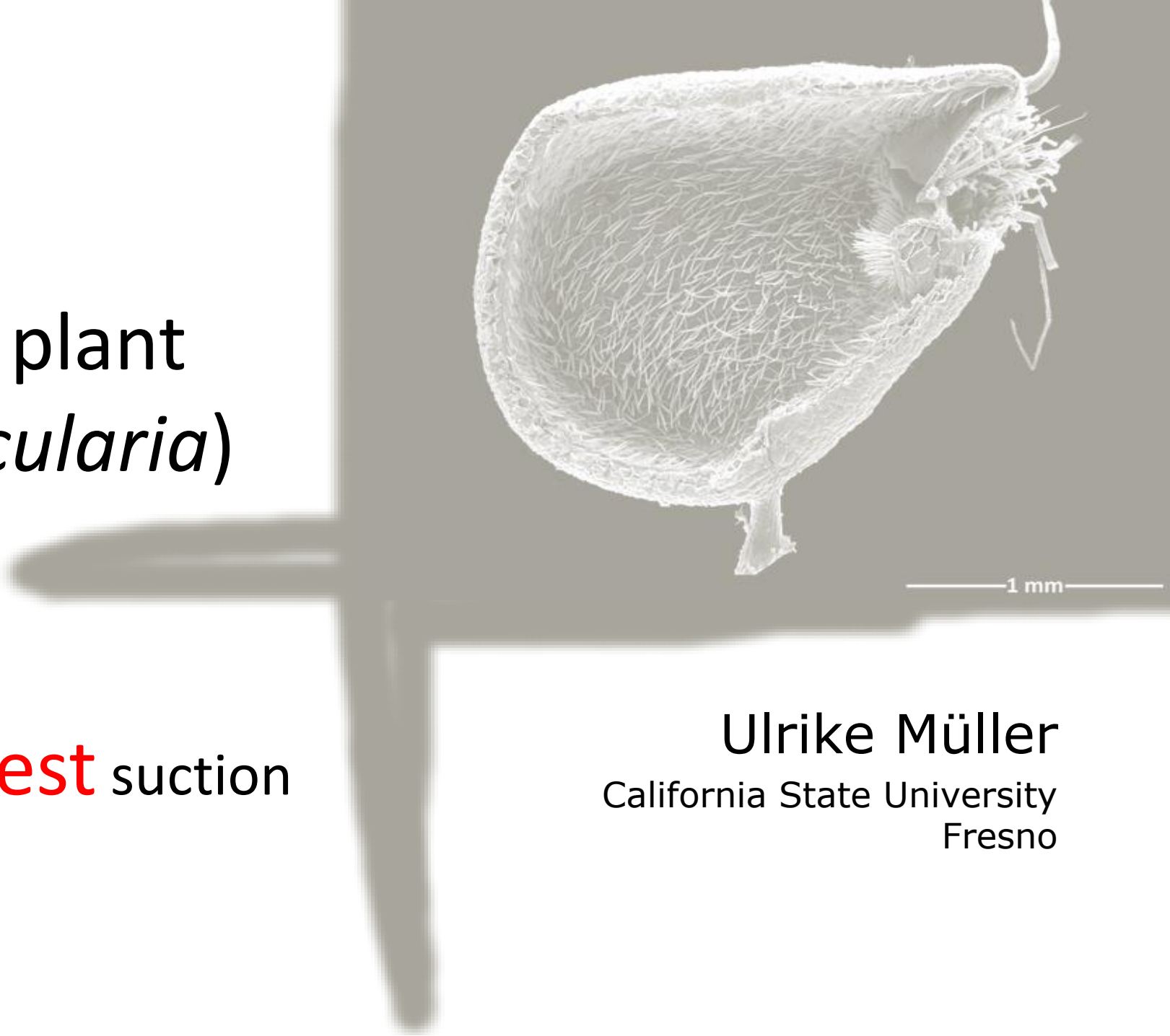
Suction feeding in the carnivorous plant bladderwort (*Utricularia*)

lessons from

the smallest and fastest suction feeders

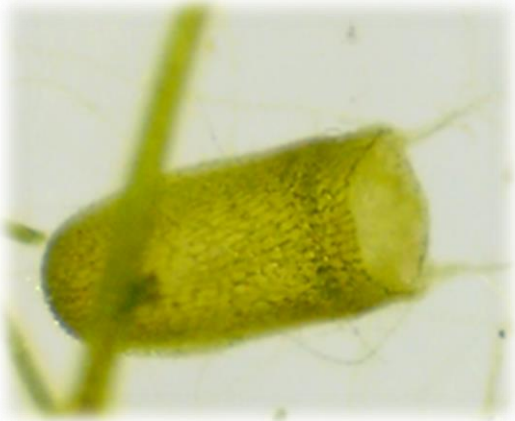


Ulrike Müller
California State University
Fresno

Bladderwort (*Utricularia inflata*)

Bladderwort traps

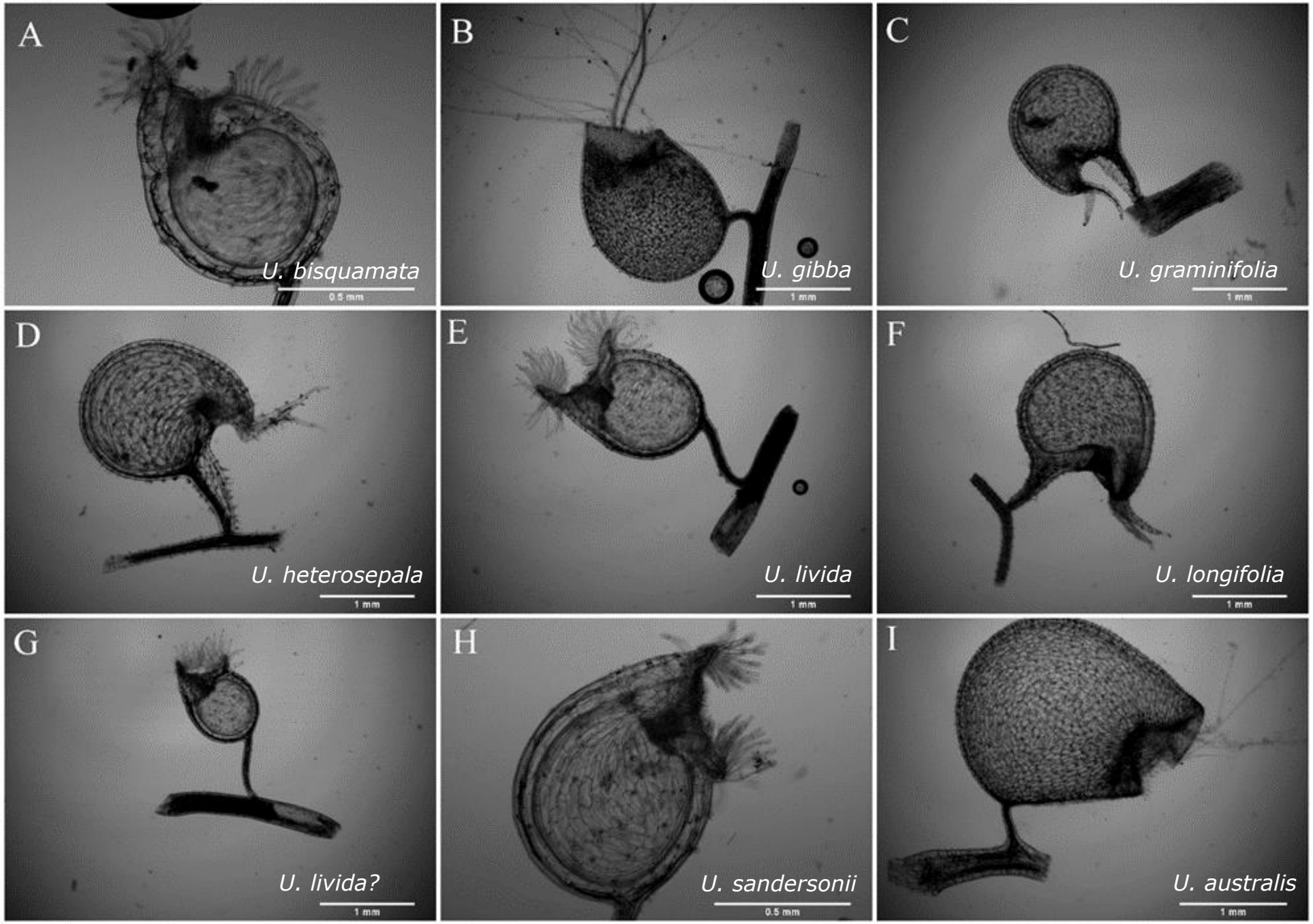
(*Utricularia australis*)



