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Hadrien Oliveri, Feng Zhao, Olivier Ali, Jan Traas, Christophe Godin. Stress-based regulation of multicellular plant growth: a finite element modeling approach applied to planar leaf morphogenesis. ICSB 2018 - 19th International Conference on Systems Biology, Oct 2018, Lyon, France. hal-01897027

HAL Id: hal-01897027

<https://inria.hal.science/hal-01897027v1>

Submitted on 17 Oct 2018

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Stress-based regulation of multicellular plant growth: a *finite element* modeling approach applied to planar leaf morphogenesis

Hadrien Oliveri*, Feng Zhao, Olivier Ali, Jan Traas, Christophe Godin

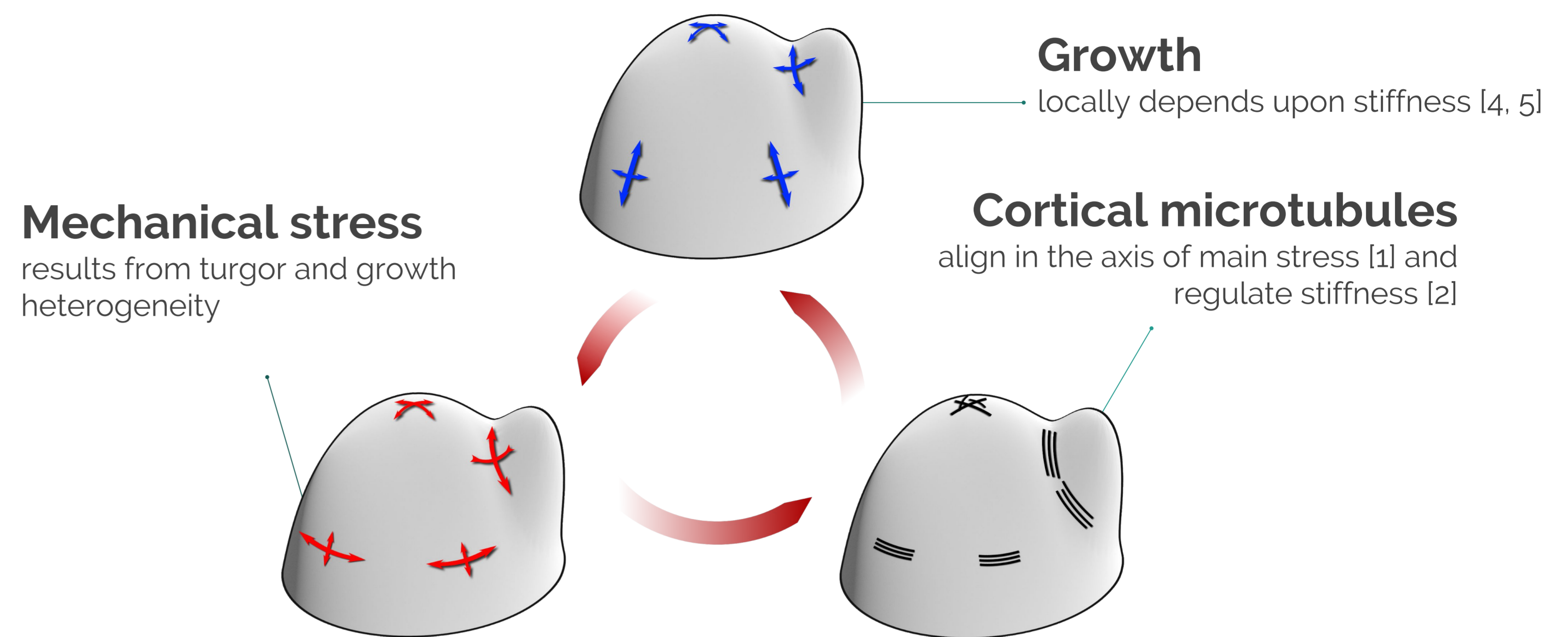
Laboratoire Reproduction et Développement des Plantes, Univ Lyon, ENS de Lyon, UCB Lyon 1, CNRS, INRA, Inria, F-69342, Lyon, France

How do plant cells locally control their growth to coordinately produce macroscopic shapes?

➤ Mechanical tensions hypothetically provide cues governing local cell growth regulation [1,2].

What kind of emergent dynamical behavior can a stress-sensing tissue display?

