Dynamics and robustness of plant form

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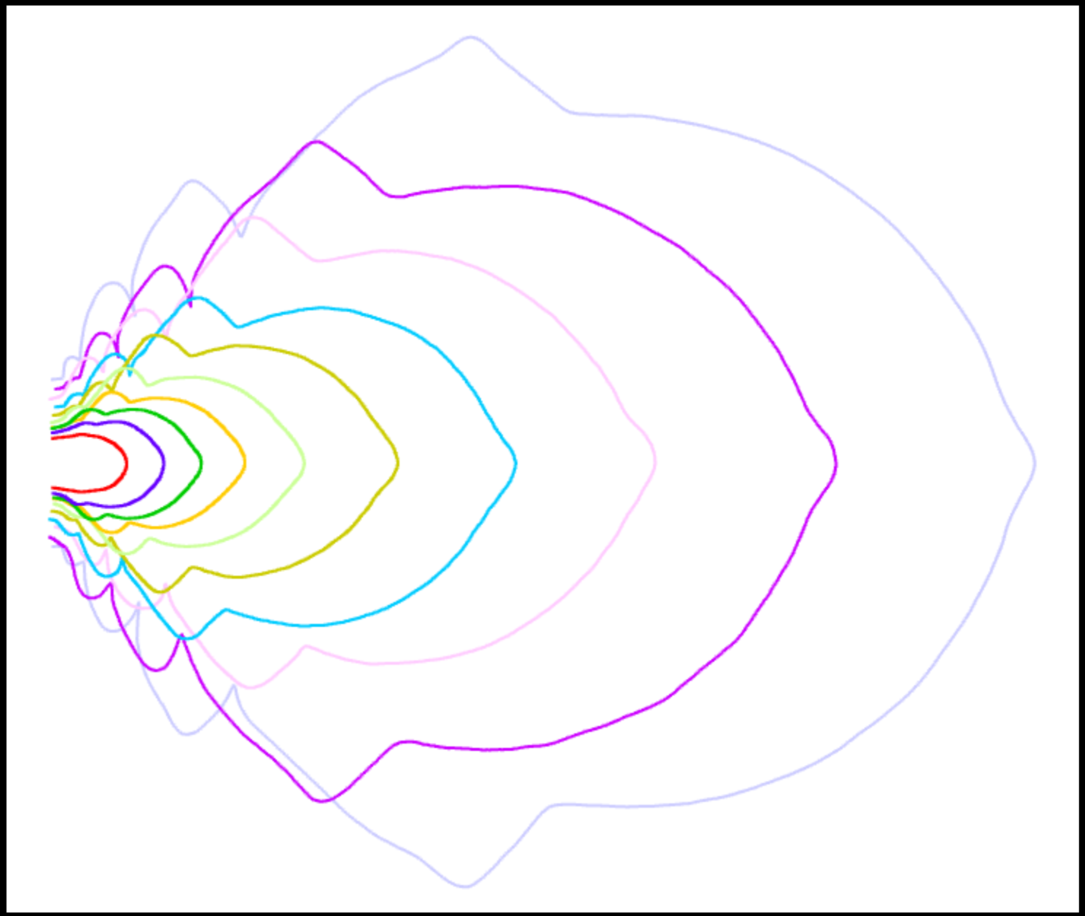

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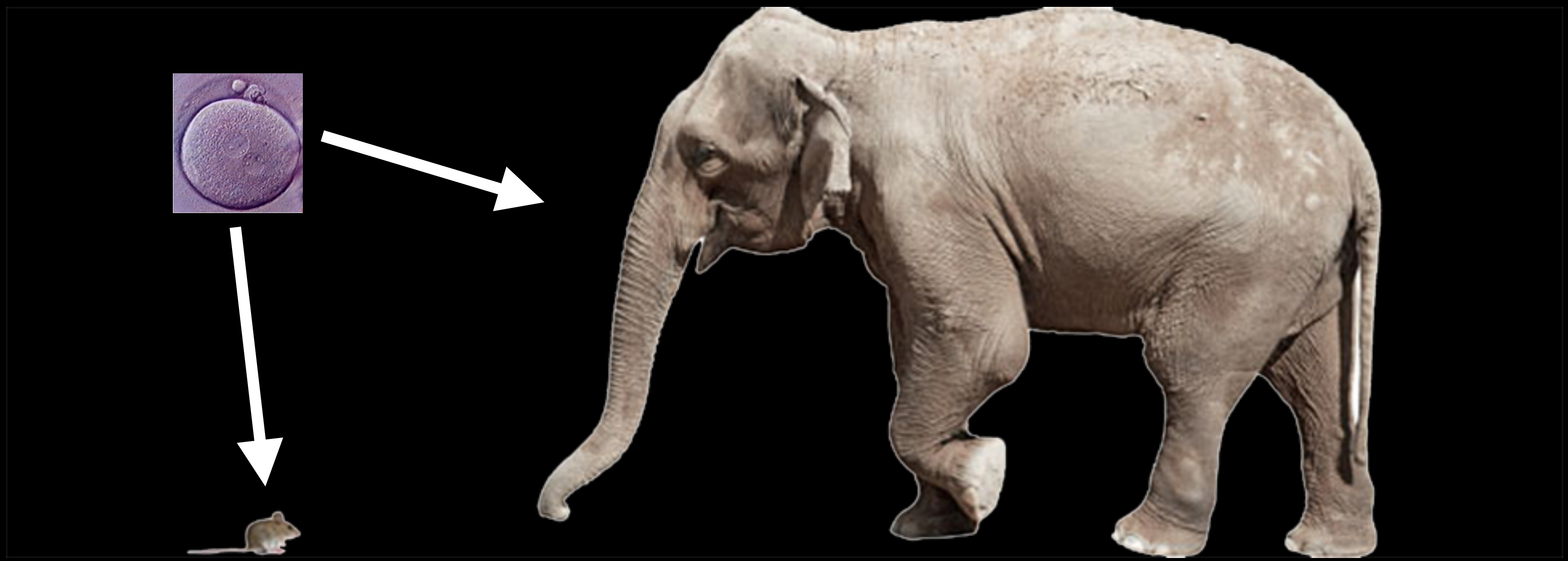


http://www.icr.org/article/6739/

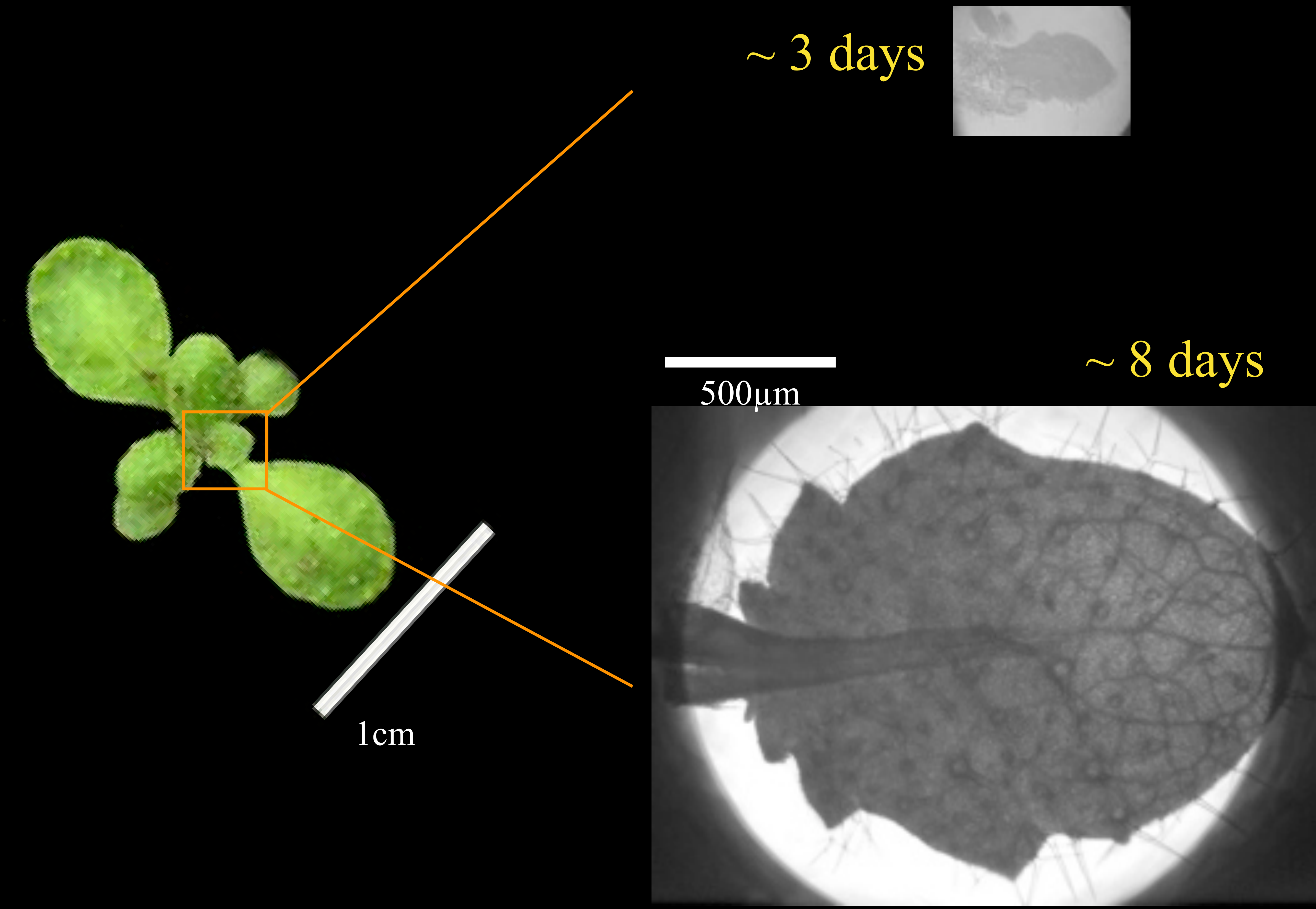
Arabidopsis thaliana

What determines the trajectory in the space of shapes?

Outline

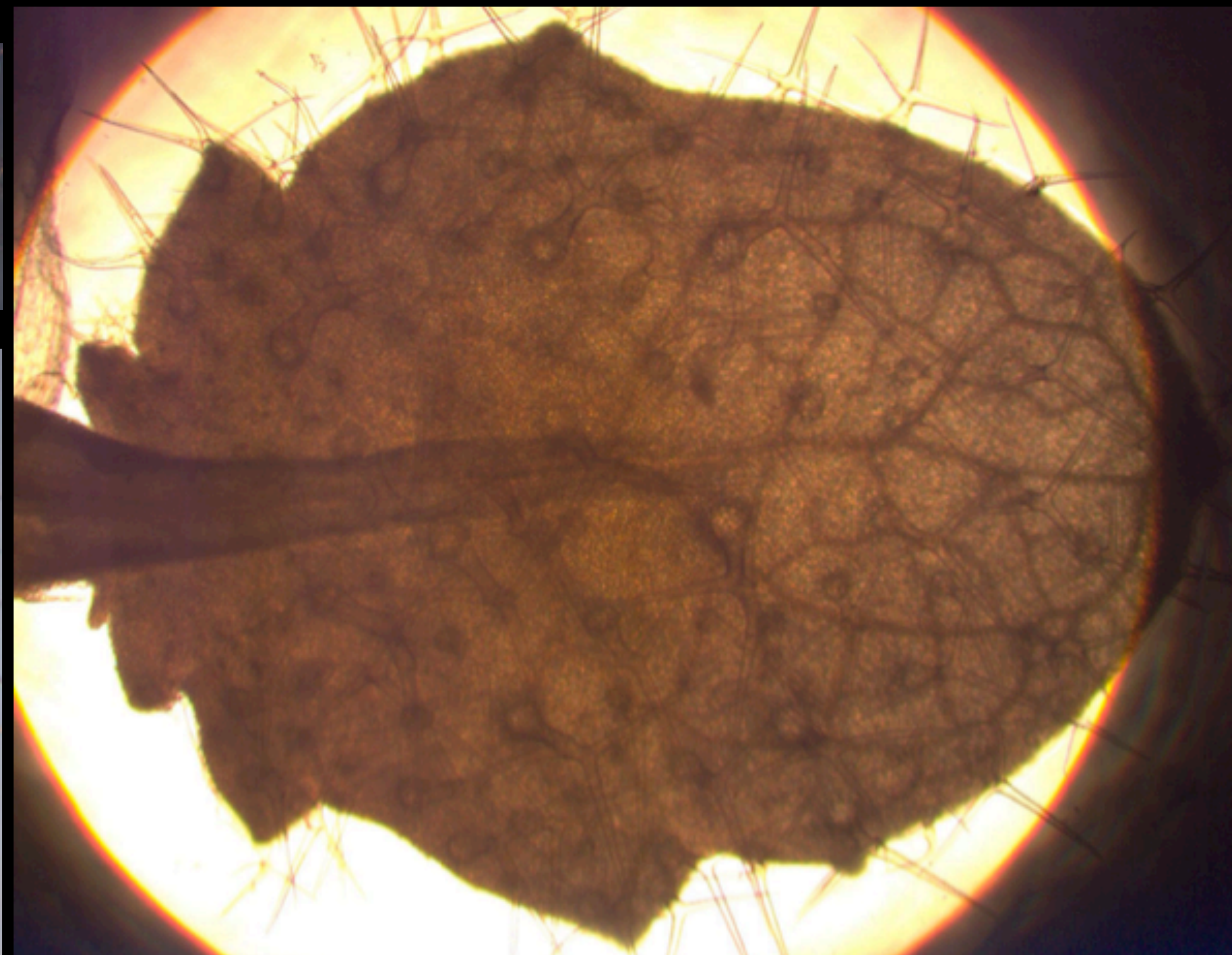
- Average dynamics of leaf contours
- From leaf contour to leaf blade
- Distributions of flower shape