underwater traps
length 0.5 to 8 mm ‡

(*Utricularia aurea*)

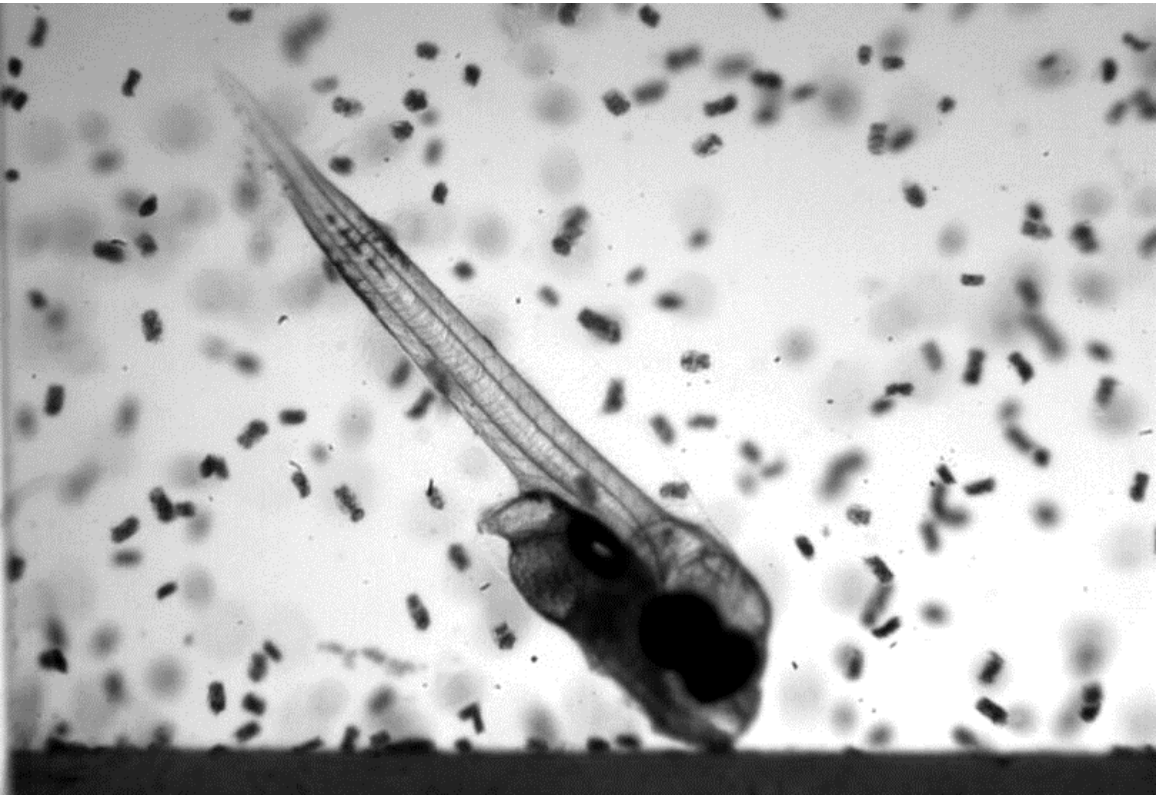
*Vincent *et al, Proc. Roy. Soc. B* (2011); ‡Poppinga et al., *AoB Plants* (2016);

