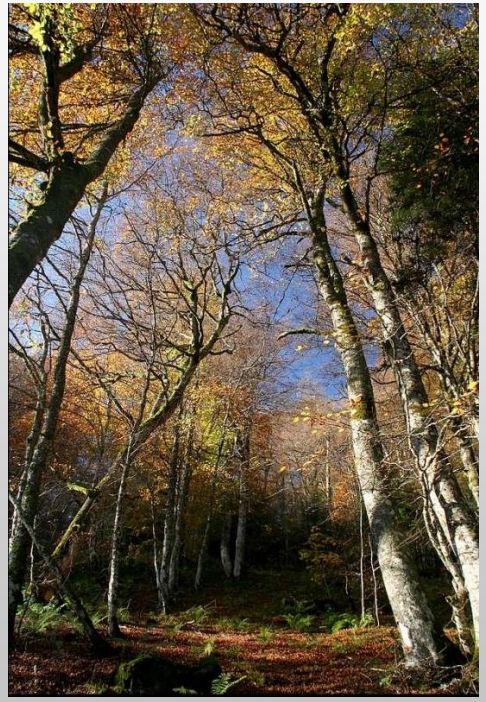
Linking genes to plant global morphogenesis beyond the SAM

: the role of tropisms

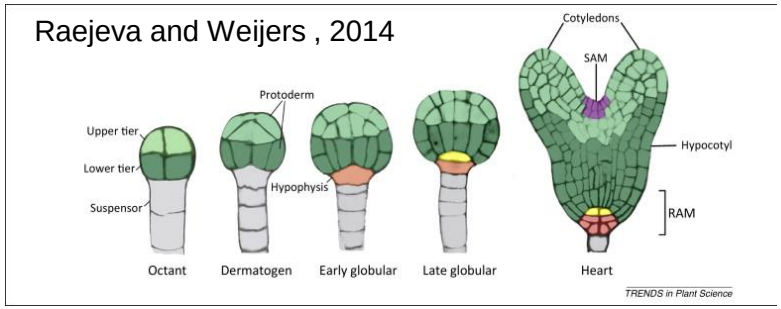


PIAF
INRAE
French National Research Institute for Agriculture, Food and Environment
UCA
Université Clermont Auvergne

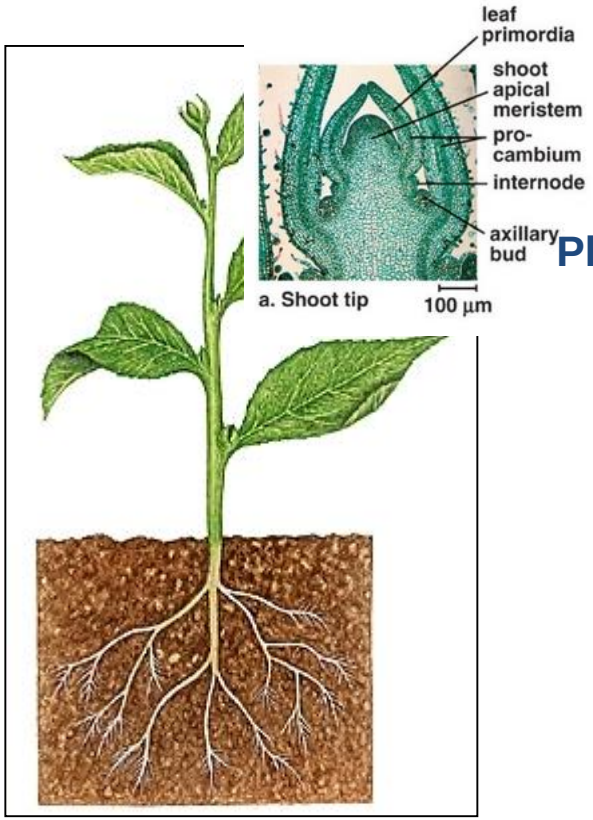
Bruno Moulia

Research Director Inrae
MECA Group
Plant MechanoBiology

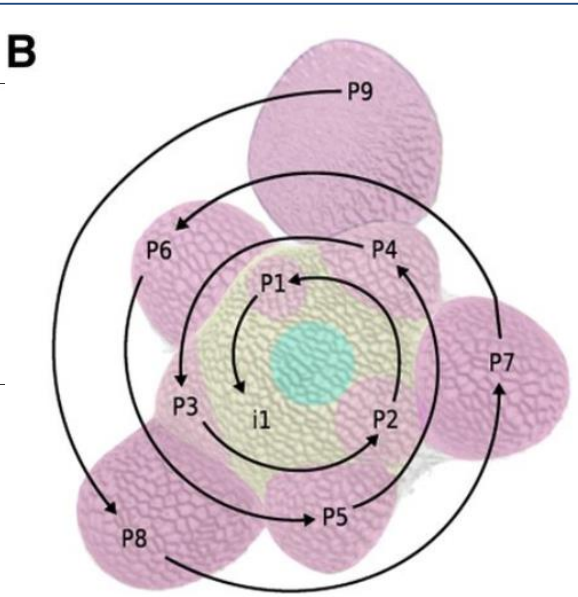
morphogenesis :SAM but also …. beyond !

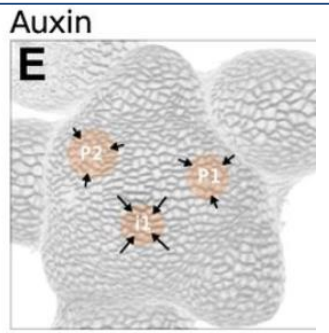


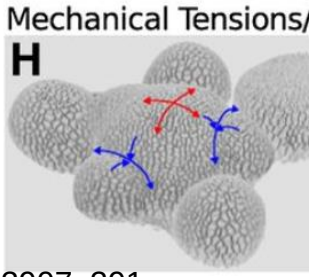
Embryogenesis



Post-embryotic morphogenesis !







Murray et al 2012 The Plant Cell, 24: 3907–391

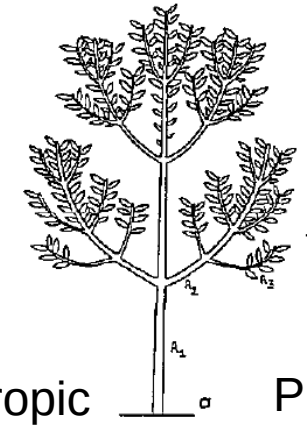
Phyllotaxis at the Shoot Apical Meristem: a dynamic cristal

A lot of post SAM morphogenesis !

