Engineering and physical challenges to engineered crops

KAARE H. JENSEN
DEPARTMENT OF PHYSICS
TECHNICAL UNIVERSITY OF DENMARK

DTU

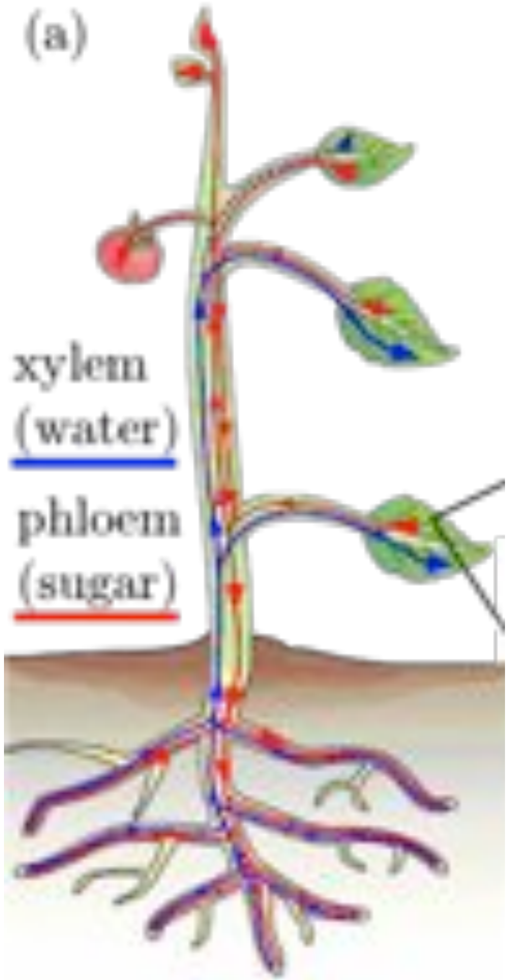
Why study sugar transport in plants?

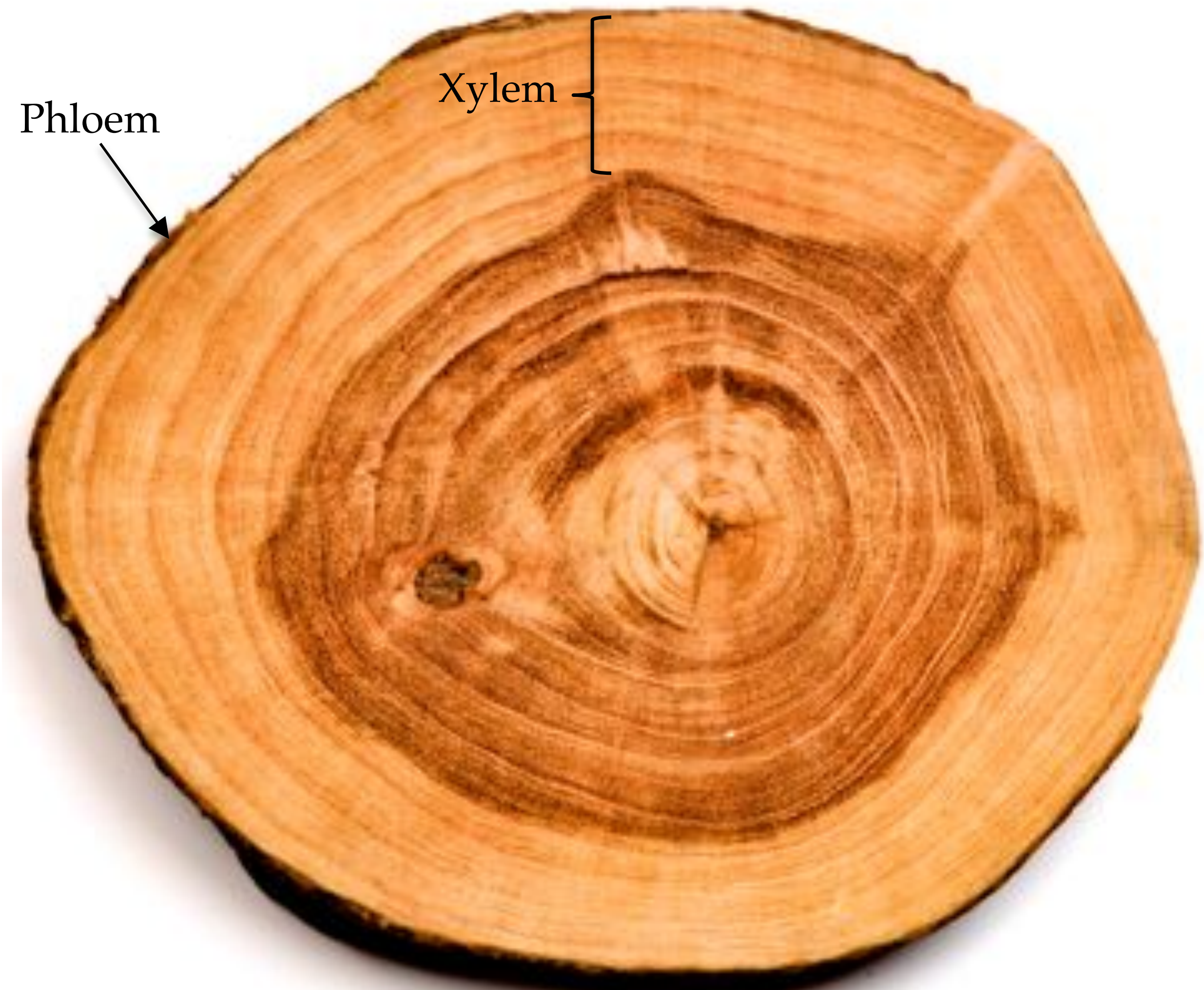




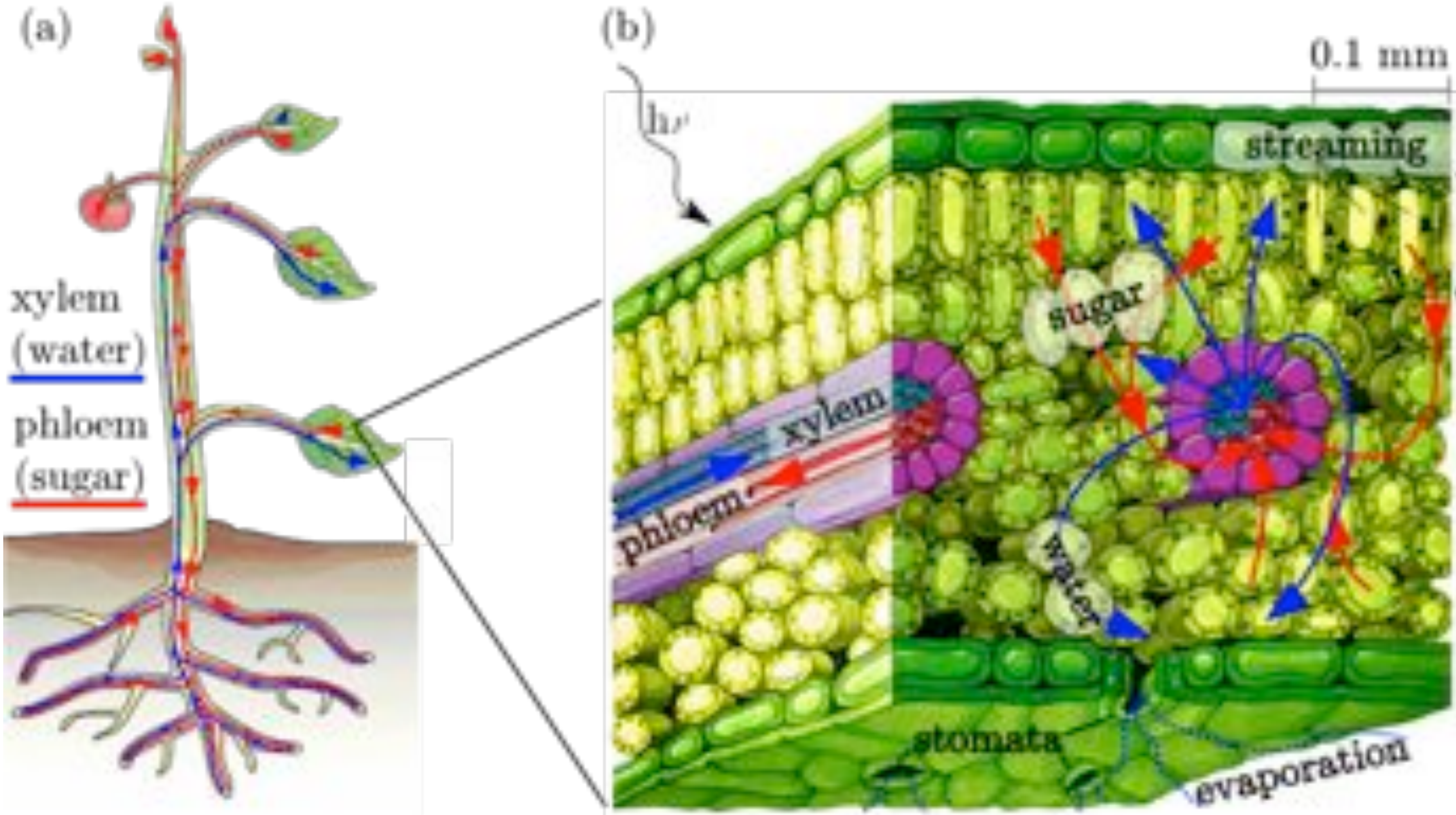
www.wikipedia.org

Liquid dynamics in plants





Liquid dynamics in plants



Liquid dynamics in plants

Phloem

- Sugar transport
  - Sugar: 1 kg/day
  - Water: 4 kg/day

Xylem

- Water transport
  - Water uptake: 100 kg/day
  - Evaporation: 95 kg/day
  - Photosynthesis: 1 kg/day
  - Phloem: 4 kg/day

Phloem

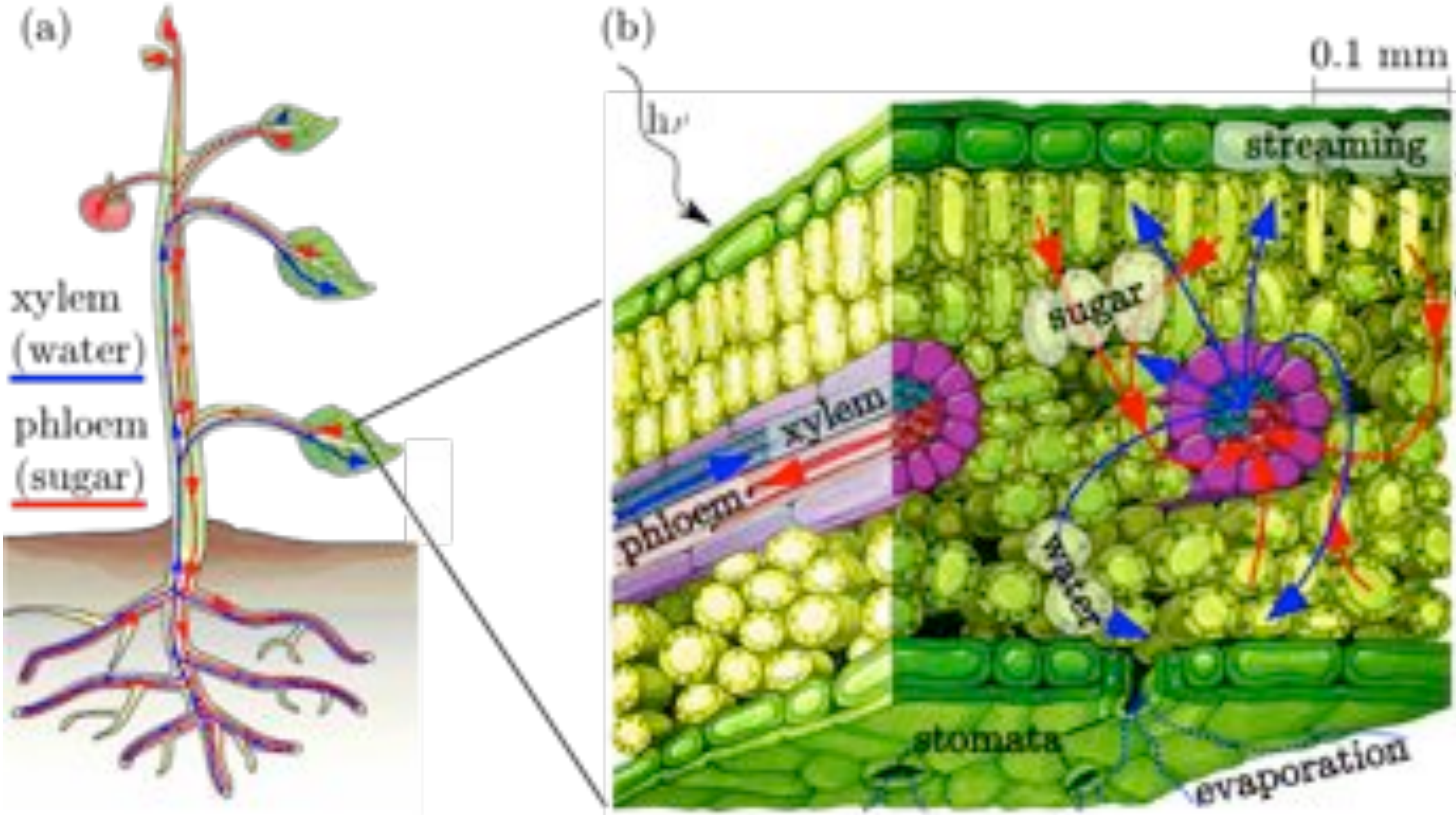
- Cell diameter: 10 μm
- Flow velocity: 100 μm/s
- Reynolds number: 10^{-3}