Leaves in the model plant *Arabidopsis thaliana*



It is highly difficult to follow the same living leaf

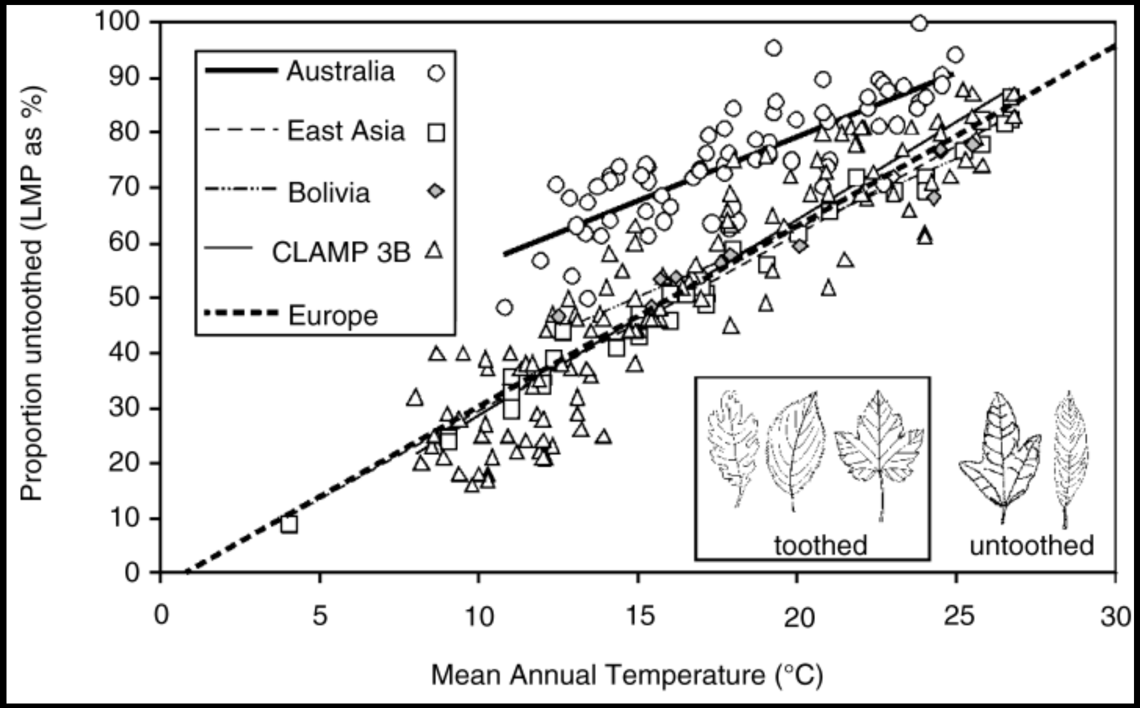
samples 6th leaf in Arabidopsis



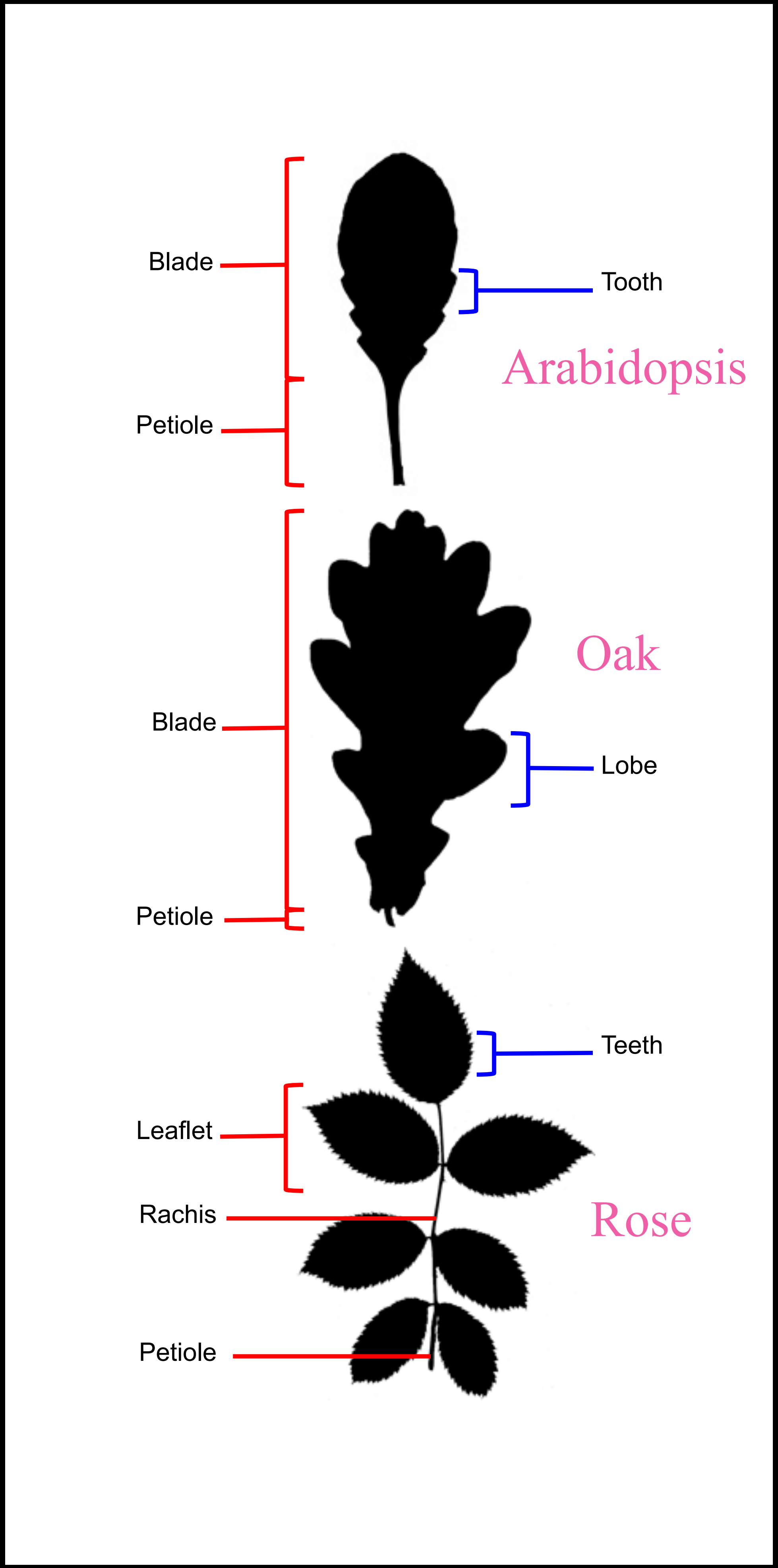
How to obtain a trajectory in shape space from independent samples?

Why leaves?

- Source of energy (photosynthesis)
- Diverse shapes: *simple, lobed, compound; toothed, untoothed*
- Shape ~ paleoclimates?



