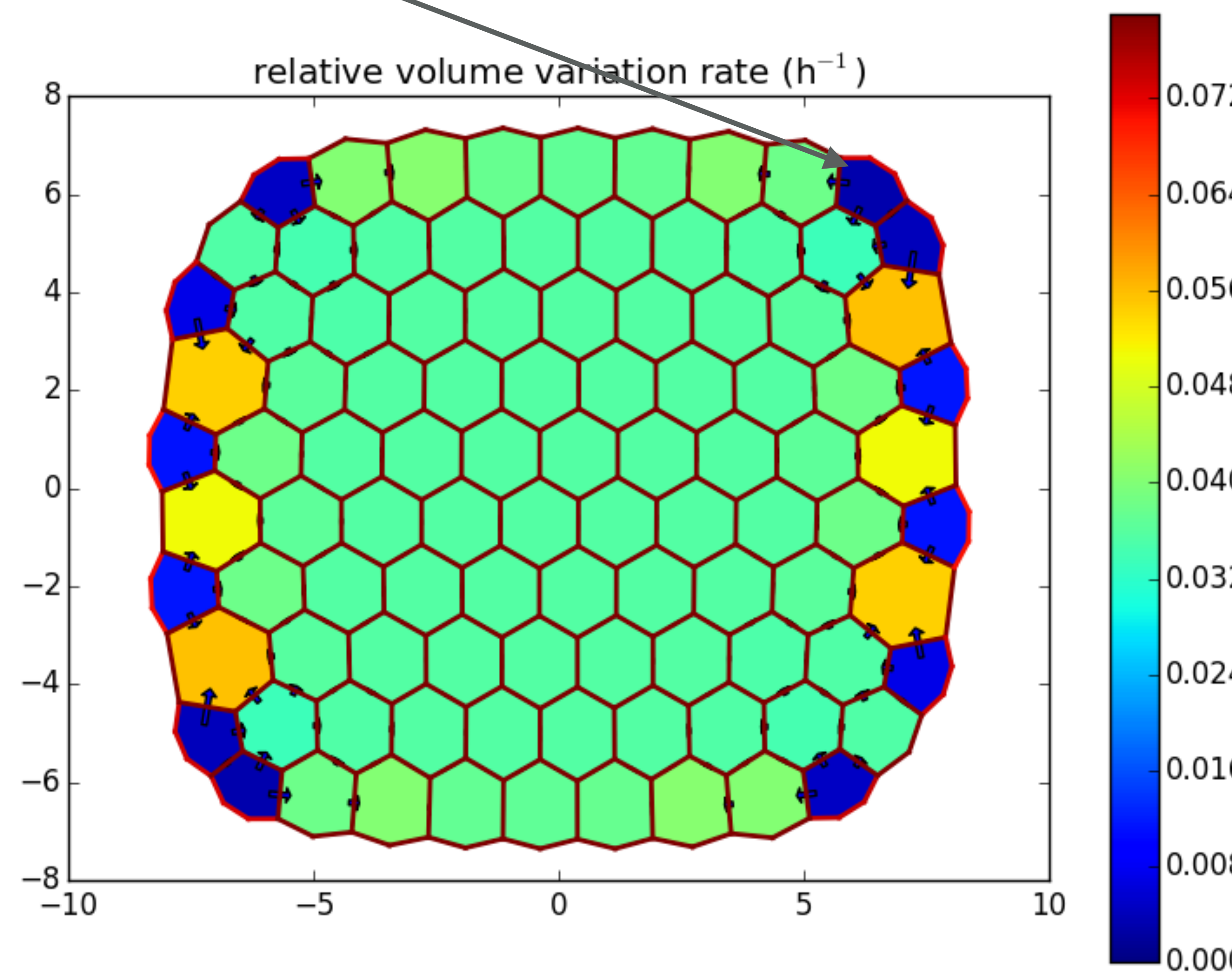
On the corner:

Slower growth, **higher turgor ⇒ symplasmic fluxes**

TURGOR

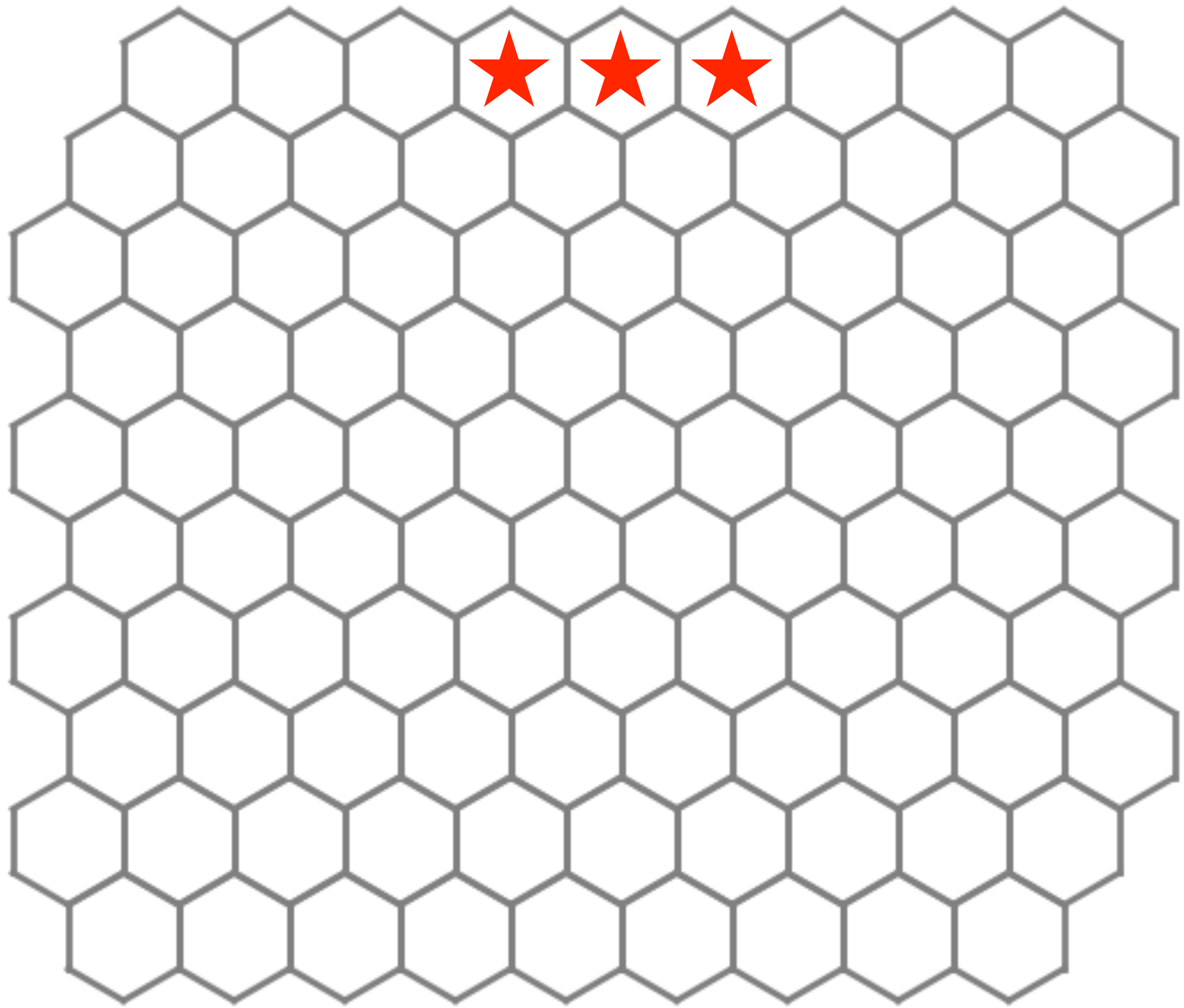