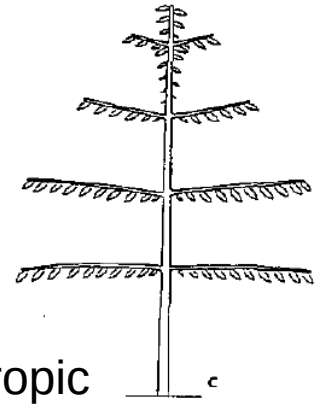
1- botanical architecture and tropism

Characterizing the axes : phyllotaxis, sexuality, secondary growth and… tropism

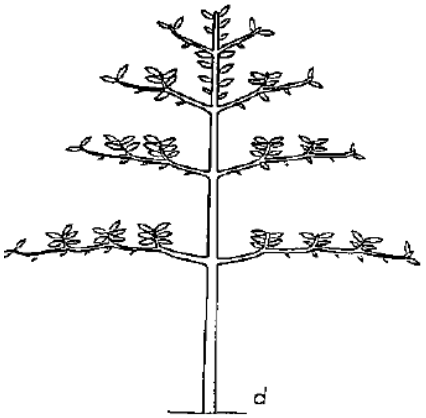
F Hallé

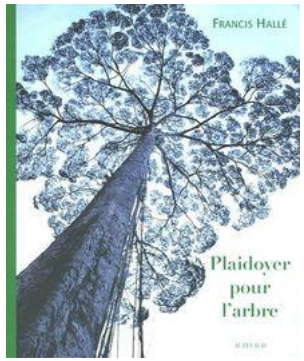


Ortho-tropic



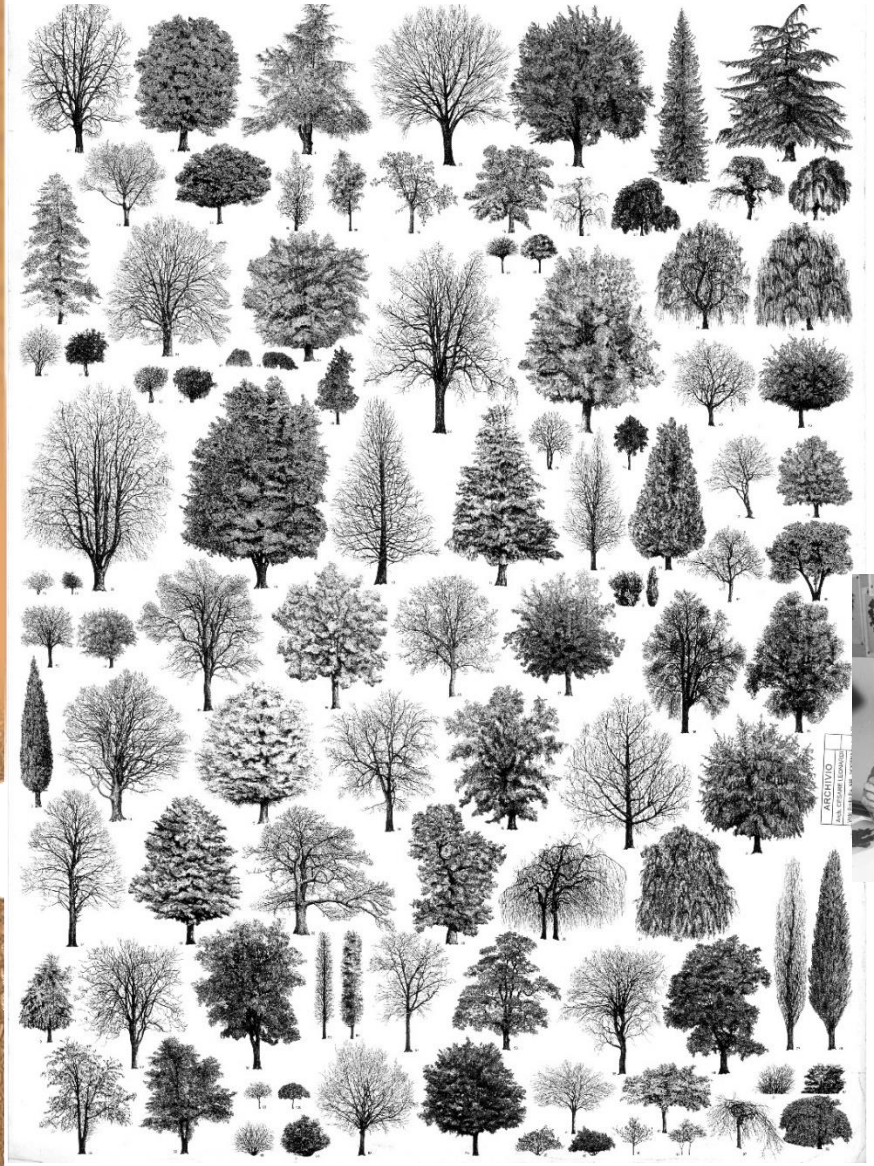
Plagio-tropic

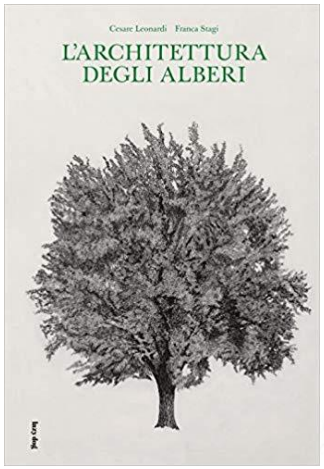




↳ **What controls the shaping and orientation of each axis ?**

2- crown shaping (isolated free standing plants)





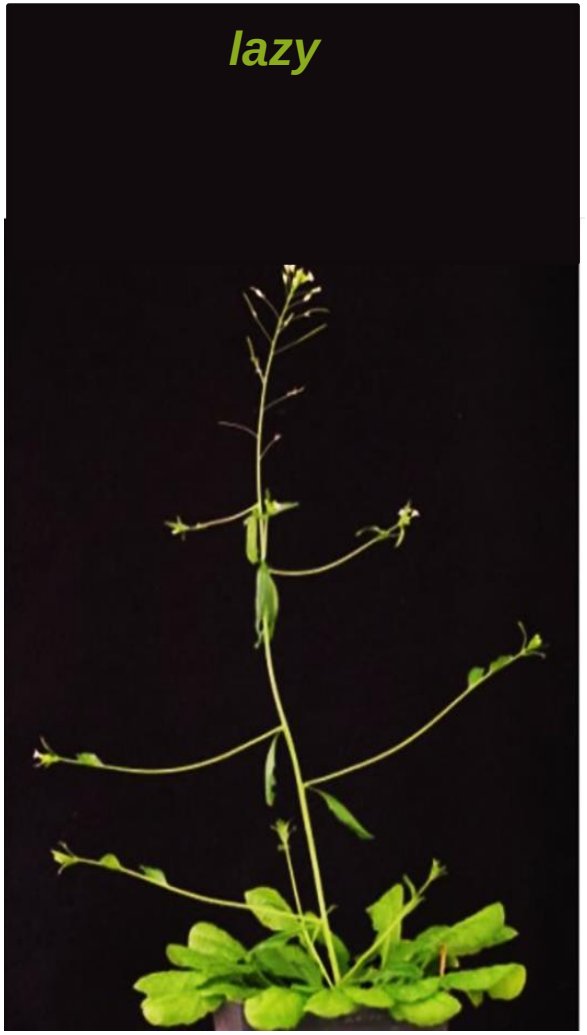
Landscsape architects
Cesare Leonardi , Franca Stagi

↳ **What controls the shaping of the crown edge, at various developmental stages ?**

3- Genetic control

major genes:

TAC1 ⟷ *LAZY*

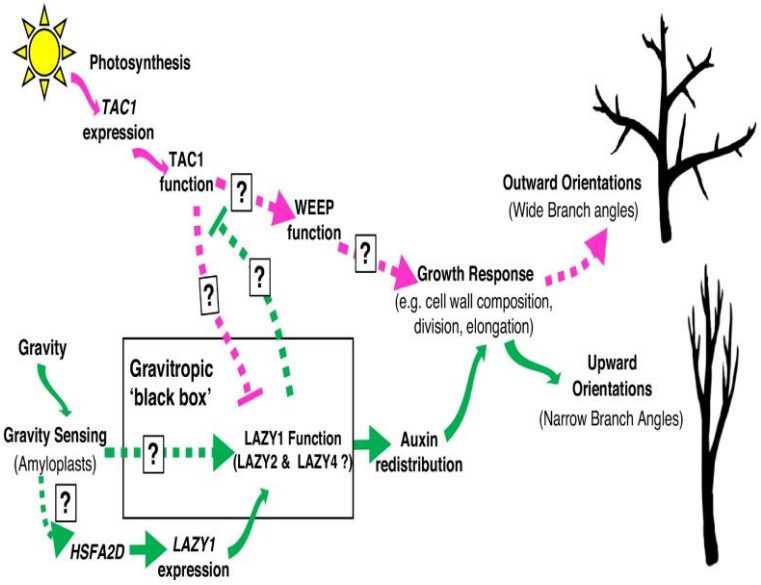


3- Genetic control

2 major genes:

TAC1 ⇄ ***LAZY***

	Arabidopsis	*Poplar*	*Plum*	*Peach*
TAC1				
tac1				



How these genes can control axis and crown shaping ?

the shaping of plant axes and crowns

❶ What controls the shaping and orientation of each axis ?

❷ What controls the shaping of the crown edge (at various developmental stages) ?

❸ How can we account for both the genetic control and the environmental plasticity of plant shaping ?