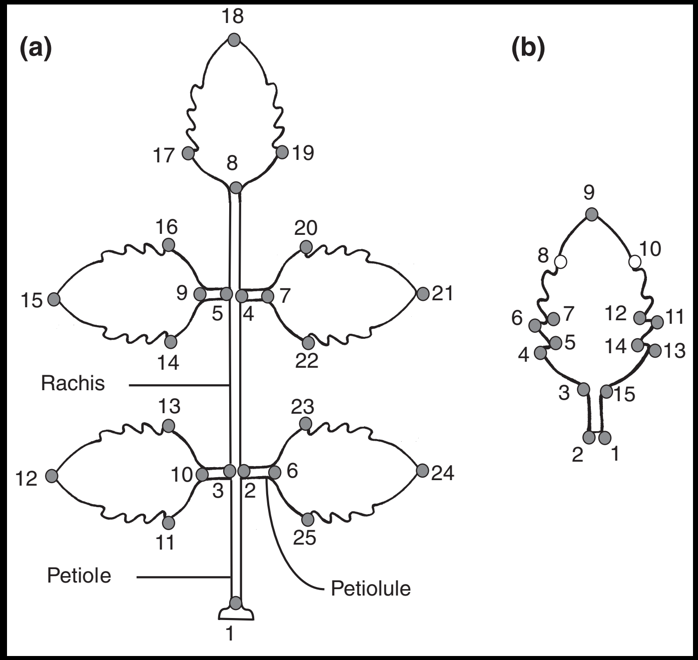
Greenwood, New Phytol 2005



Some of the previous approaches for leaves

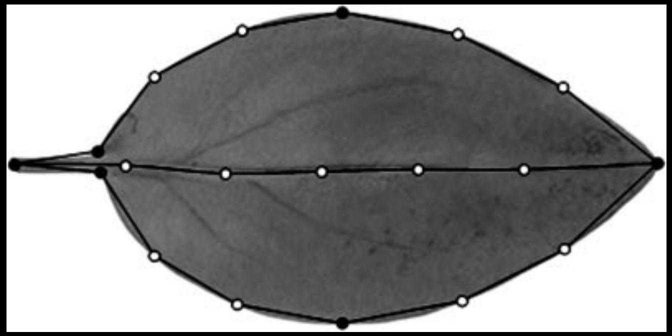
Landmarks + PCA

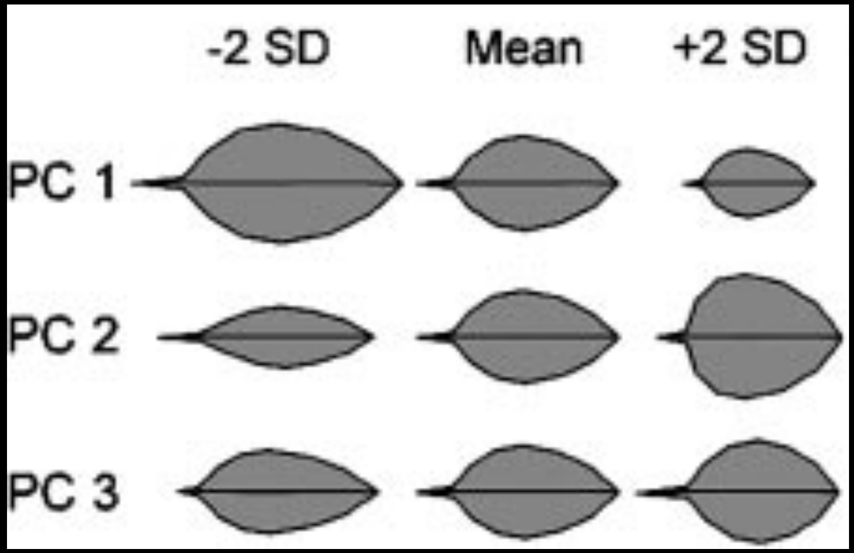
Klingenberg
J Evol Biol 2012



Discretised contour + PCA

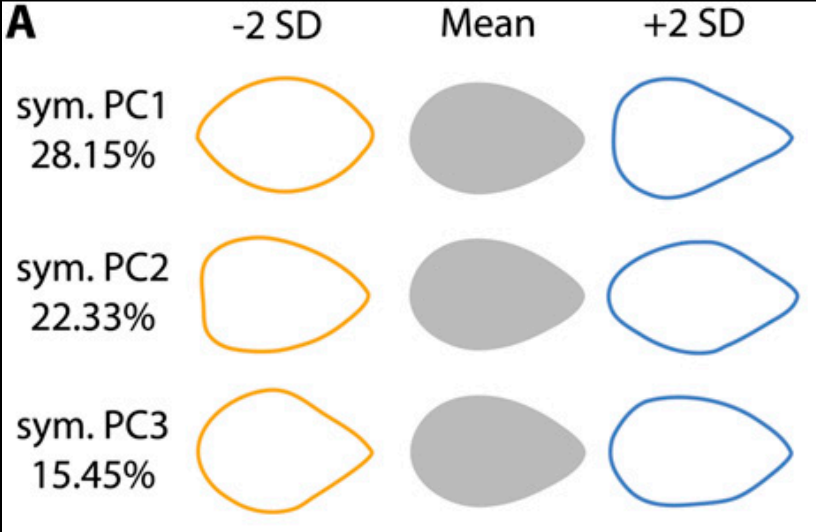
Langlade et al.
PNAS 2005





Fourier modes + PCA

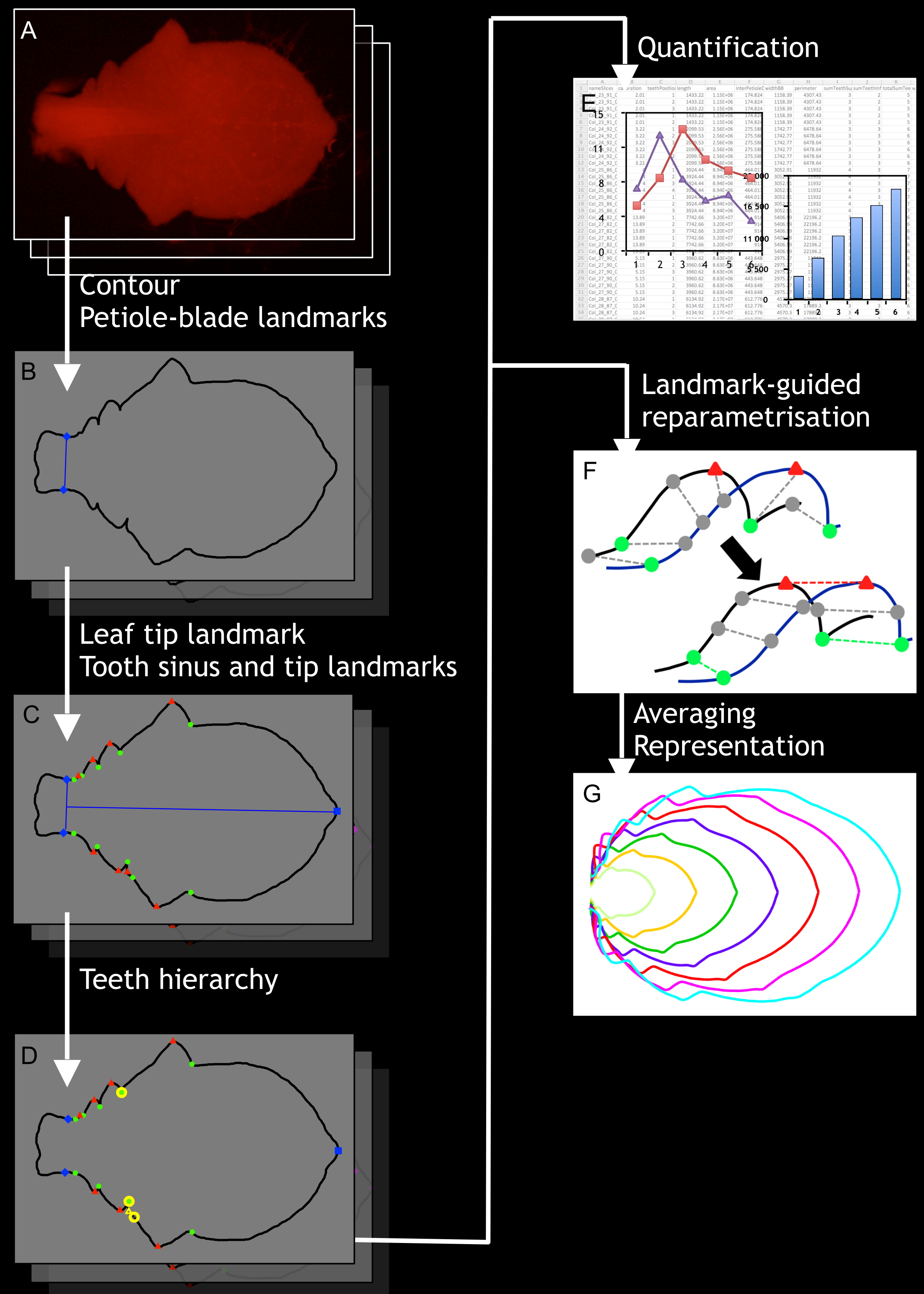
Chitwood et al.
Plant Physiol 2012



Little investigation of developmental trajectories

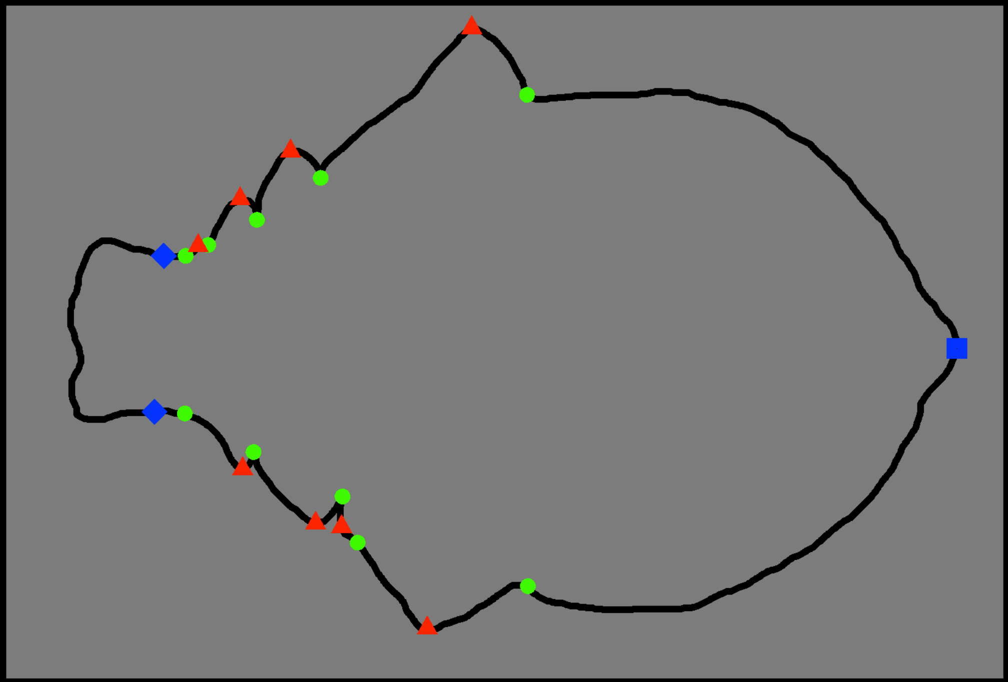
Combining landmarks and contours to analyse leaf morphogenesis

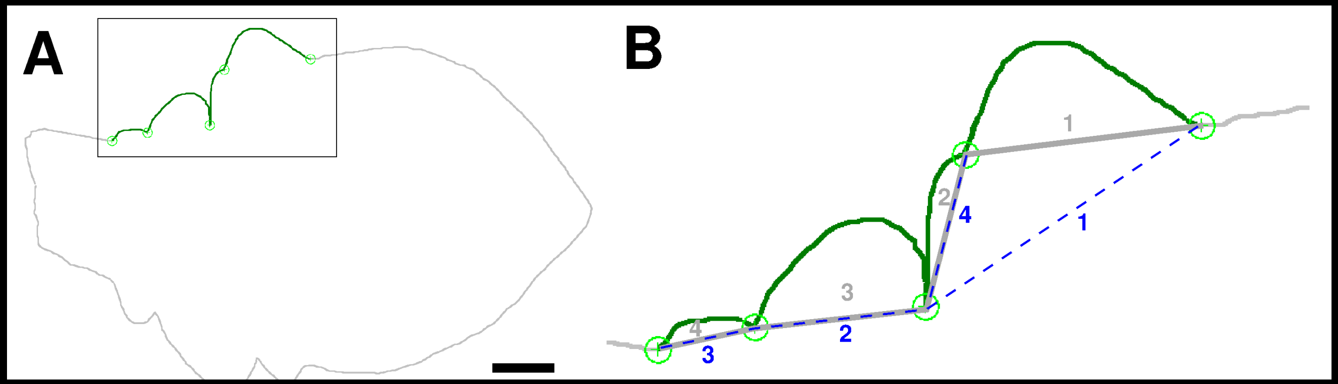
Collect a large number of samples (~300)



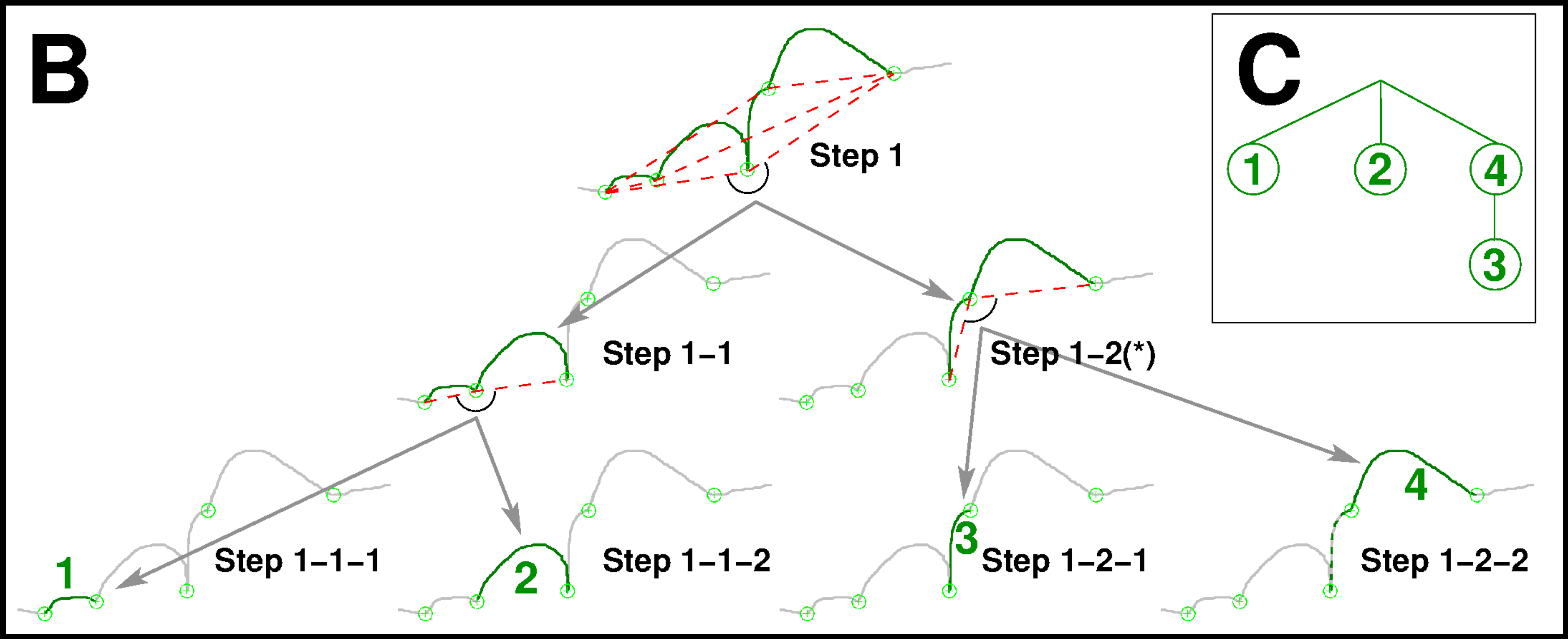
Identifying landmarks

- Basis, 2 points: expert
- Leaf tip: distance from basis
- Sinuses: curvature
- Tooth tips: curvature or symmetry

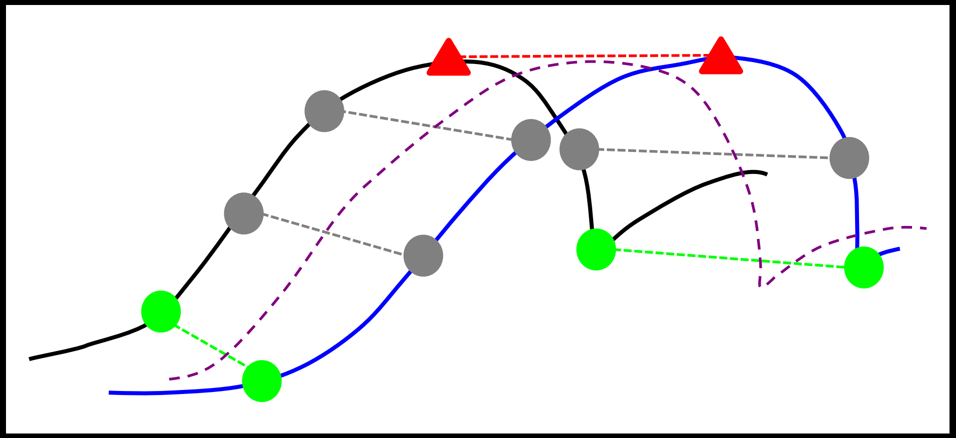




- Identifying primary sinuses: iterative tests based on angles (one parameter: limit angle)



Registration and reparametrisation



Contours $\mathbf{f}_i(s),\ i \in \{0,\ldots,n\},\ s \in [0, s_{i,\omega}]$

Landmarks $\{s_{i,\alpha}\},\ \alpha \in \{0,\ldots,\omega\}$ with $s_{i,0} = 0$

- Co-reparametrisation:

$\varphi_i : [0, s_{i,\omega}] \to [0,1]$ piecewise affine, such that $\varphi_i(s_{i,\alpha}) = \dfrac{\langle s_{i,\alpha}\rangle_i}{\langle s_{i,\omega}\rangle_i}$

Co-parametrised contours: $g_i = f_i \circ \varphi_i$

- Co-registration

Minimise the distance between contours modulo rotation-translation (R_i) and scaling (ρ_i) :