➤ Finite element multicellular model coupling **growth** and **stress feedback**



MODEL / SIMULATION LOOP

FEM (Sofa FW [6])
with pressurized structures

Update microfibril angular density according
to growth field

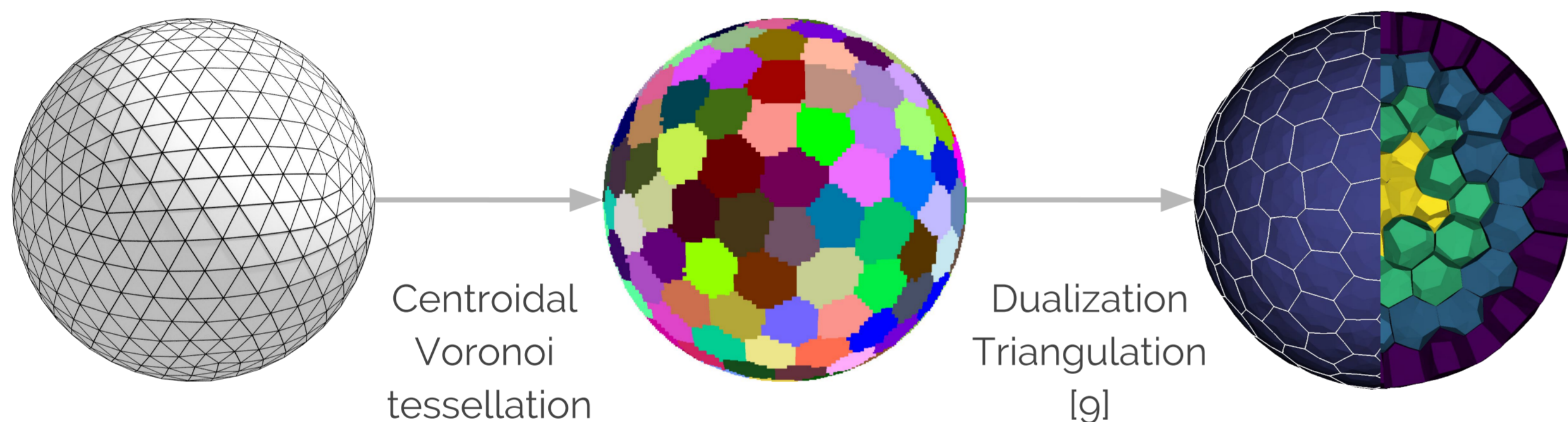
Func. of low-frequency Fourier coef. of
microfibril angular distribution [7, 8]



Update element rest state [4]:
 $\partial_t \mathbf{F}_g \propto (\mathbf{E} - \mathbf{E}_0)_+ \cdot \mathbf{F}_g$

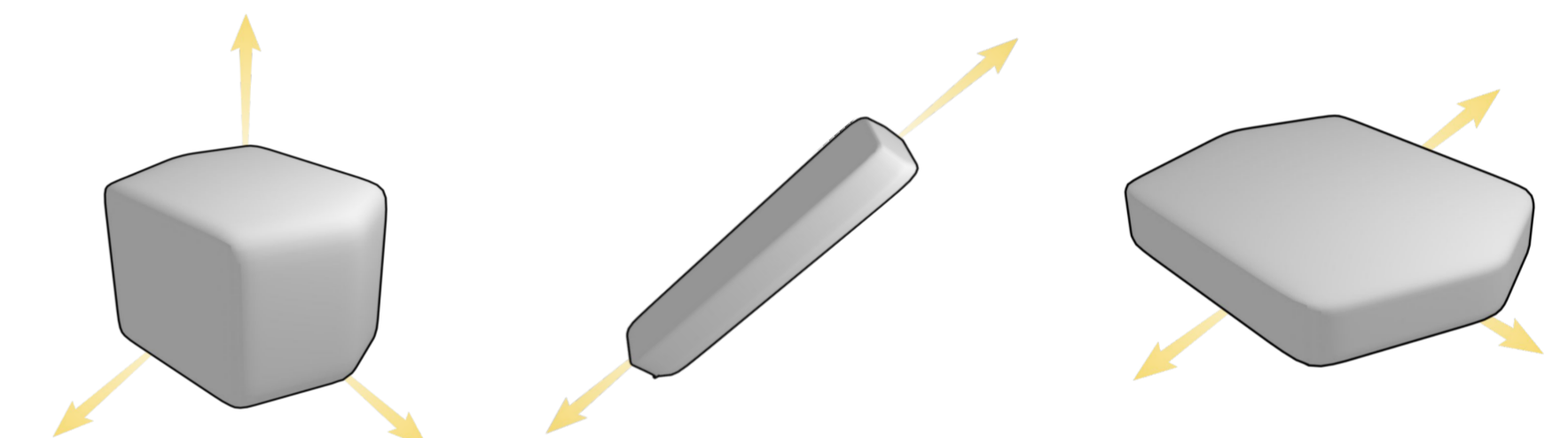
Stress-dependent microfibril polym. [7]
 $\rho^+(\theta) \propto e^{\gamma S_\theta}$

