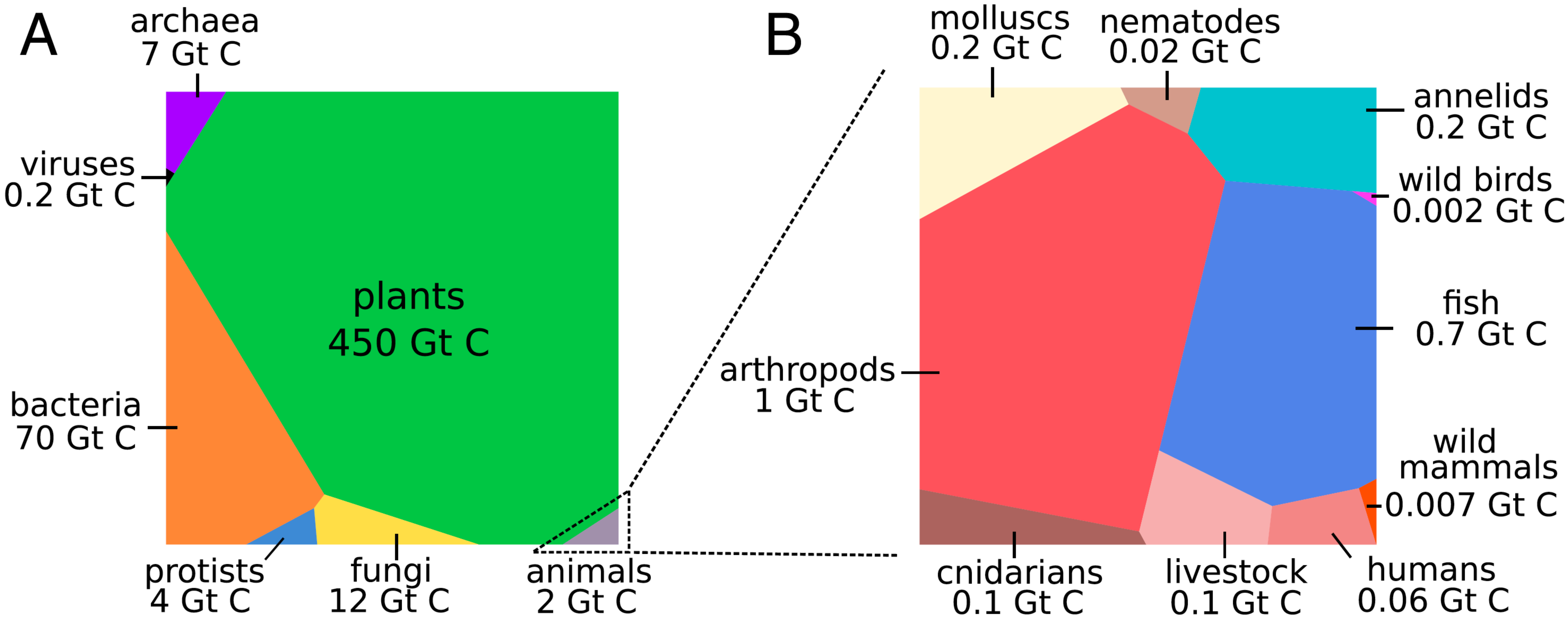
Plant Development: Genes, Mechanics, Cells

Meyerowitz Laboratory: SCAM

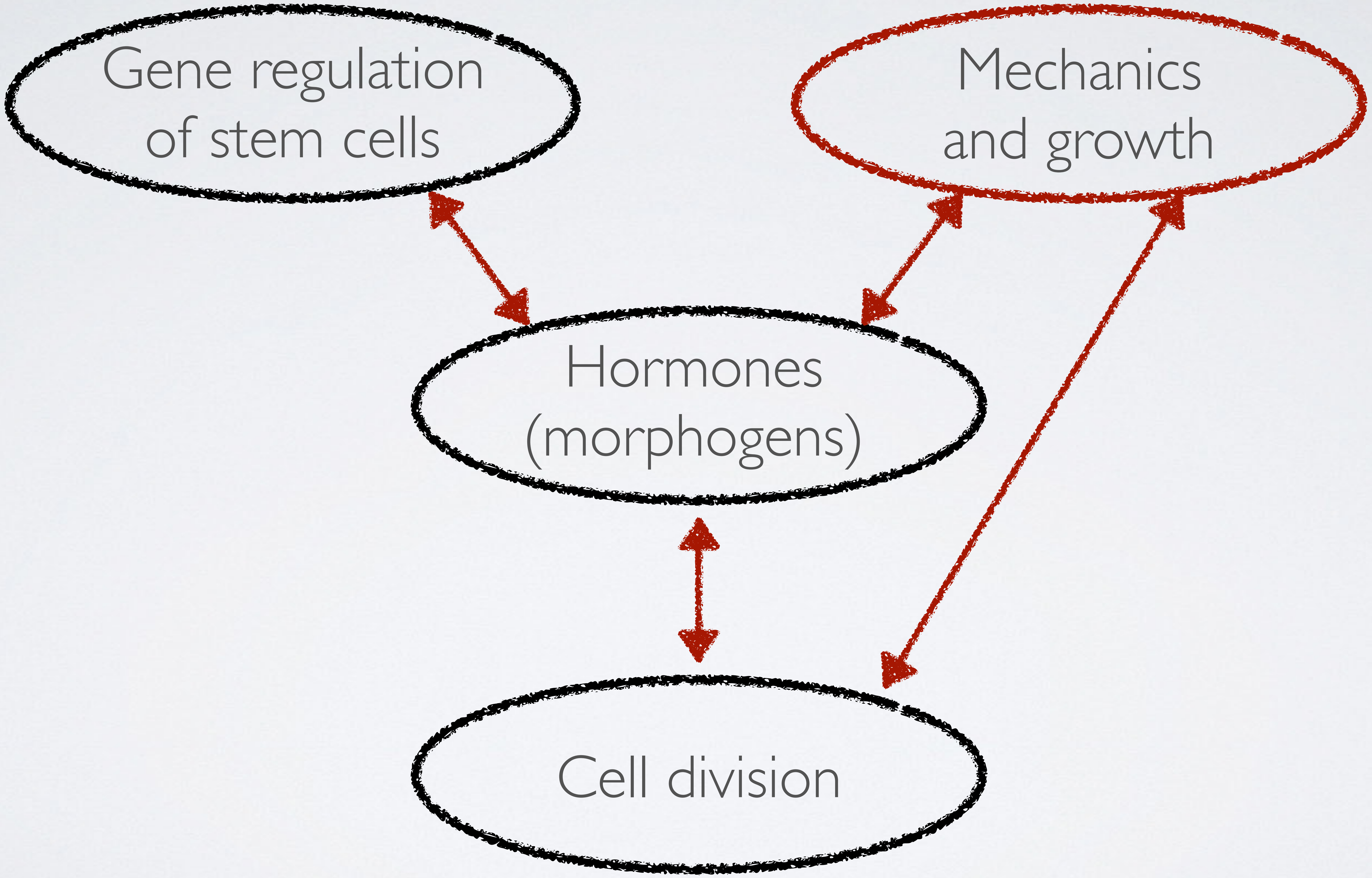
(Soft Condensed Active Matter)

The sum of the biomass across all taxa on Earth is ≈550 Gt C, of which ≈80% (≈450 Gt C) are plants, dominated by land plants (embryophytes). The second major component is bacteria (≈70 Gt C), constituting ≈15% of the global biomass. Other groups, in descending order, are fungi, archaea, protists, animals, and viruses, which together account for the remaining <10%.



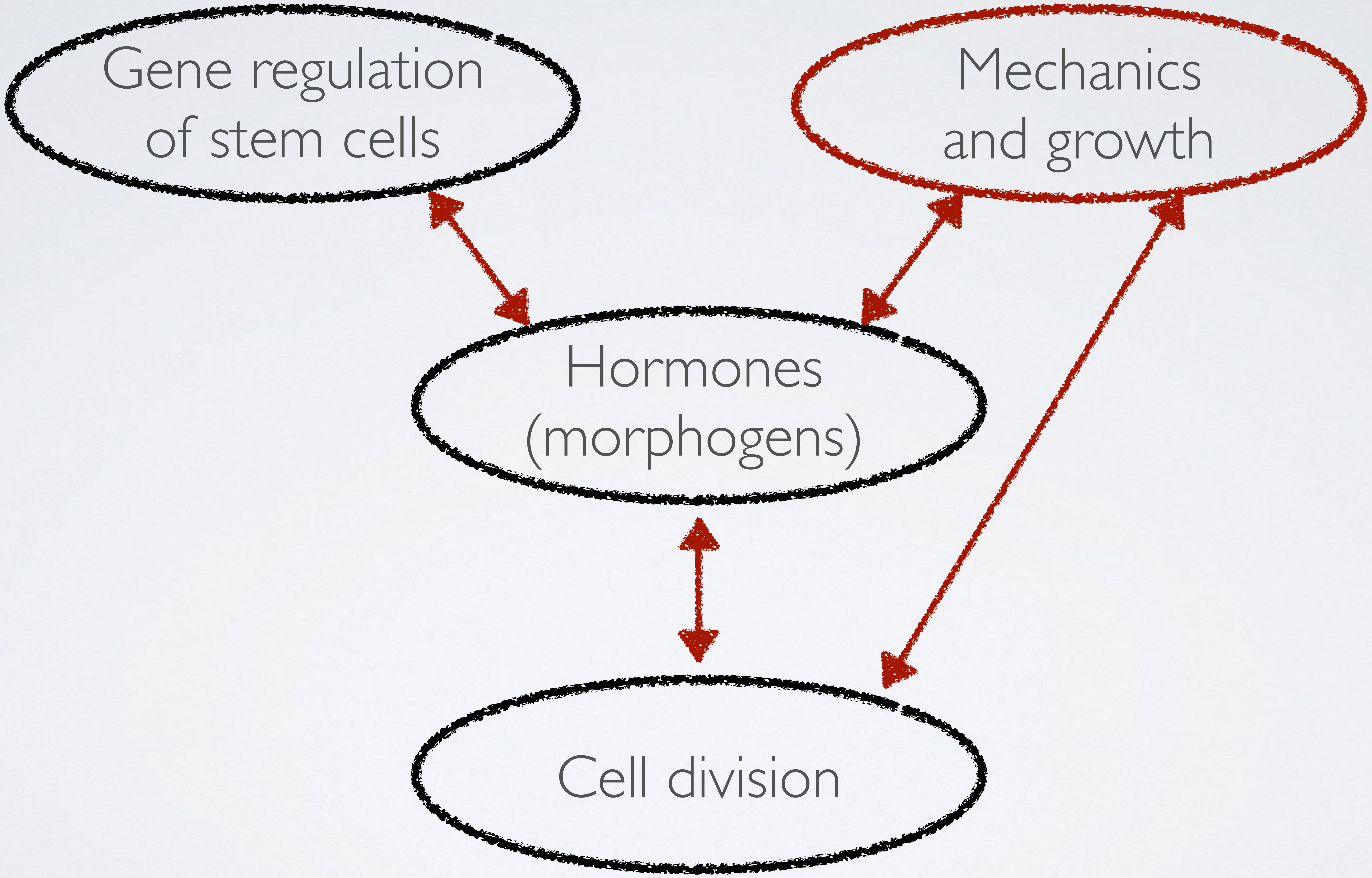
Bar-On, Phillips and Milo: PNAS | June 19, 2018 | vol. 115 | no. 25 www.pnas.org/cgi/doi/10.1073/pnas.1711842115

How to generate shape



Jönsson, Meyerowitz

COMPUTATIONAL MORPHODYNAMICS



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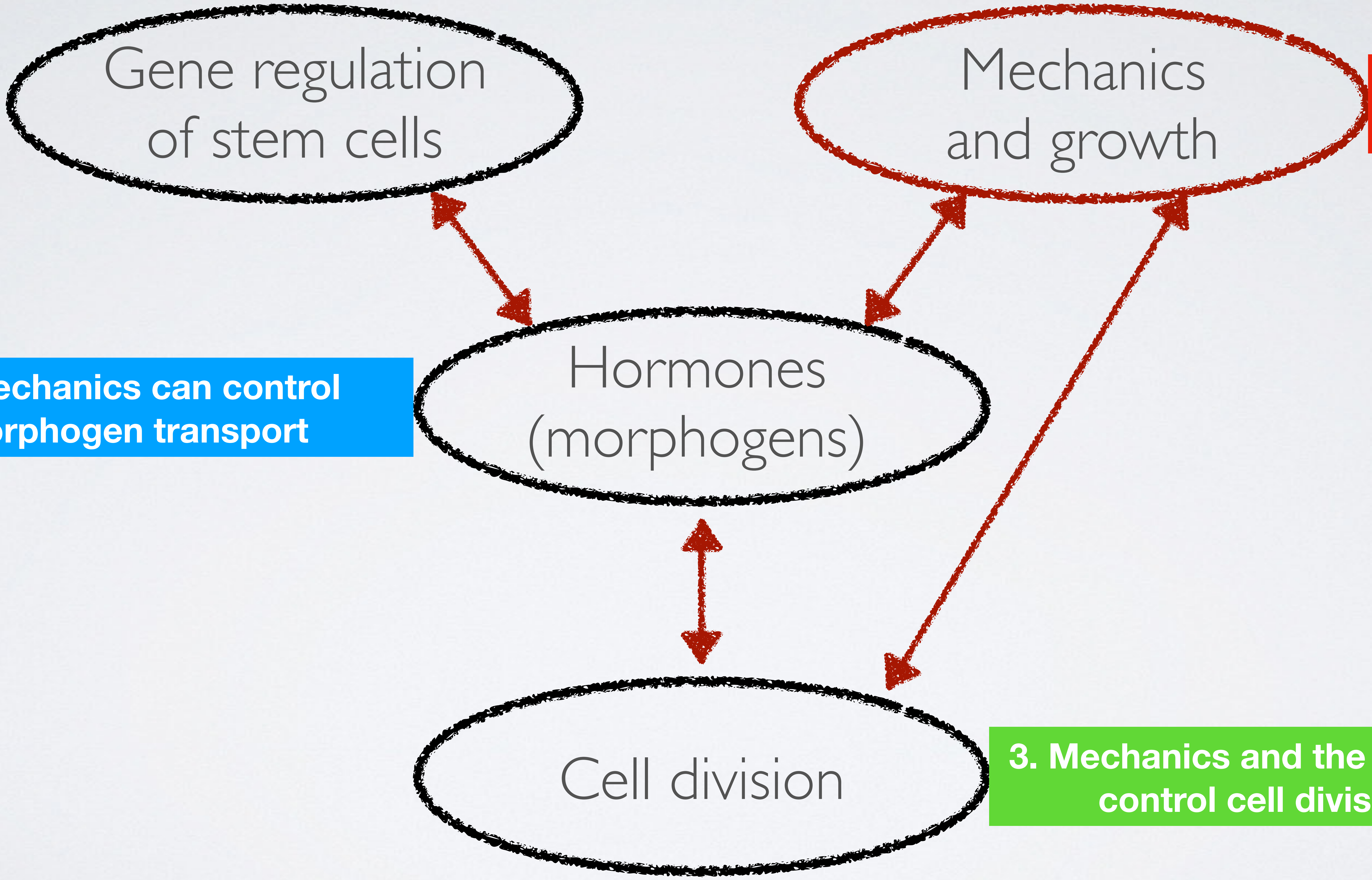
COMPUTATIONAL MORPHODYNAMICS

0. Introduction to plant growth (brief)



1. Shape controls growth, growth creates shape

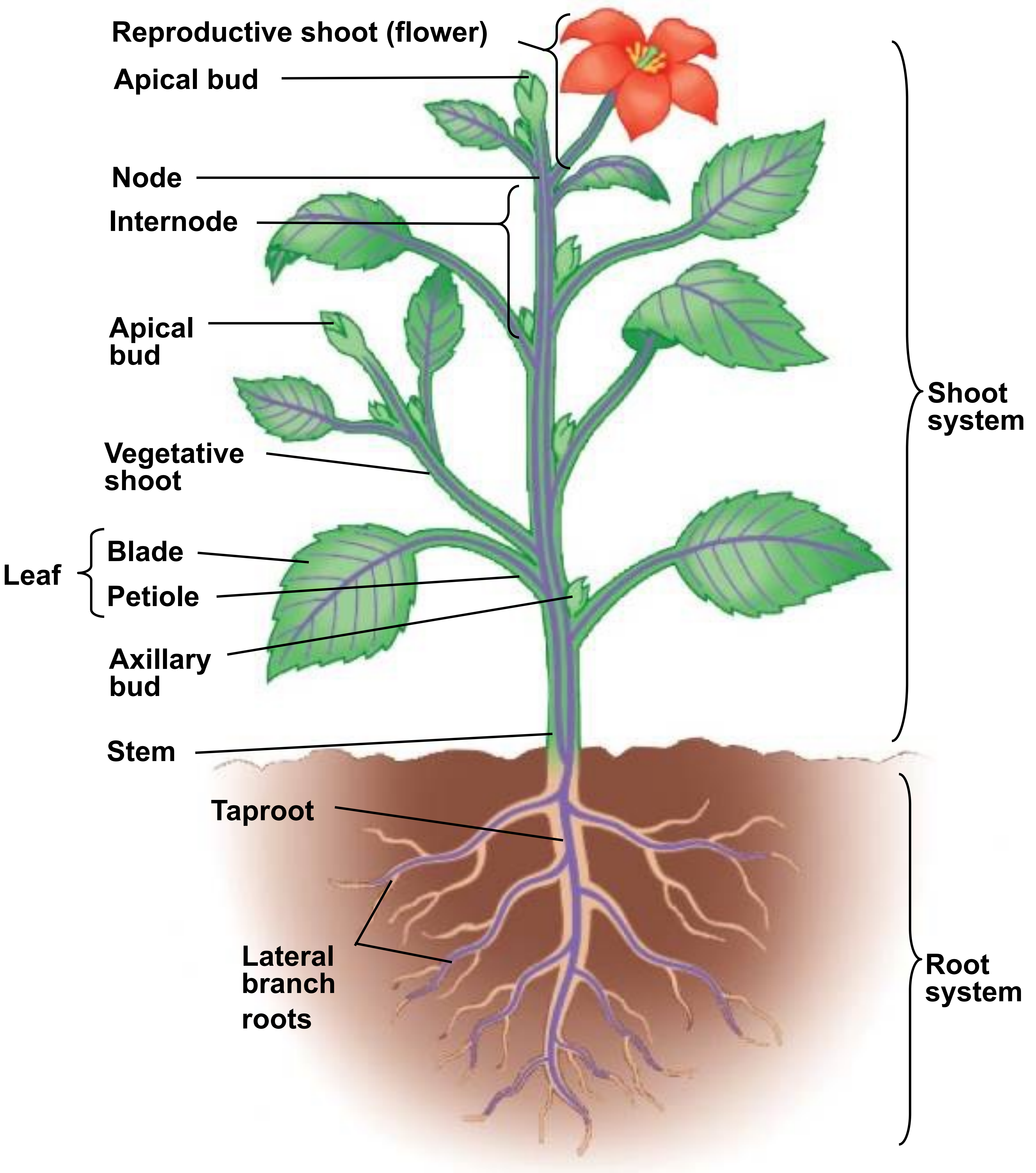
2. Mechanics can control morphogen transport

3. Mechanics and the cell wall control cell division

Jönsson, Meyerowitz

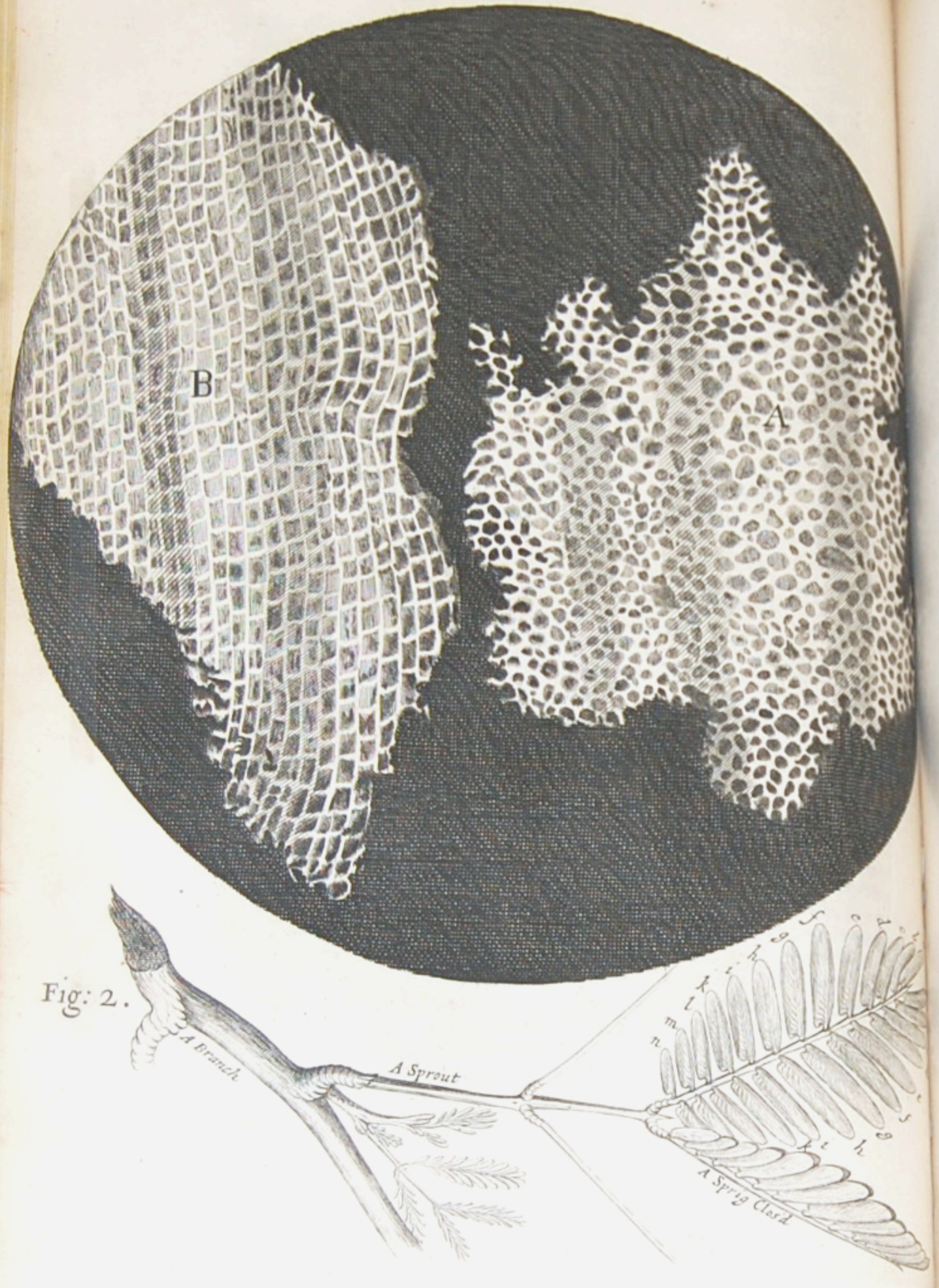
Arabidopsis thaliana

Fig. 35-2



Reproductive shoot (flower)
Apical bud
Node
Internode
Apical bud
Vegetative shoot
Leaf
Blade
Petiole
Axillary bud
Stem
Taproot
Lateral branch roots
Shoot system
Root system

Fig: I.



of other Vegetables to do to their bulk. But of theſe pores I have ſaid more elſewhere.

To proceed then, Cork ſeems to be by the tranſverſe conſtitution of the pores, a kind of *Fungus* or Muſhrome, for the pores lie like ſo many Rays tending from the center, or pith of the tree, outwards; ſo that if you cut off a piece from a board of Cork tranſverſly, to the flat of it, you will, as it were, ſplit the pores, and they will appear juſt as they are expreſs'd in the Figure B of the XI. *Scheme*. But if you ſhave off a very thin piece from this board, parallel to the plain of it, you will cut all the pores tranſverſly, and they will appear almoſt as they are expreſs'd in the Figure A, ſave onely the ſolid *Interſtitia* will not appear ſo thick as they are there repreſented.

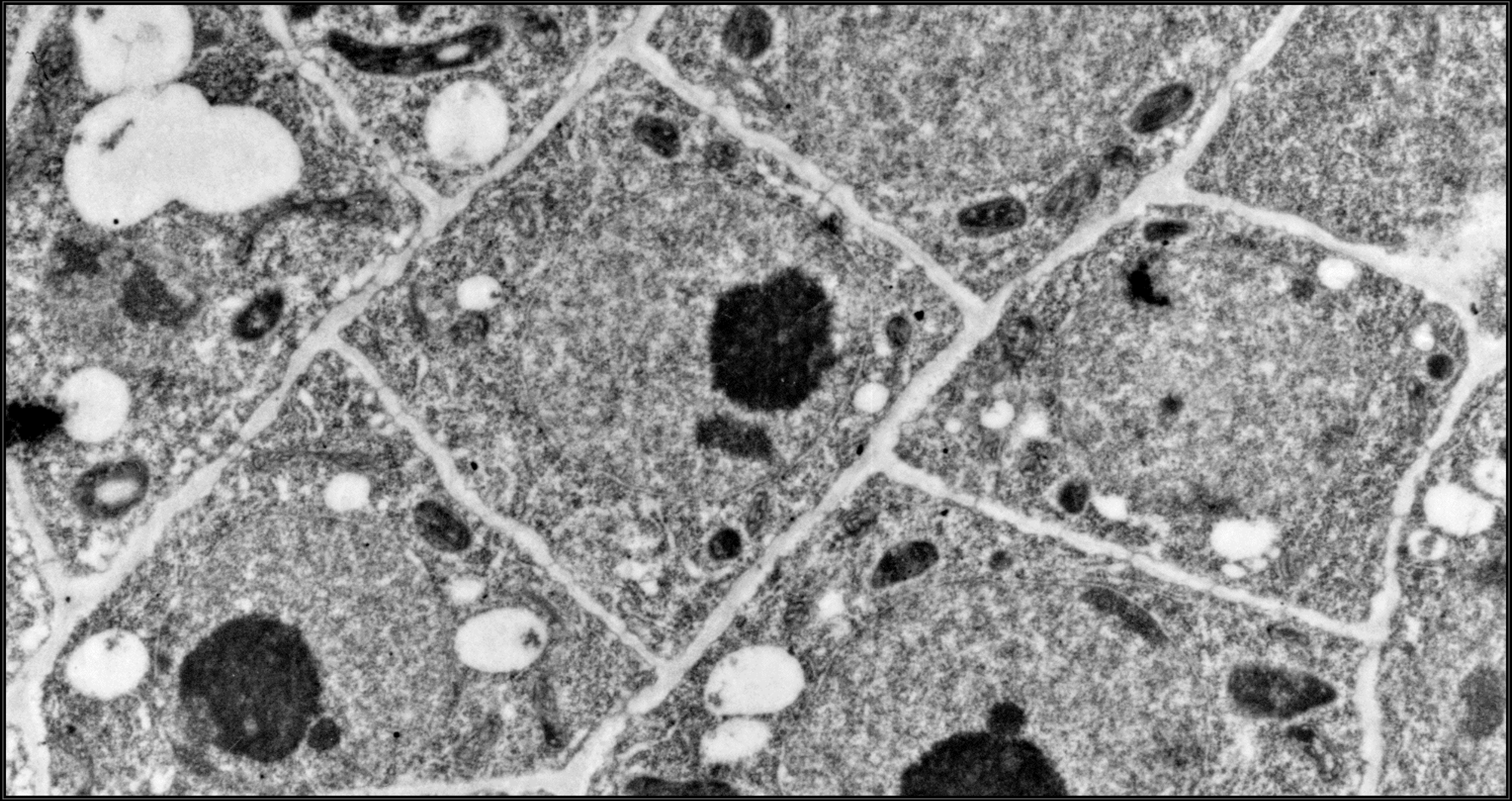
So that Cork ſeems to ſuck its nouriſhment from the ſubjacent bark of the Tree immediately, and to be a kind of excreſcence, or a ſubſtance diſtinct from the ſubſtances of the entire Tree, ſomething *analogus* to the Muſhrome, or Moſs on other Trees, or to the hairs on Animals. And having enquir'd into the Hiſtory of Cork, I find it reckoned as an excreſcency of the bark of a certain Tree, which is diſtinct from the two barks that lie within it, which are common alſo to other trees; That 'tis ſome time before the Cork that covers the young and tender ſprouts comes to be diſcernable; That it cracks, flaws, and cleaves into many great chaps, the bark underneath remaining entire; That it may be ſeparated and remov'd from the Tree, and yet the two under-barks (ſuch as are alſo common to that with other Trees) not at all injur'd, but rather helped and freed from an external injury. Thus *Jonſtonus* in *Dendrologia*, ſpeaking *de Subere*, ſays, *Arbor eſt procera, Lignum eſt robuſtum, dempto cortice in aquis non fluitat, Cortice in orbem detracto juvatur, craſceſcens enim praſtringit & ſtrangulat, intra triennium iterum repletur: Caudex ubi adoleſcit craſſus, cortex ſuperior denſus carnoſus, duos digitos craſſus, ſcaber, rimoſus, & qui niſi detrahatur dehiſcit, alioque ſubnaſcente expellitur, interior qui ſubeſt novellus ita rubet ut arbor minio picta videatur.* Which Hiſtories, if well conſider'd, and the tree, ſubſtance, and manner of growing, if well examin'd, would, I am very apt to believe, much confirm this my conjecture about the origination of Cork.

Nor is this kind of Texture peculiar to Cork onely; for upon examination with my *Microſcope*, I have found that the pith of an Elder, or almoſt any other Tree, the inner pulp or pith of the Cany hollow ſtalks of ſeveral other Vegetables: as of Fennel, Carrets, Daucus, Bur-docks, Teaſels, Fearn, ſome kinds of Reeds, *&c.* have much ſuch a kind of *Schematiſme*, as I have lately ſhewn that of Cork, ſave onely that here the pores are rang'd the long-ways, or the ſame ways with the length of the Cane, whereas in Cork they are tranſverſe.

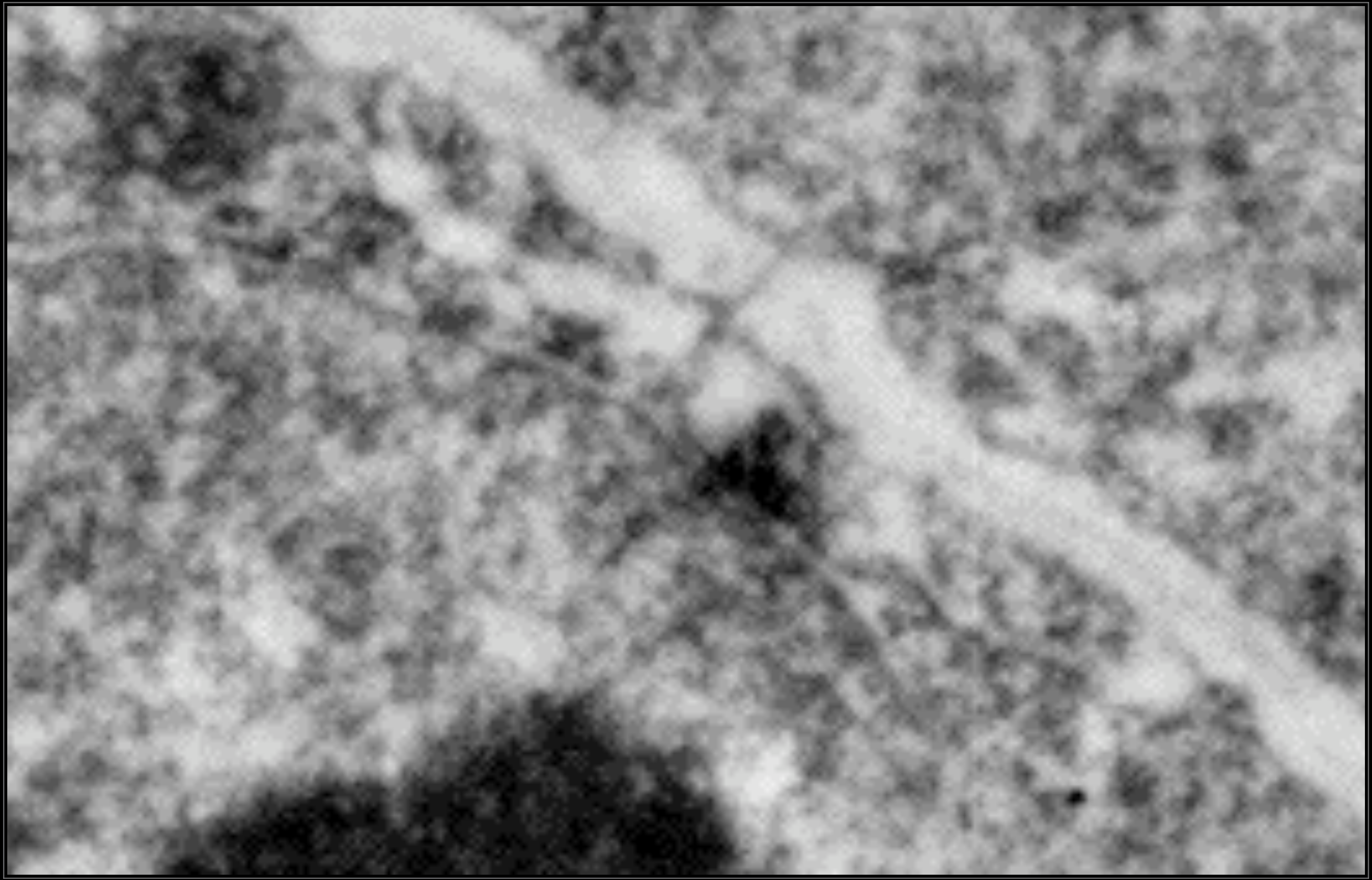
The pith alſo that fills that part of the ſtalk of a Feather that is above the Quil, has much ſuch a kind of texture, ſave onely that which way ſoever I ſet this light ſubſtance, the pores ſeem'd to be cut tranſverſly; ſo that I gheſs this pith which fills the Feather, not to conſiſt of abundance of long pores ſeparated with Diaphragms, as Cork does, but to be a kind

1665

Cell Walls, Turgor Pressure, Absence of Movement



Cells are Connected



Anatomy of the Plant Cell

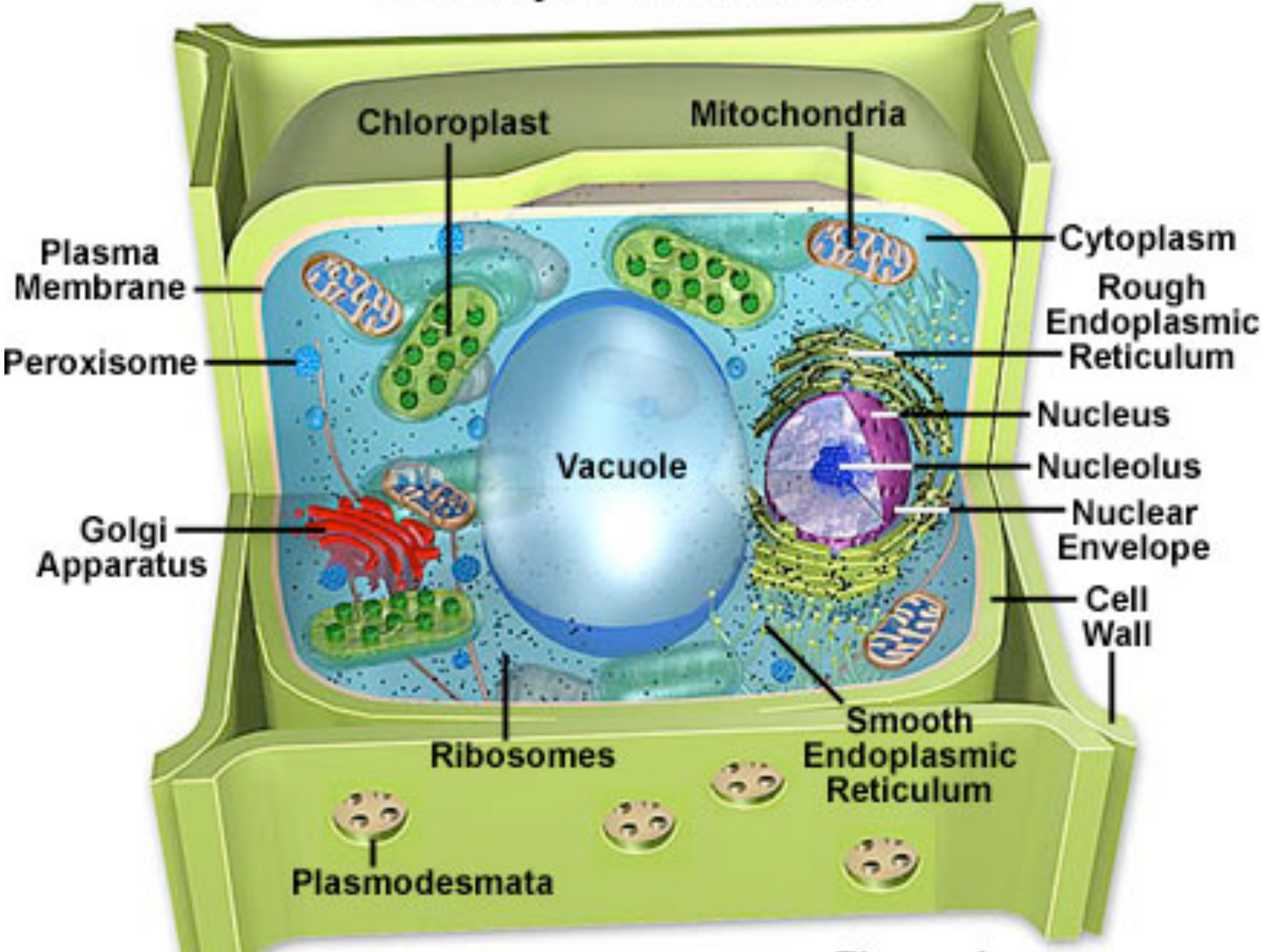
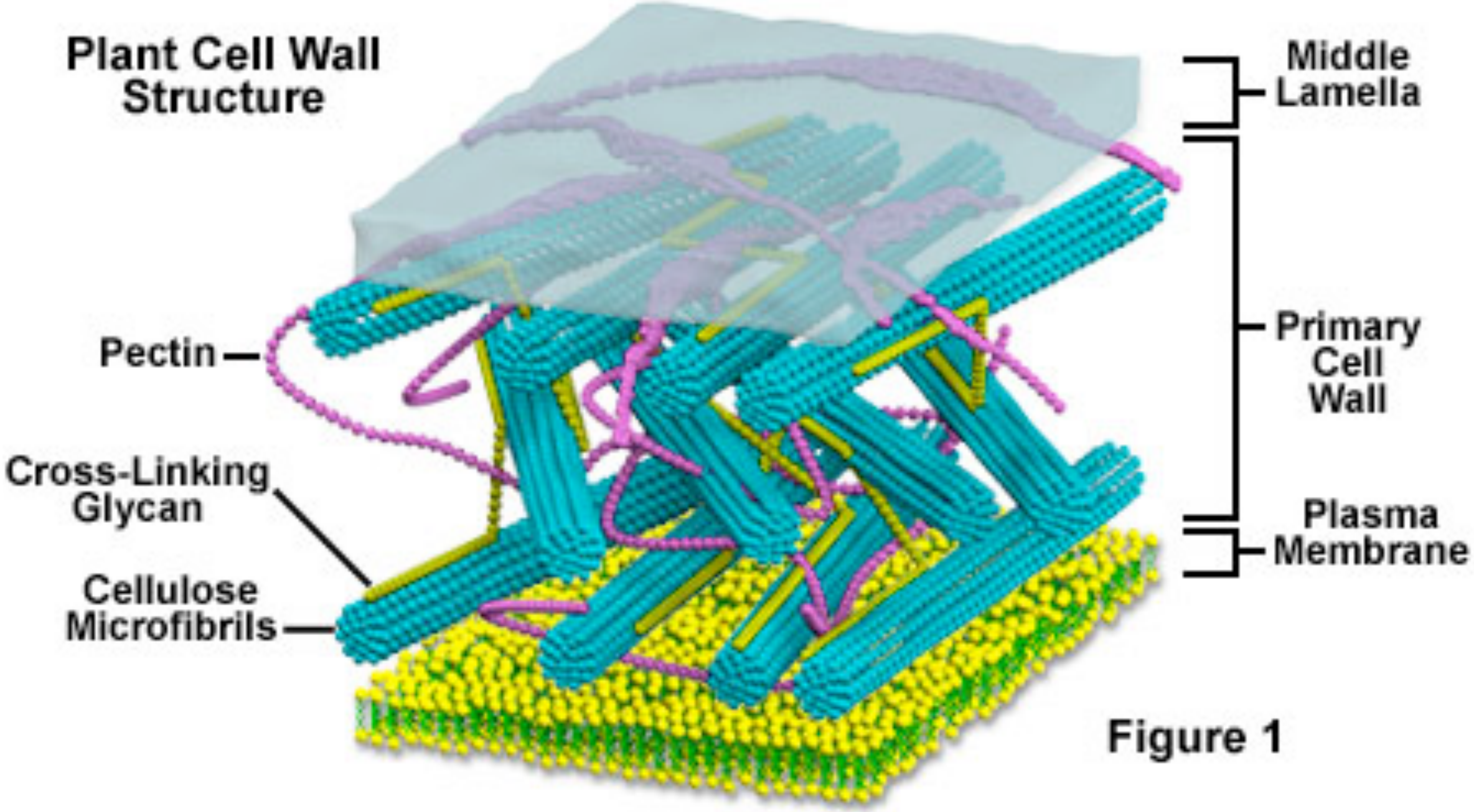
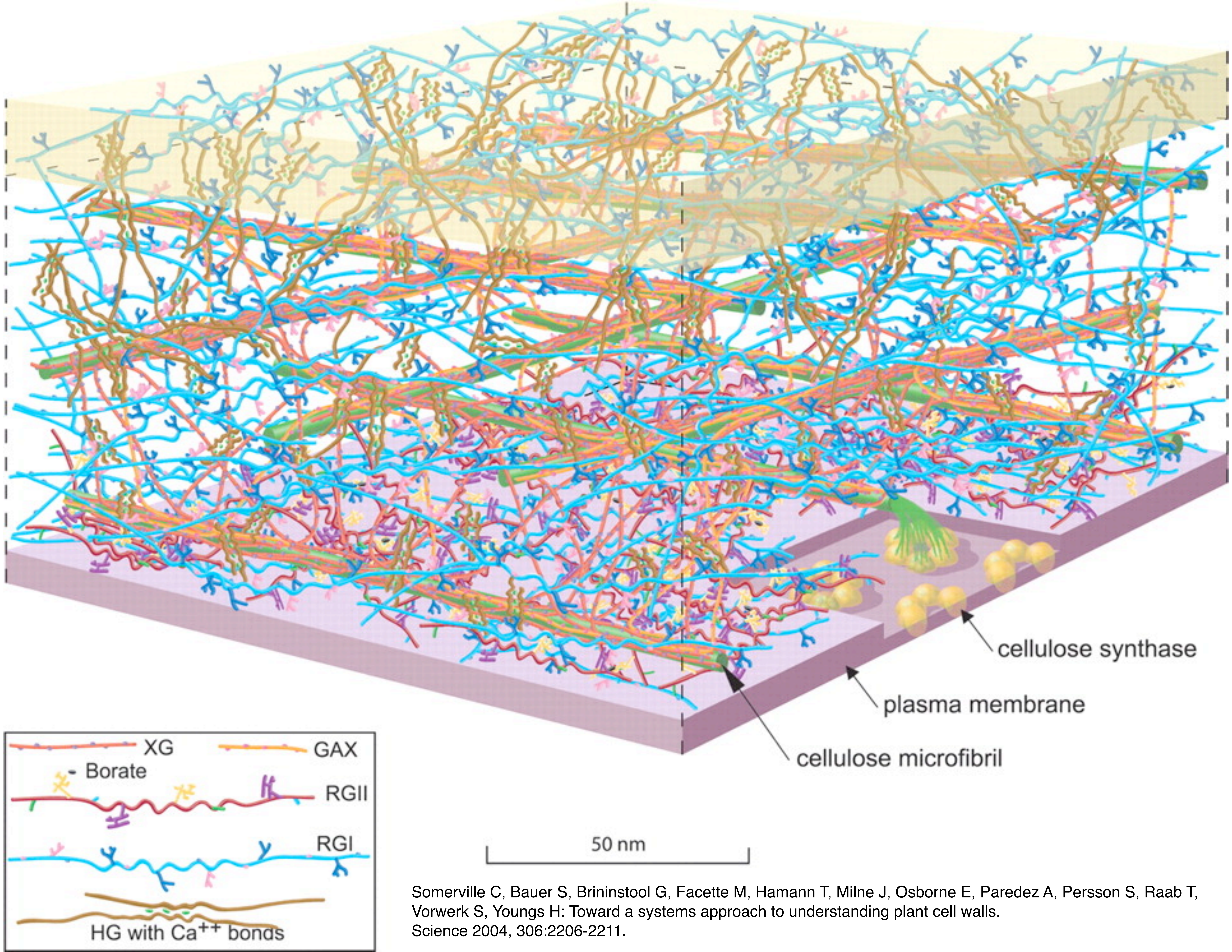