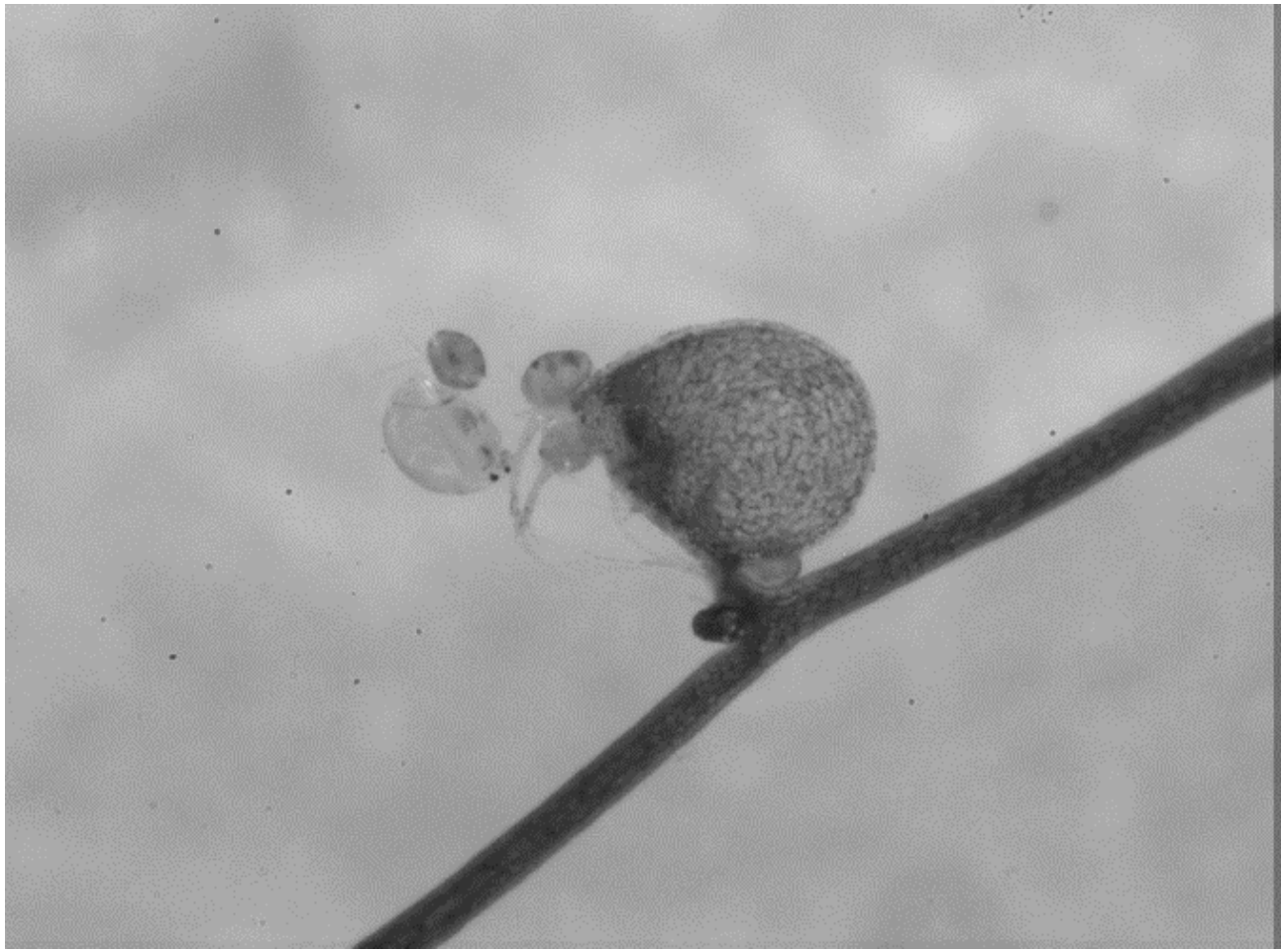


> 200 species | trap sizes: 0.5 to 8 mm Poppinga et al., *AoB Plants* (2016)

sucking while small – does size limit performance?

Fish larva
gape ~200 µm
peak flow near mouth 1 mm/s





Bladderwort
gape ~200 µm
peak flow near mouth 1 m/s

China & Holzman, *PNAS* (2014)

Question

Small suction feeders:
what's the fluid mechanics?

How do small suction feeders overcome the relatively large viscous forces?

Hypothesis

Bladderwort operate within **inviscid (inertial) flow**, which lowers the relative contribution of friction and increases flow speed.