Xylem

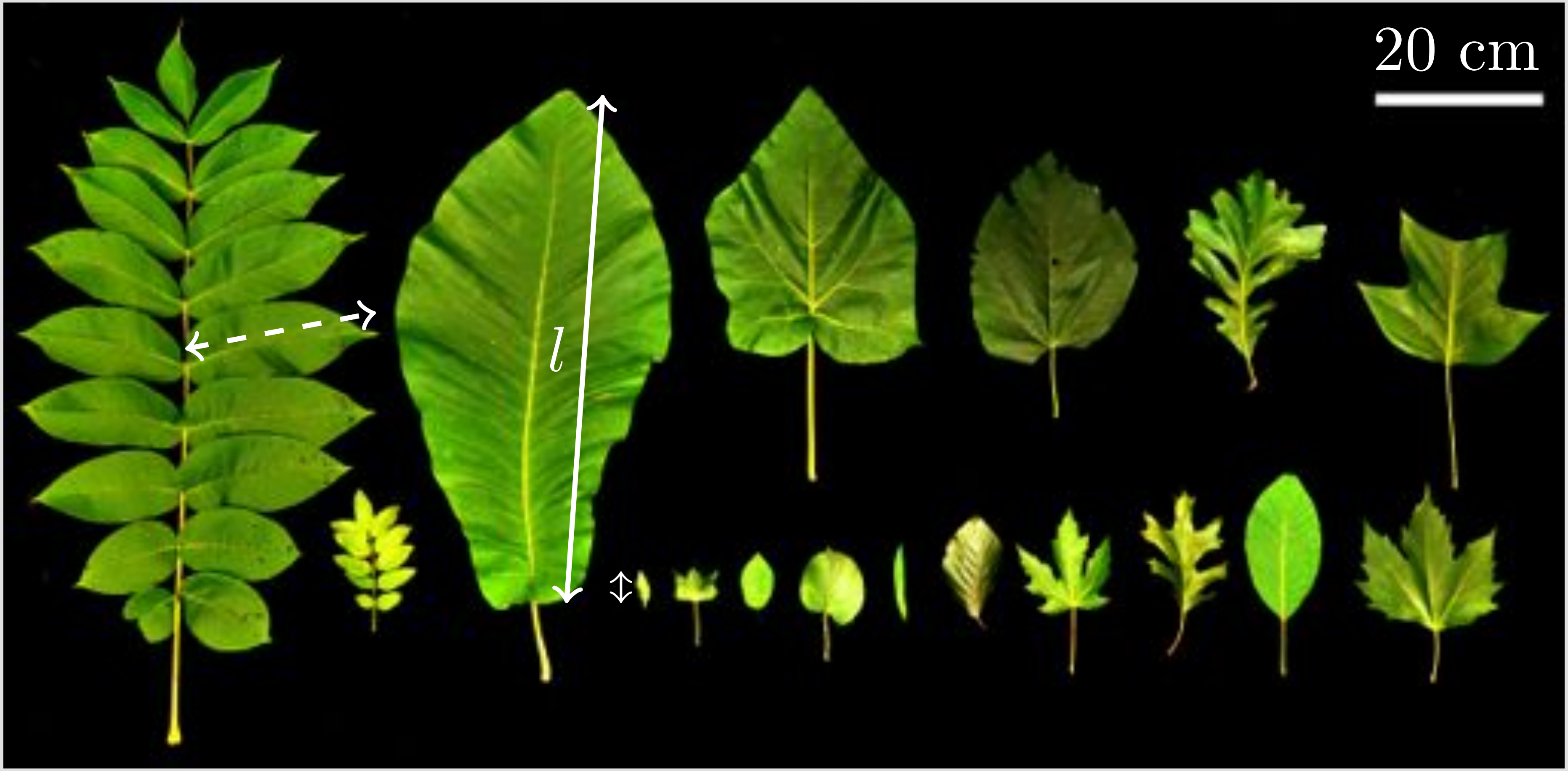
- Cell diameter: 100 μm
- Flow velocity: 1 mm/s
- Reynolds number: 10^{-1}

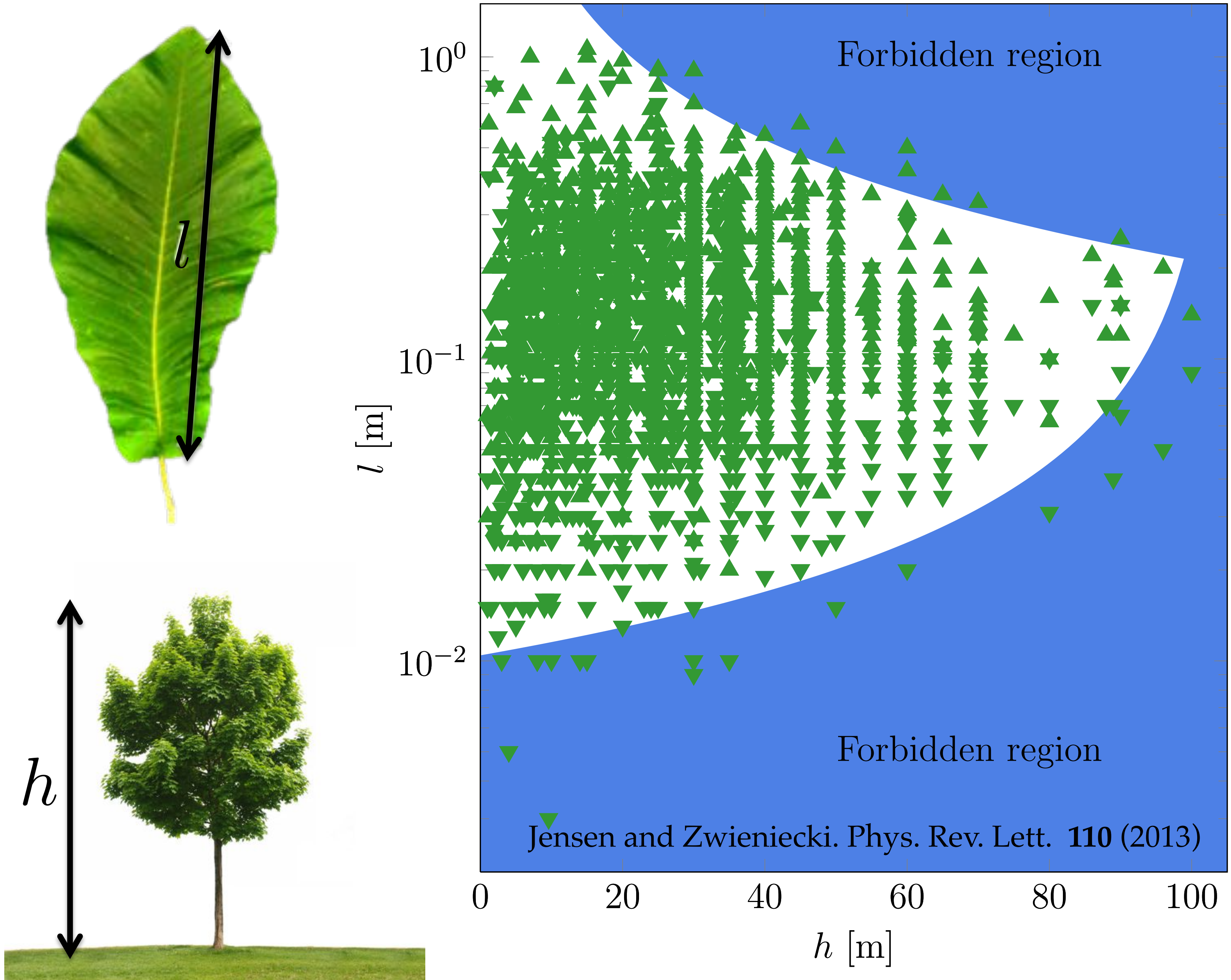
See e.g. Vogel, *The life of a Leaf* (2012).

Physical challenges



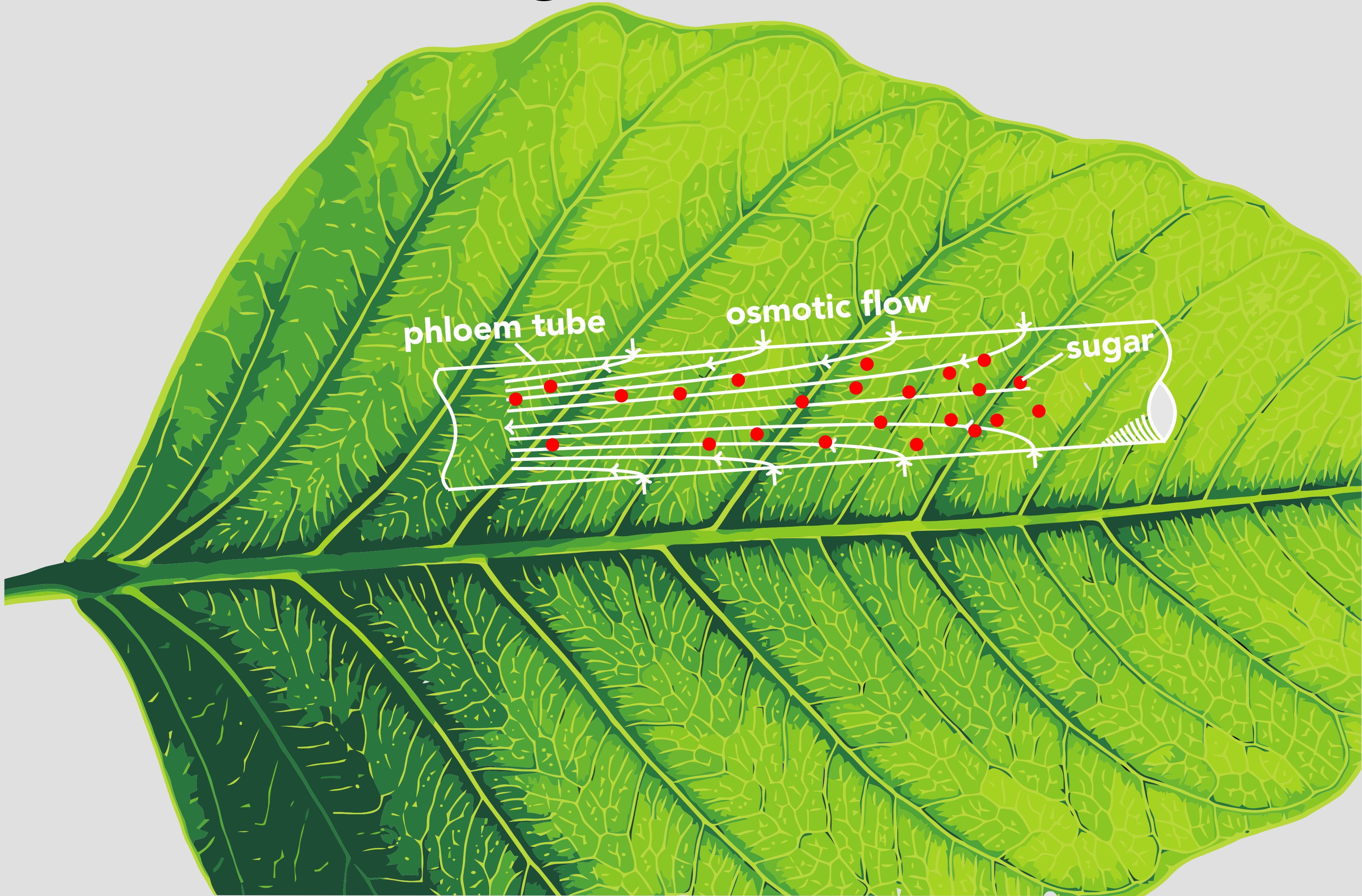
Leaf size



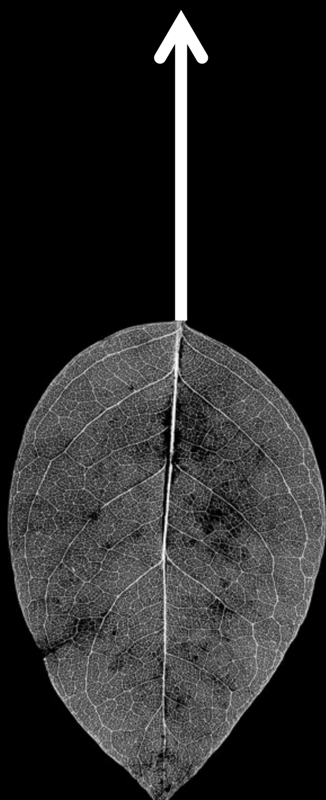


l
h
Forbidden region
Forbidden region
10^0
10^{-1}
10^{-2}
l [m]
0
20
40
60
80
100
h [m]
Jensen and Zwieniecki. Phys. Rev. Lett. **110** (2013)