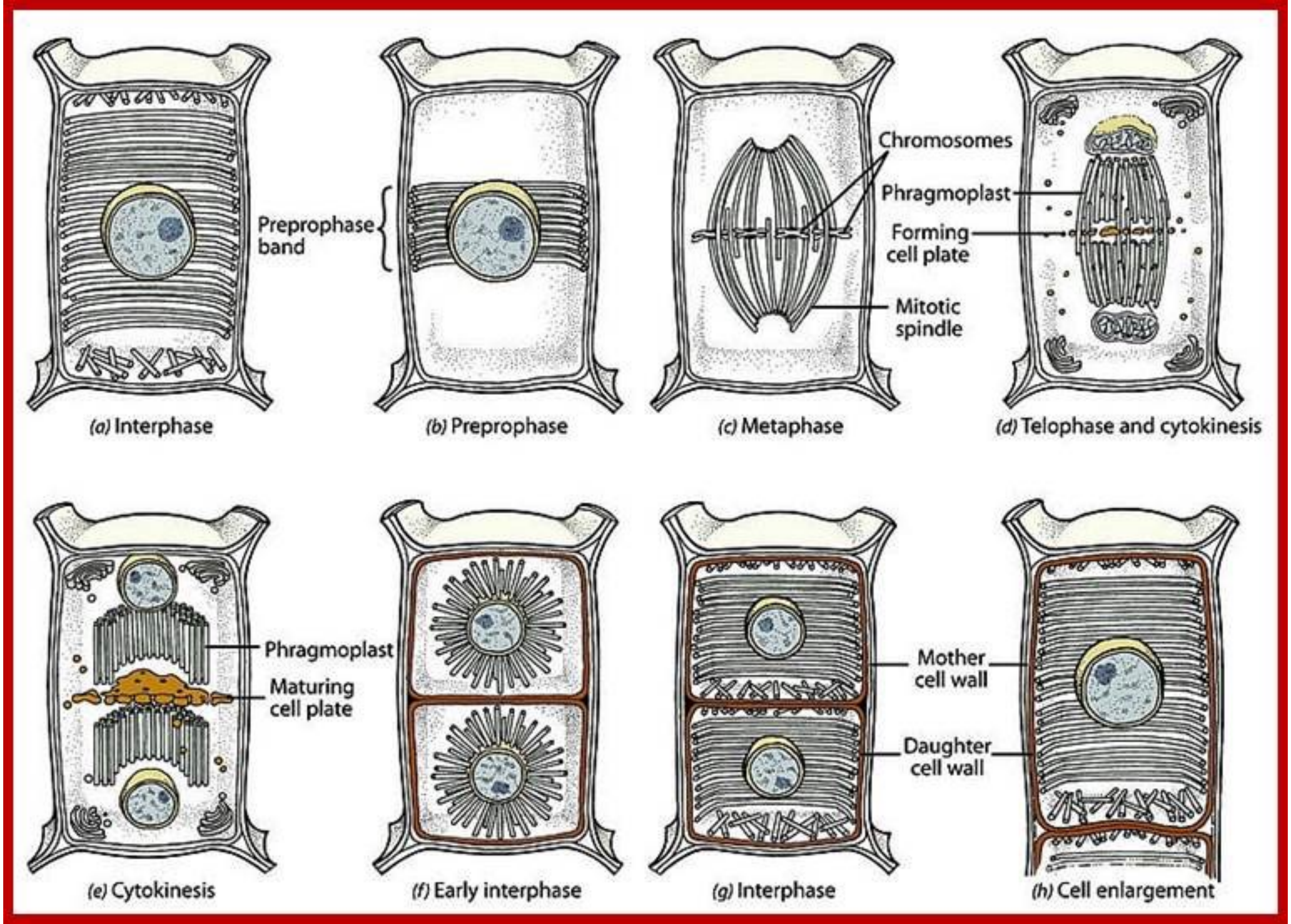
Figure 1



http://micro.magnet.fsu.edu/cells/plants/cellwall.html

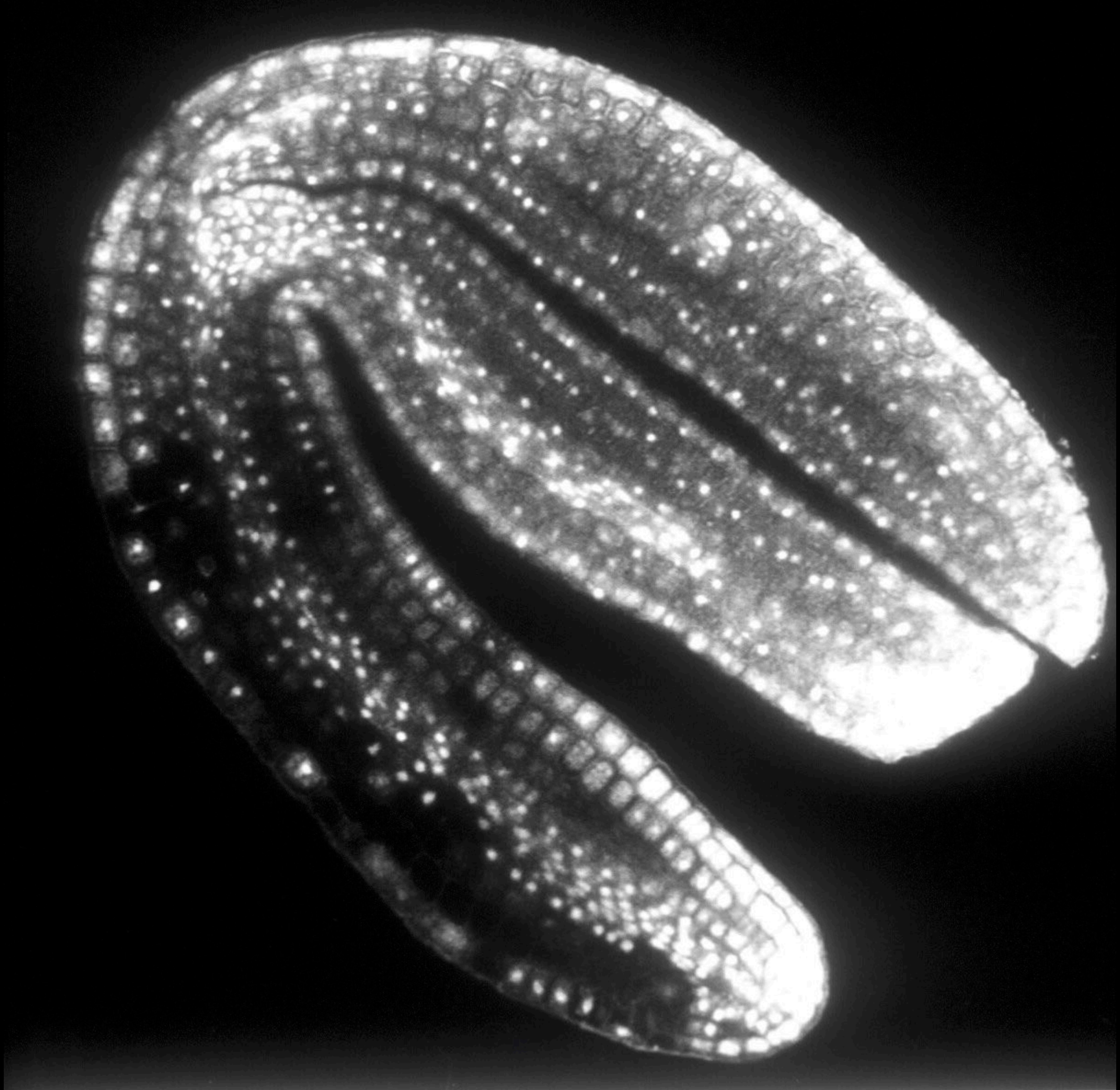


Somerville C, Bauer S, Brininstool G, Facette M, Hamann T, Milne J, Osborne E, Paredez A, Persson S, Raab T, Vorwerk S, Youngs H: Toward a systems approach to understanding plant cell walls.
Science 2004, 306:2206-2211.

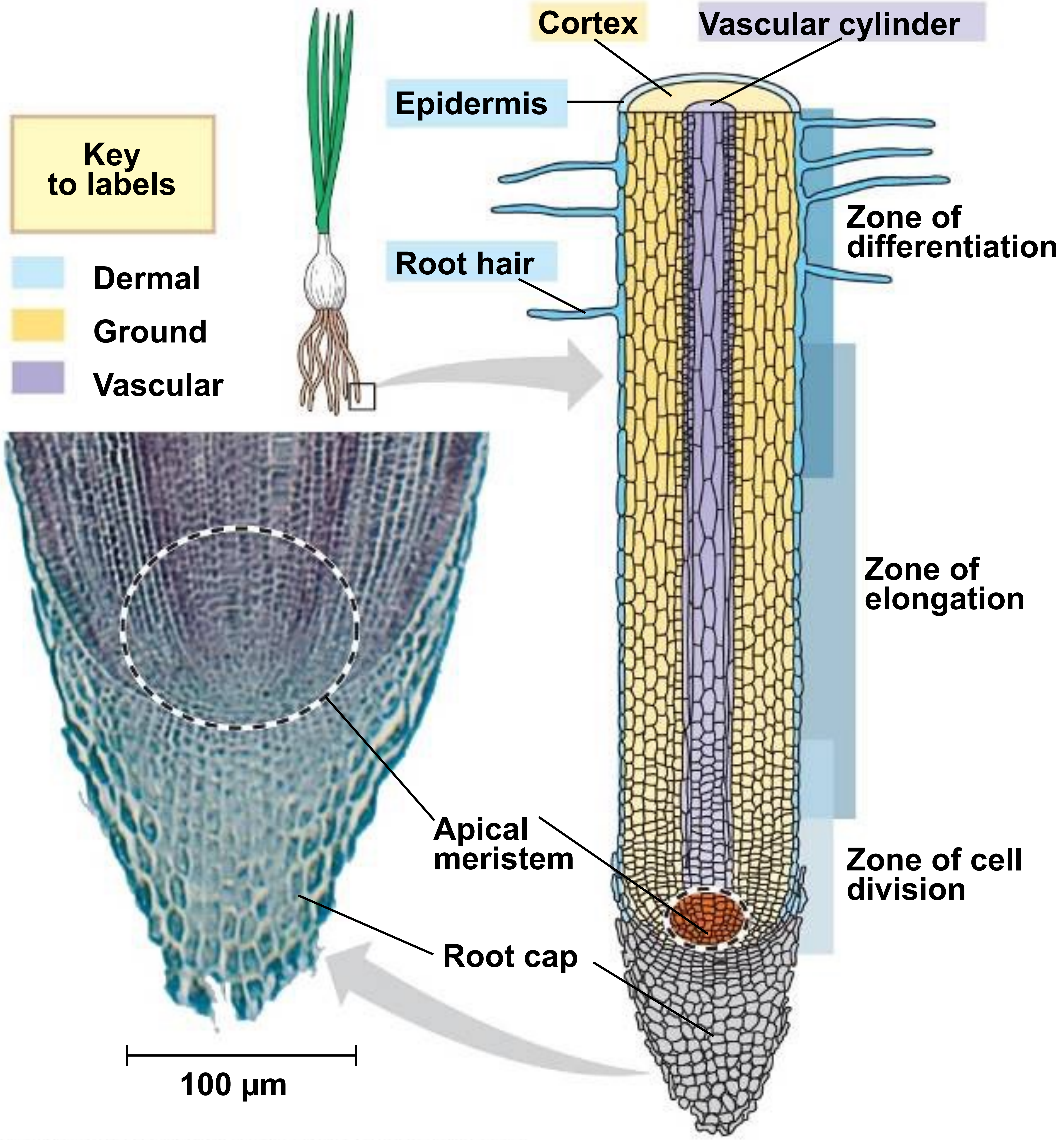


http://plantcellbiology.masters.grkraj.org/html/Plant_Cell_Division1-Cell_Division_files/image075.jpg

Yan et al. Scientific Reports 6, Article number: 31195 (2016)



ROOT APICAL MERISTEM



CAMBIUM
(VASCULAR SYSTEM STEM CELLS)

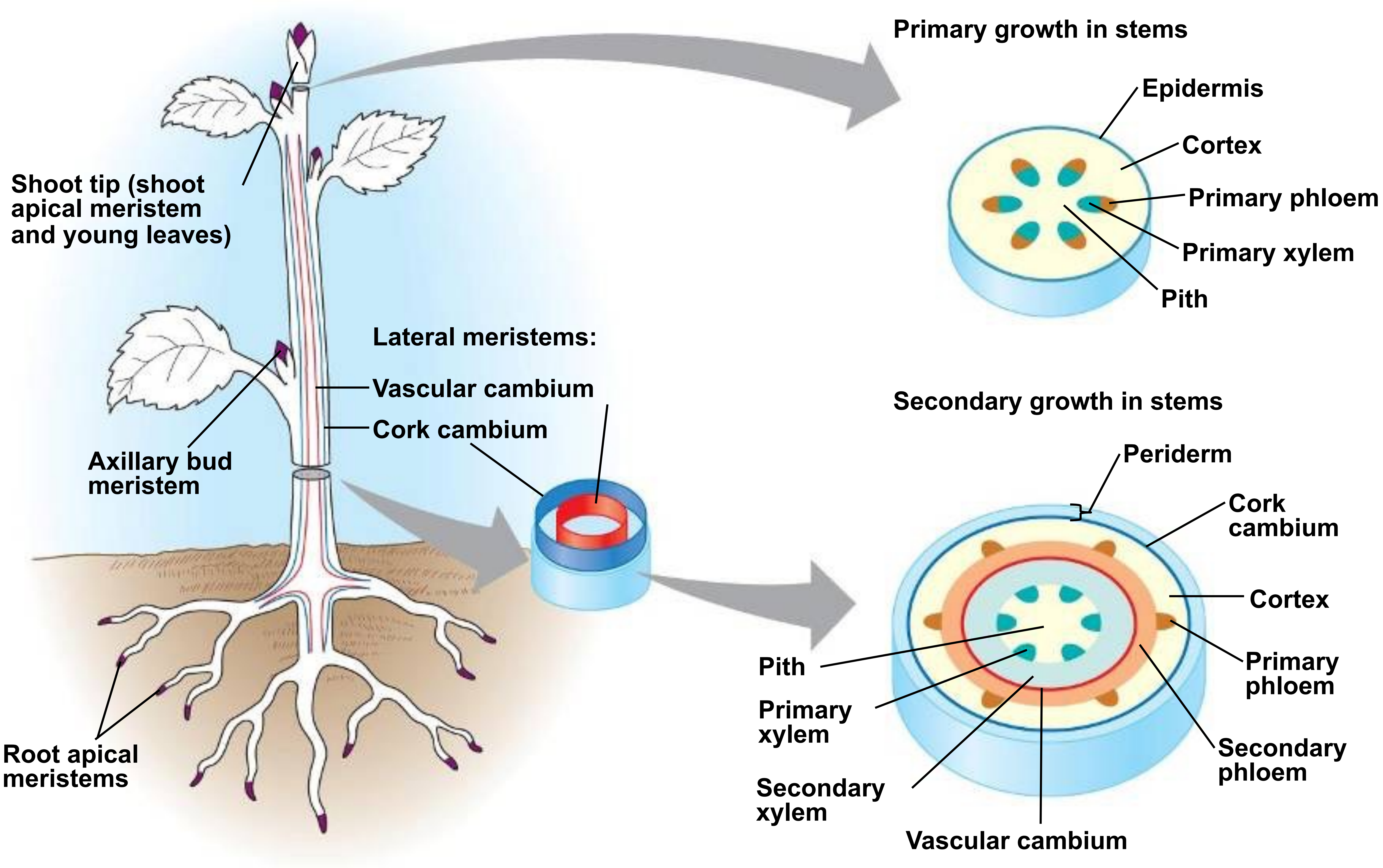
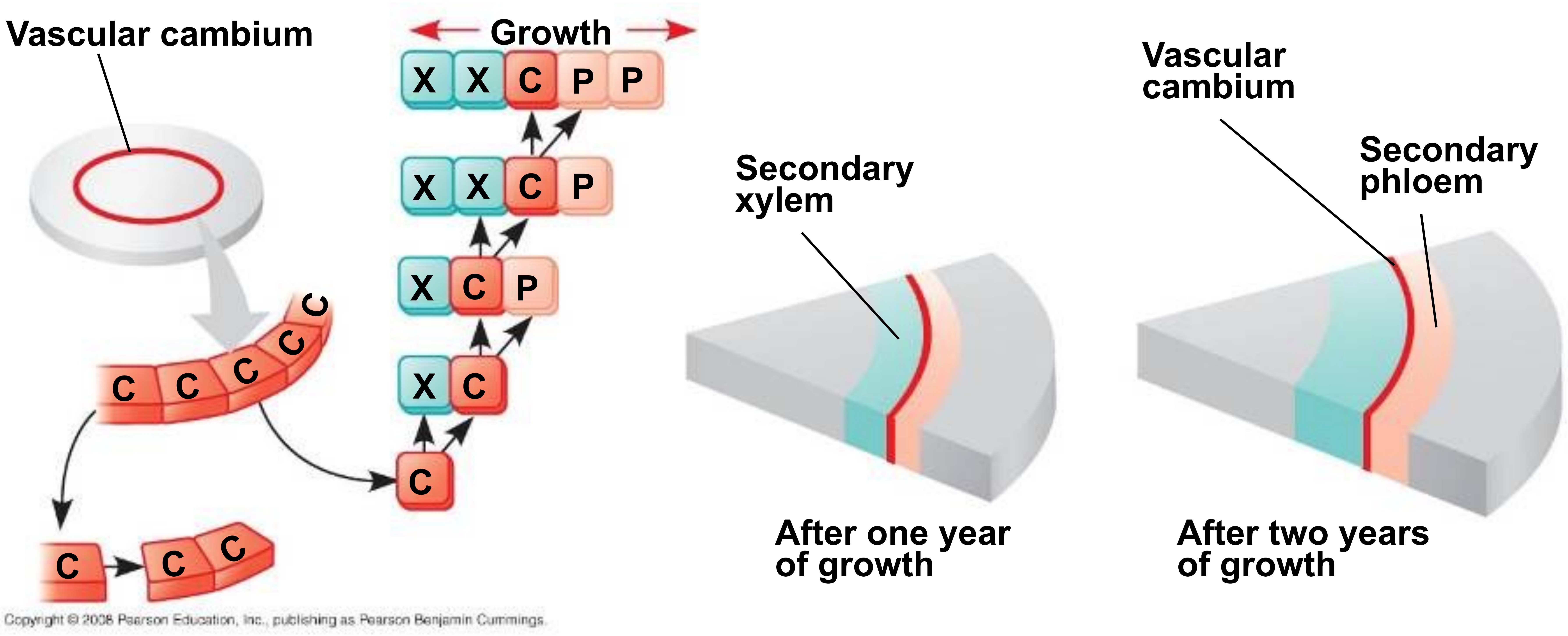
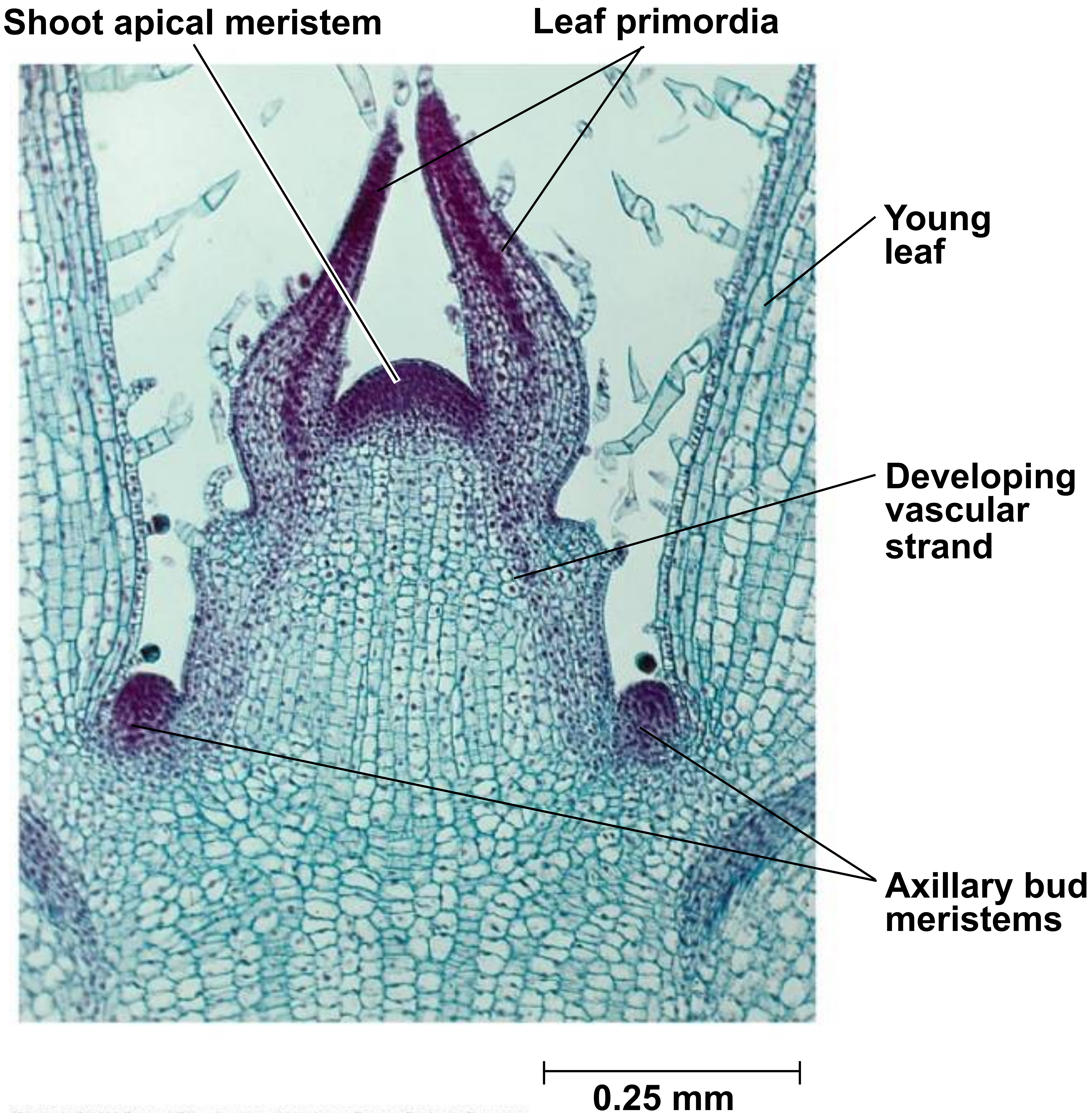


Fig. 35-20


Vascular cambium
Growth
X X C P P
X X C P
X C P
X C
C
C C C C C
C C C
Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings.
Secondary xylem
After one year of growth
Vascular cambium
Secondary phloem
After two years of growth