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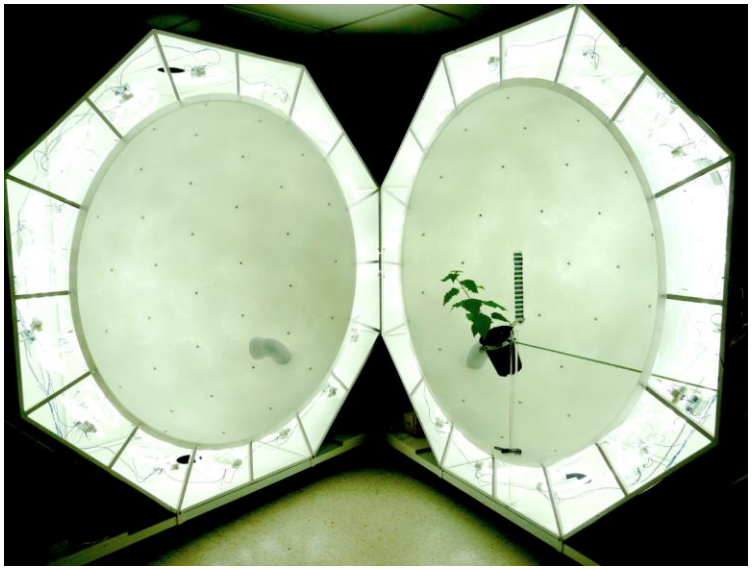
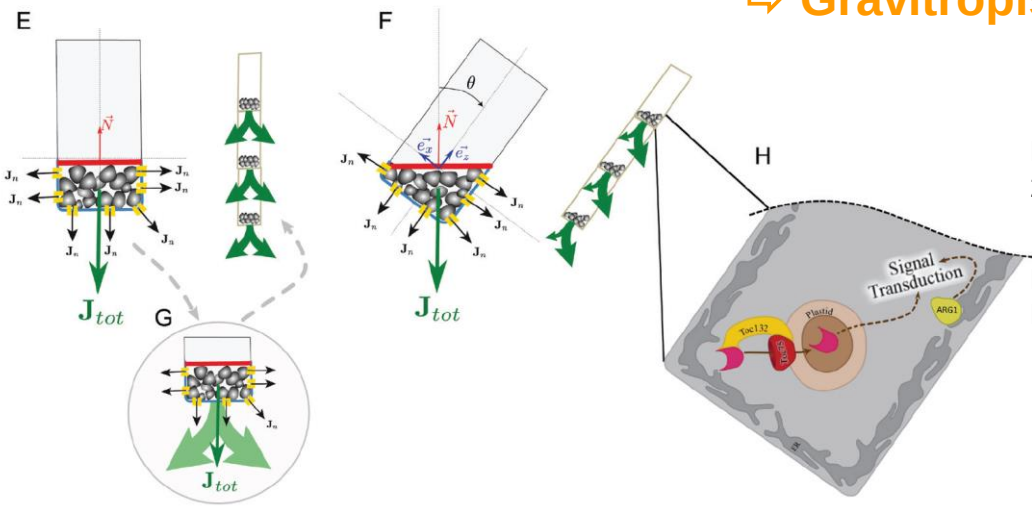
What controls the shaping and orientation of each axis ?

More than light



Coutand *et al* and Moulia 2019 Plos One

Gravity cue: position sensing (LAZY protein)

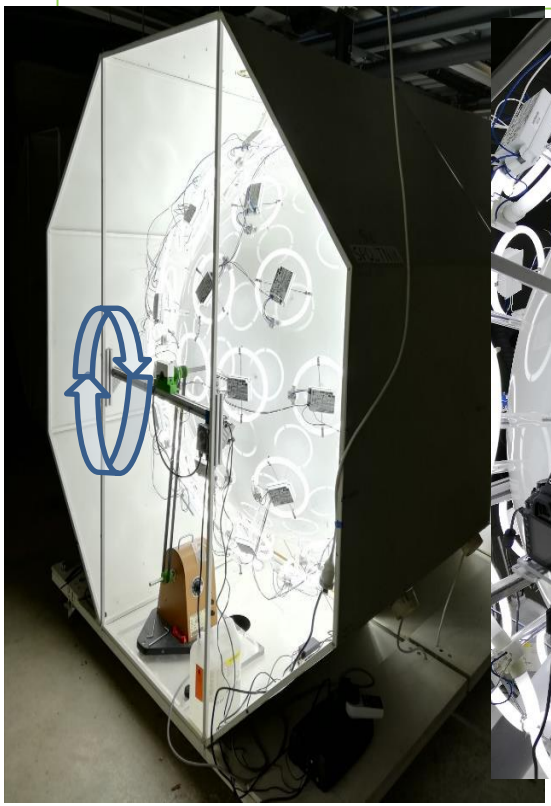


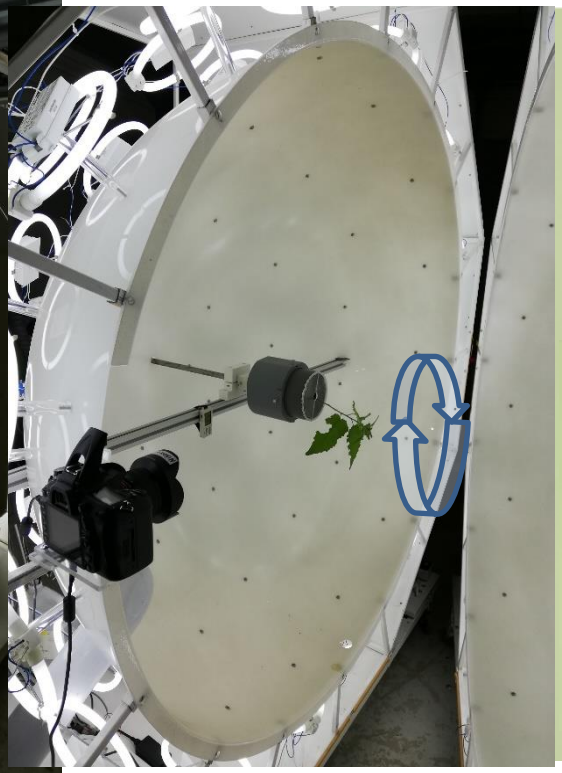
⇨ **Gravitropism**

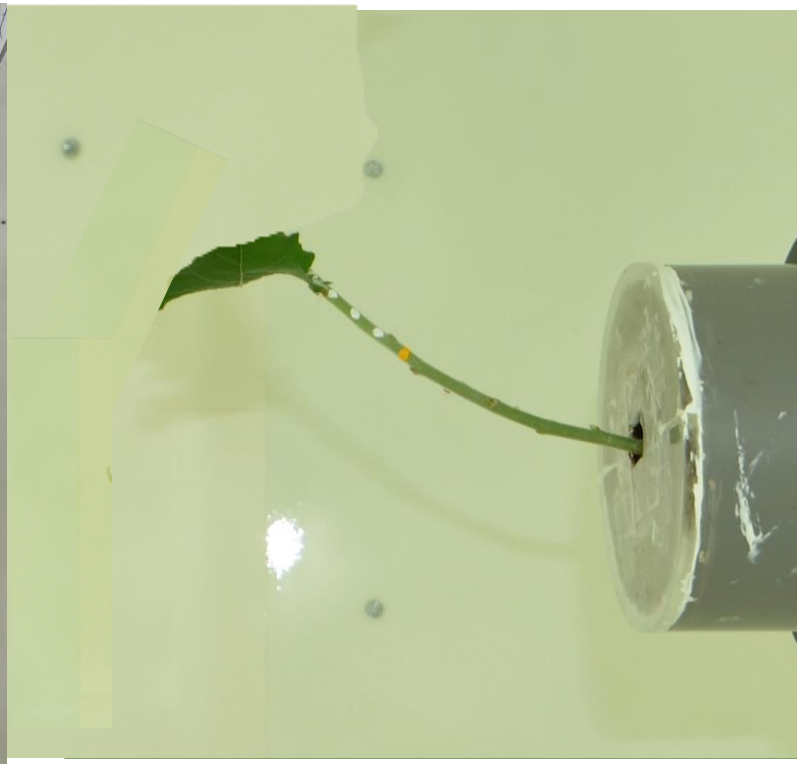
Pouliquen *et al* and Moulia 2017 Physical Biology