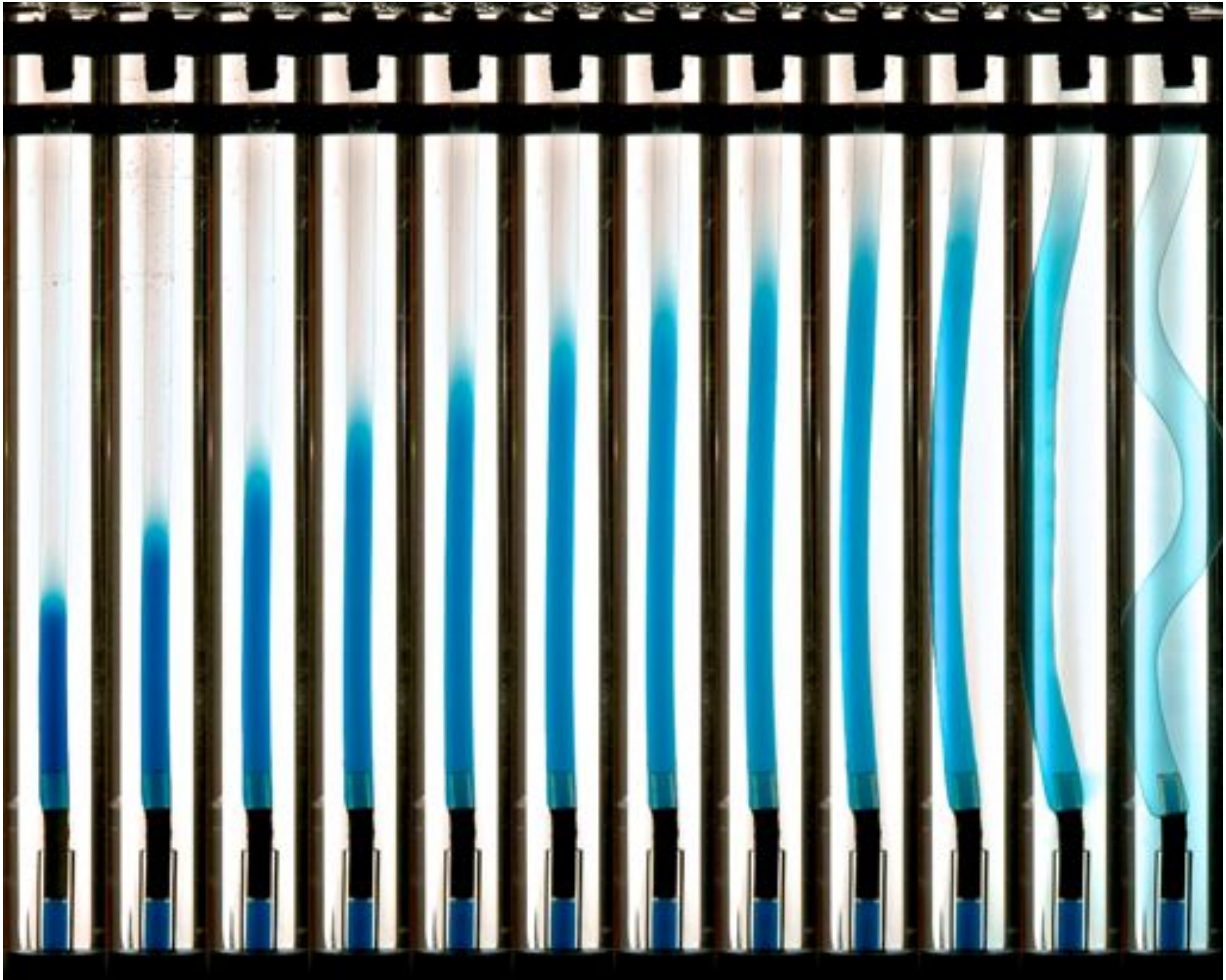
Sugar flow



The leaf, an osmotic pump



1 cm, 5 frames/hour



Jensen, Rio, Hansen, Clanet, Bohr. J.Fluid Mech. **636** (2009)

Sugar speed – scaling analysis

- Leaf dominant $R_l = \dfrac{1}{2\pi r l L_p}$

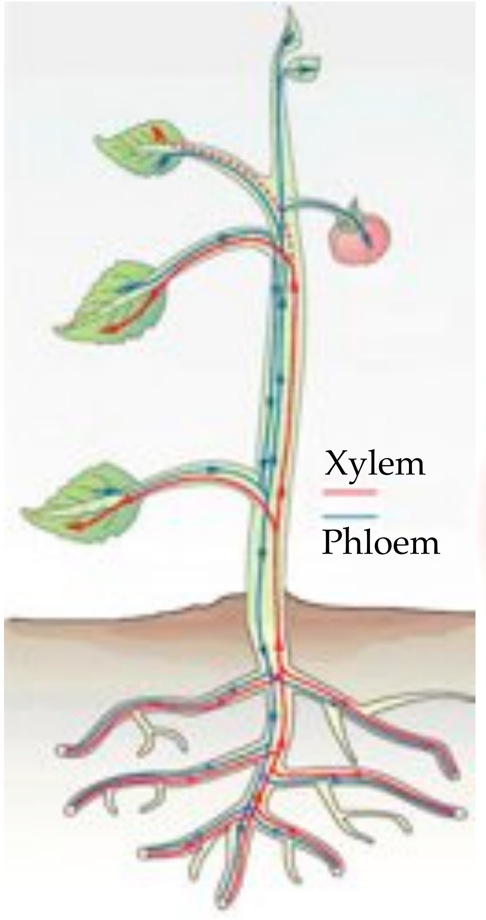
$$u = \frac{2L_p l}{r}\Delta p$$

- Stem dominant $R_s = \dfrac{8\eta h}{\pi r^4}$

$$u = \frac{r^2}{8\eta h}\Delta p$$

- Münch number

$$M\ddot{u} = \frac{\text{STEM}}{\text{LEAF}} = \frac{16 L_p \eta l h}{r^3}$$



Engineering challenge #1: Measuring phloem flow speed

- Radioactive tracers

  Minchin and Troughton
  Ann. Rev. Plant Physiol. **31** (1980)

- Fluorescent dye

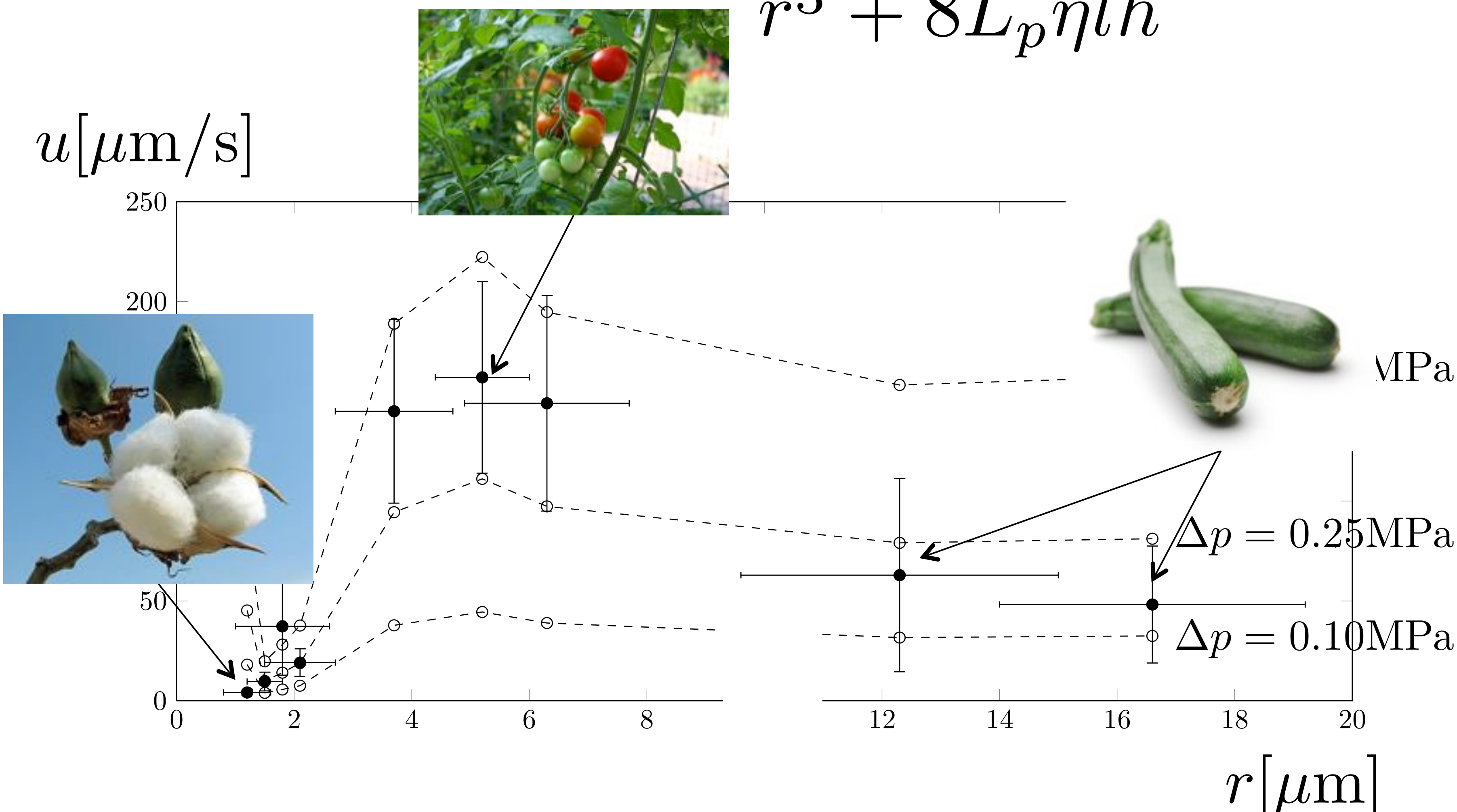
  Savage, Zwieniecki, Holbrook
  Plant Physiology **163** (2013)

- Nuclear magnetic resonance imaging (NMR)

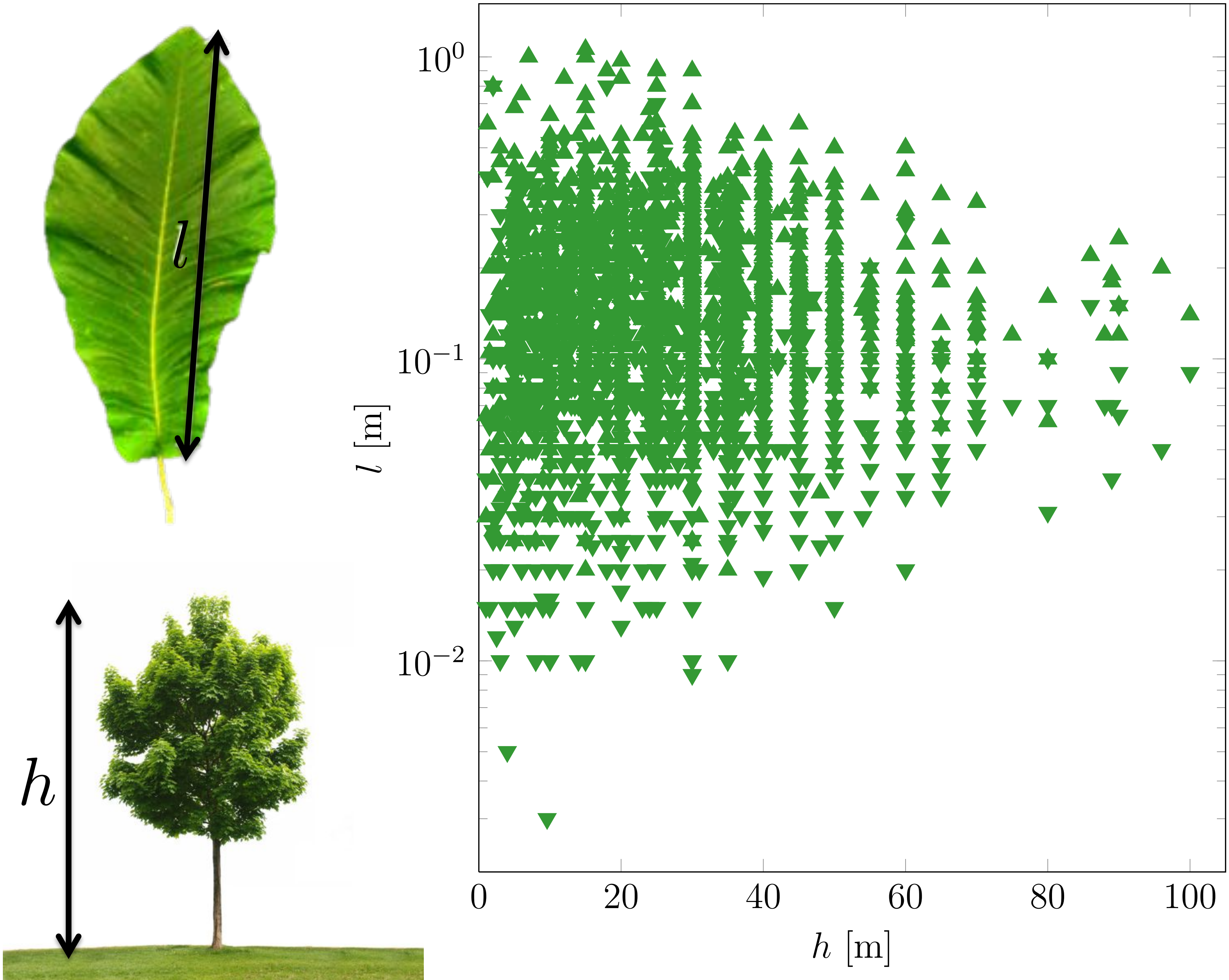
  Windt *et al*. Plant, Cell & Environment **29** (2006)