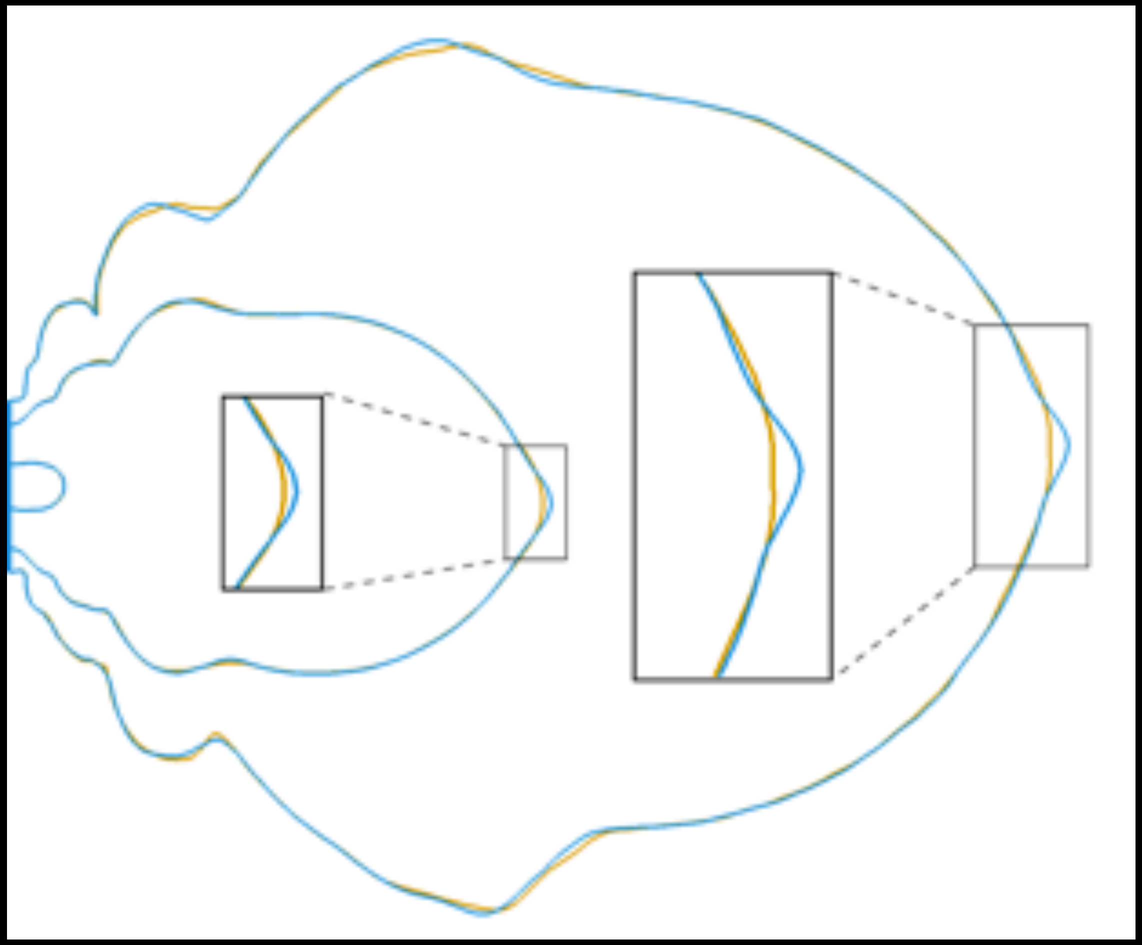
$$\mathcal{E}\left(\{\rho_i, \mathrm{R}_i\}\right) = \sum_{i>j} \int_0^1 \mathrm{d}\tilde{s}\,\left(\rho_i \mathrm{R}_i \mathbf{g}_i(\tilde{s}) - \rho_j \mathrm{R}_j \mathbf{g}_j(\tilde{s})\right)^2$$

solved through iterated Procustes transformations to an averaged contour

- Outcome:

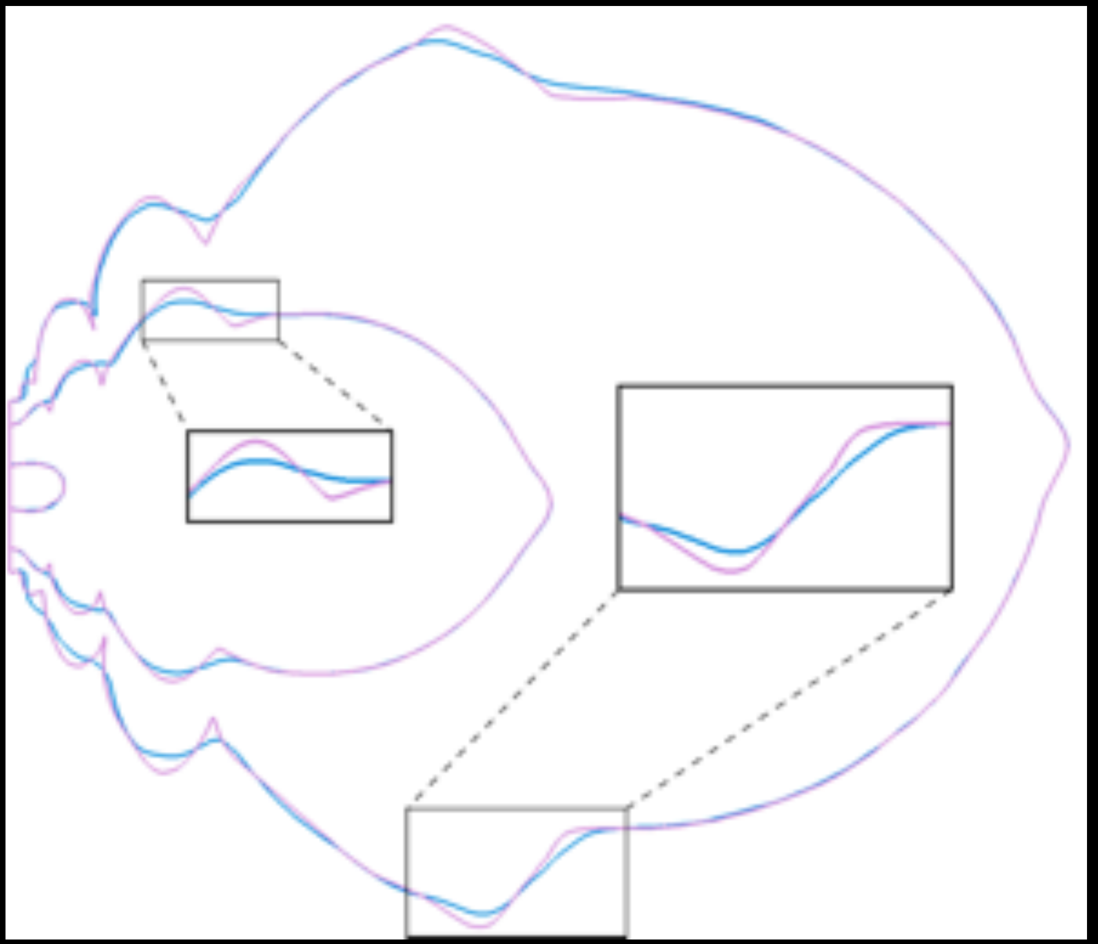
Registered contours/landmarks $\mathrm{R}_i \mathbf{f}_i(s)$, to keep size information