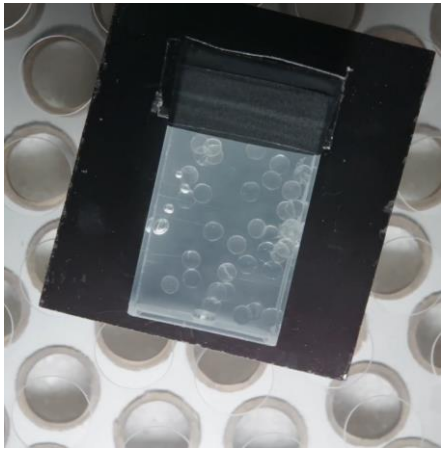
Bérut *et al* and Forterre 2018 PNAS

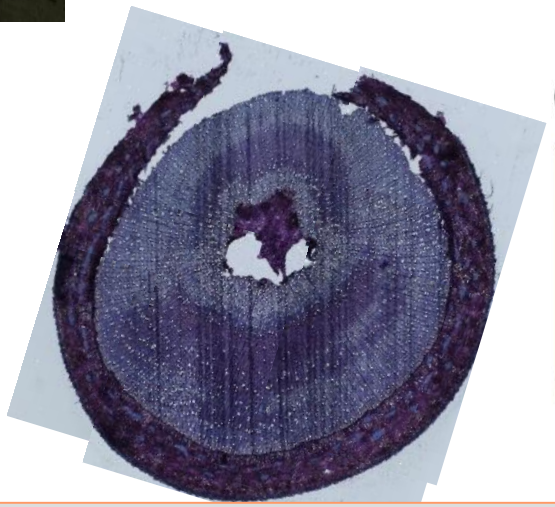
Proprioceptive cue: woody stem

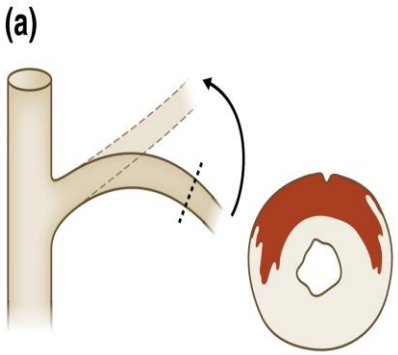


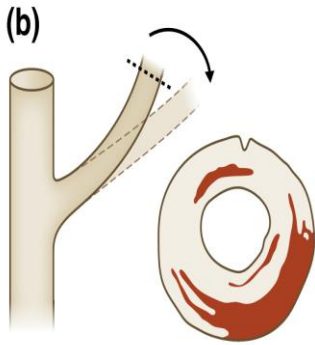








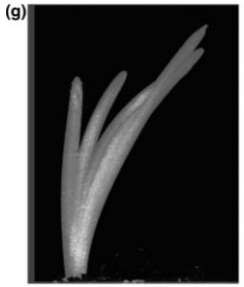


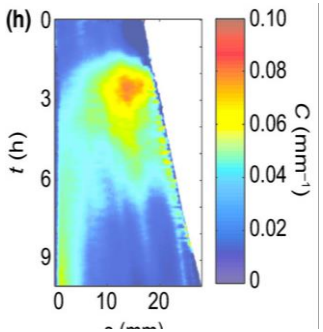


⇨ Controlled by gravitropic sensing and proprioception

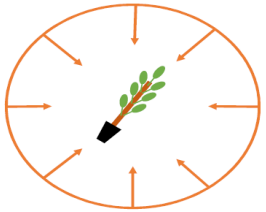
Moulia et al. 2021
Science

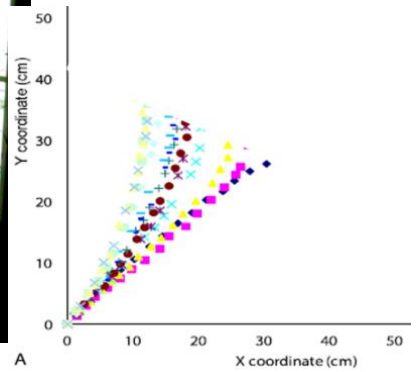
What controls the shaping and orientation of each axis ?
Shedding light

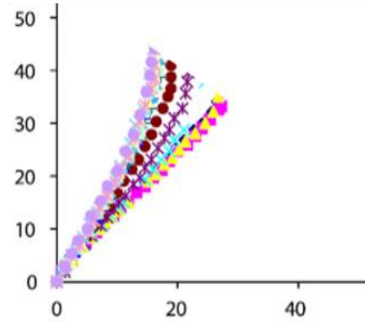




Bastien, Douady, Moulia, 2015 Computational Biol



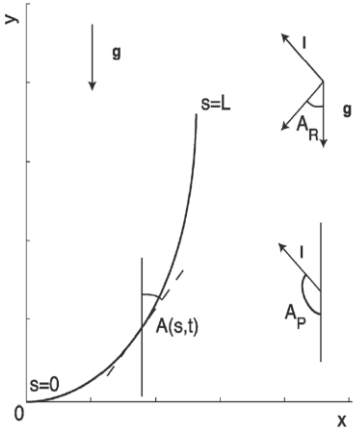




The A_rC model

$$\frac{\partial C(s,t)}{\partial t} = -\beta A(s,t) - \gamma C(s,t) - v(A(L,t) - A_P)$$

gravitropic proprioceptive phototropic



Bastien *et al* 2013 Pnas, Bastien, Douady, Moulia, 2015 Computational Biol , Moulia *et al.* 2021 Science

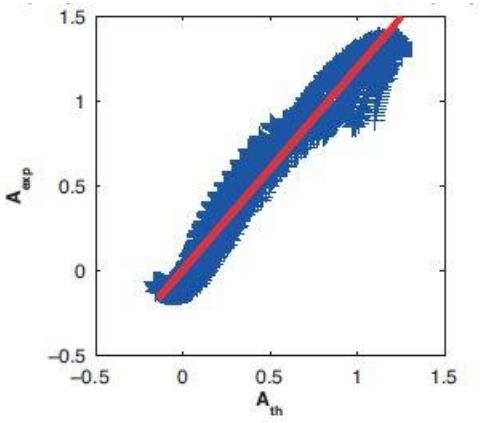
↳ Dynamics controlled by only 2 dimensionless numbers

Balance Number B
=gravisensitivity / propriosensitivity

$$B = \frac{\beta}{\gamma} L_0$$

Motion Pointing number M
=gravisensitivity / photosensitivity

$$M = \frac{\beta}{v}$$



assessed on a set of 13 species sampling the phyllogeny of land angiosperms (4 for the phototropic part)

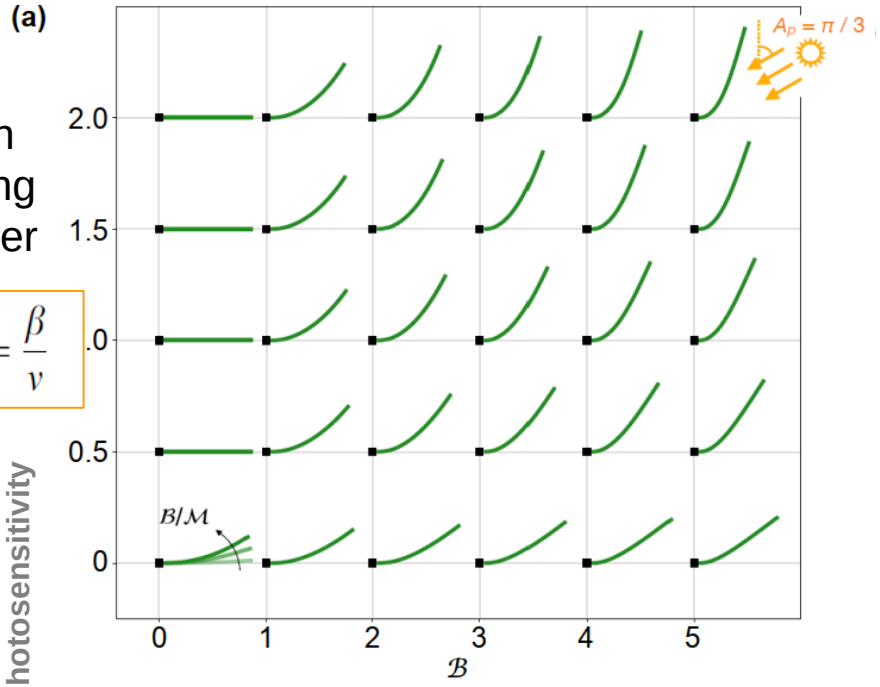
combining experiments and the ArC Model ⇨Estimates of B and M (quantitative phenotyping)

