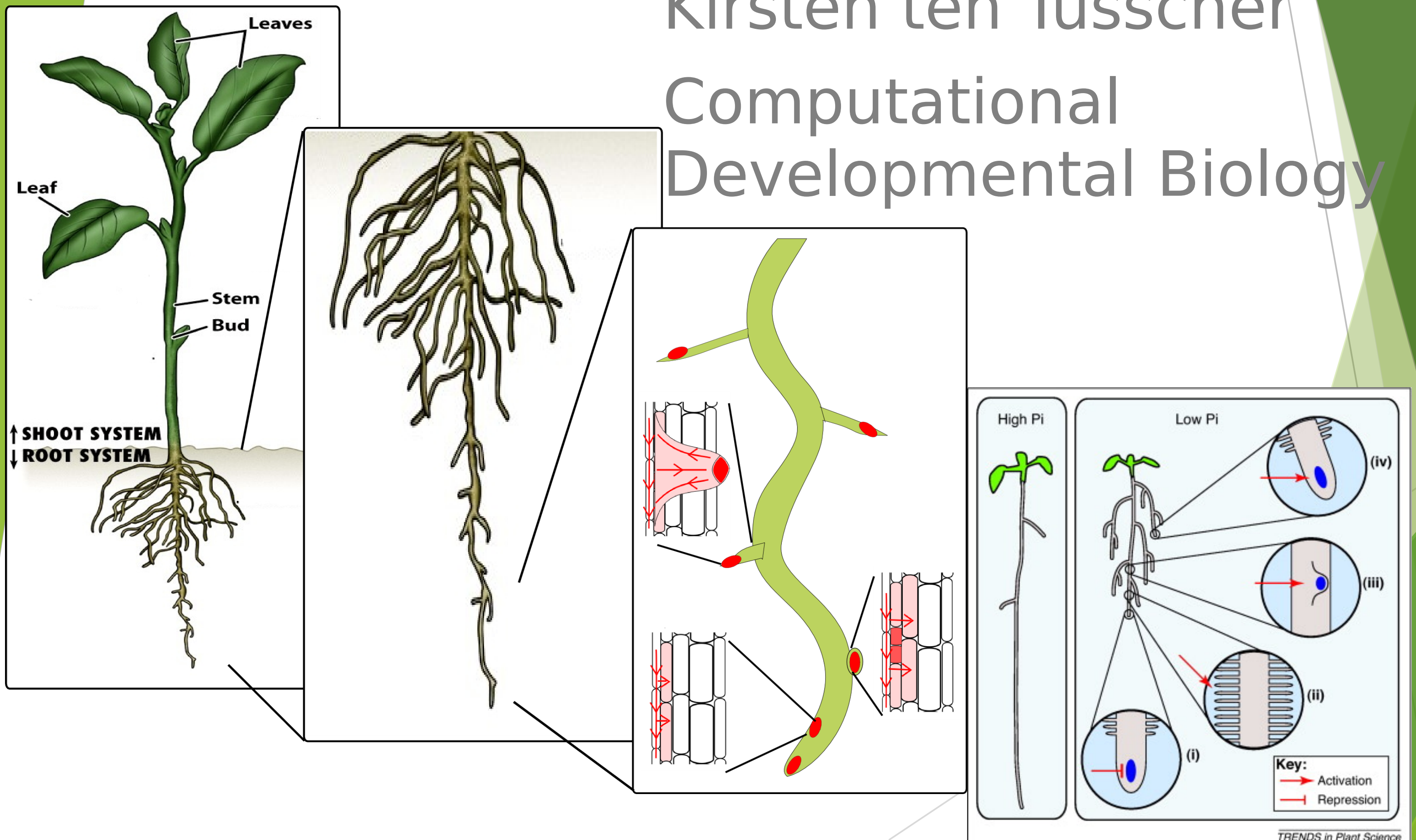
Plant root patterning

Kirsten ten Tusscher

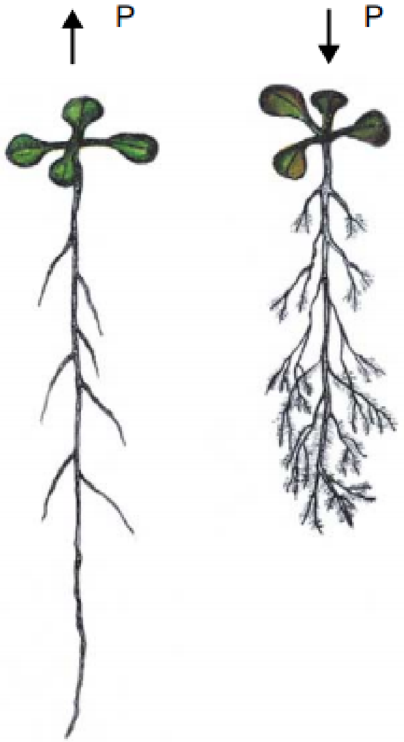
Computational Developmental Biology



RSA and LR formation

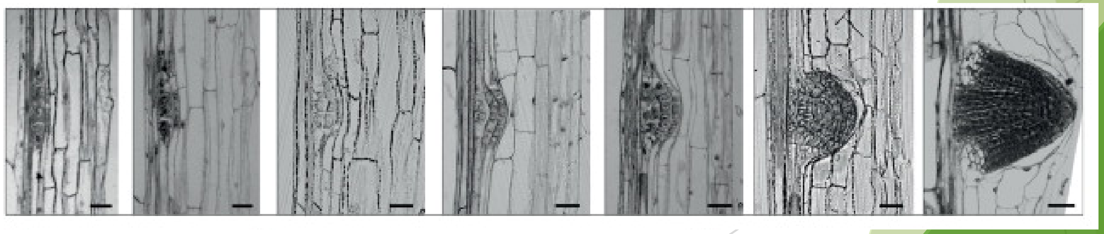
RSA arises from repeated LR root formation

What determines where new LRs formed?



Lopez-Bucio, 2003

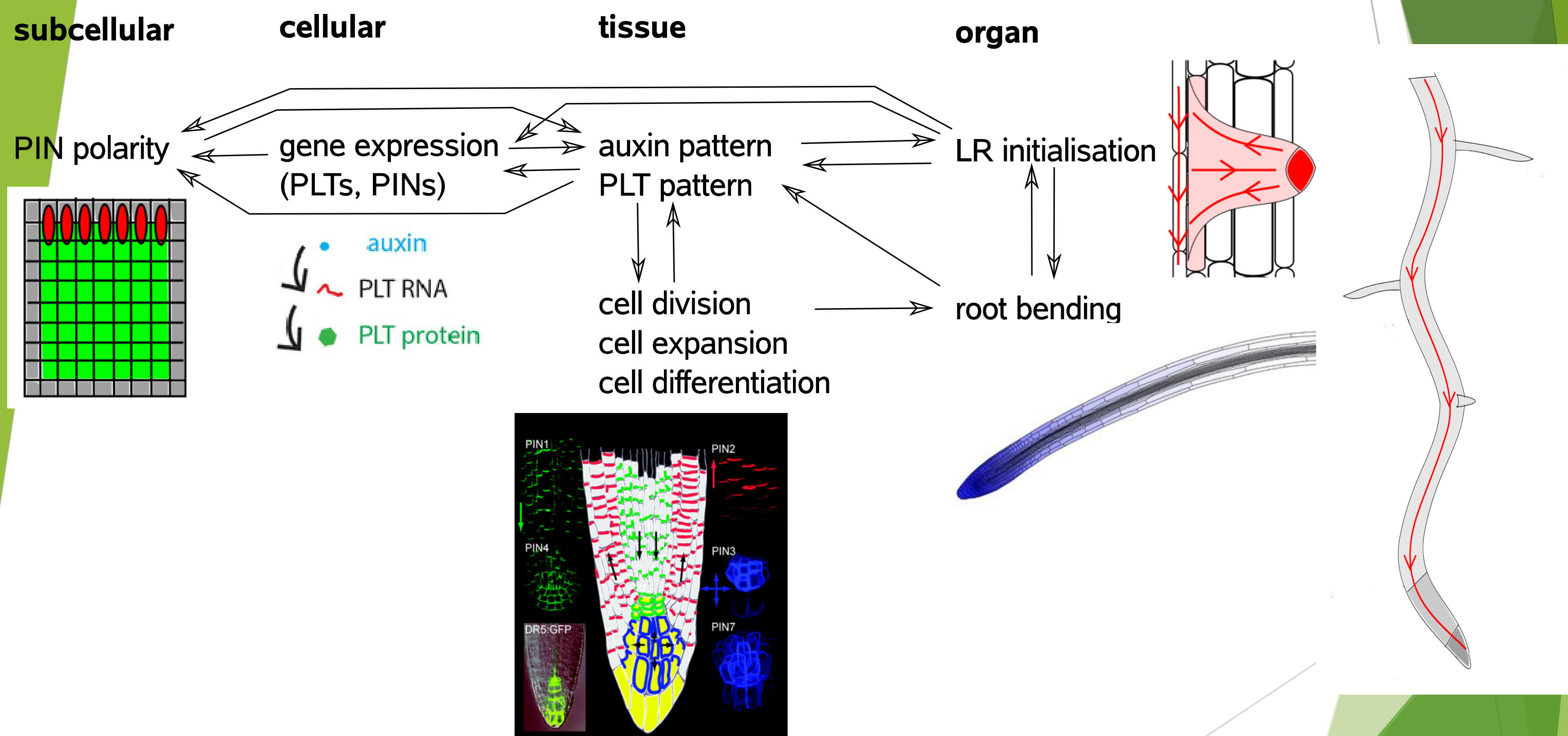
Roots develop through sequence of stages; What controls these?



