Differential dynamical patterning during cellular growth and division

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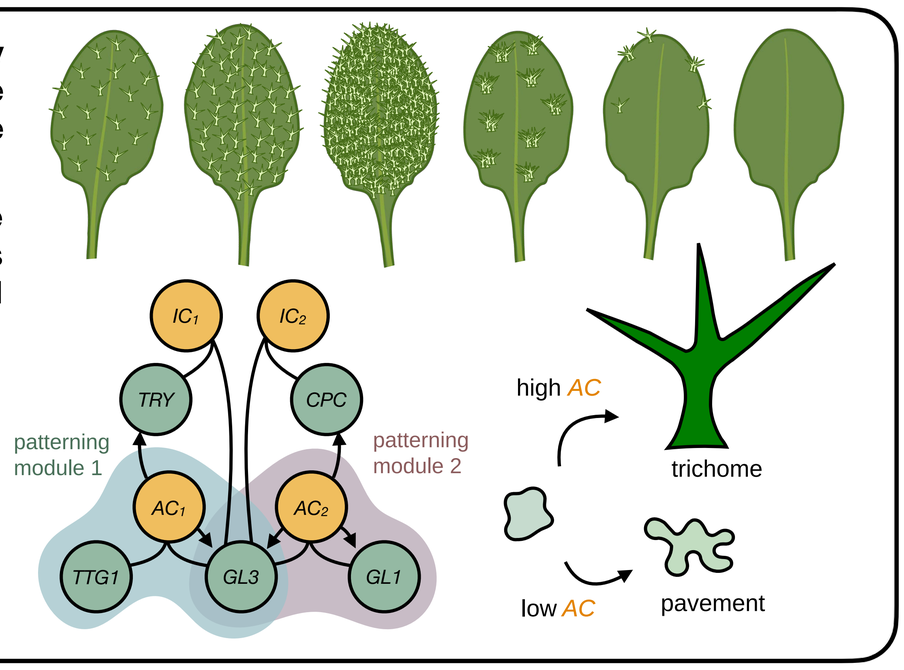
Motivation

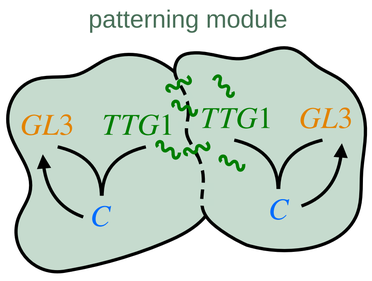
- **Phenotypic variation**: crucial role in evolutionary biology; acts as the substrate on which selection can act to drive evolutionary change.
- Understanding the **origins of phenotypic variation** requires a detailed characterization of the underlying **developmental processes**, how these emerge as outcomes of gene regulatory networks, and how they interact with the environment.
- **Plant trichomes**: specialized epidermal cells that protect plants from insect herbivores and UV light, increase tolerance to freezing, regulate plant water loss and temperature.
- Trichomes are usually organized in **regular patterns**, but they display high variability upon environmental perturbations and mutations. Younger leaves display different trichome patterns than older leaves (heteroblasty).

Objectives

- Understand how the **trichome gene regulatory network** gives rise to regular patterns. What are the minimal requirements for pattern formation, given the complexity of the network?
- Determine the structure of the **genotype-phenotype map** for trichome patterns: how can we understand this **phenotypic variation** using **dynamical systems** and **bifurcation theory**?
- Understand the **developmental constraints** inherent in the structure of the genotype-phenotype map. Which patterns are possible and which are not?
- Beyond static tissues: trichome patterns are formed during leaf growth. How does patterning occur when **cells grow and divide**?



Trichome patterning modules display rich dynamical behaviors, leading to pattern diversity

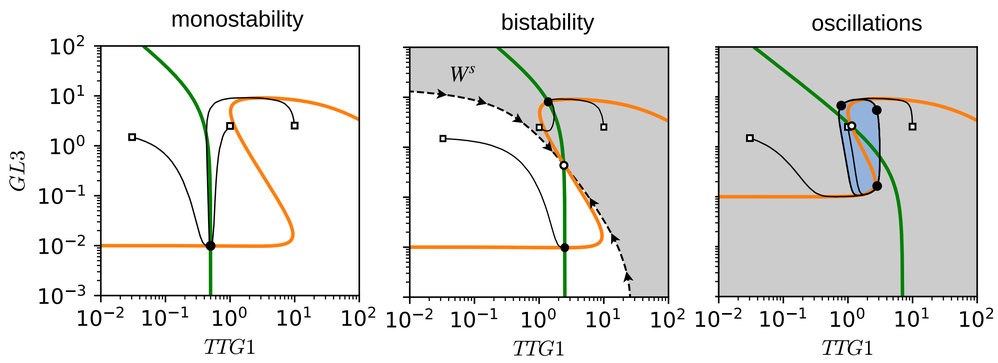


$$\frac{dT_i}{dt} = \alpha_0 - d_T T_i - k_c T_i G_i + D_T(T_j - T_i)$$ *TTG1 movement*