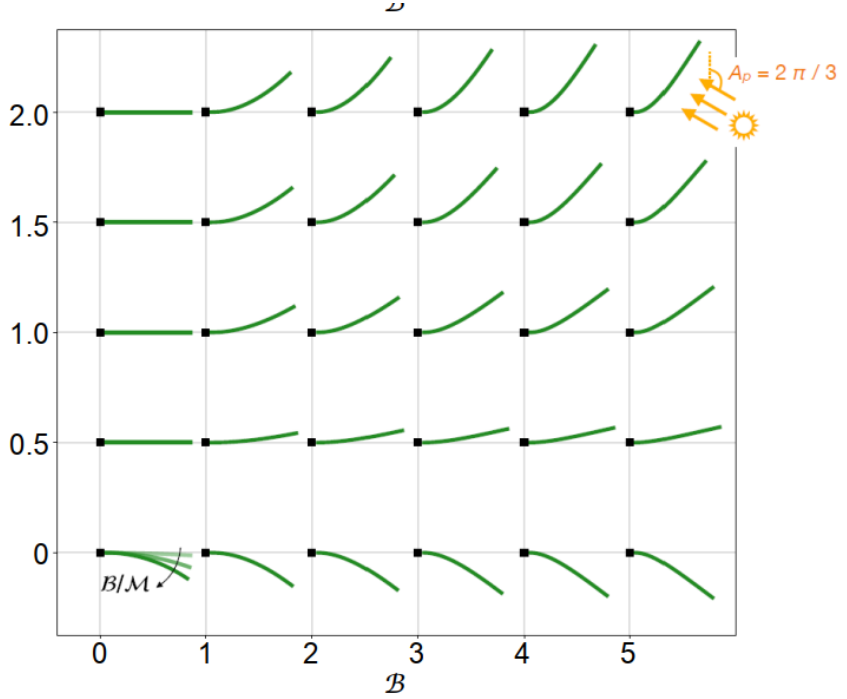
$\mathcal{BM}$ Photogravitropic MorphoSpace

Motion pointing Number

$$M = \frac{\beta}{v}$$

=gravisensitivity / photosensitivity





Balance Number

$$B = \frac{\beta}{\gamma} L_0$$

=gravisensitivity / propriosensitivity

❷ *What controls the shaping of the crown edge, at various developmental stages ?*

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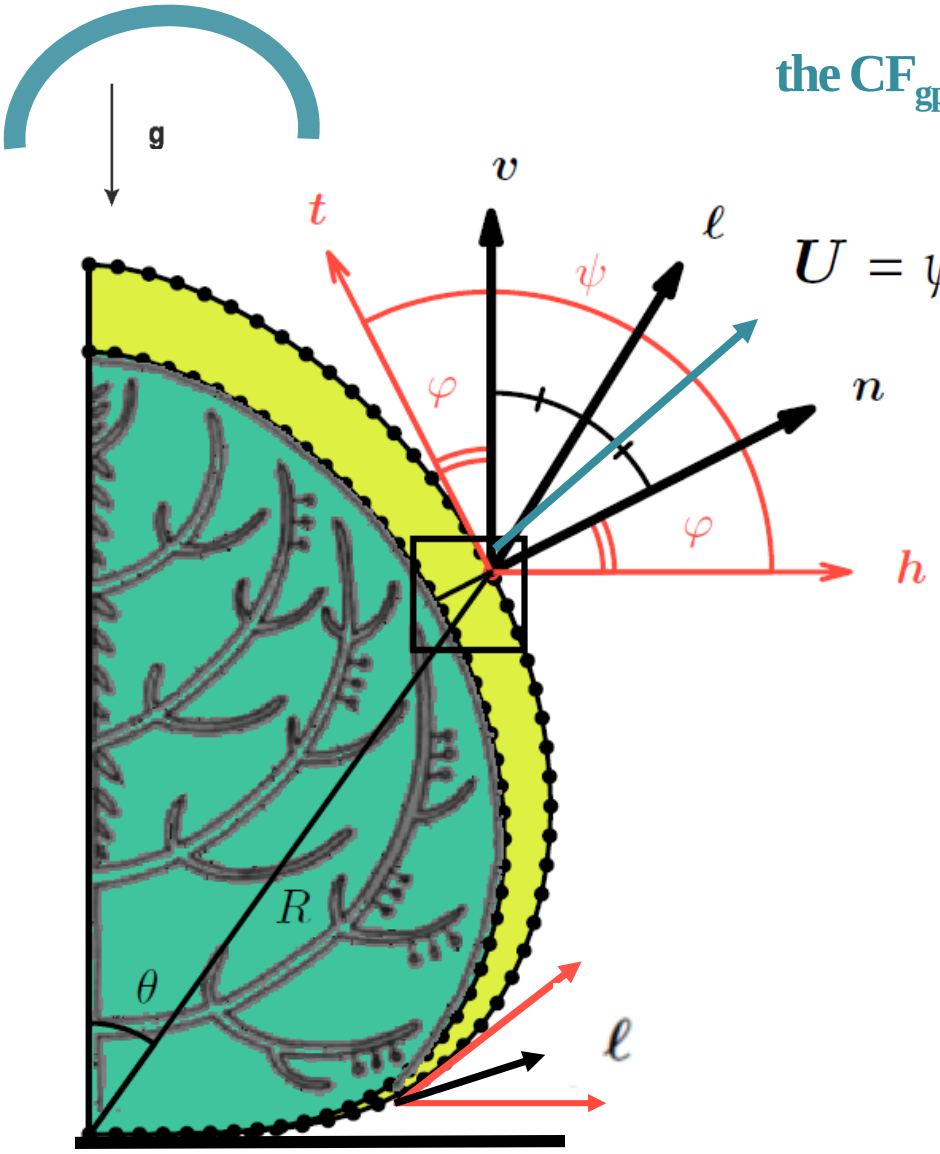
A crown front dynamics, driven by the gravi-phototropic orientation:

the CF_{gp} model



$$\boldsymbol{U} = \psi \frac{\boldsymbol{n} + \alpha_g \boldsymbol{v} + \alpha_p \boldsymbol{\ell}}{\left|\boldsymbol{n} + \alpha_g \boldsymbol{v} + \alpha_p \boldsymbol{\ell}\right|} + \gamma_s \kappa_s \boldsymbol{n}$$