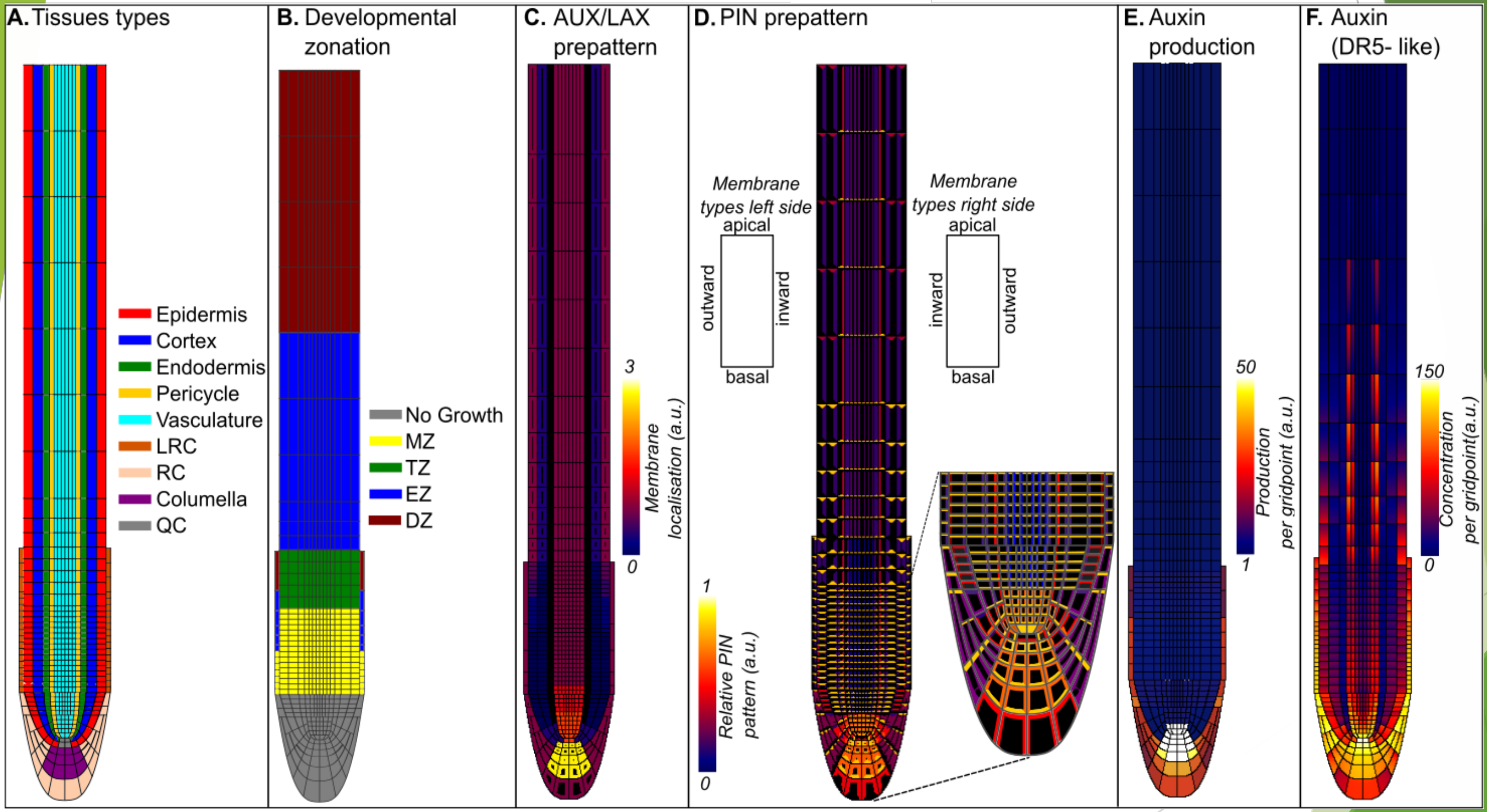
Orman-Ligeza,2013

Modeling root development

Multi-scale multi-process multi-feedback models



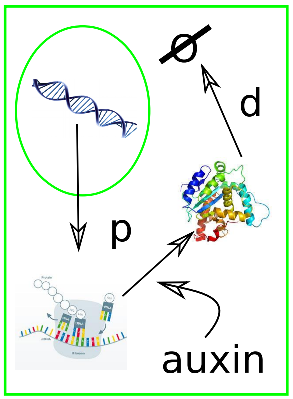
Modeling tissue layout

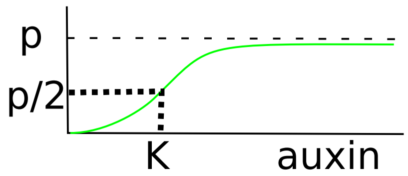


Modeling gene expression

Cell-level ODE computations

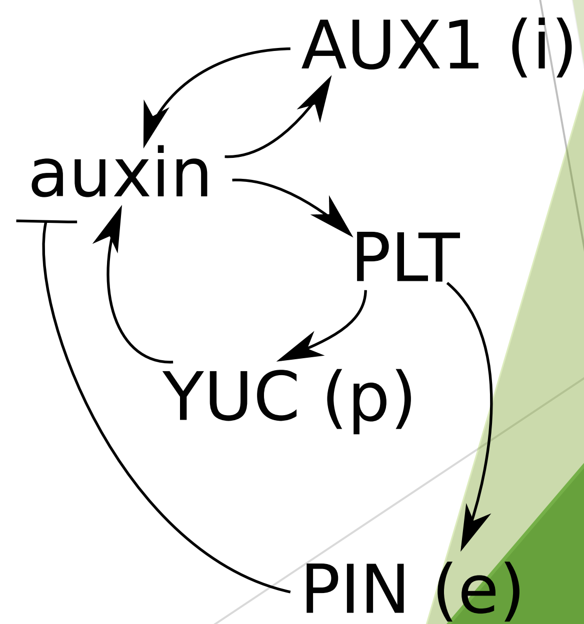
$$\frac{dP_q}{dt} = p * \frac{auxin_q^2}{auxin_q^2 + K^2} - d * P_q$$





p maximum production
K saturation constant
d degradation

Gene expression networks

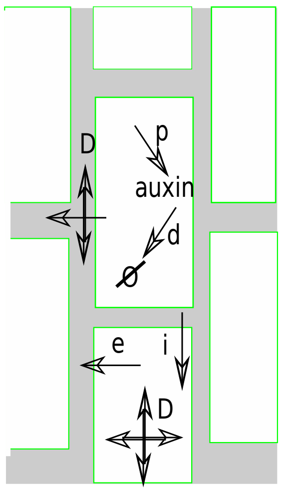


Multistability
Bifurcations
Wave patterns

Modeling auxin dynamics

Grid-level PDE computations

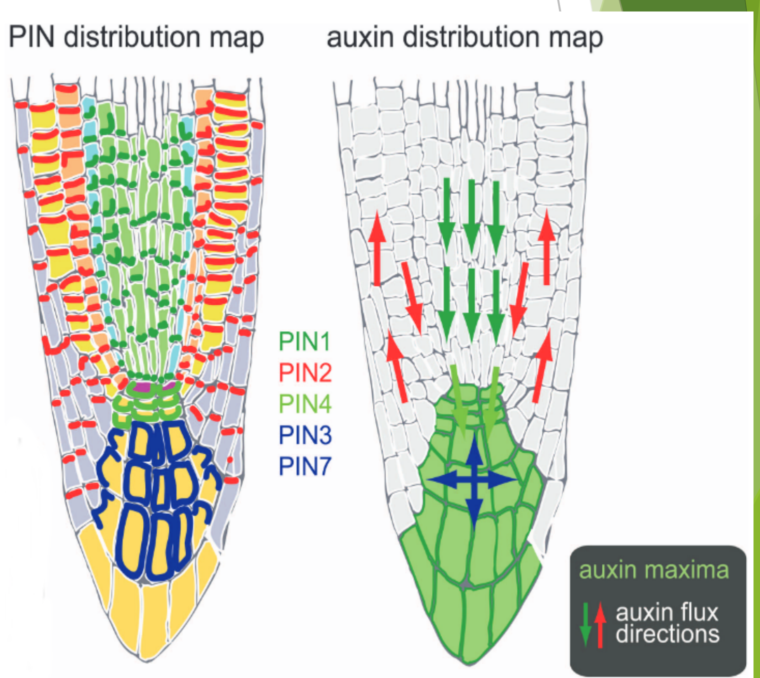
Very stiff → ADI integration



$$\frac{\delta\, auxin_{int}}{\delta t} = p - d * auxin_{int} + i * auxin_{ext} - e * auxin_{int} + D * \frac{\delta^2 auxin_{int}}{\delta x^2}$$

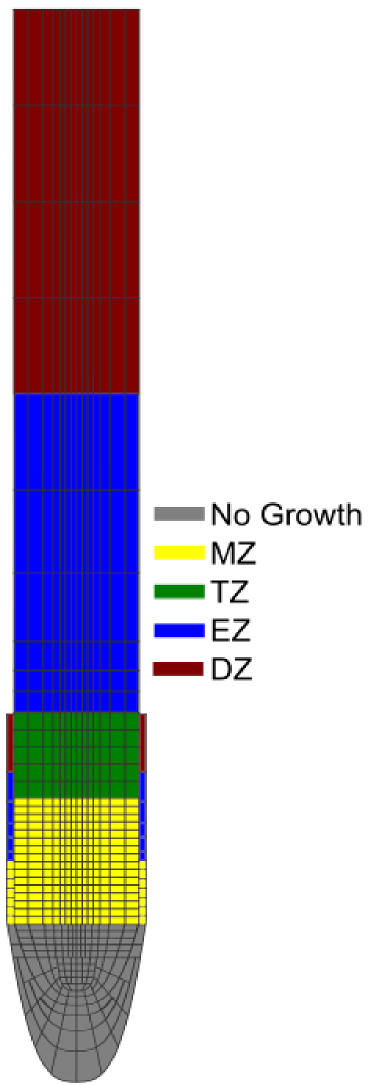
p	production (in cells)
d	degradation (in cells)
i	influx (cell wall -> cell)
e	efflux (cell -> cell wall)
D	diffusion (in cells, in cell wall)

Specific efflux transporter layout



Modeling growth

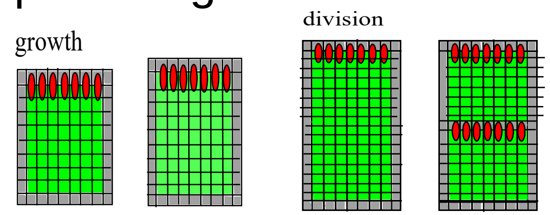
Growth zones



Cellular behaviour

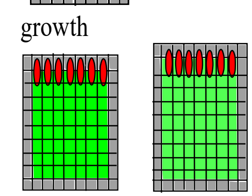
If (MZ -yellow)

Cytoplasmic growth & division



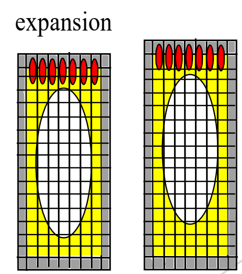
Else if (TZ – green)

Cytoplasmic growth



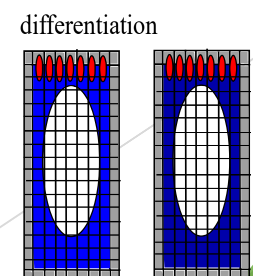
Else if (EZ – blue)