GROWTH RATE



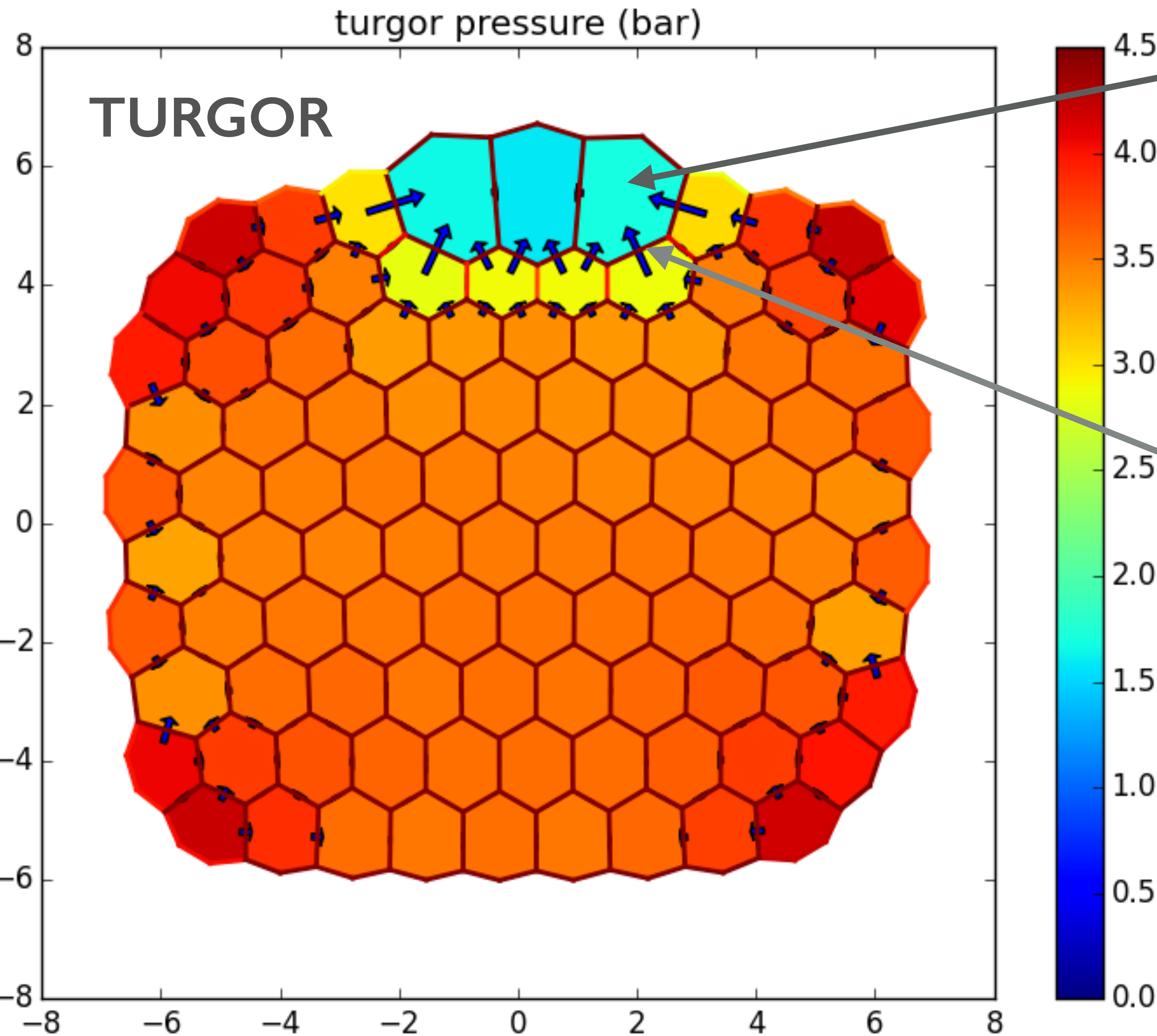
Heterogeneous, non constant turgor and **growth rate**