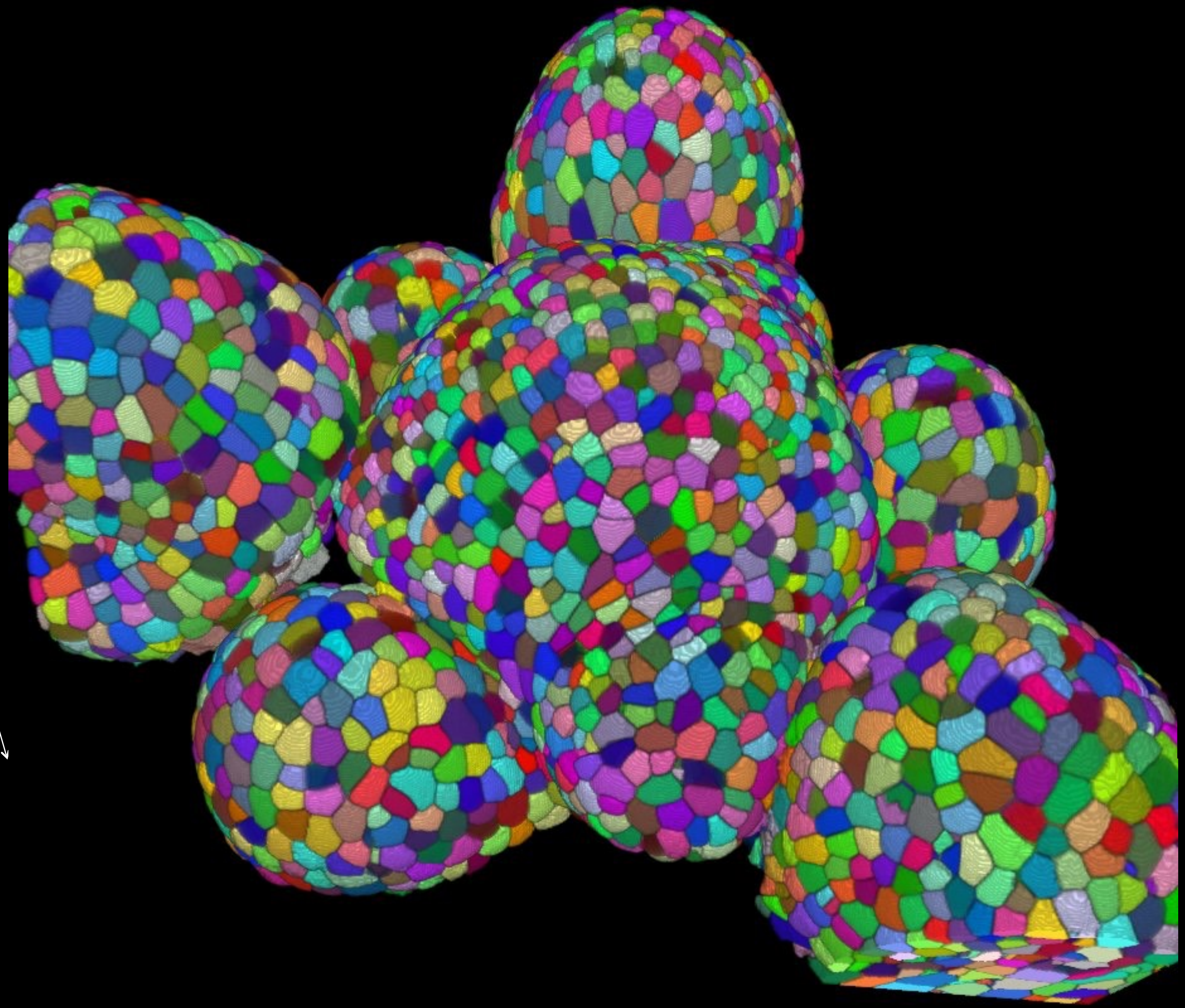
SHOOT APICAL MERISTEM

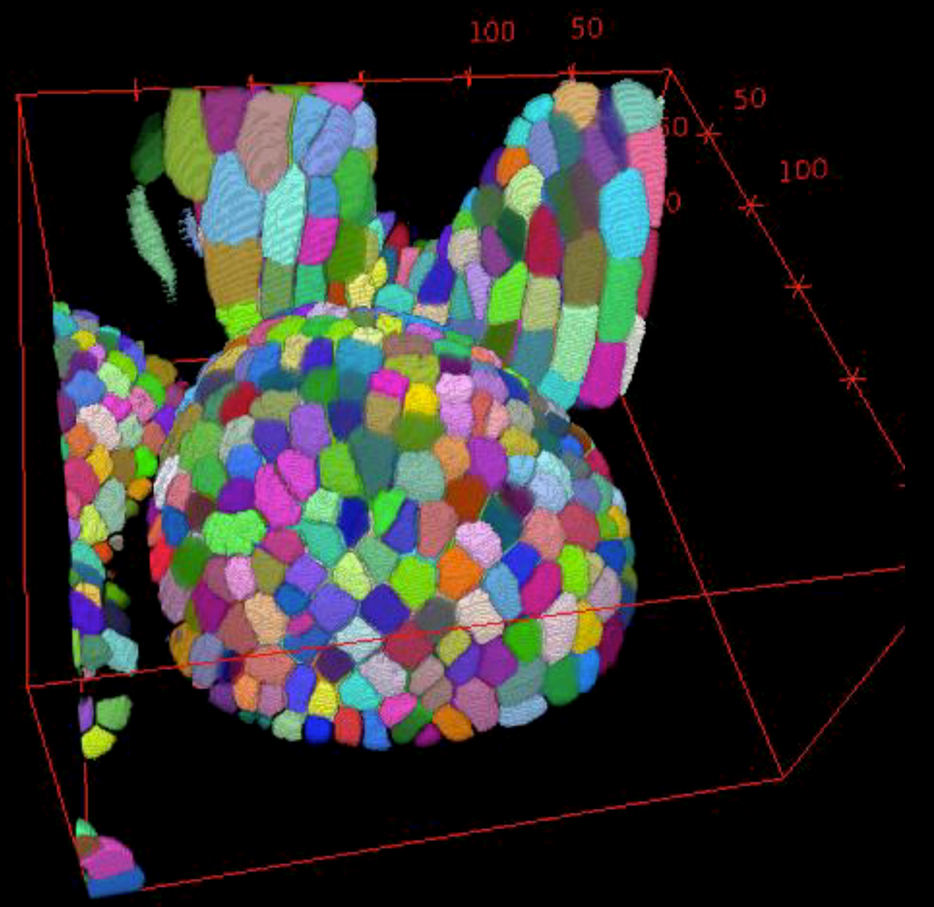


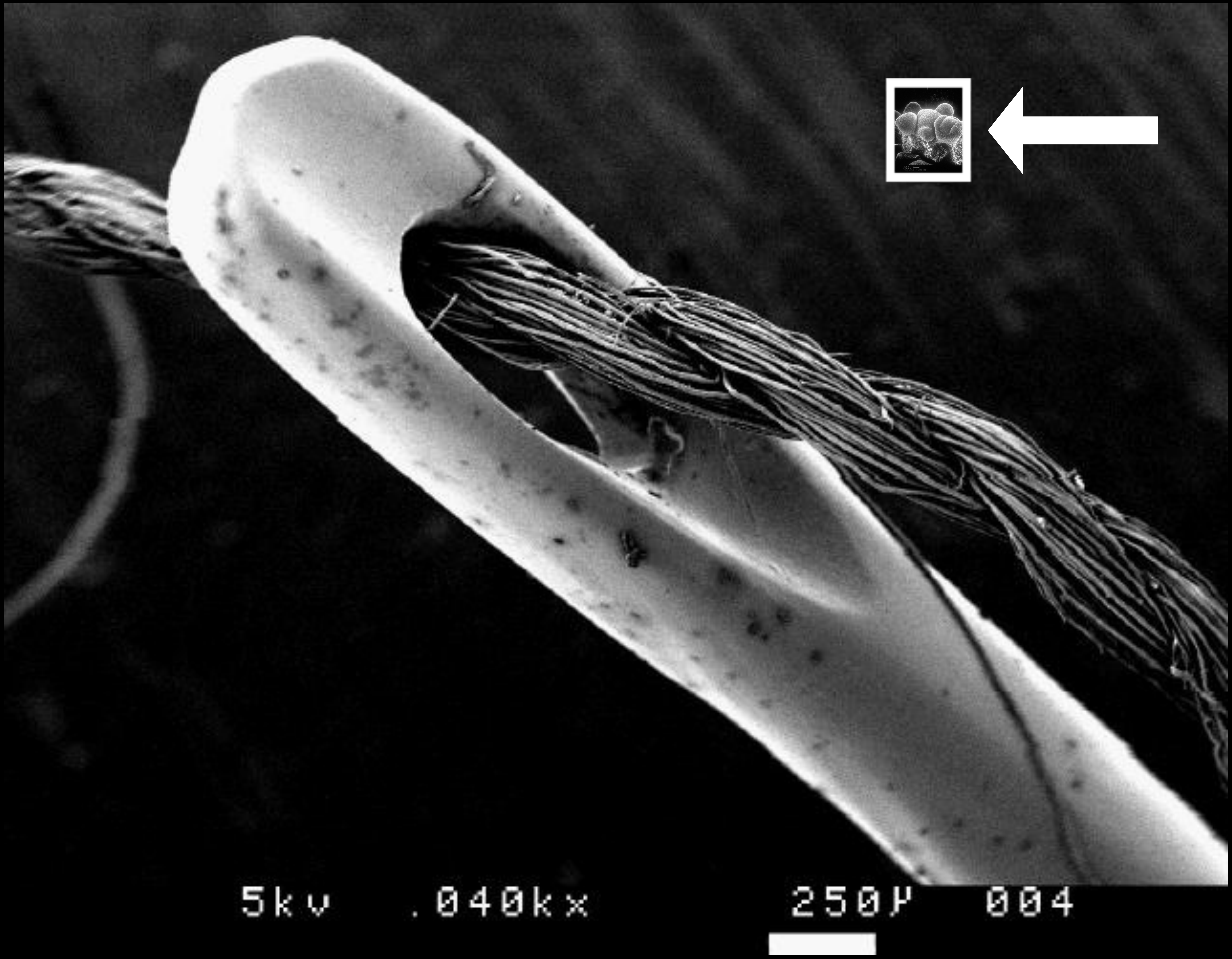

Shoot apical meristem

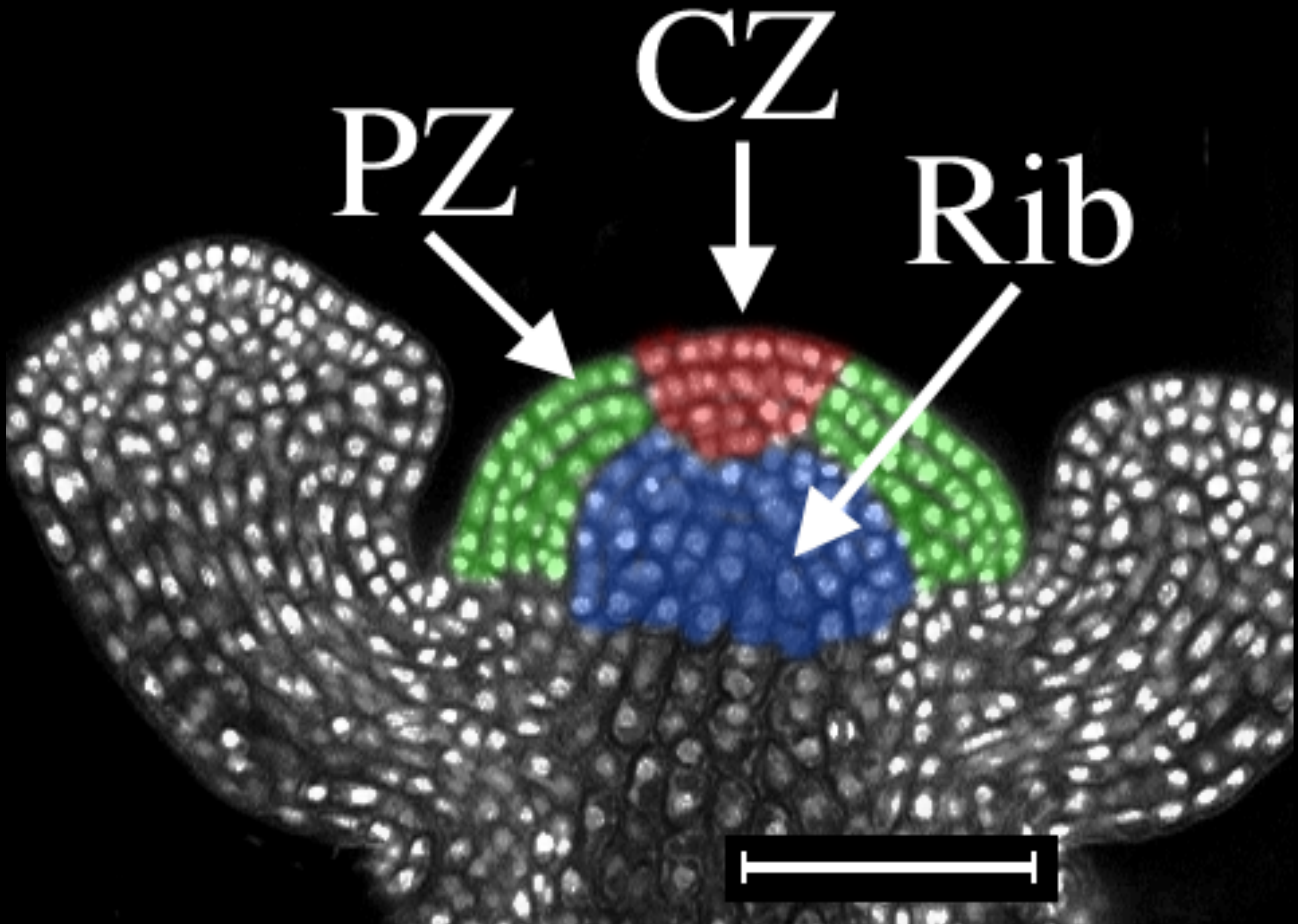
Shoot Apical Meristem and Flowers

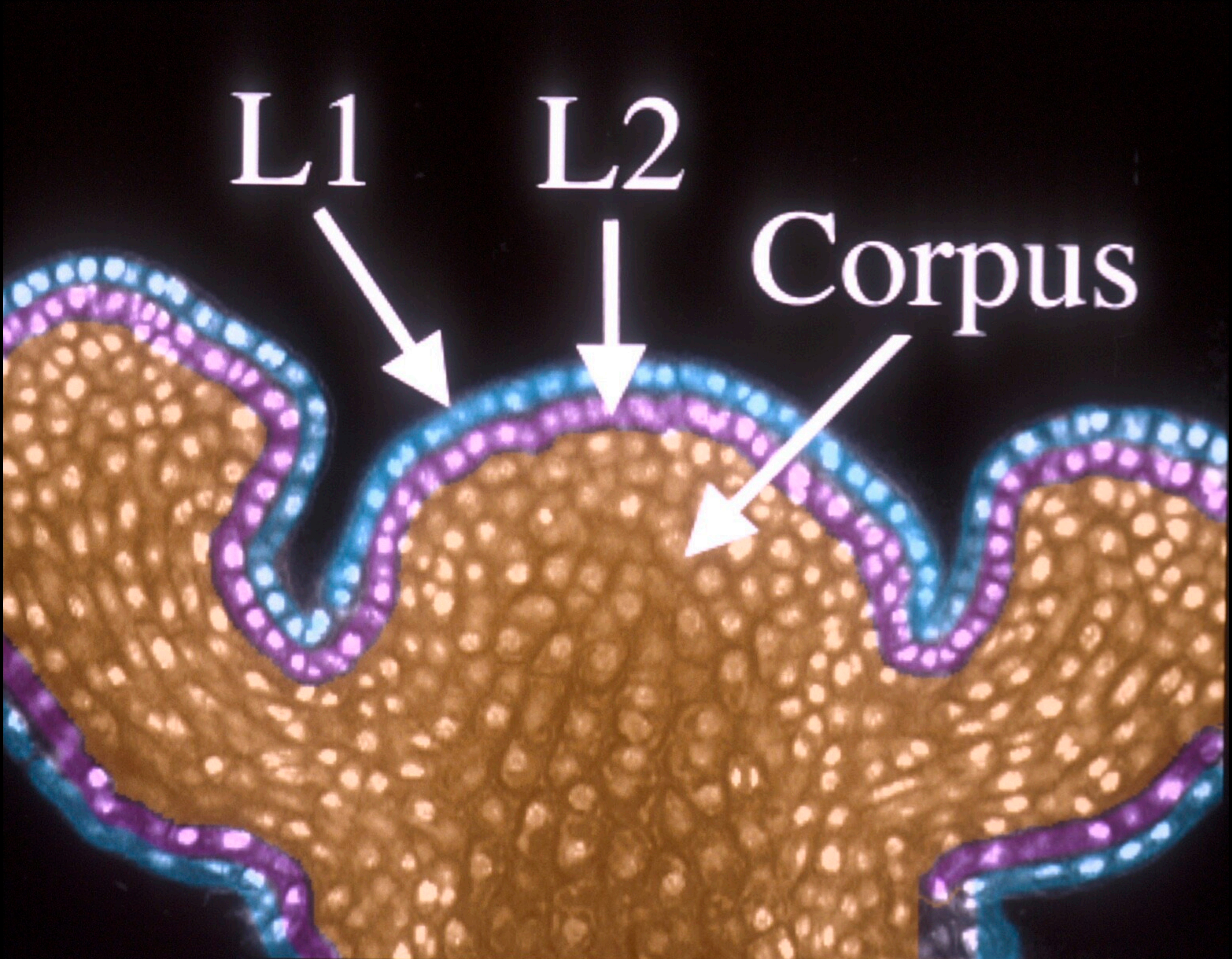
Arabidopsis



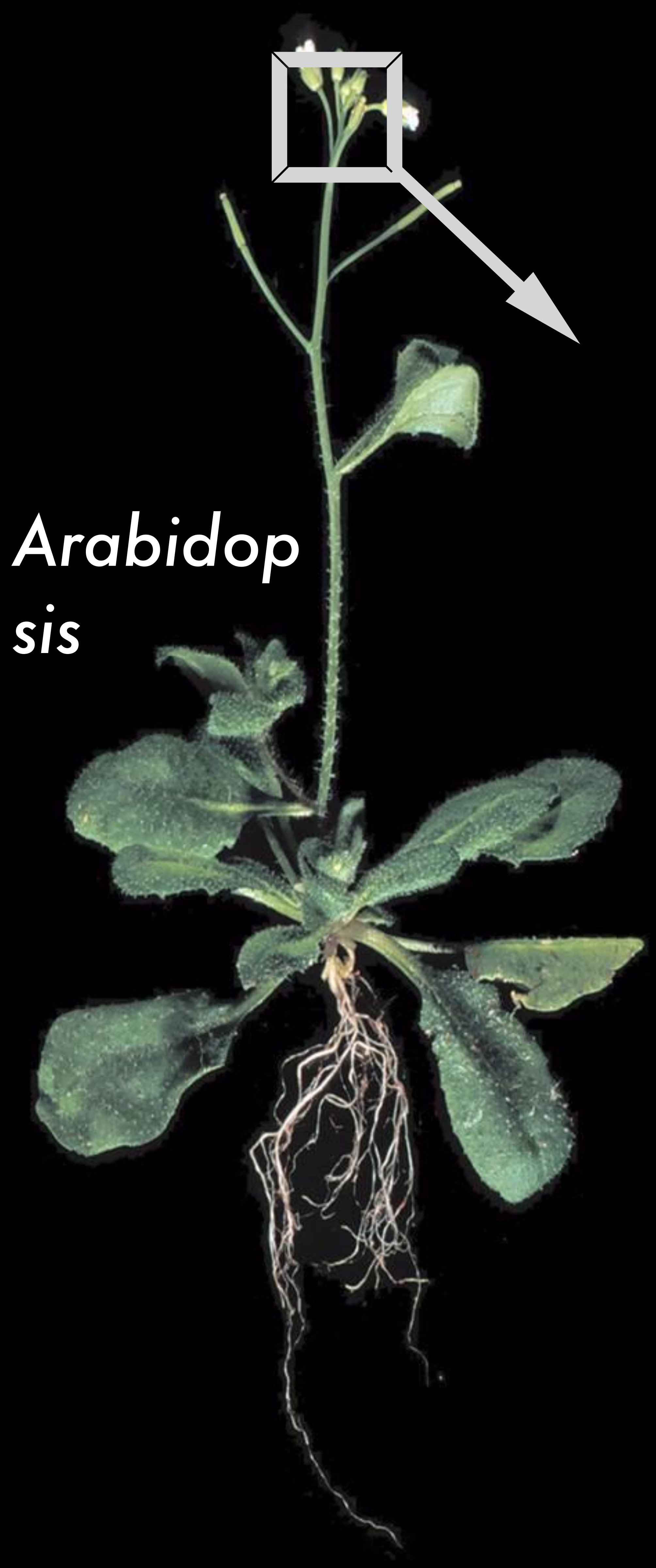


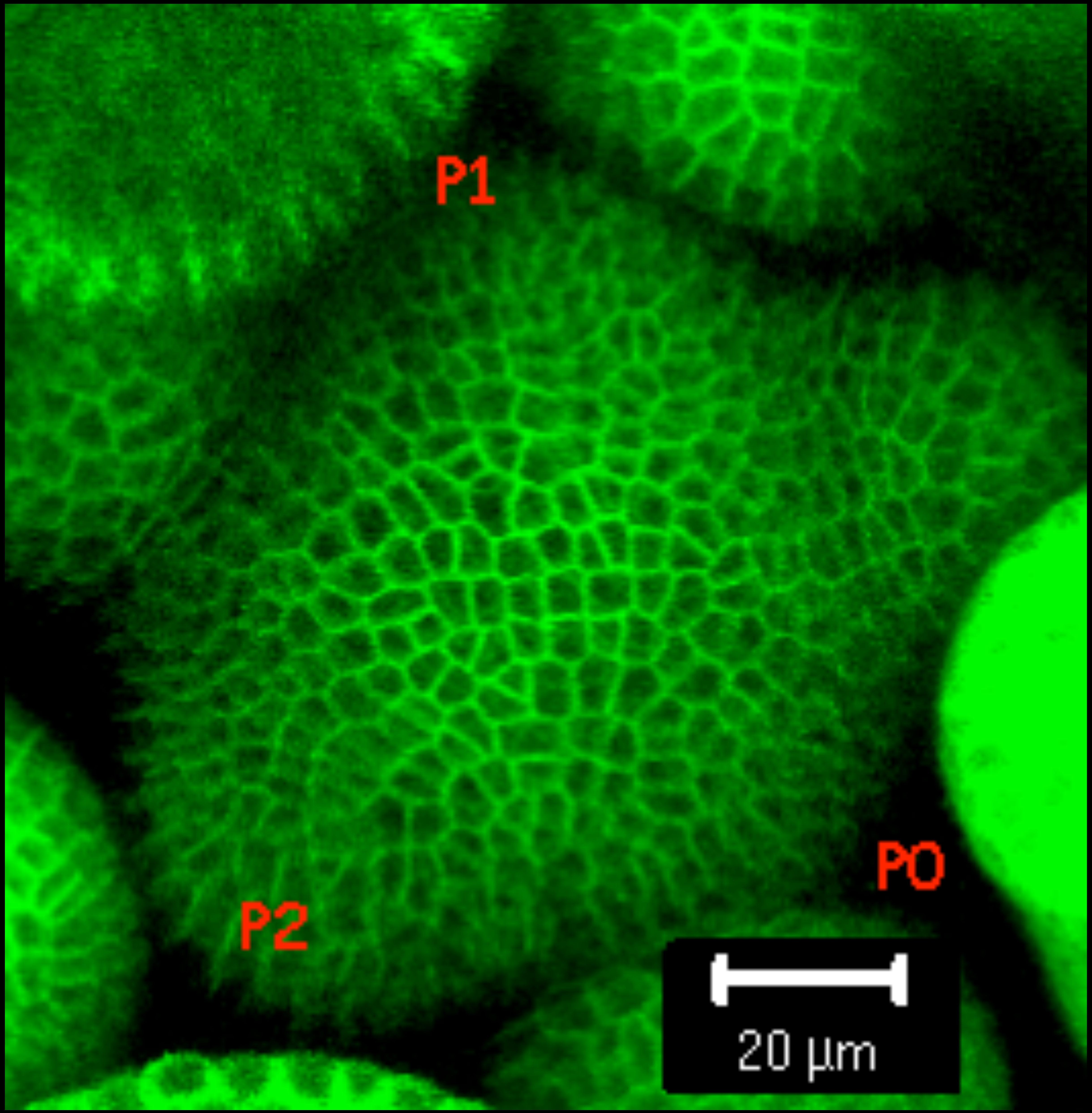

5kv .040kx 250µ 004


CZ
PZ
Rib

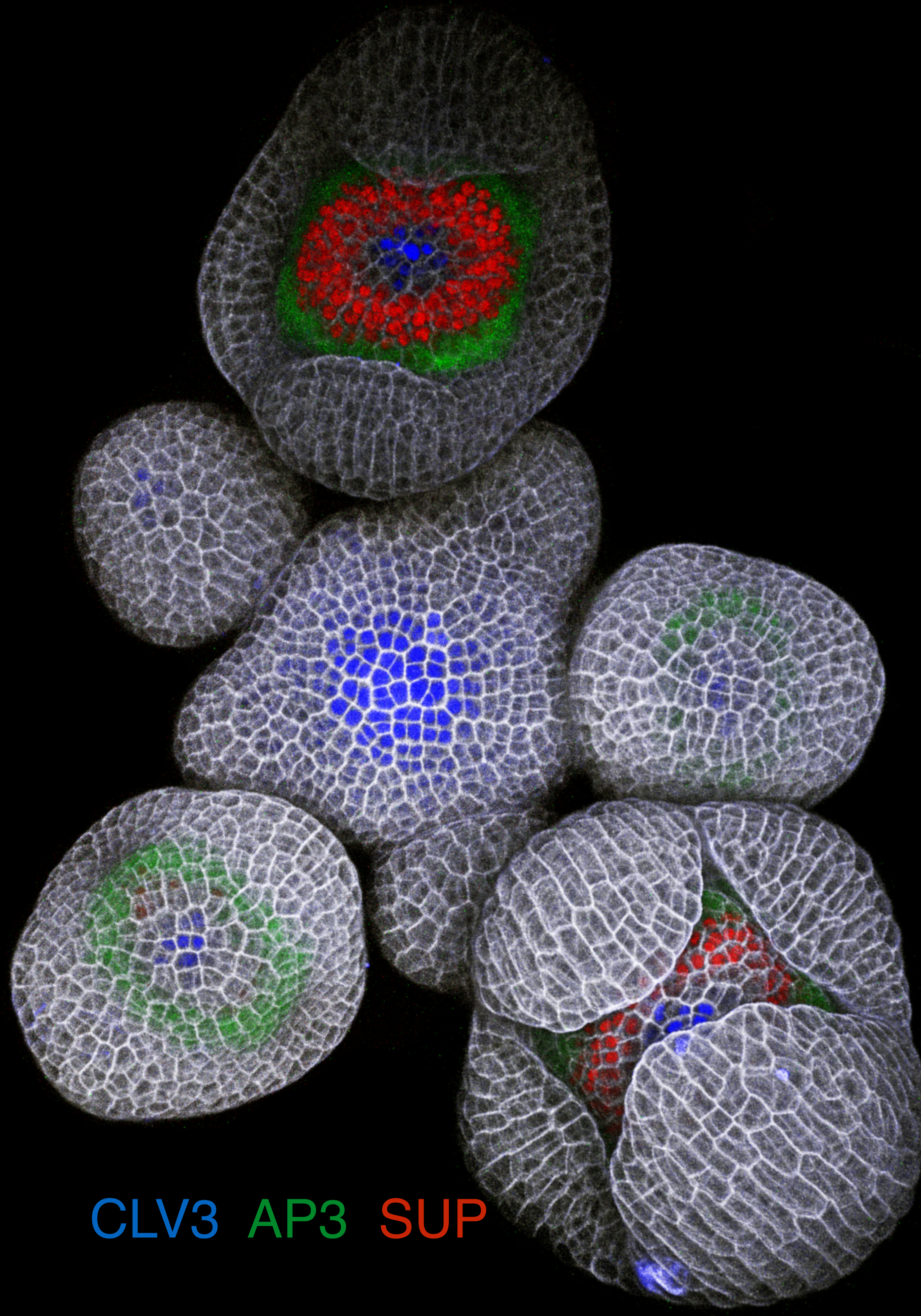

L1
L2
Corpus

Shoot Apical Meristem

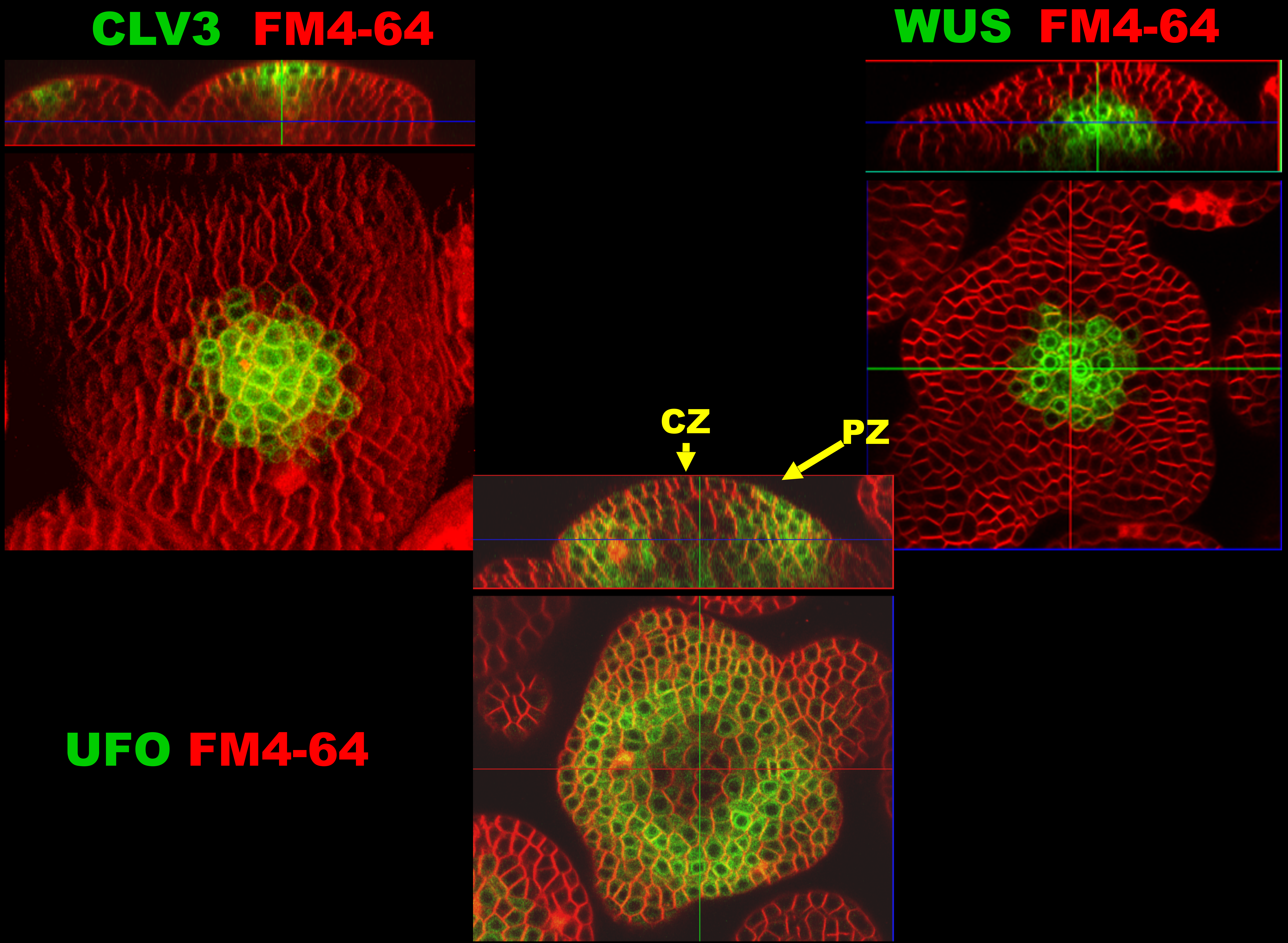




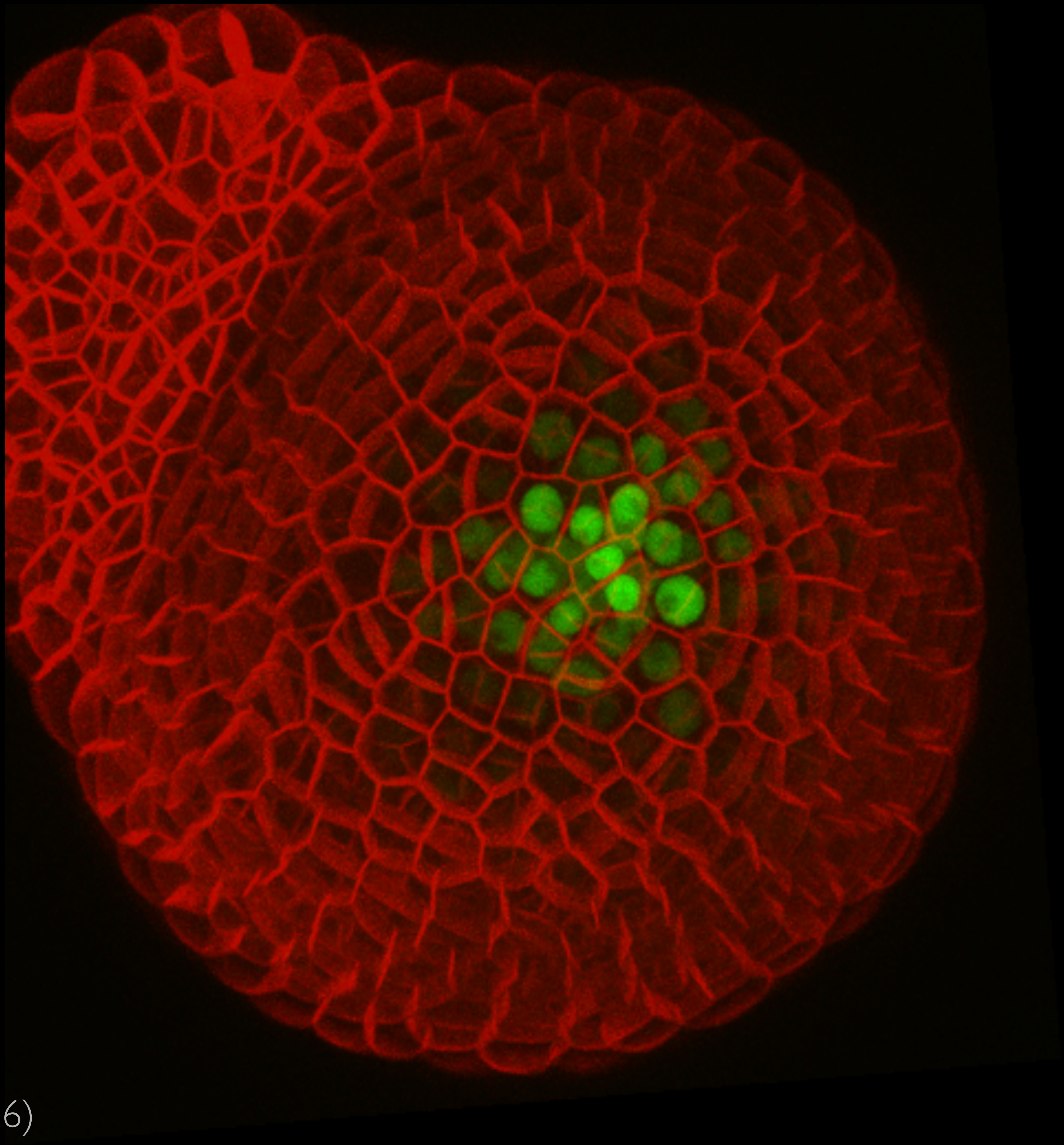
Venugopala Reddy



Nathanaël Prunet

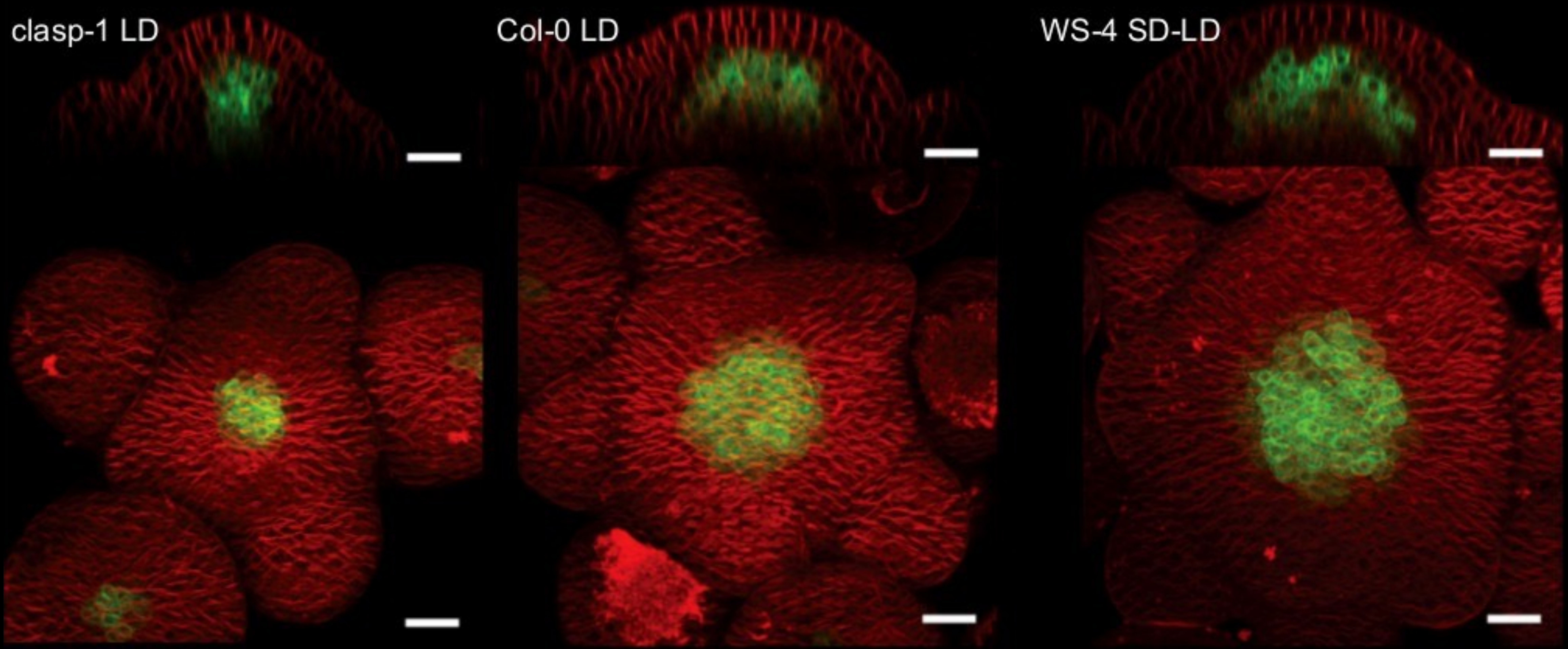

CLV3 FM4-64
WUS FM4-64
CZ
PZ
UFO FM4-64

Constant gene expression in a changing substrate



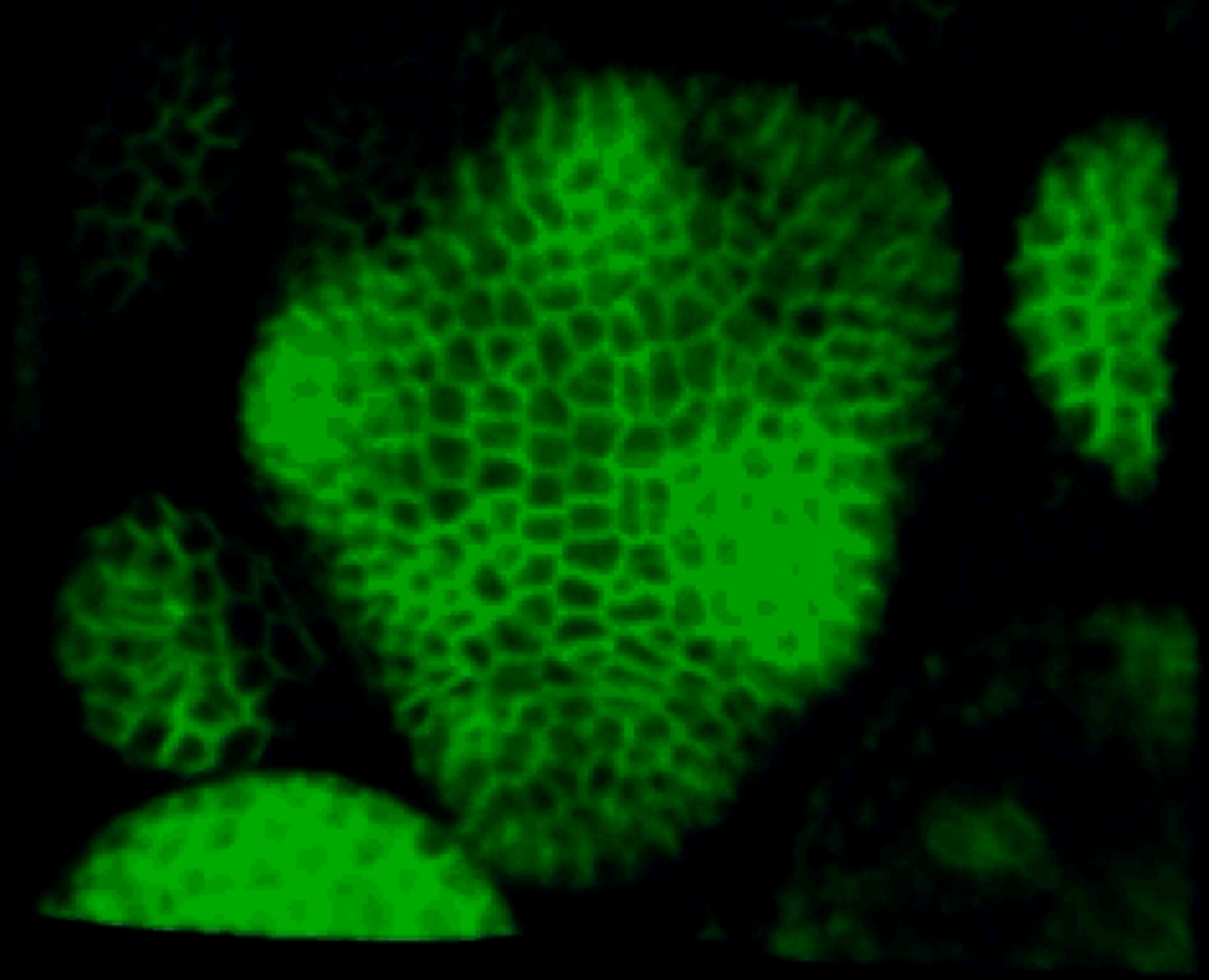
Willis et al (2016)

size influences expression regions

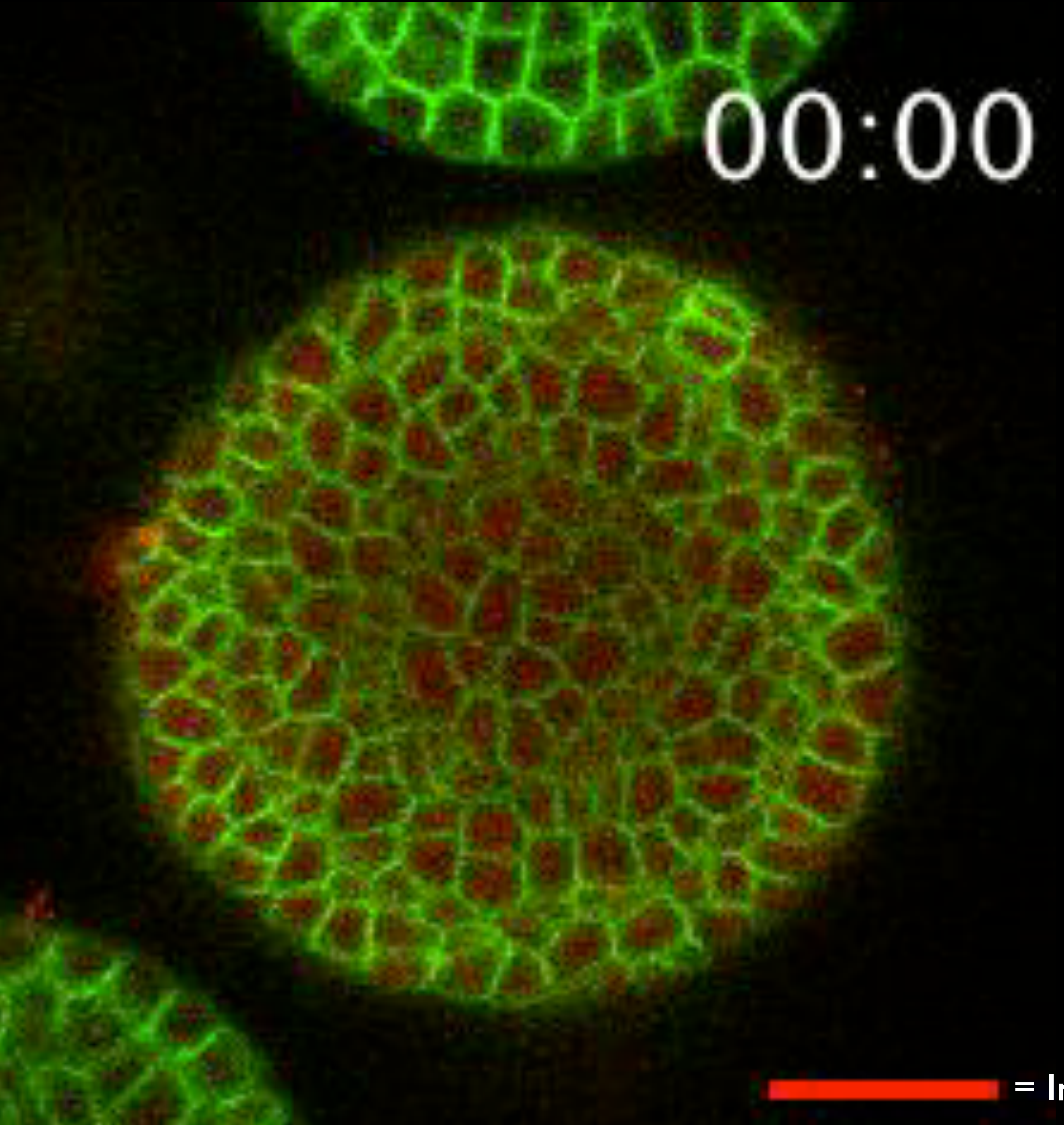


Gruel et al (2016)

PIN1 GFP is expressed relative to new floral primordial



Marcus Heisler



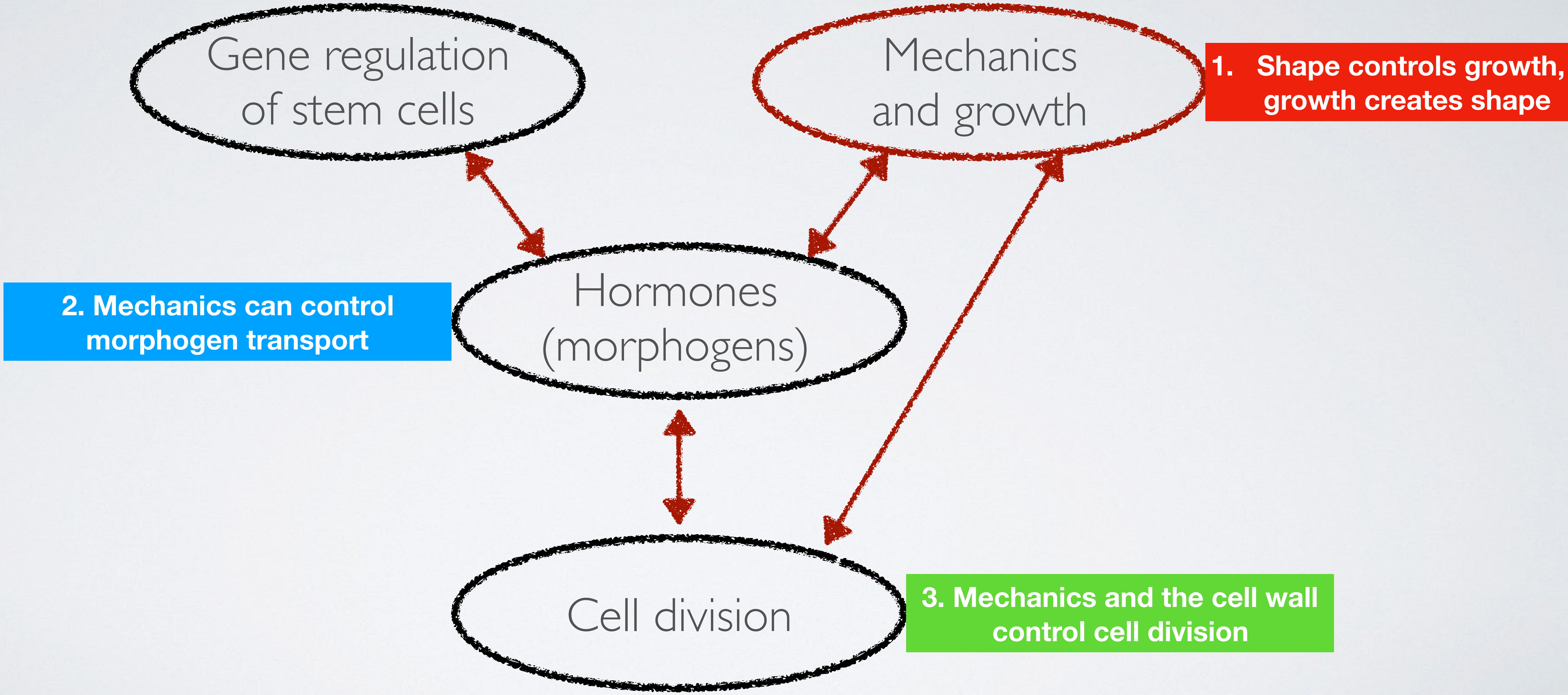
Gene Expression Isn't Everything: The Meristem Responds to Mechanical Force