Contours+ landmarks



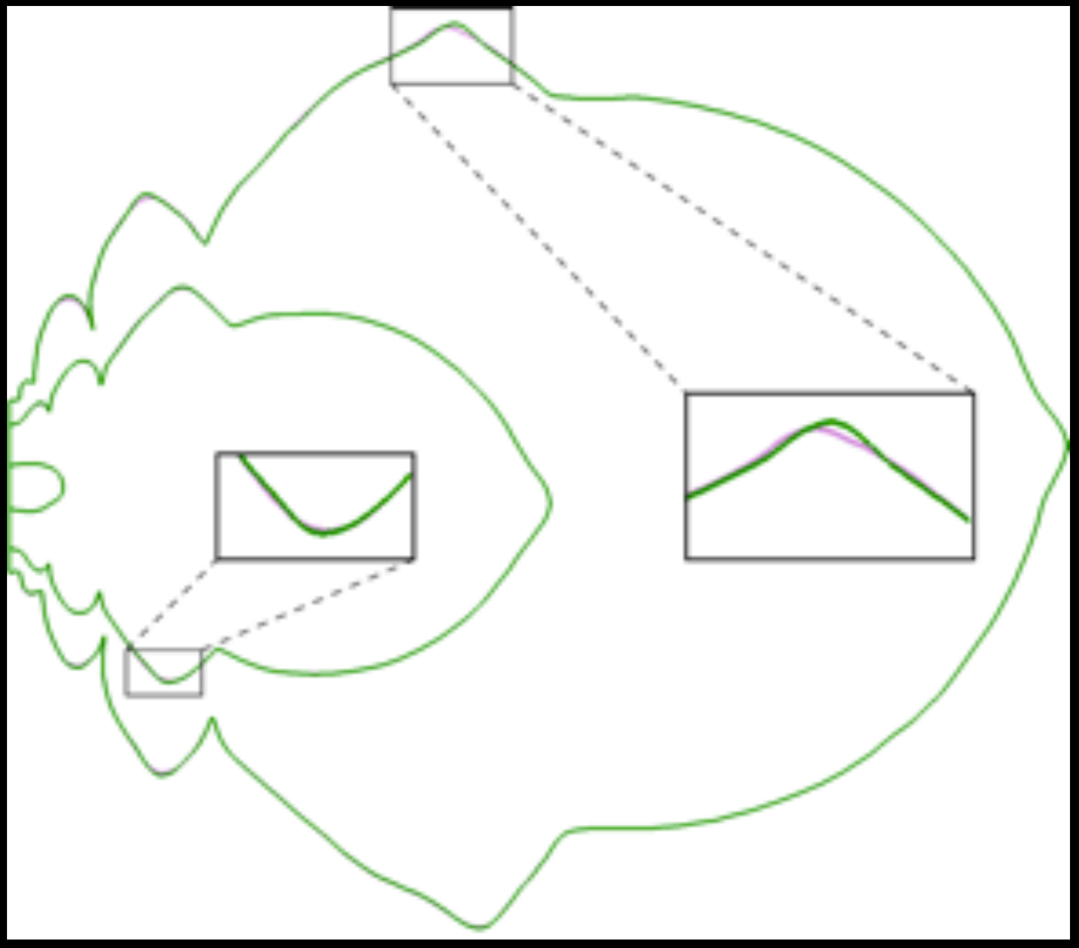
Leaf tip vs. no landmark

Adding sinuses

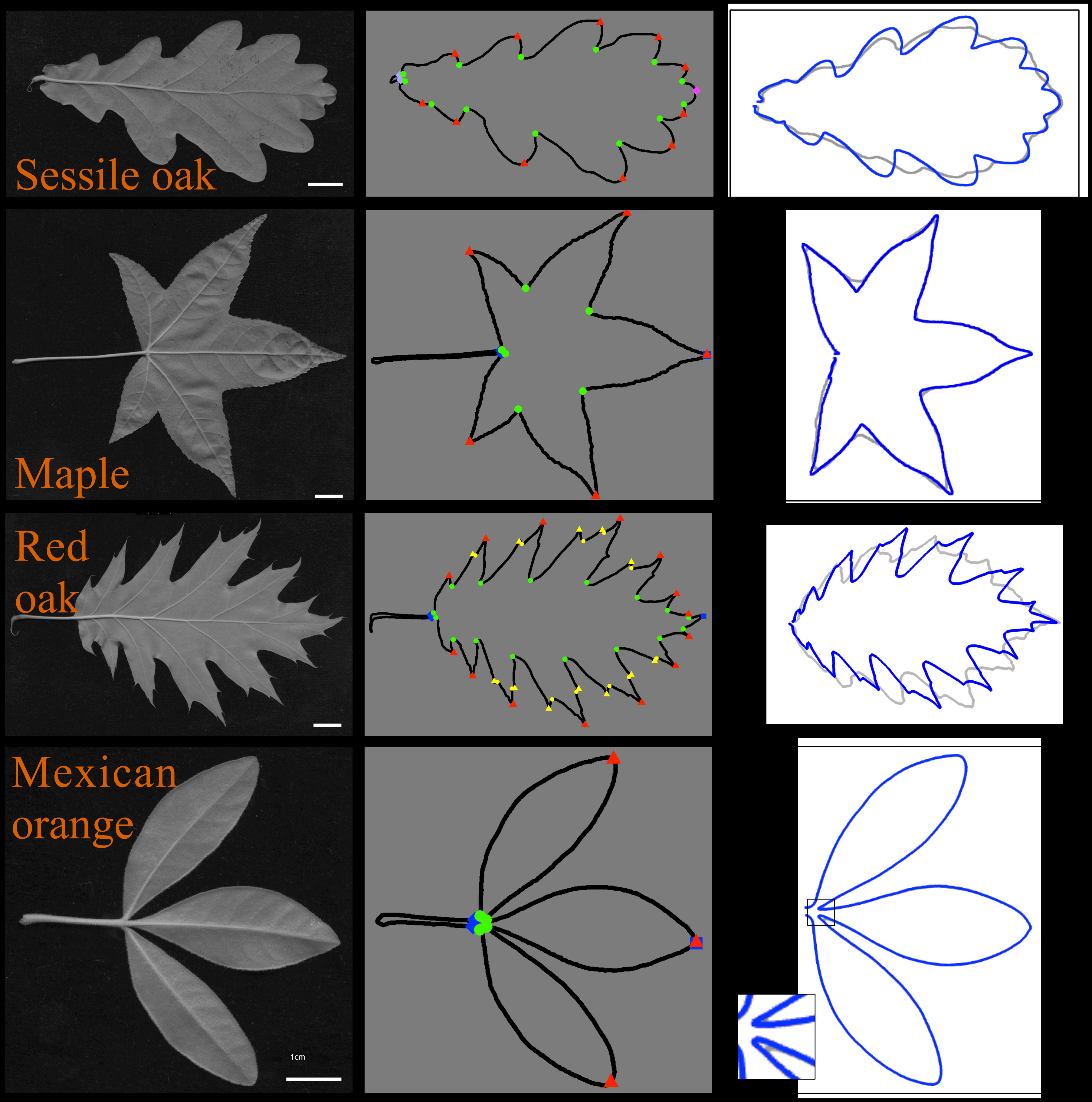


Arabidopsis

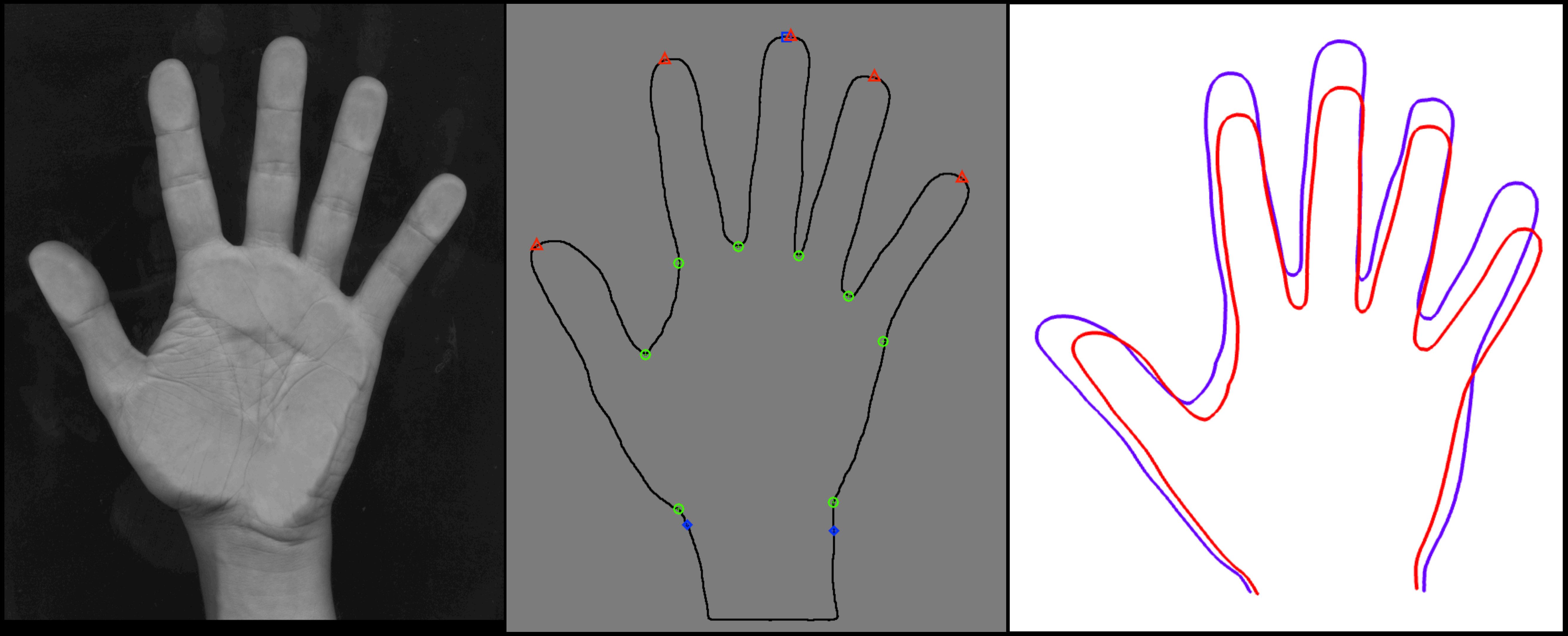
Adding teeth tips



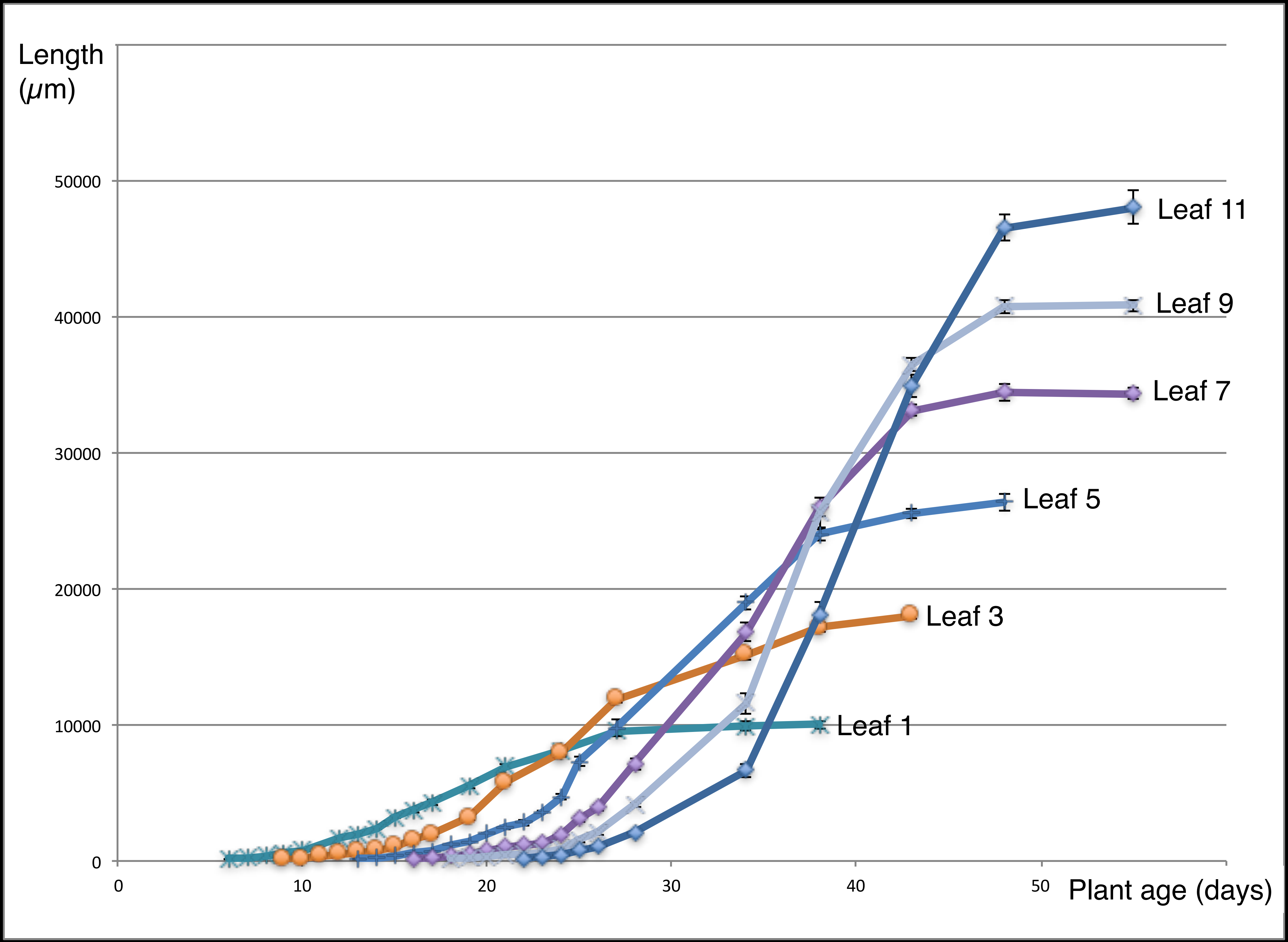
Contours+ landmarks



Contours+ landmarks



Developmental trajectories

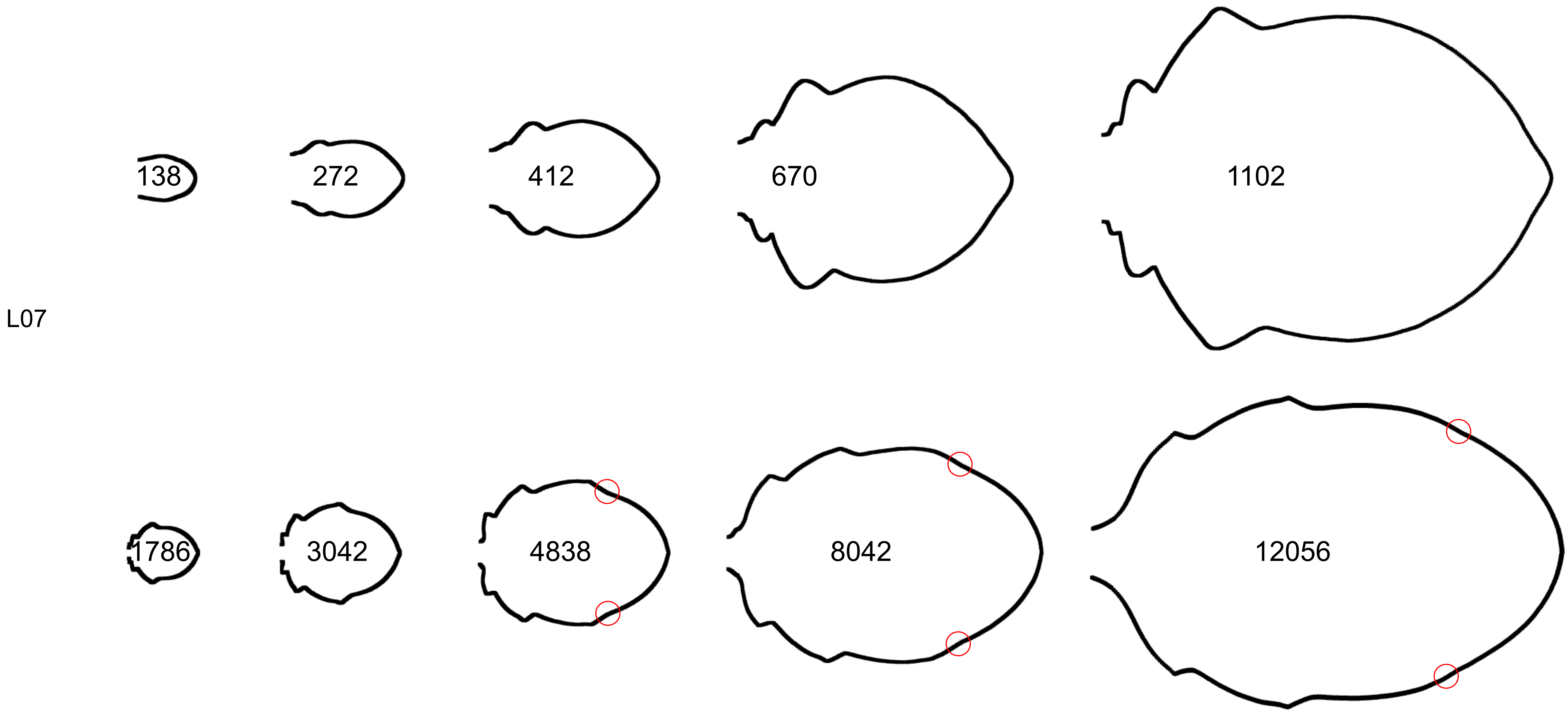


Developmental trajectories

Sliding average (Gaussian kernel)