Predictions

from fluid dynamic models

1. inviscid flow model

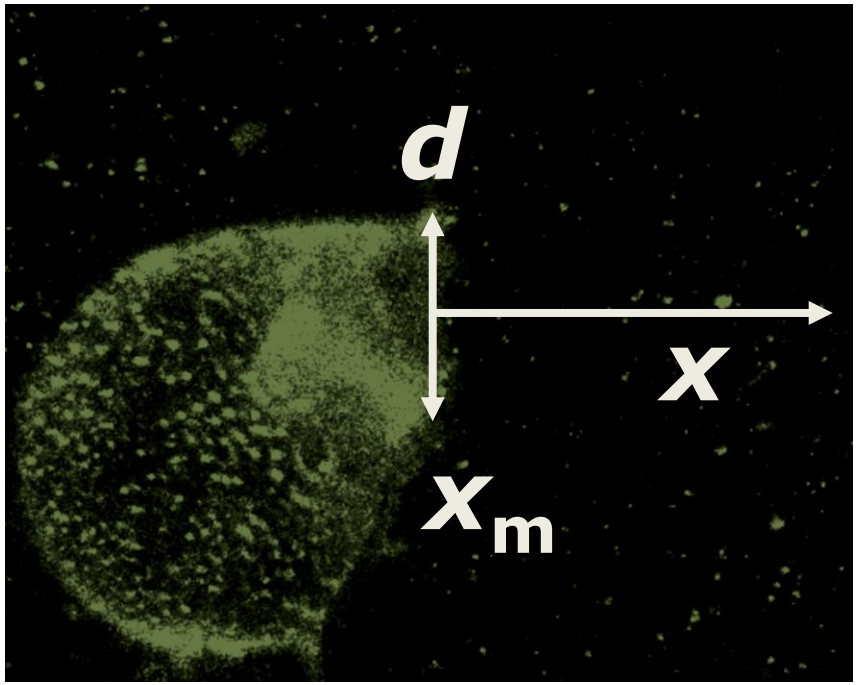
2. viscous flow model

Analytical model of **inviscid** vs **viscous** flow outside the trap*

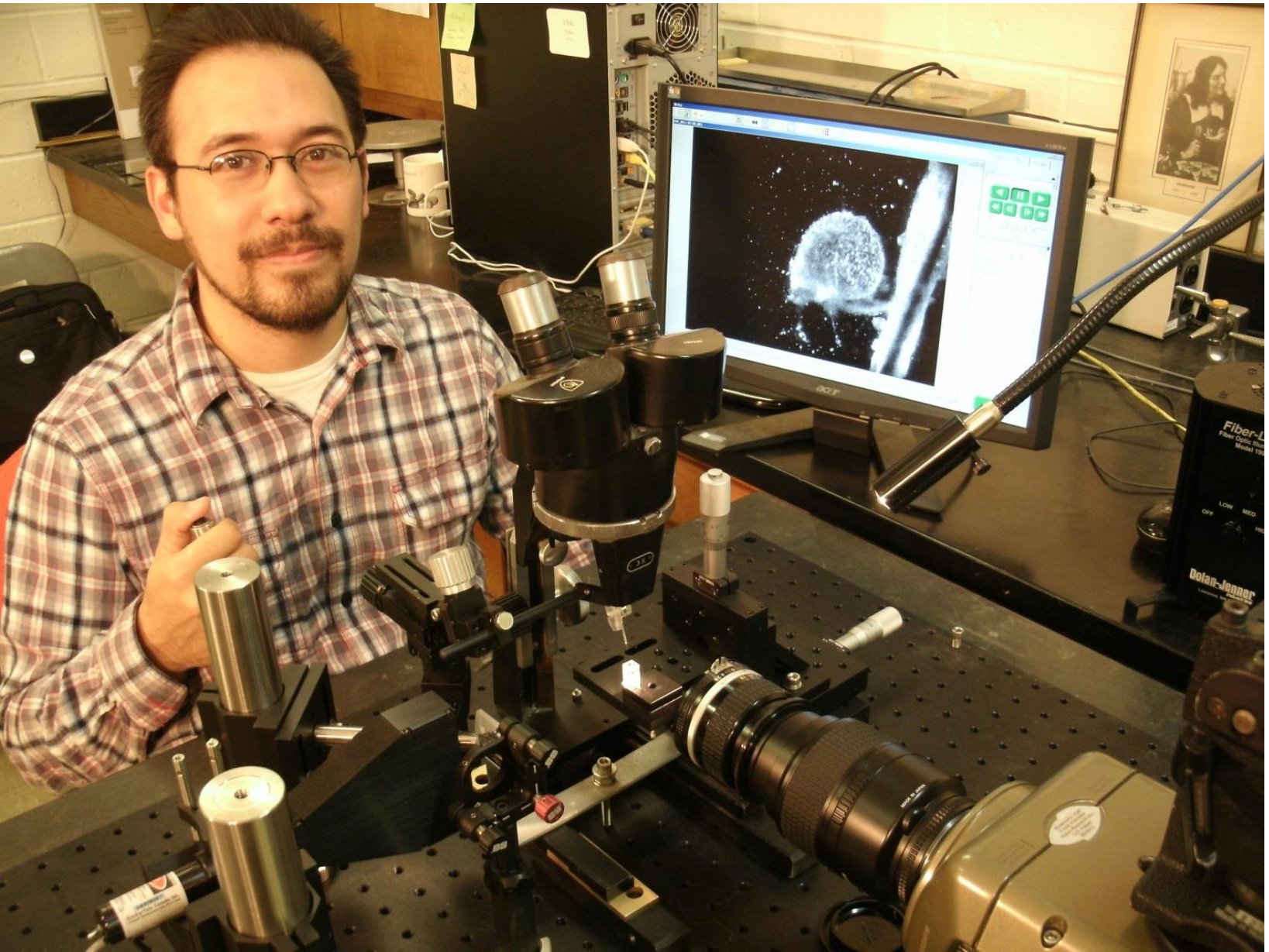
$$\frac{u}{u_{d/2}} = \frac{\frac{u_m}{u_{d/2}}\left(\frac{1}{2}\right)^3}{\sqrt{\left\{\left(\frac{x-x_m}{d}\right)^2+\left(\frac{1}{2}\right)^2\right\}^3}}$$

$$\frac{u}{u_{d/2}} = \frac{\left(\frac{u_m}{u_{d/2}}\right)}{\left(\frac{x-x_m}{d}\right)^2+1}$$

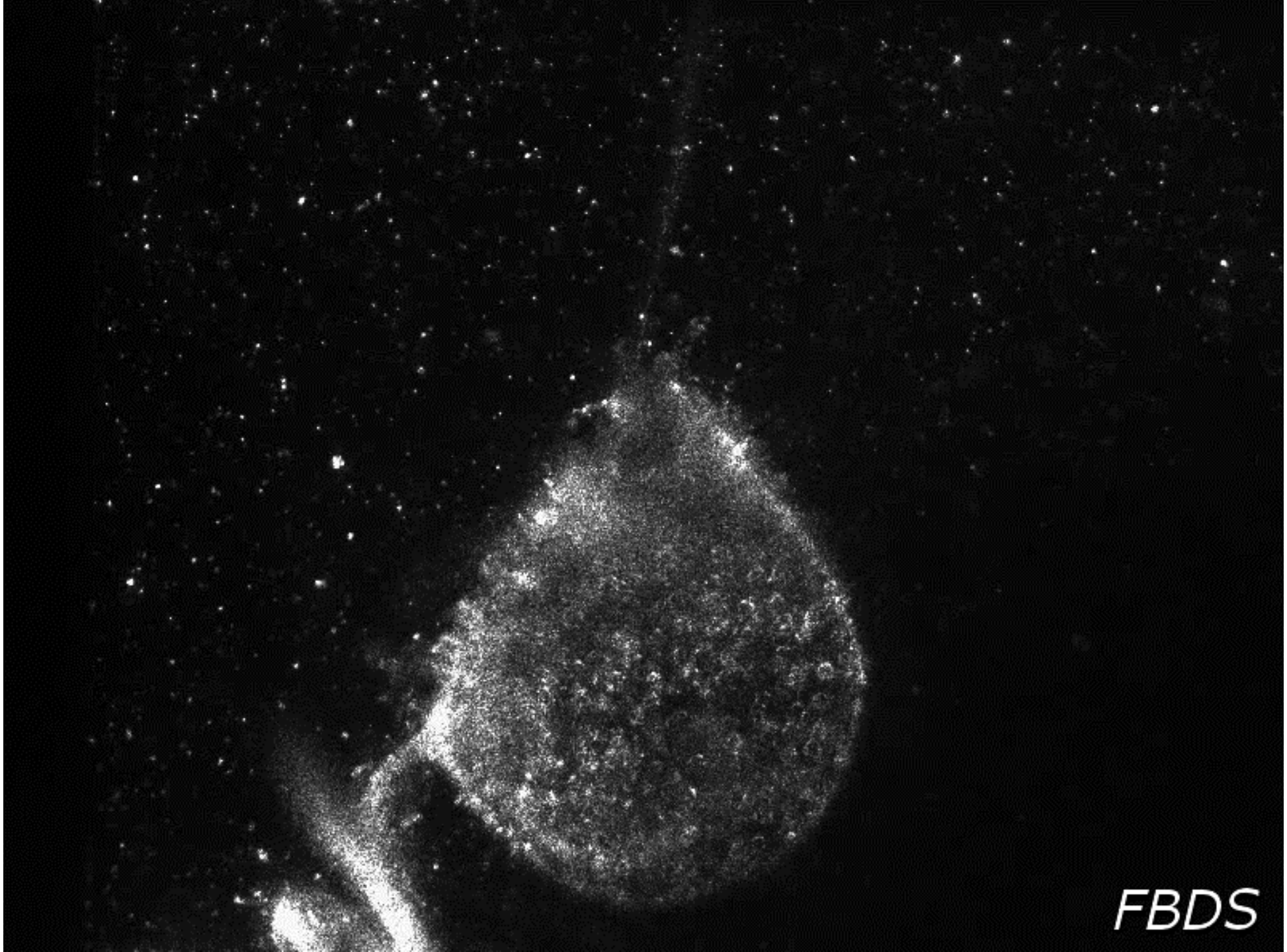
x : axial coordinate
x_m : axial position of mouth plane
u_m : fluid velocity at mouth plane
d : gape diameter
$u_{d/2}$: fluid velocity at ½ gape