= Increased Calcium ion level in cell cytoplasm

Ting Li

COMPUTATIONAL MORPHODYNAMICS

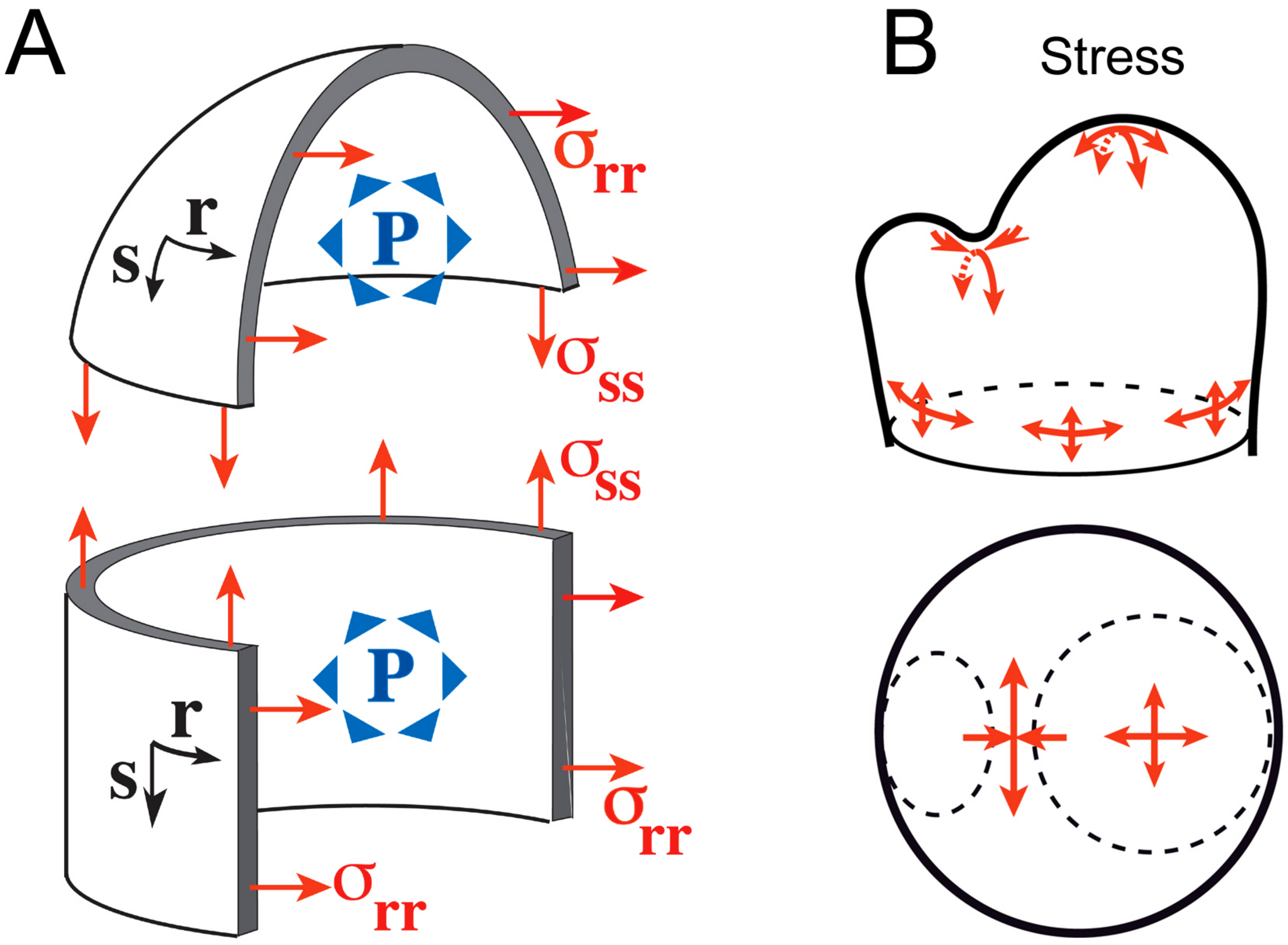
0. Introduction to plant growth (brief)



Jönsson, Meyerowitz

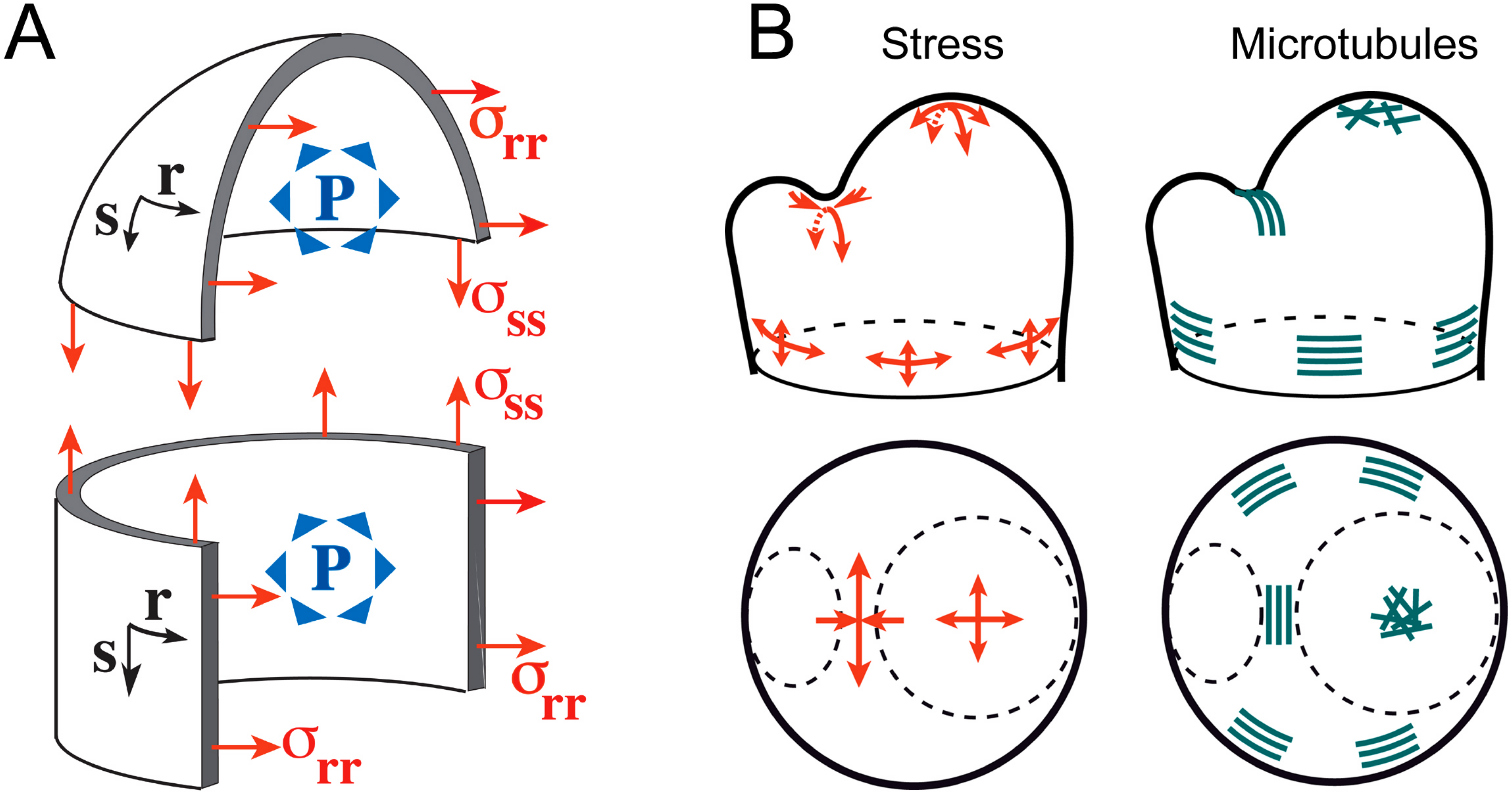

Hofmeister 1859, 1863; Sachs, 1865
http://science-mattersblog.blogspot.com/2013/05/dandelion-curls.html

Stress Pattern in SAM Epidermis



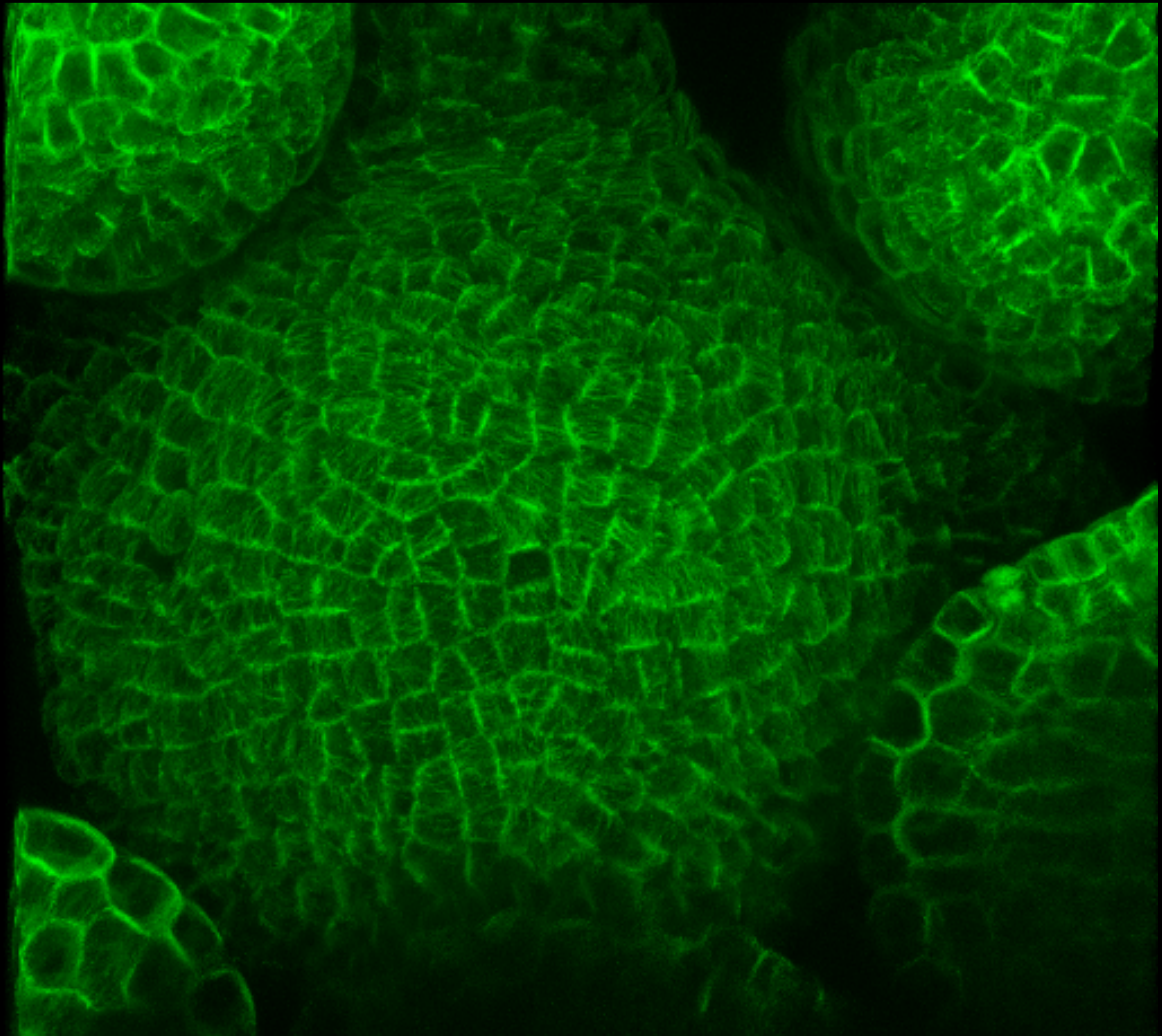
Hamant et al. 2008

Stress Pattern in SAM Epidermis

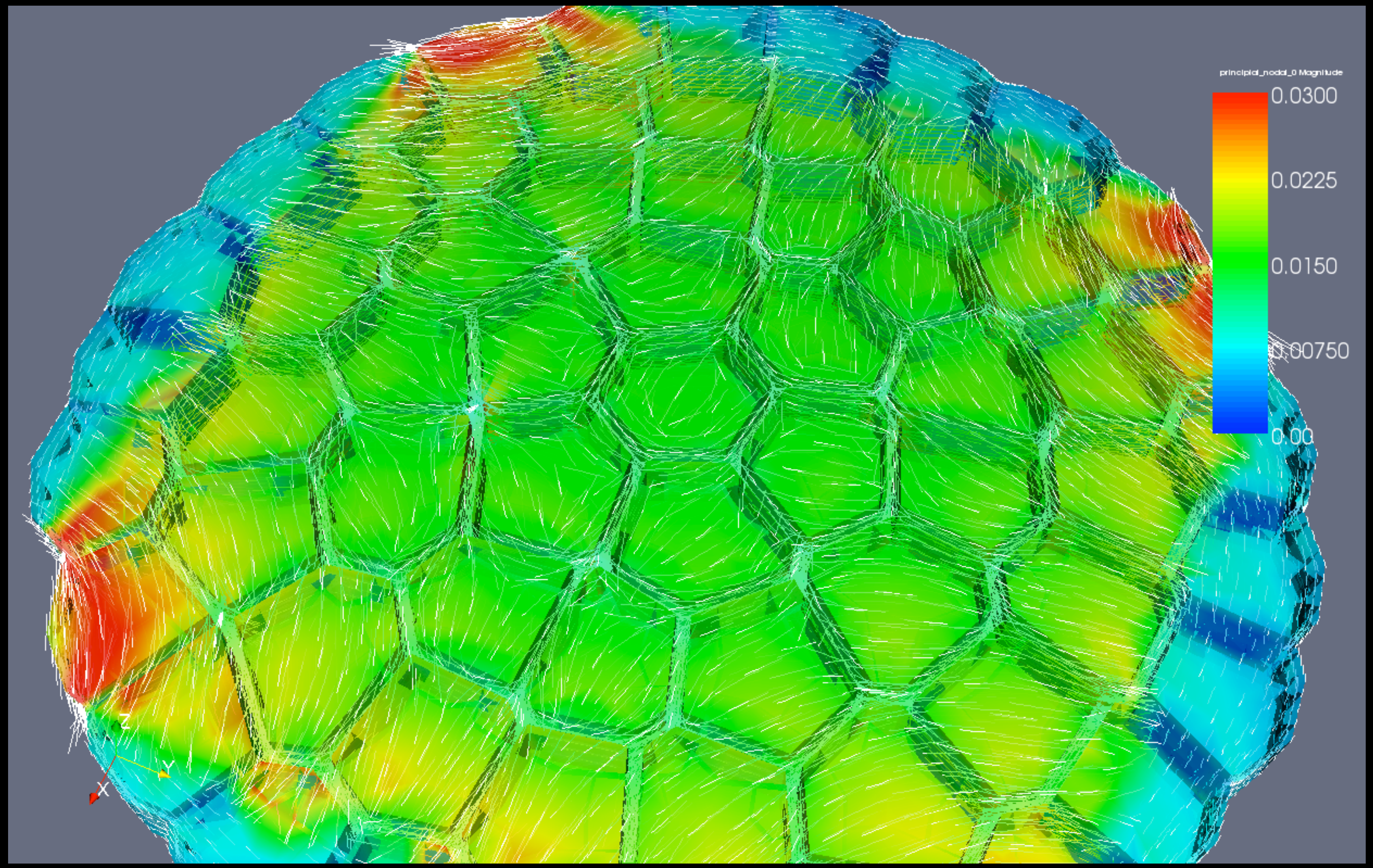


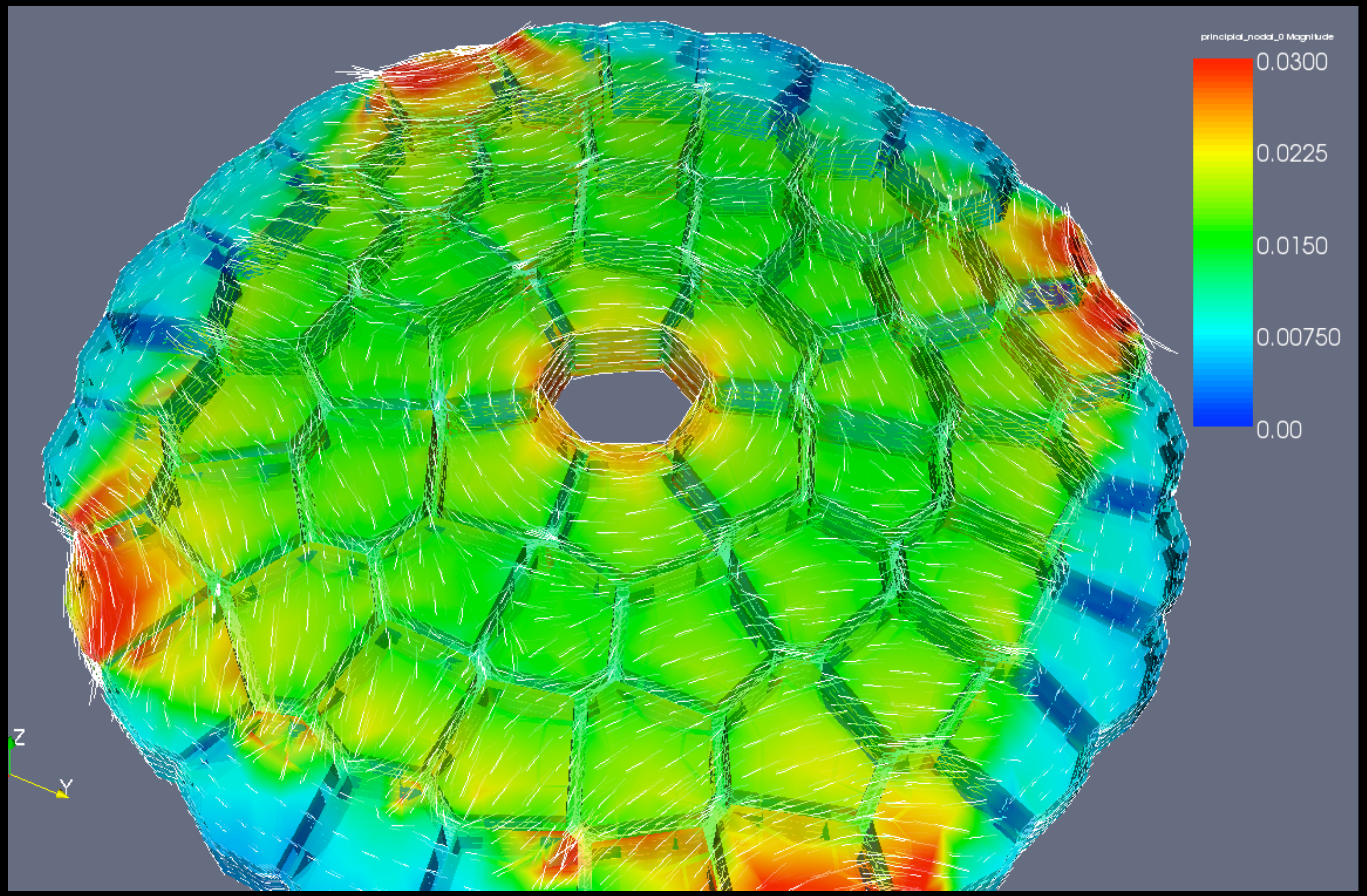
Hamant et al. 2008

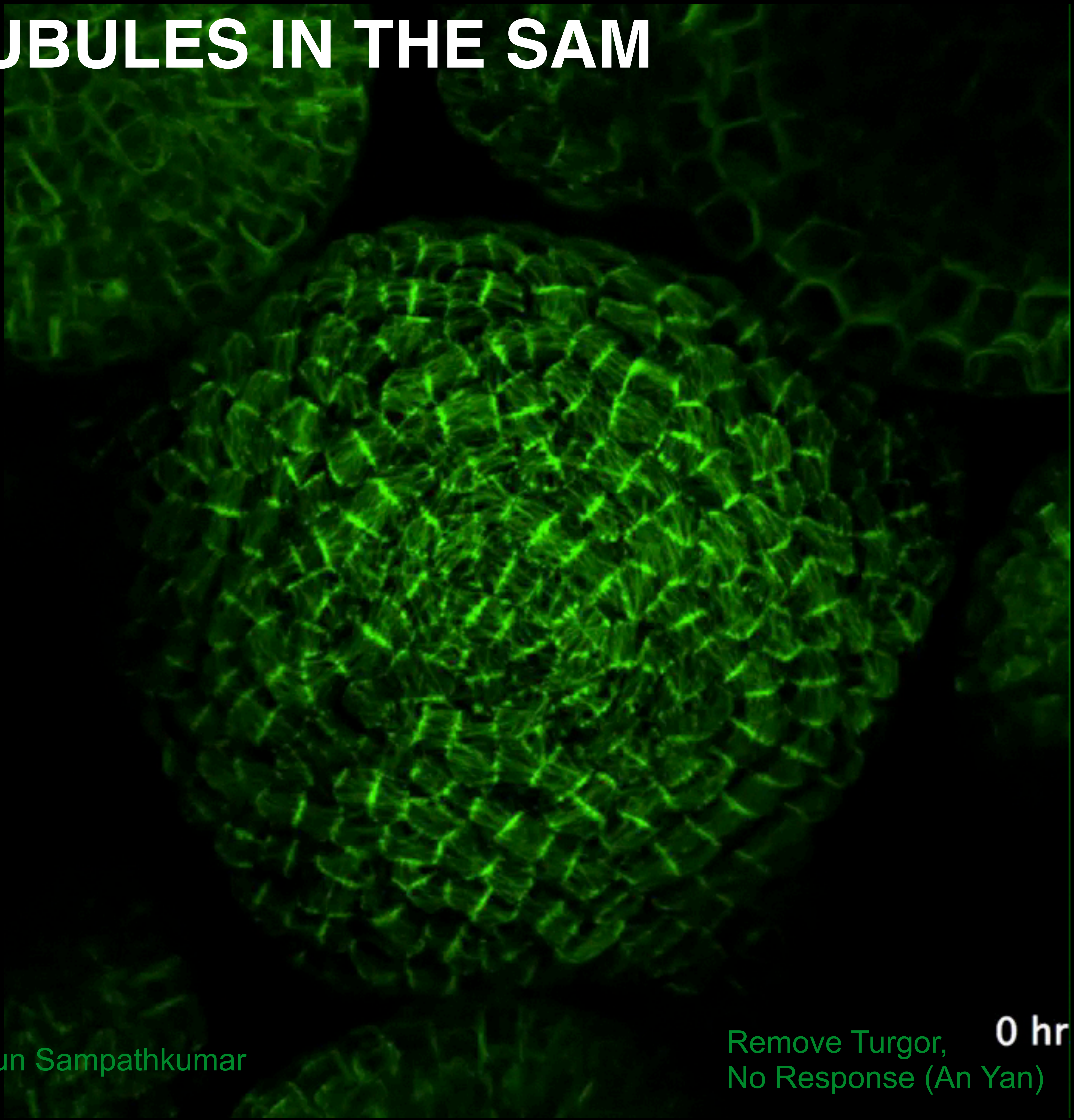
MICROTUBULES IN THE SAM



MICROTUBULES IN THE SAM

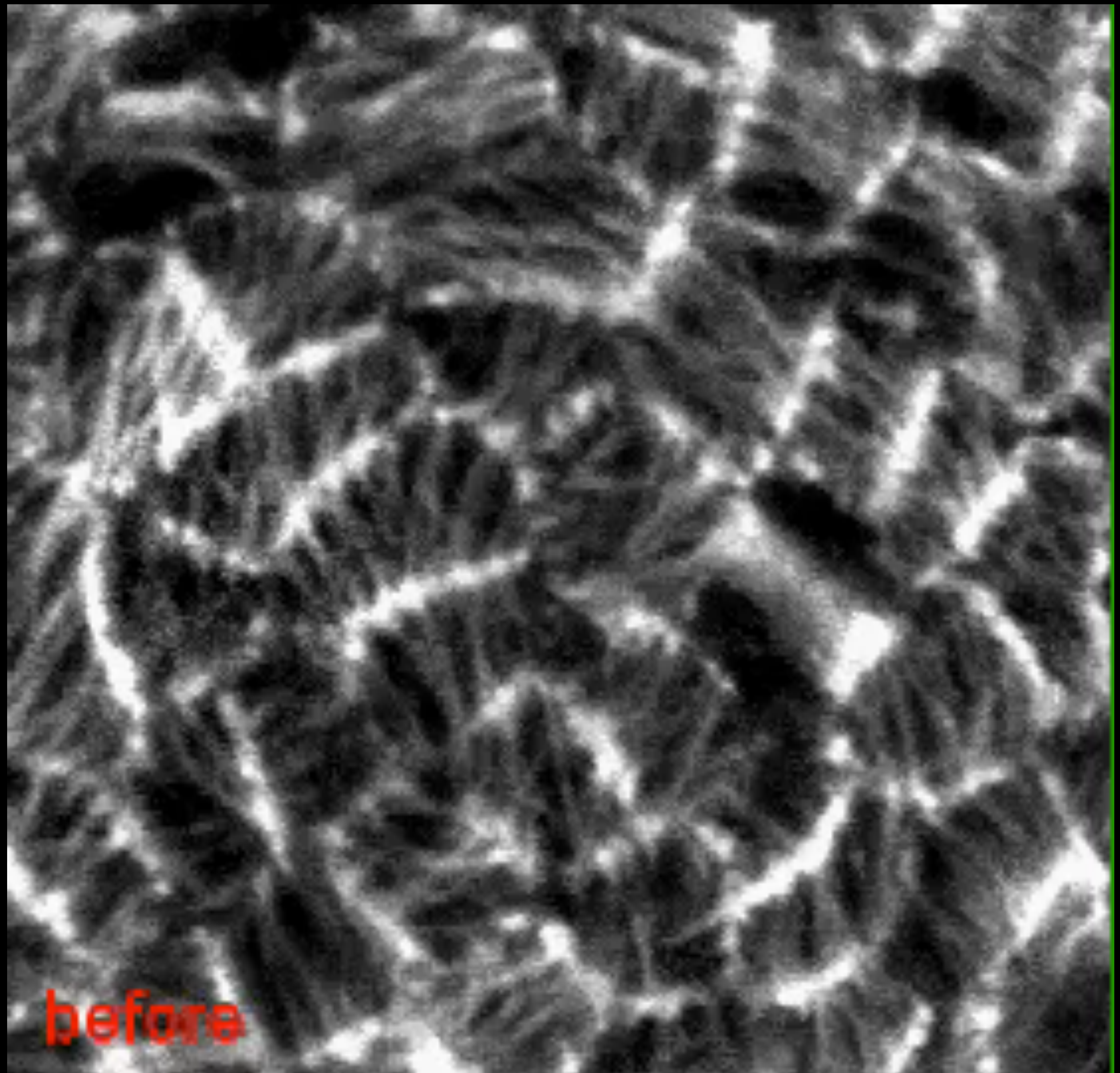


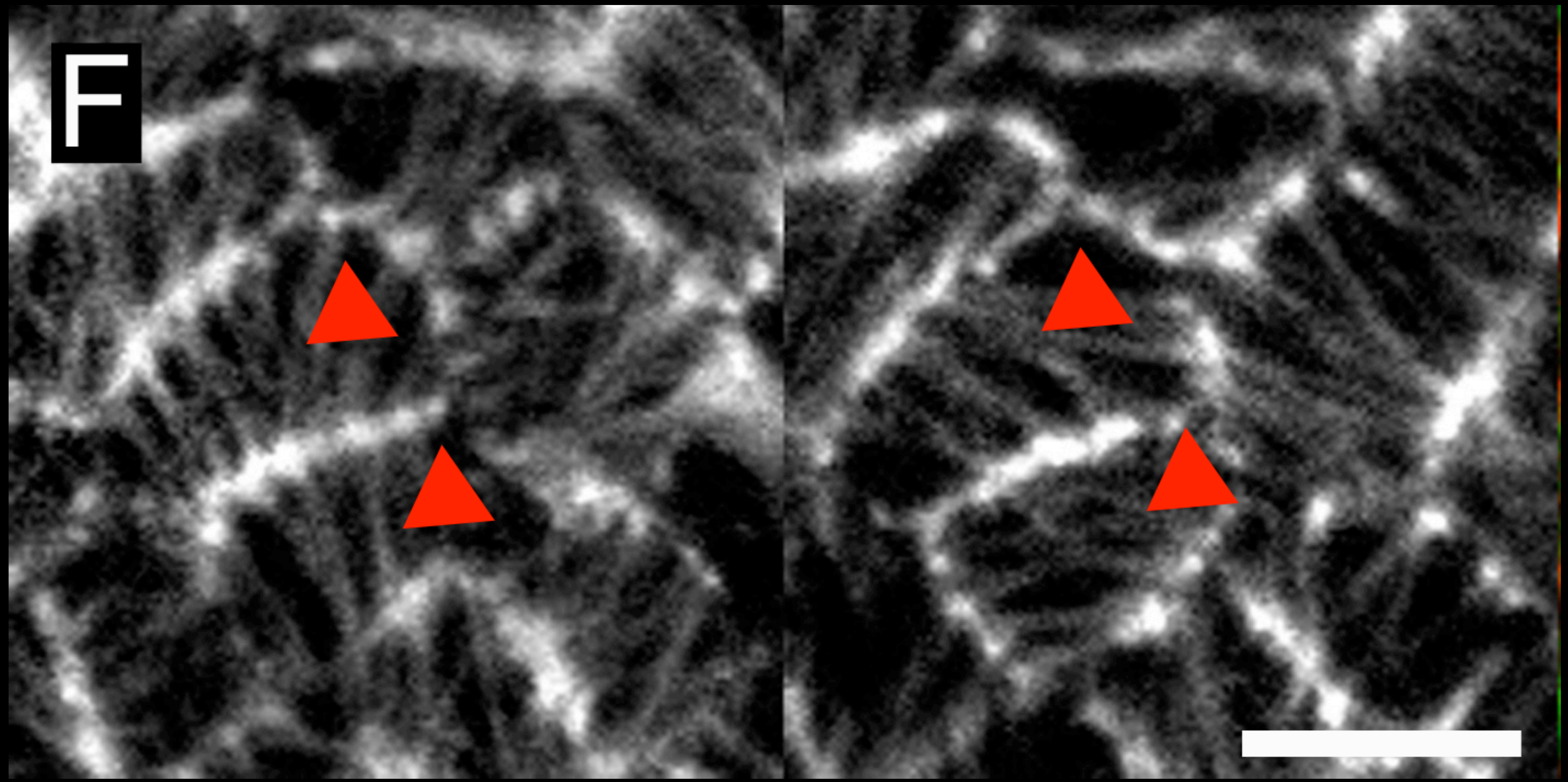




Arun Sampathkumar

Mt Orientations 6 Hrs Following Compression

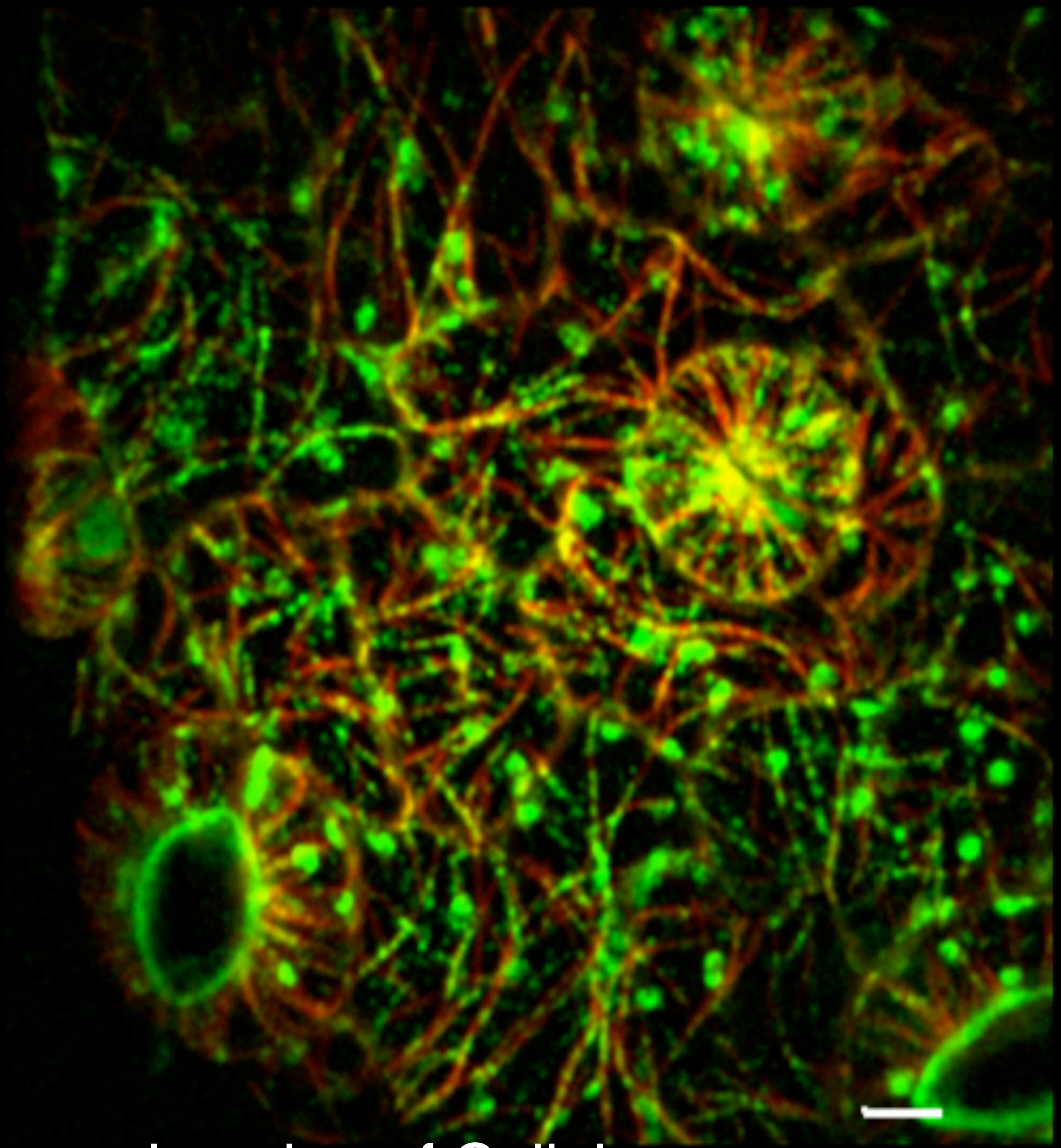




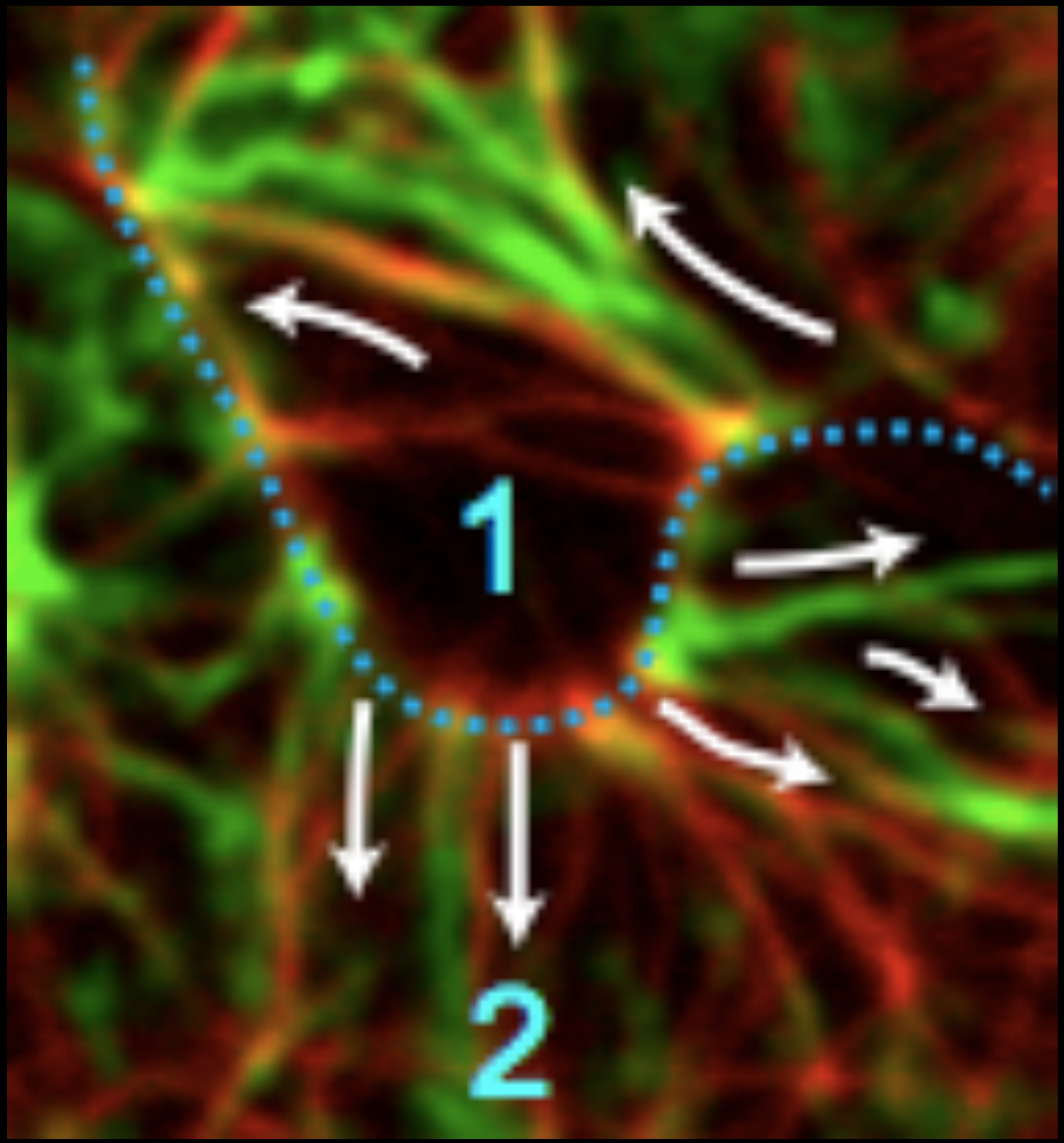
Hamant et al. 2008

Cellulose Synthesis Follows Microtubules

mCherry::TUA5 CESA3::GFP

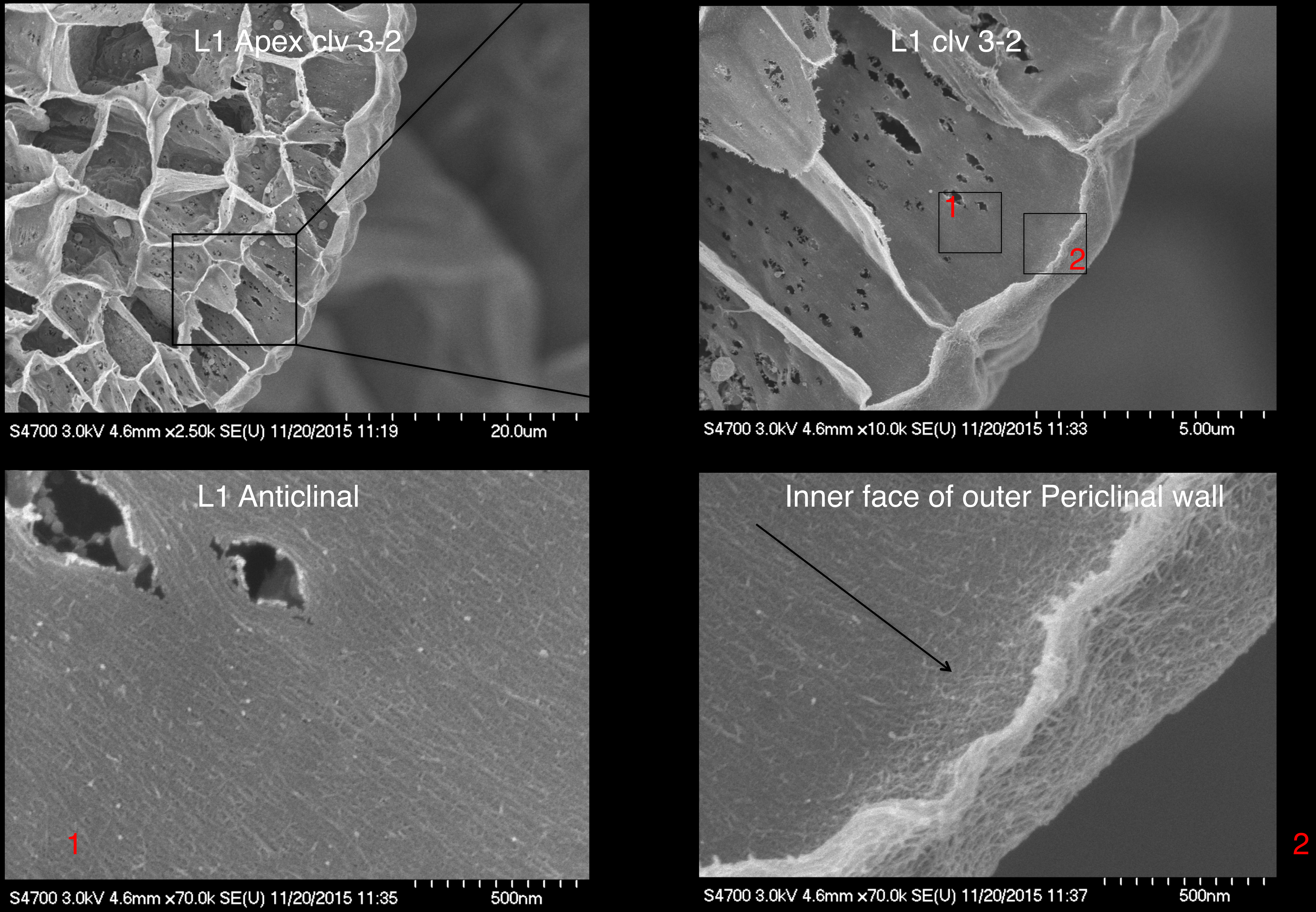


Imaging of Cellulose synthesizing complexes in pavement cells and shoot apical meristem