Sugar speed – scaling analysis

$$\bar{u} = \frac{L_p l r^2}{r^3 + 8 L_p \eta l h} \Delta p$$



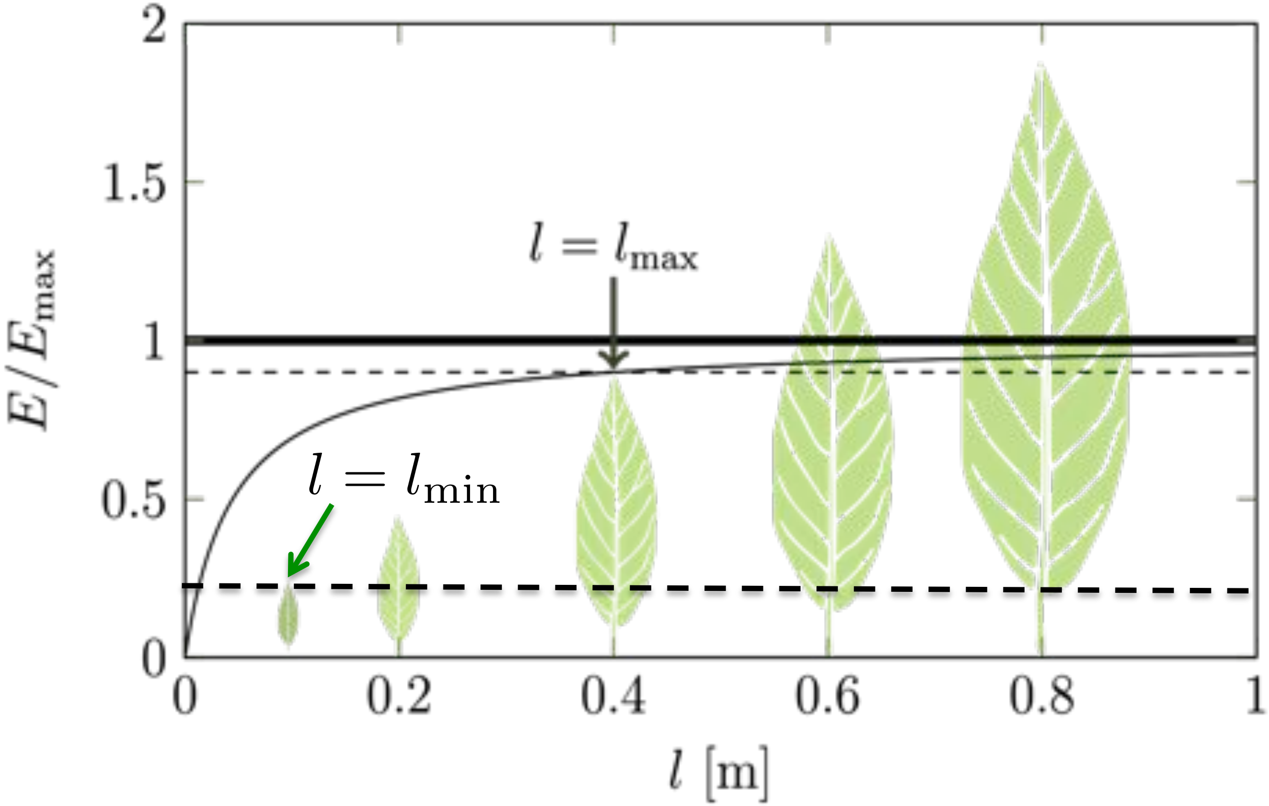
Jensen, Lee, Bohr, Bruus, Holbrook, Zwieniecki. J. Roy. Soc. Interface (2011)



l
h
10^0
10^{-1}
10^{-2}
l [m]
0
20
40
60
80
100
h [m]

Limits to Leaf Size

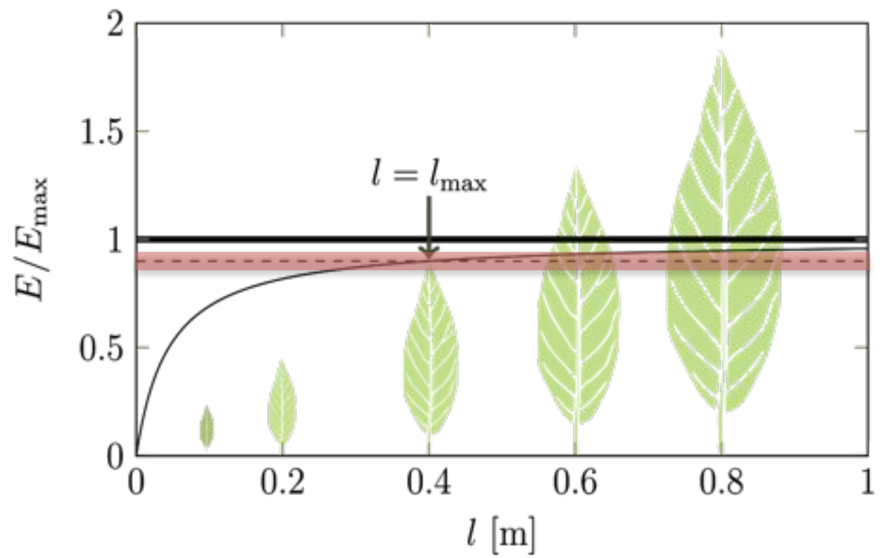
- Energy flux $E = kcu = \dfrac{2r^2 L_p l}{r^3 + 16 L_p \eta l h} kc\Delta p.$



$$E_{\max} = \frac{1}{8}\frac{r^2}{\eta h} kc\Delta p.$$

Upper limit to leaf size

- Large leaf, fast flow
  - Cost of maintaining vasculature
    $\mathcal{C} = \gamma l \pi r^2$



$$E - \mathcal{C} = 0 \Rightarrow \quad l_{\mathrm{max}} = \frac{1}{16} \frac{2r^2 L_p k c \Delta p - \gamma r^3}{\gamma L_p \eta} \frac{1}{h}$$

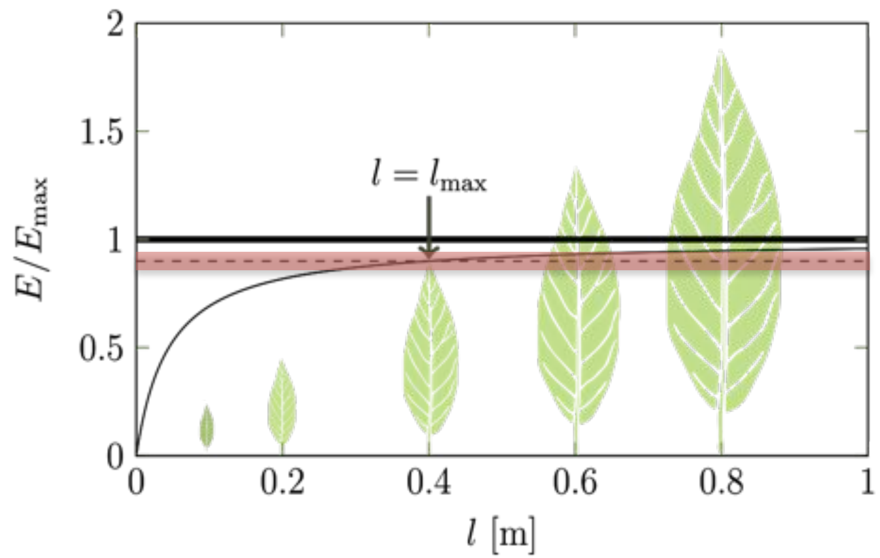
$$\boxed{l_{\mathrm{max}} \sim \frac{1}{h}}$$