Vacuolar expansion



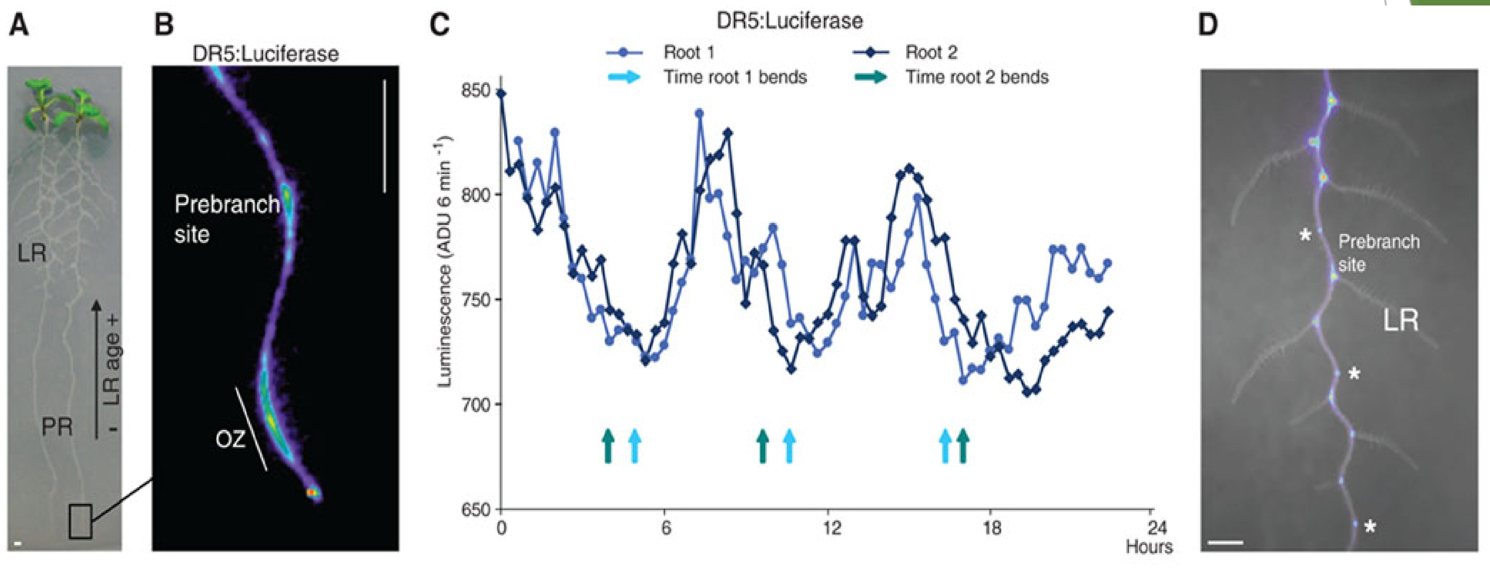
Else

Differentation



LR priming

Prepatterning of competent sites

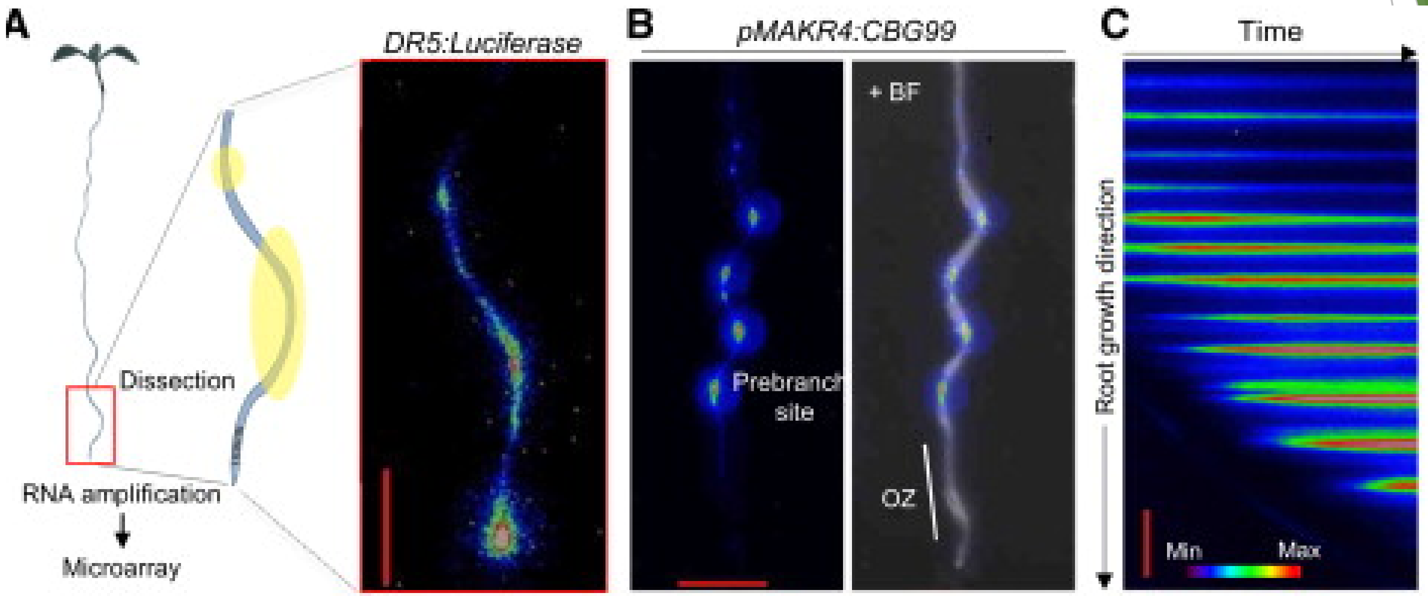


Moreno-Risueno, 2010

Temporal oscillations in auxin (response) & expression of many genes

LR priming

Prepatterning of competent sites

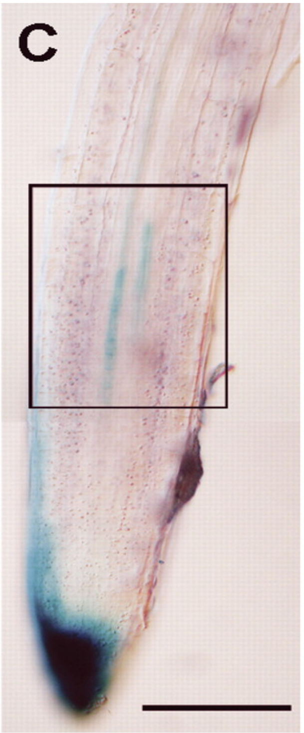


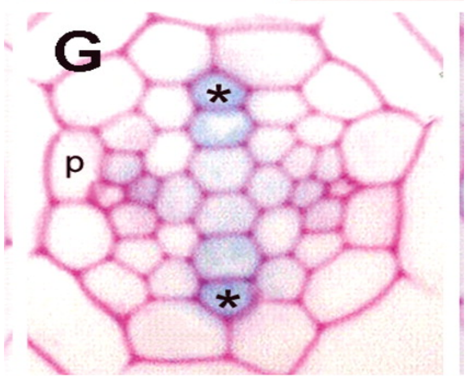
Xuan et al., 2015

Through growth temporal oscillations becomes spatial pattern of competent sites

LR priming

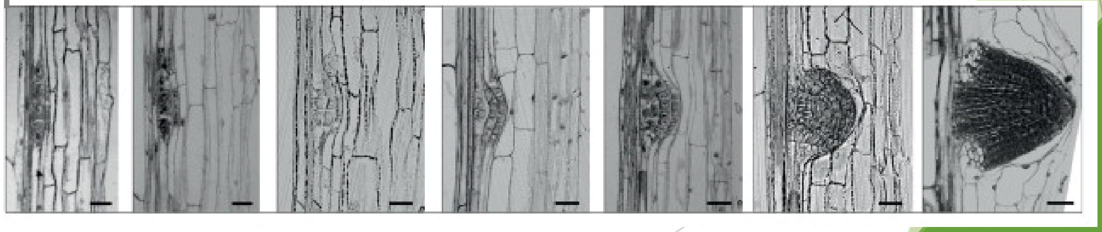
Prepatterning occurs inside vasculature





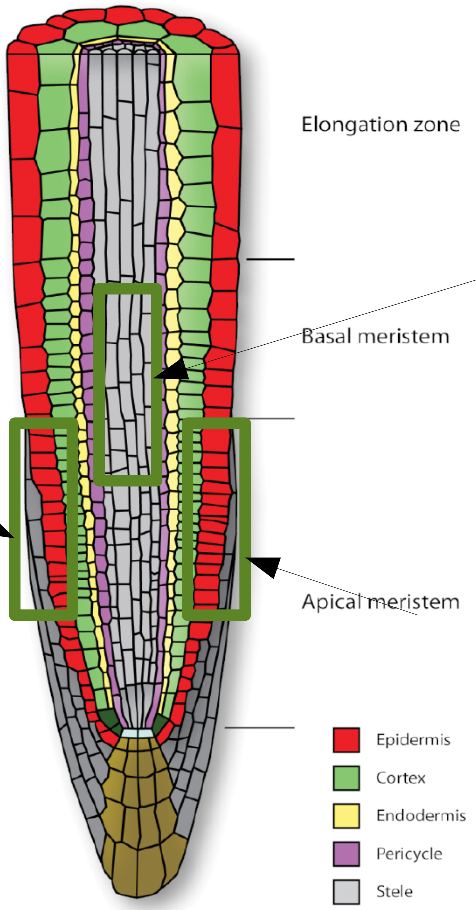
De Smet 2007

New roots have to emerge from inside parent root



Orman-Ligeza,2013

What does data say?



Correlation with regular lateral root cap apoptosis (Xuan, 2016)

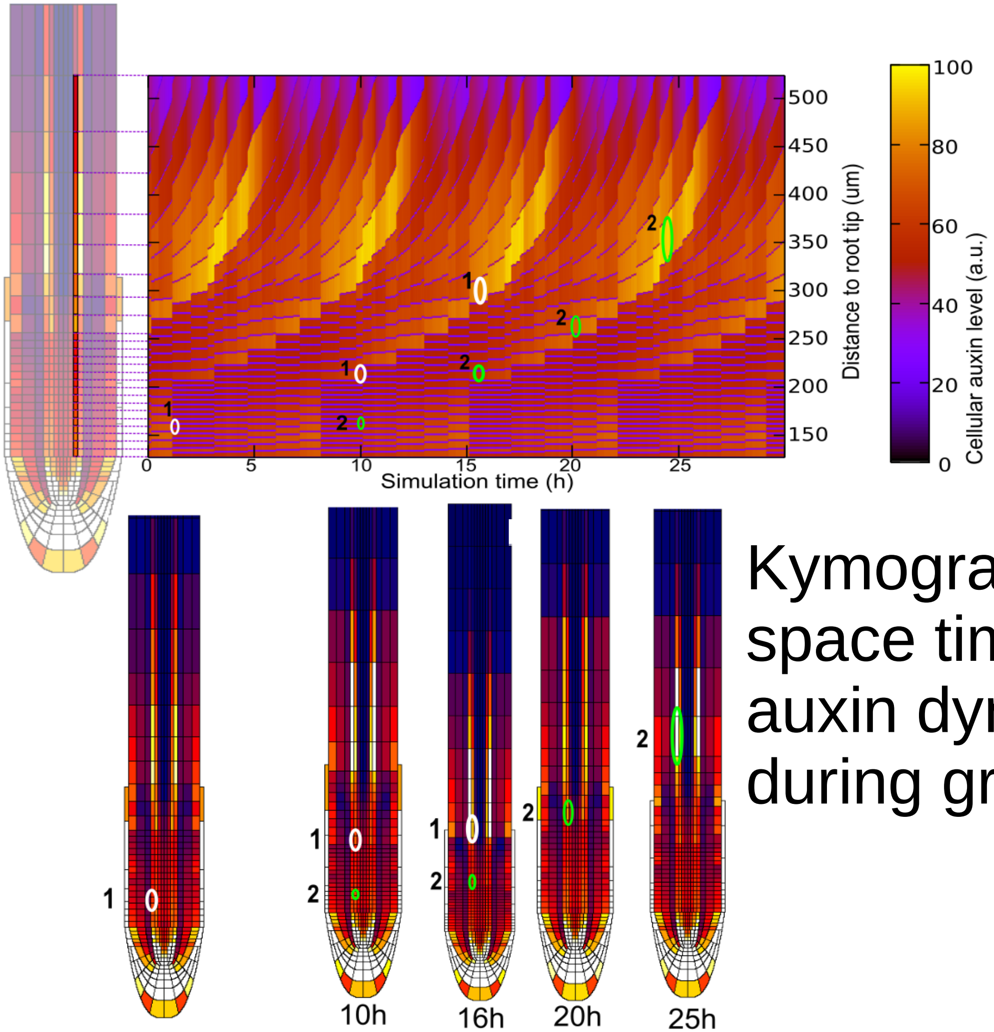
Auxin sensing in vasculature (De Smet, 2007)

Auxin production In lateral root cap (Xuan, 2015)

Hypothesis:

Combination of growth & auxin transport

Emergent auxin oscillations

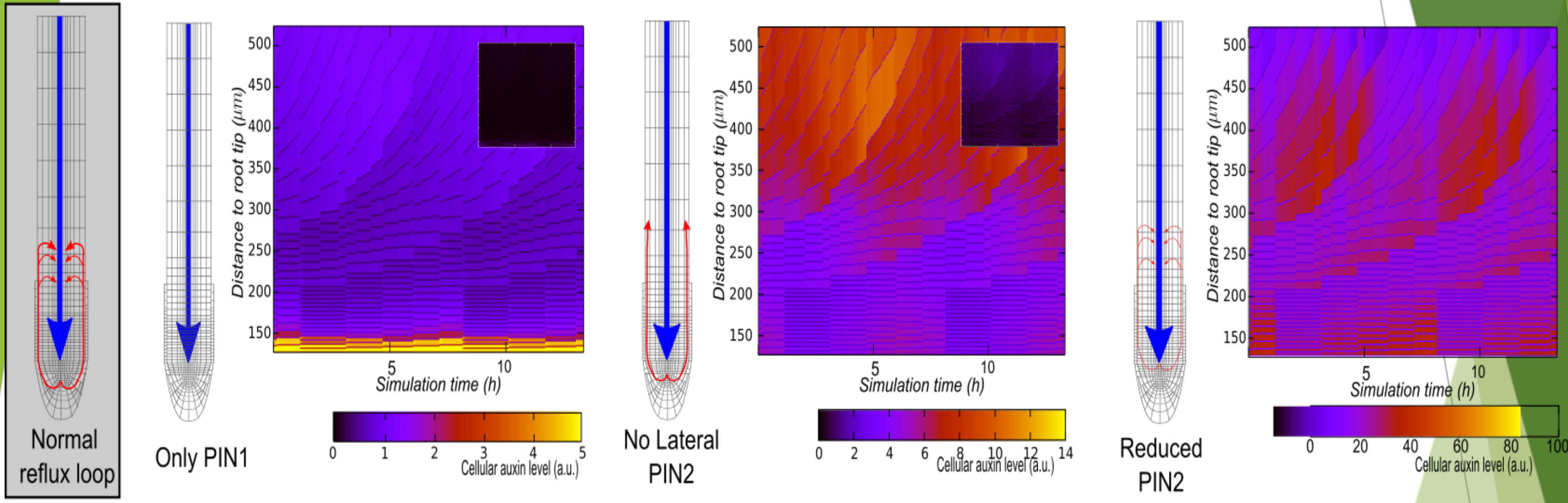


Kymograph: space time plot of auxin dynamics during growth

Thea v/d Berg

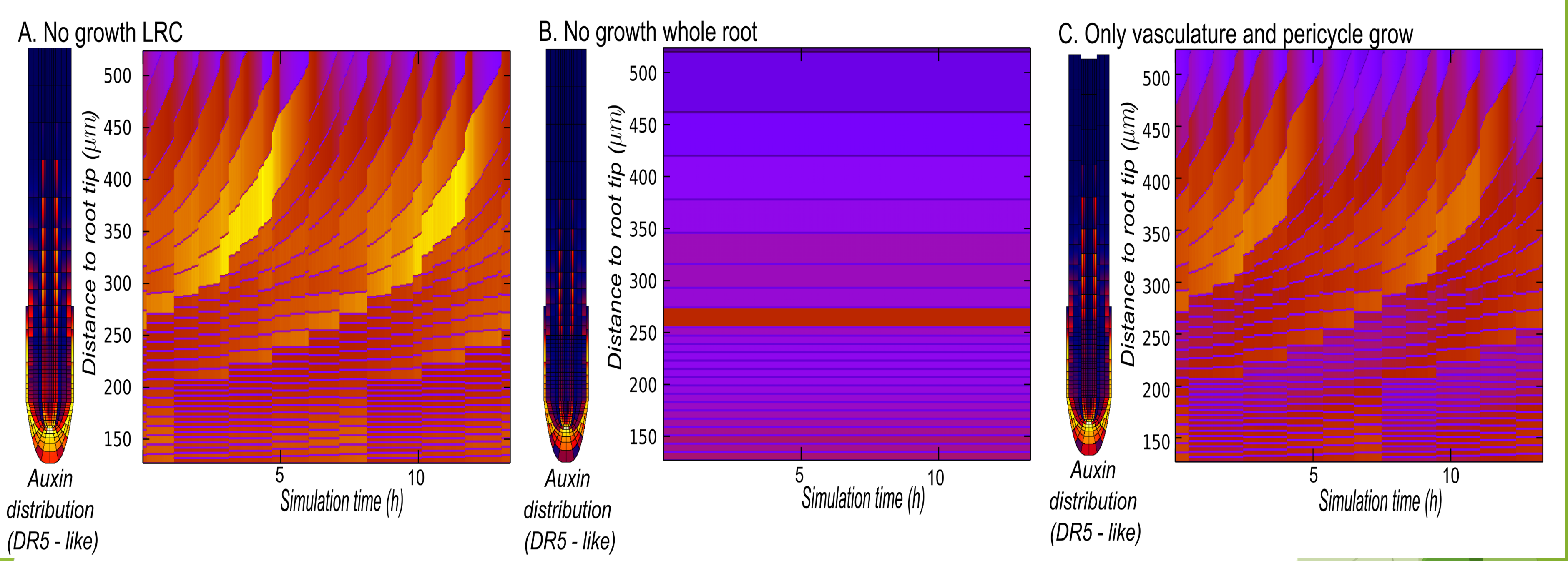
Oscillations pericycle specific!