*Sampson, *Proc R Soc London A* 1891; ‡ Muller *et al.*, *J Theor Biol* 1982



recording
at up to
50 000 frames/s

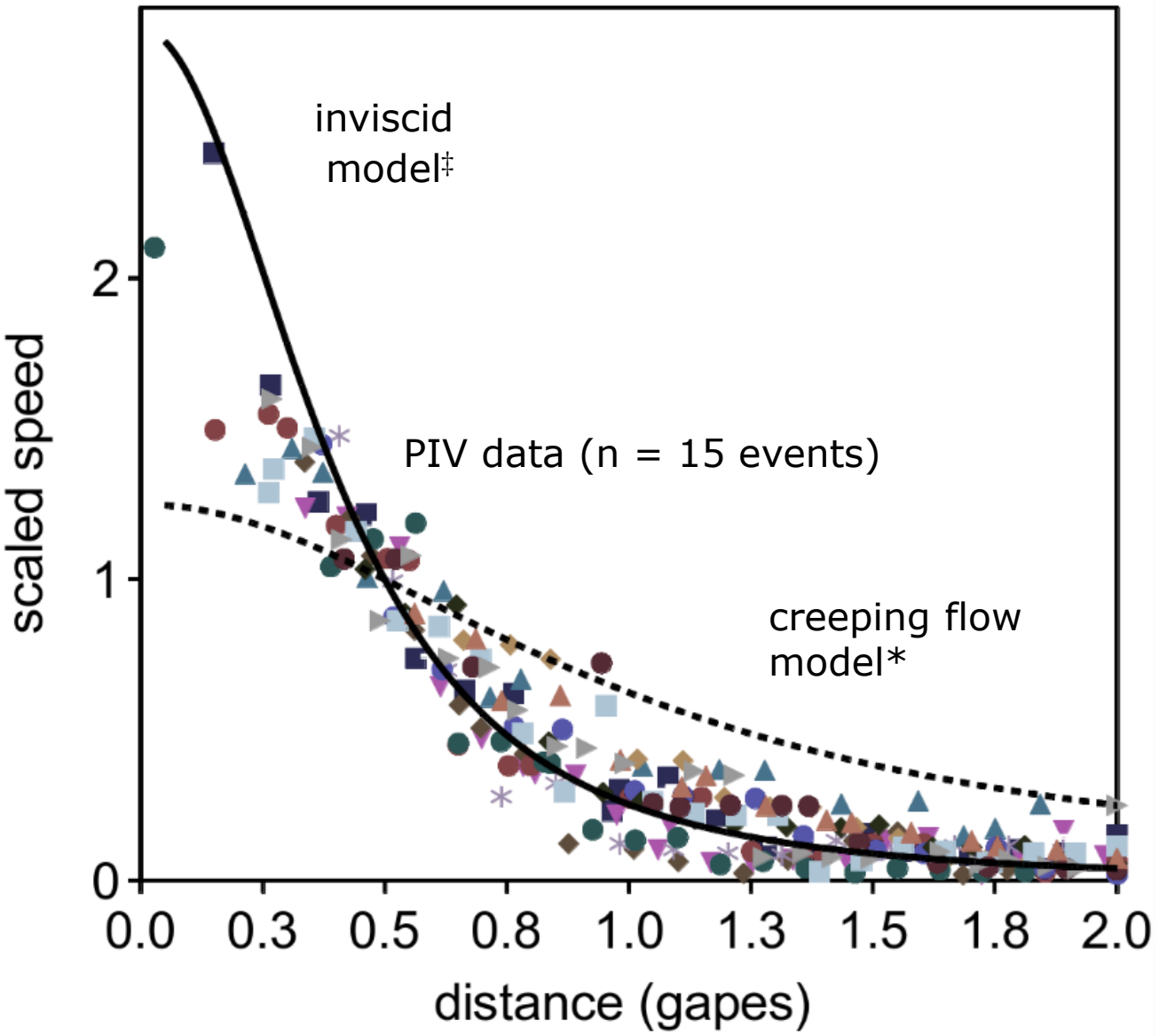

FBDS

Bladderwort operate in **inviscid (inertial) flow,**

which lowers the contribution of friction and increases flow speed.

maximum acceleration: **5000 *g***

maximum flow speed: **5 m/s**



*Sampson, *Proc R Soc London A* 1891; ‡Muller *et al.*, *J Theor Biol* 1982

Conclusion

bladderwort trap

flow is inviscid

can generate fast flows

despite their small size

Question 2

How do bladderwort traps keep the flow inviscid?

What do bladderwort differently from larval fish?

Hypotheses

Bladderwort operate within

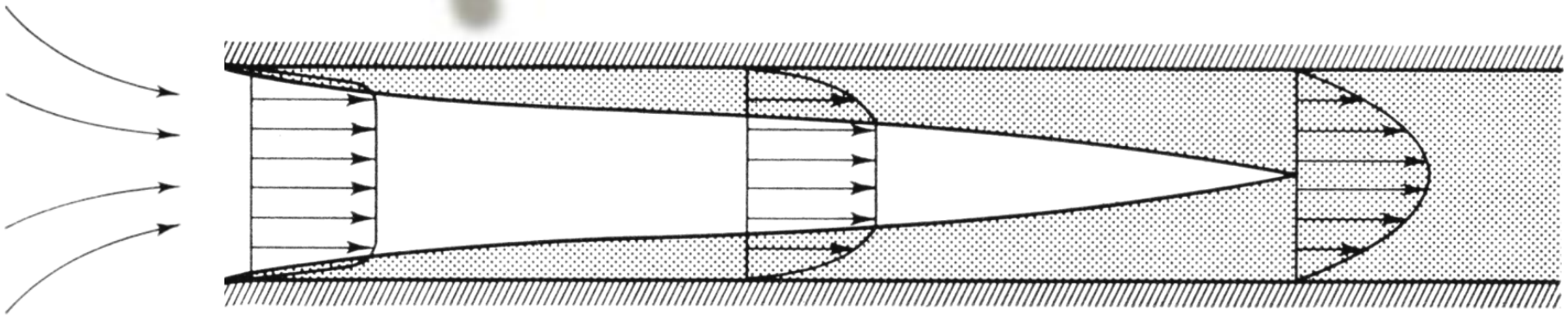
H1: undeveloped flow or

H0: developed inertial flow,

which lowers the relative contribution of friction and increases flow speed.

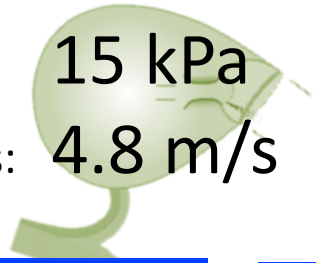
What enables bladderwort to generate effectively inviscid suction flows?