Upper limit to leaf size

- Large leaf, fast flow
  - Stop growth when close to max output

$$E \sim (1-\tau)E_{\mathrm{max}} \qquad \tau \ll 1$$

$$l_{\mathrm{max}} = \frac{1}{16}\frac{r^3}{\tau L_p \eta}\frac{1}{h}$$



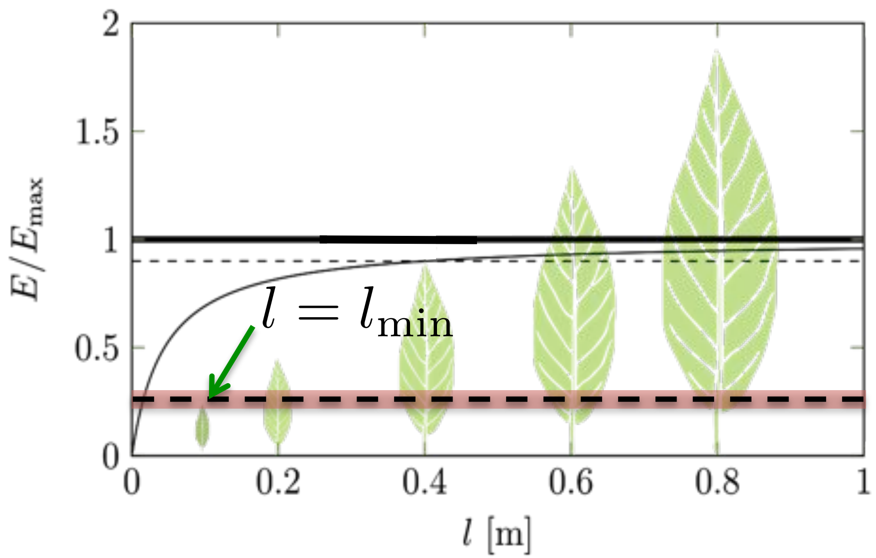
$$l_{\mathrm{max}} \sim \frac{1}{h}$$

Lower limit to leaf size

- Small leaf, slow flow
  - Bulk flow faster than diffusion

$$Pe = \frac{uL}{D} \geq 1$$

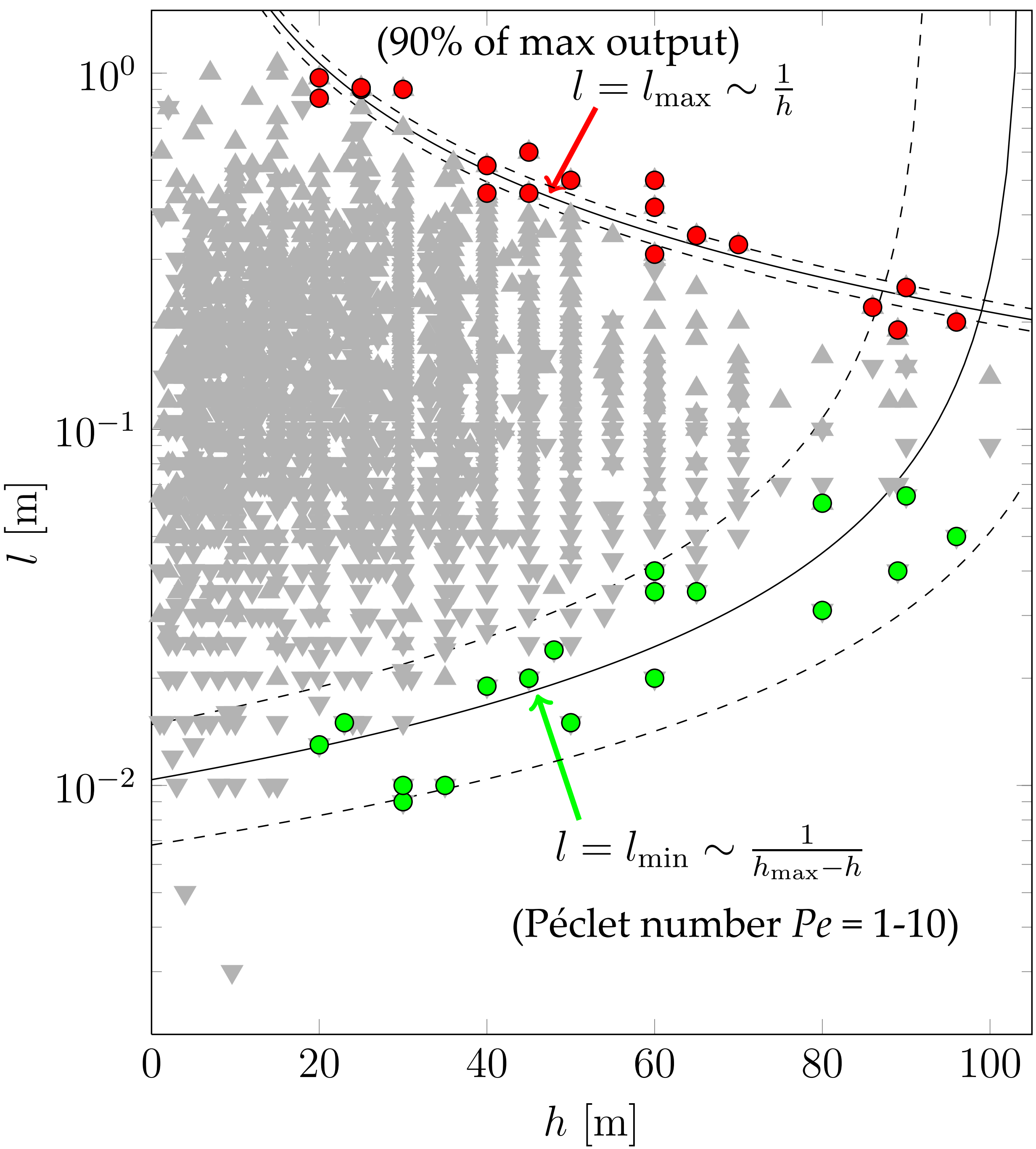
Péclet number



L	Characteristic cell-to-cell distance (10-100 μm)
D	Diffusivity

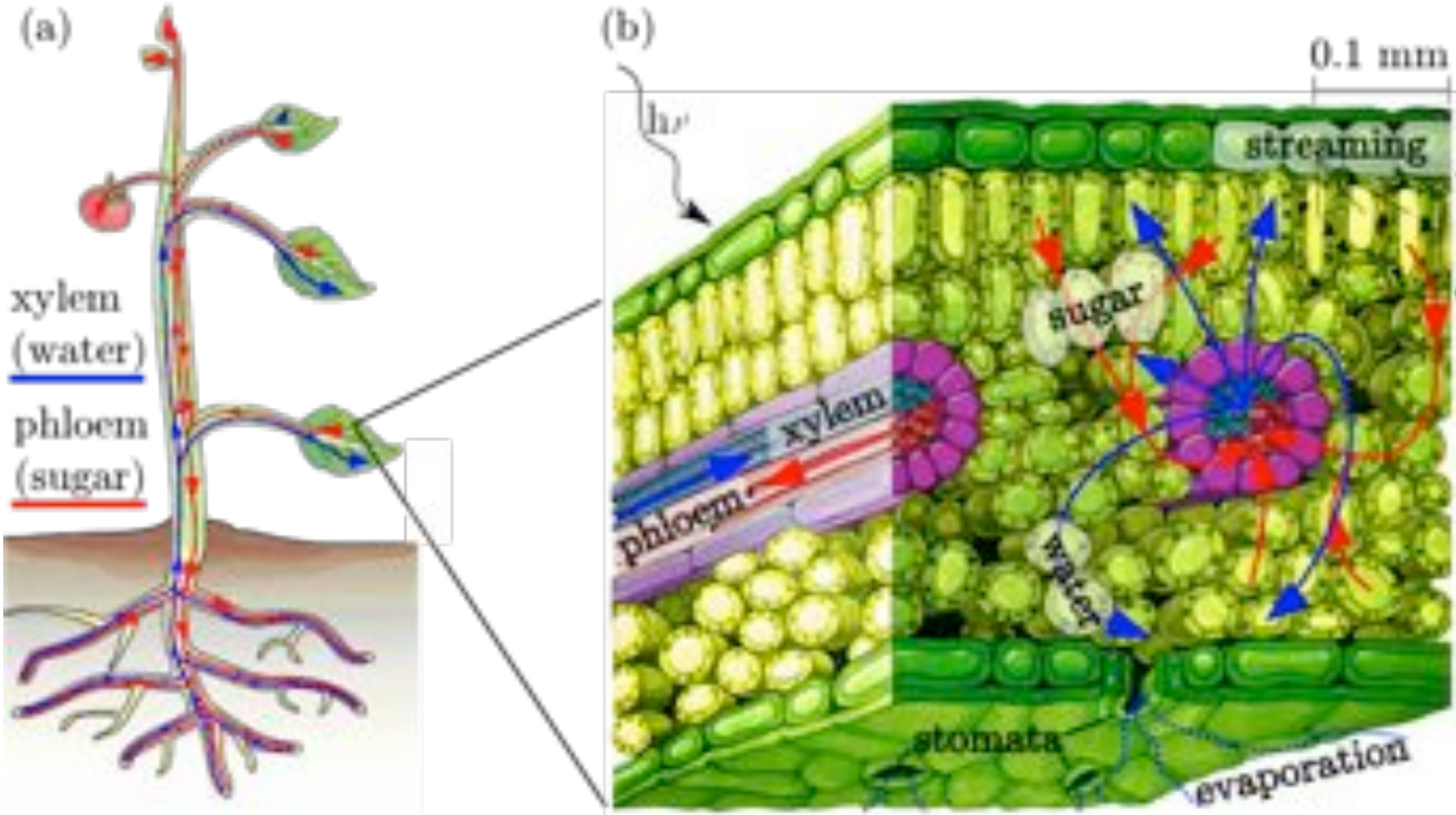
$$l_{min} = \frac{1}{16} \frac{r^3}{L_p \eta} \frac{1}{(h_{max} - h)}$$

$$h_{max} = \frac{r^2 L \Delta p}{8 \eta D} \frac{1}{Pe}$$



(90% of max output)
$l = l_{\max} \sim \frac{1}{h}$
$l = l_{\min} \sim \frac{1}{h_{\max}-h}$
(Péclet number Pe = 1-10)
10^0
10^{-1}
10^{-2}
l [m]
0
20
40
60
80
100
h [m]

Physical challenges



Engineering challenge #2: Mapping the vascular architecture

Serial light micrographs

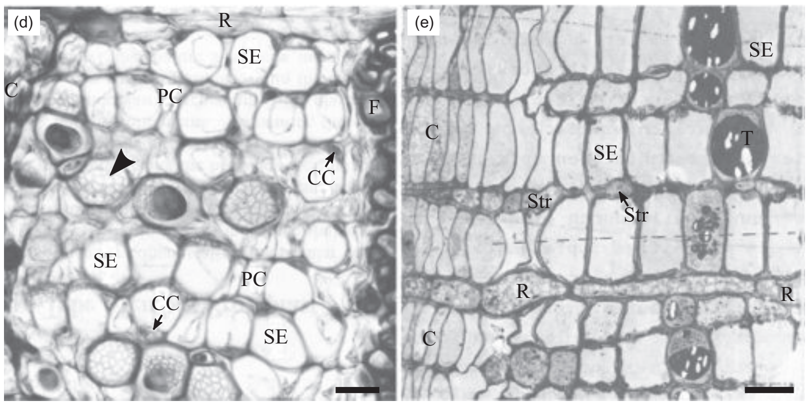
X-Ray Computed tomography

Zwieniecki *et al.*
Plant, Cell & Environment **29** (2006)

Brodersen *et al.* New Phytologist **191** (2011)
Lee *et al.* Microscopy Res. Tech. **76** (2013)

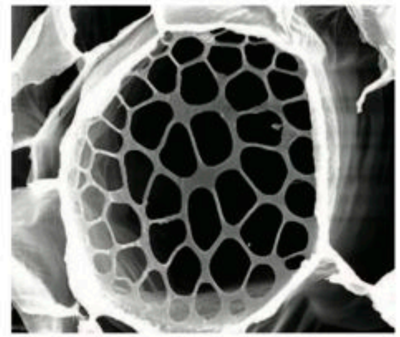
Size of individual phloem tubes

Black locust Norway spruce

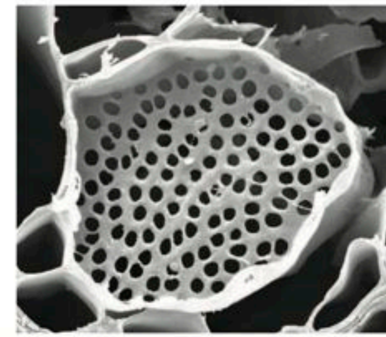


20 μm

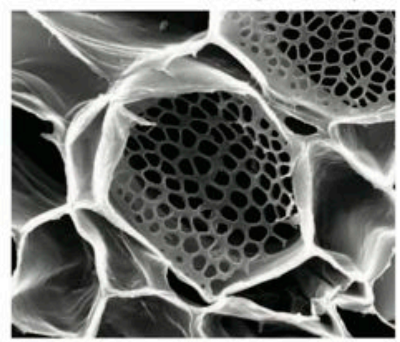
Squash 30μm



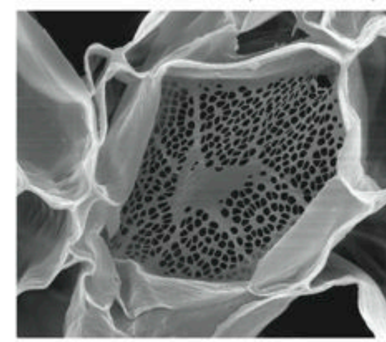
Bamboo 10μm



Green bean 10μm



Castor bean 20μm



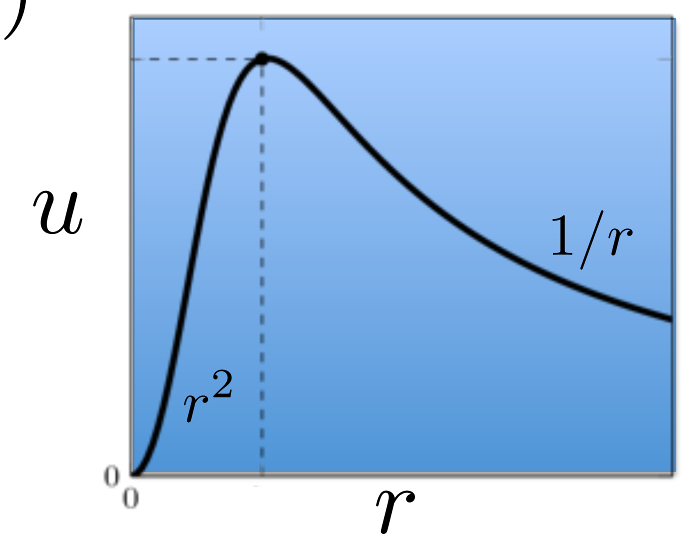
Mullendore *et al.* Plant Cell **22** (2010)
Jensen, Liesche, Bohr, Schulz. Plant, Cell & Environment **35** (2012)
Jensen, Mullendore, Holbrook, Bohr, Knoblauch. Front. Plant Sci. **3** (2012)