BUILDING ABSTRACT 3D CELLULAR MESHES



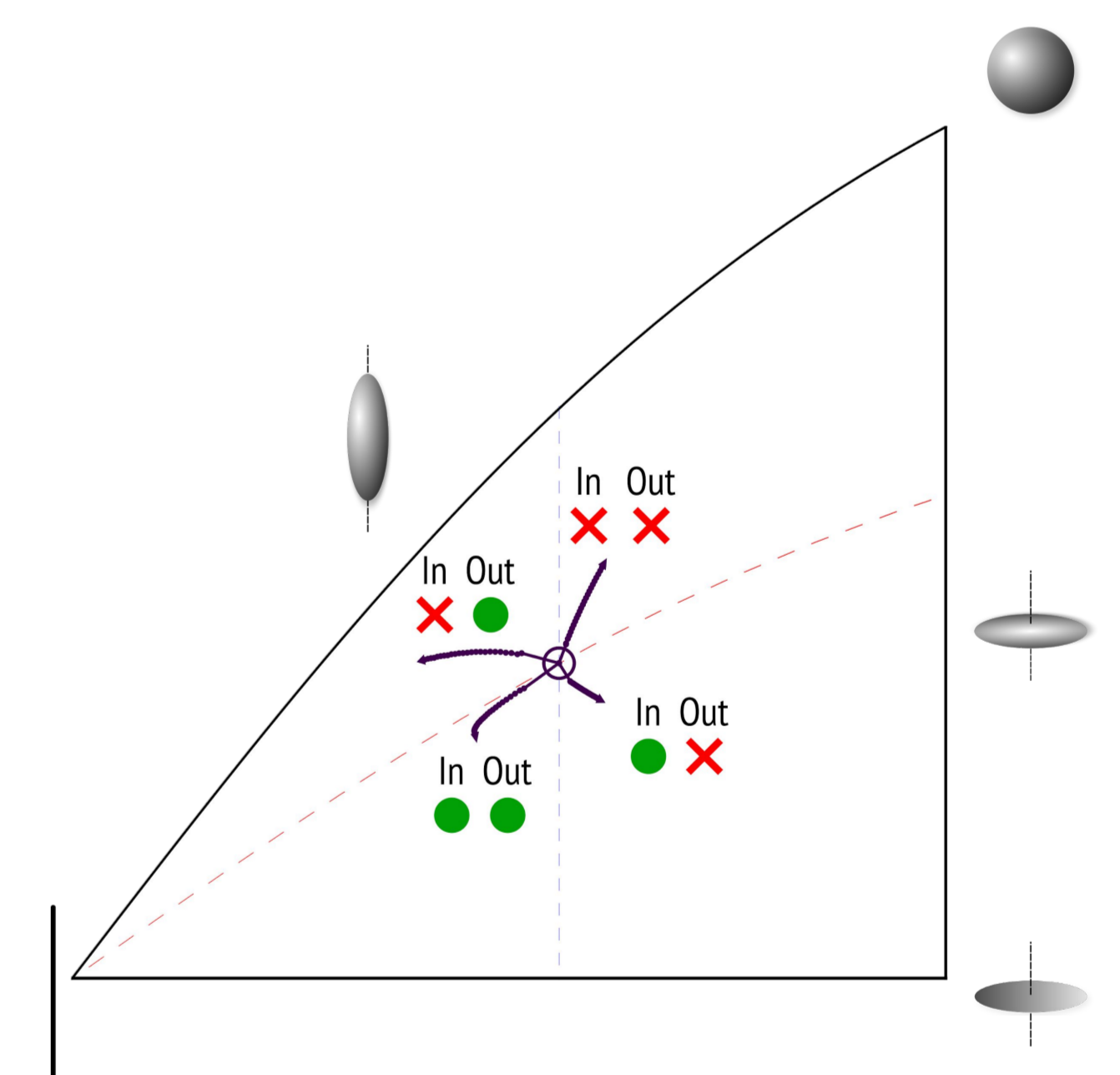