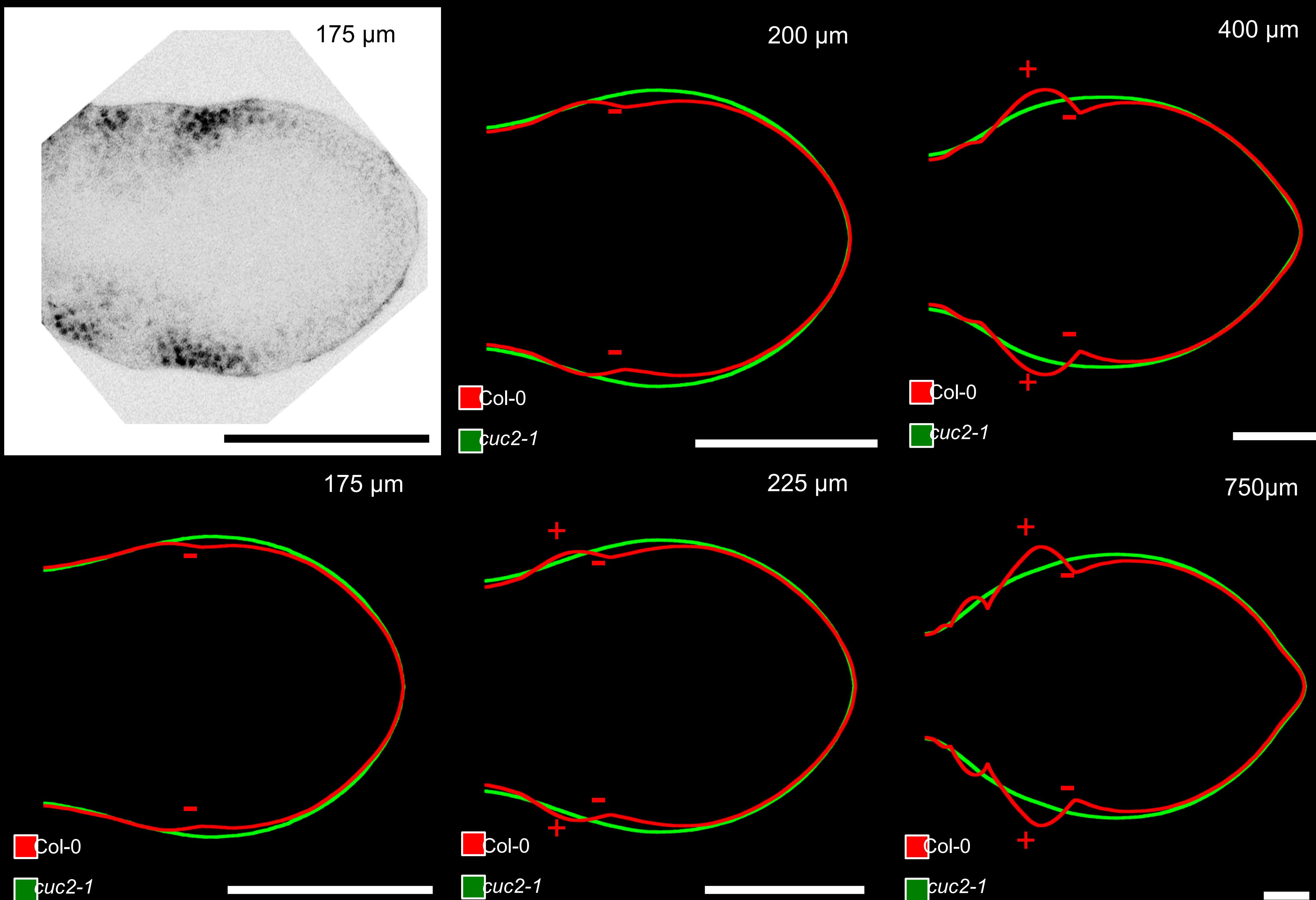
\+ *quantification of leaf shape / teeth*

Developmental trajectories

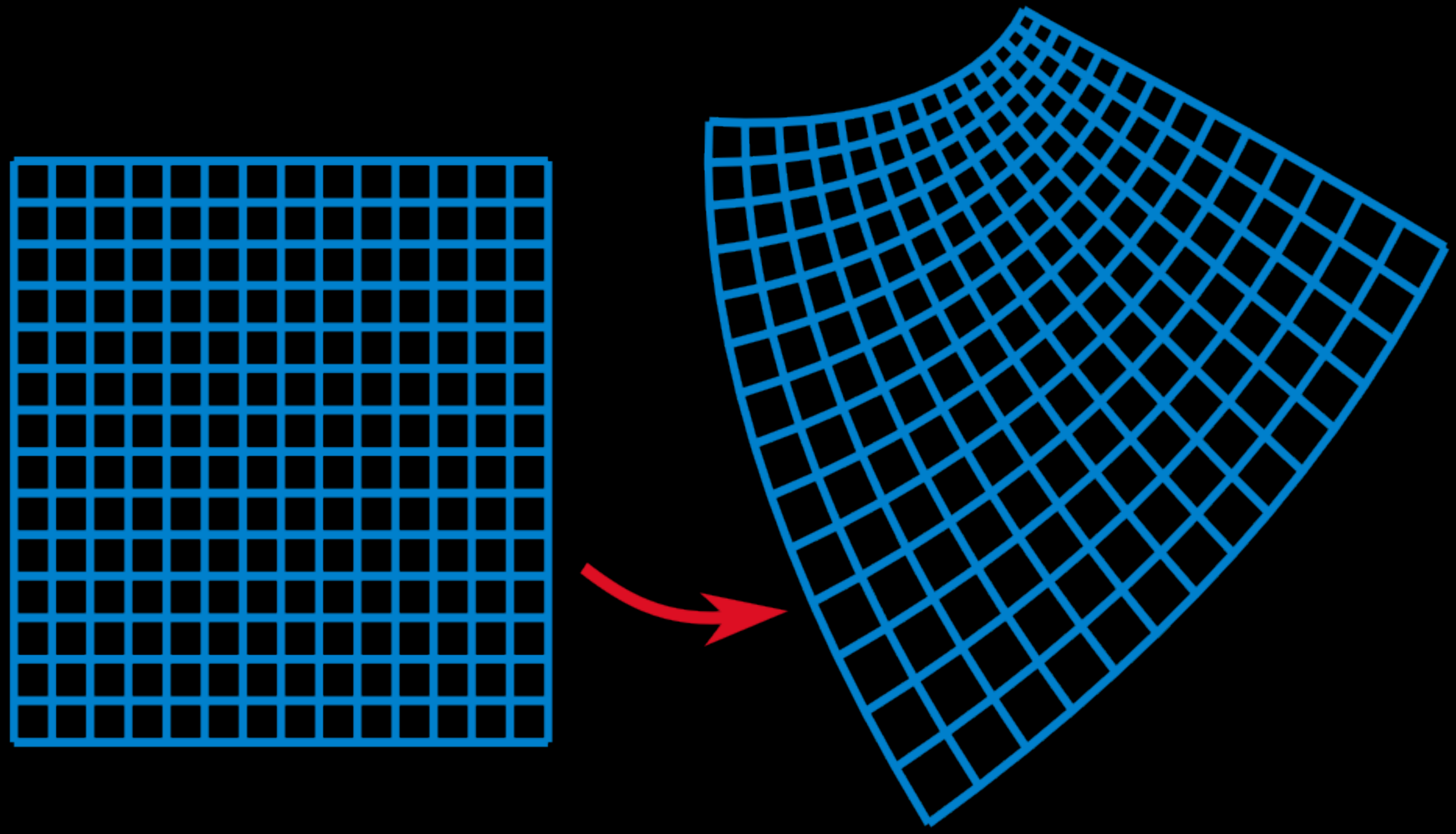


+ quantification of leaf shape / teeth

Comparison wild-type / mutant



From leaf contours to leaf blade

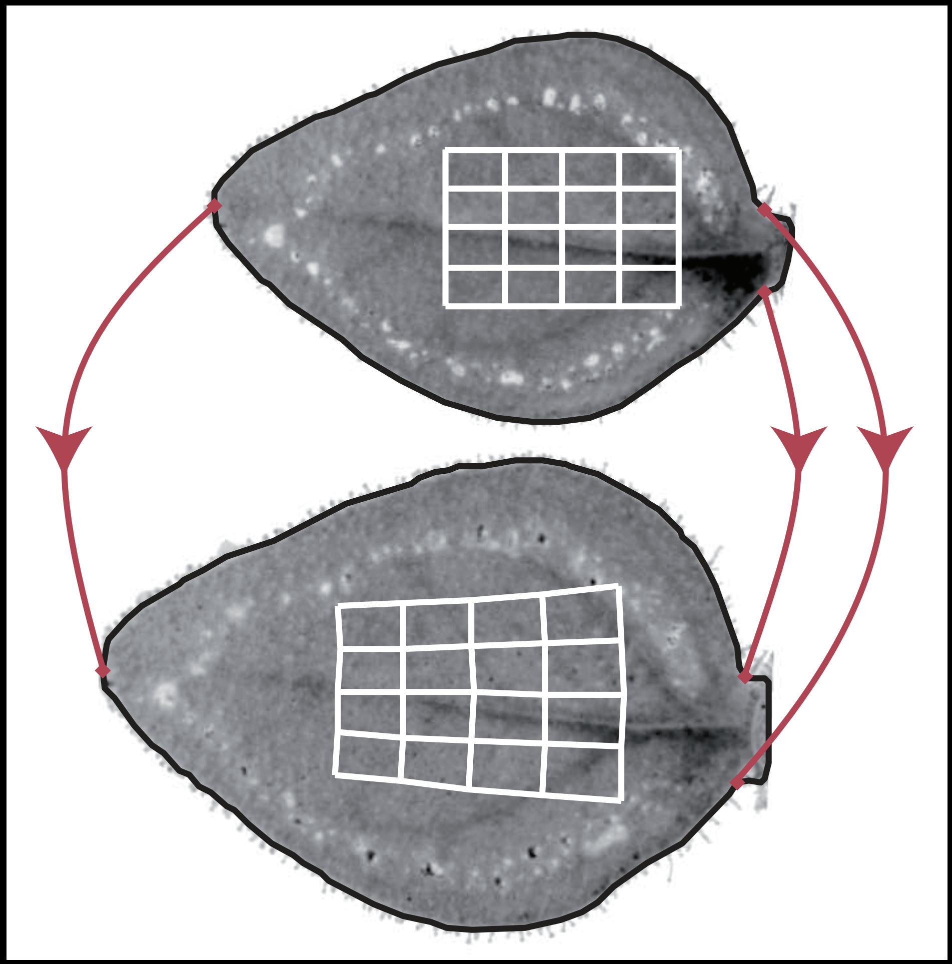


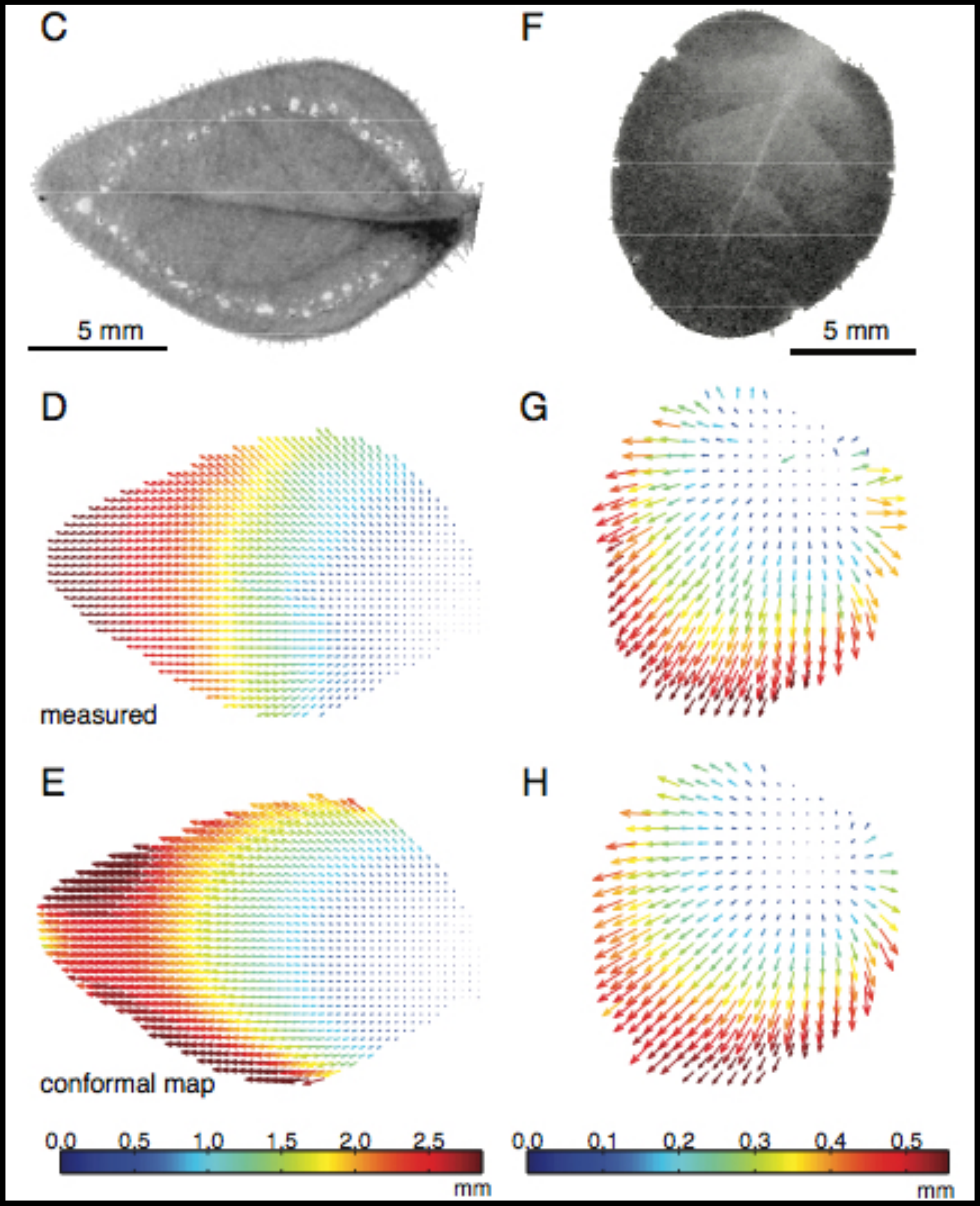
Conformal maps: transformations that keep the same angles
In 2D, the contours define all the transformation!