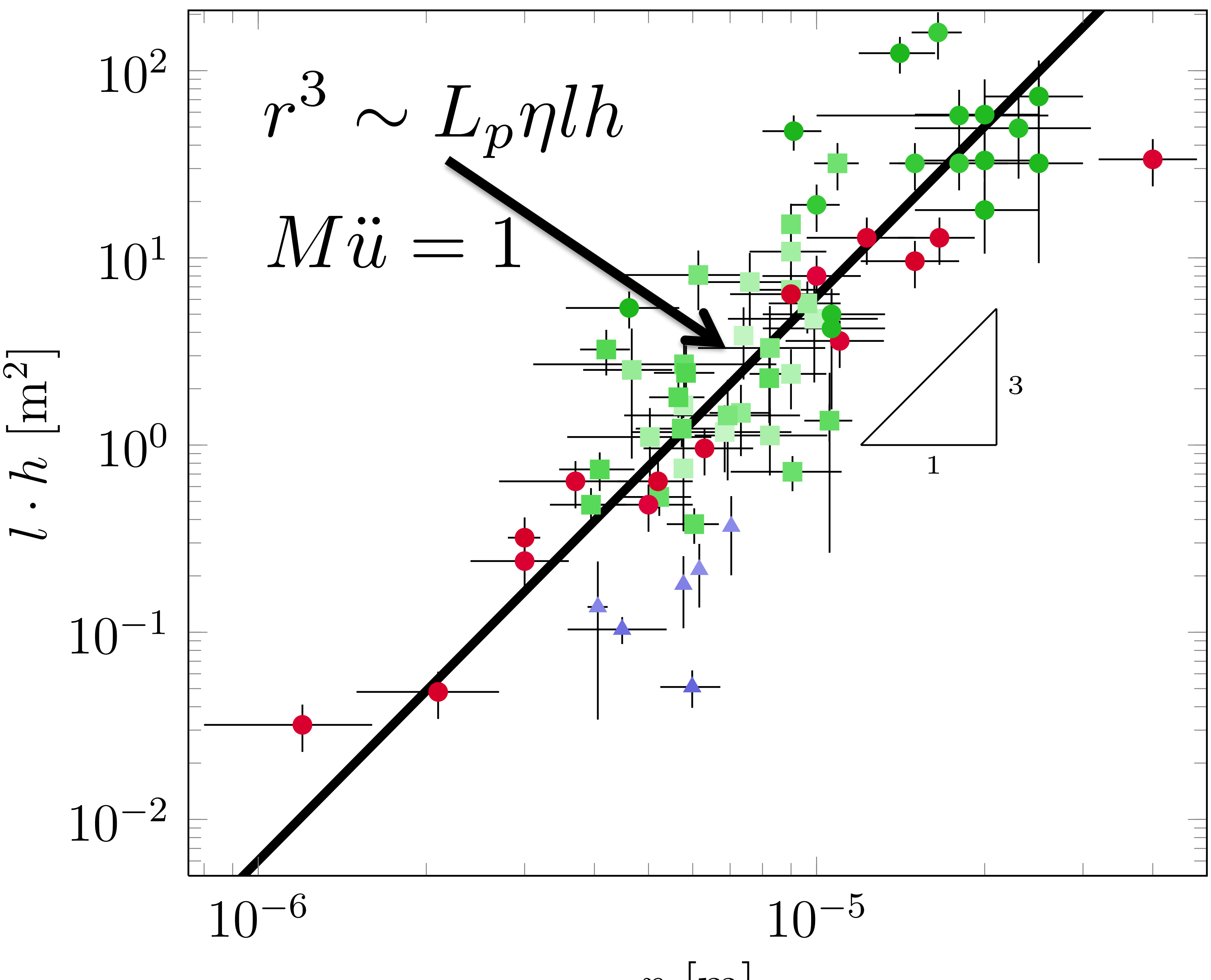
Sugar speed depends on the phloem tube size

$$u = \frac{2r^2 L_p l}{r^3 + 16\eta L_p l h} \Delta p$$

- Fixed leaf and stem length, speed optimal when $R_s = R_l$ $(M\ddot{u} = 1)$

$$r^3 \sim L_p \eta l h$$





Jensen, Lee, Bohr, Bruus, Holbrook, Zwieniecki. J. Roy. Soc. Interface (2011)

Phloem Sap Composition

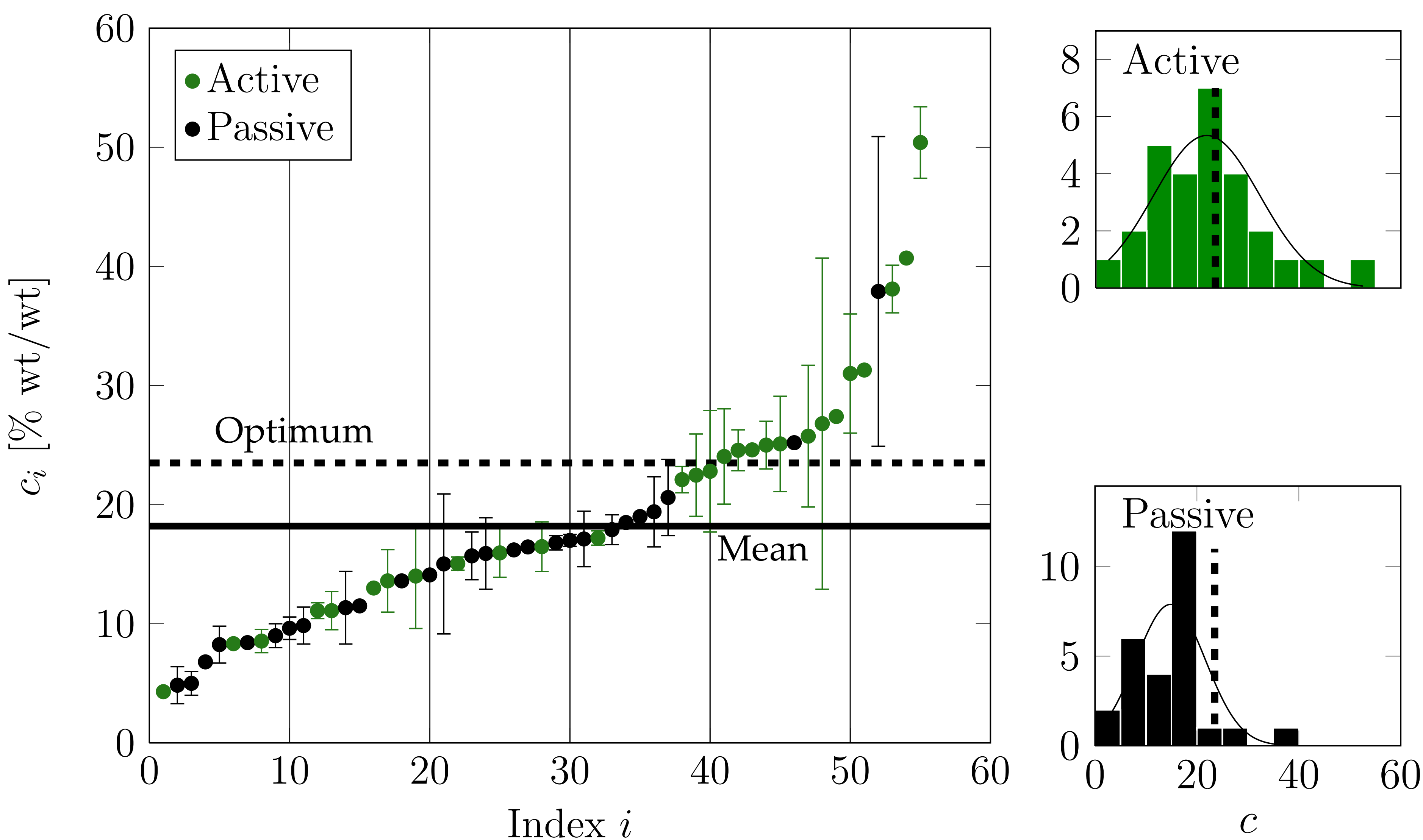
- ~ 20 % sugars
  - **sucrose,** glucose, fructose, sorbitol, mannitol, raffinose, stachyose…
- ~ 1 %
  - Proteins, amino acids, hormones, signaling molecules

Engineering challenge #3: Drawing blood from a plant

- Bleeding
- Aphid stylectomy

Fisher and Frame. Planta **161** (1984)
Munns (Ed.) Plants in Action (2010)

Zimmerman. Plant Physiology **32** (1957)



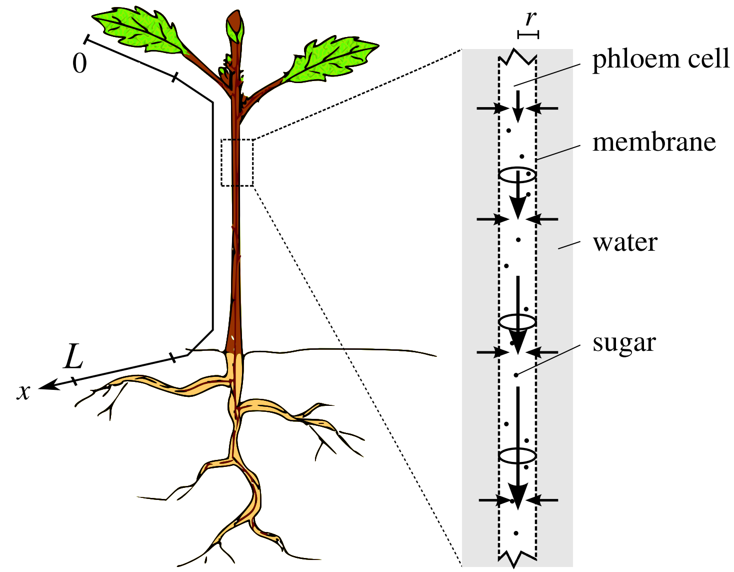
Jensen, Lee, Holbrook, Bush.
J. Roy. Soc. Interface **10** (2013)

Jensen, Savage, Holbrook.
J. Roy. Soc. Interface **10** (2013)