1. inertial flow → large pressure: >10 kPa
2. start-up effect → brief event: < 1 ms
3. entrance effect → short channel: <200 µm

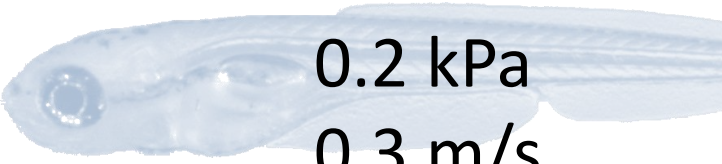


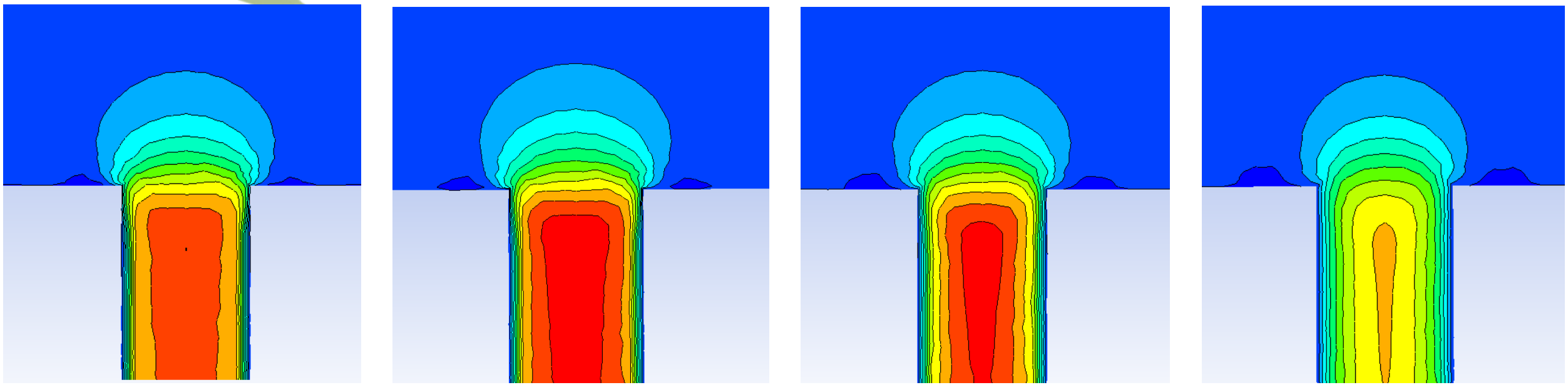
what causes the effectively inviscid flow in bladderwort traps?

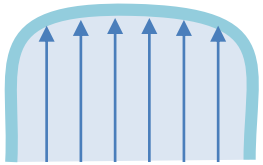
1 high pressure

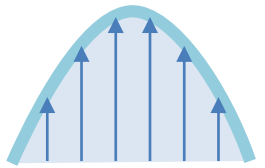


pressure:	15 kPa	5 kPa	1 kPa	0.2 kPa
flow speed @1ms:	4.8 m/s	2.5m/s	1.0 m/s	0.3 m/s



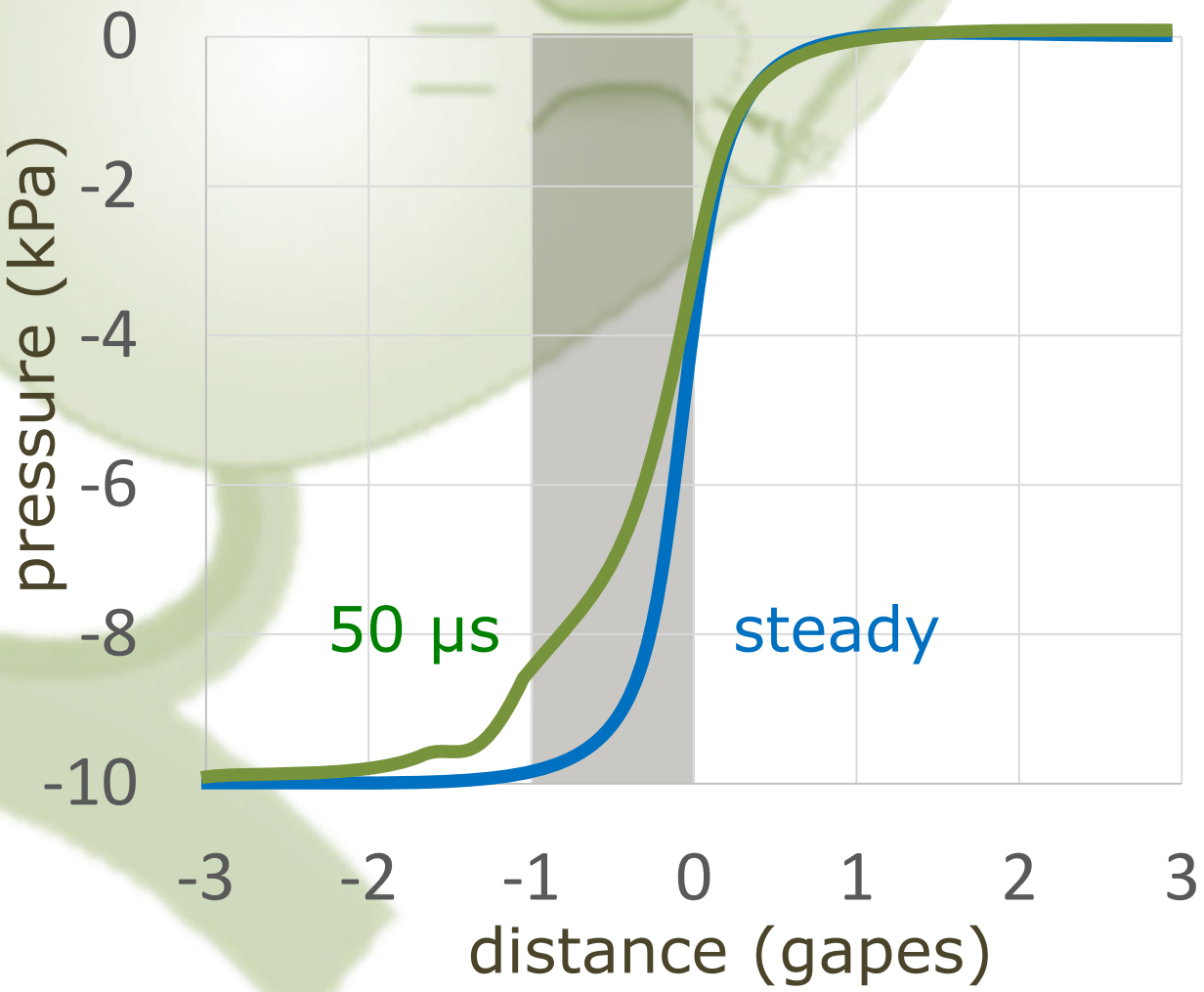






what causes the effectively inviscid flow in bladderwort traps?