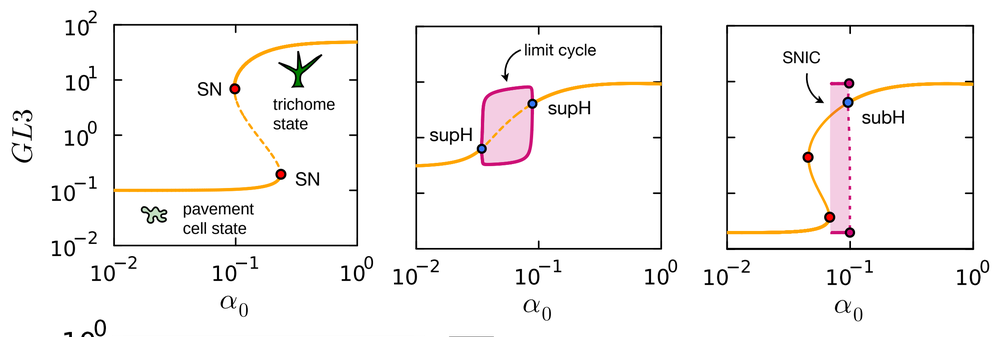
$$\frac{dG_i}{dt} = \beta_0 + \beta \frac{C_i^2}{C_i^2 + k^2} - d_G G_i - k_c T_i G_i$$ *complex formation*

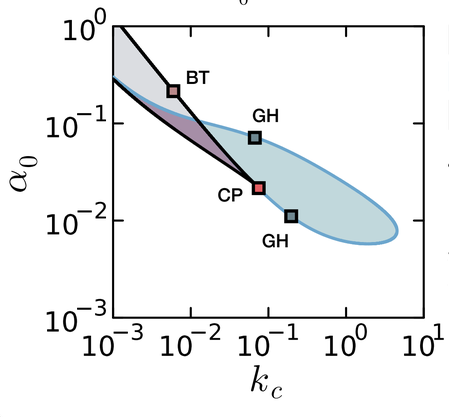
$$\frac{dC_i}{dt} = k_c T_i G_i - d_C C_i$$ *complex activates GL3*

Single-cell dynamics: monostability, bistability, oscillations, excitability



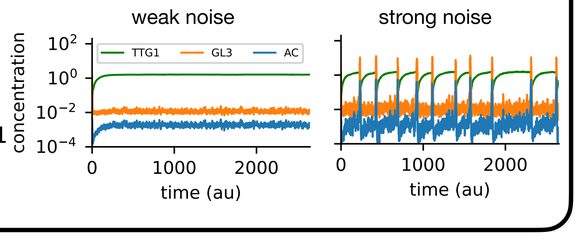
Stability and bifurcations





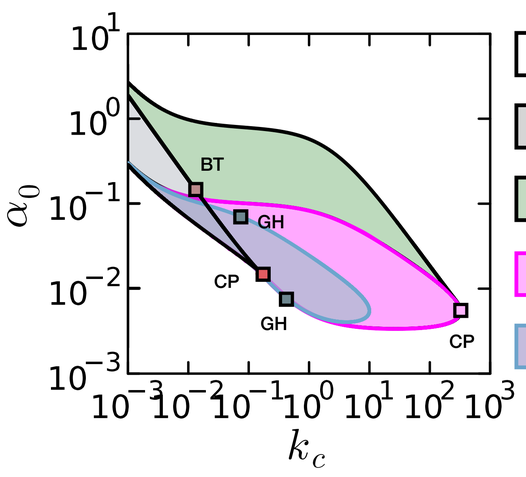
- Bistability
- Oscillations
- Coexisting fixed point and limit cycle