A LITTLE HETEROGENEITY



★Twice **softer** walls

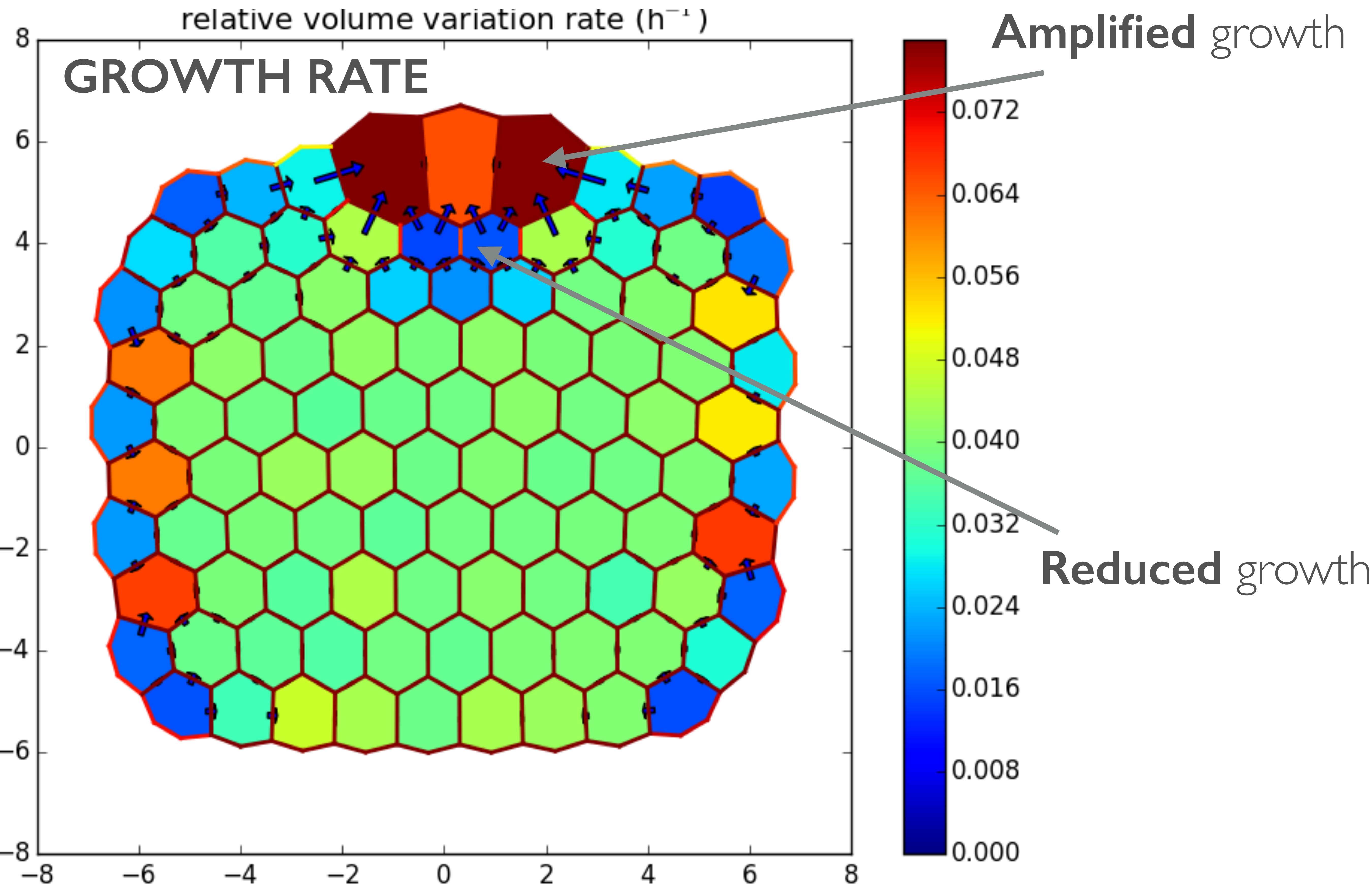
LARGE GROWTH RATE HETEROGENEITY



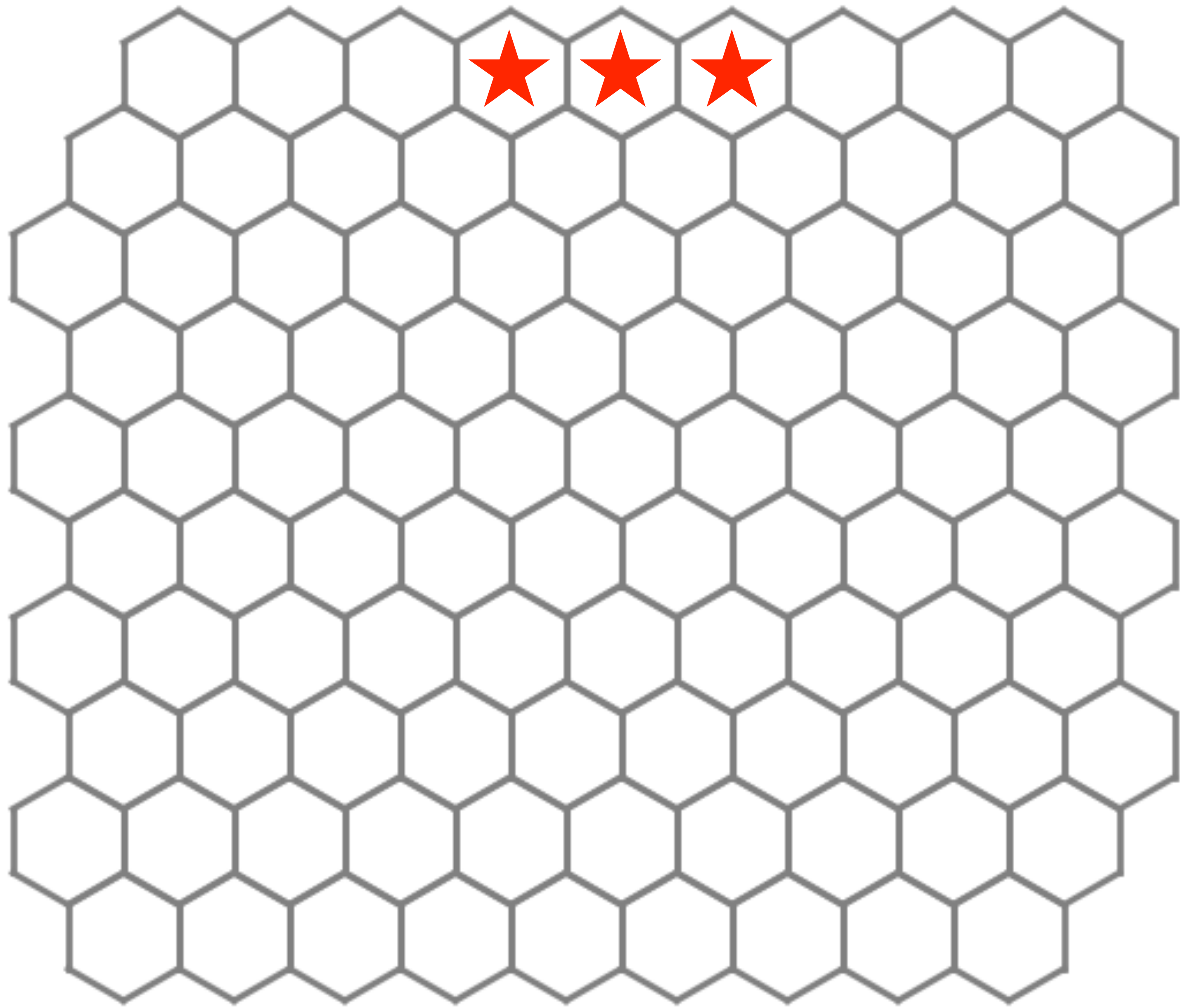
Lower turgor

⇒ Large symplasmic fluxes

LARGE GROWTH RATE HETEROGENEITY