Oscillations require a functional reflux loop



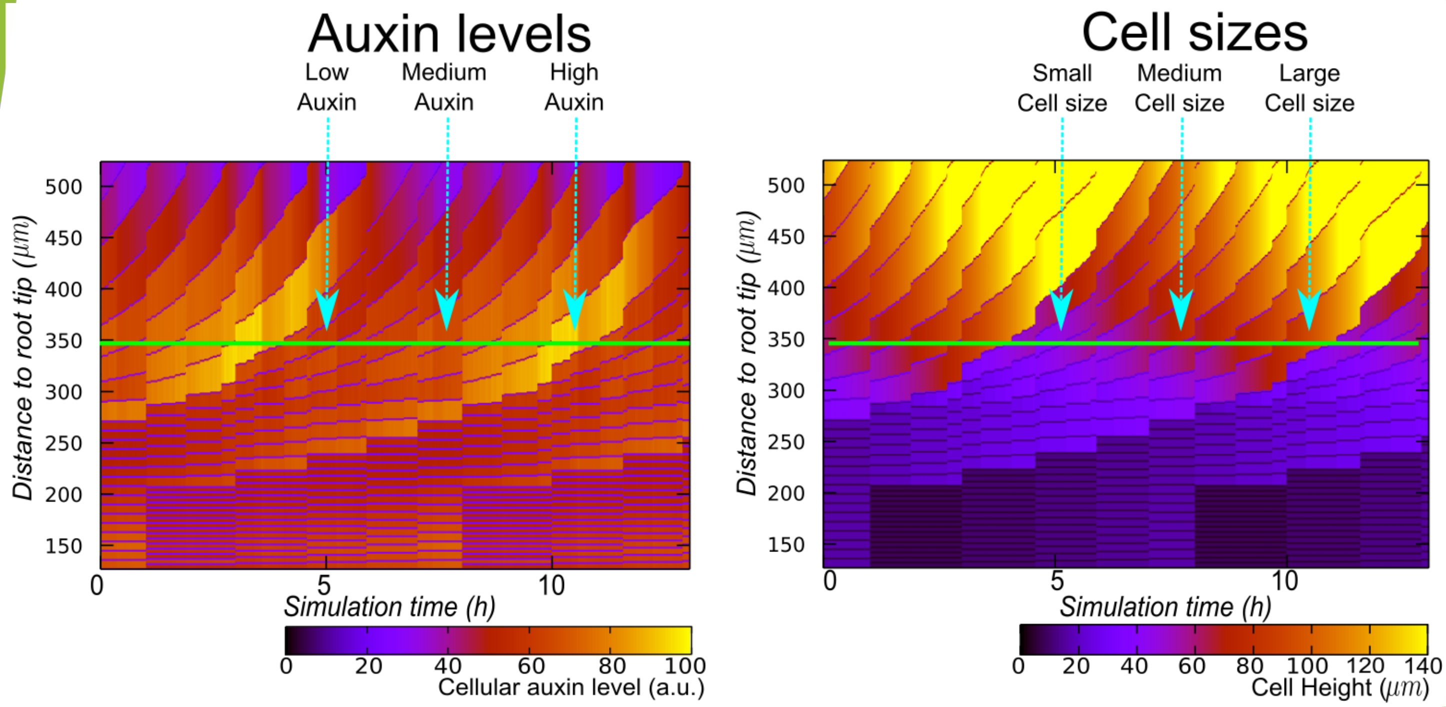
Reflux loop generates “auxin loading zone” at shootward end of the meristem

Oscillations require growth of vasculature and pericycle



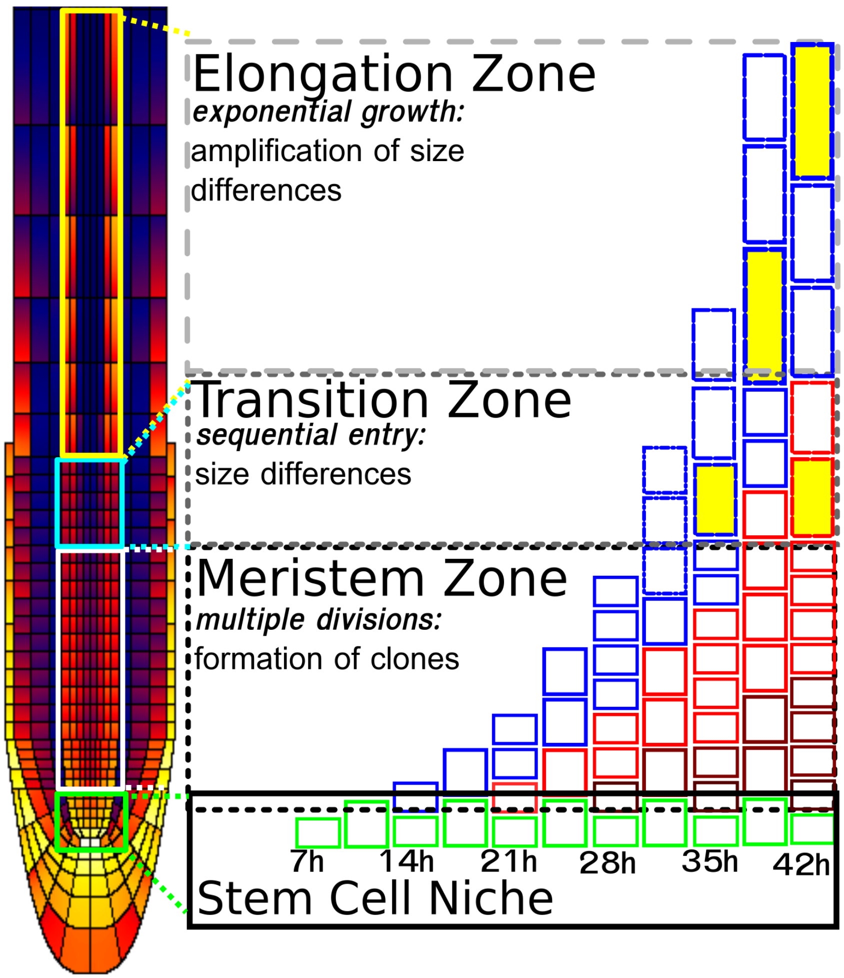
Growth in primed tissues necessary

Auxin transport & growth?
Auxin peaks correlate with cell size



Cell that arrives largest at loading zone becomes primed:
Largest auxine loading potential

Growth produces periodic variations in cell size

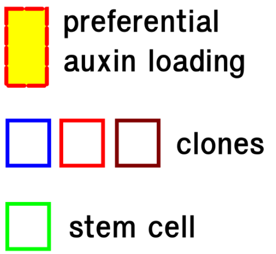


Repeated generation of large-small cell pairs:

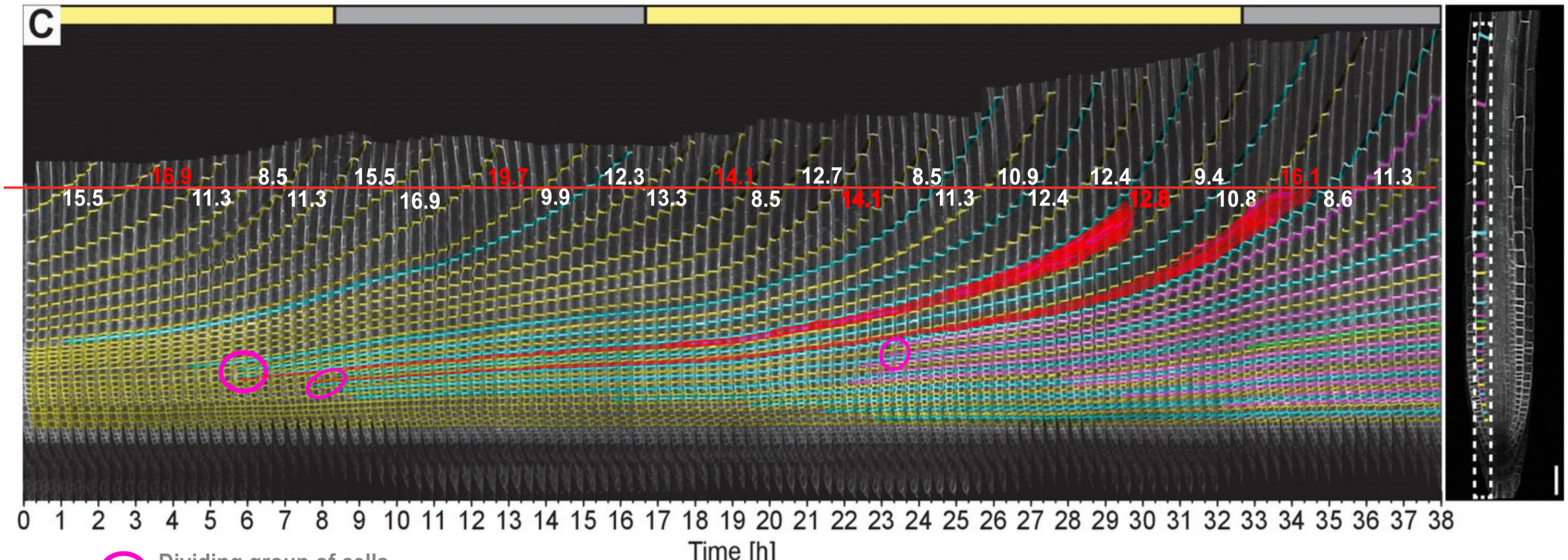
large cell: entered TZ just *before* next division
small cell: next cell entering TZ just *after* division

Exponential growth
amplifies size differences

Small cell enhances growth & loading time large cell



Periodic cell size variations also observed experimentally



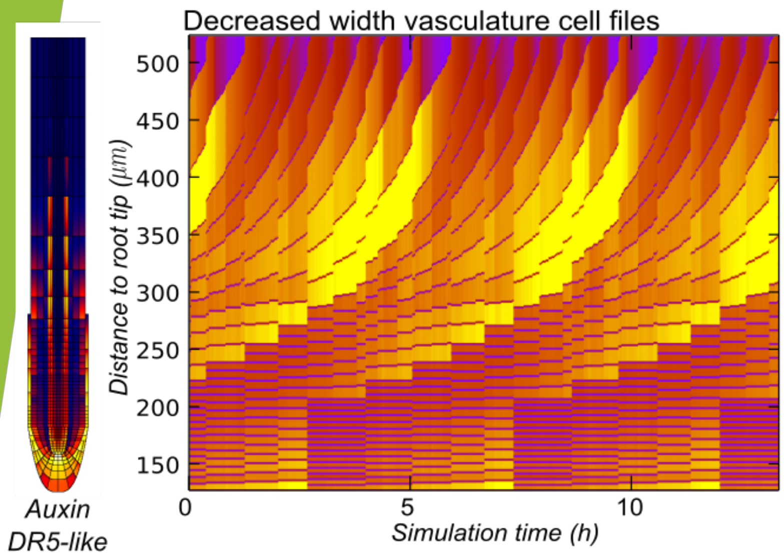
Dividing group of cells

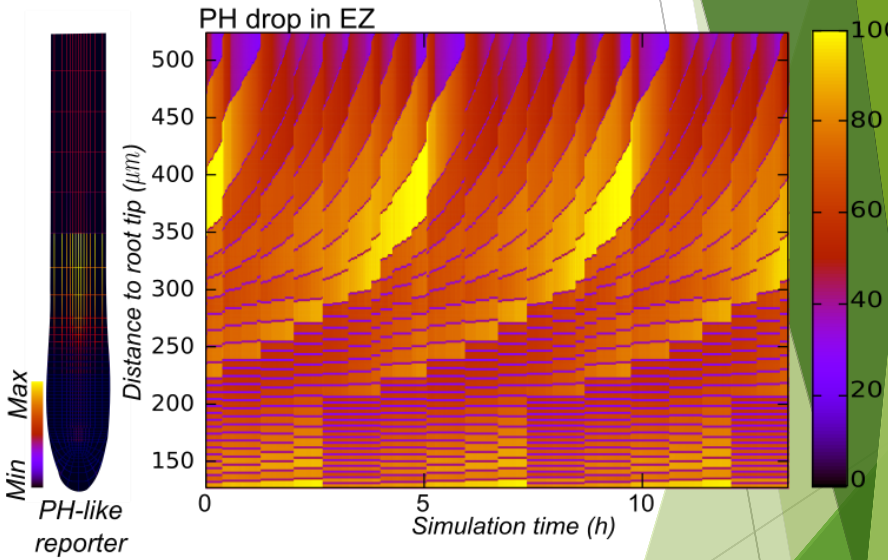
Last cell of a dividing group of cells

Adapted from: Von Wangenheim *et al.*, Live tracking of moving samples in confocal microscopy for vertically grown roots, *Elife (2017)*