- Noise-induced excitability, coherence resonance

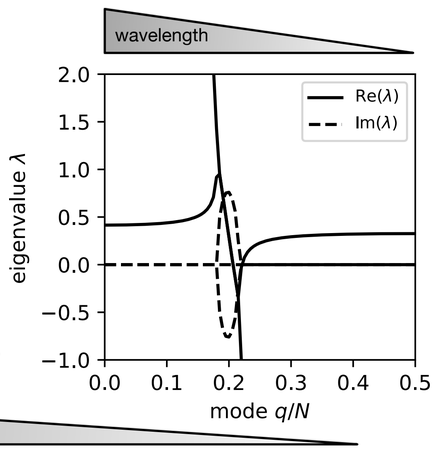


Multicellular dynamics: pattern diversity and plasticity

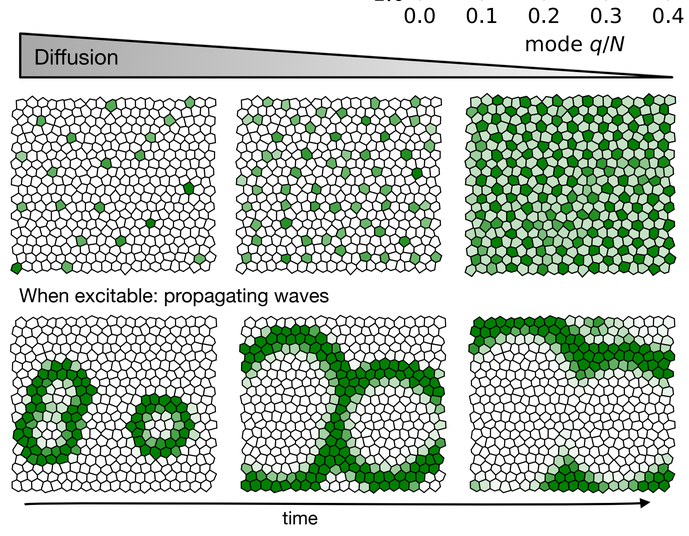
The model displays very flat dispersion relations: **mode coexistence** unless very close to instability



- Homogeneous states (no pattern)
- Single-cell bistability: random patterns dependent on initial conditions
- Nonlinear (localized) patterns: locally defined wavelength, dependent on i.c.
- Spontaneous patterns: globally defined wavelength, weak dependence on i.c
- Bulk oscillations, patterns, dependent on initial conditions

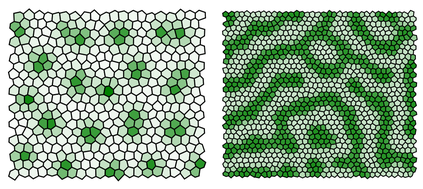


Patterns with different wavelengths: salt-and-pepper, trichome clusters and very separated trichomes.

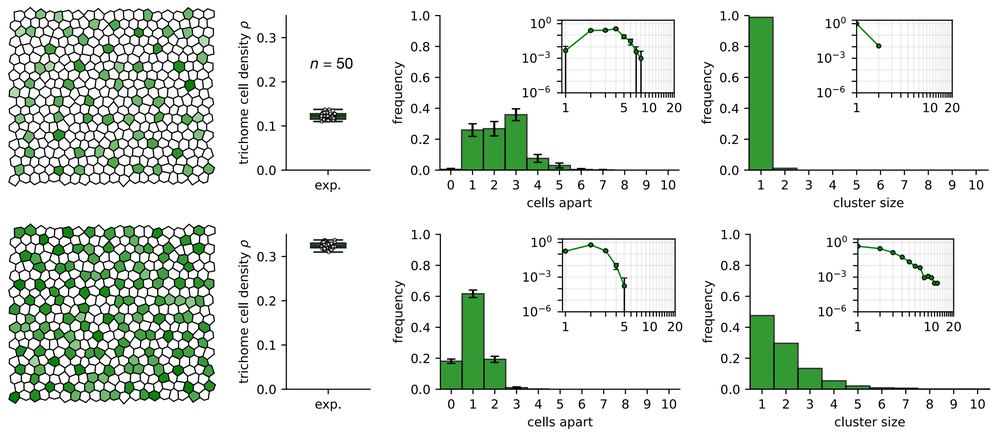


Other kinds of possible patterns:

When both ***TTG1*** and ***GL3*** diffuse: spots and stripes



Spatial statistics to quantitatively compare the model with real trichome patterns

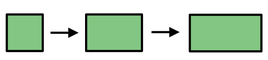


- Different patterning regions lead to different spatial statistics
- Given a pattern, can we infer (at least partially) the underlying mechanisms or parameter space region from the spatial statistics?