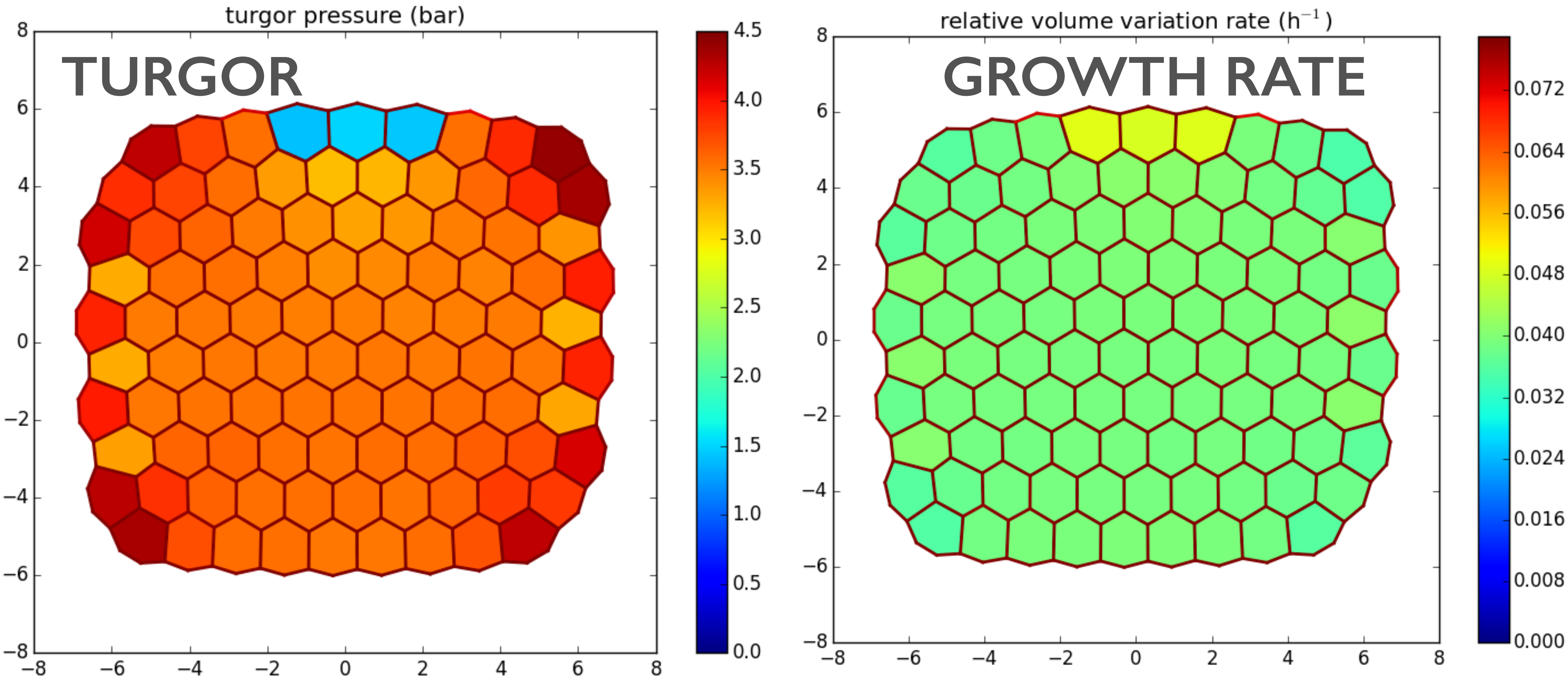
ROLE OF **SYMPLASMIC FLUXES**



★Twice **softer** walls

\+ **inhibition** of symplasmic fluxes

SYMPLASMIC FLUXES INHIBITED

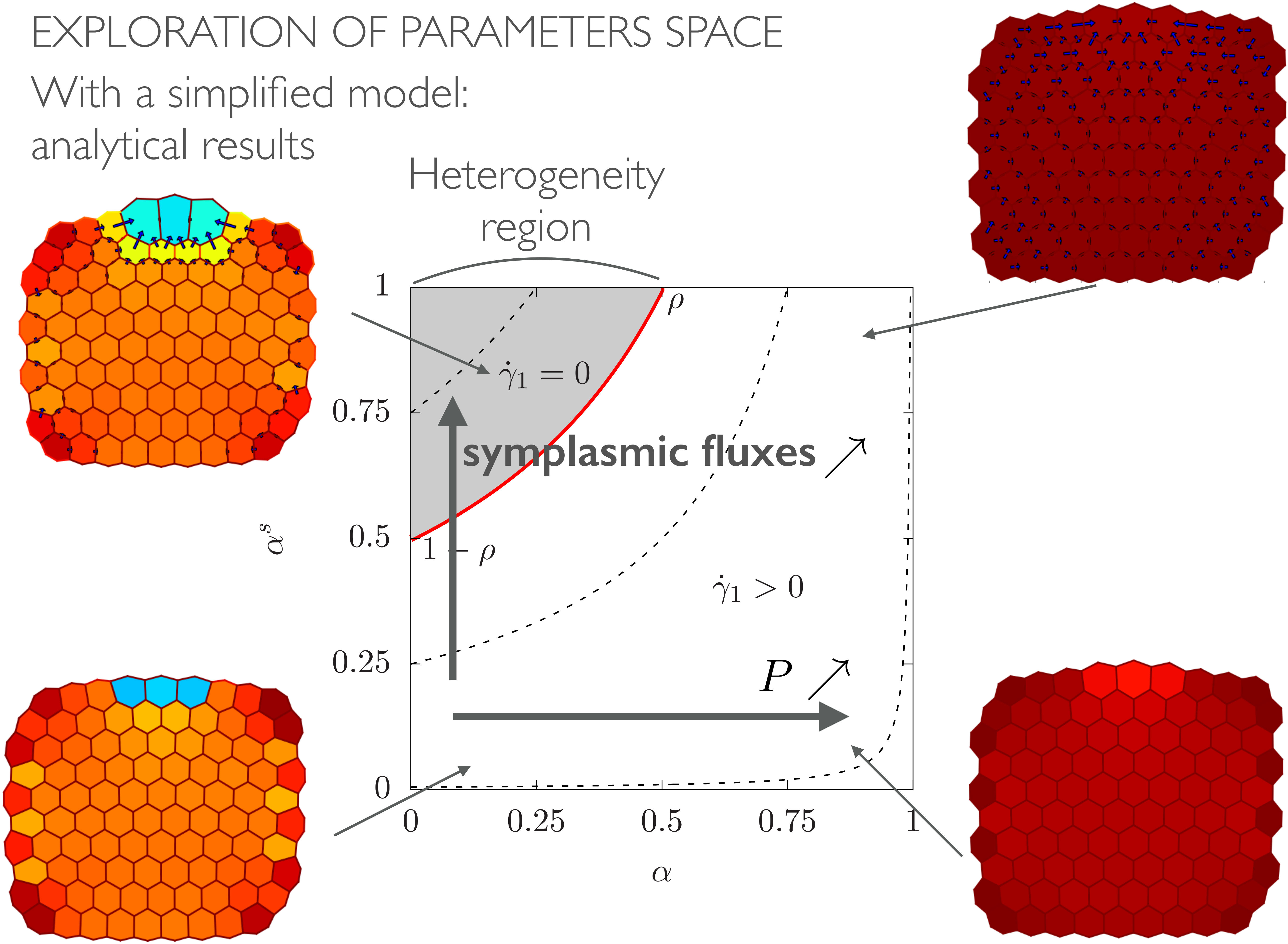


No symplasmic fluxes,
Low growth heterogeneities