Larger surface/volume ratio prioritizes vasculature

Vasculature cells most narrow, expand earliest

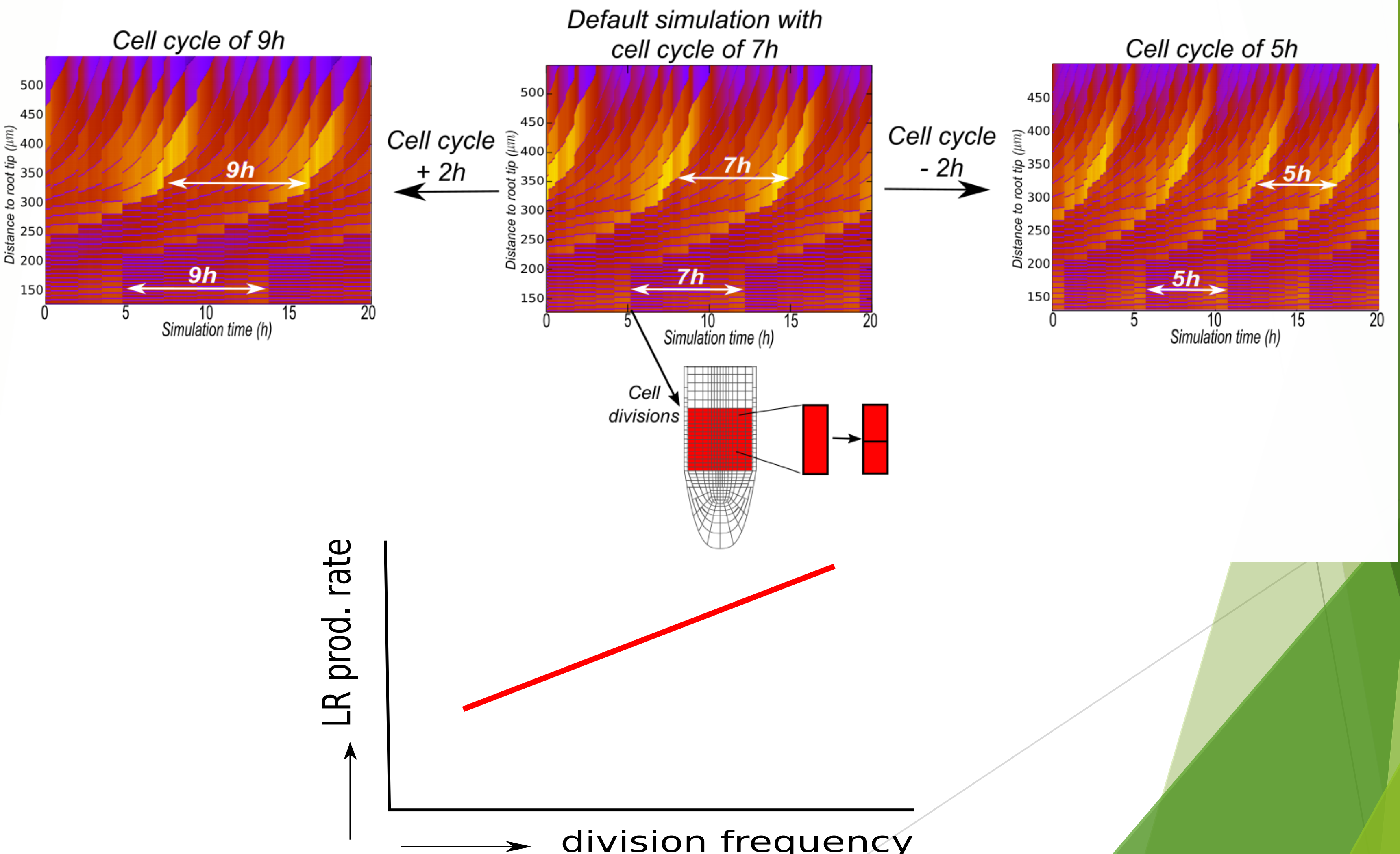




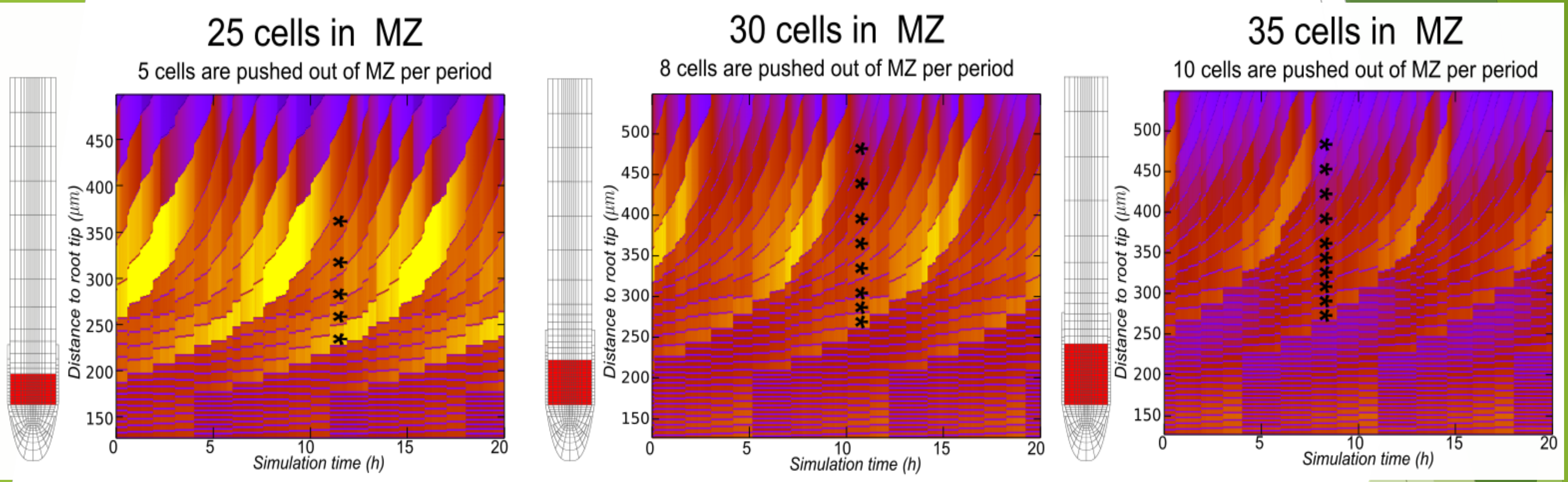
Even narrower → higher peaks

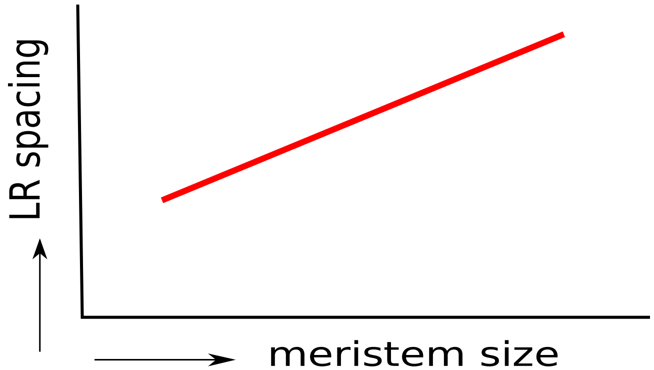
pH lower: more background influx → higher peaks

Division rate drives priming frequency

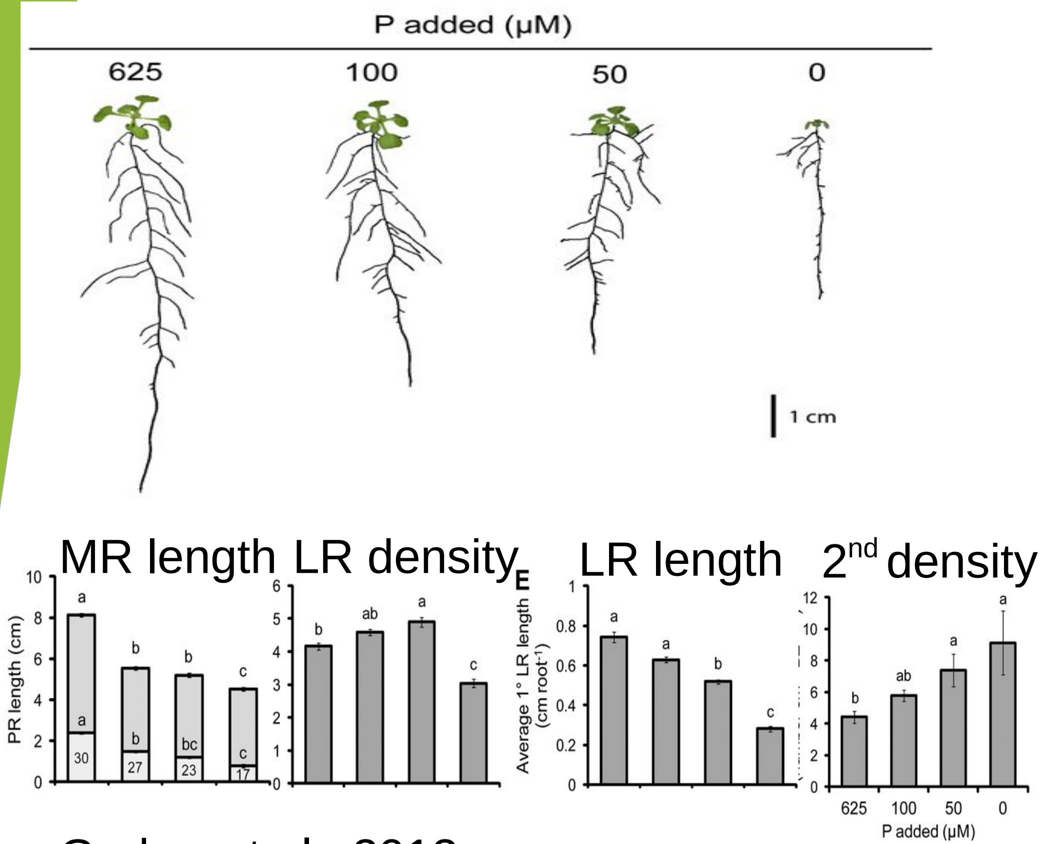


Meristem size determines density

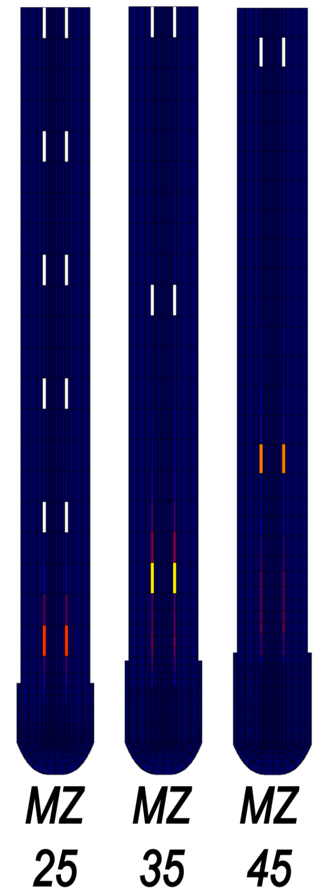




Experimental data: Inverse relation MR length and LR density



Gruber et al., 2013

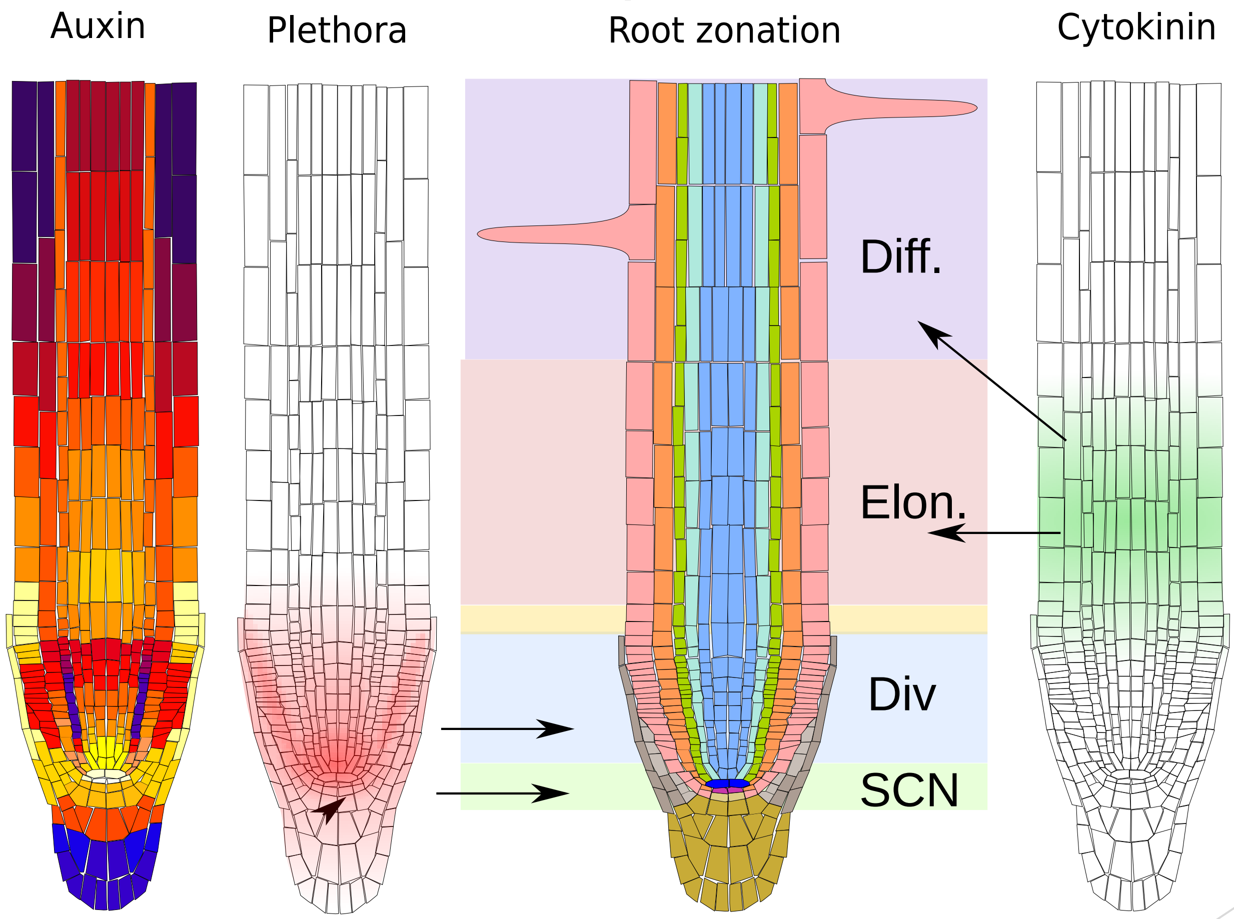


Two sides of the same coin?