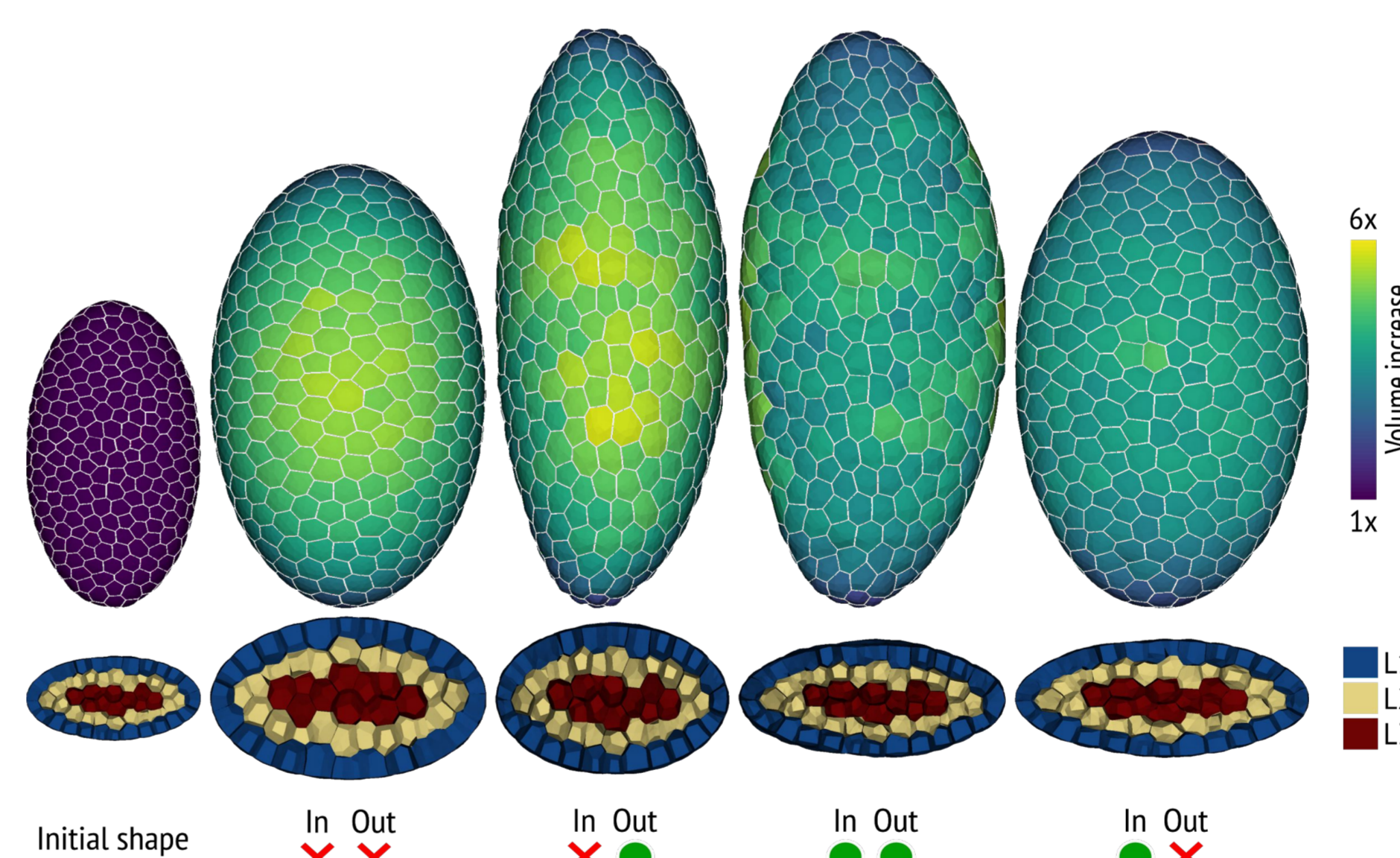
STABILITY OF PLANT GROWTH