Sugar flow in the stem

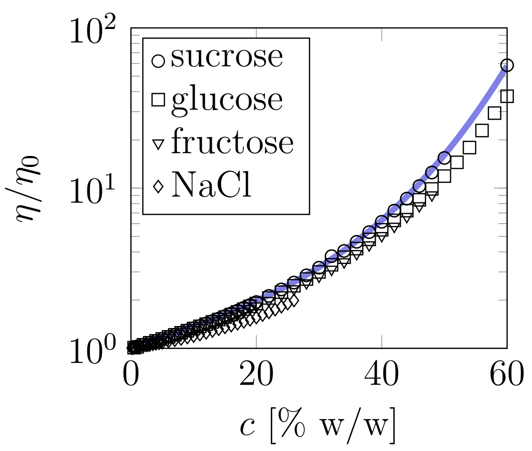
- Volume flow

$$Q = \frac{\pi r^4}{8} \frac{\Delta p}{L} \frac{1}{\eta(c)}$$

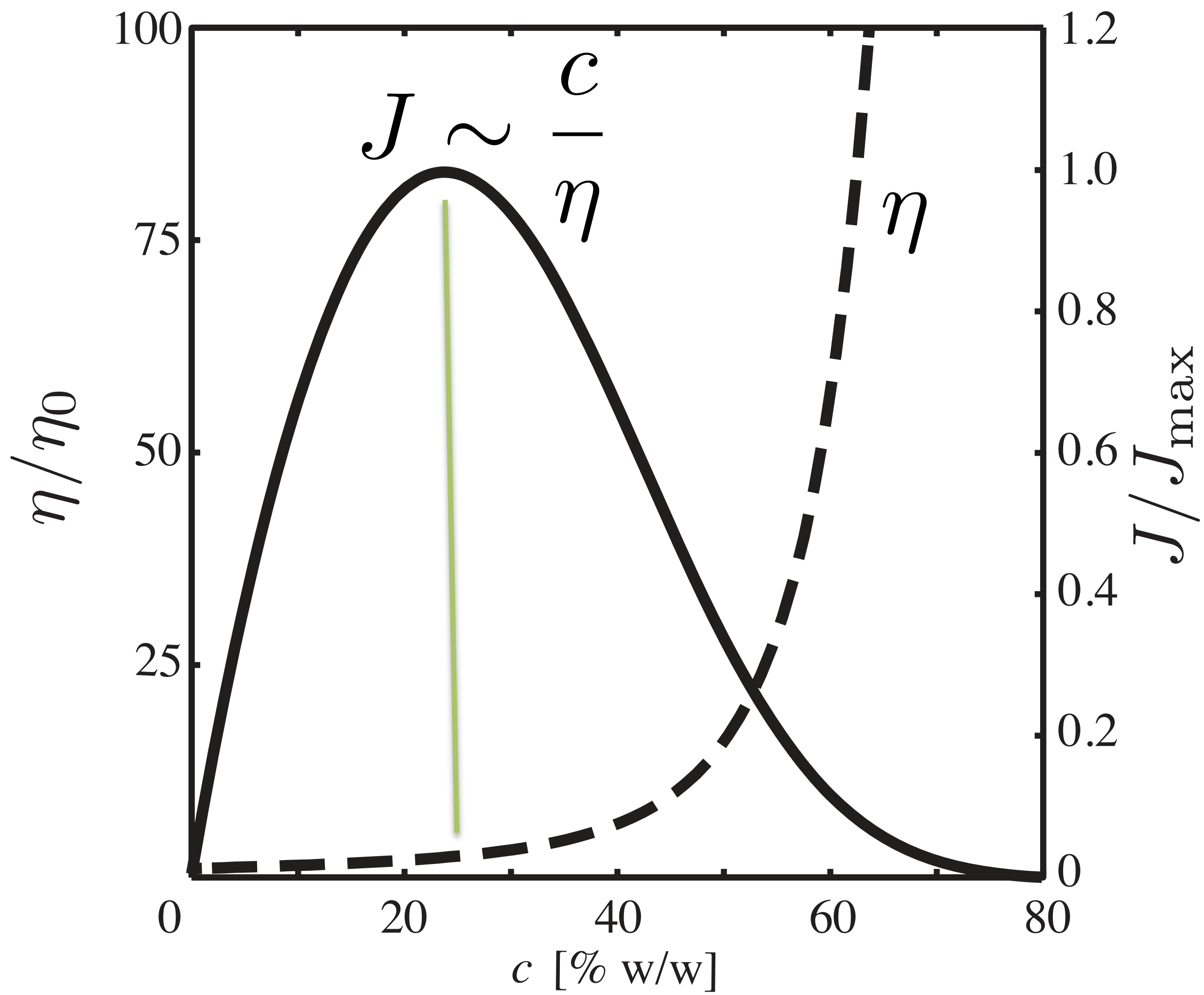


- Sugar mass flow $J = Qc$

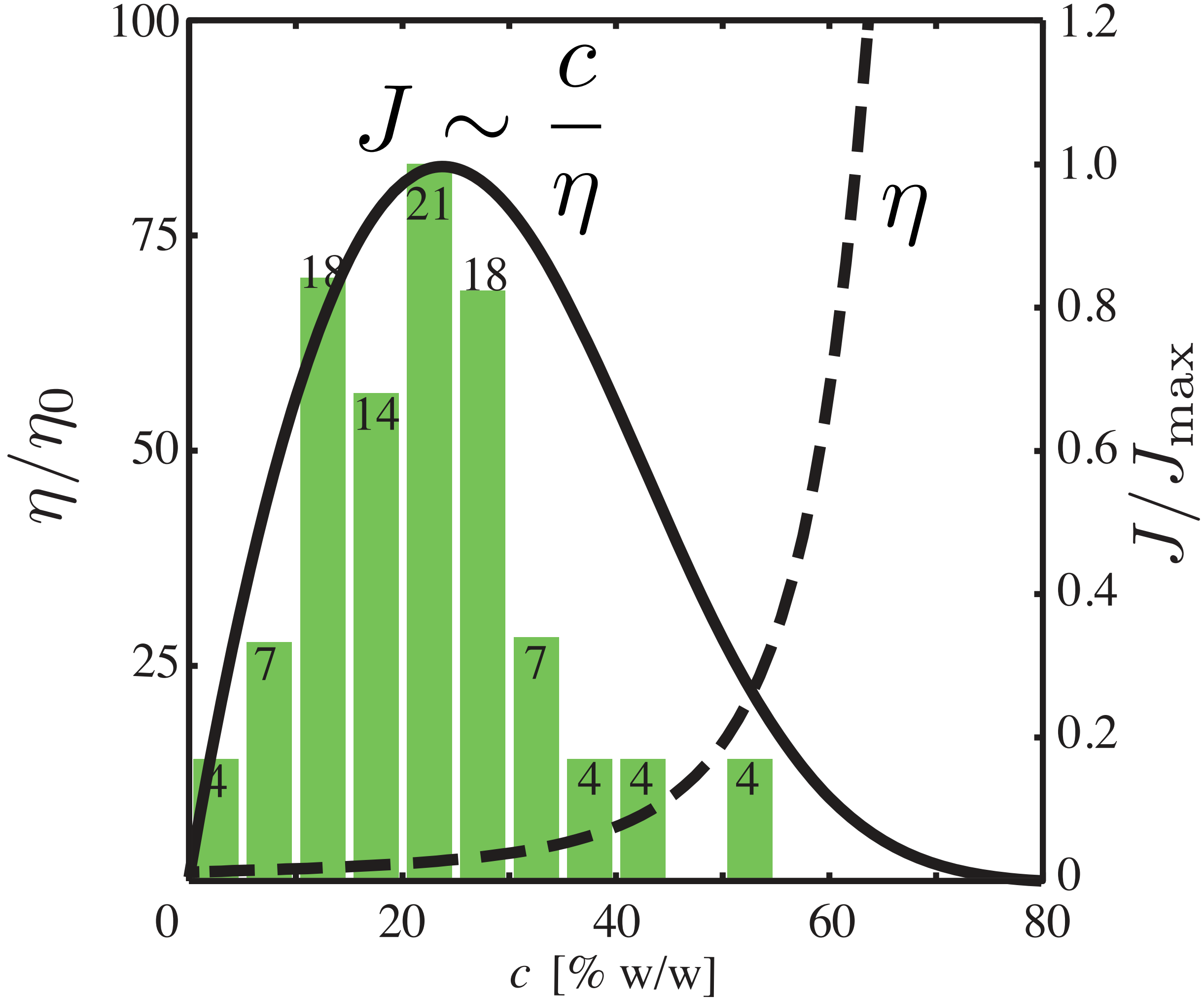
$$J = \left(\frac{\pi r^4}{8} \frac{\Delta p}{L} \right) \frac{c}{\eta(c)}$$



Sugar mass flow



Sugar mass flow

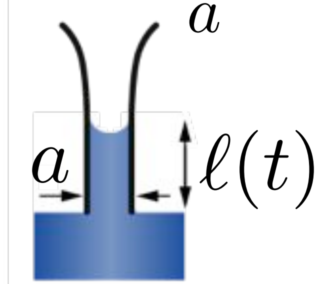


Nectar Drinking

Hummingbirds

- Surface tension
  - Drink through cylindrical tube formed by folding tongue

$$\Delta p = \frac{2\sigma}{a}$$



Sugar uptake

$$J = c\frac{\pi a^2 \ell(T)}{T + T_0}$$

$$\pi a^2 \frac{d\ell}{dt} = \frac{\pi a^4}{8\eta l}\Delta p$$

$$\ell = \left(\frac{a\sigma t}{2\eta}\right)^{1/2}$$

$$J \sim \frac{c}{\eta^{1/2}}$$

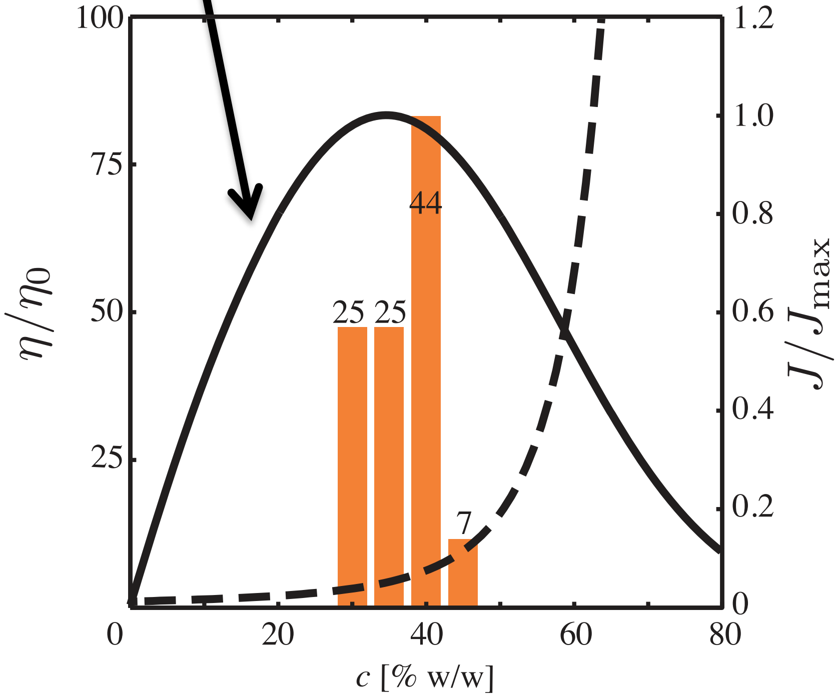
Kim and Bush. J. Fluid Mech. **705** (2012)