Arun Sampathkumar with David Ehrhardt
(SLCU/Caltech) (Carnegie/ Stanford)

Field Emission Scanning Electron Microscopy of Cellulose

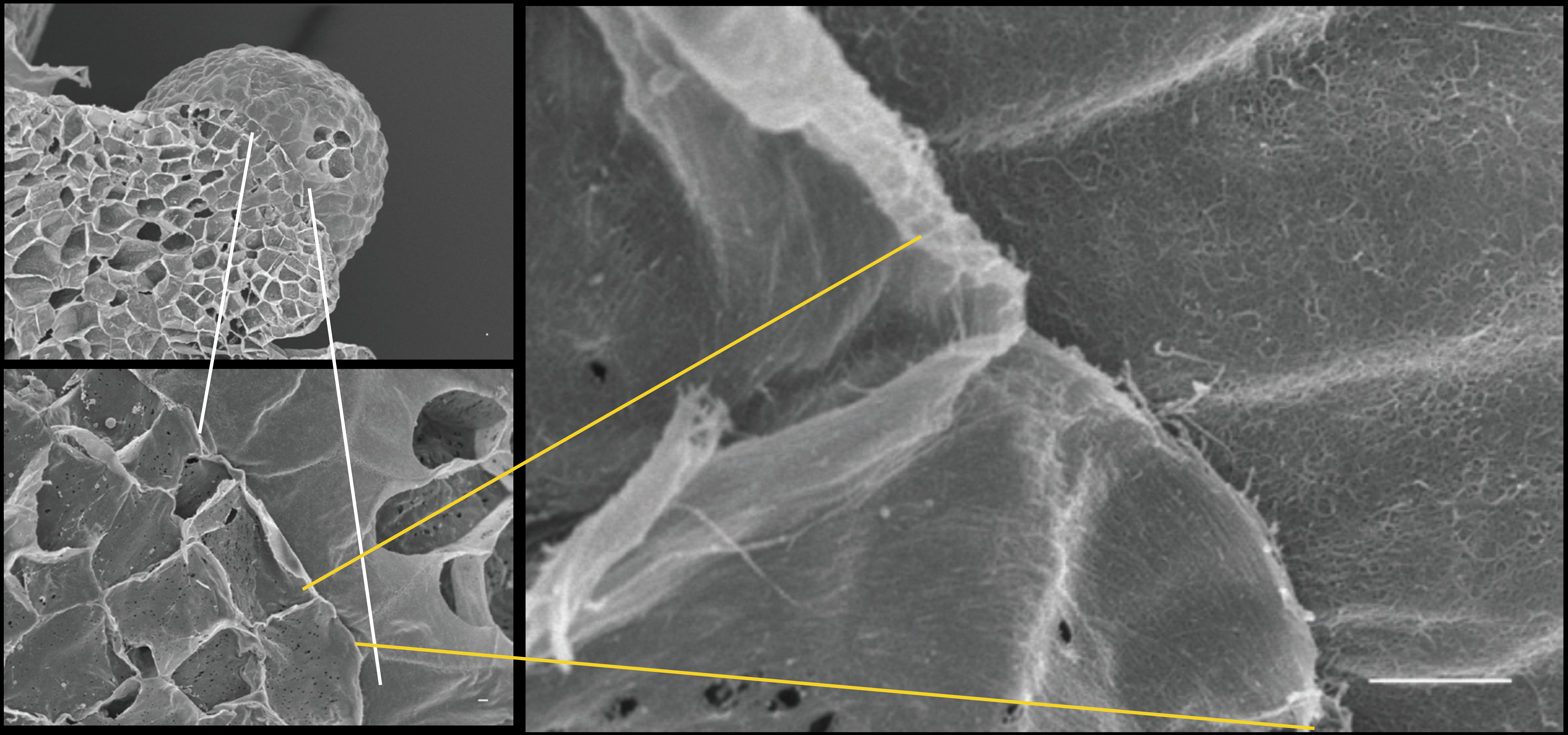


Hitachi S4700 FESEM

Sampathkumar et al. (2019)

Collaboration with Miki Fujita, Geoffrey Wasteneys

Field Emission Scanning Electron Microscopy of Cellulose

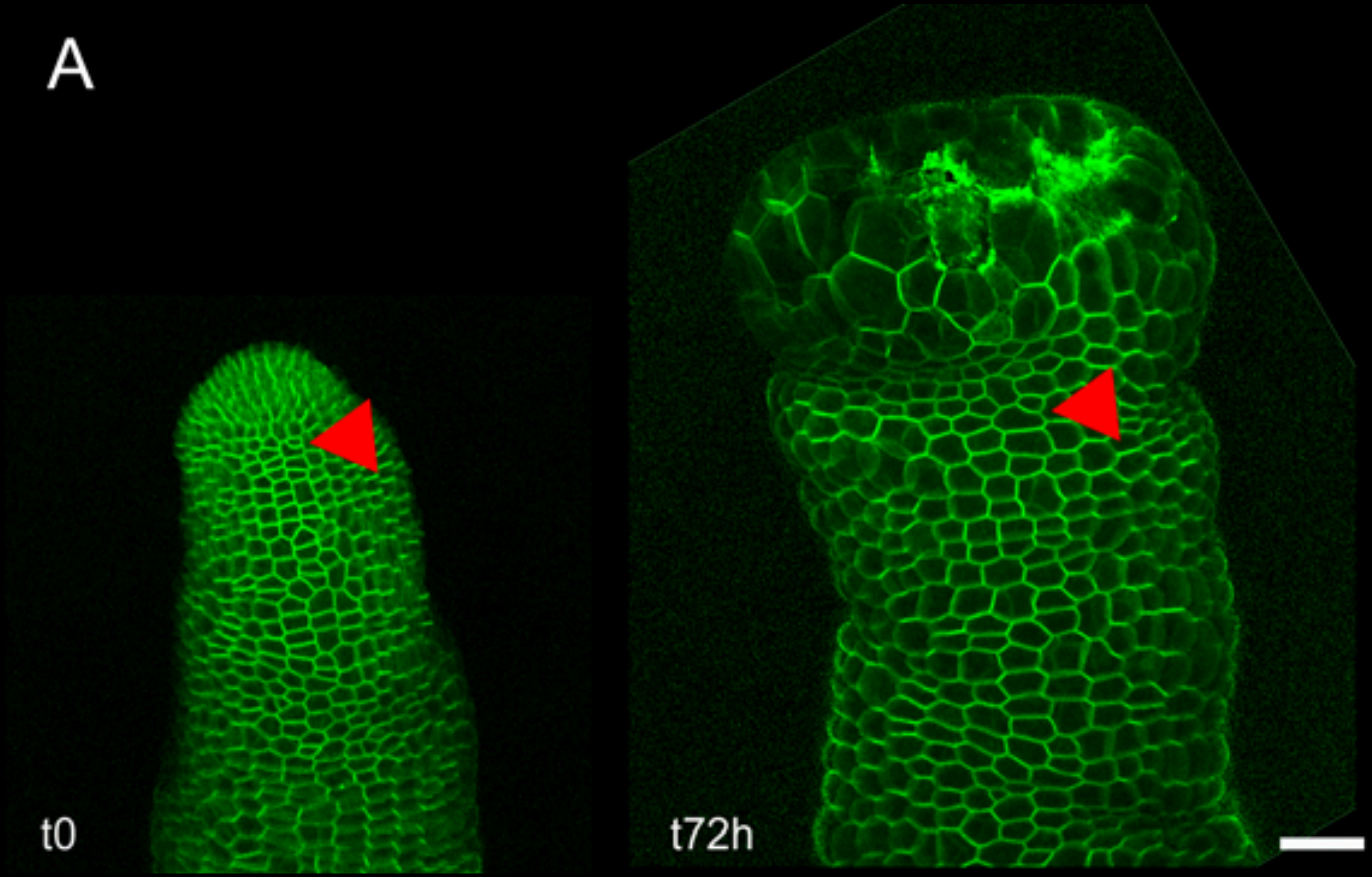


Sampathkumar et al. (2019)

Collaboration with Miki Fujita, Geoffrey Wasteneys

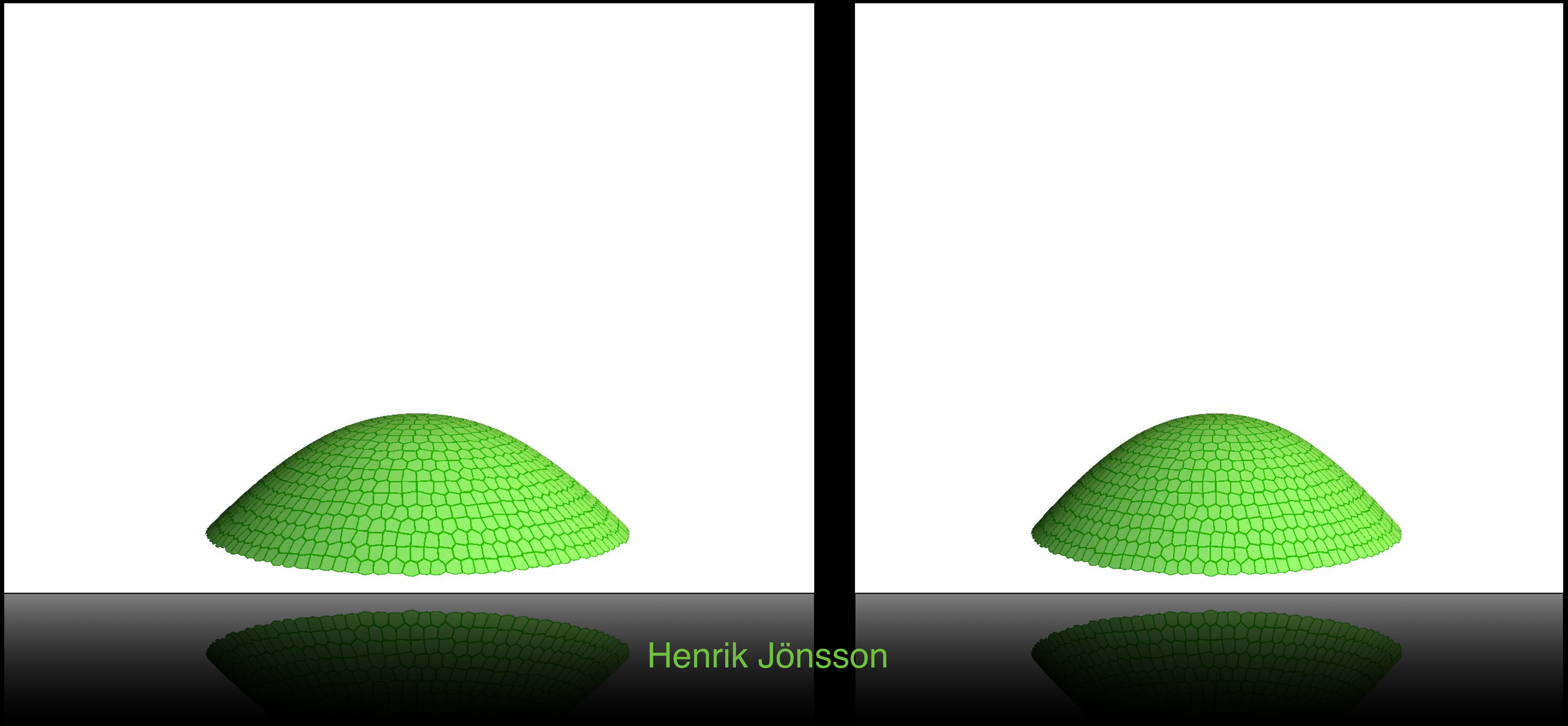
Depolymerize Microtubules, Shape is Lost

Hamant et al. (2008) Science 322, 1650



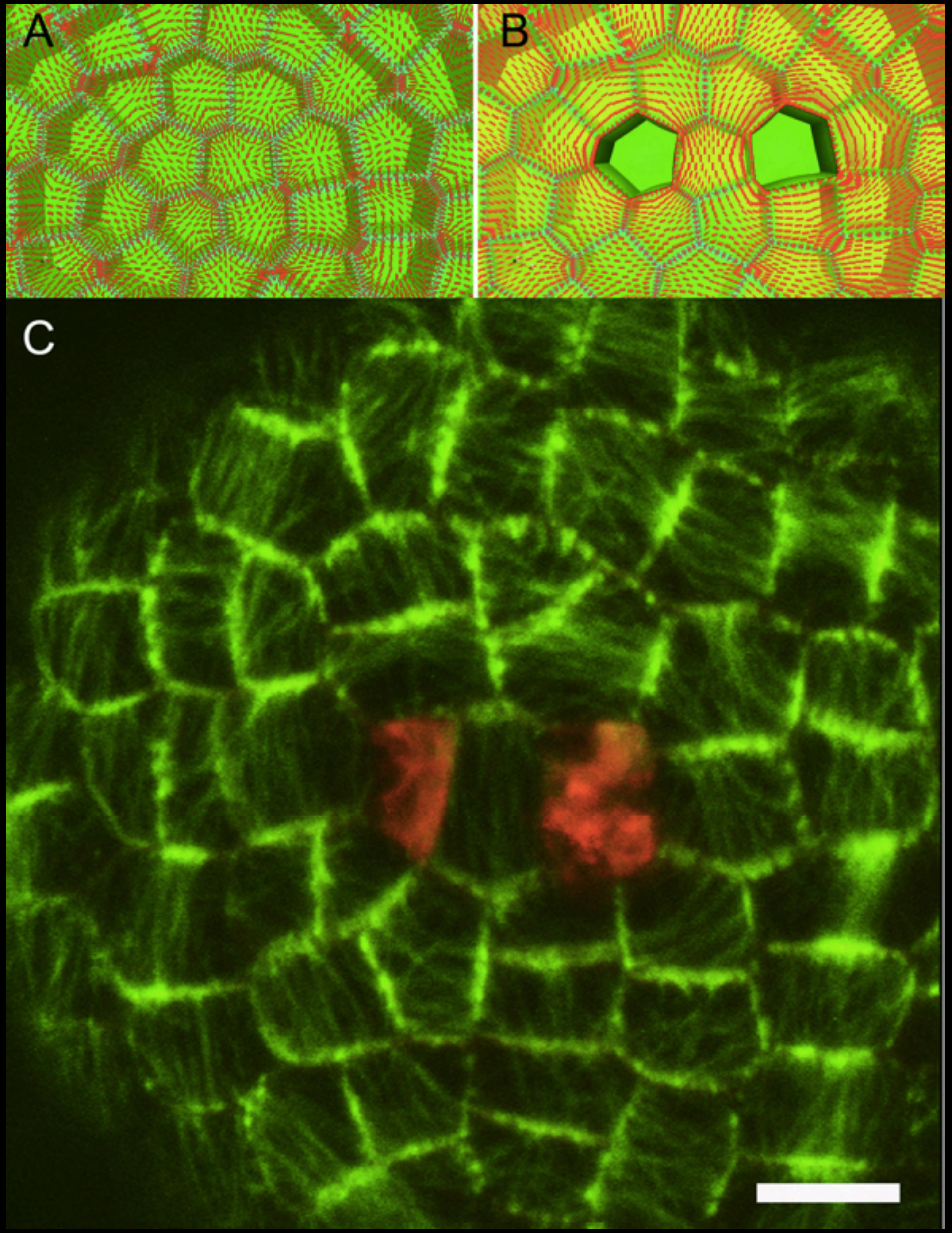
Hamant et al. 2008

Development of finite element based model of growth and morphogenesis

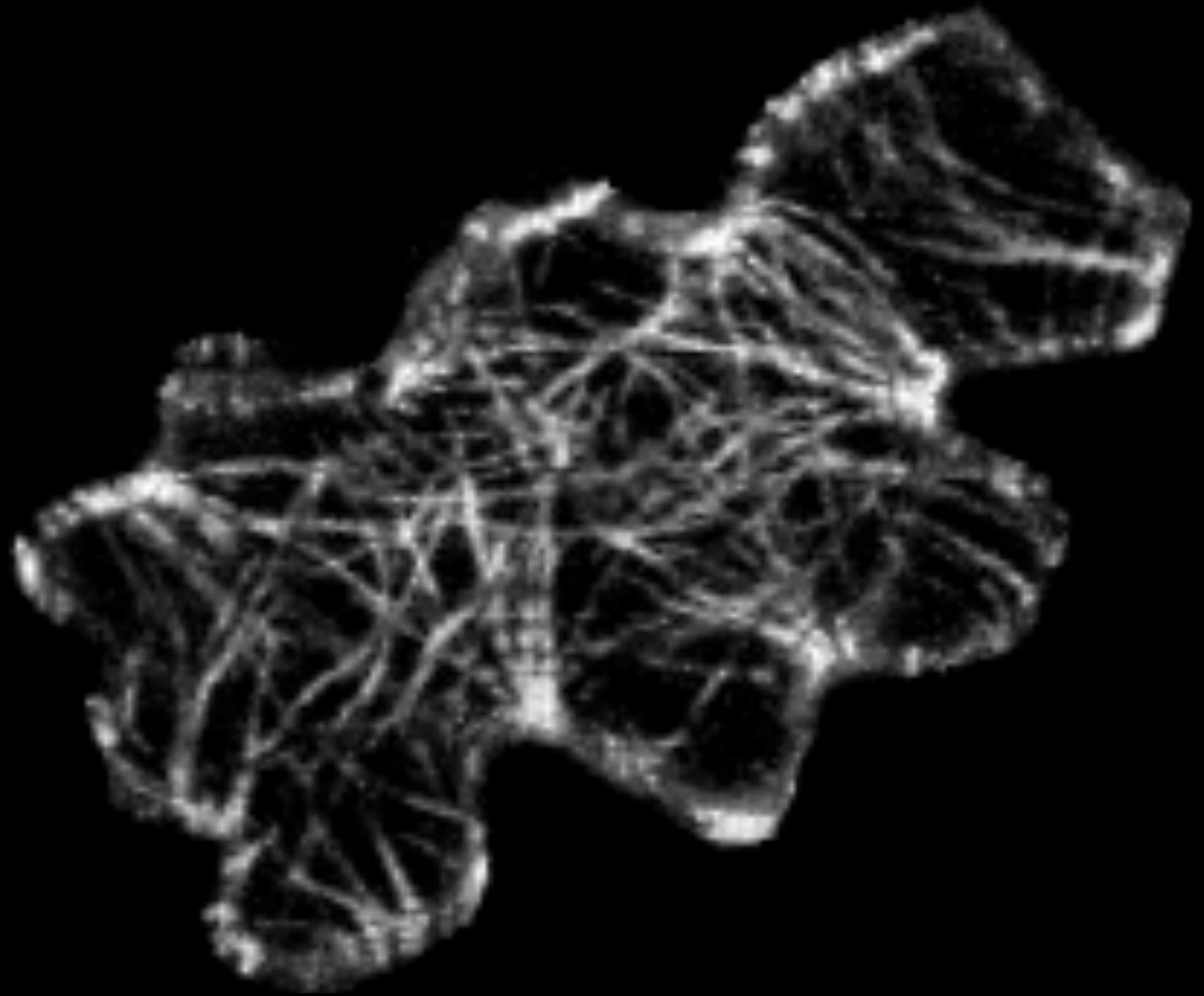


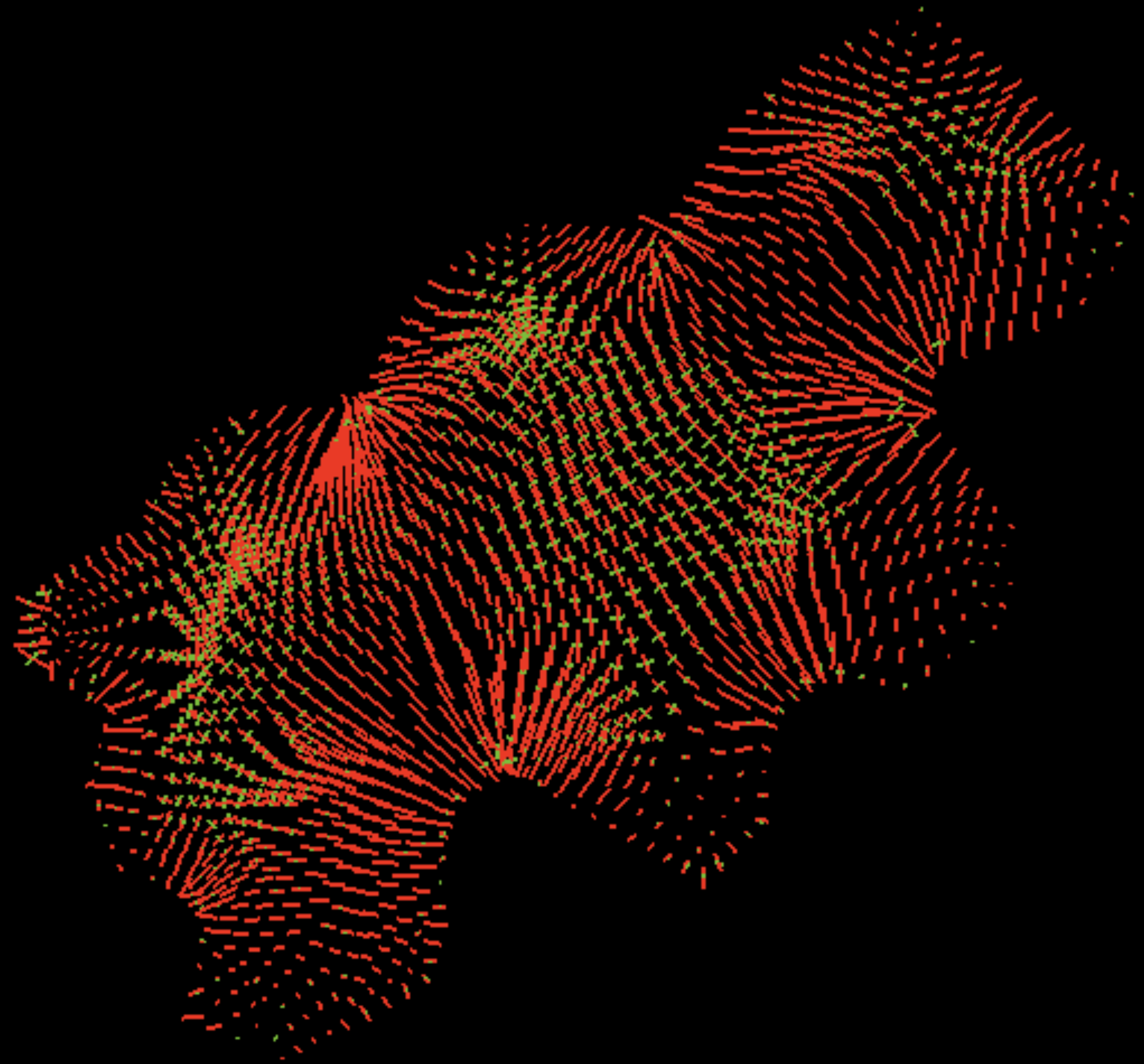
Henrik Jönsson

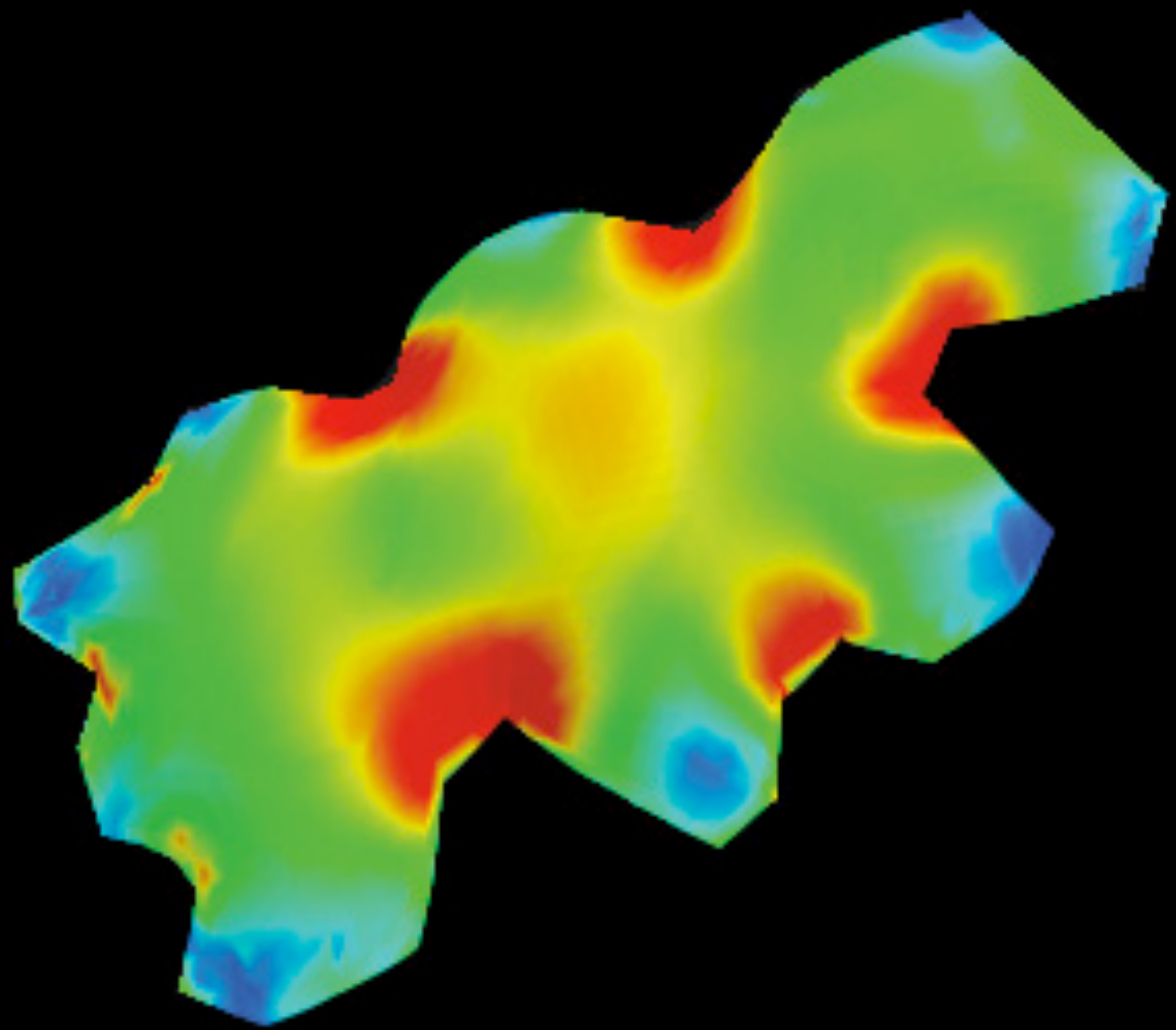
- Stress is generated by tissue shape and an epidermis in tension
- This mechanical stress controls the cytoskeleton, and thus cellulose direction in the walls
- Cellulose controls subsequent cell expansion, which in turn changes the stress pattern
- TISSUE SHAPE IS SENSED LOCALLY BY CELLS, LEADING TO FUTURE CHANGES IN



MICROTUBULE PATTERNS CORRESPOND TO PHYSICAL STRESS PATTERNS - EVEN SUBCELLULAR

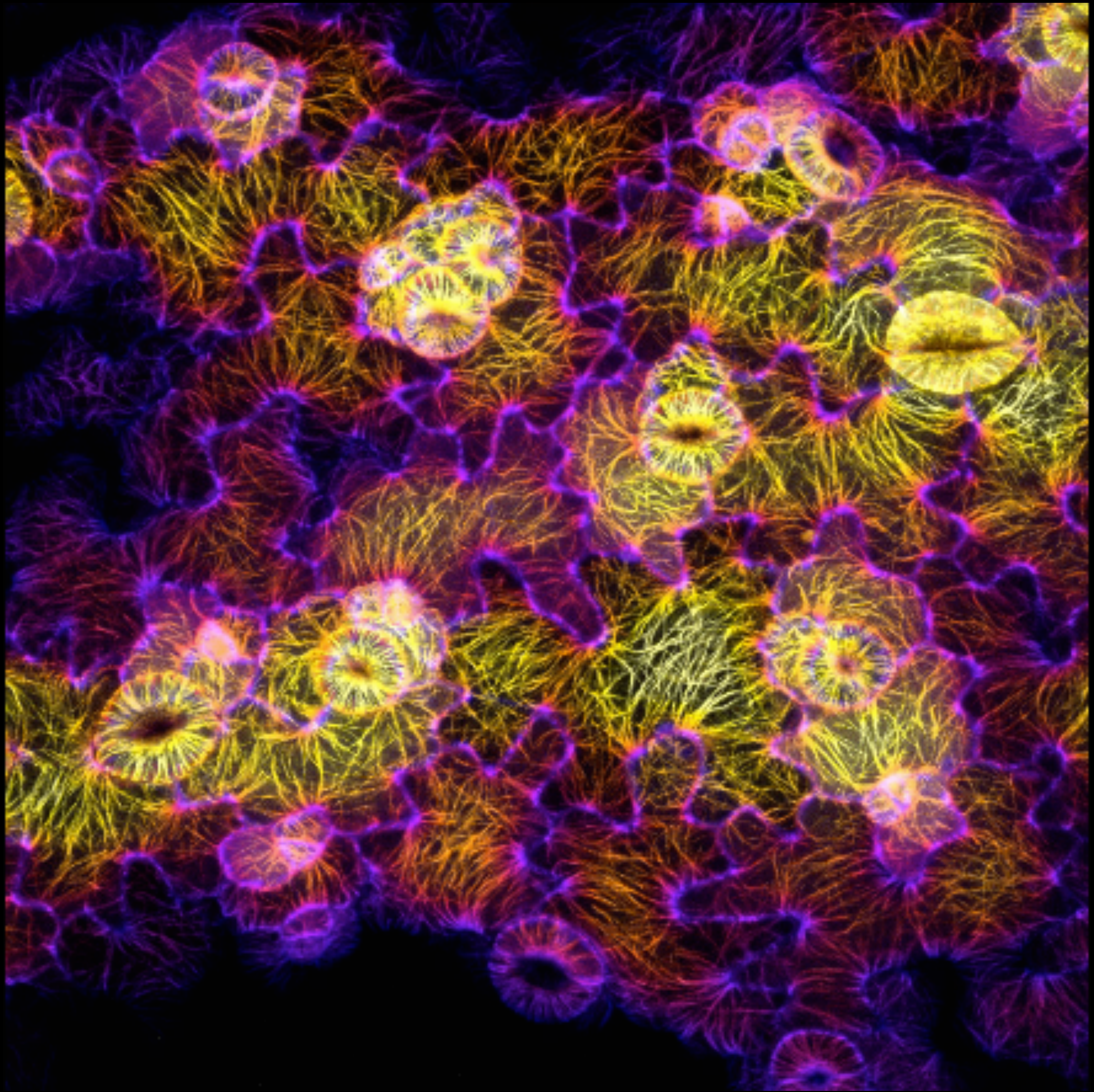


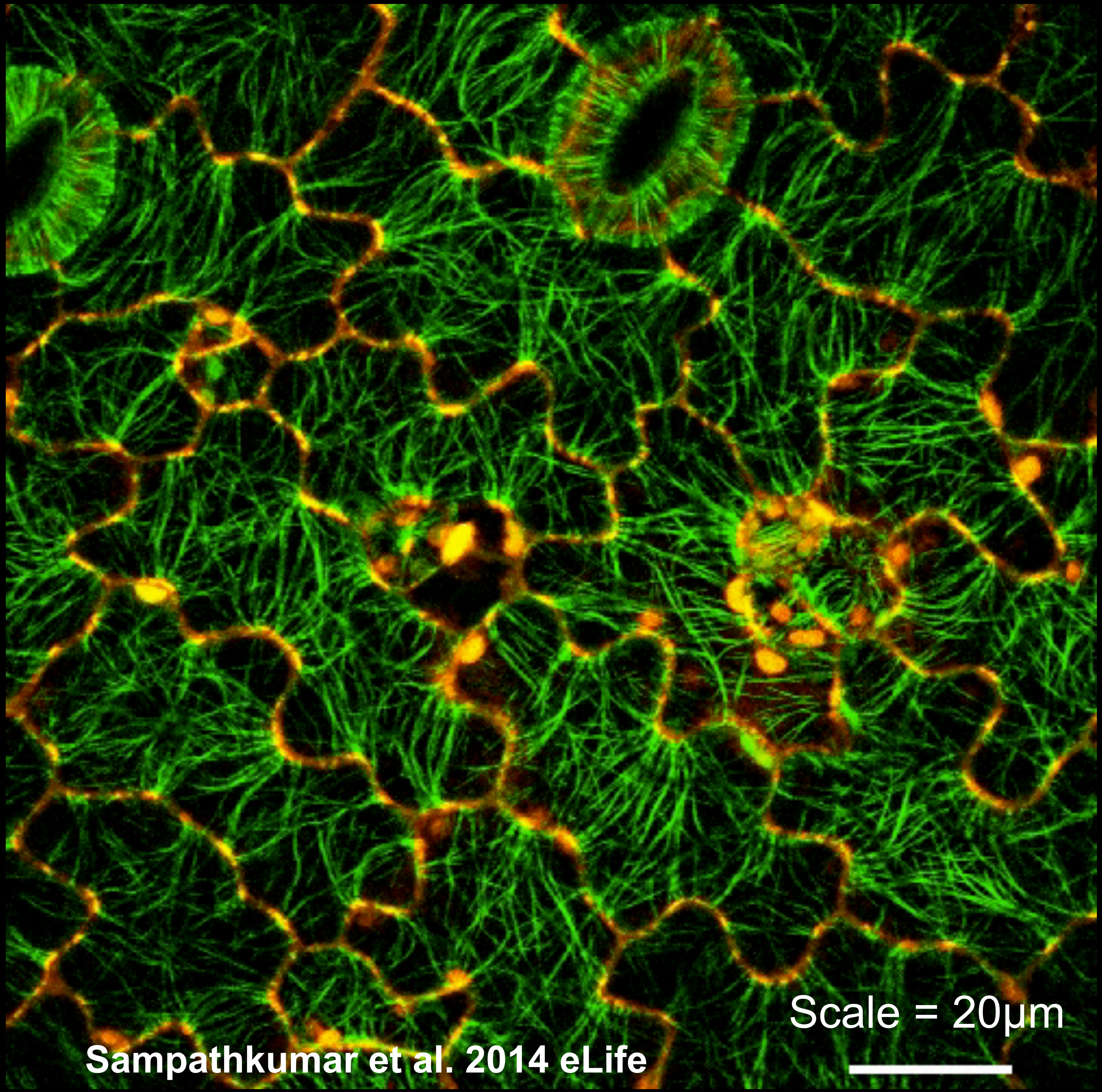




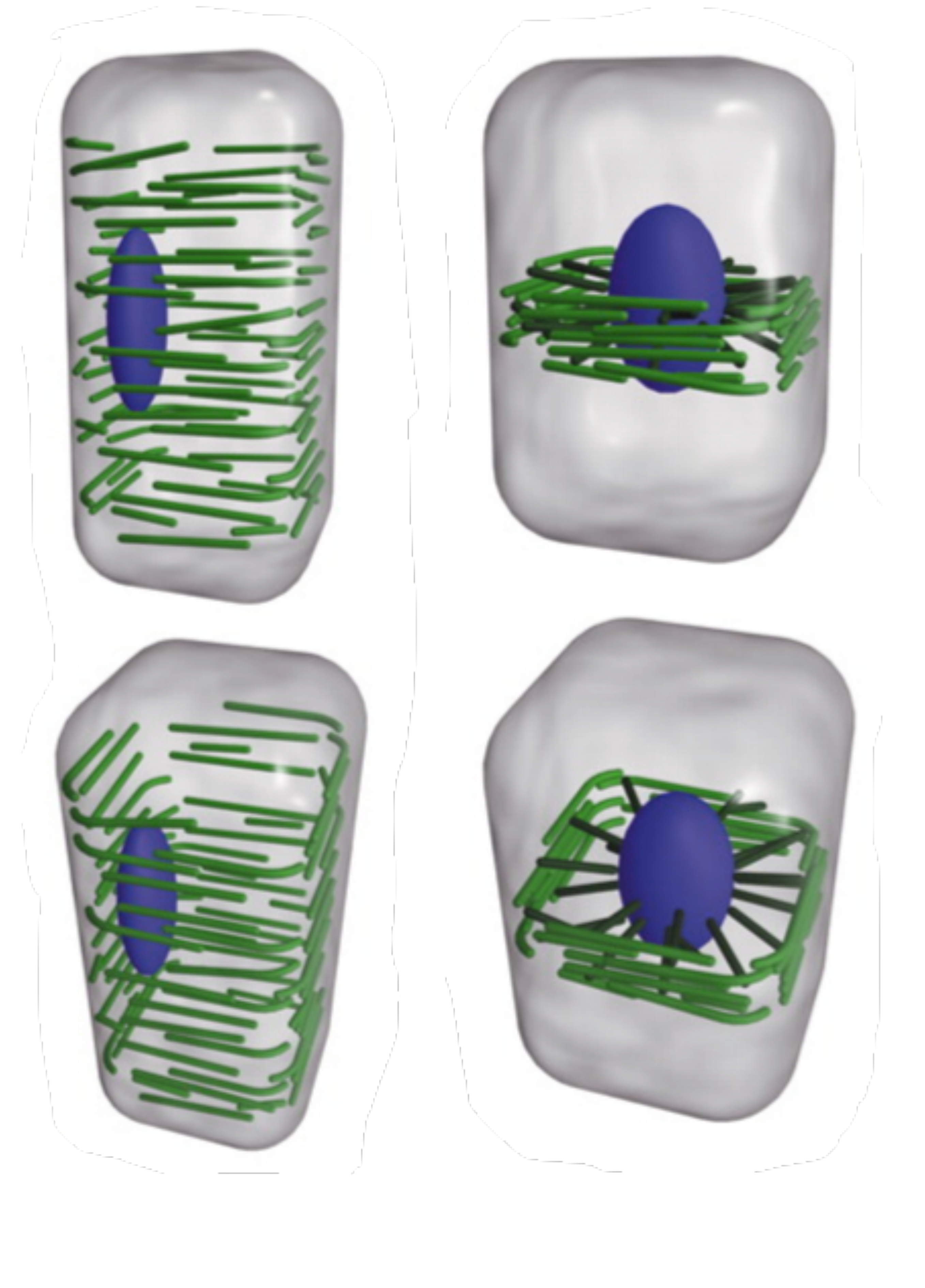
Sampathkumar et al. 2014 eLife

Re-Orientation of Cortical Microtubules in the Presence of Mechanical Stress - Laser Ablation