Vd Berg et al.
BioRxiv 2018

Growing new roots

Auxin, PLT and CK pattern zonation



Growing new roots

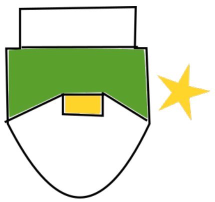
How to **initiate**,

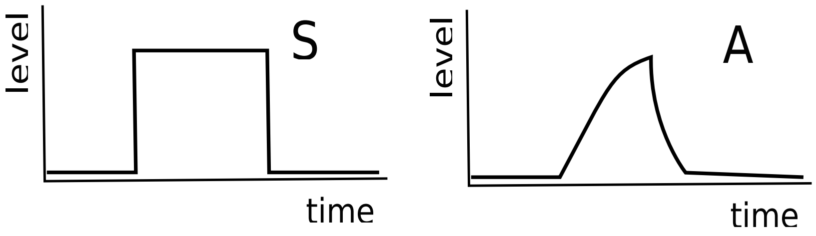
bootstrap,

grow

& tame new meristems?

$$S \longrightarrow A$$





$$\frac{dA}{dt} = p\,S - d\,A \qquad A = \frac{pS}{d}$$

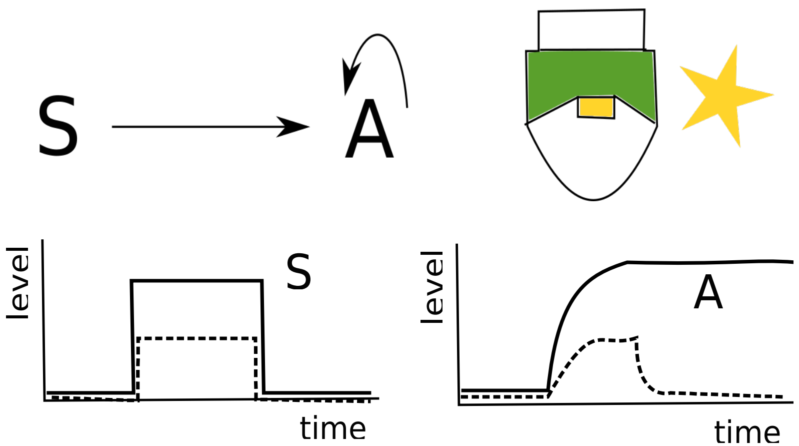
Growing new roots

How to initiate,

bootstrap,

grow

& tame new meristems?



$$\frac{dA}{dt} = p\left(S + \frac{A^2}{A^2 + K^2}\right) - d\,A$$

Bistability, A=0 or A>0 eq.

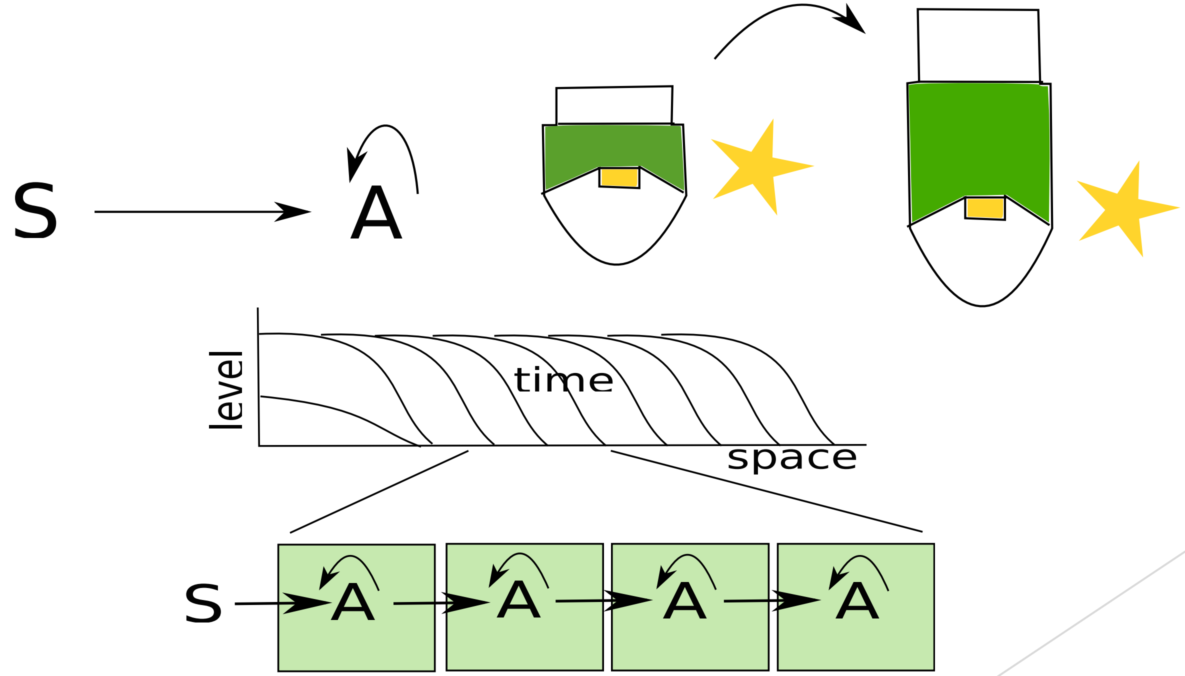
Growing new roots

How to initiate,

bootstrap,

grow

& tame new meristems?



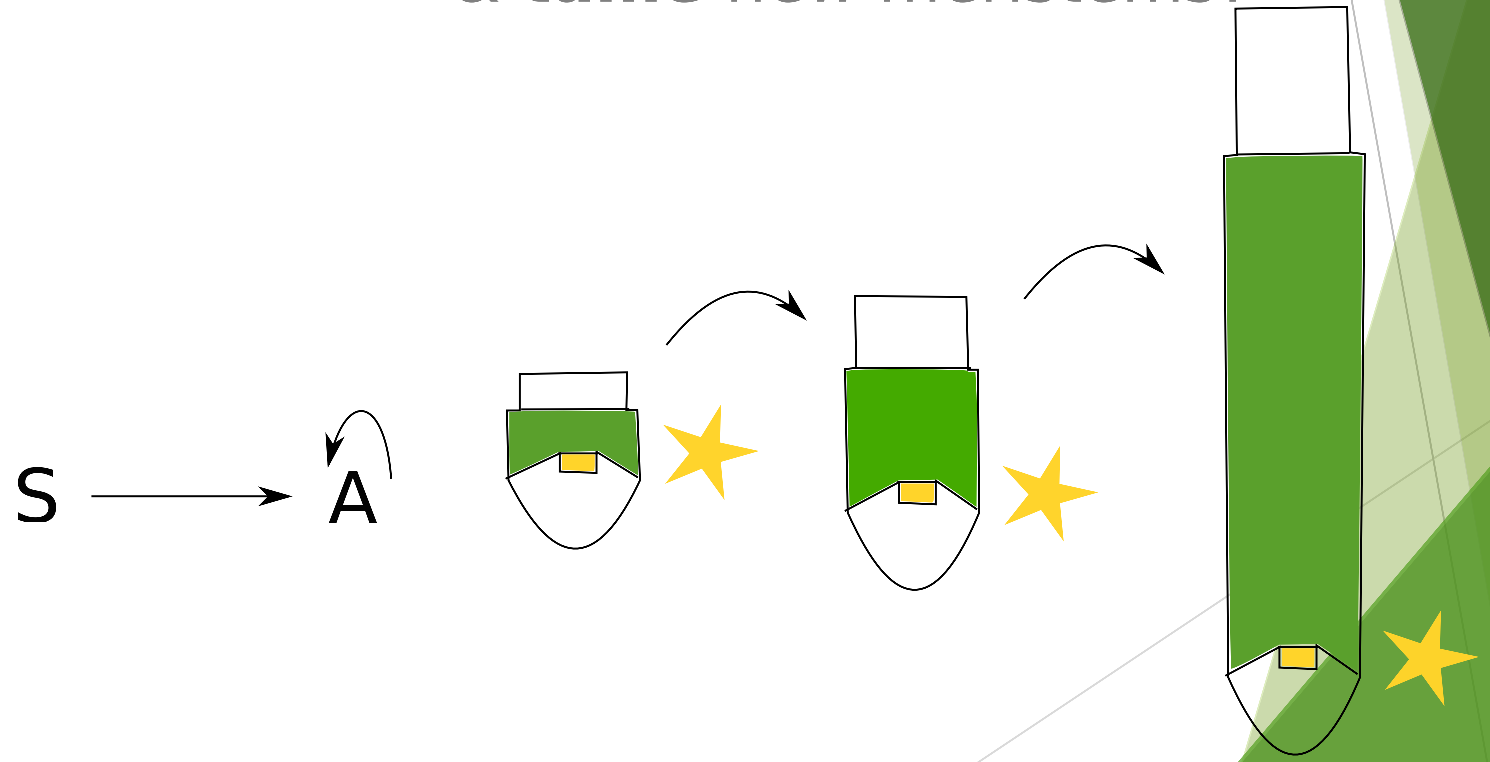
Growing new roots

How to initiate,

bootstrap,

grow

& **tame** new meristems?



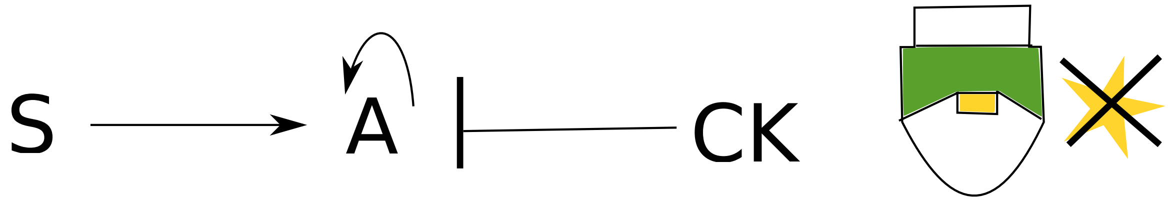
Growing new roots

How to initiate,

bootstrap,

grow

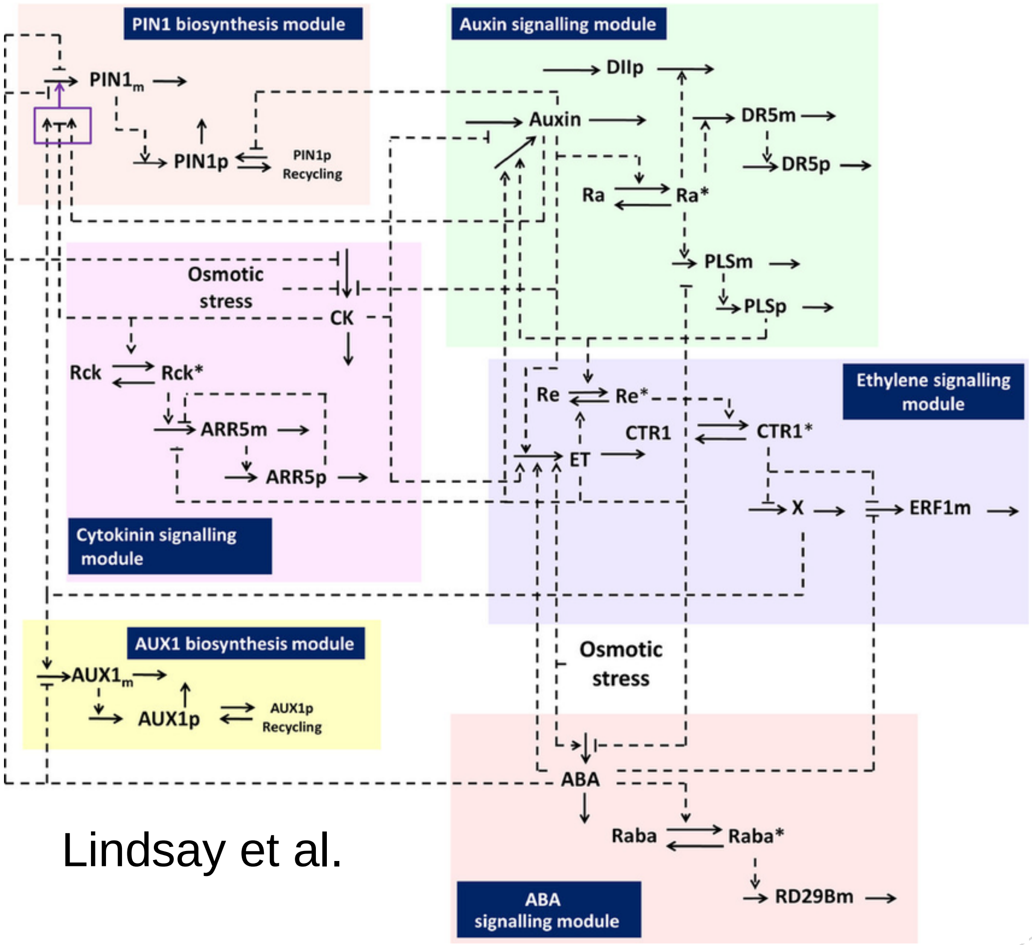
& **tame** new meristems?