Nectar Drinking

Hummingbirds

- Surface tension

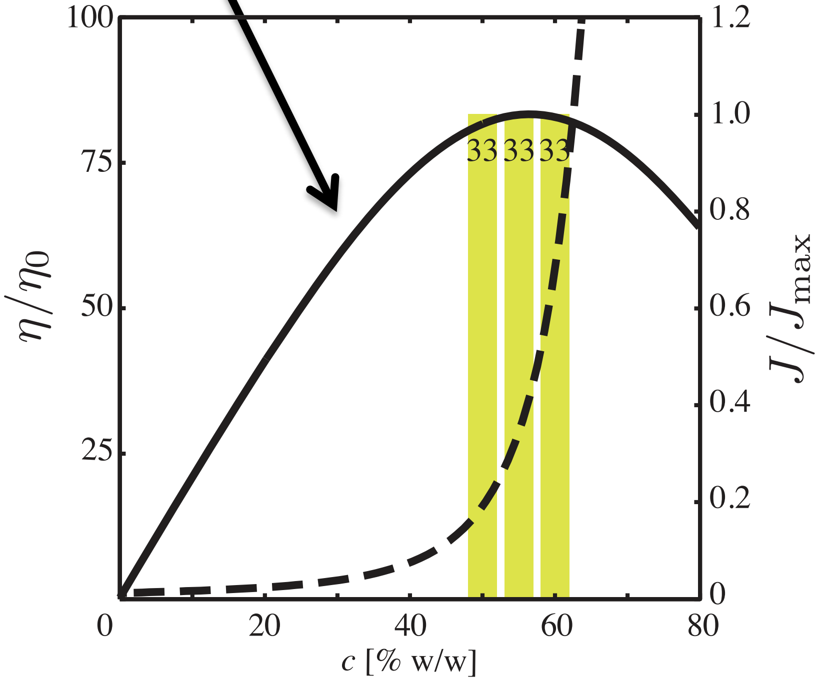
$$J \sim \frac{c}{\eta^{1/2}}$$



Bees

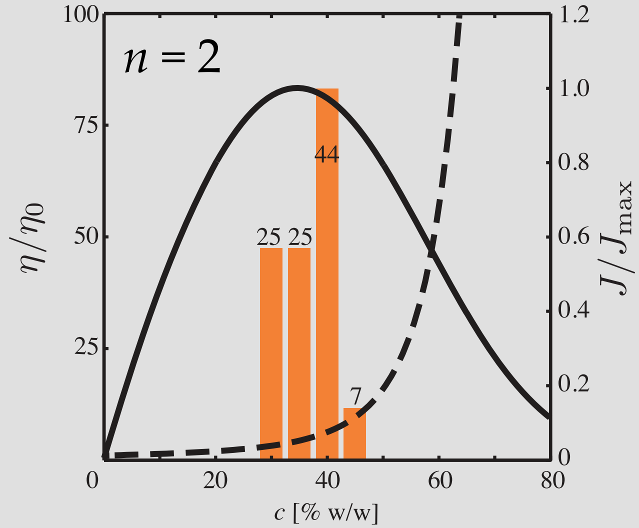
- Viscous dipping

$$J \sim \frac{c}{\eta^{1/6}}$$

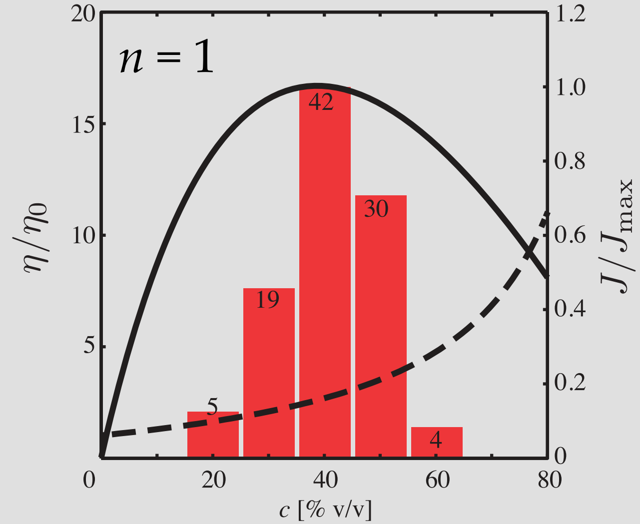


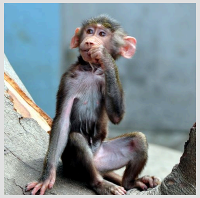
$$J \sim \frac{c}{\eta^{1/n}}$$

Surface tension

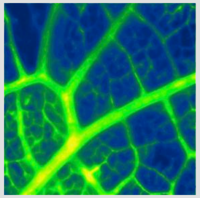


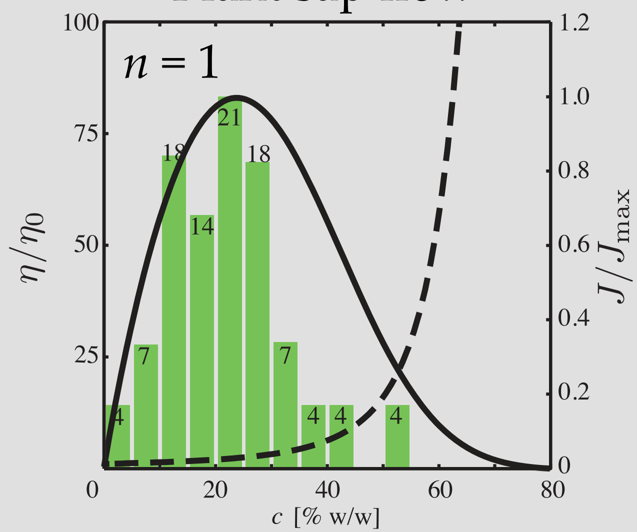
Blood flow



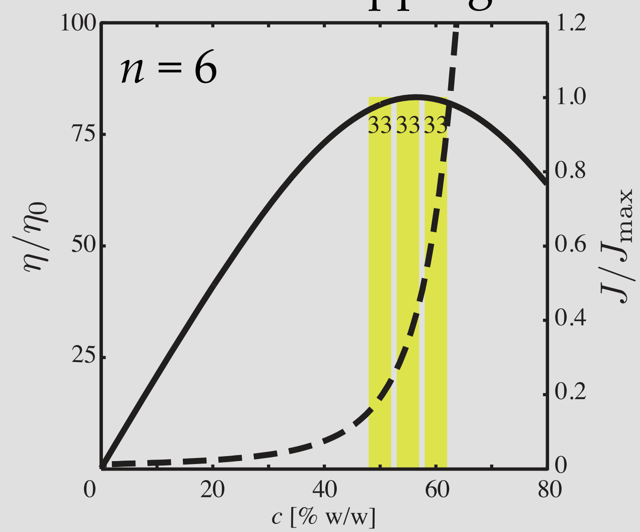


Plant sap flow





Viscous dipping



Simple Model for Flow Impeded by Concentration

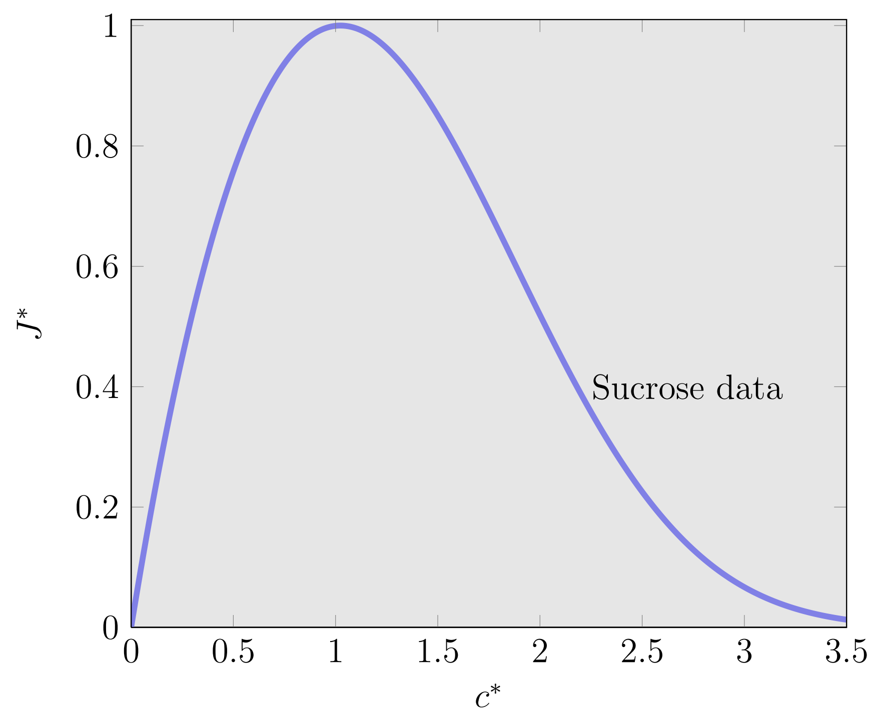
$$c^* = \frac{c}{c_{\text{opt}}} \qquad \eta^* = \frac{\eta}{\eta(c_{\text{opt}})} \qquad J^* = \frac{J}{J(c_{\text{opt}})}$$

$$\frac{\partial J^*}{\partial c^*} = A - Bc^*$$

$$J^*(0) = 0$$

$$J^*(1) = 1$$

$$\left.\frac{\partial J^*}{\partial c^*}\right|_{c^*=1} = 0$$



Simple Model for Flow Impeded by Concentration

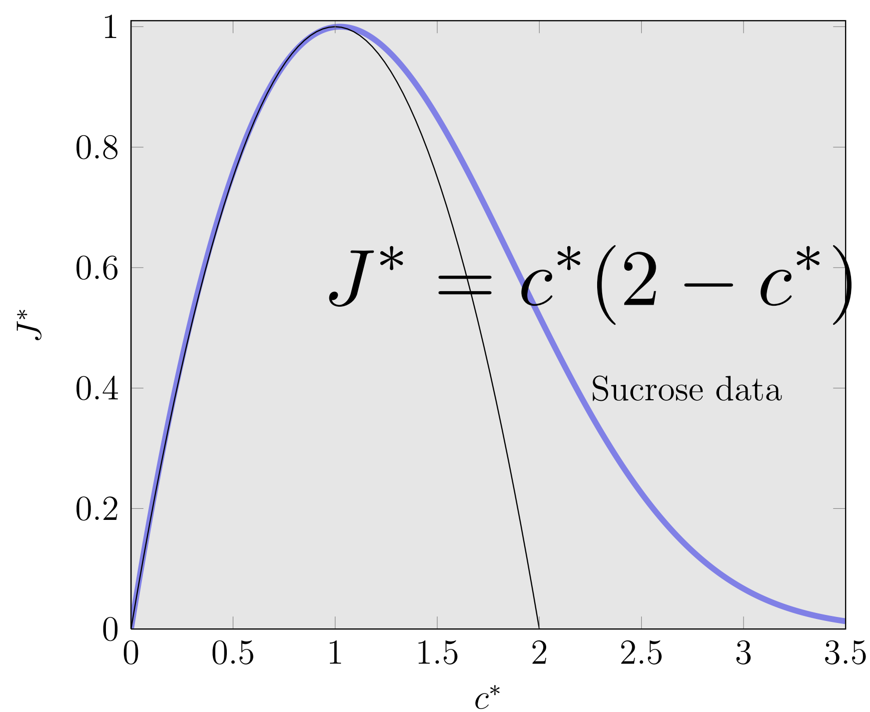
$$c^* = \frac{c}{c_{\text{opt}}} \qquad \eta^* = \frac{\eta}{\eta(c_{\text{opt}})} \qquad J^* = \frac{J}{J(c_{\text{opt}})}$$

$$\frac{\partial J^*}{\partial c^*} = A - Bc^*$$

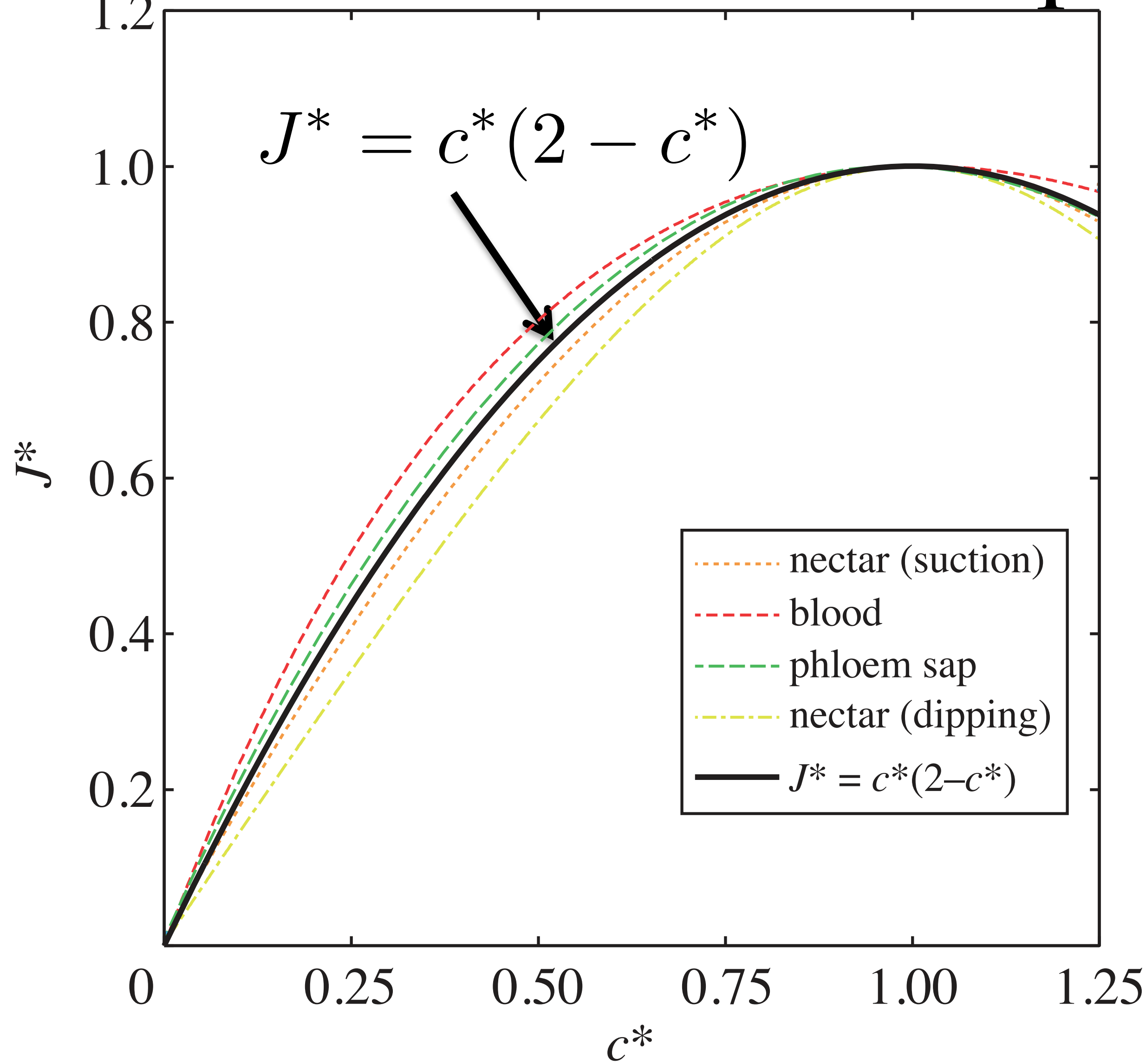
$$J^*(0) = 0$$

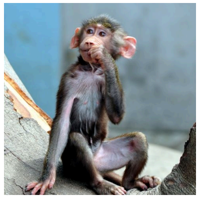
$$J^*(1) = 1$$

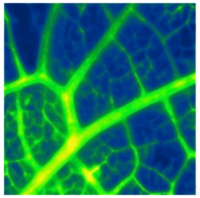
$$\left.\frac{\partial J^*}{\partial c^*}\right|_{c^*=1} = 0$$



Data collapse

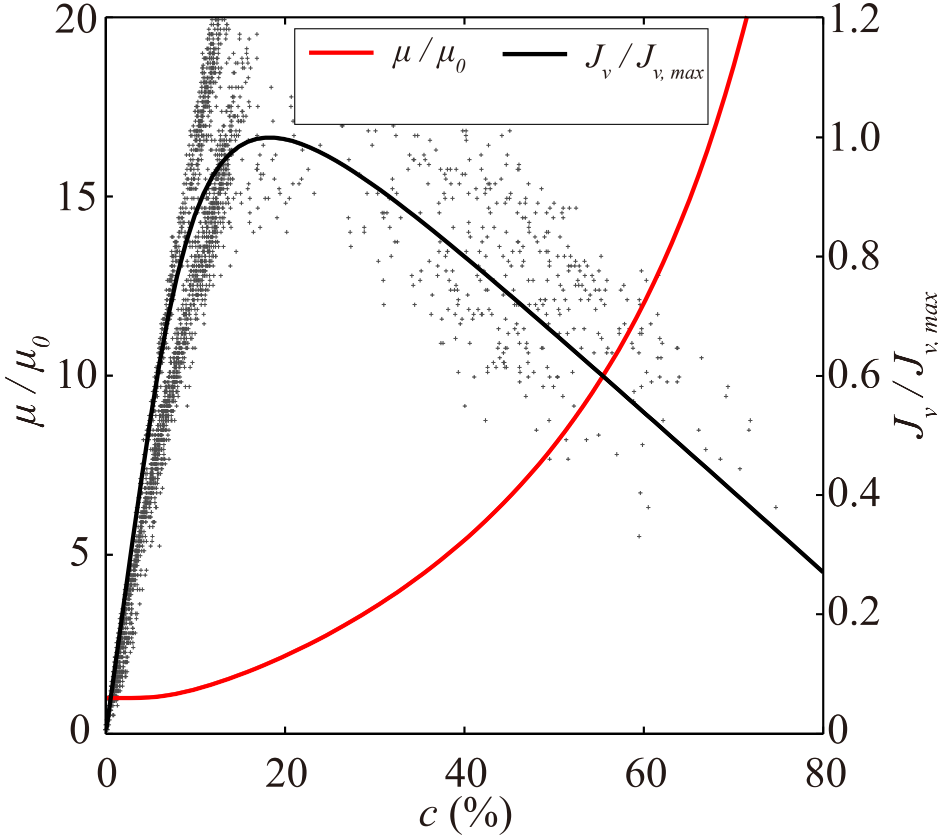






Jensen, Lee, Holbrook, Bush.
J. Roy. Soc. Interface **10** (2013)

Traffic flows



Lighthill and Whitham. Proc. Roy. Soc. A **229** (1955)
Helbing. Rev. Mod. Phys **73** (2001)
Jensen, Lee, Holbrook, Bush. J. Roy. Soc. Interface **10** (2013)



CARLSBERGFONDET

THE DANISH COUNCIL FOR INDEPENDENT RESEARCH

NSF

mrsec @harvard

materials science at the interface

DTU