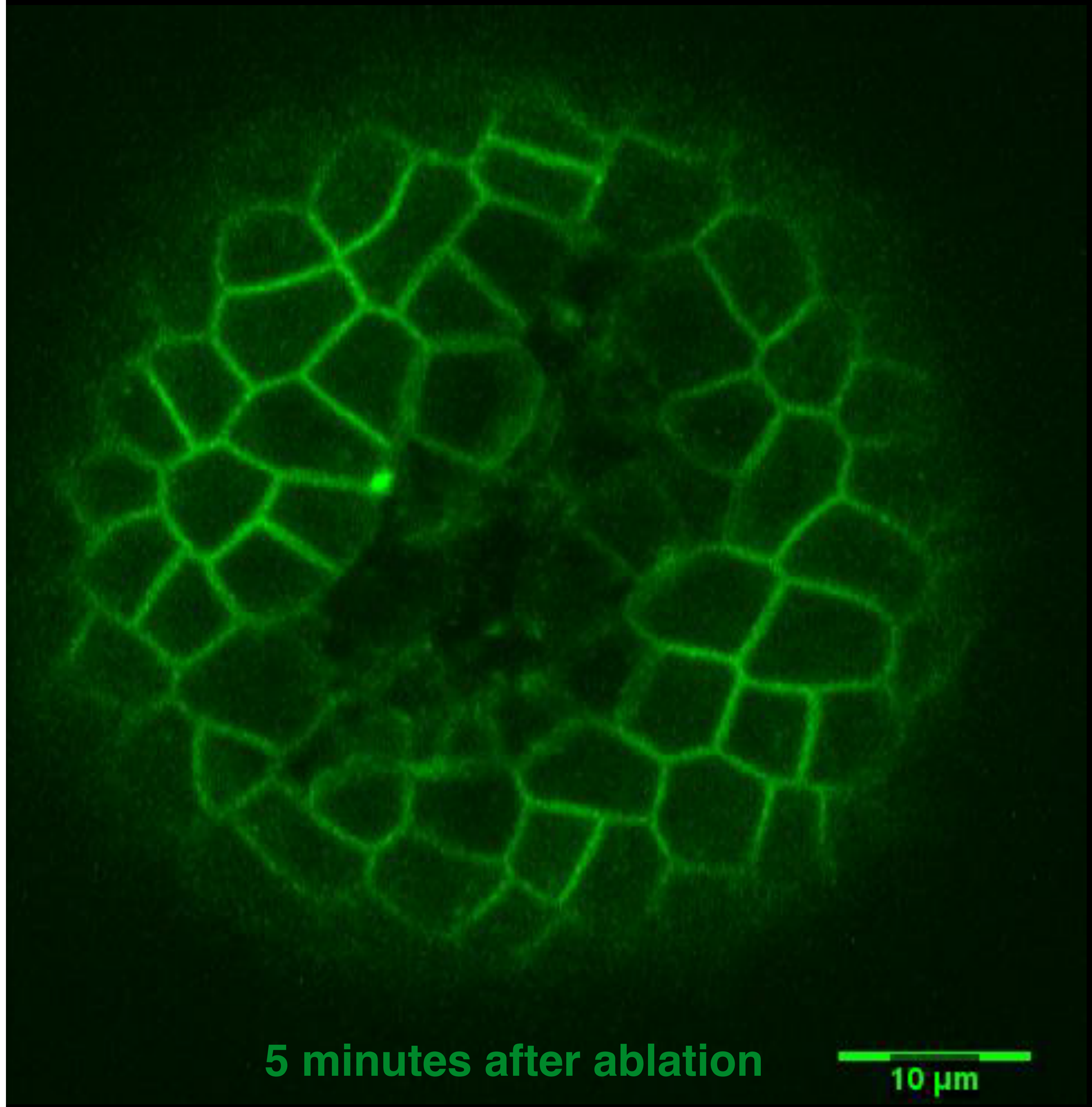


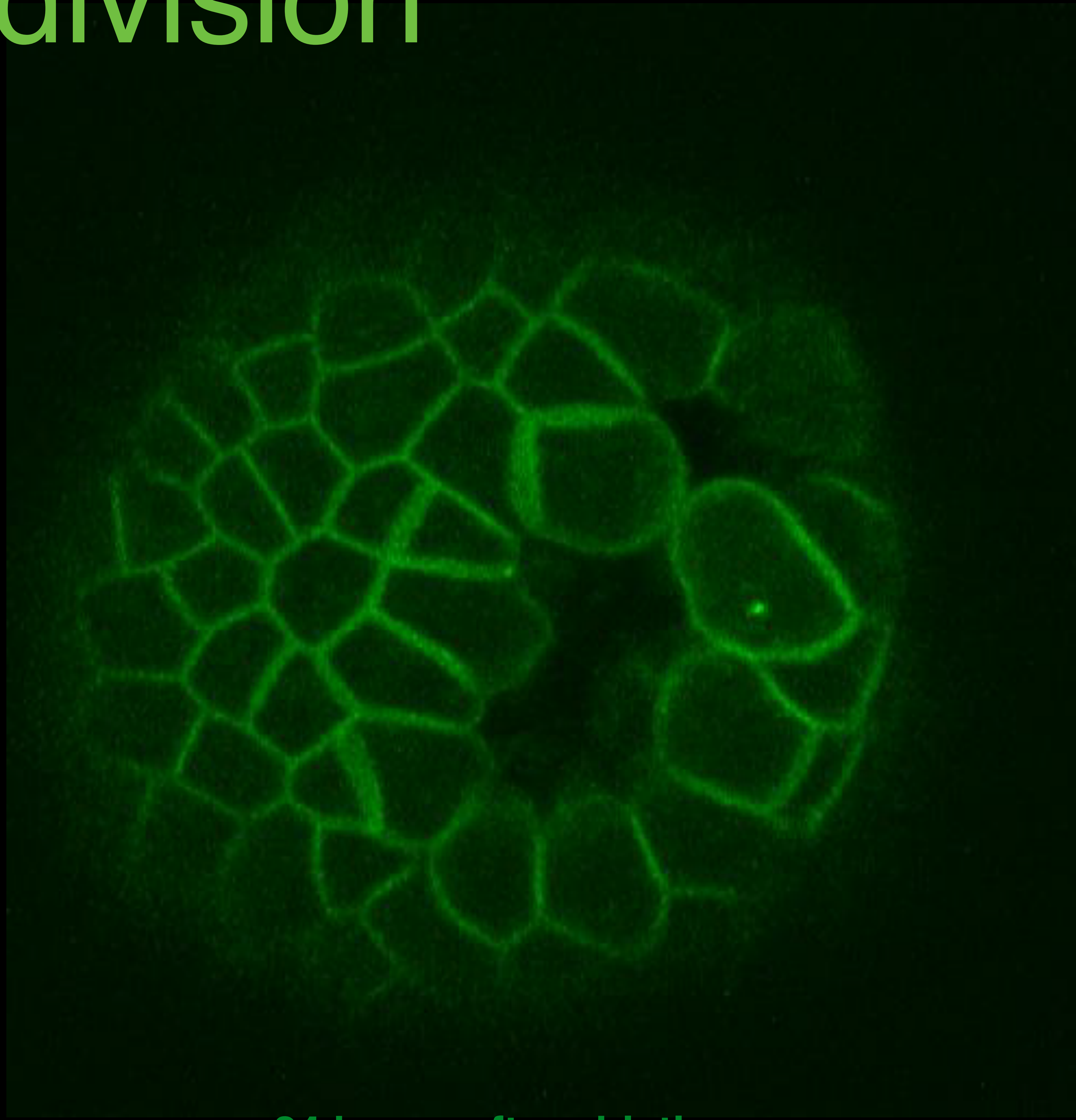


Microtubules and therefore tissue shape determine cell division



Wasteneys G O J Cell Sci 2002;115:1345-1354

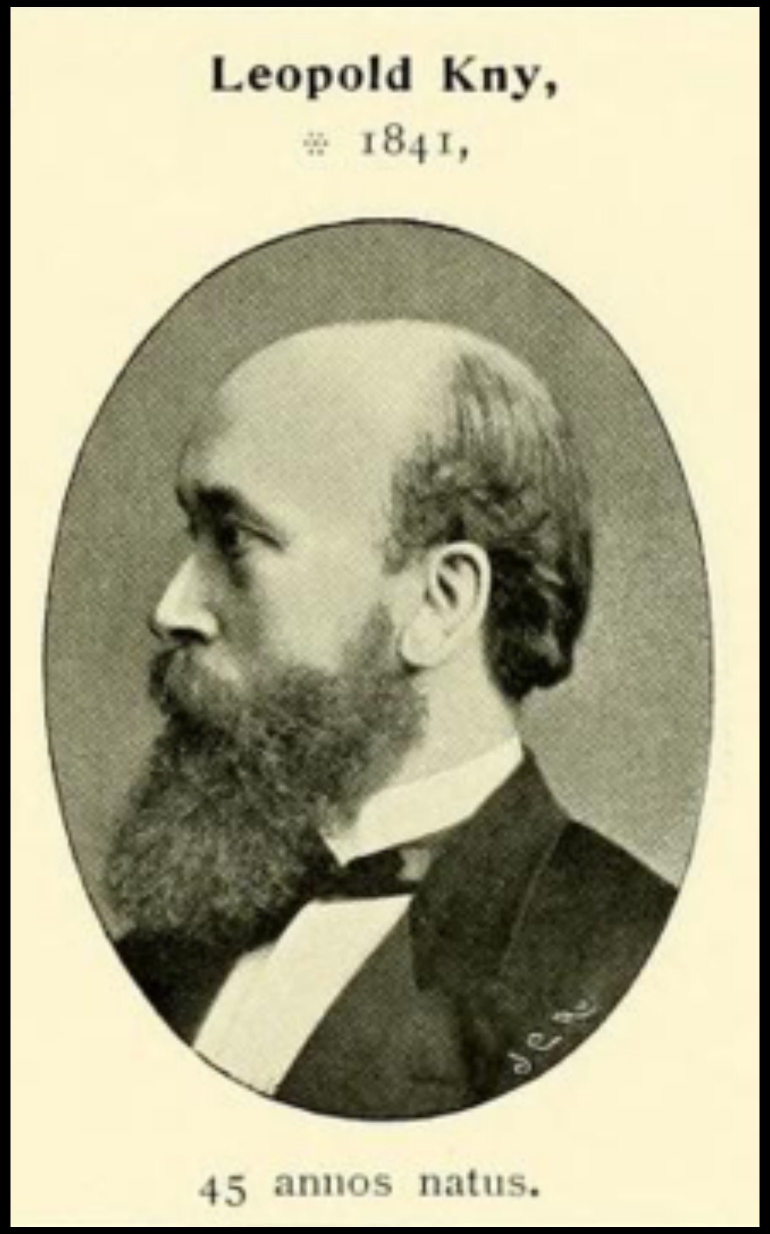




Hamant Group in: Cell division plane orientation based on tensile stress in Arabidopsis thaliana, Louveaux, Julien, Mirabet, Boudaoud, and Hamant PNAS July 26, 2016 113

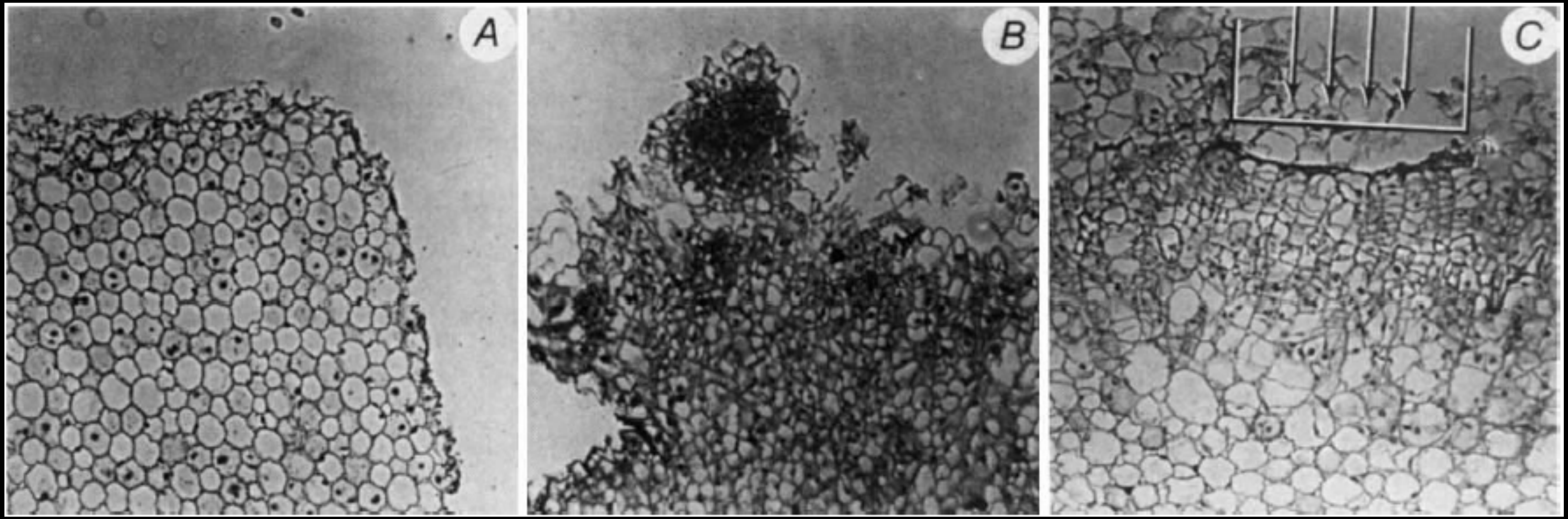
An Yan 燕安

THAT PHYSICAL STRESS IN PLANT TISSUES CONTROLS CELL DIVISION WAS SHOWN



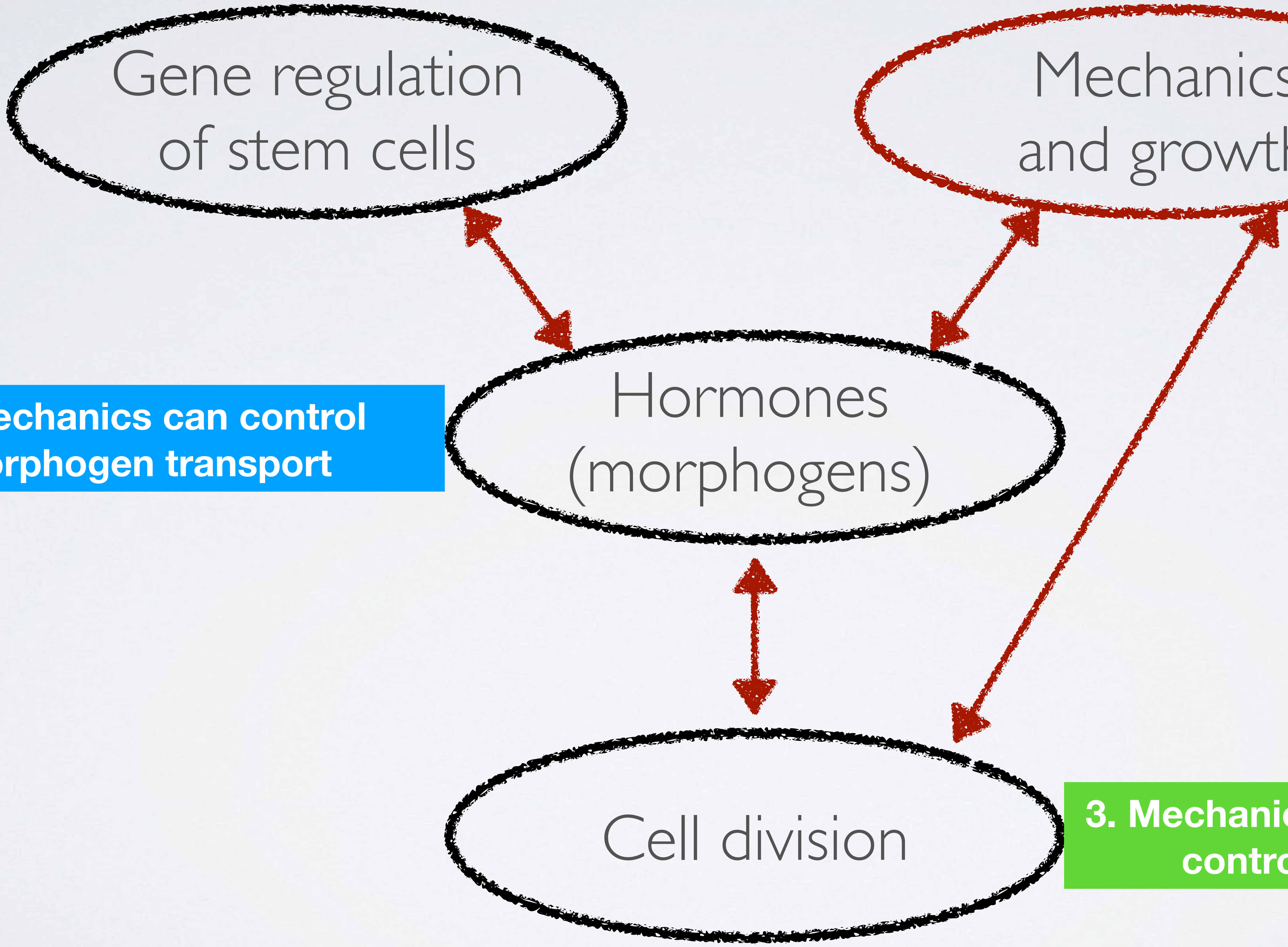
Kny (1896) Ber. d. bot. Gess. 398 (*Equisetum* spores)
(1901) Jahrb. f. wiss. Bot. 37, 55 (*Impatiens* pith)

Stress-induced alignment of division plane in plant tissues grown *in vitro*
Philip M. Lintilhac & Thompson B. Vesecky (1984) Nature 307, 363:



COMPUTATIONAL MORPHODYNAMICS

0. Introduction to plant growth (brief)



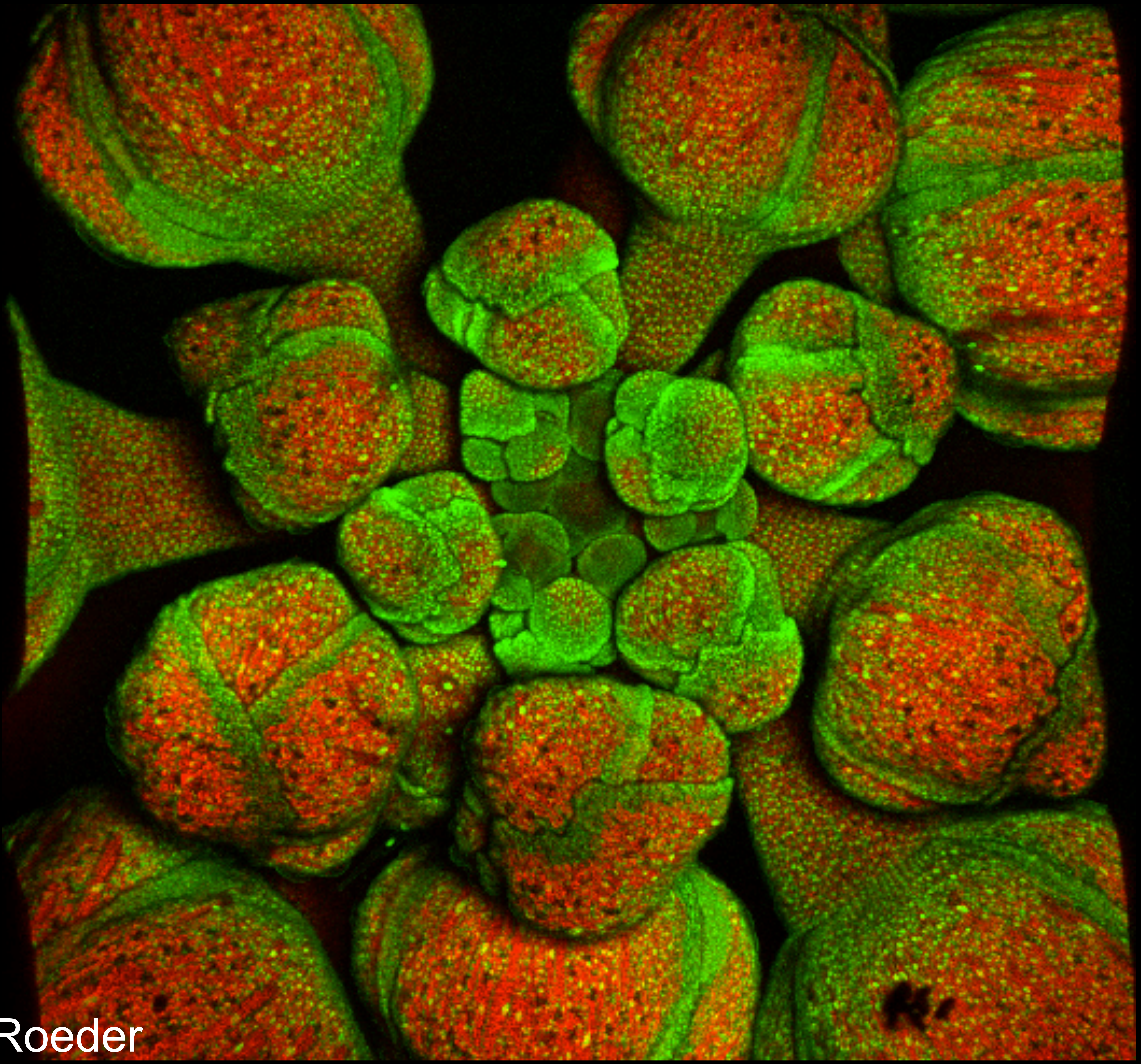
1. Shape controls growth, growth creates shape

2. Mechanics can control morphogen transport

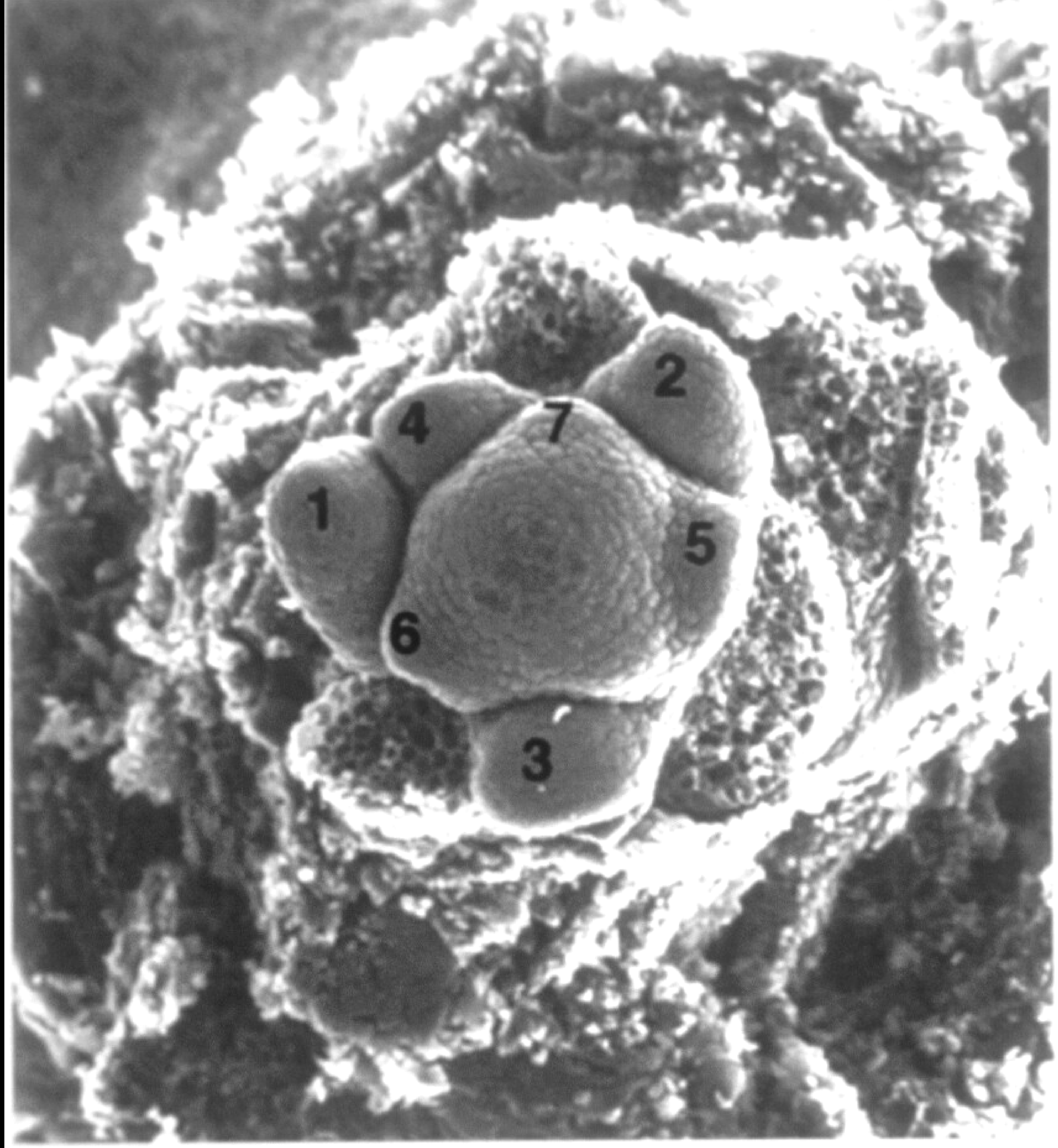
3. Mechanics and the cell wall control cell division

Jönsson, Meyerowitz

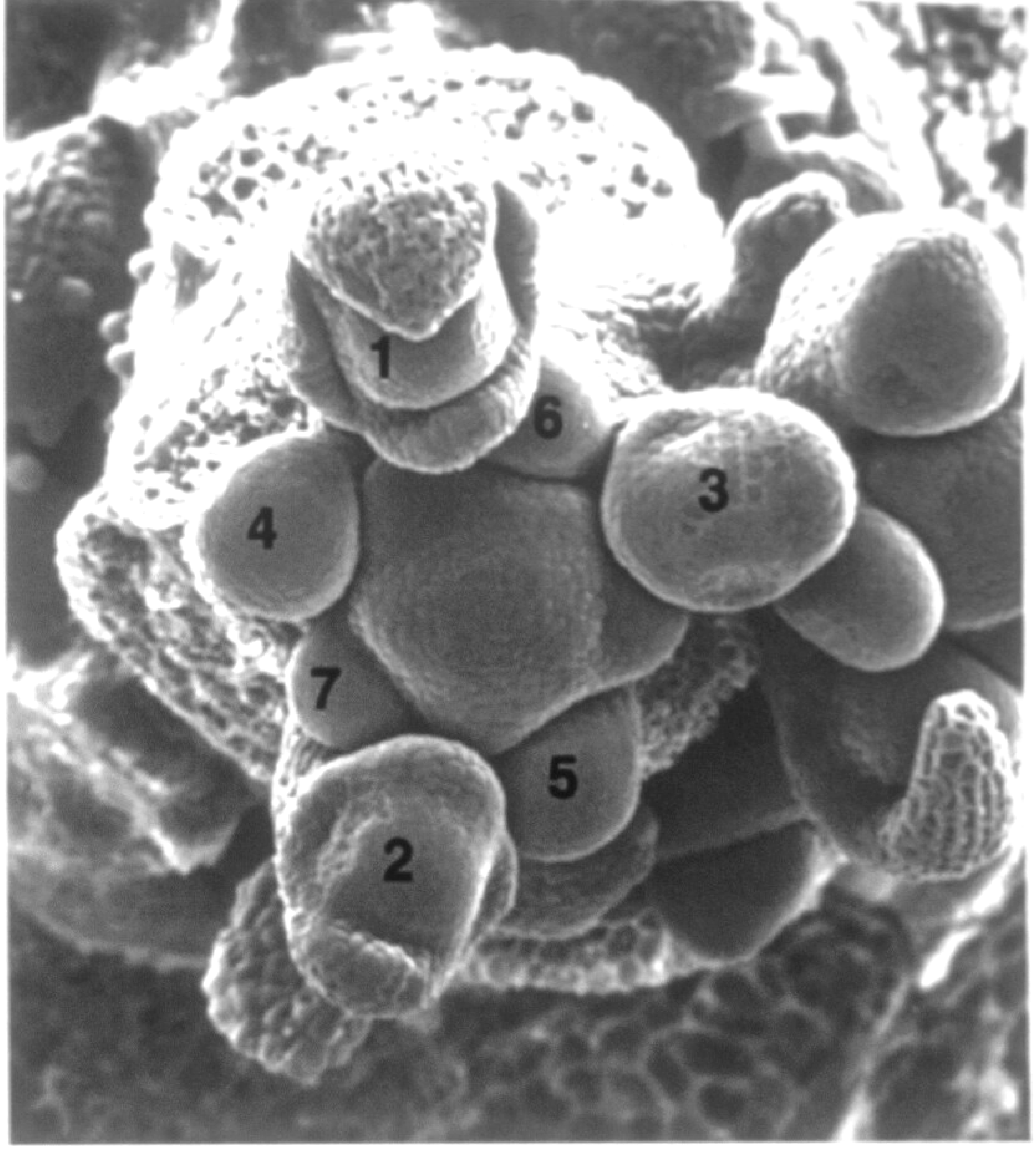
Arabidopsis Phyllotaxis



Adrienne Roeder



Vegetative SAM

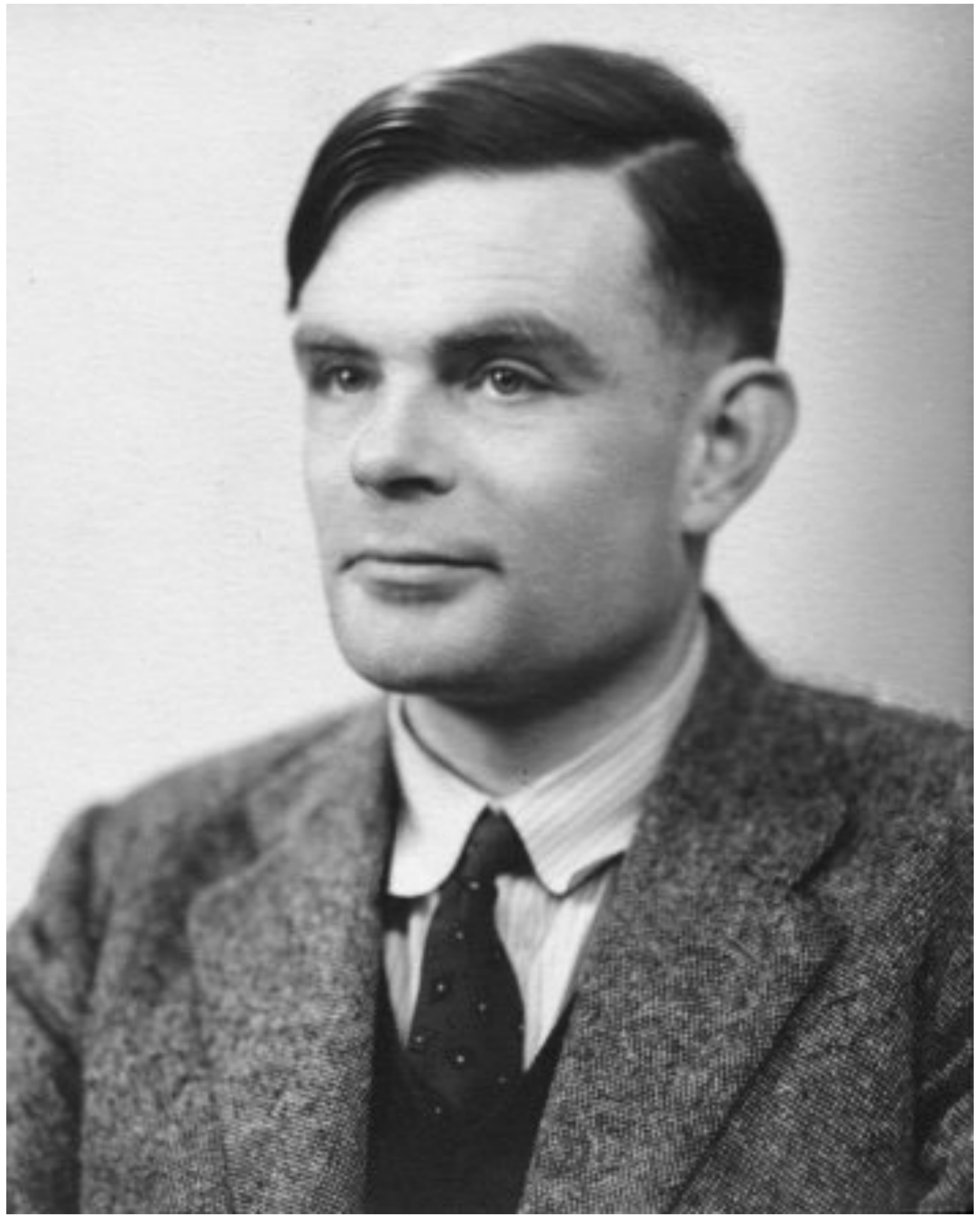


Inflorescence SAM

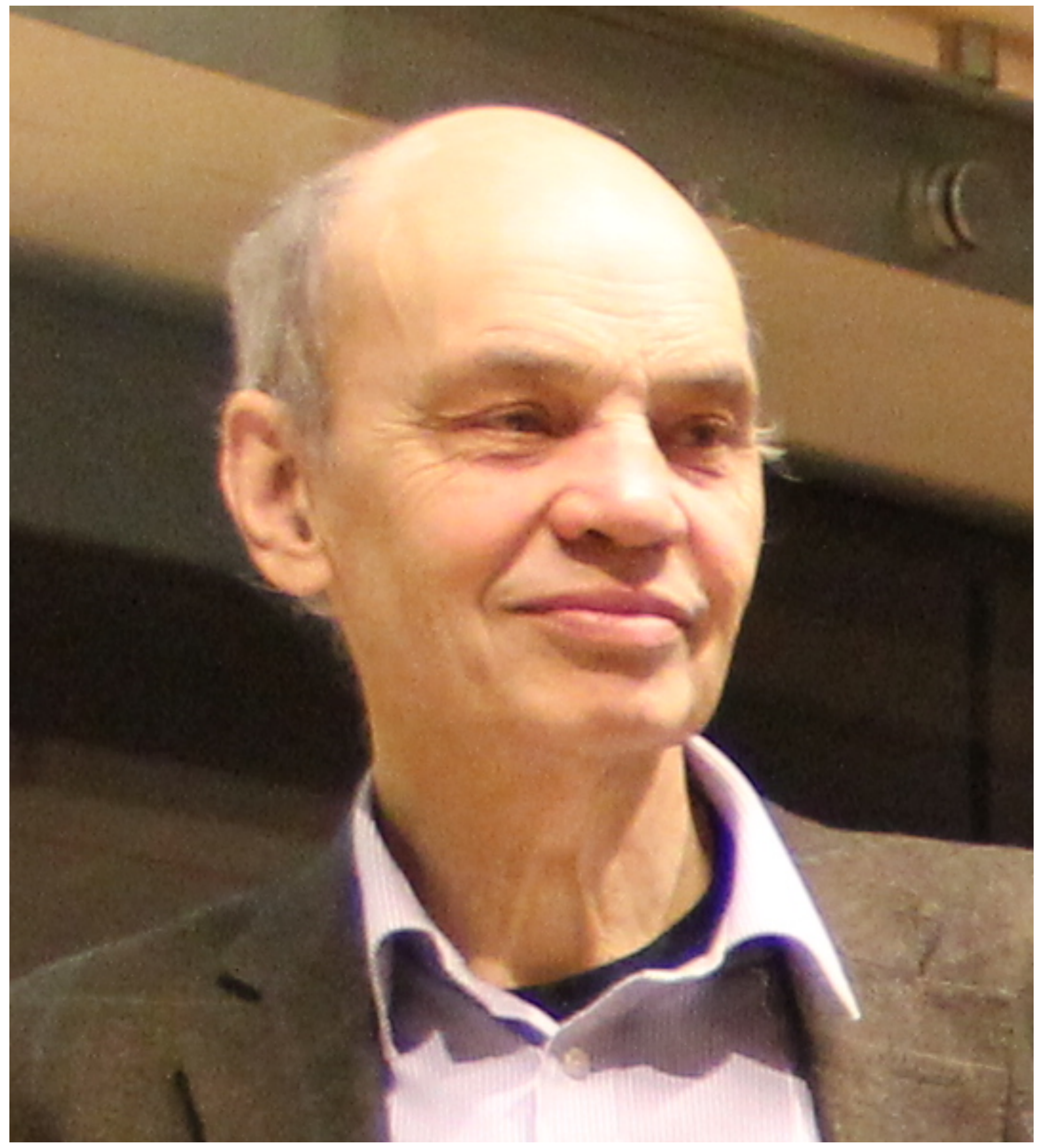
SPIRAL PHYLLOTAXIS

Hofmeister, W.(1868) Handbuch der physiologischen Botanik; Band 1,
Abteilung 2, Allgemeine Morphologie der Gewächse (W. Engelmann, Leipzig), pp 405–664

Turing, 1952 The Chemical Basis of Morphogenesis,
Phil. Trans. Roy. Soc. B 237, 37-72



SPIRAL PHYLLOTAXIS

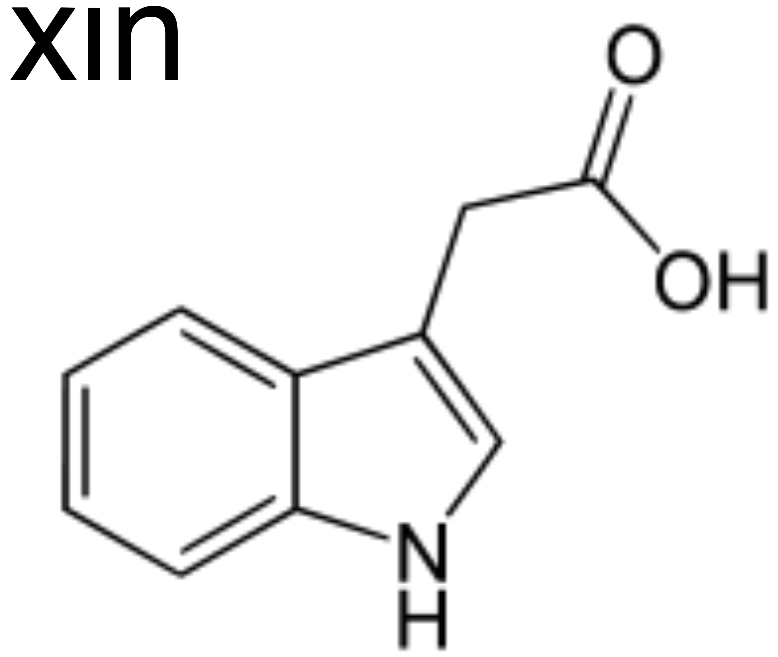


Douady and Couder (1992) Physical Review Letters **68**, 2098
Douady and Couder (1998) J. Theor. Biol. **178**, 255