Non linear effect: fluxes amplify heterogeneities

EXPLORATION OF PARAMETERS SPACE

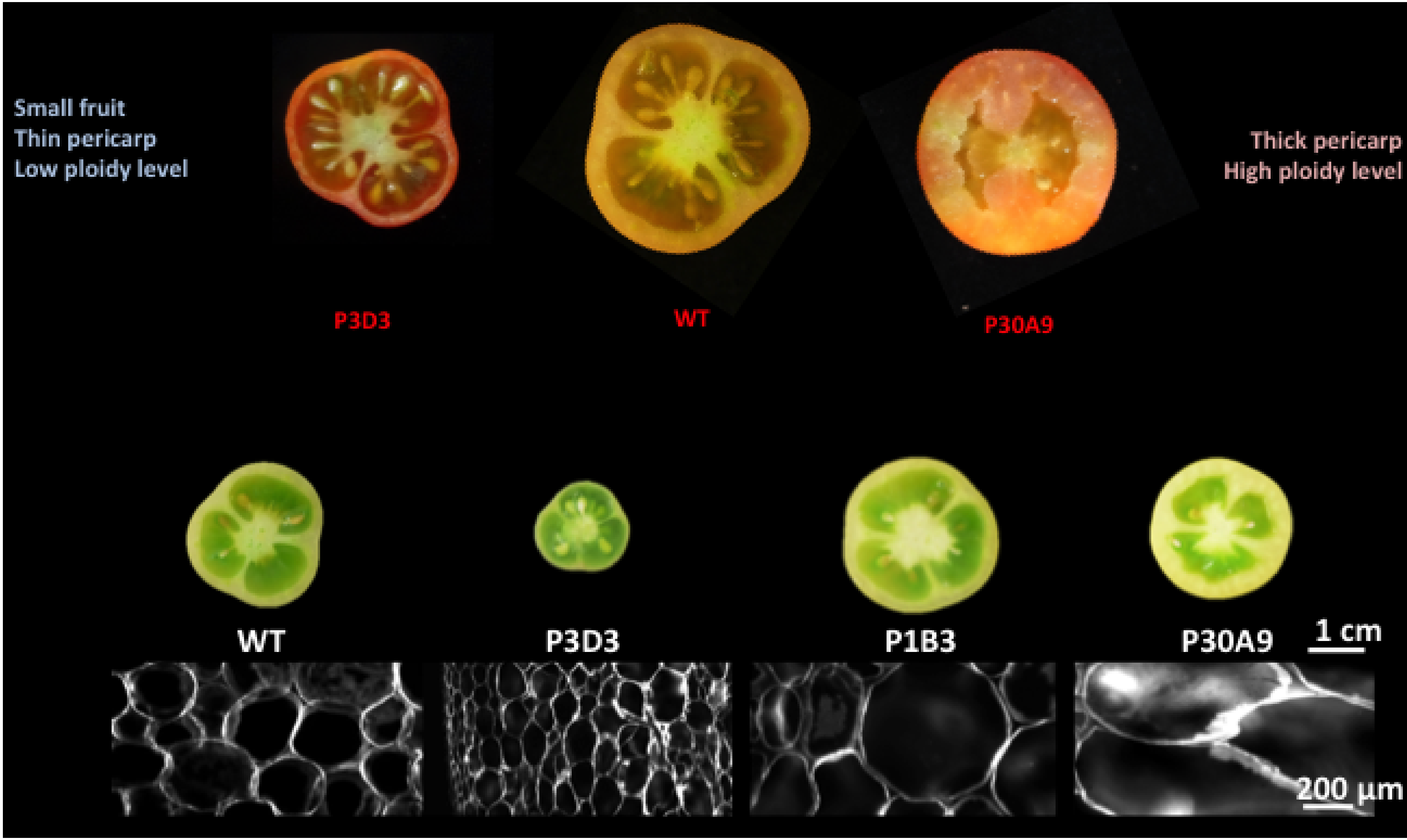
With a simplified model: analytical results



CONCLUSION

- Coupling **hydraulics / mechanics**
- **Physically consistant** model
- **Realistic parameters**, fully explored
- **Complex**, **non linear** behavior
- Fluxes can **amplify heterogeneities**
- Extensible in **3D**
- Allows **comparison with experiments:**
    - Measurement of turgor, mechanical properties
    - **Shape evolution** ⇒ development, morphogenesis