Motion pointing Number

$$M = \frac{\beta}{v}$$

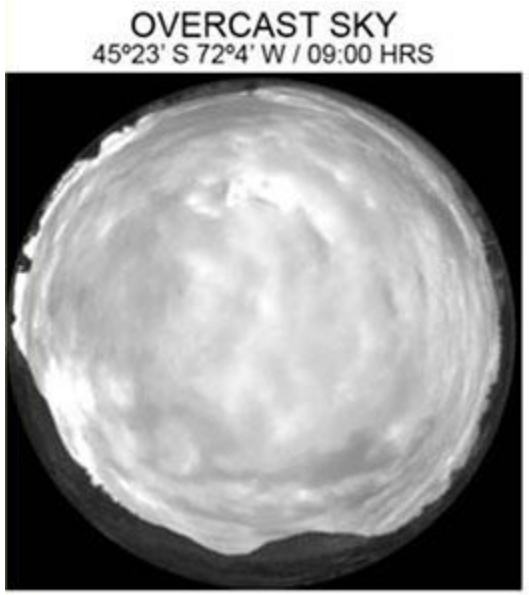
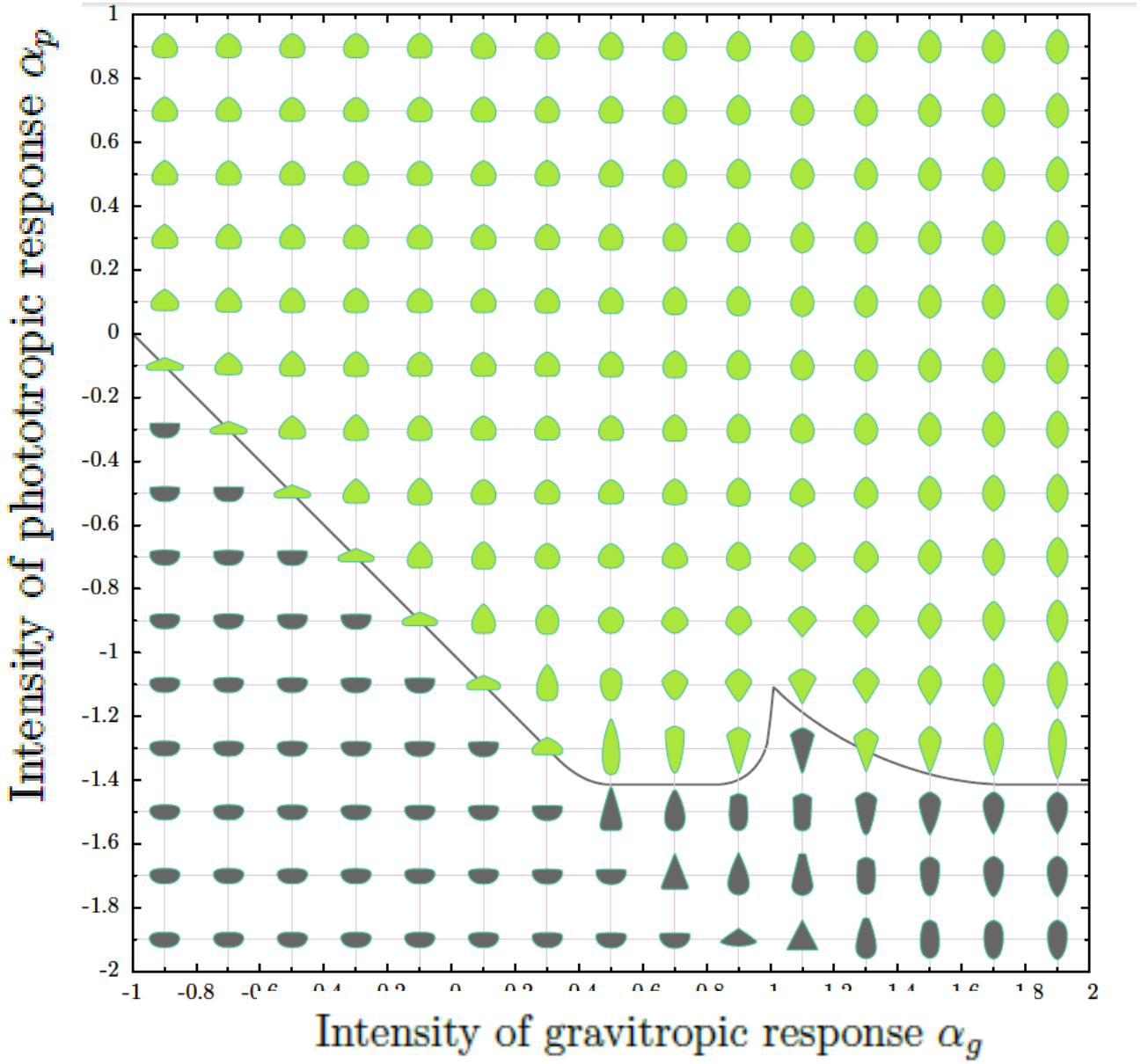


Figure 1. Sketch of a growing tree crown. $\boldsymbol{h}$ and $\boldsymbol{v}$ are unit horizontal and vertical vectors respectively, $\boldsymbol{n}$ and $\boldsymbol{t}$ are the unit vectors respectively normal and tangent to the front and the unit vector $\boldsymbol{\ell}$ points towards the mean direction of light, which is the first bisector of $(\widehat{\boldsymbol{h},\boldsymbol{t}})$. The angle $\psi = \varphi + \pi/2$ represents the local amount of sunlight intercepted for this axisymmetric shape. The inset shows a zoom around the front to highlight the conditions for self-similarity of the growing shape.

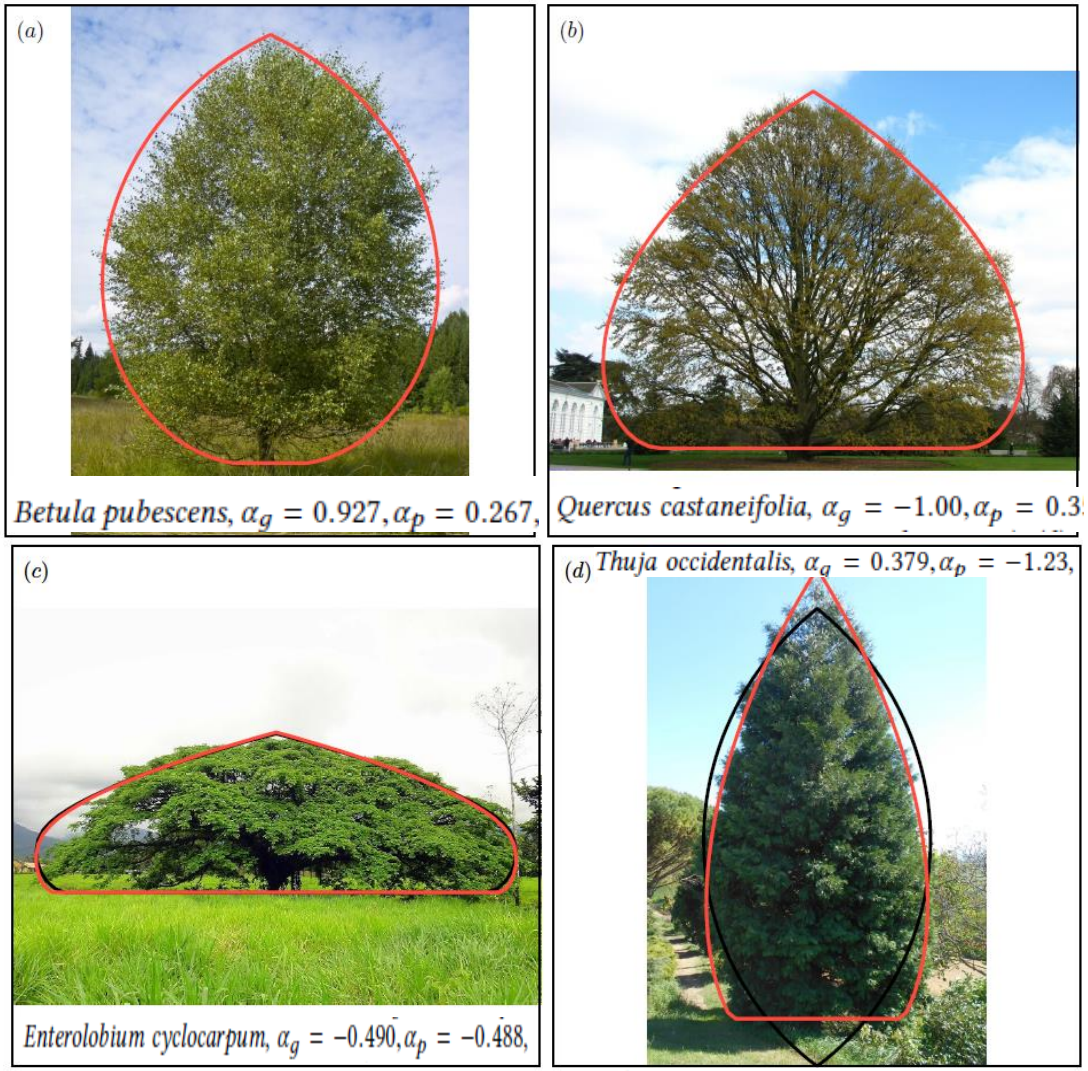
Duchemin, Eloy, Badel, Moulia
2018 J Royal Soc Interface

CF_{gp} model

$$U = \psi \frac{\boldsymbol{n} + \alpha_g \boldsymbol{v} + \alpha_p \boldsymbol{\ell}}{|\boldsymbol{n} + \alpha_g \boldsymbol{v} + \alpha_p \boldsymbol{\ell}|} + \gamma_s \kappa_s \boldsymbol{n}$$



CF_{gp} Model fitting at the Architectural Unit and Mature Stages (undisturbed isolated trees)



Comparison between real tree crowns and self-similar shapes of the model

The red curve represents the best fit and the black curve the best fit with $\alpha_p > 0$.