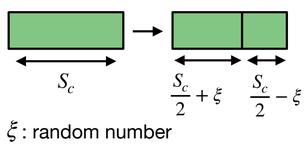
Trichome patterning in **growing tissues**

Dynamics of **trichome intercalation**: how do new trichomes appear (or not) during tissue growth?

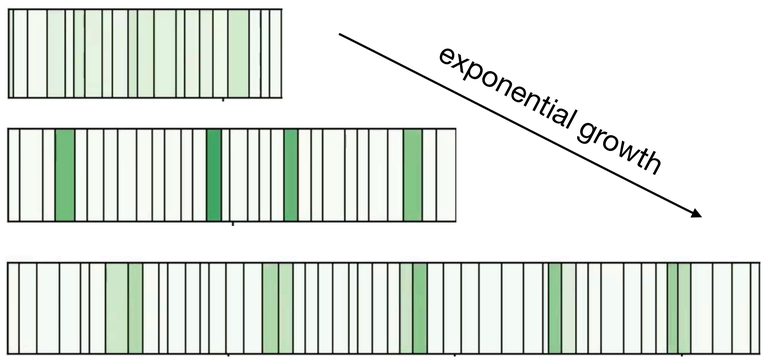
- 1d cellular tissue with exponential cell growth — cell size $S_i = S_0 e^{\alpha t}$



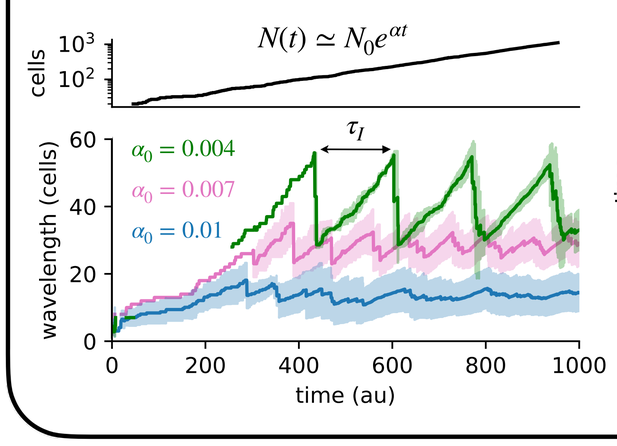
- Stochastic cell division (sizer) $S_i = S_c \rightarrow S_1 = S_c/2 + \xi$, $S_2 = S_c/2 - \xi$



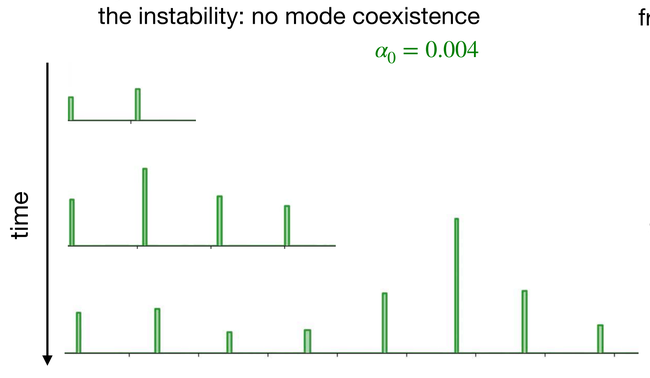
ξ : random number



Wavelength dynamics:

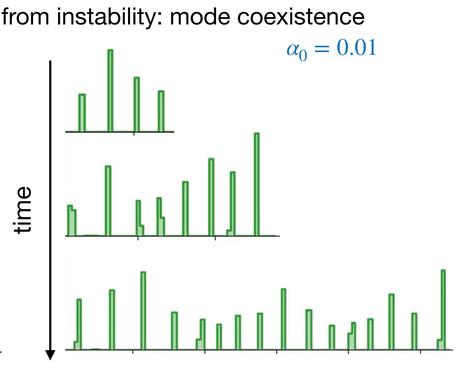


Synchronized intercalation close to the instability: no mode coexistence



Intercalation time: $\tau_I \simeq \ln 2/\alpha$ (tissue doubles its size)

Unsynchronized intercalation far from instability: mode coexistence



No characteristic intercalation time

Conclusions

- We propose a theoretical framework to understand the diversity of trichome patterns using dynamical systems theory.
- By analyzing the spatiotemporal dynamics of a minimal trichome network, we explore the fundamental mechanisms underlying the routes to patterning.
- Our framework provides a direct way to compare theory and experiments through quantitative spatial statistics.
- Starting point to understand patterning dynamics in growing tissues. Each region in parameter space has a different patterning behavior upon tissue growth.

References

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