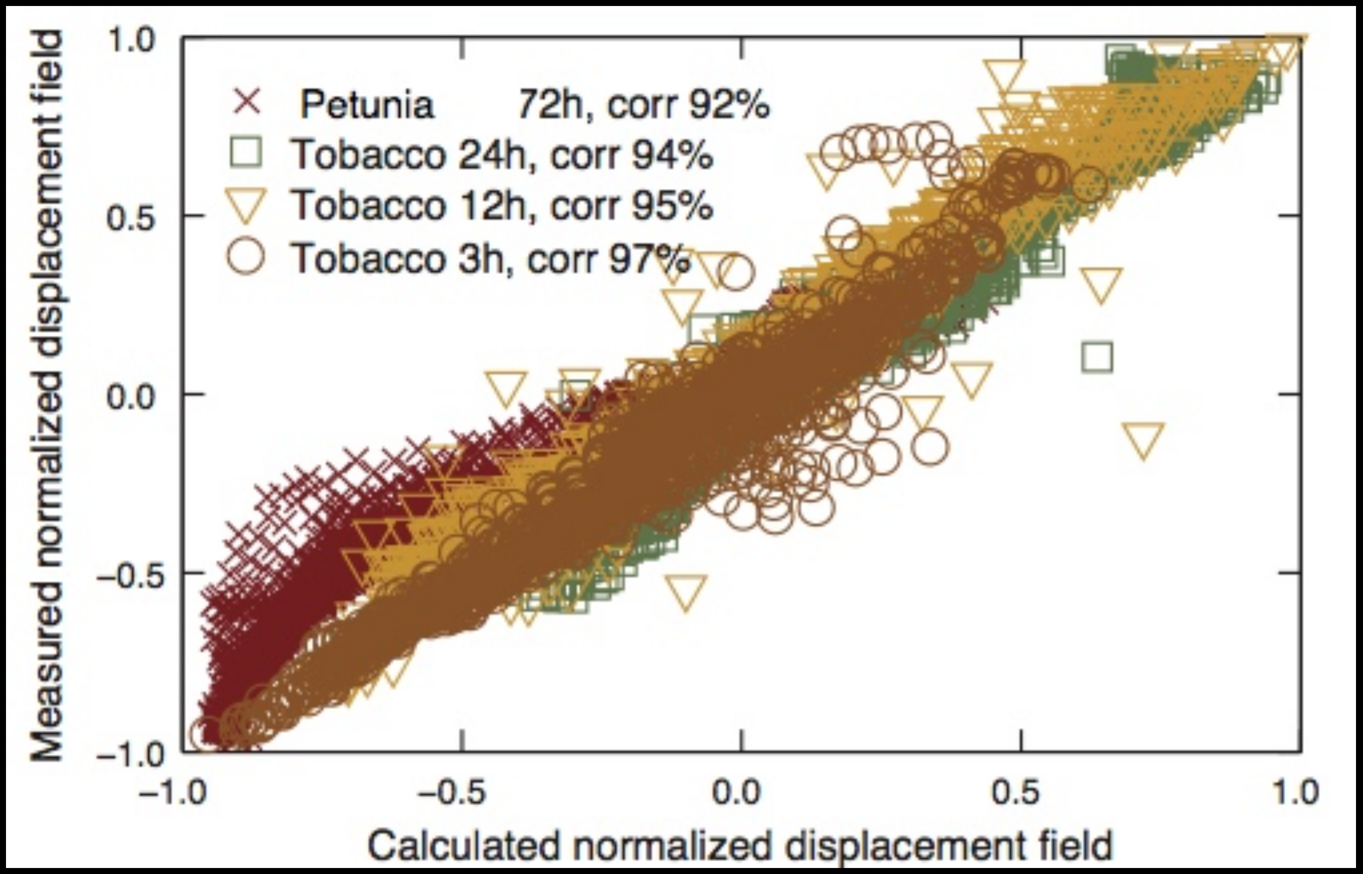
Applying conformal maps to leaves

Approach:

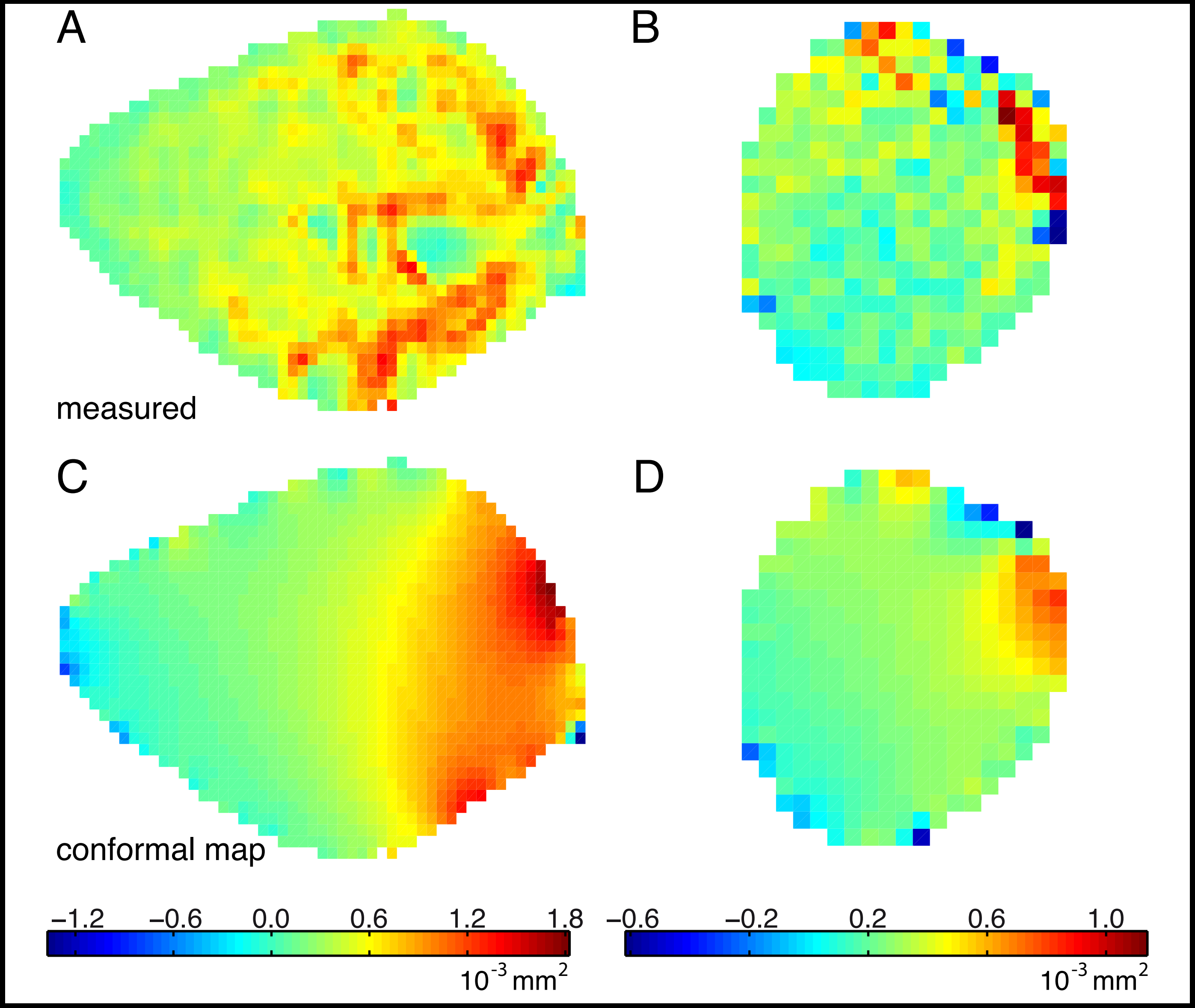
- Observe growing leaves
- Quantify contours and predict growth assuming conformal map (Schwartz-Christoffle)
- Quantify growth in the lamina
- Compare ‘predicted’ and measured growth