Special requirements on the brake!

- delay ?
- spatial domain?
- constrained?

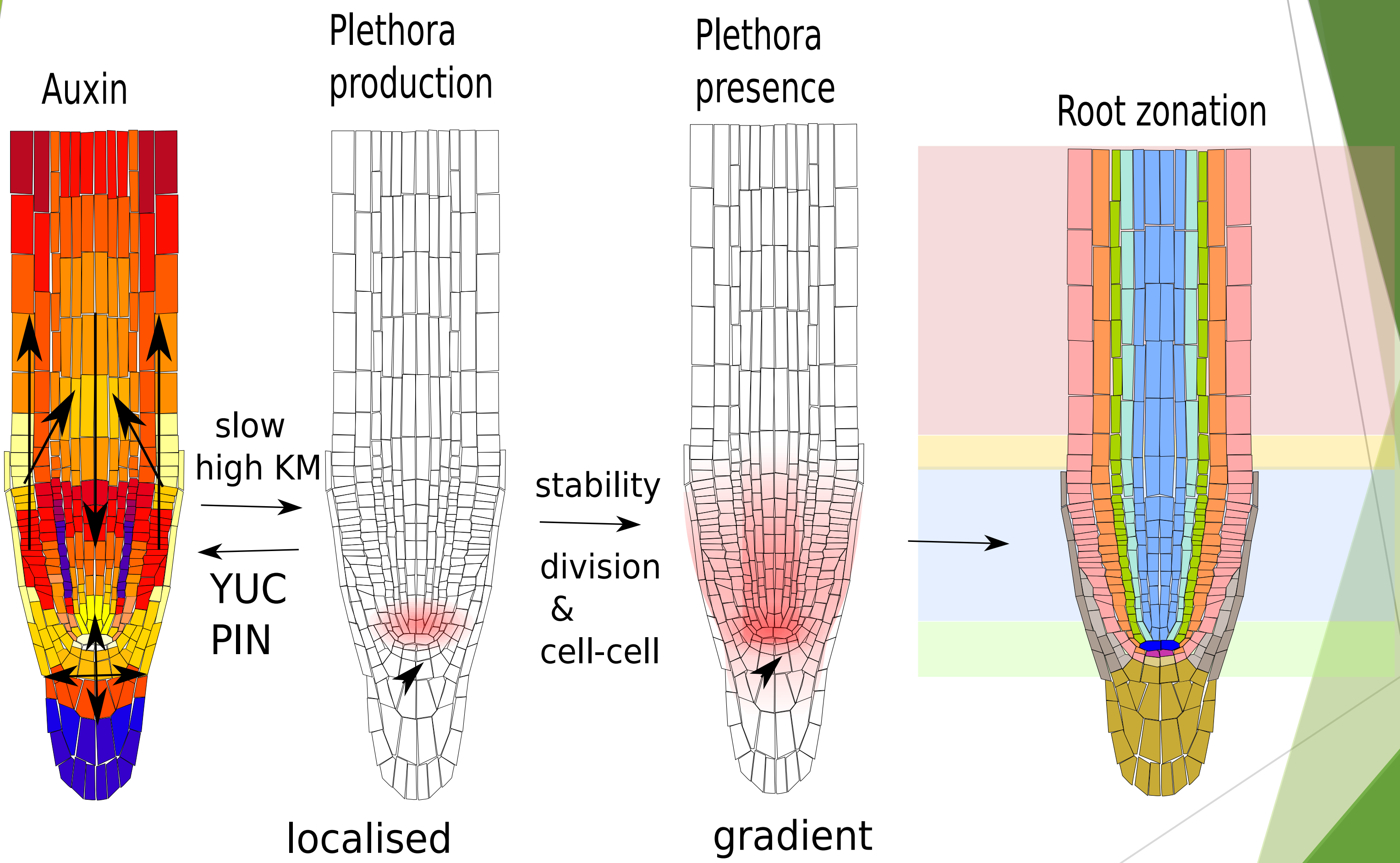
Auxin-Cytokinin crosstalk



Lindsay et al.

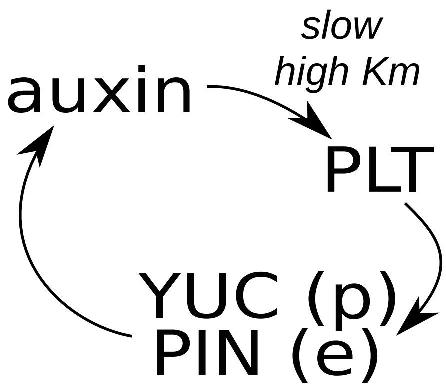
Not very insightfull…………

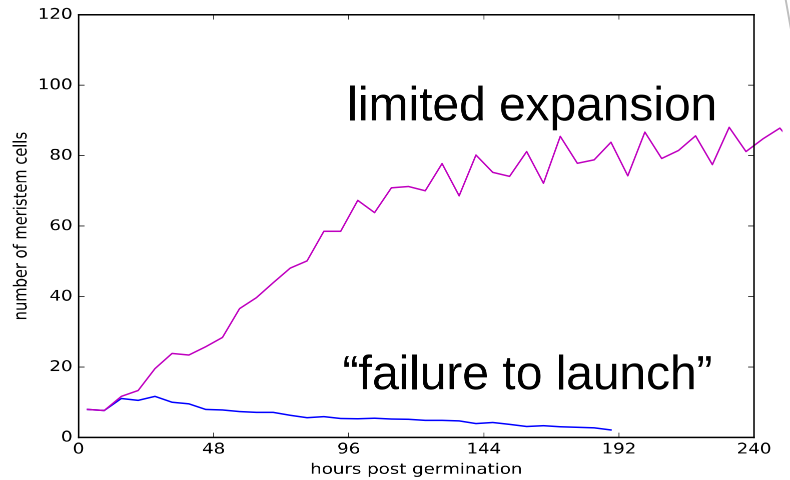
Auxins interesting partner in crime: Plethoras



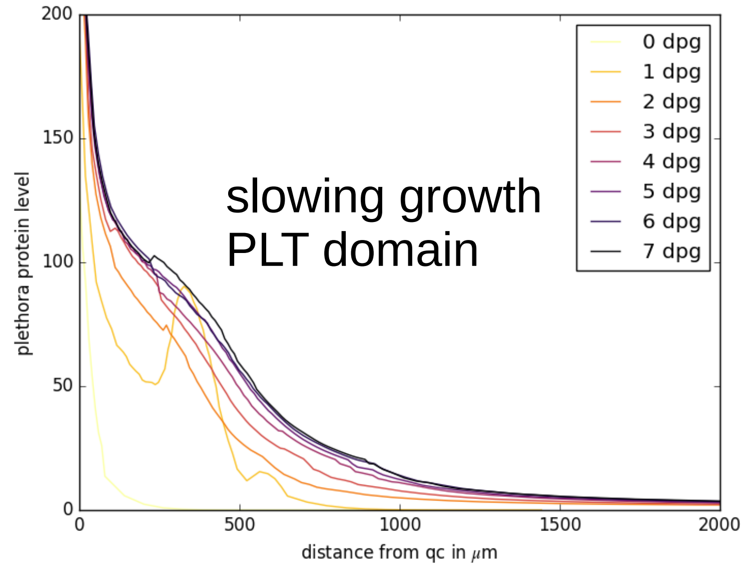
Growth → Gradient → Growth

A limit without a brake



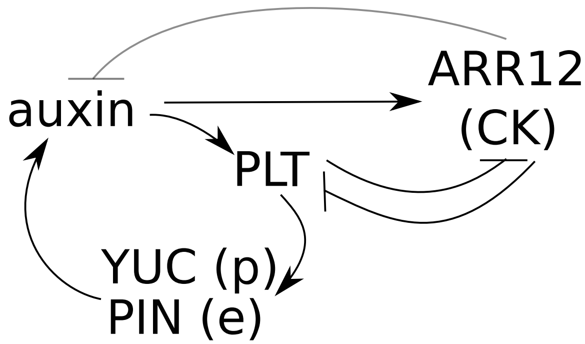


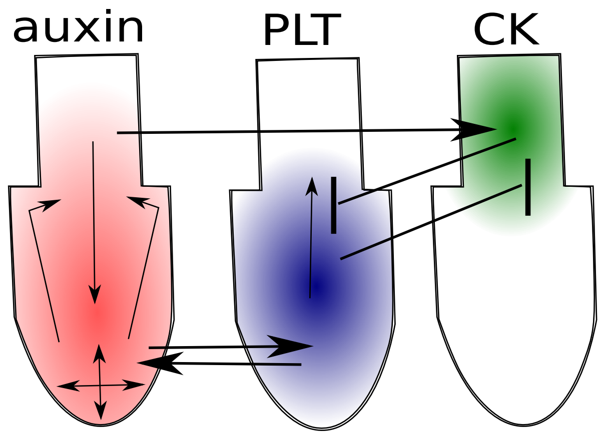
PIN reflux focusses auxin maximum & PLT production domain