Mitchison G.J. 1977 Phyllotaxis and the Fibonacci series. Science, **196**, 270

DR5 Auxin Reporter
Cory Tobin

Auxin



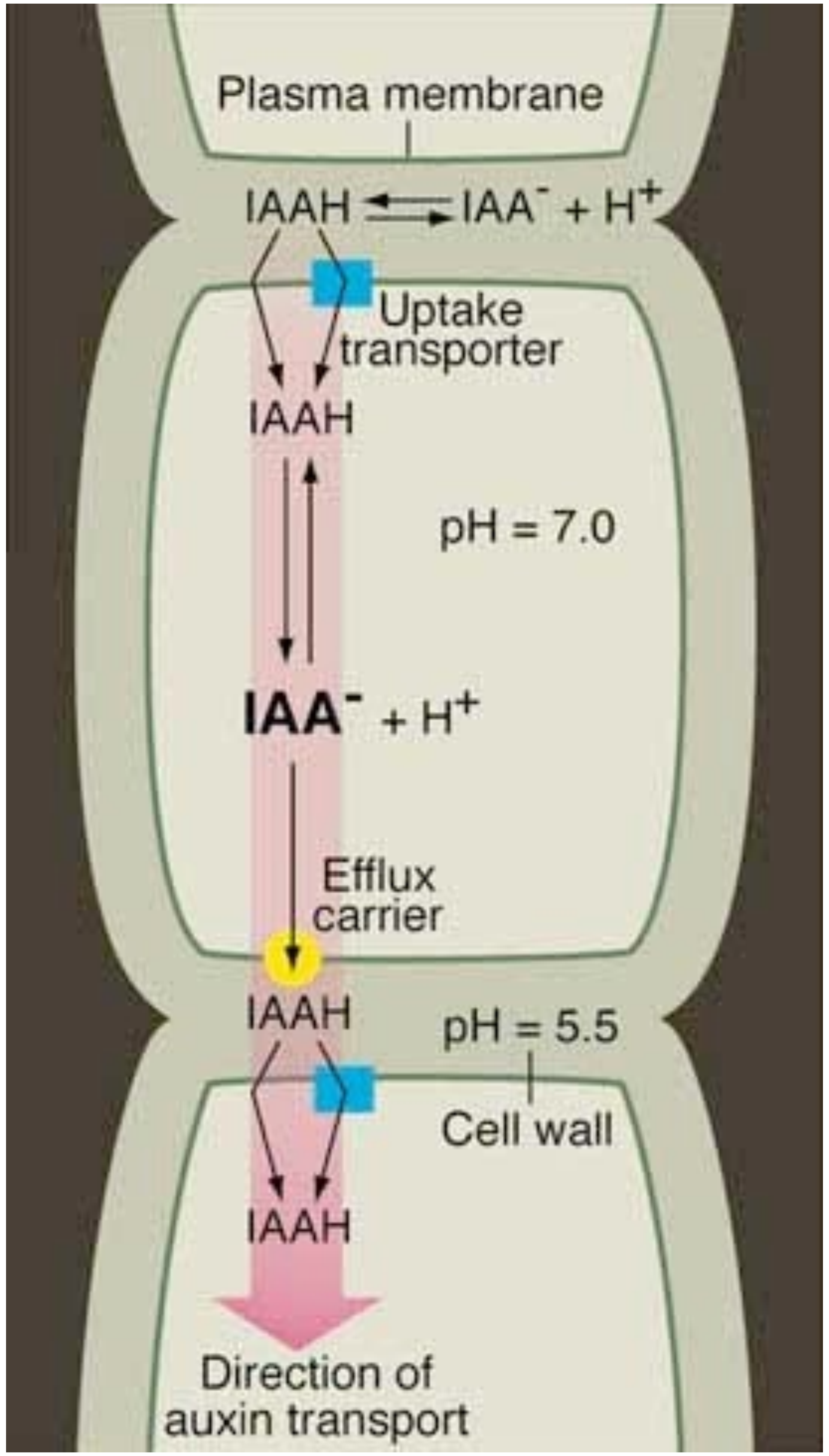
Induces new leaves and flowers

Causes shoot cell expansion

Causes changes in gene activity

Has private circulatory system

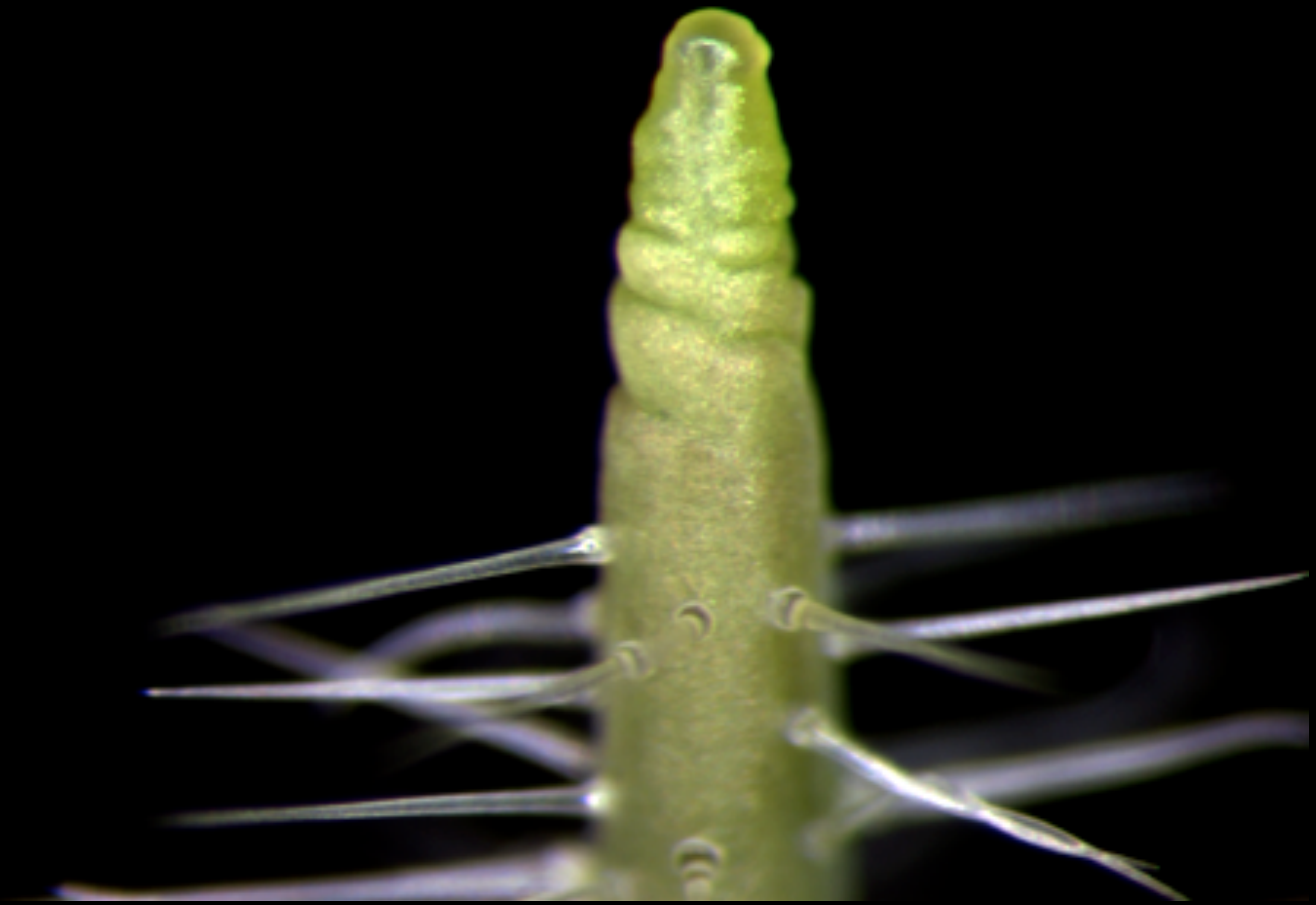
Gets out of cells through a specific efflux carrier, PIN

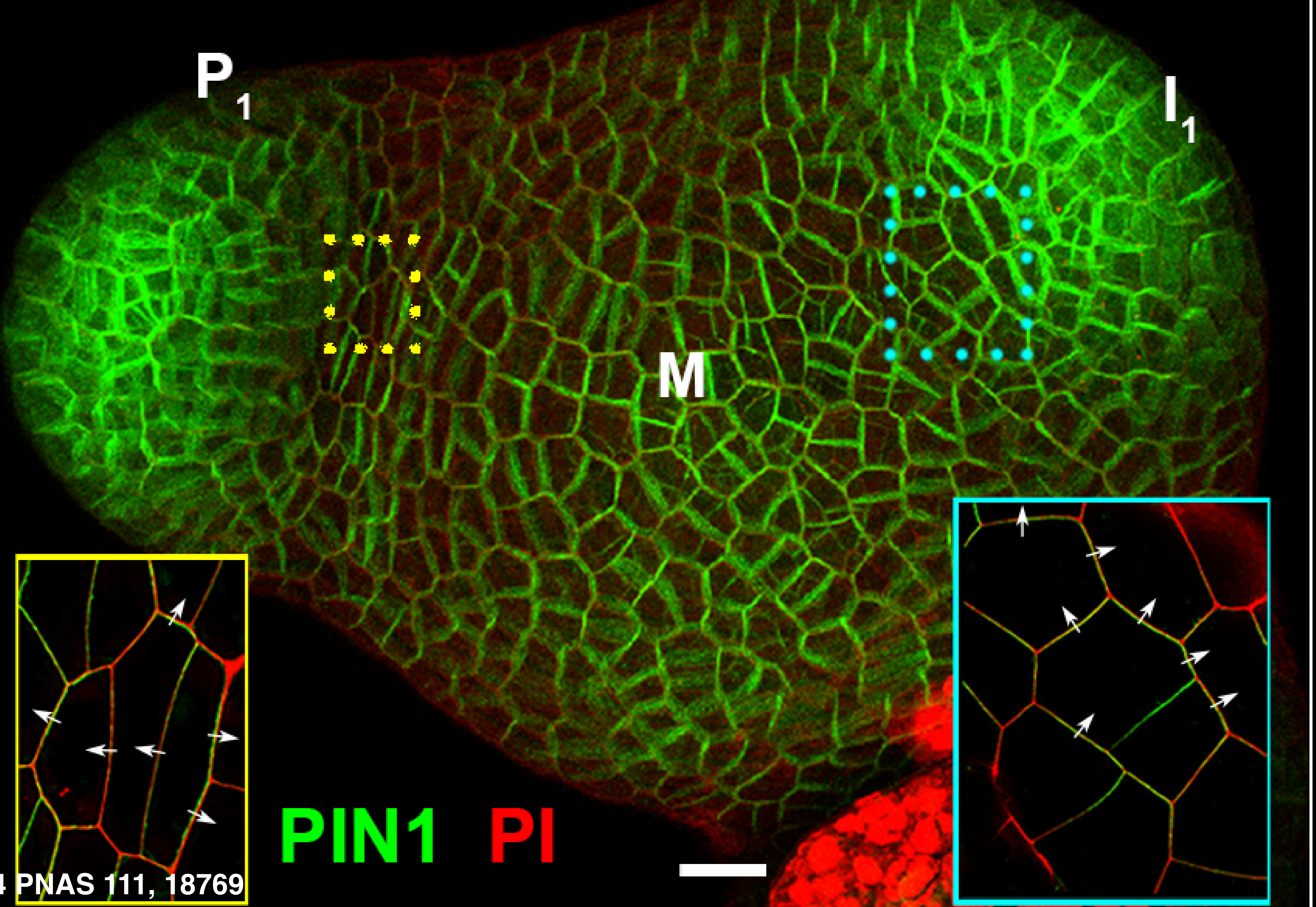


Jones, A.M.
Science (1998) 282, 2201

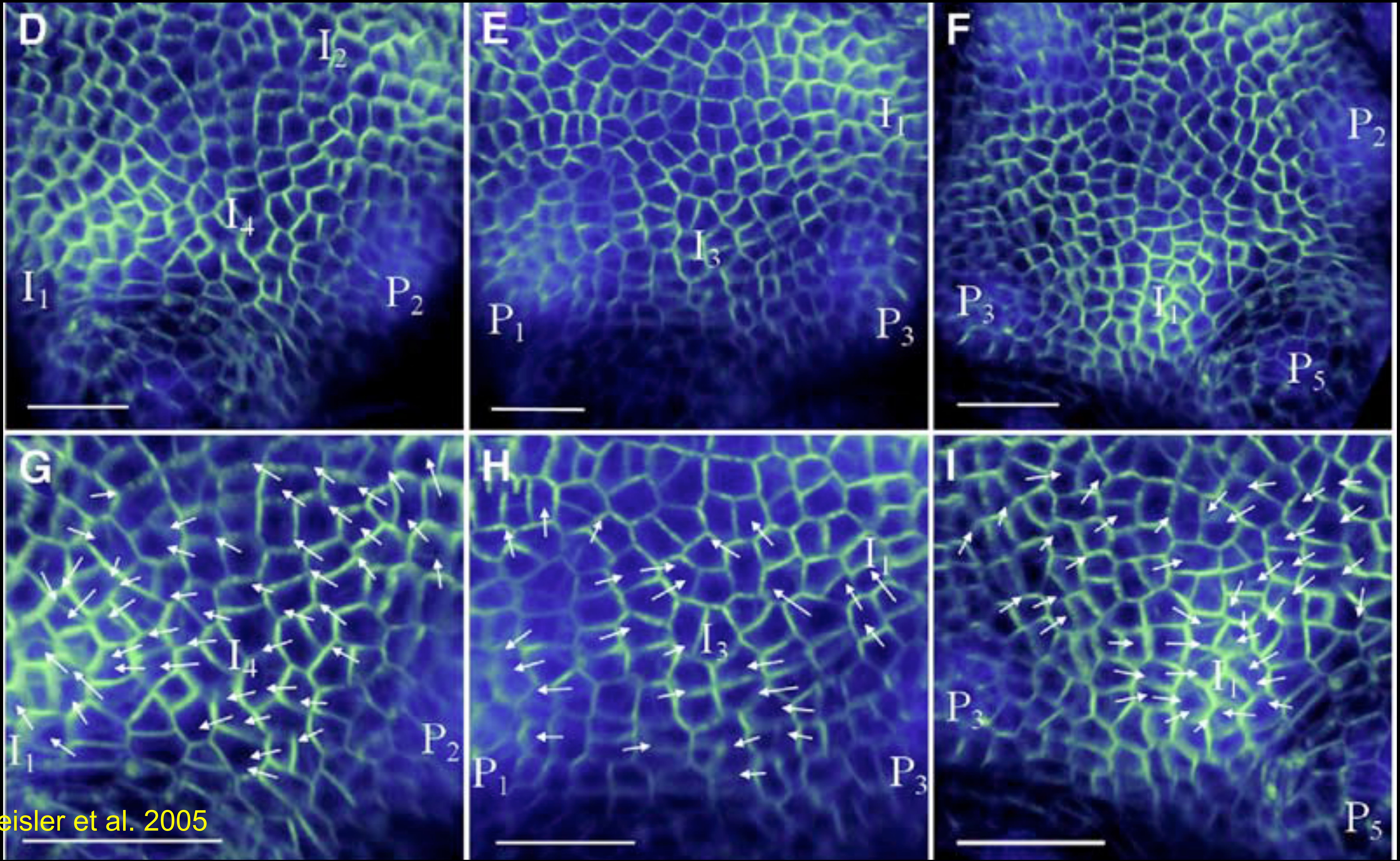
pin1 Mutant (Okada, 1991);

PIN1 is the efflux carrier (Luschnig et al. 1998; Chen et





Qi et al. 2014 PNAS 111, 18769



Heisler et al. 2005

MODEL

1) Local high auxin concentration causes new primordia, and it gets high locally by transport and diffusion

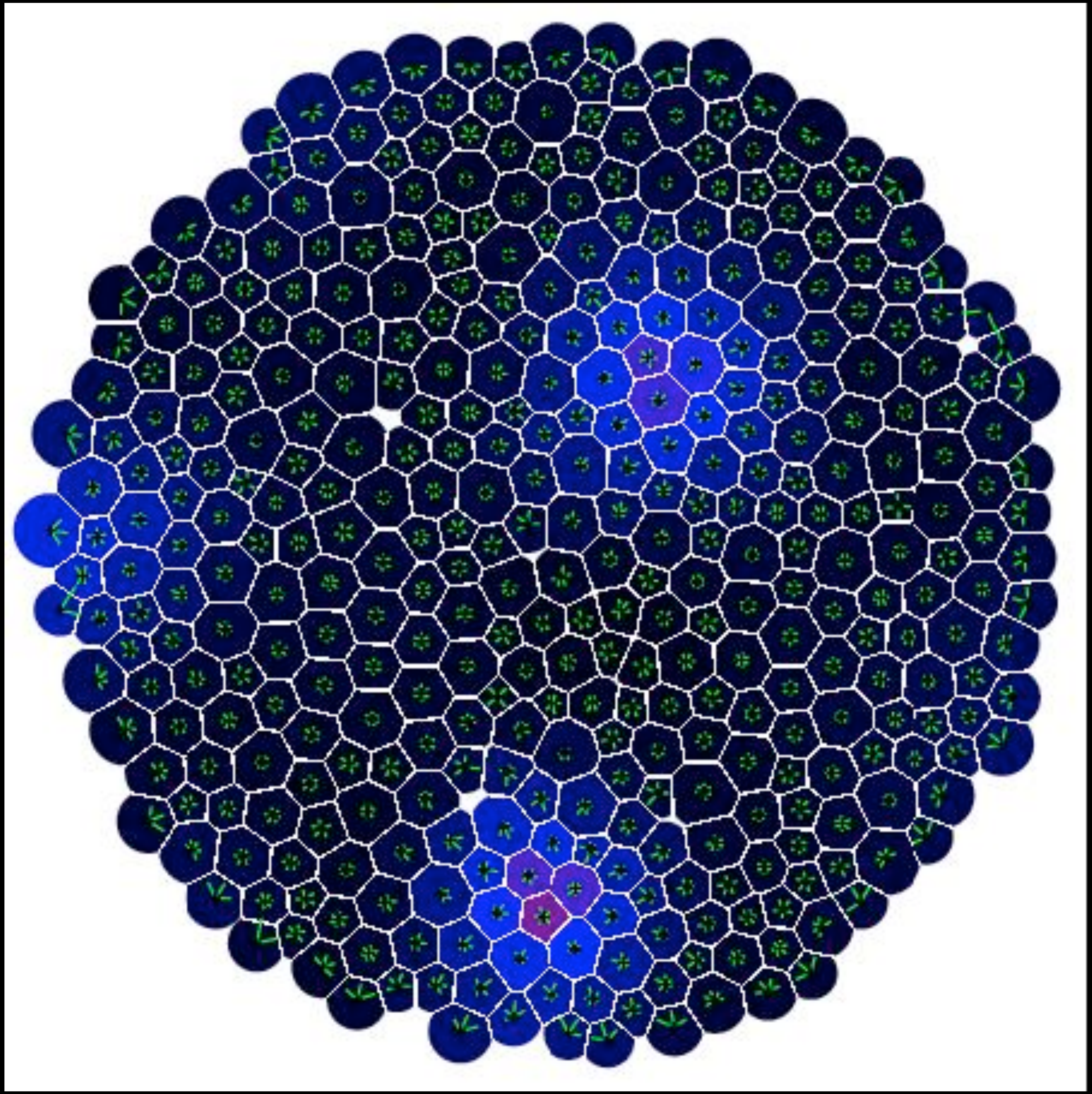
2) Auxin efflux carrier moves auxin, and its gene is auxin-induced - so rate of transport from a cell depends on the auxin level in the cell

3) Auxin efflux carrier is polarized in cells, and points toward neighboring cells with the highest auxin concentration

$$
\begin{aligned}
\frac{dA_i}{dt} &= c_{\mathrm{A}} - d_{\mathrm{A}} A_i + \frac{1}{V_i} \left[p_{\mathrm{AH}} \sum_{k \in \mathcal{N}_i} a_{ik} \left(f_{\mathrm{AH}}^{\mathrm{wall}} A_{ik} - f_{\mathrm{AH}}^{\mathrm{cell}} A_i \right) \right. \\
&+ \left. p_{\mathrm{A}^-} \sum_{k \in \mathcal{N}_i} a_{ik} P_{ik} \left(f_{\mathrm{A}^-}^{\mathrm{wall}} N_{\mathrm{influx}} \frac{A_{ik}}{K_{\mathrm{A}} + A_{ik}} - f_{\mathrm{A}^-}^{\mathrm{cell}} N_{\mathrm{efflux}} \frac{A_i}{K_a + A_i} \right) \right], \\
\frac{dA_{ij}}{dt} &= -d_{\mathrm{A}} A_{ij} + \frac{1}{V_{ij}} \left[a_{ij} \left\{ p_{\mathrm{AH}} \left(f_{\mathrm{AH}}^{\mathrm{cell}} A_i - f_{\mathrm{AH}}^{\mathrm{wall}} A_{ij} \right) \right. \right. \\
&+ \left. p_{\mathrm{A}^-} P_{ij} \left(f_{\mathrm{A}^-}^{\mathrm{cell}} N_{\mathrm{efflux}} \frac{A_i}{K_a + A_i} - f_{\mathrm{A}^-}^{\mathrm{wall}} N_{\mathrm{influx}} \frac{A_{ij}}{K_{\mathrm{A}} + A_{ij}} \right) \right\} \\
&+ \left. D_{\mathrm{A}} \left\{ \frac{a_{ijij_{\mathrm{l}}}}{d_{ijij_{\mathrm{l}}}} \left(A_{ij_{\mathrm{l}}} - A_{ij} \right) + \frac{a_{ijij_{\mathrm{r}}}}{d_{ijij_{\mathrm{r}}}} \left(A_{ij_{\mathrm{r}}} - A_{ij} \right) + \frac{a_{ijji}}{d_{ijji}} \left(A_{ji} - A_{ij} \right) \right\} \right], \\
\frac{dP_i}{dt} &= \frac{1}{V_i} \sum_{k}^{N_i} a_{ik} \left(k_2 P_{ik} - P_i \frac{k_1 A_k^n}{K^n + A_k^n} \right), \\
\frac{dP_{ij}}{dt} &= P_i \frac{k_1 A_j^n}{K^n + A_j^n} - k_2 P_{ij}.
\end{aligned}
$$

Jönsson et al. 2006

The auxin concentration model



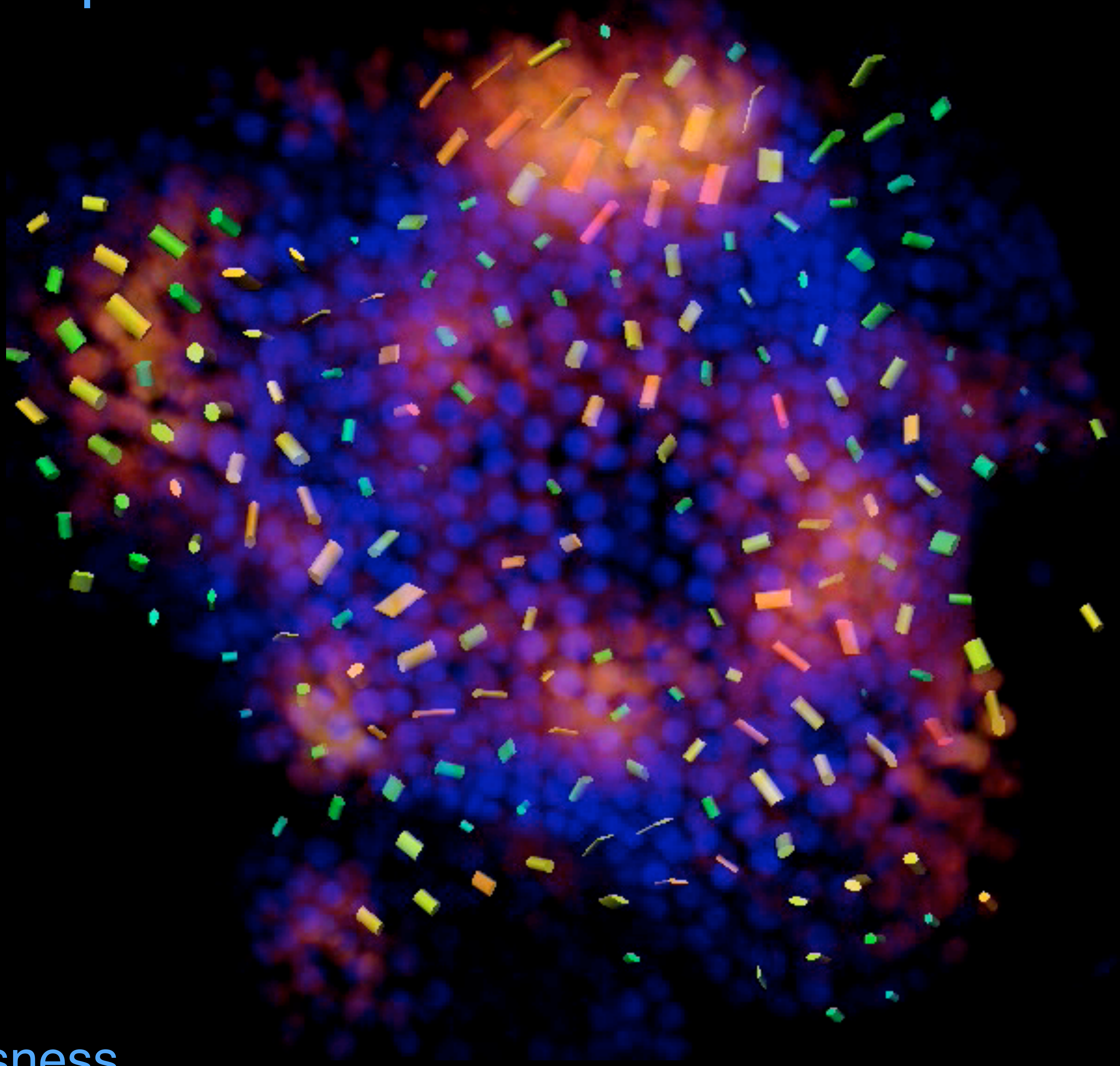
Jönsson et al. 2006

Local high auxin concentration causes new primordia, and it gets high locally by transport and diffusion

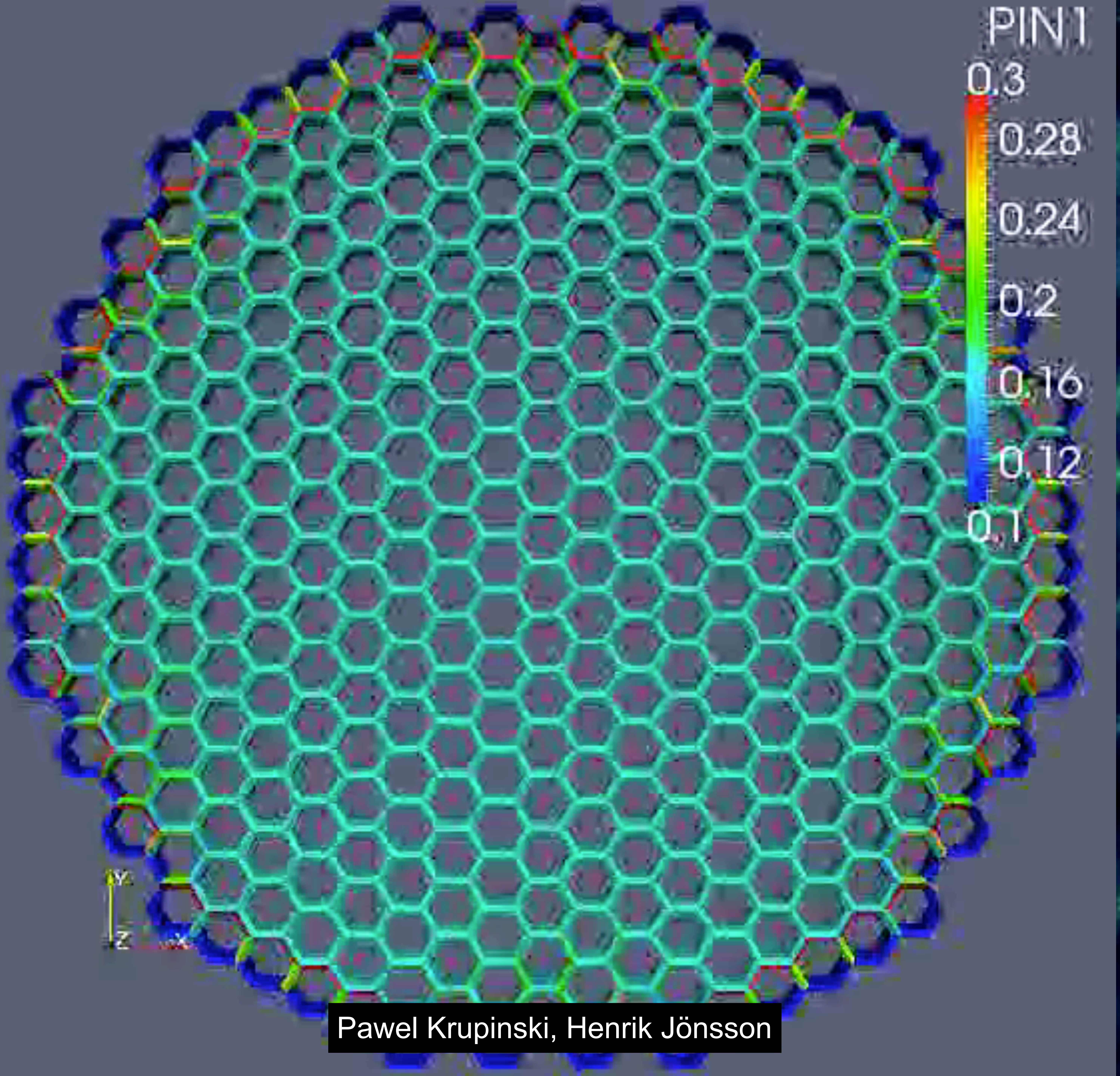
Auxin efflux carrier moves auxin, and its gene is auxin-induced - so rate of transport from a cell depends on the auxin level in the cell

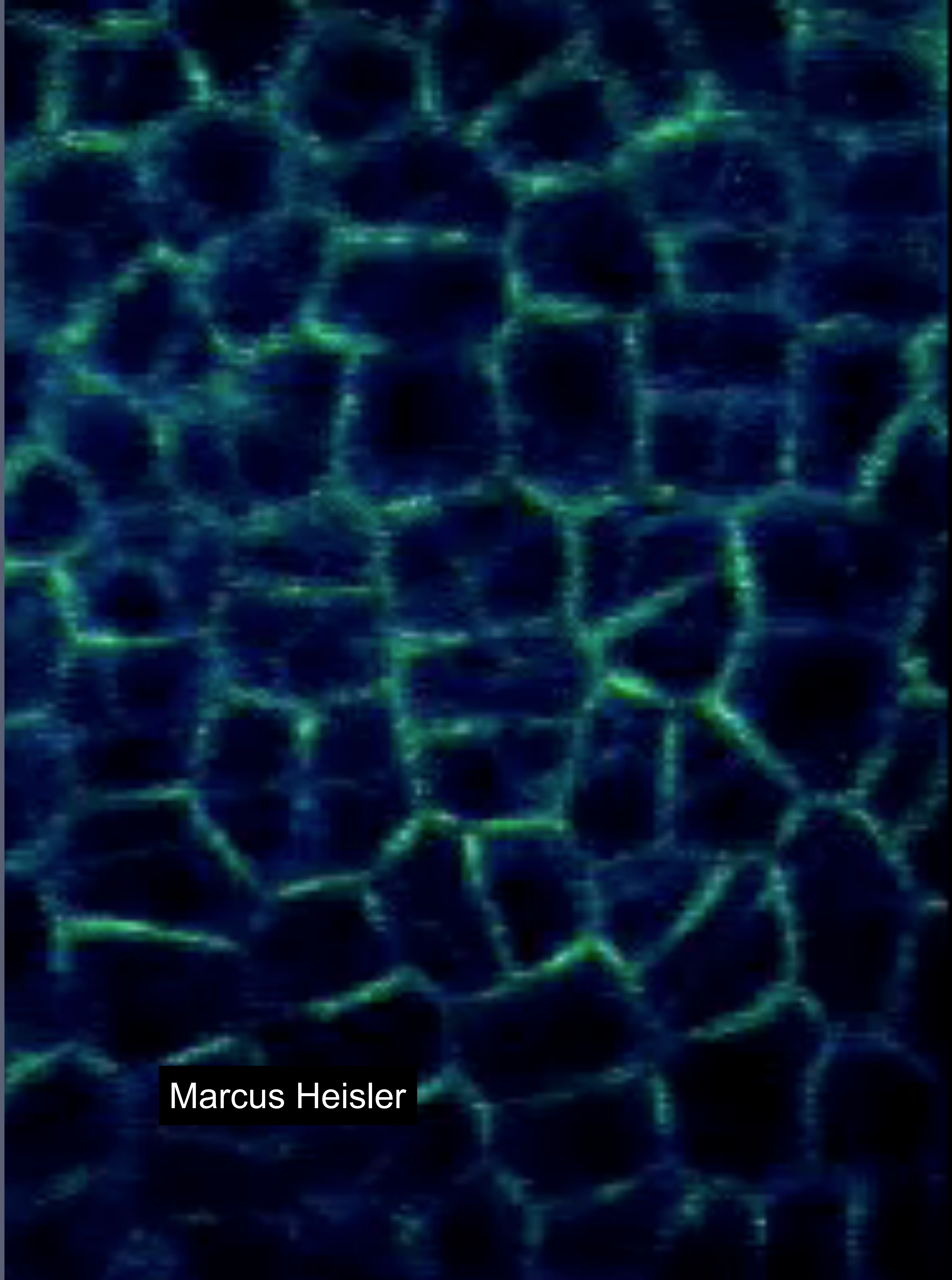
Auxin efflux carrier is polarized in cells, and points toward neighboring cells with the highest auxin concentration