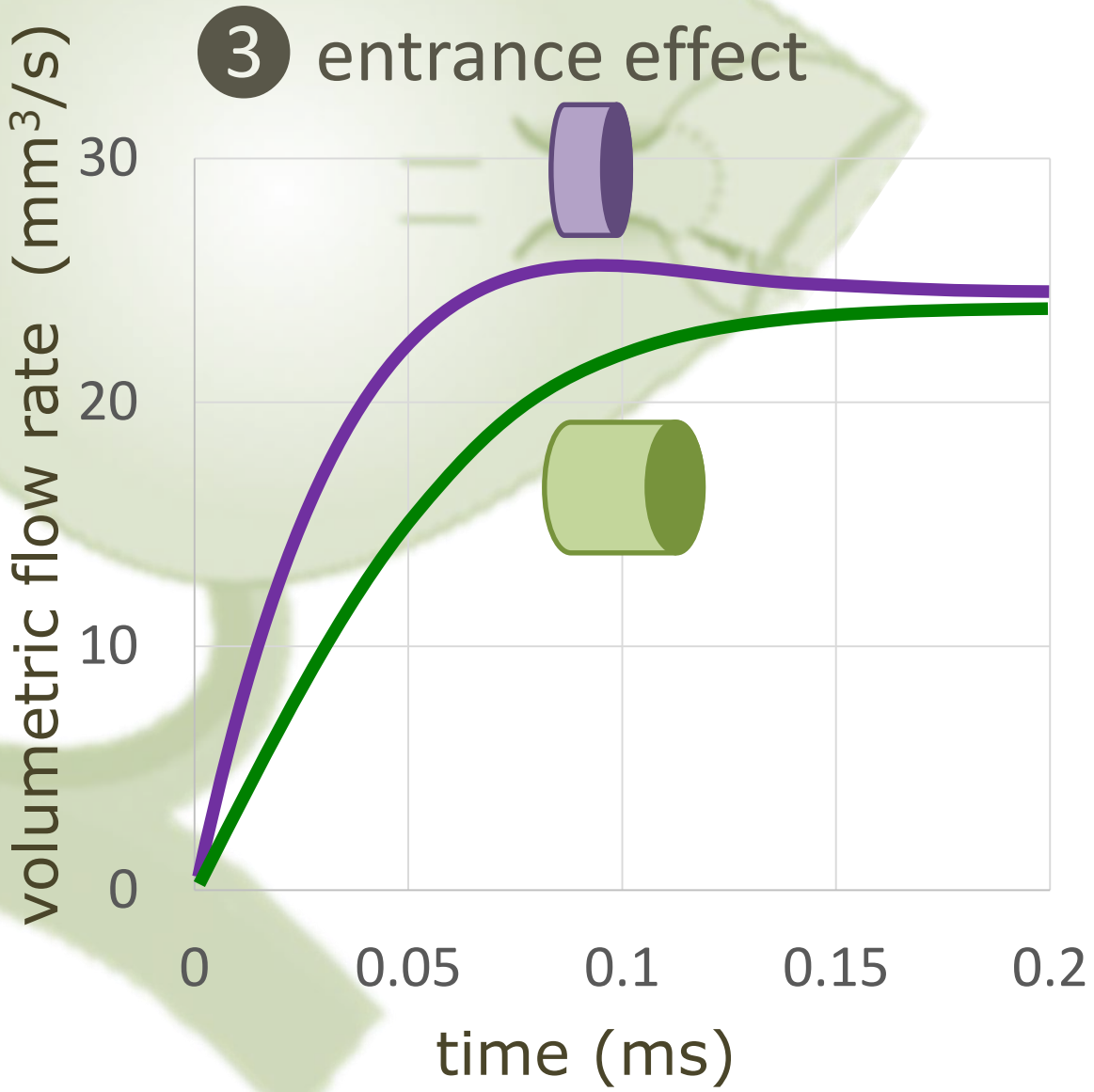
❷ start-up effect



start-up effect:

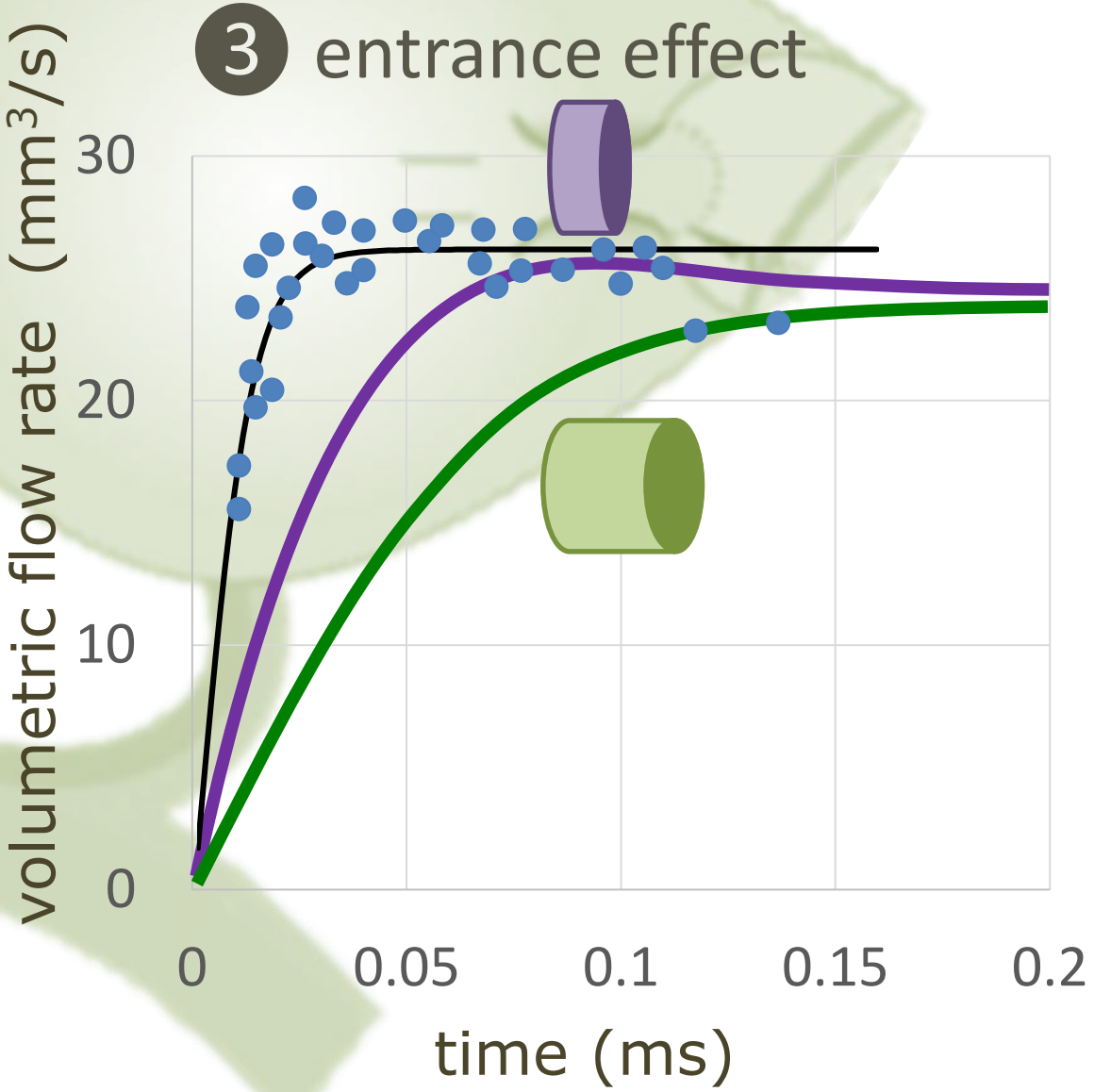
- **lowers** ΔP inside the mouth 'funnel'
- does **not** change performance in front of mouth

what causes the effectively inviscid flow in bladderwort traps?