Puts a halt on extension

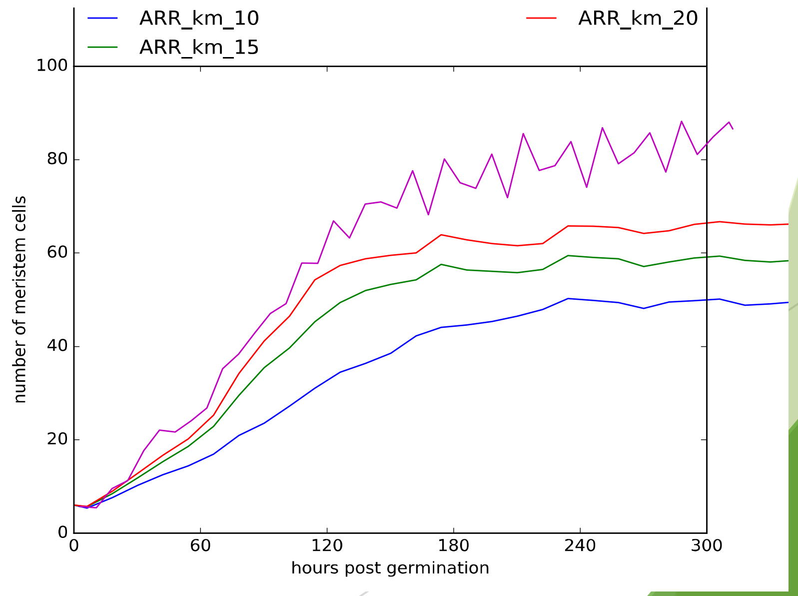
An early brake controlling PLTs



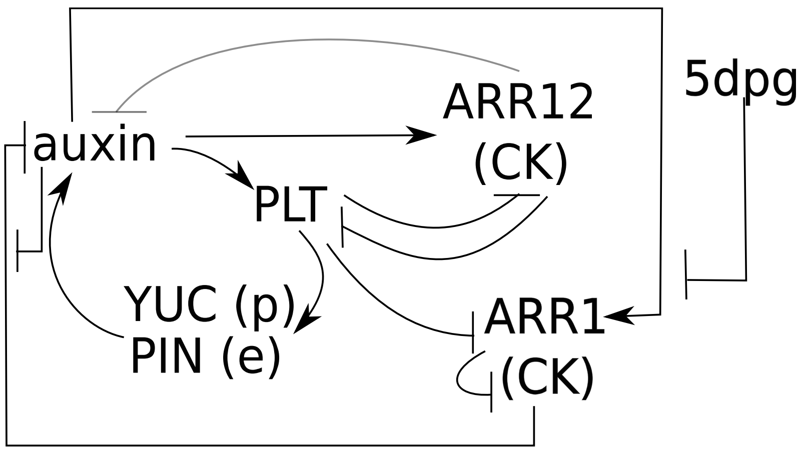


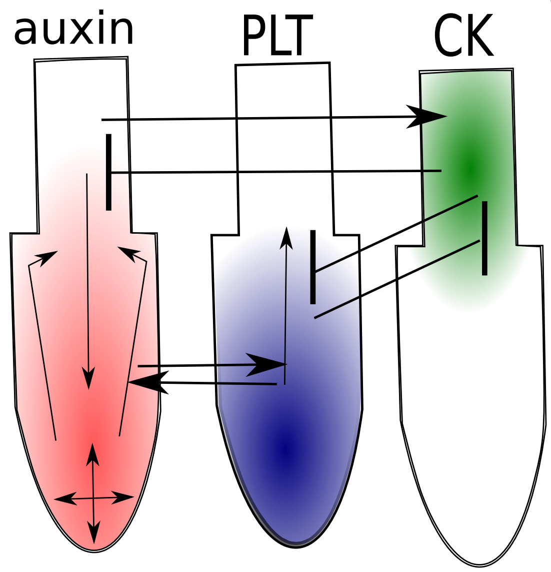
Brake targets PLT production directly

Influences growth rate



A late brake controlling auxin

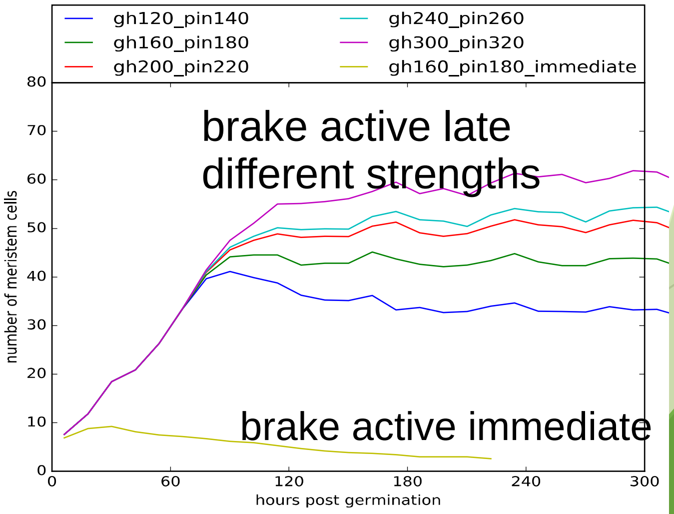




Brake targets PLTs indirect via auxins

As auxins travel this covers distance

Delay on brake
Brake on brake



Conclusions

Periodic cell size differences and auxin transport generate oscillatory lateral root priming

→ importance of growth dynamics

→ importance of size, surface/volume etc

Incoherent FFL between auxin, PLTs and CK enables activation of own brake yet keeping it at a distance

In late stages an indirect brake on PLT is more effective due to localised PLT production and extended PLT gradient

Brake requires its own brake for stability

Questions?

UU Comp. Bio group

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PhD Vacancy!

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Funding:

NWO – Vidi
NWO – Building blocks of Life
NWO/TTW - PIP

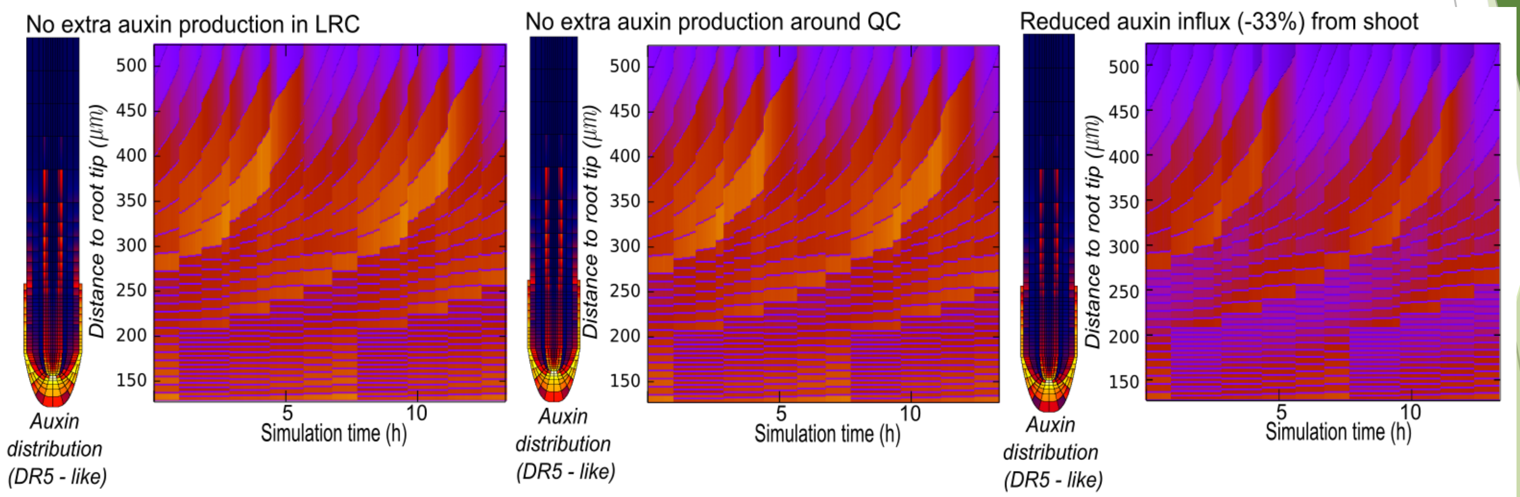
NWO Netherlands Organisation for Scientific Research

RIJK ZWAAN

Limagrain

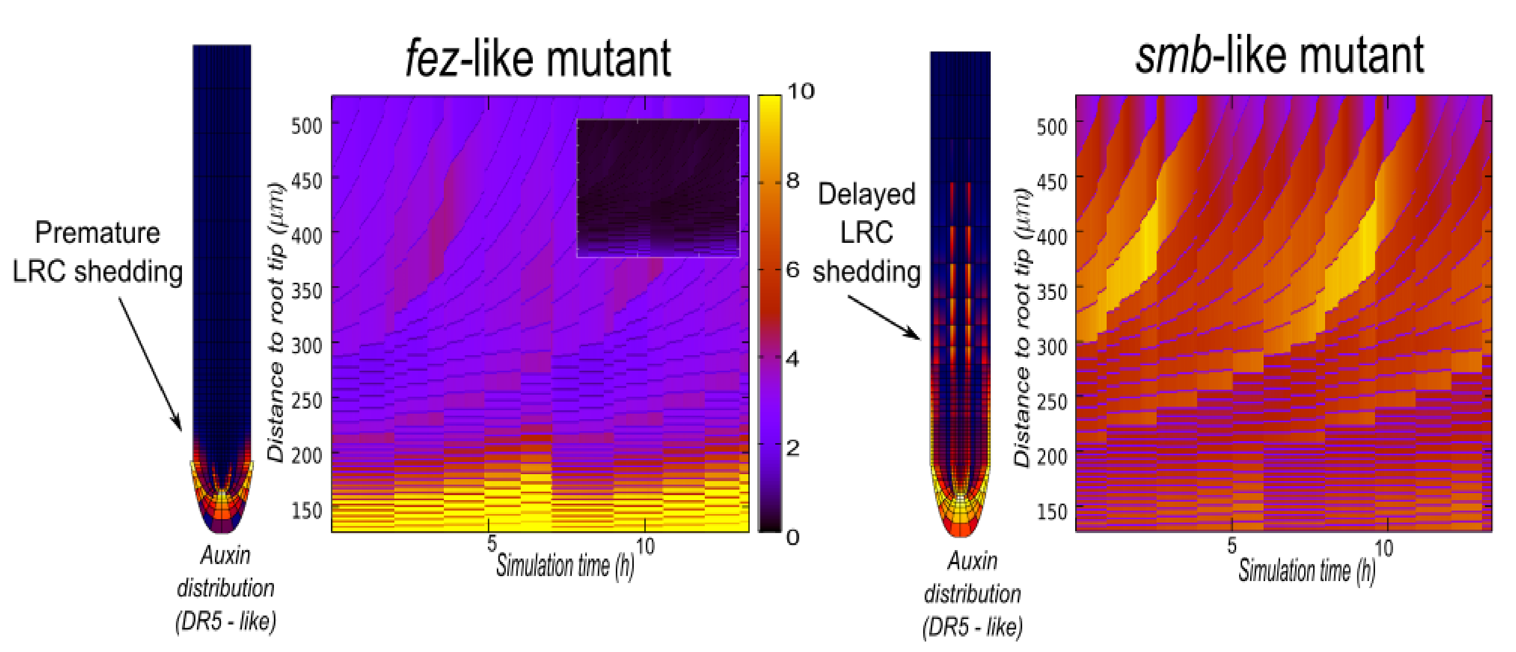
Oscillations require sufficient auxin availability

Location of auxin production not relevant



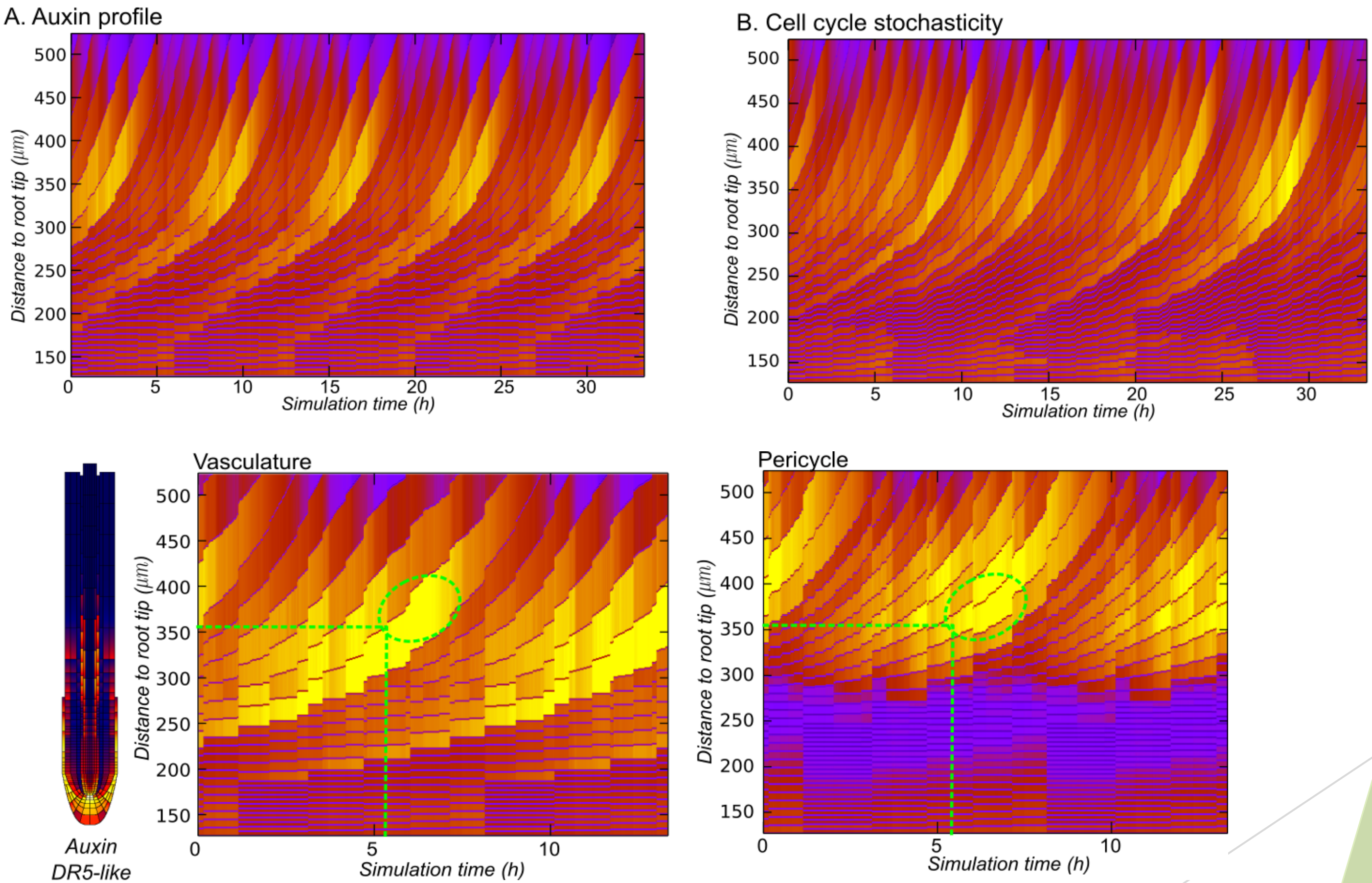
Consistent with IBA mutants having less LRs: reduced priming success

Oscillations require minimal lateral root cap size



Prediction that fez mutants have no/hardly priming

Oscillations are independent of precise growth dynamics



Division rate drives priming frequency ; not always 1 to 1