Local Cell Expansion in Meristem Matches Auxin Concentration

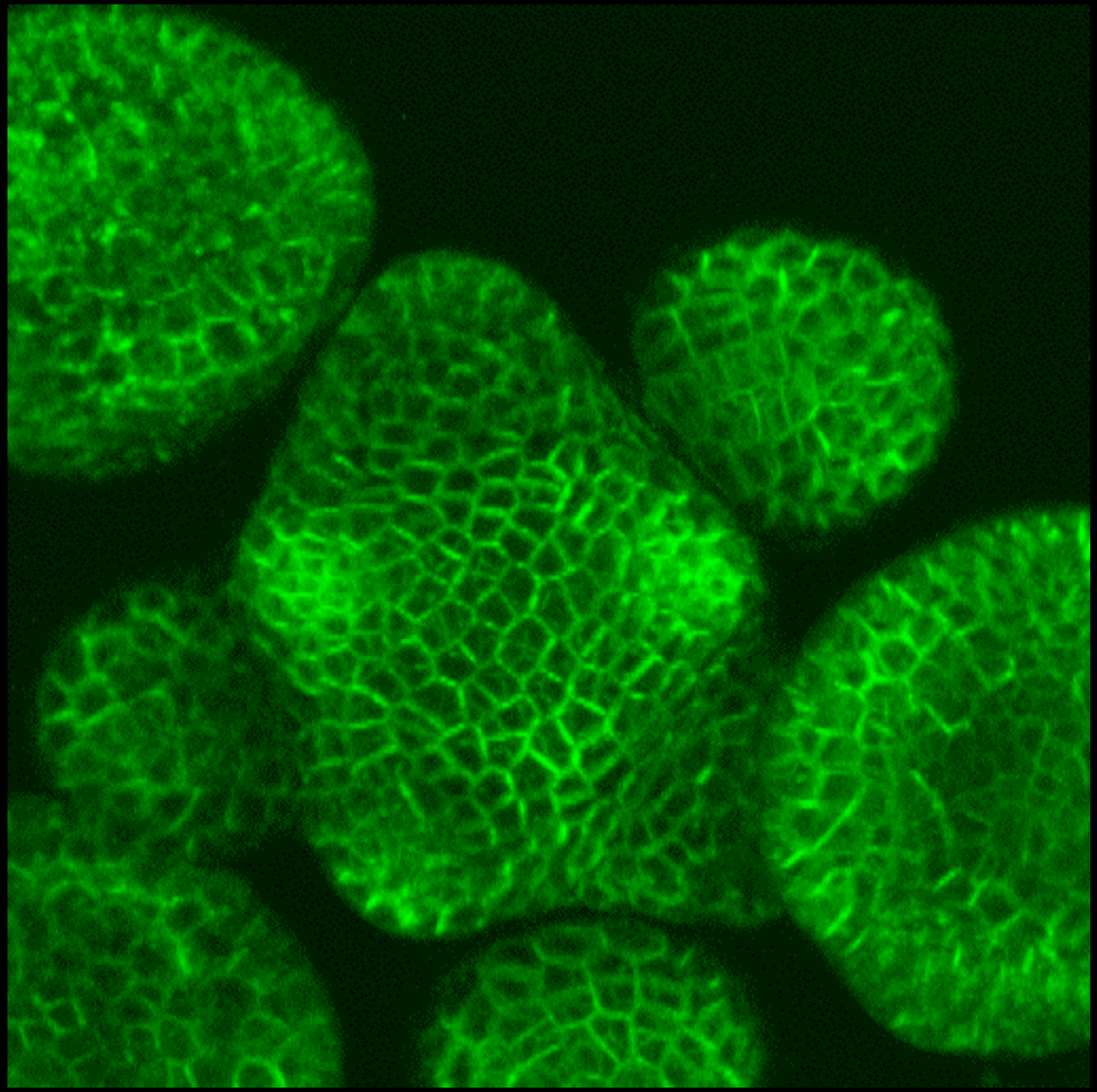


Bacarian and Mjolsness

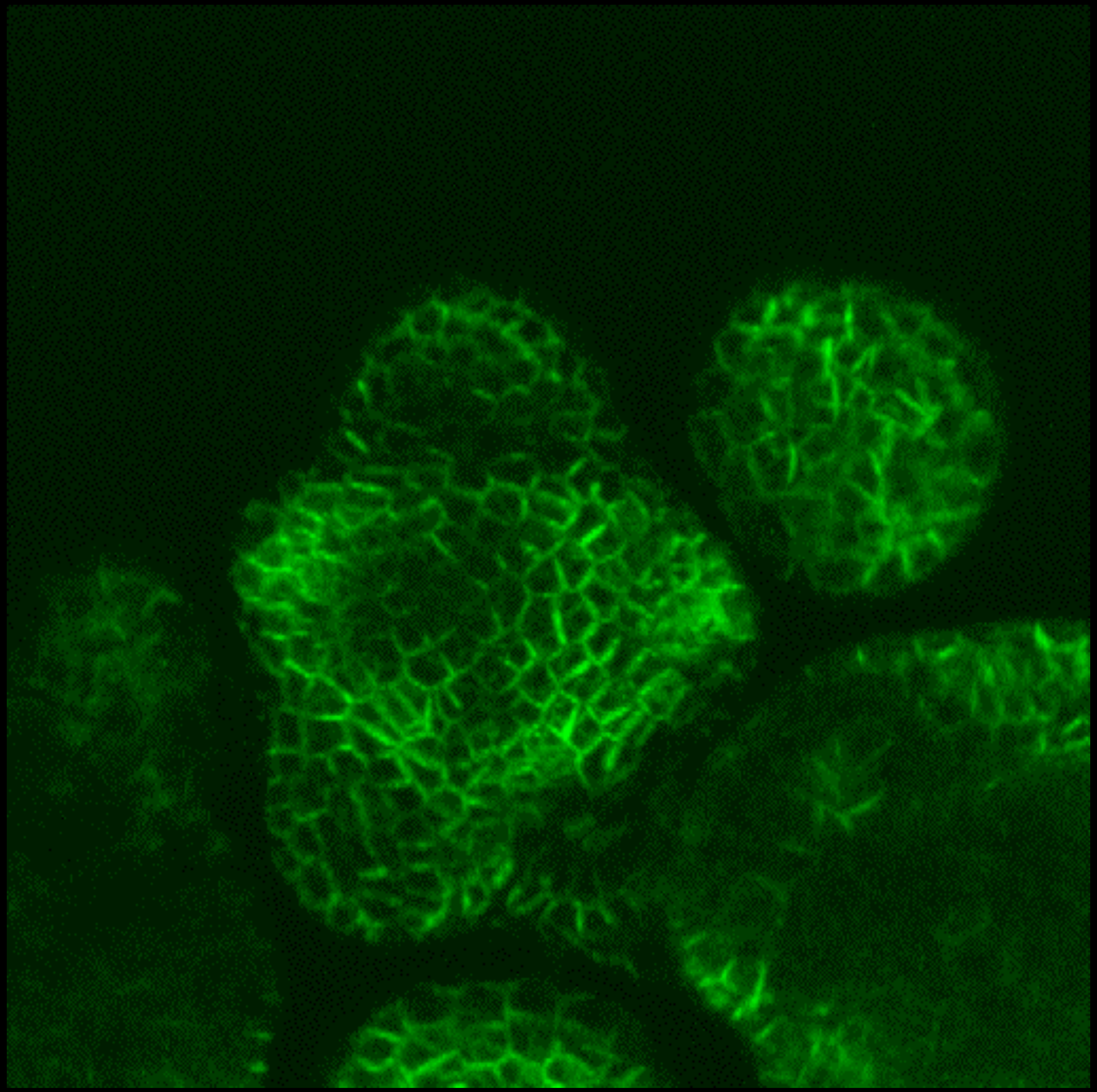

PIN1
0.3
0.28
0.24
0.2
0.16
0.12
0.1
Pawel Krupinski, Henrik Jönsson


Marcus Heisler

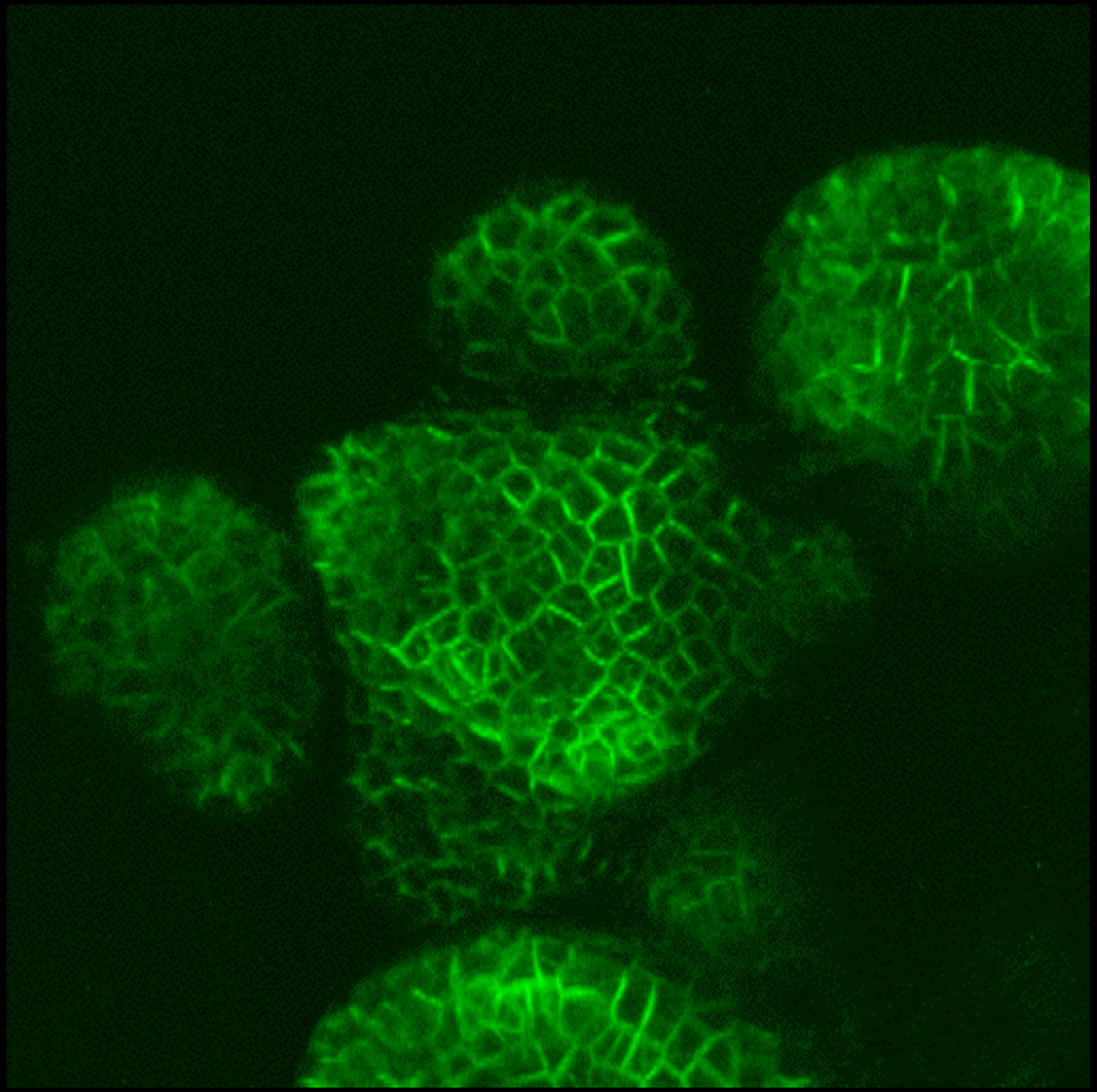
Effects of Cell Wall



Prior to treatment



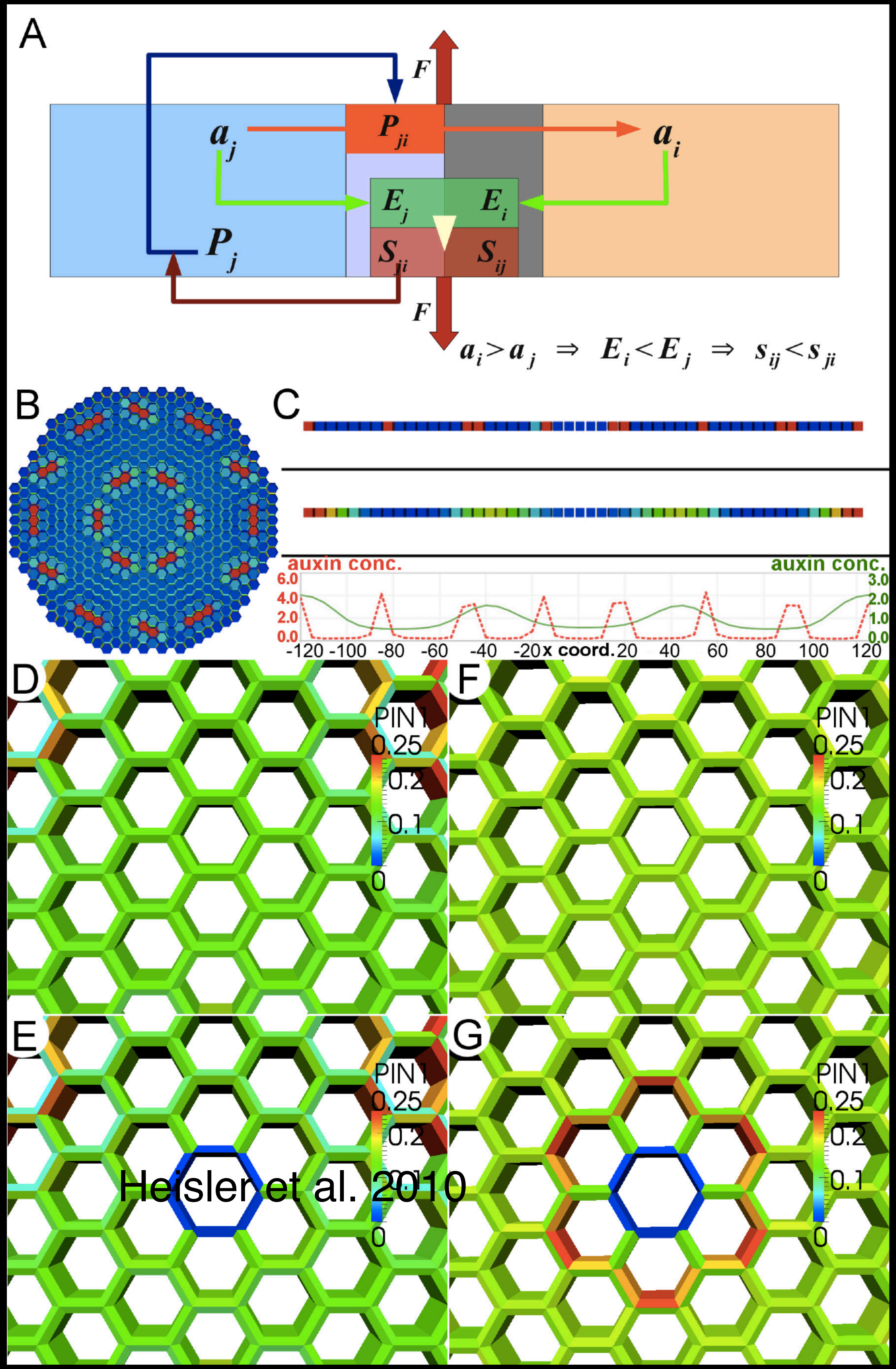
Cellulase Bead 18h



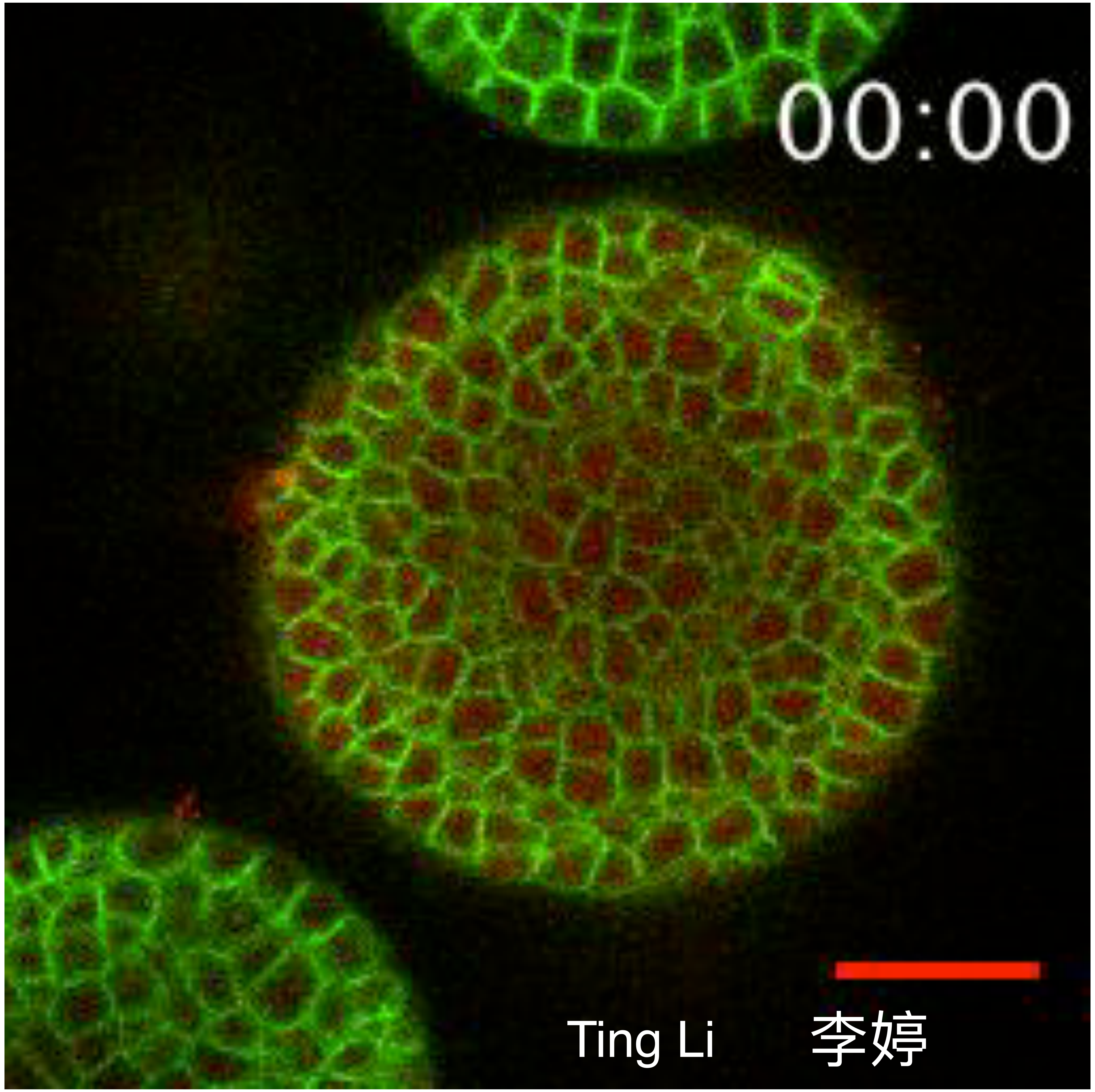
24h Recovery

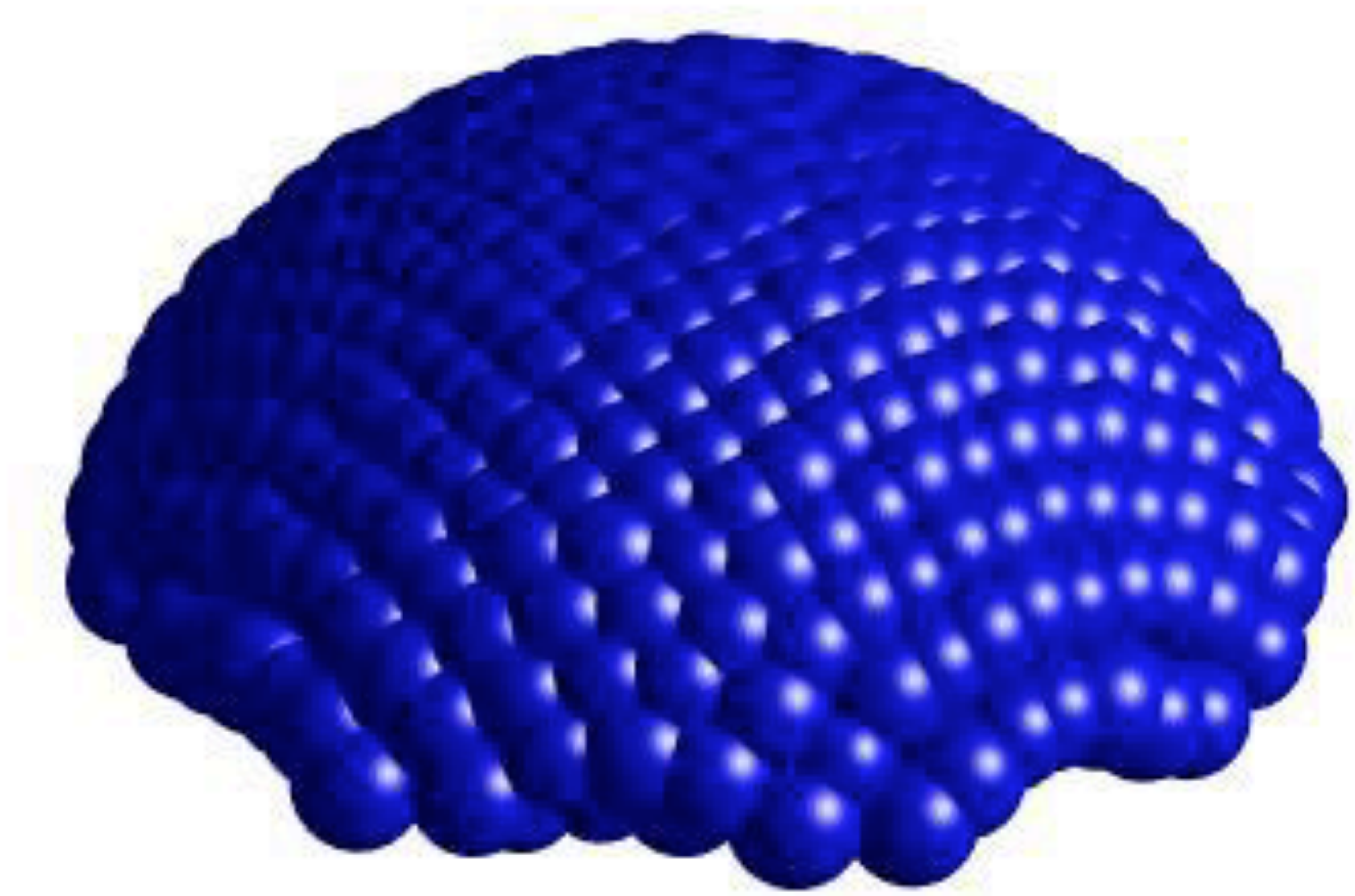
An Yan

- Auxin causes cell expansion
- Resulting mechanical stress controls auxin transport from neighbors
- New auxin peaks changes which cells are expanding
- Thereby changing auxin flow again
- NOVEL DEVELOPMENTAL MECHANISM: REGULATED TRANSPORT OF A



Calcium Waves in SAM

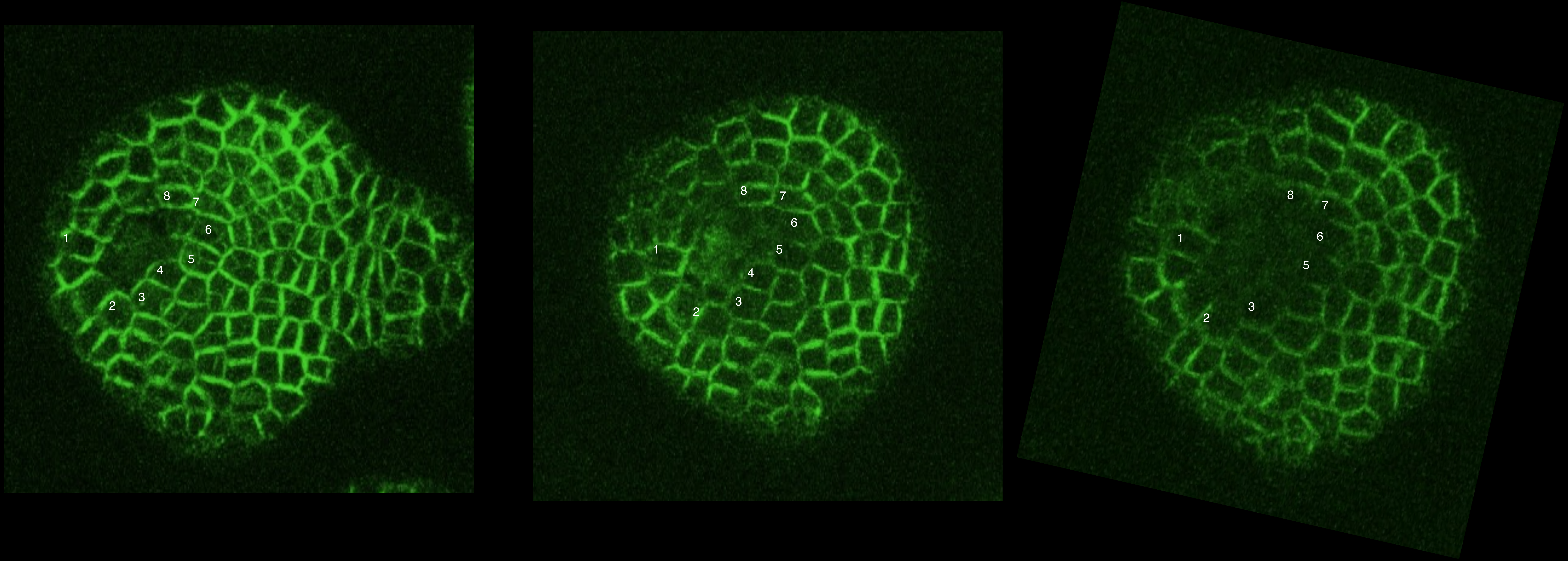




An Yan 燕安

Calcium Response Is Necessary for Later PIN1 Mechanical Response

- Pretreat 5mM LaCl3 0h, 3h, recover 3h



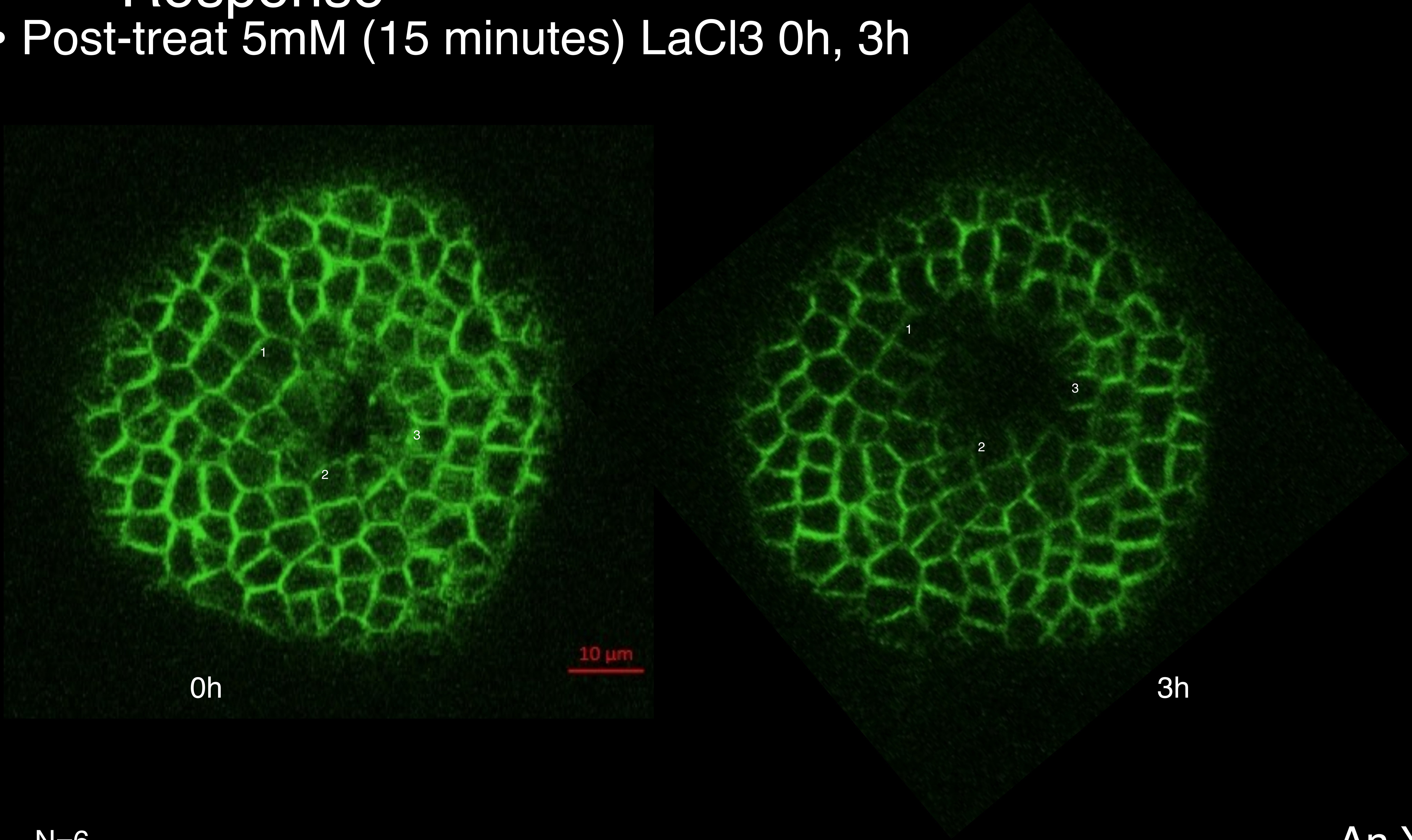
0h 3h recover3h

N=4

An Yan

Calcium Wave Only Needed for Initial Response

- Post-treat 5mM (15 minutes) LaCl3 0h, 3h

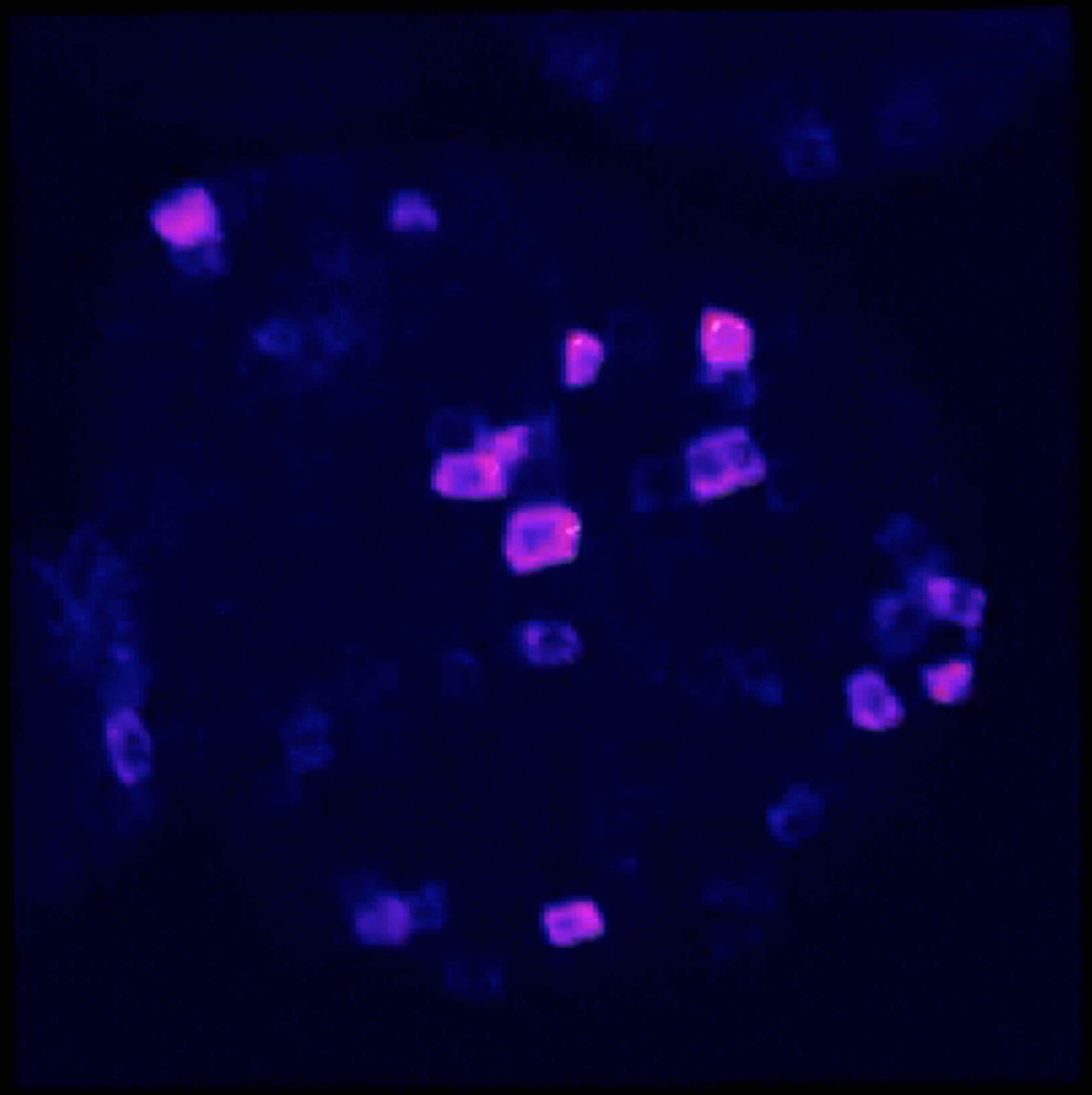


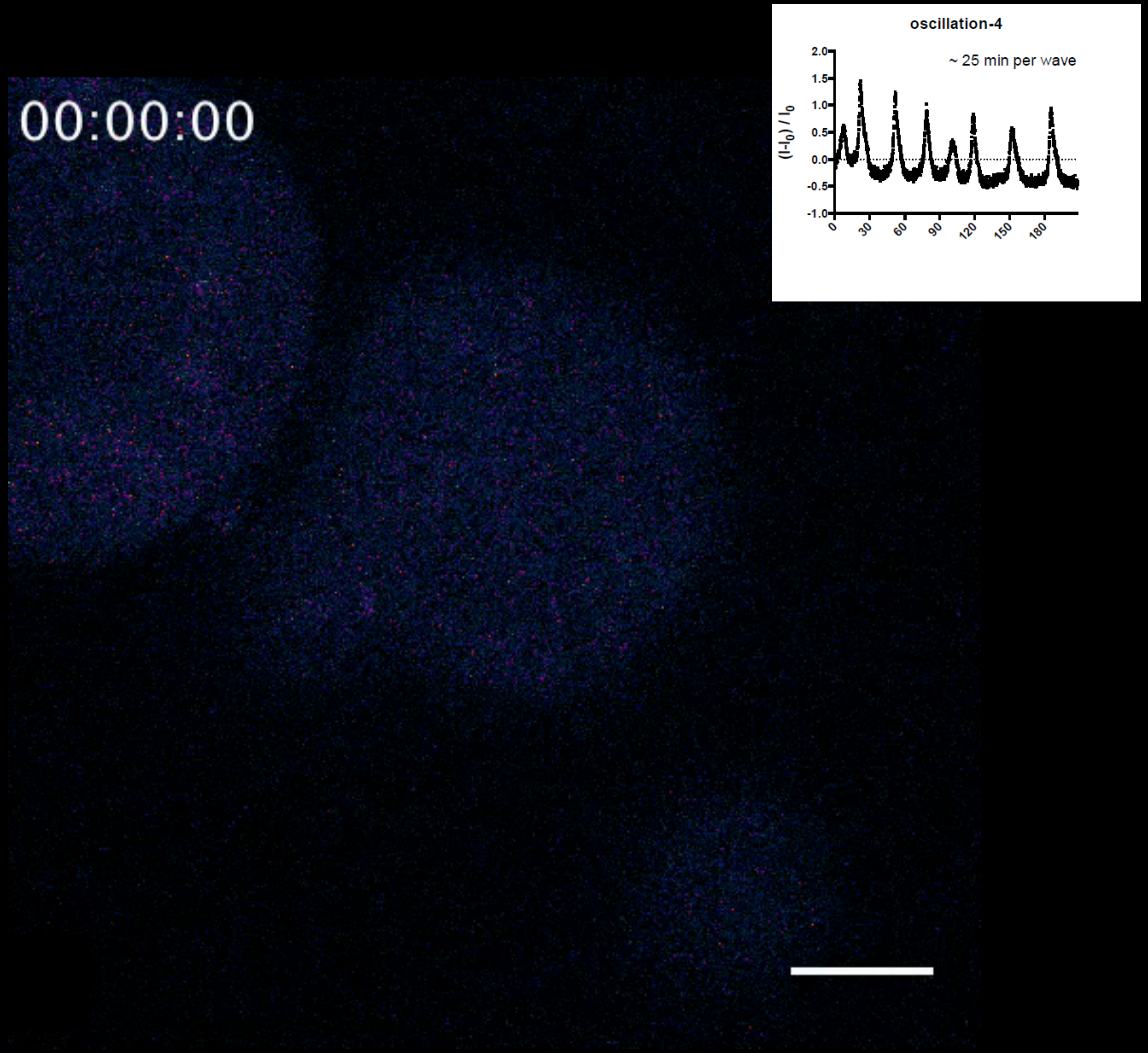
N=6

An Yan

Spontaneous Single-Cell Calcium Activation and Oscillations

Each frame 3.8 sec. 13 z per stack, 33 stacks, 2.1 min





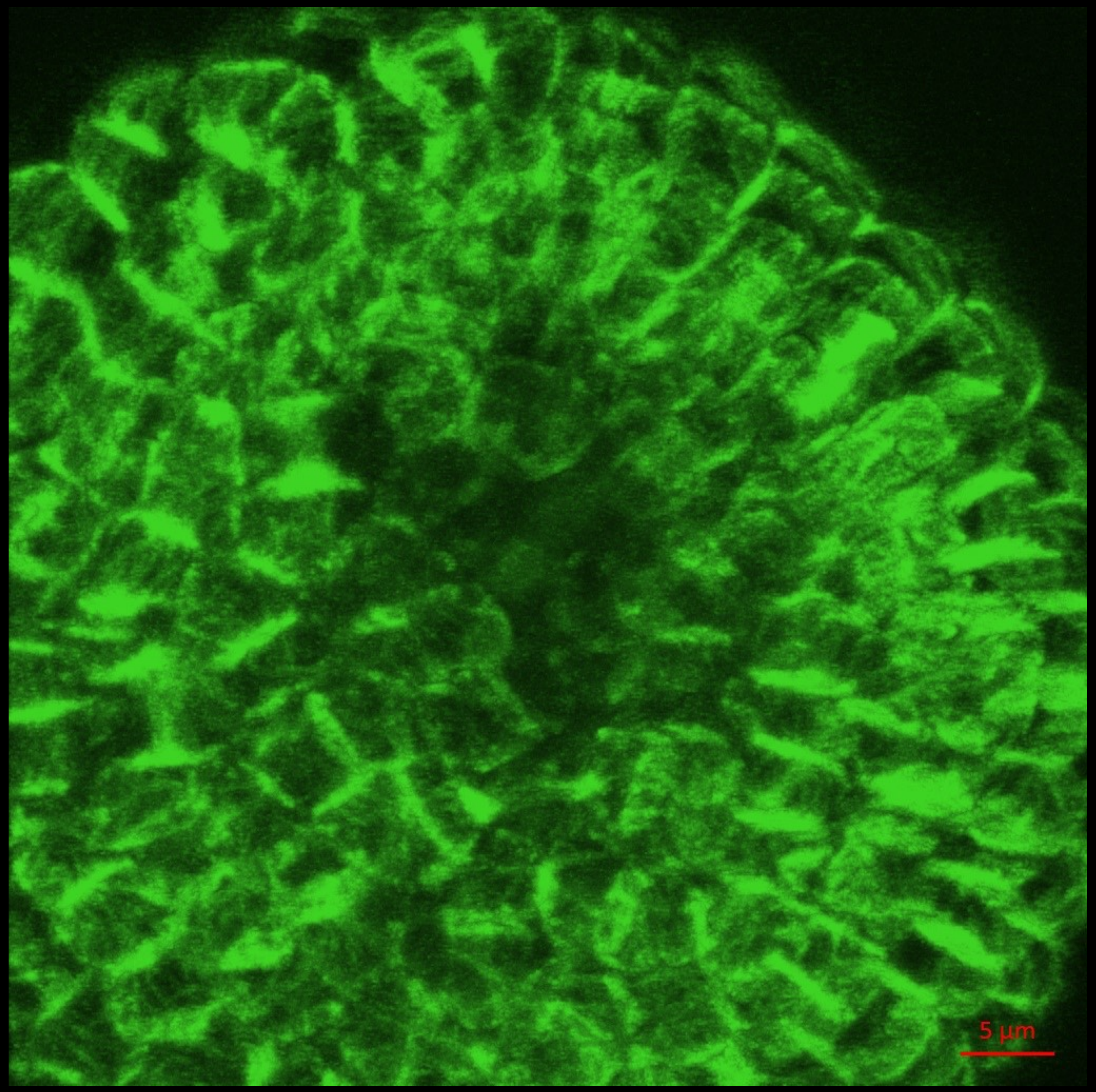
20 um

Ting Li, Neha Bhatia, Marcus Heisler

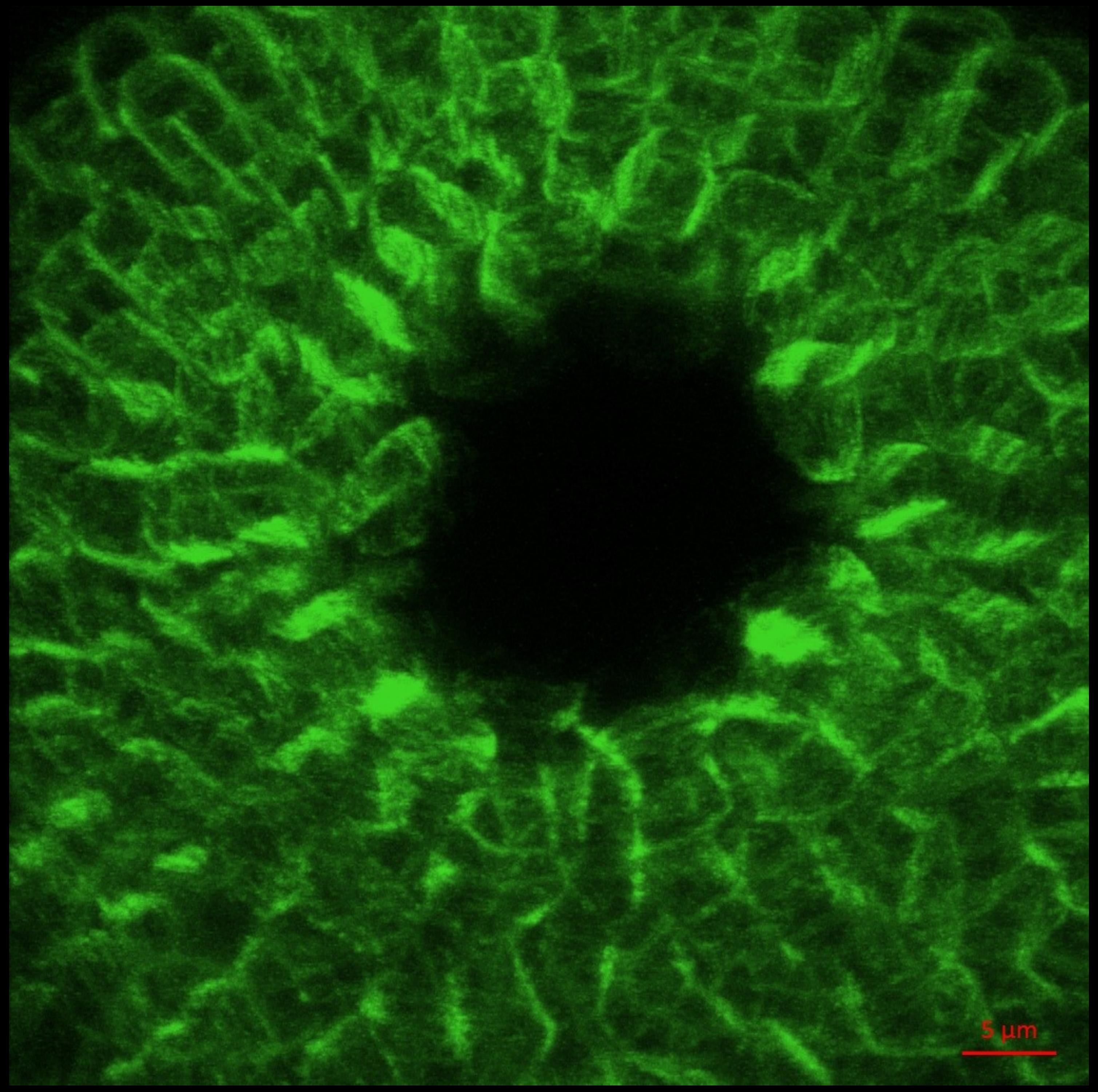
Ting Li

Calcium Wave Is Not Precursor To MT Mechanical Response

- 2mM BAPTA 6h



2mM_BAPTA_MTKill_0h



2mM_BAPTA_MTKill_6h

N=6

An Yan 燕安

hhmi GATSBY ERA-CAPS NASA NSF MARIE CURIE ACTIONS

Henrik Jönsson
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Cambridge University

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Olivier Hamant
INRA Lyon

Arun Sampathkumar
MPI for Plant
Physiology

Jan Traas
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