Reasonnable fit
(not a full validation)

The shaping of trees by mechanical (and optical) signals

❶ What controls the shaping and orientation of each axis ?

Sensing
position vs gravity/light
self-shape,

$\mathcal{BMW}$-ε_l

Dimentionless numbers :
↳morphogenetic regimes

$$B = \frac{\beta}{\gamma} L_0$$

Balance Number

$$M = \frac{\beta}{v}$$

Motion pointing Number

$$\mathcal{W} = \frac{\kappa_{AGO} R}{\gamma}$$

(active) Weeping number

$$\varepsilon_l = \frac{L_0}{l_e}$$

Elastic sagging number

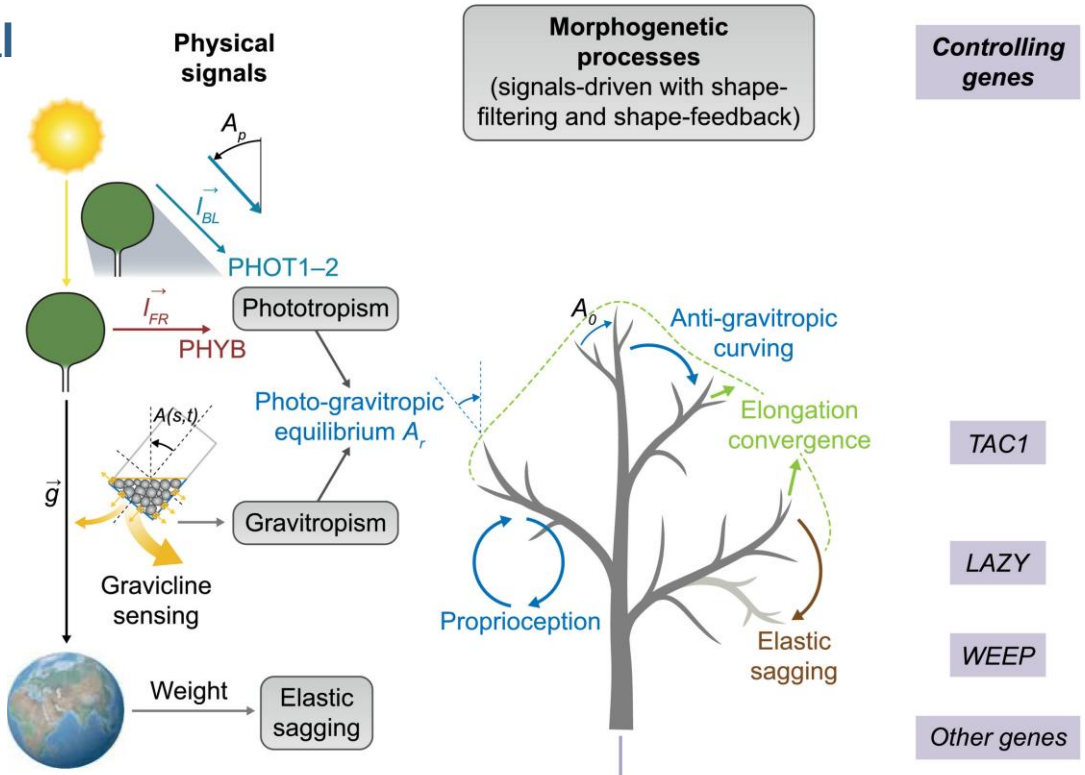
❷ What controls the shaping of the crown edge ?

$\mathcal{BMW}$-ε_l+ crown feedback

Crowns~ tropic droplets with global shape feedback (shade)

❸ How can we account for both the genetic control and the environmental plasticity of plant shaping ?

Environmental control



Model-assisted quantitative phenotyping

The interdisciplinary collective shaping of these researches

❶ What controls the shaping and orientation of each axis ?

R Bastien

PhD Physics
INRAE , PIAF

S Douady

Soft Matter
Physics MSC

T Bohr

Theoretical Physics,
DTU, Niels Bohr
Institute Dk

C Coutand plant
Biomechanics
NRAE PSH

H Chauvet

Geophysics

UCA, PIAF

V Legué,
Plant Biology

UCA, PIAF

Y Forterre

Soft Matter Physics IUSTI

O Pouliquen

M Decourteix

Functionnal genomics
UCA PIAF

F Hartmann

Computational Biol
INRAE , PIAF

S Ploquin

Iechnician NRAE
, PIAF

A Caulus

INRAE , PIAF
PhD -Biology

❷ What controls the shaping of the crown edge (at various developmental stages) ?

L Duchemin

Non linear physics PMMH

C Eloy

Non linear physics IRPHE

E Badel Plant and wood
biomechanics INRAE PIAF

New Phytologist

Editor-in-Chief: Alistair M. Hetherington

Impact Factor : 10.151

Review

New Phytologist

Tansley review

The shaping of plant axes and crowns through tropisms and elasticity: an example of morphogenetic plasticity beyond the shoot apical meristem

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2022

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Thank you for your attention

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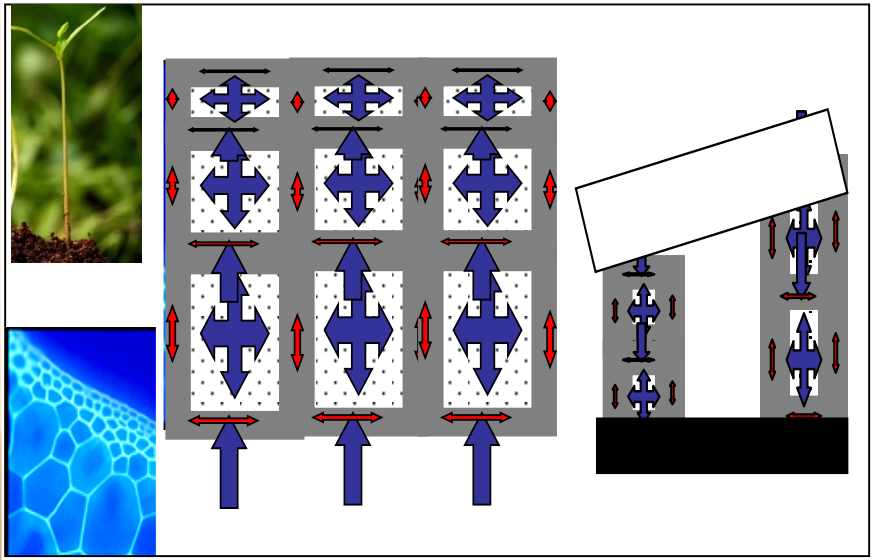
http://pauloctavious.com/leanwithit/

Comparative Biology /
cross-phyllum understanding
(ecological awareness)