PROSPECTS: TOMATO PERICARP MODEL

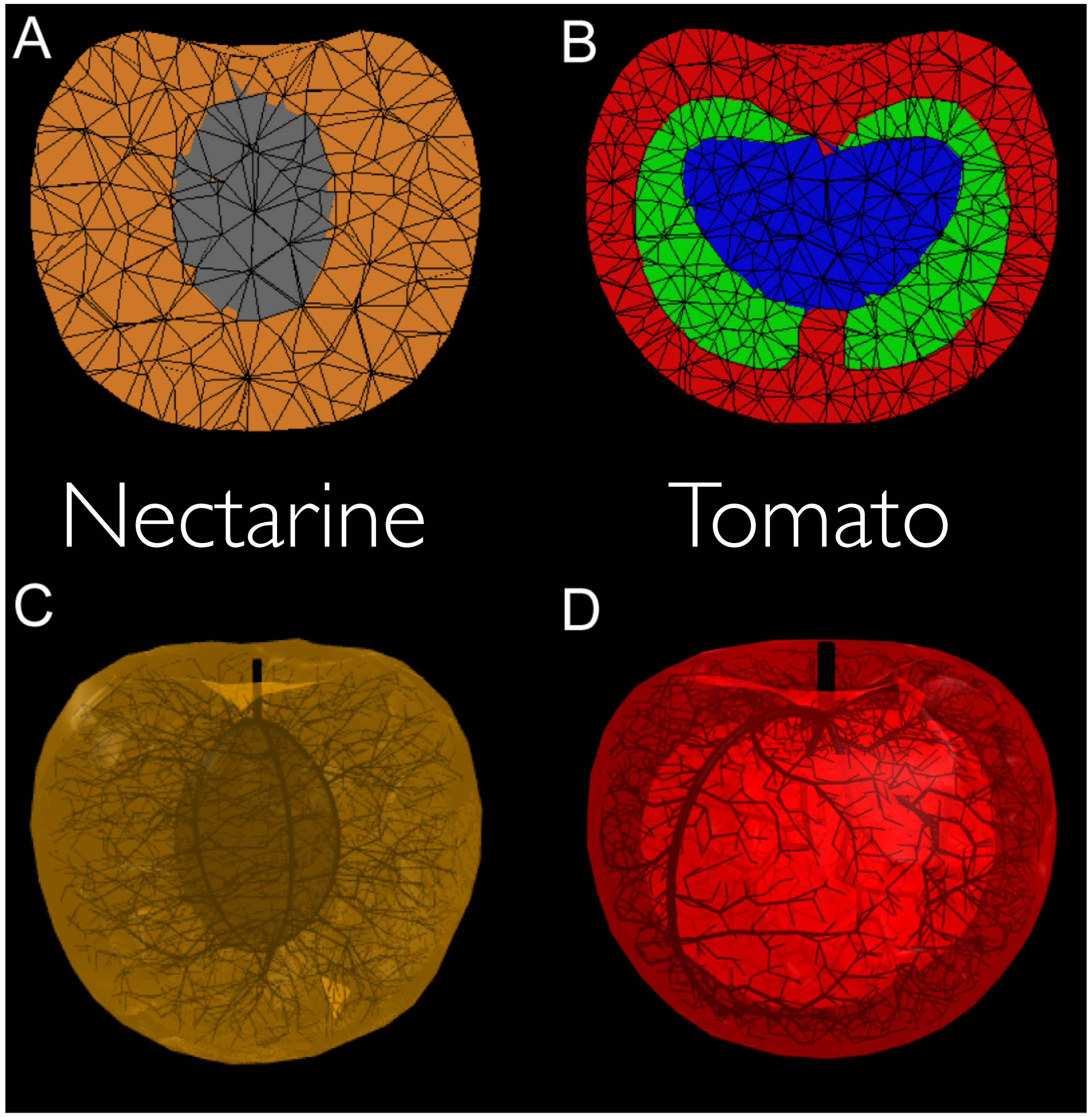


C. Rothan, L. Fernandez (INRA Bordeaux)

PROSPECTS: 3D FRUIT MODEL WITH VASCULATURE

Previous work in our group: Mik Cieslak

[M. Cieslak, IC, F. Boudon, V. Baldazzi, M. Génard, C. Godin, N. Bertin 2016: submitted]



- 3D reconstruction
- Fruit divided in tetraedra
- Vasculature reconstruction
- Prediction of water and sugar fluxes

Physiology + 3D mechanics + hydraulics ???