Several typical growth modes. Can a stress feedback mechanism capture them?

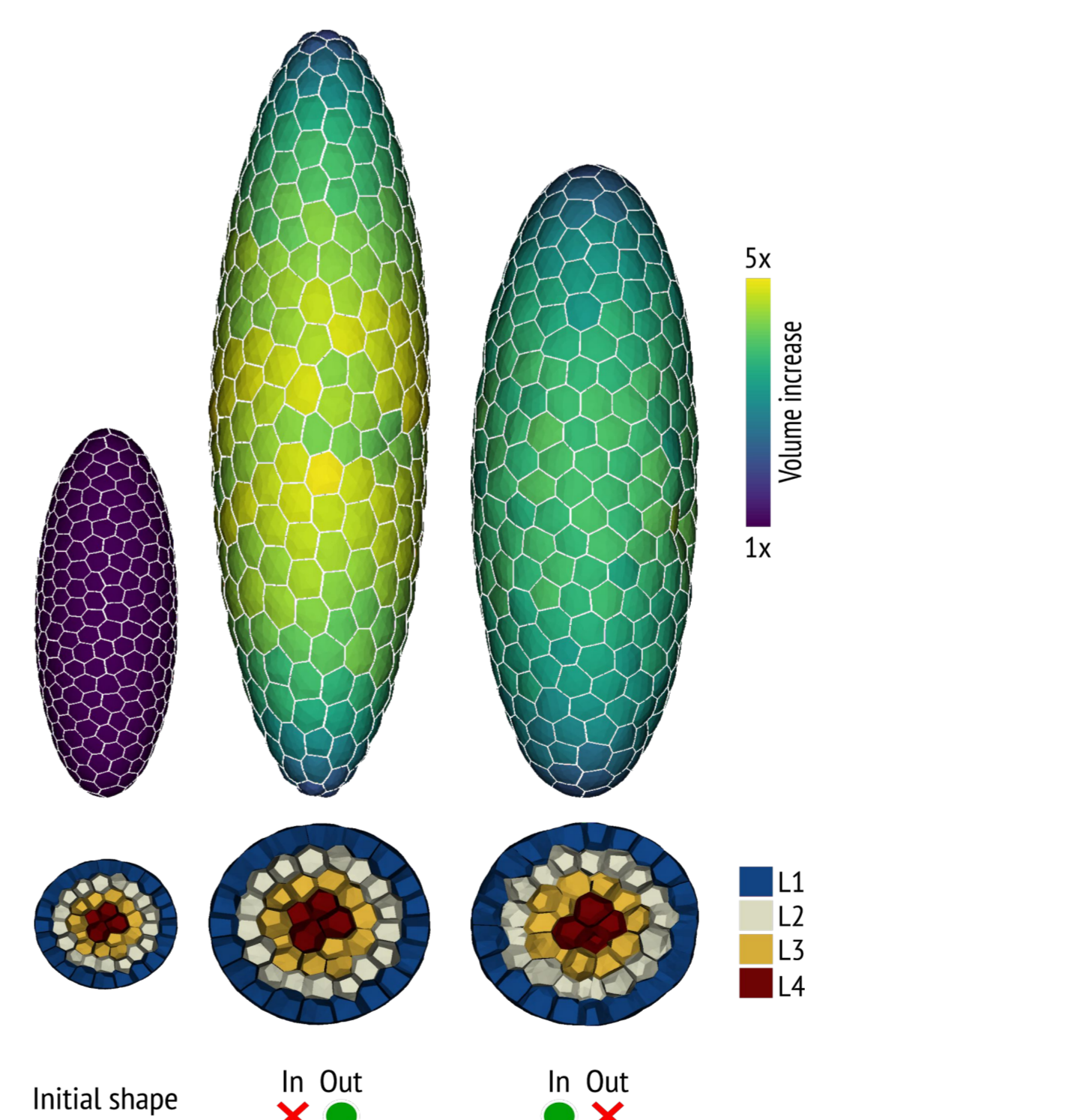


SOME RESULTS

- We simulate the local dynamics of various abstract shapes (ellipsoids) mimicking flat shape (~800-cell meshes).
- Epidermal feedback or inner feedback stabilize axial elongation of axisymmetric shapes.
- Flat expansion requires inner stress feedback: microtubules align in the axis of thickness to resist thickening.
- This mechanism allows amplification of organ asymmetry.
- Coupling inner and epidermal feedback leads to conflicting microtubule alignment (not shown) → possible mechanical instability?



Morphospace



TAKE-HOME MESSAGE

A single mechanism accounts for flat and axial expansion mode depending on initial shape.

Coupling inner and epidermal stress feedback reveals nontrivial behavior and possibly unstable regimes. → Need for additional regulation?

References: [1] Hamant et al., 2008, Science; [2] Bozorg et al., 2014, PLOS Comp. Biol.; [3] Paredes et al., 2006, Science; [4] Boudon et al., 2015, PLOS Comp. Biol.; [5] Bozorg et al., 2016, Physical Biology; [6] Faure et al., 2012, in Soft Tissue Biomechanical Modeling for Computer Assisted Surgery. [7] Oliveri et al., 2018, J. of Mathematical Biology; [8] Cox, 1952; British J. of Applied Physics; [9] Cerutti et al., 2017, Frontiers in Plant Science.