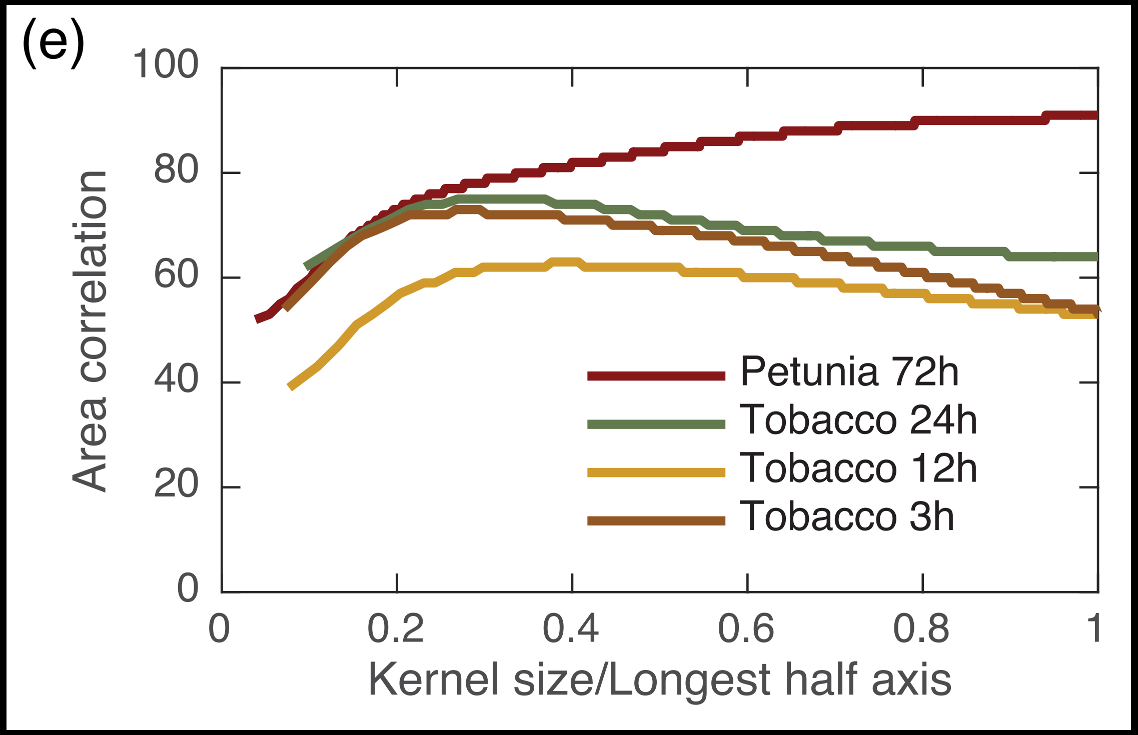






Good ‘prediction’ of displacements

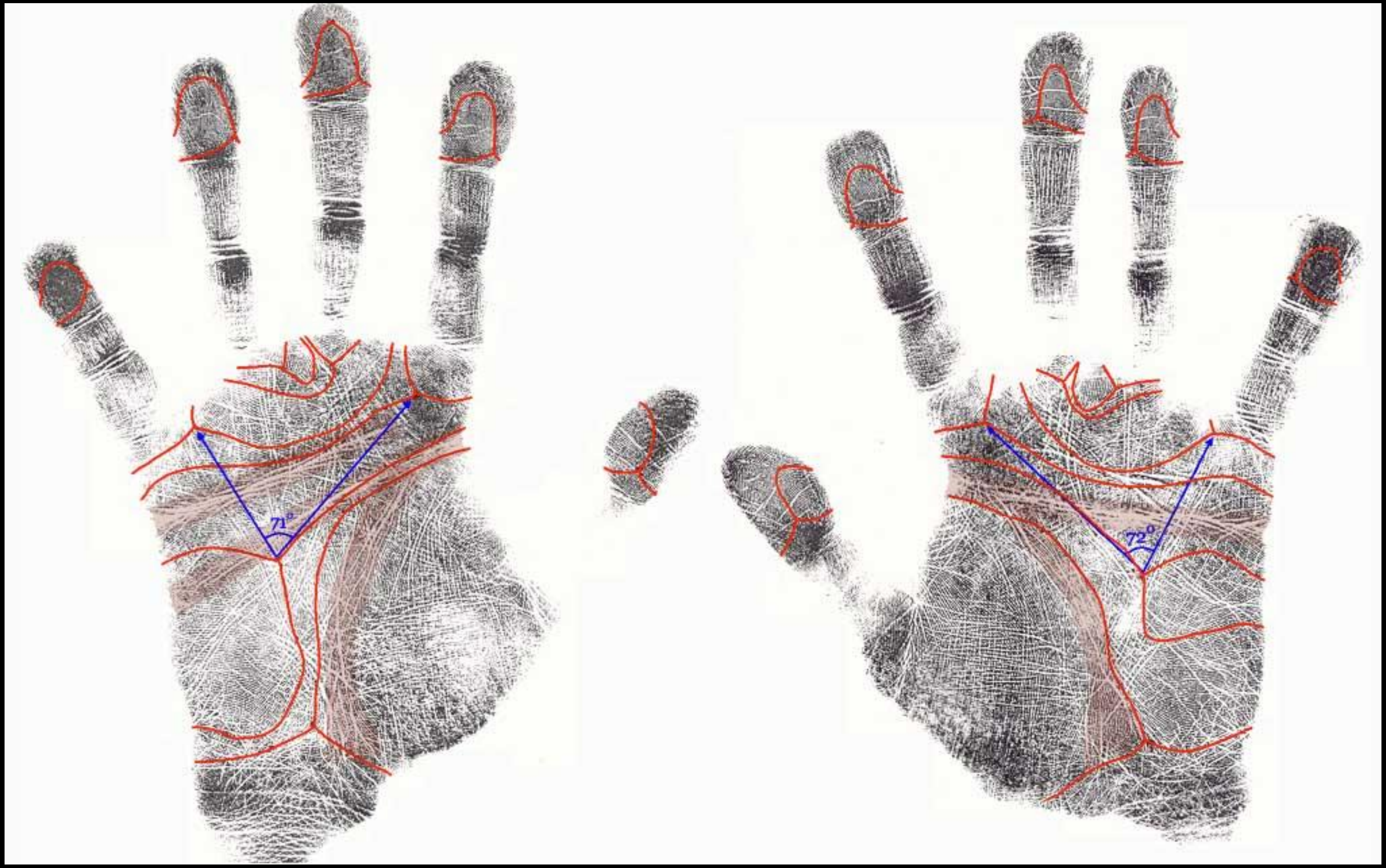




Prediction of smoothed growth distribution

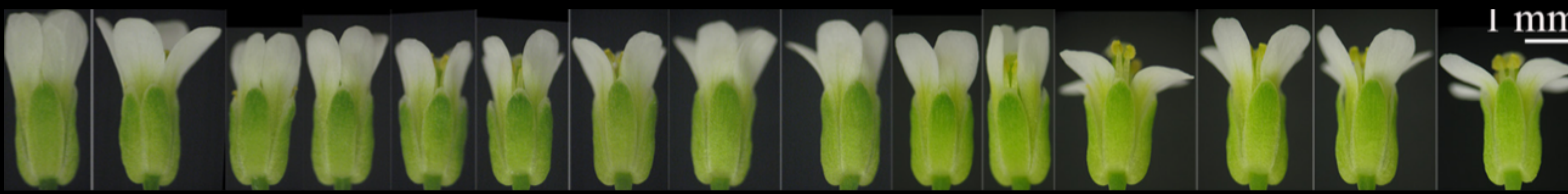
Robustness of form

Shape and size are robust in spite of internal and external perturbations



Bilateral symmetry

Shape and size are robust in spite of internal and external perturbations



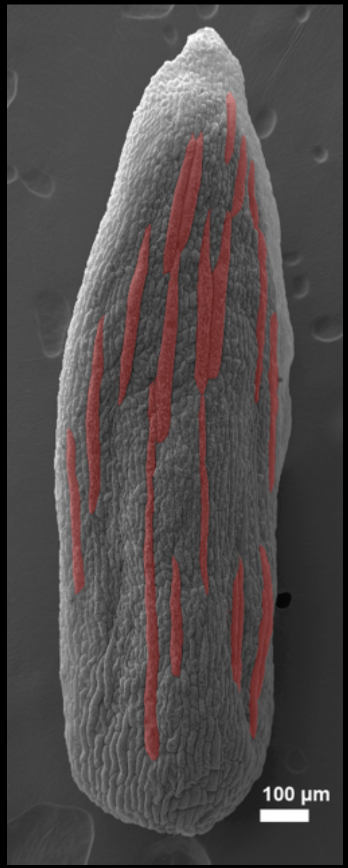
Flower size in *Arabidopsis* varies by about 5%

The sepal as a model system

abaxial sepal

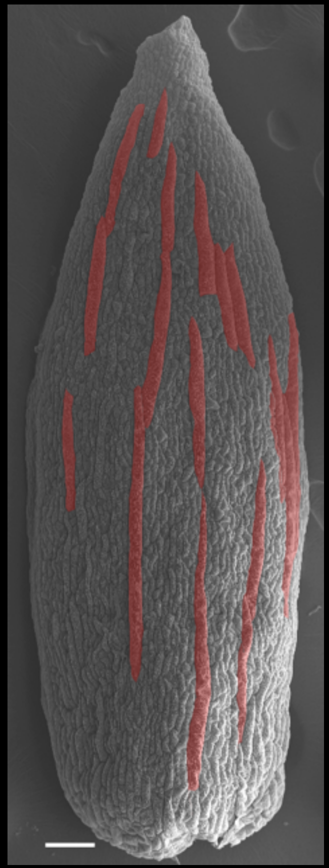
tip

tip



tip

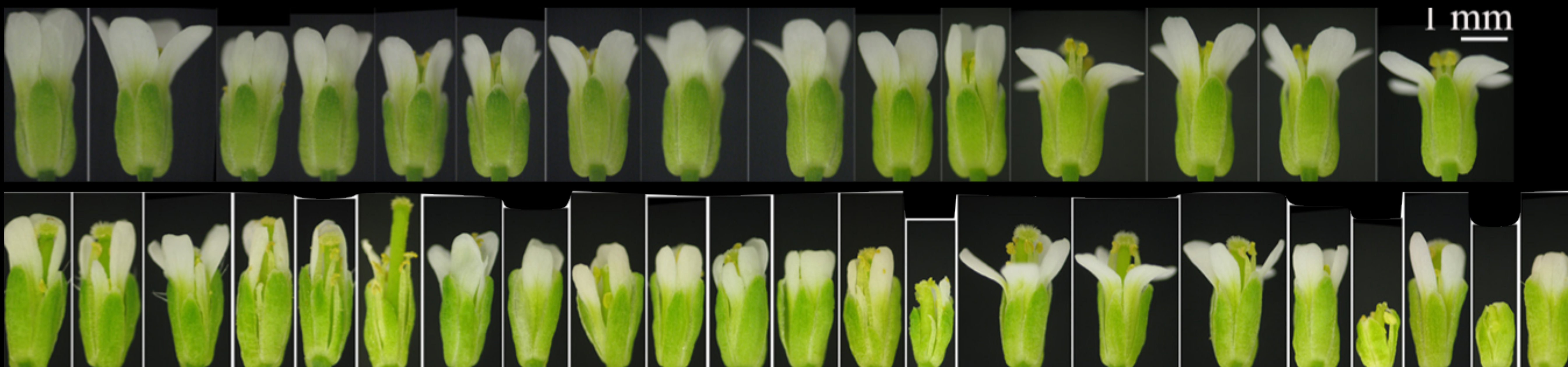
tip



Genetic screen for variability:

Individual plants in which sepals are variable in size

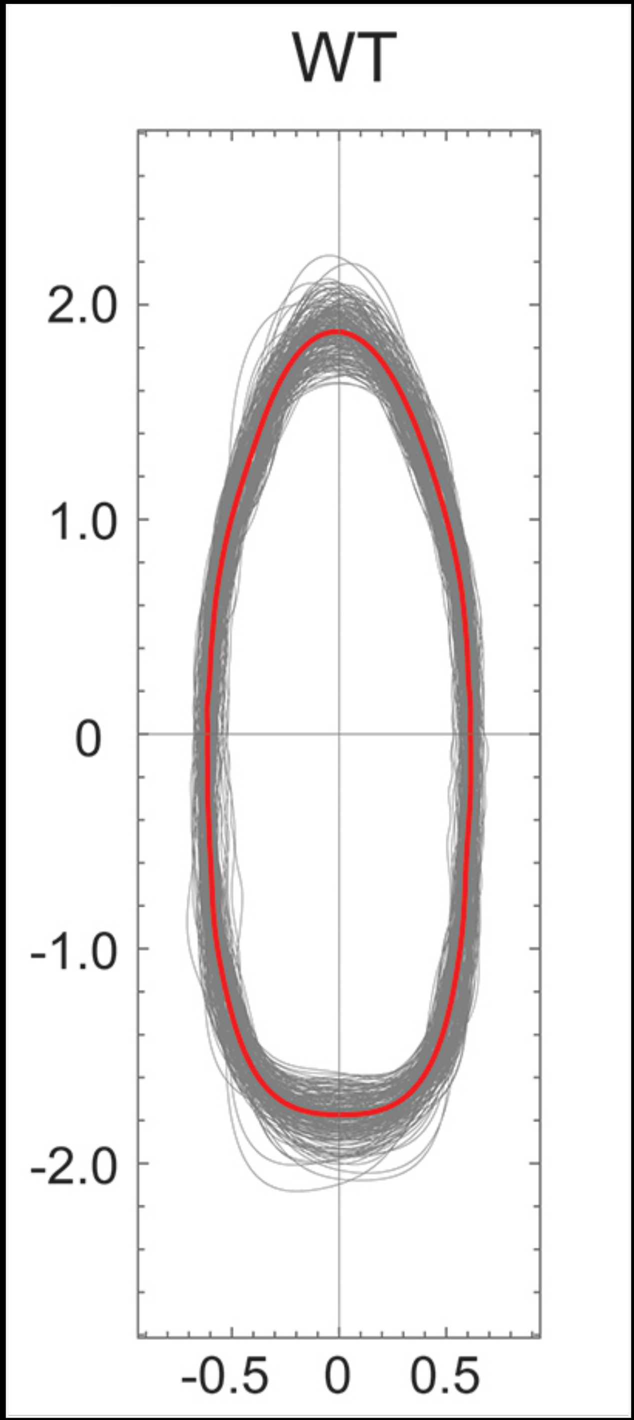
flowers from a single WT plant



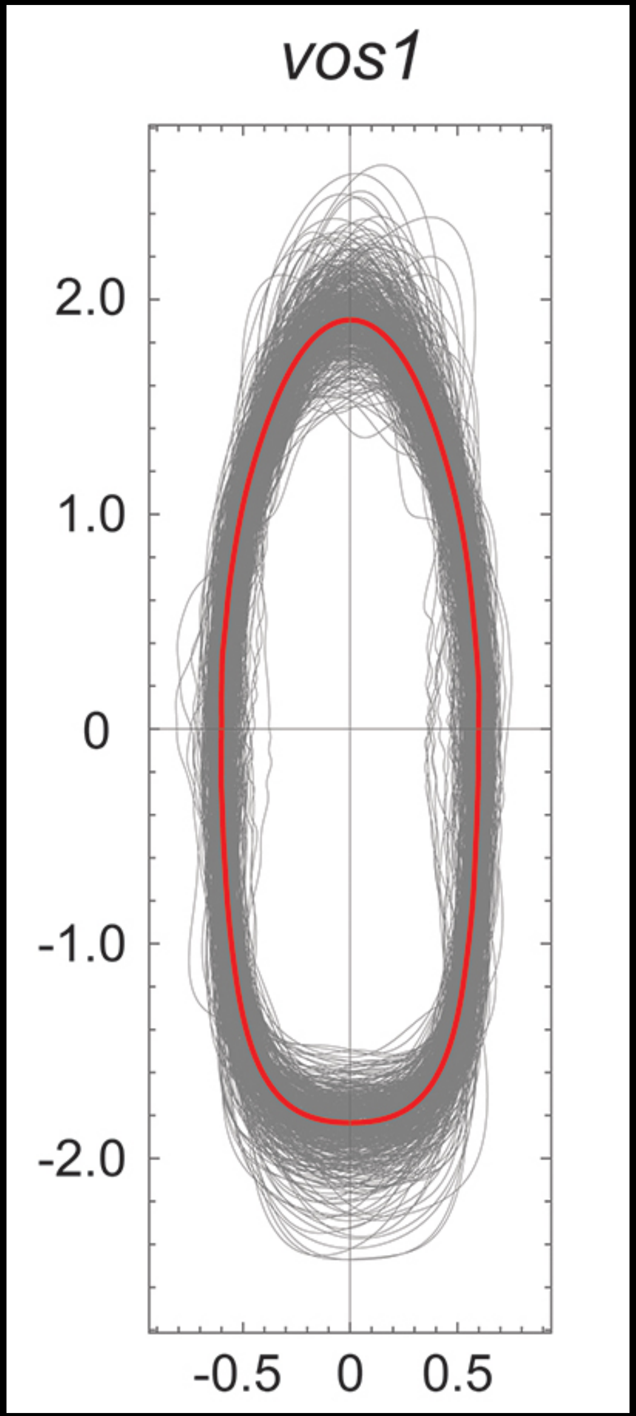
flowers from the single *vos1* plant

Genetic screen for variability:
Individual plants in which sepals are variable in size

WT sepals



vos1 mutant sepals



Towards a 3D analysis

- Image in 3D (confocal microscopy)
- Binary images (supports) of many sepals
- Distance = overlap between supports
- Co-registration
- Probabilistic sepal

Summary

- Combining landmarks and contours to analyse leaf shape during morphogenesis

- Contours give all information for 2D isotropically growing systems

- Work in progress: variability of contours, 3D shape

Biot et al. Development 2016
Alim et al. Phys. Biol. 2016
Hong et al. Dev Cell 2016
Mollier et al. in progress