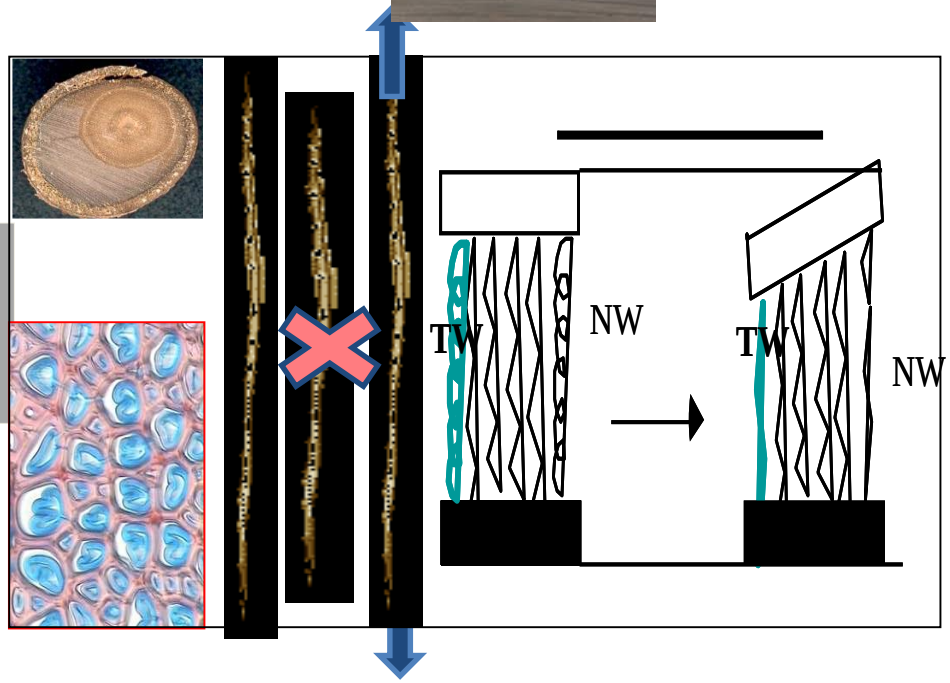
INRAE Auvergne-Rhône-Alpes
UCA Université Clermont Auvergne
U.M.R. PIAF

annexes

2 – two motors



•M1: Osmo-Hydraulic motors
(living tissues) typ σ = 0.5 MPa

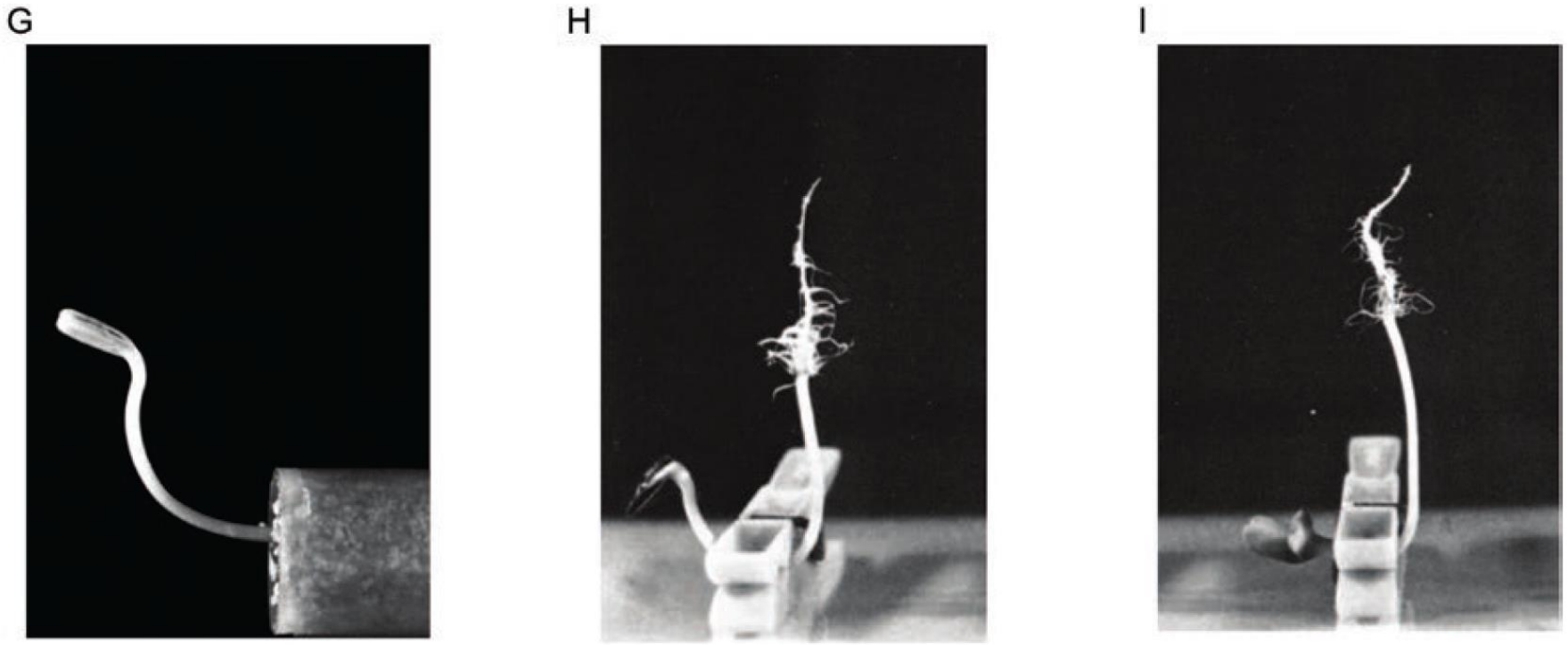


•M2: Polymeric shrinkage motors
=> Tension woods (lignified tissues)
typ σ = 5 to 30 MPa

⇨**Plants produce motor capacity as they grow**

⇨**Growth mechanics = internal free energy = additionnal stresses**

A puzzle
How do you interpret the ourtcome of Firn and Digby 1979 experiment ?



(G–I) Steady-state shapes of the sunflower (*Helianthus* sp.) hypocotyl after tilting to $A0=\pi/2$ and clamping at the collar (G), in the middle of the hypocotyl (H), or just below the cotyledons. from R. D. Firn and J. Digby, A study of the autotropic straightening reaction of a shoot previously curved during geotropism, Plant, Cell & Environment 2, 149–154, 1979. c1979 Blackwell Scientific Publications.

B

↳continous process of balance along development

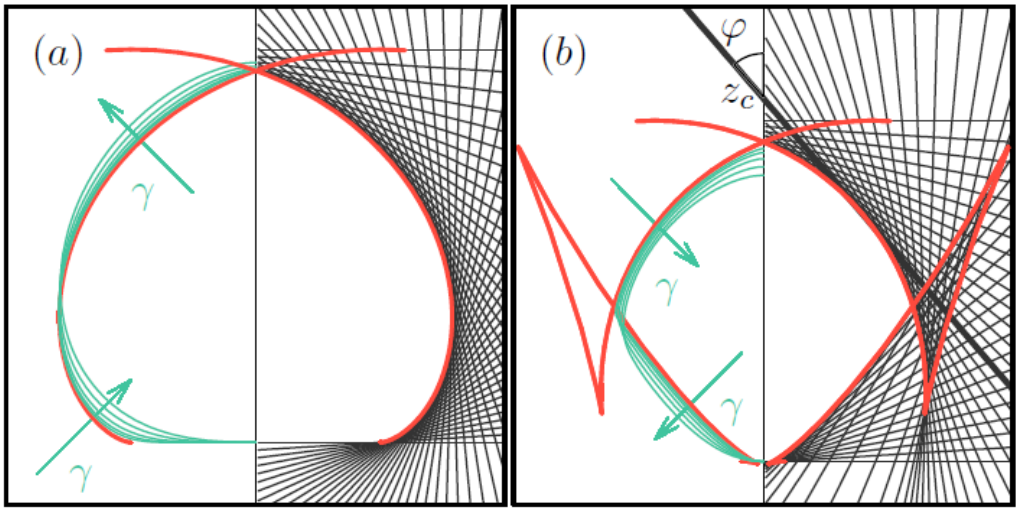
和

Hiroshige Utagawa, 1856 "View of Konodai and the Tone River" in the series of 100 views of Edo

INRA SCIENCE & IMPACT Auvergne-Rhône-Alpes
UCA UNIVERSITÉ Clermont Auvergne
U.M.R. PIAF

Thank you !

Analytical solving and geometric construction



swallowtail

Phase Diagram