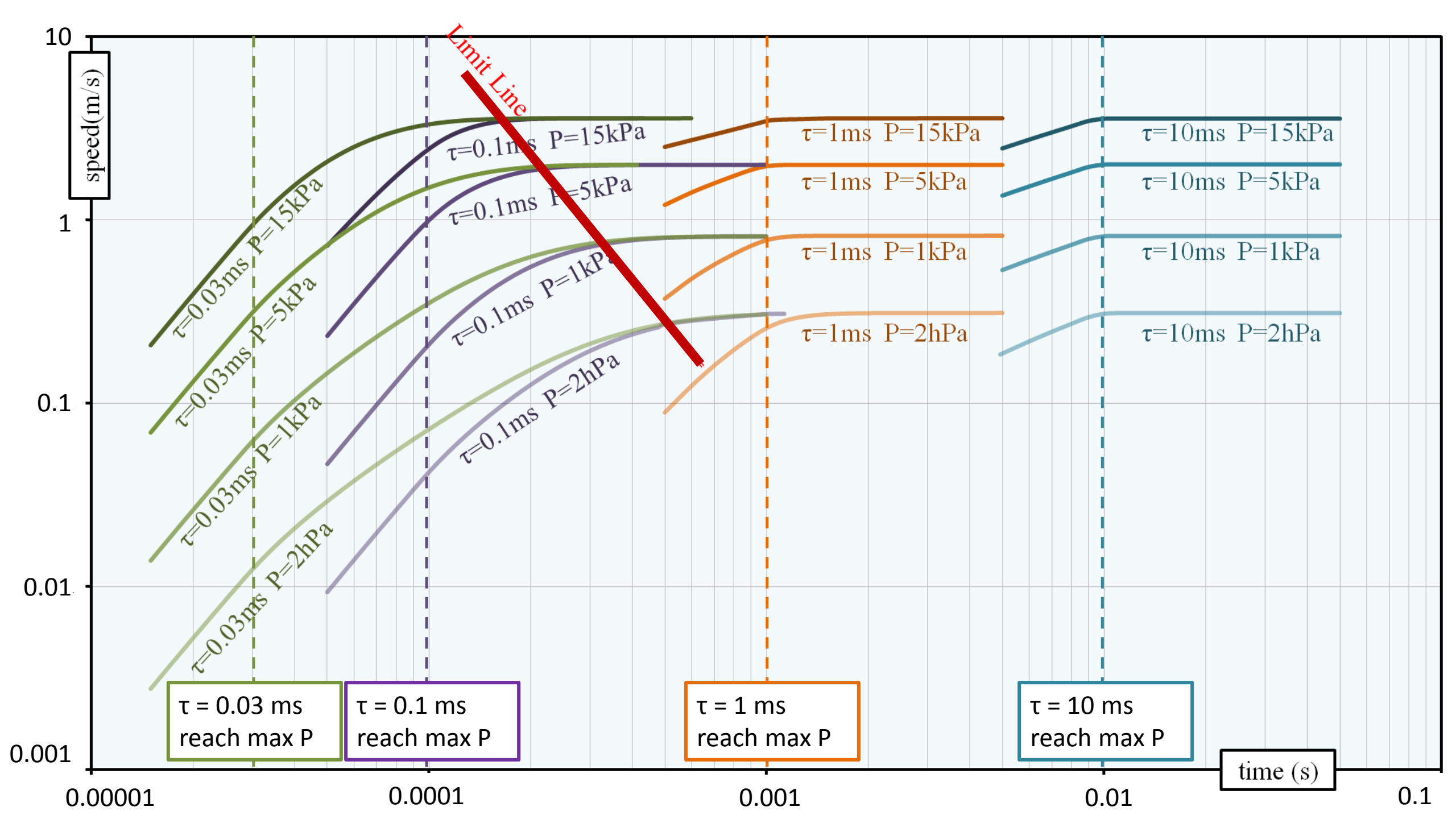


- 1:1 L:D funnel has monotonically increasing flow
- a shorter funnel speeds up the onset, has transient peak

what causes the effectively inviscid flow in bladderwort traps?

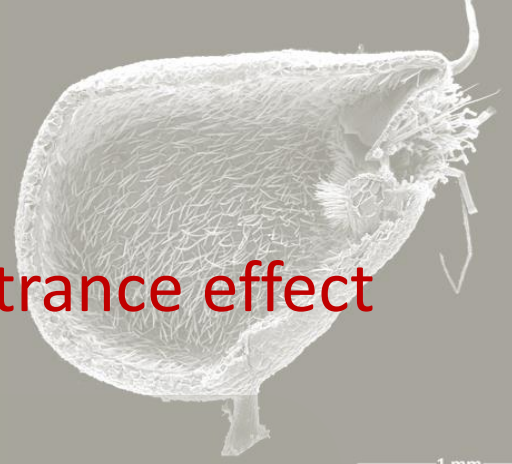


- 1:1 L:D funnel shows monotonically increasing flow with plateau after 0.15 ms
- a shorter funnel speeds up the onset of fast flow
- experimental data (●) suggest that funnel is functionally very short


10
1
0.1
0.01
0.001
speed(m/s)
Limit Line
τ=0.03ms P=15kPa
τ=0.03ms P=5kPa
τ=0.03ms P=1kPa
τ=0.03ms P=2hPa
τ=0.1ms P=15kPa
τ=0.1ms P=5kPa
τ=0.1ms P=1kPa
τ=0.1ms P=2hPa
τ=1ms P=15kPa
τ=1ms P=5kPa
τ=1ms P=1kPa
τ=1ms P=2hPa
τ=10ms P=15kPa
τ=10ms P=5kPa
τ=10ms P=1kPa
τ=10ms P=2hPa
τ = 0.03 ms
reach max P
τ = 0.1 ms
reach max P
τ = 1 ms
reach max P
τ = 10 ms
reach max P
0.00001
0.0001
0.001
0.01
0.1
time (s)

How to avoid viscous effects?

1 high pressure 2 start-up 3 entrance effect



	1	2	3
fast flow:	✓	✗	(✓)
fast onset:	✓	✗	✓

Conclusion 2

bladderwort traps generate **inviscid flow** by

- H0: generating high pressure
- H1: sucking thru a very short throat
- ~~H1: a fast onset of flow (start-up effect)~~

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